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Counter Rotating Galaxies

Counter Rotation (Barred Galaxies)

Type	Galaxy	Rotation	Name
Gas Versus Stars	E	Extended	NGC 5898
	E	Extended	NGC 7097
	E	Extended	NGC 3528
	E	Extended	Anon1029-459
	E	Outer ring	IC 2006
	E	Extended	NGC 5354
	SO	Extended	NGC 7007
	SO	Extended	NGC 1216
	SO	Extended	NGC 2768
	SO	Extended	NGC 4379
	SO	Core	IC 4889
	SBO	Extended	NGC 7332
	SO	Extended	NGC 128
	SBO	Extended	NGC 4546
	SBO	Inclined ring	NGC 2217
	Sp	Along the bar	NGC 4684
	SBO	Extended	NGC 7079

	SB	Outer ring	NGC 4826
	Sp	Inclined ring	NGC 5297
	Sp	Extended	NGC 3626
	Sp	Extended	NGC 3593
	SB	Extended	NGC 718
	Sp	Extended	NGC 4138
	Sb	Inclined ring	NGC 818
	Sp	Inclined ring	NGC 5962
	Irr	Core	NGC 6621/6622
	Irr	Double wave	UGC 9922
Stars Versus Stars	E	Core	IC 1459
	E	Core	NGC 4365
	E	Core	NGC 5322
	E	Core	NGC 3608
	SBO	Double wave	IC 456
	SBO	Double wave	NGC 2983
	SBO	Double wave	NGC 6684
	SBO	Double wave	NGC 7079
	SBO	Double wave	NGC 1574
	SO	Double wave	NGC 4477
	Sp	Double wave	NGC 936
	Sp	Extended	NGC 4550
	SB	Extended	NGC 7217
	Sp	Core	NGC 3593
	Sp	Double wave	NGC 6701
	Sp	Double wave	NGC 3835
	Sp	Double wave	A0840+1427
Gas Versus Gas	E	Two inclined disks	NGC 1052
	Sp	Inner vs. outer	NGC 497
	Sp	Outer ring	NGC 4826
	Irr	Inner vs. outer	NGC 7252

	IB	**Part of the bar**	**NGC 4449**

Counterrotation and Barred Galaxies,
https://ui.adsabs.harvard.edu/link_gateway/1996ASPC...91..429G/ADS_PDF

Counter Rotation (Core Versus Arms)

“Two-dimensional stellar kinematical maps (mean velocity and dispersion) reveal the presence of a ~60 pc diameter counter-rotating core (CRC), the smallest observed to date.”

A 60 PC counter-rotating core in NGC 4621, ***Astronomy & Astrophysics, 2002, 396, 73-81***

“In this work, we focus on galaxies with a specific kinematic irregularity, a kinematically distinct stellar core (KDC), in particular, counter-rotating galaxies where the core and main body of the galaxy are rotating in opposite directions.”

“Investigating the stellar and gaseous properties of both the core and outer region/main body of galaxies with a counterrotating

core will give us an understanding of their formation and evolutionary pathways, however there have been a number of limitations, mainly related to observational equipment, that have made studies of such properties difficult.”

ID	**Z**	**10^6 Solar Mass**	**Age (Ga.)**	**Type**
8143-3702	**0.025**	**6,384**	**0.852**	**AGN**
8155-3702	**0.023**	**11,110**	**0.553**	**AGN**
8606-3702	**0.024**	**15,960**	**N/A**	**AGN**
8989-9101	**0.033**	**23,180**	**0.814**	**AGN**
8995-3703	**0.055**	**21,740**	**0.976**	**AGN**
8615-1902	**0.02**	**5,974**	**0.775**	**Star Forming**
9027-3703	**0.021**	**2,443**	**0.335**	**Star Forming**
9872-3701	**0.02**	**5,556**	**0.743**	**Star Forming**
8143-1902	**0.041**	**7,967**	**0.984**	**Unclassified**
8335-1901	**0.055**	**21,740**	**0.976**	**Unclassified**
9027-1902	**0.022**	**3,657**	**0.8958**	**Ambiguous**

Spatially Resolved Properties of Galaxies, Astronomy & Astrophysics, 2021, 647, A181

“We confirm the presence of a stellar kinematically distinct core with a diameter of 2.8 kpc, counter-rotating with respect to the main stellar body of the galaxy. We find that the counter-rotating core consists of an old stellar population, not significantly different from the rest of the galaxy. The ionized gas is strongly warped and extends out to 6.5 kpc in the polar direction

and in a filamentary structure.”

“To change the angular momentum of a large mass of gas and create large kinematic misalignments or counterrotation, one would need a significant amount of energy, unlikely to be met by secular processes in the galaxy.”

The active S0 galaxy NGC 5077, ***https://doi.org/10.1051/0004-6361/202040248***

“Several mechanisms have been proposed in recent years to explain kinematic decoupled cores (KDCs) in early type galaxies as well as the large differences in angular momentum between KDCs and host galaxy. Most of the proposed scenarios involve large fractions of merging events, high speed interactions with dwarf spheroidal galaxies, cusp effect of the dark matter density profiles, etc.”

“As has been previously reported, it is found that ~30% of all Kinematically Decoupled Cores (KDCs) are counter rotating; can models account for such a large fraction of cores with a spin opposite to the global one?

•Statistical differences in orientations and radial velocity amplitude appear between counter rotating and prograde rotating cores; is there a unique family of KDCs in spheroidal galaxies?

•It has been reported that most of the KDCs do not show different colors or chemical properties respect to the host galaxy, nor it is apparent a difference between high and low density environments; can this result be concealed with the capture and merging hypothesis for KDCs?”

Counterrotation or Just Warping, ***International Journal of Astronomy and Astrophysics, 2016, 6, 198-205***

“IC2006 is an isolated spherical galaxy surrounded by a counter-rotating outer ring of HI.”

“Virgo galaxies NGC 4550and NGC4551 from an r-band image taken at the Cerro-Tololo Interamerican Observatory 0.9-m telescope. There is no evidence of Morphological peculiarity in either galaxy. (Middle) Major-axis velocities inNGC4550, from the stellar Ha absorption(open symbols) and from the counter-rotating emission disk (filled symbols). The counter-rotating stellar disk absorption at Ha is masked by the emission, except for that barely showing at -15' N. (Bottom) Absorption lines from prograde and retrograde stellar disks (here shown dark) in the region blueward of [OIII] 5007 (bright line at right).”

Galaxy dynamics, ***PNAS, 1993, 90, 4814-4821***

Decoupled cores of NGC 3607 and NGC3608, ***Astronomical & Astrophysical Transactions, 2007, 26:4, 311-337***

“Counter-rotating cores are found in a considerable fraction of giant early-type galaxies.”

A counter-rotating core in the dwarf elliptical galaxy VCC 510, Astronomy & Astrophysics, 2006, 445, L19-L22

“Diffuse (or dwarf) elliptical galaxies are a numerically dominating population in dense regions of the Universe, but their origin and evolution still remain unknown.”

Young Nuclei in Dwarf Elliptical Galaxies, Astronomy Letters, 2007, Vol. 33, No. 5, 292-298.

“In addition to hosting a faint young nuclear spiral within a possible intermediate-scale stellar disk, CG-611 has accreted an intermediate-scale, counter-rotating gas disk.”

“The inner three data points additionally display evidence for a kinematically distinct core (KDC) in the form of mild counter rotation.”

“There is additionally tentative evidence for a kinematically distinct component (KDC) in the form of a counter-rotating stellar core involving the inner ~0.8 to ~1.6 arcsec (0.25–0.5 Radius).”

“Accretion of gas in CG-611 is apparent from the counter rotation of the gas relative to most of the stars, and from the non-symmetrical nature of the gas rotation curve about the photometric center of the galaxy.”

“This ETG’s ionized gas is observed to counter-rotate with respect to the majority of stars in the inner radius.”

Early-type Dwarf Galaxy LEDA 2108986, *The Astrophysical Journal, 2017, 840:68*

“Misalignment of gas and stellar rotation in galaxies can give clues to the origin and processing of accreted gas. Integral field spectroscopic observations of 1213 galaxies from the Sydney-AAO Multi-object Integral field spectrograph (SAMI) Galaxy Survey show that 11 per cent of galaxies with fitted gas and stellar rotation are misaligned by more than 30◦ in both field/group and cluster environments. Using SAMI morphological classifications and Sersic indices, the misalignment fraction is 45 ± 6 per cent in early-type galaxies (ETGs), but only 5 ± 1 per cent in late-type galaxies (LTGs).”

Angle	Quantity	Percent
0 to 180	486	100.00%
>30	55	11.32%
>40	42	8.64%
30 to 150	38	7.82%
40 to 140	24	4.94%
>140	18	3.70%
>150	17	3.50%

Description	Angle	Angle	E	E–S0	S0	S0–E-Spiral	E-Spiral	E/L Spiral	L-Spiral
All GAMA			17	16	29	48	102	57	202
GAMA	>30◦		9	8	11	5	4	2	12
Fraction-GAMA	>30◦		0.53	0.5	0.38	0.1	0.04	0.04	0.06
GAMA	>40◦		8	7	9	4	3	2	6
Fraction-GAMA	>40◦		0.47	0.44	0.31	0.08	0.03	0.04	0.03
GAMA	30◦	-150◦	6	5	9	2	2	1	11
Fraction-GAMA	30◦	-150◦	0.35	0.31	0.31	0.04	0.02	0.02	0.05
GAMA	40◦	-140◦	5	4	7	1	1	1	4
Fraction-GAMA	40◦	-140◦	0.29	0.25	0.24	0.02	0.01	0.02	0.02
All Clusters			19	10	16	21	31	15	19
Clusters	>30◦		6	1	0	3	2	2	0

Fraction-Clusters	>30◦		0.32	0.1	0	0.14	0.06	0.13	0
Clusters	>40◦		3	1	0	2	0	2	0
Fraction-Clusters	>40◦		0.16	0.1	0	0.1	0	0.13	0
Clusters	30◦	-150◦	5	1	0	2	2	1	0
Fraction-Clusters	30◦	-150◦	0.26	0.1	0	0.1	0.06	0.07	0
Clusters	40◦	-140◦	2	1	0	1	0	1	0
Fraction-Clusters	40◦	-140◦	0.11	0.1	0	0.05	0	0.07	0
All GAMA Clusters			36	26	45	69	133	72	221
All	>30◦		15	9	11	8	6	4	12
Fraction-All	>30◦		0.42	0.35	0.24	0.12	0.05	0.06	0.05
All	>40◦		11	8	9	6	3	4	6
Fraction-All	>40◦		0.31	0.31	0.2	0.09	0.02	0.06	0.03
All	30◦	−150◦	11	6	9	4	4	2	11
Fraction-All	30◦	−150◦	0.31	0.23	0.2	0.06	0.03	0.03	0.05
All	40◦	−140◦	7	5	7	2	1	2	4
Fraction-All	40◦	−140◦	0.19	0.19	0.16	0.03	0.01	0.03	0.02

The SAMI Galaxy Survey, *MNRAS, 2019, 483, 458-479*

Galaxy	Angle	Angle	Radius
NGC-0057	100		6.31
NGC-0315	218	222	9.2
NGC-0410	211	161	7.57
NGC-0545	287		9.71
NGC-0547	254		10.55
NGC-0741	202		9.74
NGC-0777	311	8	5.89
NGC-0890	159	101	6.62
NGC-1016		262	9.47
NGC-1060	351	342	6.38
NGC-1129	185	179	16.13
NGC-1453	25	35	6
NGC-1573	181	190	5.43

NGC-1600	**18**		**9.14**
NGC-1700	**87**	**268**	**4.45**
NGC-2258	**74**	**71**	**5.76**
NGC-2274	**231**	**288**	**6.57**
NGC-2340	**53**		**14.27**
NGC-2693	**172**	**169**	**5.63**
NGC-4874		**335**	**19.2**

Radius, kilo parsec

Stellar Velocity Profiles and Kinematic Misalignments, ***The Astrophysical Journal, 2020, 891:65***

The circumnuclear GASEOUS disks are often decoupled from the circumnuclear stellar disks and are even stronger inclined to the outer disk planes; in fact, we have found a considerable ‘population’ of inner polar rings. Inner gas polar rings are found as in spiral galaxies with the massive outer gas disks co-planar to the main symmetry planes as well in many lenticular galaxies. The latter are HI-rich lenticulars, and the orientations of the outer gas rings/disks appear to be decoupled from the inner polar rings. We think that the polar orientation of the inner gas rings relates in some way to bars or other triaxial structures in the galaxies under consideration.

Extragalactic globular clusters in the near-infrared, Astronomy & Astrophysics, 2002, 391, 453–470

Counter Rotation (Formation-Mystery)

“Kinematic decoupled cores (KDC) in bright galaxies have been well studied in the past two decades. Most well known are counterrotating cores in elliptical galaxies (Bender 1990), which have been explained with mergers of unequal ellipticals, or with mergers of spiral galaxies, either with or without dissipative gas dynamics. Some kinematic reversals in elliptical nuclei might be the result of projection effects on triaxial ellipticals. Counterrotating bulges may originate in mergers of dwarf galaxies onto large disk galaxies. We note that counterrotation may appear in primordial collapses as well.

For dwarf galaxies, while mergers can in principle yield counterrotation, we concur with de Rijcke that high group velocity dispersions make those highly improbable. Other processes, studied for the cases of counterrotation in spiral galaxies, may apply to dwarfs. These include: scattering of stars by a bar (Evans & Collett 1994); the evolution of a polar ring in a triaxial halo (Tremaine & Yu 2000); and even simple projection effects on triaxial or non-planar stellar disks.”

Origin for kinematic substructures, ***Astronomy & Astrophysics, 2005, 444, 803-812***

“The general term of “counter-rotation” indicates there are two components of a galaxy that rotate in opposite directions from each other. This phenomenon has been observed in galaxies over the full Hubble sequence, from ellipticals to irregulars, including barred galaxies. Counter-rotating galaxies are classed by the nature (stars vs. stars, stars vs. gas, gas vs. gas) and size (counterrotating cores, rings, disks) of the counter-rotating components.”

“Our results, combined with previous studies in the literature, rule out the internal scenario as the origin of counter-rotation in the studied galaxies. In contrast, the merger scenario cannot be completely ruled out, given the low statistics available. Thus, a larger sample is needed to identify the most efficient mechanism.”

Counter-rotating stellar disks of NGC 3593 and NGC 4550, ***Astronomy & Astrophysics, 2013, 549, A3***

“The formation scenario of extended counter-rotating stellar disks in galaxies is still debated. In this paper, we study the S0 galaxy IC 719 known to host two large-scale counter-rotating stellar disks in order to investigate their formation mechanism.”

“Among these, the presence of structural components with remarkably different kinematics represents a fascinating case. A large variety of phenomena enters in this category, such as counter-rotating gas disks, counter-rotating stellar disks, orthogonal bulges, orthogonal gaseous structures, and decoupled stellar cores.”

“However, the details of the formation mechanisms of large counter-rotating stellar disks are still under debate, and their existence still represents a puzzle in the broad context of formation and evolution of galaxies.”

“It has been further developed and successfully applied by several teams to a number of disk galaxies with stellar counter-rotation: NGC 524, IC 719, NGC 448, NGC 1366, NGC 3593, NGC 4138, NGC 4191, NGC 4550NGC 5102 and NGC 5719. The technique was also applied to study orthogonally decoupled structures such as polar rings and photometrically distinct components such as bulge and disk.”

Counter-rotating stellar disk from gas acquired by IC 719, ***Astronomy & Astrophysics, 2018, 616, A22***

“The formation of massive counter-rotating discs is not yet fully understood. It is unlikely that counter-rotating systems result from the galaxy formation process, because in a uniformly rotating protogalactic cloud a subsequent splitting of the angular momentum distribution into a strongly bimodal one appears ‘anti thermodynamic.’ It is more natural to look for a second event scenario in the form of a merger as the origin of the formation of this kind of system, because infalling satellites do contain much specific angular momentum with arbitrary orientation. Although only a few cases of massive counter-rotating discs are known, counterrotation in galaxies seems to be a common phenomenon.”

Formation Of Massive Counter-Rotating Discs, ***Astrophysics and Space Science, 2001, 276:909-914***

How to Rejuvenate an S0 Galaxy, Galaxies 2015, 3, 192-201

Elliptical Galaxies
GAS VS. STARS
Anon 1029-459
IC 2006
NGC 3528
NGC 5354
NGC 5898
NGC 7097

STARS VS. STARS
IC 4889
IC 1459
IC 4889
NGC 1439
NGC 1700
NGC 4472
NGC 3608
NGC 4816
NGC 5322
NGC 7796

GAS VS. GAS
NGC 1052
IC 4889

Disk Galaxies
GAS VS. STARS
36 SO galaxies

STARS VS. STARS
NGC 4550
NGC 4138
NGC 7217

GAS VS. GAS
NGC 4826
NGC 5252
NGC 7332

Counter-Rotation in Disk Galaxies, ***http://aspbooks.org/publications/486/051.pdf***

"The presence of counter-rotating (CR) components in galaxies is not that rare but their origin is still unclear. Important clues to the formation and evolution of CR galaxies are provided by galaxy kinematics, such as the mass distribution and the shape of the gravitational potential."

Spotting a counter-rotating galaxy, ***https://doi.org/10.1017/S1743921319008676***

Counter Rotation (Gas Discs)
"When present, they reveal a very peculiar kinematics, including counter-rotation, warps or radial flows. b) A new case of gas counter-rotation has been found: NGC 7079."

A survey of the stellar rotation, ***Astronomy & Astrophysics, Supplement Series, 1997, 124, 61-74***

"A counter-rotating gas disk has been detected in the SA0 galaxy IC 560 located at the periphery of a sparse group of six late-type galaxies."

"Kuijken et al. (1996) also noted that the fraction of S0 galaxies with a counter-rotating stellar component in the disk is much lower, no greater than one percent. This is consistent with the apparent absence of current star formation in the gas disks of most S0 galaxies."

"We then studied a sample of absolutely isolated S0 galaxies, i.e., objects in an extremely rarefied environment, and exactly half of the gas disks among absolutely isolated S0 galaxies turned out to exhibit apparent counterrotation with respect to the stars in projection on the line of nodes of the stellar disks (Katkov et al. 2015); this means that in the idealized situation of the arrival of external gas from an arbitrary direction all gas disks in isolated S0 galaxies were acquired through recent accretion. There is seemingly some paradox here: if a galaxy is absolutely isolated, then there is no visible accretion source near it."

"In this paper we present yet another new example of an S0 galaxy with a counter-rotating gas disk, this time not a strictly isolated one but belonging to a very sparse group of galaxies."

Counter-rotating Gas Disk in the S0 Galaxy IC 560, ***Astronomy Letters, 2016, Vol. 42, No. 12, 783–789***

"We probe the HI properties and the gas environments of three early-type barred galaxies harboring counter-rotating ionized gas: NGC 128, NGC 3203 and NGC 7332. Each system has one or more optically identified galaxy at a similar or as yet unknown redshift within a 50-kpc projected radius. Using HI synthesis imaging data, we investigate the hypothesis that the counter-rotating gas in these galaxies has been accreted from their neighbors. In NGC 128 and NGC 3203, we find 9.6×10^7 and 2.3×10^8 M of HI, respectively, covering almost the entire stellar bodies of dwarf companions that appear physically connected. Both the HI morphology and kinematics are suggestive of tidal interactions. In NGC 7332, we do not find any directly associated HI. Instead, NGC 7339, a neighbor of a comparable size at about 10 kpc, is found with 8.9 × 10^8 M of HI gas.”

The H I environment of counter-rotating gas, ***MNRAS, 2012, 422, 1083-1091***

“Since disc galaxies with counter-rotating components were first discovered in 1987 by Galletta, their origin has been discussed

extensively by observational and theoretical studies. Despite the fact that counter-rotation has been observed across the whole Hubble sequence, counter-rotation is more frequent in early-type disc galaxies.”

Galaxies with counter-rotating gas discs, MNRAS, 2017, 471, L87-L91

“Both galaxies have many peculiar features in common: each has two global exponential stellar disks with different scale lengths, each possesses a circumnuclear inclined gaseous disk with a radius of 300 pc, and each has a global counterrotating subsystem, a gaseous one in NGC 7742 and a stellar one in NGC 7217. We suggest that a past minor merger is the probable cause of all these peculiarities, including the appearance of nuclear star-forming rings without global bars; the rings might be produced as resonance features by tidally induced oval distortions of the global stellar disks.”

“Both galaxies, NGC 7742 and NGC 7217, have circumnuclear gaseous disks with radii of some 300 pc, highly inclined to the global disk planes; the outer gas disks are, on the contrary, close to the main galactic symmetry planes. Both galaxies also possess some counterrotating subsystems. NGC 7742 has all its gas in counterrotation with respect to all its stars, with the exception of some newly born stellar population in the ring, while in NGC 7217 the gas outside R ¼ 300 pc corotates with the bulk of stars, but there are some 30% of all stars in the inner disk that counterrotate.”

Nature Of Nuclear Rings In Unbarred Galaxies, ***The Astronomical Journal, 2006, 131:1336-1346***

“To find them, we have undertaken complex spectral observations including integral-field spectroscopy for the central parts of the galaxies and long-slit deep spectroscopy to probe the external parts. The line-of-sight velocity fields have been constructed and compared to the photometric structure of the galaxies. As a result, we have revealed full-size counterrotating gaseous disks, the one coplanar to the stellar disk in NGC 2551 and the other inclined to the main stellar disk in NGC 5631.”

“However neither NGC 2551 nor NGC 5631 has a close neighbor within the circle of 100 kpc radius to provide interaction and smooth gas accretion that is suggested by Thakar & Ryden (1996) to be the most probable mechanism of massive counterrotating disk formation. The only alternative which is available for NGC 2551 and NGC 5631 is a minor merger with a gas-rich satellite. We do not know what morphological type the galaxies NGC 2551 and NGC 5631 had before merging, and if they have had their own (corotating) gas. But in any case the accreted gas had to suffer instantaneous star formation triggered by shock compression during the merging.”

Two More Disk Galaxies With Global Gas Counterrotation, ***The Astrophysical Journal, 2009, 694:1550–1558***

“Here we present optical spectra of the spiral galaxy NGC3626, which clearly show the presence of counter-rotating ionized gas; combining these results with preexisting atomic hydrogen data' leads to an estimate of 10^9 M0 for the mass of the gas.”

A massive counter-rotating gas disk in a spiral galaxy, ***Nature, 1995, 375, 661-663***

Counter Rotation (General Frequency)

Shape High Gap Low Gap High Offset Low Offset
Relaxed Unrelaxed

Total Number	39		37		82		72		35		29	
Misalignment(MA)	20.5%	5.9%	35.1%	6.7%	28.0%	6.6%	18.3%	6.7%	20.0%	5.7%	37.9%	6.5%
Counter-rotating(CR)	10.3%	5.9%	2.7%	6.7%	6.1%	6.6%	9.9%	6.7%	11.4%	5.7%	3.4%	6.5%

Kinematics of Stars and Gas in Brightest Group Galaxies, *The Astrophysical Journal, 2021, 908:123*

Counter Rotation (Lenticular Galaxies)

The Lenticular Galaxy NGC 524,

“This component disappears at about R ≈ 20″, where we see a sharp drop in the velocity dispersion and radial velocities increasing outwards, suggesting the counter-rotation with respect to the main disk.”

“The dynamically hot inner part without much rotation is a manifestation of the compact central pseudo-bulge, while at R >20″ we see the presence of a counter-rotating disk component that is supported by the drops in the velocity dispersion (300 to < 100 km s −1) and metallicity (0.0 to −0.3 dex) profiles. The origin of NGC 524 has to be investigated in detail using state-of-art numerical simulations. Right now we can speculate about its evolution based on the observational results we have. NGC 524 might have originated from the face on collision of two initially counter-rotating co-planar giant disk galaxies”

Baltic Astronomy, 2011, 20, 453-458

Counter rotating Large-Scale Stellar Disk,

“We have obtained and analysed long-slit spectral data for the lenticular galaxy IC 719. In this gas-rich S0 galaxy, its large-scale gaseous disk counterrotates the global stellar disk. Moreover, in the IC 719 disk, we have detected a secondary stellar component corotating the ionized gas.”

The Astrophysical Journal, 2013, 769:105

Counter Rotation (Stellar Discs)

“This allowed us to address the frequency of counter-rotation in spiral galaxies. It turns out that less than 12% and less than 8% (at the 95% confidence level) of the sample galaxies host a counter-rotating gaseous and stellar disc, respectively. The comparison with S0 galaxies suggests that the retrograde acquisition of small amounts of external gas gives rise to counter-rotating gaseous discs only in gas-poor S0s, while in gas-rich spirals the newly acquired gas is swept away by the pre-existing gas. Counter-rotating gaseous and stellar discs in spirals are formed only from the retrograde acquisition of large amounts of gas exceeding that of pre-existing gas, and subsequent star formation, respectively.”

Ionized gas and stellar kinematics of seventeen nearby spiral galaxies*, Astronomy & Astrophysics, 2004, 424, 447-454*

“The Sa spiral NGC 4138 is known to host two counter-rotating stellar disks, with the ionized gas co-rotating with one of them.”

“Large-scale counter-rotating disks of stars and/or gas have been detected in several lenticular and spiral galaxies, and different mechanisms have been proposed to explain their formation.”

“Table 1. Stellar kinematics along the major axis of NGC 4138.”

Two counter-rotating stellar disks of the spiral galaxy NGC 4138, *Astronomy & Astrophysics, 2014, 570, A79*

“The presence of stars counter-rotating with respect to other stars and/or gas has been detected in several disc galaxies and is commonly interpreted as the end result of a retrograde acquisition of external gas and subsequent star formation (see Bertola & Corsini 1999 for a review). Nevertheless, some special cases of counterrotating stellar discs could have an internal origin induced by the presence of a bar (e.g. Evans & Collett 1994). The demography of gaseous and stellar counter-rotating components in S0 galaxies and spirals is a key to understand their assembly process. The fraction of lenticular galaxies with a counter-rotating gaseous disc is consistent with the 50 per cent that we expect if all the gas in S0 galaxies is of external origin (Bertola, Buson & Zeilinger 1992). In contrast, less than 10 per cent of them host a detectable fraction of counter-rotating stars."

The spiral galaxy NGC 5719*, MNRAS, 2011, 412, L113-L117*

"The Large Magellanic Cloud is observed to have a counter-rotating stellar population in its disc, which has not been reproduced in previous simulations of the Magellanic system. We propose a new scenario in which the origin of this counter-rotating stellar population is the result of a minor retrograde merger with another dwarf galaxy more than 3 Gyr ago, and investigate this scenario using our hydrodynamical simulations. Our simulations show that such merging can result in a counter-rotating stellar component and a co-rotating gaseous component. We show that this counter-rotating population would not be radially concentrated, but found throughout the Large Magellanic Cloud."

"Therefore, we propose that this took place with a different dwarf galaxy, which merged with the LMC to create a counter-rotating population of stars. This is supported by the clear counter-rotating stellar component present in our simulation results. There is existing evidence supporting the counter rotation proposal over the inclined co-rotating disc that Olsen et al. (2011) also suggest. Subramaniam & Prabhu (2005) found that, out to a radius of 3° , there is a distinct counter-rotating region in the core of the LMC. Importantly, we do not find any counter rotation in the gaseous component, which is consistent with the lack of detection of any gas counter rotation in observations."

"Subramaniam & Prabhu (2005) found that, out to a radius of 3°, there is a distinct counter-rotating region in the core of the LMC. Importantly, we do not find any counter rotation in the gaseous component, which is consistent with the lack of detection of any gas counter rotation in observations. Since the kinematically distinct population is thought to make up ∼5 per cent of the LMC's stars, the mass of the merged companion must have been small relative to the LMC. To make up 5 per cent of the LMC's stellar content, the companion would need to have a total mass of approximately 5×10^{10} M_o."

Formation of a counter-rotating stellar population*, MNRAS: Letters, 2018, 480, 141-145*

"The main peculiarity of NGC 4550 is its two equal weighted counterrotating stellar disks, and therefore the stellar line-of-sight velocity field for this galaxy is of particular interest."

"The low stellar velocity dispersion of both counterrotating components proves them to be disks. The fact that the relative intensity of two counterrotating stellar components varies along the z-axis (in the direction orthogonal to the line of nodes) is indicative of different inclinations. Adopting the hypothesis of two stellar disks with different inclinations for NGC 4550 allows us to reinterpret the brightness profiles of the decomposed components obtained by Scorza et al."

"The most comprehensive analysis of the regular S0/a galaxy NGC 4138 has been performed by Jore, Broeils, & Haynes (1996), who investigated the H i distribution and kinematics, broadband (I filter) morphology, and differential photometry, and made long-slit kinematic observations of stars and ionized gas, which make up the most impressive part of their work. The above authors found that gas—both neutral and ionized—counterrotates with respect to the major stellar component; however, there is also a counterrotating stellar component, which exhibits disklike velocity dispersion and is concentrated toward the gaseous ring of radius 2200 (1.7 kpc)."

NGC 4138 AND NGC 4550*, The Astronomical Journal, 124:706-721, 2002*

"We have discovered a unique pattern of stellar and gas kinematics over the inner 30% of the optical galaxy. One stellar disk is rotating such that the north is receding and the south is approaching. Over the same radial distances, a gas disk is counterrotating with respect to the stars, such that the north is approaching, the south is receding."

“However, NGC 4550 is spectacular since it is the first system known in which there is a second stellar population orbiting along with the counterrotating gas. Thus, the inner one-third of the galaxy has complex kinematics; a disk of stars orbits prograde and

coexists with a disk of stars and gas which orbits retrograde. Because these two co-spatial counterrotating disks extend over a sizable portion of the galaxy, we may be detecting a phenomenon different from that observed in elliptical galaxies with counterrotating or skew small nuclear disks. Our observations illuminate yet another example of the complexity which exists within some elliptical galaxies.”

“The presence of two co-spatial and counterrotating stellar velocity systems is so bizarre that we have made every effort to establish the reality of the double-valued absorption features. We discuss briefly a few of the questions we have attempted to address.”

Co-Spatial Counterrotating Stellar Disks, ***The Astrophysical Journal, 1992, 394:L9-L12***

“We report the discovery of two counterrotating stellar disks in the early-type spiral galaxy NGC 3593. The major axis kinematics shows the presence of two dynamically cold counterrotating components. The surface brightness profile is well reproduced by the sum of the contributions of two exponential disks of different scale lengths (r1 = 40"; r2 = 10") and different central surface brightness = 19.9; = 18.5 mag arcsec -2).

The v and o radial profiles are easily reproduced by the means of a kinematical model adopting the above photometric parameters. An ionized gas disk is present. It corotates with the smaller scale length and less massive (M2 = 2.7 x 10^9 M_0) disk, and counterrotates with the larger and more massive (M1 = 1.2 x 10^{10} M_0) one. We conclude that the smaller stellar disk is the result of a slow adiabatic acquisition of a conspicuous amount of counterrotating gas (4.3 x 10^9 M_0) by the preexisting galaxy, originally constituted mainly by a gas-free stellar disk (disk 1). The counterrotating gas settled into the equatorial plane and then formed the inner stellar disk (disk 2).”

Counterrotating Stellar Disks In Early-Type Spirals: NGC 3593, ***The Astrophysical Journal, 1996, 458: L67-L70***

Simulations show that stellar counterrotation in galaxies could emerge thanks to two different processes: dissipative and dissipationless mergers. Confirming the suggestion of Kormendy (1984), Balcells & Quinn (1990) have shown that unequal mass mergers of elliptical galaxies can produce counterrotation if the orbit of the encounter is retrograde with respect to the spin of the primary. They also pointed out that the rotation seen in the counter-rotating component is a tracer of the orbital angular momentum and that both primary and secondary stars counterrotate at the core.

Hernquist & Barnes (1991) show that counter-rotating central gas disks can form as a result of retrograde mergers between two gas-rich spiral galaxies, discussing the possibility that star formation in such disks could produce components with decoupled kinematics, as in the core of some elliptical galaxies.

Some years later, Balcells & González (1998) showed that kinematically peculiar cores may be also generated in retrograde stellar spiral-spiral mergers. In this picture, the central bulges transport orbital angular momentum inward to the center of the remnant, while the outer parts keep the spin signature of the precursor disks.

Also Bendo & Barnes (2000) put in evidence the possibility of forming counterrotation at large radii, simulating mergers between equal-mass disk galaxies. Finally, Jesseit et al. (2007), studying the 2D kinematics of a sample of simulated disk merger remnants, show that counter-rotating cores made of old stellar populations are almost exclusively formed in equal-mass mergers where a dissipative component is included. Evidently, both mechanisms (the dissipative and dissipationless ones) can occur in real systems, producing a variety of kinematically decoupled components of different ages and physical extensions (McDermid et al. 2006).
Old stellar counter-rotating components in early-type galaxies, ***Astronomy & Astrophysics, 2008, 477, 437-442***

“Proposed explanations of galactic rotation curves (RC = tangential velocity vs. equatorial radius, determined from Doppler measurements) involve dramatically different assumptions. A dominant, original camp invoked huge amounts of unknown, non-baryonic dark matter (NBDM) in surrounding haloes to reconcile RC simulated using their Newtonian orbital models (NOMs) for billions of stars in spiral galaxies with the familiar Keplerian orbital patterns of the few, tiny planets in our Solar System. A competing minority proposed that hypothetical, non-relativistic, non-Newtonian forces govern the internal motions of galaxies. More than 40 years of controversy has followed."

"Geometry of spiral galaxies, as approximated in oblate spheroid and disk models: (a) Visual image of nearly face-on NGC 7742, type SA(r), by the Hubble Heritage Team (AURA/STScI/NASA), and publicly available from http://hubblesite.org). This particular ring galaxy is counter-rotating"

Debated Models for Galactic Rotation Curves, *Galaxies, 2020, 8, 47*

"Counter-rotating galaxies are those that host two components that rotate in opposite directions to each other. These peculiar objects have been observed in all morphological types, from ellipticals to spirals. They are classed by the nature (stars vs. stars, stars vs. gas, gas vs. gas) and size (counter-rotating cores, rings, discs) of the counter-rotating components (see Bertola & Corsini [1999] for a review). In this work, we investigate the peculiar class of counter-rotating galaxies with two counter-rotating stellar discs of comparable size."

NGC 3593. An isolated, highly inclined, S0/a spiral at a distance of 7 Mpc. It is characterised by a patchy spiral dust pat- tern in the centre. The two counter-rotating stellar discs have different scale lengths, but the same intrinsic flattening. The secondary component dominates the innermost 500 pc. The ages of the two components date the accretion event to between 2.0 and 3.6 Gyr ago, i.e., 1.6 ± 0.8 Gyr after the formation of the main stellar disc (Coccato et al., 2013).

NGC 4550. An E7/S0 galaxy in the Virgo Cluster, at a distance of 16 Mpc, and it is often indicated as the prototype of galaxies with counter-rotating stellar discs. It has an elliptical galaxy nearby, NGC 4551, to the northeast of NGC 4550 at a projected distance of 14 kpc. An interaction in the past between these two systems could have produced the counter-rotating stellar disc in NGC 4550, although no photometric signatures of the interaction, such as tidal tails or gas streams, have been detected. The two counter-rotating stellar discs in NGC 4550 have the same scale lengths, but slightly different ellipticity (main = 0.6, second = 0.5) meaning that they have different scale heights. The measured ages date the accretion event ~ 7 Gyr ago, i.e. less than 1 Gyr after the formation of the main stellar disc (Coccato et al., 2013).

NGC 5719. An Sab galaxy at a distance of 23 Mpc, and a member of a rich group. It is currently interacting with the Sbc galaxy NGC 5713, which is to the west of NGC 5719 at a projected distance of 77 kpc. The interaction between the two systems is traced by a bridge of neutral hydrogen (Vergani et al., 2007), which fuels the secondary counter-rotating stellar component in NGC 5719. The two stellar components in NGC 5719 have similar luminosity, but the secondary is less massive because of its younger age. Moreover, the youngest ages are observed in the secondary component at ~ 700 pc from the centre, where the Hß emission lines are more intense (Coccato et al., 2011). The ages of the two components date the accretion event between 1.3 and 4.0 Gyr ago, i.e. 2.7 ± 0.9 Gyr after the formation of the main stellar disc (Coccato et al., 2011).

Counter-rotating Stellar Discs in Galaxies,
https://www.eso.org/sci/publications/messenger/archive/no.151-mar13/messenger-no151-33-36.pdf

The counter-rotation phenomenon in disc galaxies directly indicates a complex galaxy assembly history which is crucial for our understanding of galaxy physics. Here, we present the complex data analysis for a lenticular galaxy NGC 448, which has been recently suspected to host a counter-rotating stellar component.

The counter-rotating component contributes ˜30 per cent to the total galaxy light. We estimated its stellar mass to be 9.0×10^{9} M_o. The radial scale length of counter-rotating disc is ˜3 times smaller than that of the main disc.

The main challenge in the studies of galaxies possessing counterrotating components is to establish a possible source of material with a different direction of the angular momentum and to clarify at least some details of the counter-rotating disc formation.

It is generally accepted that the presence of counter-rotating stars within the main stellar disc is a result of external material acquisition (Corsini 2014). Nevertheless, Evans & Collett (1994) suggested a scenario of internal origin of counter-rotating stars where stars take retrograde orbits during the bar dissolution process (separatrix crossing). From the stellar population point of view, only counter-rotating stellar discs with identical stellar population properties can be produced in the framework of this scenario. Hence, we decline it in the case of NGC 448 because the two discs have significantly different stellar population properties. Moreover, Evans & Collett (1994) suggested the separatrix crossing as a natural mechanism for building identical (with the same ages and scale lengths) counter-rotating discs in NGC 4550. However, the applicability of such mechanism for counter-rotating discs with very different scale lengths is not obvious.

Many recent detailed studies of disc galaxies with largescale counter-rotating components support the external origin of counter-rotating stars. In all studied galaxies, stellar population properties derived from the spectra play an important role. It has been shown that the counter-rotating components detected in NGC 3593, NGC 5719, NGC 4191, NGC 4550, and IC 719 (Coccato et al. 2011, 2013, 2015; Johnston et al. 2013; Katkov et al.

2013) have younger stellar populations compared to the main stellar discs, and their ionized gas rotates in the same direction as the secondary stellar components, i.e. it also counter-rotates with respect to the main disc. These findings favour the scenario where counterrotating stars have been formed in situ from the externally accreted gas.

Cosmological filaments and gas-rich satellites are considered as main candidate sources of external cold gas. However, it is often difficult to unambiguously disentangle between them. In both scenarios, one can expect to find either metal-poor or metal-rich counterrotating stellar population with respect to the main disc, depending on the star formation history while the brief duration of the subsequent star formation event results in the a-element enhancement.

The diversity of properties is observed. For instance, NGC 3593 and NGC 5719 indicate lower stellar metallicity in their counterrotating discs with respect to the main discs while for NGC 4550 and NGC 4191 both discs have similar populations; and the counterrotating stars in IC 719 and NGC 448 are more metal rich than their main stellar discs. The duration of the accretion events can be also various that results in the different a-element to iron ratios. For instance, short time-scales result in the super-solar a-element to iron ratios in the counter-rotating stellar populations while prolonged formation of a counter-rotating component should produce a solar a/Fe abundance ratio and/or significant age gradient.

In conclusion, several recent studies, including ours, demonstrate that various scenarios to form counter-rotating stellar components can take place in real galaxies. It is important to expand the sample of disc galaxies with counter-rotation studied in detail, in order to produce quantitative conclusions on the probability of different formation scenarios supported by the statistics.
Stellar counter-rotation in lenticular galaxy NGC 448, ***MNRAS, 2016, 461, 2068-2076***

ESO 297-27, an intermediate-to-late-type spiral galaxy, exhibits a rare counter-winding spiral structure in which two sets of nonoverlapping arms open in opposite senses.

To date, we have identified ESO 297-27 as only the second clear-cut example of a counter-winding spiral pattern, suggesting either that such patterns are very transient or that extraordinary circumstances are needed to produce them. It is important to emphasize that counter-rotation is not necessarily synonymous with a counter-winding spiral structure. Currently, there are no known cases of counter-rotation that show counter-winding spirals as strong as what is seen in ESO 297-27.

We further challenge the assumption of trailing spiral structures in the presence of counter-winding spirals. These rare spirals have two sets of arms existing in different parts of the disk and appear to be opening in opposite directions. The orientation of the spiral arms to each other implies that one set of arms must be leading instead of trailing as previously assumed.

To date, the best-known example of a counter-winding spiral is the nearly face-on southern galaxy NGC 4622. Byrd et al. (1989) first noticed its unusual structure in a photograph published by Shu (1982). Interestingly, the two sets of arms are separated by a bright inner ring, and there is no trace of a bar. Inside the ring, a single spiral arm opens counter clockwise while two stronger arms unwind clockwise outside of the ring (Buta et al. 1992). The counter-winding patterns are best seen in a Hubble Space Telescope (HST) V -band image (Buta et al. 2003) and can be made even more obvious with Fourier decomposition (Buta et al. 1992, 2003). NGC 4622 is positioned deep within a cluster, giving it many substantial companions which may be responsible for perturbing the galaxy's disk into this odd morphology. With only one clear-cut example of counter winding spiral structures identified to date, any additional possible examples of leading spiral patterns are of great interest and should be investigated more thoroughly.

Galaxies like ESO 297-27 and NGC 4622 pose a dilemma for spiral structure theories because of the difficulty of maintaining leading spirals. The maintenance of spirals is thought to depend on an outward transport of angular momentum, and only trailing spirals can do this effectively (Lin & Lau 1979). Angular momentum may propagate outward through an exchange with the outer Lindblad resonance, gas dissipation, or an interaction with the galaxy's halo. However, Lin & Lau (1979) argue that the angular momentum of long wave leading spirals, the only kind that have an outward group velocity beyond corotation, is not easily absorbed. This makes it difficult for a stellar disk to maintain a conspicuous leading spiral.

The presence of a counter-winding spiral pattern within a galaxy does not conclusively mean that the galaxy has a leading spiral structure. There is a real possibility that the two sets of spiral arms exist in counter-rotating disks. Currently we have no evidence, either for ESO 297-27 or for NGC 4622, that counter-rotation is at the heart of counter-winding spirals. If the domains of the patterns are dominated by counter-rotating stars, then conceivably both patterns could be trailing. Each spiral would then be able to transfer angular momentum outward and maintain itself. However, it is unclear whether such an arrangement could last very long.

Counter-Winding Spiral Structure In ESO 297-27, ***The Astronomical Journal, 2008, 136:980-993***

Counterrotating Large-Scale Stellar Disk

"The neutral and ionized hydrogen in the disc of NGC 5719 are counter-rotating with respect to the main stellar disc. The counter-rotating stellar disc contains about 20% of the stars in the system, and has the same radial extension as the main stellar disc. This is the first interacting system in which a counter-rotating stellar disc has been detected."

"Fig. 7. (Bottom panel) Heliocentric radial velocities as function of position along the optical major axis."

NGC 5719/5713: A counter–rotating stellar disc, Astronomy & Astrophysics, 2007, 463, 883-892

"We have obtained and analysed long-slit spectral data for the lenticular galaxy IC 719. In this gas-rich S0 galaxy, its large-scale gaseous disk counterrotates the global stellar disk. Moreover, in the IC 719 disk, we have detected a secondary stellar component corotating the ionized gas."

Counter rotating Large-Scale Stellar Disk, The Astrophysical Journal, 2013, 769:105

Chemical Inhomogeneities In The Milky Way Stellar Halo

Ring Galaxies

https://en.wikipedia.org/wiki/List_of_ring_galaxies

Ring Galaxies

"Besides this unresolved (in the magnesium index) structure, we have found a ring of younger stellar populations than those in the nucleus and in the bulge; the radius of this ring is about 600 (400 pc). A similar ring, distinguished by high magnesium- and iron-index values and bordered by H emission at its inner edge, with a radius of 600 (500 pc), is found in NGC 4429. We try to relate the ringed structure of the chemically decoupled cores in these galaxies with past, now dissolved, large-scale bars whose remnants are now seen in NGC 4429 and NGC 7013 as lenses between the bulges and global disks. An analysis of the gas and star kinematics in the centers of the galaxies has revealed the presence of an inclined circumnuclear disk in NGC 7013 and the existence of minibar in NGC 4429."

"However, many cases are known where there are rings but there is no bar in a galaxy. Particularly, the case of NGC 7217 where there are three different-scale rings but no bar has been analyzed in detail by Buta."

Galaxies NGC 4429 and NGC 7013, Astronomy & Astrophysics, 2002, 385, 1-13

“We here distinguish two counter-rotating stellar components in NGC 4191 and characterize their physical properties such as kinematics, morphology, age, and metallicity.”

“There are galaxies with two counter-rotating stellar disks of similar sizes (e.g., NGC 4550) and galaxies where the counter-rotation is visible only in the innermost regions (e.g., NGC 448,”

Counter-rotating components in NGC 4191, Astronomy & Astrophysics, 2015, 581, A65

“An especially interesting case is that of NGC 4513, where the ring counter-rotates with respect to the disc. Strong shear in the region between the disc and the ring is associated with unusually strong dynamo drivers in such counter-rotators. The effect of the strong drivers is found to be unexpectedly moderate. With counter-rotation in the disc, a generic model shows that a steady mixed parity magnetic configuration that is unknown for classical spiral galaxies, may be excited, although we do not specifically model NGC 4513.”

“In other words, observations of magnetic fields in galaxies with counter-rotating rings have the potential to provide a strong test for current galactic dynamo concepts.”
Magnetic fields in ring galaxies, Astronomy & Astrophysics, 2016, 592, A44

We present results from MUSE observations of the nearly face-on disk galaxy NGC 7742. This galaxy hosts a spectacular

nuclear ring of enhanced star formation, which is unusual in that it is hosted by a non-barred galaxy, and because this star formation is most likely fueled by externally accreted gas that counter-rotates with respect to its main stellar body.

Investigation of galaxies with counter-rotating components, such as NGC 7742, is important for understanding galaxy evolution, as it gives us information on previous merger and accretion events and the role of these events in the evolution of galaxies.

Again, NGC 7742 is a special galaxy here, in that only about 10% of spiral galaxies have counter-rotating disks.
The counter-rotating nuclear ring in NGC 7742, Astronomy & Astrophysics, 2018, 612, A66

The method described in this paper applied automatic detection to identify a set of 443 ring galaxy candidates, 104 of them were already included in the Buta + 17 catalogue of ring galaxies in SDSS, but the majority of the galaxies are not included in previous catalogues.
Automatic detection of full ring galaxy candidates, MNRAS, 2020, 491, 3767-3777

Ring galaxies can be identified as polar rings, collisional rings, bar-driven or tidally driven resonance rings, ringed barred spiral galaxies, and Hoag-type objects. The “Hoag’s Object” was discovered in 1950, and its discovery was followed by the identification of other ring galaxies.

A Catalog of Automatically Detected Ring Galaxy, The Astrophysical Journal Supplement Series, 2017, 231:2

Atlas and catalogue of collisional ring galaxies, The Astrophysical Journal Supplement Series, 2009, 181:572–604

Ring Galaxies (Double)
“As discussed by Madore et al. (2009), it is also a potential member of a rare subclass of collisional ring galaxies: those with double rings. The putative second ring is thought to be the diffuse stellar material which can be seen in the left panel of Figure 1 at much greater radius than the dominant ring. However, it is unclear whether this material can truly be considered another ring or is simply the low surface brightness extension of the disk.”

Musings On Am1354-250: Collisions, Shocks, And Rings, The Astrophysical Journal, 2016, 819:165

Ring Galaxies (Empty)
“ESO474 has the appearance of an empty RG on sky survey images. We started this investigation in an attempt to understand its nature, origin and evolution. The results from the SALT observations show that the ring is not

complete and uniform, but at least some of its elements (knots) contain considerable fractions, by mass, of old stellar populations while also forming young stars; e.g. knot F is essentially very young. Each of the knots appears as a dwarf galaxy containing older stellar populations, while also undergoing present SF."

"After summarizing our findings, we now discuss various scenarios by which the object could acquire its present appearance.

These were already mentioned in Section 1: resonances in discs, galaxy collisions, and accretion of material from another galaxy or from the intergalactic space. None of these scenarios fits ESO474 perfectly."

The empty ring galaxy ESO 474-G040, MNRAS, 2015, 451, 4114-4125

Several theories have been developed to explain the formation of ring galaxies, including Lindblad resonances driven by the galactic, accretion from nearby gas-rich galaxies, merger of galaxies and encounters between a disk galaxy and a companion dwarf galaxy. The resonance theory explains the formation of O-type inner and outer galactic rings that do not have nearby companion galaxies. Many of the polar ring galaxies can be represented by cold accretion or by the galaxies merging. The P-type galaxies with a companion galaxy are collisional ring galaxies.

Ring Galaxies Through Off-center Minor Collisions, The Astrophysical Journal, 2018, 864:72

Ring Galaxies (Formation)

Although the two-tiered structure and the chemically distinct nucleus obviously have a common origin and owe their existence to some catastrophic restructuring of the protogalactic gaseous disk, the origin of this remains unclear, since the galaxy lacks any manifestations of perturbed morphology or triaxiality.

However, rings are also found, albeit less frequently, in galaxies without bars. To explain such cases, the presence of a triaxial halo (NGC 7217 [5]) or transient bars that have disappeared by the time of the observations have been hypothesized]. However, it remains unclear whether a circumnuclear ring can develop in an absolutely axisymmetric galaxy; e.g., in a galaxy with regular round isophotes at all galactocentric radii.

Resolving these problems may also shed light on the origin of lenticular galaxies: it is possible that NGC 80 was previously a giant late type spiral galaxy that lost its gas as a result of catastrophic events whose consequences we have just discovered.

Structure of the S0 Galaxy NGC 80, Astronomy Reports, 2003, Vol. 47, No. 2, 88-98

Collisional Ring Galaxies, The Astrophysical Journal, 2018, 863:43

They found that red spirals have more concentrated light distribution than blue spirals, and hence red spirals are unlikely to originate from blue spirals. It is still unclear how red spirals formed and the star formation was quenched.

Massive Red Spiral Galaxy Formation, The Astrophysical Journal, 2020, 897:162

Ring Galaxies (Hoag)

The structure and stability of orbits in Hoag-like ring systems, MNRAS, 2018, 476, 3269-3277

UGC 4599: a Hoag-type ring galaxy, MNRAS, 2011, 413, 2621-2632

Elliptical Galaxy Internal Kinematics

"With these data, it is possible to test whether an S0 could result from a minor merger such that its kinematics become dominated by random motions. The inner parts are fitted quite well with a disk that is rotationally supported, but the outer parts would suggest a minor merger event. Information like this on more systems is required to answer the basic questions."

Galaxy Disks, ARAA, 2011. 49:301–371

"Some observations have sufficient spatial and spectral resolution to derive the mass and age of the stars in the inner 50 pc. In the few cases for which this was done (e.g., Davies et al. 2007), the velocity field is dominated by random motion typical of a spherical system and the stellar mass is of the order of 10^8 M_o."

Active Galactic Nuclei, ARAA, 2015. 53:365–408

"Elliptical galaxies were revealed to be "hot" stellar systems, in which most of the support against gravitational collapse comes

from essentially random motions, rather than "cold" systems, like spiral galaxies, in which ordered rotation contributes most of

the internal kinetic energy. Two questions immediately arose from these observations: What produces the observed flattening;

and, given that rotation plays only a minor role, are elliptical galaxies axisymmetric or fully triaxial?"

"Although the interpretation of this fine structure is still a matter of debate. it seems clear at least that elliptical galaxies are far less uniform in their structure and formation histories than was previously thought."

Dynamics of Elliptical Galaxies, Science, 1993, 259, 1867-1871

"A bimodal distribution exists in many aspects of galaxies, such as morphology (spiral vs. elliptical), colour (blue vs. red), and kinematics (rotation vs. random motion)."
Downsizing of Massive Green Valley Galaxies, The Astrophysical Journal, 2018, 855:10

"The amount of kinematic support from ordered versus random motions (V/sV,0) provides information about the internal structures of galaxies. In particular, low values of V/sV,0 may indicate that a galaxy has a thick disk and high gas turbulence, while galaxies with high V sV,0 tend to have ordered, thin disks."
Evolution of Star-forming Galaxies, The Astrophysical Journal, 2020, 894:91

"Based on the stellar orbit distribution derived from orbit-superposition Schwarzschild models, we decompose each of 250 representative present-day galaxies into four orbital components: cold with strong rotation, warm with weak rotation, hot with dominant random motion, and counter-rotating (CR)."

Galaxies across the Hubble sequence, MNRAS, 2018, 479, 945-960

"Thus, any physical mechanism for transforming rotationally supported systems into ones dominated by random motion is required."
Formation of Blue-cored Dwarf Early-type Galaxies, The Astrophysical Journal, 2019, 879:97

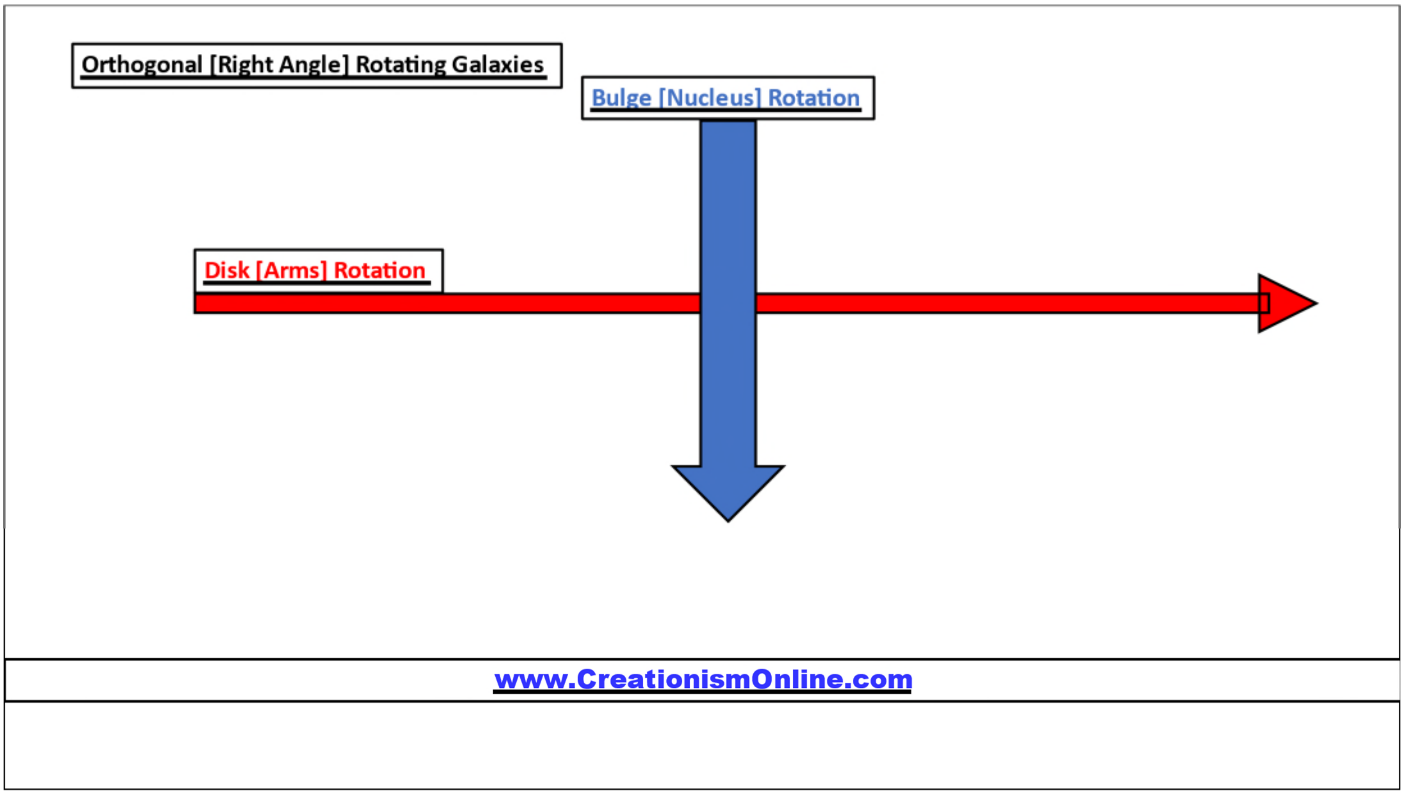
Lenticular Galaxy Internal Kinematics

“The two galaxies NGC 4550 and NGC 4473 stand out because of a significant tangential anisotropy ($\gamma < 0$). In both cases, the IFS data shows a characteristic and peculiar enhancement of the stellar velocity dispersion σ along the galaxy’s major axis, with two symmetric peaks in σ along the major axis, qualitatively suggesting the presence of a counter-rotating disk [for NGC 4550, this confirms the results by Rix and Rubin].”

Structure and Kinematics of Early-Type Galaxies, ARAA, 2016. 54:597–665

Orthogonal Rotation

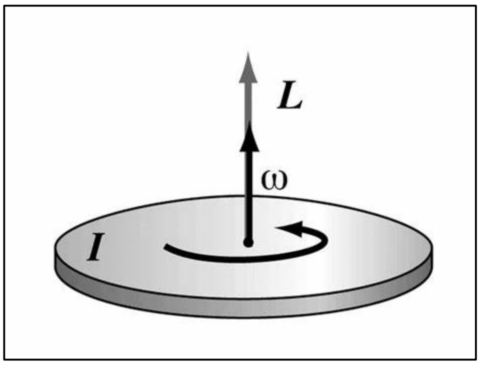
Orthogonal rotation occurs when two objects are rotating at right angles to each other. If a galaxy formed from a rotating gas cloud, we would expect that like the Solar System everything rotates in the same plane and direction. Many galaxies are exactly the opposite where the core and the arms rotate at right angles. Evolutionists have a lot of trouble explaining this.



www.CreationismOnline.com

Moment of Inertia - Solid Disk

It would take an almost infinite amount of force or energy to rearrange parallel rotation to right angle rotation.



$$I = \frac{Mr^2}{4}$$

Angular momentum rotating disk

$$a = \frac{Msr^3}{4t}$$

T= rotation time, seconds

S = arc length

R= radius

Angular energy rotating disk

$$e = \frac{1}{2} \times \frac{Mr^2}{4} \times \left(\frac{sr}{t}\right)^2$$

$$e = \frac{Mr^2}{8} \times \left(\frac{sr}{t}\right)^2$$

Momentum Inertia Sphere

$$I = \frac{2Mr^2}{5}$$

Momentum rotating Sphere

$$m = \frac{4\pi Mr^2}{5t}$$

Angular energy rotating sphere

$$e = \frac{1}{2} I w^2$$

$$w = \frac{sr}{t}$$

W – angular velocity

Search areas volume:

$$V = \frac{4\pi {R_3}^3}{3}$$

R_3=Search radius, kilometers

$$t = \frac{V \div v \div C}{\pi (R_1 + R_2)^2}$$

T= Search time seconds

v= travel velocity, kilometers/second

C= number of galaxies

R_2= Galaxy 2 radius, kilometers

R_1= Galaxy 1 radius, kilometers

Orthogonal Rotation (Bulge Versus Disk)
"We report the case of the early-type disk galaxy NGC 4672 as a new example of a galaxy characterized by the orthogonal geometrical decoupling between bulge and disk. The morphological features of this galaxy are discussed as well as the velocity curves and velocity dispersion profiles of stars and ionized gas along both its major and minor axis. We conclude that NGC 4672 has structural (i.e. a bulge elongated perpendicularly to the disk) and kinematical (i.e. a stellar core rotating perpendicularly to the disk) properties similar to those of the Sa NGC 4698. The presence of the isolated core suggests that the disk component is the end result of the acquisition of external material in polar orbits around a pre-existing oblate spheroid as in the case of the ring component of AM 2020-504, the prototype of polar ring ellipticals."

"In the framework of massive acquisition processes, we present NGC 4672 as a new case of a disk galaxy characterized by a geometric and kinematical orthogonal decoupling between its bulge and disk."

“The mass of the orthogonally rotating material is negligible (Mass gas < 10^9 M.) with respect to the total dynamical mass of the host galaxy in the minor-axis dust-lane elliptical galaxies (Sage & Galletta 1993).”

An early-type disk galaxy, Astronomy & Astrophysics, 2000, 360, 439-446

“The rings do not always lie in the main plane of the disk; there are cases of clearly inclined, or even polar, compact rings.”

“It appears that the gas in the very center of the galaxy is distributed in and rotates in a plane that is polar relative to the plane of the stellar disk and bar.”

“NGC 6893. This galaxy has no bar, but does have a set of rings. The inner ring, with a radius of about 13 , is inclined to the plane of the galaxy, as is indicated by the reversal of the isophote major axis at this radius and the open red (dust) arc.”

The Structure of the Stellar Disks, Astronomy Reports, 2016, Vol. 60, No. 1, 73–86

“The R-band isophotal map of the Sa galaxy NGC 4698 shows that the inner region of the bulge is elongated perpendicularly to the major axis of the disc. At the same time a central stellar velocity gradient is found along the minor axis of the disc. The same properties have also been recognized in the Sa galaxy NGC 4672. This remarkable geometric and kinematic decoupling is a direct indication that a second event occurred in the history of these galaxies suggesting that acquisition phenomena could play a primary role in the formation of early-type spirals.”

“In the course of an investigation of the kinematic properties of early-type spiral galaxies we encountered the peculiar case of the Sa galaxy NGC 4698. In addition to an out-of-the-ordinary geometric decoupling between bulge and disc, whose apparent major axes appear orientated in an orthogonal way on simple visual inspection of the galaxy images (e.g. see Panels 78, 79 and 87 in Sandage and Bedke, 1994), the stellar rotation curve along the major axis exhibits an unusual zero velocity plateau in the central regions. A subsequent spectrum obtained along the minor axis of the disc shows the presence of a strong stellar velocity gradient. This geometric and kinematic decoupling is a direct indication that a ‘second event’ occurred in the history of NGC 4698.”

The Orthogonal Bulge-Disc Decoupling In NGC 4698, Astrophysics and Space Science, 2001, 276:467-473

“The early-type spiral NGC 4698 is known to host a nuclear disc of gas and stars which is rotating perpendicularly with respect to the galaxy main disc. In addition, the bulge and main disc are characterized by a remarkable geometrical decoupling. Indeed, they appear elongated orthogonally to each other. In this work, the complex structure of the galaxy is investigated by a detailed photometric decomposition of optical and near-infrared images. The intrinsic shape of the bulge was constrained from its apparent ellipticity, its twist angle with respect to the major axis of the main disc and the inclination of the main disc. The bulge is actually elongated perpendicular to the main disc and it is equally likely to be triaxial or axisymmetric.”

“The geometrical and kinematical orthogonal decoupling of NGC 4698 can hardly be explained without invoking the acquisition of external material from the galaxy outskirts (see Bertola & Corsini 2000).”

“The kinematical decoupling between two components of a galaxy suggests the occurrence of an accretion event or merging (Bertola & Corsini 1999). Therefore, it is straightforward to explain the existence of the orthogonally rotating dynamically cold nuclear disc in NGC 4698 as the end result of the acquisition of external gas by the pre-existing galaxy. Gas dissipation is indeed a necessary ingredient since purely stellar dynamical mergers cannot form a nuclear disc (Hartmann et al. 2011). In NGC 4698, the accreted gas settled on the principal plane perpendicular to the shortest axis of the triaxial bulge (i.e. perpendicular to the galaxy main disc) and formed stars."

Polar bulges and polar nuclear discs, MNRAS, 2012, 423, L79-L83

"The R-band isophotal map of the Sa galaxy NGC 4698 shows that the inner region of the bulge structure is elongated perpendicularly to the major axis of the disk; this is also true for the outer parts of the bulge if a parametric photometric decomposition is adopted. At the same time, the stellar component is characterized by an inner velocity gradient and a central zero-velocity plateau along the minor and major axes of the disk, respectively. This remarkable geometric and kinematic decoupling suggests that a second event occurred in the formation history of this galaxy."

"This galaxy is characterized by a remarkable geometric decoupling between bulge and disk; in fact, their apparent major axes appear oriented in an orthogonal way at a simple visual inspection of the galaxy images."

"The orthogonal decoupling of the bulge and disk in NGC 4698 indicates that a second event occurred in the formation history of this galaxy."

Orthogonal Decoupling In Galaxies: NGC 4698, The Astrophysical Journal, 1999, 519:L127-L130

Orthogonal Rotation (Ring)

"We study the nearby S0 galaxy IC 5181 to address the origin of the ionized gas component that orbits the galaxy on polar orbits."

"The galaxy hosts a geometrically and kinematically decoupled component of ionized gas. It is elongated along the galaxy minor axis and in orthogonal rotation with respect to the galaxy disk. Conclusions. We interpret the kinematical decoupling as suggesting that there is a component of gas, which is not related to the stars and having an external origin. The gas was accreted by IC 5181 on polar orbits from the surrounding environment."

"In addition, there are disk galaxies where the angular momenta of the main stellar body and decoupled gaseous component are even orthogonal to each other. This is the case of polar ring galaxies. The accretion of external material through the capture of gas clouds or merging with formed galaxies (Spavone et al. 2010; Combes et al. 2013) is also invoked to explain the formation of this class of relatively rare objects"

The S0 galaxy IC 5181, Astronomy & Astrophysics, 2013, 560, A14

"We have discovered a total of almost thirty galaxies with chemically decoupled nuclei. Having come across this phenomenon, we also analyzed other galaxy properties—the kinematics of gas and stars in the central region, its structure, and peculiarities of

the global galactic structure, etc.—in an attempt to guess which of them could be related to the origin of the chemically decoupled nuclei."

"In these cases, it is hard to suggest that the captured gas with an orthogonal angular momentum immediately reached the center of the capturing galaxy by avoiding collisions with clouds of its own gas; besides, the galaxies turned out to be isolated.”

A Chemically Decoupled Nucleus, SBb Galaxy NGC 4548, Astronomy Letters, 2002, Vol. 28, No. 4, 207-216

“The dust lane is orthogonal to the derived rotation axis which in turn is aligned with the radio source. The upper limit to the mass is 1.1 x 10^{12} MG (based on a spherical model) and is comparable to that of NGC 1961”

Rotation of the large lenticular galaxy NGC 612, MNRAS, 1980, 190:23-26

“Galaxies with polar rings consist of two subsystems, a disk and a ring, which rotate almost in orthogonal planes.”

“Galaxies with polar rings are good candidates for this role. At the moment, about 400 polar ring galaxy candidates and confirmed polar ring galaxies are listed in two catalogues.”

The polar ring galaxy NGC660, Open Astronomy, 2017, 26:88-92

“The central 150 pc region of the starburst galaxy NGC 253 is shown to have a distinct gaseous kinematic subsystem, exhibiting rotation in a plane perpendicular to the galactic disk, and an interior region with possible counterrotation in the plane of the disk. In addition, solid-body rotation in the same sense as the galactic disk is observed in the outer parts of the central region. We suggest that this kinematic subsystem in NGC 253 may be indicative of a secondary bar inside the known primary bar. Alternatively, it may be a signature of a merger or an accretion event during the history of the galaxy. The dynamical mass within a radius of 5 degrees is 3 x 10^8 Mo.”

“This is interpreted as evidence for three distinct rotations in the central region—a solid-body rotation in the same sense as the outer galaxy, a rotation in a perpendicular plane with almost twice the speed, and, finally, a possible counterrotating inner core. Thus, NGC 253 becomes the first nuclear starburst galaxy to exhibit a gaseous kinematic subsystem in its interior region.”

“In summary, one possible model that can explain the observed velocity field shown in Figure 1b consists of three nested rings or disks of ionized gas rotating like solid bodies. The outermost ring, with a velocity gradient of 12 km/sec arcsec, rotates in the plane of the galaxy and is likely to be a part of the general solid-body rotation found near the center on larger scales (Pence 1981; Canzian et al. 1988; Puxley & Brand 1995). The second ring, which is interior to the outer disk, dominates the velocity field in the central region with a gradient of 24 km/sec arcsec, and it is oriented perpendicular to the outer disk and likely to be tilted with respected to the line of sight. It should be noted that the data only imply that the spin axis of this ring lies in the plane of the galaxy and need not necessarily be aligned with the projected major axis of the galaxy’s outer disk. The third and the most interior disk, the evidence for which is tentative because of the coarse angular resolution, is in the plane of the galaxy and appears to be rotating counter to the outermost disk.”

“The main result of our modeling of the S-shaped velocity field is that the ionized gas in the central region of NGC 253 seems to form a kinematic subsystem, distinct from the main outer galaxy, consisting of two perpendicular rotations (the rotation in an orthogonal plane and the central counter rotation in the plane).”

Orthogonal Rotating Gaseous Disks Near The Nucleus Of NGC 253, The Astrophysical Journal, 1996, 466: L13-L16

"We used deep, long-slit spectra and integral-field spectral data to study the stars, ionized gas kinematics, and stellar population properties in the lenticular barred galaxy NGC 7743. We show that ionized gas at distances larger than 1.5 kpc from the nucleus settles in the disk, which is significantly inclined toward the stellar disk of the galaxy. Making different assumptions about the geometry of the disks and including different sets of emission lines in the fitting, under the assumption of thin, flat-disk circular rotation, we obtain the full possible range of angles between the disks to be 34◦ ± 9◦ or 77◦ ± 9◦ . The most probable origin of the inclined disk is the external gas accretion from a satellite orbiting the host galaxy, with a corresponding angular momentum direction. "

“Numerous examples and detailed discussion and references can be found, for instance, in the papers by Afanasiev et al. (1989), Corsini et al. (2003), Moiseev et al. (2004), Sarzi et al. (2006), and Coccato et al. (2007). Unfortunately, observational evidence of large-scale (beyond the 1 kpc central region), kinematically decoupled subsystems is still quite rare (see Sil’chenko et al. 2009 and references therein). Therefore, every new example of similarly peculiar objects is interesting. In this paper, we demonstrate that the main fraction of the ionized gas in NGC 7743 rotates on the orbits, considerably inclined toward the main stellar disk of the galaxy, which may be a result of external gas accretion or tidal destruction of a small gas-rich companion.”

“All ionized gas at radii of 1.5–5.4 kpc is confined to the disk and inclined strongly toward the main stellar disk of NGC 7743. The angle between two disks is estimated; two possible solutions are obtained, 34◦ ± 9◦ or 77◦ ± 9◦ , depending on the mutual disk orientation in space. The most probable origin of this inclined gaseous disk is the accretion from the gas-rich environment of NGC 7743. The main contributor to gas excitation is the shock waves, probably induced by inclined-orbit gas clouds, that cross the main stellar disk.”

Stars And Ionized Gas In The S0 Galaxy NGC 7743, The Astrophysical Journal, 2011, 740:83

“We found that the stellar disk rotates along the photometric major axis, while both ionized and molecular gas distribute and rotate approximately along the minor axis. These orthogonal rotational pattern supports that the gas in PGC 38025 is originated externally. However, accretion from cosmic web, which usually generates a metal poor gas reservoir, can be ruled out.”

PGC 38025: A Star-forming Lenticular Galaxy, The Astrophysical Journal, 2021, 915:1

“I also estimate the fraction of nearby lenticular galaxies having inner polar gaseous disks by exploring the volume-limited sample of early-type galaxies of the ATLAS-3D survey. By inspecting the two-dimensional velocity fields of the stellar and gaseous components with the running tilted ring technique, I have found seven new cases of inner polar disks. Together with those, the frequency of inner polar disks in nearby S0 galaxies reaches 10%, which is much higher than the frequency of large-scale polar rings. Interestingly, the properties of the nuclear stellar populations in the inner polar ring hosts are statistically the same as those in the whole S0 sample, implying similar histories of multiple gas-accretion events from various directions.”

“First, these disks are indeed polar: though all the gaseous rings whose rotation axes are inclined to the stellar rotation axes by more than 50° have been considered, the distribution of the mutual inclinations peaks strongly at 90°. Second, they can be found mostly in early-type galaxies: more than half of all known inner polar disks belong to (mostly) lenticular and elliptical galaxies; however, a few belonging to very late-type dwarfs are also known. The typical radii of the inner polar disks range from 0.2 to 2.0 kpc; the outer boundary is quite real, revealing the relation of the inner polar disks to bulge-dominated areas, while the inner limit results from the finite spatial resolution of ground-based integral-field spectroscopy.”

Galaxy	Stellar Inclination	Error	Gas Radius	Gas Inclination	Error
NGC	Degrees	Degrees	Arc Seconds	Degrees	Degrees
2962	47	3	6–11	63.5	2.5
2962	47	3	13–18	78	1
3499	48	8	5–11	62	5.5
3648	54	7	1–4	66	3
3648	54	7	5–8	67	1
4690	18	10	3–6	71	4
4690	18	10	7–8	65	13
5507	64	5	2–6	64	4

Inner Polar Disks In Lenticular Galaxies, The Astronomical Journal, 2016, 152:73

Orthogonal Rotation (Common)

“This phenomenon is observed all along the Hubble sequence of disk galaxies, but it is particularly frequent in early-type spirals.”

“This has been attributed to the presence of a kinematically-decoupled gaseous component in orthogonal rotation with respect to the galaxy disk, namely an inner polar disk. The case and origin of inner polar disks are discussed and the list of their host galaxies is presented.”

“For this reason we observe in the bulge-dominated region a zero-velocity plateau along the disk major axis (or at least a shallower velocity gradient depending on the amount of decoupled gas and spatial resolution of the kinematic data) and a velocity gradient along the disk minor axis. The innermost gas component can be identified with an inner polar gaseous disk.”

“Galaxies hosting an inner polar disk are a new class of objects, since these orthogonally-decoupled structures have been discovered in the last few years. The investigation of their structural properties and formation processes offers some clues about the processes driving secular evolution of gaseous and stellar components in galaxy centers.”

Galaxy Name	Distance Meg-Parsec	Inclination Degrees	Polar Disk Composition	Disk Radius Parsecs	Disk Vs. Galaxy Radius Ratio
Arp-220	72.1	77	gaseous disk	100	0.01
NGC-253	3.4	79	gaseous ring	150	0.01
NGC-2217	19.1	22	gaseous disk	190	0.01
NGC-2681	13.3	25	gaseous/stellar disk	130	0.02
NGC-2841	9.8	64	gaseous disk	190	0.02
NGC-2855	22.3	27	gaseous disk	220	0.03
NGC-3368	9.8	47	gaseous disk	100	0.01
NGC-4548	17	37	gaseous disk	250	0.02
NGC-4672	39.9	75	stellar disk	580	0.05
NGC-4698	17	65	gaseous/stellar disk	250	0.03
NGC-5850	32.4	30	gaseous disk	630	0.03
NGC-6340	19.8	26	gaseous disk	480	0.05
NGC-7049	29.6	47	gaseous disk	430	0.02
NGC-7217	16.4	35	gaseous disk	240	0.03
NGC-7280	26.3	52	gaseous disk	260	0.03
IC-1689	63	55	gaseous/stellar ring	2140	0.24
UGC-5600	37.6	46	gaseous ring	1090	0.14

Minor-axis velocity gradients in spirals, Astronomy & Astrophysics, 2003, 408, 873-885

Orthogonal Rotation (Candidates)

Galaxy NGC	Stellar Inclination Degrees	Gas Radius Arc-Seconds	Gas Inclination Degrees
2962	47	6–11	63.5
2962	47	13–18	78
3499	48	5–11	62
3648	54	1–4	66
3648	54	5–8	67
4690	18	3–6	71
4690	18	7–8	65
5507	64	2–6	64

“NGC 4026. This galaxy is strictly edge-on. In the central part the gaseous component looks like a disk seen edge-on, inclined by some 50° to the main galactic plane. Farther from the center, the gaseous disk warps and lies in the galactic plane.”

“By adding to the nine inner polar disks mentioned above the galaxies listed by Moiseev (2012), we claim the detection of 21 inner polar disks among the full sample of 200 nearby lenticulars. Therefore, the frequency of strongly inclined inner gaseous disks in the nearby S0s is about 10%.”

“Stellar and gaseous LOS velocity fields of two edge-on galaxies: NGC 1121 (upper plots) and NGC 4026 (lower plots). In the central parts the gaseous disks are inclined to the main galactic planes by some 50°.”

Stellar Nuclei And Inner Polar Disks, The Astronomical Journal, 2016, 152:73

“Galaxies with polar rings (PRGs) are a unique class of extragalactic objects. Using these, we can investigate a wide range of problems, linked to the formation and evolution of galaxies, and we can study the properties of their dark haloes. The progress that has been made in the study of PRGs has been constrained by the small number of known objects of this type. The Polar Ring Catalogue (PRC) by Whitmore et al. and their photographic atlas of PRGs and related objects includes 157 galaxies.”

“Our SDSS-based Polar Ring Catalogue (SPRC) contains 70 galaxies that we have classified as ‘the best candidates’. Among these, we expect to have a very high proportion of true PRGs, and 115 good PRG candidates. There are 53 galaxies classified as PRG-related objects (mostly galaxies with strongly warped discs, and mergers). In addition, we have identified 37 galaxies that have their presumed polar rings strongly inclined to the line of sight (seen almost face-on).”

https://vizier.cfa.harvard.edu/viz-bin/VizieR-3?-source=J/MNRAS/418/244

A new catalogue of polar-ring galaxies, MNRAS, 2011, 418, 244-257

Galaxy	R, Kpc	Δi, Deg	Galaxy	R, Kpc	Δi, Deg	Galaxy	R, Kpc	Δi, Deg
Arp-220	0.3	-	NGC-2855	4	-	NGC-4552	5	-
IC-1548	1.5	-	NGC-2911	4	75	NGC-4579	18	-
IC-1689	10	30	NGC-3227	0.9	-	NGC-4672	6	-
M-31	180	40	NGC-3368	3	-	NGC-4698	5	-
Mrk-33	12	47	NGC-3379	3	-	NGC-4941	2	-
Mrk-370	11	-	NGC-3384	5	-	NGC-5014	22	80
NGC-253	5	60	NGC-3414	9	60	NGC-5198	4	-
NGC-474	32.7	256	NGC-3599	7	-	NGC-5850	6	-
NGC-1068	2	-	NGC-3607	2	-	NGC-6340	12	40-60
NGC-2217	20.7	20	NGC-3608	4	-	NGC-7049	5	-
NGC-2655	15	-	NGC-3626	4	-	NGC-7217	3	-
NGC-2681	5	-	NGC-4100	12	60	NGC-7280	2	80
NGC-2732	5	30-70	NGC-4111	8	-	NGC-7468	6	60
NGC-2768	16	30-60	NGC-4233	7	90	NGC-7742	0.36	26

NGC-2787	**7.5**	**72**	**NGC-4424**	**3**	**-**	**UGC-5600**	**10**	**60**
NGC-2841	**5**	**-**	**NGC-4548**	**3**	**-**			

Inner Polar Rings and Disks, Astrophysical Bulletin, 2012, 67:2, 147-159

Orthogonal Rotation (Formation Theory)

“Several theories have been developed to explain the formation of ring galaxies, including Lindblad resonances driven by the galactic bars, accretion from nearby gas-rich galaxies, merger of galaxies and encounters between a disk galaxy and a companion dwarf galaxy. The resonance theory explains the formation of O-type inner and outer galactic rings that do not have nearby companion galaxies. Many of the polar ring galaxies can be represented by cold accretion or by the galaxies merging. The P-type galaxies with a companion galaxy are collisional ring galaxies.”

“The mass of the intruder galaxy increases from 1 x 10^{11} Mo to 3 x 10^{11} Mo (the top panels to the bottom panels), and the half-mass radius decreases from 3.8 kpc » 1.1h to 1.2 kpc » 0.3h (from the left-hand panels to the right-hand panels). No rings form when the mass for the dwarf galaxy 1 x 10^{11} Mo is, which is ≈3% of the mass for the target galaxy. The projected density of the ring is larger when the mass of the intruder galaxies increases, and the ring is clearer when the size (i.e., the half-mass radius) of the intruder galaxy decreases. Thus, a clearer galactic ring forms when there is a more compact and more massive intruder galaxy.”

Ring Galaxies Through Off-center Minor Collisions, The Astrophysical Journal, 2018, 864:72

Kinematically Decoupled Core

Many disk galaxies host two extended stellar components that rotate in opposite directions. The analysis of the stellar populations of the counter-rotating components provides constraints on the environmental and internal processes that drive their formation. Aims. The S0 NGC 1366 in the Fornax cluster is known to host a stellar component that is kinematically decoupled from the main body of the galaxy. Here we successfully separated the two counter-rotating stellar components to independently measure the kinematics and properties of their stellar populations. Results. We found that the counter-rotating stellar component is younger, has nearly the same metallicity, and is less =Fe enhanced than the corotating component. Unlike most of the counter-rotating galaxies, the ionized gas detected in NGC 1366 is neither associated with the counter-rotating stellar component nor with the main galaxy body. On the contrary, it has a disordered distribution and a disturbed kinematics with multiple velocity components observed along the minor axis of the galaxy. Conclusions. The different properties of the counter-rotating stellar components and the kinematic peculiarities of the ionized gas suggest that NGC 1366 is at an intermediate stage of the acquisition process, building the counter-rotating components with some gas clouds still falling onto the galaxy.

Different processes have been proposed to explain the formation of a galaxy with two counter-rotating stellar disks, and each formation scenario is expected to leave a noticeable signature in the stellar population properties of the counter-rotating components. A counter-rotating stellar disk can be built from gas accreted with an opposite angular momentum with respect to the pre-existing galaxy from the environment or from a companion galaxy. The counter-rotating gas settles on the galaxy disk and forms the counter-rotating stars. In this case, the gas is kinematically associated with the counter-rotating stellar component, which is younger and less massive than the main body of the galaxy. Another viable, but less probable, formation process is related to the major merger between two disk galaxies with opposite rotation. The difference in age of the two counter-rotating components depends on the stellar population of the progenitors and on the timescale of the star formation triggered by the binary merger.

However, this raises the question about the origin of the newly supplied and kinematically decoupled gas since there is no clear donor candidate in the neighborhood of NGC 1366.

S0 galaxy NGC 1366, Astronomy & Astrophysics, 2017, 600, A76

Central drops in the velocity dispersion can indicate decoupled dynamics in the nucleus, e.g. by a nuclear disc find that a significant fraction of spiral galaxies in the SAURON survey show that this feature and kinematically decoupled components are actually a common phenomenon.

NGC 1808 observed with SINFONI, Astronomy & Astrophysics, 2017, 598, A55

VST Early-type Galaxy Survey, Astronomy & Astrophysics, 2017, 603, A38

These authors suggested, however, that the entire profile, including the ring, which corresponds to 1.2% of the integrated B-band luminosity, is well approximated by a $r^{1/4}$ law, which means that the galaxy is a bona fide elliptical. Schweizer found that the ring overlaps with an HI counter-rotating ring at a radius of about 150'', inclined about 37.5° with respect to the plane of the sky.

The nucleus of NGC 1366 has a relatively young luminosity-weighted age of 5.9 Gyr within re/8 found by Annibali. Morelli found that NGC 1366 hosts a nuclear kinematically decoupled component that is younger than the host bulge. To explain the properties of the counter-rotating component, Morelli suggested that enriched material has recently been acquired through interaction or minor merging.

The UV structure of 11 galaxies, Astronomy & Astrophysics, 2017, 602, A97

NGC 404 has likely experienced a recent interaction/ merger, leading to a kinematically decoupled core and an HI shell around the galaxy.

Discovery of a dwarf spheroidal galaxy, Astronomy & Astrophysics, 2018, 620, A126

Formation of S0 galaxies through mergers, Astronomy & Astrophysics, 2017, 604, A105

A polar galaxy merger origin? Astronomy & Astrophysics, 2017, 606, A62

NGC 3311 in the Hydra I cluster, Astronomy & Astrophysics, 2018, 609, A78

The major-merger remnant NGC 7252, Astronomy & Astrophysics, 2018, 614, A32

We also modelled the flux of several H_2O lines observed with Herschel using a radiative transfer code that includes excitation by collisions and far-infrared photons. The disc of the MRK 273 north nucleus has two components with decoupled kinematics. The gas in the outer parts (Radius 1.5 kpc) rotates with a south-east to north-west direction, while in the inner disc (Radius 300 pc) follows a north-east to south-west rotation. The central 300 pc, which hosts a compact starburst region, is filled with dense and warm gas, and contains a dynamical mass of 4.5×10^9 M_o, a luminosity of L0 HCN = 3.4×10^8 K km/sec. pc^2, and a dust temperature of 55 K.

The northern nucleus of MRK 273, Astronomy & Astrophysics, 2018, 617, A20

The 96 S0-like remnants also present normal structures attending to their radial surface brightness profiles, as well as typical rotation curves and velocity dispersion profiles, with clear signs of hosting kinematically-decoupled components at the centre, which is also frequent in real S0s.

Formation of S0 galaxies, Astronomy & Astrophysics, 2018, 617, A113

We present major and minor-axis kinematics of stars and ionized gas as well as narrow and broad-band surface photometry of the Sa spiral NGC 2855. In the nuclear regions of this unbarred and apparently undisturbed spiral galaxy the gas is rotating perpendicularly to the galaxy disk. We suggest that this kinematically-decoupled component is the signature of an acquisition process in the history of this galaxy.

The recent findings by Bettoni on the higher gas content of counter-rotators and polar ring galaxies with respect to normal galaxies gives further support to the idea that kinematically-decoupled components are the end result of one or more second events that occurred in the history of the host. Yet, even with this insight, the undisturbed appearance with no evident signatures of interaction characterizing most of galaxies with kinematic peculiarities raises questions about the effective rate of second events and on their role in determining Hubble types.

Recently the presence of a velocity gradient along the minor axis of the disk has been reported in the innermost region of two Sa spirals, namely NGC 4698 and NGC 4672, characterized by an uncommon and remarkable orthogonal geometrical decoupling between bulge and disk. In NGC 4698 the minor-axis velocity gradient is observed in both stars and ionized gas, while in NGC 4672 only in the stellar component.

Such a stellar rotation along the disk minor axis indicates the presence of a kinematically isolated core, which is rotating perpendicularly with respect to the disk component.

The analysis of the HST images of the nucleus of NGC 4698 shows that in this case the isolated core is a nuclear stellar disk with a scale length of a few tens of pc. According to Bertola & Corsini the presence of these orthogonally-rotating isolated cores indicates that the entire disk of the galaxy could be the end result of the acquisition of external material in polar orbits around a pre-existing oblate spheroid, which became the bulge of the present galaxy. In this scenario the isolated core has been formed by the gaseous material settled down in the symmetry plane of the oblate spheroid during the acquisition process.

The analysis of the velocity curves of stars and ionized gas along both the major and minor axis of NGC 2855 shows a kinematical decoupling between the gas in the innermost regions of the galaxy and the remaining gas.

We therefore interpret the observed ionized-gas velocity field as being due to the presence of two kinematically decoupled gaseous components, which are rotating around two roughly orthogonal axes. They are the shortest and the longest axes of the triaxial bulge. In this picture the innermost gas is moving onto the equilibrium plane orthogonal to the equatorial one, where both the galaxy disk and outer gas component are settled. If this is the case, the kinematical decoupling is also consistent with an abrupt inner warp of the ionized-gas component.

Kinematical decoupling between two components of a galaxy suggests the occurrence of a second event, so it is easy to explain the existence of the innermost orthogonally-rotating gas as being due to external material acquired from a direction close to the bulge equilibrium plane orthogonal to that of the galaxy disk.

Kinematical decoupling in the Sa spiral NGC 2855, Astronomy & Astrophysics, 2002, 382, 488-494

32% of the examined galaxies contain kinematically decoupled stellar components, the size of these cores was 0.40 0.28 kpc, in each case the core was smaller than 1 kpc. Analysis of the kinematics reveals in 49% of the sample galaxies the signature of a stellar disk component, in 15% this is uncertain. There is evidence that the phenomenon of kinematically decoupled components is present in the whole class of early-type galaxies.

One of the most notable features observed in ellipticals are kinematically decoupled core components. The most extreme cases are peculiar cores which are characterized by angular momentum vectors which are opposite or perpendicular with respect to the main body of the galaxy. Merging seems to be a plausible explanation for the origin of the decoupled component. This is also supported by the fact that the metallicities of the core component as measured through the absorption line indices appear to be enhanced with respect to the rest of the galaxy. In about 30% of the nearby luminous ellipticals peculiar core kinematics are detected. Taking however projection effects into account, it is estimated that more than 50% of all luminous ellipticals should contain a kinematically decoupled core.

Galaxy	Kinematics	Galaxy	Kinematics
N3258	**boxy, with weak rotation**	**N4033**	**decoupled central component**
N2380	**boxy, without rotation**	**N3250**	**decoupled central component:**
N2663	**boxy, without rotation**	**N3617**	**decoupled central component:**
N4261	**boxy, without rotation**	**N7196**	**decoupled central component:**
N5903	**boxy, without rotation**	**N3585**	**decoupled central component; disk like**
I5297	**boxy, without rotation**	**N2271**	**decoupled central component; disk like**
N2434	**boxy, without rotation**	**I2311**	**decoupled central component; disk like**
N2887	**boxy, without rotation**	**N3260**	**disk like**
N2865	**boxy, without rotation**	**I4797**	**disk like**
N3302	**boxy, without rotation:**	**I1729**	**disk like:**
N3904	**decoupled central component**	**N1549**	**E0; boxy, with weak rotation**
N4105	**decoupled central component**	**N5061**	**E0; boxy, with weak rotation**
N1404	**decoupled central component**	**N3636**	**E0; boxy, without rotation**
N1427	**decoupled central component**	**N3224**	**normal E-galaxy**
N2699	**decoupled central component**	**N1537**	**normal E-galaxy**
N2888	**decoupled central component**	**N3309**	**normal E-galaxy**
N2986	**decoupled central component**	**N3377**	**normal E-galaxy**
N3078	**decoupled central component**	**N3557**	**normal E-galaxy**
N3087	**decoupled central component**	**N4697**	**normal E-galaxy**
N3557B	**decoupled central component**	**N7049**	**normal E-galaxy**

Velocity distributions of 53 early-type galaxies, Astronomy & Astrophysics Supplement, 2000, 145, 71-82

We present, for the first time, photometric and kinematical evidence, obtained with FORS2 on the VLT, for the existence of kinematically decoupled cores (KDCs) in two dwarf elliptical galaxies: FS76 in the NGC 5044 group and FS373 in the NGC 3258 group. Both kinematically peculiar subcomponents rotate in the same sense as the main body of their host galaxy but betray their presence by a pronounced bump in the rotation velocity profiles at a radius of about 1''. The KDC in FS76 rotates at 10 ± 3 km/sec, with the host galaxy rotating at 15 ± 6 km/sec; the KDC in FS373 has a rotation velocity of 6 ± 2 km/sec while the galaxy itself rotates at 20 ± 5 km/sec. FS373 has a very complex rotation velocity profile with the velocity changing sign at 1.5 Re. The velocity and velocity dispersion profiles of FS76 are asymmetric at larger radii. This could be caused by a past gravitational interaction with the giant elliptical NGC 5044, which is at a projected distance of 50 kpc. We argue that these decoupled cores are most likely not produced by mergers in a group or cluster environment because of the prohibitively large relative velocities.

Dwarf elliptical galaxies with kinematically decoupled cores, Astronomy & Astrophysics, 2004, 426, 53-63

The instabilities found in the central gaseous velocity field are not seen in the solid body stellar rotation curve, indicating that stars and gas are kinematically decoupled in this galaxy.

Gas kinematics in ESO 400-G43, Astronomy & Astrophysics, 2004, 419, L43–L47

We suppose that morphological peculiarities and the possible existence of two large-scale kinematically-decoupled subsystems in ESO 603-G21 can be explained as being a result of dissipative merging of two spiral galaxies or as a consequence of a companion accretion onto a pre-existing spiral host.

The global kinematical structure of ESO 603-G21 – stellar rotation along two orthogonal position angles - suggests that the object is a polar-ring galaxy. The host galaxy is probably an early-type galaxy with an exponential-like surface brightness distribution. The central galaxy is surrounded by a warped star-forming ring or disk. In general, ESO 603-G21 looks similar to other classic PRG (e.g. NGC 4650A).

ESO 603-G21: A strange polar-ring galaxy, Astronomy & Astrophysics, 2002, 383, 390-397

Context. The presence of non-circular and off-plane gas motion is frequently observed in the inner regions of disk galaxies.

Aims. With integral-field spectroscopy we have measured the surface-brightness distribution and kinematics of the ionized gas in

NGC 2855 and NGC 7049. These two early-type spiral galaxies were selected as possibly hosting a kinematically-decoupled gaseous component in orthogonal rotation with respect to the galaxy disk.

Methods. We have modeled the ionized-gas kinematics and distribution of both galaxies assuming that the gaseous component is

distributed either on two orthogonally-rotating disks or in a single and strongly warped disk.

Results. In both galaxies the velocity field and distribution of the inner gas are consistent with the presence of an inner polar disk. In NGC 2855 it corresponds to the innermost and strongly warped portion of the main disk. In NGC 7049 it is a central and geometrically decoupled disk, which is nested in the main disk.

The acquisition of external gas via merging or accretion on nearly polar orbits by a pre-existing galaxy, and the transfer of gas onto highly inclined anomalous orbits of a triaxial bulge or a bar, which is tumbling about its short axis, are both viable mechanisms to build a orthogonally-rotating disk. According to these different scenarios, it can be either a geometrically-decoupled structure or the inner portion of a strongly warped and larger gaseous disk. Therefore, constraining the structural properties of a sample of IPDs will give some clues to understand the processes driving their formation.

NGC 2855 and NGC 7049, Astronomy & Astrophysics, 2007, 465, 777–786

In the central regions, the rotation curve shows the existence of a kinematically decoupled stellar component, offset with respect to the photometric center.

This inversion within the central regions with respect to the overall trend, reveals the presence of a counter-rotating decoupled core.

These features strongly suggest the existence of a small core (~600 pc) kinematically decoupled from the whole galaxy. Such anomalous Kinematically Decoupled Cores (KDC) are common in early-type galaxies and show very similar features to those observed in the nuclear regions of HCG62a: the velocity profile is characterized by a central asymmetry, to which corresponds an unusual central isophotal flattening

Kinematics of NGC 4778, Astronomy & Astrophysics, 2006, 457, 493–500

The prototype of polar ring galaxies NGC 4650A contains two main structural components, a central spheroid, which is the host galaxy, and an extended polar disk. Both photometric and kinematic studies revealed that these two components co-exist on two different planes within the central regions of the galaxy.

The PRGs are multi-spin systems composed of a central spheroid, which is the host galaxy, and a polar structure, which orbits nearly perpendicularly to the equatorial plane of the host galaxy. The latest studies on PRGs have revealed that this morphological type of galaxies includes both polar rings and polar disks, which have a different structure.

Why is it interesting to study PRGs? The multi-spin morphology of PRGs cannot be explained by the collapse of a single proto-galactic cloud, but some kind of interaction (galaxy/galaxy or galaxy-environment) needs to be invoked in the formation history of these systems.

Moreover, the existence of two orthogonal components of the angular momentum makes the PRGs the ideal laboratory to derive the three-dimensional shape of the gravitational potential.

How could a PRG form? To date, three main formation scenarios have been proposed for PRGs: 1) a major dissipative polar merger of two disk galaxies with unequal mass 2) the tidal accretion of external material (gas and/or stars), captured by an early-type galaxy on a parabolic encounter 3) the cold accretion of pristine gas along a filament

The polar disk galaxy NGC 4650A, Astronomy & Astrophysics, 2014, 569, A83

The obvious and main result is that stars and ionized gas have decoupled kinematics. Along the major axis the stars show ∼180 km/sec rotation at the outer radius. In the inner 1.5–2.0 arcsec (∼500 pc) the gas is counter-rotating compared to the stars, with the velocity steeply rising to ∼100 km/sec.

IC 4200: a gas-rich early-type galaxy, Astronomy & Astrophysics, 2006, 453, 493–506

We report the discovery of a kinematically decoupled core in NGC 4128.

HST observations of nuclear stellar disks, Astronomy & Astrophysics, 2004, 428, 877–890

At smaller radii, this disk is kinematically decoupled from the central stellar body; hence, in the region of the bright, central stellar

body, NGC 2685 appears to consist of two disks that share a common center, but have different orientation: a bright stellar lenticular body apparently devoid of dust and gas, and a heavily warped low-surface brightness disk containing stars, gas, and dust. The low surface-brightness disk changes its orientation gradually and at large radii assumes the orientation of the central stellar S0 disk. Since, according to our analysis, the intrinsic orientation of the low-surface-brightness disk changes through 70◦, the gaseous disk is coherent, and is at no radius oriented perpendicularly with respect to the central stellar body, NGC 2685 is not likely to be a classical polar-ring galaxy.

The warped "Spindle" NGC 2685, Astronomy & Astrophysics, 2009, 494, 489–508

All galaxies in the NS clump are fast rotators early type galaxies (ETGs), many of which show distinct nuclear components and kinematically decoupled cores.

This would explain the high fraction of kinematically decoupled components in the galaxies belonging to the clump.

The Fornax Deep Survey, Astronomy & Astrophysics, 2020, 639, A14

Results. The galaxy shows the following kinematically decoupled components (KDCs): a disk and a NSC. Our orbit-based dynamical Schwarzschild model revealed that the NSC is a distinct kinematic feature, and it constitutes the peak of metallicity and old ages in FCC 47. The main body consists of two counter-rotating populations and is dominated by a more metal-poor population.

This explains the negligible rotation in the outskirts of the galaxy as the two counter-rotating populations with warm orbits cancel each other’s rotation signatures while still showing a high velocity dispersion. This kinematic feature has been routinely observed in galaxies hosting extended counterrotating stellar components.

The early-type galaxy FCC 47, Astronomy & Astrophysics, 2019, 628, A92

These structures are generally decoupled both morphologically and kinematically from the host galaxy disk.

Moreover, these nuclear tori or disks appear to be decoupled from their host galaxies both morphologically and kinematically.

Studying the mechanisms responsible for this decoupling as well as the physical scales where they operate is thus crucial for proceeding in our understanding of the general question of the fueling and nuclear obscuration of active galaxies.

They detected apparent counterrotation in the nuclear region of this galaxy and interpreted this kinematic signature as evidence

of the warping of a thin inner molecular disk starting at an approximately outer radius of 1’’.

Seyfert galaxy NGC 3227, Astronomy & Astrophysics, 2019, 628, A65

We study the kinematically distinct components in two early-type galaxies NGC 448 and NGC 4365 aided by integral-field observations with the Multi-Unit Spectroscopic Explorer (MUSE) on the Very Large Telescope. The former galaxy has previously been shown to host a counter-rotating stellar disc while the latter harbors a central (apparently) decoupled core that has been suggested to not be physically distinct from the main body and instead stems from the different orbital types in the core and main body due to its triaxial nature. We aim to measure the brightness profiles, kinematics, and stellar population properties of the peculiar kinematic structures in these galaxies and shed light on their true nature and formation mechanism.

The two kinematically decoupled stellar components in NGC 448 have similar ages, but different chemical compositions. The distinct kinematic feature in NGC 448 has a nearly exponential surface-brightness light profile, dominates in the innermost 10’’, is smaller in size, and is very likely an embedded counter-rotating disc as also indicated by its kinematics. It has higher metallicity than the main galaxy stellar body and lower /Fe overabundance. By contrast, we do not find evidence for true decoupling in the two distinct kinematic components in NGC 4365. This confirms earlier work suggesting that the kinematically distinct core is likely not a separate dynamical structure, but most certainly likely a projection effect stemming from the orbital structure of this galaxy that was previously found to be intrinsically triaxial in shape.

Conclusions. Our findings indicate that the kinematically decoupled component in NGC 448 is truly decoupled, has external origin, and was formed through either the acquisition of gas and a subsequent star-formation episode or from the direct accretion of stars from a companion. Conversely, the presence of a kinematically distinct component in NGC 4365 is not associated to a true kinematic decoupling and is instead most likely due to a projection effect stemming from the triaxial nature of this galaxy.

NGC 448 and NGC 4365, Astronomy & Astrophysics, 2019, 623, A87

We present the discovery of a small kinematically decoupled core of (60 parsecs) in radius as well as an outflow jet in the archetypical AGN–starburst “composite” galaxy NGC 7130.

We interpret this as a tiny (radius 60 pc) kinematically decoupled nuclear disc, with a rotation axis offset by around 90 from that of the main body of the galaxy. Such discs are not uncommon.

AGN connection: NGC 7130, Astronomy & Astrophysics, 2019, 621, L5

Medium-resolution (MUSE) and high-resolution (Fabry-Perot) IFU spectroscopy confirms that the ionized gas is kinematically decoupled from the stellar component and indicates the presence of two kinematically distinct structures in the stellar disc.

This stellar velocity field shows a kinematically decoupled structure on the elongated feature emitting in Hα and in the nucleus of the galaxy not seen in previous data. This feature suggests that the stellar component associated with the nuclear starburst has a different origin than the outer disc.

Tracing Ionized Gas Emission, Astronomy & Astrophysics, 2018, 620, A164

Spiral Galaxy Internal Kinematics

“These galaxies may be supported dominantly by random motions.”

Structure of Star-forming Galaxies, The Astrophysical Journal, 2018, 854:70

“The other four AGNs, which do not show any rotation in the narrow component of Hα, may also have gravitational kinematics, such as a random motion.”

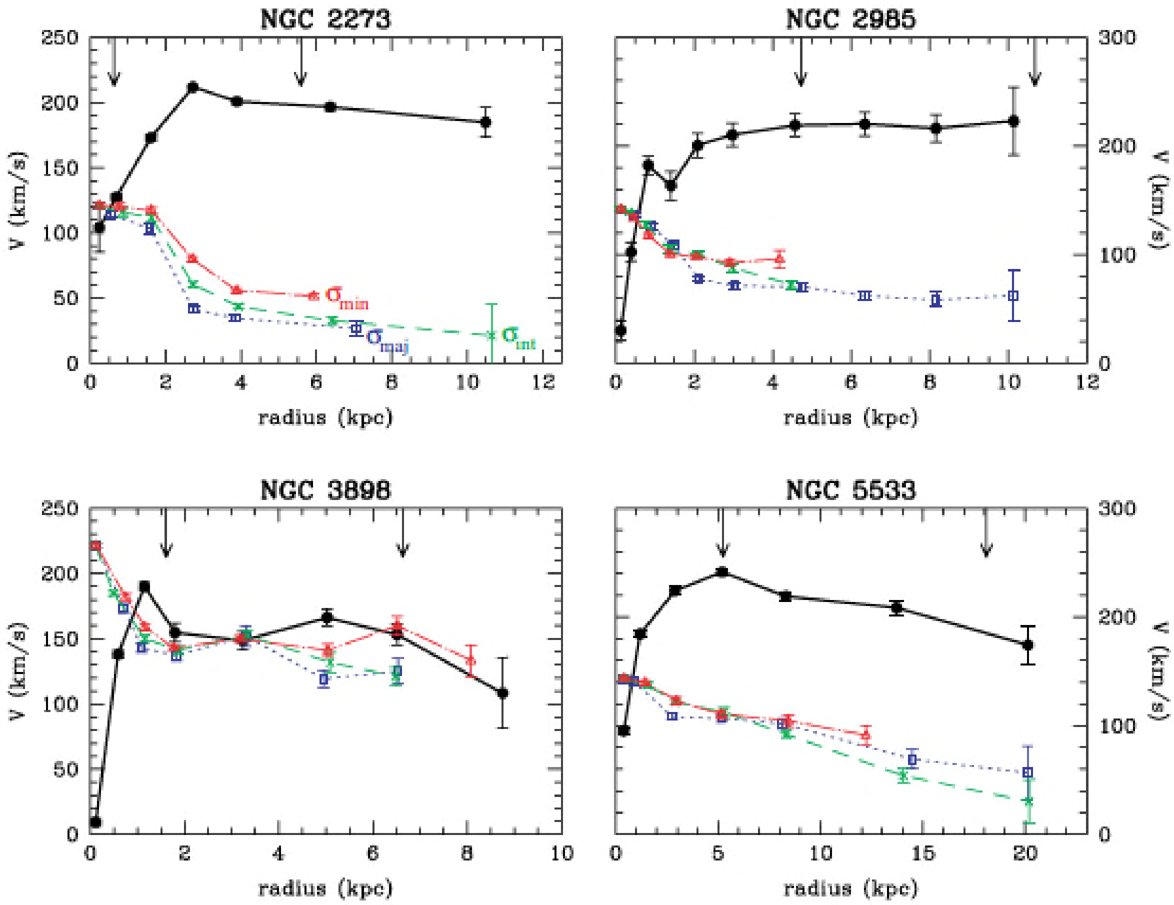
Spectroscopy of 20 Local AGNs, The Astrophysical Journal, 2017, 837:91

“The analysis of rotational over random motions in early-type galaxies, for instance, has led to the realization that bright early type galaxies are likely triaxial objects supported by orbital anisotropy, rather than rotation.”

Stellar kinematics across the Hubble sequence, Astronomy & Astrophysics, 2017, 597, A48

“The star-forming simulation we have compared the Milky Way to is not a particularly good match to it. Thus, the results presented here have focused on trends, not on detailed matches to observations. On the other hand, the very fact that this quite generic model produces trends that are also seen in the Milky Way argues very forcefully that the model captures the essential physics that produces these non-trivial trends, unless we are prepared to accept a quite remarkable coincidence.”

The bulge of the Milky Way, MNRAS, 2017, 469, 1587-1611



“This ‘asymmetric drift’ is exactly what one expects if the stars also have significant random velocities, so that the radial structure of the galaxy is not entirely supported against gravity by its rotational motion.”

Exploring disc galaxy dynamics, MNRAS, 2008, 388:1381-1393

“The radial profiles of the cylindrical rotation velocity (vf) and the velocity dispersions (σR, σf, σz) indicate that the models are dominated by random motion in their central region.”

“Thus, a spheroidal structure dominated by random motions—a bulge—is created after the short bar is destroyed.”

A New Channel of Bulge Formation, The Astrophysical Journal, 2020, 888:65

“Some observations have sufficient spatial and spectral resolution to derive the mass and age of the stars in the inner 50 pc. In the few cases for which this was done (e.g., Davies et al. 2007), the velocity field is dominated by random motion typical of a spherical system and the stellar mass is of the order of 10^8 M_o.”

Active Galactic Nuclei, ARAA, 2015. 53:365–408

“We investigate the manner in which lenticular galaxies are formed by studying their stellar kinematics: an S0 formed from a fading spiral galaxy should display similar cold outer disc kinematics to its progenitor, while an S0 formed in a minor merger should be more dominated by random motions.”

“However, at larger radii the kinematics undergo a gradual but major transition to random motion with little rotation.”

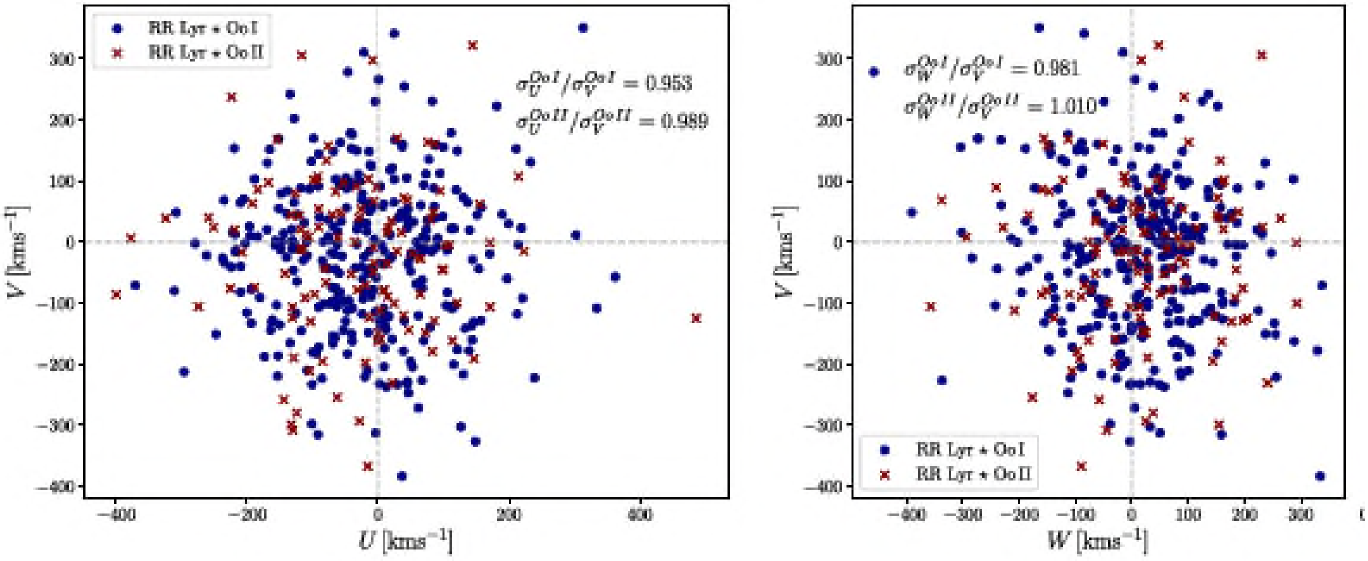
“As a result, the PN system becomes dominated again by random motions outside a radius of about 250 arcsec (14 kpc), with rotation only being dominant at intermediate radii (between 1.7 and 13 kpc).”

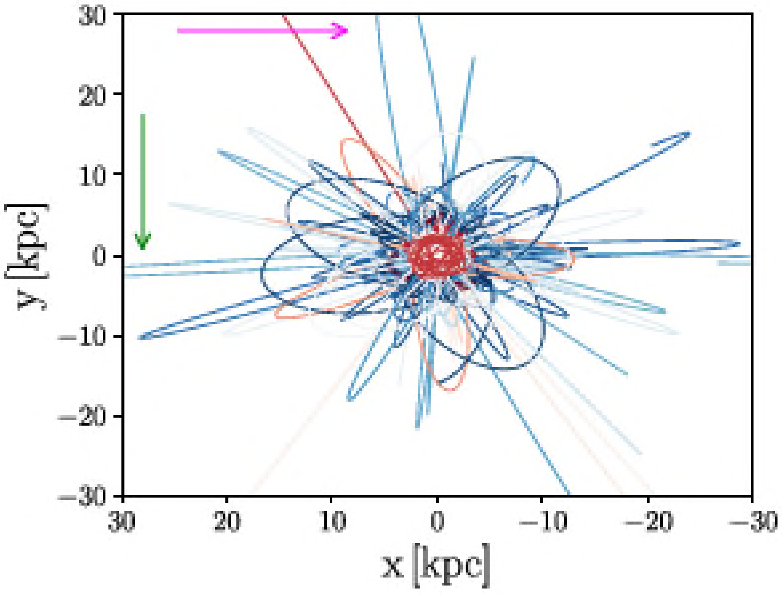
“Outside four disc scale lengths, the kinematics become completely dominated by random motions.”

Nebula kinematics in NGC 1023, MNRAS, 2008, 384:943-952

“Classical bulges formed via these processes seem to have little rotation as compared to the random motion. On the other hand, various observational measurements have confirmed that classical bulges in spiral galaxies possess rotation (Kormendy & Illingworth 1982; Cappellari et al. 2007) about their minor axis and in most cases in the same sense as the disc rotates. It is also known that classical bulges rotate faster than elliptical galaxies and that often their rotation velocities are comparable to that of an isotropic oblate rotator model (Binney 1978). So the origin of the systematic rotational motion observed in the classical bulges remains unclear.”

Classical bulges in barred galaxies, MNRAS, 421, 2012, 333-345





“The movement of the studied stars in the central region of the Galactic bulge is consistent with random motions expected for a classical bulge component.”

Oosterhoff dichotomy in the Galactic bulge, MNRAS 487, 2019, 3270-3278

Galaxy	Type	Rotation	Randomness	Galaxy	Type	Rotation	Randomness
NGC 4387	E	Fast	61%	NGC 2549	S00	Fast	44%
NGC 4564	E	Fast	42%	NGC 4150	S00	Fast	42%
NGC 4660	E	Fast	51%	NGC 3489	SAB0+	Fast	33%
NGC 2699	E:	Fast	57%	NGC 2695	SAB00	Fast	46%
NGC 5845	E:	Fast	64%	NGC 3032	SAB00	Fast	73%
NGC 3379	E1	Fast	86%	NGC 4526	SAB00	Fast	46%
NGC 4278	E1-2	Fast	81%	NGC 1023	SB0−	Fast	65%
NGC 2974	E4	Fast	30%	NGC 3384	SB0−	Fast	56%
NGC 4473	E5	Fast	78%	NGC 4262	SB0−	Fast	76%
NGC 4621	E5	Fast	75%	NGC 4546	SB0−	Fast	40%
NGC 3377	E5-6	Fast	51%	NGC 4477	SB0−	Fast	79%
NGC 2768	E6	Fast	76%	NGC 2685	SB0+	Fast	12%
NGC 821	E6	Fast	74%	NGC 4458	E0-1	Slow	88%
NGC 4270	S0	Fast	60%	NGC 4552	E0-1	Slow	95%
NGC 4570	S0	Fast	47%	NGC 5846	E0-1	Slow	97%
NGC 7332	S0	Fast	68%	NGC 4486	E0-1+	Slow	98%
NGC 5308	S0−	Fast	55%	NGC 4374	E1	Slow	97%
NGC 5838	S0−	Fast	49%	NGC 5813	E1-2	Slow	86%
NGC 7457	S0−	Fast	38%	NGC 5198	E1-2	Slow	93%

NGC 3156	**S0:**	**Fast**	**12%**	**NGC 3608**	**E2**	**Slow**	**95%**
NGC 524	**S0+**	**Fast**	**71%**	**NGC 5831**	**E3**	**Slow**	**92%**
NGC 4382	**S0+**	**Fast**	**84%**	**NGC 5982**	**E3**	**Slow**	**92%**
NGC 4459	**S0+**	**Fast**	**55%**	**NGC 3414**	**S0**	**Slow**	**91%**
NGC 474	**S00**	**Fast**	**79%**	**NGC 4550**	**SB00**	**Slow**	**90%**

“We construct the anisotropy diagram, which relates the ratio of the ordered and random motion in a galaxy (V/σ) to its observed ellipticity (ε), for the 48 E/S0 galaxies from the SAURON survey.”

Orbital anisotropy of elliptical and lenticular galaxies, MNRAS, 379, 2007, 418-444

Double Barred Galaxies

Column (1) Galaxy name.

Column (2) Position angle of the outer disk.

Column (3) Bar/disk position angle.

Column (4) Bar/disk semimajor axis of maximum isophotal ellipticity a (lower limit on bar size).

Column (5) Semi-major axis of minimum ellipticity arc min outside a.

Column (6) Semi-major axis.

Column (7) Length bar (upper limit on bar size – usually the minimum of arc min and the semi-major axis).

Column (8) Maximum isophotal ellipticity of the bar or inner disk.

Column (9) Nuclear ring present?

1	2	3	4	5	6	7	8	9
Double-Barred Galaxies								
NGC 357	**20**	**120**	**21**	**28**	**27**	**27**	**0.44**	
*		**45**	**3.1**	**5.7**	**4.4**	**4.4**	**0.16**	
NGC 718	**5**	**152**	**20**	**33**	**30**	**30**	**0.23**	**Y**
*		**15**	**1.6**	**4**	**3.6**	**3.3**	**0.19**	
NGC 1068	**98**	**12**	**54**	**75**	**89**	**75**	**0.24**	**Y**
*		**47**	**15**	**27**	**...**	**17**	**0.45**	
NGC 1097	**134**	**147**	**88**	**120**	**...**	**107**	**0.67**	**Y**
*		**30**	**7.5**	**8.1**	**7.7**	**7.7**	**0.46**	
NGC 1241	**145**	**110**	**18**	**24**	**23**	**18**	**0.6**	**Y**
*		**0**	**1.5**	**...**	**2.1**	**1.8**	**0.31**	
NGC 1291	**...**	**171**	**89**	**130**	**140**	**130**	**0.39**	
*		**15**	**18**	**26**	**24**	**24**	**0.24**	

NGC 1317	**78**	**150**	**41**	**59**	**58**	**58**	**0.27**	**Y**
*****		**56**	**6.3**	**11**	**9.7**	**6.4**	**0.44**	
NGC 1433	**21**	**97**	**74**	**110**	**150**	**90**	**0.7**	**Y**
*****		**32**	**6.2**	**13**	**12**	**12**	**0.38**	
NGC 1543	**…**	**92**	**63**	**95**	**…**	**95**	**0.49**	**Y**
*****		**26**	**7.9**	**12**	**12**	**11**	**0.29**	
NGC 1808	**133**	**144**	**80**	**114**	**…**	**114**	**0.66**	**Y**
*****		**158**	**3.3**	**5.9**	**4.8**	**4.8**	**0.53**	
NGC 2217	**5**	**136**	**37**	**…**	**…**	**50**	**0.47**	
*****		**112**	**7.8**	**11**	**14**	**11**	**0.19**	
NGC 2642	**140**	**115**	**25**	**…**	**29**	**26**	**0.64**	**Y**
*****		**145**	**1.5**	**2.7**	**2.7**	**2**	**0.3**	
NGC 2646	**…**	**82**	**16**	**21**	**21**	**21**	**0.48**	
*****		**8**	**2.2**	**4.6**	**3.5**	**3.5**	**0.25**	
NGC 2681	**140**	**30**	**50**	**75**	**60**	**60**	**0.23**	**Y**
*****		**73**	**18**	**23**	**19**	**19**	**0.33**	
*****		**20**	**1.7**	**3.9**	**3.3**	**3.3**	**0.26**	
NGC 2859	**90**	**162**	**34**	**52**	**43**	**43**	**0.4**	**Y**
*****		**62**	**4.1**	**11**	**6.2**	**6.2**	**0.31**	
NGC 2950	**120**	**162**	**24**	**41**	**31**	**31**	**0.43**	**Y**
*****		**85**	**3.2**	**6.3**	**3.9**	**3.9**	**0.33**	
NGC 2962	**10**	**168**	**29**	**43**	**…**	**43**	**0.3**	
*****		**93**	**3.5**	**…**	**4.2**	**4.2**	**0.03**	
NGC 3081	**97**	**69**	**33**	**41**	**…**	**35**	**0.65**	**Y**
*****		**122**	**5.7**	**8.6**	**7.1**	**5.8**	**0.5**	
NGC 3275	**122**	**120**	**28**	**36**	**48**	**36**	**0.58**	**Y**
*****		**172**	**2.1**	**3.5**	**2.7**	**2.6**	**0.31**	
NGC 3358	**125**	**98**	**16**	**21**	**24**	**21**	**0.42**	
*****		**136**	**4.9**	**8.3**	**11**	**8.3**	**0.32**	
NGC 3368	**172**	**115**	**61**	**80**	**75**	**75**	**0.4**	**Y**
*****		**129**	**3.4**	**6.8**	**5.9**	**5**	**0.35**	
NGC 3393	**…**	**157**	**13**	**16**	**23**	**16**	**0.44**	

*		146	1.9	3.5	3.1	3.1	0.2	
NGC 3941	10	166	21	36	32	32	0.47	
*		85	3.2	4.7	4.4	4.4	0.21	
NGC 3945	158	72	32	41	39	39	0.29	Y
*		90	2.6	3	3	3	0.11	
NGC 4303	138	179	29	50	48	34	0.5	Y
*		40	1.8	2.8	2.5	2.5	0.29	
NGC 4314	65	146	67	90	111	80	0.64	Y
*		136	4.5	5.8	5.6	5.6	0.23	
NGC 4321	153	107	55	61	80	58	0.54	Y
*		110	8.2	15	10	10	0.62	
NGC 4340	95	31	39	51	48	48	0.39	Y
*		25	3.4	5.1	4.7	4.5	0.11	
NGC 4503	12	6	23	27	...	27	0.48	
*		45	2.9	4.8	6	4.8	0.25	
NGC 4725	40	50	118	130	170	125	0.67	
*		141	5.6	7.3	6.8	6.8	0.2	
NGC 4736	113	90	125	170	...	170	0.23	Y
*		25	11	21	20	20	0.22	
NGC 4785	81	66	11	13	16	12	0.57	Y
*		127	0.9	1.1	1.2	1.1	0.21	
NGC 4984	15	95	30	...	38	32	0.3	Y
*		64	4	5	4.9	4.9	0.23	
NGC 5365	4	108	25	33	31	31	0.25	Y
*		35	3.7	16	5.3	5.3	0.28	
NGC 5728	2	33	56	71	...	71	0.71	Y
*		86	1.8	4.2	3.7	3.7	0.49	
NGC 5850	163	116	63	84	...	75	0.68	Y
*		50	5.9	9.2	7.6	7.1	0.3	
NGC 6654	0	17	26	47	38	38	0.51	
*		135	2.7	4.4	4.2	4.2	0.15	
NGC 6684	36	150	26	33	29	28	0.25	

*		68	2.9	6.2	4.1	4.1	0.35	
NGC 6782	45	178	25	30	33	30	0.54	Y
*		147	3.4	4.5	4.3	3.8	0.47	
NGC 7098	75	46	38	53	56	53	0.57	
*		71	9.1	12	18	12	0.32	
NGC 7187	134	66	19	28	22	19	0.37	Y
*		54	2.5	3.8	3.5	3.5	0.19	
NGC 7280	72	55	11	29	27	27	0.4	
*		115	1.2	2.2	1.6	1.6	0.3	
NGC 7716	35	25	22	28	25	25	0.35	
*		57	3.1	5.4	5.6	5.4	0.38	
MRK 573	…	0	9	12	…	12	0.33	Y
*		83	1.2	3.1	…	2.1	0.31	
UGC 524	120	143	8.5	11	12	11	0.54	Y
*		167	1	1.1	1.3	1.1	0.43	
ESO 215-G031	130	147	38	…	…	47	0.63	Y
*		153	5.3	9.5	6.2	6.2	0.48	
ESO 320-G030	121	142	23	…	41	37	0.64	
*		107	3.9	5.2	4.5	4.5	0.32	
ESO 443-G039	14	27	11	19	25	19	0.51	
*		44	1.8	2.4	2.7	2.4	0.24	
ESO 447-G030	35	133	13	15	14	14	0.17	Y
*		177	2.8	9.7	3.6	3.6	0.36	
IRAS 03565+2139	…	4	13	18	20	15	0.6	Y
*		124	1.6	3.3	3	1.9	0.33	
Inner-Disk Galaxies								
NGC 151	75	152	18	23	21	21	0.44	Y
*		74	4.3	7.1	6.1	6.1	0.32	
NGC 470	155	18	21	30	26	26	0.55	
*		152	2.7	7.4	11	7.4	0.46	
NGC 1398	96	9	38	46	44	44	0.36	
*		96	2.9	8.2	7.9	7.9	0.18	

NGC 2787	**109**	**160**	**29**	**36**	**36**	**36**	**0.34**	
*****		**113**	**18**	**22**	**21**	**21**	**0.34**	
NGC 2880	**144**	**82**	**8**	**9**	**10**	**9**	**0.2**	
*****		**138**	**3**	**5.6**	**4.5**	**4.5**	**0.22**	
NGC 3266	**85**	**8**	**10**	**14**	**13**	**13**	**0.29**	**Y**
*****		**90**	**0.8**	**2.4**	**1.8**	**1.8**	**0.12**	
NGC 3368	**172**	**115**	**61**	**80**	**75**	**75**	**0.4**	**Y**
*****		**162**	**21**	**35**	**30**	**30**	**0.3**	
NGC 3384	**50**	**132**	**15**	**...**	**17**	**17**	**0.05**	
*****		**46**	**2.7**	**15**	**11**	**11**	**0.4**	
NGC 3412	**153**	**100**	**15**	**21**	**21**	**21**	**0.26**	
*****		**154**	**1**	**8.3**	**6.1**	**6.1**	**0.33**	
NGC 3945	**158**	**72**	**32**	**41**	**39**	**39**	**0.29**	**Y**
*****		**158**	**10**	**19**	**18**	**18**	**0.36**	
NGC 4143	**144**	**163**	**17**	**...**	**28**	**28**	**0.38**	
*****		**142**	**4.2**	**6.2**	**...**	**6.2**	**0.25**	
NGC 4262	**153**	**18**	**13**	**20**	**16**	**16**	**0.34**	
*****		**155**	**3.5**	**4.4**	**4.7**	**4.4**	**0.1**	
NGC 4386	**140**	**134**	**25**	**36**	**...**	**36**	**0.52**	
*****		**141**	**2.4**	**3.2**	**...**	**3.2**	**0.28**	
NGC 4612	**143**	**83**	**17**	**24**	**20**	**20**	**0.22**	
*****		**144**	**3**	**5.7**	**5.5**	**5.5**	**0.21**	
NGC 4754	**23**	**142**	**23**	**27**	**30**	**27**	**0.23**	
*****		**22**	**6.7**	**9.4**	**12**	**9.4**	**0.23**	
NGC 4785	**81**	**66**	**11**	**13**	**16**	**12**	**0.57**	**Y**
*****		**83**	**5.2**	**6.7**	**8.4**	**6.7**	**0.41**	
NGC 7007	**2**	**116**	**6.2**	**8.1**	**7.6**	**7.6**	**0.26**	
*****		**0**	**2.3**	**3.7**	**2.9**	**2.9**	**0.2**	
NGC 7187	**134**	**66**	**19**	**28**	**22**	**19**	**0.37**	**Y**
*****		**134**	**7.2**	**9.4**	**8.6**	**8.6**	**0.12**	
UGC 6062	**25**	**159**	**12**	**17**	**15**	**15**	**0.39**	
*****		**27**	**1.9**	**2.8**	**3.4**	**2.8**	**0.39**	

ESO 378-G020	**34**	**81**	**6.9**	**8.3**	**8.8**	**8.3**	**0.37**	
*****		**39**	**0.8**	**1.3**	**…**	**1.3**	**0.42**	
ESO 443-G017	**23**	**160**	**9.6**	**15**	**12**	**12**	**0.48**	
*****		**31**	**2.3**	**5.5**	**4.2**	**4.2**	**0.28**	

Column (1) Galaxy name.

Column (2) Difference in position angle between inner bar or disk and outer bar.

Positive = inner bar/disk leads outer bar,

Negative = inner bar/disk trails,

Values in parentheses are for galaxies where the sense of rotation is undefined.

Column (3) The semi-major axis.

Column (4) The bar length.

Column (5) The semi-major axis relative to galaxy size.
Column (6) The bar length relative to galaxy size.

“I present a catalog of 67 barred galaxies which contain distinct, elliptical stellar structures inside their bars. Fifty of these are double-barred galaxies: a small-scale, inner or secondary bar is embedded within a large-scale, outer or primary bar. I provide homogenized measurements of the sizes, ellipticities, and orientations of both inner and outer bars, along with global parameters for the galaxies. The other 17 are classified as inner-disk galaxies, where a large-scale bar harbors an inner elliptical structure which is aligned with the galaxy’s outer disk. Four of the double-barred galaxies also possess inner disks, located in between the inner and outer bars.”

Double-barred galaxies, Astronomy & Astrophysics, 2004, 415, 941-957

“Double-barred galaxies account for almost one third of all barred galaxies, suggesting that secondary stellar bars, which are

embedded in large-scale primary bars, are long-lived structures. However, up to now it has been hard to self-consistently simulate a disc galaxy that sustains two nested stellar bars for longer than a few rotation periods.”

“However, the lifetime of any nuclear bar must be long enough to be compatible with the high frequency of double-bars: 30% of barred galaxies or 20% of all galaxies.”

How can double-barred galaxies be long-lived? Astronomy & Astrophysics, 2015, 575, A7

The ratio of pattern speeds in double-barred galaxies, MNRAS, 2014, 444, L85-L89

“Double bars are thought to be important features for secular evolution in the central regions of galaxies. However, observational evidence about their origin and evolution is still scarce.”

“Still, little is known about the origin of inner bars and now, 40 yr later, NGC 1291 strikes again providing a new piece of evidence to unveil the formation of the central regions of galaxies.”

The double-barred galaxy NGC 1291, MNRAS, 2019, 482, L118-L122

“Double-barred galaxies are structurally complex systems due to the coexistence of several axisymmetric and non-axisymmetric components within a disc galaxy, namely disc, outer bar, inner bar, and most likely a bulge. Other structures, such as spiral arms, inner discs, and lenses, may be present as well.”

Deconstructing double-barred galaxies, MNRAS, 2020, 494, 1826-1837

Galaxy	DB	NR	NRS	OPG	NS	ID	Dusty
NGC-718	**DB**	**NR**					
NGC-936			**NRS**				
NGC-2273		**NR**			**NS**		
NGC-2655				**OPG**			**Dusty**
NGC-2681	**DB**	**NR**					
NGC-2685				**OPG**		**ID**	
NGC-2787				**OPG**		**ID**	**Dusty**
NGC-2859	**DB**	**NR**					
NGC-2880						**ID**	
NGC-2950	**DB**		**NRS**				
NGC-2962	**DB**						
NGC-3032					**NS**		
NGC-3412						**ID**	
NGC-3489		**NR**					**Dusty**
NGC-3941	**DB**			**OPG**			
NGC-3945	**DB**		**NRS**			**ID**	
NGC-4143		**ID**			**NS**	**ID**	
NGC-4203				**OPG**			
NGC-4245		**NR**			**NS**		
NGC-4314	**DB**				**NS**		
NGC-4386						**ID**	
NGC-4643					**NS**	**ID**	
NGC-5377		**NR**			**NS**		
NGC-5701					**NS**		
NGC-6654	**DB**						
NGC-7280	**DB**			**OPG**			
NGC-7743					**NS**		

‘‘DB’’ = galaxy is double barred (i.e., inner/secondary bar found inside primary bar);

‘‘ID’’ = inner disk;

‘‘NR’’ = nuclear ring;

‘‘NRS’’ = stellar nuclear ring;

‘‘NS’’ = nuclear spiral;

‘‘OPG’’ = evidence for off-plane gas or dust (such as a polar ring);

‘‘Dusty’’ = too dust obscured to determine presence or absence of central stellar structures.

Double Bars, Inner Disks, And Nuclear Rings, The Astronomical Journal, 2002, 124:65-77

Globular Cluster Internal Kinematics

“Our results show that for some systems the bimodality in GC color is also present in GC kinematics. The kinematics of the red GC subpopulations are strongly coupled with the host galaxy stellar kinematics. The blue GC subpopulations are more dominated by random motions, especially in the outer regions, and decoupled from the red GCs. Peculiar GC kinematic profiles are seen in some galaxies: the blue GCs in NGC 821 rotate along the galaxy minor axis, whereas the GC system of the lenticular galaxy NGC 7457 appears to be strongly rotation supported in the outer region.”

Kinematics for over 2500 globular clusters, MNRAS 428, 2013, 389-420

“The GCs with extended HB are more massive than normal GCs and are dominated by random motion with no correlation between kinematics and metallicity.”

Kinematic Decoupling Of Globular Clusters, The Astrophysical Journal, 2007, 661:L49-L52

“Velocities of the members of M15 plotted against radius. The velocity dispersion decreases as expected with radius until about 7@. The velocity dispersion then appears to increase again. The point at negative radius indicates the inferred mean and its uncertainty. In this case the probability distribution is symmetric.”

“Velocities for all the stars observed in this study plotted against their radial positions. The cluster stands out as the clump with

velocity near [107 km s~1. The stars around zero velocity are disk stars, while the stars with very negative velocities probably belong to the halo.”

Global Kinematics Of The Globular Cluster M15, The Astronomical Journal, 1998, 115:708-724

“Violent relaxation is a collisionless process driven by fluctuations in the cluster potential during collapse. Thereafter, once the cluster has reached a steady state, the system undergoes collisional relaxation: over time, as stars experience two-body interactions that affect small changes to their orbits, their motions become more random, i.e., they move toward isotropy.”

Catalogs Of Galactic Globular Clusters, The Astrophysical Journal, 2015, 803:29

“For 6 out of the 11 rotating GCs we find counter clockwise rotation (positive values of the mean t) while the other 5 display clockwise rotation. This is consistent with a random distribution of rotation patterns, indicating that the observed rotation is not due to systematics.”

The internal rotation of globular clusters, MNRAS, 2018, 481:2125-2139

“The kinematics of the red GC subpopulations are strongly coupled with the host galaxy stellar kinematics. The blue GC sub populations are more dominated by random motions, especially in the outer regions, and decoupled from the red GCs.”

“Our analysis suggests that in the inner regions both GC subpopulations have isotropic or tangential orbits, whereas in the outer regions there is a hint that some red GC systems might have radial orbits. We recognise that in both cases the GC orbits are still consistent with being isotropic.”
Kinematics and dynamics of extragalactic globular clusters, Swinburne University, Vincenzo Pota, 2014

“A typical GC star completed hundreds of orbits within the cluster potential and the chance of interaction with another star, which changes its orbit, is significant. The effect of a large number of interactions is to randomize the directions of individual orbits and to lead toward an isotropic velocity distribution tending to a Maxwellian-like distribution.”

“The relative strength of ordered over random motions (ξ) appear to weakly correlate with the half-mass relaxation time, with the GCs with longer relaxation times rotating faster. This suggests a primordial origin for the rotation of these stellar systems which is

progressively erased by both internal and external dynamical processes.”

Proceedings IAU Symposium No. 351, 2019, https://doi.org/10.1017/S1743921319007099

In particular, since the distribution of orbital planes relaxes much more rapidly than the distribution of the magnitude of angular momentum and the radial action, the relaxation process reaches an internal statistical equilibrium in the corresponding part of phase space while the whole cluster is generally out of equilibrium, in a state of quenched disorder.

Their method is based on the assumption that the rate of precession is much faster than the rate at which the orbital planes change their orientation.

The coherent evolution of the angular momentum directions (i.e., the orbital planes) is self quenching because as the orbital planes pivot, so do the torques they generate.

While Equation (9) breaks down when the orbital planes have on average changed by ∼1 rad, a better description is provided by the angular correlation function C(μ, Δt), which specifies how the angular momentum direction distribution function at time t0 correlates with that at time t0 + Δt for angular separations μ = cosθ.

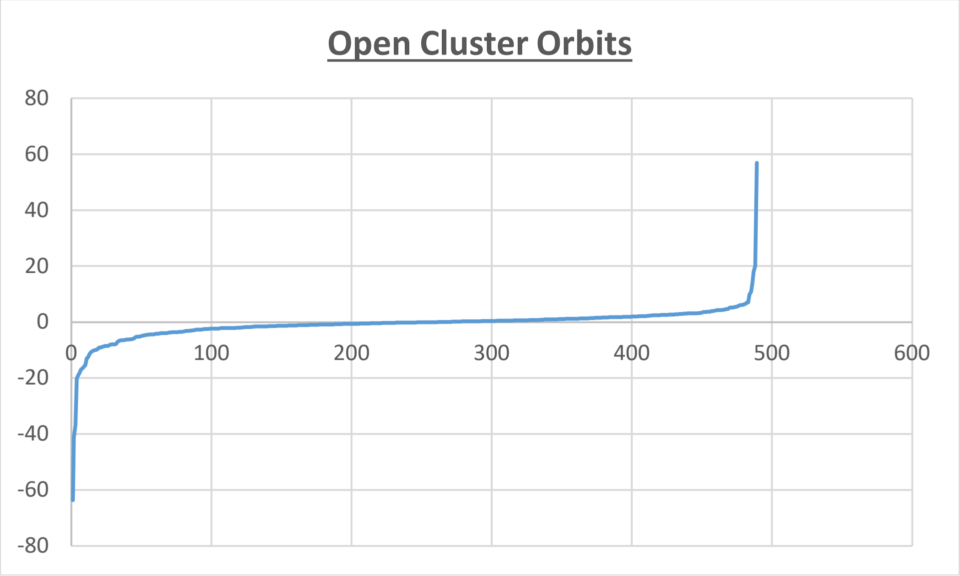
In particular, since the distribution of orbital planes relaxes much more rapidly than the distribution of the magnitude of angular momentum and the radial action, the relaxation process reaches an internal statistical equilibrium in the corresponding part of phase space, while the whole cluster is generally out of equilibrium, in a state of quenched disorder.

Resonant Relaxation in Globular Clusters, The Astrophysical Journal, 2019, 878:138

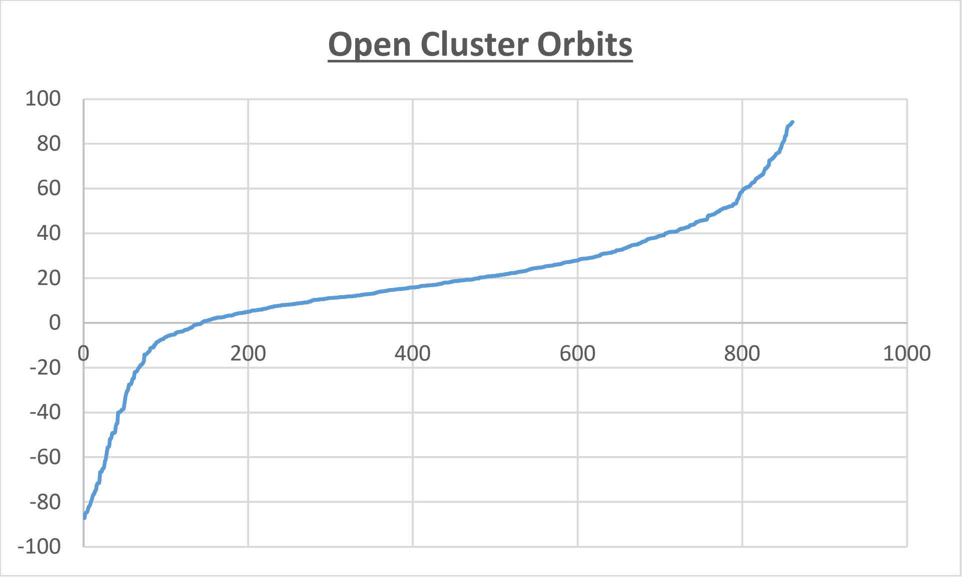
Globular Cluster Orbits

The orbits of open clusters in the Galaxy

Orbit	Orbit	Orbit	Qty	Percent
Anti-Center	**Prograde**	**North**	**97**	**19.88%**
Anti-Center	**Prograde**	**South**	**109**	**22.34%**
Anti-Center	**Retrograde**	**North**	**1**	**00.20%**
Center	**Prograde**	**Equatorial**	**1**	**00.20%**
Center	**Prograde**	**North**	**130**	**26.64%**
Center	**Prograde**	**South**	**151**	**30.94%**



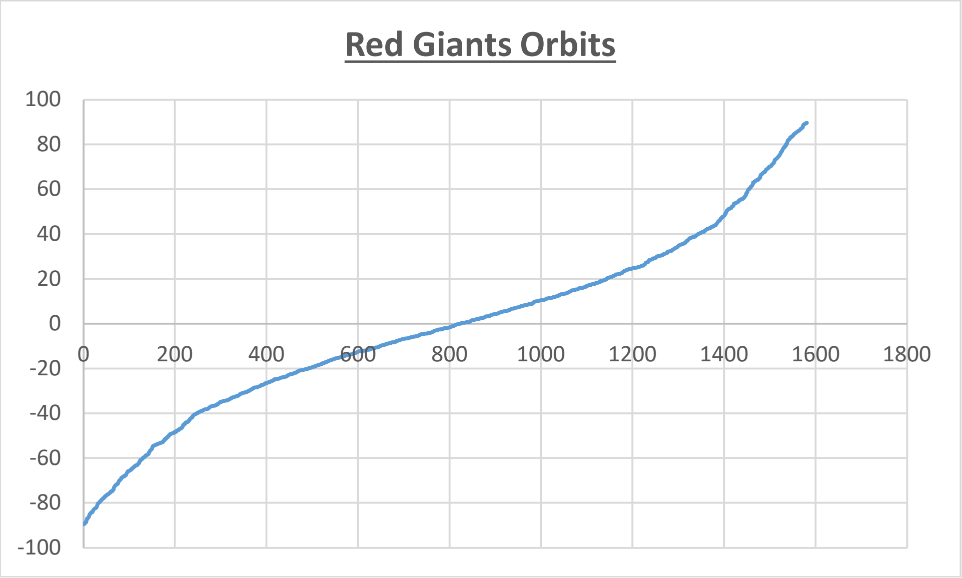
The orbits of open clusters in the Galaxy, *MNRAS, 2009, 399:2146-2164*



Open cluster kinematics with Gaia DR2, Astronomy & Astrophysics, 2018, 619, A155

Red Giant orbits in the outer Halo

Orbit	Orbit	Orbit	Qty	Percent
Anti-Centre	**Retrograde**	**North**	**14**	**27.45%**
Anti-Centre	**Retrograde**	**South**	**13**	**25.49%**
Centre	**Prograde**	**South**	**1**	**01.96%**
Centre	**Retrograde**	**North**	**8**	**15.69%**
Centre	**Retrograde**	**South**	**15**	**29.41%**



The Origin Of Globular Clusters In The Milky Way, *The Astrophysical Journal, 2013, 769:87*

Globular Cluster orbits in the outer Halo

X	**Y**	**Z**	Quantity	Percent
Centre	**Retrograde**	**South Pole**	24	47.06%
Anti-Centre	**Retrograde**	**South Pole**	4	7.84%

Anti-Centre	**Retrograde**	**North Pole**	22	43.14%
Anti-Centre	**Prograde**	**North Pole**	1	1.96%

The Origin Of Globular Clusters In The Milky Way, *The Astrophysical Journal, 2013, 769:87*

Orbit	Orbit	Orbit	Red Giants	Red Giants	Globular	Globular
X	Y	Z	Qty	%	Qty	%
Anti-Center	Prograde	North	97	19.88%	1	1.96%
Anti-Center	Prograde	South	109	22.34%	0	0
Anti-Center	Retrograde	North	1	0.20%	22	43.14%
Centre	Prograde	Equatorial	1	0.20%	0	0
Centre	Prograde	North	130	26.64%	0	0
Centre	Prograde	South	151	30.94%	0	0
Centre	Retrograde	South	0	0	24	47.06%
Anti-Centre	Retrograde	South	0	0	4	7.84%

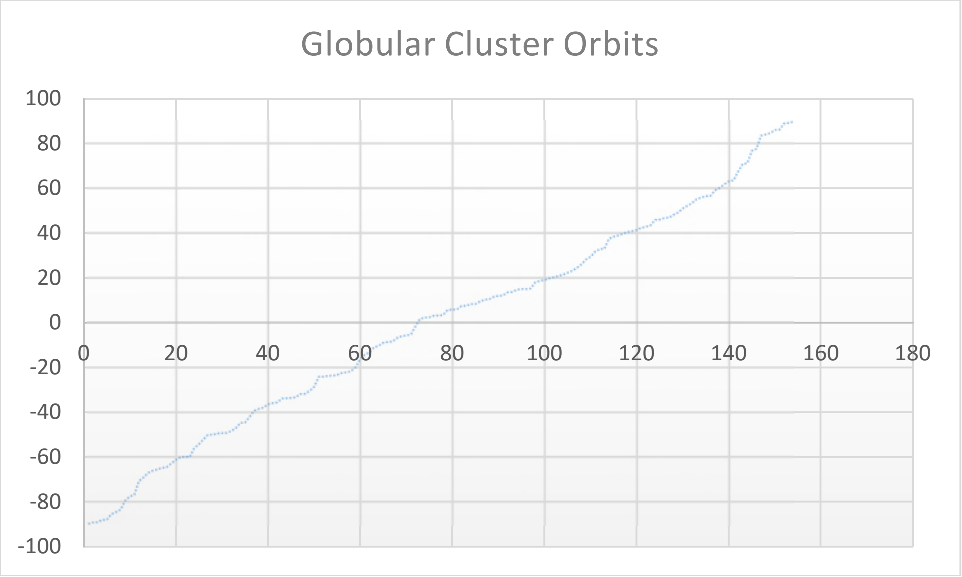
The Origin Of Globular Clusters In The Milky Way, *The Astrophysical Journal, 2013, 769:87*

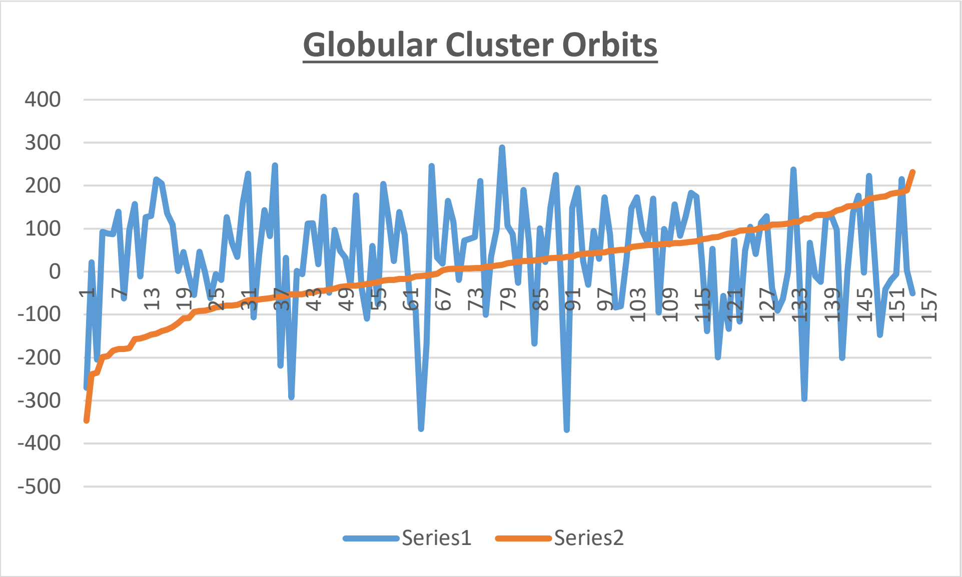
Orbit	Orbit	Orbit	Open	Open	Globular	Globular
X	Y	Z	Qty	%	Qty	%
Anti-Center	Prograde	North	97	19.88%	1	1.96%
Anti-Center	Prograde	South	109	22.34%	0	0
Anti-Center	Retrograde	North	1	0.20%	22	43.14%
Center	Prograde	Equatorial	1	0.20%	0	0
Center	Prograde	North	130	26.64%	0	0
Center	Prograde	South	151	30.94%	0	0
Centre	Retrograde	South	0	0	24	47.06%
Anti-Centre	Retrograde	South	0	0	4	7.84%

The Origin Of Globular Clusters In The Milky Way, *The Astrophysical Journal, 2013, 769:87*

“This plot shows a system dominated by random motion, with the GC kinematics concentrated around the M87 systemic velocity Vsys = 1308 km s-1, together with a scattered distribution of high- and low-velocity objects on both sides of the galaxy.”

Globular Clusters in the Core of the Virgo Cluster, The Astrophysical Journal, 2018, 864:36





Galactic globular clusters, MNRAS, 2019, 482, 5138-5155

Globular Cluster Formation Theories

“Several other problems with the major merger model were pointed out in Forbes, Brodie & Grillmair. For example, they showed that there is a correlation between SN and the fraction of metal-poor GCs, such that the highest SN galaxies also have the highest proportion of metal-poor GCs.”

“Scannapieco, Weisheit & Harlow (2004) proposed a somewhat similar mechanism, in which gas in minihaloes is shock-compressed by galaxy outflows. The momentum of the shock strips the gas from the halo, nicely solving the dark-matter problem. However, this model predicts a mass–radius relation for individual GCs, and the observed lack of such a relation may deal this picture a fatal blow.”

Extragalactic Globular Clusters and Galaxy Formation, ARAA, 2006. 44:193-267

The globular cluster system of NGC 1399, Astronomy & Astrophysics, 2010, 513, A52

The globular cluster system of NGC 4278, MNRAS, 2013, 436, 1172-1190

“A number of theories have been put forward to explain the observed anomalies, most of which invoke the formation of a second

stellar population within an existing massive cluster (the first generation) from material processed in the first stellar generation. These theories, while explaining many of the chemical and photometric anomalies, all have a ‘mass budget problem’, and require the first generation to have been significantly more massive than observed today, in conflict with observations of the nearby Fornax dwarf galaxy.”

Constraining globular cluster formation, MNRAS, 2013, 436, 2852-2863

Constraining globular cluster formation, MNRAS, 2014, 445, 378-384

First Evidence Of Globular Cluster Formation, The Astrophysical Journal Letters, 2012, 751:L35

“One of the remarkable observational facts about the stellar content of galaxies is the ubiquity of globular star clusters. These clusters can be found in almost all but the least massive galaxies. Generally globular clusters come in two major families of comparable mass: metal-poor, old blue clusters and metal-richer, younger, red clusters.”

Globular Cluster Formation And Galaxy Evolution, The Astrophysical Journal, 2009, 691:1248-1253

“A self-consistent description of the formation of globular clusters remains a challenge to theorists. A particularly puzzling observation is the apparent bimodality, or even multimodality, of the color distribution of globular cluster systems in galaxies ranging from dwarf disks to giant ellipticals.”

The Metallicity Distribution Of Globular Clusters, The Astrophysical Journal, 2010, 718:1266-1288

The Origin Of Globular Clusters In The Milky Way, The Astrophysical Journal, 2013, 769:87

“Number density maps of Virgo’s GCs show a complex 2D structure surrounding the large early-type galaxies in the cluster. Many of the GCs are located near the core of the Virgo cluster, the massive subcluster Virgo A. The Virgo cluster contains a total population of 67,300 ± 14,400 GCs, with a significant fraction (~35%) of these lying within the GC systems of M87 and M49 alone.”

Globular Clusters In The Core Of The Virgo Cluster, The Astrophysical Journal, 2014, 794:103

Their formation is an exciting but yet unsolved problem. For instance, it is still an open question whether Galactic halo GCs formed out of gas already chemically enriched (pre-enrichment models) or whether they produced their own heavy elements through an earlier generation of stars within the GC progenitor itself (self -enrichment models).

Self-enrichment of Galactic halo globular clusters, MNRAS, 2004, 351, 585–598

Formation of globular clusters in galaxy mergers, The Astrophysical Journal, 2004, 614:L29–L32

“The formation of GCs remains poorly understood (see Brodie & Strader 2006 for a summary).”

Globular Cluster Formation within a Cosmological Context, The Astrophysical Journal, 2009, 706:L192–L196

Dwarf Detachment and Globular Cluster Formation, http://aspbooks.org/custom/publications/paper/423-0032.html

“We test an alternate model in which metal rich GCs form in dwarf galaxies that become stripped as they merge with the main halo. This process is inconsistent with observed metal-rich globulars in the Milky Way because it predicts spatial distributions that are far too extended.”

“These observations have motivated a number of competing galaxy and GC formation scenarios, which attempt to explain the bimodal colours, but no conclusive theory has emerged. However, the very existence of the bimodal colors is indicative of two epochs of star formation. In view of the large amount of data collected, there is a strong need for more detailed theoretical work that will provide specific predictions of where and when GCs formed.”

“In contrast with the extensive gains from observational studies of GCs, it has proven very difficult to predict the full range of observed GC properties in a self-consistent manner from theoretical models. The mass and spatial scales needed to study the physical conditions of GC formation are very difficult to simulate numerically in large models.”

“The Milky Way metal-rich GC population is more centrally concentrated than is the metal-poor one. This is a problem for any formation model that invokes accretion from haloes more massive, and hence later forming than those used to define the metal-poor population.”

Globular Cluster Formation, MNRAS, 2010, 405, 375–386

Modeling Formation of Globular Clusters, X

“The origin of ultracompact dwarf (UCD) galaxies, compact extragalactic stellar systems, is still a puzzle for present galaxy formation models.”

“We conclude this paper with a brief discussion on the origin of UCDs. One can break down the currently discussed formation channels (see Introduction) into two concepts.

(i) UCDs are tidally stripped remnants of more extended galaxies, hence of Galaxia origin. As such, they would also trace the

tidal disruption of low-mass dwarf galaxies.

(ii) UCDs are massive star clusters – or mergers thereof – whose formation is closely linked to the formation of the bulk of the

globular cluster population.”

Galaxies in the Fornax Cluster, MNRAS, 2011, 412, 1627–1638

“The chemical abundance of stars is a fossil record of how the stars are formed. Thus, we can assess the origin of a globular cluster (GC), which still remains unresolved in spite of many previous observational and theoretical efforts, if we detect some signal characteristic of a specified nucleosynthesis result in the abundances of its member stars.”

First evidence of globular cluster formation, The Astrophysical Journal Letters, 2012, 751:L35

The self-enrichment of galactic halo globular clusters, Astronomy & Astrophysics, 1999, 352, 138–148

“More than 70 years ago in a monograph entitled ‘’Star Clusters’’ Harlow Shapley wrote, ‘’It is encouraging to see how

fragile and futile are the majority of astronomical theories and speculations … for the futility of speculations emphasizes the

importance and durability of observations and indicates the steady progress of the science’’ (Shapley 1930, p. 193). These

words are particularly true for the models of globular cluster (GC) formation. Extensive observational surveys of GC systems

in the Milky Way and other galaxies have been compiled during the past two decades (e.g., Harris 2001). At the same time, despite a wide variety of proposed models, a self-consistent scenario of GC formation is yet to be constructed.”

“The main obstacle to building a realistic and self-consistent physical model of globular cluster formation has always been the uncertainty in the initial conditions. In fact, all of the models mentioned above would produce star clusters in environments where the conditions agree with the model assumptions. Another unknown is the connection between globular clusters and galaxies. On the one hand, the largest globular clusters have masses comparable to those of dwarf spheroidal galaxies (107 M). On the other, globular clusters do not seem to have extended dark matter (DM) halos (e.g., Moore 1996) and in that respect differ fundamentally from galaxies. There is also significant disparity between the densities, velocity dispersions, and structural parameters of dwarf galaxies and globular clusters (Kormendy 1985). In order to understand these differences, we need a self consistent model that ties the formation of globular clusters to the realistic formation and evolution of their parent galaxies.”

Formation of globular clusters in hierarchical cosmology, The Astrophysical Journal, 2005, 623:650–665

“2. If the in falling gas has no angular momentum, the GCs form in this model with highly radial orbits. Were this the case, and were these orbits to survive until the present day, this would be inconsistent with observation, at least for the Galaxy (van den Bergh 1993; Cohen & Ryzhov 1997). However, collisions with other condensations early in the history of the fragments will randomize the orbits. This, combined with out lack of knowledge about the distribution of angular momenta of the in falling gas, means that a detailed comparison with observation is not possible.”

The Astrophysical Journal, 1999, 526:L13–L16

“The origin of the extended globular clusters is not well understood. They are apparently comparatively rare objects, at least in luminous galaxies.**” An Extended Globular Cluster**

“Such abundance variations in metal-rich globular clusters is undoubtedly one of the most intricate challenges for the current theory of stellar evolution, and further observations with larger samples would be interesting.”

The Globular Cluster M71

“The origin of globular clusters (GCs) is one of the important unsolved astrophysical problems. One can divide all proposed scenarios for GC formation into two large categories: 1) in situ formation (when GCs are formed inside their present day host galaxies), and 2) pregalactic formation (when GCs are formed in smaller galaxies which later merge to become a part of the present day host galaxy).” **Globular Clusters With Dark Matter Halos**

“There have been several theoretical models for the formation of globular clusters (GCs), including primary models where clusters form before galaxies (e.g. Peebles & Dicke 1968), secondary models where clusters form with galaxies (e.g. Fall & Rees 1985; Harris & Pudritz 1994), tertiary models where clusters form after galaxies, such as in mergers (Ashman & Zepf 1992), and unified models (Elmegreen & Efremov 1997). Models have been reviewed by Harris (1991); Ashman & Zepf (1998), and Carney & Harris (2001).” **Formation Of Globular Clusters**

“Their formation is an exciting but yet unsolved problem. For instance, it is still an open question whether Galactic halo GCs formed out of gas already chemically enriched (pre-enrichment models, e.g. Harris & Pudritz 1994) or whether they produced their own heavy elements through an earlier generation of stars within the GC progenitor itself (self-enrichment models). In the second class of models, the issue of their formation is directly related to the origin of their metal content (Cayrel 1986; Brown, Burkert & Truran 1995; Parmentier et al. 1999).” **Galactic Halo Globular Clusters**

Harris W.E., Pudritz R.E. 1994, ApJ 429, 177
Cayrel R. 1986, A&A 168, 81
Brown J.H., Burkert A., Truran J.W. 1995, ApJ 440, 666
Parmentier G., A.A. 1999, A&A 352, 138

“The dynamical evolution of GCs has been studied for many decades, and is considered to be well-understood. However, the formation of GCs is still an open question.” **Initial Conditions for Globular Cluster Formation**

“Currently no models of GC formation explain all the observed properties of these star clusters (Djorgovski & Meylan 1994; McLaughlin 2000).” **Initial Conditions for Globular Cluster Formation**

Djorgovski, S., & Meylan, G. 1994, AJ, 108, 1292

McLaughlin, D. E. 2000, ApJ, 539, 618

“The exact formation mechanism of GCs has been the subject of much recent debate. Many models for GC formation have been proposed including gaseous mergers (Ashman & Zepf 1992), in situ formation (e.g. Harris et al. 1995), multiphase collapse (Forbes et al. 1997), dissipationless hierarchical merging (e.g. Côté et al. 1998, 2000, 2002) and hierarchical clustering (Beasley et al. 2003).” **Astronomy And Astrophysics, 2005, Volume, 439, Pages 913-919**

Ashman & Zepf, 1992, ApJ, 384, 50

Harris, 1995, ApJ, 441, 120

Forbes, 1997, AJ, 113, 1652

Côté, P., 1998, ApJ, 501, 554

Côté, P., 2000, ApJ, 533, 869

Côté, P., 2002, ApJ, 567, 853

“The average star density in a Globular Cluster is about 0.4 stars per cubic parsec. In the dense center of the cluster, the star density can increase from 100 to 1000 per cubic parsec.”

http://www.astro.keele.ac.uk/workx/globulars/globulars.html

“They are very dense - at their centres, the typical distance between individual stars is comparable to the size of the Solar System, or 100 to 1000 times closer than the corresponding distances between stars in the solar neighborhood.”

https://www.eso.org/public/news/eso0107/

“The stellar density in the cluster’s center is so high (up to a few thousand stars per cubic light year) that it is generally impossible to separate the individual stars from ground-based observations.”

http://www.astro.caltech.edu/~george/ay20/eaa-globcl.pdf

https://arxiv.org/pdf/1307.6035.pdf

https://www.cfa.harvard.edu/news/su200712

Galaxy Formation Theories

“The problem of cold gas supply for the disks of spiral galaxies remains unsolved so far.”

“This conclusion disproves completely the commonly accepted scenario of S0 formation from spirals at intermediate redshifts. Spirals and lenticulars may be relatives, but judging on their disk stellar population properties, it is spirals that have emerged from lenticulars, and not vice versa.”

Unsolved problems in the galaxy evolution paradigm, Astronomische Nachrichten, 2013, 334, No. 8, 781-784

“According to modern concepts, lenticular galaxies form from spirals and acquire their final morphology in small groups, subsequently accreting into clusters where they are currently the dominant population, together with their groups (see, for example, [3]).

However, the specific mechanism bringing about this transformation has not been clear: many possible physical mechanisms capable on a time scale of only one to four billion years of removing gas from the disk of a spiral galaxy, bringing an end to star formation, and dynamically “heating” the disk, thereby suppressing spiral structure, have been proposed. These can be divided into “gravitational” mechanisms, associated with the interaction of forming S0 galaxies with other galaxies and with the overall gravitational potential of the group, and “gas-dynamical” mechanisms, associated with the interaction of cool gas of the galactic disk and hot intergalactic gas.”

Structure of the Galaxies of the NGC 80 Group, Astronomy Reports, 2009, Vol. 53, No. 12, 1101–1116

“This question may seem to sound strange: if a main baryonic component, stars which are formed from the own gas of the galaxy, rotates in the galactic disk symmetry plane, how may the polar gas be of local origin?”

“We have found that only at least two independent gas-rich minor-merger events can provide a full list of properties: the inner polar disk is formed by an accretion of a gas-rich dwarf from an inclined retrograde orbit, and the outer flaring ringed star forming disk is shaped by merging a prograde-orbiting satellite. The necessity of two minor mergers is due to the fact that minor merging from a retrograde orbit gives an inclined inner gaseous disk but does not thicken the large-scale stellar disk. The latter feature requires minor merging from a prograde orbit. Since the star formation burst in the outer disk of NGC 7217 is very young, we conclude that the minor merging from a retrograde orbit was the first event, and minor merging from a prograde orbit was the last, quite recent one.”

Inner Polar Gaseous Disks: Incidence, Ages, and Possible Origin,

http://aspbooks.org/custom/publications/paper/486-0027.html

“Spheroidal stellar systems on various scales include elliptical galaxies, dwarf spheroidal galaxies, and globular stellar clusters. Elliptical galaxies are thought to be formed by major mergers of disk galaxies: it is the easiest way to create dynamically hot stellar systems without rotation, whose shape is supported only by anisotropic chaotic motions (by stellar velocity dispersion). However some recent observational findings have put into doubt this commonly accepted scenario. Some features of elliptical galaxies structure can only be explained if minor merging has mostly shaped these spheroidal stellar systems. The dwarf spheroidal galaxies represent quite certainly former disk galaxies shaped and transformed by tidal interactions with their large host galaxies. Globular clusters differ from the (dwarf) spheroidal galaxies by an absence of their own dark matter component. So they cannot be either downscaled version of galaxies nor the direct precursors of elliptical galaxies during the hierarchical gravitational clustering of baryons. However they are the oldest stellar systems in the Universe - it is an observational fact. The formation mechanisms of the oldest globular clusters represent a puzzle yet.”

“However, when the scenario has been inserted into the global picture of the Universe evolution in the frame of the concordant cosmological model (the LCDM one currently), it begins to contradict multiple observational data. Since the merging must proceed hierarchically, the largest elliptical galaxies are predicted to form the last and so must possess the youngest stellar populations among all ellipticals, if merging is accompanied by star formation bursts.”

“1. Dwarf spheroidal galaxies have been formed from disk galaxies by some external mechanisms of secular evolution.

2. Globular clusters may form during merger events, but the extreme metal poor globular clusters may represent the primordial population.

3. The formation mechanisms of elliptical galaxies are now quite unclear, but the combination of some early monolithic collapse of a gas cloud with the later minor mergers seems to be the most promising scenario.”

Formation Mechanisms for Spheroidal Stellar Systems, http://www.astro.utoronto.ca/~cclement/vshalocl.pdf

“The bimodality in observed present-day galaxy colours has long been a challenge for hierarchical galaxy formation models, as it requires some physical process to quench (and keep quenched) star formation in massive galaxies.”

“Although physically motivated quenching models can produce a red sequence, interesting generic discrepancies remain that indicate that additional physics is required to reproduce the star formation and enrichment histories of red and dead galaxies.”

“Despite the accumulating wealth of data, the physical origin of the bimodality in galaxy properties remains poorly understood.”

“There are several fairly generic difficulties in understanding quenching in the context of the observed galaxy population and its evolution. These are similar among all models of quenching we have examined, and hint at an underlying failure in our understanding or our current modelling techniques. One issue is that there is an intrinsic tension between producing a strong knee in the luminosity or stellar mass function, and having blue galaxies exist in substantial numbers up to the highest stellar masses. The former would imply a very sharp quenching of star formation at a particular mass (stellar or halo), while the latter implies that quenching is a much more gradual function of mass. It is unclear how one can resolve this tension. Neither of our scenarios is able to do so, with merger quenching yielding large blue galaxies, and halo mass quenching producing a more pronounced truncation of the most massive galaxies.”

(ii) Quenching of hot mode accretion alone does not produce a viable red sequence, showing that late time accretion continues

via cold mode in massive galaxies. Further quenching wind mode accretion produces a red sequence, but a highly discrepant LF.

(iii) Our preferred merger quenching model rules out the reformation of discs after gas-rich mergers, because such re-formation

leads to the build up of too many massive galaxies.

(iv) The halo mass quenching model is quite sensitive to the threshold halo mass: Mc ≈ 10^{12} M_o yields the best match to the red galaxy LF.

(v) Both of these models yield an excess of bright red galaxies due to mergers after the quenching process, and both yield some what too few galaxies around ∼ L∗ ; these problems are more severe in the merger-based model.

(vi) Both models yield red sequences with too shallow slopes in the CMD, likely due to near-constant mean stellar metallicity along the red sequence.

(vii) In both models, the red sequence is too blue by ∼0.1 mag, likely owing to simulated galaxies being too metal-poor by nearly

two times compared to real galaxies.

How is star formation quenched in massive galaxies? MNRAS, 2010, 407, 749-771

“Although thick stellar discs are detected in nearly all edge-on disc galaxies, their formation scenarios still remain a matter of debate.”

“Many important aspects of galaxy evolution remain not fully understood despite the great progress in the astronomical instrumentation and increasing resolution and complexity of numerical simulations. One such unsolved problem is the formation of thick discs, important and widespread structural elements of spiral and lenticular galaxies.”

The diversity of thick galactic discs, MNRAS, 2016, 460, L89-L

“The development of bulges and inner discs is, however, poorly understood observationally due to the small number of studies focusing on the stellar populations of these systems.”

“The formation of double-barred galaxies has been a matter of debate for more than two decades.”

“More double-barred galaxies are needed to perform a proper statistical analysis and to draw conclusions on this matter.”

“It is important to be aware of the fact that in order to disentangle the formation sequence of inner bars observationally, not only the star-formation history but also the dynamical evolution of the different structures needs to be known. In fact, inner bars are dynamically distinguished structures and their formation might have a dynamical origin with no effect over their stellar populations. Recovering both the star-formation history and the dynamical evolution of a structurally complex system such as a double-barred galaxy is a very challenging goal.”

“Disentangling the dynamical evolution of inner bars is again mandatory to make final conclusions on their stability.”

The inner bars of double-barred galaxies, MNRAS, 2013, 431, 2397–2418

“The ‘missing satellite problem’ is a particularly striking example of how satellite galaxy studies can constrain cosmology and galaxy evolution. The problem highlights an apparent mismatch between the large number of self-bound sub haloes found in ΛCDM simulations of the formation of haloes like those of the Milky Way (MW) and M31, and the much smaller number of satellite galaxies observed around these two Local Group galaxies.”

“They compared their observational results with a mock redshift survey based on the SAM of Croton et al. (2006), finding significant discrepancies. In particular, the model overpredicted the number of faint satellites in massive haloes and produced too many red satellites. The fraction of blue central galaxies was also too high at high luminosities. Weinmann et al. (2006b) argued that the satellite problems most likely reflect an improper treatment of tidal stripping or of the truncation of star formation, while the central problem may reflect an overly simple treatment of dust or of AGN feedback.”

“At lower stellar masses there are too many red galaxies in the simulation, again reflecting the problem noted above and discussed in detail by Weinmann et al. (2011): at low masses the simulated satellite galaxies are too uniformly red.”

Satellite abundances around bright isolated galaxies, MNRAS, 2012, 424, 2574–2598

“The evolution of galaxies in different environments is still poorly understood, as is the relative importance of the different processes involved.”

Spectroscopic bulge–disc decomposition, MNRAS, 2012, 422, 2590–2599

“More than half of the stellar mass in the local Universe is observed to reside in disc galaxies (Driver et al. 2007; Weinzirl et al. 2009), yet the evolutionary history of these systems remains poorly understood. Simulations of galaxy formation tend to produce spiral galaxies with most of their stellar mass fraction in a bulge component, and a direct comparison between observations and these simulations is usually not straightforward.”

“This plethora of disc heating theories reflects the limited constraints provided by measurements in a single galaxy.”

Disc heating agents across the Hubble sequence, MNRAS, 2012, 423, 2726–2735

“In the standard picture of galaxy formation, mass and angular momentum are the two main parameters that determine the properties of disc galaxies. The details of how the gas inside dark matter haloes is transformed into a luminous disc, however, depend strongly on the physics of star formation, feedback and cooling, which are poorly understood.”

“Currently, the main uncertainties in our picture of galaxy formation are related to the intricate processes of cooling, star formation and feedback. In particular, we need to understand how efficient feedback is in expelling baryons from dark matter haloes, and how it enriches the intergalactic medium (IGM). This, in turn influences the cooling efficiencies, which influences the subsequent star formation rates, which influences the subsequent amount of energy that is fed back into the IGM, etc. The importance of this complicated loop of ‘gastro-physics’ has long been realized. The first detailed models of galaxy formation by White & Rees (1978) revealed an important problem intrinsic to any hierarchical formation scenario in which small-mass clumps merge to form larger and larger structures. At early times, collapsed objects have much higher densities, and therefore much shorter cooling times than at the present time. Consequently, when these objects merge to form larger and larger structures (i.e. galaxies and clusters), the vast majority of their baryons have already cooled, so that by the present time there is basically no gas left to make up the intergalactic or intra cluster medium observed throughout the Universe. This problem has become known as the ‘cooling catastrophe’ and is generally interpreted as a requirement for some sort of feedback mechanism that can pump energy back into the gas to lower its cooling efficiency (see Balogh et al. 2001 for an overview of the current status).”

“However, an important problem is that so far none of these models has been able to fit all observables successfully. This is probably a consequence of the simplicity of the phenomenological descriptions used. An additional problem is that assumptions have to be made concerning poorly constrained model ingredients such as stellar populations, the stellar initial mass function, dust extinction, etc. Often ignorance regarding these ingredients is hidden in free model parameters, which have hampered the ability of the model to place direct, stringent constraints on the efficiencies of cooling and feedback. Finally, the galaxy models are poorly (in the case of numerical simulations) or not at all (in the case of most semi-analytical models) spatially resolved, which can complicate a direct comparison with observations.”

“The appropriate conversation ratios, however, are still relatively uncertain. Even more problematic is inferring the total virial mass from the photometry and kinematics of the luminous component. An important focus of this paper, therefore, is to identify those observables that are best suited as indicators of both Mass galactic and Mass virial.”

“Introducing feedback only aggravates the problem: the SN-induced mass ejection quenches later star formation, thus producing faint galaxies that are extremely red.”

“This indicates a generic problem for any hierarchical picture of galaxy formation in which more massive systems form later.”

“Consequently, in disc galaxies, which have relatively young stellar populations, the mass–metallicity relation is not strong enough to invert the color–magnitude relation. Therefore, the color–magnitude relation problem is more severe for late type galaxies than for early-type galaxies.”

“Currently the largest uncertainties in galaxy formation modelling are related to the efficiencies of cooling, feedback and star formation. In particular, we need to understand how these efficiencies regulate what fractions of available baryons are converted into luminous matter, what fractions are ejected out of the dark matter haloes by feedback processes, and what fractions remain in the hot phase because of inefficient cooling.”

“It remains to be seen whether more sophisticated modelling of the chemical enrichment and feedback processes, combined with a treatment of dust extinction can solve this intricate problem.”

The impact of cooling and feedback on disc galaxies, MNRAS, 2002, 332, 456–472

“Using simple disc formation models we show that it is particularly challenging to understand why Rj is independent of halo mass, while the galaxy formation efficiency (GF; proportional to the ratio of galaxy mass to halo mass) reveals a strong halo mass dependence. We argue that the empirical scaling relations between GF, Rj and halo mass require both feedback (i.e. galactic outflows) and angular momentum transfer from the baryons to the dark matter (i.e. dynamical friction).”

“However, current hydrodynamical simulations of galaxy formation, which should include these processes, seem unable to reproduce the empirical relation between GF and Rj. We conclude that the angular momentum build-up of galactic discs remains poorly understood.”

The angular momentum of disc galaxies, MNRAS, 2012, 421, 608–620

“Understanding how early-type galaxies (ETGs) formed and evolved along the Hubble time is still a formidable challenge.”

“The problem is twofold: on the one hand, it must be explained how and when star formation is quenched in both massive and small haloes, which is necessary to reconcile the theoretical prediction with the observed galaxy mass function (see e.g. Bundy et al. 2006); on the other hand, it should be also clarified how such massive systems can form at very high redshifts.”

“Given these considerations, a more detailed treatment of the ISM not only is urgent but may also cure part of the problems encountered with overcooling.”

Formation and evolution of early-type galaxies, MNRAS, 2012, 427, 1530–1554

“A central issue in the study of galaxy formation is to understand the connection between the mass of galaxies and the mass of their associated dark matter haloes. This problem is not trivial: whilst the mass function of dark matter haloes predicted by the cold dark matter paradigm has a relatively steep slope ($d \log N/d\log M \sim -0.9$ over the range of halo masses relevant to the galaxy formation), the observed mass function of galaxies is characterized by a shallow Schechter function.”

“Both models overpredict the abundance of the lowest mass galaxies, although this problem is reduced in the MS model.”

What shapes the galaxy mass function? MNRAS, 2012, 422, 2816–2840

“Given our conclusions, we must stress that a clearer picture on the core formation problem has still to be drawn. The problem needs to be studied within a larger class of haloes with different merger histories and masses, and idealized simulations are probably required to shed more light on the core formation process in clusters.”

Mass distribution in clusters of galaxies, MNRAS, 2012, 422, 3081–3091

$$t = \frac{d}{v} \div \frac{\pi r^2}{4\pi R^2}$$

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