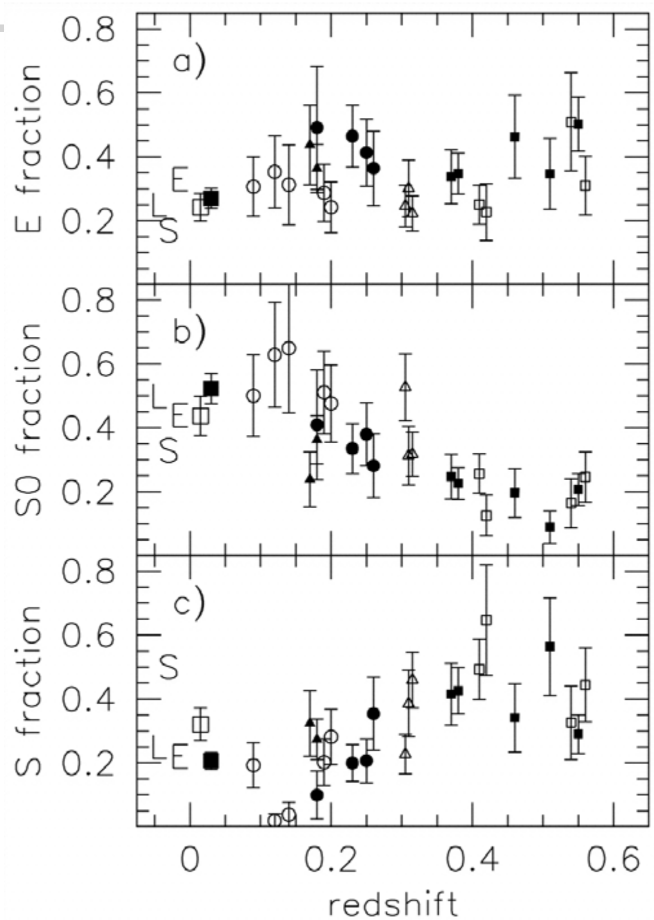
Stellar and Ionized Gas Kinematics of Peculiar Virgo Cluster Galaxies

Juan R. Cortés
Departamento de Astronomia
Universidad de Chile

Morphological Evolution of Cluster Galaxies

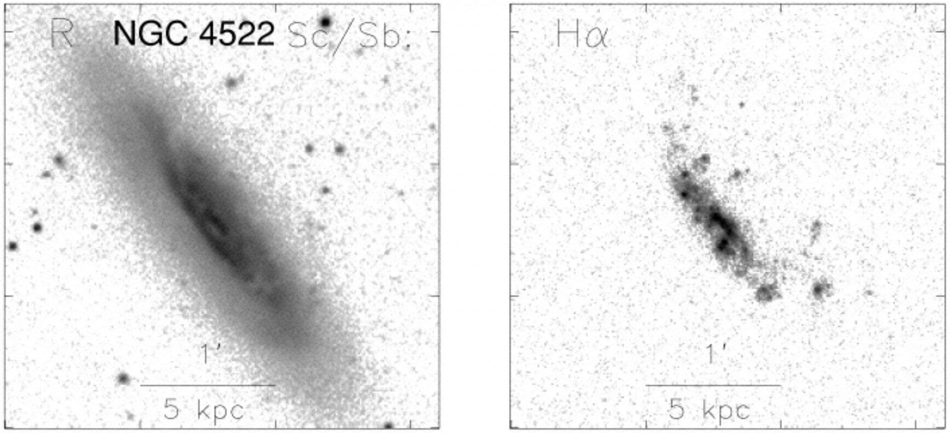
- Galaxy population in clusters:
  - Depends on environment (Morph-density rel.)
  - Evolves with time (Butcher & Oemler effect)
  - Morphological transformation from Sp to S0 seems to be happening (e.g. Dressler et al 1997)

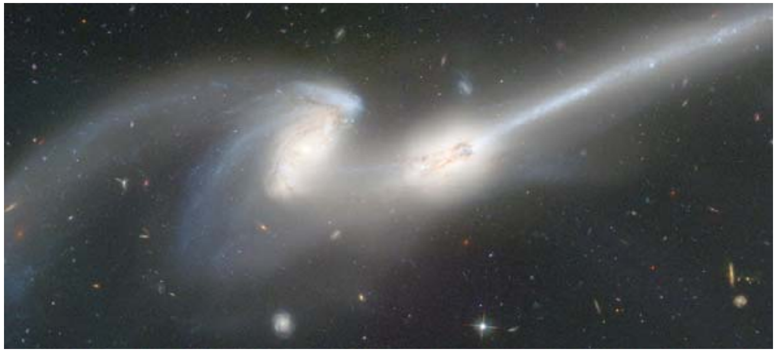


Fasano et al., 2001

Koopmann et al (2001)

- Different processes have been proposed as main drivers of morph. evolution of galaxies in clusters:
  - Processes affecting the gas
    - ICM-ISM stripping
    - Gas Accretion
    - Starvation
  - Processes affecting stars & gas:
    - Mergers
    - Tidal interactions between galaxies
    - Tidal interaction with the cluster as a whole





- All or most of these processes occur in cluster of galaxies, but it is still unknown which processes are the dominant drivers of galaxy evolution
- Different studies of galaxies in clusters reach different conclusions regarding the processes driving galaxy evolution
- Complexity & disagreement show that detailed studies of morphology, and kinematics are needed.

This Project

- Goals:
  - Identify the physical processes that drive galaxy evolution in clusters.
    By "evolution" I mean morphological transformation from Sp to S0

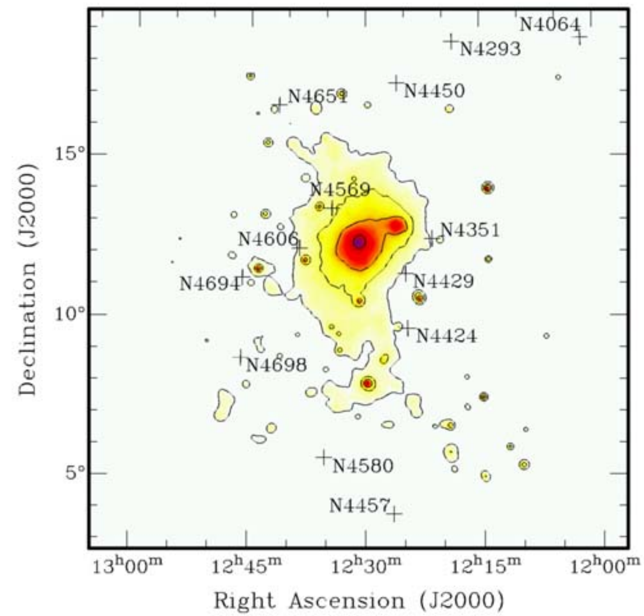
  - Understand what actually happens in each of these processes;
    - How efficient is ram pressure in stripping the gas?
    - How do mergers in clusters differ from those in the fields?
    - What actually happens in tidal interactions?

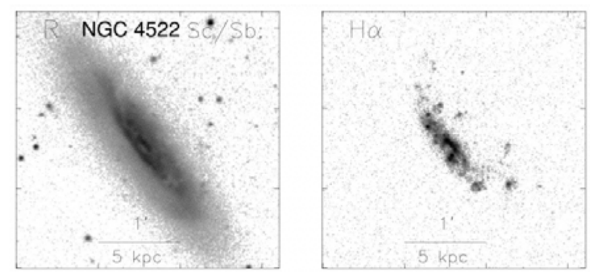
- The Project itself: Study of 13 peculiar galaxies in Virgo Cluster. First study of cluster galaxies with 2-D stellar kinematics
- Part of big study of most of Spirals galaxies in Virgo cluster:
  - J. Kenney (Yale) P.I, J. van Gorkom (Columbia), B Vollmer (Strasbourg*)* , and C. Struck (Iowa St.)

- Why Virgo?
  - Nearest cluster with
    - Large range of different galaxy Morph. types. Different possible environmental processes.
    - Great number of gas-truncated gal. Some consistent with ICM-ISM stripping, and some others not.
- Why peculiar galaxies?
  - Reflect different kinds of interactions
  - Objects in process of morph. transformation: Sp -> S0. So, they are snapshots of morphological transformation processes

The Sample

- Selection:
  - Candidates selected from their stellar and Hα morph. and known kinematics.
  - Focus on galaxies with peculiarities not yet understood.
  - Not uniform selection criteria.

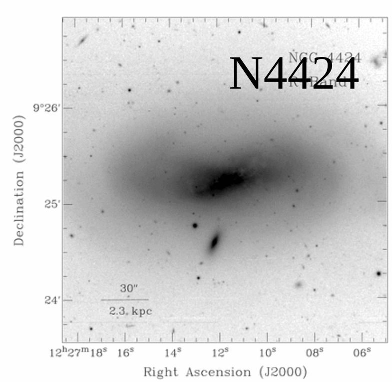


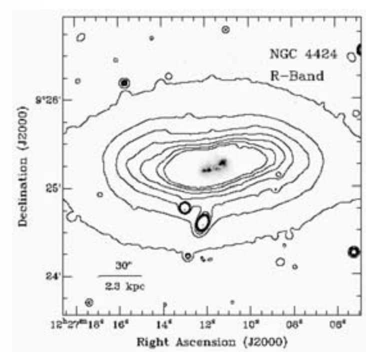


ICM-ISM Stripping. Not in sample

- 13 galaxies brighter *than* B=13 mag (0.1 L*).

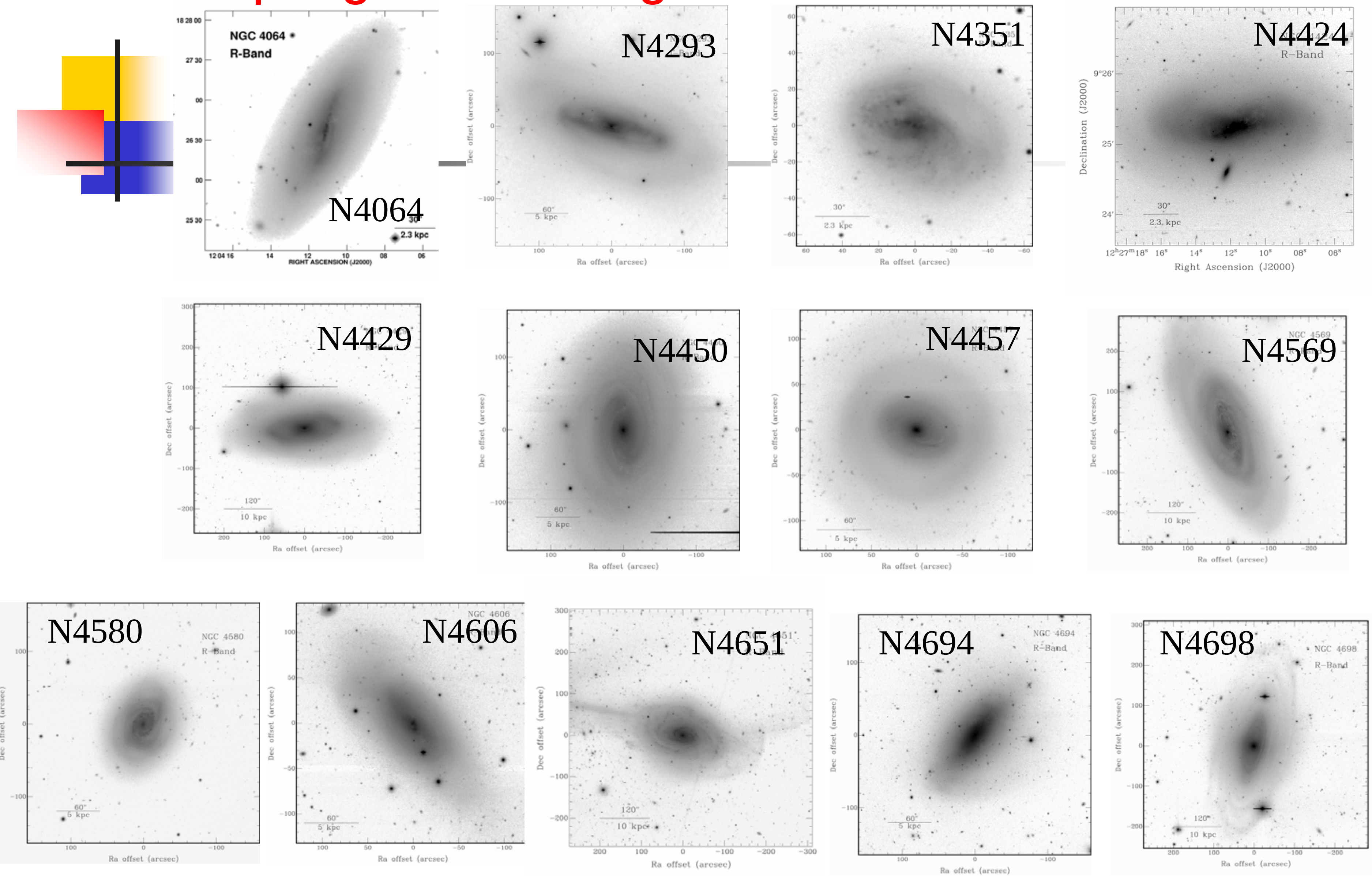
- ~ 12 % *of* bright spiral galaxies in Virgo.





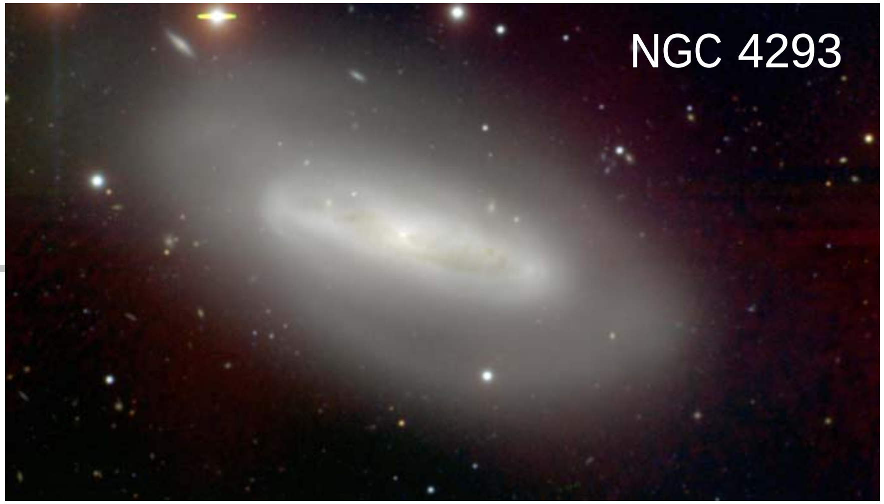
No just stripping. Sample galaxy!

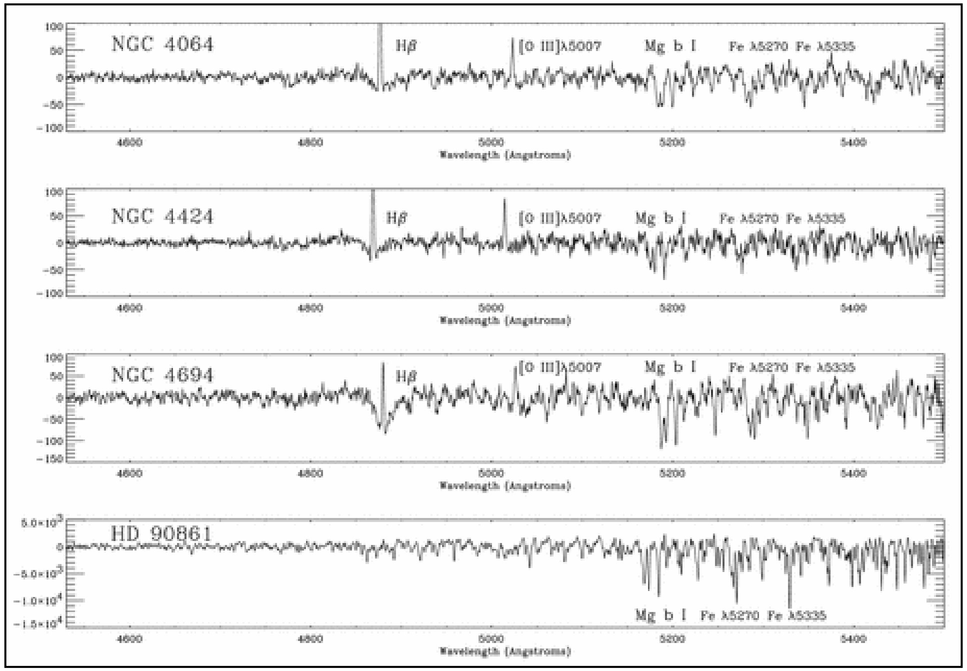
Sample galaxies images



The data

- Optical Imaging with WIYN telescope
  - FOV~10’, seeing 0.4”-1.0”
  - R, Hα (13/13), B-R (7/13), B,V,R (4/13)
- Integral Field Spectroscopy (WIYN)
  - 90 fibers, 70% coverage, FOV~30”x45” (2.3 x 3.5 kpc)
  - Stellar & Ionized gas kinematics (13/13)

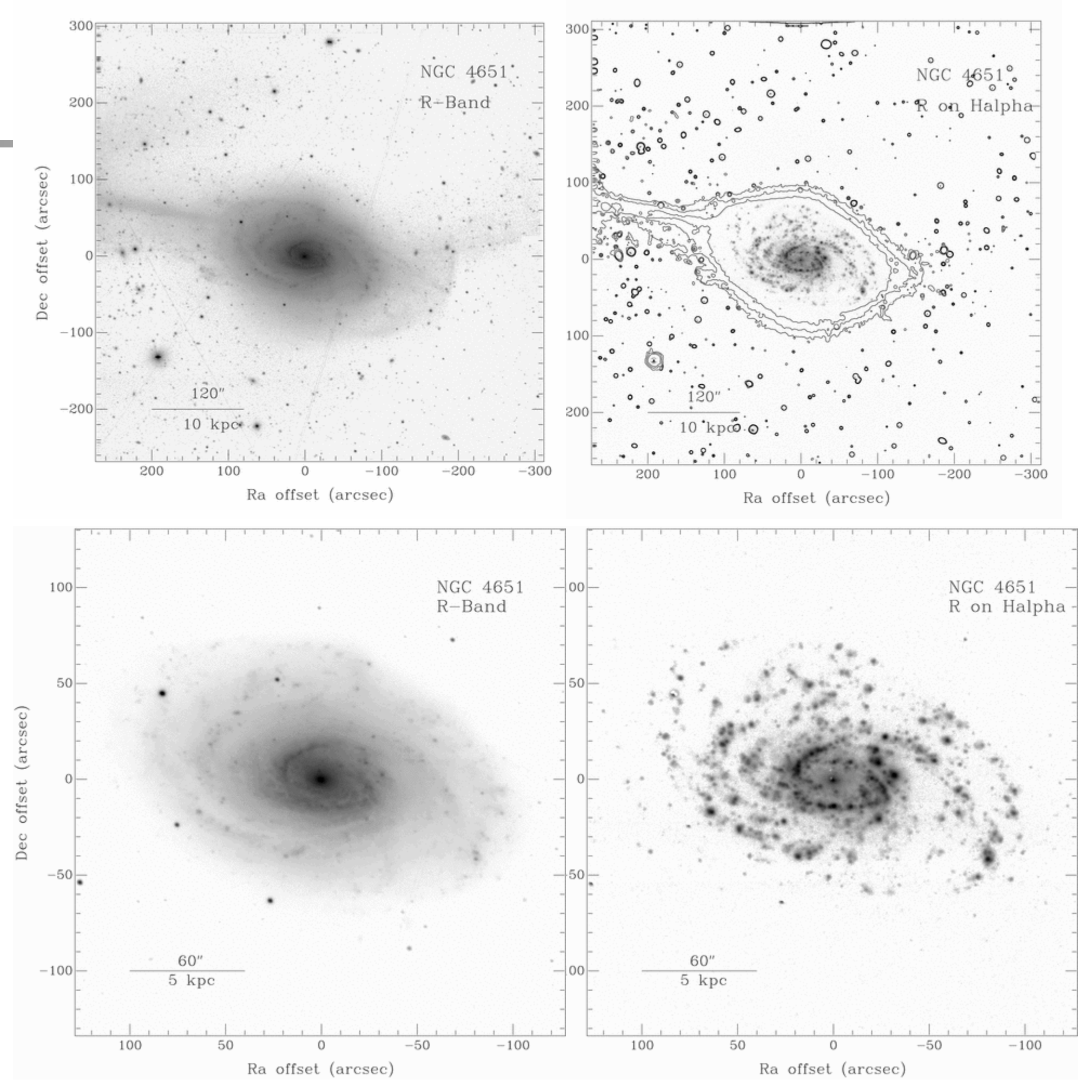


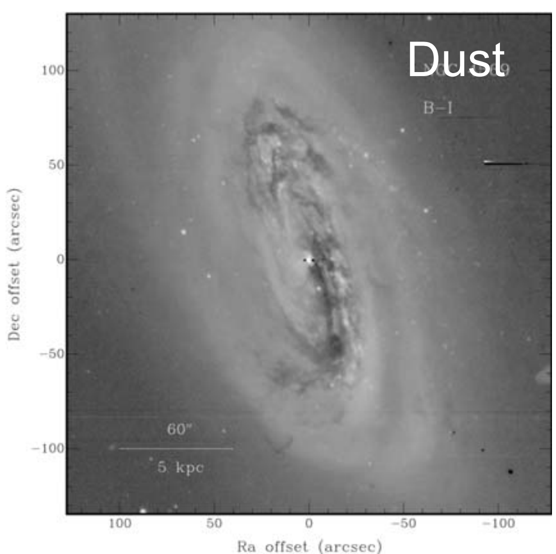


Example of dataset:

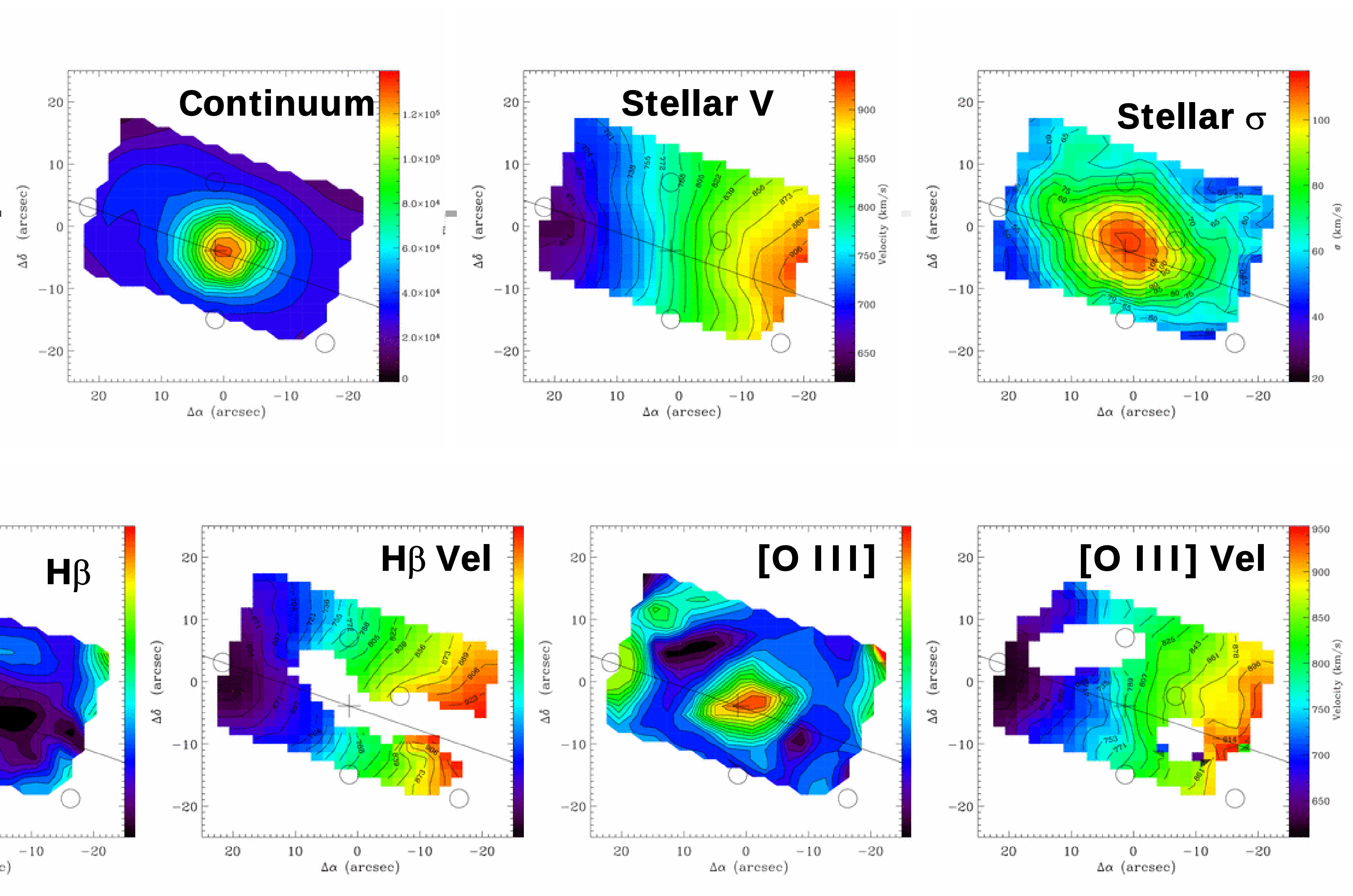
- R, Hα band, dust
- Continuum map, gas line intensity map
- Stellar and Gas velocity fields
- Stellar velocity dispersion

R-band | Hα

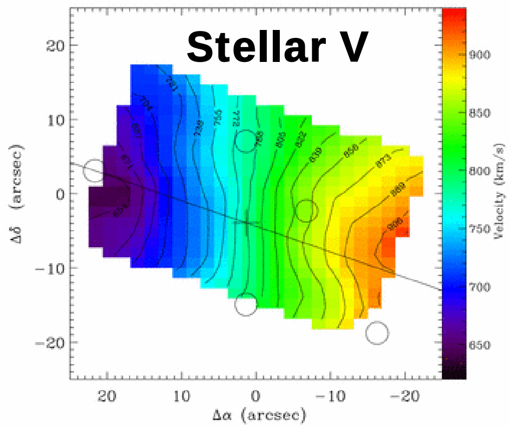


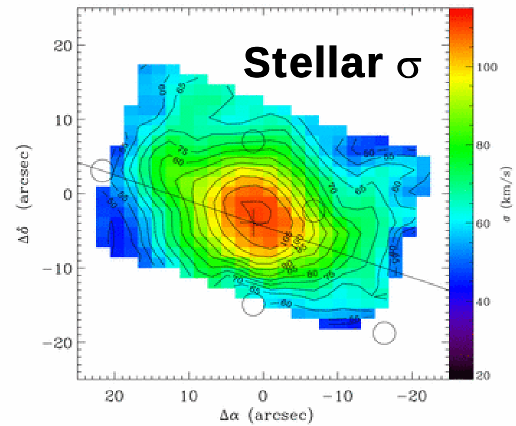


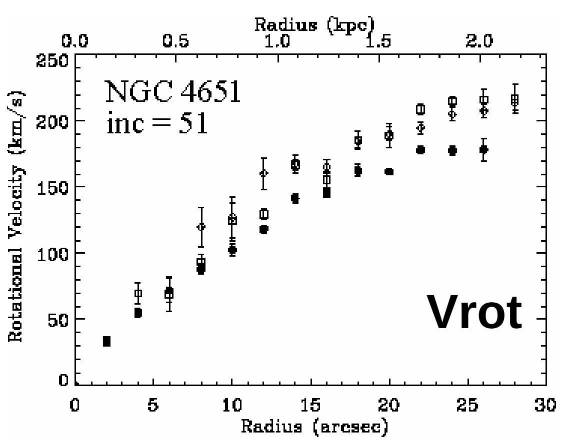
Stellar and Gas Kinematics of NGC 4651

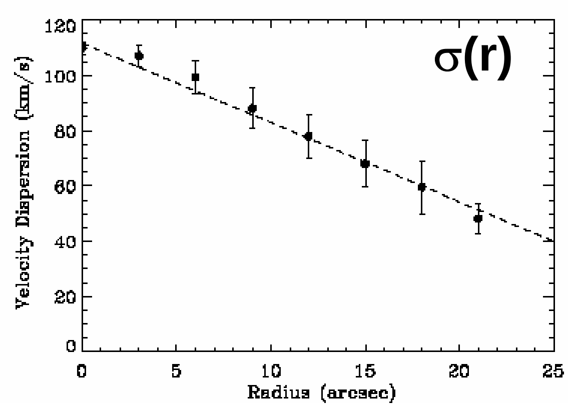


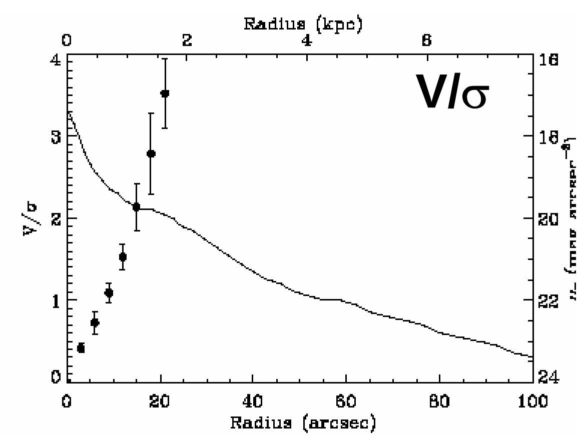
- Kinematical Analysis. Rotation curves, σ profiles and V/σ profiles. Useful for establish mass, distance, and kinematical support





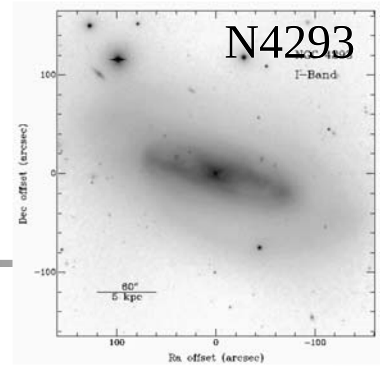


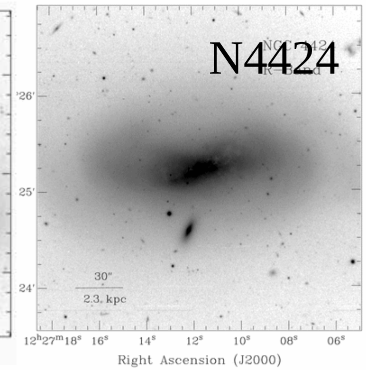


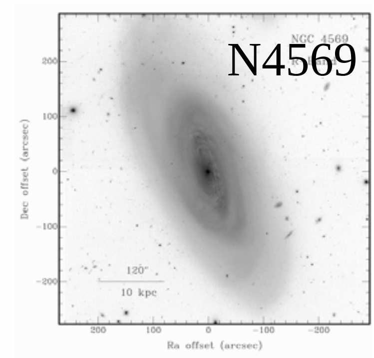


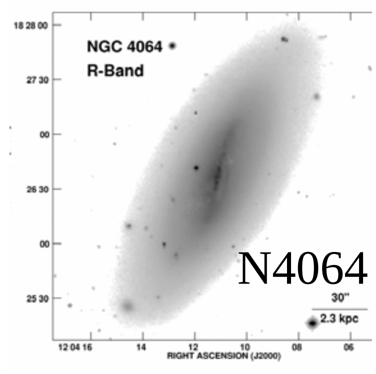
The Results

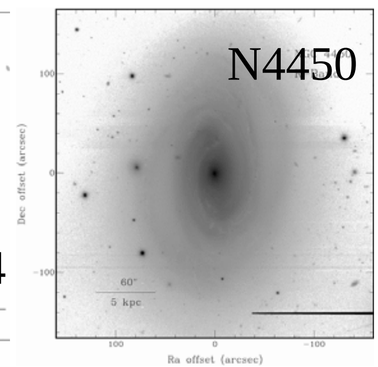
- Optical Morphology
  - Disturbed outer stellar disks in 6 galaxies: Grav. inter.
  - Signatures of bar and lenses in 3 galaxies. Non-elliptical isophotes in 5 gal.
  - Disturbed dust distribution in 6 galaxies. 4/6 show disturbed inner stellar disk.

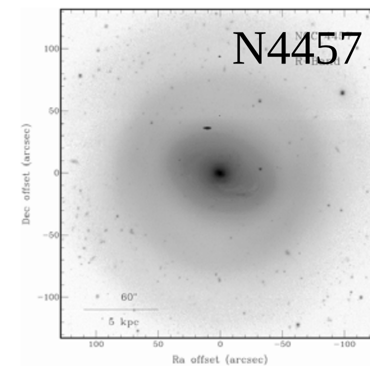


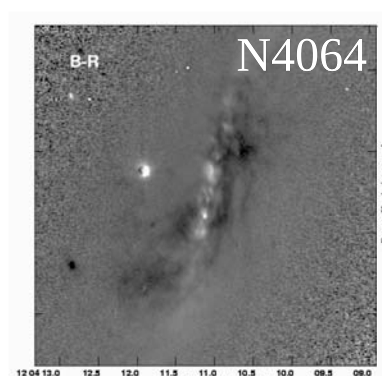


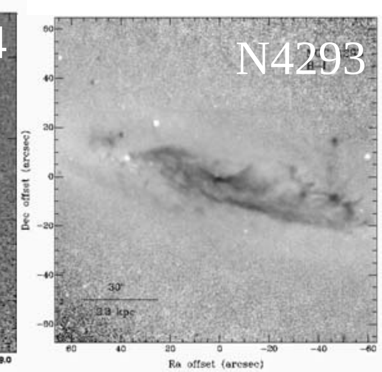


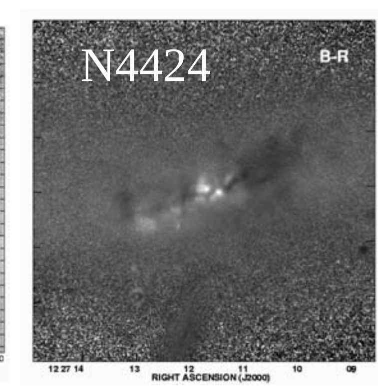








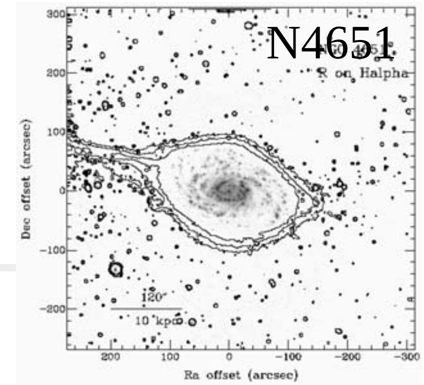




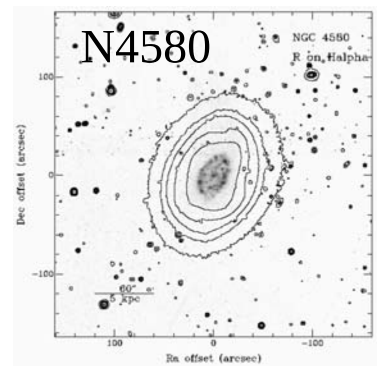
Disturbed dust distribution

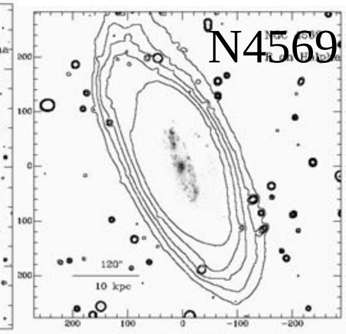
- Hα morph:
  - Only one galaxy with “normal” Hα SFR. No stripping. Dist. outer isophotes. Minor merger.
  - 5 galaxies Truncated/normal. Possible ICM-ISM stripping. 3 distur. outer isophotes.
  - 3 galaxies Truncated/Compact. All distur. Stellar disk gas inner 1 kpc. Stripping + grav. Interactions.
  - 4 galaxies Truncated/Anemic and Anemic. old stripped galaxies.

“Normal” Hα

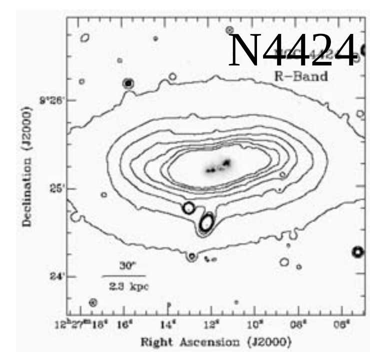


T/N

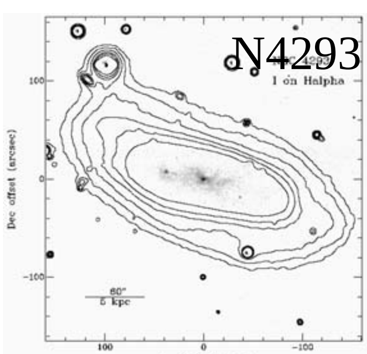




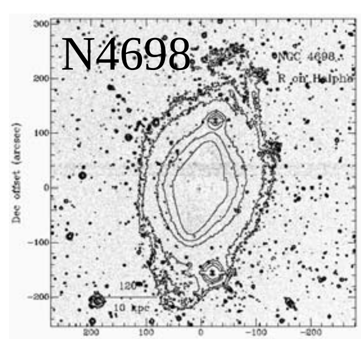
T/C



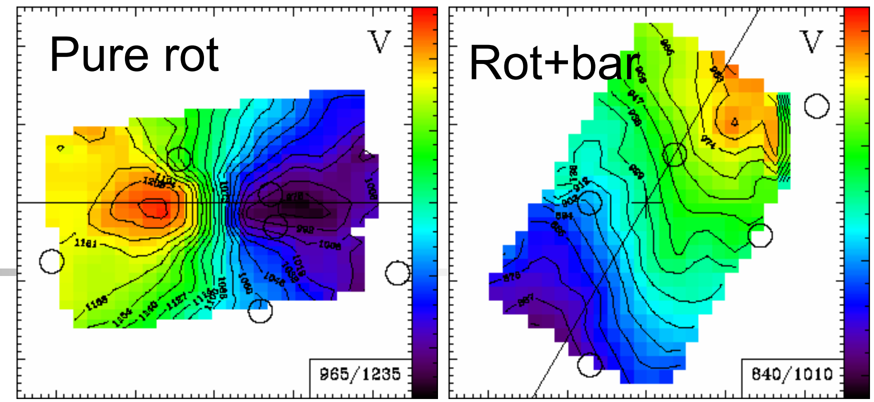
T/A

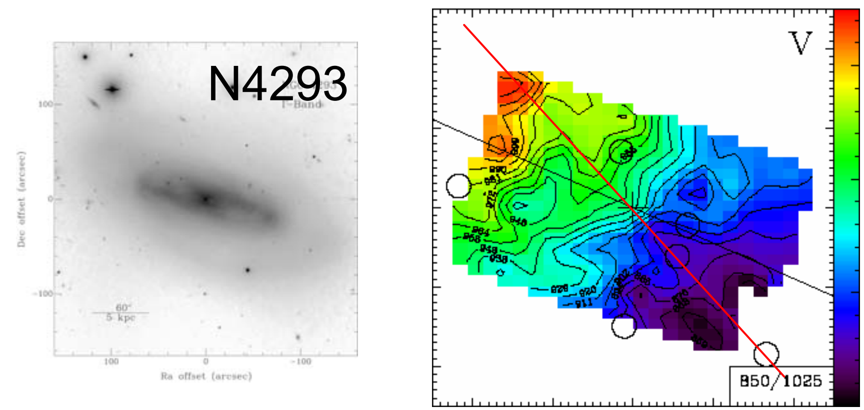


Anemic

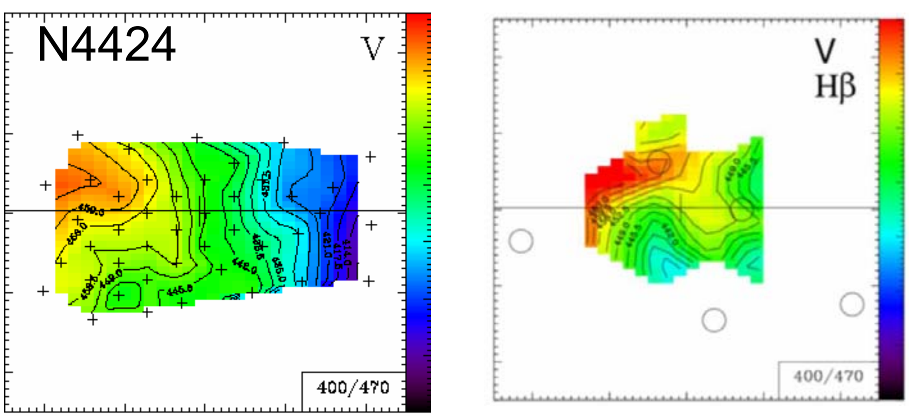


- Stellar and ionized gas kinematics
  - Stellar V. field in most galaxies (12/13) consisting with rotational pattern. Except N 4064; strong non-circ motions due to bar
  - Kinematical misalignment in N4064 (bar) and NGC 4293 (Δ P.A ~ 20deg). Δ P.A < 10 deg in 3 gal.
  - 7 gal. show differences between stellar and gas kinematics (e.g. isovel. contours not consistent with rotation).

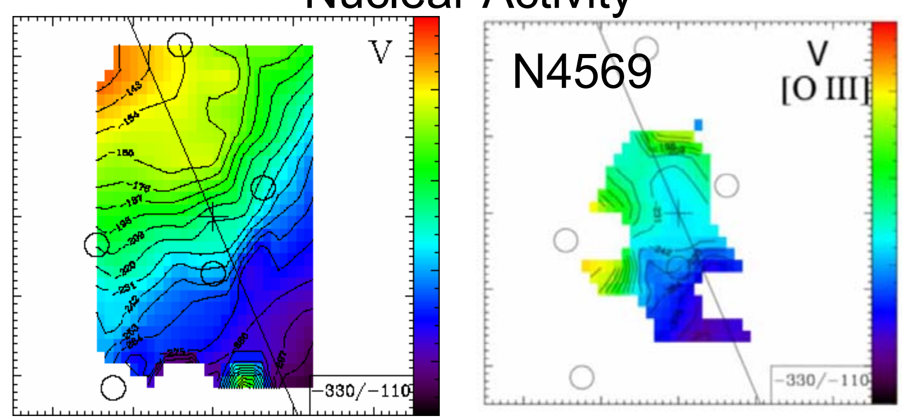




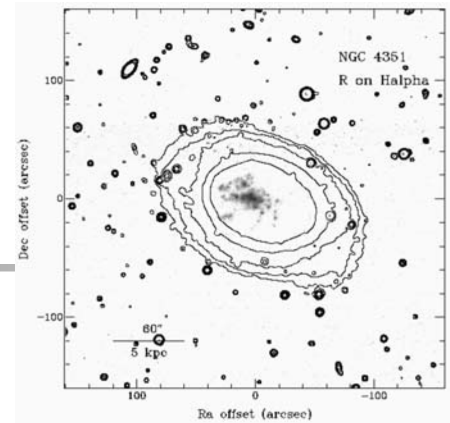
Possible gas C-R

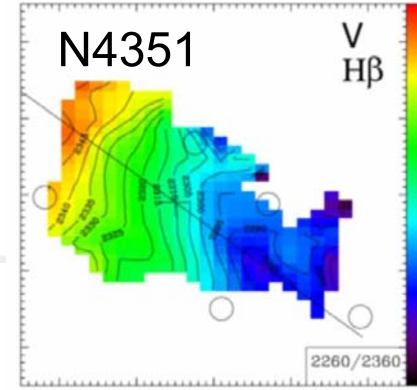


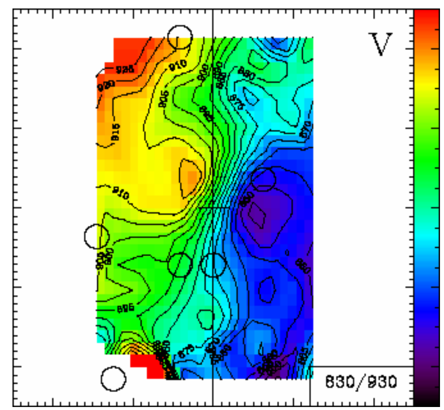
Nuclear Activity

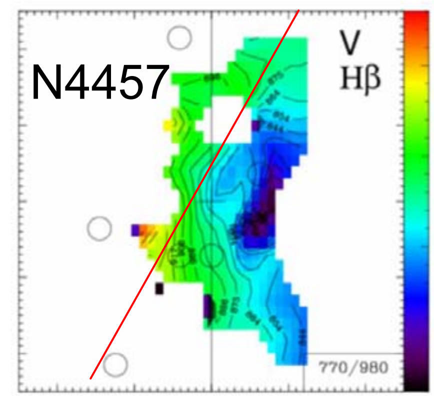


Curvatures in isovelocity contours not consistent with rotation can be due to ICM-ISM stripping.



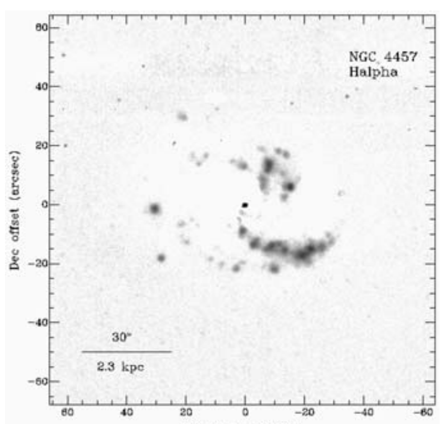




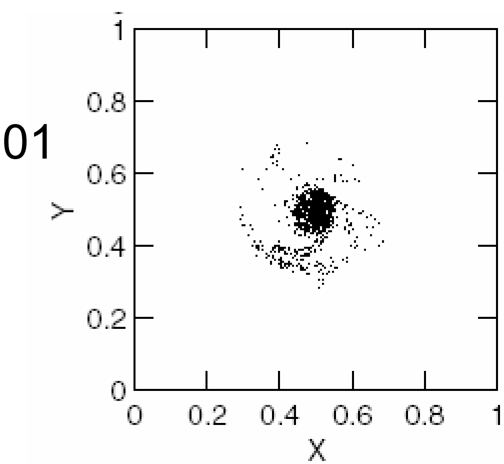


- ISM displaced w/r to stellar disk in N4351.
- Anomalous arm in N4457

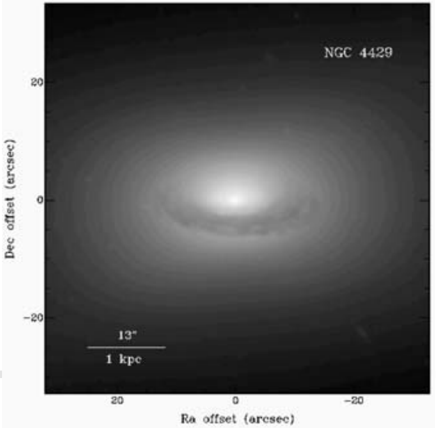
Bending due to stripping



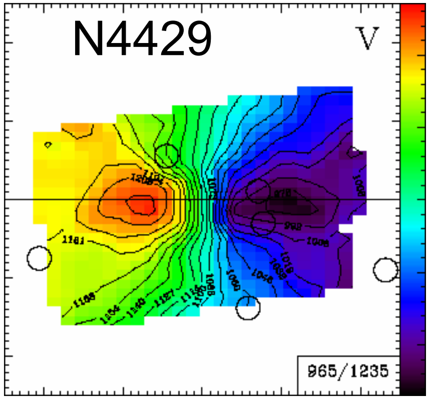
Schulz & Struck 2001

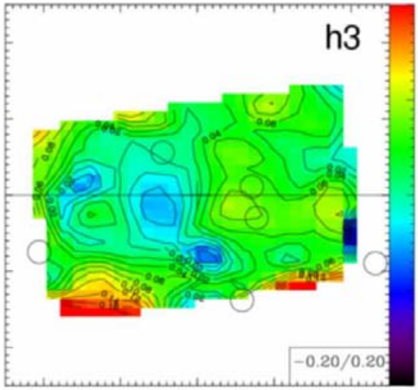


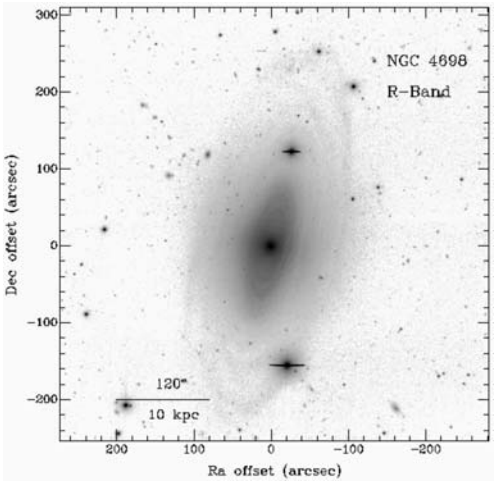
- KDC (Kinematically decoupled components) in at least two galaxies.
  - Circumnuclear stellar disk. N4429, and N4450. Infalling of gas to the center. Gas accretion, minor mergers, or m=2 disturbances such as bars.

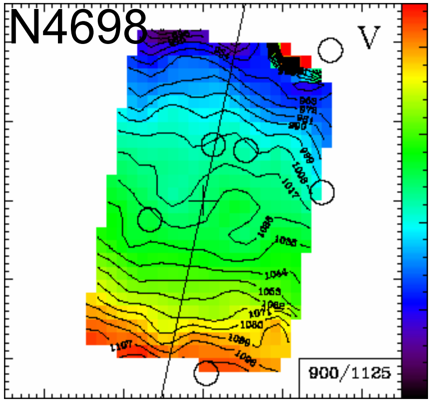


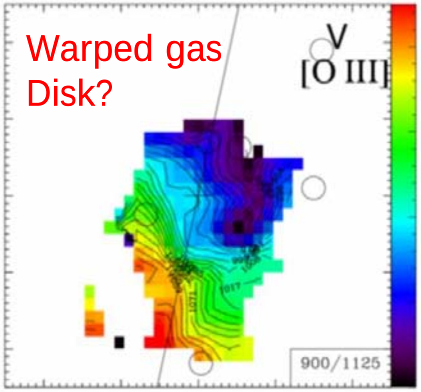
  - Orthogonally stellar rotating cores: N4698. Big merger? Or massive gas accretion?. Ionized gas appears to have reverse spin!
  - No signatures of stellar counter-rotation. Maybe these galaxies are rare.



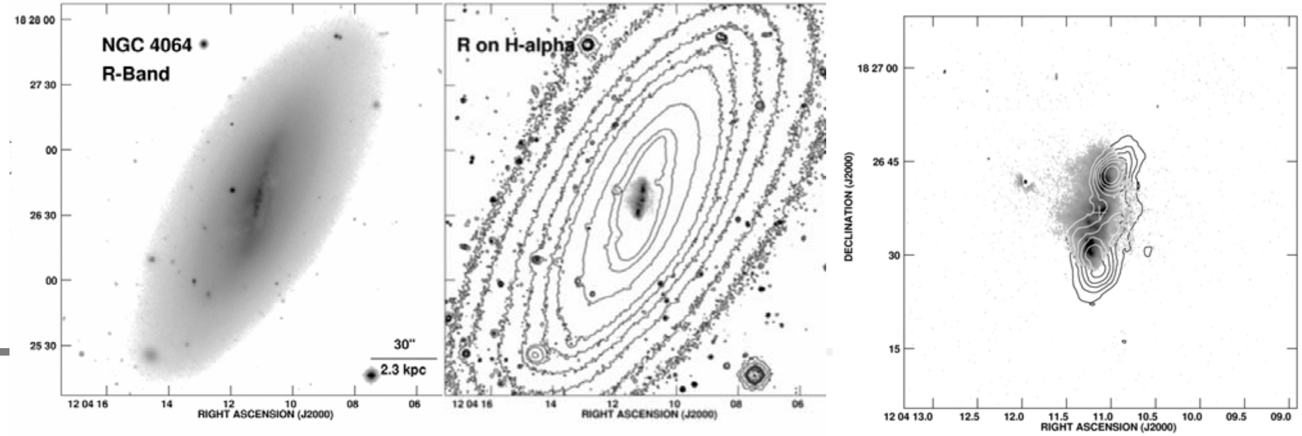






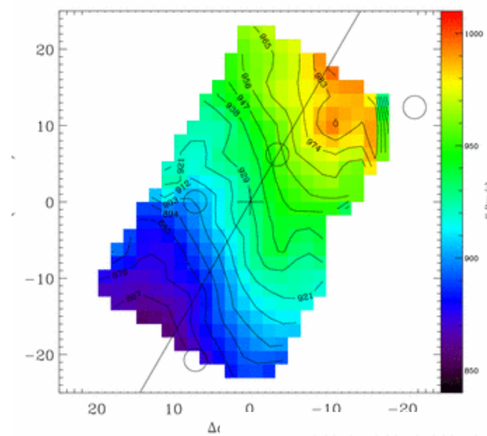


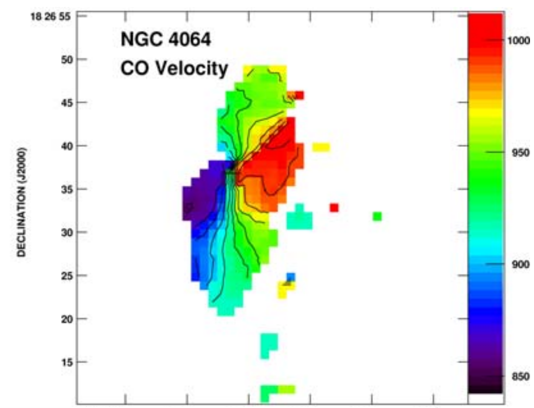
NGC 4064

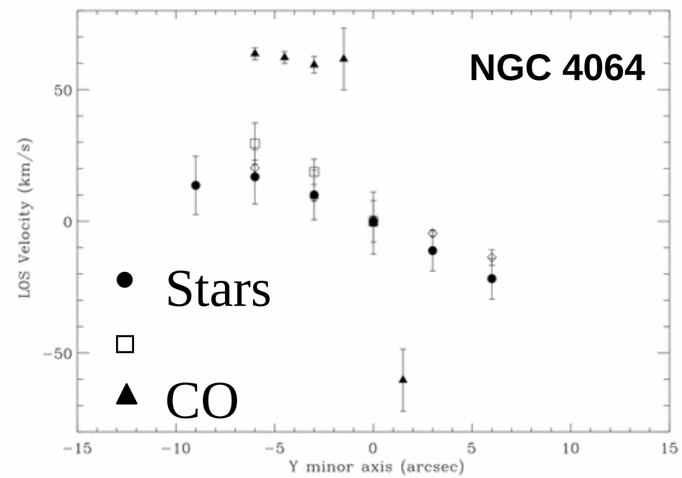


- Extremely Hα-truncated galaxies exhibit peculiar kinematics and mixed morphologies:
  - N4064; bar, undist. outer stellar disk, dist. Dust distrib., radially infalling molecular gas. Old-stripped galaxy + minor merger
  - N4606; undisturbed stellar disk, disturbed dust, flat σ. Possible tidal interaction with companion 4067
  - N4694; amorphous stellar morph, dist dust, flat σ, displaced

  Gas. Collision with companion?







Cortes et al (2006, AJ in press)

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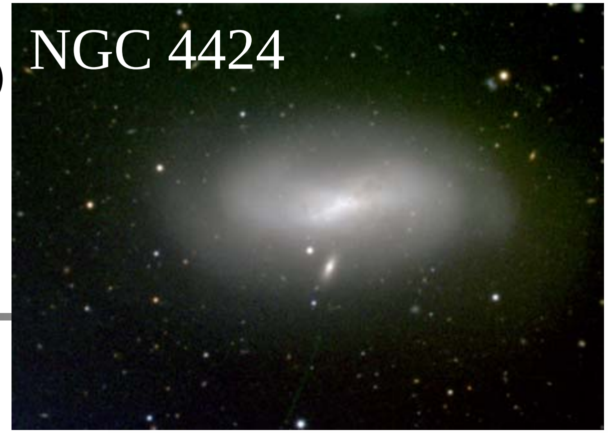
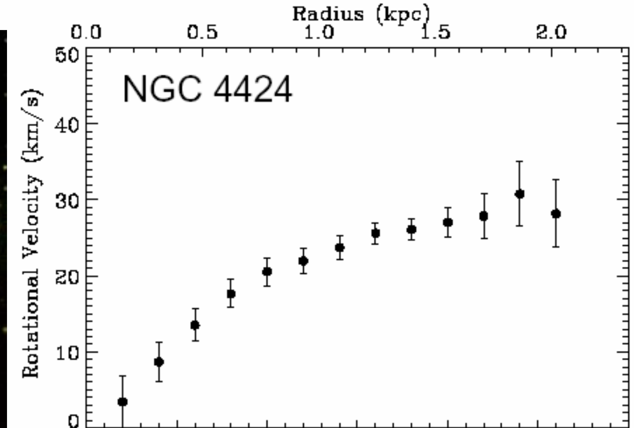
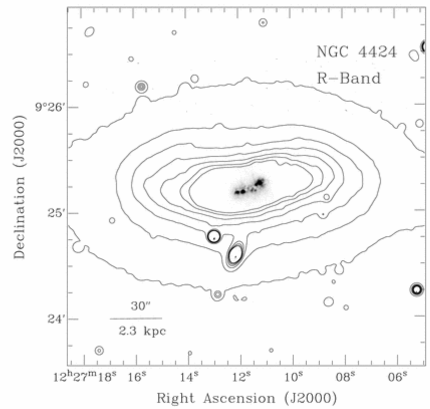
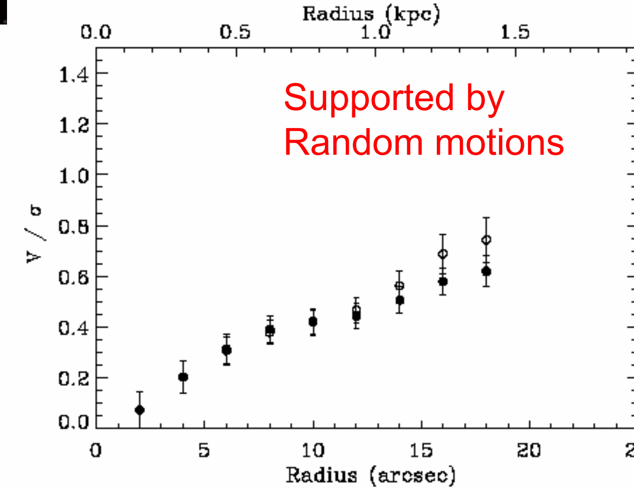
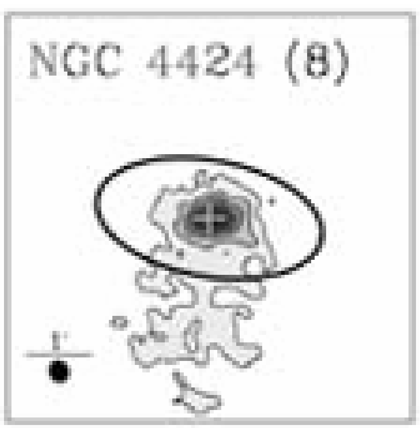




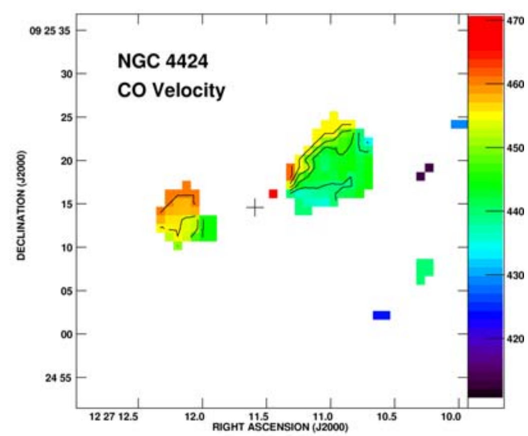
- N4424 :
  - disturbed stellar disk
  - disturbed gas kinematics
  - elliptical-like kinematics
  - Stripping + intermediate merger
  - Truncated/Compact galaxies product of ICM strip + grav interactions





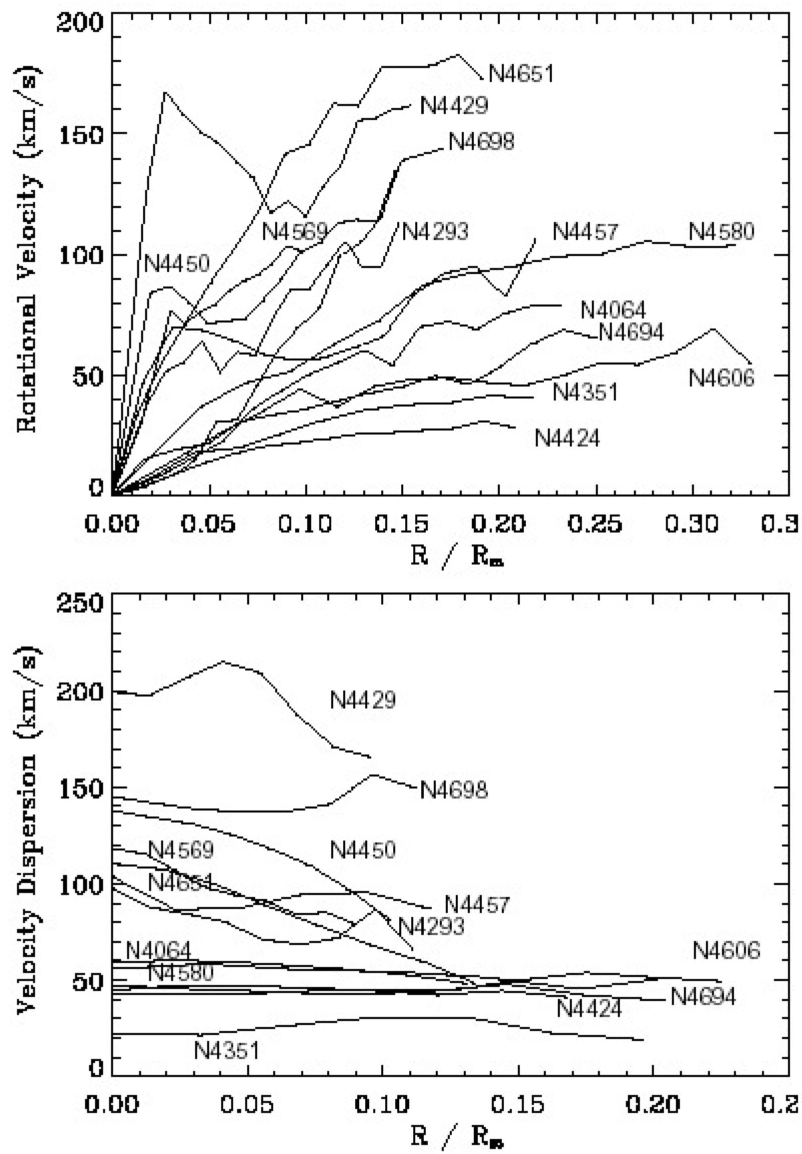


HI tail in N4424!
(Chung et al 2005)



Disturbed gas kinematics

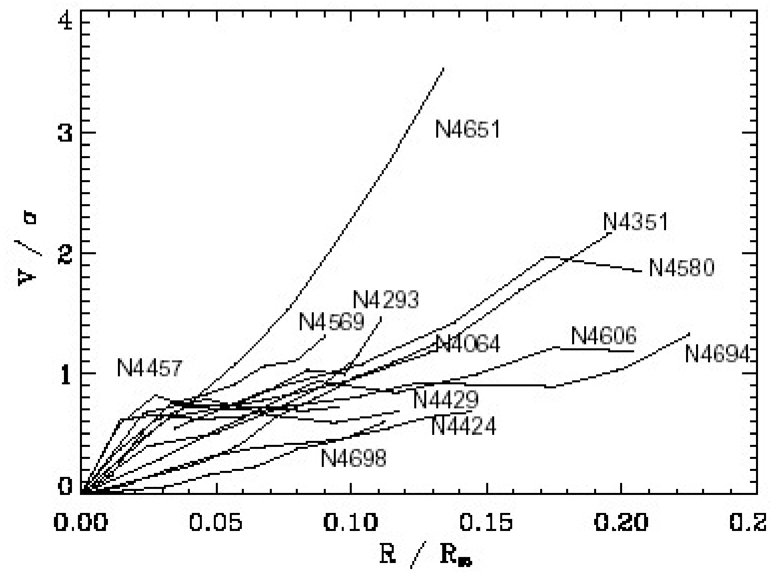
- General Kinematics
  - Stellar rotation curves have a varied range of amplitudes
  - Stellar σ has diverse profiles.
    - Slope varies from -40 to -10 km/s kpc^{-1}
    - 4 galaxies exhibit very flat σ. T/C + N4698

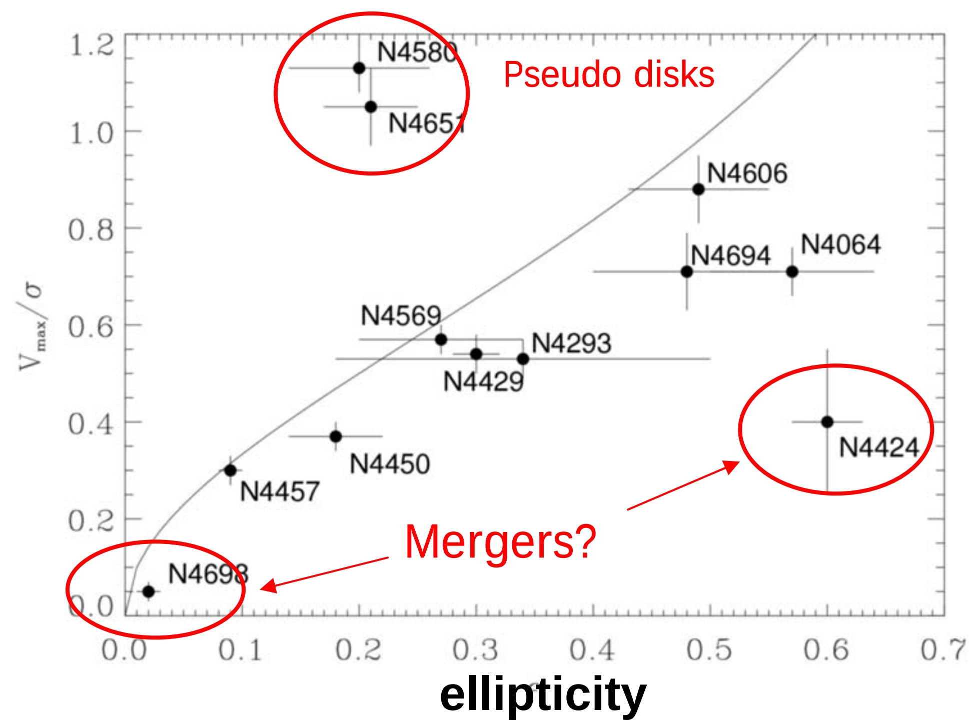


- V/σ ranges from 0.3 to 4. Two galaxies with extremely low V/σ (< 0.5!)

- Vmax/σ-ε diagram. Most galaxies located close to isotropic line.

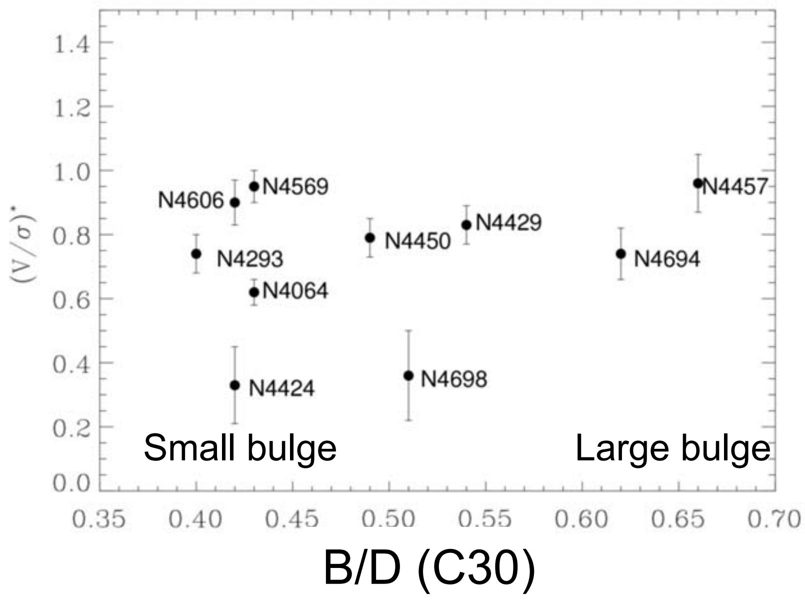
- N 4580 and N 4651 exhibits disk kinematics. N 4424, and N 4698 elliptical-like kinematics. Interm. and major mergers

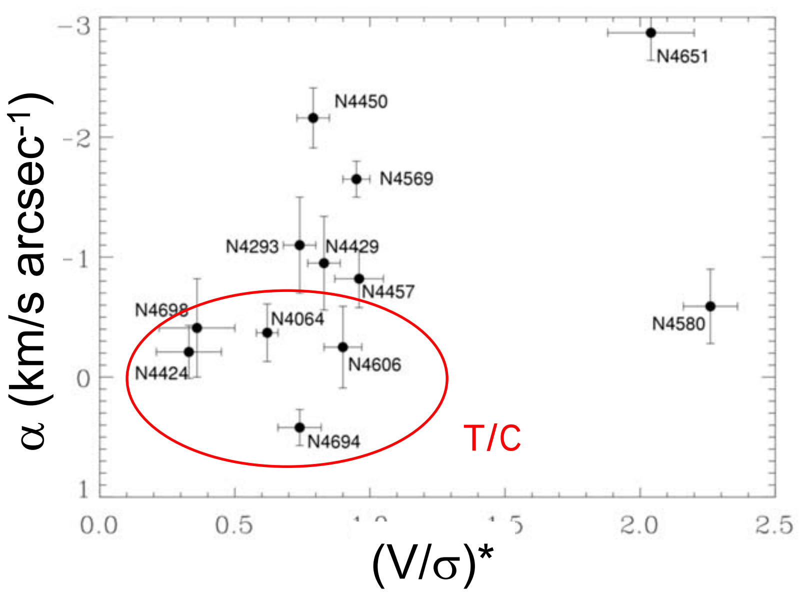




- No correlation between B/D ratio (C30) with V/σ and σ flatness. Bulge size is not the cause of flat σ and low rotation wrt σ.

- Galaxies with smaller V/σ tend to have flatter σ.

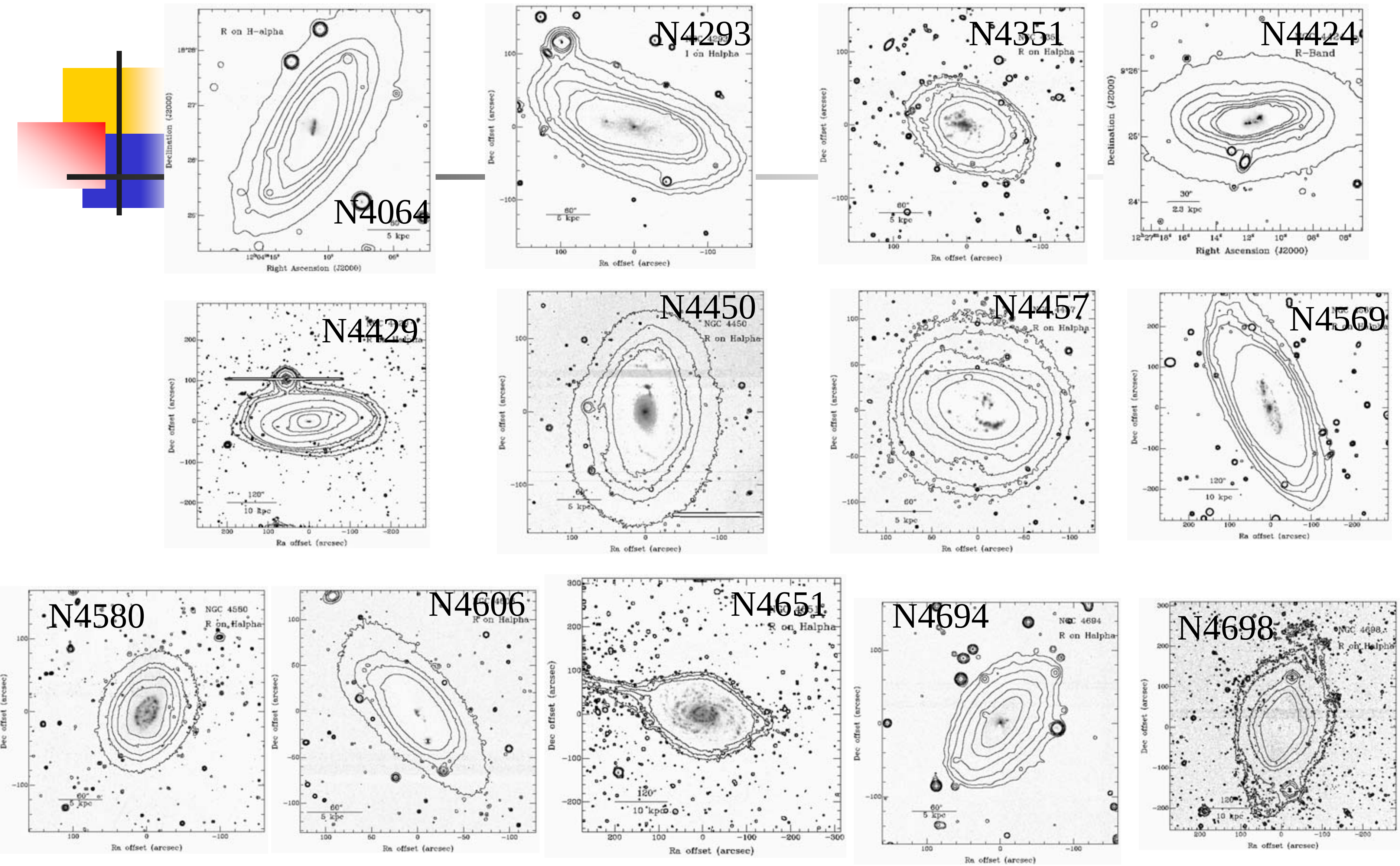




Summary

- Most galaxies exhibit signatures of recent grav interaction (9/13) and ICM-ISM stripping. Tidal inter, minor merger & intermediate merger.
- Only 2 galaxies do not exhibit signatures of recent grav int, but *rather* recent ICM-ISM stripping.
- Grav interactions are important in driving galaxy evolution. Significant *number of* cluster galaxies experience both grav. Inter. & ICM-ISM stripping.
- Gravitational interactions alter morph. from S->S0. Drive gas inwards. ICM-ISM stripping is responsible for gas depletion in outer disk. Pre-processes galaxies in the core of the cluster.
- Both (Grav. Interactions and ICM-ISM stripping) are crucial in formation of T/C galaxies.

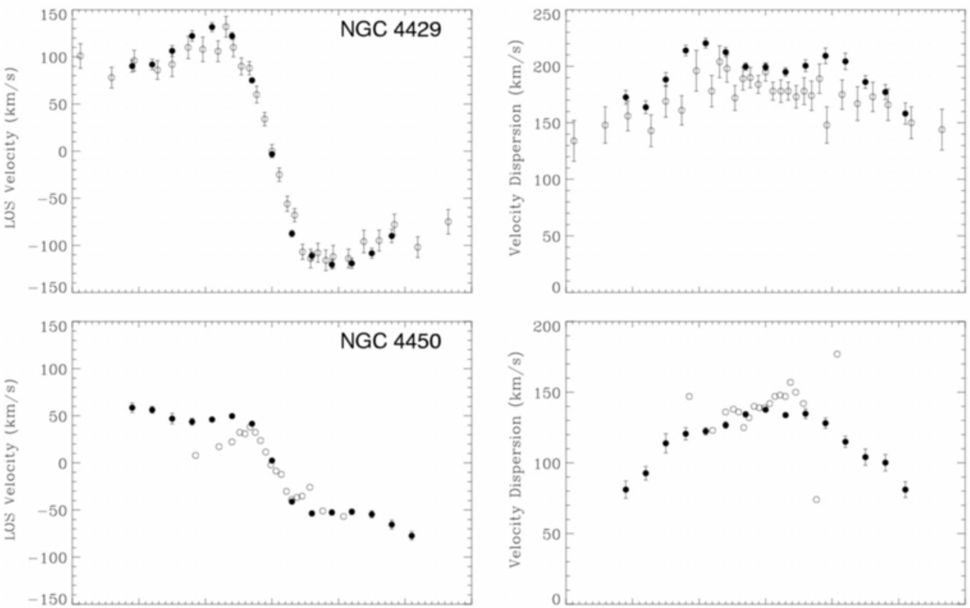
EXTRAS


N4064
R on H-alpha
Right Ascension (J2000)
Declination (J2000)
N4293
I on Halpha
N4351
R on Halpha
N4424
R-Band
Right Ascension (J2000)
N4429
N4450
NGC 4450
R on Halpha
N4457
R on Halpha
N4569
N4580
NGC 4580
R on Halpha
N4606
R on Halpha
N4651
R on Halpha
N4694
NGC 4694
R on Halpha
N4698
NGC 4698
R on Halpha
Ra offset (arcsec)
Dec offset (arcsec)

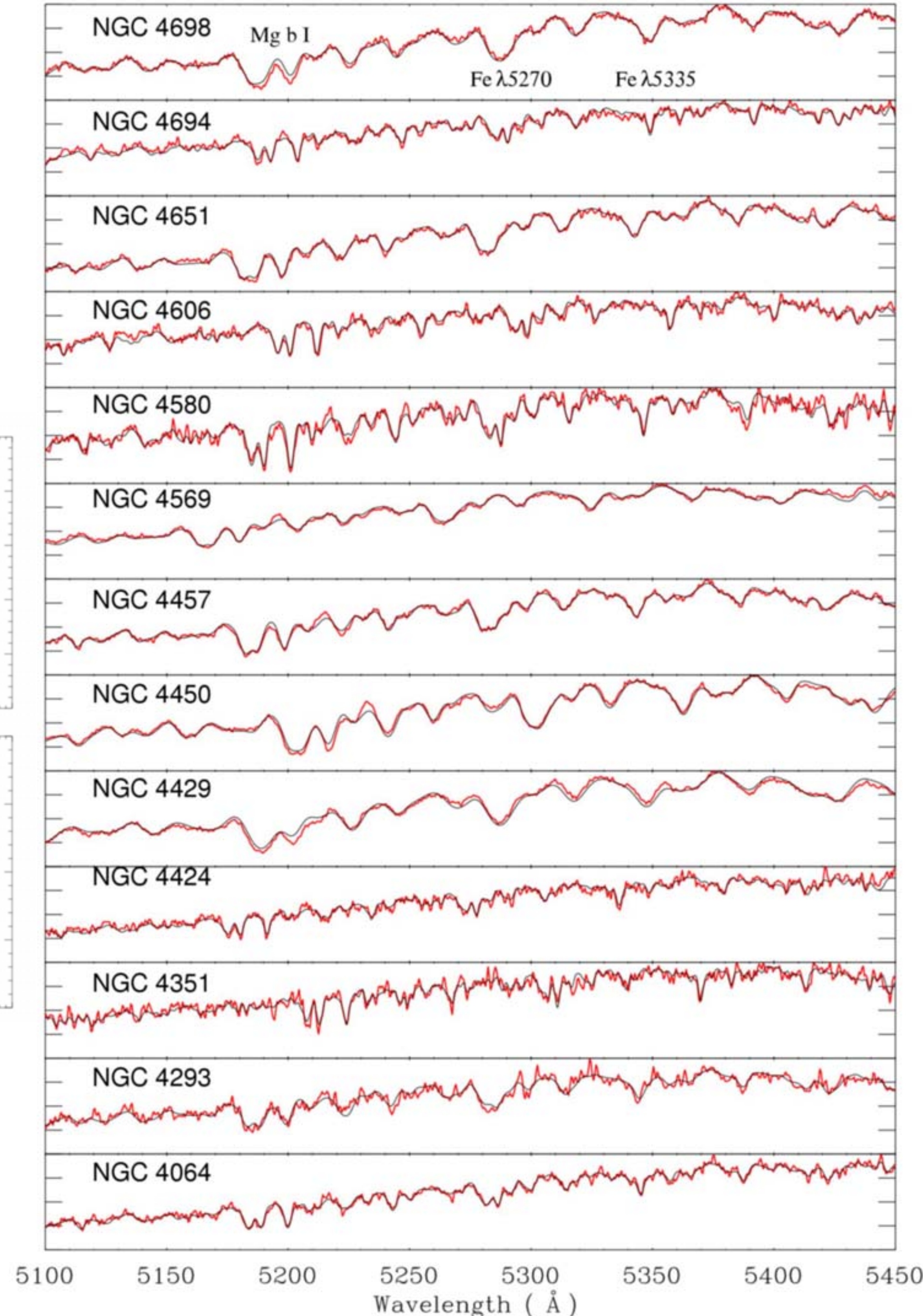
–Sample properties

Name	SF Class	RSA/BST	B	L/L*	Dist M87	HI Def
NGC 4064	T/C	SB(s)	12.3	0.18	8.8°-2.5 Mpc	0.99
NGC 4293	T/A	Sa pec	11.2	0.49	6.4°-1.8 Mpc	>1
NGC 4351	T/N(s)	Sc(s) II.3	13.0	0.09	1.7°-470 kpc	0.58
NGC 4424	T/C	Sa pec	12.3	0.17	3.1°-870 kpc	1.1
NGC 4429	-	Sa pec	10.9	0.64	1.5°-420 kpc	>1
NGC 4450	T/A	Sab pec	10.9	0.63	4.7°-1.3 Mpc	1.3
NGC 4457	T/N(s)	Rsb(rs) II	11.8	0.29	8.8°-2.5 Mpc	1.0
NGC 4569	T/N(s)	Sab(s) I-II	10.3	1.17	1.7°-470 kpc	0.99
NGC 4580	T/N(s)	Sc/Sa	12.5	0.15	7.2°-2.0 Mpc	1.3
NGC 4606	T/C	Sa pec	12.7	0.12	2.5°-700 kpc	>1
NGC 4651	N	Sc(r) I-II	11.4	0.42	5.1°-1.4 Mpc	-0.16
NGC 4694	T/N	Amorph	12.2	0.2	4.5°-1.3 Mpc	1.2
NGC 4698	A	Sa	11.5	0.36	5.8°-1.6 Mpc	0.25

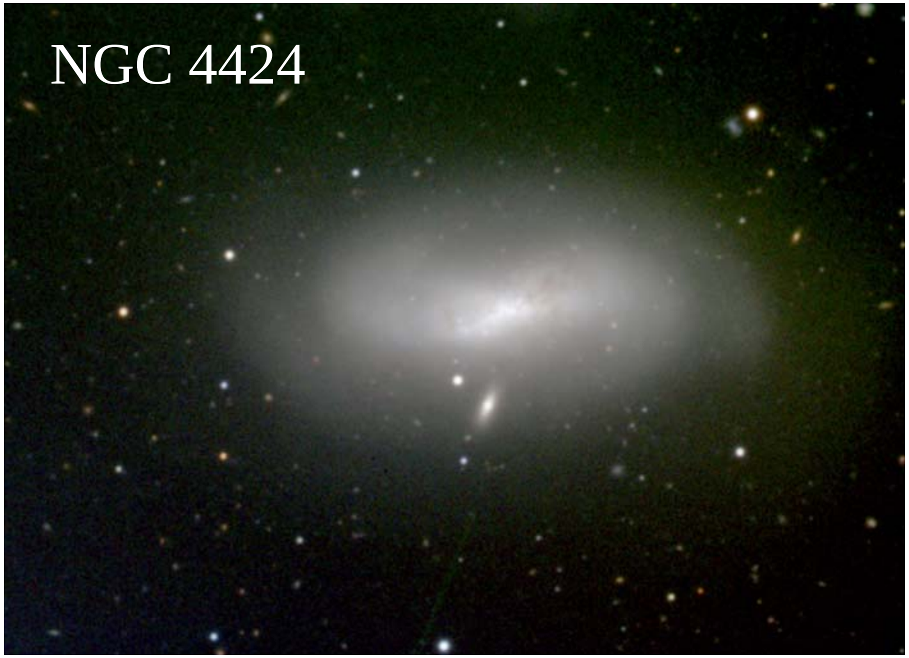
Central Spectra for the 13 Peculiar Galaxies.



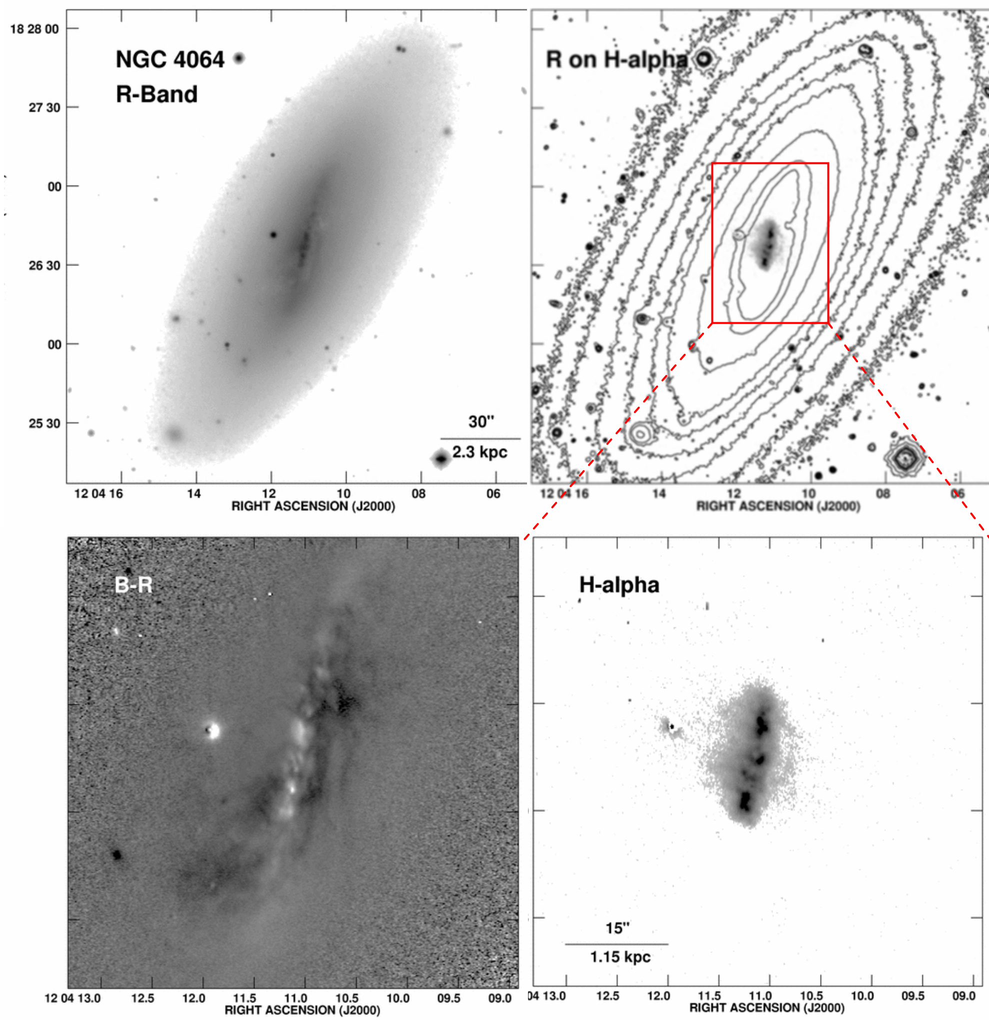
Comparison with other data sets



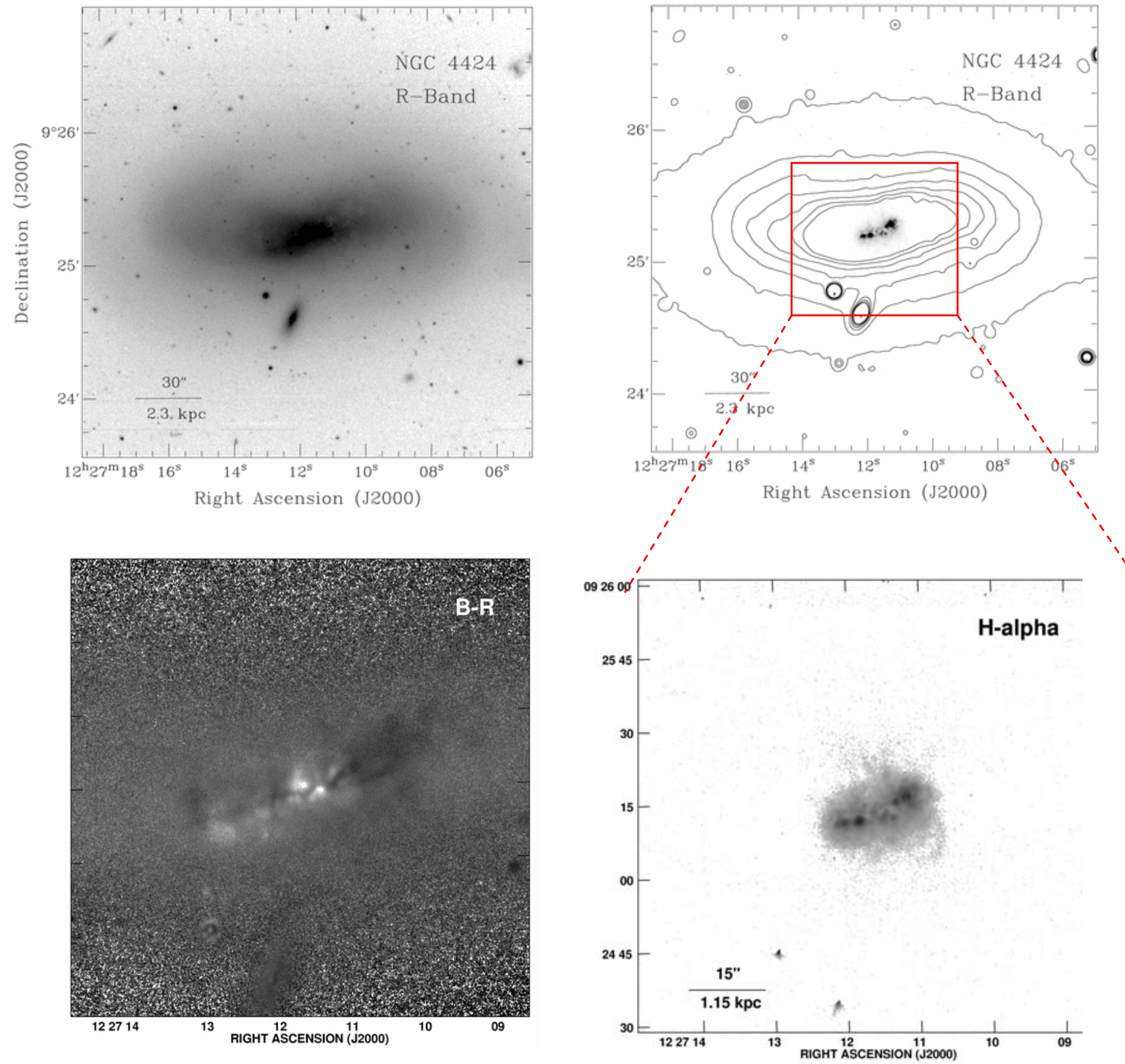
- Nature of the Peculiar Virgo Cluster Galaxies NGC 4064 & NGC 4424
  - Best examples of Truncated/Compact Hα morphology.
  - Not just stripped galaxies. What happened to them?



- Morphology & Kinematics
  - NGC 4064: Optical morphology
    - Small bulge
    - Disturbed dust lanes
    - Bar which turns into open spiral arms
    - Compact Hα emission
    - Few HII SF complexes aligned with bar
    - Hα Filaments

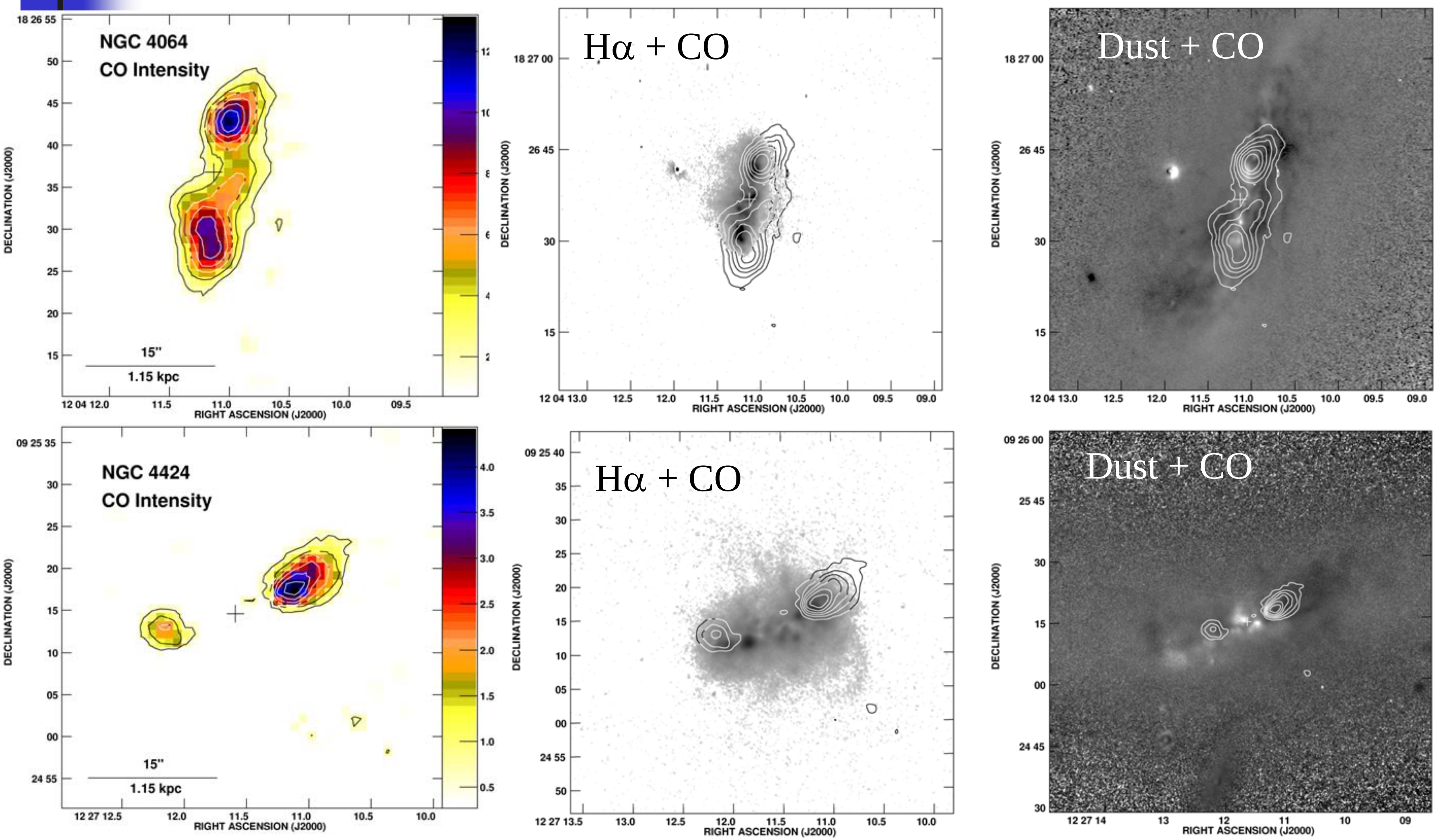


- NGC 4424 Optical Morphology
  - Disturbed stellar disk
  - Shells+heart shaped stellar distribution
  - Disturbed dust lanes
  - Compact Hα emission
  - Few HII SF complexes

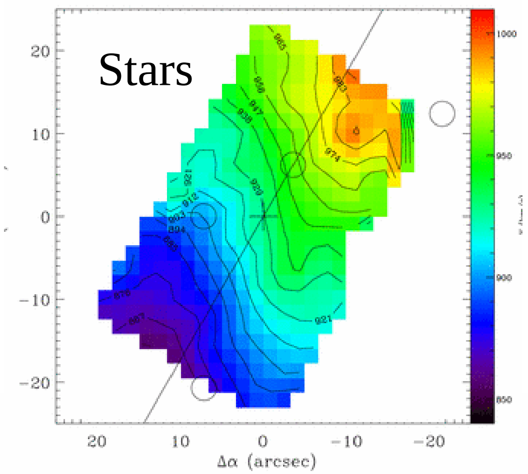


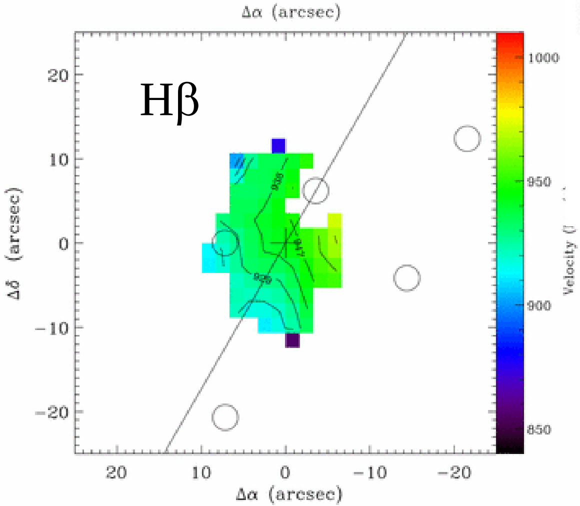
- CO (1-0) Interferometry:Reveals complex geometry and kinematics.
  - OVRO mm array, spatial resolution 2”-4”, velocity resolution 5-10 km s-1.
  - Moment maps and Position-Velocity maps. Comparison with stellar and ionised gas kinematics.

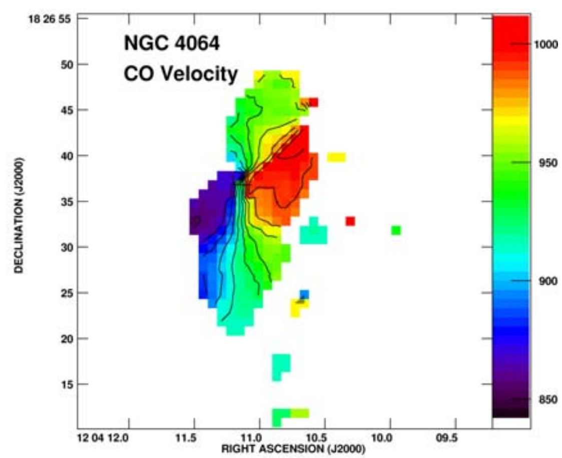
- Both galaxies has CO bi-lobal structure
- Hα emission inside CO lobes. Time sequence in the star formation process
- Some correlation with dust lanes, but dust is more extended

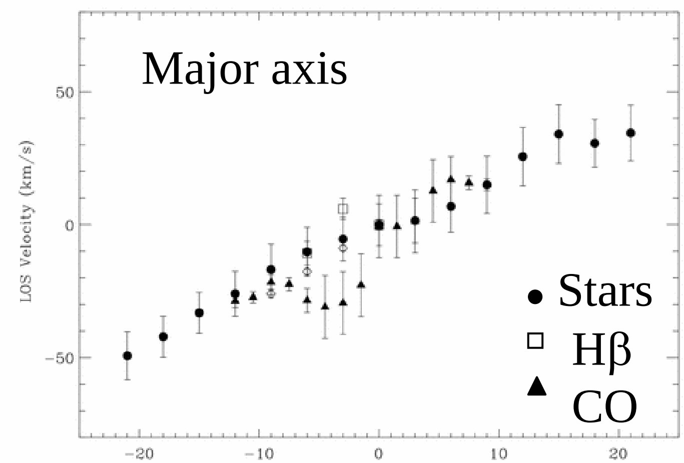


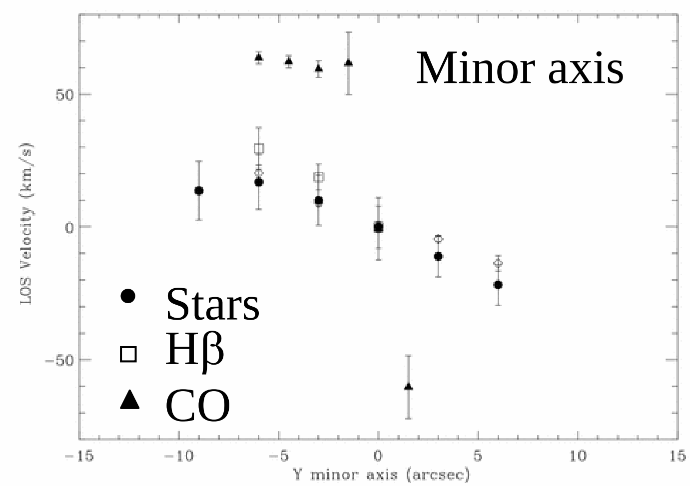
- Kinematics:
  - N4064:
    - Stellar V field: rotation + bar-like streaming motions
    - Hβ gas V. field: rotation + bar-like streaming motions
    - CO V. field : strong non-circular streaming motions. Inward radial motion



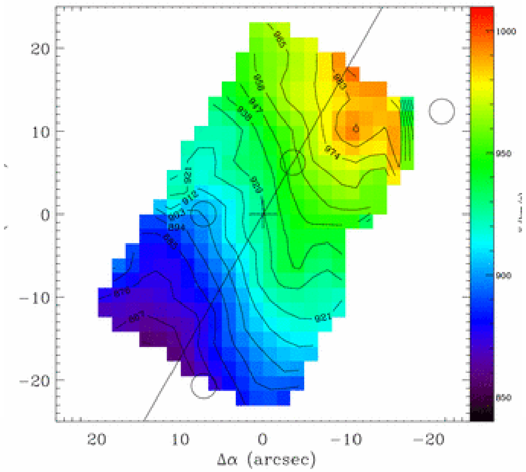


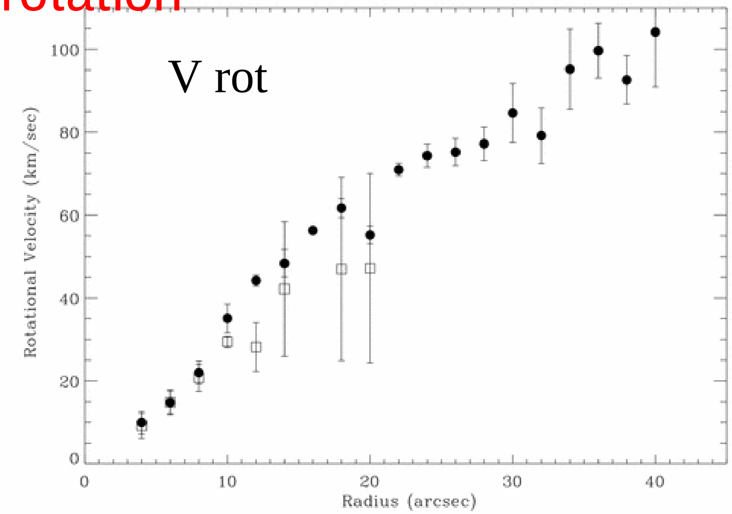


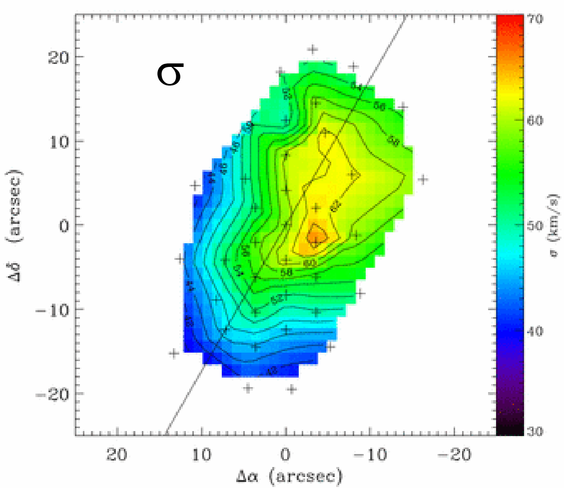


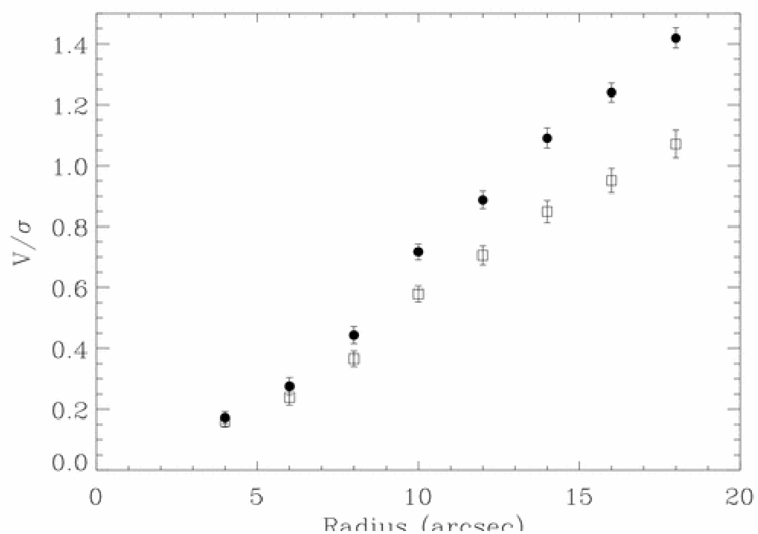


- Maximum measure stellar rot. velocity ~85 km/s
- Radial stellar streaming motions ~ 20 km/s
- Velocity dispersion peak ~ 65 km/s
- Galaxy dominated by rotation



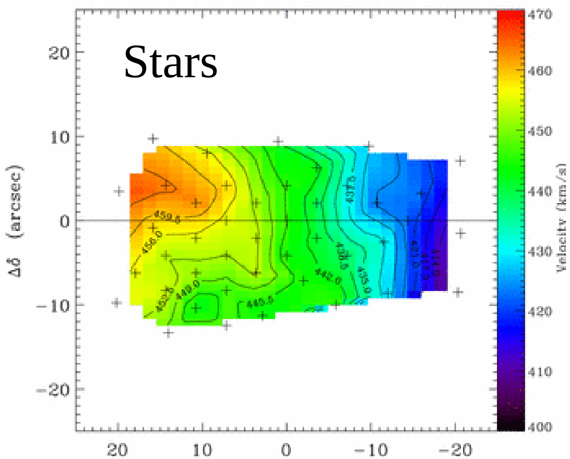


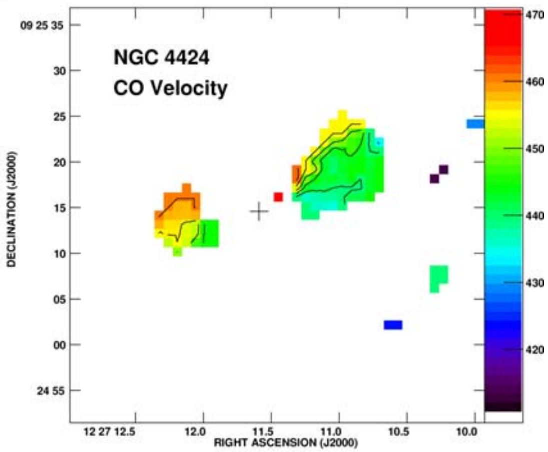


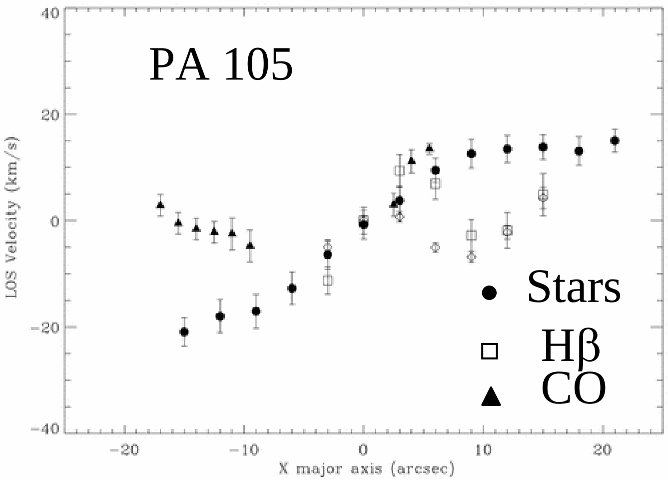


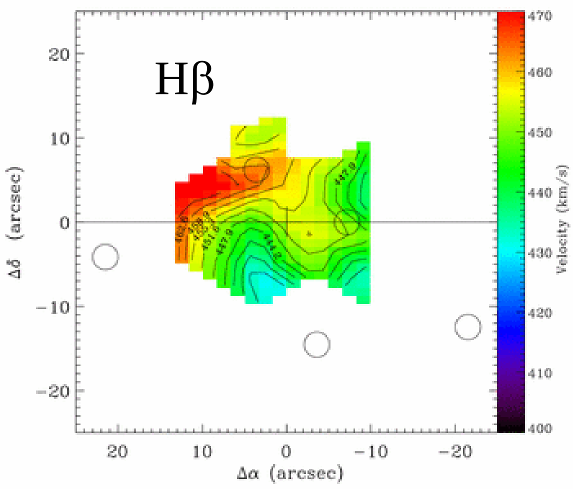
NGC 4424

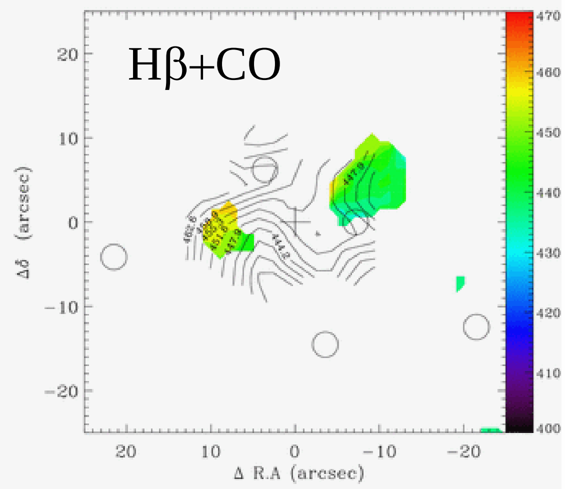
- Stellar velocity field: consistent with rotation
- Ionized gas V. field: very different from stellar kinematics.
- CO V. field: Strong non-circular streaming motions

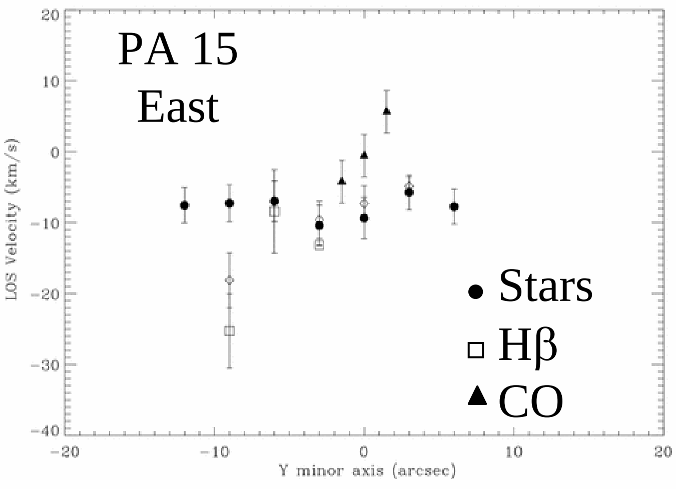




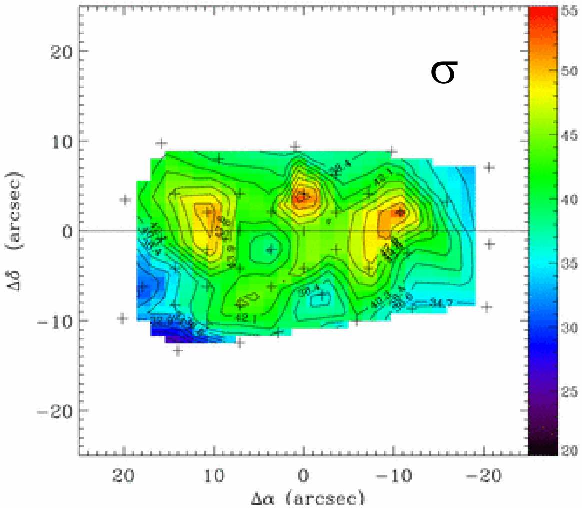


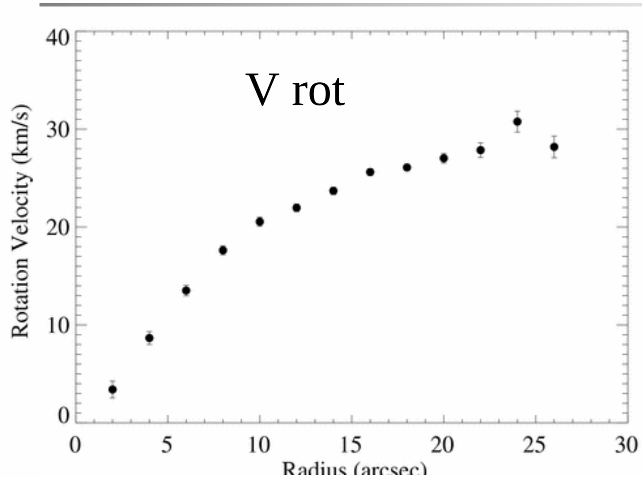


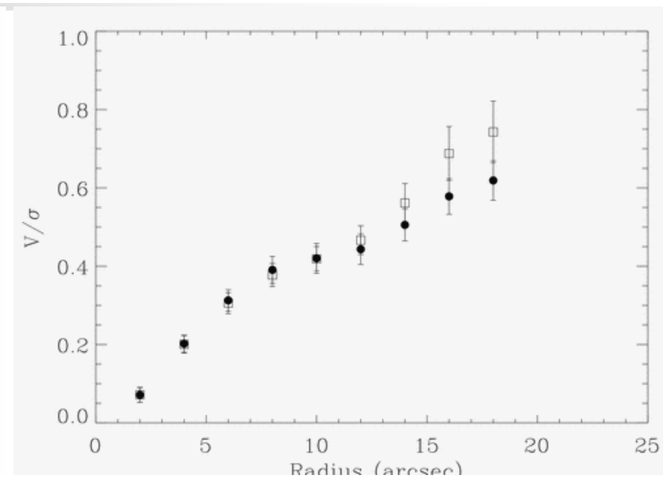


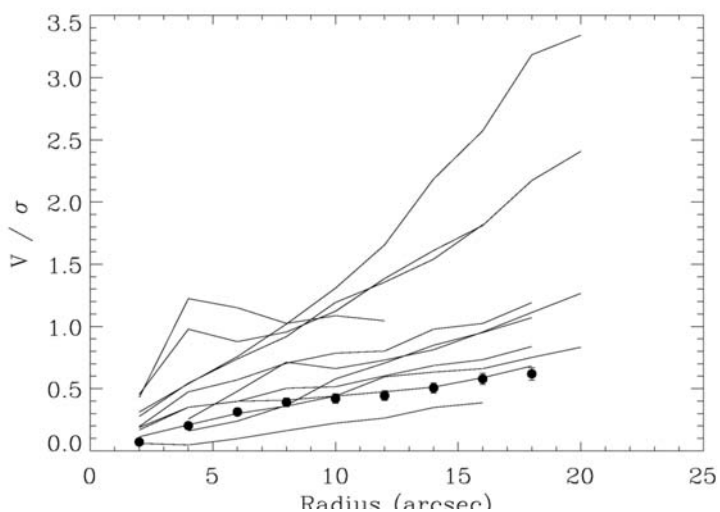


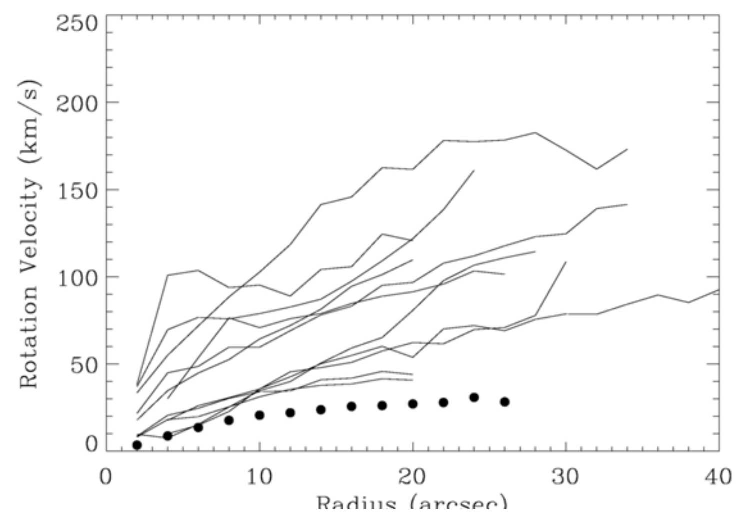
- Slow rotator Vrot ~ 30 km/s. Slowest rotator in galaxy sample!
- Symmetric V disp field
- V disp > Vrot
- Inner 20” supported by random motions





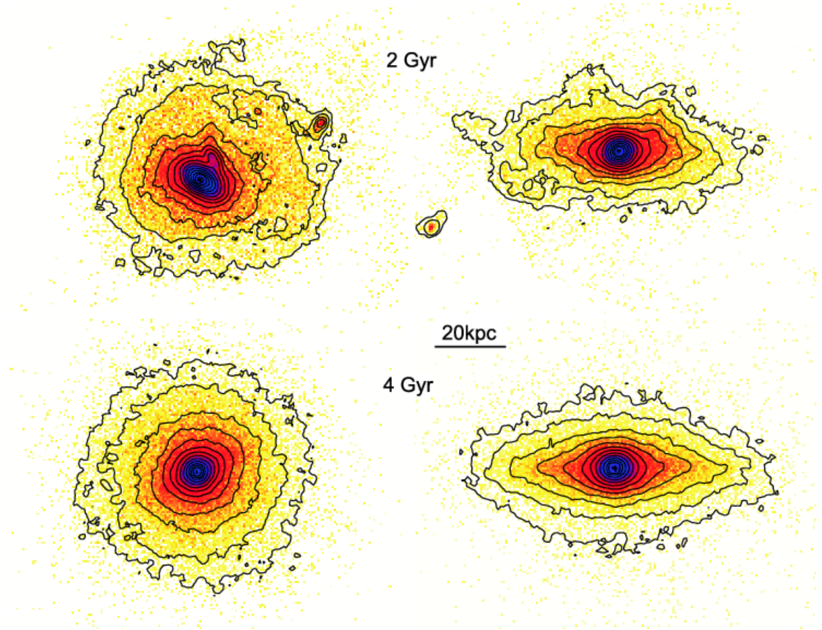


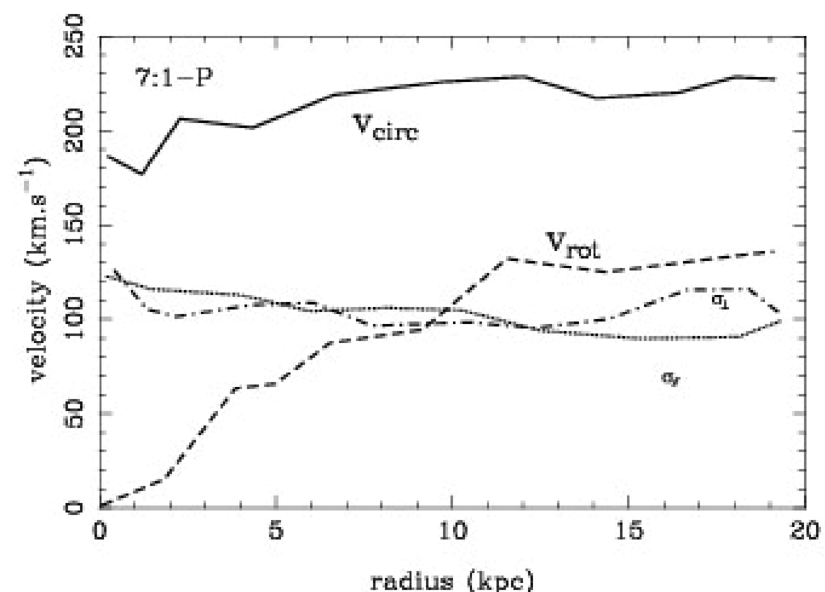




- Nature of NGC 4064 and NGC 4424
  - Similar features:
    - CO peaks
    - Compact Hα emission
    - Disturbed dust lanes
  - NGC 4424
    - Disturbed morphology, and severe truncation suggest merger event
    - Merger could drive gas to center, triggering SF
    - Disk-like morphology, and elliptical-like kinematics suggest 1:10-1:4 merger
    - No star formation out of 1 kpc, Have ISM-ICM stripping devoid outer disk of gas?

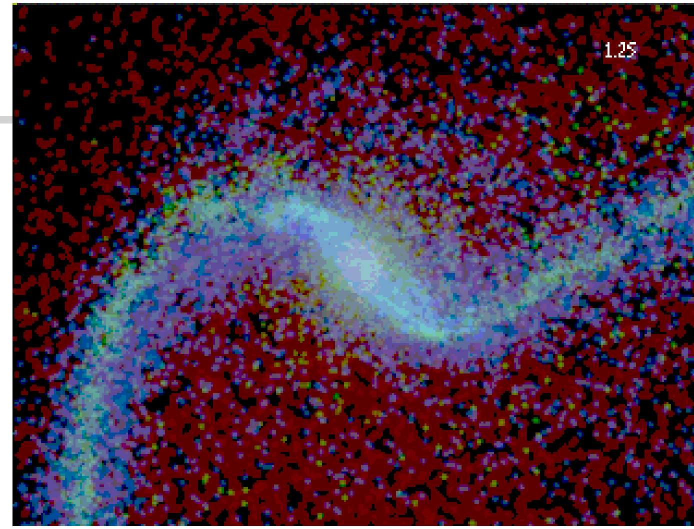
Intermediate mass merger sim.

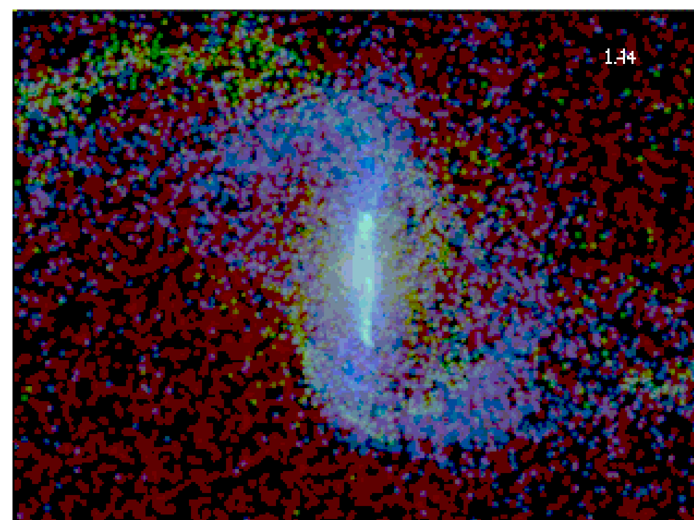




- NGC 4064
  - Disturbed dust lanes and strong SF activity suggest gravitational interaction
  - Undisturbed outer morphology contradicts merger scenario
  - Bar-like structures and gas concentrated in the center could be explained also by tidal interactions.
  - Closest companion small Irr galaxy NGC 4049 (~130 kpc, similar l-o-s vel)
  - ICM-ISM stripping could have a role in depleting outer gas but long time ago (2 Gyr)

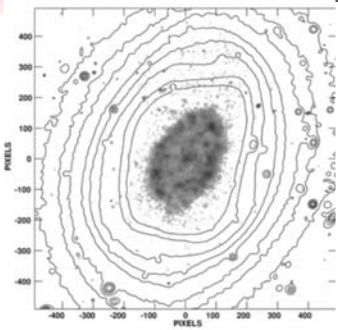
Disturbance cause by tidal forces.



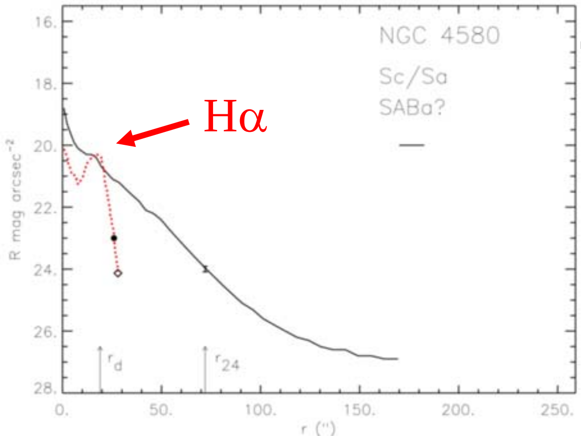


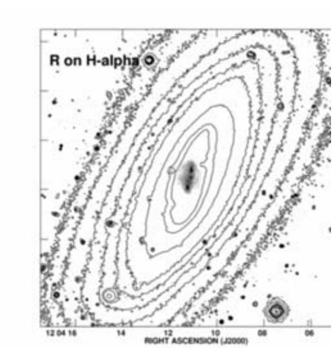
Name	SF Class	Dist M87	HI Def	Perturbed morphology	Pec kin	Possible Processes
NGC 4064	T/C	8.8°-2.5 Mpc	0.99	dist dust+bar	Flat σ+bar	Old Strip + minor merger
NGC 4293	T/A	6.4°-1.8 Mpc	>1	dist dust+star	Kin mis	Old Strip + tidal inter
NGC 4351	T/N(s)	1.7°-470 kpc	0.58	lopsided	gas	Strip + tidal?
NGC 4424	T/C	3.1°-870 kpc	1.1	dist dust +star	gas+star	Merger + ongoing strip
NGC 4429	-	1.5°-420 kpc	>1	No	Stellar CND	Old strip
NGC 4450	T/A	4.7°-1.3 Mpc	1.3	No	gas	Sat accretion?
NGC 4457	T/N(s)	8.8°-2.5 Mpc	1.0	gas	gas	Recent strip
NGC 4569	T/N(s)	1.7°-470 kpc	0.99	dist dust +gas	gas+star ?	Strip + small tidal inter
NGC 4580	T/N(s)	2.5°-700 kpc	1.3	no	no	Recent stripping
NGC 4606	T/C	2.5°-700 kpc	>1	dist dust	Flat σ	Merger +strip?
NGC 4651	N	5.1°-1.4 Mpc	-0.16	Stellar Tail	no	Ongoing Minor merger
NGC 4694	T/N	4.5°-1.3 Mpc	1.2	dist dust	Flat σ + gas	Strip ?+ collision
NGC 4698	A	5.8°-1.6 Mpc	0.25	No	star+gas	Merger +strip?

Star Formation Classes

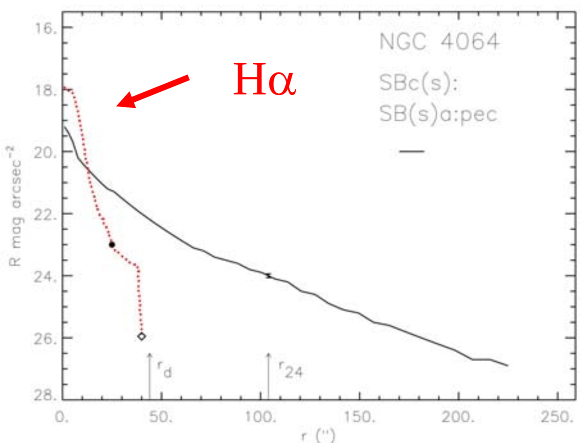


Truncated/Normal

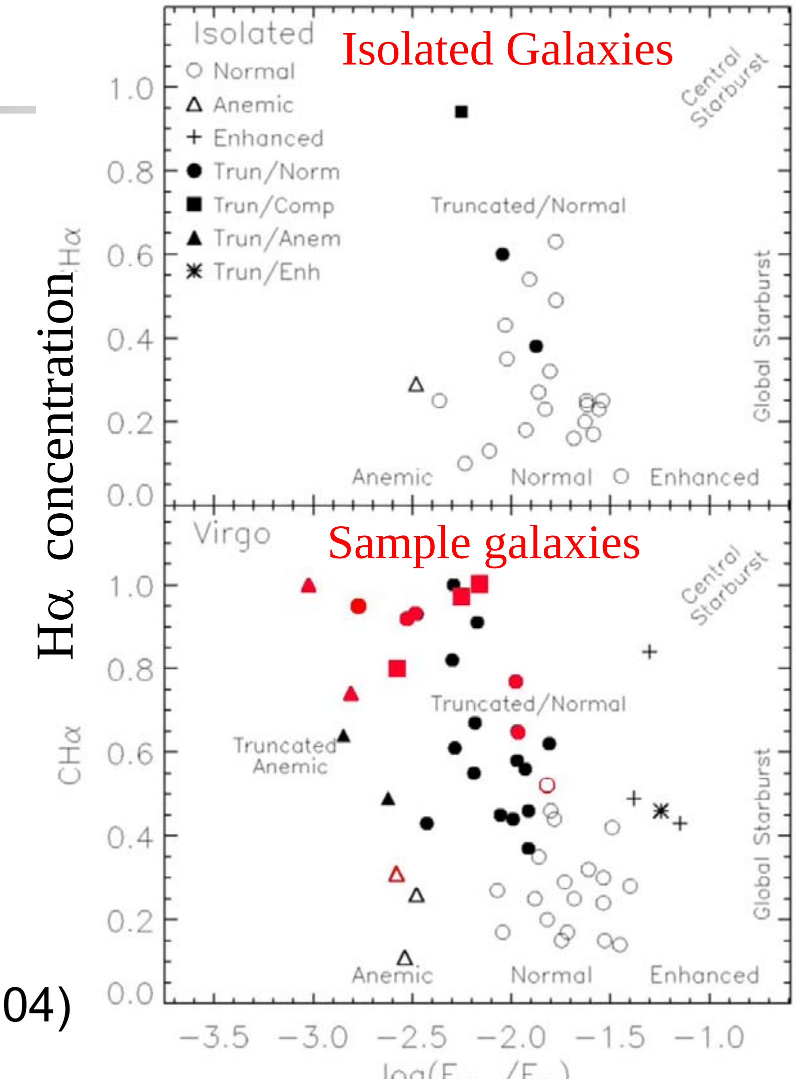




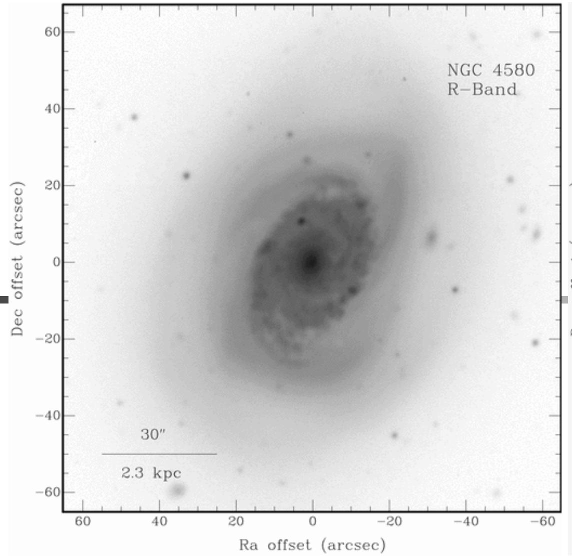
Truncated/compact

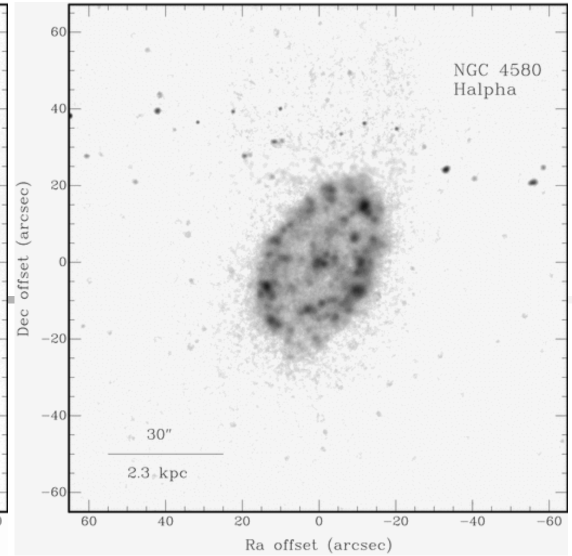


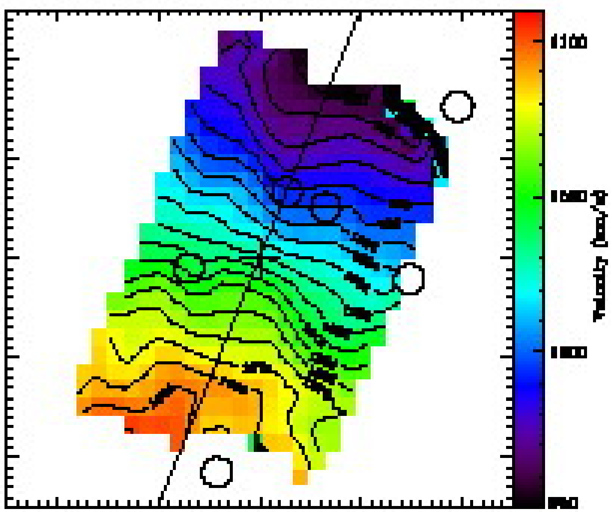
Koopmann & Kenney (2004)

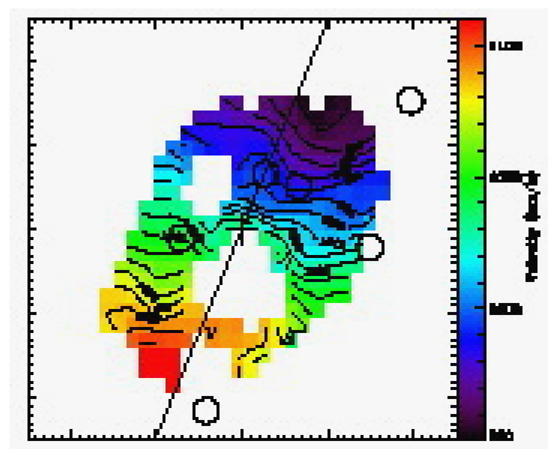


Star Formation rate





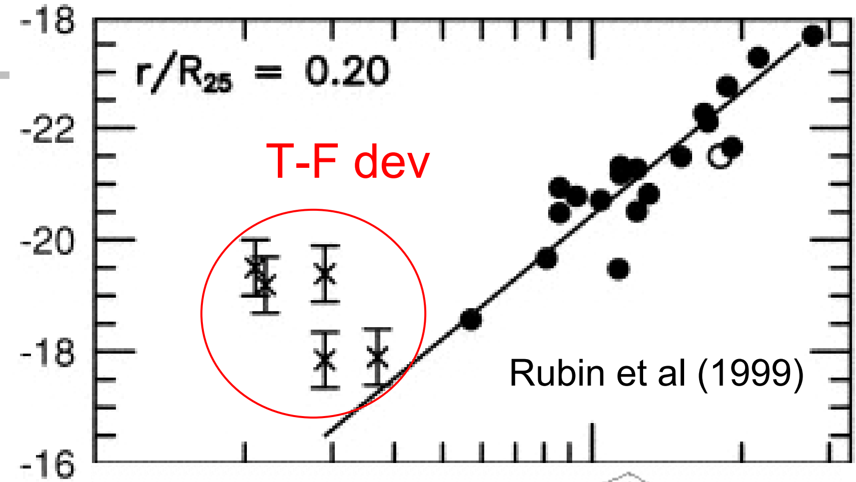


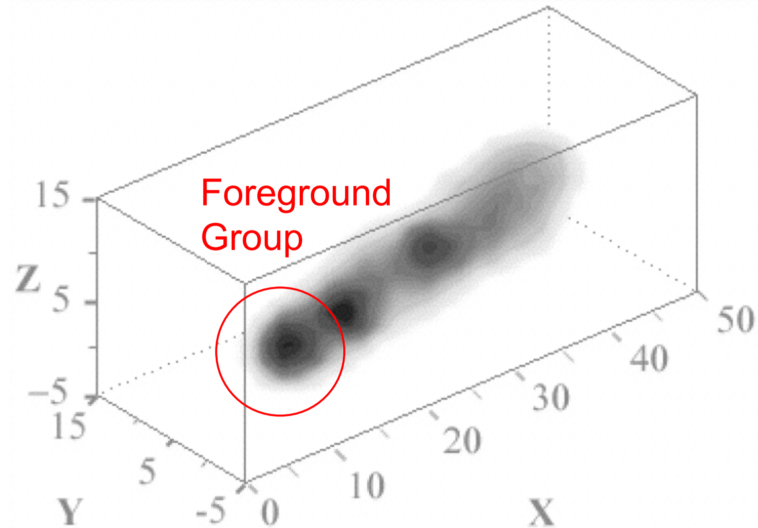


NGC 4580 a case for annealing disk?

Distance estimation in HI-deficient Galaxies

- Some HI deficient galaxies have anomalously low rot. vel, so they deviate from standard Tully-Fisher relation
- Foreground objects ? (Solanes et al 2002) Or observed linewidths are poor tracers of galaxy mass?.
- Open questions:
  - Why some Virgo spirals disagree with T-F rel? Environmental effects?
  - How do they affect previously derived 3-D structure of the cluster?



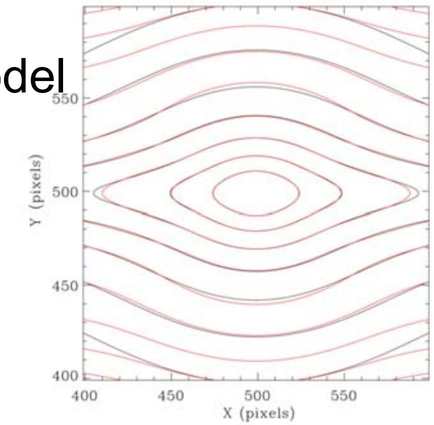


Sanchis et al. (2002)

2-integral models: synopsis

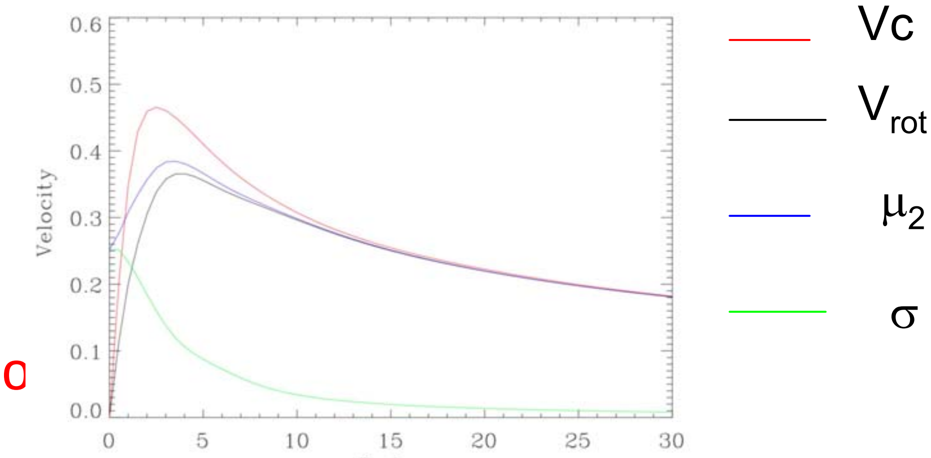
- Multi-Gaussian Expansion (MGE, Cappellari 2002) de-projection;
  - ρ (R,z).
  - Simple formalism.
  - $Vc^2 = R\, \partial\Phi / \partial R$

Plummer model
a=b=1

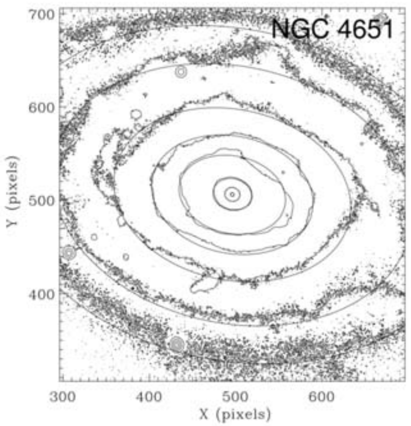


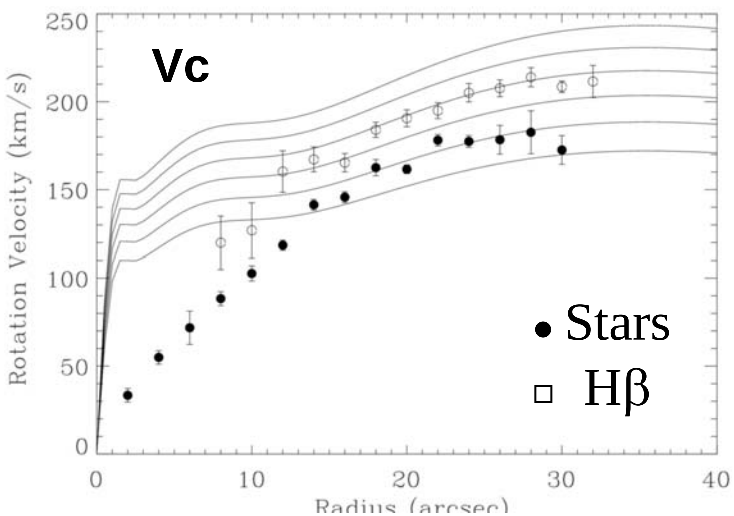
- 2-integral models $f(E,L_z)$
  - axisymmetric systems.
  - Solves Jeans Equations.
  - Fully consistent models.

- Test: Plummer model. Reproduce analytical solutio

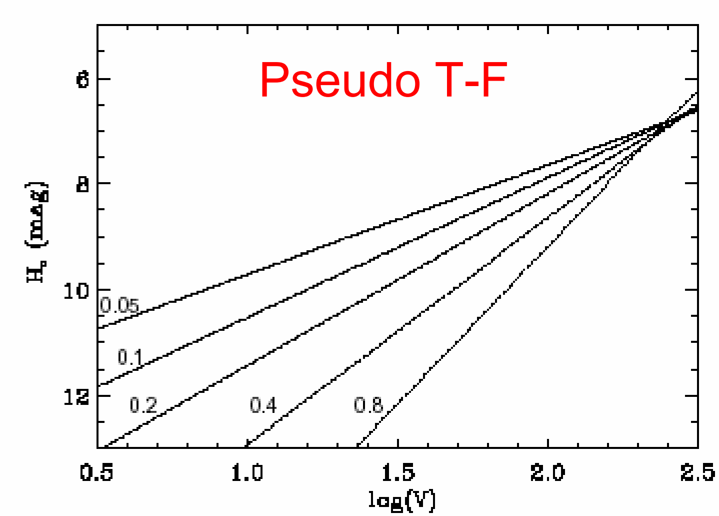


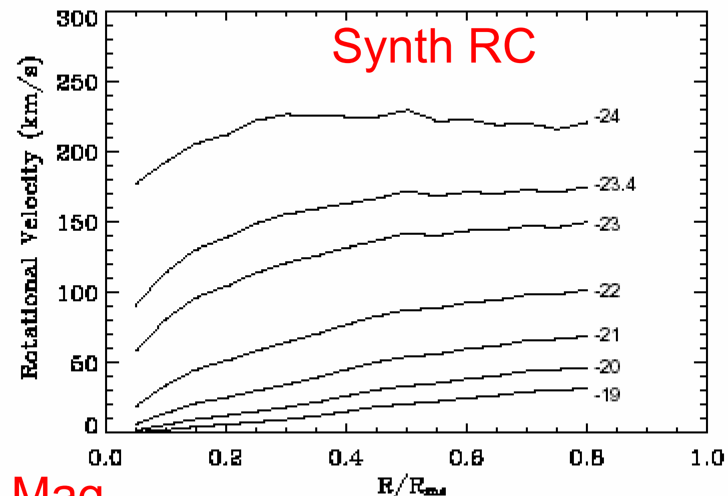
- Distances to HI-deficient galaxies.
  - Gas velocities cannot be used. Environmental effects
  - Use stellar kinematics. But we must include σ!
  - MGE Two-integral axisymmetric modeling: to solve Jeans Equations.
  - Models do not include dark matter.
  - Challenging in Sp galaxies: Dust, bars, anisotropy in velocity ellipsoid
  - They produce reliable Vcirc.

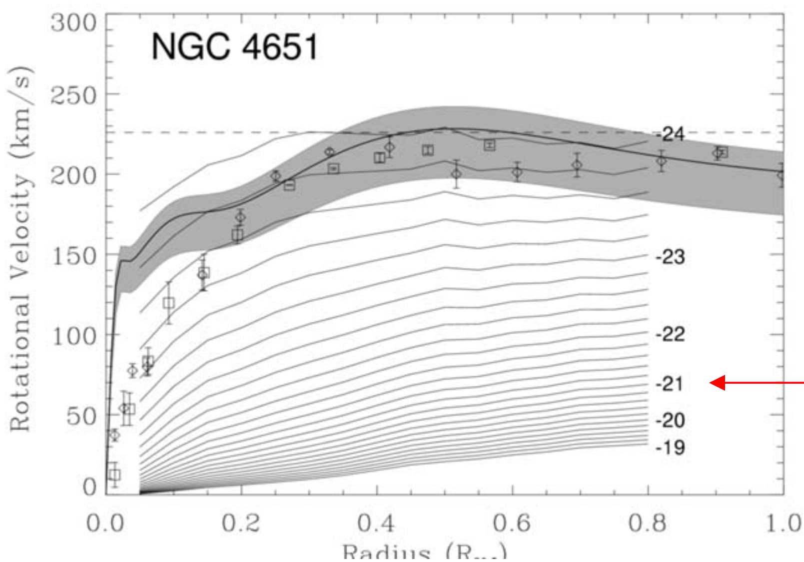




- No DM; we restrict to inner parts.
- We use NIR pseudo T-F relations to build Hα synthetic rotation curves for different abs. magnitude.
- Comparison between Stellar Vc and Hα Synth. RC; distance modulus and mass-to-light ratio.







Abs Mag

- T/C galaxies show distances discrepant by a factor 2 w/r to HI-based distances.
- Most galaxies are located within 4 Mpc from the core of Virgo.
- One galaxy is background. One galaxy out max reb. radius with sign of stripping! Possible ICM-ISM stripping in most galaxies.
- No evidence of existence of possible foreground group in Virgo. We exclude 40% of galaxies.