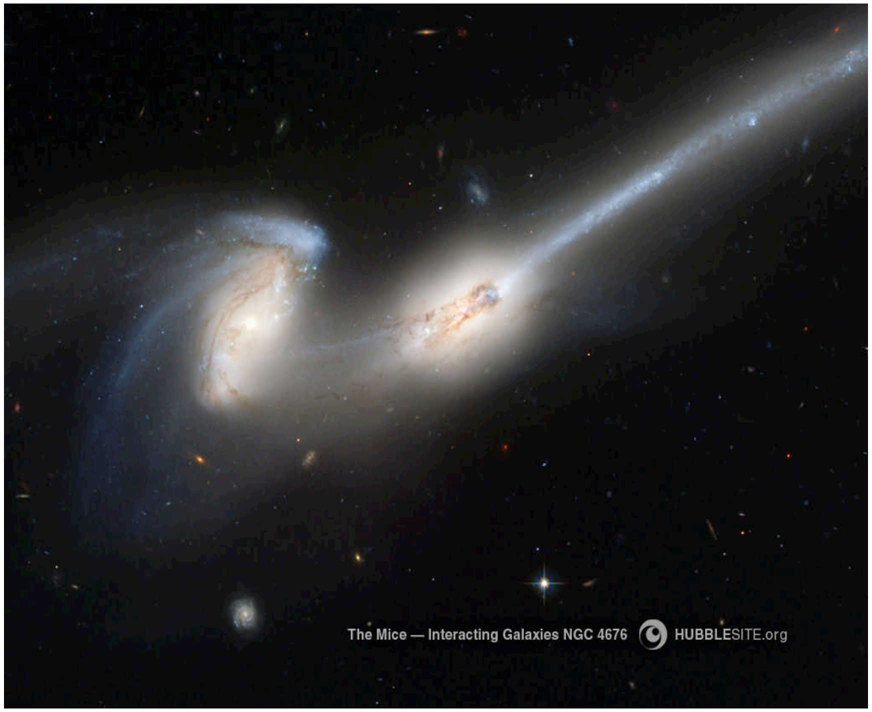
Uncovering the Formation History of Elliptical Galaxies



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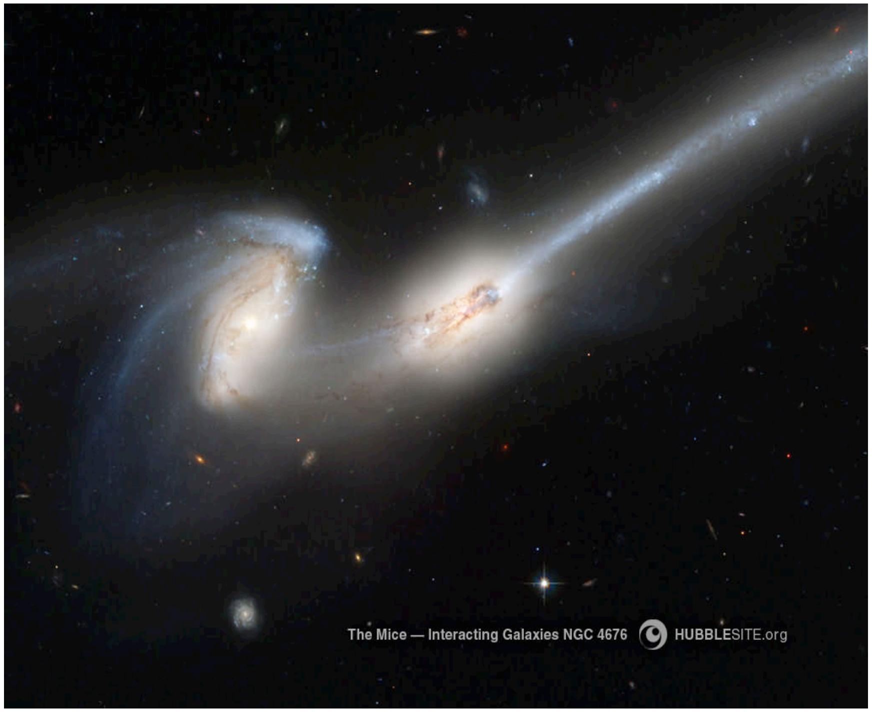
Uncovering the Formation History of Elliptical Galaxies

- **Motivation:** cosmology, hierarchical galaxy formation and the importance of mergers

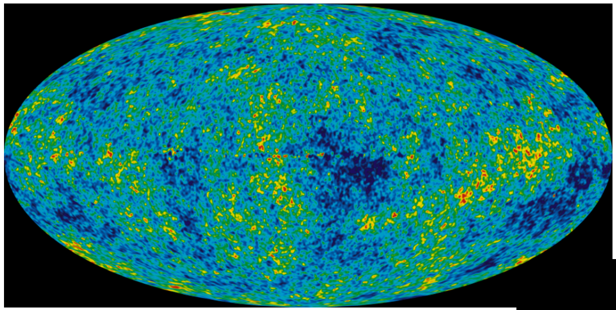
- **Methods:** employing numerical simulations to study these processes

- **Galaxy Mergers:** an overview, generic outcomes, and shortcomings of this model

- **Observational diagnostics of an elliptical galaxy's merger history**

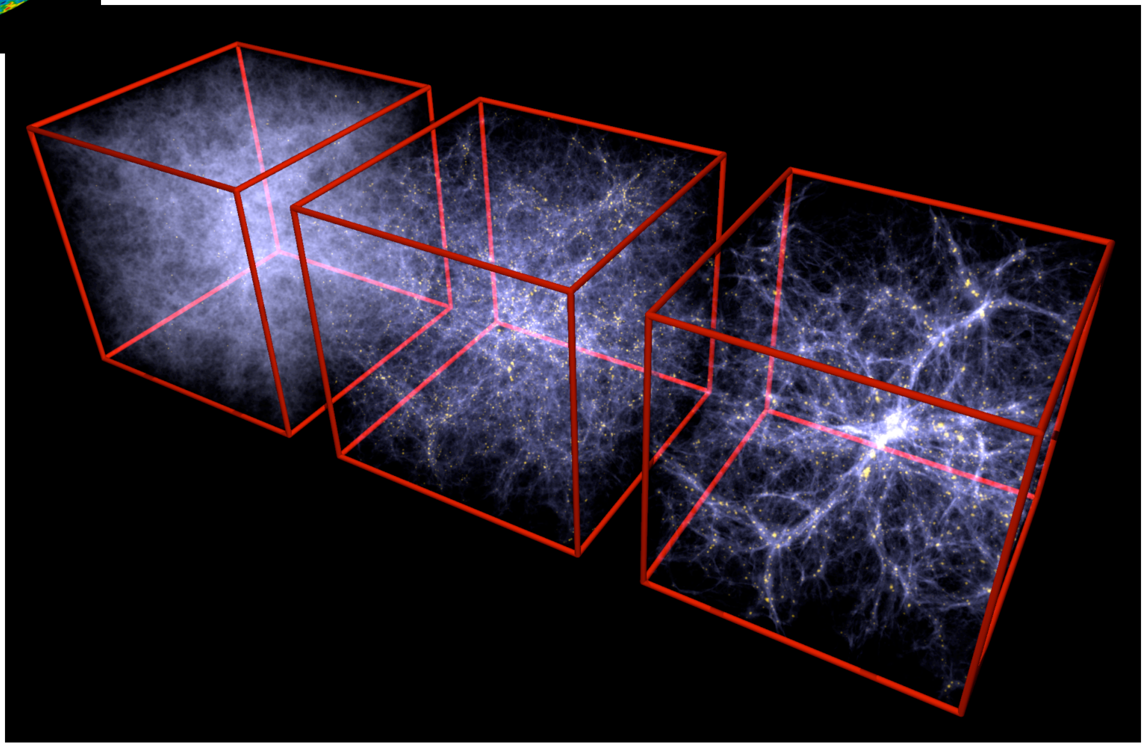


Cosmological Framework



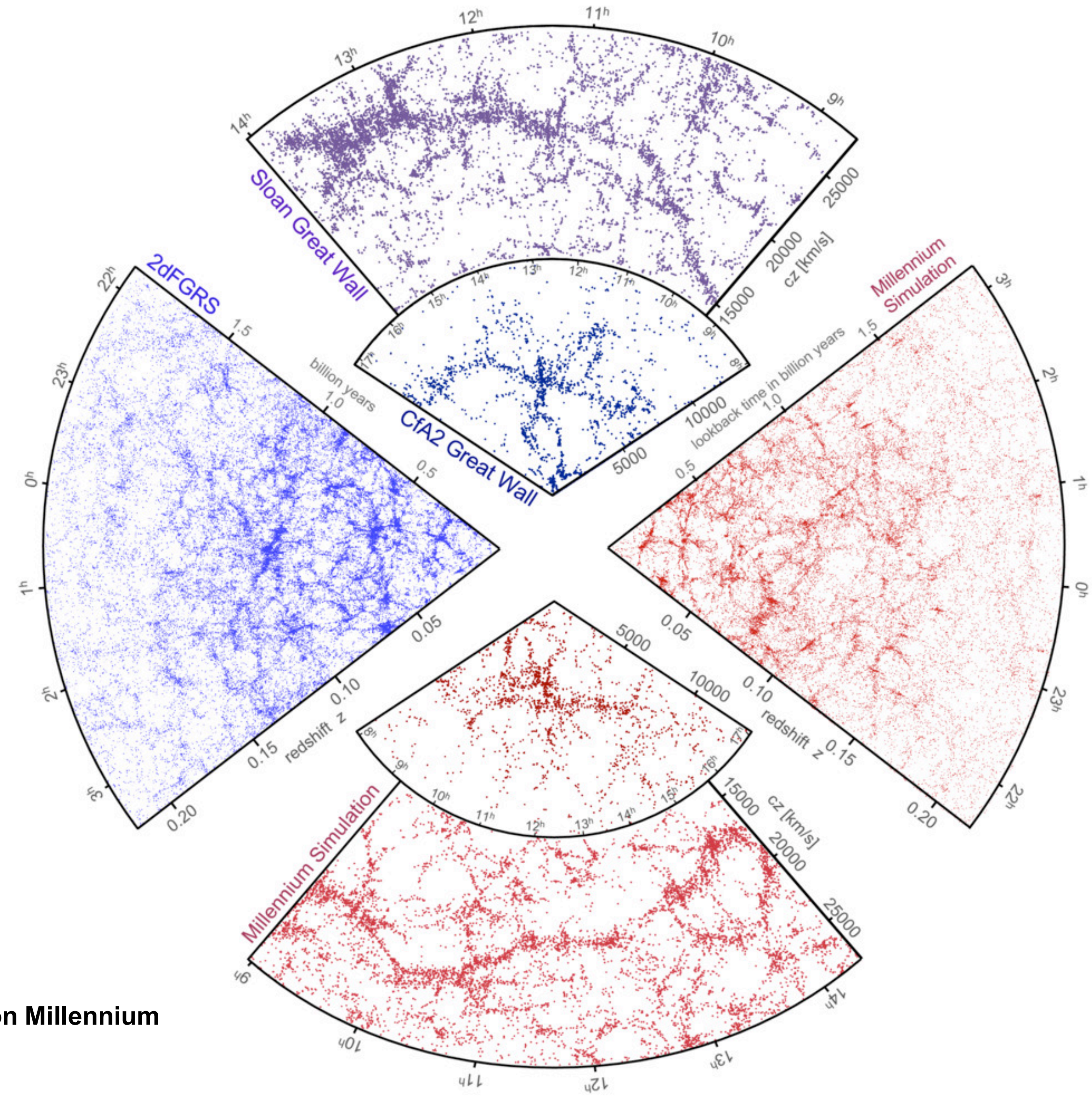
NASA/WMAP Science Team

Theories for the formation and evolution of galaxies now work within a well-understood cosmological framework.



Springel (2001)

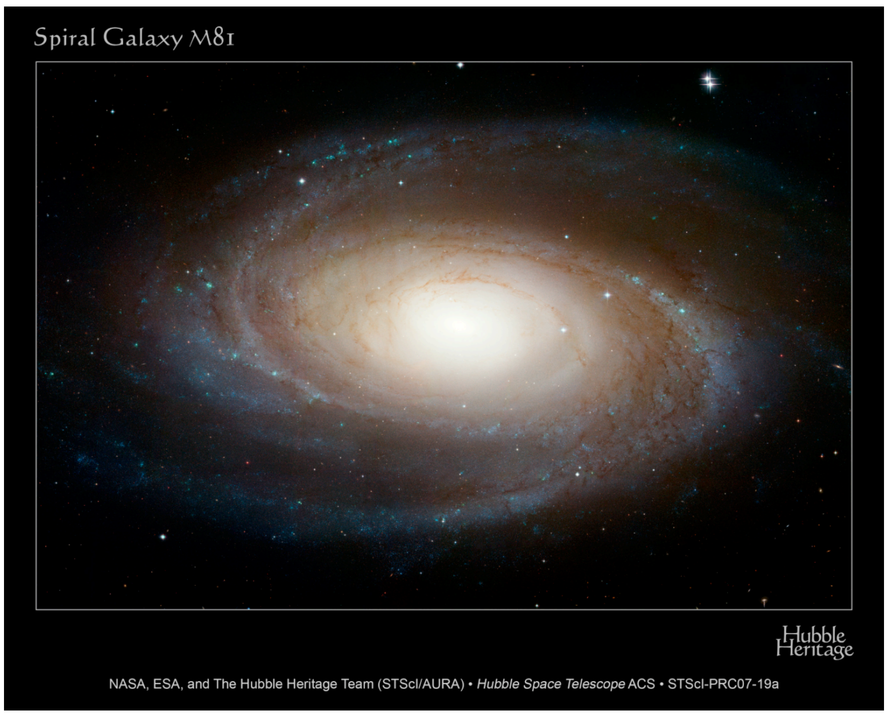
Success on Large Scales



Croton/Springel/Lemson Millennium Simulation (2006)

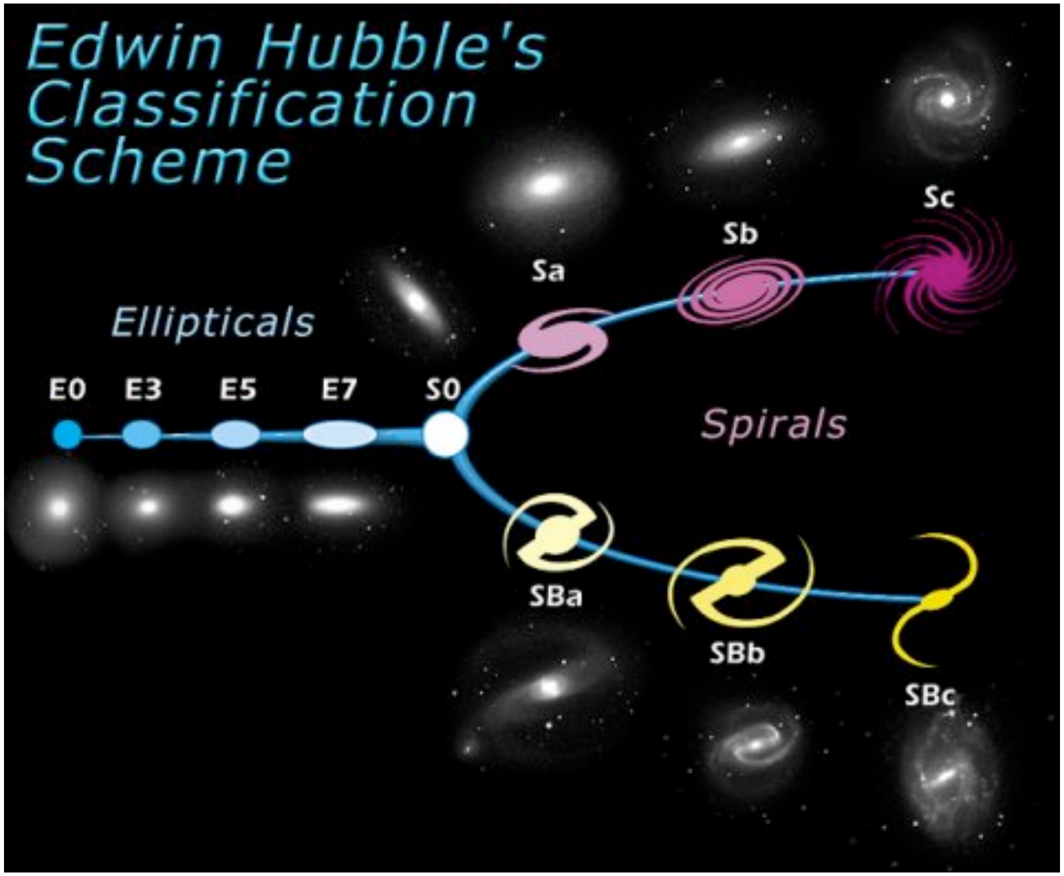
But what about small scales?

Successes in understanding the formation of galaxies within a cosmological framework has been elusive.



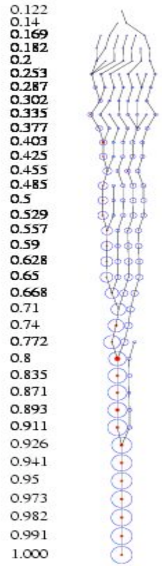
Galaxy Formation

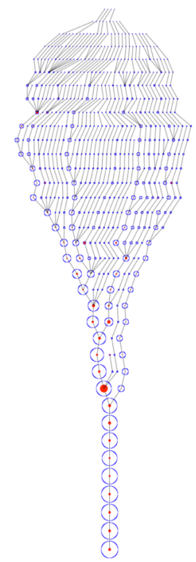
Information regarding the formation of galaxies is encoded in their morphology, dynamics, and stellar populations.



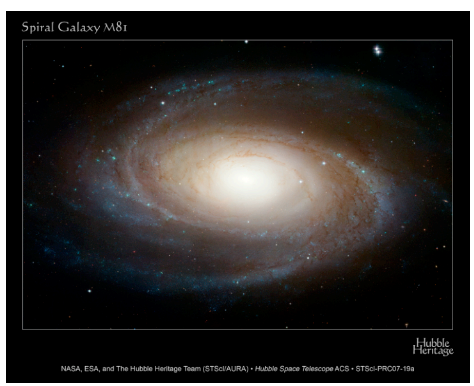
Hierarchical Formation of Galaxies

The prevailing idea for the formation of galaxies is that the characteristics of individual galaxies are determined by their (hierarchical) merger history.



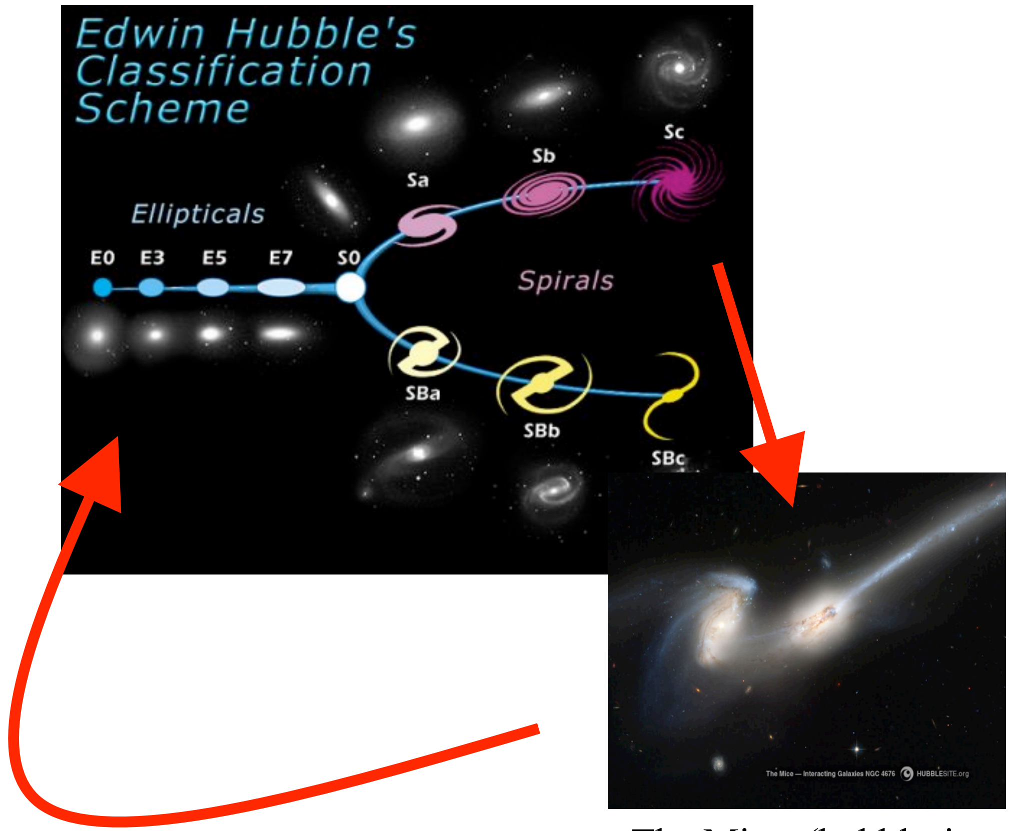


Wechsler et al. 2002 (but see also Lacey & Cole, and Fakhouri & Ma)



The Merger Hypothesis

In 1977, Alar Toomre postulated that the remnants of spiral-galaxy interactions were early-type, i.e., elliptical, galaxies.

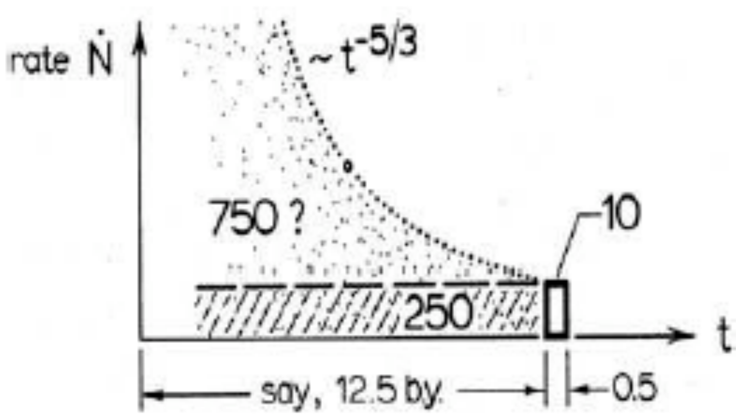


The Mice (hubblesite.org)

The Merger Hypothesis

In 1977, Alar Toomre postulated that the remnants of spiral-galaxy interactions were early-type, i.e., elliptical, galaxies.

He further suggested that, if the merger rate was much larger in the past, all observed ellipticals could be produced through such a process.



NGC:
10/4000
are
mergers

typical merger
timescale ~ 0.5 Gyr

The Merger Hypothesis

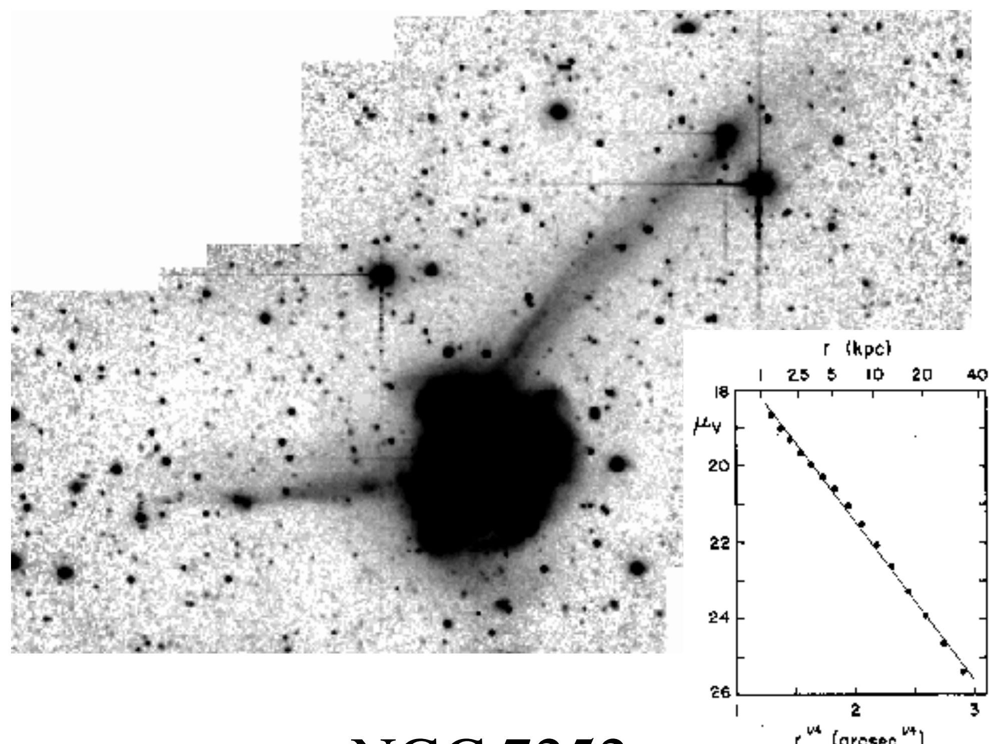
The last 30 years have produced a wealth of evidence that supports the general assertion of the merger hypothesis.

* profiles of merger remnants

* kinematic subsystems

* fine structure

* globular clusters



NGC 7252
Schweizer (1982)

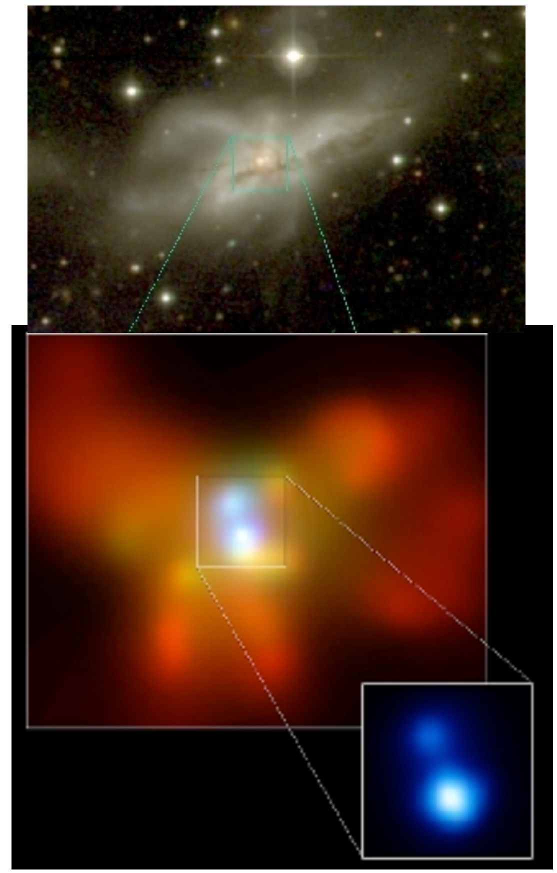
The Merger Hypothesis (?)

Much work over the last ~20 years has uncovered that mergers are also related to star formation and, more recently, black hole growth.   This paints a bigger, more comprehensive picture than originally envisioned by Toomre's merger hypothesis.

* starbursts

* AGN activity

* MBH-sig relation



NGC 6240
Komossa et al. (2003)

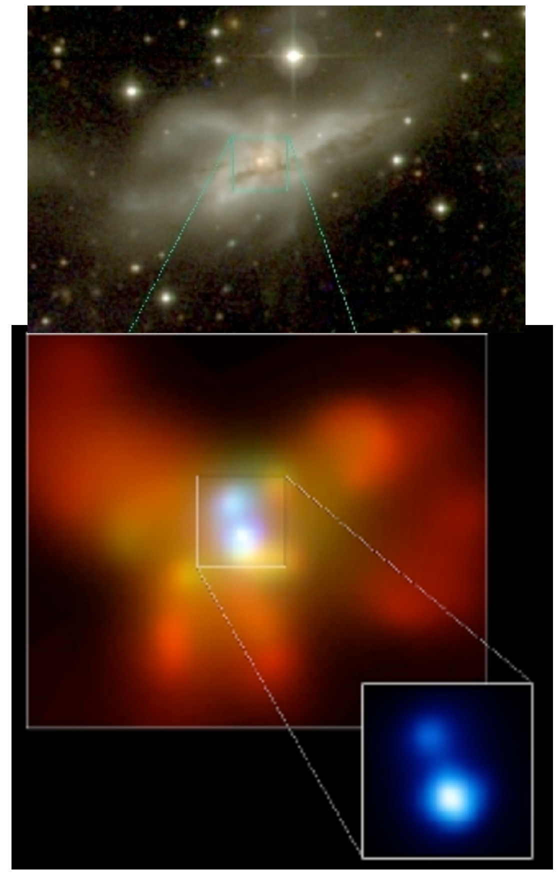
The Merger Hypothesis (?)

Open questions:

- Are mergers, starbursts/ULIRGs, quasars, and ellipticals part of a common evolutionary scenario?

- Do all galaxy mergers trigger this sequence?

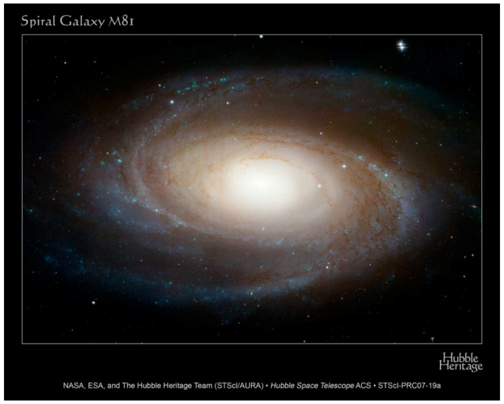
- Is there any dependence upon redshift? And if so, how do high-redshift systems, such as LBGs, EROs, SMGs, etc. relate to low-redshift systems?

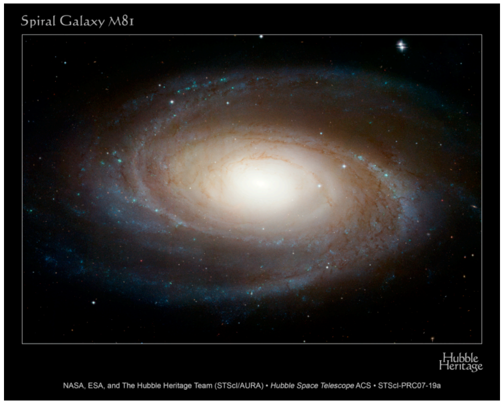


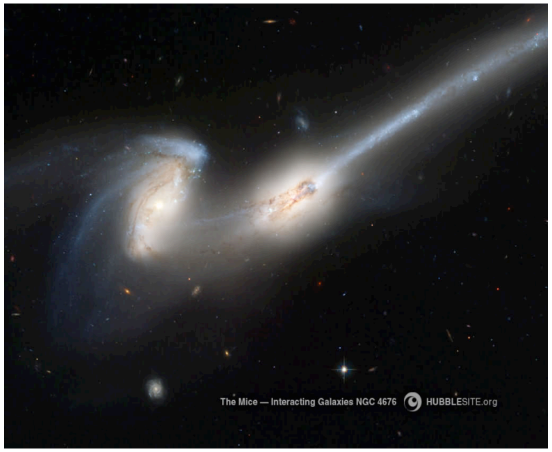
NGC 6240
Komossa et al. (2003)

An Evolutionary Sequence?

What we really want is to place these images in a chronological order in which we can move the clock backwards and forwards in order to better understand the merger process itself, and how it shapes the participant galaxies.

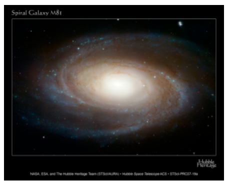






Differing Merger Histories

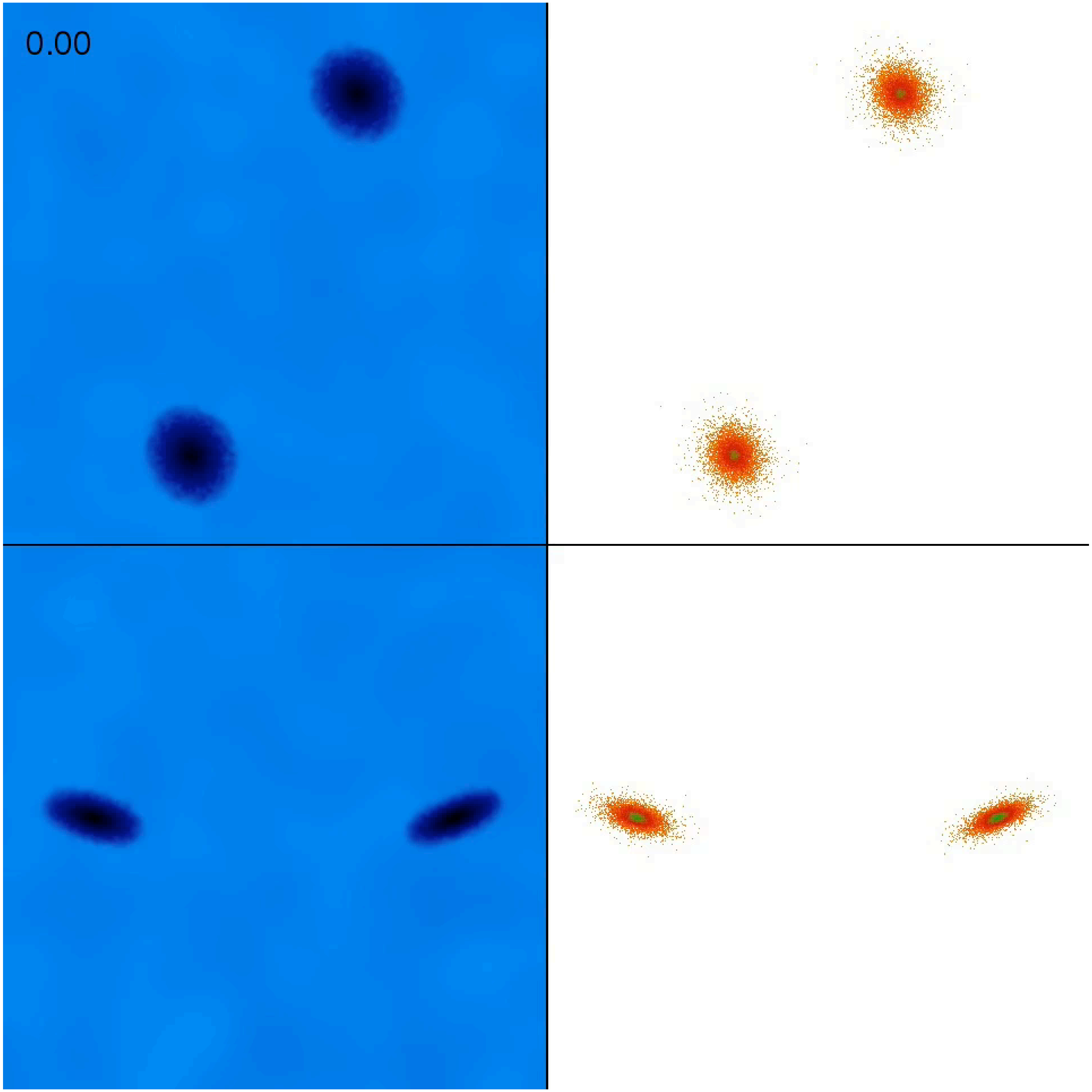
Since we can't witness these processes in action (at least within our lifetime), are there observational diagnostics that can be used to distinguish between formation scenarios?



low-luminosity ellipticals are consistent with being oblate isotropic rotators, they have cuspy profiles, and a variety of shapes

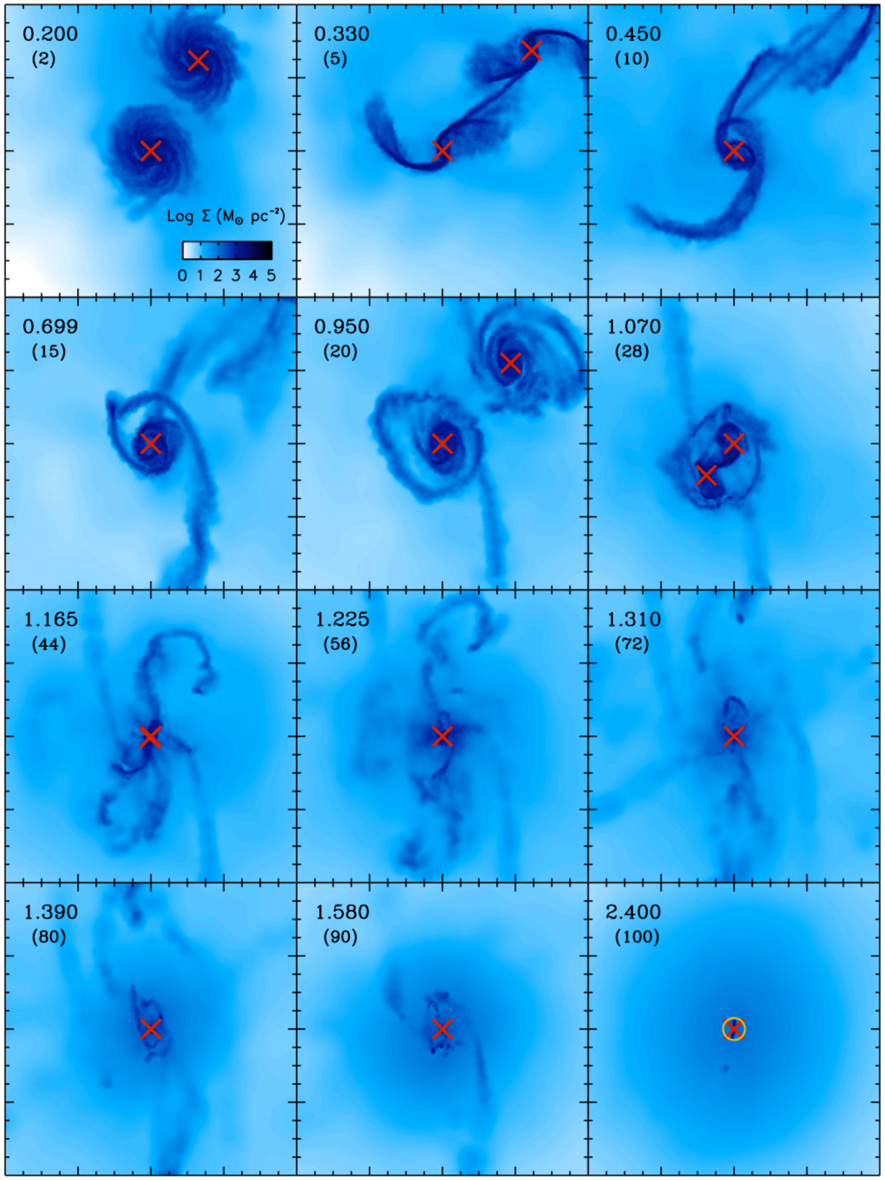
high-luminosity ellipticals have very little rotation, core profiles, and are predominantly boxy in shape.

Movie of a typical disk-disk merger



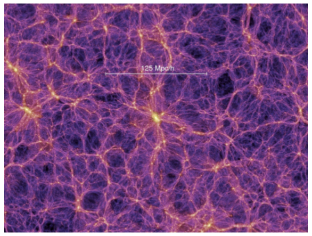
Simulating Galaxy Mergers

- Simulations: 3-D, time-dependence (GADGET2, Springel 2005)
- Consider: star formation, supernova feedback (sub-resolution), black hole growth, feedback (sub-resolution)
- ~10^6 particles (soon to increase substantially)
- Binary mergers of disk galaxies with a variety of masses, on a variety of orbits, with different disk orientations
- (new/in progress ….) Re-mergers, multiple-galaxy mergers



Why not use cosmological simulations?

1. Need $>10^3$ more particles than the Millennium simulations.



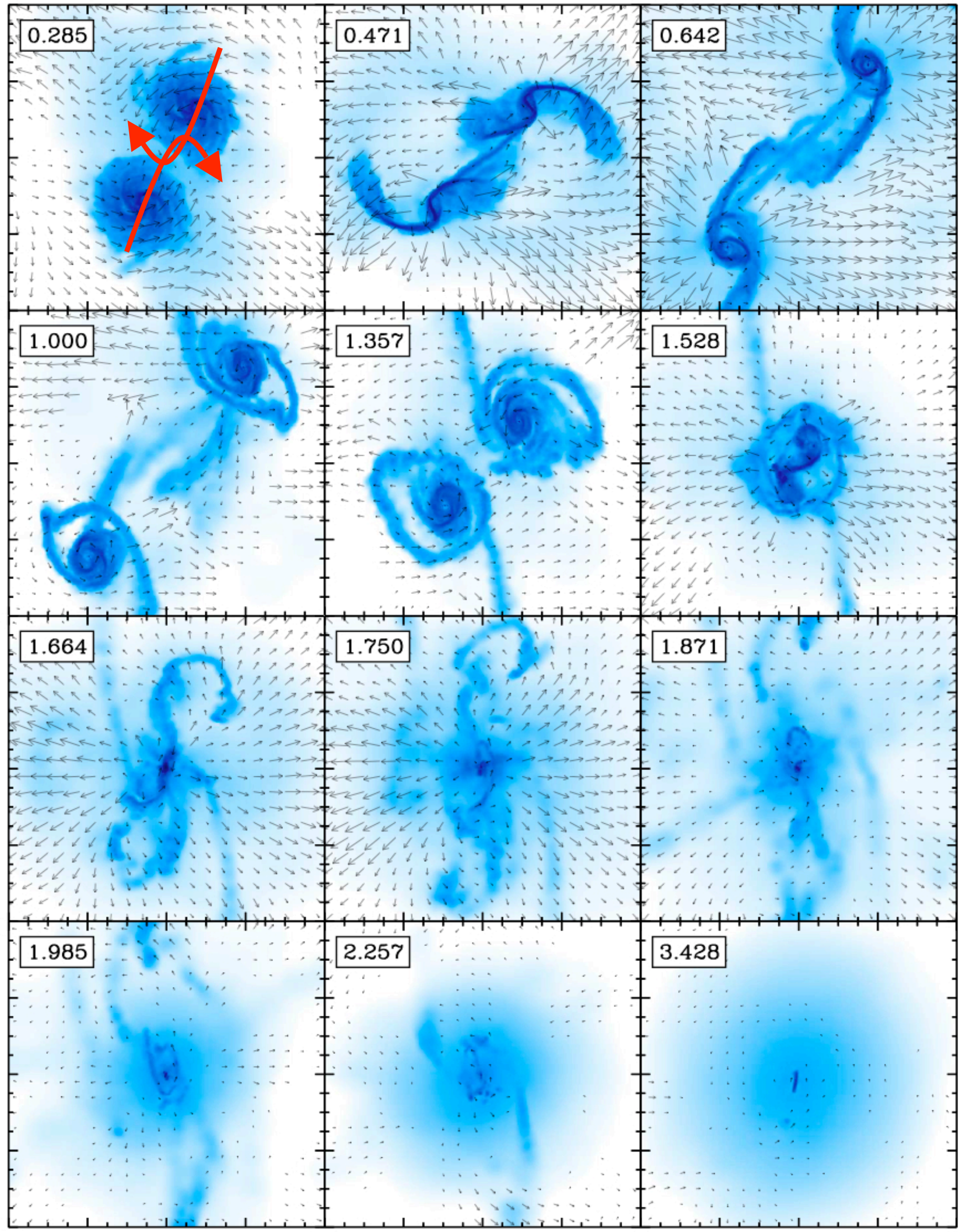
2. We don't understand the formation of disk galaxies (the proposed building blocks of elliptical galaxies).

Generic Outcome of Gas-Rich Galaxy Mergers

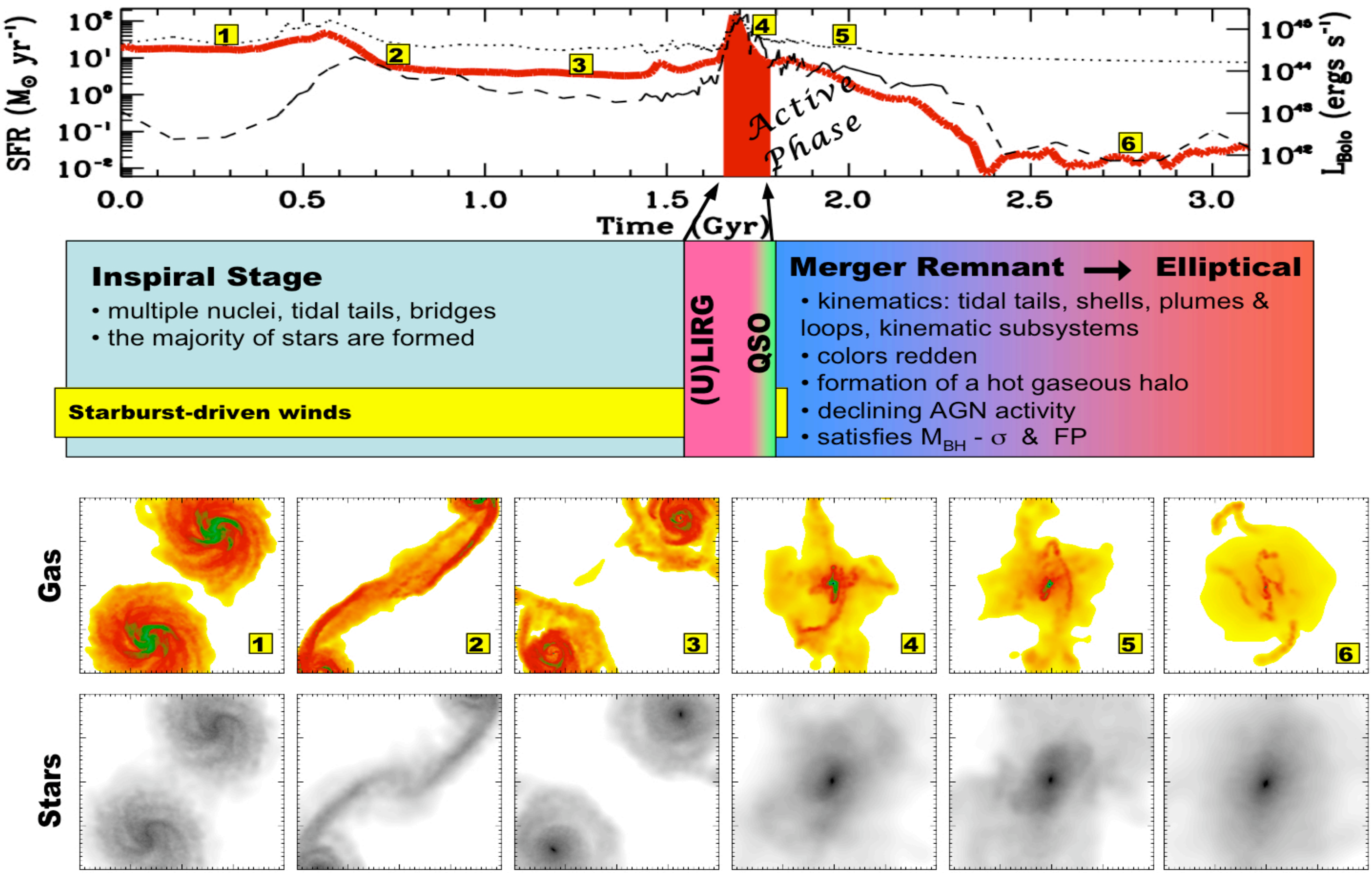
- Tidal torques induce large, rapid gas inflows (e.g., Barnes & Hernquist 1991)
- Triggers starburst (e.g., Mihos & Hernquist 1996)
- Feeds BH growth (e.g., Di Matteo et al. 2005)
- BH Feedback disperses gas and reveals optical QSO
- Merging stellar disks grow spheroid

Requires:

- Major (>3:1) merger
- supply of cold (i.e., rotationally supported) gas



Proposed Chronology of a Galaxy Merger



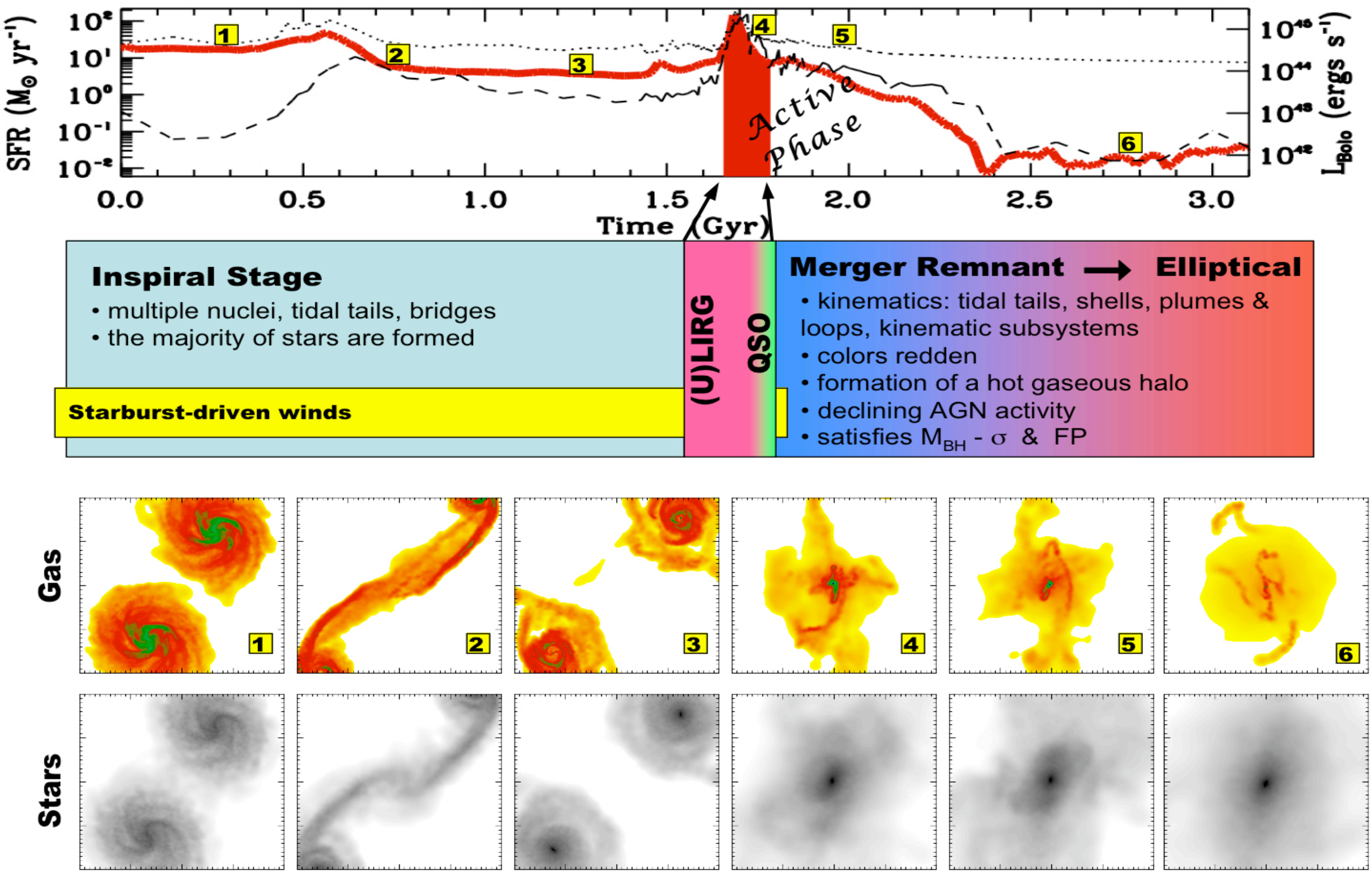
Cox et al. (2008)

Clarifying Common Misconceptions

- Major galaxy mergers are NOT the only mechanism to trigger AGN activity
- Feedback from the black hole accretion does NOT destroy the galaxy.
- Nor does BH feedback leave the remnant galaxy devoid of gas.
- SMBH growth by other modes (radiatively inefficient, or “radio” mode) is possible, but sub-dominant.
- Spheroid growth by gas-free (“dry”) mergers is possible.

Di Matteo, Springel & Hernquist (2005)

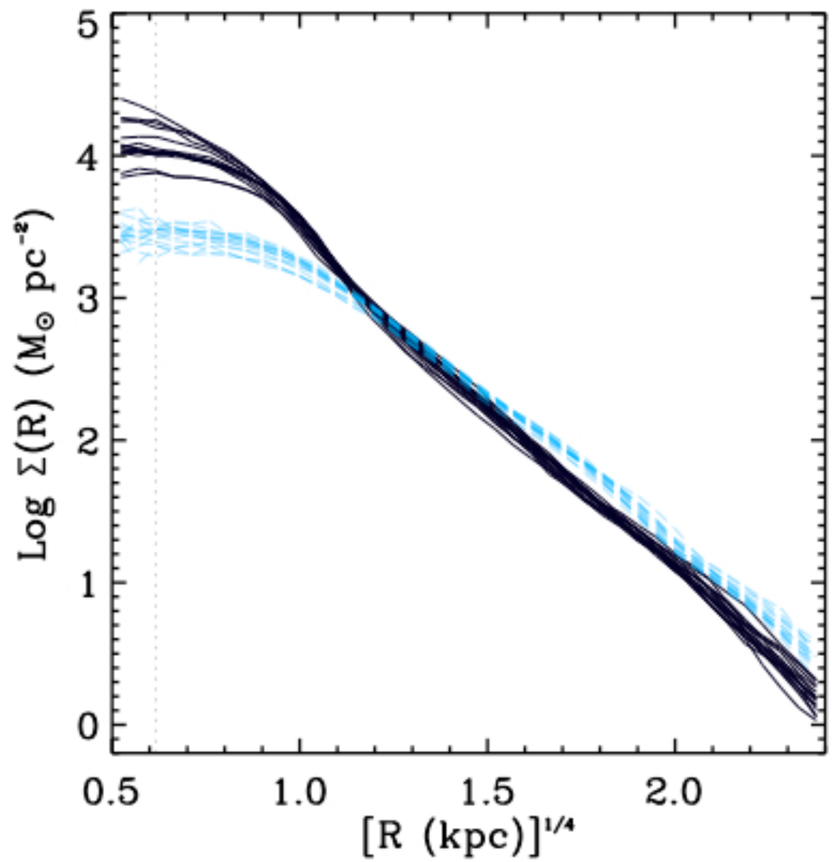
Proposed Chronology of a Galaxy Merger



Cox et al. (2008)

Successes of this Model

- Profiles: $R^{1/4}$ with a distinct centrally-concentrated component owing to the merger-induced starburst

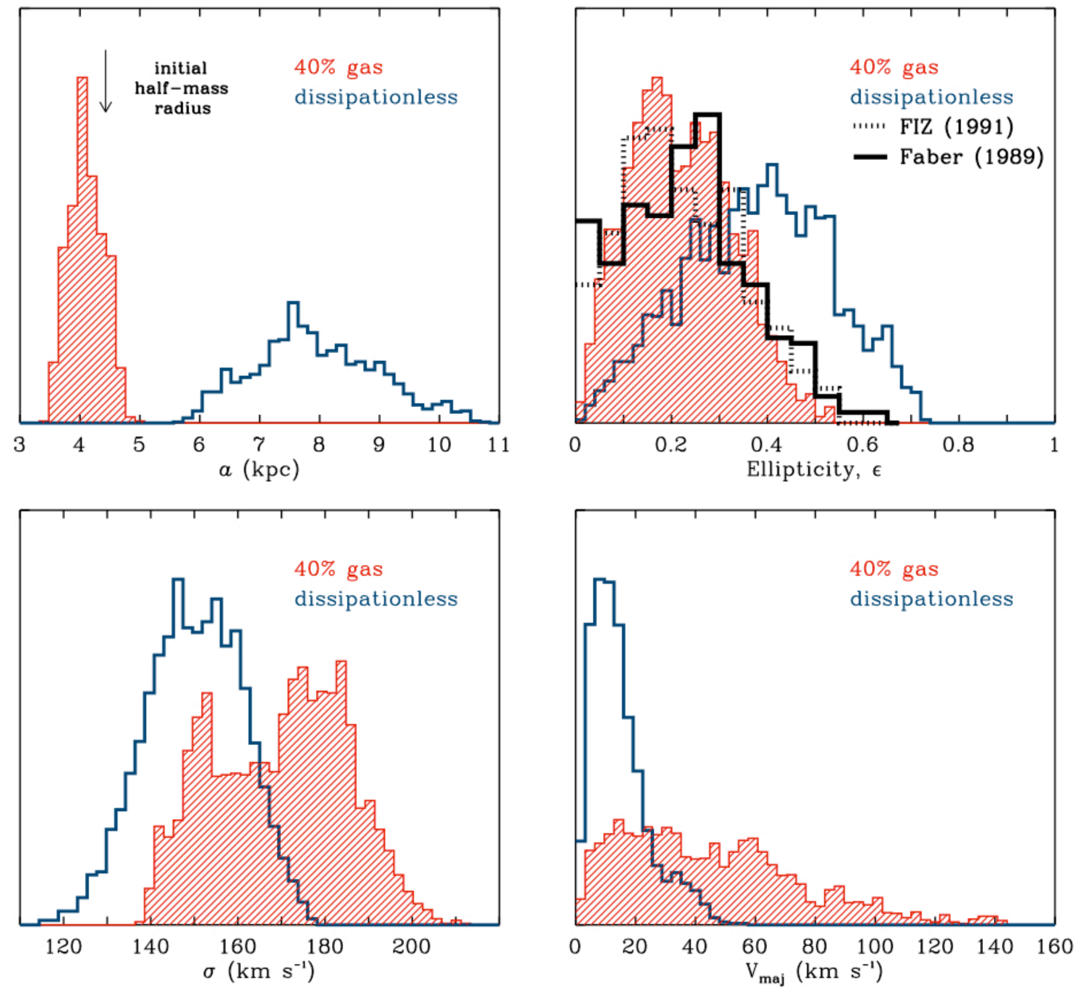


Cox et al. (2006), but see also Barnes, Mihos & Hernquist, Hernquist, Springel, Naab & Burkert, and look for a new series by Phil Hopkins.

Successes of this Model

- <u>Profiles</u>: $R^{1/4}$ with a distinct centrally-concentrated component owing to the merger-induced starburst

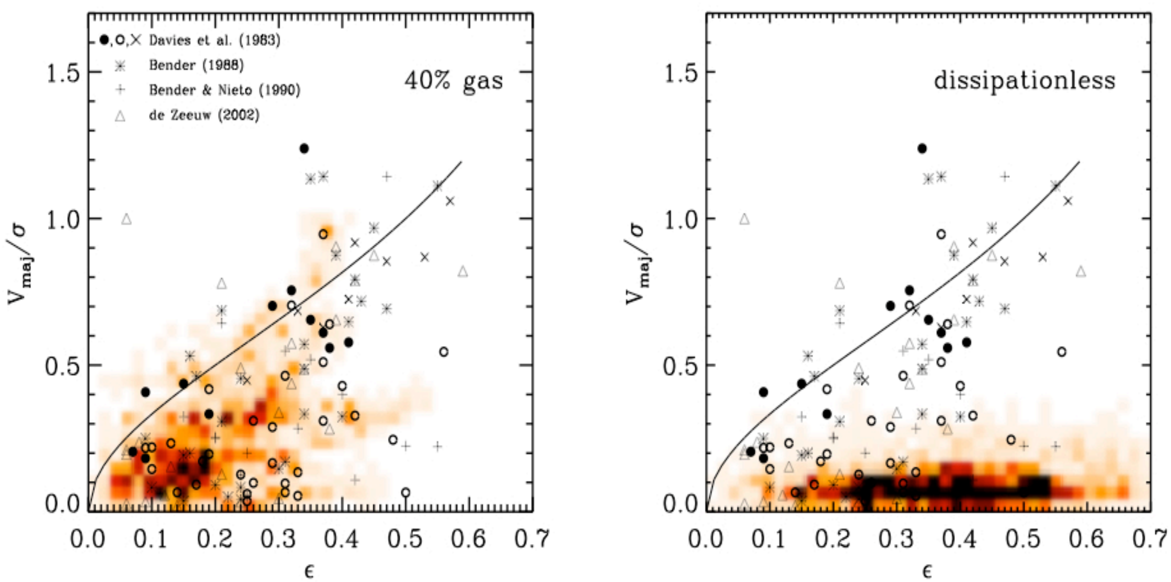
- <u>Shapes</u>: smaller and more spherical



Cox et al. (2006) - data from Franx et al. (1991), Faber et al. (1989), see also Naab & Burkert (2003)

Successes of this Model

- Profiles: $R^{1/4}$ with a distinct centrally-concentrated component owing to the merger-induced starburst
- Shapes: smaller and more spherical
- Rotation/Anisotropy Diagram: many/most are consistent with oblate isotropic rotators



Cox et al. (2006) - see also Naab & Burkert (2003), and Naab, Jesseit, & Burkert (2006)

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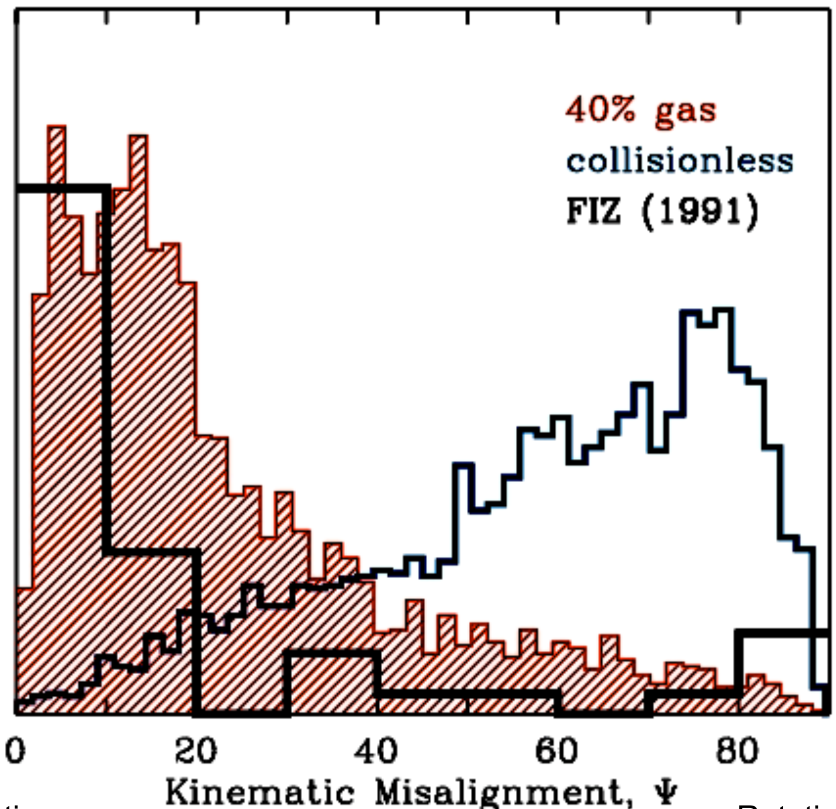
- Kinematic Misalignment: rotation is predominantly along the major axis

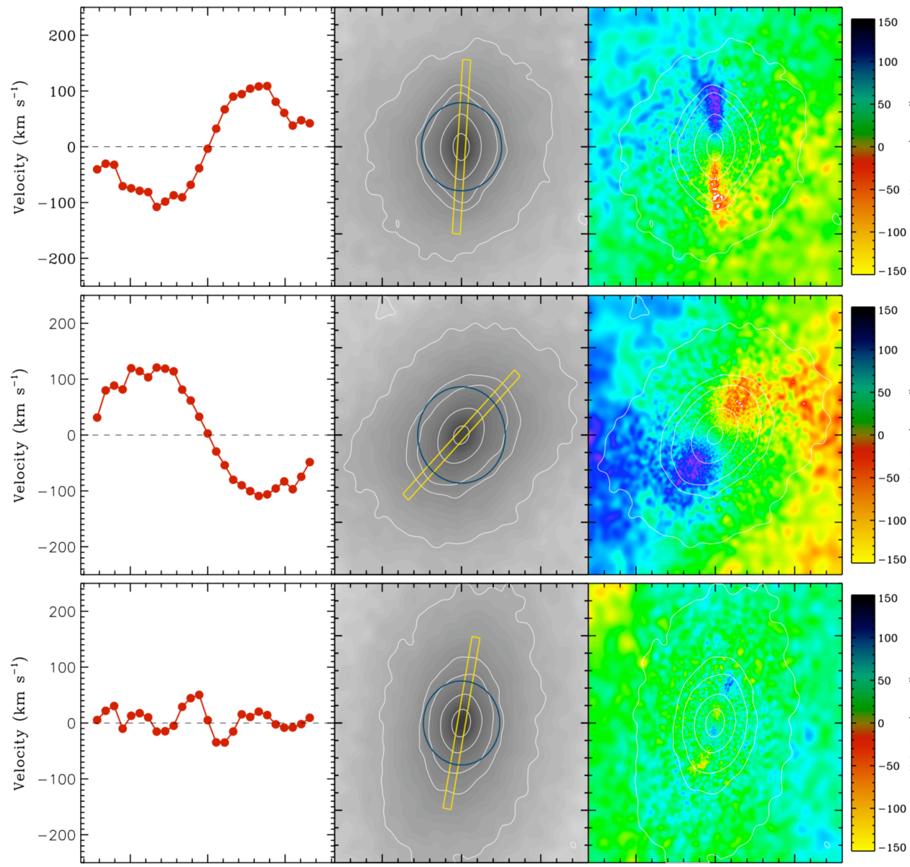


Rotation along major axis

Rotation along minor axis

Successes of this Model

- <u>Profiles</u>: $R^{1/4}$ with a distinct centrally-concentrated component owing to the merger-induced starburst
- <u>Shapes</u>: smaller and more spherical
- <u>Rotation/Anisotropy Diagram</u>: many/most are consistent with oblate isotropic rotators
- <u>Kinematic Misalignment</u>: rotation is predominantly along the major axis
- <u>Kinematic Subsystems</u>: centrally-concentrated, young (compared to the rest of the stars), decoupled stellar components



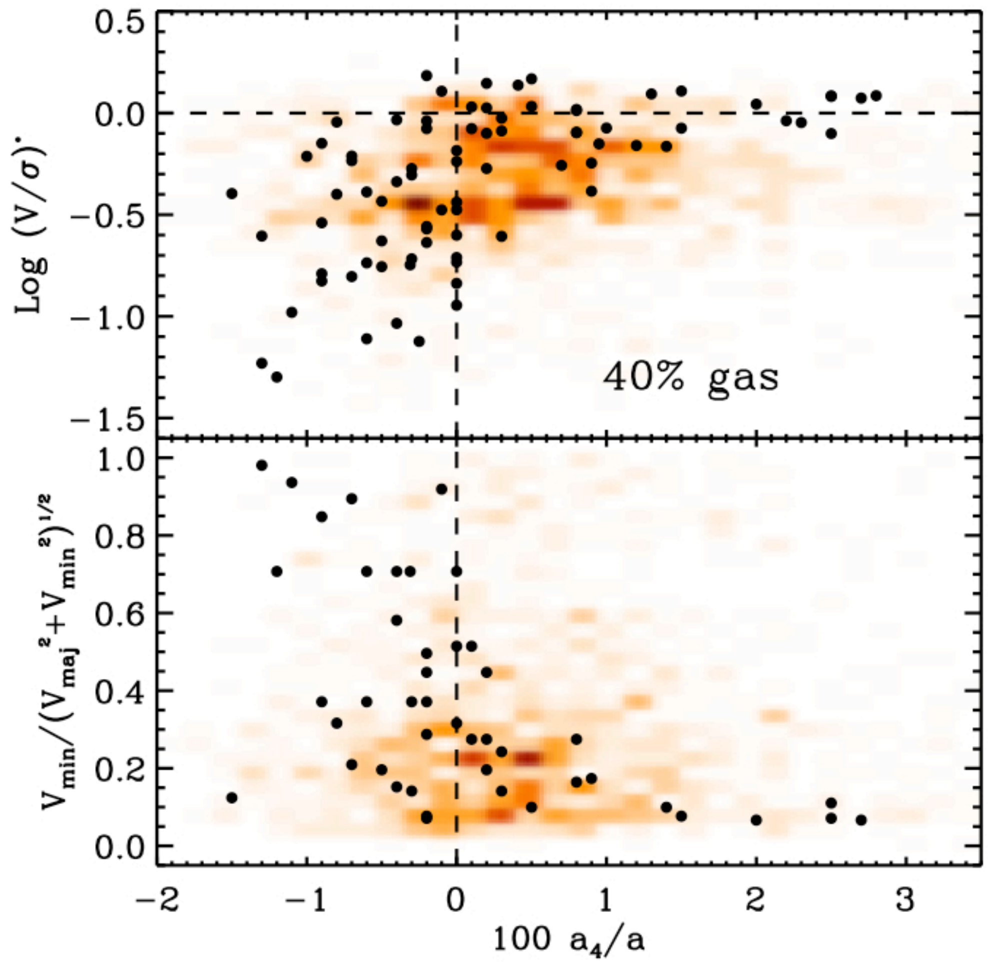
Cox et al. (2008) - see also Balcells (1998/9), (Bendo &Barnes (2000), Jessiet, Naab, Peletier & Burkert (2007)

What doesn’t work

Gas-rich merger remnants are both disky and boxy. And they are nearly oblate isotropic rotators. However, they cannot produce:

- uniformly boxy, slowly-rotating ellipticals (see also Naab & Burkert 2003)

- enough X-ray luminosity (likely results from not including stellar mass-loss and cosmological infall)



Cox et al. (2006) - data from Kormendy & Bender (1996)

Uncovering the Formation History of Elliptical Galaxies

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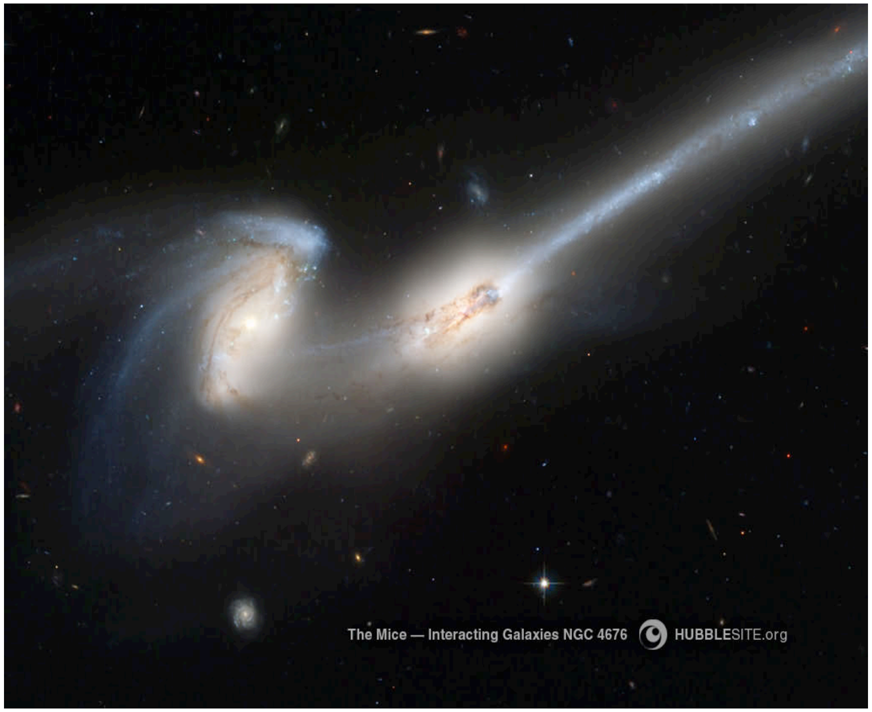
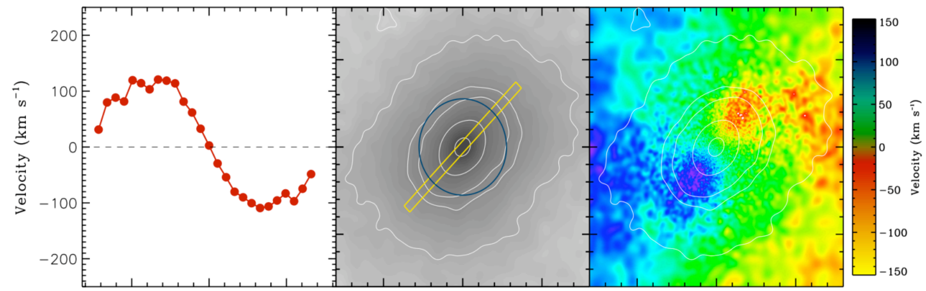


Observational diagnostics of an elliptical galaxy's merger history

- Kinematic Subsystems



- Fine Structure

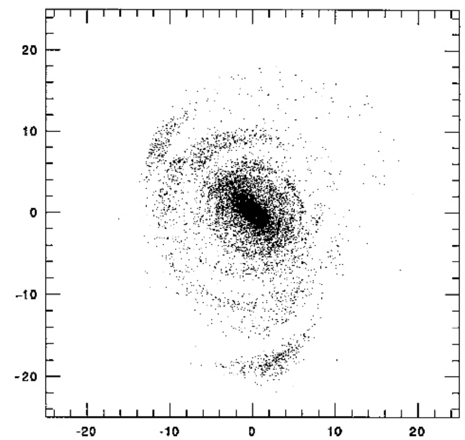
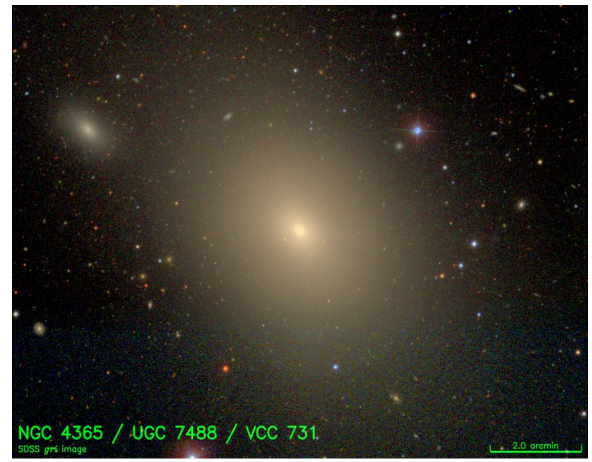


FIG. 2b

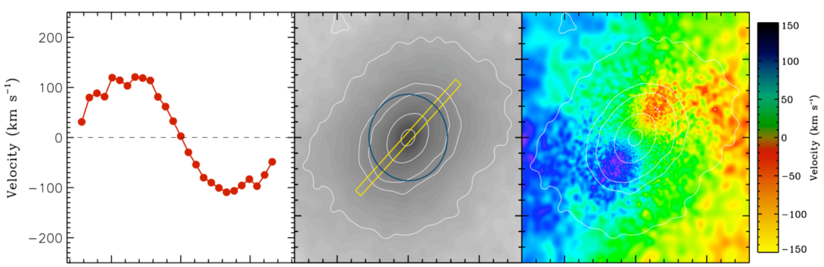
Kinematic Subsystems

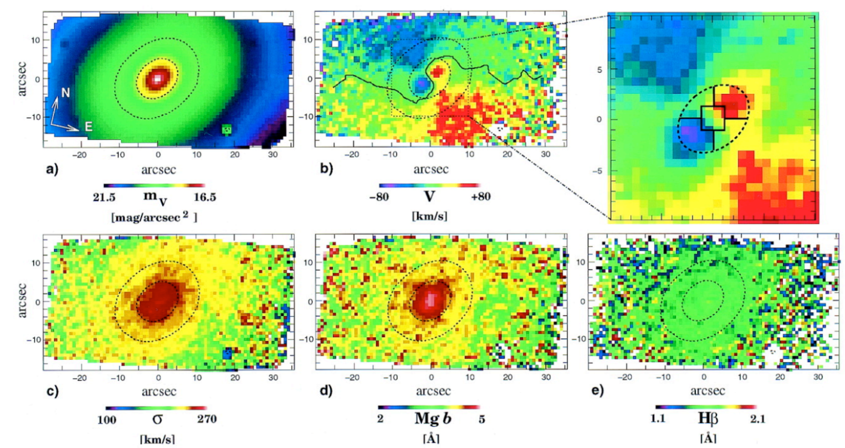
- Simulations naturally produce remnants that have centrally-concentrated, young (compared to the rest of the stars), decoupled stellar components.

- Observational studies (SAURON: McDermid et al. 2006, Falcon-Barroso et al. 2006, or older studies: Jedrzejewski & Schechter 1988, Franx et al. 1989, Zeeuw & Franx 1991, Schweizer 1998) suggest that between 10-40% of spheroids have kinematic subsystems.



D. Hogg's RC3 website

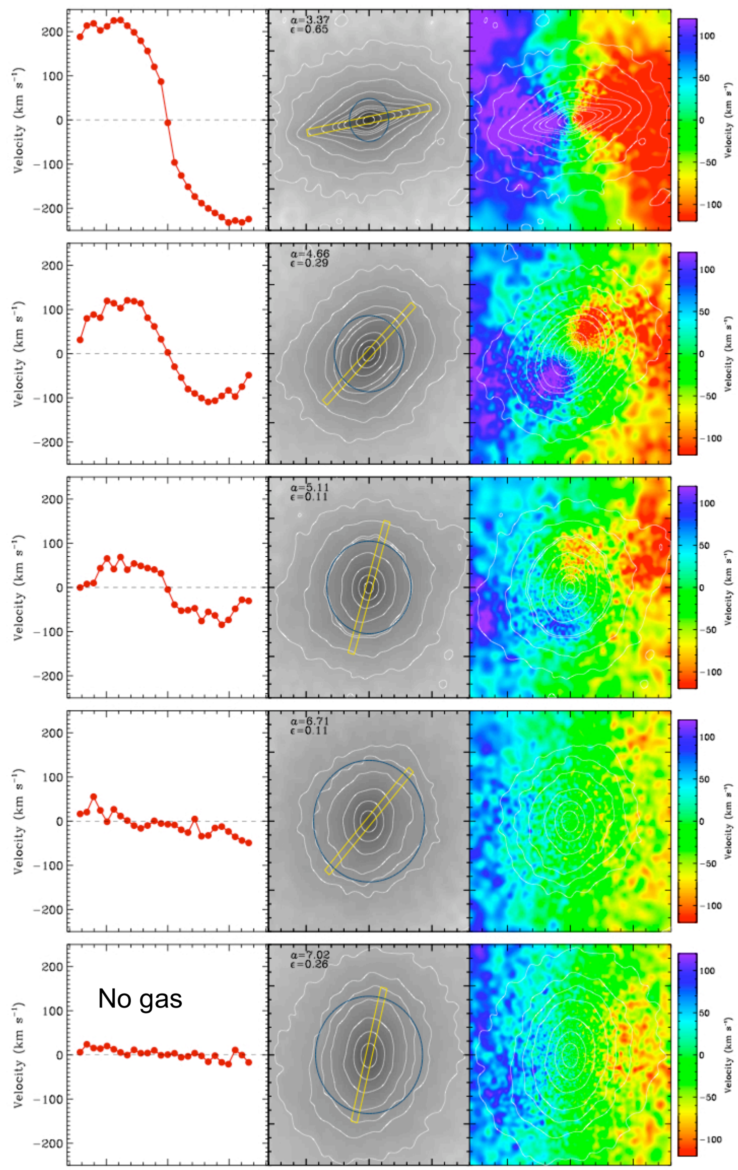




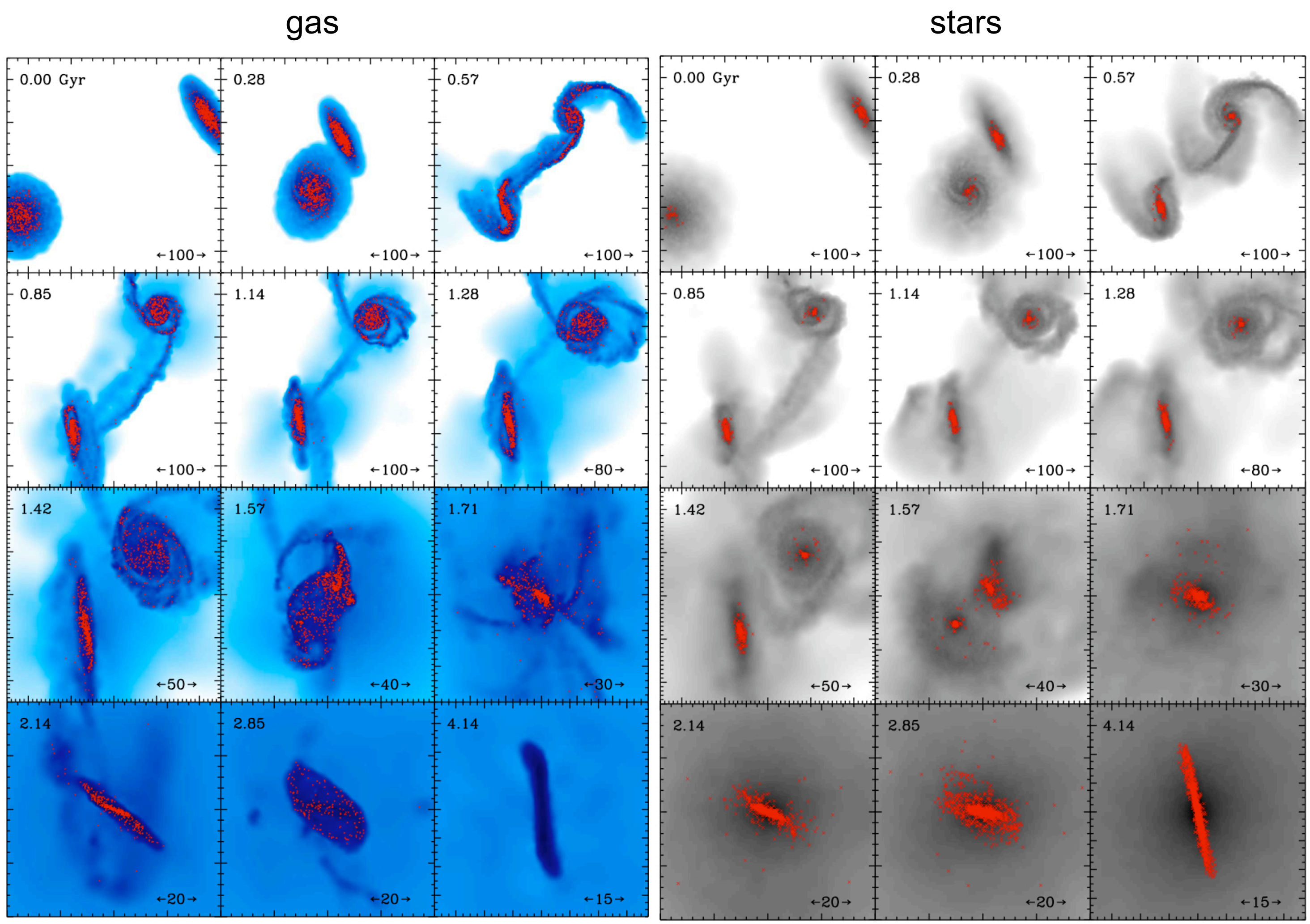
NGC 4365, Davies et al. (2001)

The Influence of Dissipation

- Rotation near the galactic center is dominated by stars born during the final coalescence.
- These stars also dominate the shape/potential.

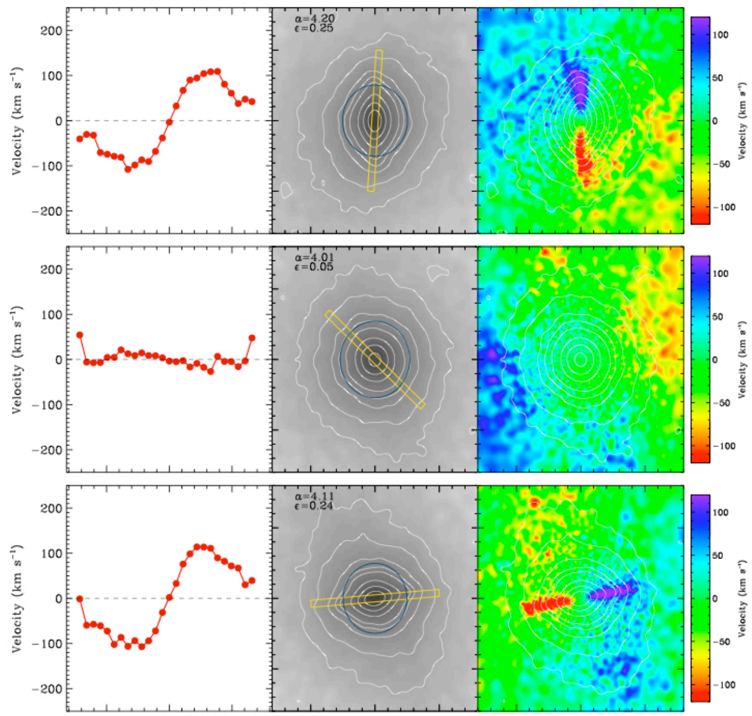


The Origin of Kinematic Subsystems

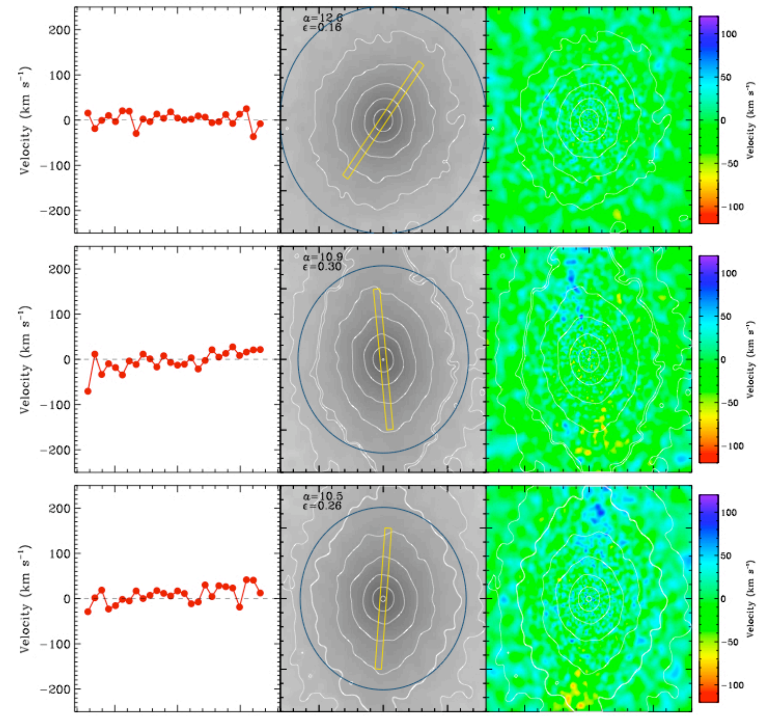


The Origin of Kinematic Subsystems

two gas-rich spirals

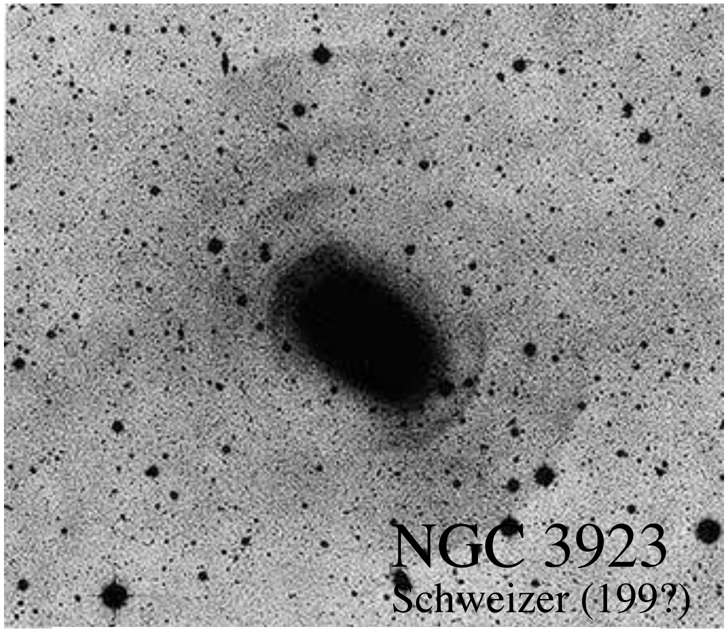


one gas-rich spiral, plus one collisionless



Fine Structure

- Shells in ellipticals: phase-wrapping of "cold" stellar material (Quinn 1984; Quinn & Hernquist 1986)
- From debris in tidal tails (Hernquist & Spergel 1992)
- NOT signature of major mergers of spheroids, just the opposite!
- Fragile! (more later)



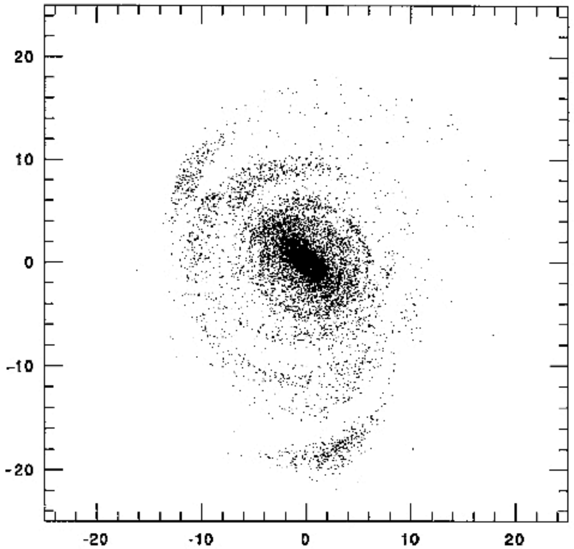


FIG. 2b

Fine Structure

Shells probe the energy distribution of the stars the originally formed them.

- Major mergers produce shells at all radii (Hernquist & Spergel 1992)
- Satellite accretion events produce shells only at large radii (Quinn 1984, Quinn & Hernquist 1986, Hernquist & Quinn 1989)

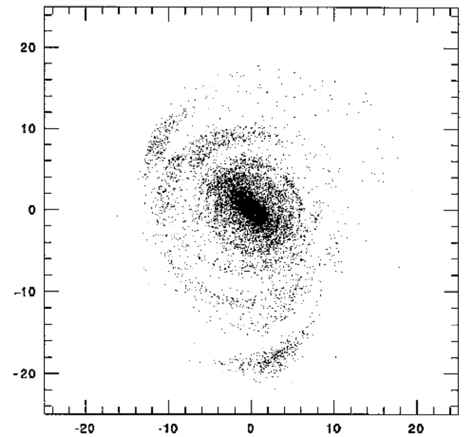
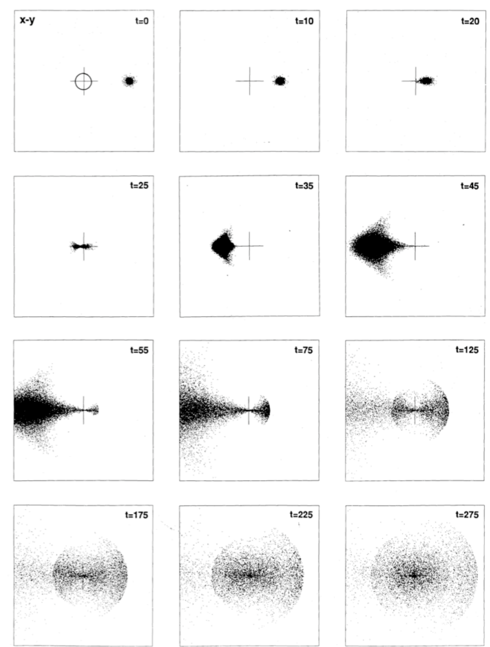
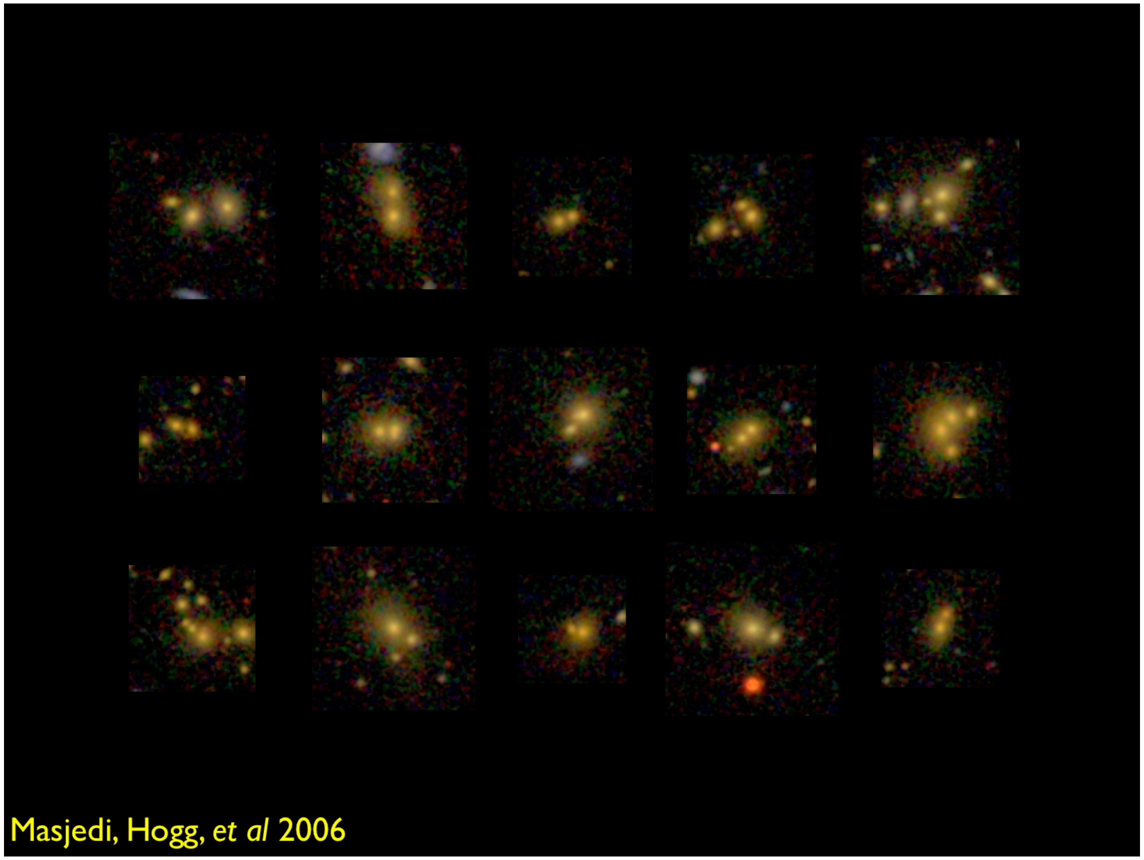


FIG. 2*b*

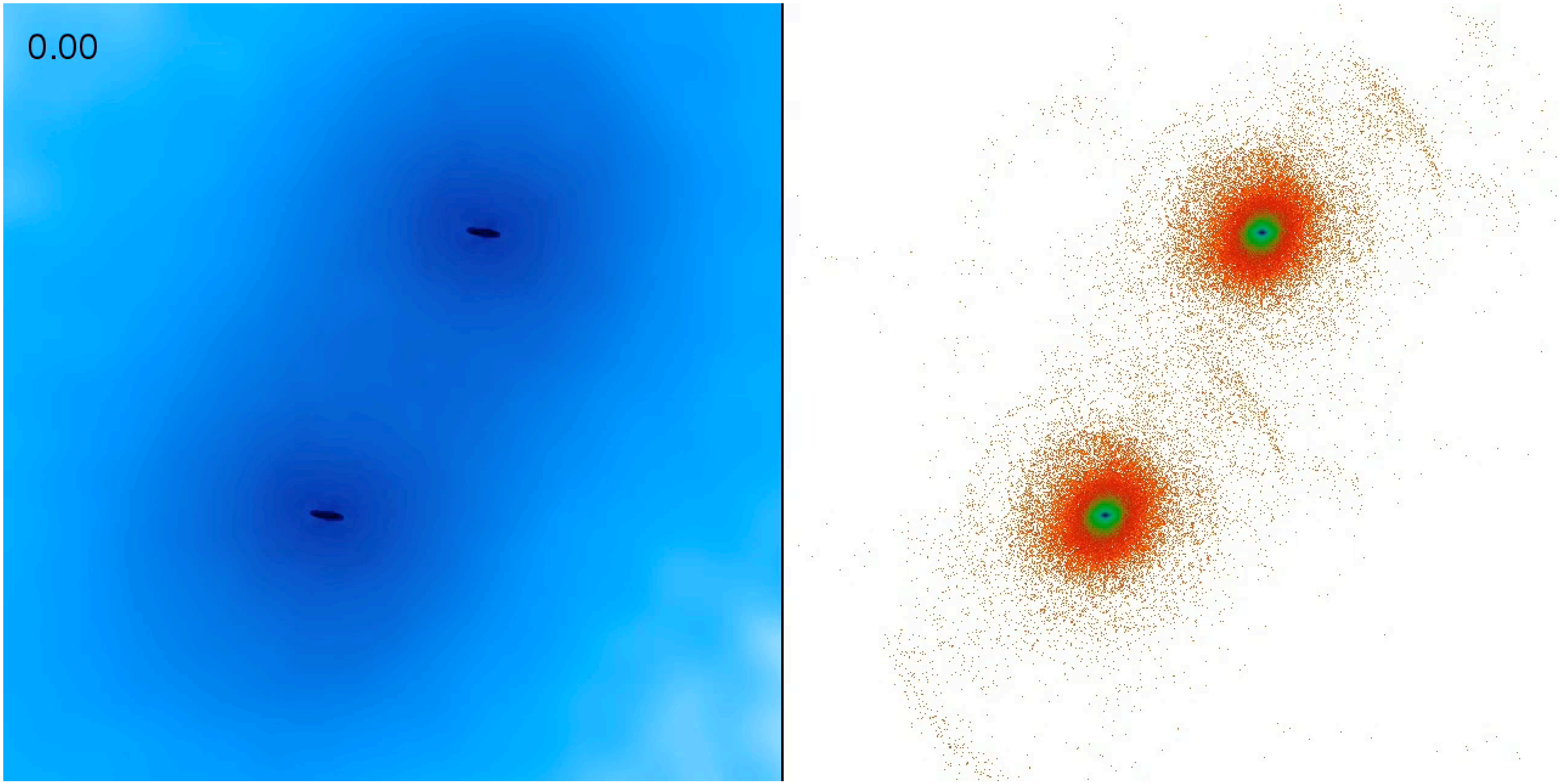


Persistence of Features

Both kinematic subsystems and fine structure are fragile, which brings into question their long-term survivability. Especially given a vigorous merging history.

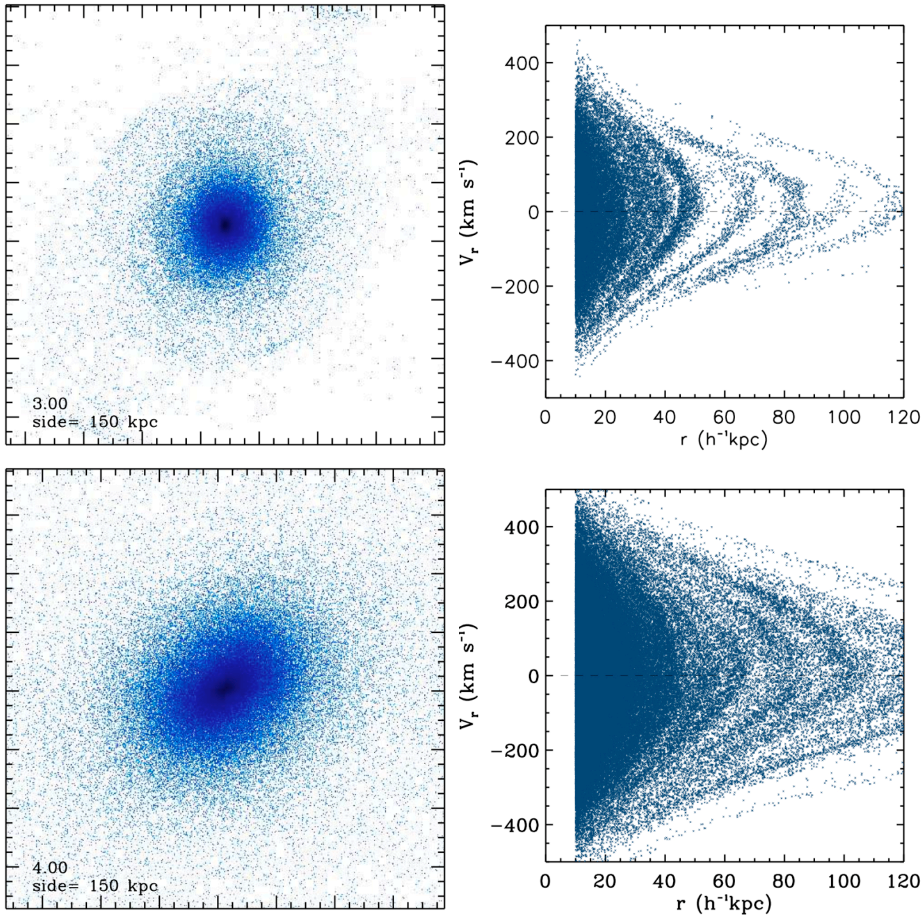


Movie of a “re-merger”



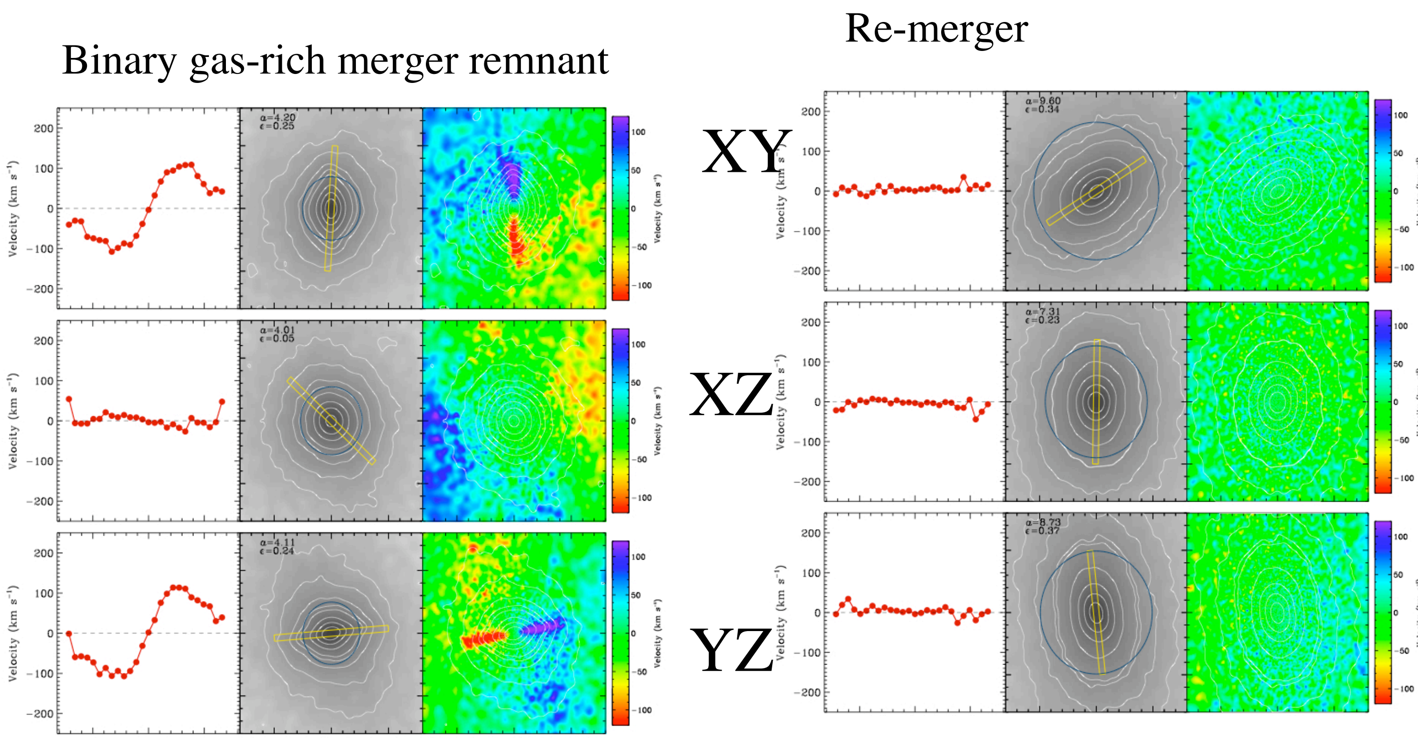
Persistence of Fine Structure

Fine structure is washed out by subsequent remerging.



Persistence of Kinematic Subsystems

Kinematic subsytems are also washed out by subsequent remerging.



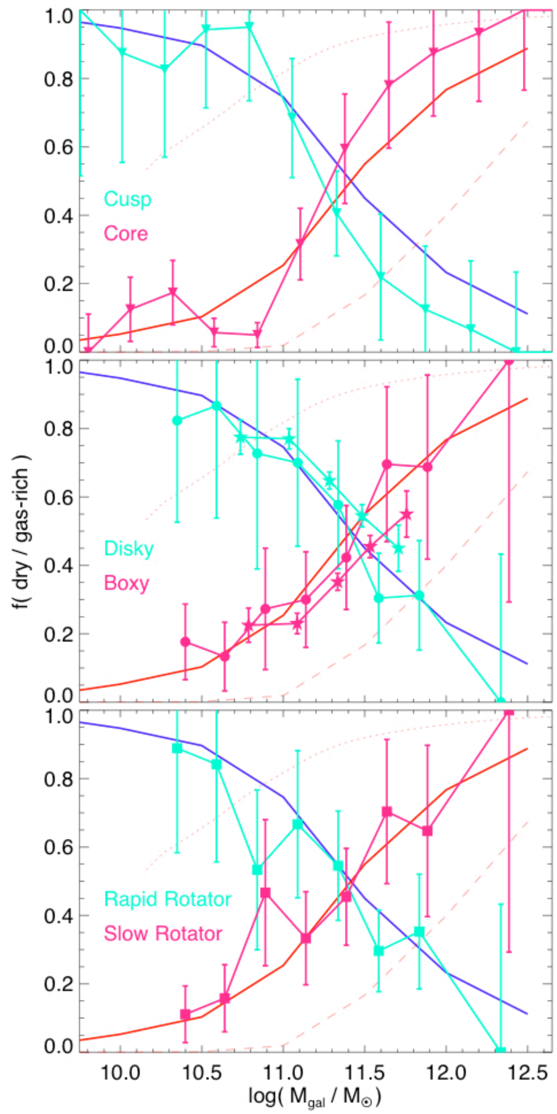
Unraveling the Merger History

Observed properties → What this implied about the merger history.

Rotation and Shape

Rotation and diskiness are both consistent with a dissipative (gas-rich disk-disk merger) origin.

Suggestive of no subsequent spheroid-spheroid remerging, however satellite accretion and futher dissipative merger may occur.



Hopkins et al. (2007)

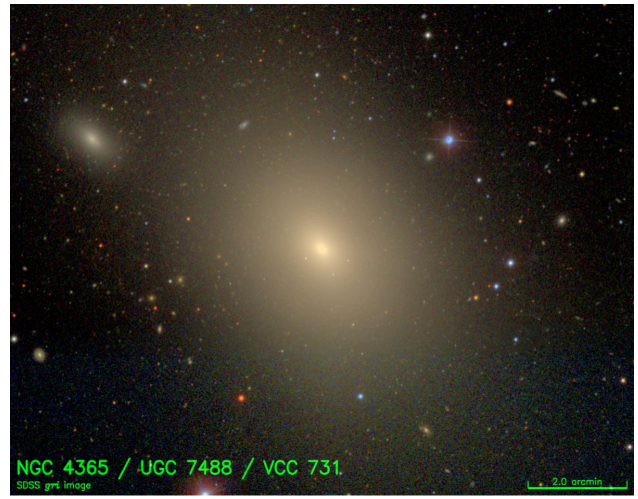
Kinematic Subsystems

Kinematic subsystems are consistent with a dissipative (gas-rich disk-disk merger) origin.

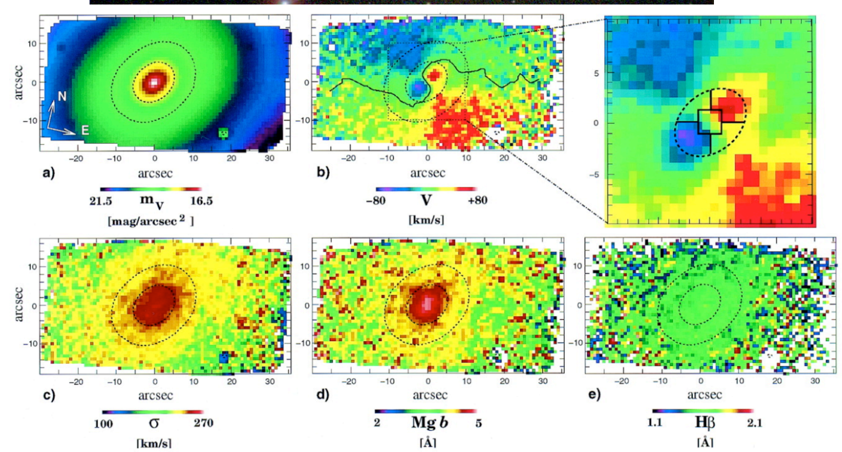
May also be produced in a subset of non-equal mass mergers (see Bendo & Barnes 2002)

Because of their fragility, their presence is suggestive of no subsequent remerging.

*** More data is needed!



D. Hogg's RC3 website



NGC 4365, Davies et al. (2001)

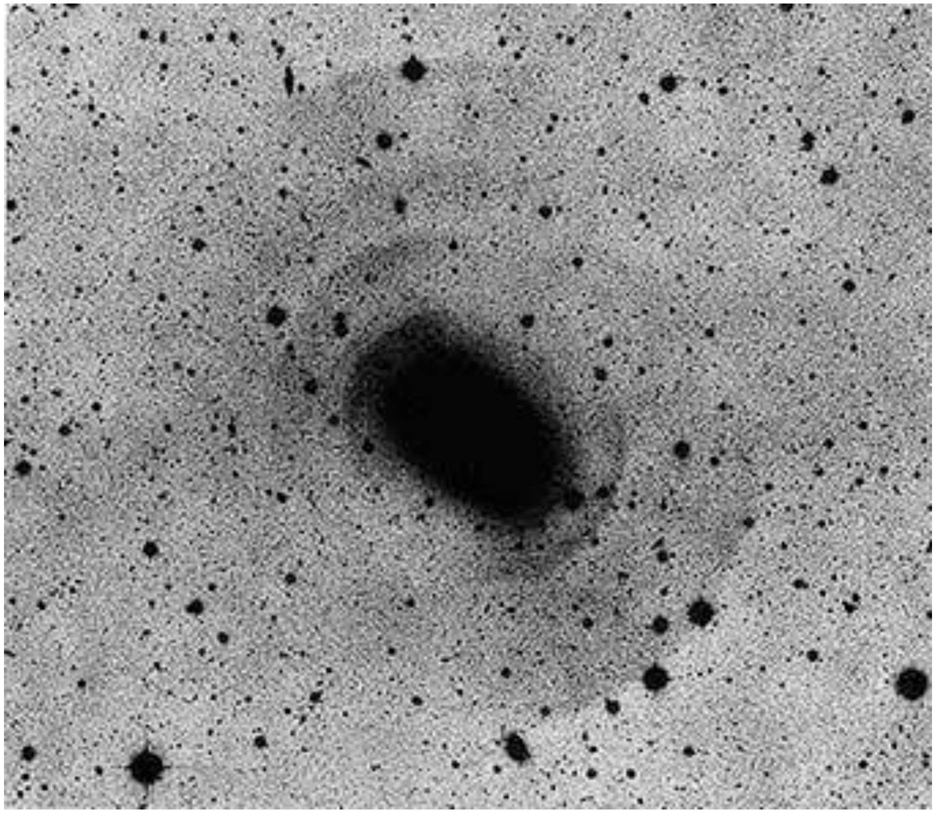
Fine Structure

Fine structure is a signature of the accretion of dynamically cold (relative to the host) material.

•If this material has a range of energies (shells at large and small radii) then it is consistent with tidal material infalling during a spiral-spiral merger.

• If the shells are only present at large radii, this is consistent with the accretion of smaller satellites.

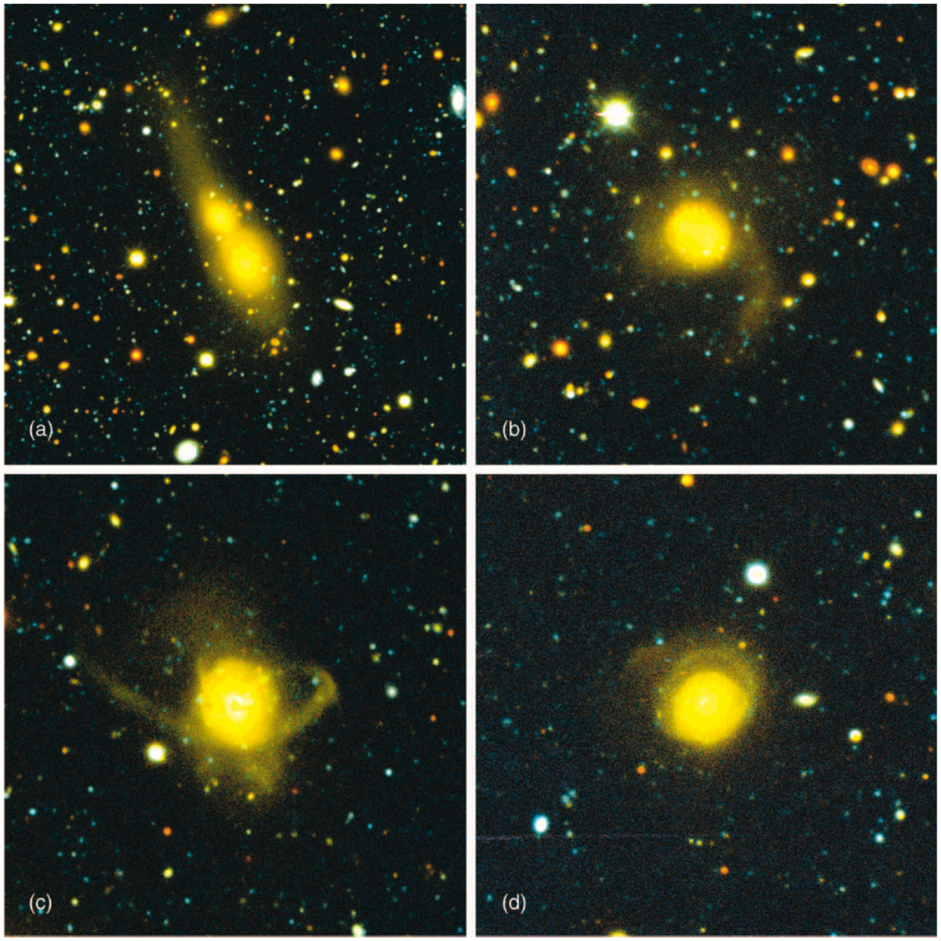
*** More data is needed!



NGC 3923
Schweizer (1994)

Fine Structure & “Red” mergers

Fine structure (no matter the color) is a signature of dynamically cold material.



van Dokkum (2005)

Conclusion

- Merging is an important process during the formation and evolution of galaxies.

- Numerical simulations are an important tool to understand this process.

- A gas-rich disk-disk major merger is a plausible mechanism to produce starbursts, quasars, and (some) elliptical galaxies.

- There are a number of observational diagnostics that can uncover the merger history of elliptical galaxies.