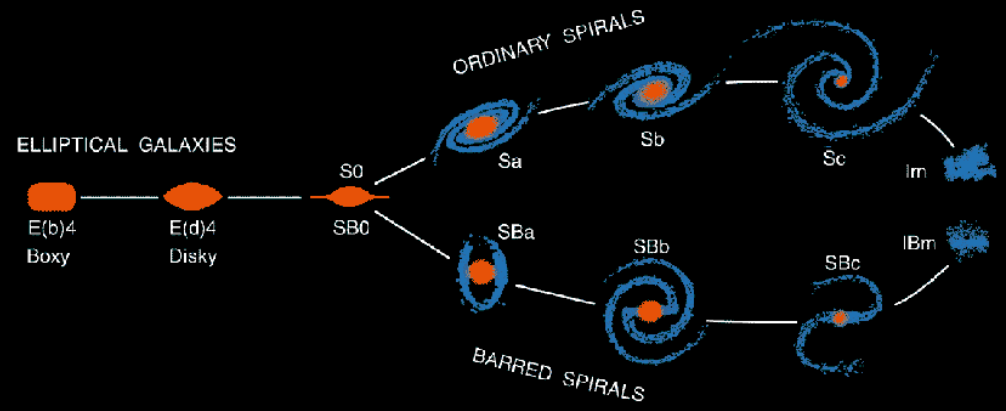
The Hubble Sequence



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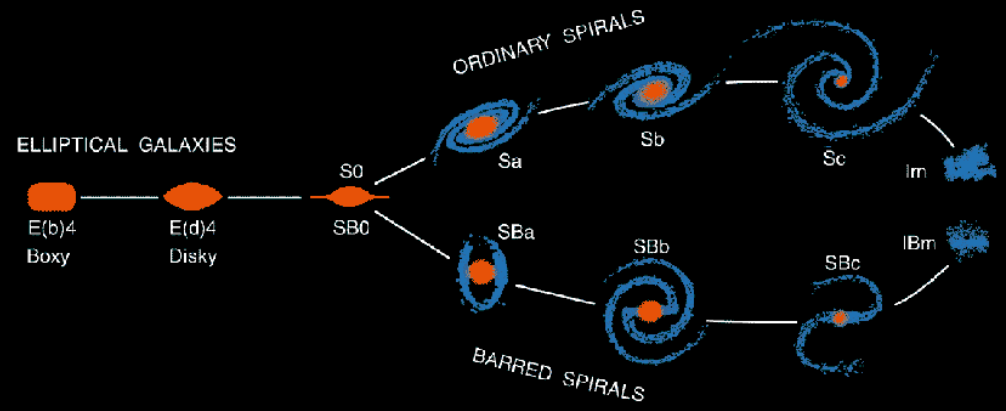
The Hubble Sequence



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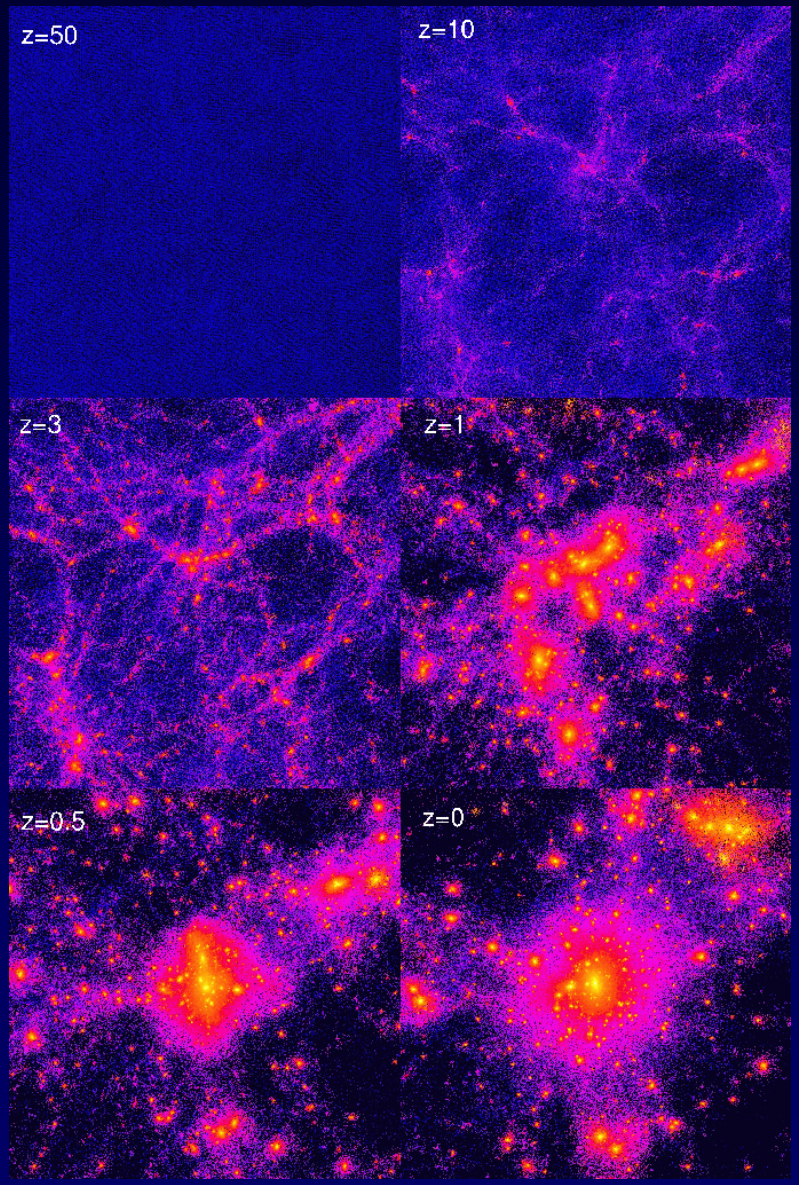
Galaxy Formation in the CDM Scenario

- Structure formation by hierarchical merging.
- Spiral galaxies: merging of small, gas-rich substructures.
- Elliptical Galaxies: merging of equal-mass substructures (Toomre & Toomre 1972).

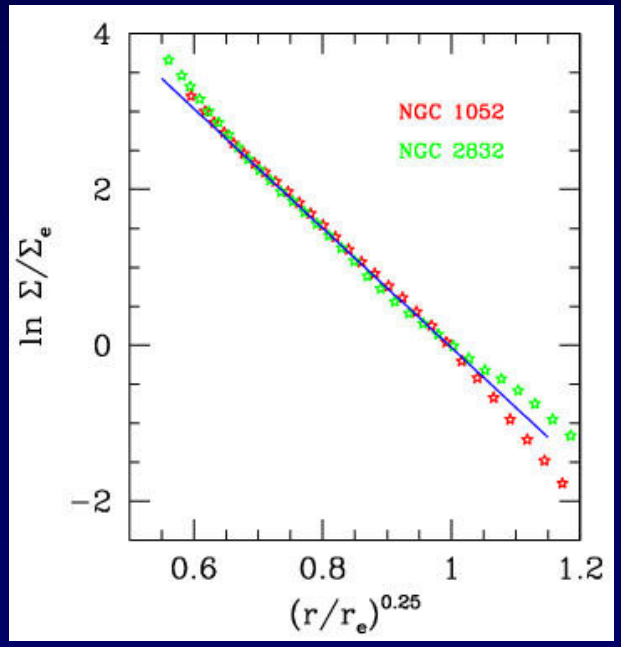
Spiral galaxies → Elliptical Galaxies



(Moore 2000)

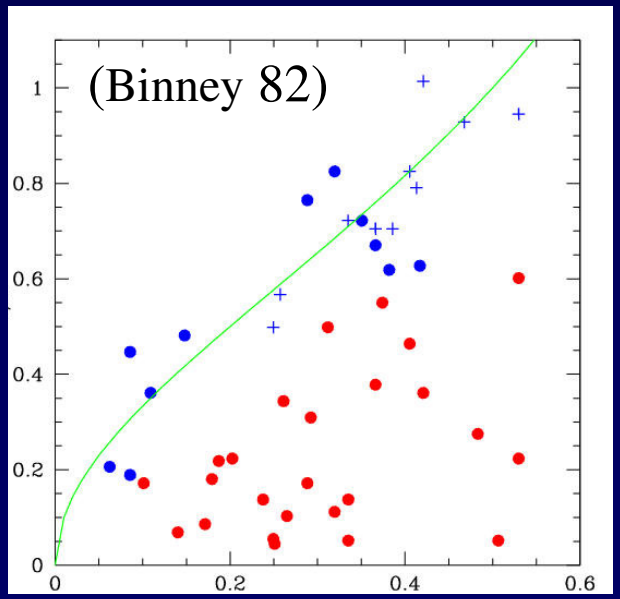
Testing the Merger Hypothesis

- The merger hypothesis has been investigated numerically
  (Barnes 92; Hernquist 92,93; Mihos & Hernquist 93,96, Cox et al. 04)
- Remnants
  - spheroidal and follow a de Vaucouleurs law
  - slowly rotating and anisotropic



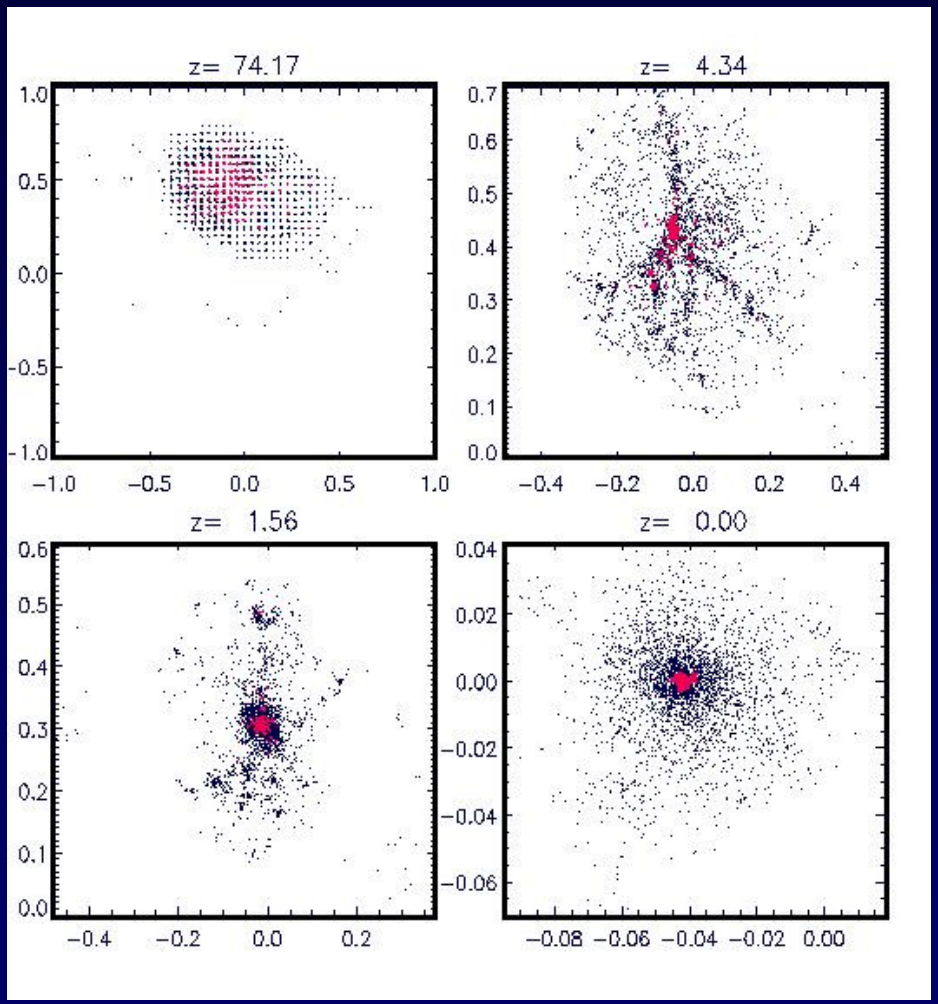
Anisotropy:

$$\left(\frac{v}{\sigma}\right)^{*} = \frac{v/\sigma}{\sqrt{\varepsilon/(1-\varepsilon)}}$$

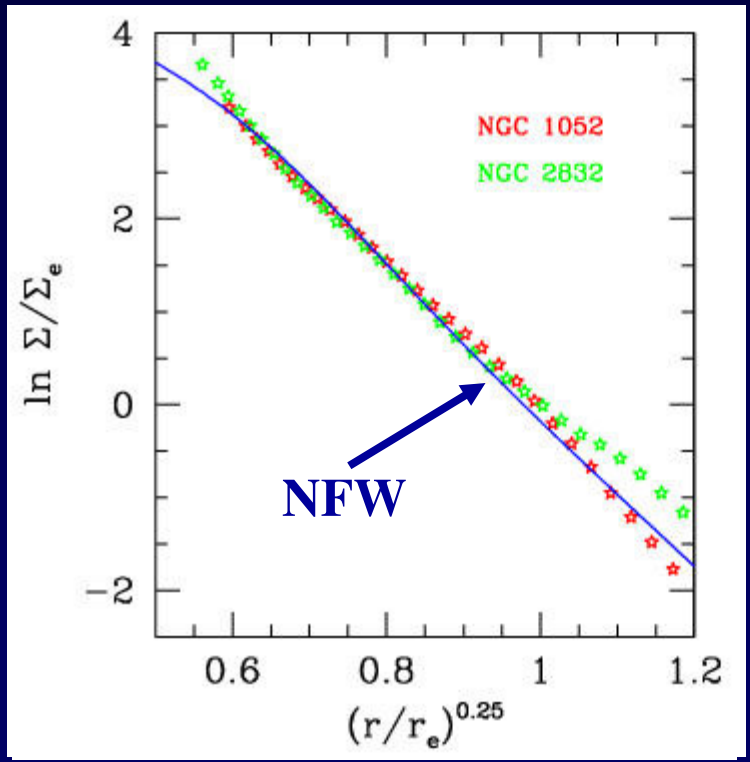


Violent Relaxation of Collisionless Particle Systems

ΛCDM simulation



DM density profile



(Hetznecker & Burkert)

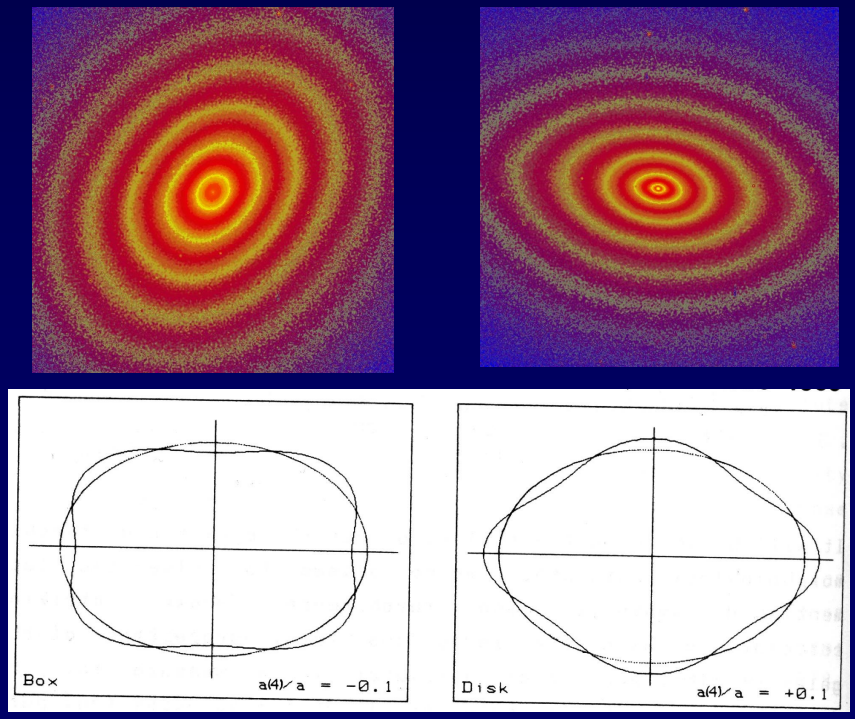
Isophotal Shapes

- More insight requires a more detailed investigation of

1. departures from pure elliptical isophotes
2. the line-of-sight velocity distributions

Boxy and disky ellipticals:

- boxy: $a_4 < 0$
- disky: $a_4 > 0$



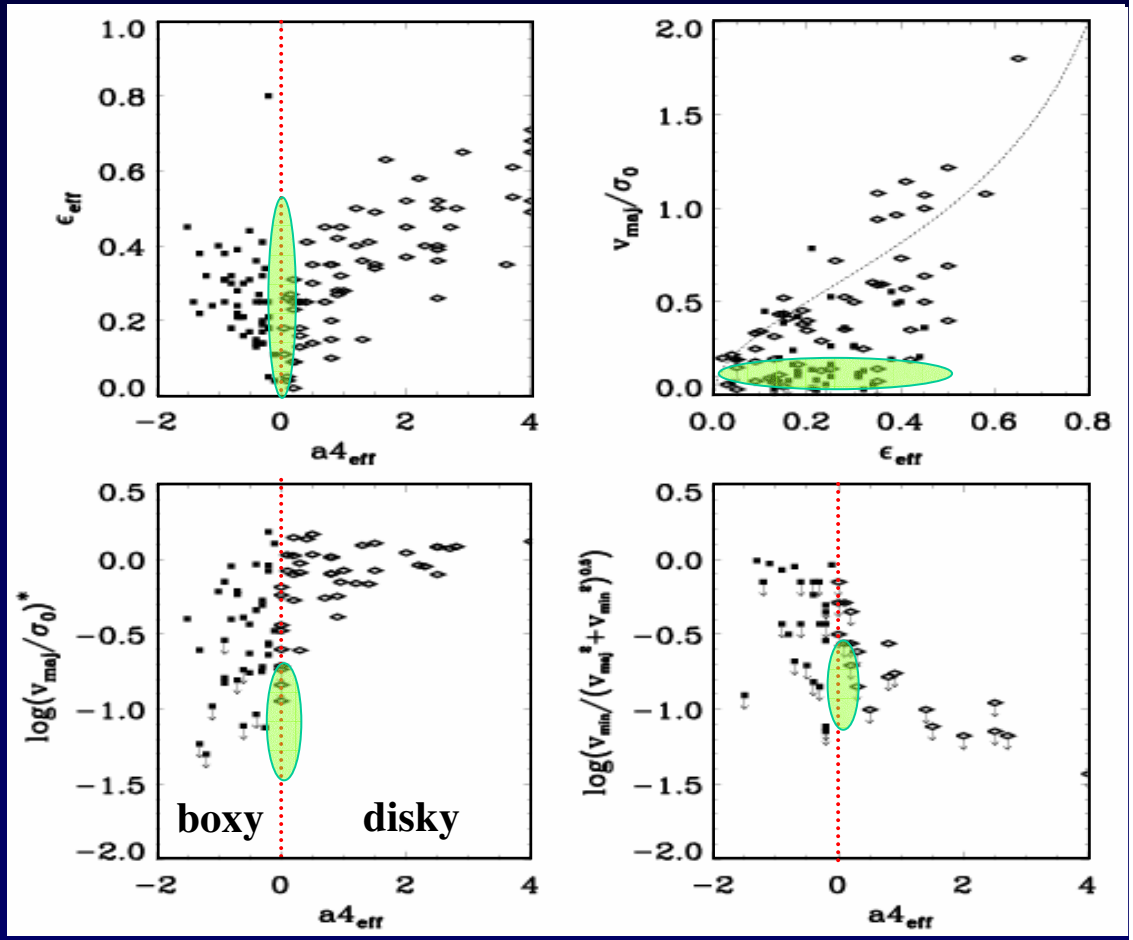
(Bender 1987)

Disky and Boxy Ellipticals

Boxy and disky ellipticals form two distinct groups with different kinematical properties (Bender et al. 88,89).

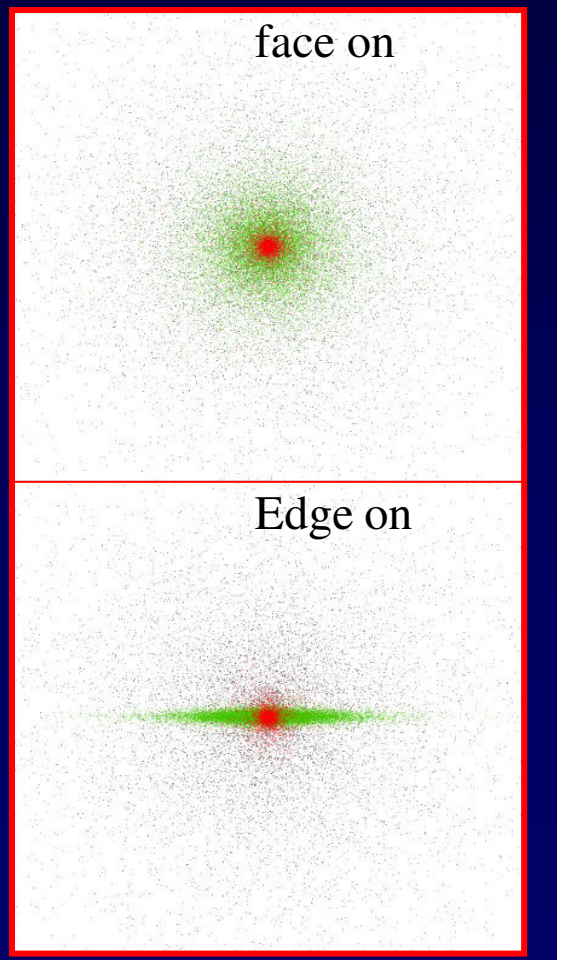
Violent relaxation cannot explain these observations.

Can the merger scenario explain this dichotomy?



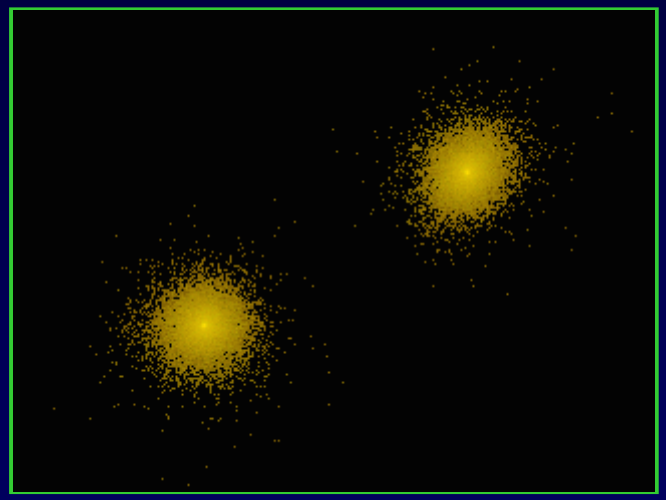
Initial Conditions

- High-resolution merger simulations with mass ratios 1:1, 2:1, 3:1, and 4:1 (Naab & Burkert 99, 00, 01, 02, 03, 04).
- Spirals consist of disk, bulge and dark halo.
- Scaling relations, as expected from the Tully-Fisher-relation.
- 15 different orientations for parabolic orbits with fixed pericenter distance.
- 60 merger remnants analysed, seen in 500 random projections.



Collisionless Merger Simulations

Equal-mass merger



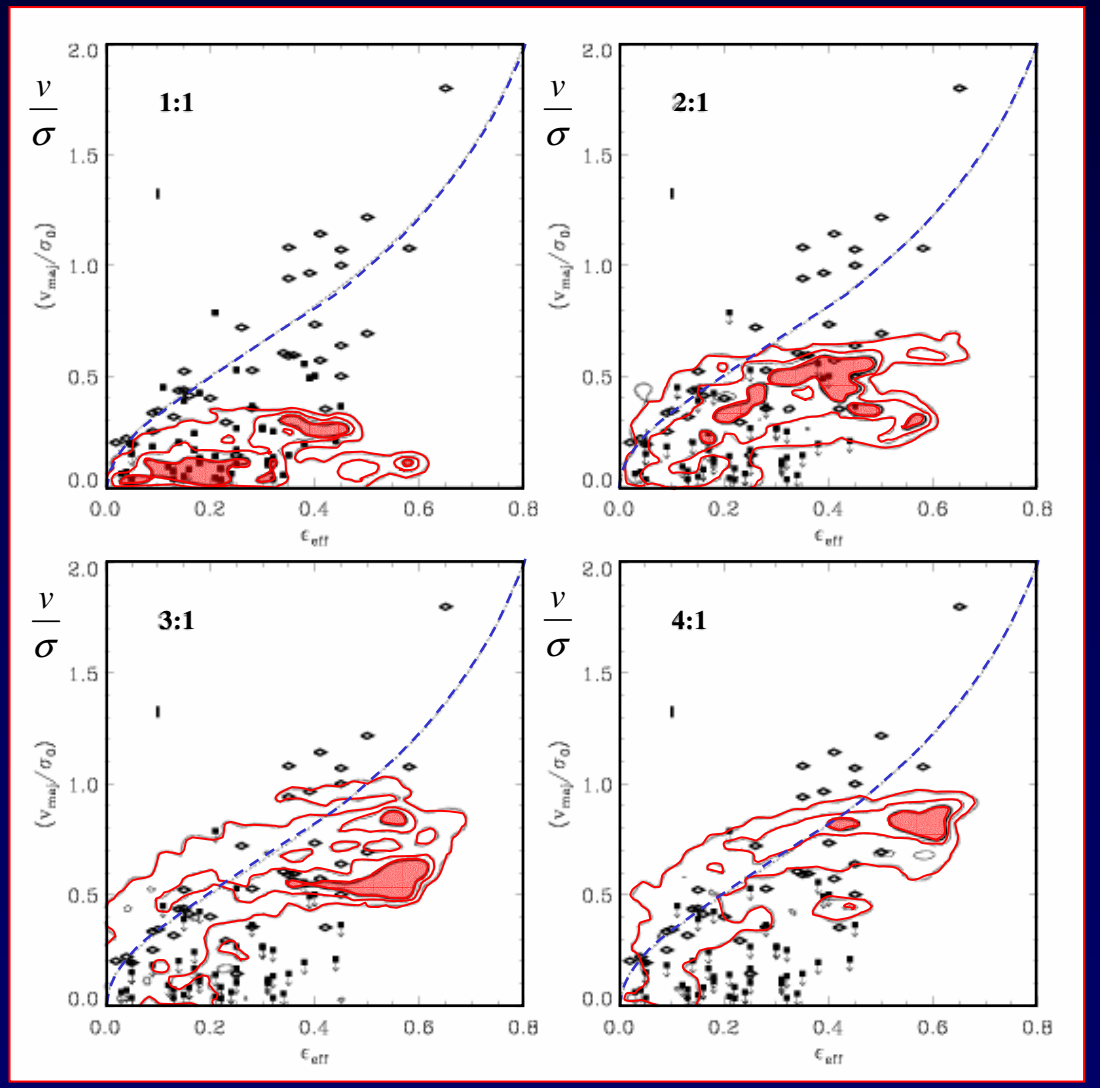
Analysis of the remnant based on the same methods as used by observers.

Rotation of Merger Remnants

v/σ versus ε

- Equal mass mergers rotate slowly.
- 3:1 and 4:1 remnants rotate fast.
- 2:1 remnants show intermediate rotation

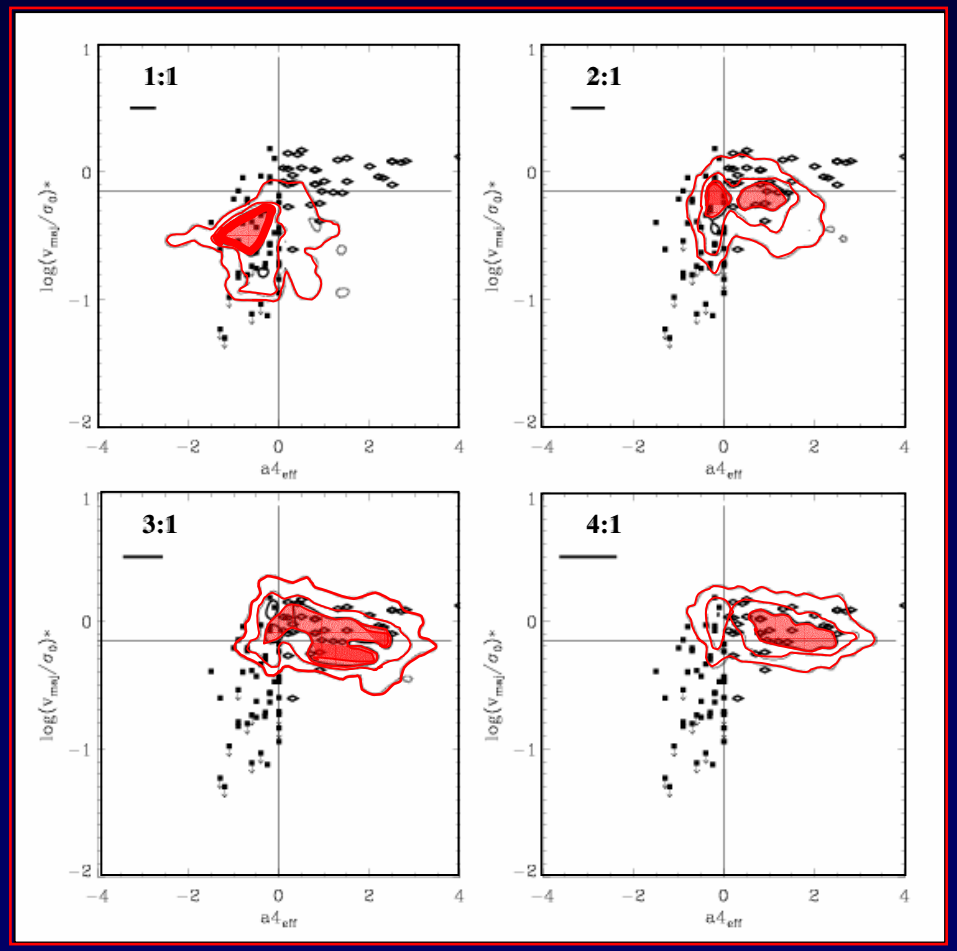
- Rotation depends on the mass ratio.



Anisotropy of Merger Remnants

$\log\left(\frac{v}{\sigma}\right)^{*}$ versus a_4

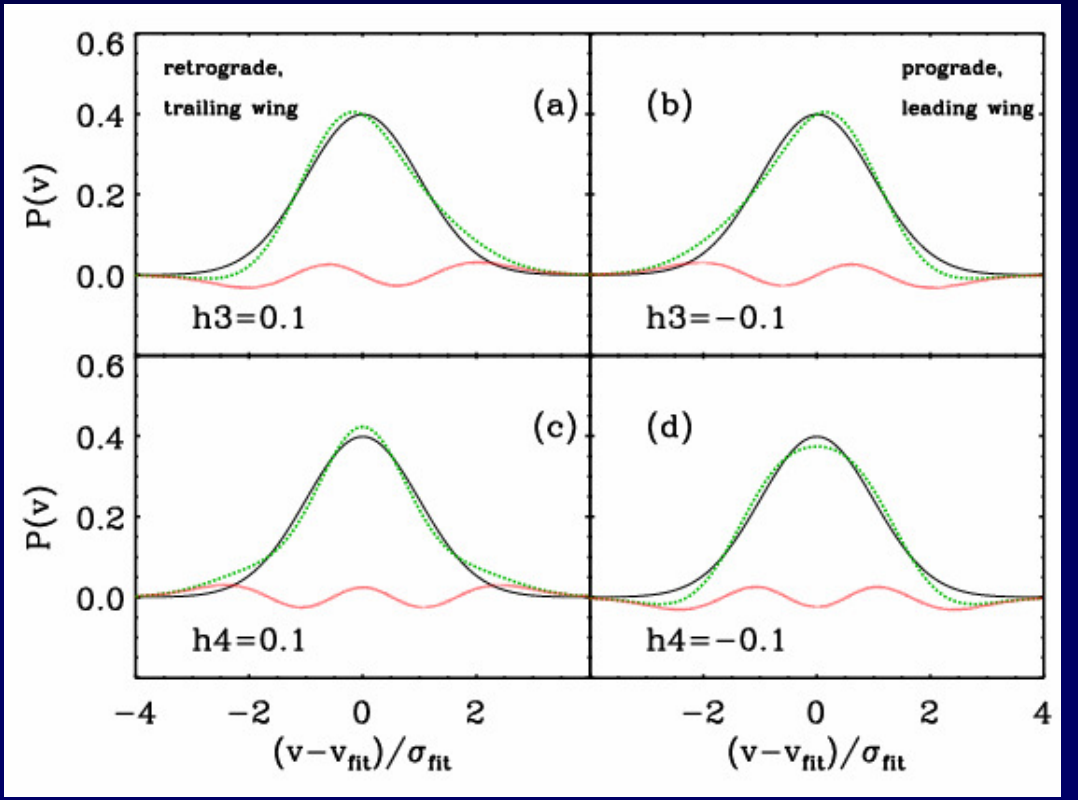
- Equal mass mergers are anisotropic and boxy
- 3:1 and 4:1 remnants are fast, isotropic rotators and disky
- 2:1 remnants show intermediate properties
- Anisotropy and isophotal shape depends on the mass ratio.



The Skewness of Elliptical Galaxies

- Bender, Saglia & Gerhard (94) studied the line-of-sight velocity distribution of elliptical galaxies.
- They detected small deviations from a Gaussian distribution that can be characterized by Gauss-Hermite-functions.

- $h_3 > 0$: shift to negative v
- $h_3 < 0$: shift to positive v



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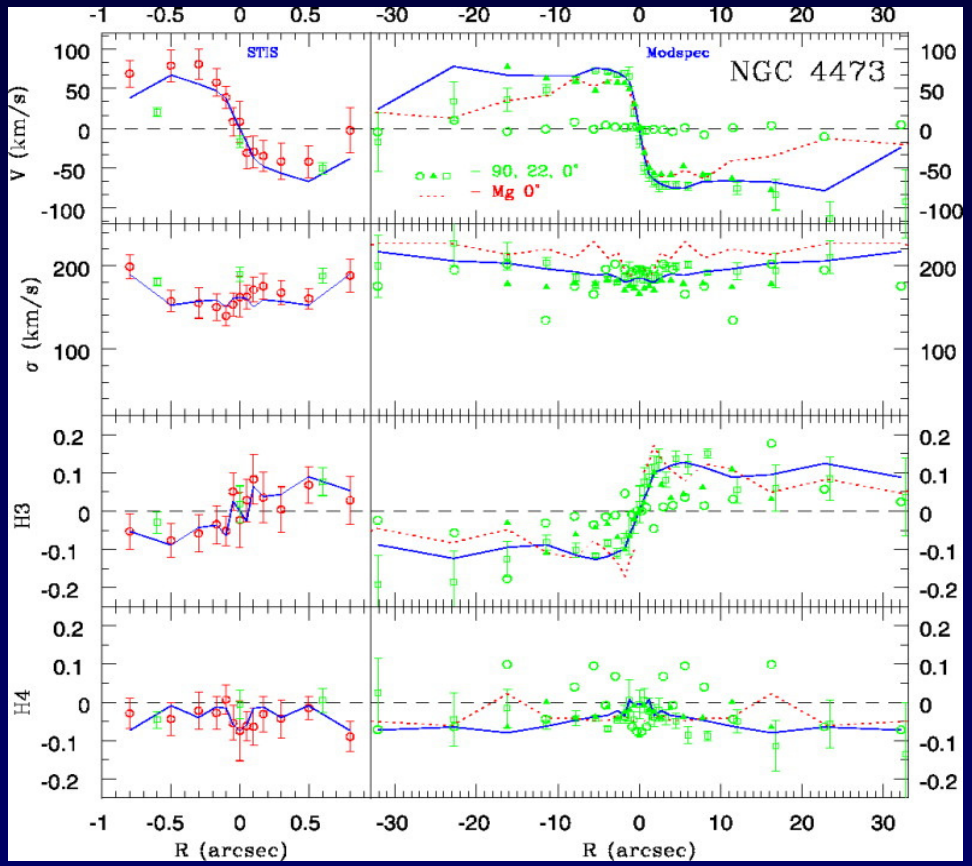
Ellipticals show a distinct correlation between their local h_3 and v/σ .



(Pickney et al. 03)

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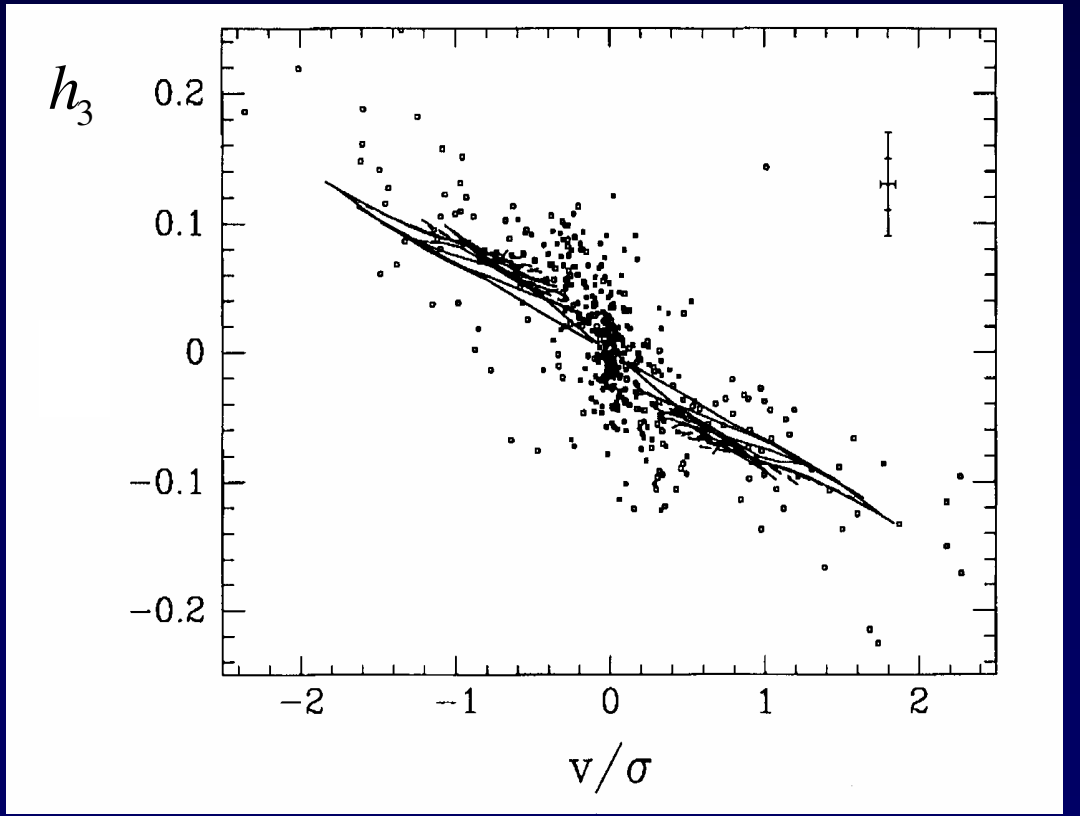
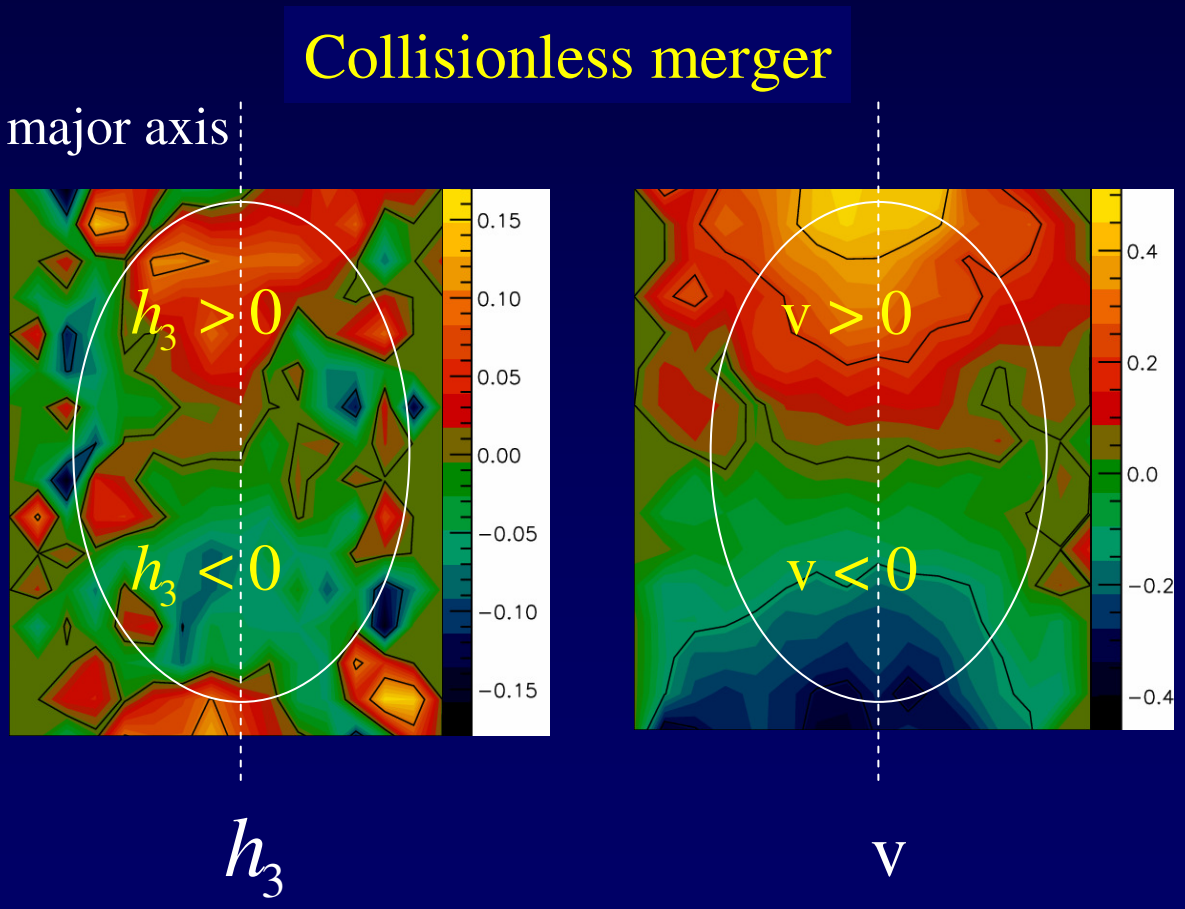


(Bender et al. 94)

The Skewness of Collisionless Merger Remnants

- 2 dimensional analysis of the LOSVD on a grid superimposed on the merger remnant.



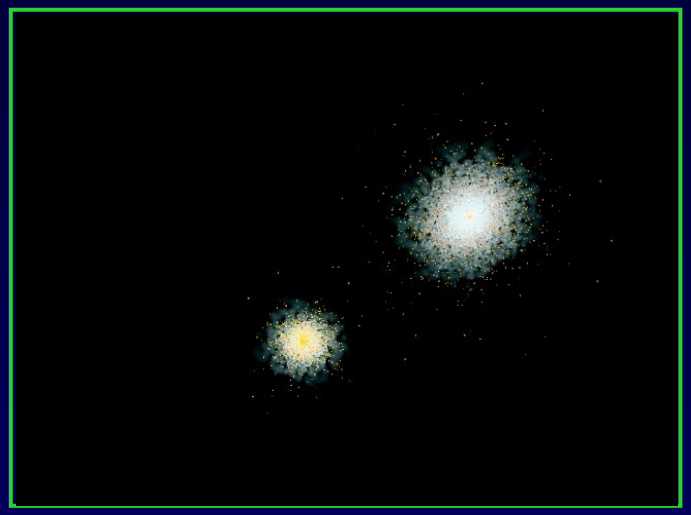
The Role of Gas in Major Mergers

Colliding Galaxies NGC 4038 and NGC 4039 HST • WFPC2

PRC97-34a • ST ScI OPO • October 21, 1997 • B, Whitmore (ST ScI) and NASA

Gas-rich Merger Simulations

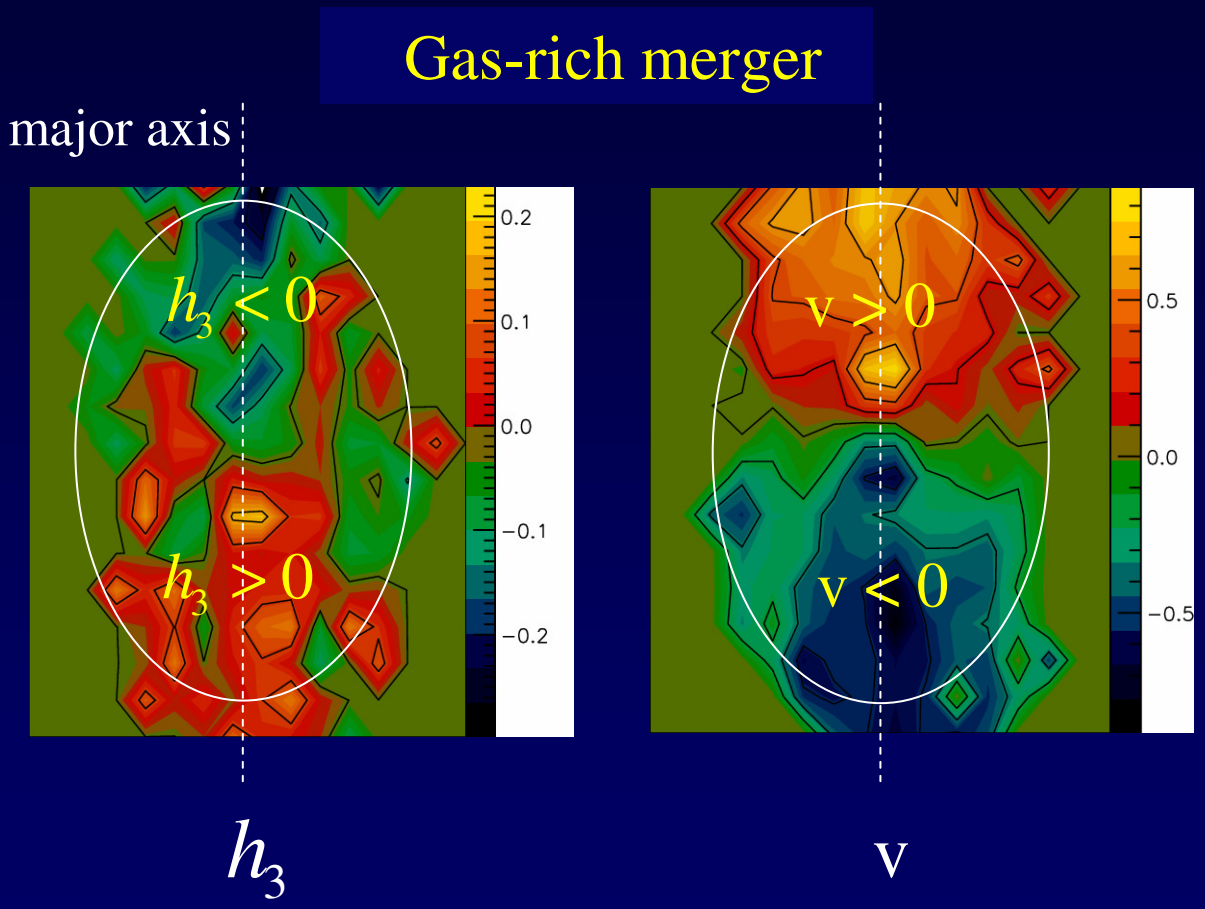
Gas-rich 3:1 merger

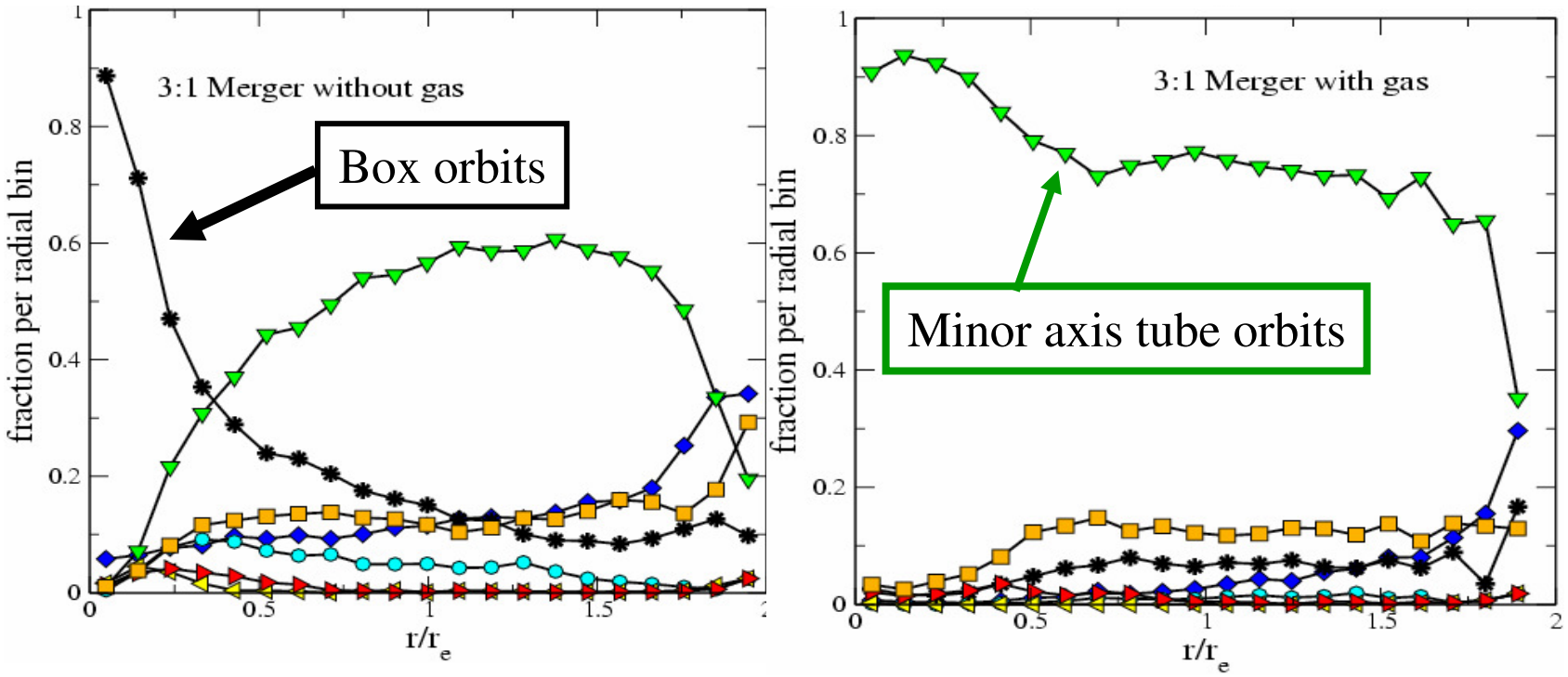


Gas plays in important role in fueling central star bursts and central black holes. leading to AGN, ULIRG, Quasars ...

(Dasyra et al. 06a,b; Di Matteo et al. 05; Croton et al. 06)

Evidence for Gaseous Mergers

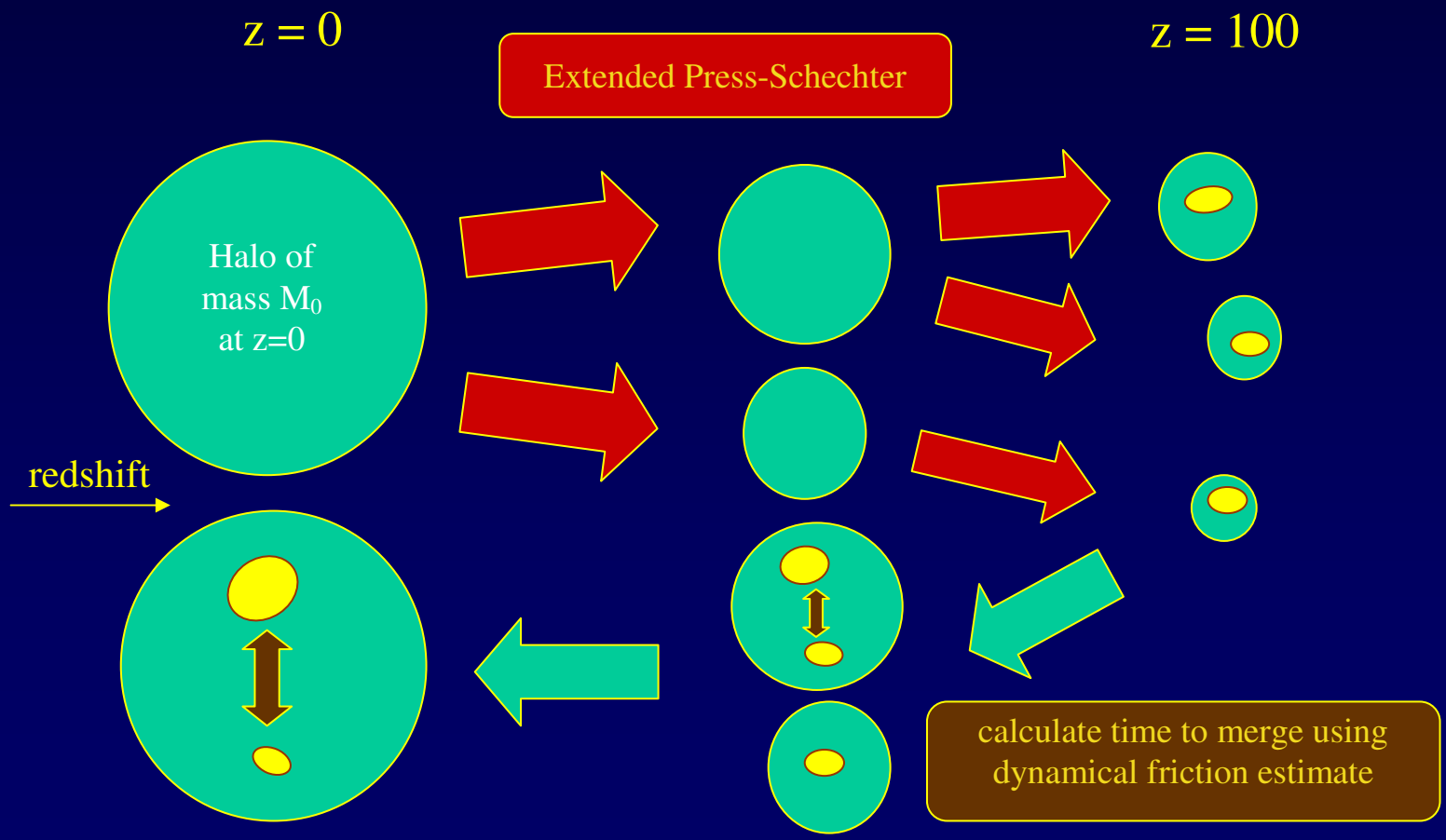




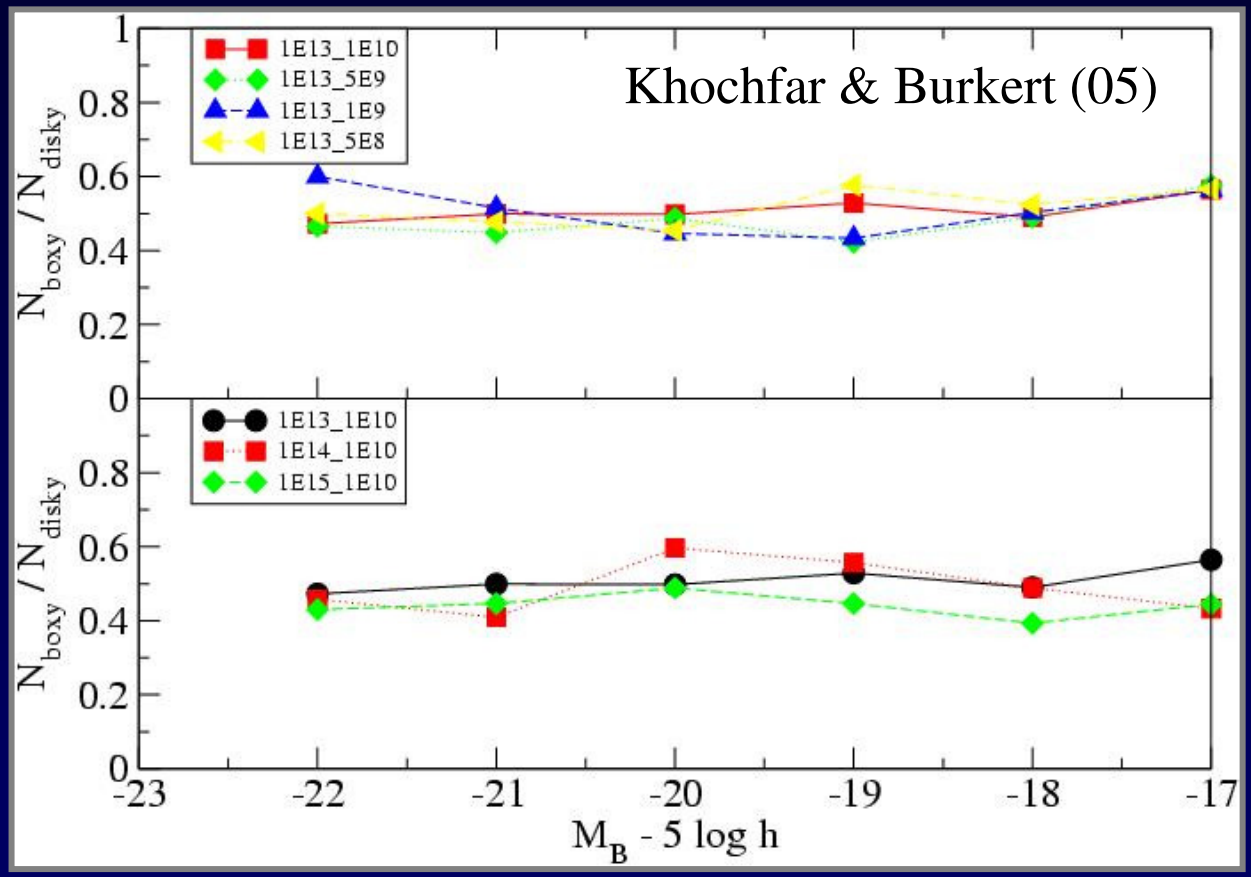
(Jesseit et al. 05, 06)

The merging history of elliptical galaxies

The extended Press-Schechter theory (Kauffmann & White 93; Khochfar & Burkert 00, 01, 02, see also Croton 06, De Lucia et al. 06).

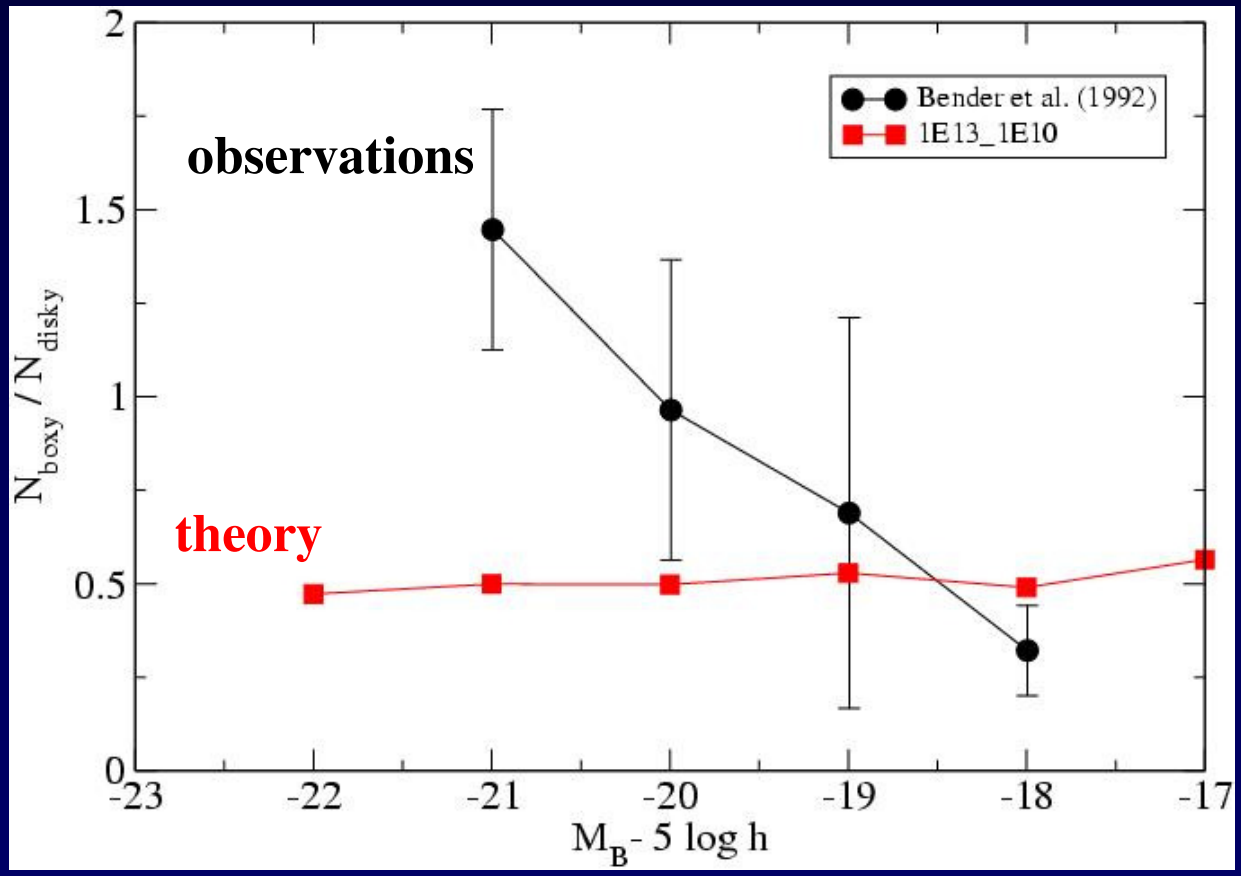


The Frequency of Boxy and Disky Ellipticals



The ratio of boxy-to-disky ellipticals should be independent of luminosity

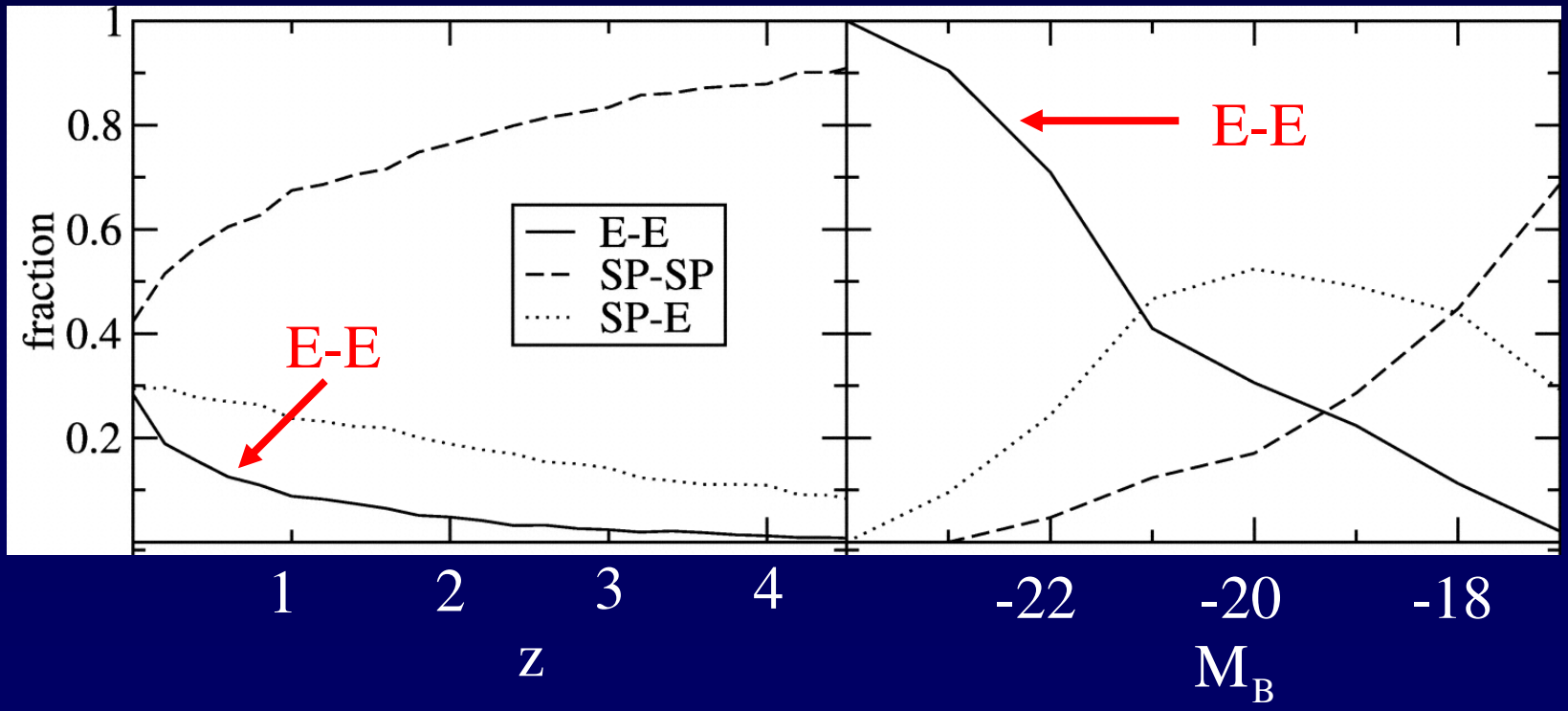
The Frequency of Boxy and Disky Ellipticals



Khochfar & Burkert (05)

Spheroidal and Mixed Mergers

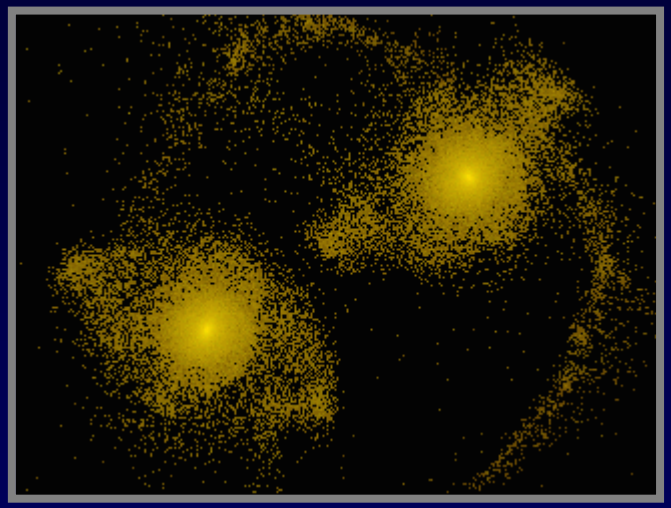
The merger fraction between galaxies of different morphologies depends strongly on redshift and mass (Khochfar & Burkert 03).



Massive boxy ellipticals might result from E-E mergers.

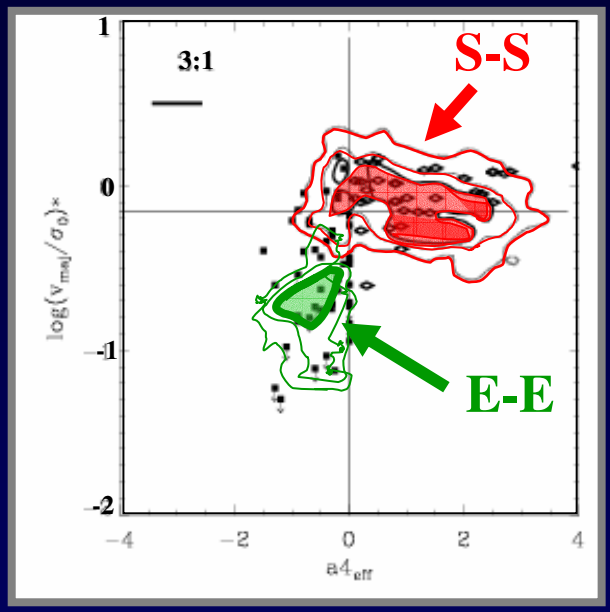
Early-Type Merger Simulations

E-E merger simulation



(Khochfar & Burkert 05; Naab et al. 06)

$\log(v/\sigma)^*$



$a4_{eff}$

E-E merger remnants are boxy and very anisotropic even for large mass ratios of 3:1 or 4:1.

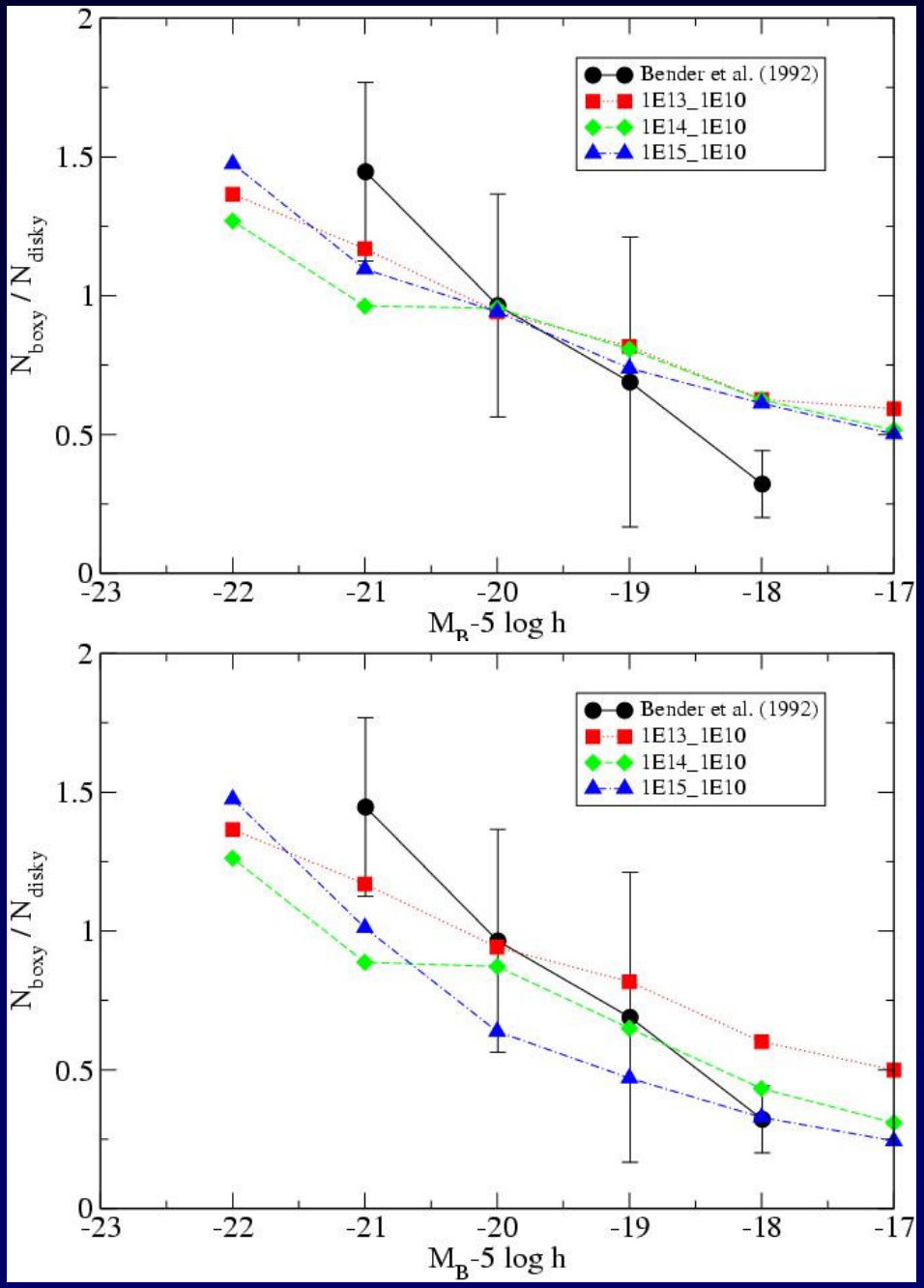
Assumption 1:

E-E mergers → boxy

Assumption 2:

More than 20% gas accretion

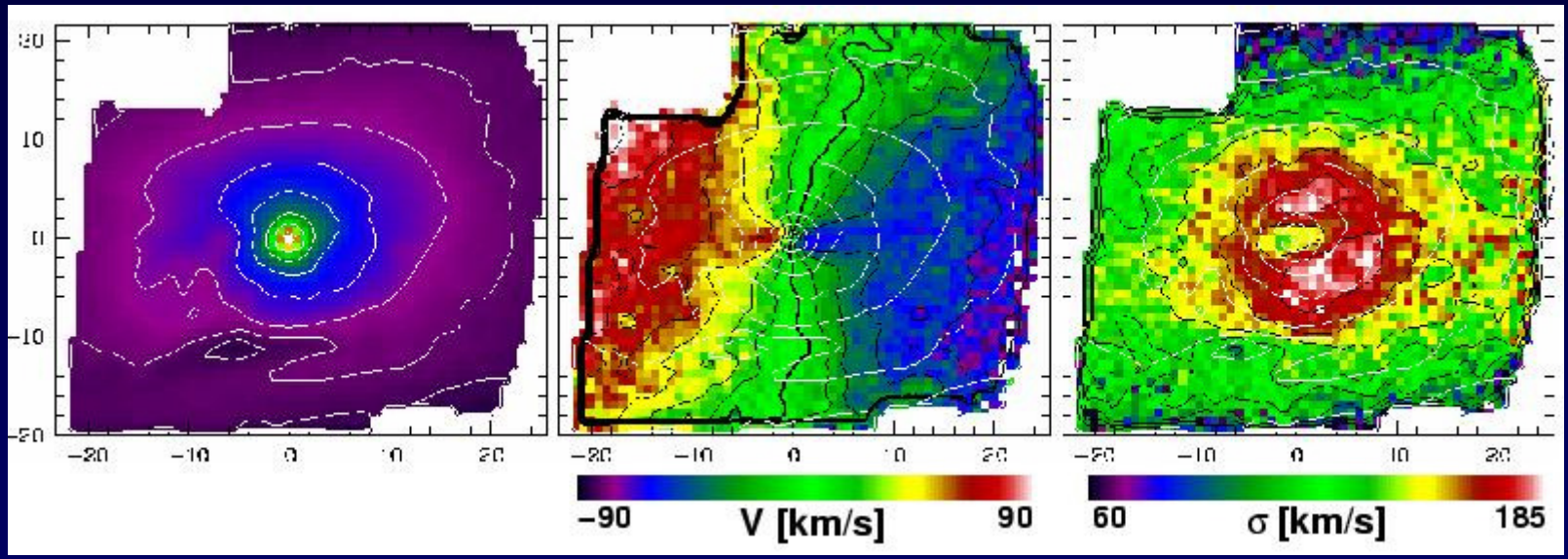
→ disky



SAURON Integral Field Kinematics

(Bacon et al. 01; de Zeeuw et al. 02)

The central stellar disk in NGC 3623



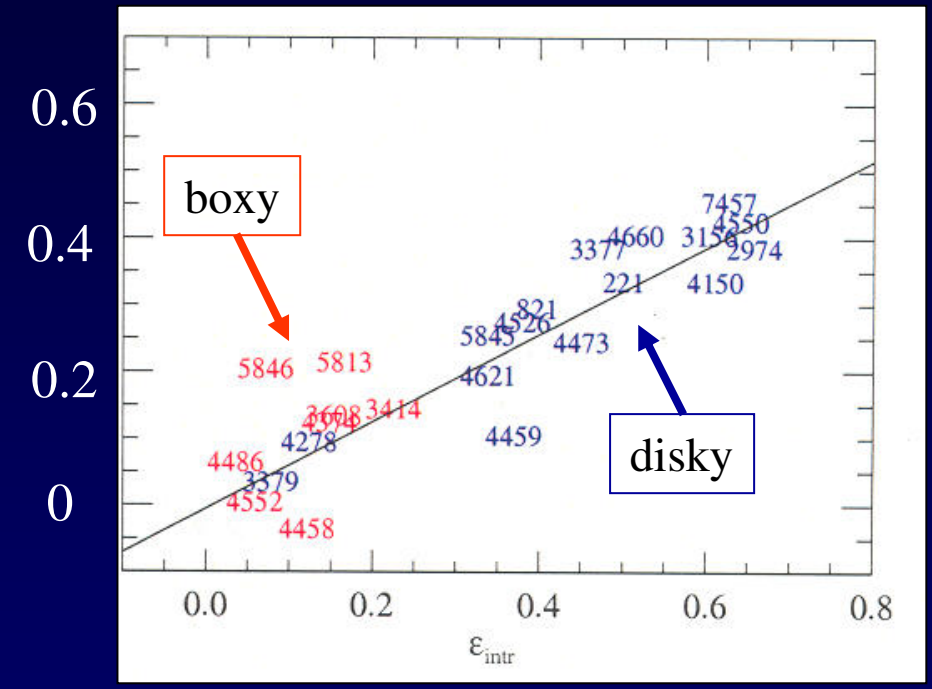
- **Intrinsic** properties from axisymmetric three-integral **Schwarzschild models.**

SAURON Integral Field Kinematics

(Cappellari et al. astro-ph/0509470)

- **Intrinsic** properties from axisymmetric three-integral **Schwarzschild models.**

$$\delta = \frac{\Pi_{xx} - \Pi_{zz}}{\Pi_{xx}}$$

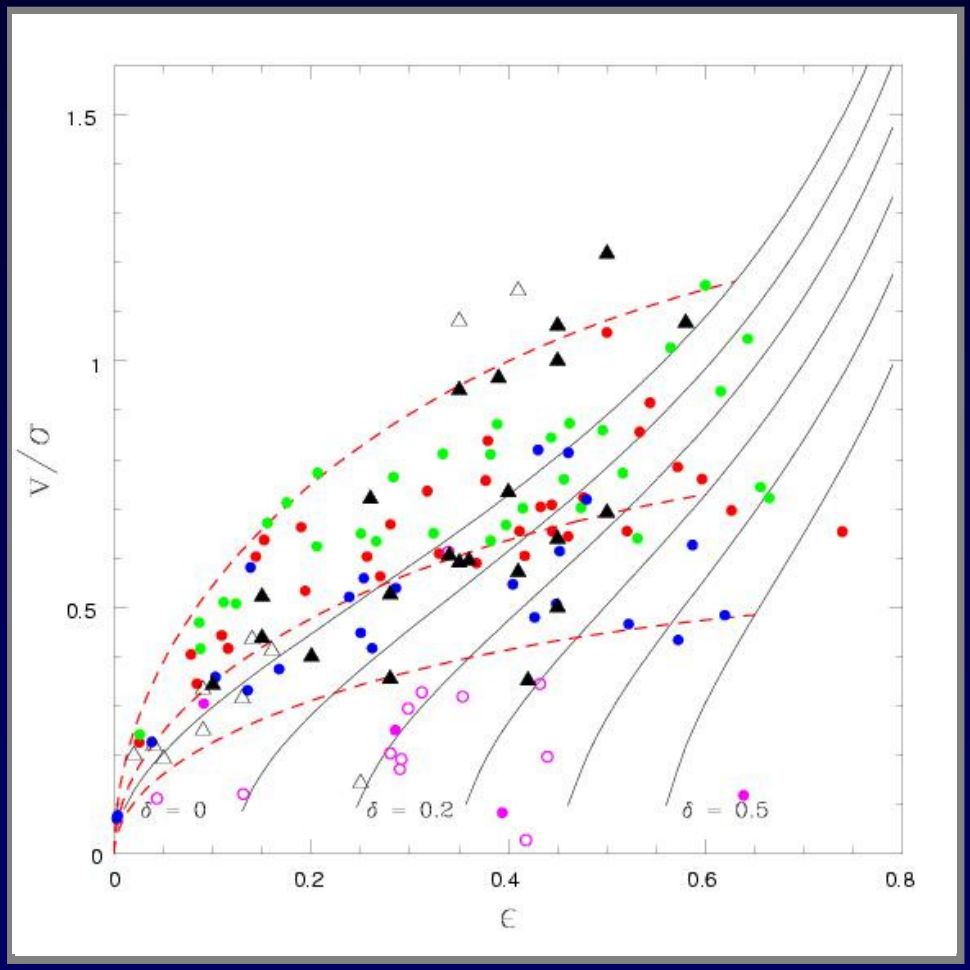


- **Disky** ellipticals are **anisotropic** with high **ellipticities**.
- **Boxy** ellipticals are **isotropic** and **round.**

$$\delta \approx 0.6 \cdot \varepsilon_{int}$$

The anisotropy diagram

v/σ



ε

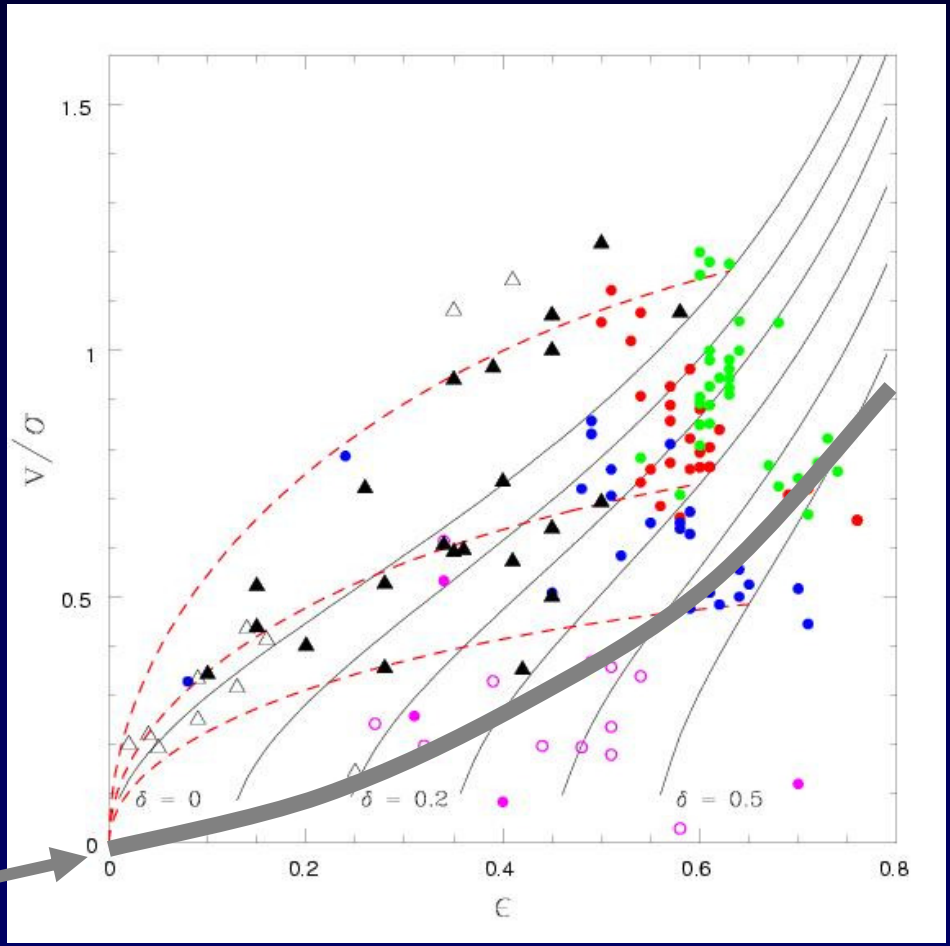
$\delta \approx 0.6 \cdot \varepsilon_{int}$

(Burkert & Naab, 05)

Projection effects lead to large uncertainty

SAURON's Challenge of the Major Merger Scenario

v/σ



$\delta \approx 0.6 \cdot \varepsilon_{int}$

ε

Conclusions

- The major merger scenario is very successful in explaining the structure of elliptical galaxies.
- Kinematics and isophotal shape of merger remnants is determined by their mass ratio:

  1:1-2:1 → anisotropic + boxy

  3:1-4:1 → fast rotating + disky.

- Low luminosity ellipticals experienced substantial gas inflow after the last major merger → disky systems, independent of mass ratio of last major merger
- Very luminous, boxy ellipticals might have formed from gas-poor, early-type mergers, independent of mass ratio of major mergers.

- However: Numerical simulations are not in agreement with predictions resulting from integral field spectroscopy