On the Formation of Elliptical Galaxies

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Two Opposing Theories

- Monolithic collapse
  - Global star formation event creates ellipsoidal galaxies
  - Most accrete gas and form disks
- Hierarchical clustering
  - First galaxies are generally disks
  - Disks merge to form ellipsoids

Outline

- Toomre and Toomre (1972) suggest that Elliptical galaxies (Es) may form by mergers
- Numerical simulations show what kinds of mergers produce what kind of galaxies
- Mergers explain internal structure of Es
- Observations continue to present challenges for existing models

Origin of the Merger Hypothesis

- Toomre & Toomre (1972) study tidal interactions between neighboring galaxies
- Their hypothesis: gravity is responsible for galactic bridges and tails
- Simulated "massless" particles pulled by $1/r^2$ forces from two colliding mass-points

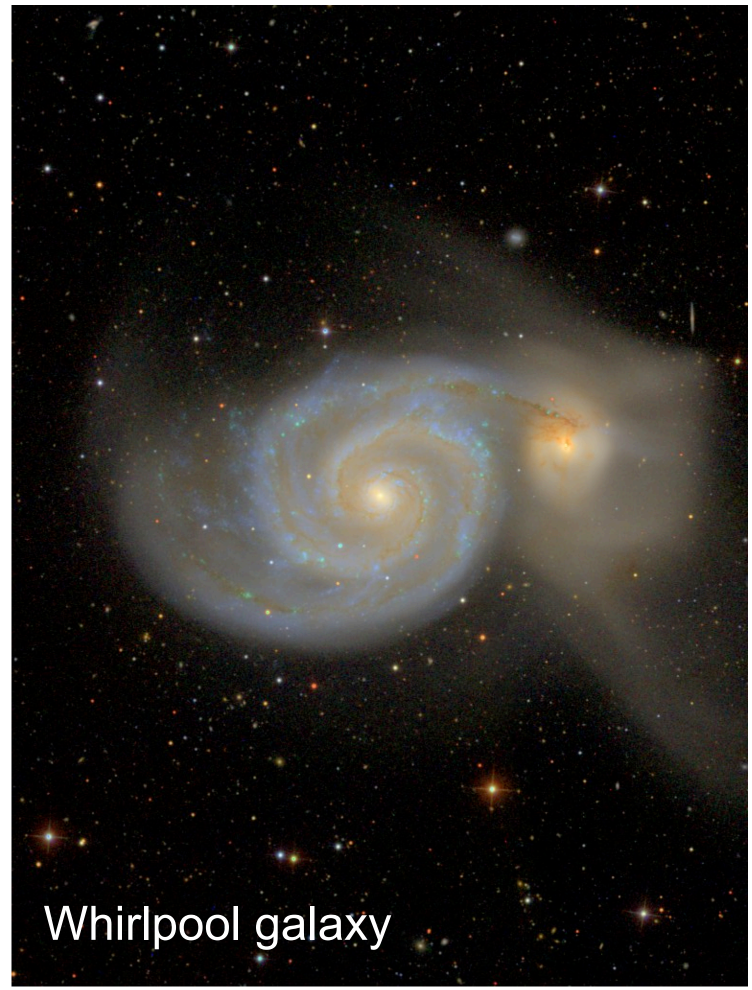
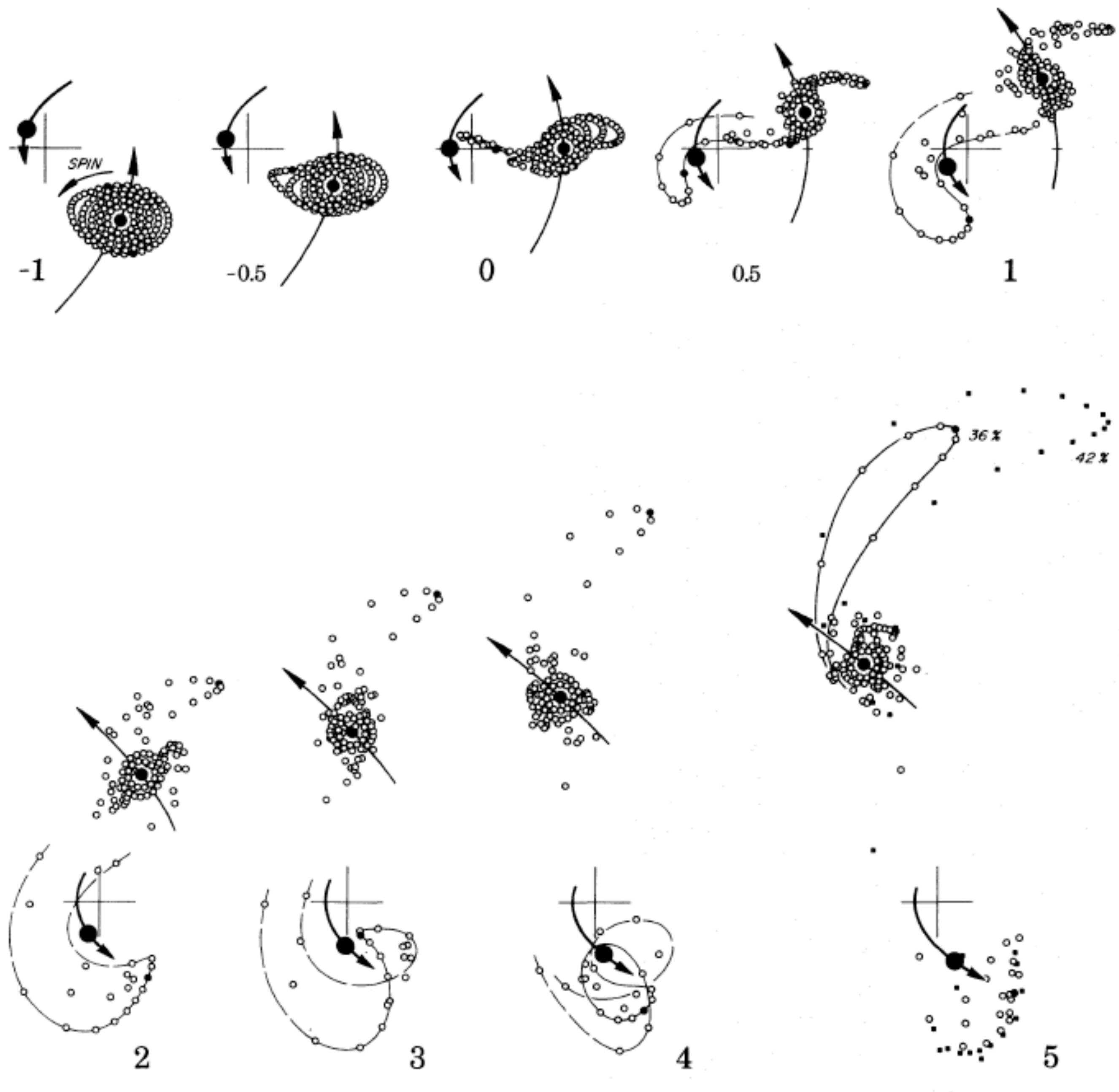


Image: David W. Hogg, Michael R. Blanton, and the SDSS Collaboration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-0.5
0
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1
36 %
42 %
2
3
4
5

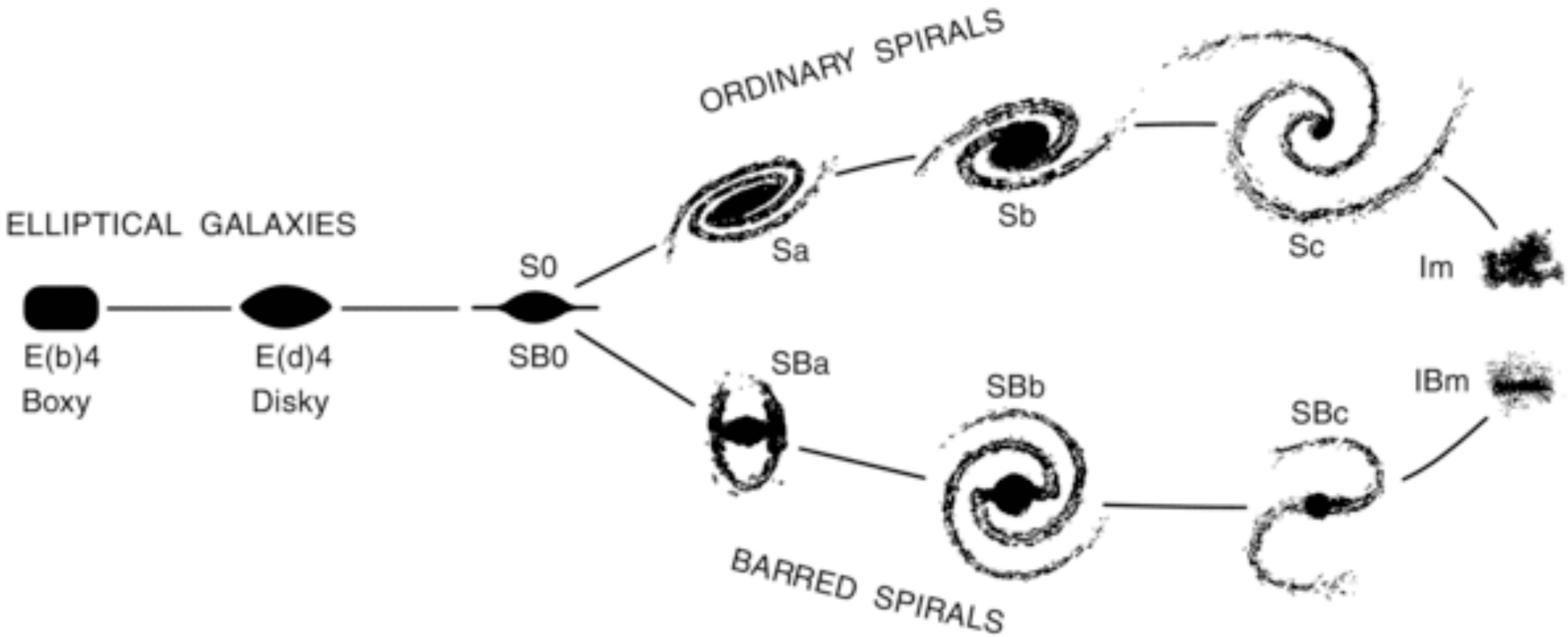
"…as in medicine, pathology seems instructive"

- Tidal interactions are adequate to violently disturb galaxies – can they totally disrupt a disk?
- Tails carry away a significant fraction of the rotational energy of merging galaxies
  - "And hence would not their remnants drop into orbits of progressively shorter periods, until at last they lose altogether their separate identities and simply blend or tumble into a single three-dimensional pile of stars?"
- But does it work?
  - Simulations seek to demonstrate that mergers can account for observed Es

Classes of Elliptical Galaxies

- Brightest elliptical galaxies – absolute magnitude < -21
  - Boxy
  - "Pressure supported" (i.e. low net angular momentum)
  - Triaxial
  - Low eccentricity
  - Excavated core
- Intermediate and dwarf elliptical galaxies
  - Disky
  - Rotationally supported
  - Oblate-spheroidal
  - Rather flat
- Dwarf spheroidal galaxies
  - Apparently unrelated to the above
  - Probably not formed by mergers
    - Possibly disturbed late-type galaxies

* This classification follows Kormendy et al. (2009) ApJS

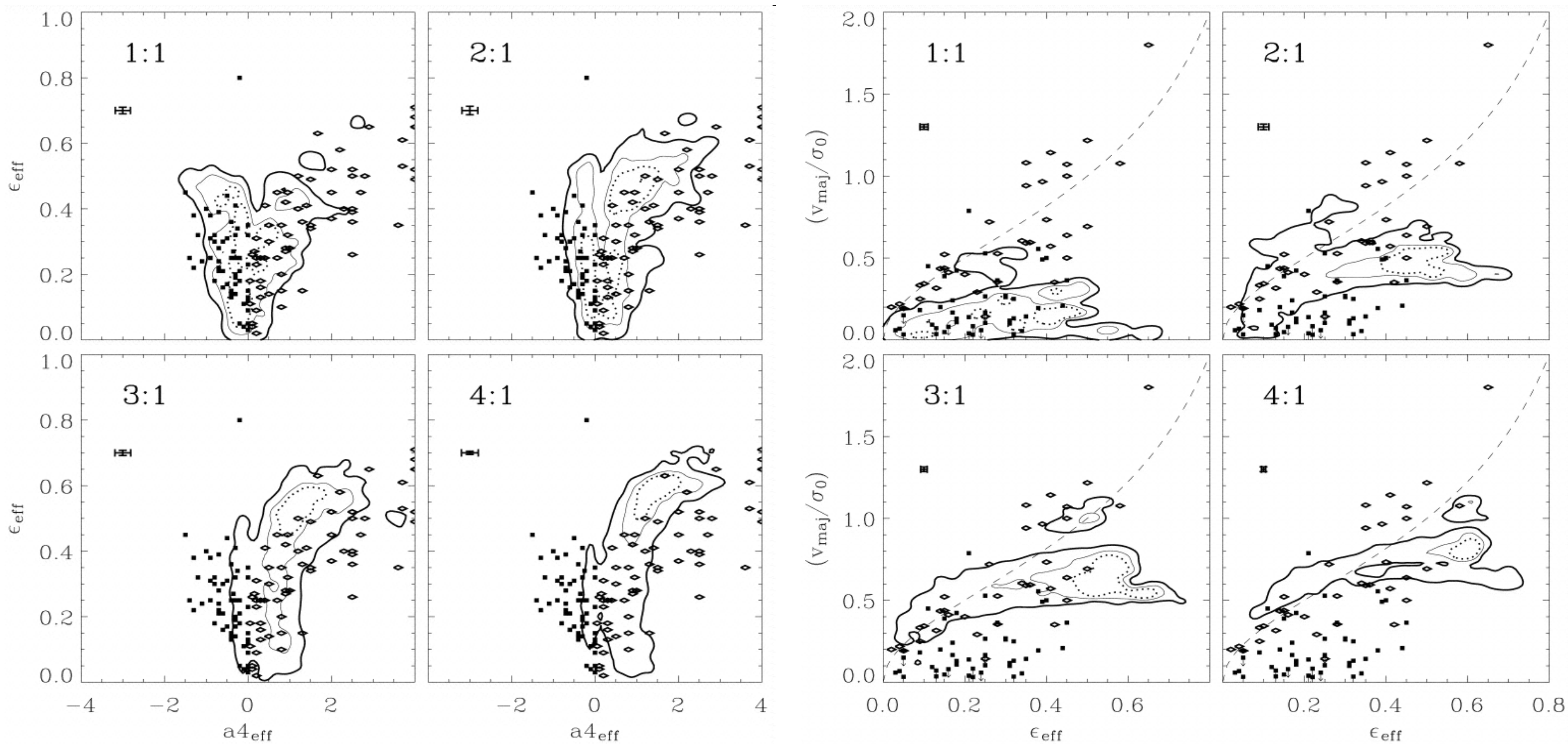


Kormendy, J. & Bender, R. 1996, ApJ, 464, L119

Binary Disk-Disk Mergers

- Naab and Burkert (2003) simulate binary mergers
- N-Body: 250k-400k particles
- Stars and dark matter only (no gas)
- Collisionless
- Mass ratios of 1:1-4:1
- Collision geometry
  - Near parabolic trajectory with fixed pericenter
    - Khochfar, S. 2003, Ph.D. thesis, Univ. Heidelberg
  - Rotational orientation varied isotropically
    - 4x4 model orientations
- 112 simulations total

Results



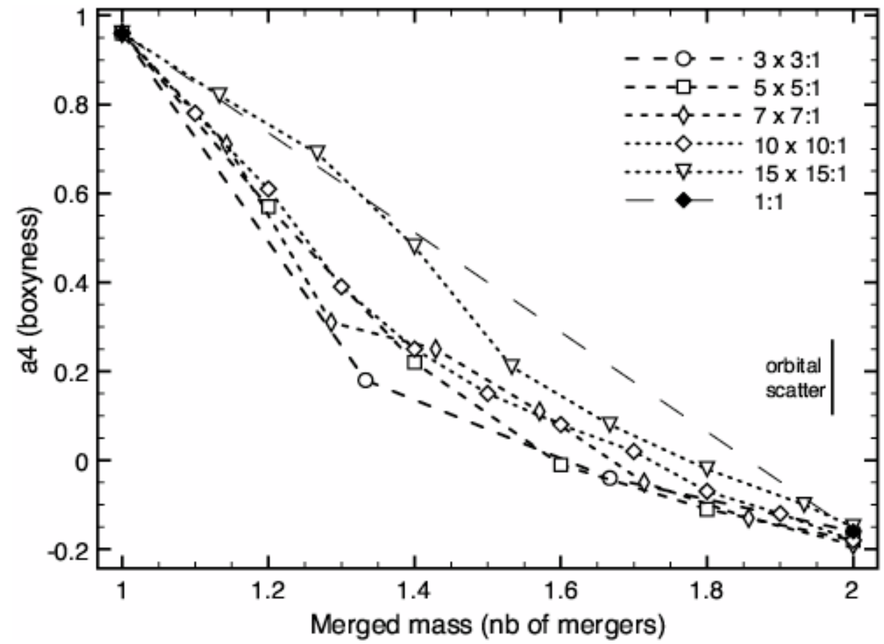
Disky galaxies reproduced better than boxy ones

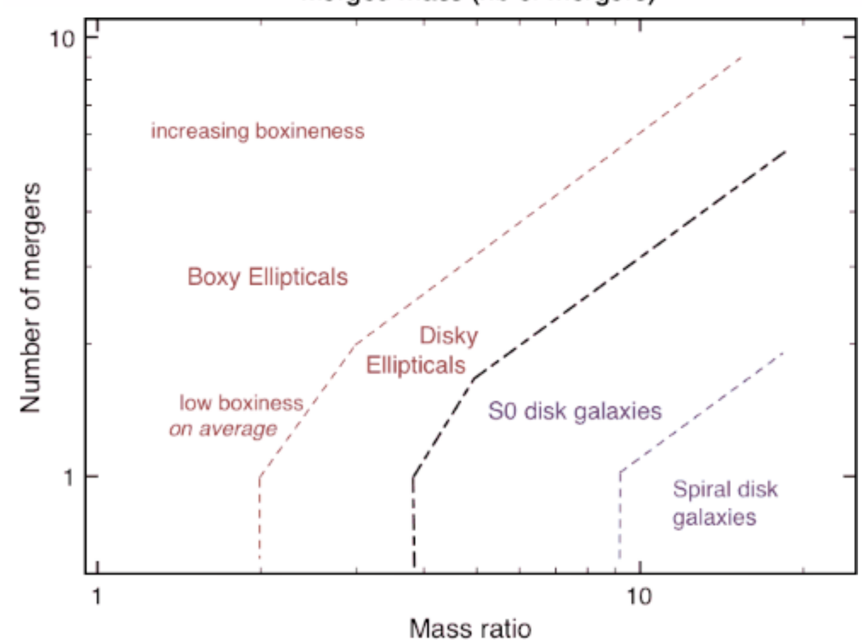
Naab & Burkert Conclusions

- 3:1 and 4:1 mergers produce rotating, disky ellipticals
  - Good candidate for E(d) formation
- Properties of 1:1 mergers depend on geometric parameters
  - Only certain geometries produce E(b)
  - 28% don't resemble any observation!
    - Disky, elongated, might be mistaken for S0?
- E(b) galaxies most likely did not form this way

Multiple mergers

- Bournaud, Jog, and Combes (2007) simulated multiple minor mergers
  - Gas and star-formation included
- Conclusions: Structural properties depend on total mass accreted, not the number of mergers
- Multiple major mergers increase boxiness, good candidate for E(b)

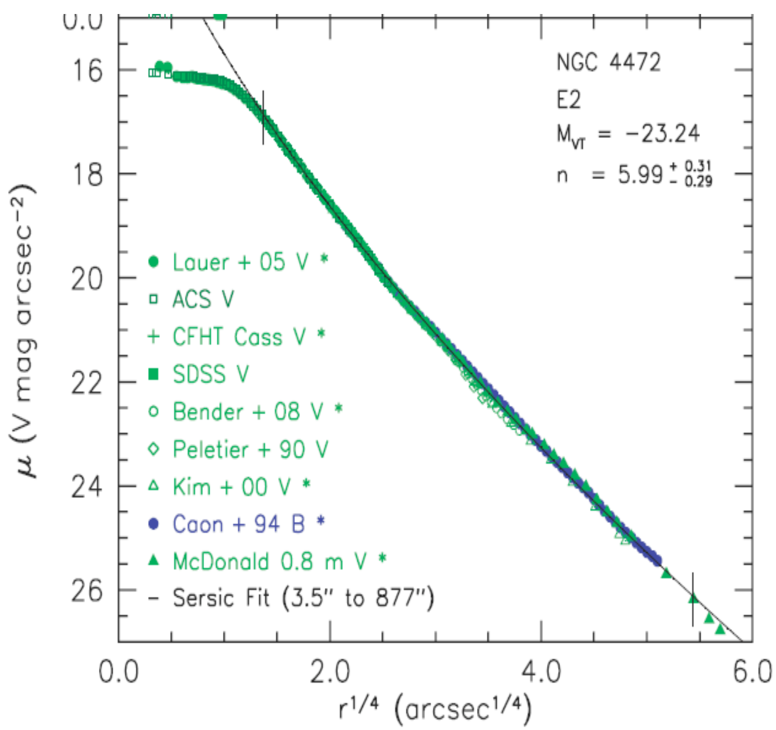


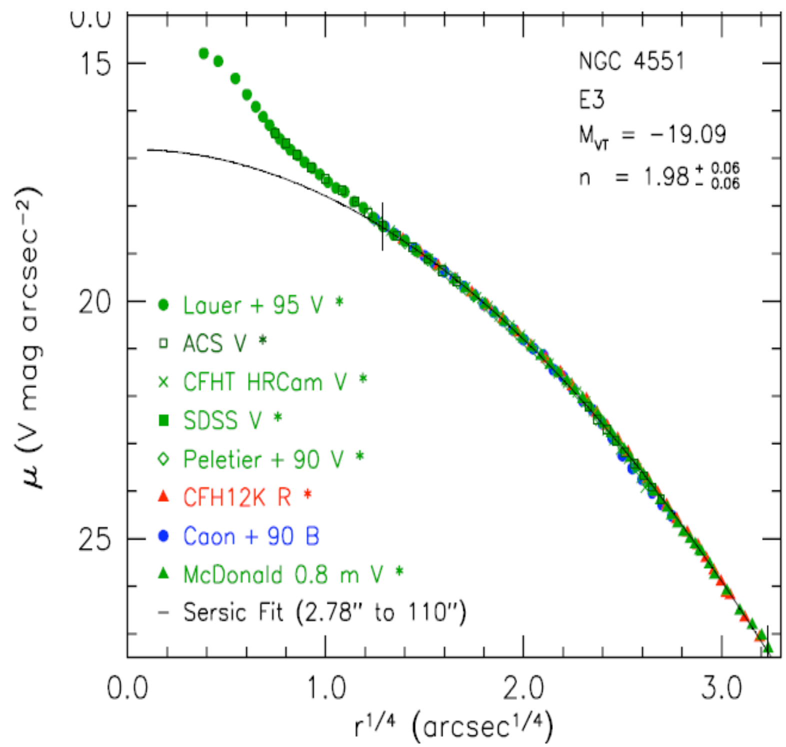


Core and Extra-Light Es

- Kormendy et al. (2009) suggest the following dichotomy
- Core Es
  - Center of galaxy shows light loss
  - Associated with large, boxy Es
    - E(b)
- Extra-Light Es
  - Just the opposite: extra light in galactic center
  - Associated with smaller, disky Es
    - E(d)
- Analyzed observations of the Virgo cluster from WFPC1&2, ACS and other sources
  - Lauer, T. R. et al. 2005, AJ
  - Côté, P. et al. 2004 ApJS

Cores vs No Cores





Core of missing light

Extra light in center

All “core” Es are brighter than absolute magnitude -21.6 M_{VT}

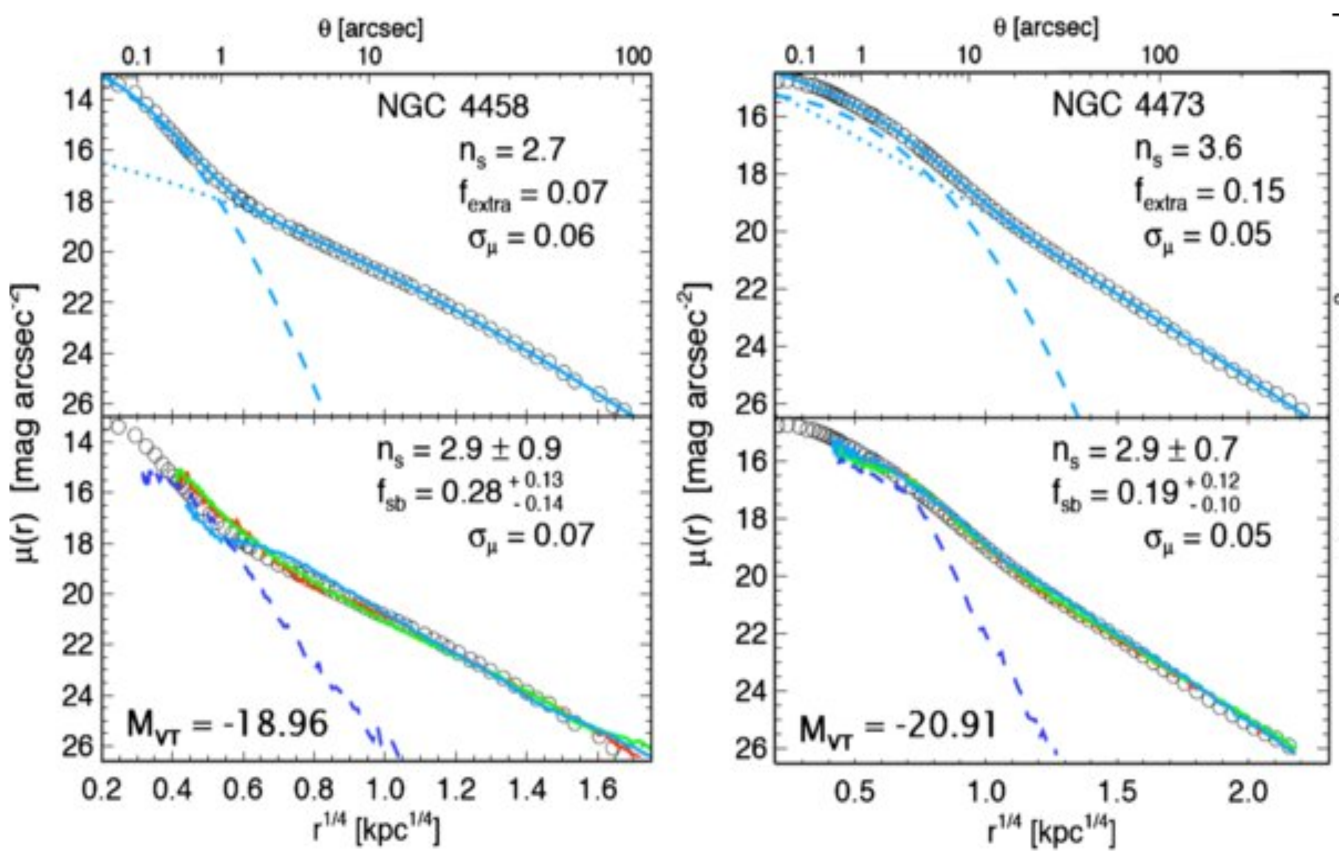
No “extra light” E is brighter than absolute magnitude -21.6 M_{VT}

All coreless Es have extra light!

How the light was won (and lost)

- Mergers of galaxies creates binary black holes that "scour" the center of stars
  - Coalescing black holes may sling-shot nearby stars with gravity waves (Meritt et al. 2004, ApJ)
- So why don't these processes happen to smaller galaxies?
  - Disky galaxies are typical of "wet" mergers
  - Gas aggregates at galactic center, cools and creates a starburst
  - Problem 1: Above scenario requires gas to coalesce slower than black holes or else it gets scoured too
  - Problem 2: why gas not heated/expelled by AGN feedback?
  - Nevertheless, simulations show wet mergers creating central starbursts (Cox et al. 2006, Hopkins et al. 2008 & 2009)

Simulations verify extra light from wet mergers



Simulations: Hopkins, P. F., Cox, T. J., Dutta, S. N., Hernquist, L., Kormendy, J., & Lauer, T. R. 2009a, ApJS, 181, 135

Challenges to merger hypothesis

- Hard to account for great age of stars in Es
  - Stars in most Es are formed 8-10 Gyr's ago, compared with mean stellar age ~5Gyr in Milky Way
  - If stars in disk galaxies are younger than stars in Es, then where did E stars come from?
    - The large, old S ancestors are absent.
- Es have high metallicity
  - They evolve passively, so we expect constant metallicity
  - We expect that Es formed before $z \approx 1$, but disks at these redshifts have much lower metallicity than required
- Both issues more problematic for larger Es
- Possible solution is some mixture of hierarchical clustering and monolithic collapse to create the progenitors of giant Es
  - Es are preferentially found in overdense regions (clusters)
  - Naab & Ostriker 2007 ApJ

Summary

- Simulations show that mergers can create elliptical galaxies
- Observations of two classes of Es (core and extra-light) are consistent with the merger hypothesis
- Unsolved problems remain

References

- Toomre, A. & Toomre, J. 1972, ApJ, 178, 623
- Naab, T. & Burkert, A. 2003, ApJ, 597, 893
- Bournaud, F., Jog, C. J., & Combes, F. 2007, A&A, 476, 1179
- Kormendy, J et al. 2009, ApJS,182, 216
- Naab, T. & Ostriker, J. P. 2009, ApJ, 690, 1452

- Further reading: Renzini, A. 2006, ARA&A, 44, 141