What nearby clusters can teach us about galaxy formation and evolution

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Fornax, Virgo, Coma et al.

Stellar Systems in High Density Environments

ESO Garching, 27 June – 1 July 2011

Outline

- Why clusters? Why nearby?
  - A reminder why Fornax, Virgo, Coma et al. are special and important
- What are the questions to answer?
  - Some current problems in understanding the formation and evolution of stellar systems in high-density environments
- What is the state of the art and the issue of the day?
  - A selective and subjective tour of the recent literature, highlighting some areas of particular interest and/or controversy
- Where do we go from here?
  - Some problems to address and some observations to make

Why clusters?

- "Clusters are laboratories for galaxy evolution"
  - Widest available range of local densities/environments
  - High rates of interaction, short dynamical timescales
  - First stellar populations to form (so oldest, most evolved)
  - The most massive halos, with highest galaxy occupancies
  - Contain both the most and the least massive galaxies
- Observationally efficient - dense, compact, varied
- But potentially misleading - highly atypical environments (everything is a selection effect until proved innocent)

Why nearby?

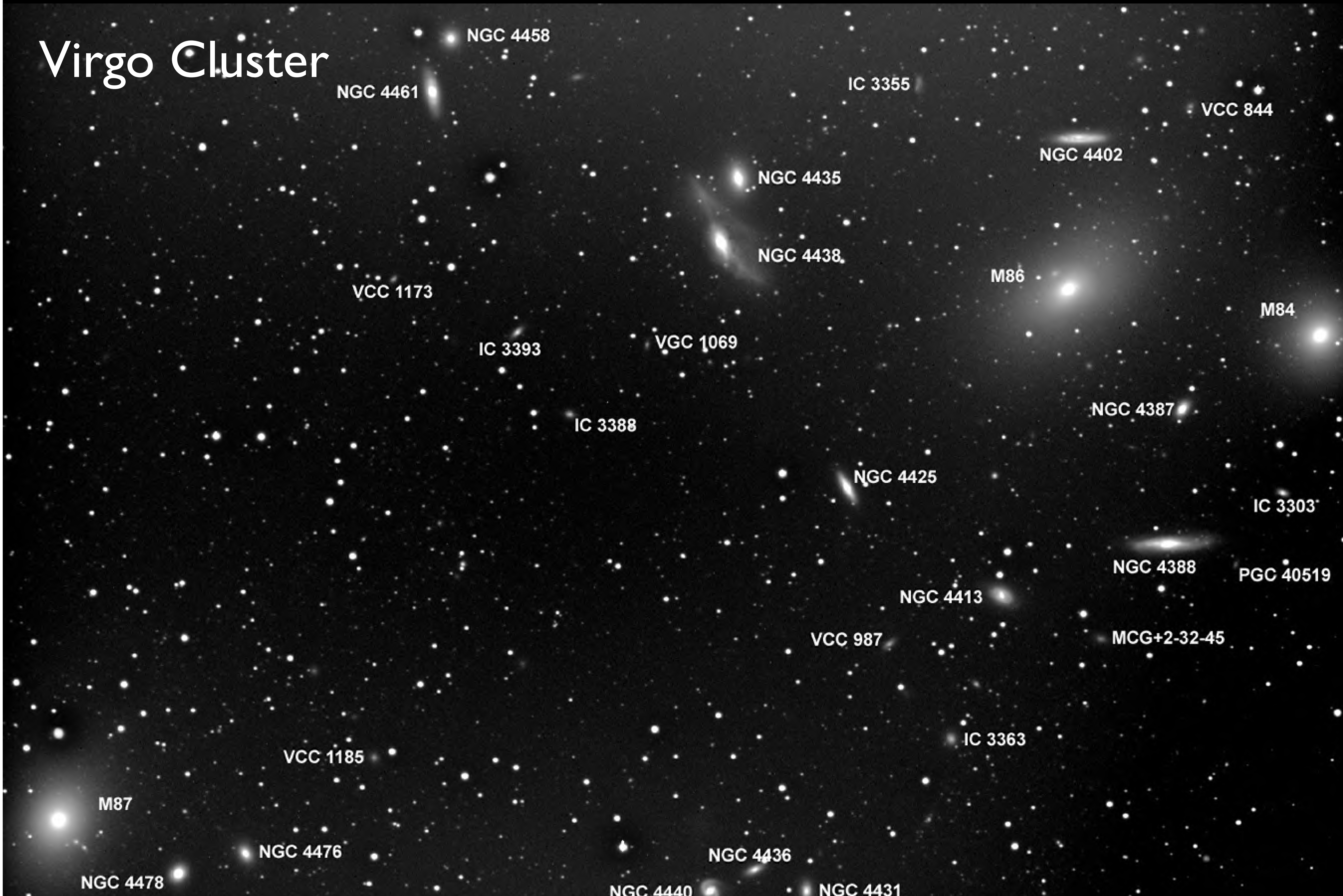
- Observationally efficient *and* easy…
- Allows studies at high spatial resolution, relatively readily resolving galaxy substructures and small components
- Allows studies to reach far down the luminosity function and surface brightness distribution to the faintest objects
- Less $(1+z)^4$ surface brightness dimming (especially important for resolved integral-field spectroscopy)
- Can in principle measure distances and reconstruct the full 3D real-space structures (though this is *not* easy)
- But only one epoch of cosmic history (so studies are necessarily archaeological, not evolutionary)

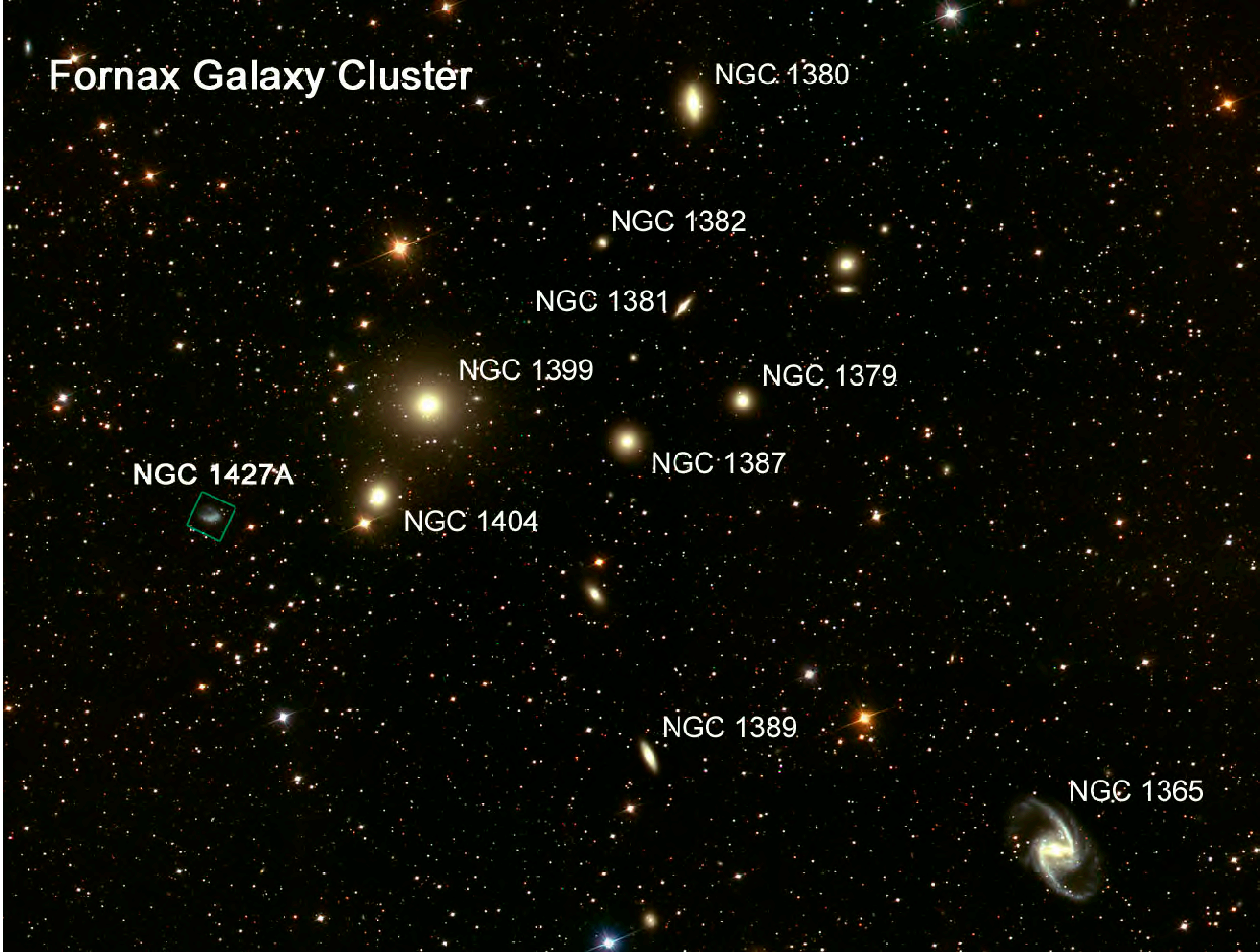
Virgo, Fornax and Coma

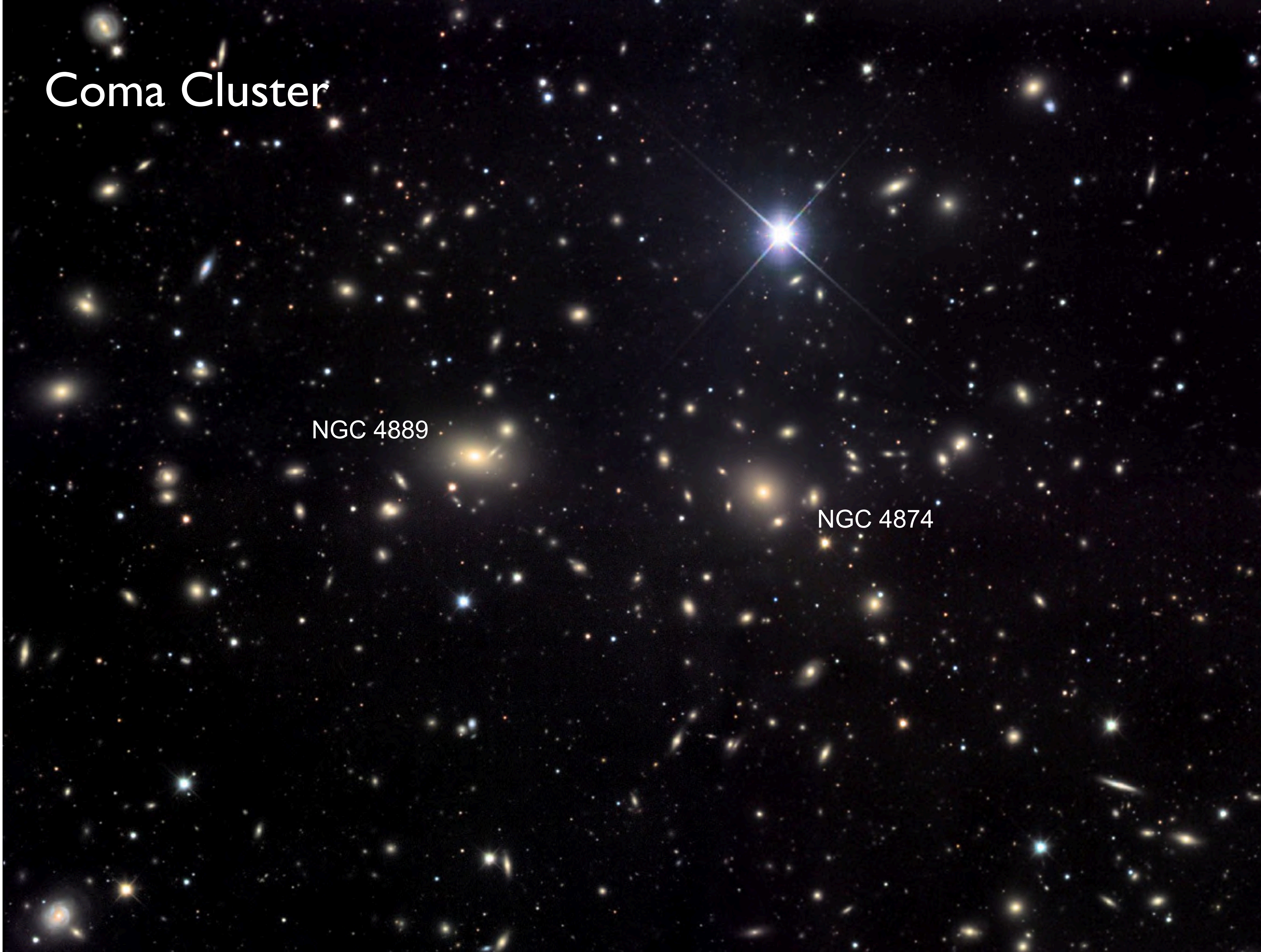
Property	Virgo	Fornax	Coma
Richness class	1	0	2
B-M type	III	I	II
Mass ($M_\odot$)	$4–7 \times 10^{14}$	$0.5–0.9 \times 10^{14}$	$11–16 \times 10^{14}$
Distance (Mpc)	16.5	19.3	96.5
$\langle cz \rangle$ (km s^{-1})	1094 ± 42	1493 ± 36	6853 ± 54
σ_v (km s^{-1})	760	374	1082
r_c (Mpc)	~0.60	~0.25	~0.25
n_0 (gal Mpc^{-3})	~250	~500	~600
N (gal)	1170	235	~2000
$f_{E+dE+S0+dS0}$	0.80	0.87	~0.85
$\langle kT \rangle_X$ (keV)	2.6	1.2	8
Scale (kpc/arcsec)	0.080	0.094	0.468

Jordán et al., 2007; Colless & Dunn 1996; Colless 2006; NED; and references therein

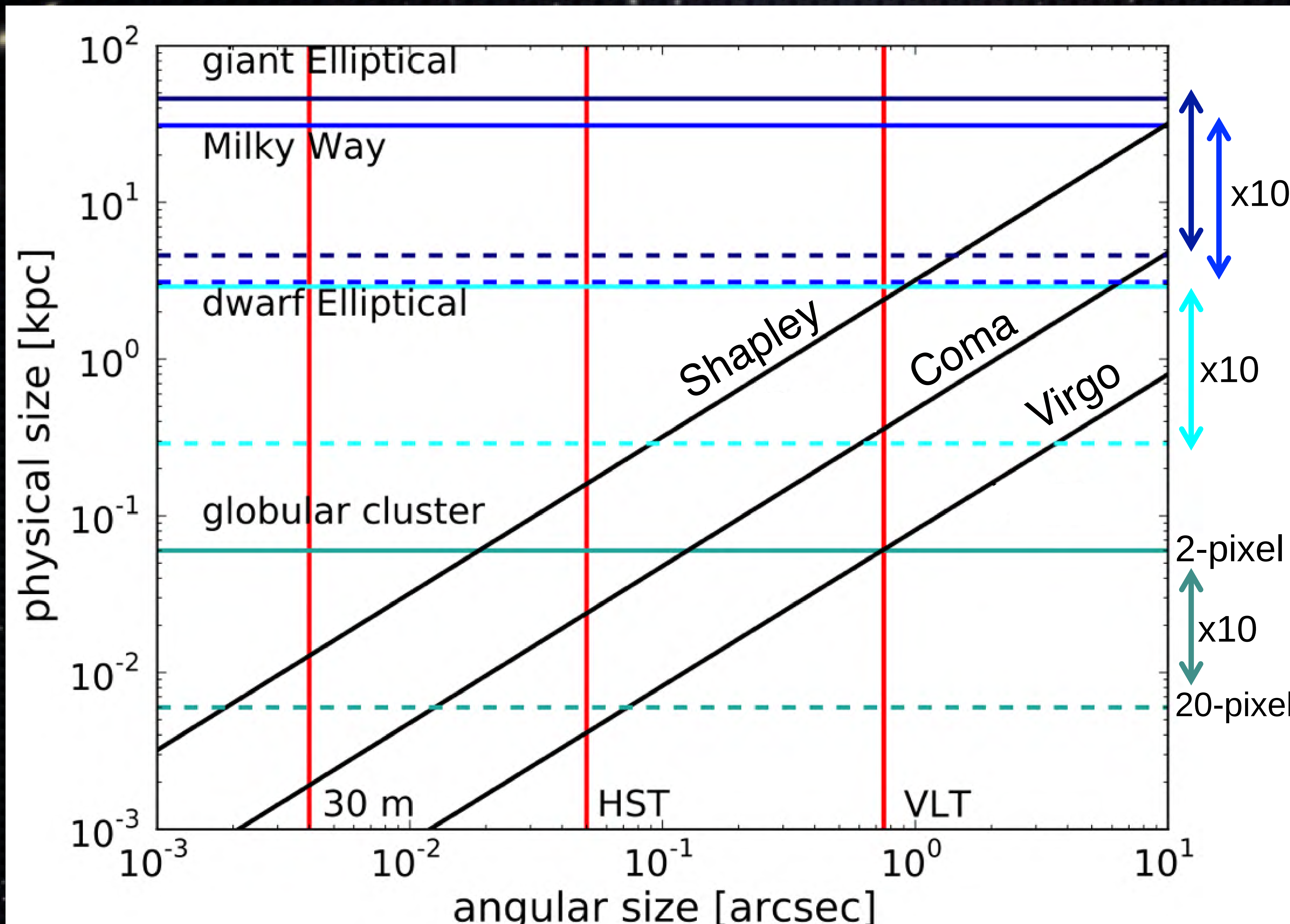
Virgo Cluster




Fornax Galaxy Cluster
NGC 1380
NGC 1382
NGC 1381
NGC 1399
NGC 1379
NGC 1387
NGC 1427A
NGC 1404
NGC 1389
NGC 1365

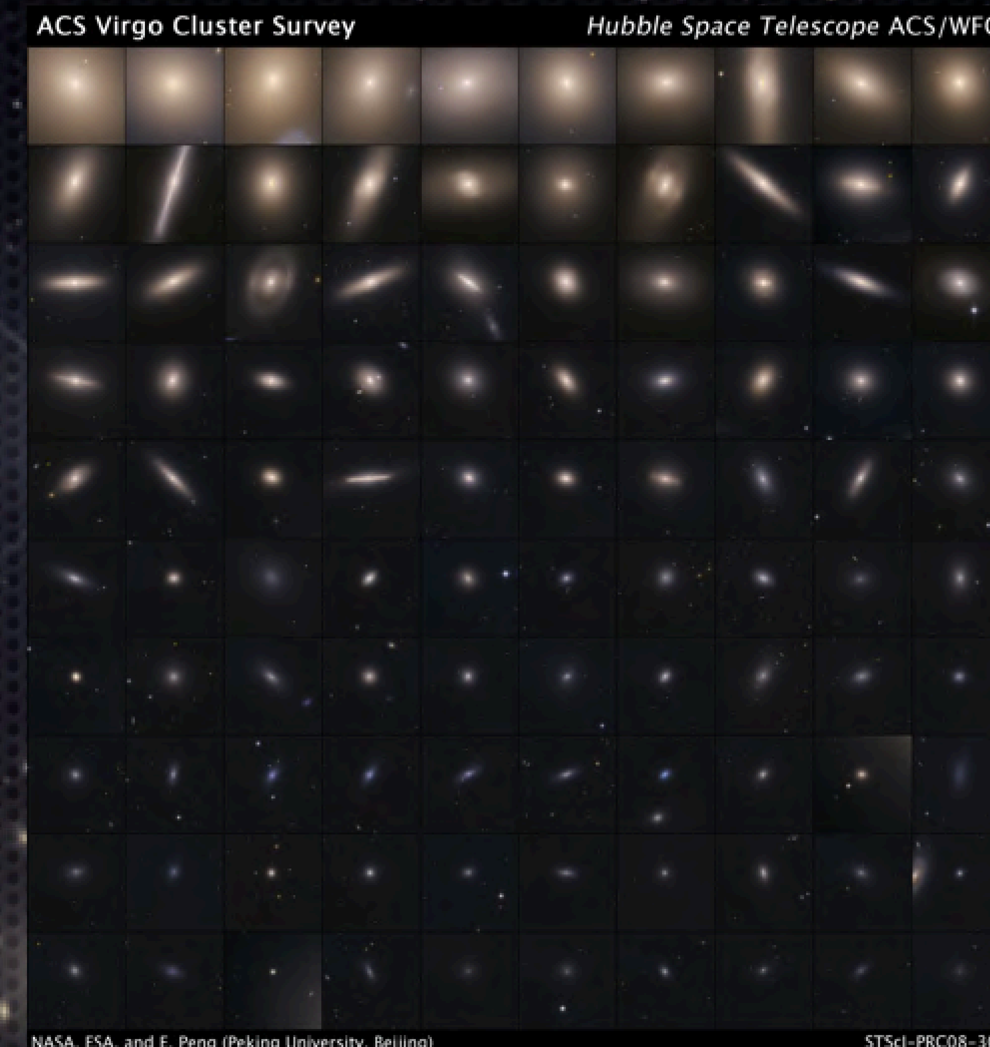

Coma Cluster
NGC 4889
NGC 4874

Resolution in nearby clusters



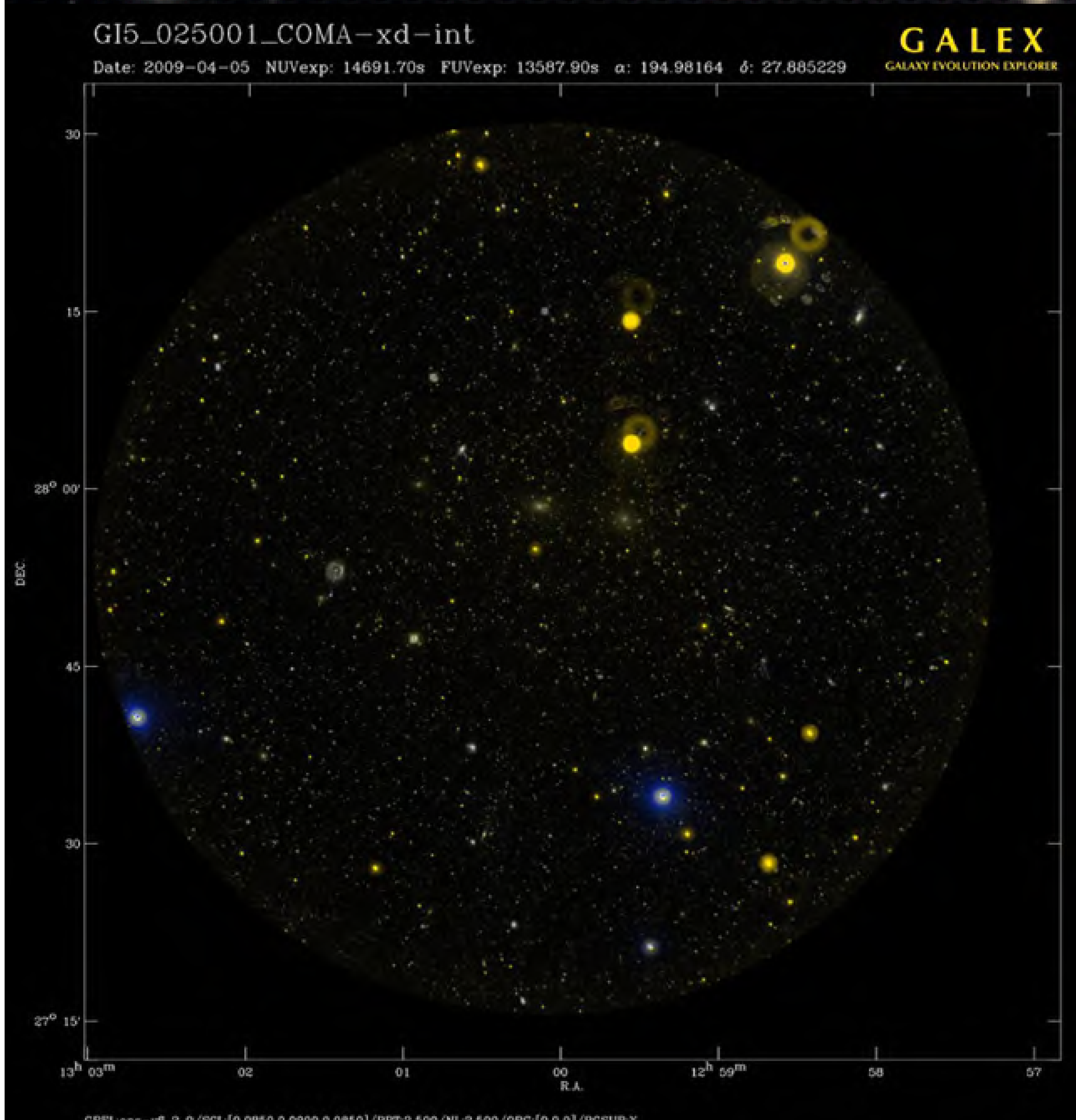
Cluster surveys

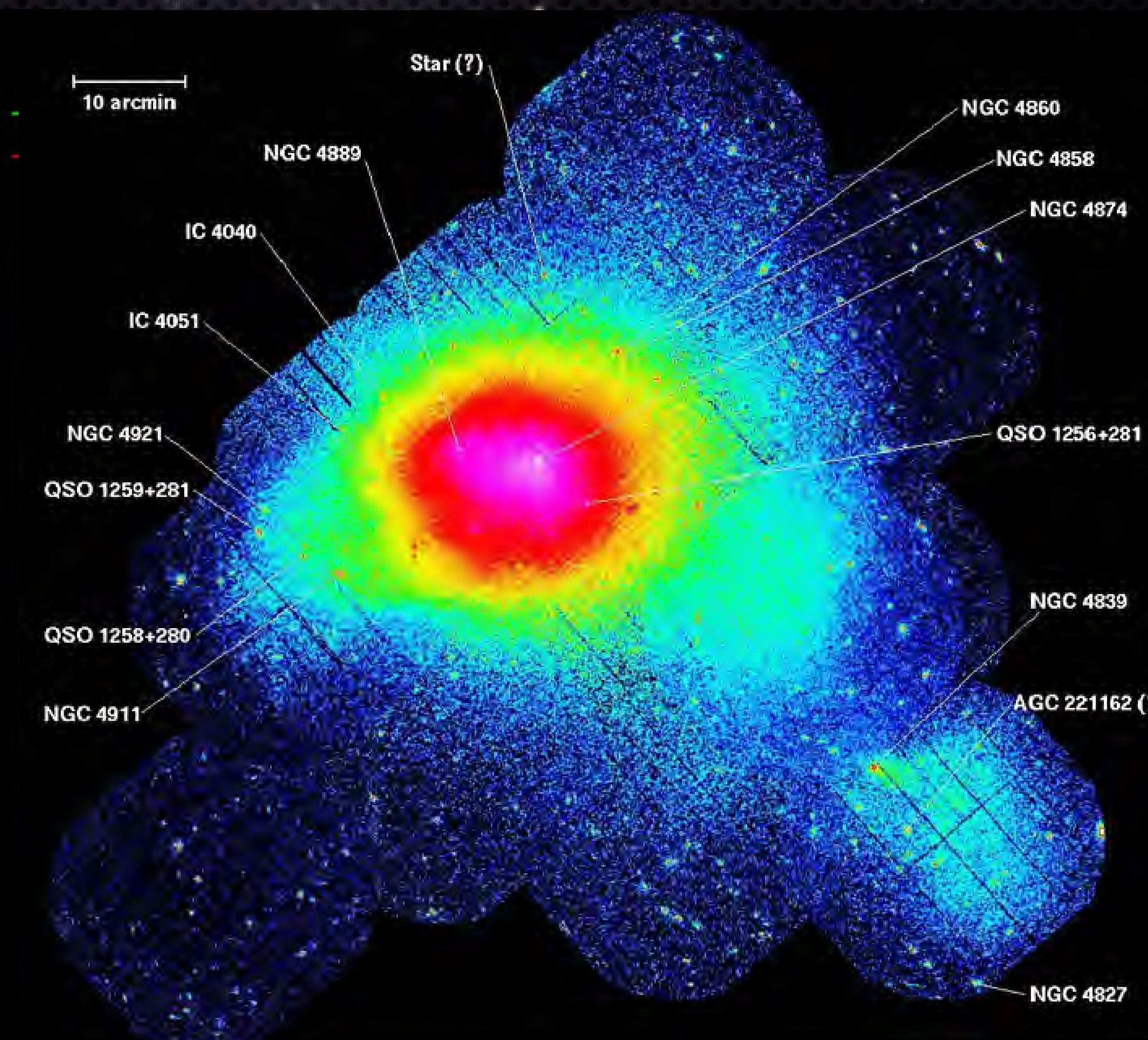
- Virgo
  - HST/ACS Virgo Cluster Survey
  - Next Generation Virgo Survey
  - Herschel Virgo Cluster Survey
  - GALEX UV Virgo Cluster Survey
- Coma
  - HST/ACS Coma Cluster Treasury Survey
  - Subaru Hα Coma Cluster Survey
- Fornax
  - HST/ACS Fornax Cluster Survey
- Spectroscopic surveys (esp. resolved IFU spectroscopy)



Multi-wavelength imaging

- High-resolution HST optical imaging is supplemented by high-quality imaging at other wavelengths





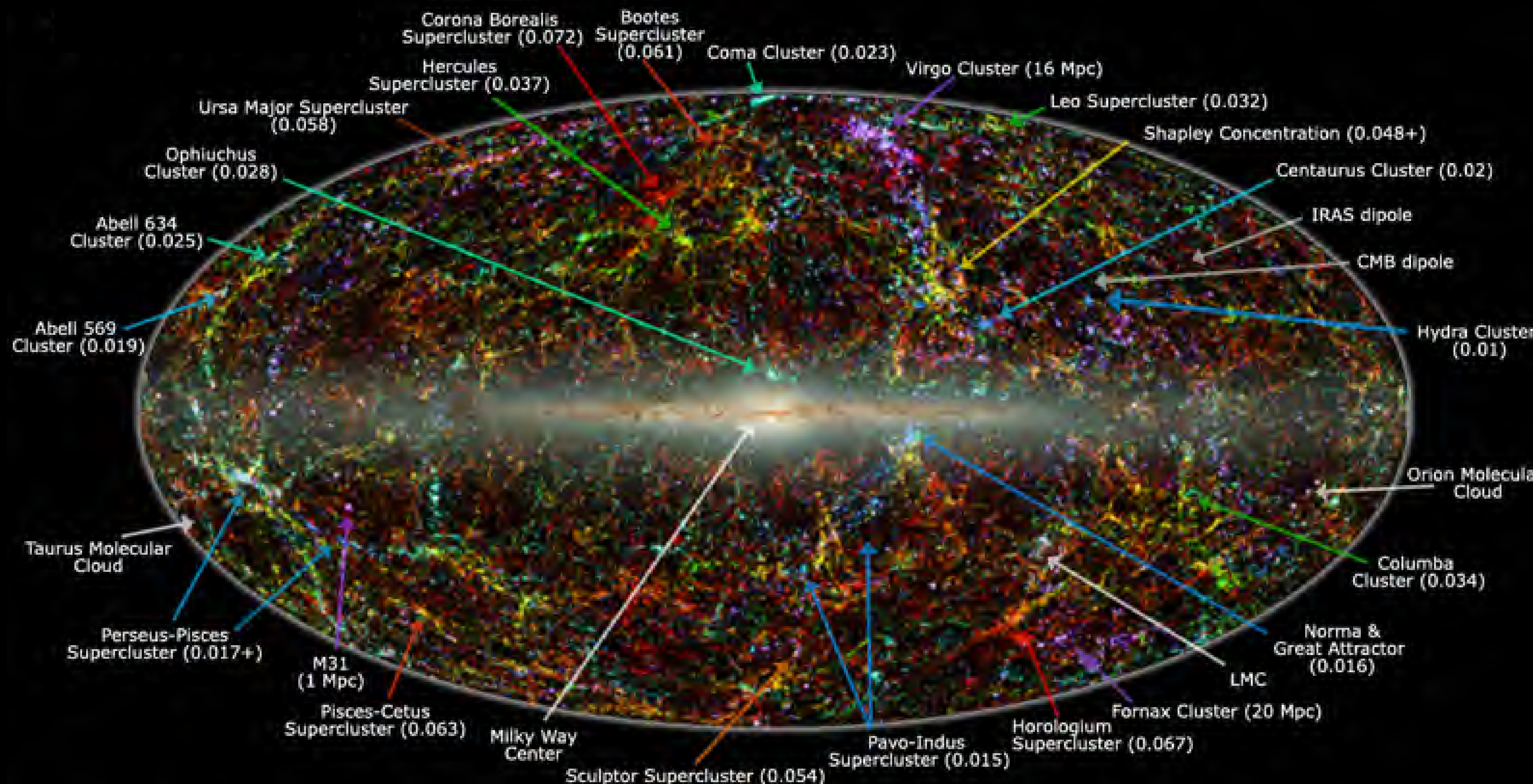
Coma Cluster of galaxies

Image courtesy of U. Briel, MPE Garching, Germany

Other nearby clusters

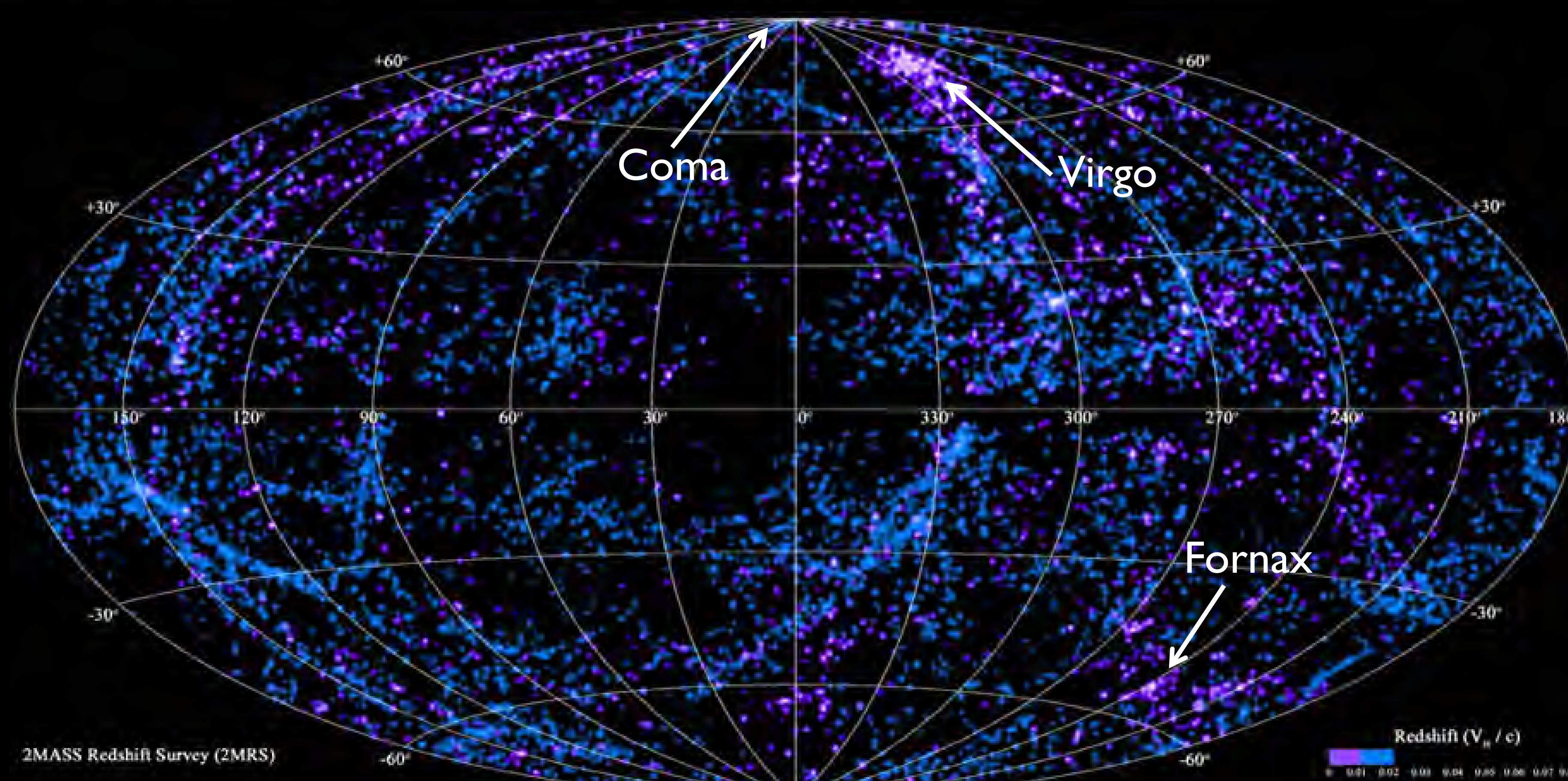
- Although Virgo, Fornax and Coma are the best studied nearby clusters, there are also some other significant but less well-studied nearby clusters…
  - Hydra, Antlia, Hercules, Centaurus…
  - Norma, a massive cluster hidden behind Galactic Plane and part of the Great Attractor
  - The Shapley Supercluster at cz=14000 km/s includes 25 Abell clusters (7 ~ as rich as Coma), and is the most massive large-scale over-density in the $z<0.1$ universe
  - Maps of the galaxy distribution in the local universe show the diversity of environments and the relative sparsity of rich clusters

2MASS Galaxy Catalog



2MASS Redshift Survey

0 < z < 0.02



Huchra et al., 2011, ApJS, in prep. (images by Tom Jarrett; tdc-www.harvard.edu/2mrs/)

Nearby clusters

- In sum, nearby galaxy clusters provide…
  - volumes containing the highest-density, most non-linear large-scale environments in the universe
  - samples of the oldest, most evolved, most diverse, and most (and least) massive galaxies in the universe
- …and all this in an observationally convenient form!
- Consequently, nearby clusters are the targets of choice for studying the formation and evolution of stellar systems.

What are the questions?

- So what are the questions we would like to answer, and how can studying nearby clusters help?

Mass assembly

Star formation history

Morphological evolution

Feedback processes

Growth of black holes

Nature vs nurture

Special stellar systems

- The following is a highly <u>selective</u> and <u>subjective</u> tour of the recent literature addressing some of the above questions

Mass assembly

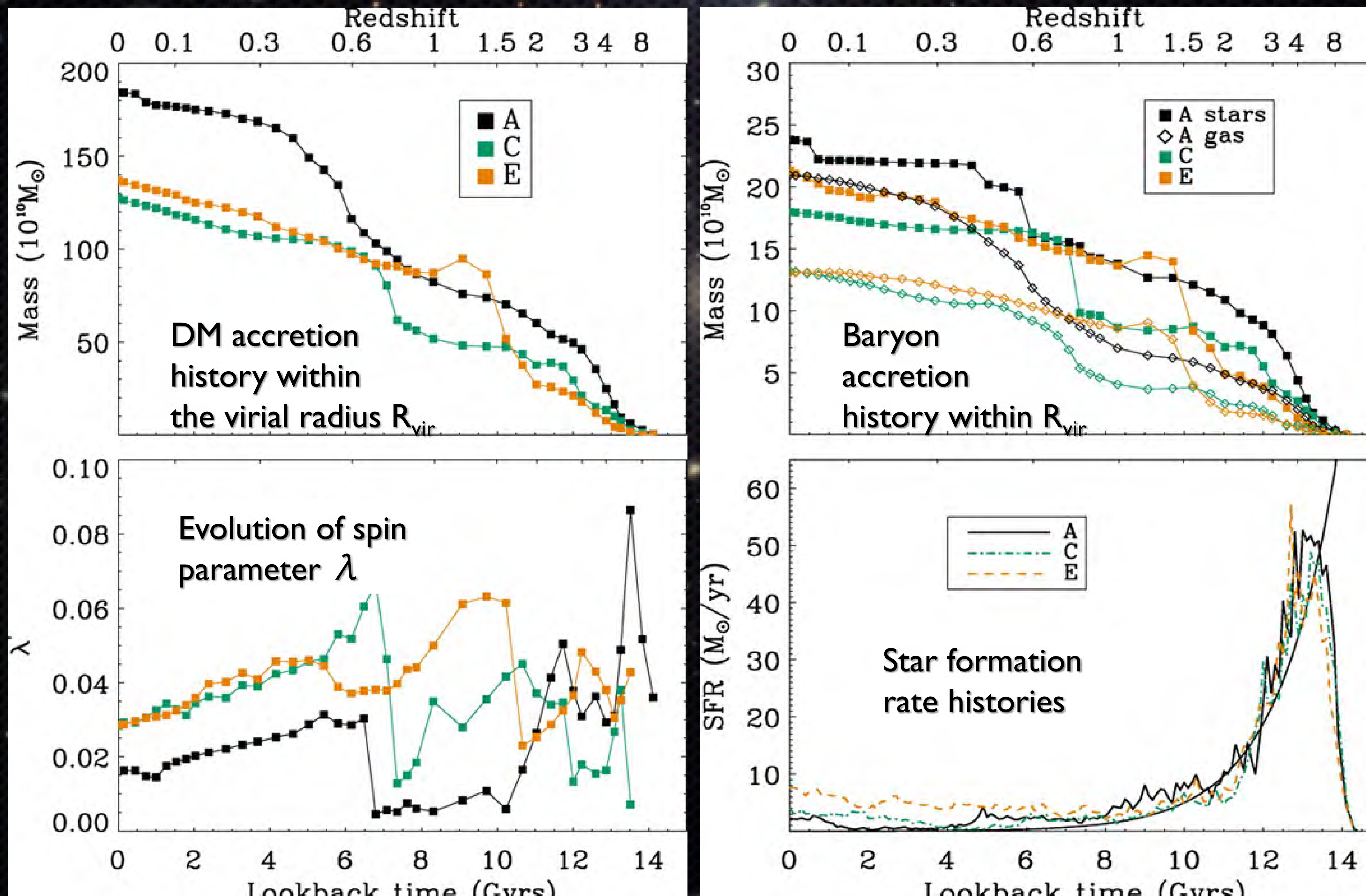
- How are the dark matter and the baryons assembled into the galaxies and clusters we see in the nearby universe?
- To what extent does the nature and timing of mass assembly depend on halo mass, and to what extent does it depend on environment (i.e. local and global density)?
- In what ways do star-formation and black hole formation impact the assembly of dark matter and baryons?
- How well do our curent galaxy formation models predict the observations? Do the models suggest new tests or new observations?

Assembly of DM and baryons

- Possible to form objects fairly similar to early-type galaxies *without* AGN or SNe feedback (see e.g. SPH simulations by Naab et al., 2007, ApJ, 658, 710)

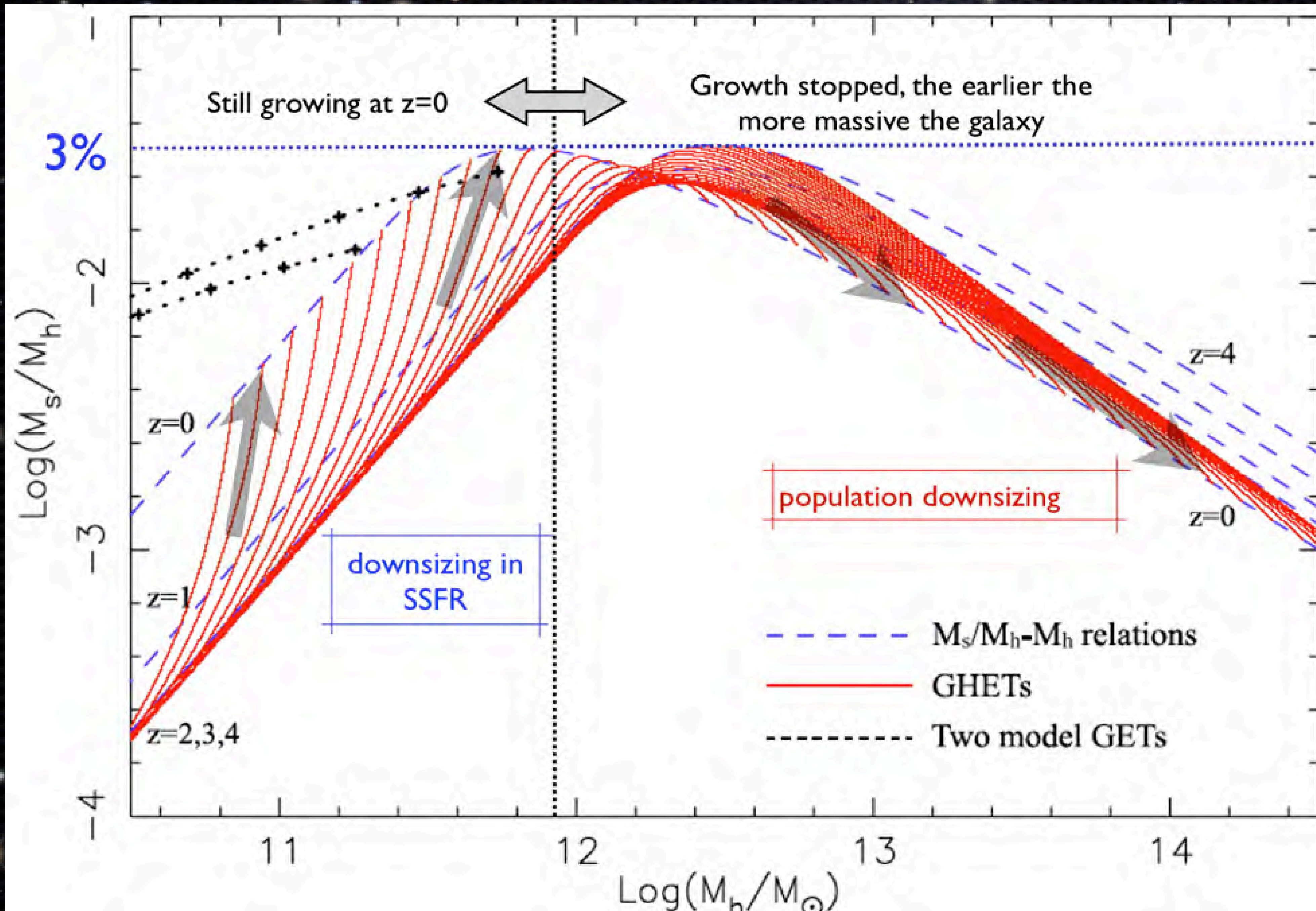
At 2<z<8 assembly is mainly by wet mergers & in-situ star formation (a messy form of dissipative collapse)

At z<2, stellar accretion via minor/major mergers is increasingly important & dominates at z<1



Stellar/DM assembly histories

- Using abundance matching (or CLFs or HODs) to link predicted ΛCDM halo mass functions and observed stellar mass functions, a picture emerges of joint stellar/DM assembly histories behind 'downsizing' phenomenon



Firmani et al. (2010, ApJ, 723, 755; also Avila-Reese & Firmani 2011, astro-ph/1103.4329)

Issues with galaxy assembly

- This picture tells us broadly what happened, but not why. Key questions for which we have only partial answers have been highlighted by, e.g., Avila-Reese & Firmani (2011)
- Why is the stellar mass assembly of low-mass galaxies systematically delayed w.r.t. the assembly of their halos? It is not clear if this can be explained by SNe-driven outflows
- Why is it that more massive galaxies assemble most of their stellar mass earlier? Natural enough in hierarchical assembly, but is AGN feedback efficient enough to quench their SF?
- Why do more massive galaxies transit earlier from active to passive stellar growth regimes? What causes SF quenching regime to smoothly evolve from high- to low-mass galaxies?

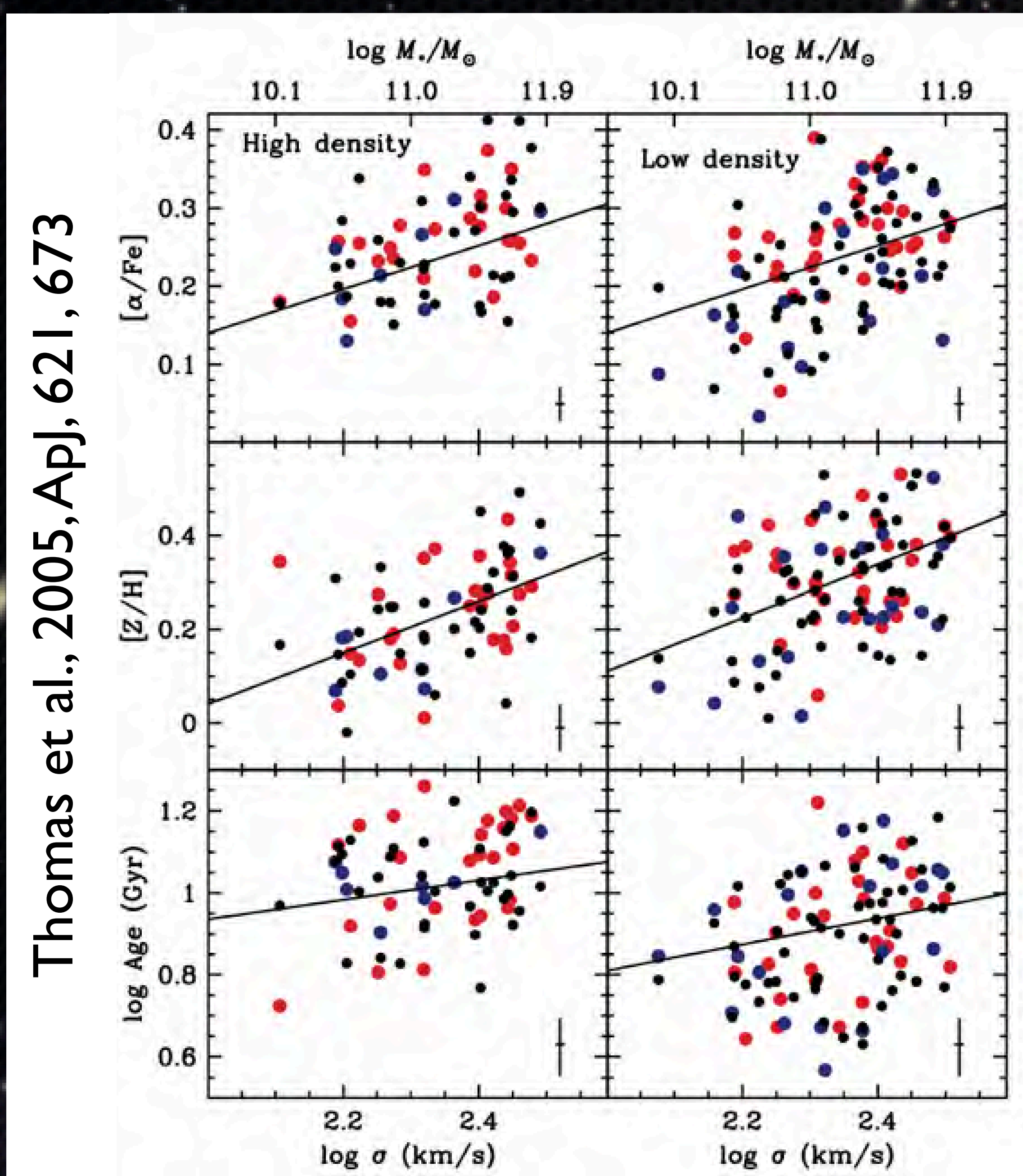
Star formation history

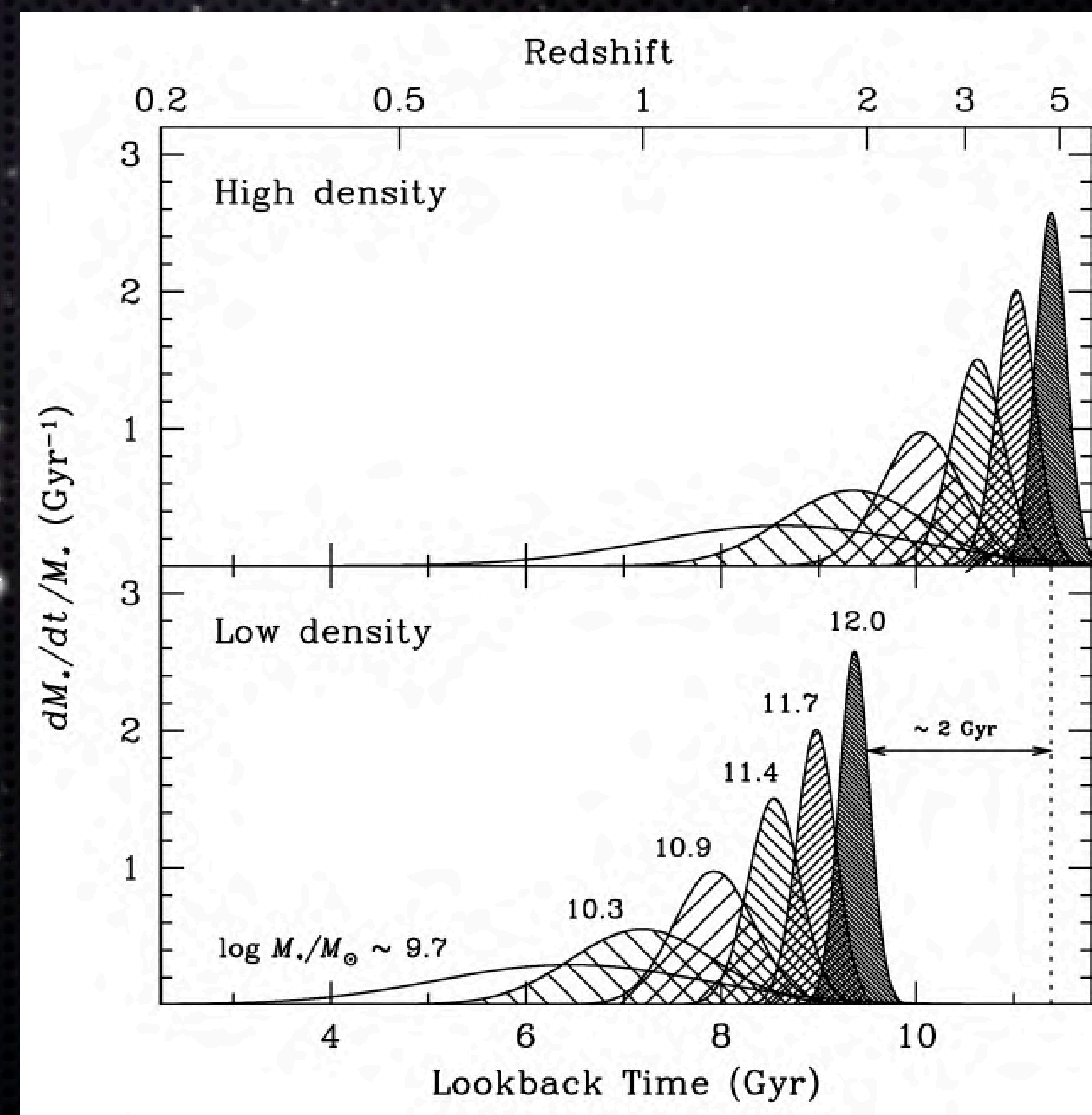
- Within the broad outline of the downsizing model for stellar mass assembly, how varied are the detailed star formation histories of old stellar systems?
- How do the typical star formation histories of massive and dwarf galaxies in clusters differ?
- How much of the star formation history is determined by mass and how much by environment? And how do we disentangle these effects of ‘nature’ and ‘nurture’?
- How does the process of falling into a cluster affect a galaxy’s star formation history? Does it matter exactly *how* a galaxy ‘falls into a cluster’ – i.e. how dependent on the details of cluster mass assembly is star formation?

Star formation histories

- SFHs for early-type galaxies, as inferred from spectral line indices, show not only the downsizing mass sequence but also a lag between high- and low-density environments

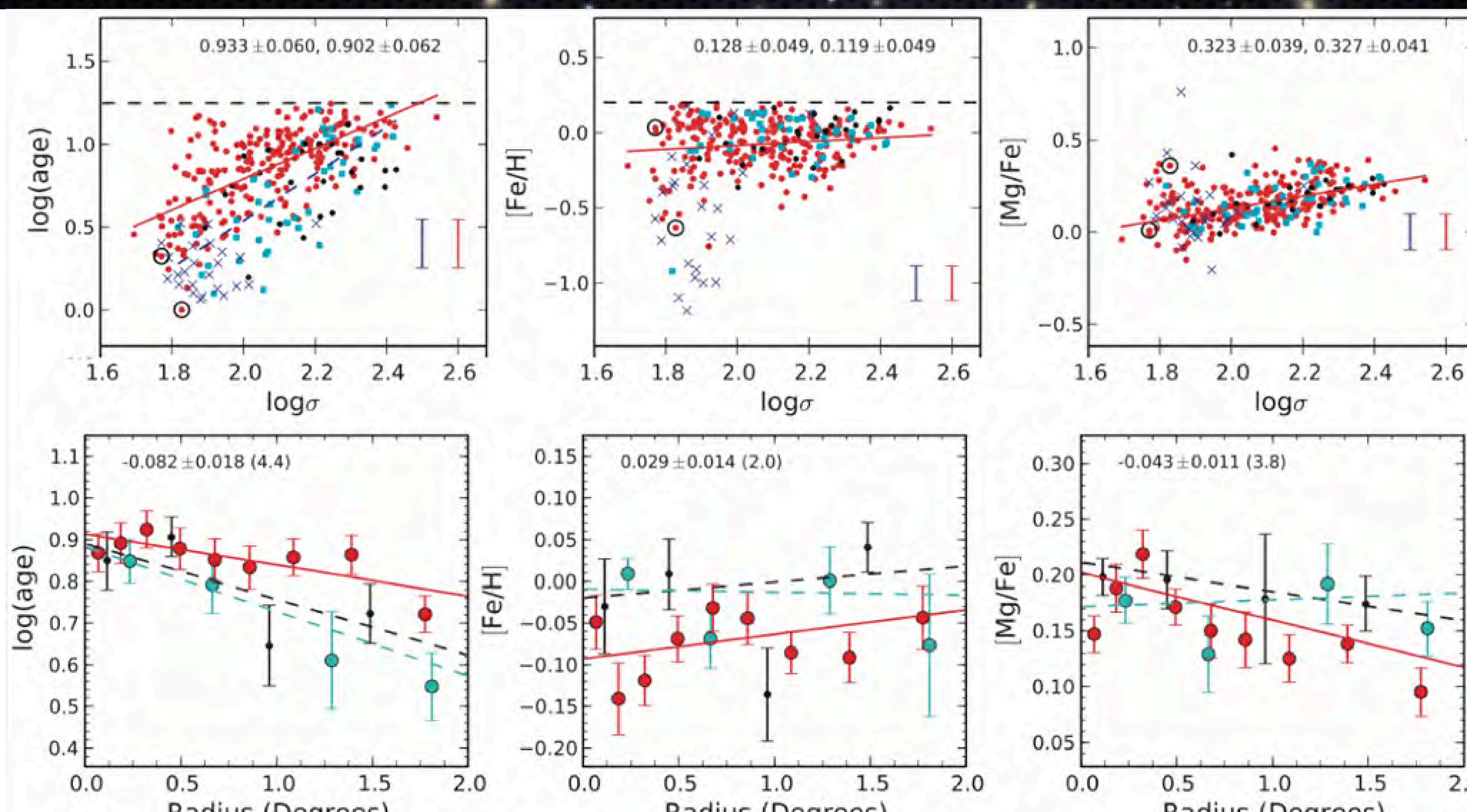
Thomas et al., 2005, ApJ, 621, 673





Stellar population trends

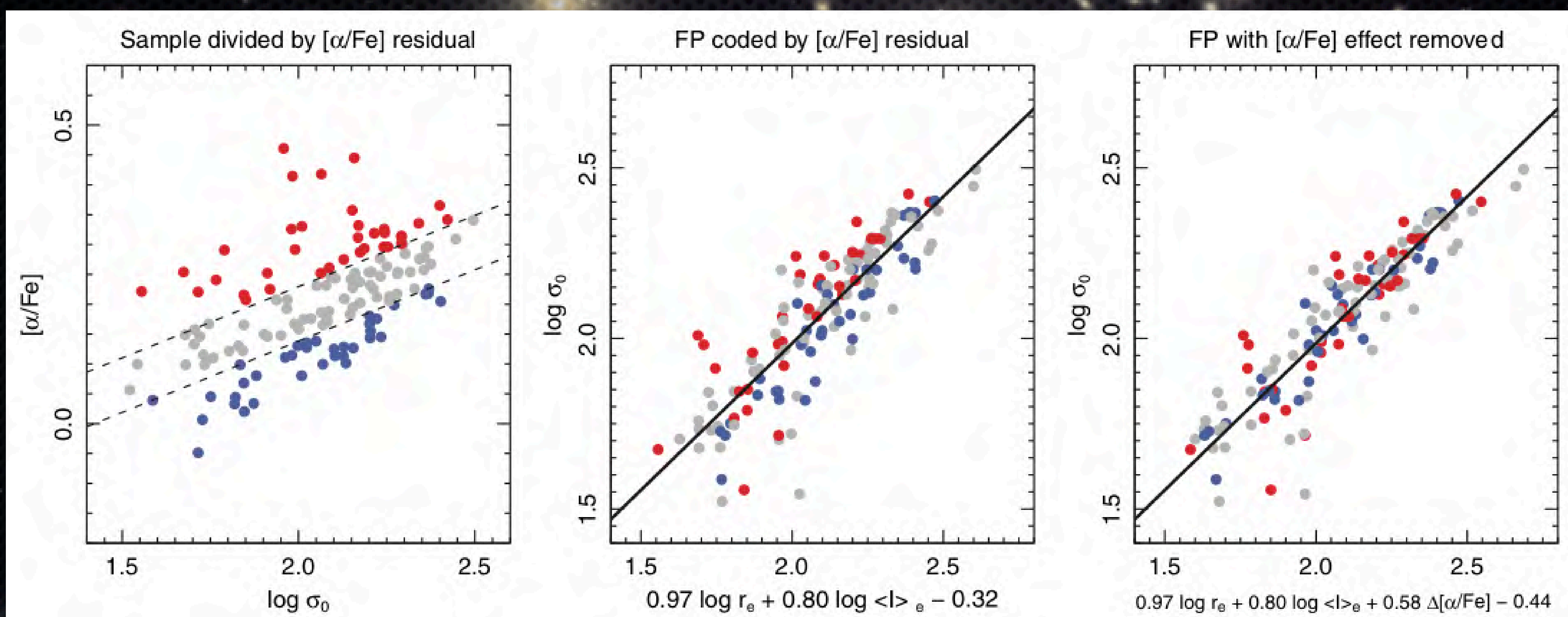
- Single Stellar Population (SSP) models fitted to absorption line indices yield ages, metallicities, [α/Fe] and other stellar population measures
- Both nature and nurture effects are evident – e.g. Price et al. (2011) look at 356 Coma galaxies and find stellar population trends with both velocity dispersion (galaxy mass) and cluster radius (environment)



Price et al. (2011, MNRAS, 411, 2558)

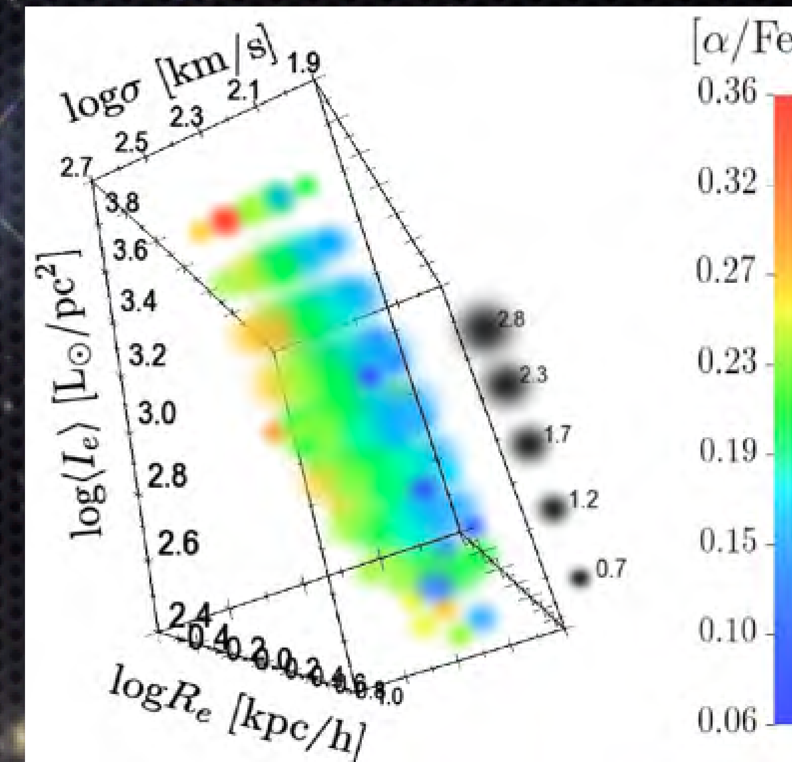
Stellar pop. trends & the FP - I

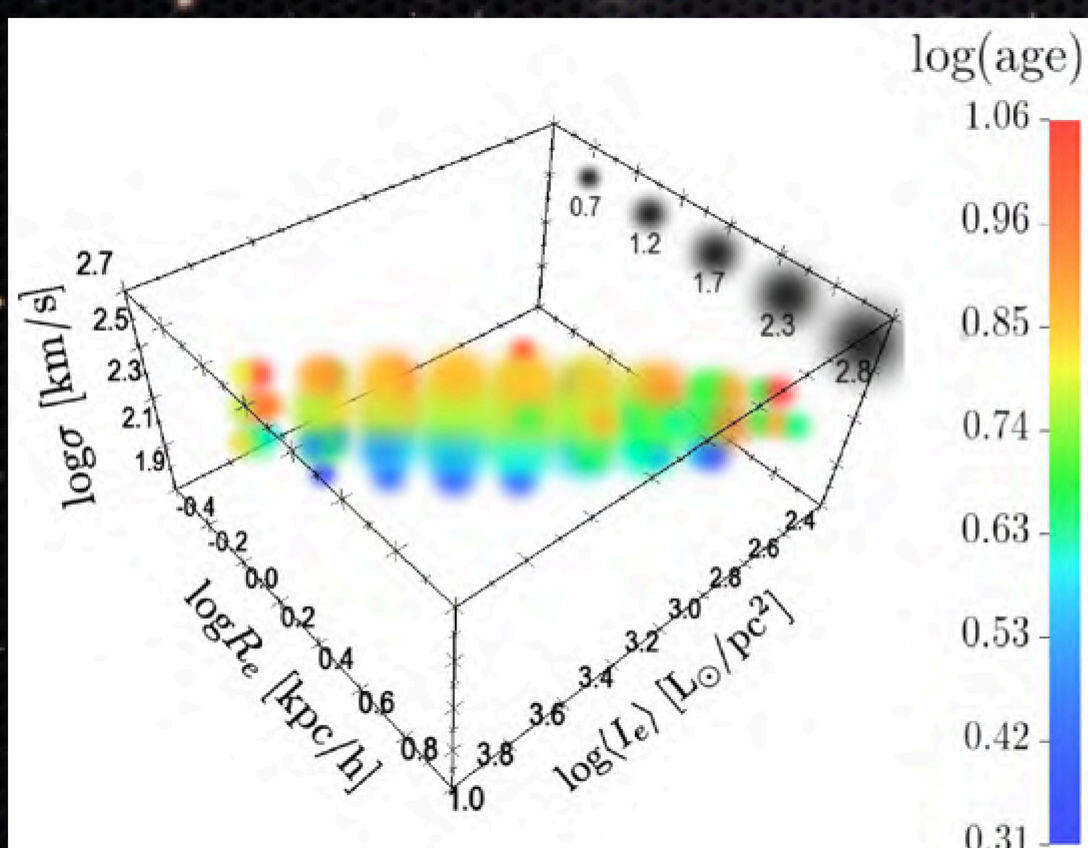
- Gargiulo et al. (2009, MNRAS, 397, 75) examined 141 early-type galaxies in the Shapley supercluster and find that the scatter about the Fundamental Plane (FP) correlates with both age and [α/Fe]
- The total (intrinsic) FP scatter can be reduced by 30% (50%) by taking into account residuals from the mean [α/Fe] vs σ relation

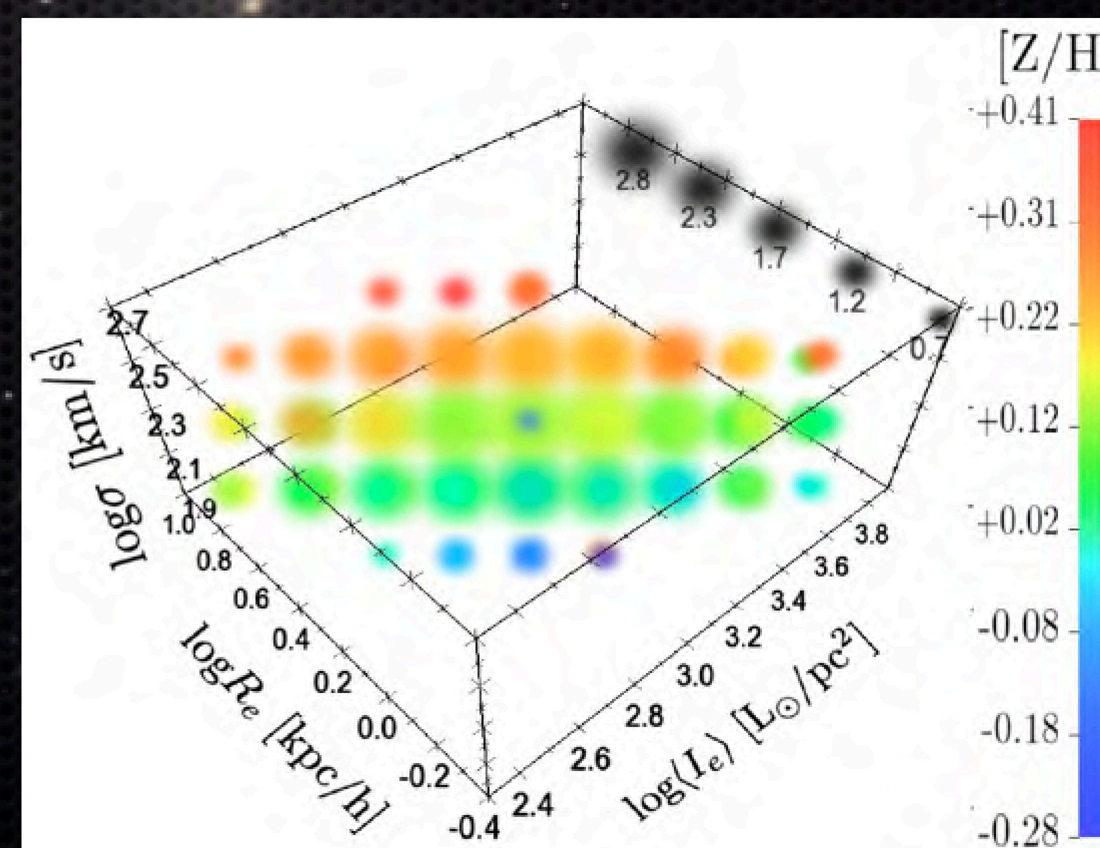


Stellar pop. trends & the FP - 2

- Springob et al. (2011, MNRAS, submitted) study 7000 nearby early-type galaxies in the 6dF Galaxy Survey and find significant trends both *through* and *across* the FP for age, metallicity and [α/Fe]
- Age (and to a lesser extent [α/Fe]) could be used to reduce FP scatter – but this is limited by the large errors in age for individual galaxies





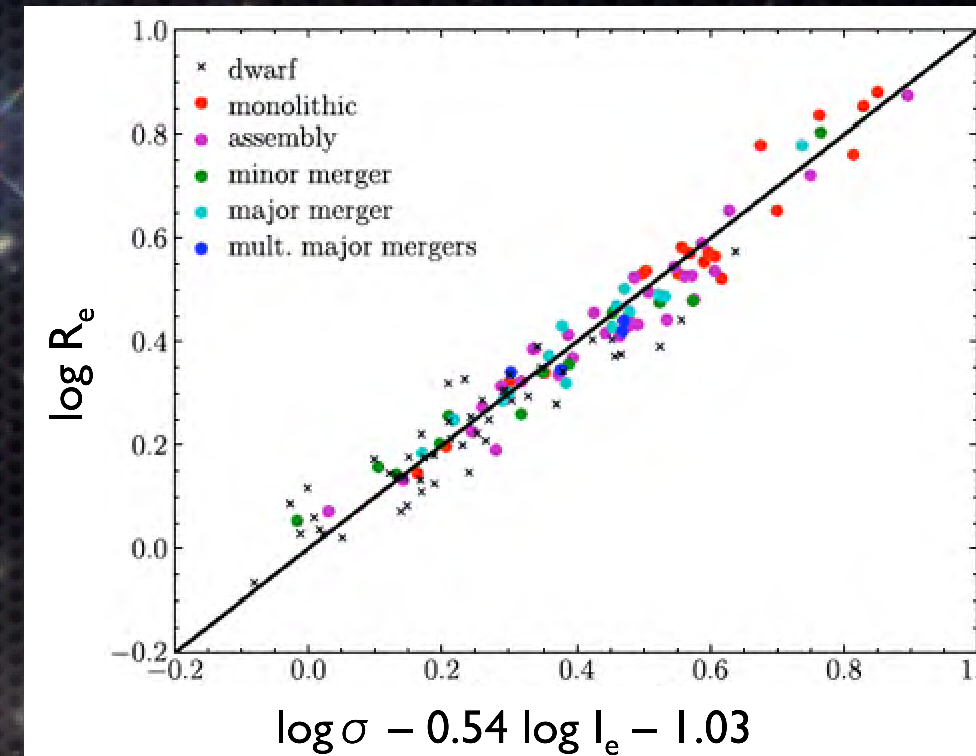


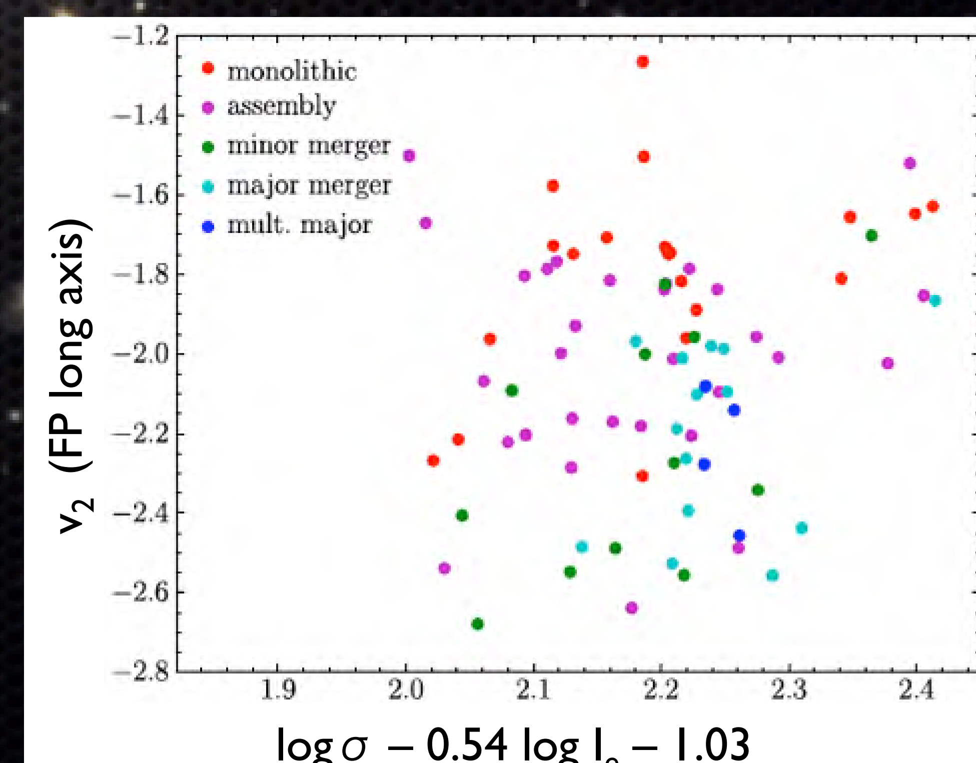
Mergers and the FP

- Springob et al. also find that no stellar population parameter varies along the long (v_2) axis of the FP; this axis is approximately luminosity density

FP parameter	$\nabla_{\hat{\mathcal{F}}} A$	ϵ	χ	$\nabla_{\hat{\mathcal{F}}}[Fe/H]$	ϵ	χ	$\nabla_{\hat{\mathcal{F}}}[\alpha/Fe]$	ϵ	χ
v_1	**-1.47**	**0.12**	**12.25**	**0.37**	**0.10**	**3.70**	**-0.24**	**0.05**	**4.80**
v_2	-0.04	0.04	1.00	0.05	0.02	2.50	-0.01	0.01	1.00
v_3	0.08	0.09	0.89	**0.26**	**0.04**	**6.50**	**0.16**	**0.02**	**8.00**
r	**-0.70**	**0.08**	**8.75**	**0.37**	**0.06**	**6.17**	-0.03	0.03	1.00
s	**1.16**	**0.11**	**10.55**	-0.11	0.08	1.38	**0.29**	**0.04**	**7.25**
i	**-0.57**	**0.08**	**7.13**	**0.25**	**0.05**	**5.00**	-0.02	0.03	0.67
m	**0.32**	**0.05**	**6.92**	0.03	0.03	0.88	**0.11**	**0.02**	**6.44**
l	**-0.39**	**0.04**	**11.01**	**0.20**	**0.03**	**7.62**	-0.02	0.01	1.19
$m-l$	**0.60**	**0.04**	**14.51**	**-0.14**	**0.03**	**4.72**	**0.11**	**0.02**	**6.96**

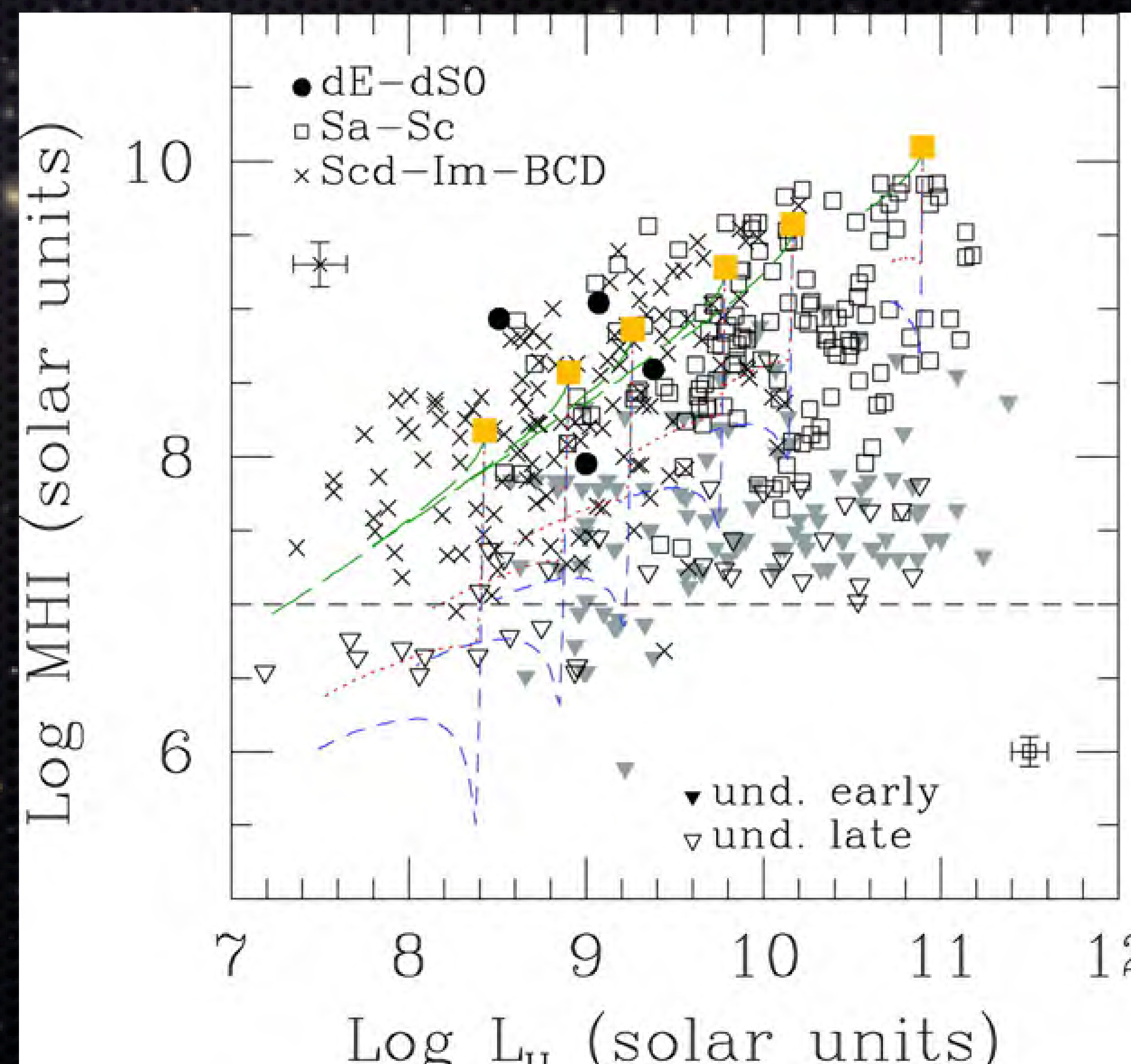
- Springob et al. suggest that the extent of the FP in this axis is driven by merger history, as suggested by the simulations of Kobayashi (2005, MNRAS, 361, 1216)





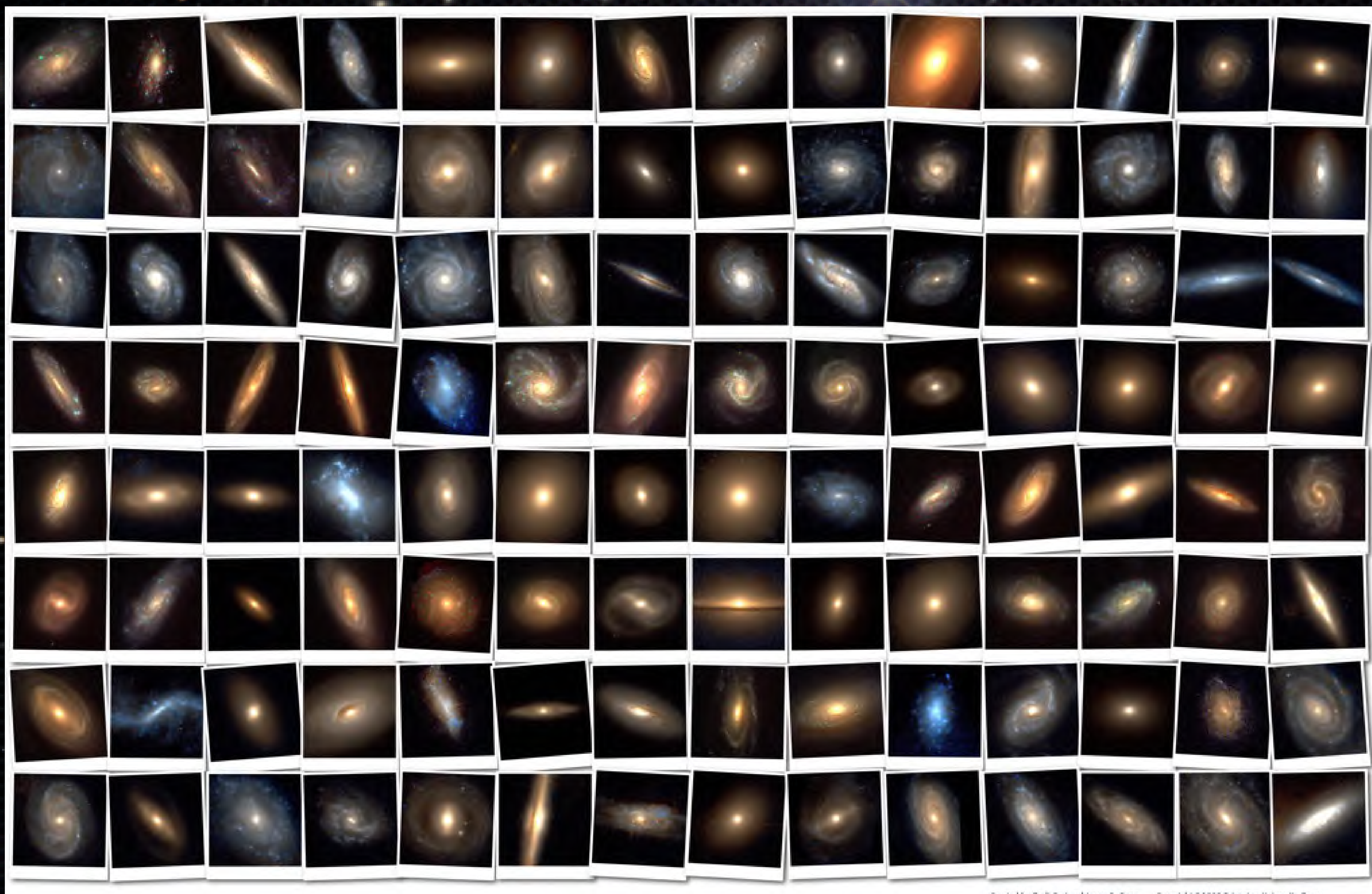
Dwarf galaxy evolution

- Were the quiescent dEs that dominate the faint end of the Virgo galaxy luminosity function initially star-forming systems that were quenched – perhaps by gas removal via ram pressure stripping?
- Boselli et al. (2008, ApJ, 674, 742) argue that star-forming dwarfs entering Virgo lose almost all atomic gas in repeated ram-pressure stripping events, and star-formation is quenched rapidly on timescales ≤150 Myr
- As a consequence, these dwarf galaxies soon become red, quiescent, gas metal-rich objects with properties similar to dEs



Galaxy morphologies

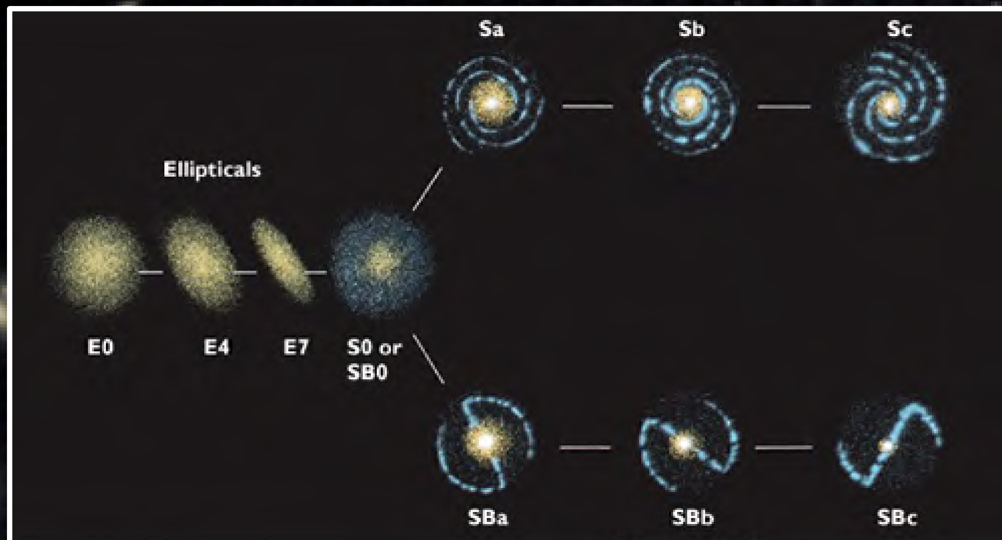
➠ How do we explain the rich diversity of galaxy morphologies?

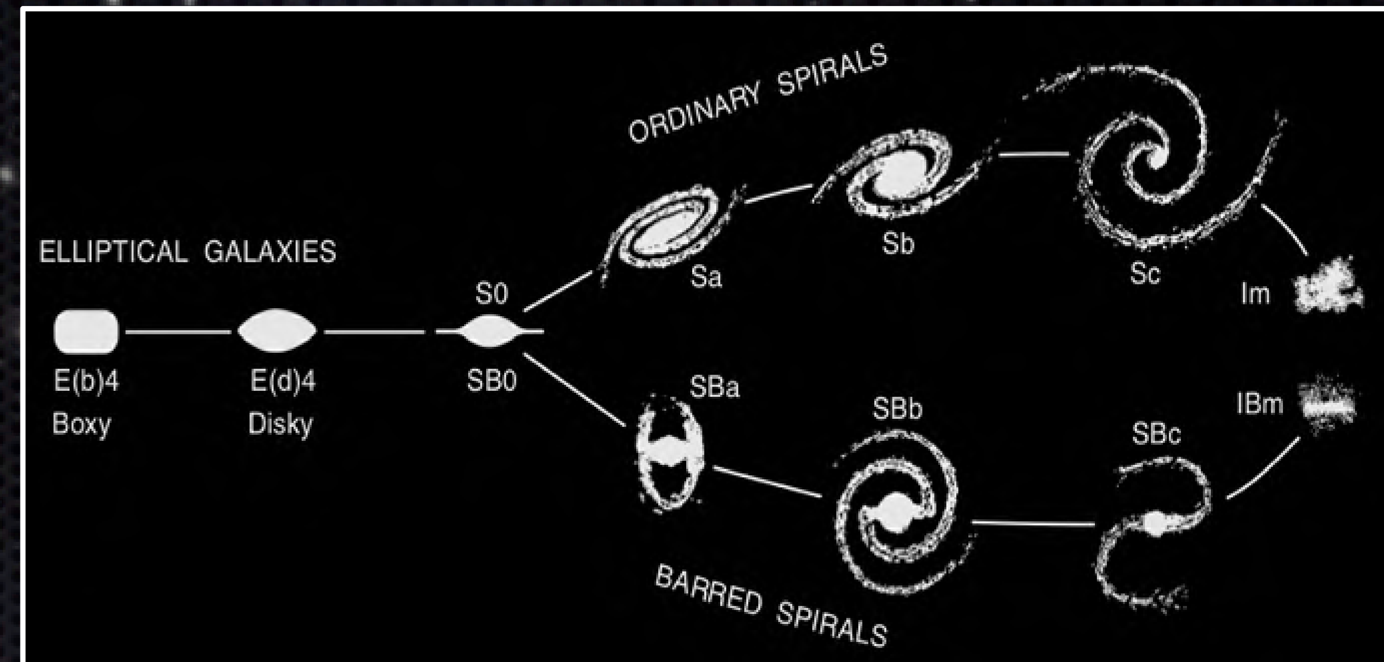


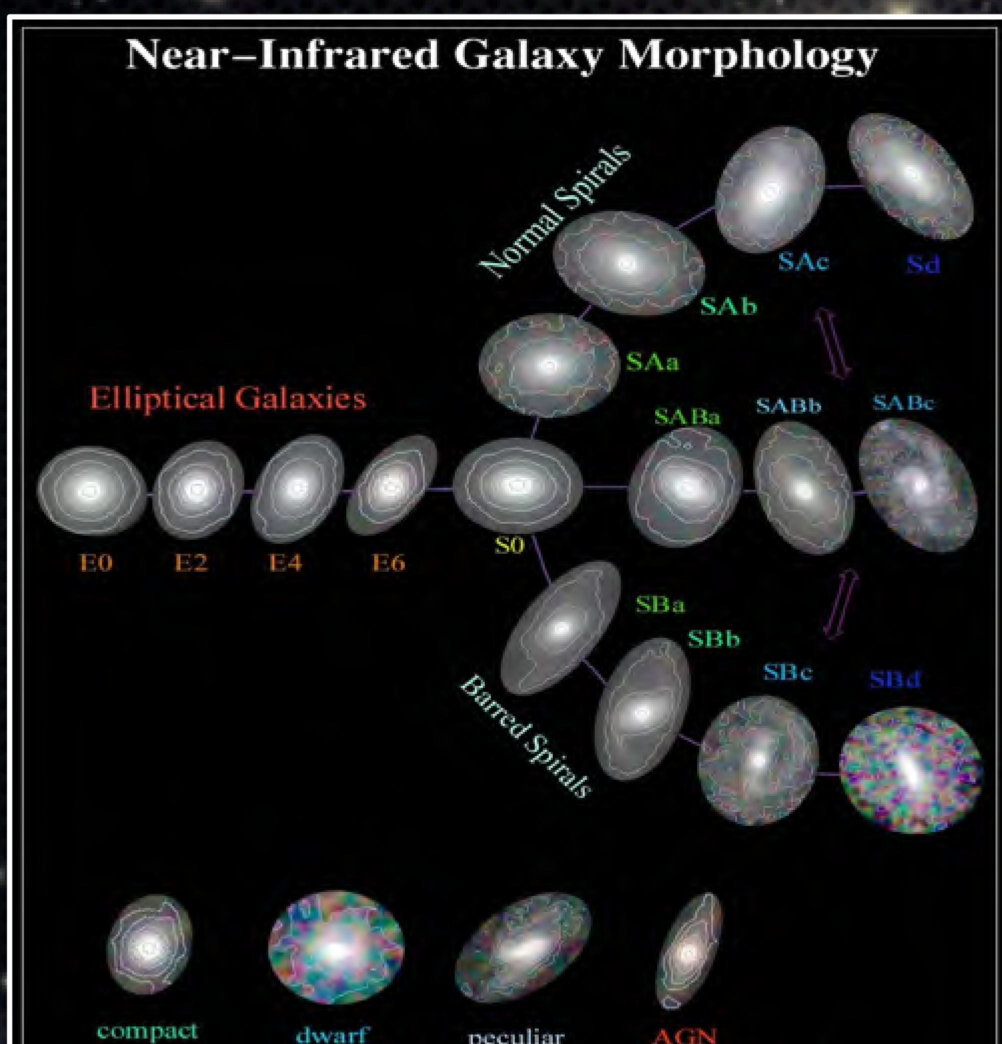
Morphological evolution

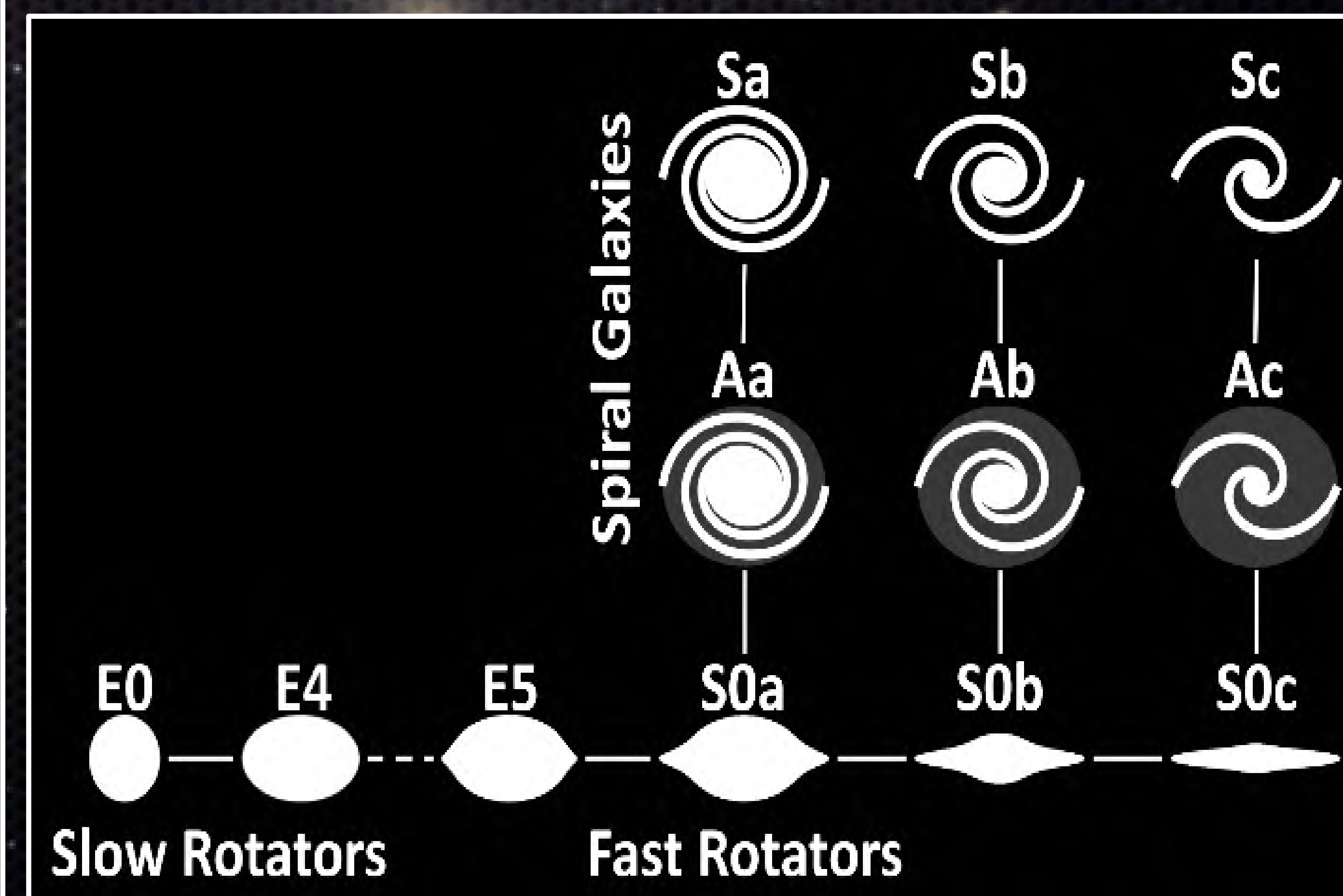
- What are the processes causing morphological evolution?
- Which morphological transformations are secular and which are environmental?
- Which processes are more important, and under what circumstances, or at what epochs?
- What is the relative importance of local versus global environment on morphological evolution?
- How well do current galaxy formation models account for the morphologies of galaxies in clusters, the morphology-density relation, and the correlations of morphology with other galaxy properties?

Morphological schemata



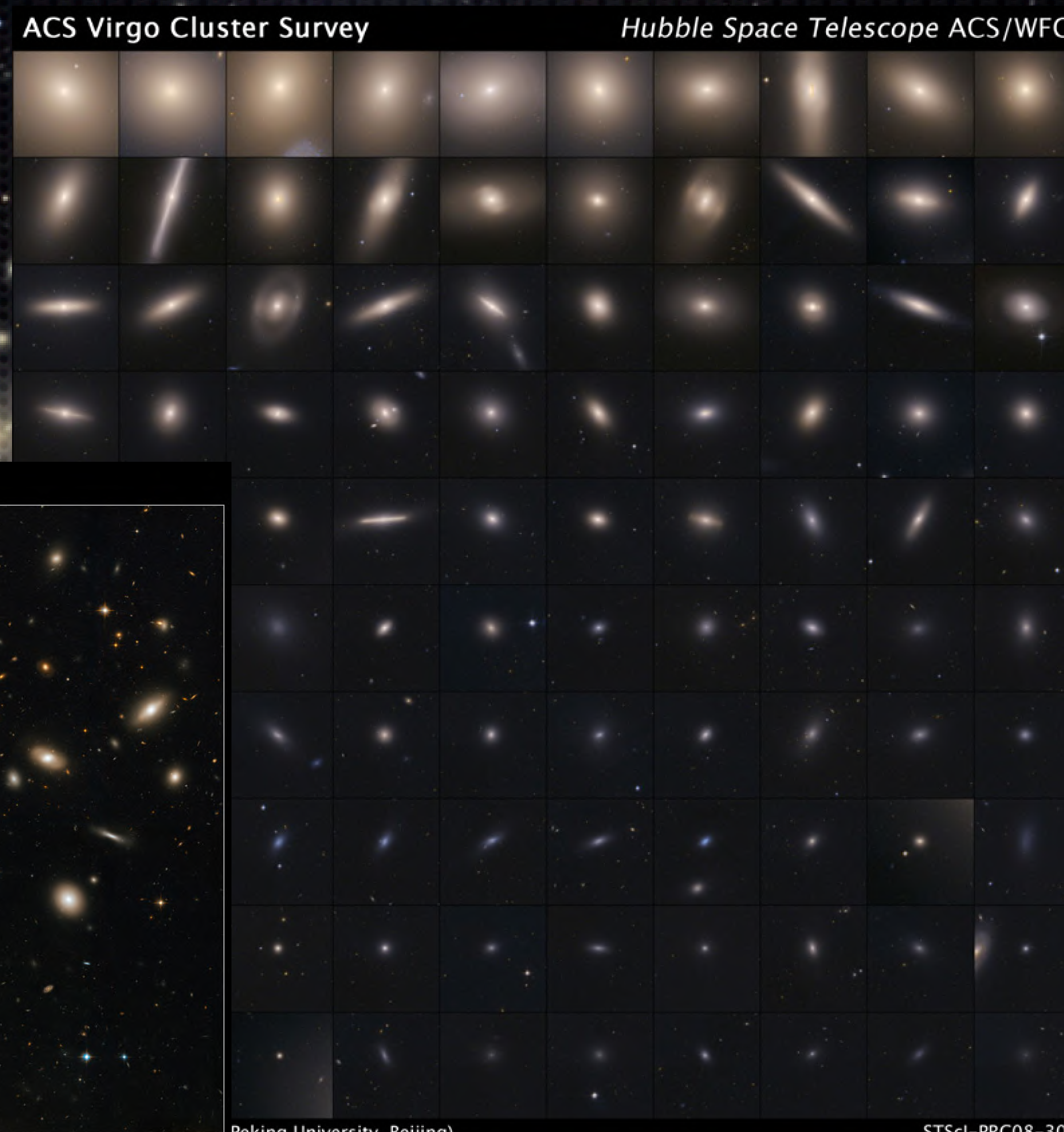






ACS Virgo/Fornax/Coma Surveys

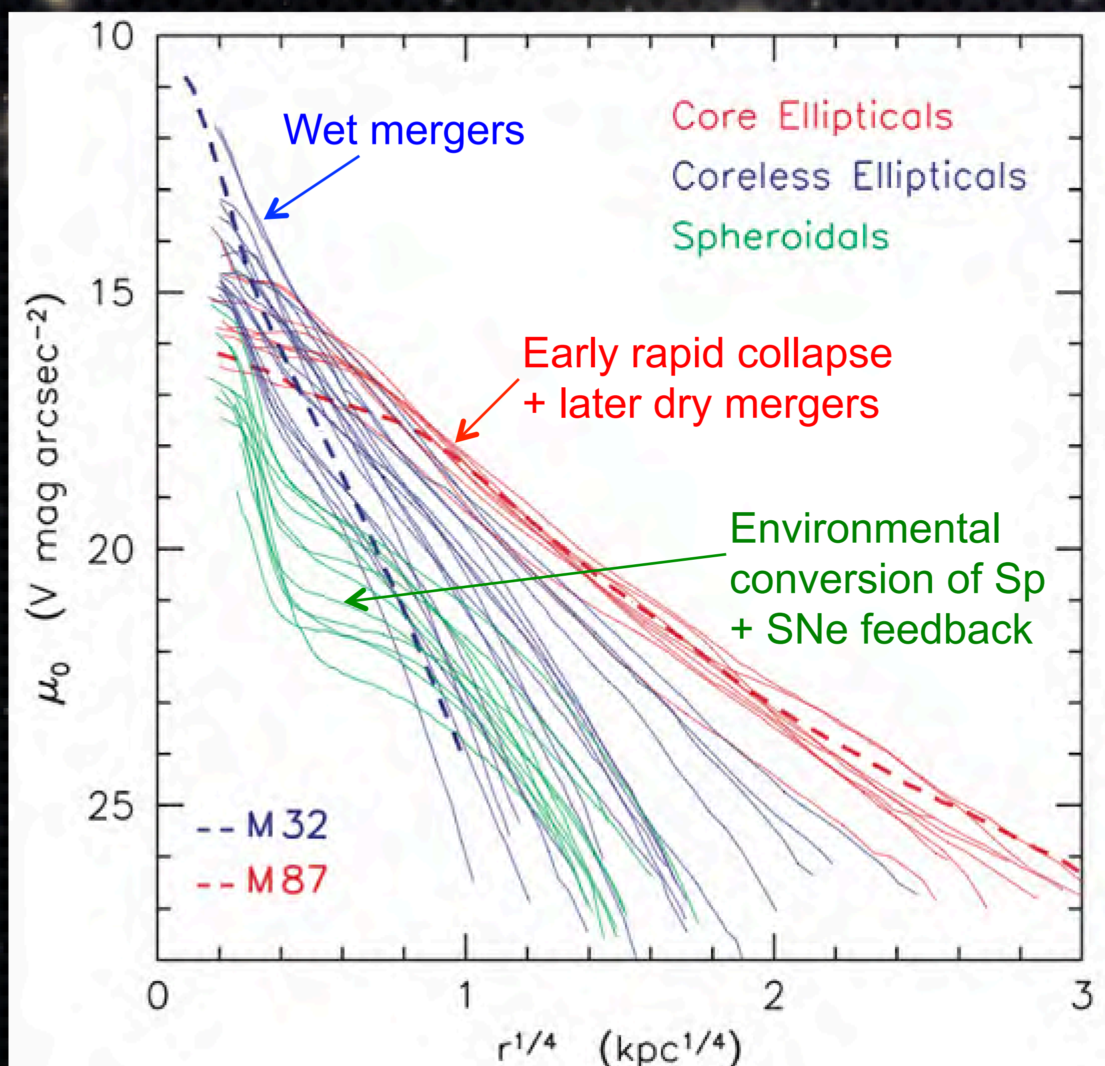
- The HST/ACS surveys of Virgo, Fornax and Coma provide high-quality, high-resolution imaging
- But this has not yet resolved all these morphology issues

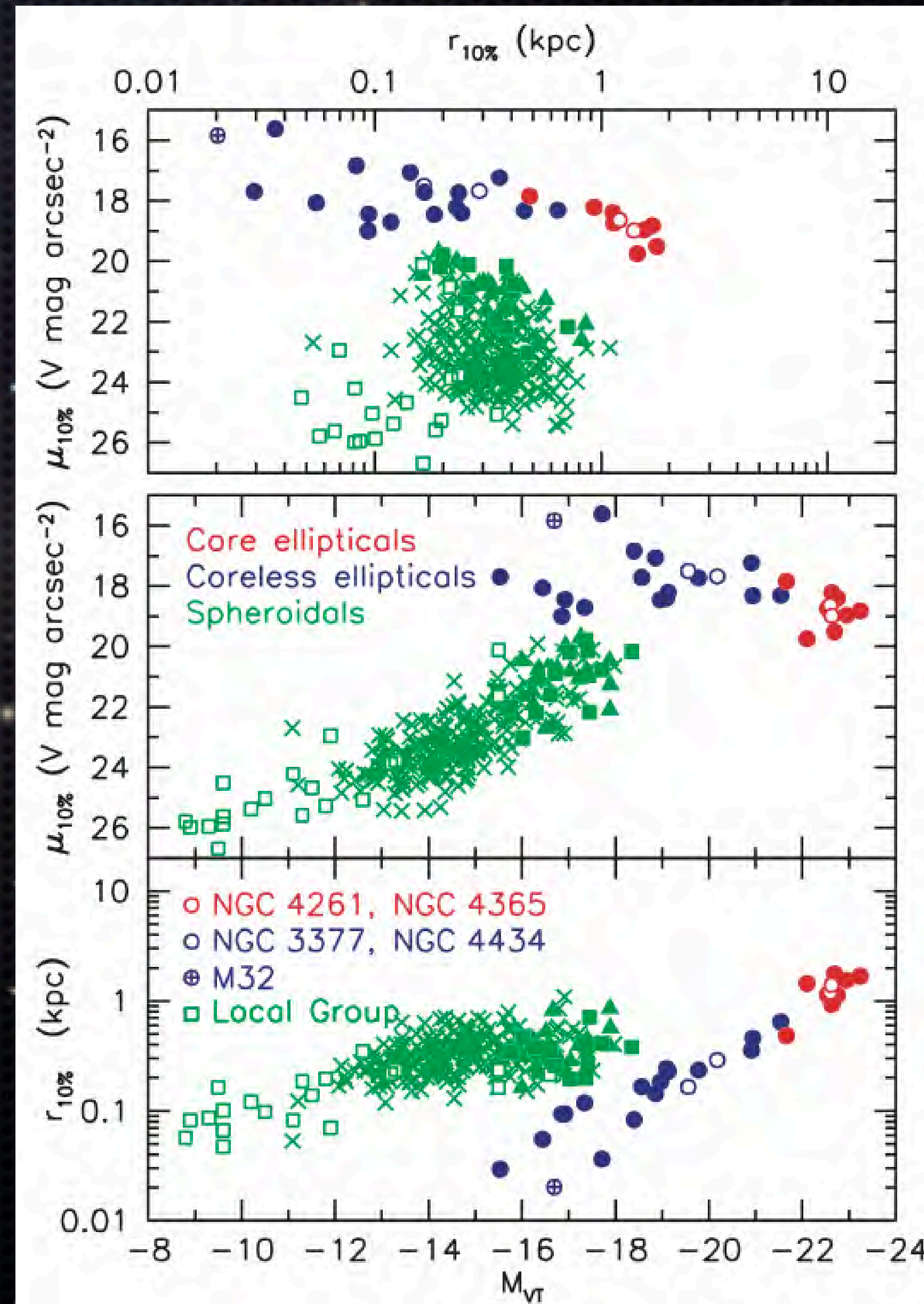


E-E-Sph differences?

Kormendy et al. (2009, ApJS, 182, 216) argue for essential differences in the structure of Sph (a.k.a. dE) & E galaxies, and between intermediate & bright E's, reflecting different formation histories

HST + ground-based imaging of Virgo galaxies

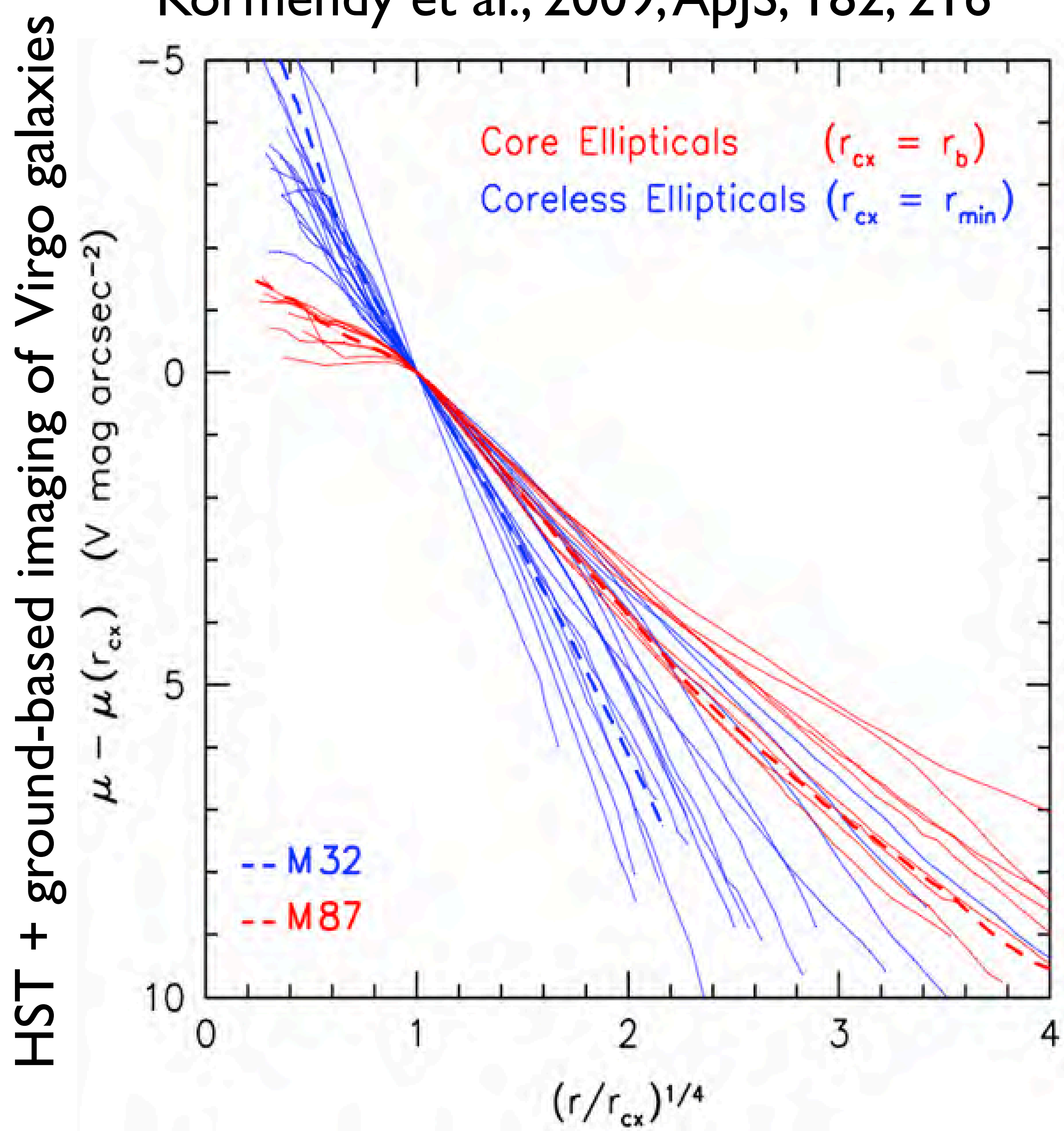




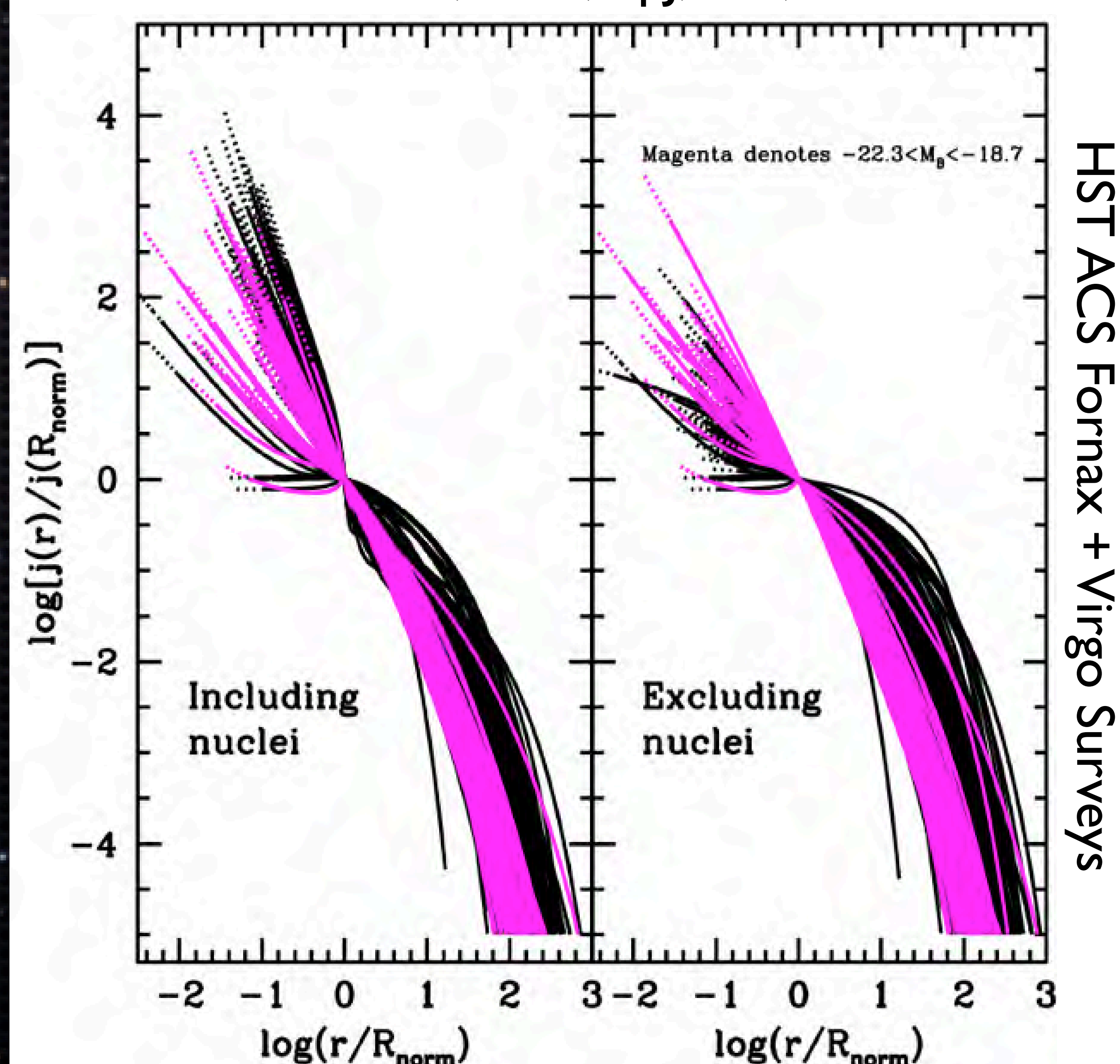
Dichotomy or continuum?

- Ferrarese, Côté and co-workers dispute the claim there is a dichotomy between E's with central cores and excesses

Kormendy et al., 2009, ApJS, 182, 216

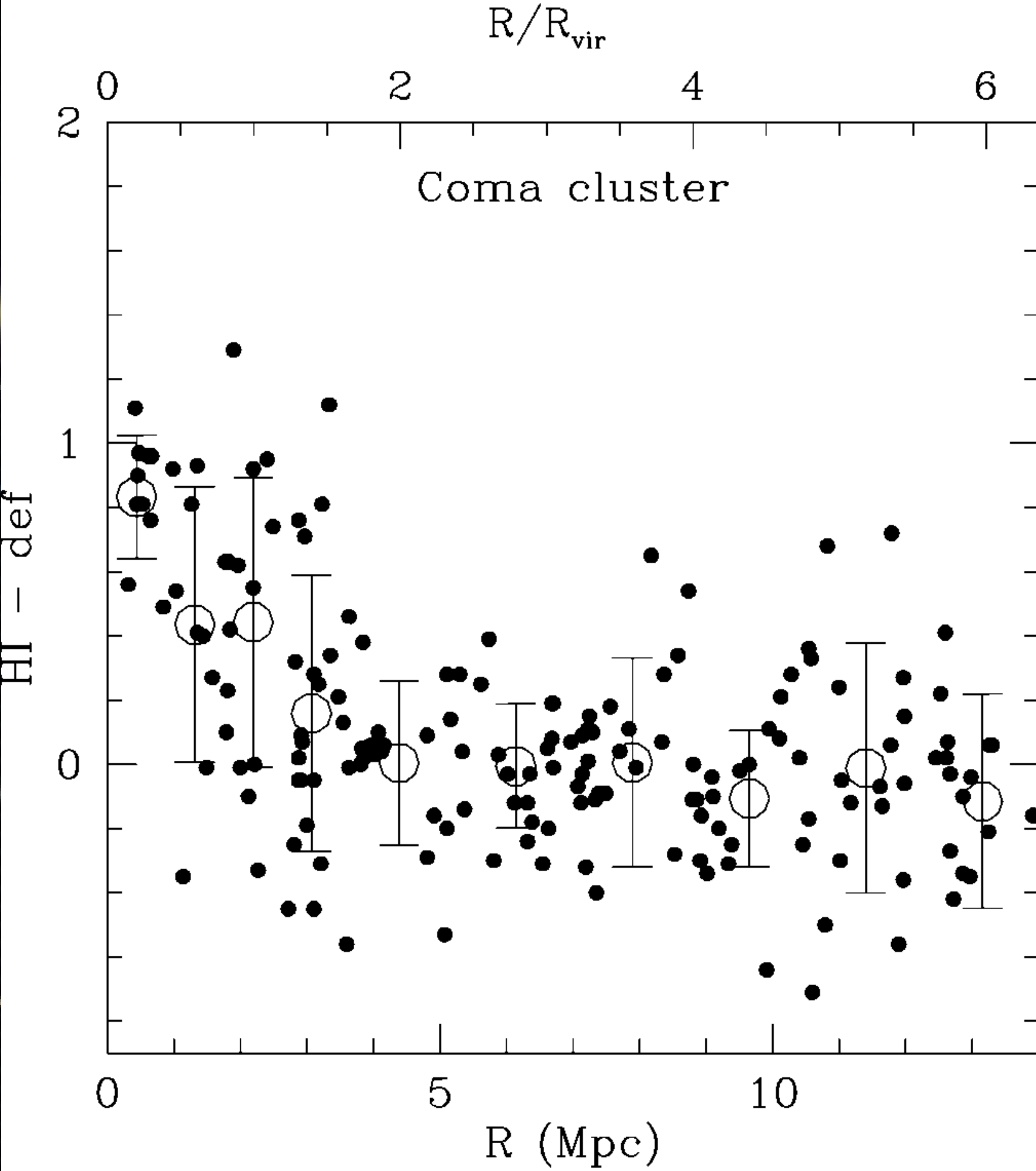


Glass et al., 2011, ApJ, 726, 31



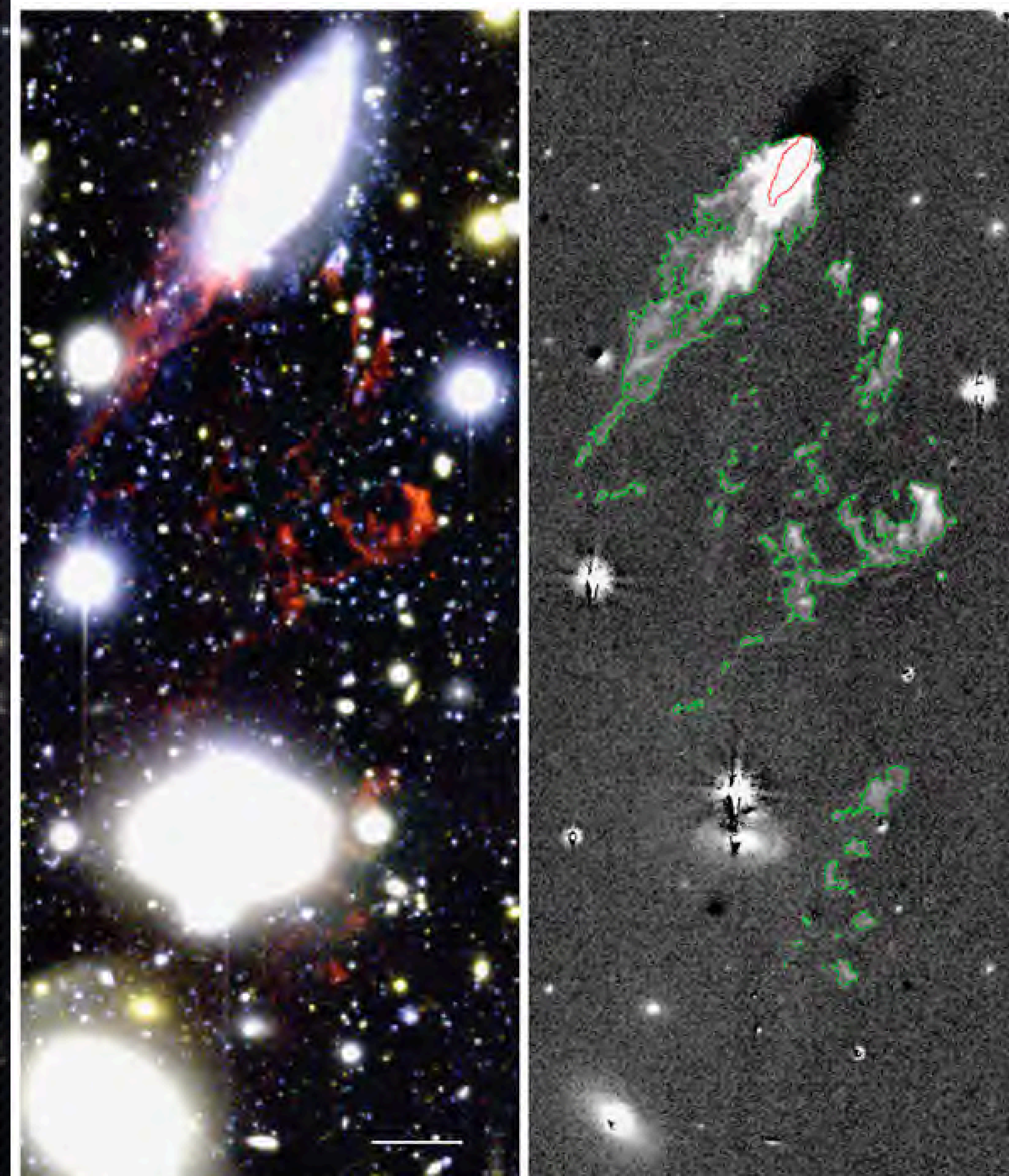
Gas stripping in clusters

HI gas deficits



Bosselli & Gavazzi, 2006, PASP, 118, 517

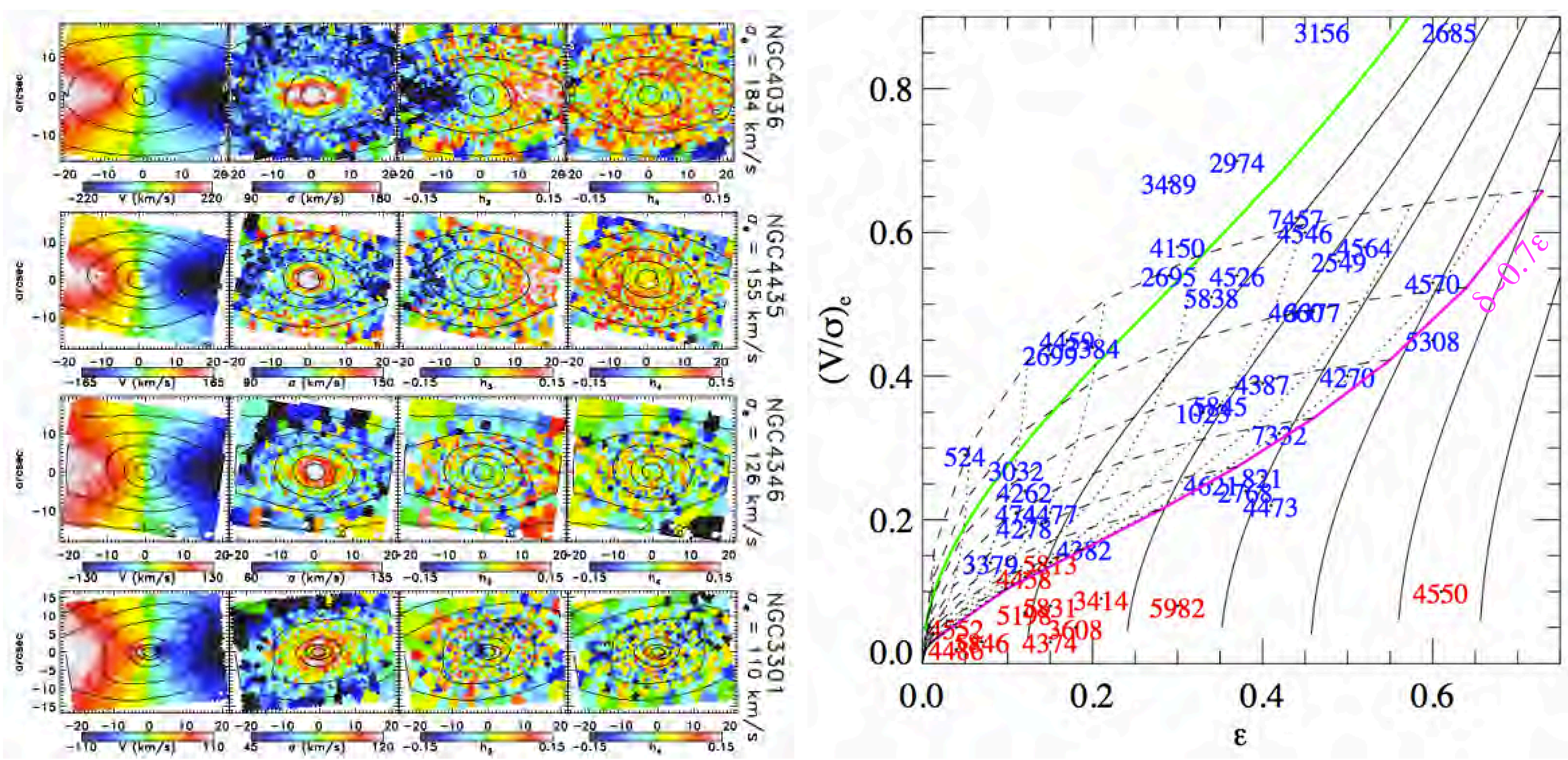
Hα plumes and streamers



Yagi et al., 2010, AJ, 140, 1814

Early-type kinematic classes

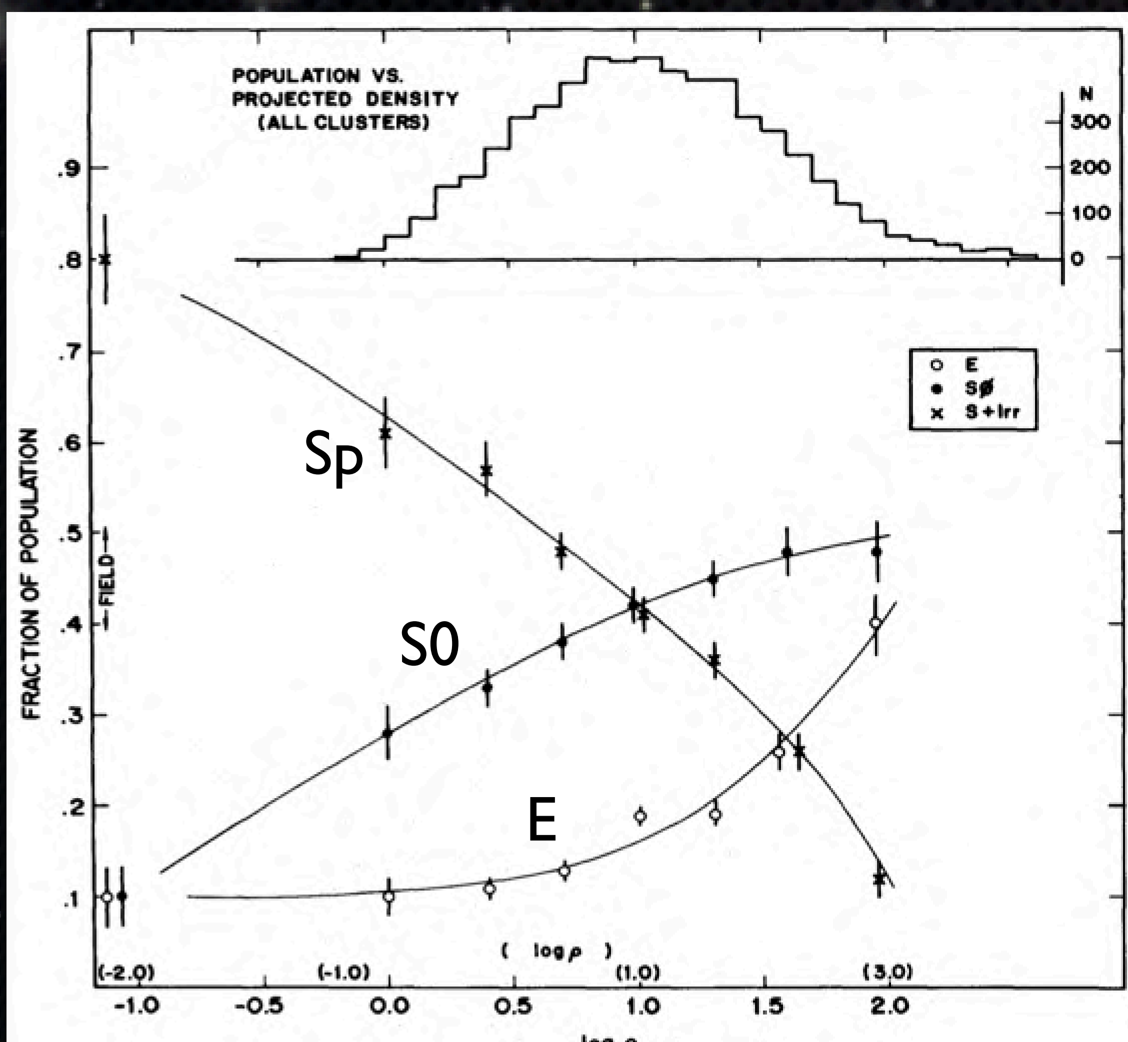
- The internal kinematics of early-type galaxies reveal their merger histories: gas-rich wet mergers yield fast-rotating systems; gas-poor dry mergers yield slow-rotating systems



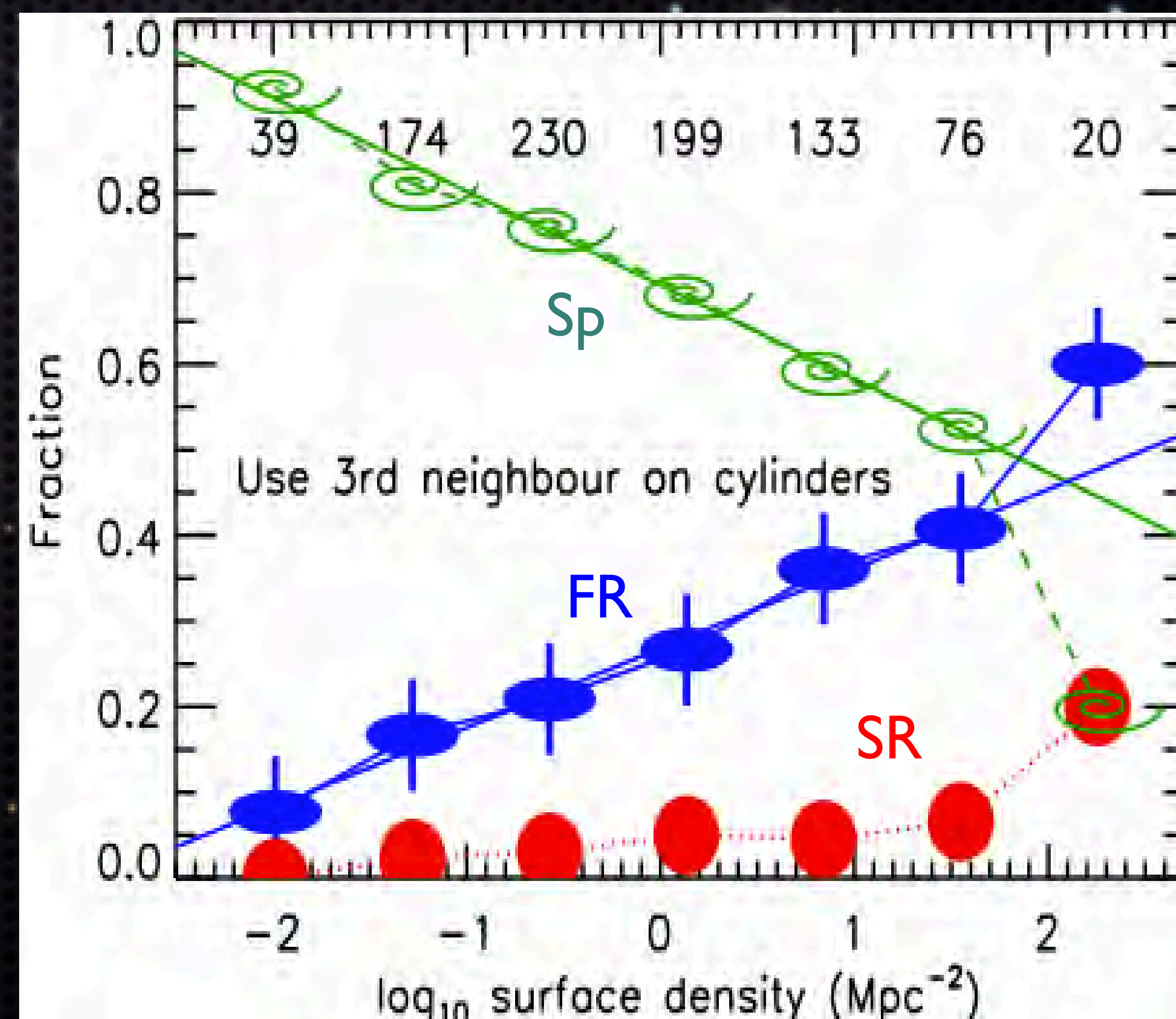
Cappellari et al. 2007, MNRAS, 379, 418; Cappellari et al. 2010, astro-ph/1012.1551

Kinematic T–Σ relation

- Compare visual and kinematic morphology-density (T–Σ) relations: slow rotators are rarer than E's in all environments; kinematic T–Σ is smooth log-linear relation over 10^4 range in surface density; rapid drop in Sp and rise in *both* fast and slow rotators at highest densities



Dressler 1980, ApJ, 236, 351



Cappellari et al. 2011, astro-ph/1104.3545

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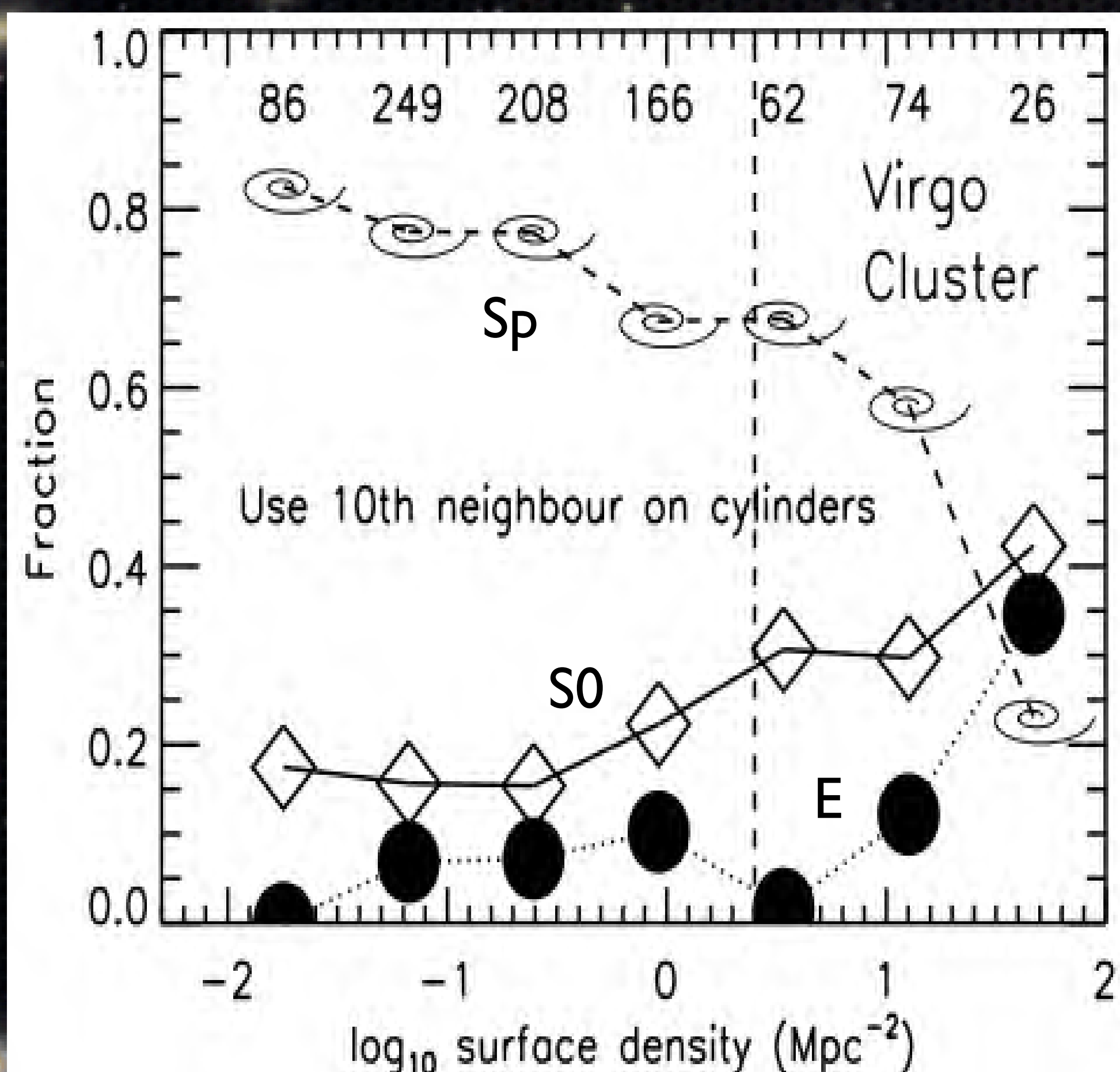
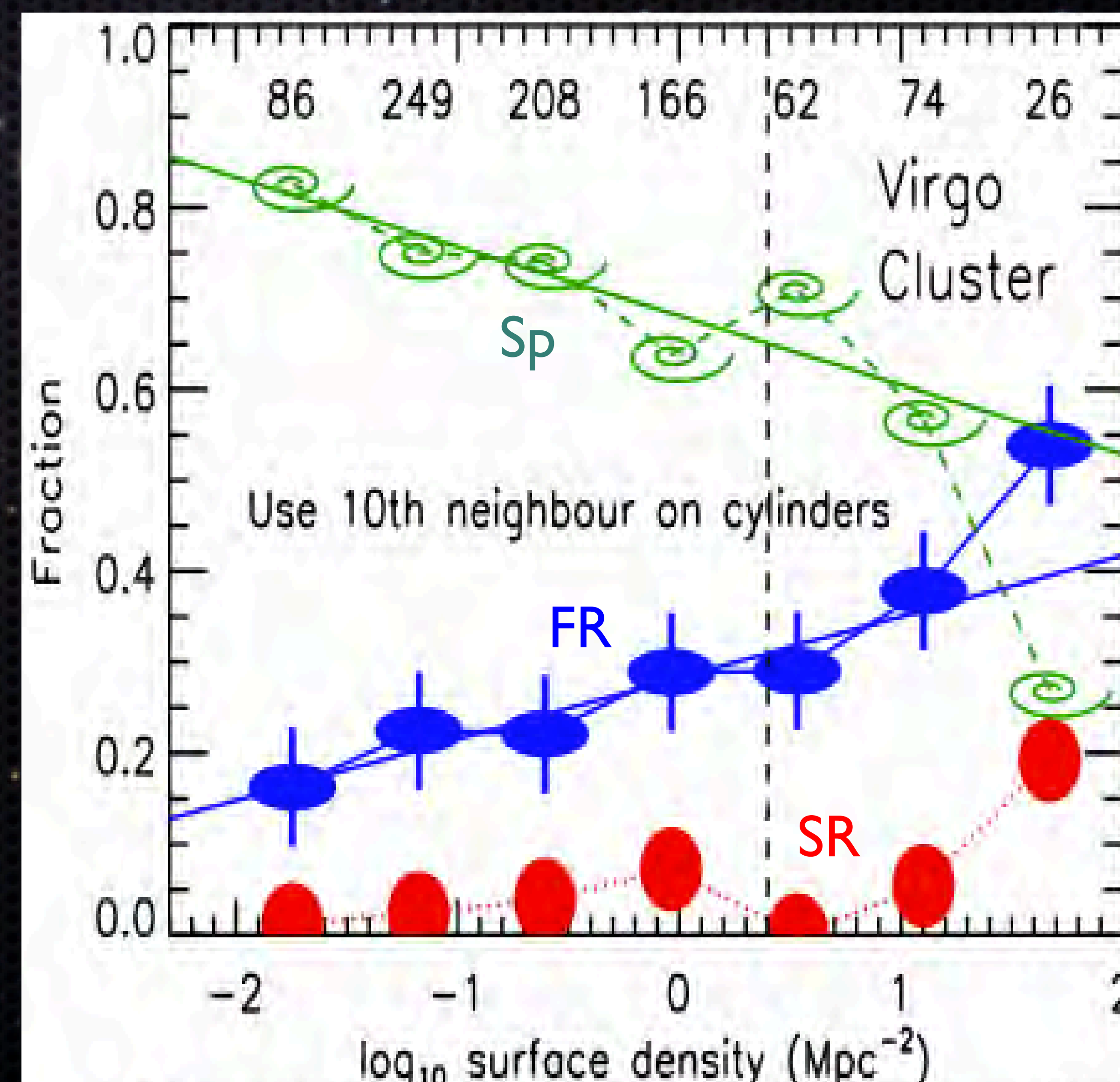
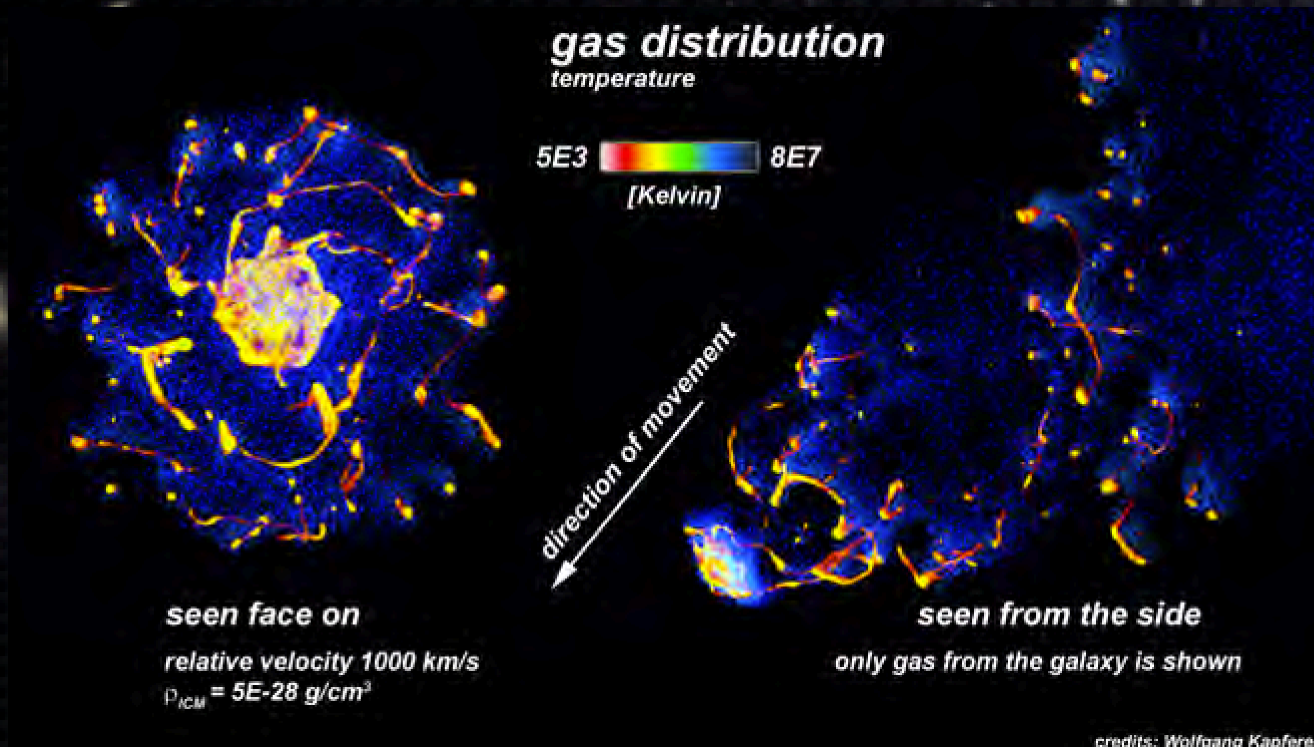


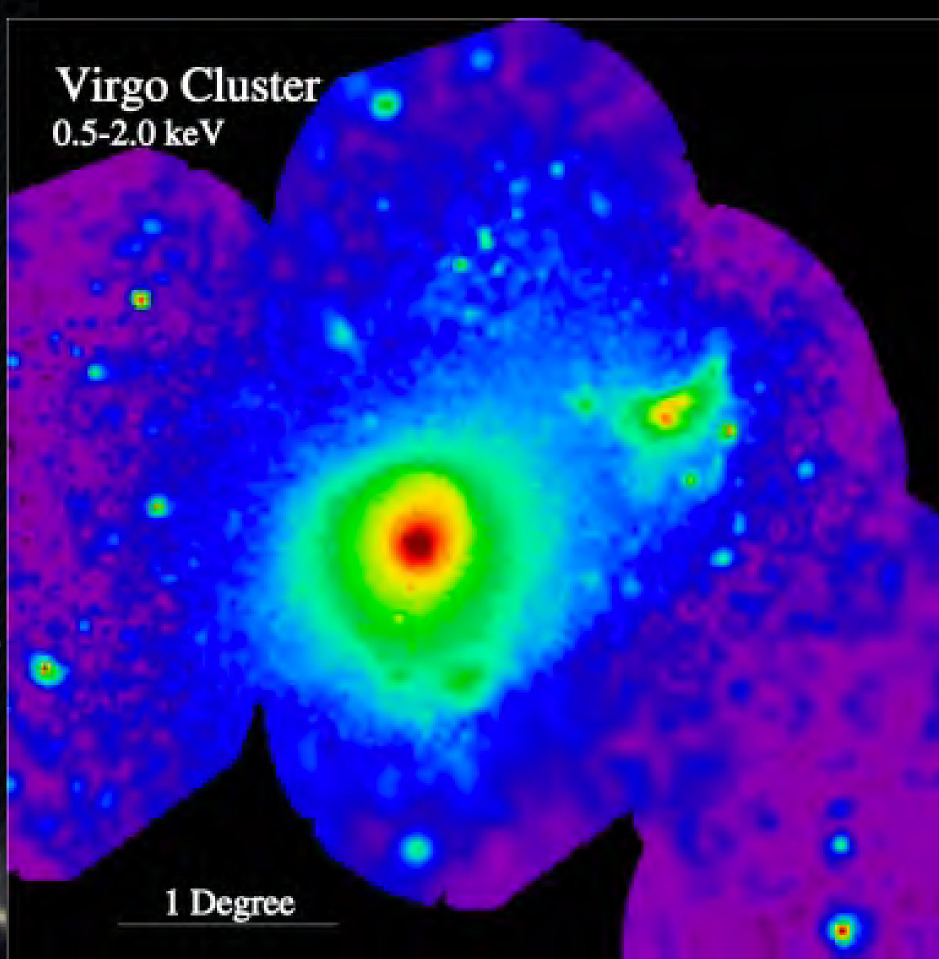


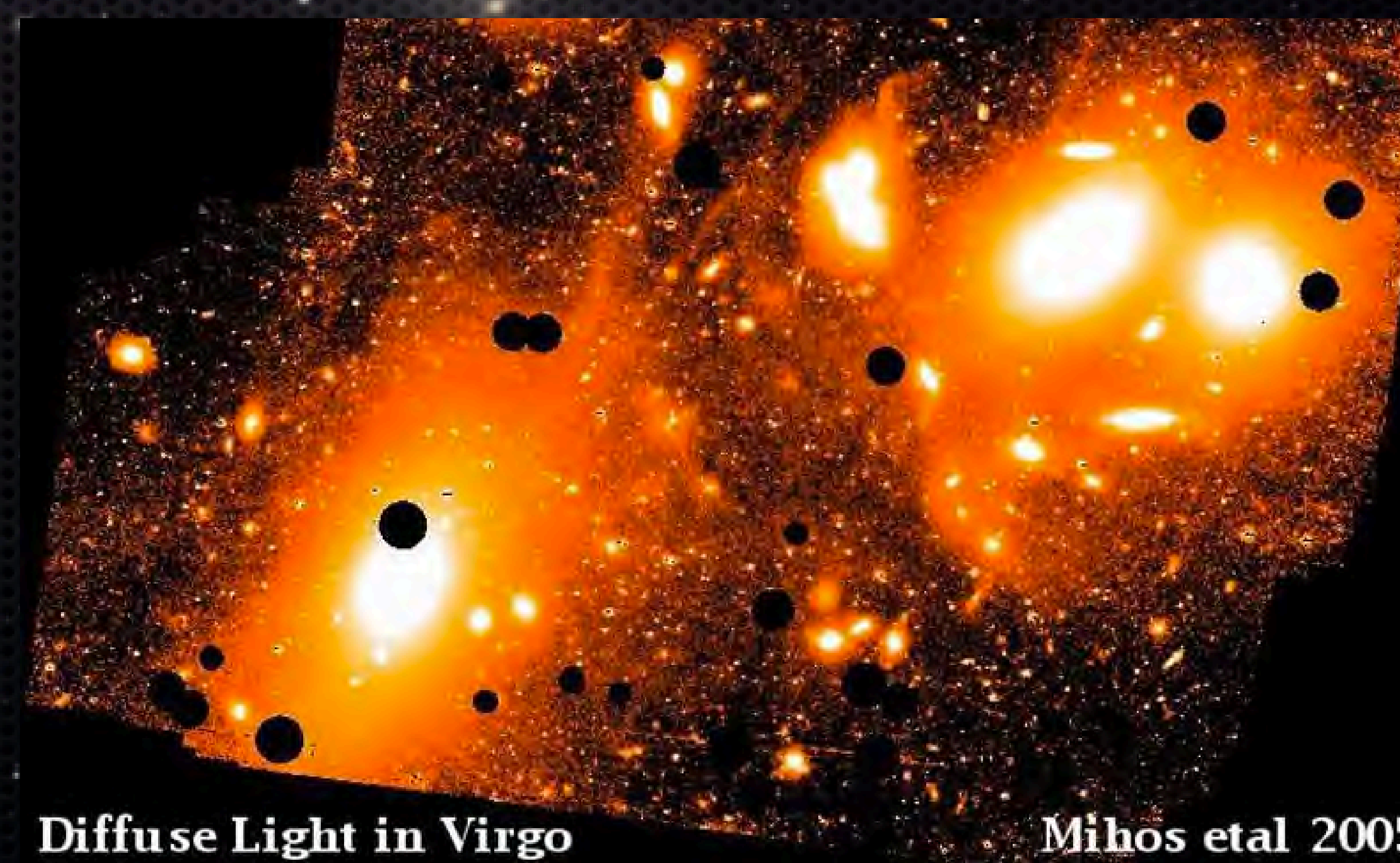
Feedback processes

- How are baryons cycled around and between the primordial gas, the stars, the interstellar medium and the intracluster medium?
- How do star-formation and supernovae figure in this cycle? Under what circumstances are they important (dominant)?
- How do SMBH formation and AGN activity contribute to this cycle? When are they important (dominant)?
- What is the interplay between star-formation and the hot X-ray gas? How does the X-ray gas affect galaxy evolution?

Gas ➠ stars ➠ ICM…



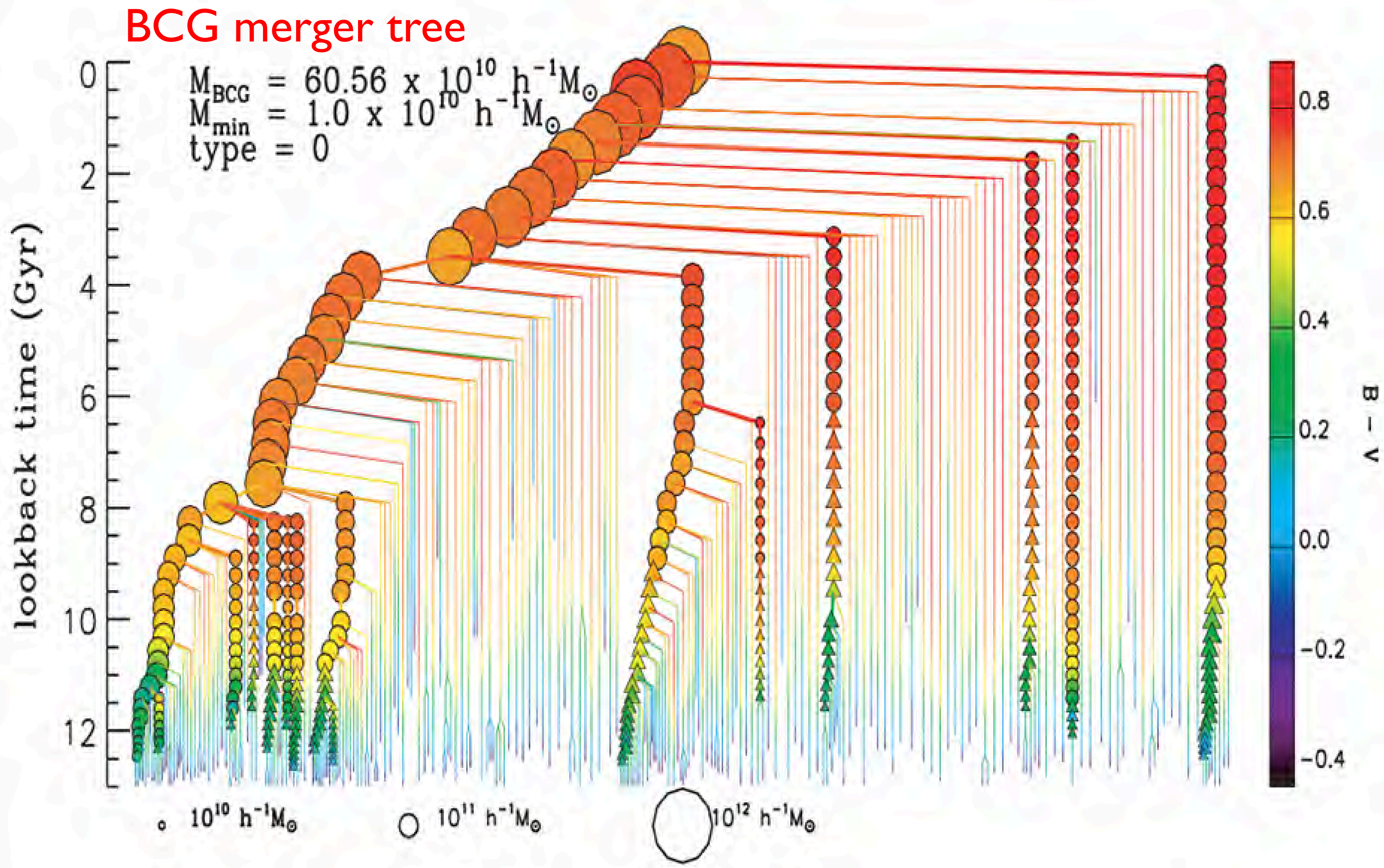


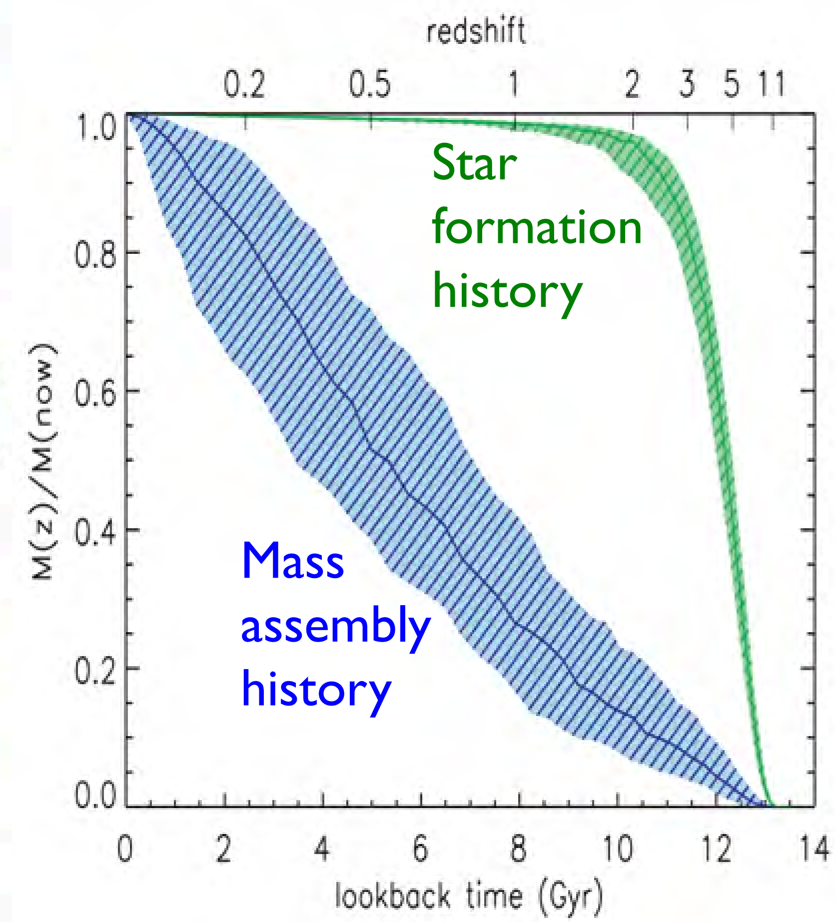


Special objects in clusters

- How are brightest cluster galaxies (BCGs) formed and what (if anything) makes them special? What is the interplay between BCG morphology and the dynamical state of clusters?
- Why are giant and dwarf ellipticals so prevalent in clusters and not elsewhere? To what extent is this nature (formation) and to what extent nuture (environment)?
- What are ultra-compact dwarf (UCD) galaxies? How do they relate to globular clusters?
- Can we account for the observed intracluster light (and its various stellar, PNe, globular cluster components)?

Brightest cluster galaxies - I

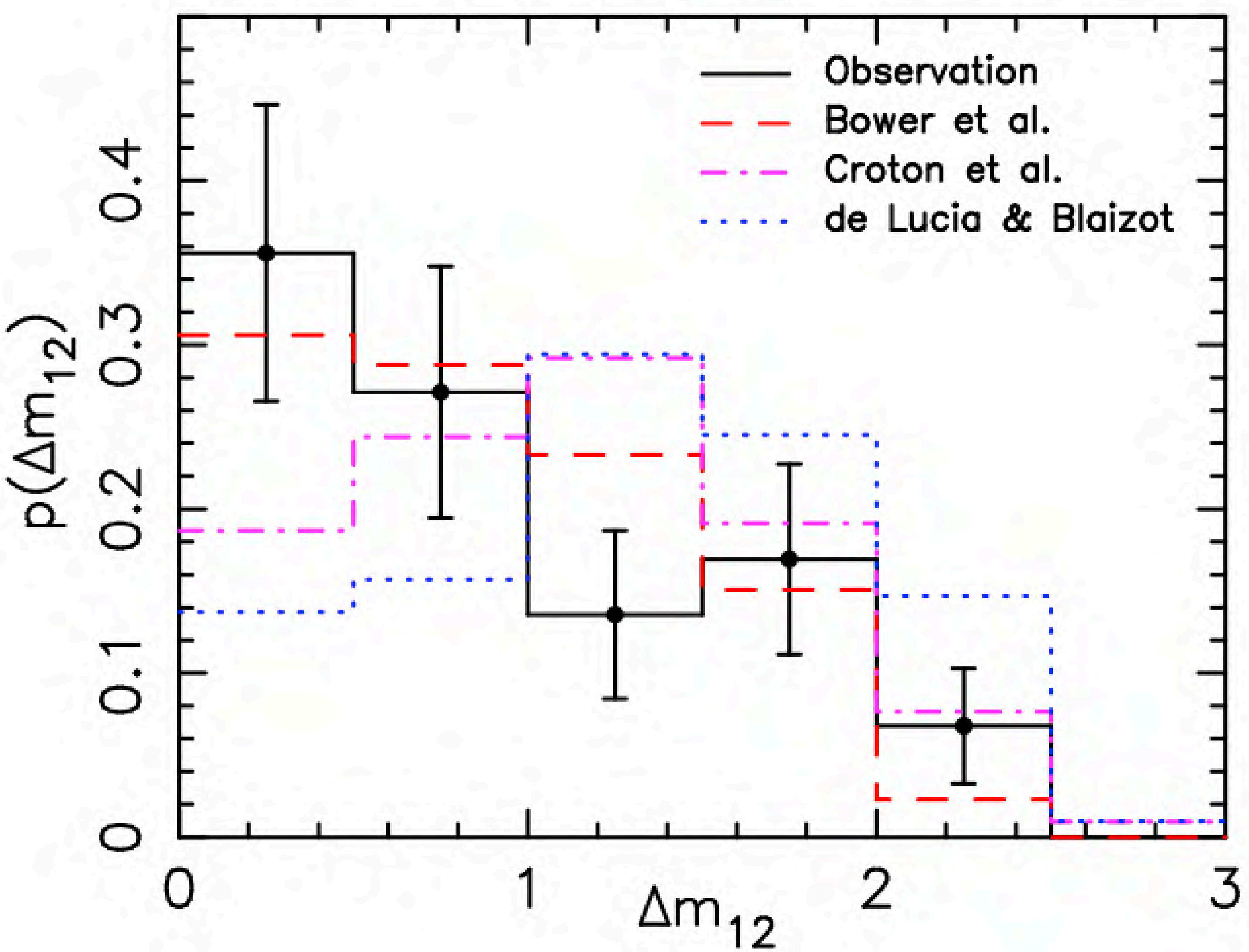




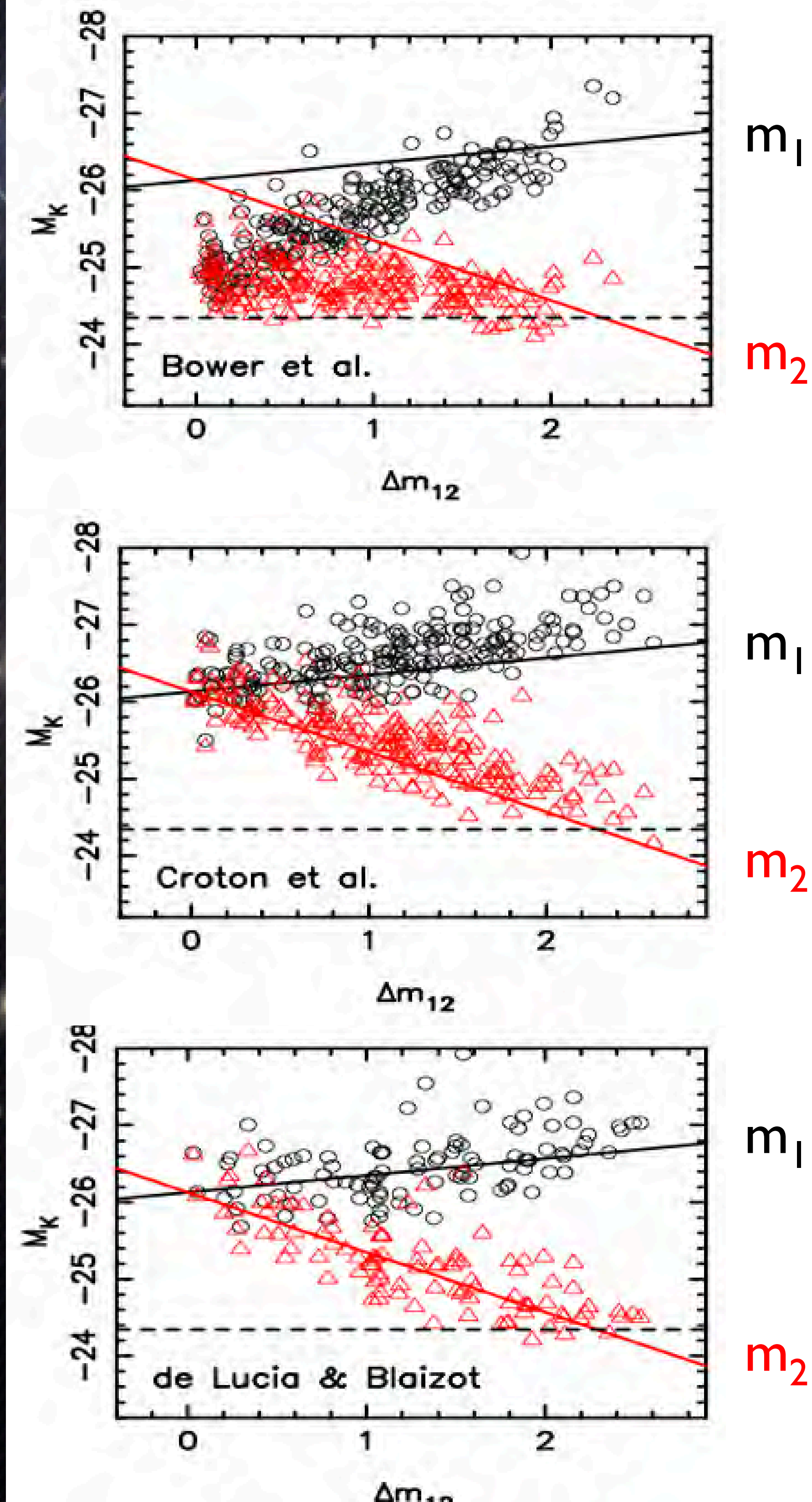
- Models (e.g. De Lucia & Blaizot, 2007, MNRAS, 375, 2) suggest that…
  - Stars in BCGs form early (80% at z>3) by rapid cooling in many small galaxies
  - But the BCGs assemble late (50% at z<0.5) through multiple dry mergers

Brightest cluster galaxies - 2

- However there are some significant discrepancies between the models and the properties of low-z BCGs

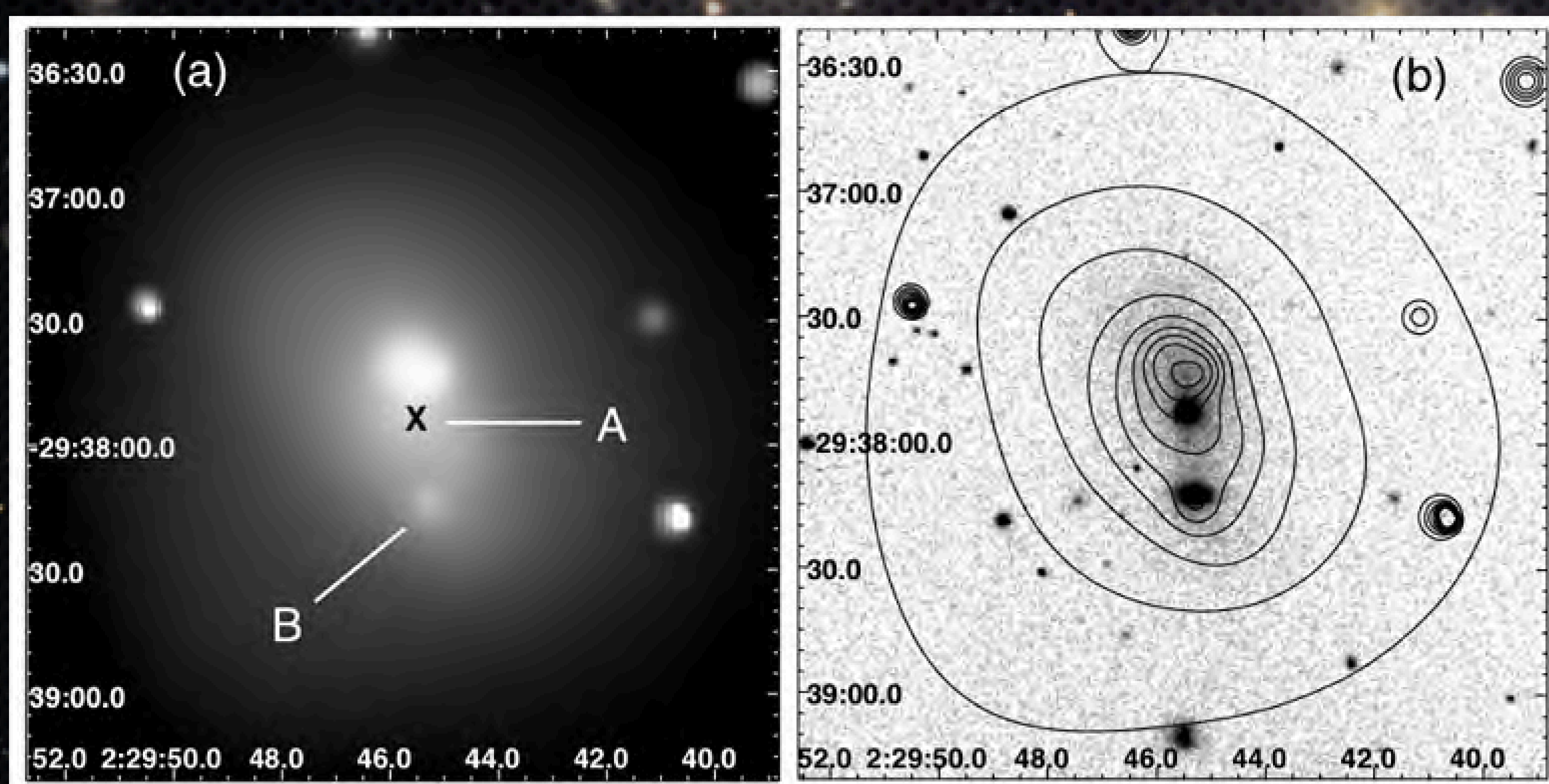


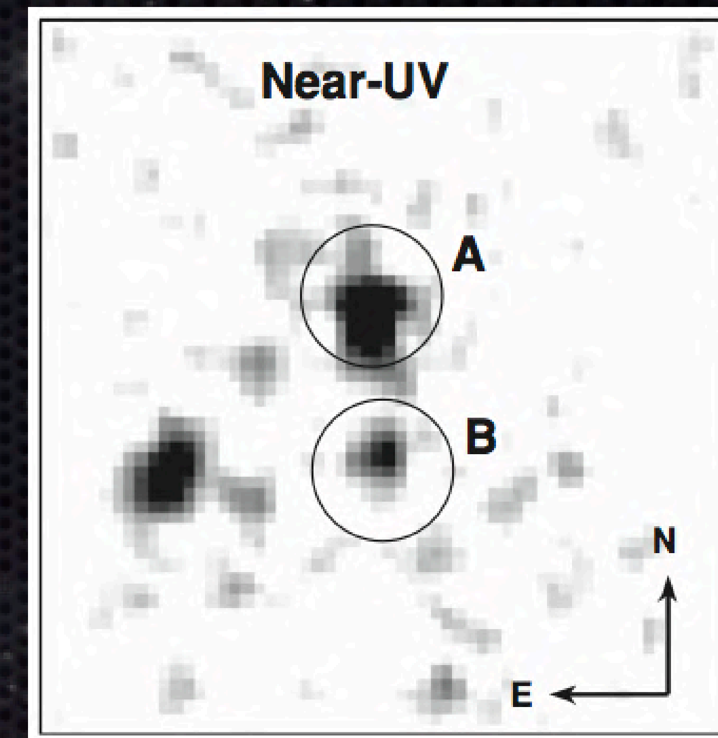
Smith et al., 2010, MNRAS, 409, 169

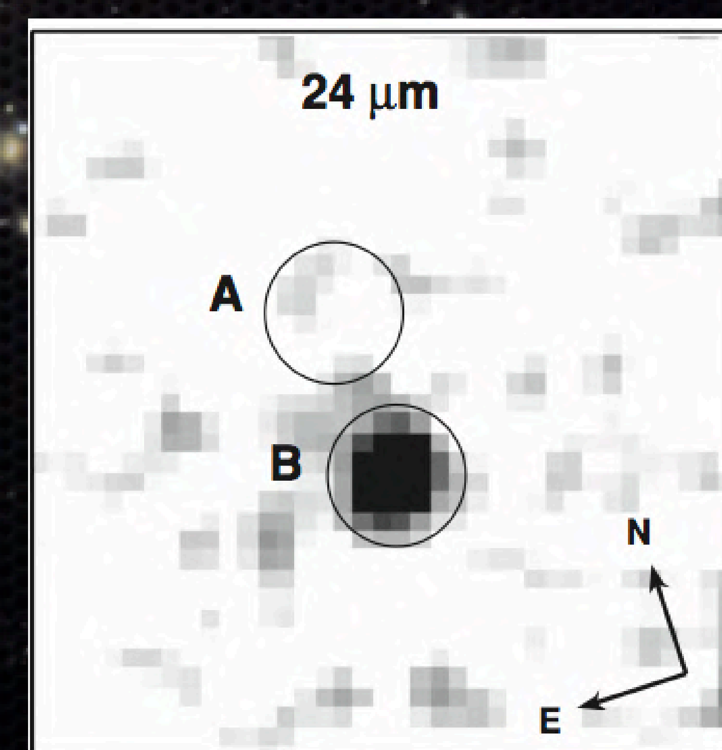


Brightest cluster galaxies - 3

- Rasmussen et al. (2010, ApJ, 717, 958) study a BCG forming (over next ~0.5 Gyr) from a merger in the nearby poor X-ray cluster MZ 10451 (z~0.06)
- Combined Chandra, GALEX, Spitzer and Magellan observations imply obscured star formation in the smaller galaxy, suggesting that not <u>all</u> late-time mergers are perfectly dry



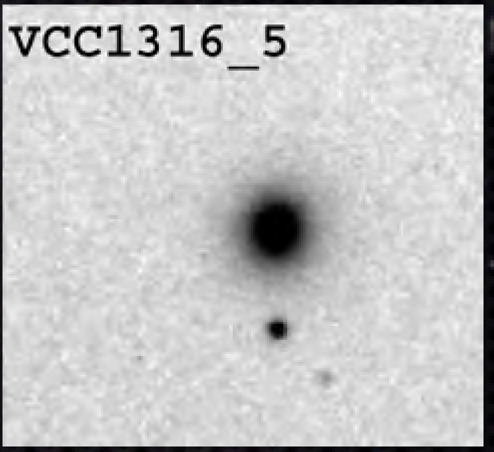


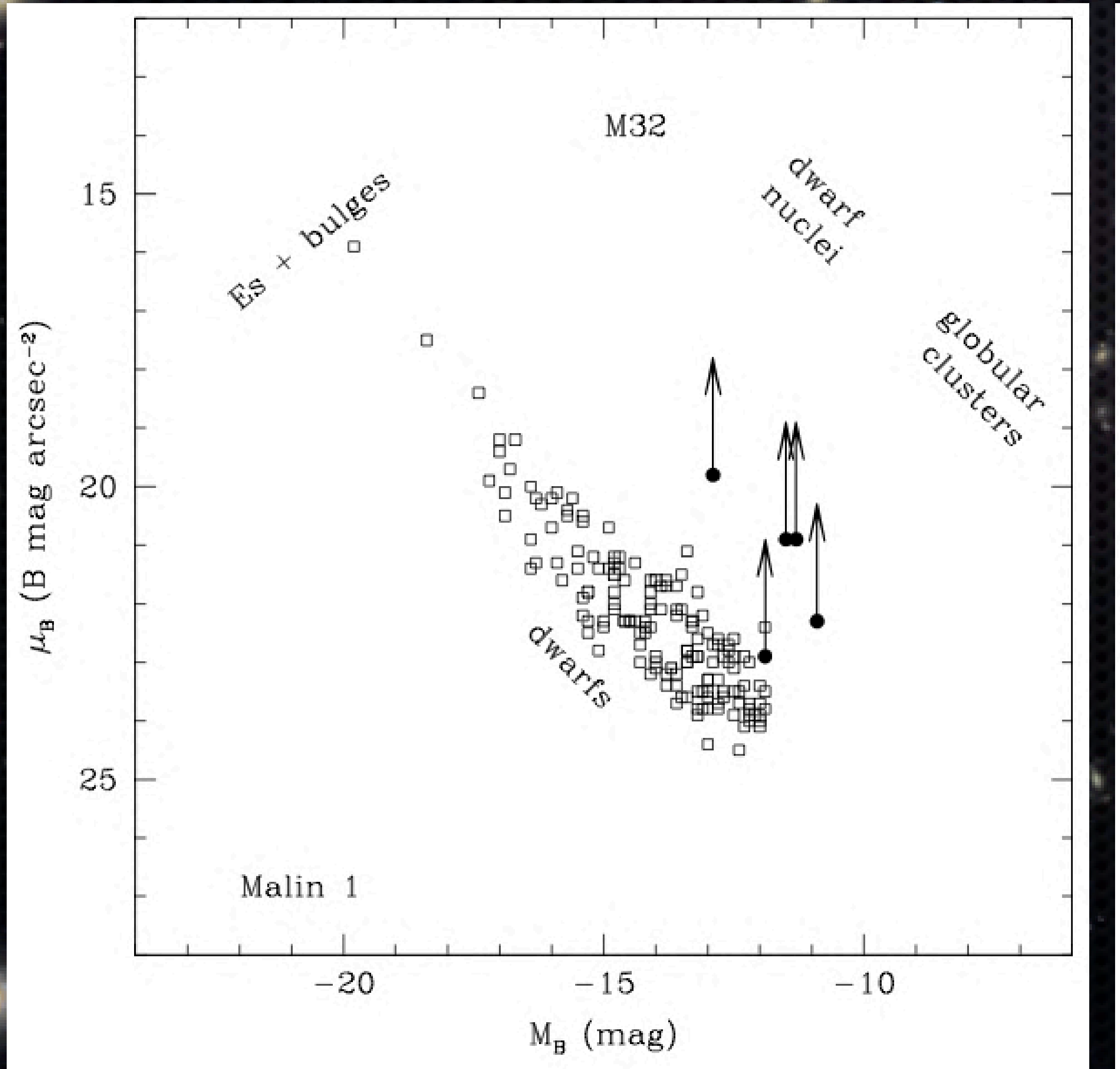


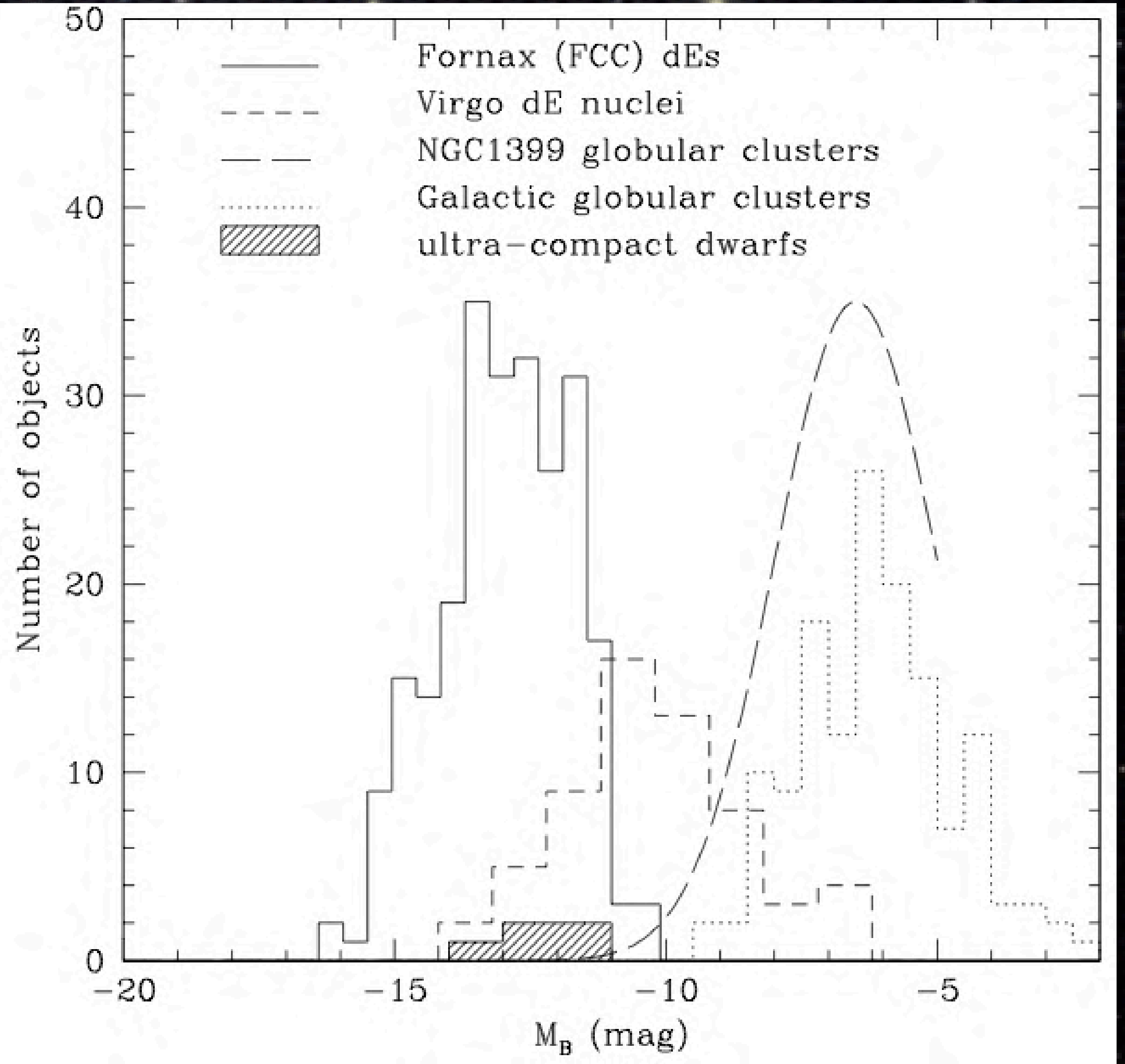
- See also Wang et al., 2010, MNRAS, 401, 433

Ultra-Compact Dwarfs - I

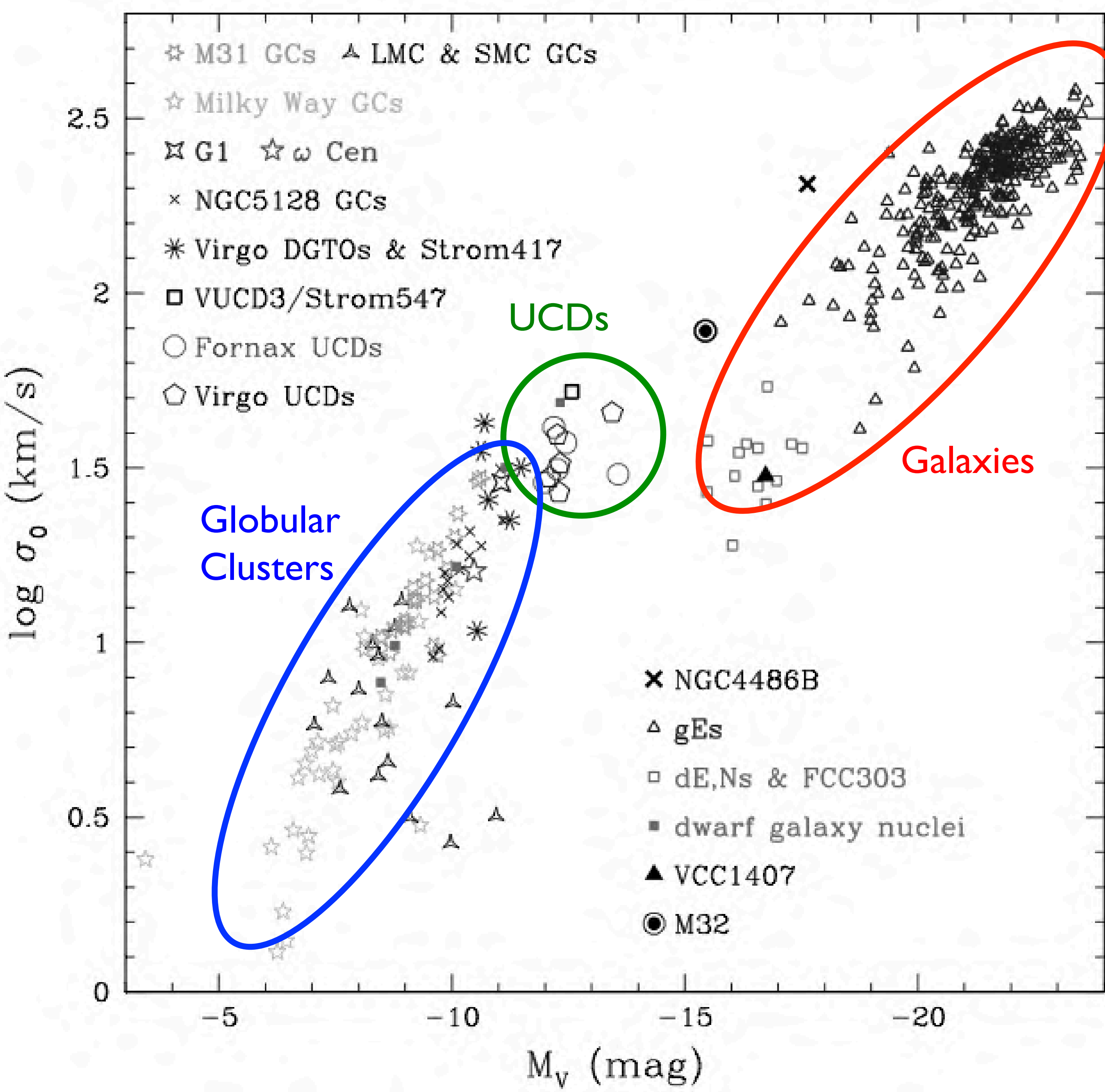
- What are UCDs? a new type of galaxy? the nuclei of 'threshed' dE's? extreme globular clusters?



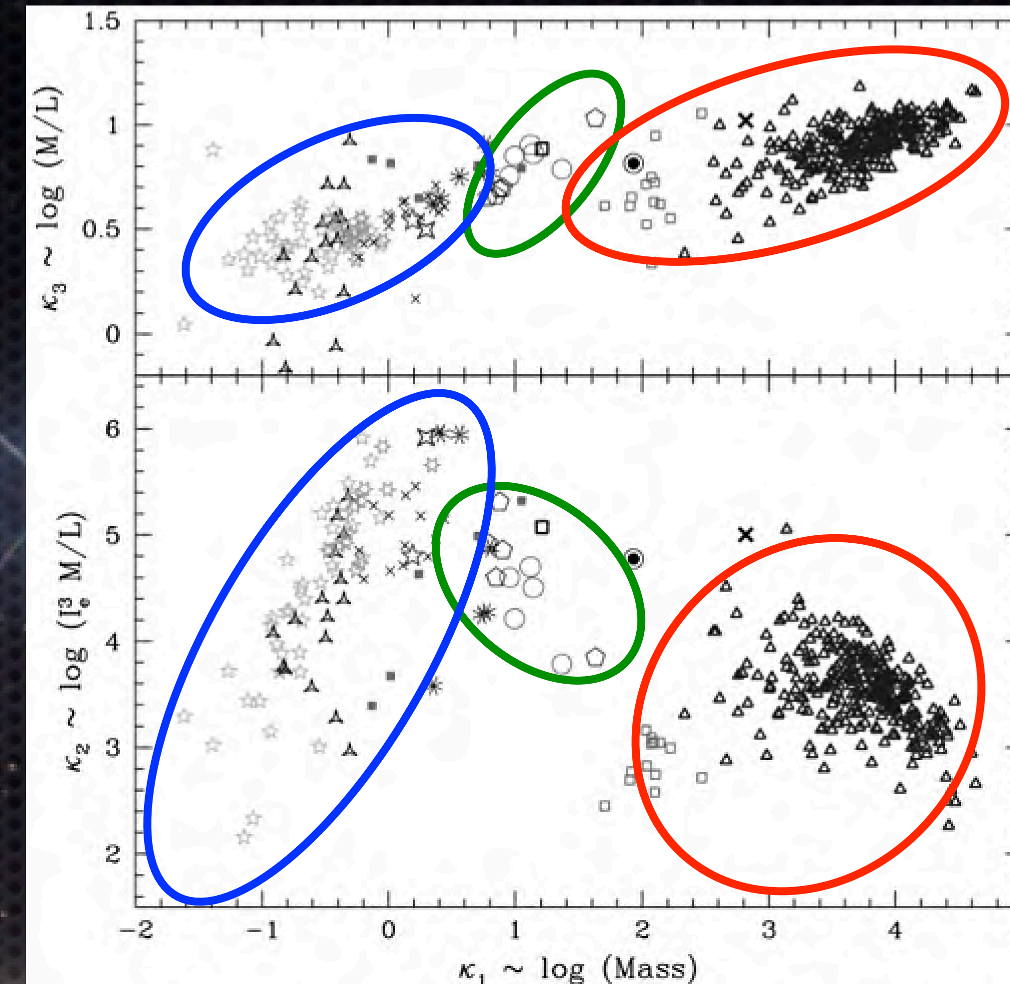


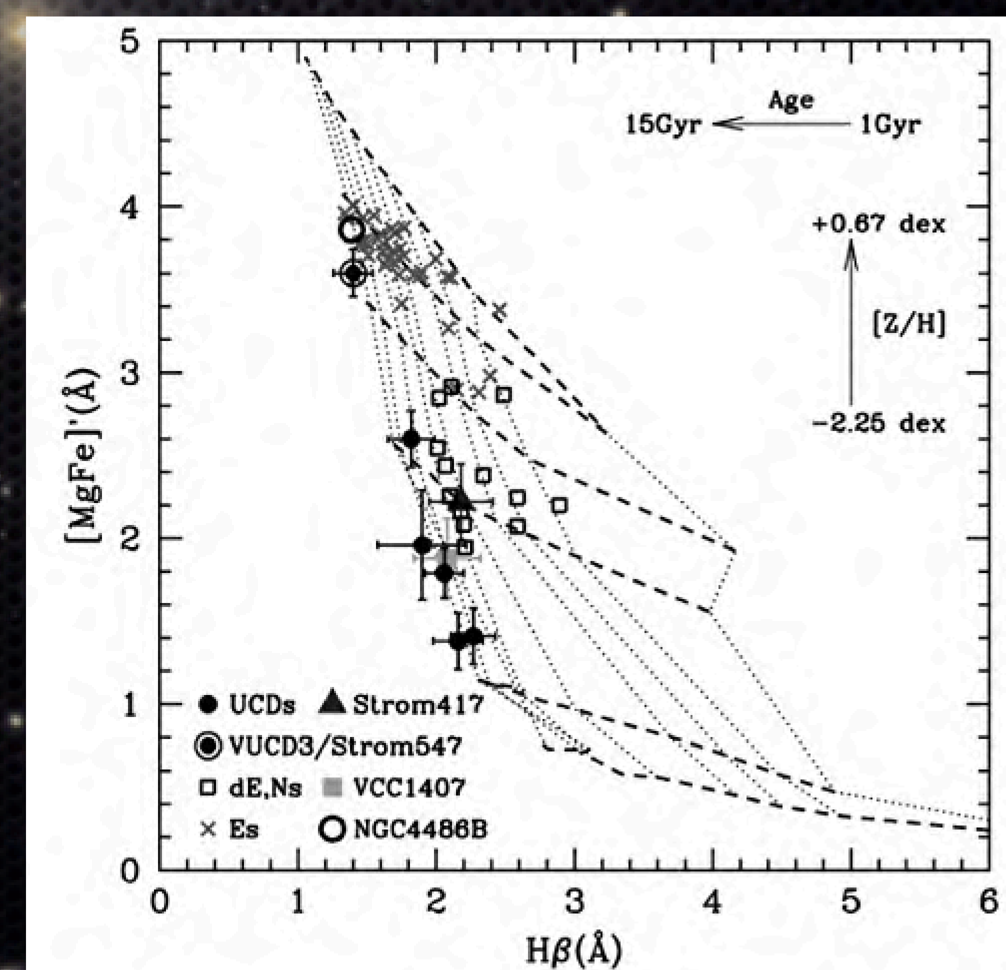


UCDs - 2



Evstigneeva et al., 2007, AJ, 133, 1722





Nearby clusters – the future

- High spatial resolution multi-wavelength imaging
  - State-of-the-art surveys: HST/ACS surveys, GALEX, NGVS, etc.
  - Future surveys: ALMA, JSWT, ELTs, SKA
- IFU spectroscopy of galaxies with good spatial resolution
  - State-of-the-art surveys: SAURON, ATLAS-3D (samples ~ 10^2)
  - Next-generation surveys: SAMI, MANGA (samples ~ 10^4)
  - Future surveys: multi-IFUs on ELTs with GLAO/MCAO/MOAO
- Larger samples to greater distances at higher spatial resolution and higher spectral S/N will provide a wealth of new information on galaxies in 'nearby' clusters
- Comparing the new data with more realistic physical models offers exciting prospects for disentangling the complex evolution of stellar systems in high-density environments.

Coma Cluster of Galaxies

Hubble Heritage