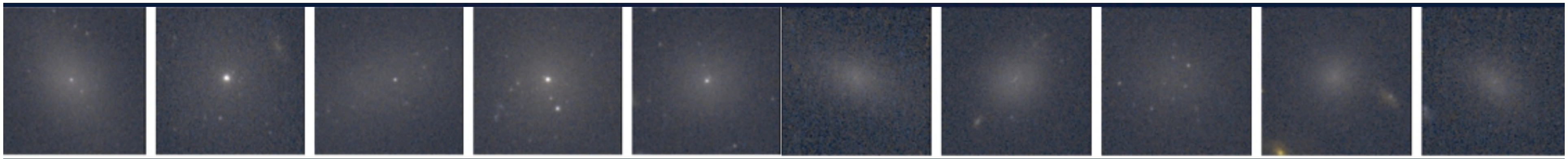
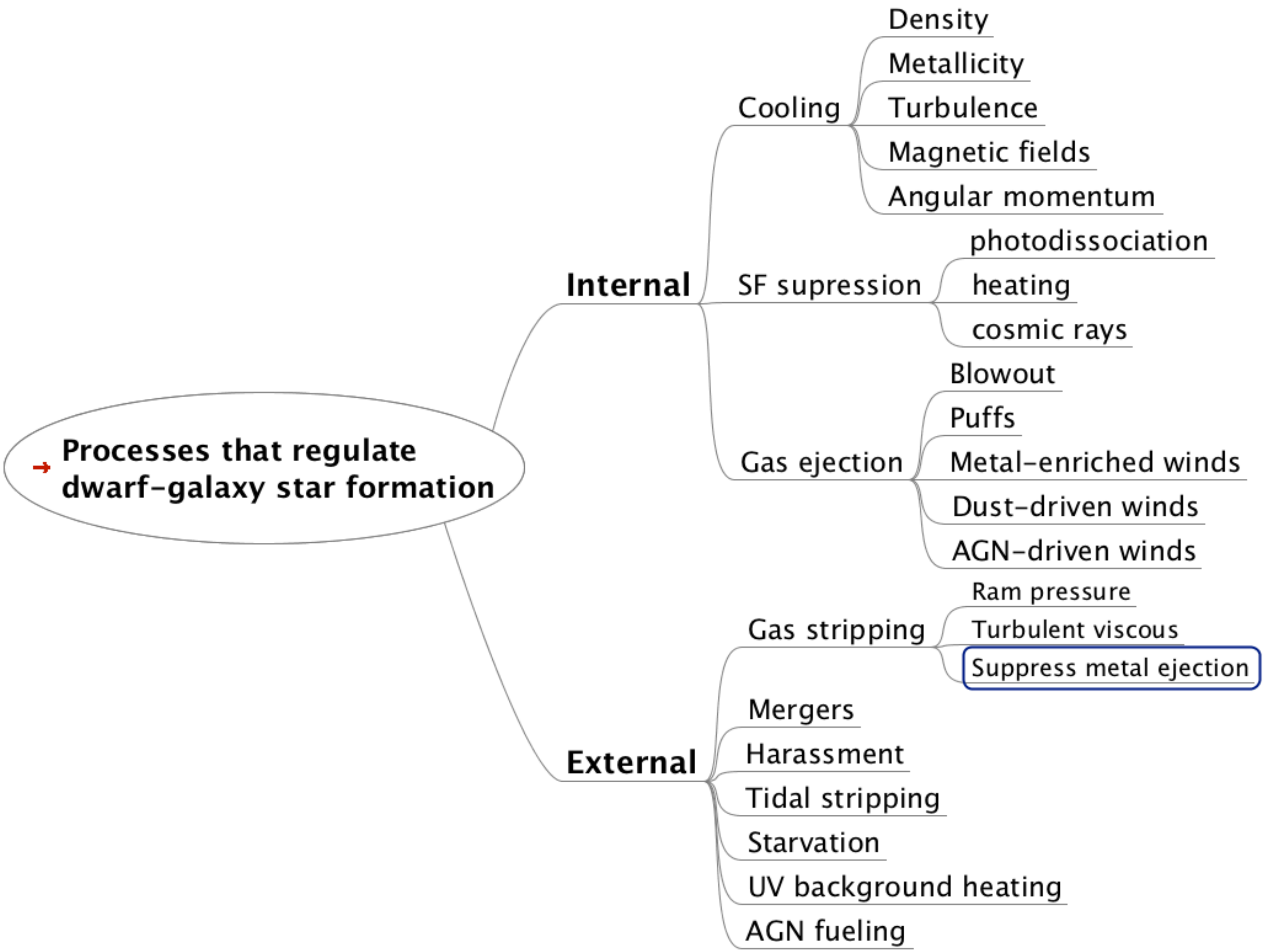


Dwarf Galaxies in nearby Groups

Henry Ferguson
Space Telescope Science Institute
11 July 2012

Key Questions

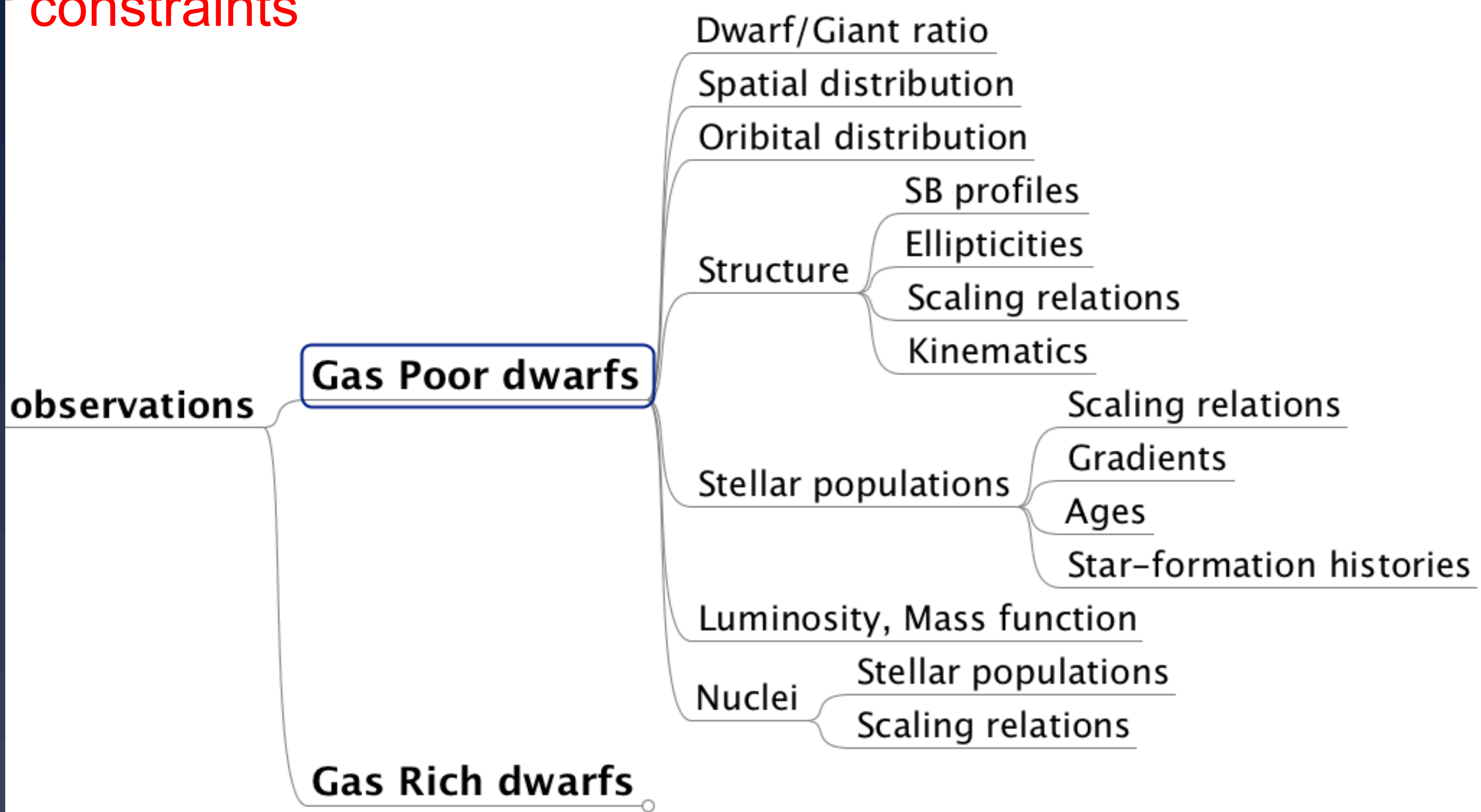
- Are the processes that govern star formation in dwarfs predominantly *internal* or *external*?
  - Was star-formation fast or slow?
  - Was this different in the past?
  - Different in the field and in groups?
  - Different for dI vs. dE galaxies?


Processes that regulate dwarf-galaxy star formation
Internal
Cooling
Density
Metallicity
Turbulence
Magnetic fields
Angular momentum
SF supression
photodissociation
heating
cosmic rays
Gas ejection
Blowout
Puffs
Metal-enriched winds
Dust-driven winds
AGN-driven winds
External
Gas stripping
Ram pressure
Turbulent viscous
Suppress metal ejection
Mergers
Harassment
Tidal stripping
Starvation
UV background heating
AGN fueling

Observations: Top-level view

- Most dwarfs in clusters are gas poor
  - dE galaxies dominate clusters
  - dE galaxies are almost never isolated
- Dwarf galaxies show rather tight scaling relations
  - Similar for dI and dE galaxies
- Nearby dwarf galaxies have diverse star-formation histories
  - But we don't have very good constraints in clusters.

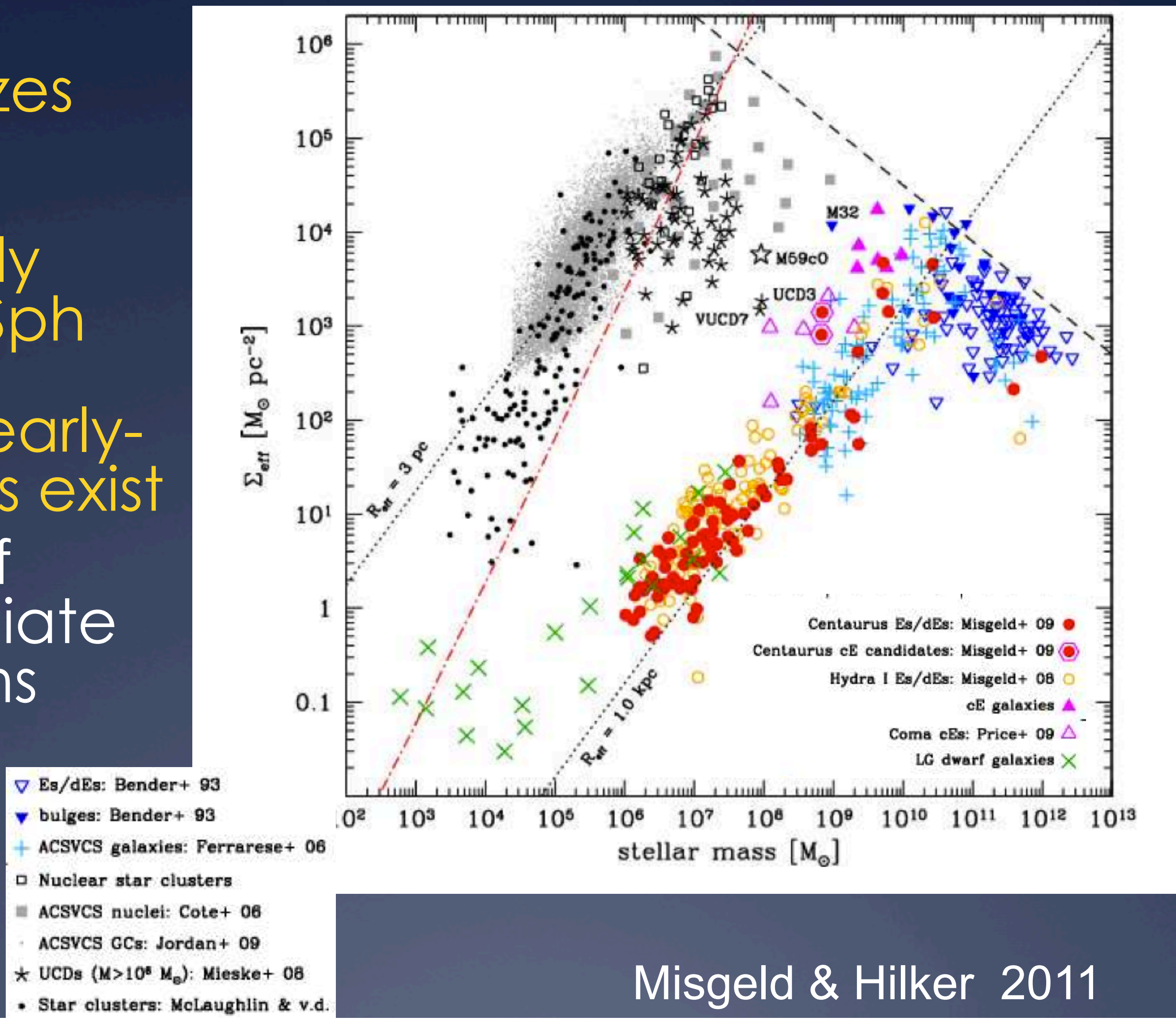
Observational constraints



Scaling Relations

Surface-brightness vs. L

- Not quite constant sizes
- Extends continuously down to dSph
- Compact early-type dwarfs exist
  - Dearth of intermediate SB systems



Misgeld & Hilker 2011

Metallicity vs. luminosity

The Astronomical Journal, 144:4 (36pp), 2012 July

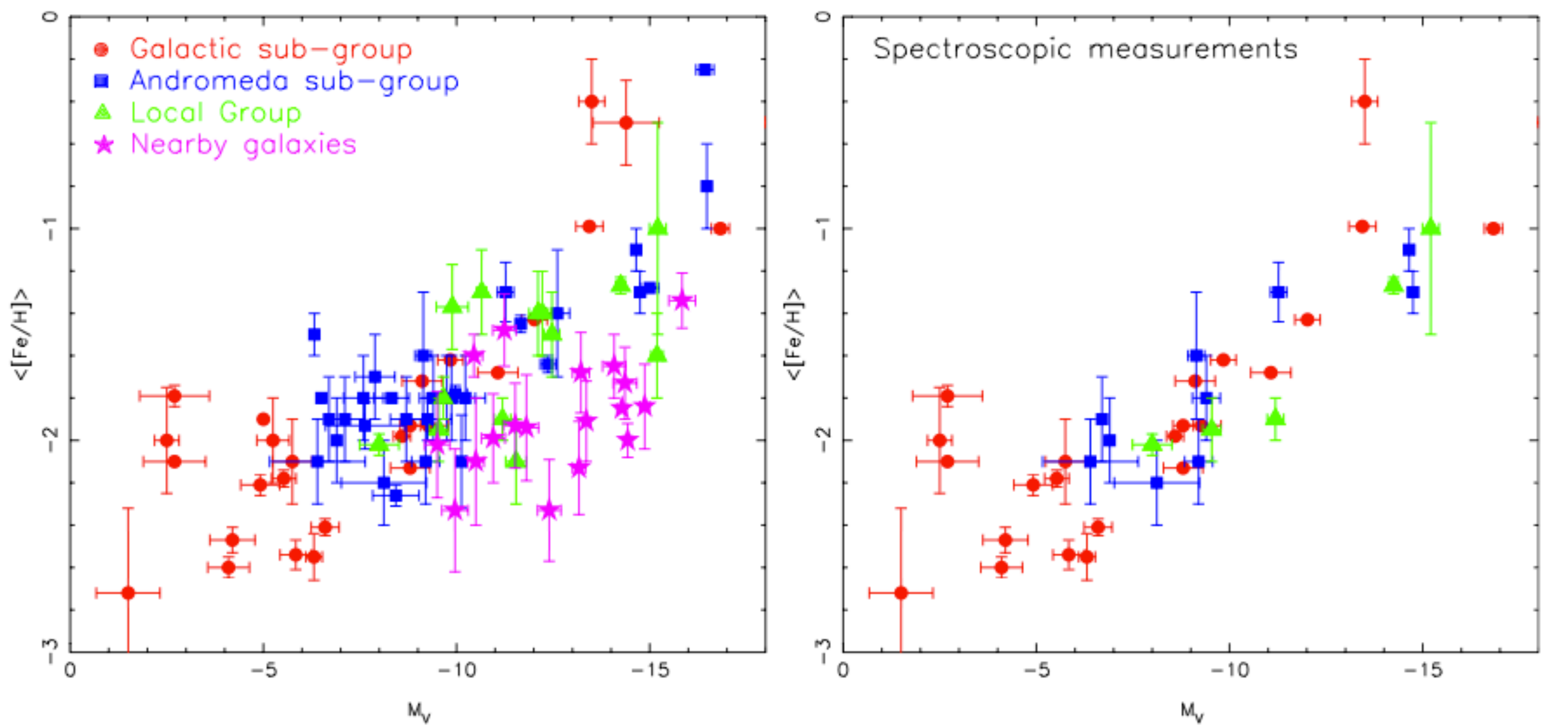
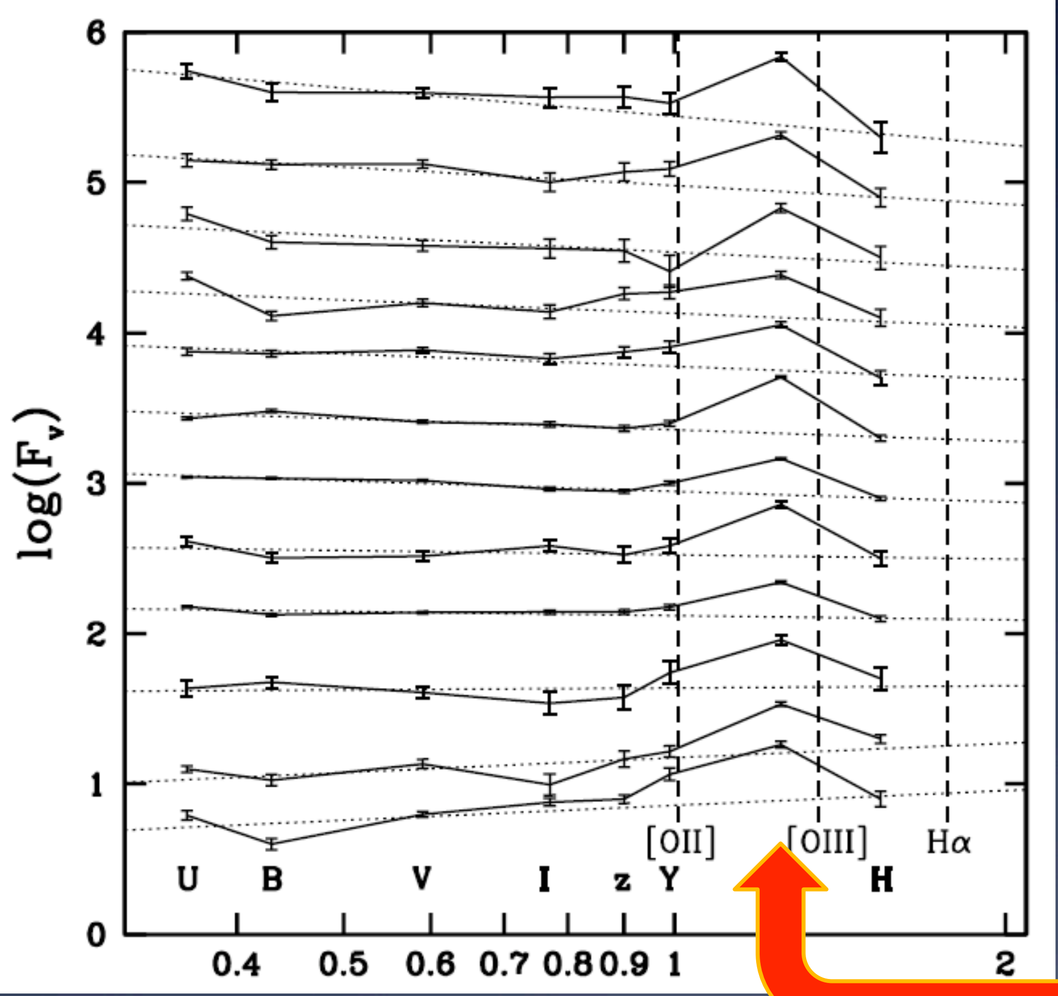


Figure 12. Absolute visual magnitude vs. stellar metallicity measurement (as listed in Table 5), for all galaxies in the sample for which this information is available. Color-coding is the same as in previous figures. The left panel shows all measurements regardless of the techniques used to estimate metallicity, whereas the right panel only shows those measurements derived from spectroscopic observations of resolved stars (typically giants).

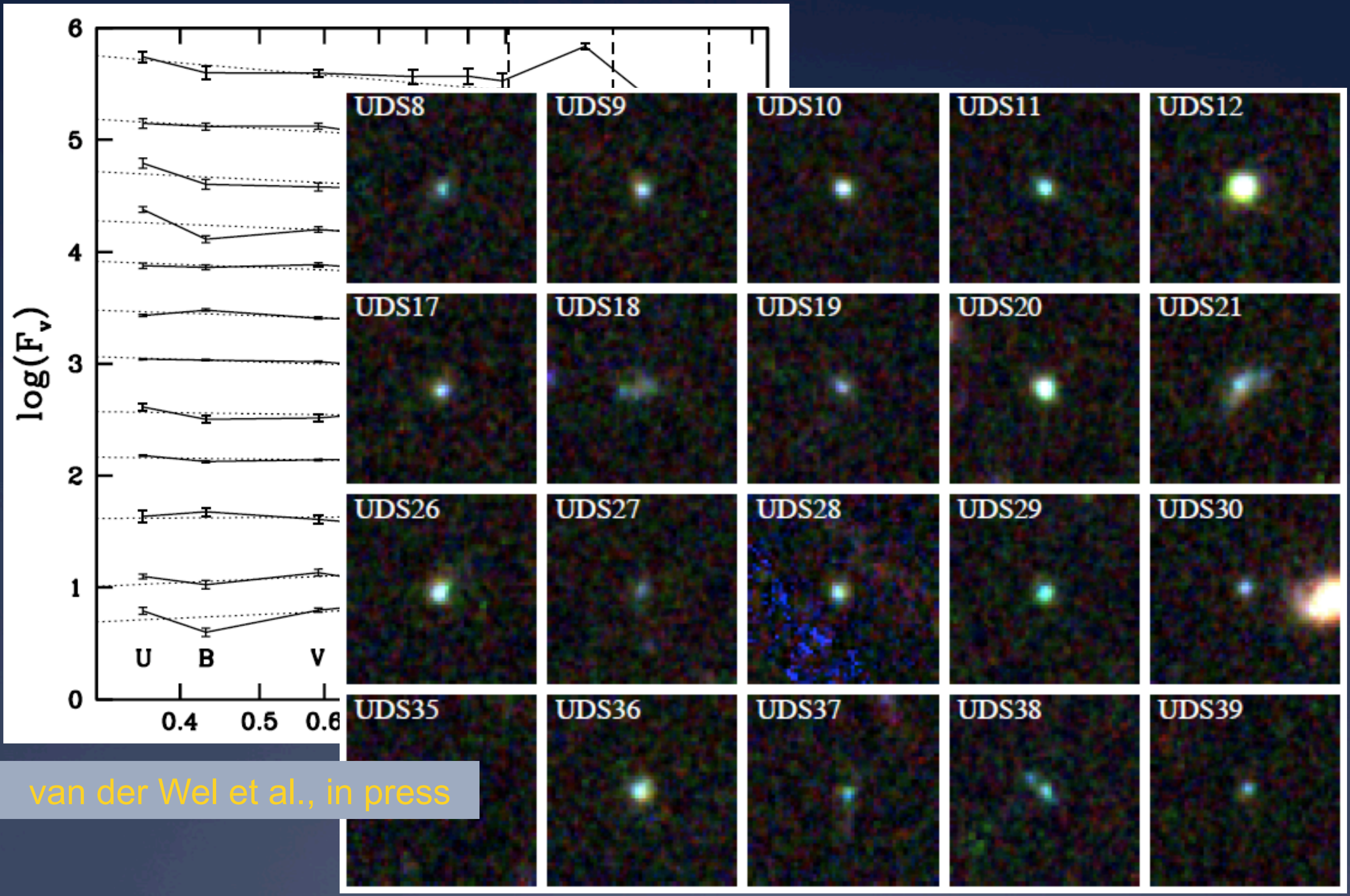
Bursting dwarfs at z ~ 1.7?



J-band excess due to Hα emission; EW up to 1000 A.

van der Wel+ 2011

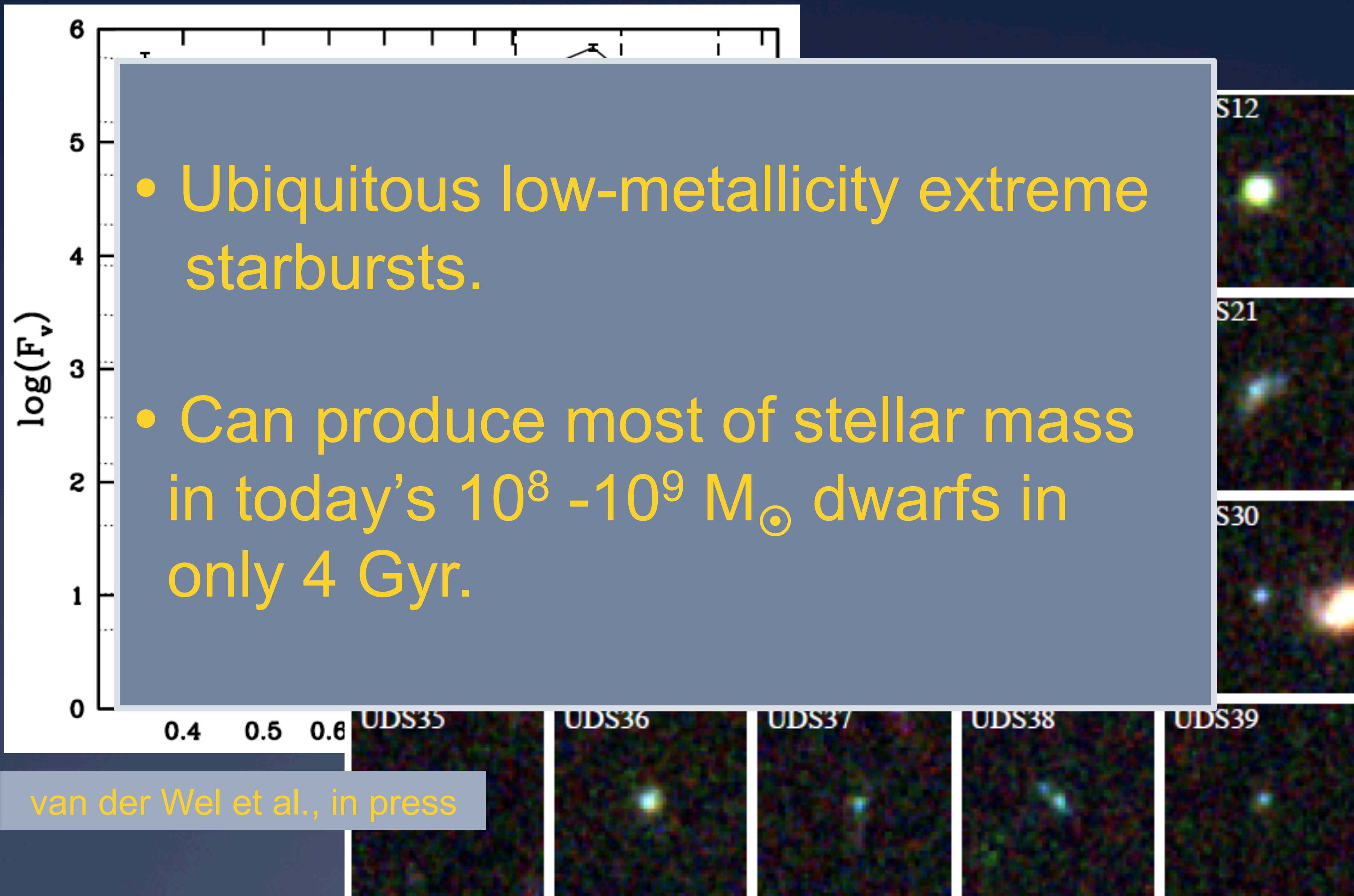
Bursting dwarfs at z ~ 1.7?



van der Wel et al., in press

Bursting dwarfs at z ~ 1.7?

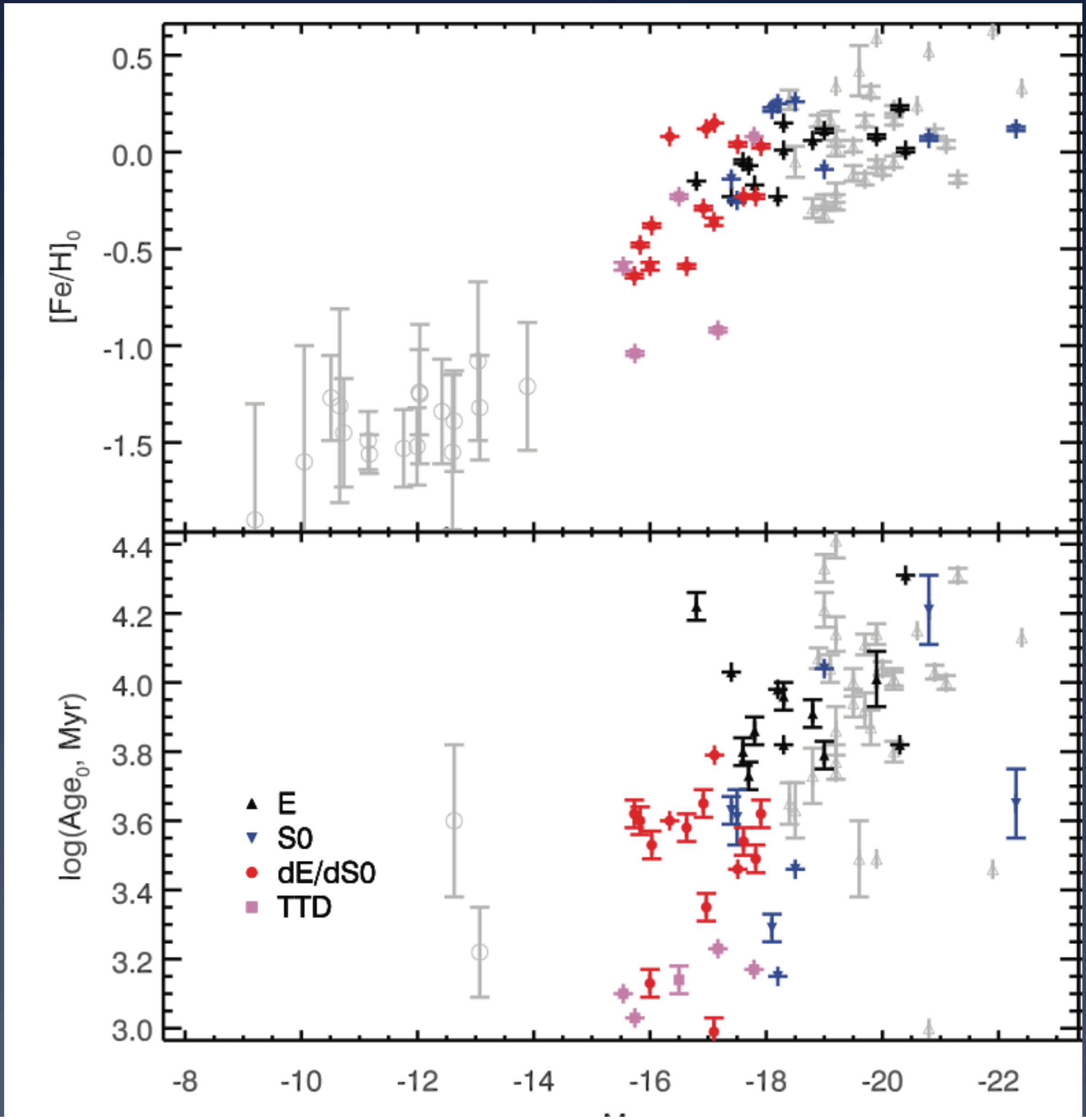
- Ubiquitous low-metallicity extreme starbursts.
- Can produce most of stellar mass in today's 10^8 -10^9 $M_\odot$ dwarfs in only 4 Gyr.



van der Wel et al., in press

Connecting to cluster dwarfs

- Cluster dwarfs fall between LG dSph and giant E in the mass-metallicity relation.
- Early-type dwarfs appear to be systematically younger than early-type giants



Koleva+ 2011

SNe wind model works remarkably well

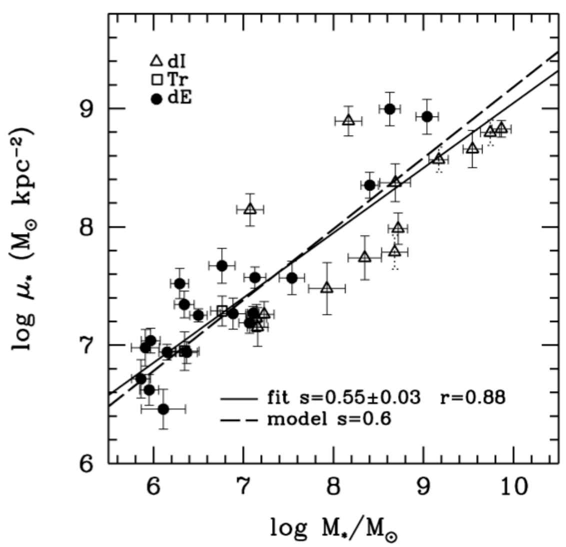


Figure 1. Central surface brightness versus stellar mass for the Local Group dwarfs (from WD). The regression line $\mu_* \propto M_*^{0.55}$ (solid), the correlation coefficient r, and the toy-model theoretical prediction $\mu_* \propto M_*^{0.6}$ normalized for best fit (dashed) are shown.

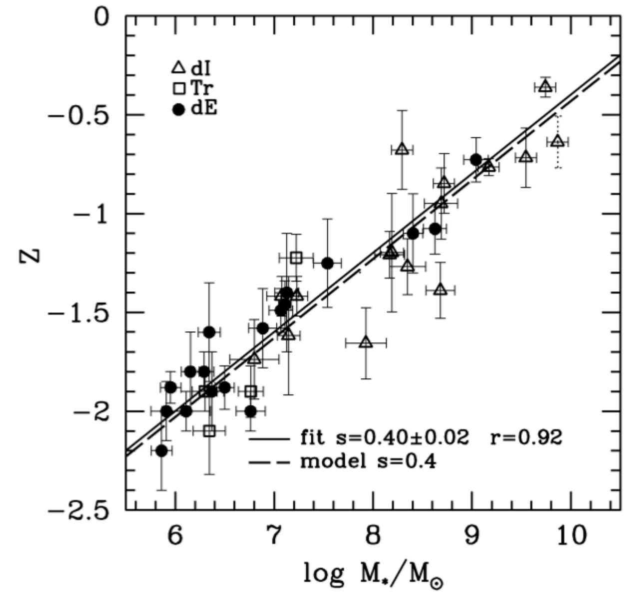


Figure 2. Metallicity versus stellar mass for the Local Group dwarfs (WD). The regression line $Z \propto M_*^{0.40}$ and the toy-model theoretical prediction $Z \propto M_*^{0.4}$ (normalized for best fit) are shown.

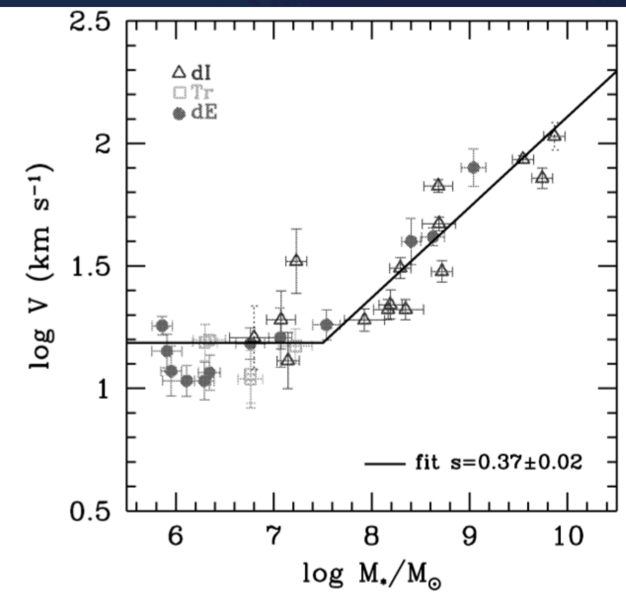
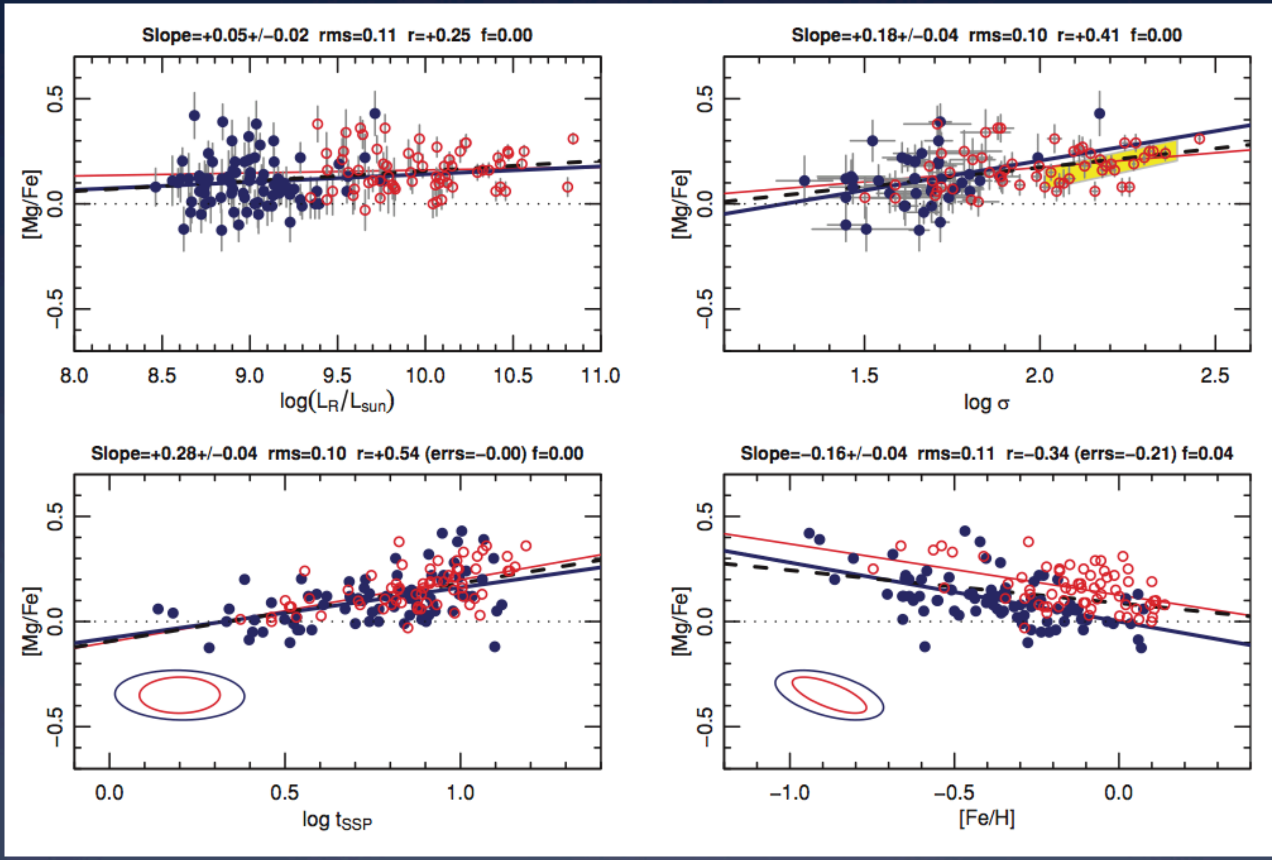


Figure 5. Velocity versus stellar mass for the Local Group dwarfs (WD), using the same data as in Fig. 3. The best fit horizontal segment below $M_* = 3 \times 10^7$ $M_\odot$ and the best fit line at larger stellar masses, $V \propto M_*^{0.37}$, are shown.

- Purely internal regulation of star formation
  - With the exception of metagalactic UV at low mass

Dekel & Woo 2003

Chemical Abundance patterns



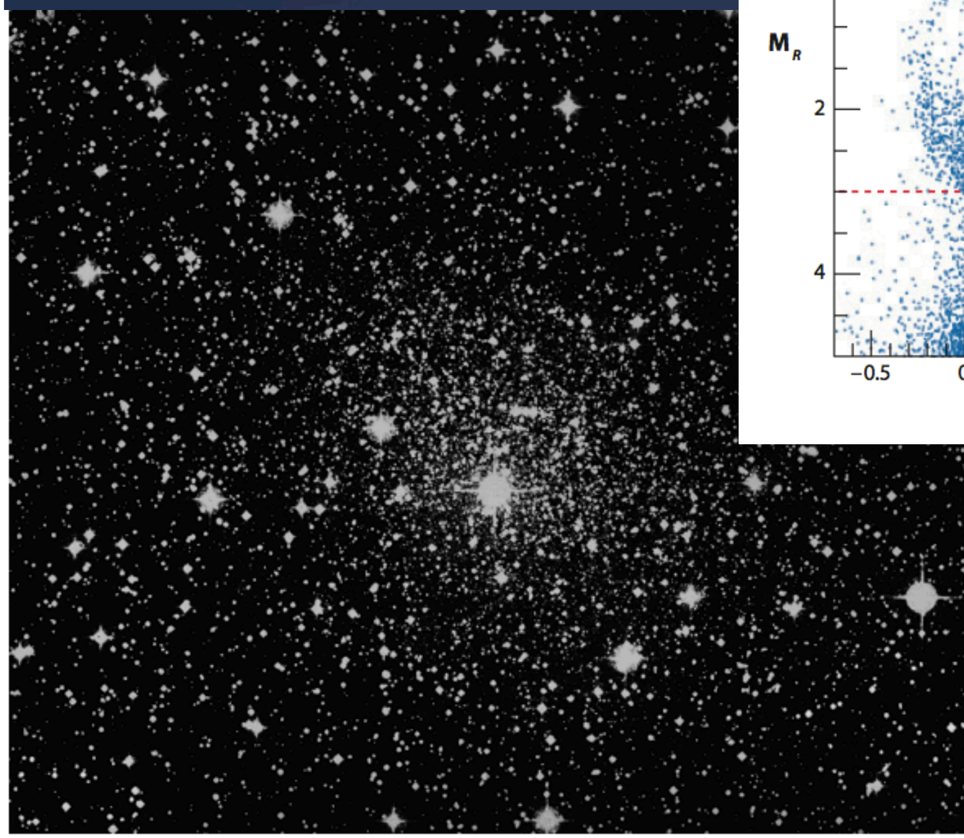
- Favor progressively slower star-formation at lower masses along the red sequence
  - Or alternatively preferential ejection of α elements (e.g. Mg).

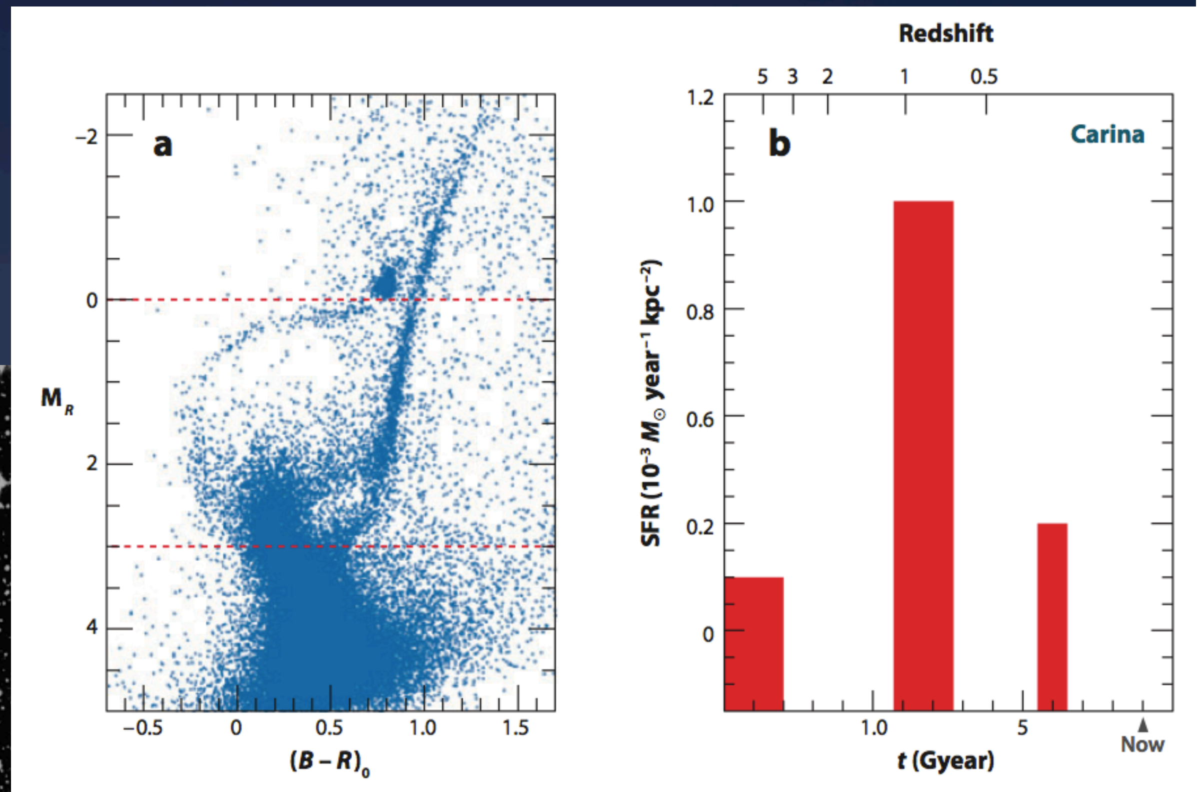
Smith+ 09

Diverse star-formation histories

Carina dSph

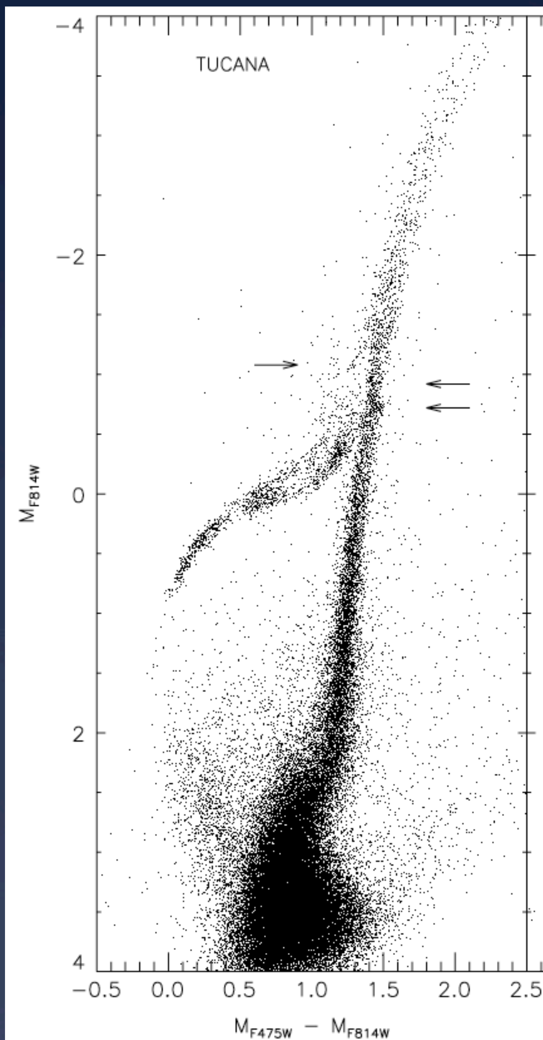
Mateo (reviewed by Tolstoy 09)

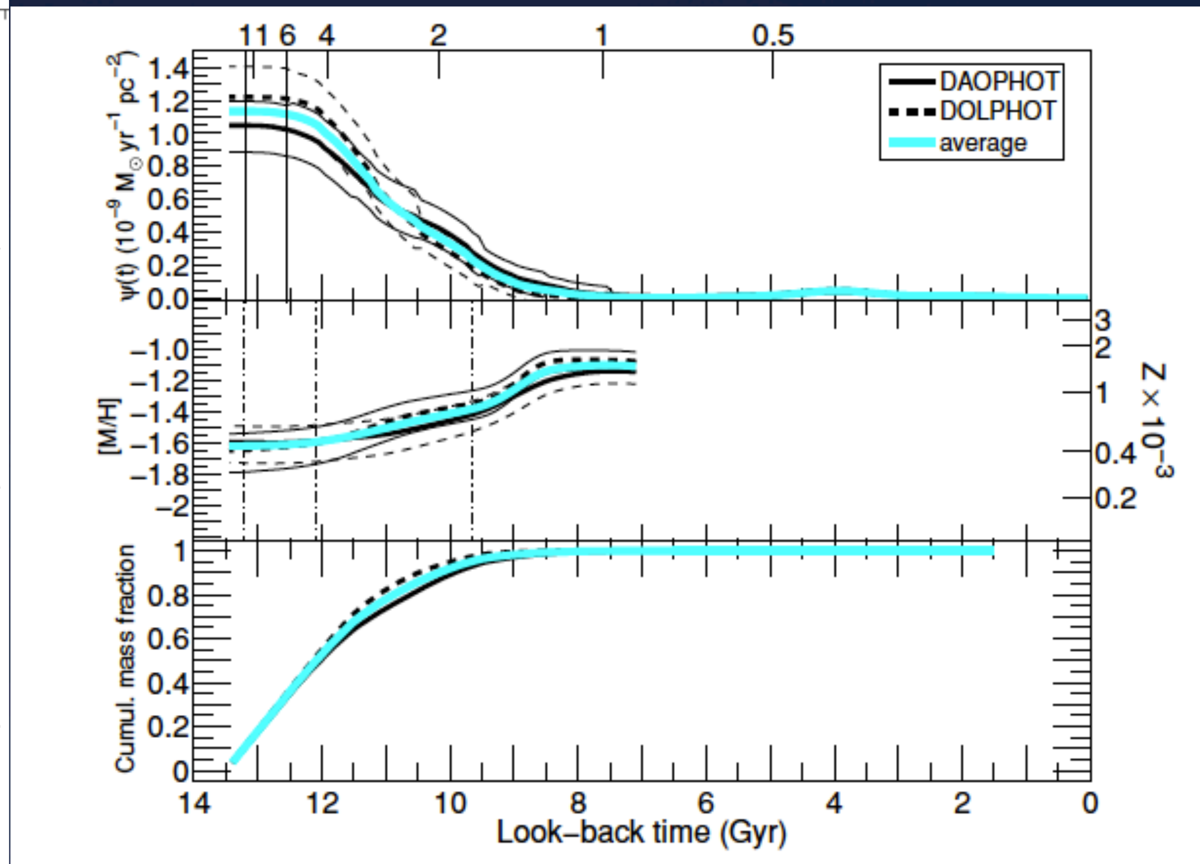




- Multiple episodes
- Long delays between episodes

Tucana (isolated dSph)

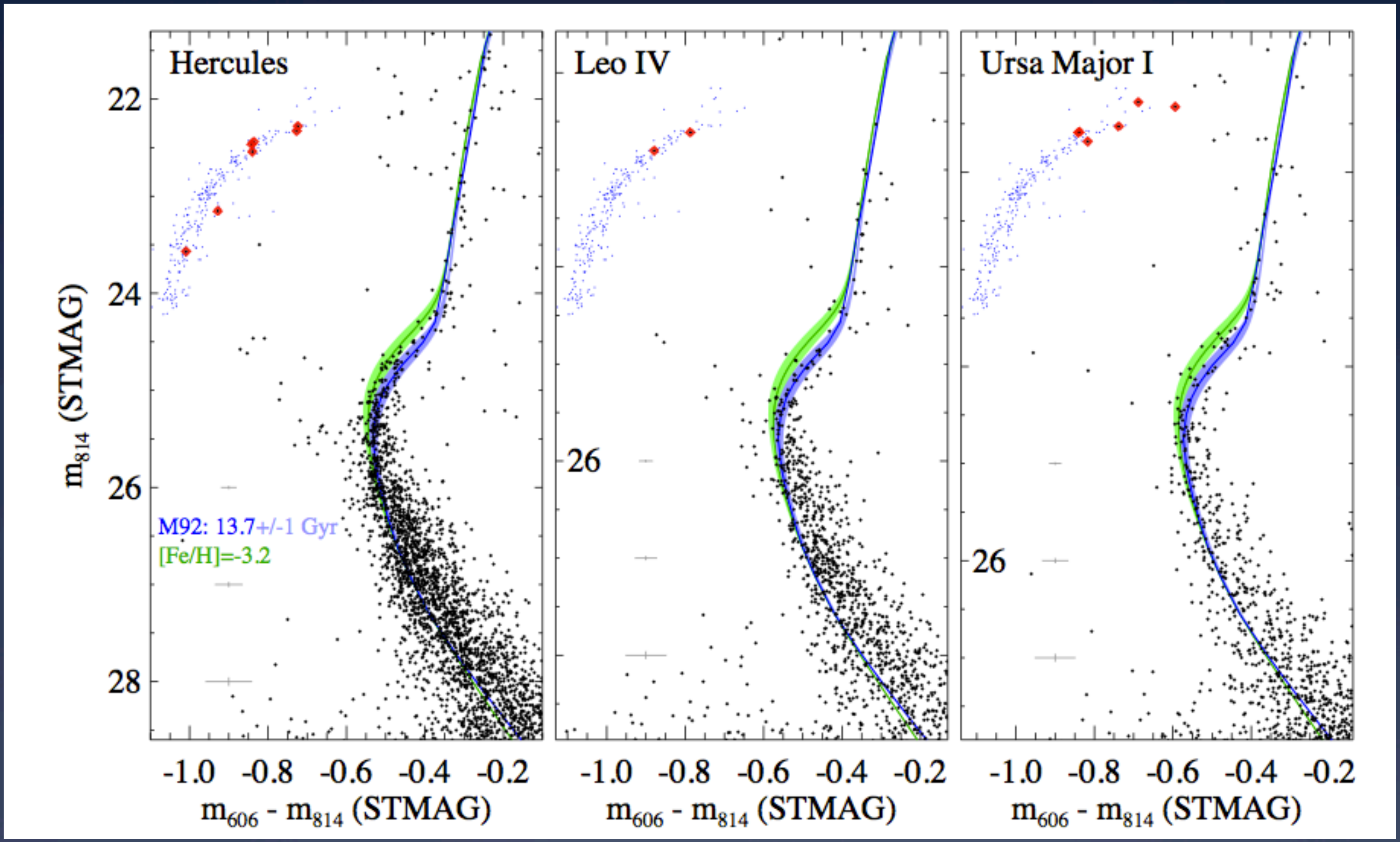




- Exclusively old
- Relatively rapid formation

Monelli+ 2010

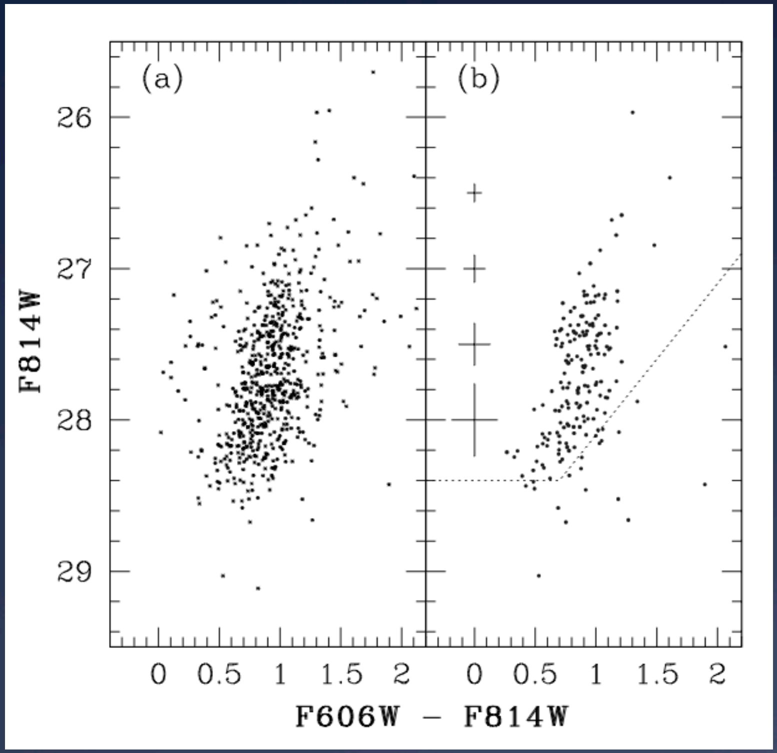
Ultra-faint Milky-Way satellites

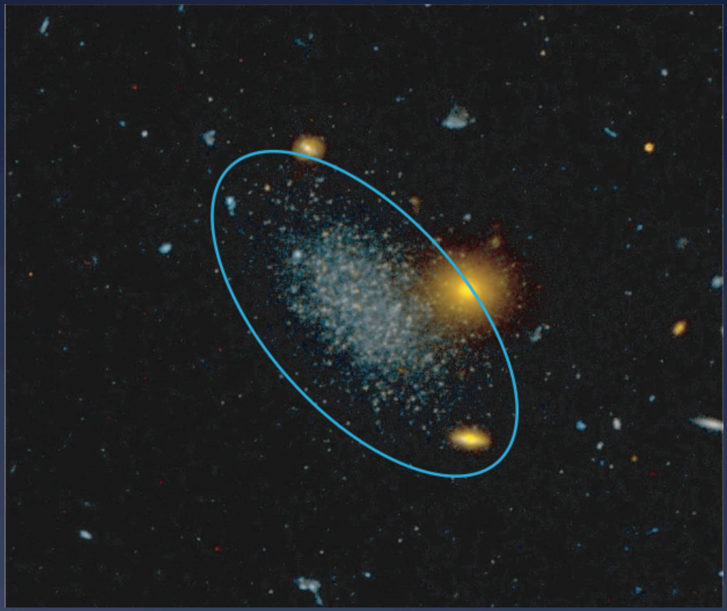


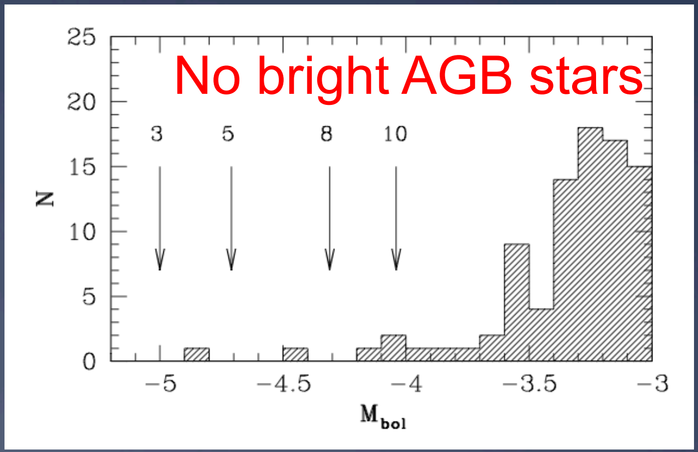
- So far, exclusively old

Brown+ 2012

Virgo cluster dE galaxy



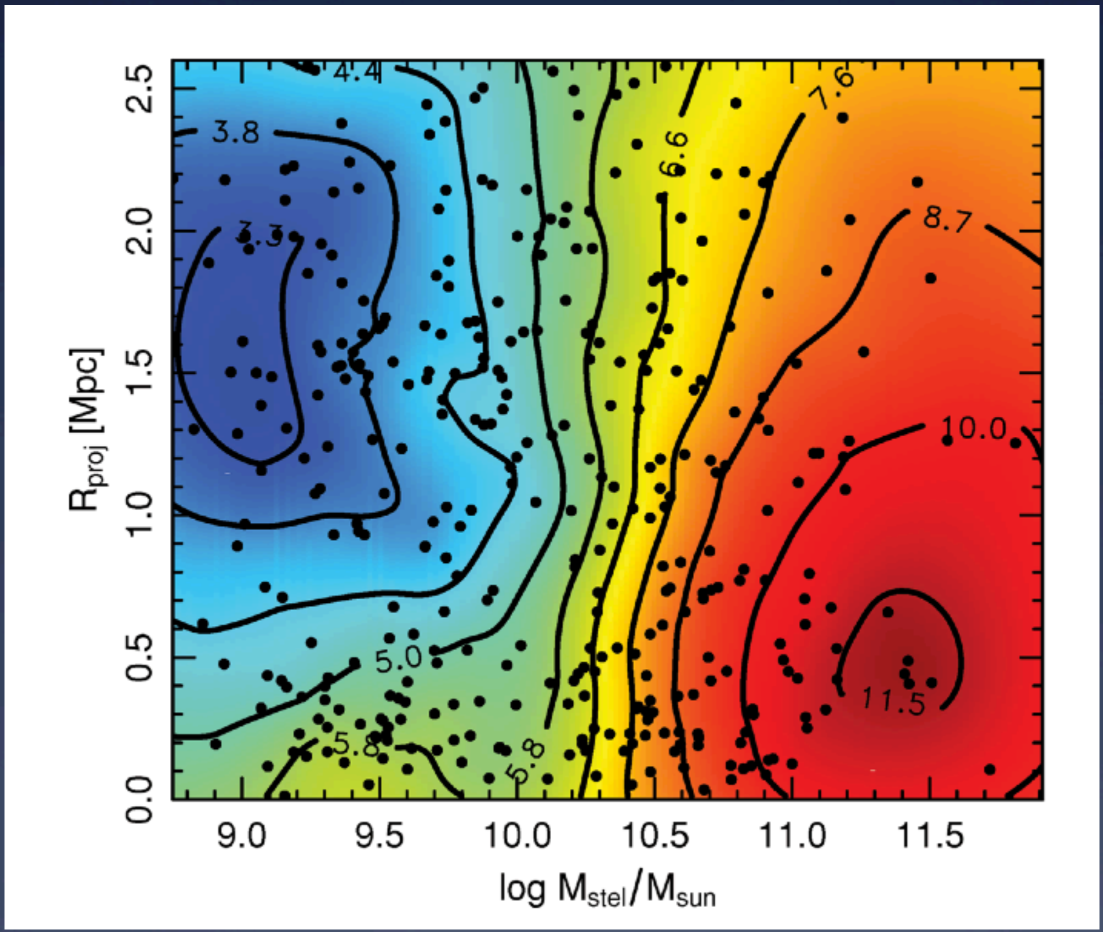




- Serendipitously imaged Virgo dE M_V = -10.6
- No evidence for youth

Durrell+ 2007

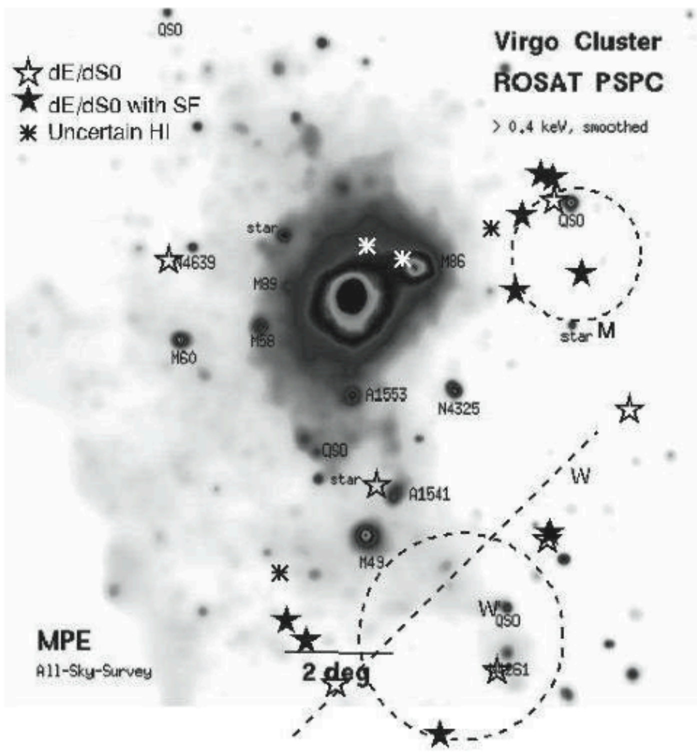
Coma Cluster: Galaxy ages from absorption lines

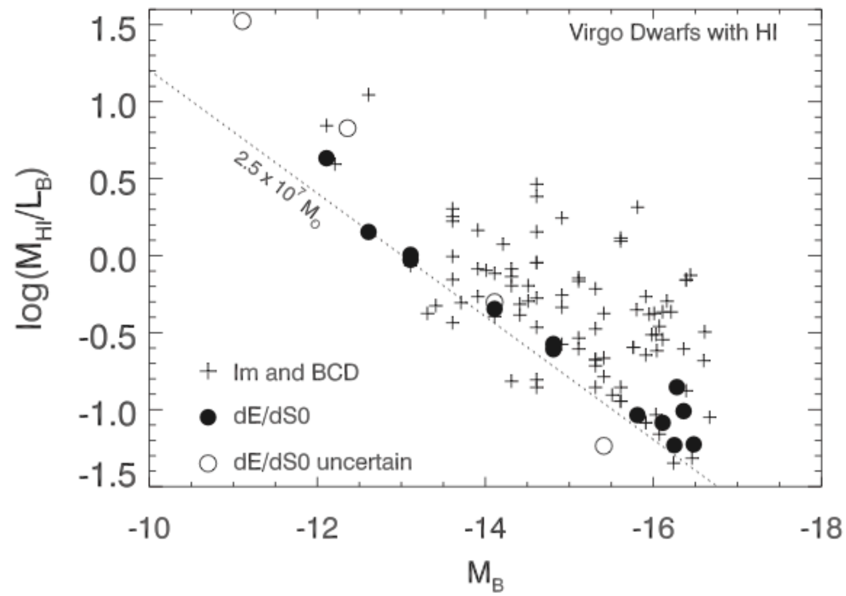


- Dwarfs are younger in the outskirts

Smith+ 2012

Only a few dE have cold gas



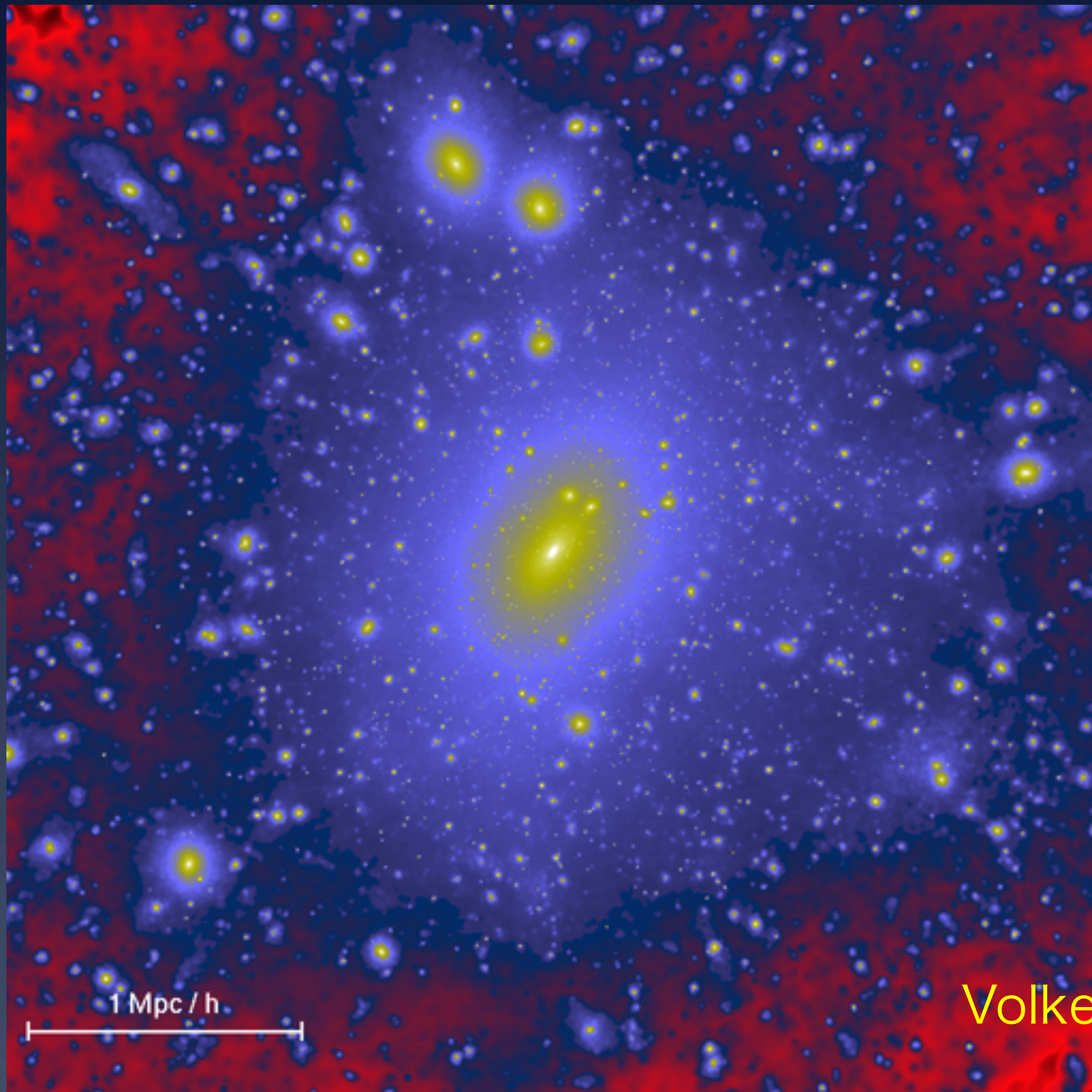


- dE detected in HI tend to be in the outskirts of Virgo

Koopman+ 2010

Cluster dwarfs and the missing satellites

- No missing satellite problem for Virgo
  - Whatever solutions work for the local-group must not break Virgo
  - True dwarfs probably vastly outnumber remnants of stripped giant galaxies
- Cluster dwarfs may survive longer
  - Some dwarfs that would otherwise merge with the central galaxy in their halo are tidally liberated when that halo merges into a larger halo
  - Not obvious that cluster dE's should have same sizes, ages, etc as satellite dE's.

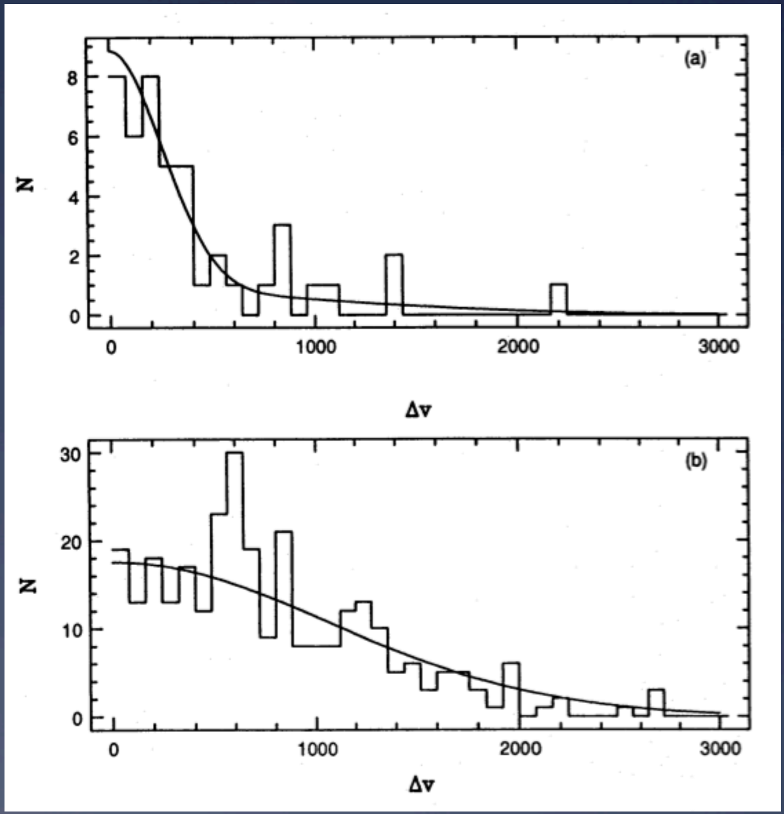


Volker Spring

Bound companions

- Some of the Virgo-cluster dwarfs are still satellites of larger galaxies.
- However, the number of bound dwarfs/giant is 1/3 that in the field
- Galaxies that might have merged with their gaint neighbor in the field due to dynamical friction are probably liberated by the tidal field of the cluster

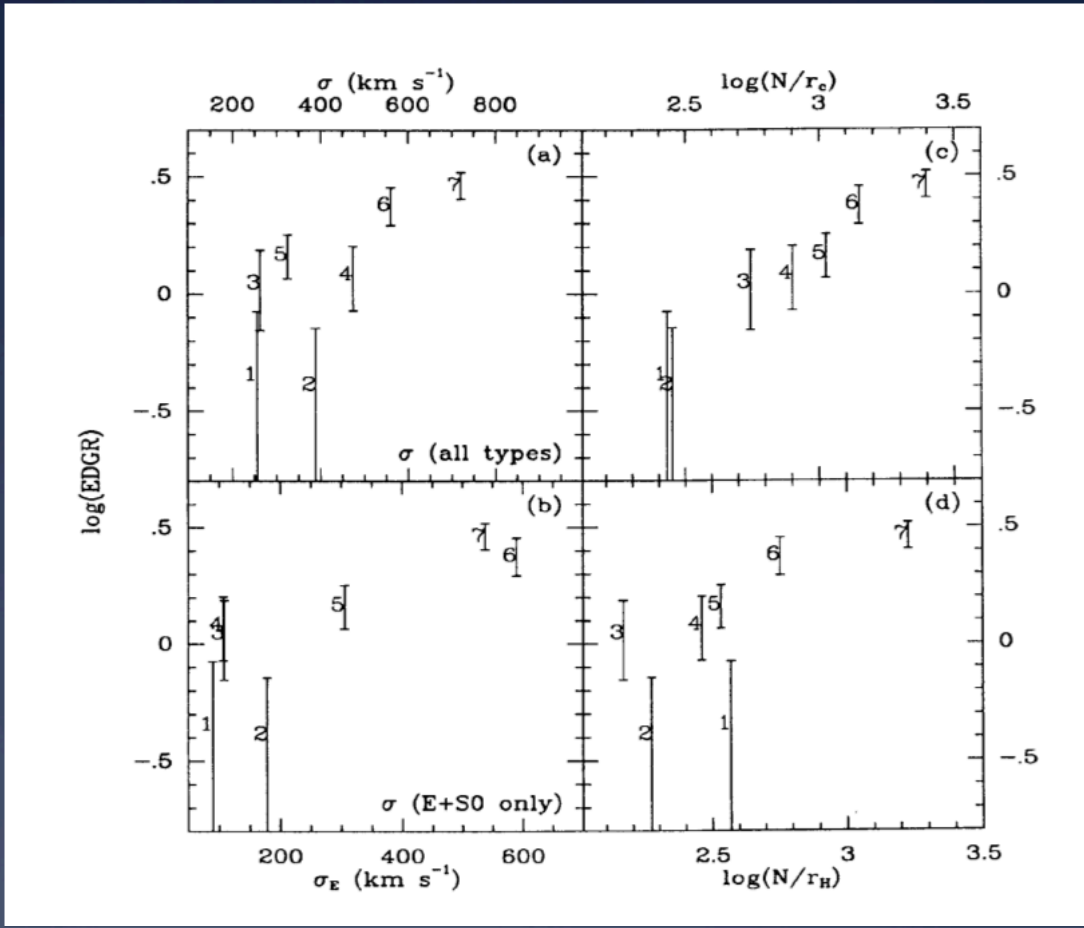
Galaxies close in projection tend to be close in velocity



Ferguson 1992

Dwarf to Giant ratio vs. richness

- More dwarfs/giant in larger halos
- Most pronounced among early types



Ferguson & Sandage 1991

- Varying dwarf/giant ratio evident in the comparison of the cluster and field LF
  - Trentham+05
  - Balogh+01 (near-IR)

790 *N. Trentham, L. Sampson and M. Banerji*

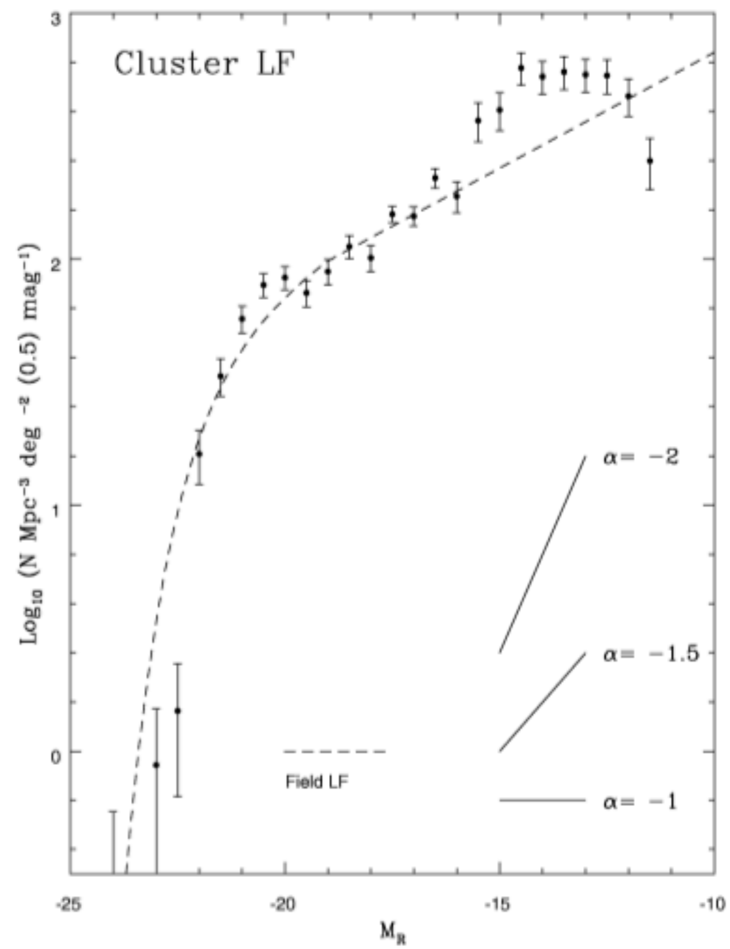


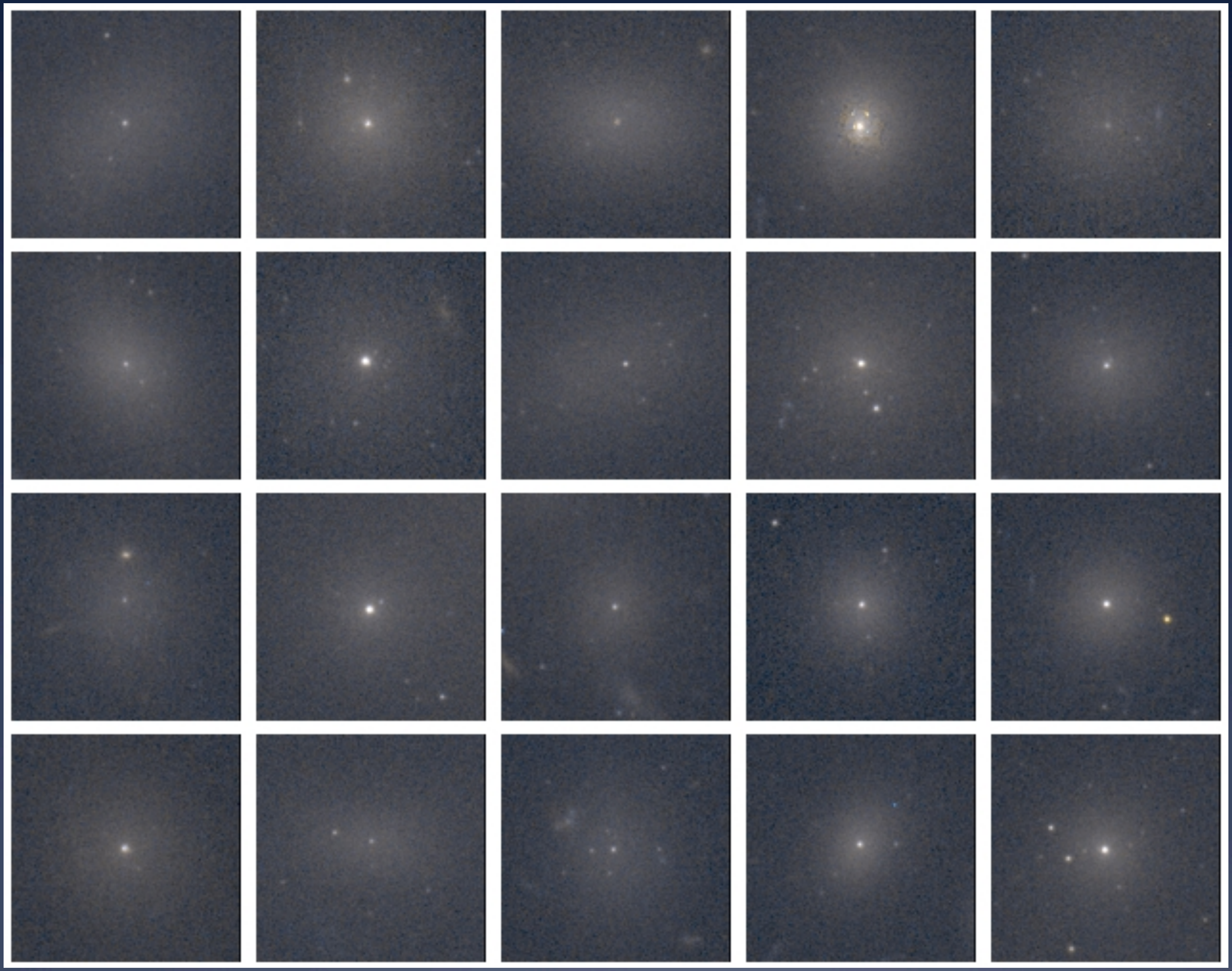
Figure 8. The galaxy cluster LF, computed as described as in the text. The normalization is arbitrarily chosen to be that appropriate for the Coma cluster at $M_R = -21$. The dashed line is the best-fitting field LF, which we approximate by a Schechter function with $M_R^* = -22.0$ and $\alpha^* = -1.28$ brightward of $M_R = -19$ and a power law with $\alpha = -1.24$ faintward of $M_R = -19$.

Trentham+ 05

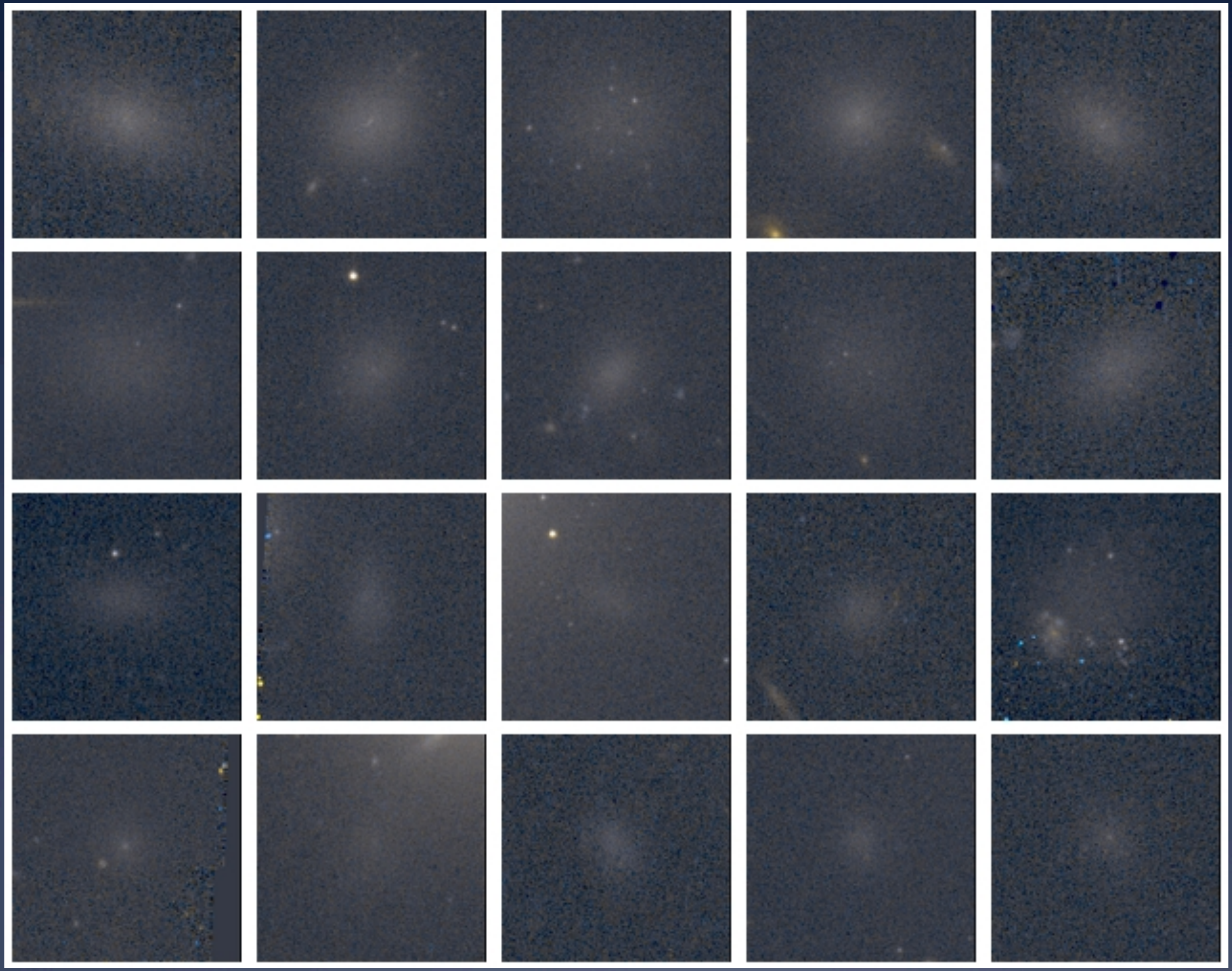
Evidence for an evolutionary sequence within the dE family

- Spatial distribution of nucleated vs. non-nucleated dE
- Ellipticity distributions
- Velocity distributions

Coma Treasury Bright dE,N



Bright dE



Properties of dE nuclei

- Nuclei represent <10% of the total light (typically ~ 2%)
  - Nuclear magnitude increases with galaxy magnitude
  - Generally brighter than globular clusters
- Radii
  - $r_{1/2}$ in Virgo range from 60 to 2 pc (median 4 pc)
- Colors
  - Color-luminosity relation
  - On average redder than surrounding galaxy, with large scatter
  - Some blue ones
- Velocity Dispersions
  - ~10-50 km/s in the brighter ones

Radial trends

Virgo

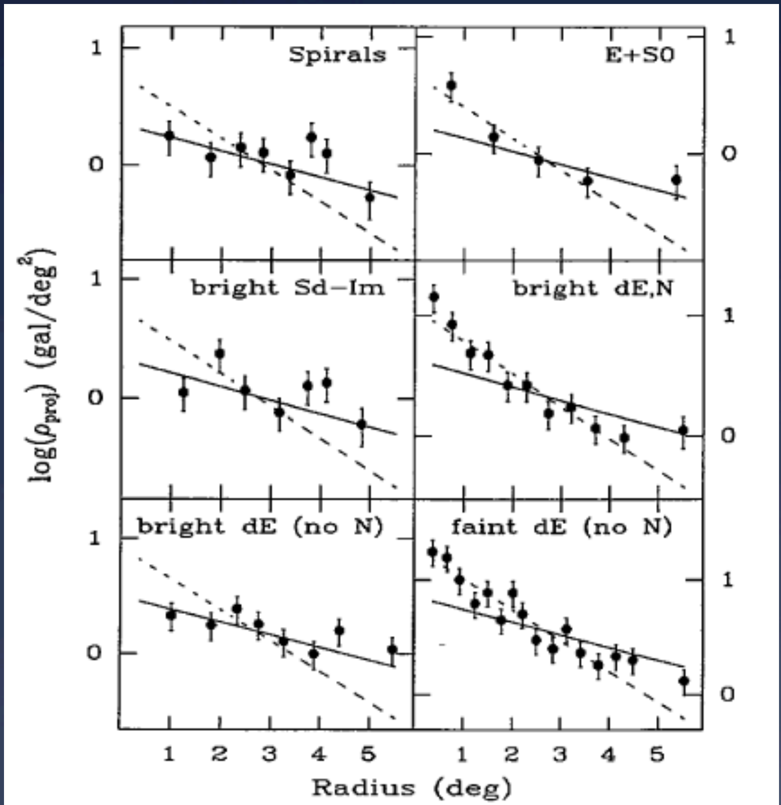


FIG. 1

Fornax

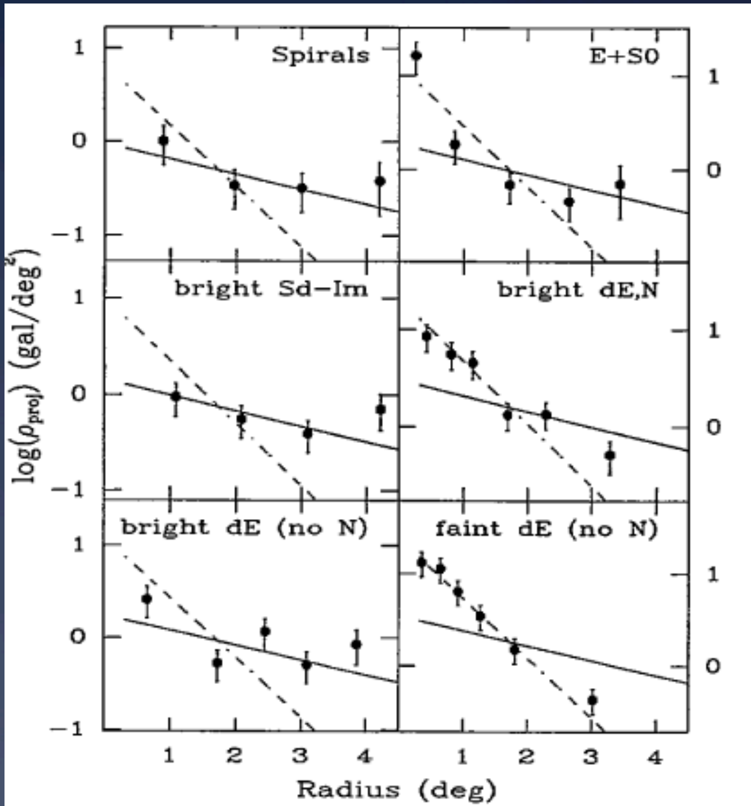


FIG. 2

- Nucleated dE are more centrally concentrated

Ferguson & Sandage 1991

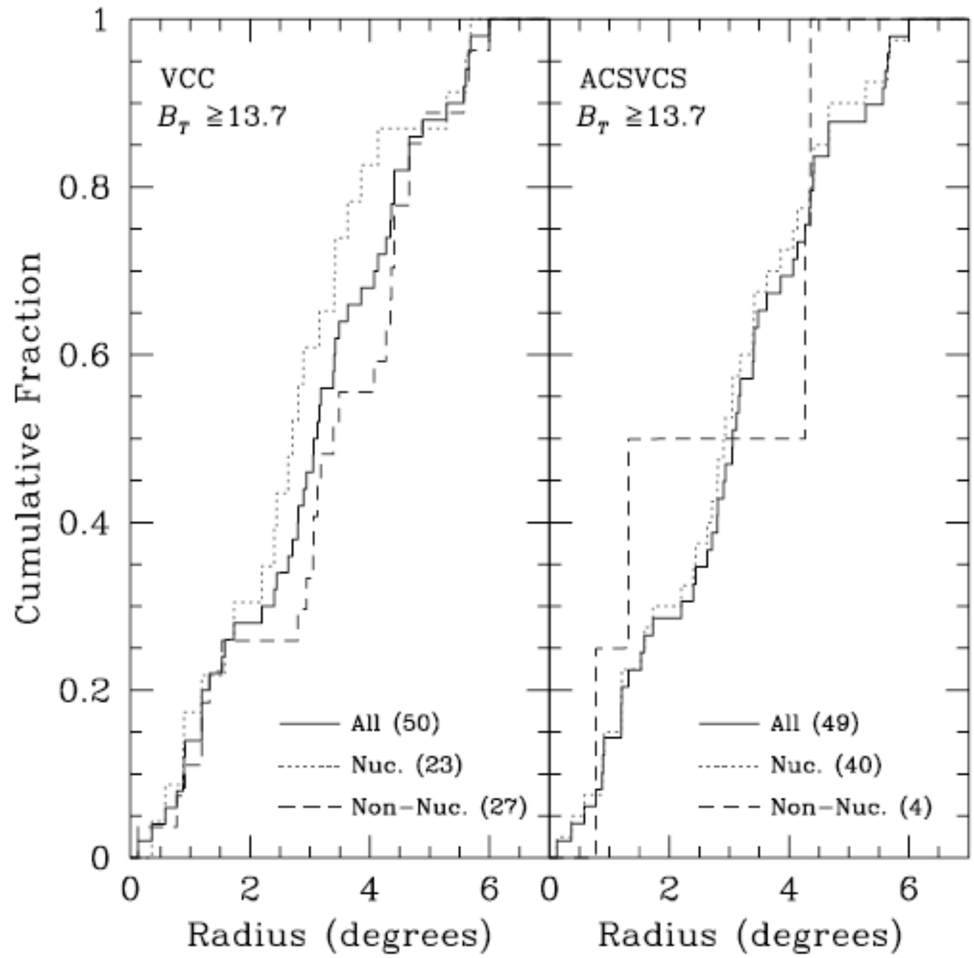


Fig. 12.—*Left*: Cumulative distribution of Virgocentric radii for the 50 galaxies from the ACS Virgo Cluster Survey fainter than $B_T = 13.7$. Using the morphological classifications from BST85, this sample is subdivided into 23 nucleated and 27 nonnucleated galaxies. The dotted and dashed curves show the cumulative distributions for these two samples. *Right*: Cumulative distribution of Virgocentric radii for the 49 galaxies from the ACS Virgo Cluster Survey fainter than $B_T = 13.7$ for which a classification as nucleated or nonnucleated is possible from our ACS images. (One galaxy in this magnitude range, VCC 571, cannot be classified due to the presence of dust.) This sample is shown subdivided into 40 nucleated (type Ia and Ib) and four nonnucleated (type II) galaxies (*dotted and dashed curves, respectively*). The five galaxies with possible offset nuclei have been ex-

Cote et al. 2006

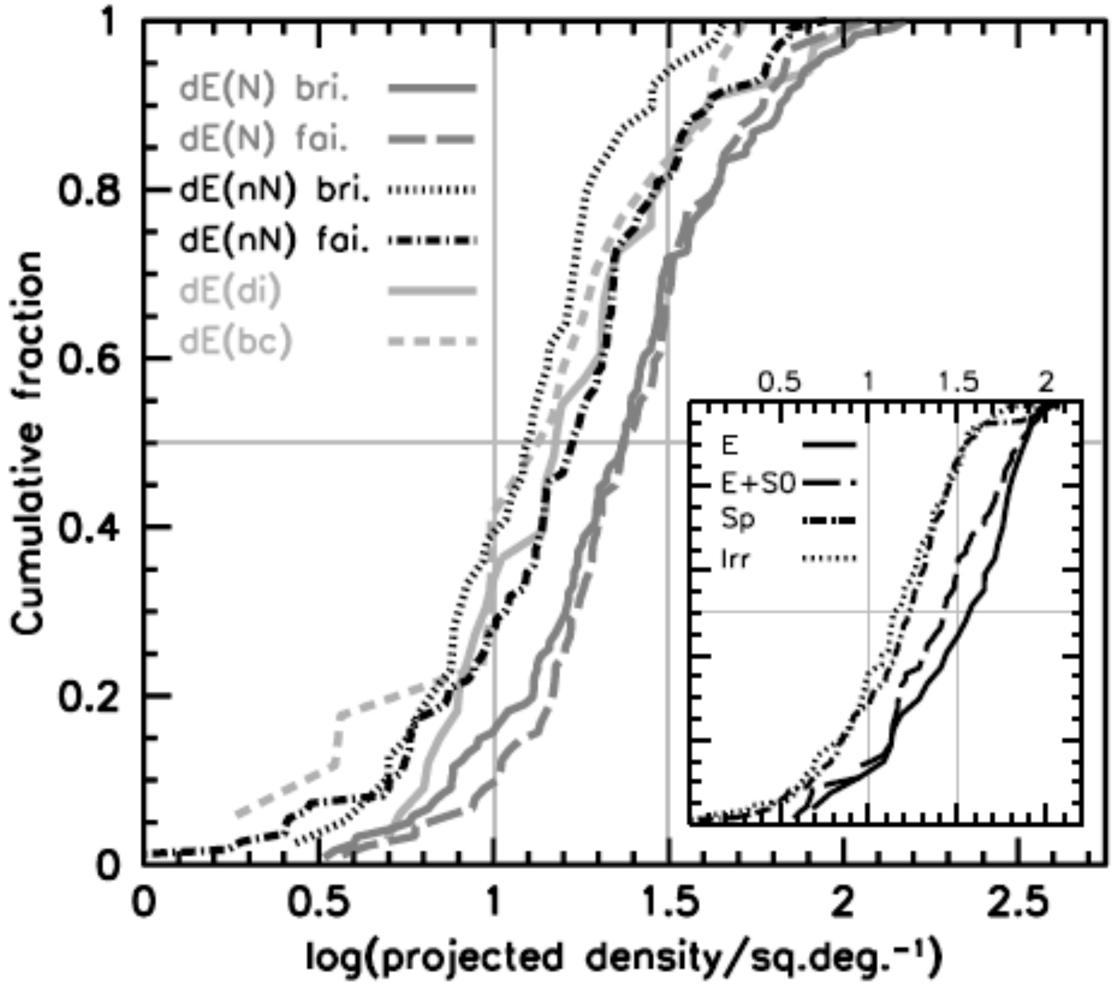
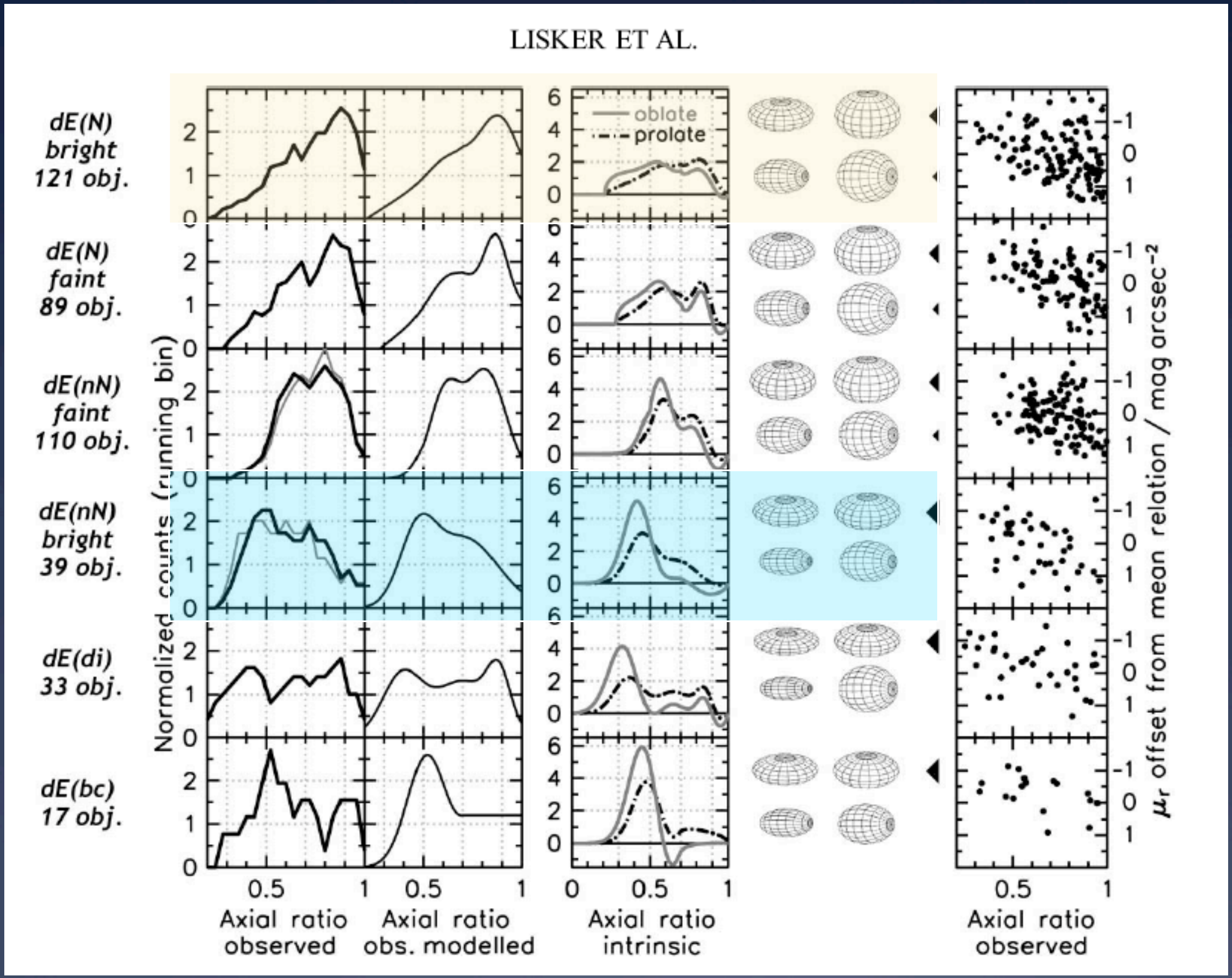


FIG. 6.—Morphology vs. density. Cumulative distribution of local projected densities of our dE subsamples and of Hubble types (*inset*). Following Dressler (1980) and Binggeli et al. (1987), we define a circular area around each galaxy that includes its 10 nearest neighbors (independent of galaxy type), yielding a projected density (number of galaxies per square degree).

Lisker et al. 2006

Virgo Cluster dE shapes (SDSS)



Kinematical distinction

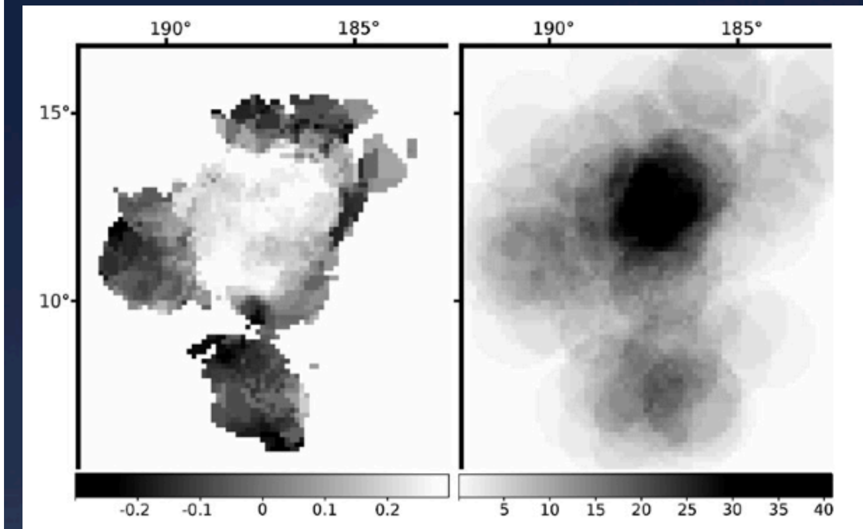
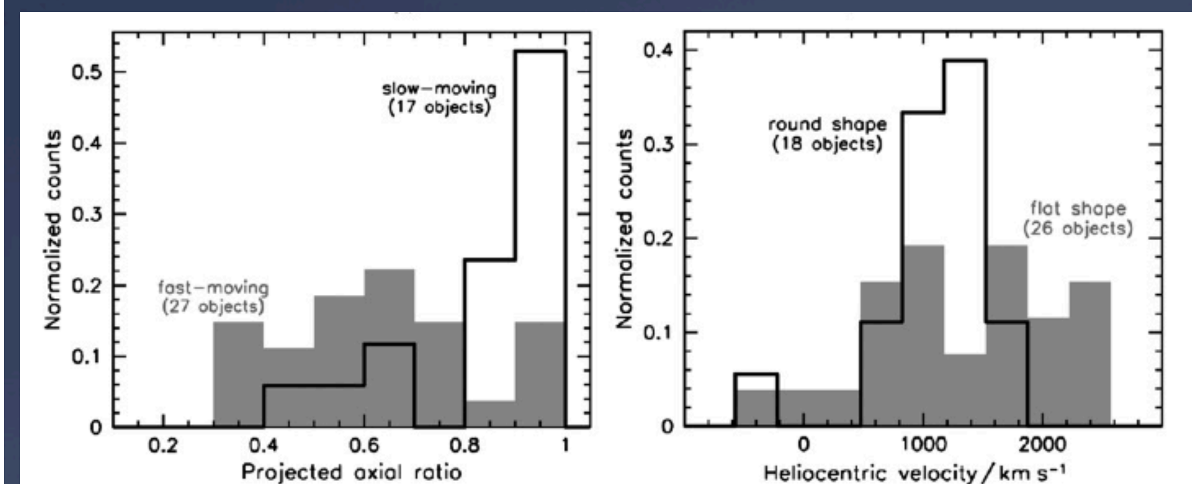


Figure 2. Map of axial ratio differences. Left: map of the Virgo cluster, with the grayscale level indicating the difference between the local median axial ratio of slow and fast galaxies, according to the scale given below the figure. In bright regions, slow galaxies are rounder than fast ones, while this is reversed in dark regions. The map was calculated using circular areas of 1°.27 radius

- Round dE tend to have lower velocities relative to the Virgo systemic velocity
- Hypothesis is that these are the old ones.



Lisker+ 2009

Emerging picture

- Dwarfs near the centers of clusters today fell in early
  - Older, redder, rounder, and nucleated
  - Probably already quenched in their group environment before the cluster formed
- Recent arrivals are
  - Younger, flatter, non-nucleated
  - Also often members of infalling groups, and hence “pre-quenched”

Emerging picture

- Tight scaling relations are a bit of a puzzle
  - Mass-metallicity relation suggests that most of the star-formation was self-regulated (probably prior to z~0.5)
    - Except at V_c<30 km/s where background UV suppression was also important.
  - Dwarfs near the center probably originally came from more massive halos at fixed present-day stellar mass.
    - A bit of a coincidence that the scaling relations are as tight as they are.
    - Should look for departures.