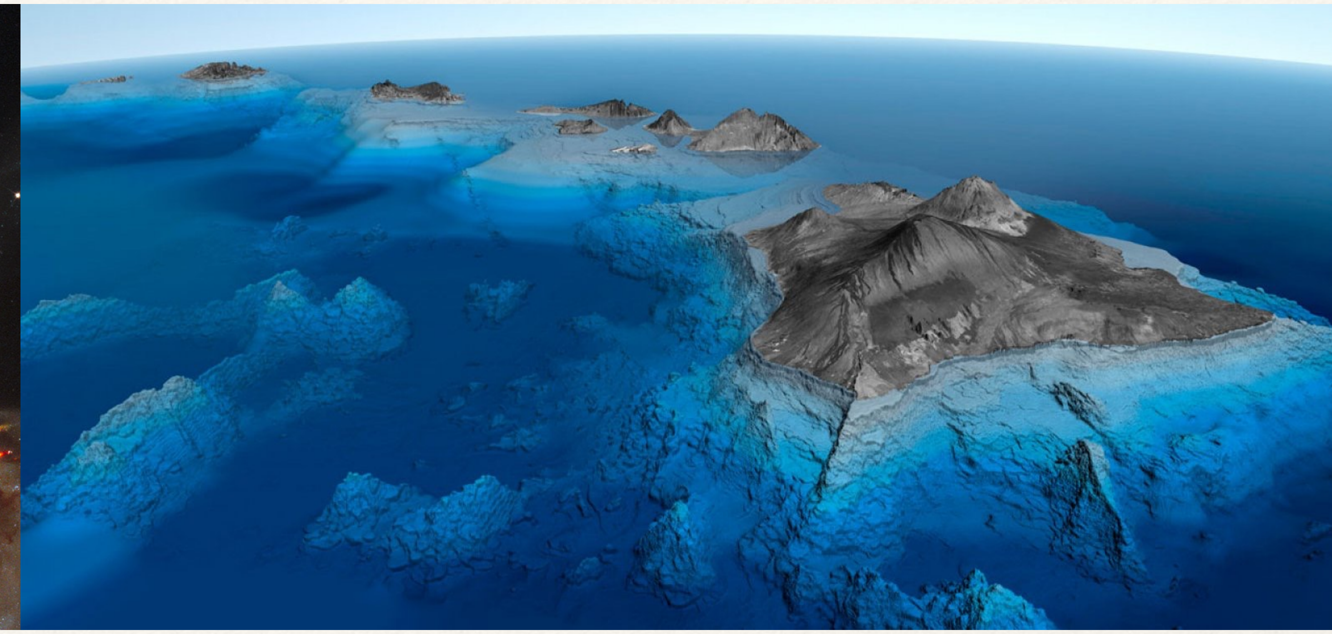


Getting to know the "island universes" out there.

Galaxies I

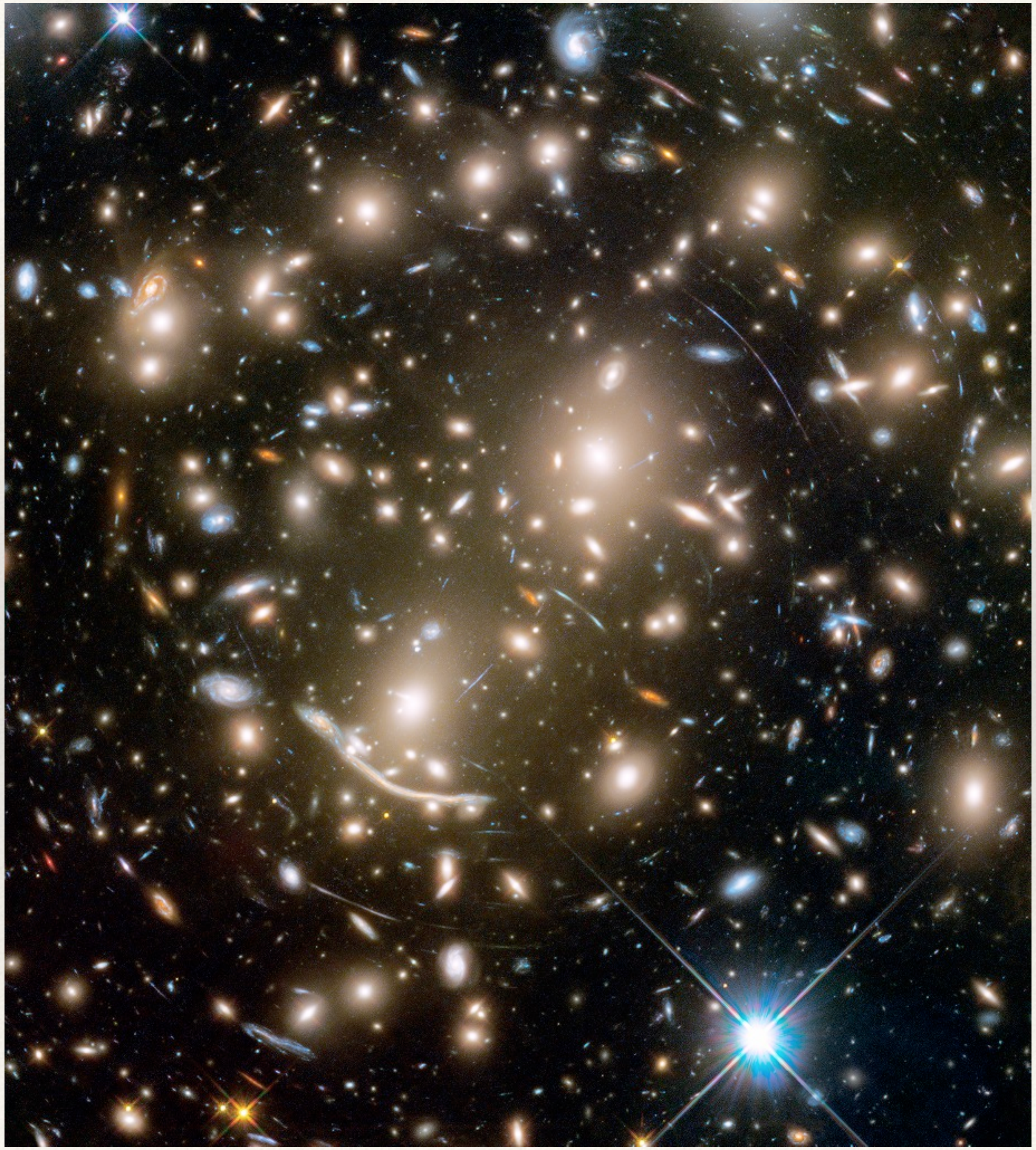
ASTR 555
Dr. Jon Holtzman

Warm-up

- Which class of galaxy is more heterogeneous — spiral galaxies or elliptical galaxies? Consider:
  - Surface brightness profiles
  - Structural components
  - Kinematics
  - Scaling relations
  - Gas and dust
  - Spectra & Stellar population(s)

Outline for Today

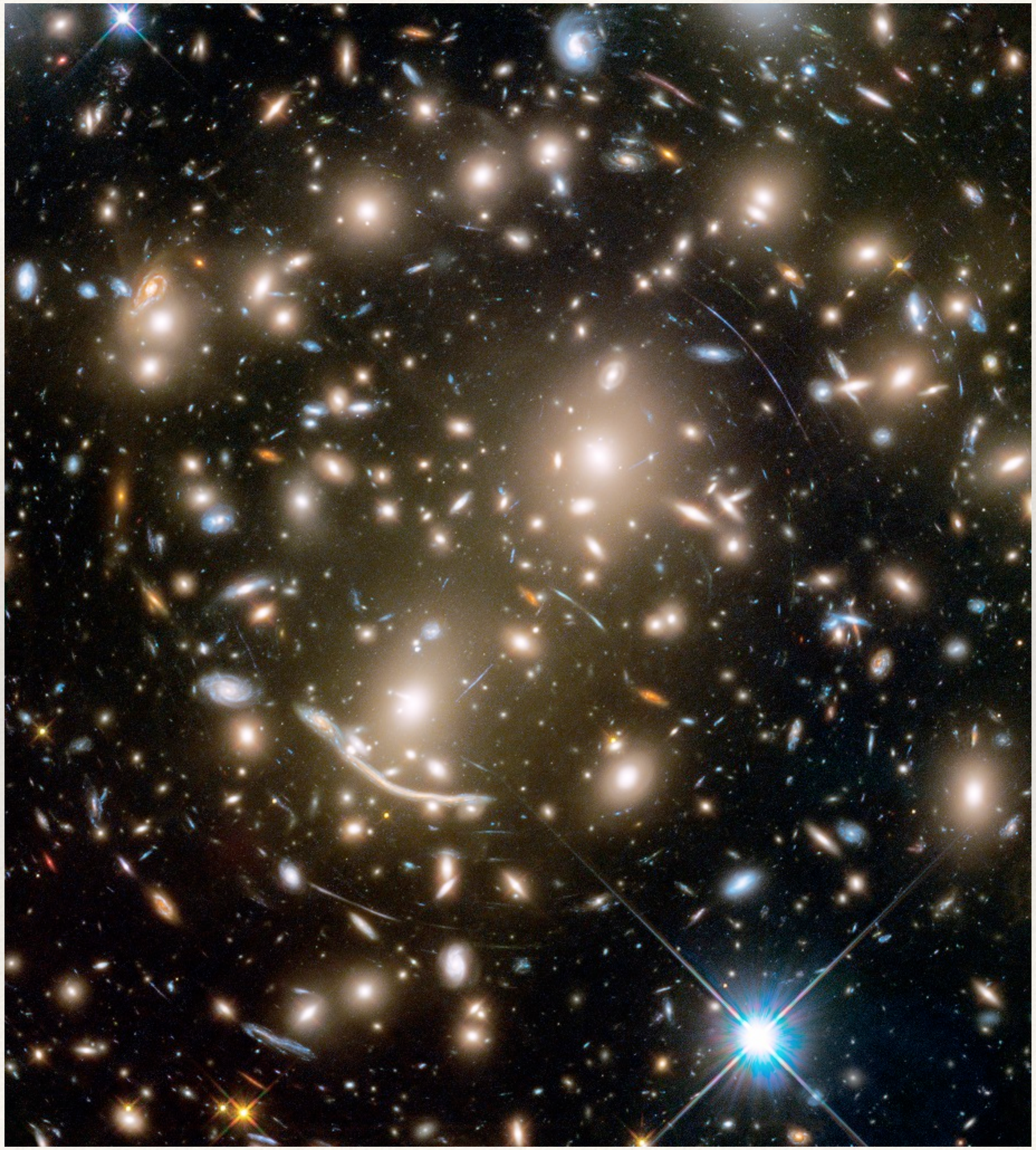
- Galaxy Population - Summary:
  - Galaxy scaling relations
- Galaxy Population - Environments:
  - Clustering
  - Galaxy Clusters and Cluster Galaxies



Abell 370 (Image Credit: NASA, ESA, J. Lotz, HFF Team STScI)

Galaxy Population - Summary: Scaling Relations

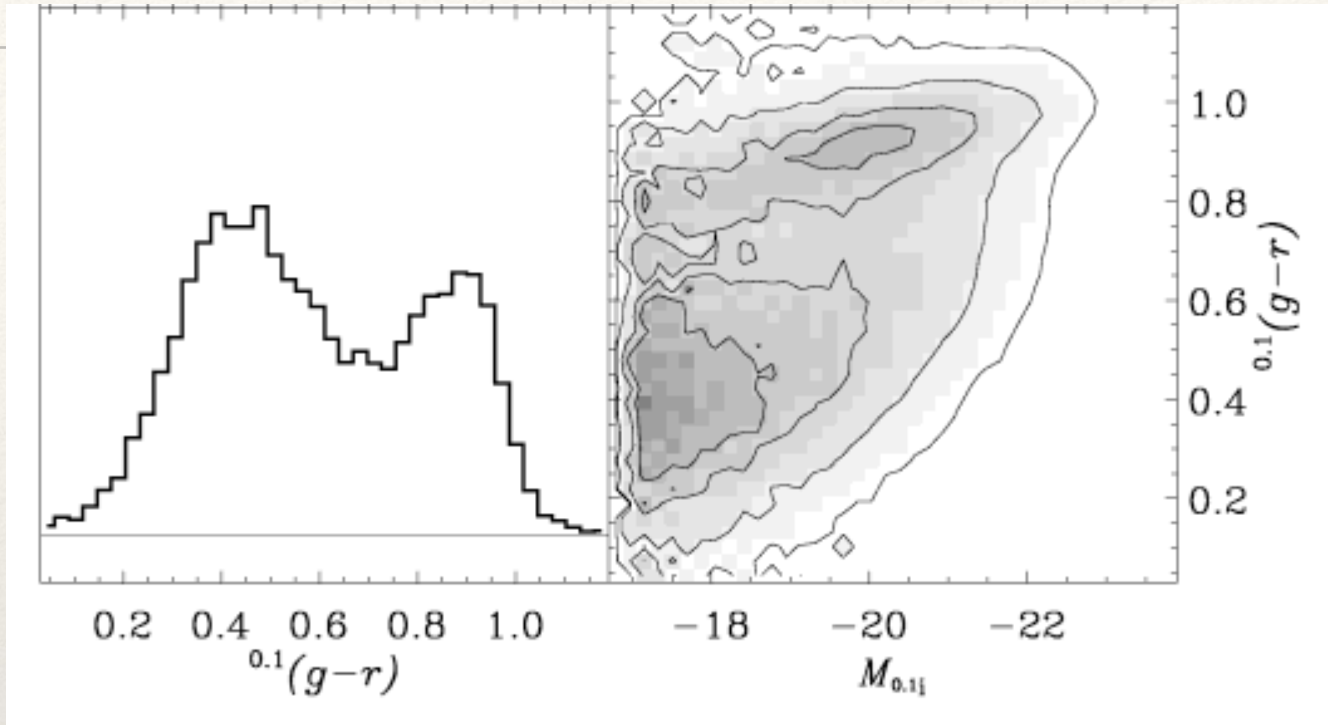
- Galaxies exhibit regularities — systematic correlations of global properties
- Must be reproduced / understood in any model for galaxy formation and evolution



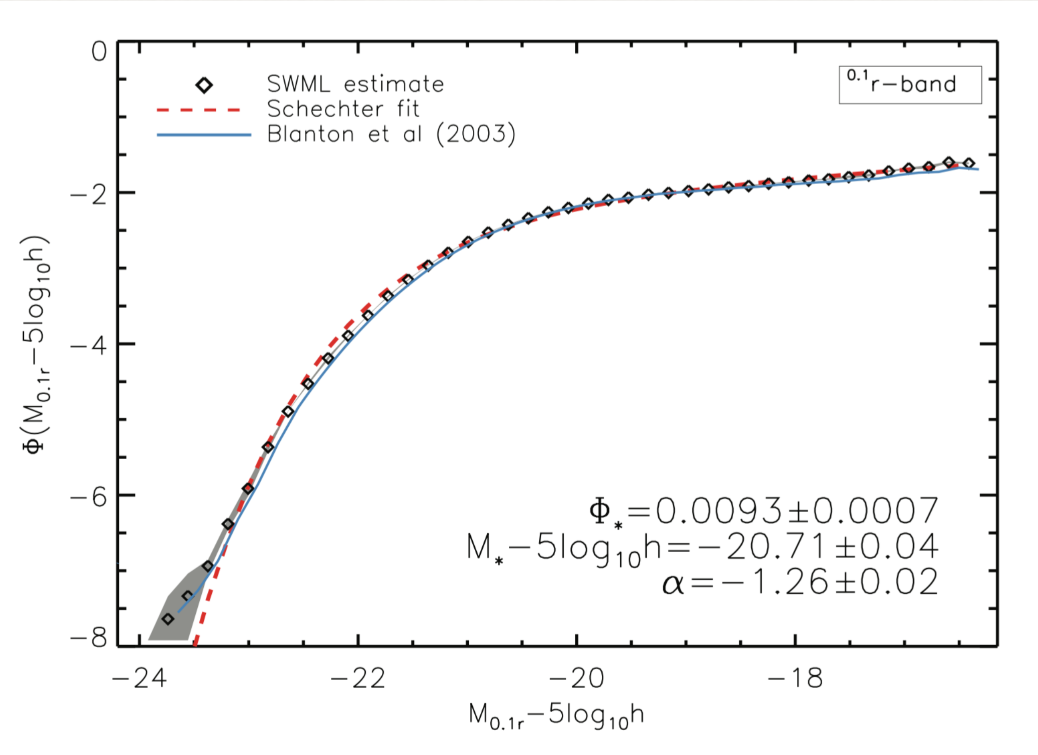
Abell 370 (Image Credit: NASA, ESA, J. Lotz, HFF Team STScI)

Galaxy Population - Summary: Scaling Relations

- **Population:**
  - Color Bimodality
    - red sequence / blue cloud
  - Luminosity Function
    - fit well with a Schechter function with certain parameters



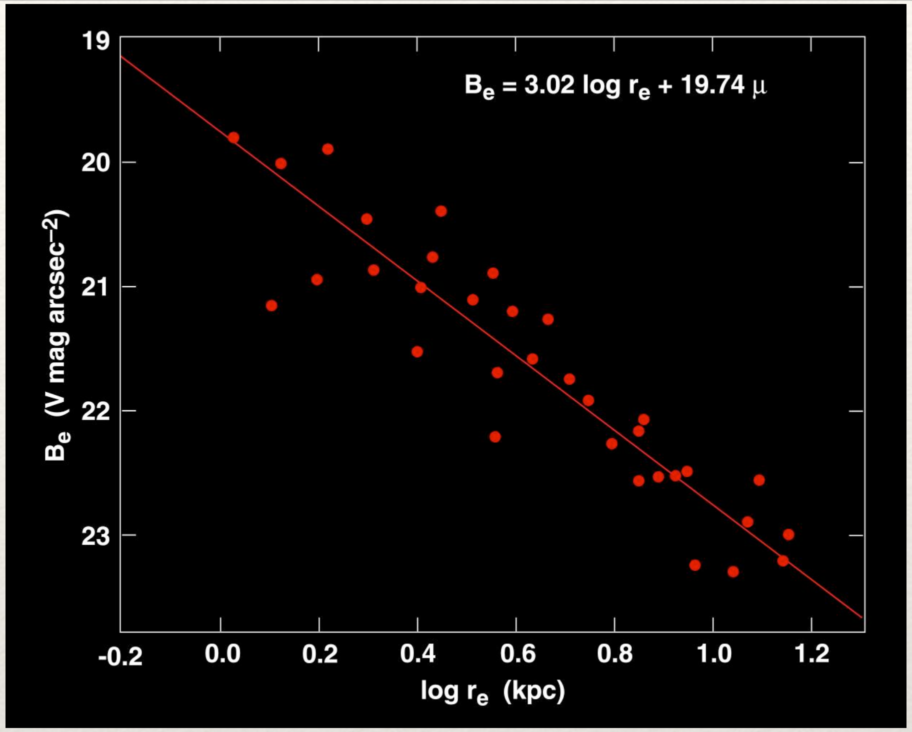
Mo, van den Bosch, & White; Figure 2.27



Montero-Dorta & Prada 2009

Galaxy Population - Summary: Scaling Relations

- **Structural:**
  - Luminosity-SB, L-r_e, Kormendy Relations
  - Isophotal shape-luminosity for ellipticals (higher L, more boxy isophotes)
  - Luminous spirals are larger and higher surface brightness



Kormendy 1977 (PhD Thesis)

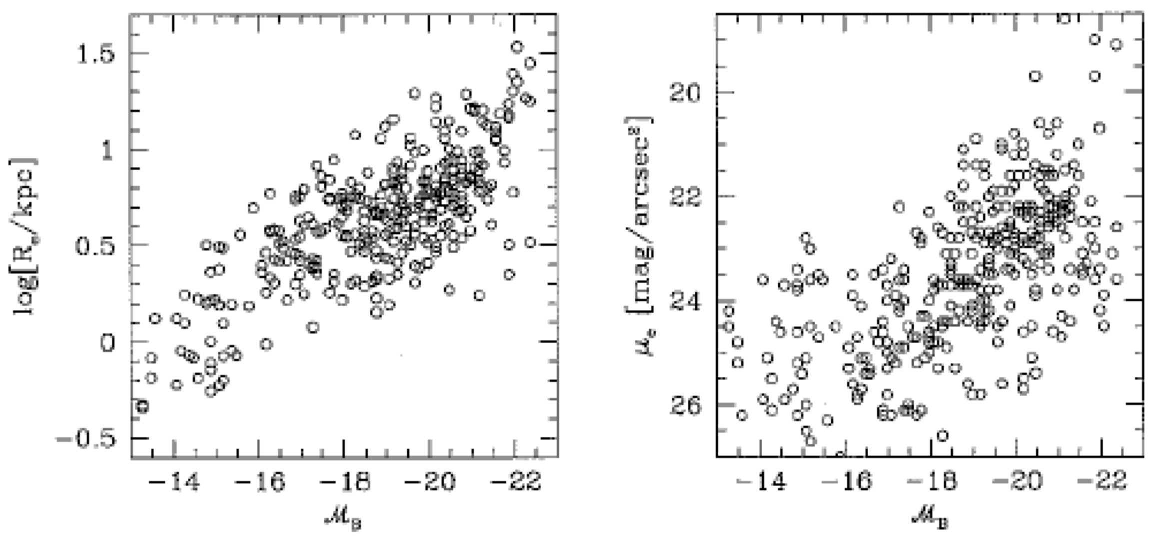


Fig. 2.20. The effective radius (left panel) and the surface brightness at the effective radius (right panel) of disk dominated galaxies plotted against their absolute magnitude in the *B*-band. [Based on data published in Impey et al. (1996b)]

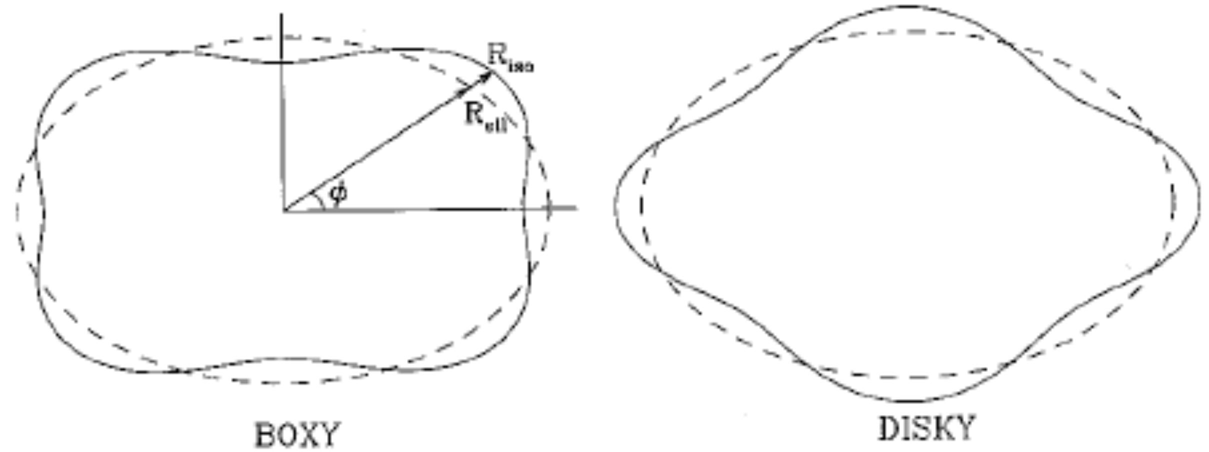


Fig. 2.15. An illustration of boxy and disky isophotes (solid curves). The dashed curves are corresponding best-fit ellipses.

Galaxy Population - Summary

- **Kinematic:**
  - Faber-Jackson Relation
  - Luminosity-rotation for ellipticals (higher L, less rotation)
  - Stellar & Baryonic Tully-Fisher Relation

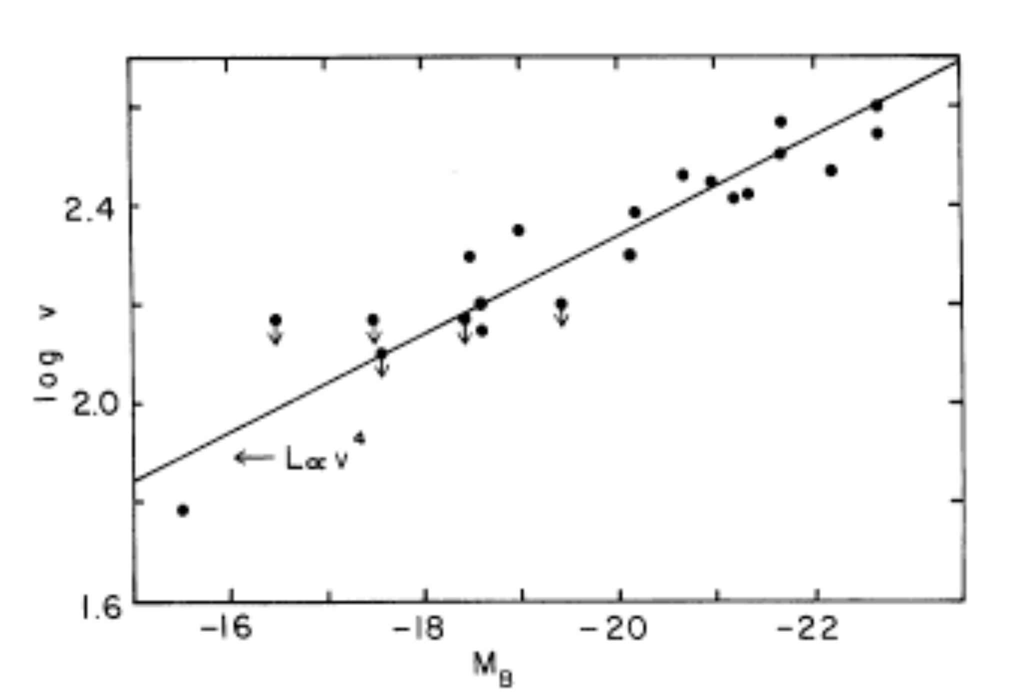
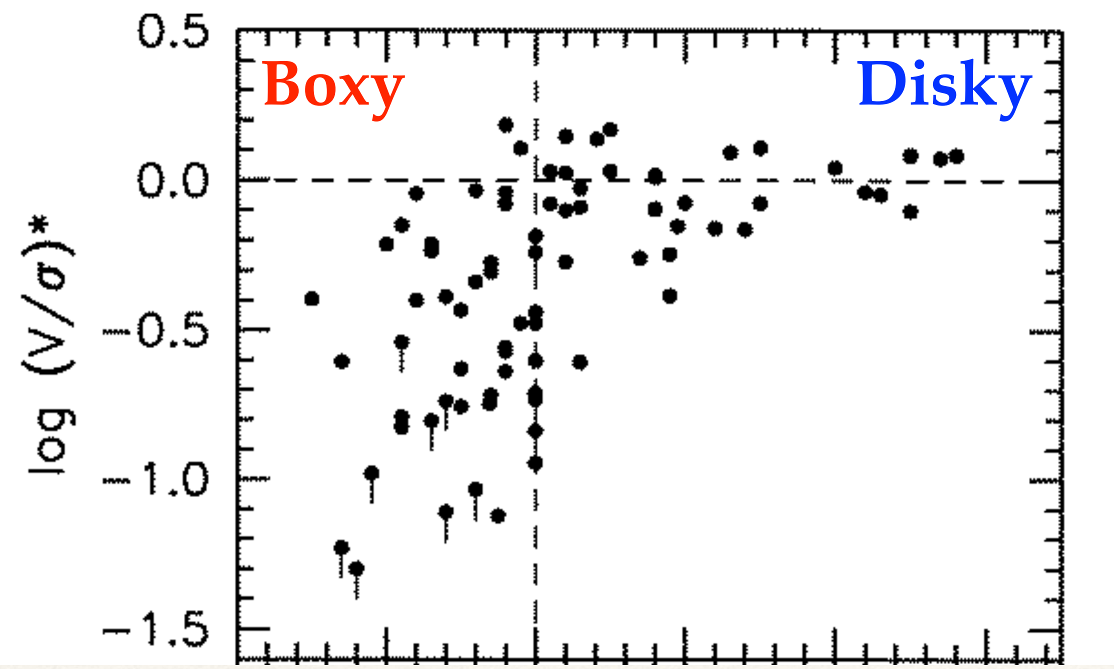


Fig. 16.—Line-of-sight velocity dispersions versus absolute magnitude from Table 1. The point with smallest velocity corresponds to M32, for which the velocity dispersion (60 km s^{-1}) was taken from Richstone and Sargent (1972).

Faber & Jackson 1976

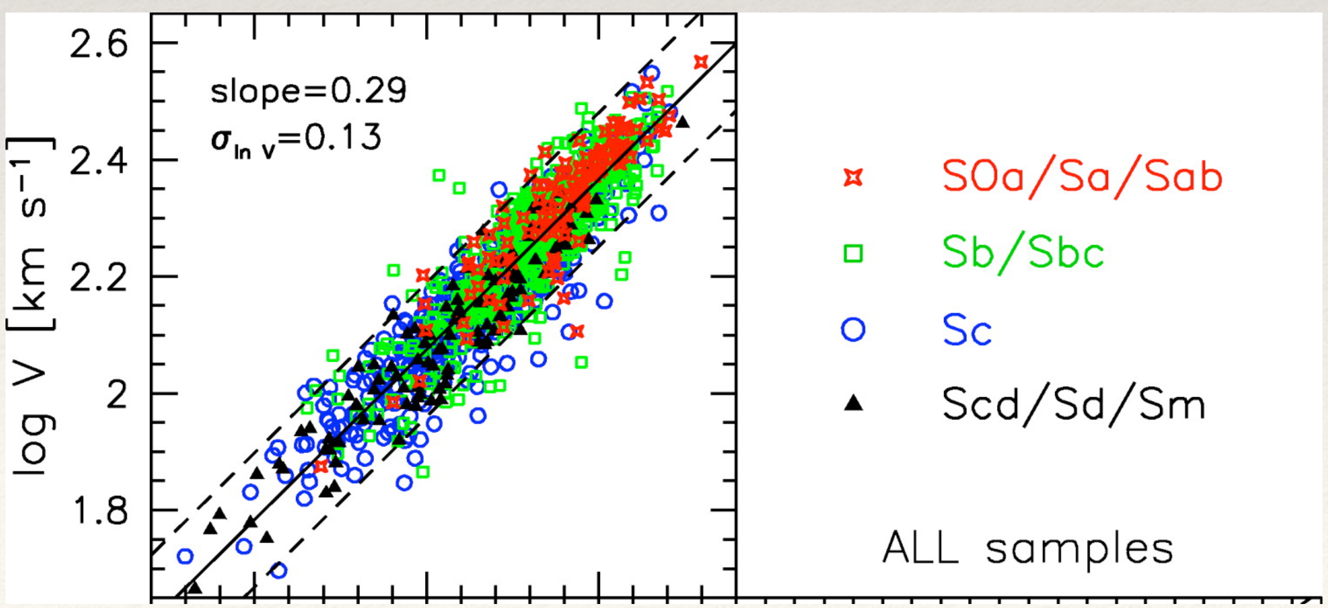
100 a_4/a



Kormendy & Bender (Fig 2)

Log(L/L_o)

Courteau et al. 2007



Galaxy Population - Summary: Scaling Relations

- **Structural/Kinematic:**
  - Fundamental Plane of elliptical galaxies
  - Well approximated by assumption of virial equilibrium

$$r_e = \mathbf{k} \left(\frac{M}{L}\right)^{-1} \sigma_0^2 I_e^{-1}$$

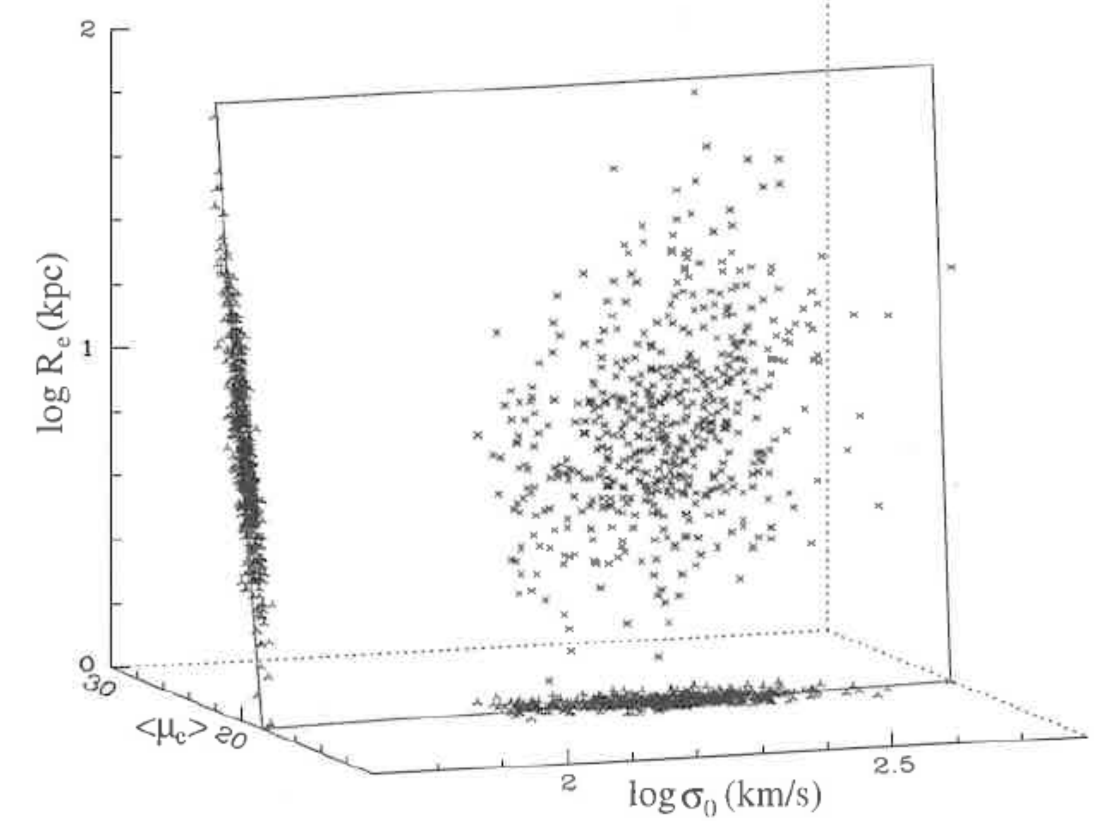
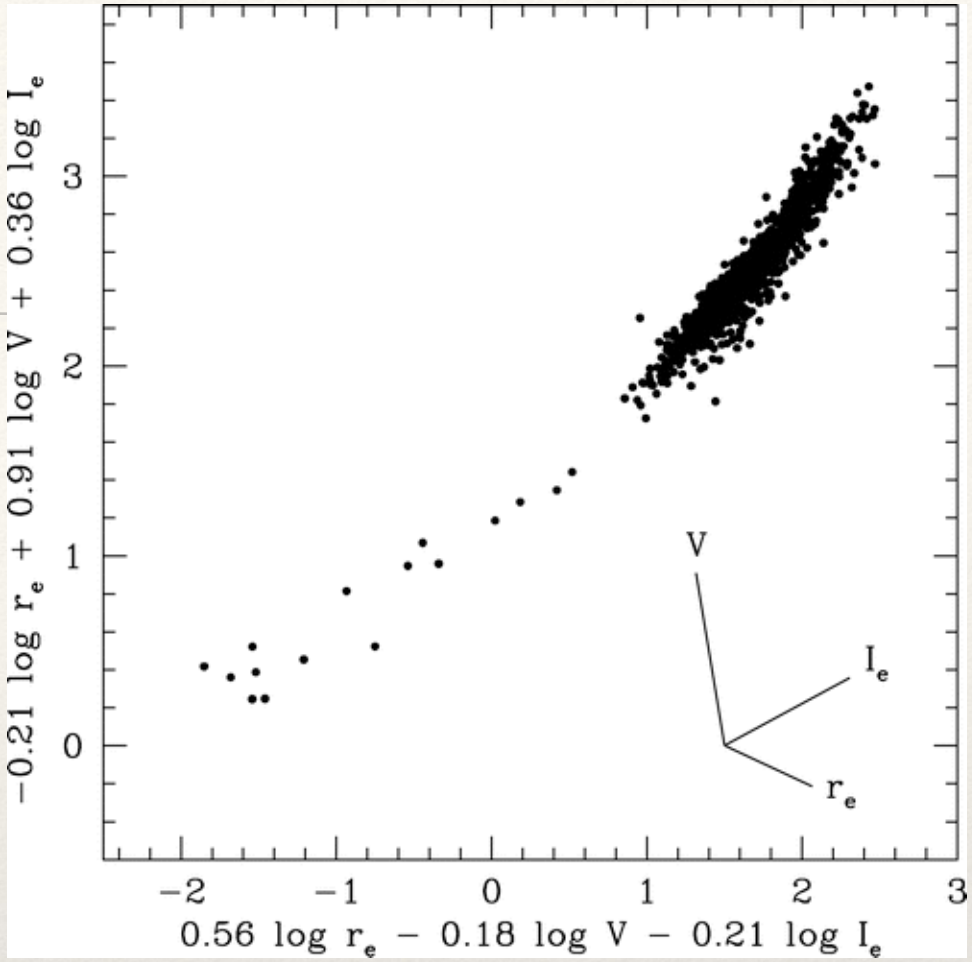


Fig. 2.18. The fundamental plane of elliptical galaxies in the $\log R_e$-$\log \sigma_0$-$\langle\mu\rangle_e$ space (σ_0 is the central velocity dispersion, and $\langle\mu\rangle_e$ is the mean surface brightness within R_e expressed in magnitudes per square arcsecond). [Plot kindly provided by R. Saglia, based on data published in Saglia et al. (1997) and Wegner et al. (1999)]

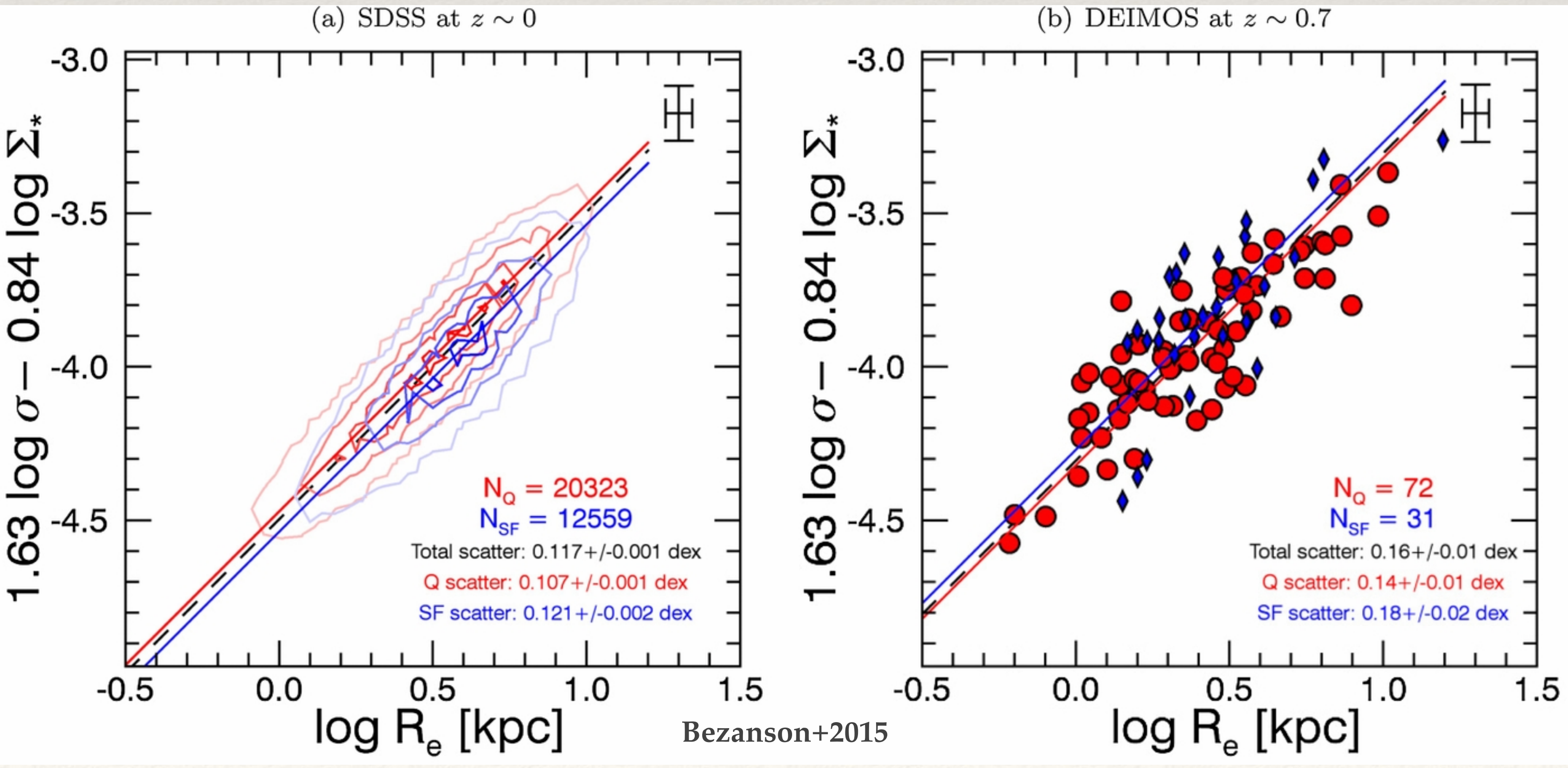
Mo, van den Bosch, & White; Fig 2.18

Galaxy Population - Summary:

- **Structural/Kinematic:**
  - “Fundamental Manifold” — global generalization to all galaxies based on radius, surface brightness, and “characteristic velocity”
  - “Mass Fundamental Plane” — quiescent & star-forming galaxies, based on radius, line-of-sight velocity dispersion, and stellar mass surface density



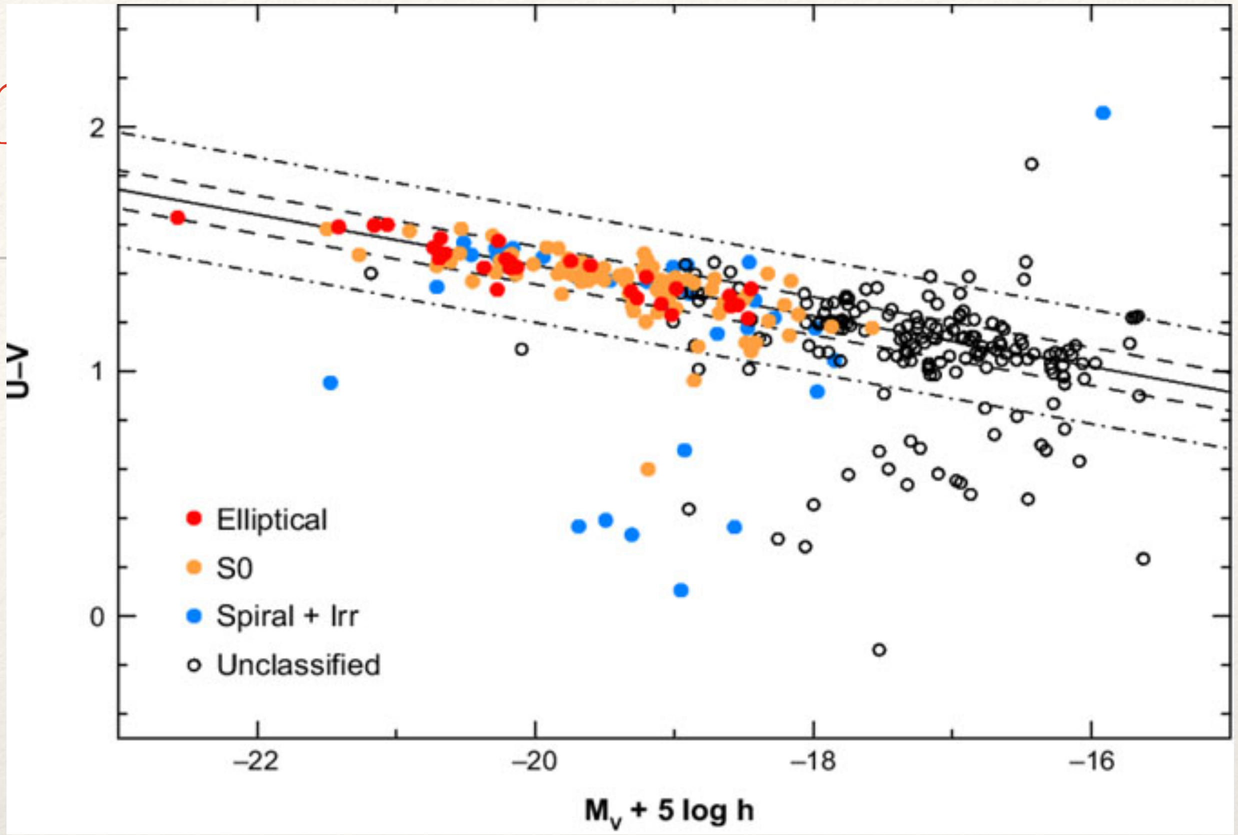
Zaritsky et al. 2008



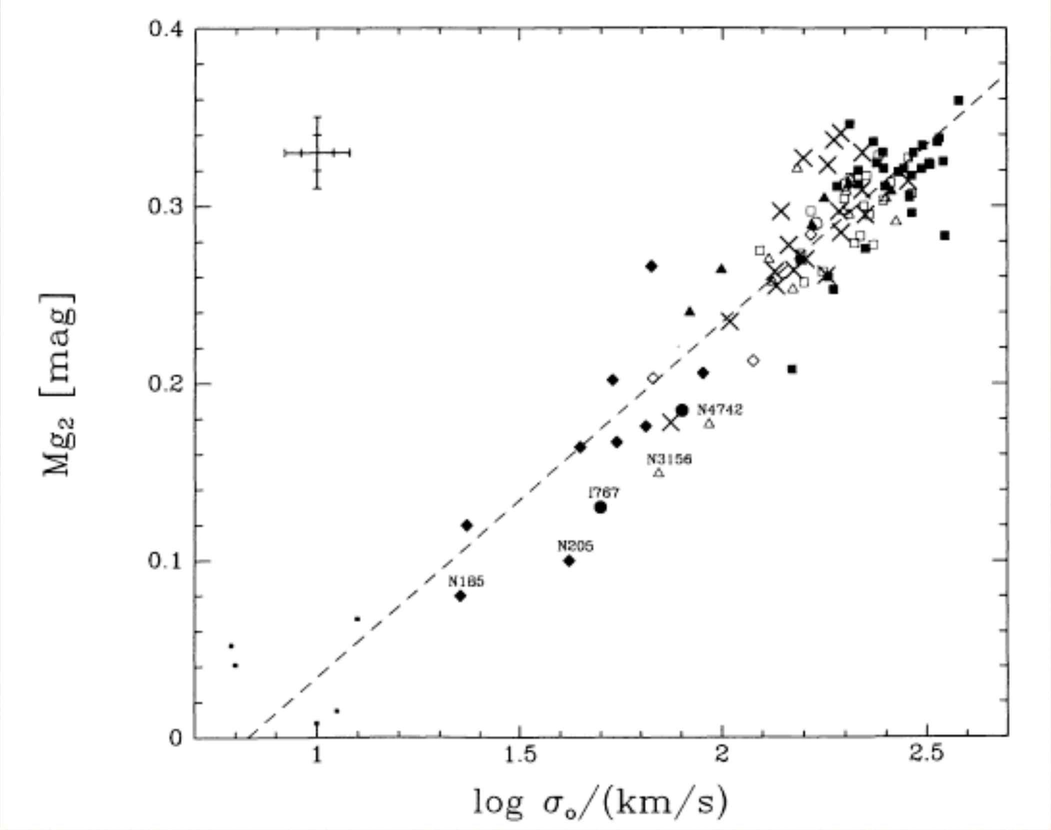
Bezanson+2015

Galaxy Population - Summ

- **Stellar populations:**
  - Color-magnitude — red sequence
  - Mg-Luminosity, Mg-σ for ellipticals
  - Enhanced Mg vs. Fe in more massive galaxies



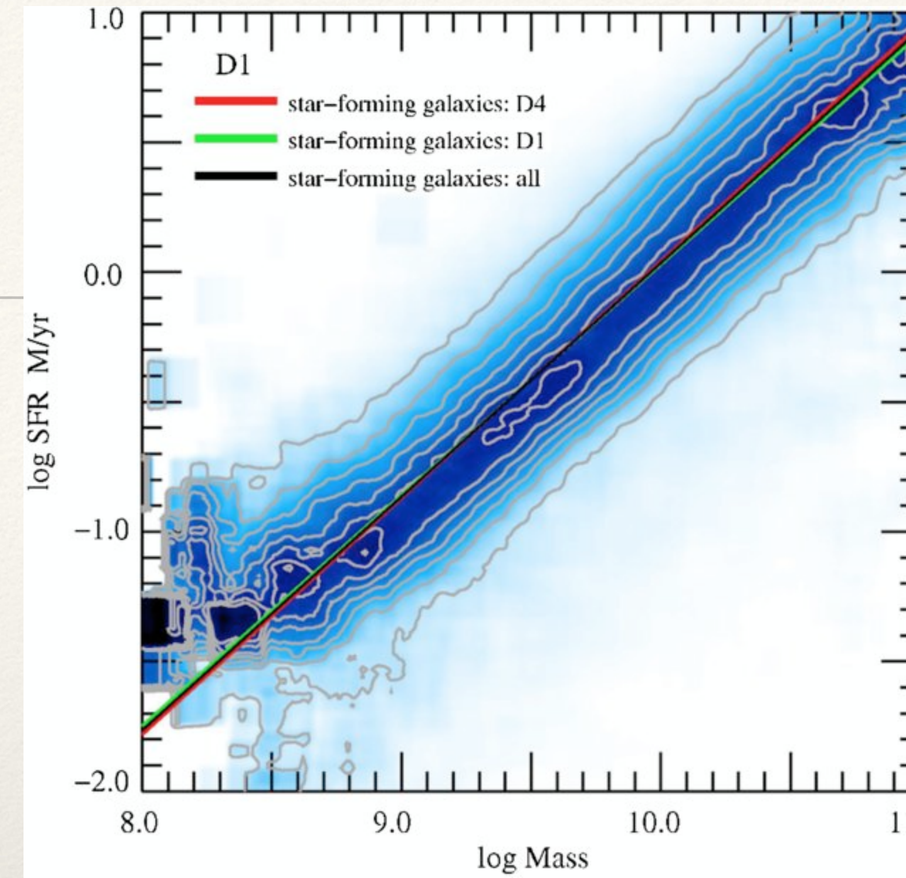
https://ned.ipac.caltech.edu/level5/March06/Renzini/Renzini3.html#Figure%206



Bender, IAU Symposium 149

Galaxy Population - Summary:

- **Gas and Star Formation:**
  - "Star-Forming Galaxy Main Sequence":
    - SFR scales with stellar mass
  - Luminosity-Metallicity, Mass-Metallicity:
    - More luminous / massive galaxies = more metal-rich



Peng et al. 2010

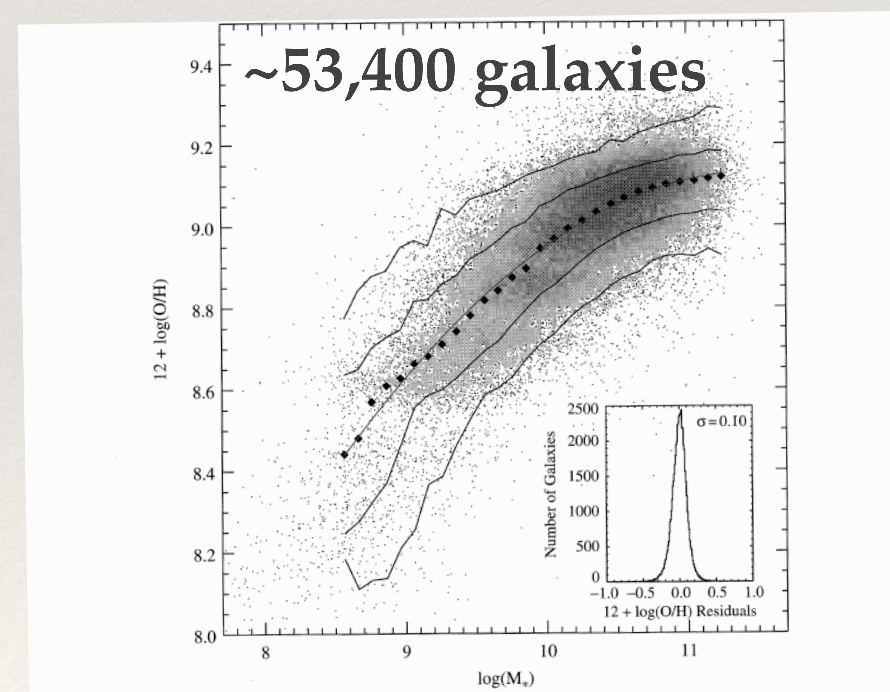
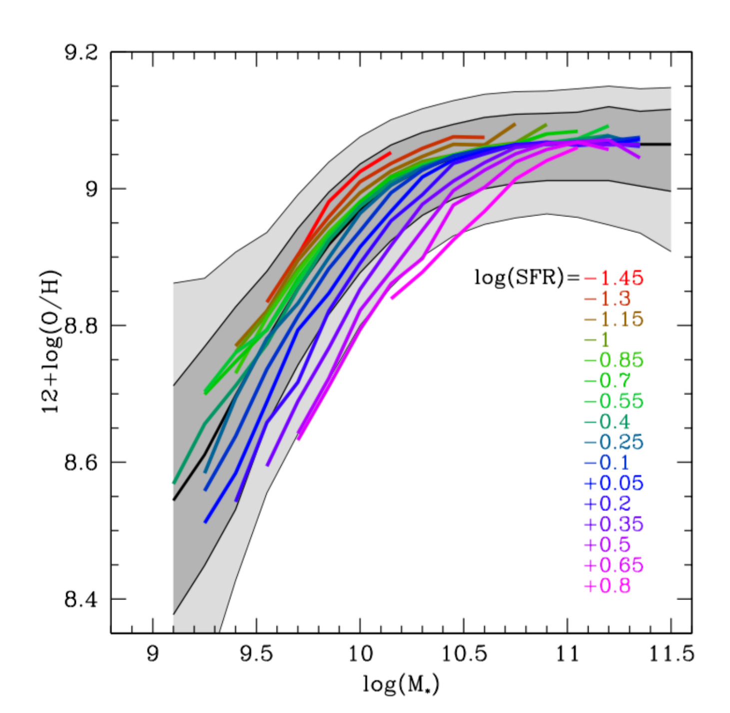


Fig. 2.28. The relation between stellar mass, in units of solar masses, and the gas-phase oxygen abundance for ~53,400 star-forming galaxies in the SDSS. For comparison, the Sun has $12 + \log[(O/H)] = 8.69$. The large black points represent the median in bins of 0.1 dex in mass. The solid lines are the contours which enclose 68% and 95% of the data. The gray line shows a polynomial fit to the data. The inset shows the residuals of the fit. [Adapted from Tremonti et al. (2004) by permission of AAS]

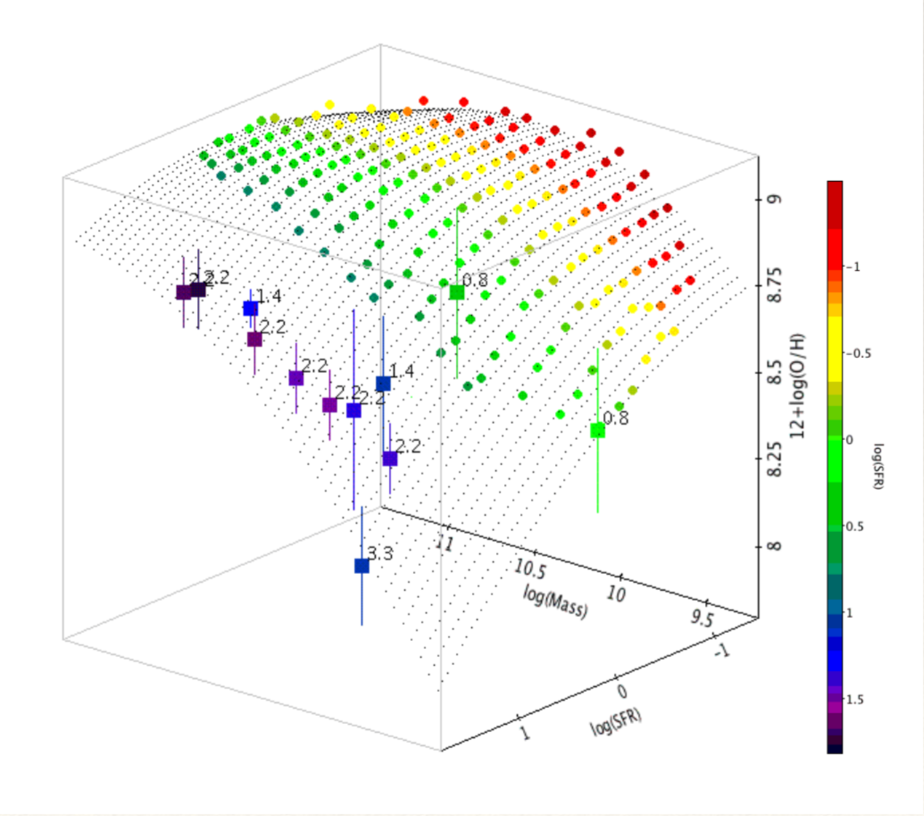
Tremonti et al. 2004

Galaxy Population - Summary: Scaling Relations

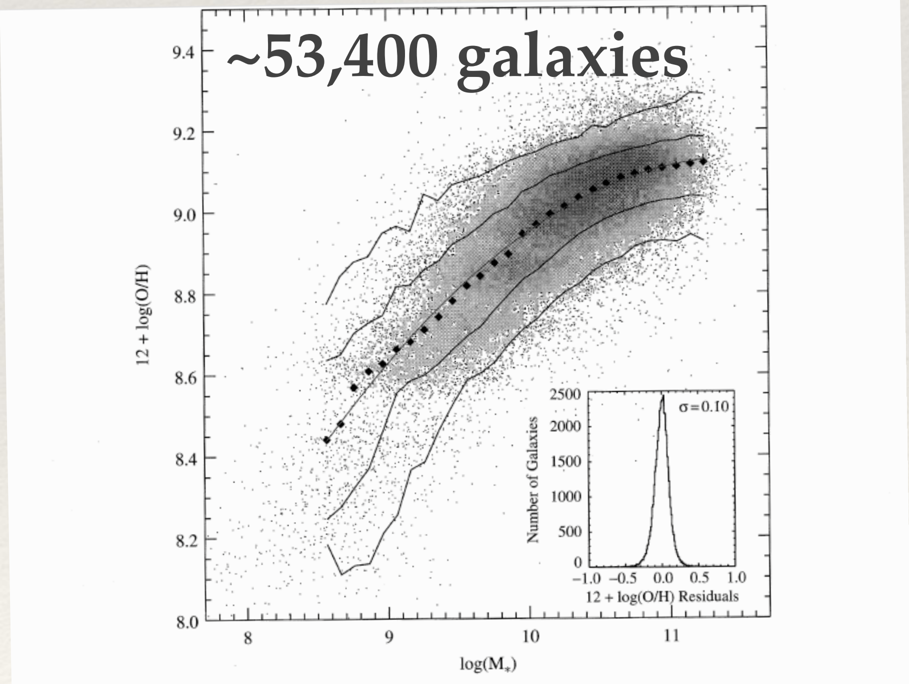
- **Gas and Star Formation:**
  - "Fundamental Metallicity Relation"
    - Star formation rate (SFR) = third parameter
    - Small scatter supports idea of smooth galaxy growth



Mannucci et al. 2010



Mannucci et al. 2010



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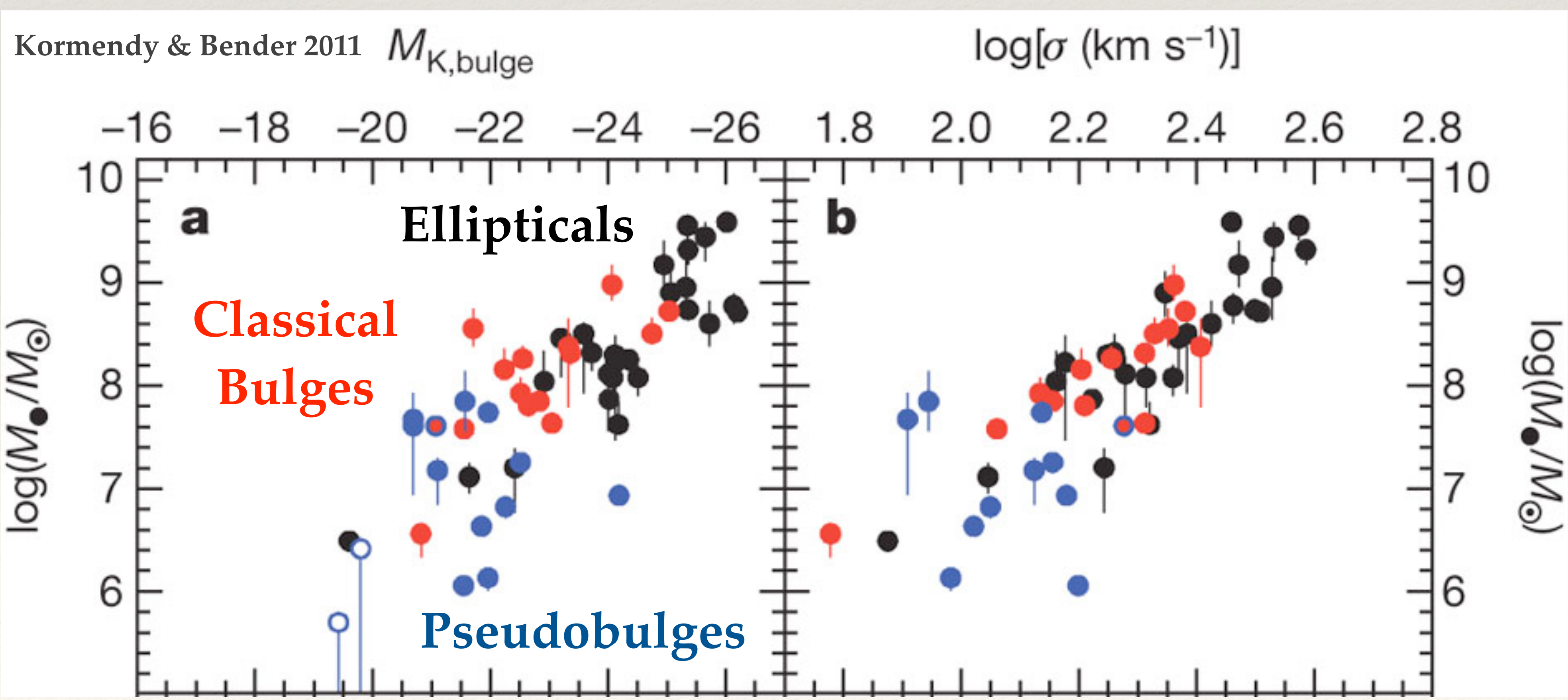
Tremonti et al. 2004

Galaxy Population - Summary: Scaling Relations

- **Black holes: M_{BH}-σ Relation**
  - More luminous galaxies (in bulge component) -> more massive black holes
  - Tightest relation with velocity dispersion: M_{BH}-σ (or M_{BH}-M_{bulge})
  - Black hole mass linked more to bulge than to total galaxy mass

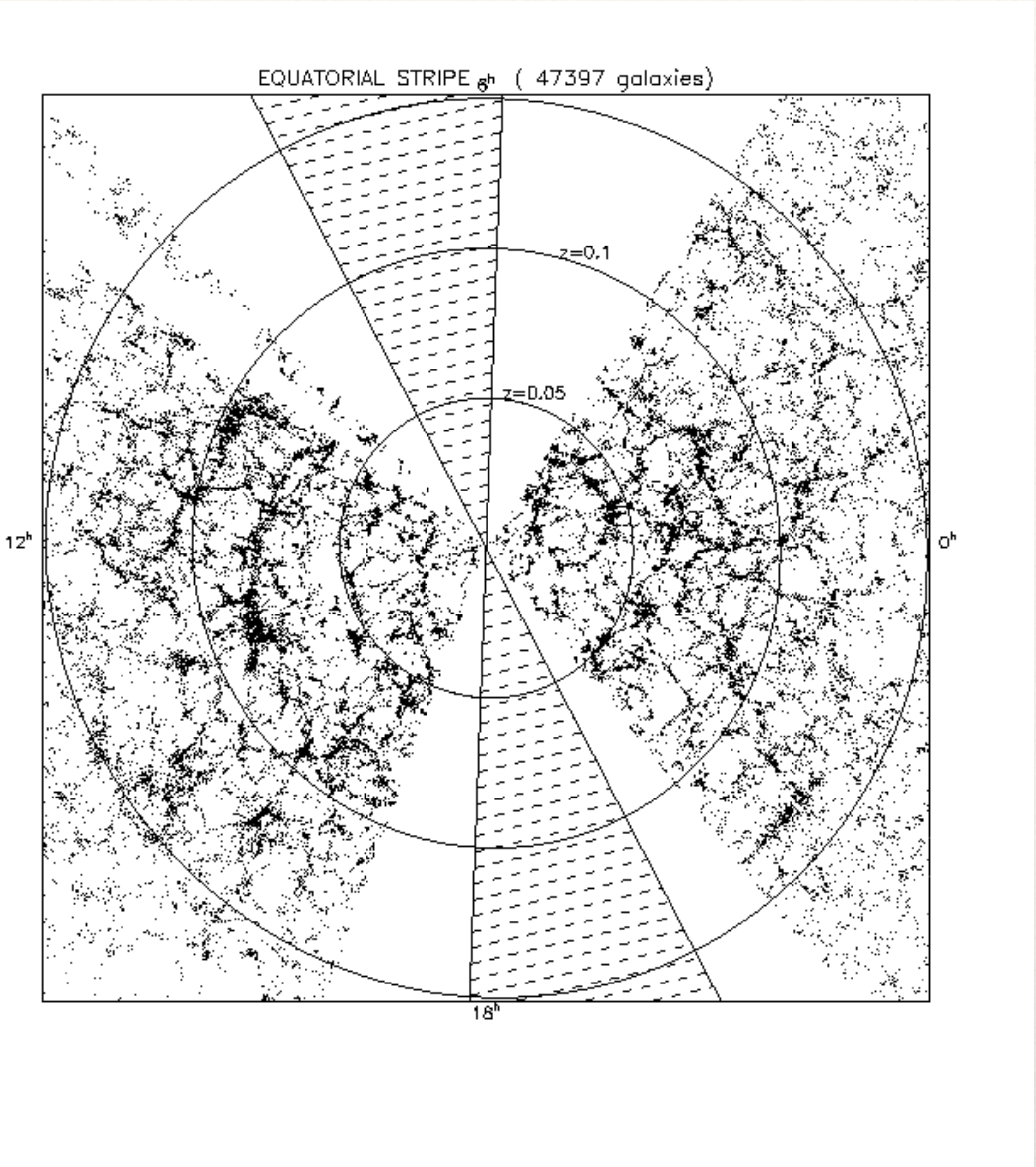


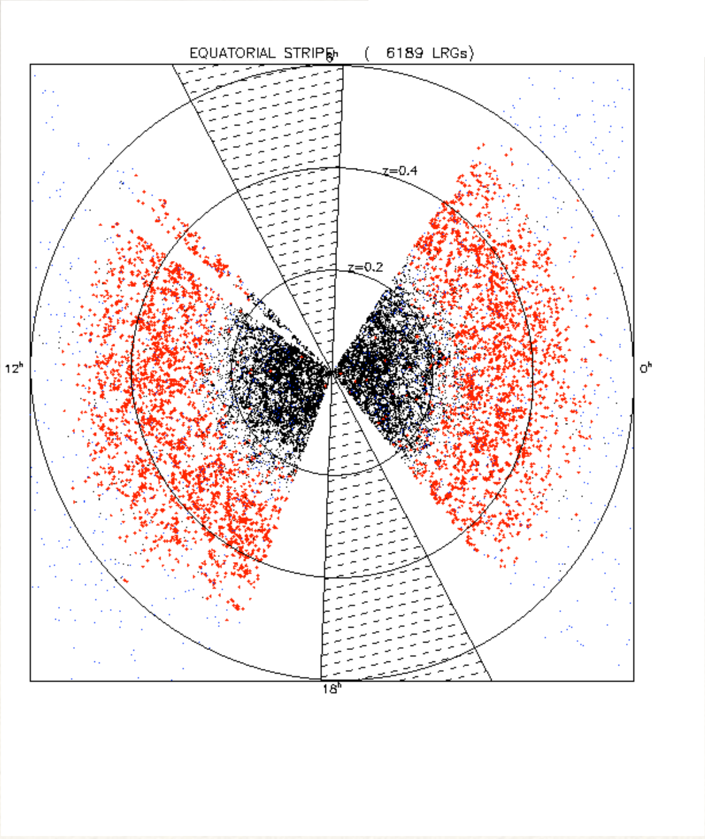
- Suggests coevolution of black hole and host galaxy bulge

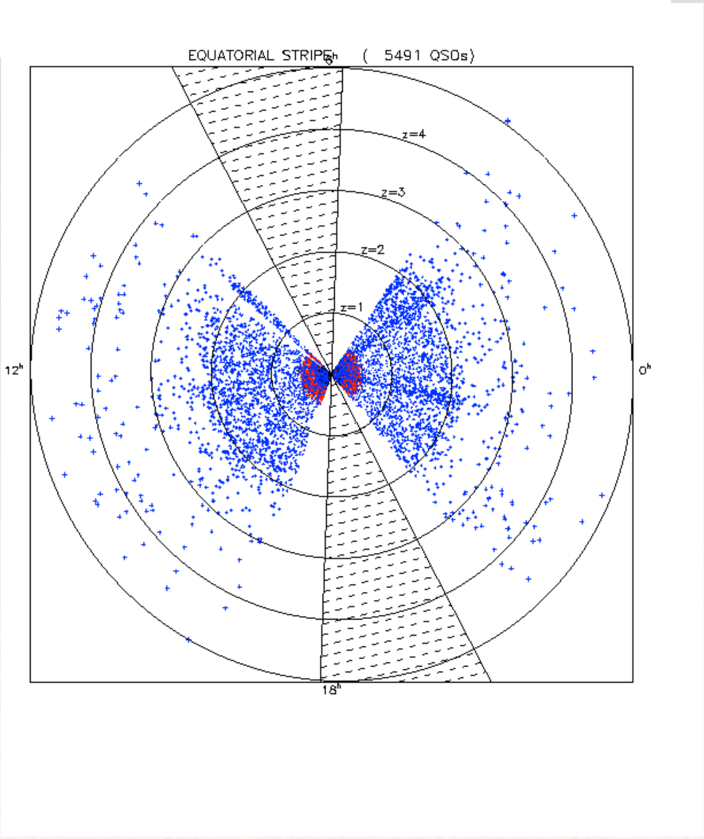
Environments: Clustering

- Galaxies are not homogeneously distributed— they are **clustered!**
- At very large scales, distribution looks homogeneous
- Clustering often described by the spatial **two point correlation function ξ(r)** —excess number of galaxy pairs over a random distribution as a function o radius

$$dP = n(1 + \xi(r))dV$$





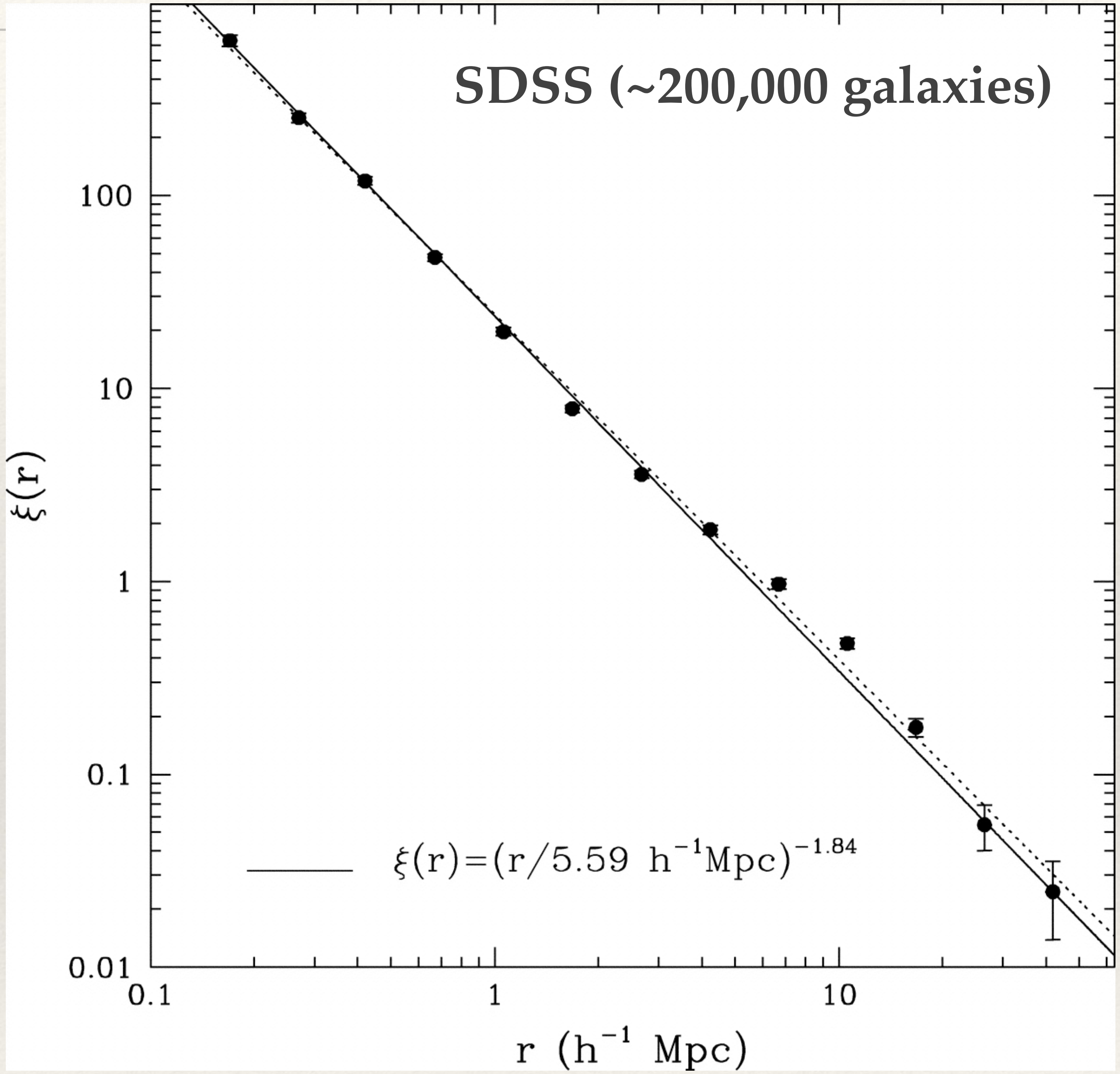


Environments: Clustering

- Measured using estimators comparing the number of galaxy pairs (**DD**) at a given separation (**r**) vs. the number of pairs in a random distribution (**RR**), e.g.,:

$$\xi_{LS}(\mathbf{r}) = \frac{DD(\mathbf{r}) - 2DR(\mathbf{r}) + RR(\mathbf{r})}{RR(\mathbf{r})}$$

- Typically, observed correlation function is well fit by a power law with $\gamma \sim 1.8$ and $r_0 \sim 5\ h^{-1}$ Mpc:



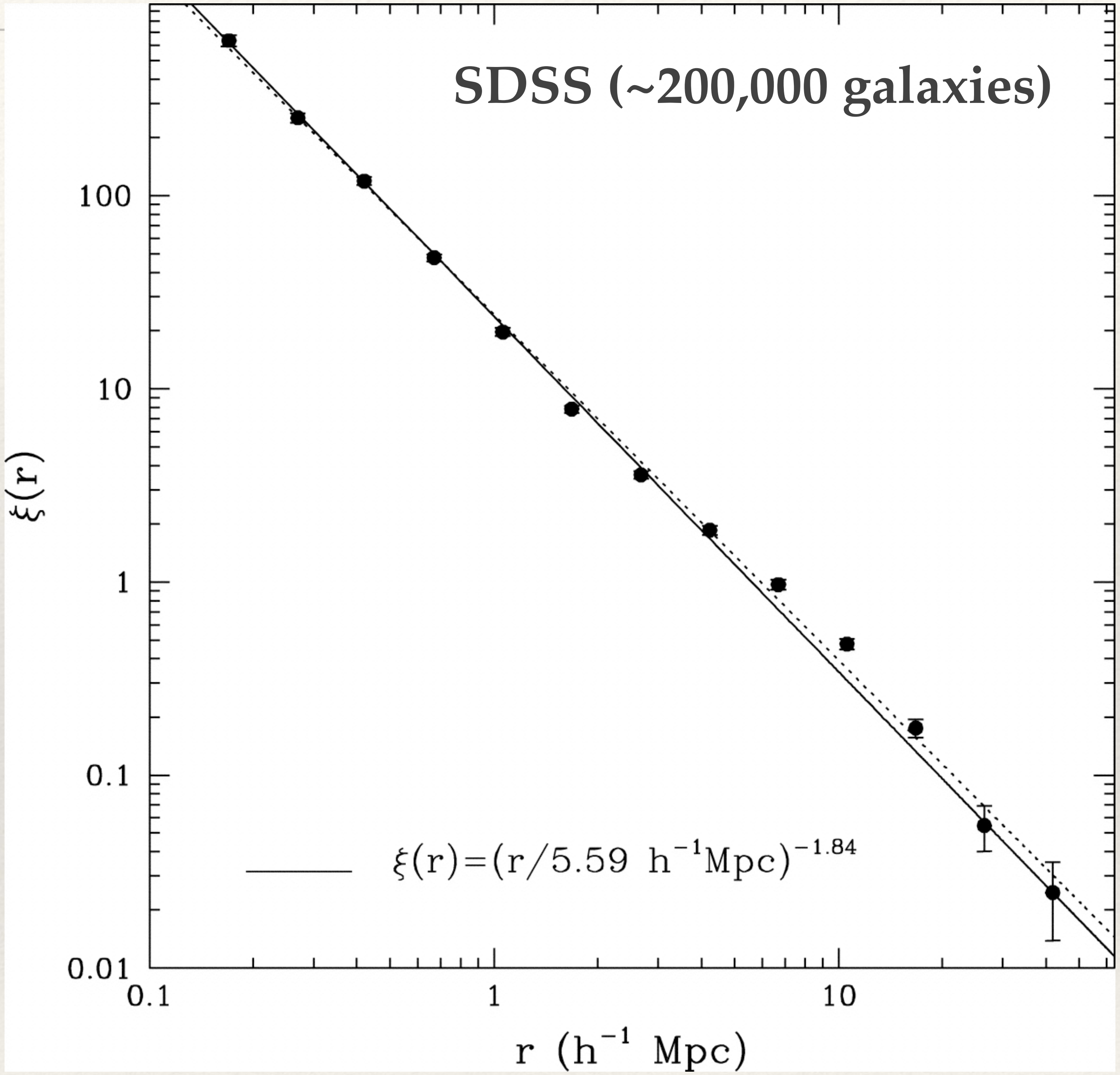
Zehavi et al 2005

$$\xi(r) = \left(\frac{r}{r_0}\right)^{-\gamma}$$

Thought Questions

- How likely is it (versus a random distribution) to find a galaxy at a separation of:
  - r=10 Mpc?
  - r=5 Mpc?
  - r=1 Mpc?

$$dP = n(1 + \xi(r))dV$$



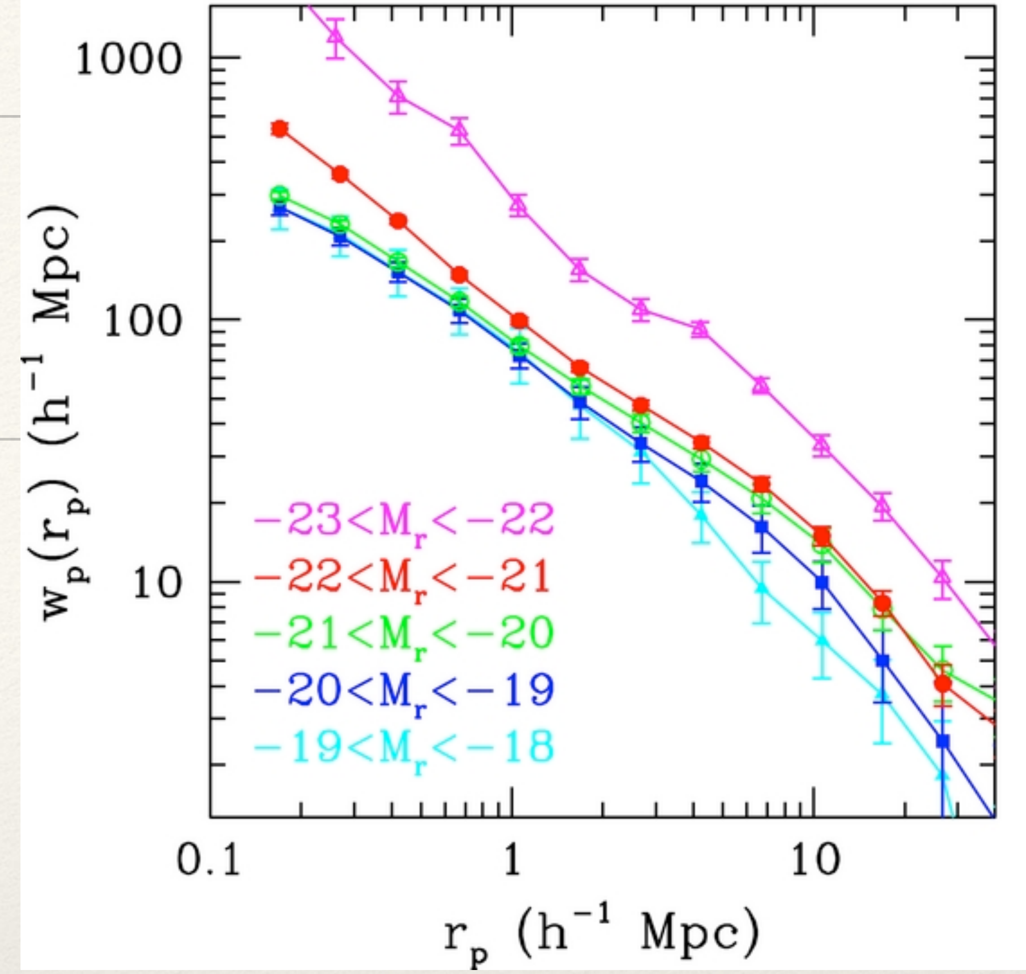
Zehavi et al 2005

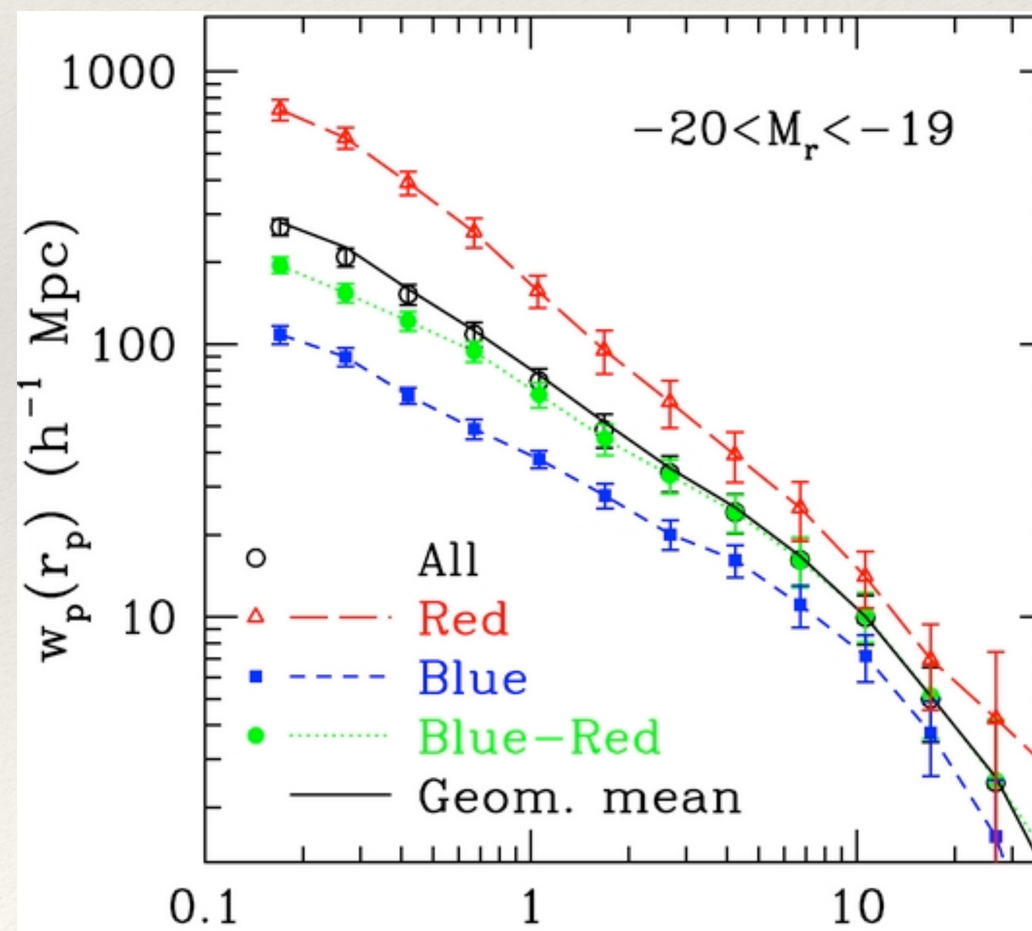
- How could you describe the correlation length in simple terms?

$$\xi(r) = \left(\frac{r}{r_0}\right)^{-\gamma}$$

Environments: Clustering

- So far have been talking about **ξ(r)** — the **spatial** two point correlation function
  - Requires redshifts and corrections for redshift-space distortions
- Often easier to measure the **angular** correlation function (projected on the sky) — $\mathbf{w_p(r_p)}$
  - more luminous/red galaxies are more clustered than less luminous/blue galaxies





Zehavi et al 2005

Clustering: Power Spectrum

- Correlation function related to even more fundamental description of distribution of objects: the power spectrum
- Power spectrum gives power as a function of wavenumber (spatial frequency, not related to wavelength of light!)
- Power spectrum can be calculated, at leasst in linear regime

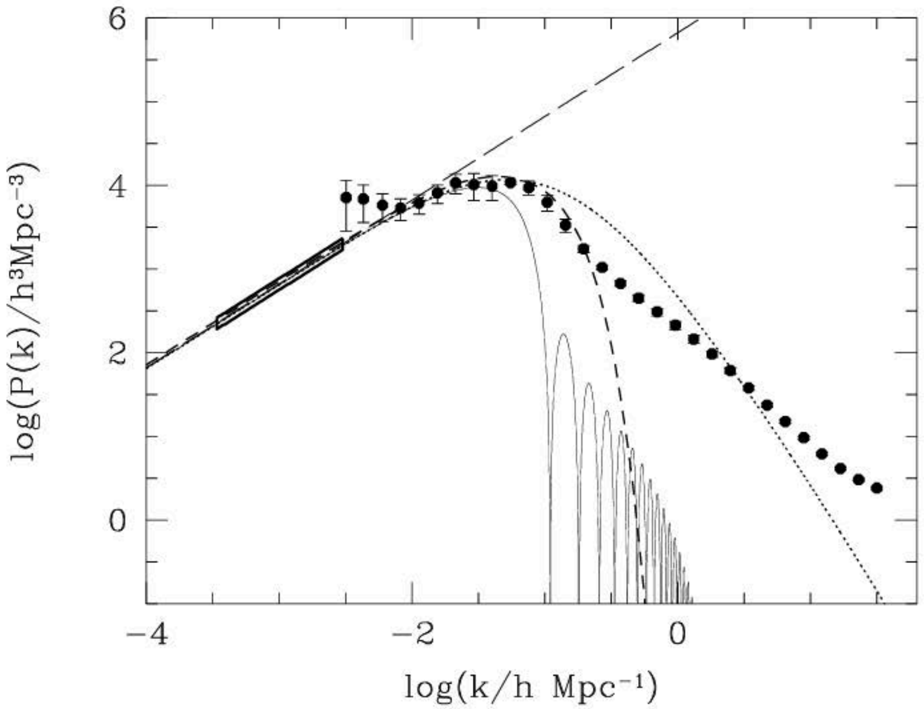
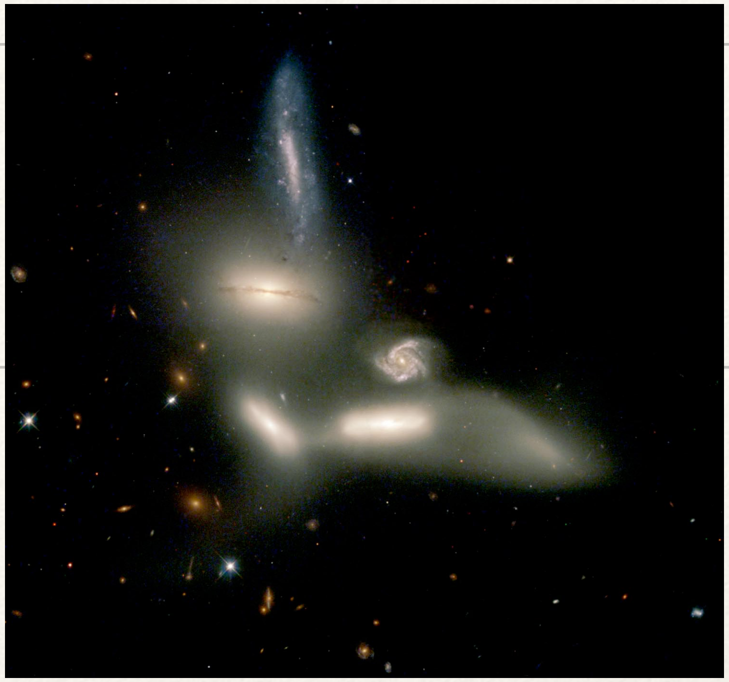


Figure 2. Examples of power spectra for universes with the critical density in mass. The long dashed line shows the Harrison–Zeldovich form of the primordial power spectrum, $P(k) \propto k$. The dotted line shows the power spectrum in a universe with the critical density in cold dark matter, the solid line shows the power spectrum when baryons contribute all the critical density, whilst the short dashed line shows a universe in which all the mass is in the form of massive neutrinos. The amplitude of the power spectra has been set to agree with the constraints from the COBE satellite measurement of temperature fluctuations in the cosmic microwave background, indicated by the box at $\log k \sim -3$. The points show a measurement of the power spectrum of galaxy clustering.

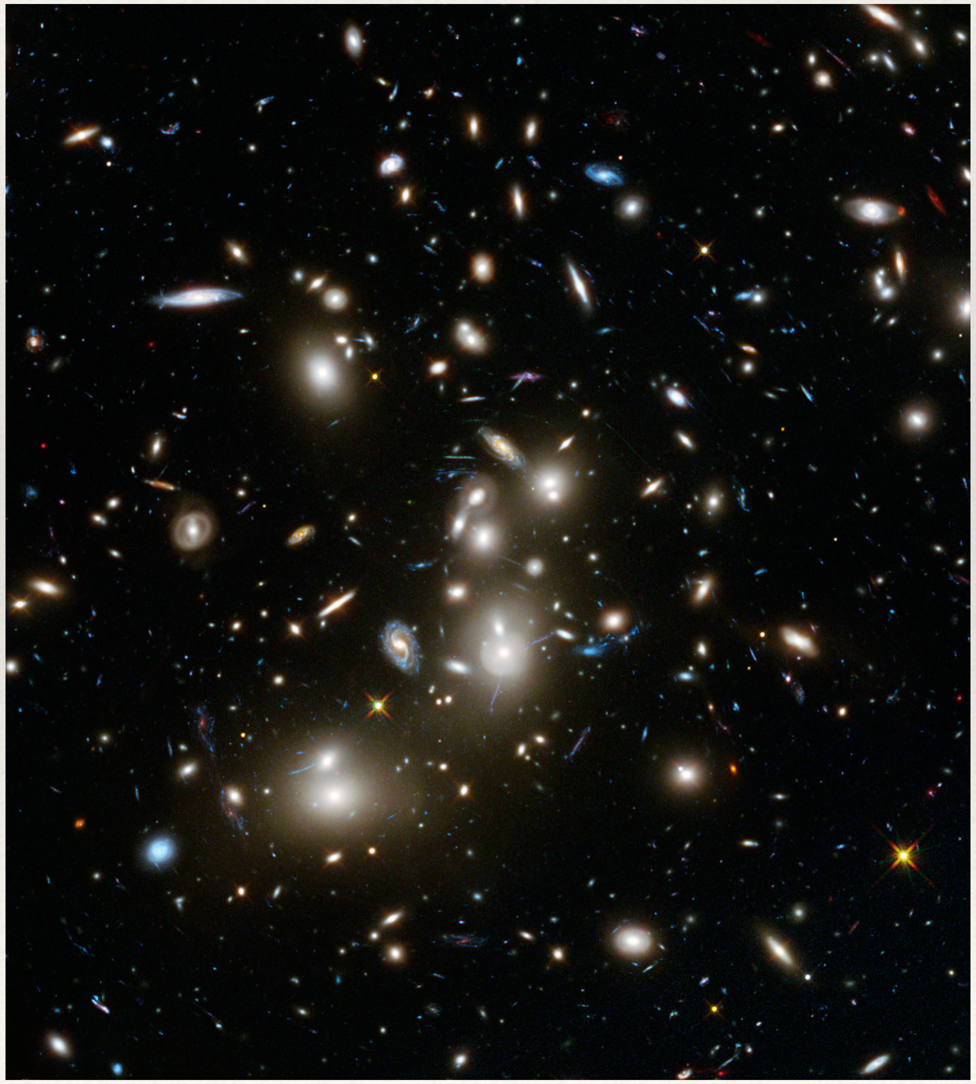
$$\xi(r) = \frac{1}{2\pi^2} \int dk\, k^2 P(k) \frac{\sin(kr)}{kr}$$

Environments: Groups & Clusters

- Many galaxies reside in groups or clusters:
  - **Galaxy groups** ~few to tens of luminous galaxies (e.g., the Local Group)
    - Typical sizes ~1-2 Mpc
    - **Compact galaxy groups** have several massive (perhaps interacting) galaxies in much closer proximity
  - **Galaxy clusters** ~dozens to hundreds of galaxies (>50 galaxies)
    - Typical sizes ~few-10 Mpc
- **Abell Cluster Catalog (1958)** — Best known catalog of local galaxy clusters, derived visually using Palomar Sky Survey (POSS) plates



Seyfert's Sextet (English et al. 2002, NASA)

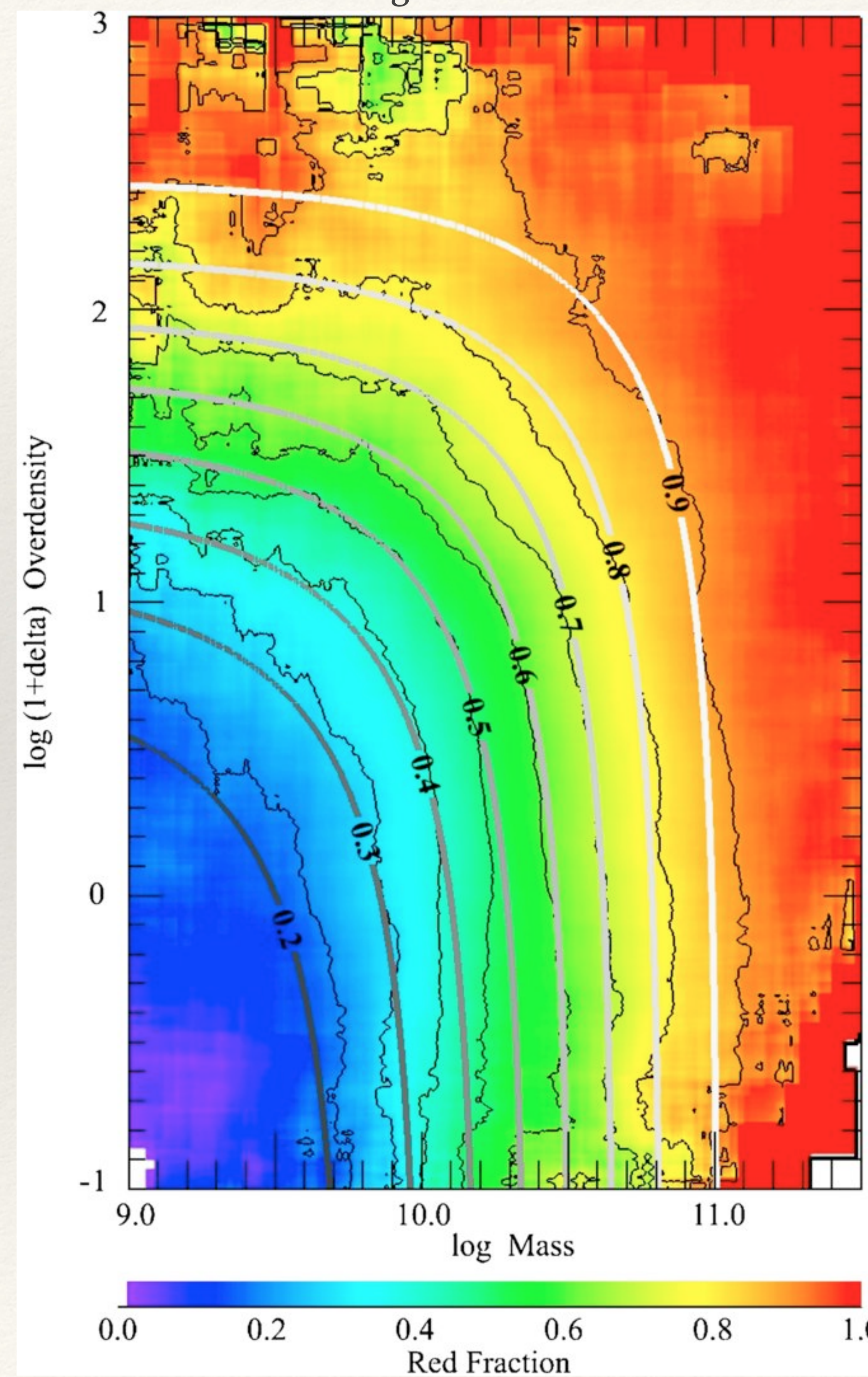


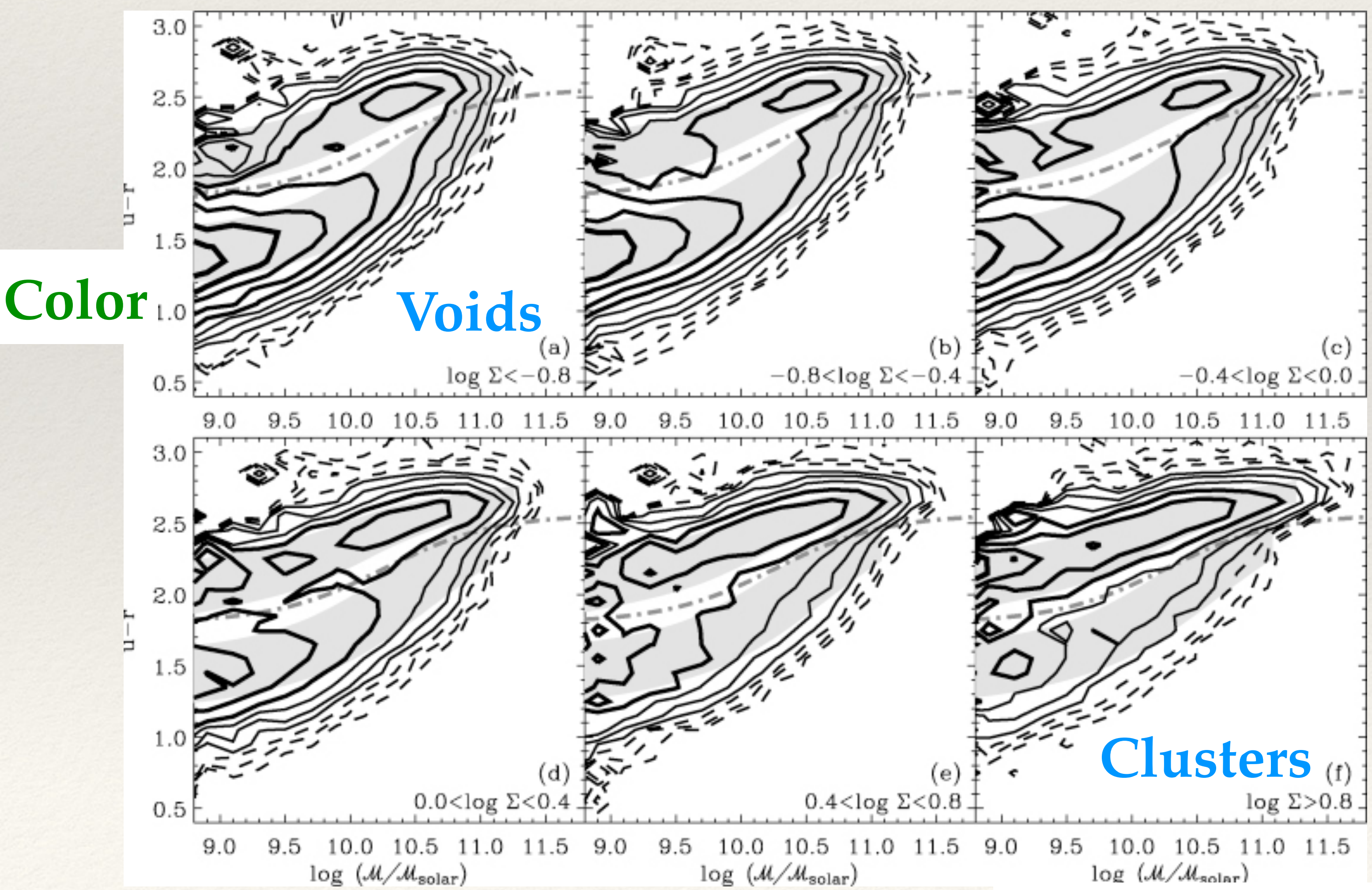
Abell 2744 — NASA, ESA, and J. Lotz, M. Mountain, A. Koekemoer, and the HFF Team (STScI).

Environments: Cluster Galaxies

- **Galaxies in galaxy clusters:**
    - Morphology-density and color-density relations
    - Fraction of red/elliptical galaxies increases in dense environments

Peng et al. 2010





Baldry et al. 2006

vs. Stellar Mass

Environments: Cluster Galaxies

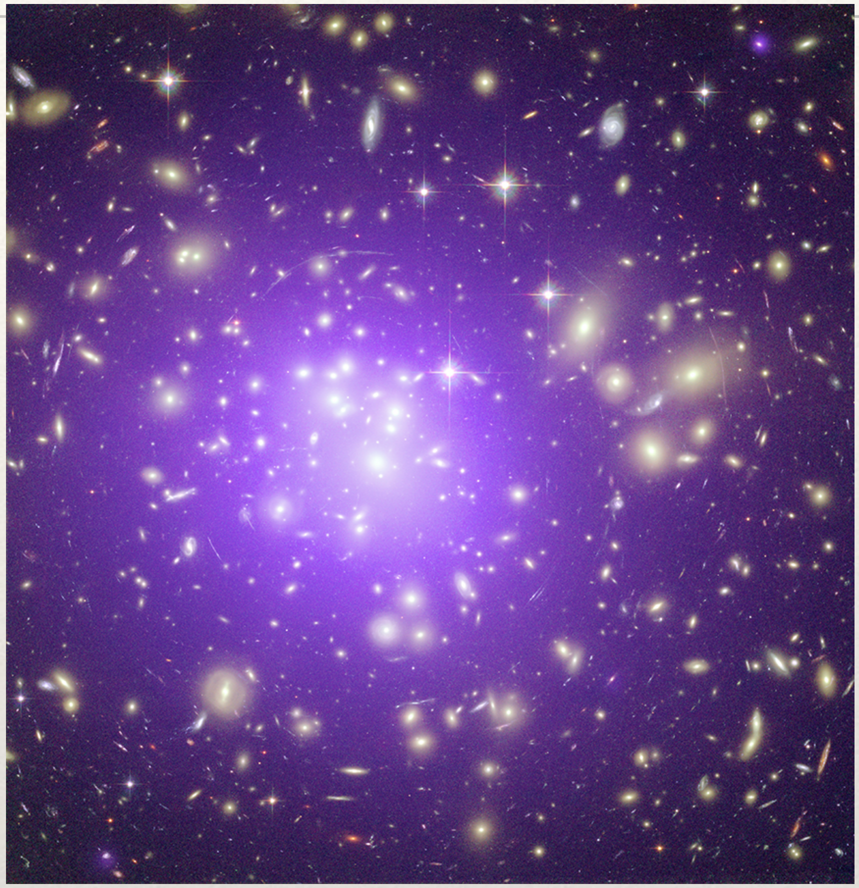
- Galaxies in galaxy clusters:
  - A higher fraction of **S0/ lenticular** galaxies
  - A higher fraction of **anemic spirals** — significantly lower gas fractions and SFR than comparable field spirals
- Evidence of effect of cluster environment

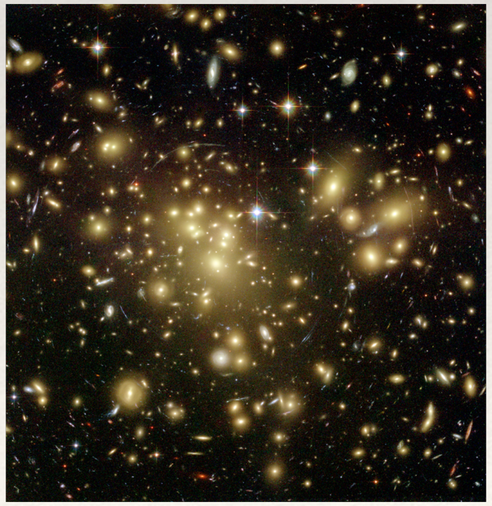
NGC 6861— lenticular, Telescopium Group member (NASA/ESA)

NGC 4921 — anemic spiral, Coma cluster member (NASA/ESA)

Environments: Galaxy Clusters

- Galaxy clusters contain hot gas:
  - Total gas mass > in stars!
  - T~10^7-10^8 K — observed in X-rays
  - Intracluster gas enriched in heavy elements, not primordial
- X-ray observations useful for estimating cluster masses:
  - under assumption of hydrostatic equilibrium
  - more accurately using density and temperature profiles

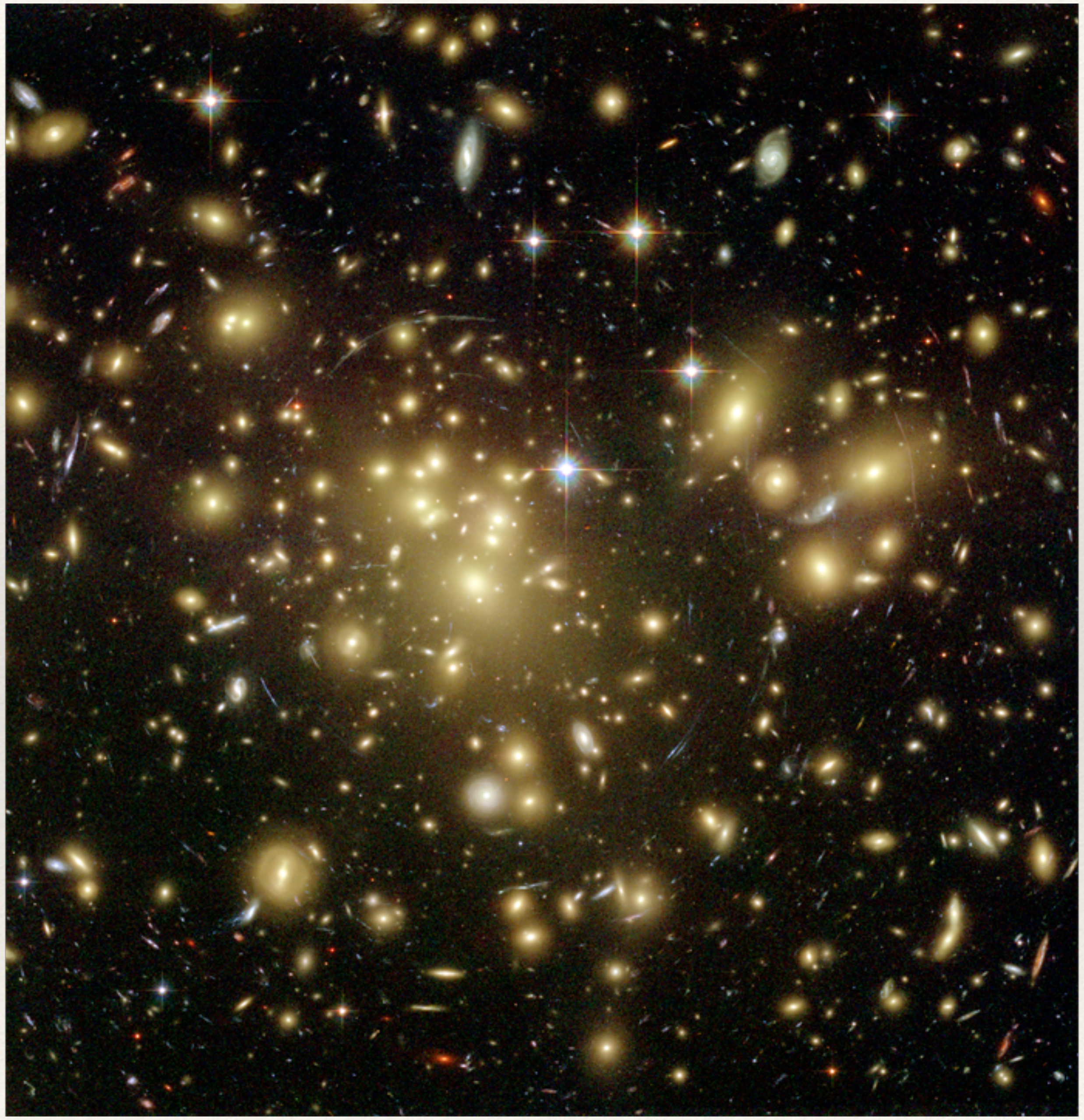




Abell 1689 (X-ray: NASA/CXC/MIT/E.-H Peng et al; Optical: NASA/STScI)

Environments: Galaxy Clusters

- Use gravitational lensing to derive total mass of clusters:
  - ~10^{14} - 10^{15} solar masses
  - Implies dark matter beyond what associated with the galaxies
- Not all clusters are in equilibrium — provides a probe of distribution of dark vs. normal matter!



Abell 1689 (NASA)