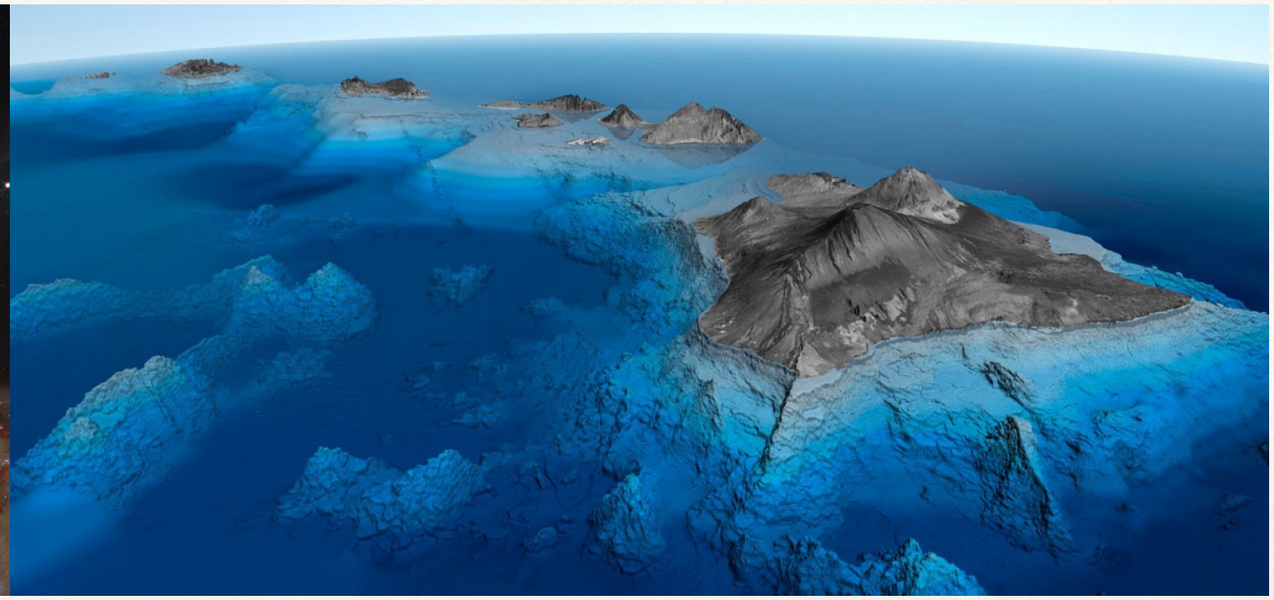


Getting to know the "island universes" out there.

Galaxies I

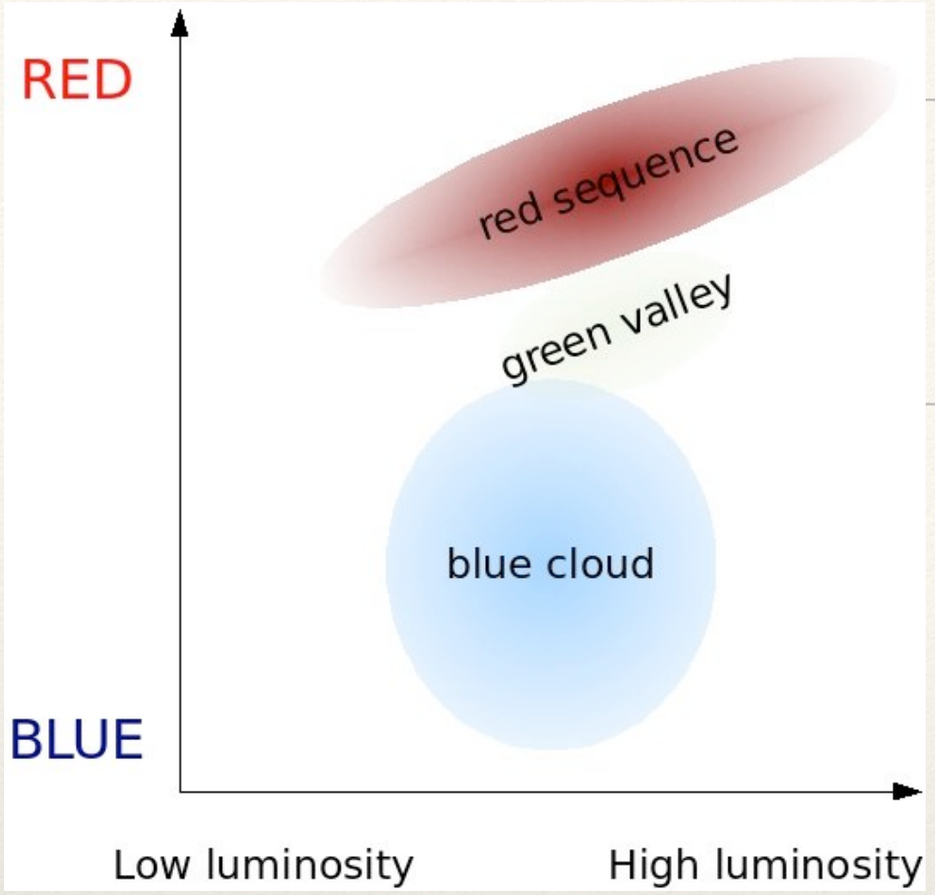
ASTR 555

Dr. Jon Holtzman

Warm-up

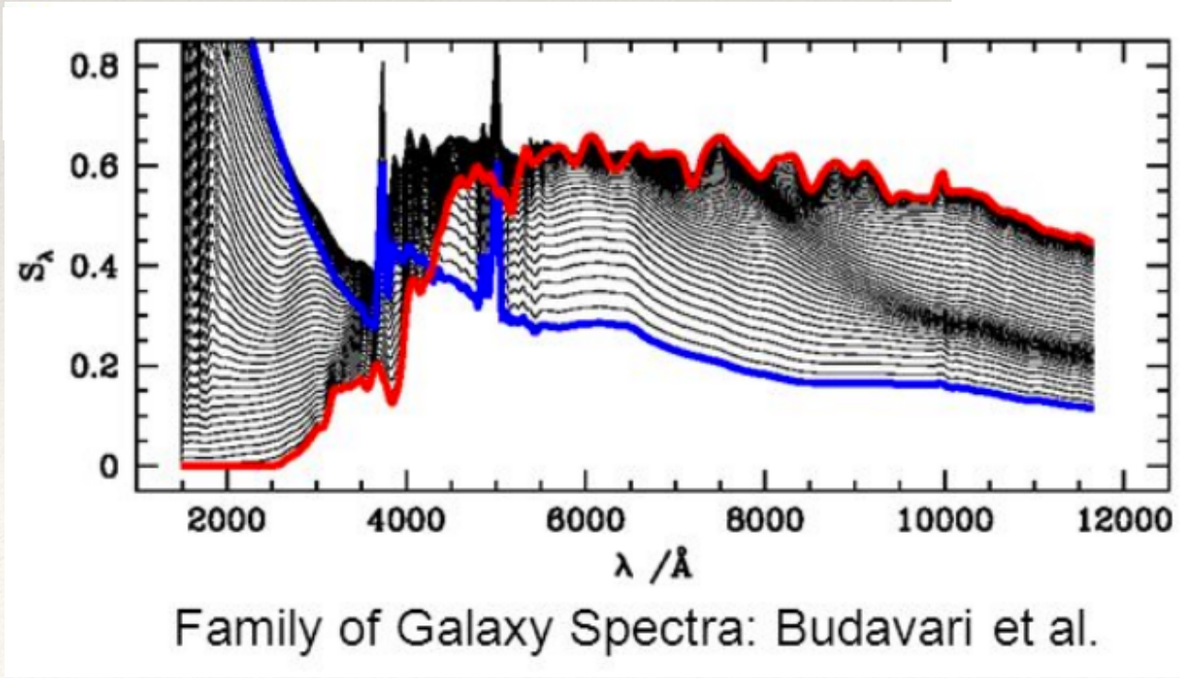
- Sketch the galaxy color-magnitude diagram. What are the main characteristics (stellar population age/color, morphology, star formation rate, stellar mass) of galaxies in different regions of the plot?
- Describe two modes by which galaxies may evolve within in the color-magnitude diagram.

Warm-up



(or stellar mass)

Image Credit: Joshua Schroeder; https://commons.wikimedia.org/w/index.php?curid=20496639



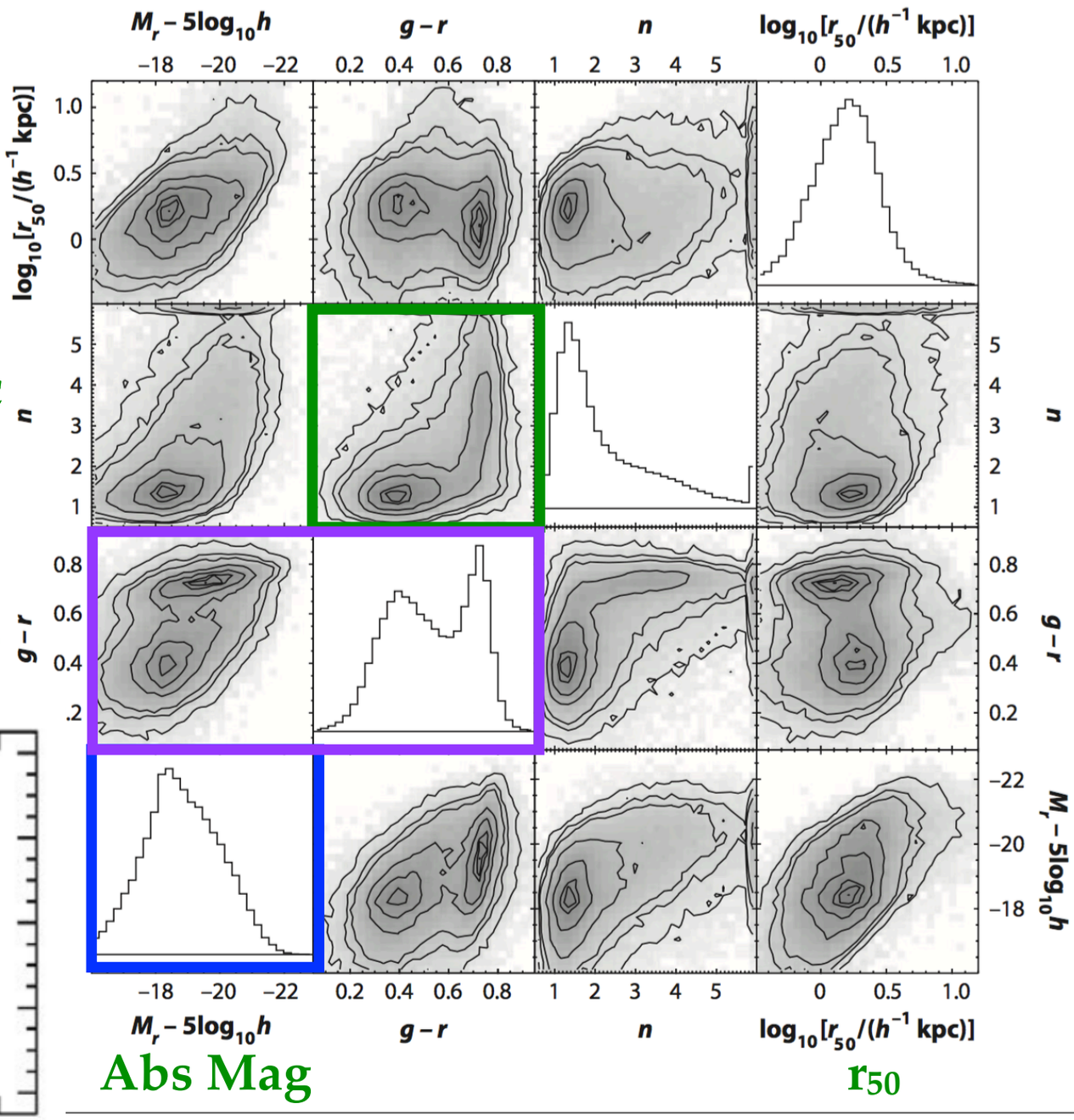
Family of Galaxy Spectra: Budavari et al.

Sersic n

Color g − r

Abs Mag $M_r - 5\log_{10}h$

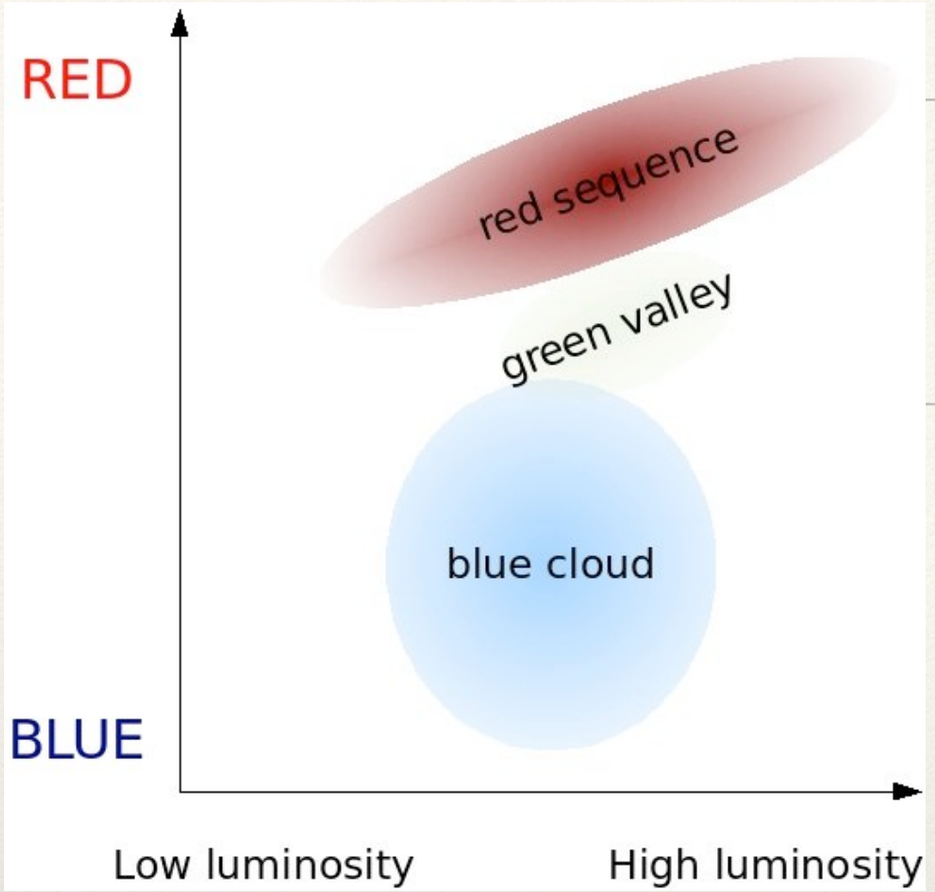
r_{50}



d-band galaxy properties in the Sloan Digital Sky Survey. The diagonal panels show the distribution of four ently: absolute magnitude M_r, $g - r$ color, Sérsic index n, and half-light radius r_{50}. A bimodal distribution in $g - r$ -diagonal panels show the bivariate distribution of each pair of properties, revealing the complex relationships rayscale and contours reflect the number of galaxies in each bin (darker means larger number).

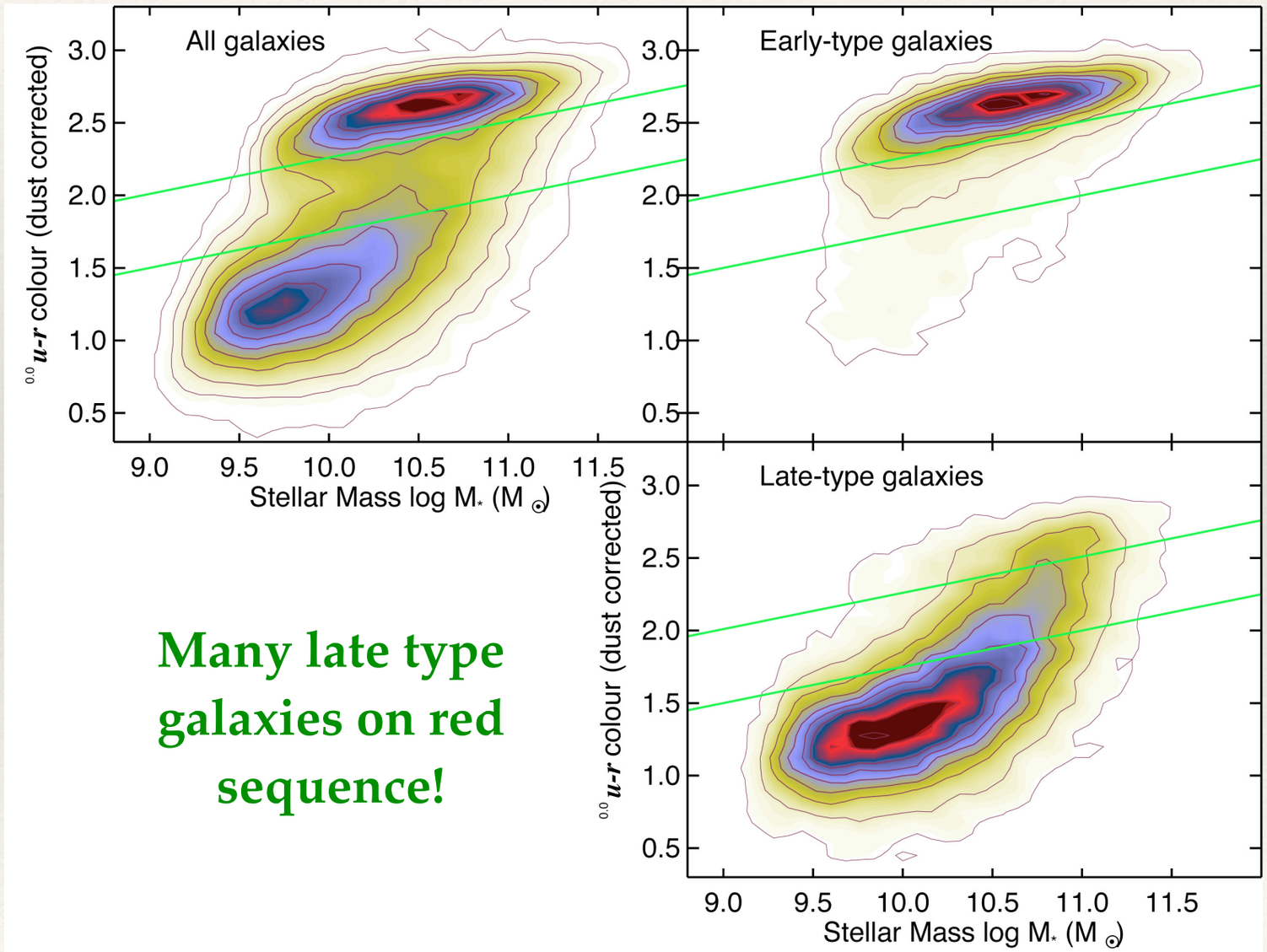
Blanton & Moustakas 2009

Warm-up



(or stellar mass)

Image Credit: Joshua Schroeder; https://commons.wikimedia.org/w/index.php?curid=20496639



Many late type galaxies on red sequence!

Schawinski et al. 2014

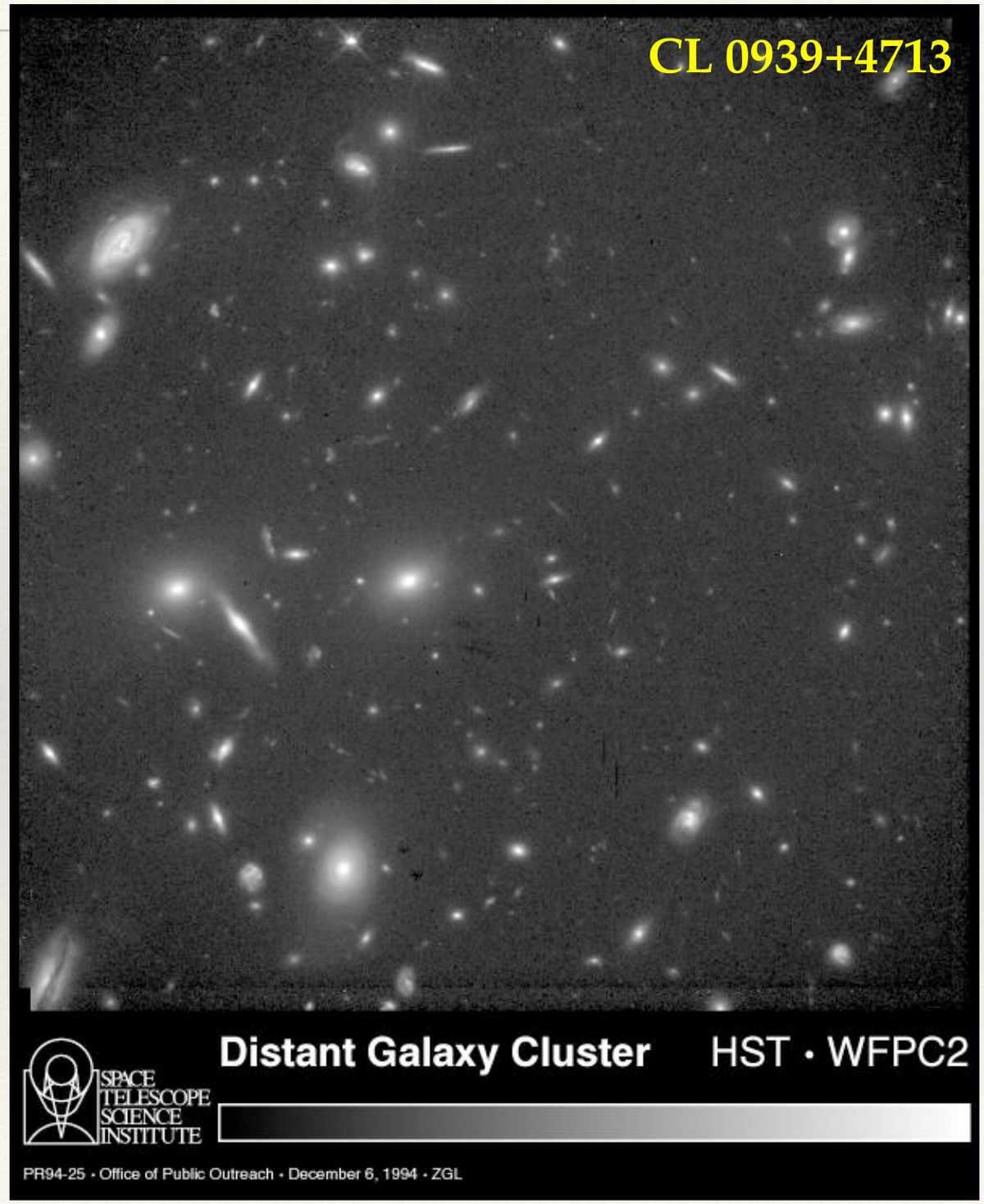
Outline for Today

- Galaxy Population - Statistical Properties:
- Luminosity Function

NGC1232 (ESO)

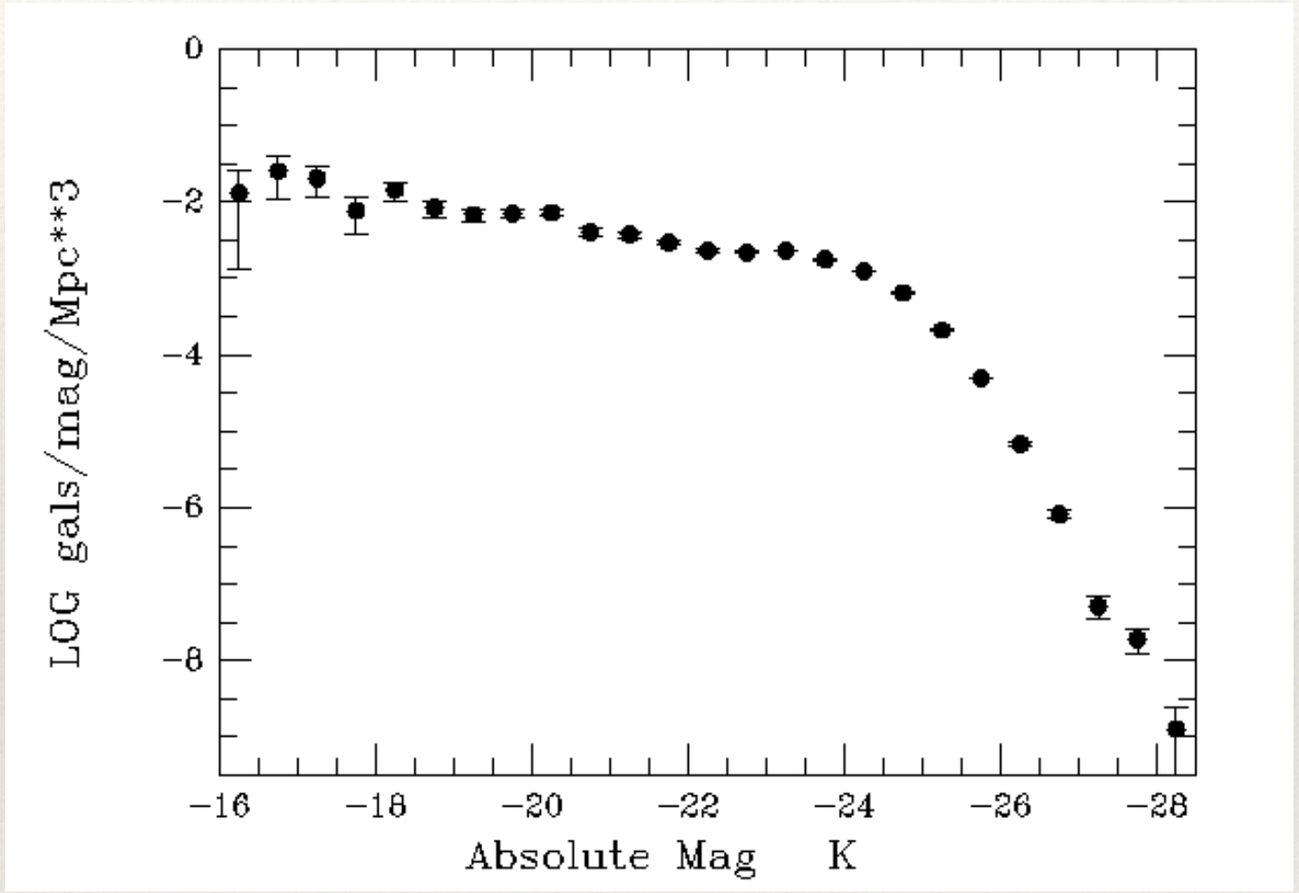
Statistical Properties: Luminosity Function

- Fundamental question: **what sets the luminosities of galaxies?**
- **Luminosity function** — the number density of galaxies as a function of luminosity



Galaxy Population - Statistical Properties: Luminosity Function

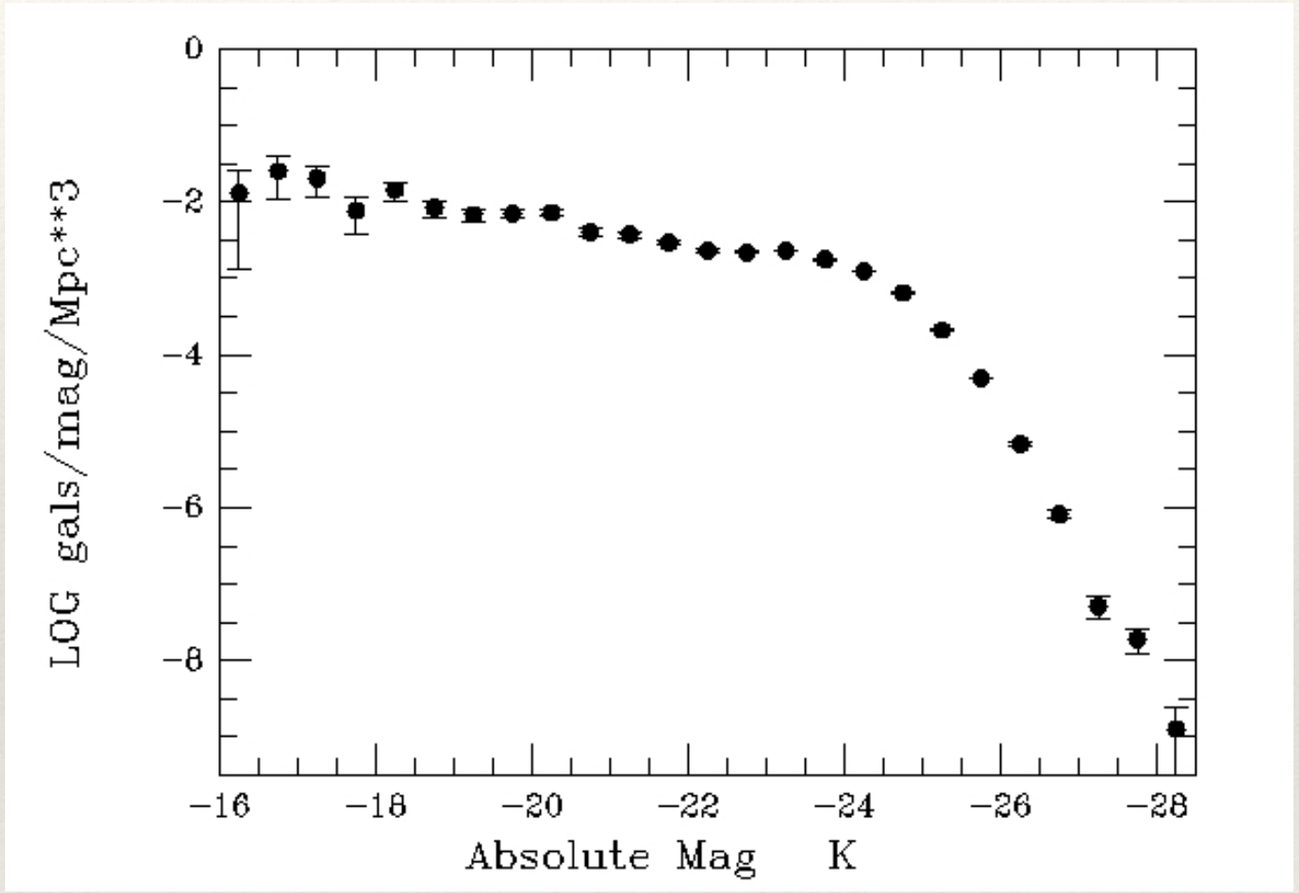
- **Luminosity function** expressed as:
  - Φ(L) = number of galaxies per unit volume with luminosity between L and L+dL
  - Φ(M) = the number of galaxies per unit volume with absolute magnitude between M and M + dM



2MASS Redshift Survey — 25,000 galaxies

Thought Questions

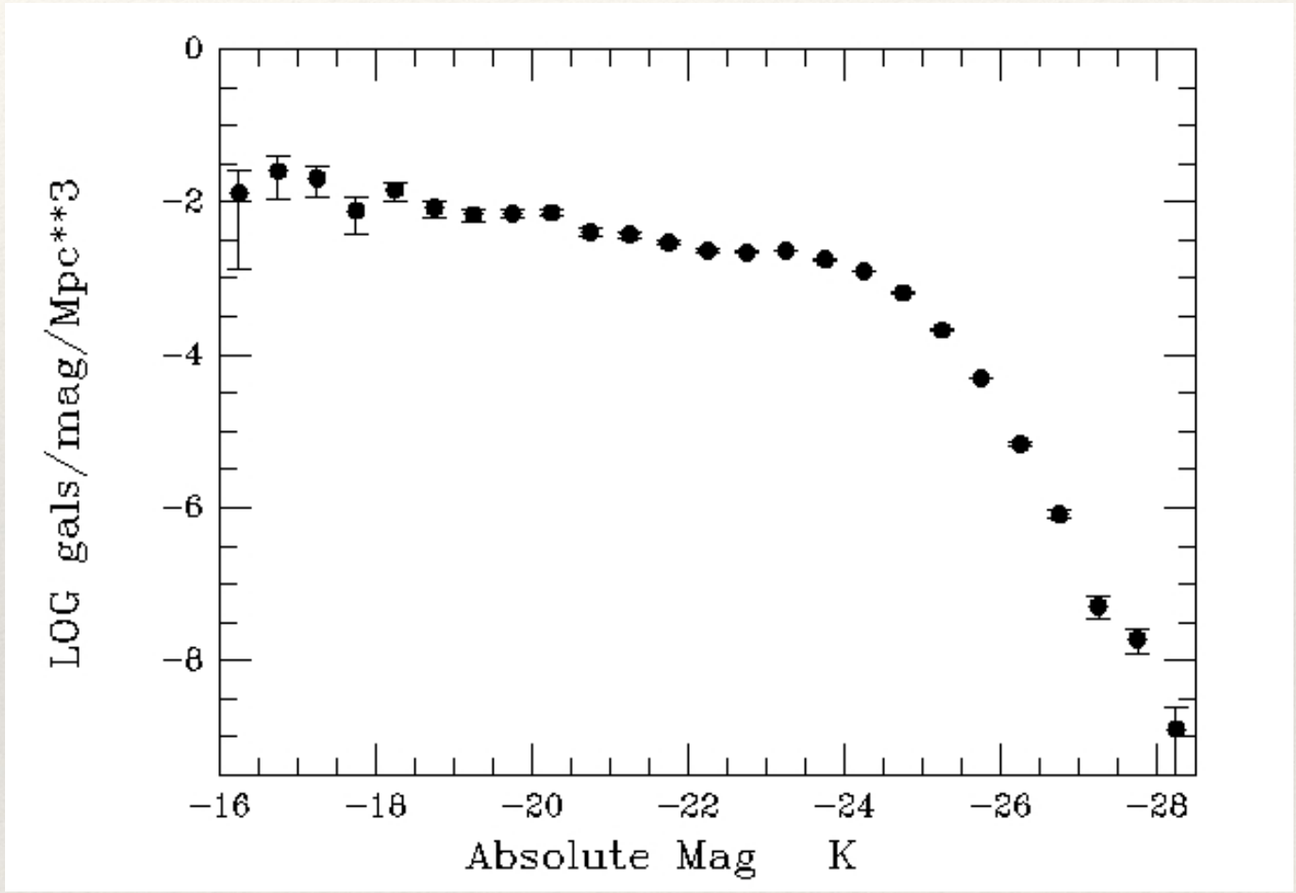
- What would we get if we integrated over the entire luminosity function?
- What astrophysical or cosmological factors might influence the galaxy luminosity function we measure?



2MASS Redshift Survey — 25,000 galaxies

Statistical Properties: Luminosity Function

- Luminosity functions are
  - a convolution of many factors
- Nevertheless:
  - a fundamental observational quantity
  - an important cosmological probe of the evolution of the galaxy population



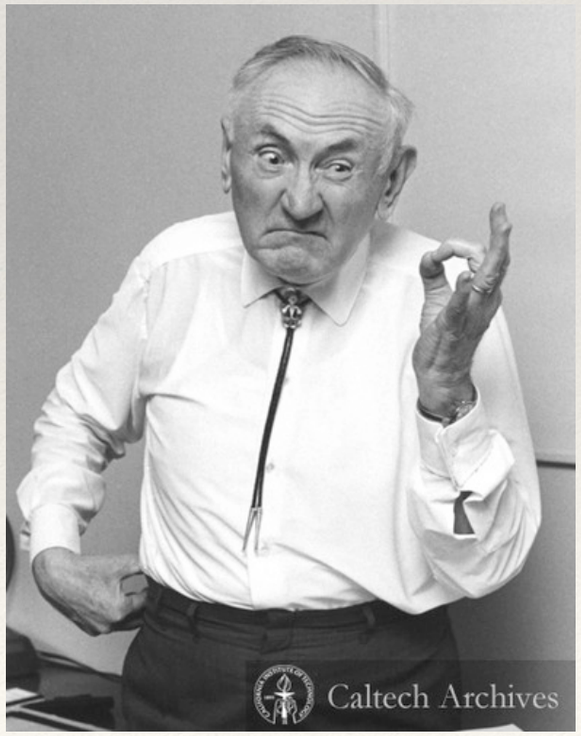
2MASS Redshift Survey — 25,000 galaxies

A successful theory of galaxy formation/evolution must reproduce the luminosity function of galaxies.

Galaxy Population - Statistical Properties: Luminosity Function

- 1930 — Hubble concluded galaxies have a narrow (Gaussian) absolute magnitude distribution
- 1942 — Zwicky argued for a rising function at low luminosities
- Measurements of the luminosity function:
  - require good **distance** measurements —> luminosity
  - require accurate knowledge of the **selection function**
  - **may depend** on, e.g., type of galaxy or environment

Edwin Hubble



Fritz Zwicky

Statistical Properties: Luminosity Function

- Methods:
  - **Galaxies in galaxy clusters**:
    - Obtain a magnitude-limited galaxy sample
    - Use cluster redshift (distance) to get luminosity (all galaxies at basically the same distance!)
    - Make a histogram in bins of luminosity: N(L)
    - Complications: must correct for foreground/background field galaxy contamination

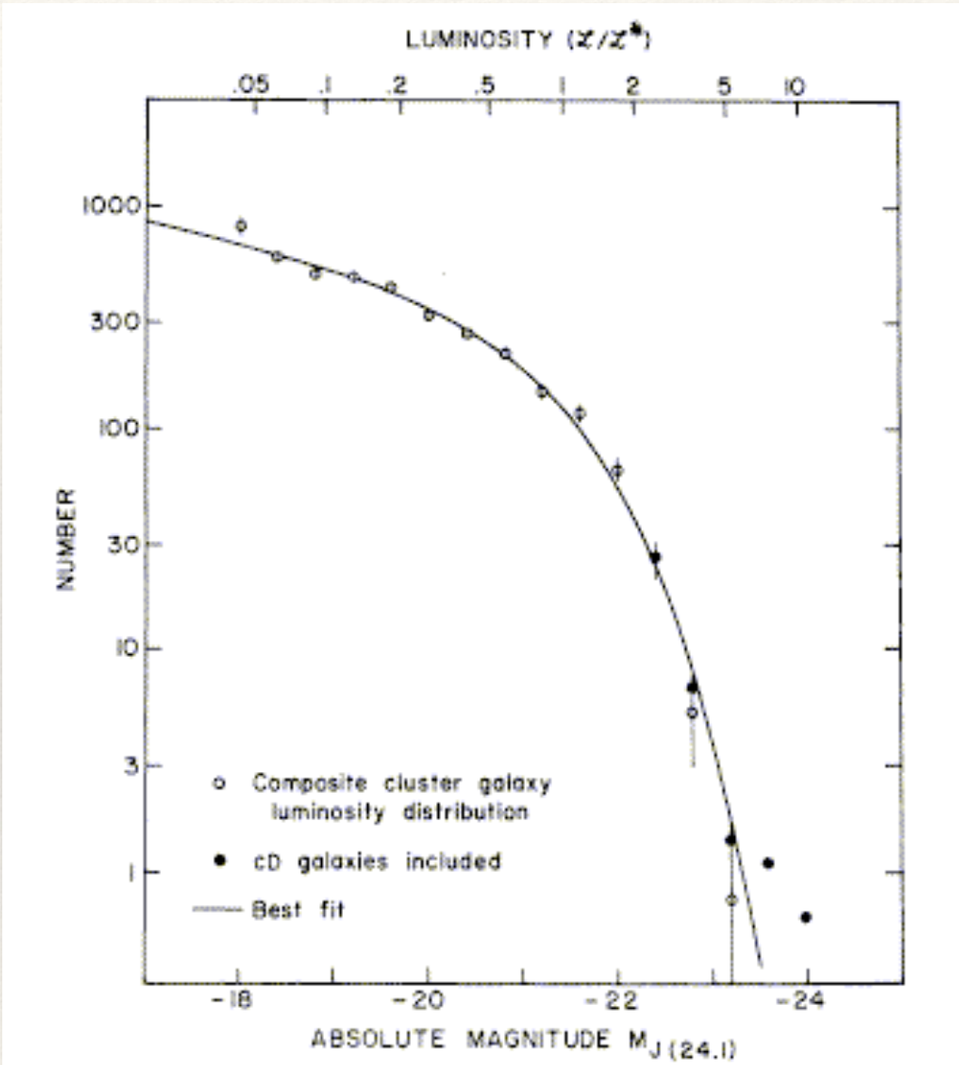
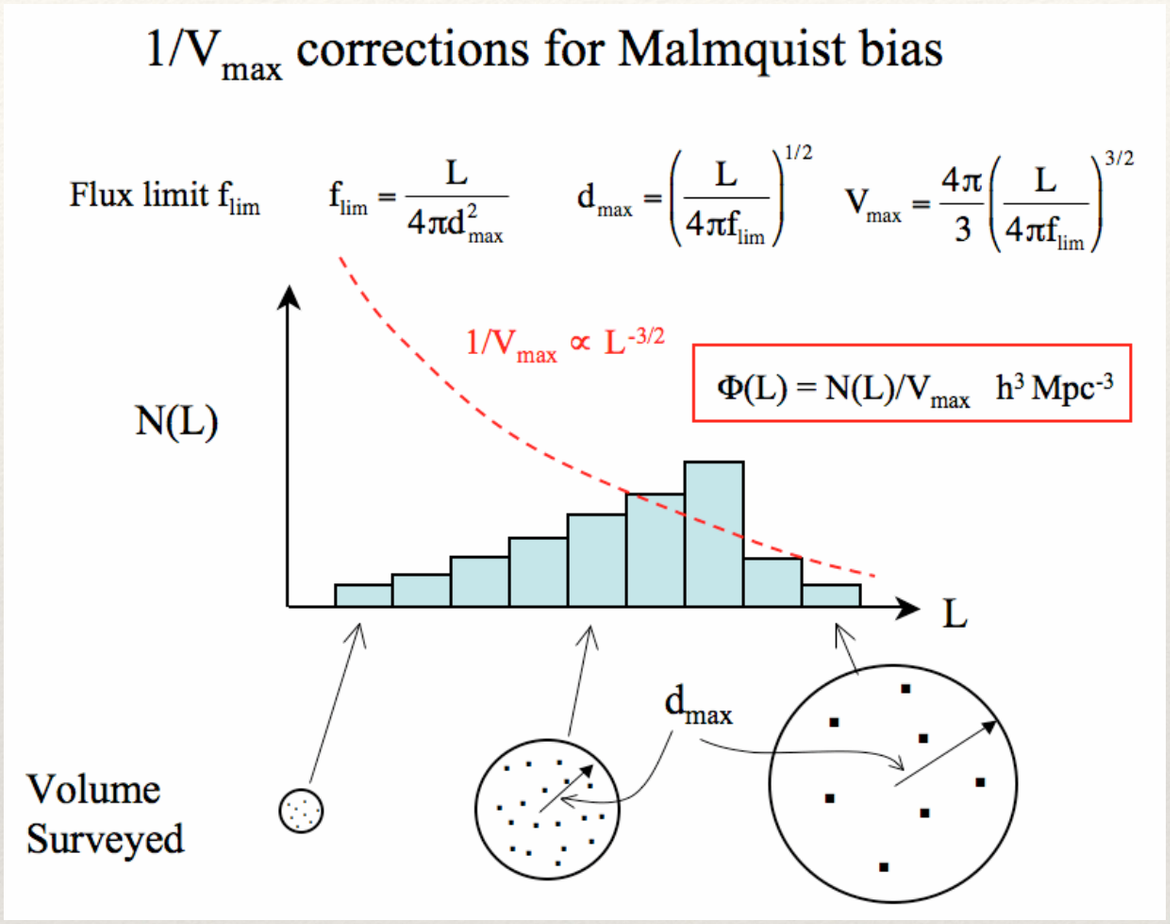


FIG. 2.—Best fit of analytic expression to observed composite cluster galaxy luminosity distribution. Filled circles show the effect of including cD galaxies in composite.

Schechter 1976

Statistical Properties: Luminosity Function

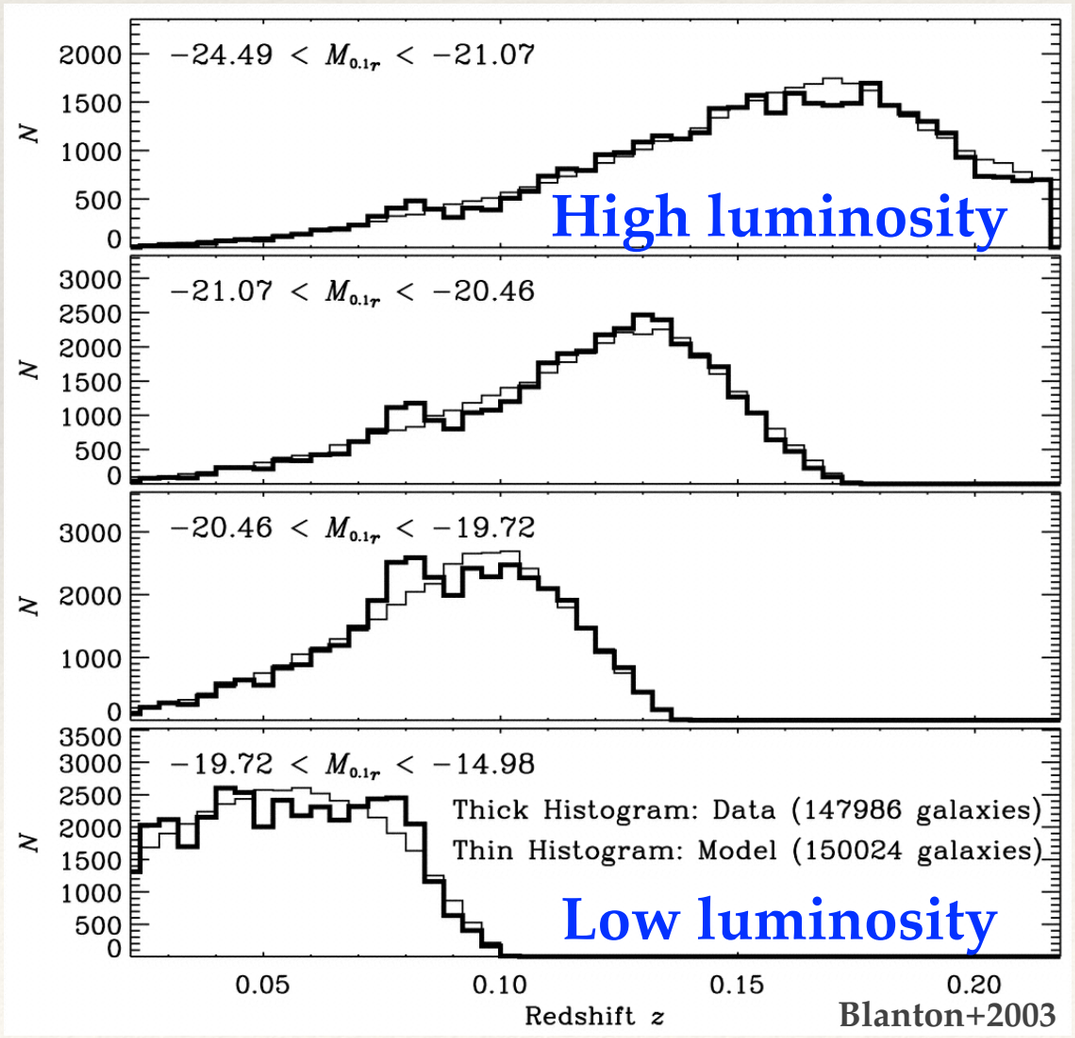
- **Field galaxies**:
  - Obtain a magnitude-limited galaxy sample
  - Use distances to get luminosity of each galaxy individually
  - Make a histogram in bins of luminosity: N(L)
  - Complication: each luminosity bin measured from a different survey volume $V_{max}(L)$

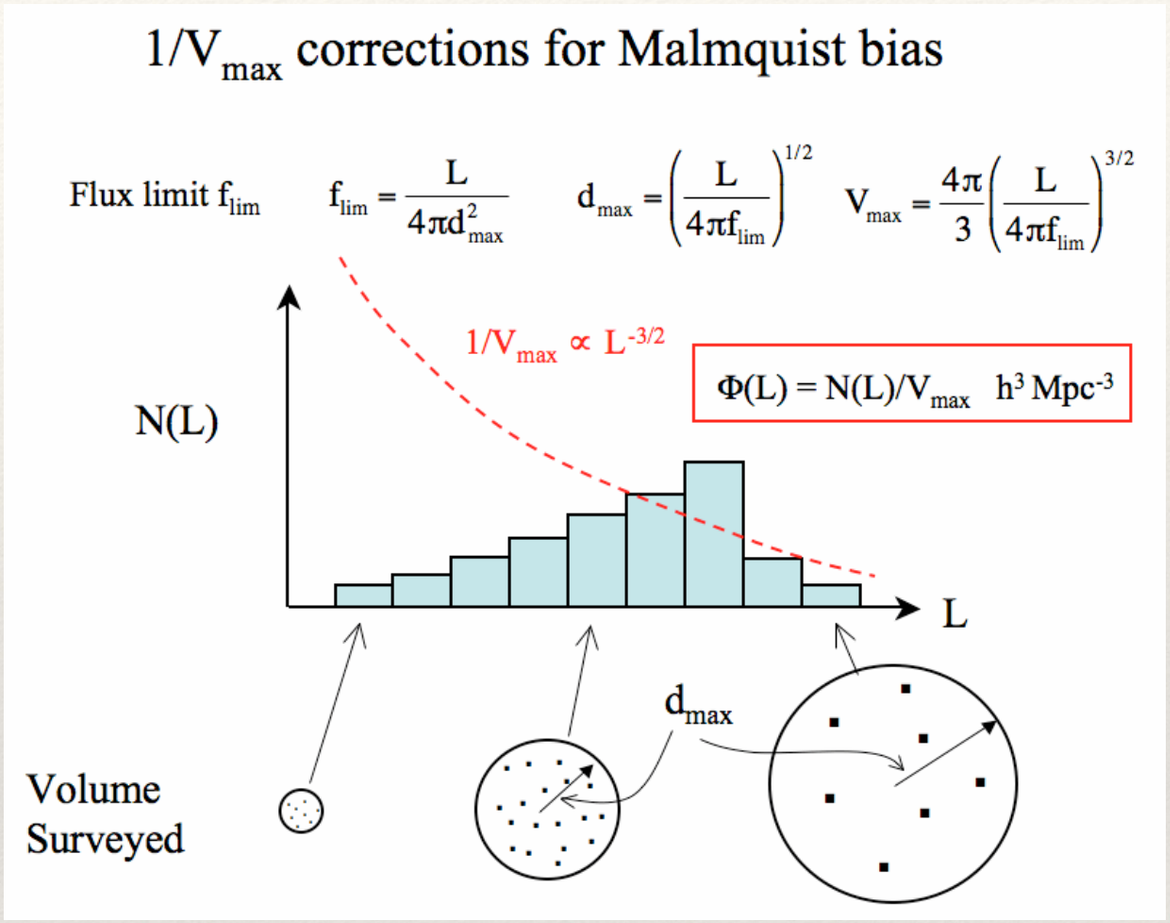


http://people.virginia.edu/~dmw8f/astr5630/Topic04/t4_malmquist.gif

Statistical Properties: Luminosity Function

- See luminous galaxies from a larger volume (Malmquist Bias)



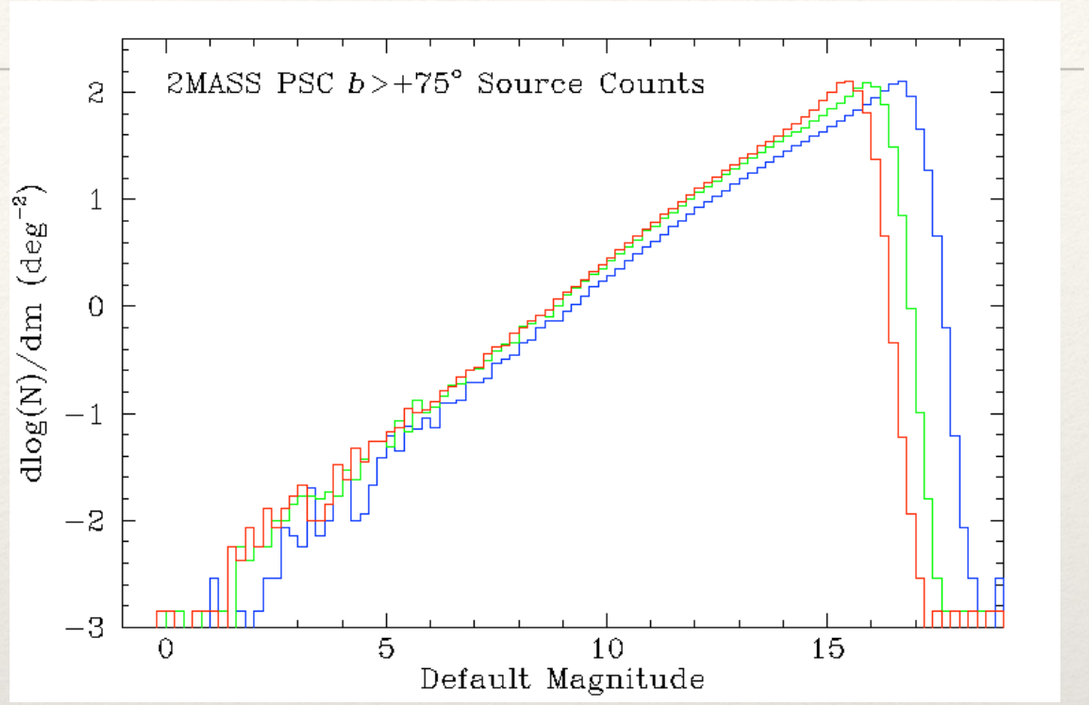


http://people.virginia.edu/~dmw8f/astr5630/Topic04/t4_malmquist.gif

- Number density at each L has to be computed using the appropriate volume
- Divide N(L) by $V_{max}(L)$ to get $\Phi(L)$

Statistical Properties: Luminosity Function

- Complication: survey **incompleteness!**
  - Start missing objects at fainter observed magnitudes
  - Use V / V_{max} test: if <V/V_{max}> = 0.5, sample complete
- Complication: have been assuming constant space density but what about **large scale structure?**
- Ensure survey large enough to overcome **cosmic variance**



MACS J0416.1–2403 (NASA/ESA)

Statistical Properties: Luminosity Function

- More sophisticated methods needed to fully account for selection function:
  - Binggelli et al (ARAA 26, 26, 1988)
  - Stepwise maximum likelihood (Efstathiou et al. 1988)
  - Schechter function determination (Sandage et al. 1979)

Statistical Properties: Luminosity Function parameterization

- 1974 — Press & Schechter calculated mass distribution of clumps emerging from the young universe
- 1976 — Paul Schechter applied same function to luminosity distribution of galaxies in clusters.
  - Schechter function:

$$\phi(L) = \frac{\phi_*}{L^*}\left(\frac{L}{L^*}\right)^{\alpha} \exp\left(-\frac{L}{L^*}\right)$$

  - with parameters: ϕ^*, L^*, and α.

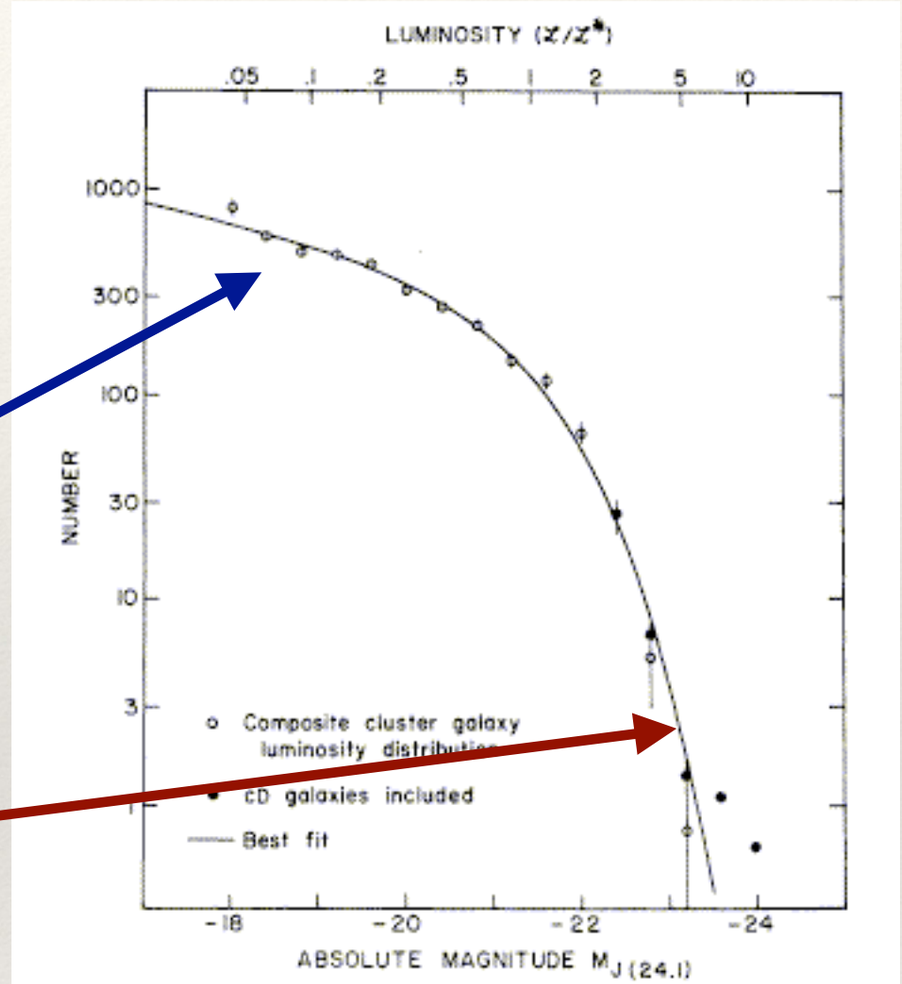


FIG. 2.—Best fit of analytic expression to observed composite cluster galaxy luminosity distribution. Filled circles show the effect of including cD galaxies in composite.

Schechter 1976

$$\phi(M) = (0.4 \ln 10)\ \phi^*\ [10^{0.4(M^*-M)}]^{1+\alpha}\ \exp[-10^{0.4(M^*-M)}]$$

Galaxy Population - Statistical Properties: Luminosity Function

- 1974 — Press & Schechter calculated mass distribution of clumps emerging from the young universe
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  - with parameters: ϕ^*, L^*, and α.

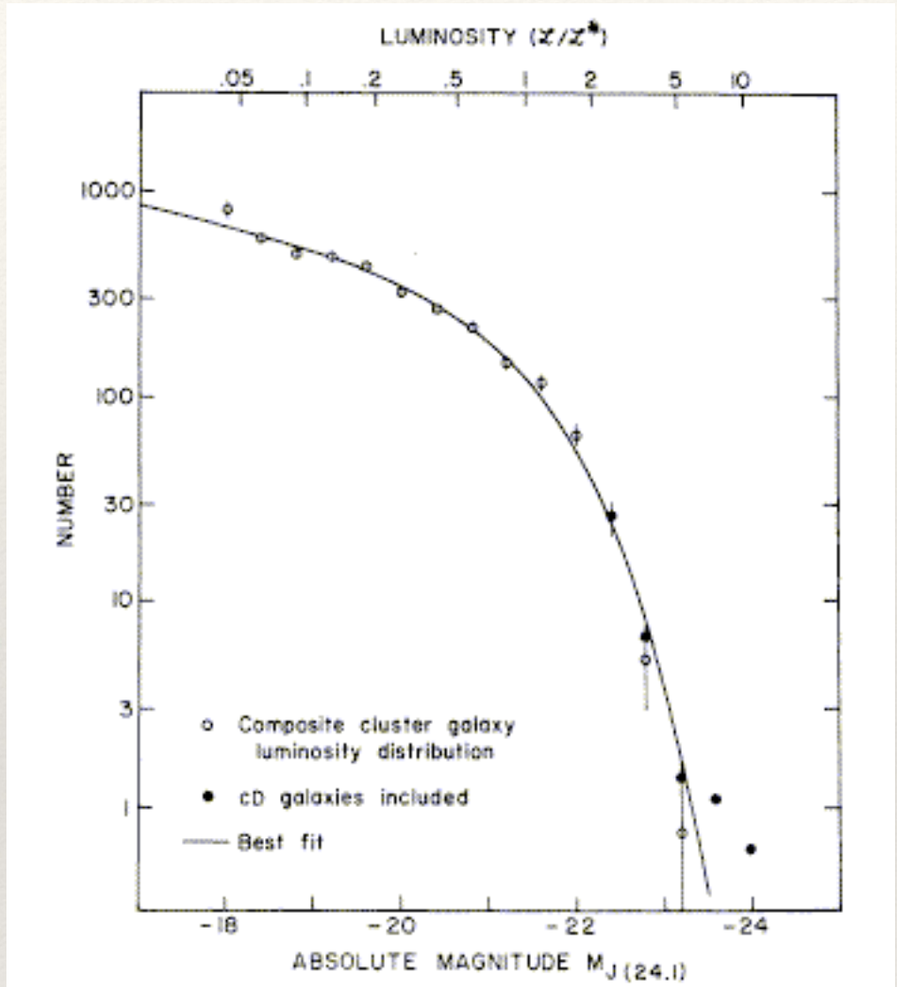
Binggeli (1987)

Schechter function fits remarkably well — don't completely understand why!

Thought Questions

$$\phi(L) = \frac{\phi_*}{L^*}\left(\frac{L}{L^*}\right)^{\alpha} \exp\left(-\frac{L}{L^*}\right)$$

- What objects would you guess dominate by number? by total luminosity?
- Sketch how the luminosity function changes if you change:
  - the overall number density
  - the typical galaxy luminosity
  - the relative number of faint vs. bright galaxies



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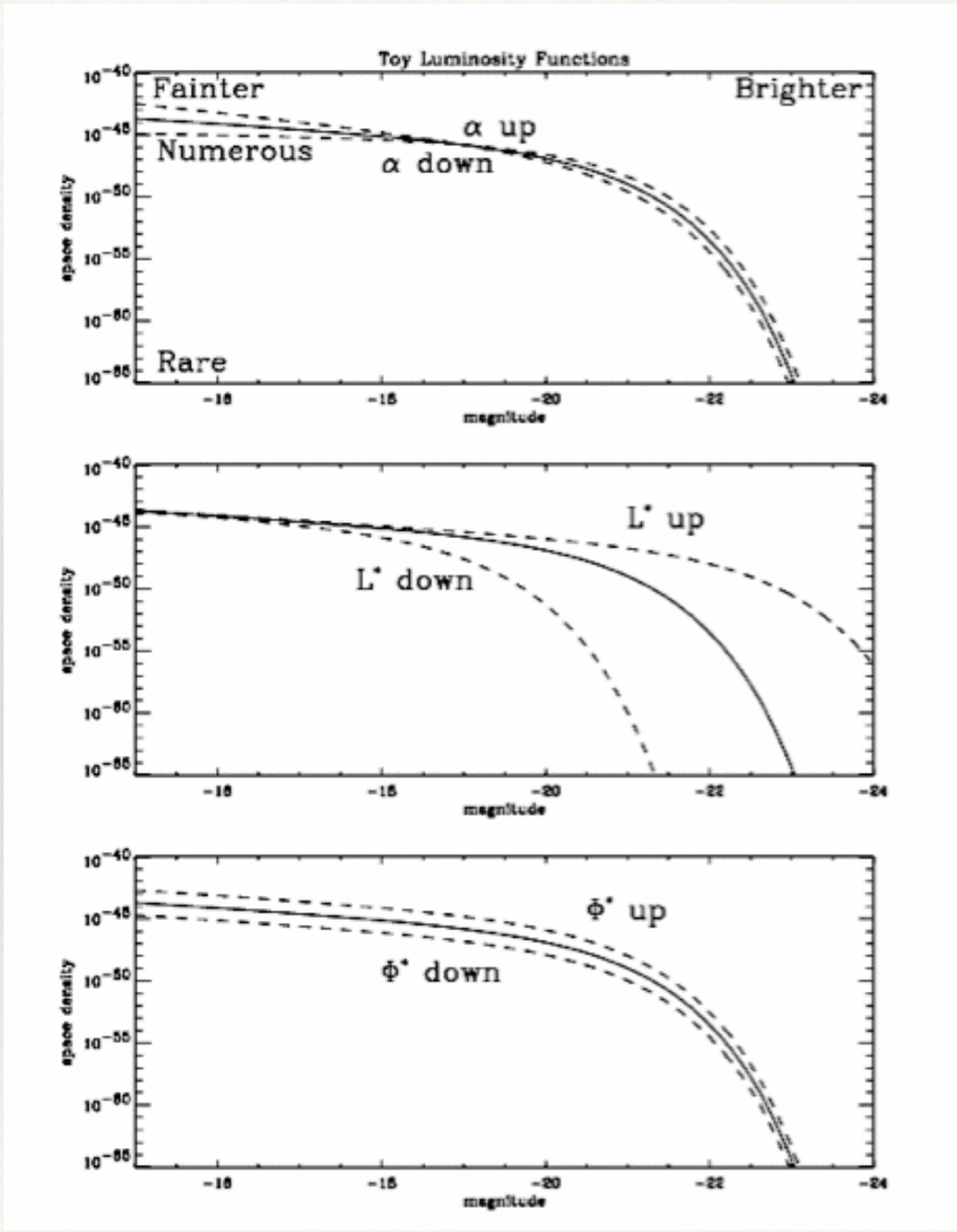
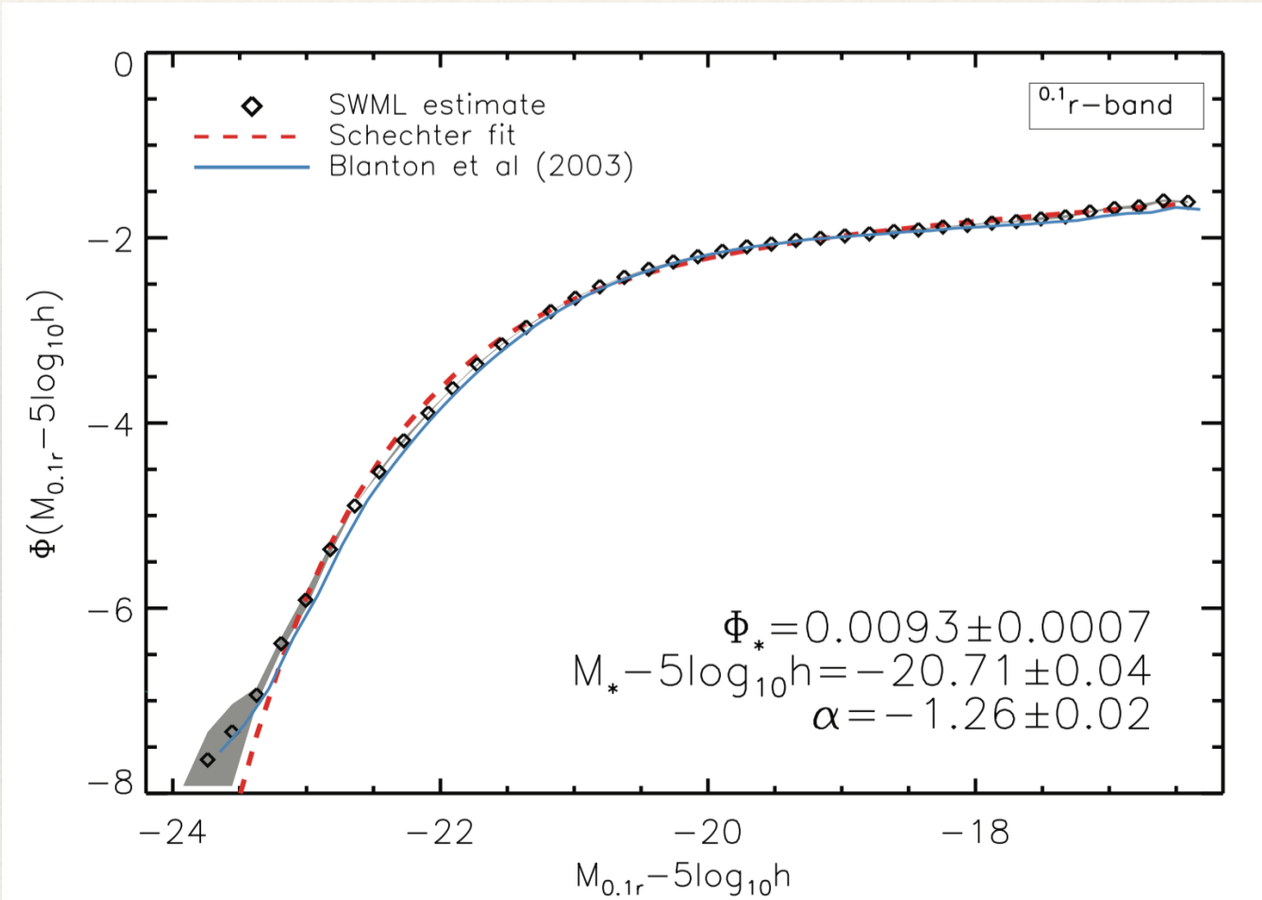


Statistical Properties: Luminosity Function

$$\phi(M) = (0.4 \ln 10)\ \phi^*\ [10^{0.4(M^*-M)}]^{1+\alpha}\ \ \exp[-10^{0.4(M^*-M)}]$$

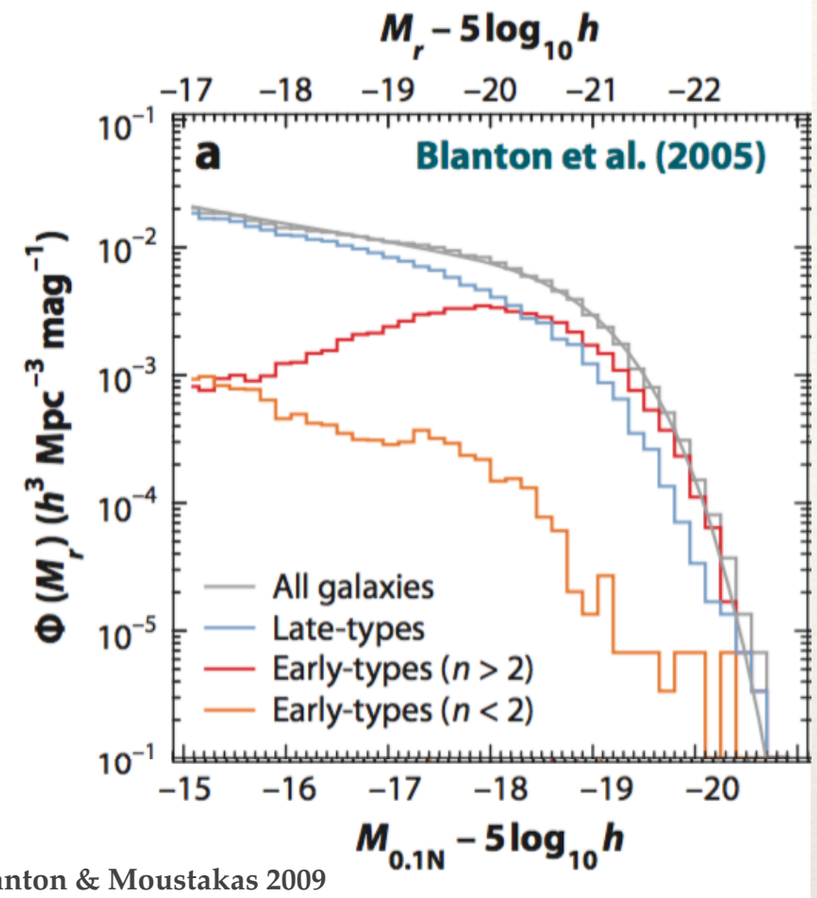
- Observed luminosity function in local universe (e.g. SDSS at z ~ 0.1):
  - $\phi^* \sim 0.015\ h^3\ Mpc^{-3}$
  - $M_{B^*} \sim -19.5$, $M_{R^*} \sim -20.5$
  - $\alpha = -1$ to -1.25



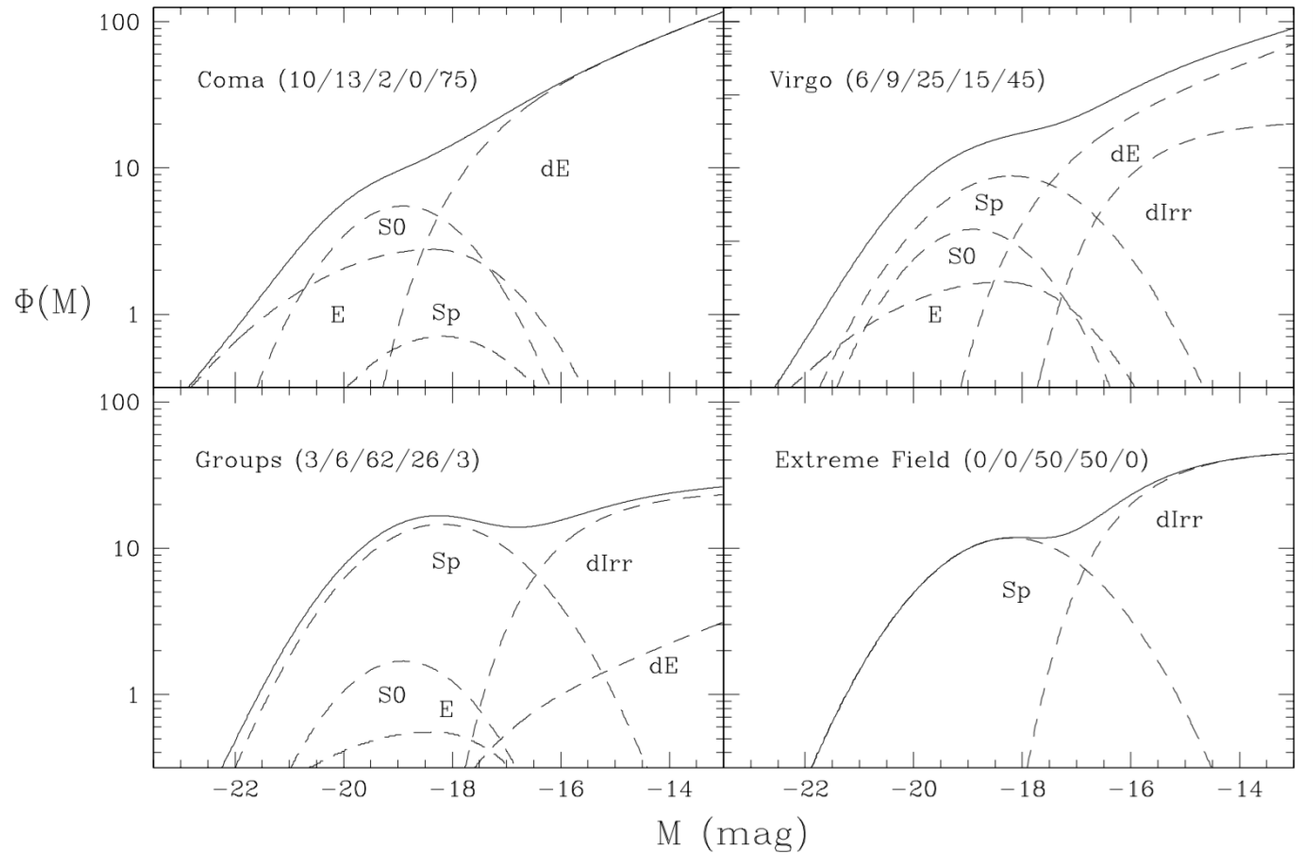
Montero-Dorta & Prada 2009

Statistical Properties: Luminosity Functic

- Different galaxy types have different luminosity functions (~independent of environment):
  - Spirals/S0s: Gaussian
  - Ellipticals: skewed Gaussian (to bright)
  - dwarf galaxies (dE, dSph, dIrr): Schechter function
- Proportions of each galaxy type depend on environment.



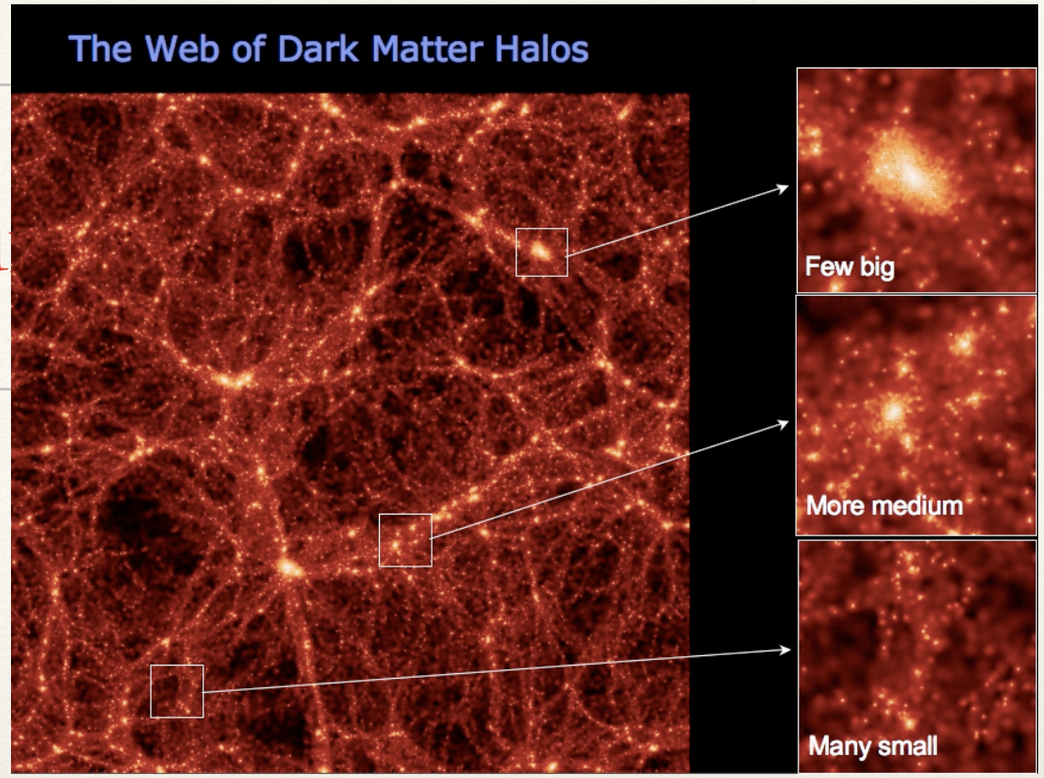
Blanton & Moustakas 2009

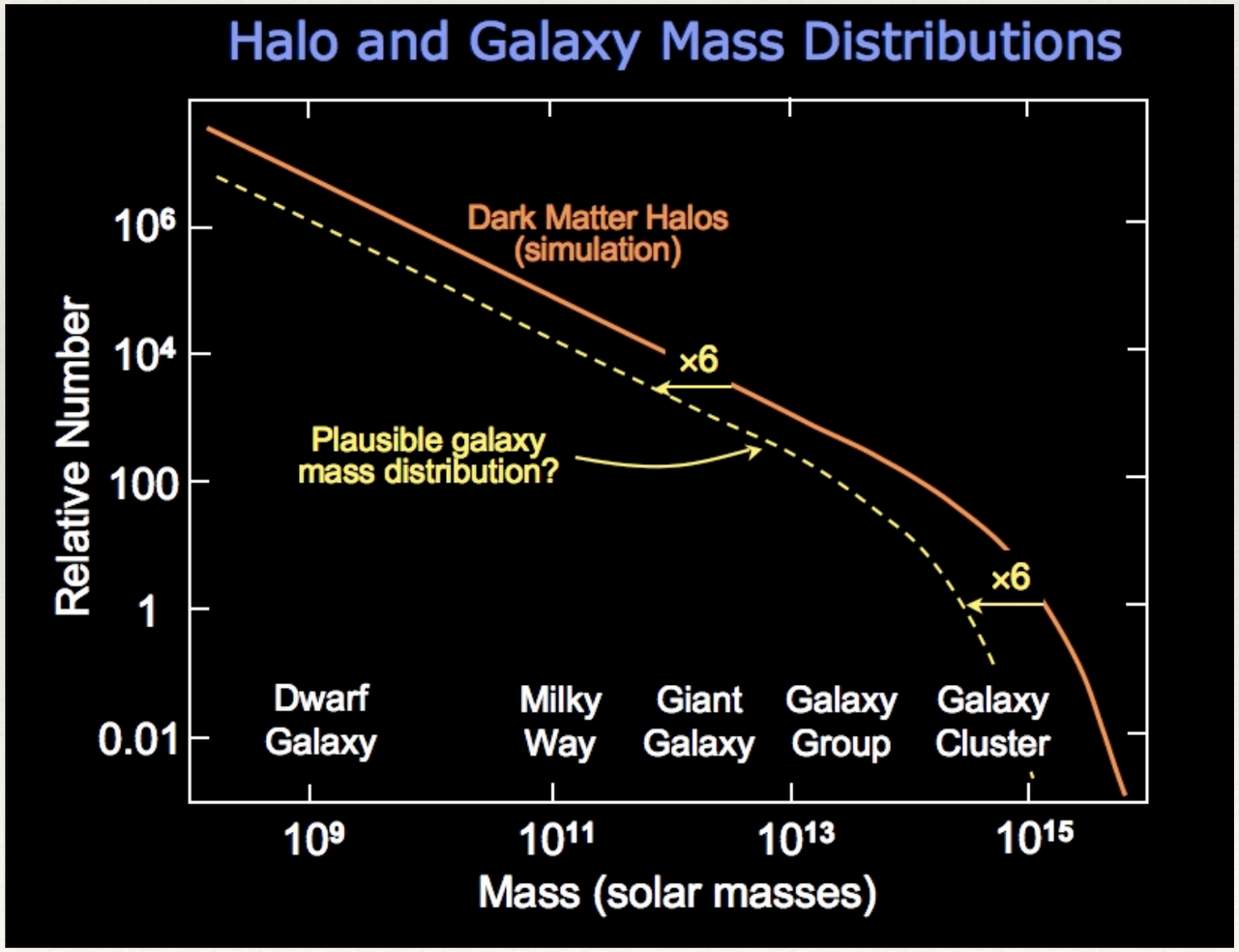


Jerjen 2006

Statistical Properties: Luminosity Fu

- What do we learn from luminosity functions?
  - **How galaxies form from primordial density fluctuations:**
    - Dark matter halos form
    - Baryonic matter fall in and make stars
    - Relative number of galaxies at different masses may be related to primordial distribution





http://people.virginia.edu/~dmw8f/astr5630/Topic04/Lecture_4.html

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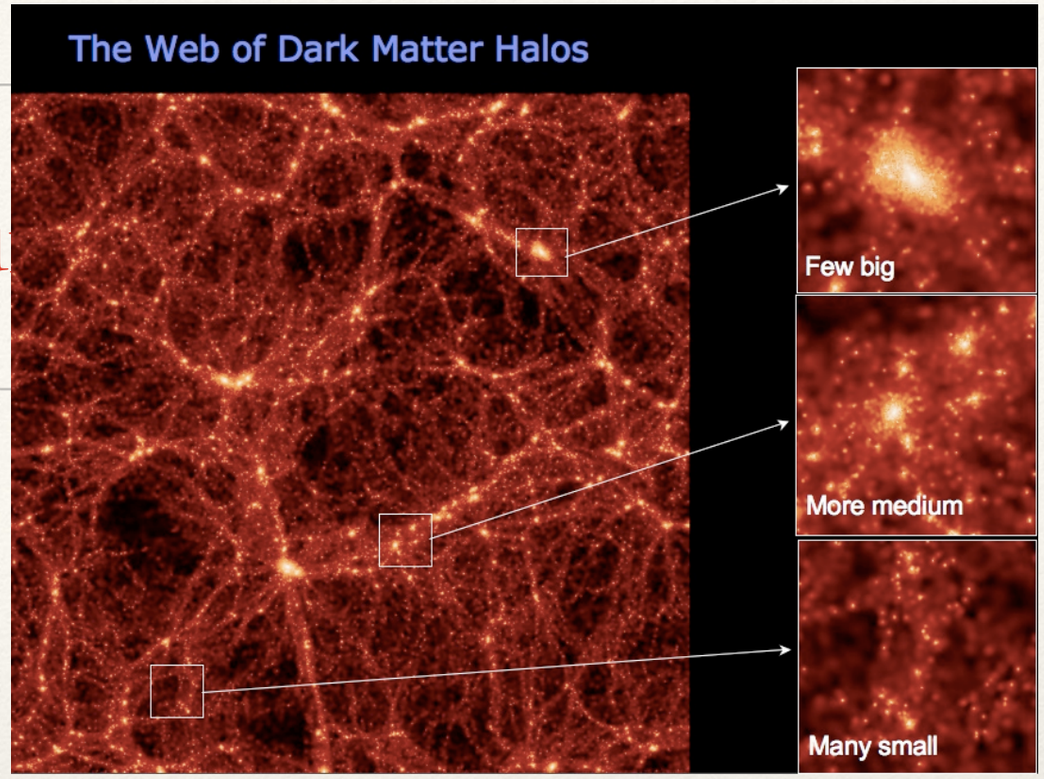

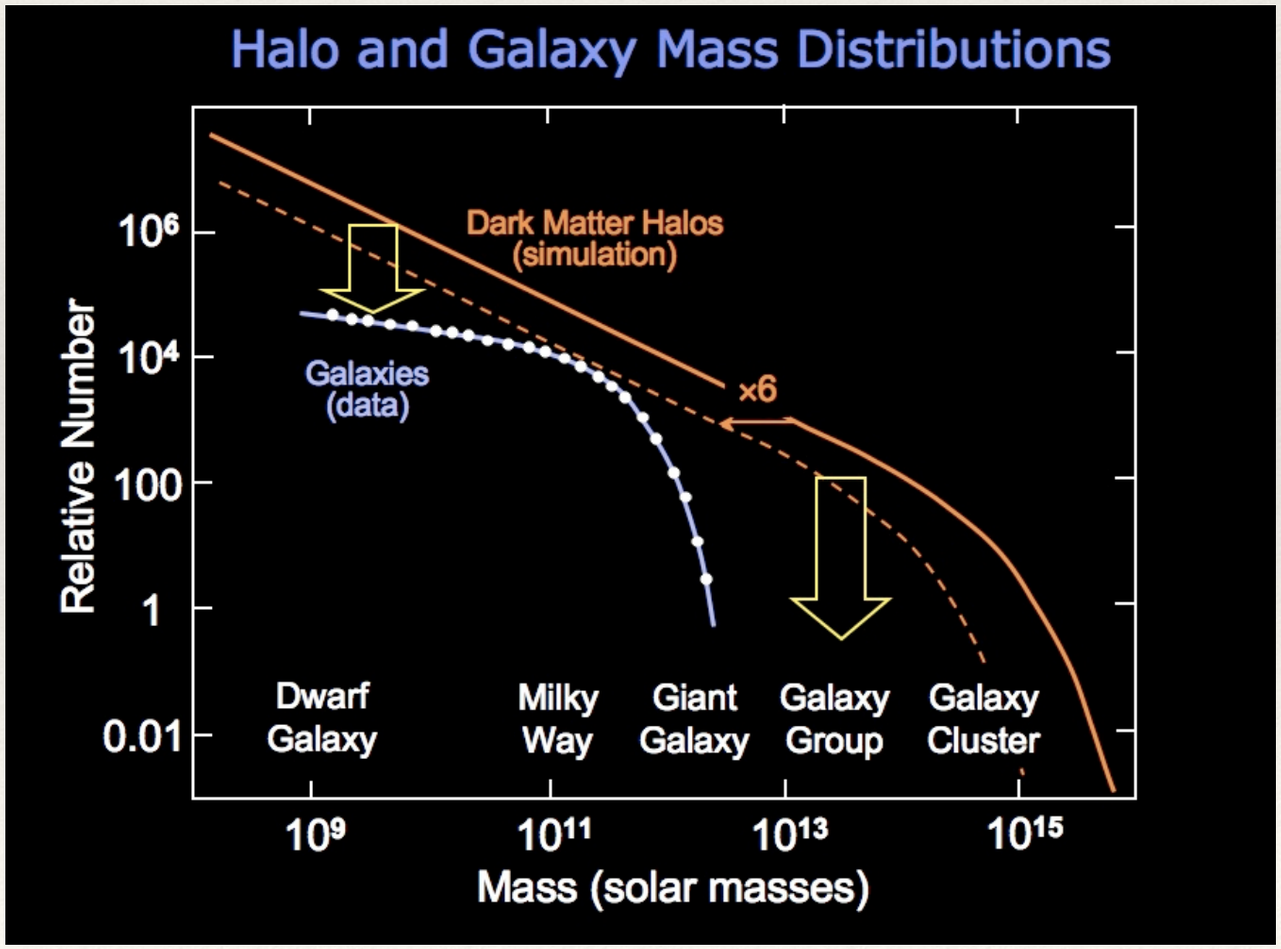

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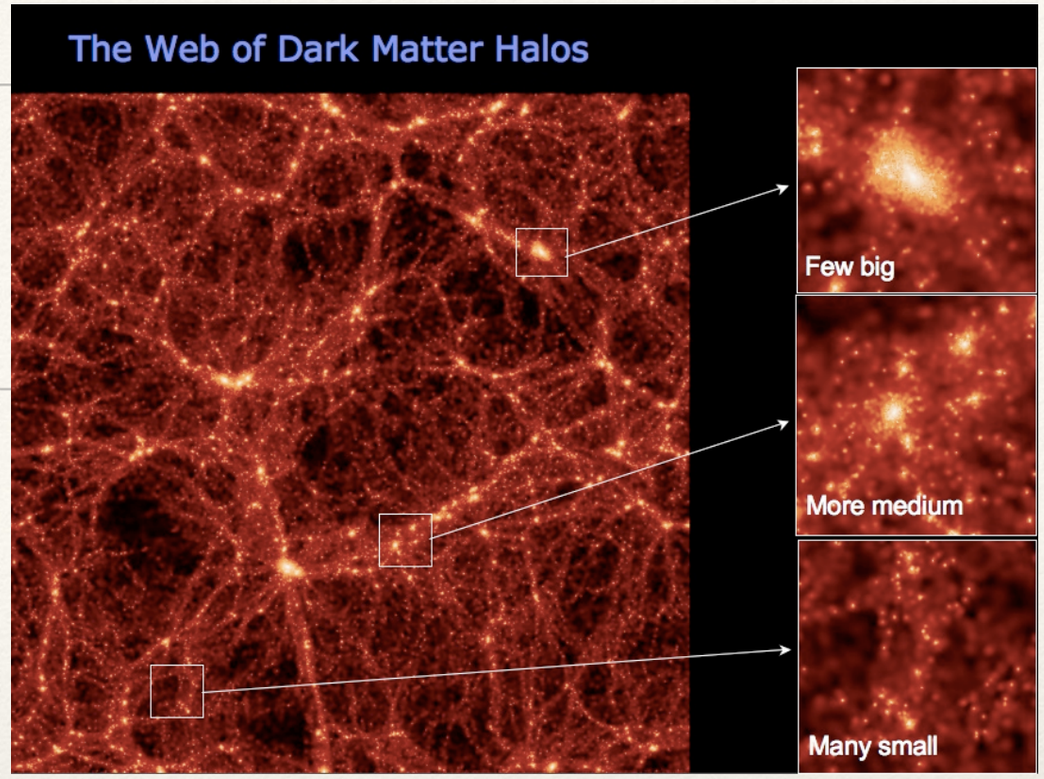
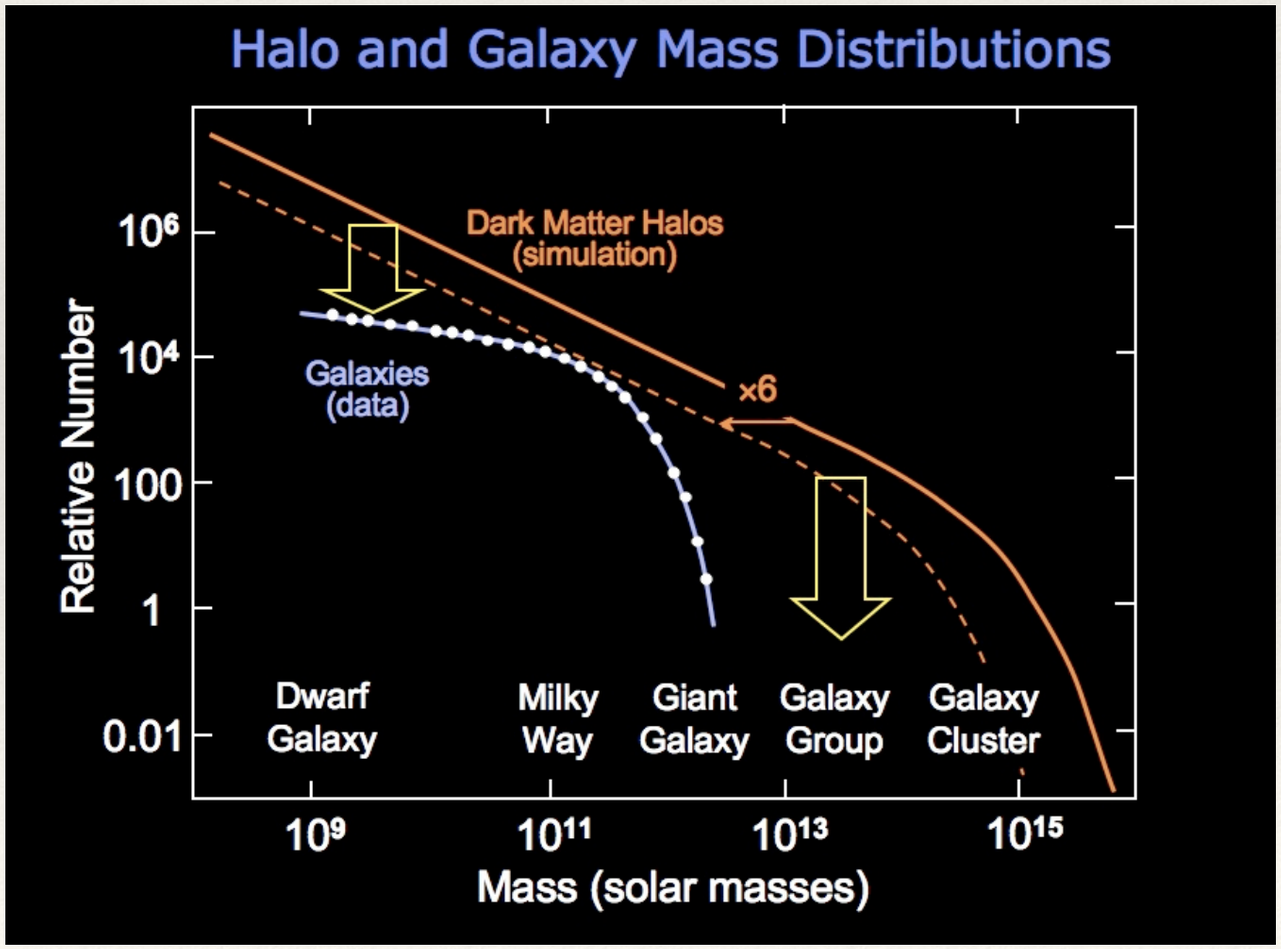
Thought Question



- What might be affecting the galaxy formation "efficiency" at higher and lower galaxy masses?



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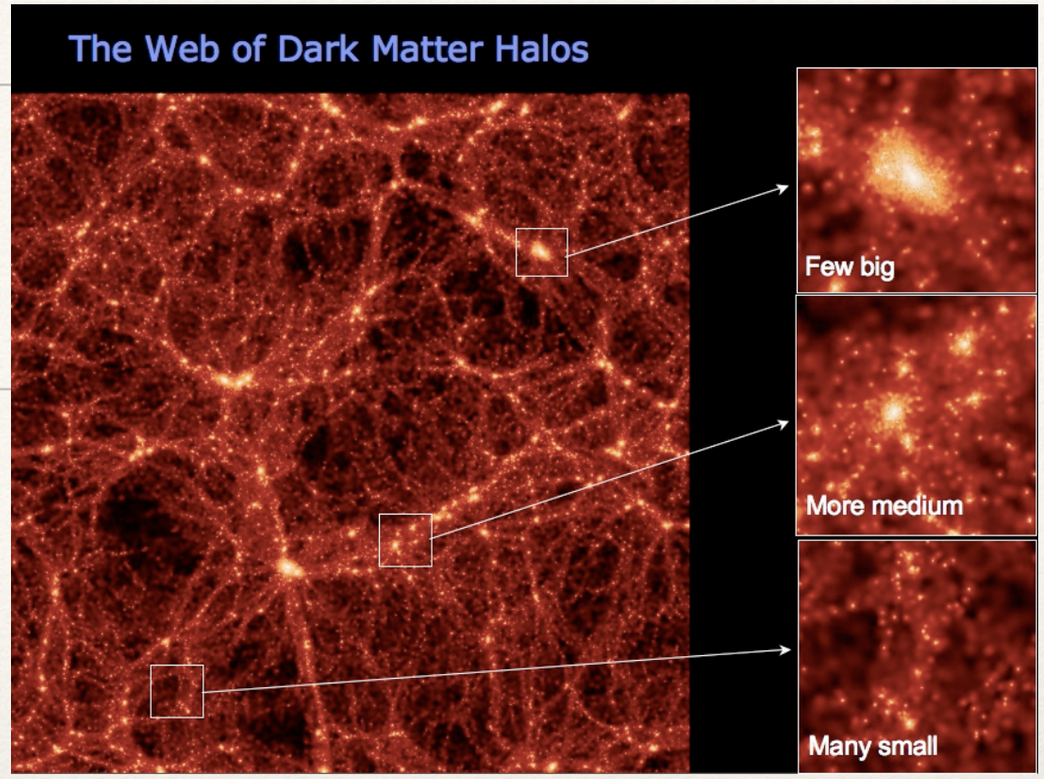

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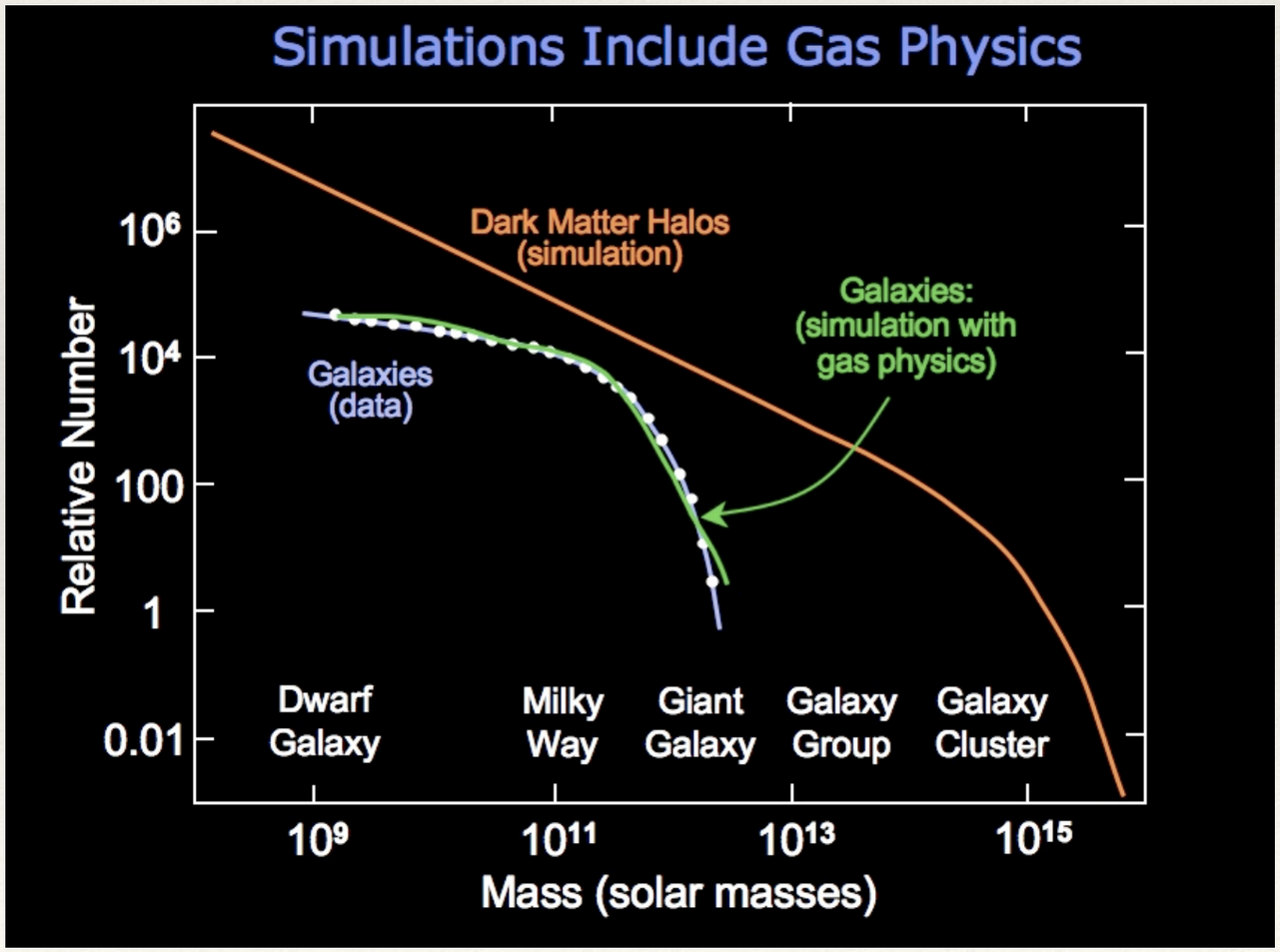


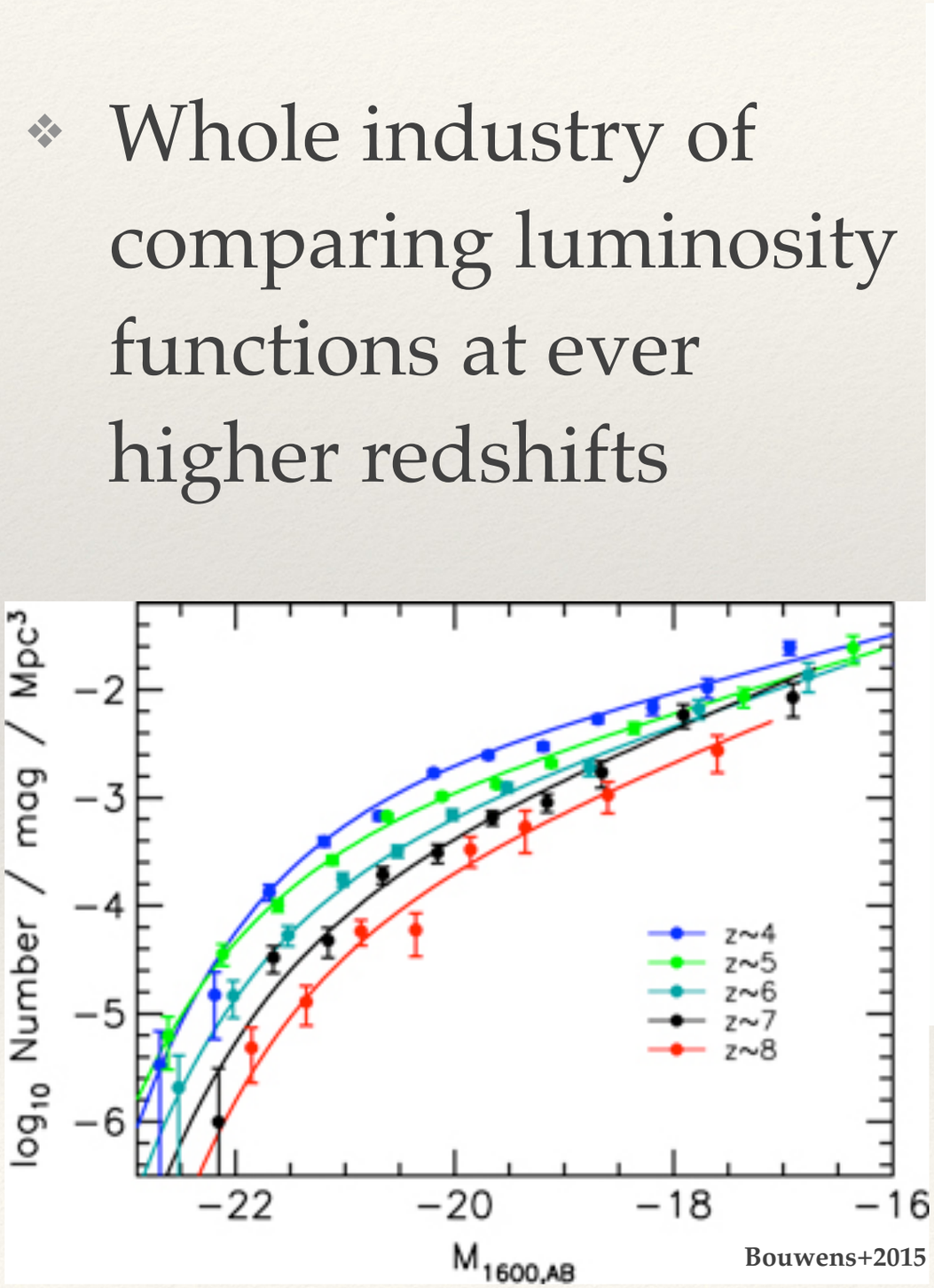
http://people.virginia.edu/~dmw8f/astr5630/Topic04/Lecture_4.html

Statistical Properties: Luminosity Function

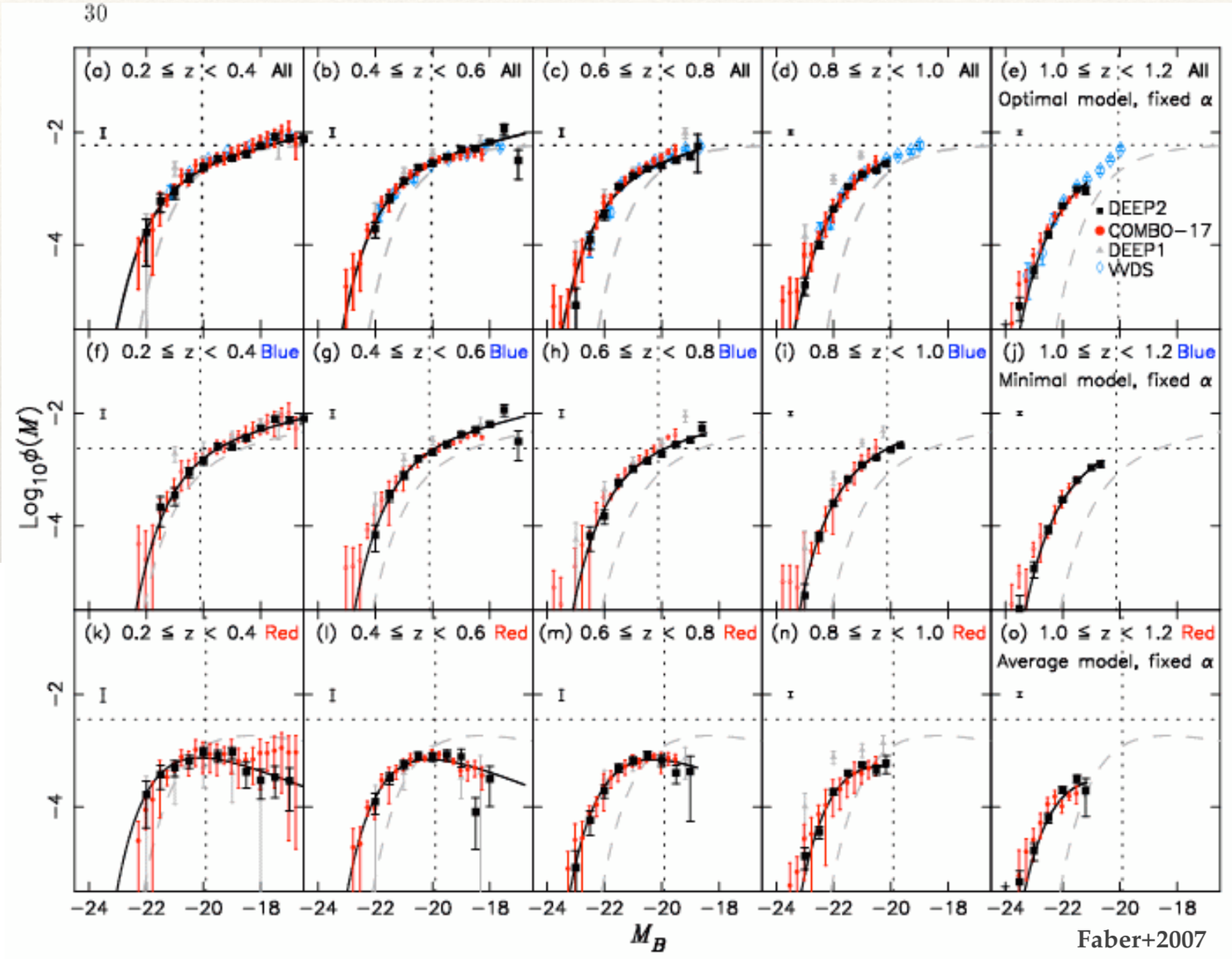
- What do we learn from luminosity functions?
  - **How galaxies evolve over cosmic time:**
    - **no evolution**: distribution of galaxy luminosities is unchanging
    - **passive evolution**: number and internal (stellar) make-up of galaxies is unchanging, but luminosity evolves as stars evolve
    - **luminosity evolution**: stellar make-up of galaxies changes with time (star formation, leading to luminosity changes)
    - **number (density) evolution**: number of galaxies changes with time with galaxies being created (formed) or destroyed (e.g., mergers) as a function of luminosity

Statistical Properties: Luminosity Function

- Whole industry of comparing luminosity functions at ever higher redshifts



Bouwens+2015



Faber+2007

- Have to disentangle observational vs. real astrophysical effects