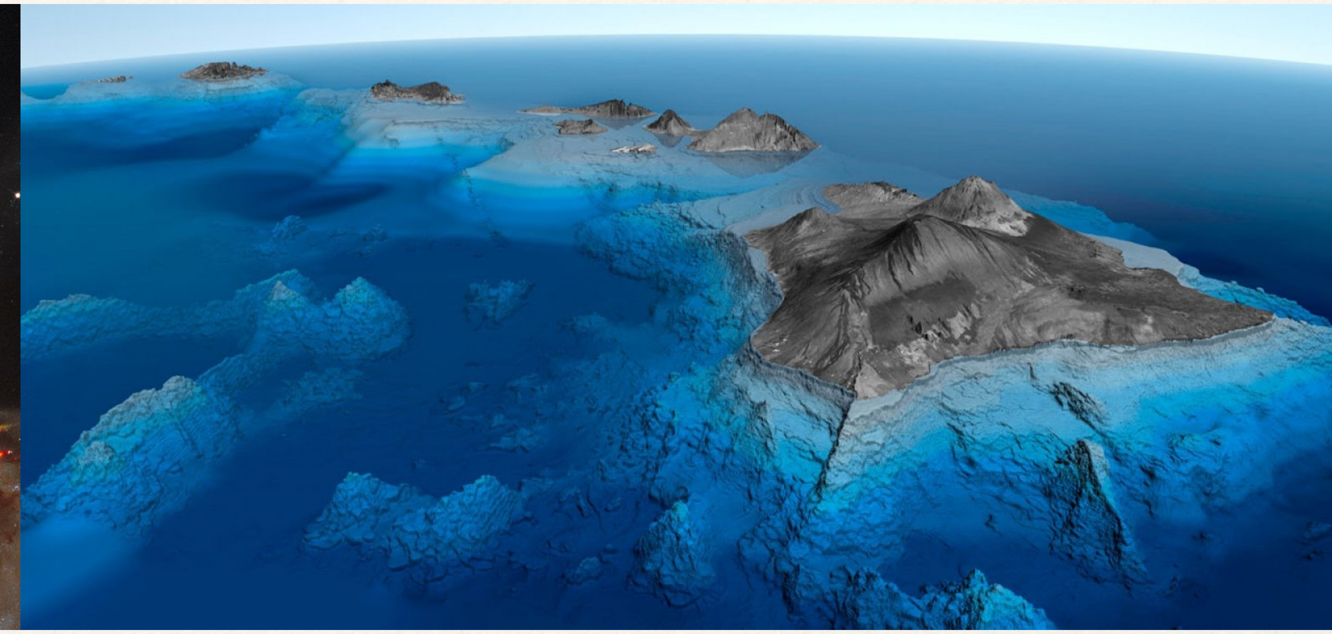


Getting to know the "island universes" out there.

Galaxies I

ASTR 555
Dr. Jon Holtzman

Group work and class feedback

Group work

- problems
- weekly summaries
- revised submission for weekly summaries

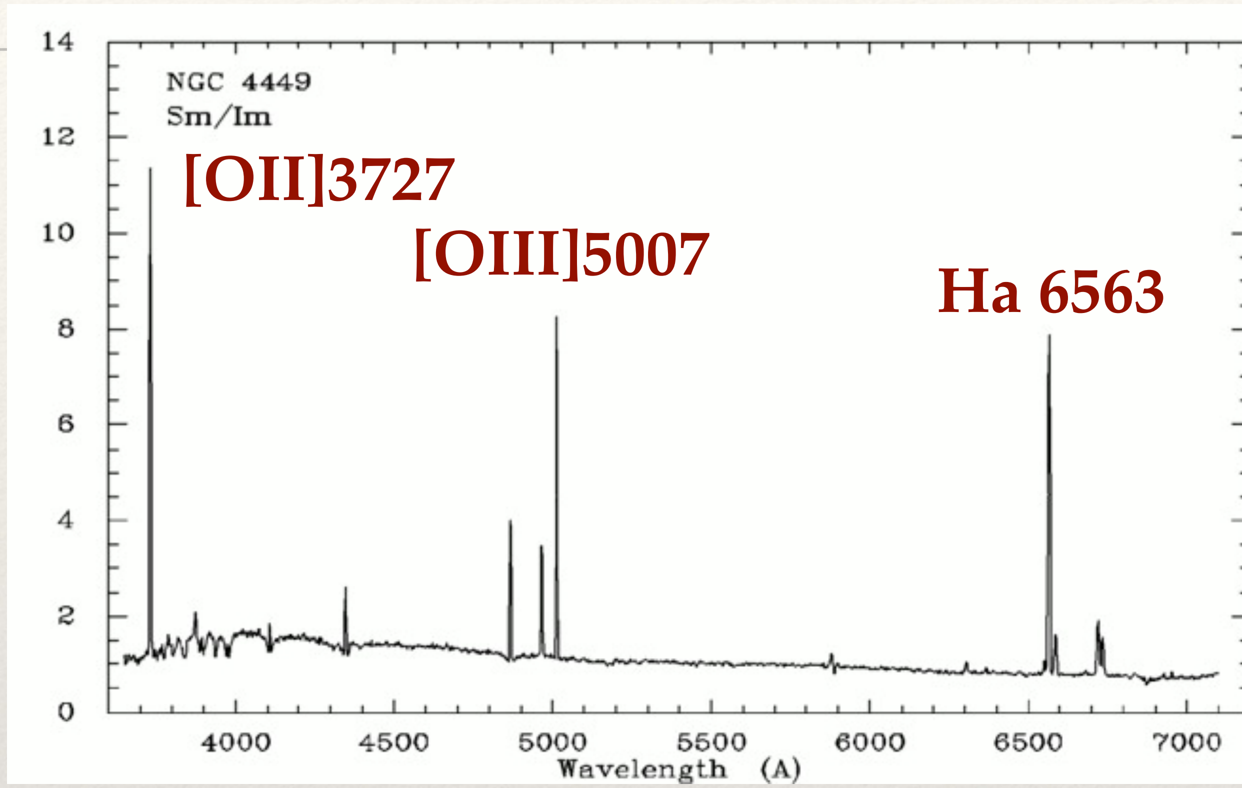
Anonymous class feedback

Assignments

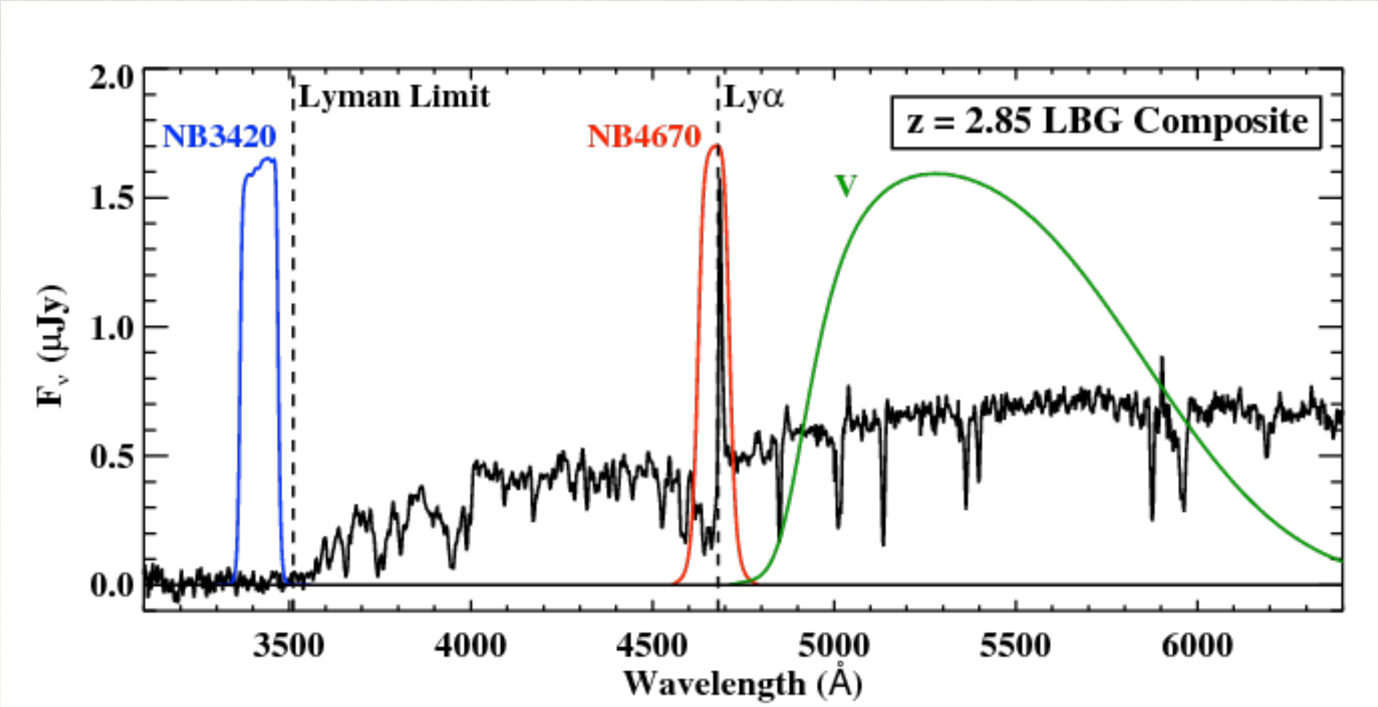
Warm-up

- Suppose you want to use a narrowband filter at 750nm to select a sample of galaxies at z~0.5 and estimate the distribution of galaxies as a function of luminosity. How will your results be biased?

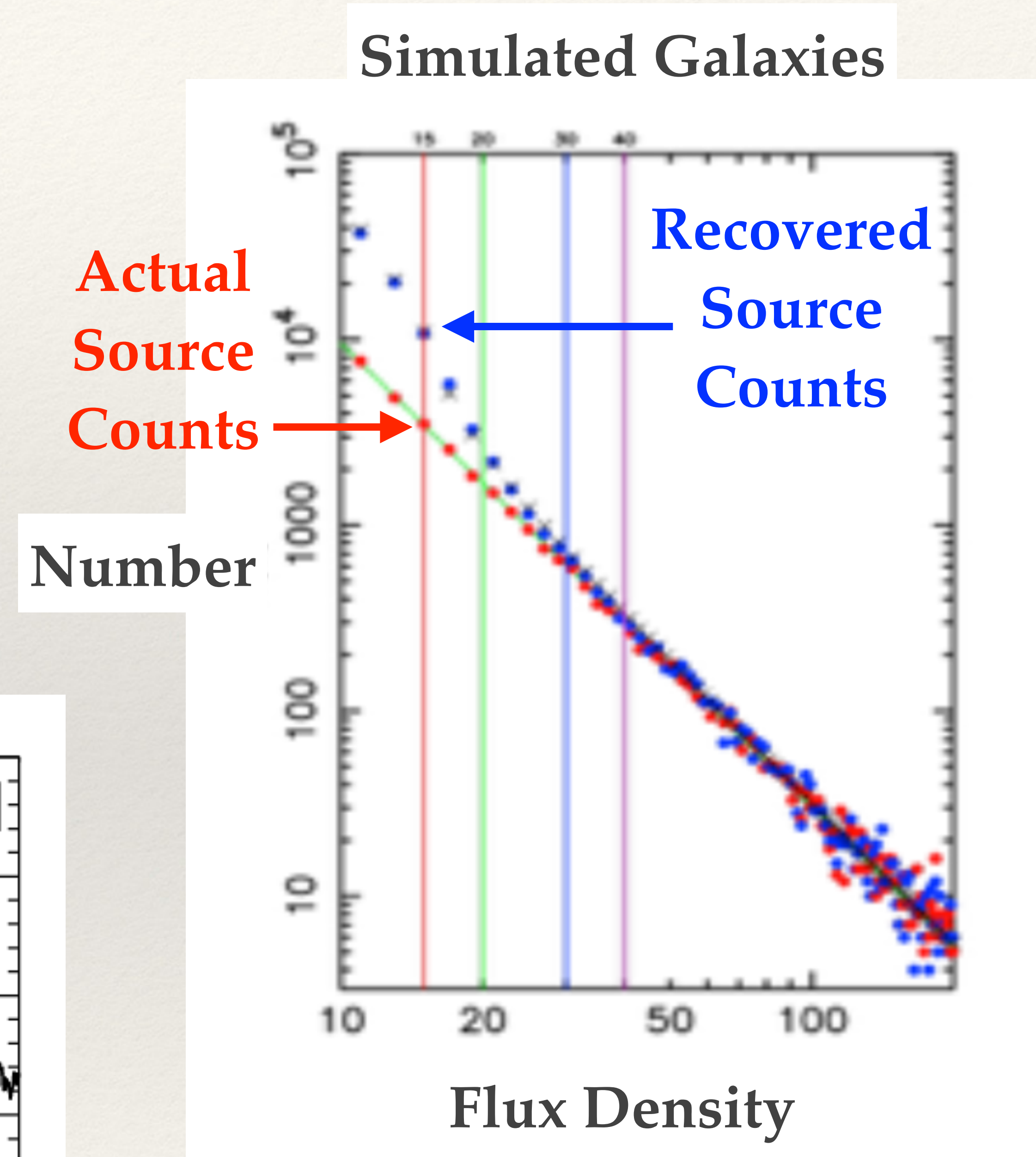
Warm-up



Kennicutt 1992



Mostardi et al. 2013



www.astro.ubc.ca/people/jvw/ASTROSTATS/lectures/PL_15_2013_www.pdf

Course Overview

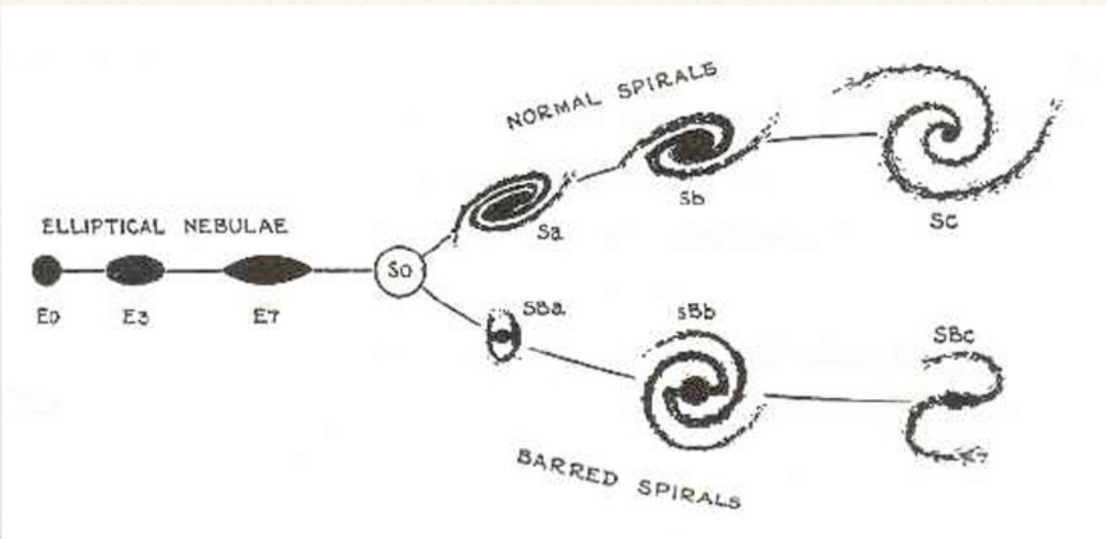
- We will aim to cover:
  - Observing Galaxies — the main techniques used for observing galaxies
  - **Galaxy Population — the observed properties of galaxies**
  - Building Blocks — the basic building blocks that make up individual galaxies
  - Milky Way — our own Galaxy

Outline for Today

- Galaxy Population - Statistical Properties:
    - Colors

NGC1232 (ESO)

Observing Galaxies - Morphology vs. Color



Hubble's (1936) "tuning fork" of galaxy morphologies.

- Galaxy morphology — one of the first things we notice but difficult to quantify and interpret consistently
- A simple alternative? — galaxy color

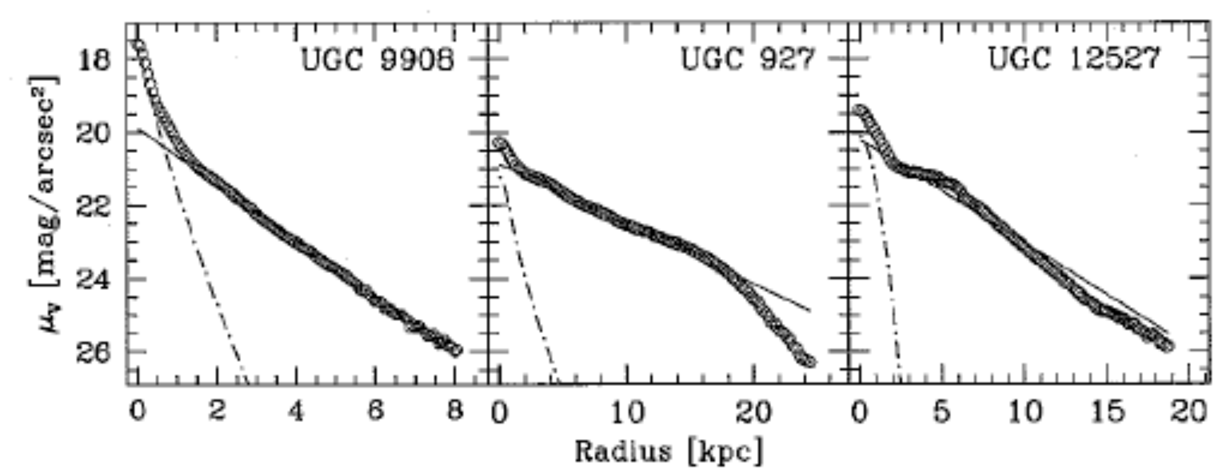
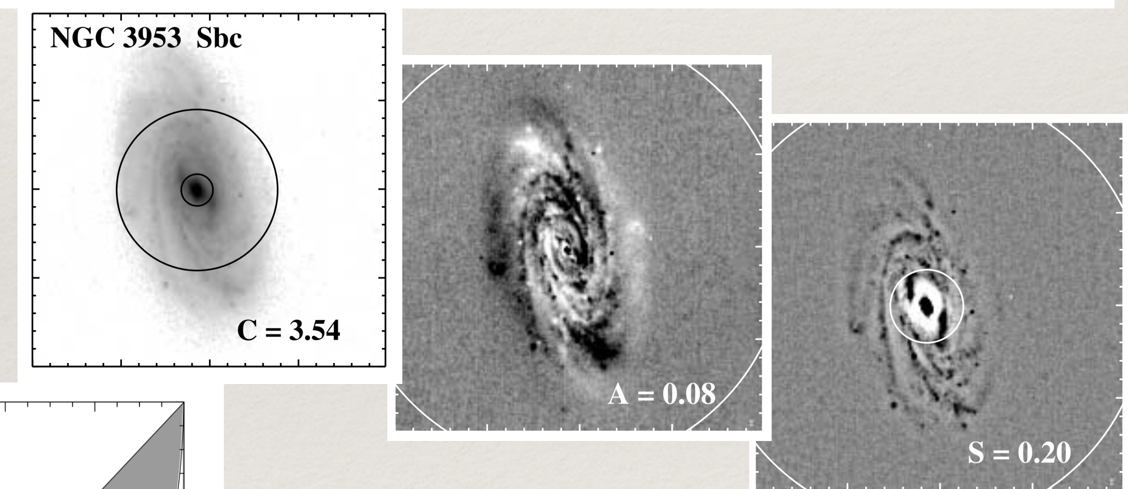


Fig. 2.19. The surface brightness profiles of three disk galaxies plus their decomposition in an exponential disk (solid line) and a Sérsic bulge (dot-dashed line). [Based on data published in MacArthur et al. (2003) and kindly made available by L. MacArthur]



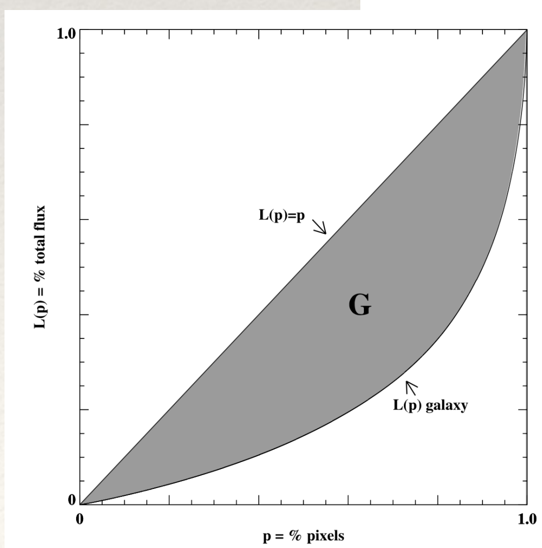
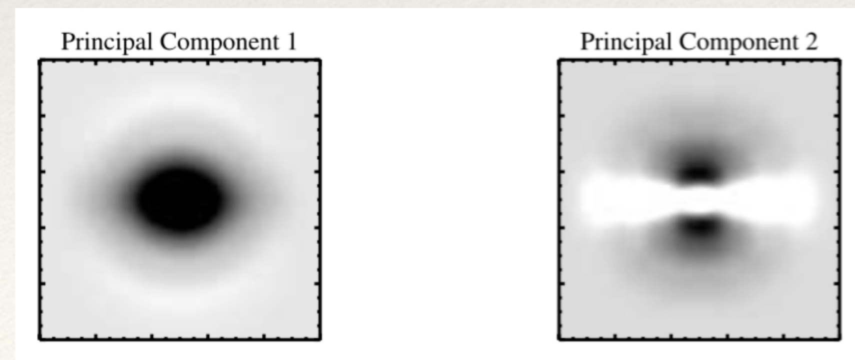
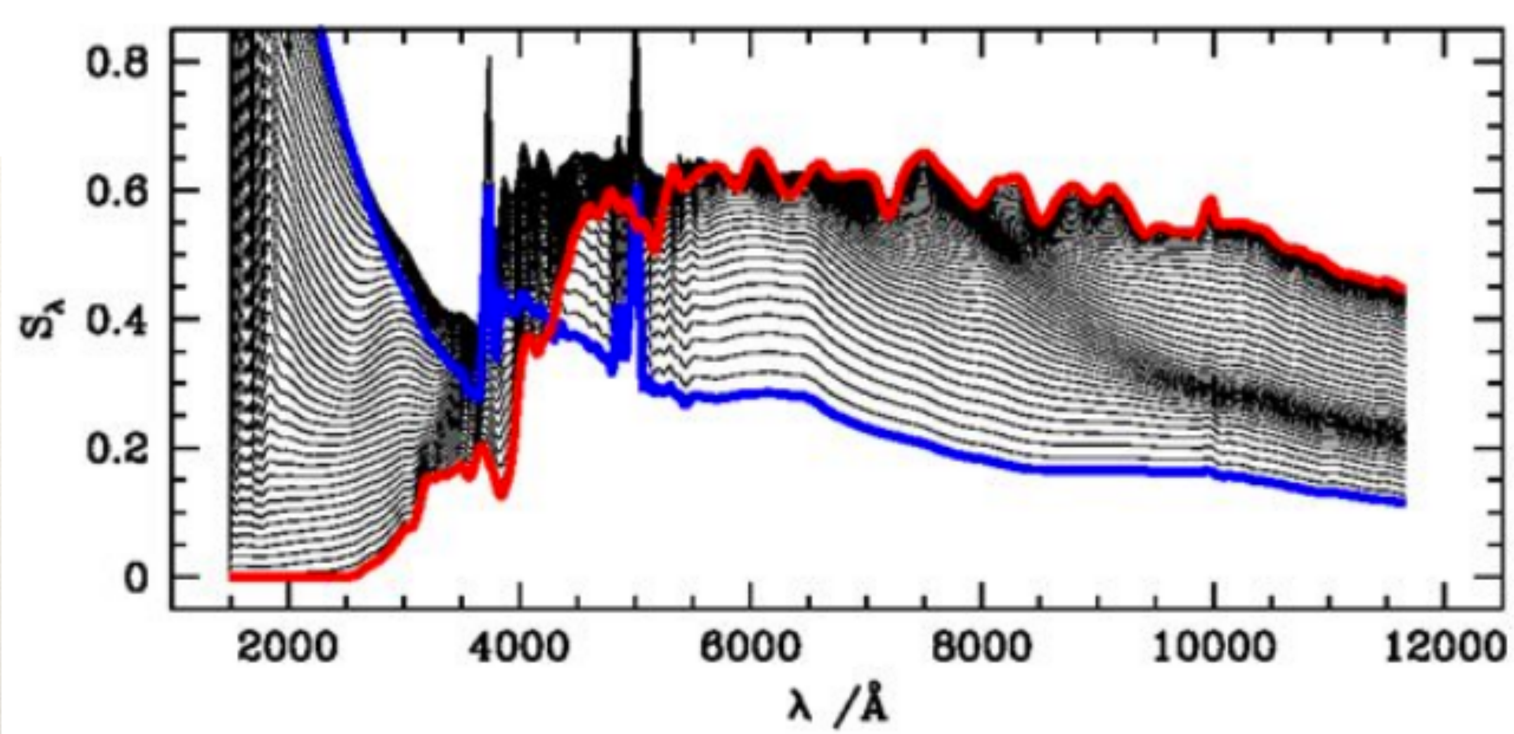


Fig. 1.—Lorenz curve: the Gini coefficient is the area between the Lorenz curve of the galaxy's pixels and that of equitable distribution (*shaded region*). The given curve is for S0 NGC 4526, $G = 0.59$.

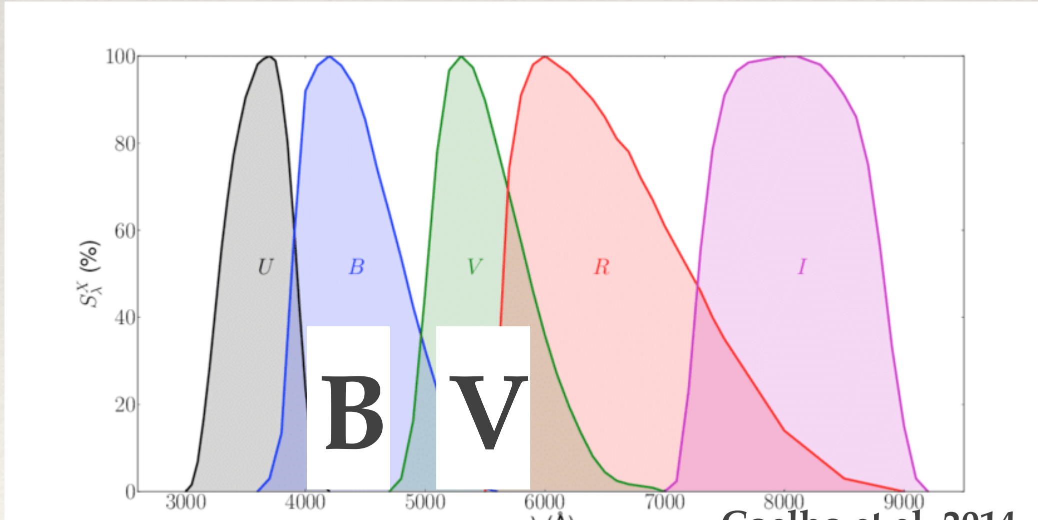


Galaxy Population - Statistical Properties: Colors

- Spectral energy distributions (SEDs) of galaxies can be approximated by **galaxy color**
- Color is easily observed and quantified, and is **connected to the underlying stellar population**
- Note: bigger number in magnitudes = redder



Family of Galaxy Spectra: Budavari et al.

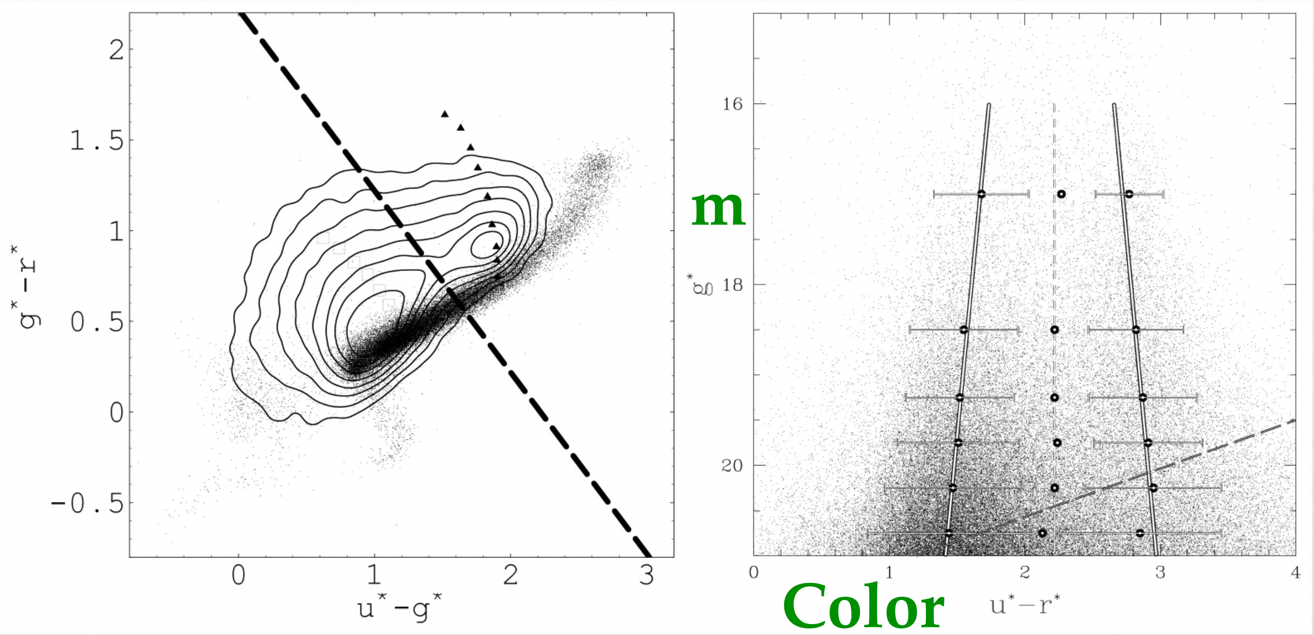


Coelho et al. 2014

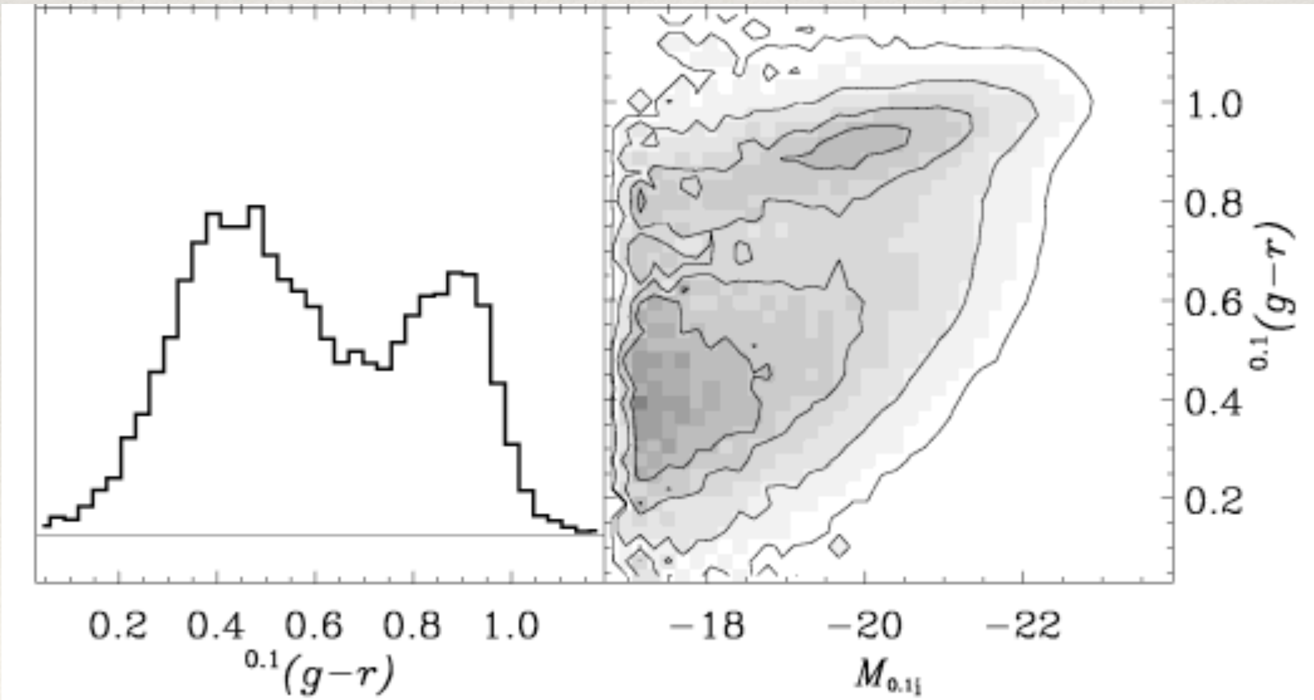
$$B - V = -2.5\log\left(\frac{F_B/F_V}{F_{B0}/F_{V0}}\right)$$

Galaxy Population - Statistical Properties: Colors

- Known since 1930s that galaxy colors correlate with morphology (sample: 100s)
- Striking bimodality in galaxy color quantified by SDSS (sample: 100,000s):
  - Lots of luminous red galaxies
  - Lots of less luminous blue galaxies
  - Few galaxies in between



Strateva et al. 2001



http://people.virginia.edu/~dmw8f/astr5630/Topic01/t1_SDSS_montage.html

See Mo, van den Bosch, & White; Figure 2.27

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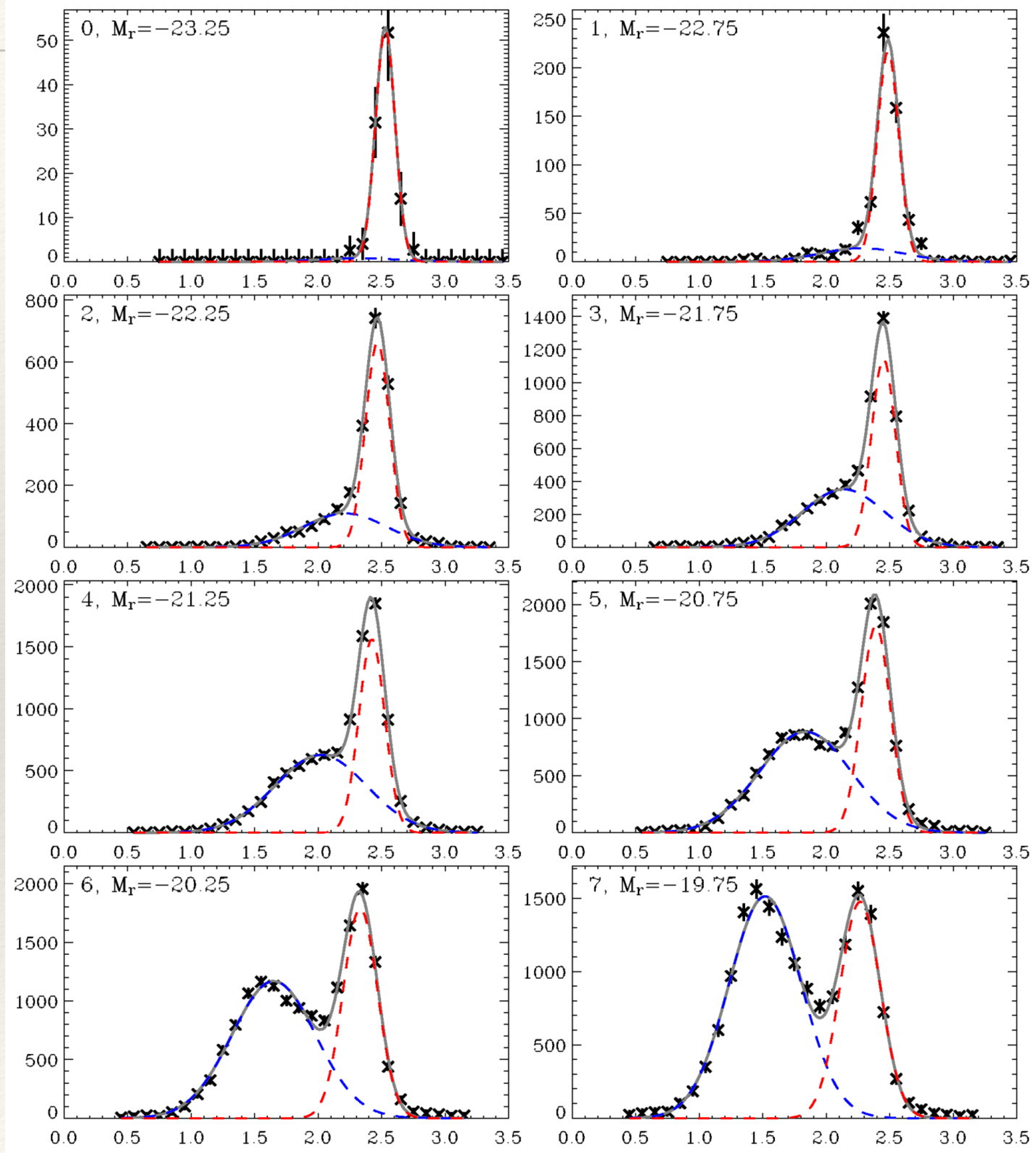

Baldry et al. 2004

Color

Galaxy Population - Statistical Properties: Colors

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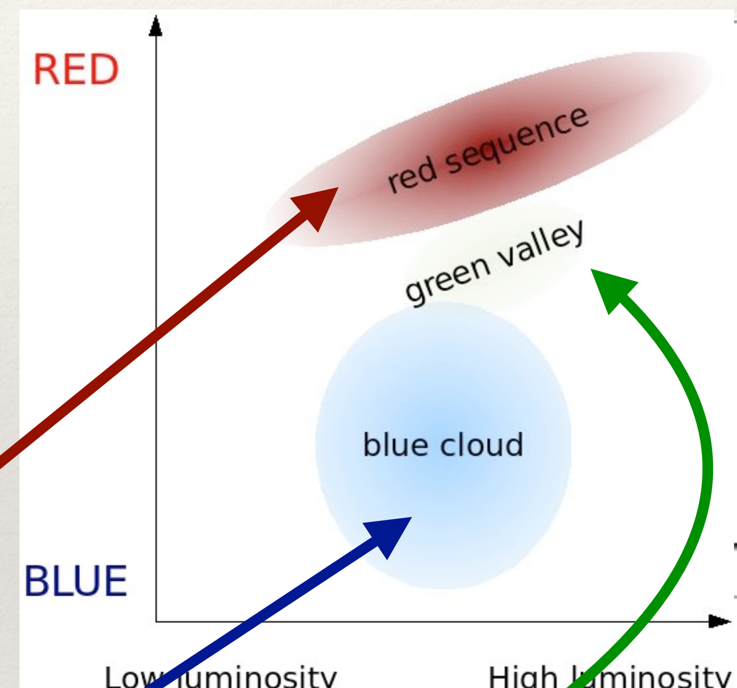
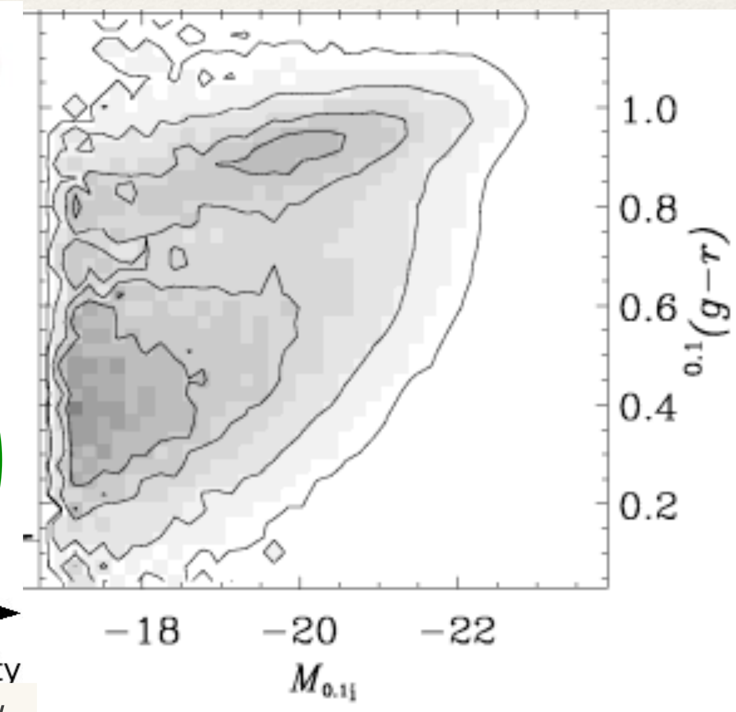


Image Credit: Joshua Schroeder; https://commons.wikimedia.org/w/index.php?curid=20496639

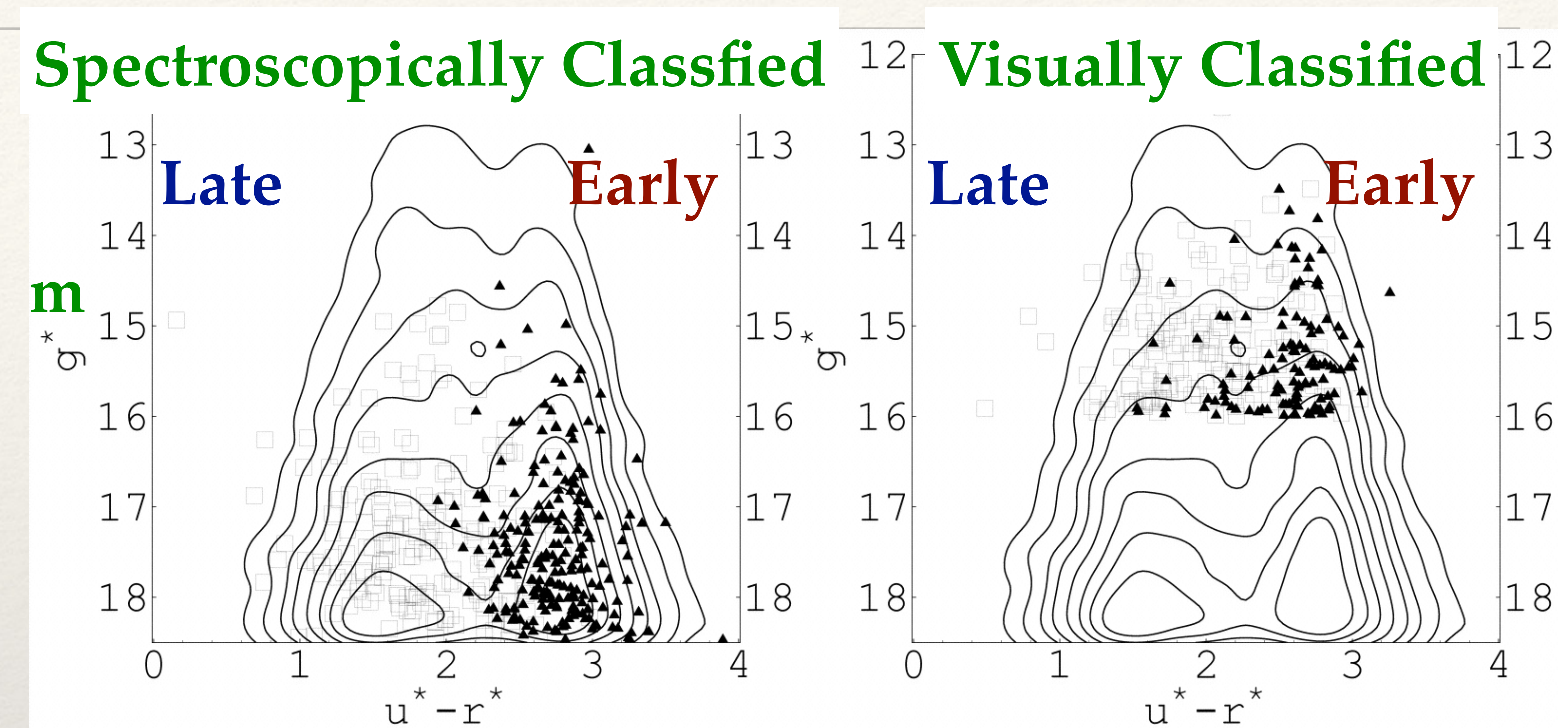


/astr5630/Topic01/t1_SDSS_montage.html

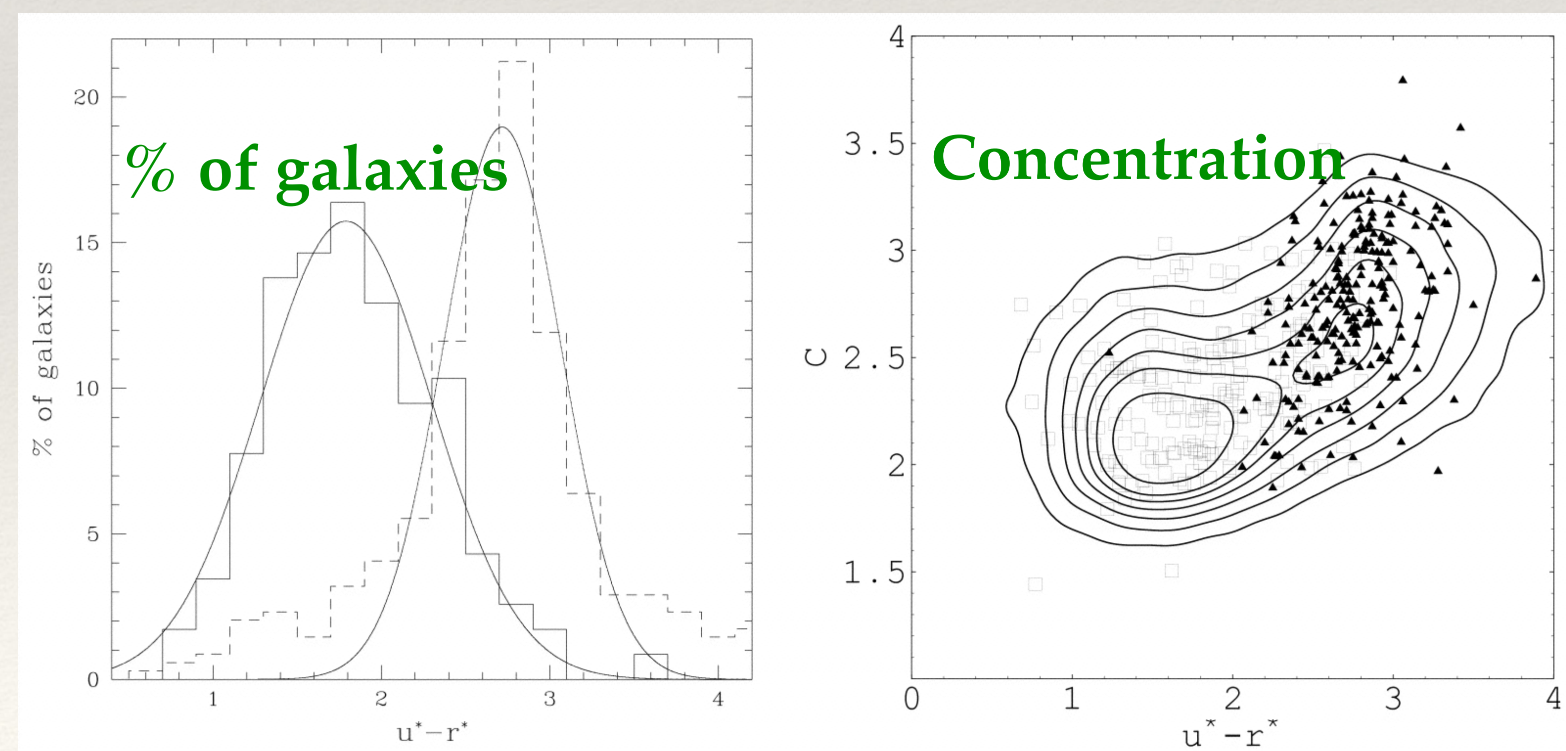
osch, & White; Figure 2.27

Galaxy Population - Statistical Properties: Colors

- Color-morphology connection:
    - **Red sequence**: ellipticals/early-type spirals, more concentrated, without much current star formation (red)
    - **Blue cloud**: later-type spirals, less concentrated, with current star formation (blue)
    - **Green valley**: galaxies in transition
- Note, that dust, bulges, metallicity all play a role too.



Color



Color

Galaxy Population - Statistical Properties: Colors

- As SDSS progressed, it became possible to study galaxy colors and other properties with huge statistical samples
- Multidimensional correlation studies support color-morphology connection

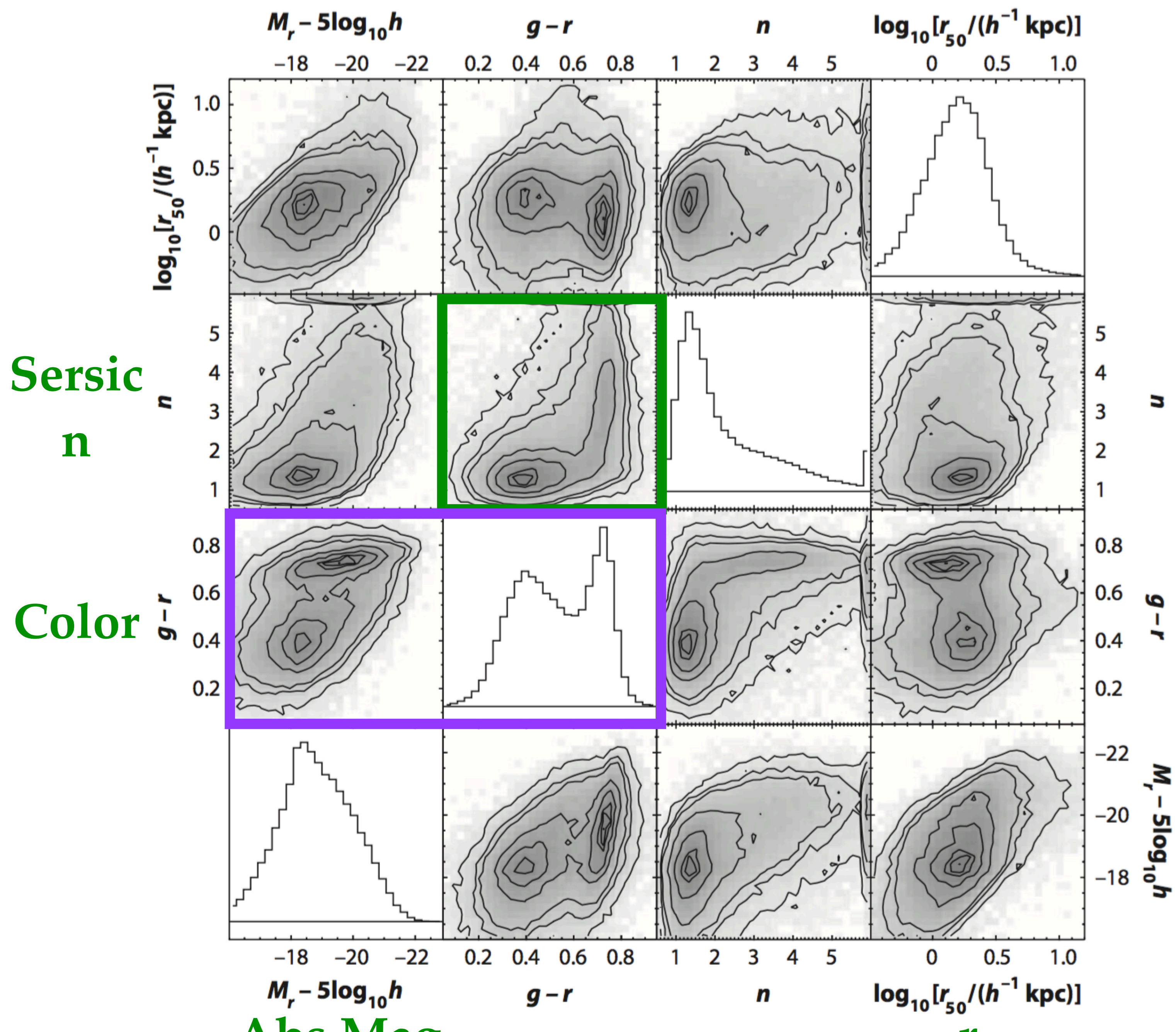


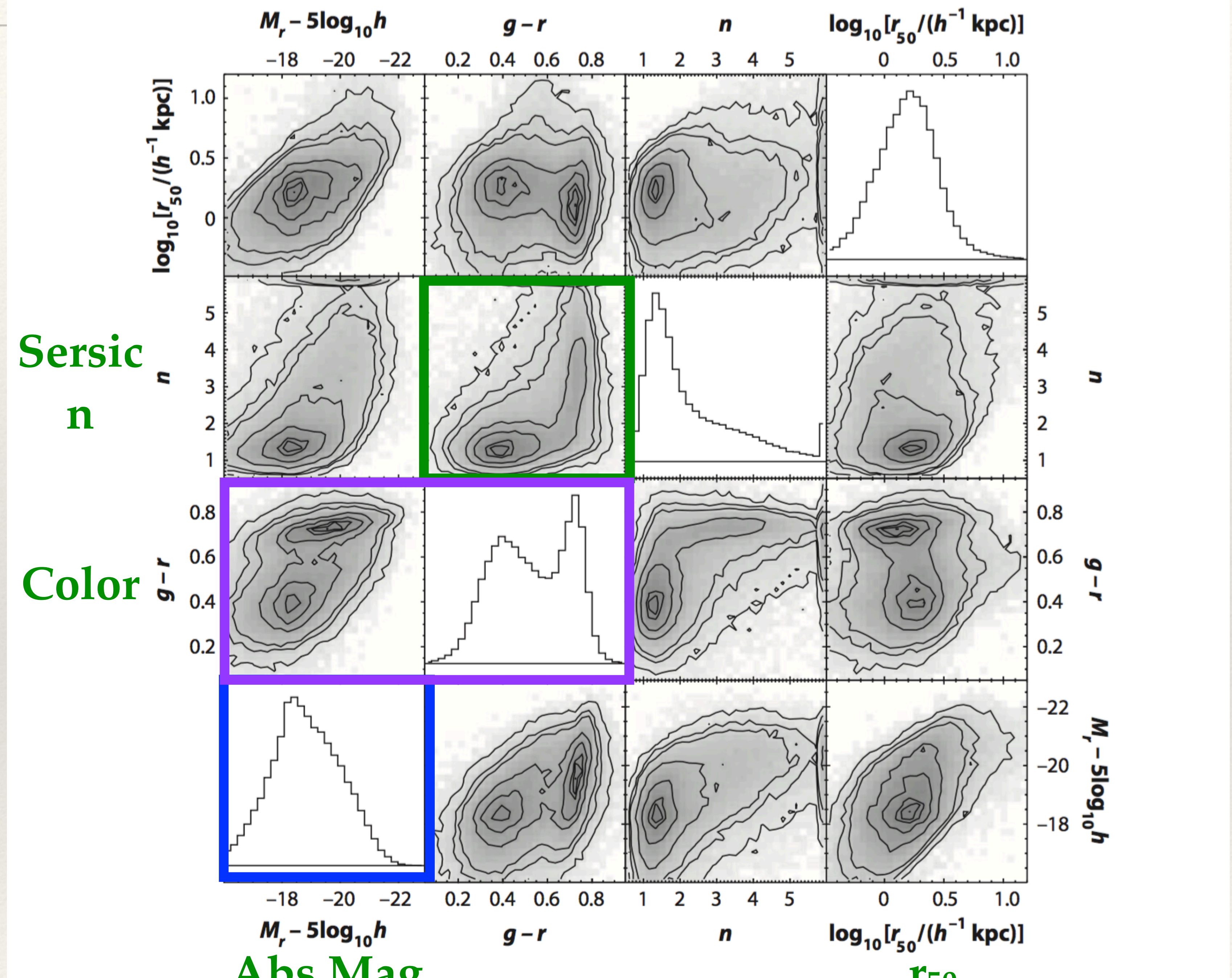
Figure 1

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

Blanton & Moustakas 2009

Thought Question

- Take a moment to digest this plot.
- Why do you think red galaxies form a tight, tilted sequence but blue galaxies form a more diffuse cloud?
- Anything surprise you about the green panel?
- Why does the distribution in the blue panel fall at faint absolute magnitudes?



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Blanton & Moustakas 2009

Galaxy Population - Statistical Properties: Colors

- Most early-type galaxies (E, S0) lie on the Red Sequence
- Very few early-types located in Blue Cloud
- Early-types tend to be luminous with a wide range of Sersic n values

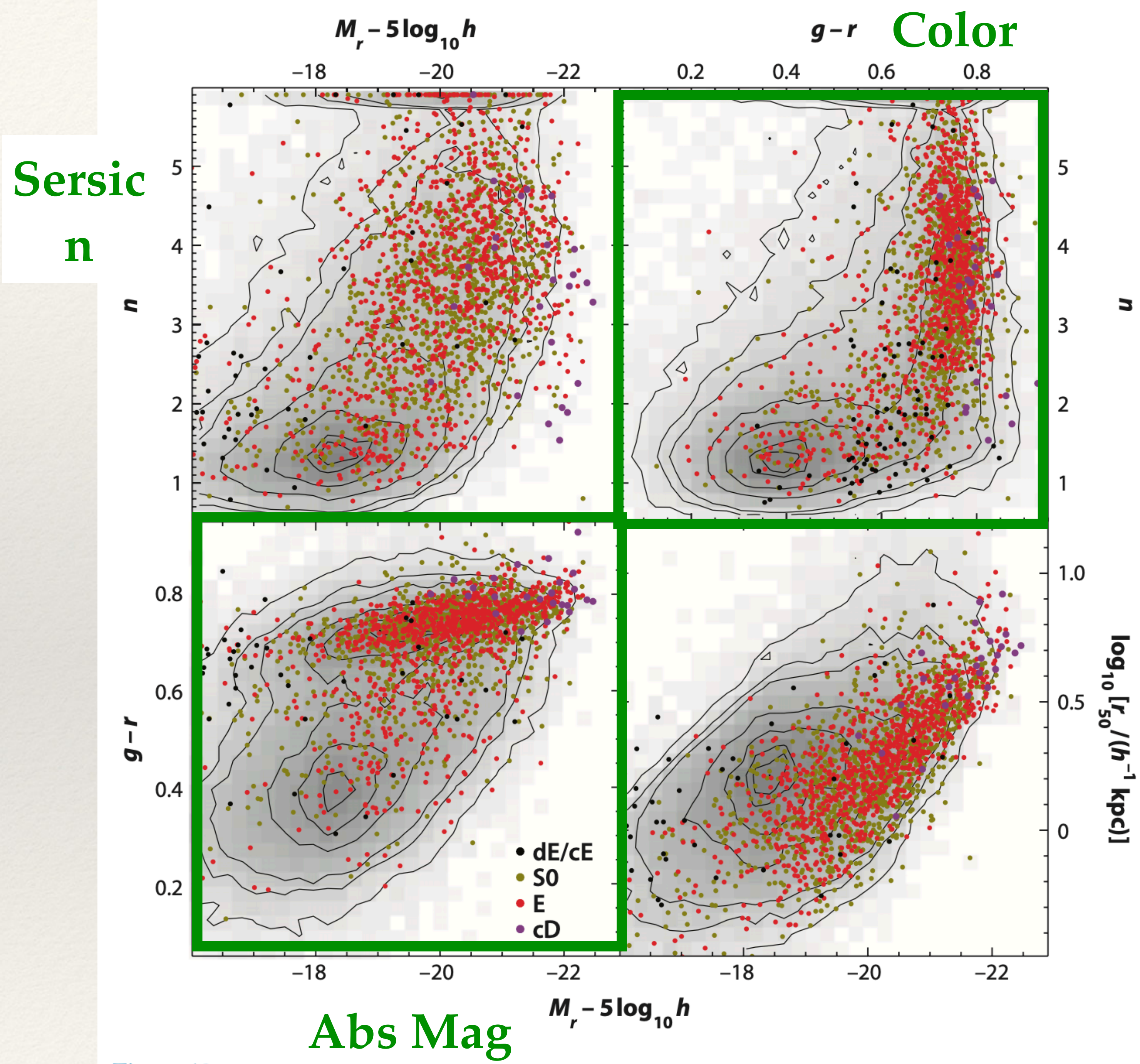


Figure 12

Distribution of elliptical and lenticular galaxy types in optical broadband properties. Similar to **Figure 8**, but now showing S0 galaxies (*brown*), E galaxies (*red*), dE galaxies (*black*), and cD galaxies (*purple*).

Galaxy Population - Statistical Properties: Colors

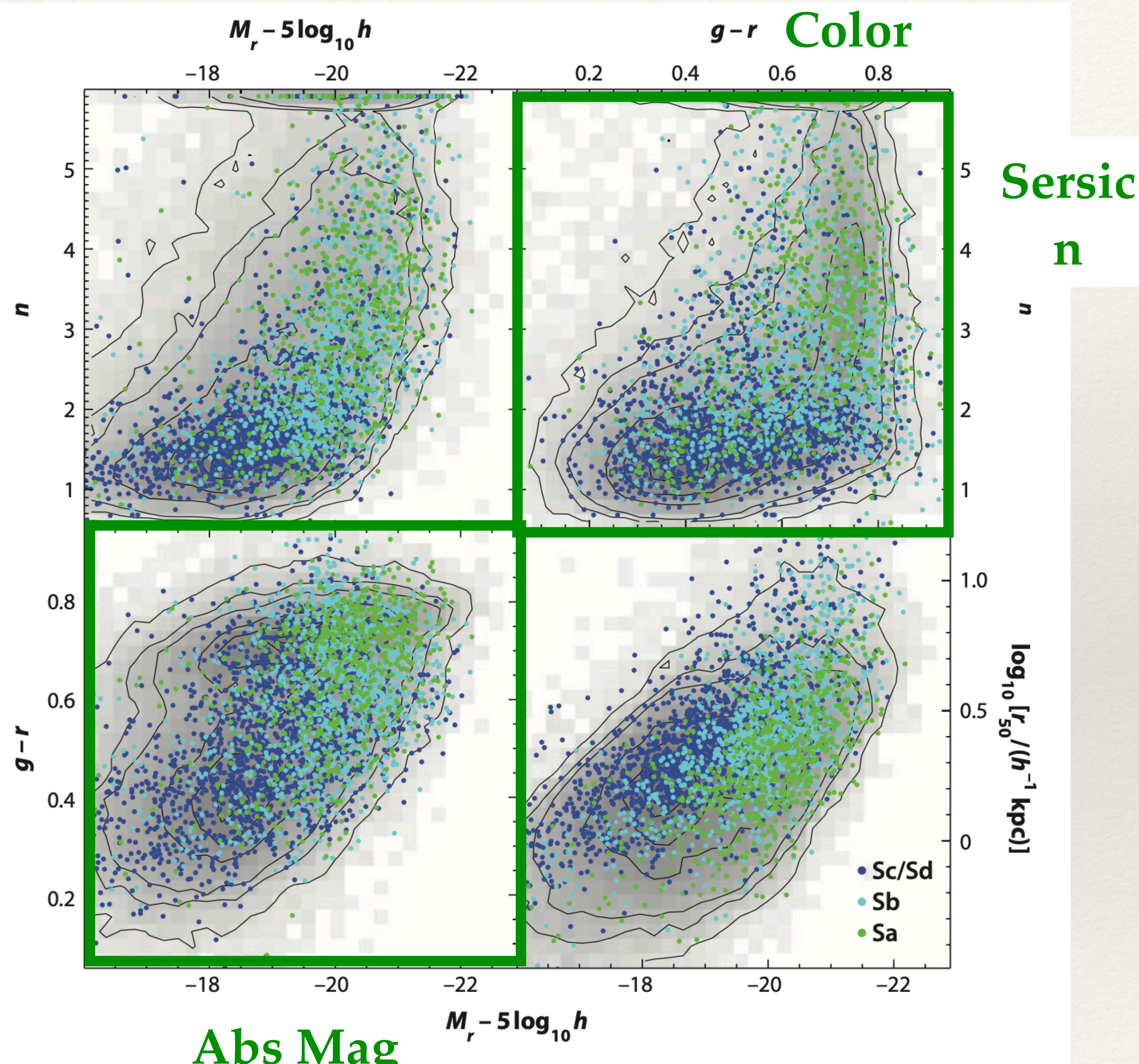
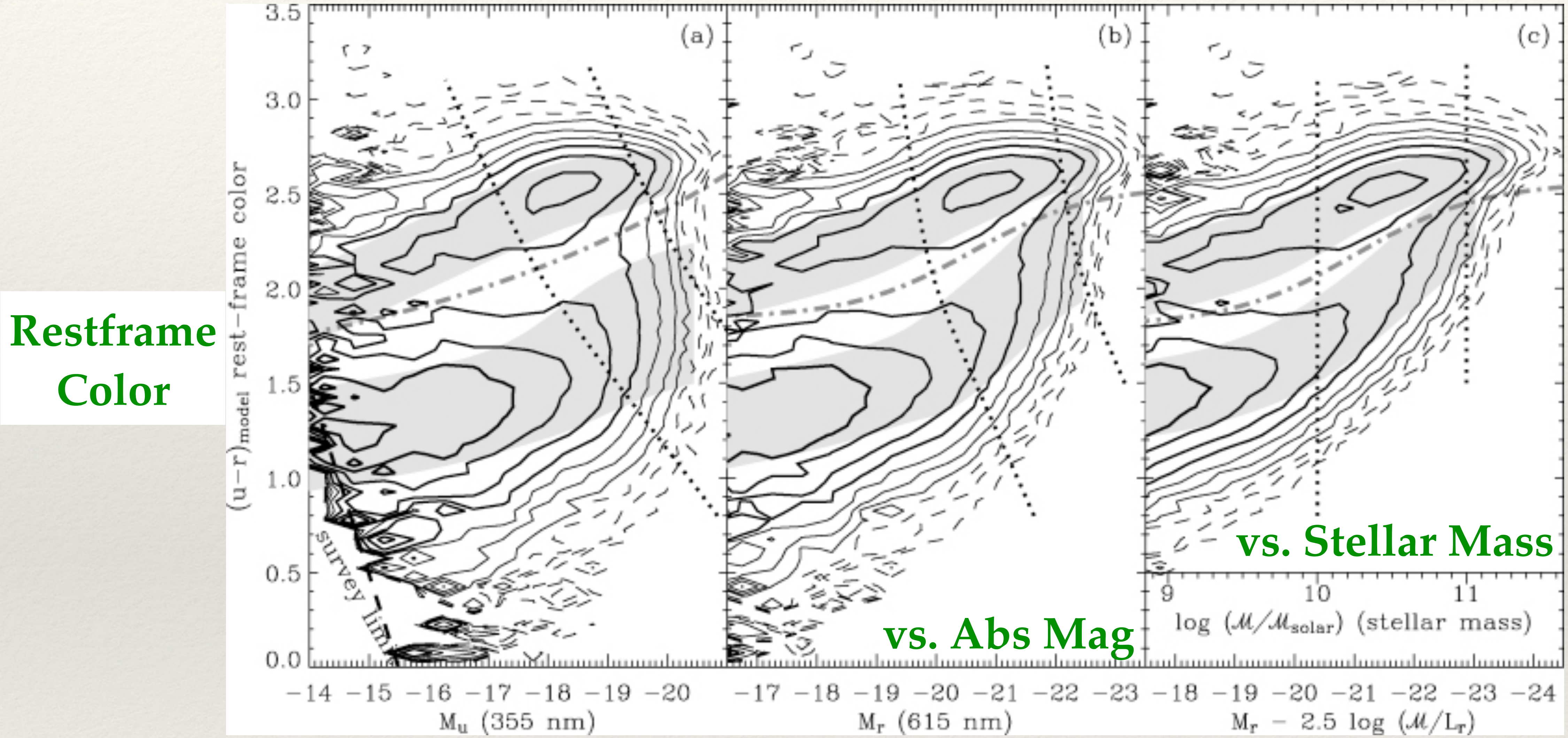


Figure 8

Distribution of various spiral-galaxy types in optical broadband properties. The underlying grayscale and contours are from the full data of **Figure 1**. Using classifications stored in NED, we overplot the positions of Sa (*green*), Sb (*cyan*), and Sc or Sd (*blue*) galaxies. We include the barred varieties.

- Blue Cloud is essentially all late-type galaxies with Sersic n~1
- However, not all Red Sequence galaxies are early-type!
- Late-type galaxies occupy an extended region in the color-magnitude diagram, with later types (**Sc/Sd**) being bluer and less luminous than earlier types (**Sa**/**Sb**)

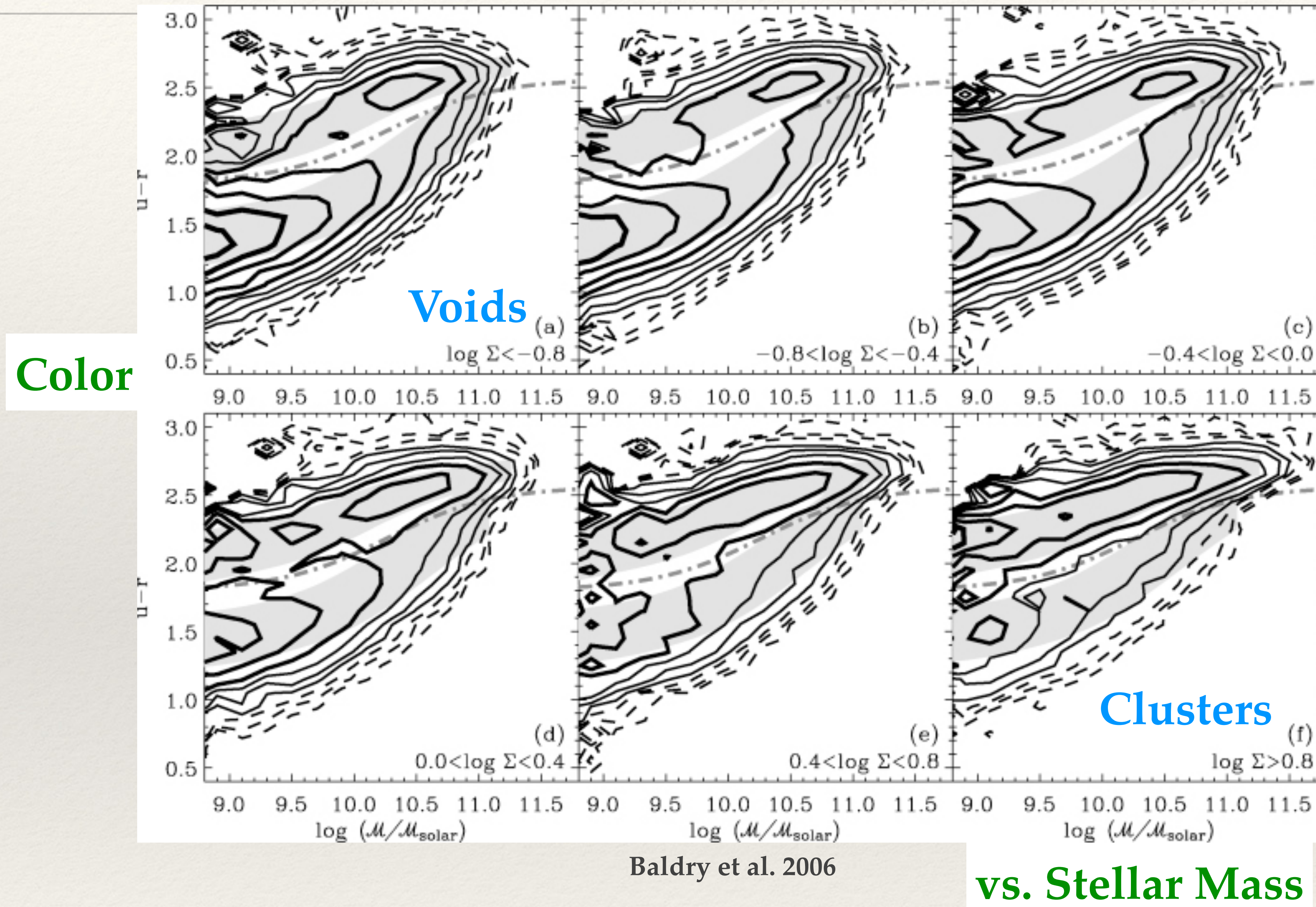
Statistical Properties: Colors vs stellar mass



Baldry et al. 2006

- Relation shifts when expressed in terms of stellar mass — different stellar populations
- Appears to be a transition stellar mass around 10^{10} solar masses

Statistical Properties: Colors with environment

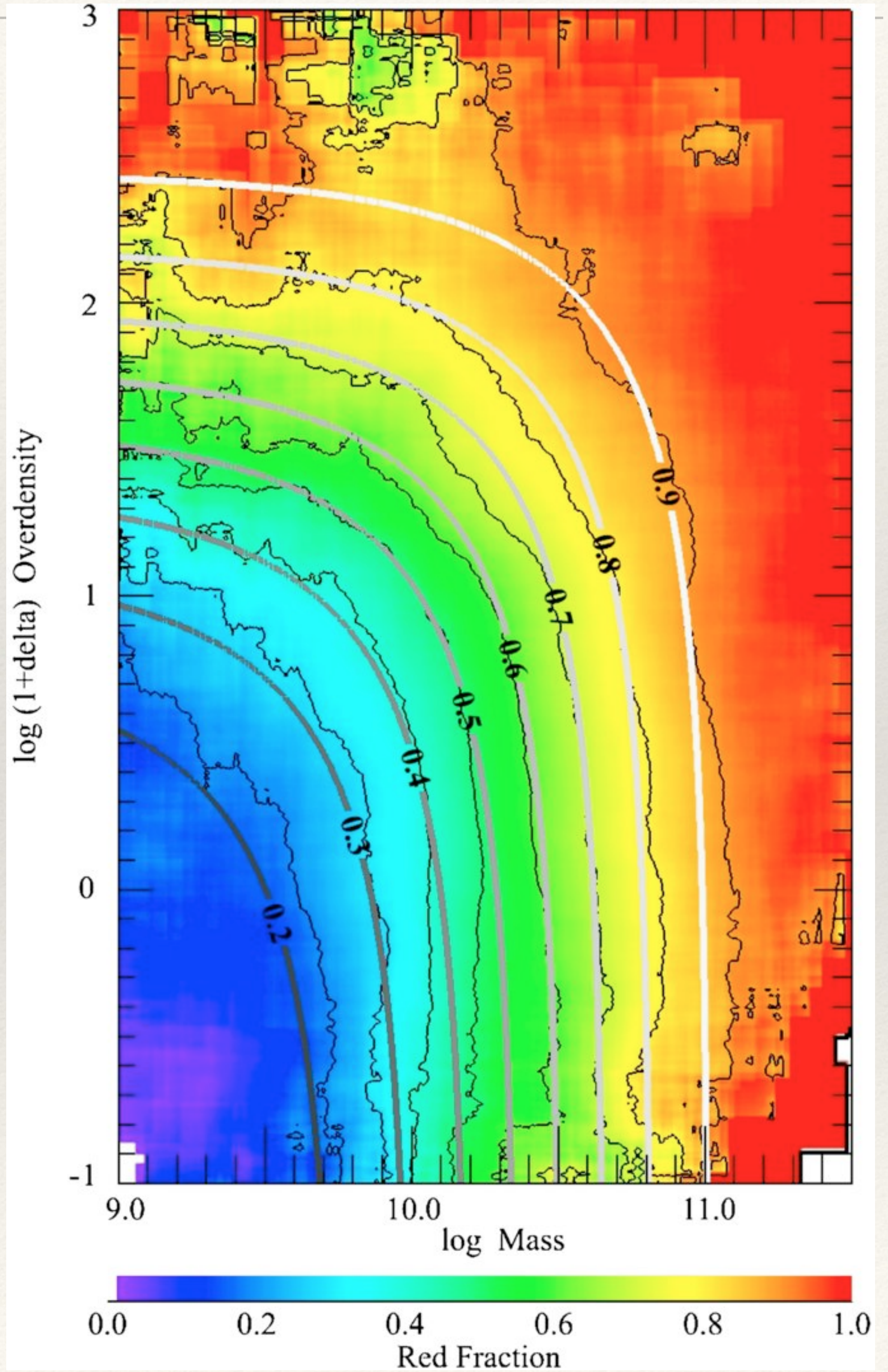


Baldry et al. 2006

- Bimodality exists in all environments, comparable sequences
- However, different relative numbers — **color-density relation**.

Galaxy Population - Statistical Properties: Colors

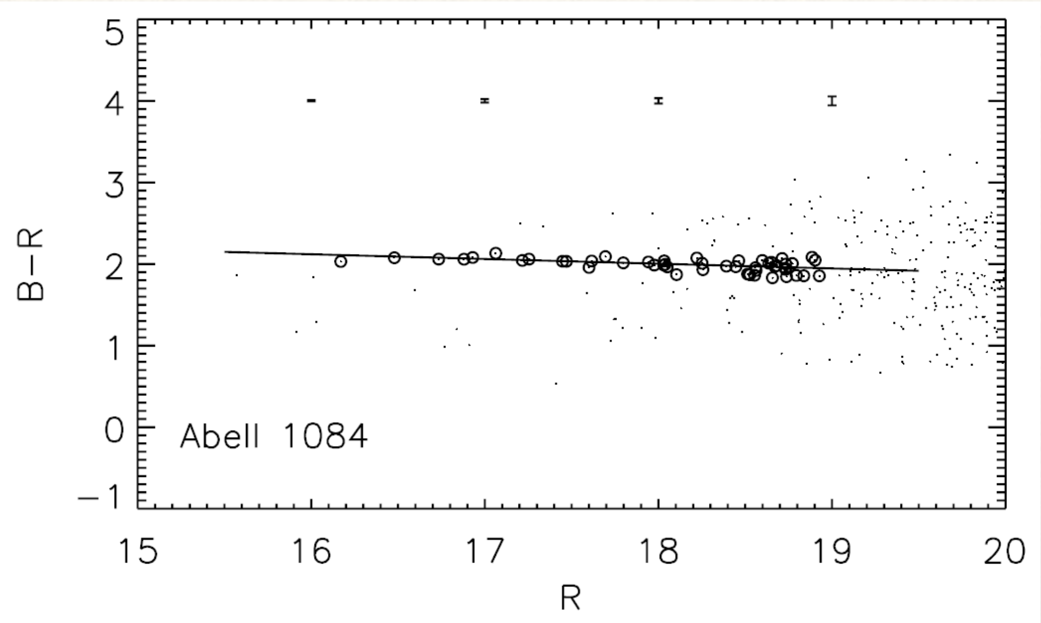
- **Red fraction** increases with density of environment and and with galaxy mass.



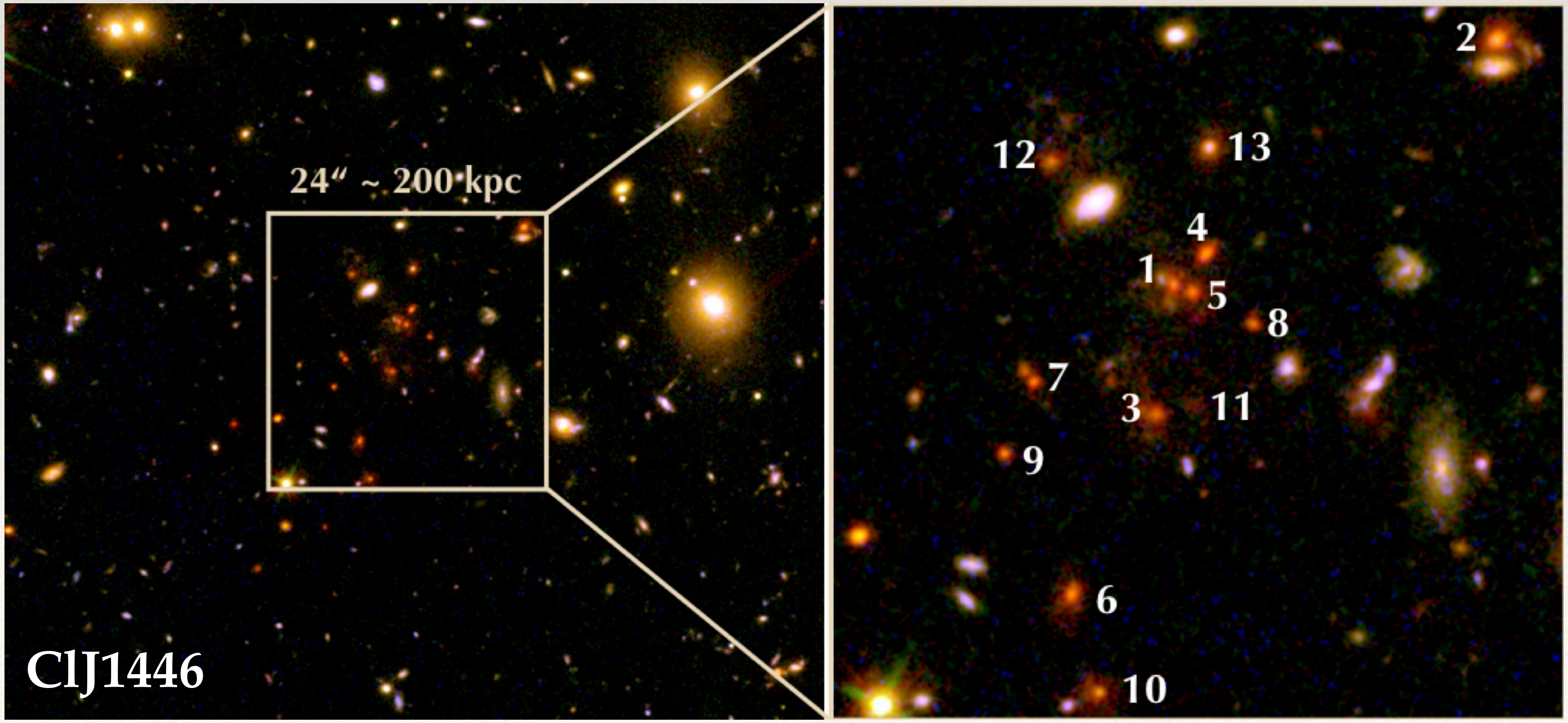
Peng et al. 2010

Galaxy Population - Statistical Properties: Colors

- Highest density regions — galaxy clusters
- High red fraction and strong red sequence makes it easy to pick them out!

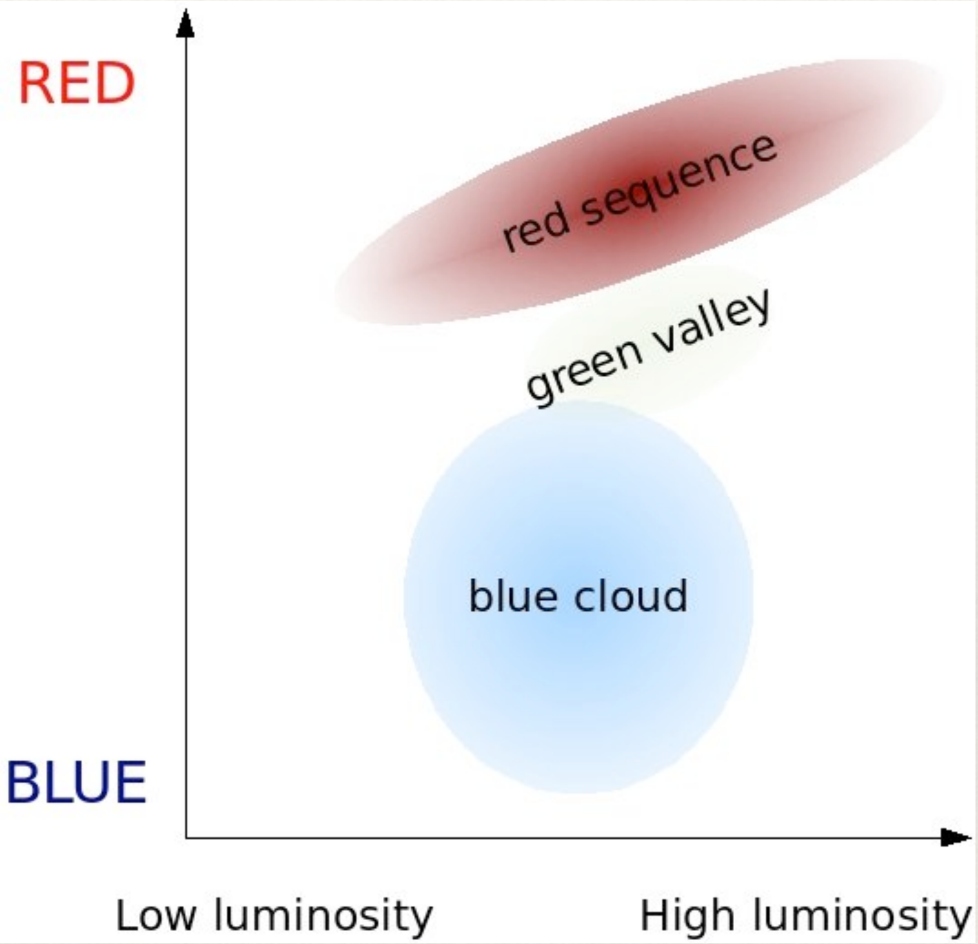


Stott et al. 2009



Thought Questions

- If a blue galaxy was forming stars for a while and then stopped, where would it move in color-magnitude space?
- If a red galaxy merged with another red galaxy, where would it move in color-magnitude space?
- Why might there be so few galaxies in the green valley?



(or stellar mass)

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

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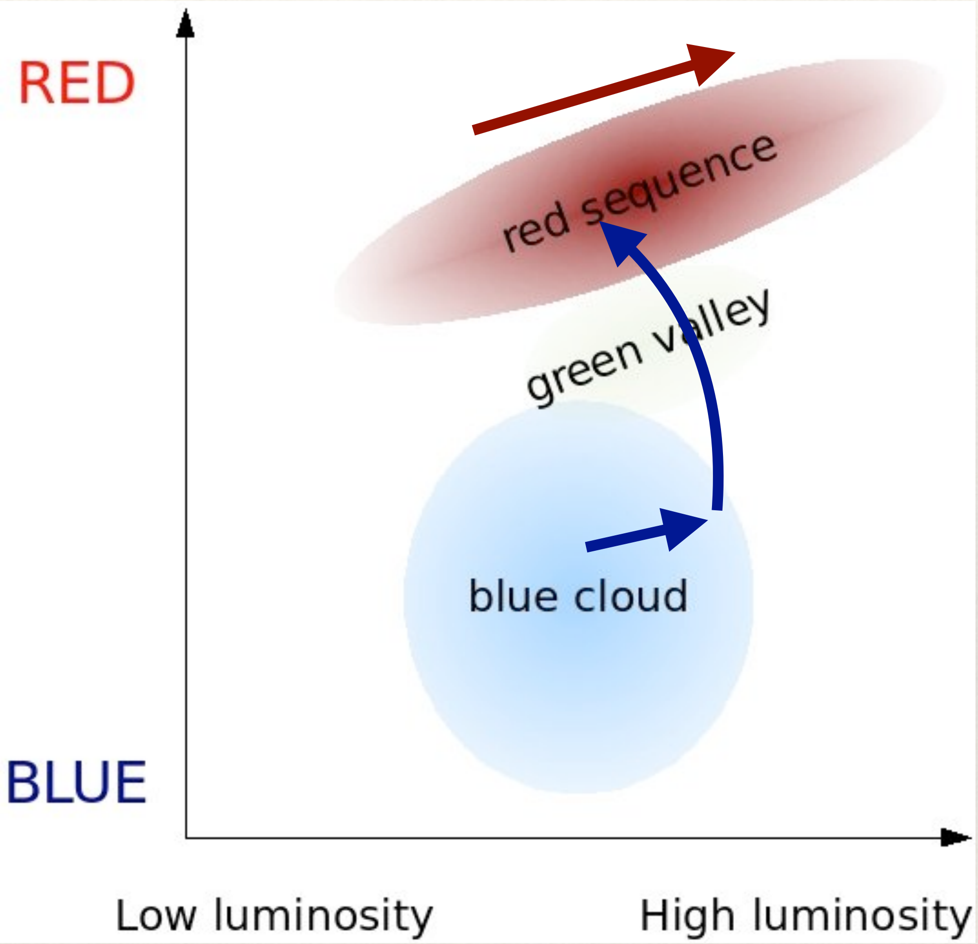

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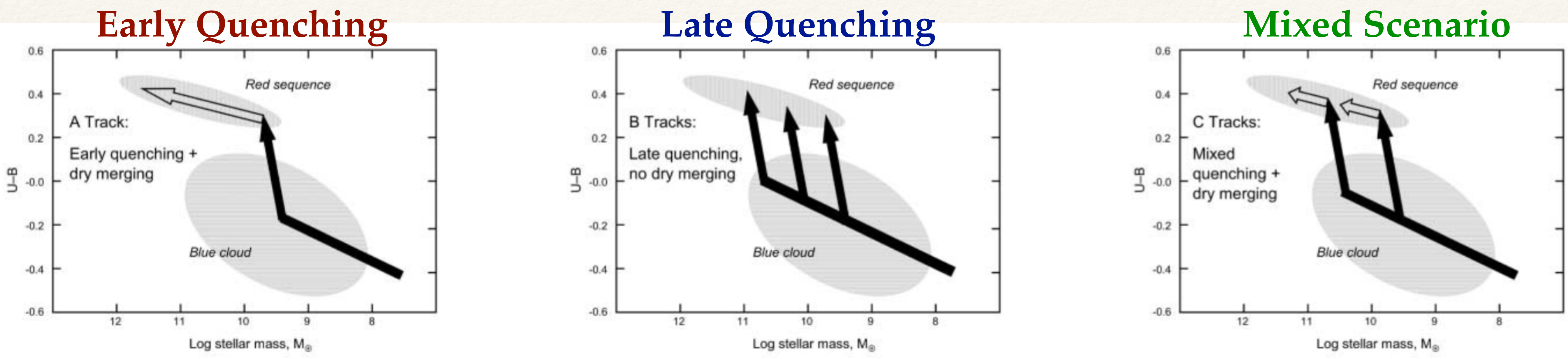
Image Credit: Joshua Schroeder; https://commons.wikimedia.org/w/index.php?curid=20496639

Galaxy Population - Statistical Properties: Colors

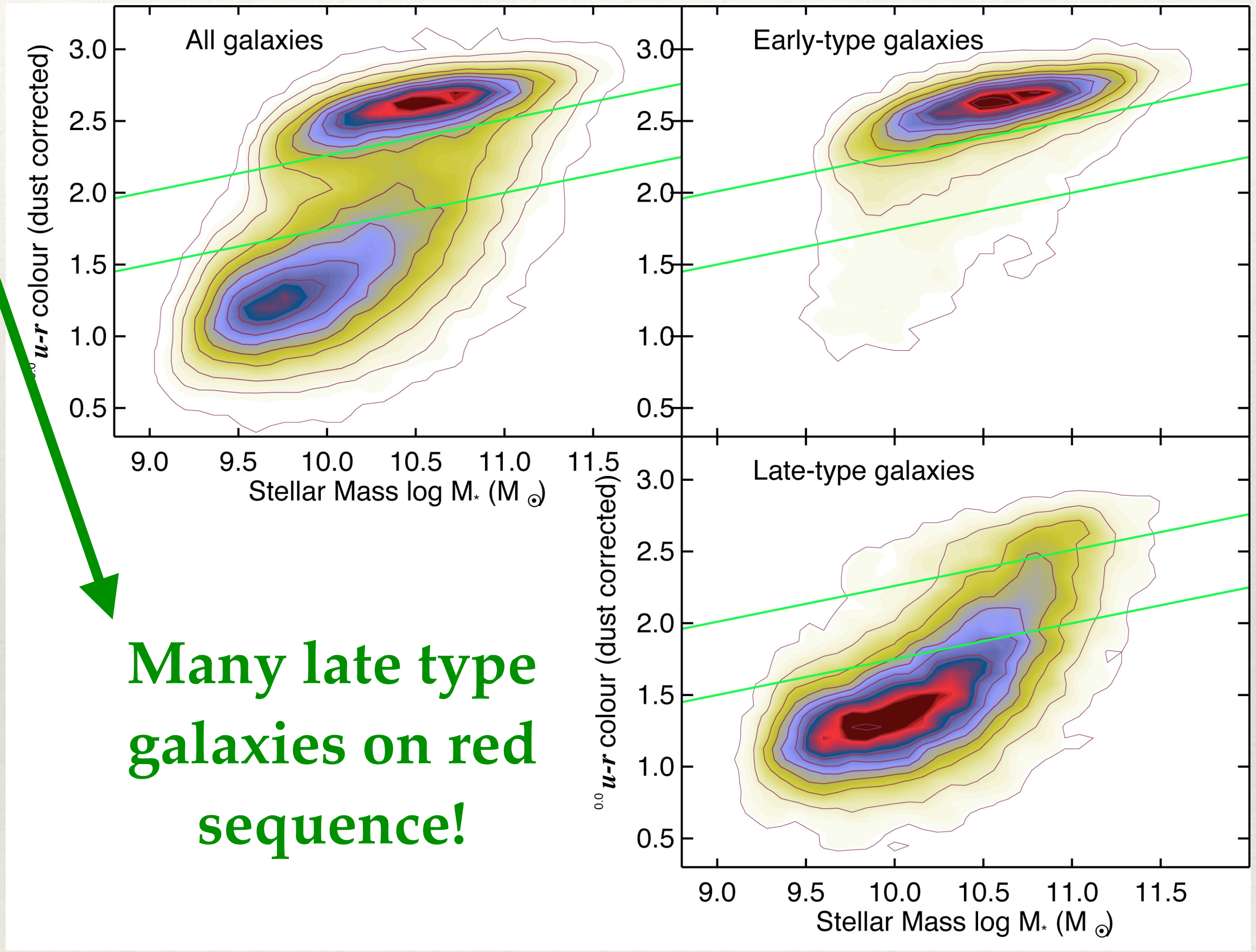


Faber et al. 2007

- Perhaps red galaxies arise from blue galaxies when star formation quenched (nearly vertical black arrows) during a major gas-rich ("wet") merger
- Once a galaxy arrives on the red sequence, evolves slowly along it through gas-poor (''dry'') mergers (white arrows)
- Do different combinations of "wet" / "dry" **mergers** plus quenching lead to bimodality?

Galaxy Population - Statistical Properties: Colors

- Galaxy Zoo morphologies allow for closer look at galaxy bimodality
  - Only a few blue galaxies move rapidly across Green Valley, transforming disk to spheroid, rapid star formation quenching.
  - Most blue galaxies retain late-type morphologies as star formation rates decline slowly.
  - Early-type galaxies require gas supply to be destroyed virtually instantaneously, transforming from disk to spheroid, rapid quenching.



Schawinski et al. 2014

The green valley is a red herring: Galaxy Zoo reveals two evolutionary pathways towards quenching of star formation in early- and late-type galaxies★

Galaxy Population - Statistical Properties: Colors

Galaxy and Mass Assembly (GAMA): Morphological transformation of galaxies across the green valley

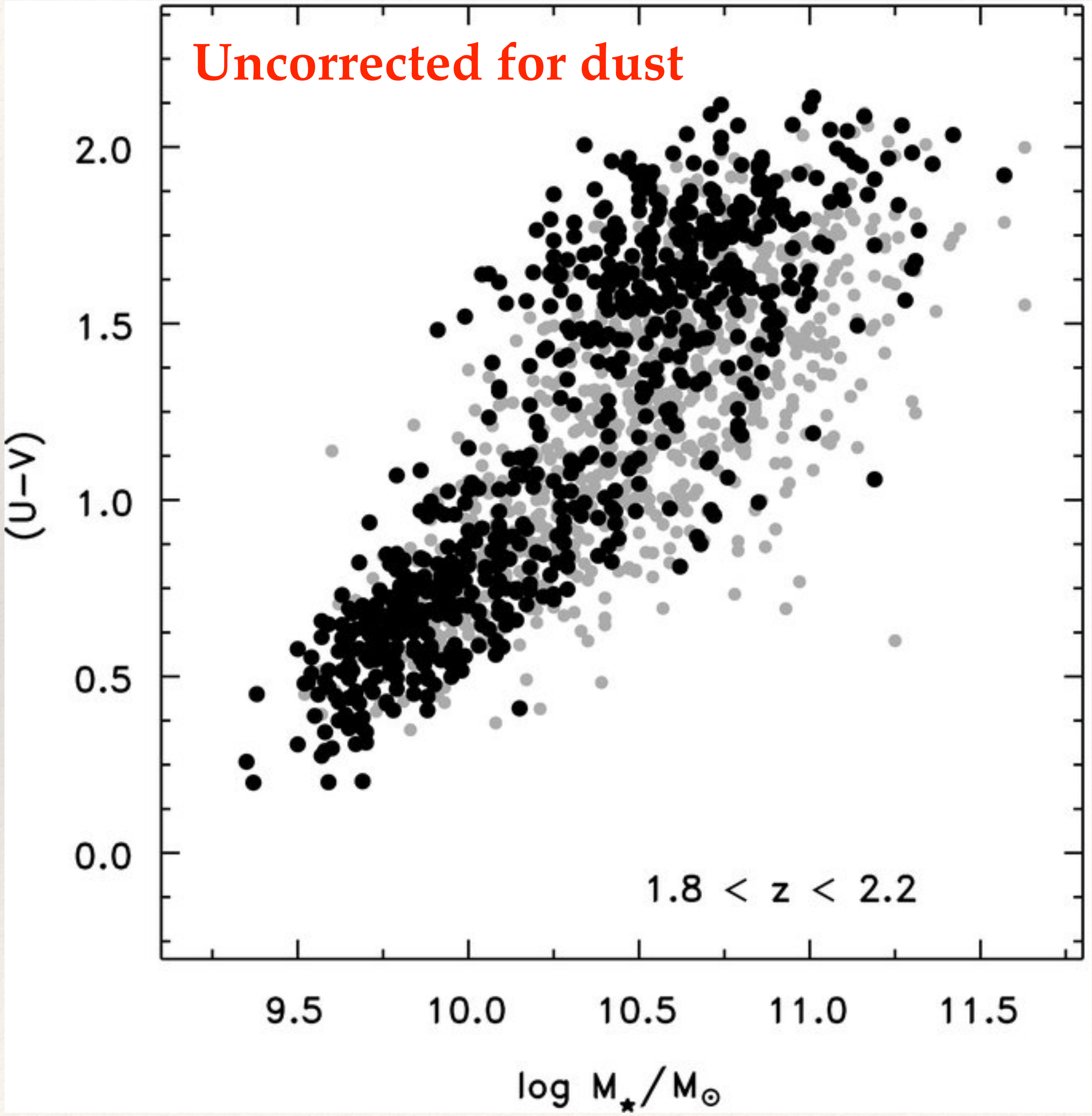
M.N. Bremer[1], S. Phillipps[1], L.S. Kelvin[2], R. De Propris[3], Rebecca Kennedy[4], Amanda J. Moffett[5], S. Bamford[4], L.J.M. Davies[5], S. P. Driver[5,6], B. Häußler[7], B. Holwerda [8], A. Hopkins[9], P.A. James[2], J. Liske[10], S. Percival[2], E.N. Taylor[11]

Bremer et al. 2018

- Most green galaxies have significant bulge and disk components —> the **blue to red evolution is driven by color change in the disk**
- Environment likely plays a role in triggering passage across Green Valley, e.g., insufficient gas supply rather than major merger event
- Relative abundance of green population suggests typical timescale to traverse Green Valley ~ 1 – 2 Gyr, independent of environment

Galaxy Population - Statistical Properties: Colors

- Moving to higher redshifts (z~2-3):
- More dusty star-forming galaxies contaminate Red Sequence and Green Valley
- With dust corrections, see same bimodality emerge
- Galaxies with old stellar populations already existed at early times



Brammer et al. 2009

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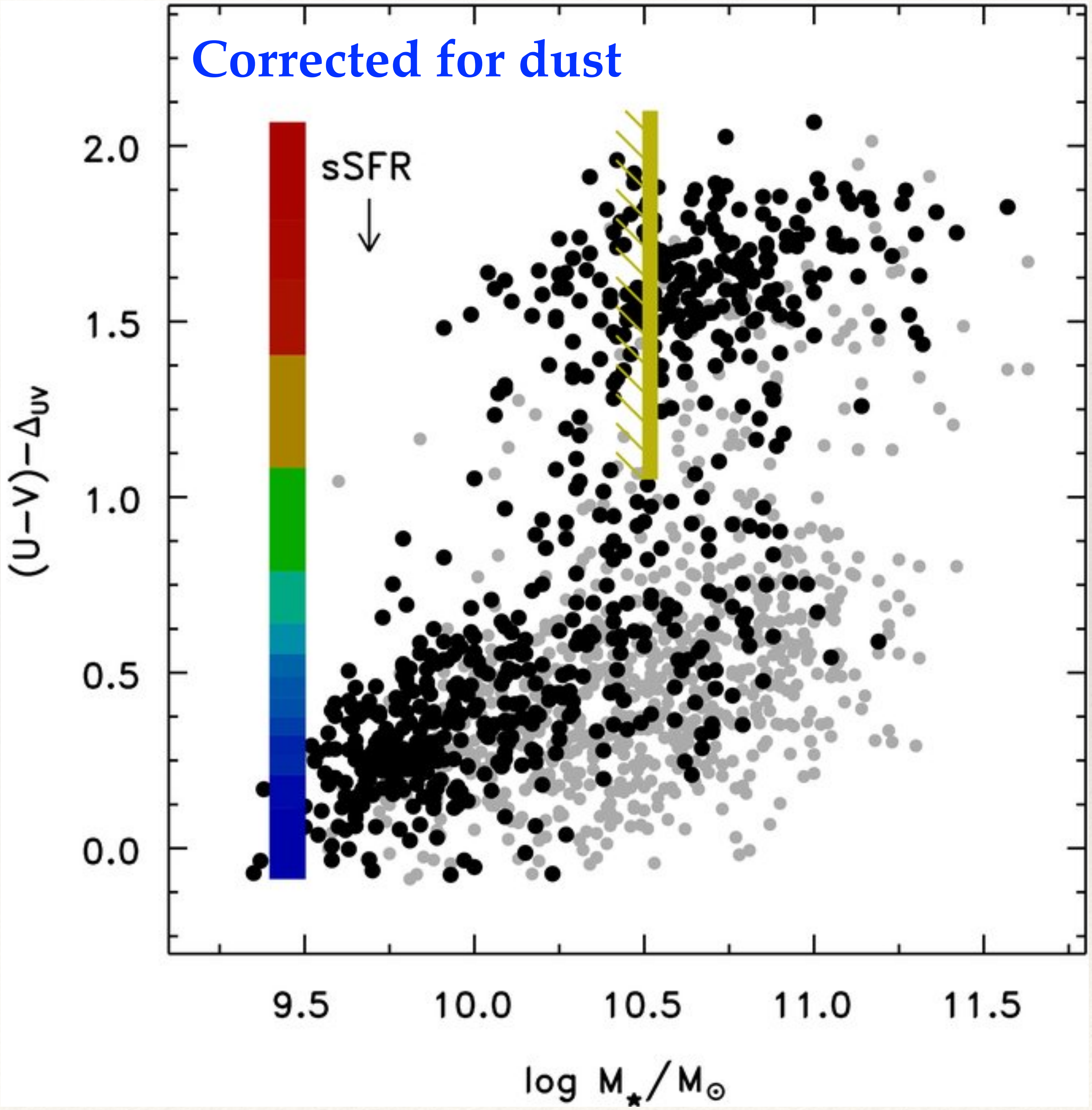
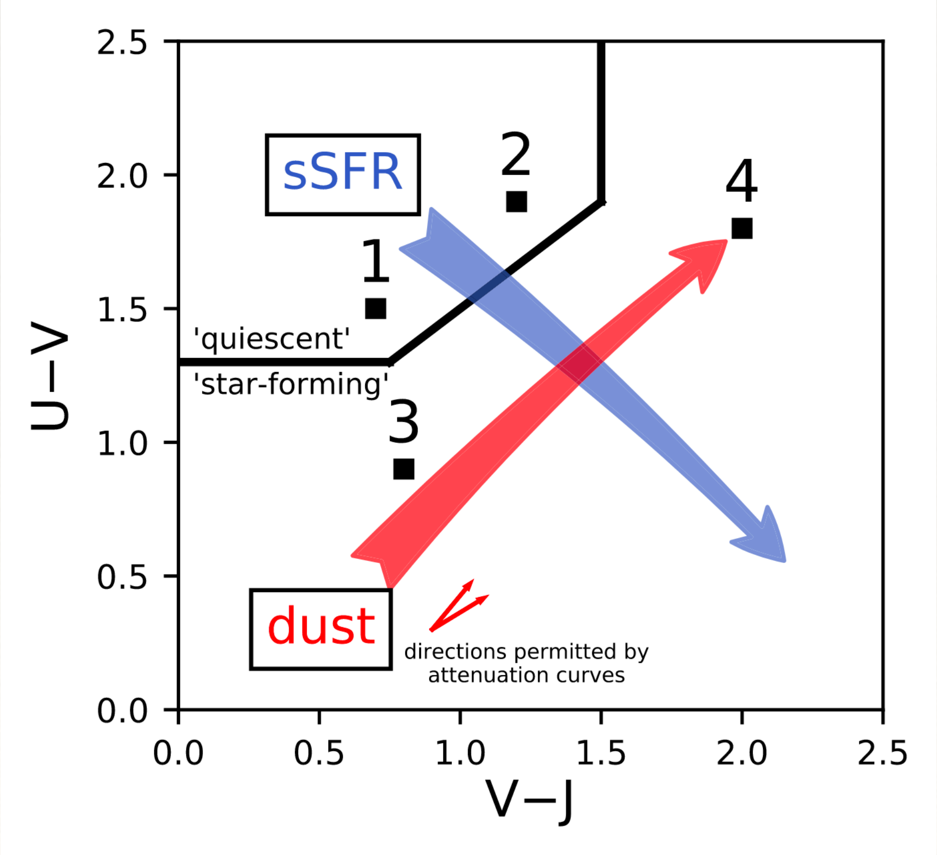


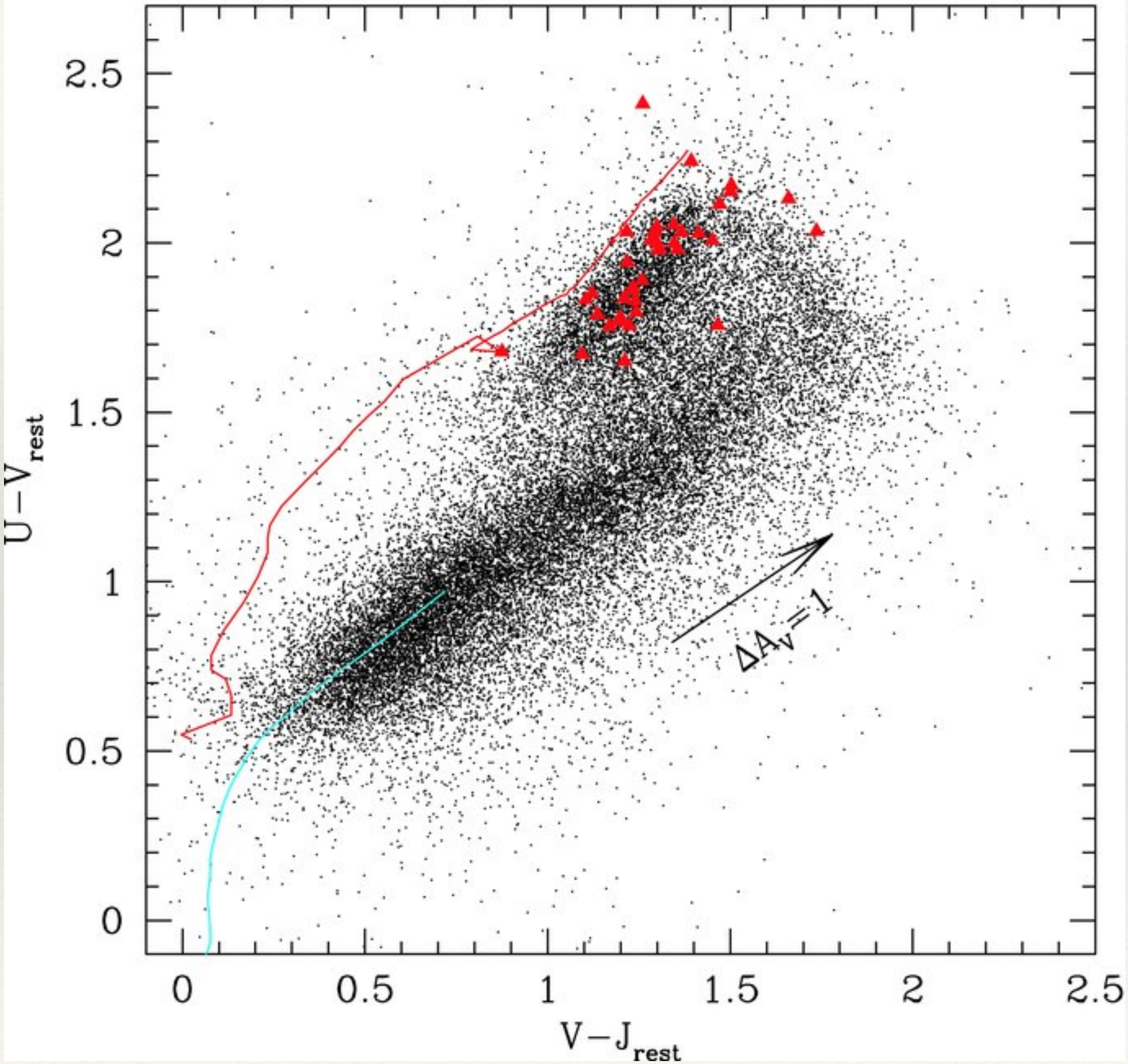
Brammer et al. 2009

Galaxy Population - Statistical Properties: Colors

- Availability of near-infrared data allows for improved separation of quiescent vs. (dusty) star-forming galaxies — the **UVJ diagram**



Leja et al. 2019



Williams et al. 2009