# Minor mergers and the mass growth of massive galaxies

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BOSS collaboration

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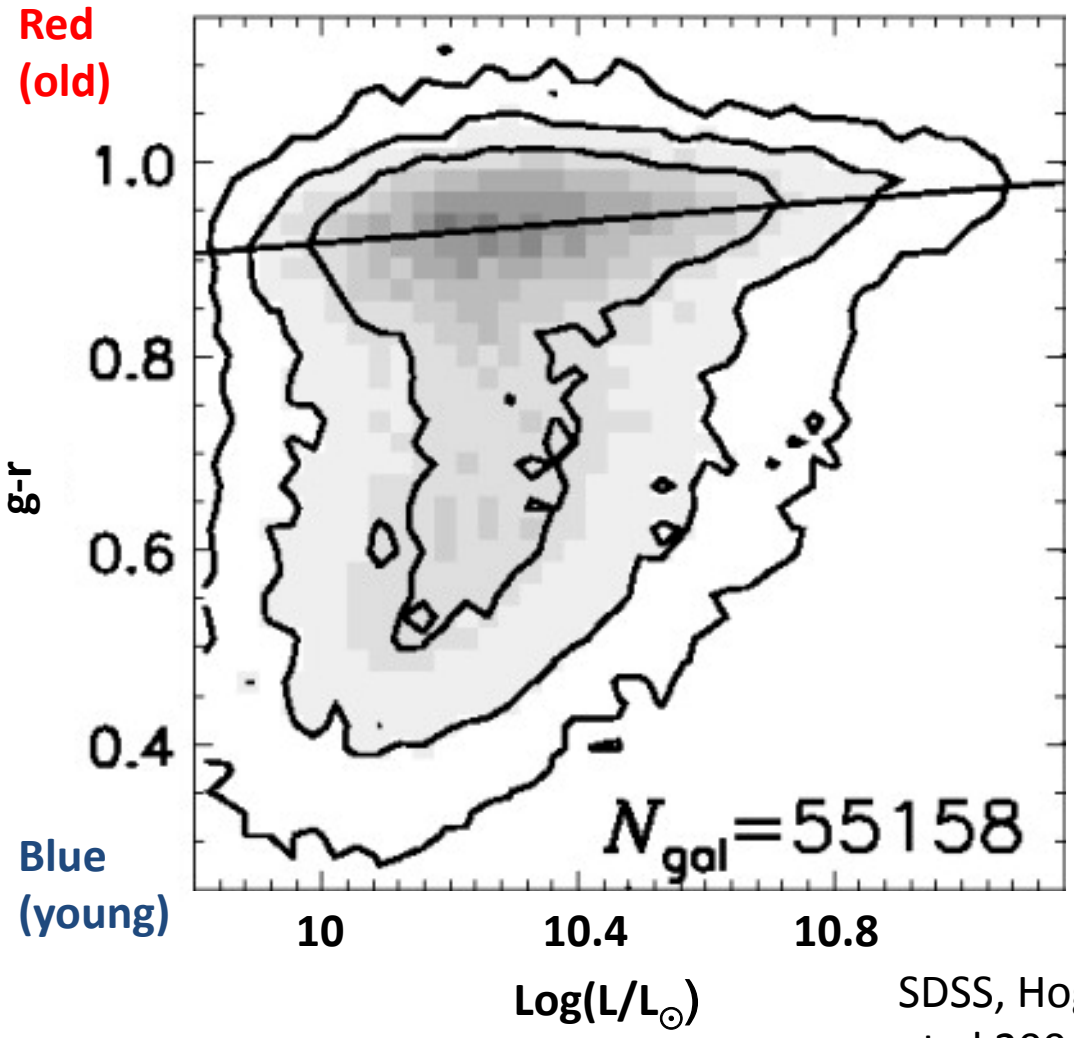
# Massive galaxies in the nearby universe

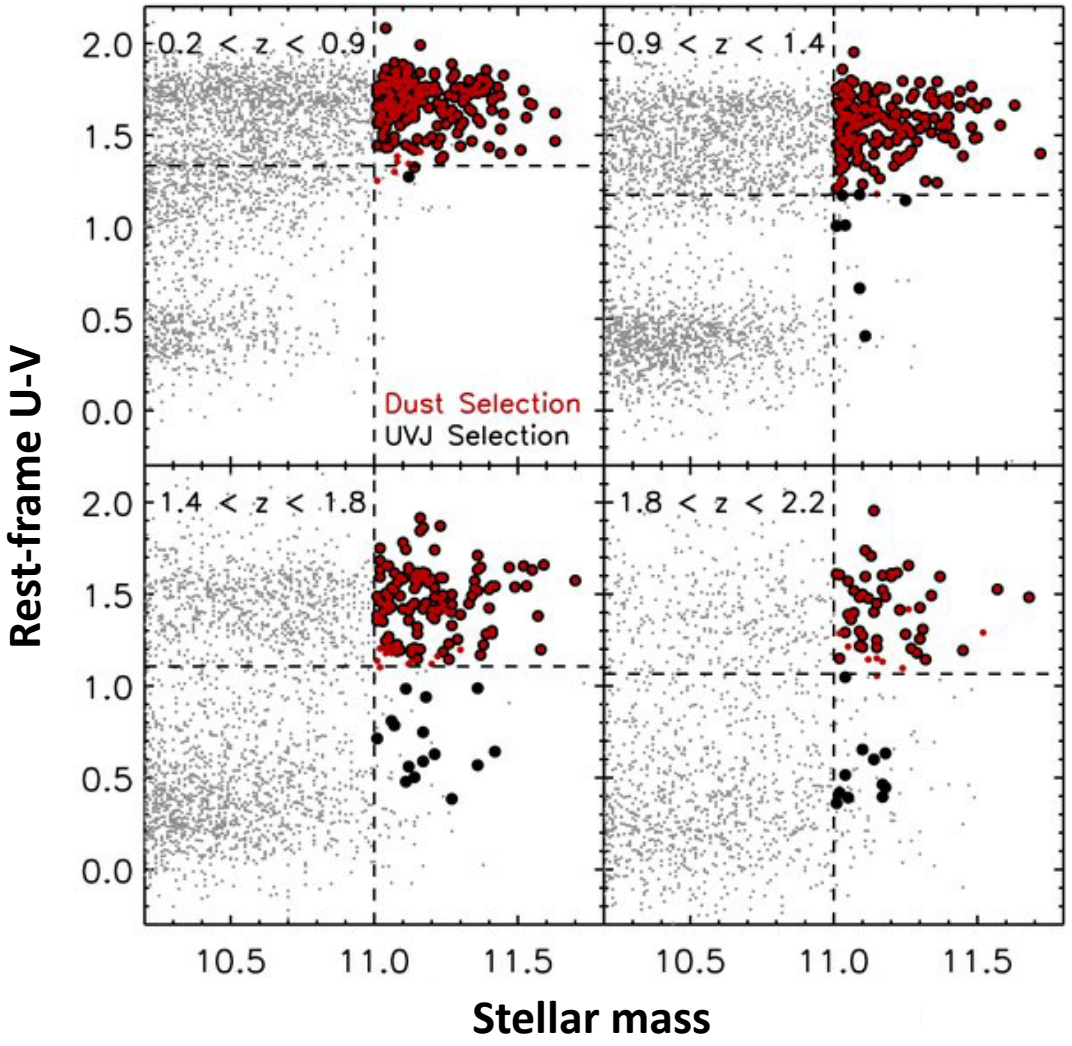
- Old stellar populations and low star formation rates
- The most massive galaxies are along the red sequence
- Spectra dominated by old stars




SDSS, Hogg et al 2004

# Massive galaxies at high-z

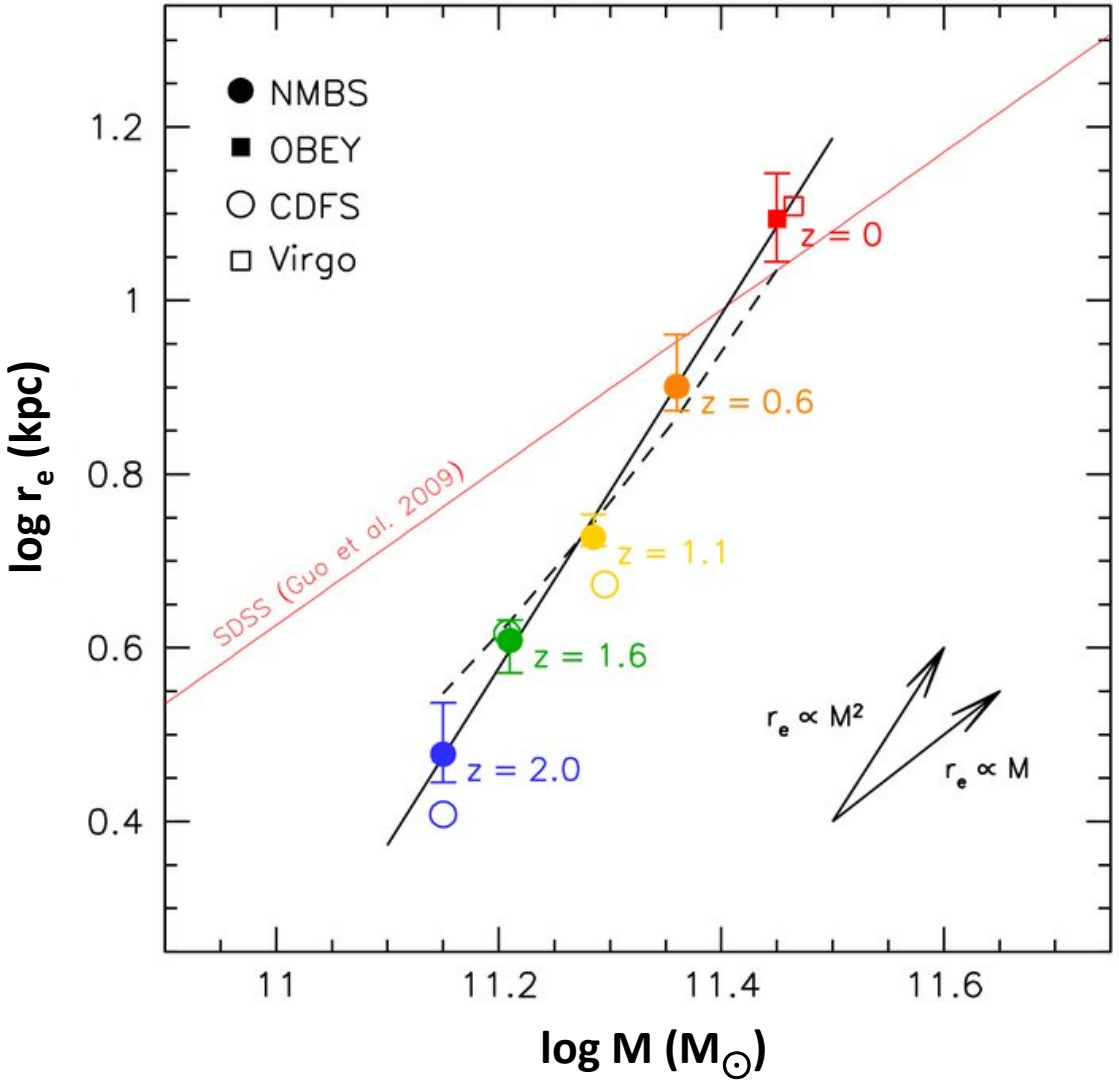
- The most massive galaxies are also the oldest out to z~2 (10 Gyr ago)
- Colors possibly imply low star formation since shortly after creation




Whitaker et al 2010

# Massive galaxies at z=2

- Continuous (and slow) mass growth from z=2 to z=0




van Dokkum et al. 2010

# How do massive galaxies grow in mass?

- Star formation rates are low at 0<z<1

  (e.g., Faber 73, Balogh+04, Worthey+92, Peletier 98, Jørgensen+99, Trager+00, , Kauffmann+03, Hogg+04, Thomas+05)

- (Major mergers)

  (e.g., van Dokkum+99, Patton+02, Tran +05, van Dokkum 05, Bell+06, Boylan-Kolchin+06, Naab+06, Bundy+06, Masjedi+06, Wake+06, McIntosh+08, Wake+08, Masjedi+08, Bundy+09)

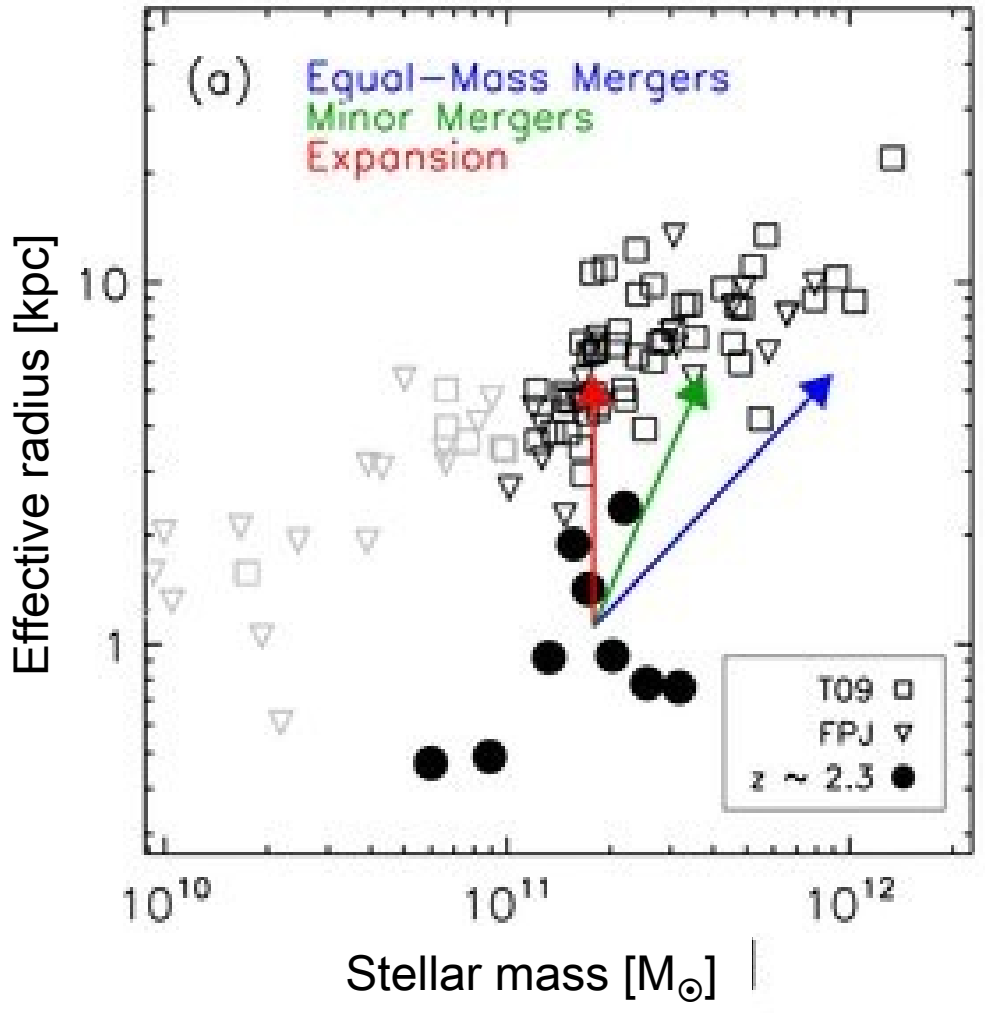
- At least some growth due to minor mergers

  (e.g., Kormendy+89, Schweizer+92, van Dokkum 05, Naab+07,09, Bournaud+07, Stewart+08, Bezanson+09, Tal+09)

- Difficult to quantify frequency and mass ratio

# Minor mergers

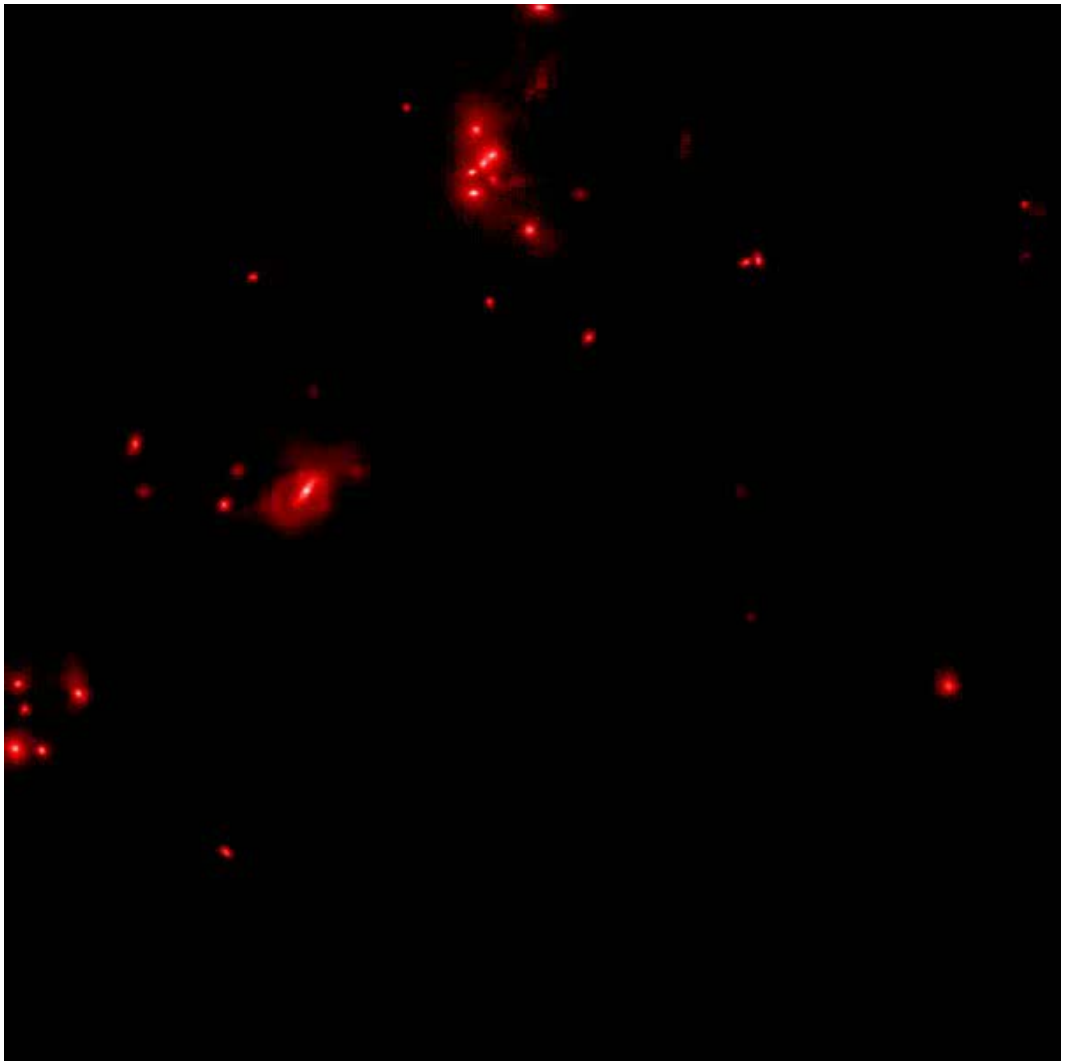
- Consistent with simple analytic calculations




Bezanson et al. 2009

# Minor mergers

- Consistent with simple analytic calculations
- Frequent in numerical simulations



Tonnesen et al. 2007

# Observing minor mergers

- Direct observations of post merger systems
  - Estimate of frequency
  - Progenitor mass ratio unknown
- Environment
  - Which galaxies are available to merge with
  - Difficult to determine membership

Direct observation of post merger systems

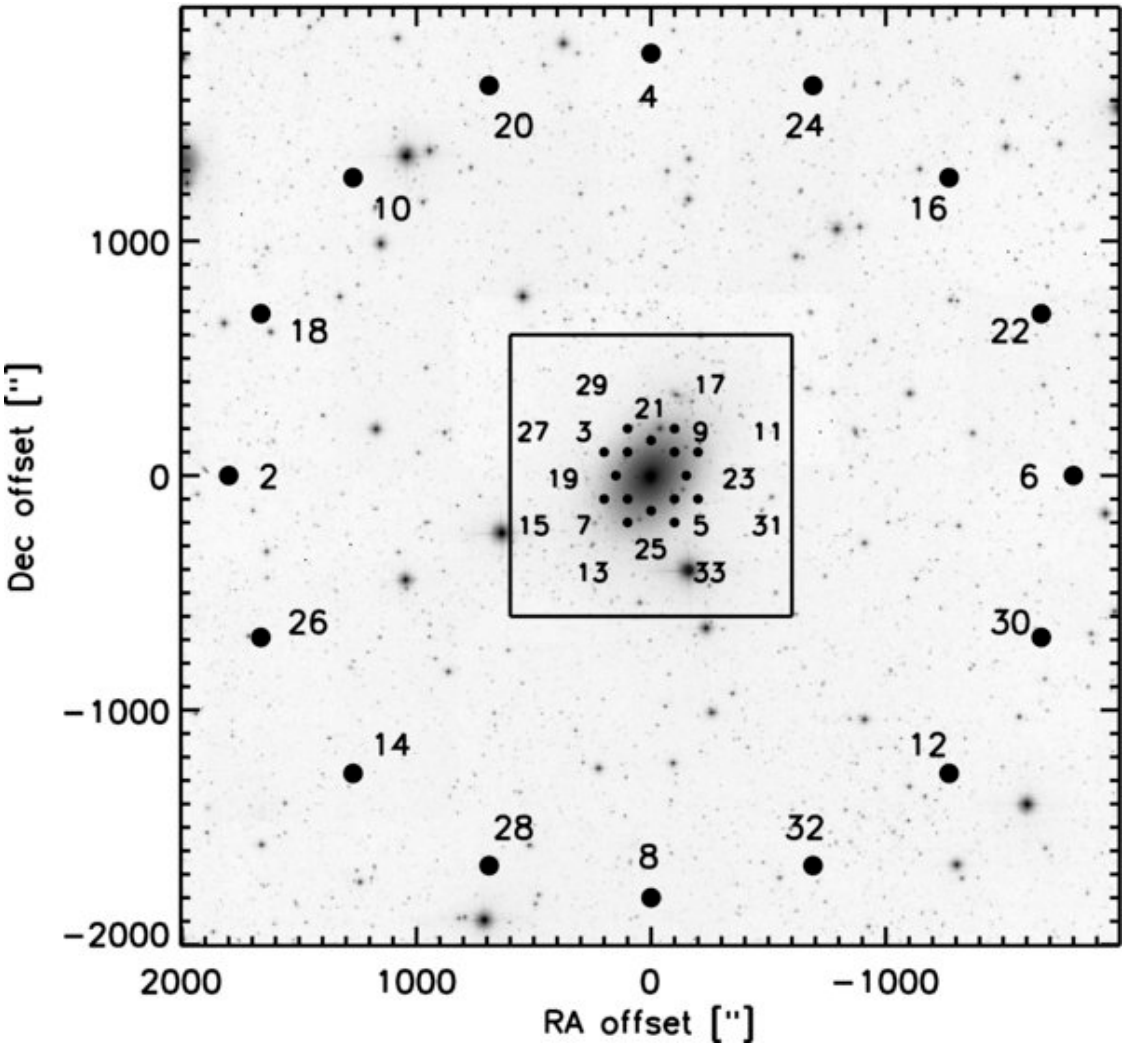
# TIDAL FEATURES AROUND MASSIVE ELLIPTICAL GALAXIES

# Tidal distortion in ellipticals

- Schweizer and Seitzer (1992)
- Hard to do – features typically faint
- Completeness

# The OBEY survey

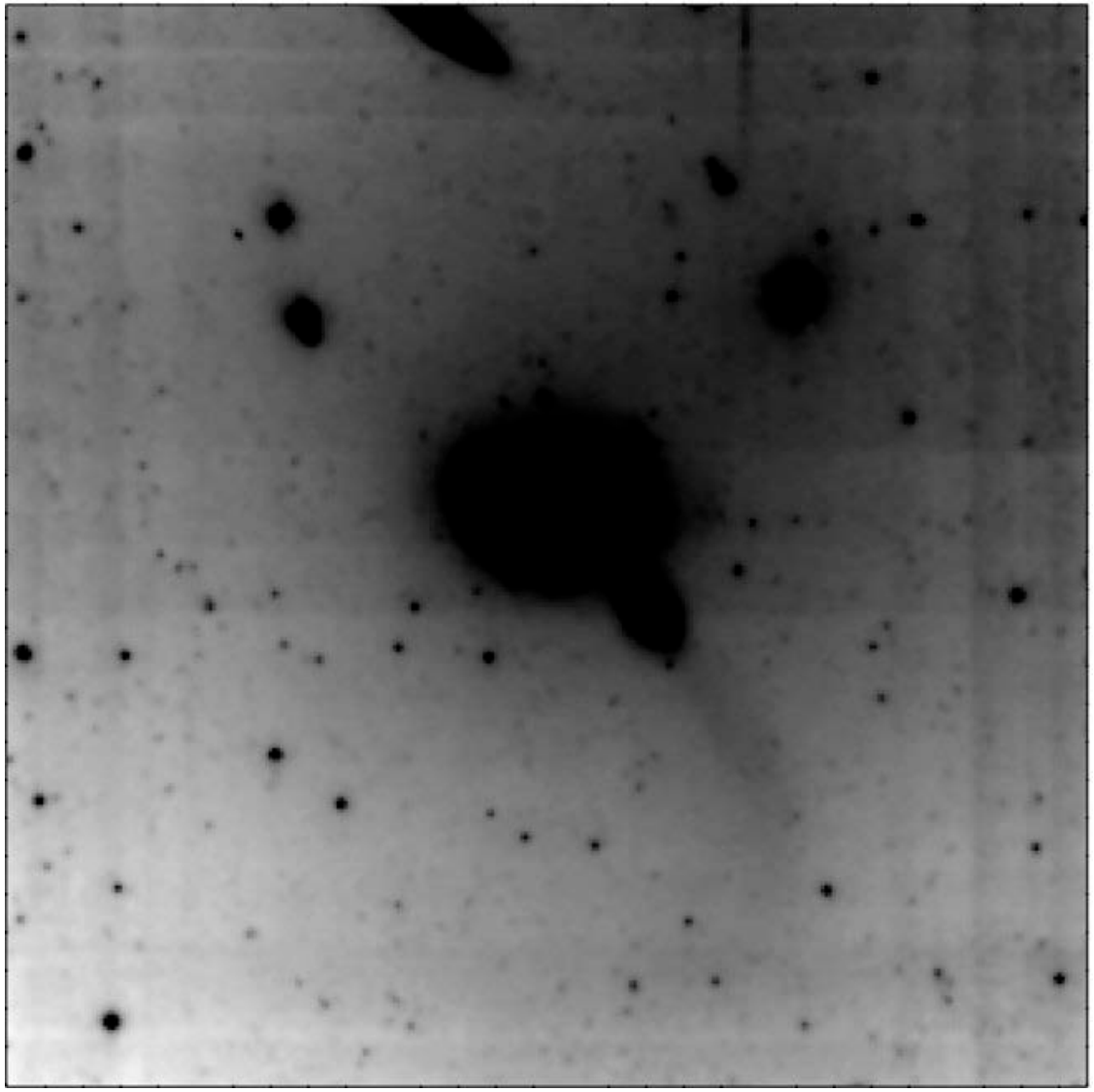
- Luminosity limited sample
- Customized observing pattern
- Only ~4x SDSS depth
- Excellent flat-fielding




Tal et al. 2009

# Flat fielding

**Without**
sky flats



Tal et al. 2009

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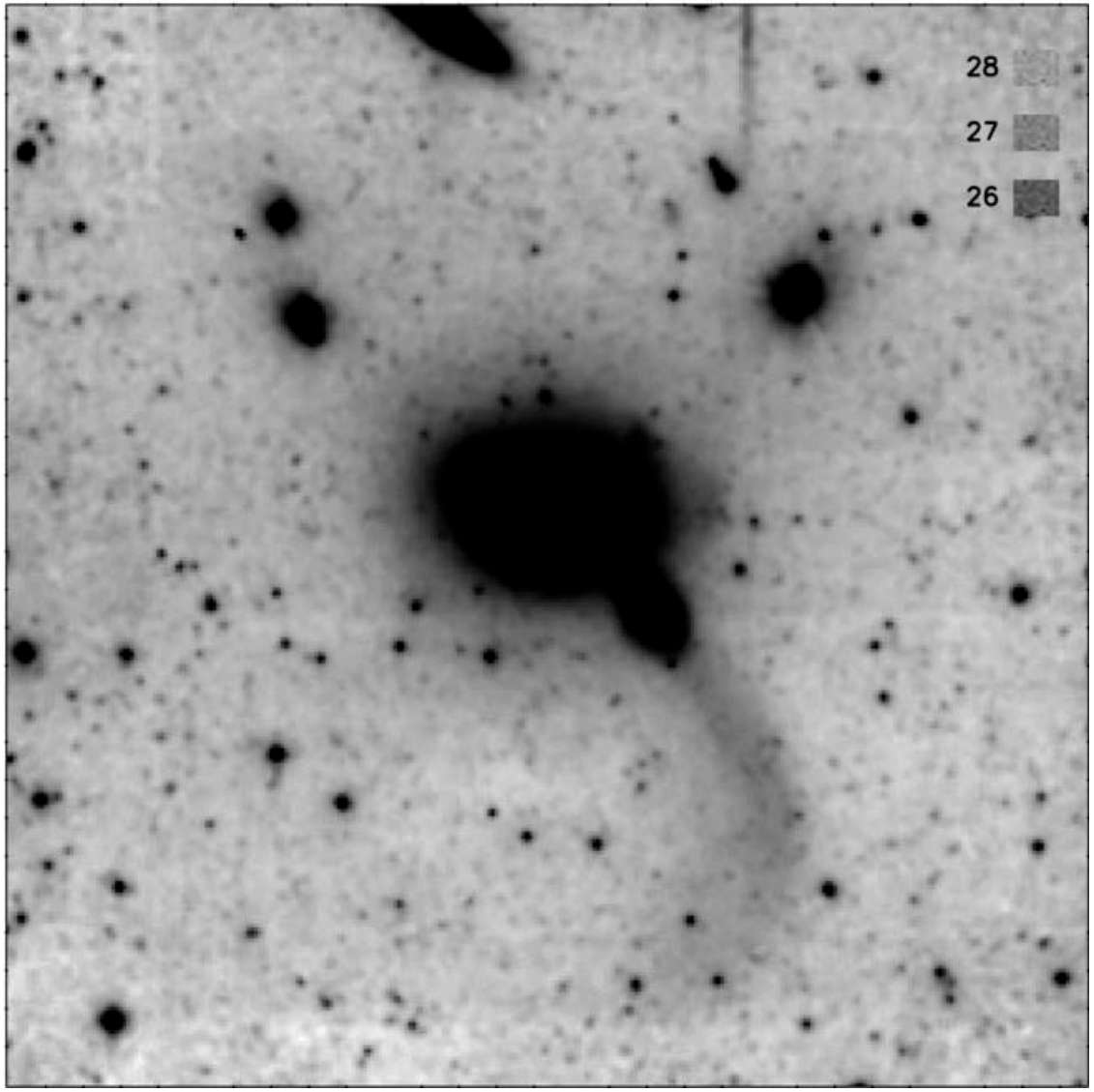
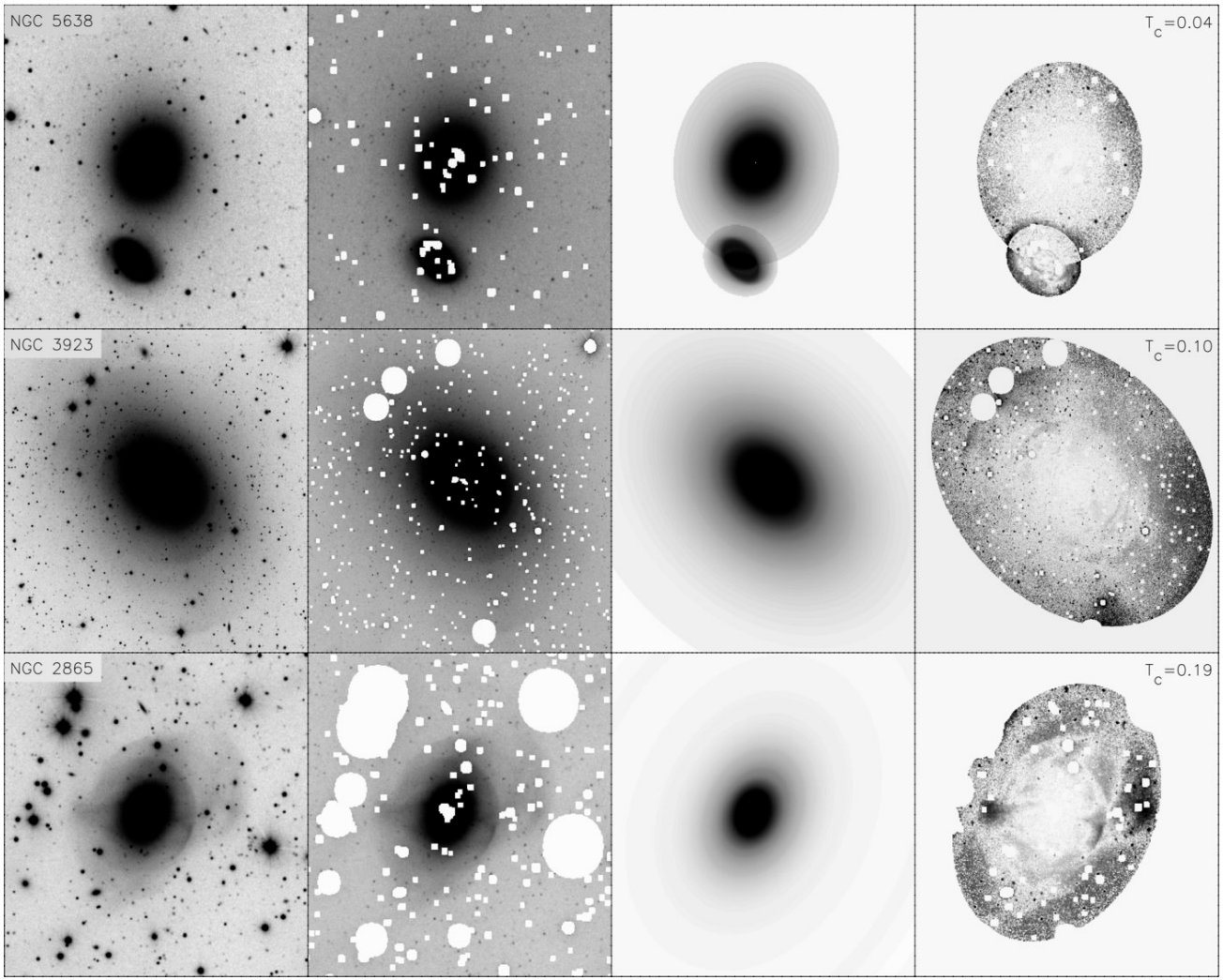



Tal et al. 2009

# Tidal parameter derivation

$T_{gal}$ parameter:

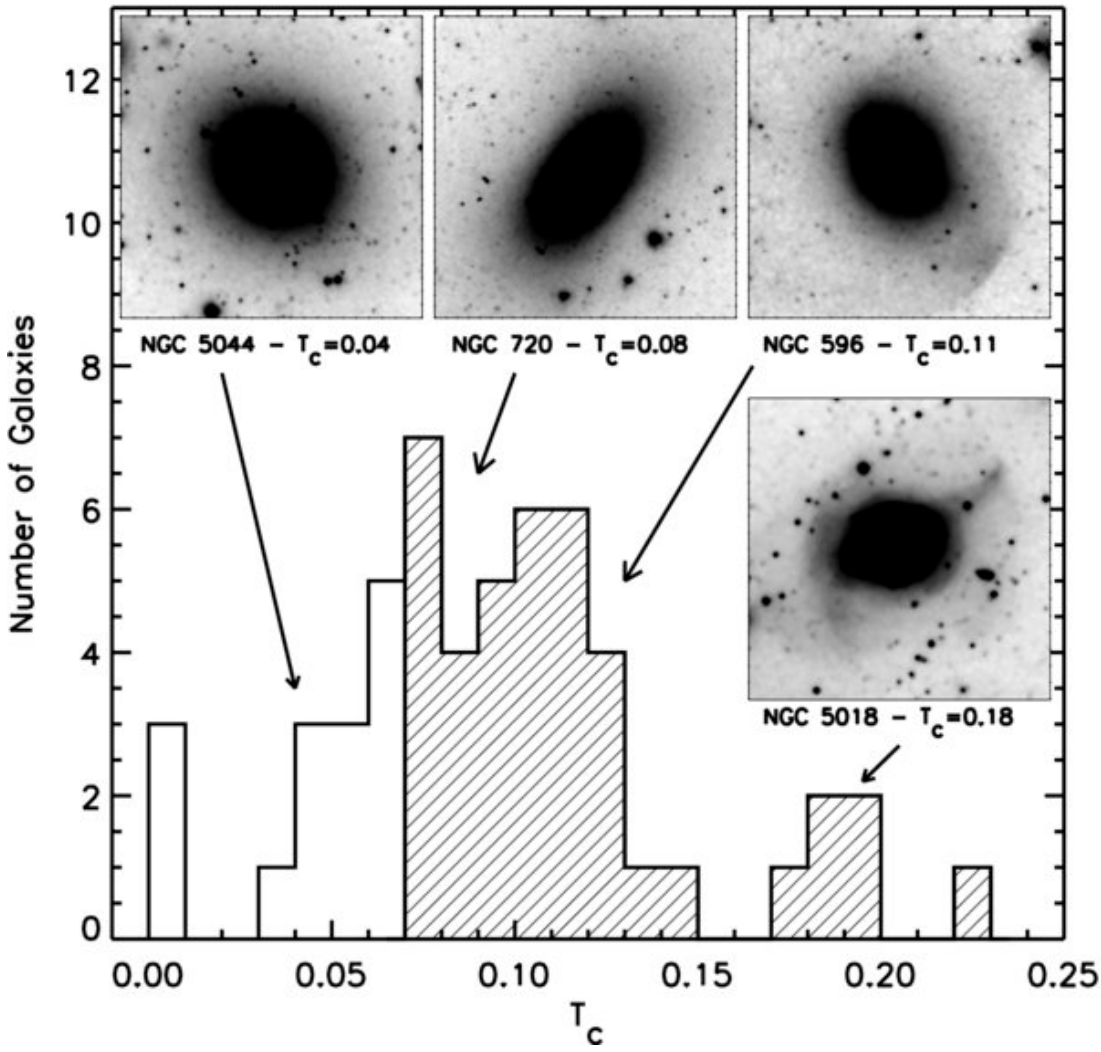
$$T_{galaxy} = \overline{\left| \frac{I_{x,y}}{M_{x,y}} - 1 \right|}$$




Tal et al. 2009

# How common are tidal features?

- 70% of all nearby ellipticals show signs of a (recent) minor interaction
- All are red with no significant star formation




Tal et al. 2009

# Mass accretion rate

- Estimate (over-simplified):

$$\frac{dM}{M} = 0.2\left(\frac{m_2/m_1}{0.1}\right)\left(\frac{f_T}{0.7}\right)\left(\frac{1}{N_0}\right)\frac{dT}{Gyr}$$

- $f_T$ - frequency of tidal features
- *m2/m1* – progenitor mass ratio
- $N_0$ – number of dynamical friction timescales it takes to dissolve a typical feature

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Massive galaxies at extremely large radii

# EVIDENCE FOR MINOR MERGERS IN THE STELLAR HALOS OF LRGS

# Mergers and stars

- Major mergers – stars from progenitors are well mixed in the resulting system

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- Minor mergers – tidal stripping distributes accreted stars preferentially in outskirts

# Stellar accretion via tidal stripping

- Energy balance:

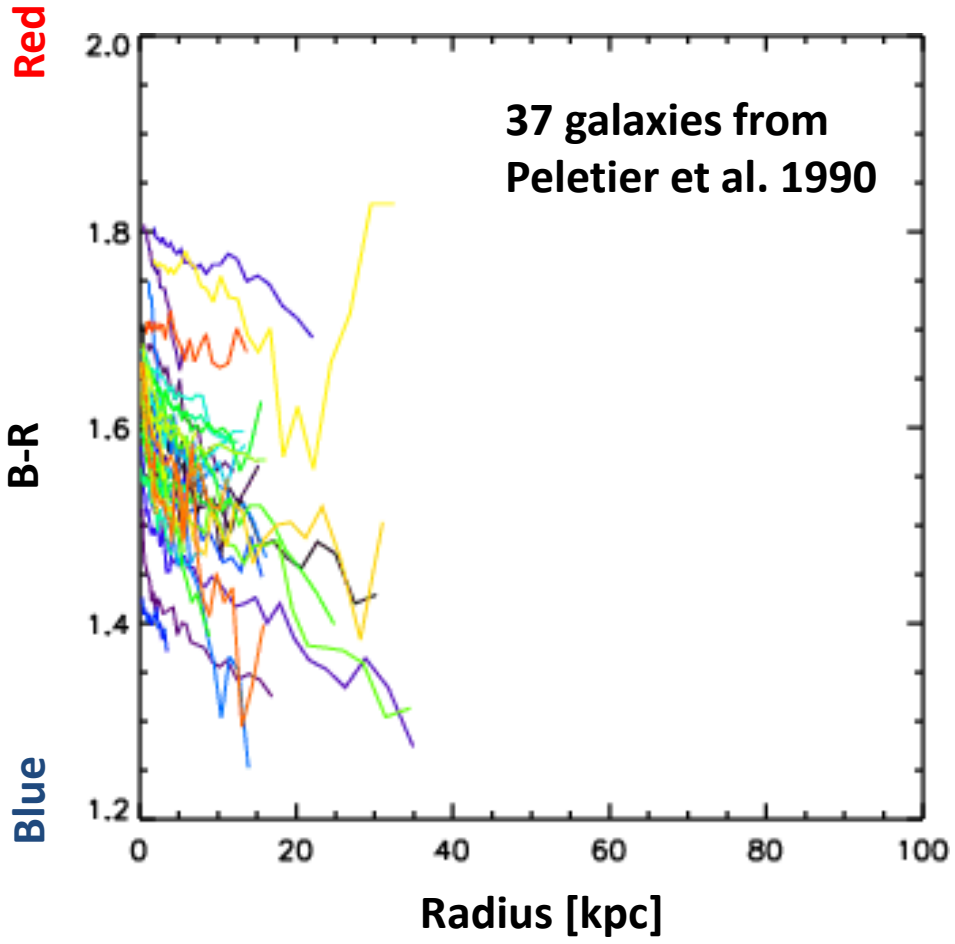
$$V_{circ}^{M} = V_{esc}^{m}$$

- “Typical” radius of accreted stars:

$$R_a = \frac{M}{m}\frac{r_m}{2}$$

# Color profile of individual ellipticals

- Steep color gradient at small radii
- Only a few galaxies with a measurement at r > 15 kpc
- Kormandy+09



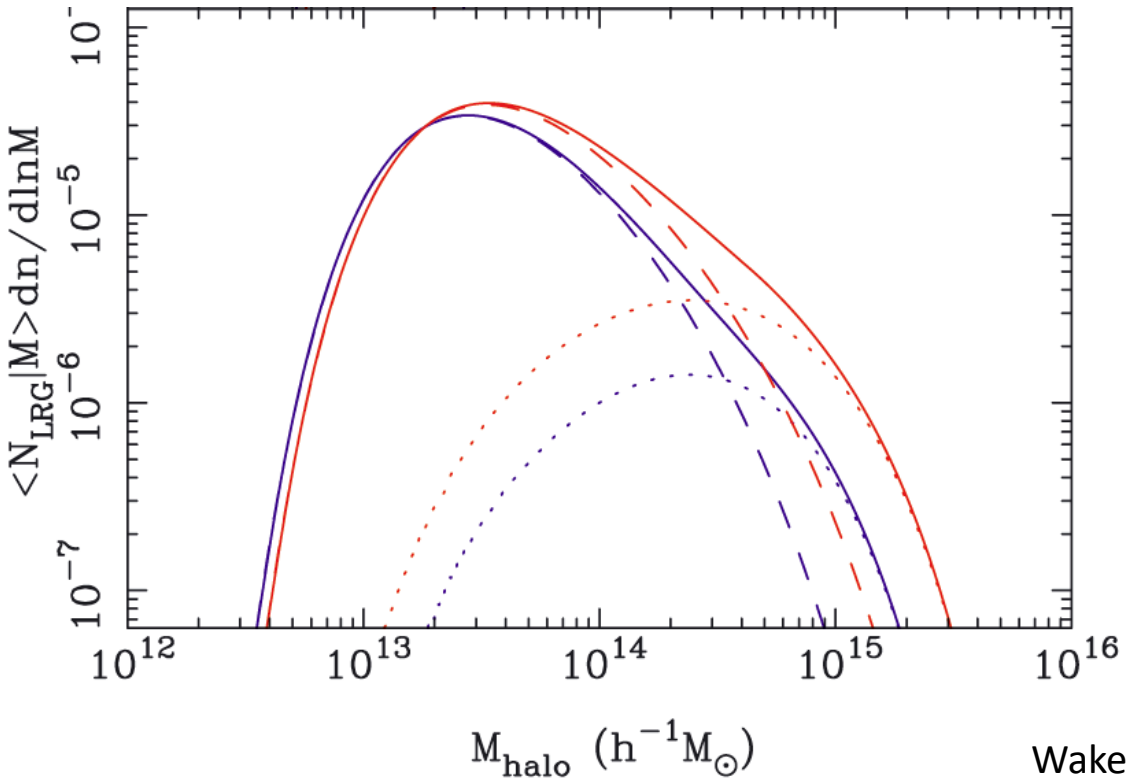
# Alternative - stacking

- Averaging a large number of galaxy images

- Well defined sample → LRGs
  - Properties of individual galaxies similatr to average properties
- Large sample → SDSS
  - Meaningful statistics

# Luminous Red Galaxies (SDSS)

- The reddest, most massive galaxies in SDSS ($10^{11}$-$10^{12}$ $M_{\odot}$)
- 90% are group centrals
- Selected in a narrow redshift bin




Wake et al. 2008

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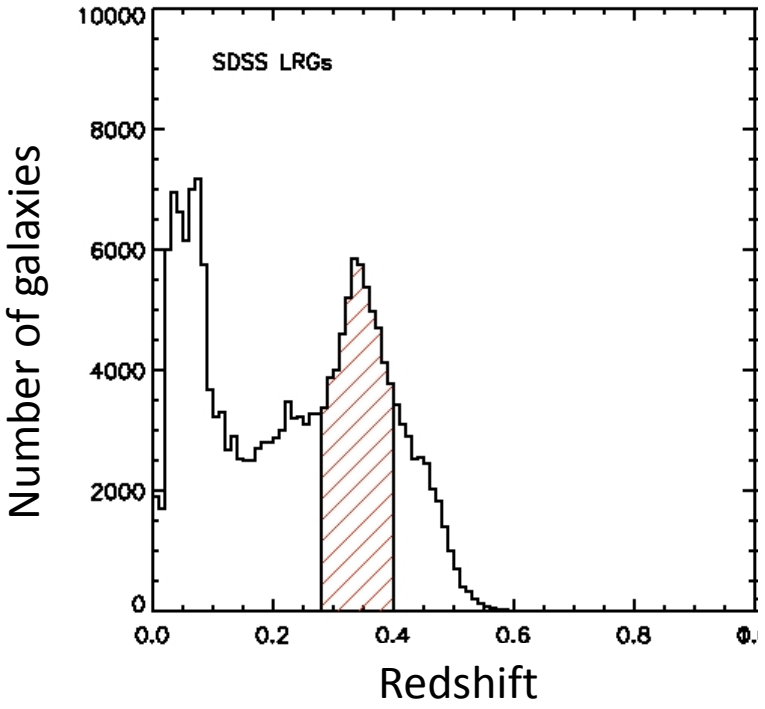
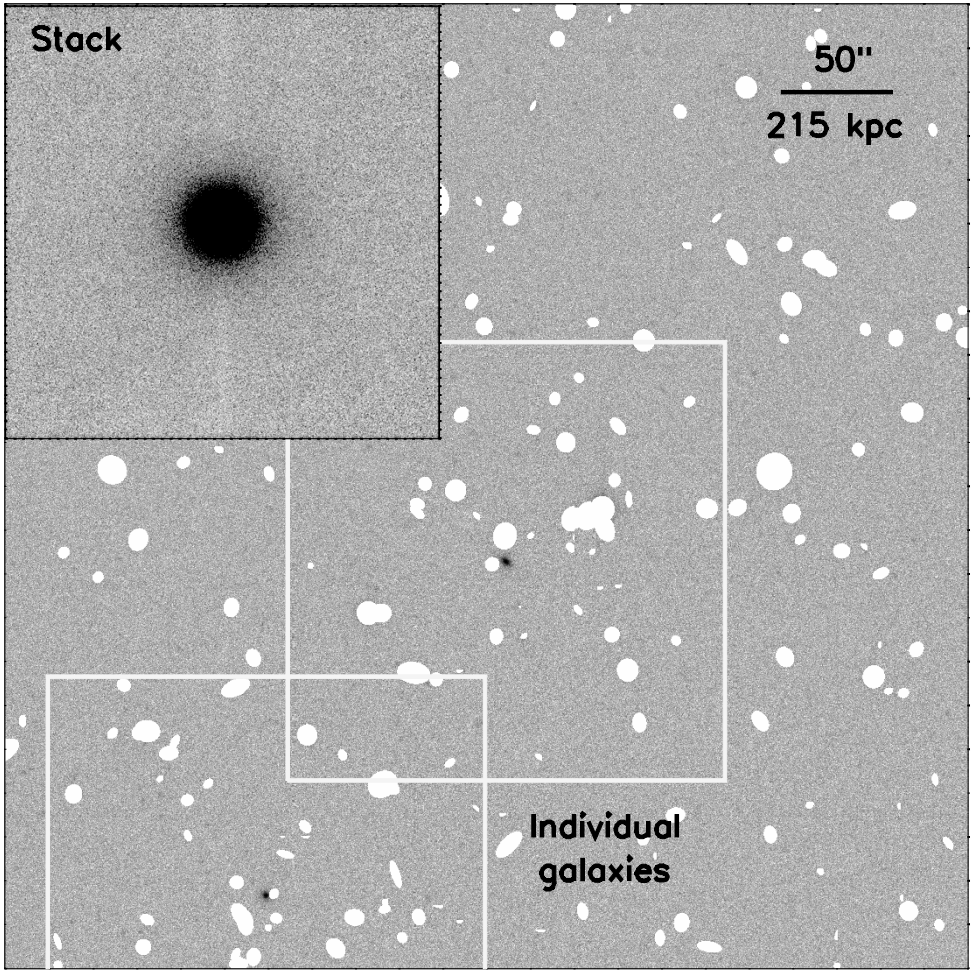


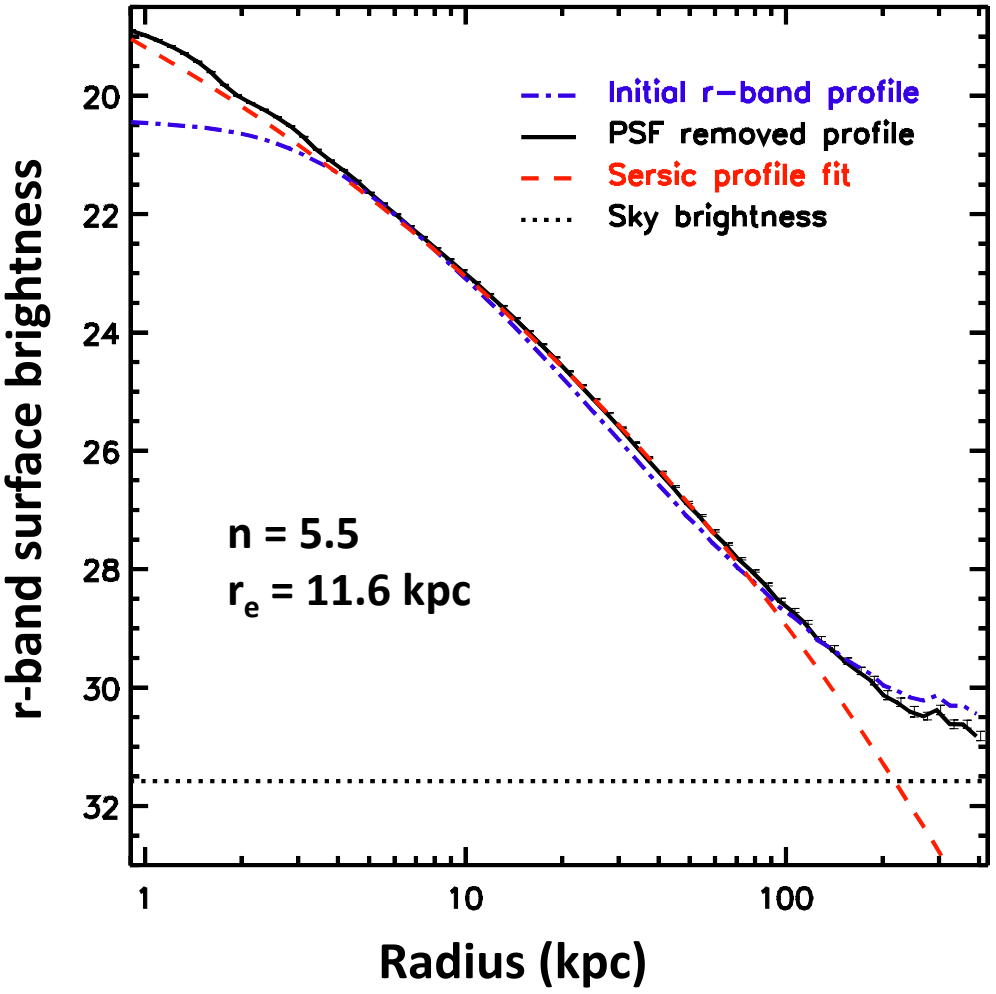
# Stacking

- 42,000 images
- 2.3 Msec integration time, equivalent to 40 hours on 10m class telescope
- Background removed using random stacks



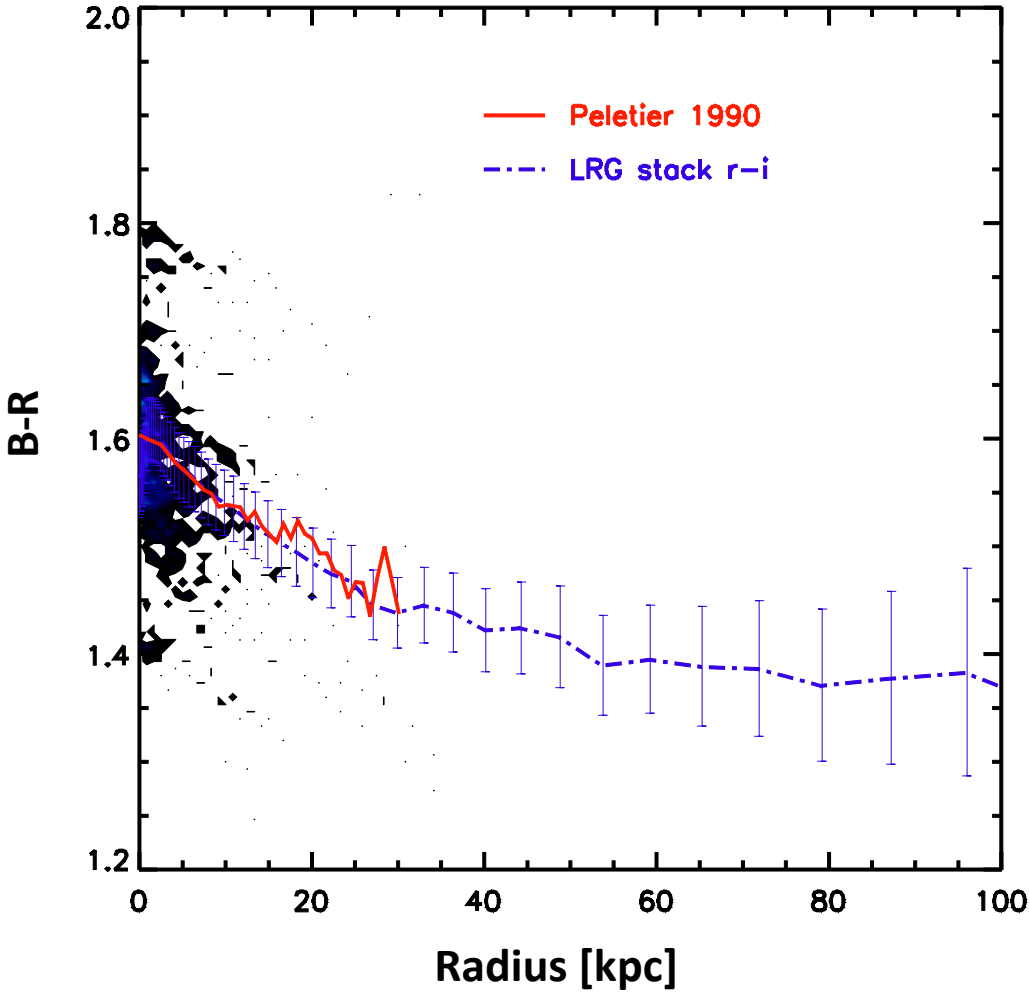
# Light Profiles

- PSF
- Reach r-band surface brightness of 31.5 mag arcsec$^{-2}$
- Well fitted with single Sersic parameter set out to 100 kpc
- Sizes typically underestimated by 10% and flux by 20%



# Color profile

- Profile in inner ~30 kpc matches nearby galaxies
- Flattens out at ~50 kpc out to 100 kpc
- Consistent with minor mergers



# Stellar accretion via tidal stripping

- "Typical" radius of accreted stars:

$$R_a = \frac{M}{m}\frac{r_m}{2}$$

$$R_a \approx 60\left(\frac{M/m}{10}\right)\left(\frac{r}{6\,kpc}\right)kpc$$

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Observations of satellite galaxies around SDSS LRGs

# THE ENVIRONMENTS OF LUMINOUS RED GALAXIES

# Environment

- Important for understanding mergers - which galaxies do massive galaxies merge with?
- Estimates of a typical mass ratio

- Difficult to identify satellite galaxies of individual environments

- Alternative - observe the average luminosity function of satellite galaxies around massive galaxies

# Statistical study of the environment

- Well defined sample → LRGs
  - Properties of individual environments close to average properties
- Large sample → SDSS+BOSS
  - Meaningful statistics
- Contamination → Important

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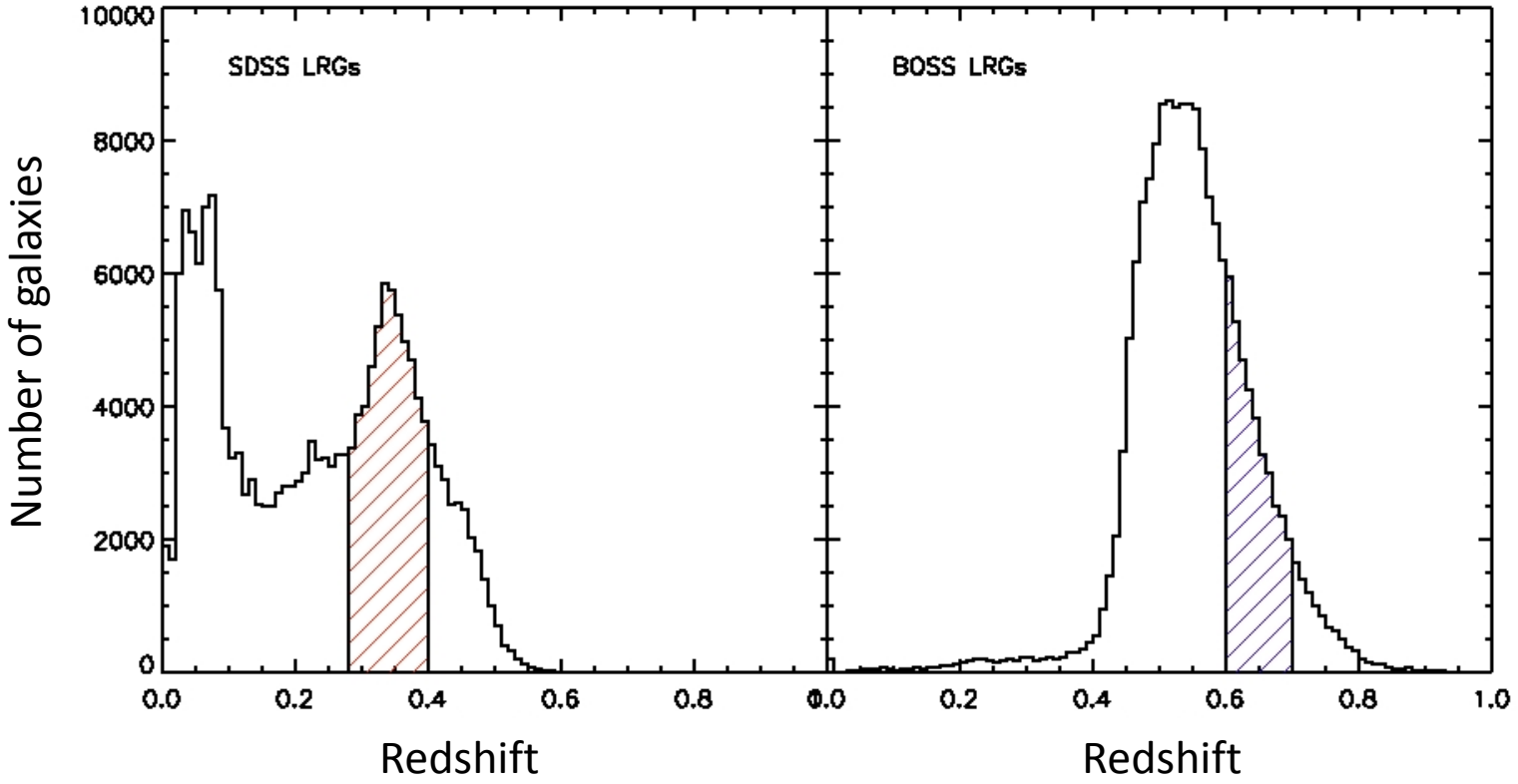
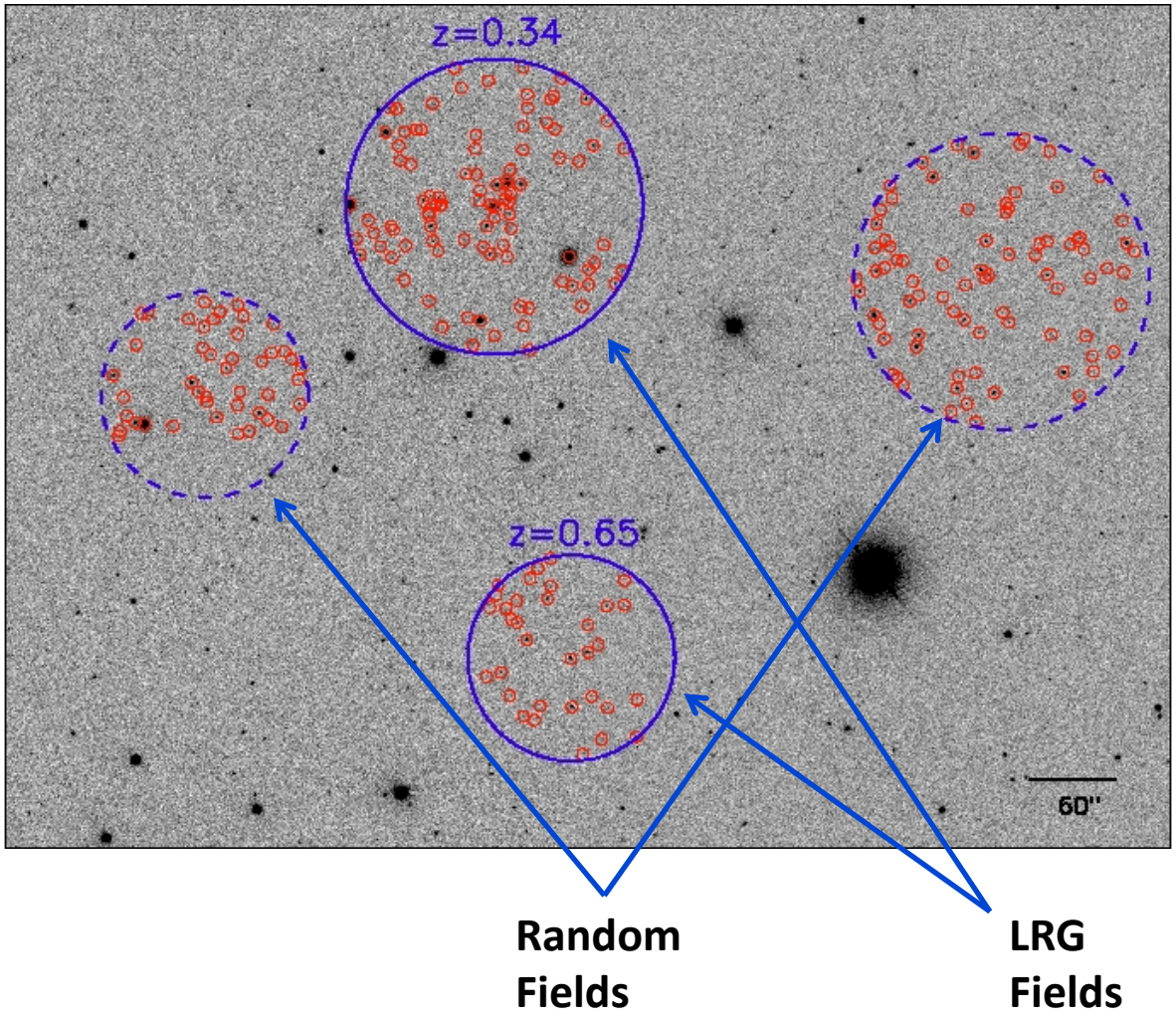
# SDSS and BOSS LRGs

- Two redshift bins:  z~0.34 and z~0.65
- Number-density matched



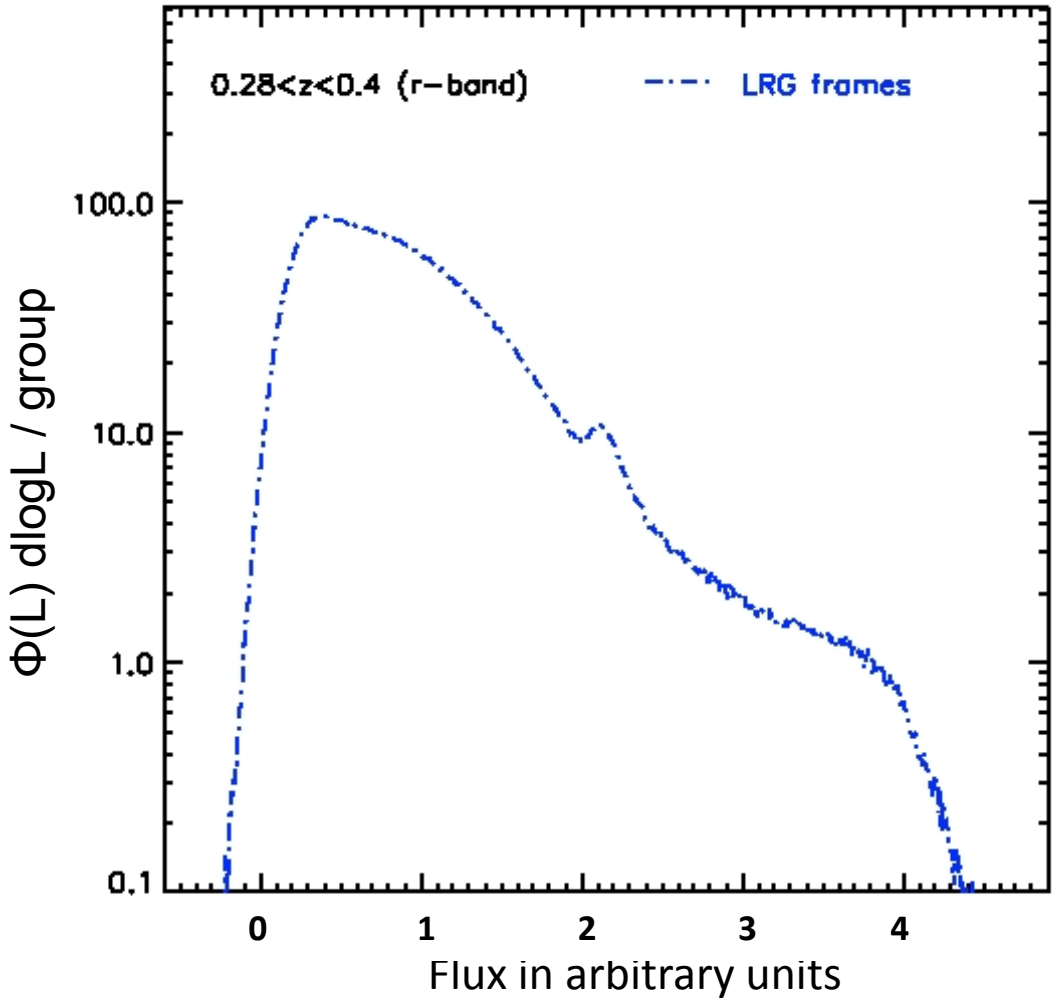
# Photometry

- Detect all objects in 500 kpc apertures around each LRG
- Low detection threshold
- Repeat in randomly selected positions within the same SDSS imaging fields



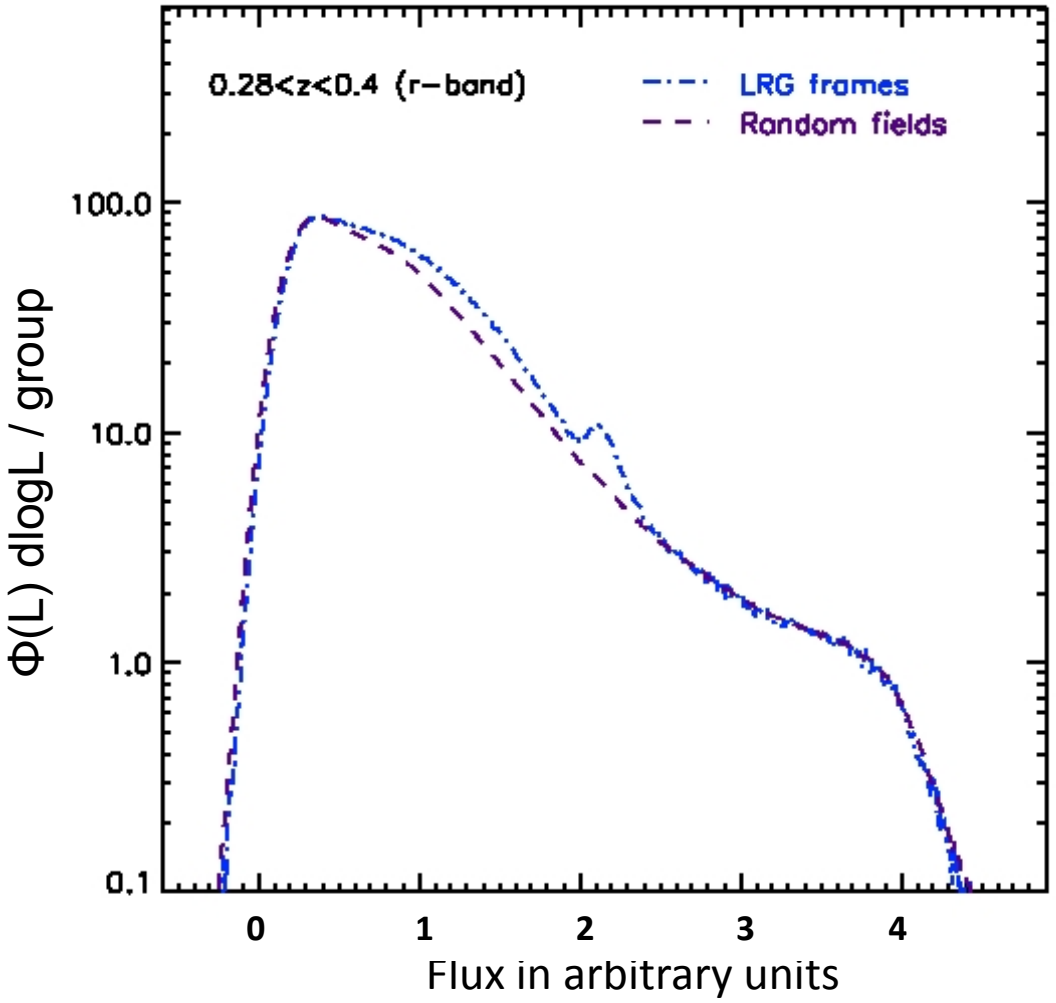
# The luminosity function of satellite galaxies

- Measure luminosity distribution in LRG fields



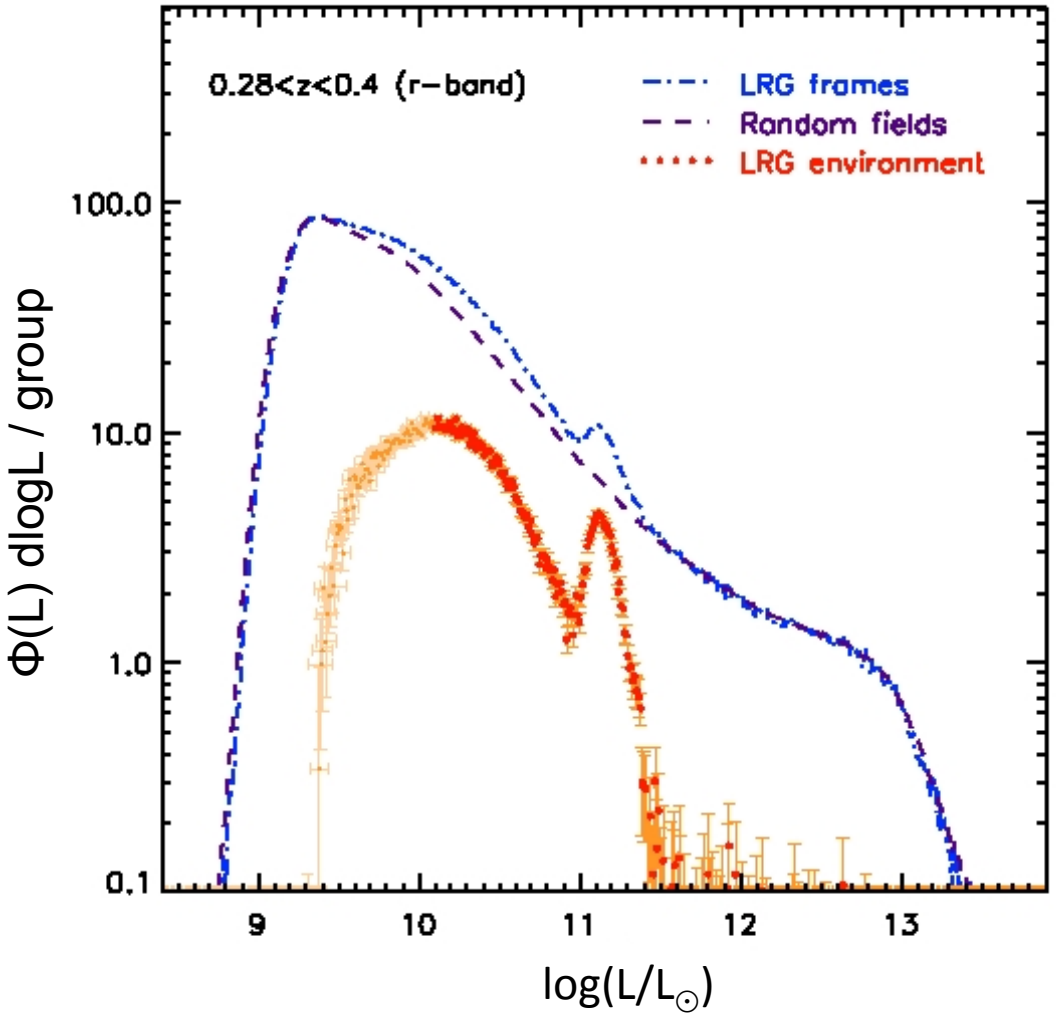
# The luminosity function of satellite galaxies

- Measure luminosity distribution in LRG fields
- Also in random fields



# The luminosity function of satellite galaxies

- Measure luminosity distribution in LRG fields
- Also in random fields
- Subtract one from the other



# The luminosity function of satellite galaxies

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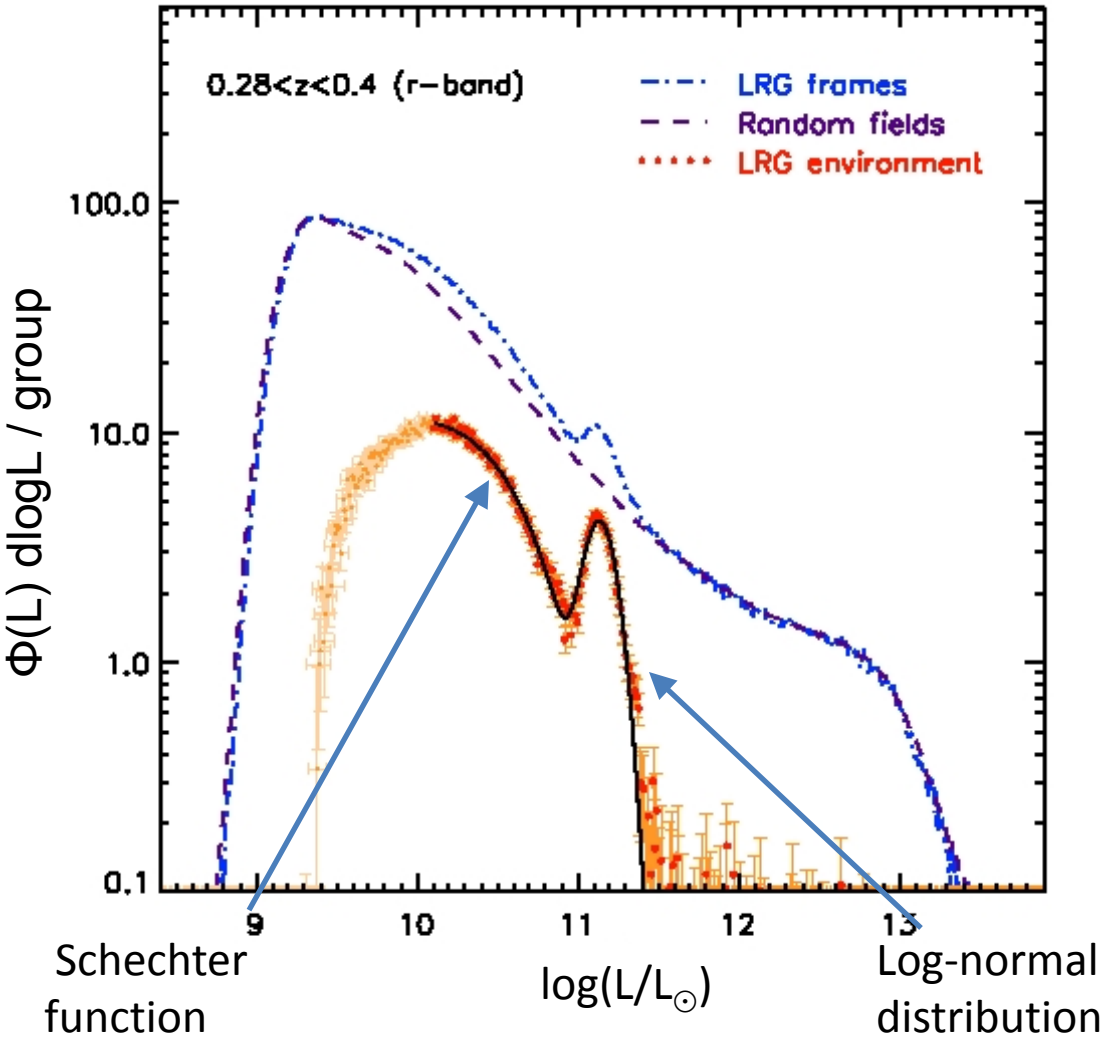
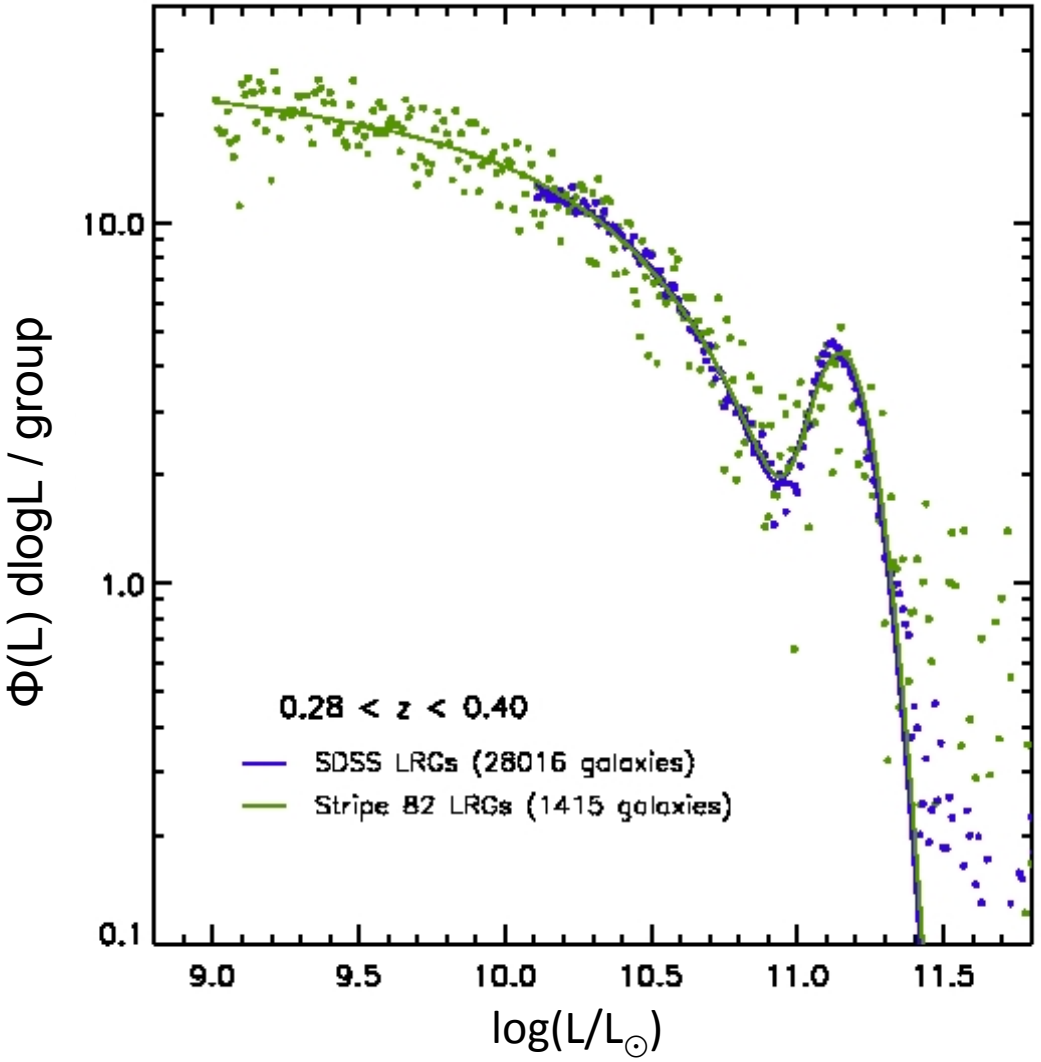
- Also in random fields
- Subtract one from the other
- **Poor fit by just a Schechter function – use two-parameter fits**



# Deep stripe 82 images

- Using deep Stripe 82 data we constrained Schechter slope, detection threshold



# Gap properties

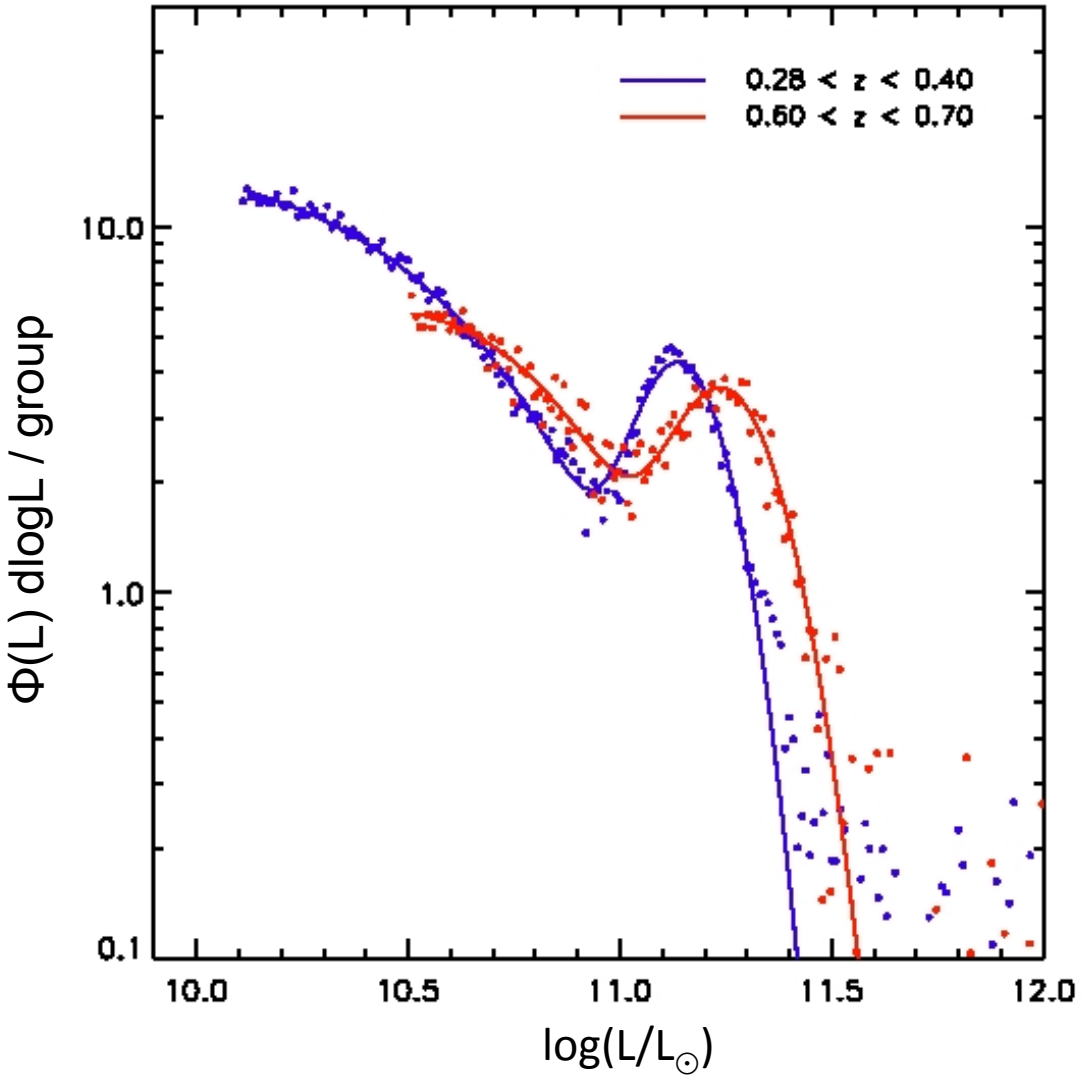
- Width measurement:

$$\int_{L_2}^{\infty} \Phi(L) d \log L = 1$$

$$\Delta M = 2.5 \log(L_2 / L_{cen}) \approx 1.3 mag$$

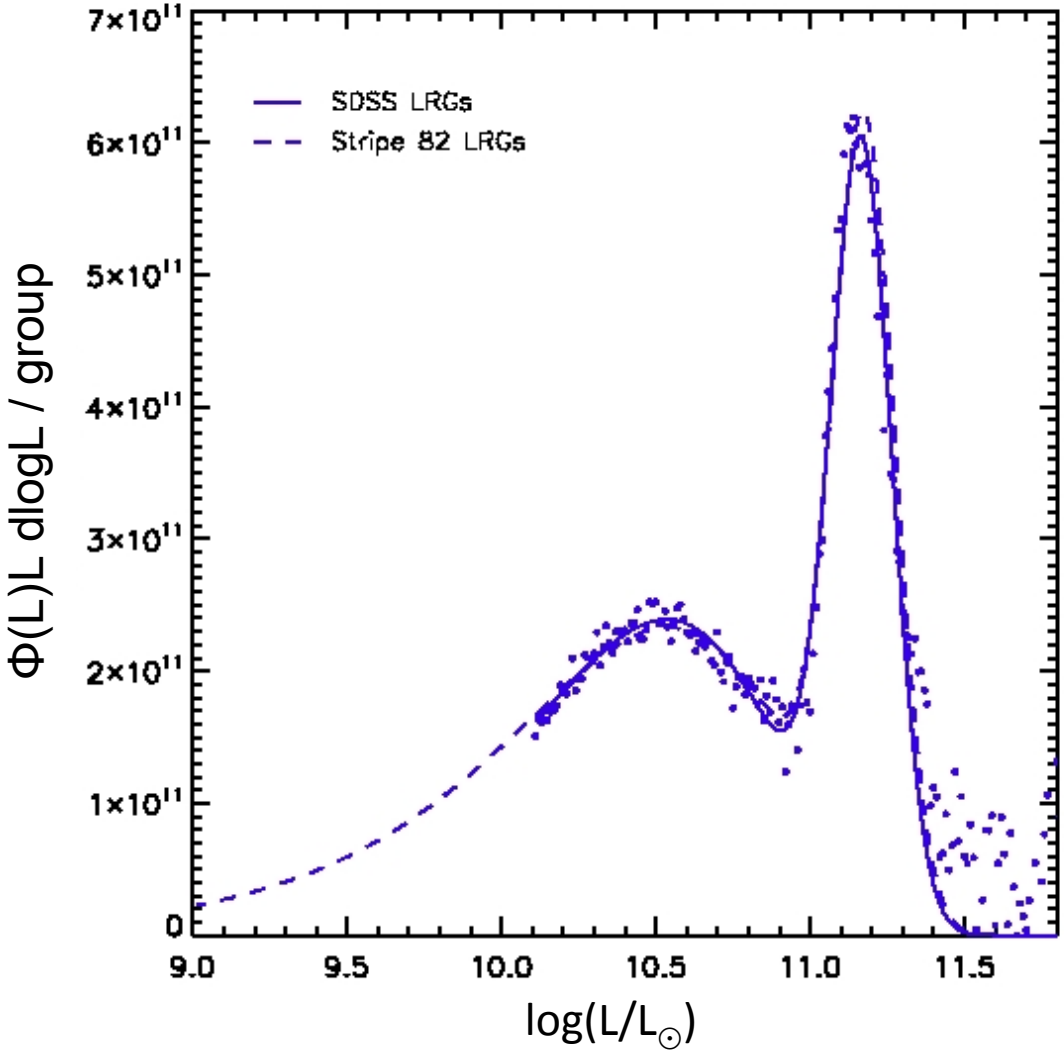
at both redshifts

- LRG peak consistent with passive luminosity evolution



# The mass growth of LRGs through mergers

- The gap width implies a typical mass ratio of 1:4 between the central galaxy and its most massive satellite
- **Mergers of higher mass ratio within the environment unlikely**



# Summary

- Three independent observations that are consistent with minor mergers being the main mode of mass growth in massive galaxies
- Tidal features (and minor mergers) are common – essentially around every nearby elliptical
- Color profile consistent with accretion of lower mass, bluer galaxies
- Luminosity gap between the central galaxy and its most luminous satellite - growth through major mergers is unlikely