Evolution of the most massive galaxies: a statistical study of SDSS LRGs

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BOSS collaboration

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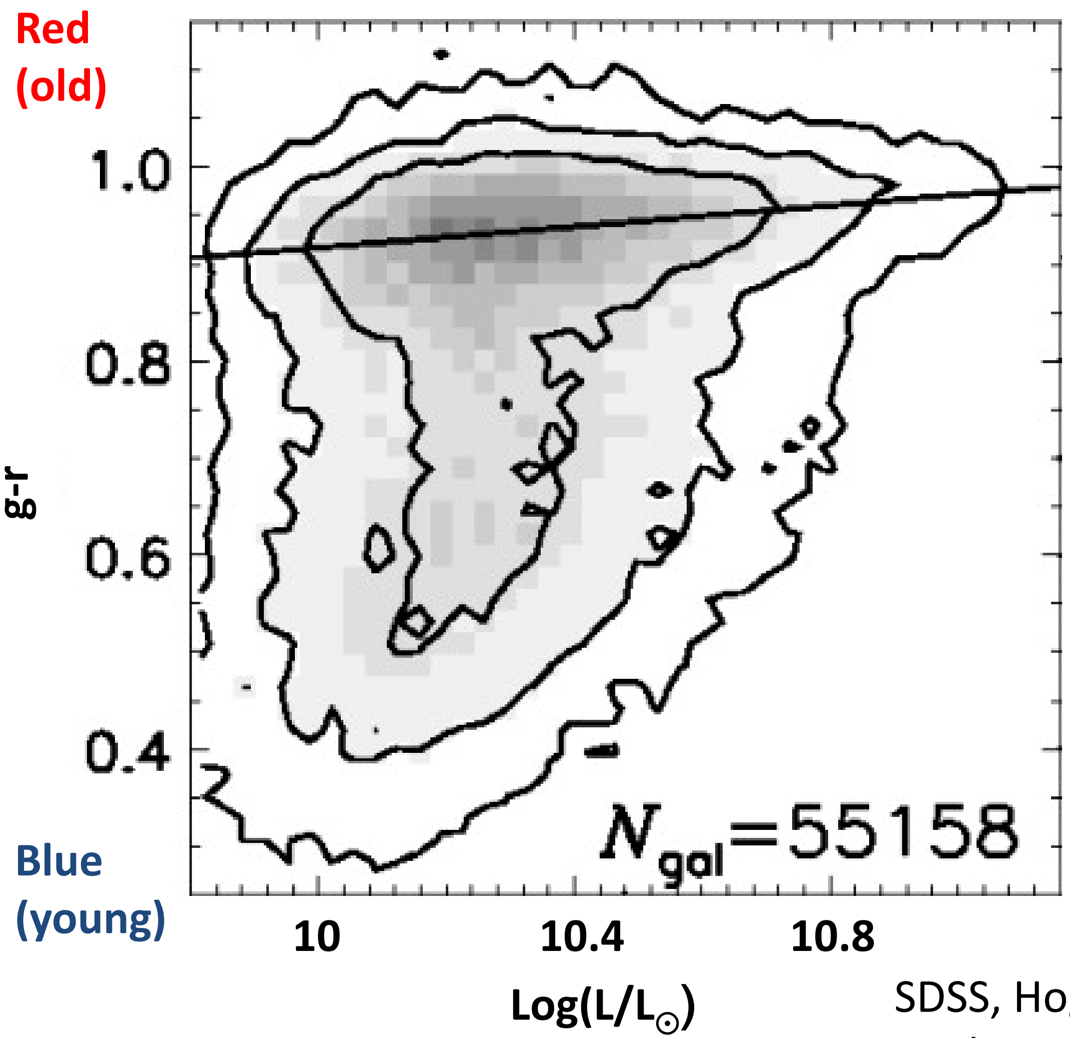
Massive galaxies in the nearby universe

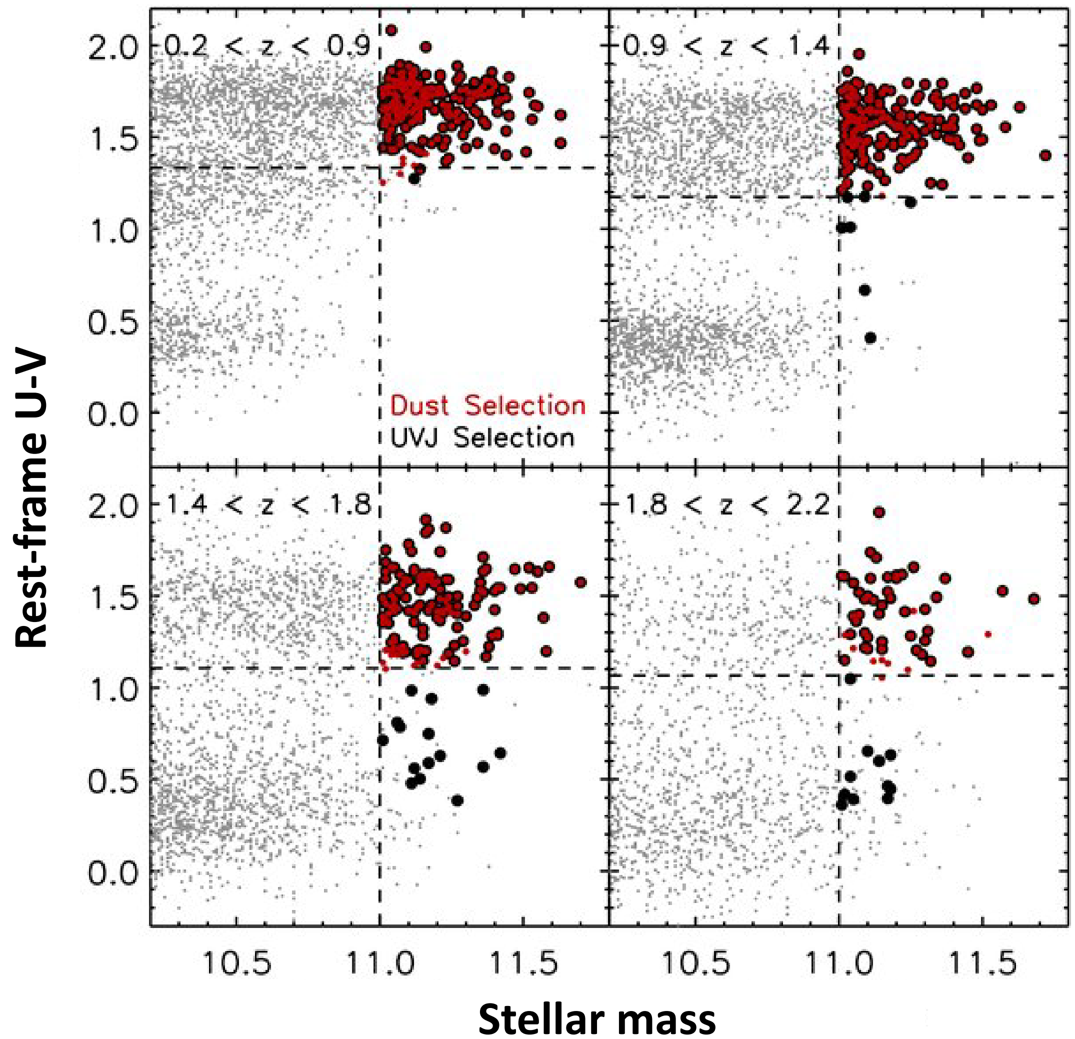
- Old stellar populations and low star formation rates
- The most massive galaxies are along the red sequence
- Spectra dominated by old stars



SDSS, Hogg et al 2004

Massive galaxies at high-z

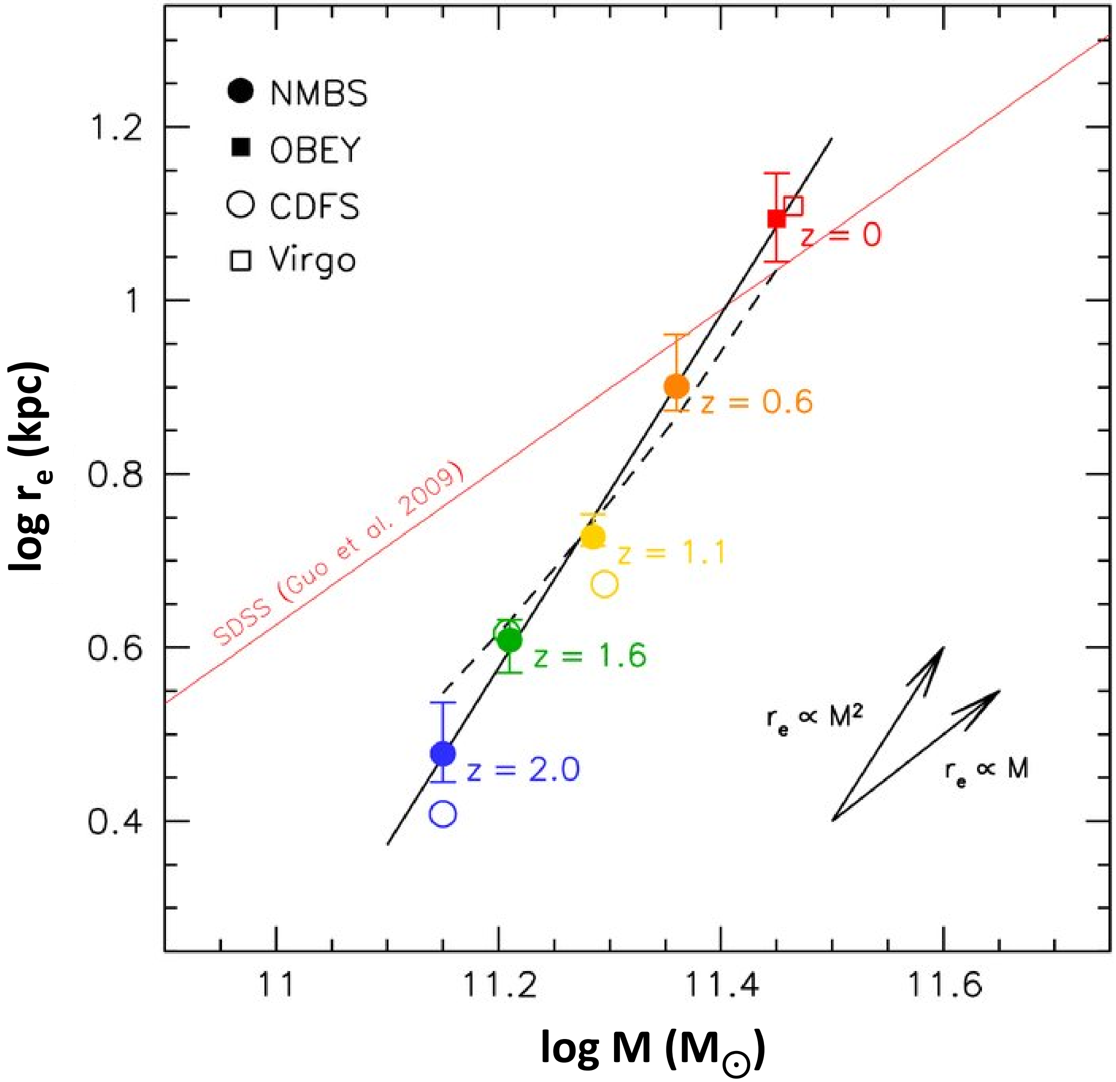
- The most massive galaxies are also the oldest out to z~2 (10 Gyr ago)
- Colors possibly imply low star formation since shortly after creation



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?

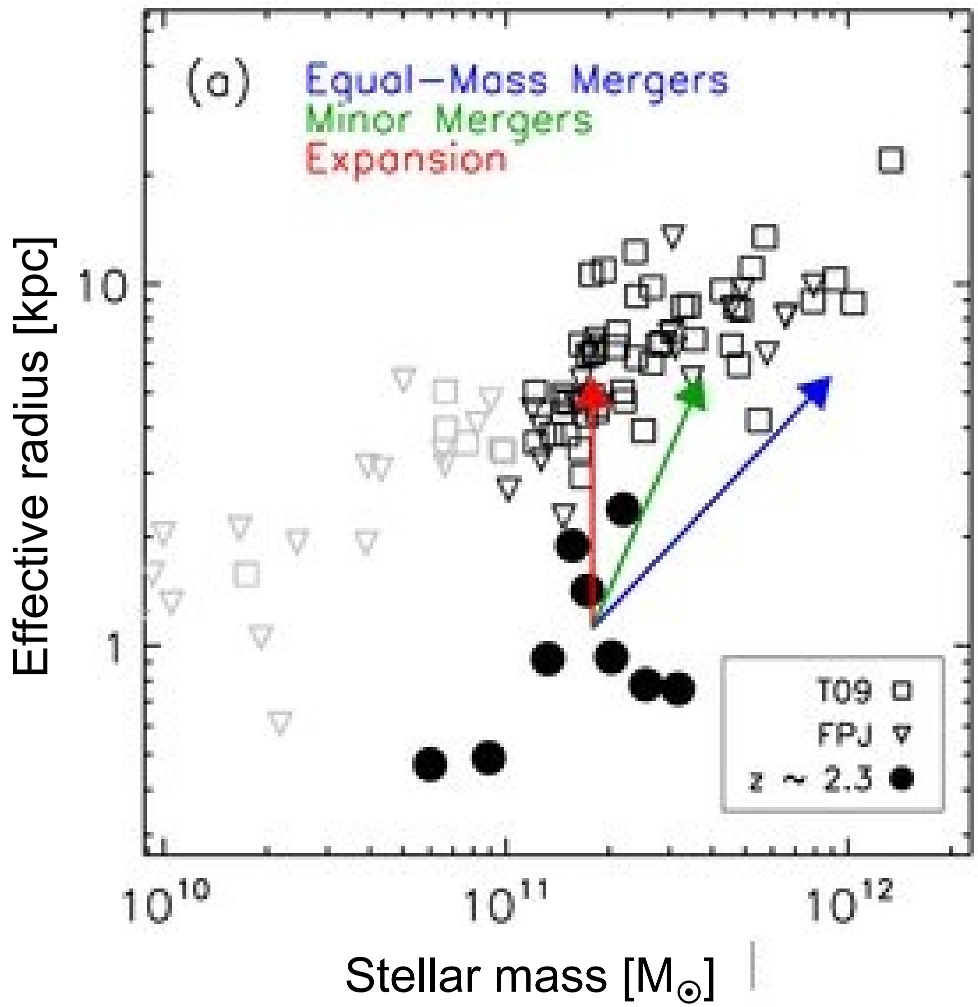
- Star formation rates are low at $0<z<1$
  (e.g., Faber 73, Balogh+04, Worthey+92, Peletier 98, Jørgensen+99, Trager+00, , Kauffmann+03, Hogg+04, Thomas+05)

- 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)

Minor mergers

- Consistent with simple analytic calculations



Bezanson et al. 2009

Observing (minor) mergers

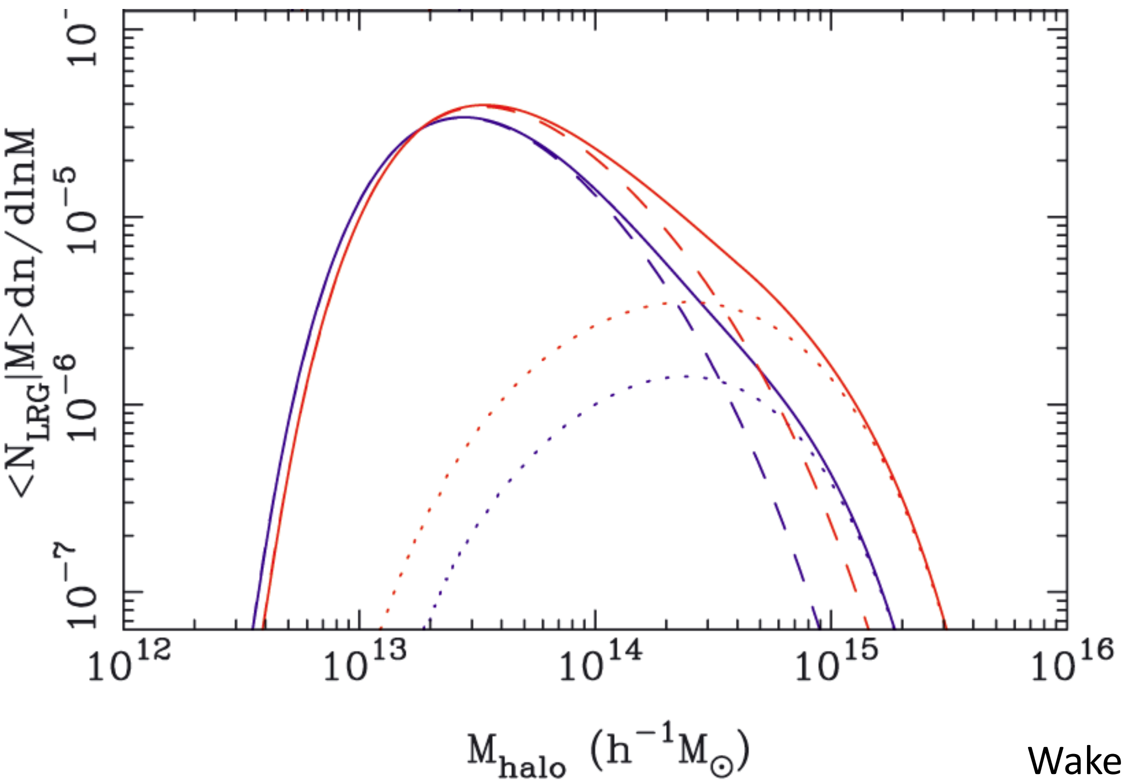
- Direct observations of individual systems and their environments
  - Detailed information from photometry and spectra (accurate sizes, colors, neighbors, dynamical state)
  - Observationally expensive: high quality images and spectra are typically limited to small samples
    - HSC survey
- Alternative – statistical analysis

Statistical study of massive galaxies

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

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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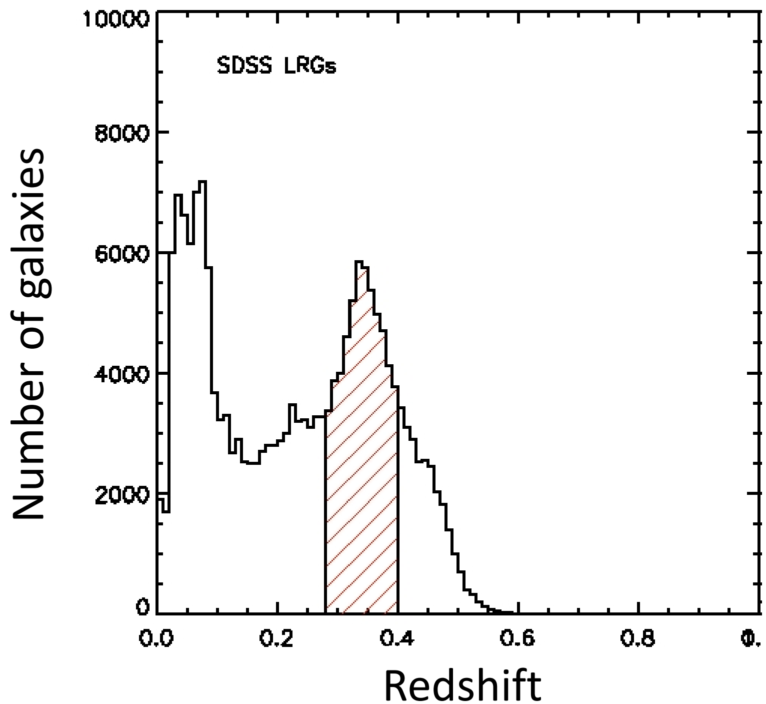

Massive galaxies at extremely large radii

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

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

Stellar accretion via tidal stripping

- Energy balance:

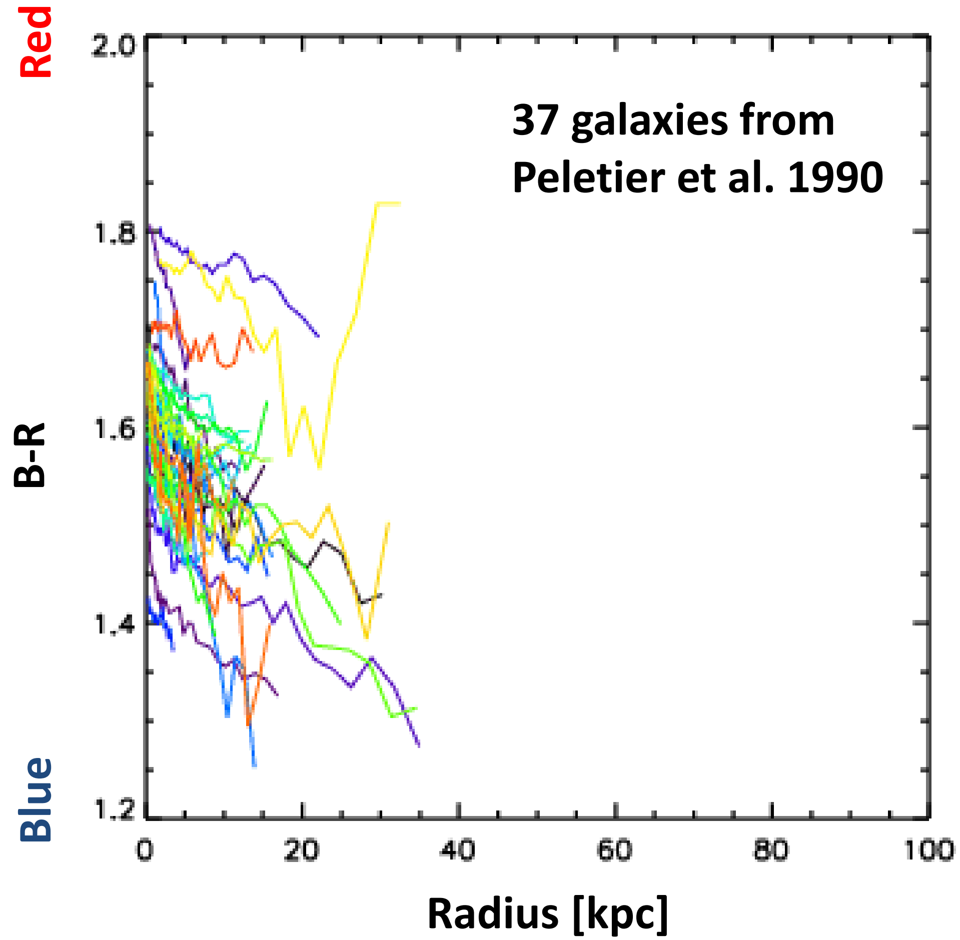
$$V_{circ}^{M} = V_{esc}^{m}$$

- “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



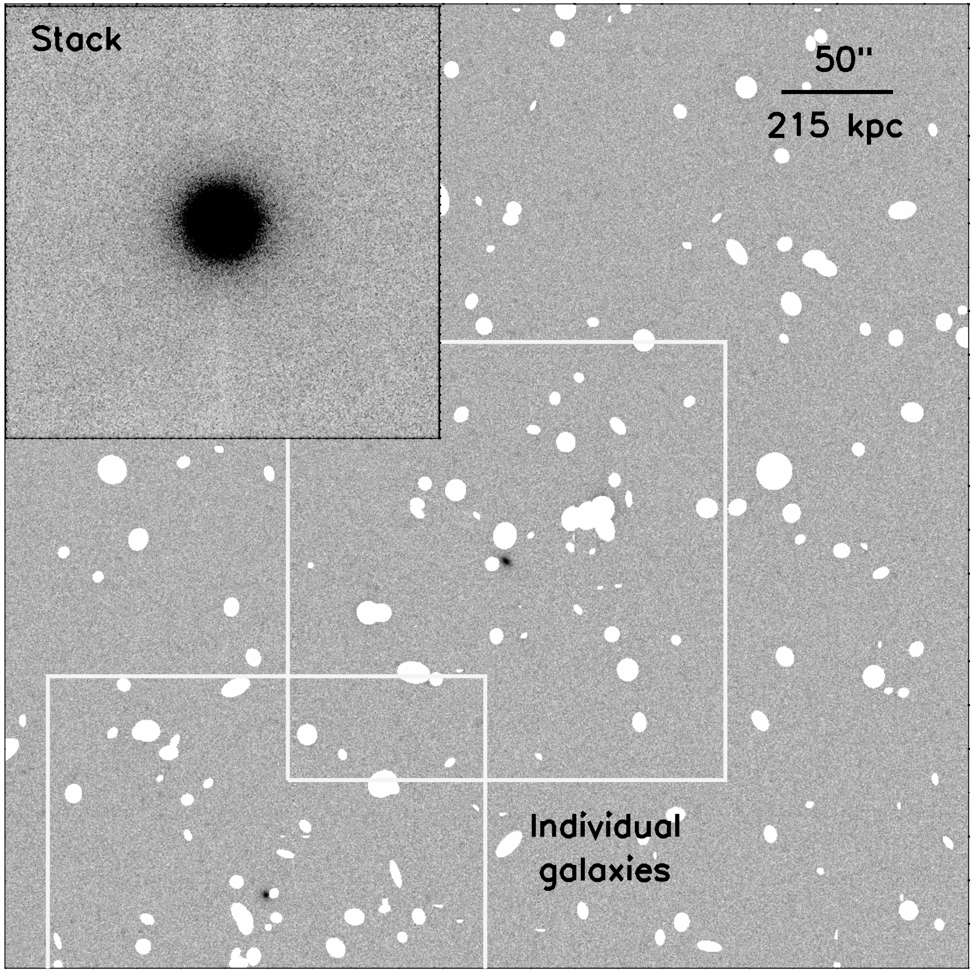
Alternative - stacking

- Averaging a large number of galaxy images
- Improve noise properties by a factor of $\sqrt{n}$
- Lose all information from any single objects

$\rightarrow$ LRGs – essentially a single parameter population of galaxies

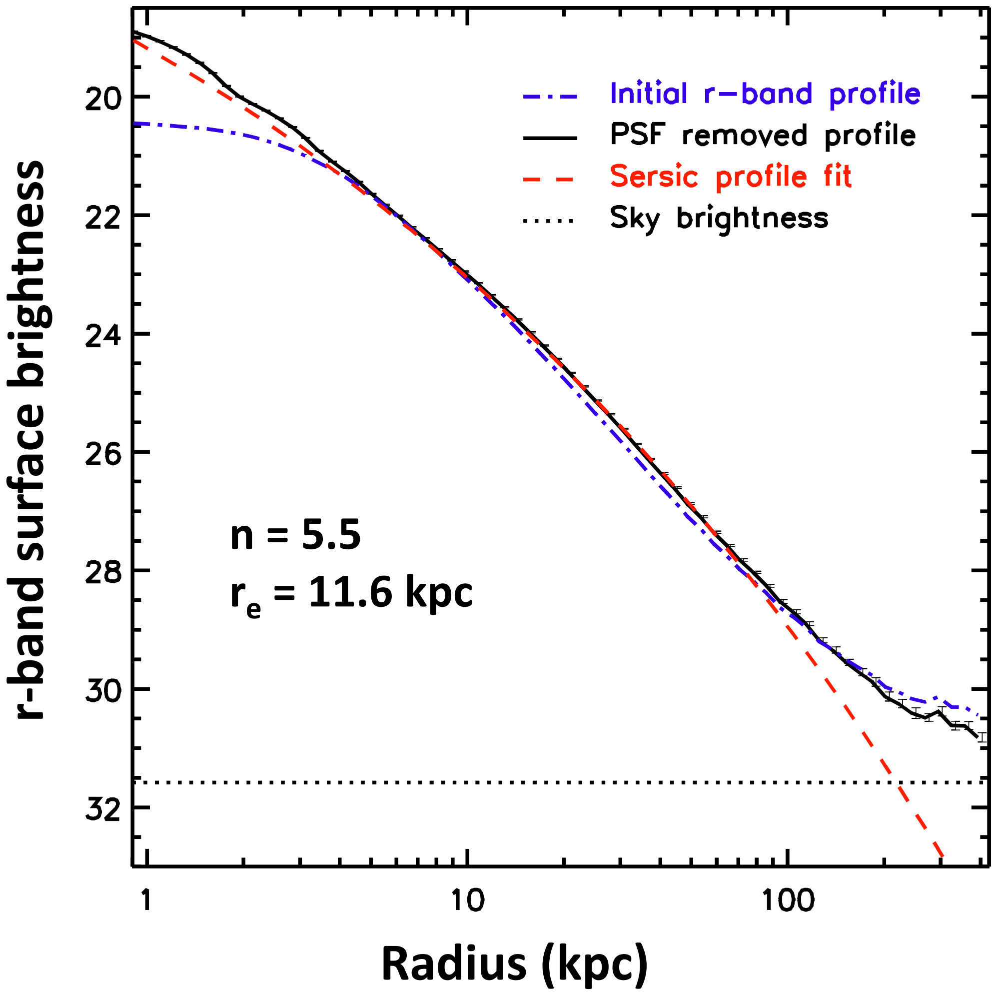
Stacking

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



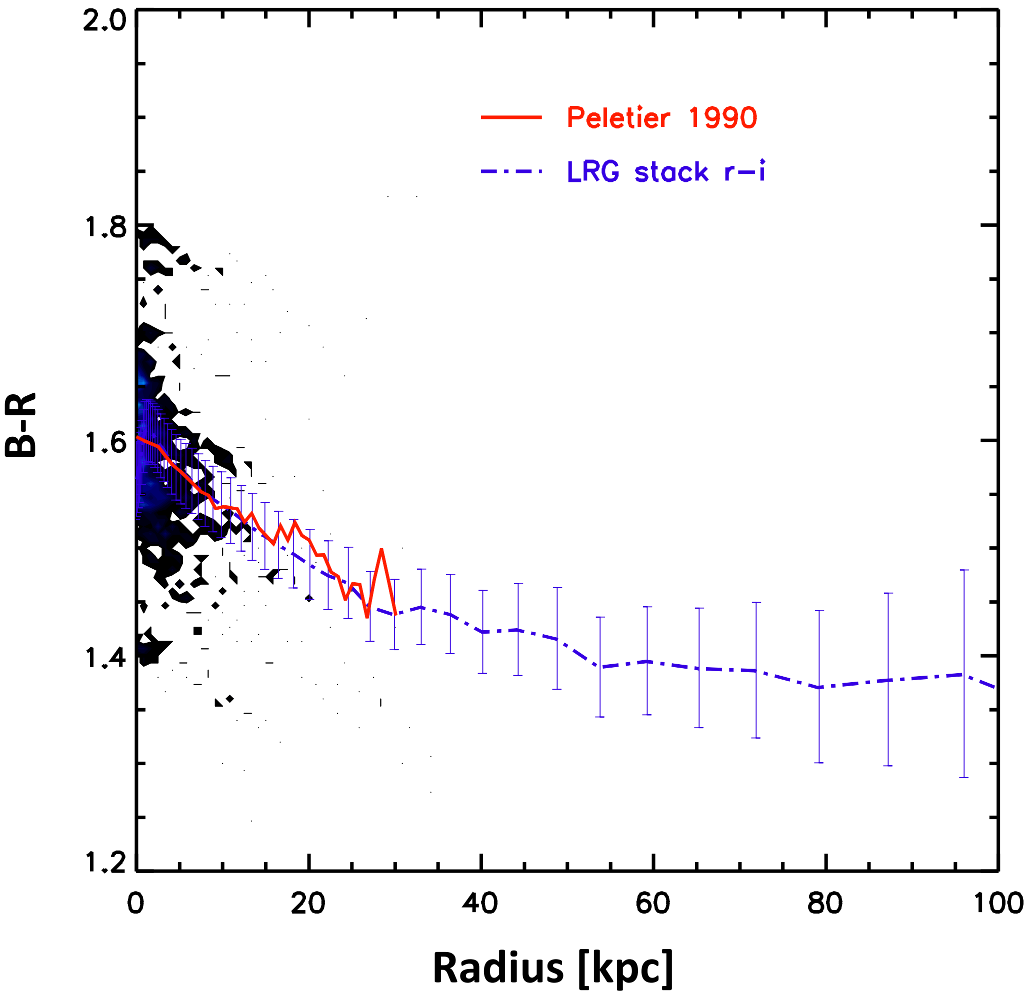
Light Profiles

- 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:

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

$$\Downarrow$$

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

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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?

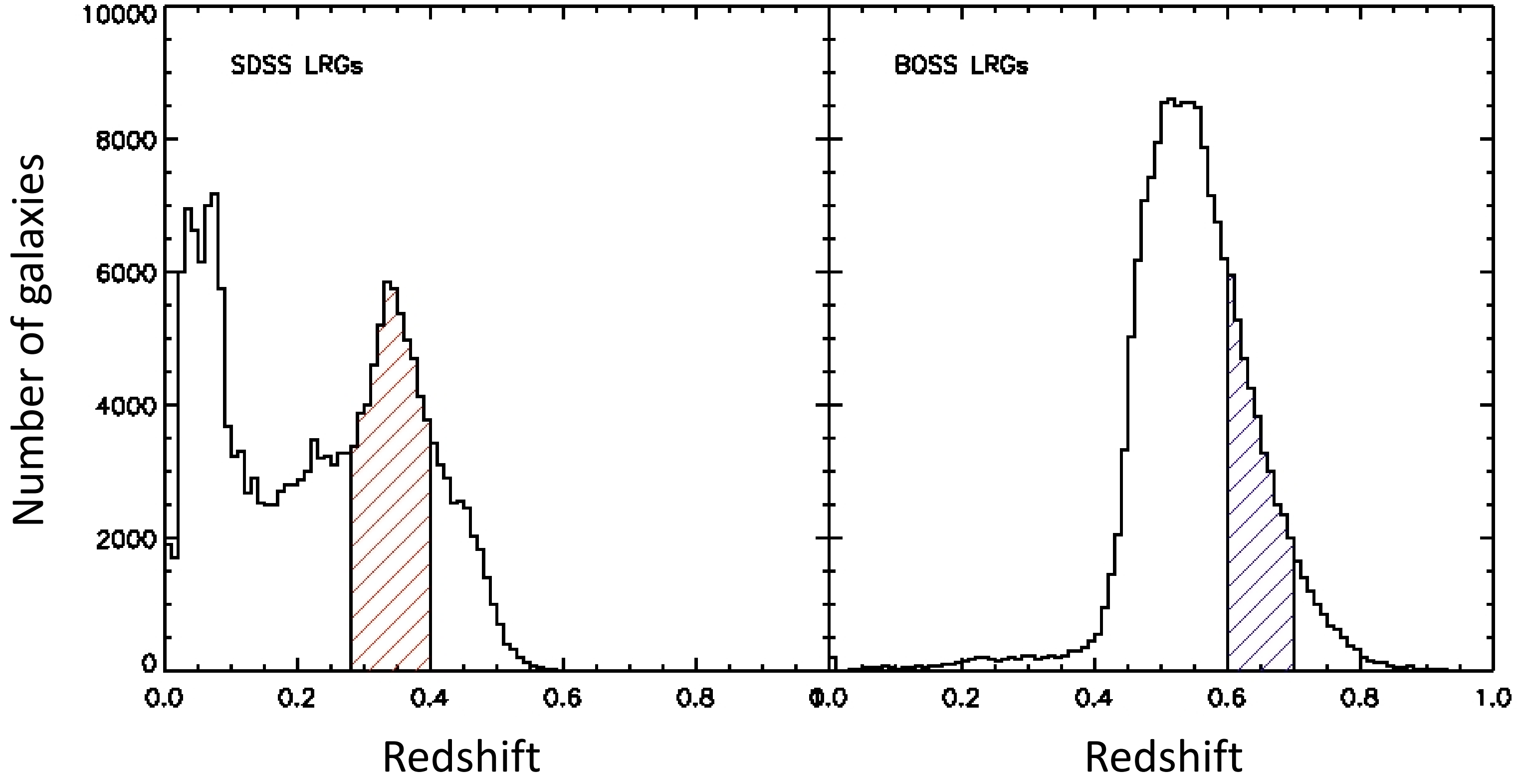
- Estimates of a typical mass ratio
- Describes the mass that surrounds (and affects) the studied galaxy

- Difficult and expensive

→ Statistical analysis of many (LRG) environments

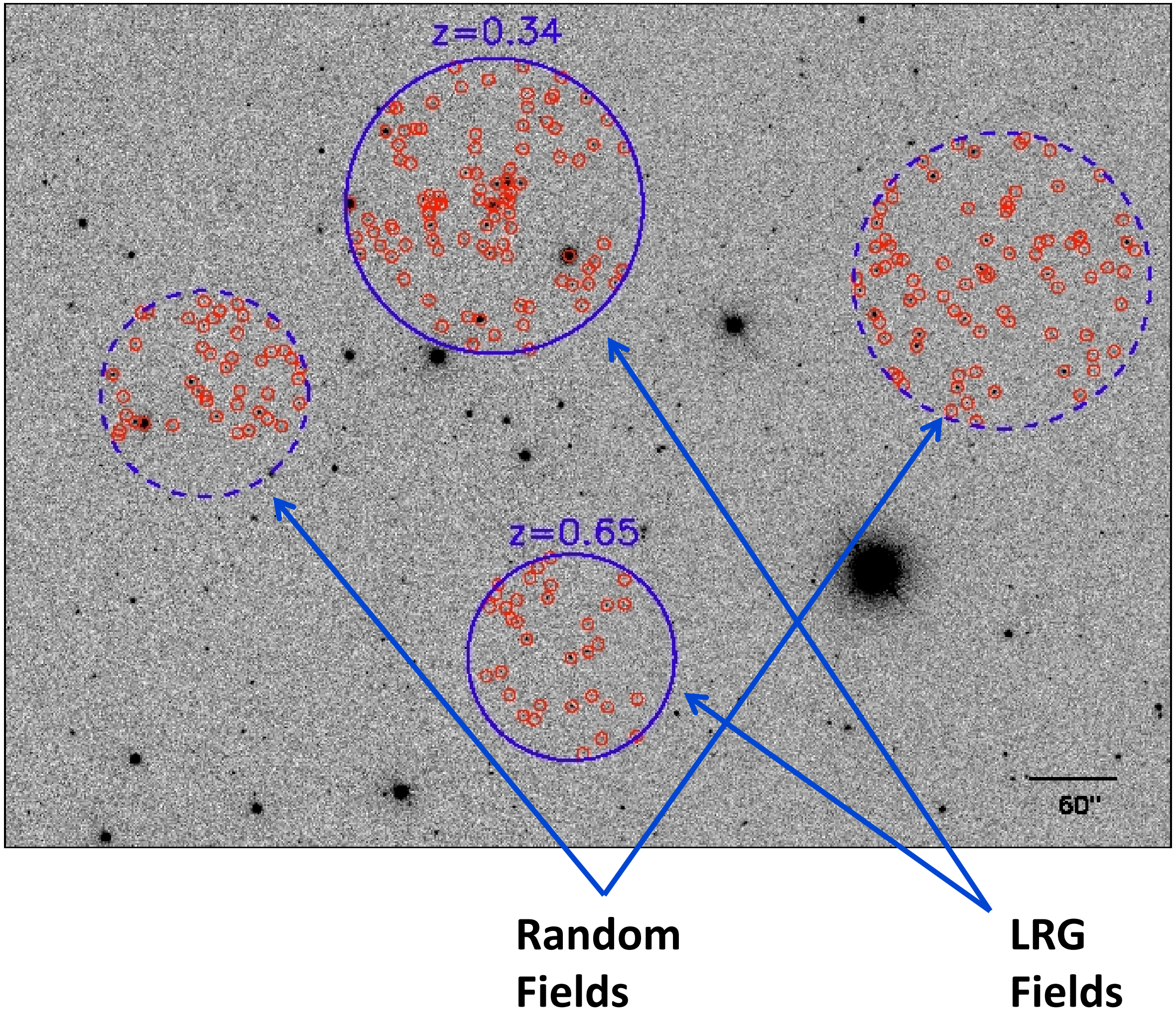
SDSS and BOSS LRGs

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



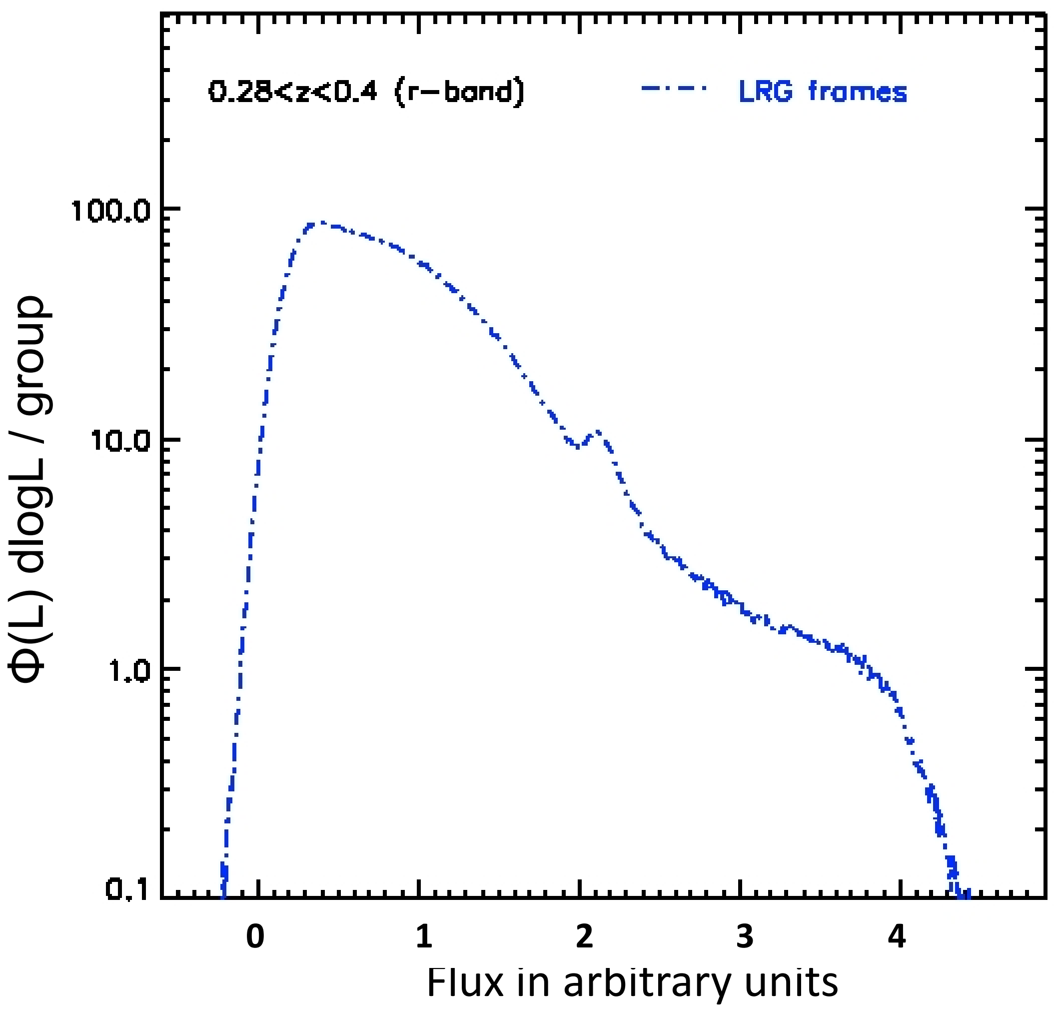
Photometry

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



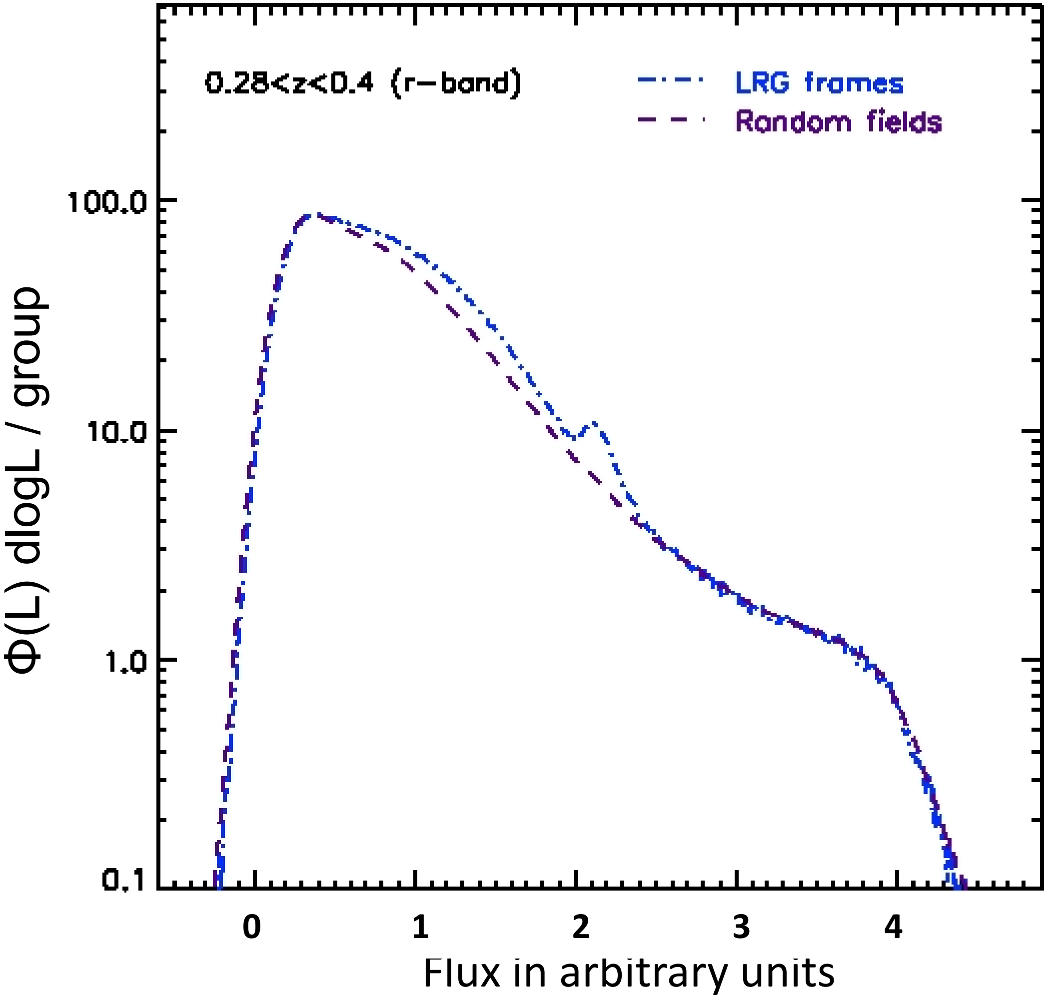
The luminosity function of satellite galaxies

- Measure luminosity distribution in LRG fields



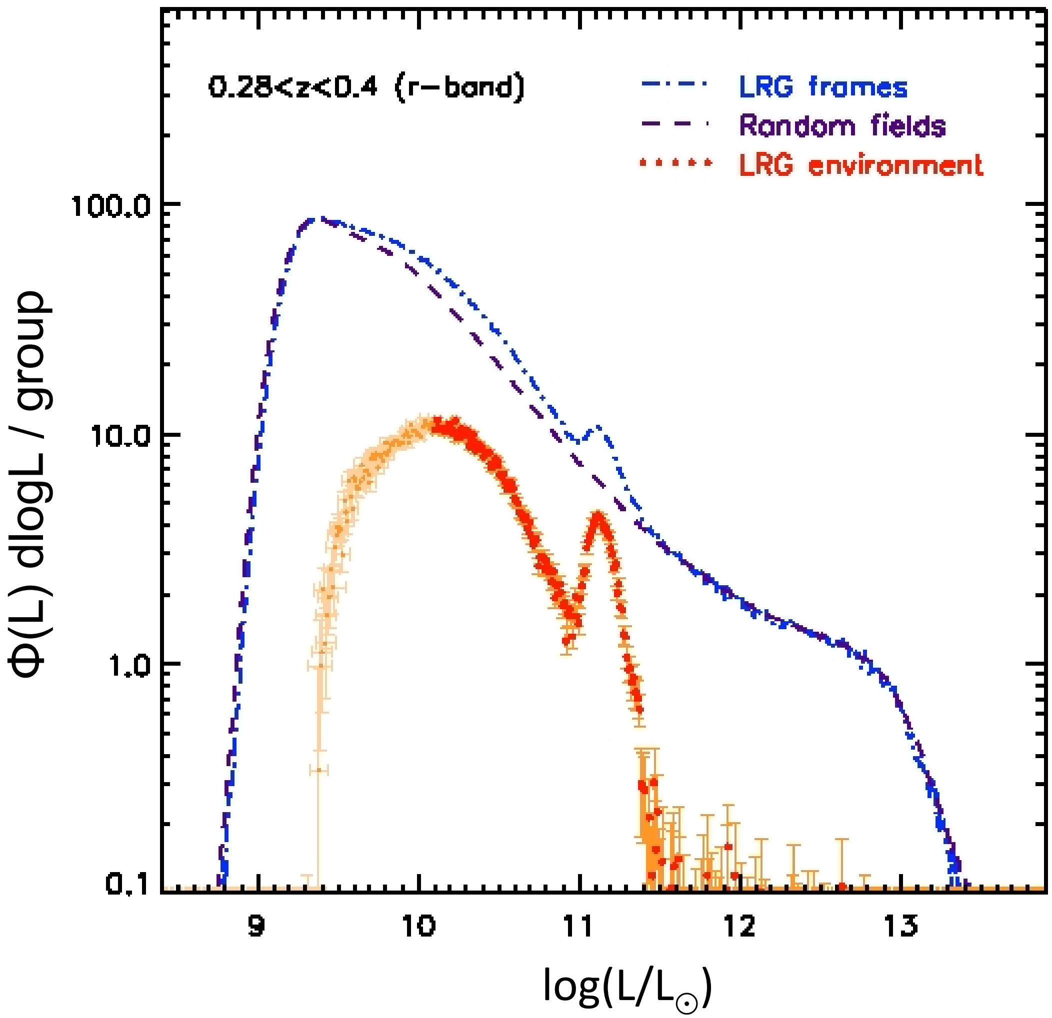
The luminosity function of satellite galaxies

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



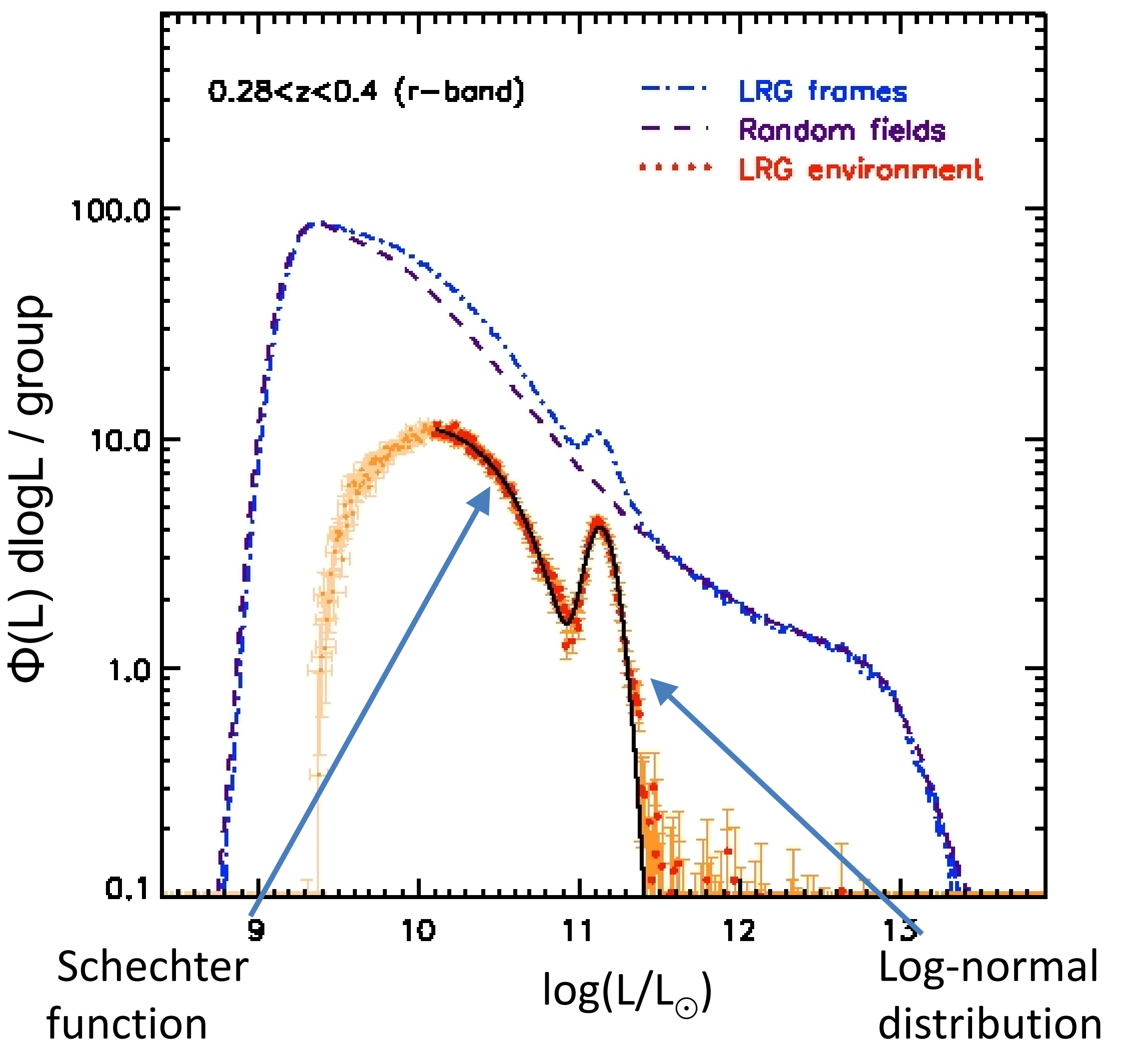
The luminosity function of satellite galaxies

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



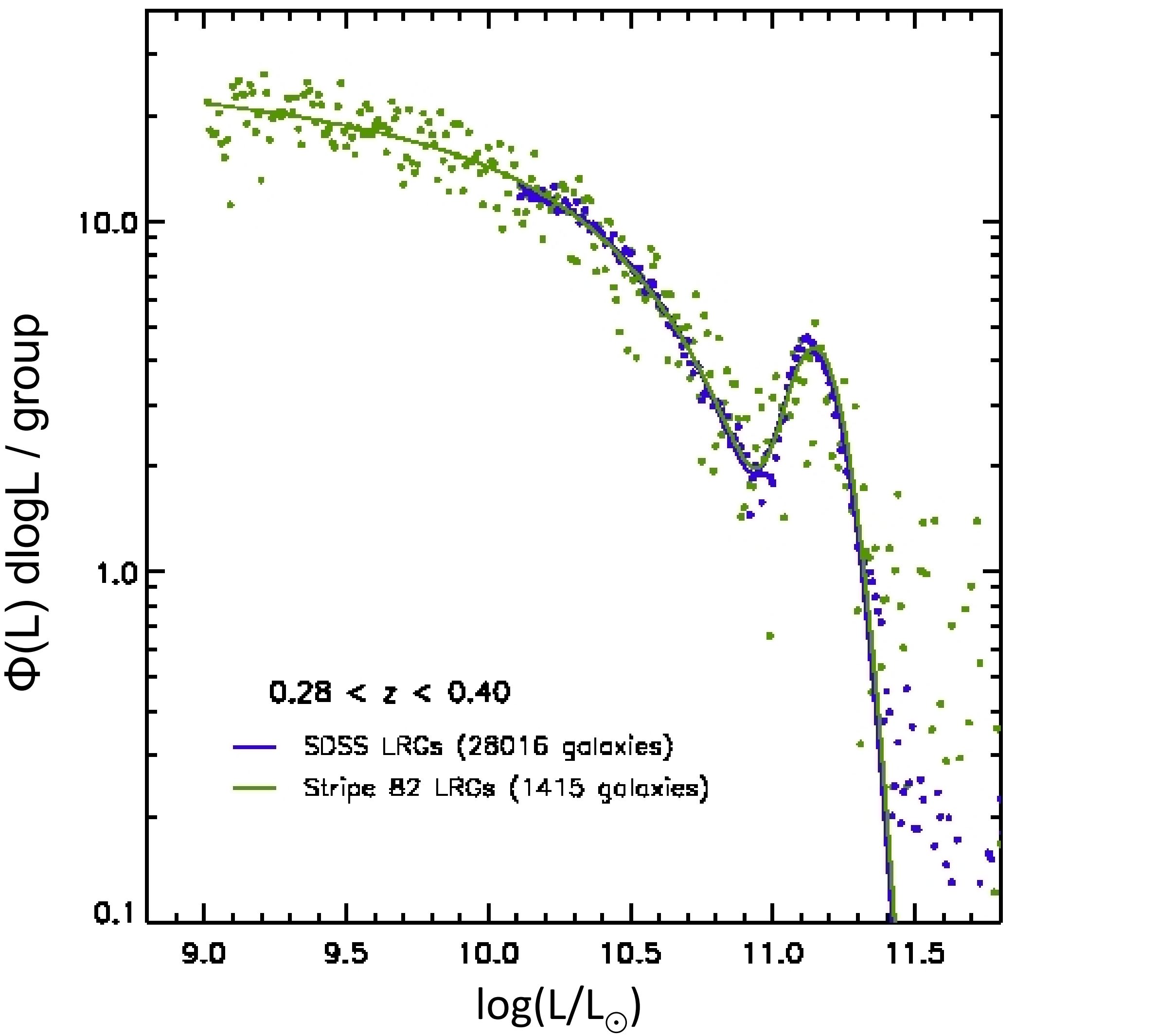
The luminosity function of satellite galaxies

- Measure luminosity distribution in LRG fields
- 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

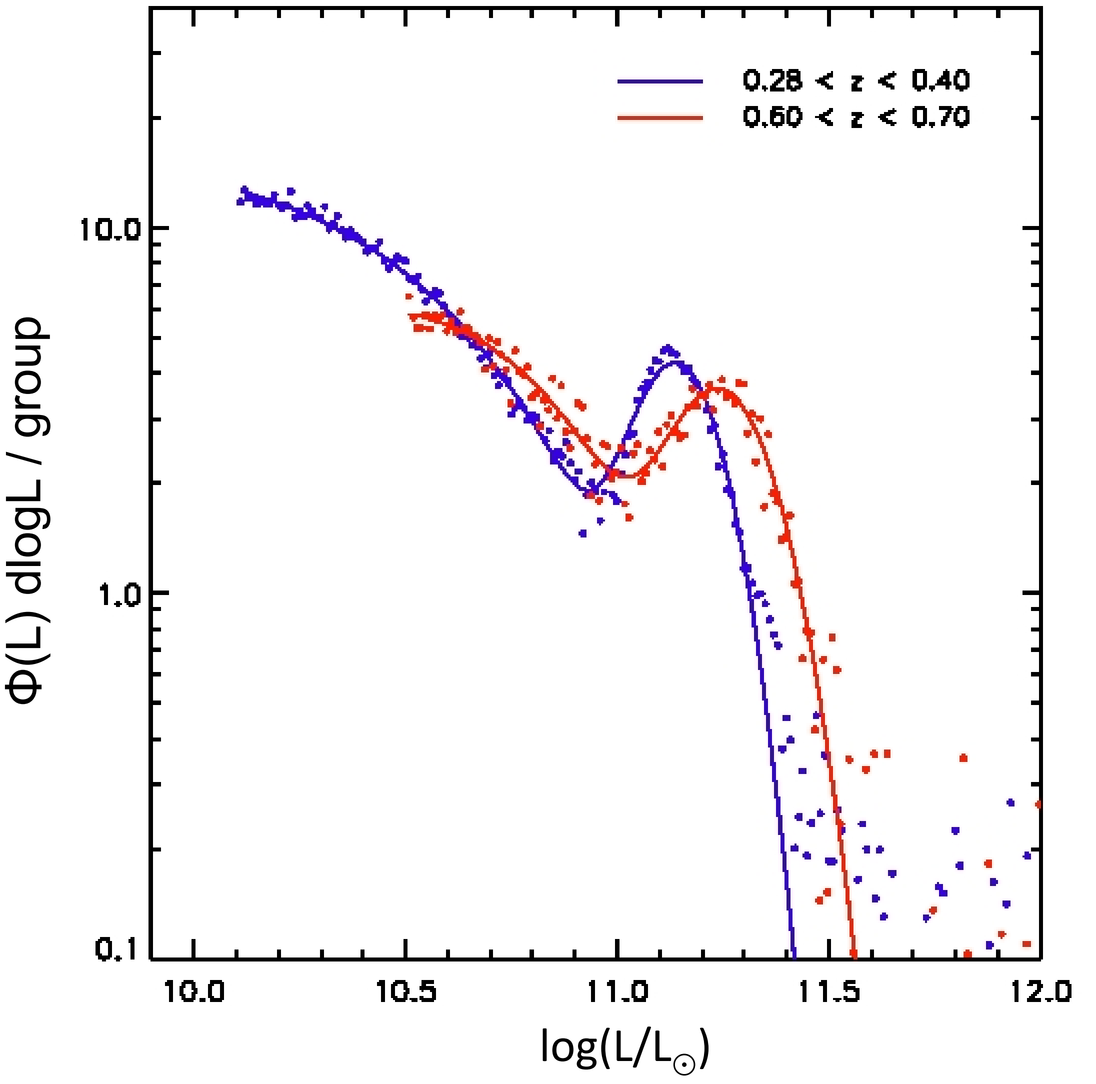
- Width measurement:

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

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

at both redshifts

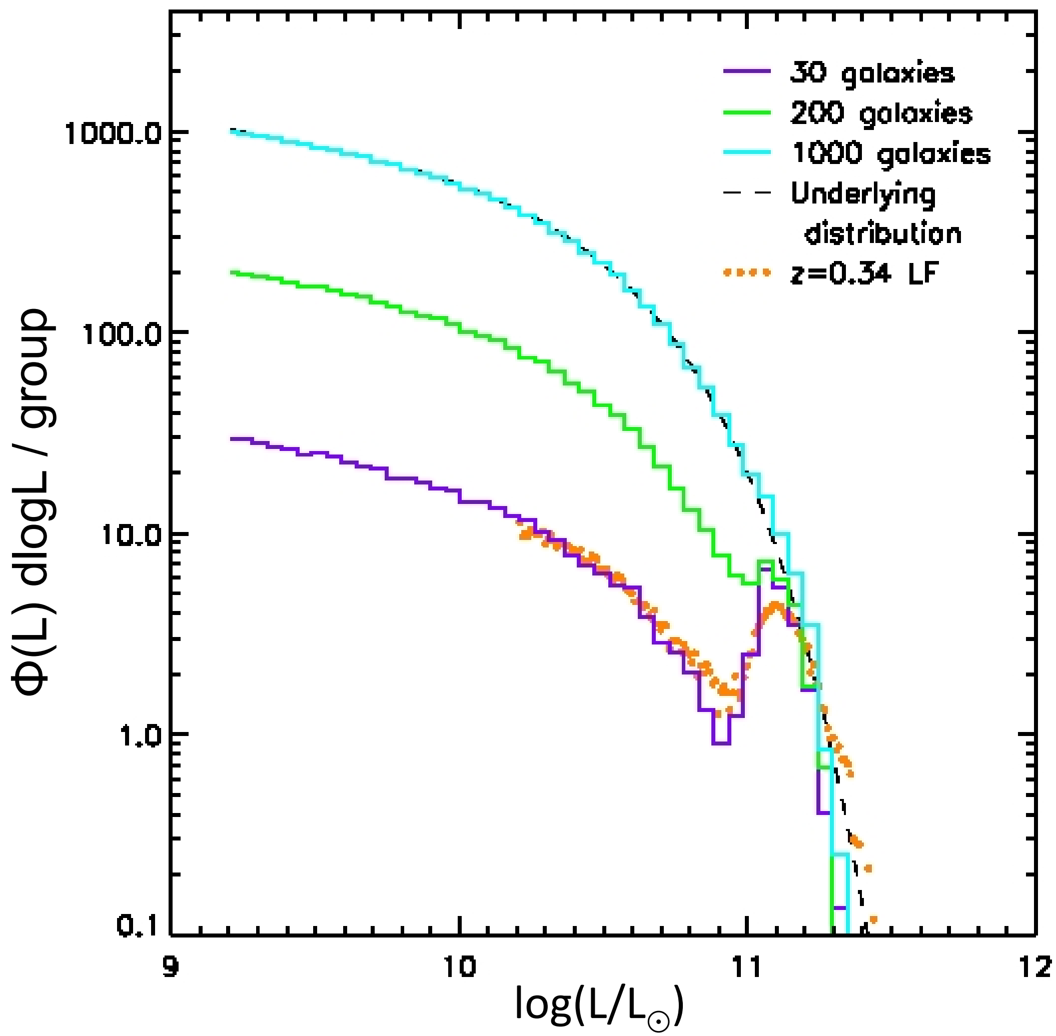
- LRG peak consistent with passive luminosity evolution



Selection and the gap

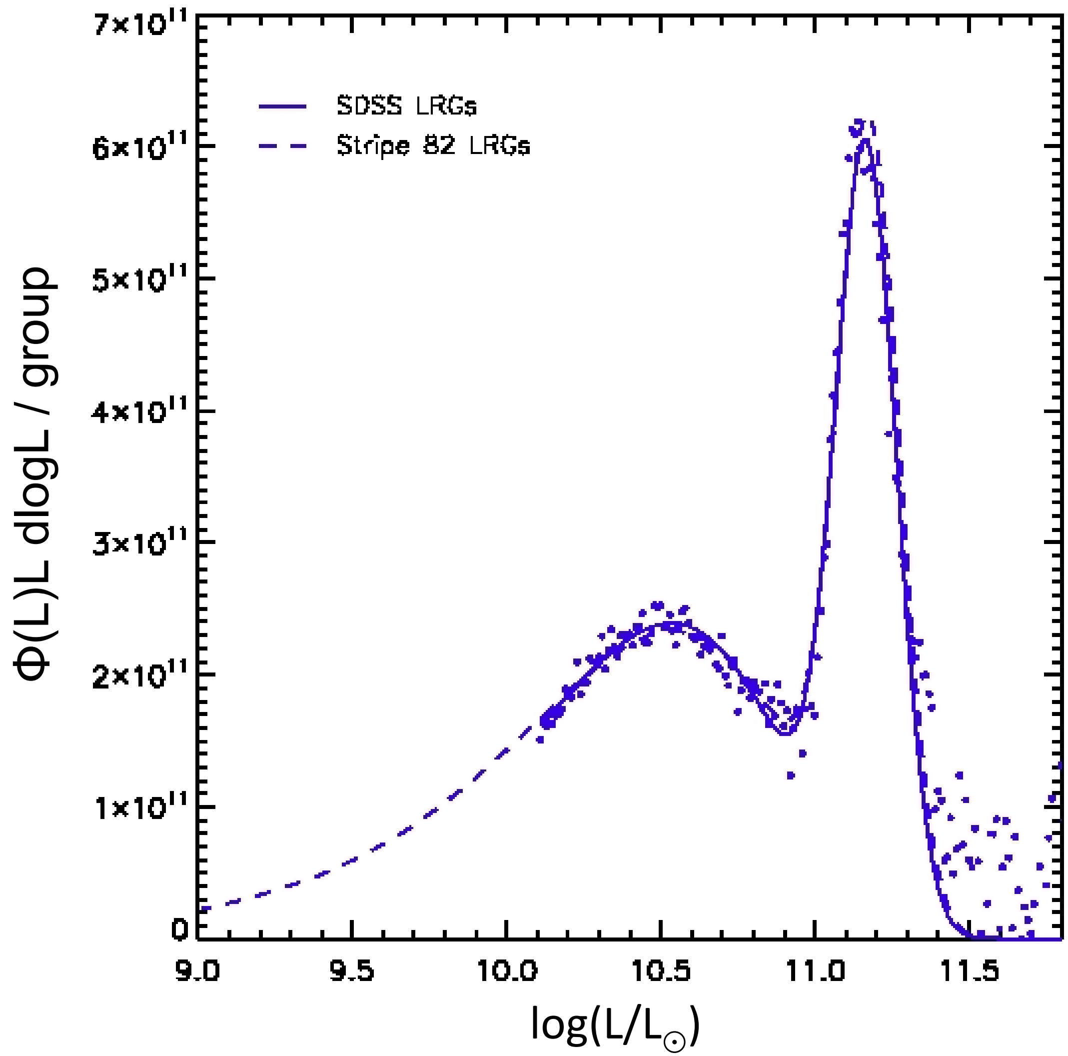
- Gap can be reproduced by randomly sampling a Schechter distribution

- Underlying luminosity distribution may not be unique



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**



The radial distribution of satellite galaxies around LRGs

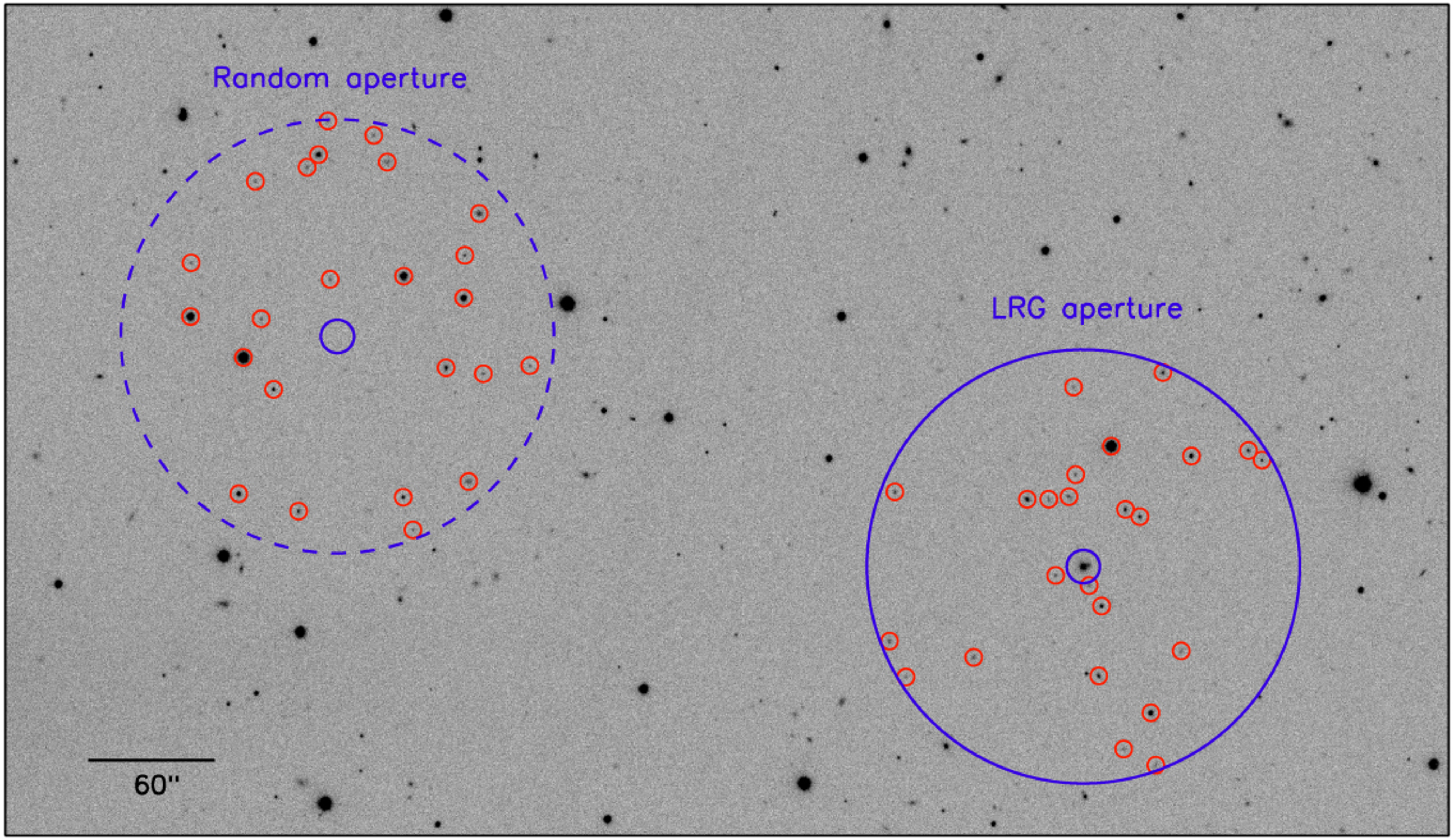
DARK AND LUMINOUS MATTER: WHAT SATELLITE GALAXIES TELL US

Where do LRGs live

- Luminous matter is only part of the story
- Really need total mass – mostly dark matter

- Cluster/group observations of dark matter are difficult
  - X-ray, lensing, clustering
- Alternative – satellite galaxies as tracers of mass
  - Already have that!

Method



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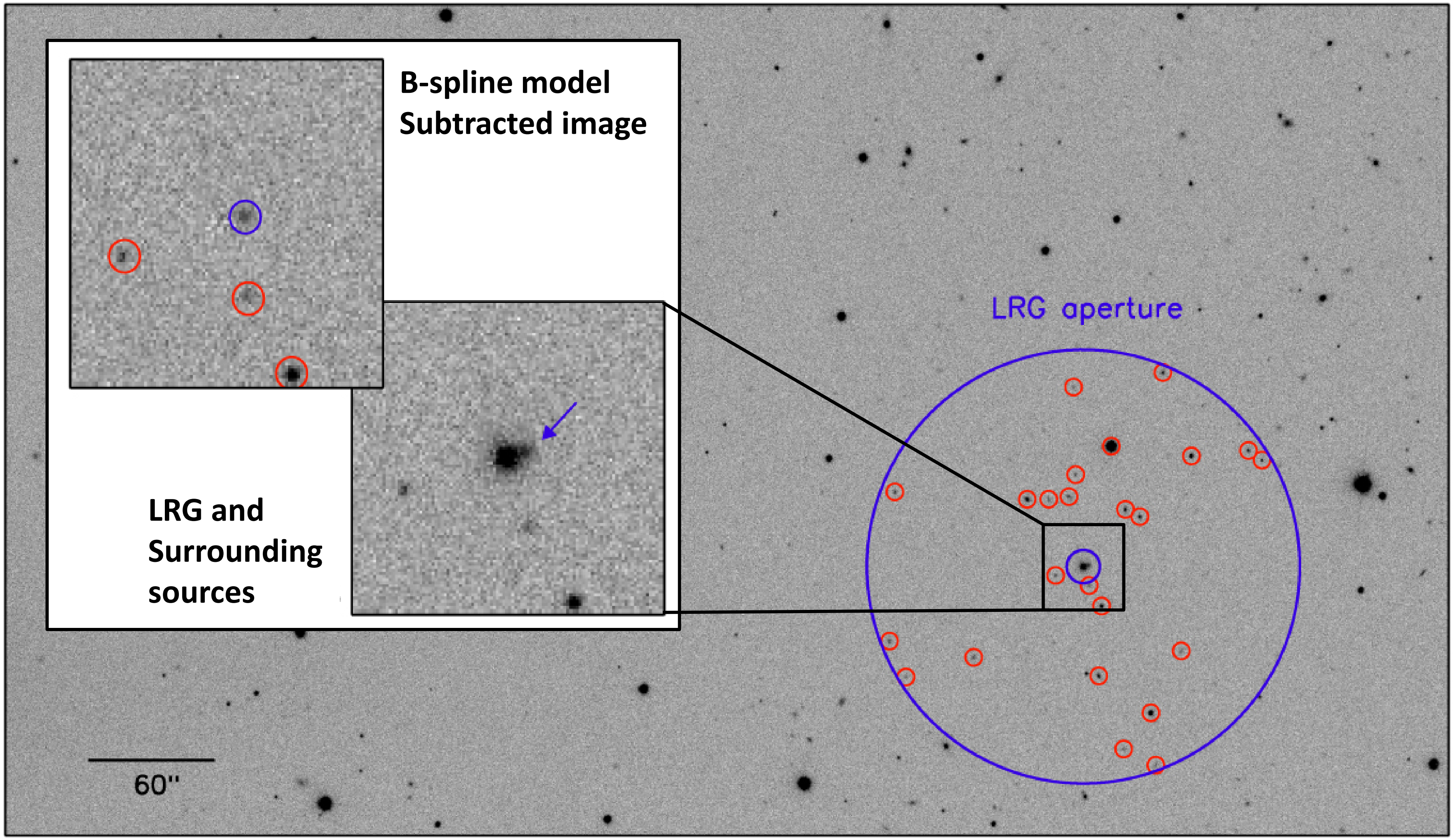
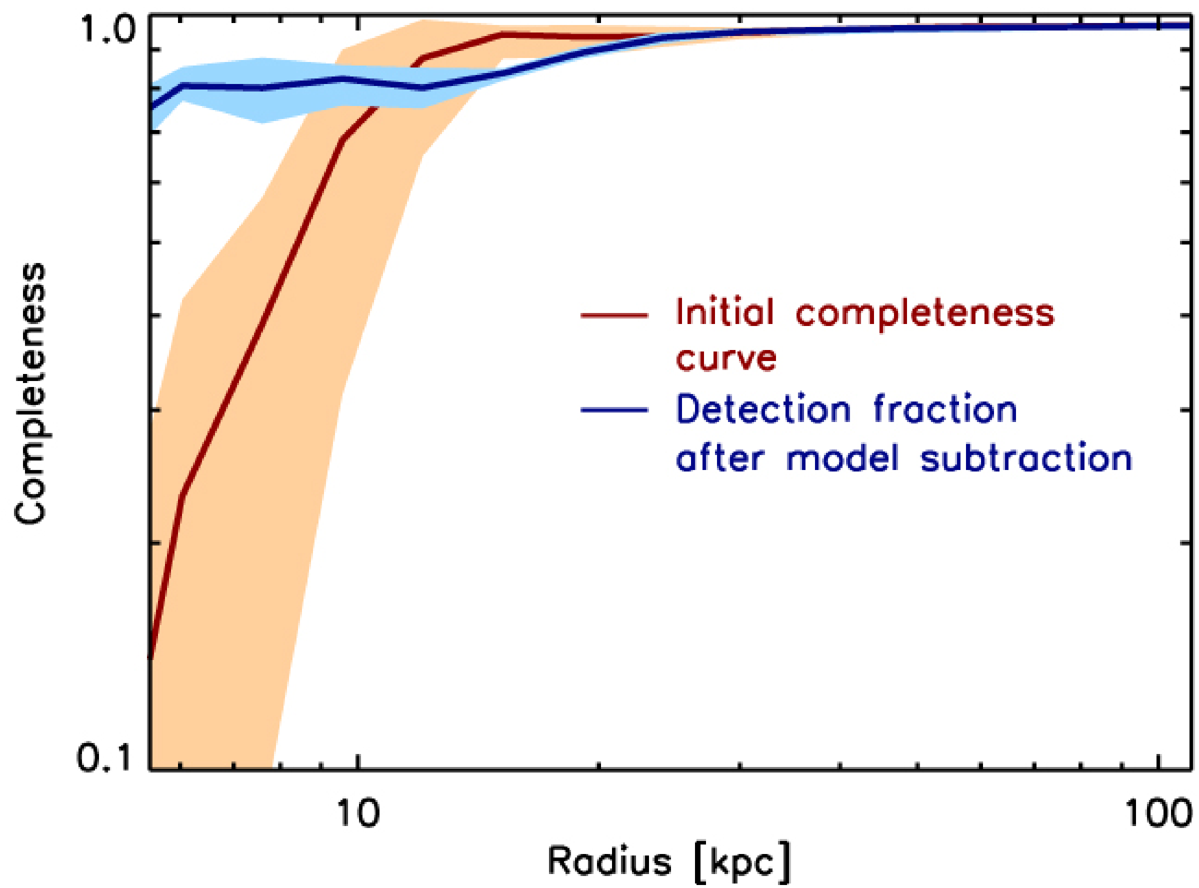

B-spline model
Subtracted image
LRG and
Surrounding
sources
LRG aperture
60"

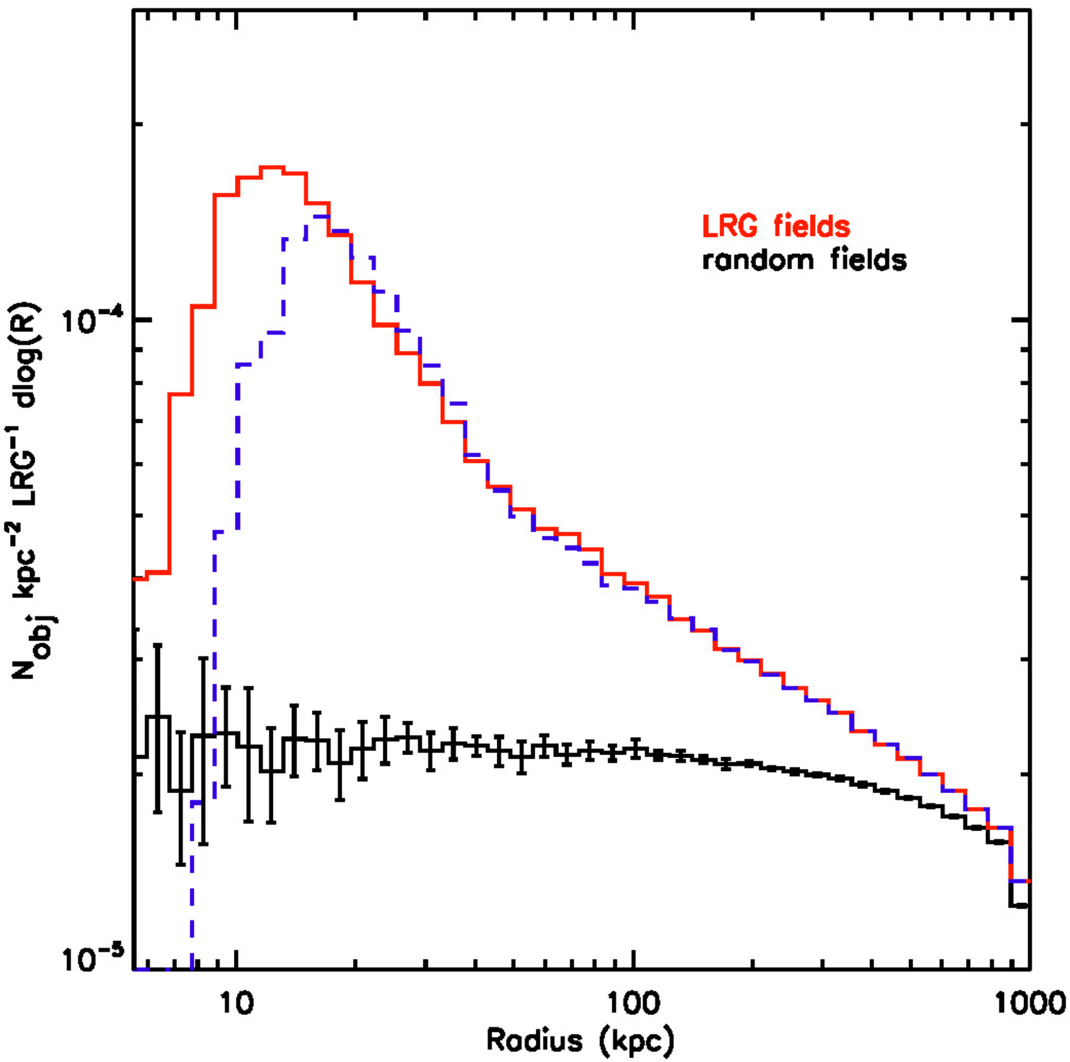
Completeness

- Radial, 4th order B-spline model fitting (Bolton+06)
- Improved source detection well inside of 10 kpc



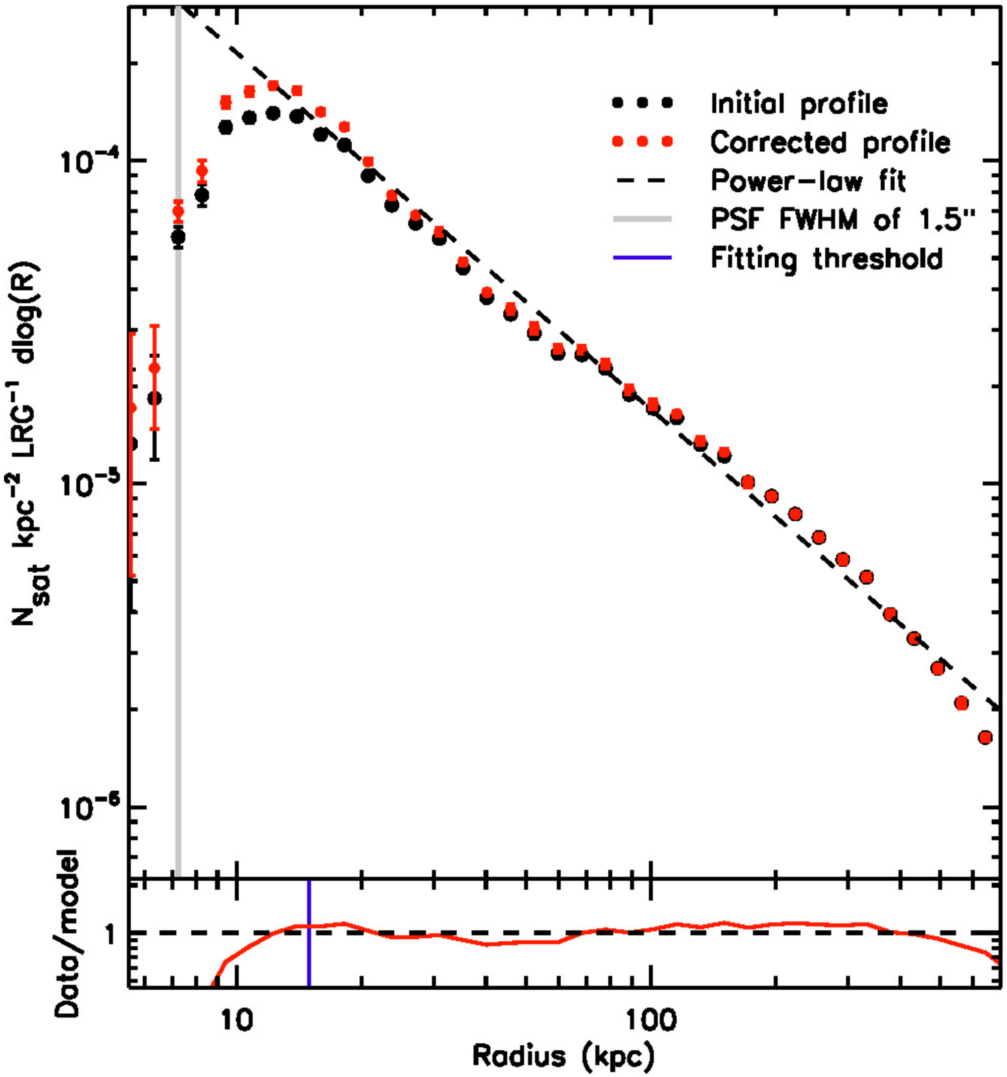
Radial binning

- Combine measurements from 28,000 fields
- Radial distribution of sources in LRG and random apertures



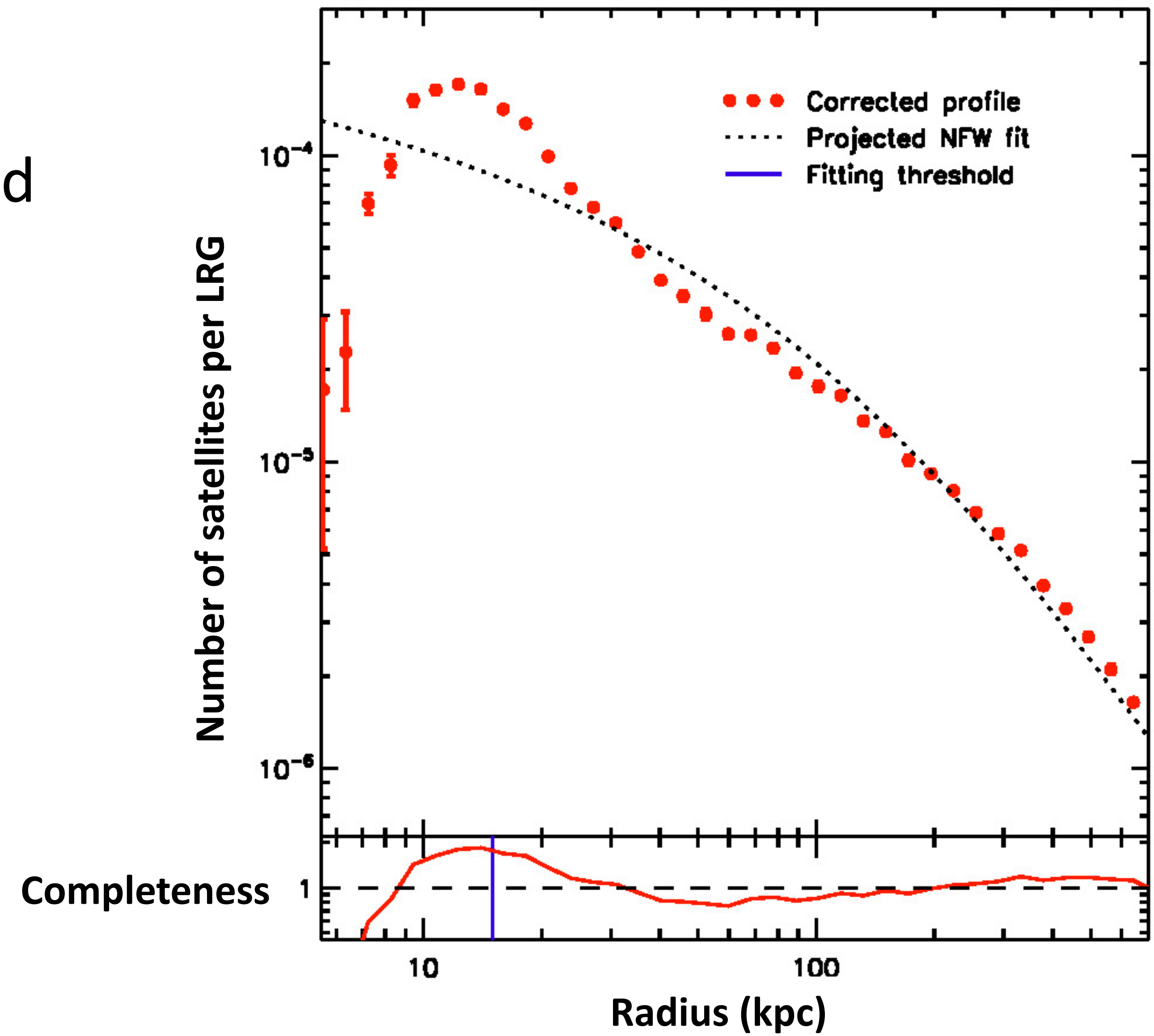
Radial profile of satellite galaxies

- Foreground and background subtracted profile –> satellite galaxies
- Profile confidently traced in the range 7<r/kpc<700
- Power-law model fit



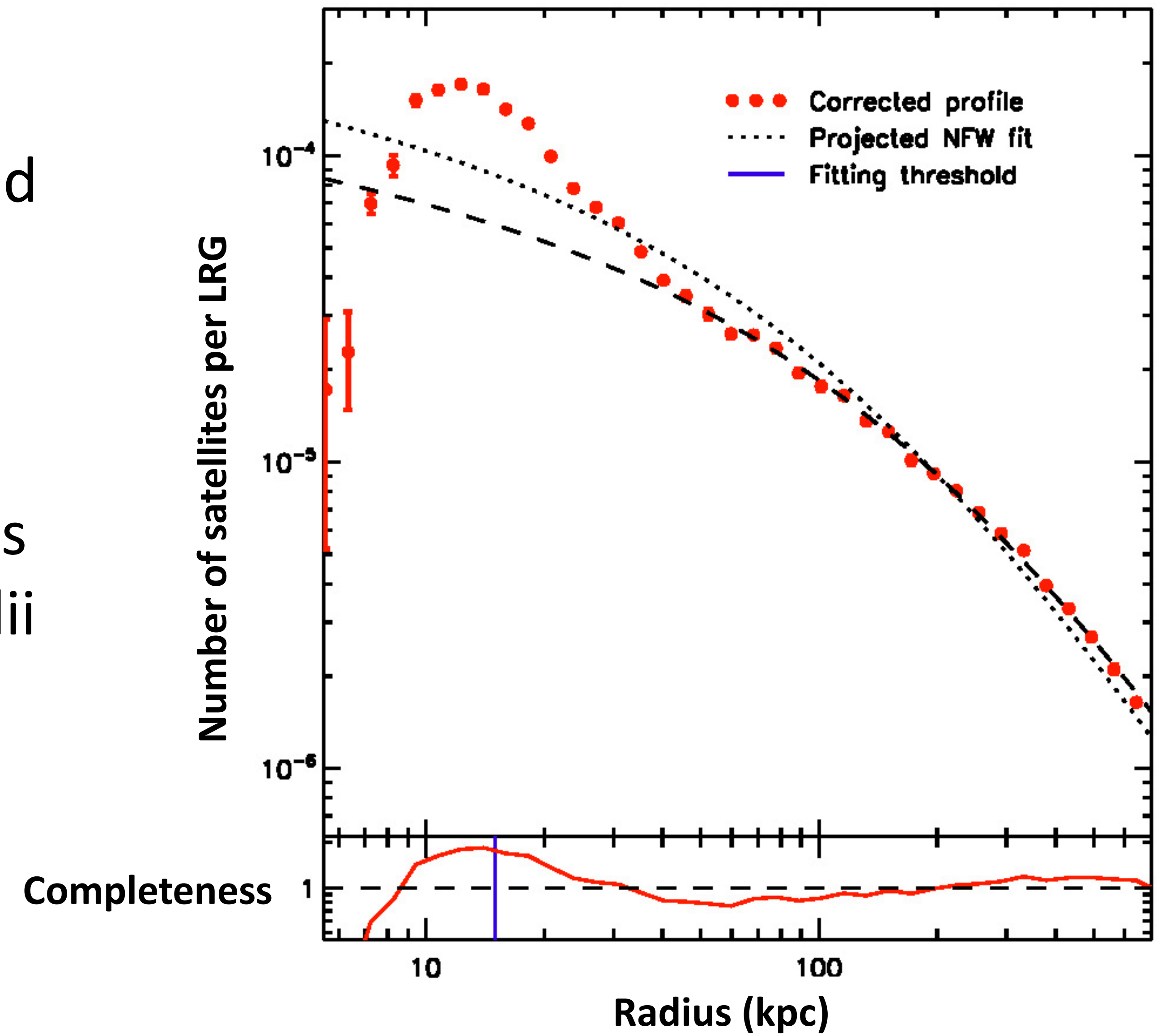
NFW model fit

- Overall well fitted by NFW

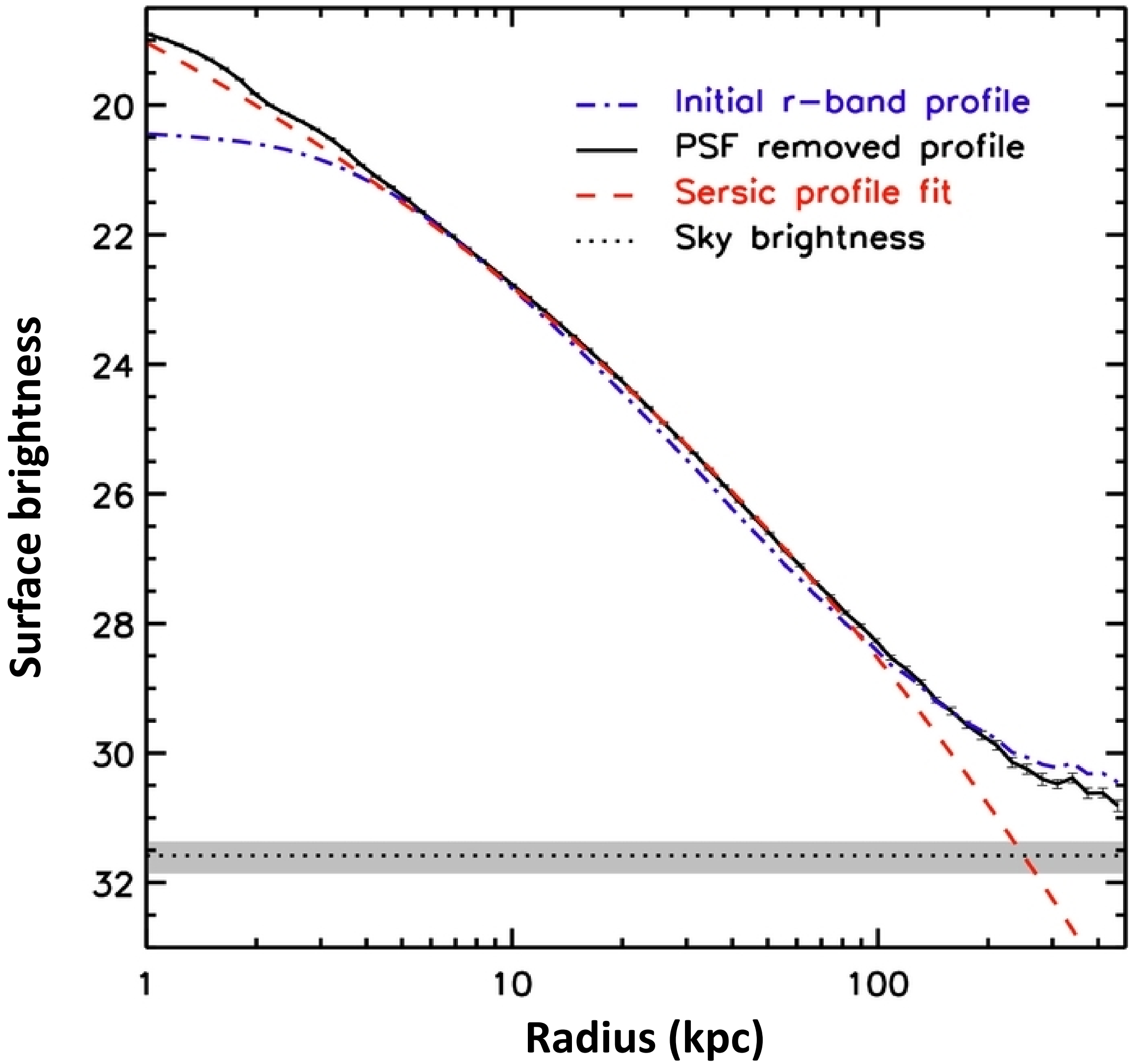


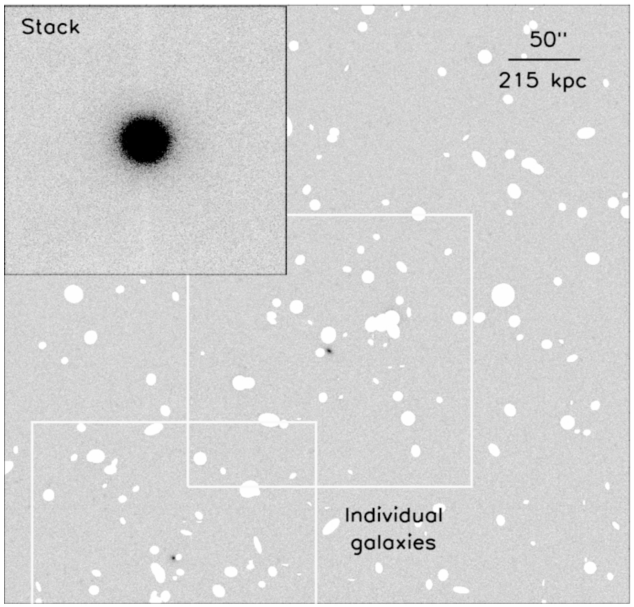
NFW model fit

- Overall well fitted by NFW
- Very good fit at large radii
- Significant excess at very small radii



Stellar light profile

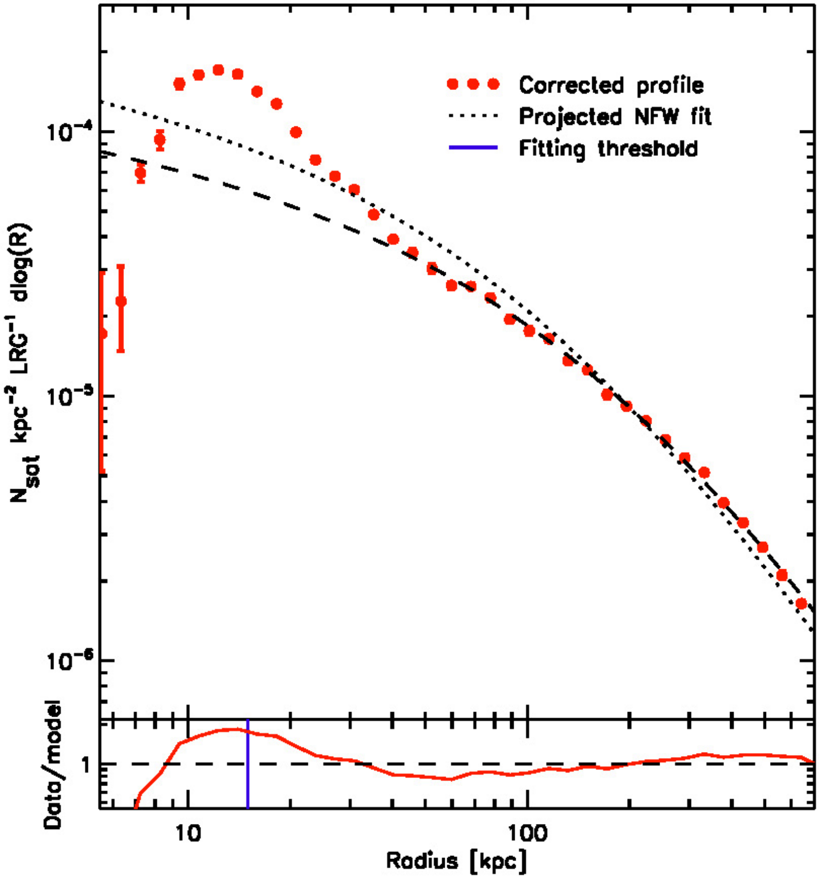


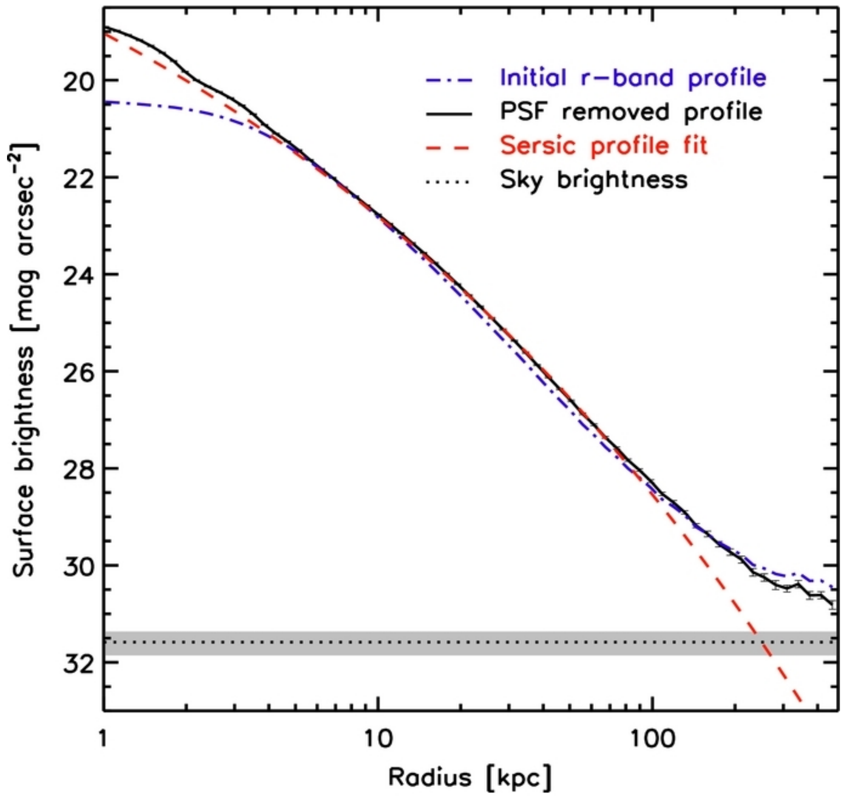


Taken from a stack of >40k LRG images at same redshift

(Tal & van Dokkum 2011)

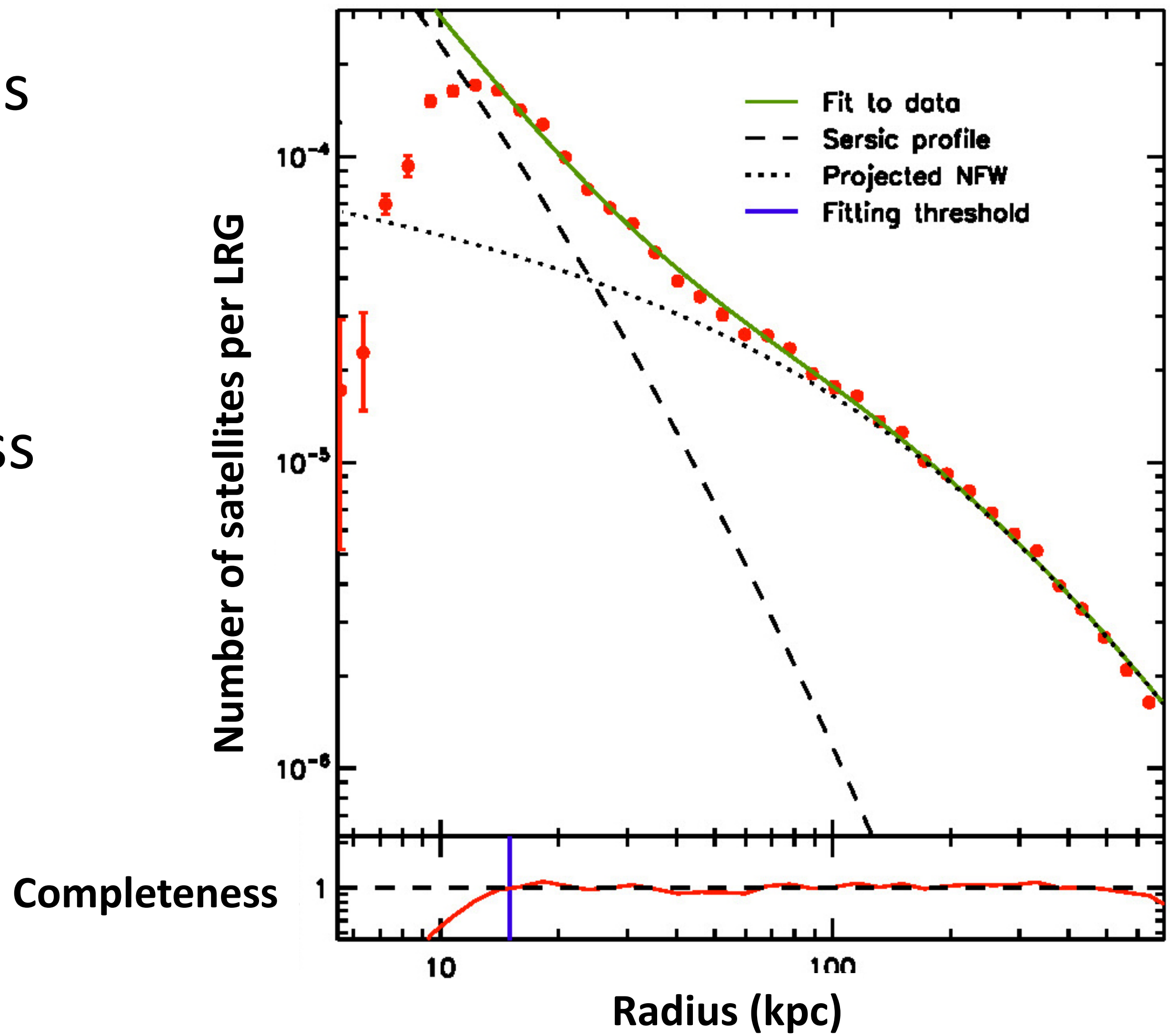
Luminous and dark mass profile





Small radii excess

- Fit to NFW+Sersic is excellent on all scales
- Consistent with Dark/baryonic mass ratio of ~80 – consistent with weak lensing measurements



Summary

- Detailed analyses using statistical tools
  - Deep stacks
  - Satellite properties and distribution
- Evolution overall consistent with growth through minor mergers
- LRGs are unique – super massive for their halos
- Next (HSC survey?)
  - Satellite galaxy properties
  - Range of central galaxy masses, colors etc.