Cosmology With Optically Selected Galaxy Clusters: Looking Forward to DES

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In Collaboration with:
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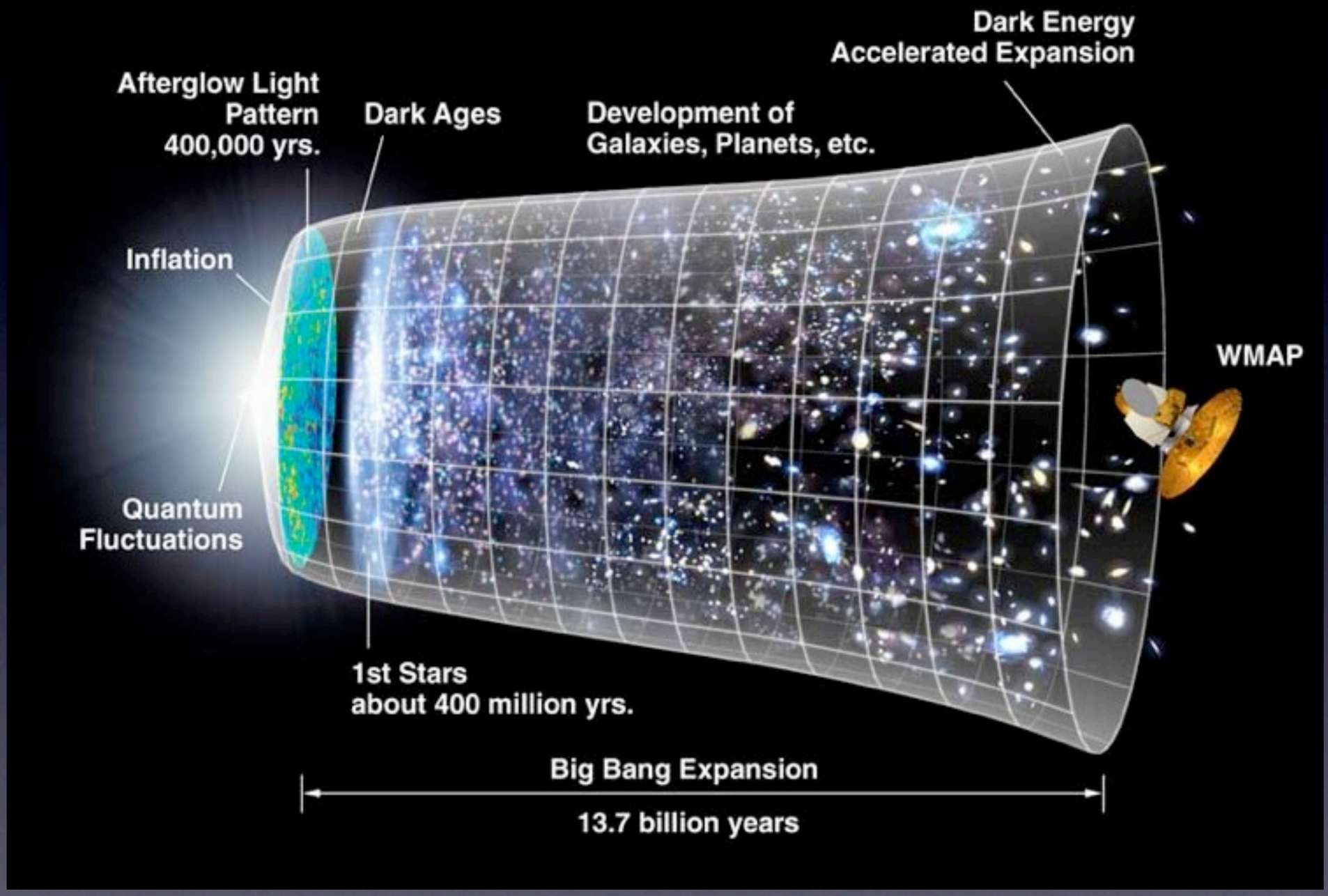
Outline

- Galaxy Clusters as Cosmological Probes
- Optical Cluster Cosmology at z<0.3
  - Cross-Correlation and the power of stacks (SDSS + ROSAT)
- Higher redshifts with DES
- Dealing with systematics: cluster richness estimation & centering
- Cluster finding and red galaxy photometric redshifts with redMaPPer

In the beginning...



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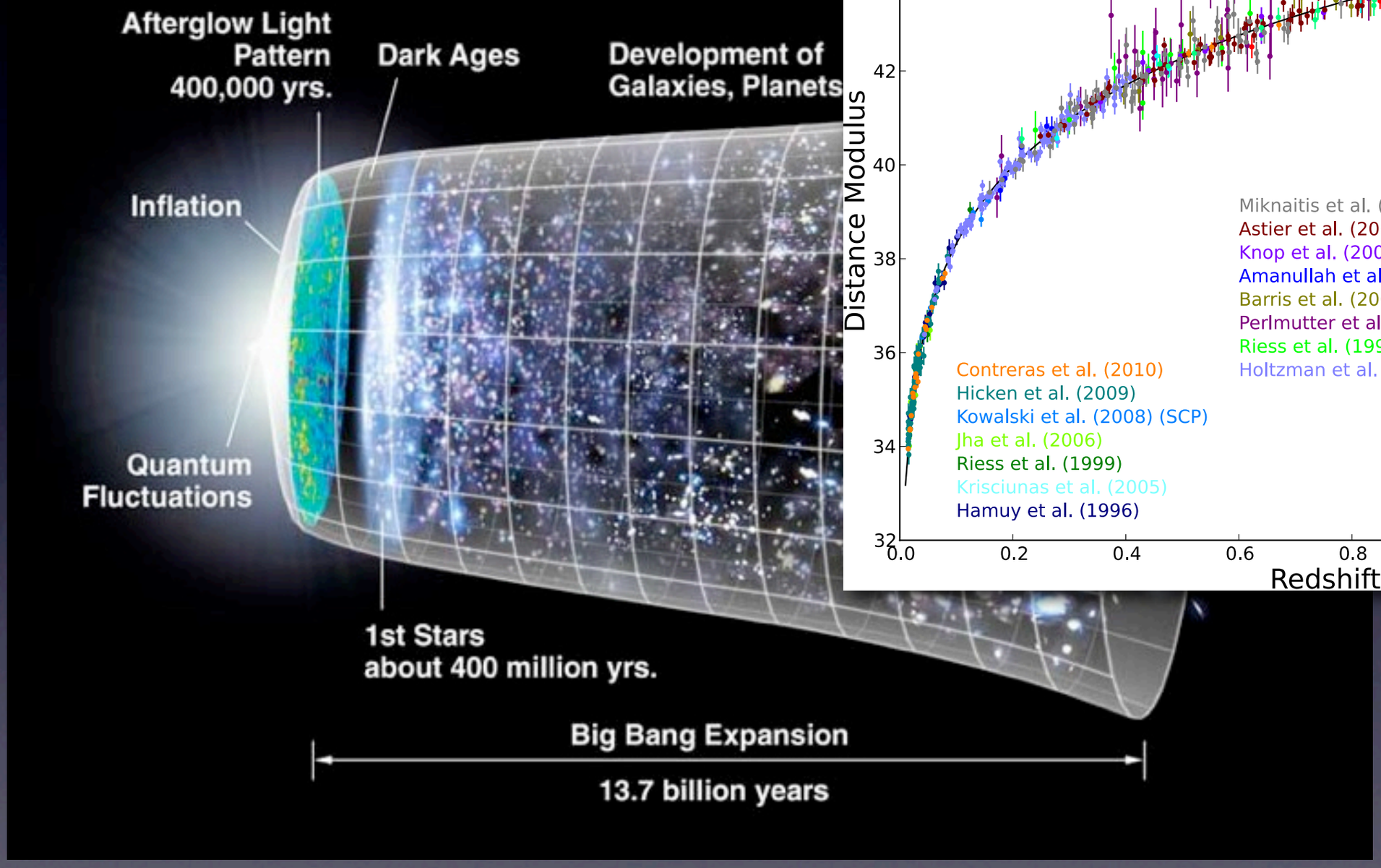

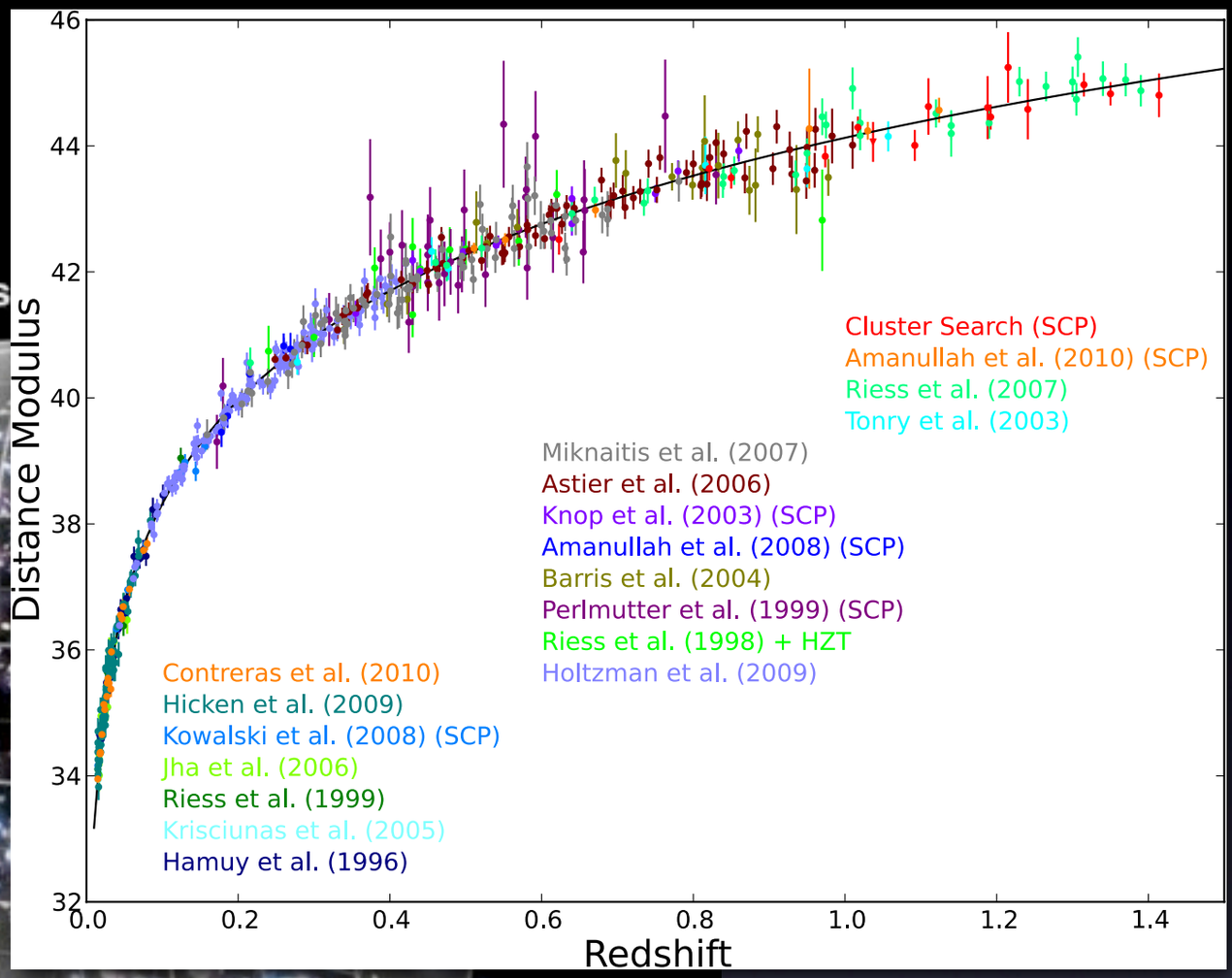

Suzuki+11

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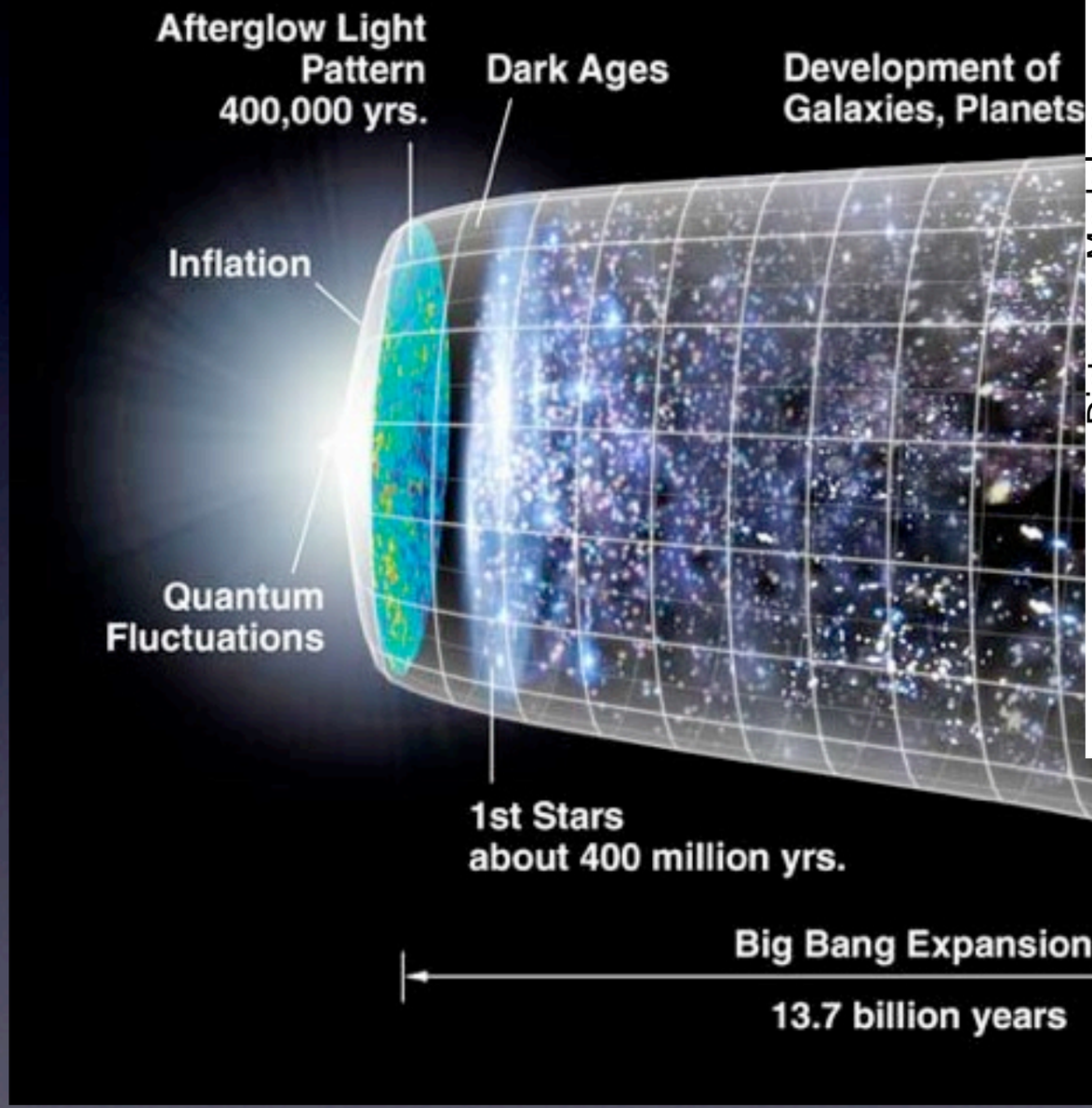
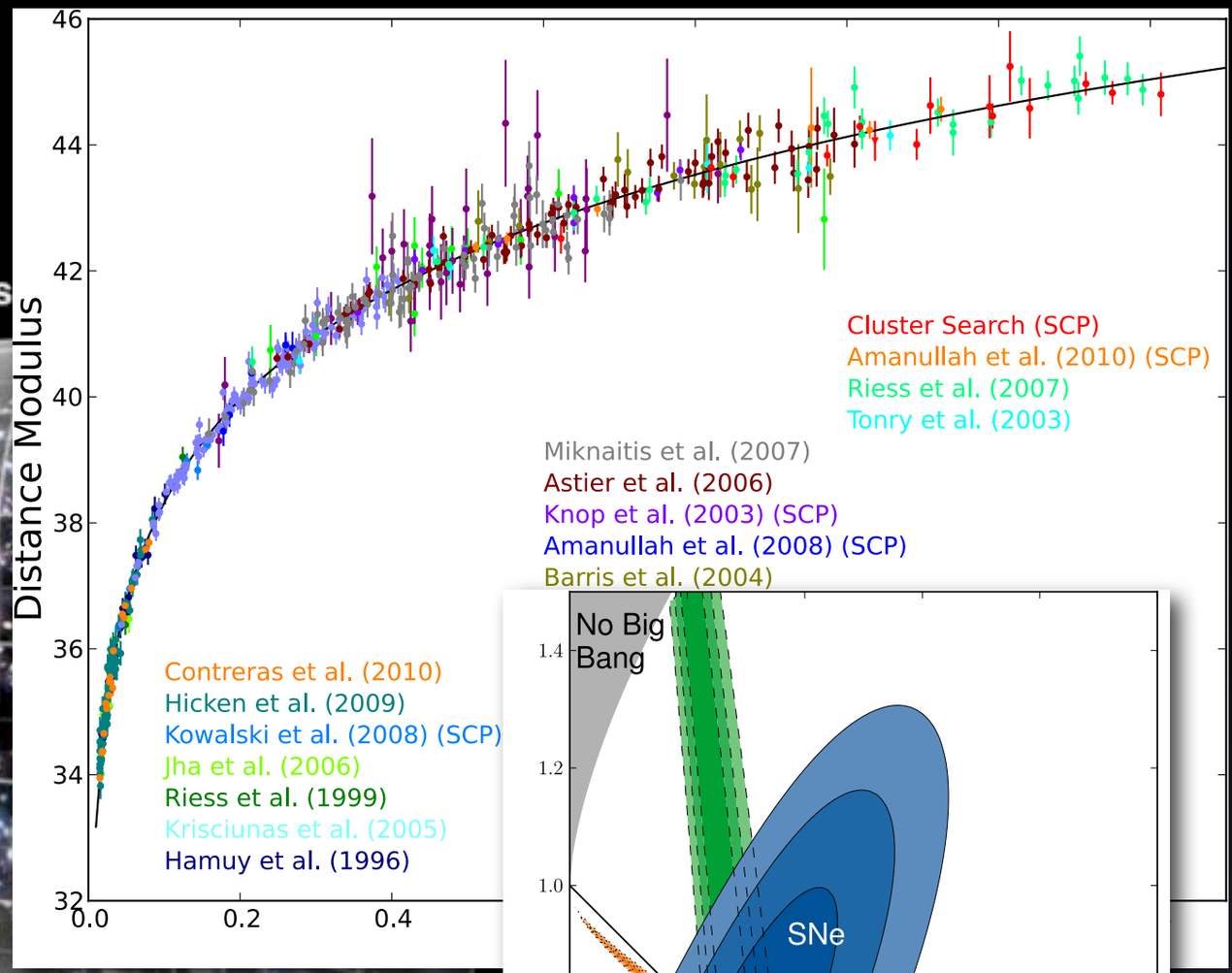
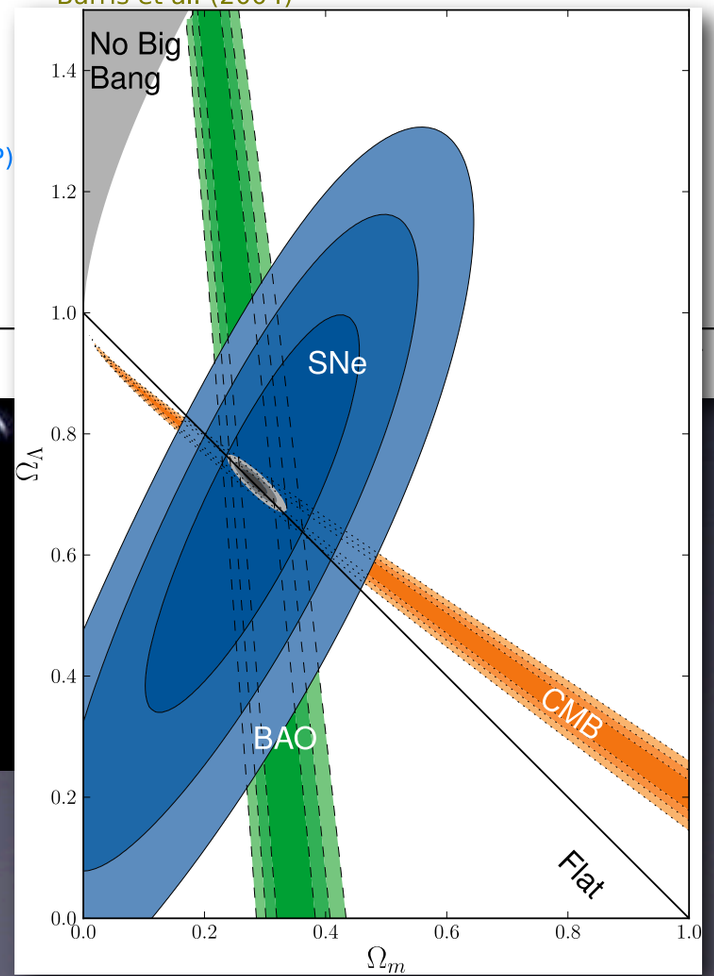
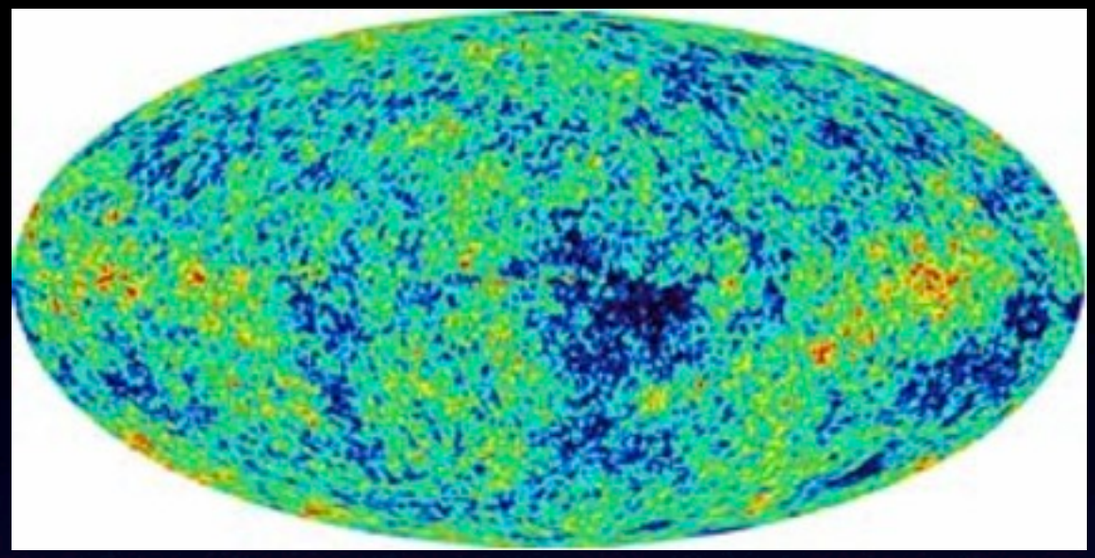




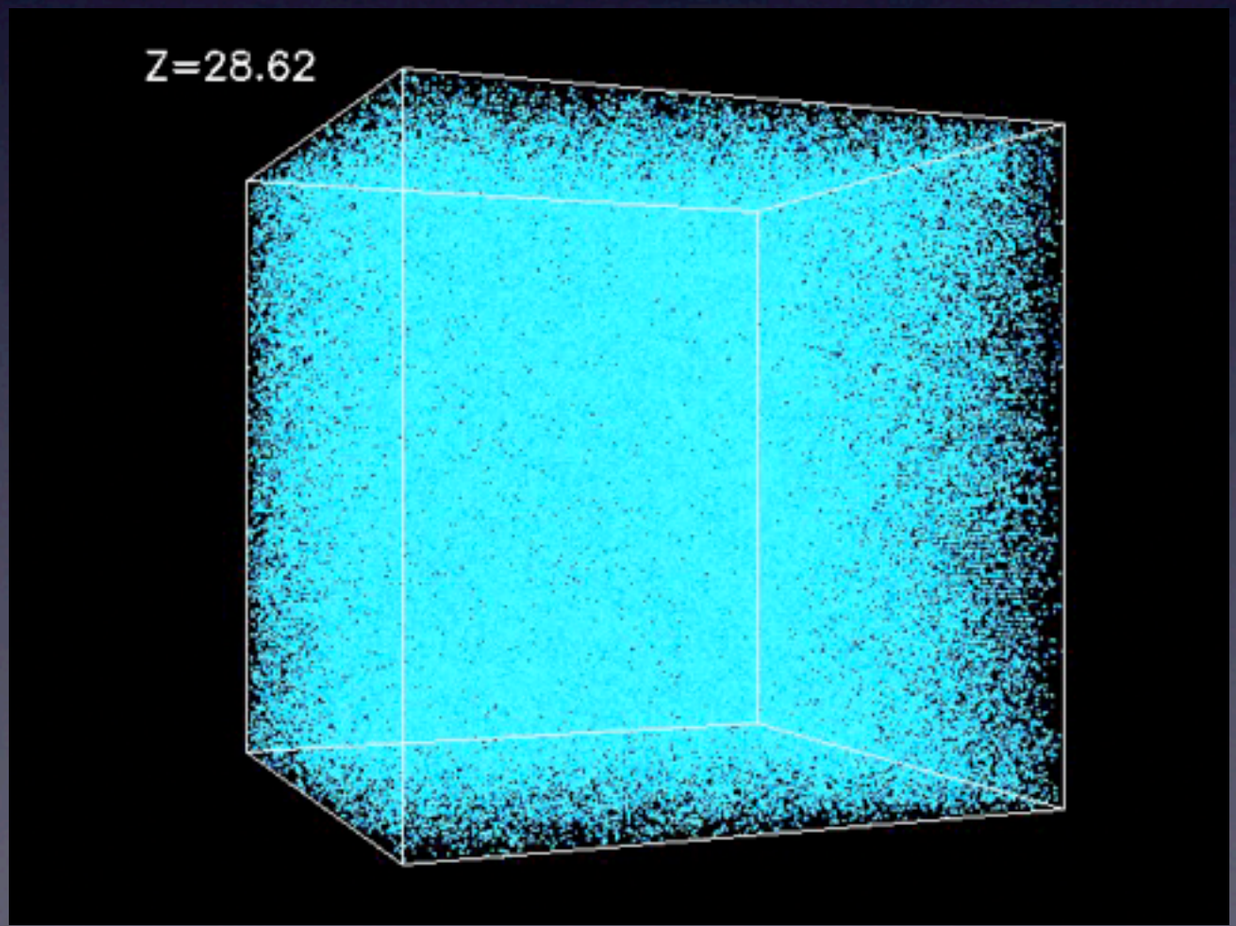


Structure Formation

- Initial fluctuations detected in the cosmic microwave background
- Growth of structure determined by cosmological parameters Ω_m and Ω_Λ (in ΛCDM)
- Predictions for the dark matter distribution are precise and robust



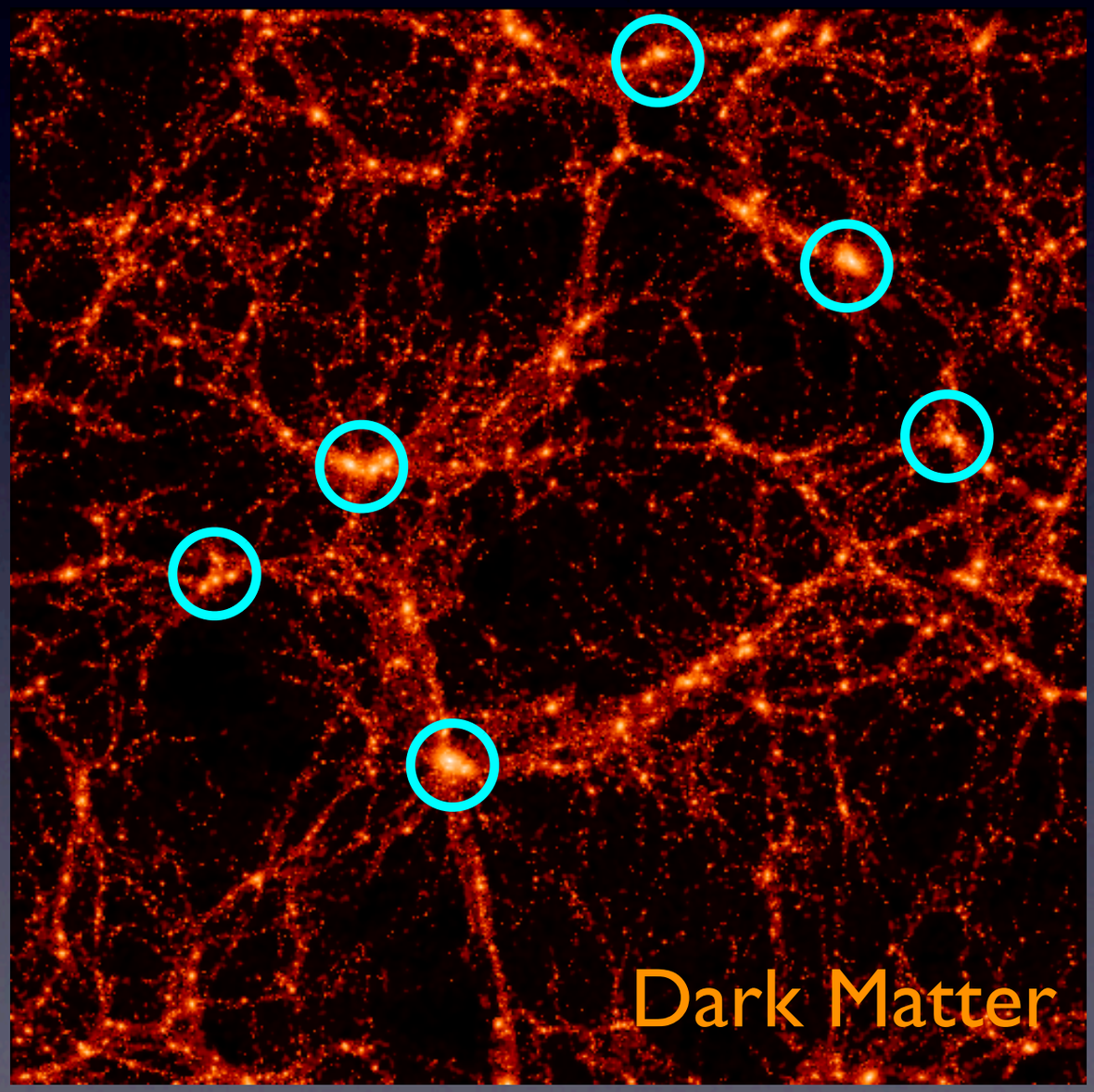
CMB from WMAP



Simulation from Andrey Kravtsov

Dark Matter Halos

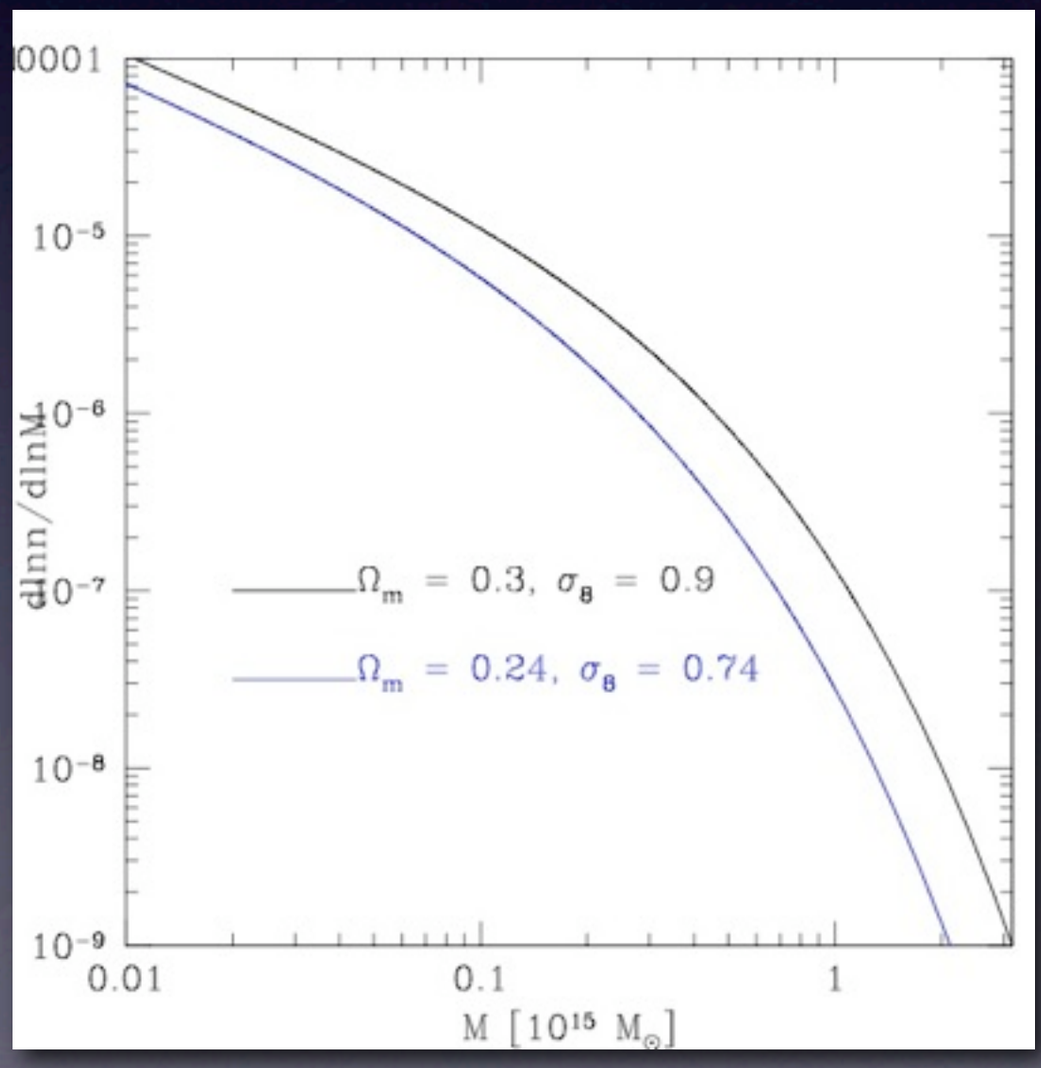
- Dark matter halos are large peaks in the matter density
  - Find the peaks on a chosen scale
  - r_{200}, radius of a sphere with mean density $200\rho_{crit}(z)$
- We see these halos because they are lit up by luminous baryons



Virgo Consortium HV sims

Halo Mass Function

- Number of halos as a function of mass and redshift: $n(M,z)$
  - Predicted with simulations (e.g. Tinker+08)
  - Shape and normalization sensitive to cosmology
- M_{200}: mass within a sphere of radius r_{200}
- Mass function depends on cosmological parameters including Ω_m, Ω_Λ, and σ_8, the normalization of the power spectrum on an 8 Mpc scale



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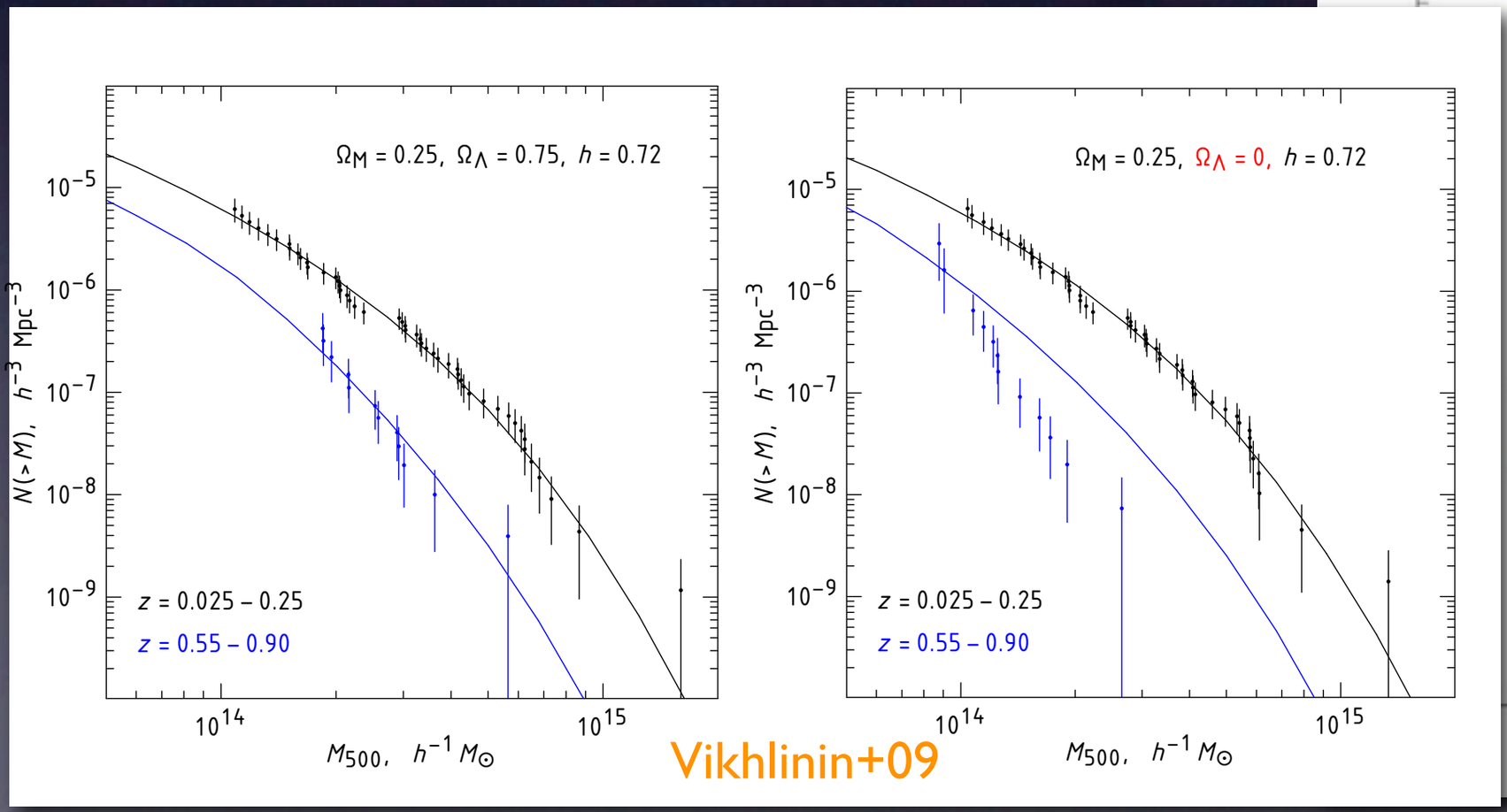
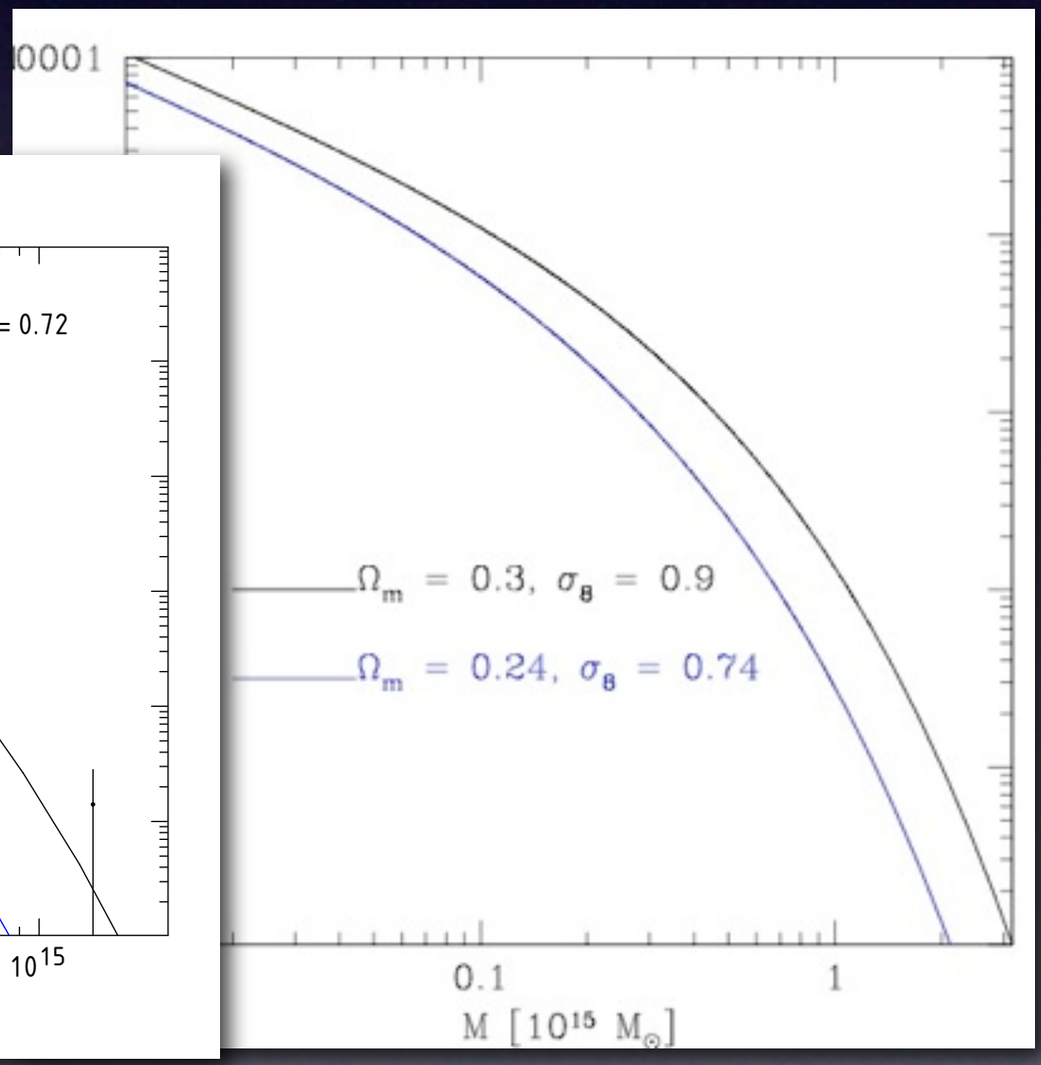


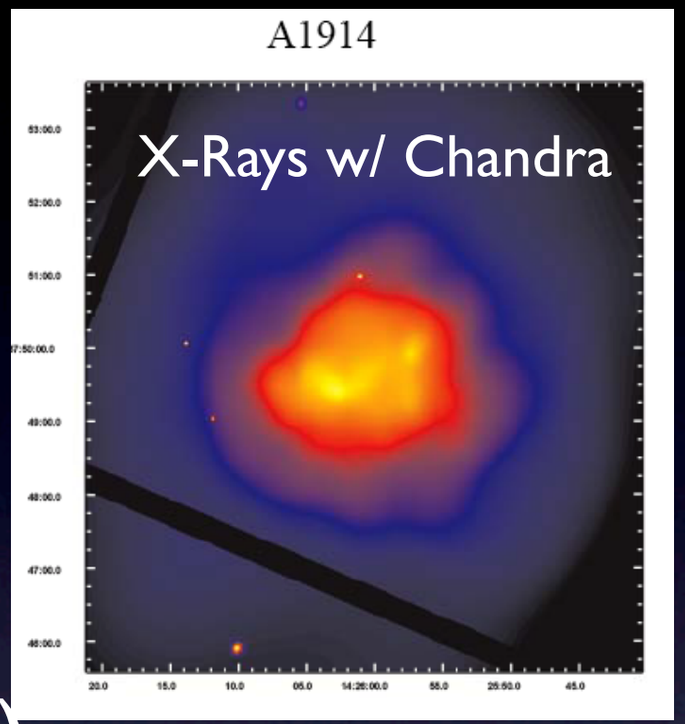
Vikhlinin+09



But...we have halos in the simulations, but clusters in observations

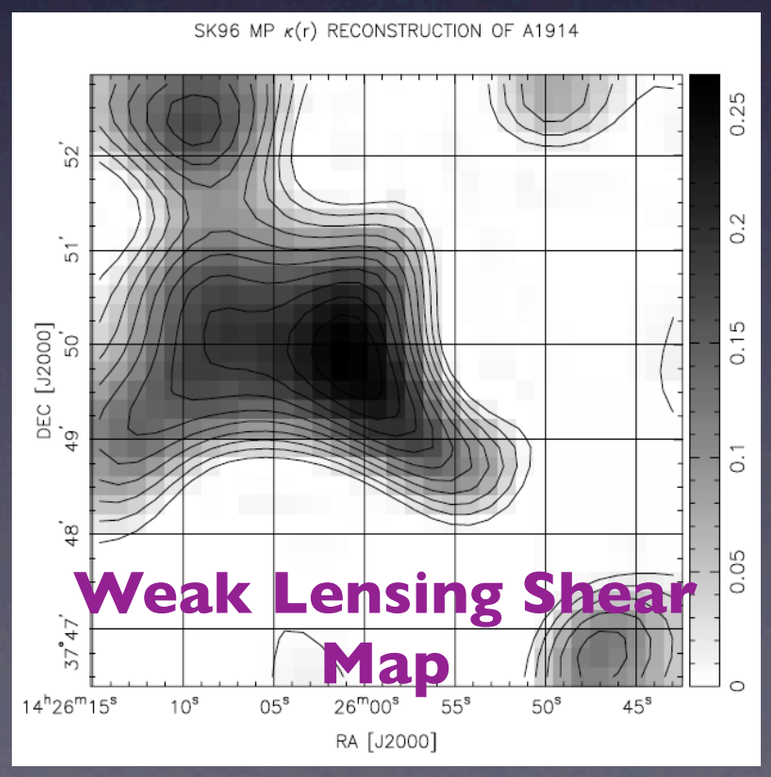
Abell 1914: Four Views

Cluster
of Galaxies
(~2% of mass)



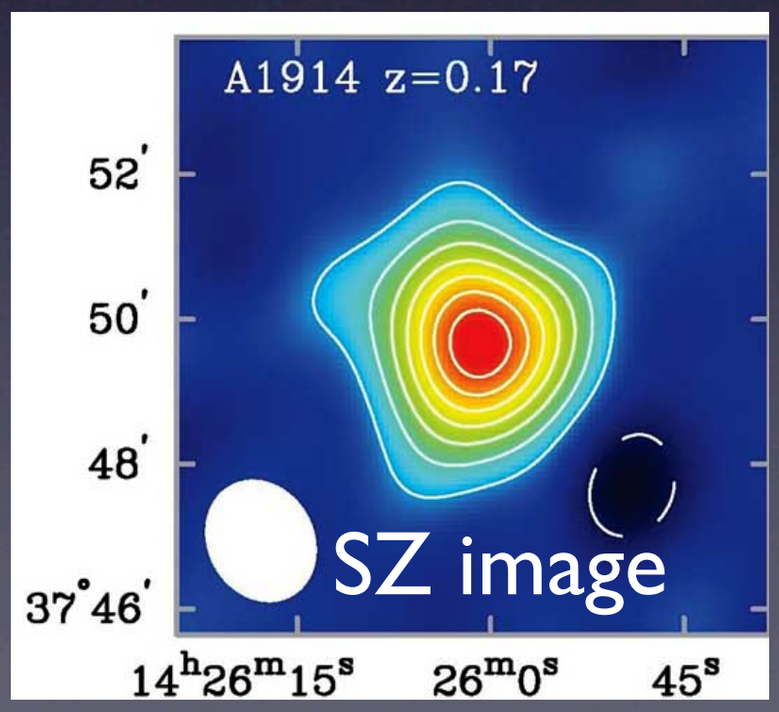
Jeltema+05

Ball of
Hot Gas
(~15% of mass)



Dahle+02

Dark Matter
Content
(~85% of mass)



Carlstrom+02

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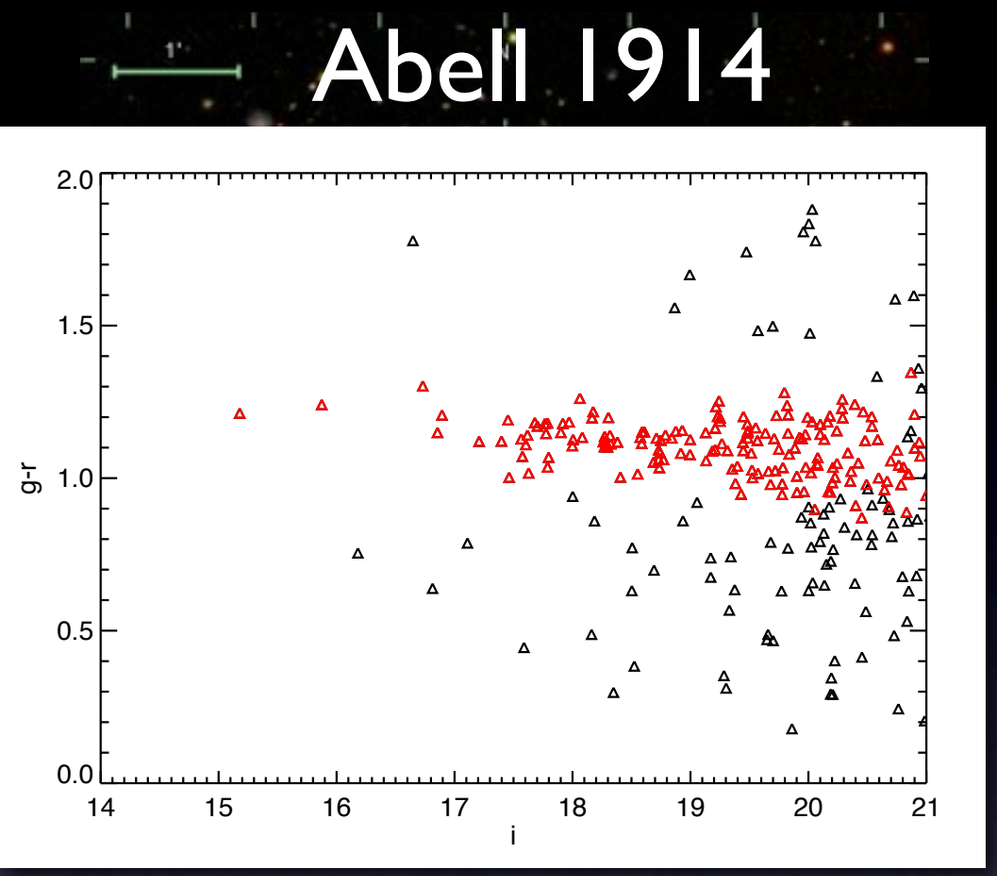

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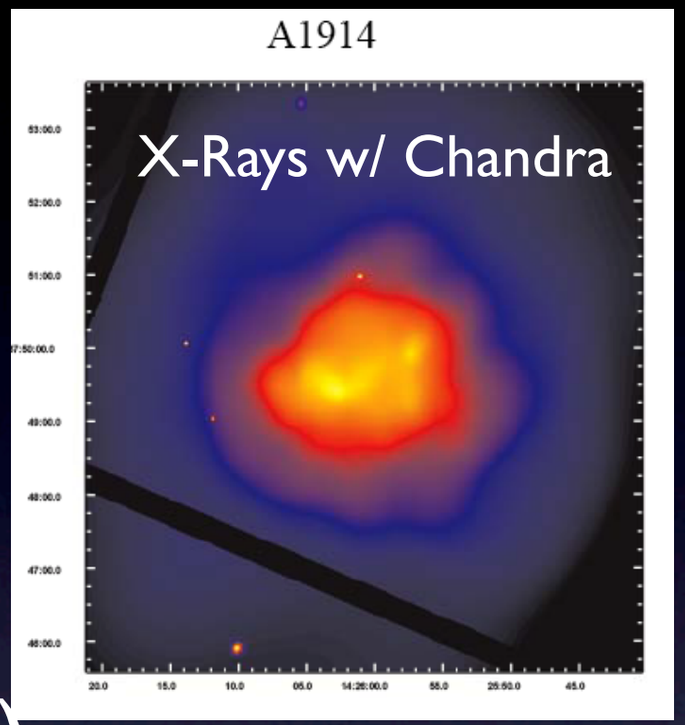

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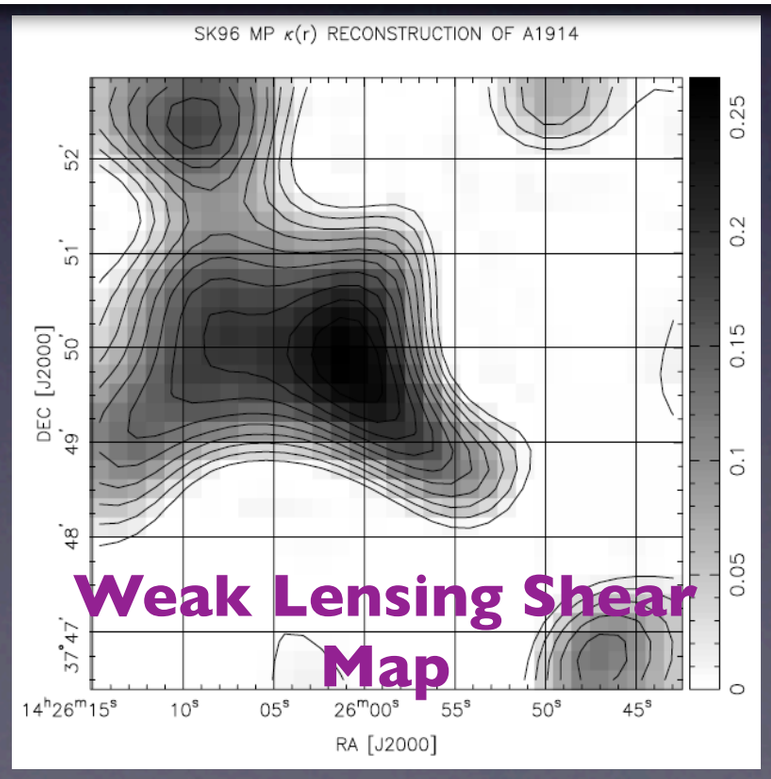

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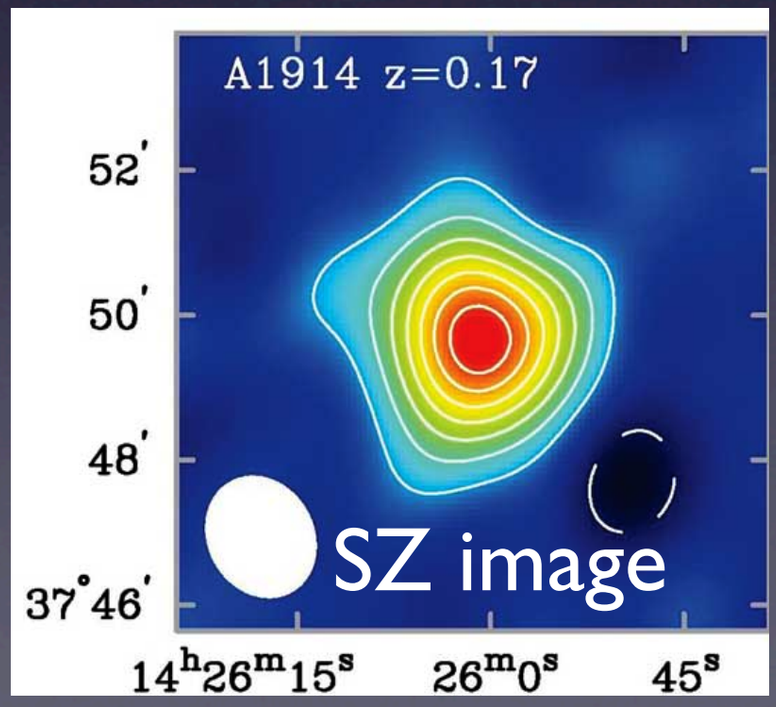
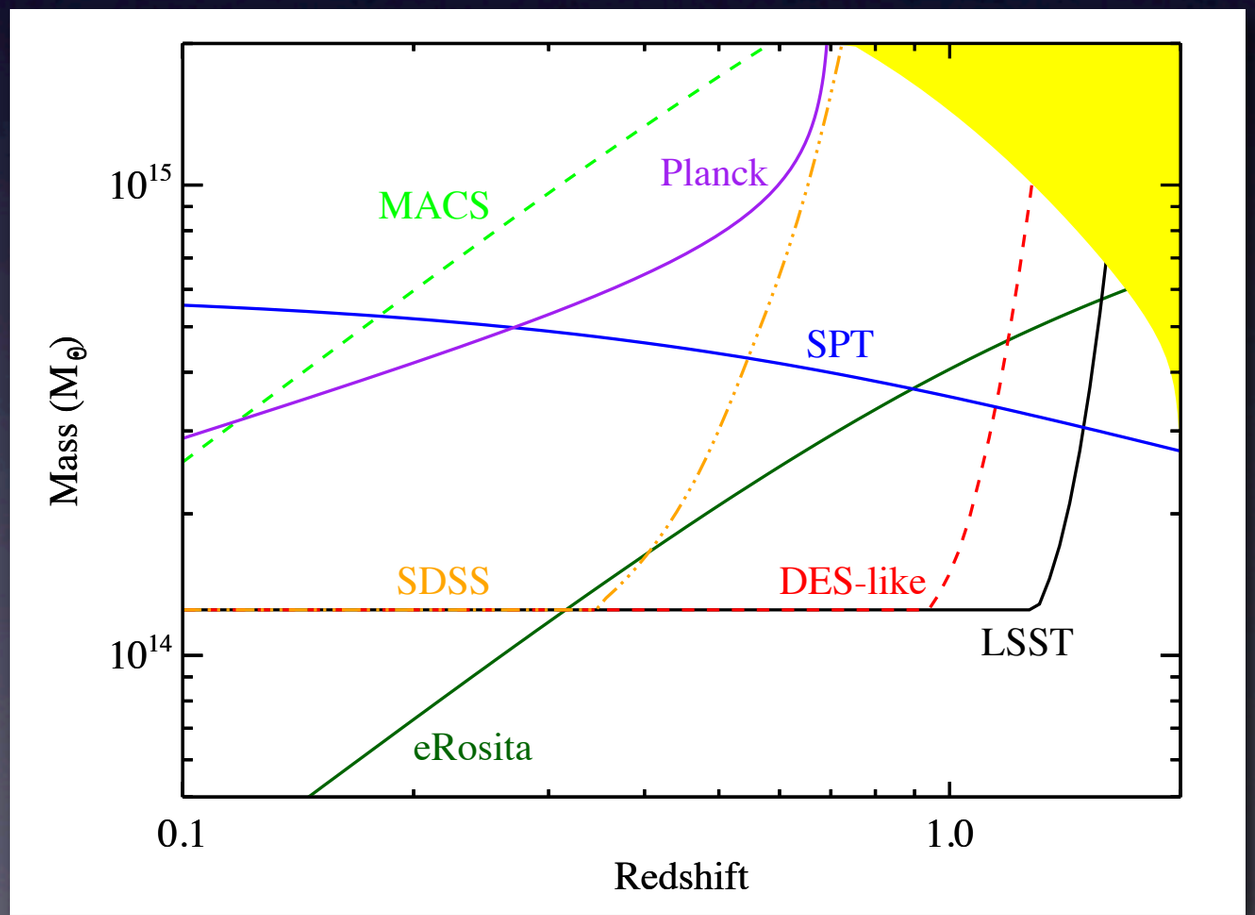
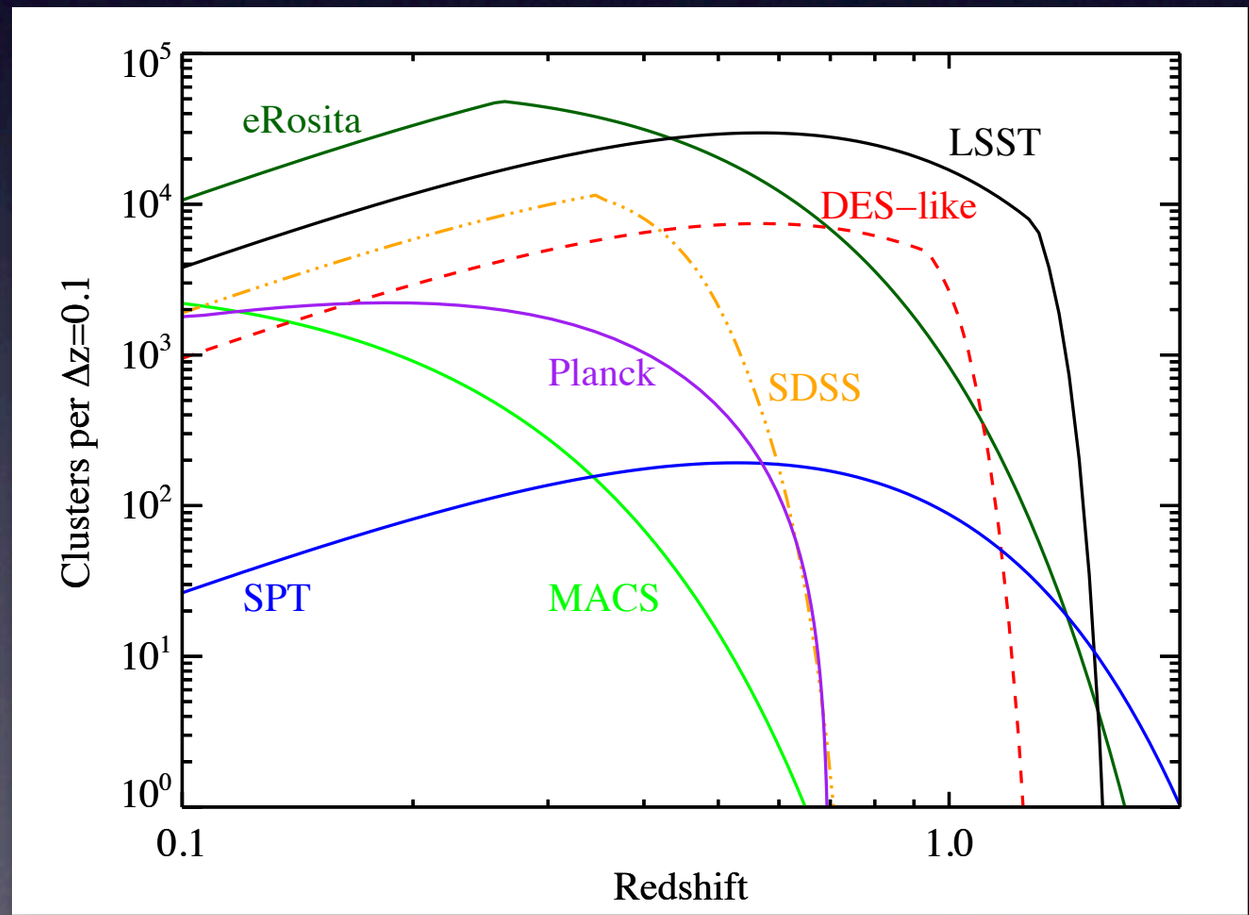


Carlstrom+02

Selection Functions

- X-ray selection: minimal projection; flux limits
- SZ selection: ~redshift independent; high mass
- Optical selection: volume limited; lower mass threshold; projection effects

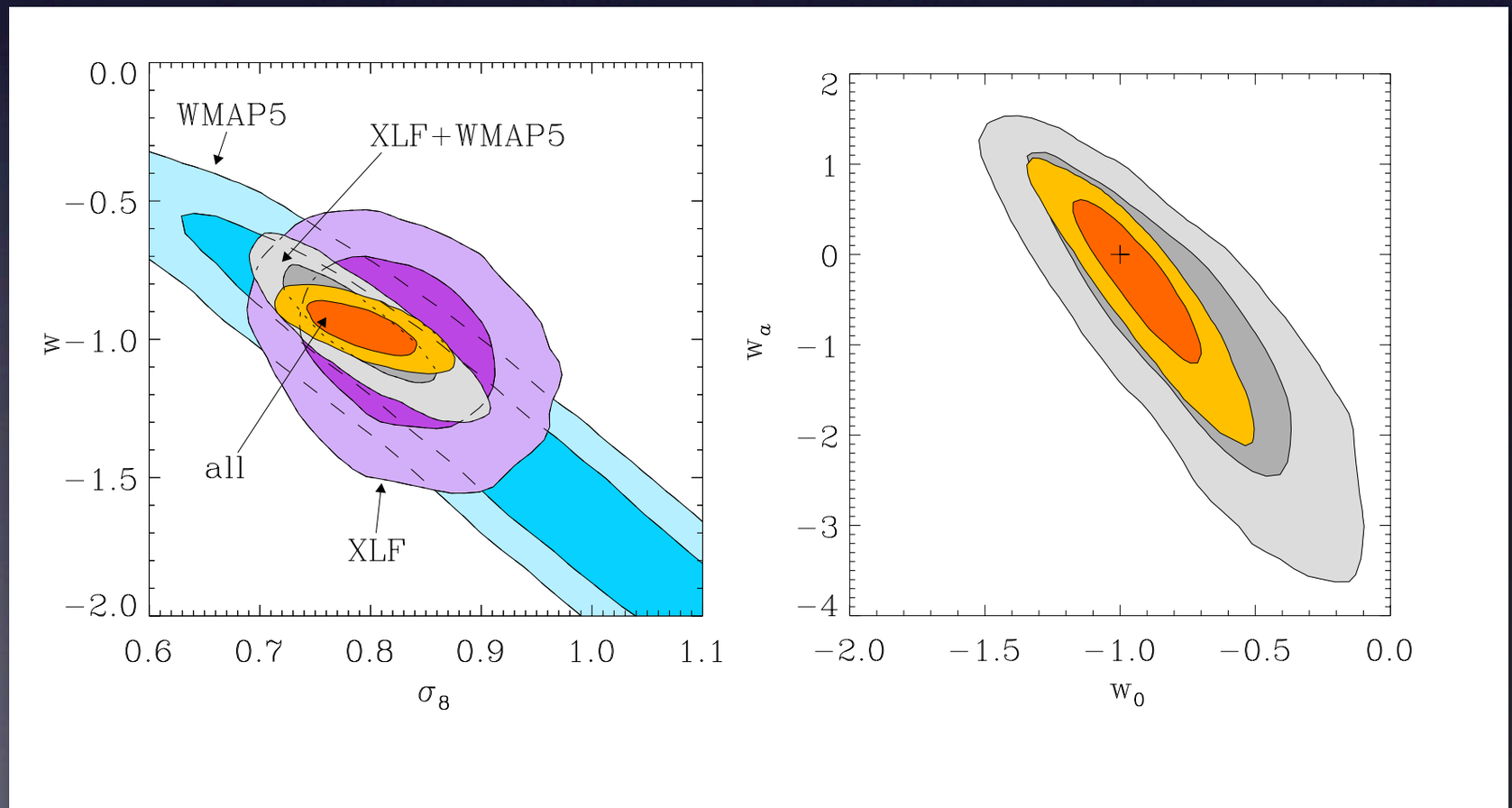




Rozo+11

Cosmological Constraints

- Using ~100 X-ray clusters, Mantz et al. measure the evolution of the X-ray luminosity function (see also Vikhlinin et al.)
- Combine with WMAP5 for constraints on σ_8, w_0, w_a

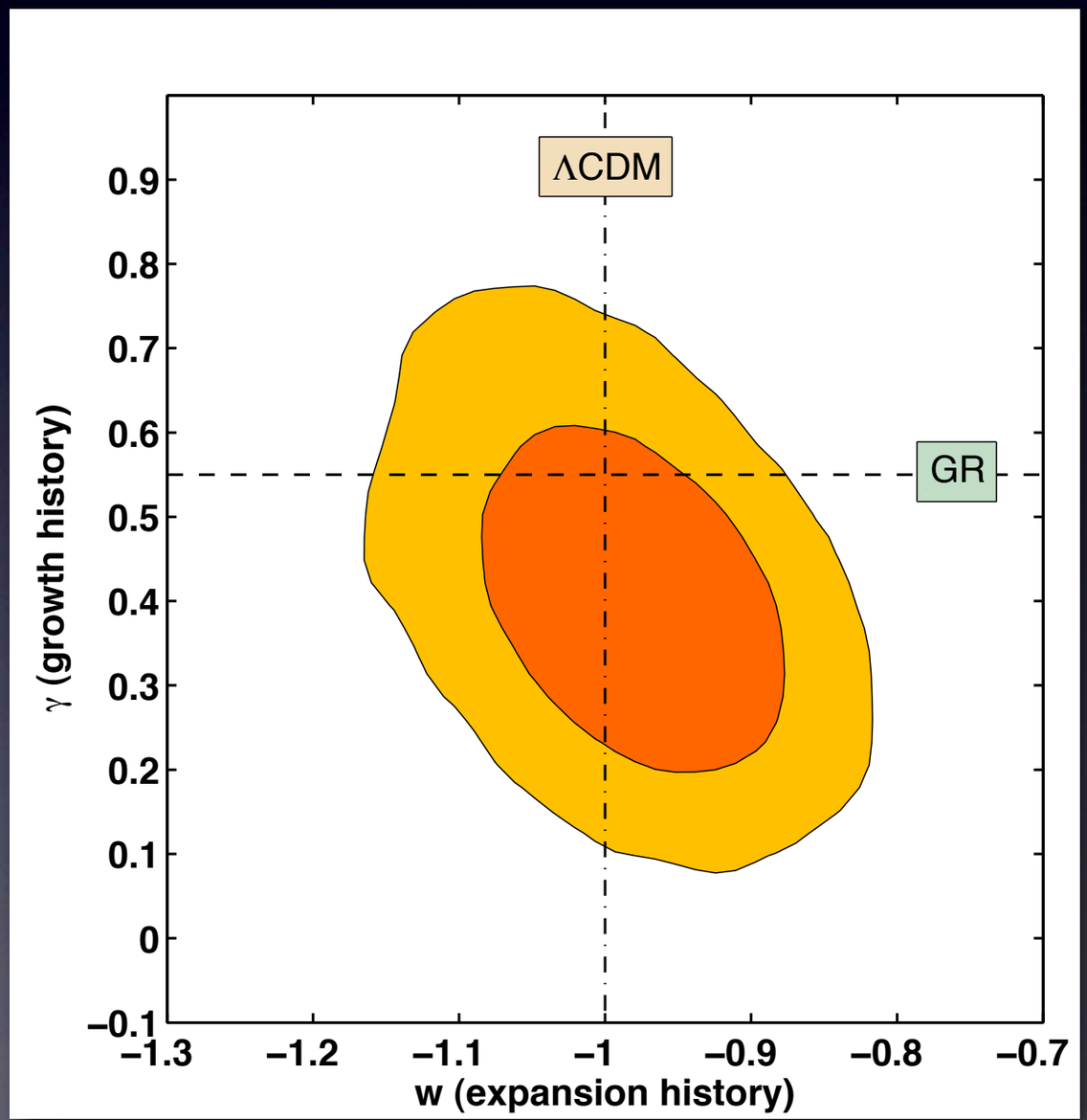


Mantz+10

General Relativity

- Given the constraints from other cosmological probes, we can predict LSS growth
- Any deviations from this would point to modified gravity

$$f(a) = \Omega_m(a)^\gamma$$

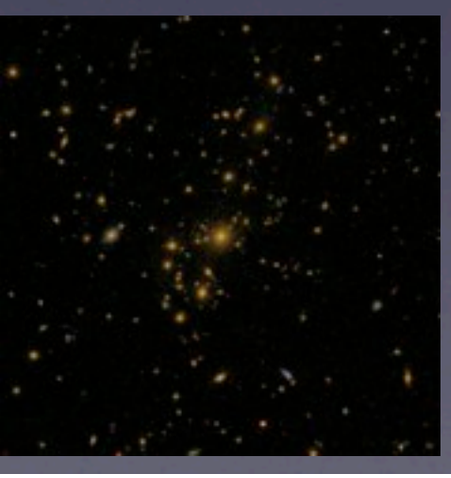


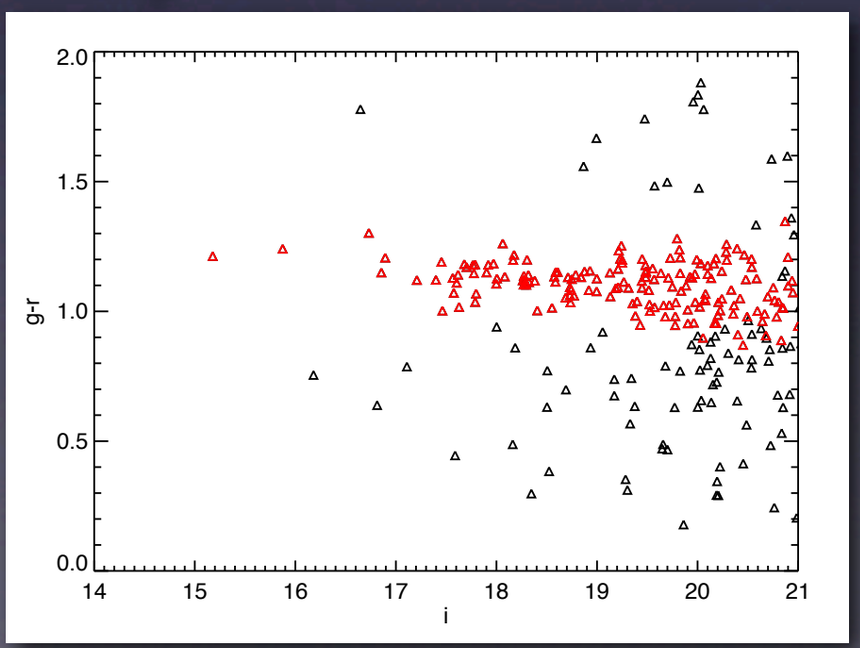
Rapetti+10

Cross-Correlation: The Power of Stacks

maxBCG Catalog Properties

- Photometric cluster catalog from SDSS DR5 (Koester+07a, 07b)
  - A maximum-likelihood algorithm that assumes each cluster has a Brightest Cluster Galaxy (BCG) and a red sequence
  - ~17,000 Clusters in 0.5 Gpc^3, $0.1 < z < 0.3$
- Cluster photo-z accuracy: $\sigma_z \sim 0.01$
- Richness: $N_{200} \geq 9$ ($\sigma > 450$ km/s)
  - Number of red galaxies brighter than 0.4 L_* in scaled aperture (r_{200})





X-Ray Stacking

- Stacking clusters allows deeper X-Ray images
  - See, eg, Dai, et al, 2006 for X-ray stacking of 2MASS clusters

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SDSS

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SDSS  RASS

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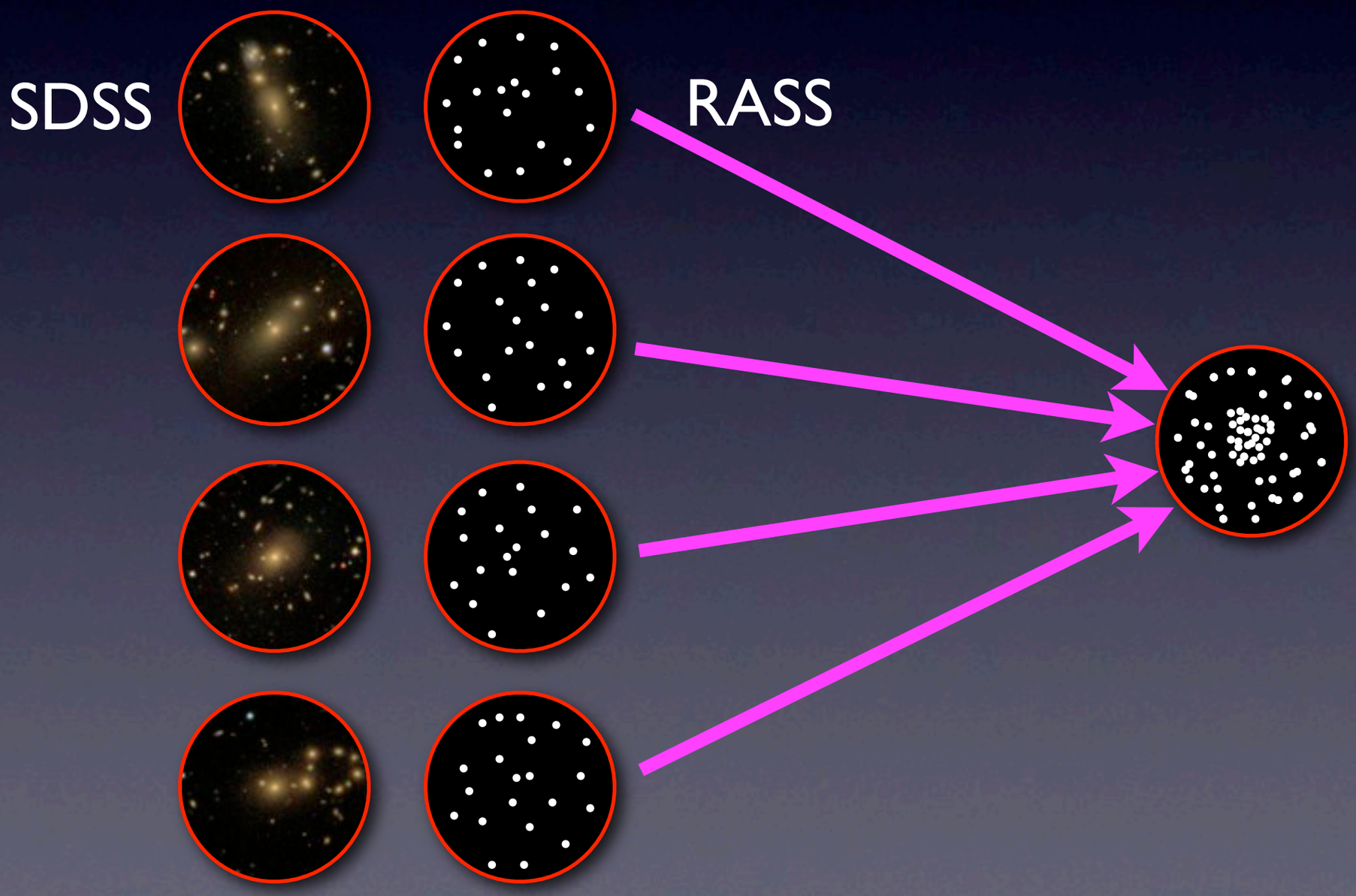

Stacking Method

- Bin according to richness: N_{200}
  - Roughly equal signal-to-noise
- Use BCG as center of each cluster
- Create an image map with photons weighted to median redshift z=0.23
- Calculate Luminosity in scaled r_{200} aperture

Rykoff+08a

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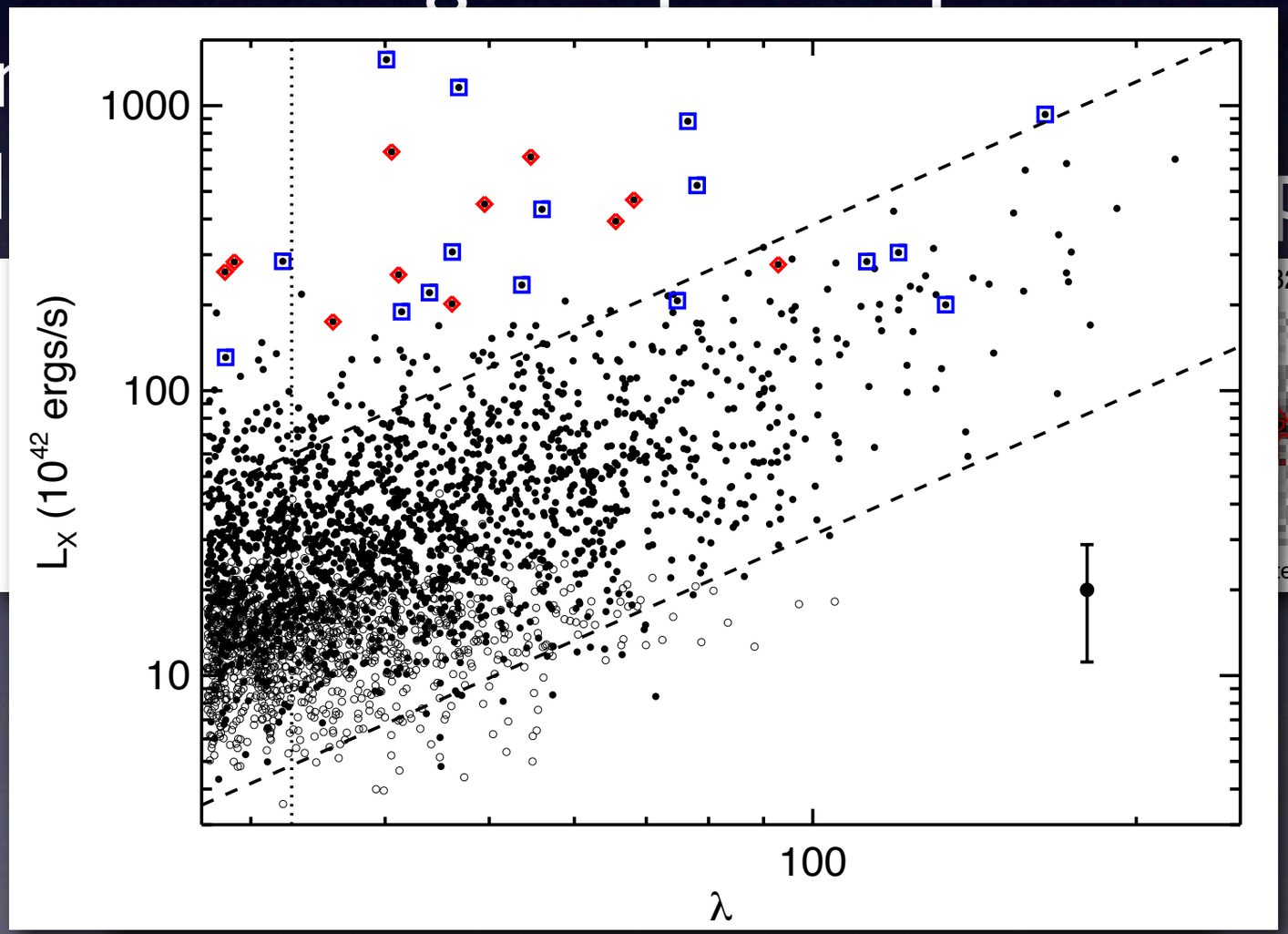
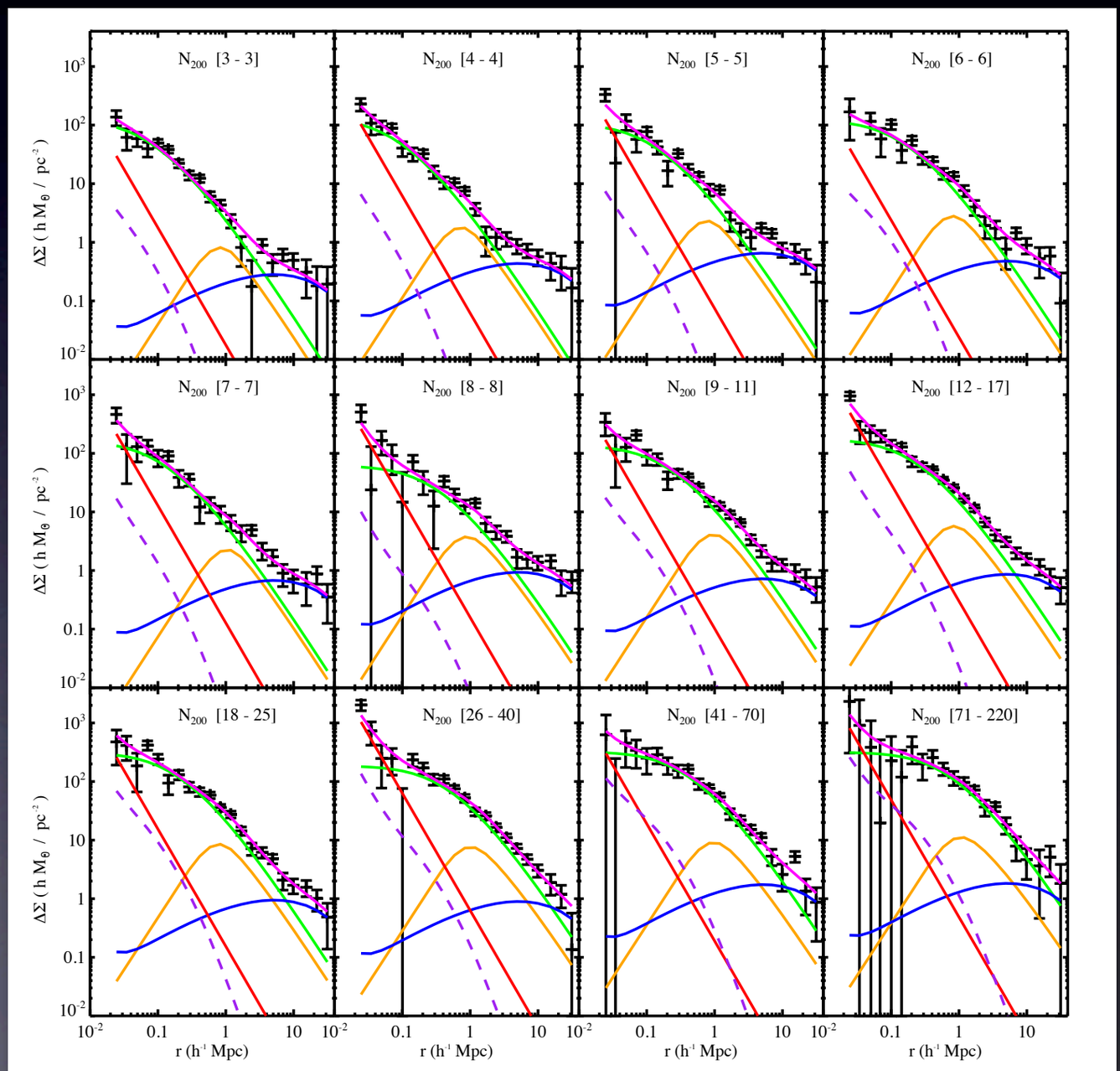


Rykoff+08a

Cluster-Mass Correlation

- We model the shear signal with...
  - Halo (NFW) contribution
  - BCG contribution
  - 2-halo term
  - Miscentering
- Centering remains a limiting systematic
- Also: photometric redshift distribution of background gals



Sheldon+07, Johnston+07

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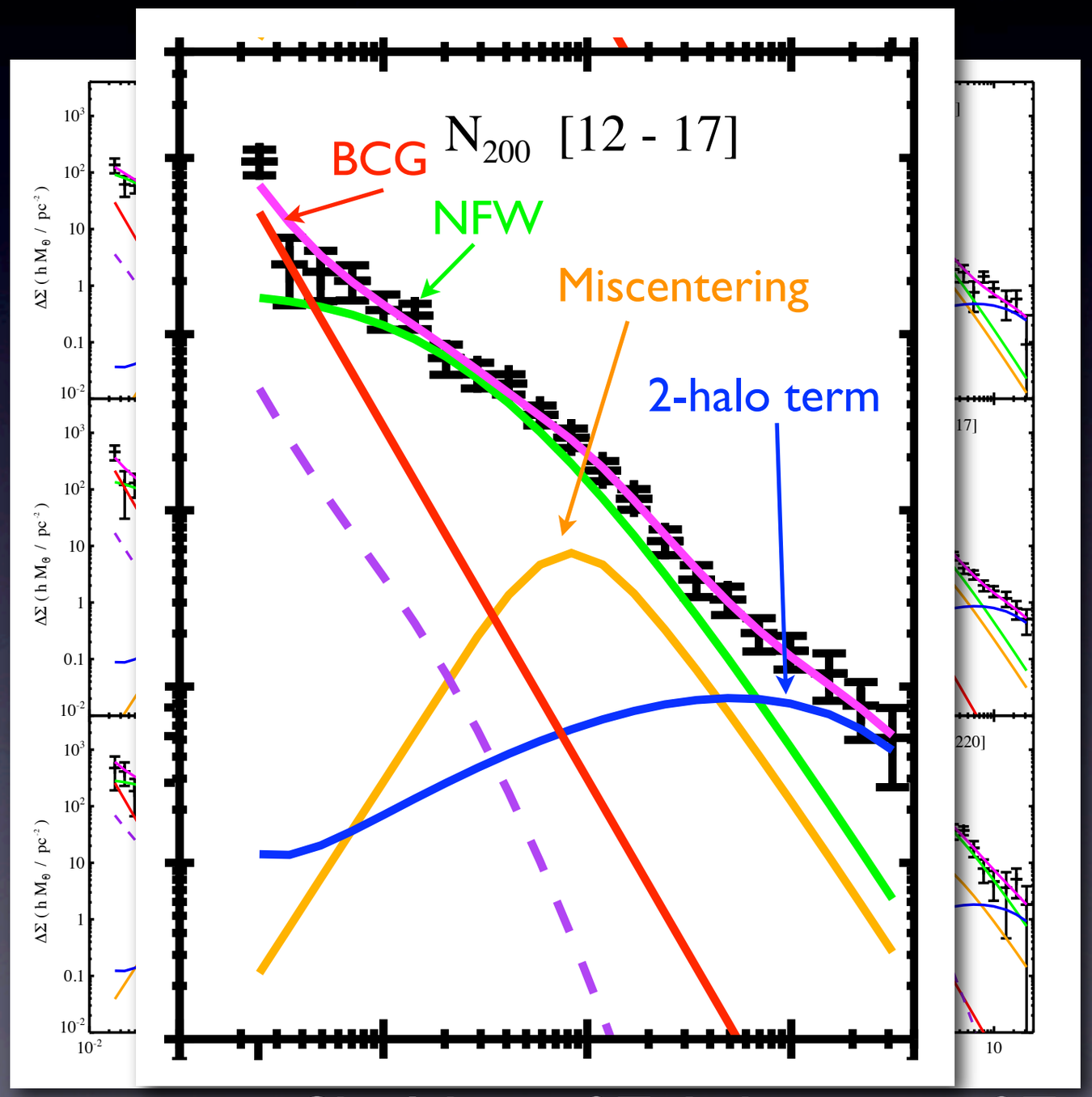
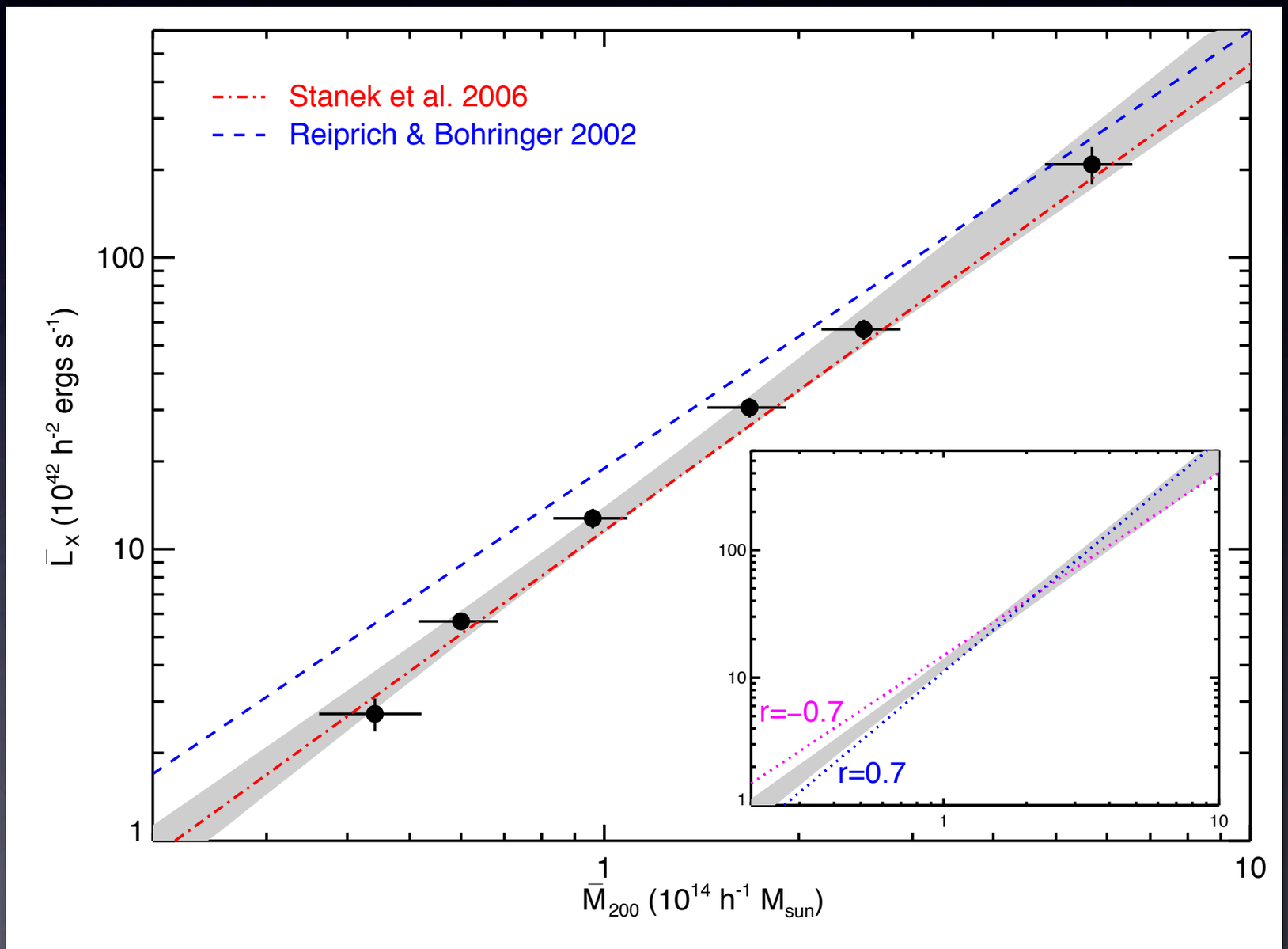


Sheldon+07, Johnston+07

L_X-M_{200}

- Optically selected clusters look like X-ray clusters (on average)



- Need to worry about the effects of covariance of N_{200}, L_X at fixed mass

Rykoff+08b

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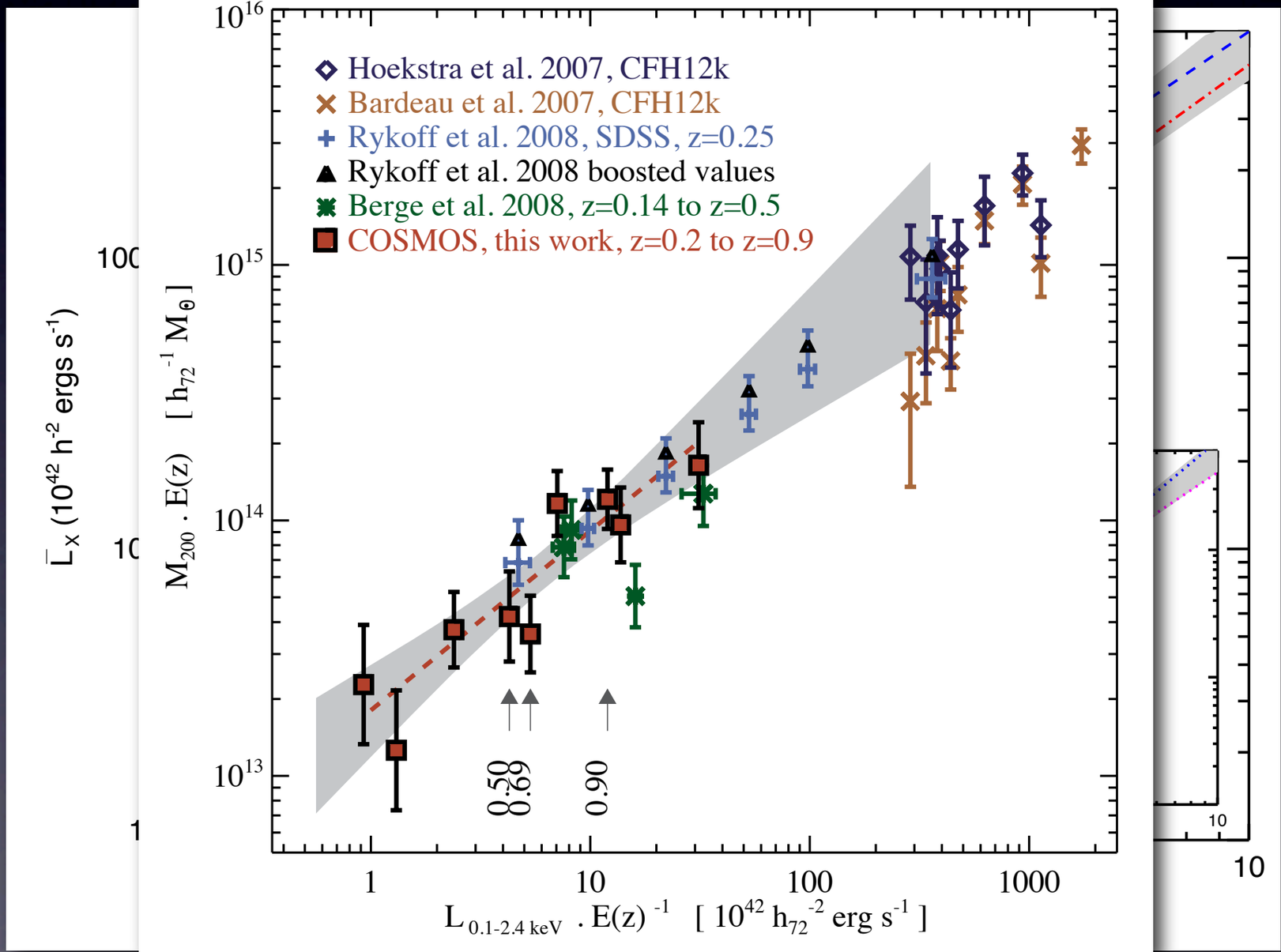

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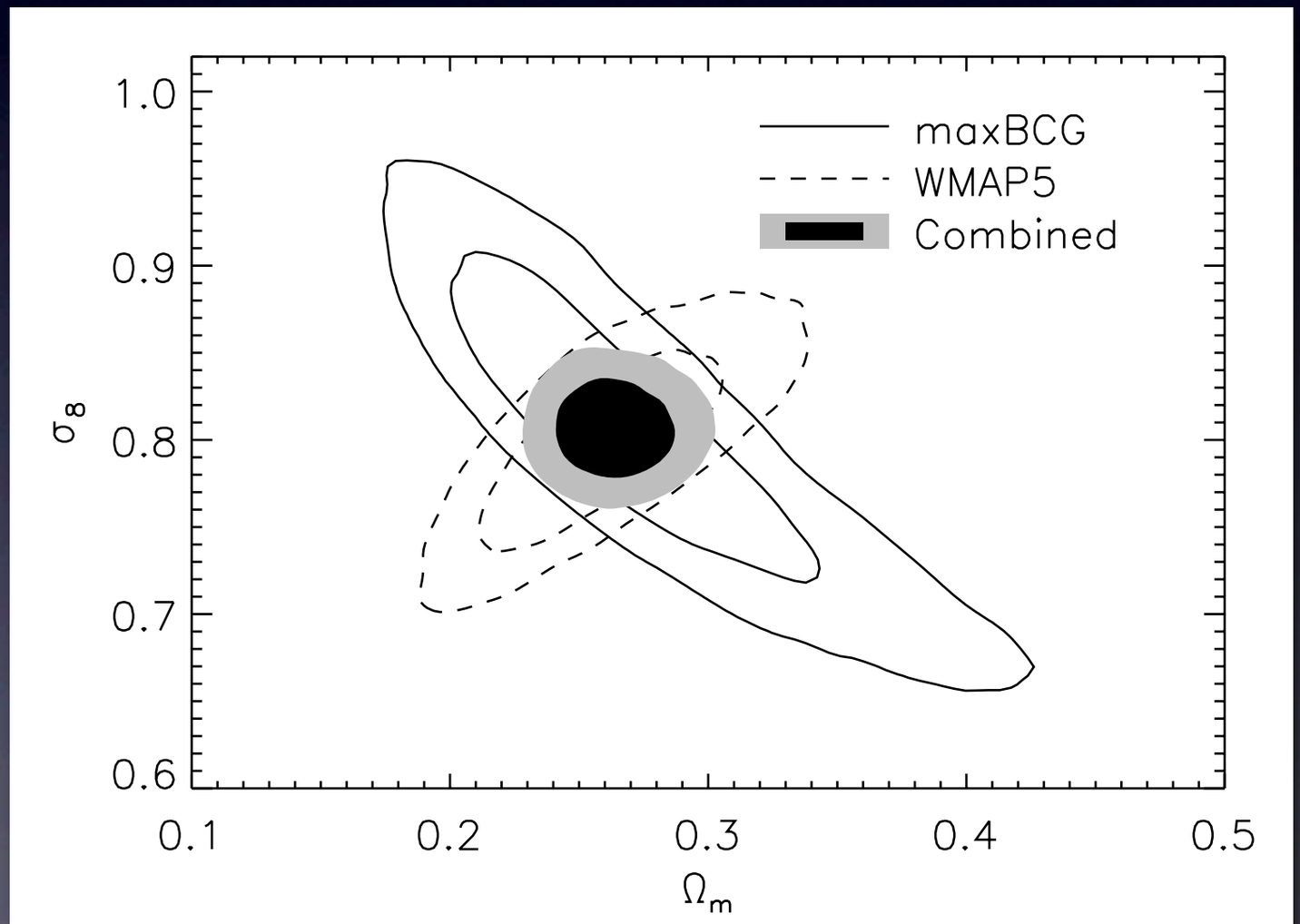
Rykoff+08b

Leauthaud+2010

maxBCG Cosmology

- Use cluster number counts, stacked WL masses, plus constraints on scatter/ covariance (see Rozo, Rykoff+09a) (plus WMAP)
- Competitive constraints on σ_8, Ω_m



Rozo, Wechsler, Rykoff+09b

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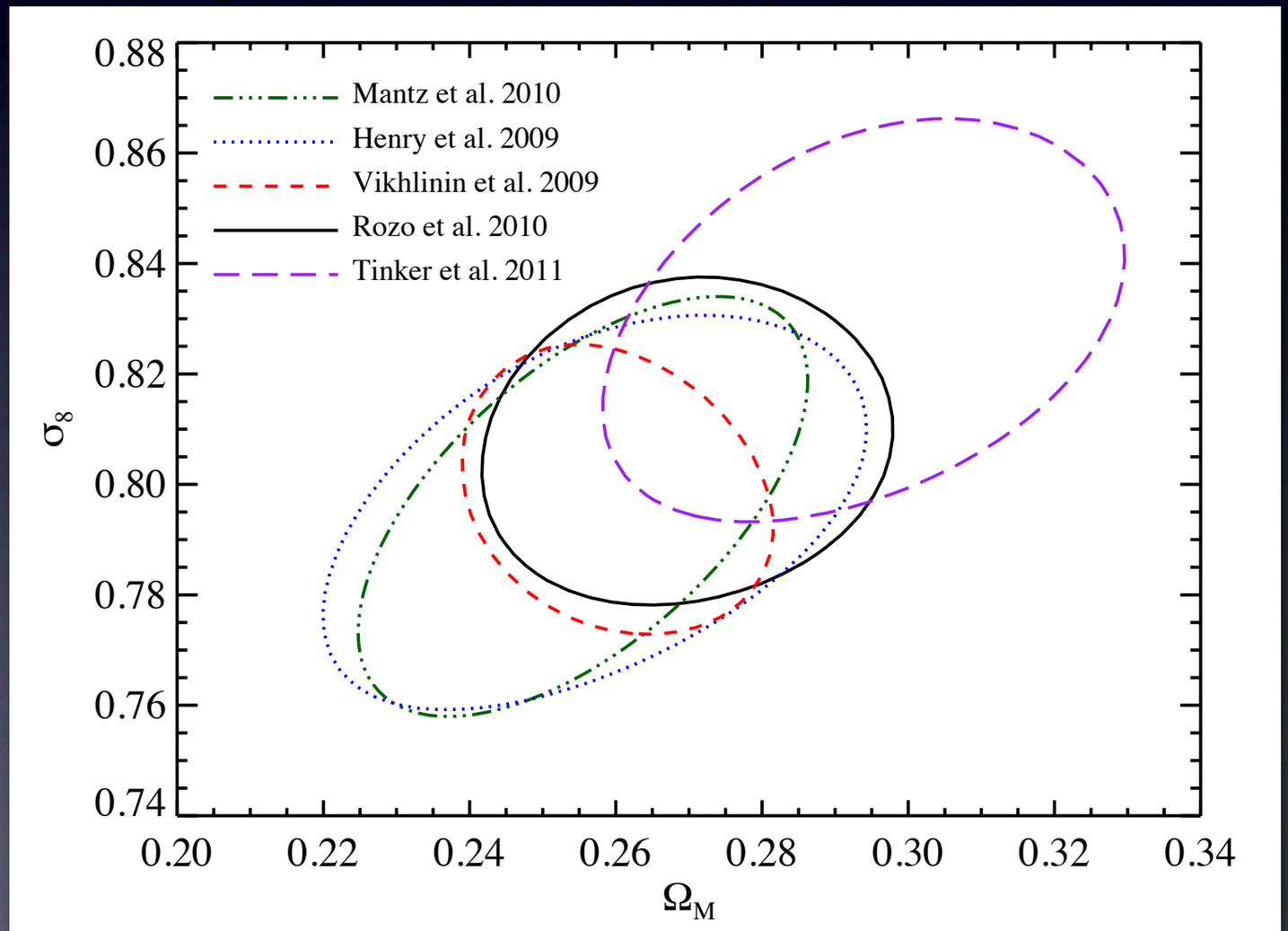
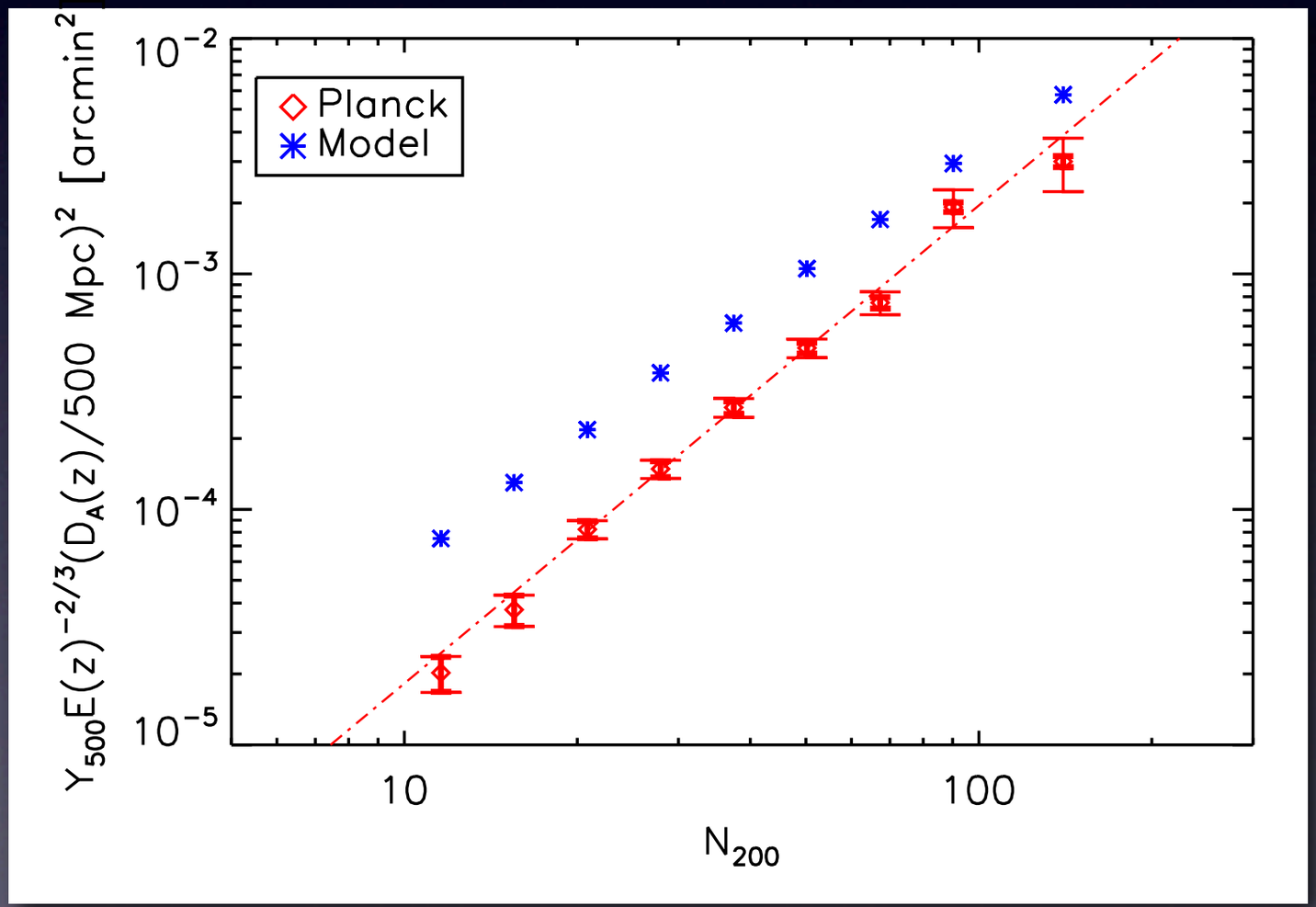


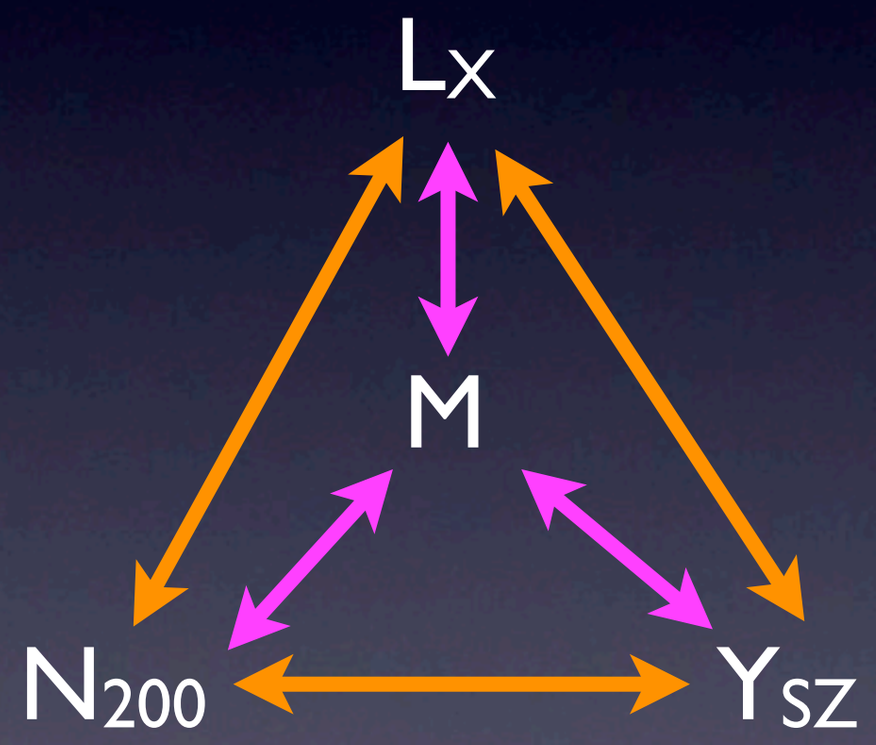
Rozo+11

maxBCG + Planck

- We have a consistent picture of N_{200} + WL + Lx
- But...



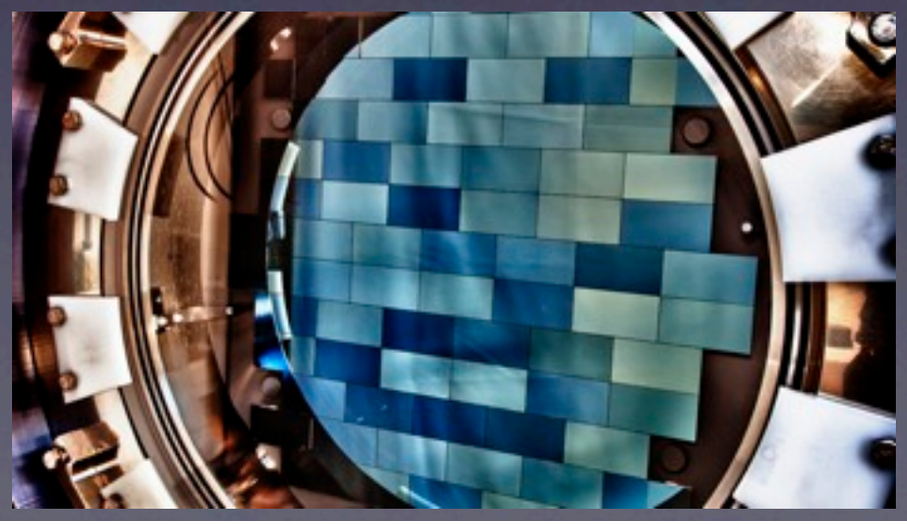
Planck Collaboration+11



Towards Higher Redshifts

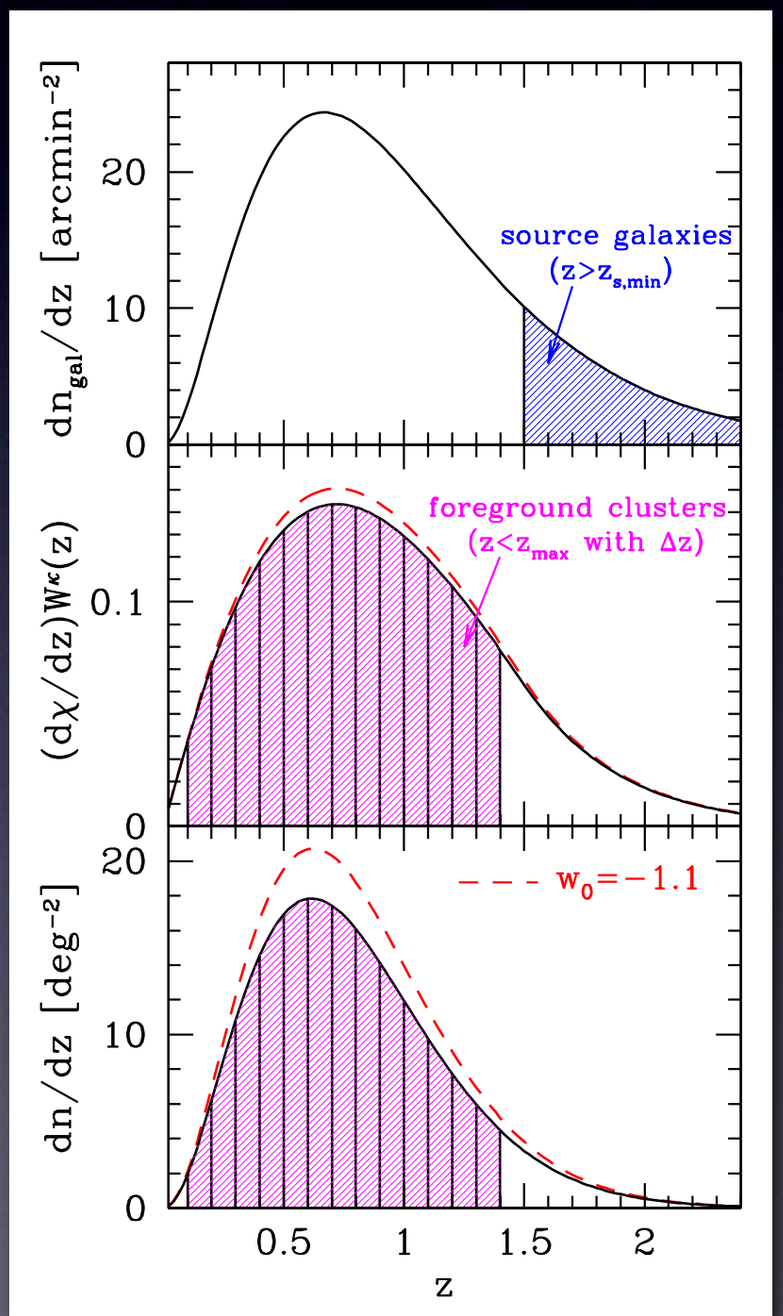
Dark Energy Survey

- DECam on the Blanco 4m telescope
  - 570 megapixel, 2.2° FOV
- 525 nights dedicated to DES
  - 5000 sq. deg.
- Cosmology using...
  - Cluster counts
  - Weak Lensing
  - Baryon Acoustic Oscillations
  - Supernovae

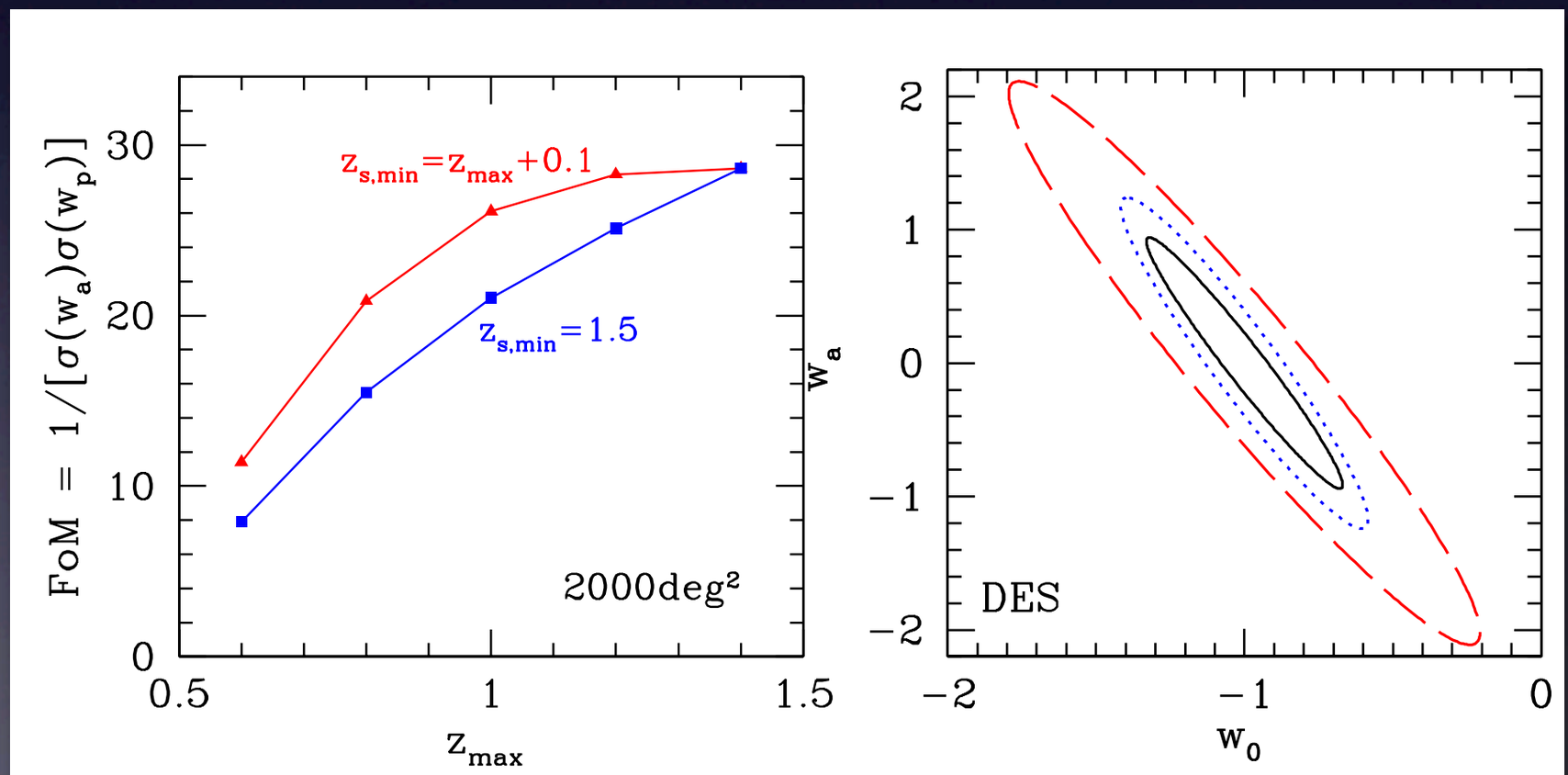


DES Constraints

- DES cluster counts + WL + Planck: FOM~30



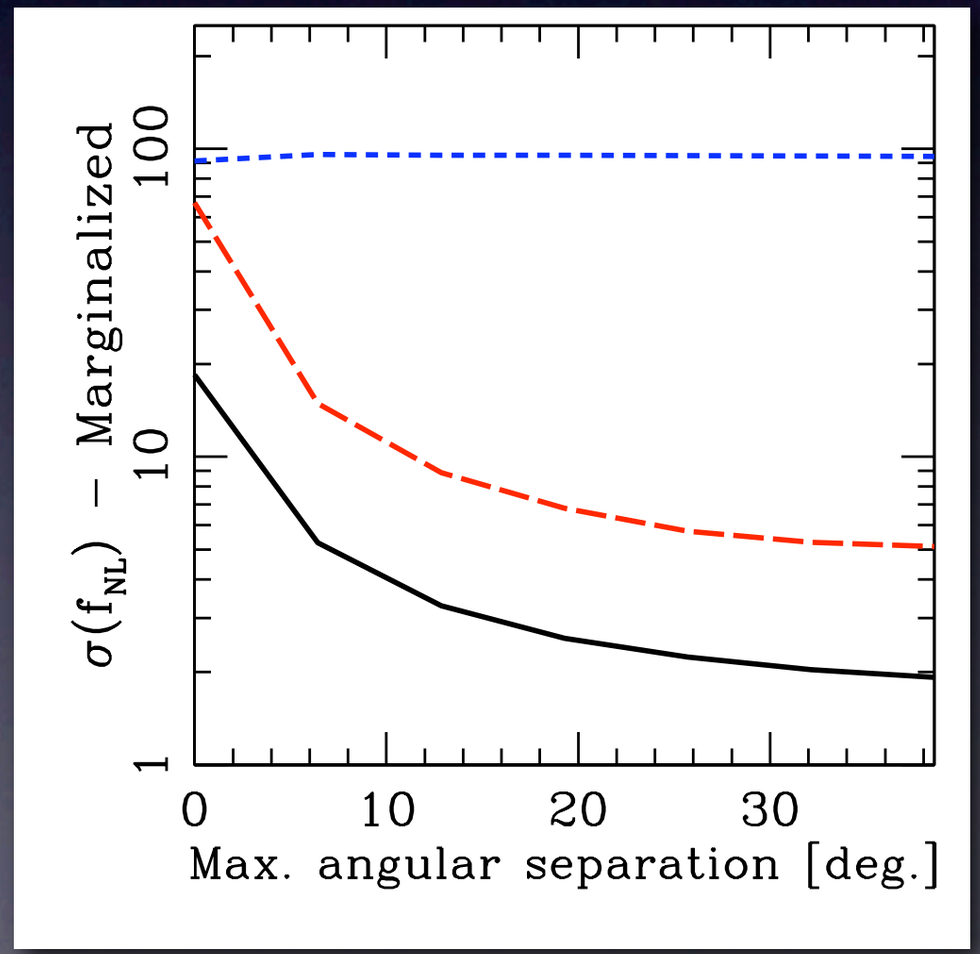
- Can double this with BAO from BOSS (complementary)



Oguri & Takada 10

Non-Gaussianity

- Single-field slow-roll inflation predicts Gaussian spatial distribution of structures
- Bias of DM halos has strong scale dependence on f_{NL} (e.g. Dalal+08)
- Use cluster counts, scatter, covariance to constrain f_{NL}
- Requires low-scatter and unbiased photozs



Cunha, Huterer, Doré 10

Goals For Precision Cosmology

- High purity/completeness
- Low scatter & unbiased photometric redshift estimation for clusters
  - Require dz<0.003, σ_z < 0.03 (Lima & Hu 02; Cunha+10)
- Reduce scatter in the mass-richness relation (e.g. Wu+08, Rozo,Rykoff+11)
- Well controlled and well understood centering
- Richness without unintended evolution
  - Smooth filter transitions

Improving our Richness Estimator

The Matched Filter

$$p(\mathbf{x}|\lambda) = \frac{\lambda u(\mathbf{x}|\lambda)}{\lambda u(\mathbf{x}|\lambda) + b(\mathbf{x})}$$

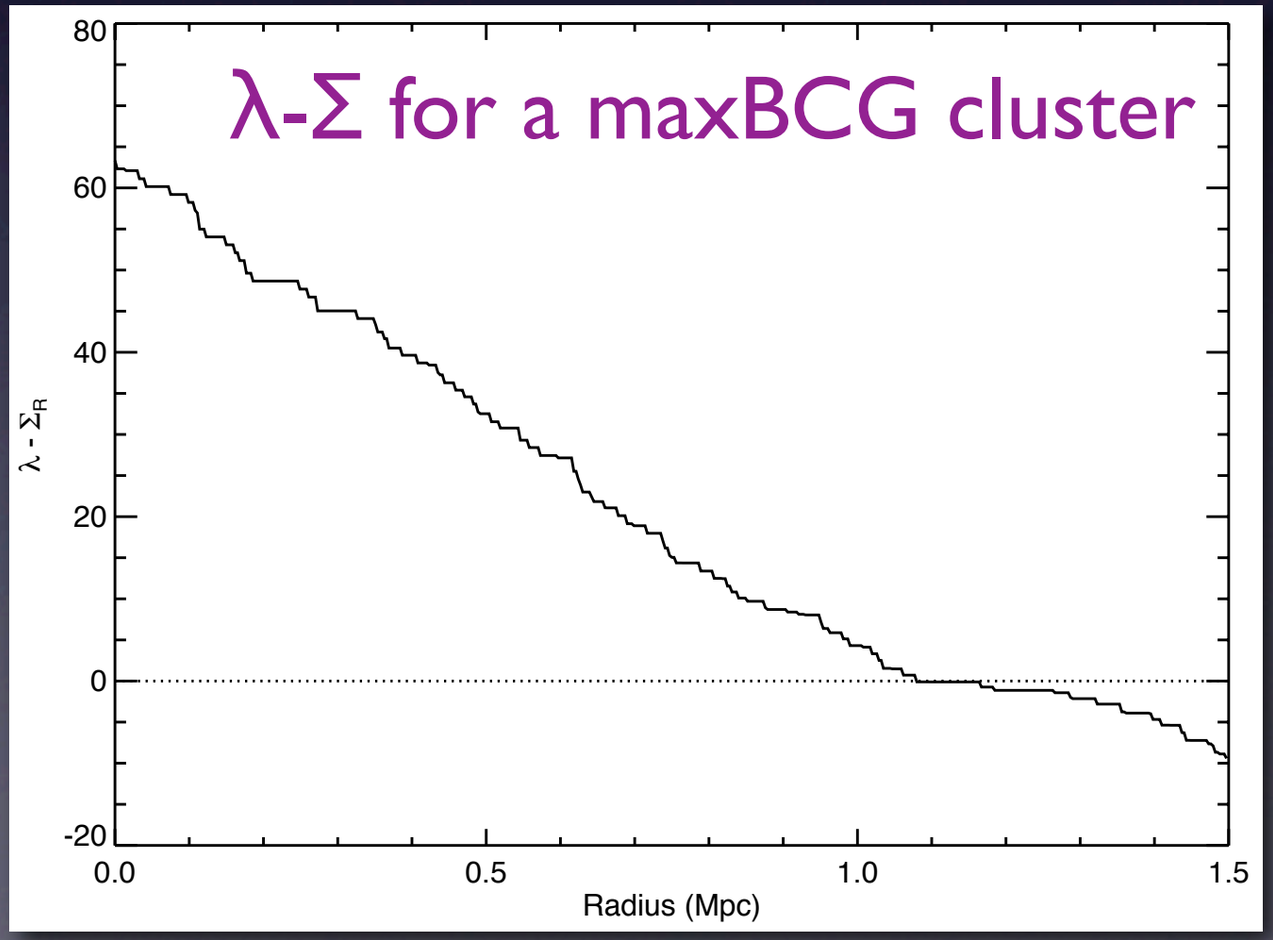
$$\lambda = \sum_{R<R_c(\lambda)} p(\mathbf{x}|\lambda)$$

$$u(x) = [2\pi R\Sigma(R)]\phi(m)G(c)$$

- Three filters: color (Gaussian); luminosity (Schechter function); radial (NFW)
- Every galaxy is given a probability that it is a cluster member
- Assume radius scales with richness:

$$R_c(\lambda) = R_0(\lambda/100)^\beta$$

Rozo, Rykoff+09b

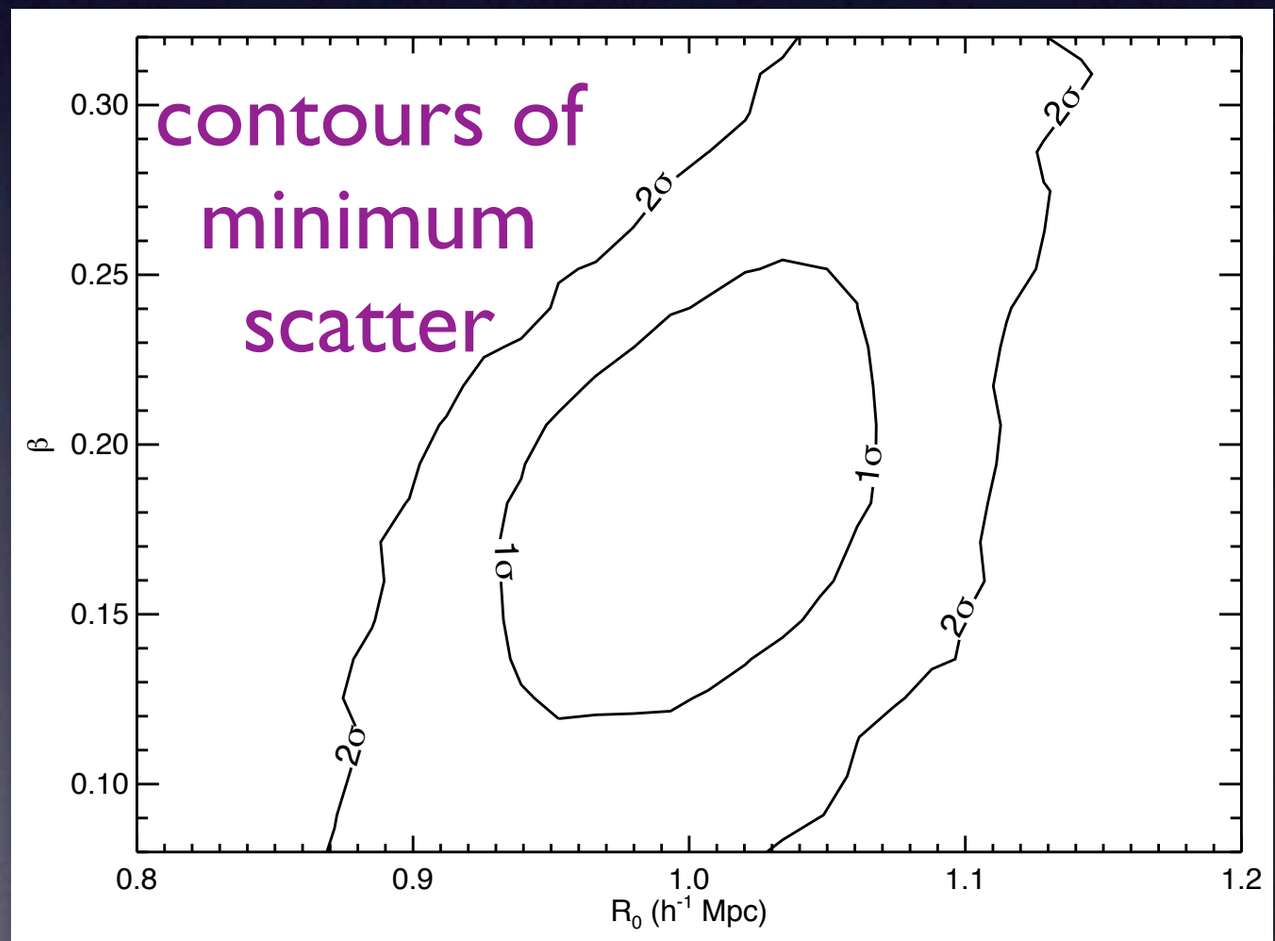


Using RASS: L_X scatter

- Use L_X as our mass proxy
- Goal: minimize the scatter $\sigma_{\ln L|\lambda}$ for the 2000 richest clusters
- Optimize radial scaling:

$$R_c(\lambda) = R_0(\lambda/100)^{\beta}$$

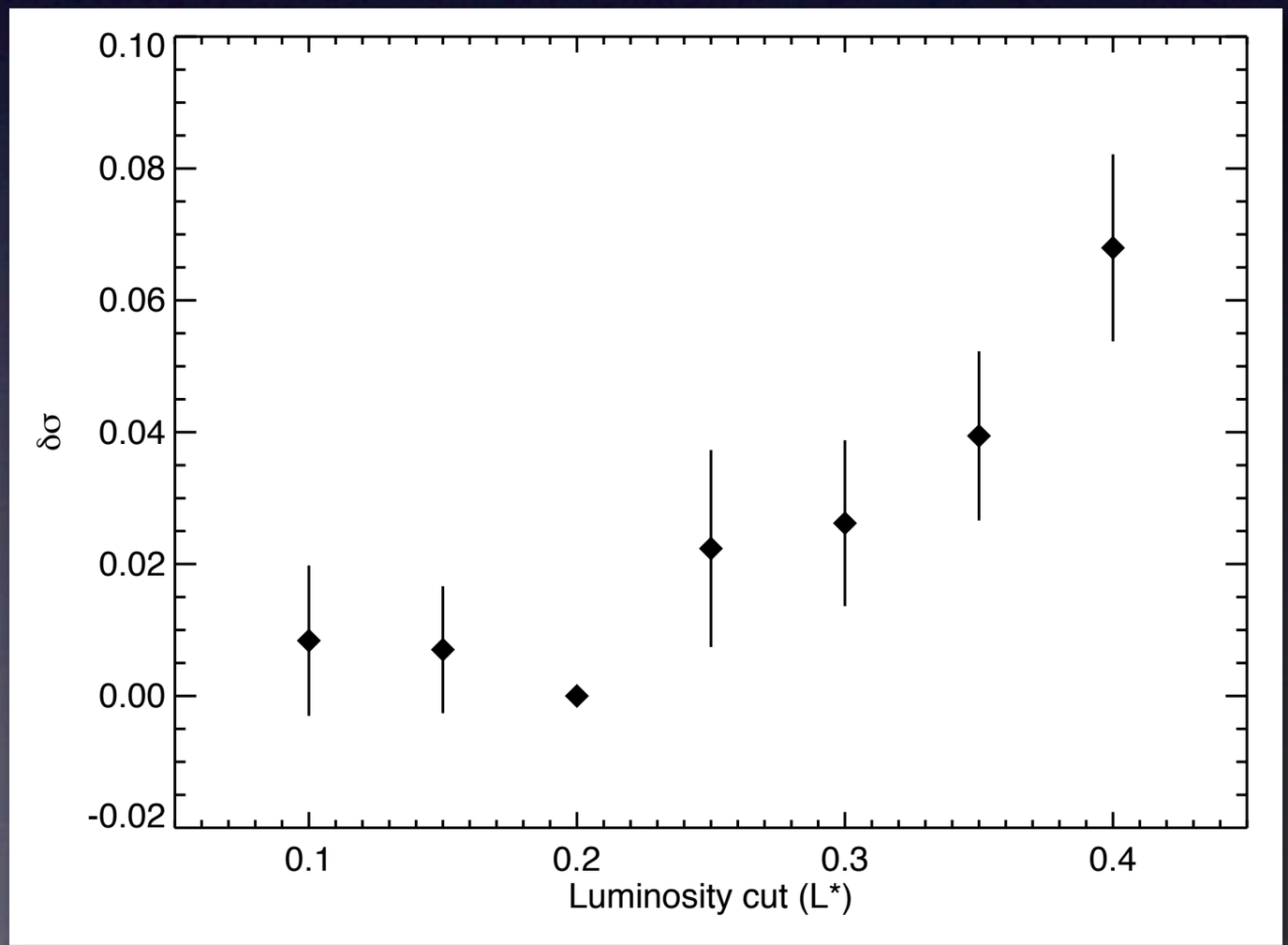
- Each R_0, β combination yields a new richness estimate
- Scatter is reduced from 86% (N_{200}) to 62% (λ)
- Gaussian color filter + radial optimization



Rozo, Rykoff+09; Rykoff+11

How Deep?

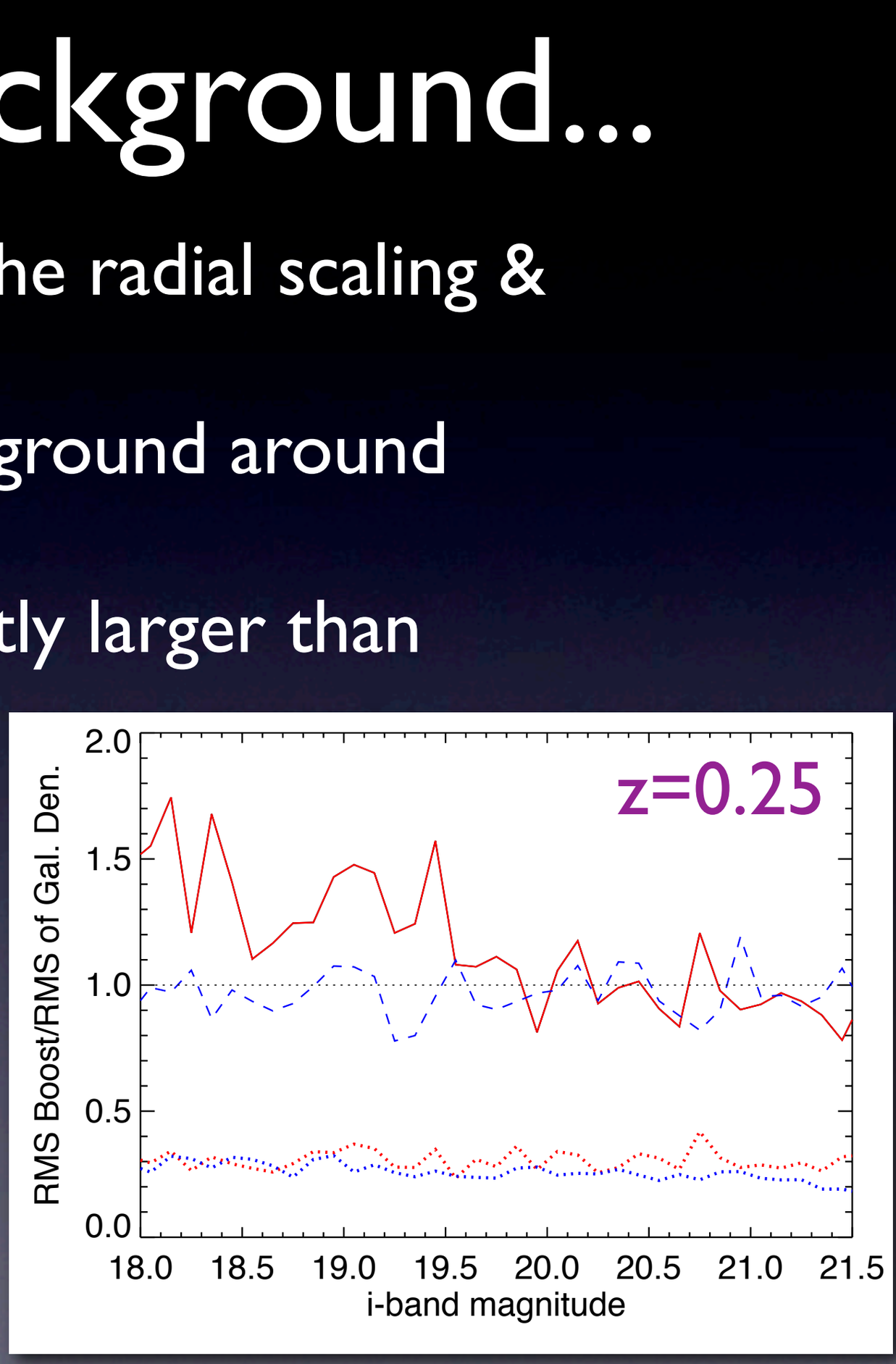
- Original N_{200} used a limit of $0.4L^*$
  - Excellent photometry in SDSS at z~0.3
- But we still can go deeper: limiting mag corresponds to $<0.1L^*$ at z=0.3
- $\sigma_{\ln L|\lambda}$ decreases to $0.2L^*$, then plateau
- Going down to limiting magnitude is not optimal



Rykoff+11

A Bit of Background...

- What is the origin of the radial scaling & depth optimizations?
- What is the local background around maxBCG clusters?
  - Variance is significantly larger than Poisson
  - Some fraction of clusters have significantly boosted background

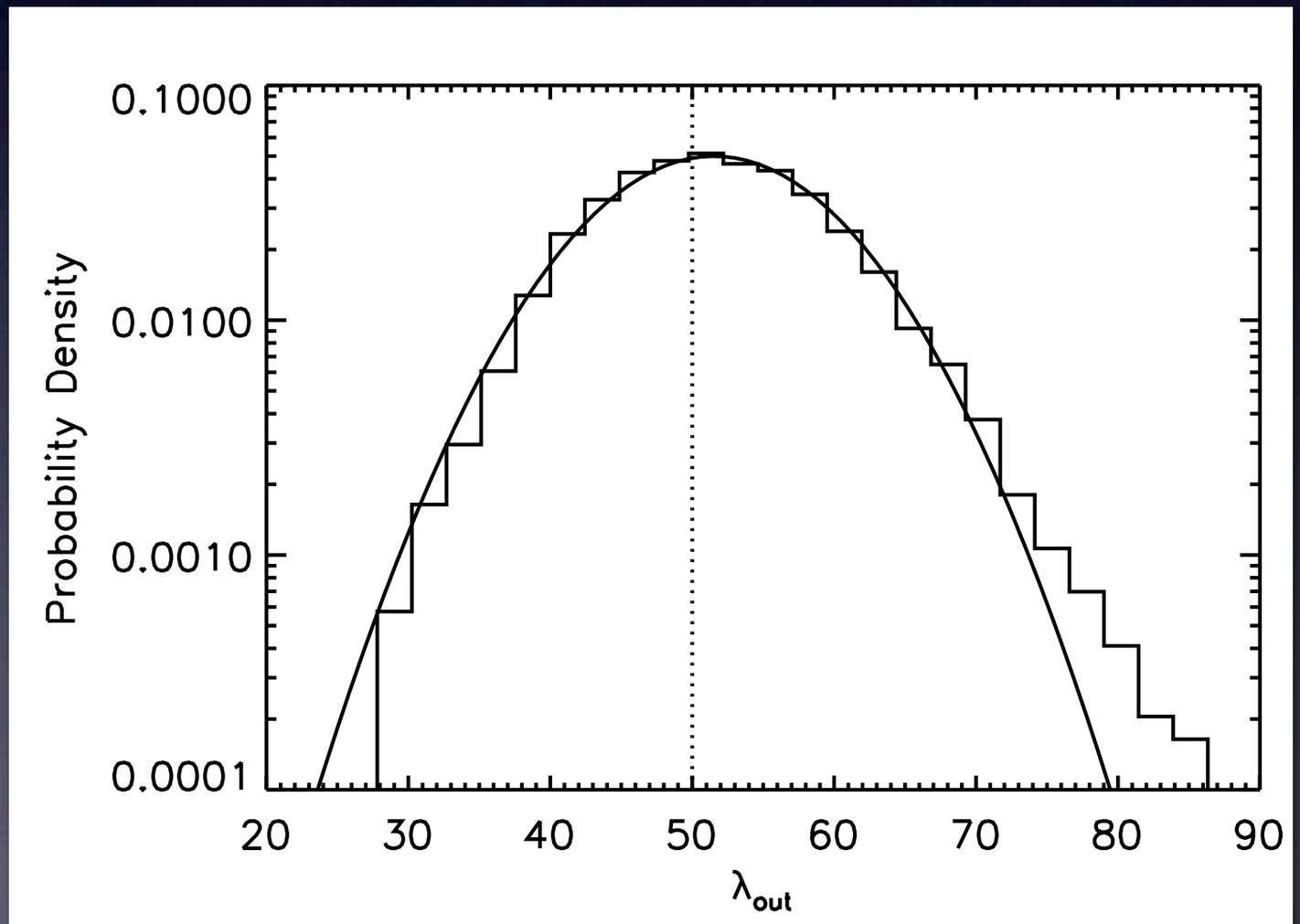


Projection Effects

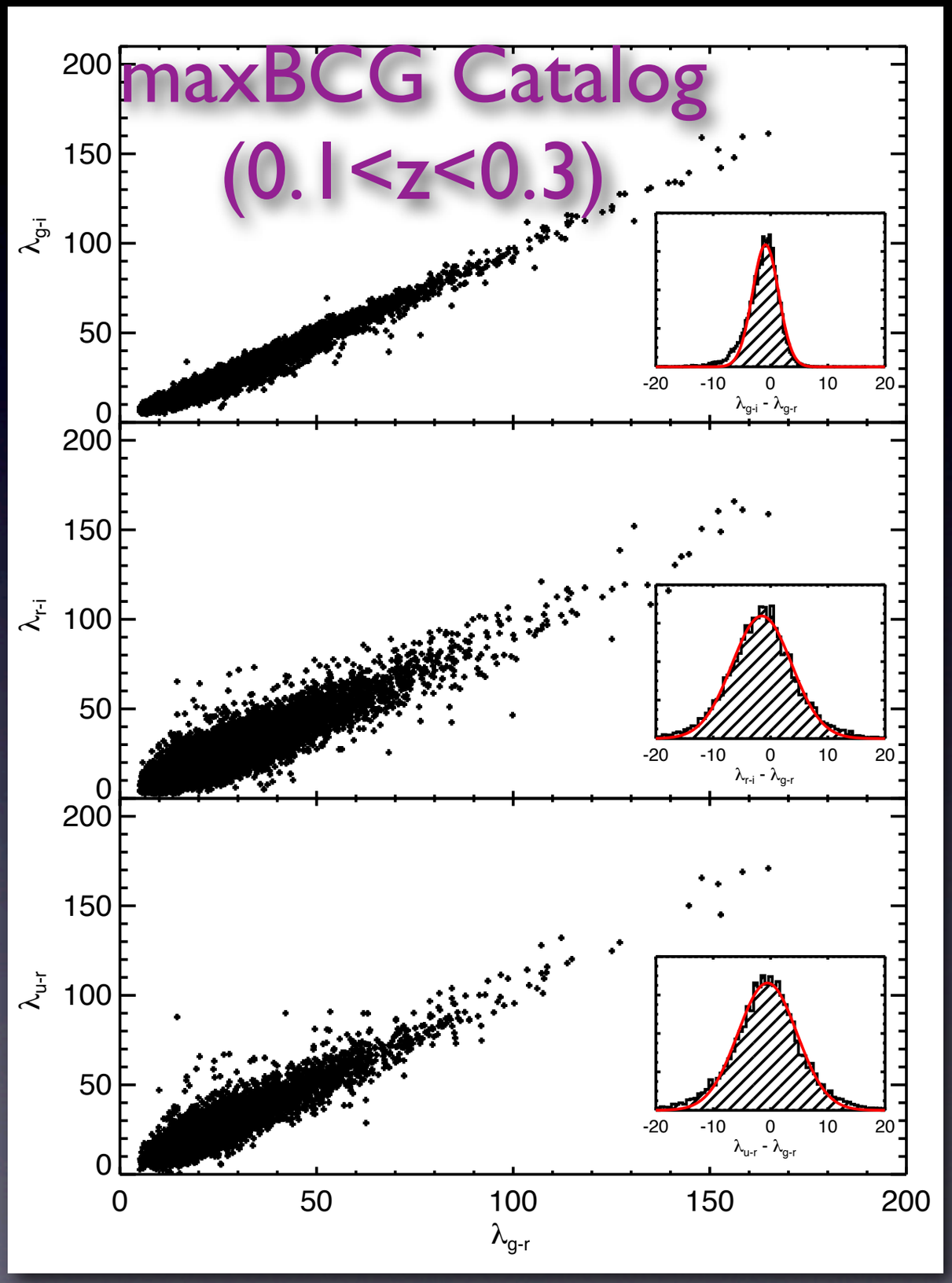
- Some fraction of clusters will have projection effects
- Using the local cluster background, we simulate galaxy catalogs to measure λ

- ~5-10% of clusters have boosted richness

- See also Cohn+07 using simulations



Robust To Filter Changes



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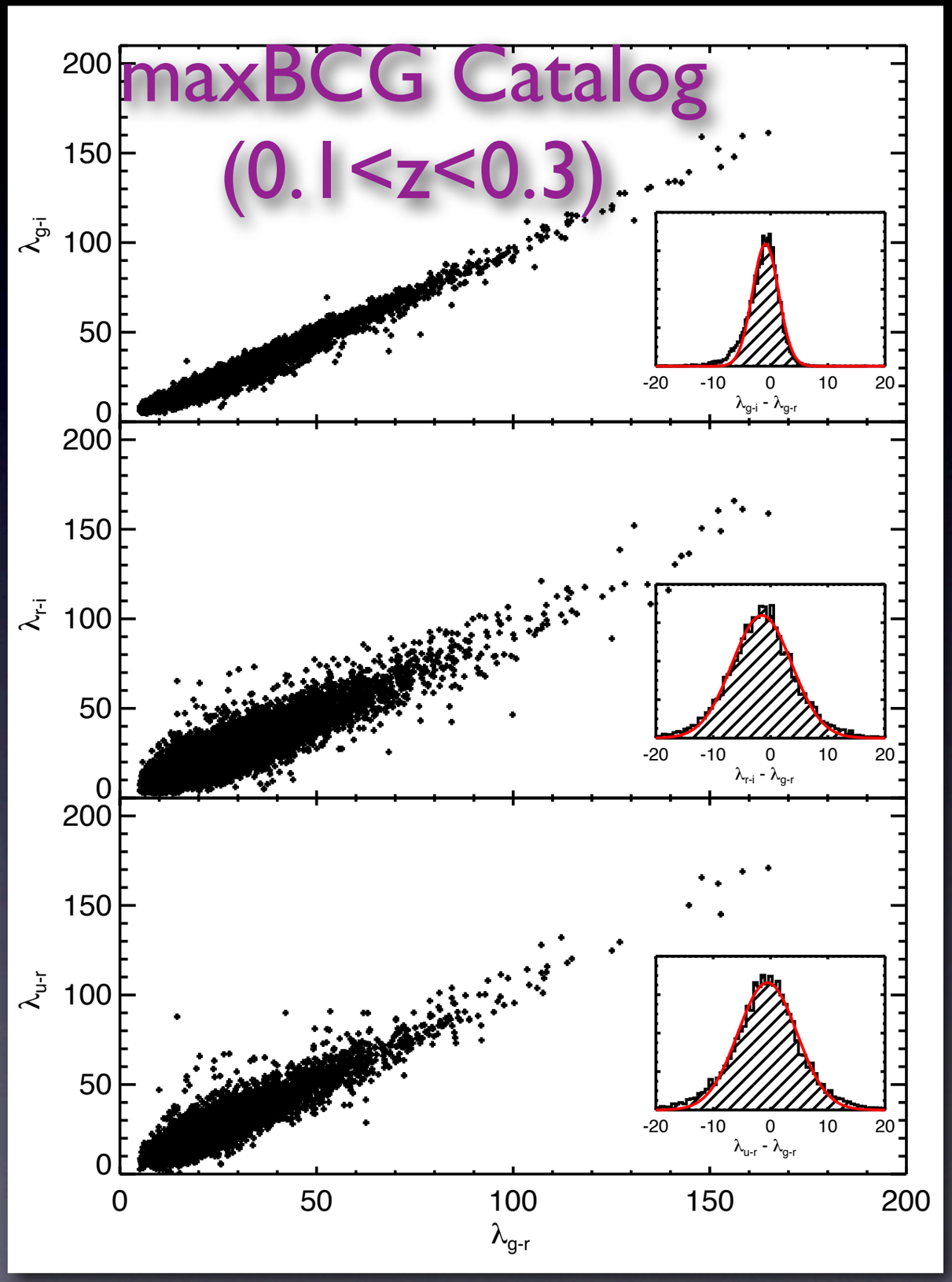
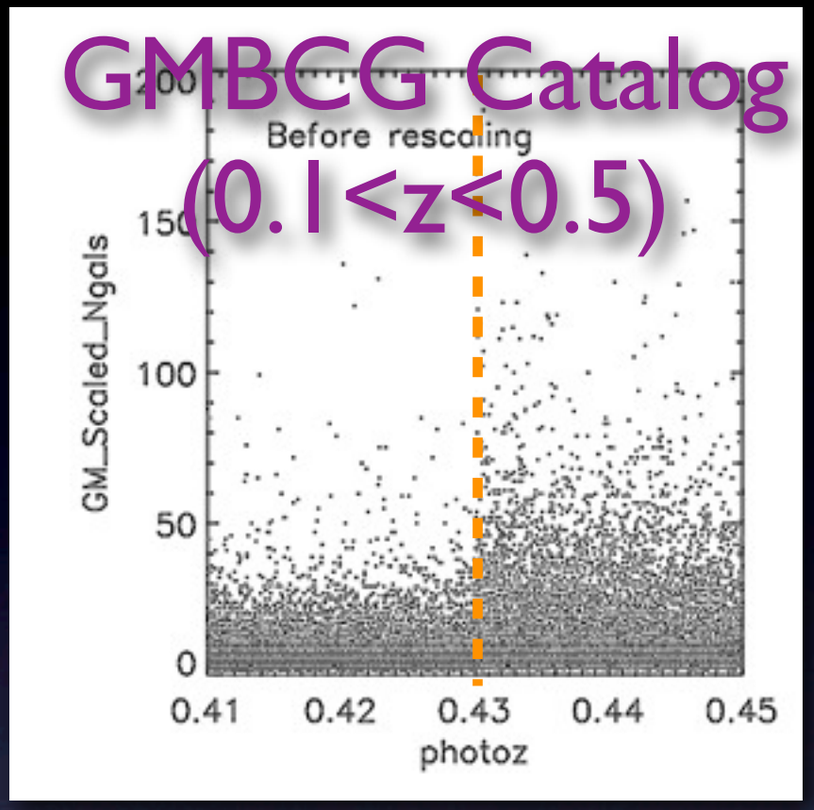
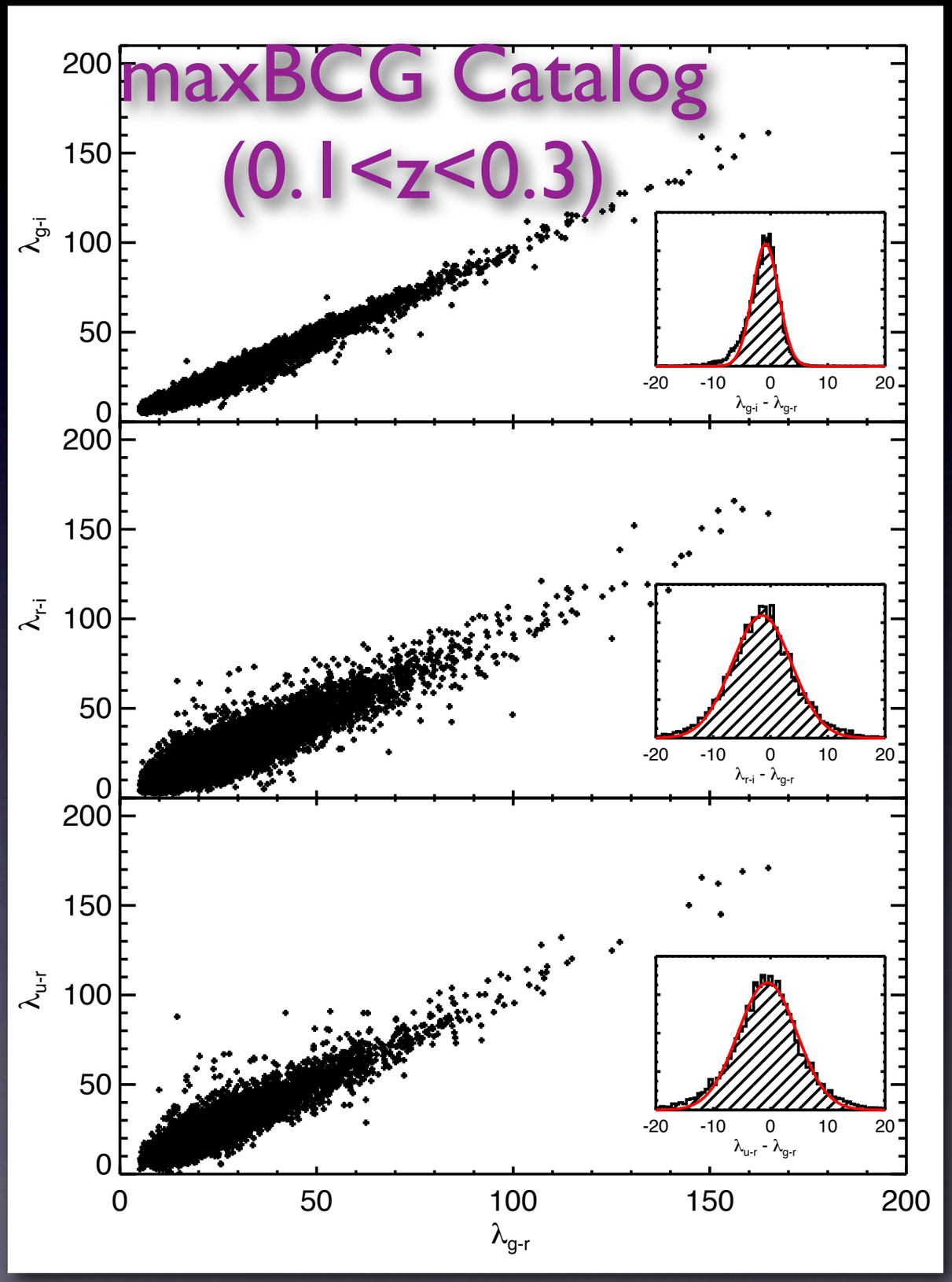
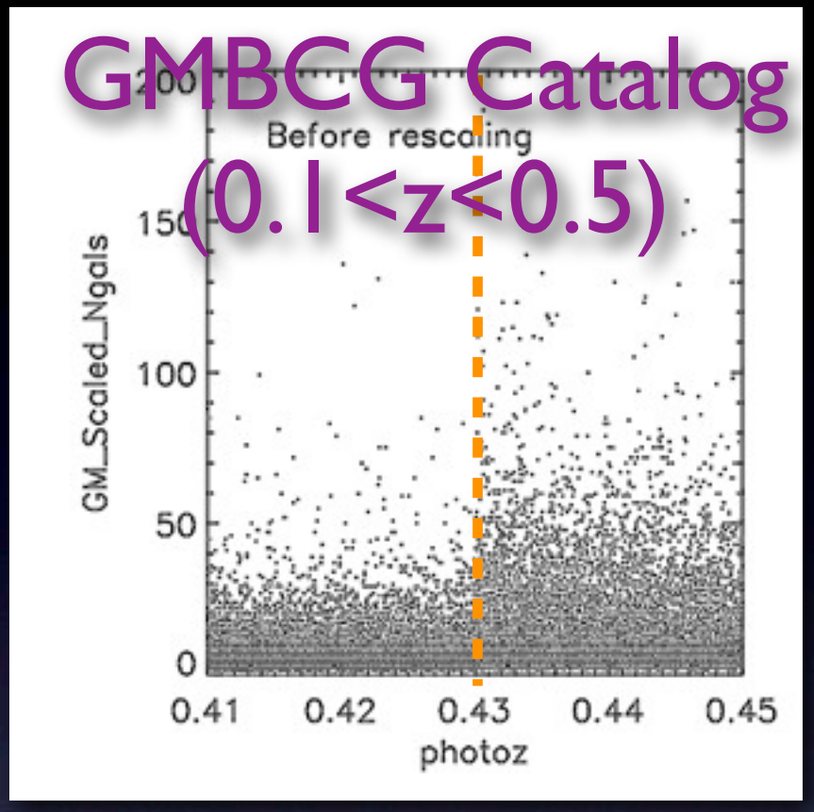




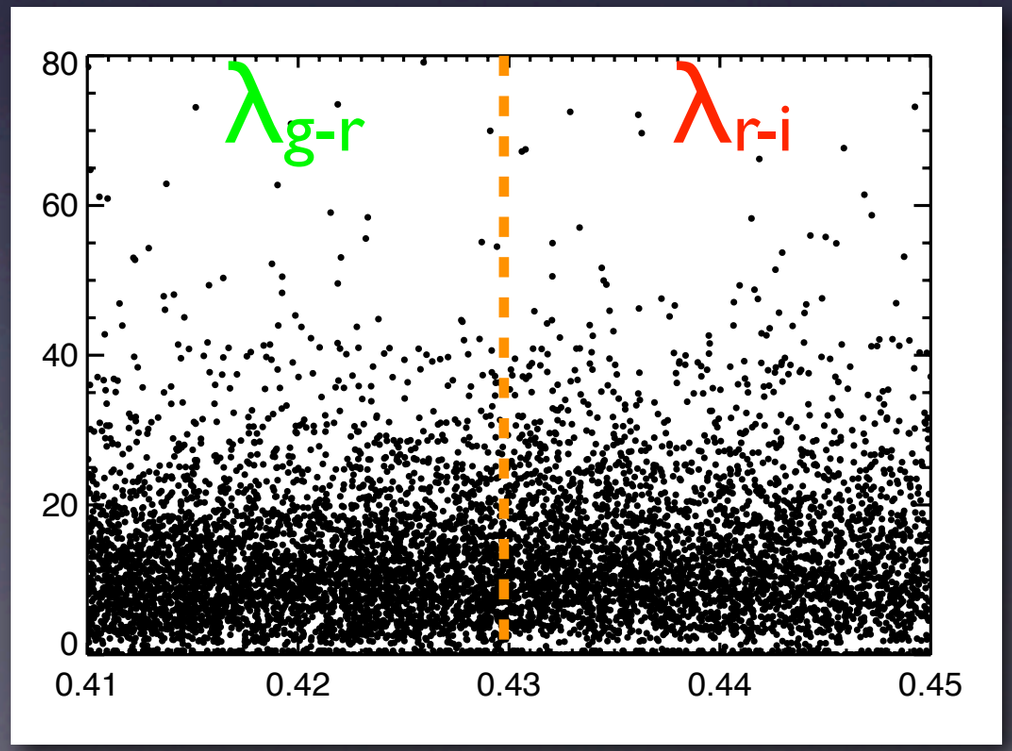
Hao+10

Robust To Filter Changes





Hao+10



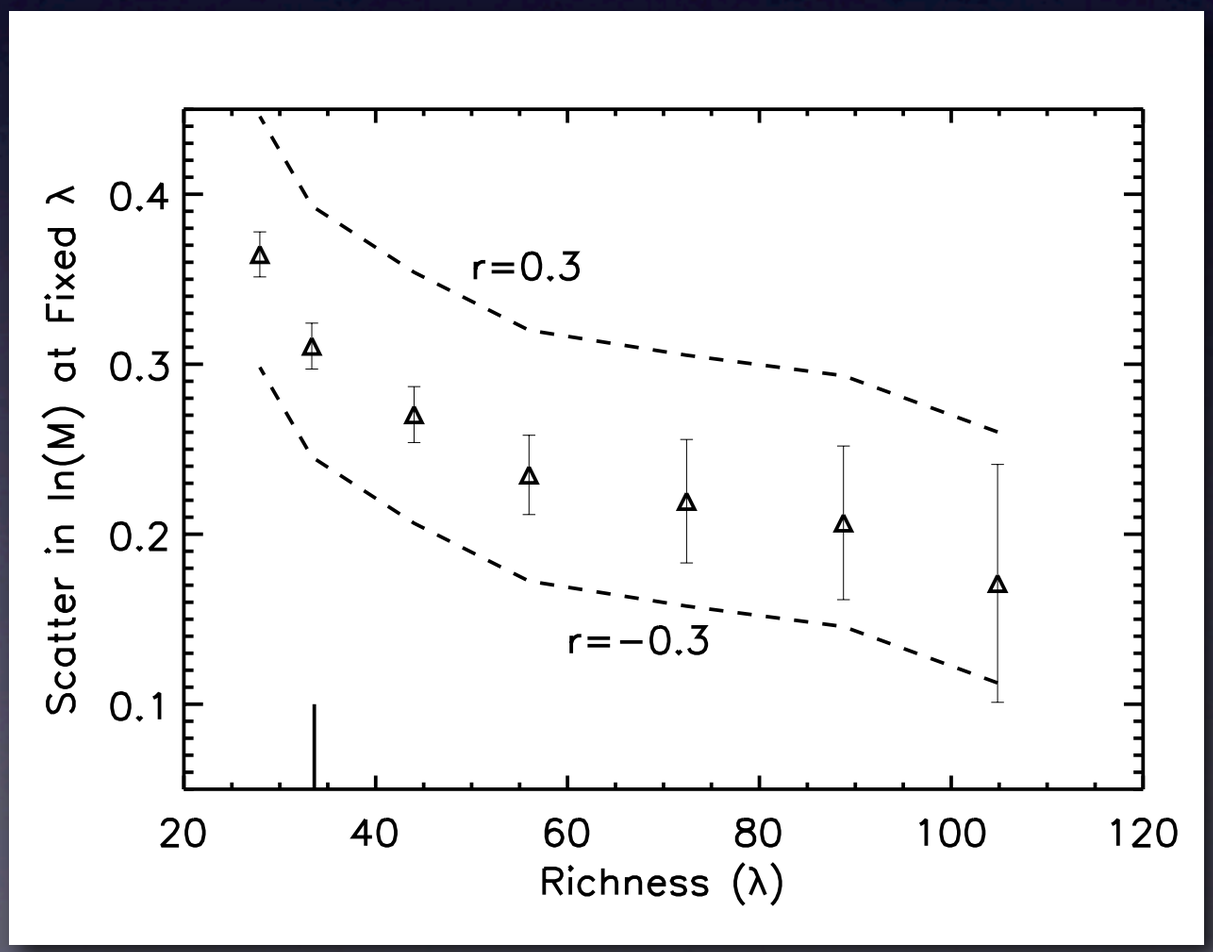
Comparing λ

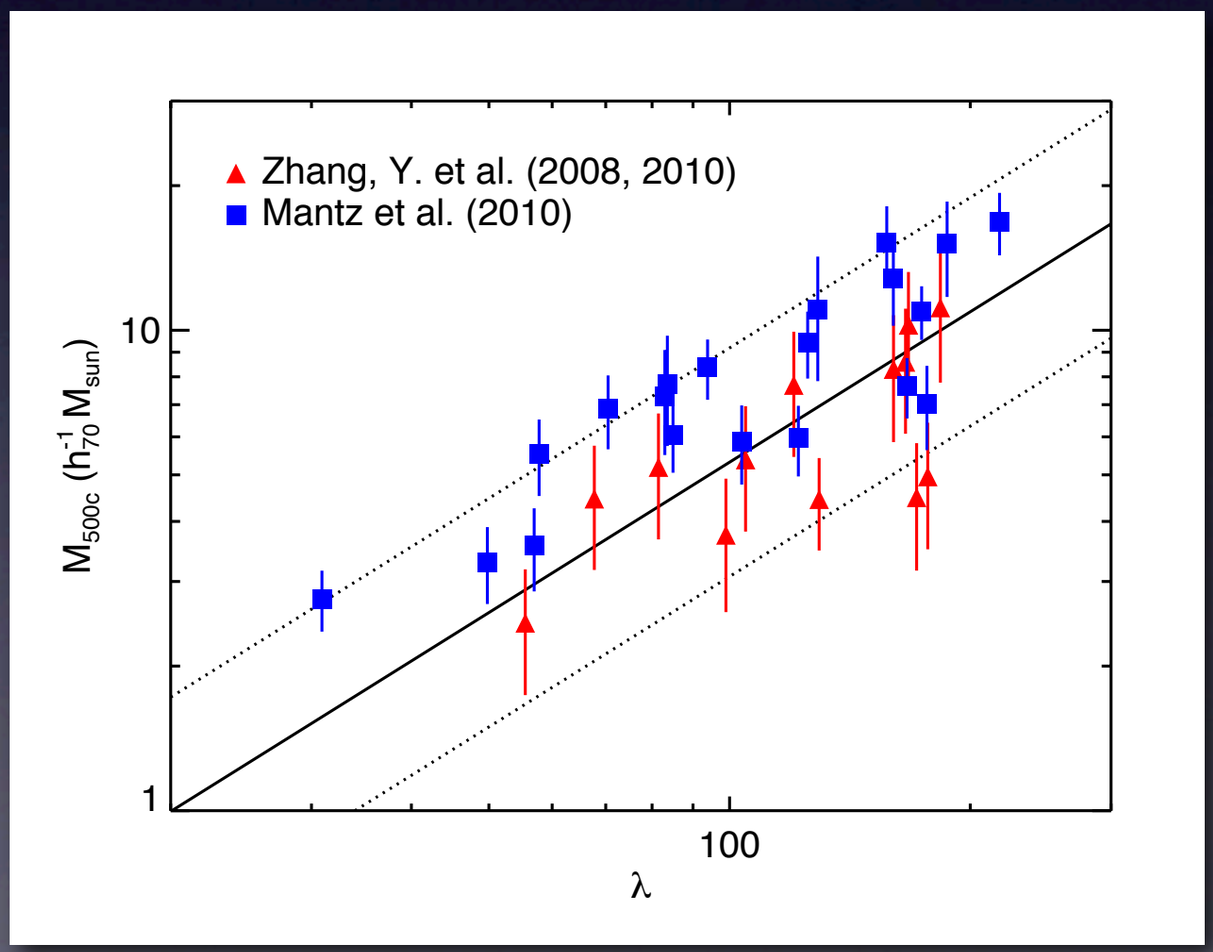
- How does (improved) λ compare to other richness estimators?
  - Red sequence measurements do well
  - photo-z based estimates (e.g. N_{WHL}, Wen et al. 2009) can be noisy
- Weighting λ by galaxy luminosity increases scatter
- We think λ is the best

Richness	$\sigma_{\ln L\|N}$
λ	0.62
N_{200}	0.86
$\Lambda_{Postman}$	0.92
Abell	1.15
B_{gc}	0.71
N_{WHL}	0.88

Mass Scatter in λ

- Use abundance matching to get mass scale
  - Infer mass scatter from LX scatter, depends on covariance
- Test with clusters with X-ray masses





Rykoff+11

redMaPPer Cluster Finder

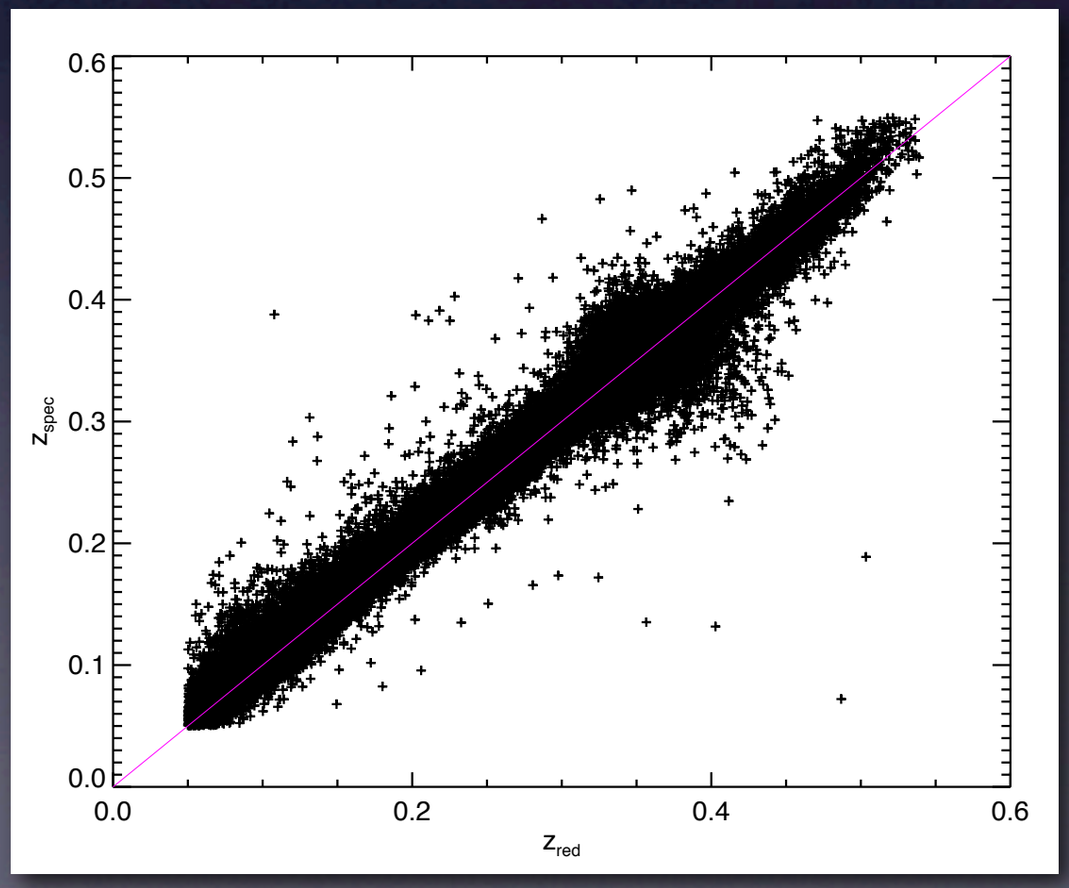
redMaPPer

- Red sequence Matched-filter Probabilistic Percolation algorithm and catalogs
  - Based on the λ richness (Rozo+09; Rykoff+11) optimized to minimize scatter in L_X-richness
- Centering Algorithm is independent module
- Have run on DR8; Stripe 82; Stripe 82 mocks & DES mocks (Wechsler, Busha)
- ~36 CPU hours for 200 deg^2 of DES depth

redMaPPer Calibration

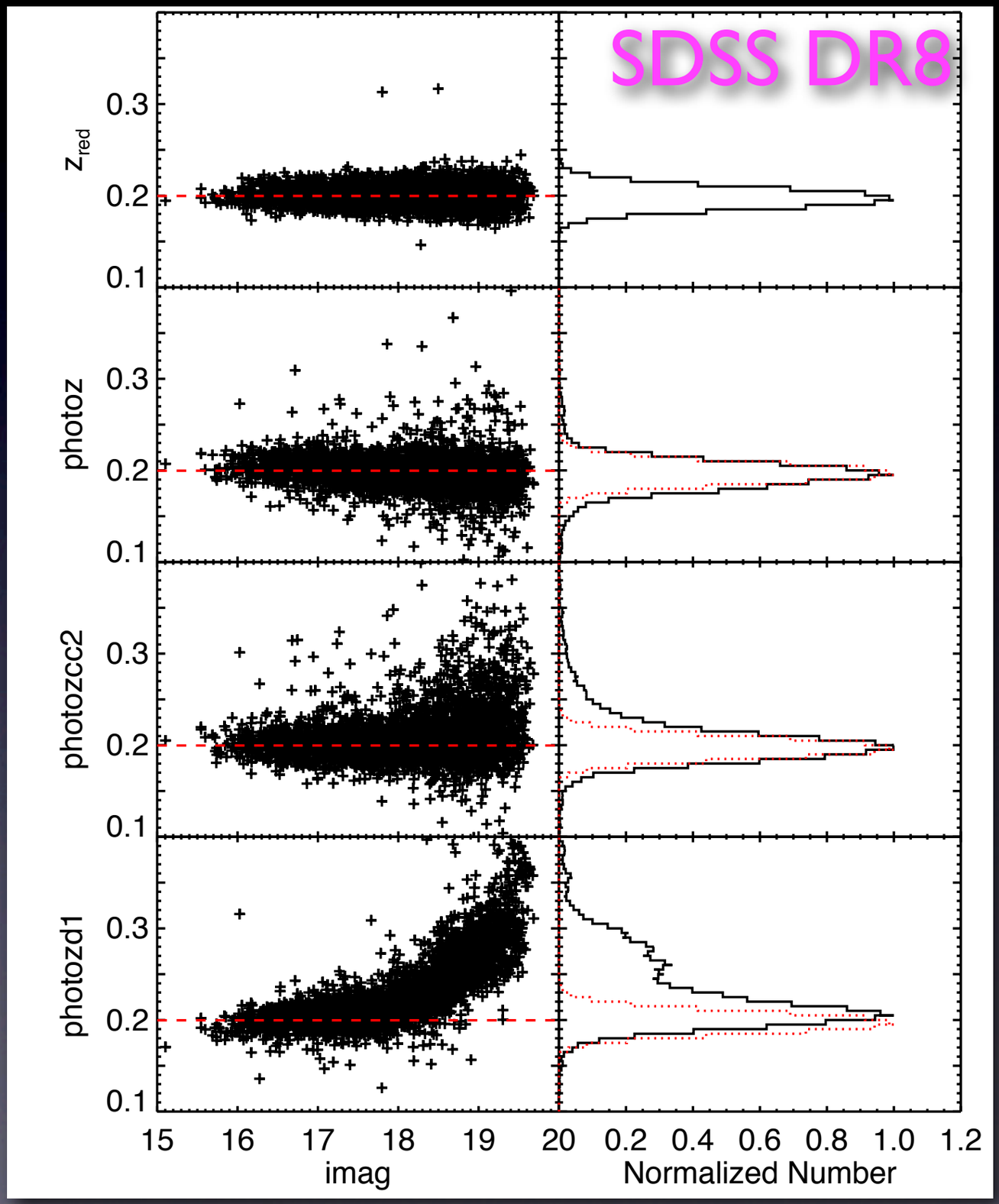
- Data-driven red sequence calibration
- Photometric redshift "z_{red}"
  - Works for red galaxies; crap for others
  - Models red sequence in *N* colors (e.g. *u-g*, *g-r*, *r-i*, *i-z*) with linear model with tilt + full covariance

- Can select purity or completeness threshold red galaxy samples
- Compared to SDSS spectra, works ~better than SDSS photoz



Photometric Redshifts

- For cluster galaxies, traditional photozs can break down
  - Faint red galaxies not well-represented in training samples
- Using clusters we can greatly improve the training/redshift estimation for cluster galaxies



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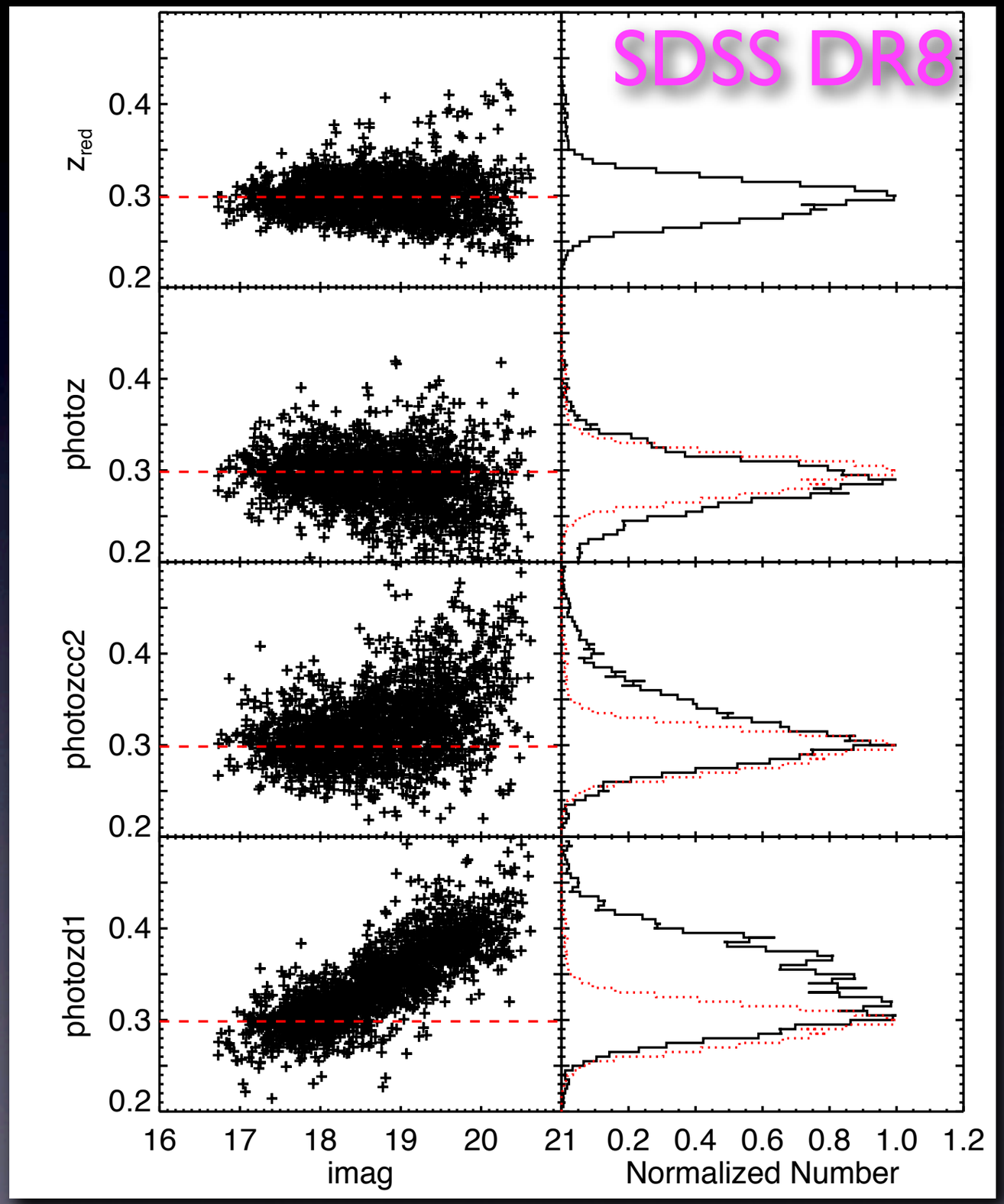

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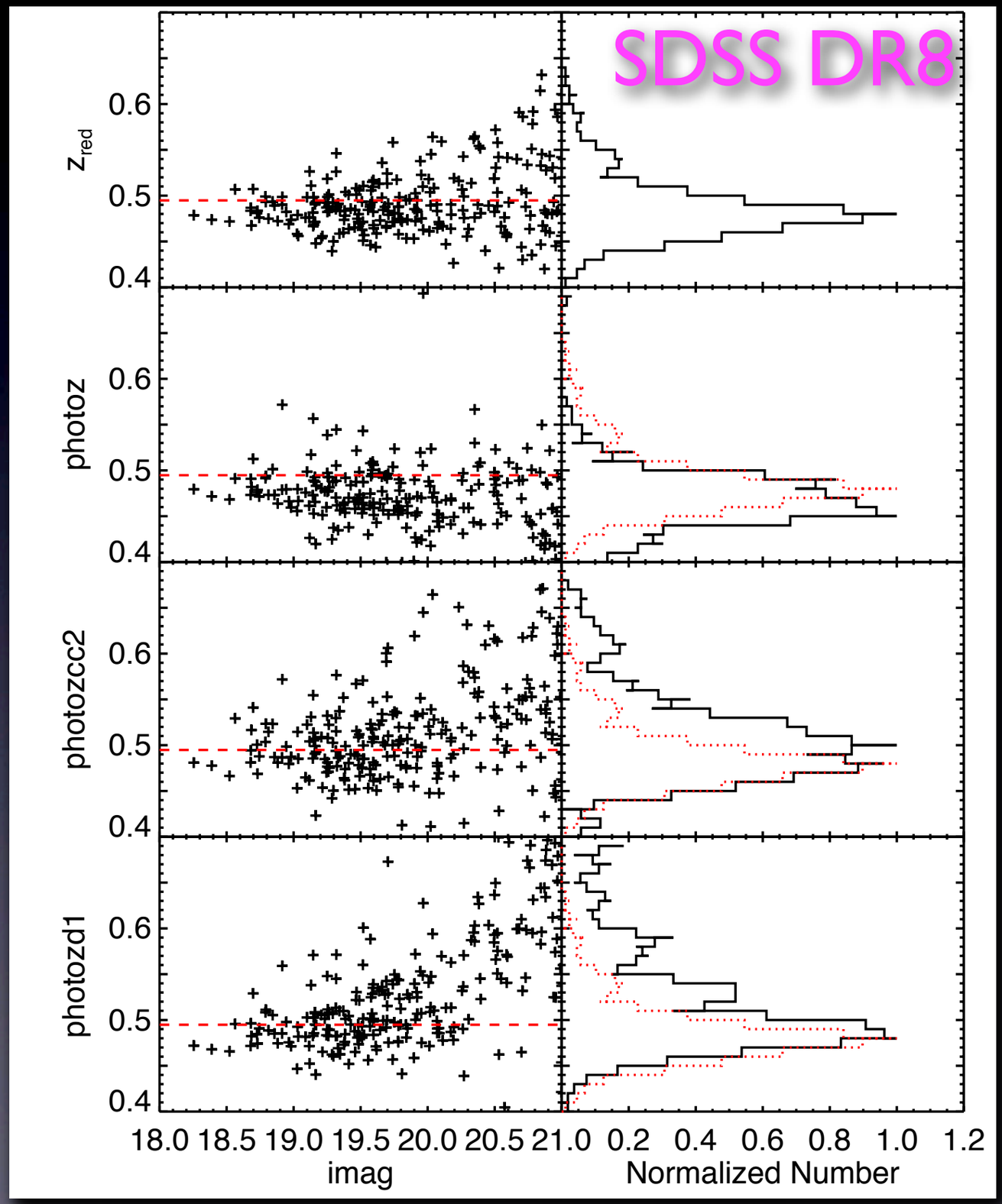


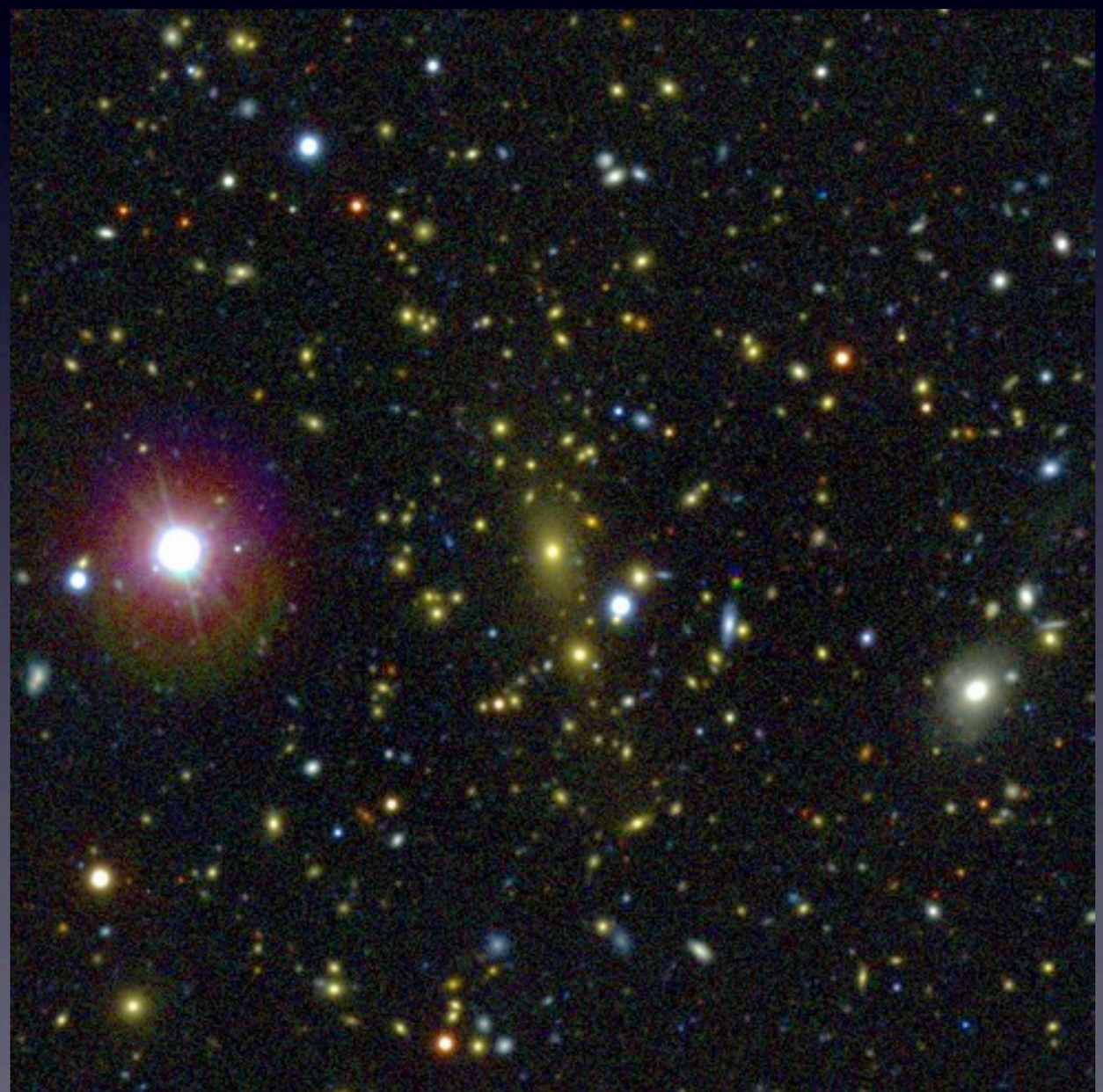
redMaPPer

- Every galaxy brighter than 0.2L* at z_{red} is a potential center
- Color filter is now a χ^2 filter: how well does each galaxy fit color model at cluster redshift?
  - A true 4D color model is not possible because background estimation doesn't scale
- Galaxies are ranked by combined likelihood of neighbors and central galaxy

Running on Stripe 82

The Cluster Catalog

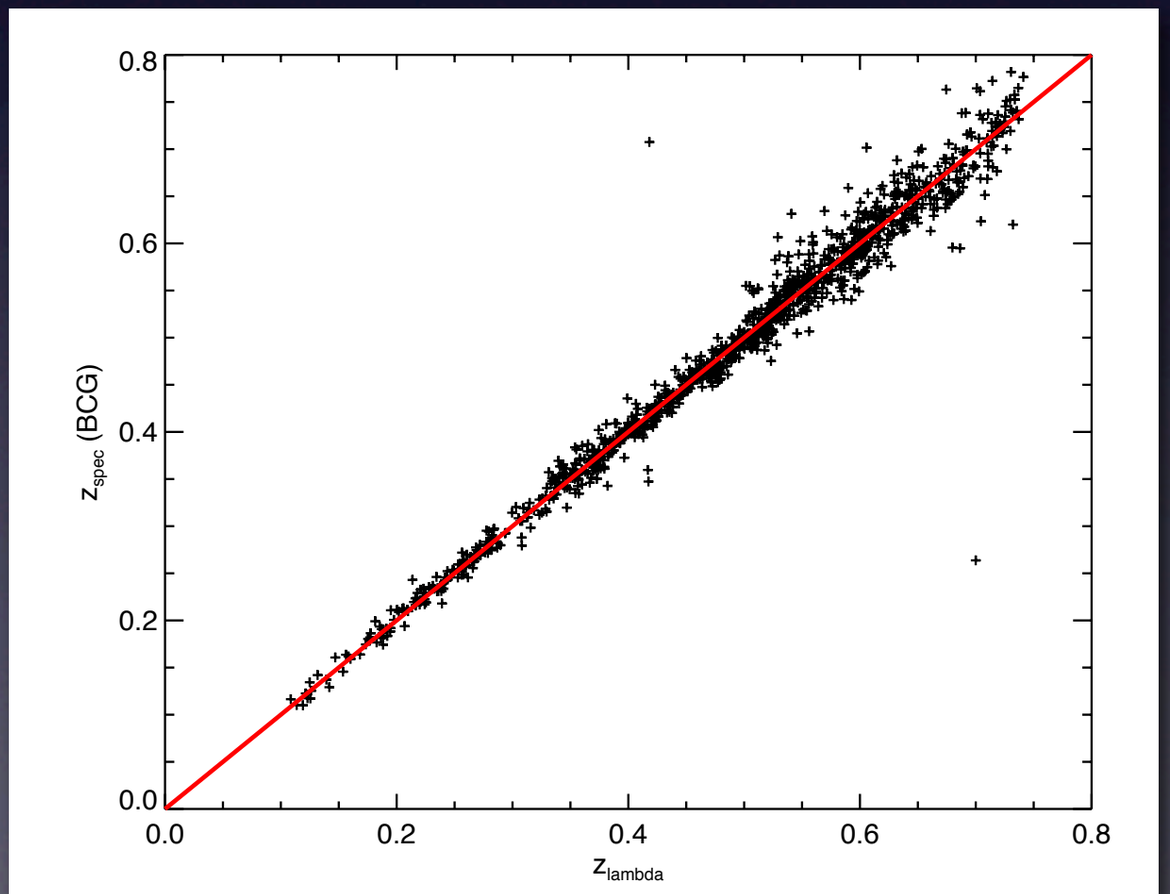
- Full Stripe 82, 0.1<z<0.6 for lensing analysis
- Use DR8 LRGs for initial training, plus some extra "BCG" spectroscopy

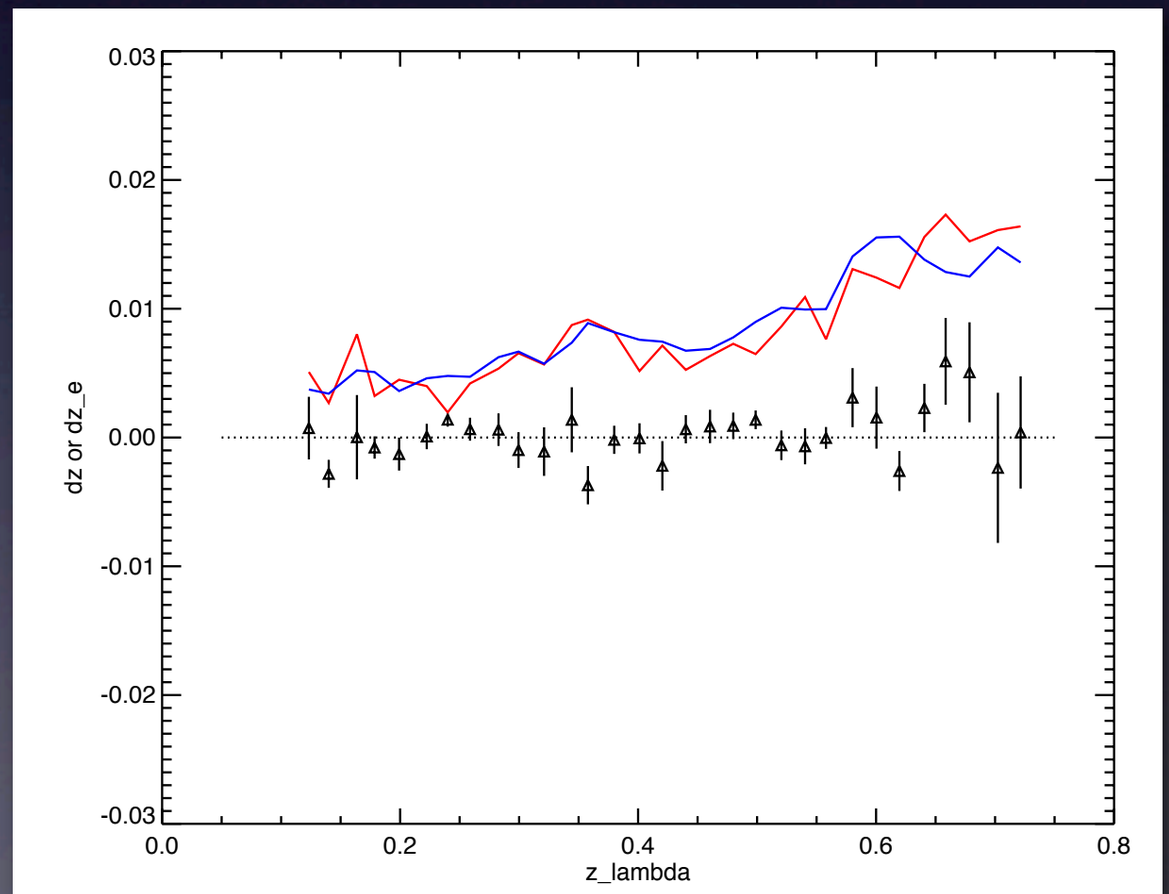


z=0.28

Cluster Redshifts

- Use mean color of cluster galaxies to estimate redshift
- Redshifts are precise and robust



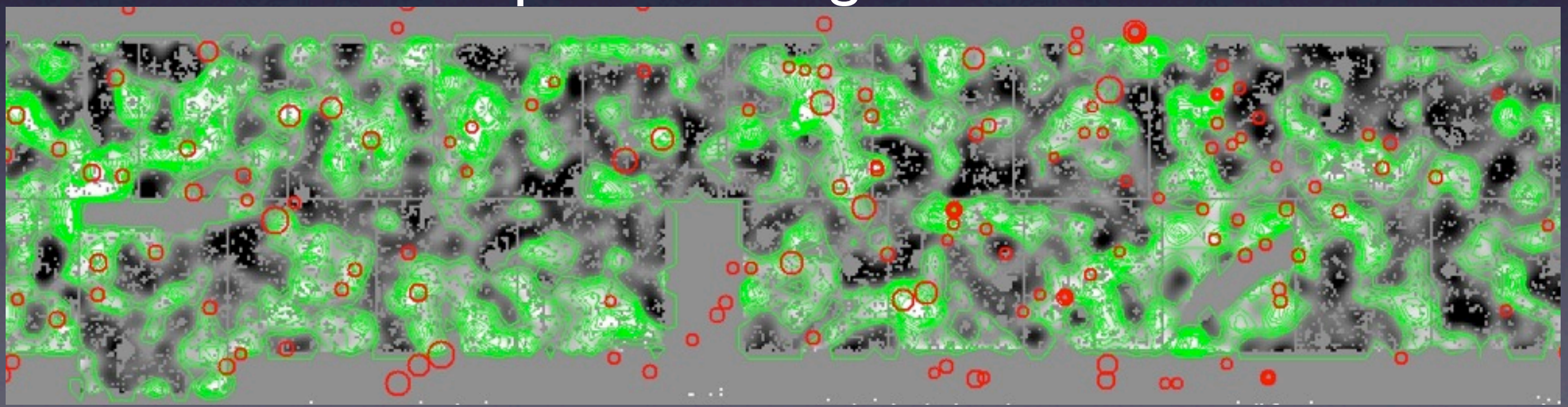


Using the Radial Profile

- What is the optimal centering algorithm?
  - Not all clusters have well-defined centers
  - Would be nice to quantify substructure
  - But we can still quantify "better" for a large cluster catalog
- Use the lensing profile to compare multiple centering algorithms
  - Larger shear signal near center means better centering
  - Work pioneered by Matt George on COSMOS data for groups
    - BCGs work better than X-ray centers!

CS82

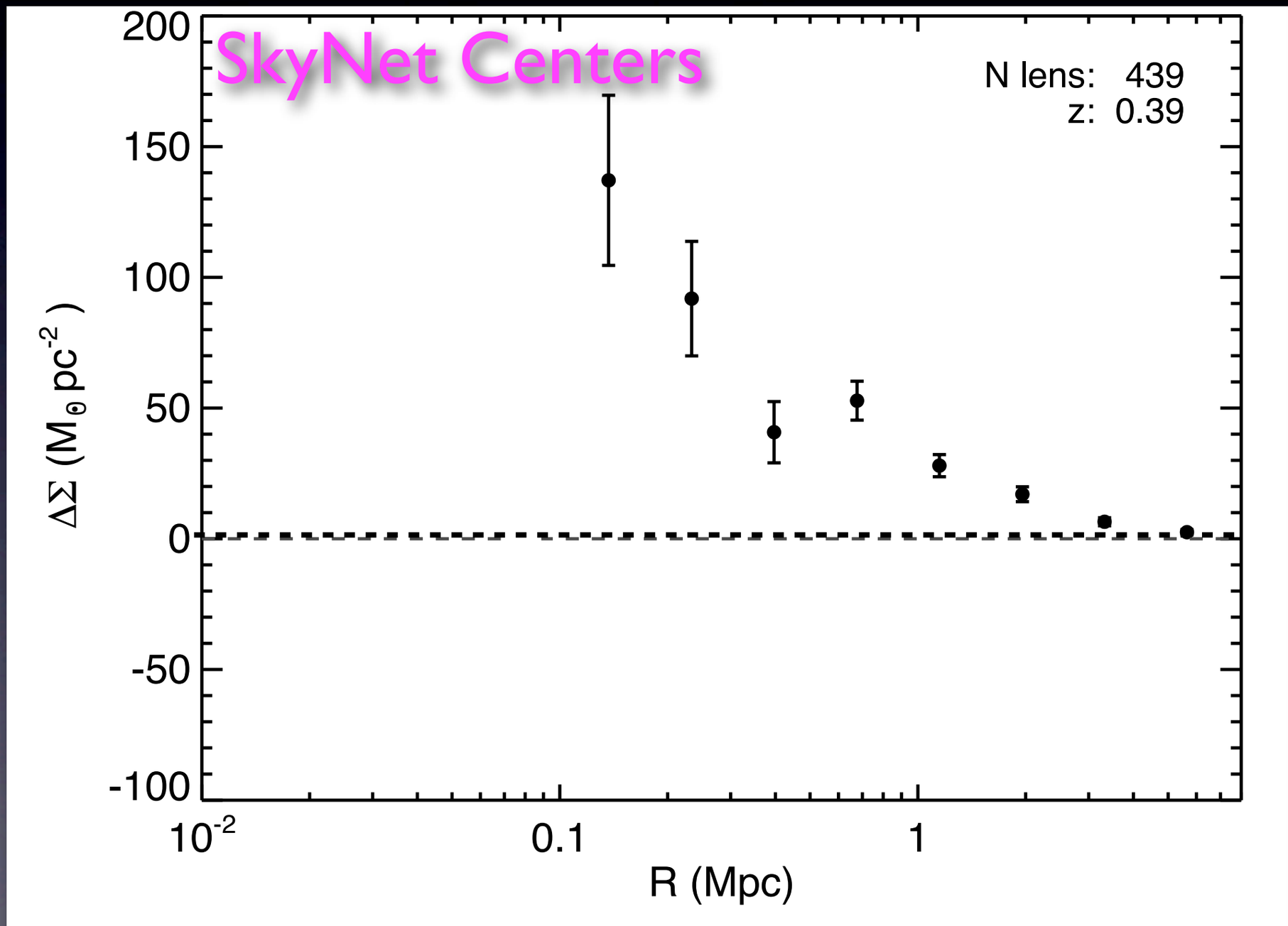
- Deep i-band (i<23.5) imaging of Stripe 82 with CFHT
  - PI: Jean-Paul Knieb
    - Alexie Leauthaud leading the work
  - -1°<Dec<1°
  - ~120 square degrees after masking
- For Stripe 82 lensing studies



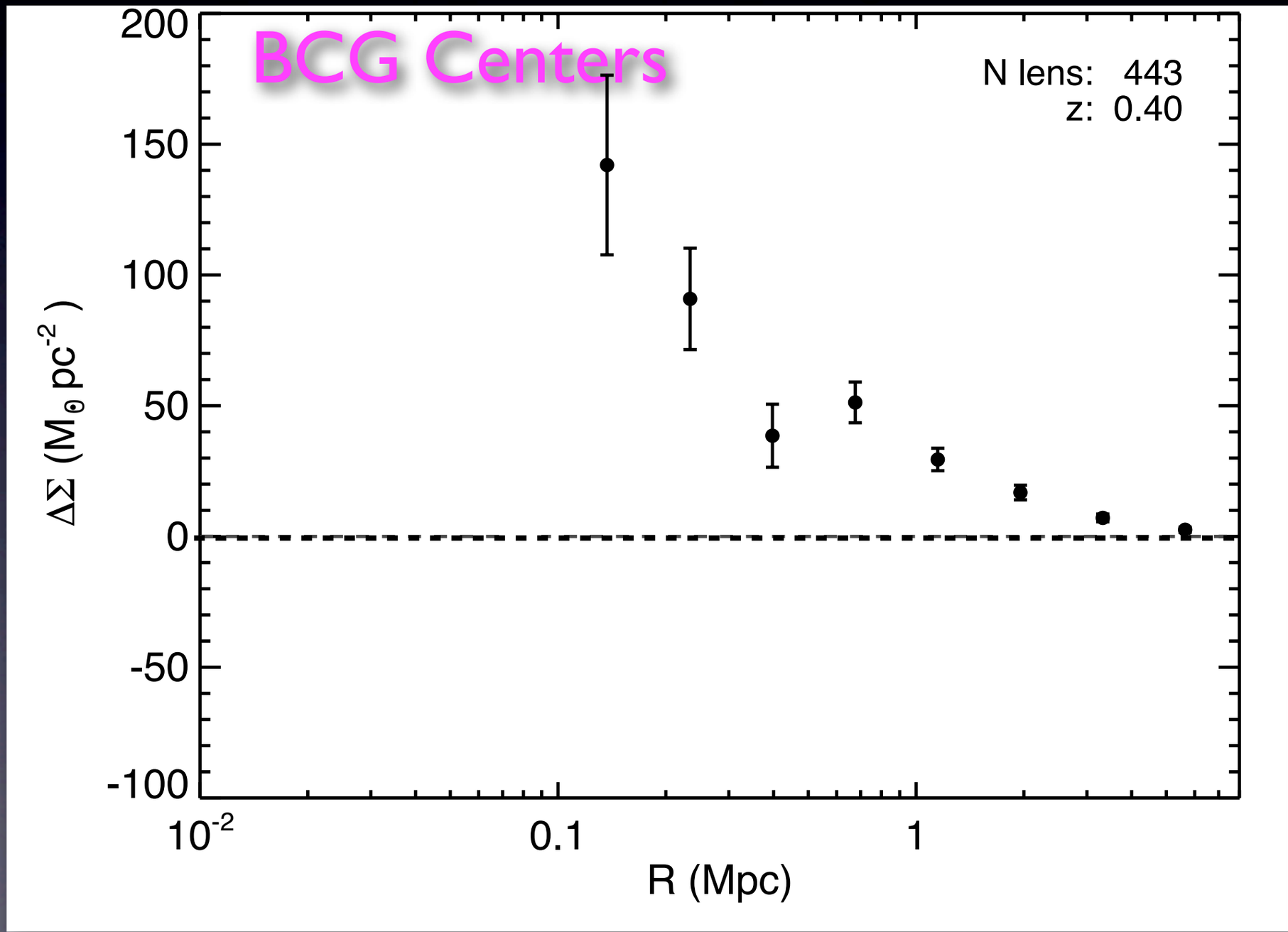
κ map from C. Welker

Radial Profiles

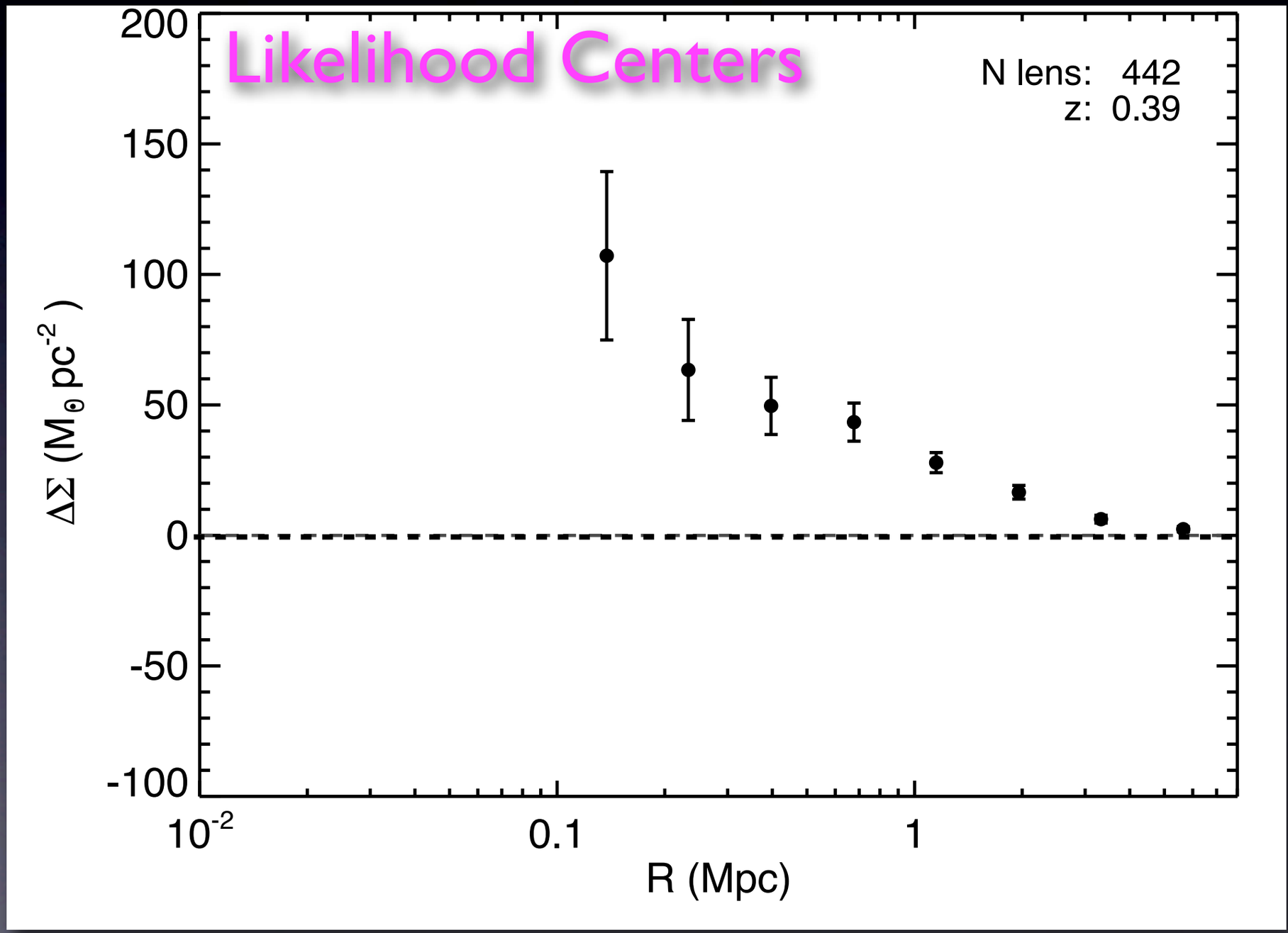
- "SkyNet" network-based centering (Nord, McKay)



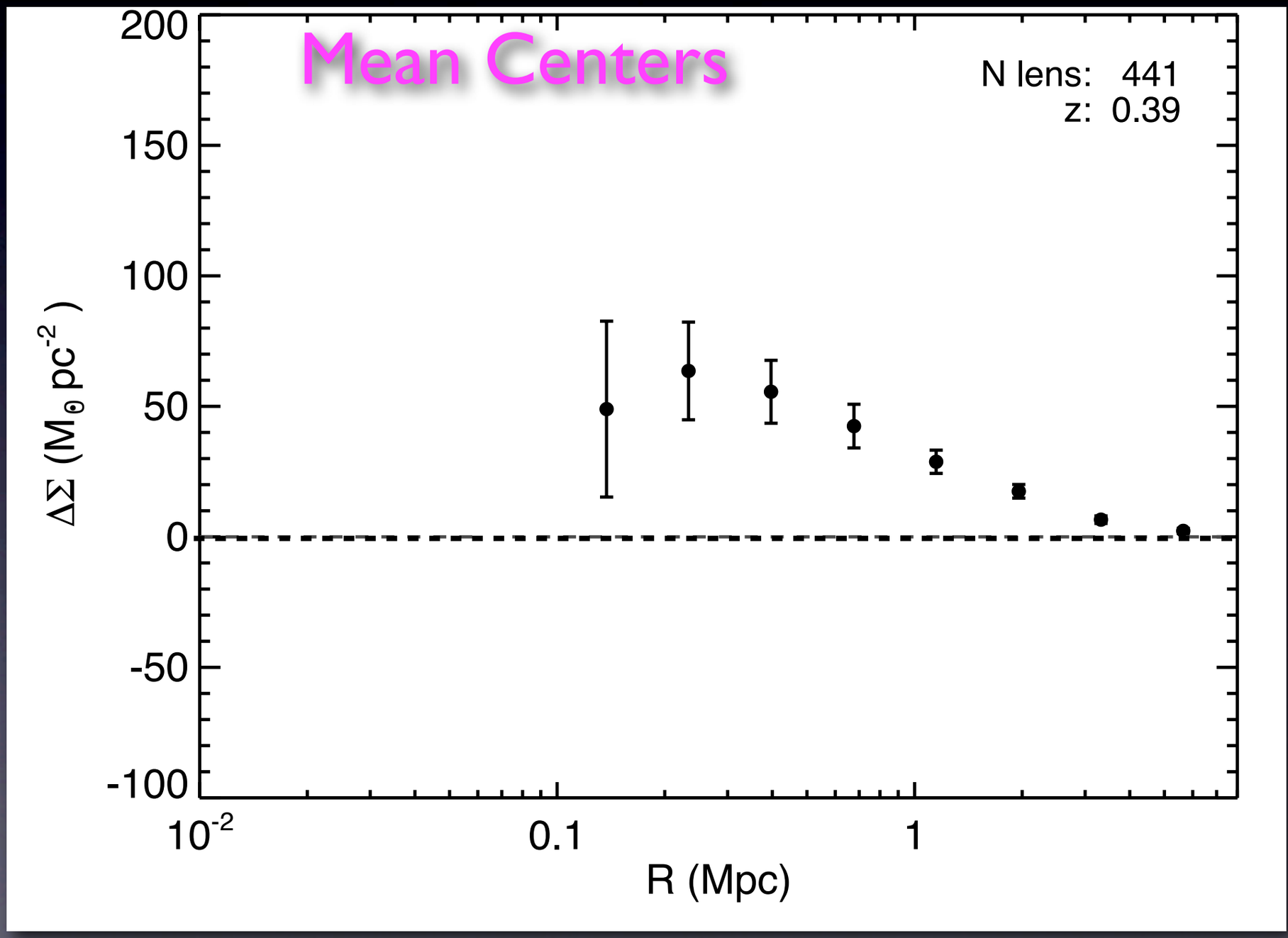
Radial Profiles



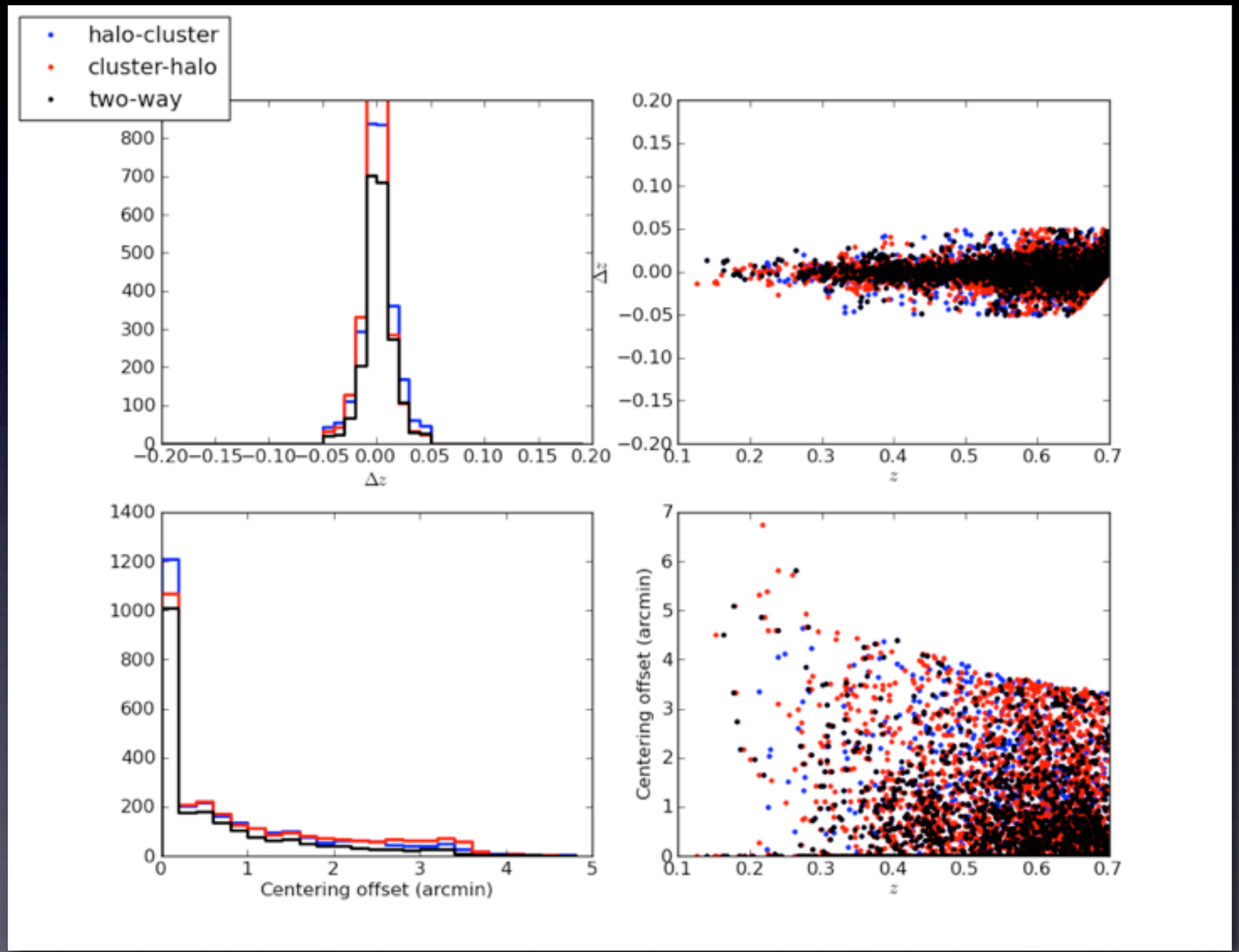
Radial Profiles



Radial Profiles



Centering on Mocks



Conclusion

- redMaPPer will build a cluster catalog that achieves our goals for precision cosmology
  - High purity & completeness
  - Excellent redshift estimation
  - Reduced mass scatter
  - Well understood centering
- DES Clusters will constrain growth of structure with unprecedented precision
  - Additional cross-correlation will also help
    - SPT & Planck SZ
    - eROSITA X-rays

One more thing...

- For you iPhone/iPod touch owning cosmologists, there is an app for that!

GravLensHD

CosmoCalc