Cosmological Constraints Using Multi-Wavelength Observations of Galaxy Clusters

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UCSB

Berkeley Cosmology Group
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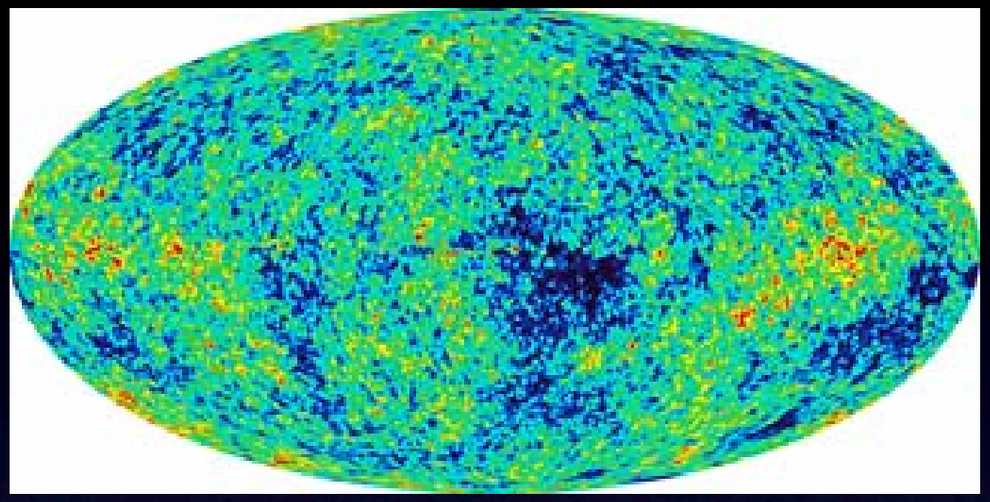
Outline

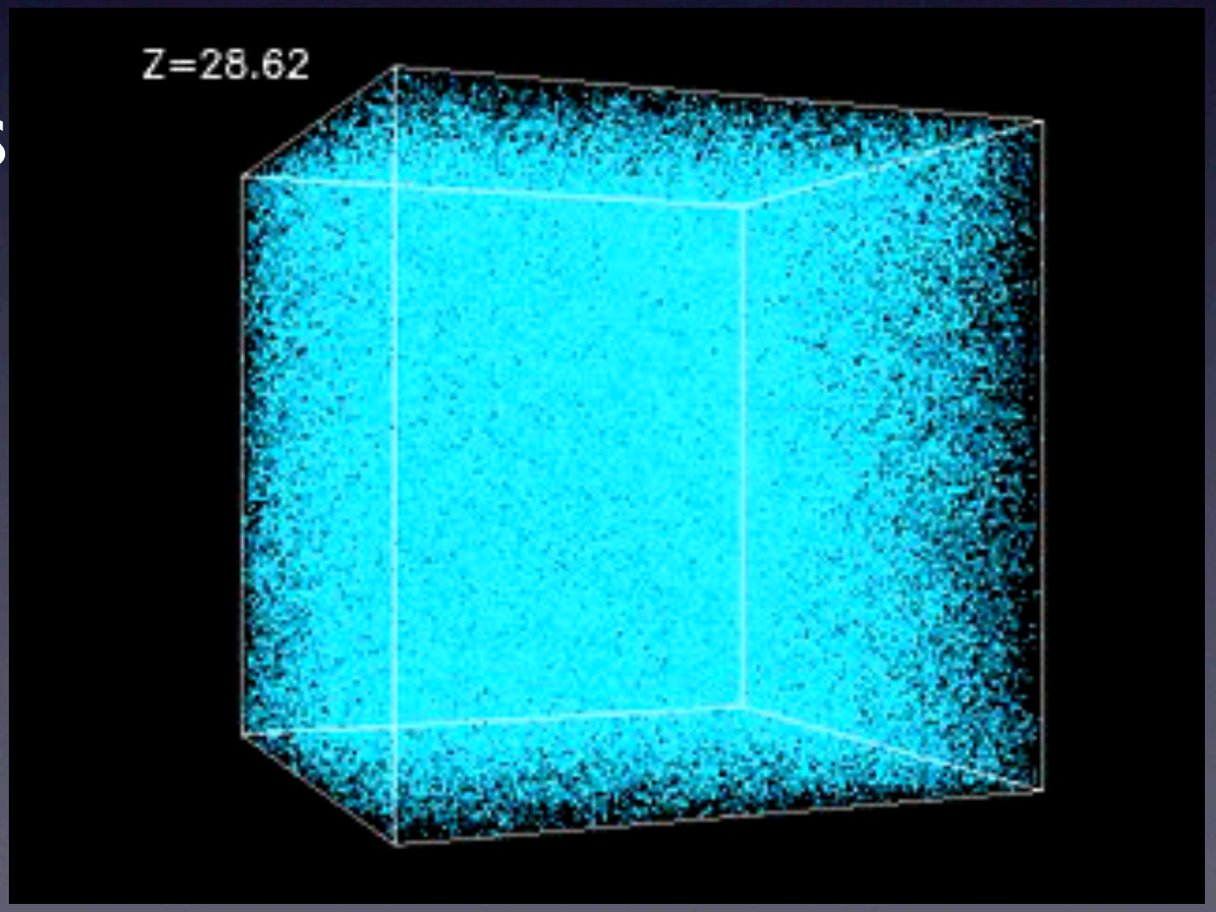
- Galaxy Clusters as cosmological probes
- The SDSS maxBCG cluster catalog
- X-ray and weak lensing observations
- Cosmological constraints
- Improving our richness estimator

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



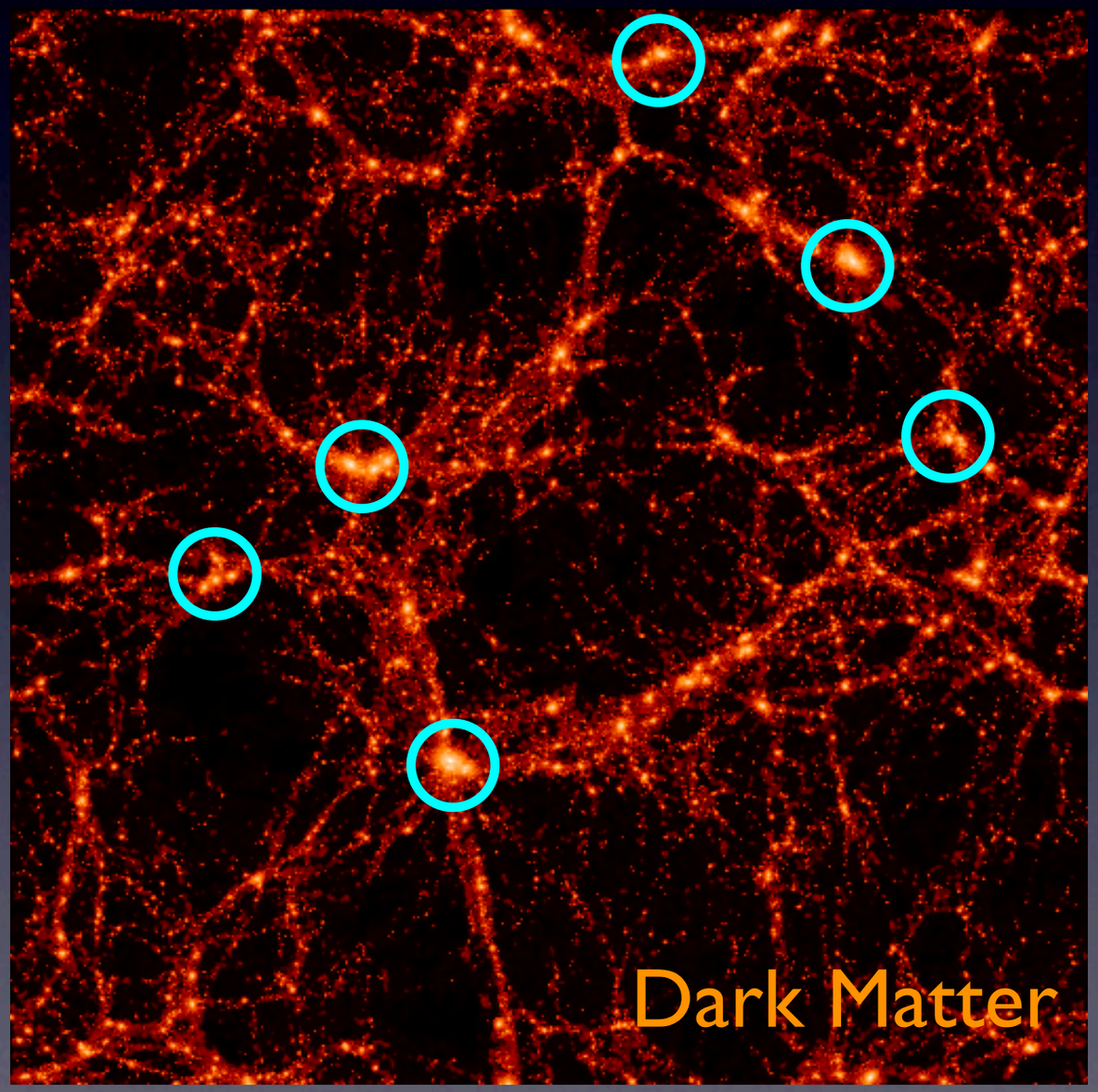
CMB from WMAP



Simulation from Andrey Kravtsov

Dark Matter Halos

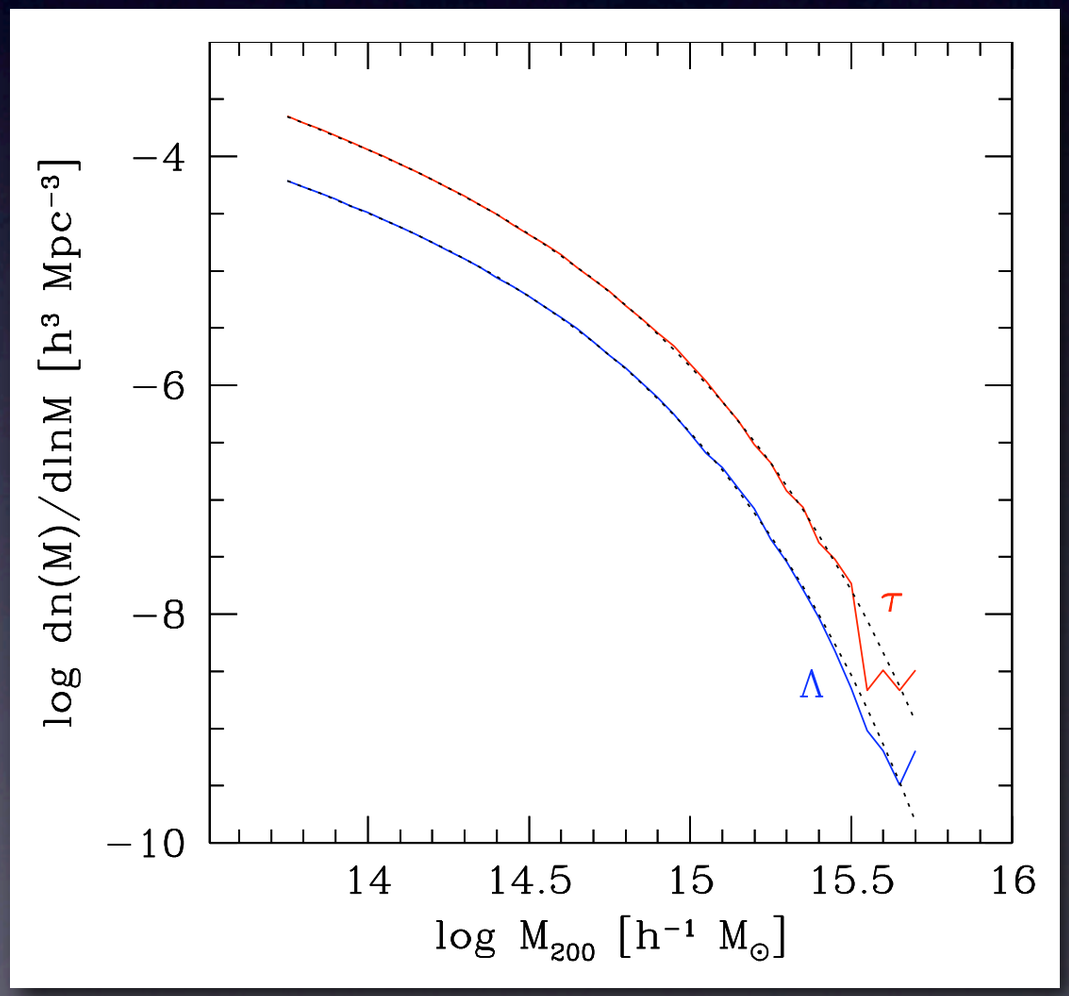
- Dark matter halos are large peaks in the matter density
  - Find the peaks on a chosen scale
  - r_{200}, radius of a sphere with mean density $200\rho_{crit}$
- We see these halos because they are lit up by luminous baryons



Virgo Consortium HV sims

Halo Mass Function

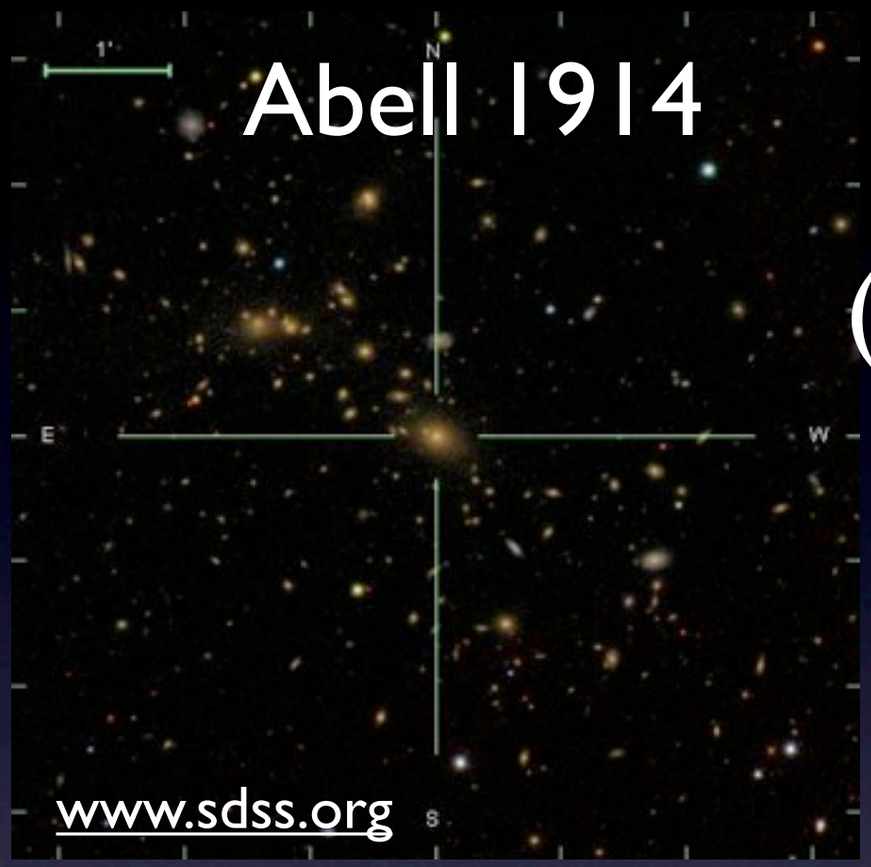
- Number of halos as a function of mass and redshift: $n(M,z)$
  - Predicted with simulations
  - Shape and normalization sensitive to cosmology
- M_{200}: mass within a sphere of radius r_{200}
- Mass function depends on cosmological parameters including Ω_m and σ_8, the normalization of the power spectrum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



Evrard, et al., 2002

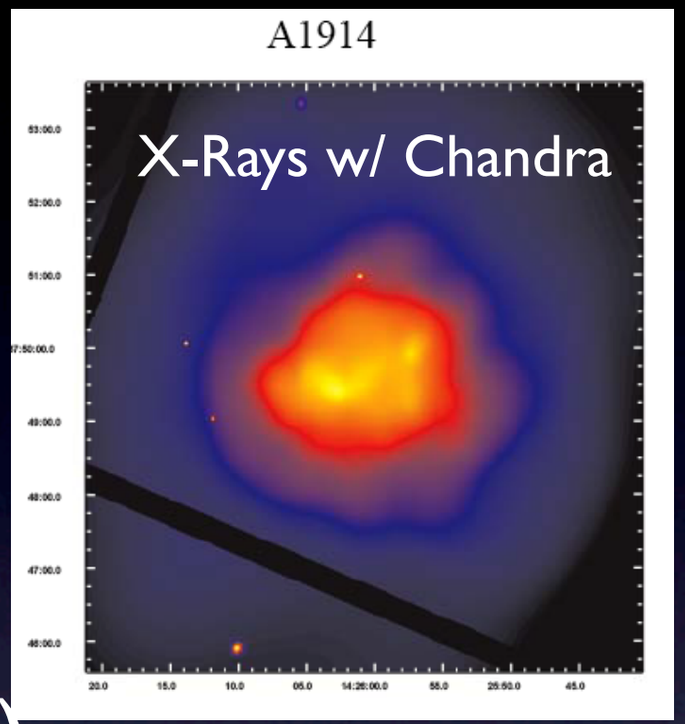
But...we can't actually measure halo mass directly

Multi-Wavelength Clusters

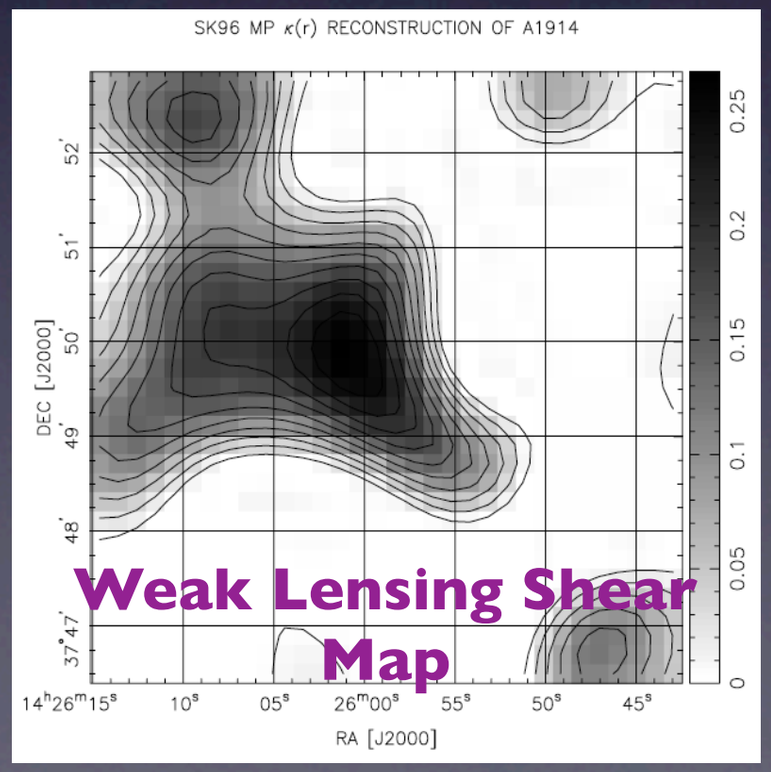


Cluster of Galaxies
(~2% of mass)

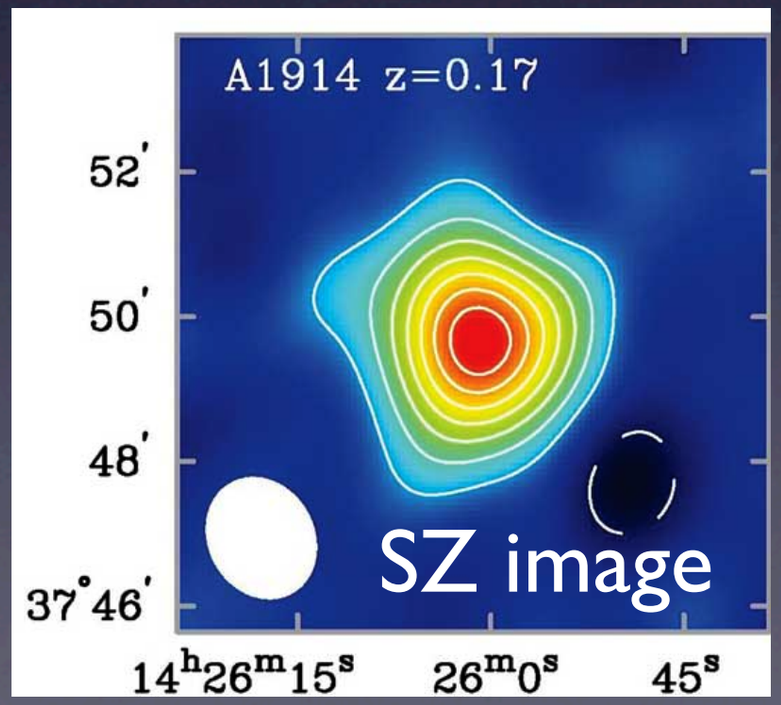
Ball of Hot Gas
(~15% of mass)



Jeltema et al. 2005



Dark Matter Halo
(~85% of mass)



Dahle et al. 2002

Carlstrom et al. 2002

Finding/Measuring Clusters

- Cluster Finding:
  - Optical selection of clusters of galaxies
  - Finding extended X-ray sources
  - Detecting SZ decrement in CMB
- Cluster mass tracers:
  - Optical richness: an optical mass tracer: counting galaxies or luminosity
  - Velocity dispersions of galaxies (requires spectra)
  - Weak lensing shear
  - X-ray luminosity/surface brightness
  - X-ray temperature and profile

maxBCG Catalog Properties

- Red-sequence photometric catalog from SDSS DR5 (Koester et al. 2007a, 2007b)
  - ~17,000 Clusters in 0.5 Gpc^3, $0.1 < z < 0.3$
  - Approximately volume limited
  - Photo-z accuracy: $\Delta z/z < 0.02$
  - Completeness & Purity > 90%
  - 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 Observations

- ROSAT All-Sky Survey (RASS) data
  - 0.1-2.4 keV, covers whole sky
- RASS has been used for X-Ray flux-limited cluster surveys
  - NORAS cluster survey (Böhringer, et al, 2000) overlaps maxBCG region
  - 89 maxBCG Clusters in NORAS
- Cross-correlate other ~17,000 maxBCG clusters with X-ray photon map
  - How do maxBCG clusters compare to X-Ray selected clusters?

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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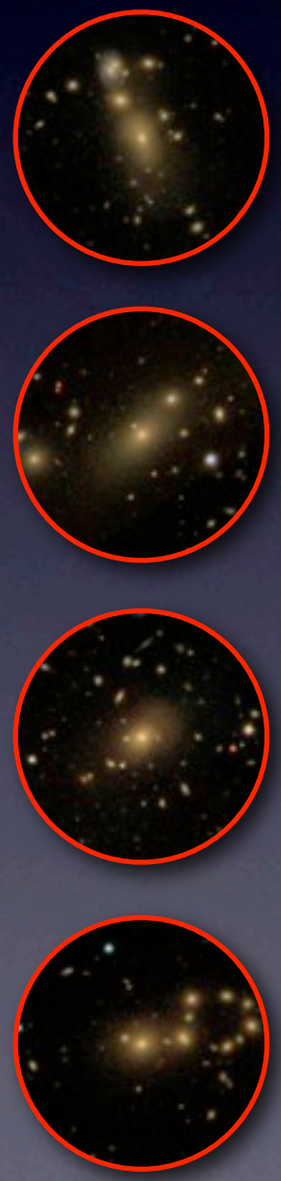
SDSS



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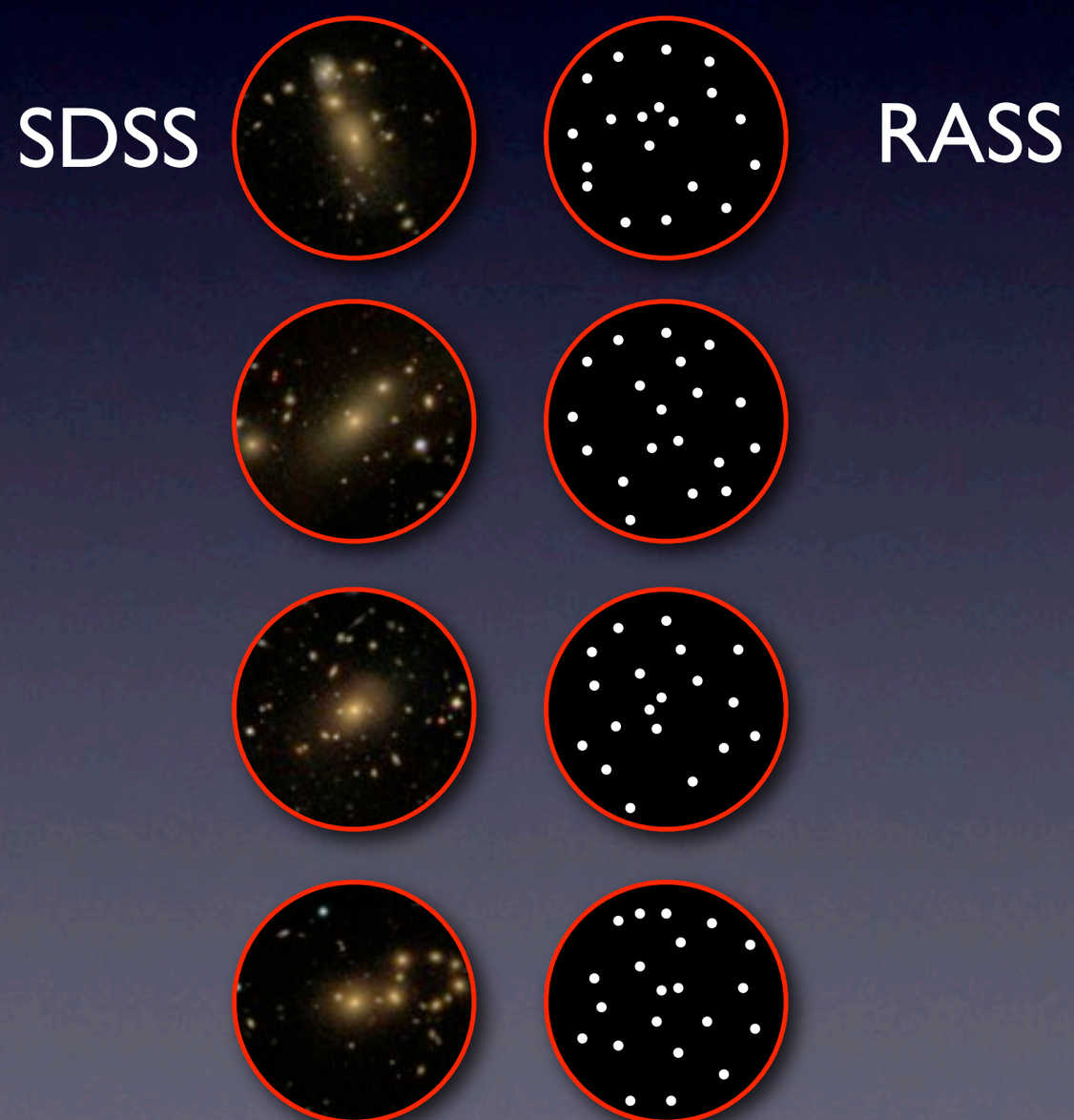

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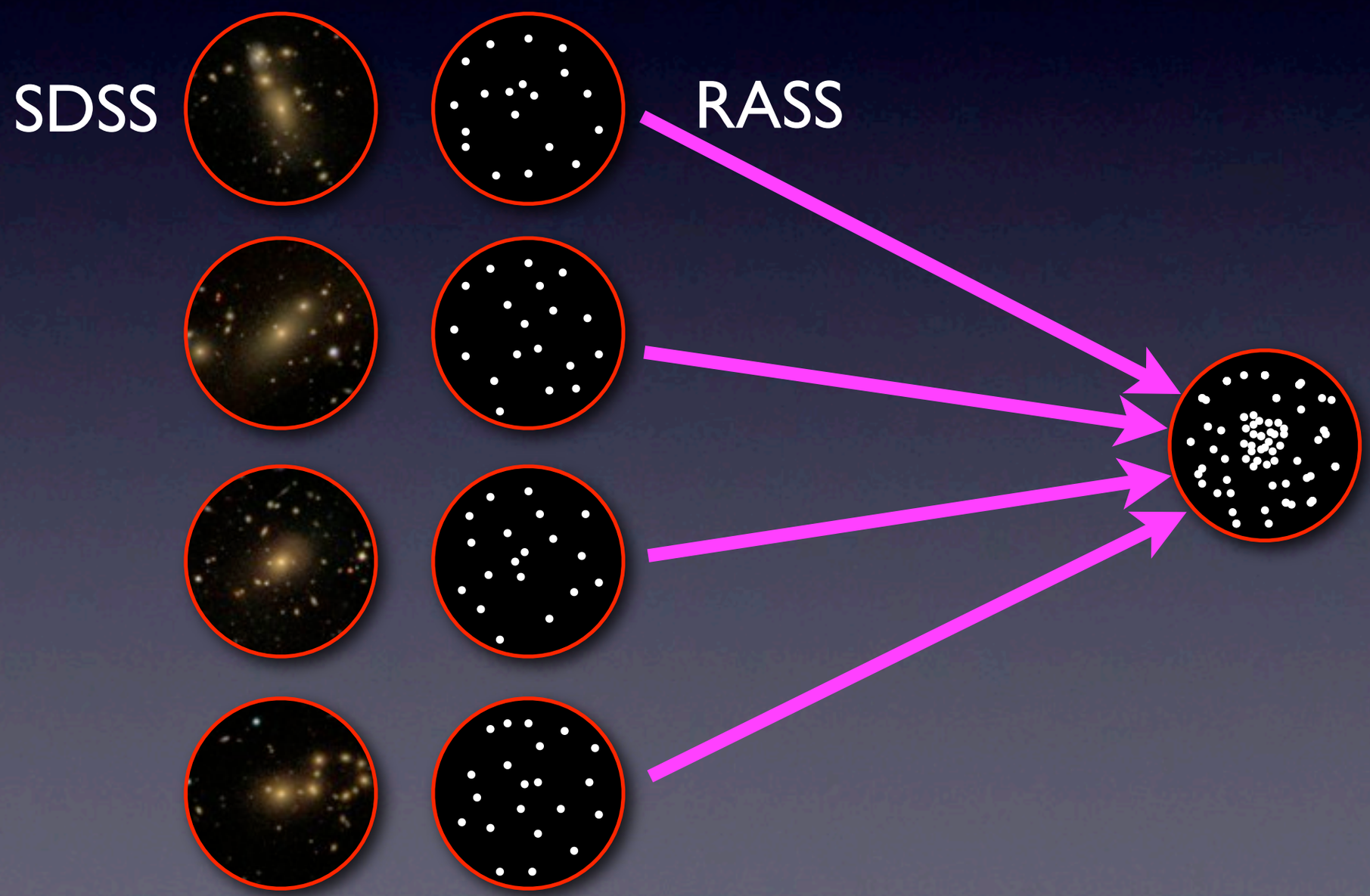
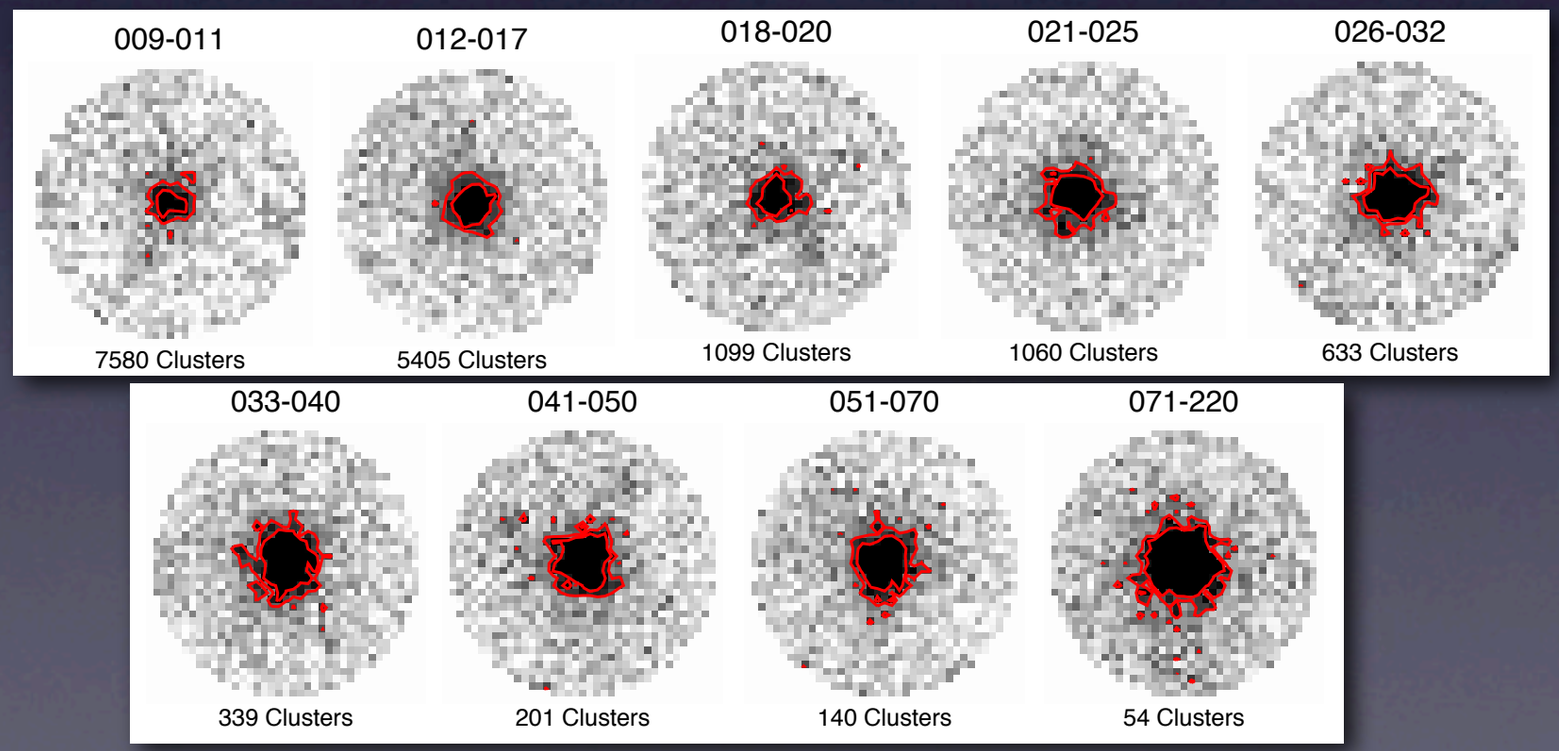


Stacking Method

- 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, et al. 2008a

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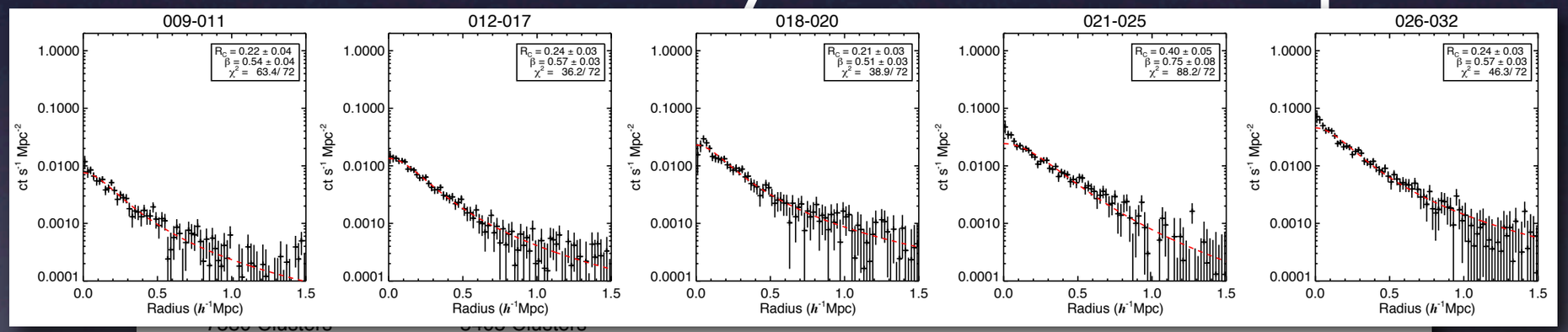
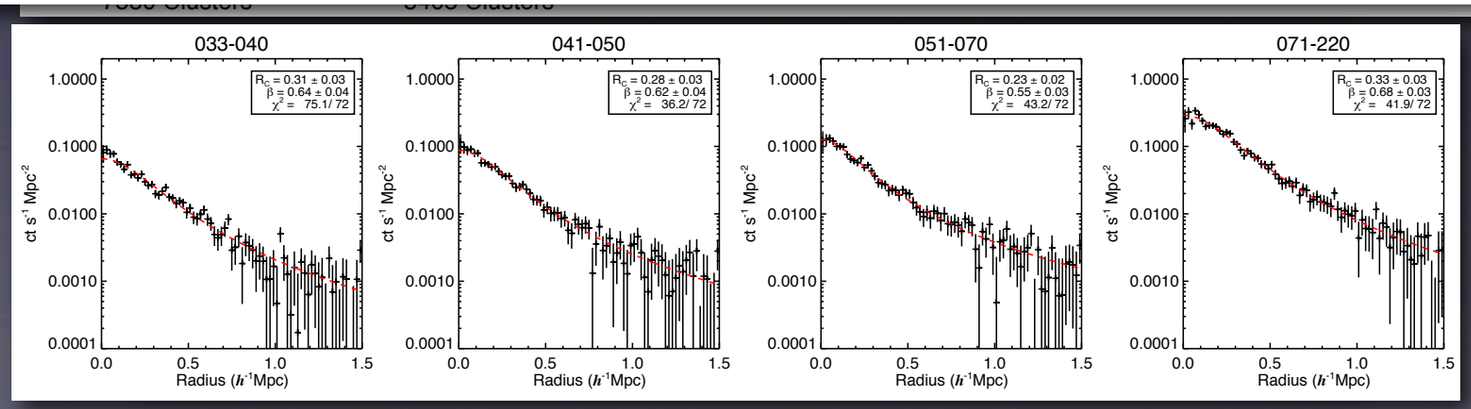




Rykoff, et al. 2008a

Scatter in L_X-N_{200}

- There is significant scatter in the L_X-N_{200} relation
  - This shifts the mean (stacked) relation
- Assume a log-normal distribution:

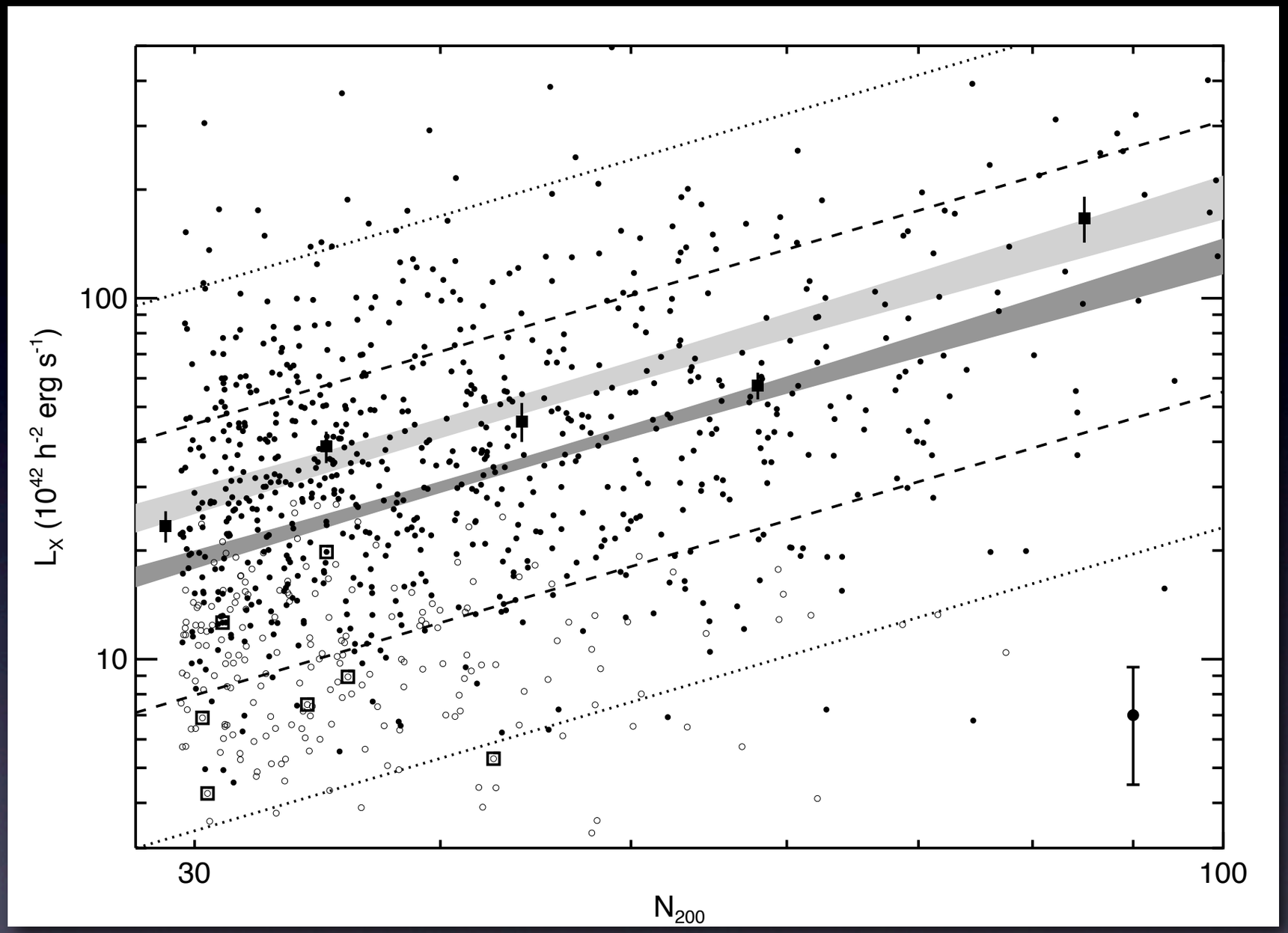
$$p(L|N_{200}) = \frac{1}{\sqrt{2\pi}\sigma_{\ln L}} \exp\left[\frac{-(\ln L_X - < \ln L_X >)^2}{2\sigma^2_{\ln L}}\right]$$

with constant scatter $\sigma_{\ln L}$, and median log luminosity that follows:

$$< \ln L_X > (N_{200}) = A + B \ln(N_{200}/40)$$

- Use Kelly (2007) linear regression to constrain scatter for richest clusters

Scatter in L_X-N_{200}



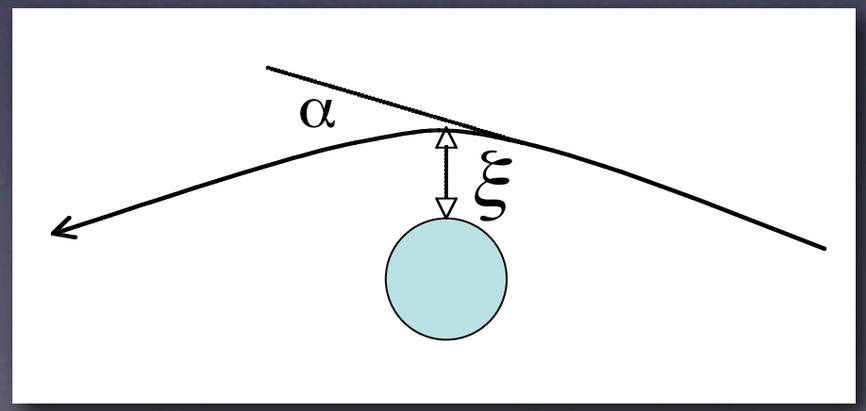
Rykoff, et al. 2008a

- Best fit $\sigma_{\ln L}$=0.86±0.03
- $\langle L_X \rangle = e^{3.40\pm0.02} (N_{200}/40)^{1.61\pm0.13}\ 10^{42}$ erg/s

Measuring Mass with Lensing

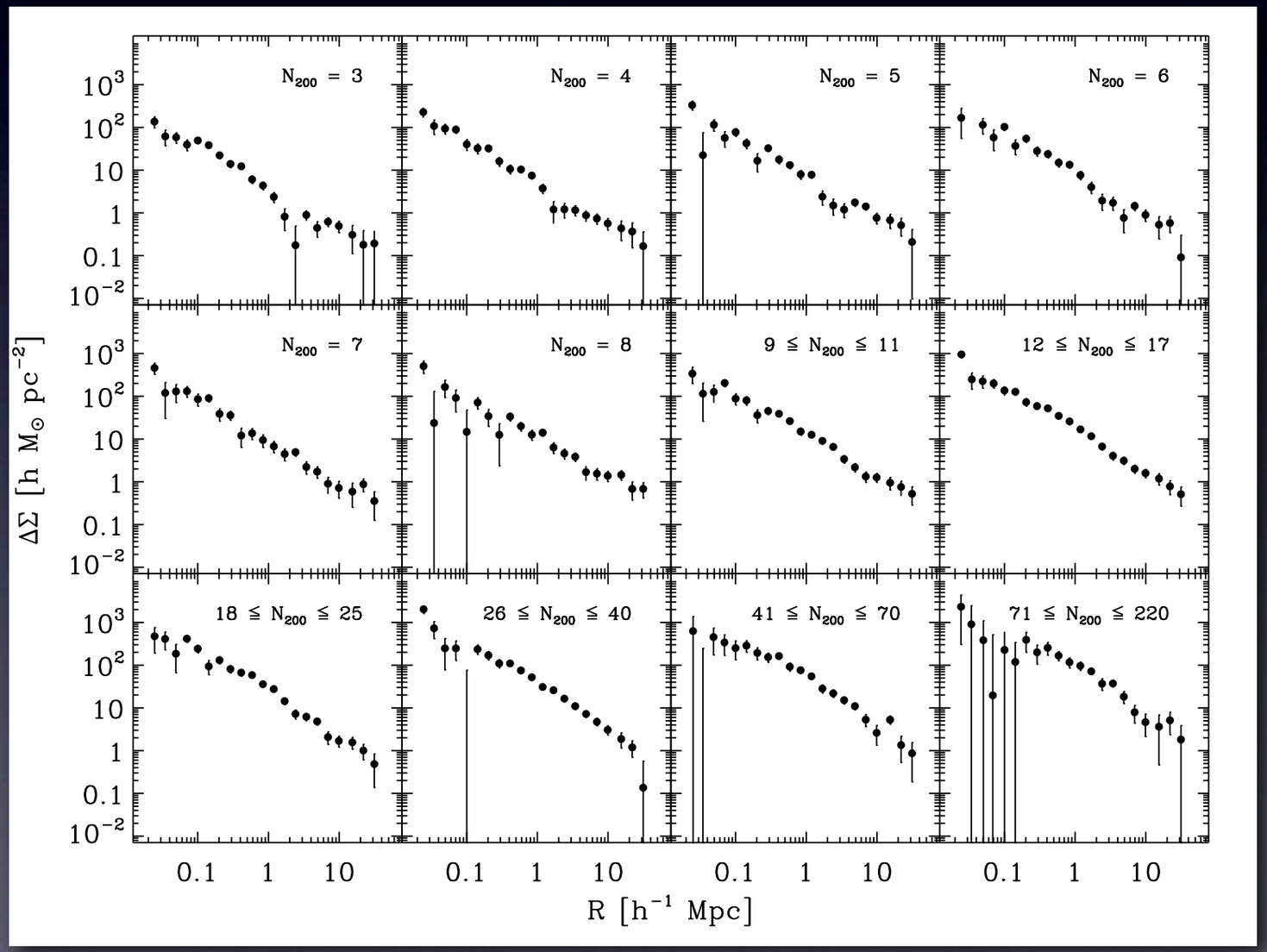
- Gravitational potential will bend light
  - Same effect as an optical lens: magnification and distortion
- We observe the distortion and displacement of background galaxies

$$\alpha = \frac{4GM}{c^2}\frac{1}{\xi}$$



Cluster-Mass Correlation Function

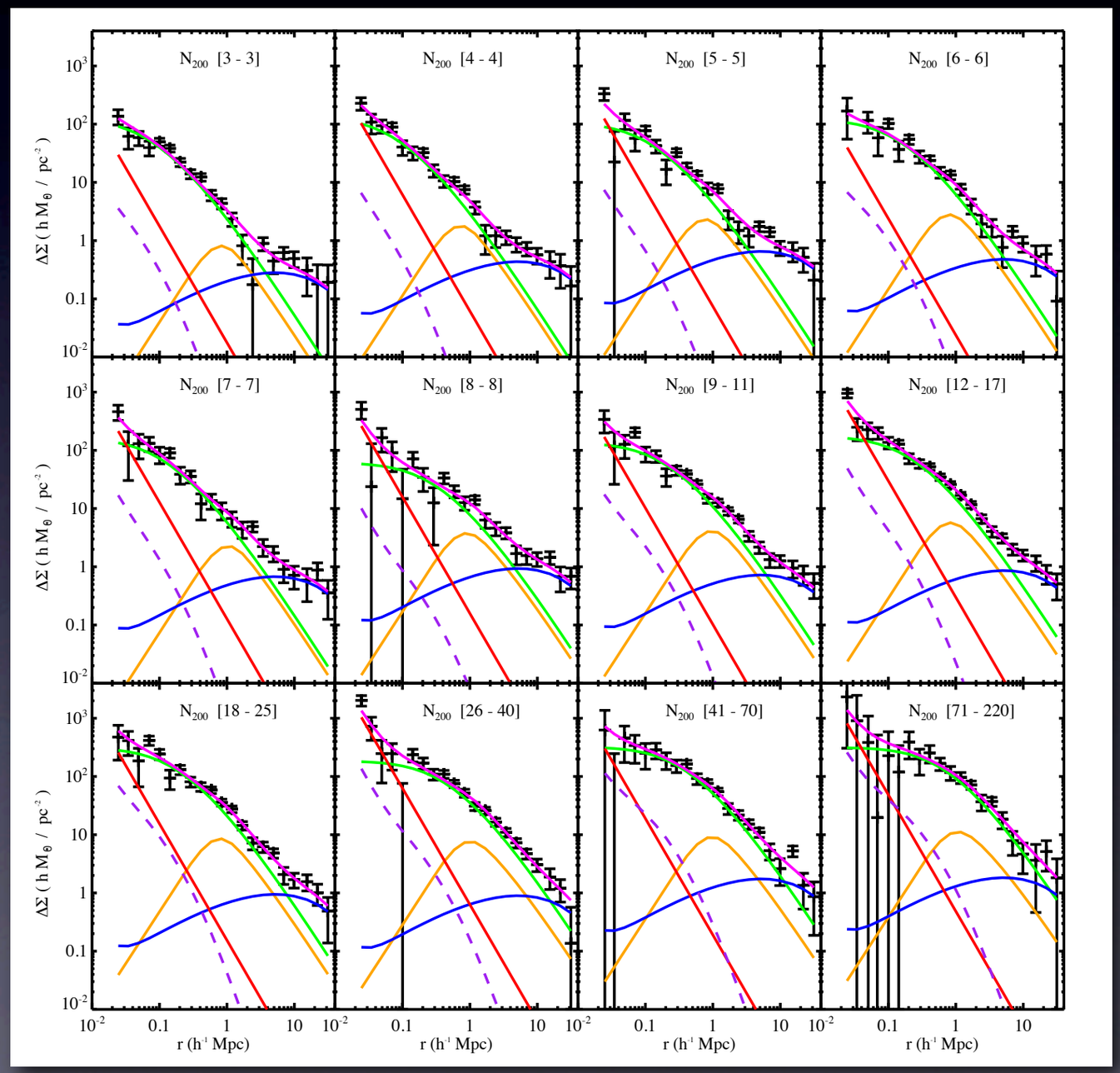
- Measure mean distortion of background galaxies behind maxBCG clusters
- Compare to random points
  - Projection effects mostly disappear
- Observe significant lensing signal to very large scales



Sheldon, et al. 2007

Modeling the Profile

- We model the shear signal with...
  - Halo (NFW) contribution
  - BCG contribution
  - 2-halo term
  - Miscentering
- We are working to understand the centering better



Johnston et al. 2007

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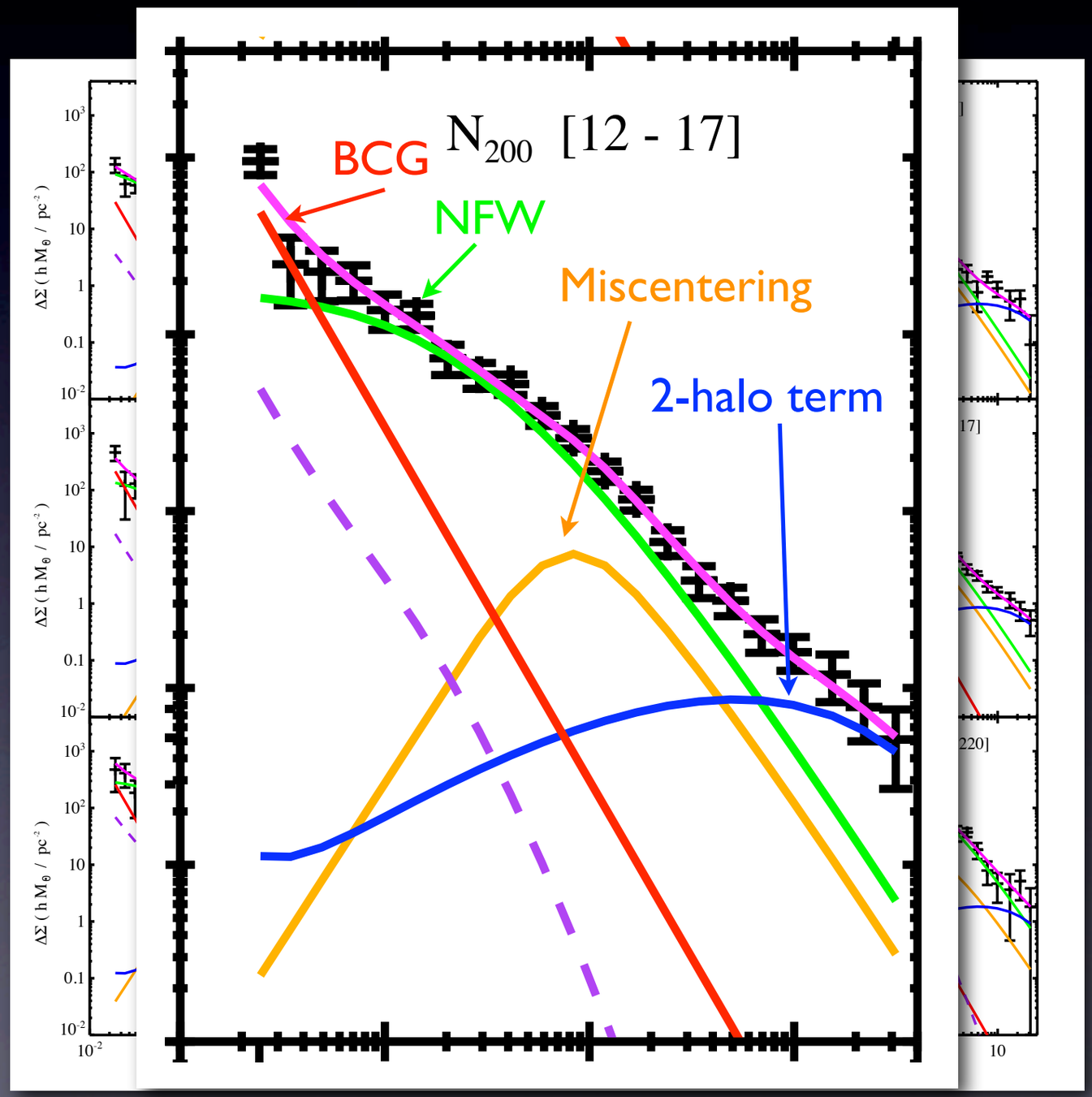
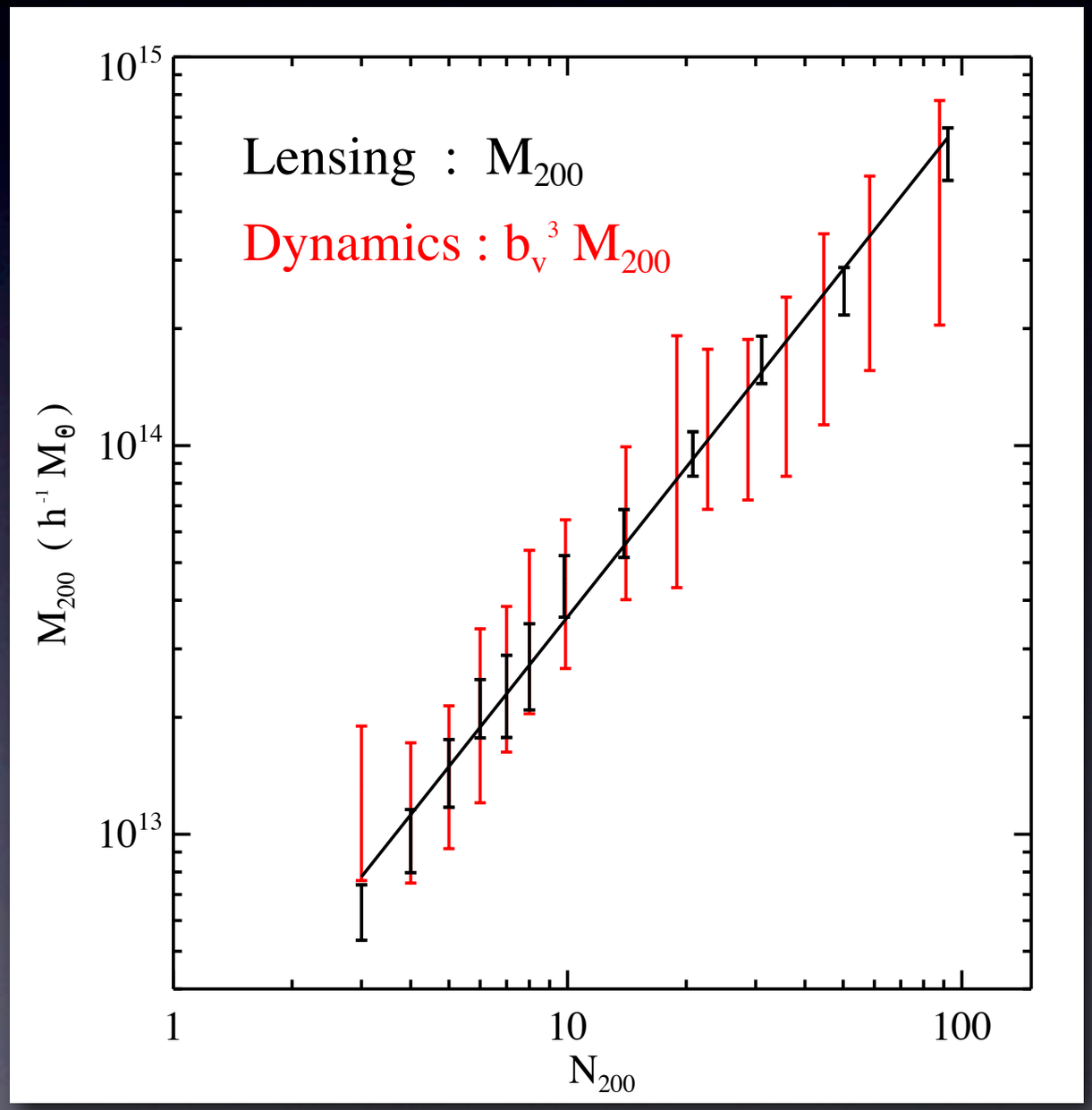


Johnston et al. 2007

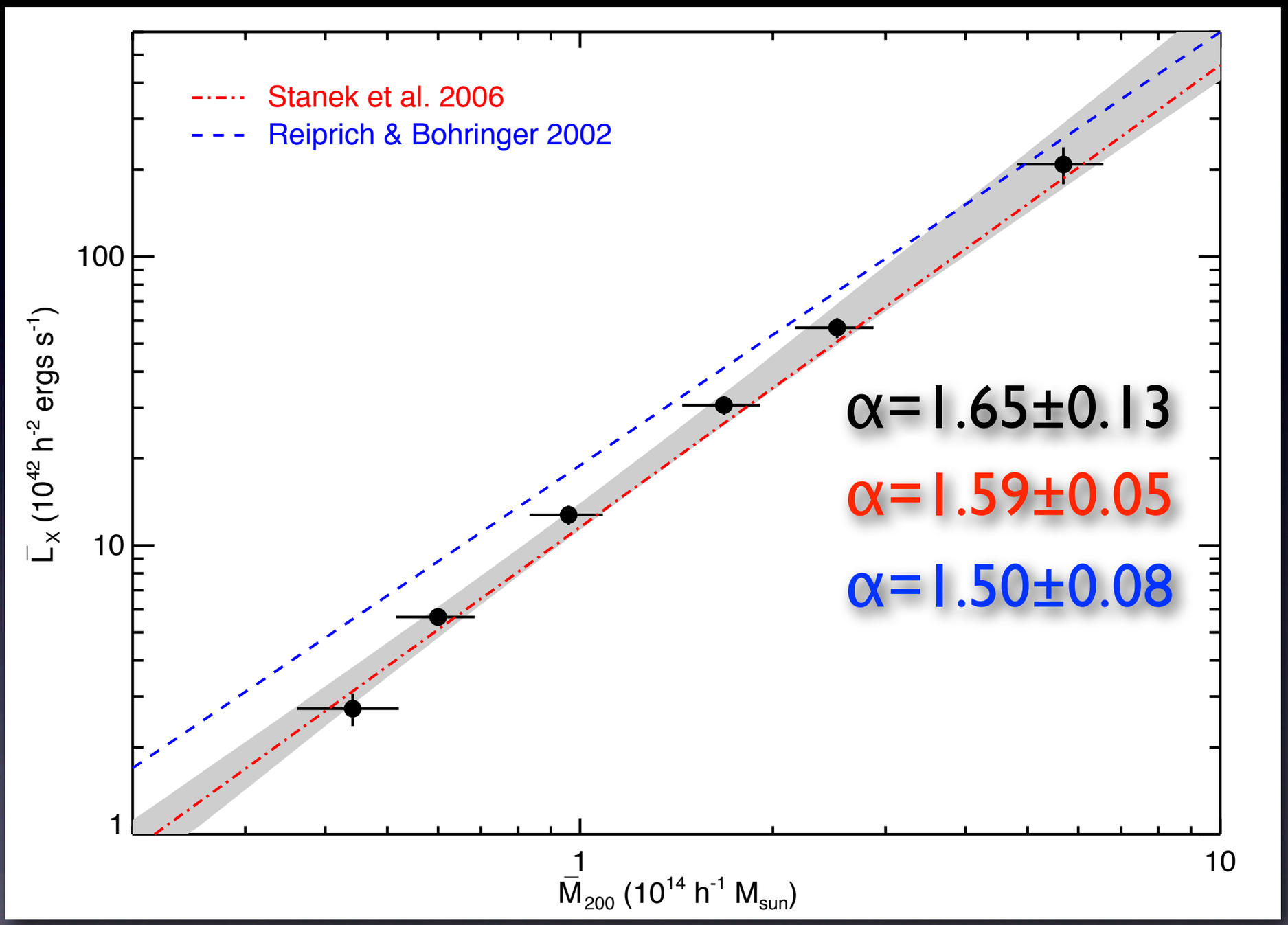
M_{200}-N_{200} Scaling

- Johnston et al. (2007) calculate the Mass-Richness relation
- Compare to masses from dynamical measurements (Becker et al. 2007)



The X-Ray Luminosity-Halo Mass Relation

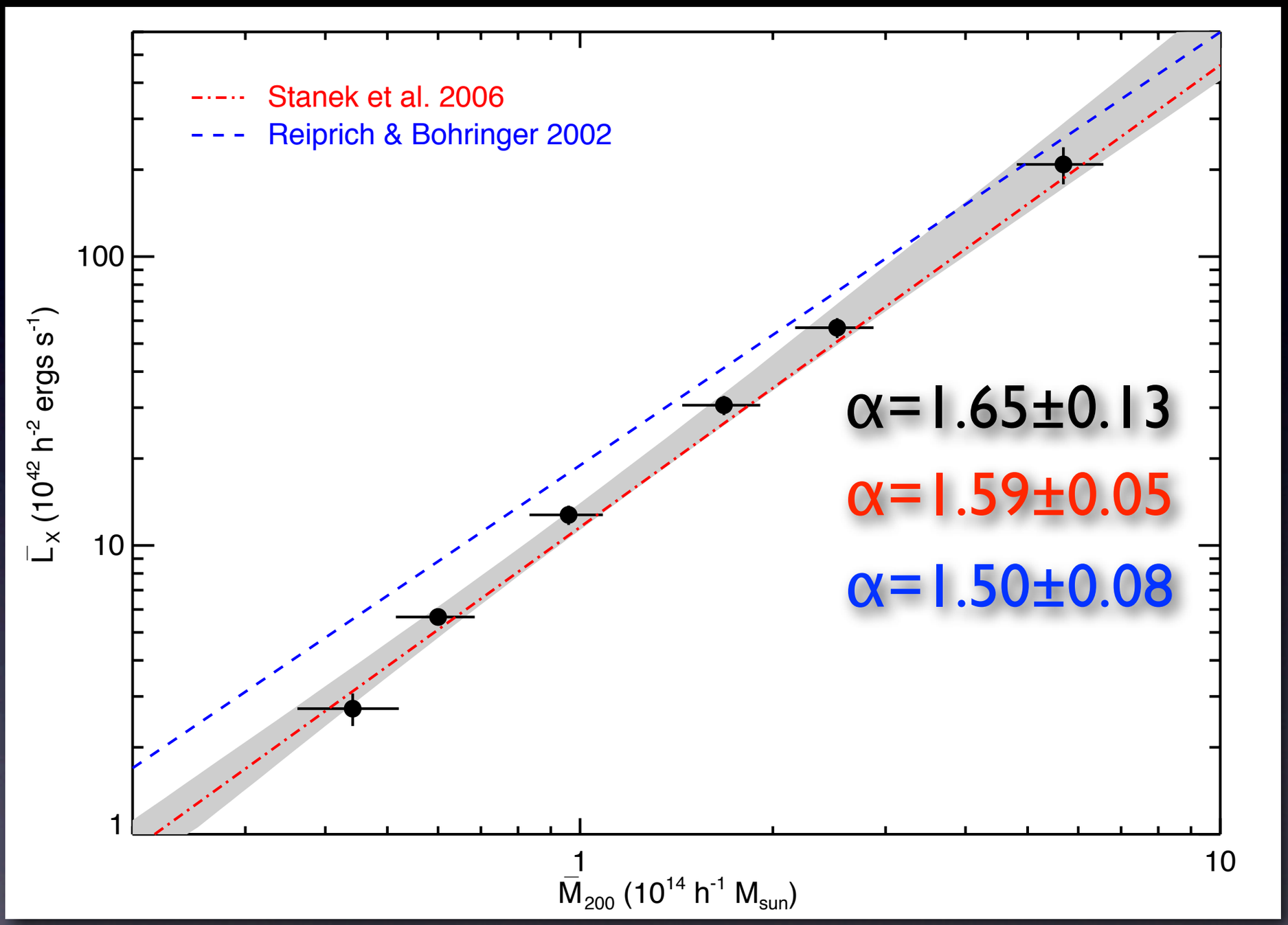
L_X-M_{200}



Rykoff, et al. 2008b

- Black: N_{200} binned from maxBCG
- Others: X-ray selected clusters
- Blue: RB02 direct using hydrostatic masses
- Red: S06 statistical arguments

L_X-M_{200}



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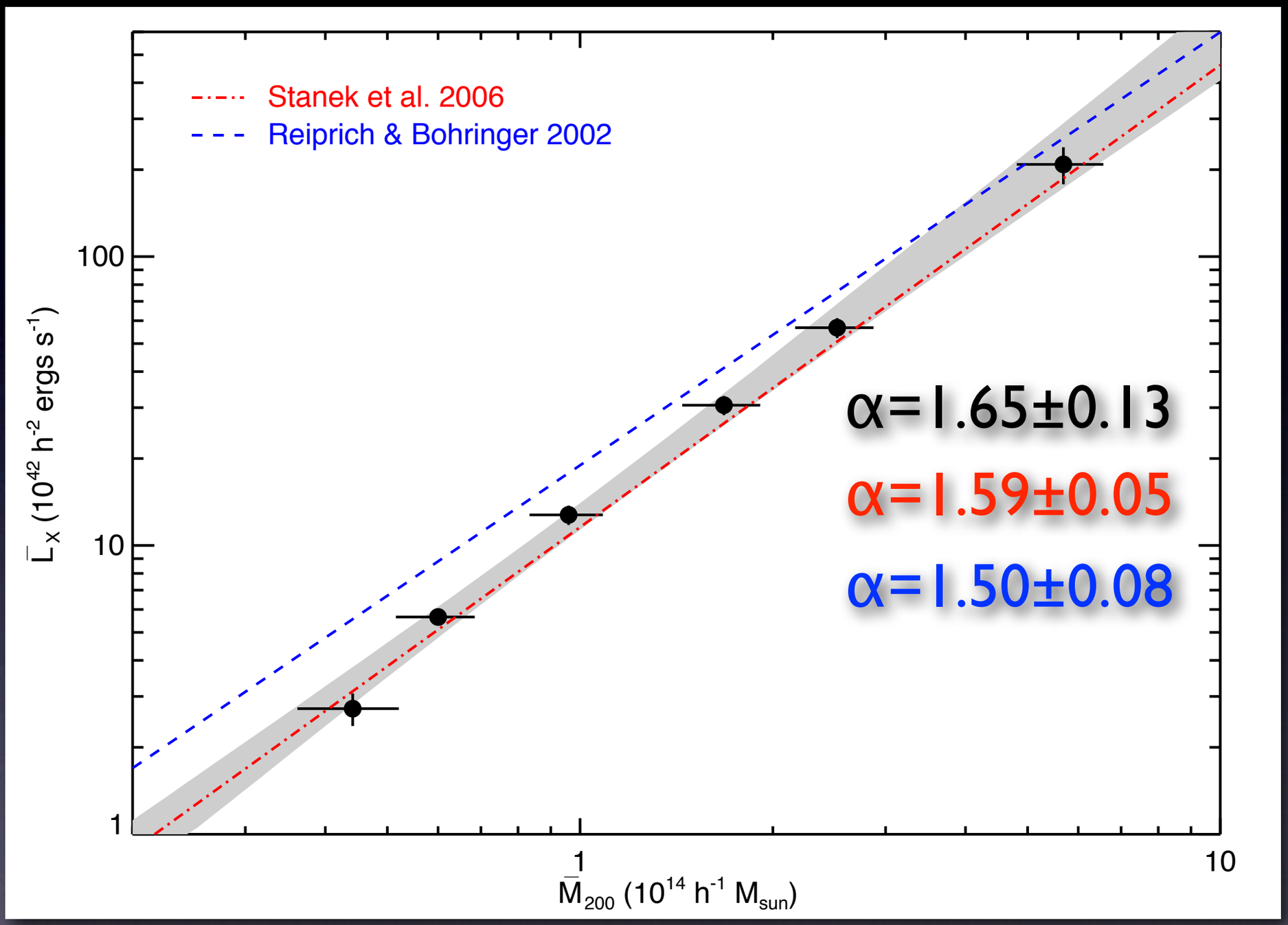
- Consistent slopes

Rykoff, et al. 2008b

L_X-M_{200}



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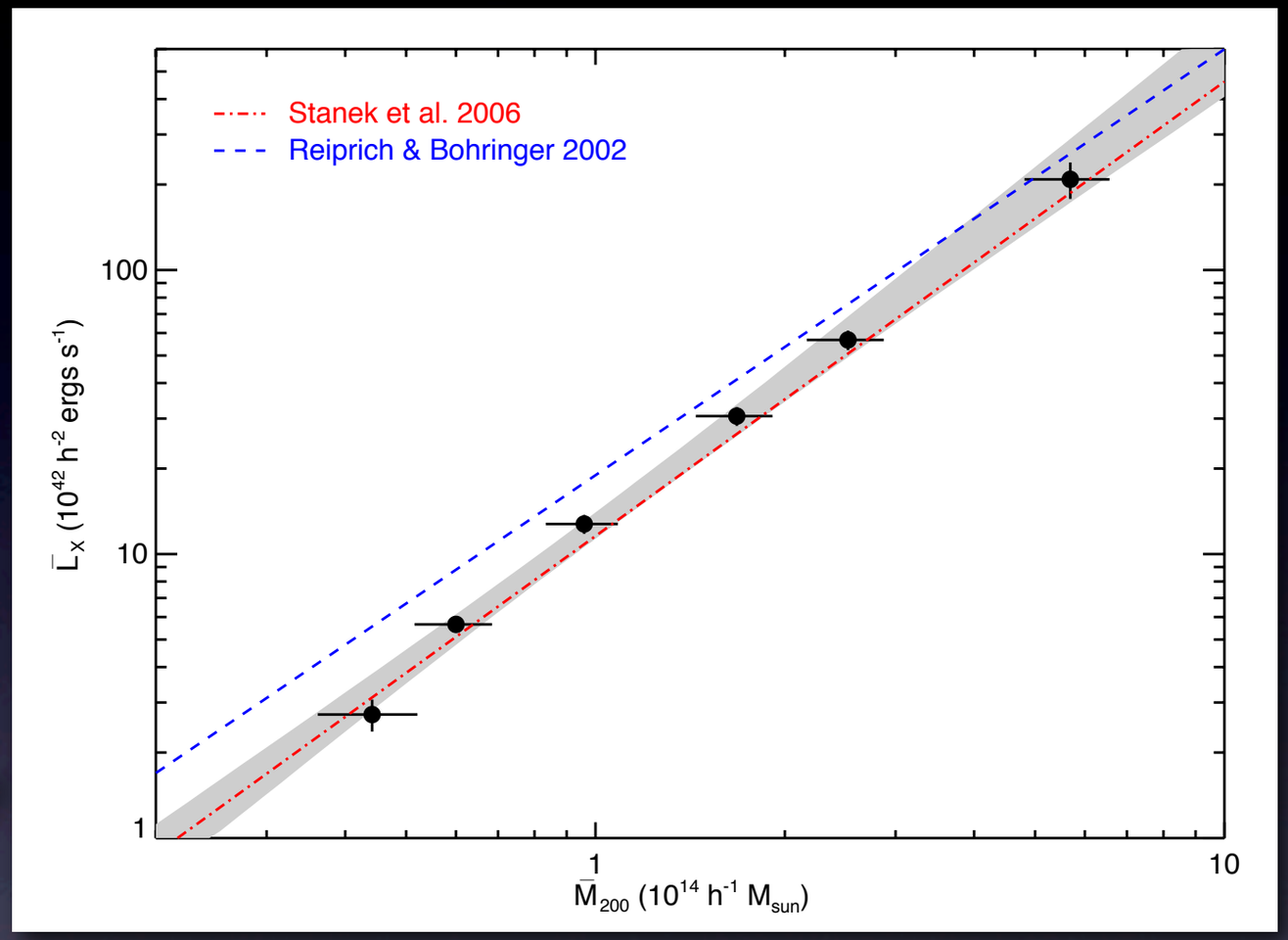
Rykoff, et al. 2008b

- Consistent slopes
- What about normalization?

L_X-M_{200}: Normalization

- Normalization of S06 is consistent with maxBCG-RASS
- Why is RB02 ~25% higher in L_X?
  - Hydrostatic mass estimates ~25% low (e.g. Nagai et al. 2007)
  - Malmquist bias in flux-limited X-ray survey
- maxBCG-RASS result cannot break this degeneracy (see S06 for details)



Rykoff, et al. 2008b

Slope & Covariance

- Assume a local power-law mass function:

$$dn/d\ln M \sim M^{-\alpha} = e^{-\alpha\mu}$$ where $\mu \equiv \ln M$

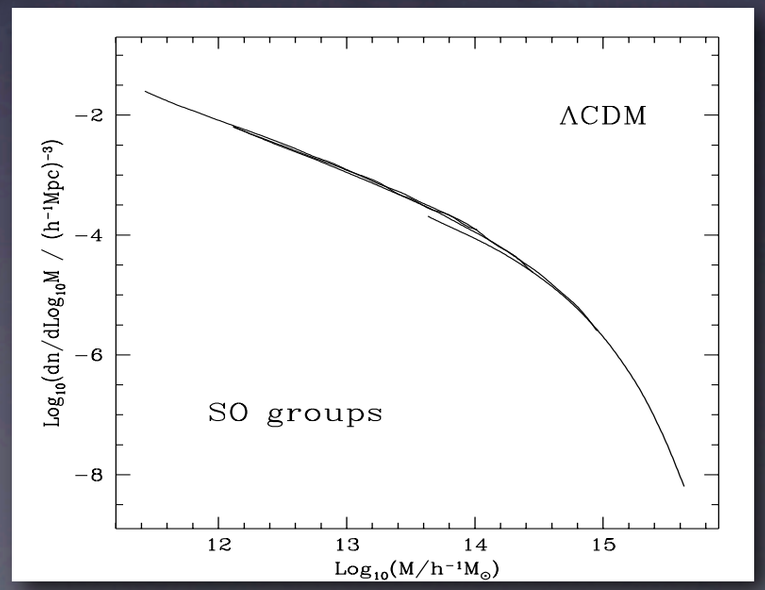
- Assuming a bivariate log-normal, we can write:

$$P(\ell, \mu|\nu)$$ where $\ell \equiv \ln L_X$ and $\nu \equiv \ln N_{200}$

- The X-ray luminosity at fixed richness is then:

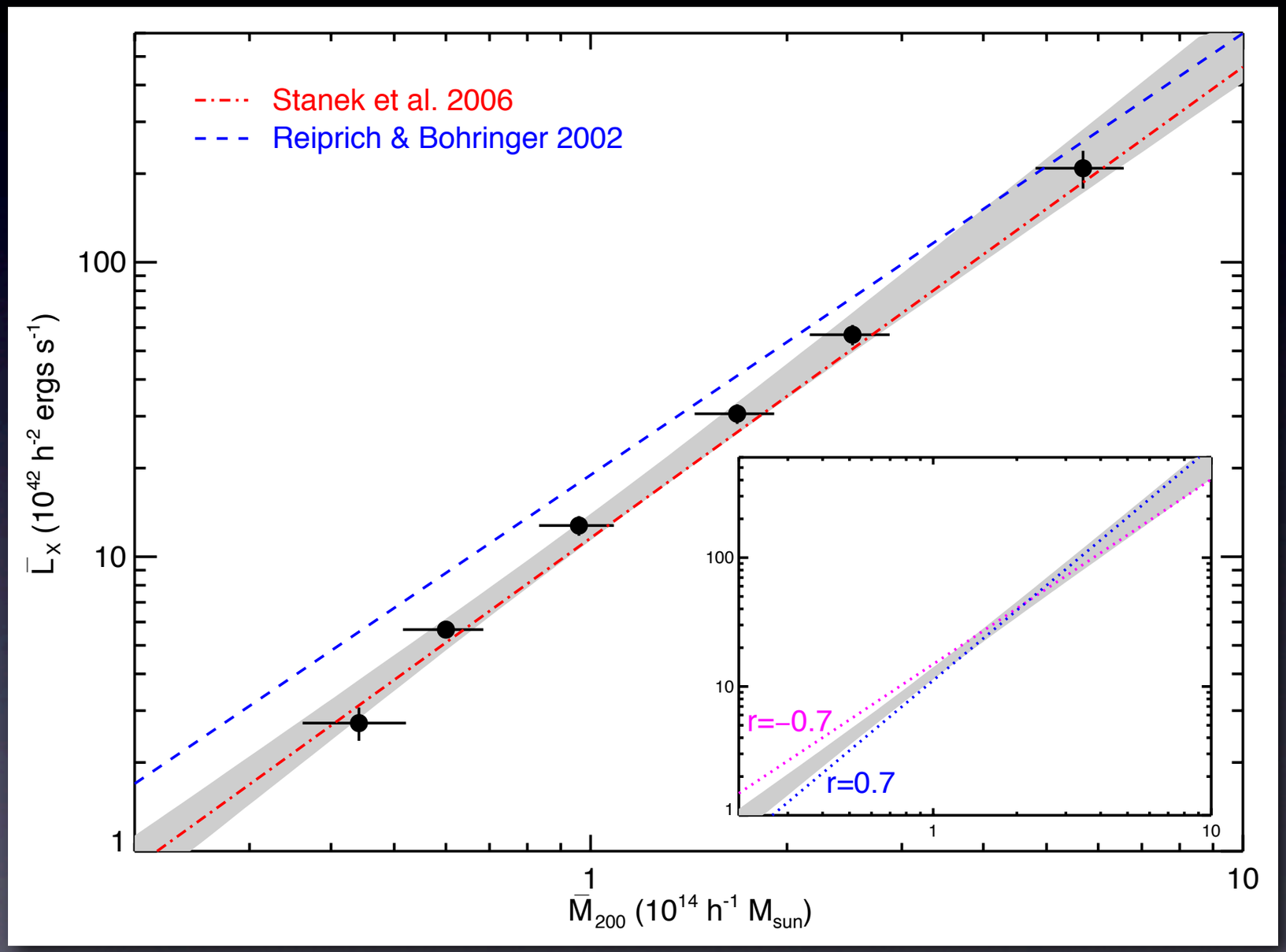
$$\bar{\ell}(\nu) \;=\; p \cdot \left(\bar{\mu}(\nu) + \alpha\, r\, \sigma_{\mu|\nu}\sigma_{\mu|\ell}\right)$$

- where p is the slope of the halo L_X-M_{200} relation and r is the normalized correlation coefficient
- If α is constant, the slope is unchanged
- In CDM models α changes with mass (e.g. Jenkins et al. 2001)



L_X-M_{200}: Covariance

$$\bar{\ell}(\nu) \;=\; p \cdot \left(\bar{\mu}(\nu) + \alpha\, r\, \sigma_{\mu|\nu}\sigma_{\mu|\ell}\right)$$



Rykoff, et al. 2008b

- r is the correlation coef. of N_{200} and L_X at fixed Mass
- Trade-off between hot and cold baryons or clusters with more baryons
- The slope of maxBCG-RASS is consistent with S06 & RB02

L_X-M_{200}: Covariance

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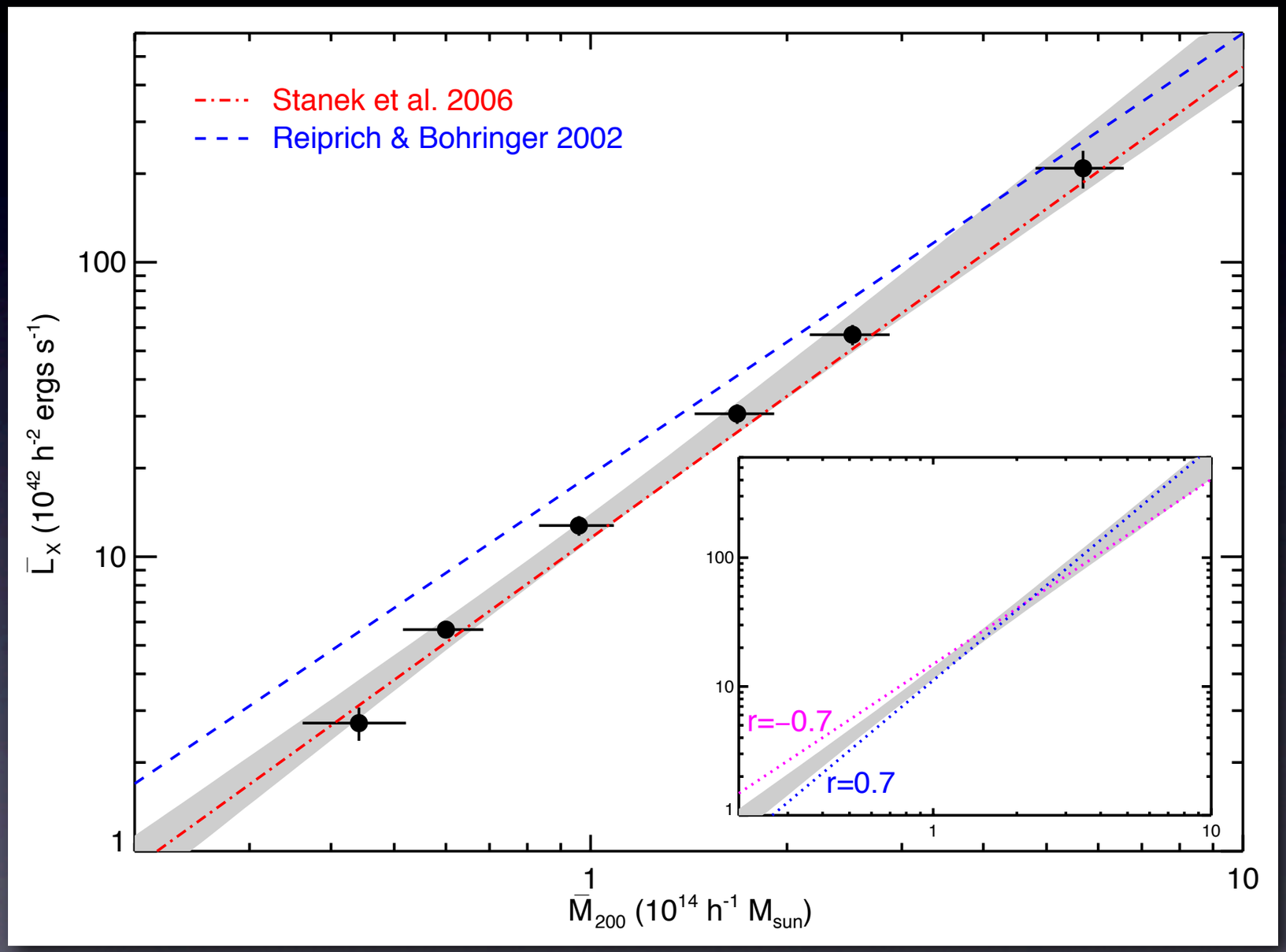

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- Covariance *at fixed mass* is not large

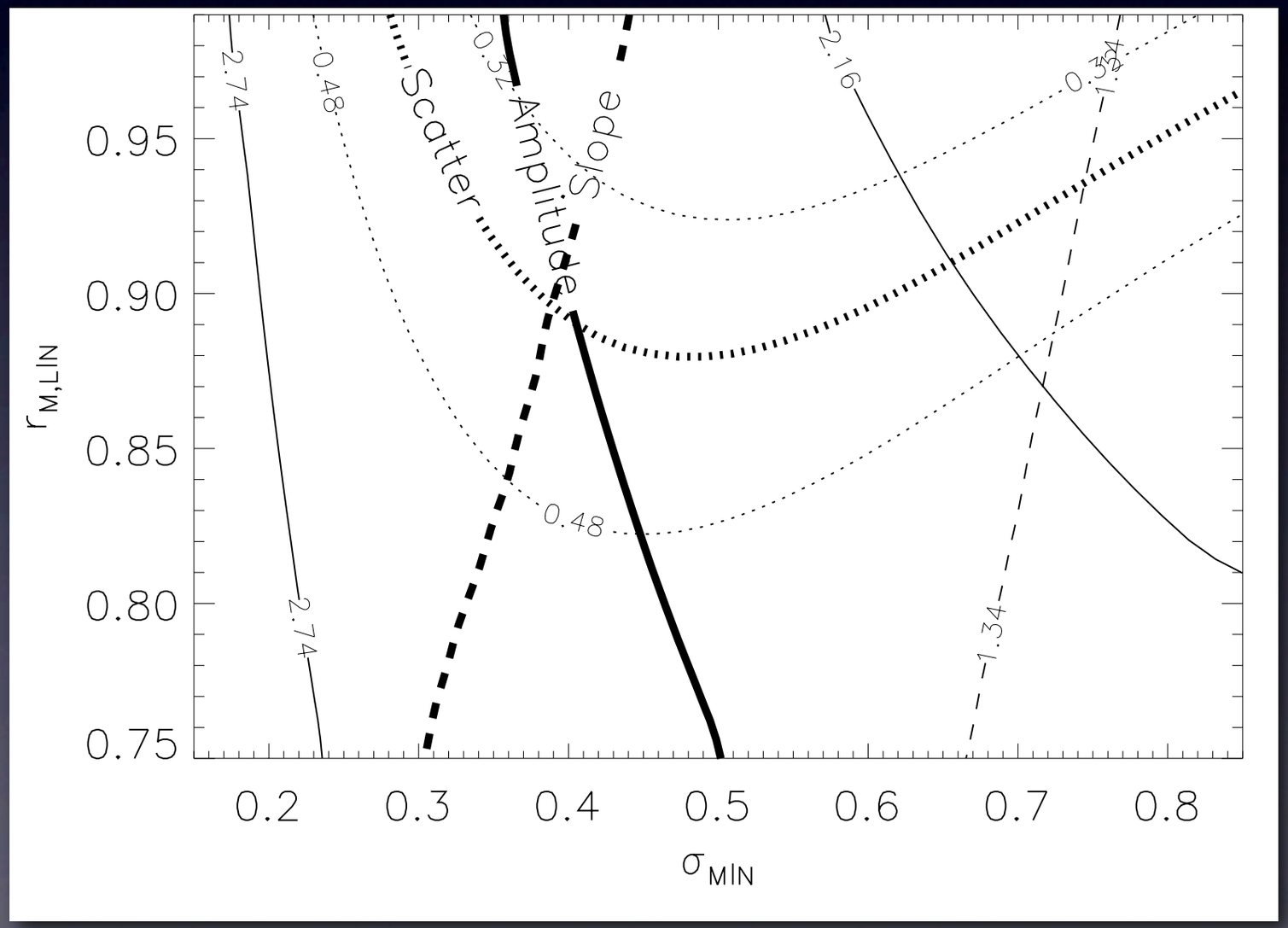
Cosmological Constraints

Another Look at Covariance

- Our analysis is based on a richness-selected sample of clusters
- We require correlation between M and L_X at fixed richness
- Use L_X-M relation from CCCP (Vikhlinin et al. 2009) as a comparison
  - High resolution Chandra imaging
  - Good treatment of Malmquist bias (vs. RB02)
  - Not sensitive to cosmology (vs. S06)

Measuring $r_{M,L|N}$

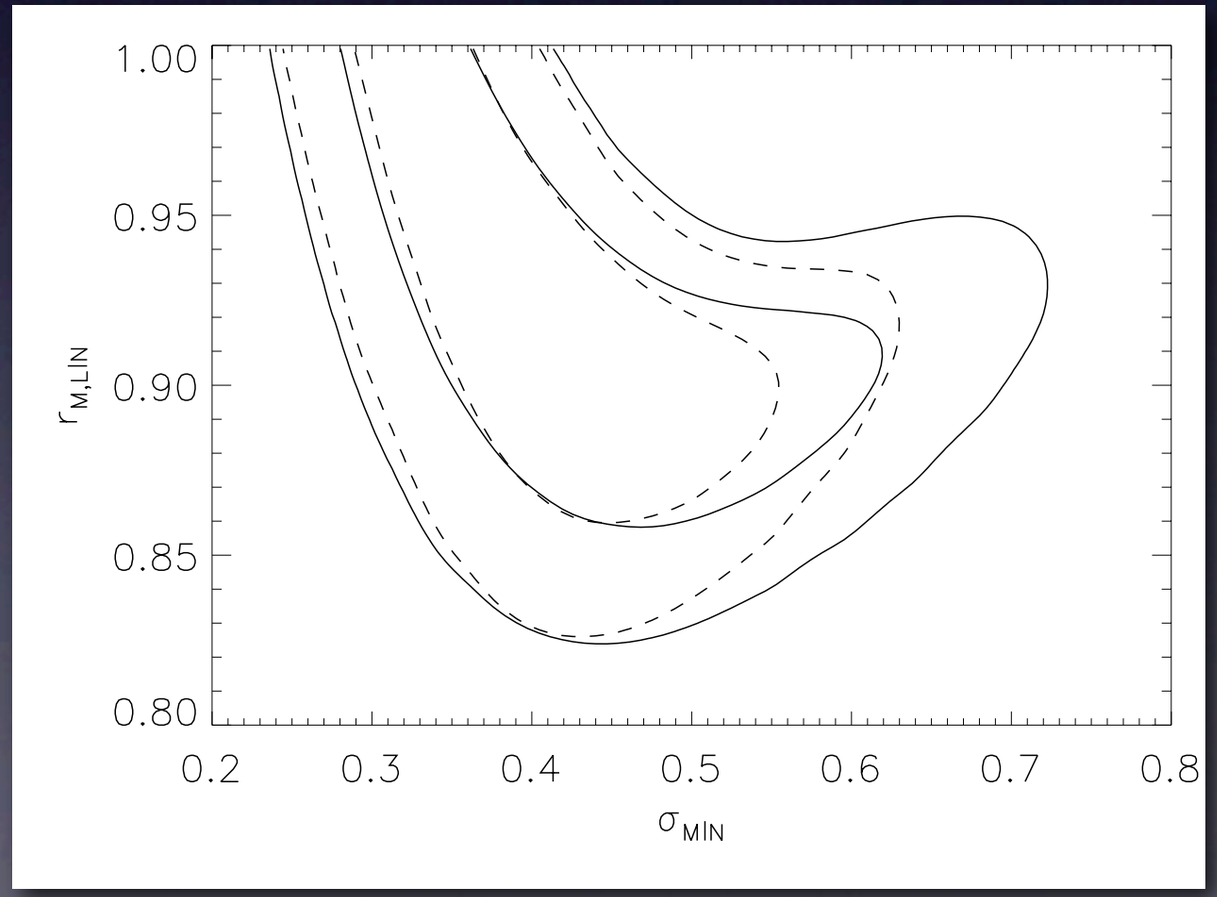
- Consider $P(M,L_X|N)$, specified by $\langle M|N\rangle$, $\sigma_{M|N}$, $\langle L_X|N\rangle$, $\sigma_{L|N}$, $r_{M,L|N}$
- Unknowns are $\sigma_{M|N}$ and $r_{M,L|N}$
- Method:
  - Guess σ, r
  - Given $n(N)$ and P, randomly assign mass, L_X to every cluster
  - Measure L_X-M and $\sigma_{L|M}$ and compare to Vikhlinin 2009



Rozo,Rykoff et al. 2009a

Quantitative Results

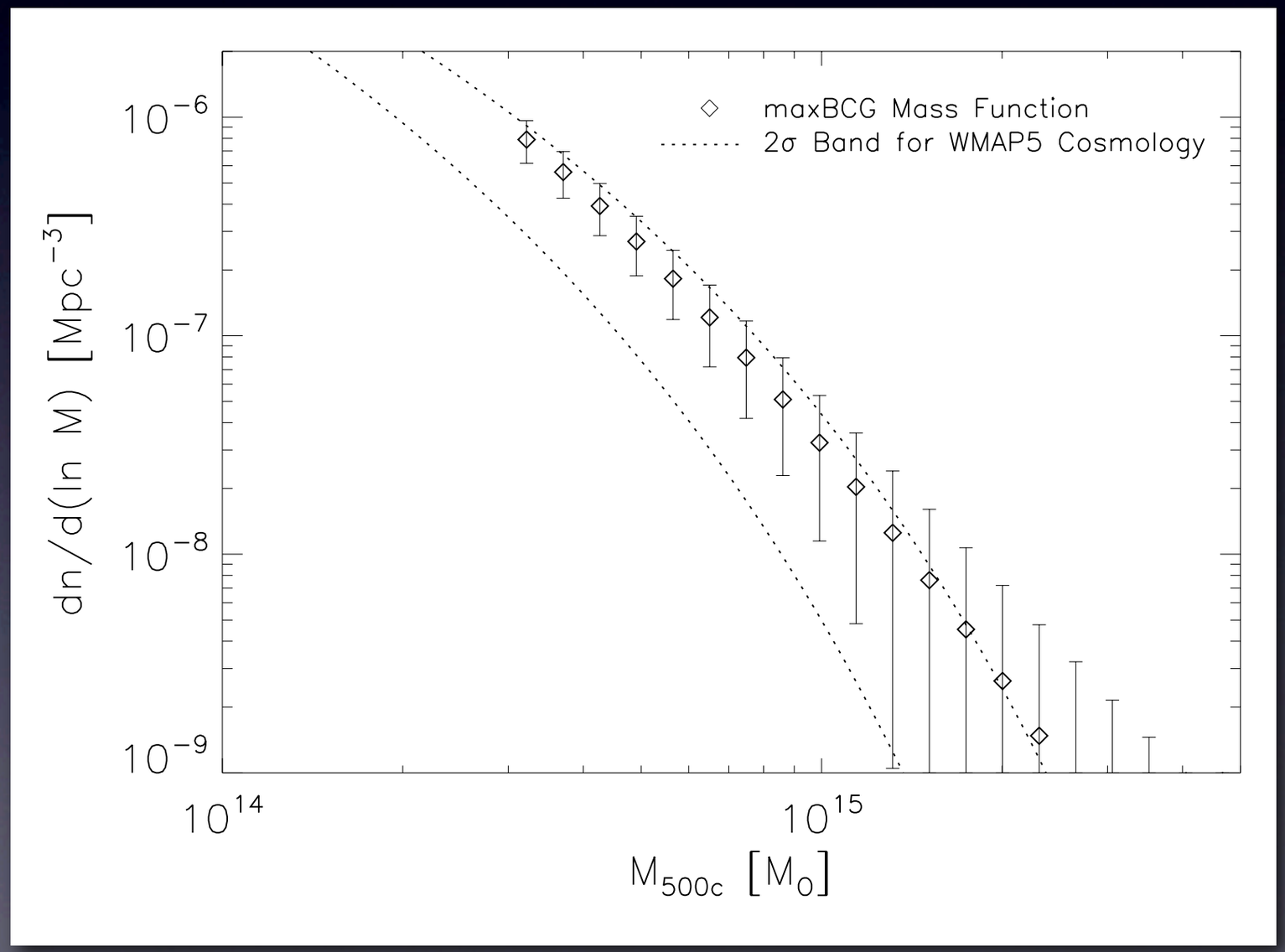
- Full Likelihood model
  - Marginalize over all parameters (abundance function, mean relations)
- $\sigma_{M|N}$ = 0.45±0.1 (1σ)
- $r_{M,L|N} \geq$ 0.85 (95% conf.)
- High L_X clusters are more massive
- First direct constraint on a correlation coefficient between two mass tracers



Rozo et al. 2009a

maxBCG Mass Function

- With $\langle M|N \rangle$ and $\sigma_{M|N}$ we get $P(M|N)$
- The maxBCG mass function is now fully specified
- How does it compare to WMAP5?



Rozo,Rykoff et al. 2009a

Cosmological Constraints

- Statistics with large number of maxBCG clusters vs. detailed analysis of relatively few clusters (e.g. Vikhlinin et al. 2009)
- Extend Rozo et al. 2007:

$$P(N_{obs}|m) = \sum_{N_T} c(N_T) P(N_{obs}|N_T) P(N_T|m)$$

- Combine cluster number counts (Rozo et al. 2007) with weak lensing masses
  - Cosmology simultaneously constrained with observable-mass relation
  - Requires we know scatter in mass at fixed richness

Cosmological Constraints

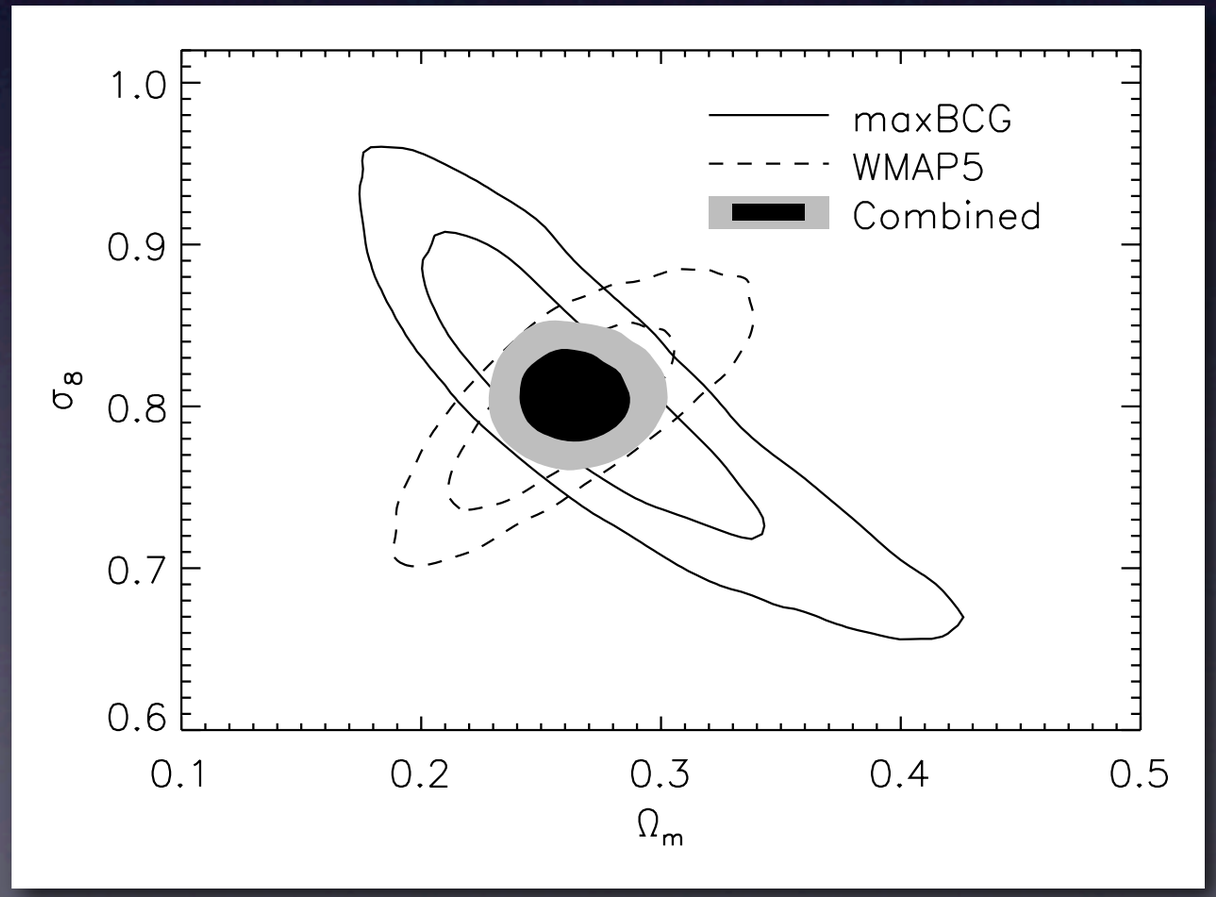
- Observables:
  - Number of clusters in richness bin (to constrain number function)
  - Total mass in each richness bin (to constrain mass scaling)
- Full Bayesian treatment, marginalizing over all parameters
  - Flat Universe, h=0.7, power spectrum tilt n=0.96
- Output σ_8, Ω_m

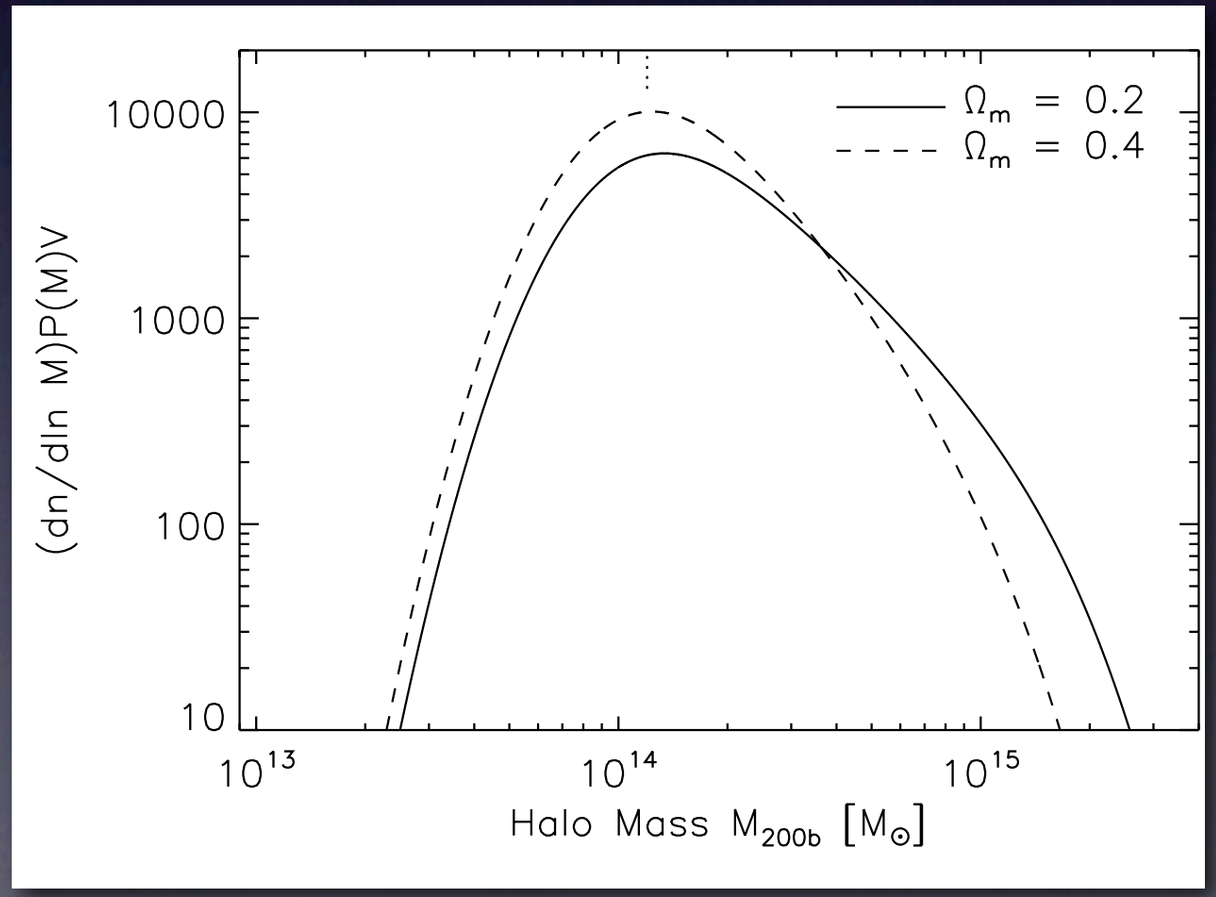
TABLE 3

Parameter[a]	Prior[b]	Importance[c]
σ_8	[0.4,1.2]	unrestrictive
Ω_m	[0.05,0.95]	unrestrictive
$\langle \ln N_{200} \| M_1 \rangle$	flat	unrestrictive
$\langle \ln N_{200} \| M_2 \rangle$	flat	unrestrictive
$\sigma_{N_{200}\|M}$	[0.1,1.5]	unrestrictive
β	1.00 ± 0.06; [0.5, 1.5]	restrictive
$\sigma_{M\|N_{200}}$ [d]	Rozo et al. (2008a)	restrictive

Cosmological Constraints

- Best constraint: $\sigma_8(\Omega_m/0.25)^{0.41}=0.83\pm0.03$
  - Degenerate on σ_8–Ω_m plane
- Using WMAP5 constraints:
  - $\sigma_8 = 0.81\pm0.02$, $\Omega_m = 0.27\pm0.02$

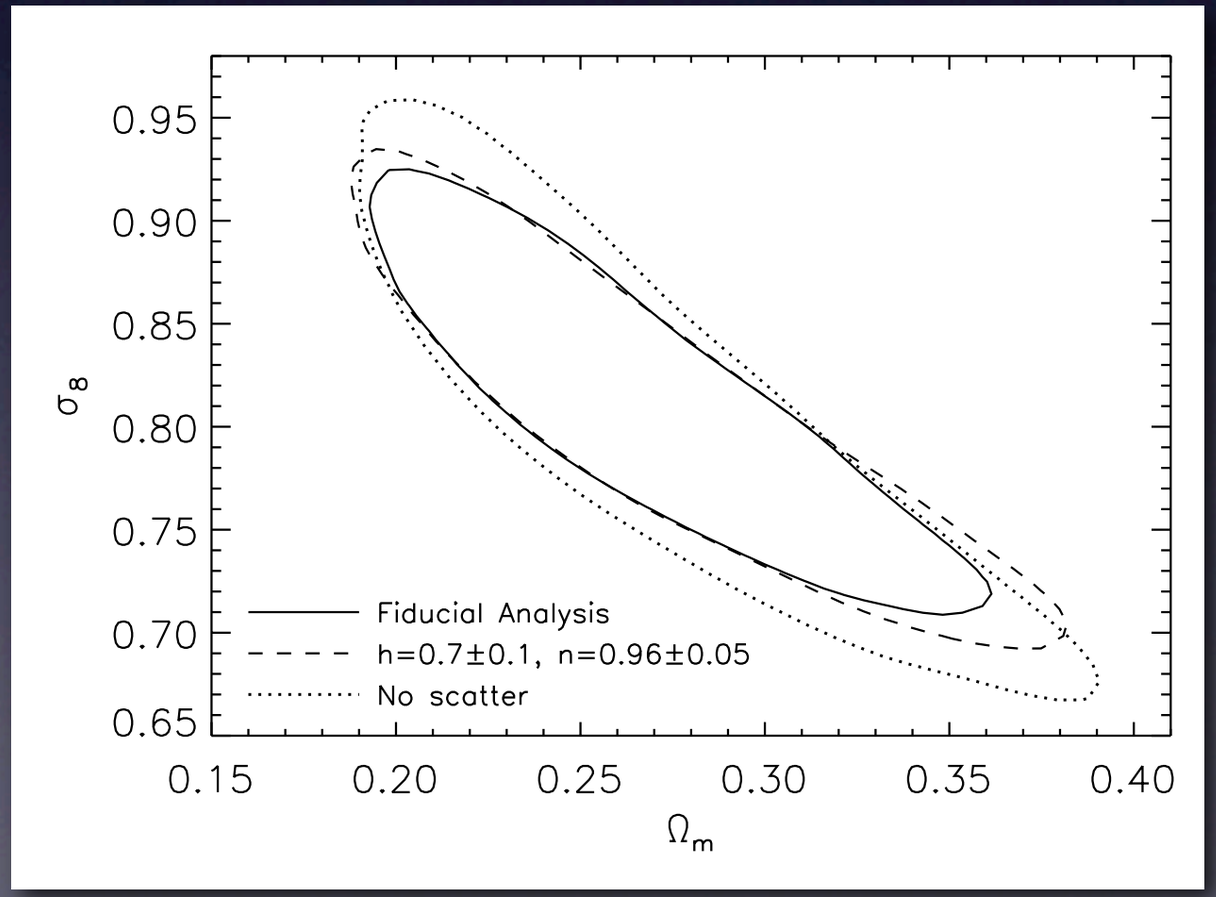


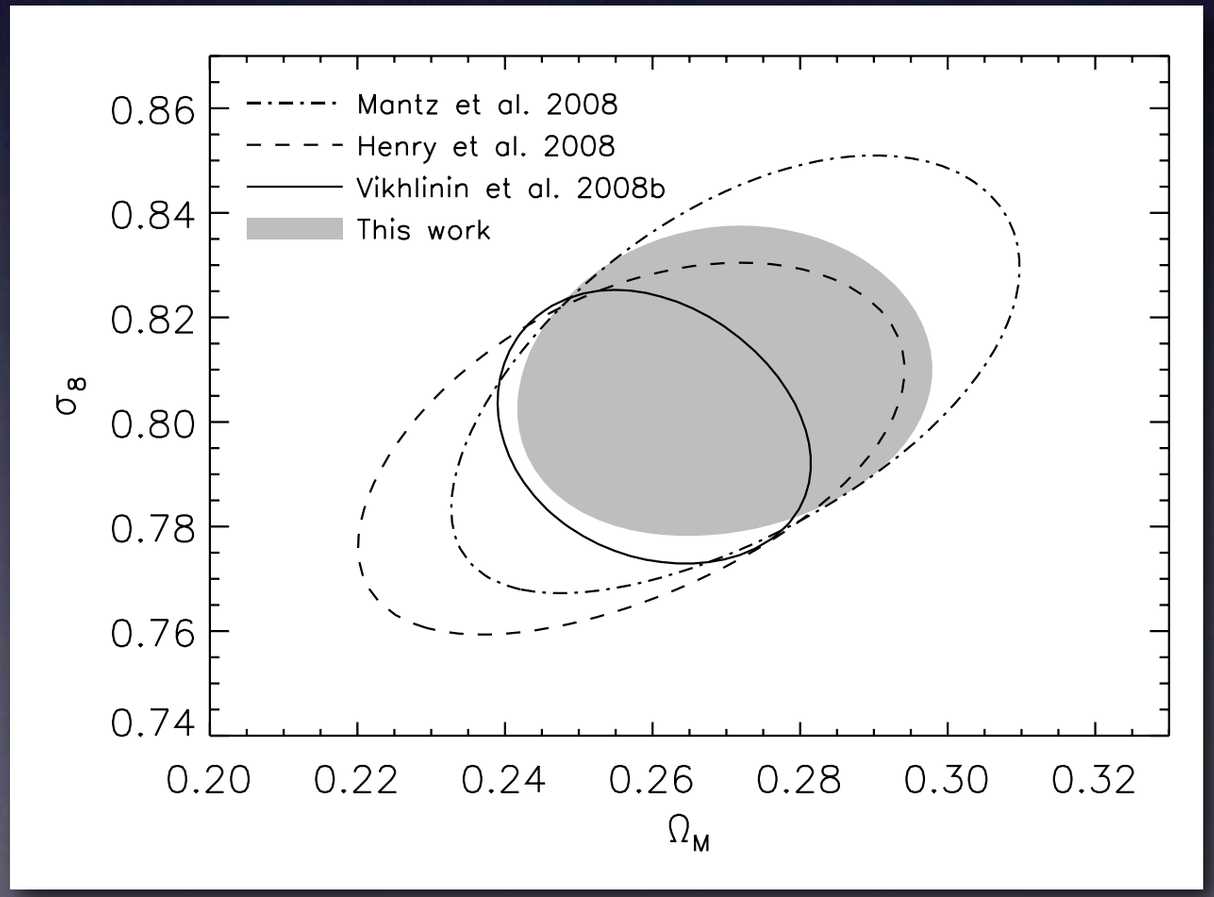


Rozo, Wechsler, Rykoff et al. 2009b

Systematics...

- The analysis is not sensitive to uncertainties in h, n, or purity/completeness
  - The prior on $\sigma_{M|N}$ is important
- Results compare favorability to X-ray studies





Rozo, Wechsler, Rykoff et al. 2009b

Improving our Richness Estimator

The Matched Filter

$$\lambda = \sum_{R<R_c(\lambda)} \frac{\lambda u(\mathbf{x}|\lambda)}{\lambda u(\mathbf{x}|\lambda) + b(\mathbf{x})}$$

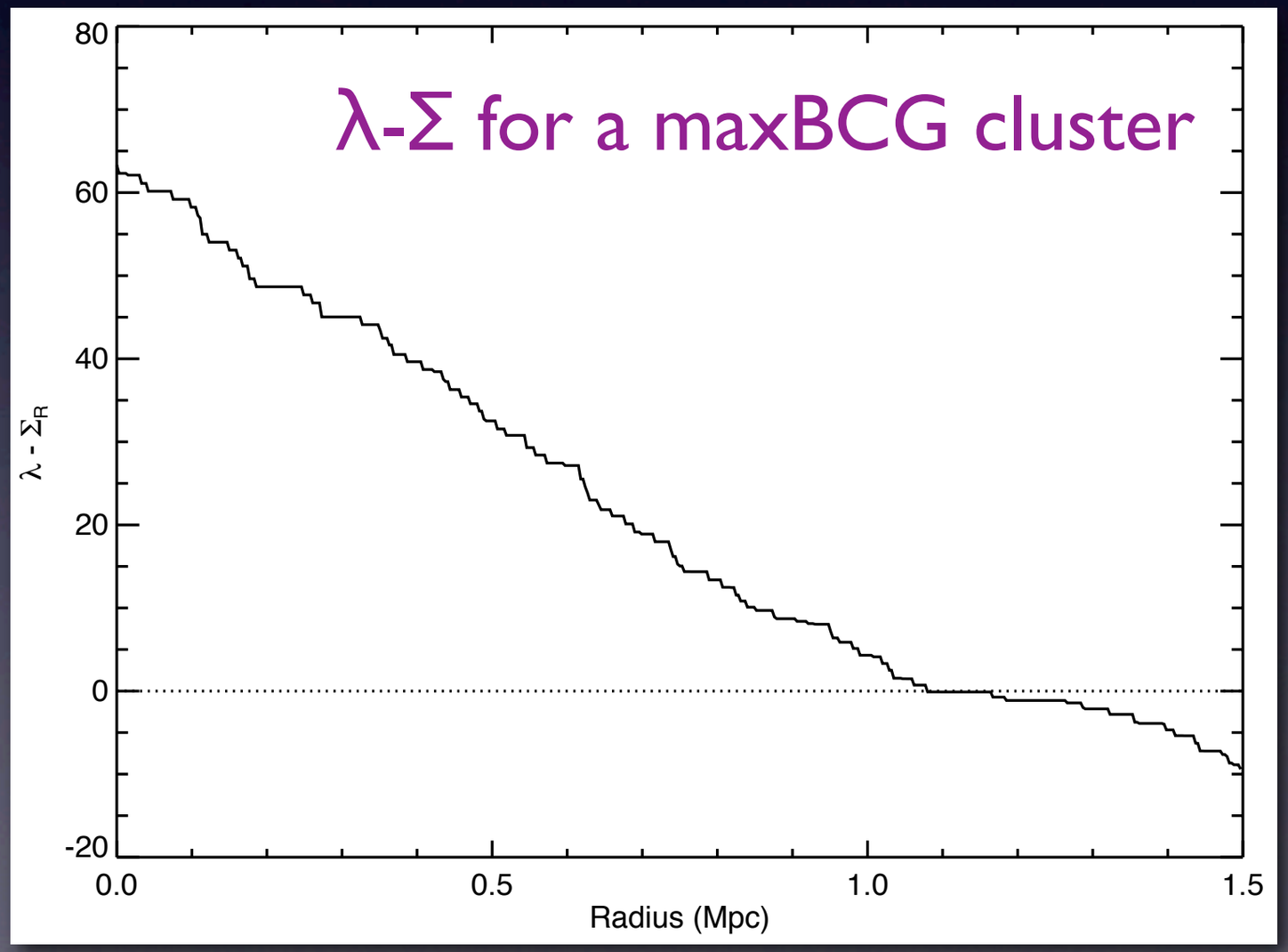
Solve for cutoff radius

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

Radial (NFW) Luminosity (Schechter) Color (Gaussian)

Assume radius scales with richness:

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

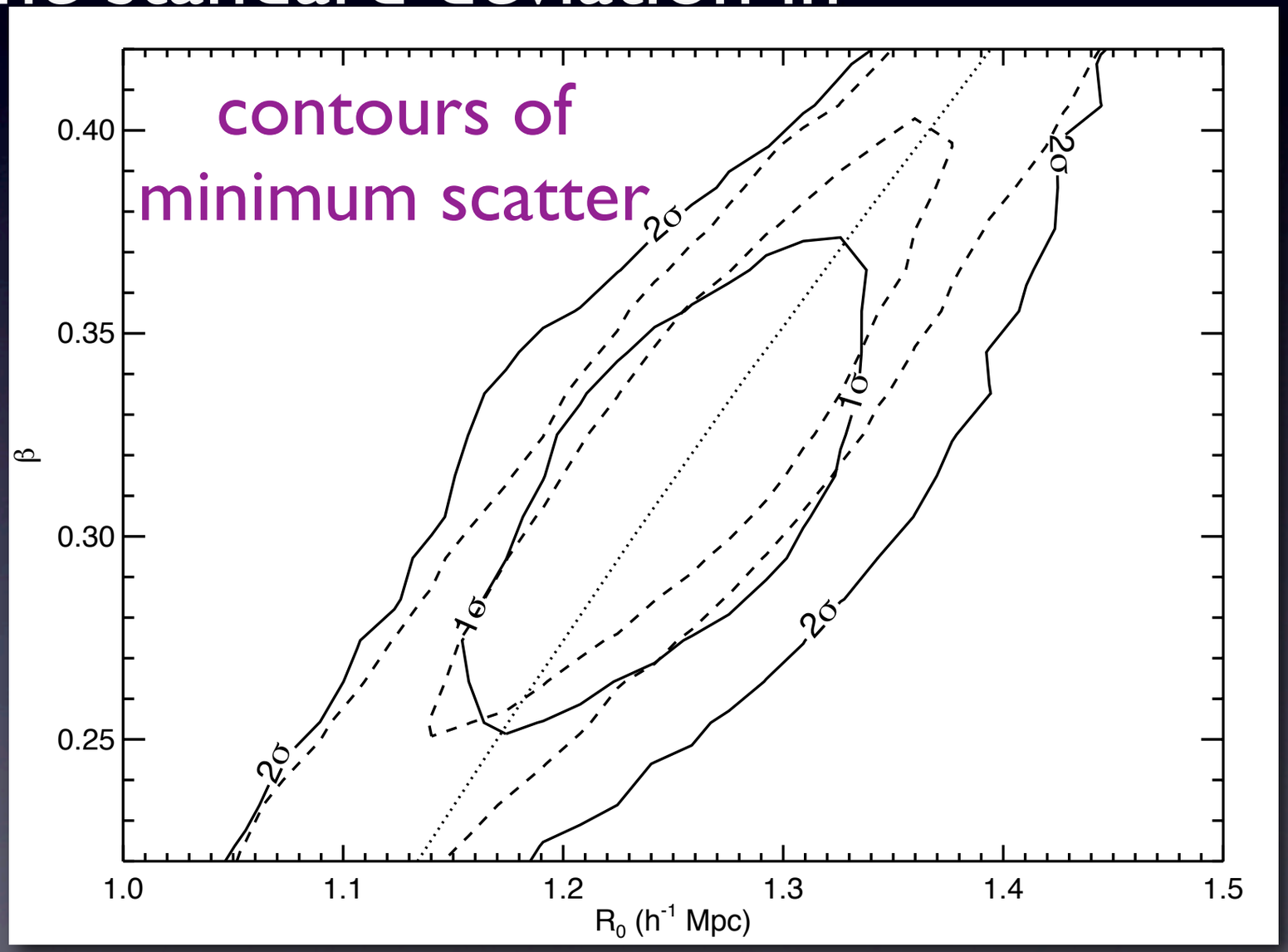


Measuring the scatter

- Each R_0, β combination gives a new set of richnesses

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

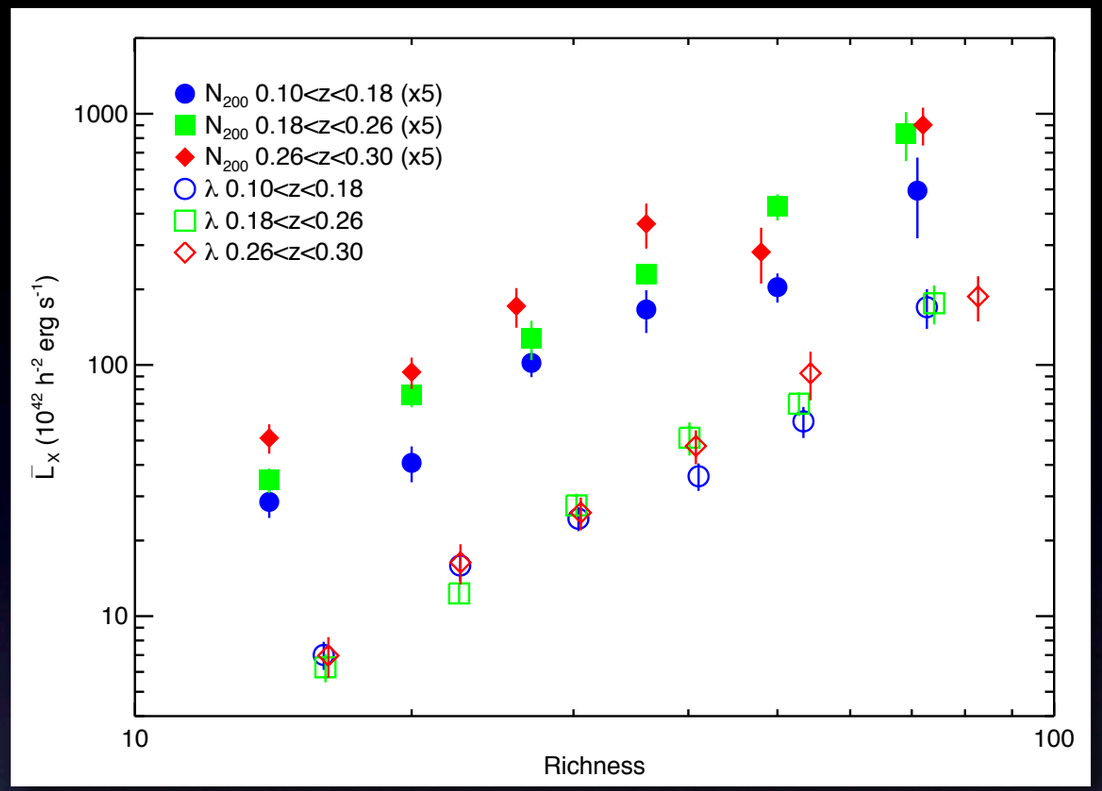
- Measure $\sigma_{\ln L|\lambda}$, the standard deviation in $\ln L_X$ at fixed λ
- Find R_0, β that minimizes scatter

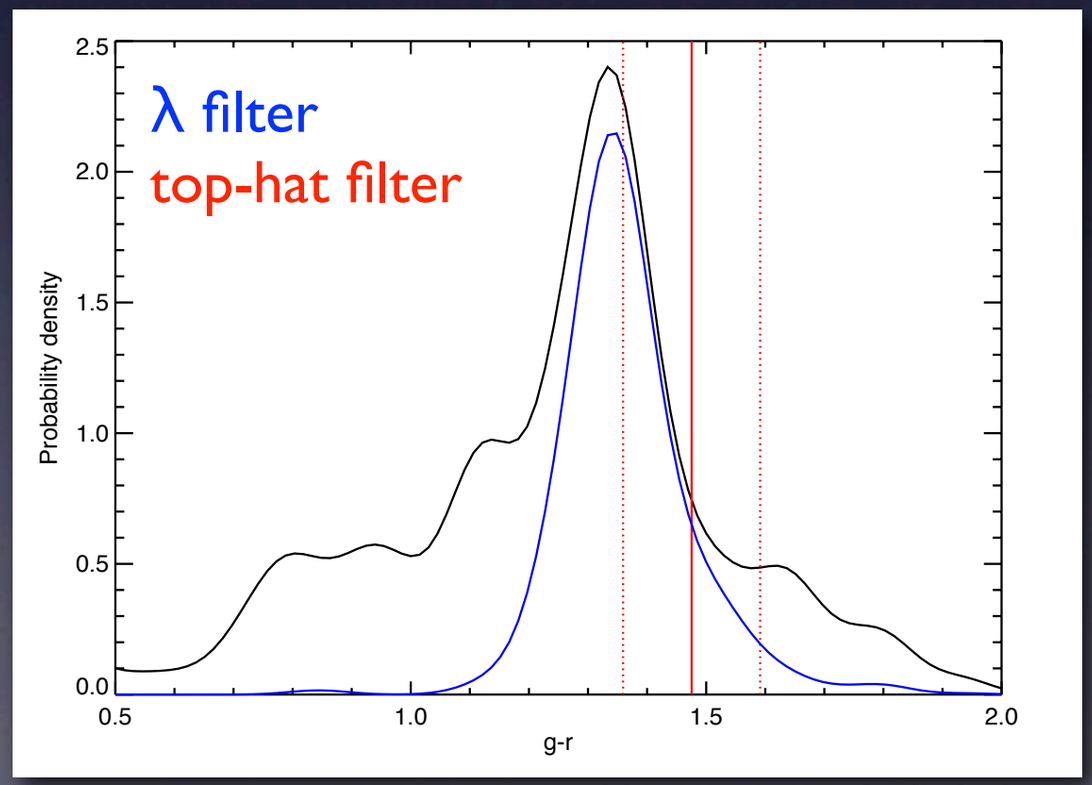


Rozo, Rykoff et al. 2009c

Improvement vs N_{200}

- N_{200} was the original maxBCG richness
  - A top-hat color filter
  - Significant redshift evolution in L_X-N_{200}
- λ removes z evolution
- For top 2000 clusters (mass >10^{14} M_{sun})
  - $\sigma_{\ln L|N}$= 0.86±0.02
  - $\sigma_{\ln L|\lambda}$= 0.69±0.02
- Gaussian color filter + radial optimization





Rozo, Rykoff et al. 2009c

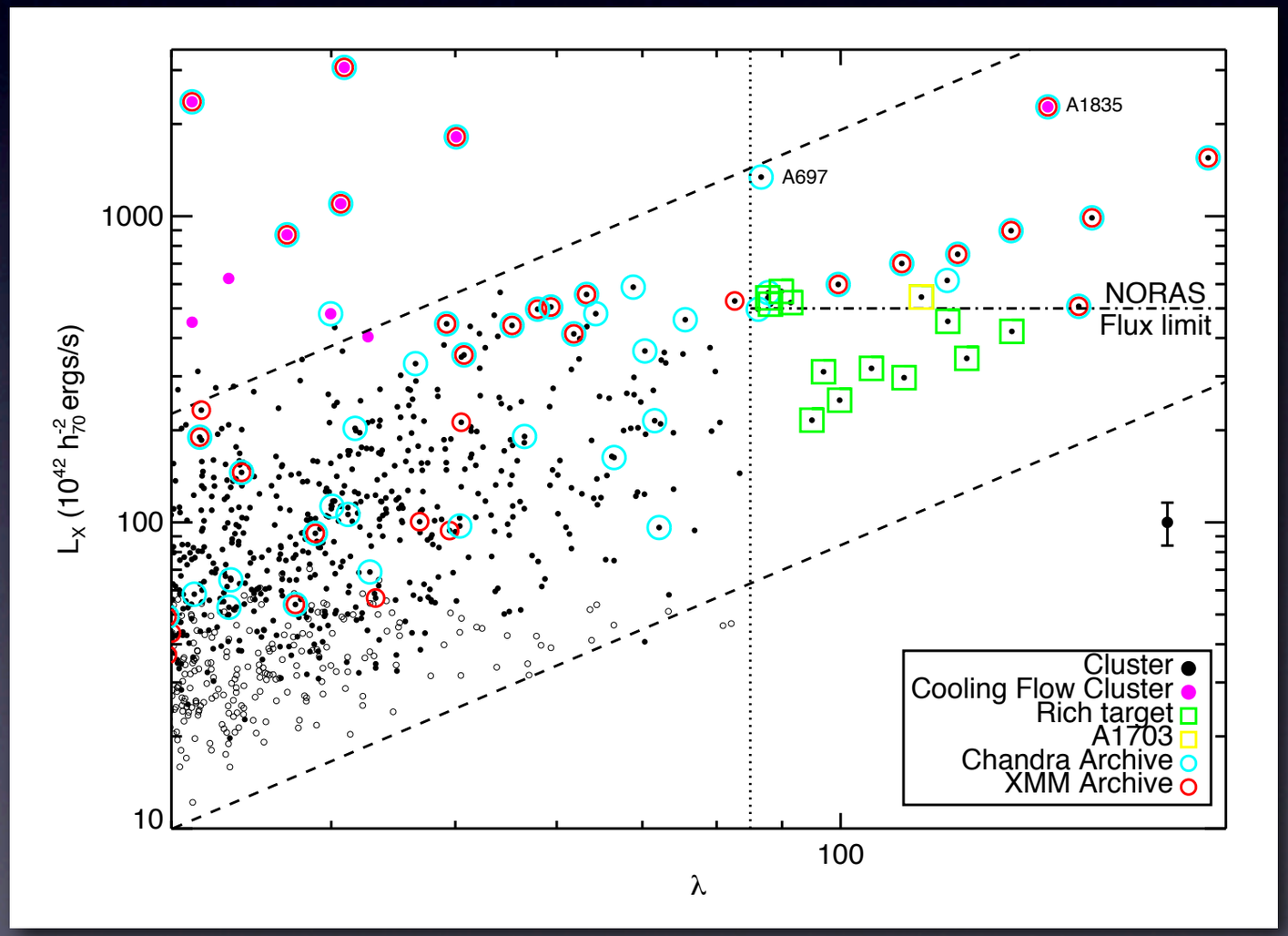
Further Improvements

- Going deeper improves things
  - But not forever...you run into correlated structure
- Counting blue galaxies makes things worse!
  - Still unclear if this is S/N or physics...
- Scatter is significantly smaller for λ vs.
  - Postman matched filter
  - Abell Richness
  - B_{gc} (Yee & Lopez-Cruz 1999)

The maxBCG “Core Sample”

The Richest Clusters

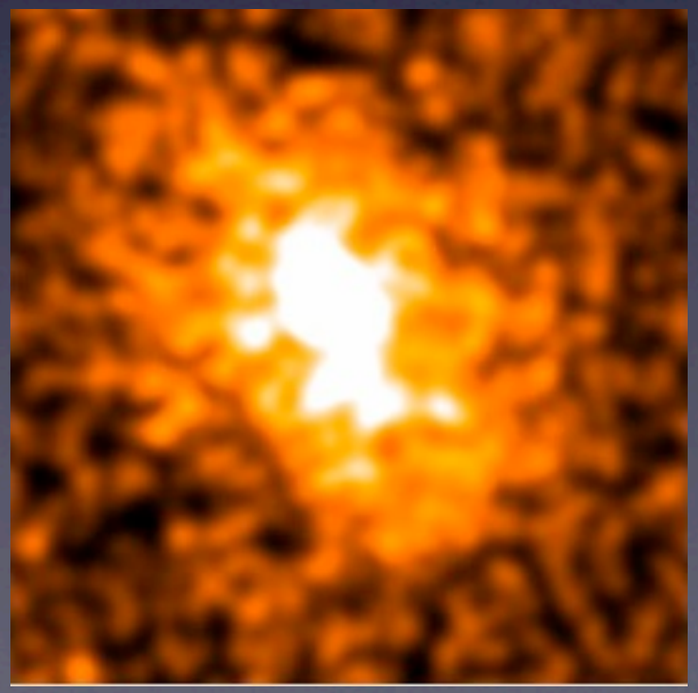
- 25 Richest clusters with 0.2<z<0.3
  - 12 with archival *Chandra/XMM* data, 12 in *Chandra* Cycle 11
- SZA data
- Look at scatter/covariance among richness, X-ray, and SZ mass estimators
- Pilot study looking forward to DES, eROSITA, SPT



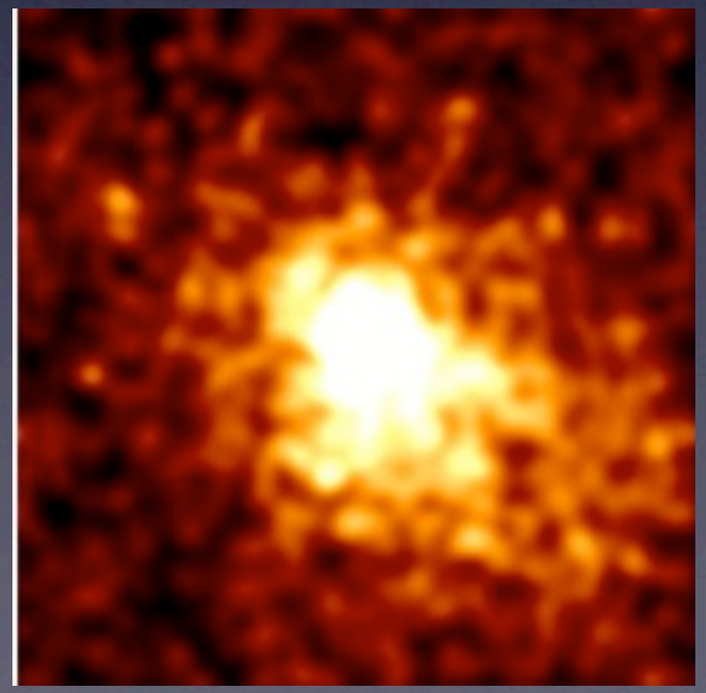
PI: Rykoff

Chandra Observations

- A2645
- NORAS cluster
- z=0.26
- 1.6×10^{44} erg/s
- ~8 keV



- J0104+0003
- not in NORAS
- z=0.28
- 1.3×10^{44} erg/s
- ~8 keV



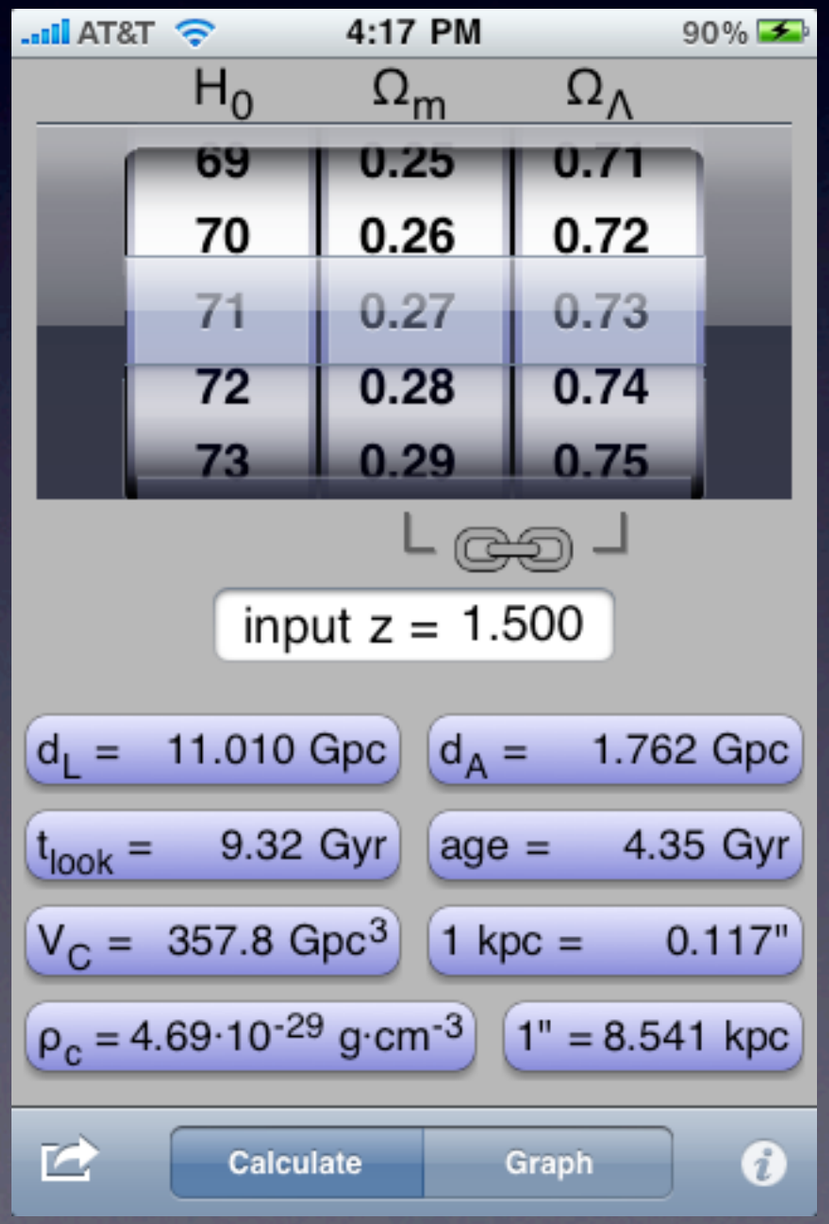
Summary

- maxBCG L_X-M relation consistent with other catalogs (see also Leauthaud et al. 2009)
- Understanding the scatter *and* covariance is necessary when binning on richness
- Several thousand optical clusters yields tight cosmological constraints
- Improvements are still being made

- One more thing...

One more thing...

- For you iPhone/iPod Touch owners, please check out these free astro apps!

GravLens

CosmoCalc