Cluster Cosmology

Eduardo Rozo
Einstein Fellow, KICP

July 10, 2012
Santa Fe, NM

Summary

In the near future, the abundance of galaxy clusters may be the most sensitive probe of the growth of LSS .

This measurement is a *necessary complement* to geometric dark energy probes (e.g. BAO/SN) in order to *test* General Relativity.

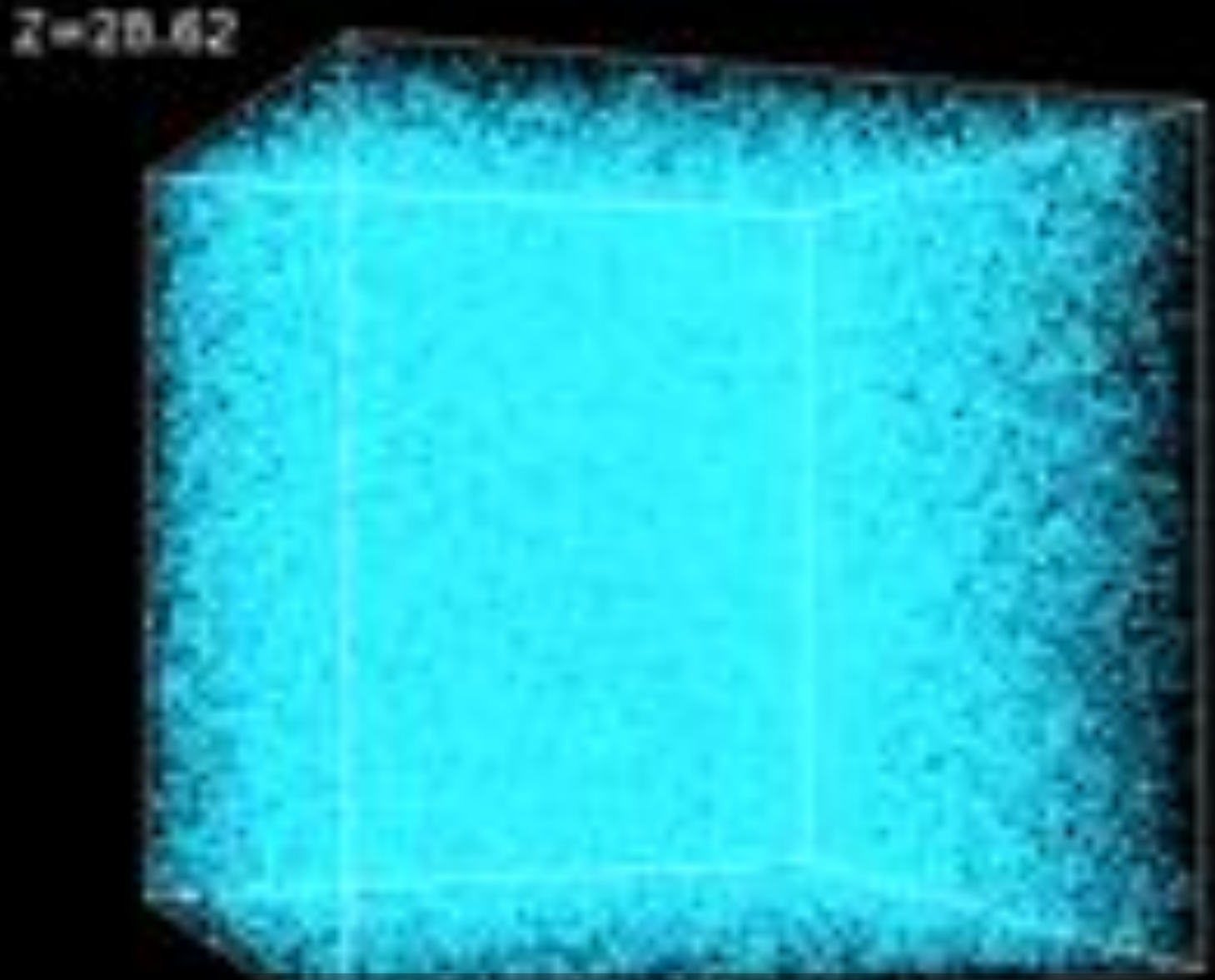
The principal limitation for cluster cosmology is uncertainty in cluster masses.

Expect WL and clustering are the only methods that will allow significant improvements relative to current results.

How Cluster Cosmology Works

Early universe is homogeneous to 1 part in 10^5.

Early fluctuations grow gravitationally.



Gravity amplifies CMB noise into LSS.

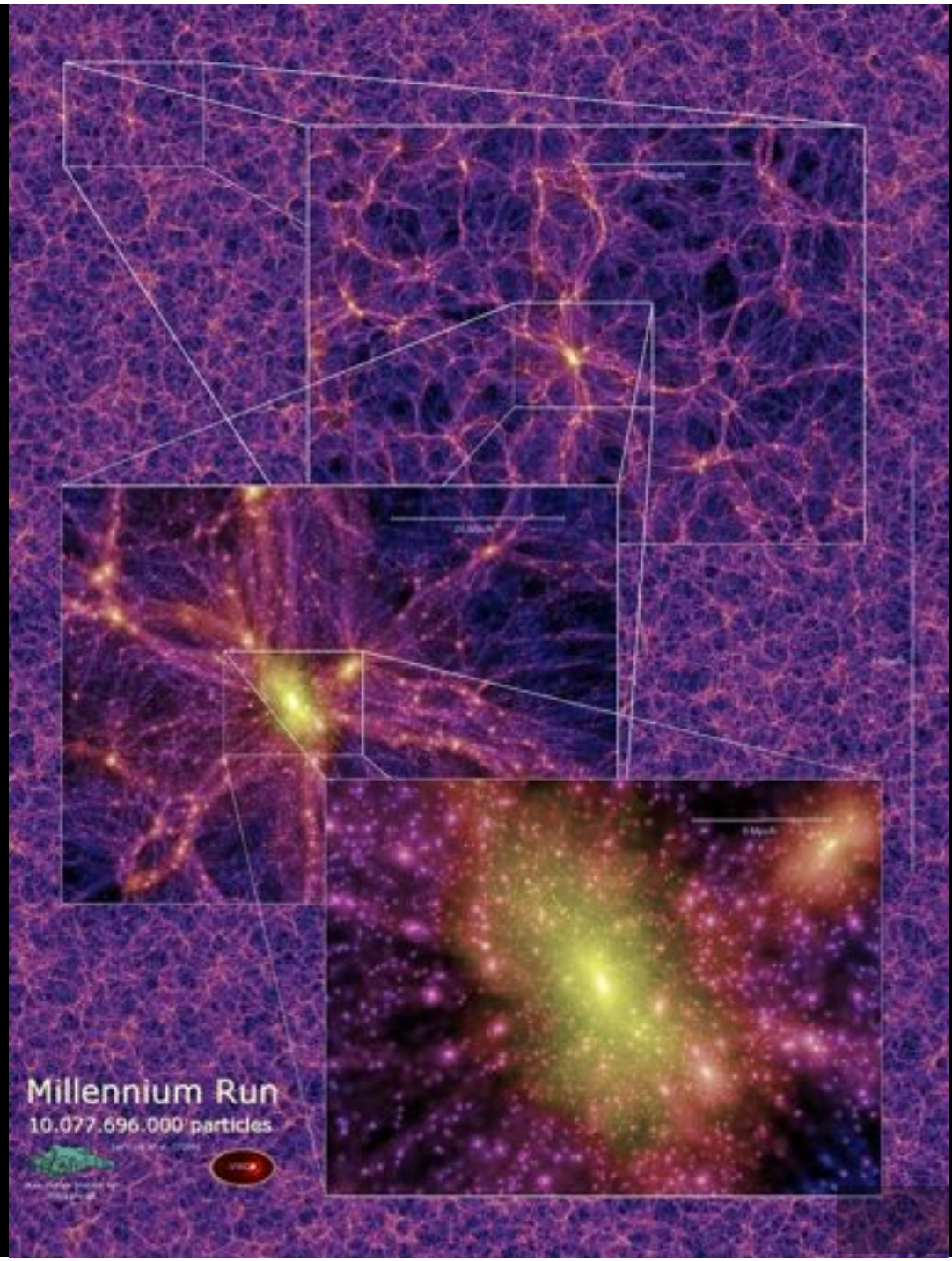
Simulation courtesy of Andrey Kravtsov.

How Cluster Cosmology Works

Early universe is homogeneous to 1 part in 10^5.

Early fluctuations grow gravitationally.

Large inhomogeneities eventually undergo gravitational collapse, and form virialized structures, i.e. ***halos.***



But how does the no. of halos depend on cosmology?

Millenium simulation.

A Cartoon Model for the Halo Abundance

An initial overdensity δ in a sphere of radius R grows according to linear theory, $\delta(a)=G(a)\,\delta_0$.

When the overdensity passes a critical threshold δ_c, it collapses to form a halo.

Number of halos with mass M or greater will scale naturally with $\mathbf{P(\delta>\delta_c)}$.

N(M) depends on the amplitude of matter fluctuations: higher amplitude -> more halos.

How Cluster Cosmology Works

Early universe is homogeneous to 1 part in 10^5.

Early fluctuations grow gravitationally.

Large inhomogeneities eventually undergo gravitational collapse, and form virialized structures, i.e. ***halos.***

Main takeaway: Measurements of the halo abundance constrain growth of matter fluctuations.

Why is This Interesting?

Dark energy is not the only possible explanation for an accelerated expansion: GR could be wrong.

To *test GR* we need two things:

1. Constrain w(a) with geometric probes like SN and/or BAO.
2. Use GR to *predict* the growth function G(a), and compare with independent observations.

Cluster provide the dynamical complement to BAO/SN required to test GR.

Cluster Cosmology in 3 Easy Steps

1. Find massive halos (i.e. clusters) using an observable signature, e.g. X-rays, or galaxy counts.
2. Determine the relation between the observable signature X and the mass M, i.e. $P(X|M)$.
3. Use $P(X|M)$ and $N_{theory}(M)$ to predict the observed abundance of clusters $N_{obs}(X)$.

Terminology

Halo: halos are honest-to-goodness mass peaks.
i.e. halos are what "God" finds when he runs his halo finder in the matter density map of the real Universe.

Cluster: clusters is what observers find, e.g.
- a group of galaxies
- an extended X-ray source
- an SZ signal in a CMB map.

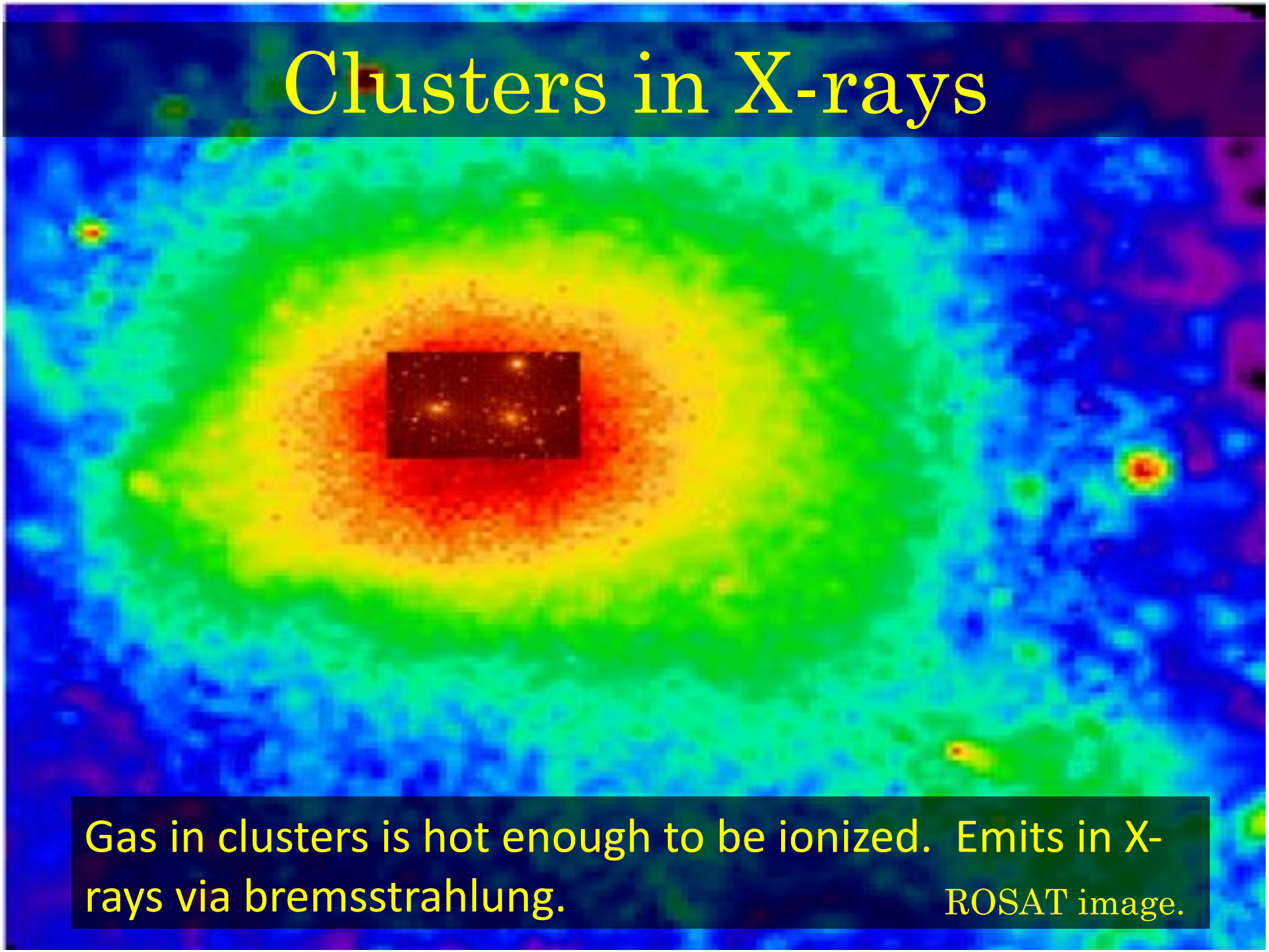
Step 1: Finding Clusters

Three main ways of detecting clusters:

- as conglomerations of galaxies (galaxy clusters).
- as extended X-ray sources.
- using the SZ-signal

Clusters in the Optical

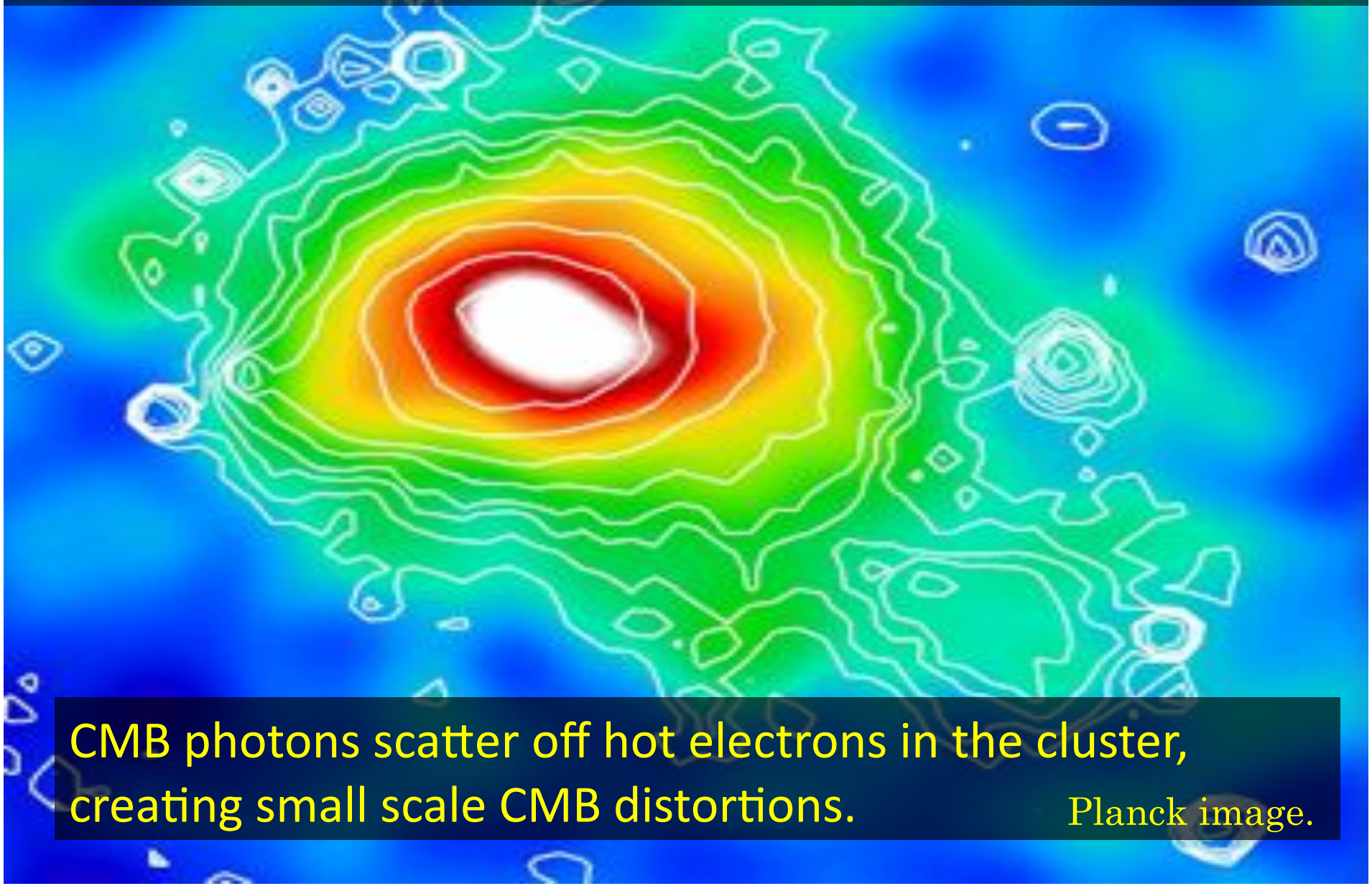
Clusters in X-rays



Gas in clusters is hot enough to be ionized. Emits in X-rays via bremsstrahlung.

ROSAT image.

Clusters in SZ



CMB photons scatter off hot electrons in the cluster, creating small scale CMB distortions.

Planck image.

Pros and Cons

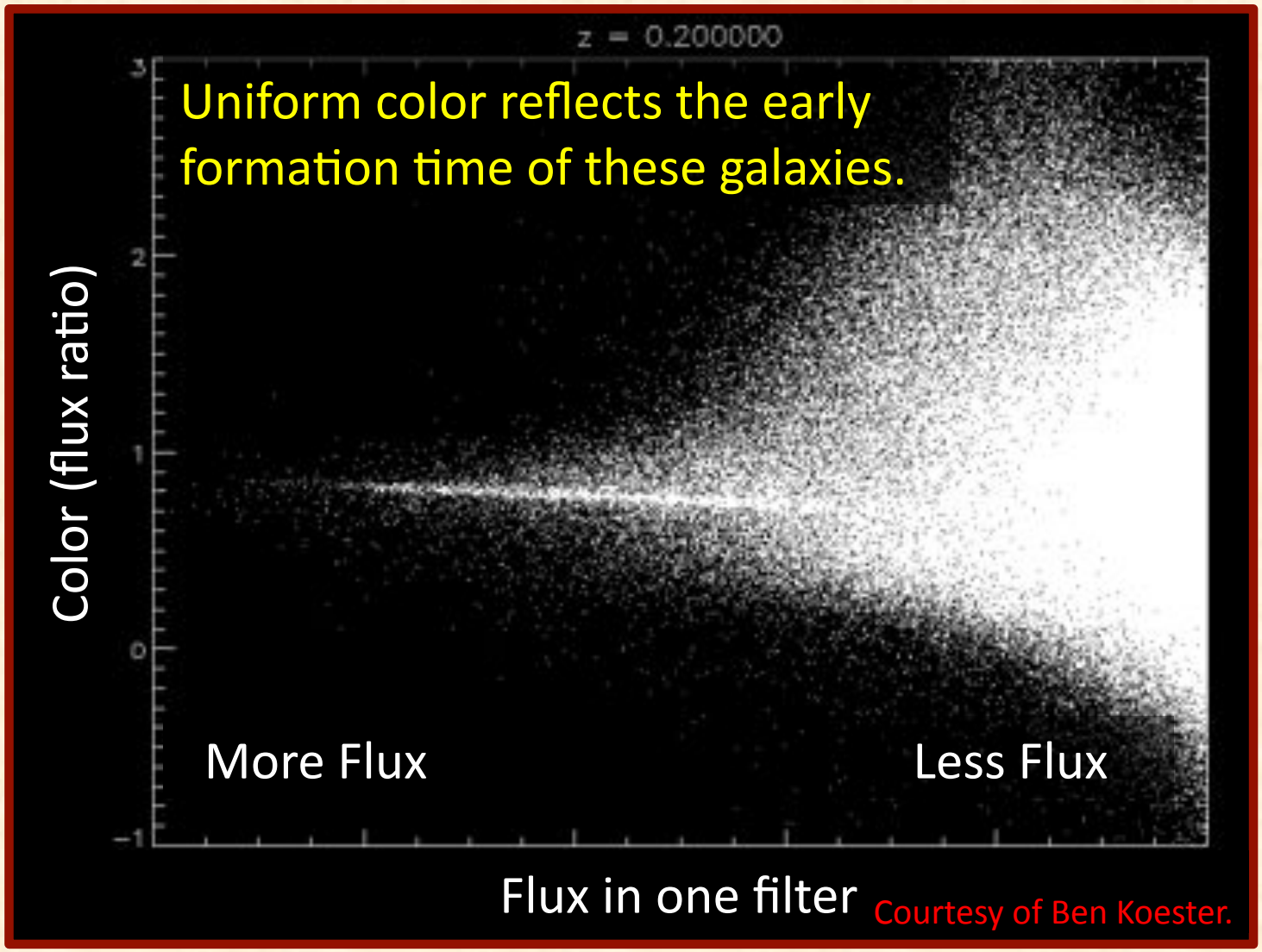
Method	Pro	Con
Optical	Low mass, no followup required	Projection effects, large scatter between richness and mass
X-rays	Projection effects are tiny	Severe cosmological dimming, requires optical followup for redshifts
SZ	No cosmological dimming	Projection effects, requires optical follow-up for redshifts.

No single method is “best”; multi-wavelength methods can improve upon single-wavelength.

(e.g. Cohn and White 2009, Cunha 2009)

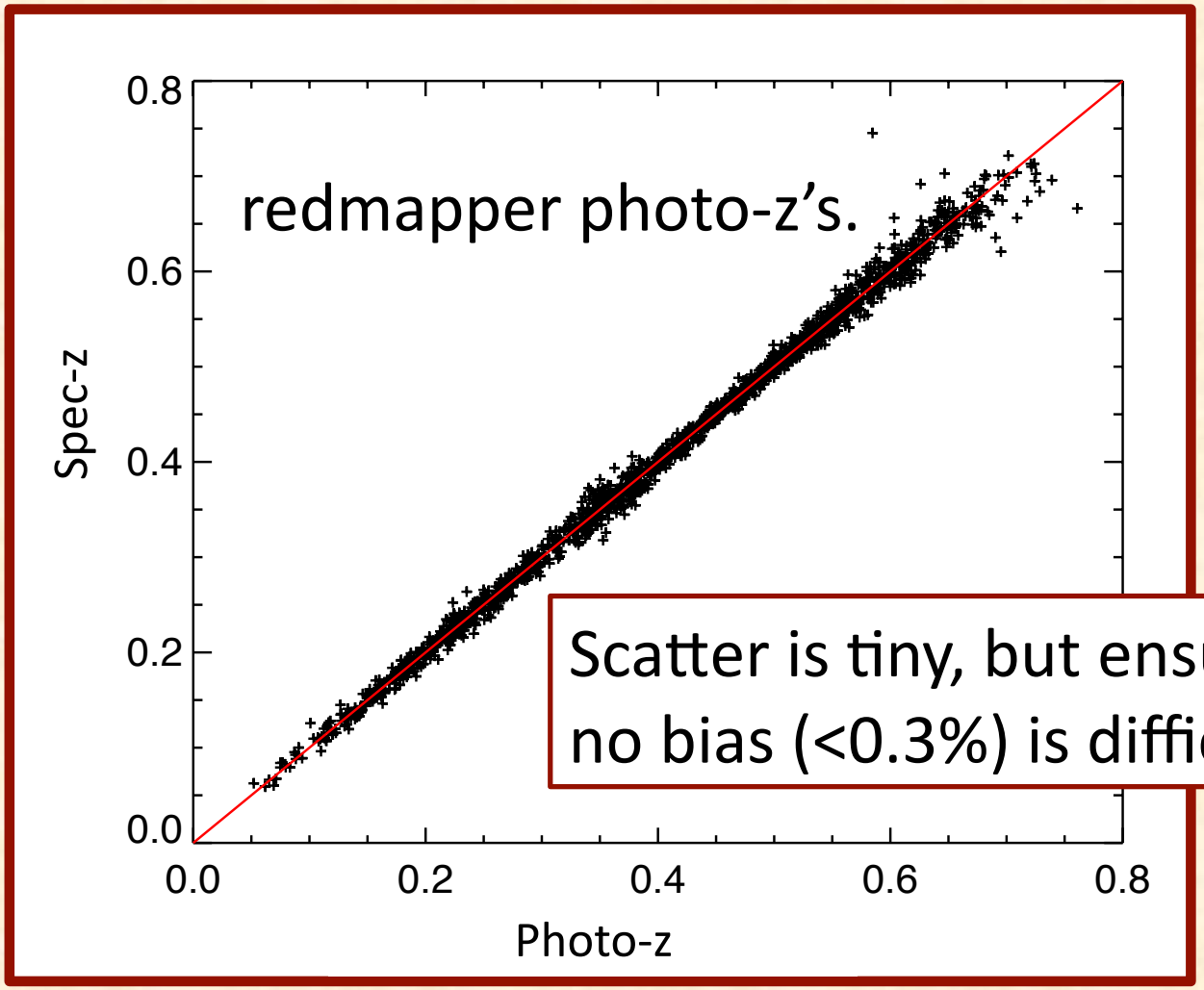
Photometric Clusters Redshifts

Clusters in the Optical



Courtesy of Ben Koester.

Cluster Photometric Redshifts in SDSS Stripe 82



Scatter is tiny, but ensuring no bias (<0.3%) is difficult.

How Well Can Halo Abundances Measure $\sigma_8(z)$?

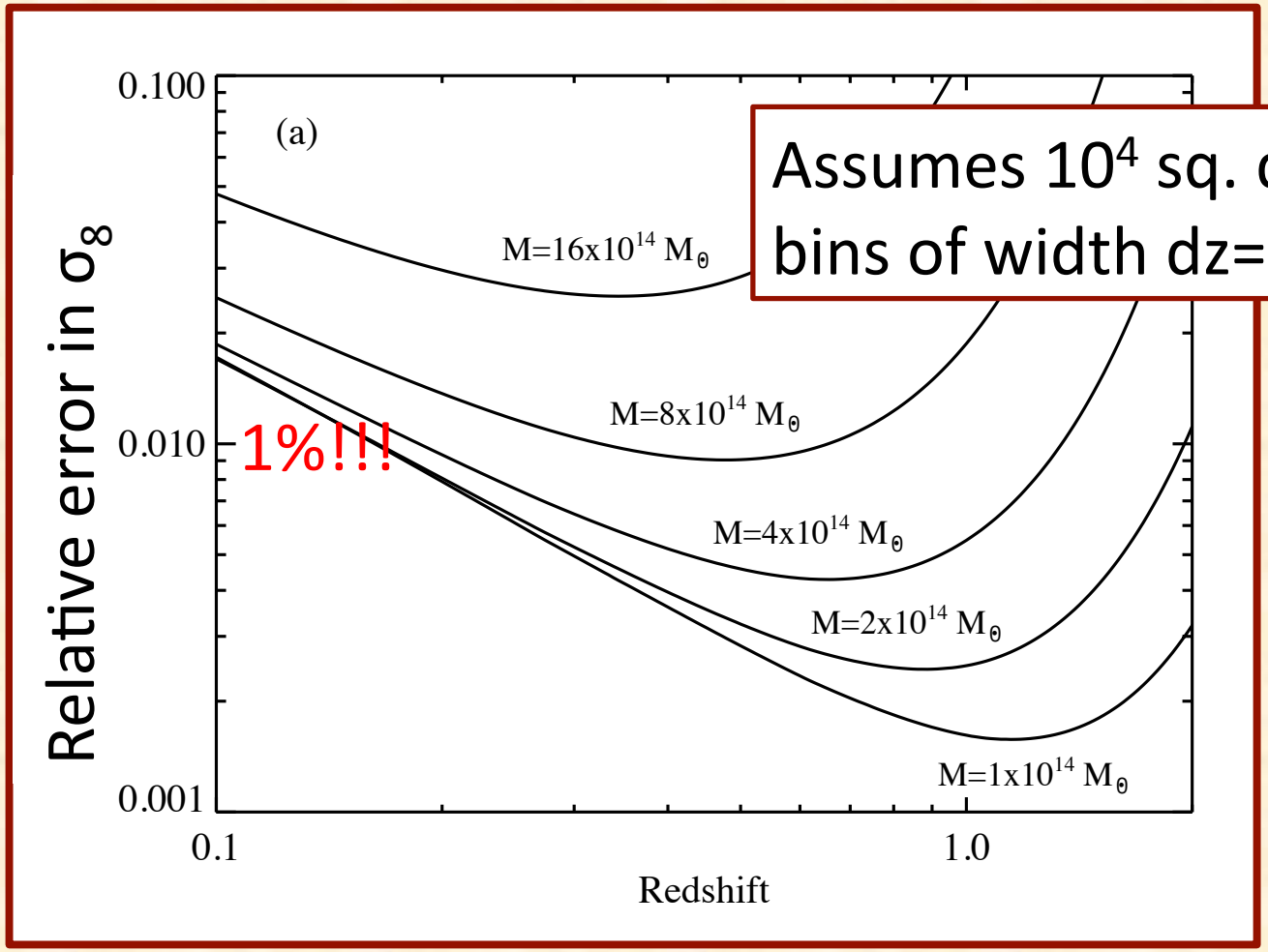
Say we measure N(M) = no. of halos of mass M.

Two sources of error in the counts:

- Poisson errors (counting).
- Sample variance:
  If the survey volume is slightly overdense or underdense, the halo counts fluctuate accordingly.

Hu and Cohn 2006, Holder 2006.

How Well Can Halo Abundances Measure $\sigma_8(z)$?



Assumes 10^4 sq. deg, bins of width dz=0.1.

Weinberg et al. 2012

Things to Note

Low mass halos have more information than high mass halos.

Errors shown are really, really tiny.

If something sounds to good to be true…

So what's missing?

Cluster Cosmology in 3 Easy Steps

1. Find massive halos (i.e. clusters) using an observable signature, e.g. X-rays, or galaxy counts.
2. **Determine the relation between the observable signature X and the mass M, i.e. P(X|M).**
3. Use P(X|M) and $N_{theory}(M)$ to predict the observed abundance of clusters.

Step 2: Measuring Masses

Mass measurements are the biggest source of error for cluster cosmology. Why?

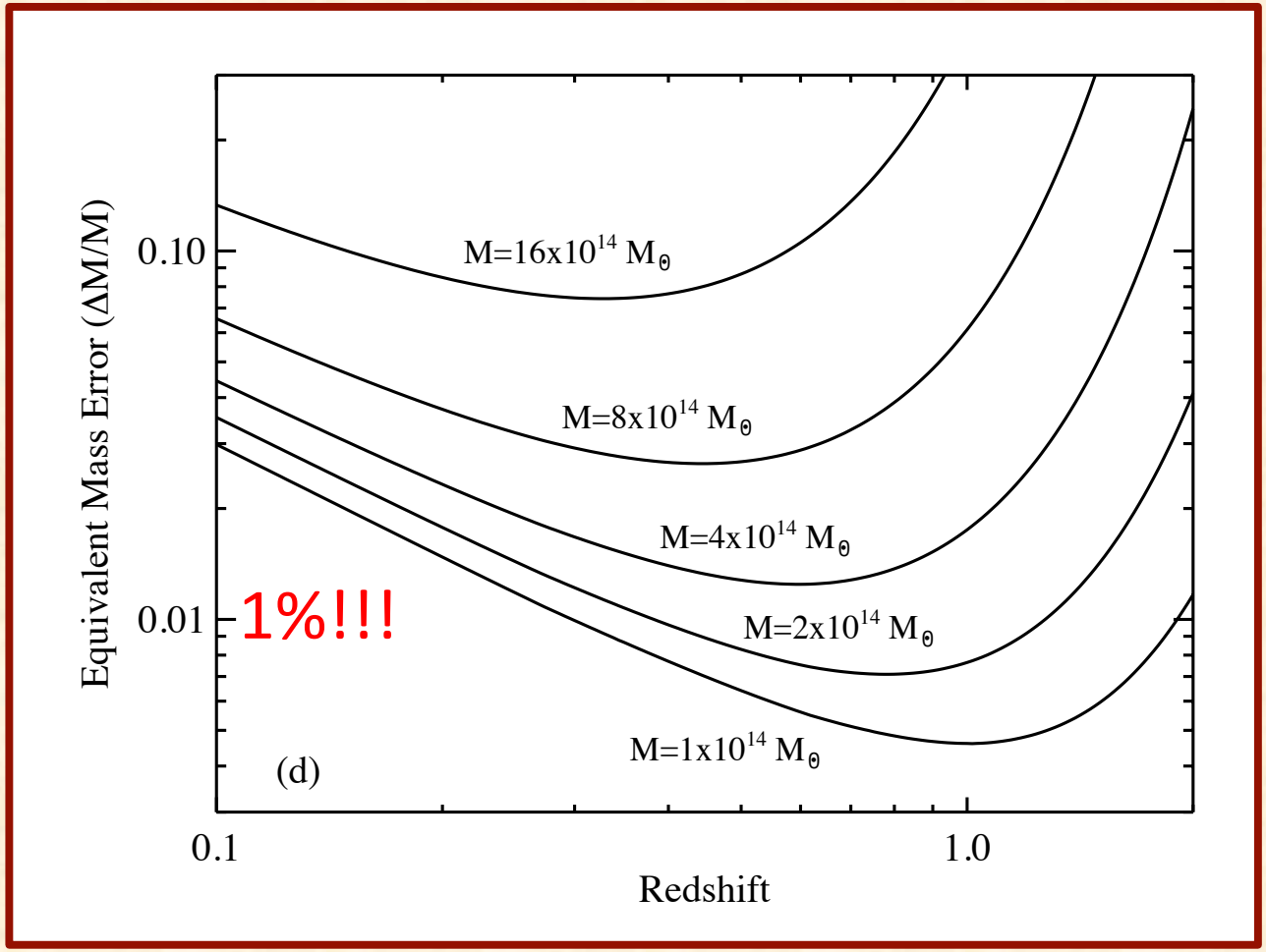
The mass function is very steep:

$dn/d\ln M \sim M^{-\beta}$ where $\beta \approx 3\text{-}5$.

A relative error in the mass $\Delta \ln M = \Delta M/M$ is equivalent to an error $\Delta \ln N = \beta \Delta \ln M$.

In the previous example, how well would we have to measure M to be dominated by the errors in the counts?

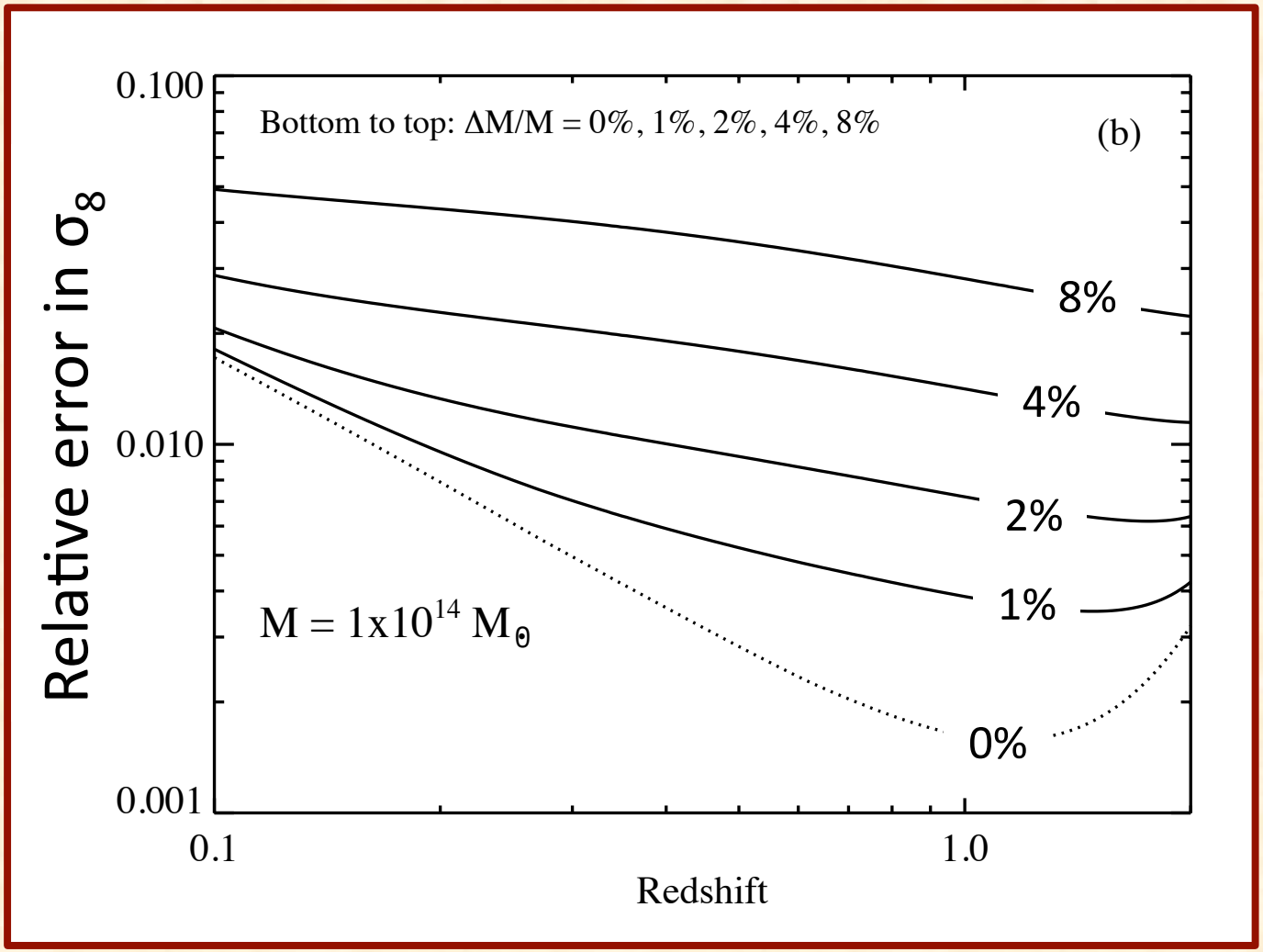
Equivalent Mass Error



Typical mass error required for a Stage III experiment to be dominated by counting statistics.

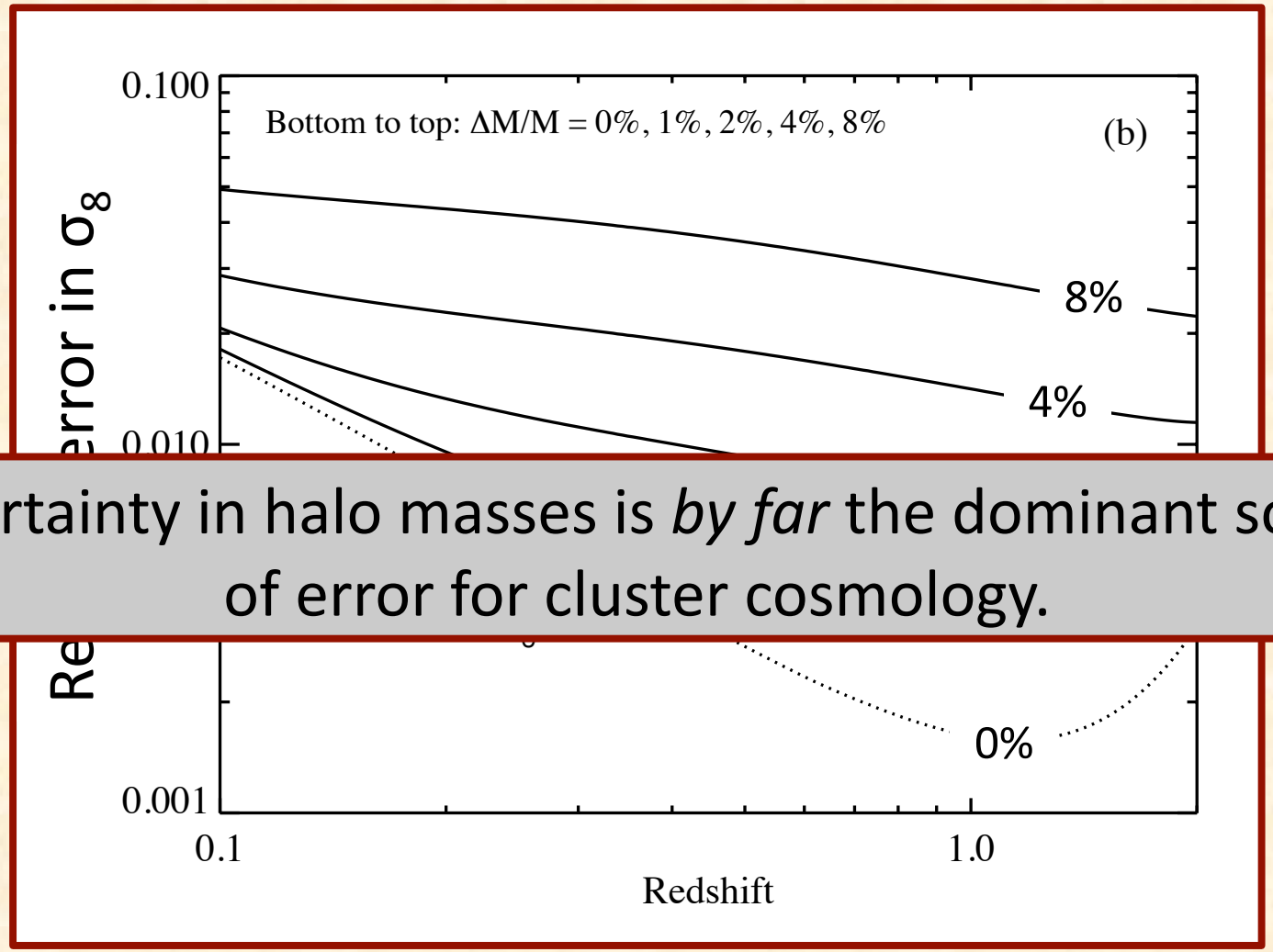
Weinberg et al. 2012

Error Degradation



Weinberg et al. 2012

Error Degradation



Uncertainty in halo masses is *by far* the dominant source of error for cluster cosmology.

Weinberg et al. 2012

How to Measure Masses?

Three main possibilities:

- Hydrostatic masses (X-rays and SZ).
- Velocity dispersions.
- Weak gravitational lensing.

How to Measure Masses

Hydrostatic masses: Assume intra-cluster gas is in hydrostatic equilibrium, and use observed pressure profile to infer mass profile.

X-ray surface brightness measures ρ^2, energy spectrum measures temperature T.

ρT = thermal pressure = gravitational pressure

Main drawbacks:

If there are other sources of pressure support, inferred mass will be biased low.

Requires expensive high resolution X-ray follow-up.

X-ray calibration limits mass accuracy to ~10%.

How to Measure Masses

Velocity dispersion: from virial equilibrium we expect

$v^2 \sim GM/R = GM^{2/3}$ or $M \sim \sigma_v^3$. (e.g. Evrard et al. 2008)

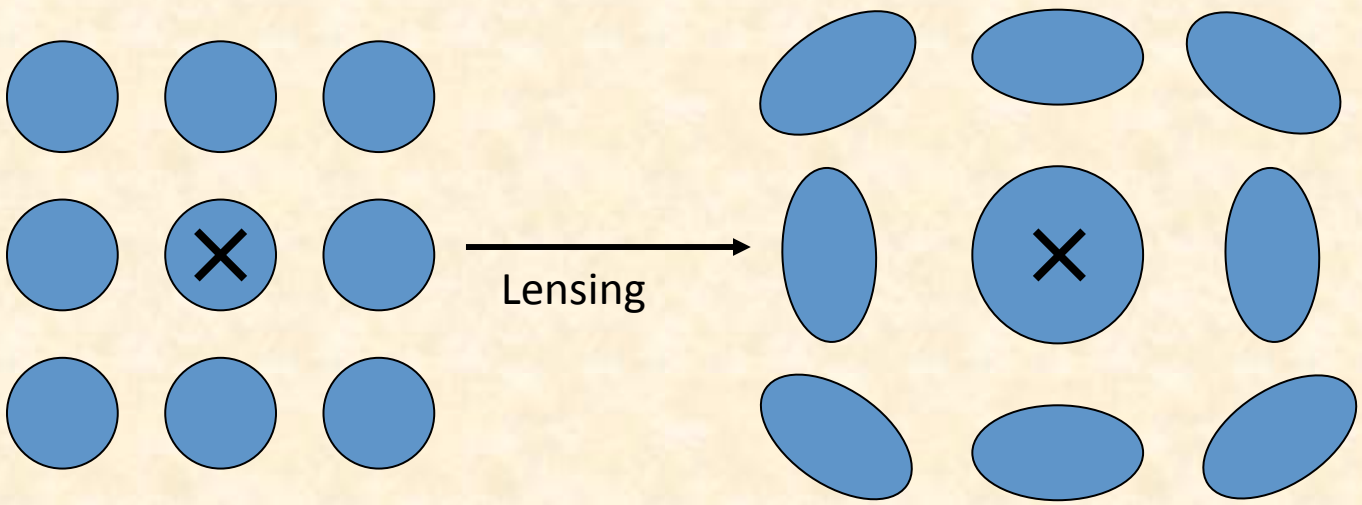
Measure LOS velocity dispersion of member galaxies to infer mass.

Main drawbacks:

- Spectroscopic follow-up is expensive.
- Member selection can be difficult, must account for group in fall, large scatter. (White, Cohn, and Smit 2010).
- Because of the cubic dependence, a small velocity bias b_V translates into a large mass bias.

How to Measure Masses

Weak gravitational lensing: lensing distorts the shapes of background galaxies, resulting in the formation of a tangential patter around clusters.



Measure the mean tangential ellipticity of background galaxies to infer cluster mass.

How to Measure Masses

Weak gravitational lensing: lensing distorts the shapes of background galaxies, resulting in the formation of a tangential patter around clusters.

Main drawbacks:

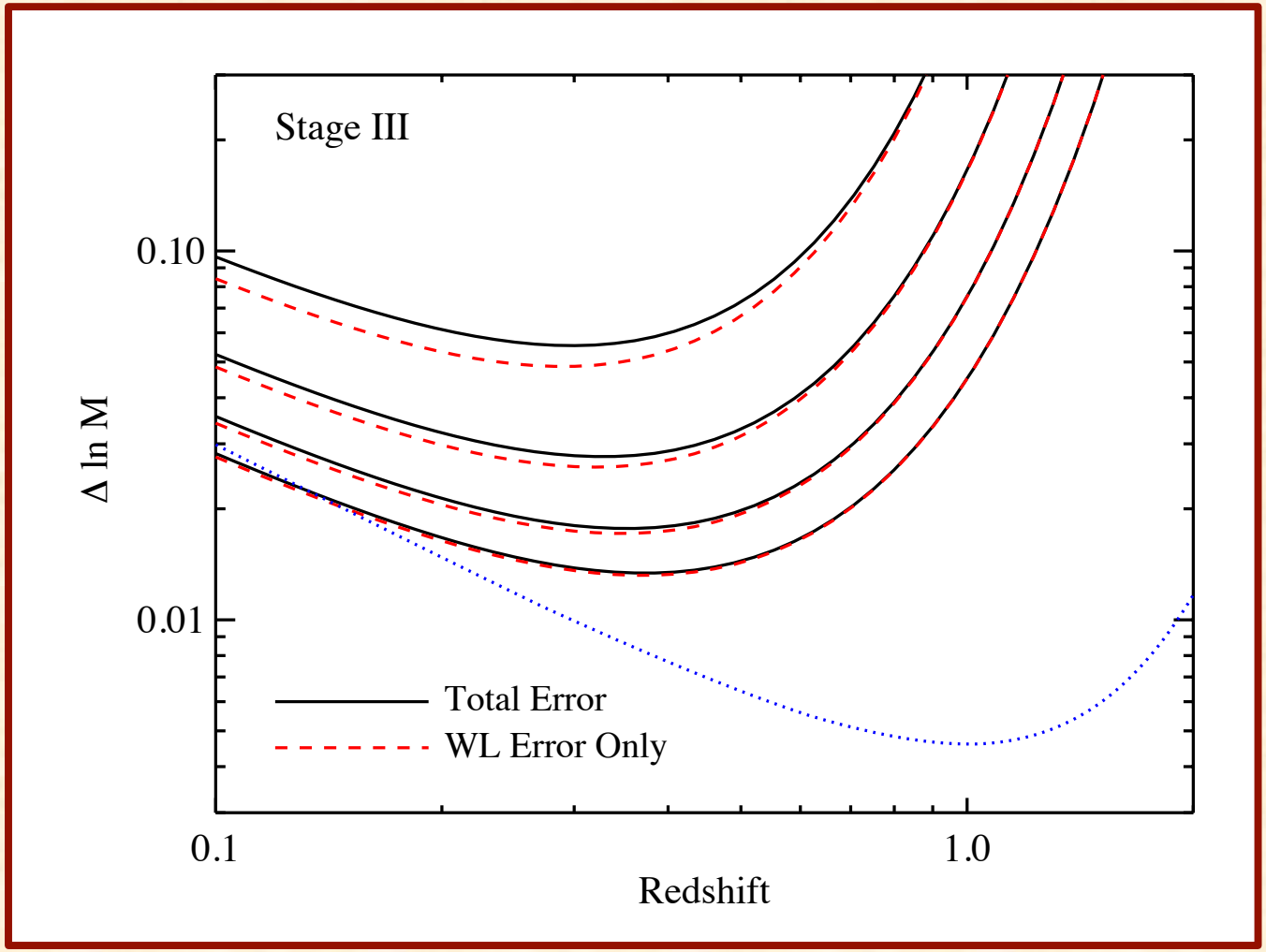
- Measurements of the tangential ellipticity may be biased.
- Relation between ellipticity and mass depends on the redshifts of background galaxies, which are uncertain.
- *Tangential* ellipticity requires that we specify a cluster center. Can we always choose the correct center?
- Low S/N for any individual galaxy cluster (must stack).

How to Measure Masses?

Method	Current Statistics or Systematics Floor	Likely to see Dramatic Improvements?
Hydrostatic	~10%-20% (Sys. limited)	Not likely.
Vel. Dispersion	~15% (Sys. limited)	Not likely. (though see Saro et al. 2012).
Weak Lensing	~10% (Comparable stat and sys error)	Yes.

How well could weak lensing do in the near future?

Mass Uncertainty for Near Future Experiments



Weinberg et al. 2012

Impact on Cosmology

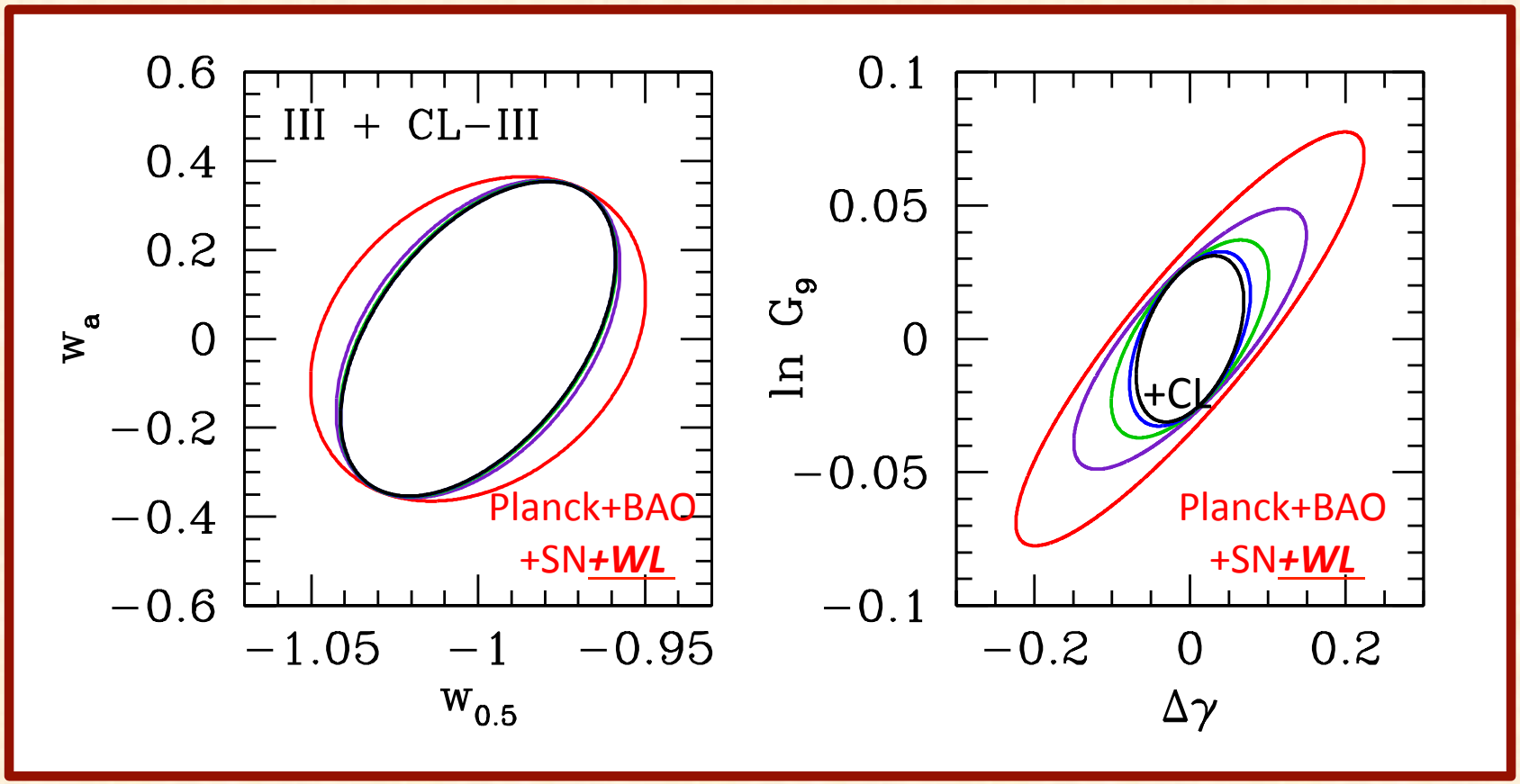
Parameterize dark energy equation of state with w_0 and w_a.

Paramerize growth of structure using the fitting function (e.g. Linder 2005):

$$\frac{d\ln G}{d\ln a} = \left[\Omega_m(z)\right]^{\gamma}$$

Growth model parameters are γ, and the initial condition G(z=9).

Impact on Cosmology



If WL systematics can be controlled, clusters should be than cosmic shear at constraining structure growth.

Weinberg et al. 2012.

You May Say That I'm a Dreamer

The resulting [cluster] constraints [marginalized over mis-centering, source redshift, and halo concentration] are in fact quite comparable to those from tomographic cosmic shear *without any marginalization over systematic errors*.

Oguri and Takada 2010.

Summary

In the near future, the abundance of galaxy clusters may be the most sensitive probe of the growth of LSS .

This measurement is a *necessary complement* to geometric dark energy probes (e.g. BAO/SN) in order to *test* General Relativity.

The principal limitation for cluster cosmology is uncertainty in cluster masses.

Expect WL and clustering are the only methods that will allow significant improvements relative to current results.

Cluster Cosmology Today, and Where We're Headed

Eduardo Rozo
Einstein Fellow, KICP

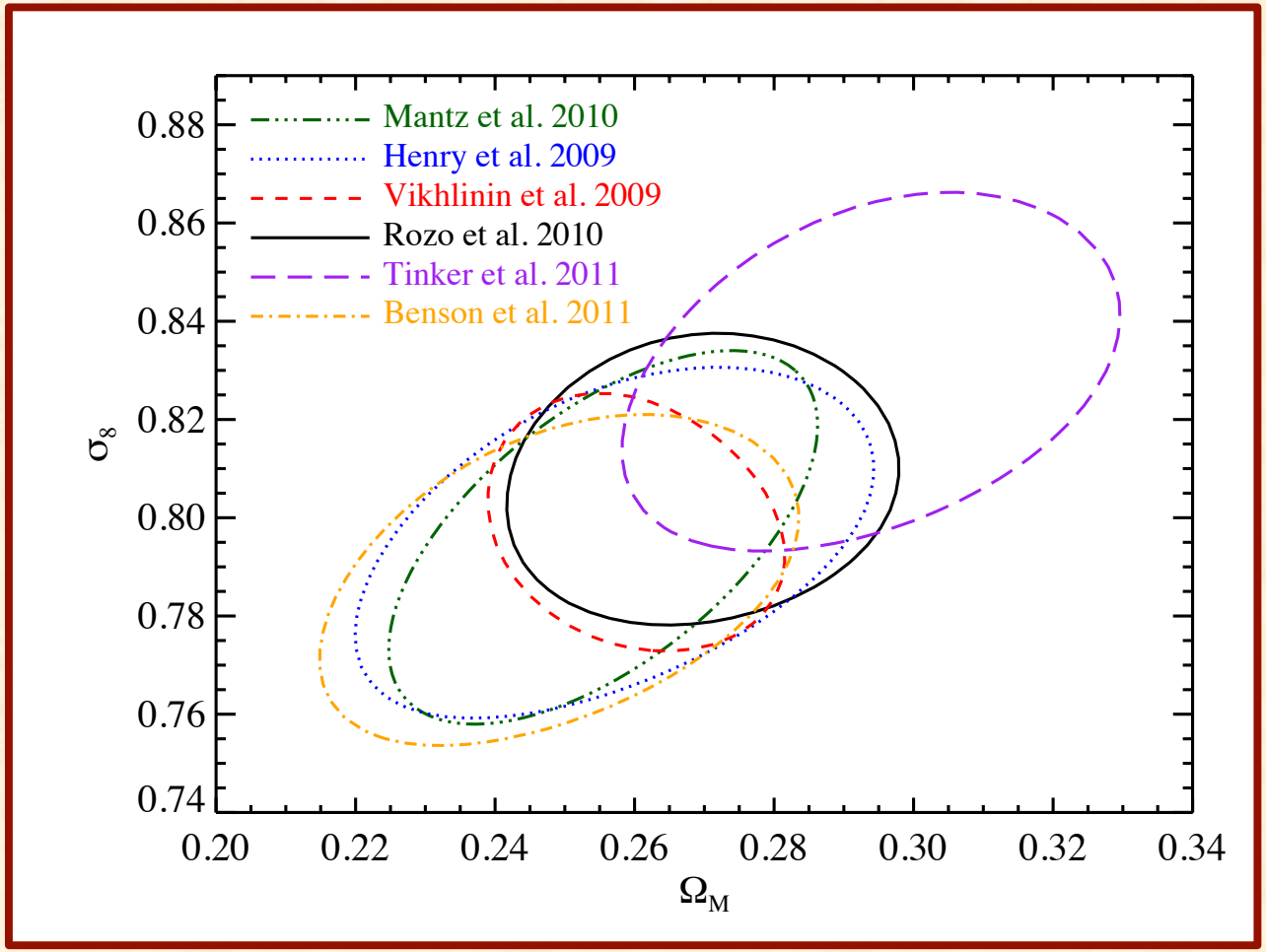
July 10, 2012
Santa Fe, NM

How to Measure Masses?

Method	Current Statistics or Systematics Floor	Likely to see Dramatic Improvements?
Hydrostatic	~10%-20% (Sys. limited)	Not likely.
Vel. Dispersion	~15% (Sys. limited)	Not likely. (though see Saro et al. 2012).
Weak Lensing	~15% (Comparable stat and sys error)	Yes.

Do they all agree?

Cosmological Constraints from Various Cluster Samples



Victory!

Regardless of how we measure masses, we find the same result.

Of course, that's hardly the whole story…

The Planck-maxBCG Measurement

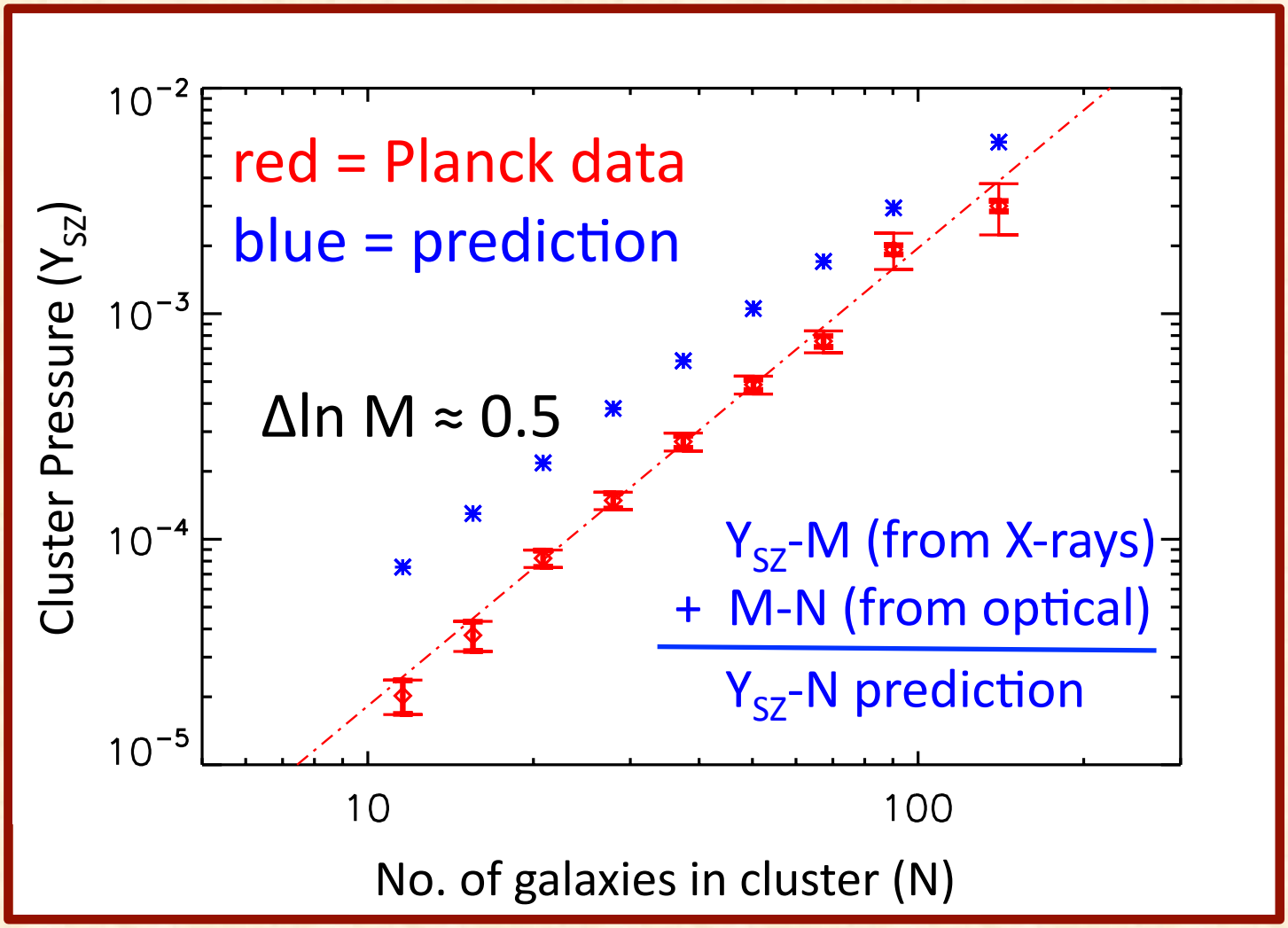
maxBCG is an *optically selected* cluster catalog drawn from the SDSS.
Planck measured the SZ signal of maxBCG clusters.

Predicting the signal:

- the relation between no. of galaxies and cluster mass was calibrated for maxBCG using weak lensing.
- the relation between Y_{SZ} and mass was calibrated using hydrostatic masses of X-ray clusters.

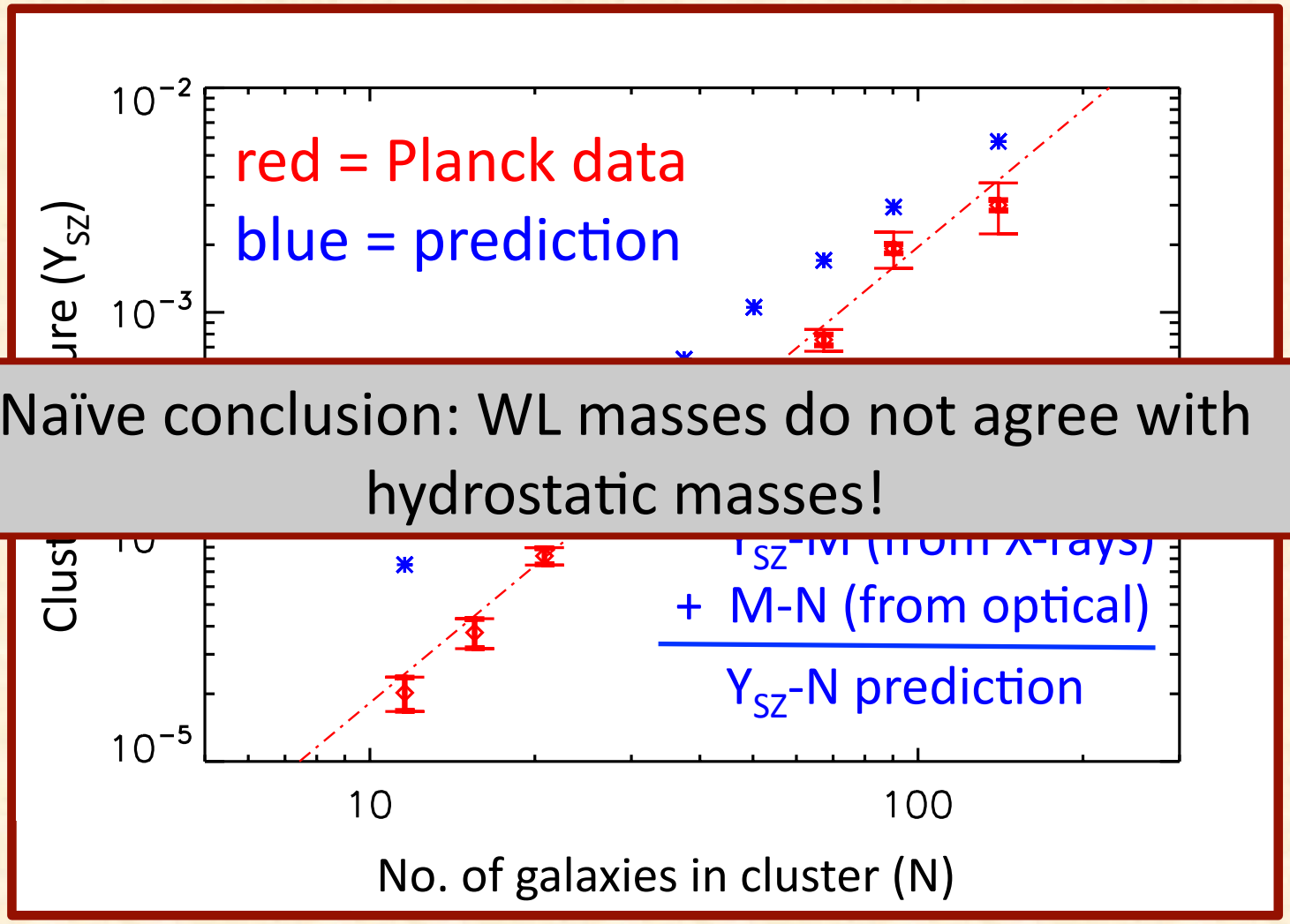
$$N \xrightarrow{\text{Weak Lensing}} M \xrightarrow{\text{Hydrostatic Eq.}} Y_X \xrightarrow{\text{ICM Modeling}} Y_{SZ}$$

Surprise!



Planck Collaboration 2011

Surprise!



Naïve conclusion: WL masses do not agree with hydrostatic masses!

Planck Collaboration 2011

But that’s not all…

The Planck-MCXC Measurement

MCXC is an *X-ray selected* cluster catalog.

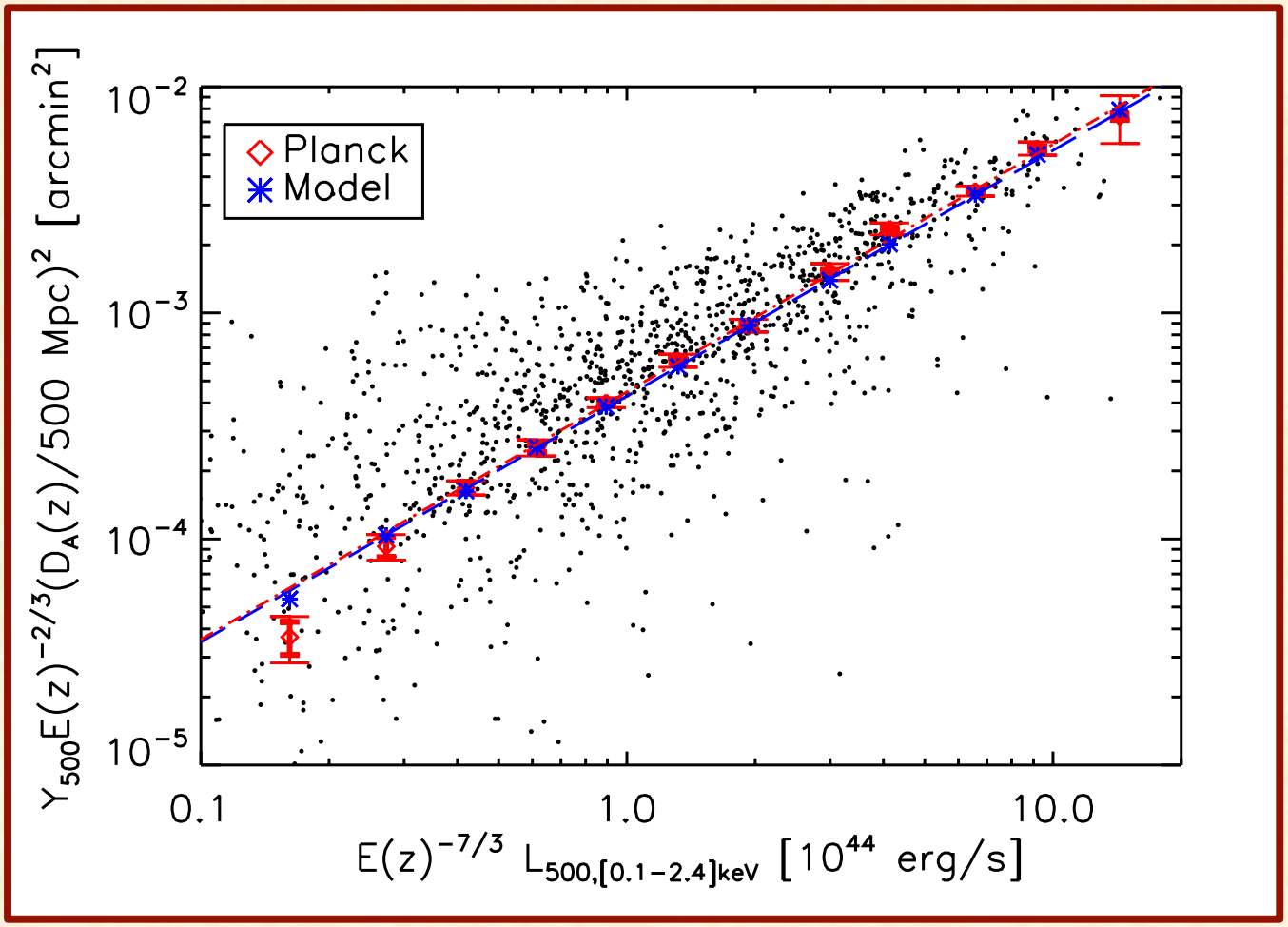
Planck measured the SZ signal of MCXC clusters.

Predicting the signal:

- the relation between X-ray luminosity L_X and cluster mass was calibrated using hydrostatic X-ray masses.
- the relation between Y_{SZ} and mass was calibrated using hydrostatic masses of X-ray clusters.

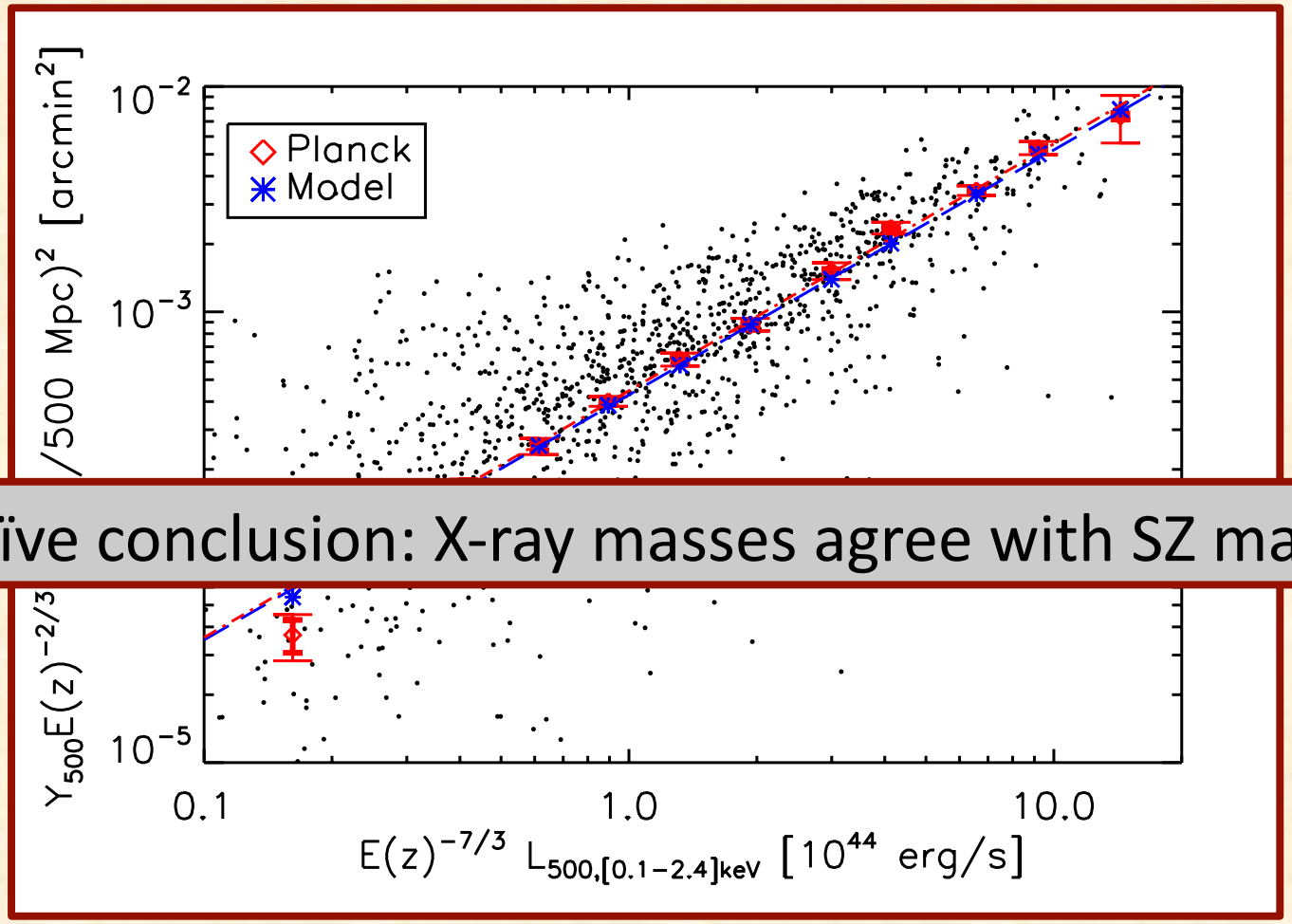
$$L_X \xrightarrow{\text{Hydrostatic Eq.}} M \xrightarrow{\text{Hydrostatic Eq.}} Y_X \xrightarrow{\text{ICM Modeling}} Y_{SZ}$$

This One Seems to Work!



Planck Collaboration 2011

This One Seems to Work!



Naïve conclusion: X-ray masses agree with SZ masses!

Planck Collaboration 2011

But that’s not all…

The maxBCG L_X-M Measurement

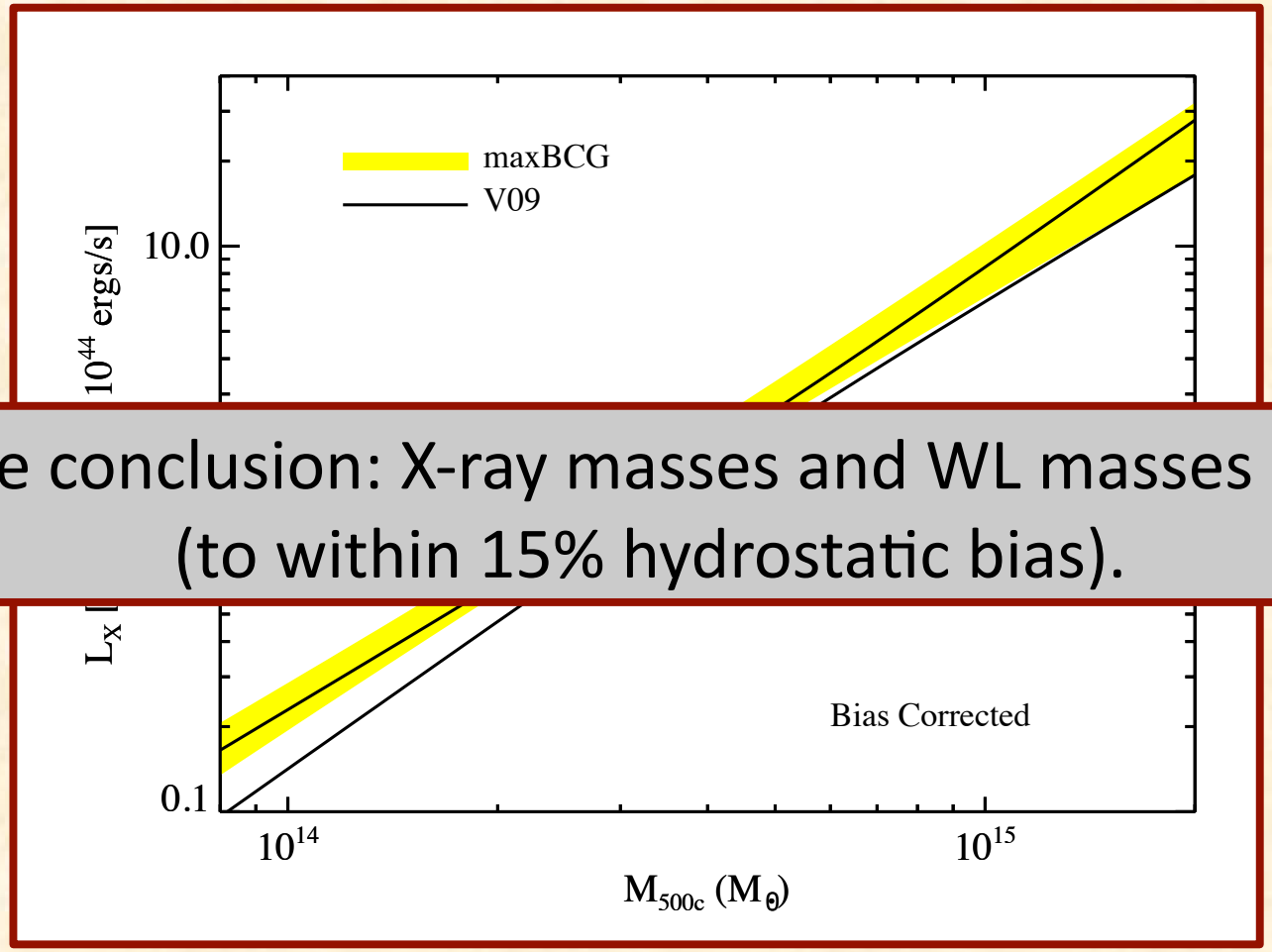
Rykoff et al. 2007 measured the relation between X-ray luminosity L_X and galaxy counts.

Sheldon et al. 2009 calibrated the relation between galaxy counts and cluster mass with weak lensing.

We can string the two together to compute L_X-M, and compare to calibration from X-ray hydrostatic masses (Rozo et al. 2009).

They agree! (Rozo et al. 2009 assumed a 15% hydrostatic bias).

Comparison of L_X-M Measurements



Naïve conclusion: X-ray masses and WL masses agree (to within 15% hydrostatic bias).

Wait- What?

Optical abundance agrees with X-rays, SZ, and WMAP. (Weinberg et al. 2012)

Optical agrees with X-rays on mass (assuming ~15% hydrostatic bias).

(Rozo et al. 2009)

X-rays agree with SZ on mass.

(Planck collaboration 2011)

Optical does ***not*** agree with SZ on mass (~50%!!! offset, Planck collaboration 2011).

Huh?

So what happened?

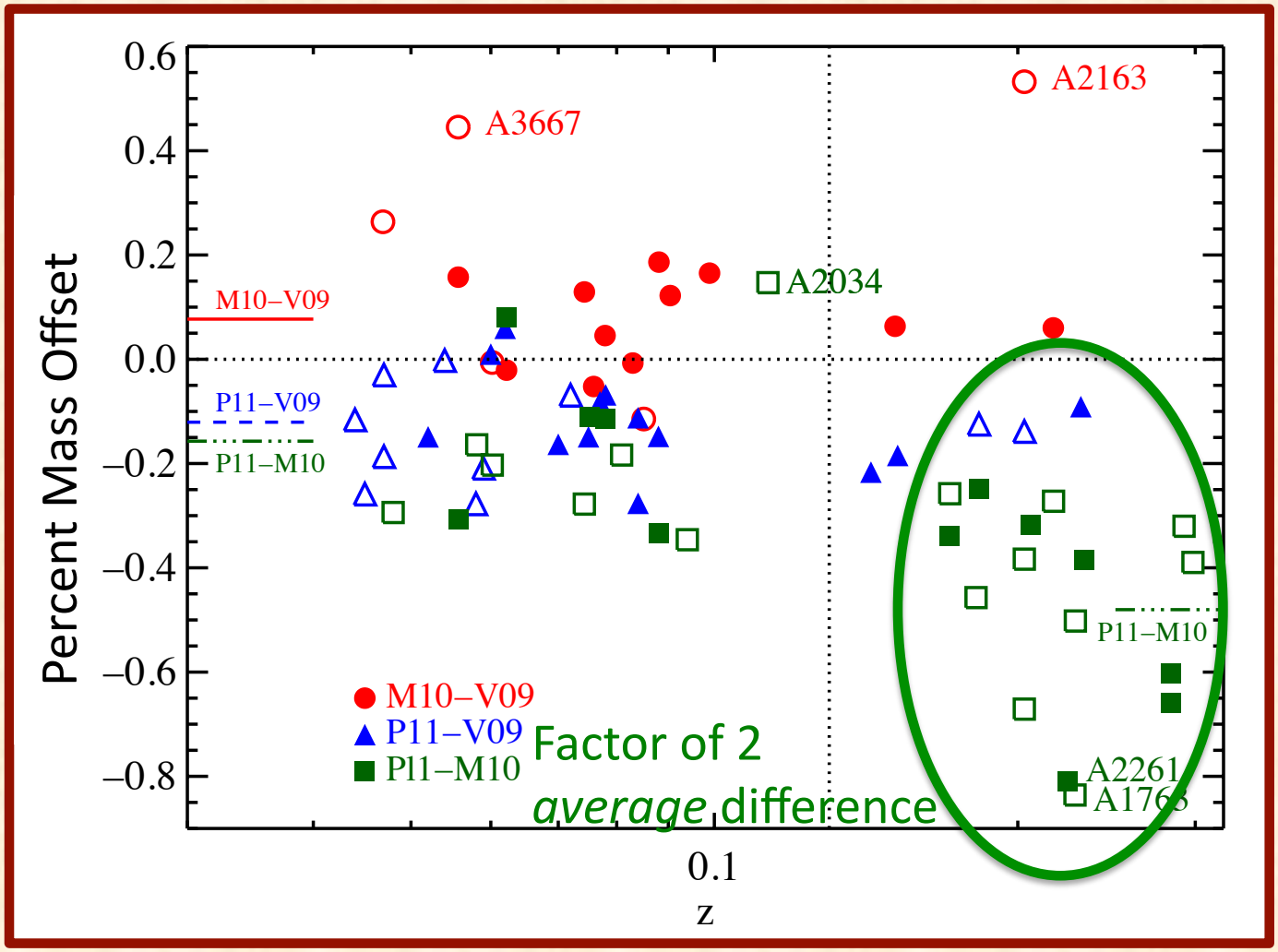
The First 20%...

$$N \xrightarrow{\text{Weak Lensing}} M \xrightarrow{\textbf{Hydrostatic Eq.}} Y_X \xrightarrow[\text{Measure it!}]{\cancel{\text{ICM Modeling}}} Y_{SZ}$$

(Rozo et al. 2012)

- The relation between Y_{SZ} and mass depends on what X-ray data set we use for calibration.

Comparing X-rays to X-rays



10%-15% systematic differences seen in T_X, Y_X.

Rozo et al. 2012

The First 20%...

$$N \xrightarrow{\text{Weak Lensing}} M \xrightarrow{\text{Hydrostatic Eq.}} Y_X \xrightarrow[\text{Measure it!}]{\cancel{\text{ICM Modeling}}} Y_{SZ}$$

(Rozo et al. 2012)

- The relation between Y_{SZ} and mass depends on what X-ray data set we use for calibration.

Had the Planck collaboration used a different X-ray data set, the tension would have been lower.

Planck masses are *lower* than those of other X-ray data sets (Vikhlinin, Mantz).

But *Why* are the X-ray Masses from Planck Different?

Hydrostatic masses depend on temperature.

There can be large (~10-15%) systematic when estimating cluster temperature.

- Instrumental calibration
- substructure masking
- background subtraction

These systematic errors in T_X result in even larger errors in the hydrostatic masses (~15%-20%).

Can We Tell Who is *right*?

There are four lines of evidence that the X-ray temperatures used by Planck are biased low:

- maxBCG results are better fit if this is the case.
- Y_{SZ}-Y_X ratio.
- X-ray abundance.
- A2261.

All four lines of evidence point in the same direction, i.e. that the X-ray temperatures used by Planck are too low.

The Second 10% - 20%: Hydrostatic Bias

A generic prediction of numerical simulations is that there is a 10%-20% hydrostatic bias.

Bias arises due to non-thermal motions of the intra-cluster gas.

The Third 10% - 20%: Covariance-Induced Biases

Weak lensing mass have large *scatter* at fixed mass.

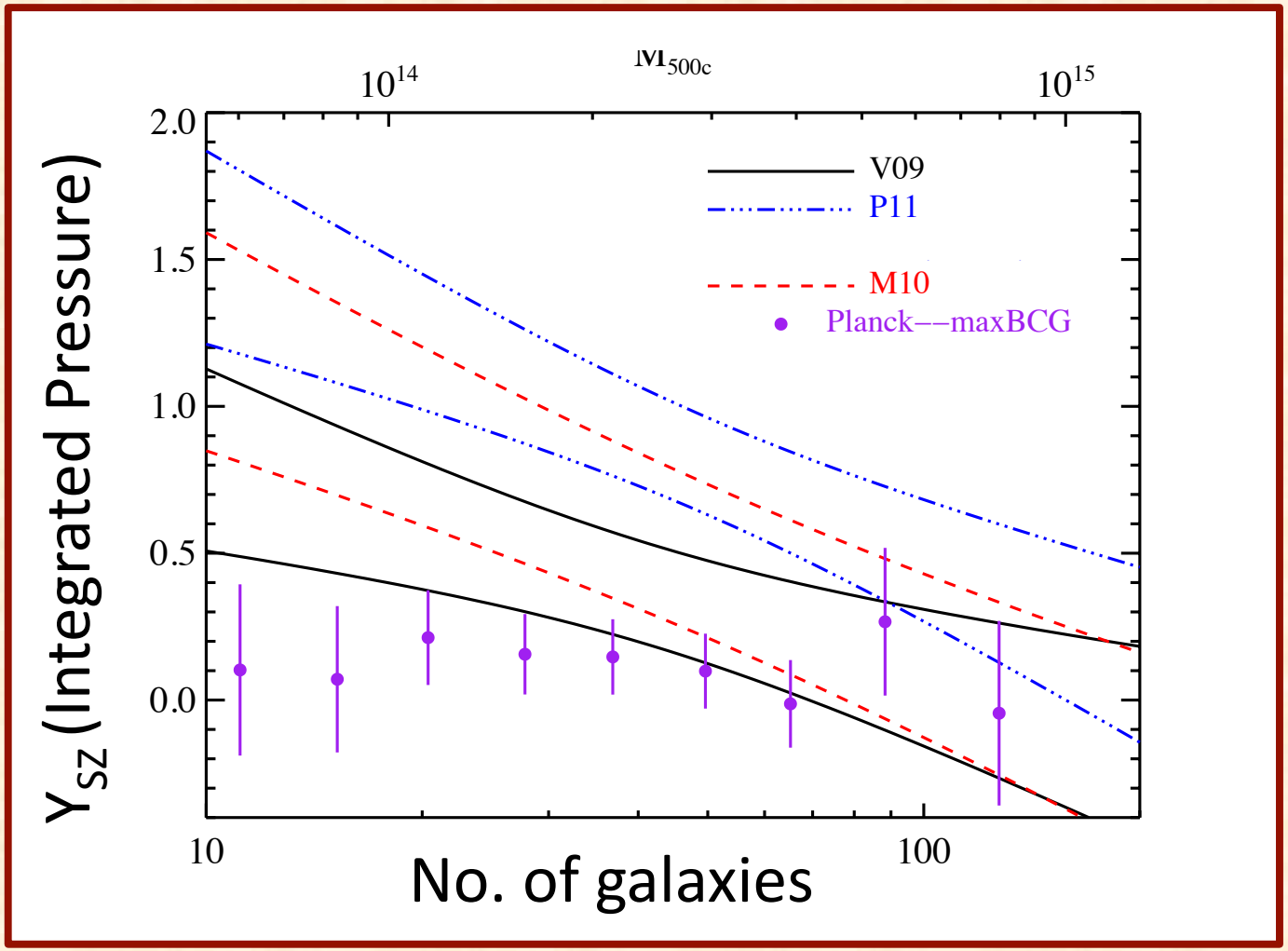
This large scatter is correlated with the scatter in richness, e.g. due to halo tri-axiality (Angulo et al. 2012, Noh and Cohn 2012).

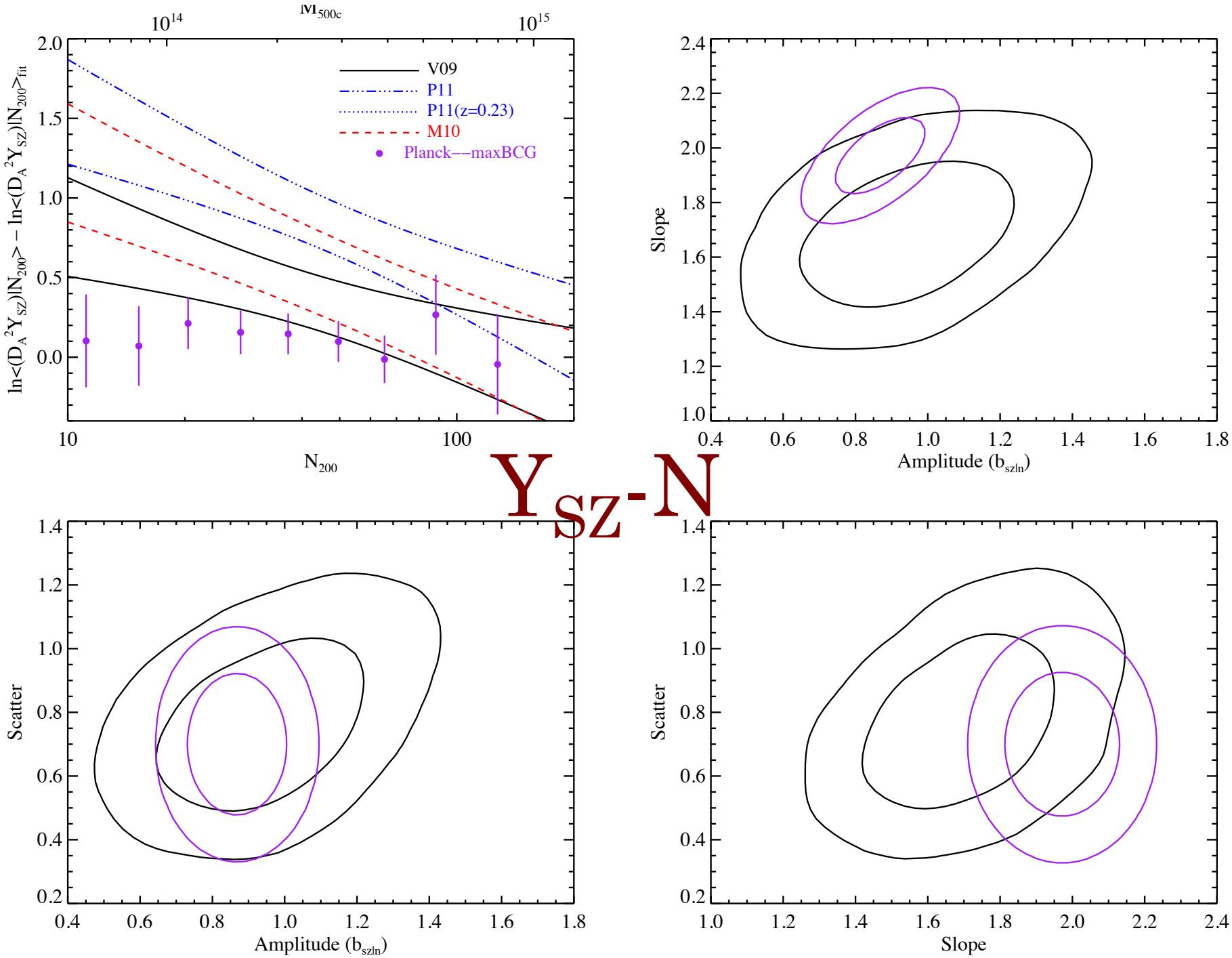
A triaxial halo along the LOS has both higher richness and higher weak lensing mass.

Correlated scatter introduces corrections, so that the mean weak lensing mass $<M_{WL}>$ we measure for optical clusters is biased *high.*

Other sources of bias possible, e.g. source photoz's.

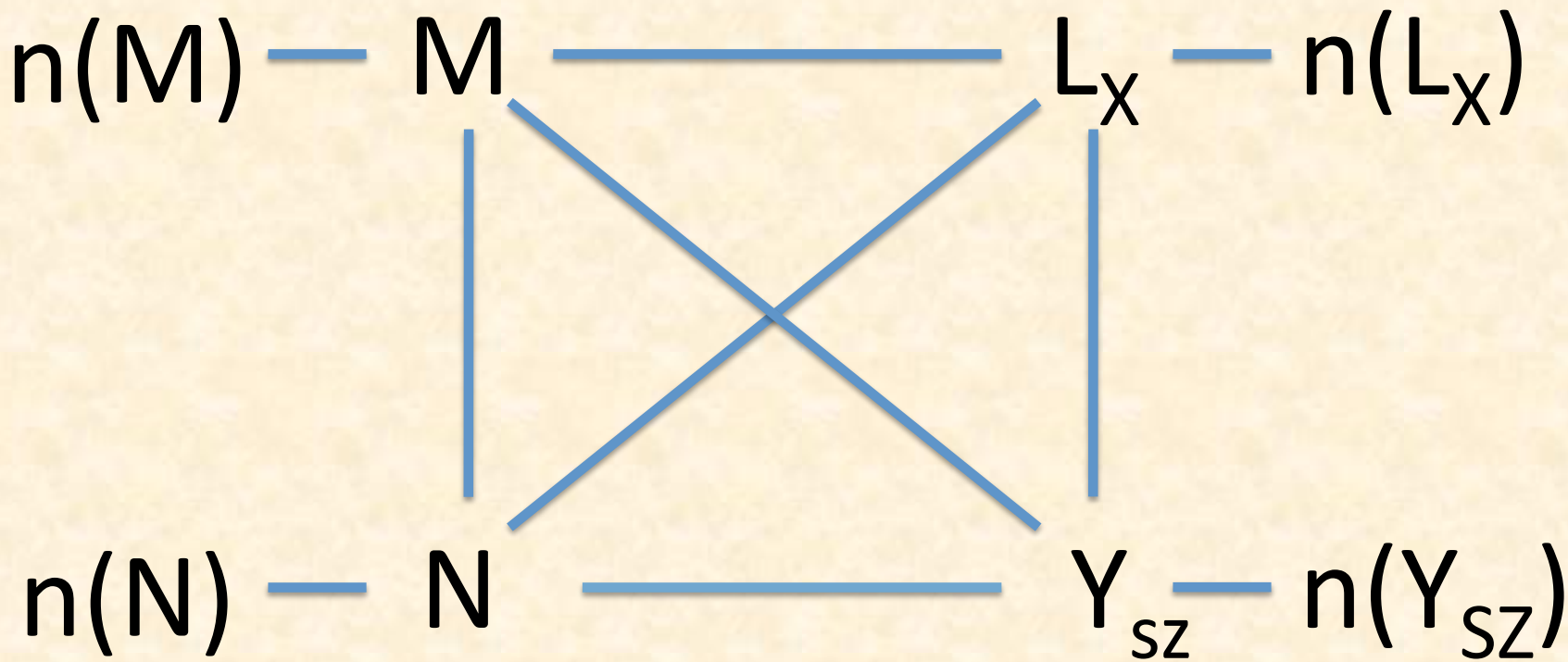
Putting It All Together




M_{500c}
10^{14}
10^{15}
V09
P11
P11(z=0.23)
M10
Planck−−maxBCG
$\ln\langle(D_A^2 Y_{SZ})|N_{200}\rangle - \ln\langle(D_A^2 Y_{SZ})|N_{200}\rangle_{fit}$
N_{200}
Slope
Amplitude (b_{szln})
Scatter
Amplitude (b_{szln})
Scatter
Slope

Y_{SZ}-N

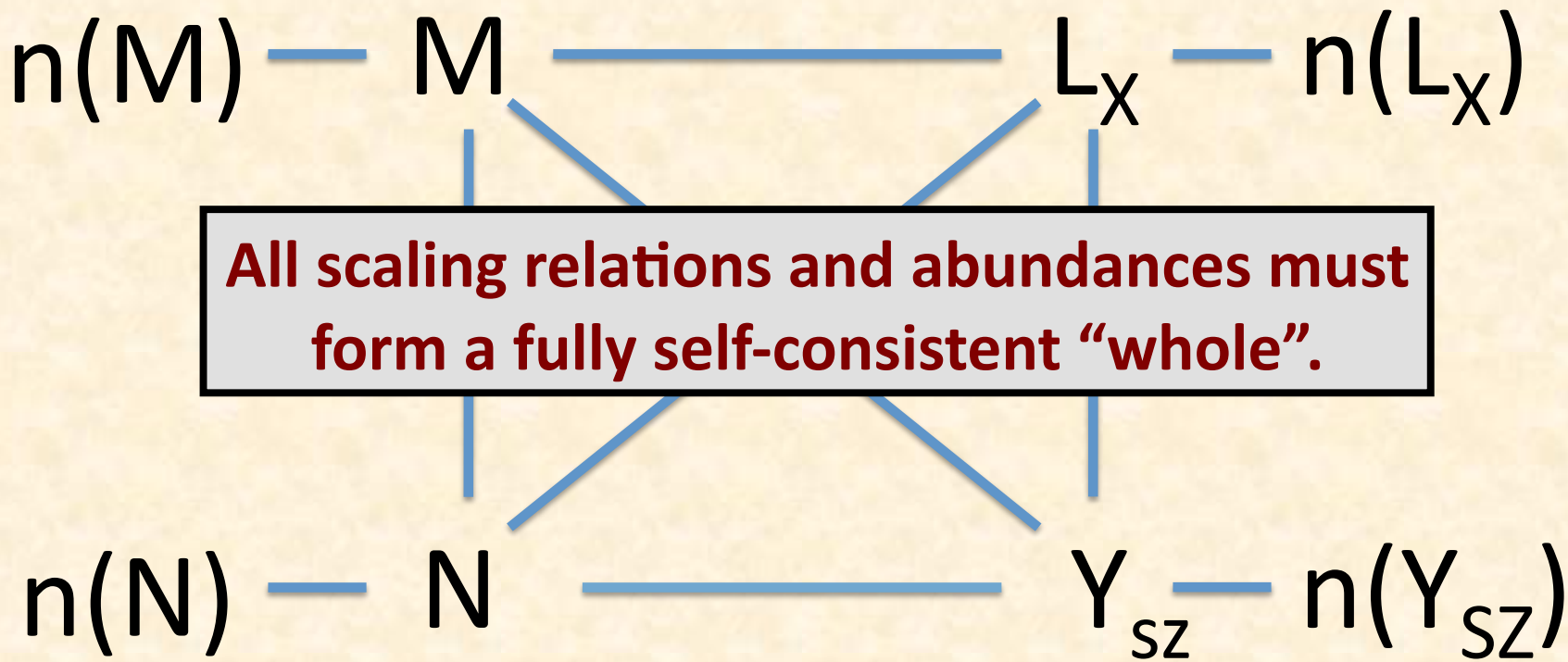
Super-Important Point



All cluster observables are tightly coupled to each other.

Changing one observable has important repercussions on the whole system.

Super-Important Point



All scaling relations and abundances must form a fully self-consistent "whole".

All cluster observables are tightly coupled to each other.

Changing one observable has important repercussions on the whole system.

Abundance Constraints

We had shown that the mass function from maxBCG was consistent with WMAP7.

If we lower the maxBCG masses by 10%-20%, is that still true?YES.

Vikhlinin et al. 2009 had shown that the mass function from X-rays was consistent with WMAP7.

If we raise the Vikhlinin masses by 15%, is that still true? YES.

Optical and X-ray abundances are linked by $P(L_X|N)$, which we measure. Does this work? YES.

Consistency Constraints

- Scaling relations from optical and X-ray samples must be consistent. E.g. L_X-M, Y_{SZ}-M.

- You can self-consistently use two scaling relations to derive a third.

- Note these consistency relations involve not just the mean and slope, but also the *scatter.*

The proposed solution fits all available data.

Rozo et al. 2012

The Take Home Message

Multi-wavelength data generates a large number of non-trivial consistency constraints.

These can detect systematic errors in the data!

Good news for future work.

However-

The Take Home Message

Planck results dramatically highlighted the importance of systematics:

~50% mass offsets are not uncommon at present!

This is a far cry from the ~10% or so systematics that is typically quoted.

Cluster mass calibration must improve dramatically in the near future to remain competitive.

It's Getting Better All the Time

Method	Current Statistics or Systematics Floor	Likely to see Dramatic Improvements?
Hydrostatic	~10%-20% (Sys. limited)	Not likely.
Vel. Dispersion	~15% (Sys. limited)	Not likely. (though see Saro et al. 2012).
Weak Lensing	~15% (Comparable stat and sys error)	Yes.

Why should we believe that WL masses will improve?

Weak Lensing Drawbacks

- Measurements of the tangential ellipticity may be biased.

  Under active development by cosmic shear community.

  Shear requirements are *more mild* than those for cosmic shear.

- Relation between ellipticity and mass depends on the redshifts of background galaxies, which are uncertain.

  SDSS was very shallow. In deeper surveys, photoz scatter is less important.

  Photoz's continue to improve thanks to better training data sets.

Weak Lensing Drawbacks

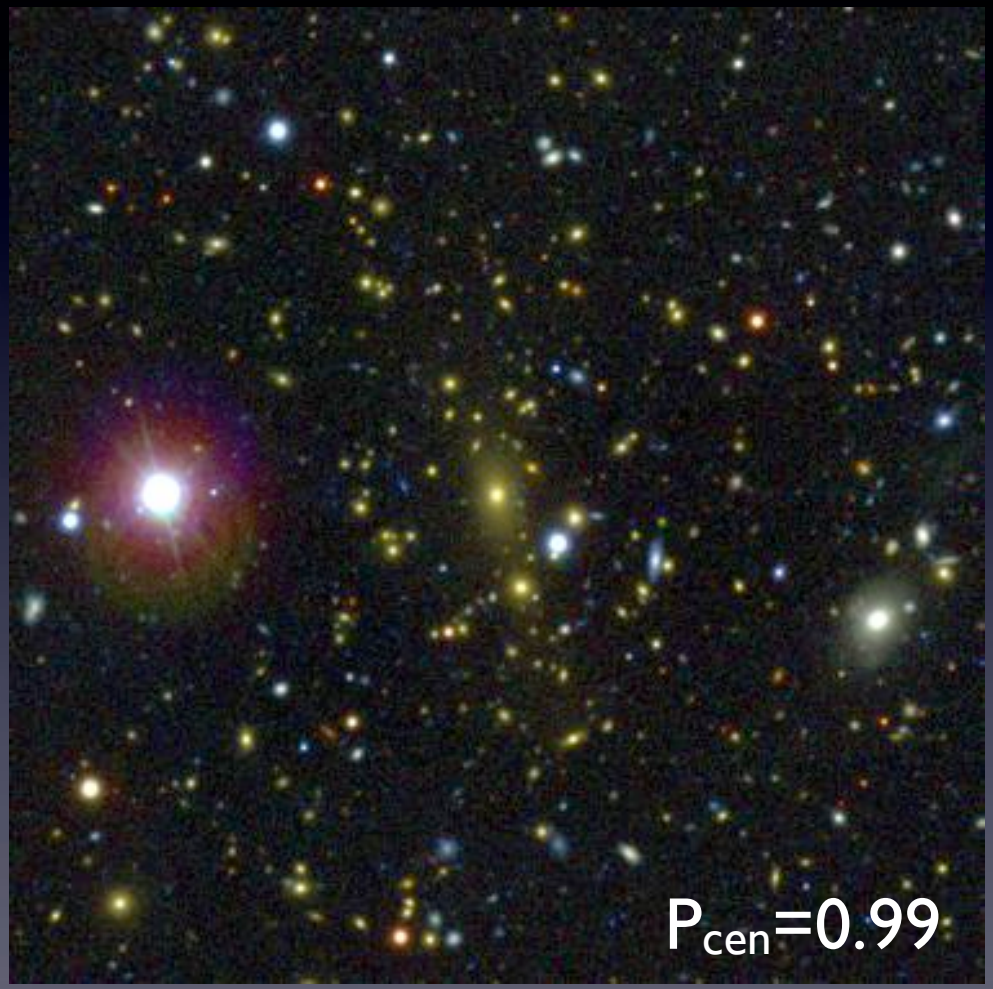
- *Tangential* ellipticity requires that we specify a cluster center. Can we always choose the correct central galaxy?

  We *don't need* to specify a central galaxy.

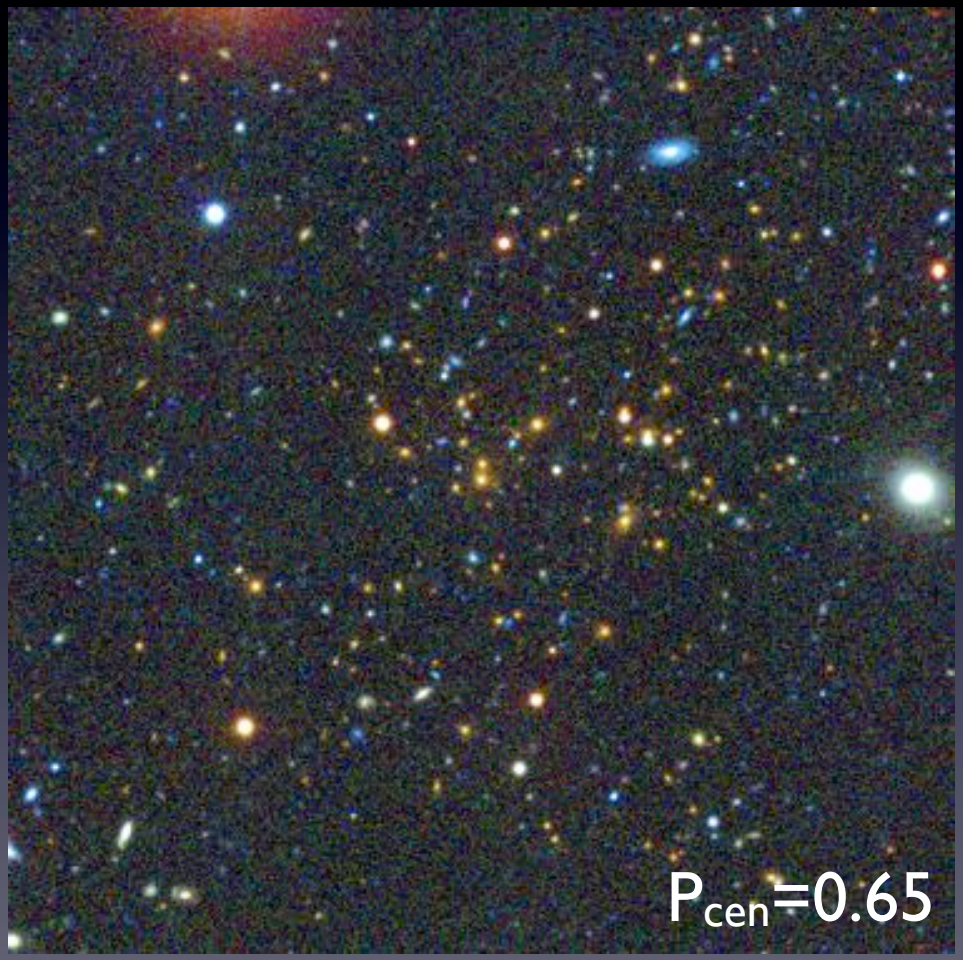
  We can consider multiple possible central galaxies, and assign them each a probability of it being the correct cluster center.

  We can use these probabilities to statistically recover the weak lensing profiles about the true central galaxy.

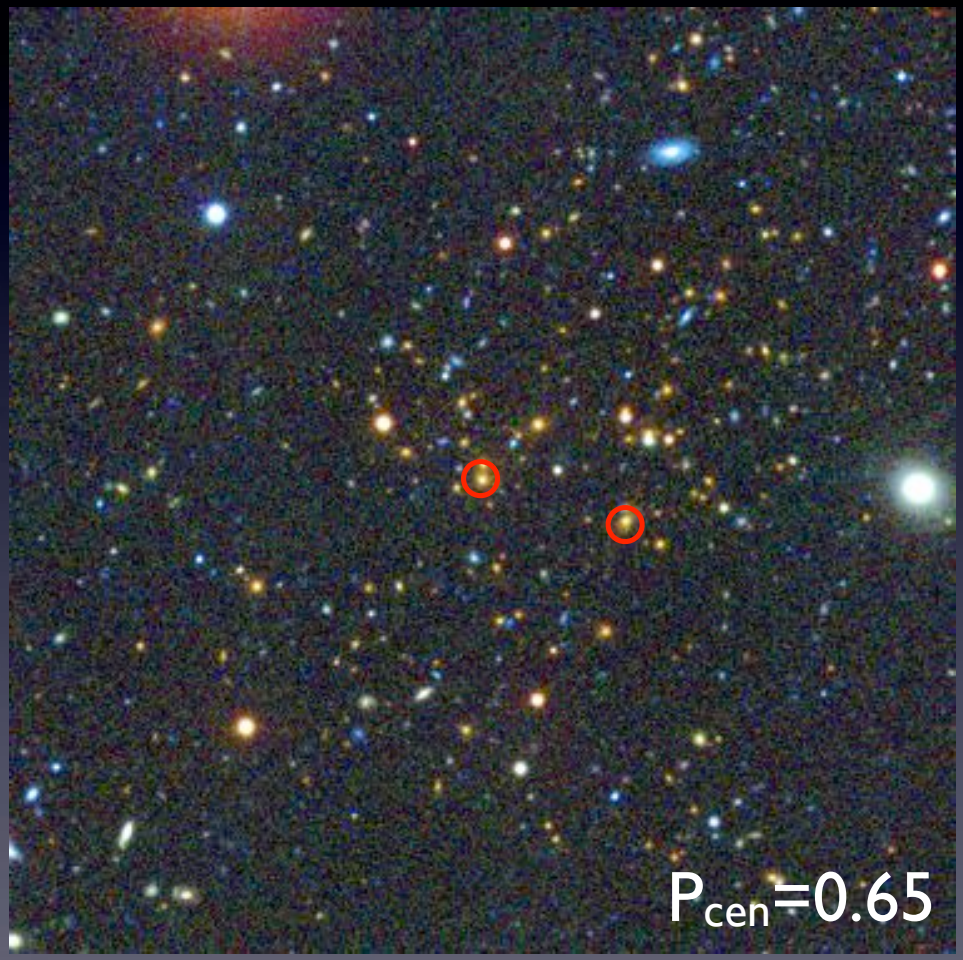
Well-Centered Cluster



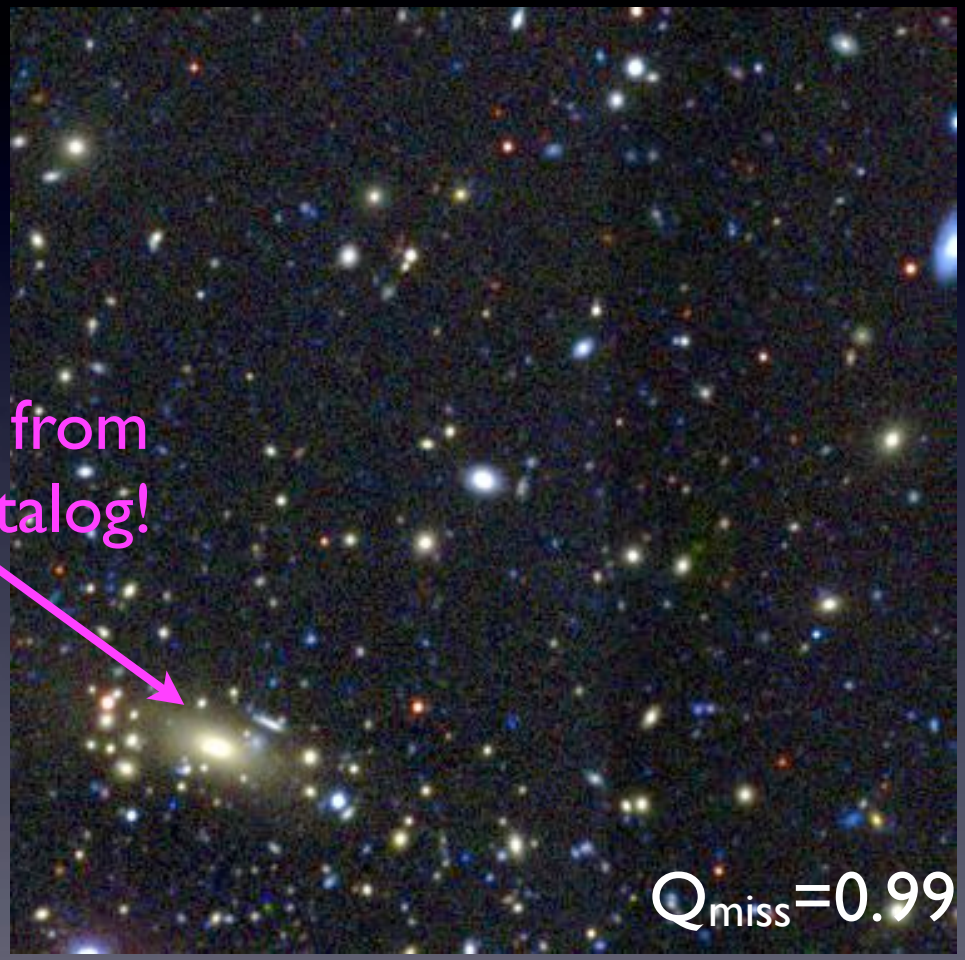
Ambiguous Center



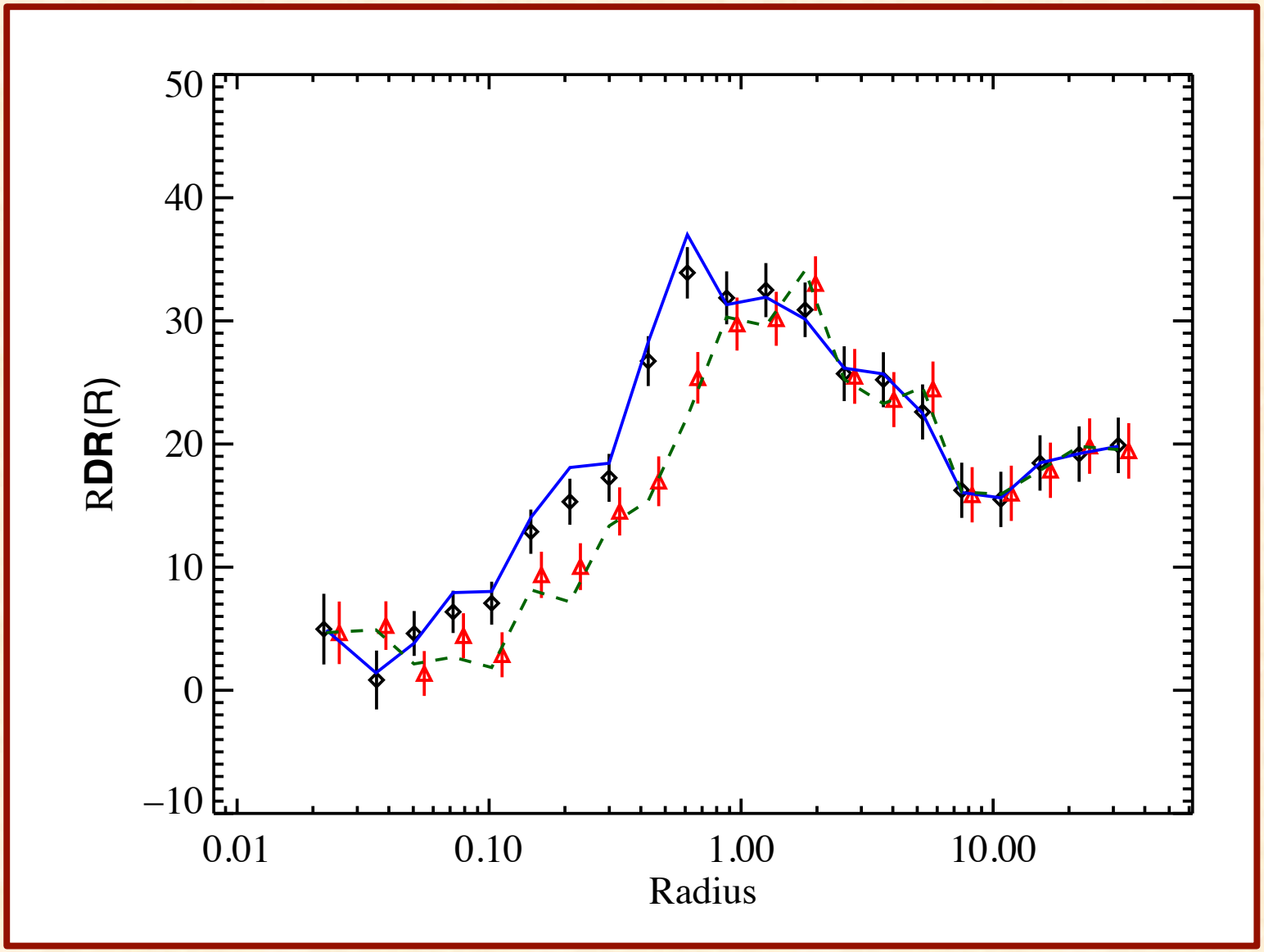
Ambiguous Center



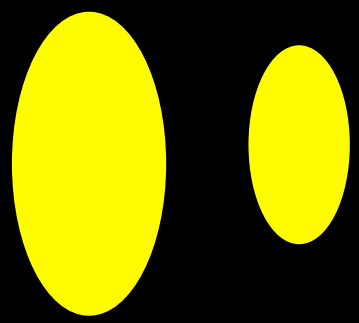
Missing Center



Center-Corrected WL Profiles



The Monster in the Dark



That's all good and well, but still…

Can we be *sure* our results are not subject to systematics?

Testing the Faith

Only one way to test if everything works as advertised:

Simulate the entire experiment.

- Run dark matter simulations with known cosmologies.
- Generate lightcone and populate with galaxies.
- Perform ray tracing and lens galaxies appropriately.
- Run cluster finding algorithms.
- Run weak lensing mass calibration pipeline.
- Run cosmological analysis, and compare with input.

Testing the Faith

This simulation program is not optional.

I expect such a program will be standard for all upcoming photometric surveys (DES, Pan-STARRS, LSST).

DES: ongoing tests with 250 deg^2.

Final challenge: 5-10 simulations of 5,000 deg^2

Will we be up to the task?

Stay tuned.

Summary

Current cosmological constraints are dominated by uncertainties in mass.

Differences in cluster mass of order ~50% exist between various data sets:

e.g. Mantz/Planck, maxBCG/Planck.

We have proposed a solution to the maxBCG/Planck offset:

50% offset = 20% bias due to T_X
+ (10%-20% hydrostatic bias)
+ (10%-20% bias in WL masses)

Summary

Proposed solution fits all available data; expect ~10% systematic uncertainty in resulting halo masses.

Importantly, all major sources of systematic error in weak lensing masses are expected to decrease in the near future.

However, believing cosmological results will require blind analysis, and extensive test on numerical simulations.

Extra Slides

Y_{SZ}-Y_X Ratio

Y_{SZ} = Integrated pressure with the cluster volume.
This is what SZ measures.

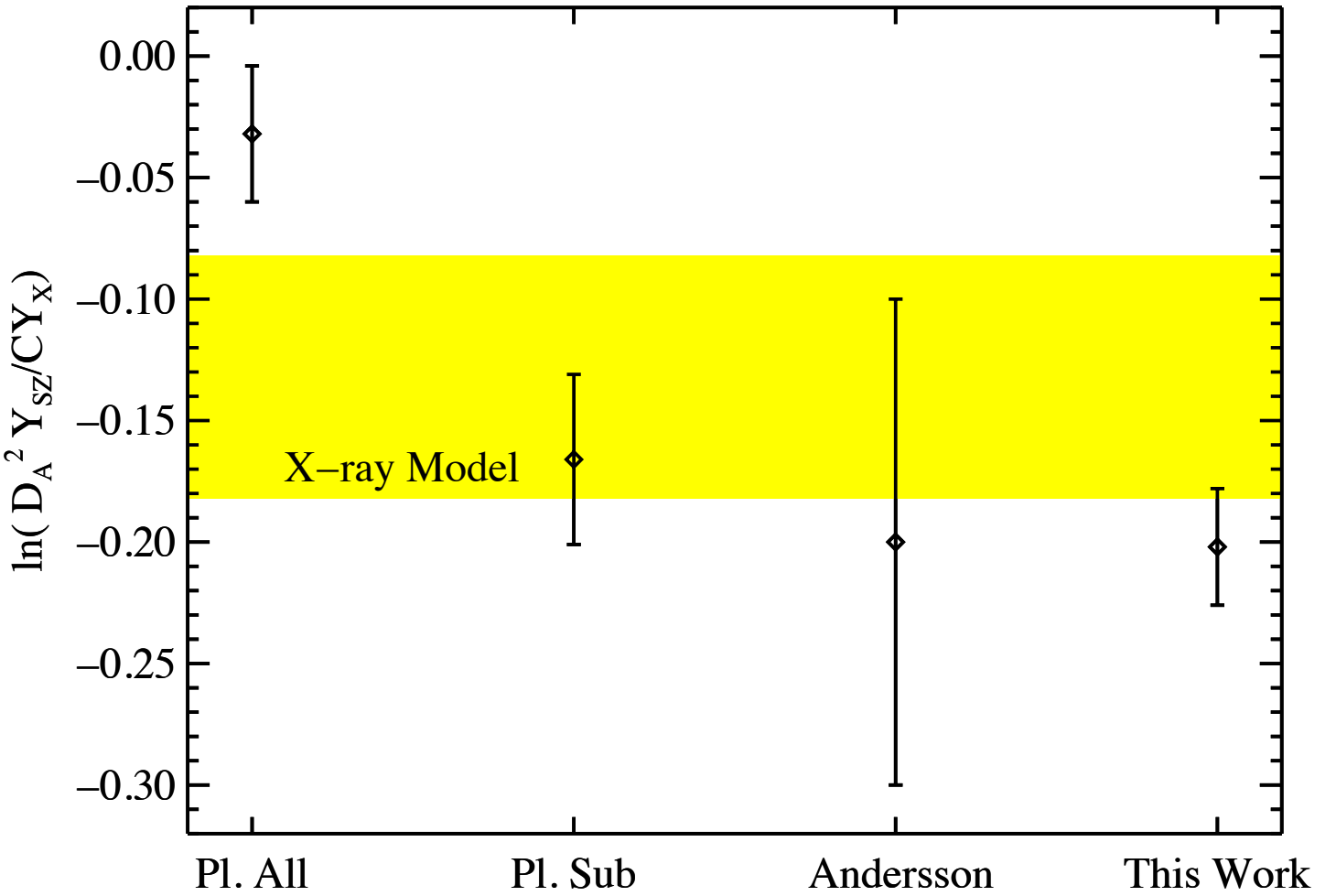
$Y_X = M_{gas}T_X$ is an X-ray analog to Y_{SZ}.

If clusters were isothermal, then $Y_{SZ} = Y_X$.

In practice, we expect $\ln(Y_{SZ}/Y_X) = -0.125 \pm 0.05$.

If T_X is biased *low*, then Y_{SZ}/Y_X will be higher than expected.

Y_{SZ}-Y_X Ratio



Rozo et al. 2012

X-ray Abundances

If X-ray masses are biased *low*, then the clusters of a given mass appear *brighter.*

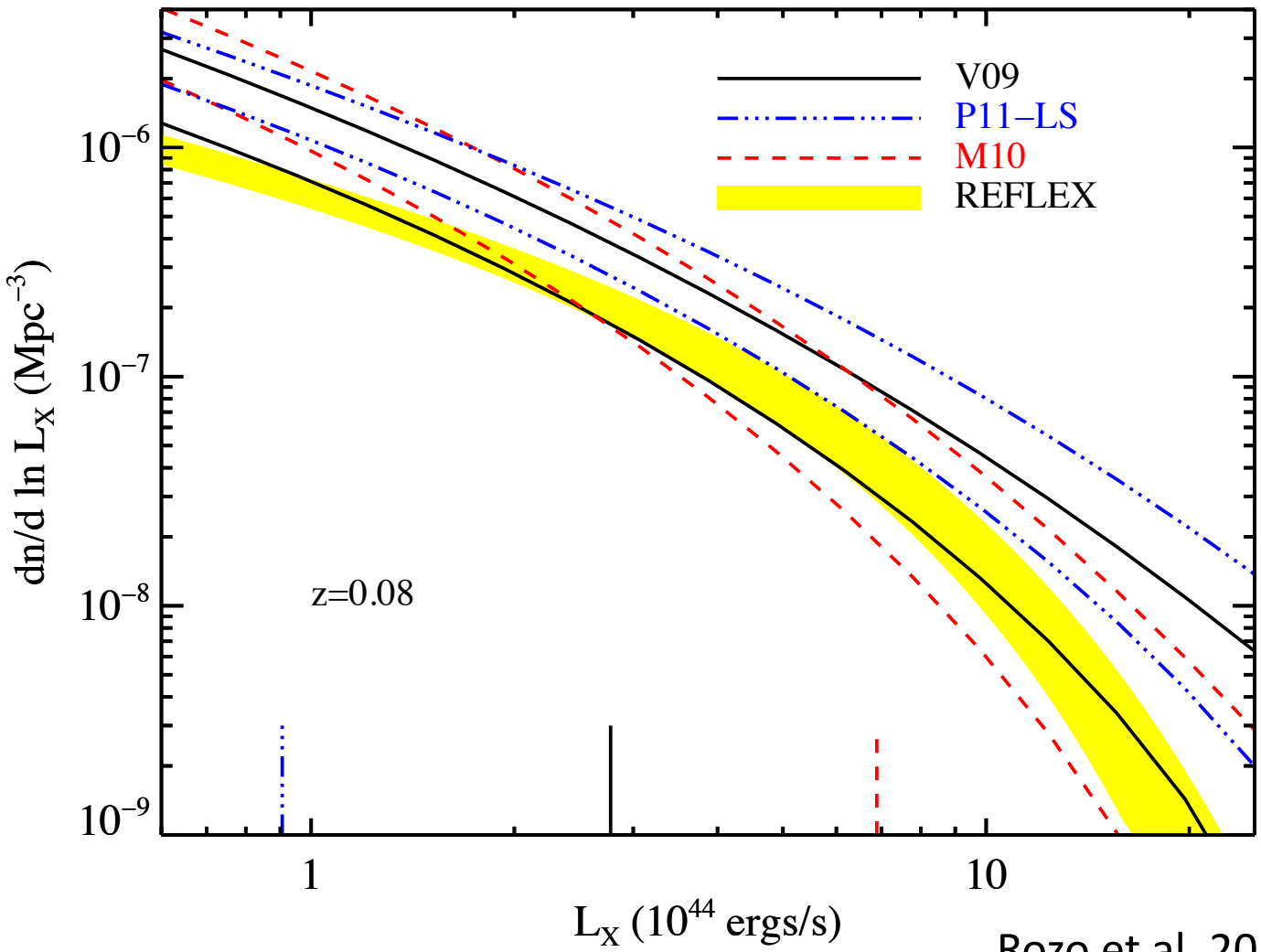
Given a fixed mass function (e.g. cosmological prediction), then the predicted X-ray abundance will be higher:

i.e. more brighter clusters.

At the pivot point of each sample, both Vikhlinin and Mantz are consistent with WMAP7+BOSS cosmology.

The Planck X-ray data set is in mild tension (3.3σ).

X-ray Abundances



Rozo et al. 2012

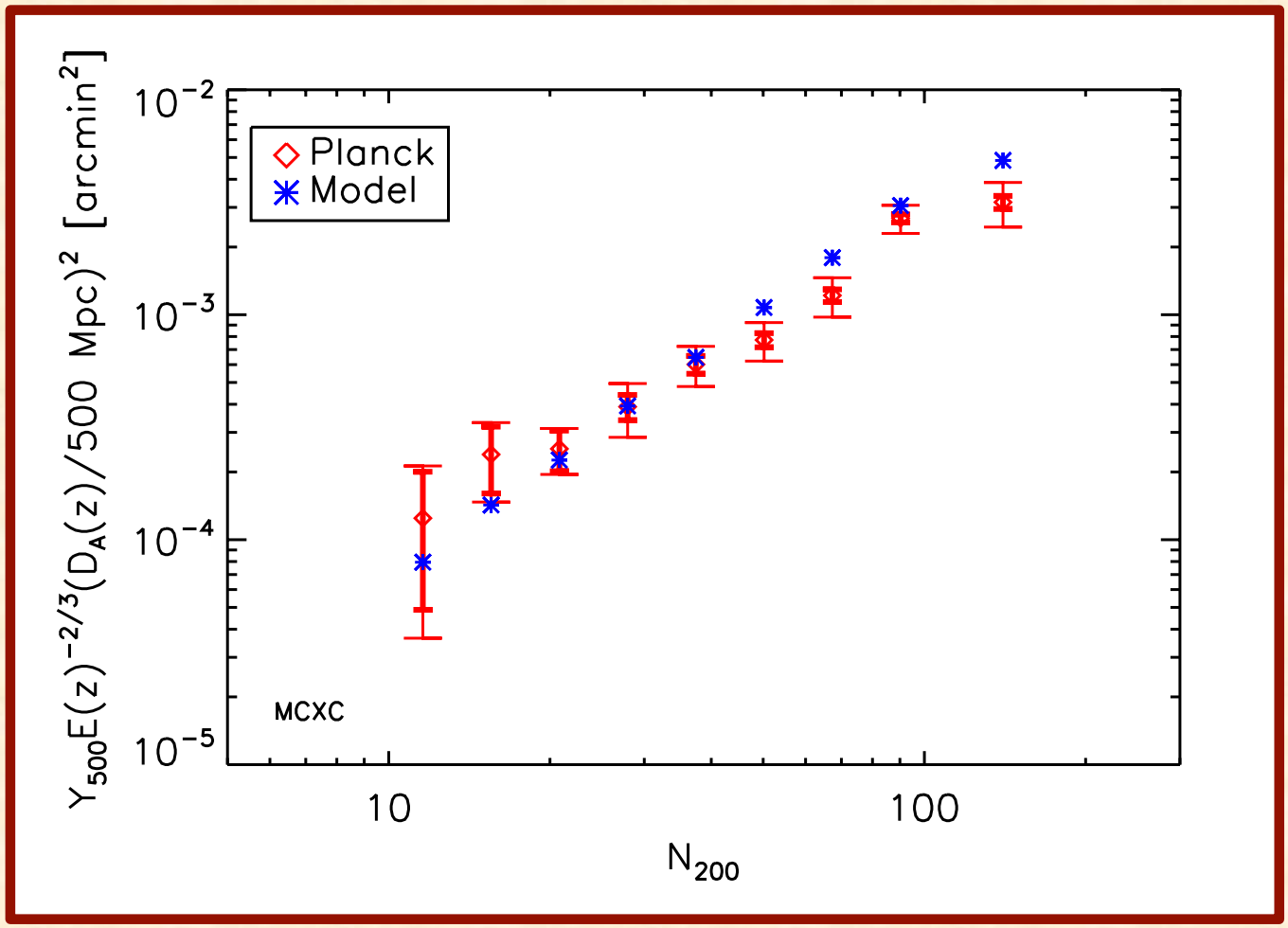
Cluster A2261

Cluster A2261 is one of two published CLASH clusters.

CLASH seeks to provide the highest quality mass measurements available from WL using 9-band HST photometry.

Planck 2011 mass for A2261 is *lower* than that from CLASH by 5σ (≈50%).

What About the X-ray Bright Sub-Sample?



What About the X-ray Bright Sub-Sample?

X-ray sub-sample is subject to *severe* selection effects.

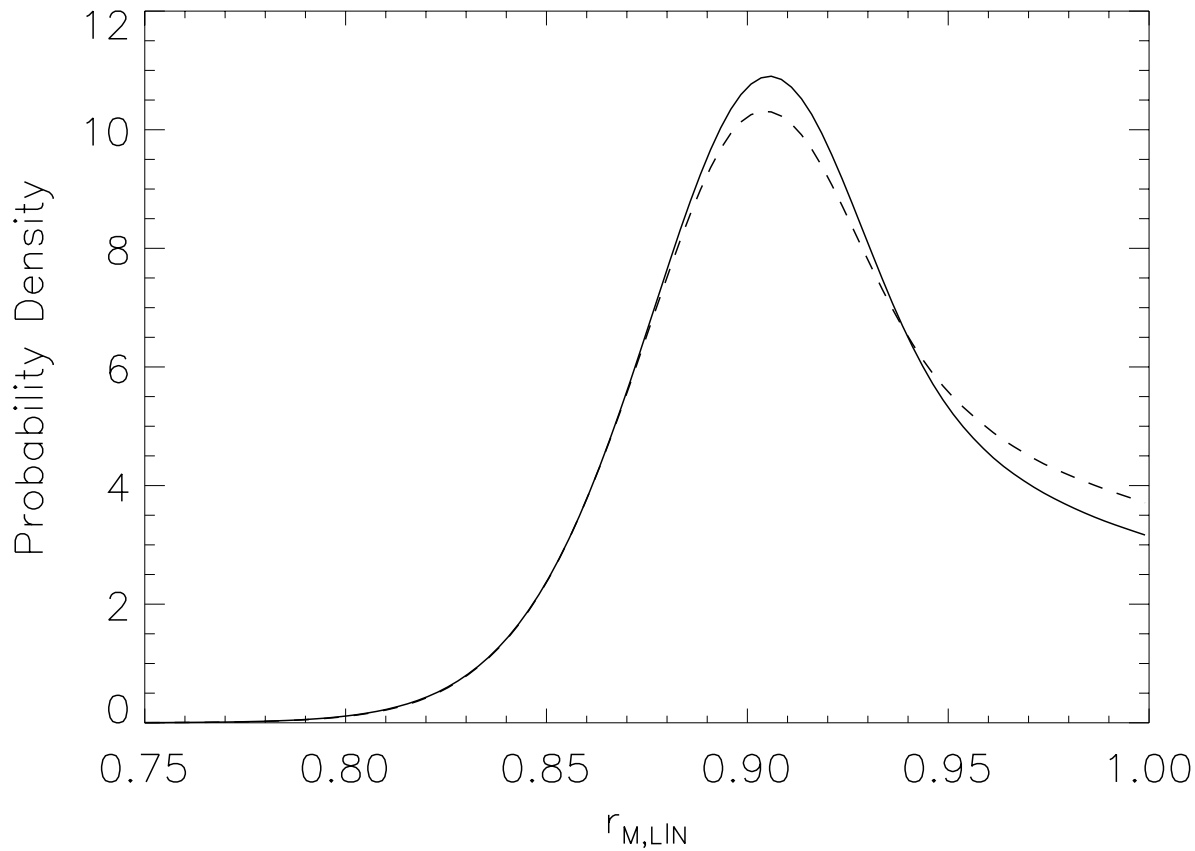
L_X is *perfectly correlated* with mass at fixed richness.

i.e. *at fixed richness,* X-ray selection = mass selection.
We are peeling off the most massive tail!

If things work properly, the original measurements would be consistent (as shown). The X-ray bright sub-sample will always fall above the original measurement.

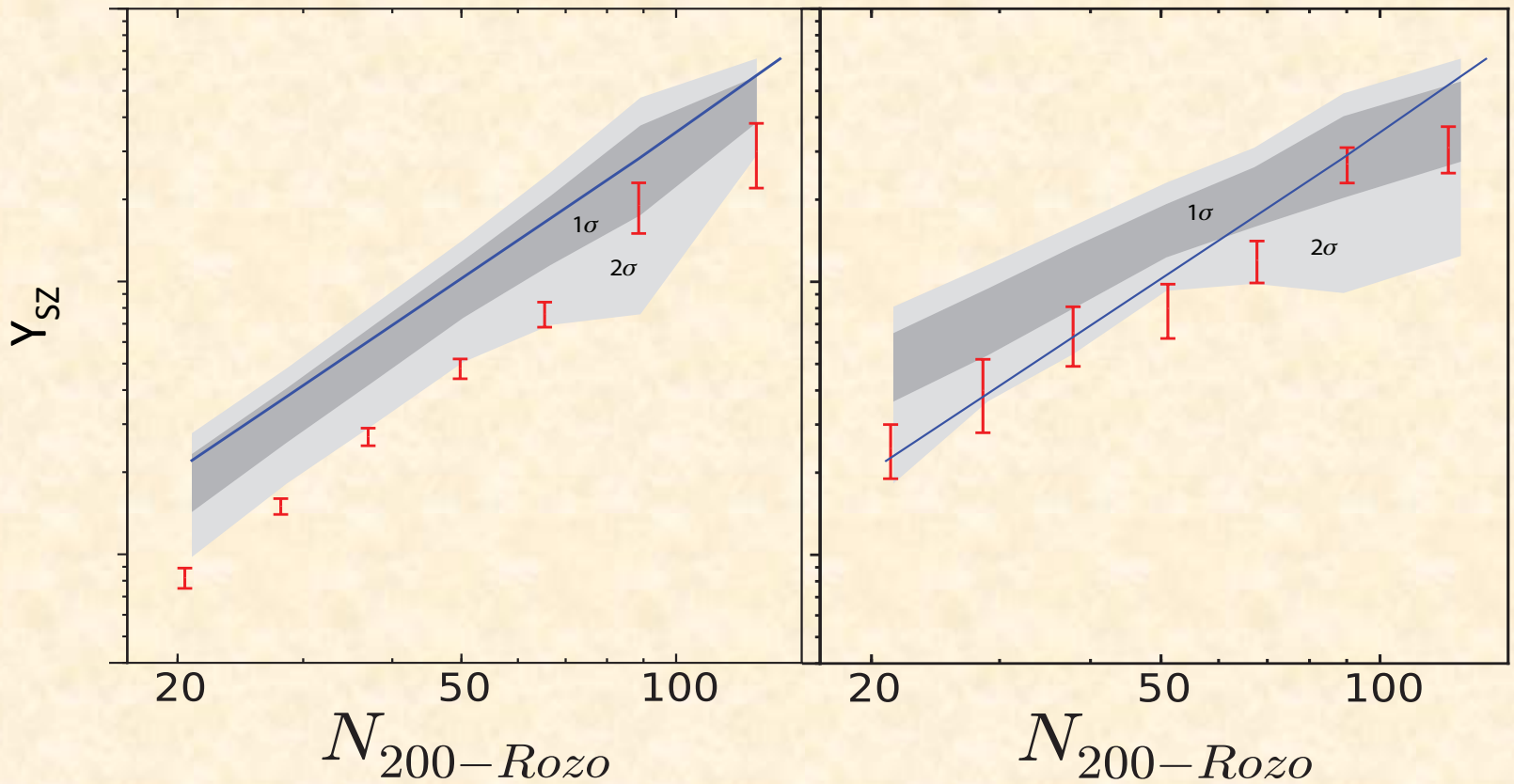
This is *not* hindsight!

Covariance Between Mass and L_X for maxBCG Clusters

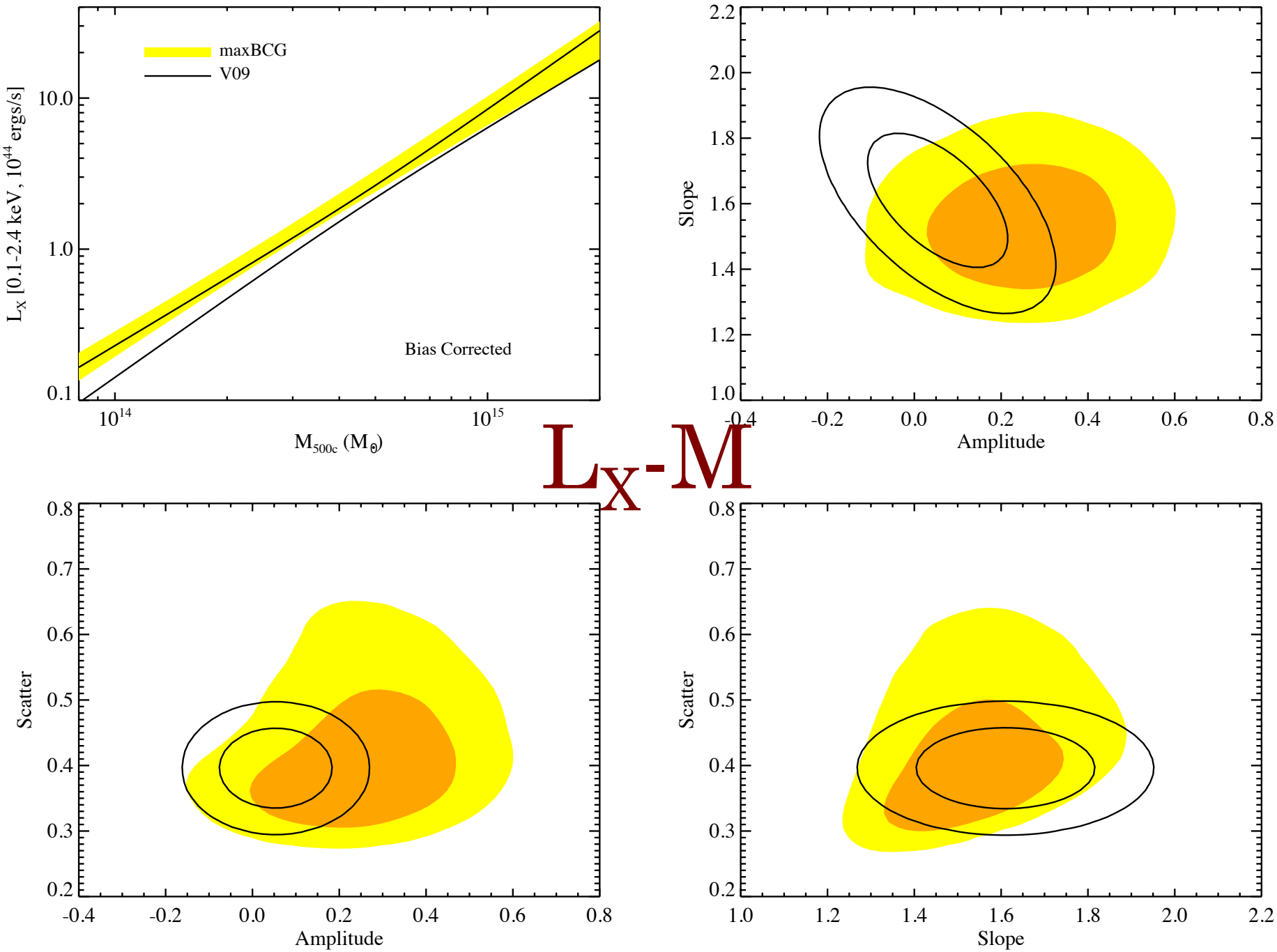


Rozo et al. 2009

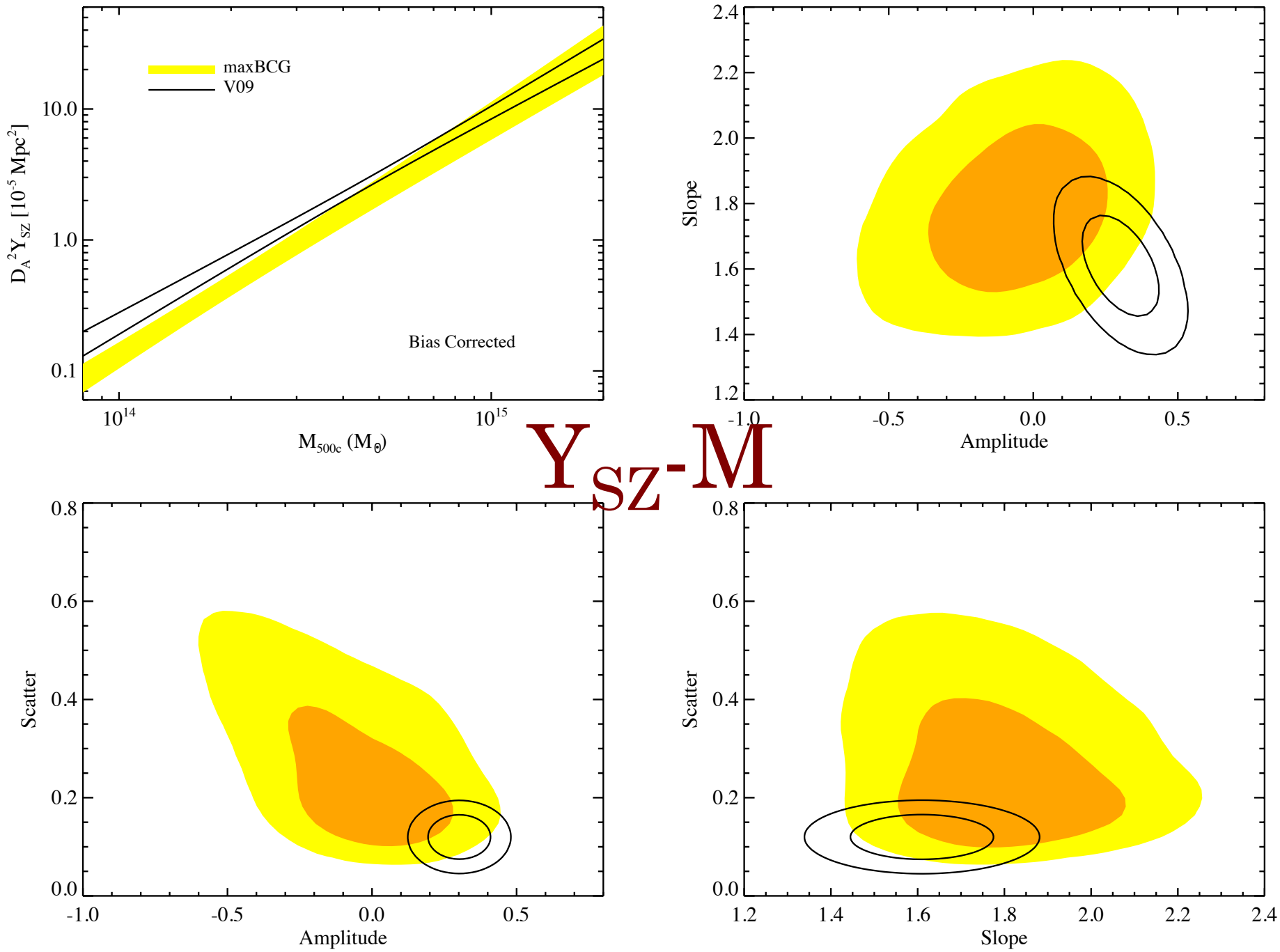
Selection Effects in X-ray Bright Sub-Sample



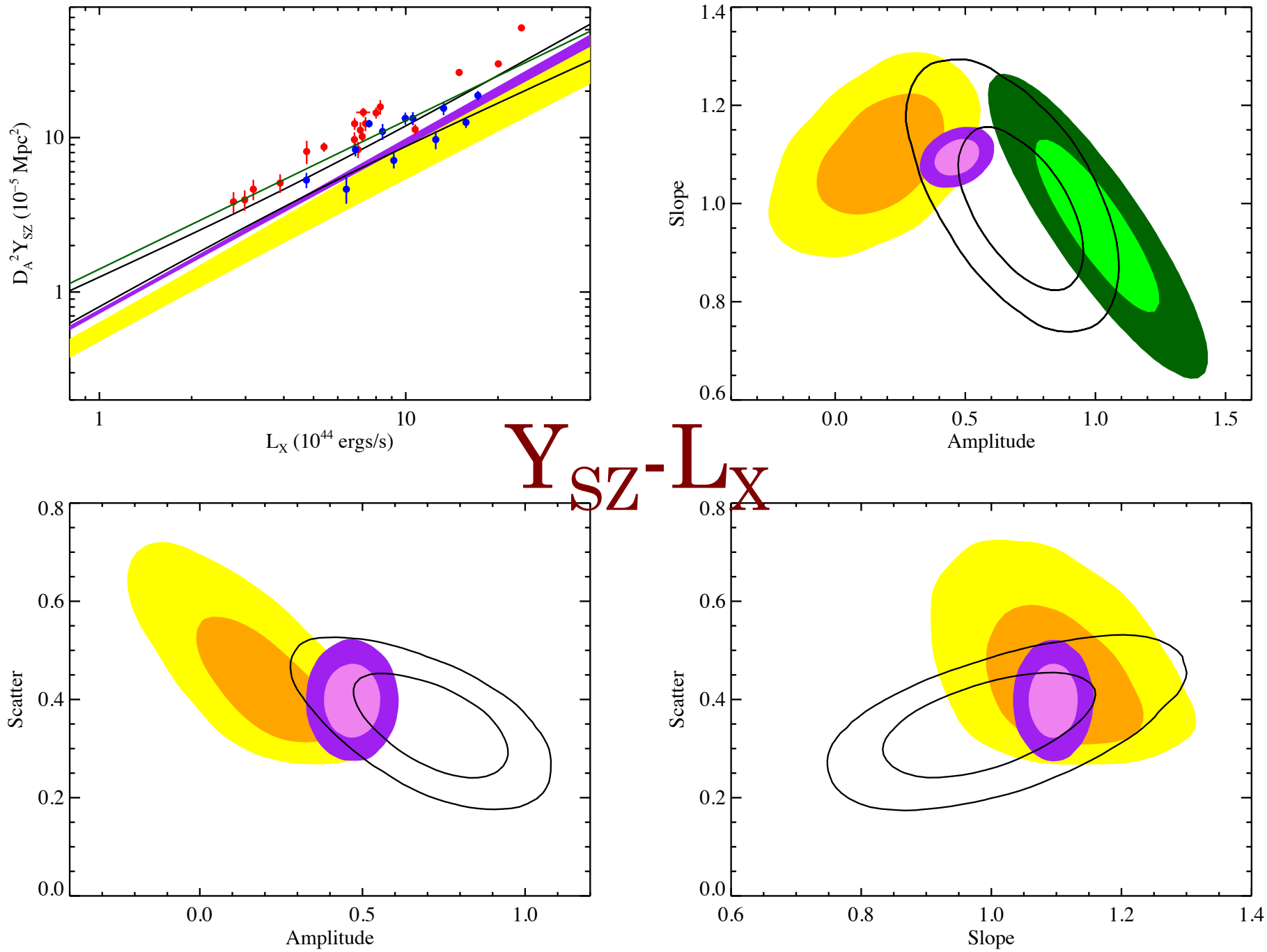
Biesiadzindski et al. 2012


maxBCG
V09
Bias Corrected
L_X [0.1-2.4 keV, 10^{44} ergs/s]
M_{500c} ($M_\odot$)
Slope
Amplitude
Scatter
Amplitude
Scatter
Slope

L_X-M

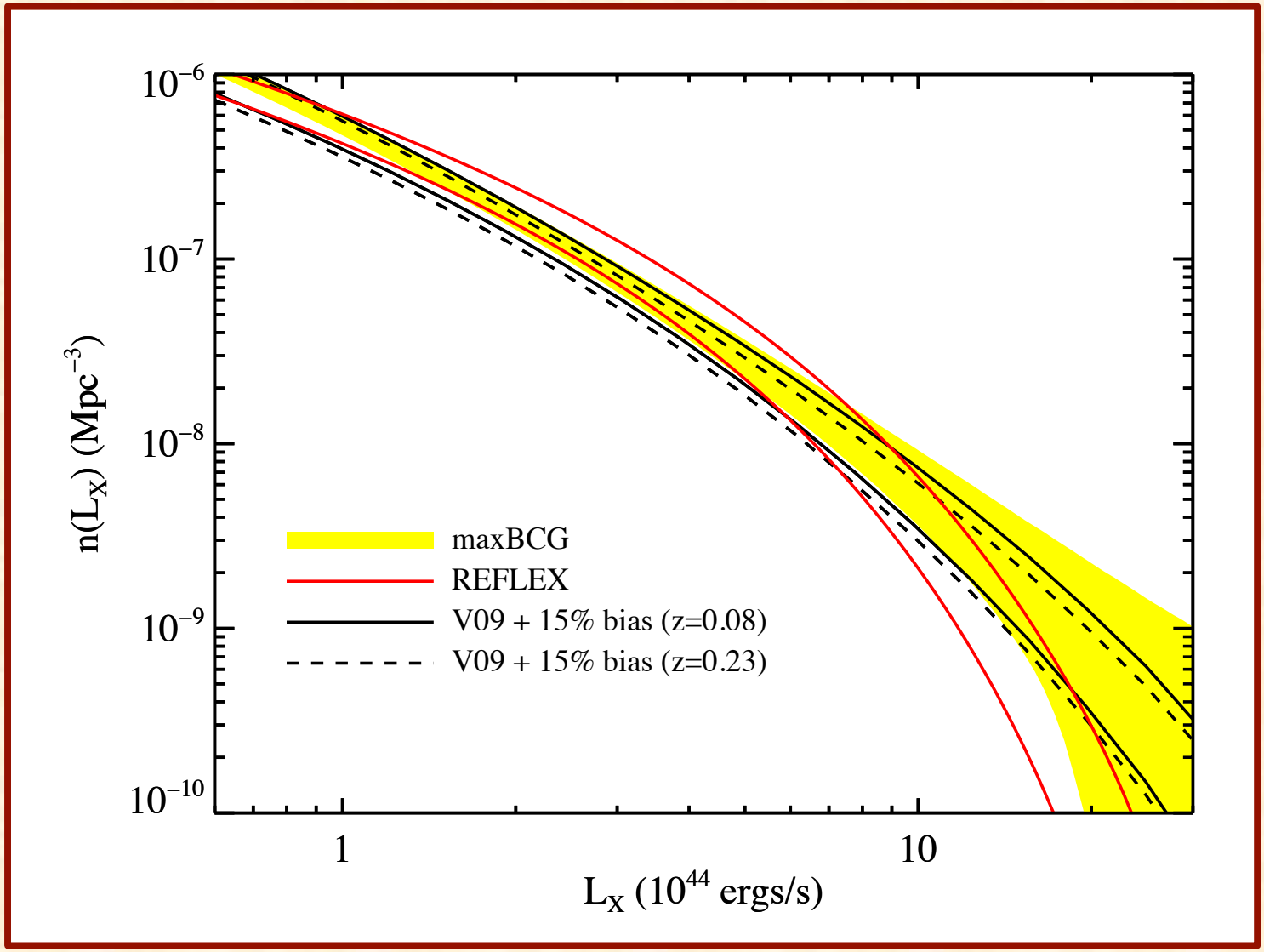
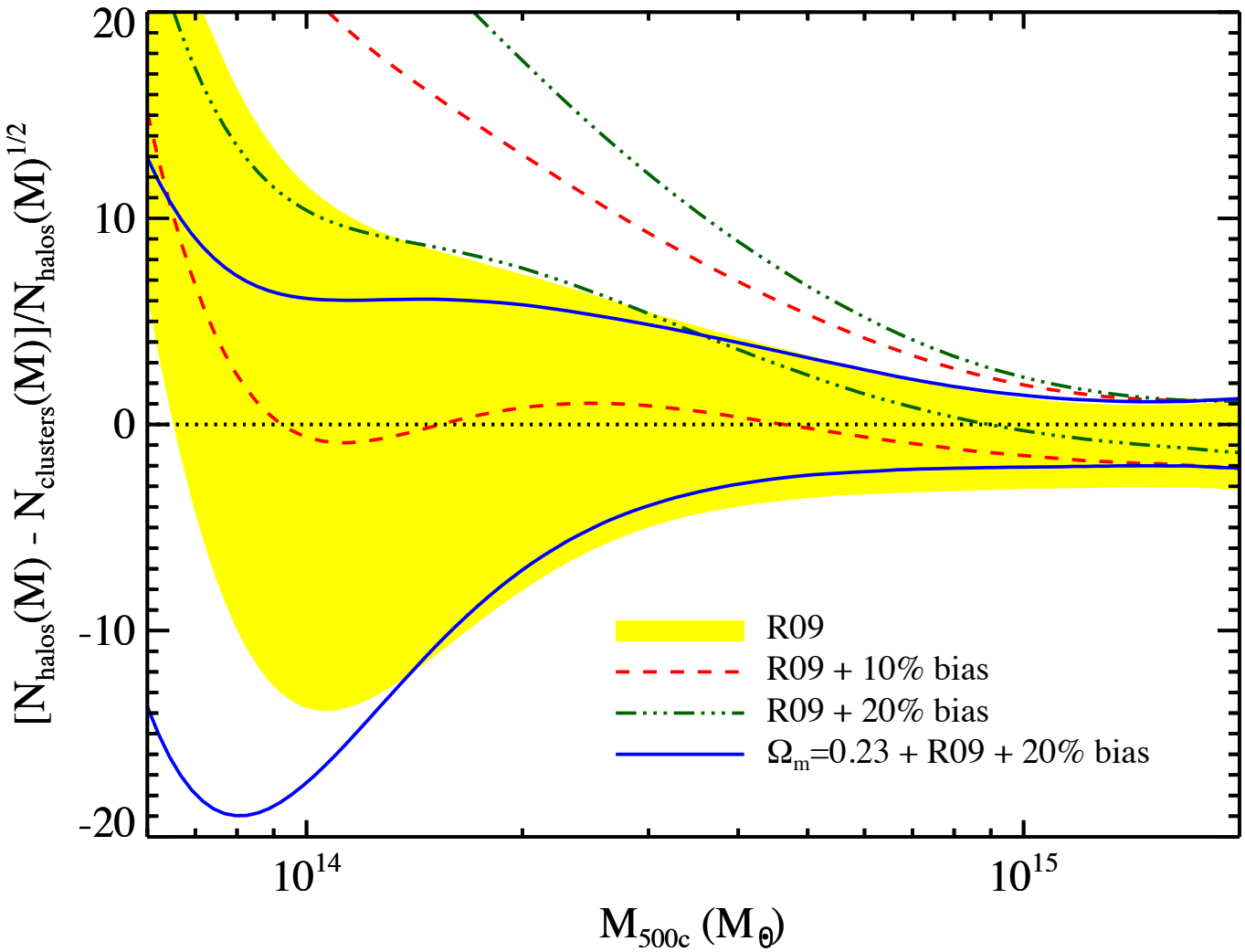

maxBCG
V09
Bias Corrected
$D_A^2 Y_{SZ}$ [10^{-5} Mpc^2]
M_{500c} ($M_\odot$)
Slope
Amplitude
Scatter
Amplitude
Scatter
Slope

Y_{SZ}-M


$D_A^2 Y_{SZ}$ (10^{-5} Mpc^2)
L_X (10^{44} ergs/s)
Slope
Amplitude
Scatter
Amplitude
Scatter
Slope

Y_{SZ}-L_X

X-ray Luminosity Function



Mass Function