Cluster Cosmology in the era of DESI and LSST

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Request to speak of:

- Role of advanced statistical techniques.
- Synergy between surveys.

My interpretation:

- What are the sticking points today?
- Can we solve these problems using complementary surveys and/or advanced statistical techniques?

Cosmology from Cluster Abundances

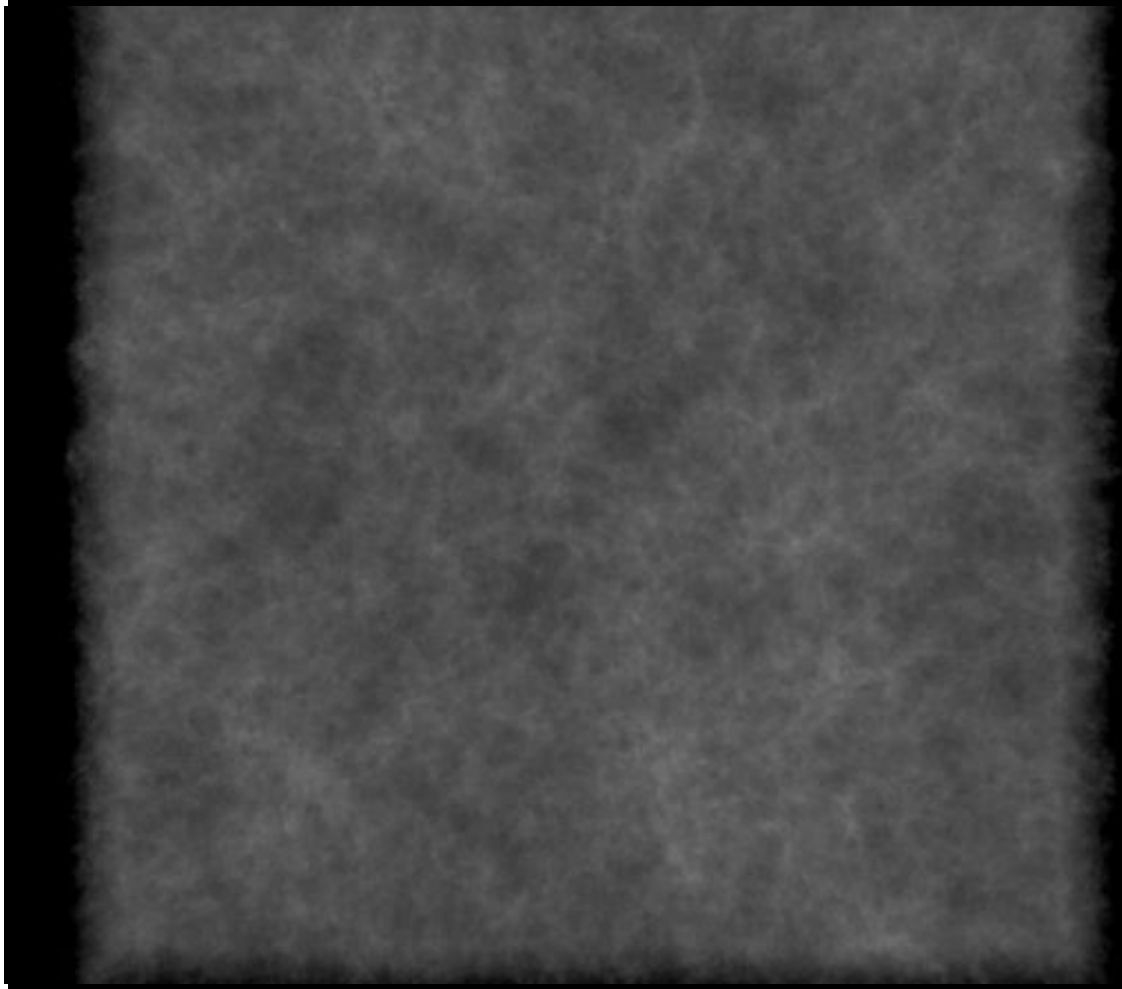
Rogue's Gallery

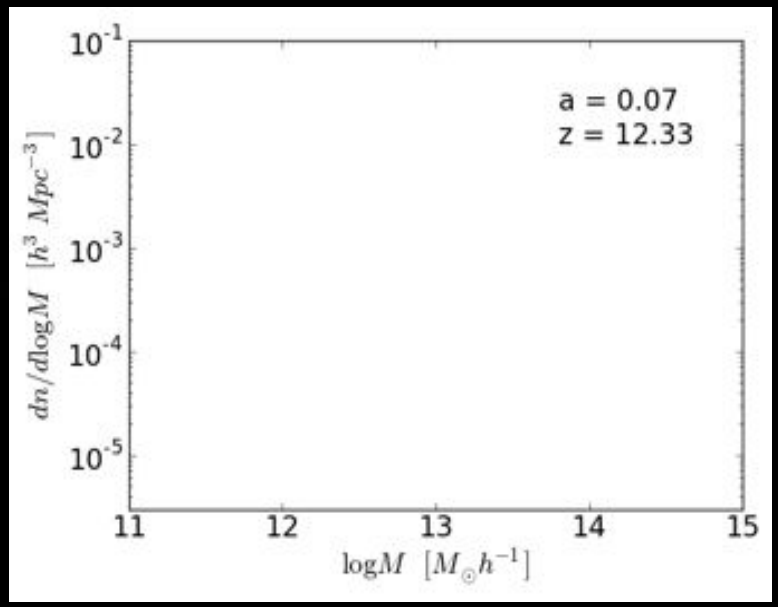
DES Collaboration, Eli Rykoff

Rogue's Gallery

Cosmology w/ Galaxy Clusters

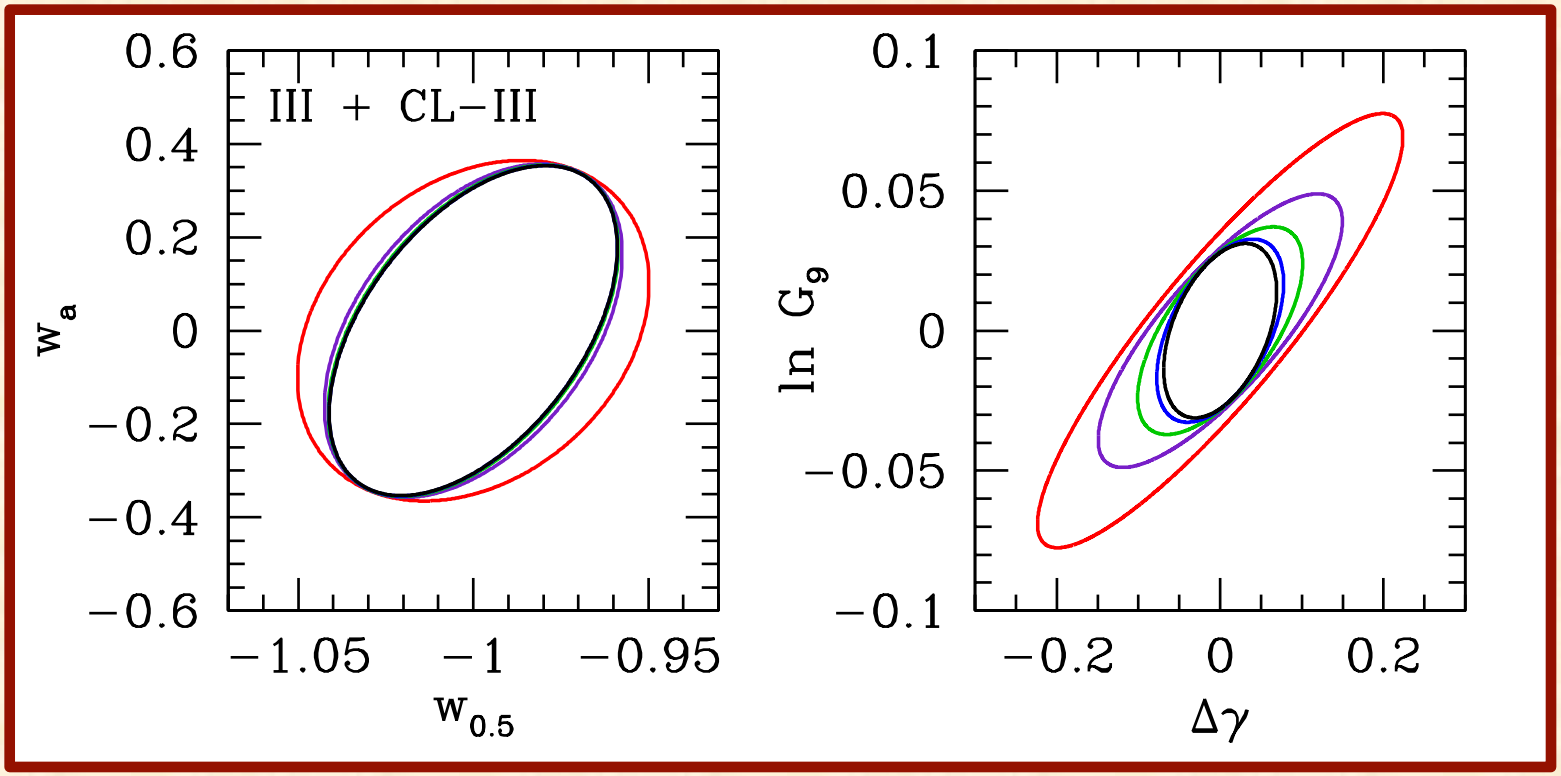
More structure = more massive halos





Abundance of halos tracks growth of structure.

Clusters Measure Structure Growth



red = WL+LSS+SN+CMB

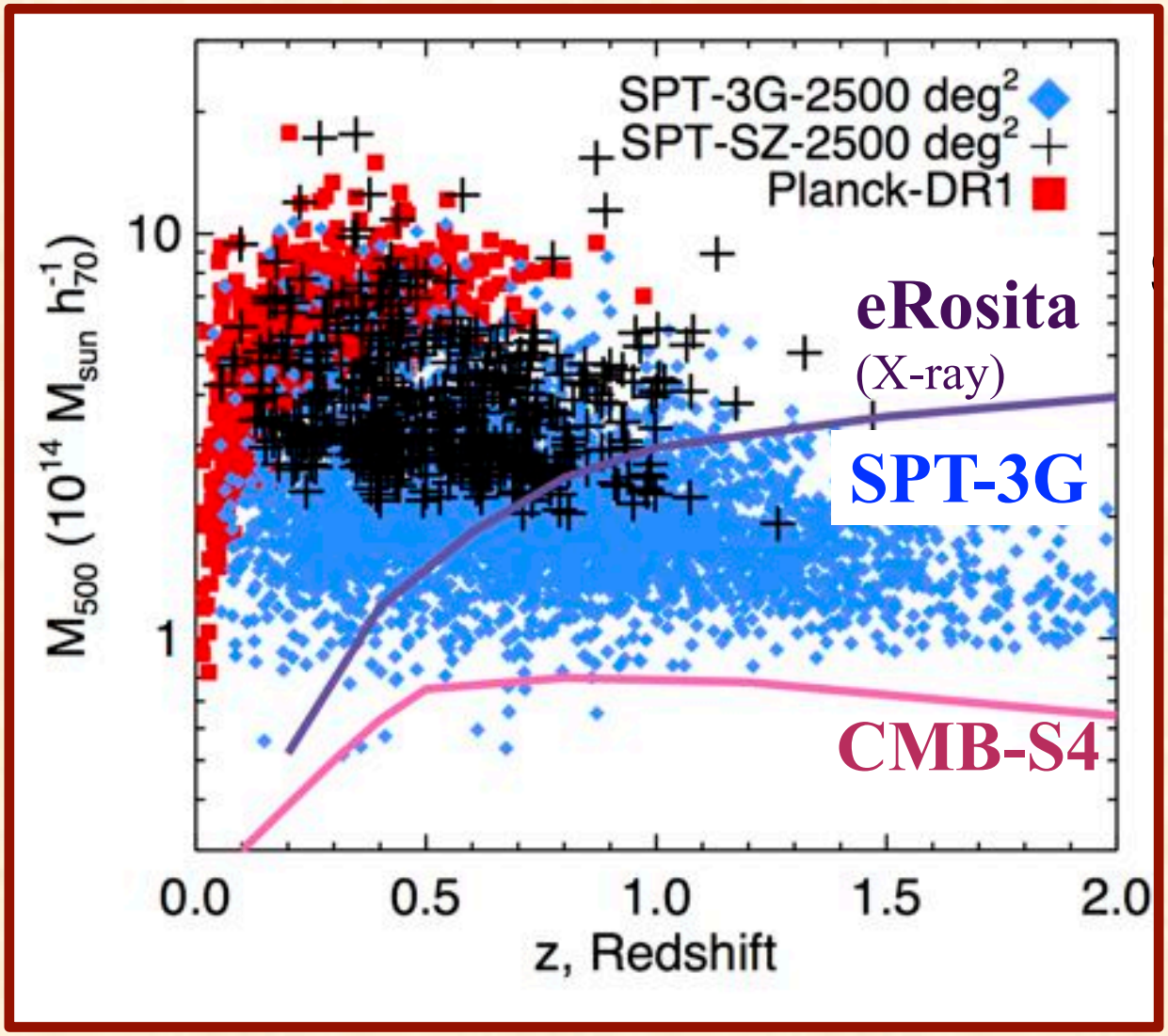
black = red+clusters

Weinberg et al. 2013

Cluster Cosmology in 3 Easy Steps

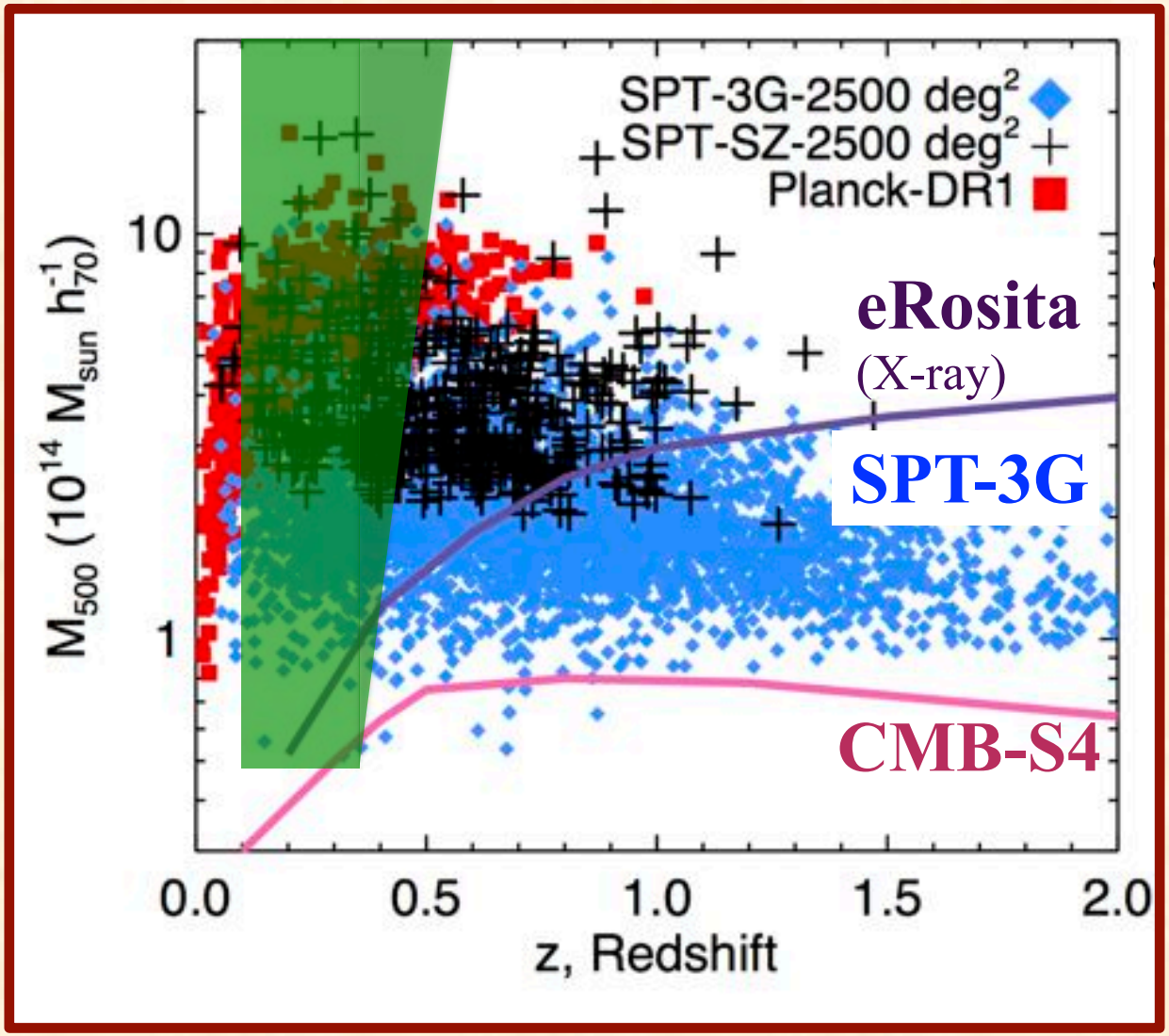
1. Find all galaxy clusters.
2. Measure cluster masses.
3. Learn about gravity and dark energy!

Cluster Selection: X-ray/SZ

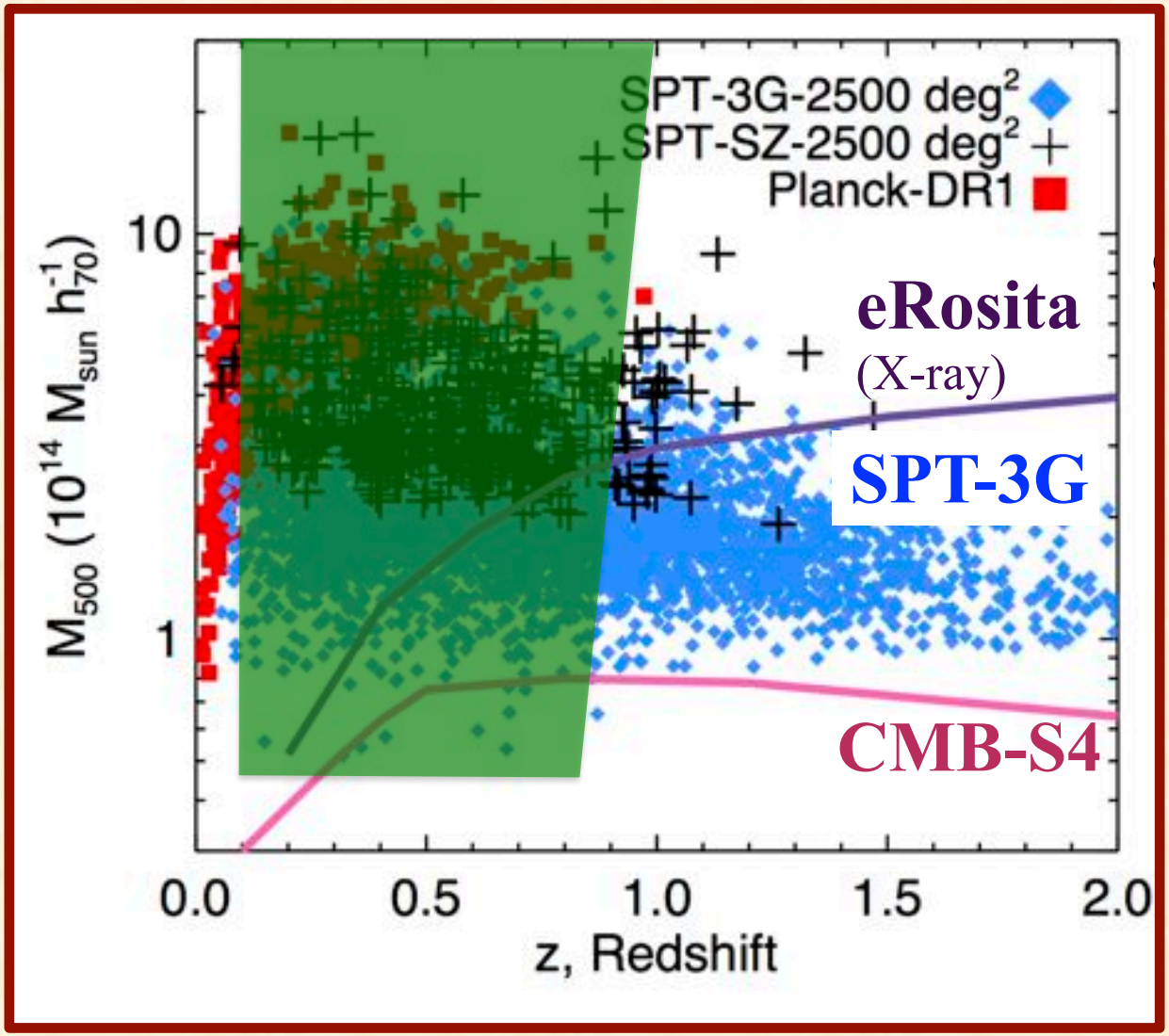


Plot by Lindsey Bleem

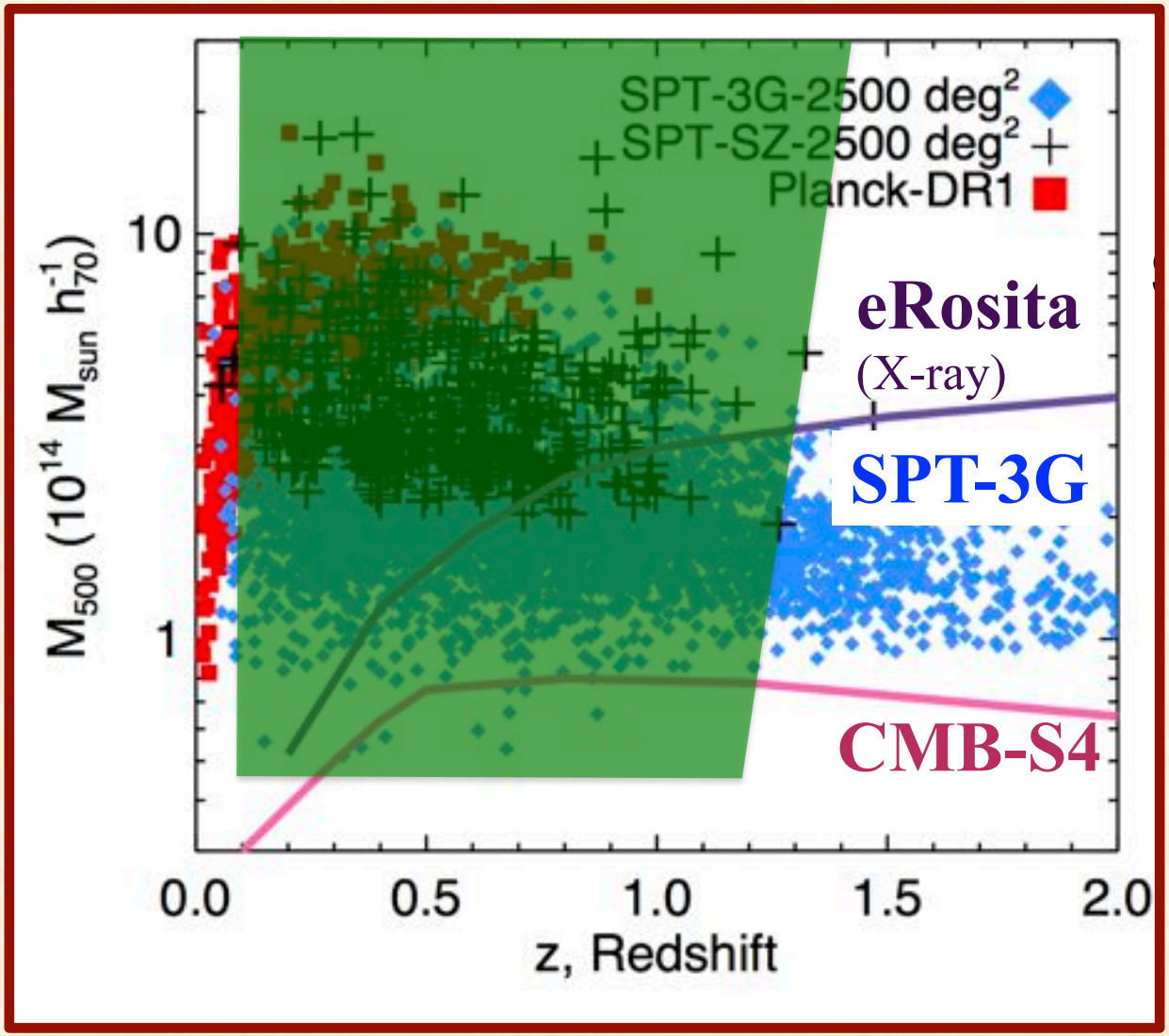
Cluster Selection: SDSS



Cluster Selection: DES



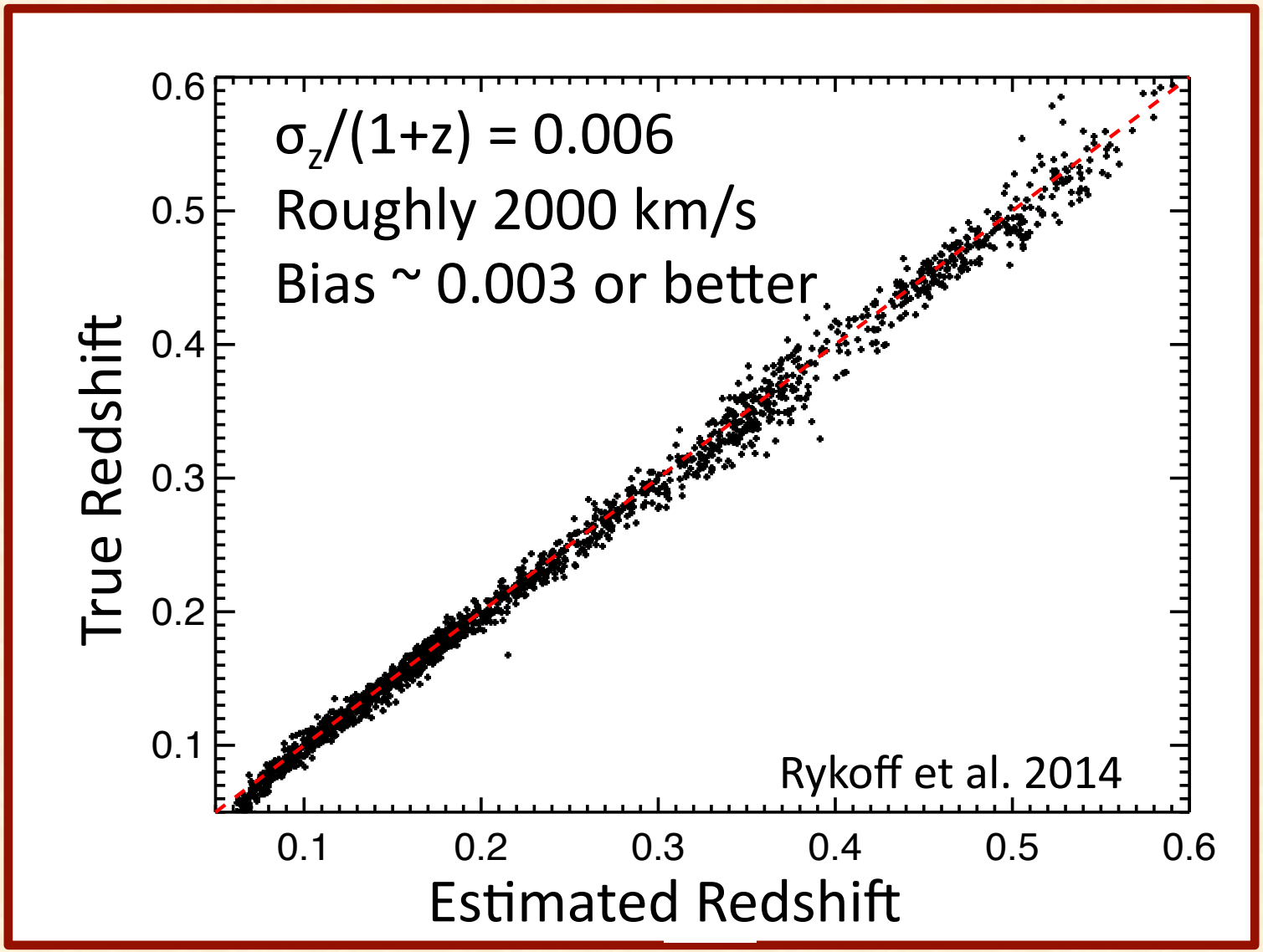
Cluster Selection: LSST



What are the Difficulties?

- Photometric redshift estimates.
- X-ray/SZ: point source contamination.
- Optical: noisy richness estimates.
- Projections.

Photometric Redshifts



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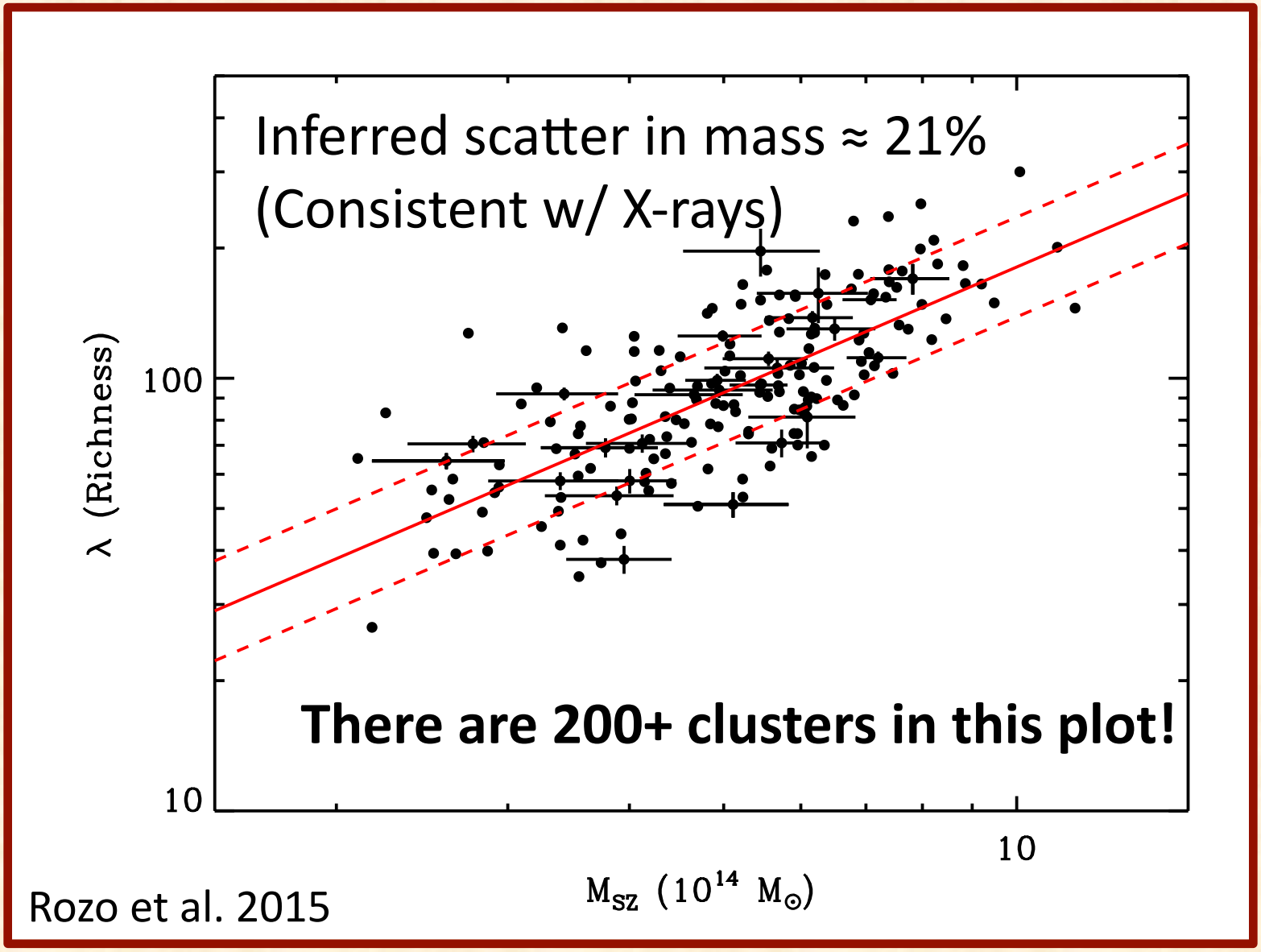
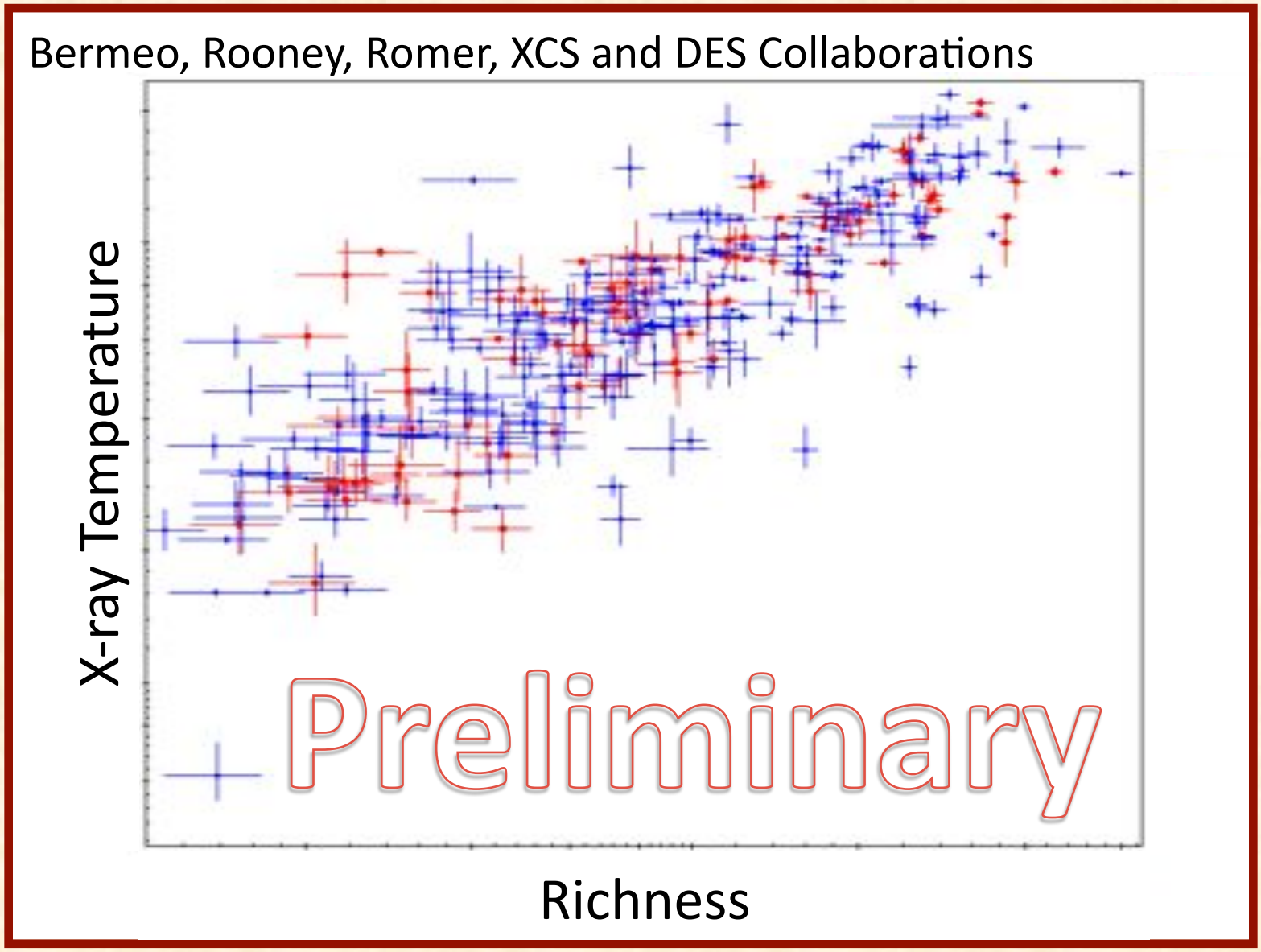
Tightly Correlated with SZ

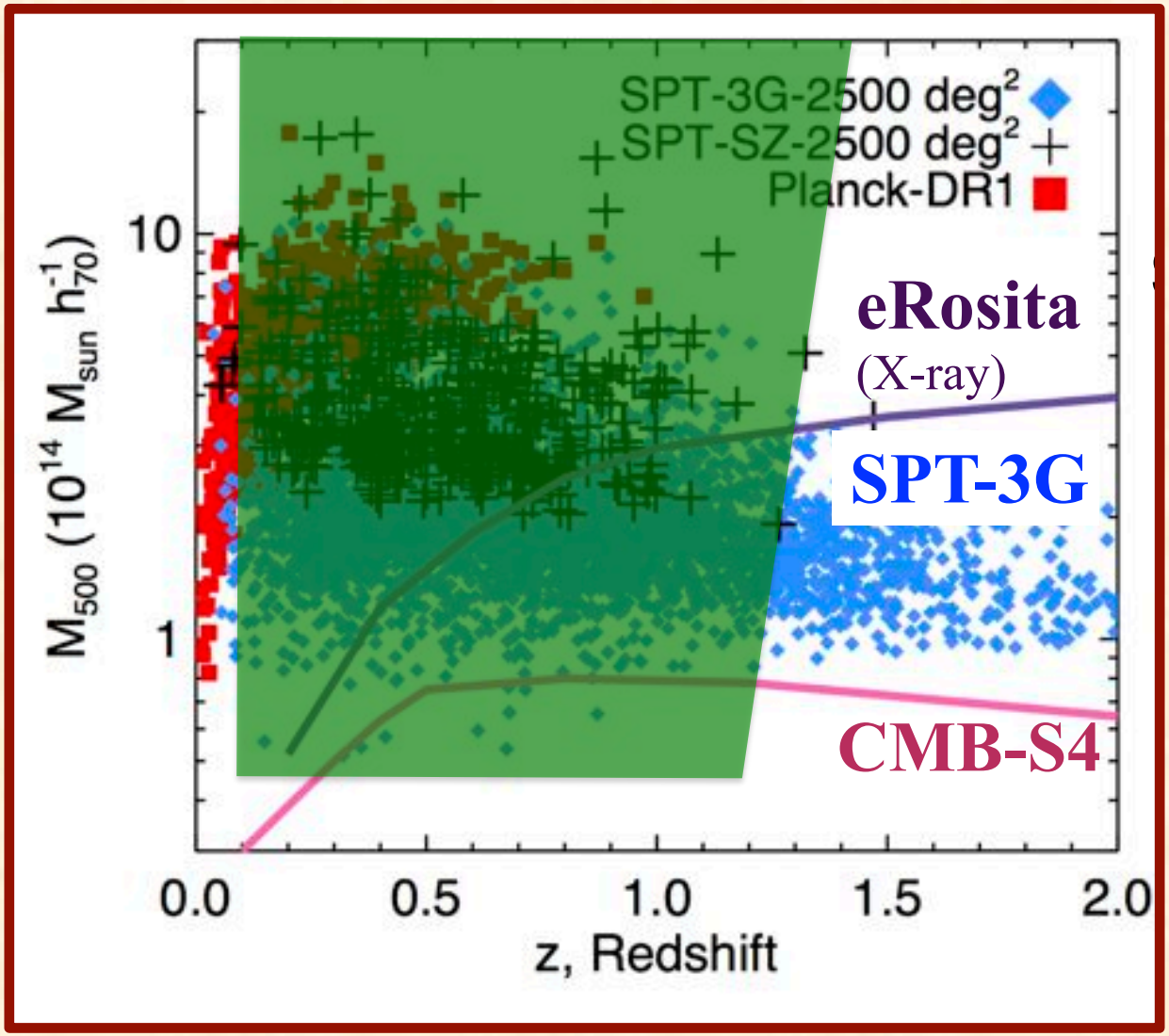


Rozo et al. 2015

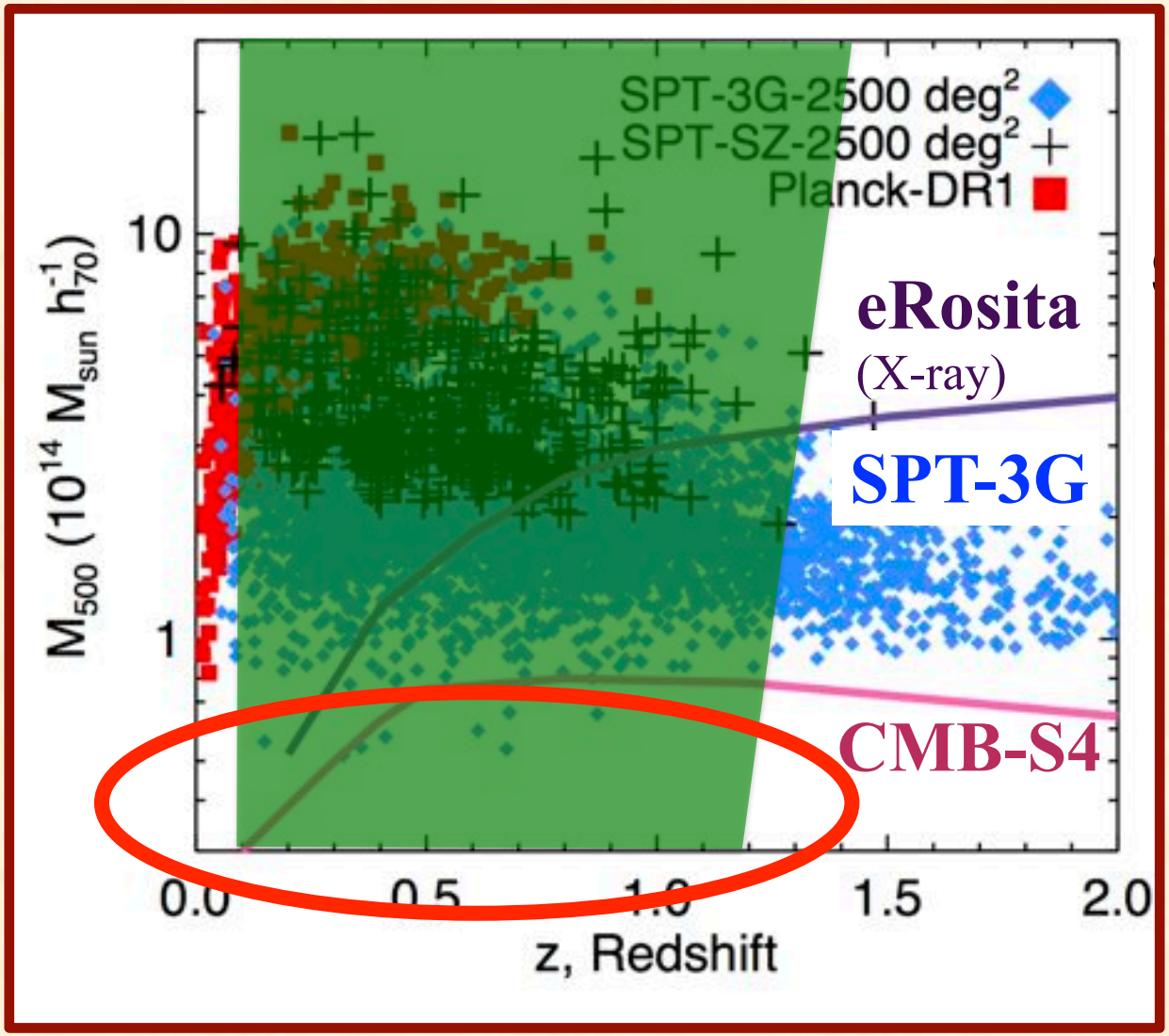
Tightly Correlated with X-rays



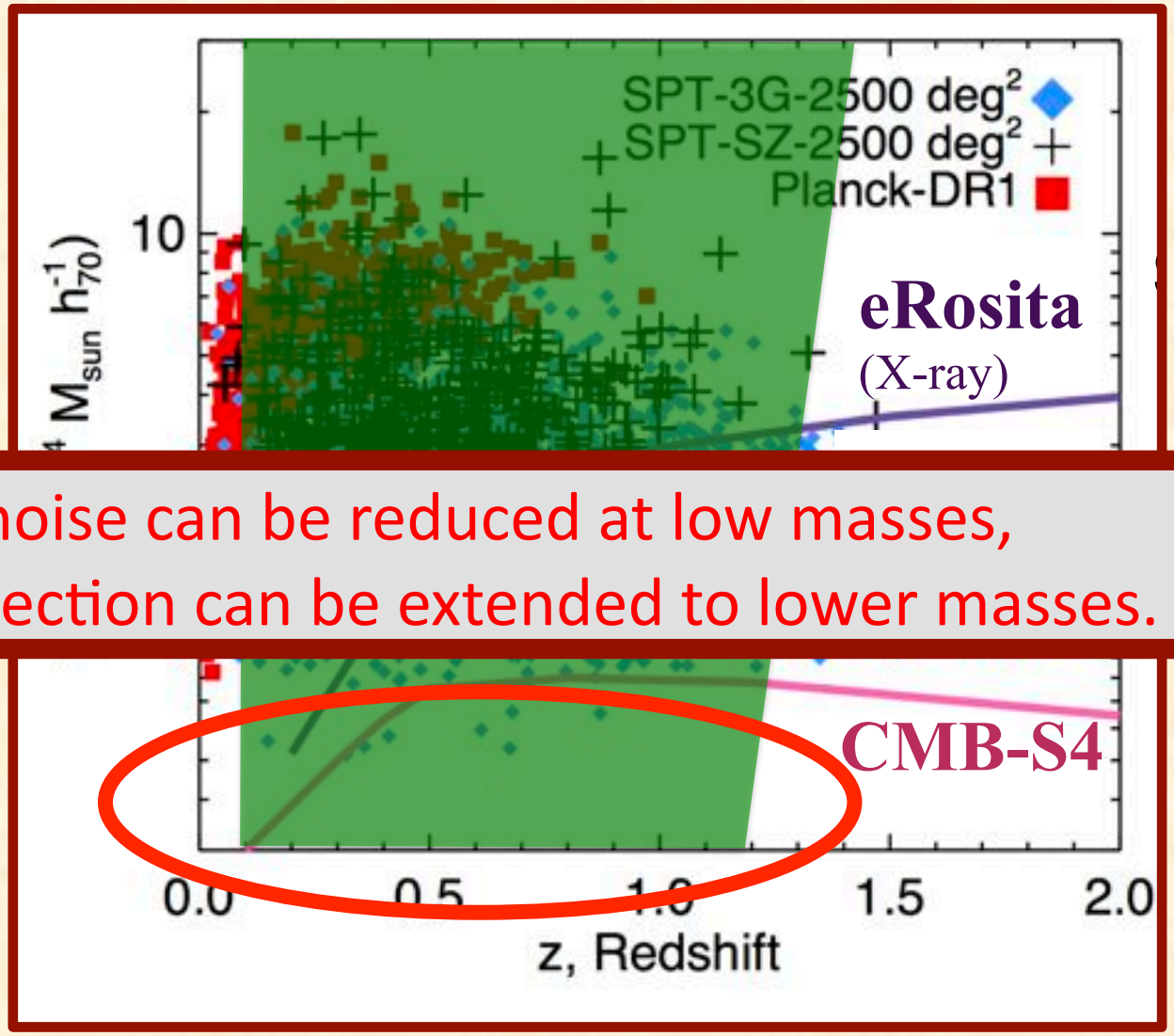
Cluster Selection: LSST



Cluster Selection: LSST?



Cluster Selection: LSST?



If noise can be reduced at low masses, selection can be extended to lower masses.

What are the Difficulties?

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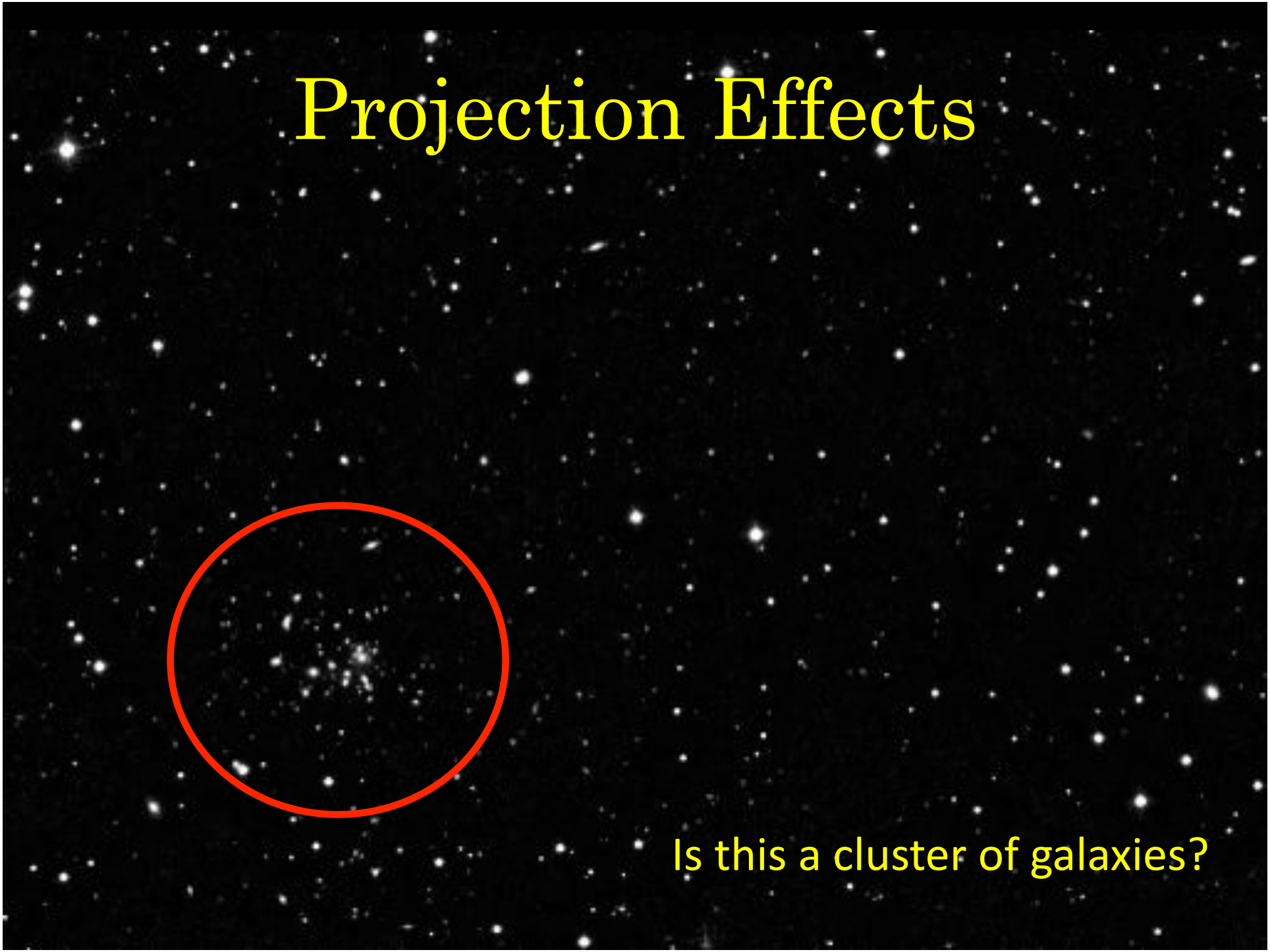
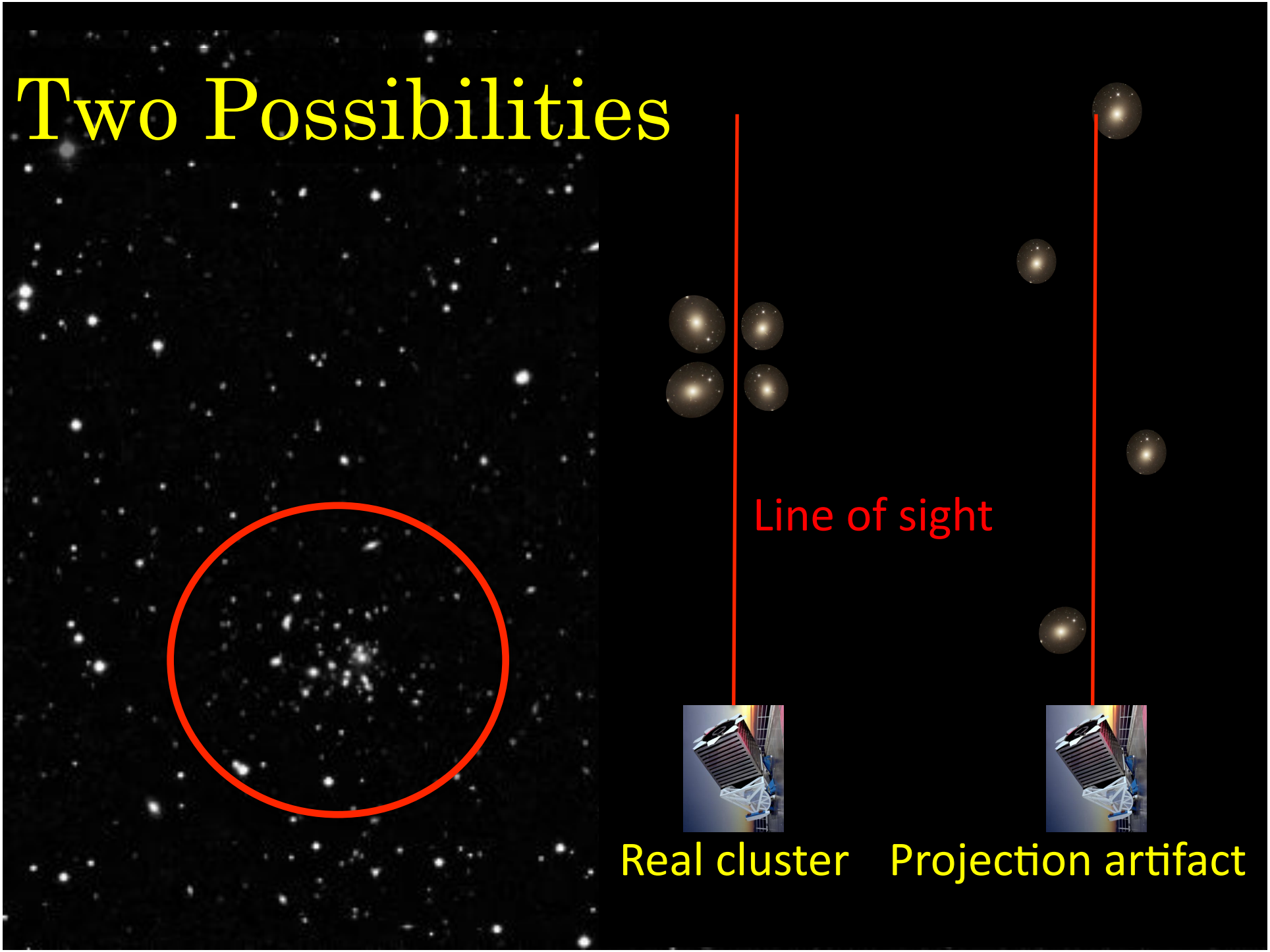
Projection Effects



Two Possibilities



The Swift-redMaPPer Sample

We wanted to target **typical** redMaPPer clusters.

Richness ≈ 30 :: these are not the rich/massive clusters!

Only hope to detect these w/ X-rays is if they are very close:

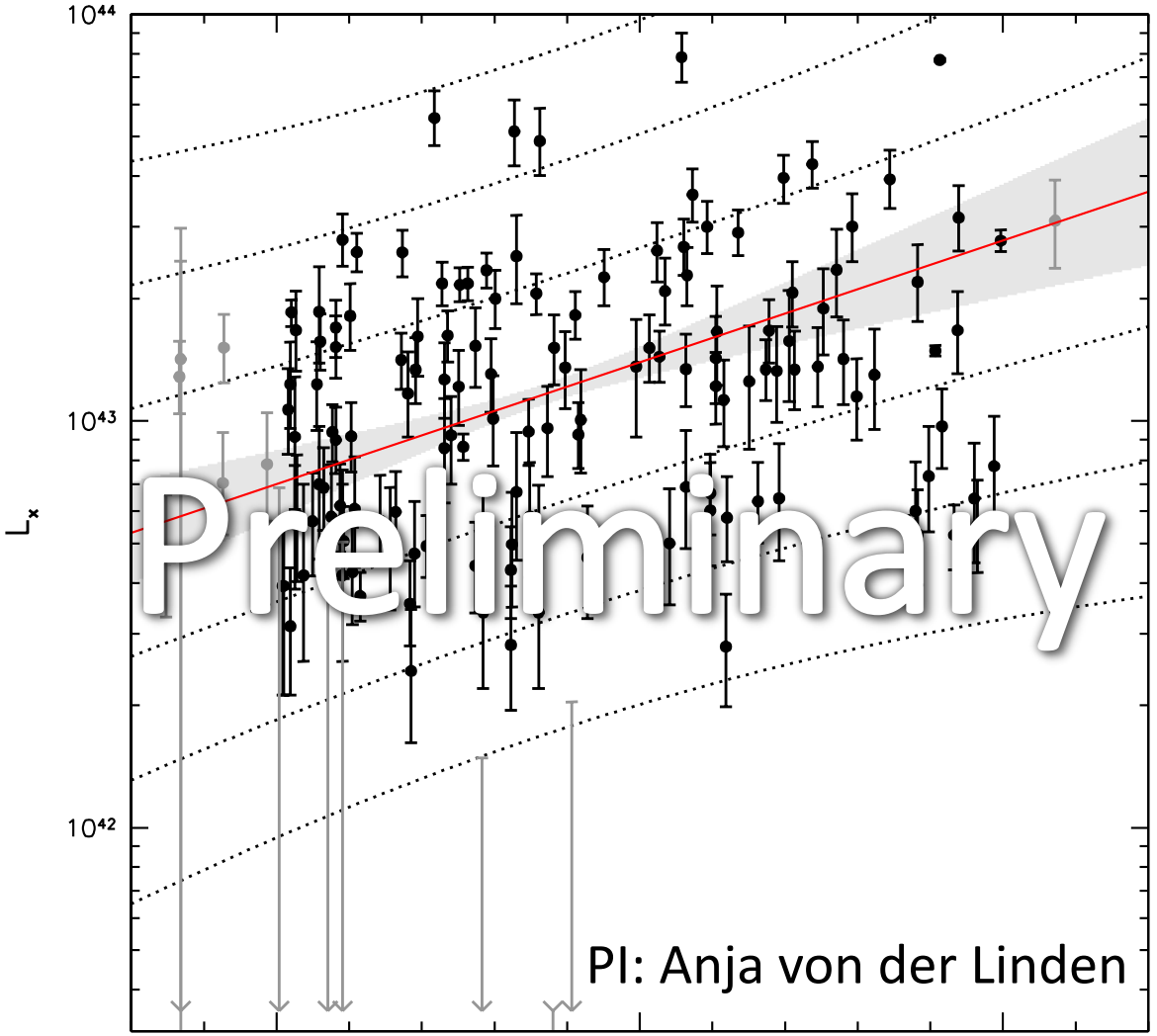
Use *Swift* to target <u>ALL</u> redMaPPer clusters with:

λ = [25,35], z = [0.08, 0.12], 154 systems total

Exposures set to get ≈50 photons/clusters.

PI: Anja von der Linden

Preliminary



Two Clusters
Same Richness and Redshift

The Swift-redMaPPer Sample

134/154 clusters imaged so far.

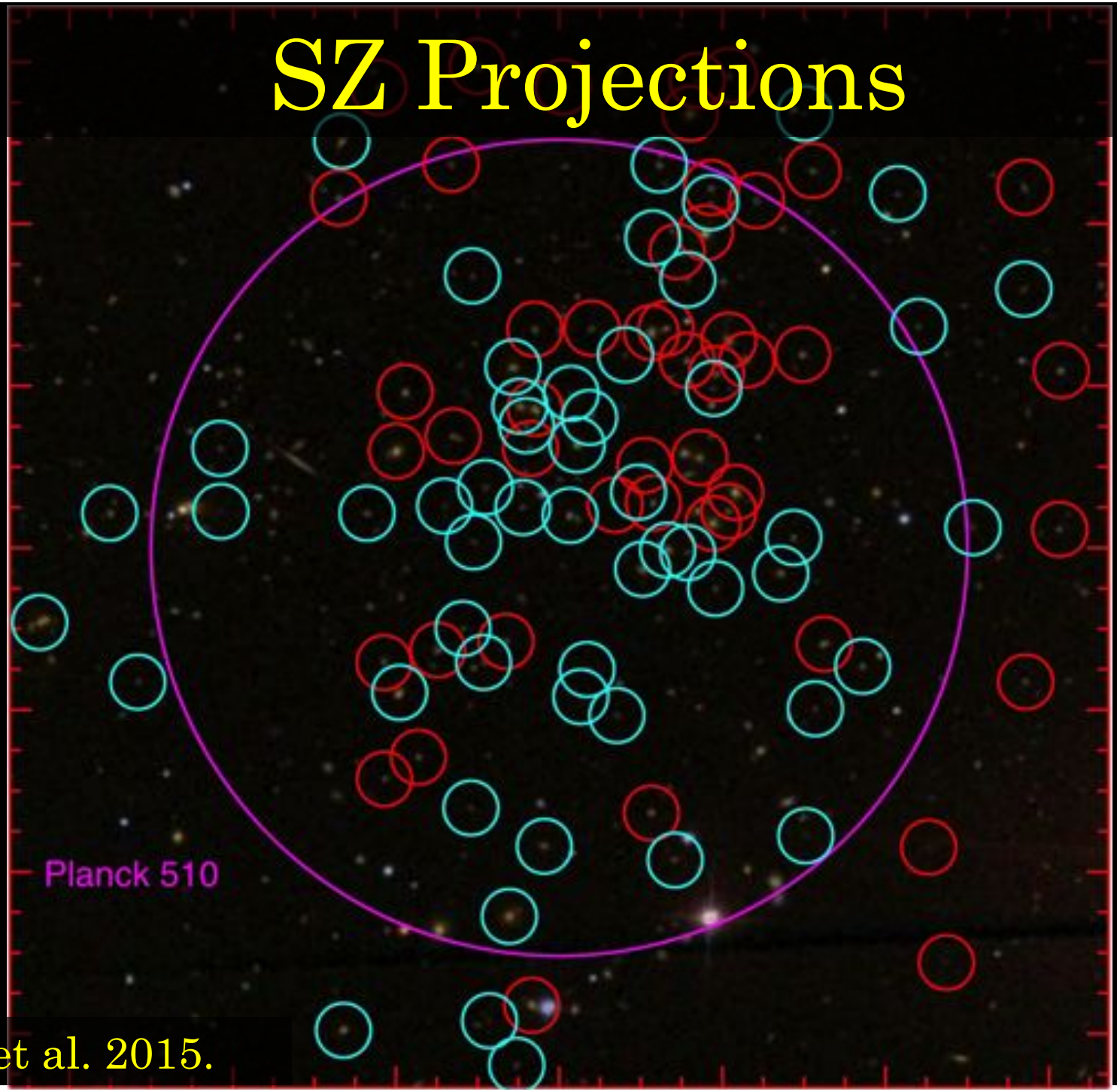
6 non-detections (though not all data is collected).

Incidence of projection effects at low richness: 4% or less.

Projection rate higher at high richness, expect 10%.

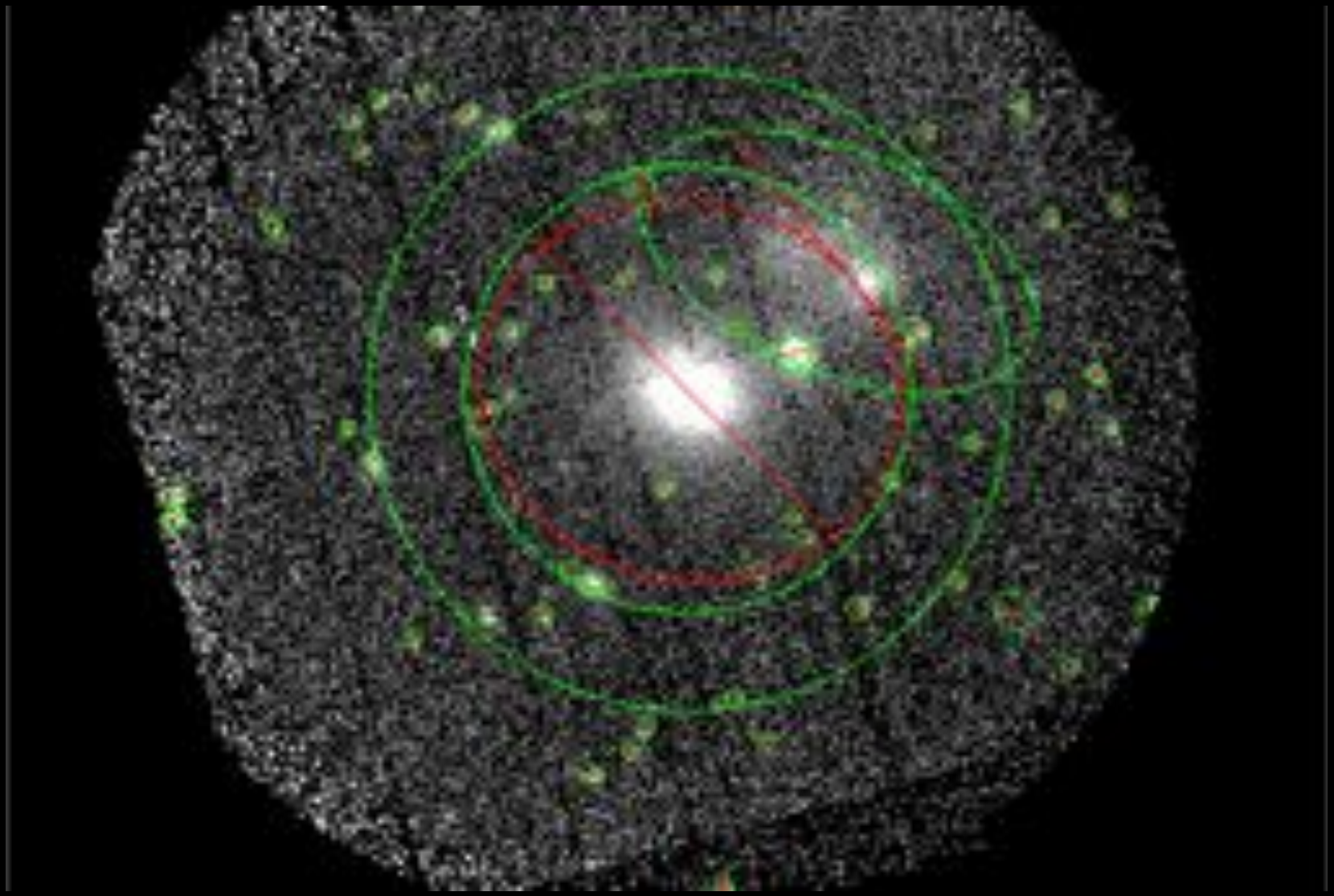
PI: Anja von der Linden

SZ Projections



Rozo et al. 2015.

X-ray Projections



Bermeo, Rooney, Romer, XCS and DES Collaborations

What are the Difficulties?

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- Optical: noisy richness estimates.
- Projections.

Bottom line:

Systematics controlled at the 5% level or better.

Easily a sub-dominant source of error today.

Next generation surveys may require improvements.

Cluster Cosmology in 3 Easy Steps

1. Find all galaxy clusters.
2. **Measure cluster masses.**
3. Learn about gravity and dark energy!

Cluster and their Masses

The problem with masses

Abundance depends on M: $n(M) \sim M^{-\beta}$, $\beta \approx 2\text{-}3$.

A fractional error σ in the mass corresponds to a fractional error $\beta\sigma$ in the abundances.

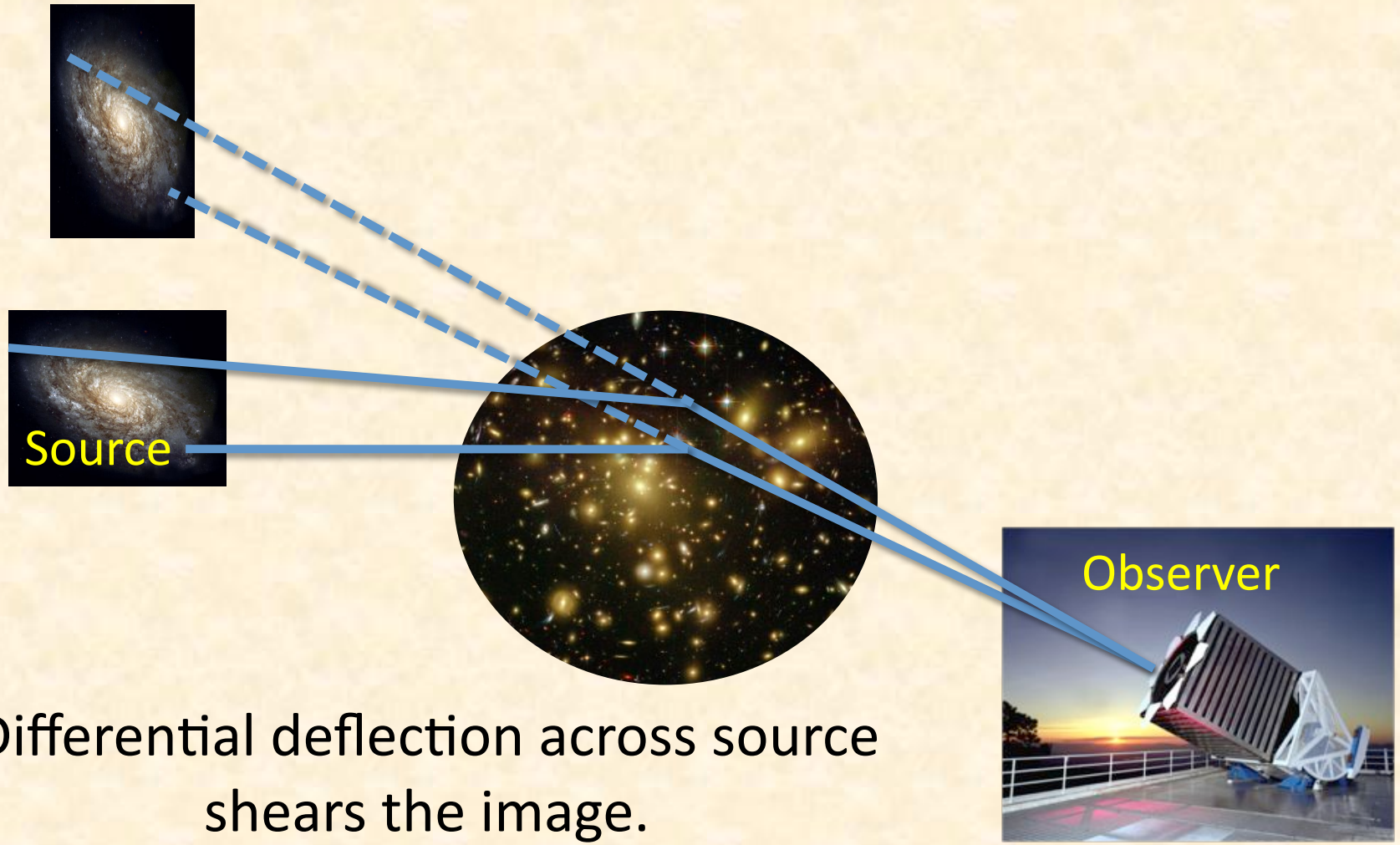
5% uncertainties in mass lead to 10%-15% uncertainties in the predicted abundances!

The Most Difficult Problem in Cluster Cosmology

How do you weigh a 10^{42} ton object that is 10^{22} km away?

Weak Lensing

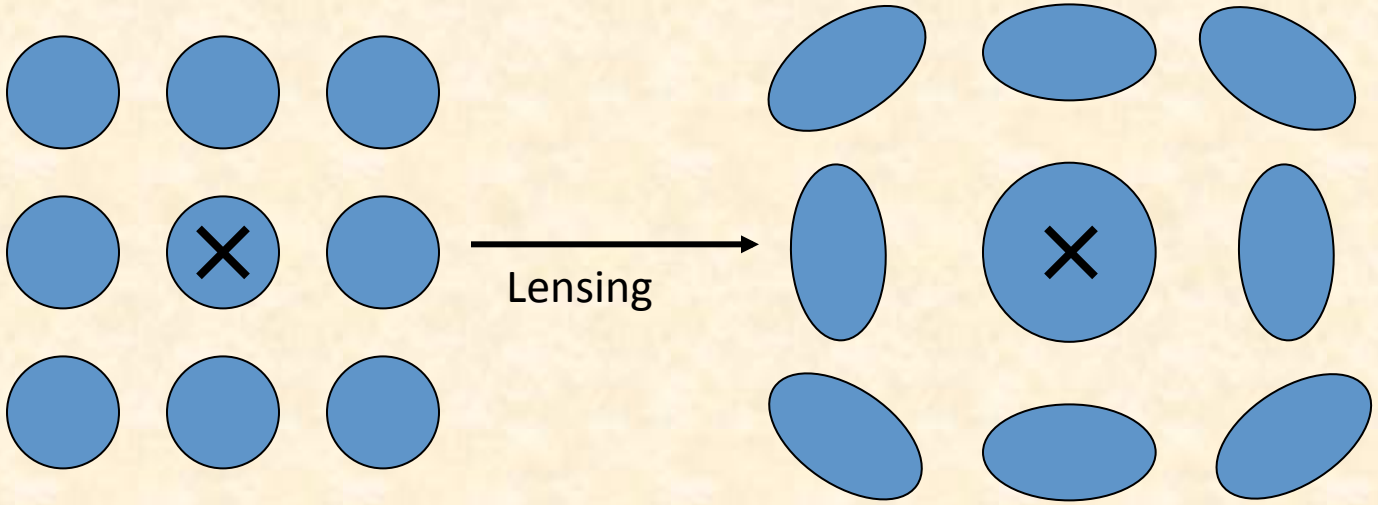
The gravity of a galaxy cluster bends the light of galaxies behind it.



Differential deflection across source shears the image.

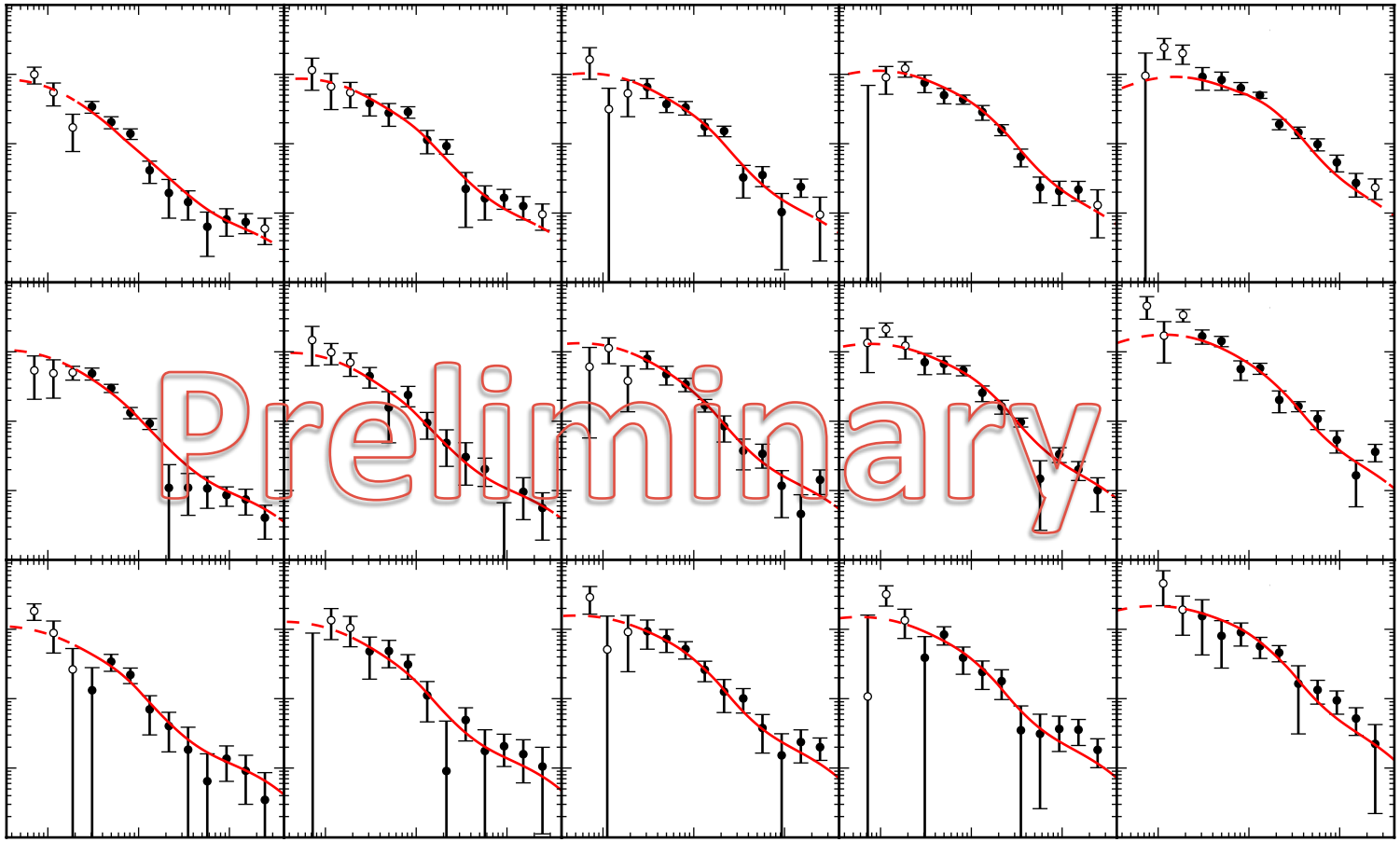
Weighing Clusters with Weak Gravitational Lensing

We can detect *shear* statistically:



The mean tangential ellipticity of *background* galaxies around galaxy clusters depends on the cluster mass.

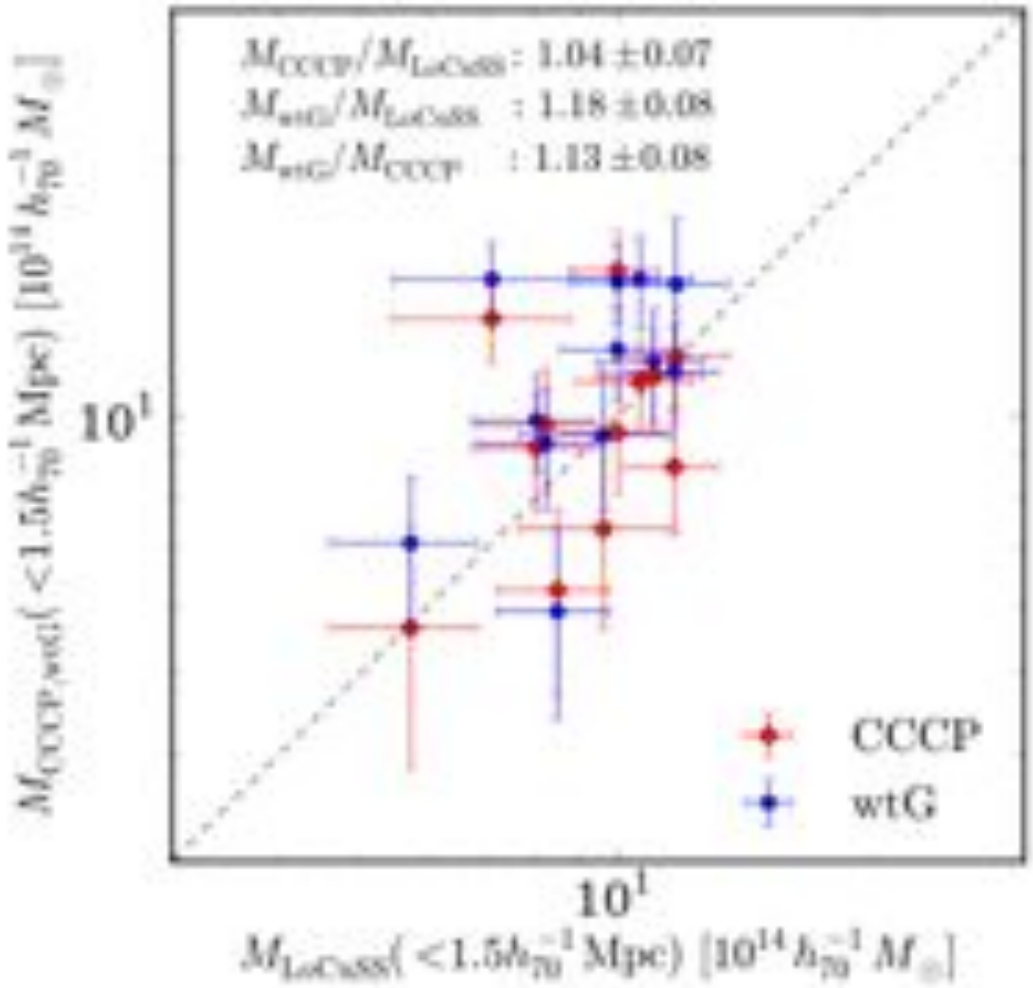
Mass Calibration of DES SV Clusters



Melchior et al., in prep.

Where Are We Now?

Okabe and Smith 2015



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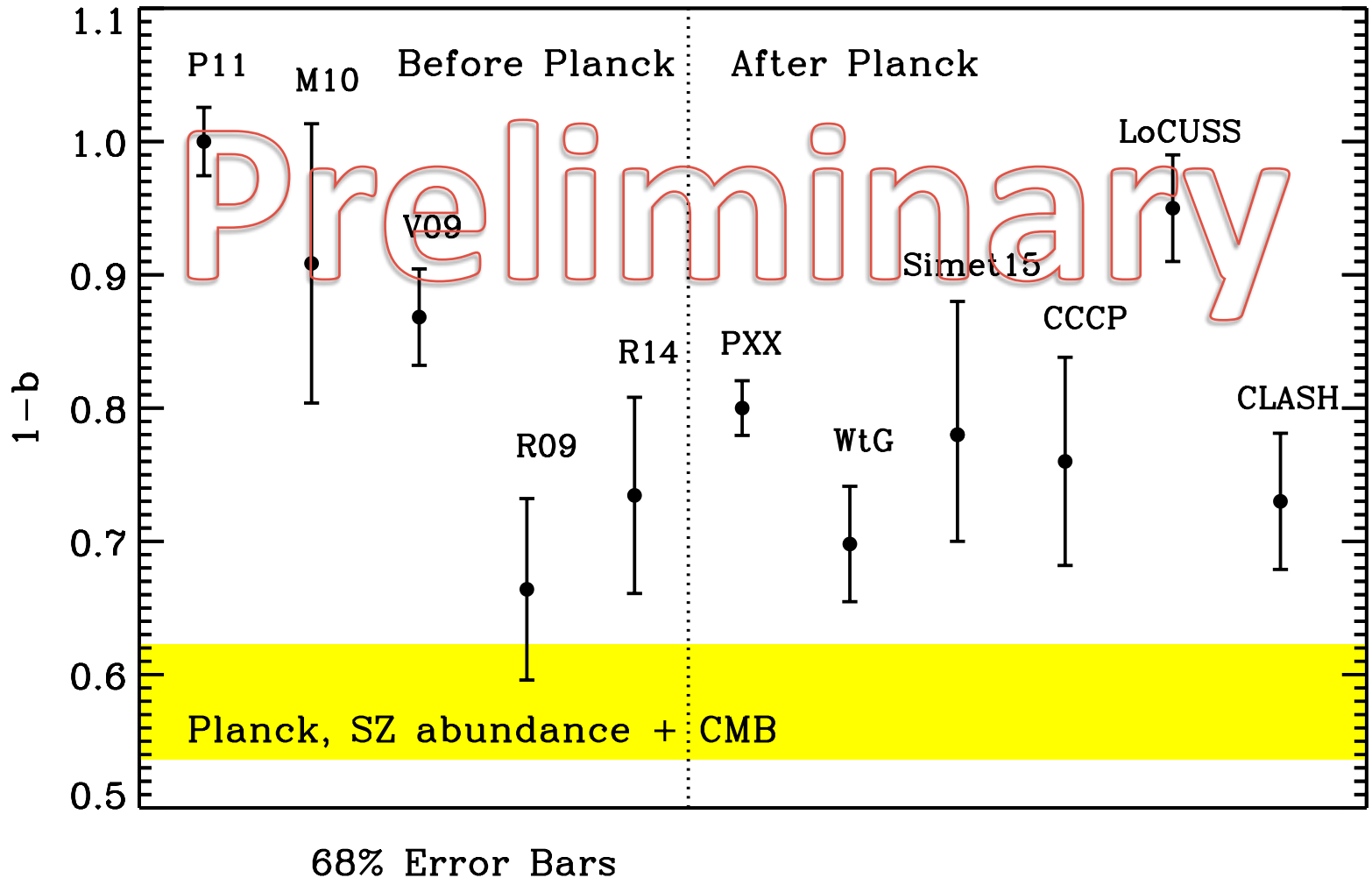
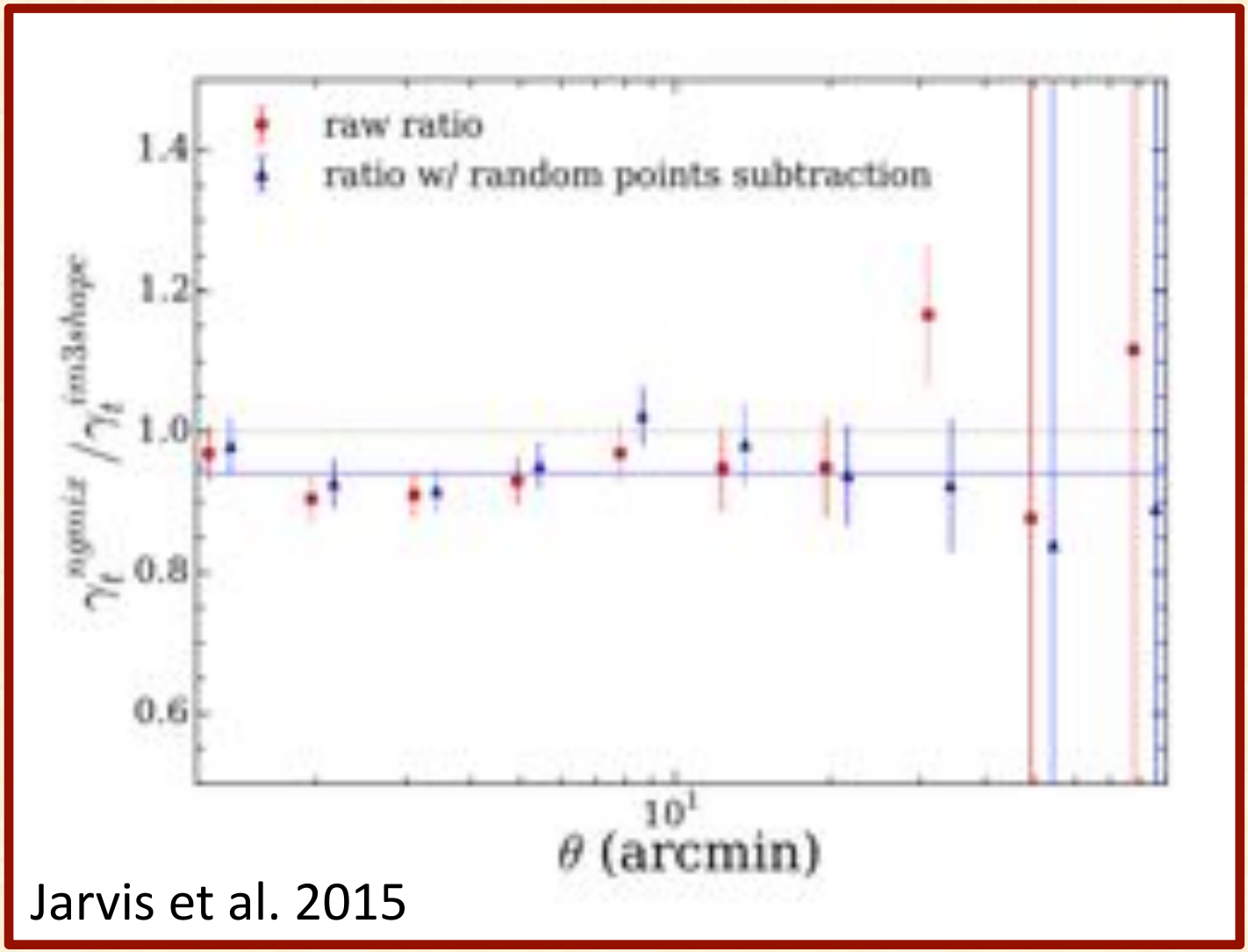


Penna-Lima et al., in prep.

What are the Difficulties?

- Measuring shapes is hard.
- Photometric redshift errors of the sources.
- Membership dilution.
- Cluster centering.
- Triaxiality
- Projections
- Modeling Systematics

Shape Systematics



Jarvis et al. 2015

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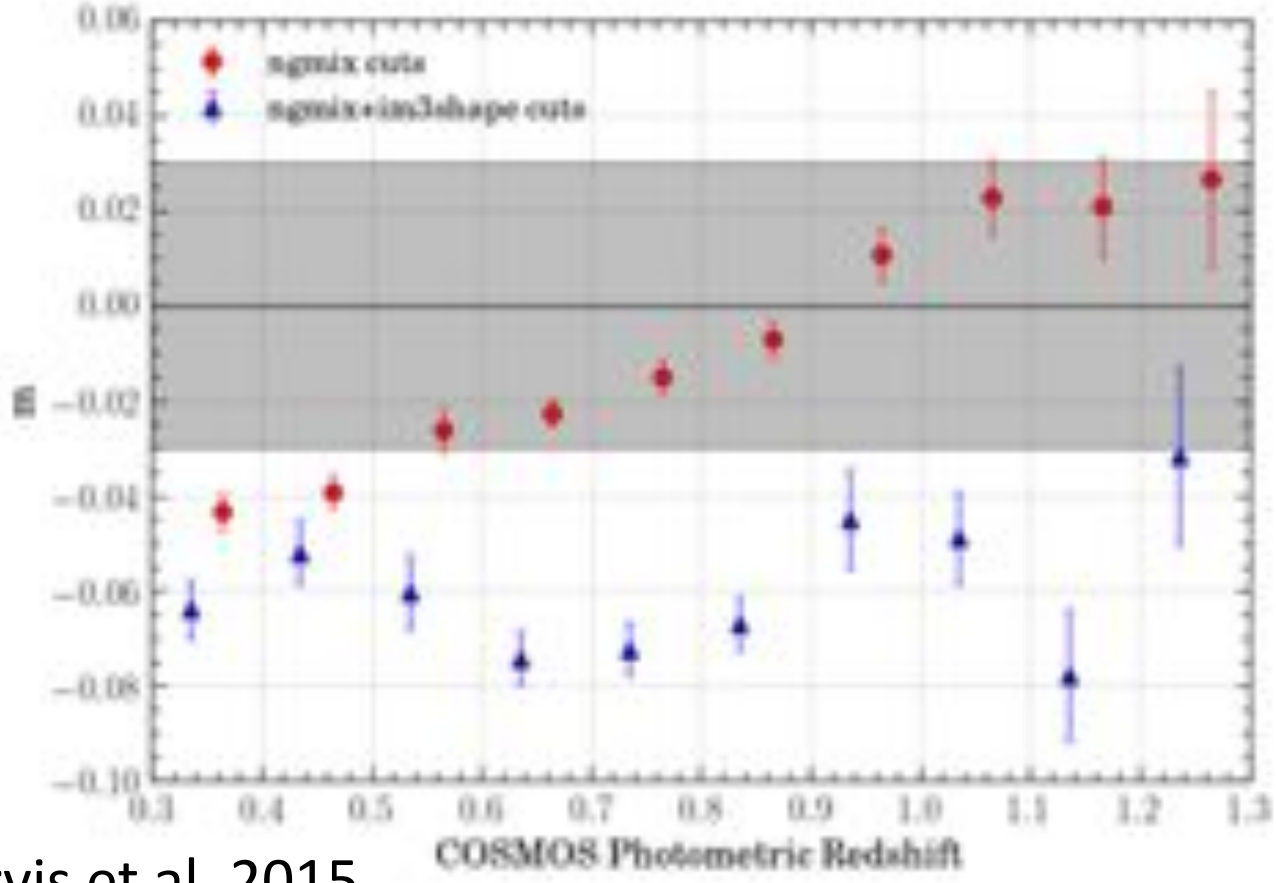

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What are the Difficulties?

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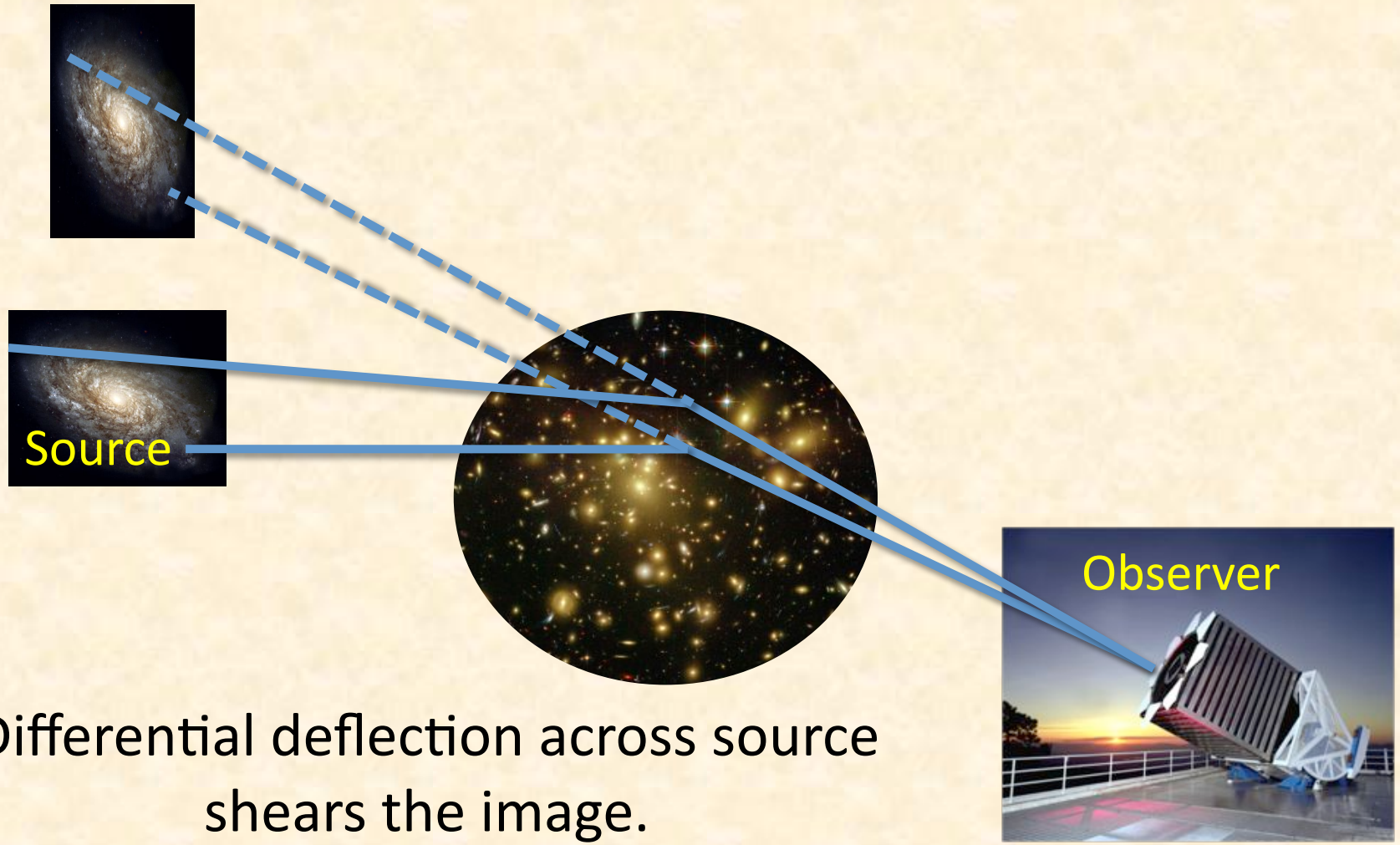
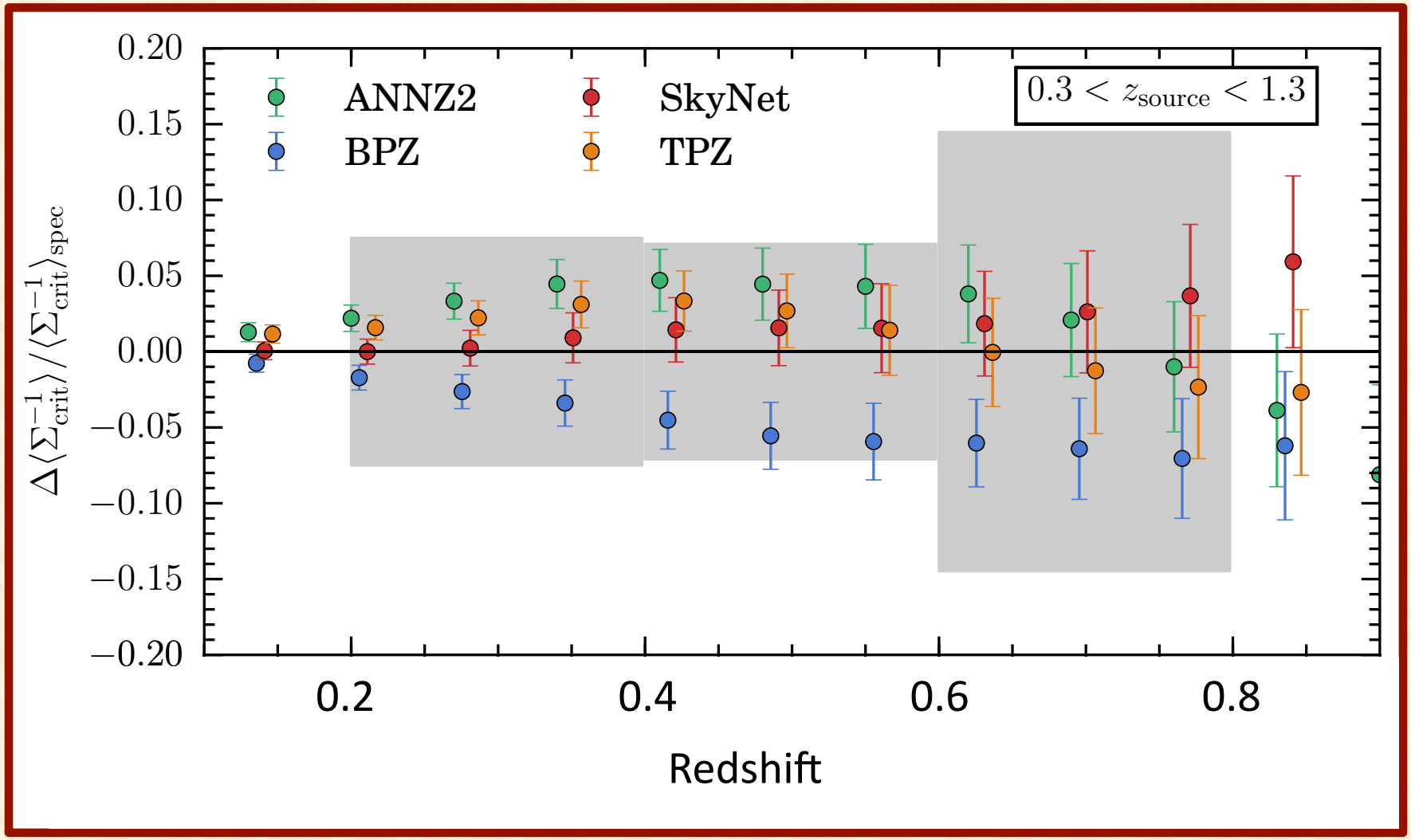


Differential deflection across source shears the image.

Photoz Systematics in DES



Bonnet et al. 2015

What are the Difficulties?

- Measuring shapes is hard (7%).
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Systematics Require us to do Everything (at least) Twice

Two independent shape catalogs.

4 independent photoz catalogs.

Significant efforts have gone into characterizing the relative performance of each.

Not optional.

What are the Difficulties?

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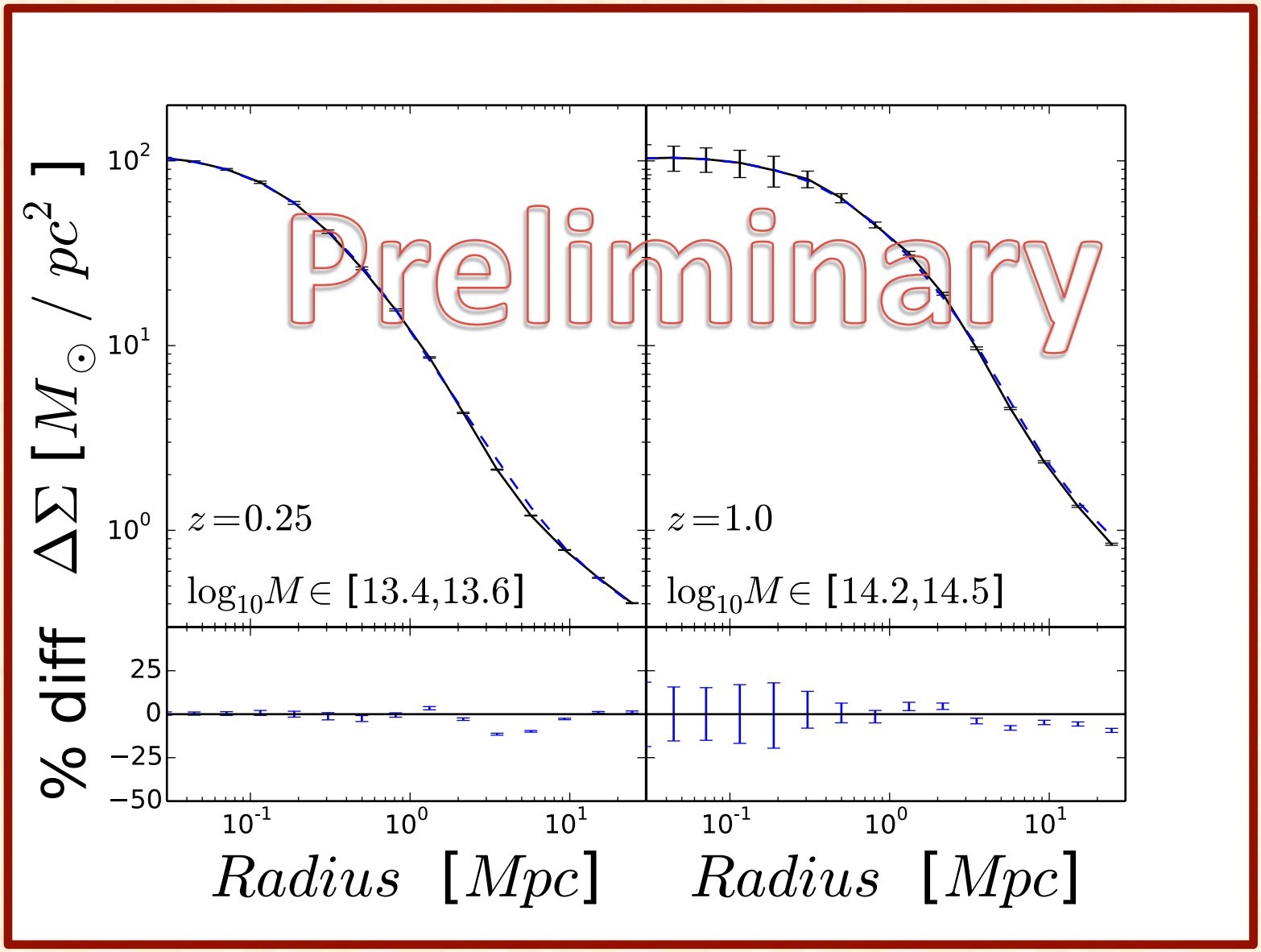
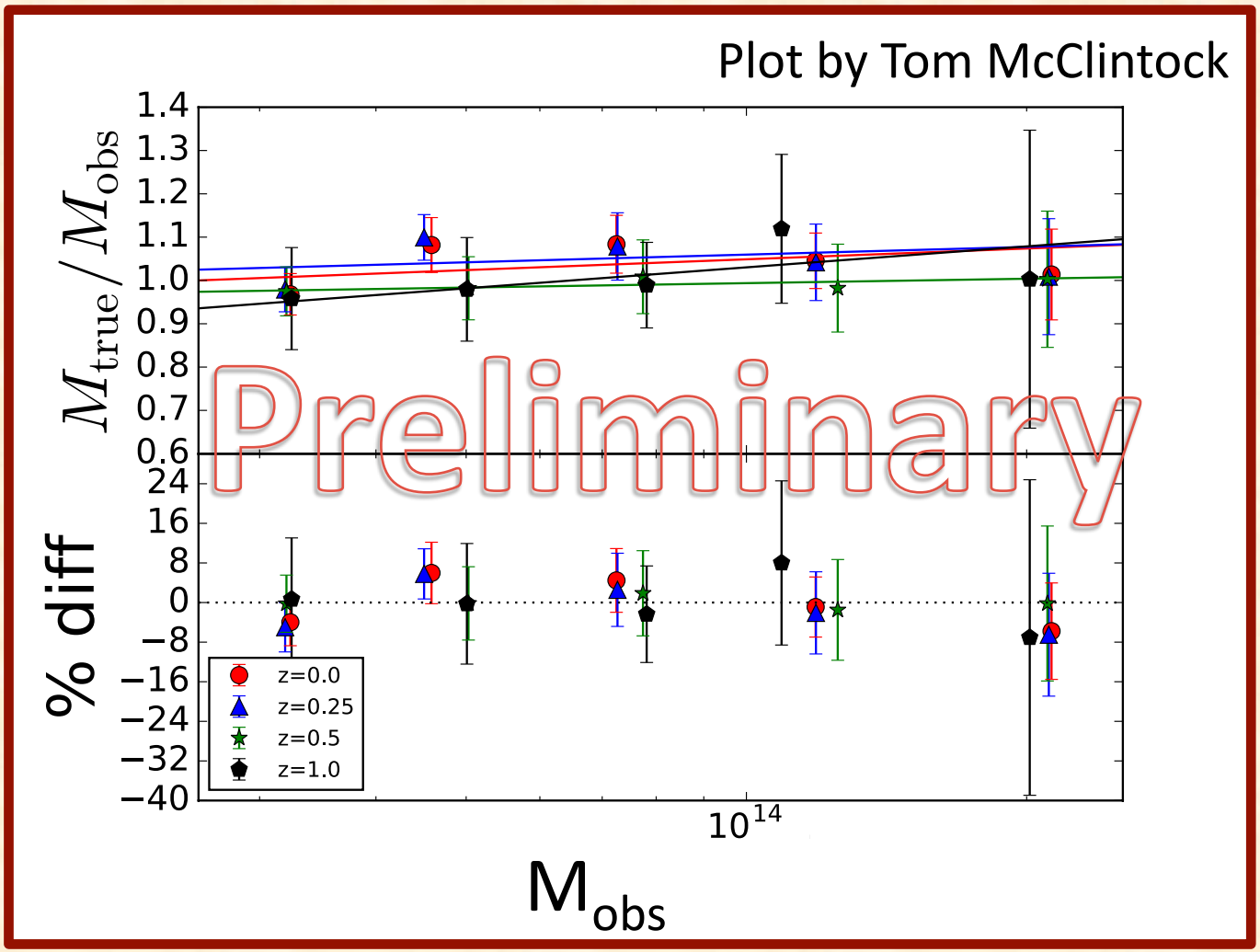
Modeling Systematics



Modeling Systematics



Melchior et al., in prep.

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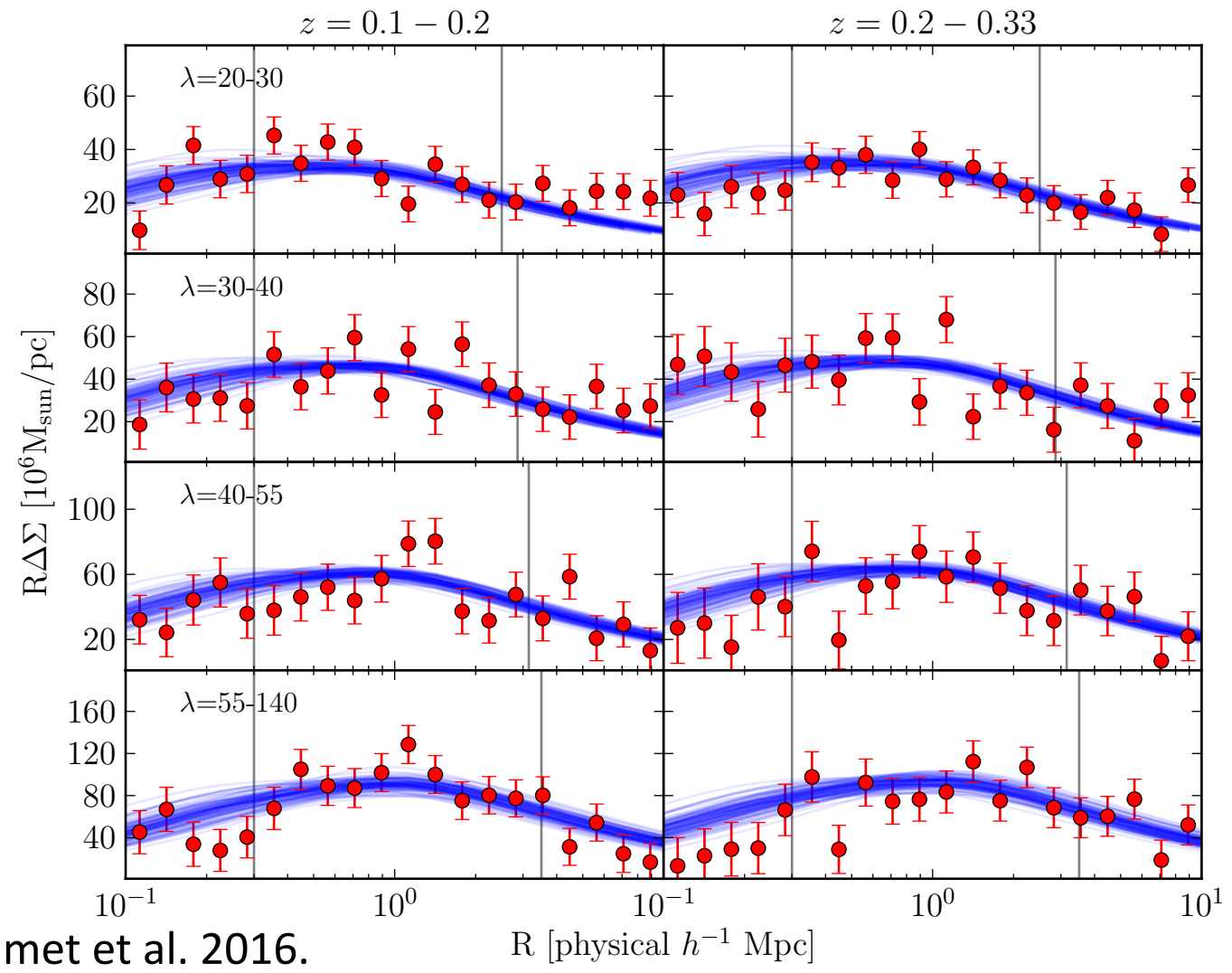
The Challenge



Simet et al. 2016.

How to Move Forward

- Measuring shapes is hard.
  - Trust that your WL friends will figure it out. (see talks by James, Michael)
  - Exploit synergies w/ other surveys!
- Photometric redshift errors of the sources.
  - Exploit synergies w/ other surveys!

Look for alternative methods of mass calibration.

Shape/Photo-z Systematics Calibration w/ Other Surveys

Shear is not the only probe of WL.

- CMB lensing
- magnification

Not as high S/N as WL for experiments like LSST.

Use it to calibrate systematic uncertainties!

Shape/Photo-z Systematics Calibration w/ Other Surveys

Shape/photoz act as a multiplicative systematic.

$$\Delta\Sigma_{obs} = A\Delta\Sigma_{true}$$

Comparing CMB/magnification measurements to WL shear can determine the systematics parameter *A*.

Comparison can be done on a single cluster stack.

CMB Lensing

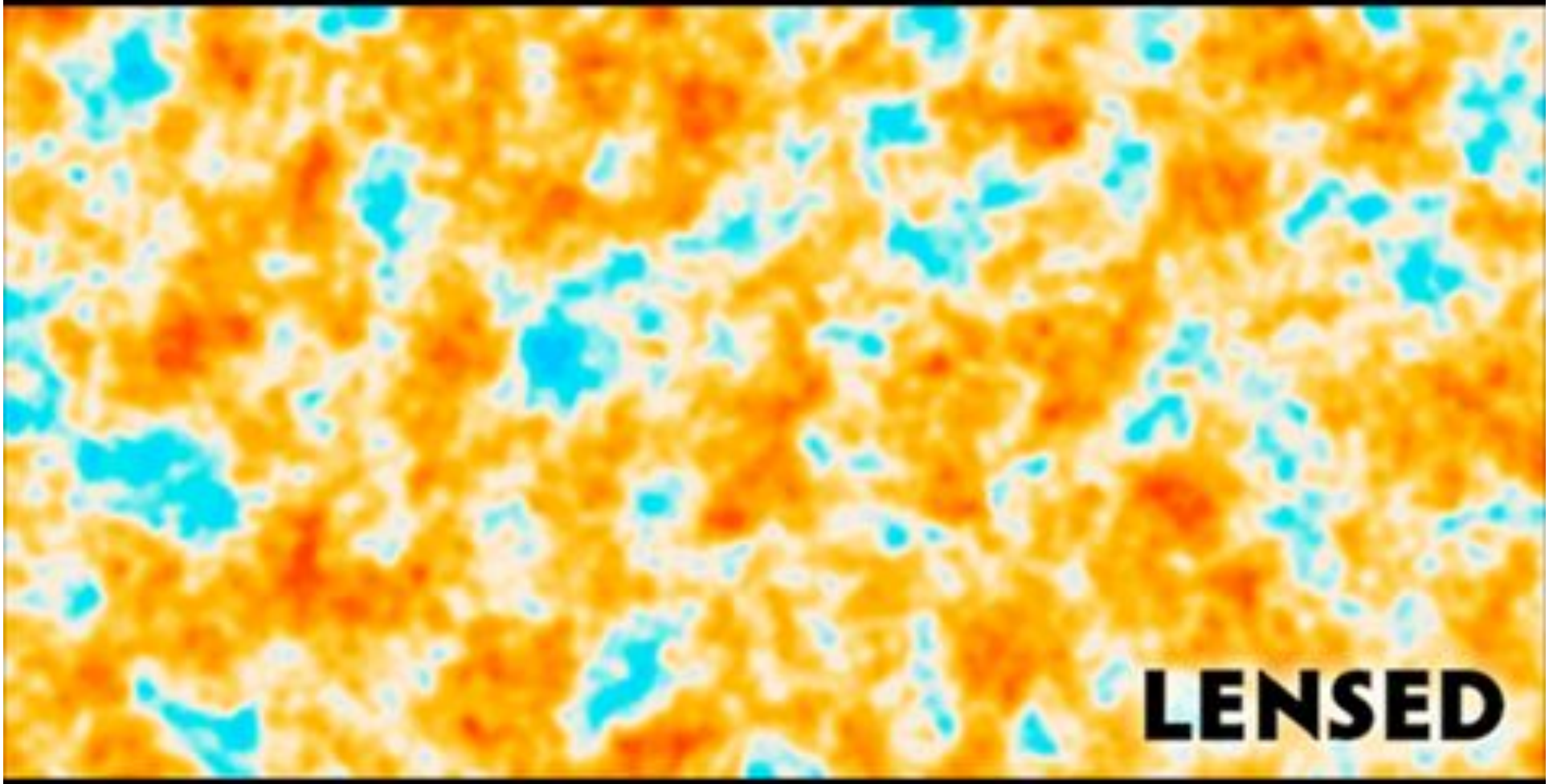
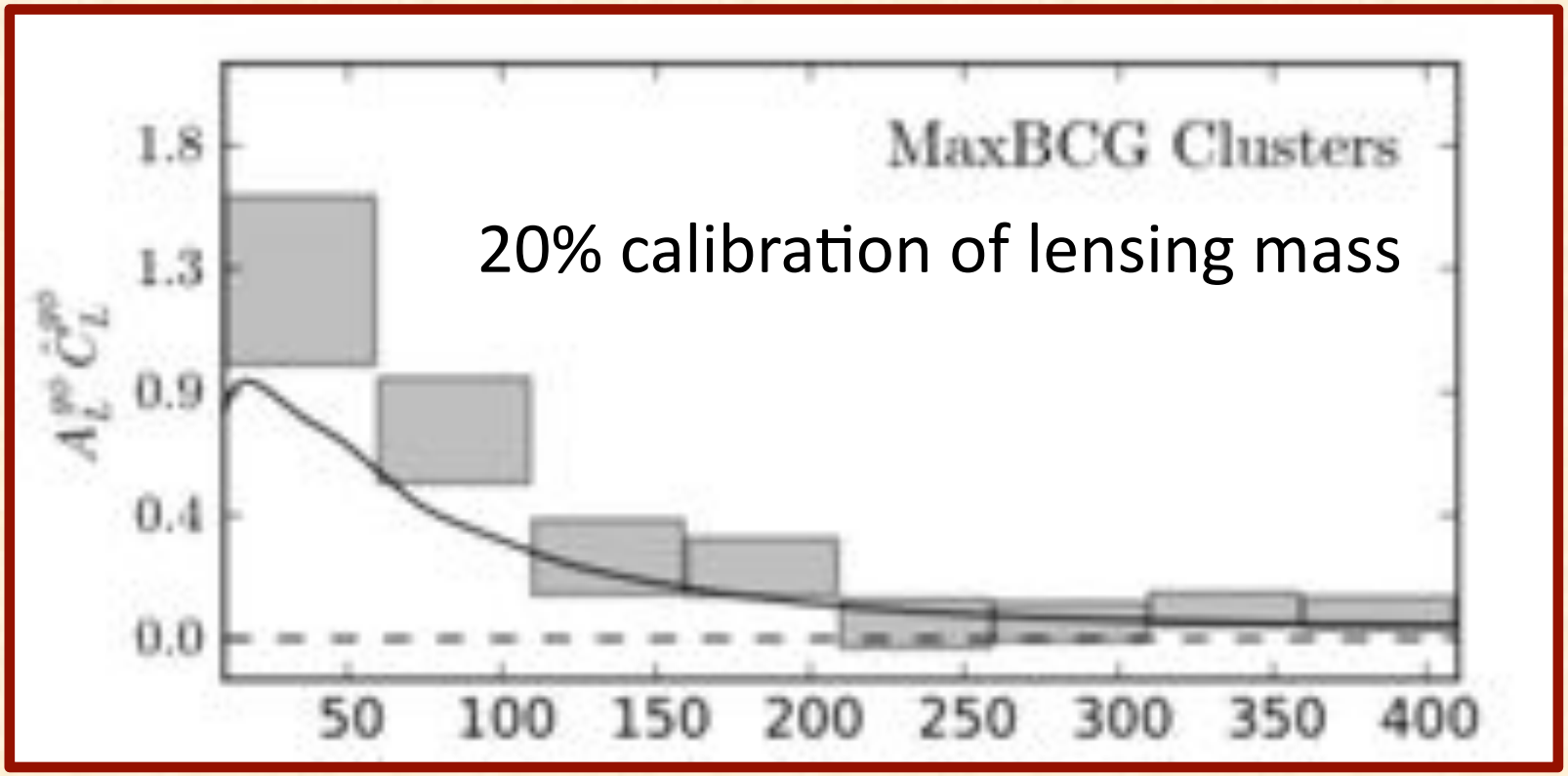


Image credit: ESA/NASA/JPL-Caltech

CMB Lensing

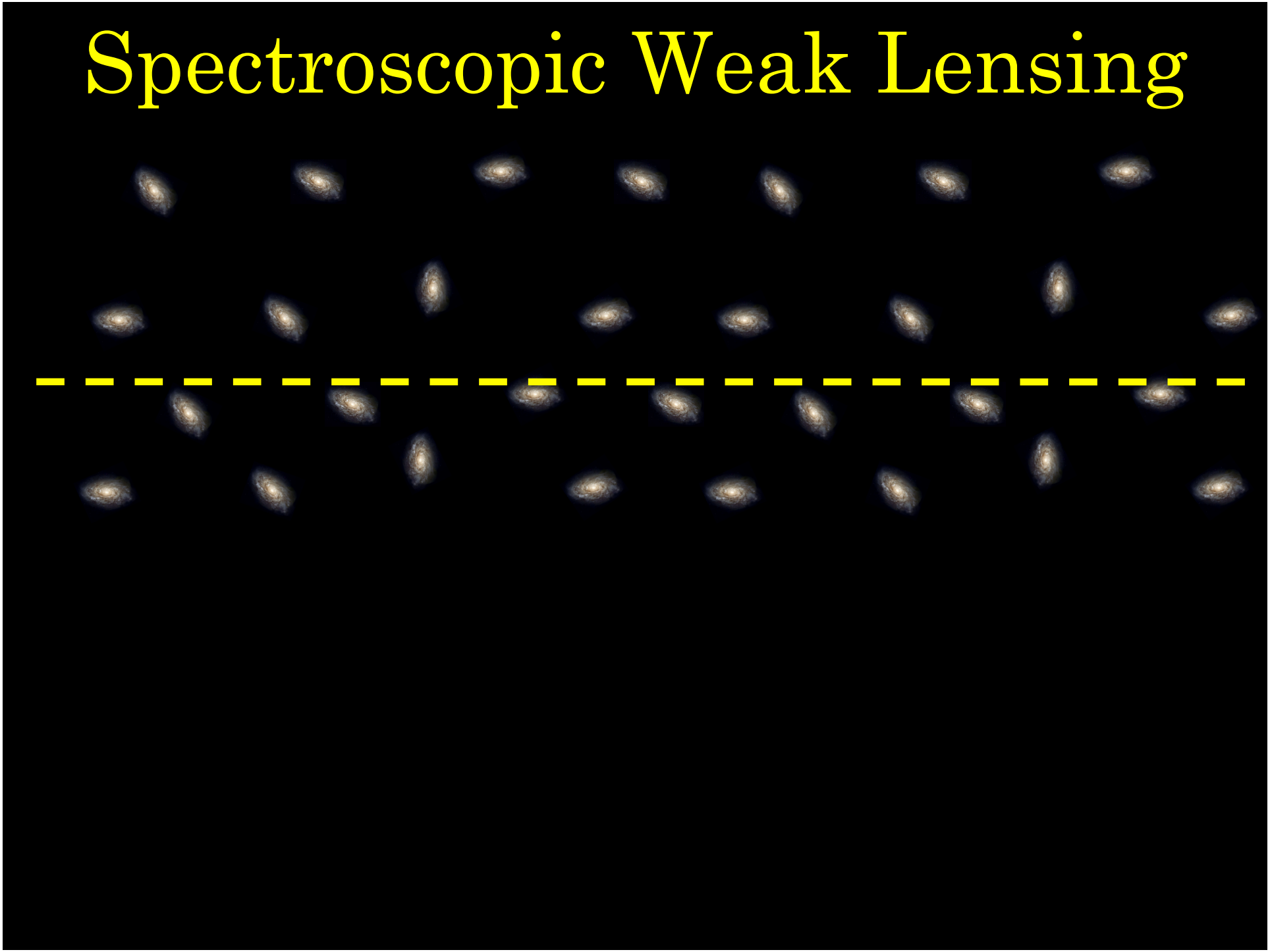


Dramatic improvements expected in near future:

- higher redshift clusters
- deeper, higher resolution CMB data

Planck XVII, 2013, see also Baxter et al. 2015, .

Spectroscopic Weak Lensing



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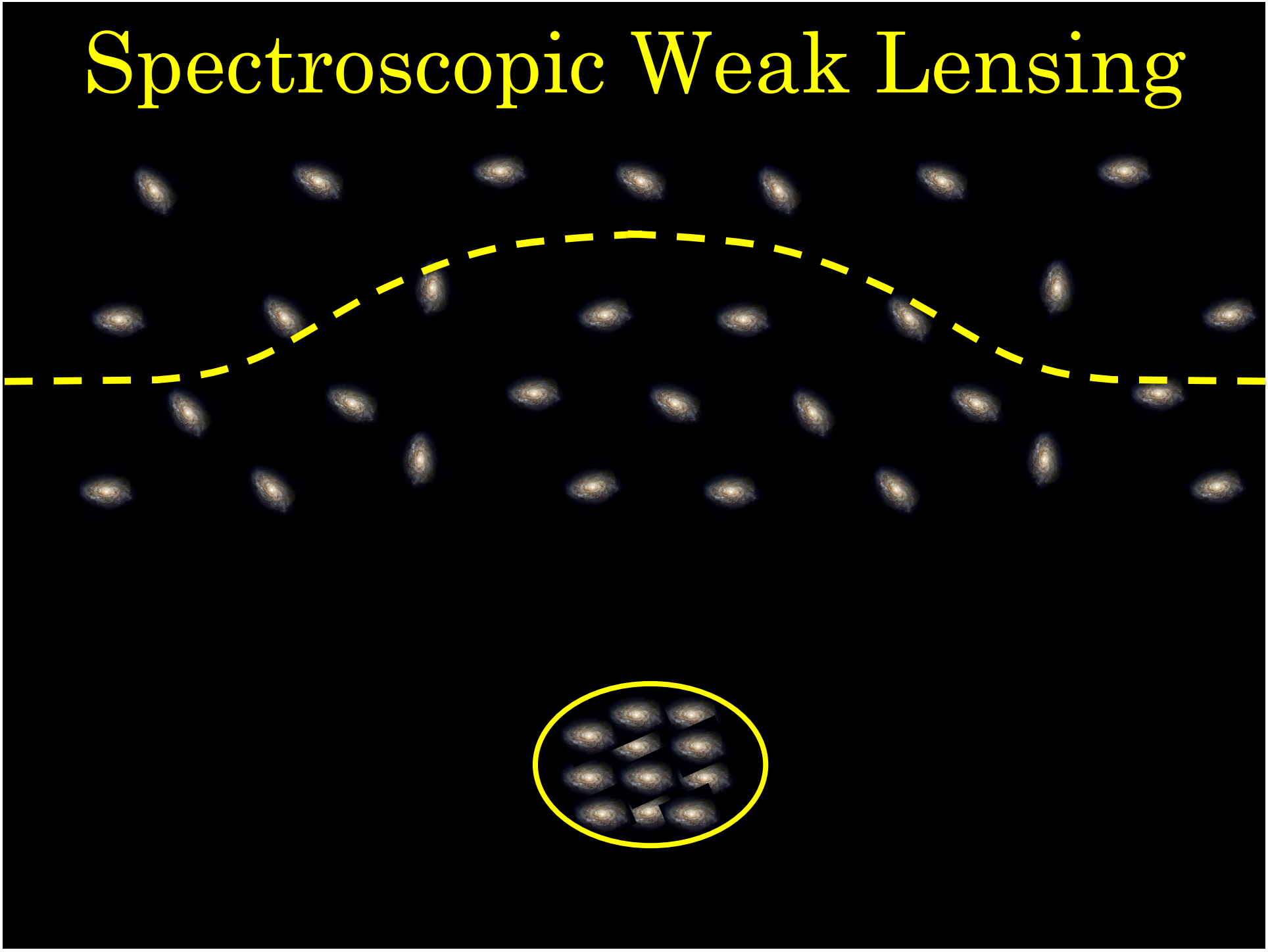

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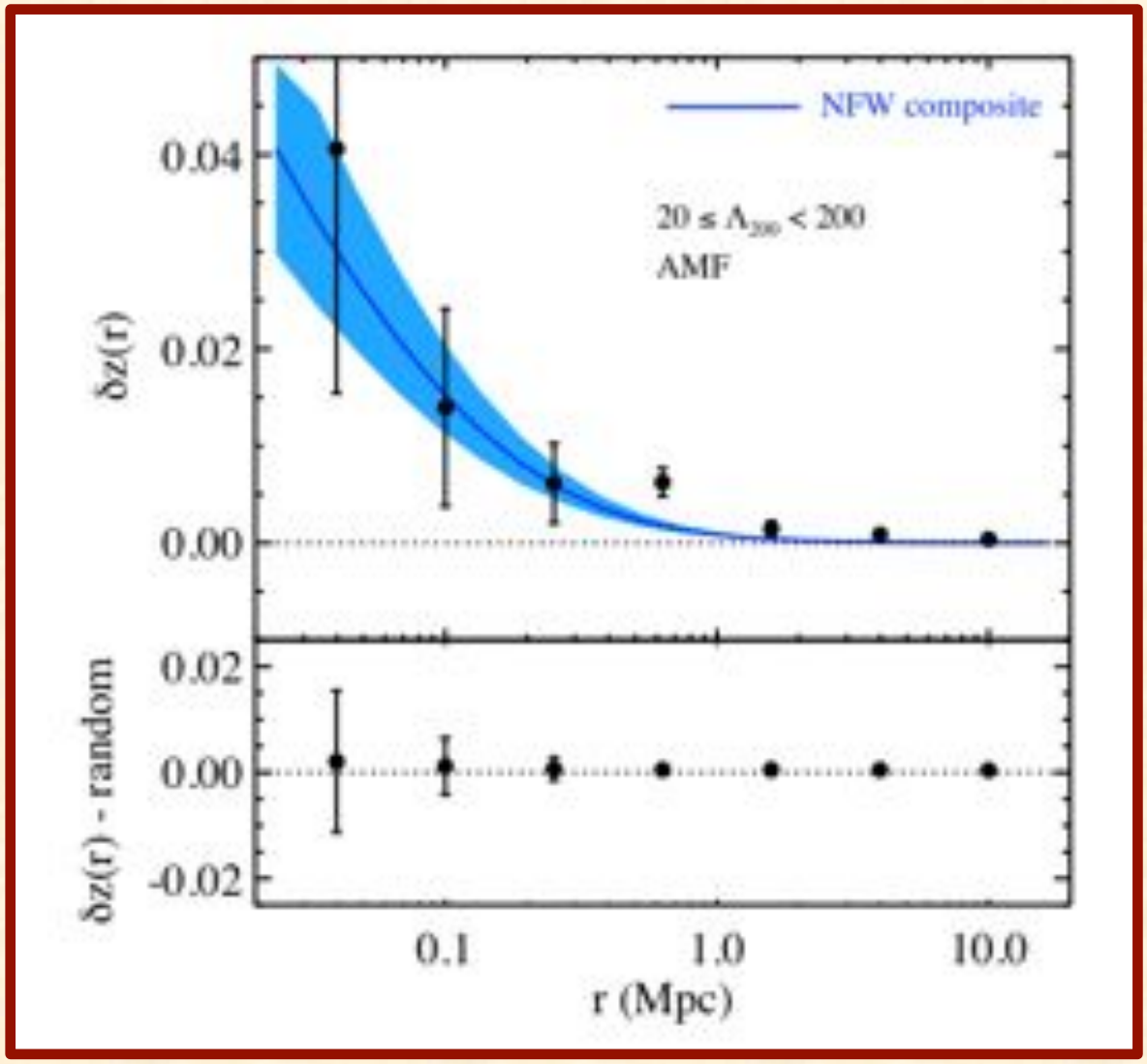
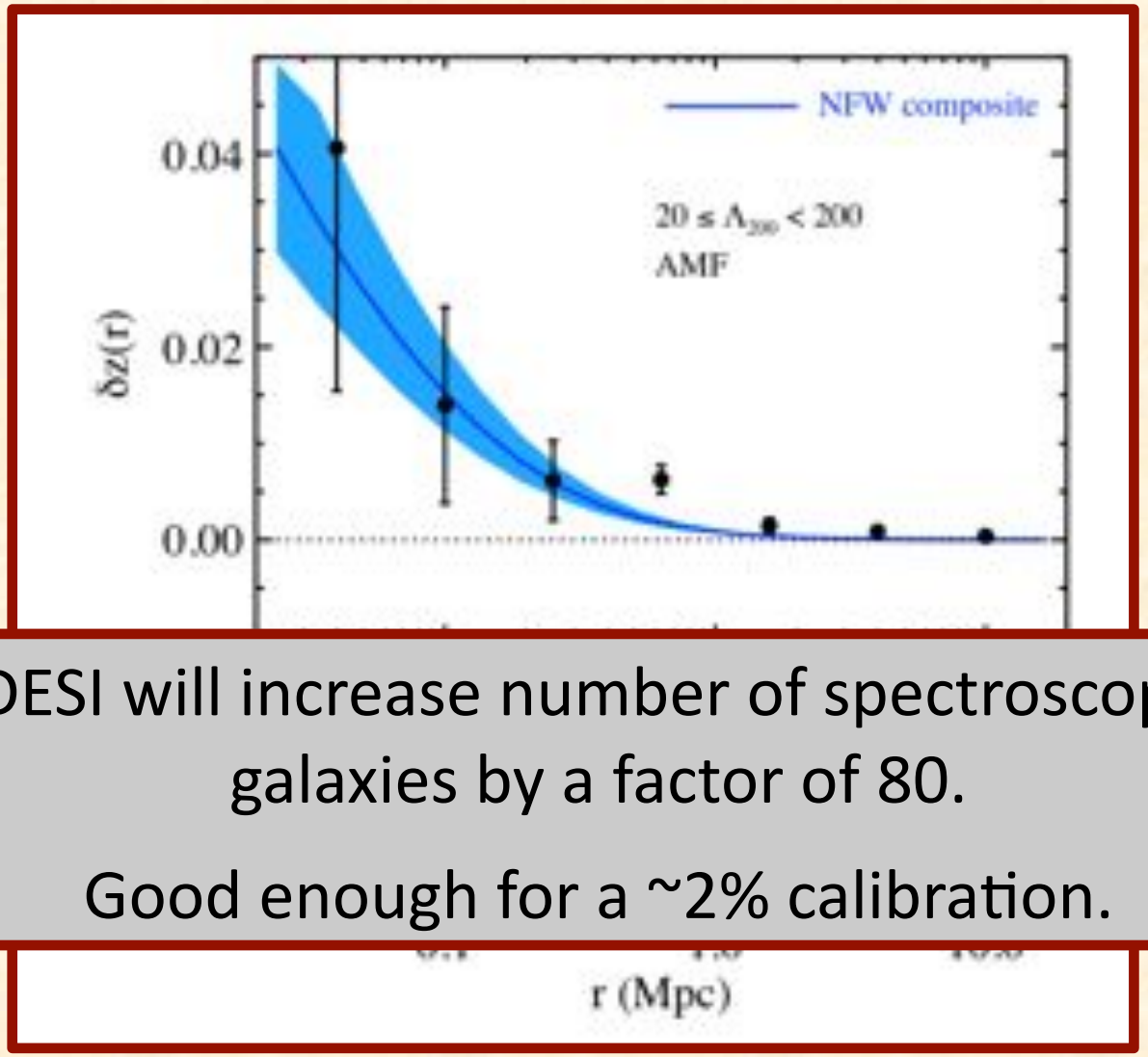


Coupon et al. 2013.

Spectroscopic Weak Lensing



DESI will increase number of spectroscopic galaxies by a factor of 80.

Good enough for a ~2% calibration.

Coupon et al. 2013.

Source Photozs

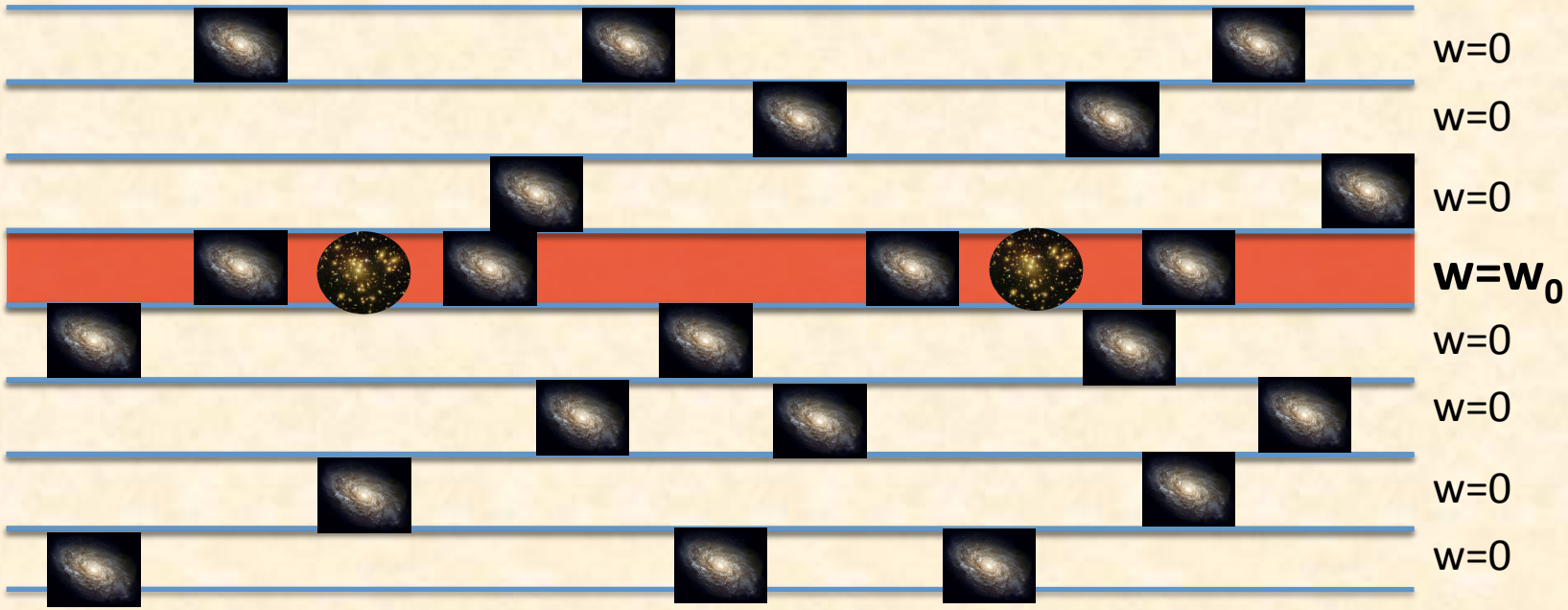
How to test photometric redshifts.

Weak lensing is statistical: we don't need the redshift of any individual galaxy, we need dN/dz

Cross-correlate lensing sources with samples of known redshift!

Cross-Correlation Method

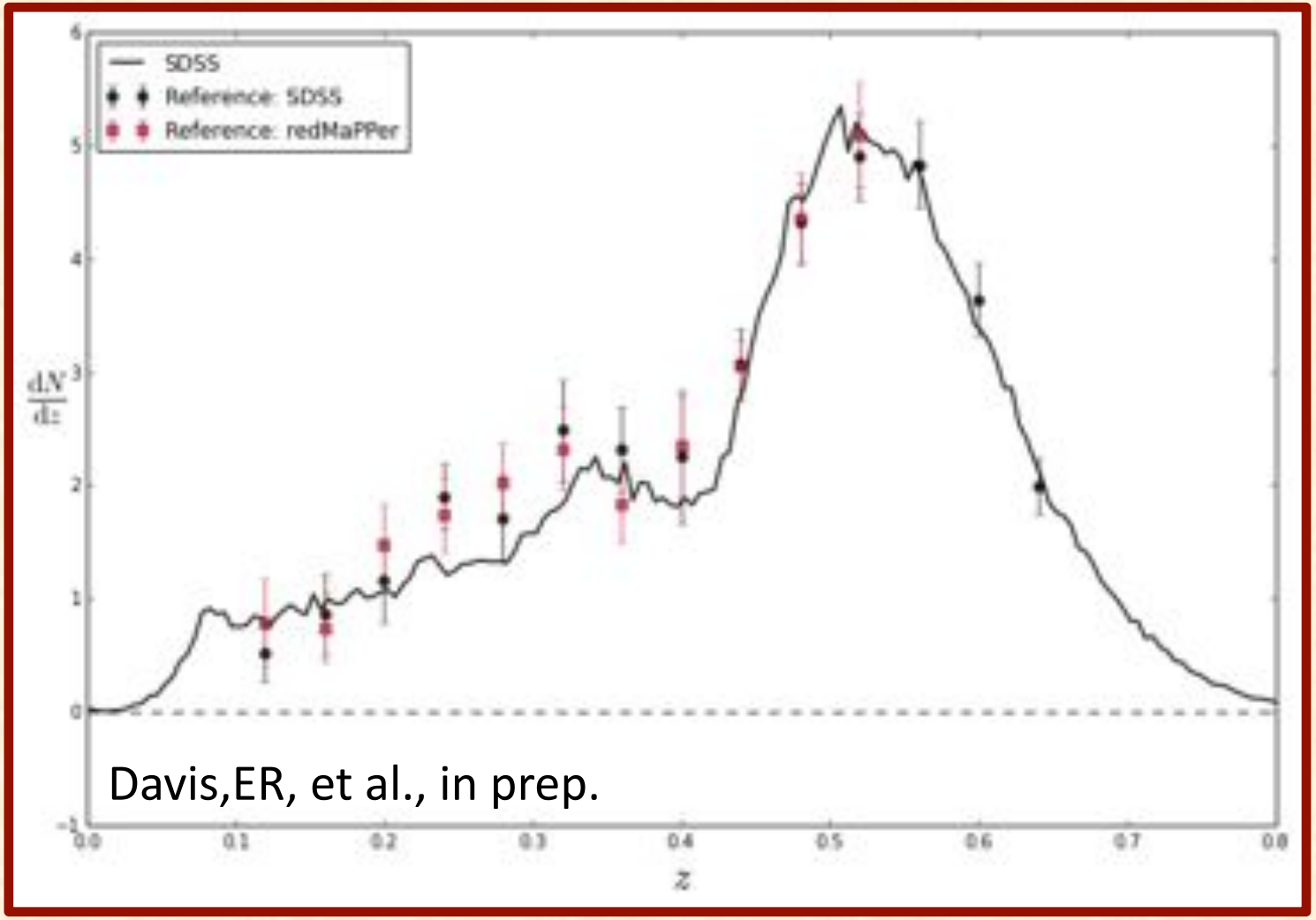
Consider cross-correlation with a single redshift bin.



$$w_{obs} = \frac{\sum N_i w_i}{\sum N_i} = \frac{N_k}{\sum N_i} w_k = P(z_k) w_k \longrightarrow w_{obs} \propto P(z_k)$$

Newmann (2008), Rahman et al. (2014)

Photoz Calibration with Clusters



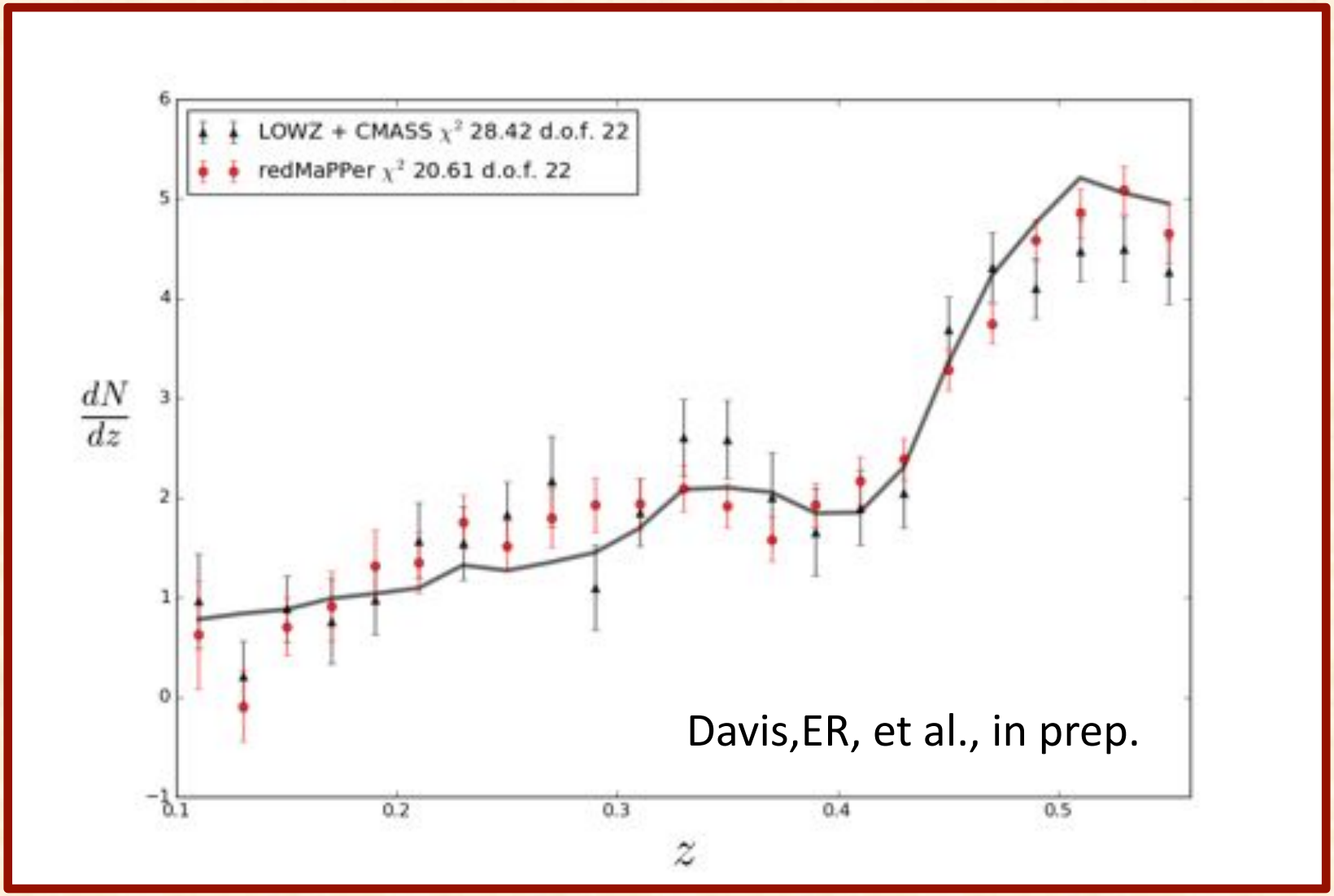
Cross-Correlation Method

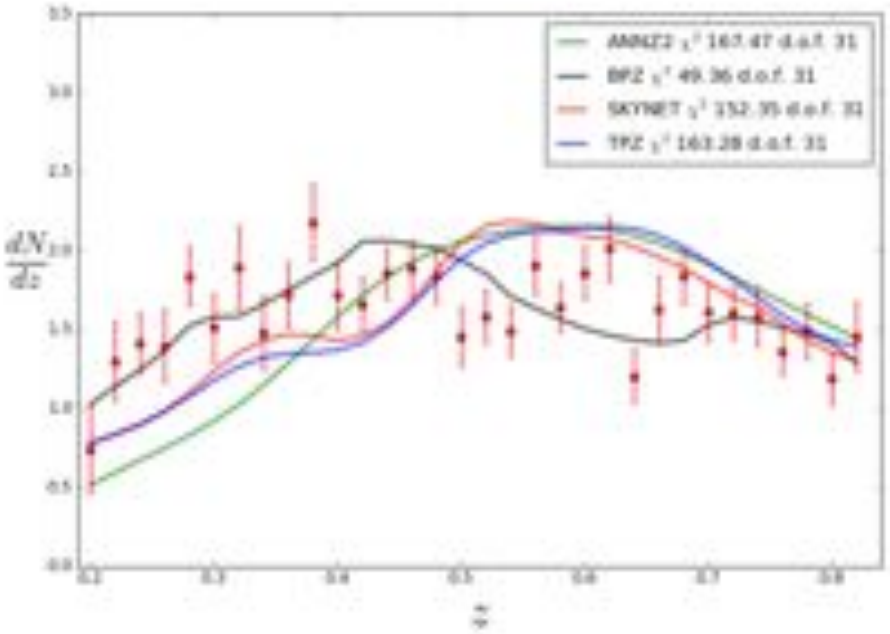
Ideally want full overlap between lensing sources and calibration sources (i.e. sources of known redshift).

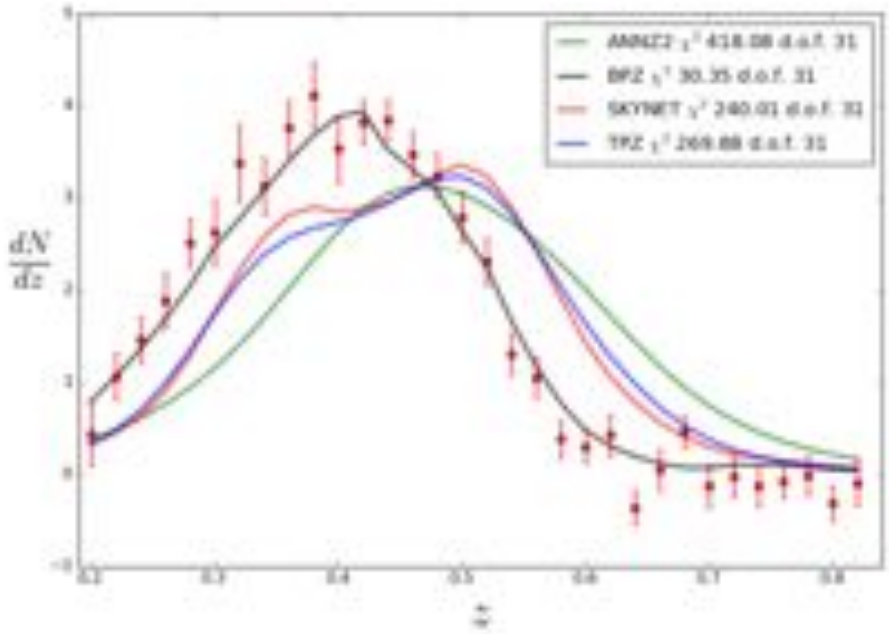
Problem: overlap between current spectroscopic surveys and photometric surveys is limited.

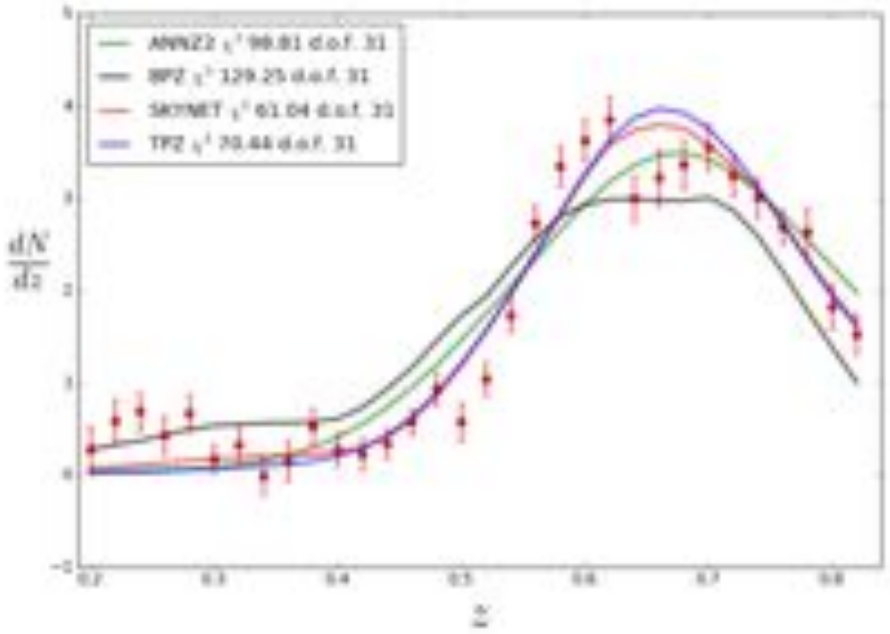
Solution: use redmapper clusters as the calibration sources!

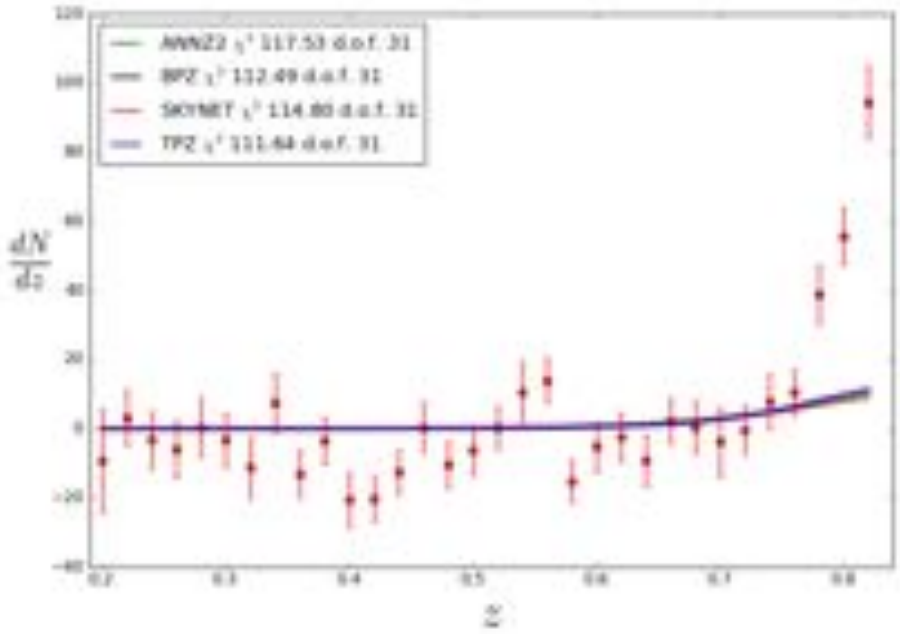
Photoz Calibration with Clusters

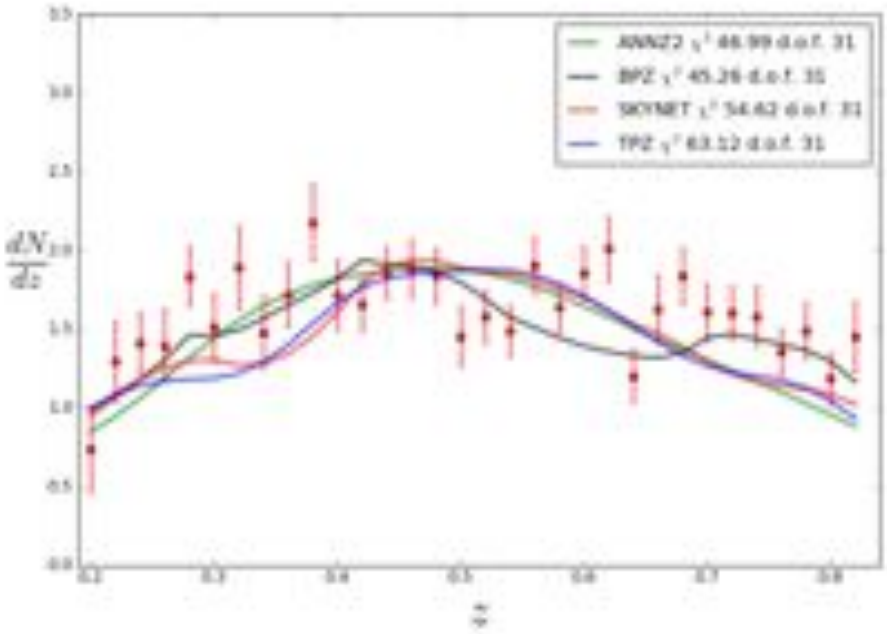


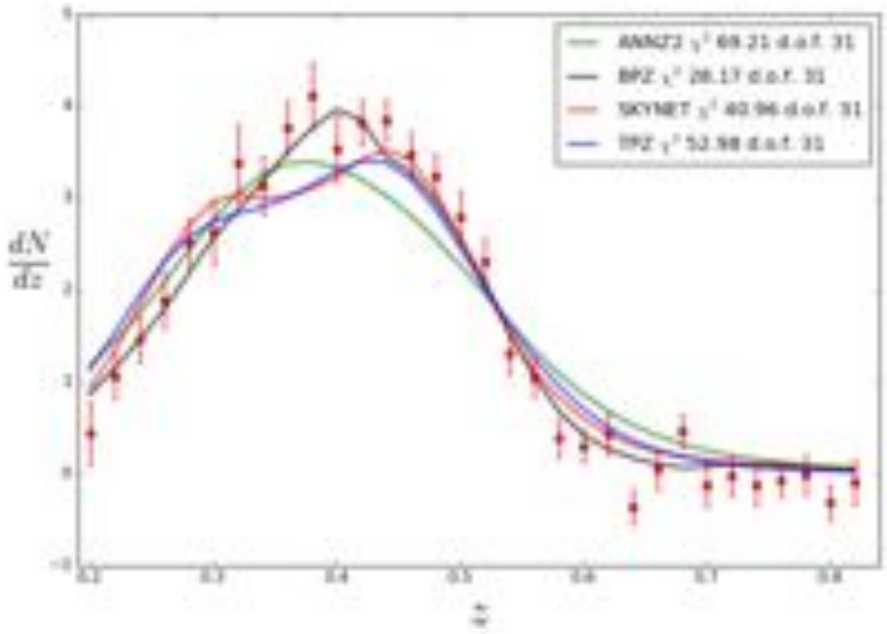

ANNZ2 χ^2 167.47 d.o.f. 31
BPZ χ^2 49.36 d.o.f. 31
SKYNET χ^2 152.35 d.o.f. 31
TPZ χ^2 163.28 d.o.f. 31
$\frac{dN}{dz}$
z

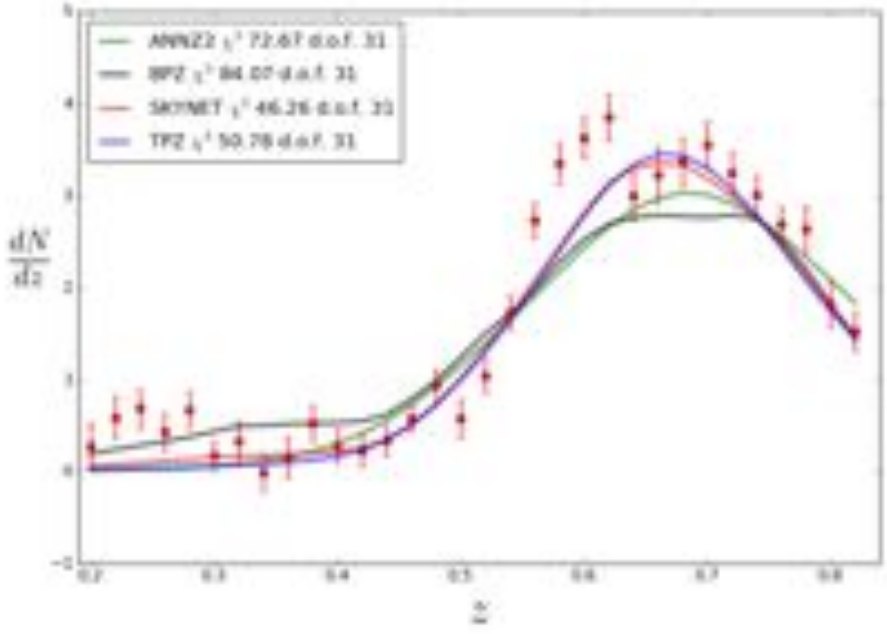

ANNZ2 χ^2 418.08 d.o.f. 31
BPZ χ^2 30.35 d.o.f. 31
SKYNET χ^2 240.01 d.o.f. 31
TPZ χ^2 269.88 d.o.f. 31
$\frac{dN}{dz}$
z

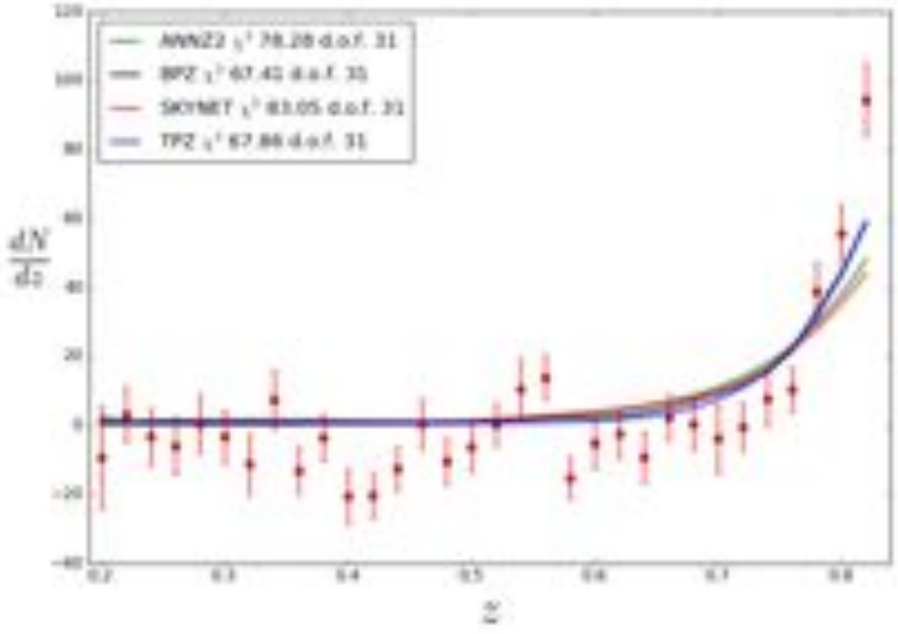

ANNZ2 χ^2 98.81 d.o.f. 31
BPZ χ^2 129.25 d.o.f. 31
SKYNET χ^2 61.04 d.o.f. 31
TPZ χ^2 70.44 d.o.f. 31
$\frac{dN}{dz}$
z


ANNZ2 χ^2 117.53 d.o.f. 31
BPZ χ^2 112.49 d.o.f. 31
SKYNET χ^2 114.80 d.o.f. 31
TPZ χ^2 111.64 d.o.f. 31
$\frac{dN}{dz}$
z

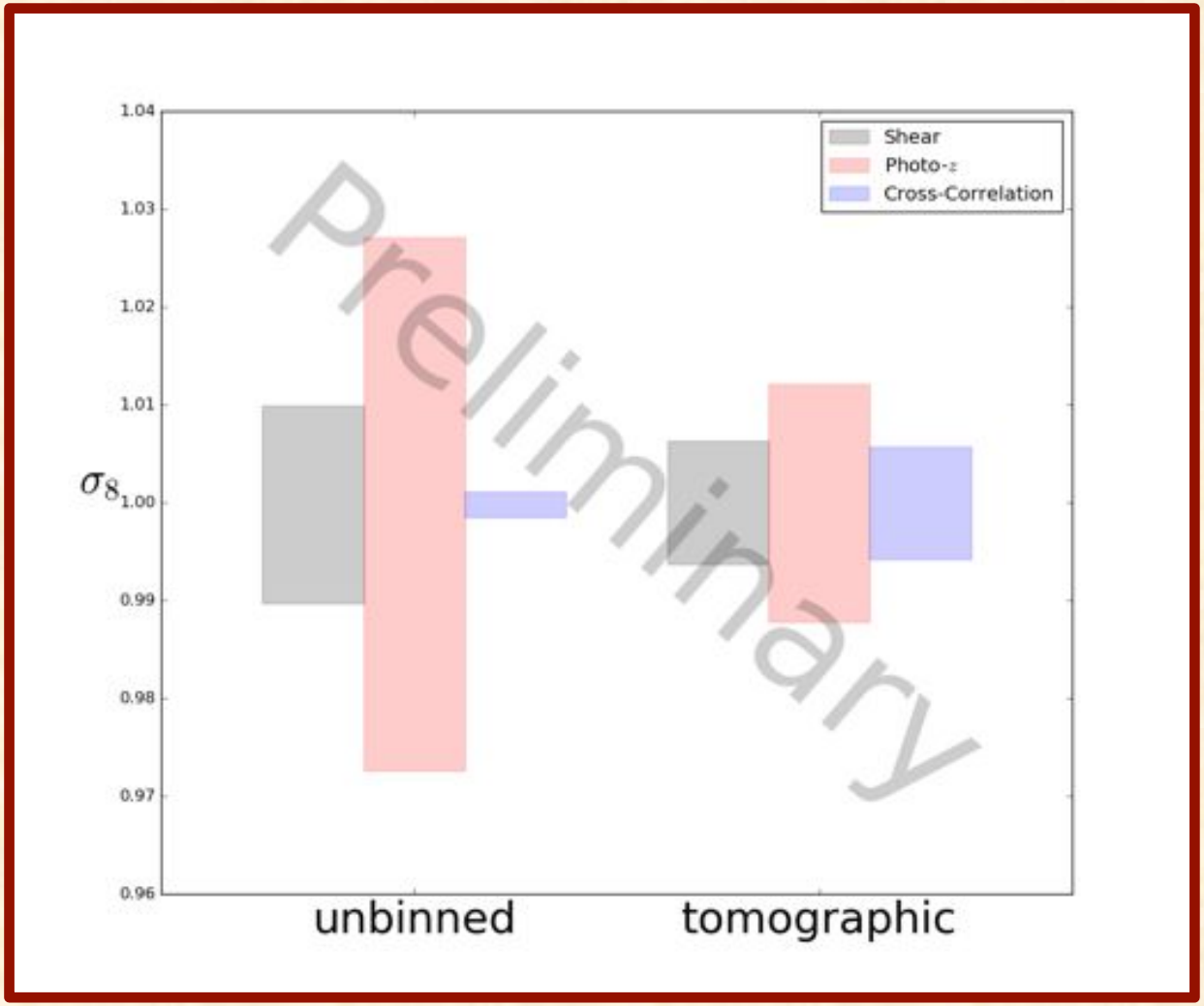

ANNZ2 χ^2 46.99 d.o.f. 31
BPZ χ^2 45.26 d.o.f. 31
SKYNET χ^2 54.62 d.o.f. 31
TPZ χ^2 63.12 d.o.f. 31
$\frac{dN}{dz}$
z


ANNZ2 χ^2 69.21 d.o.f. 31
BPZ χ^2 28.17 d.o.f. 31
SKYNET χ^2 40.96 d.o.f. 31
TPZ χ^2 52.98 d.o.f. 31
$\frac{dN}{dz}$
z


ANNZ2 χ^2 72.67 d.o.f. 31
BPZ χ^2 84.07 d.o.f. 31
SKYNET χ^2 46.26 d.o.f. 31
TPZ χ^2 50.78 d.o.f. 31
$\frac{dN}{dz}$
z

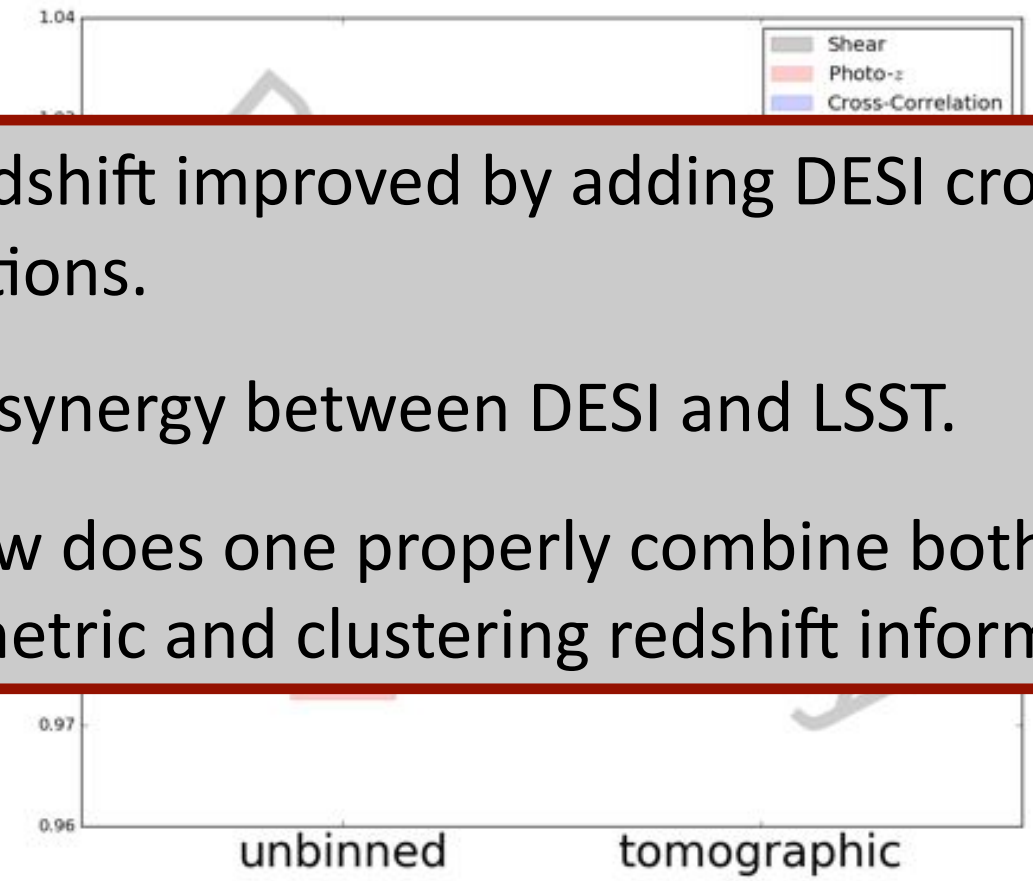

ANNZ2 χ^2 78.28 d.o.f. 31
BPZ χ^2 67.41 d.o.f. 31
SKYNET χ^2 83.05 d.o.f. 31
TPZ χ^2 67.86 d.o.f. 31
$\frac{dN}{dz}$
z

Photoz with Cross-Correlations



Davis, ER, et al., in prep.

Photoz with Cross-Correlations

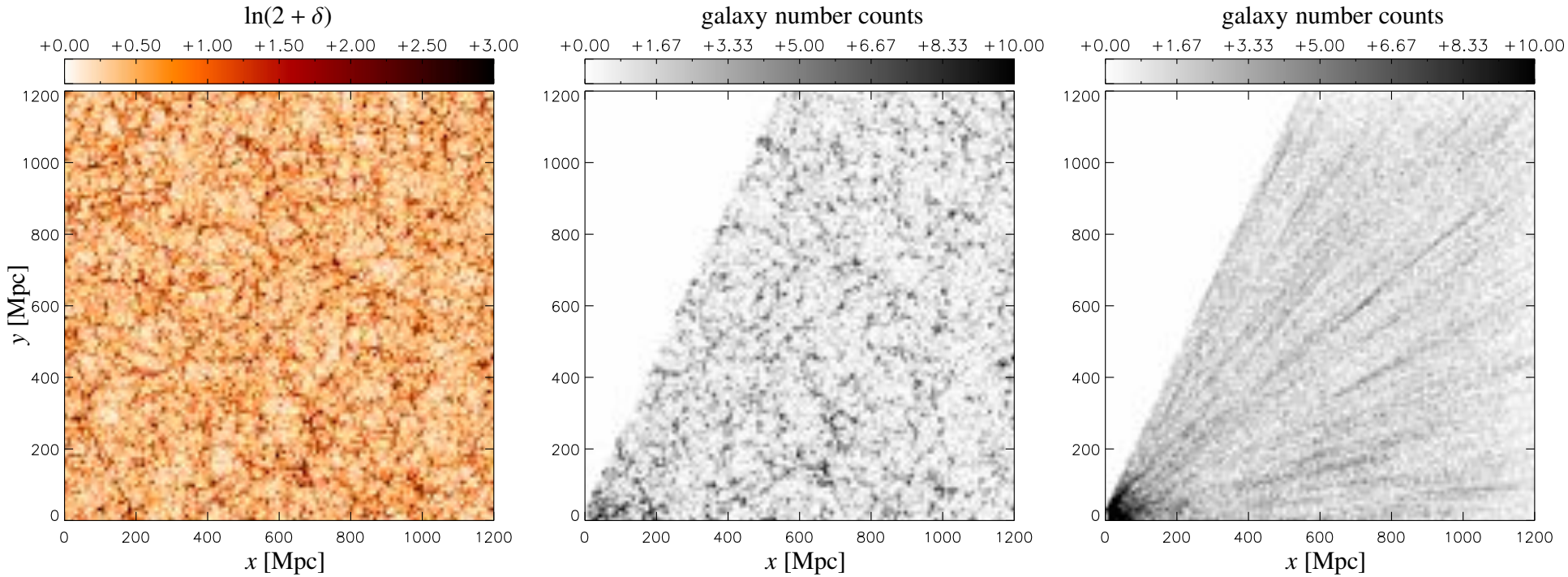


High redshift improved by adding DESI cross-correlations.

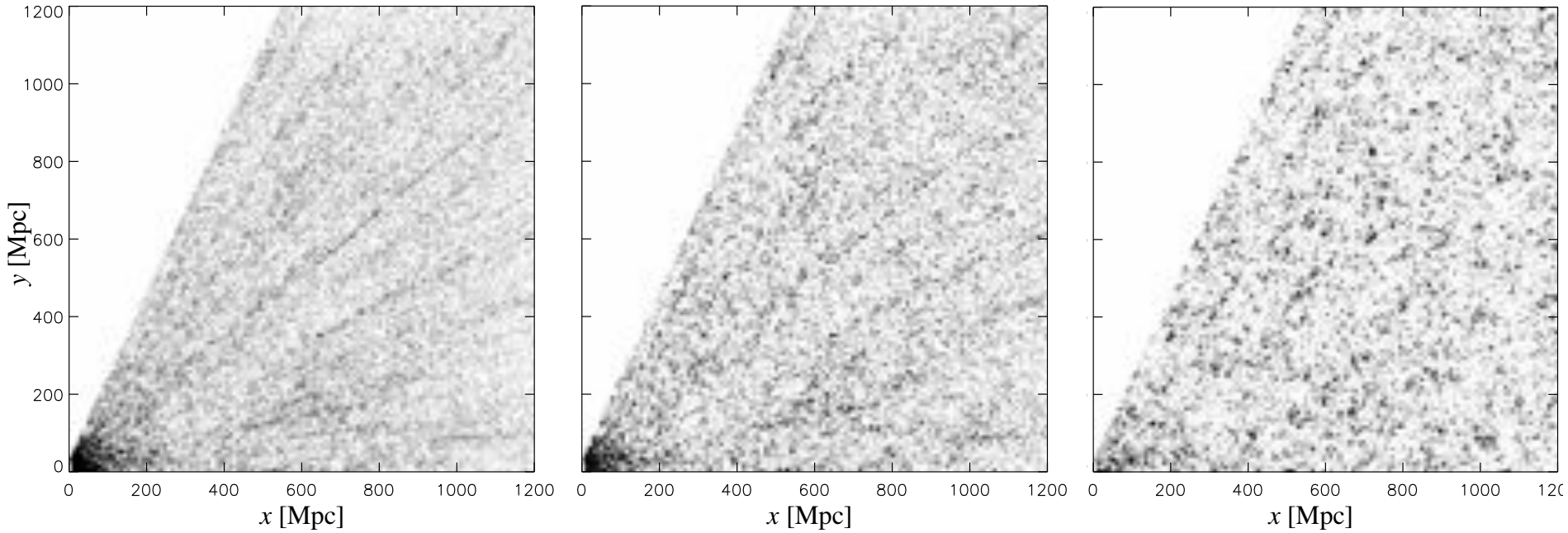
Critical synergy between DESI and LSST.

But- how does one properly combine both photometric and clustering redshift information?

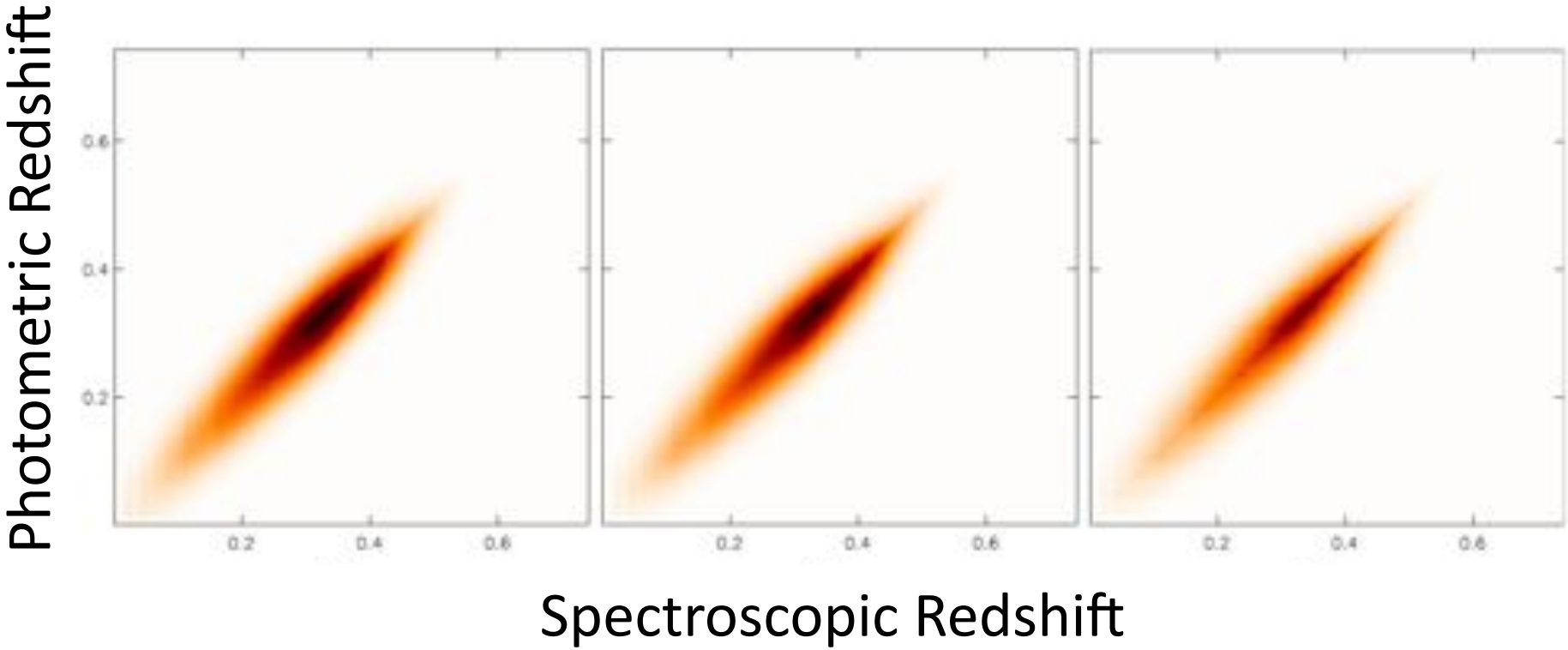
Davis, ER, et al., in prep.



Jasche and Wandelt 2012



Jasche and Wandelt 2012



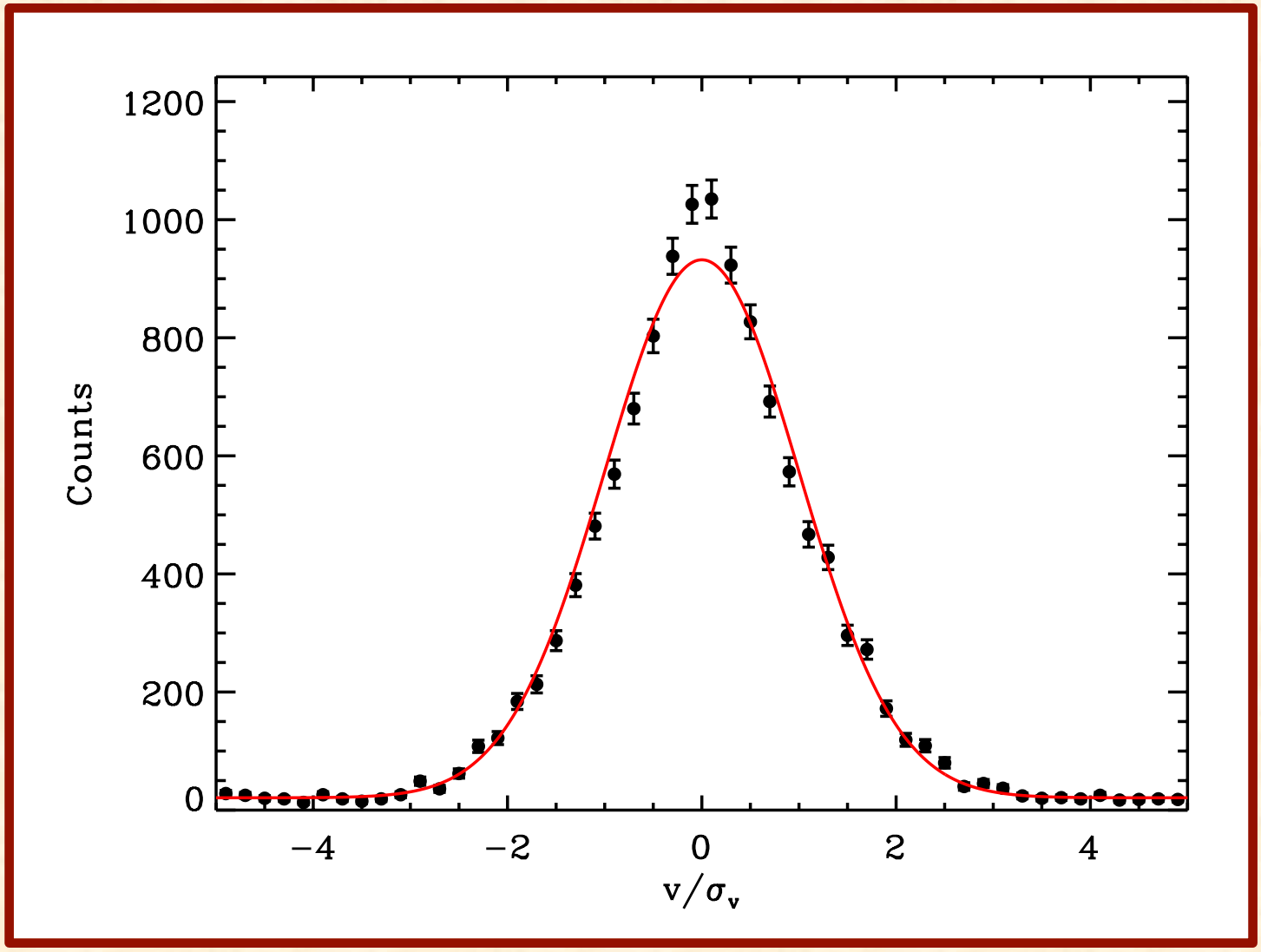
Jasche and Wandelt 2012

How to Move Forward

- Measuring shapes is hard.
  - Trust in your WL friends. (see Miachel's talk)
  - Exploit synergies w/ other surveys!
- Photometric redshift errors of the sources.
  - Exploit synergies w/ other surveys!

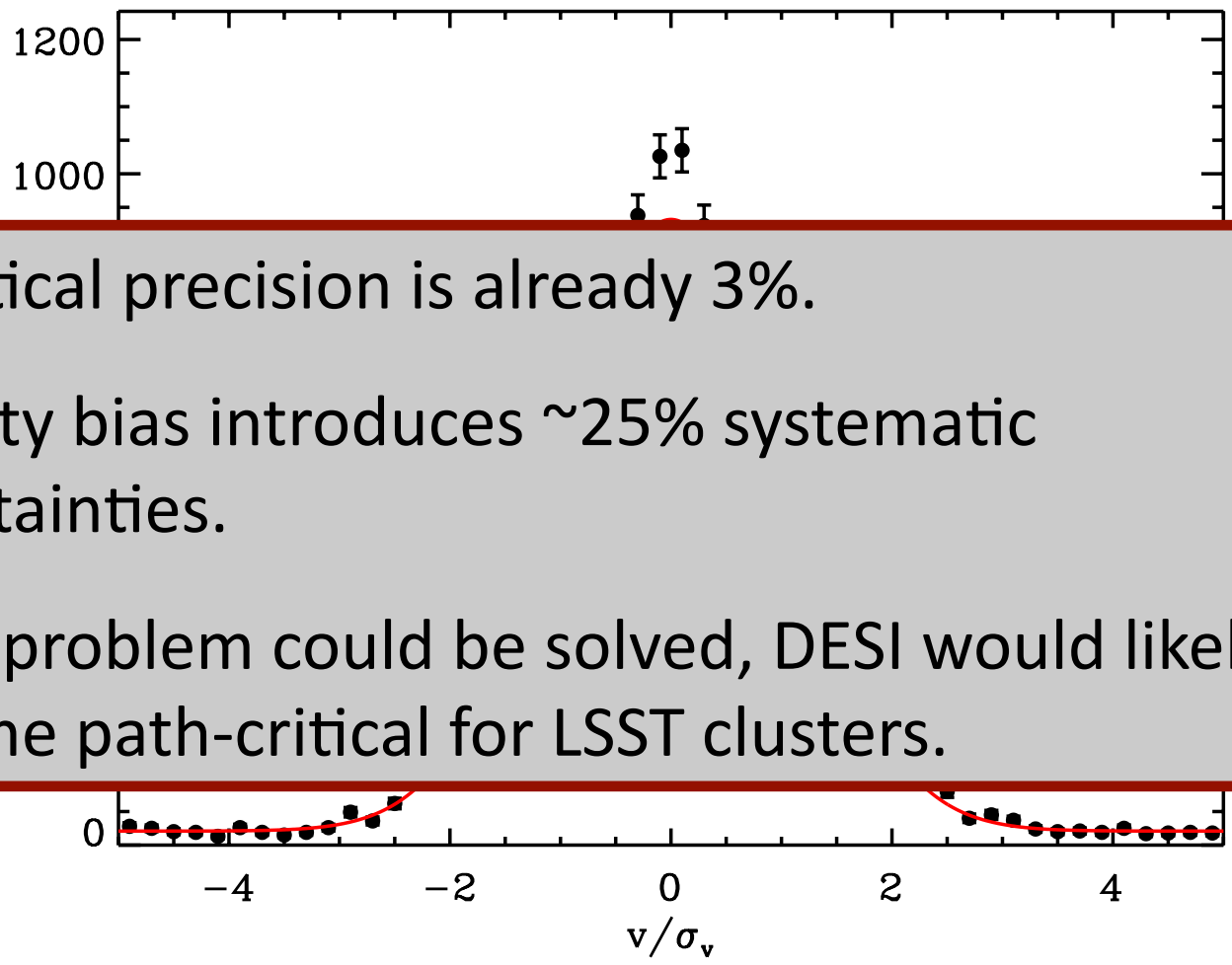
Look for alternative methods of mass calibration.

Velocity Dispersions



Rozo et al. 2015, Farahi et al. 2016

Velocity Dispersions



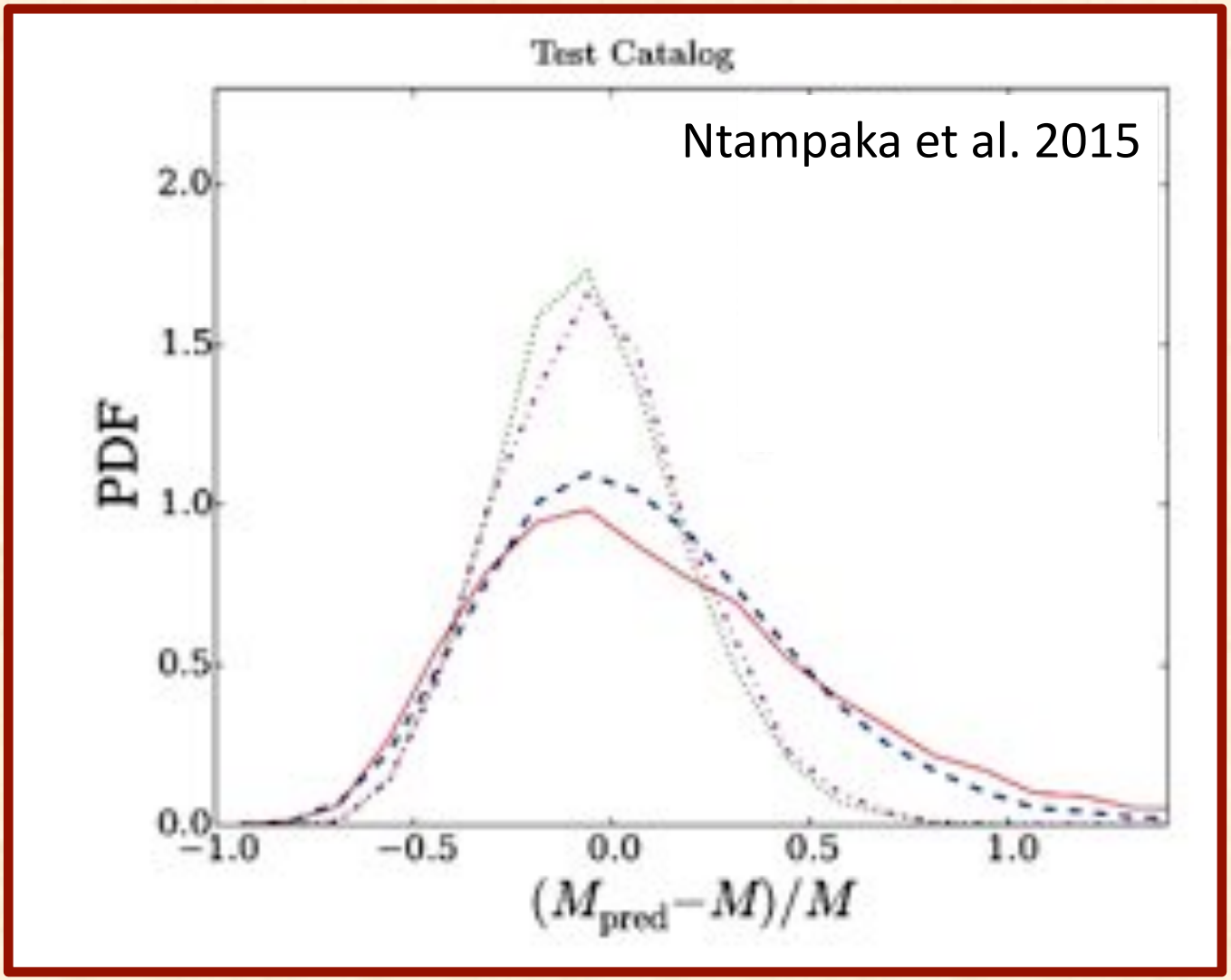
Statistical precision is already 3%.

Velocity bias introduces ~25% systematic uncertainties.

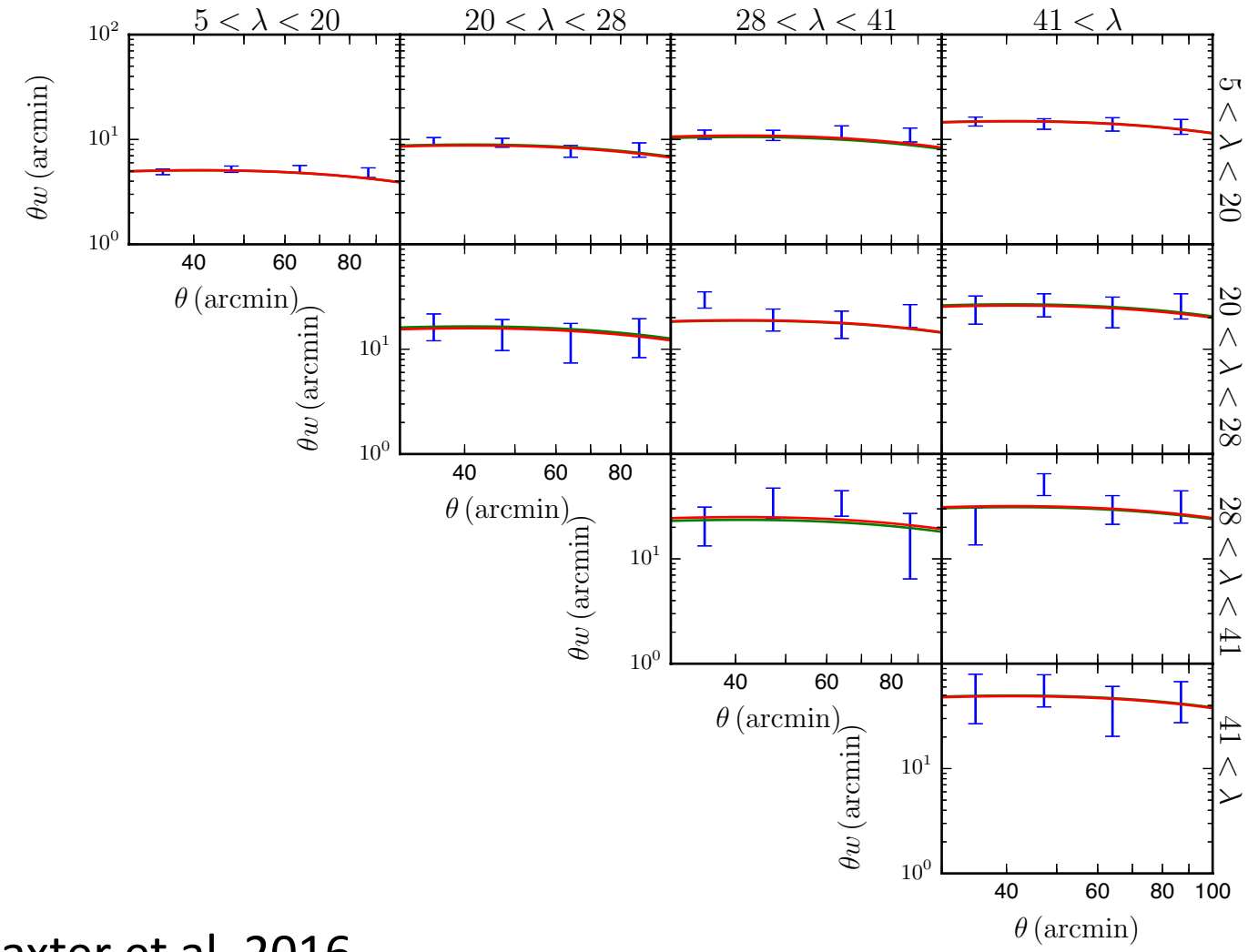
If this problem could be solved, DESI would likely become path-critical for LSST clusters.

Rozo et al. 2015, Farahi et al. 2016

Velocity Dispersions and ML

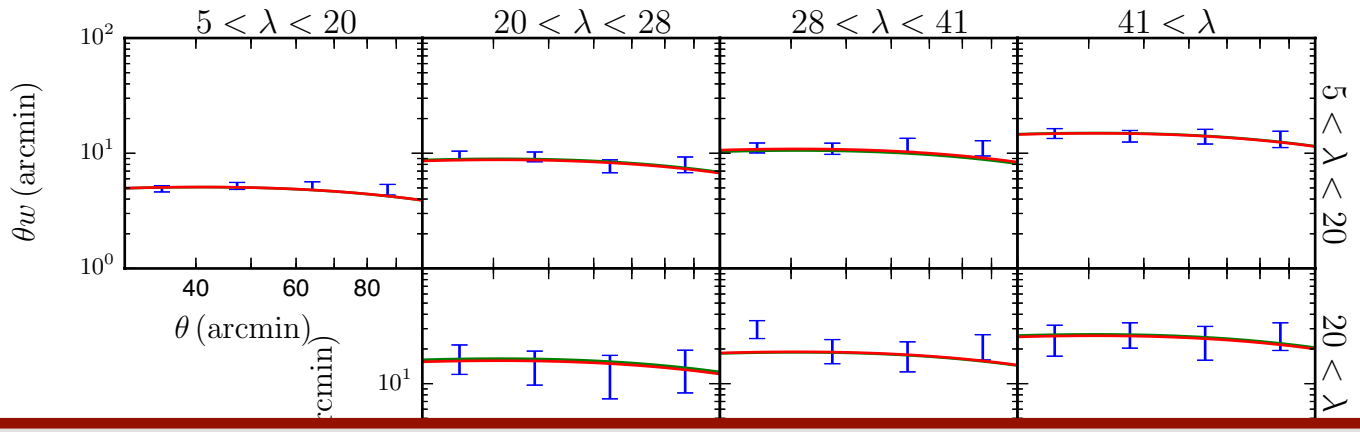


Cluster Clustering



Baxter et al. 2016

Cluster Clustering



7% precision in SDSS.

18% systematic error: dominated by uncertainty in the bias—mass relation.

Emulators/ML calibration of this relation (as a function of cosmology) critical.

Baxter et al. 2016

Other Methods?

Simple ideas can go a long way.

When your only tool is a hammer…

When your only tool is a hammer…

If we can select red galaxies in clusters, why not select red galaxies in the field?

Expect clean photozs: use as “gold sample” for photometric LSS studies.

redMaGiC

A byproduct of cluster finding is an empirical template of galaxy color as a function of redshift for red galaxies.

Template is **very** accurate.

Simple idea:

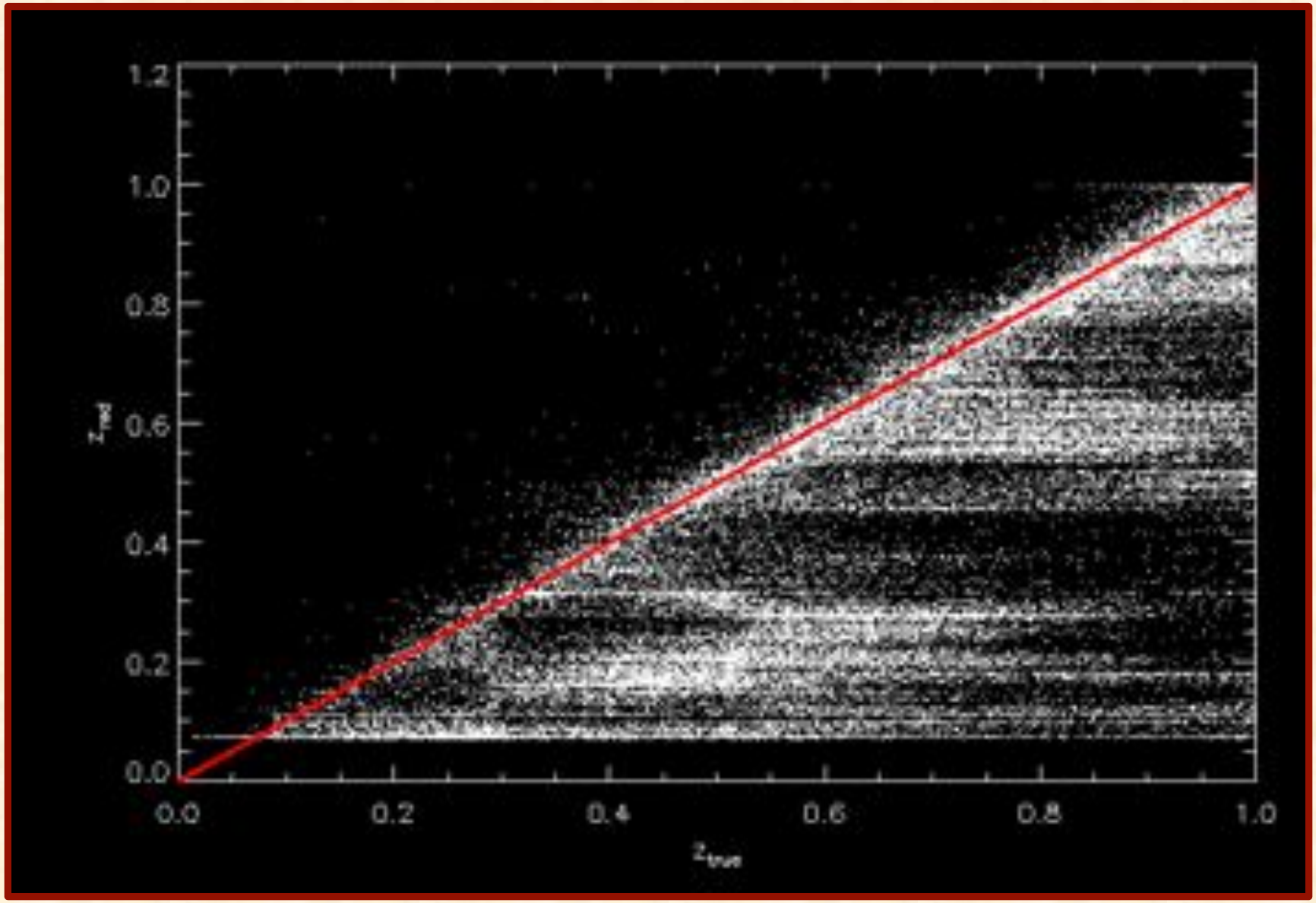
Fit **every** galaxy with a single template!

Remove bad fits.

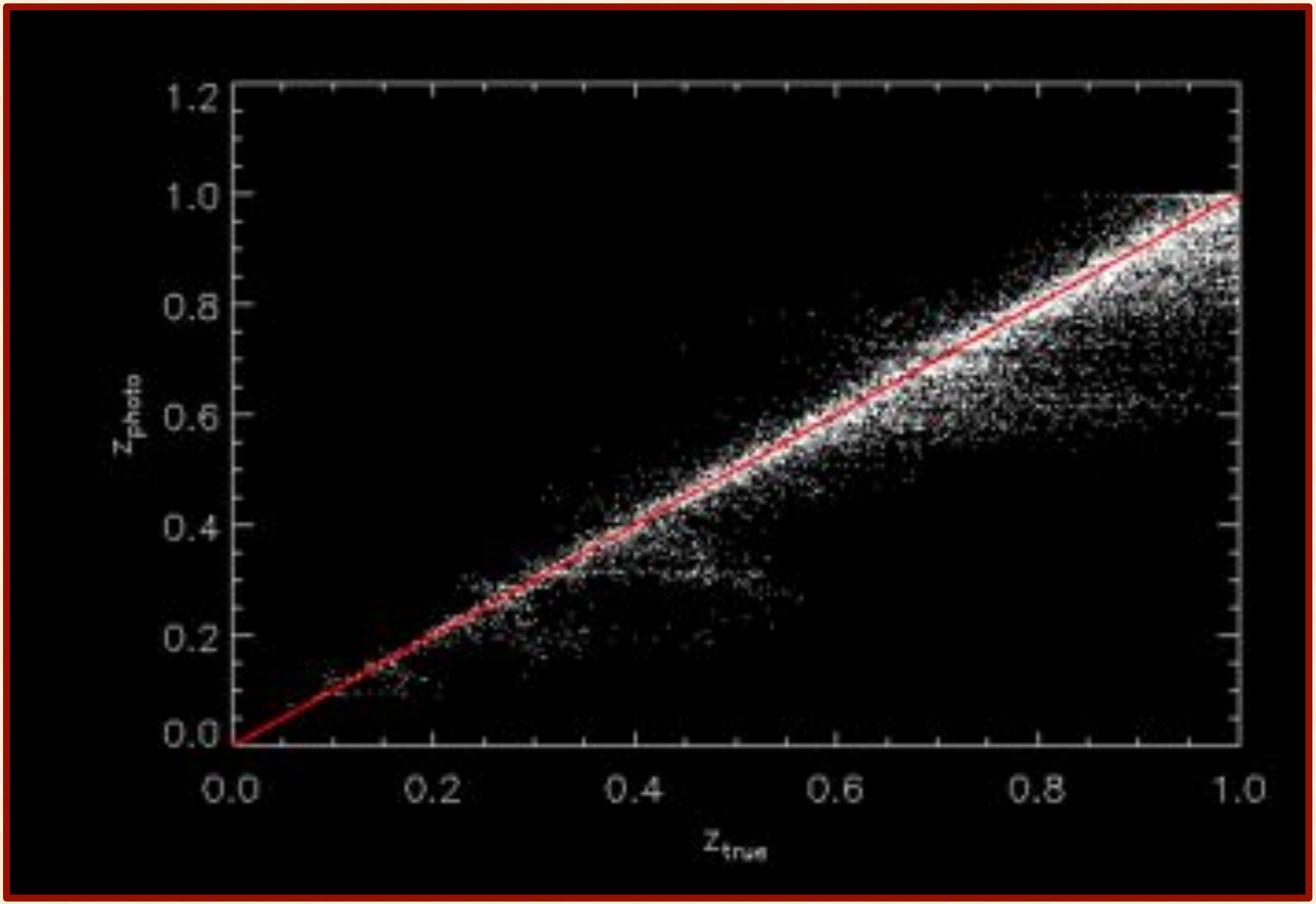
Remove faint galaxies.

End up with galaxy sample with great photozs!

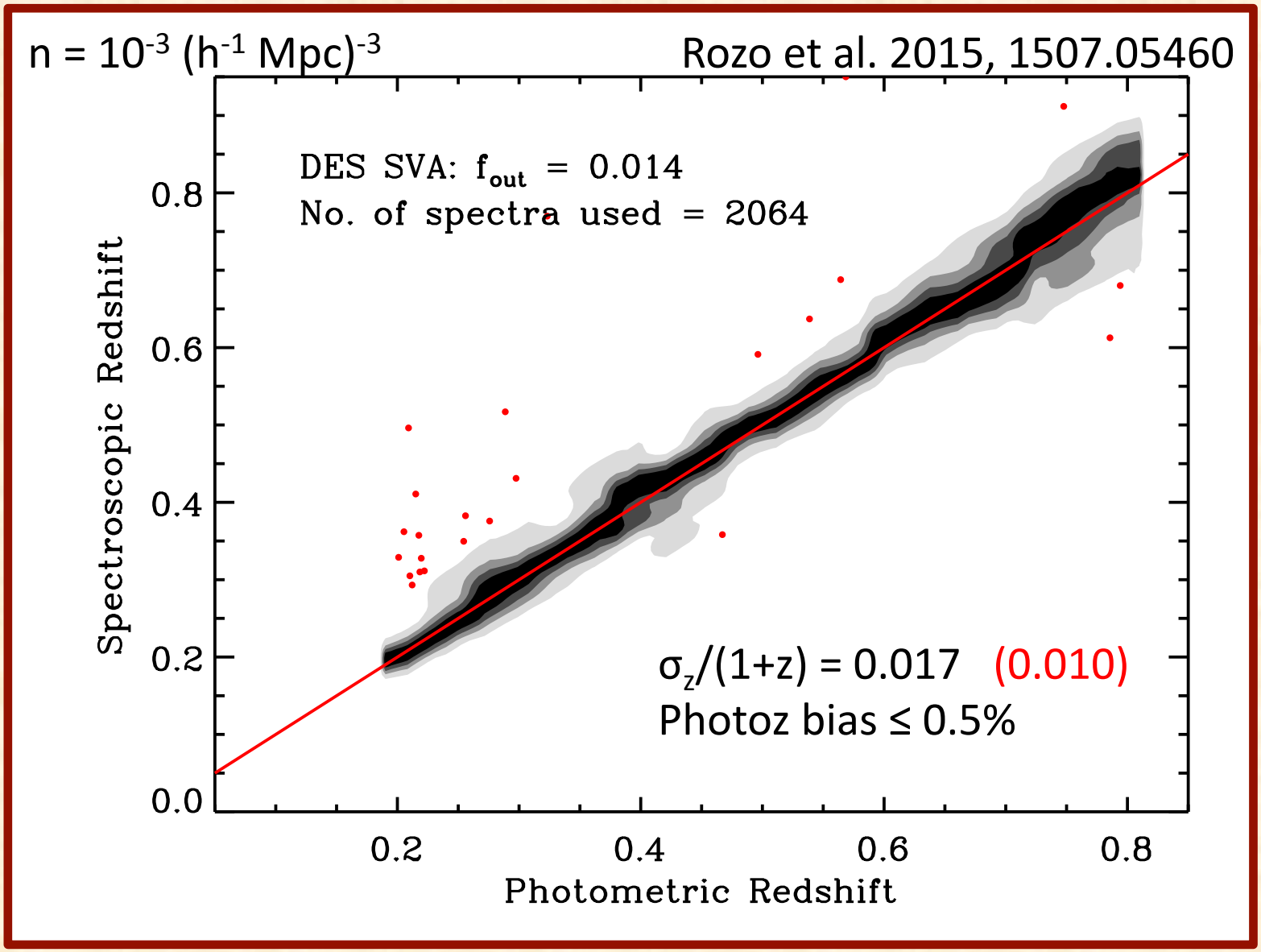
Template Redshifts: All Galaxies



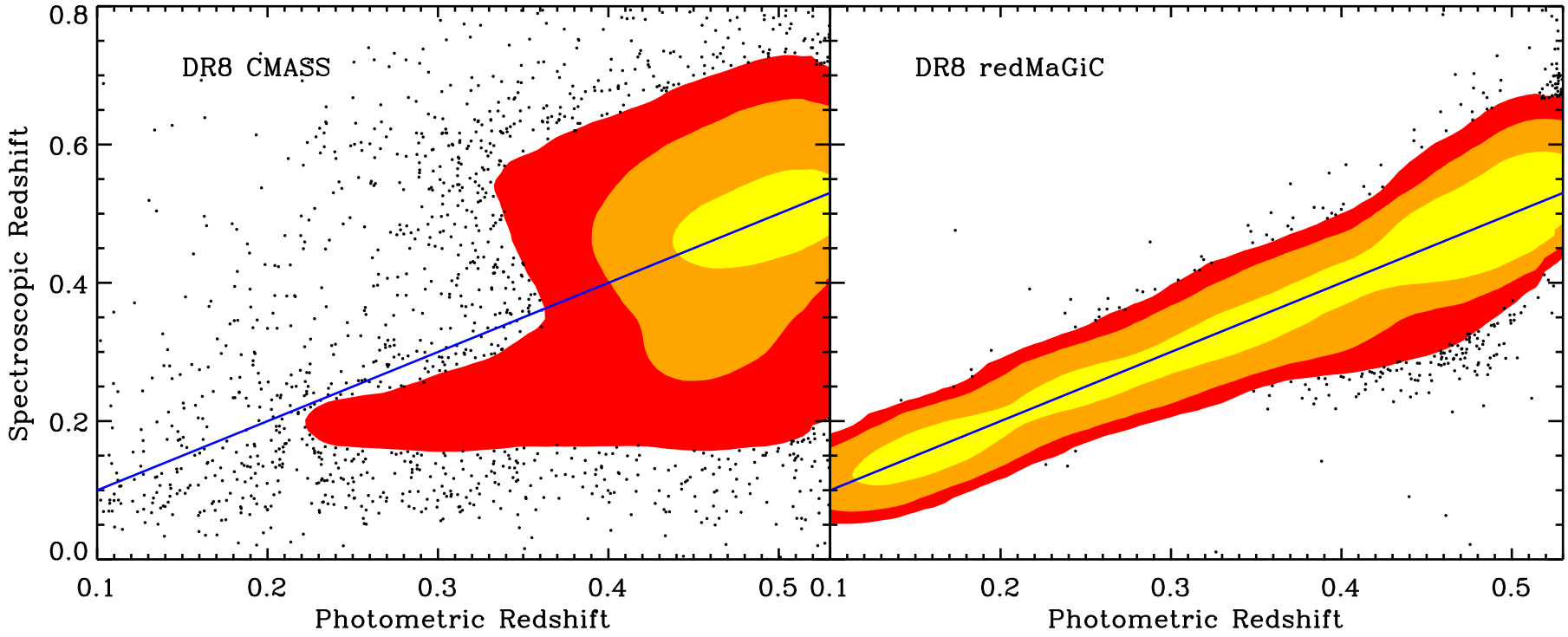
Template Redshifts: Red Galaxies



Photoz Performance (DES)



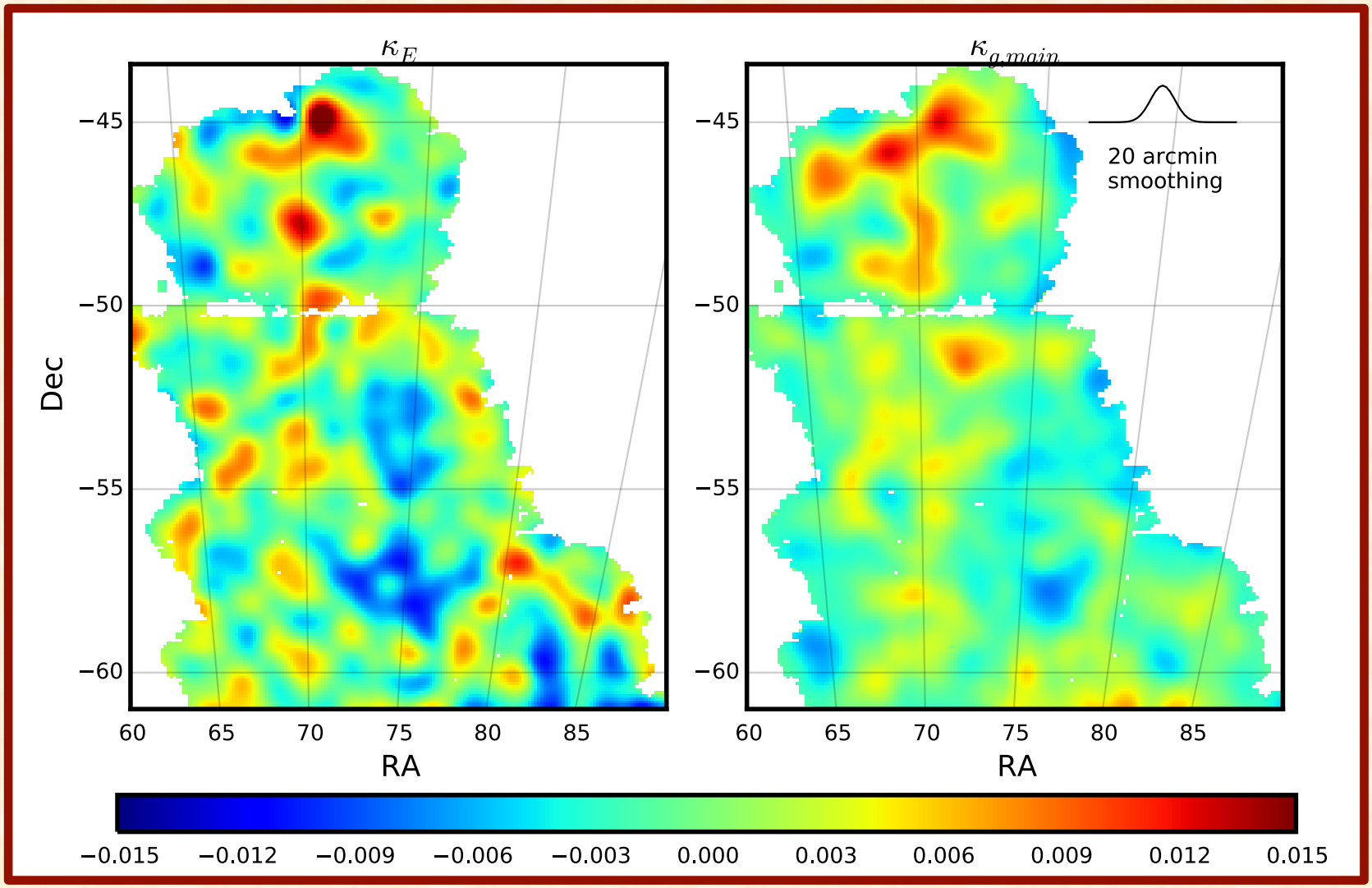
Selection Matters for Photoz Performance



Expect further improvements possible with ML techniques.

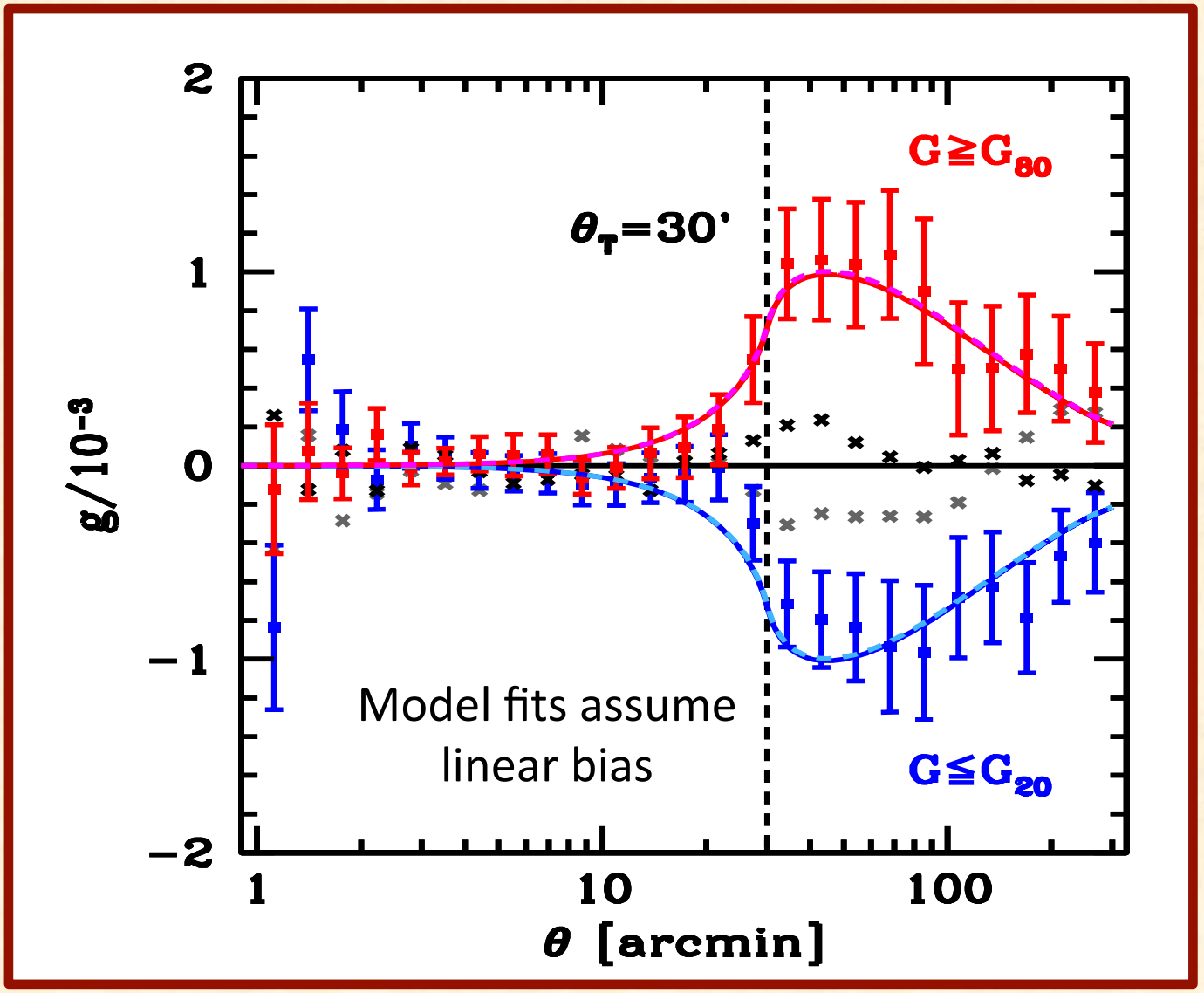
Rozo et al. 2015, 1507.05460

Comparison to WL Mass Maps



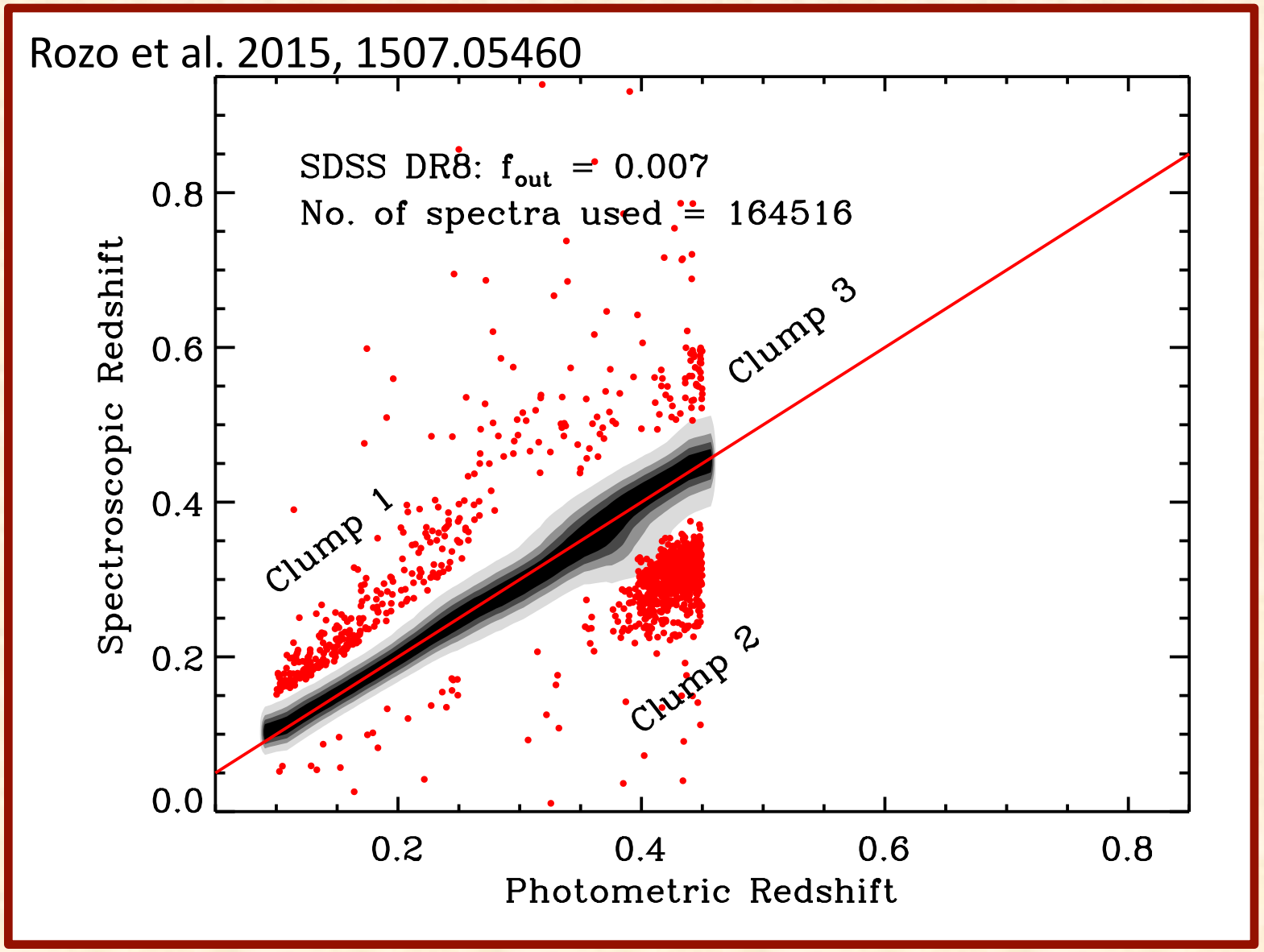
Vikram et al. 2015: 1504.03002

Trough Lensing

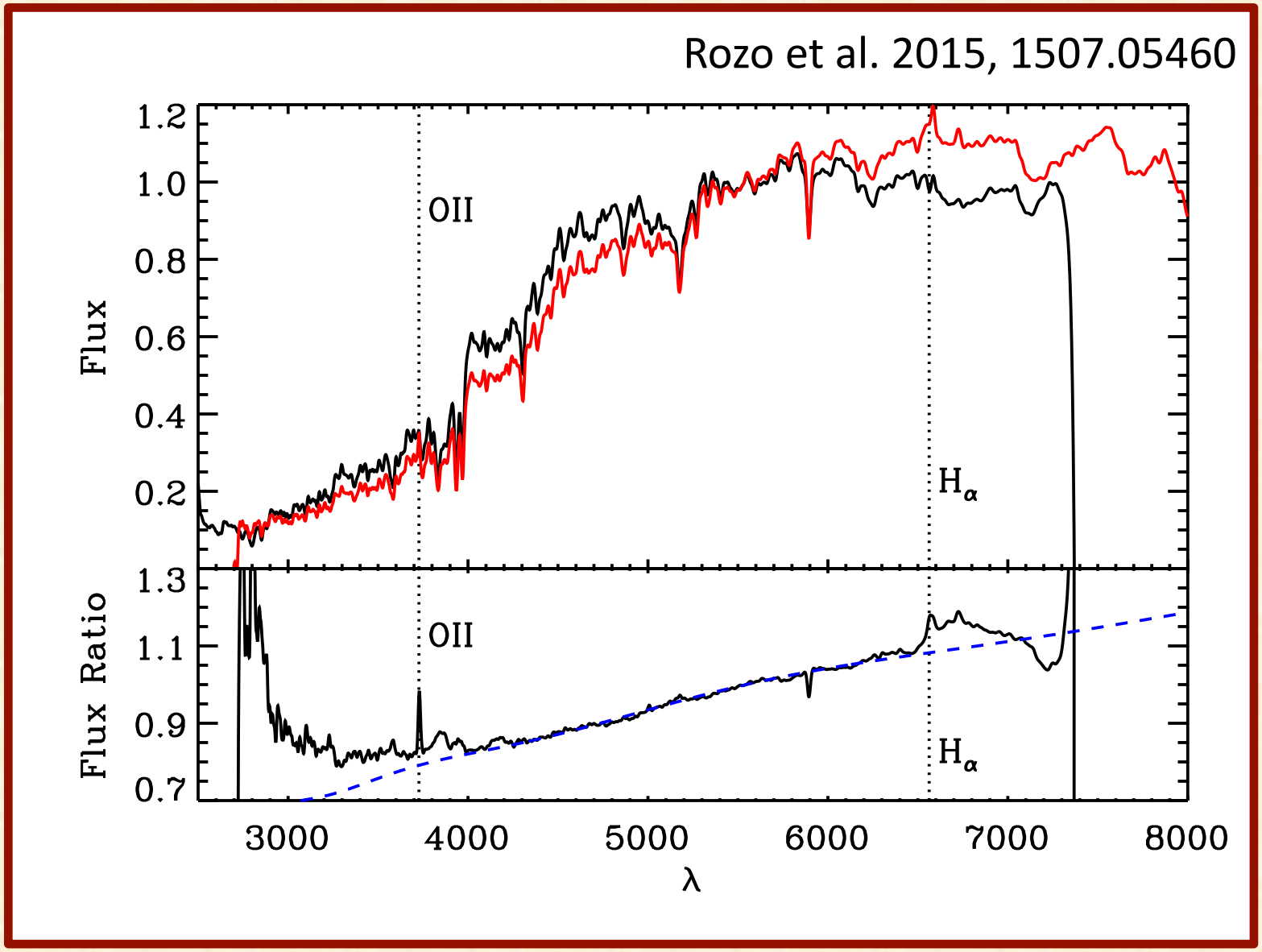


Gruen et al. 2015: 1507.05090

Photoz Performance (SDSS)



Clump 2 Galaxies



Dusty Ellipticals

Summary

Cluster cosmology currently limited by systematic uncertainties in mass calibration.

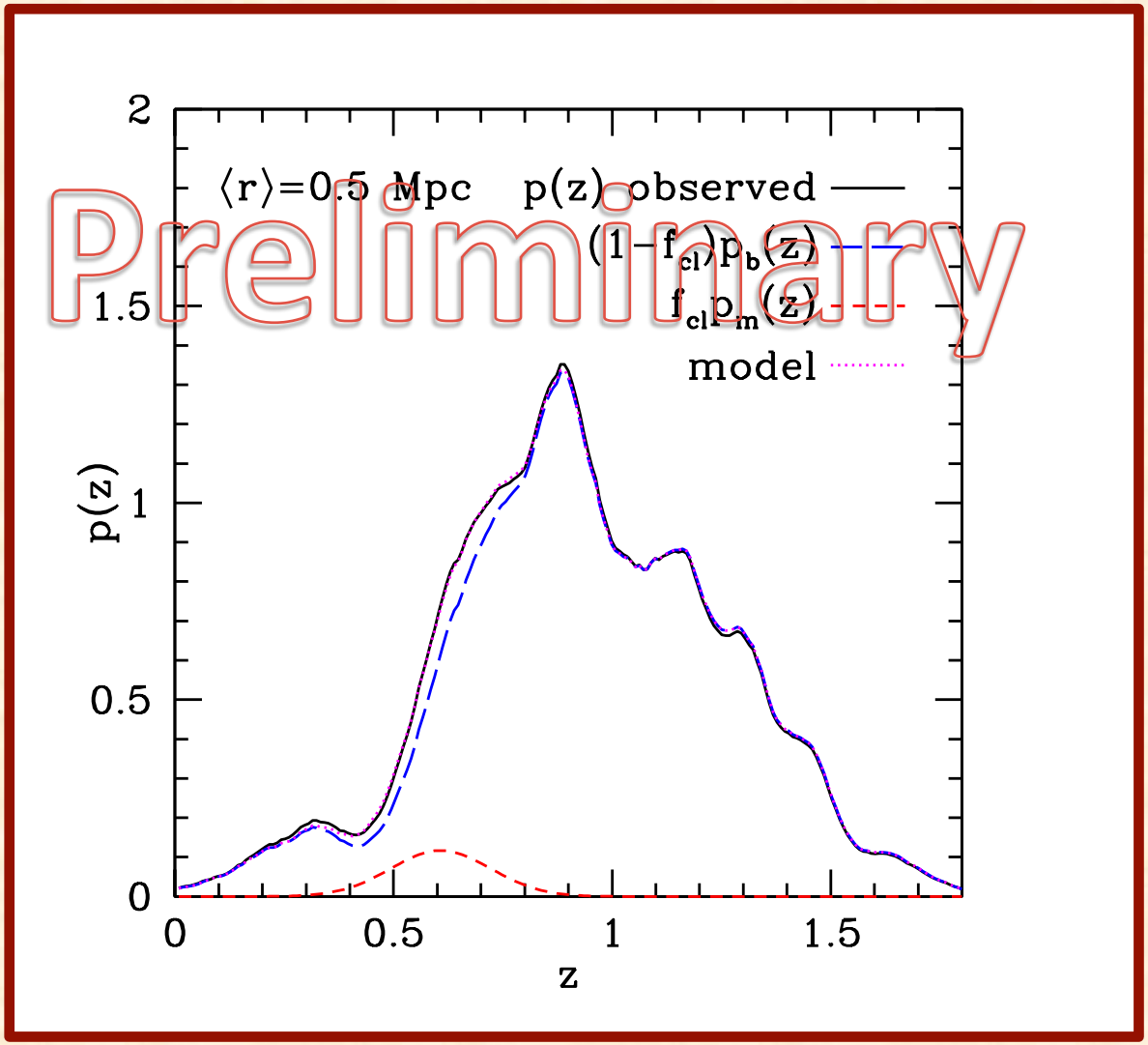
Two primary concerns at present: shape and photoz systematics.

Multiple pipelines is key to characterize systematic uncertainties.

Synergies with other surveys open the possibility of "self-calibration" of systematics.

Advanced statistical techniques are great, but there is still room for simple ideas!

Membership Dilution



Melchior et al., in prep.