Cluster and Protocluster Mass Estimation and Determination of their Dynamical States

Nick Battaglia
Princeton
GCF2017

Mat Madhavacheril (Princeton),
Elinor Medesinski (Princeton),Cristobal Sifon (Princeton),
Matt Hilton (UKZN), the ACT and HSC collaborations

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“Masses, what [are they] good for?”

-AM, Monday

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- Proper comparisons & classifications
- Cosmology
- Connection to theory/models
- Accurate & precise masses are hard

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"Boy, your talk is going to be boring"

-AM, Monday

How do we measure/infer masses?

Lessons learned from clusters

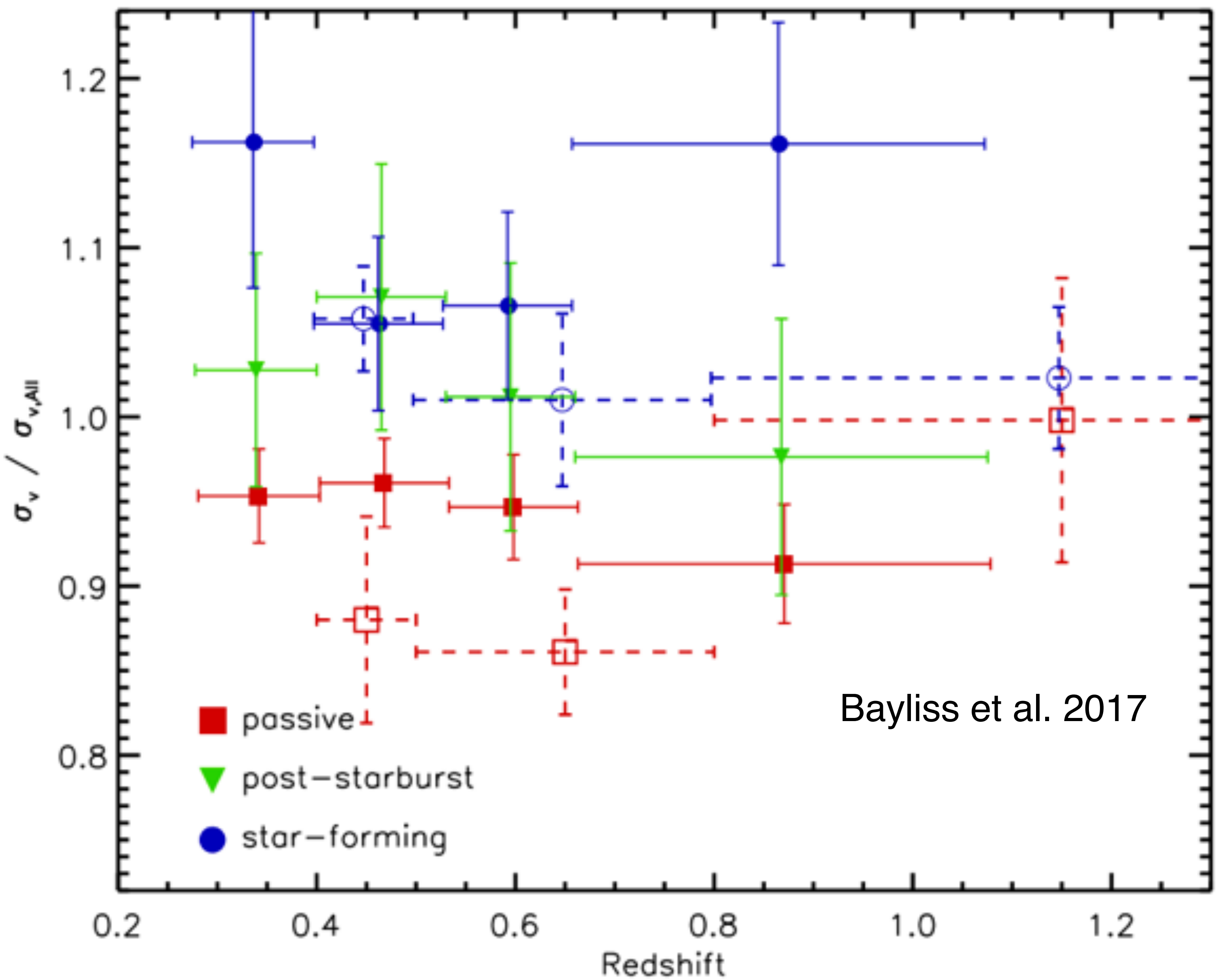
- Velocity dispersions
- X-rays: M_{gas}, L_X, T_X, M_{HSE},
- Optical: Richness, M_{star},
- thermal SZ
- Weak lensing

Lessons learned from clusters

Can we talk about velocity dispersions?

Biases and systematics just on **σ**

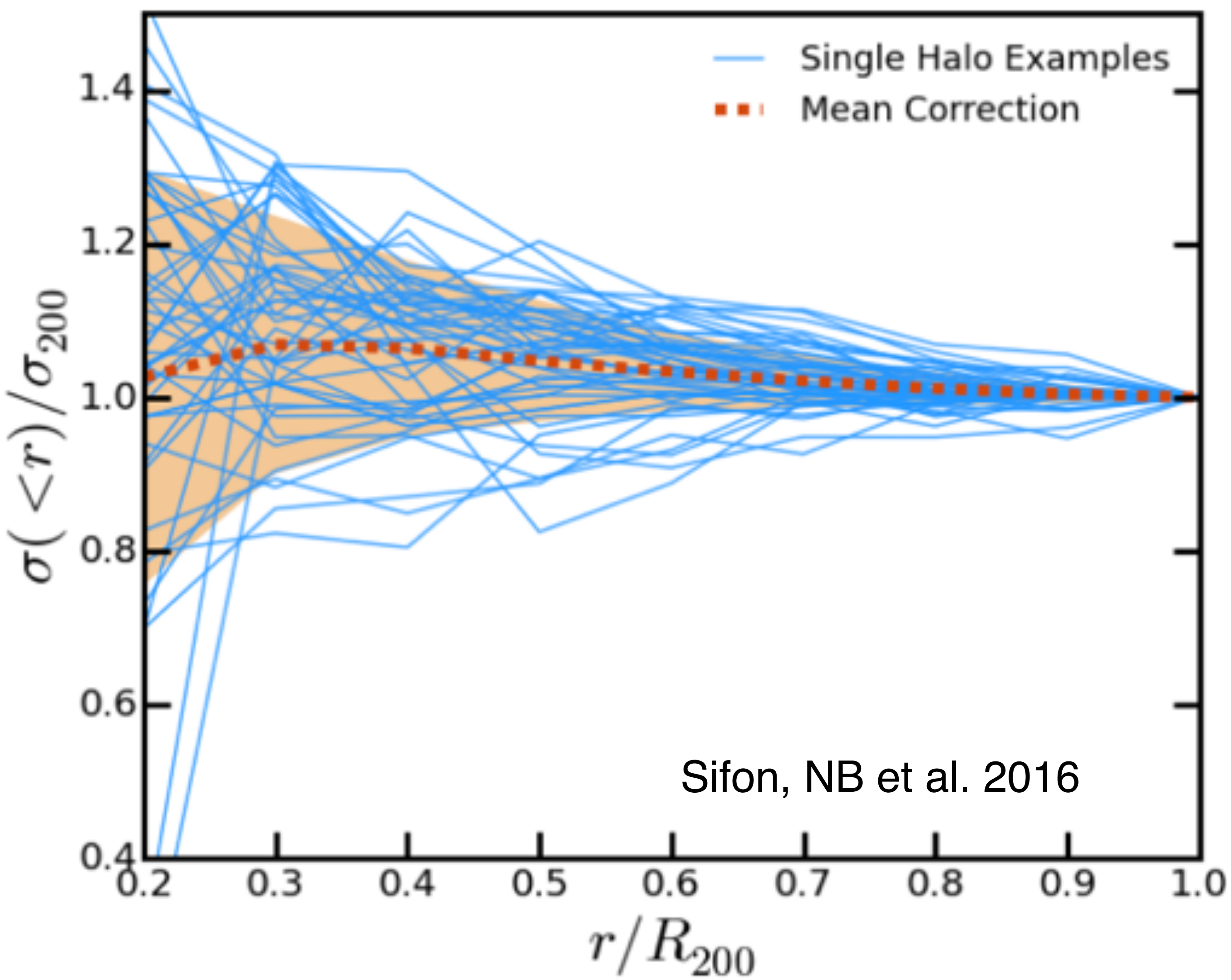
Color selection effects!

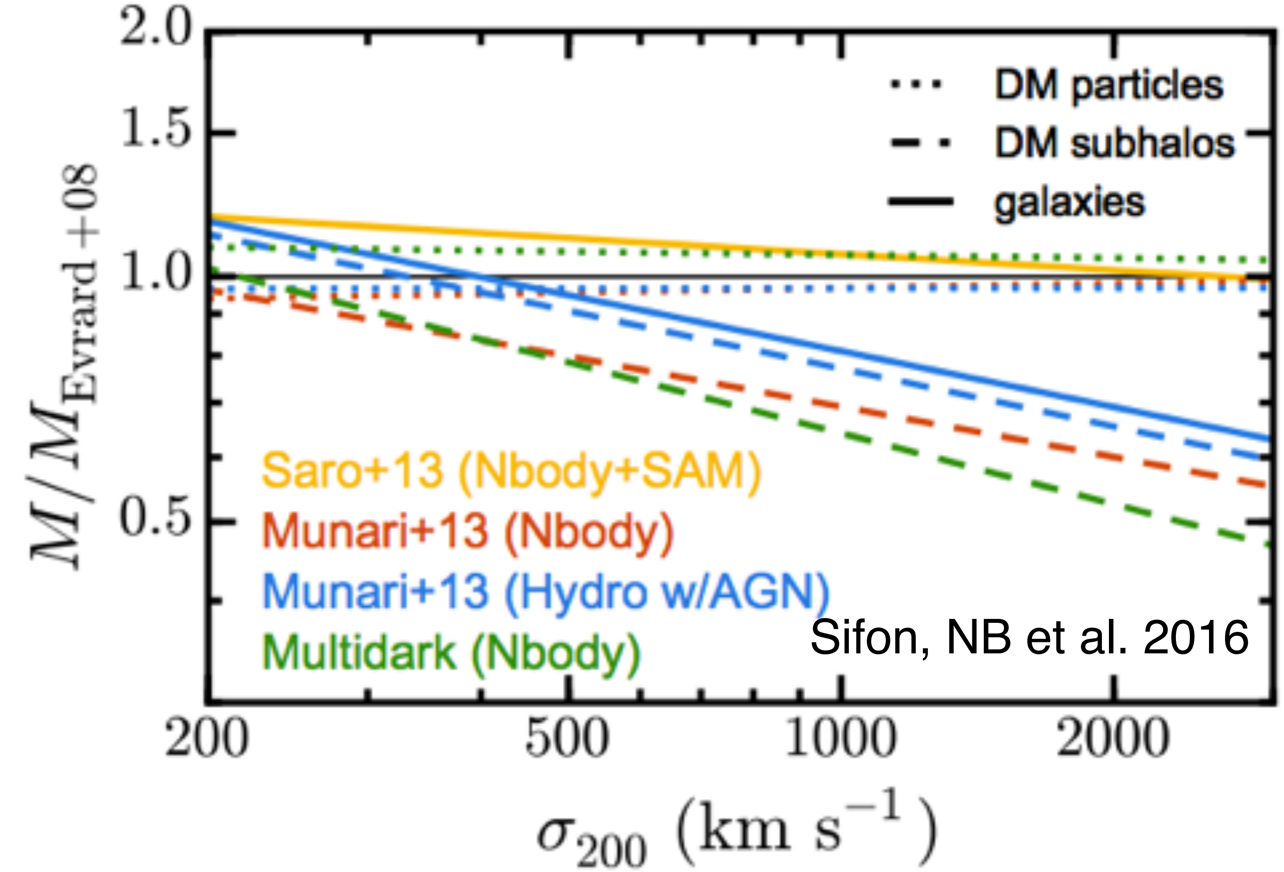


The selection of “tracers galaxies” of the potential matter

More biases and systematics

Radial selection effects





What **σ**-M relationship should one use?

Also intrinsic scatter, velocity bias, etc…
conservatively lead to ~30% systematic uncertainty

Talking about “Relaxed” systems at low-z!

“But what about the SZ?”

-Tony, Tuesday

Thermal Sunyaev-Zel'dovich Effect

Compton-y parameter

$$\frac{\Delta T}{T_{CMB}} = g_\nu \, y$$

Integrated pressure

$$y = \frac{k_b \sigma_T}{m_e c^2} \int n_e T_e \, dl$$

tSZ properties

-Total thermal energy

$Y \sim \int y \, dA \propto T_{vir} M_{vir}$

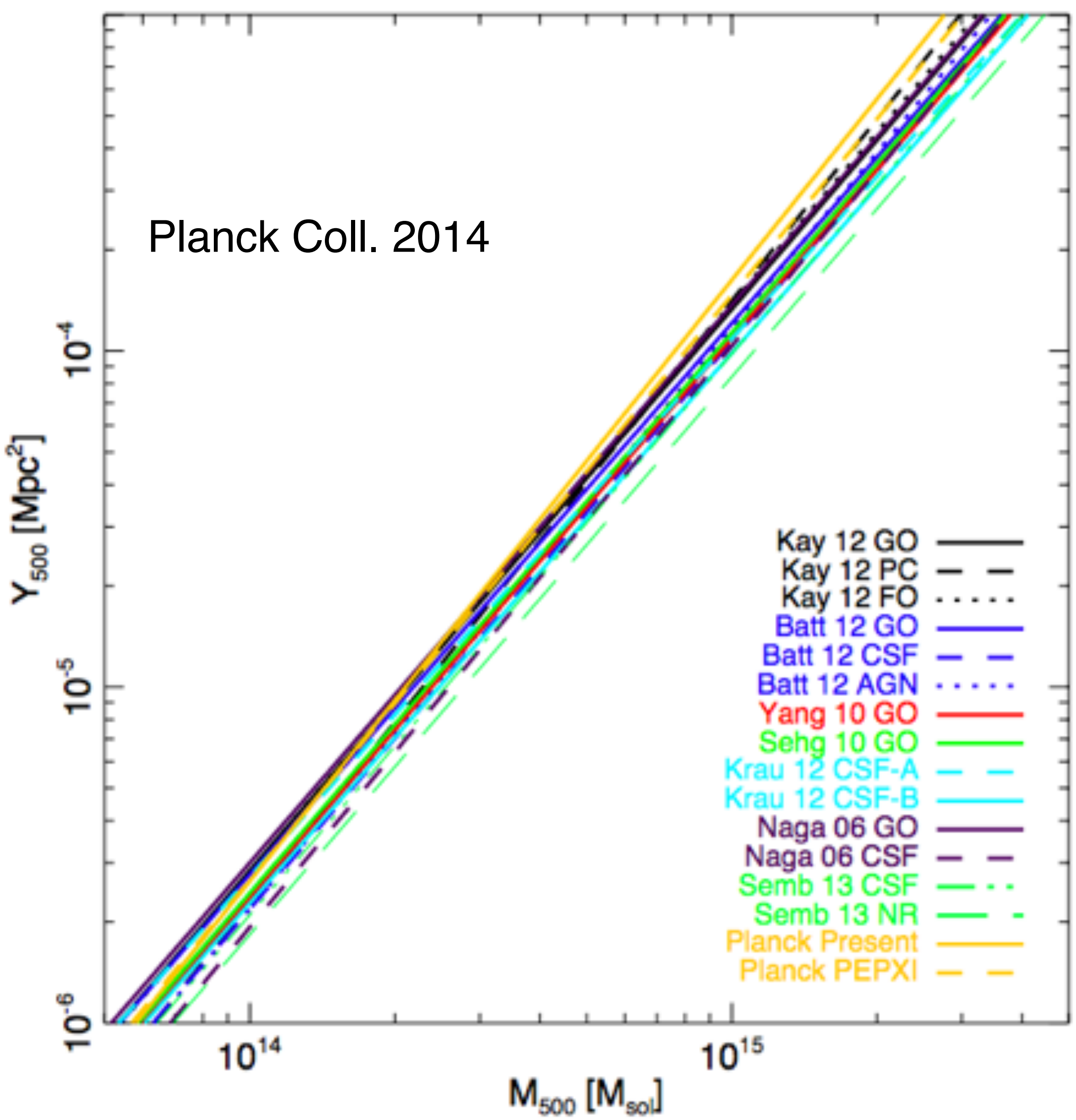
$T_{vir} \propto M_{vir} / R_{vir}$

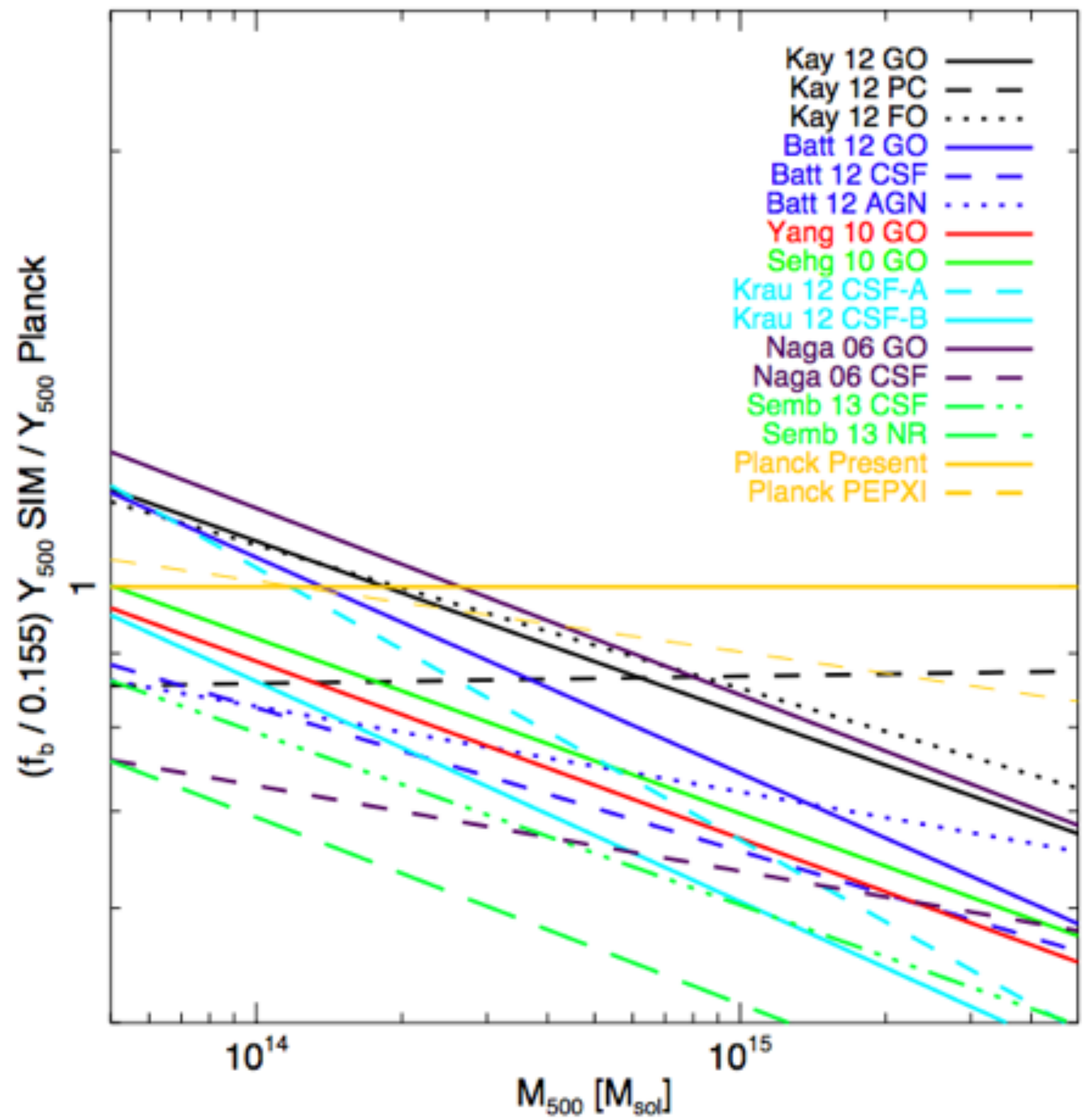
$Y \propto M_{vir}^{5/3}$

-Most massive halos

-Redshift independent

The many SZ scaling relations





What relations should one use?

Systematic error/bias in ones masses

Similarly for X-ray and Optical relations (too many references)

For SZ mass proxies

Calibrate!

Same for X-rays

Calibrate!

Same for richness

Calibrate!

For SZ mass proxies

Calibrate!

Same for X-rays

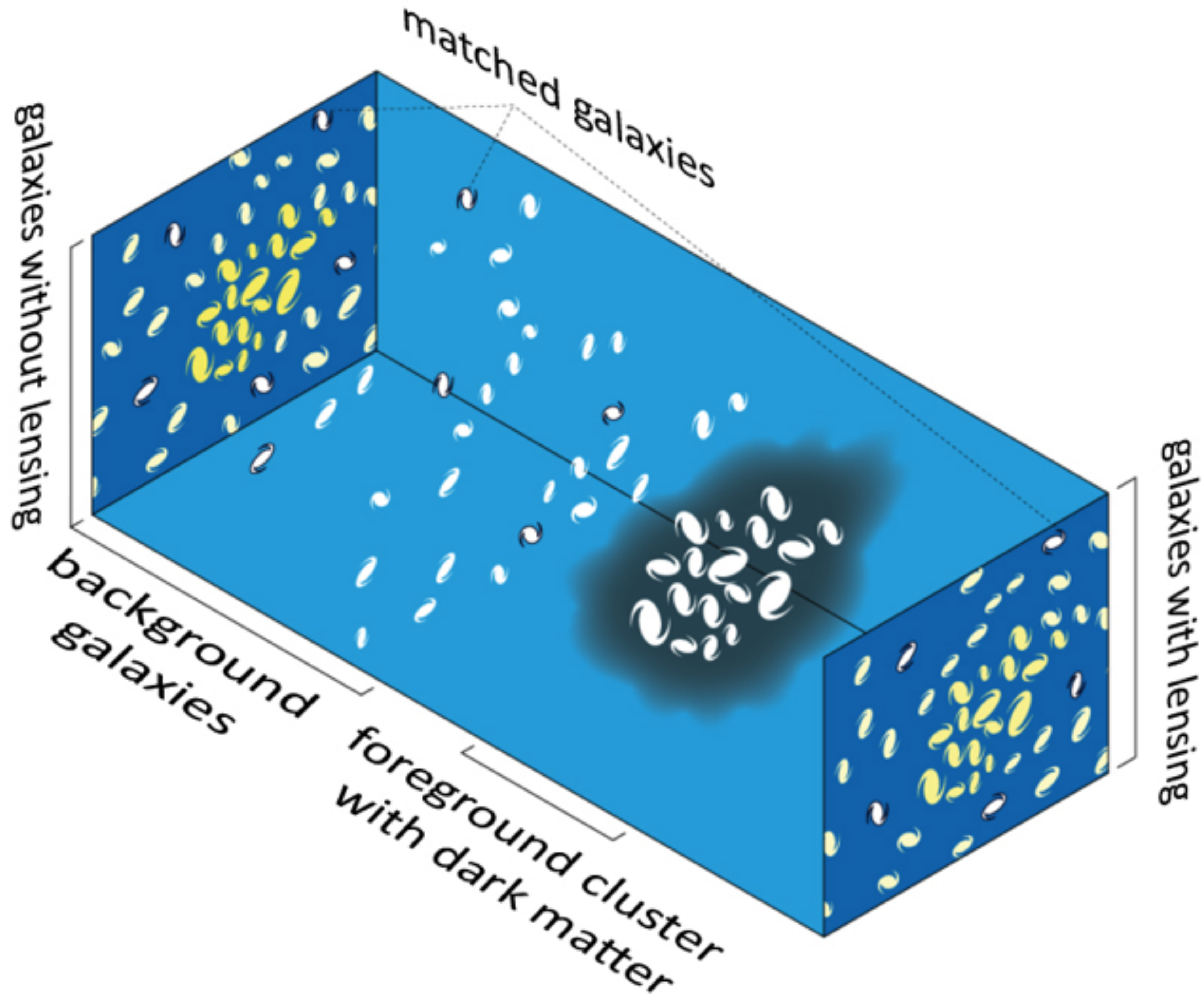
Calibrate!

Same for richness

Calibrate!

with weak-lensing measurements

Weak Gravitational Lensing

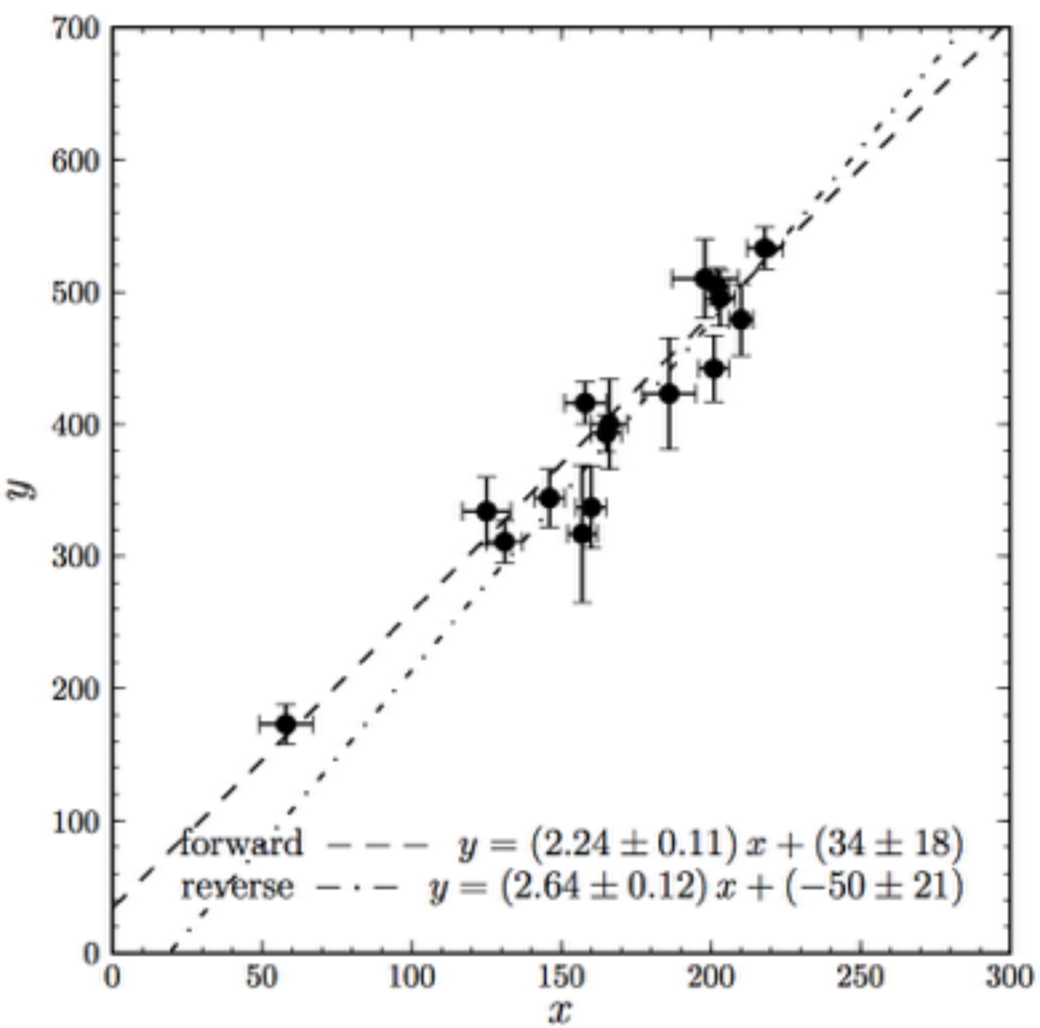


A coherent distortion of source galaxy apparent shapes
Galaxy clusters produce a tangential distortion of the shear field
- Infer total mass within given aperture

Careful calculations of scaling relations matter

Please do not "git clone" any linear regression model fitting software, since they are almost never applicable to your data set!

Example from Hogg et al. 2010



"Forward and Reverse" fitting

Comment in their caption - Don't ever do this

Careful calculations of scaling relations matter

Selection function

Mass function

Errors on x & y variables

↓

Eddington bias

Malmquist bias

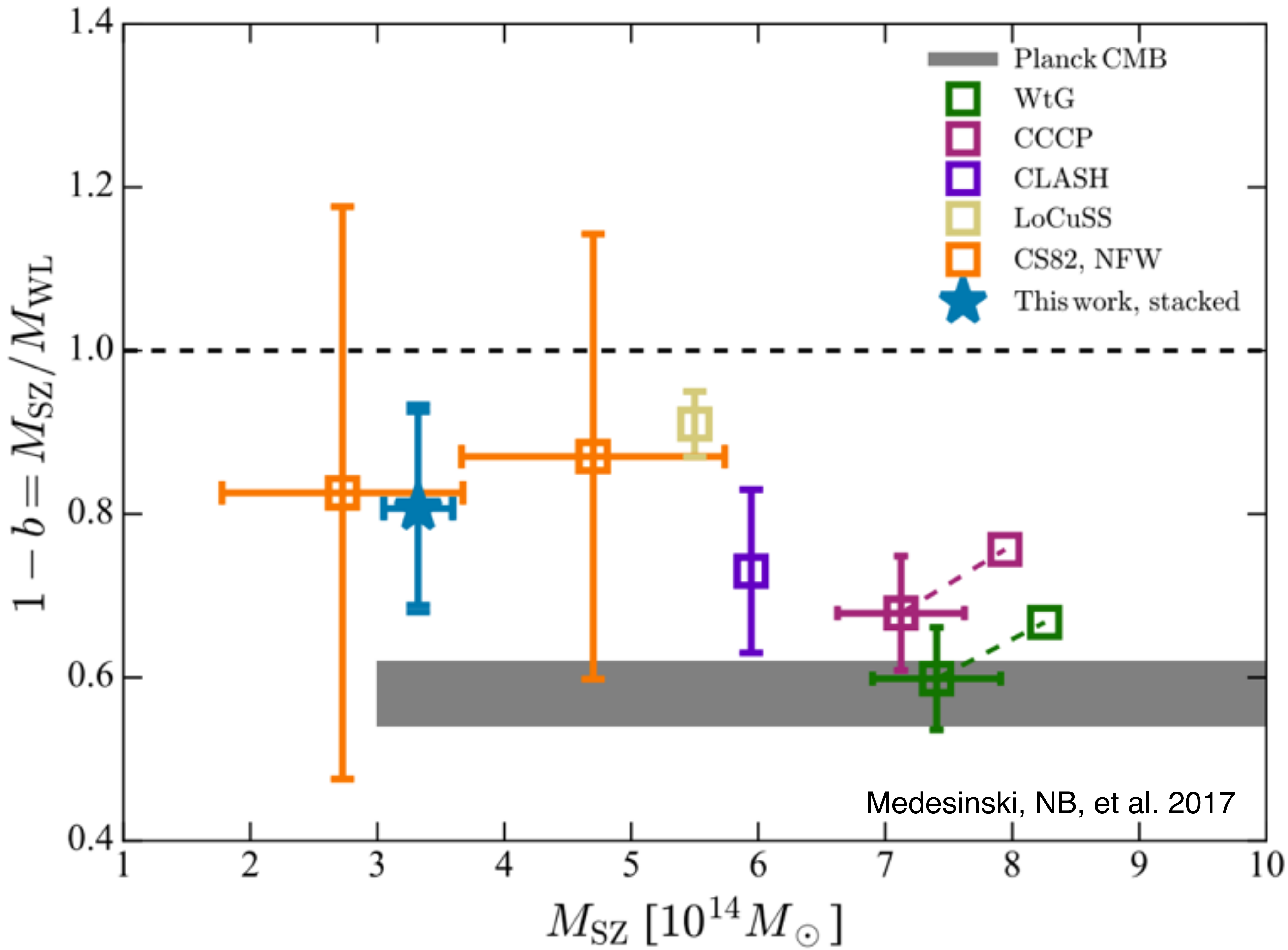
Intrinsic scatter

Intrinsic correlations

If one takes a Bayesian approach then a full maximum likelihood treatment is necessary

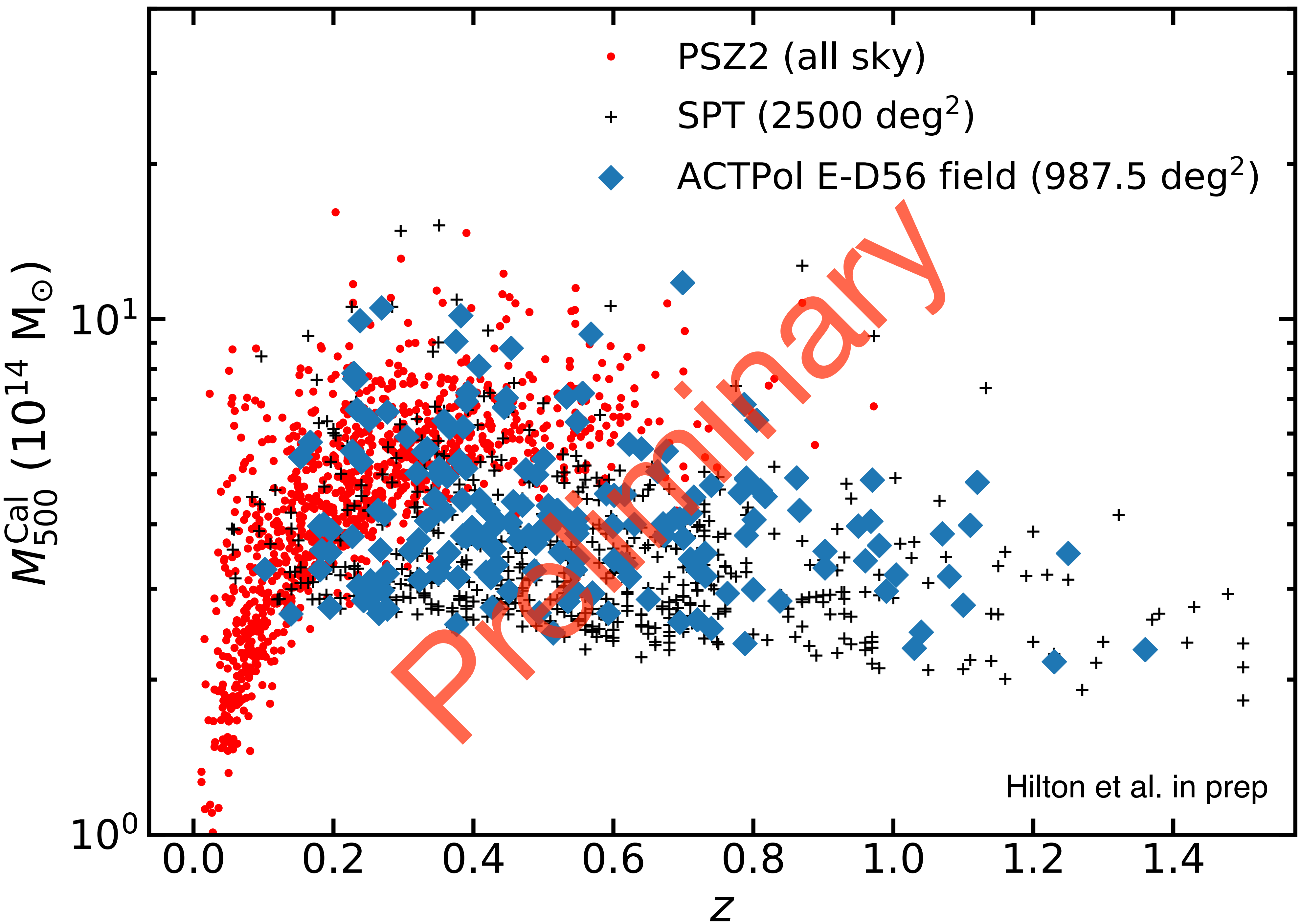
e.g., Kelly (2007), Evrard et al. (2014), Rozo et al. (2014), Munari & Ettori (2015), Sifon, NB et al. 2016, …

SZ mass calibration



Note MSZ from SPT not a fair comparison

SZ cluster detection

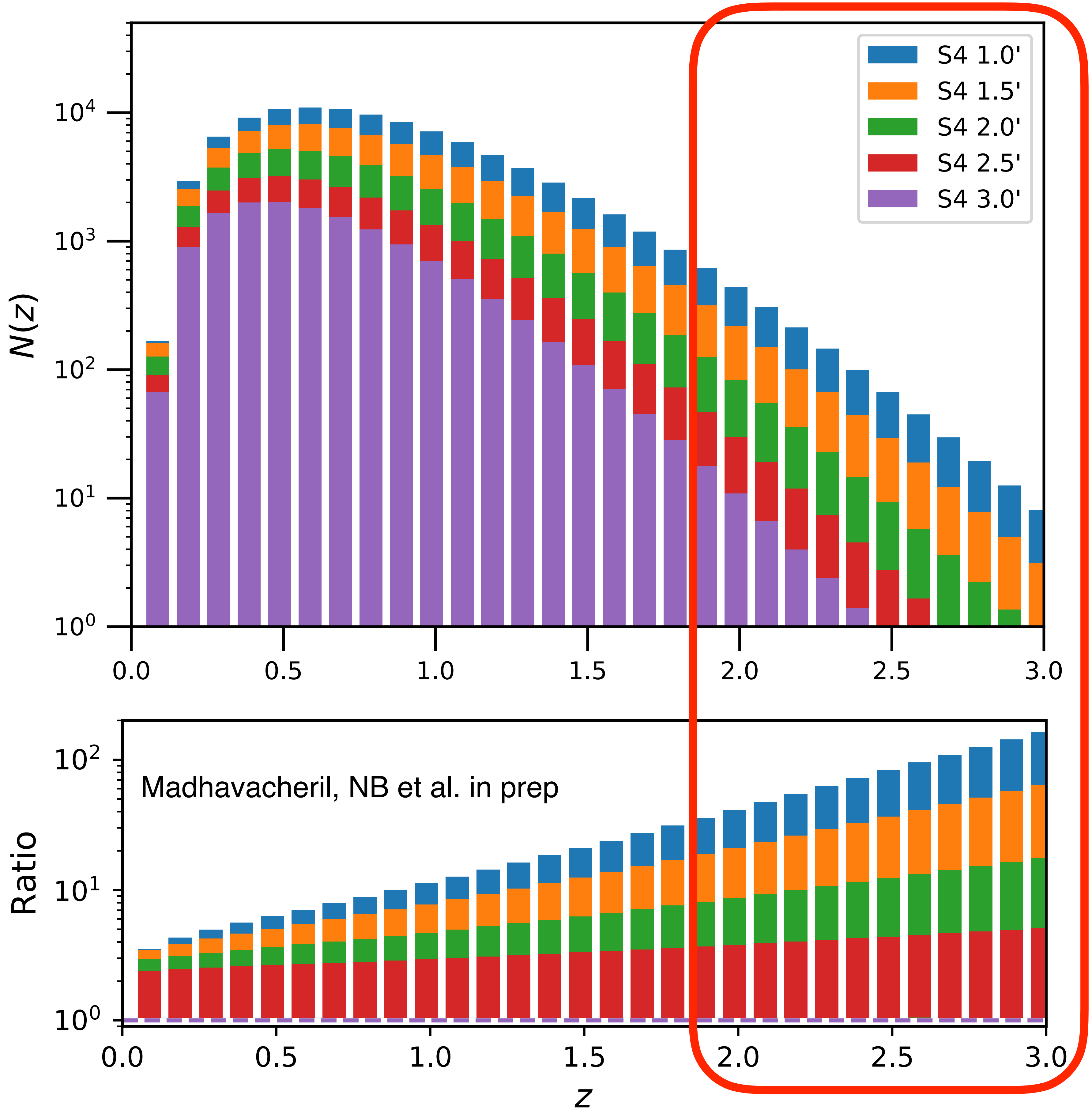


Note we have rescaled ACT to compare with SPT

- CMB-S4: a next generation ground-based program building on CMB stage 2 & 3 projects to pursue inflation, neutrino properties, dark energy and new discoveries.
- Targeting to deploy O(500,000) detectors spanning 30 - 300 GHz using multiple telescopes and sites to map most of the sky to provide sensitivity to cross critical science thresholds.
- Multi-agency effort (DOE & NSF). Complementary with balloon and space-based instruments.
- Broad participation of the US CMB community, including the existing NSF CMB groups, DOE National Labs and the High Energy Physics community

Slide Courtesy: John Carlstrom

Number of clusters “detected”



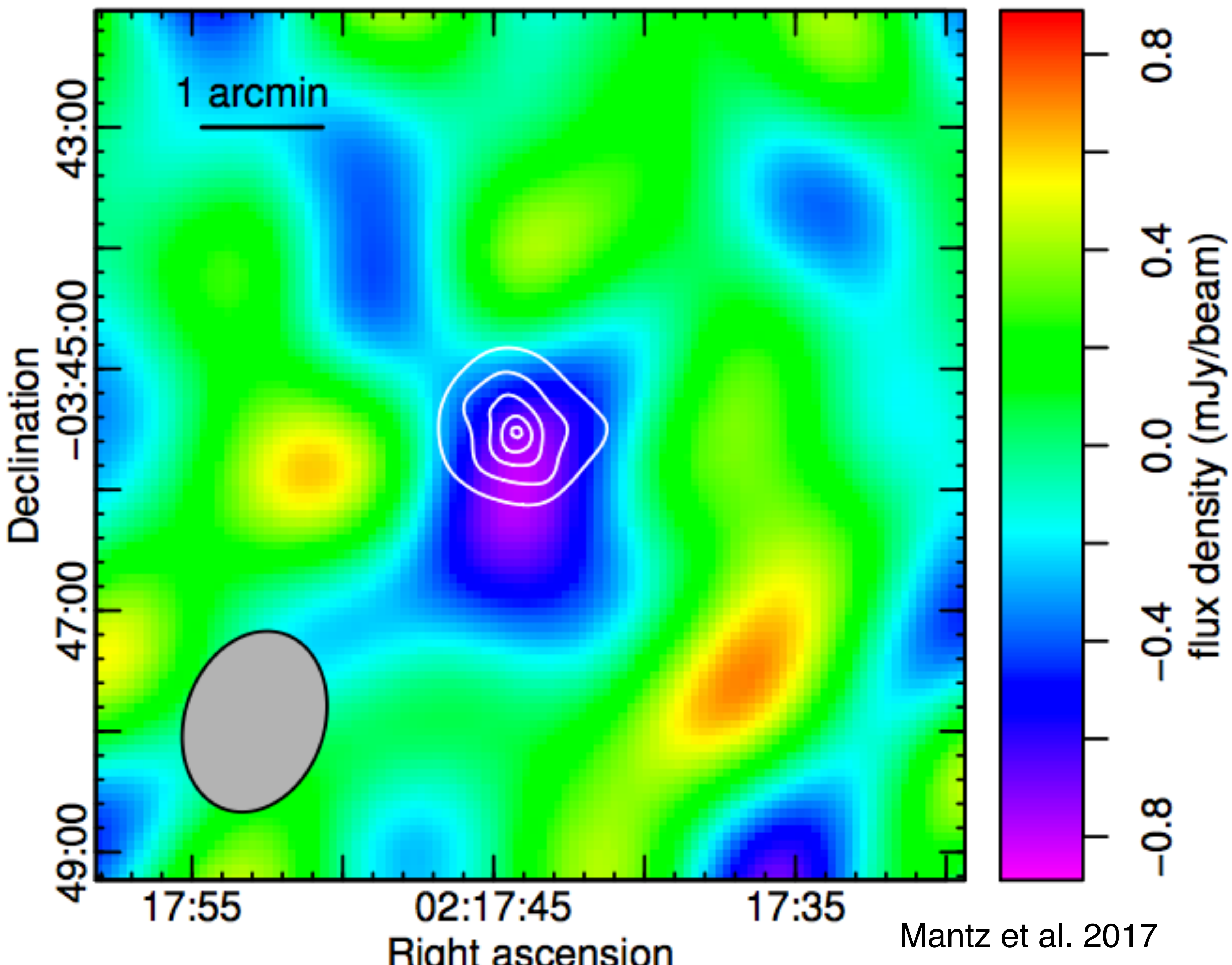
Summary

	2.0'	1.5'	1.0'
Total	43800	76800	122800
z >1.5	1420	3640	7850
z > 2.0	180	560	1390

Discovery space

Caveat
assuming that
Y-M scaling
calibrated at z ~ 0
+ self-sim evolution

Hot gas at z = 2!



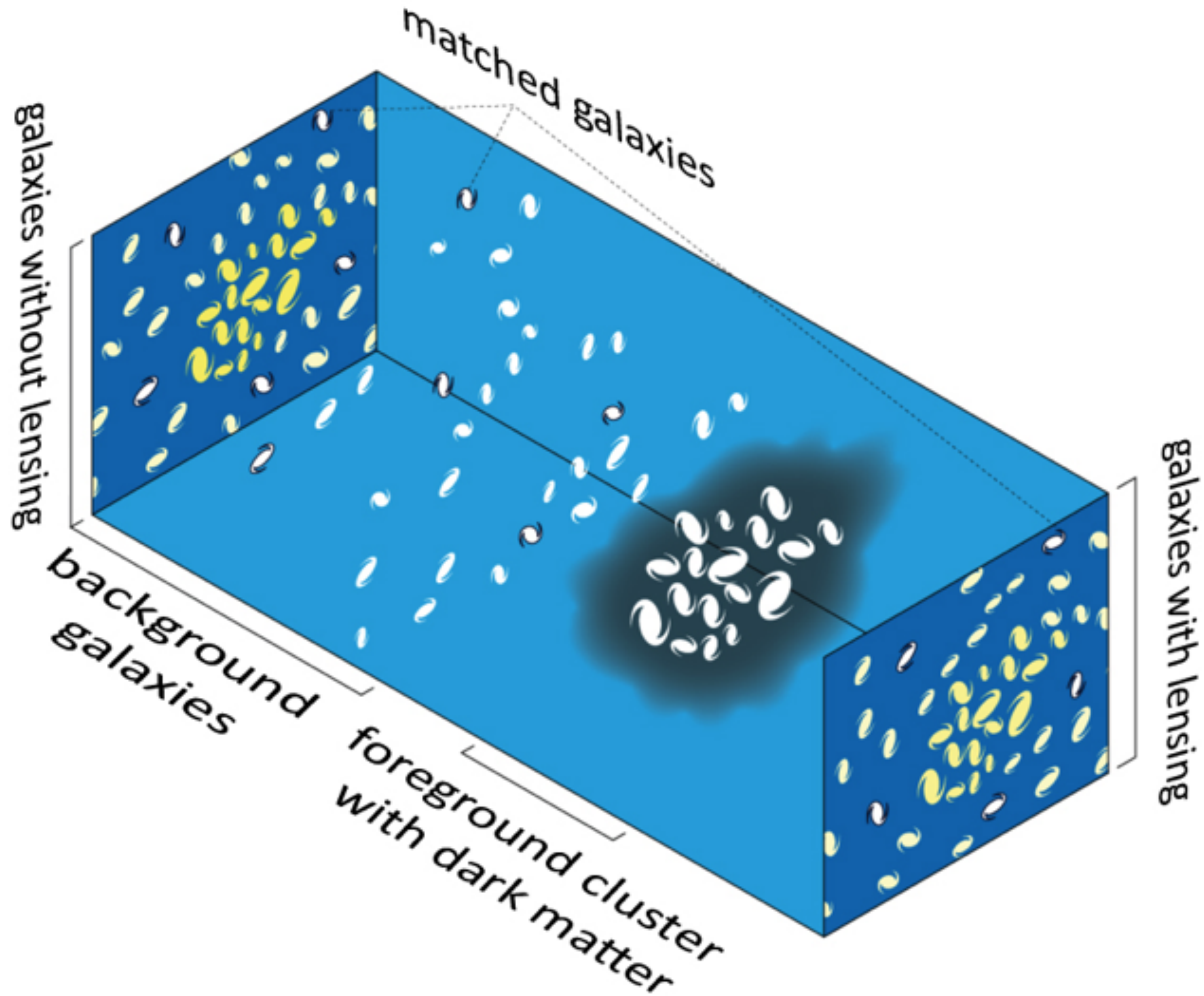
Mantz et al. 2017

CMB-S4 will find all objects like this in the southern sky and more

“Yawn, you still haven’t told me how to accurately and precisely measure masses at high redshifts”

-AM, currently

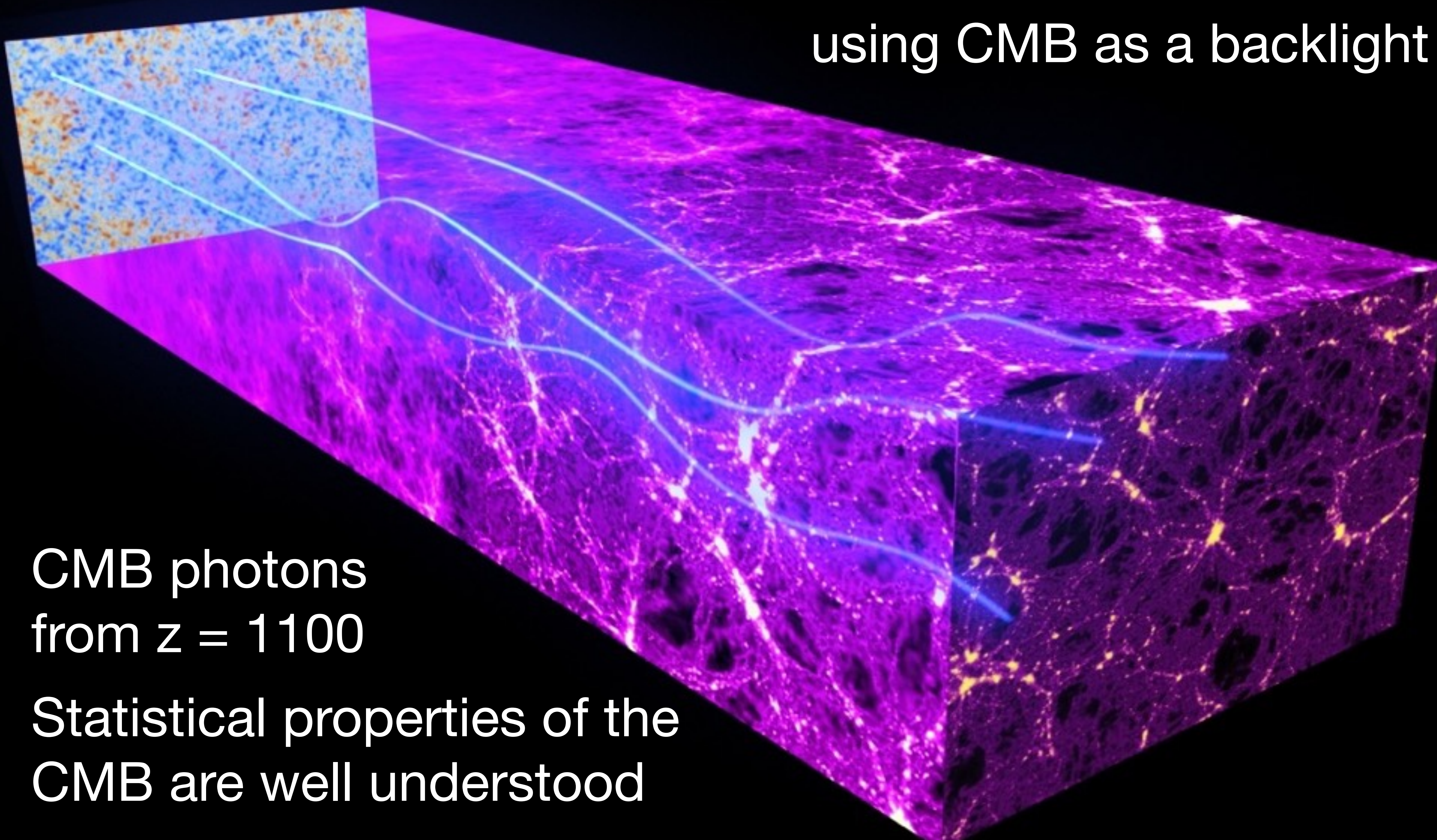
Weak Gravitational Lensing at high-z



Becomes really difficult beyond $z > 1.2$, even for LSST, Euclid

Lack of background galaxies, measuring shapes, photo-zs

CMB lensing



using CMB as a backlight

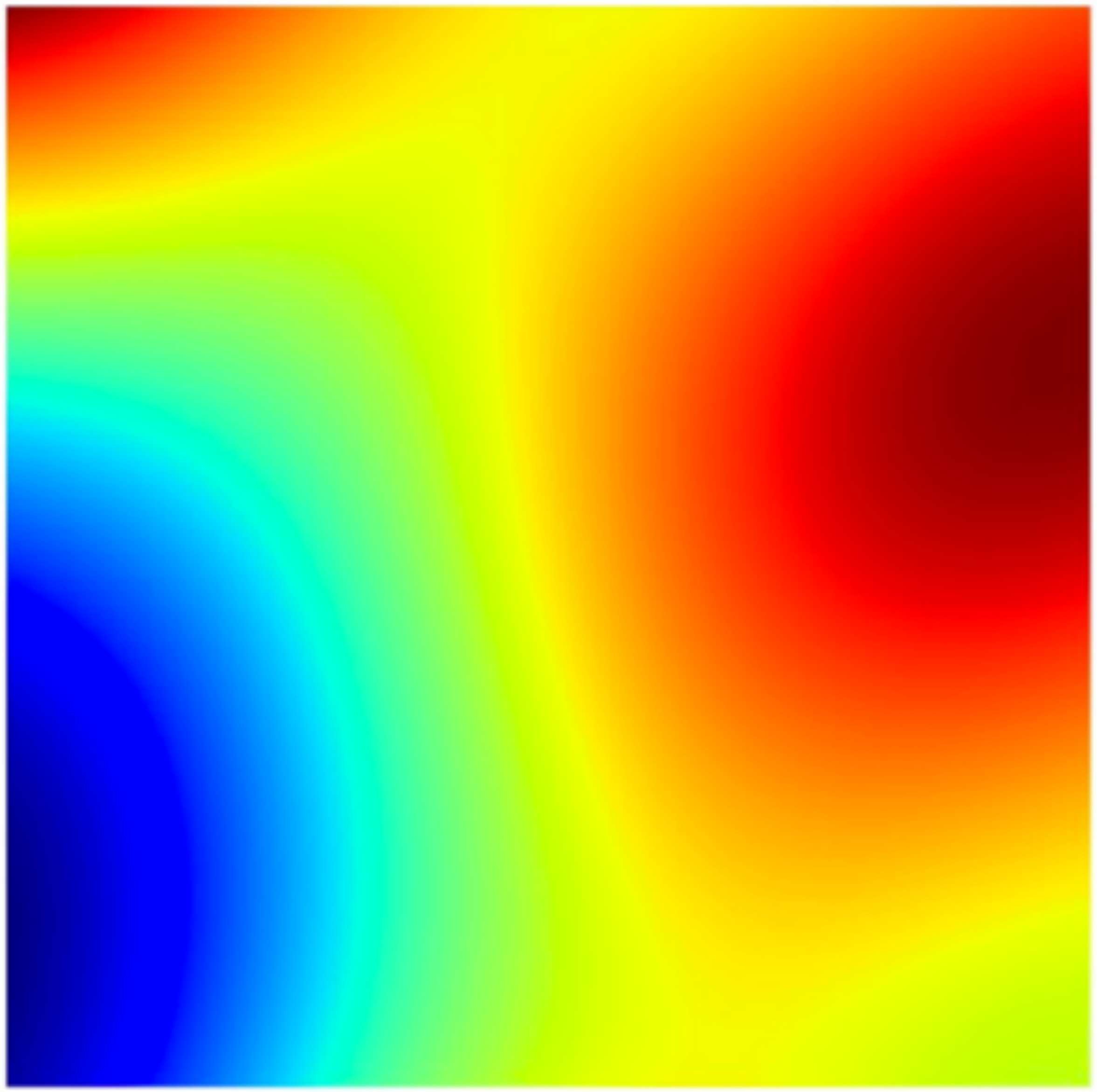
CMB photons
from z = 1100

Statistical properties of the
CMB are well understood

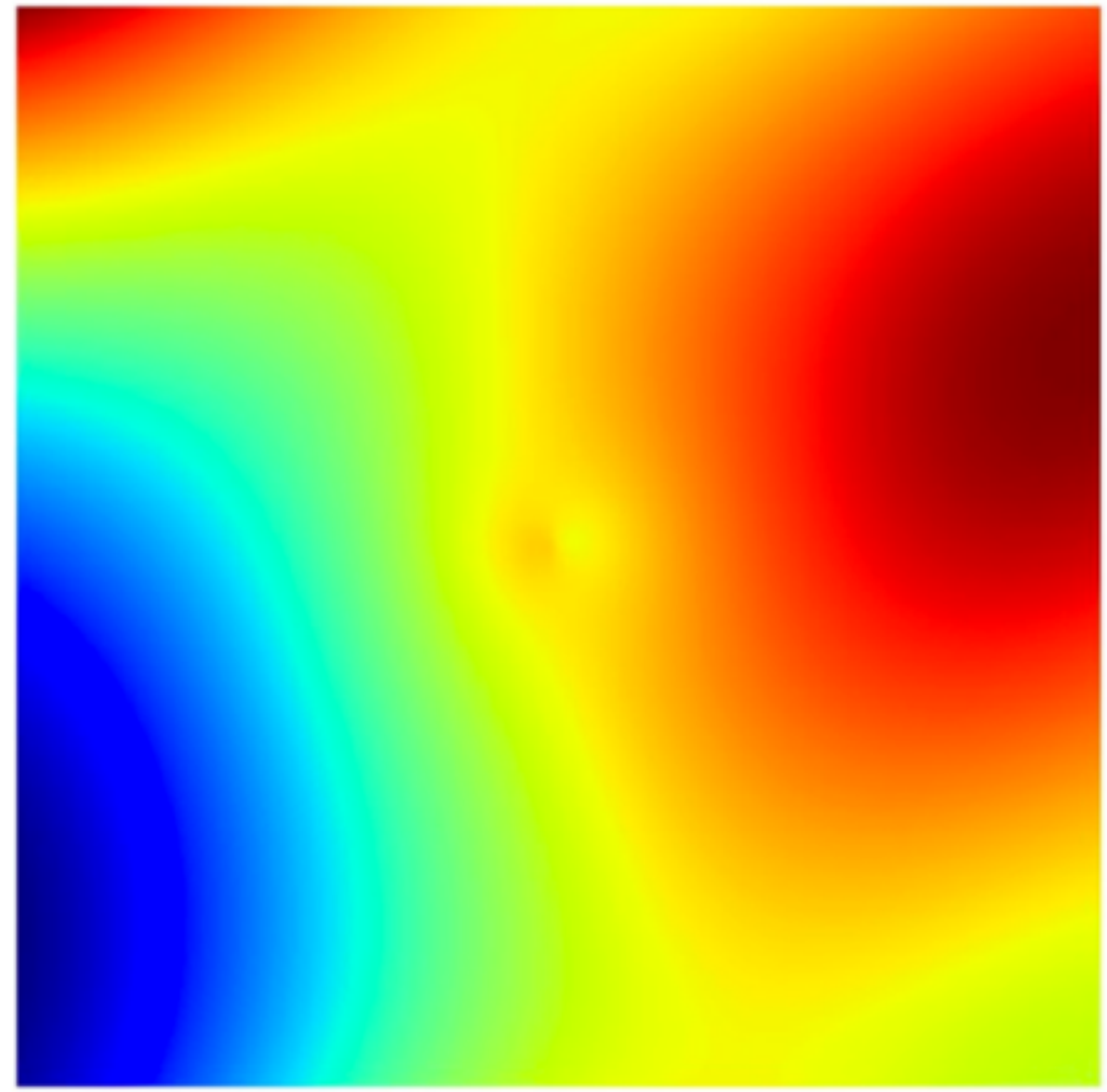
Don’t need to measure galaxy shapes!

“CMB Halo lensing” mass calibration

-Alex van Engelen

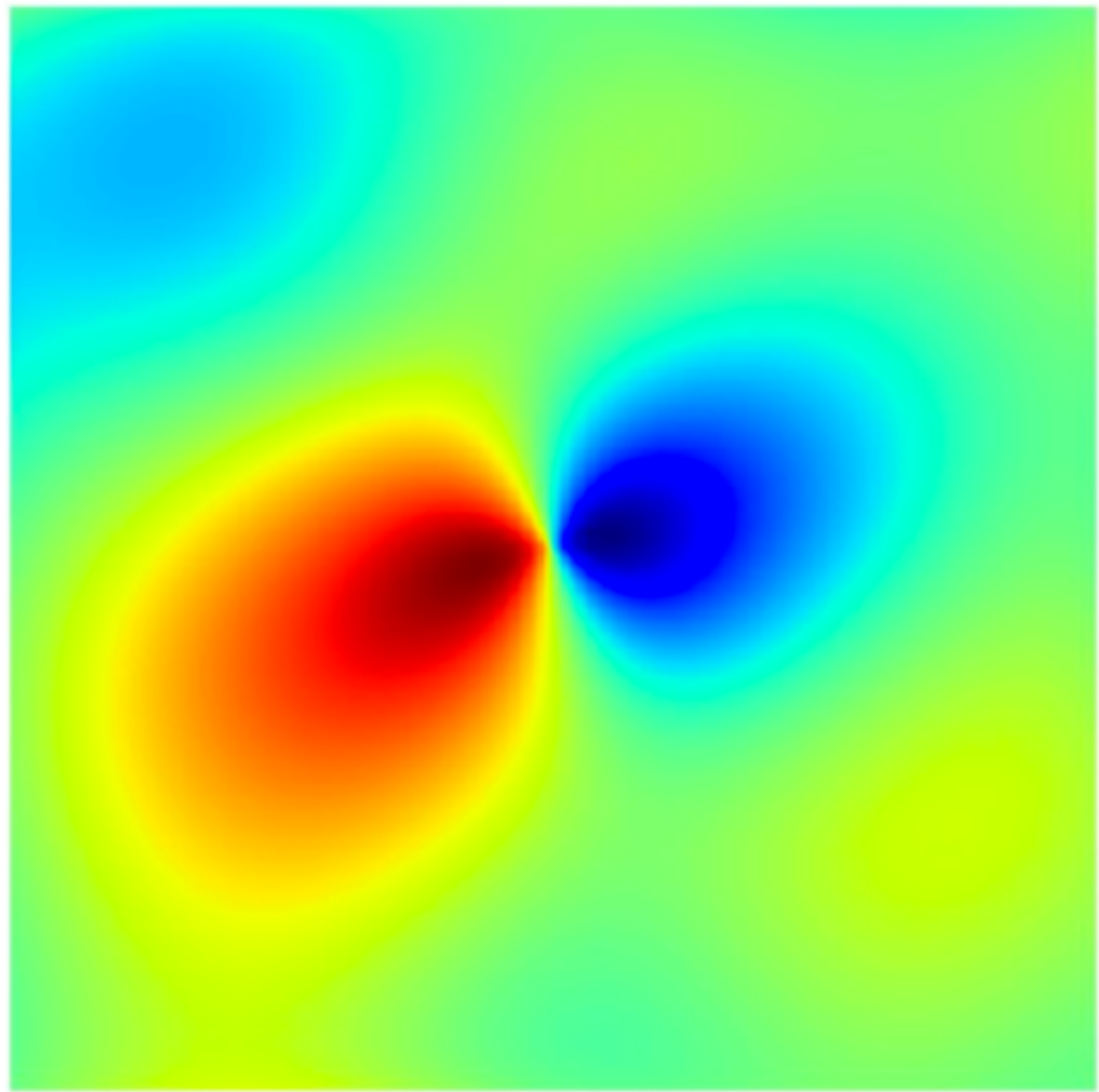


CMB



CMB + cluster

CMB Halo lensing mass calibration

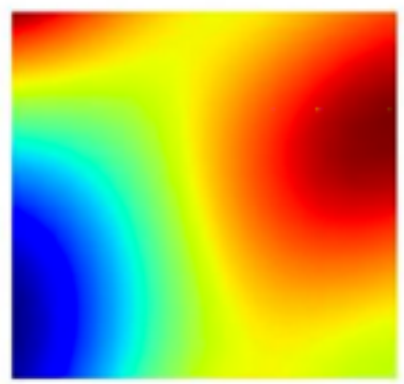


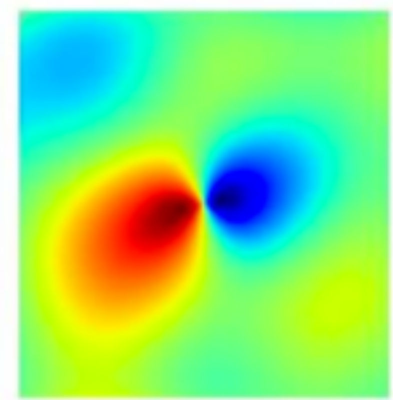
The difference is a dipole

CMB Halo lensing quadratic estimator

Large-scale gradient Small-scale dipole

$$\hat{\kappa} \propto \vec{\nabla} \cdot \left[\left[\vec{\nabla} T \right]_{\text{low}} \left[T(\vec{\theta}) \right]_{\text{high}} \right]$$





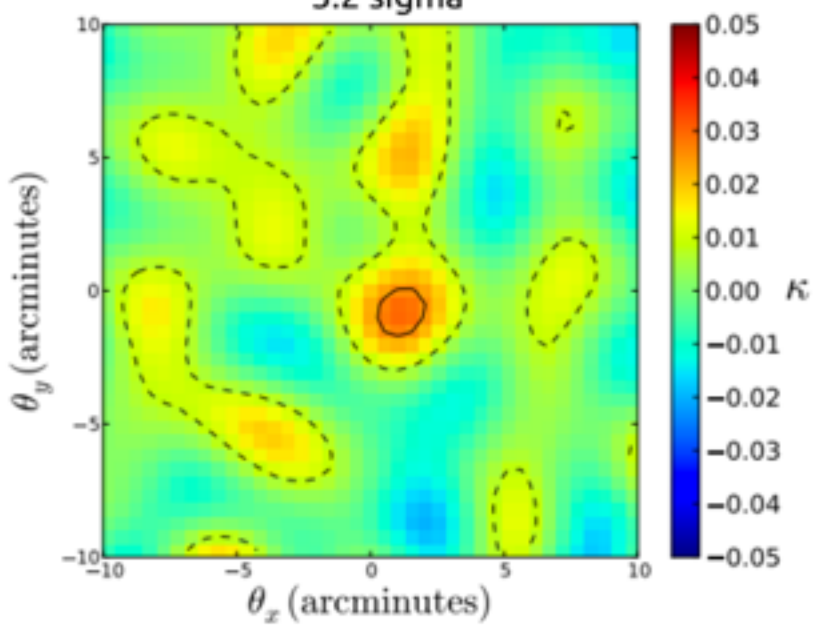
Hu, DeDeo, Vale 2007

Maximum Likelihood estimators

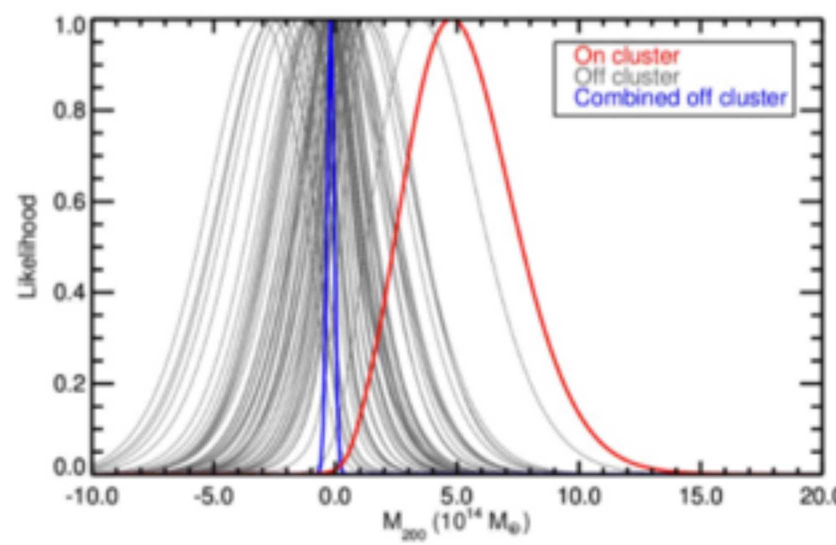
Raghunathan et al. 2017

CMB Halo lensing detections

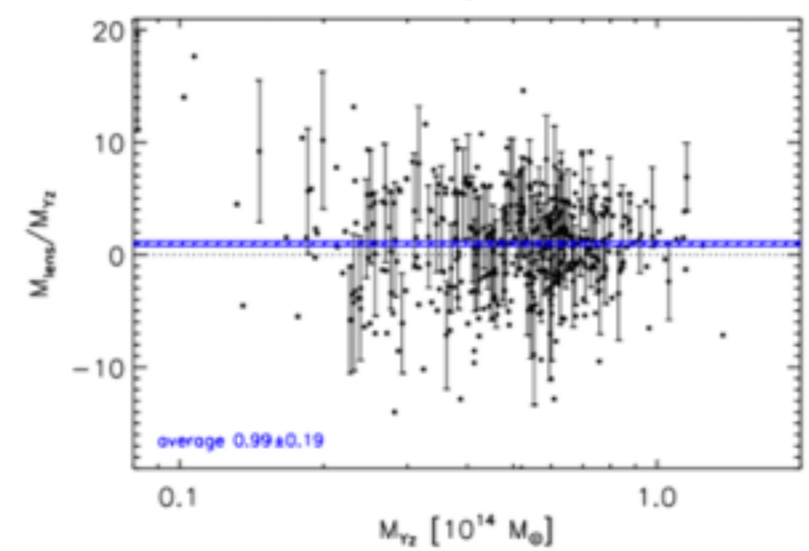
Madhavacheril + ACTPol (PRL 2015)
3.2 sigma



Baxter et. al (SPT)
3 sigma



Planck 2015
5 sigma



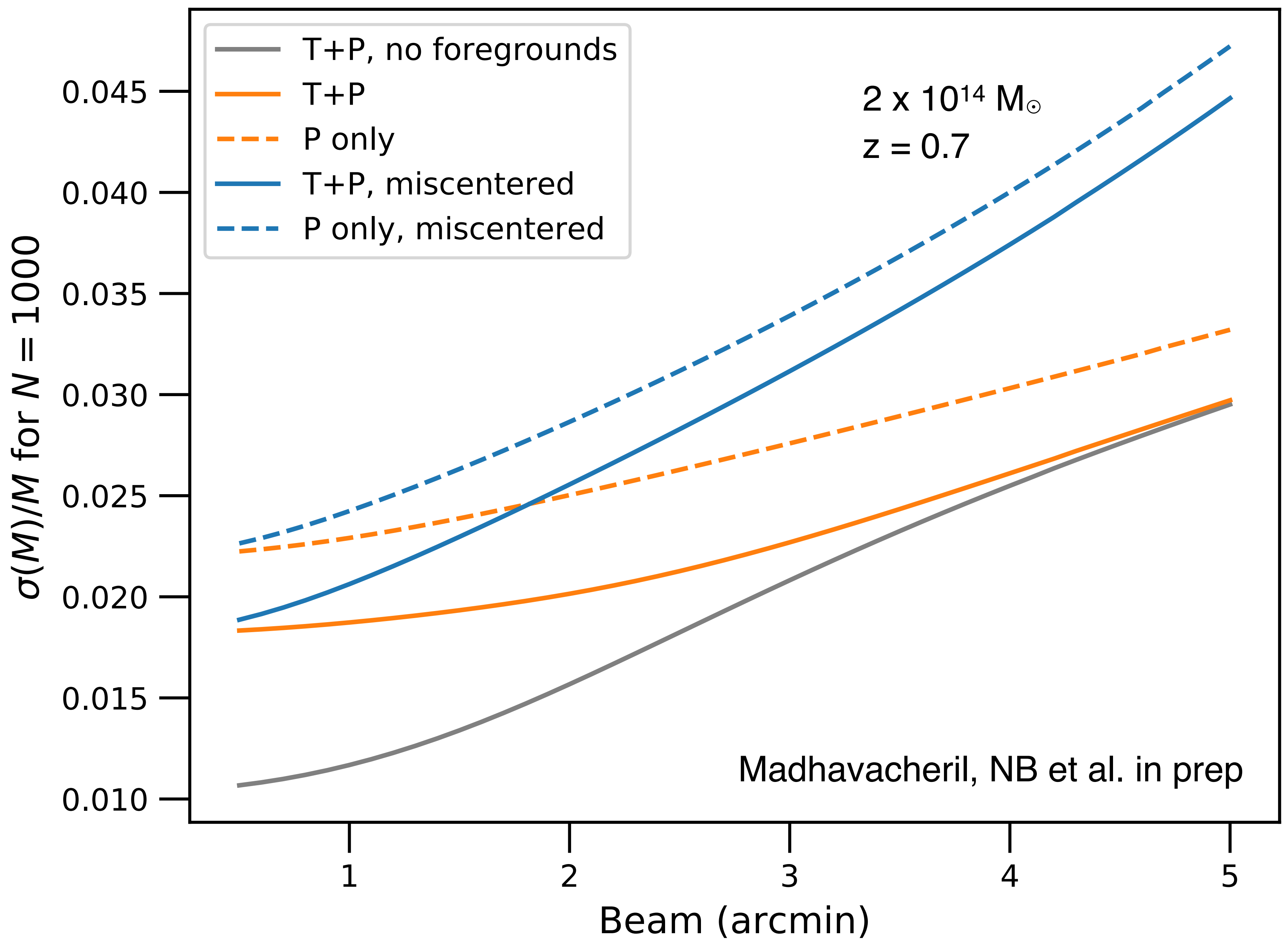
Early days for CMB halo lensing

Different techniques / estimators / samples

However, the data is getting better

CMB Halo lensing estimator - CMBS4

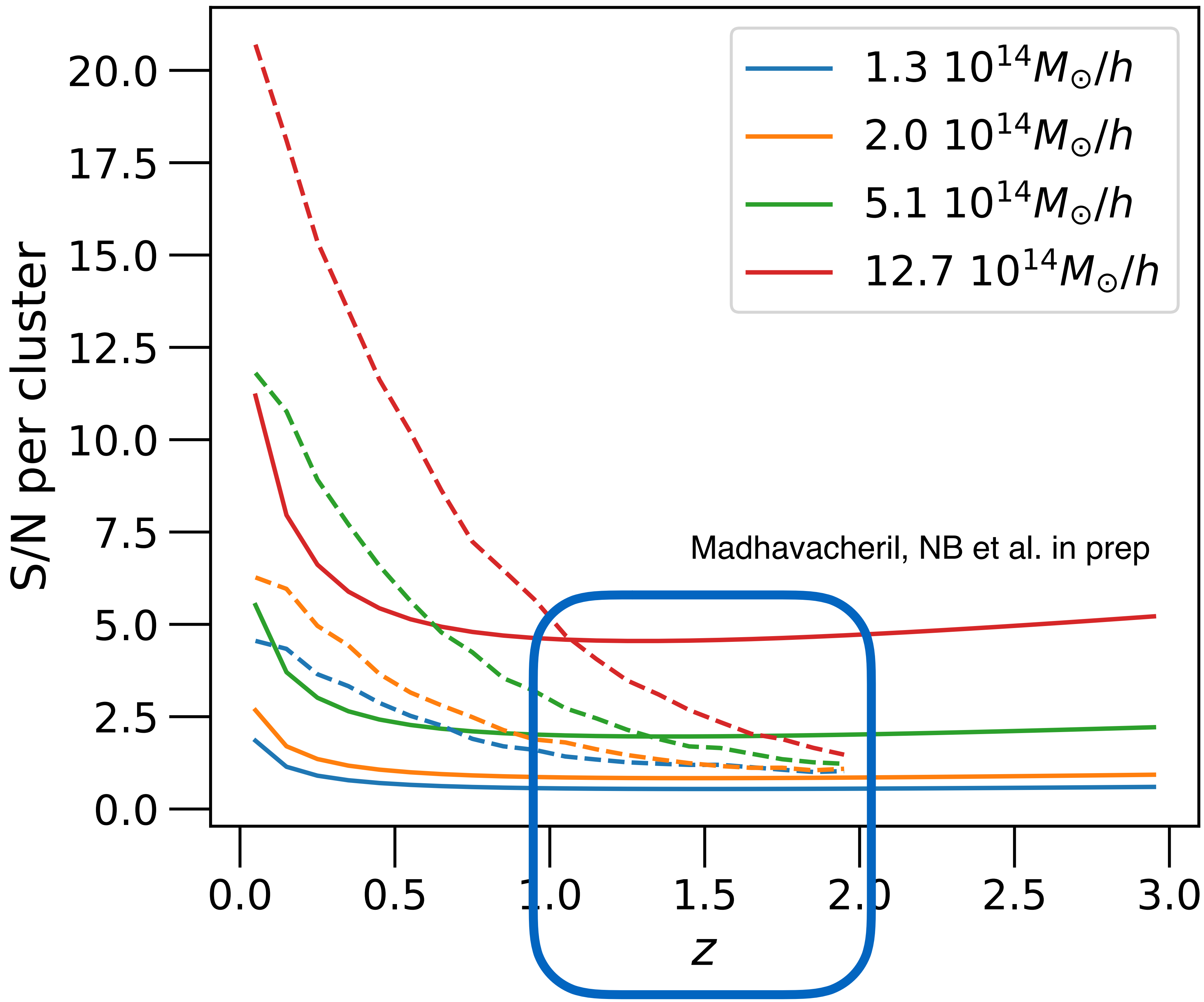
% error



Strong function of the beam size

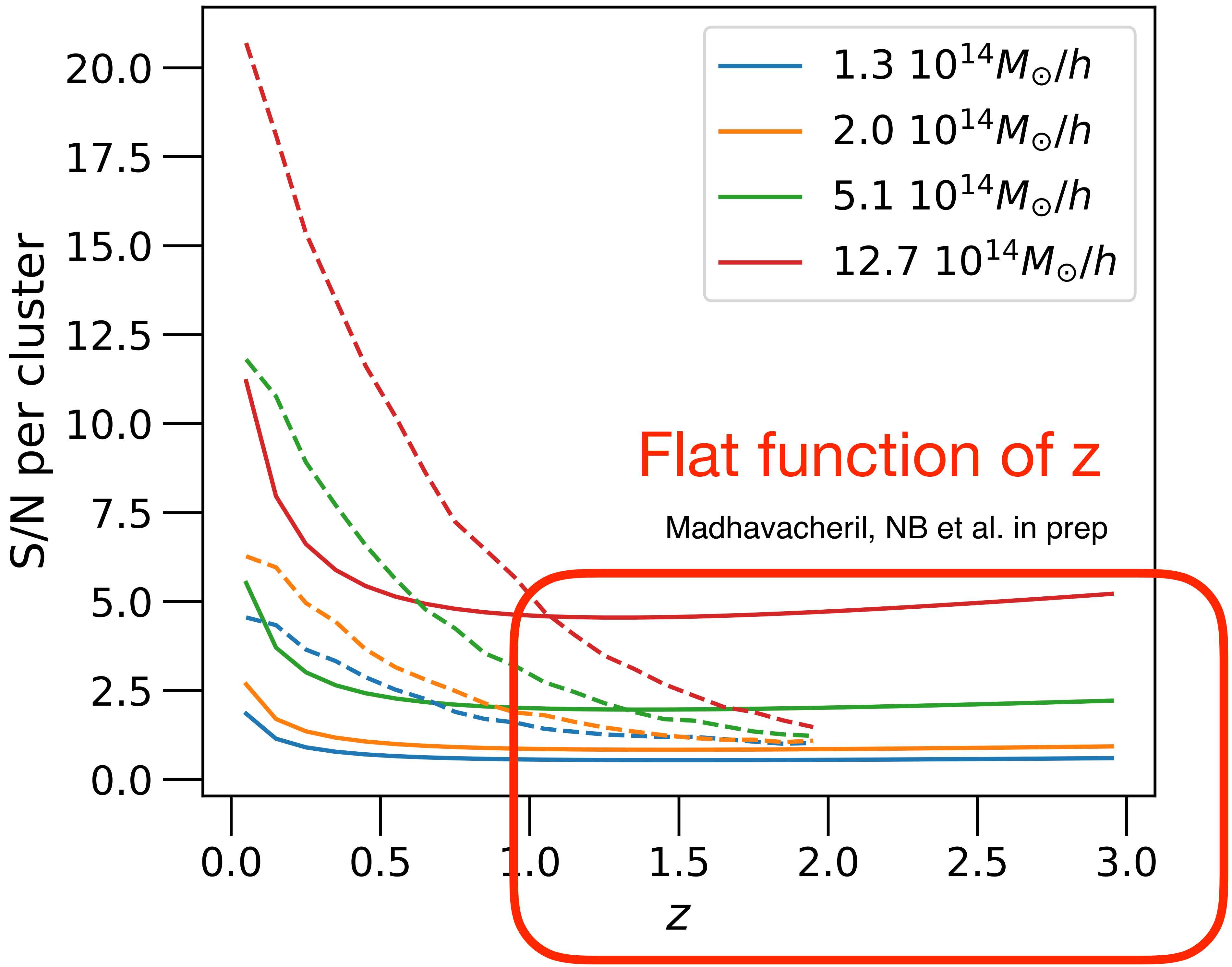
Removal of foregrounds is one of the key systematics

Optical vs CMB halo lensing



Transitions from optical to CMB halo lensing

Optical vs CMB halo lensing



Independent systematics from optical weak-lensing measurements

Take aways

-Velocity dispersions…

-Calibrate SZ, X-ray, Optical relations

-Please fit scaling relations with ML methods

-CMB-S4 will provide large, well defined sample of clusters $z > 2$

-CMB halo lensing is a new opportunity to measure masses at all redshifts

“Masses, what [are they] good for?”