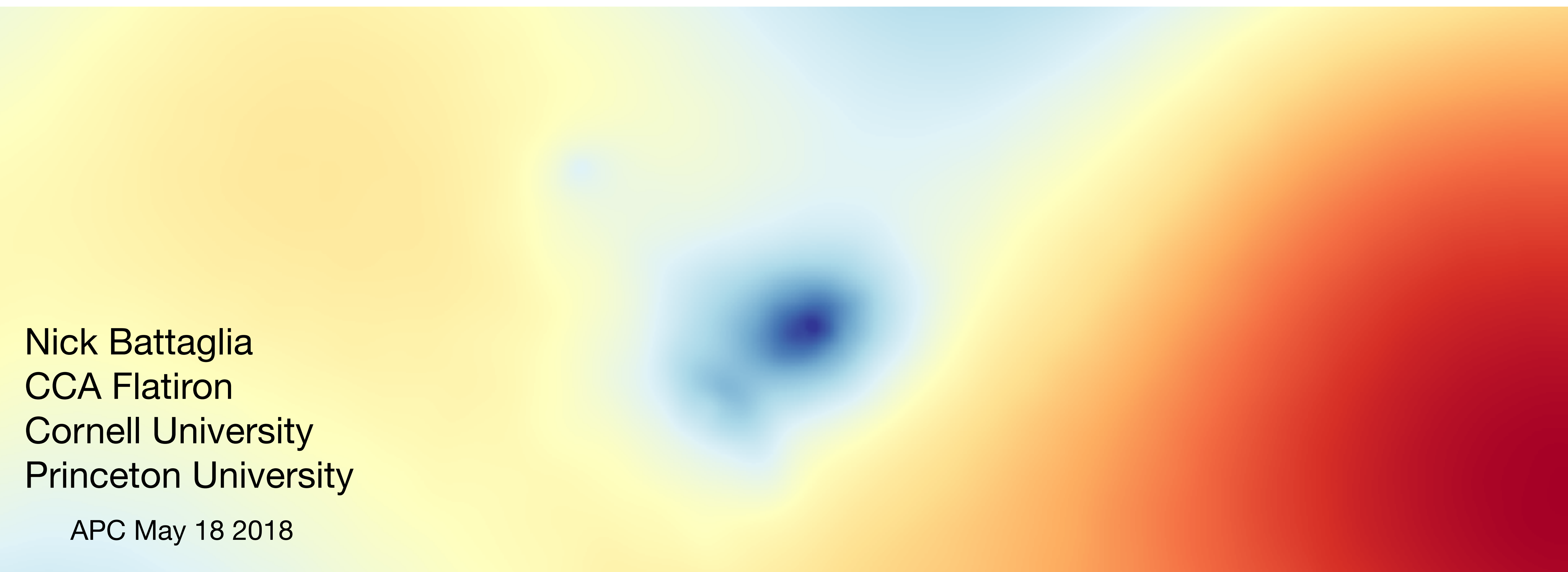
CONSTRAINING FUNDAMENTAL PHYSICS WITH THERMAL AND KINETIC SUNYAEV-ZEL'DOVICH EFFECTS



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APC May 18 2018

Collaborators

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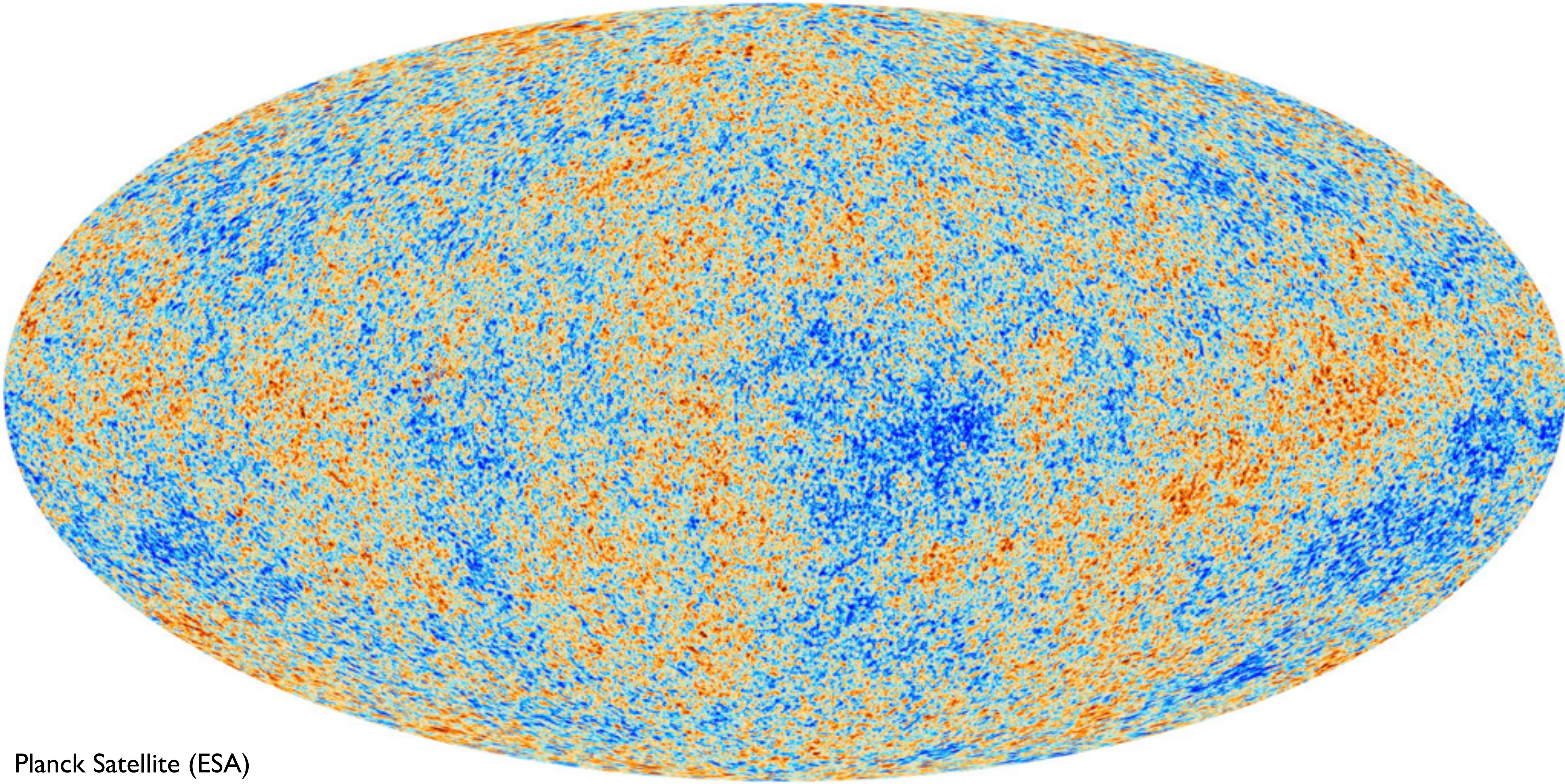
Growth of structure measurements from tSZ and kSZ observations

Systematic uncertainties current limiting factors

What are the potential constraints?

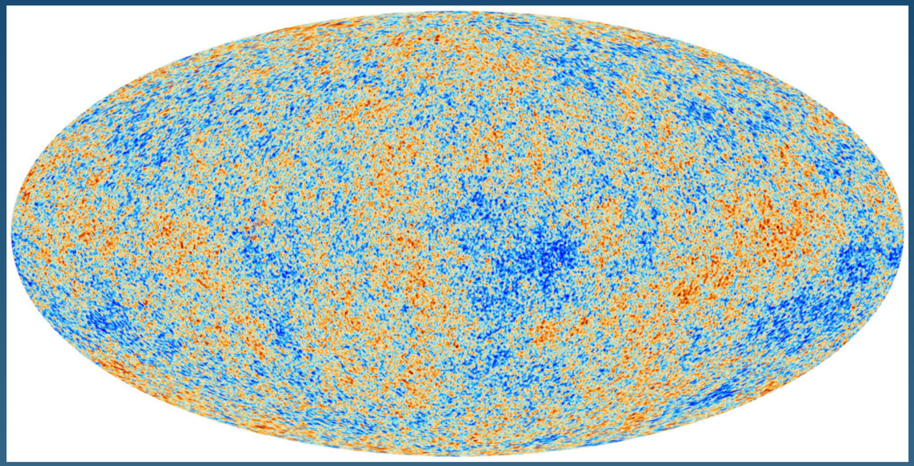
Primary anisotropies in the cosmic microwave background are the foundation of modern cosmology.

Sound waves at the surface of last scattering ($z \sim 1100$)



Planck Satellite (ESA)

Concordance ΛCDM



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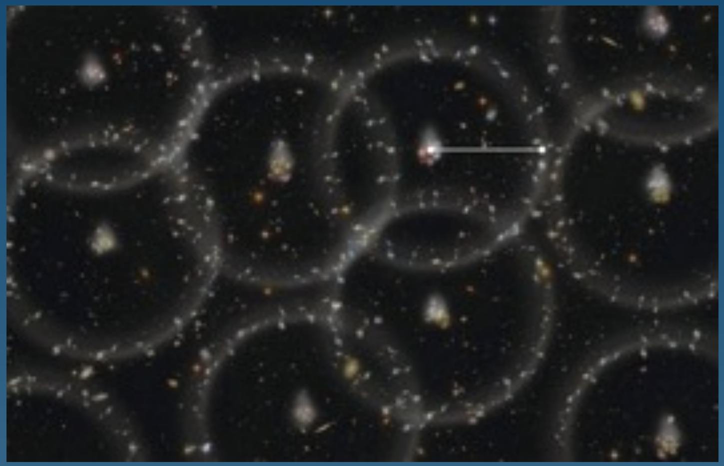

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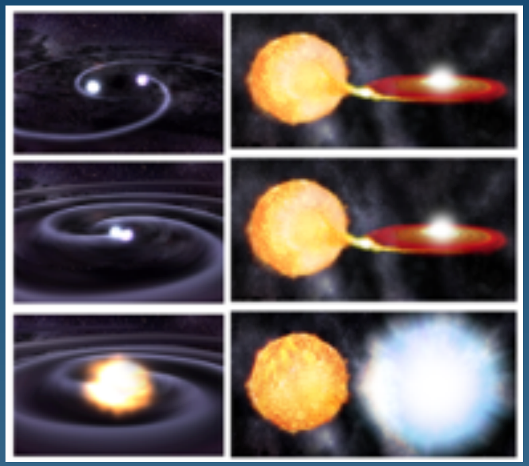
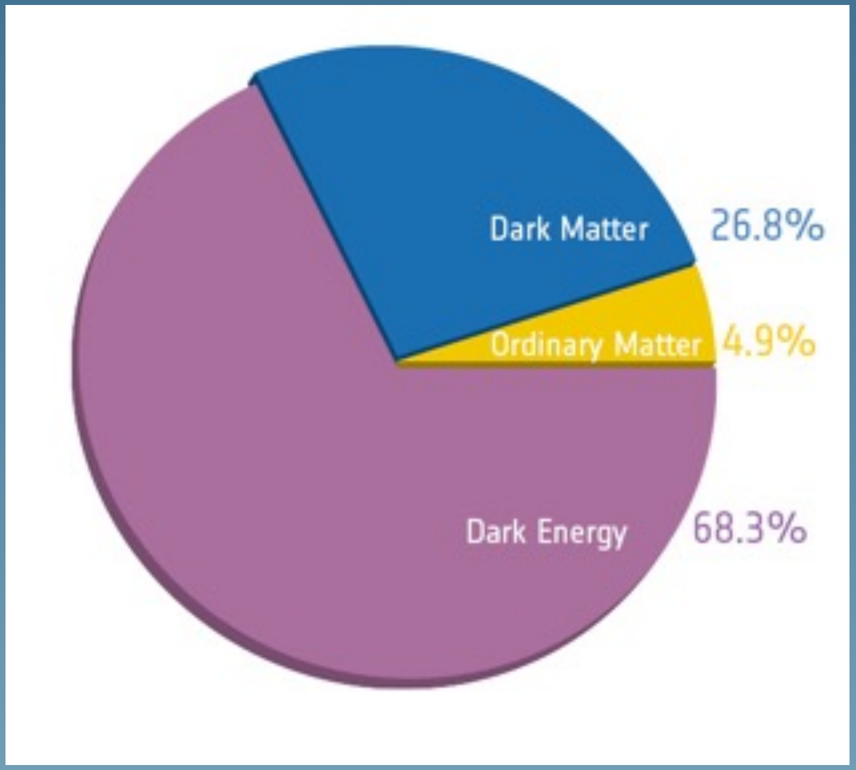


Parameter	Best fit	68% limits
$\Omega_b h^2$	0.022069	0.02207 ± 0.00027
$\Omega_c h^2$	0.12025	0.1198 ± 0.0026
$100\theta_{MC}$	1.04130	1.04132 ± 0.00063
τ	0.0927	$0.091^{+0.013}_{-0.014}$
n_s	0.9582	0.9585 ± 0.0070
$\ln(10^{10} A_s)$	3.0959	3.090 ± 0.025



Beyond Concordance ΛCDM

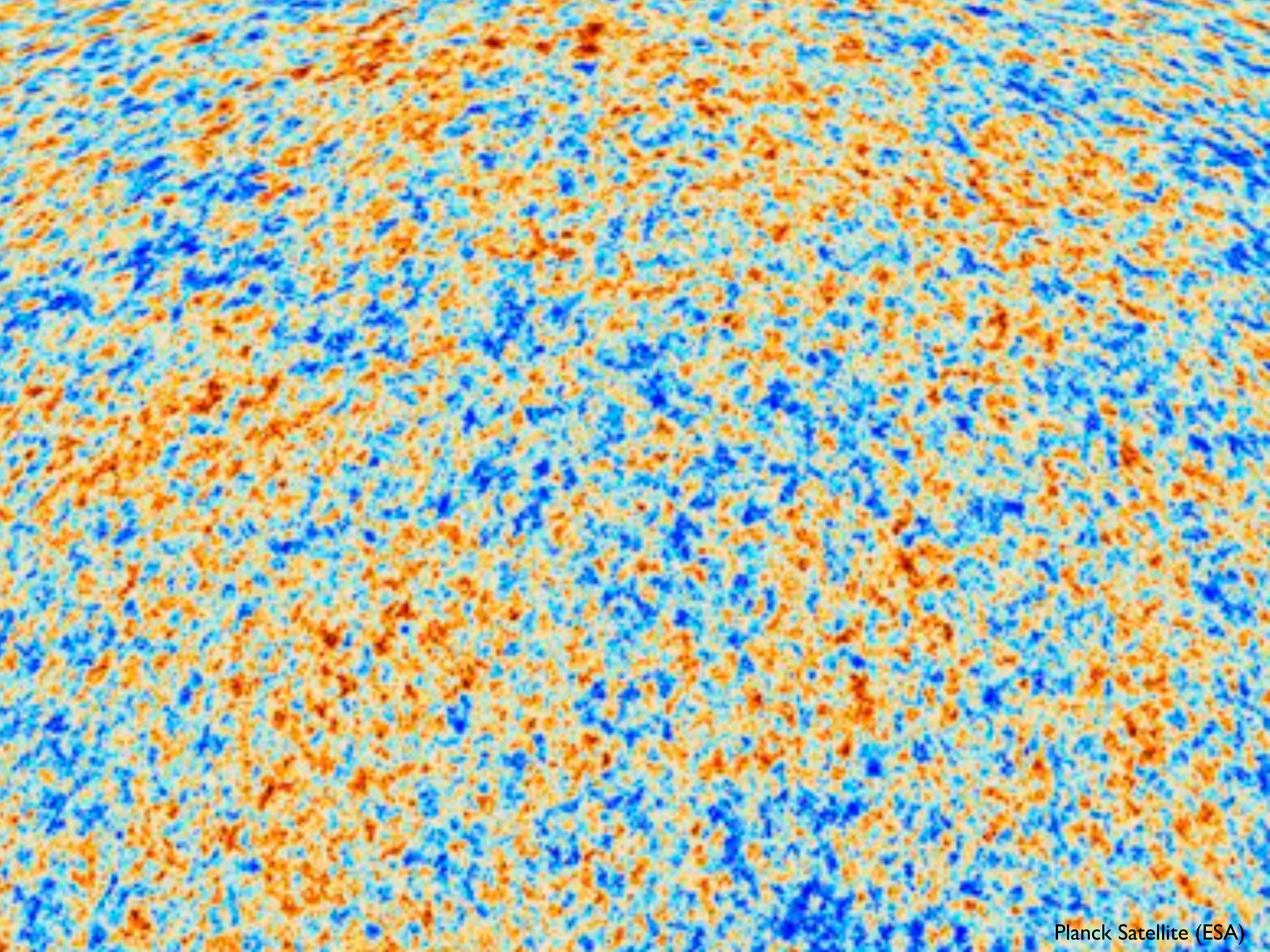
Is Dark Energy a cosmological constant?

Are modifications to GR required?

What is the sum of neutrino masses?

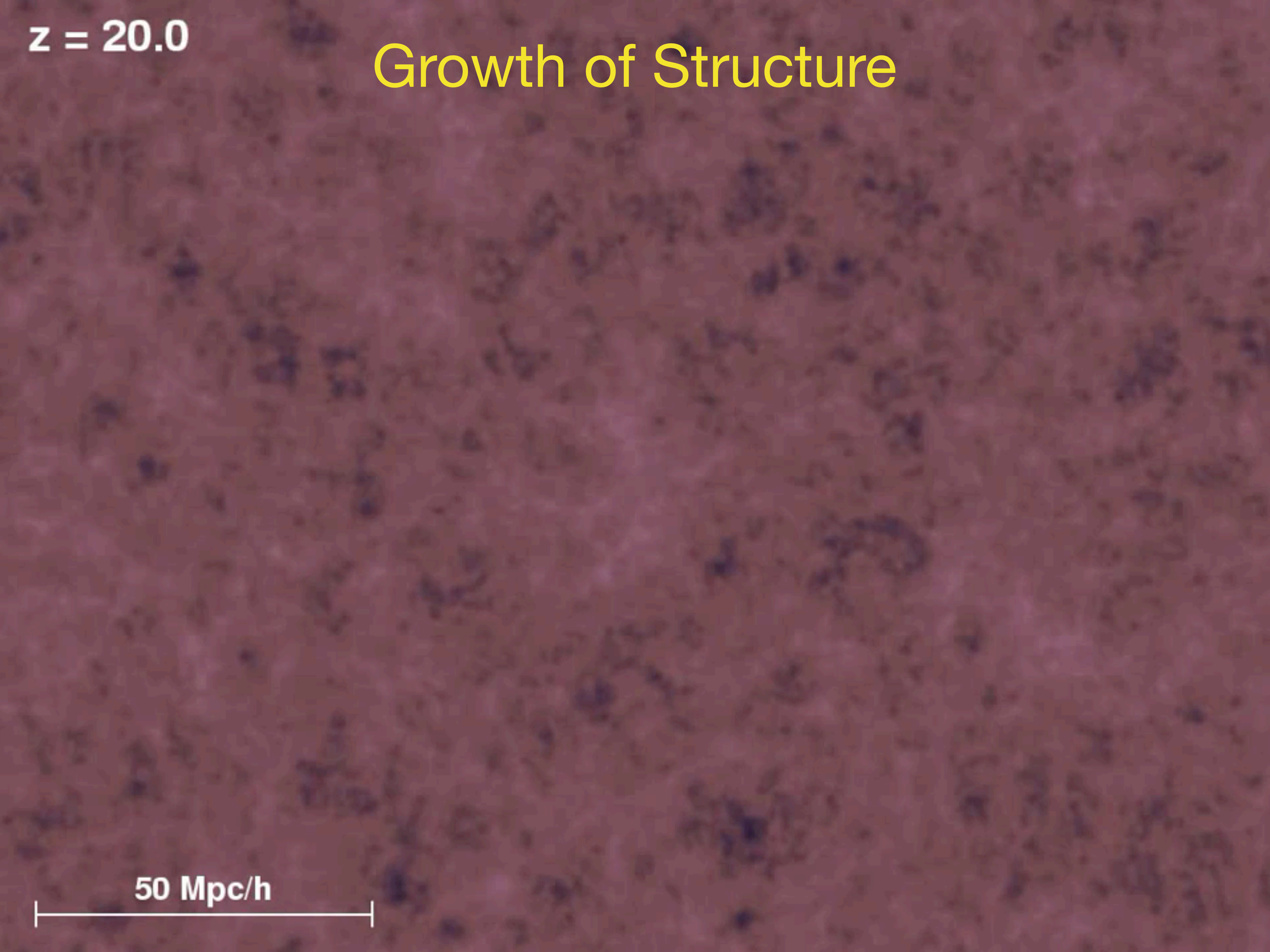
Here the CMB is limited:
- 1 snapshot in time ($z = 1100$)
- 2D surface (only so many large-scale modes)

Growth of structure measurements are 1 way to constrain these extensions

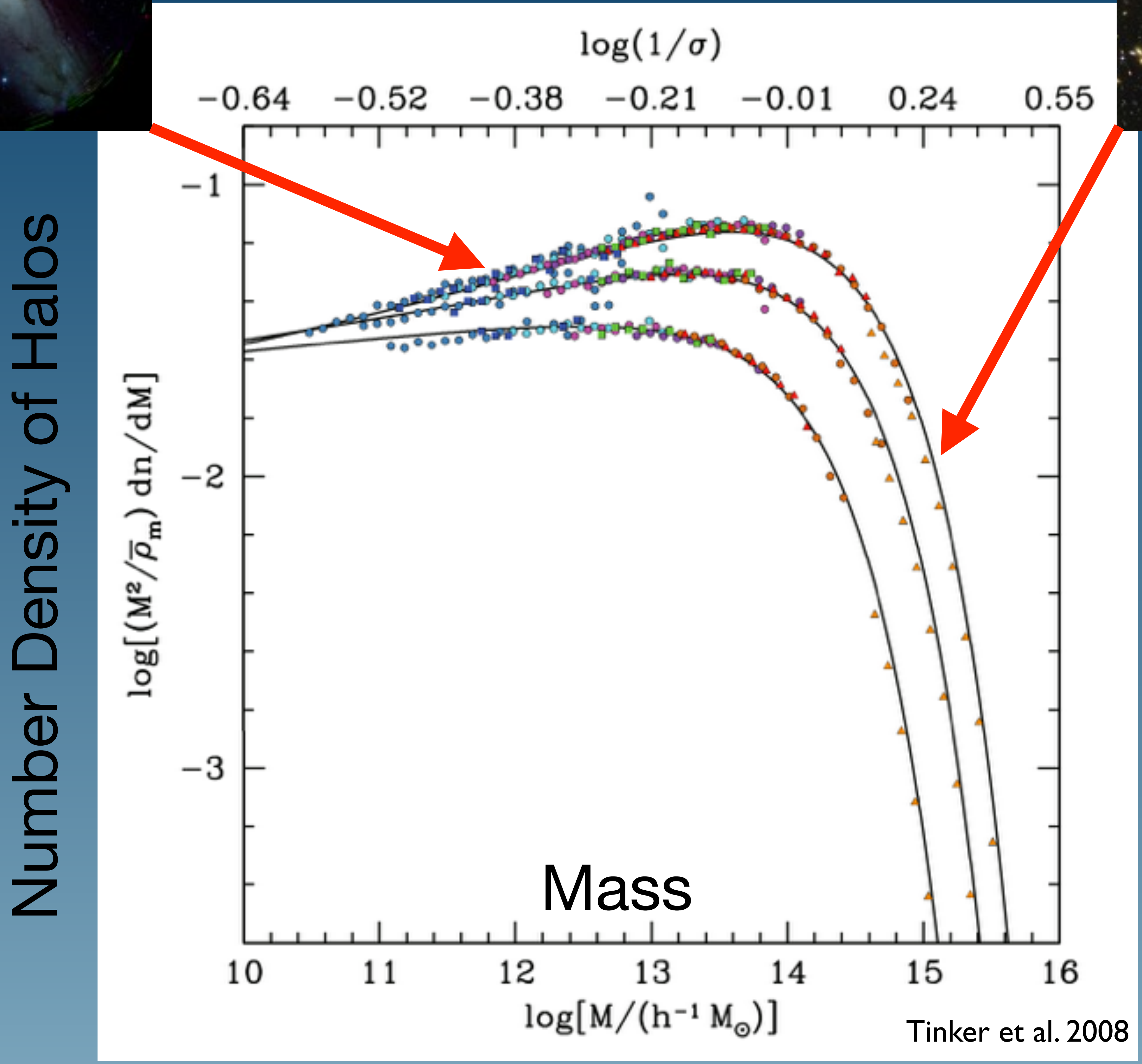


Planck Satellite (ESA)

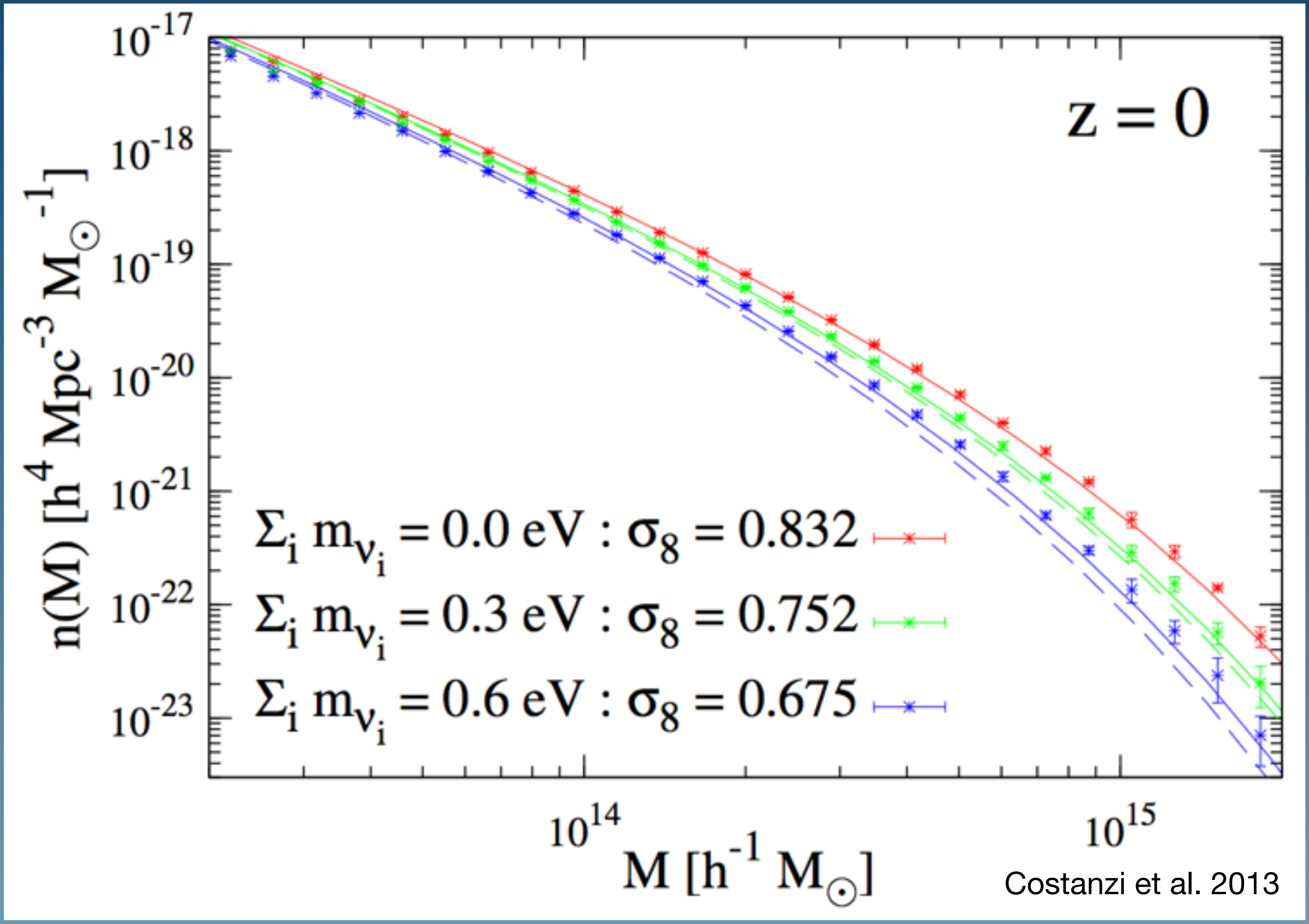
Growth of Structure



Growth of Structure
Halo Mass Function



Growth of Structure
Halo Mass Function



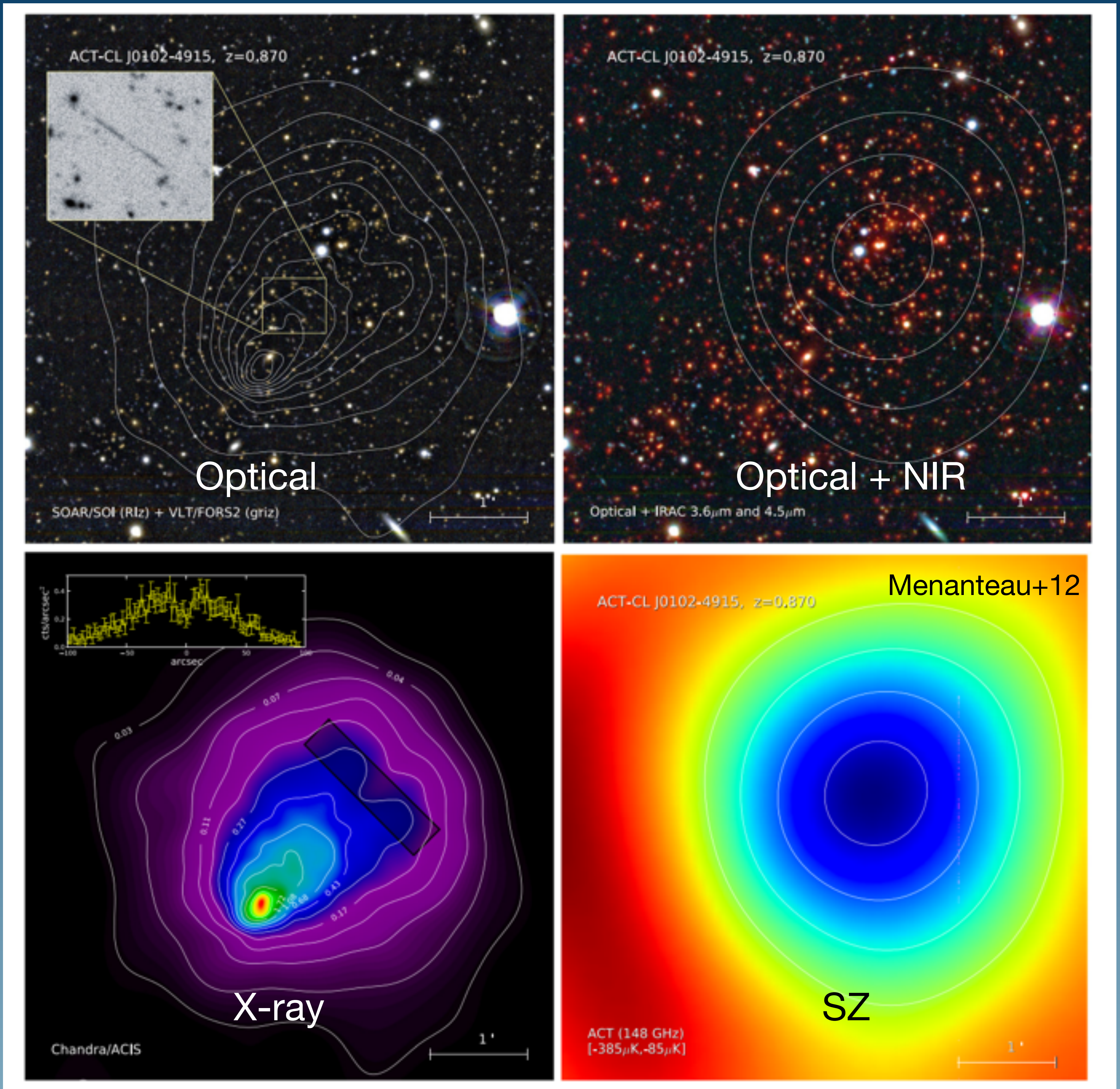
Galaxy clusters abundances are sensitive to ΛCDM extensions

Galaxy Clusters

10s to 100s
of galaxies

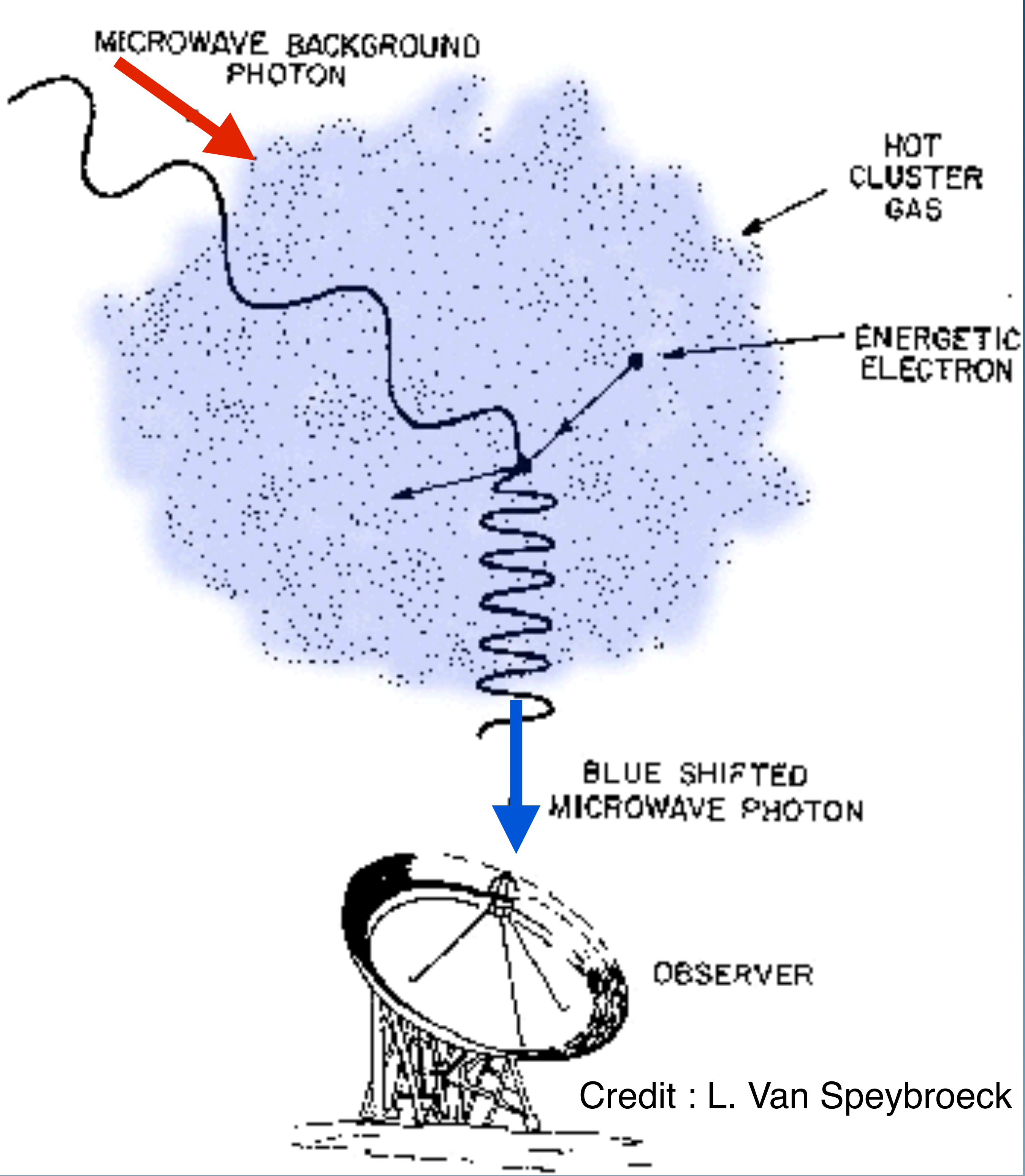
Most massive
gravitationally
collapsed objects
in the Universe

Multi-wavelength
observations

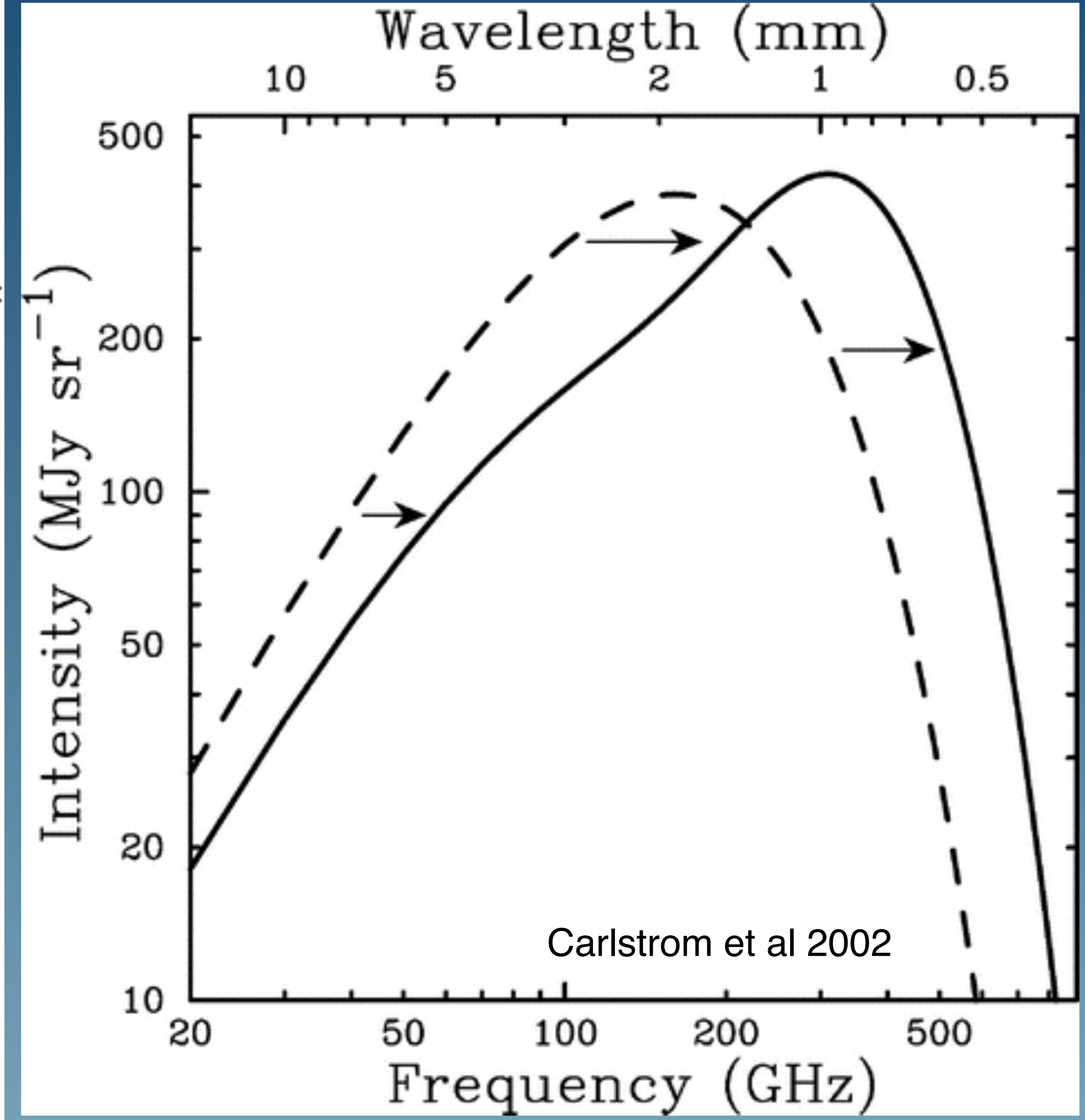


Thermal Sunyaev-Zel’dovich Effect

Inverse Compton scattering of CMB

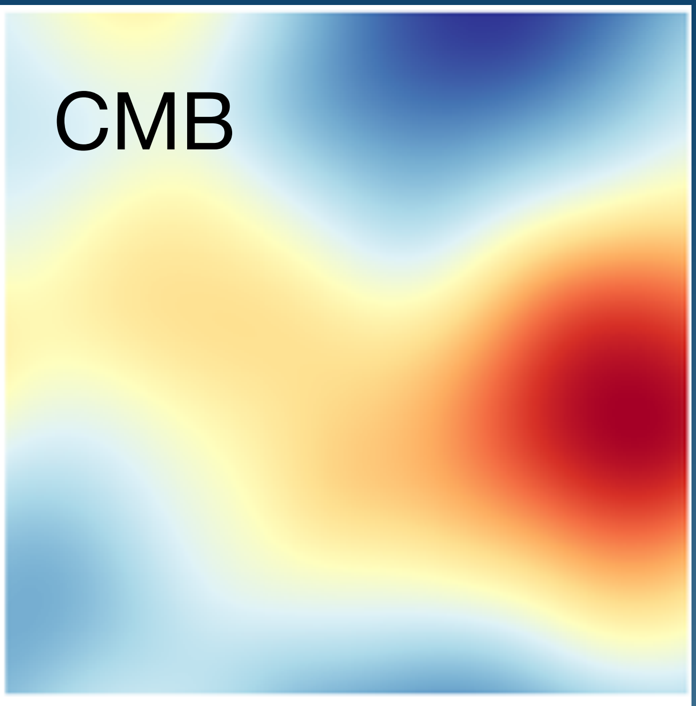


Credit : L. Van Speybroeck

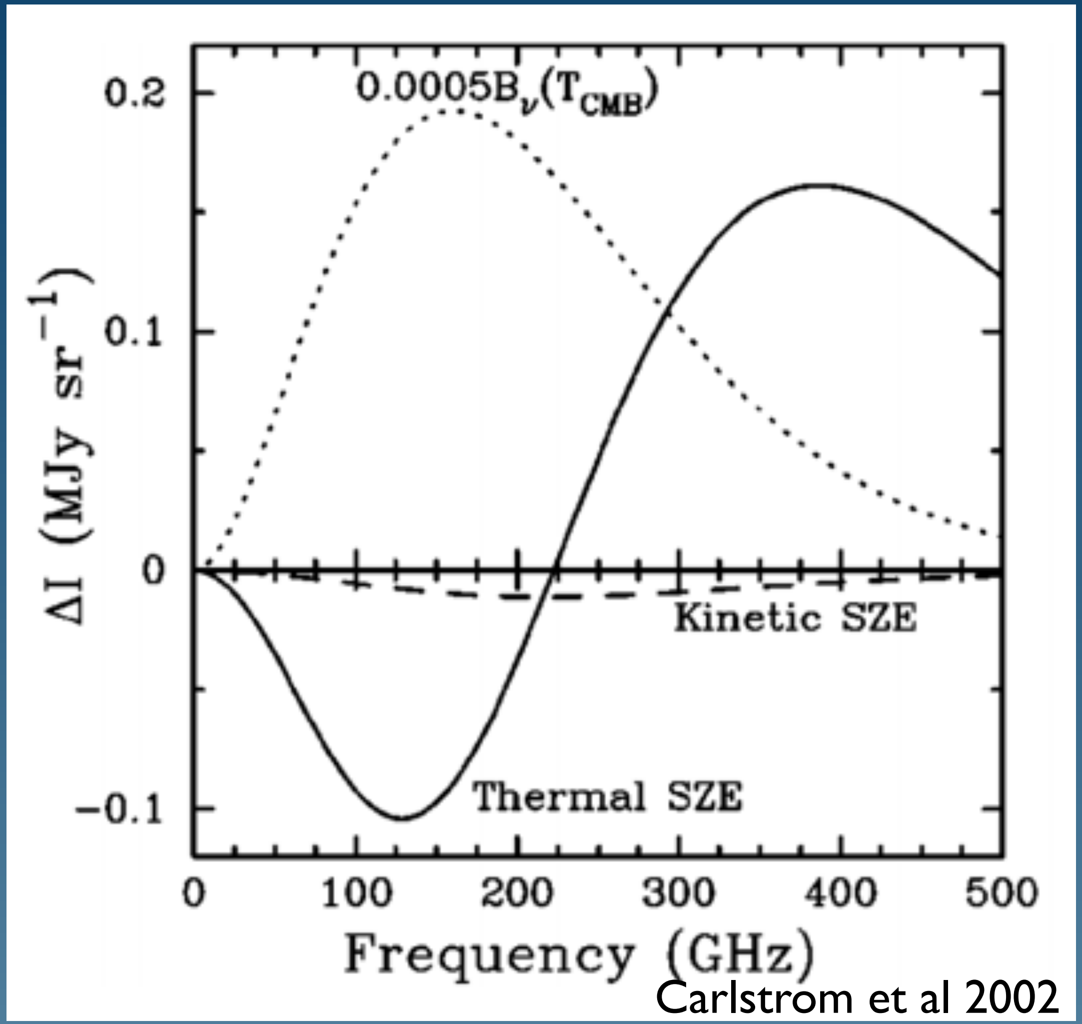


Carlstrom et al 2002

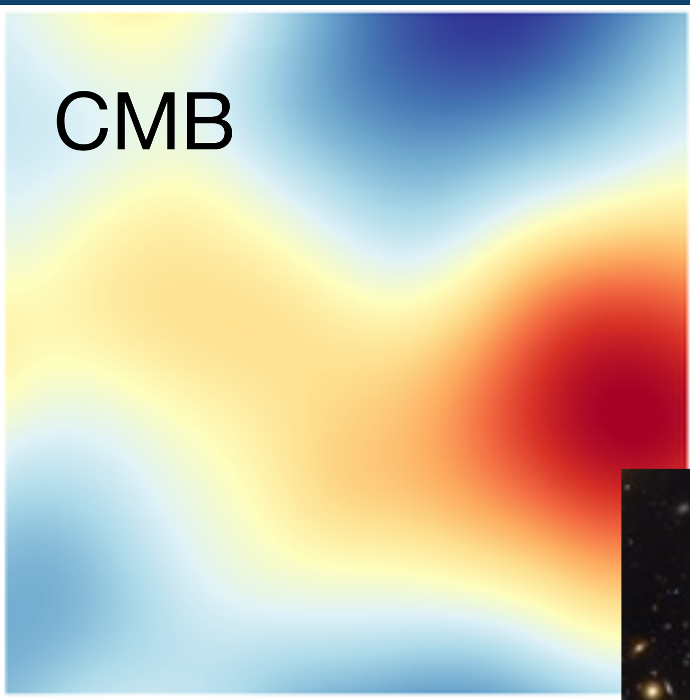
Thermal Sunyaev-Zel'dovich Effect



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



Thermal Sunyaev-Zel'dovich Effect



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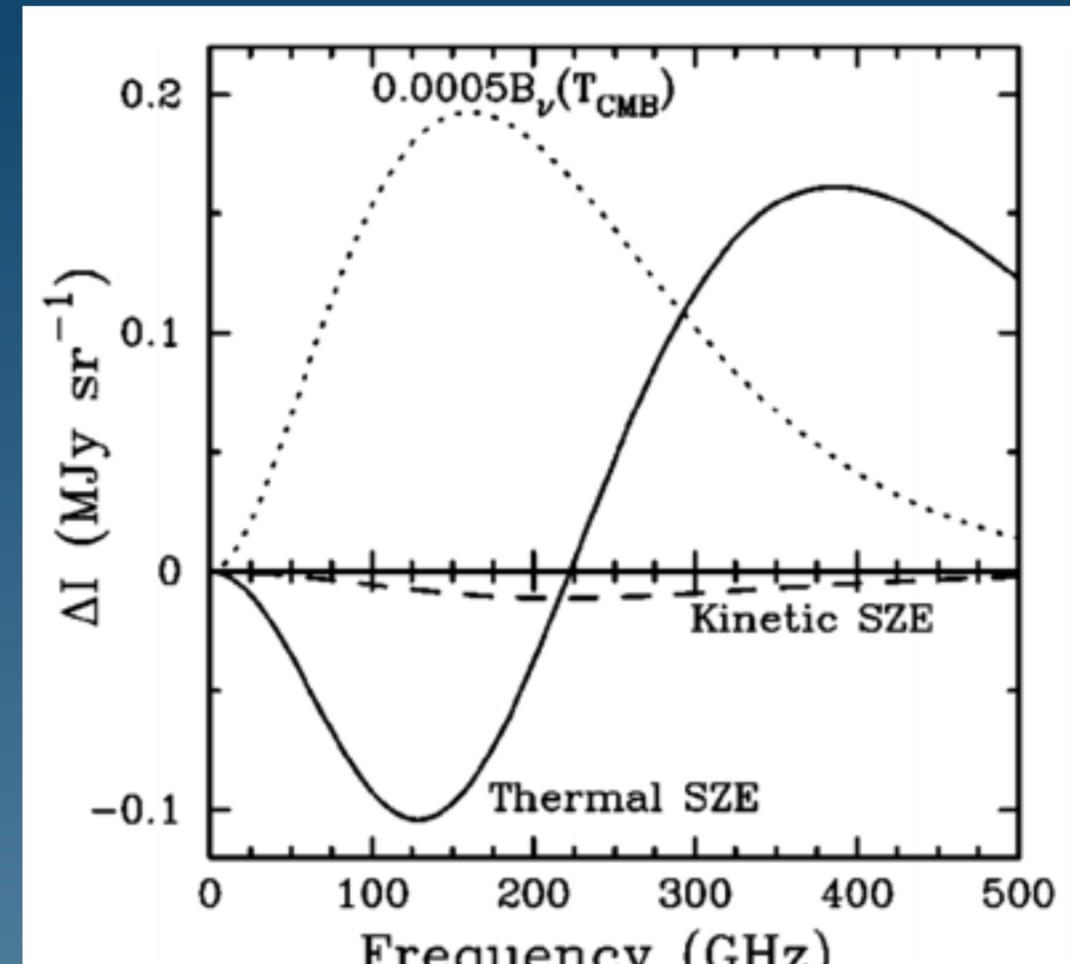
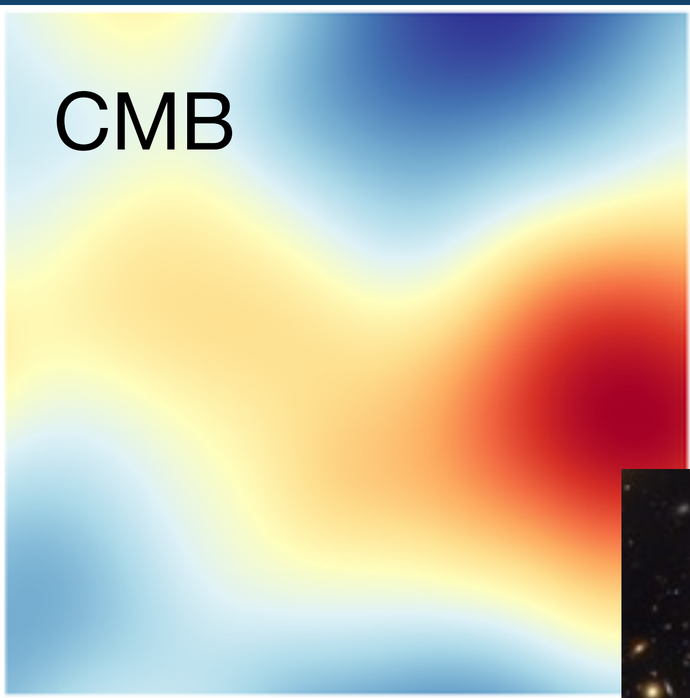
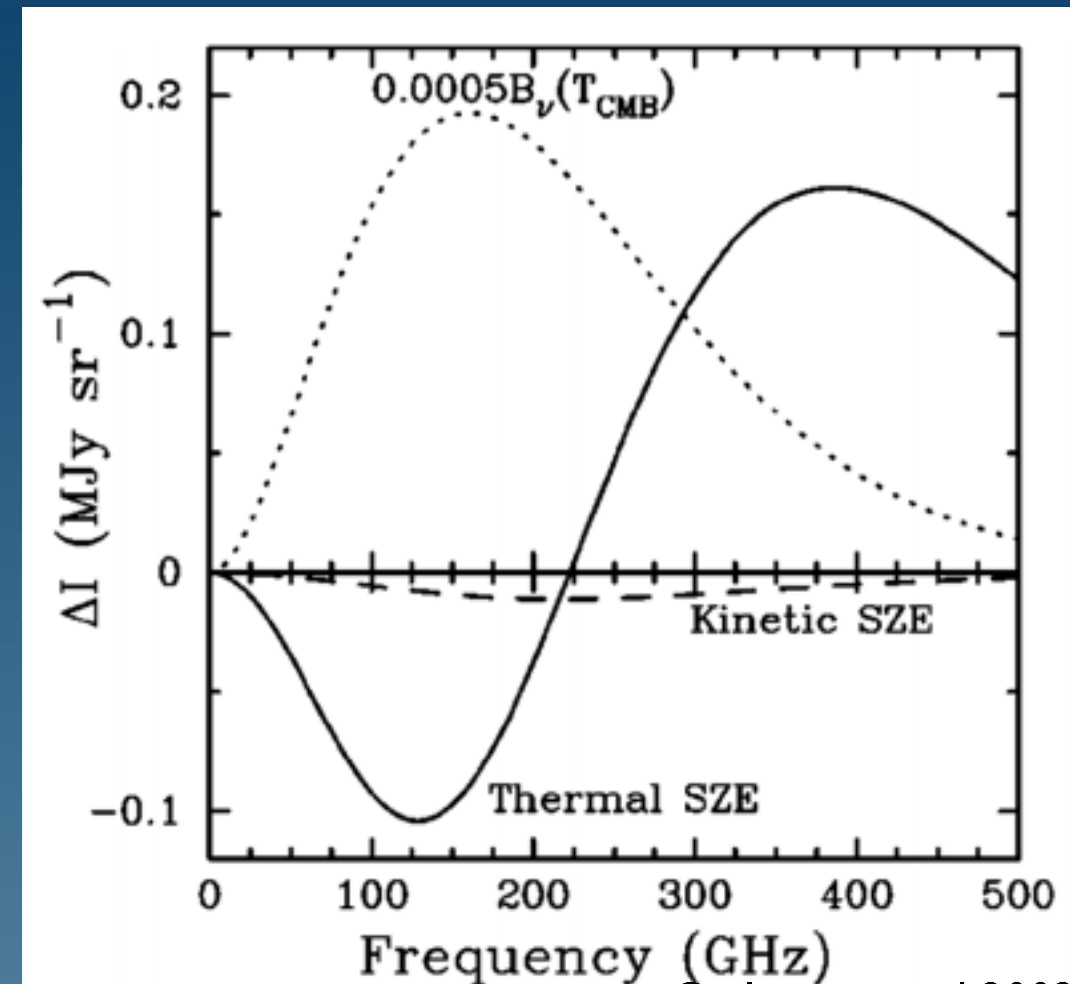


Carlstrom et al 2002

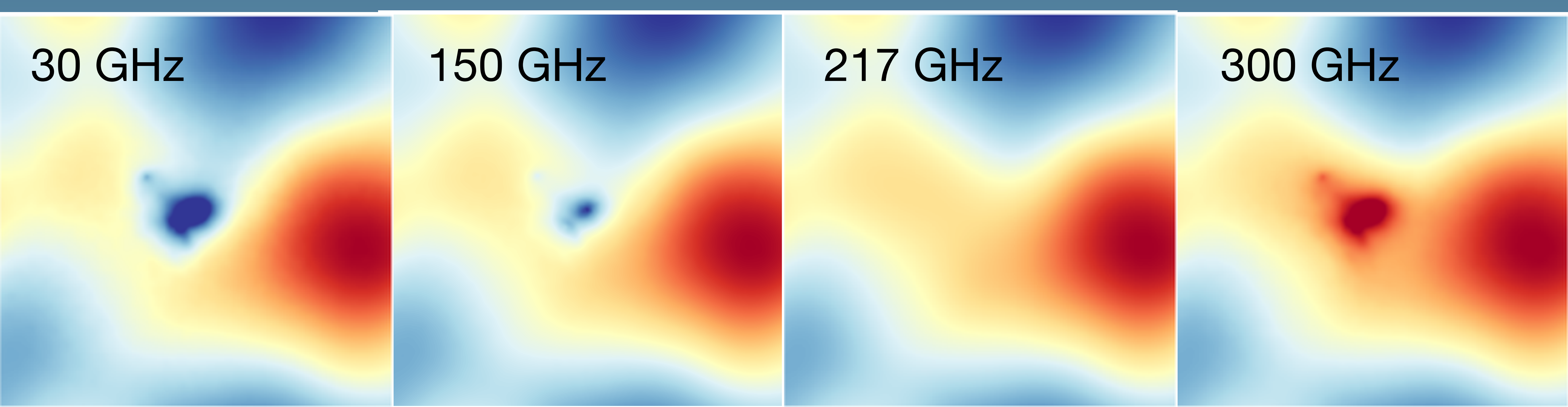
Thermal Sunyaev-Zel'dovich Effect



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



Carlstrom et al 2002



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 Pros

-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

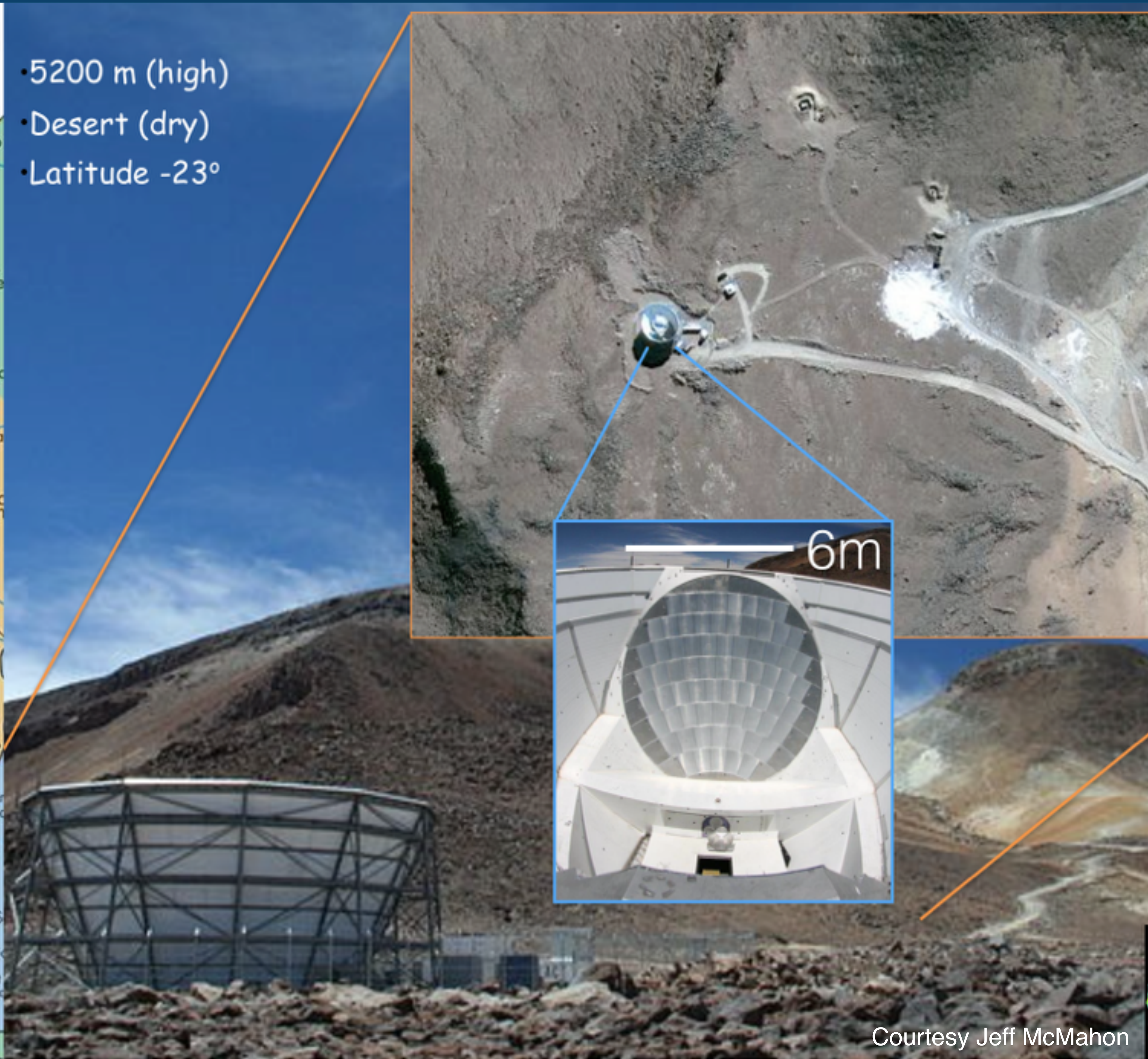
-Redshift independent

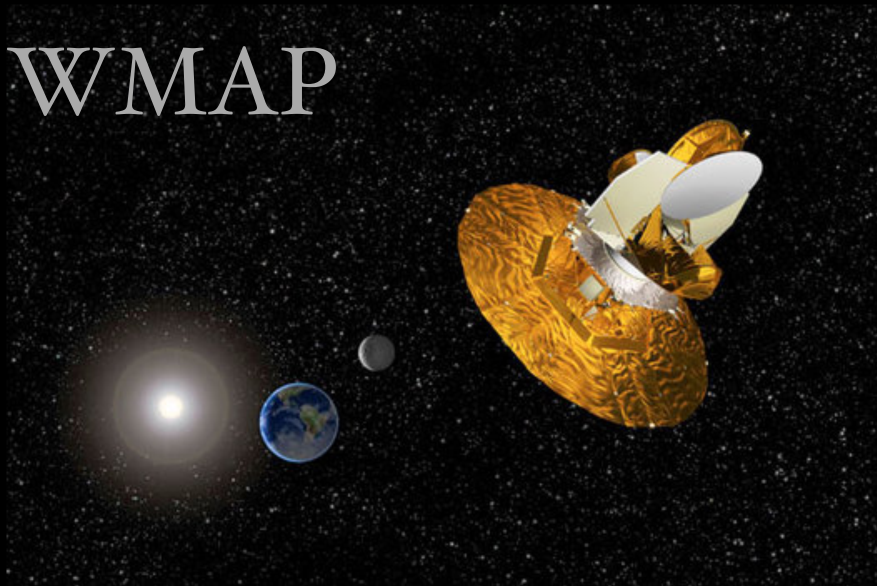
How do detect the tSZ and find clusters

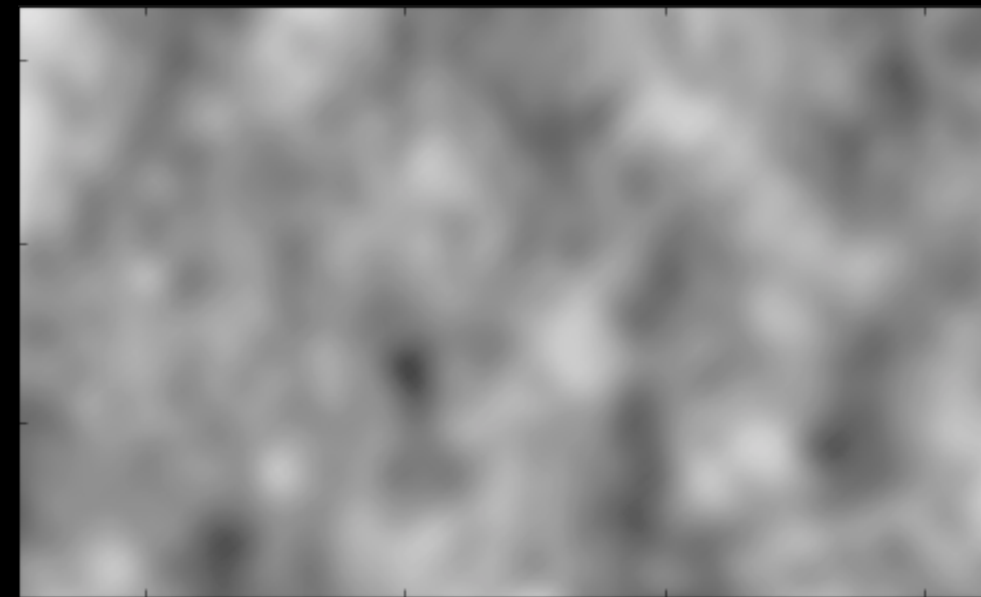
The Atacama Cosmology Telescope

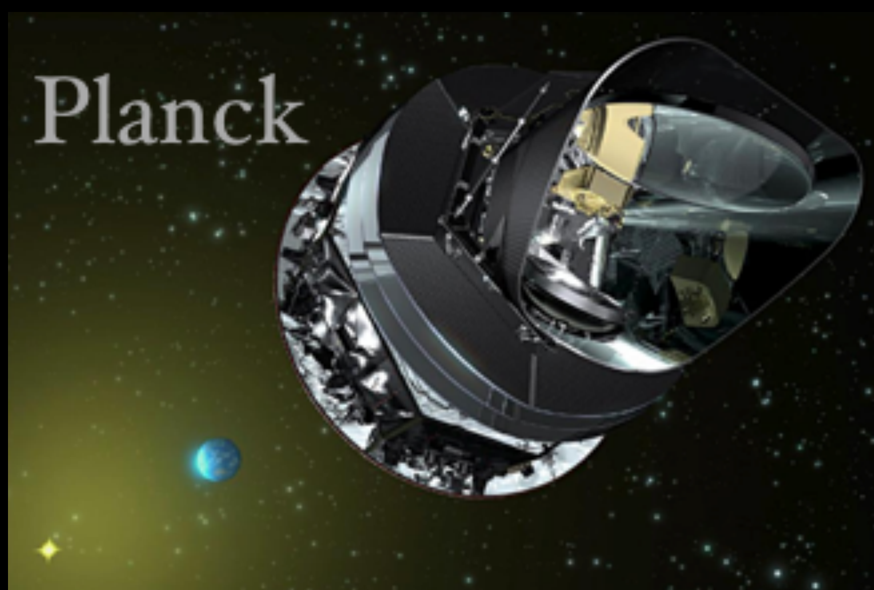
The Atacama Cosmology Telescope

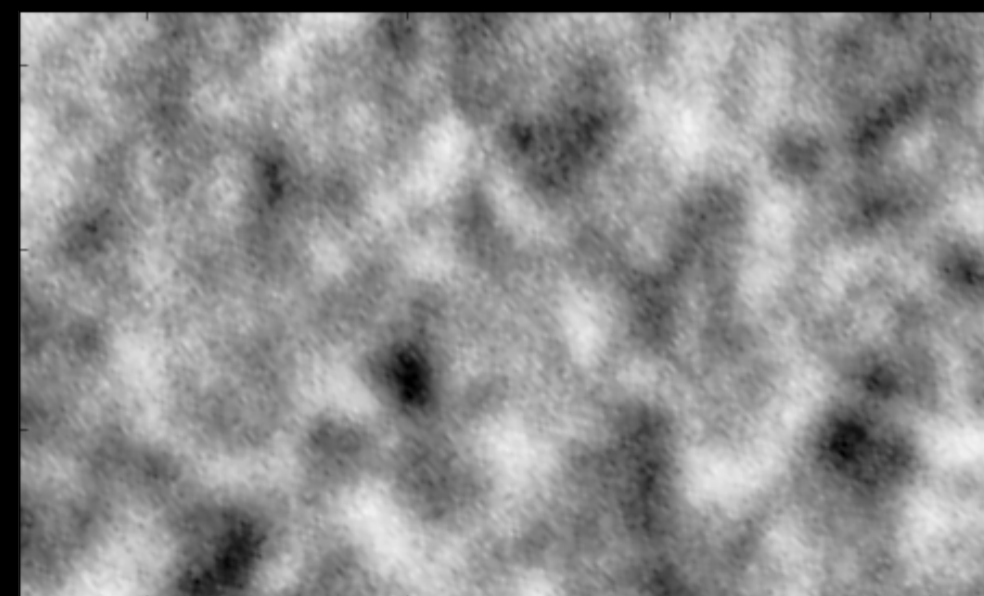
- 5200 m (high)
- Desert (dry)
- Latitude -23°

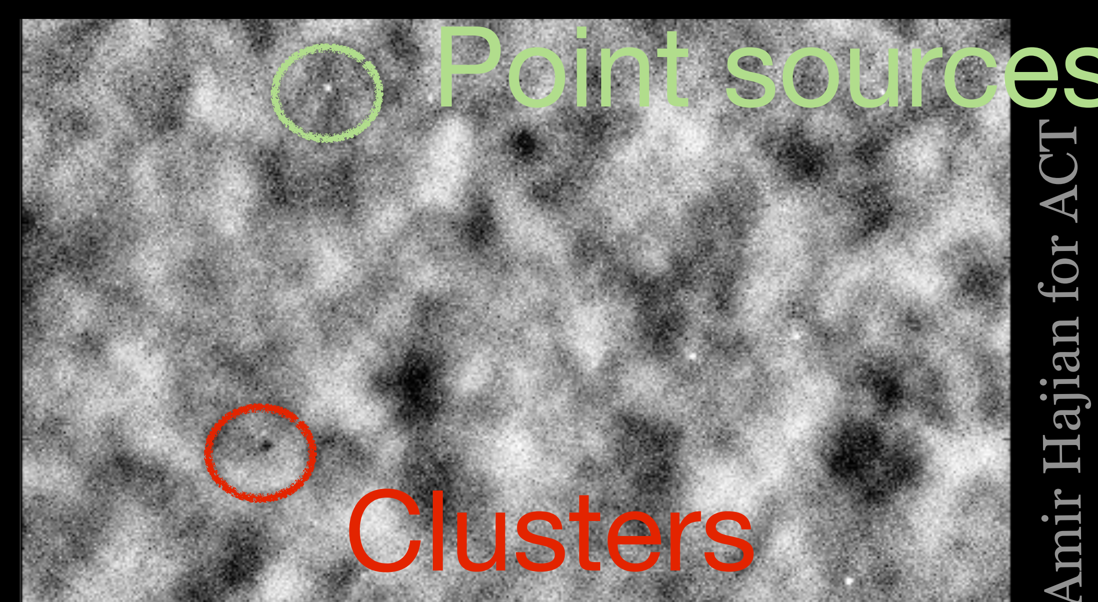








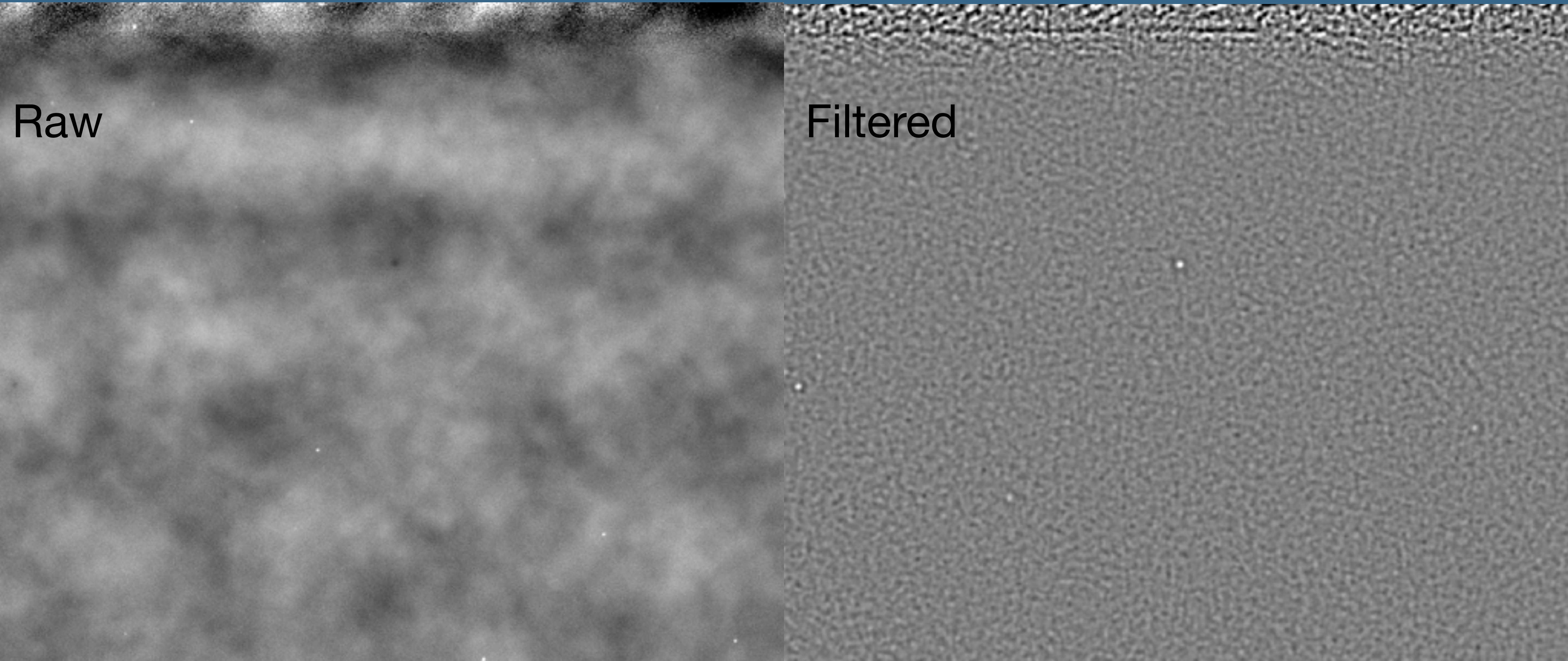




Amir Hajian for ACT

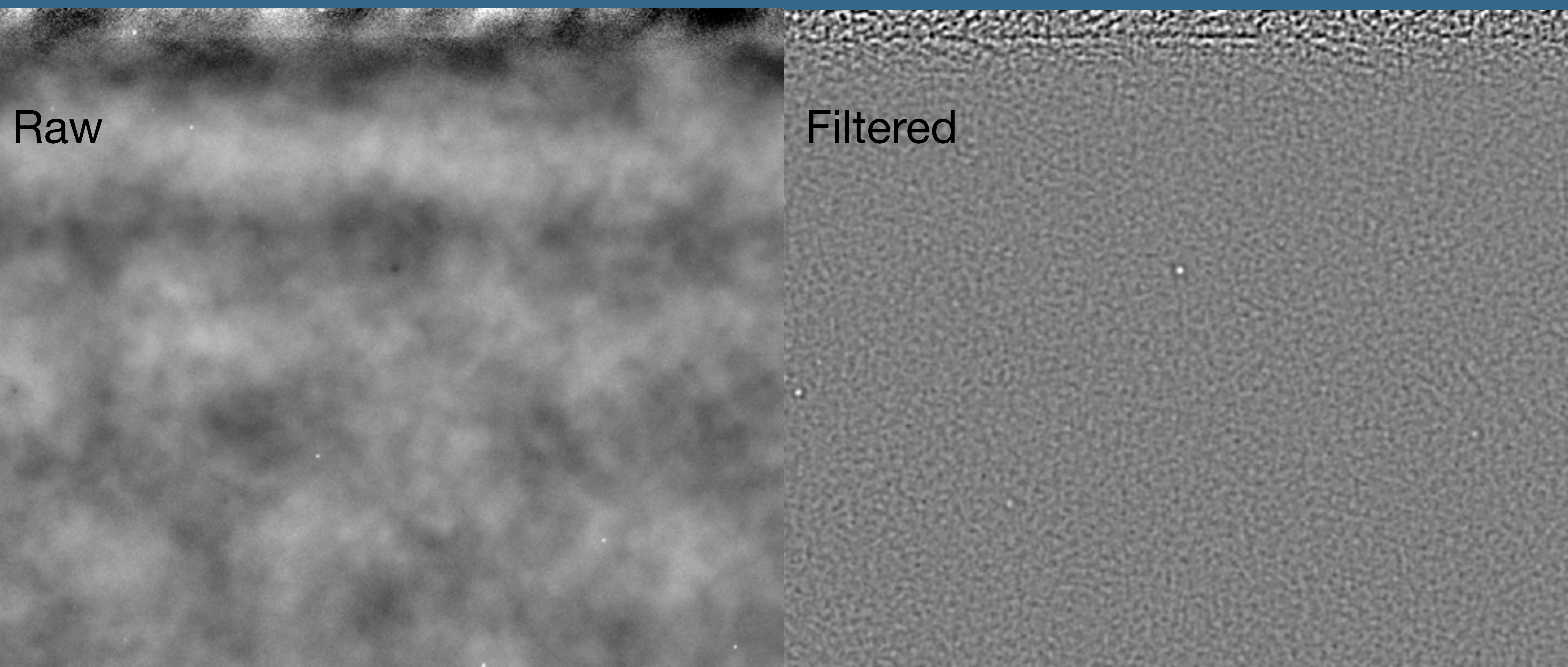
Finding SZ clusters in data

Signal processing - Match filter
Model for the signal (y-profile)
Model for the noise (CMB + Instrumental)



Characterizing SZ clusters in data

Follow-up observations
Estimate their masses
- Via the observable Y



Cosmology with clusters

Number counts

$$N = \int_0^{z_{\max}} dz \frac{dV}{dz} \int dM \frac{dn(M,z)}{dM}$$

Mass function

We do not measure mass P(M|A)

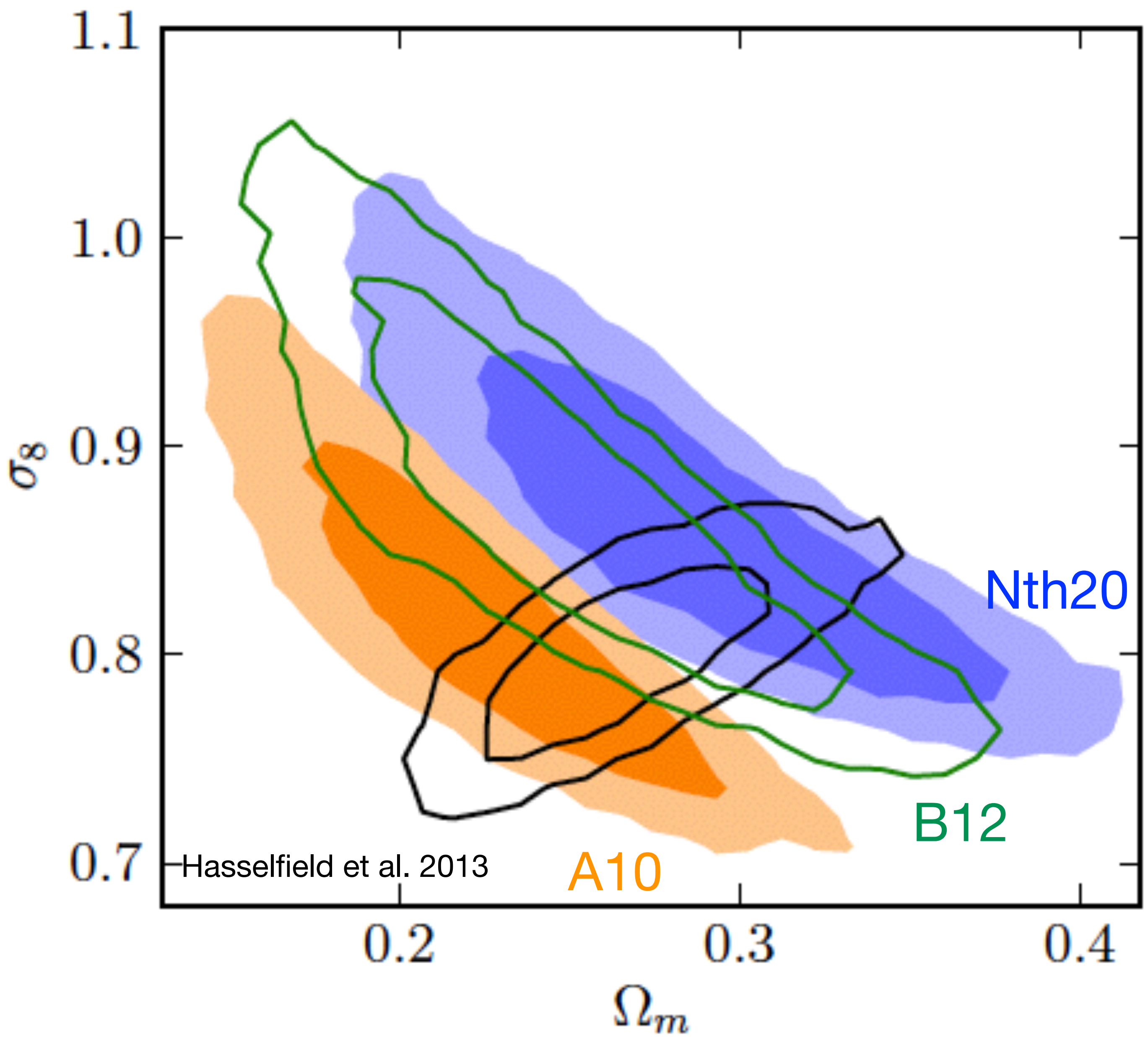
Selection function & Mass proxy

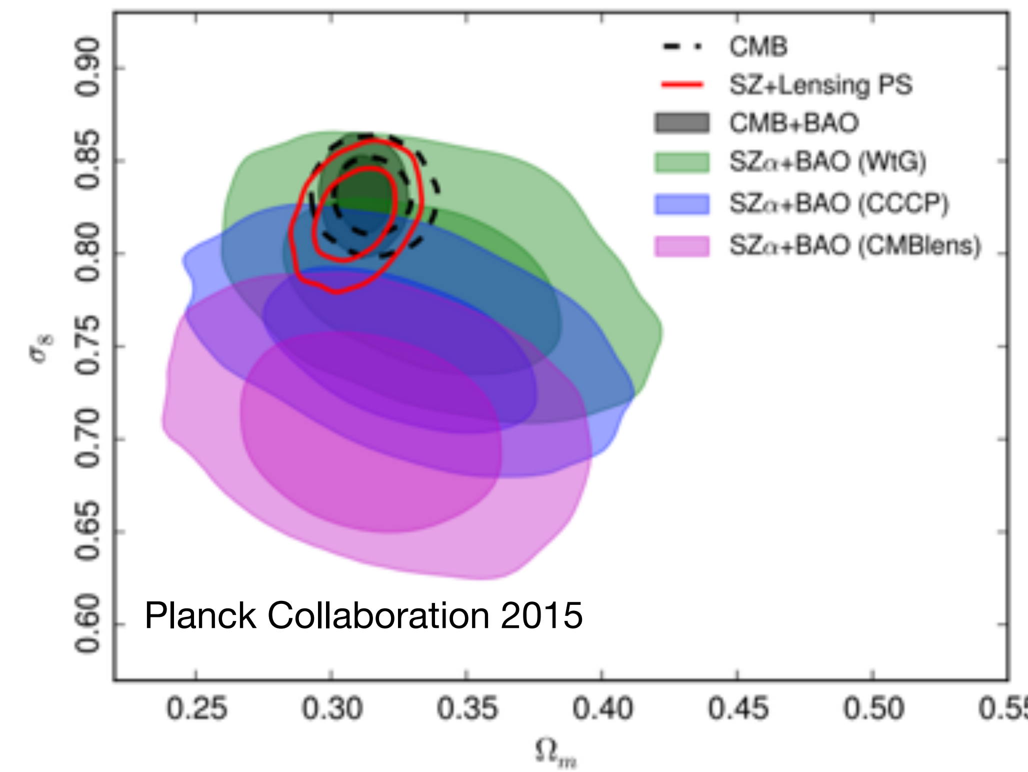
} Gastrophysics

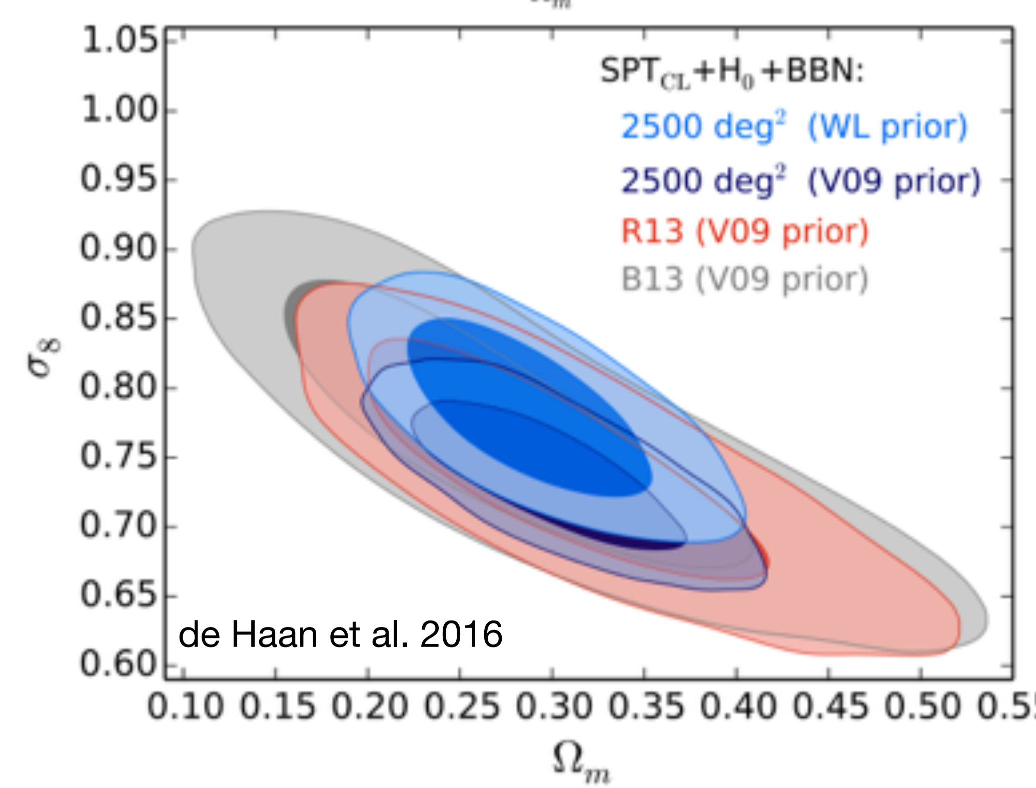
Cluster counts

Cosmological constraints from cluster counts

Status of cluster cosmology

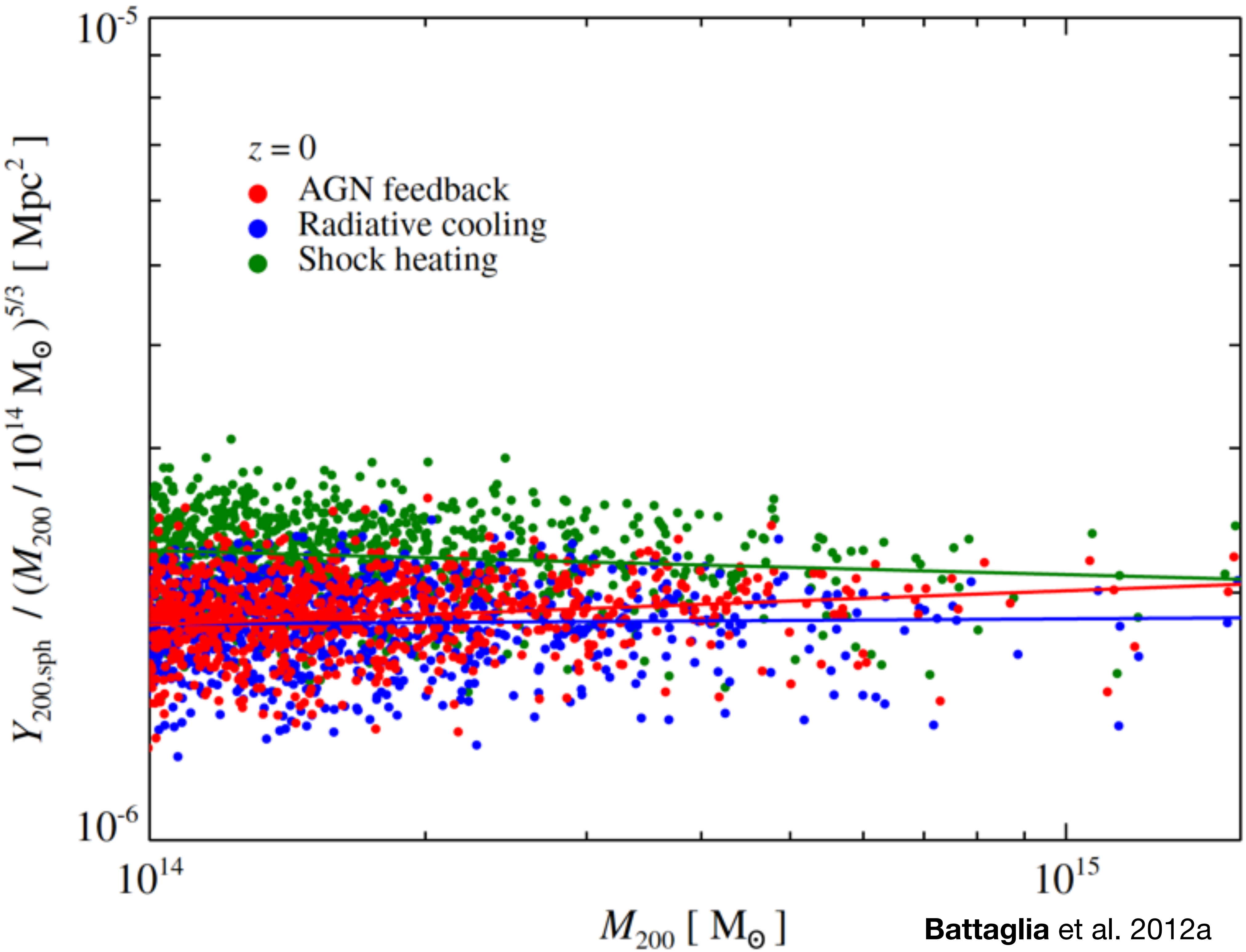






Limited by uncertainty in the Y-M relation & Pressure profile

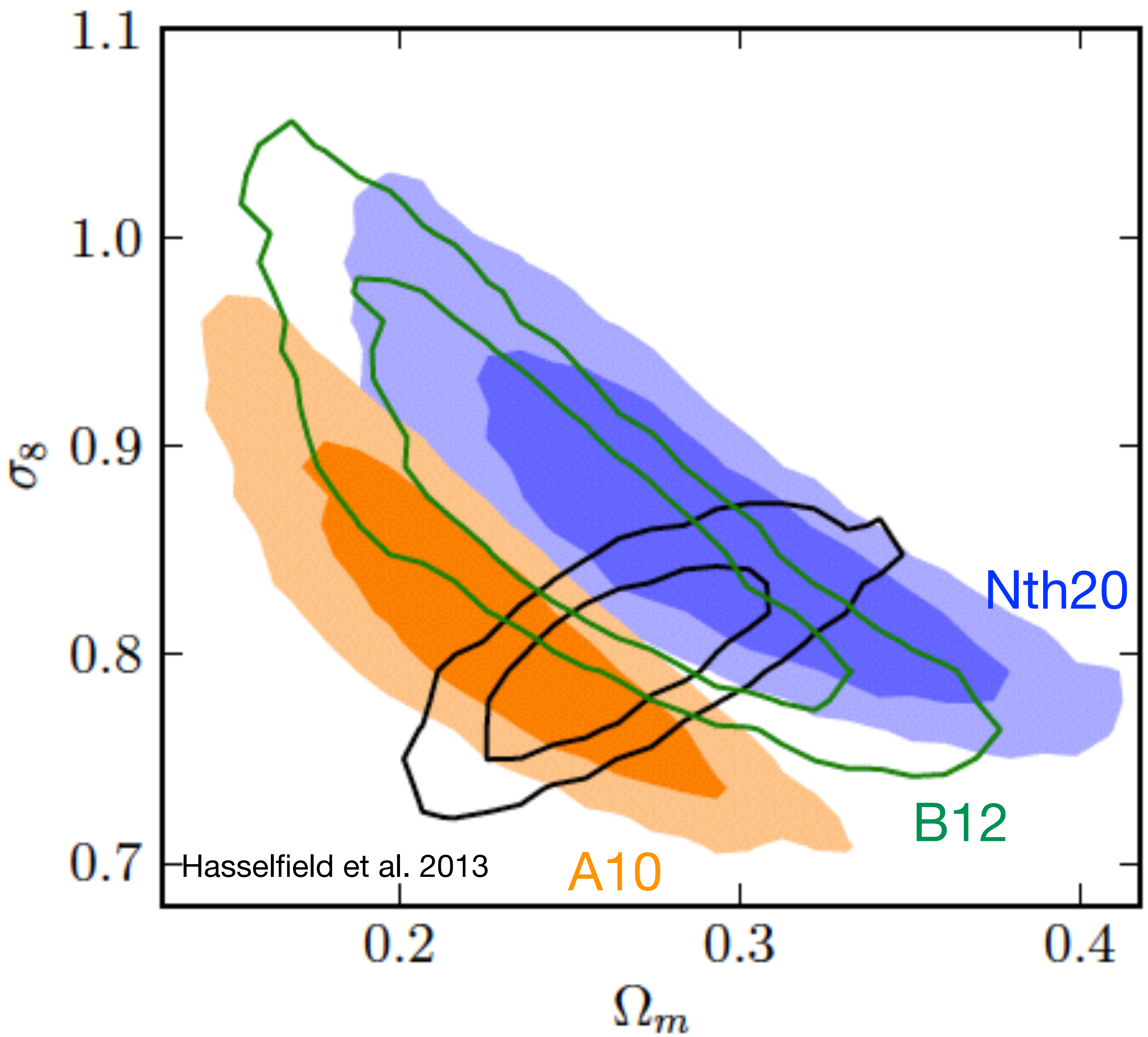
Cosmological constraints from cluster counts

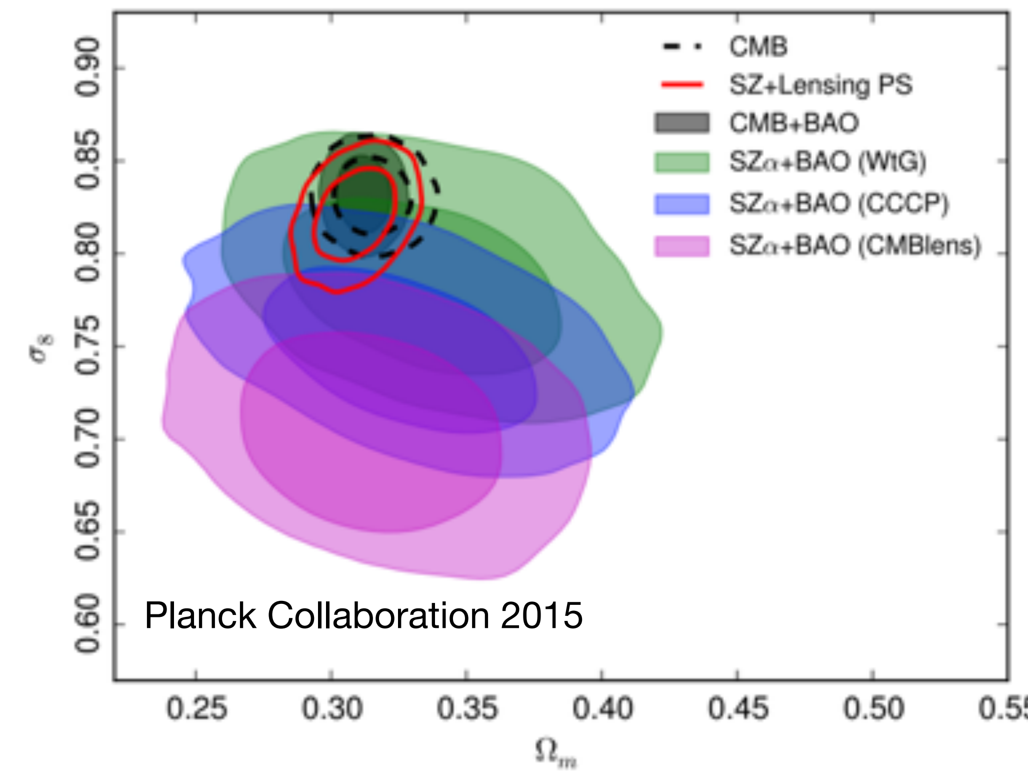


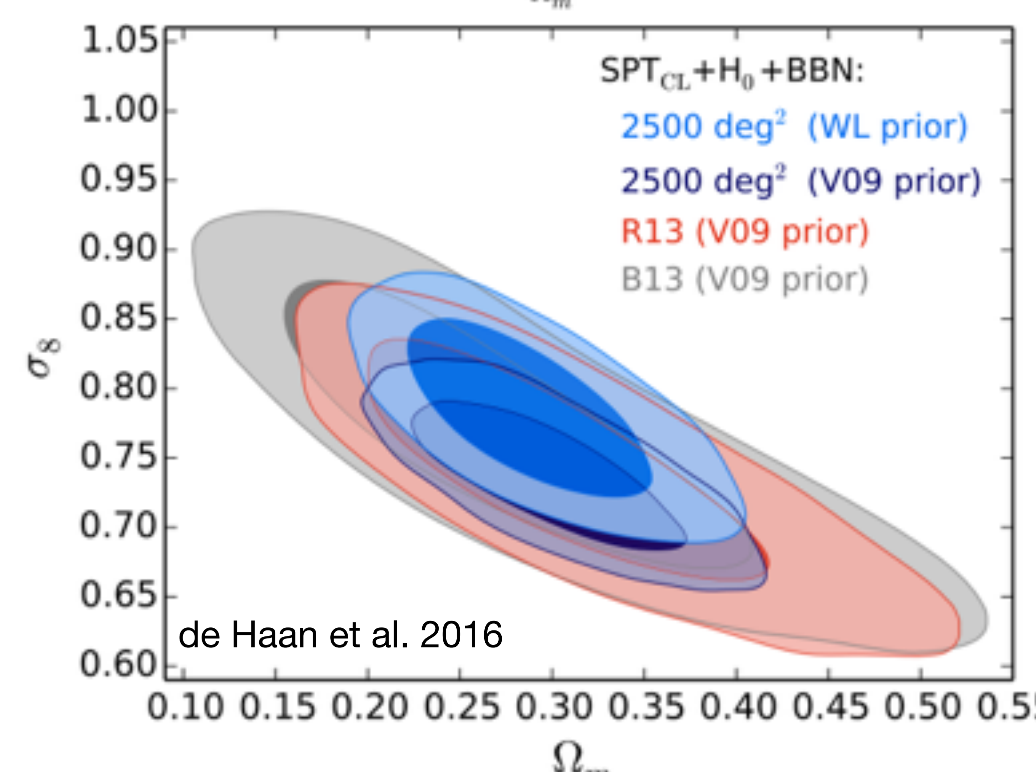
Battaglia et al. 2012a

Cosmological constraints from cluster counts

Status of cluster cosmology

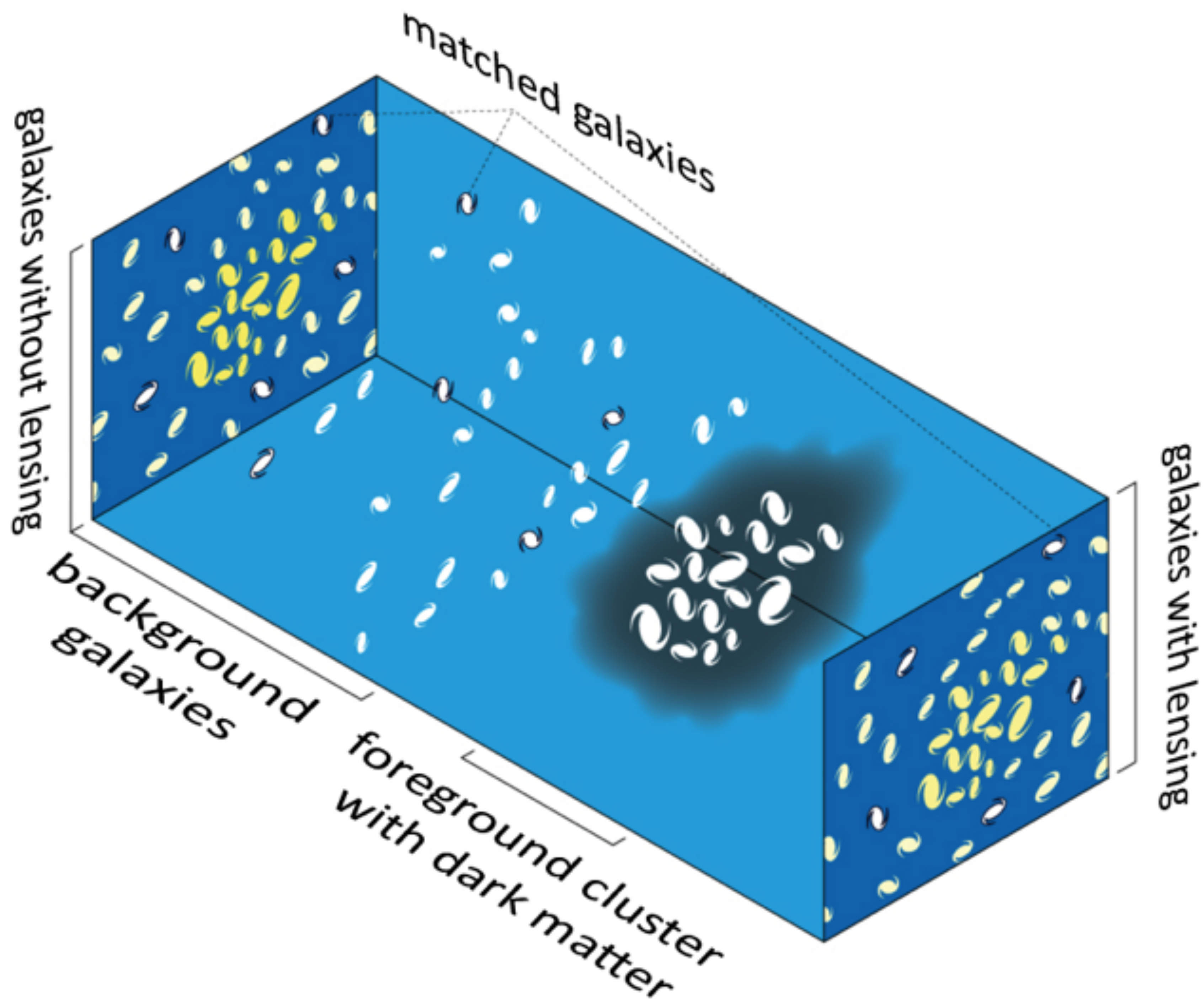






Empirically calibrate Y-M relation using weak lensing!

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

Mass calibration with CS82

CFHT Surevey of Stripe 82

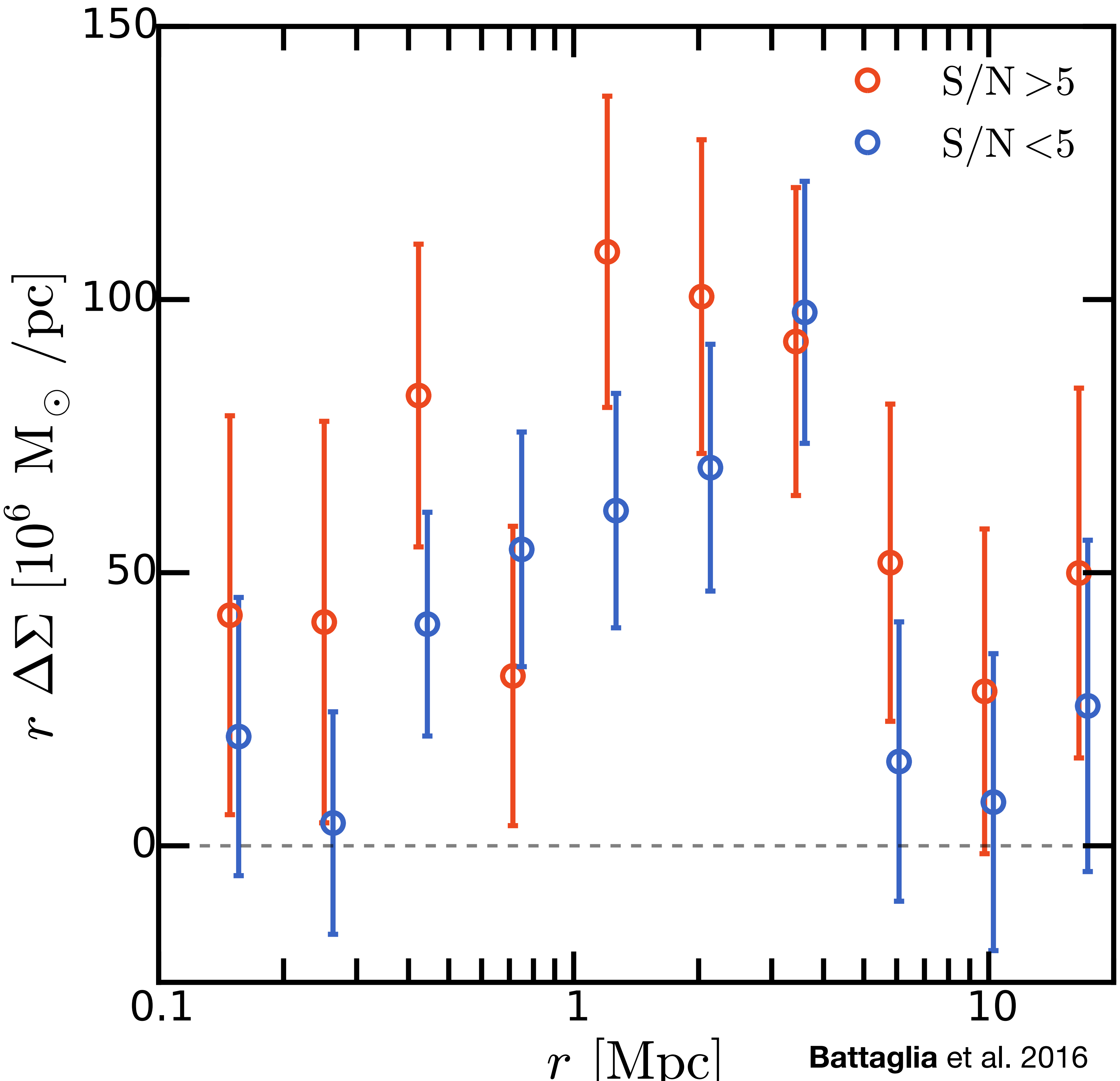
~130 sq. Deg. i′-band

Use *lens*fit for galaxy shapes

Source catalog is 4.5 galaxies per sq. arcmin

Reliably go out to z = 0.7

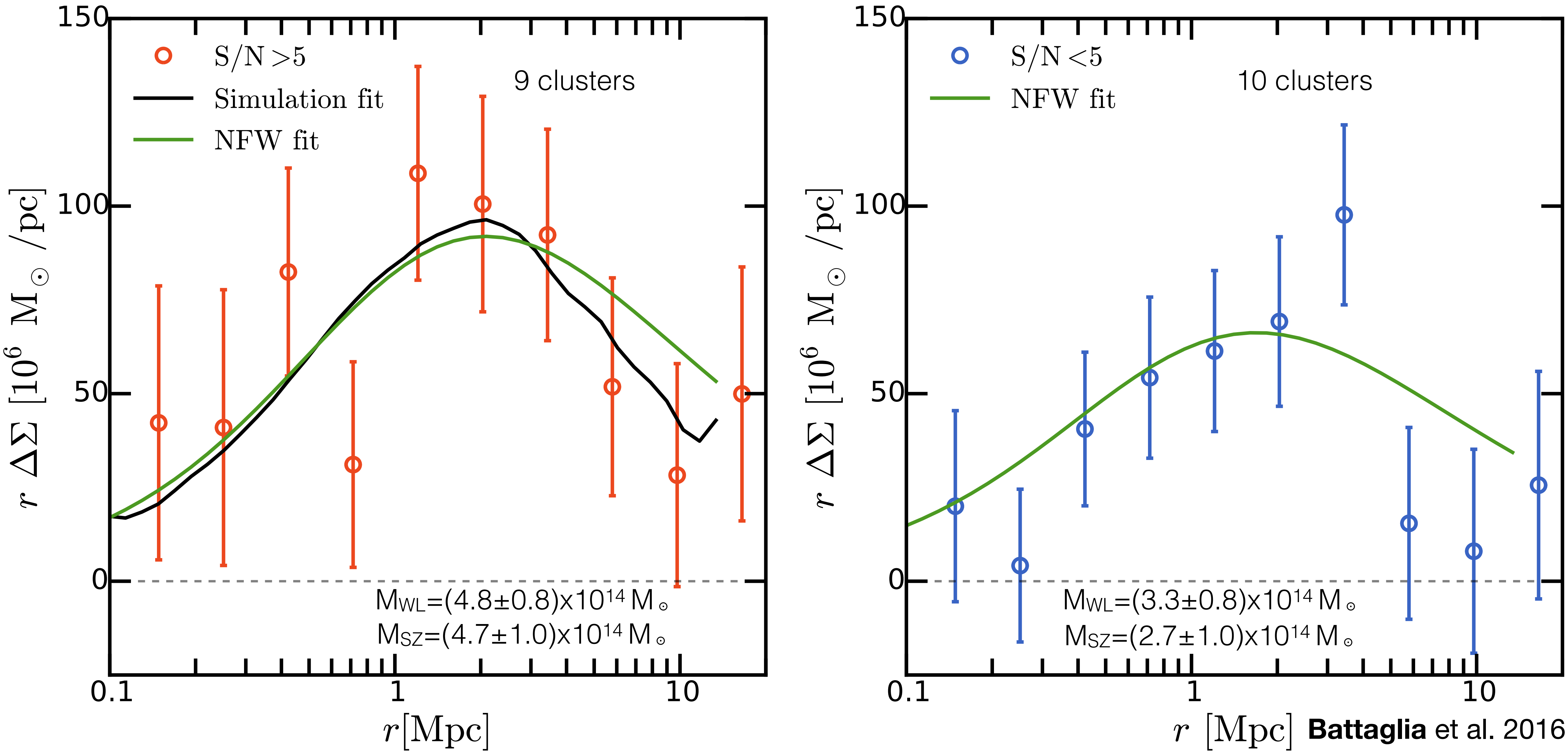
Statistical errors



Battaglia et al. 2016

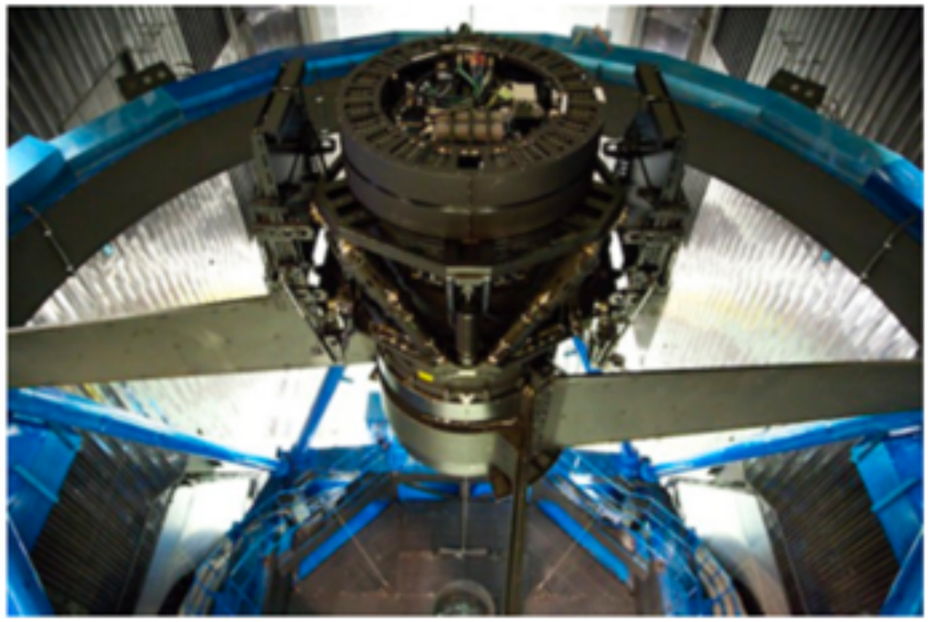
Mass Fits

- We fit the weak-lensing signal using simulations and an NFW profile.
- Use this mass calibration in upcoming ACT cluster cosmology work.



Battaglia et al. 2016

Hyper Suprime Camera

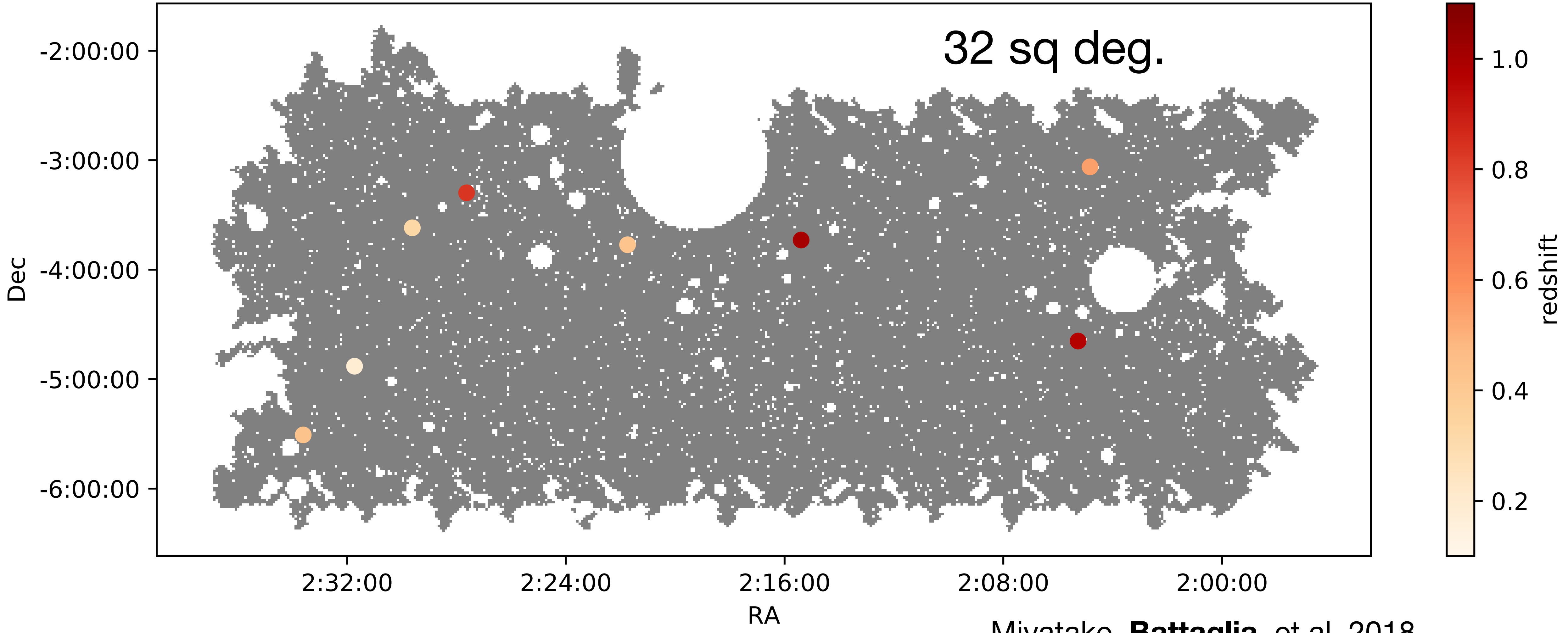


Subaru telescope

8.2 m, grizy, ~ 0.6” seeing

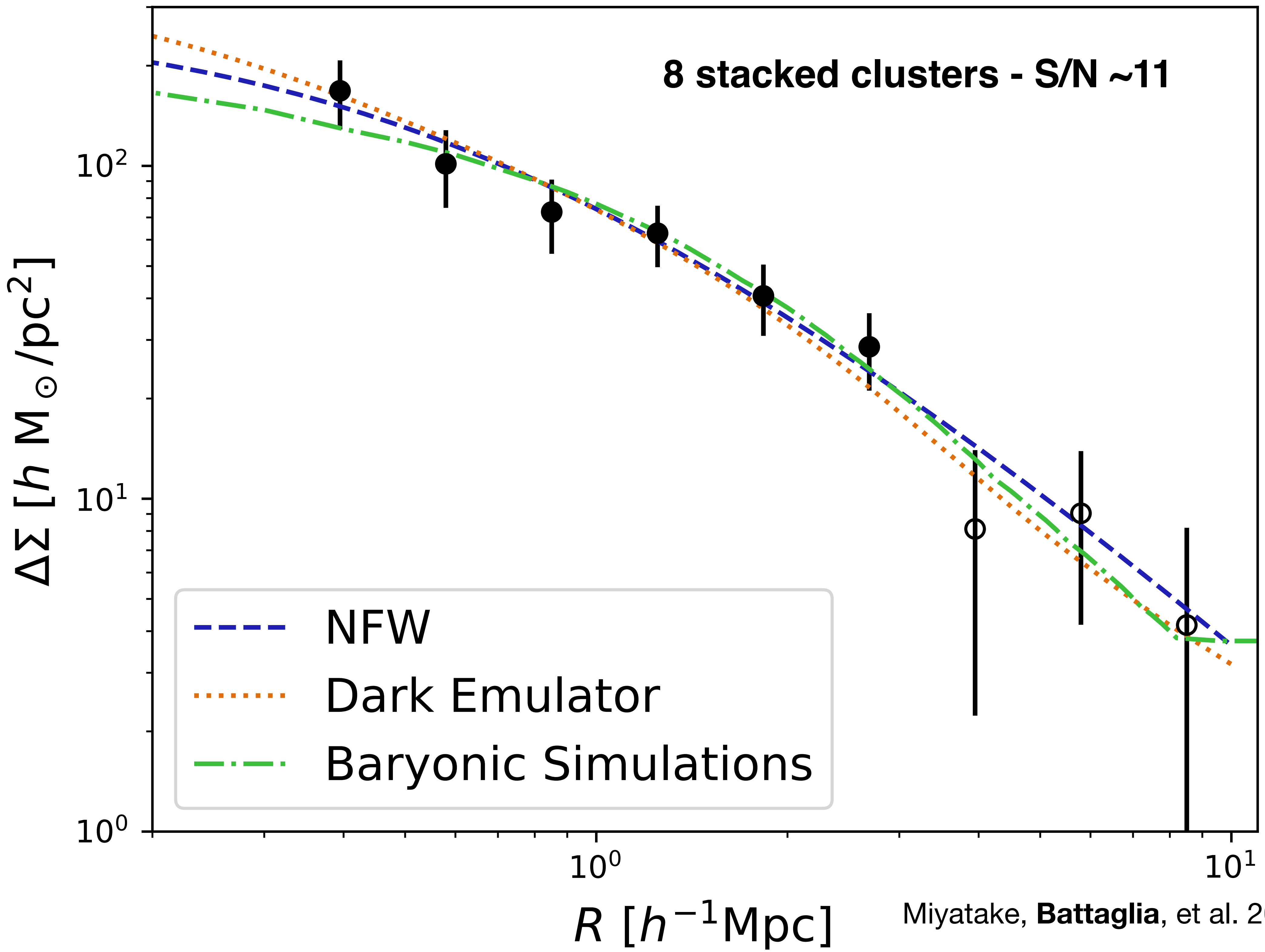
Full HSC 1400 sq deg.

Complete overlap with AdvACT



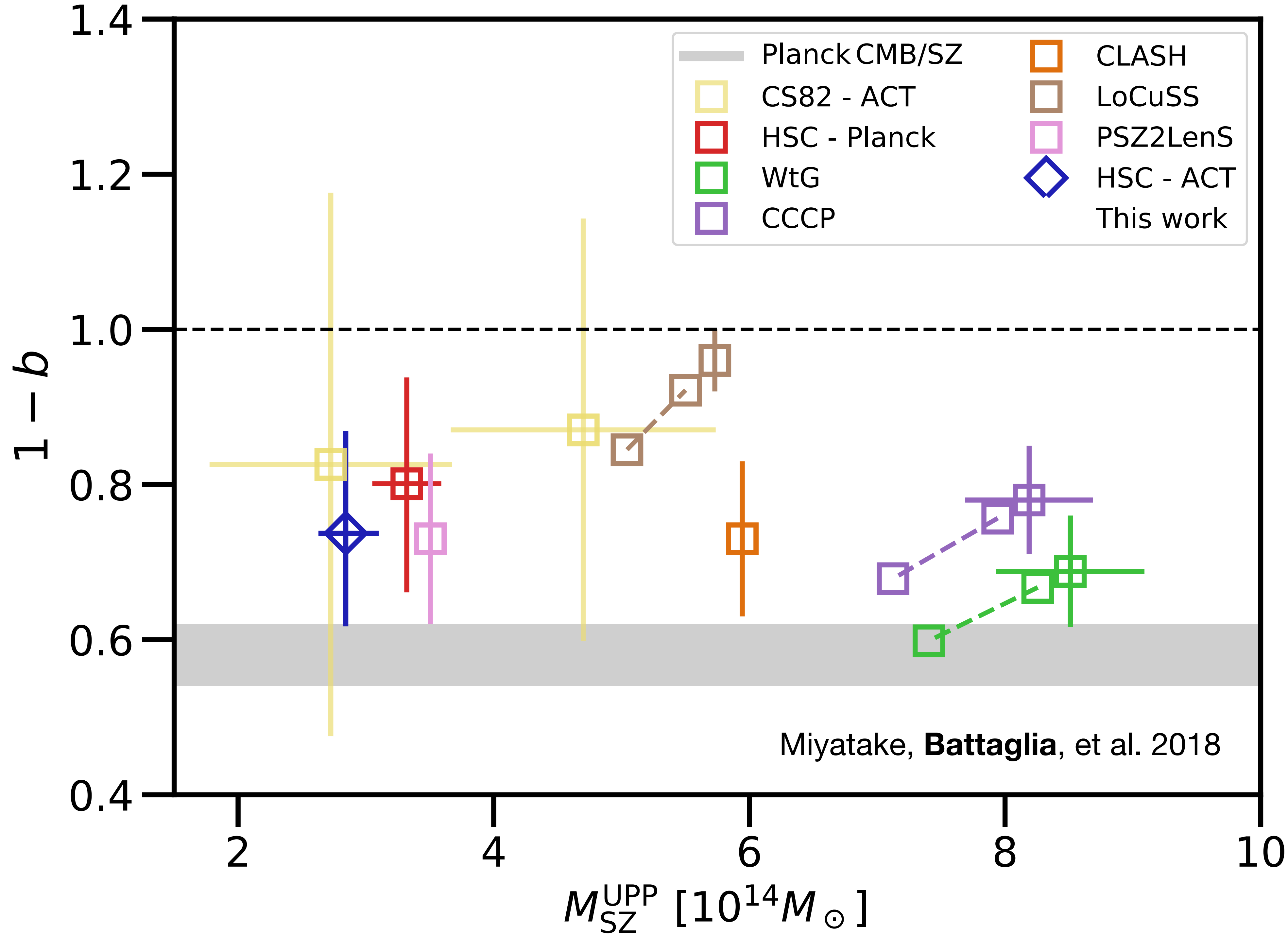
Miyatake, **Battaglia**, et al. 2018

Preliminary HSC - ACT results



Miyatake, **Battaglia**, et al. 2018

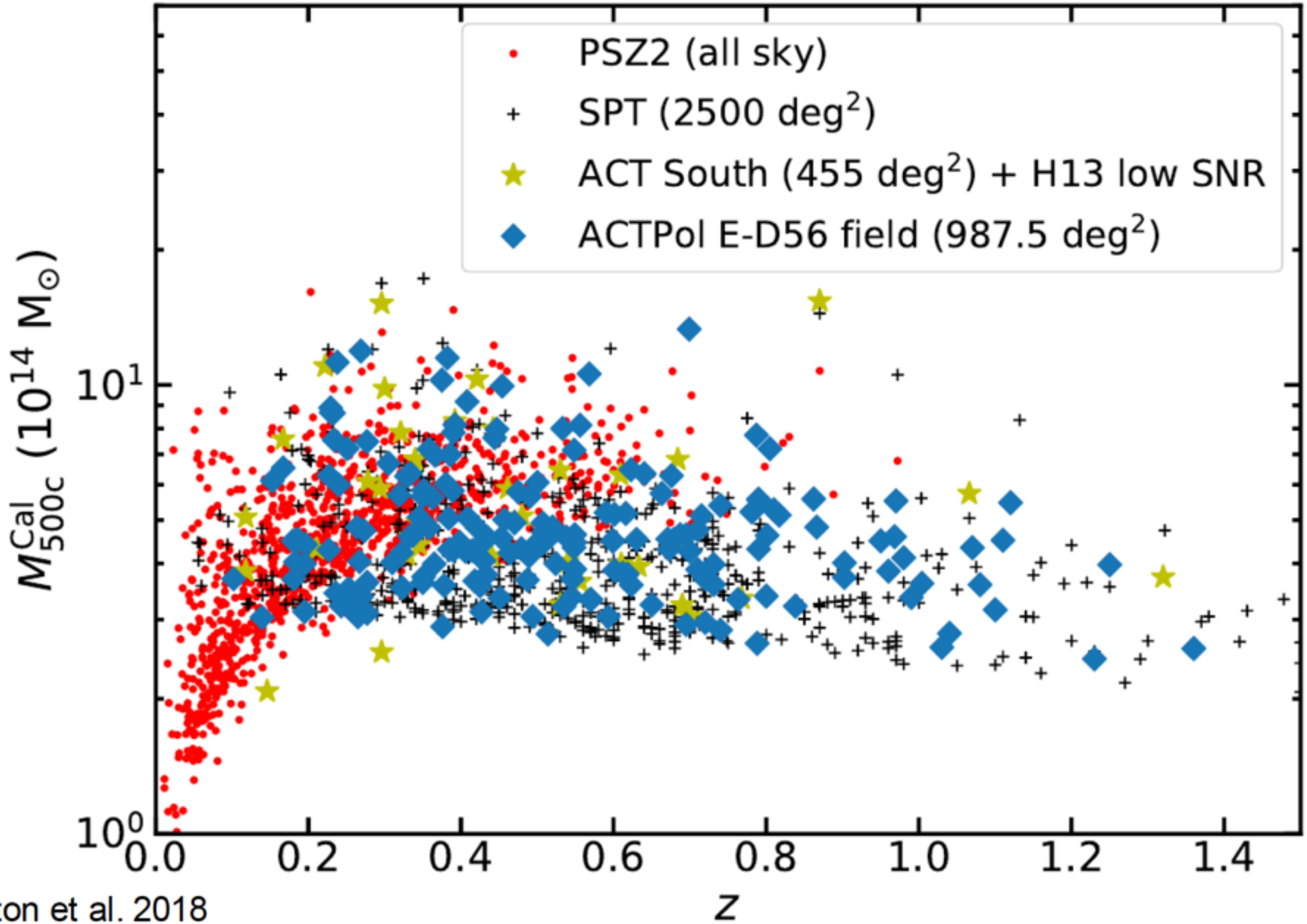
Comparison to Planck



ACT-HSC weak-lensing mass calibrations are consistent with previous results.

WL mass cal. of SZ selected clusters is progressing and will continue to.

ACTPol cluster sample

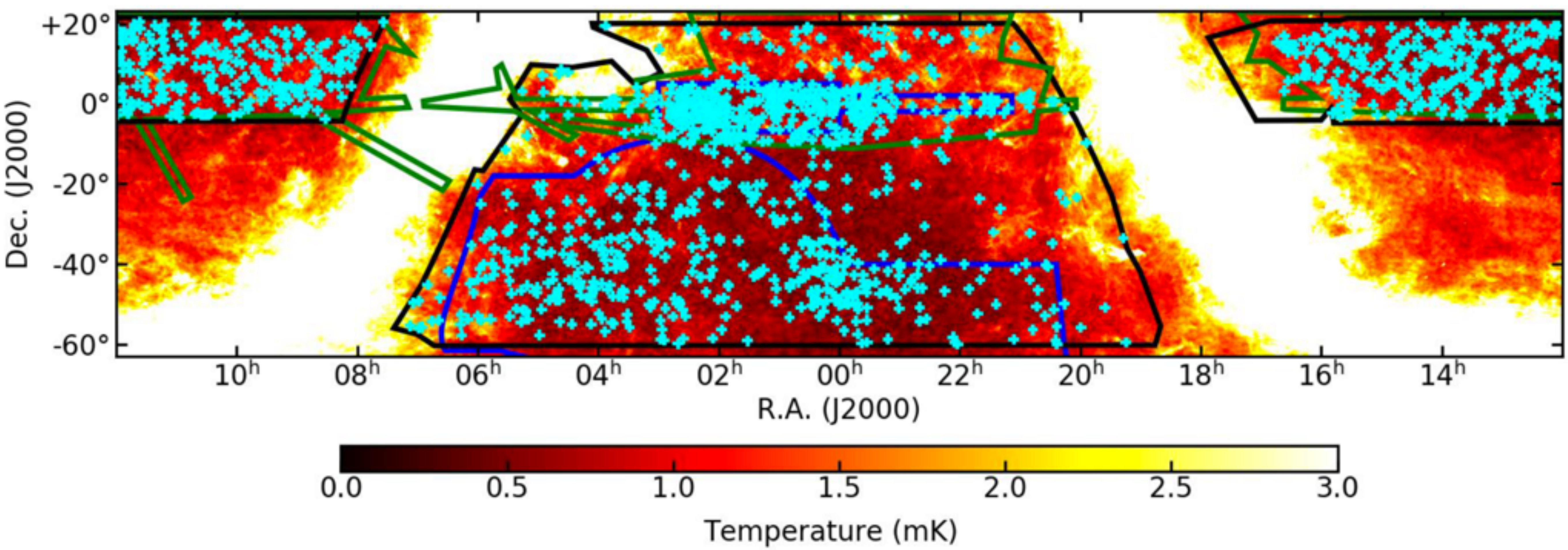


Hilton et al. 2018
(arXiv:1709.05600)

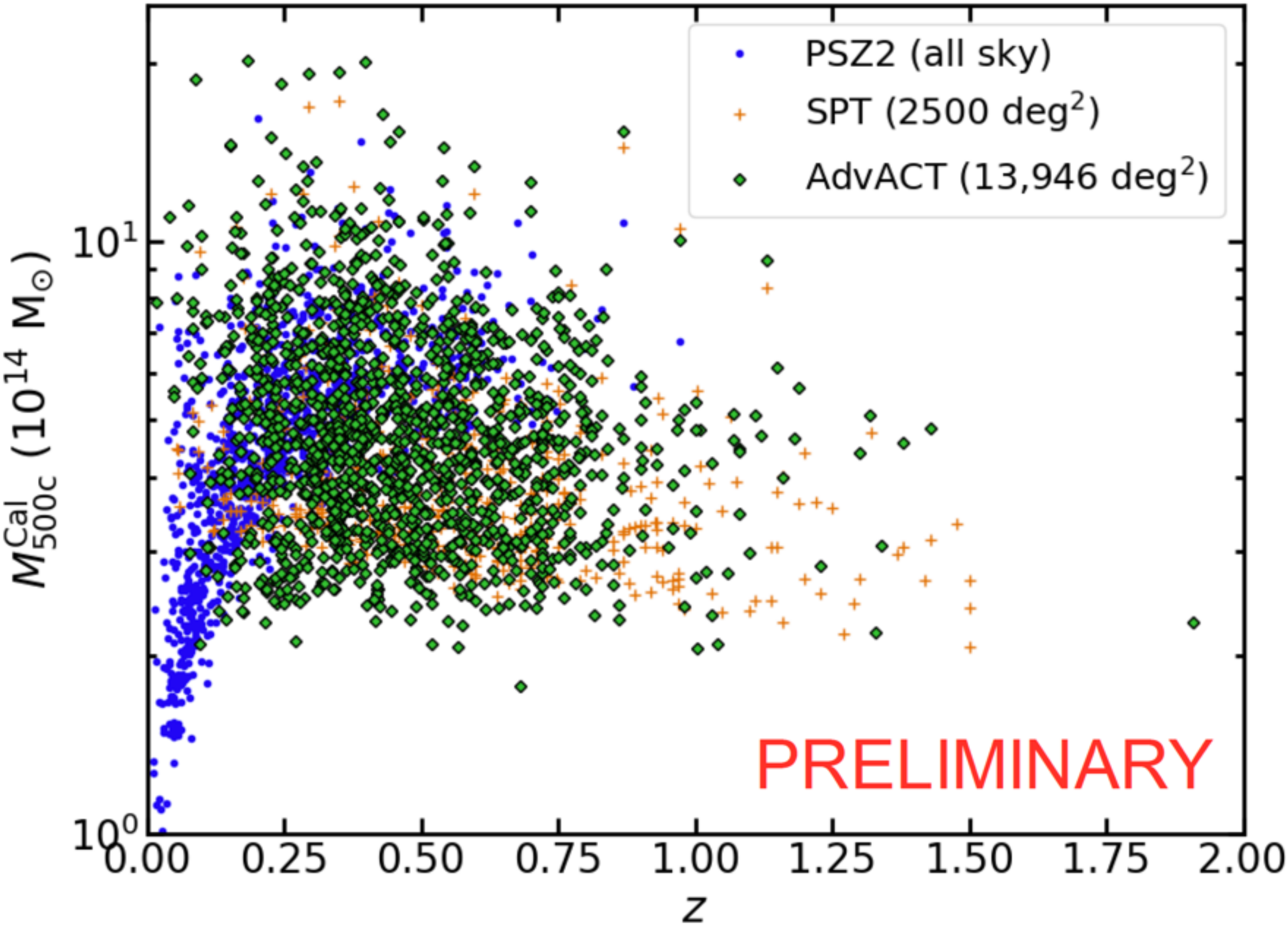
Looking ahead

Advanced ACT cluster search

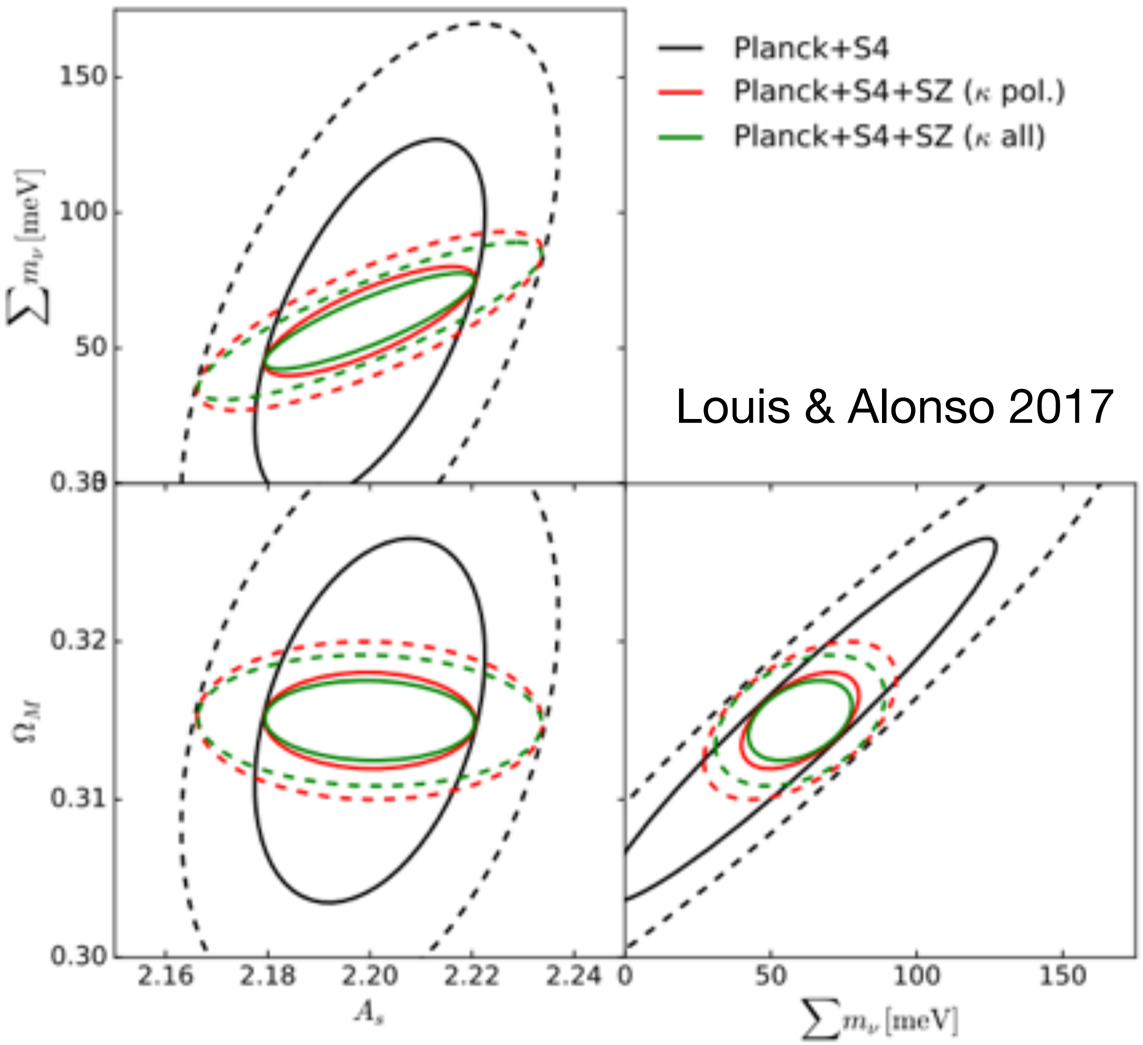
- Advanced ACT is underway – will survey southern sky in 5 bands (30 → 220 GHz) with complete LSST overlap
- Preliminary cluster search: 90 + 150 GHz multi-frequency matched filter, one season of AdvACT data + all other available ACT/ACTPol data
- **Black** = area used for a preliminary cluster search, overlaid on Planck 353 GHz map; **Blue** = DES; **Green** = SDSS – we have not done optical follow-up outside of SDSS + DES (public DR1) regions yet

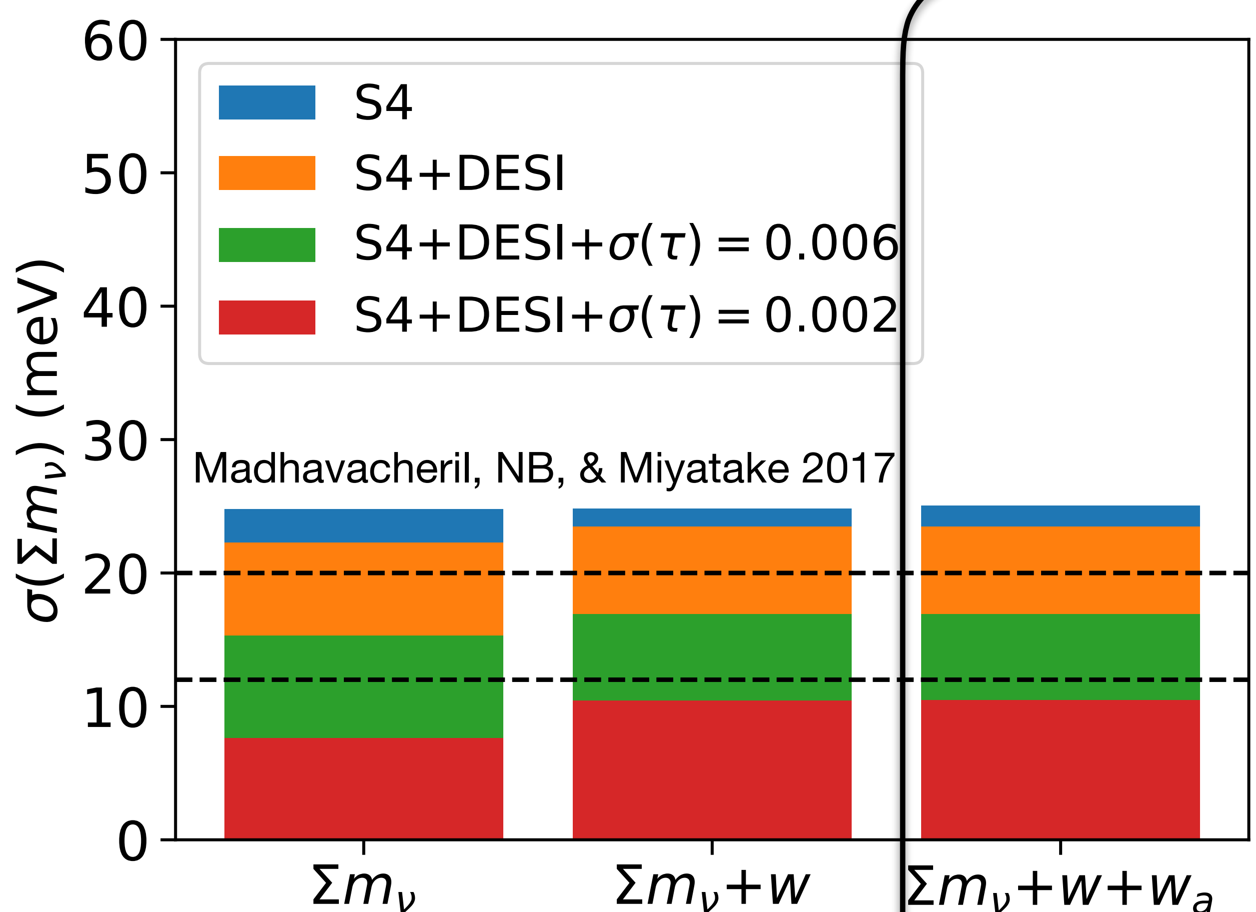


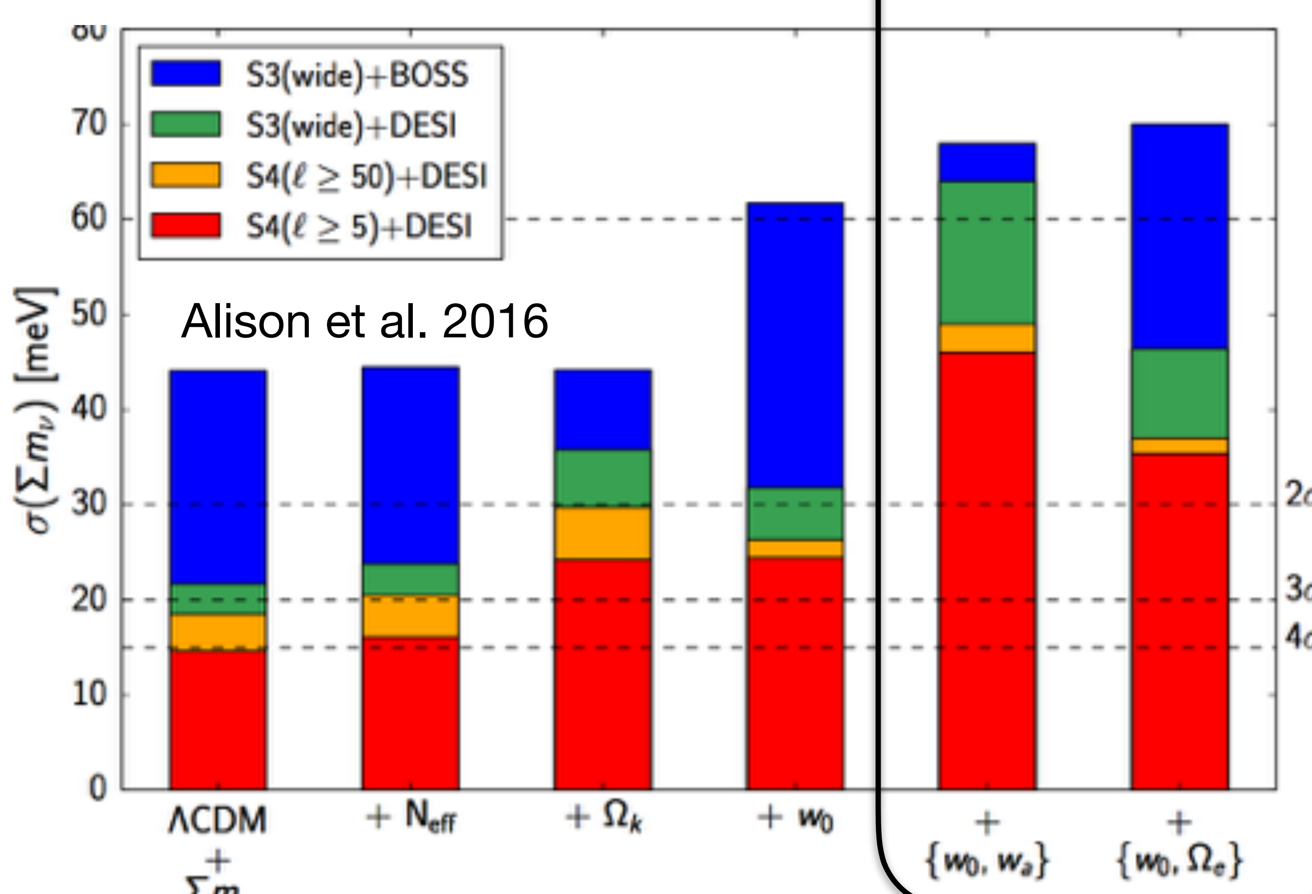
Preliminary Advanced ACT cluster sample



SZ Cluster Cosmology Forecast CMB-S4





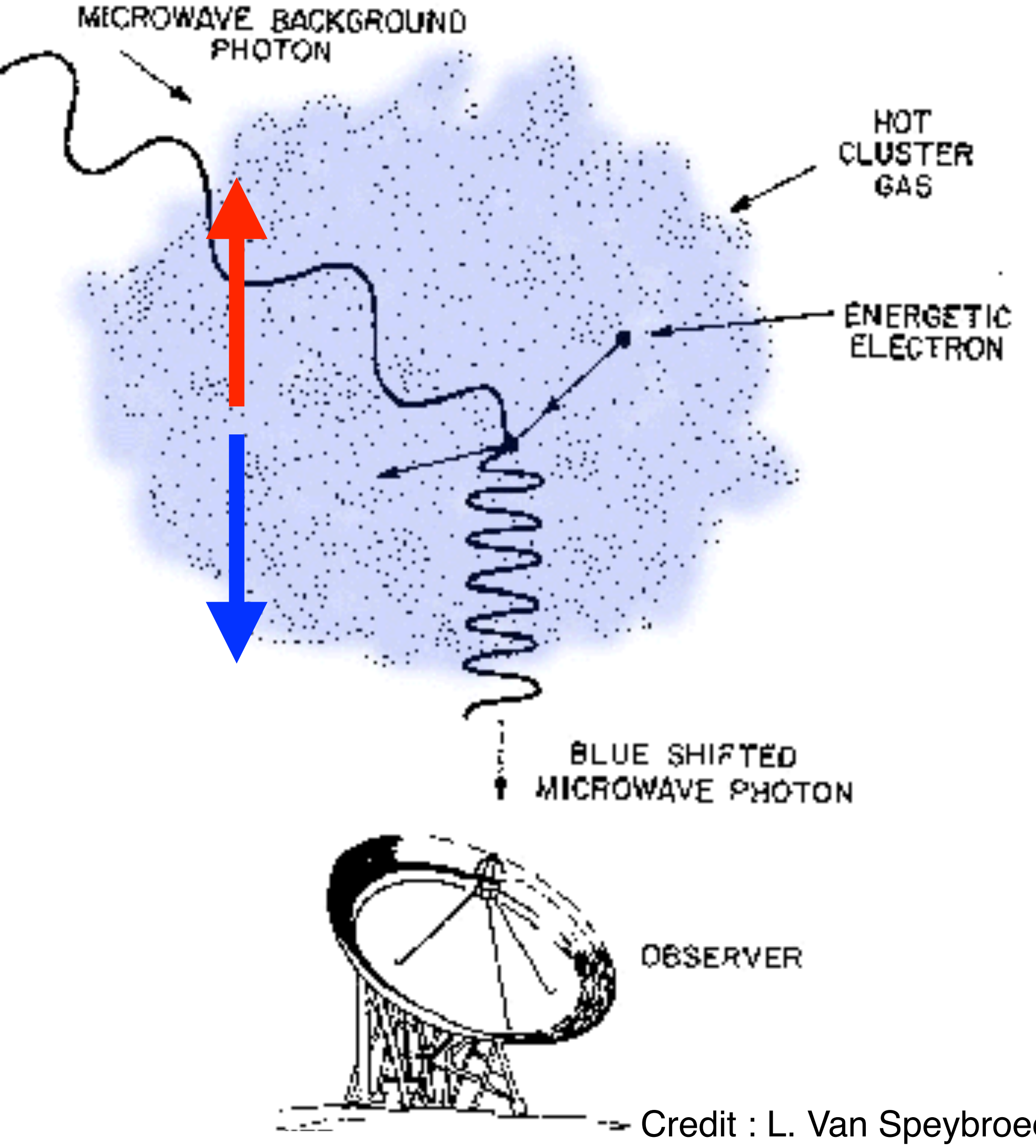


Competitive and independent constraints on Σm_ν

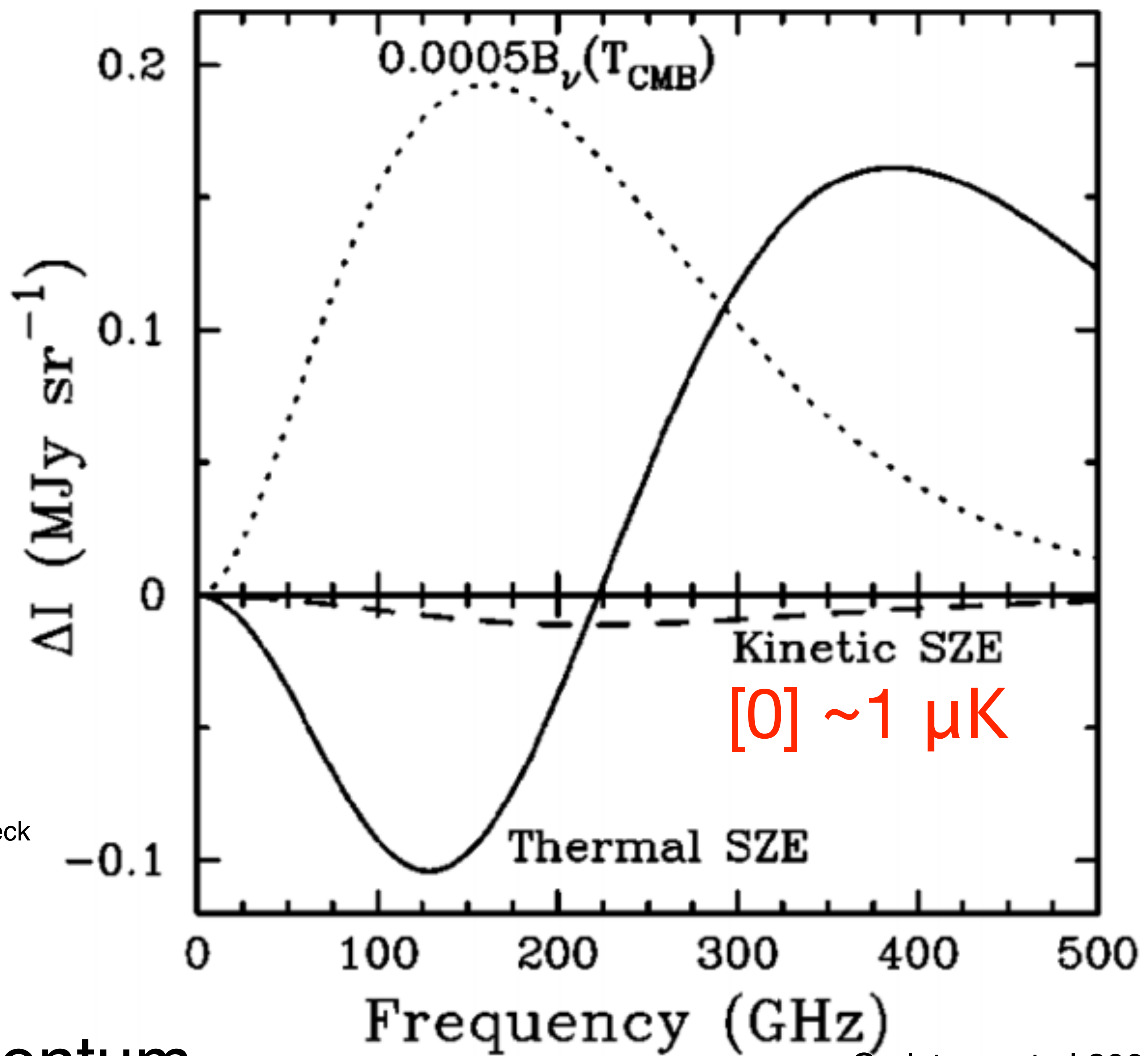
Does not suffer when opening w + w_a

kSZ late-time growth of structure

Kinetic Sunyaev-Zel'dovich Effect
Doppler boosting of CMB photons



Credit : L. Van Speybroeck

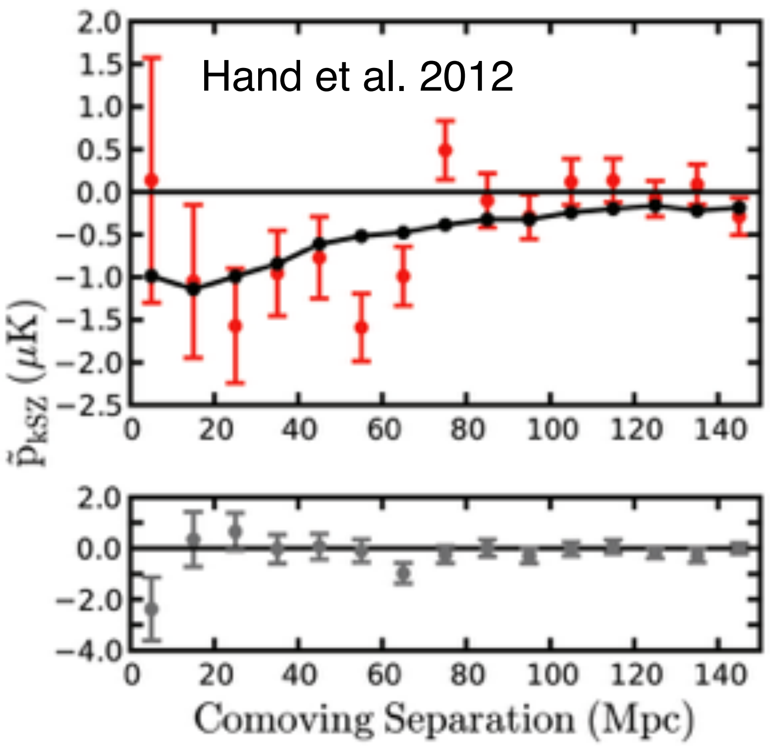


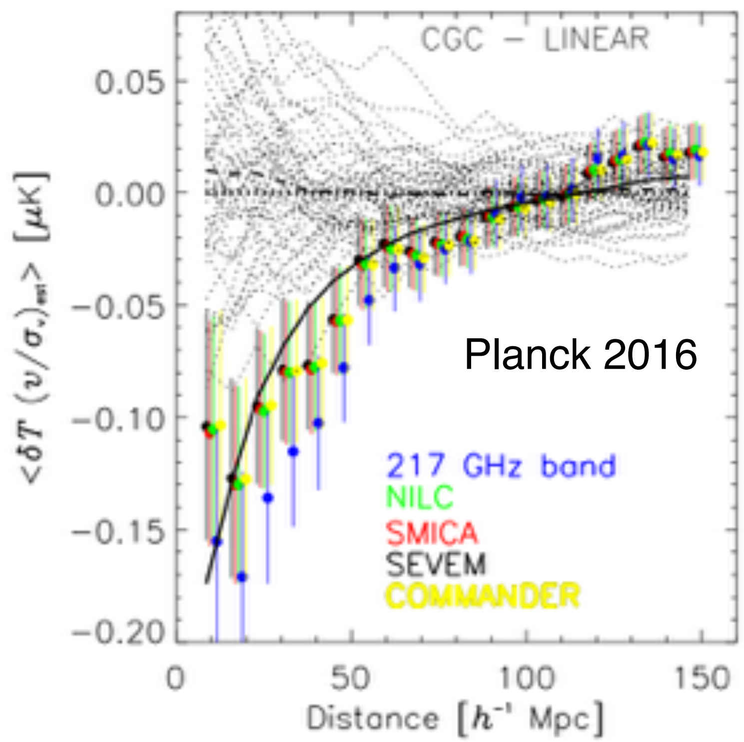
$$b \equiv \frac{\sigma_T}{c} \int n_e v_{\rm los} dl$$

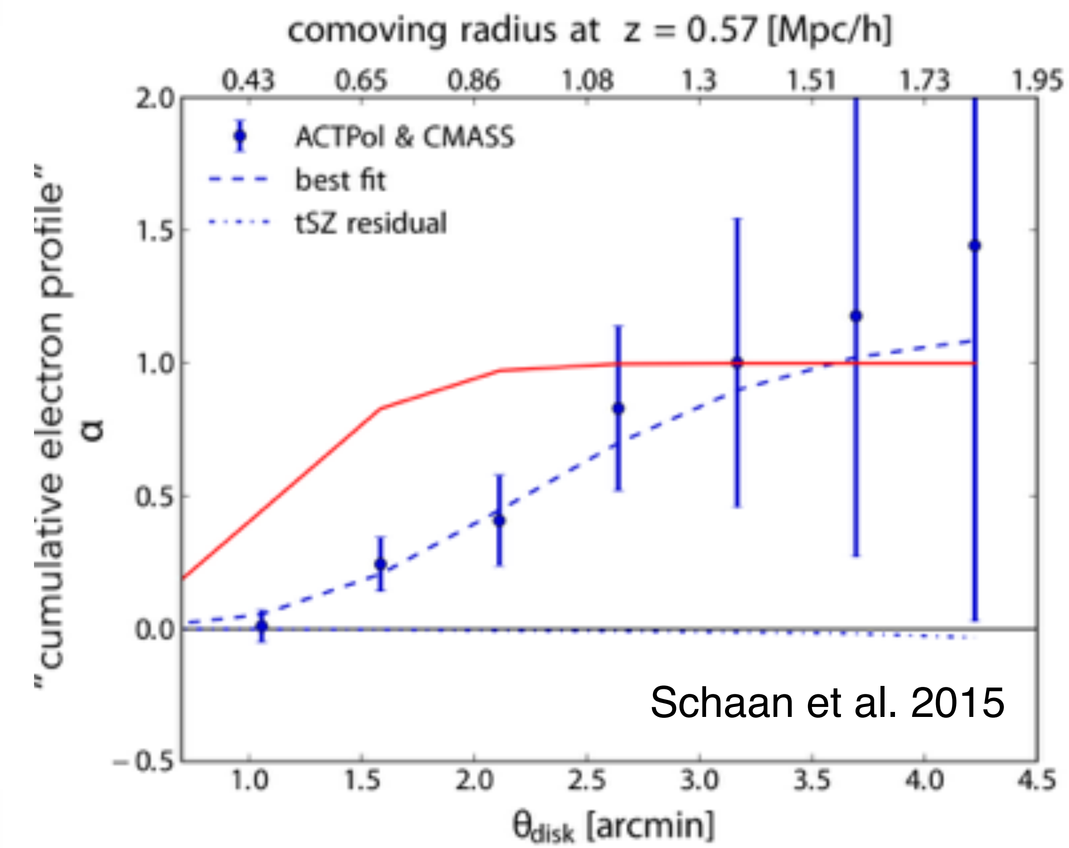
LOS Momentum

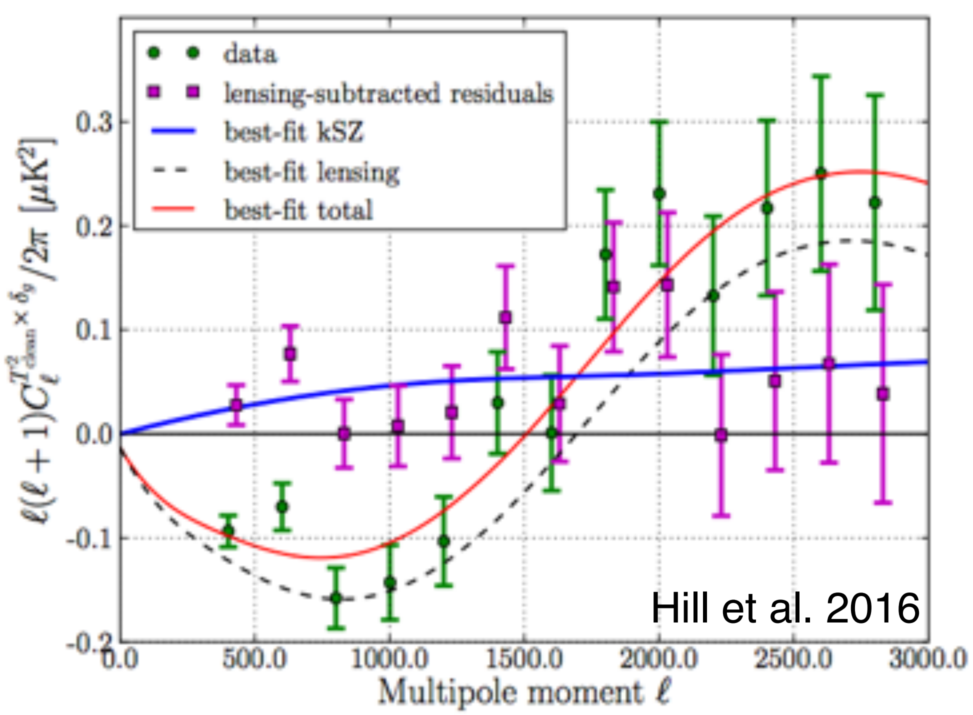
Carlstrom et al 2002

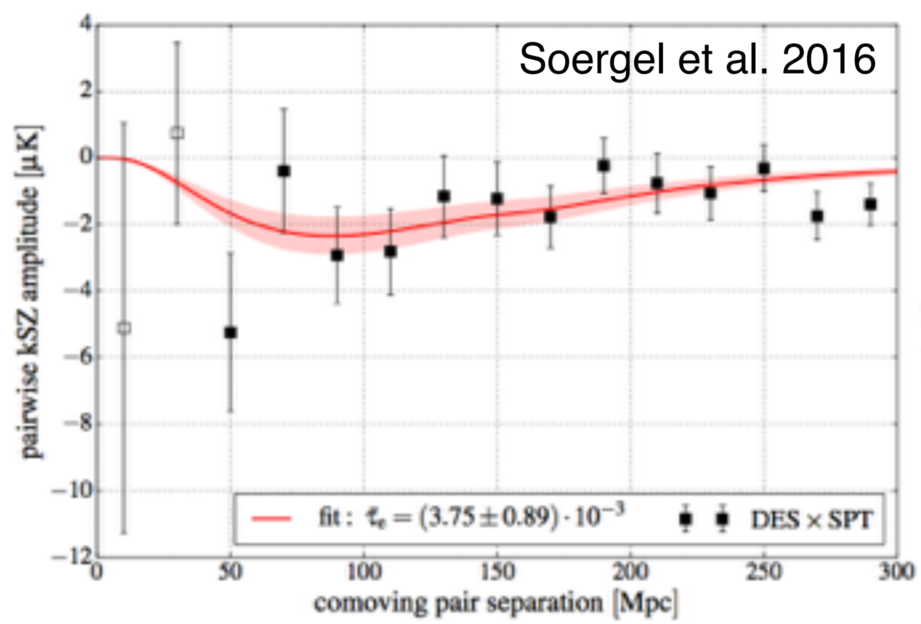
Emergence of kSZ detections

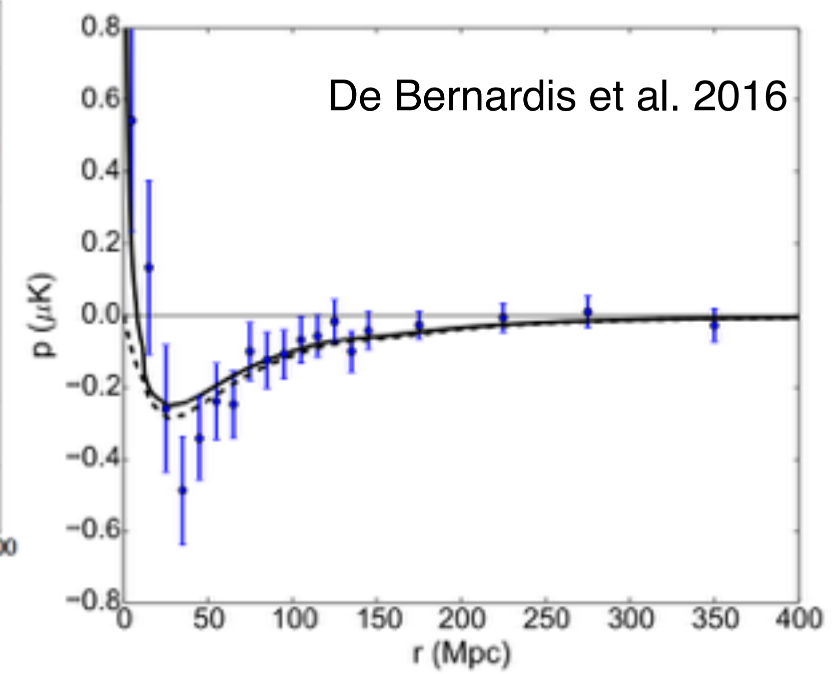








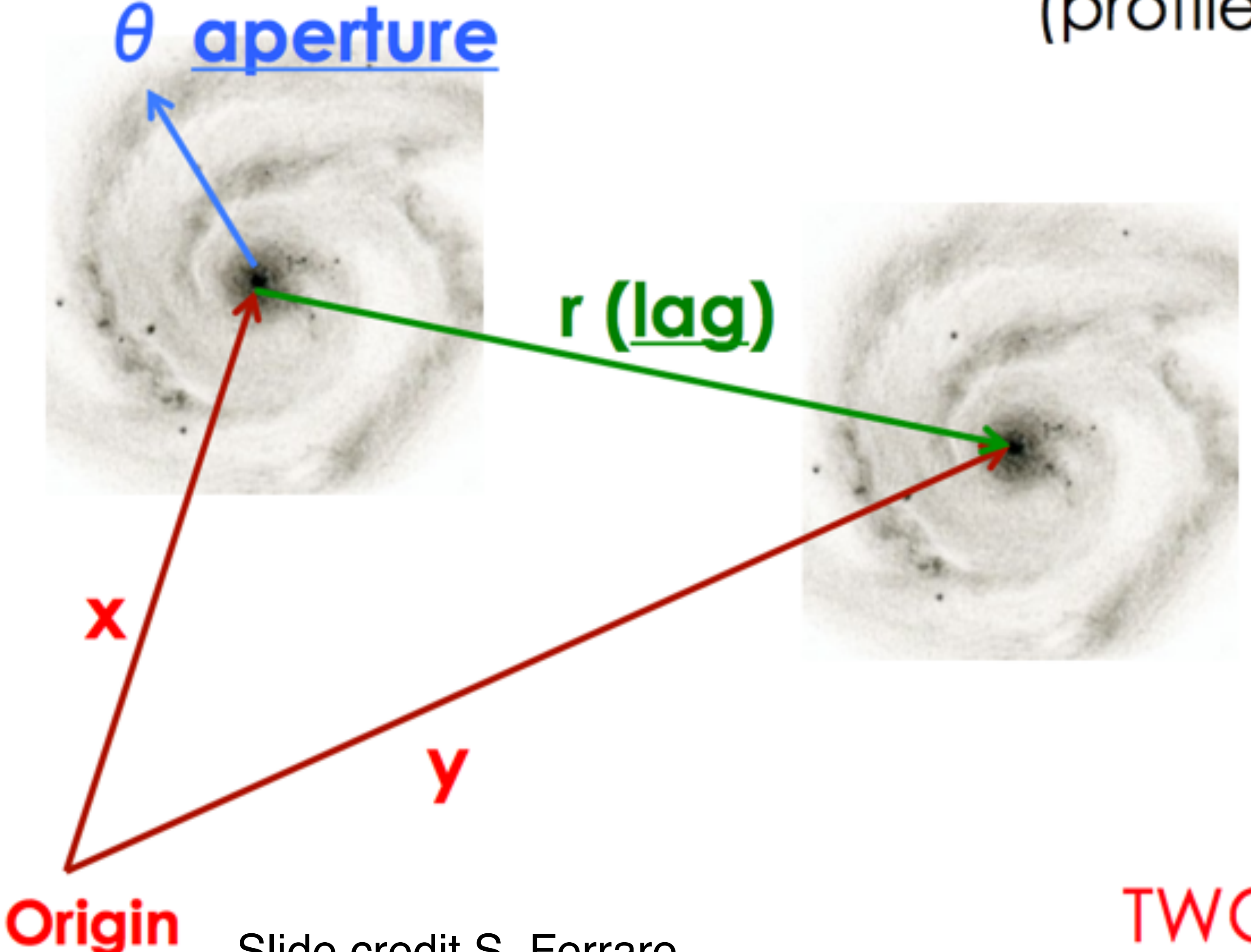




What is measured?

$$\left(\frac{\Delta T}{T}\right)_{\mathrm{kSZ}}(\mathbf{x}+\boldsymbol{\theta}) = -\tau(\boldsymbol{\theta})\ v_r(\mathbf{x}) \quad \text{(+ 2-halo)}$$

optical depth (profile) — `bulk' radial velocity

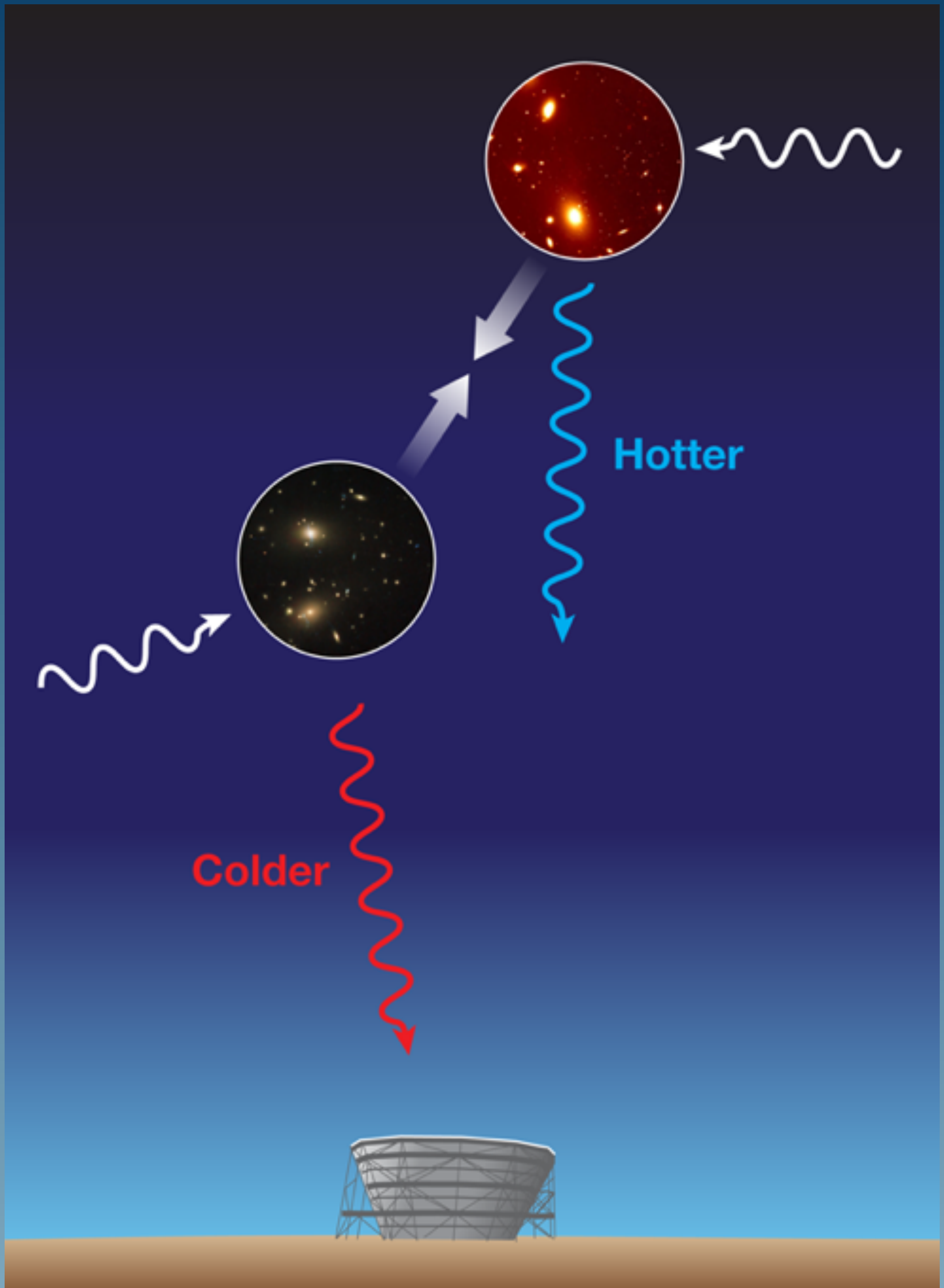


- Vary **r** at fixed $\boldsymbol{\theta}$ → velocity field on large scales
- Vary $\boldsymbol{\theta}$ at fixed **x** → gas profile and abundance.

TWO different measurements!

Slide credit S. Ferraro

Velocity field on large-scales



$$\approx -\tau_{\rm cluster}\ v_r$$

$$\mathbf{v} \approx f_g \left(aH \frac{i\mathbf{k}}{k^2} \right) \delta$$

$$f_g = \frac{d\ln\delta}{d\ln a} \approx [\Omega_m(z)]^\gamma$$

$$f_g(z,k) \approx \mu(k)\Omega_m^\gamma(z)$$

Neutrinos

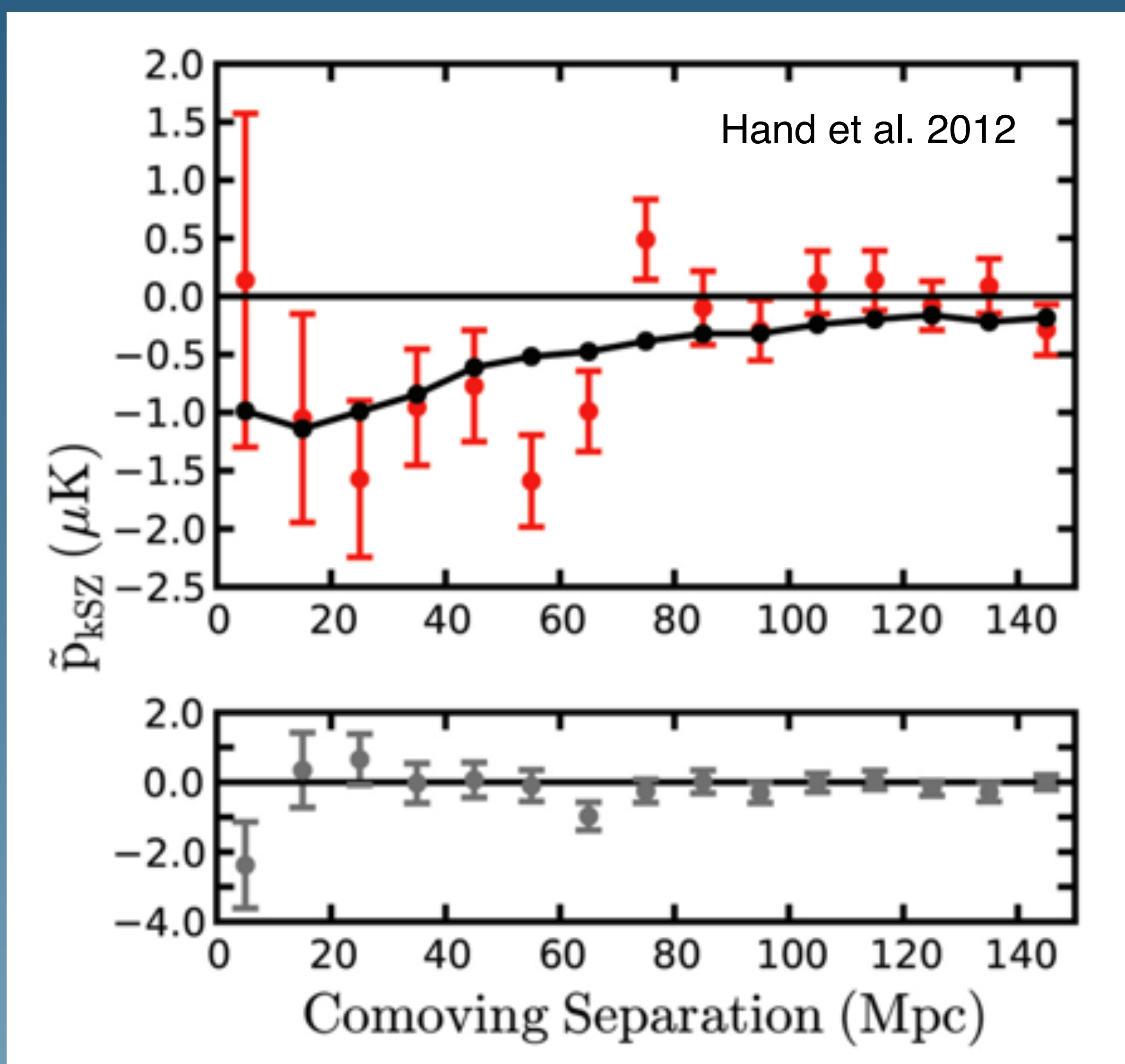
GR

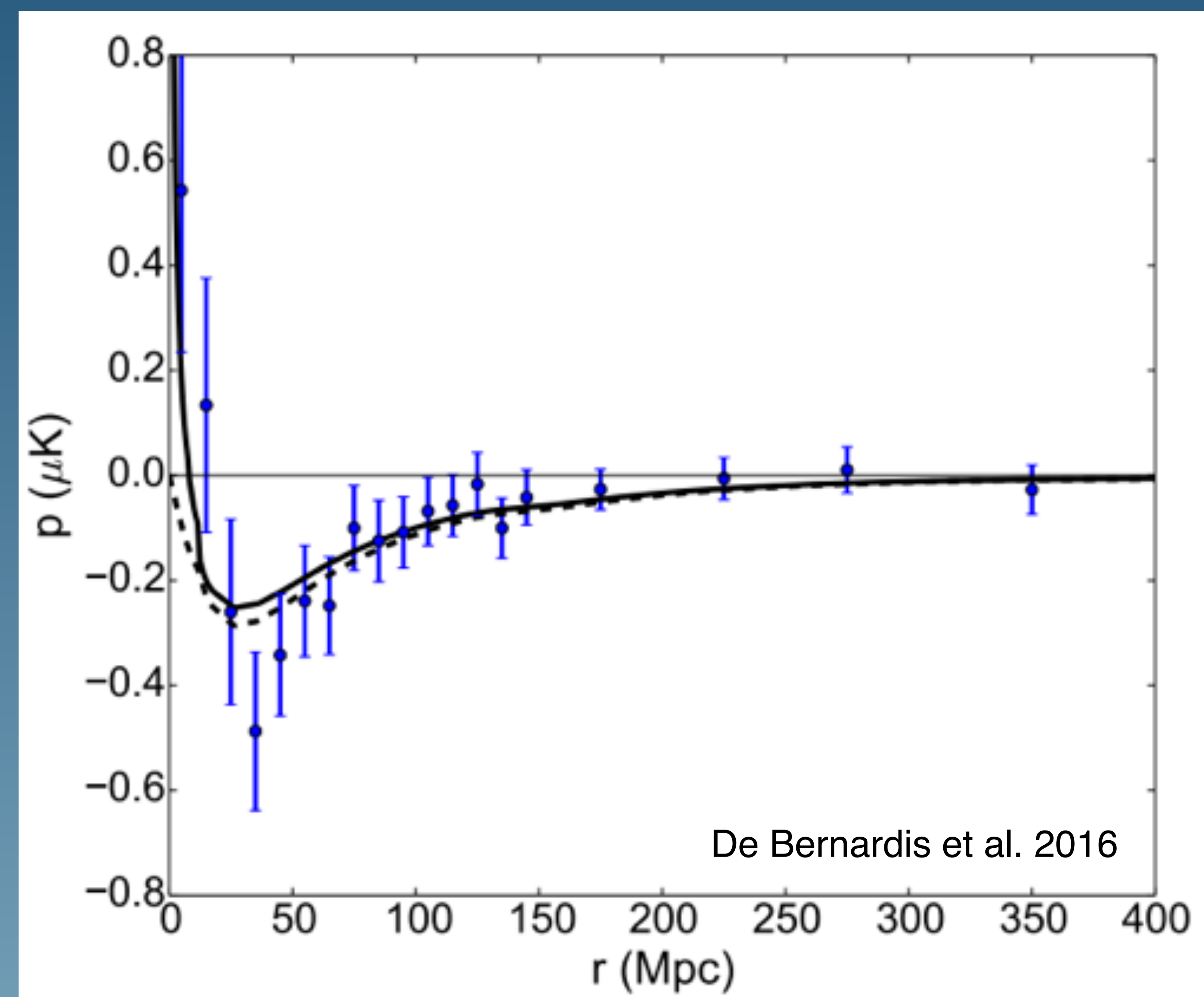
Dark Energy

$$\gamma = 0.55\ +\ 0.05(1+w)$$

Pair-wise velocity statistic & measurements

$$\left\langle \frac{\Delta T}{T}(\mathbf{x}) \;\; v_r^{\rm rec}(\mathbf{y}) \right\rangle = -\bar{\tau} \; \langle v_r^{\rm true}(\mathbf{x}) \; v_r^{\rm rec}(\mathbf{y}) \rangle$$

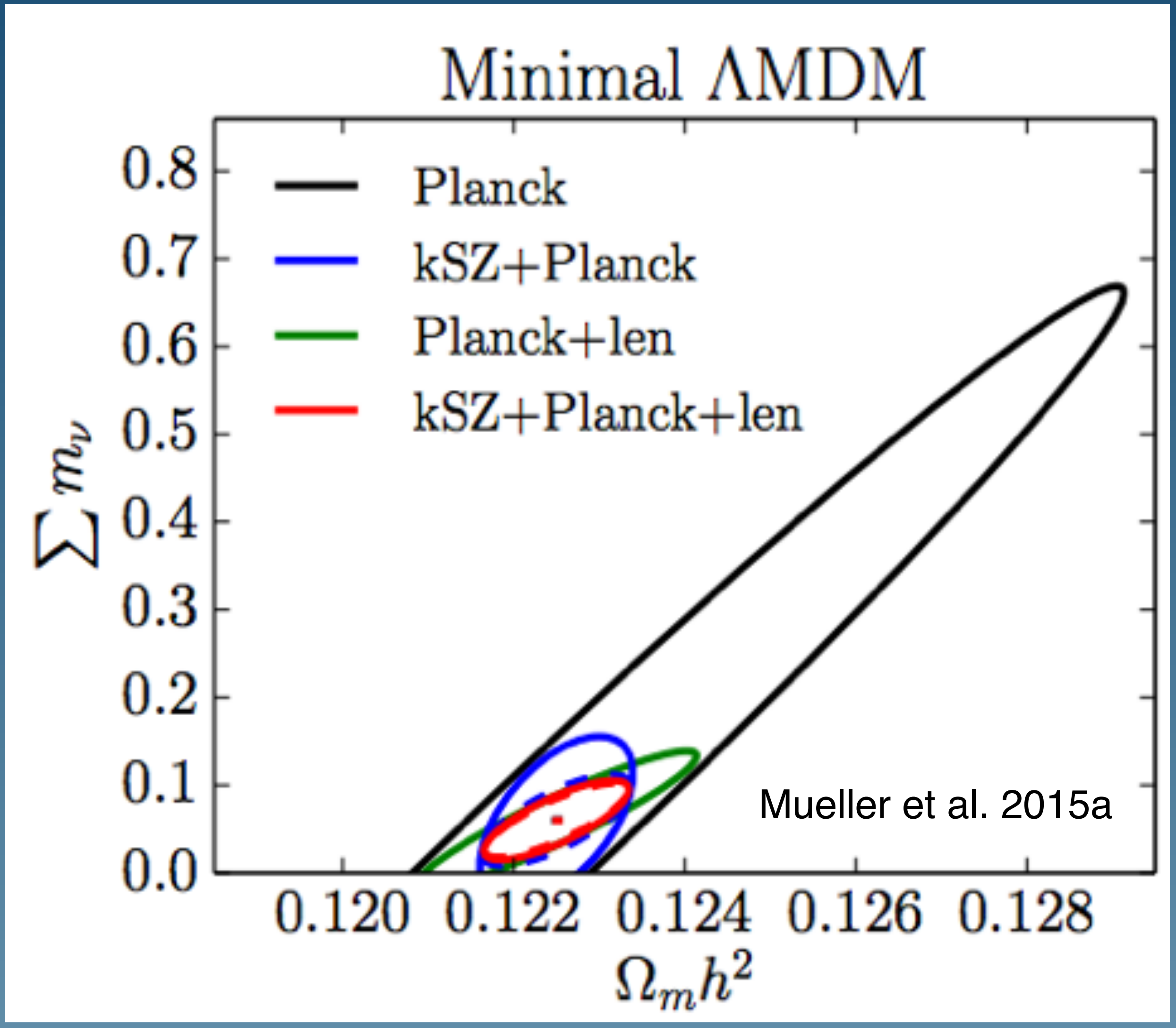


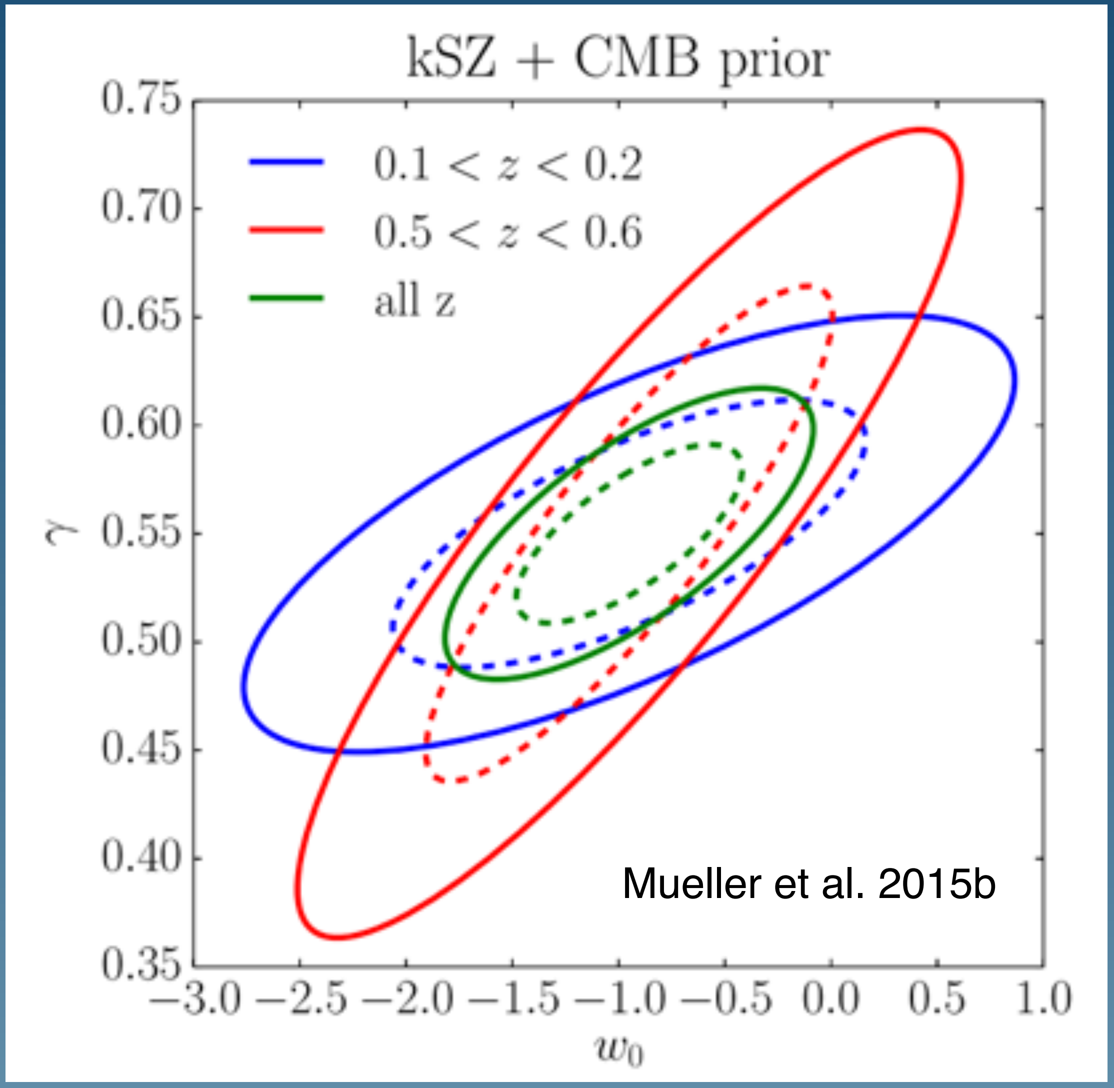


Also see Planck Coll. 2016 & SPT Soergel et al. 2016

Motivation - kSZ cosmology forecasts

Pair-wise velocity estimator





Huge potential to constrain fundamental physical parameters and extensions to the concordance cosmological model

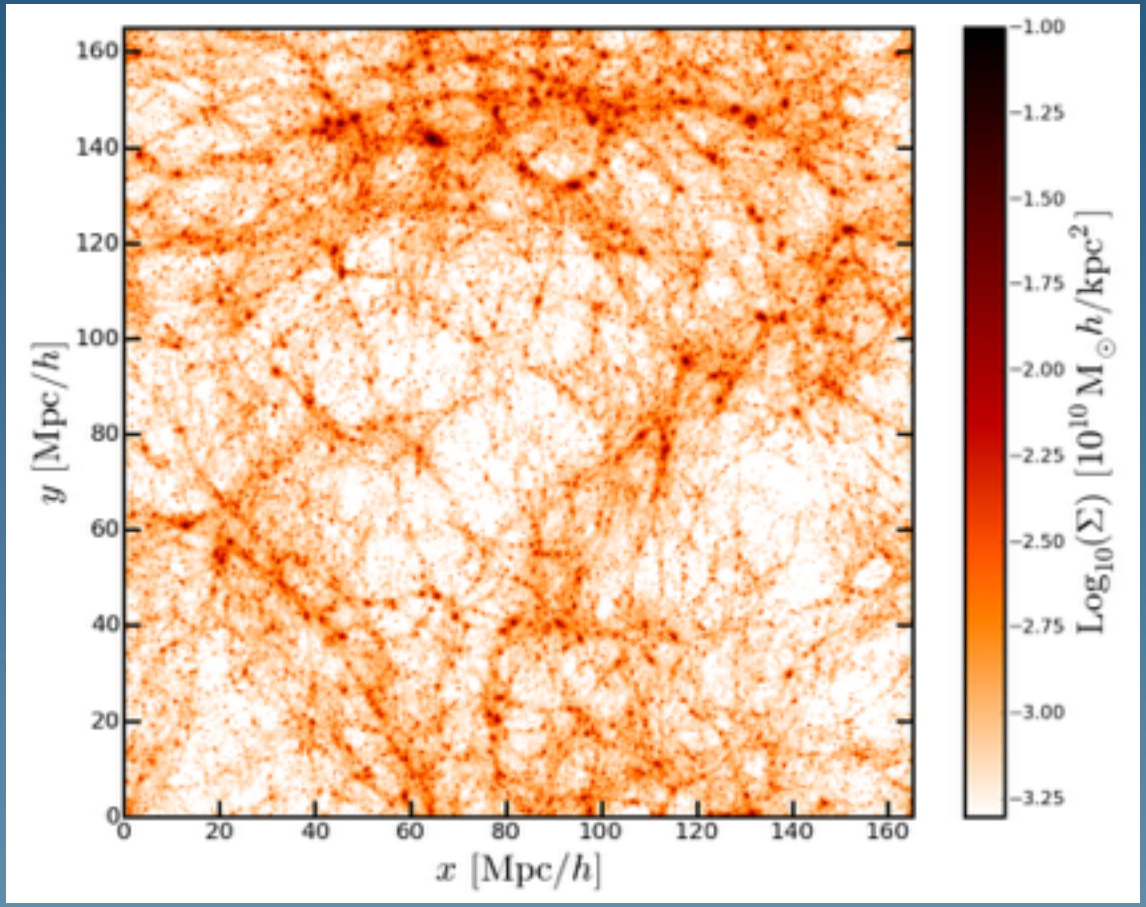
Beware of fisher forecasts

What are some of the systematics?

galaxy - gas offset

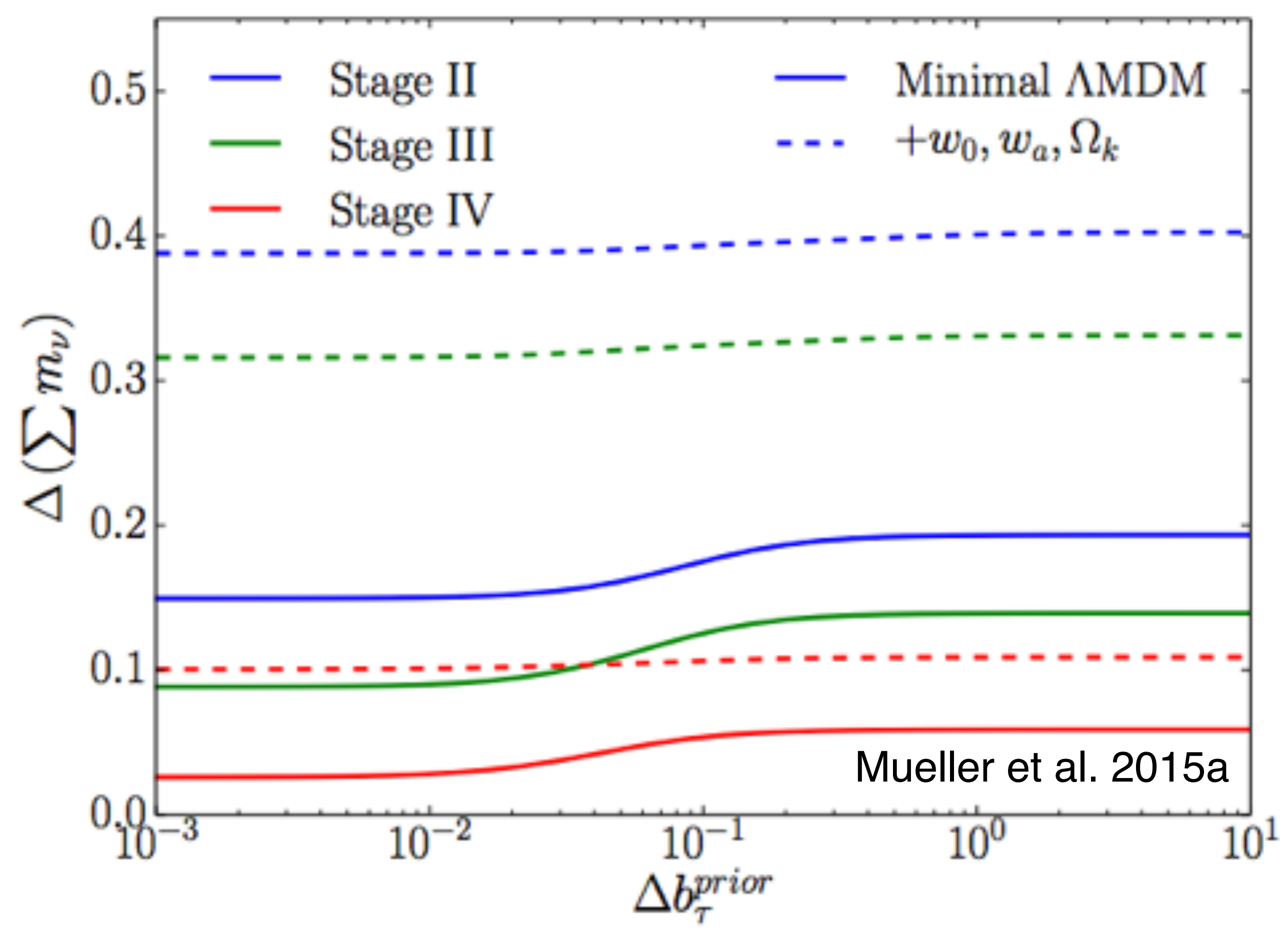
See recent work by Calafut, Bean, & Yu 2017

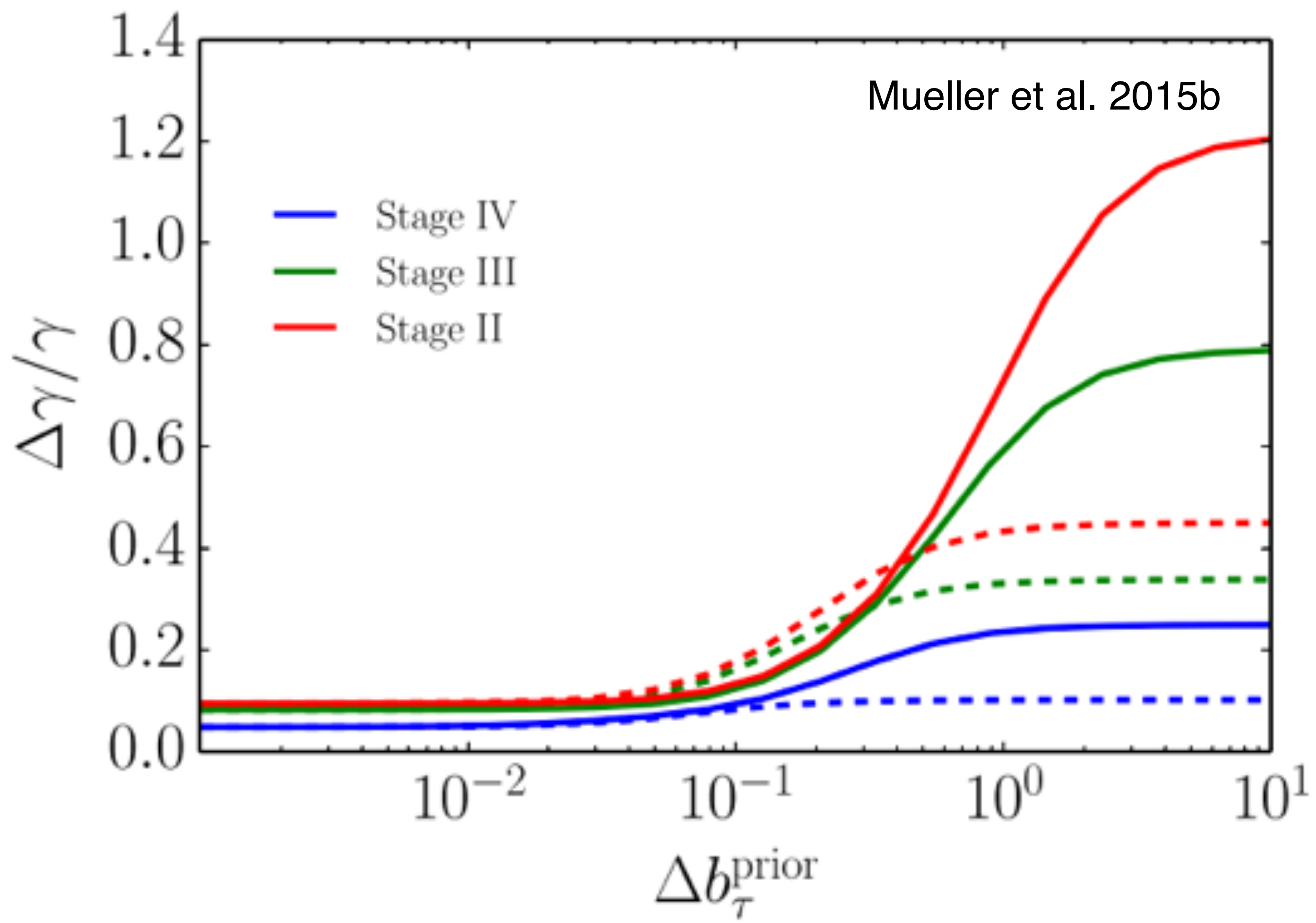
2-halo term



For a halo of a given mass, what is the optical depth?

Dependence on τ

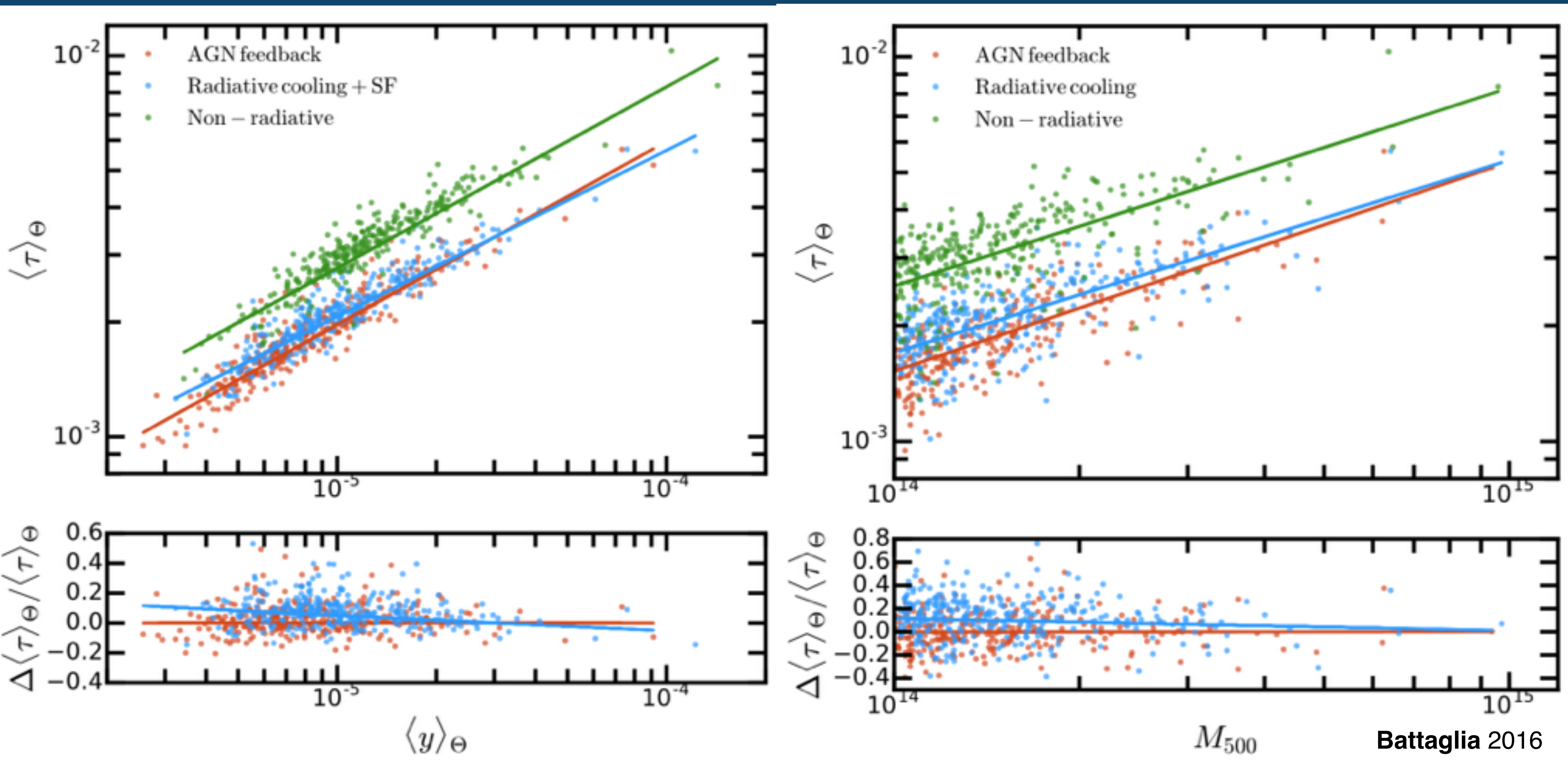




Uncertainties on τ will soon be a leading systematic uncertainty in the cosmological parameters obtained from kSZ measurements

How does one measure τ since it is not a “direct” observable?

τ - y relation an empirical solution?



Not surprisingly there is a relation between τ - y

At fixed gas mass temperature fluctuations are small
found in simulations but this appears to independent of SG-model
at the < 10% level

Astrophysics - galaxy formation

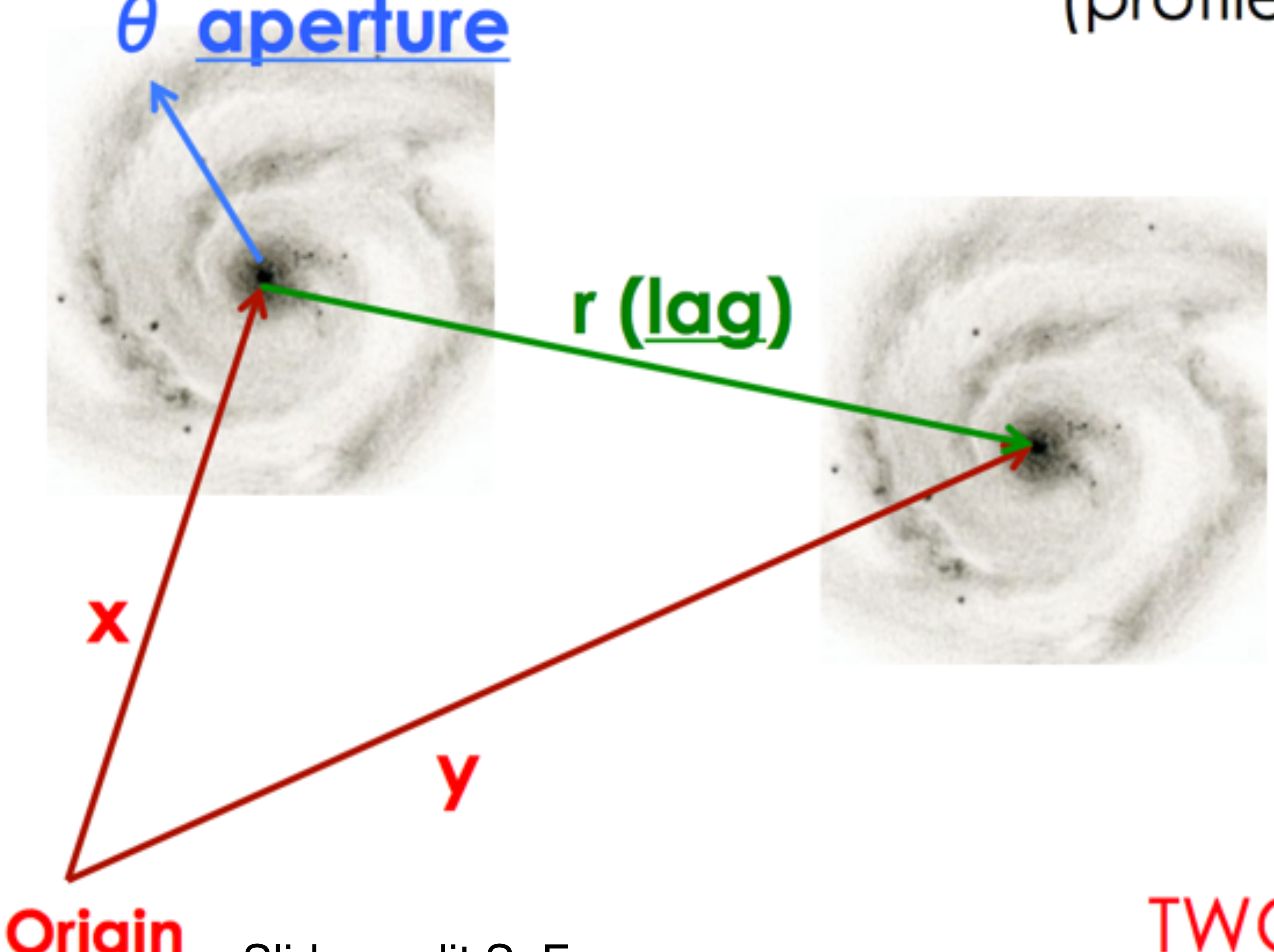
kSZ - Baryons effects & Cosmology

What is measured?

$$\left(\frac{\Delta T}{T}\right)_{\mathrm{kSZ}}(\mathbf{x}+\boldsymbol{\theta}) = -\tau(\boldsymbol{\theta})\ v_r(\mathbf{x})$$ (+ 2-halo)

optical depth (profile)

`bulk' radial velocity



- Vary **r** at fixed **θ** → velocity field on large scales
- Vary **θ** at fixed **x** → gas profile and abundance.

TWO different measurements!

Slide credit S. Ferraro

Measuring the τ profile

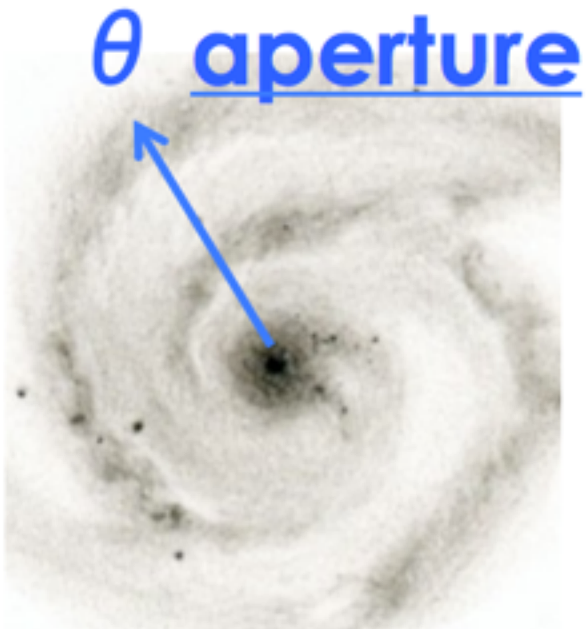
zero lag

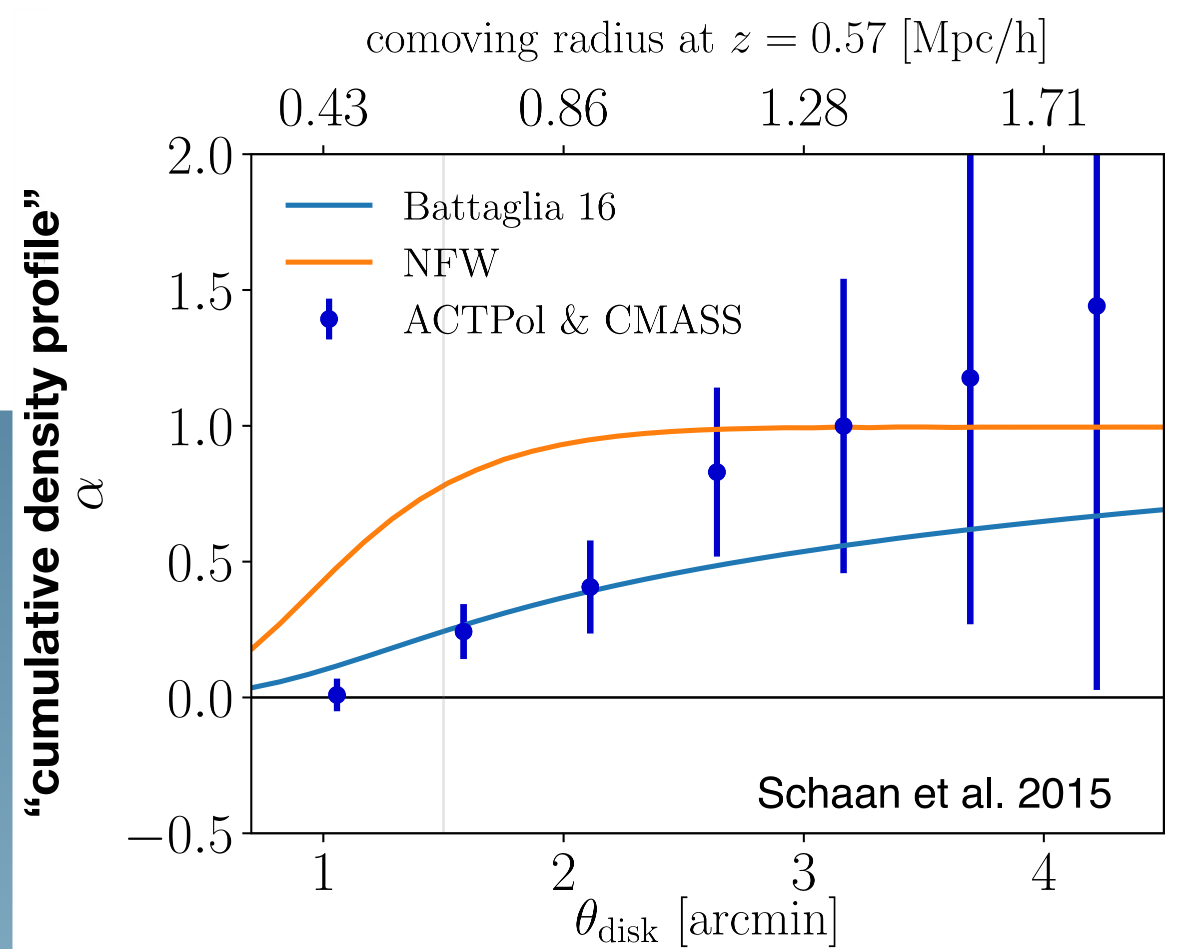
aperture

$$\left\langle \frac{\Delta T}{T}(\mathbf{x}) \quad v_r^{\mathrm{rec}}(\mathbf{x}) \right\rangle (\theta) = \sigma_{v_r}^2 \; \tau(\theta)$$

cosmology (independent of θ)

optical depth (profile)



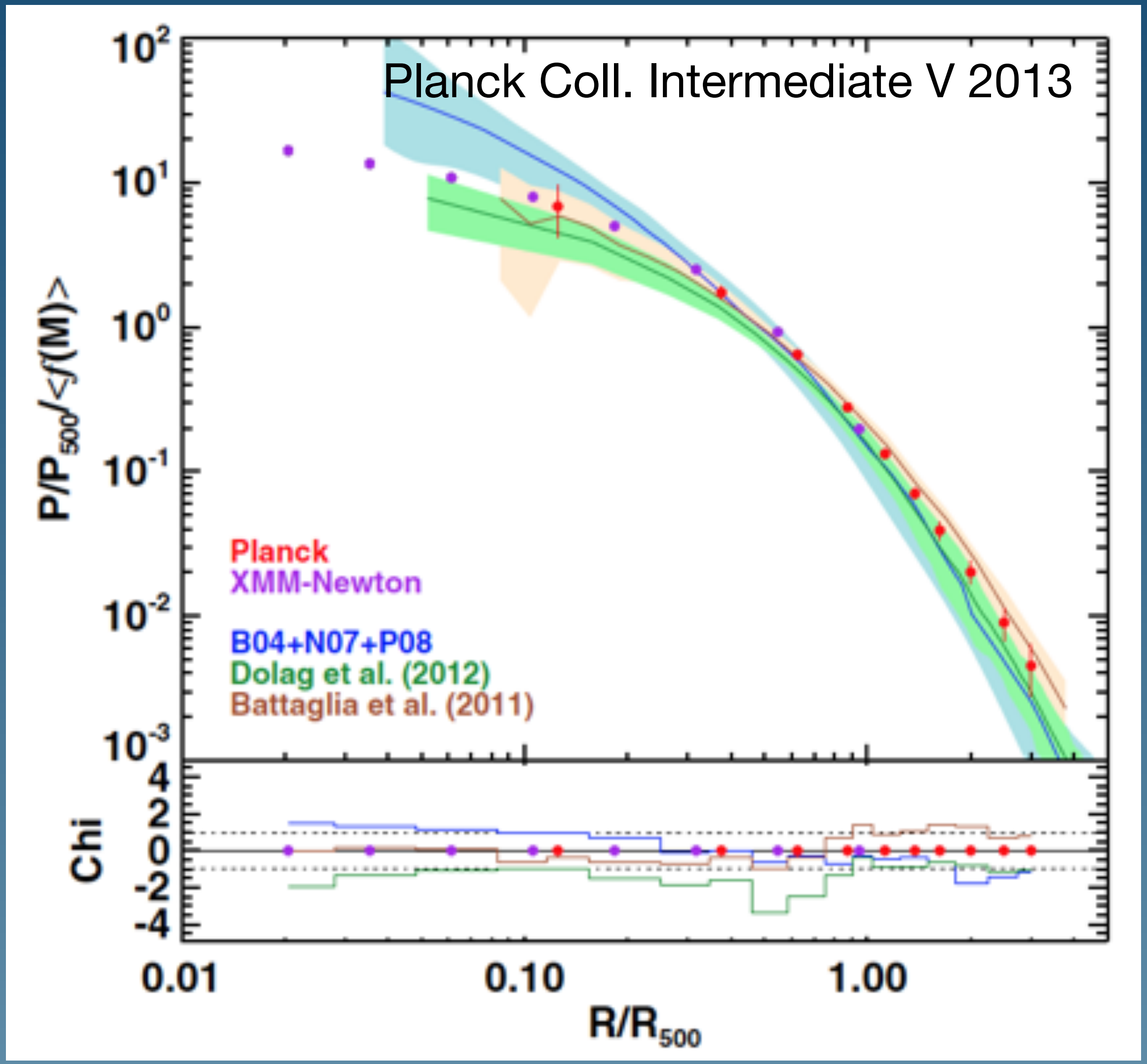


We also have measurements of the pressure!

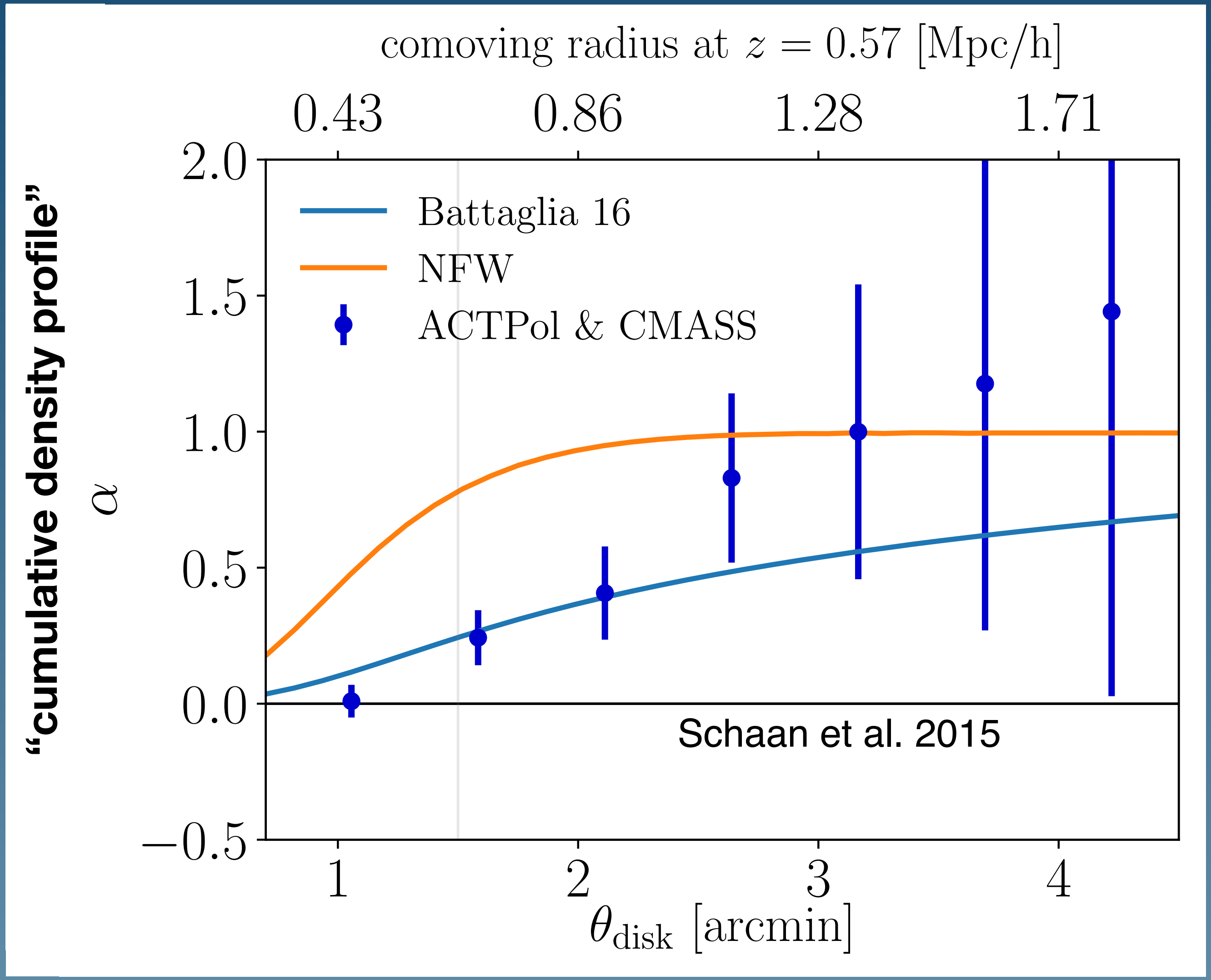
Combining tSZ & kSZ measurements

Previously, Knox+2004 Sehgal+2005 proposed to constrain T, τ & v_{pec}

Also see Erler et al 2017 (Jens' poster) & Mittal et al. 2018



+



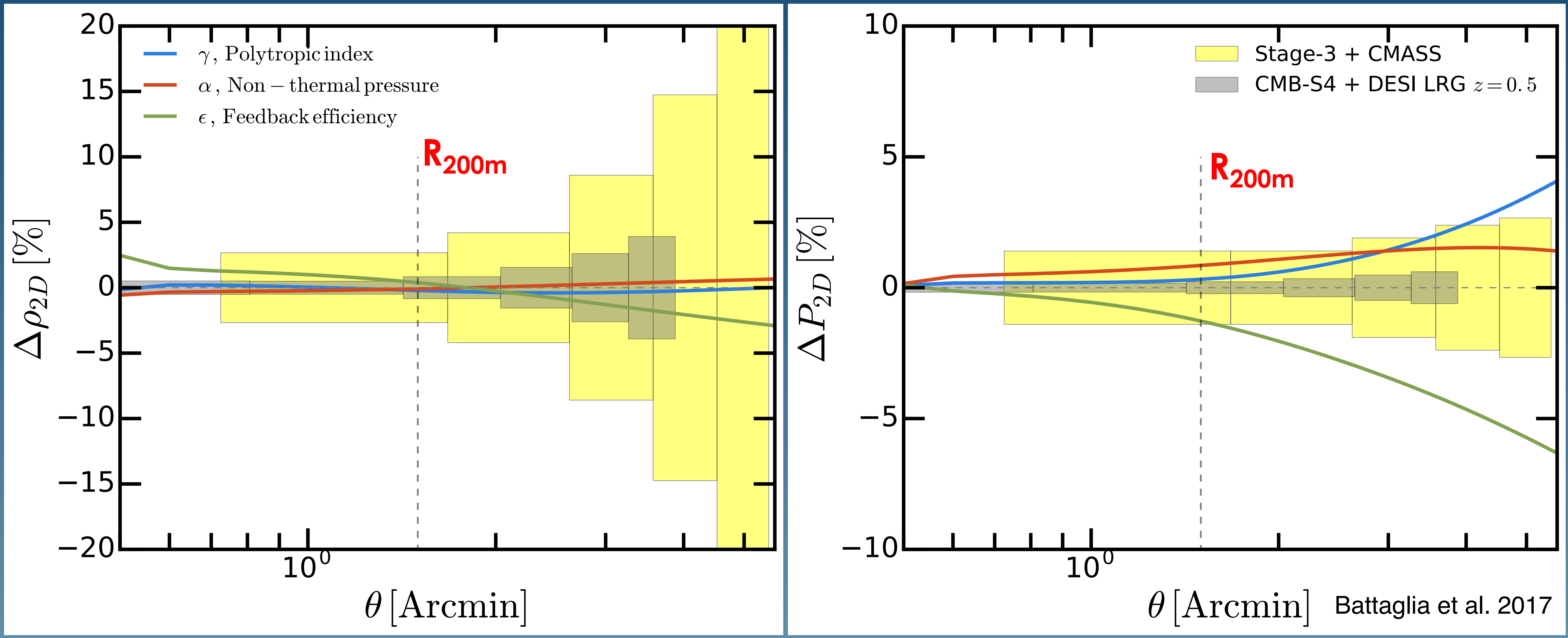
$$\underbrace{\frac{1}{3}\Phi_{\rm gas}}_{\text{from kSZ \&mass profile}} + \underbrace{\int P_{\rm th}{\rm d}V}_{\text{from tSZ}} + \underbrace{\int P_{\rm Nth}{\rm d}V}_{\rightarrow\text{inferred}} \propto P_{\rm Surface}$$

Constraint dominant physical processes in galaxy formation?

Combining tSZ & kSZ measurements forecasts

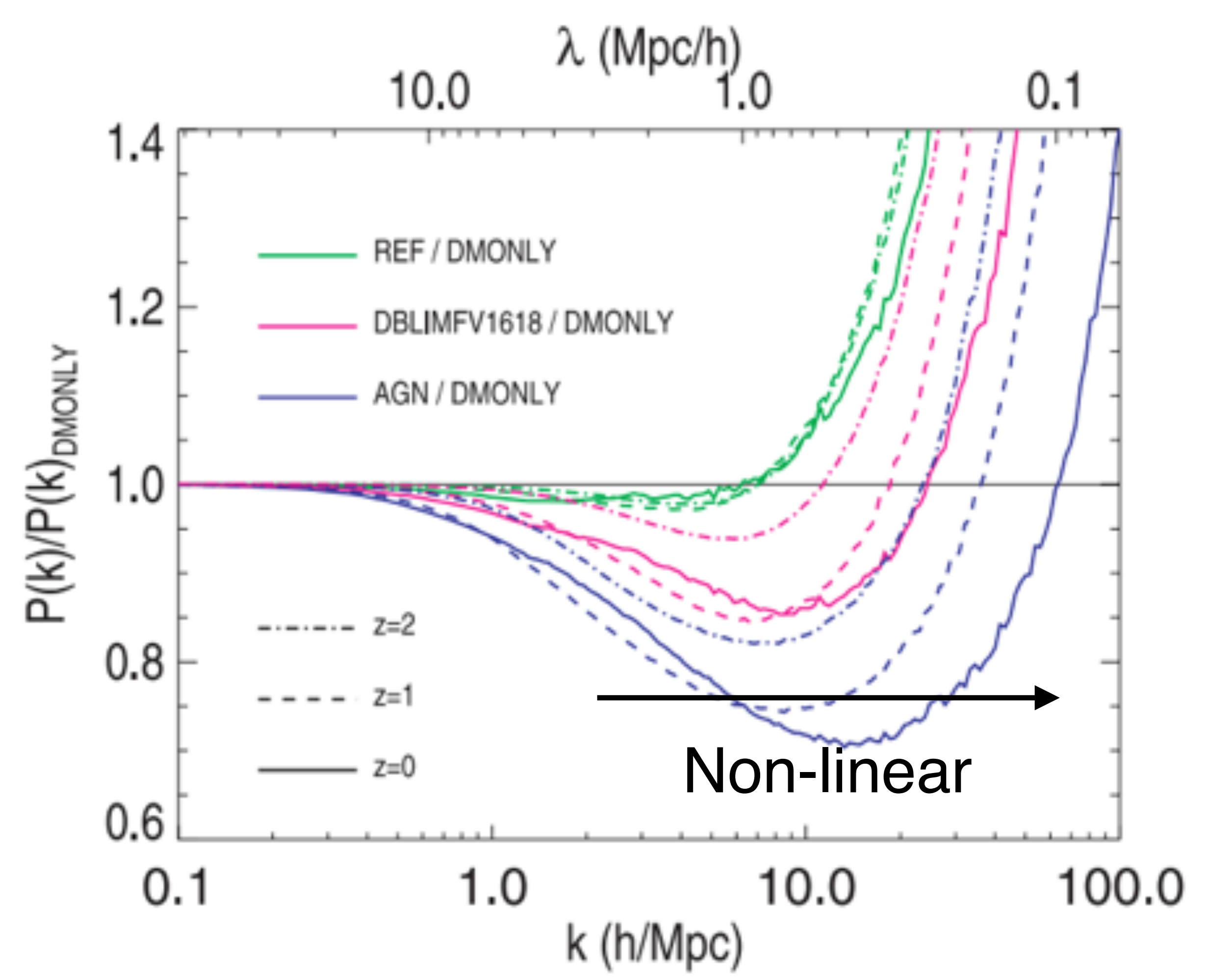
Density

Pressure



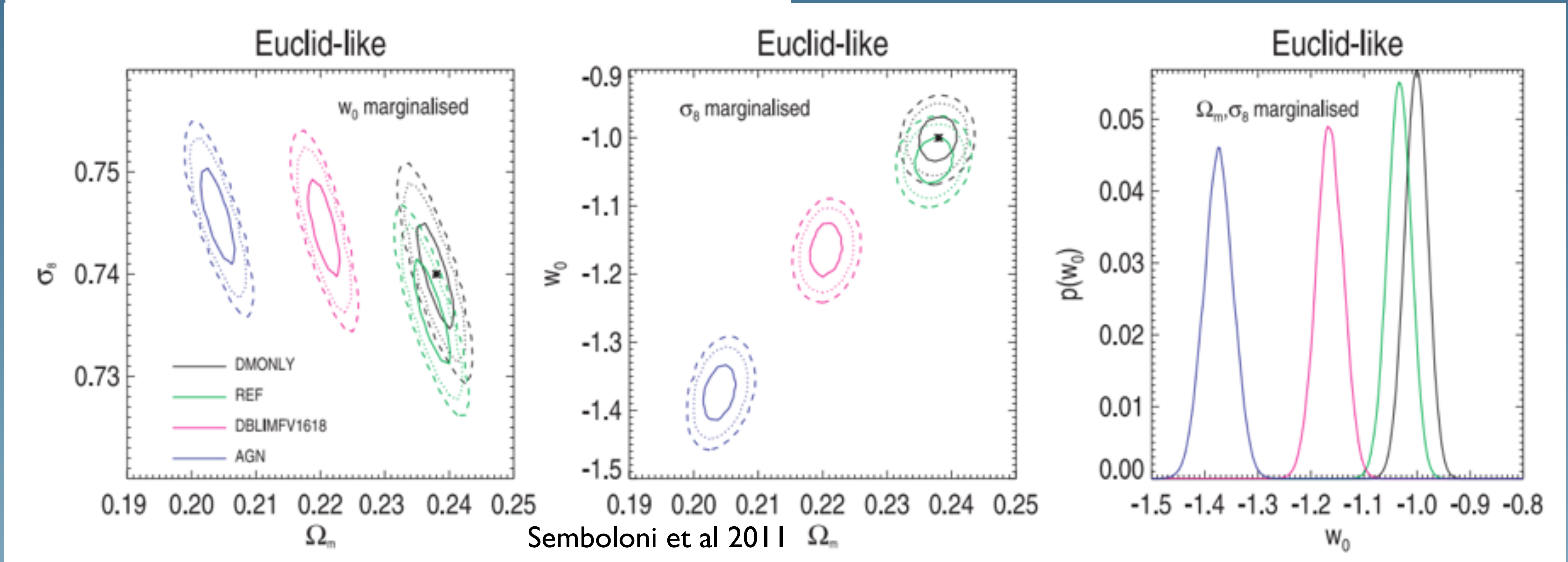
The improvement seen here is coming from:
Higher resolution, lower noise, and a larger sample

Cosmological implications



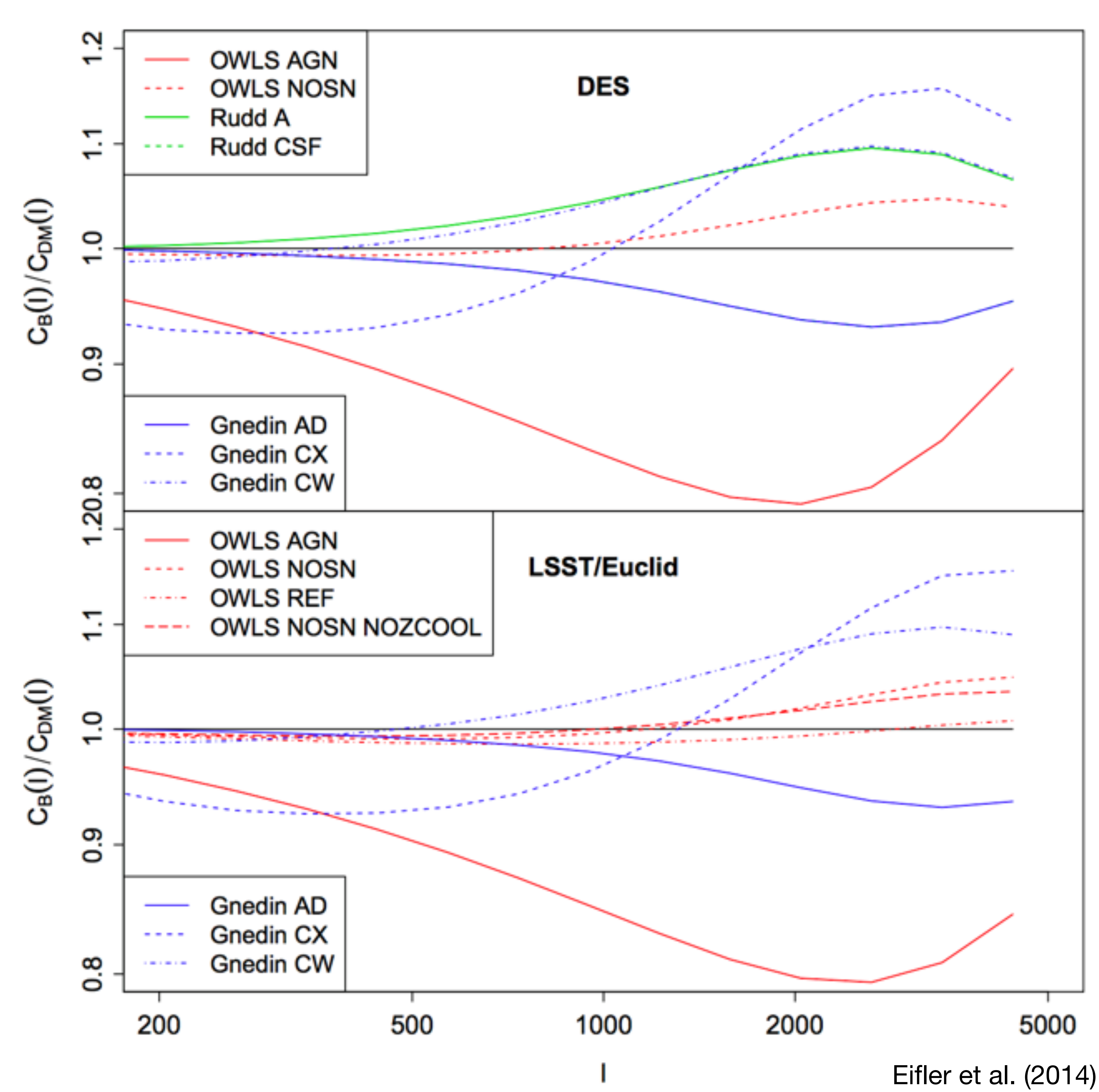
- Pushing into the non-linear regime leads to increasing the uncertainties from baryons and potential biases in the inference of cosmological parameters

- Or provides unique constraints on the main baryonic processes the govern growth of structure on these scales (galaxy formation)



Semboloni et al 2011

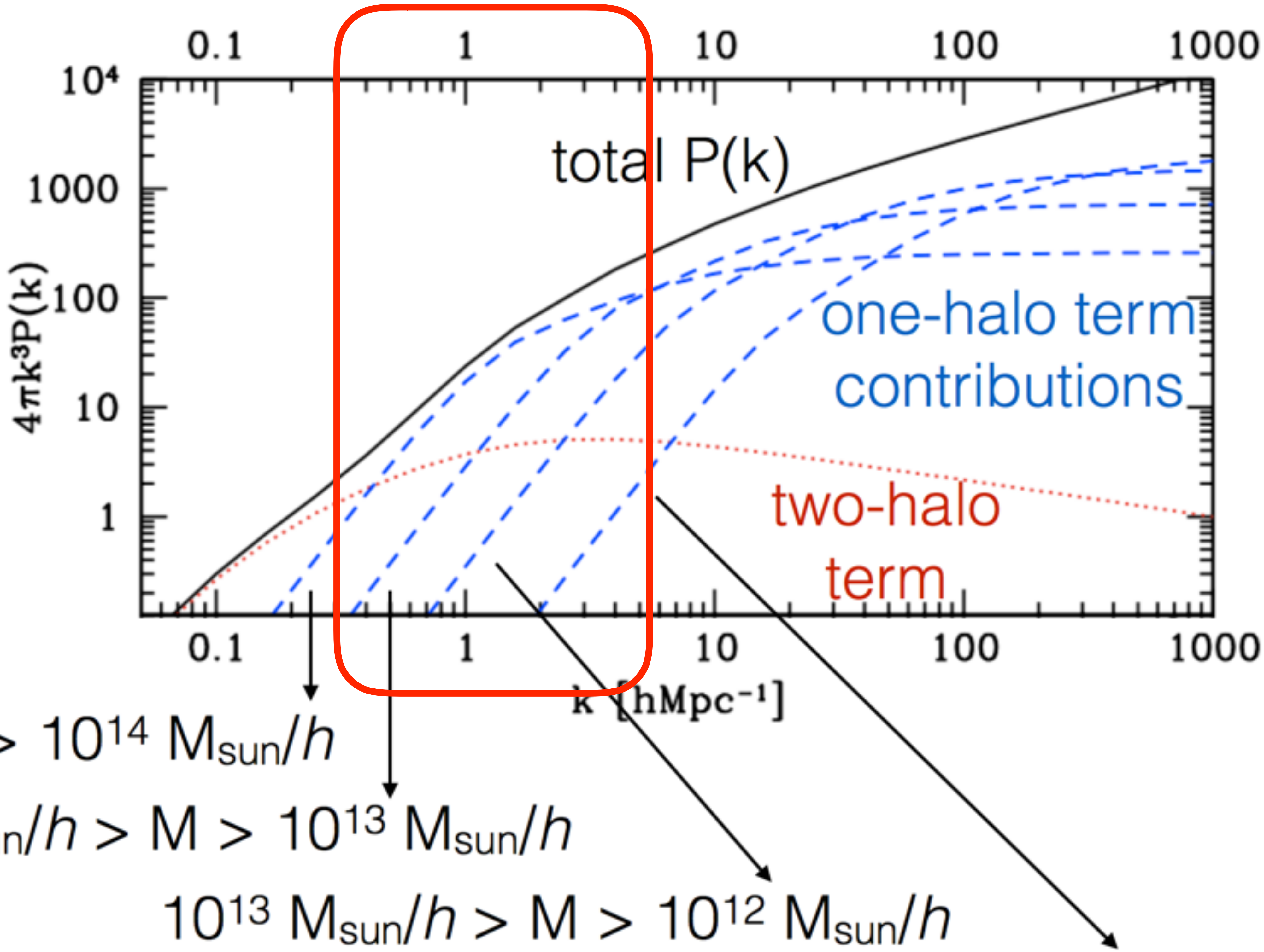
Cosmological impact of feedback



Eifler et al. (2014)

Which halos do we need to measure?

dominated by group-scale halos over relevant wavenumbers



$M > 10^{14}\ M_{sun}/h$

$10^{14}\ M_{sun}/h > M > 10^{13}\ M_{sun}/h$

$10^{13}\ M_{sun}/h > M > 10^{12}\ M_{sun}/h$

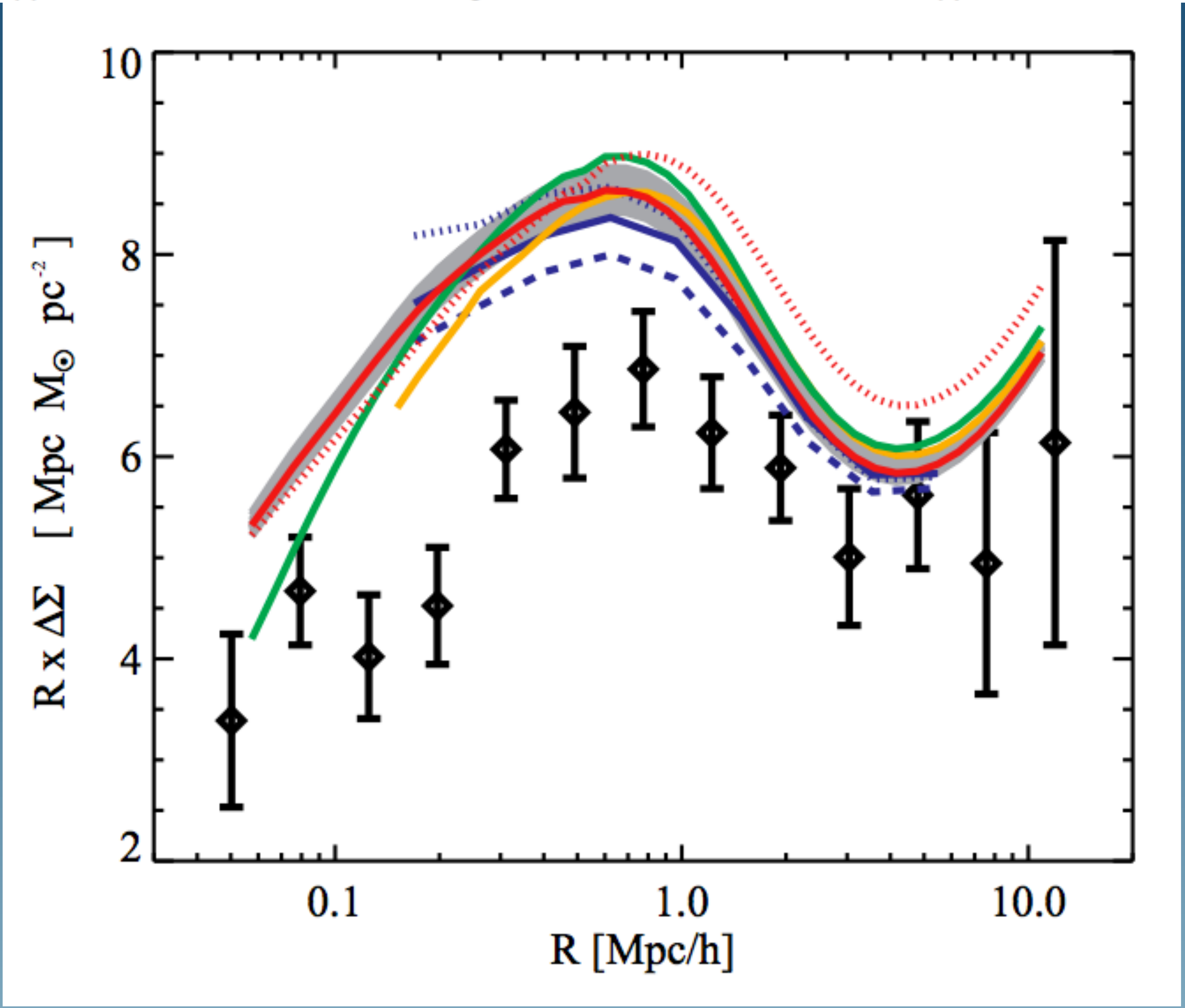
$10^{12}\ M_{sun}/h > M > 10^{11}\ M_{sun}/h$

Seljak (2000)

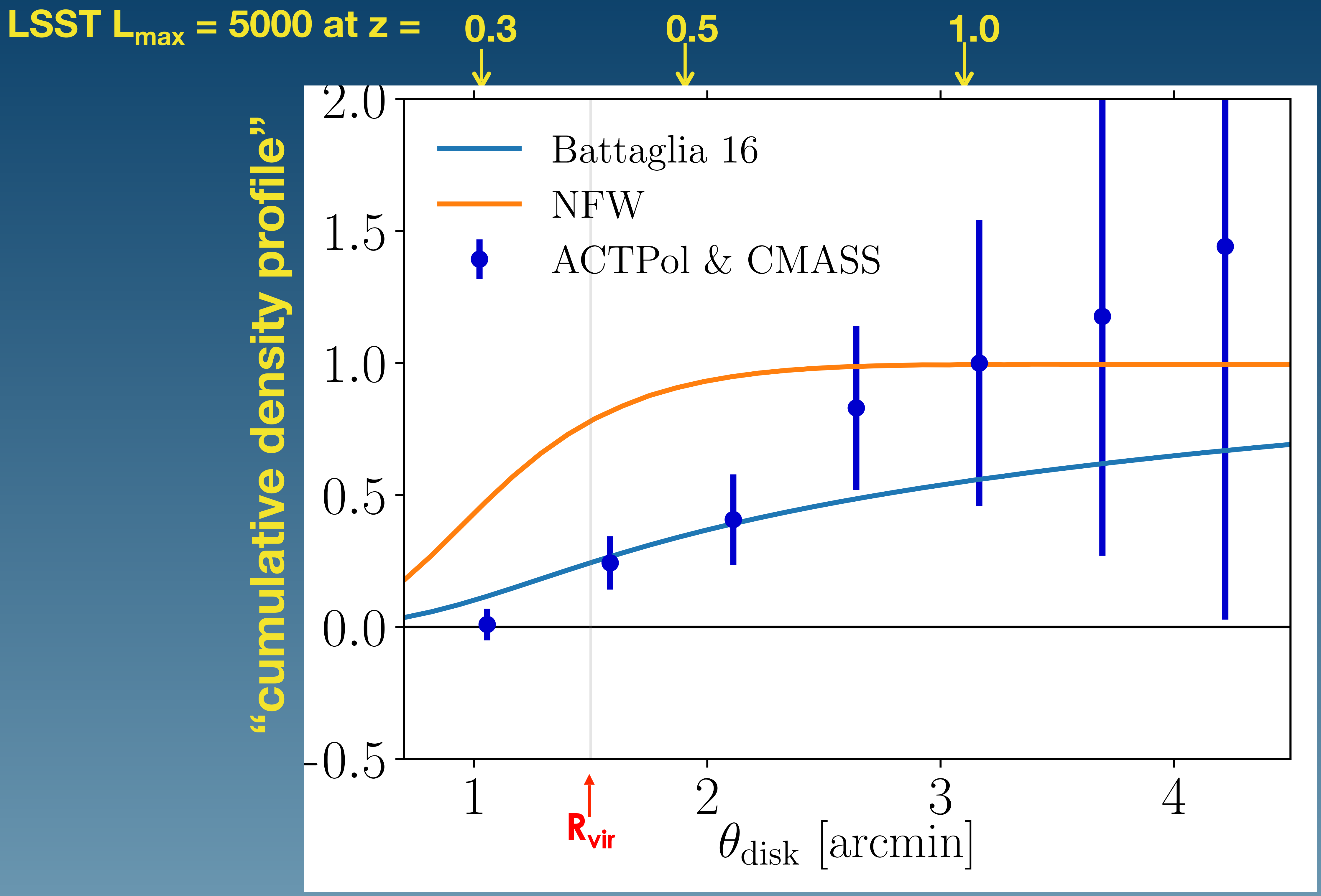
Slide credit J. C. Hill

Lensing is Low: Cosmology, Galaxy Formation, or New Physics?

Alexie Leauthaud[1,2], Shun Saito[3], Stefan Hilbert[4,5], Alexandre Barreira[3], Surhud More[2], Martin White[6], Shadab Alam[7,8], Peter Behroozi[6,9], Kevin Bundy[1,2], Jean Coupon[10],

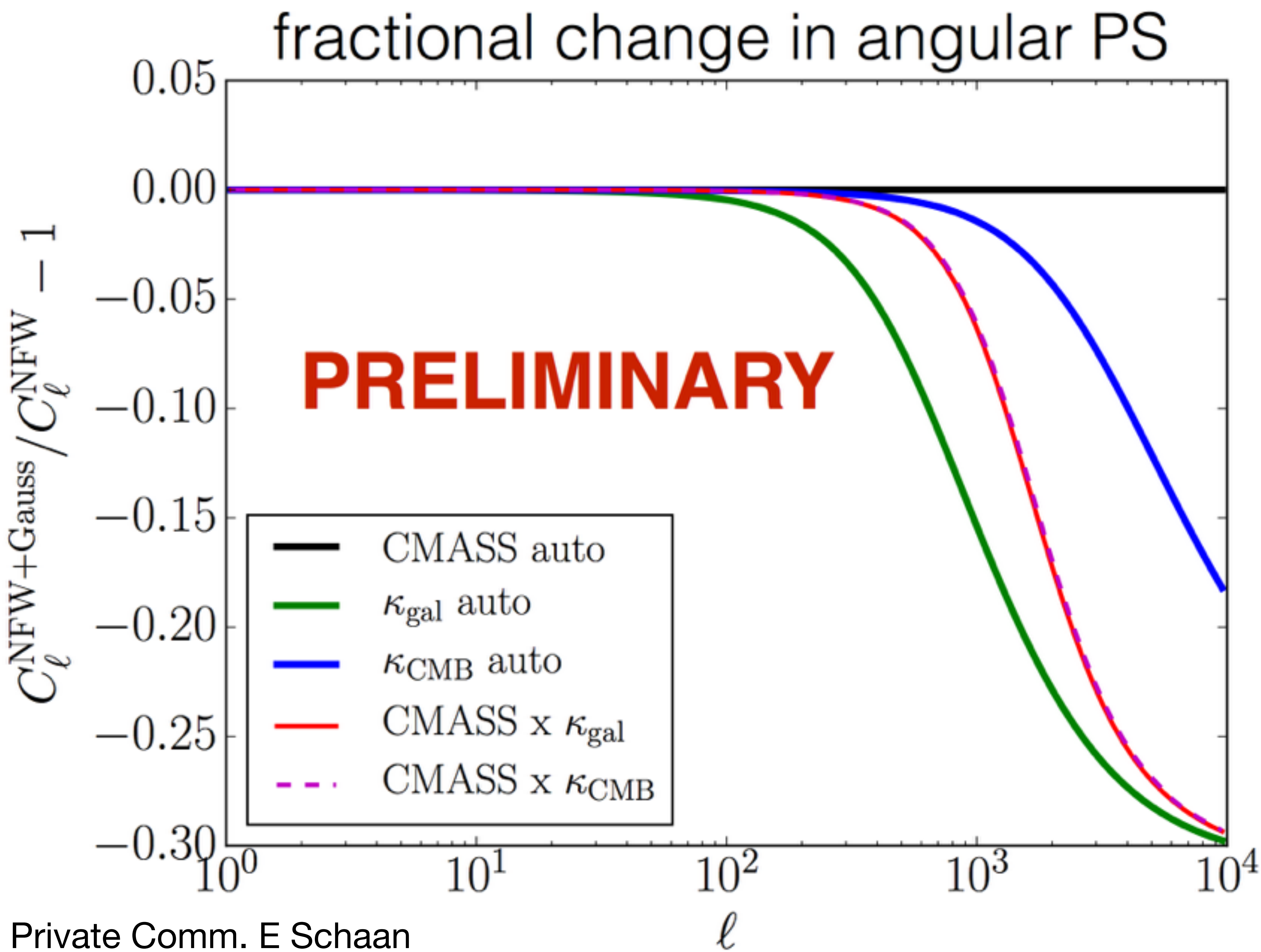


Cosmological Implications



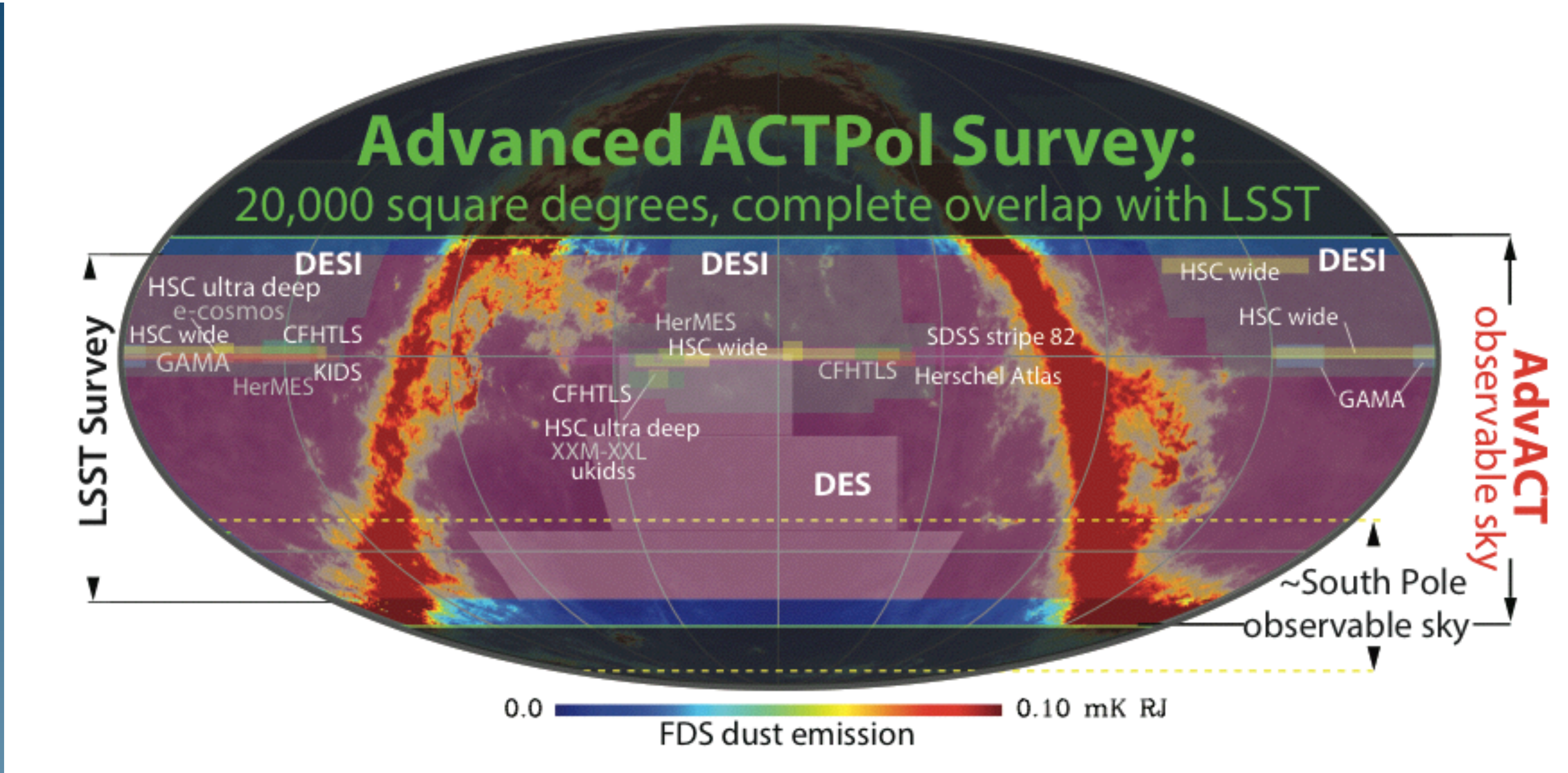
BOSS CMASS galaxies + ACTPol CMB data
z ~ 0.6, M ~ 2 x 10^{13} M_{sun}

0th order modeling of the Baryons



Private Comm. E Schaan

AdvACT + other surveys



Funded, large area, multiple frequency bands
20,000 clusters covering the entire LSST
Potential for kSZ cross correlations is large

The Simons Observatory

- **10 Countries**
- **40+ Institutions**
- **160+ Researchers**

United States

- Arizona State University
- Carnegie Mellon University
- Center for Computational Astrophysics
- Cornell University
- Florida State
- Haverford College
- Lawrence Berkeley National Laboratory
- NASA/GSFC
- NIST
- Princeton University
- Rutgers University
- Stanford University/SLAC
- Stony Brook
- University of California - Berkeley
- University of California – San Diego
- University of Michigan
- University of Pennsylvania
- University of Pittsburgh
- University of Southern California
- West Chester University
- Yale University

Japan

- KEK
- IPMU
- Tohoku
- Tokyo

Canada

- CITA/Toronto
- Dunlap Institute/Toronto
- McGill University
- Simon Fraser University
- University of British Columbia

Chile

- Pontificia Universidad Catolica
- University of Chile

Europe

- APC – France
- Cambridge University
- Cardiff University
- Imperial College
- Manchester University
- Oxford University
- SISSA – Italy
- University of Sussex

South Africa

- Kwazulu-Natal, SA

Australia

- Melbourne

Middle East

- Tel Aviv

Summary and Outlook

Growth of structure measurements
from tSZ and kSZ observations

Systematic uncertainties
current limiting factors

What are the potential
constraints?

Summary and Outlook

Growth of structure measurements from tSZ and kSZ observations

Theory needs to catch-up to the number of tSZ clusters

High S/N kSZ on coming soon

Systematic uncertainties current limiting factors

Weak-lensing calibrations to control systematics

kSZ constraints will be limited by τ

What are the potential constraints?

Competitive, independent, & complementary

Push other probes into non-linear regime

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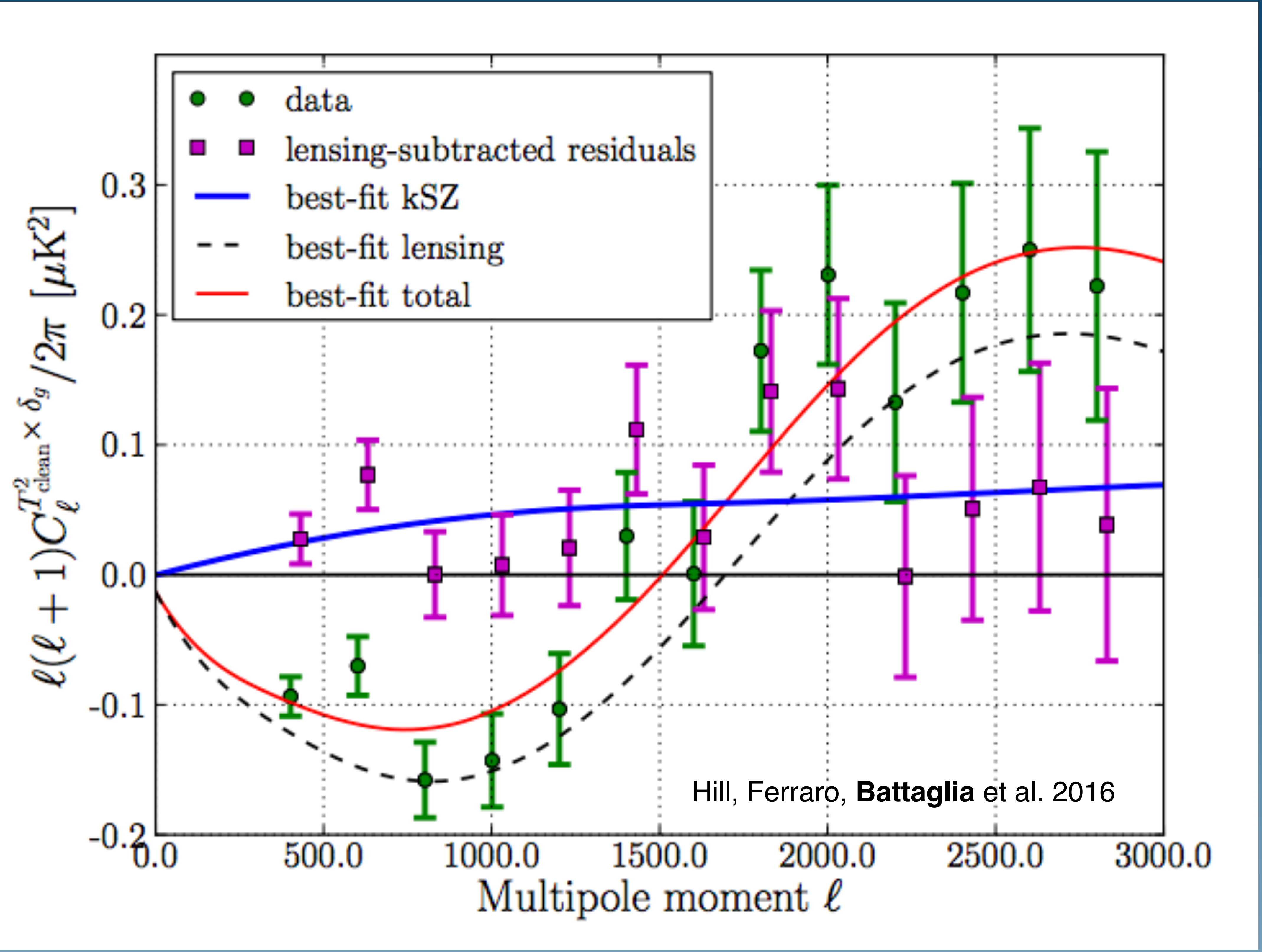
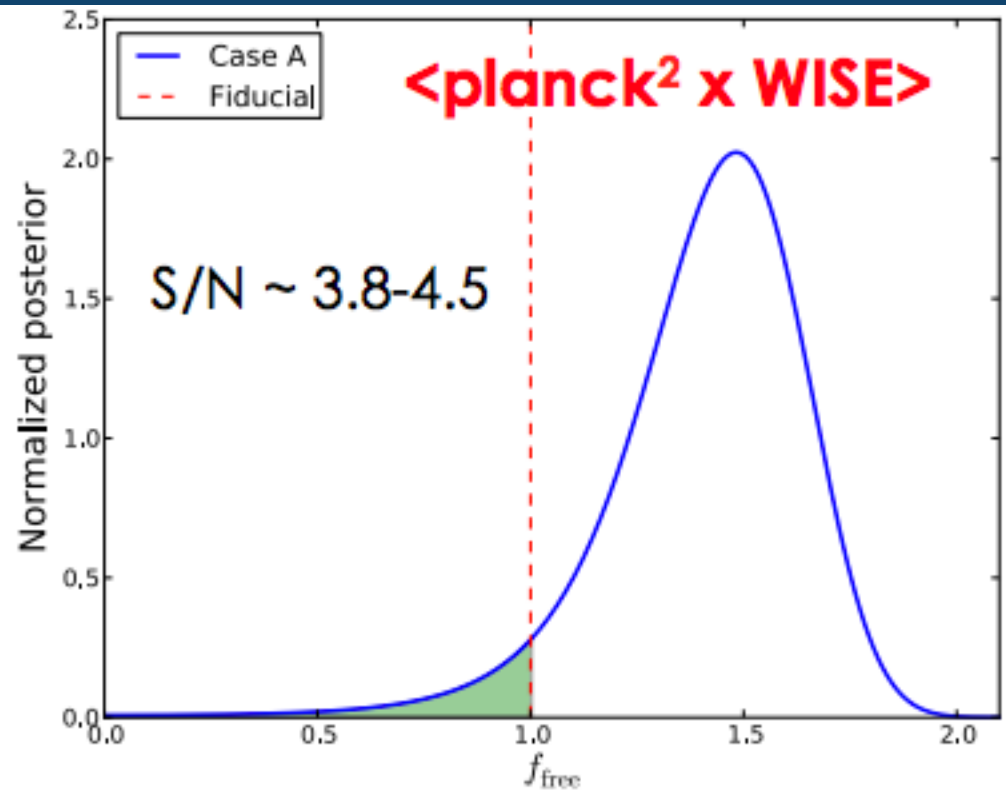
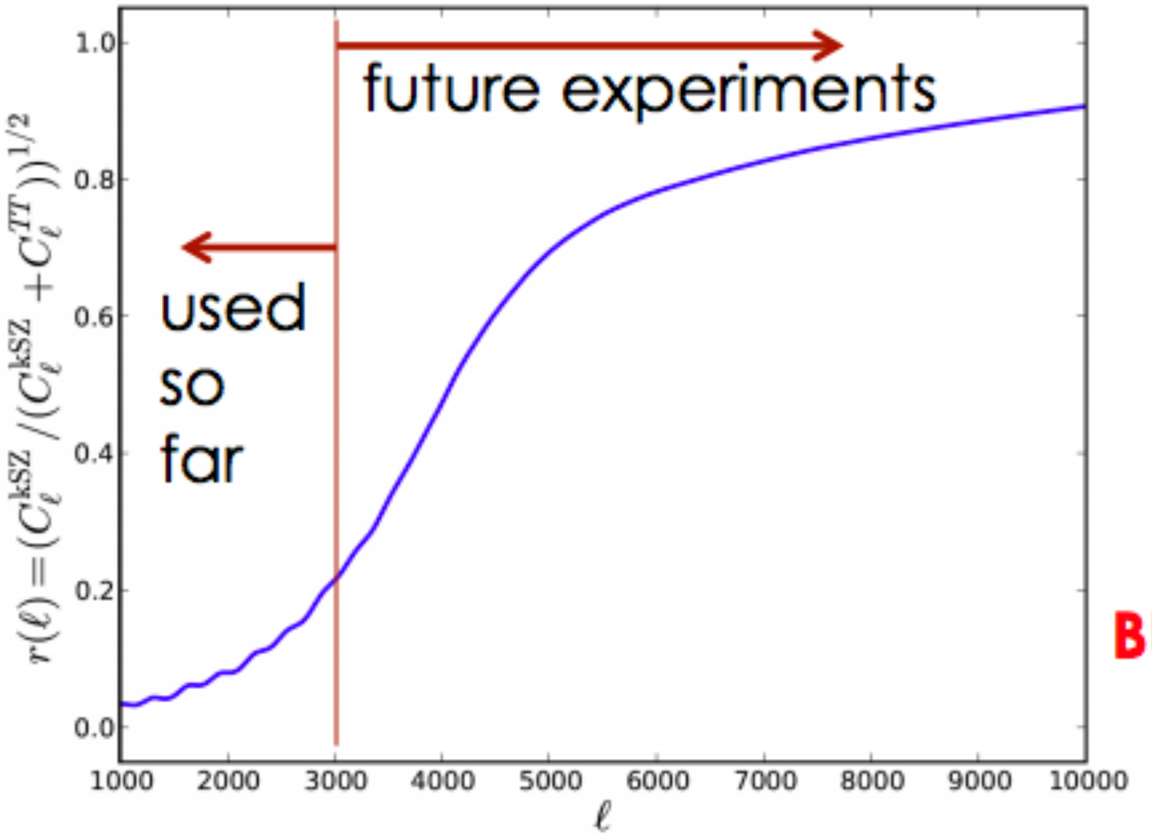
Extra kSZ

kSZ with LSST - projected fields approach



kSZ with LSST - projected fields approach





CMB experiment	beam FWHM [arcmin]	effective noise[a] Δ_T [μK-arcmin]
Planck (2015 LGMCA map)	5	47
Advanced ACTPol	1.4	10
CMB-S4 (case 1) [b]	3	3
CMB-S4 (case 2)	1	3
CMB-S4 (case 3)	3	1
CMB-S4 (case 4)	1	1

LSST 26 gal/arcmin² (preliminary)

x AdvACT	326
x CMB-S4 (case 1)	402
x CMB-S4 (case 2)	1032
x CMB-S4 (case 3)	1006
x CMB-S4 (case 4)	1230

BUT CAREFUL with SYSTEMATICS (foregrounds!)

Hill, Ferraro, **Battaglia** et al. 2016

Ferraro, Hill, **Battaglia** et al. 2016

Slide credit S. Ferraro