Constraining fundamental physics and halo energetics using Sunyaev-Zel'dovich measurements

MacNamara et al. 2009

Nick Battaglia
Princeton University

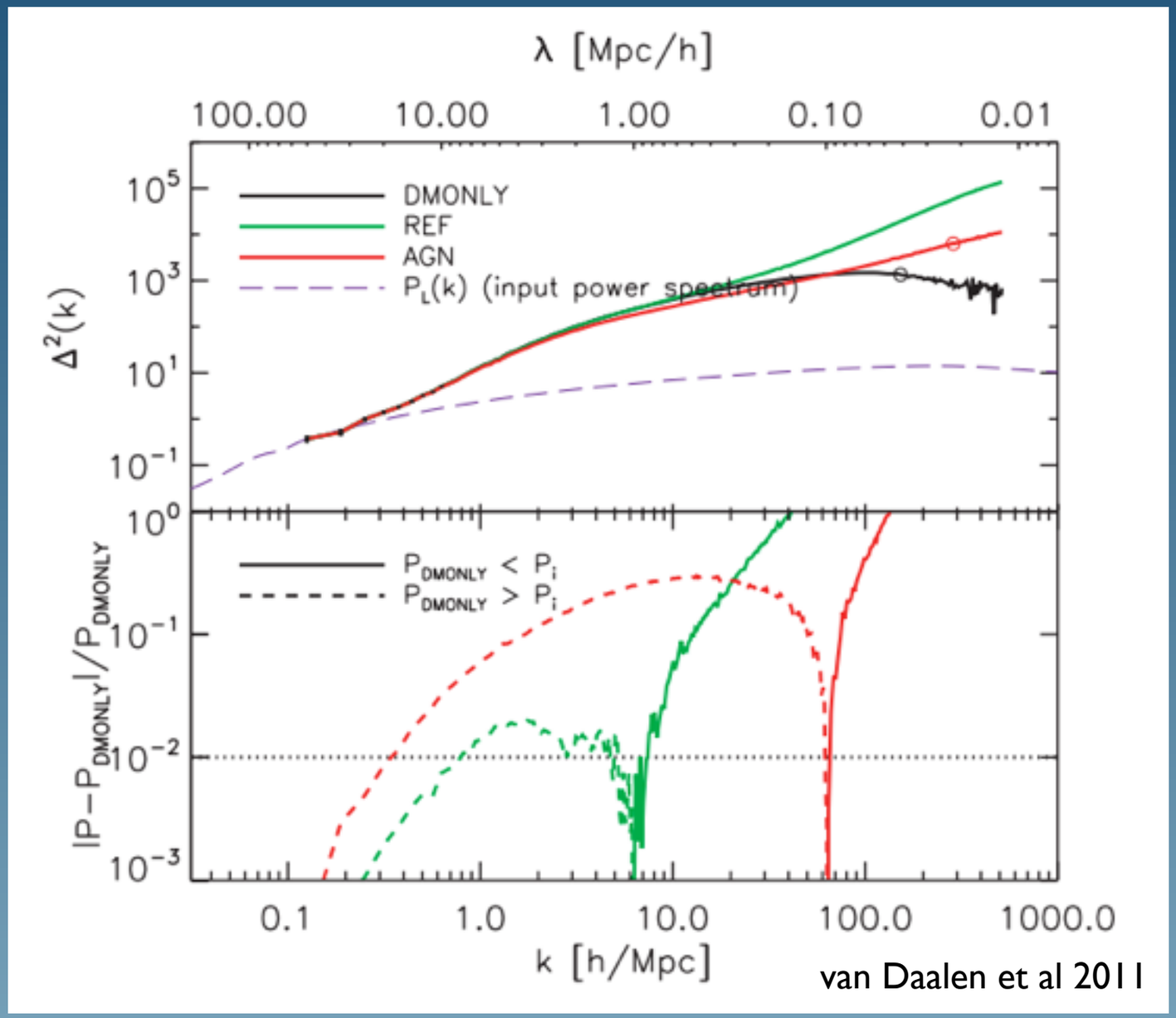
Nordita
July 27 2017

Collaborators

Emmanuel Schaan (Princeton)
Colin Hill (Columbia)
Simone Ferraro (Berkeley)
Jia Liu (Princeton)
Dick Bond (CITA)
Christoph Pfrommer (Postdam)
Jon Sievers (UKZN)
David Spergel (Princeton)

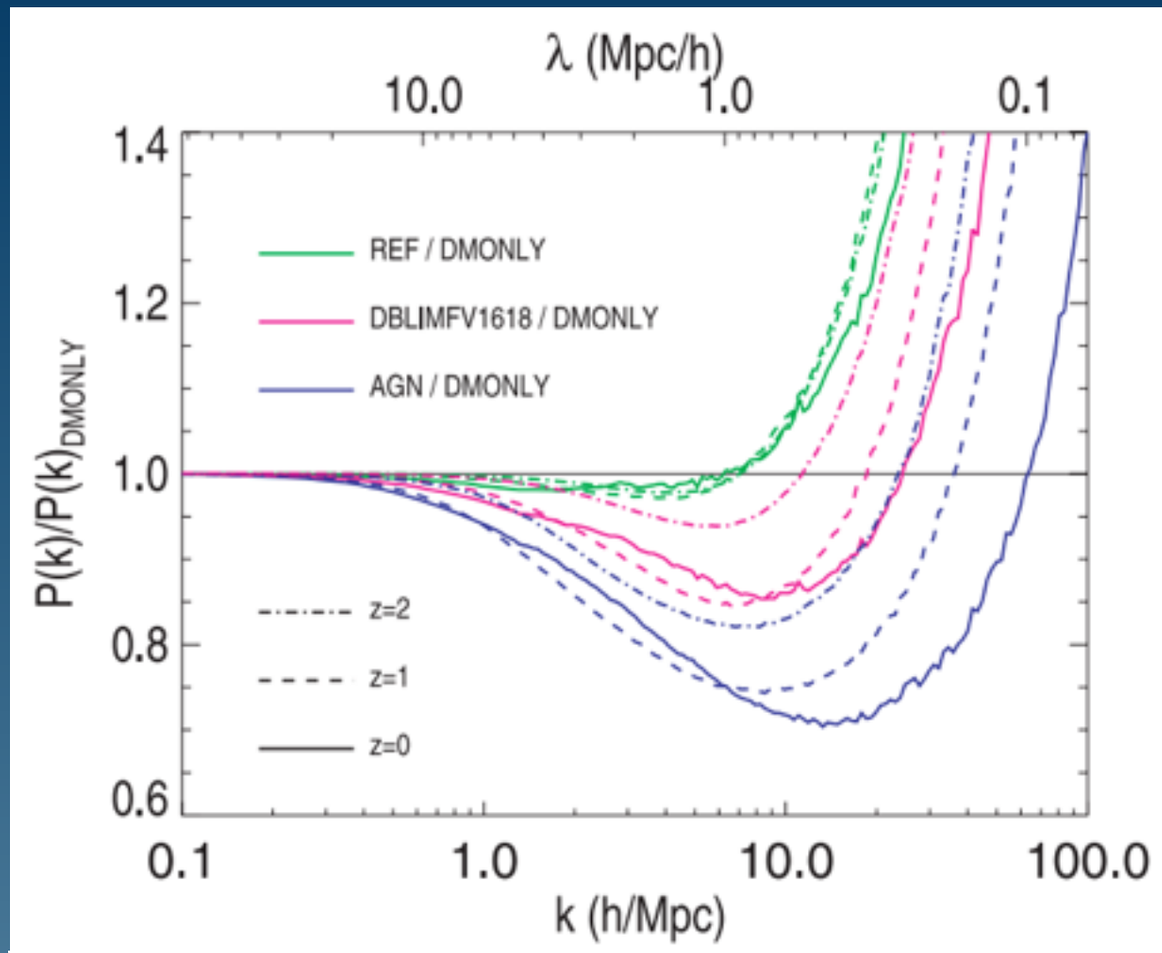
Baryons

Baryons



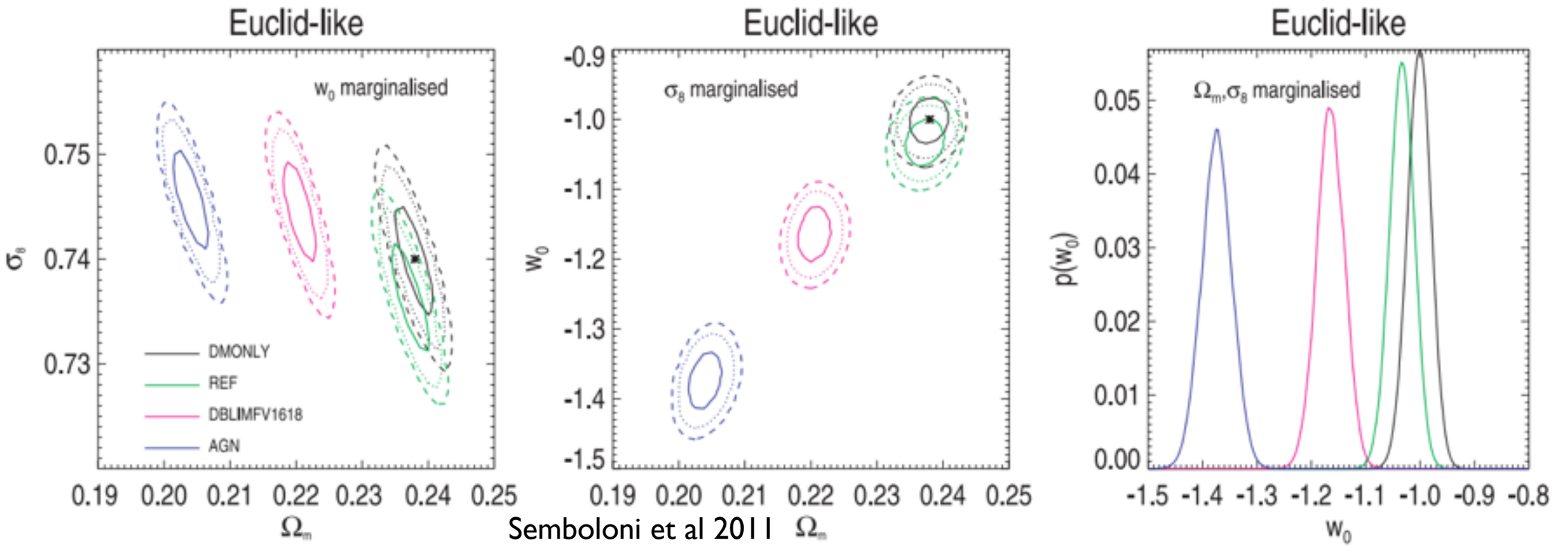
van Daalen et al 2011

Baryons - Cosmological implications



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

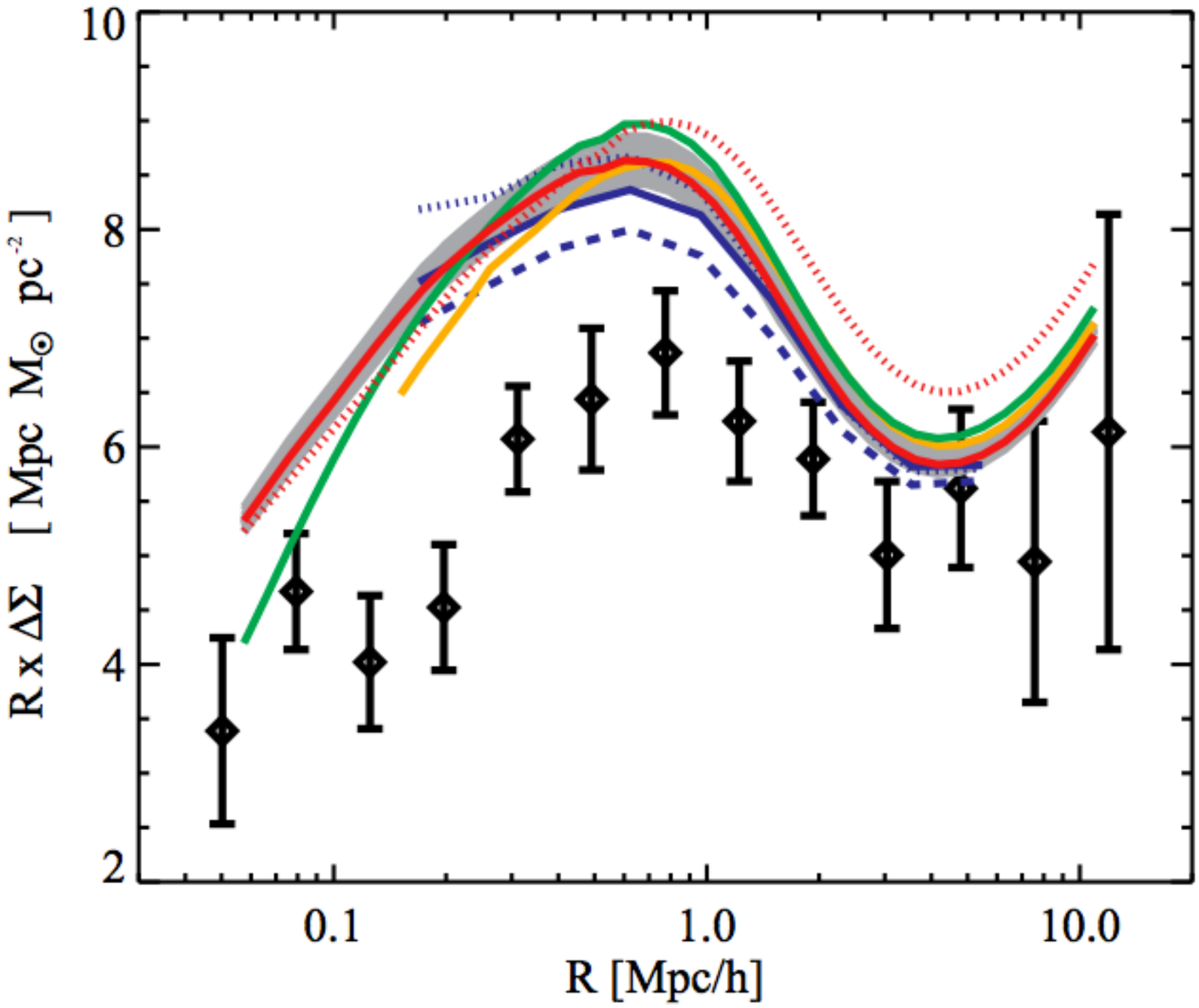
- Or provides unique constraints on the main baryonic processes the govern growth of structure on these scales (galaxy formation)



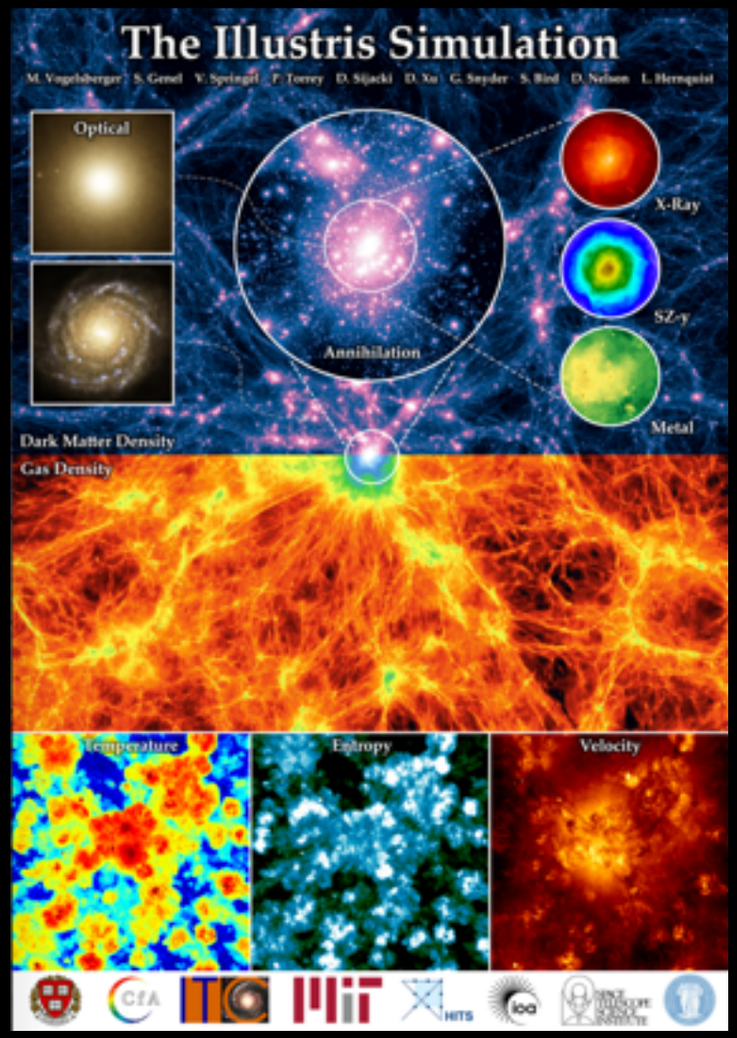
Semboloni et al 2011

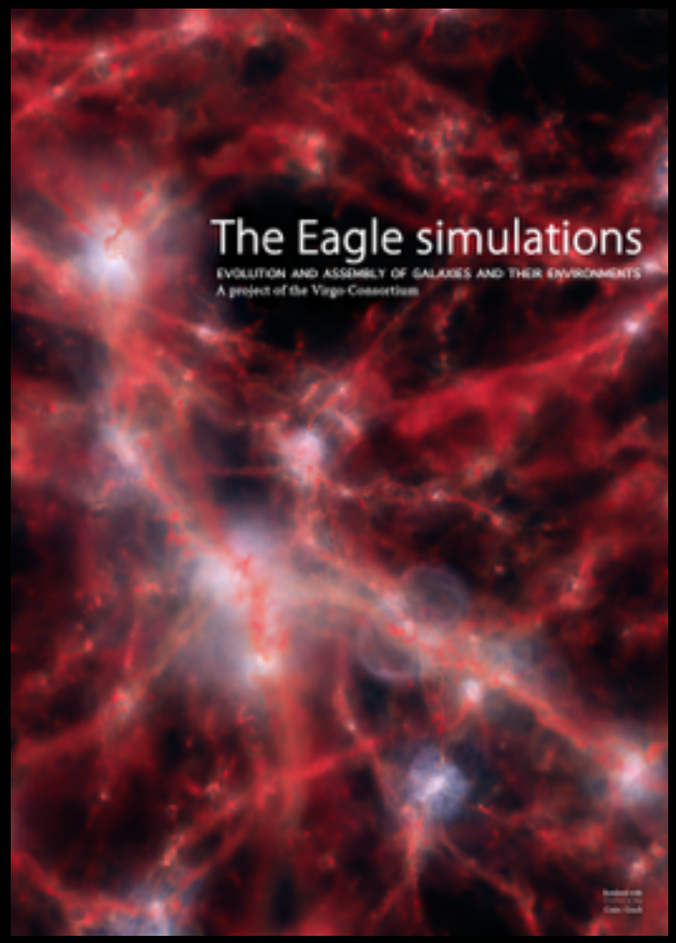
Lensing is Low: Cosmology, Galaxy Formation, or New Physics?

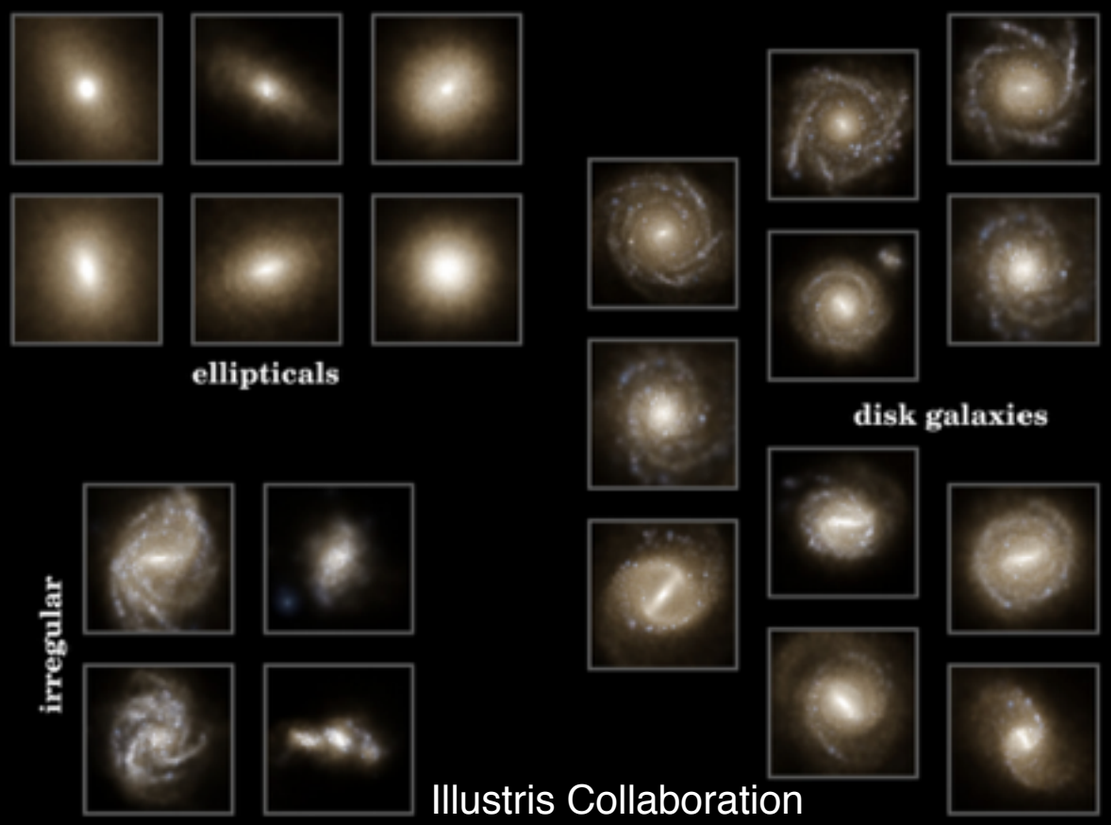
Alexie Leauthaud[1,2], Shun Saito[3], Stefan Hilbert[4,5], Alexandre Barreira[3], Surhud More[2], Martin White[6], Shadab Alam[7,8], Peter Behroozi[6,9], Kevin Bundy[1,2], Jean Coupon[10],



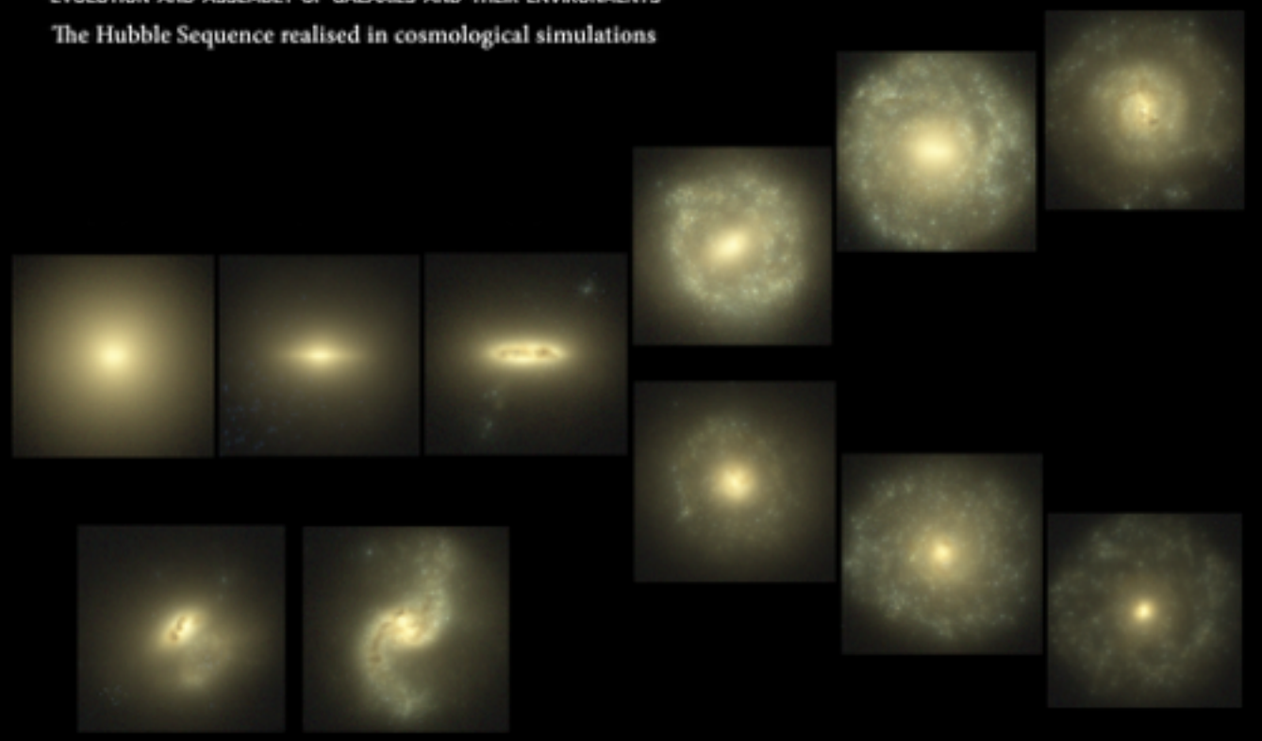
Cosmological Simulations



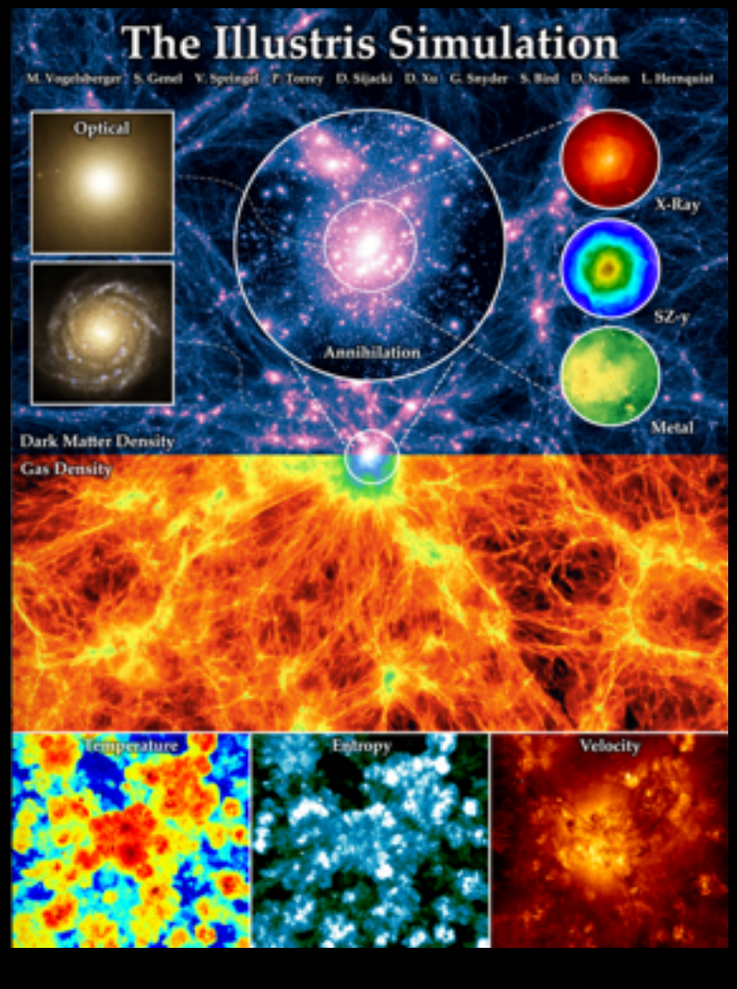


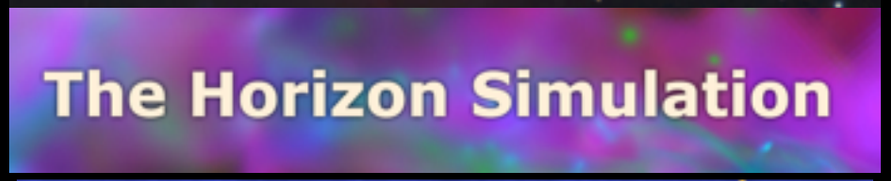


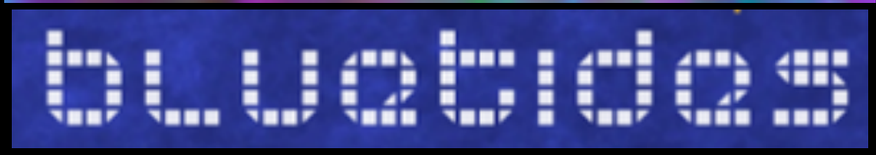
Illustris Collaboration

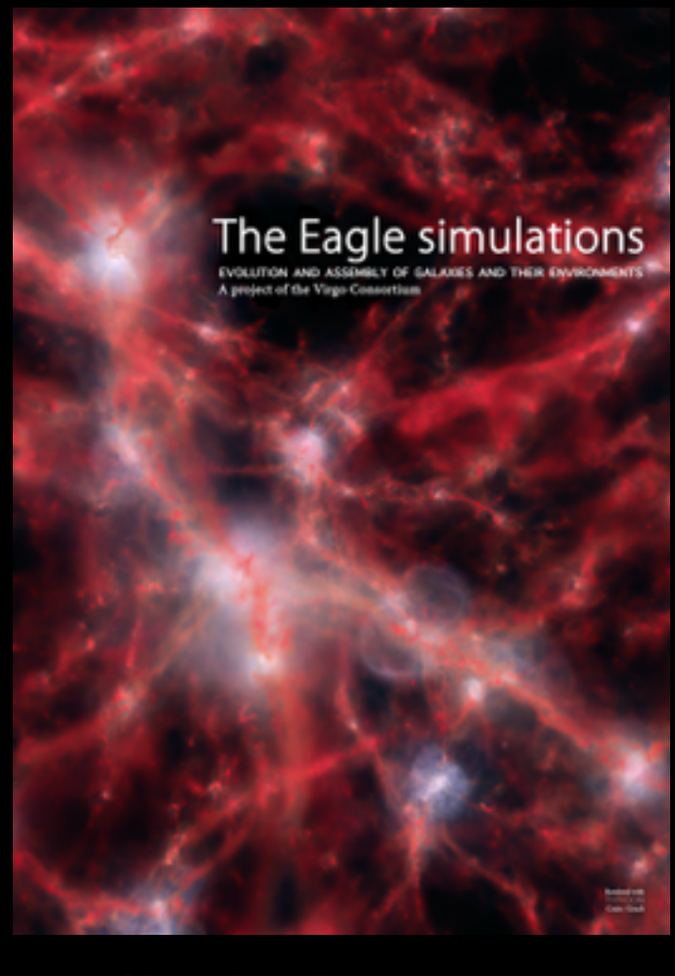


Cosmological Simulations

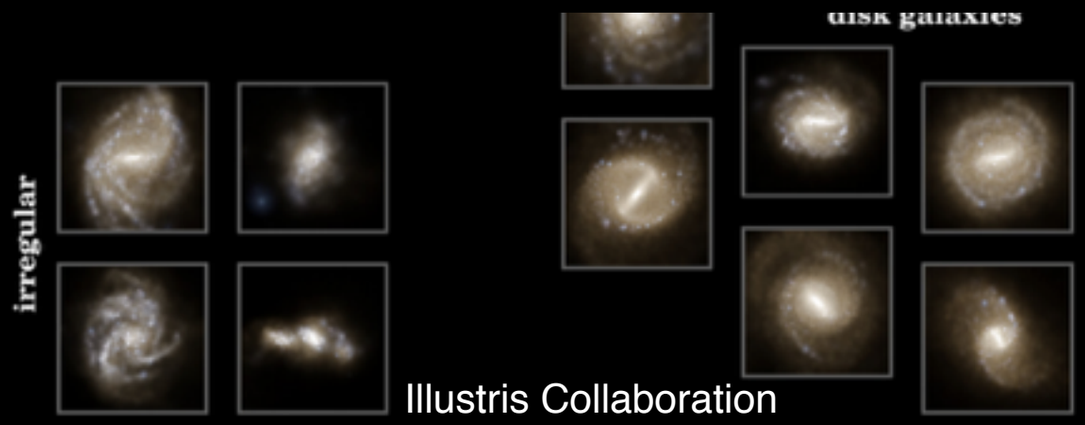




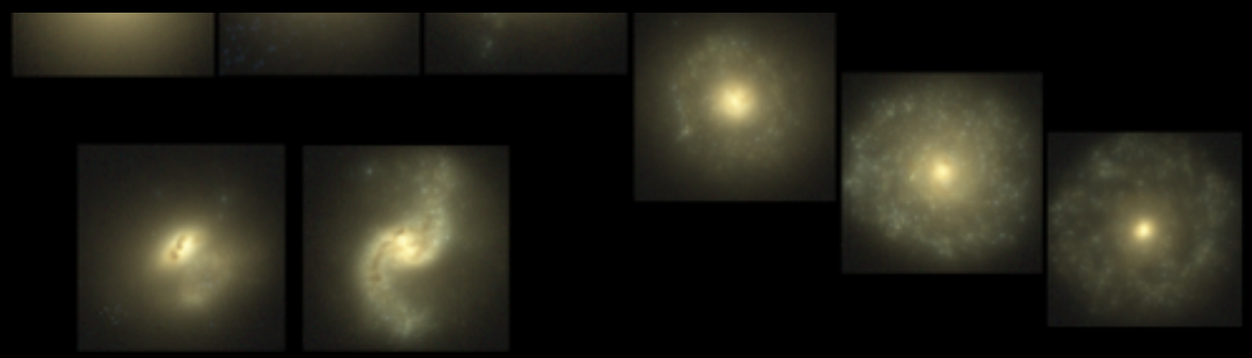




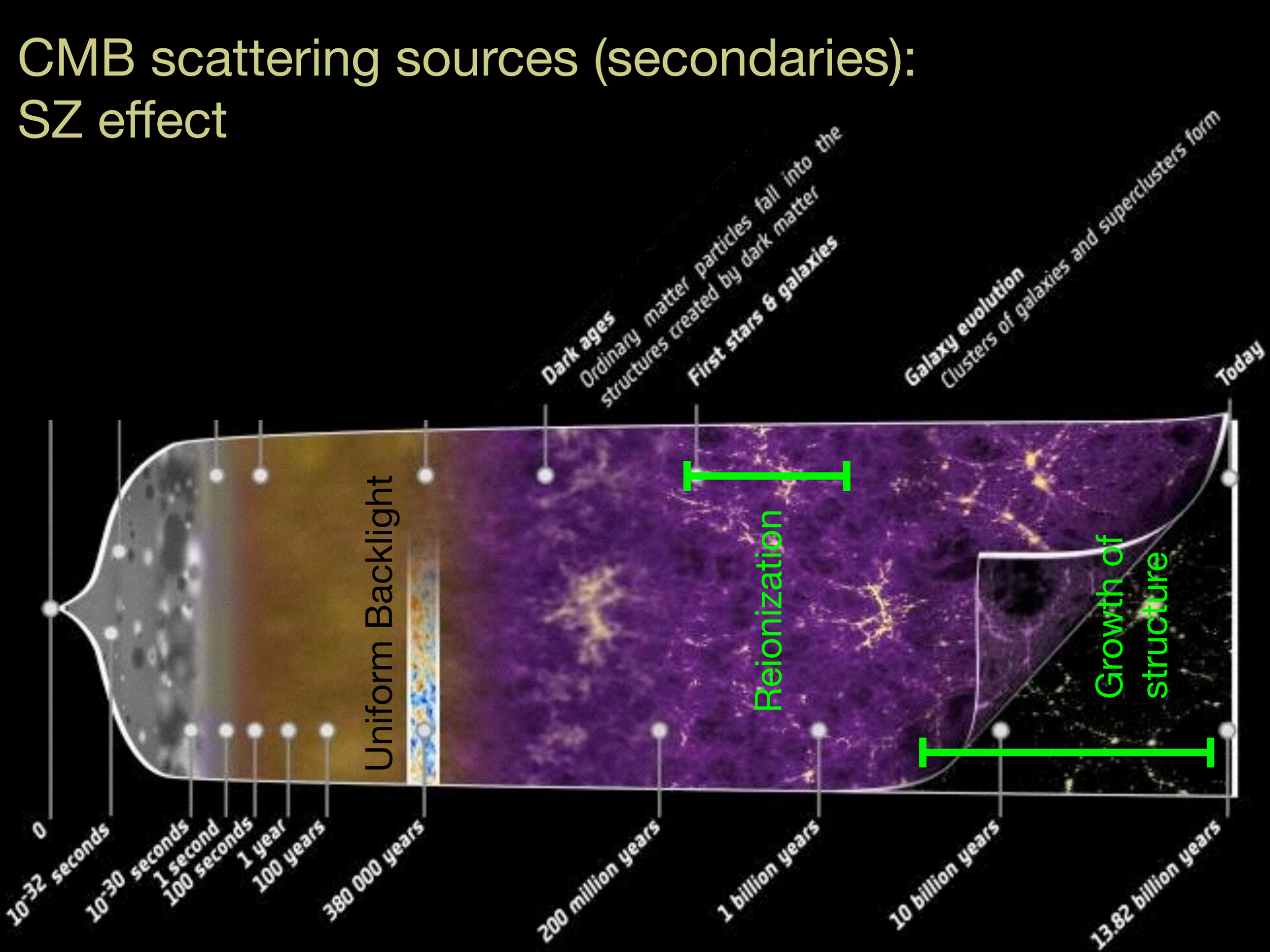
Are the sub-grid physics models realistic?
What is the work being done on these systems?
Predictions for the energetics of (massive) halos
Impact on cosmological information?



Illustris Collaboration

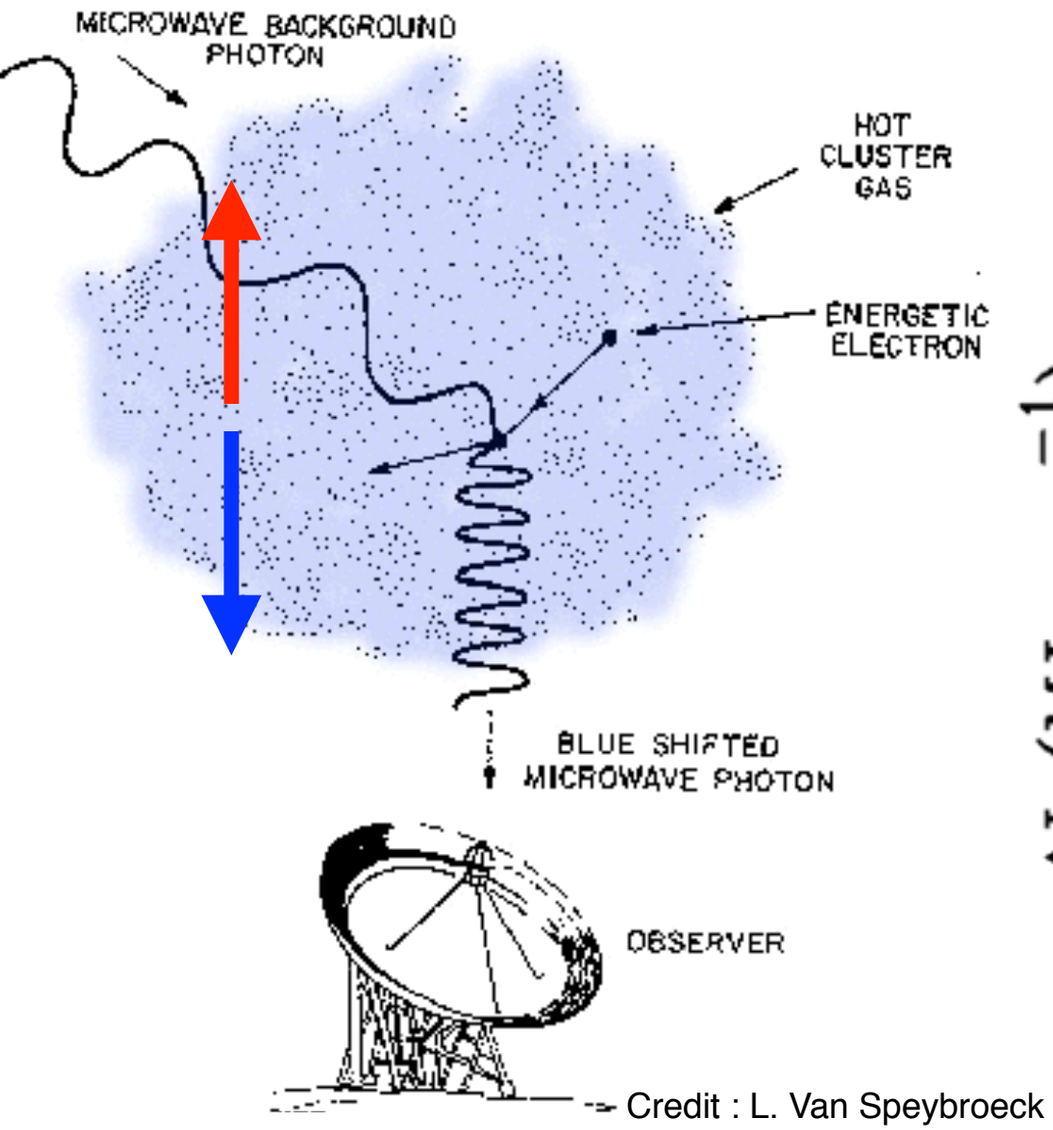


CMB scattering sources (secondaries): SZ effect



Kinetic Sunyaev-Zel'dovich Effect

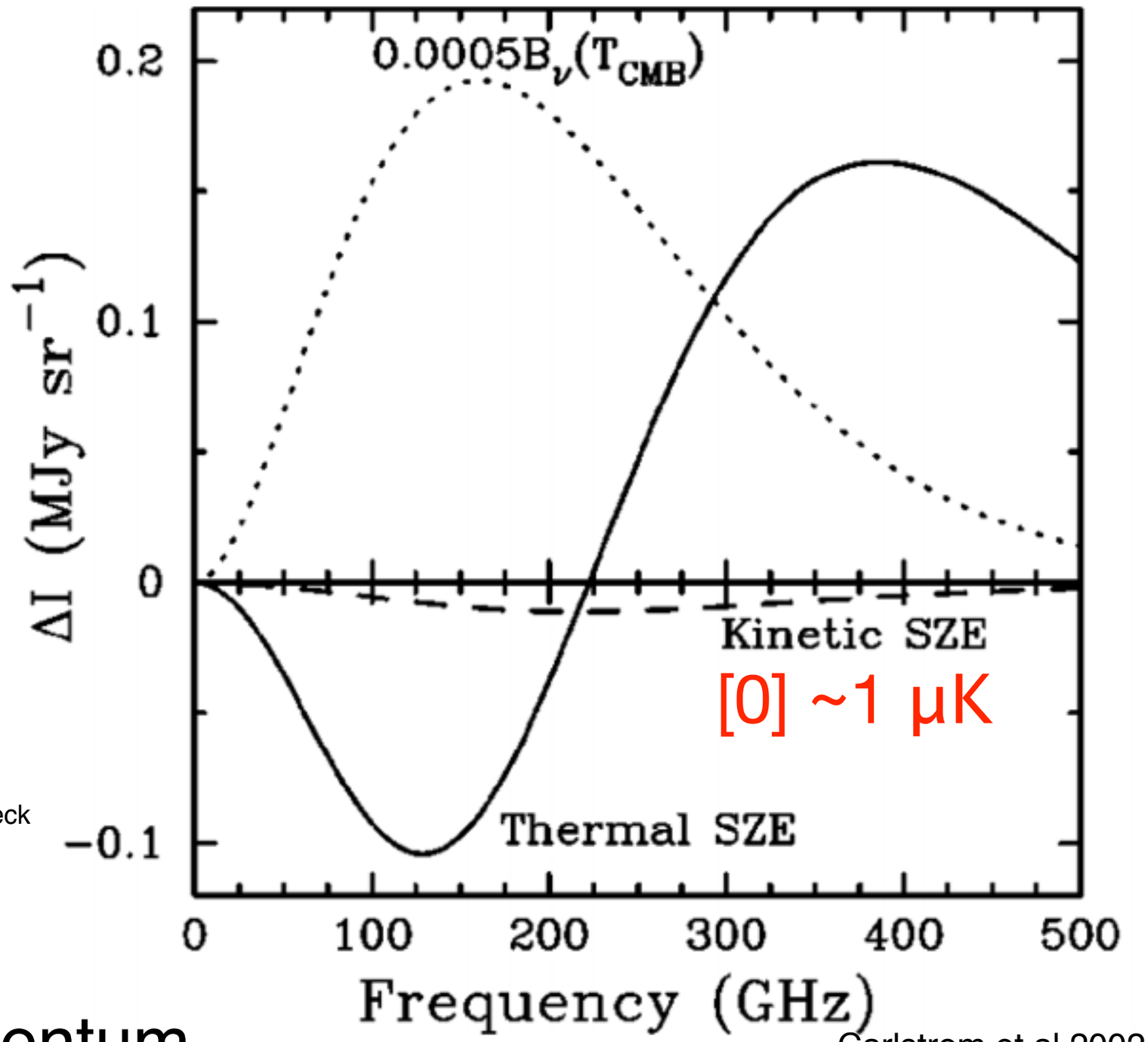
Doppler boosting of CMB photons



Credit : L. Van Speybroeck

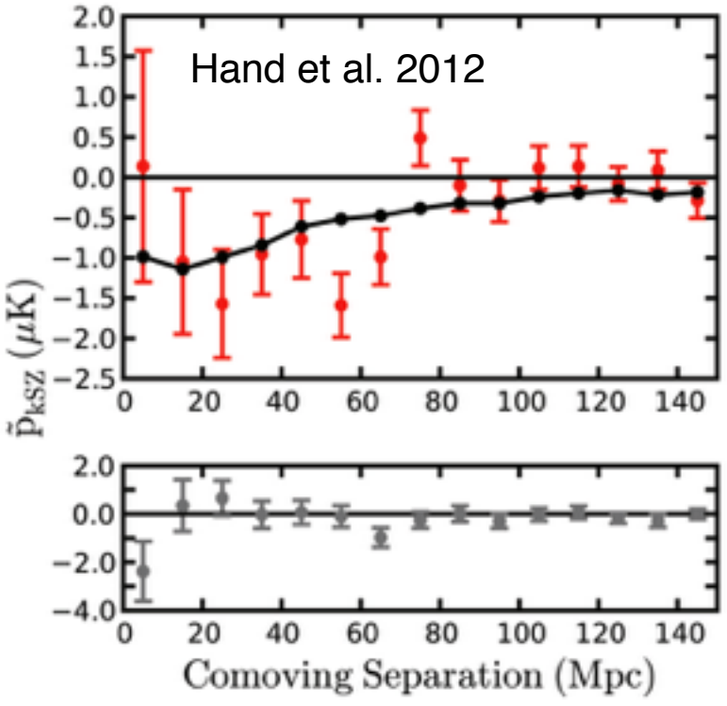
$$b \equiv \frac{\sigma_T}{c} \int n_e v_{los} dl$$

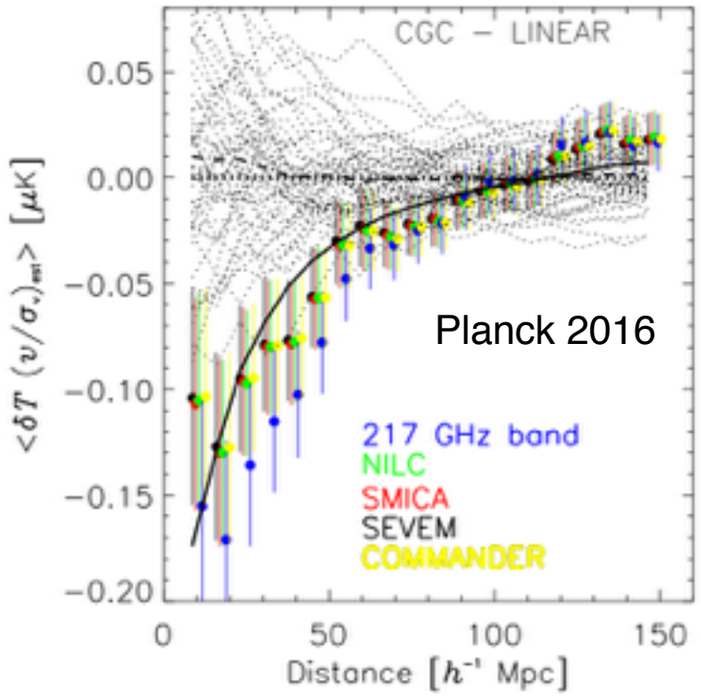
LOS Momentum

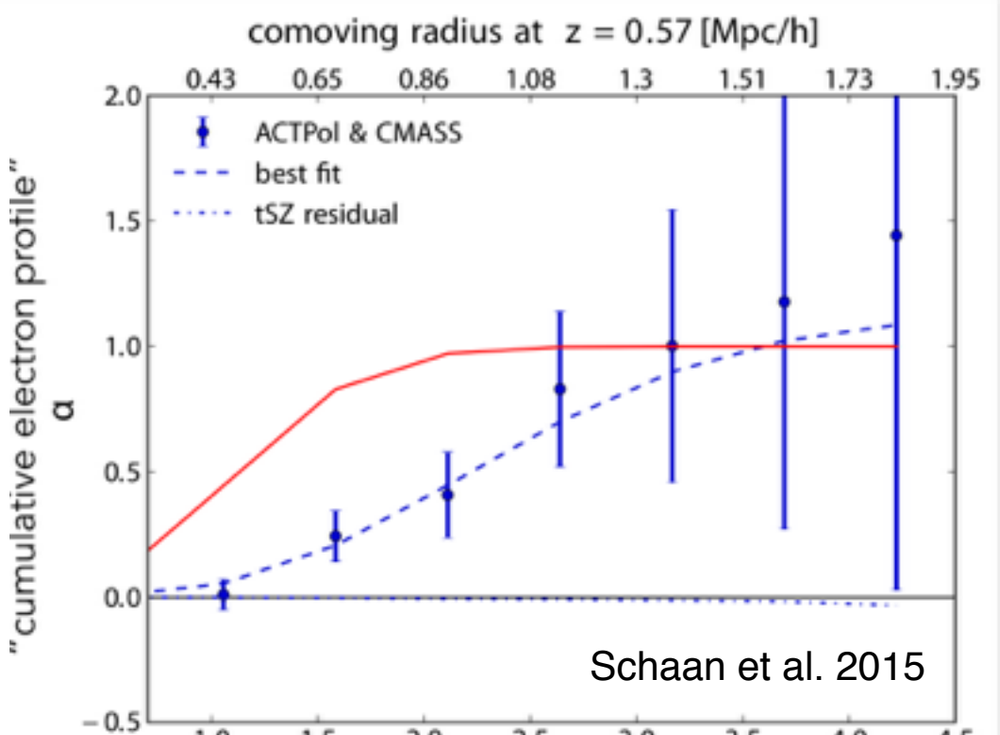


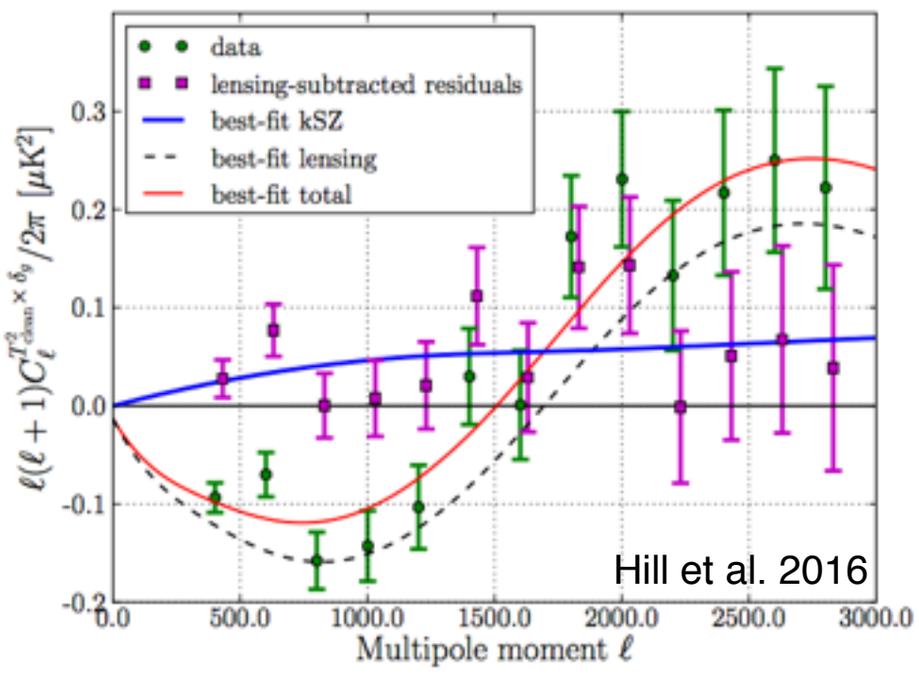
Carlstrom et al 2002

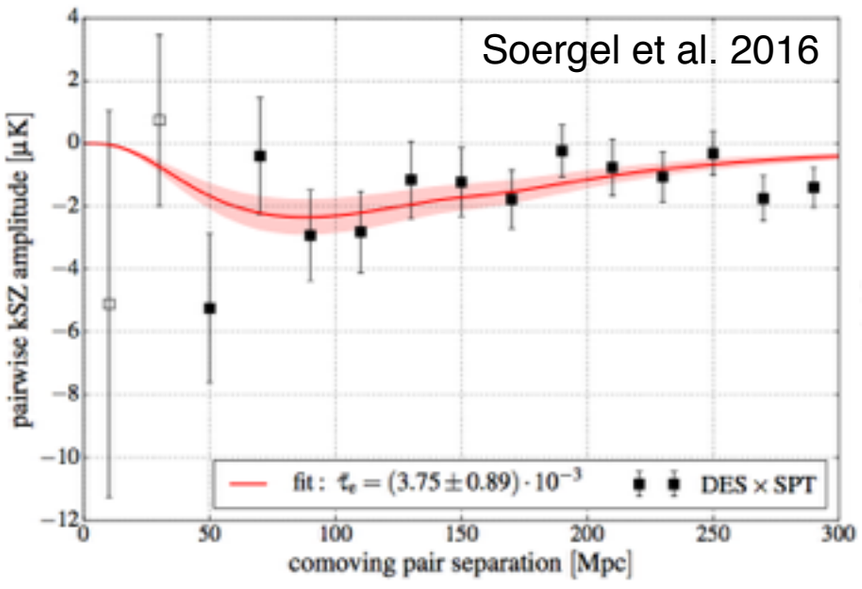
Gallery of recent kSZ results

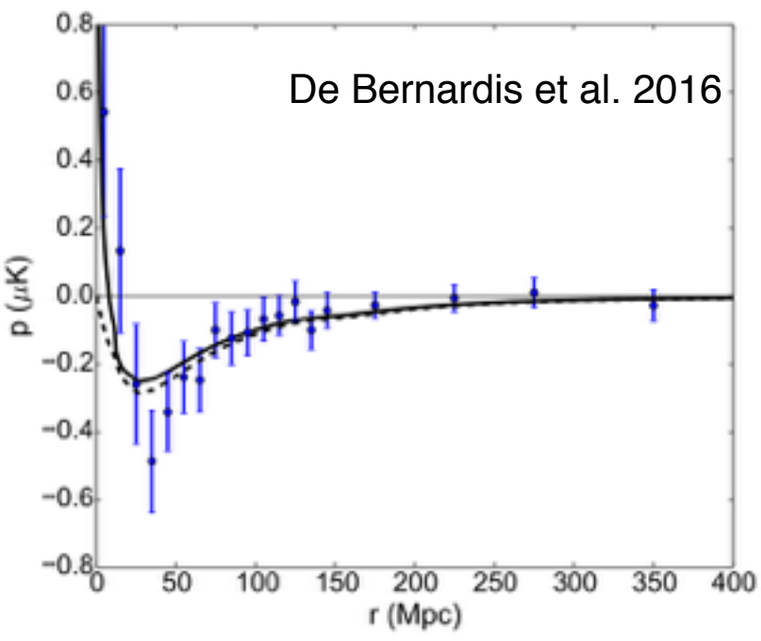










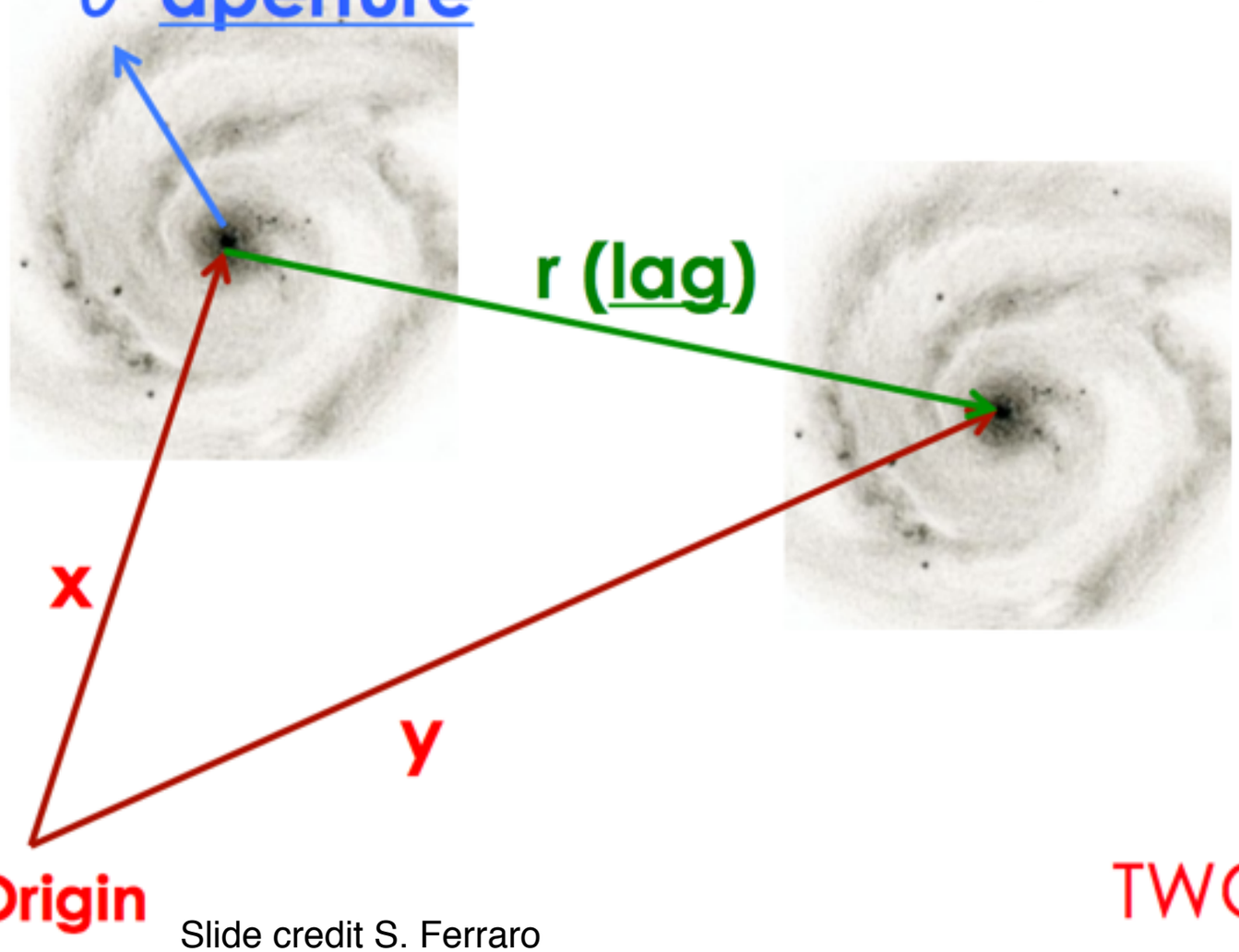


What is measured?

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

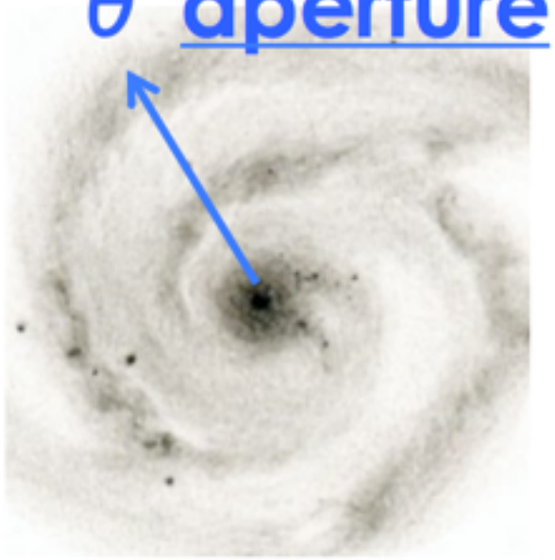
aperture

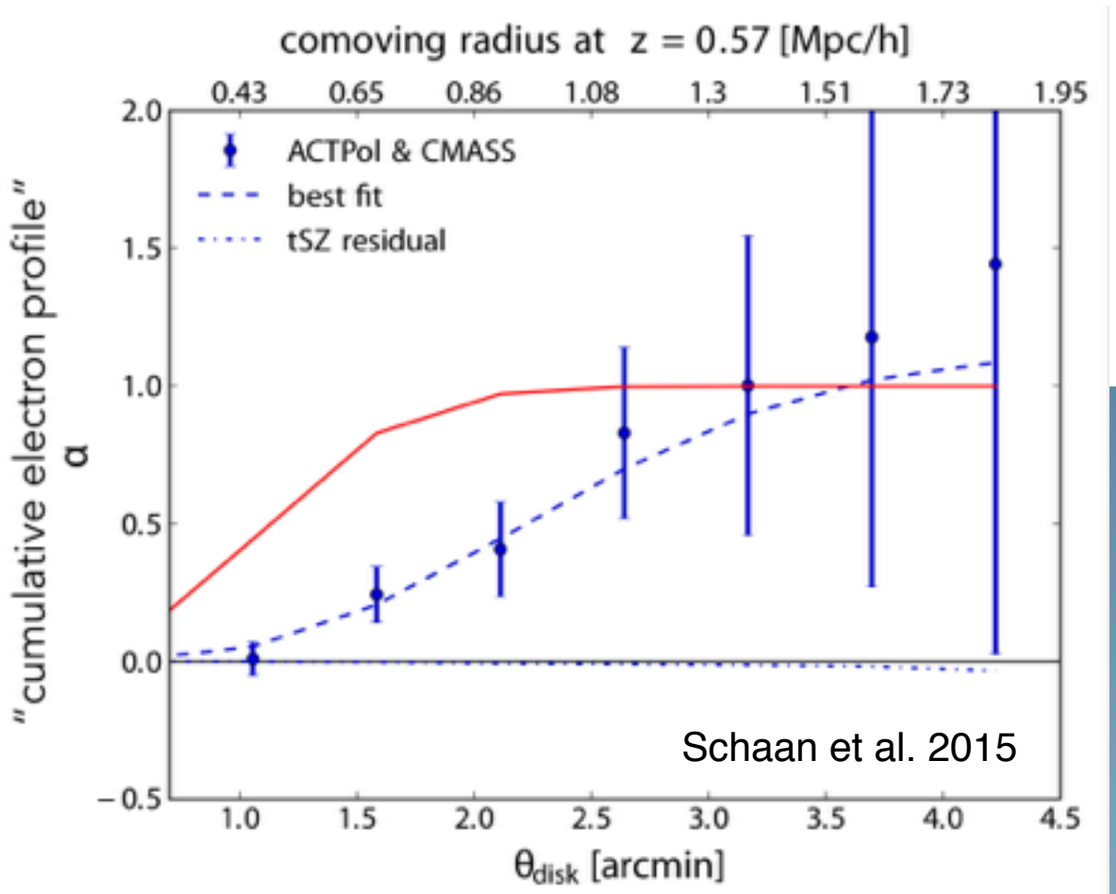
$$\left\langle \frac{\Delta T}{T}(\mathbf{x}) \quad v_r^{\rm rec}(\mathbf{x}) \right\rangle (\theta) = \sigma^2_{v_r} \ \tau(\theta)$$

cosmology (independent of θ)

optical depth (profile)

θ aperture

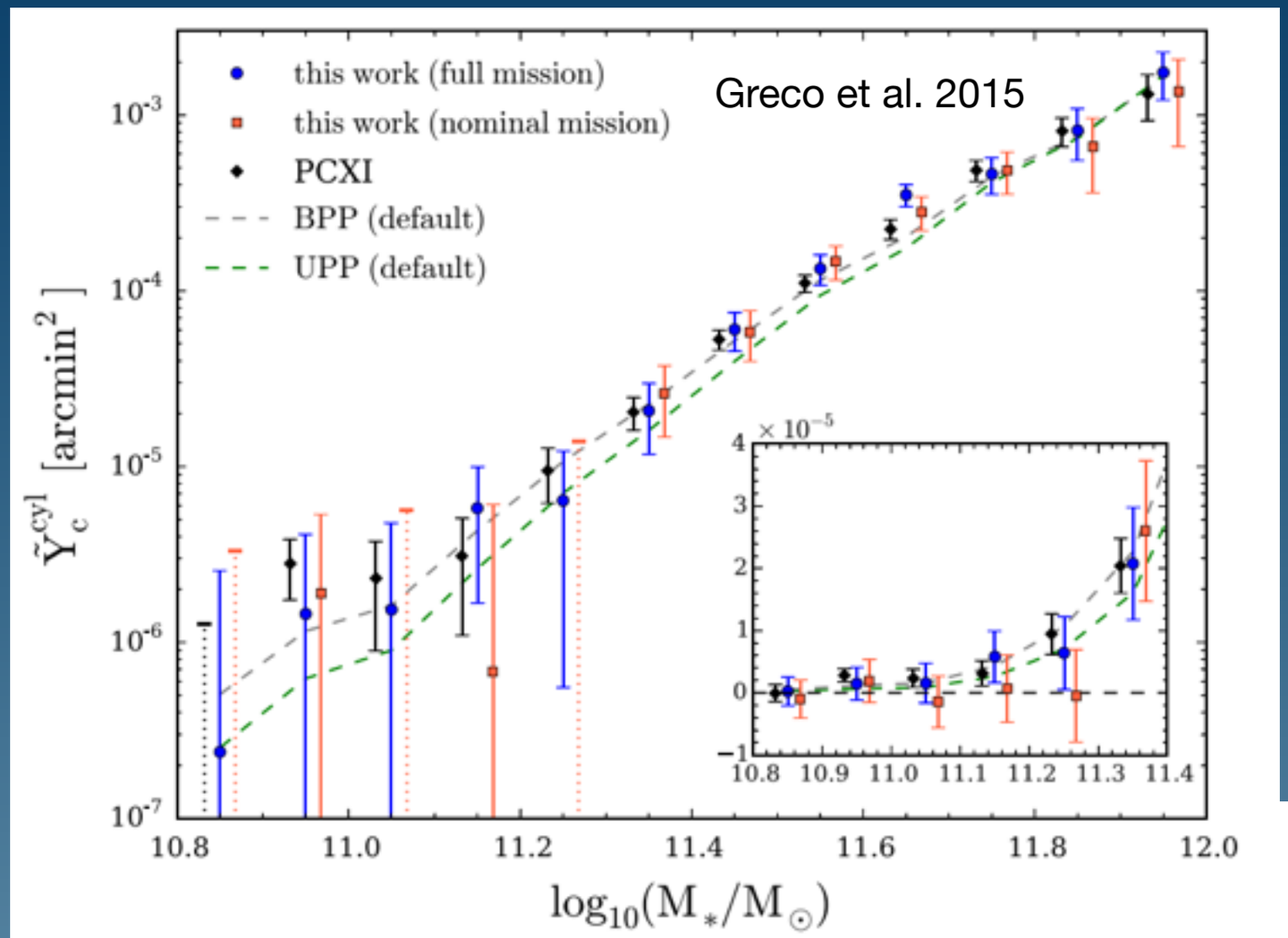


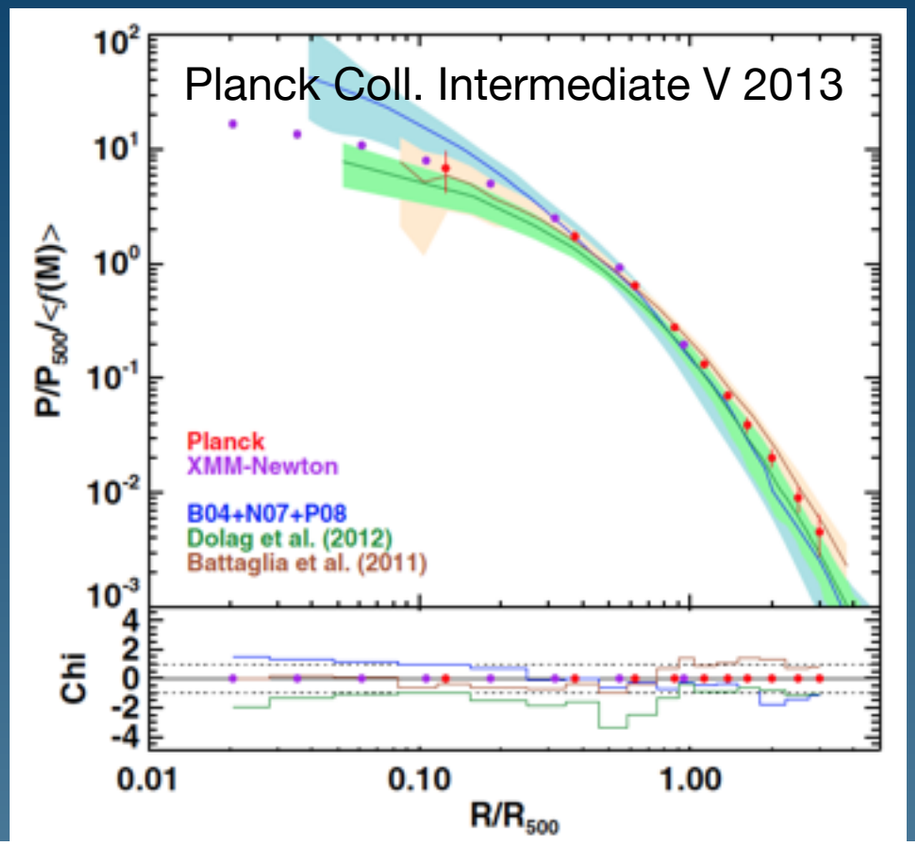


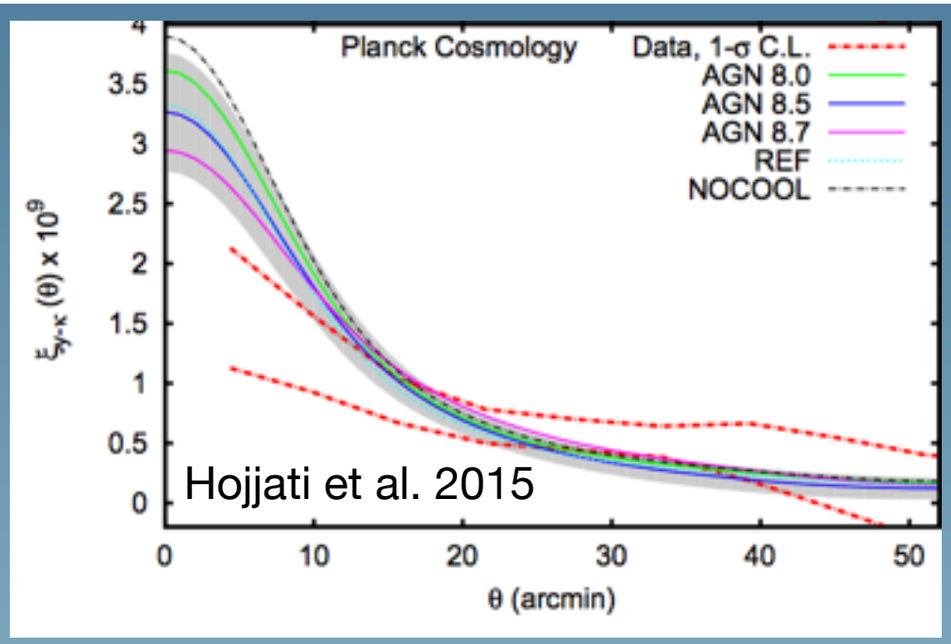
Schaan et al. 2015

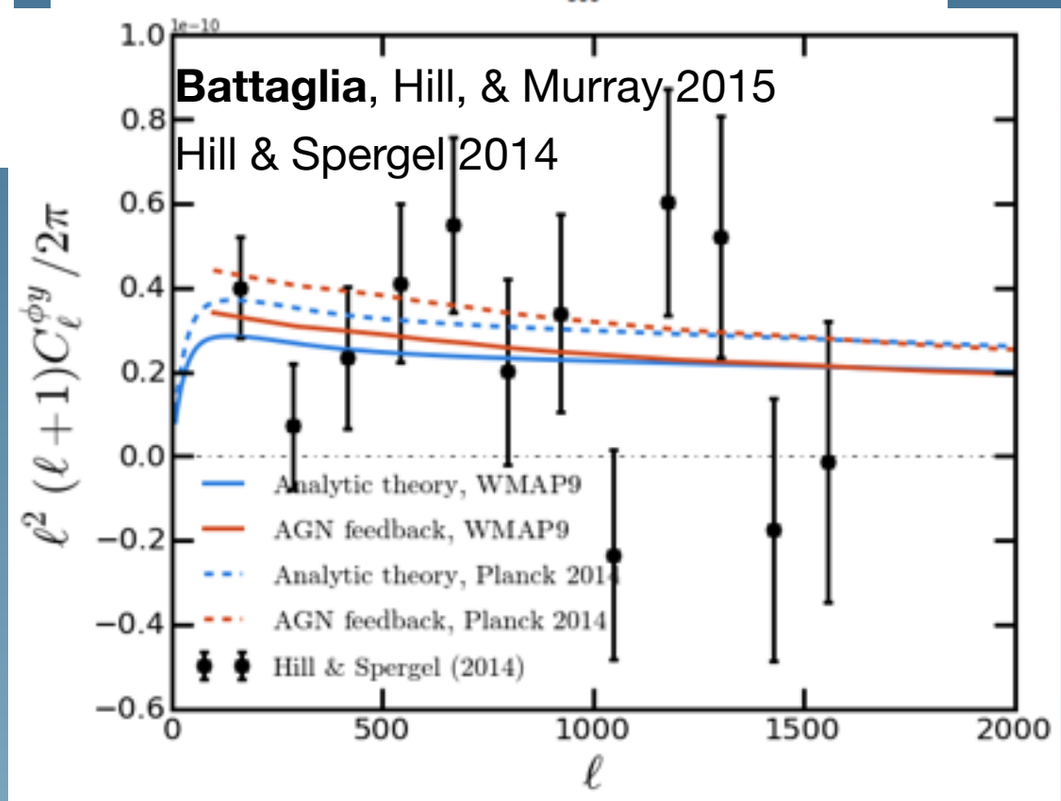
We also have measurements of the pressure!

Gallery of recent tSZ results

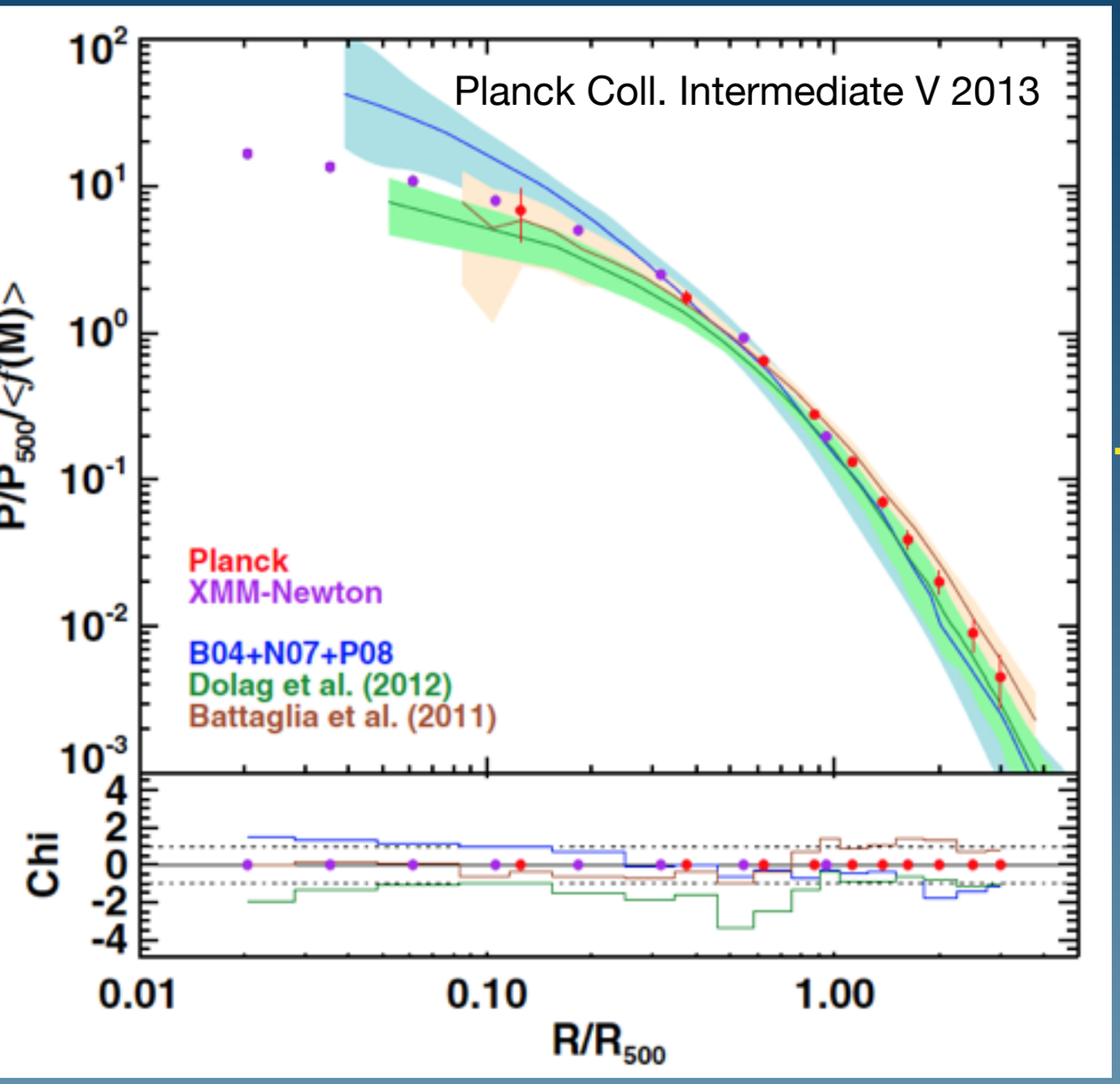




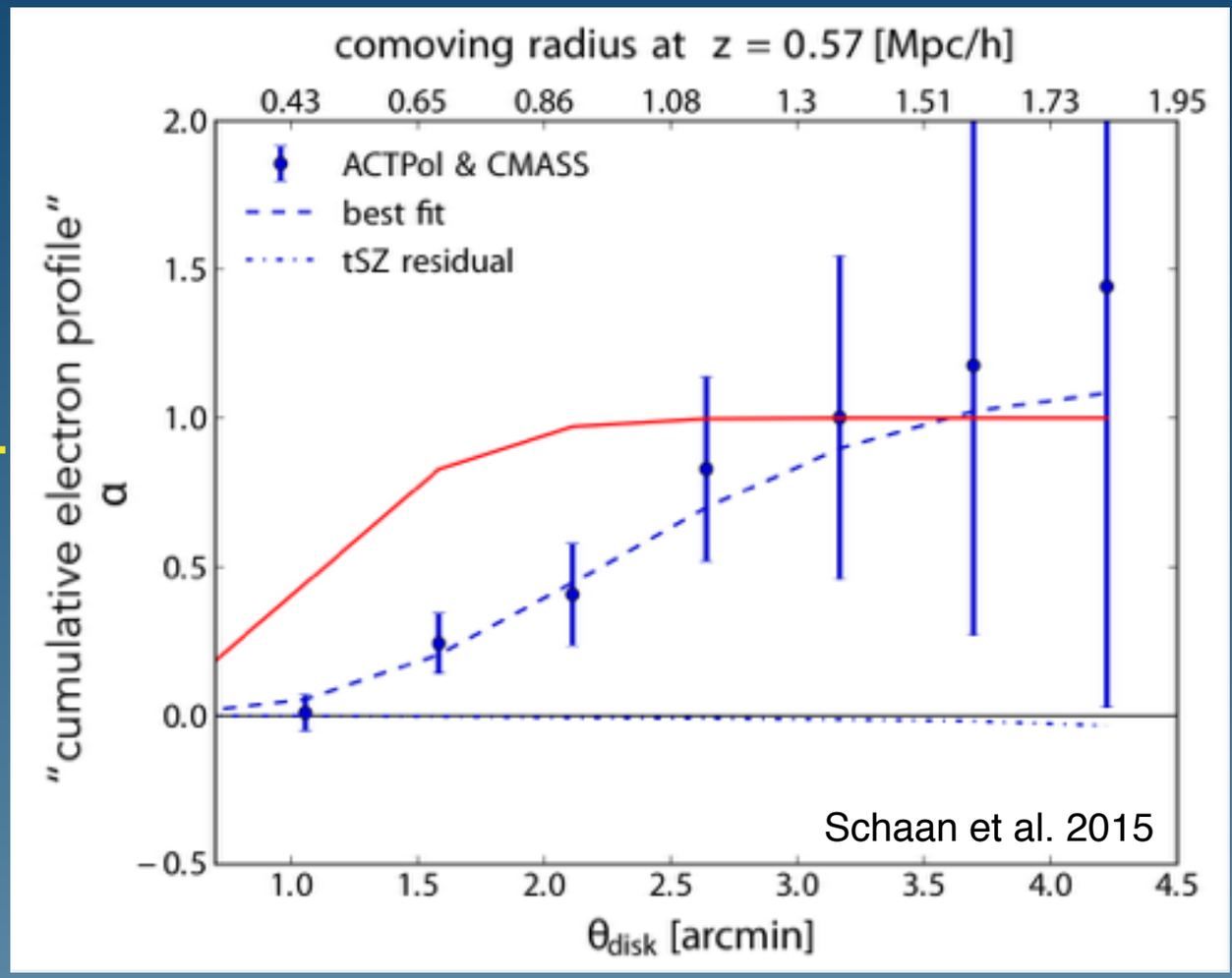




Combining tSZ & kSZ measurements



+



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

Constraint dominant physical processes in galaxy formation

Ostriker, Bode & Babul 2005

Model for the ICM with a couple parameters

γ - polytropic index

α - normalization of P_{NT}

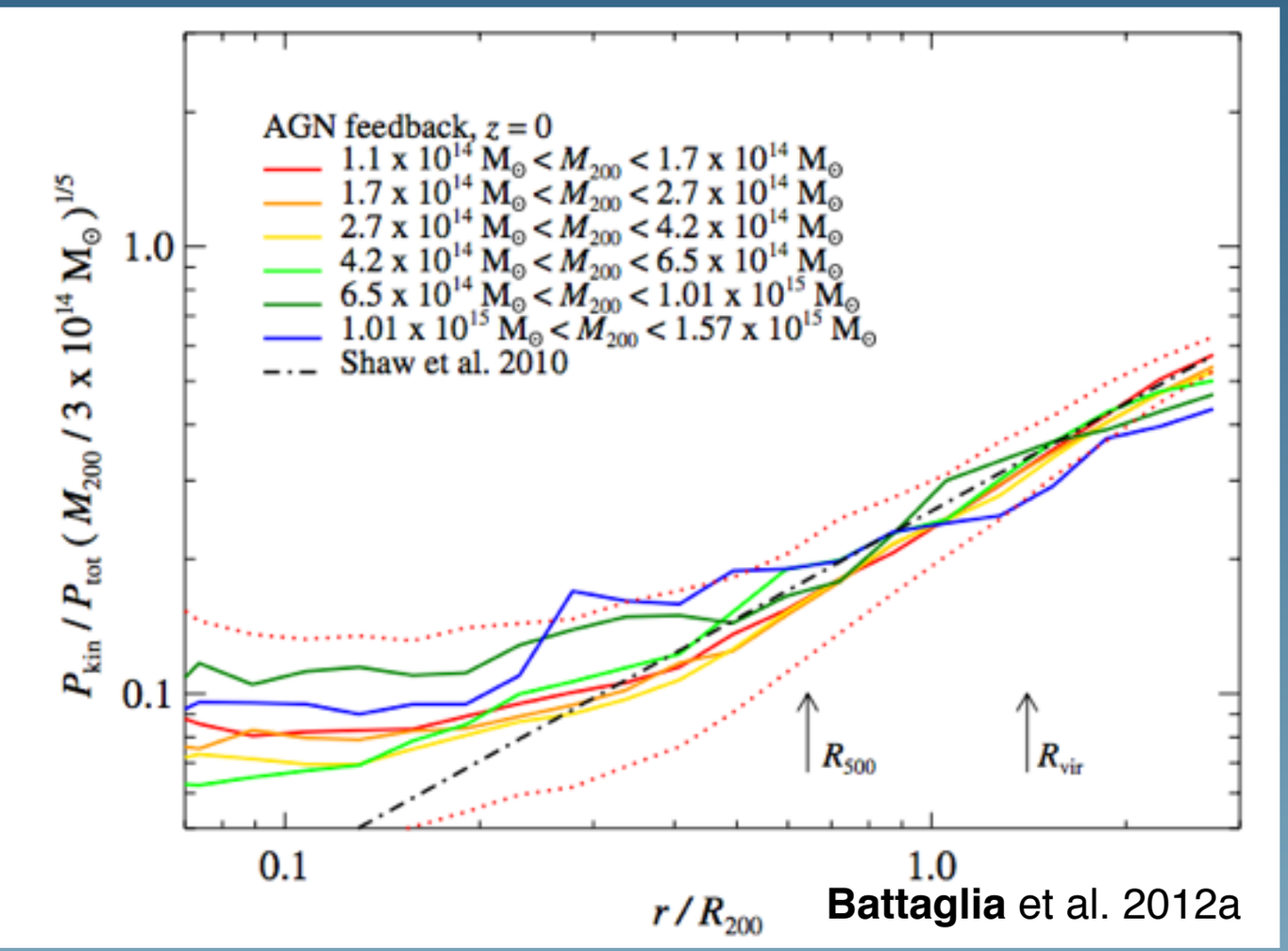
ϵ_{inj} - Eff. of energy injected

Assumptions

$P = K\rho^{\gamma}$

Spherical Symmetry

Hydrostatic Equilibrium (P_{tot})



Battaglia et al. 2012a

Conditions

$E_f = E_i + E_{inj} + \Delta E_P$

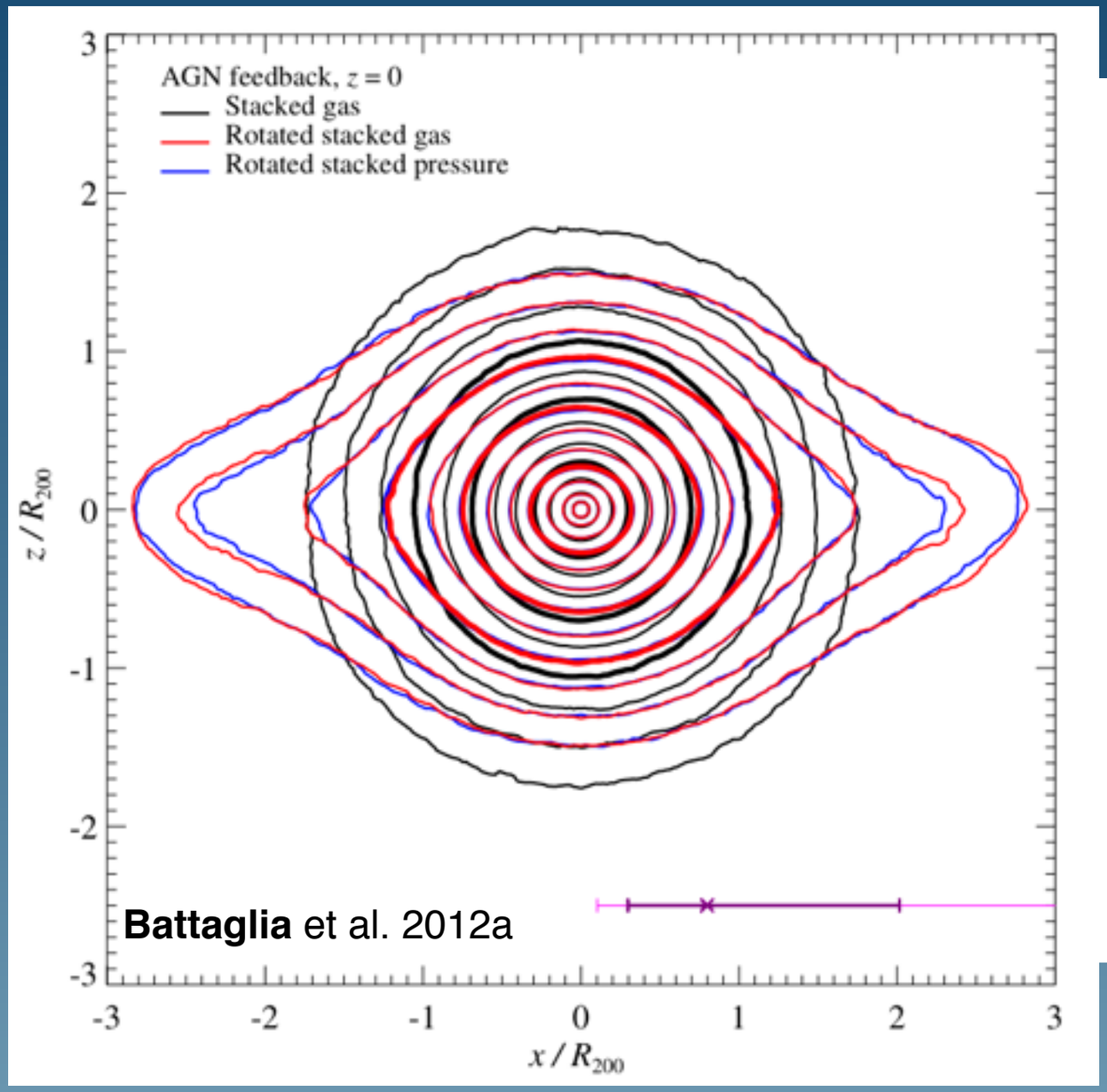
$P_{tot}\ (R_f) = P_s\ (R_{vir})$

Conservation of mass

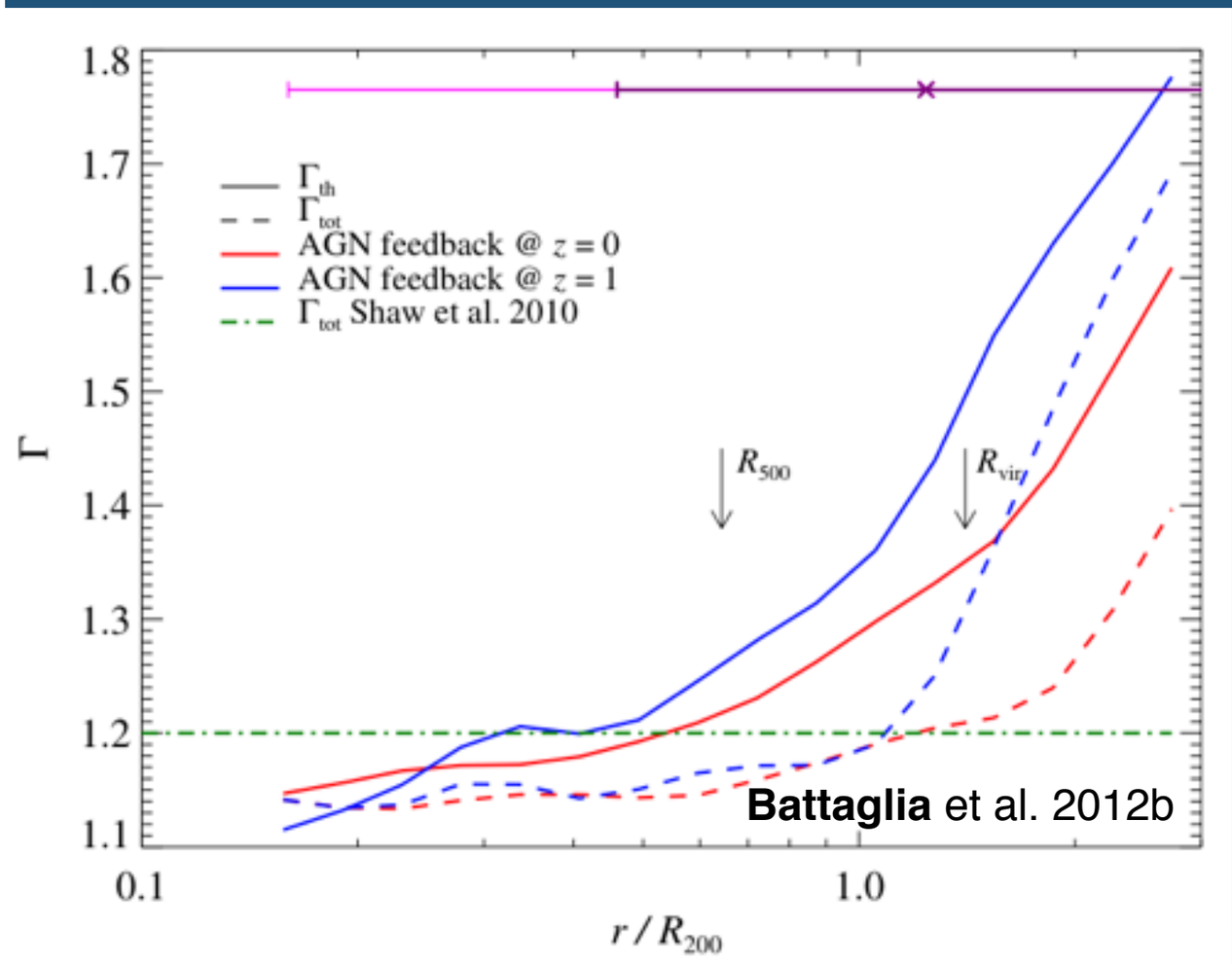
Solve for $P_{th}(r)$ and $\rho(r)$

Spherical Symmetry & Polytropic Index

How do these assumptions look in simulations?

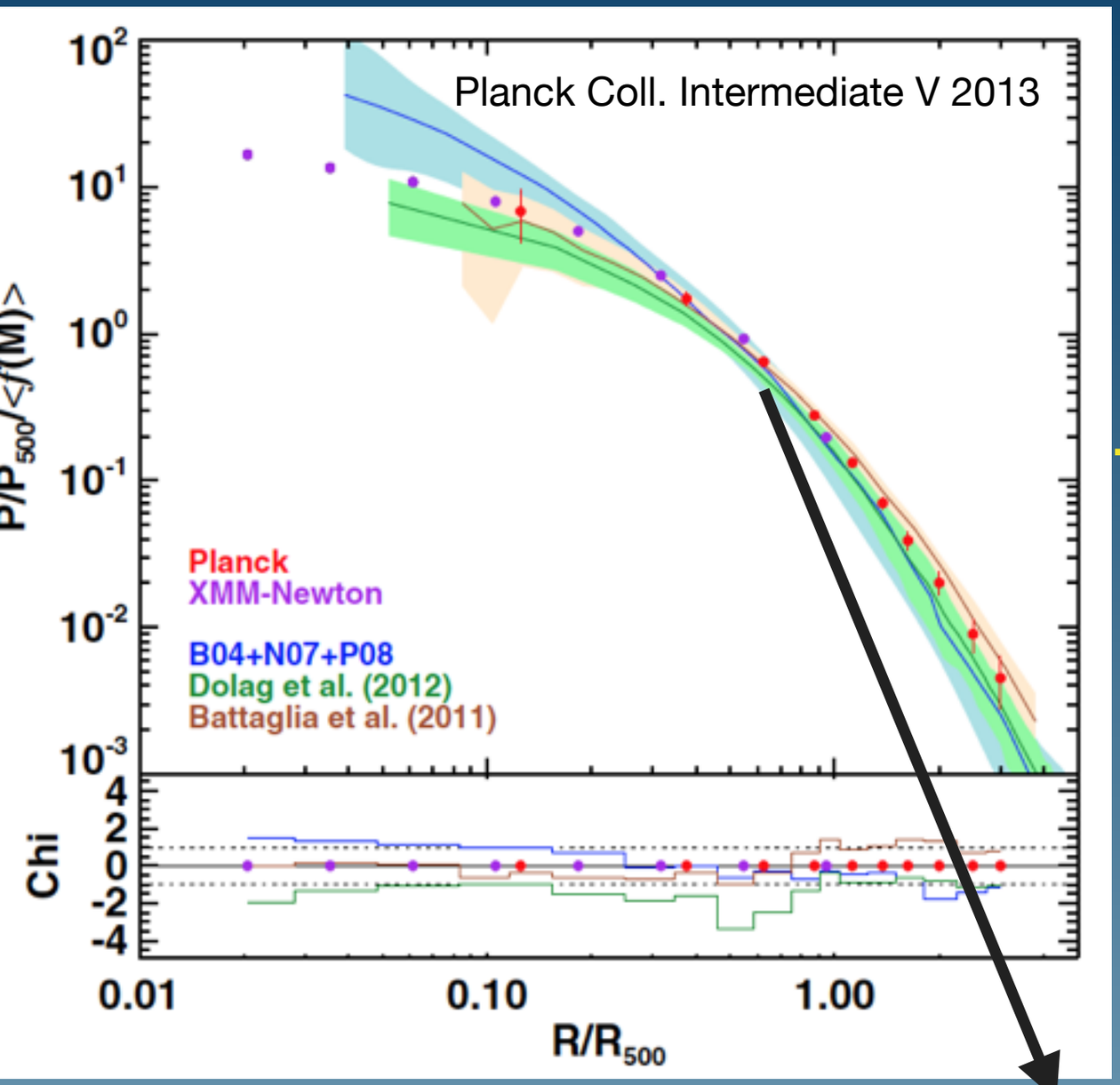


After stacking ✔

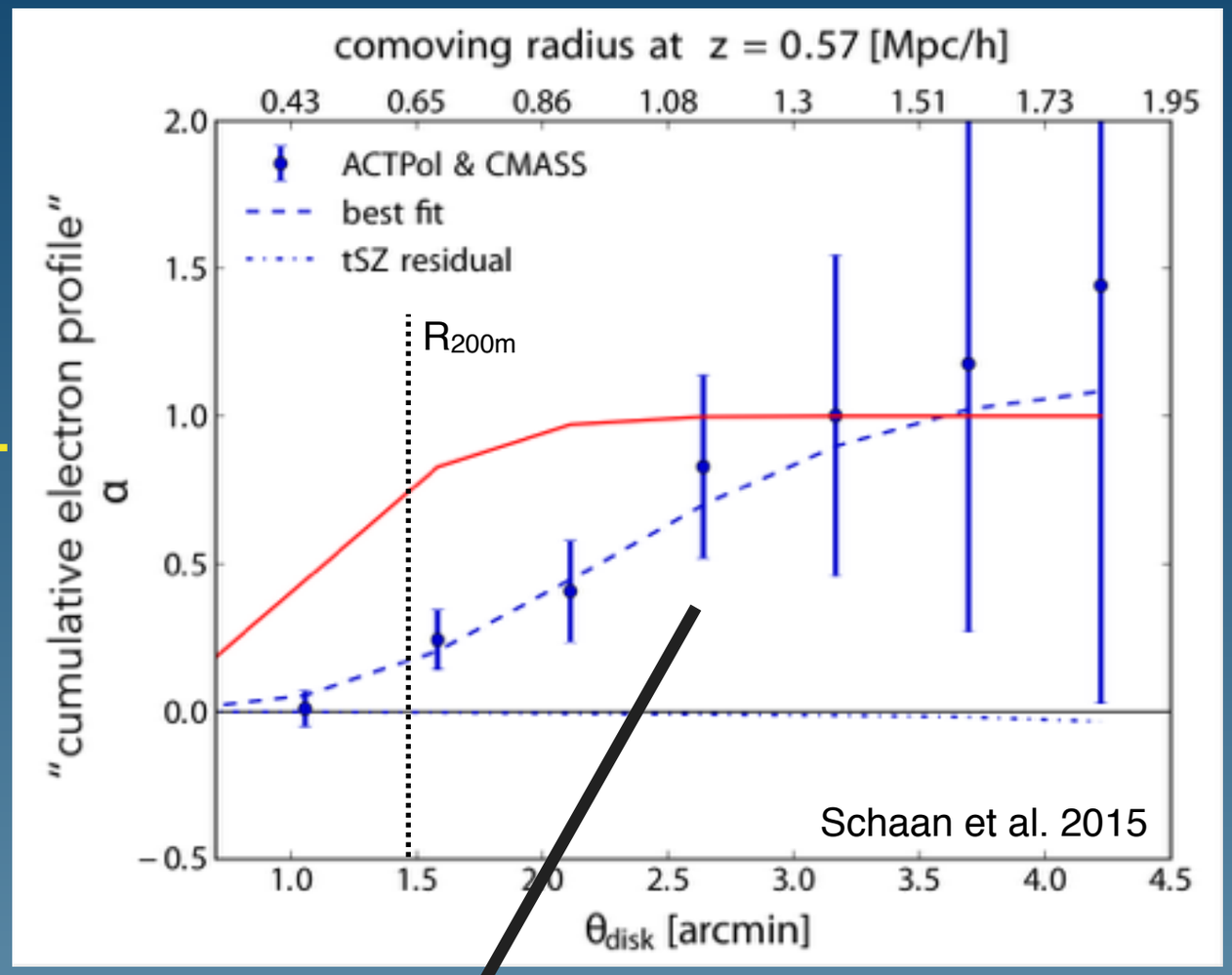


γ fairly constant ~ 2 R_{200} ✔

Combining tSZ & kSZ measurements



+

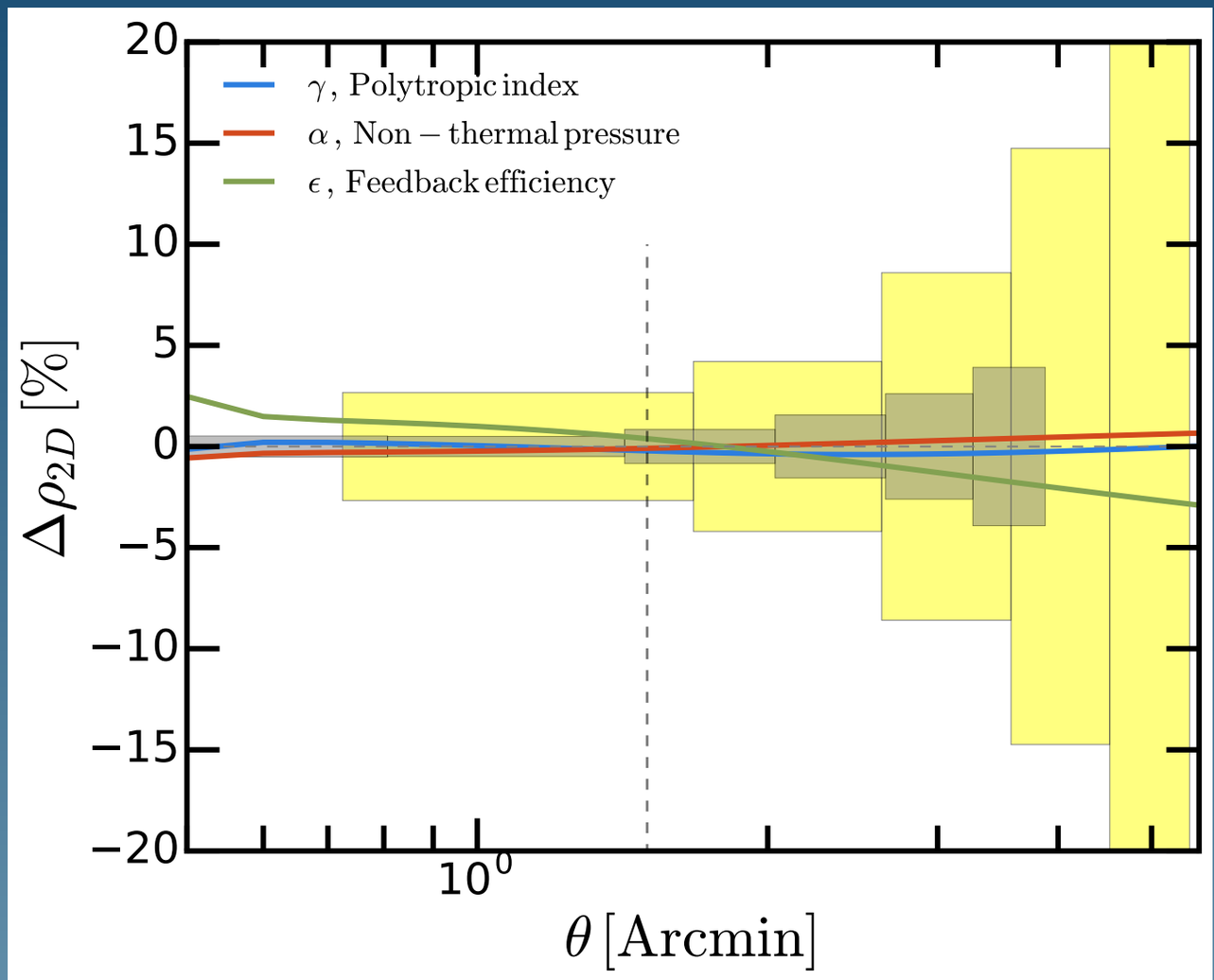


Given $P_{th}(r)$ and $\rho(r)$ from these measurements

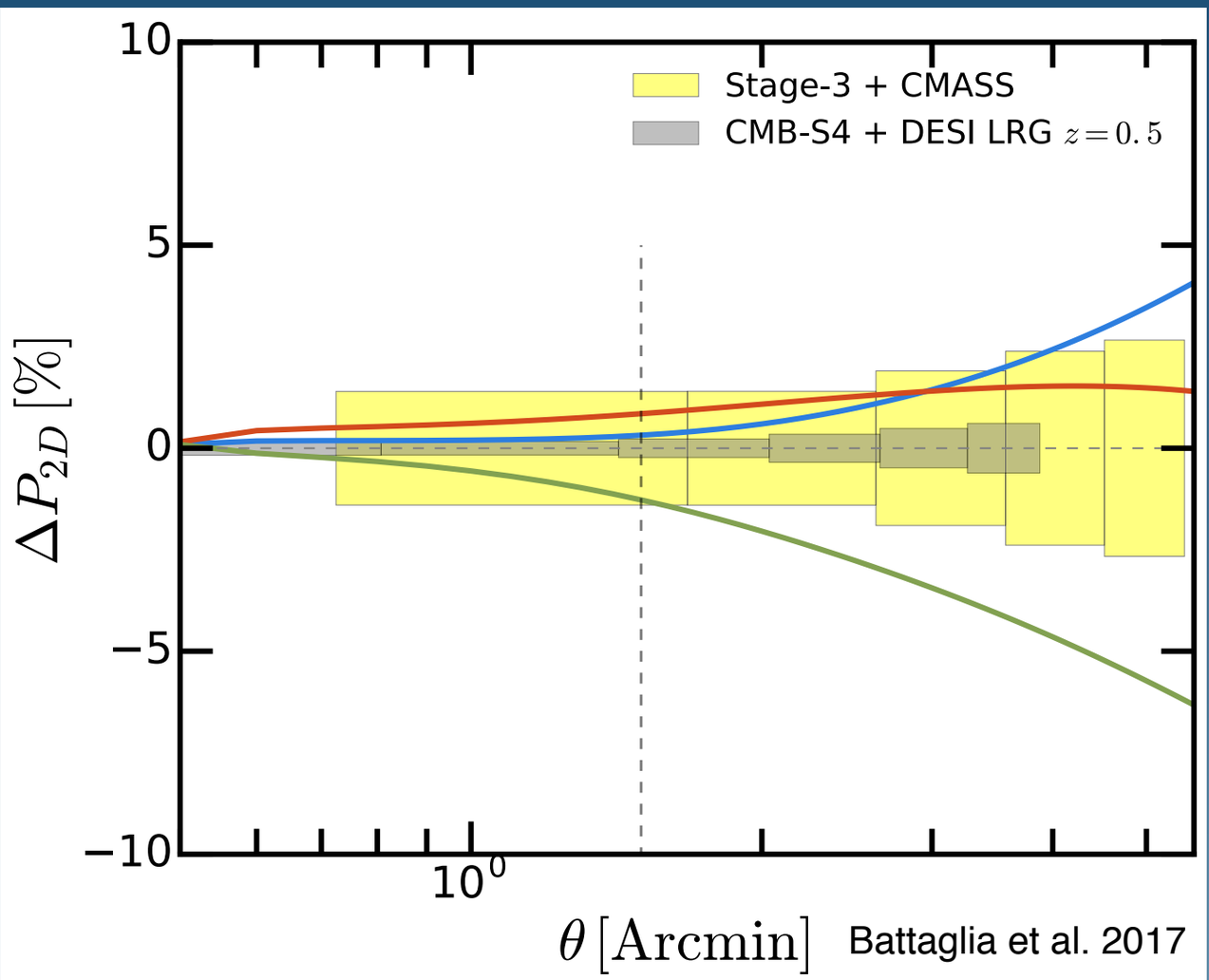
Can we constrain γ, α & ϵ_{inj} ?

Combining tSZ & kSZ measurements forecasts

Density



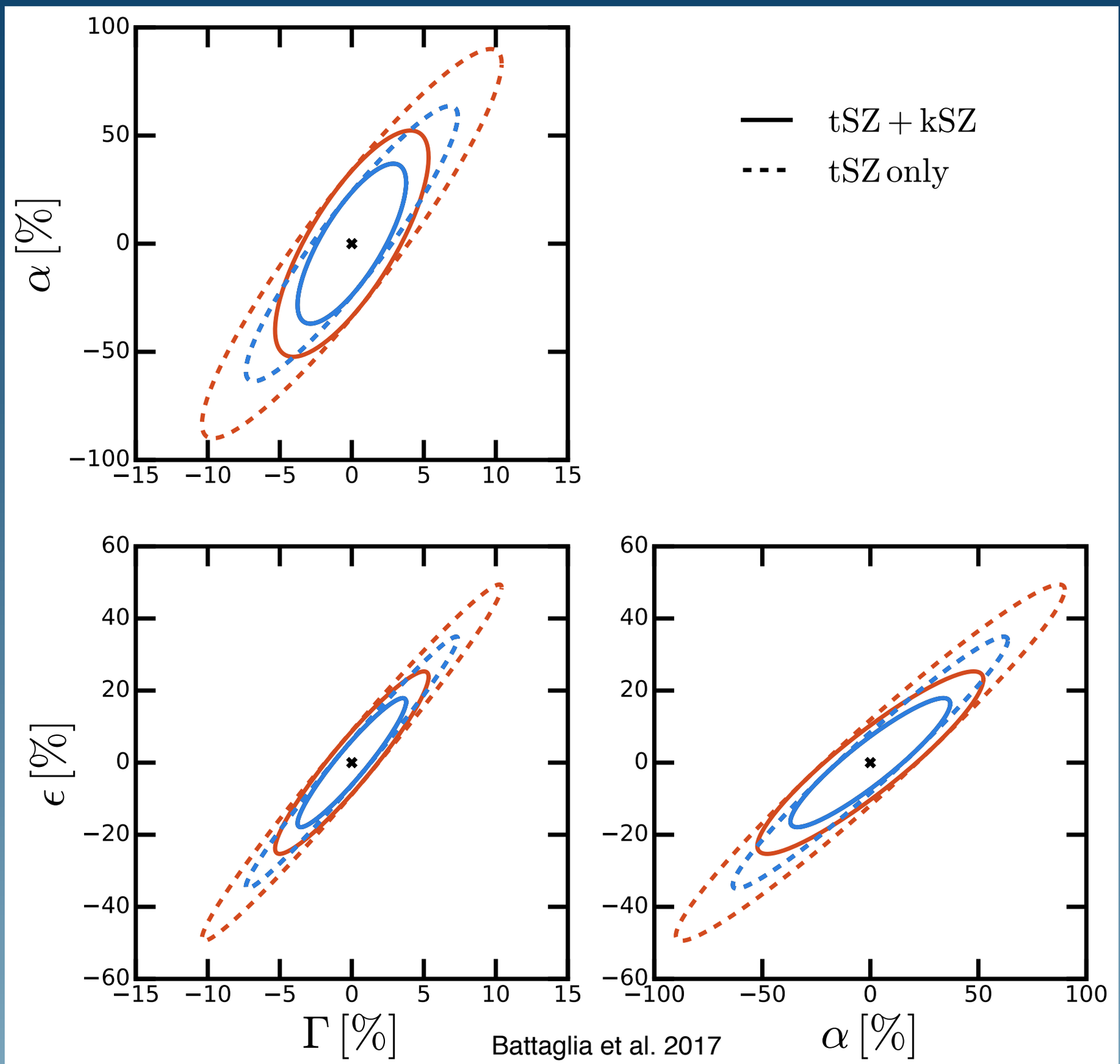
Pressure



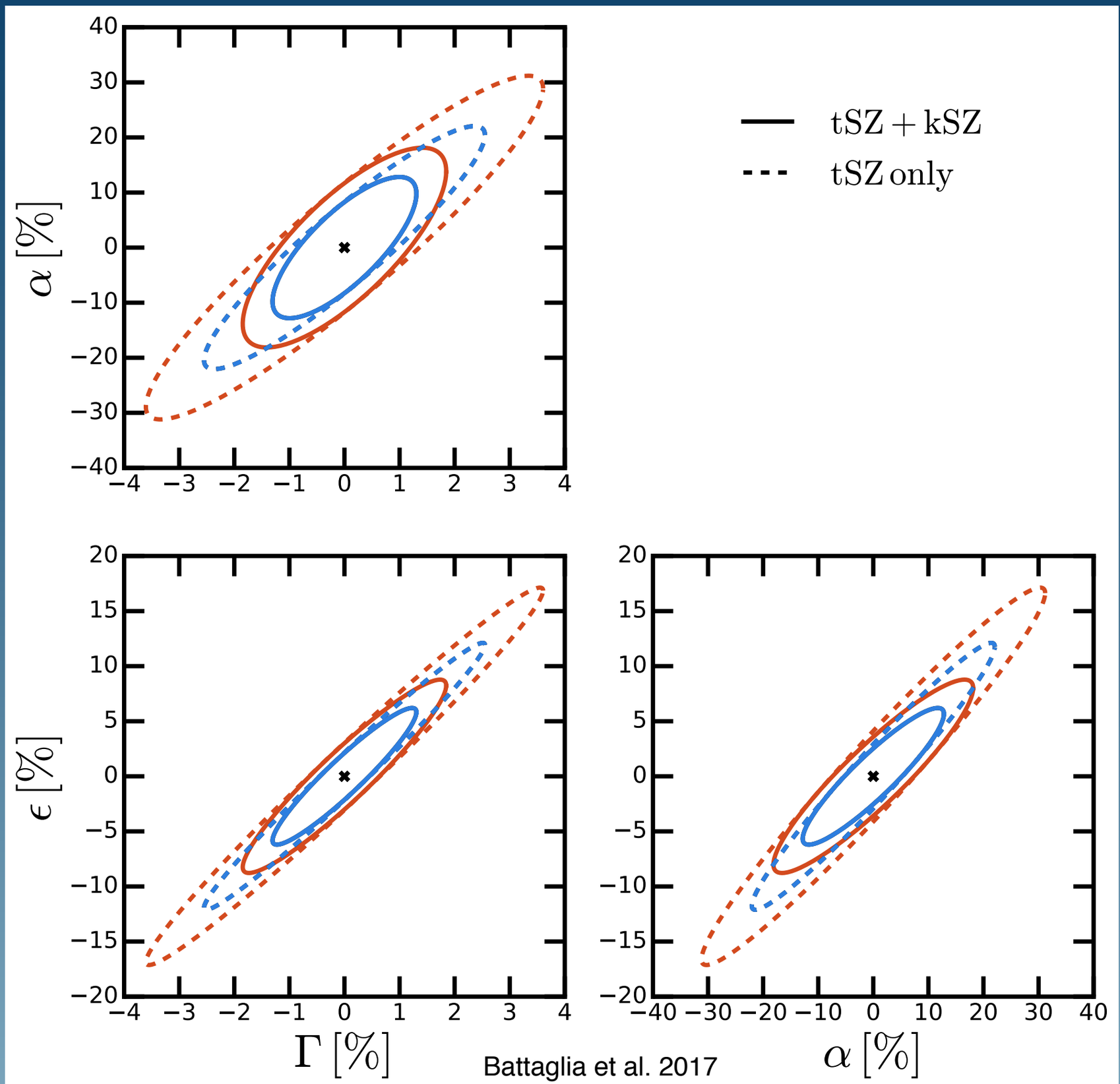
Battaglia et al. 2017

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

Combining tSZ & kSZ measurements forecast

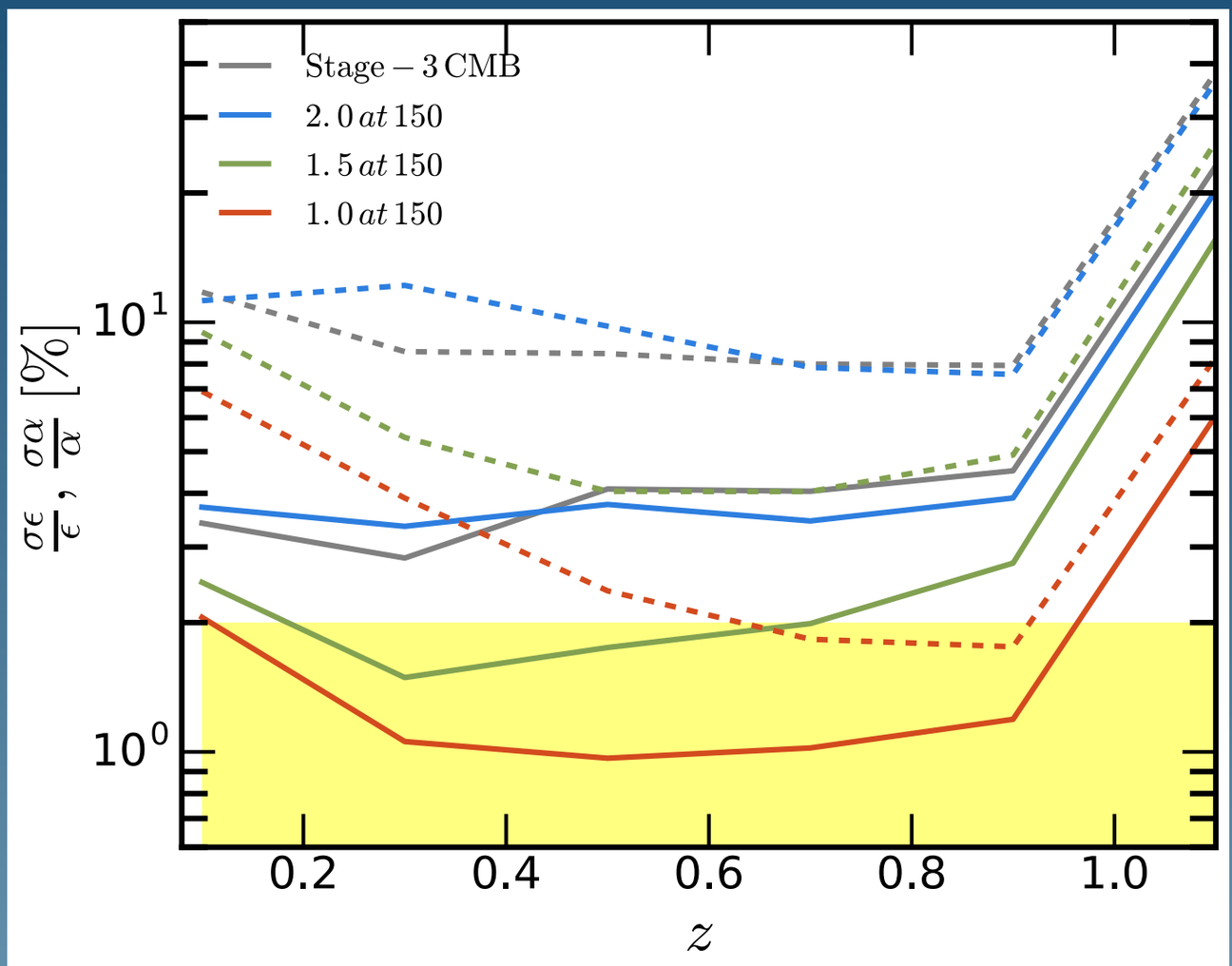


Combining tSZ & kSZ measurements forecast

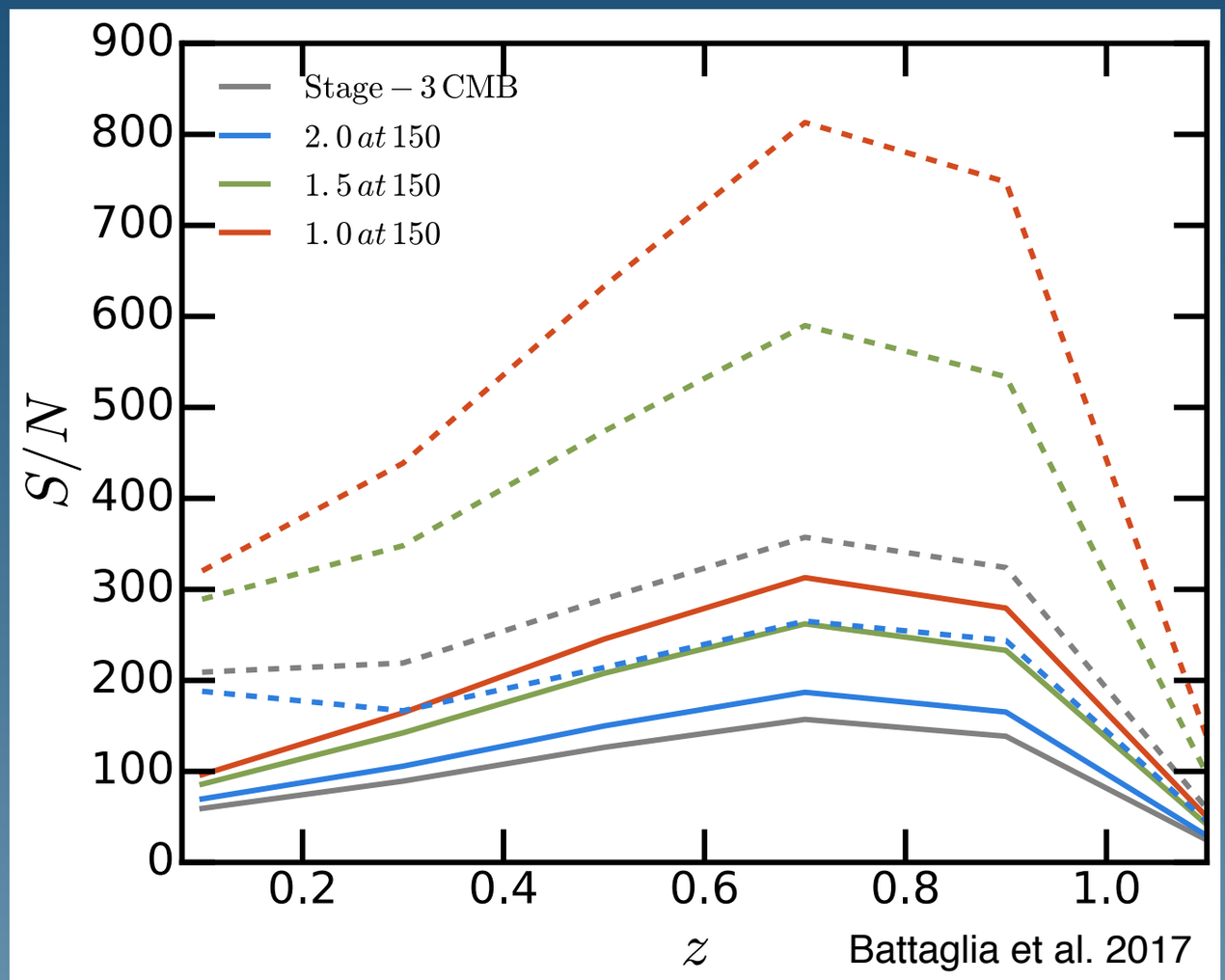


Combining tSZ & kSZ measurements forecast

Parametric



Raw S/N

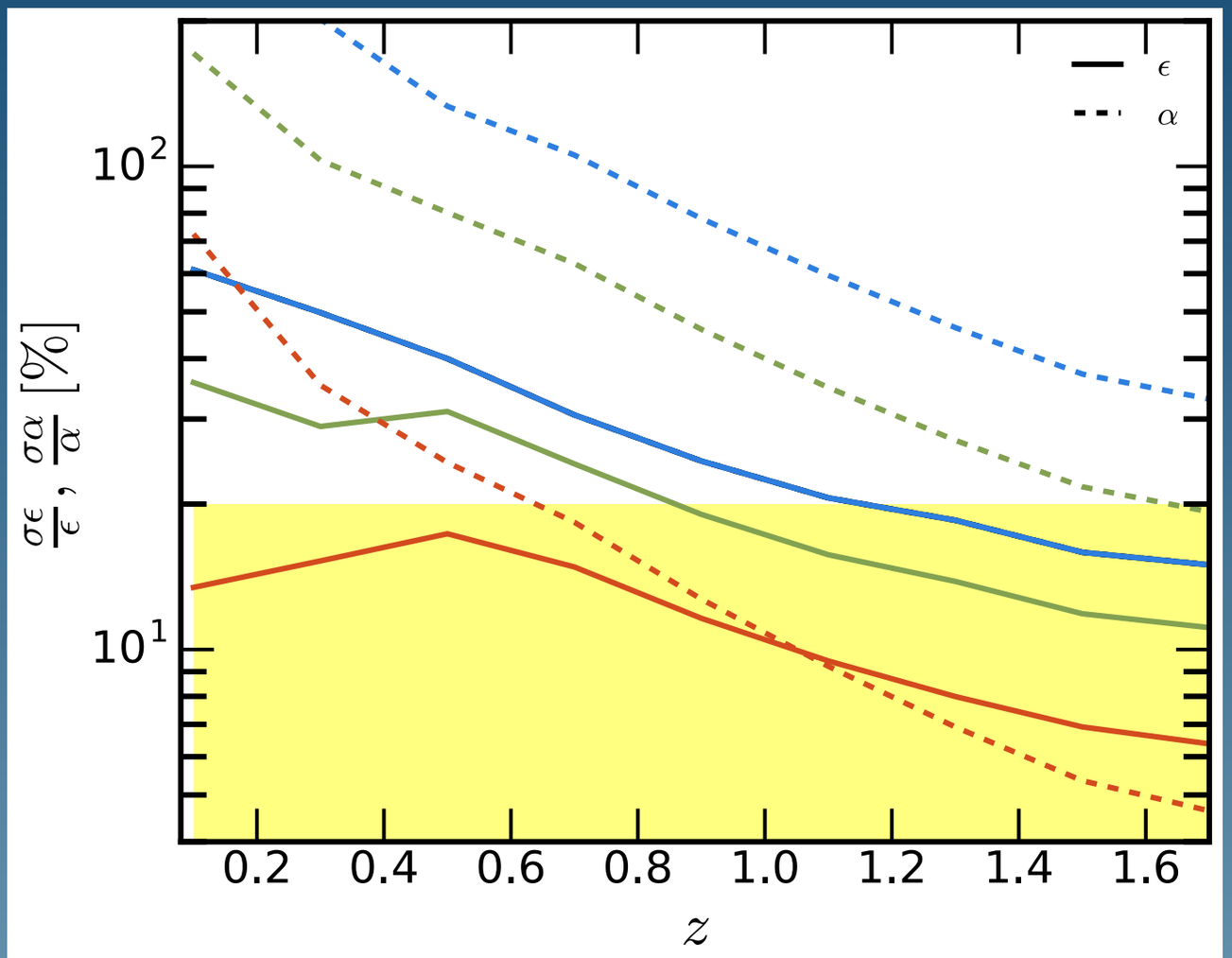


DESI LRGS extremely high fidelity measurements

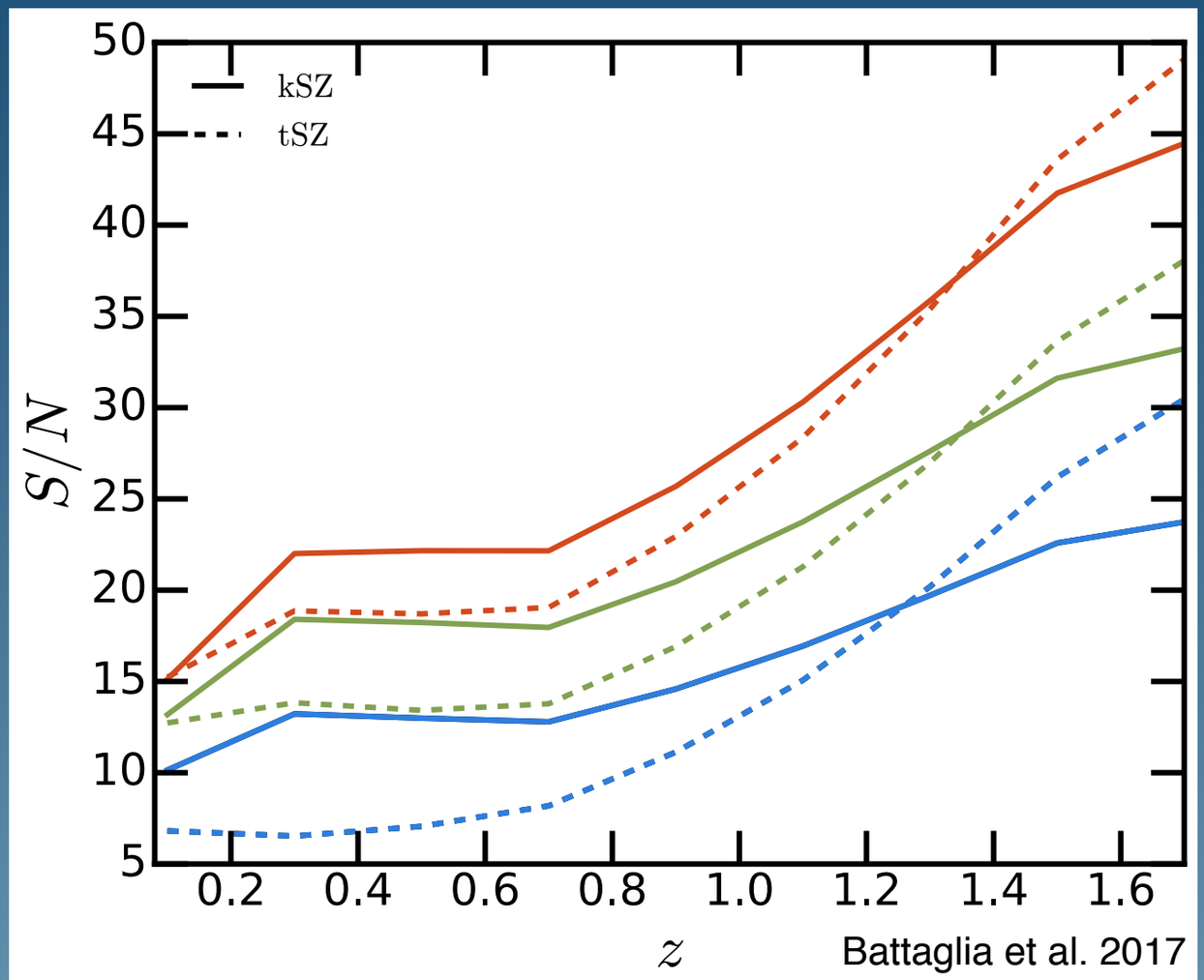
Can further sub-sample into other galaxy properties

Combining tSZ & kSZ measurements forecast

Parametric



Raw S/N



Can ask the same questions with Quasars

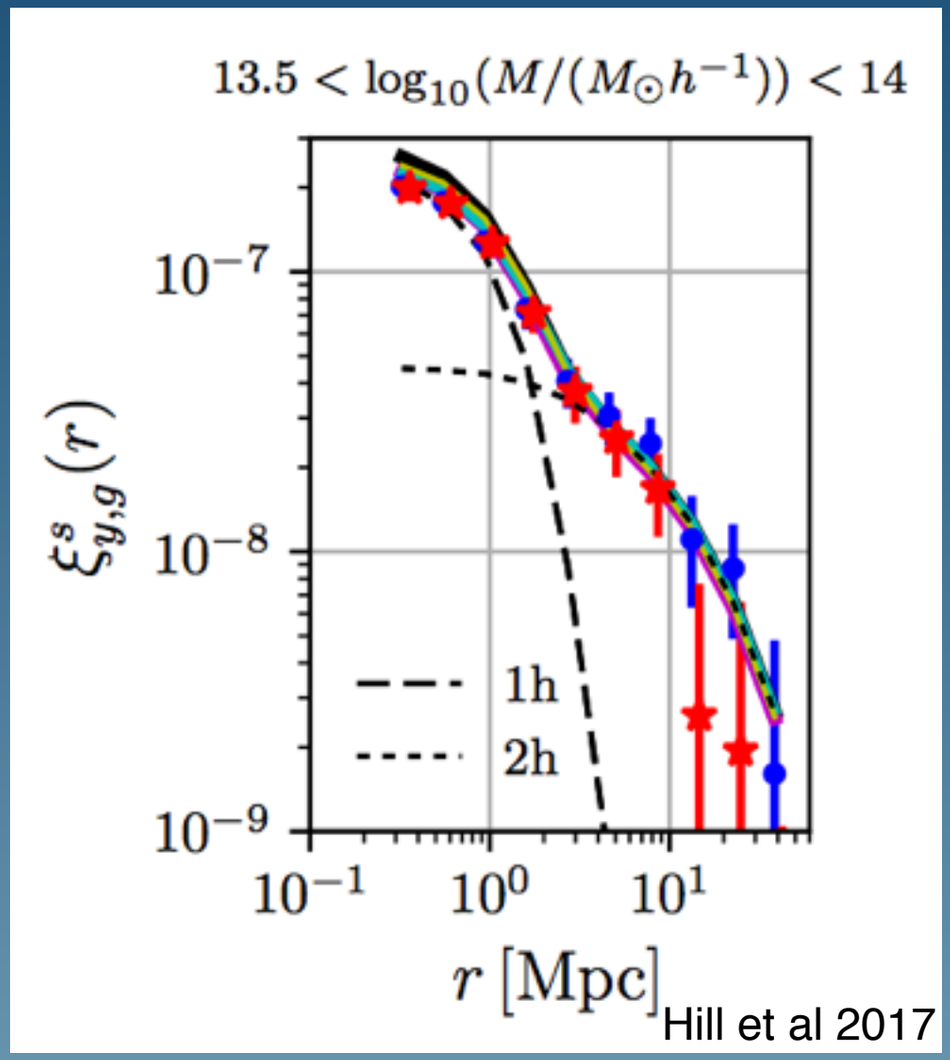
Beware of fisher forecasts

What are some of the systematics?

galaxy - gas offset

Markevitch et al 2006

2-halo term

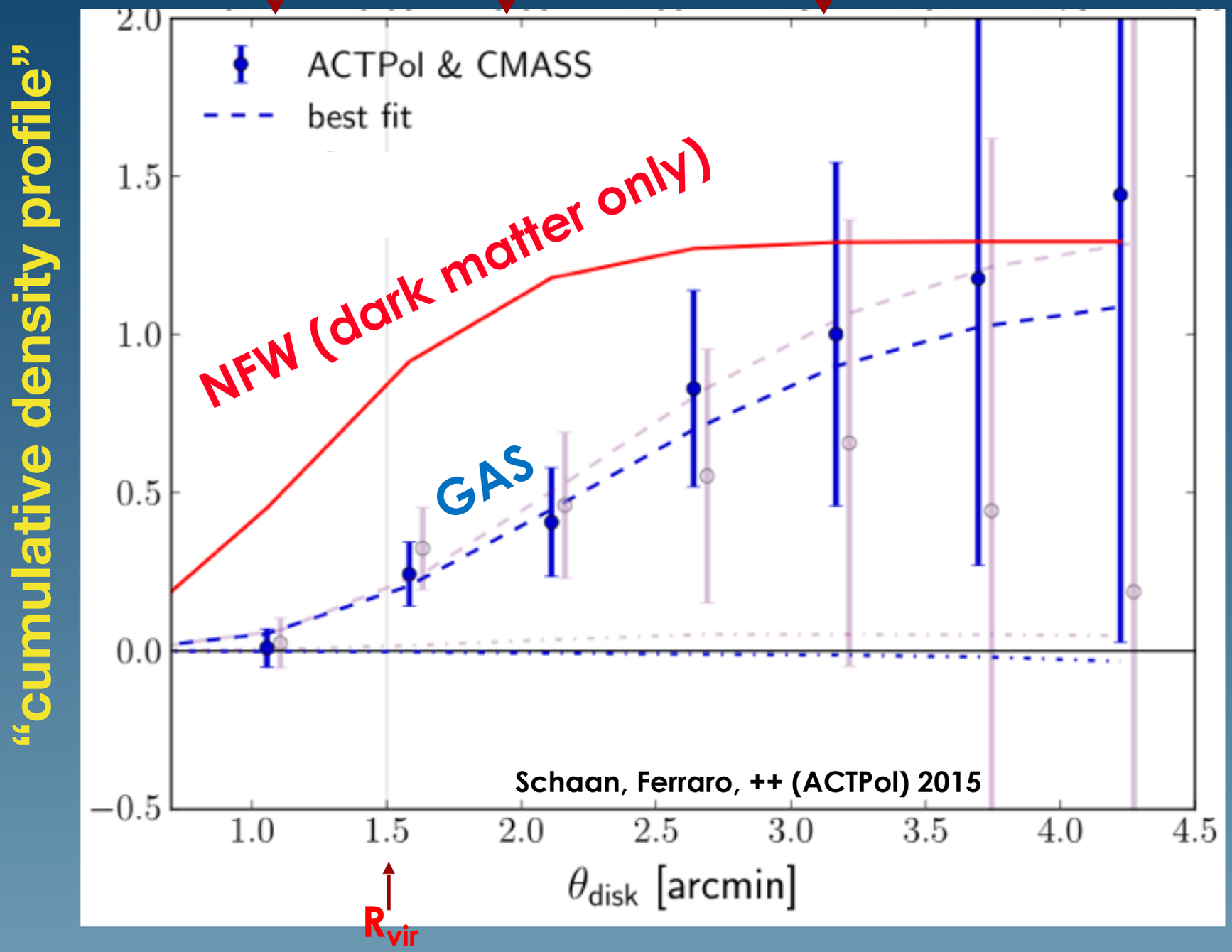


Hill et al 2017

What is the distribution of masses in the sample?

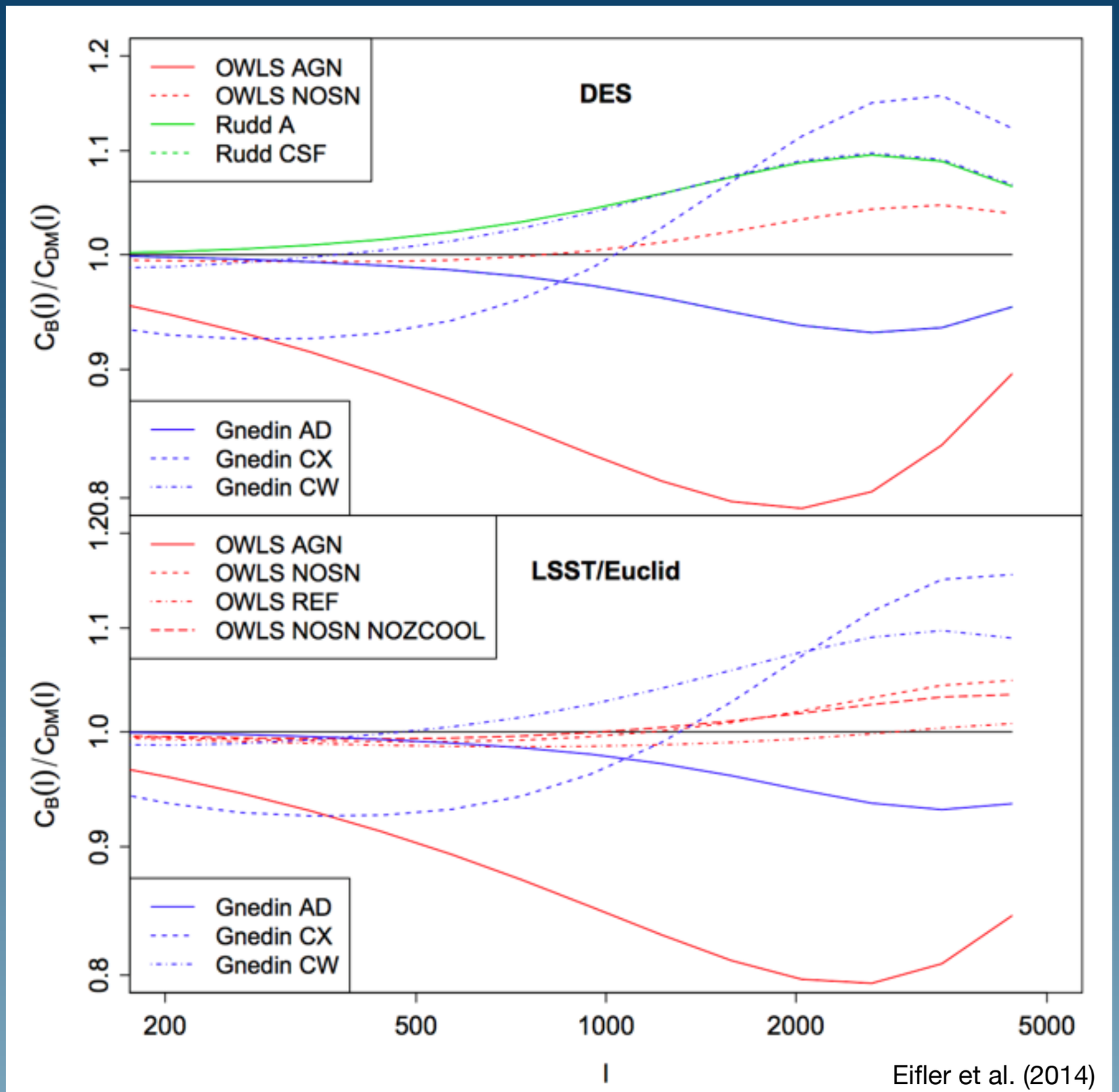
Cosmological Implications

LSST L_{max} = 5000 at z = **0.3** **0.5** **1.0**



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

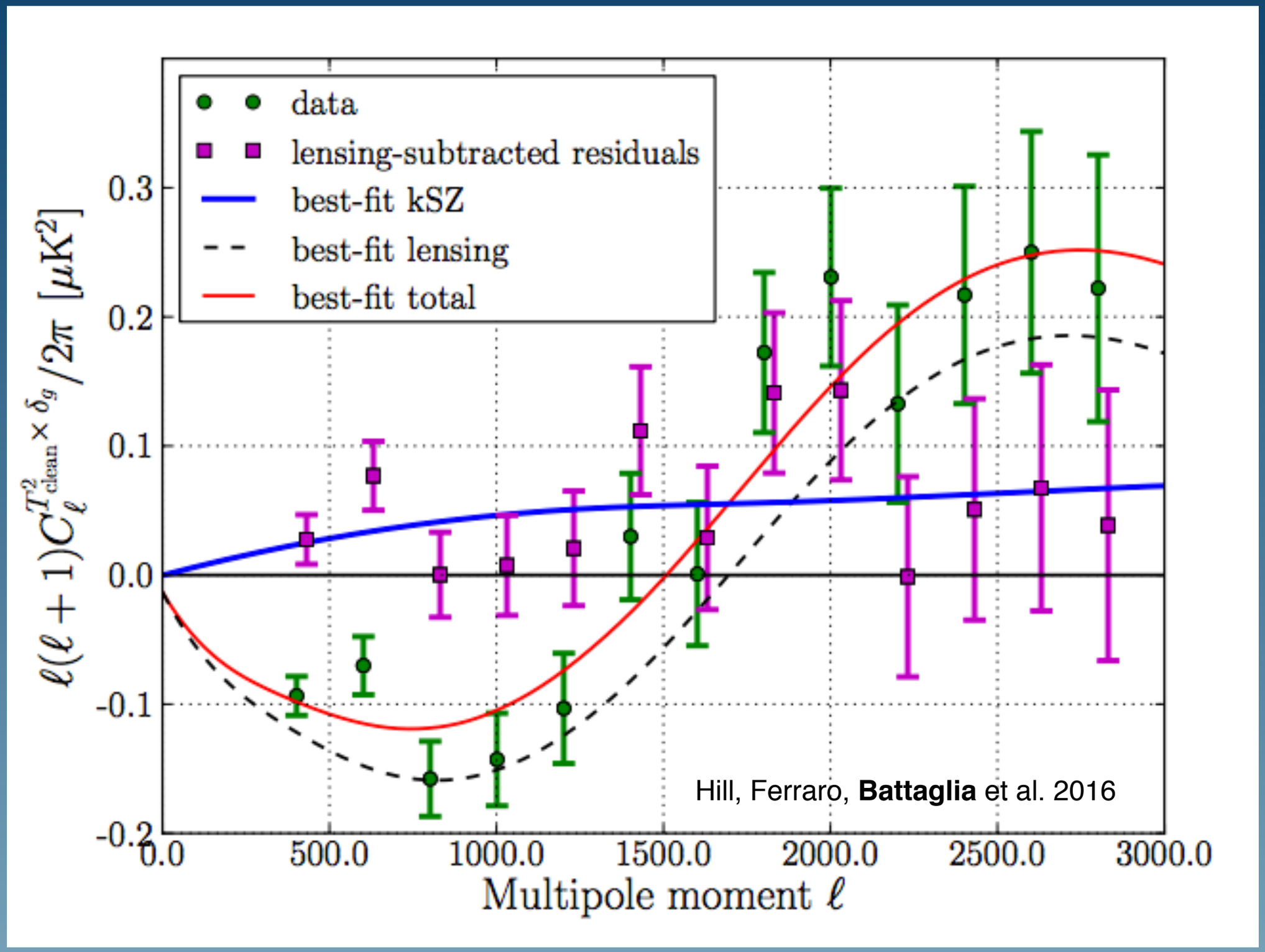
Cosmological impact of feedback



Eifler et al. (2014)

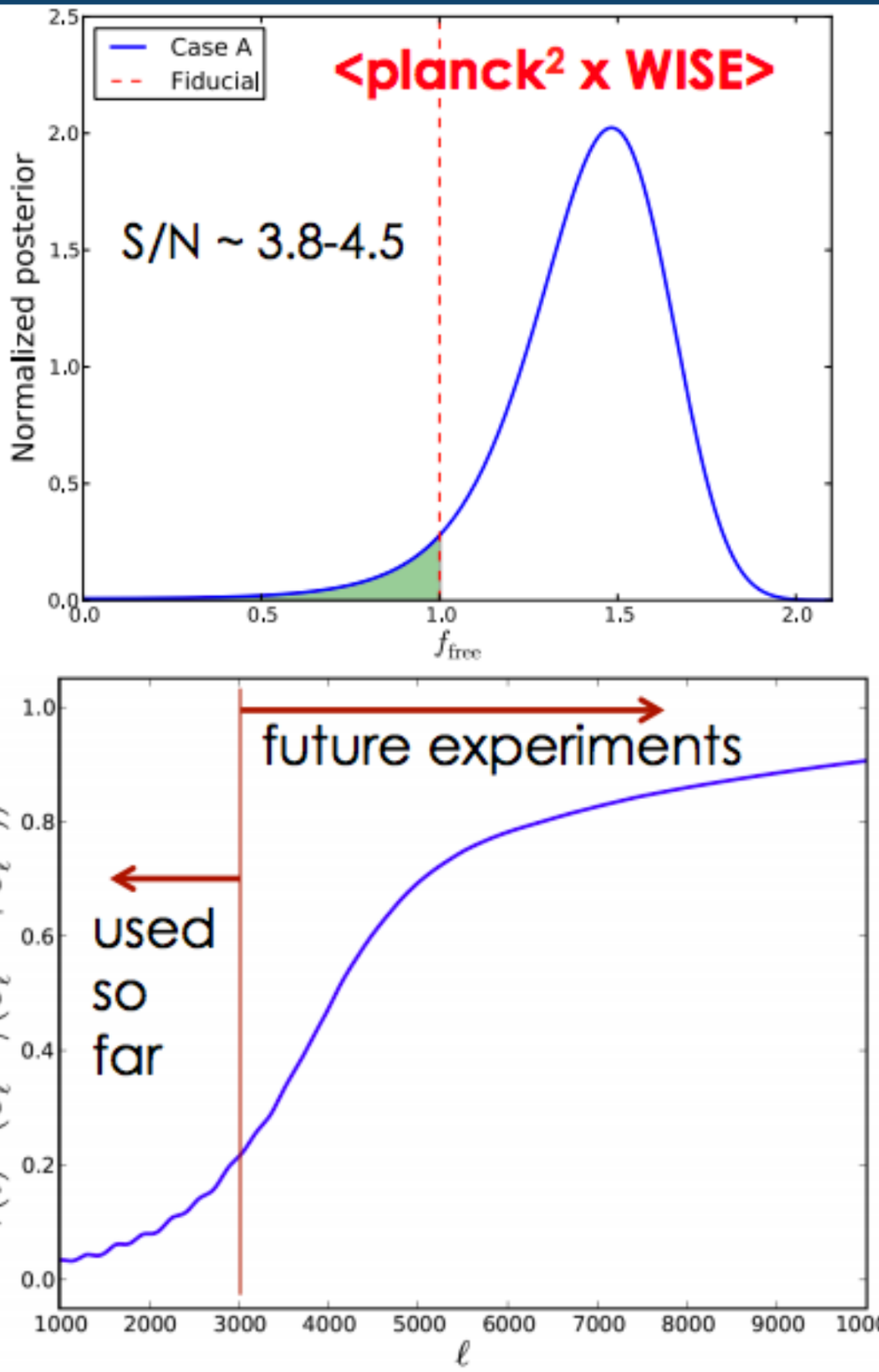
Alternatively:
Use small scale information to constrain feedback
Foreman+2016

kSZ with LSST - projected fields approach



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

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

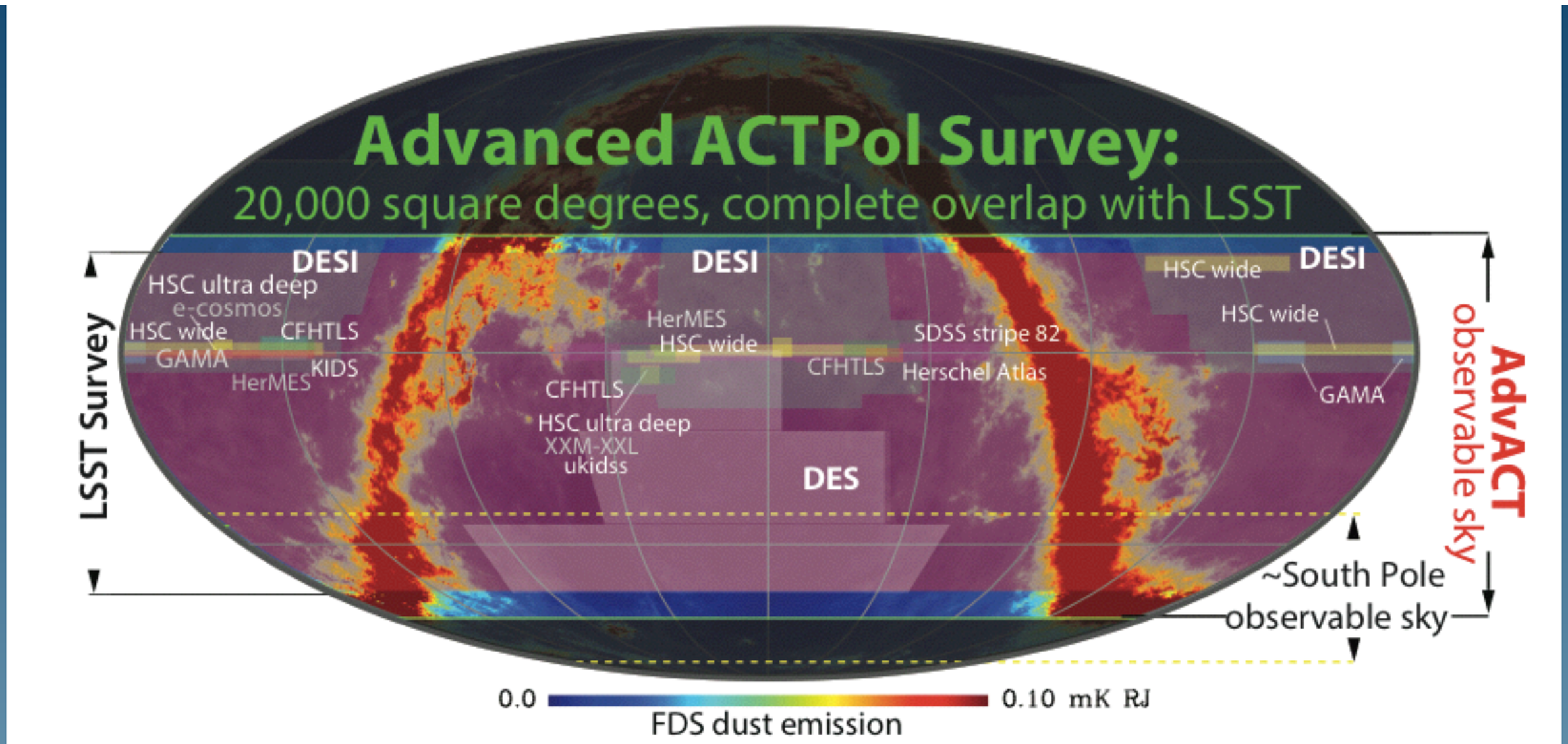
BUT CAREFUL with SYSTEMATICS (foregrounds!)

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

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

Slide credit S. Ferraro

AdvACT + LSST



Funded, large area, multiple frequency bands
Potential for kSZ cross correlations is large
Further ahead there will be Simons Obs. & CMB S4

The Simons Observatory

http://simonsobservatory.org

- A five year, $45M+ program to pursue key Cosmic Microwave Background science targets, and advance technology and infrastructure in preparation for CMB-S4.

- Merger of the ACT and POLARBEAR/Simons Array teams.

- Tentative plans include:
  - Major site infrastructure
  - Technology development (detectors, optics, cameras)
  - Demonstration of new high throughput telescopes.
  - CMB-S4 class receivers with partially filled focal planes.
  - Data analysis

ALMA

POLARBEAR/Simons Array

ACT

BERKELEY LAB · CONICYT · HEISING-SIMONS FOUNDATION · NSF · Penn · PRINCETON UNIVERSITY · SIMONS FOUNDATION · UC BERKELEY · UC SAN DIEGO · W

Summary and Outlook

Baryons

SZ cross-correlations are going to be a new window into thermodynamic process within halos

High S/N kSZ on coming soon

Learn about the physical processes
Constrain sub-grid energetics models

Push future cosmological probes into non-linear regime

CCAT-p

Thank You!

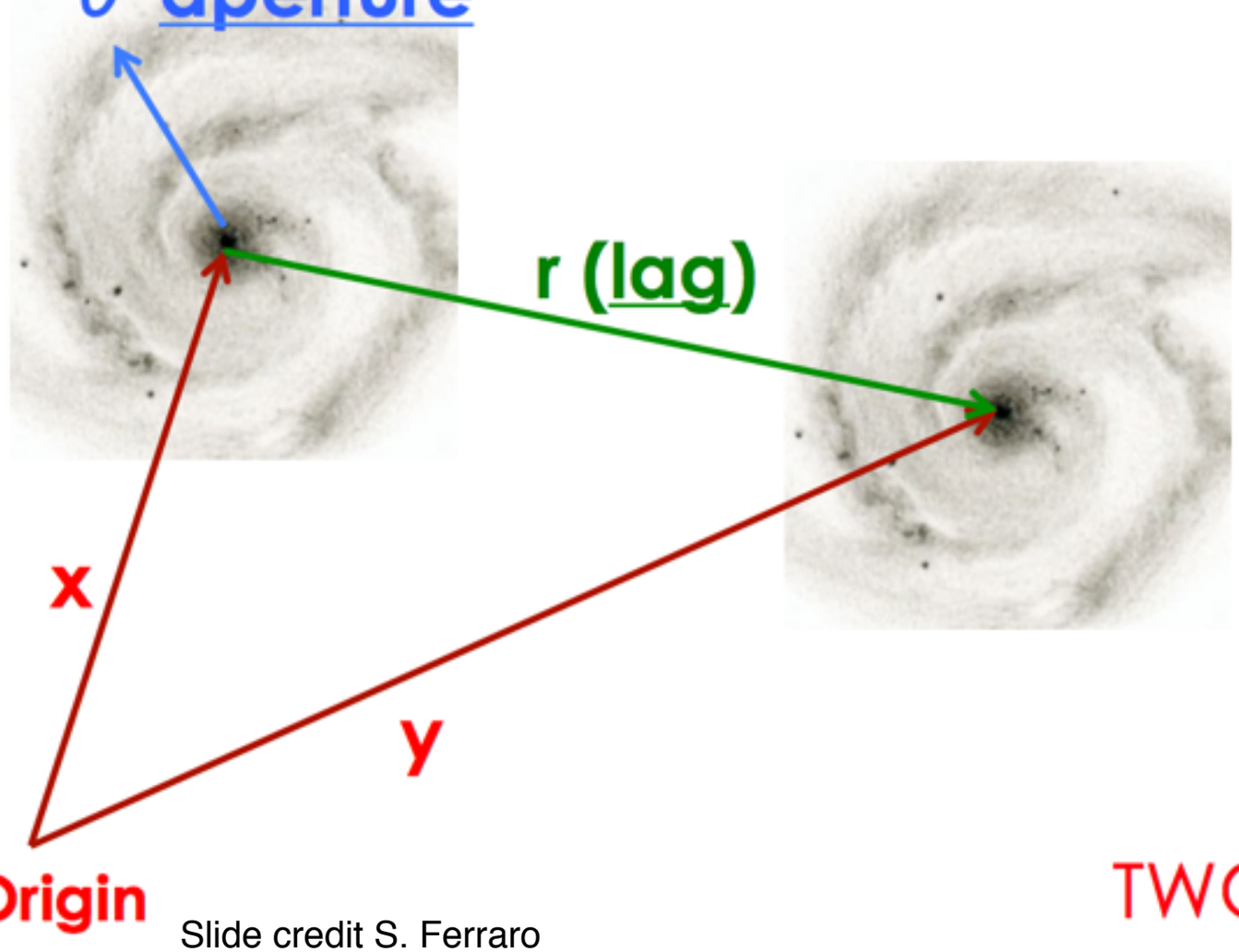
Extras

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

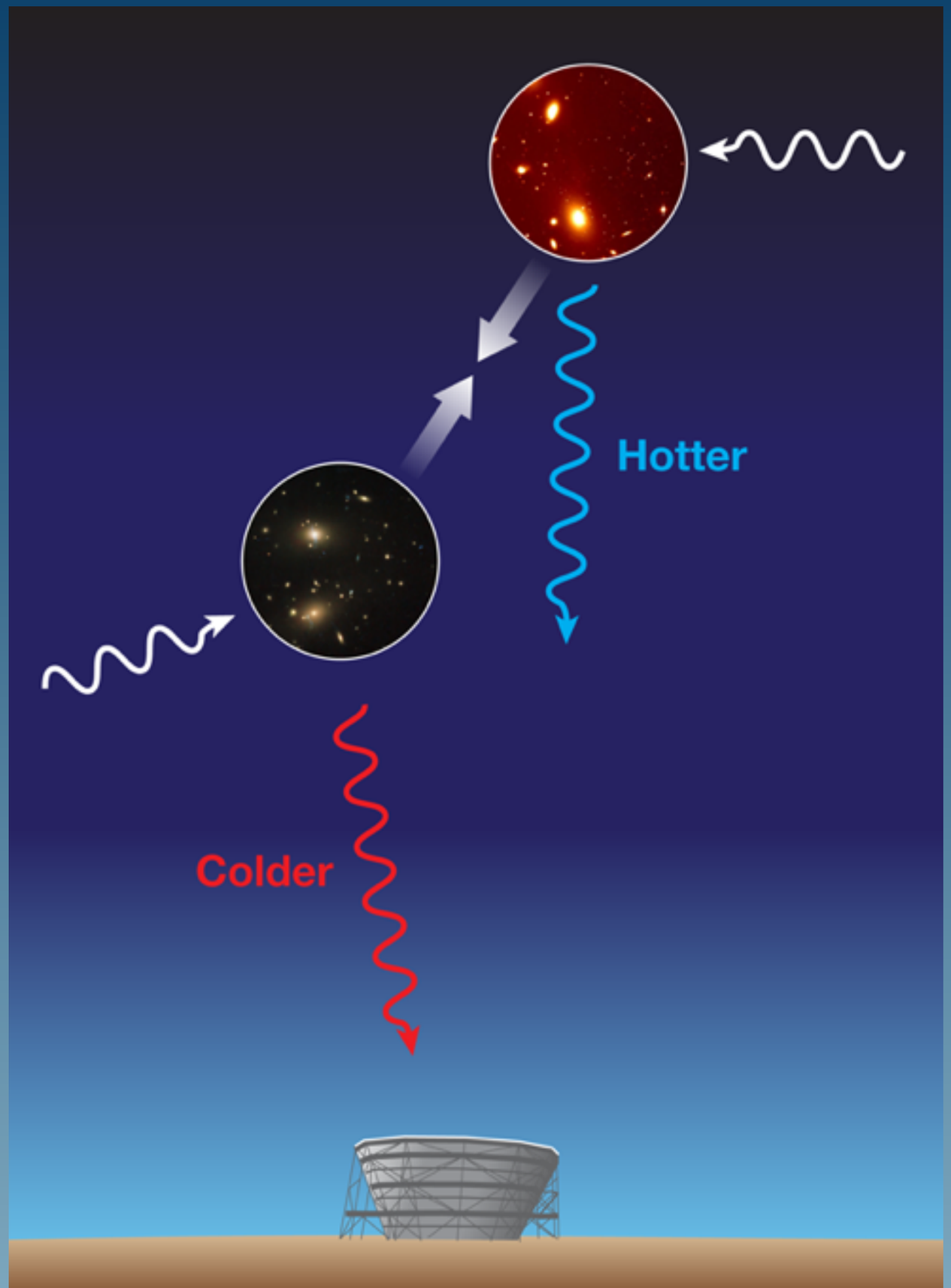


- Vary **r** at fixed θ → velocity field on large scales
- Vary θ at fixed **x** → gas profile and abundance.

TWO different measurements!

Slide credit S. Ferraro

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

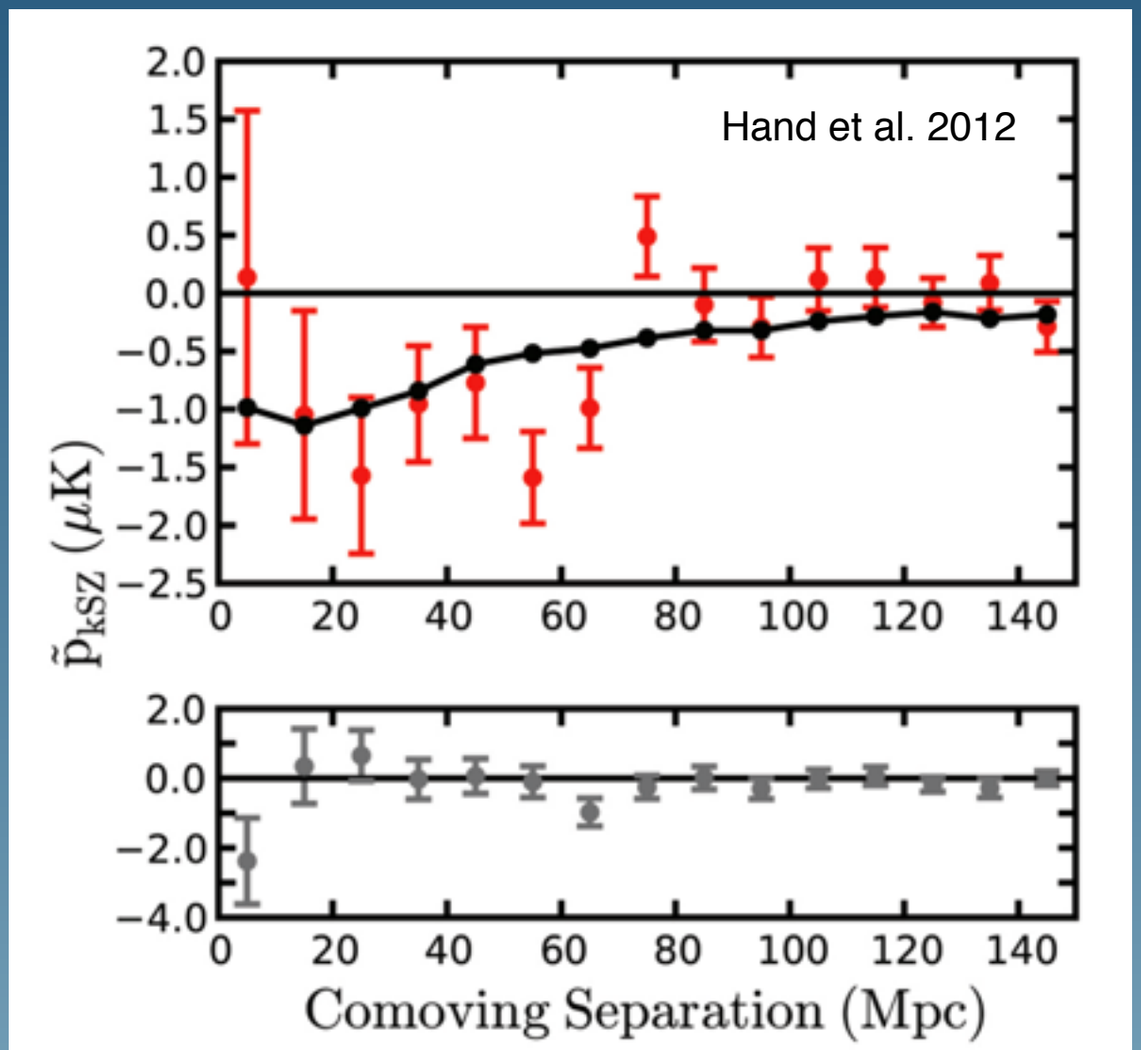
GR

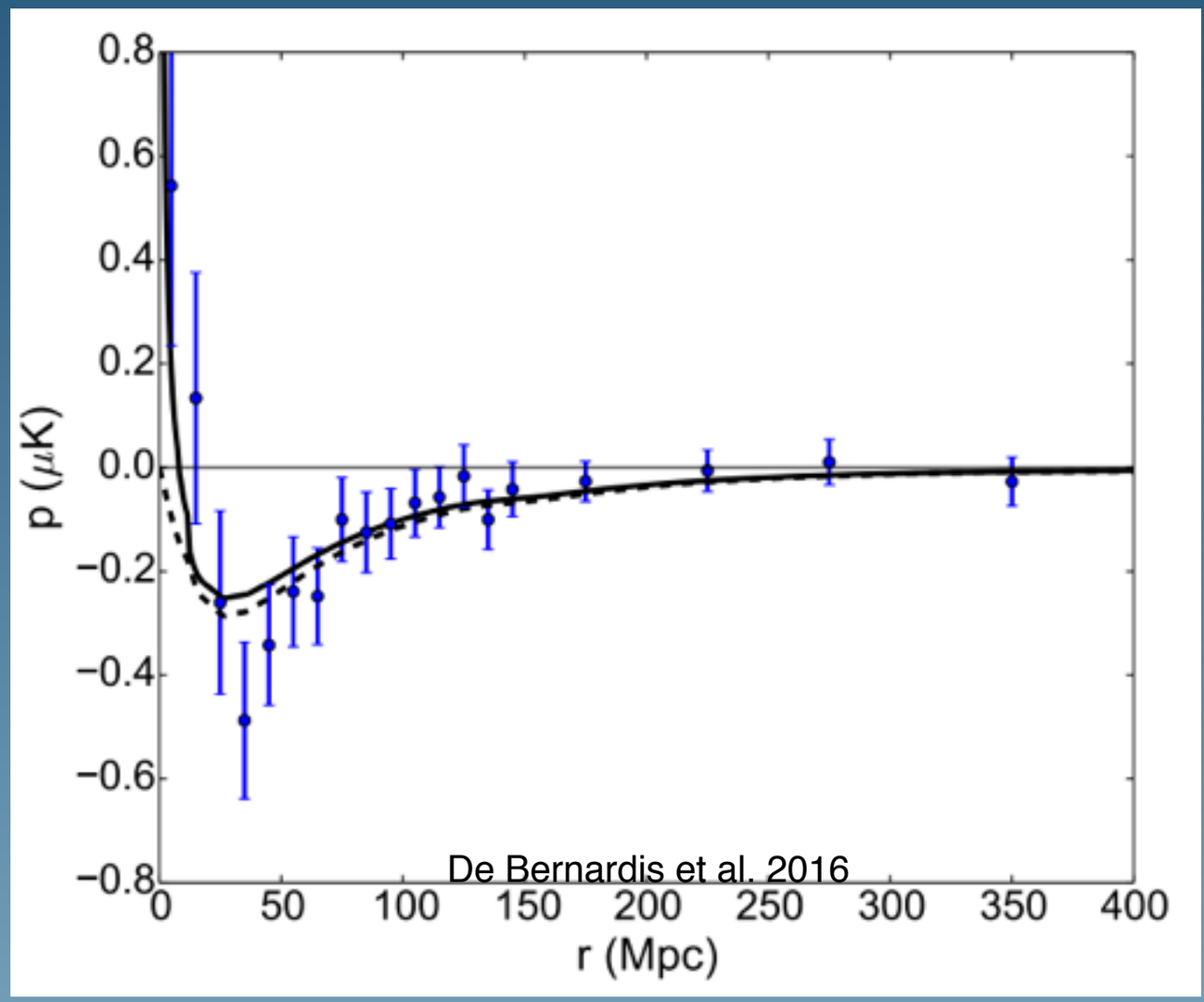
Dark Energy

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

Pair-wise velocity statistic & measurements

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

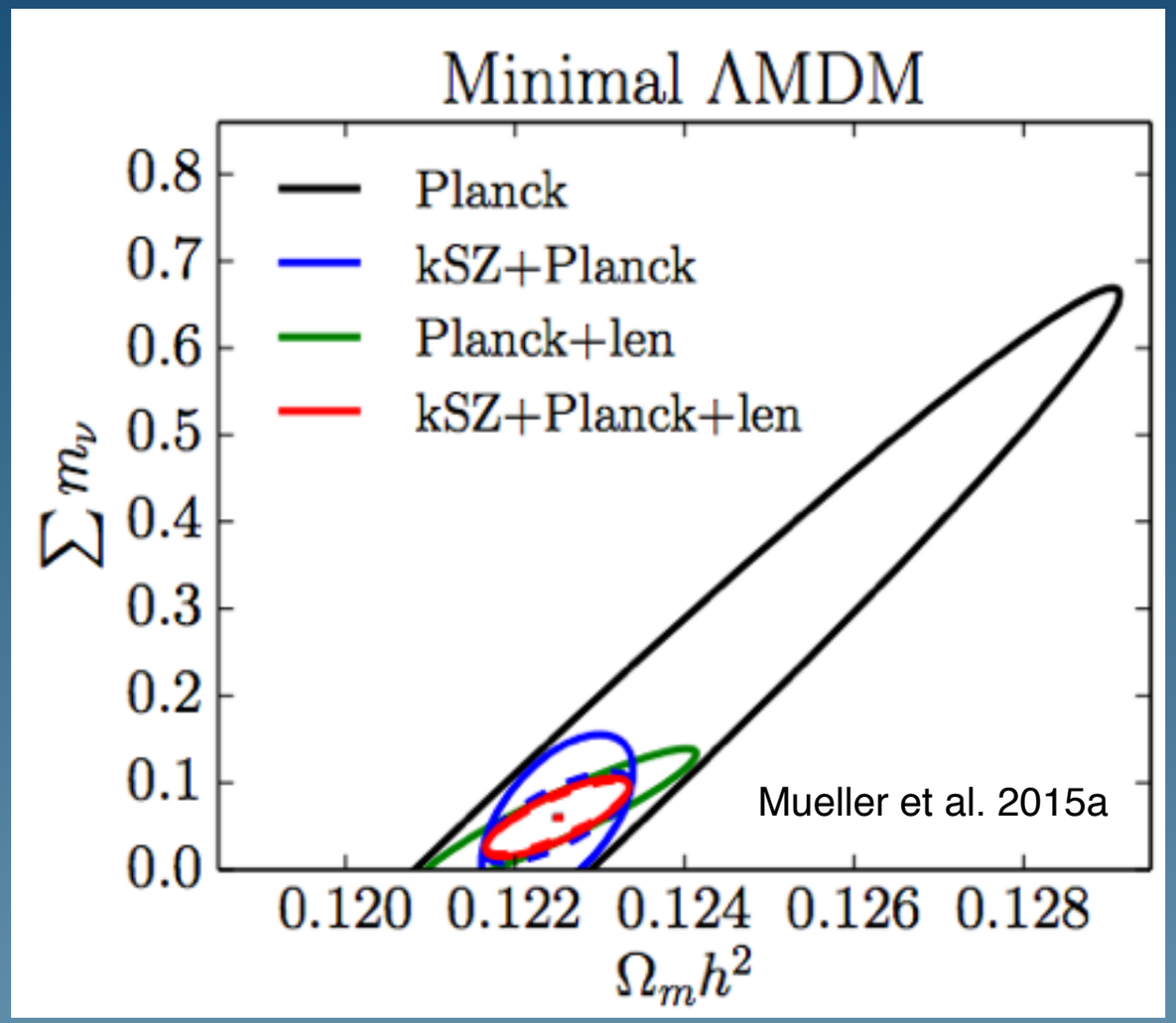


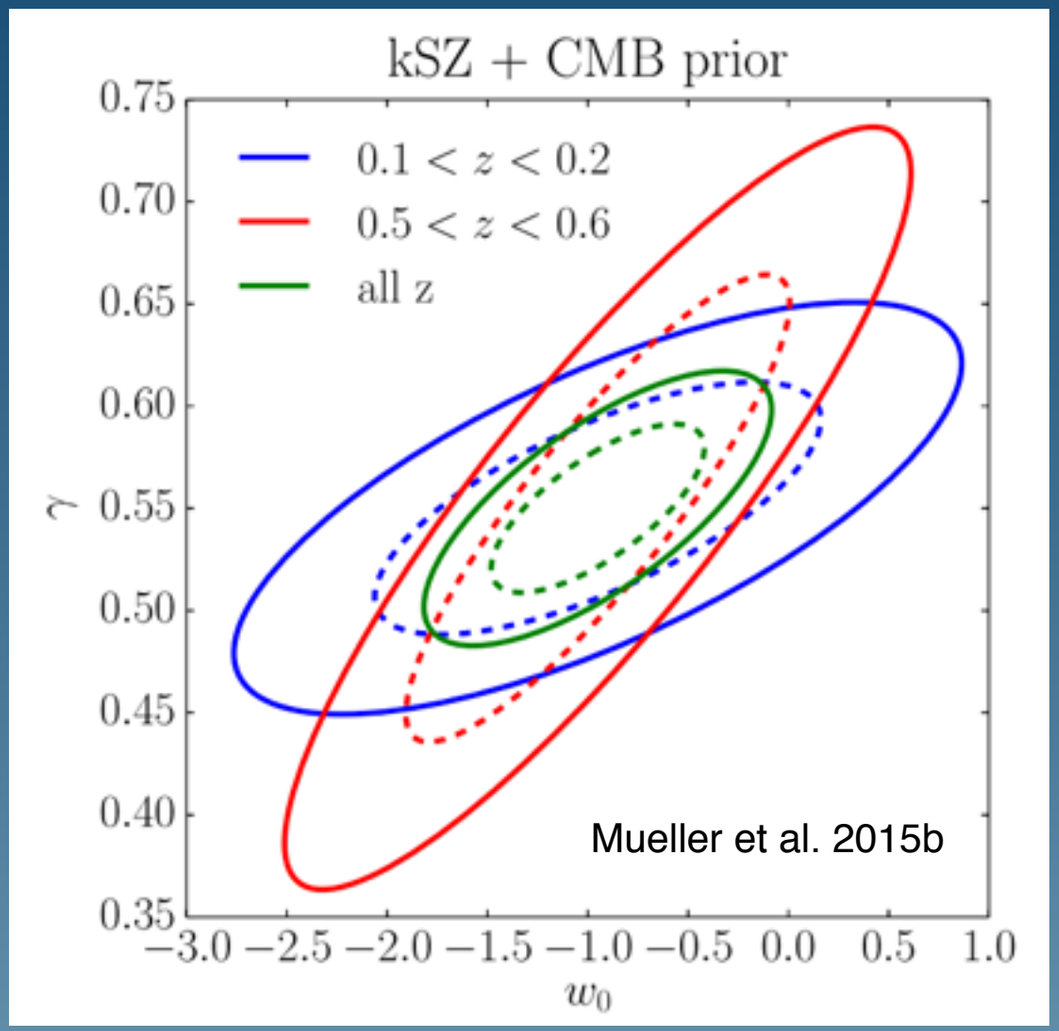


Also see Planck Coll. 2016 & SPT Soergel et al. 2016

Motivation - kSZ cosmology forecasts

Pair-wise velocity estimator





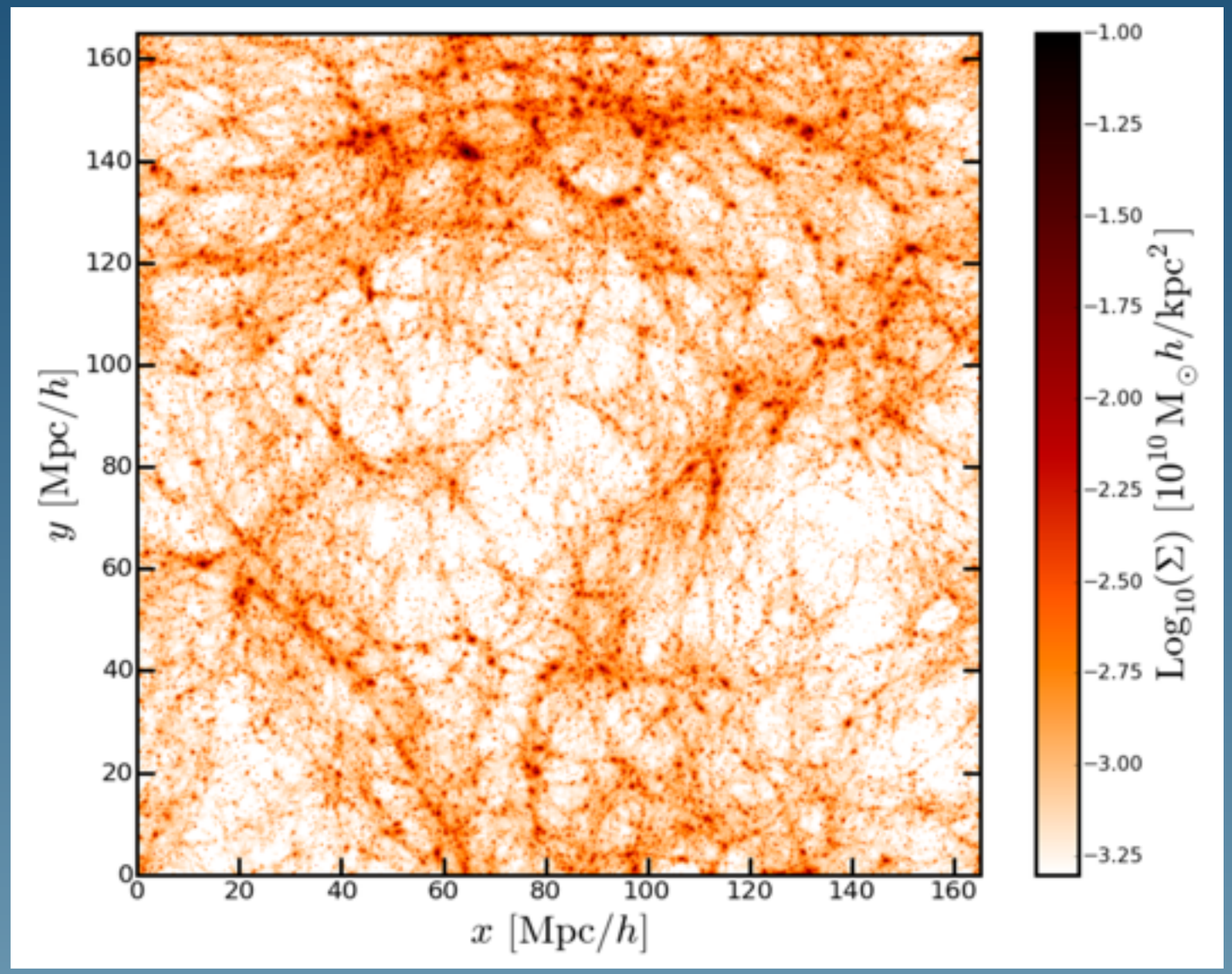
Huge potential to constrain fundamental physical parameters and extensions to the concordance cosmological model

Beware of fisher forecasts

What are some of the systematics?

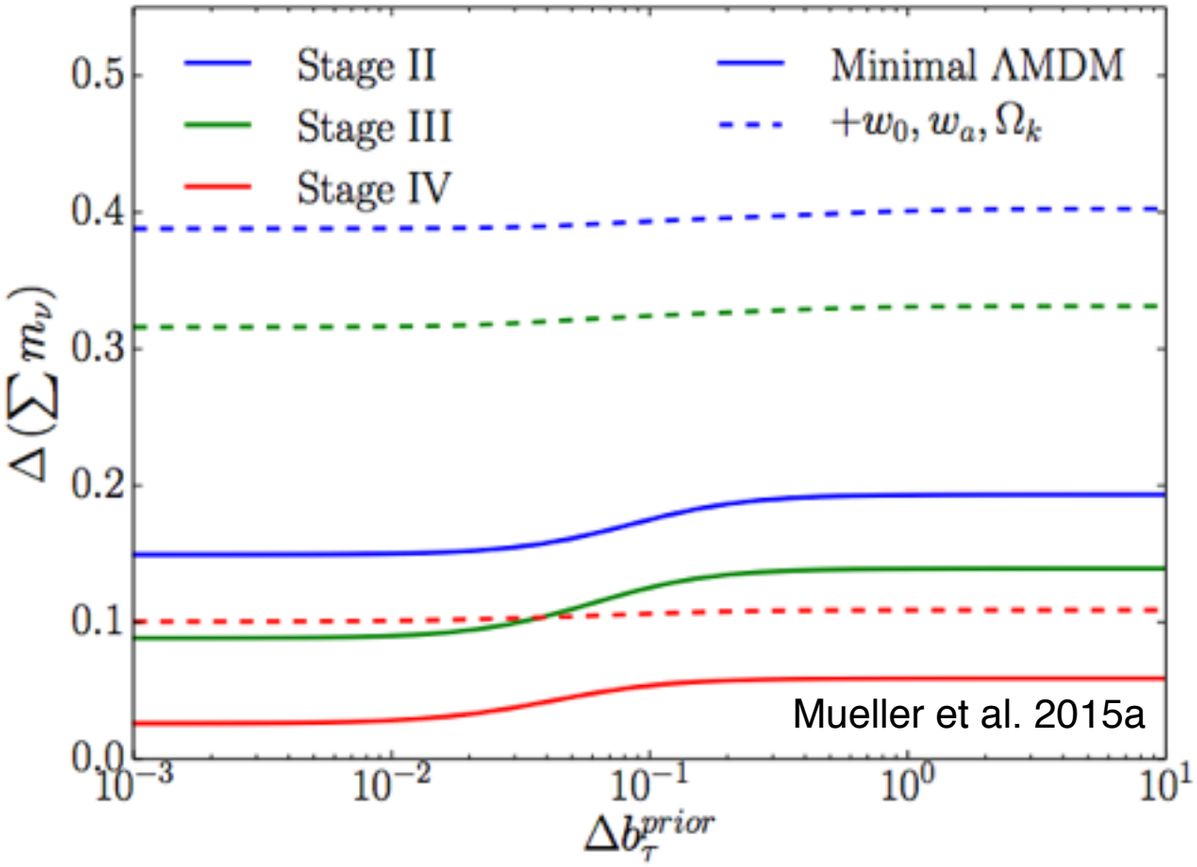
galaxy - gas offset

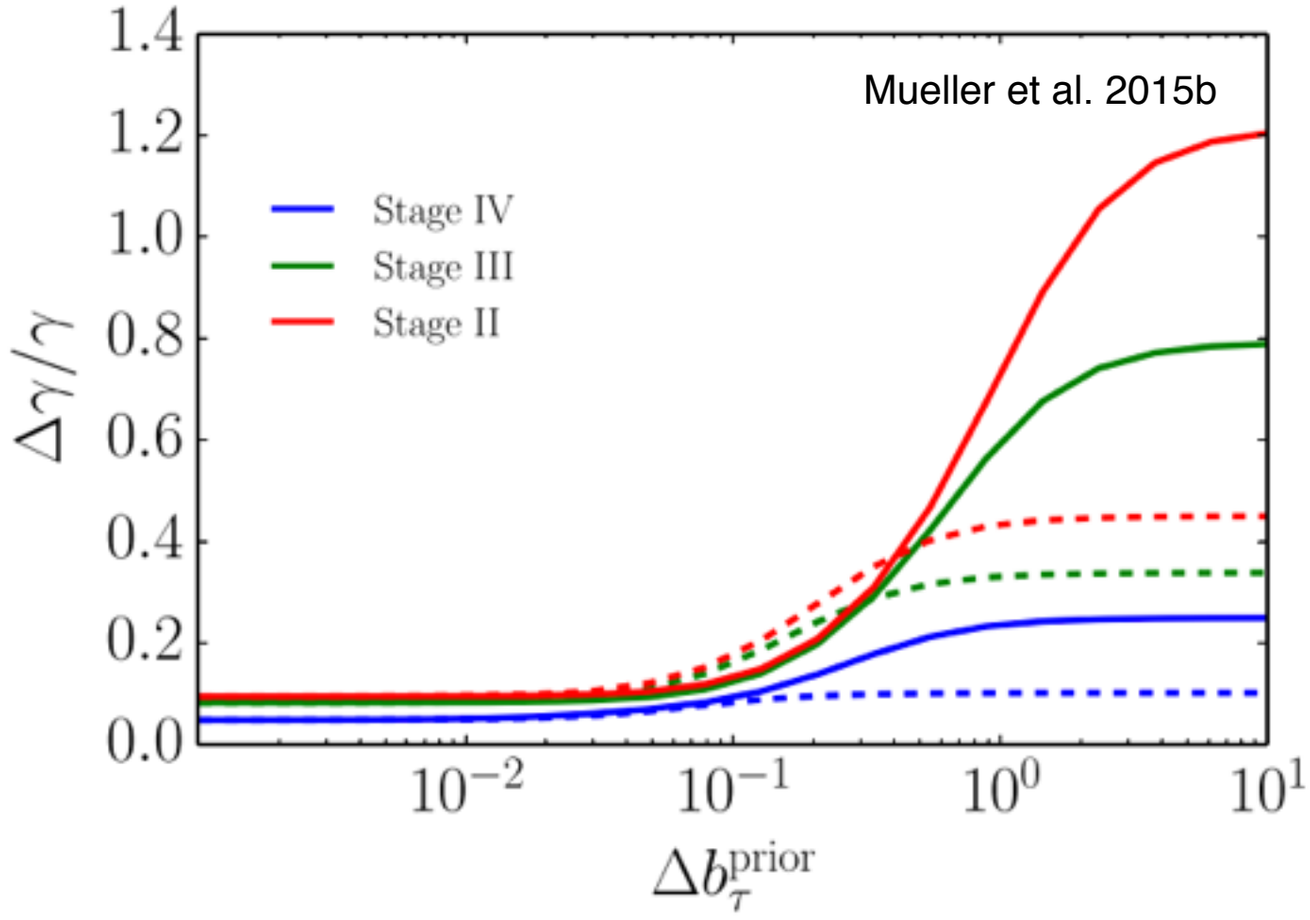
2-halo term



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

Dependence on τ

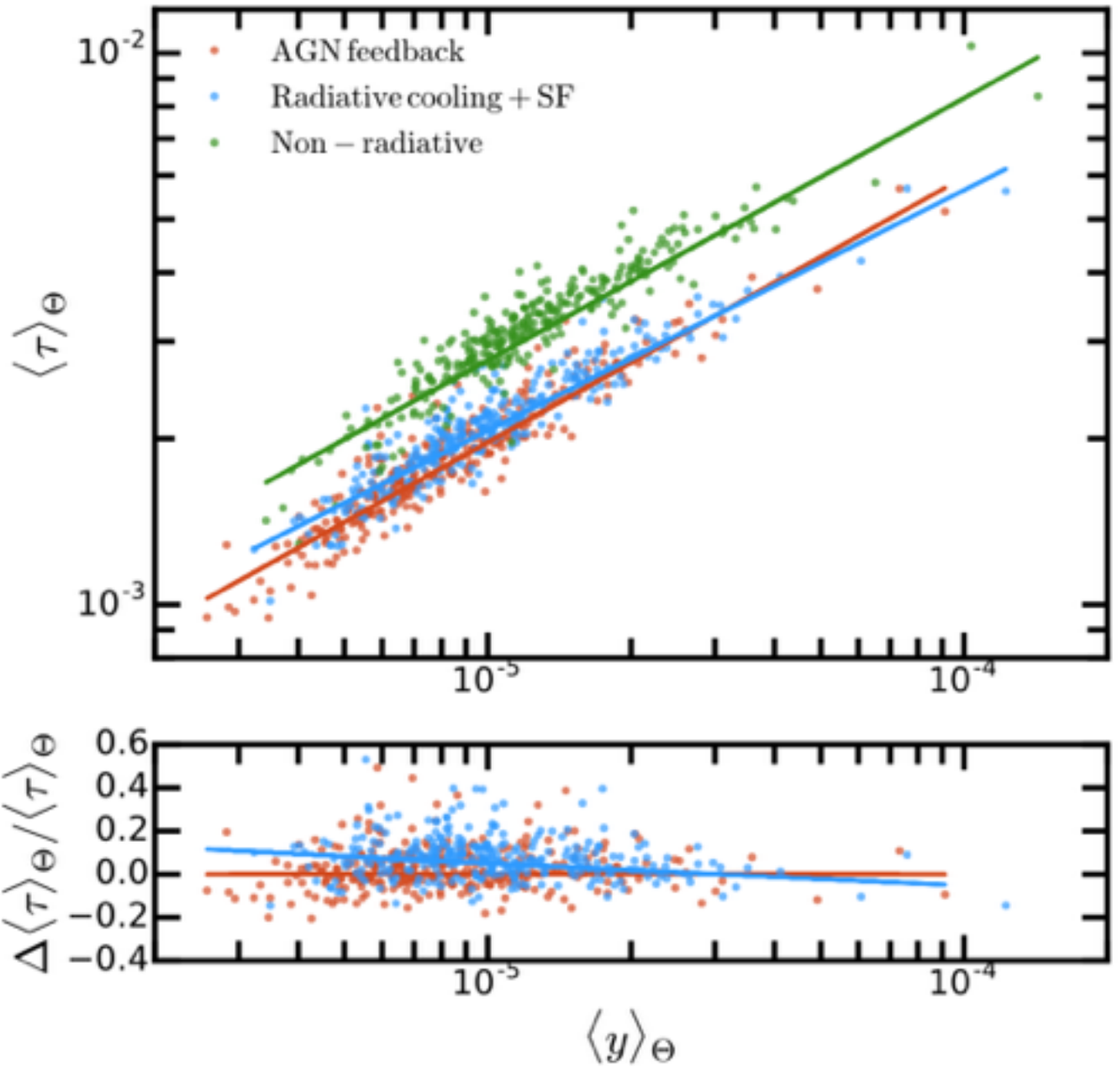


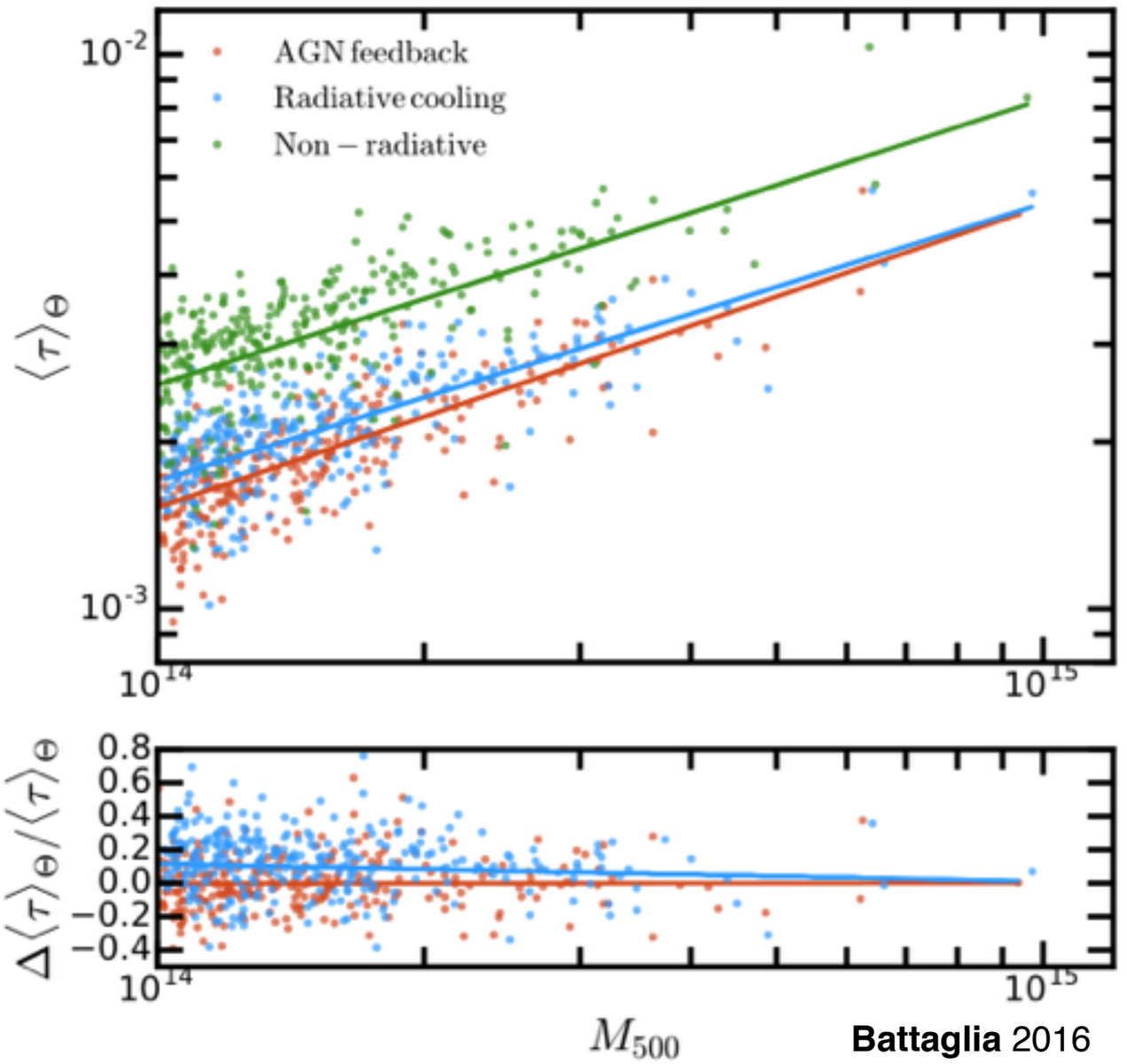


Uncertainties on τ will soon be a leading systematic uncertainty in the cosmological parameters obtained from kSZ measurements

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

τ - y relation an empirical solution?





Battaglia 2016

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