The Sunyaev-Zel'dovich Effect and Large-Scale Structure

Colin Hill

Columbia University

Junior Fellow, Simons Society of Fellows

w/ D. Spergel, N. Battaglia, N. Murray, J. Greco, B. Sherwin, K. Smith, J. Chluba, S. Ferraro, E. Schaan

1312.4525, 1409.6747, 1411.8004, 1412.5593, 1504.05598, 1507.01583

Rencontres du Vietnam, Quy Nhon

21 August 2015

Outline

- Thermal SZ (tSZ) Effect
- Probing LSS and Gastrophysics
- tSZ x Gravitational Lensing
- tSZ Statistics: Power Spectrum and Beyond
- tSZ Stacking: the Y-M Relation
- Future: the tSZ Monopole

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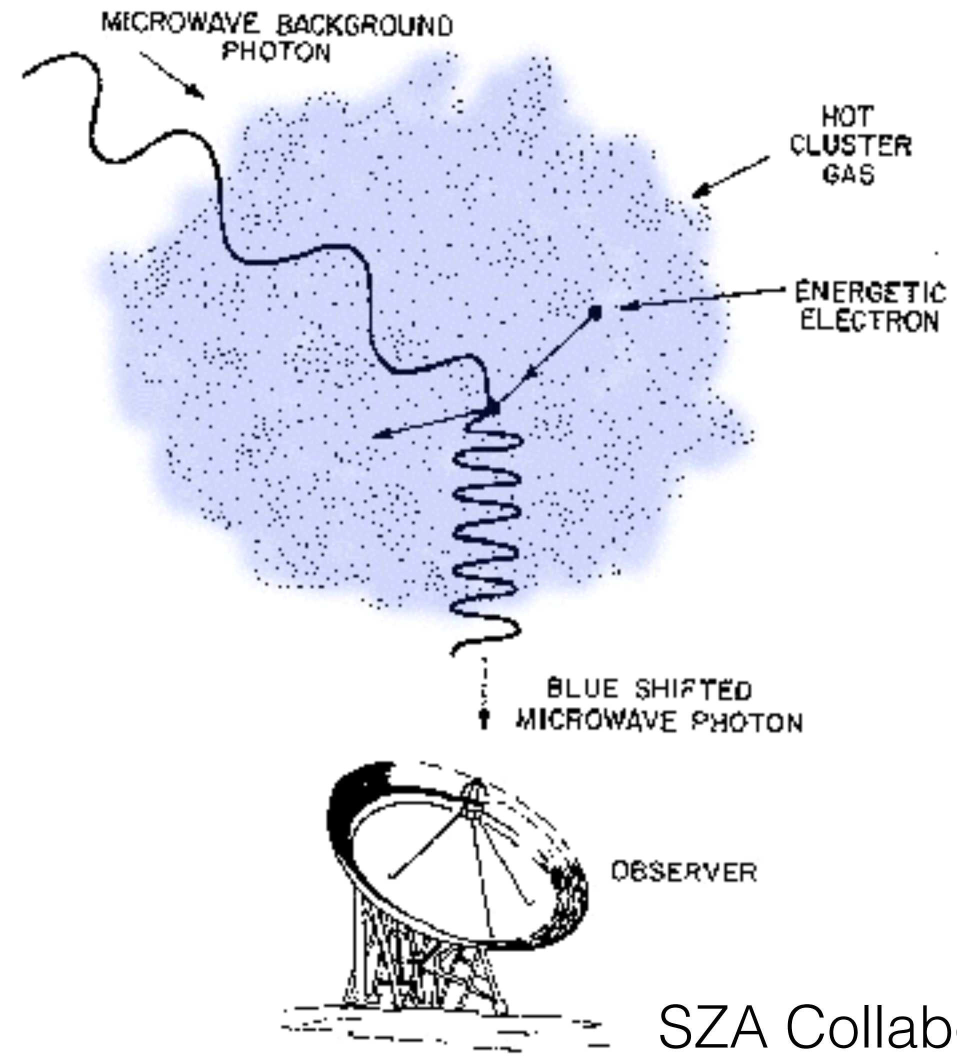
Thermal SZ Effect

Change in temperature of CMB photons due to inverse Compton scattering off hot electrons, most of which are in the intracluster medium (ICM) of galaxy groups/clusters



SZA Collaboration

Compton-y

$$\frac{\tilde{T}}{T_{\rm CMB}} = g_\nu \frac{\sigma_T}{m_e c^2} \int P_e(l)\, dl$$

temperature fluctuation

Spectral function

Electron pressure profile

Line-of-sight integral

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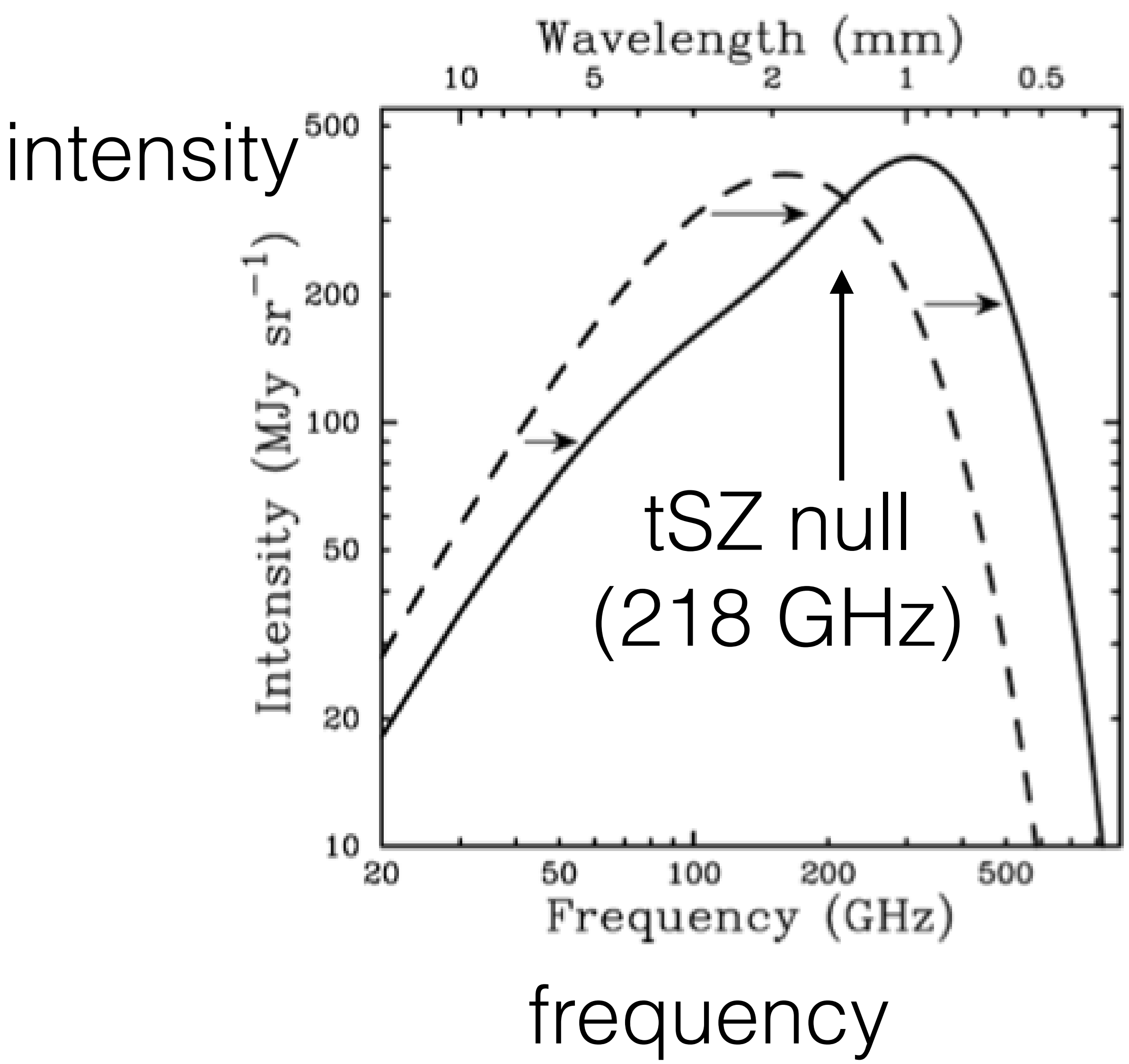
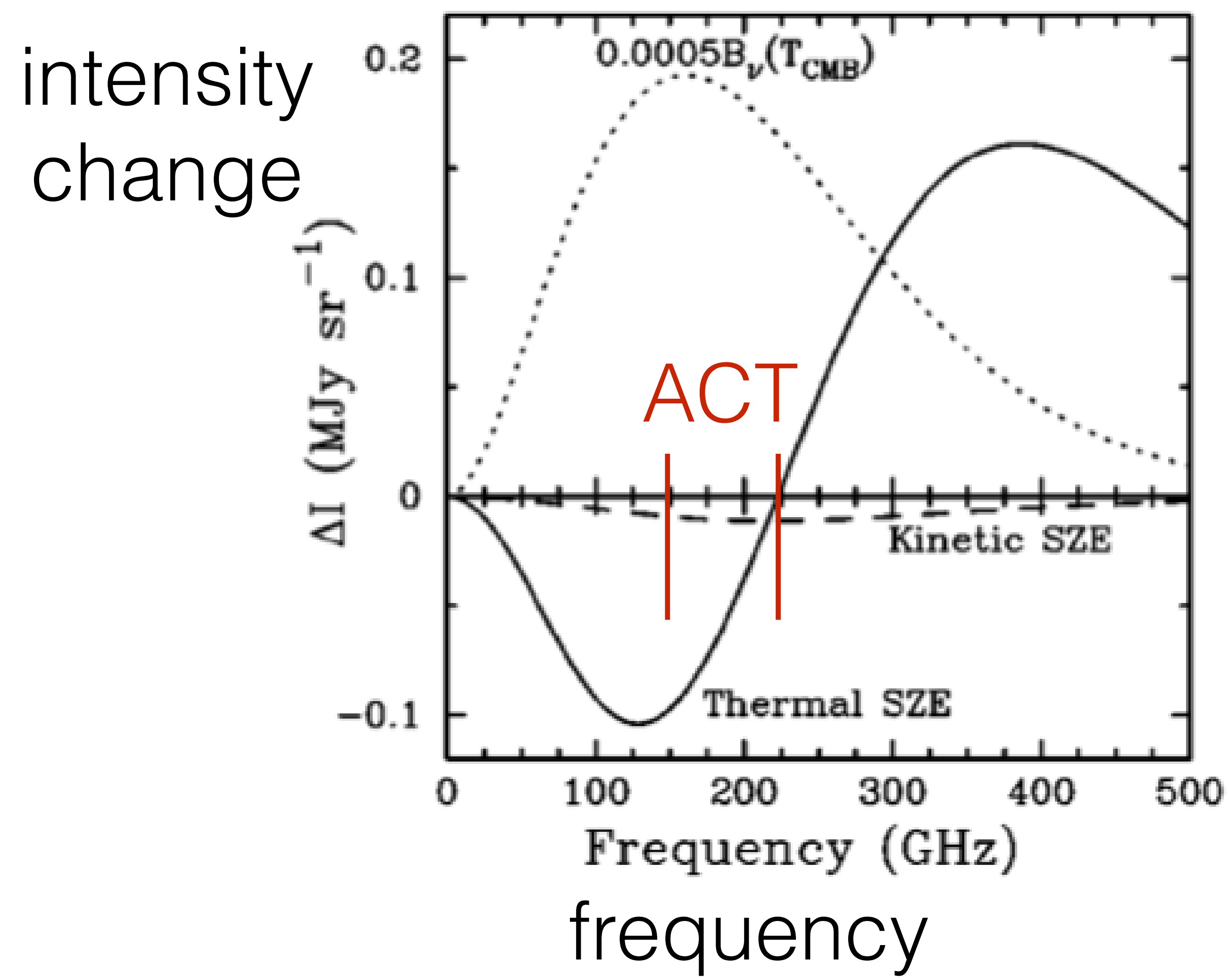
Thermal SZ Effect

Unique spectral signature





Carlstrom+ (2002)

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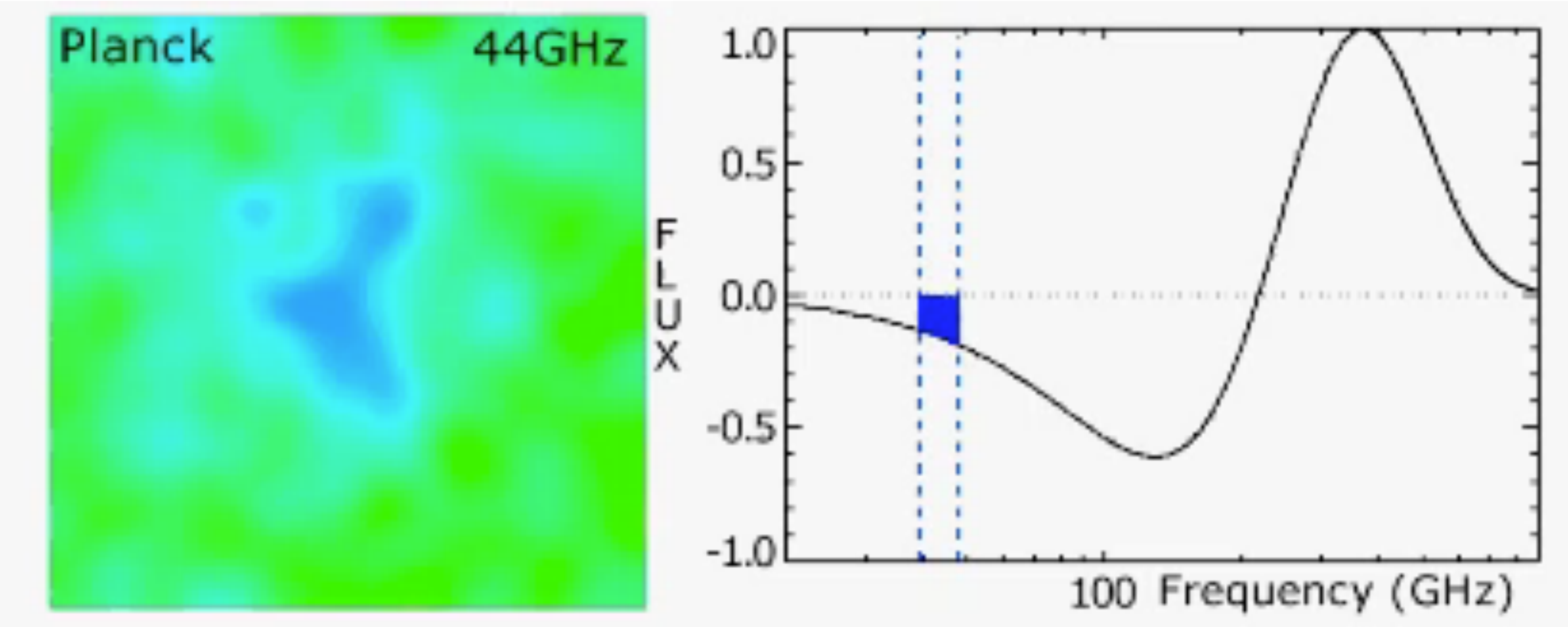
Thermal SZ Effect

simulation



ESA/Planck

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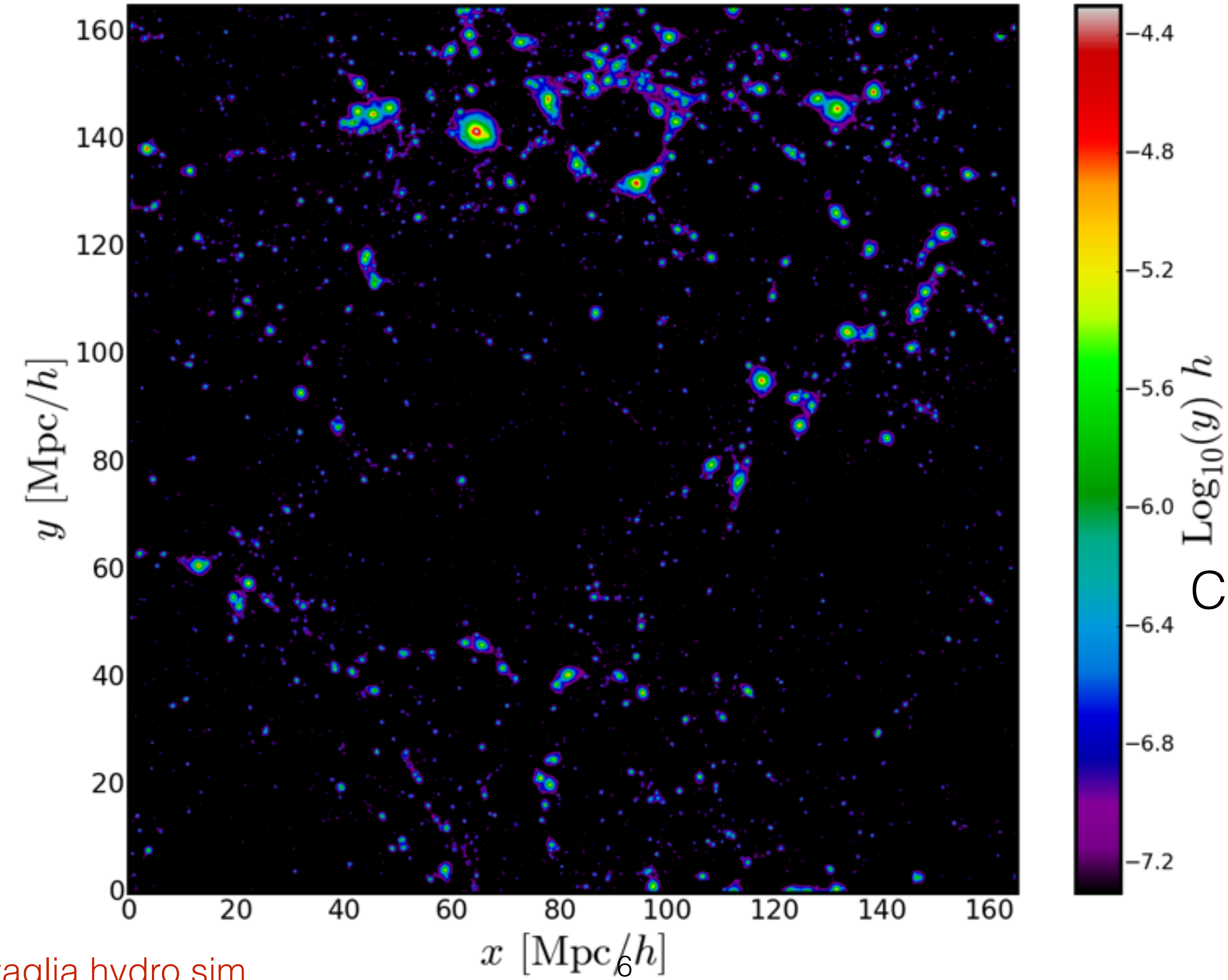
Probing Large-Scale Structure

tSZ effect in the context of LSS — strongly dominated by halos



Compton-y

from N. Battaglia hydro sim.

Probing Large-Scale Structure

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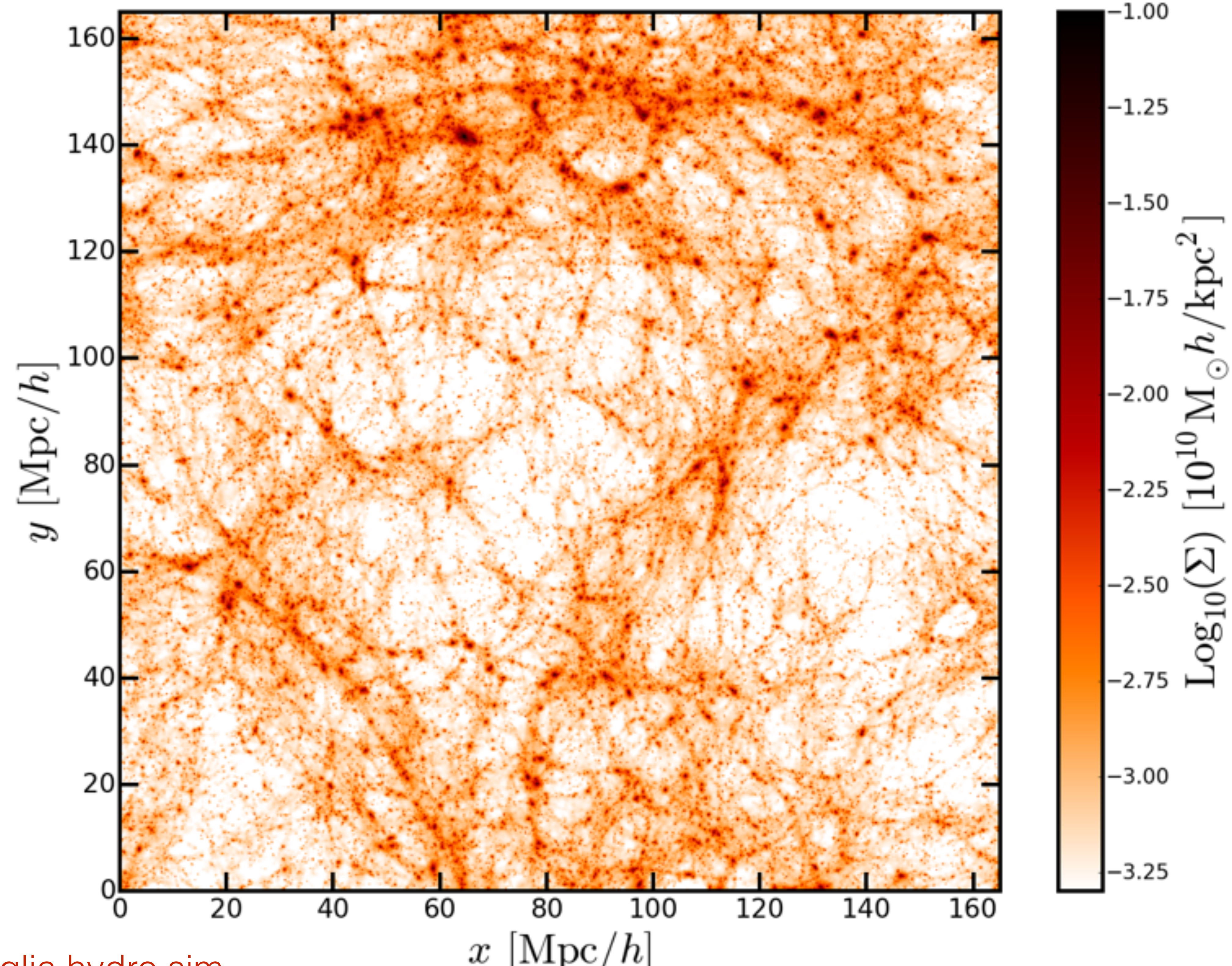
tSZ effect in the context of LSS — strongly dominated by halos



surface density

from N. Battaglia hydro sim.

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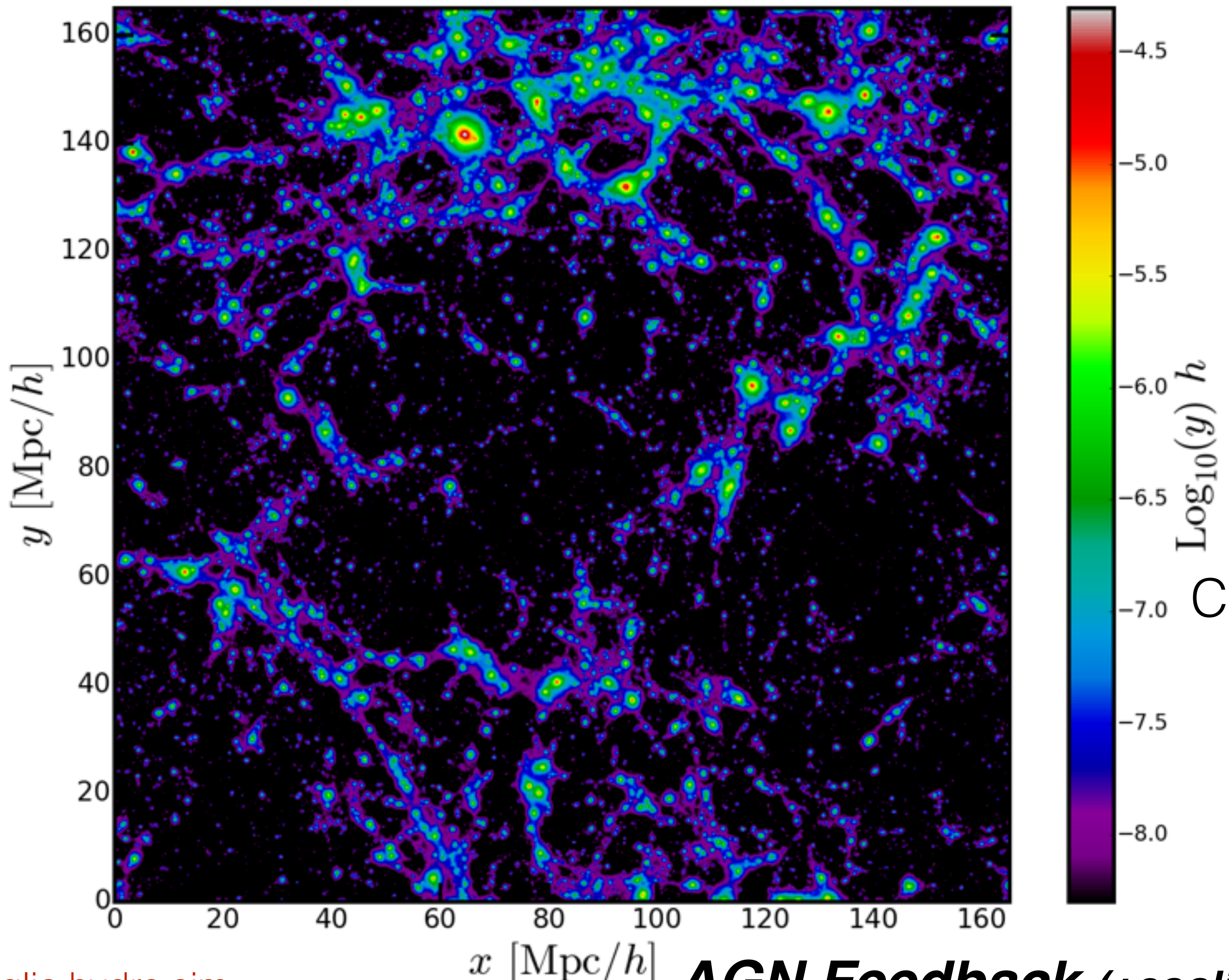
Probing Large-Scale Structure

dependence on intracluster medium "gastrophysics"



Compton-y

from N. Battaglia hydro sim.

***AGN Feedback** (+cooling+SF+…)*

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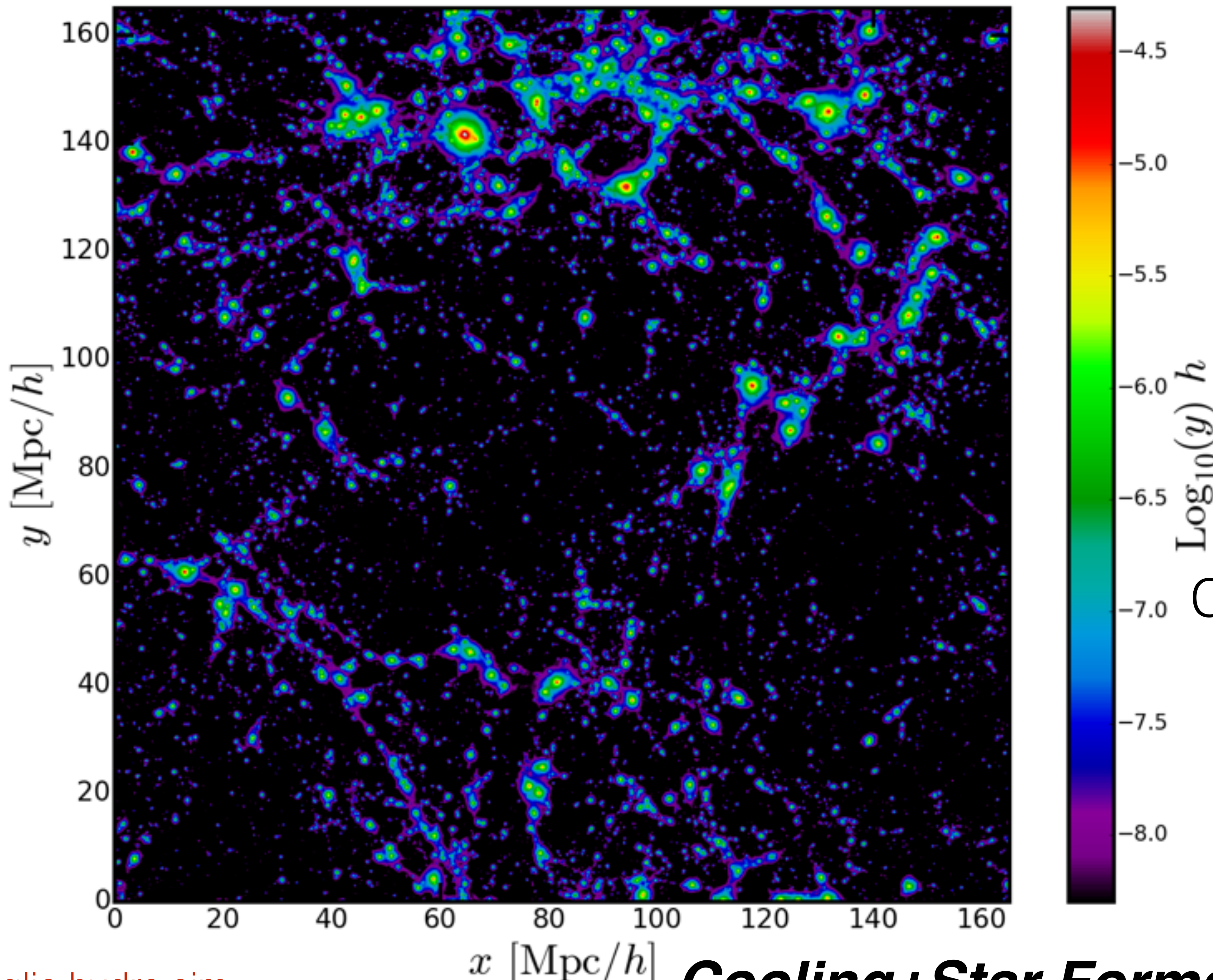
Probing Large-Scale Structure

dependence on intracluster medium "gastrophysics"



Compton-y

from N. Battaglia hydro sim.

***Cooling+Star Formation** (+…)*

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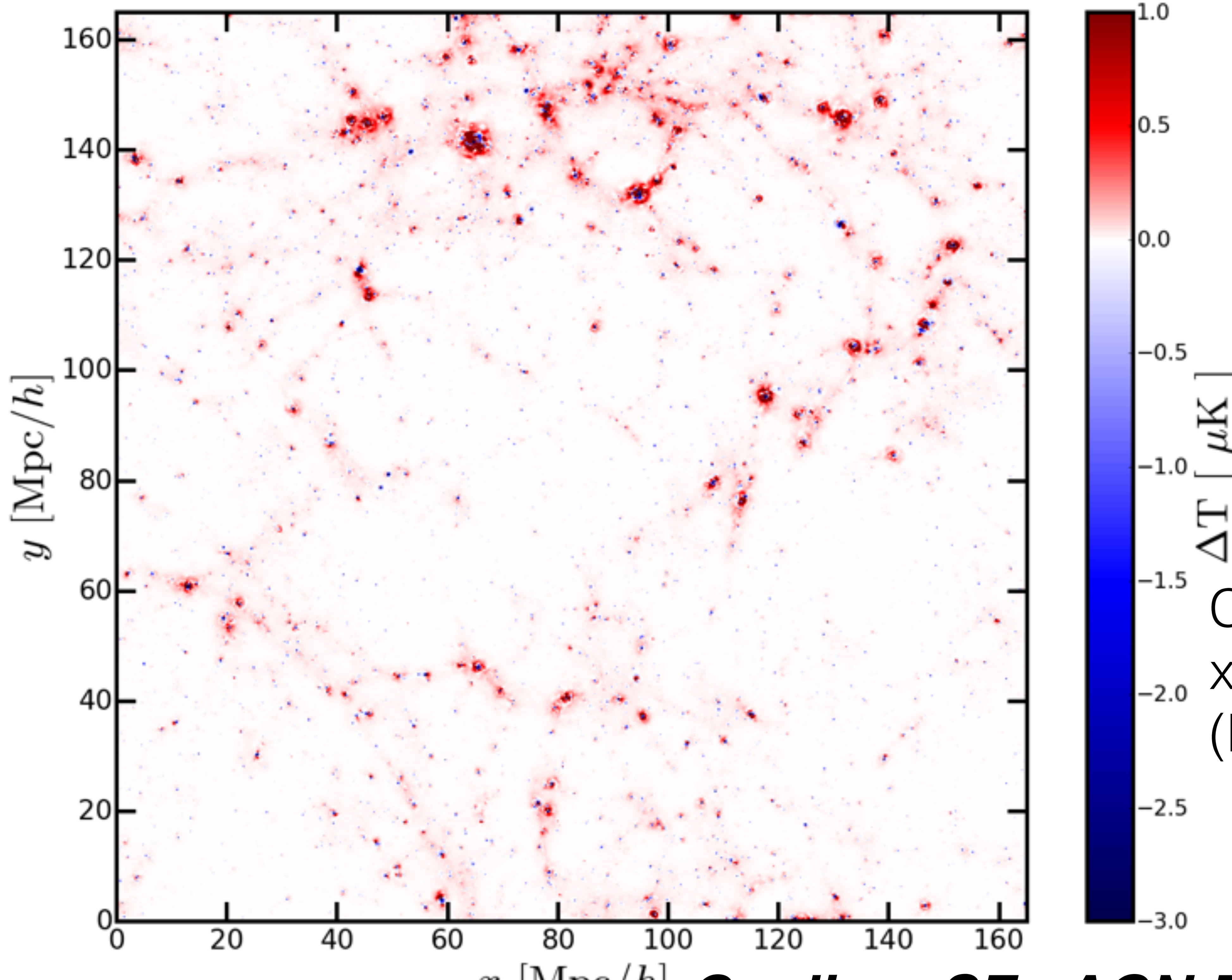
Probing Large-Scale Structure

dependence on intracluster medium “gastrophysics”



Compton-y x T_{CMB} x -2 (R-J limit)

from N. Battaglia hydro sim.

Cooling+SF - AGN Feedback

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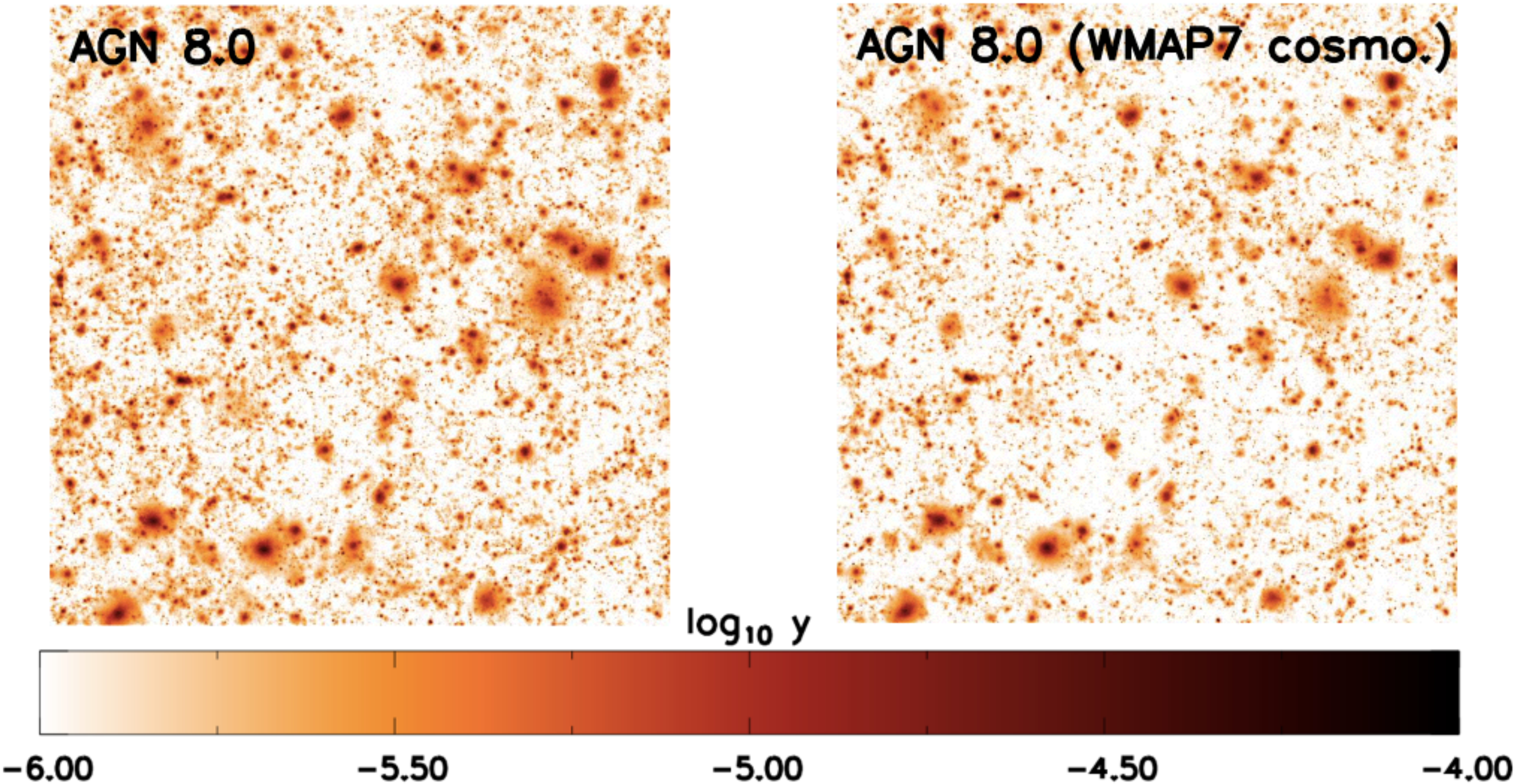
Probing Large-Scale Structure

dependence on cosmological parameters (esp. σ_8)

σ_8=0.834, Ω_m=0.318 σ_8=0.810, Ω_m=0.272



McCarthy+ (2014)

tSZ x Lensing

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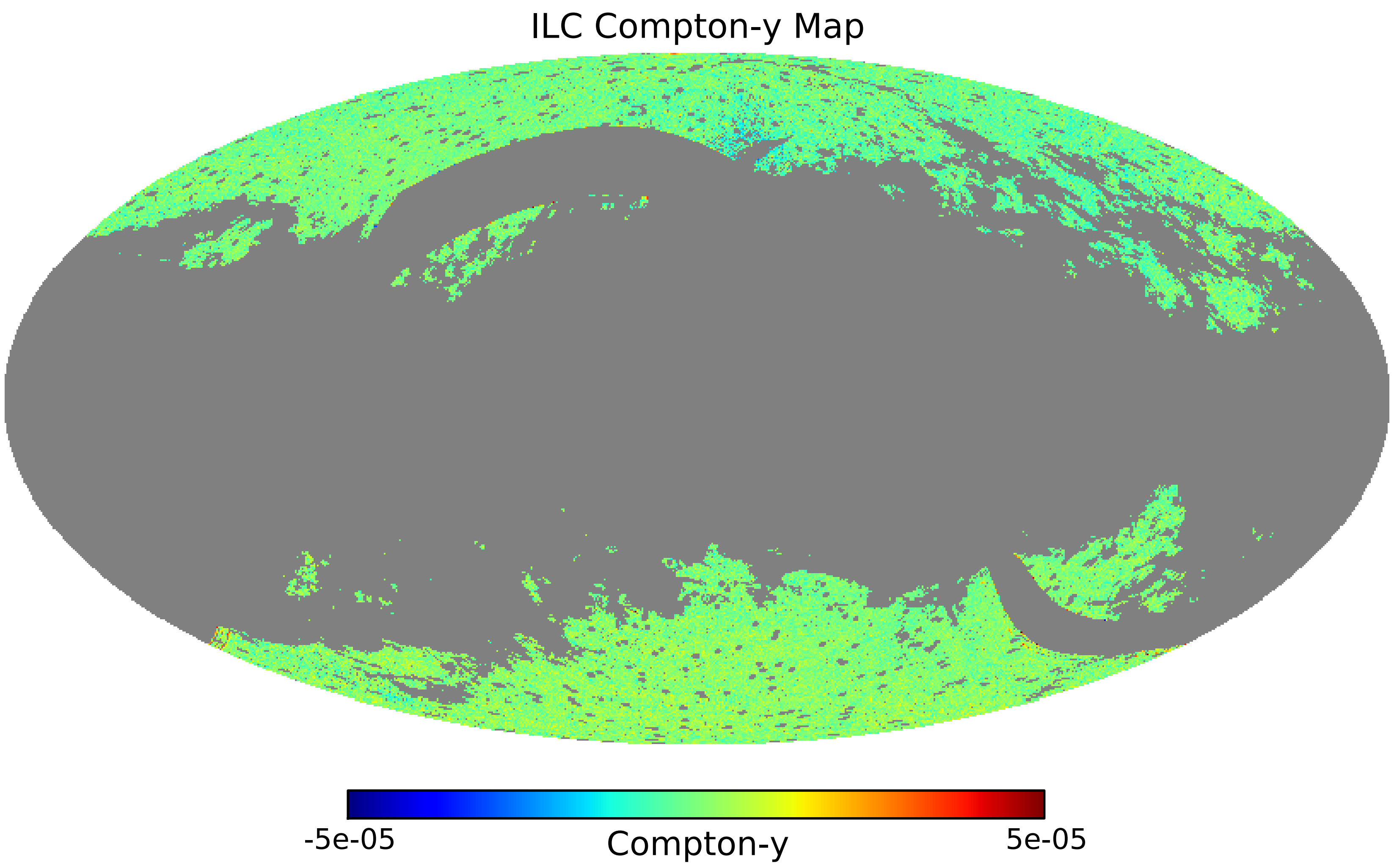
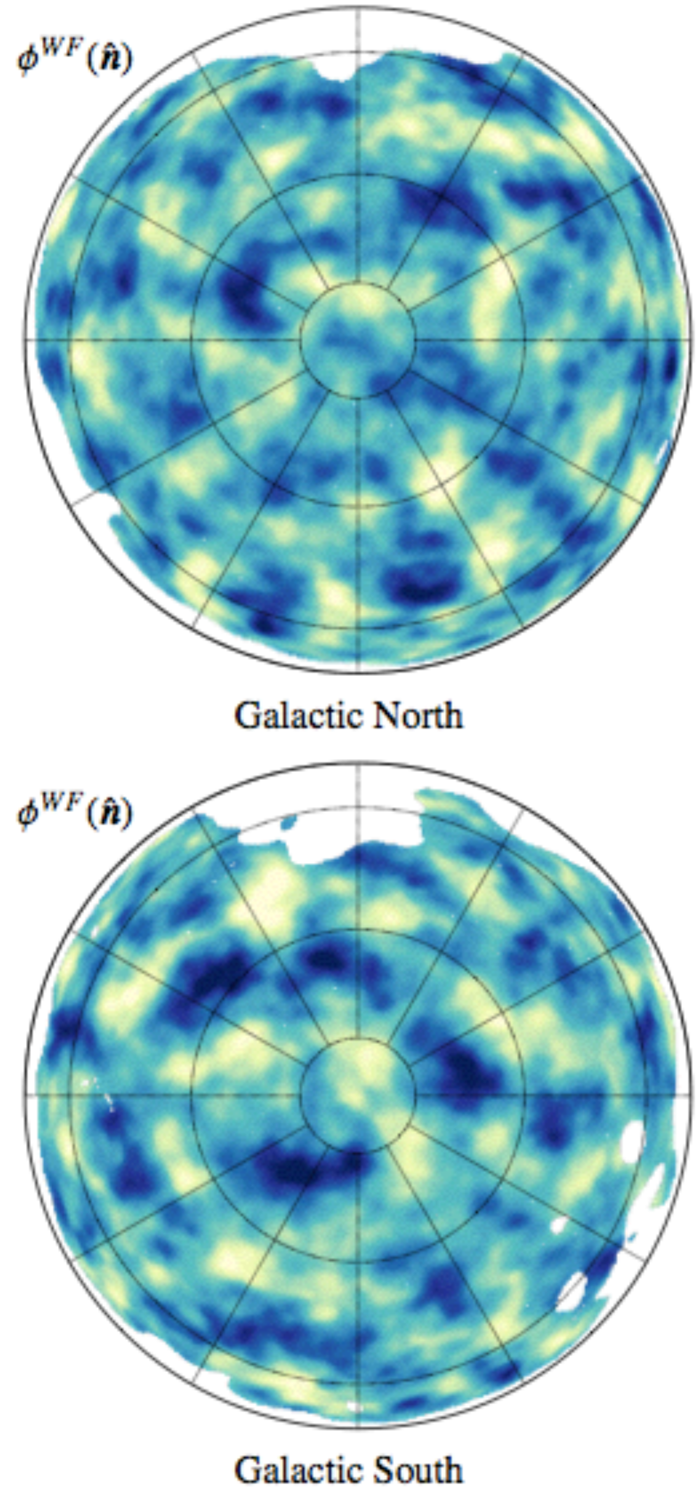
tSZ x CMB Lensing

Probe relationship of hot, ionized gas and matter density

Analysis using Planck 2013 data



X



$\kappa_L = L(L+1)\phi_L/2$

JCH & Spergel (2014)

tSZ x CMB Lensing

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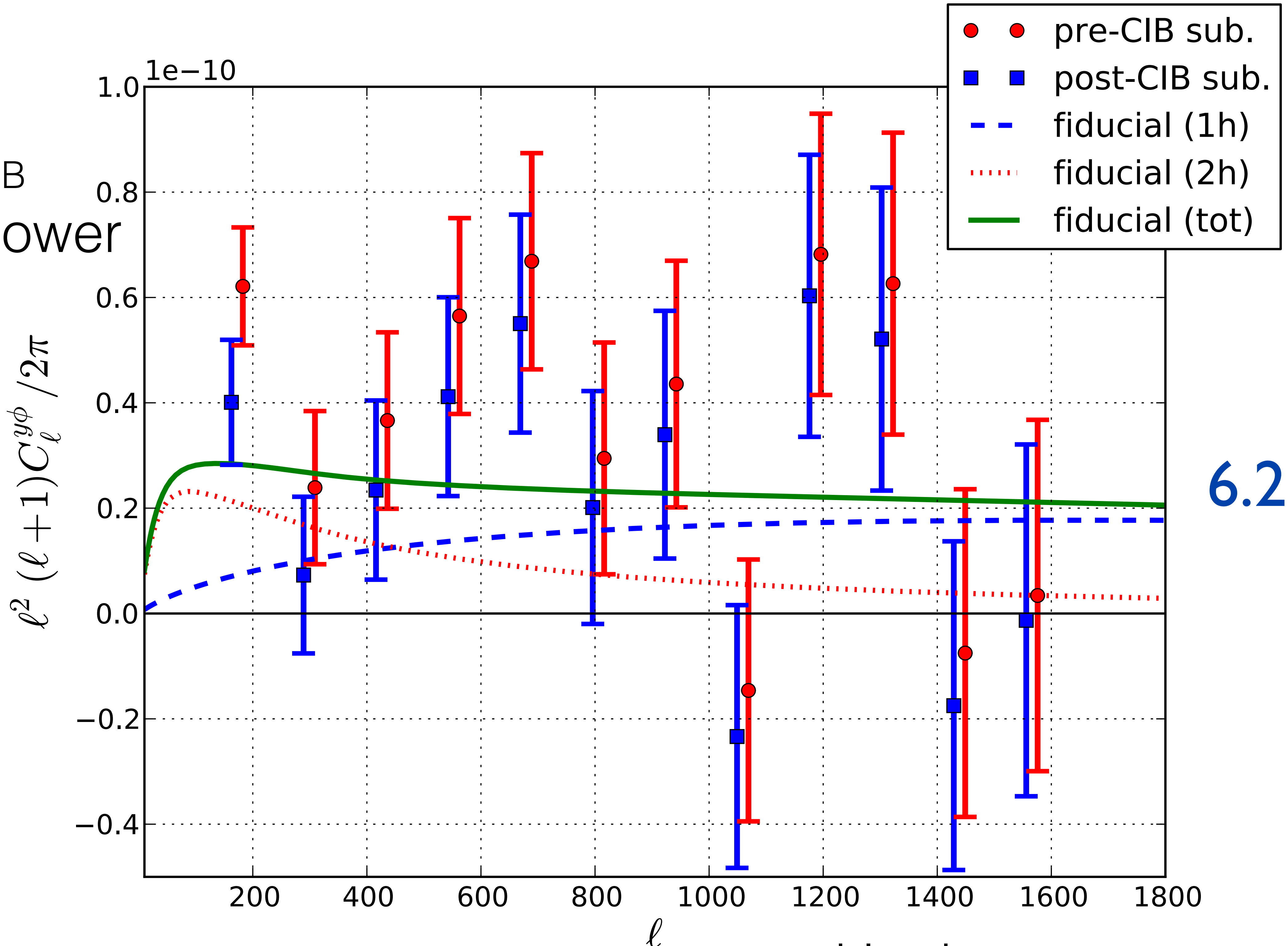
y x ϕCMB
cross-power



multipole

6.2σ

JCH & Spergel (2014)

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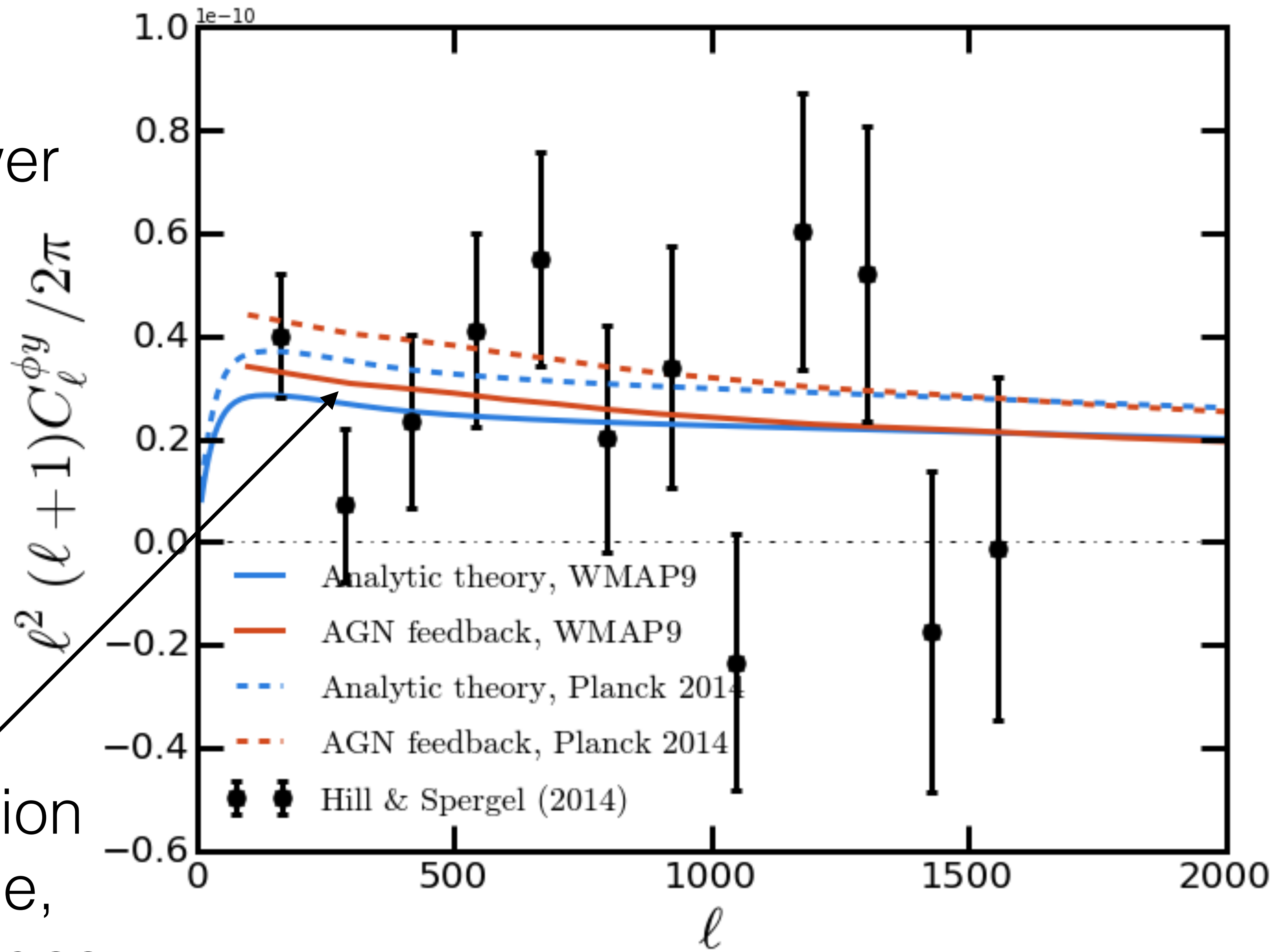
Interpretation

$\sigma_8 (\Omega_m/0.282)^{0.26} = 0.814 +/- 0.029$ (fixed gas physics)

y x ϕ_{CMB} cross-power



halo model

hydro sims

contribution of diffuse, unbound gas

multipole

Battaglia, JCH, & Murray (2014)

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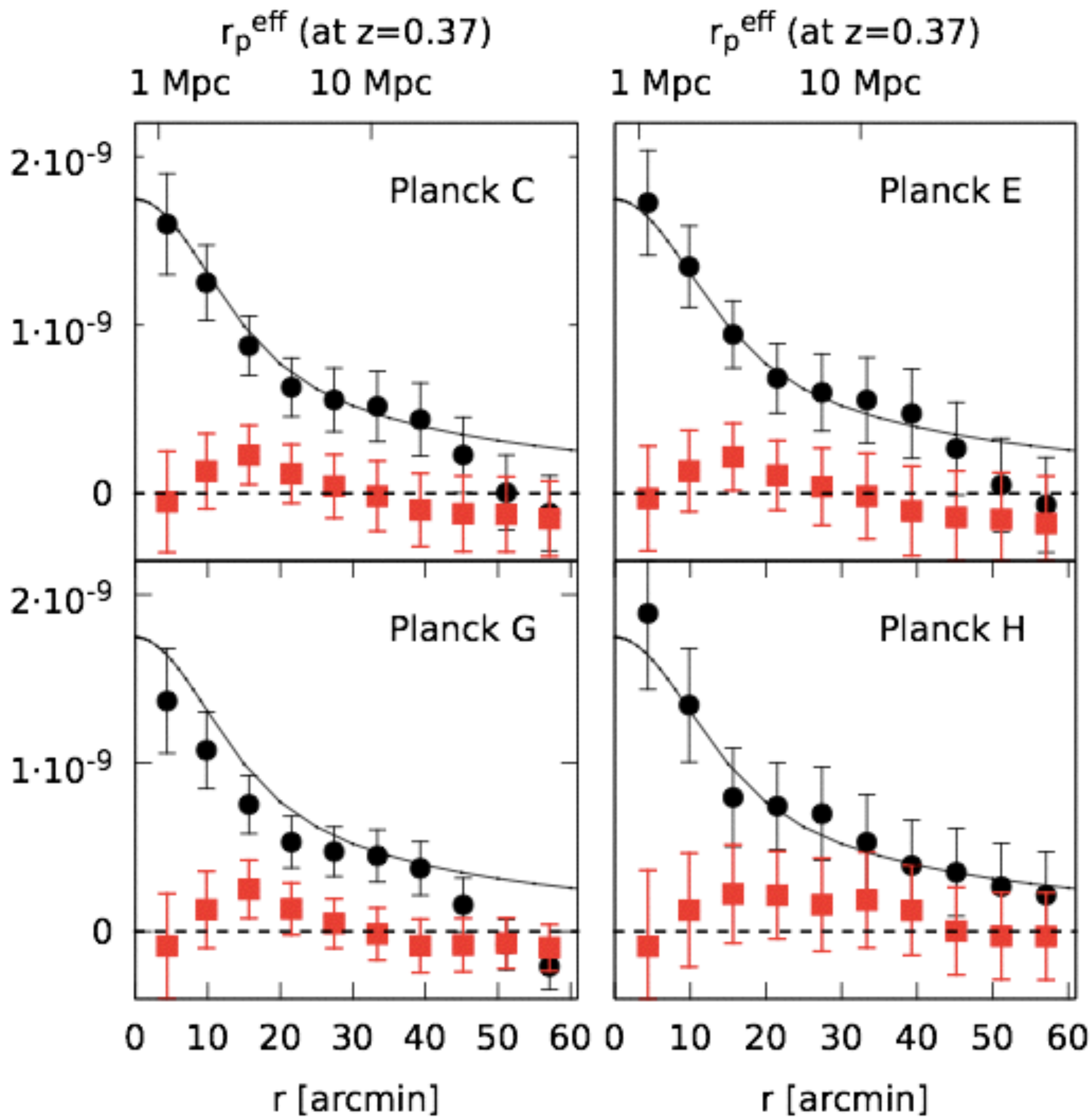
tSZ x CFHTLenS

$y \times \phi_{gal}$

real-space cross-corr. function



angular separation

"missing baryons"?

van Waerbeke, Hinshaw, Murray (2014)

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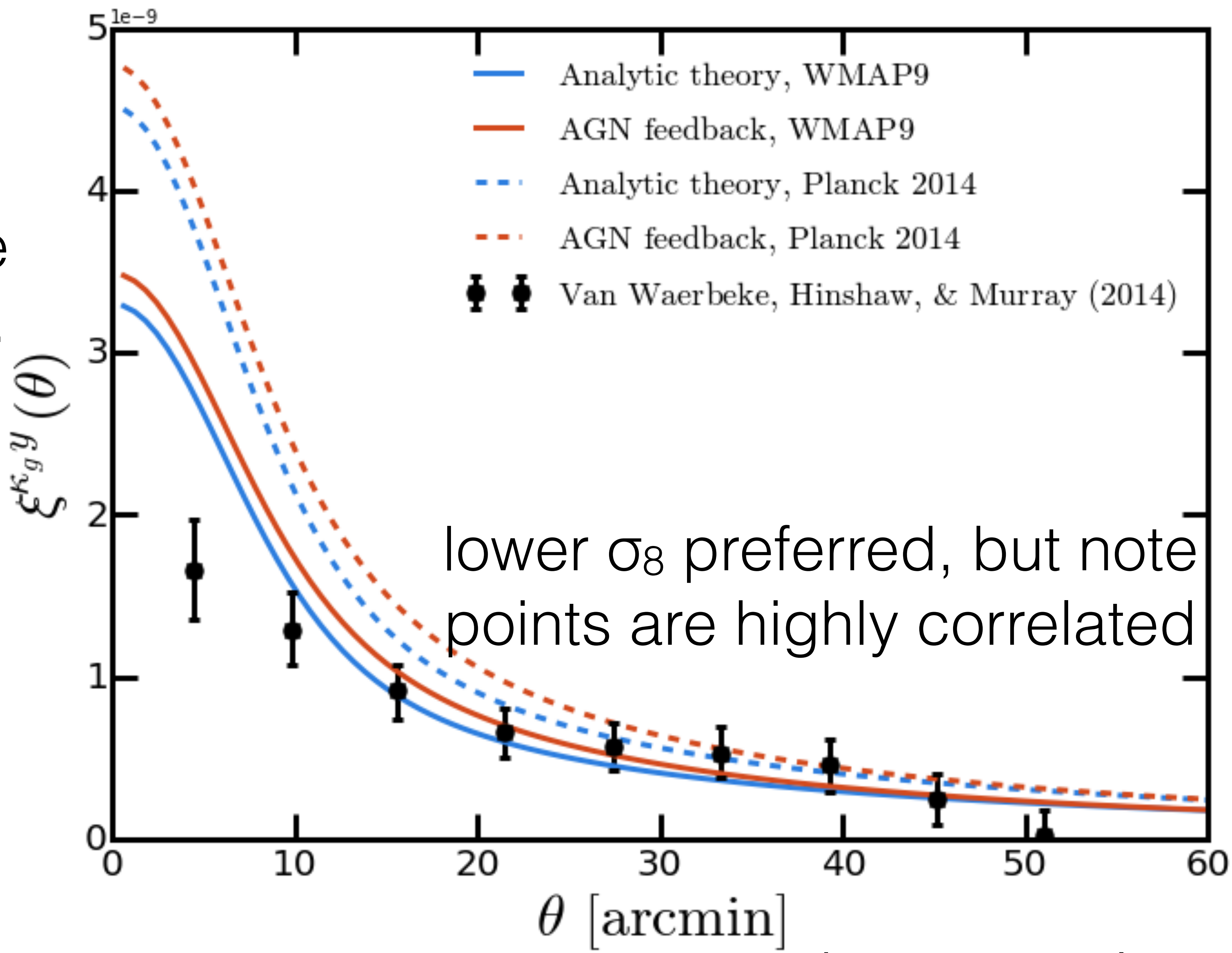
tSZ x CFHTLenS

y x ϕ_{gal}

real-space cross-corr. function



lower σ_8 preferred, but note points are highly correlated

angular separation

halo model

hydro sims

Battaglia, JCH, & Murray (2014)

see also Hojjati+ (2014)

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Takeaway

- It is extremely difficult to probe “missing baryons” with tSZ measurements, including tSZ x lensing.

  (instead: kSZ — see Blake Sherwin’s talk + Planck XXXVII (2015))

- However, these measurements are a powerful probe of the ICM electron pressure profile, i.e., of gastrophysical feedback models.

Planck tSZ x S3 CMB lensing, S4 galaxy lensing

P_0 (pressure profile amplitude)	+/- 22%
β (pressure profile outer slope)	+/- 4%
α_z (z-dependence of amplitude)	+/- 13%

Battaglia, JCH, & Murray (2014)

tSZ Statistics: Power Spectrum and Beyond

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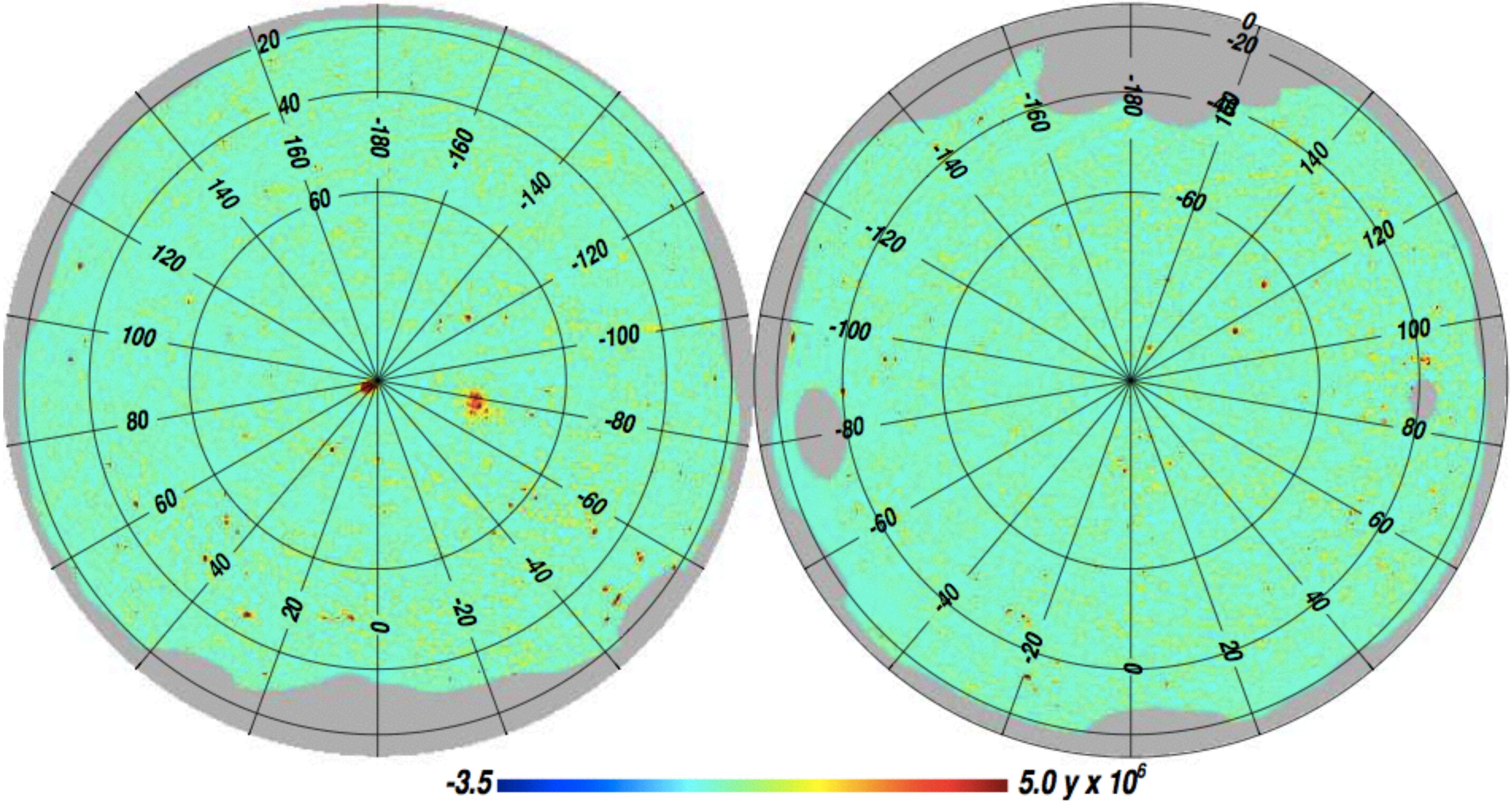
tSZ Power Spectrum



Planck 2015 Compton-y map

Planck XXII (2015)

tSZ Power Spectrum

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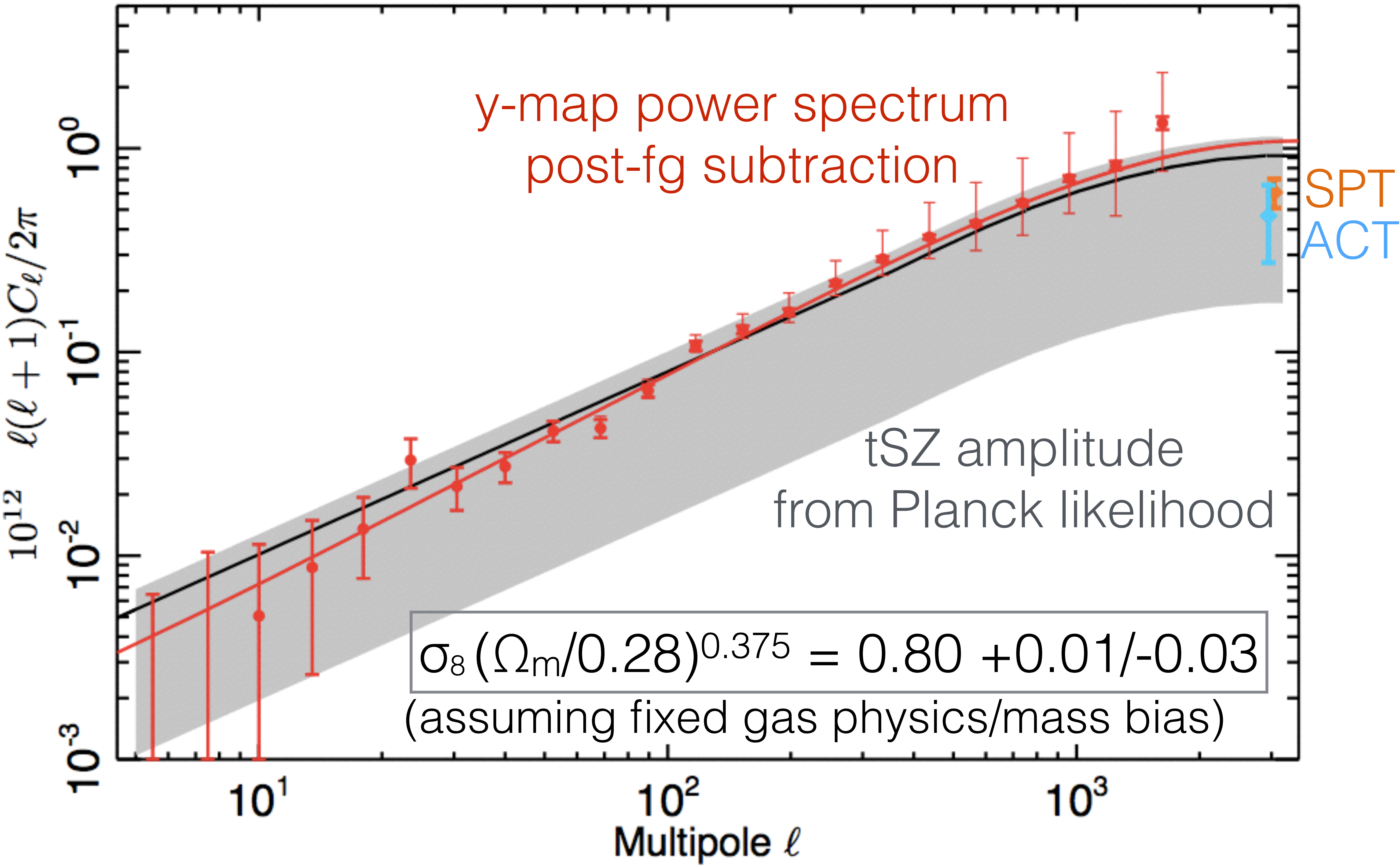

$\sigma_8 (\Omega_m/0.28)^{0.375} = 0.80\ +0.01/-0.03$

(assuming fixed gas physics/mass bias)

Planck XXII (2015)

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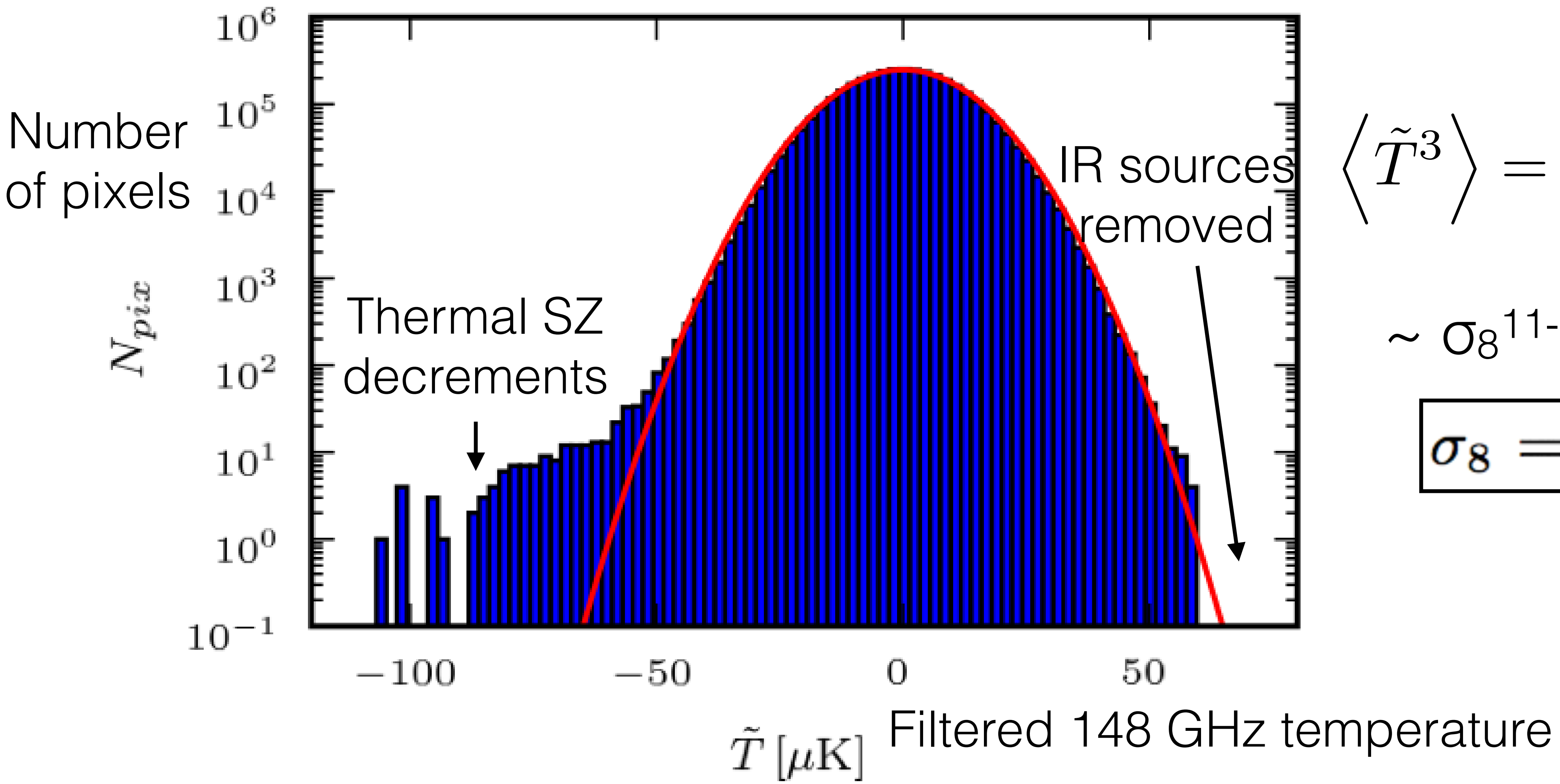
tSZ Skewness



$$\left\langle \tilde{T}^3 \right\rangle = -31 \pm 6\,\mu\mathrm{K}^3 \pm 14\,\mu\mathrm{K}^3$$

$\sim \sigma_8^{11\text{-}12}$

$$\sigma_8 = 0.79^{+0.03}_{-0.03}$$

Bonus: different tSZ statistics depend differently on cosmology (σ_8) and astrophysics (ICM pressure profile)

→ can break degeneracies (e.g., combine tSZ power spectrum amplitude with skewness)

Wilson, Sherwin, JCH+ (2012); JCH & Sherwin (2013); Crawford+ (2014)

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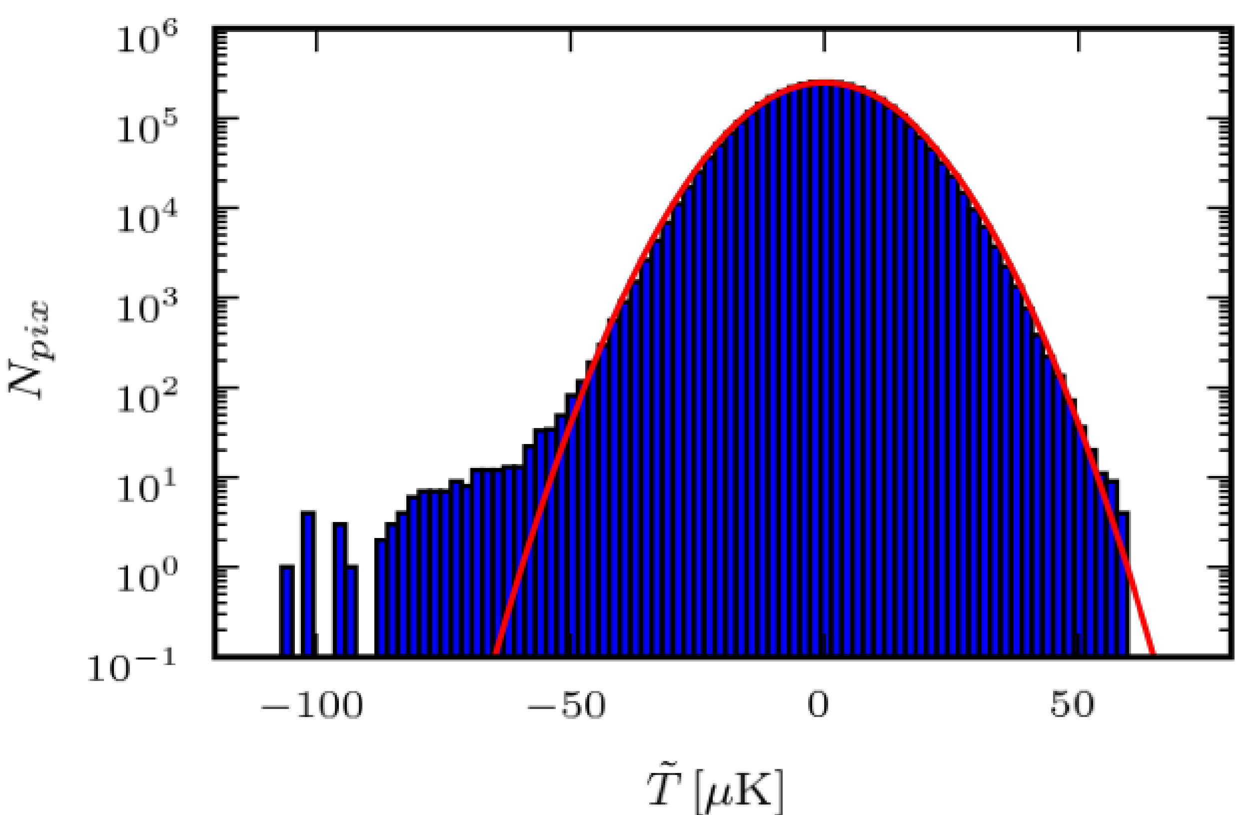
tSZ PDF

- Optimal extension of this idea: measure all the moments (the PDF)
- Probe of non-gaussian structure:
  - For a gaussian field, power spectrum already specifies the PDF

$$\sigma^2 = \sum_0^\infty \frac{2\ell+1}{4\pi} C_\ell$$

- Simple observable: histogram of pixel temperature values
- Use information from all clusters in map, including SNR<5
- Optimal cosmological tSZ statistic (very sensitive to σ_8)
- Route to breaking degeneracies between cluster gas physics and cosmological parameters



JCH+ (2014)

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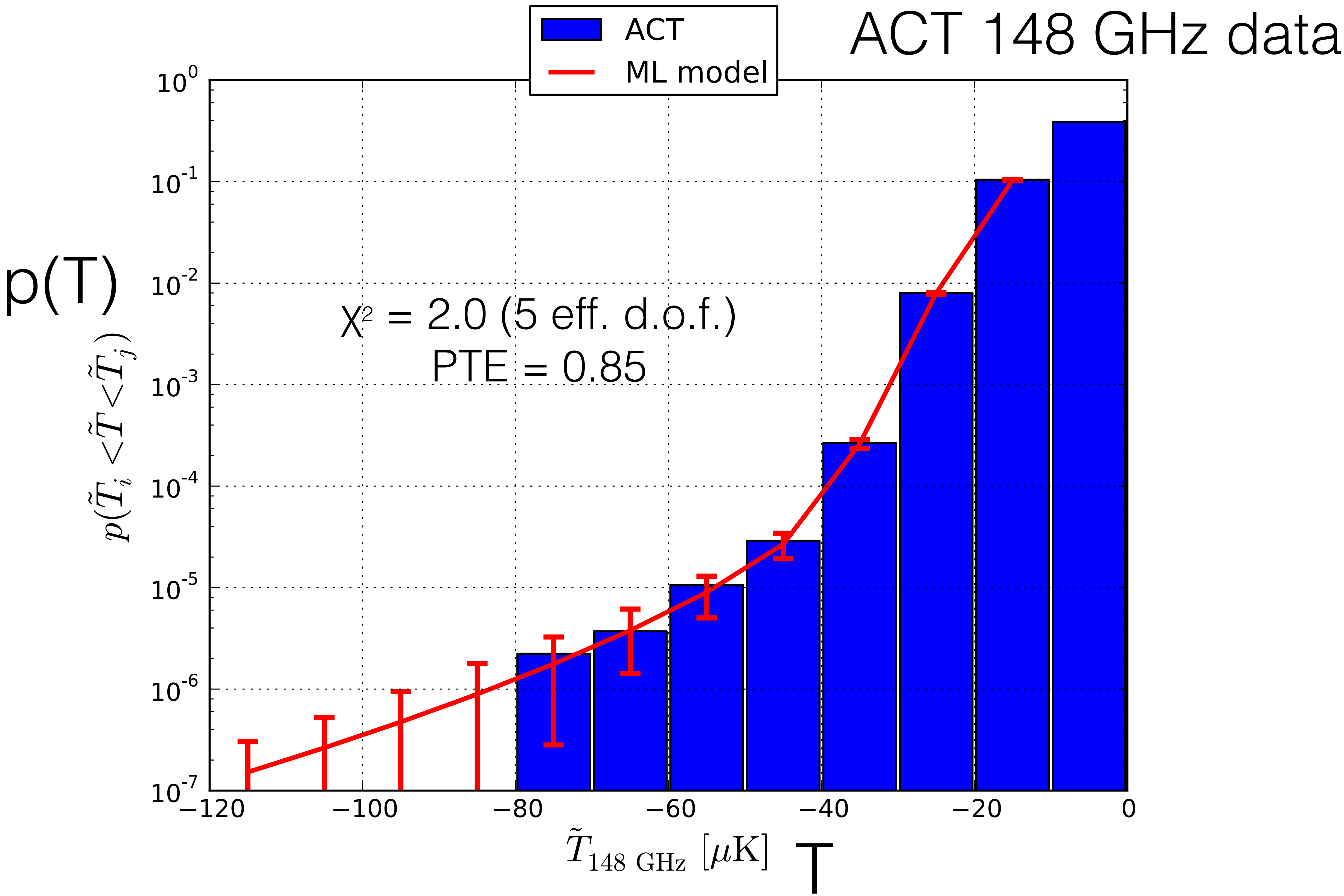
tSZ PDF



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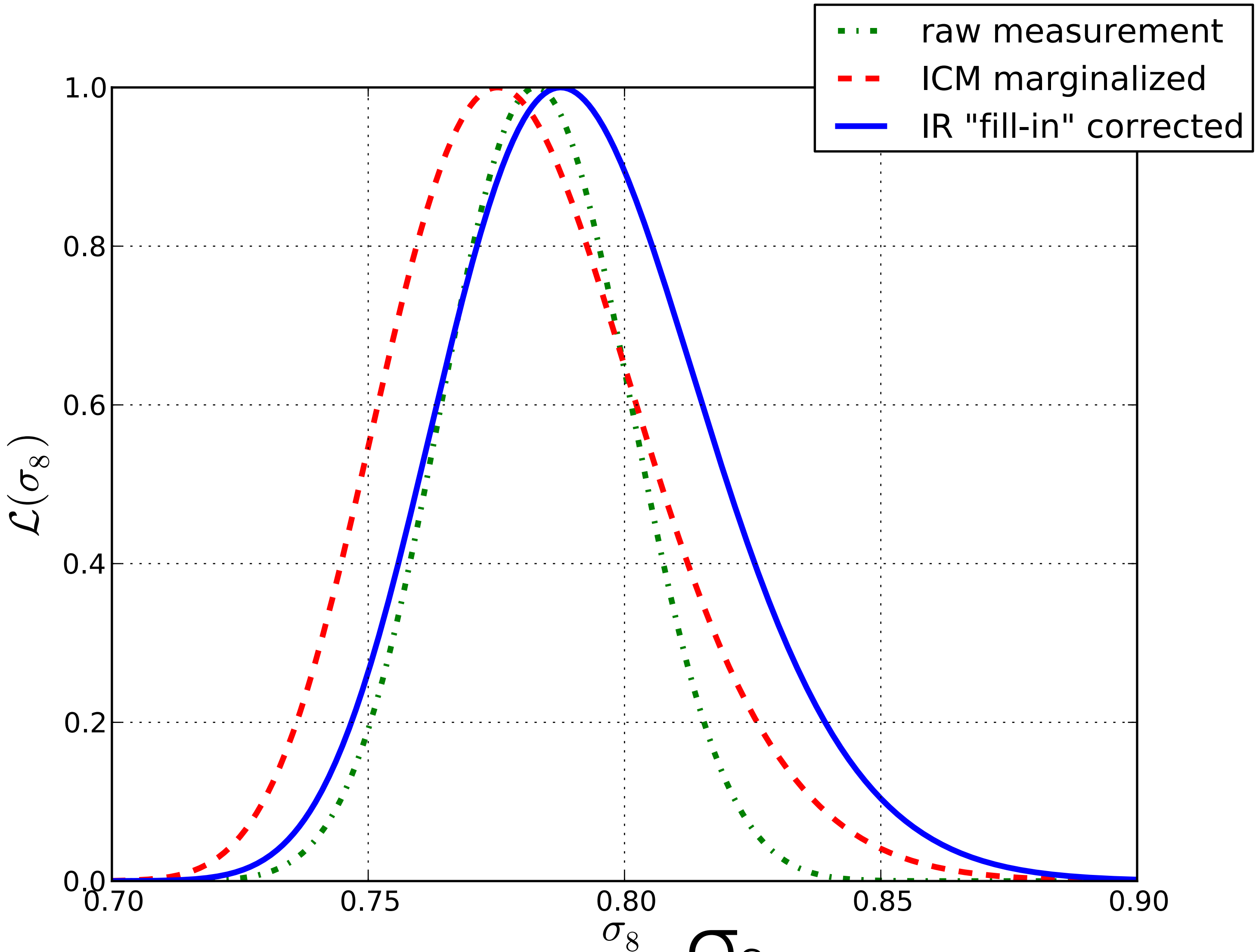
tSZ PDF

$$\sigma_8 = 0.793 \pm 0.018\,(\text{stat.}) \pm 0.017\,(\text{ICM syst.}) \pm 0.006\,(\text{IR syst.})$$

~2x smaller than stat. error from tSZ skewness alone (Wilson+12)

data unable to simultaneously constrain ICM (via P_0) and σ_8, but ACTPol/AdvACT will

likelihood



σ_8

JCH+ (2014)

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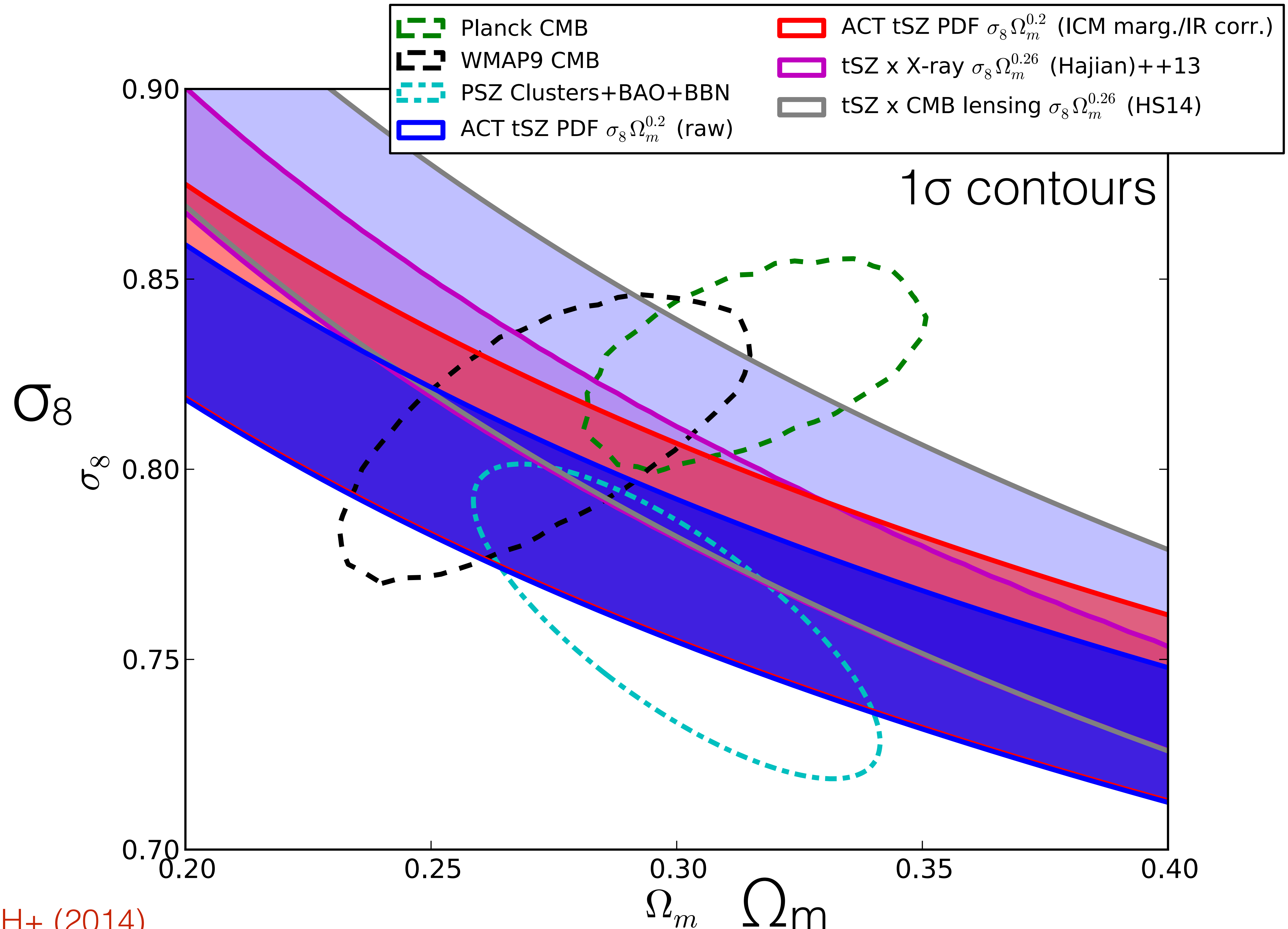
Constraints



JCH+ (2014)

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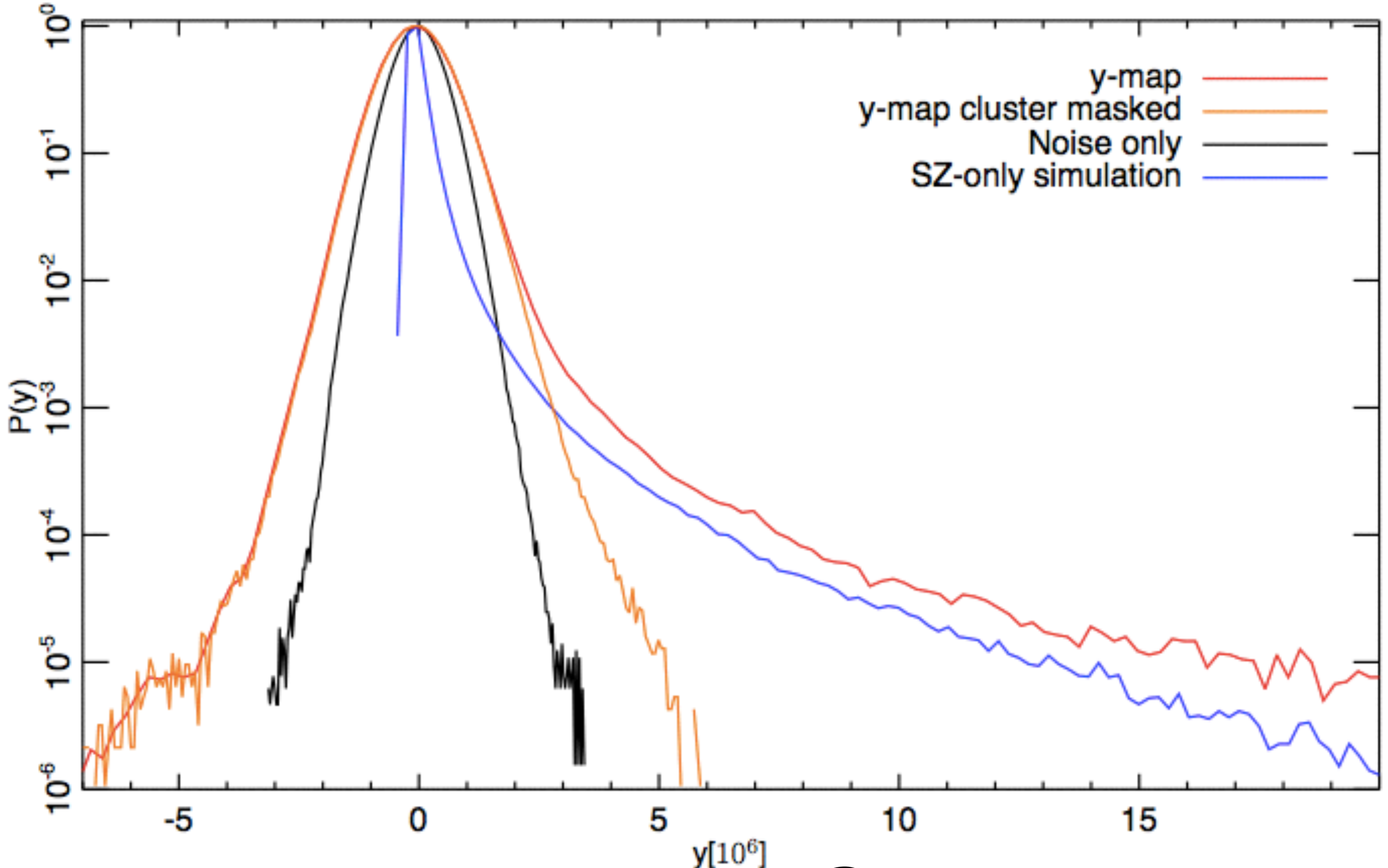
Planck y-map PDF

p(y)



Compton-y

$\sigma_8 = 0.77 \pm 0.02$ (68 % C.L.) (fixed gas physics model)

major challenge: modeling foreground propagation into y-map

Planck+ XXII (2015)

tSZ Stacking:
the Y-M Relation

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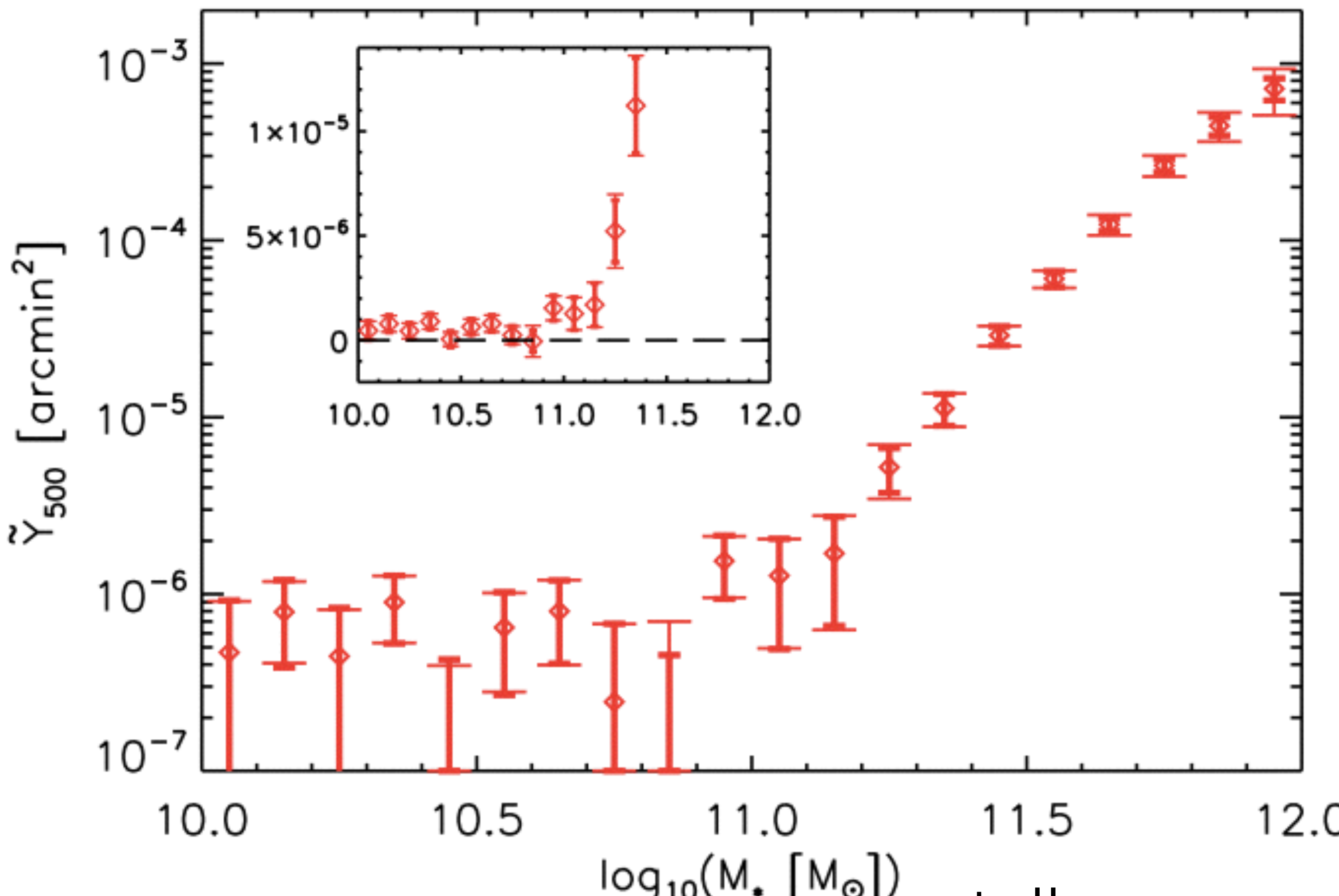
tSZ Stacking

Planck x SDSS Locally Brightest Galaxies

tSZ signal



stellar mass

well-fit by power-law Y-M relation: self-similar?

(caveat: $M_* \rightarrow M_{500}$)

Planck+ XI (2013)

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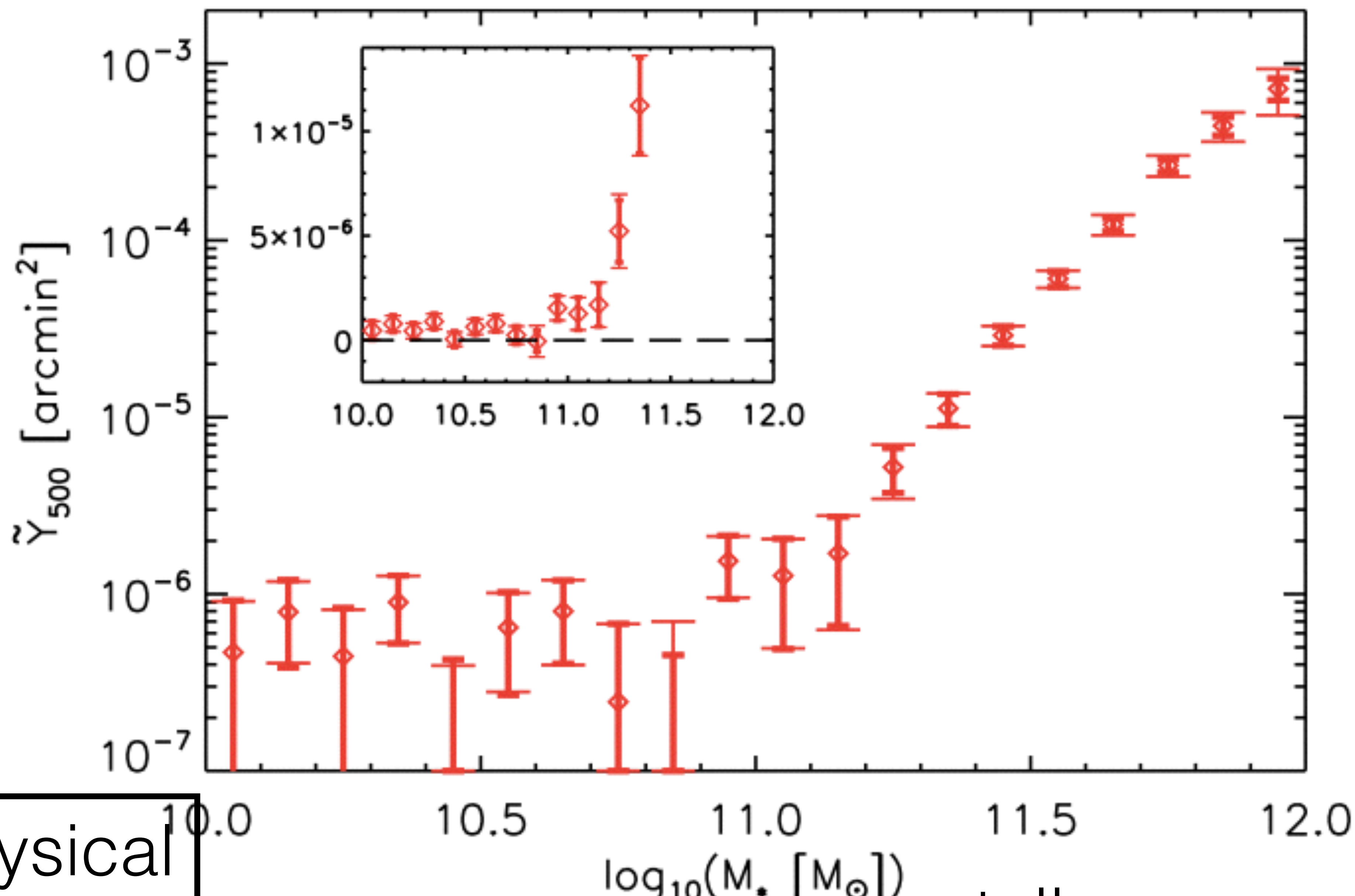
tSZ Stacking

Planck x SDSS Locally Brightest Galaxies

tSZ signal



stellar mass

not a physical observable!

Planck+ (2013), LeBrun, McCarthy, Melin (2015)

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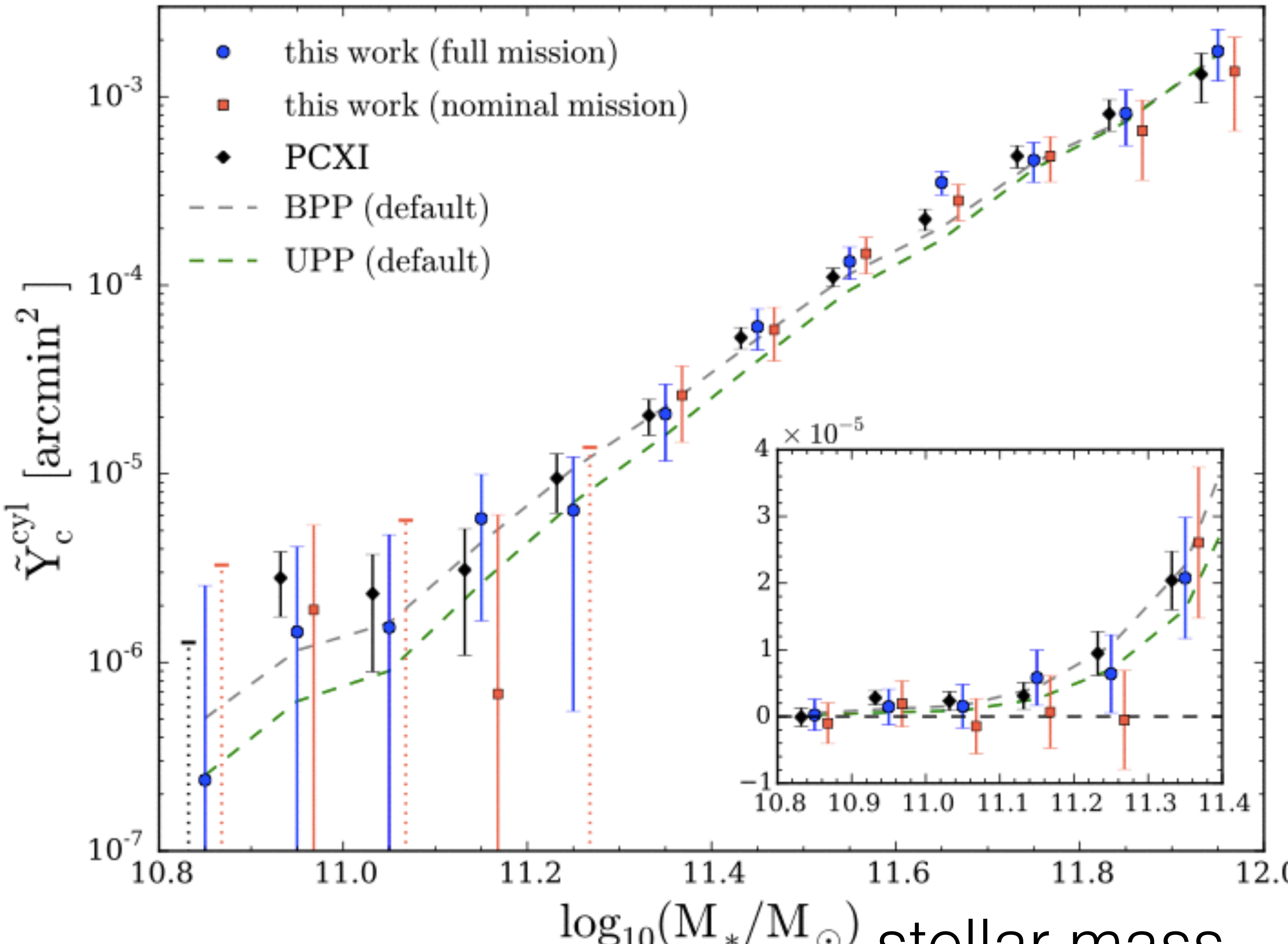
tSZ Stacking

Planck x SDSS Locally Brightest Galaxies Reconsidered

tSZ signal



stellar mass

self-similar Y-M consistent with data

Greco, JCH+ (2015)

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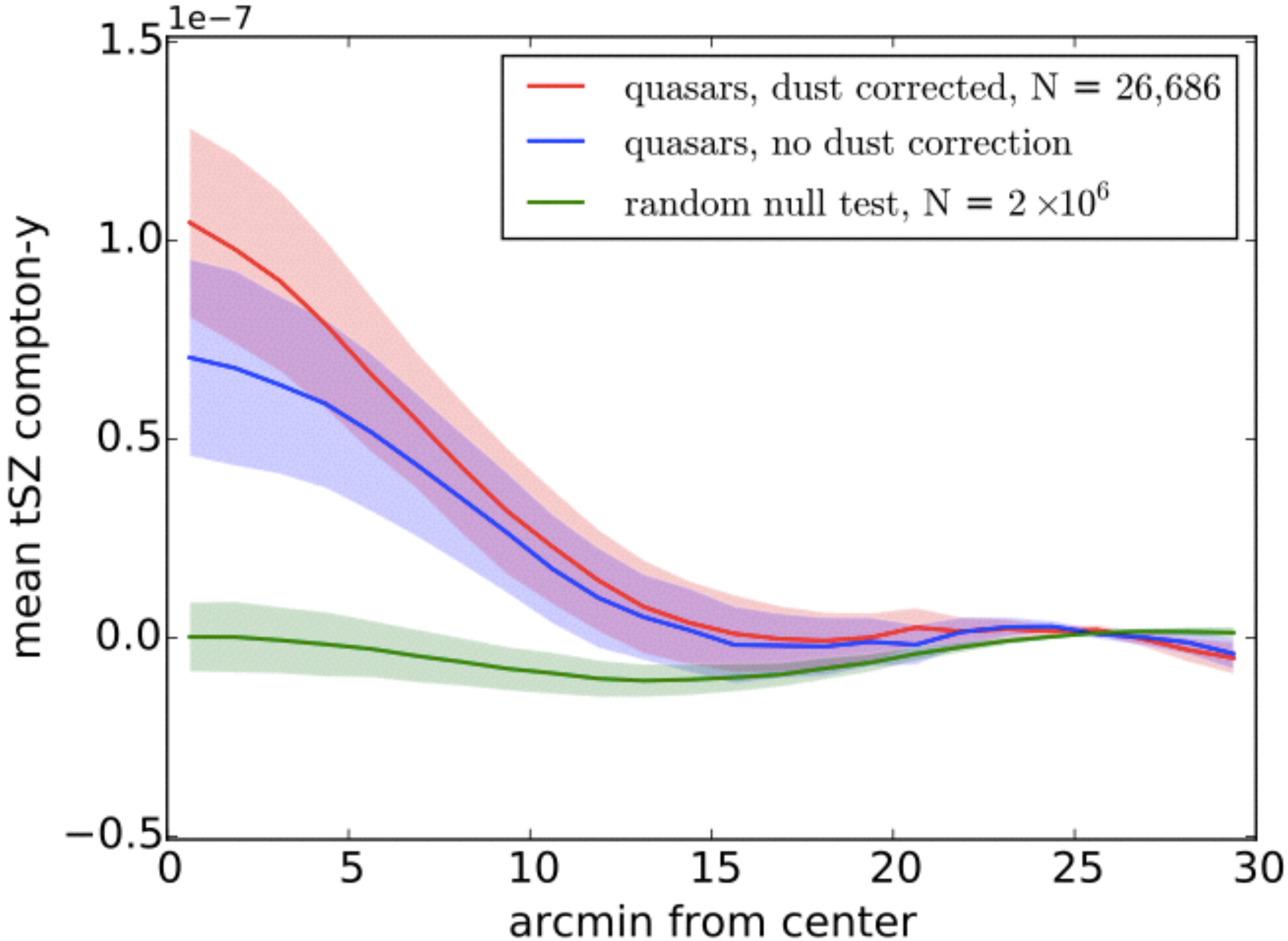
tSZ Stacking

Quasars: Feedback Signal?



Ruan+ (2015) + y-map of JCH & Spergel (2014)

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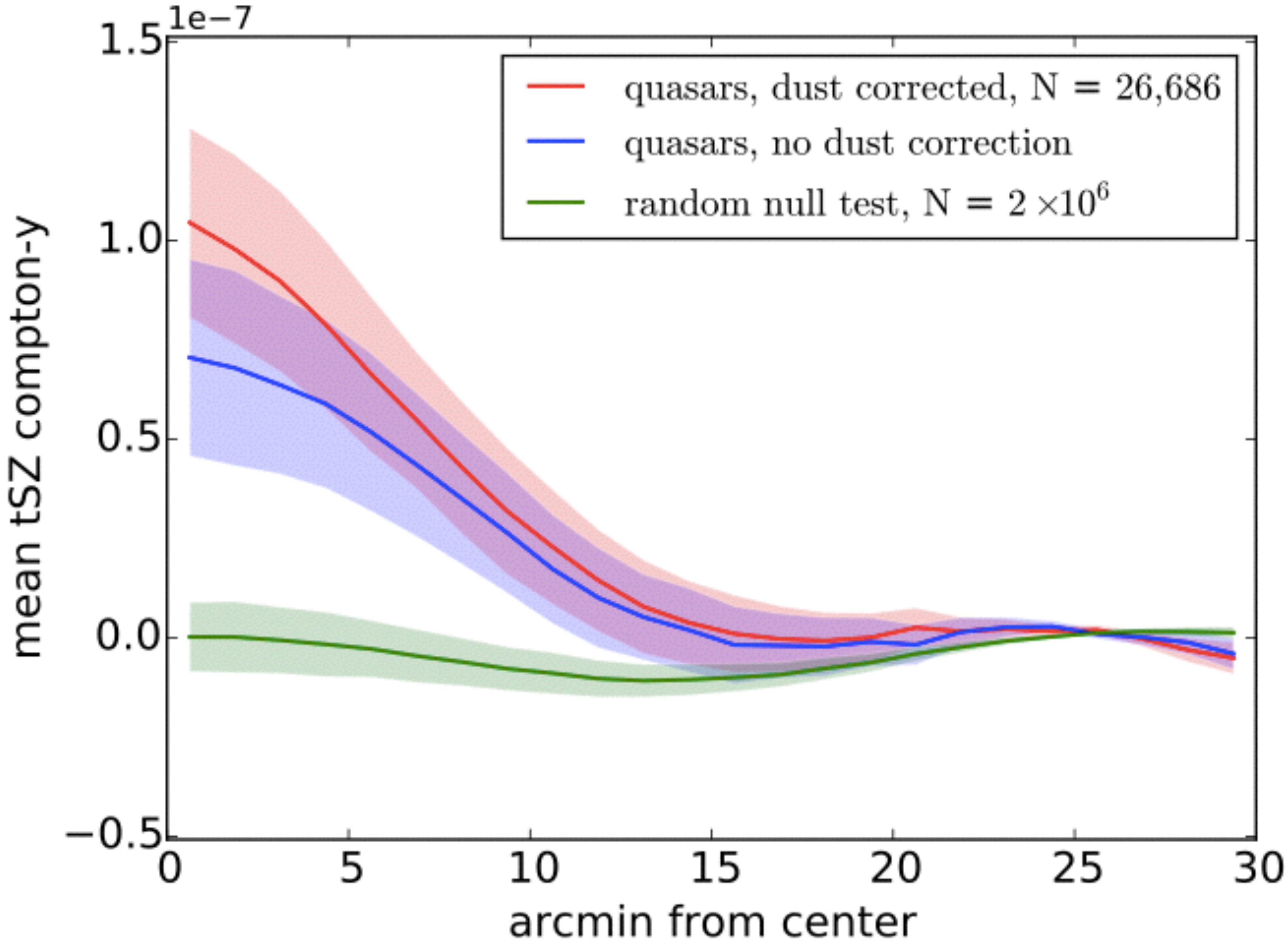
tSZ Stacking

Quasars: Feedback Signal?



A major issue: contamination from the two-halo term?

Ruan+ (2015) + y-map of JCH & Spergel (2014)

The tSZ Monopole

see also Joe Silk's talk

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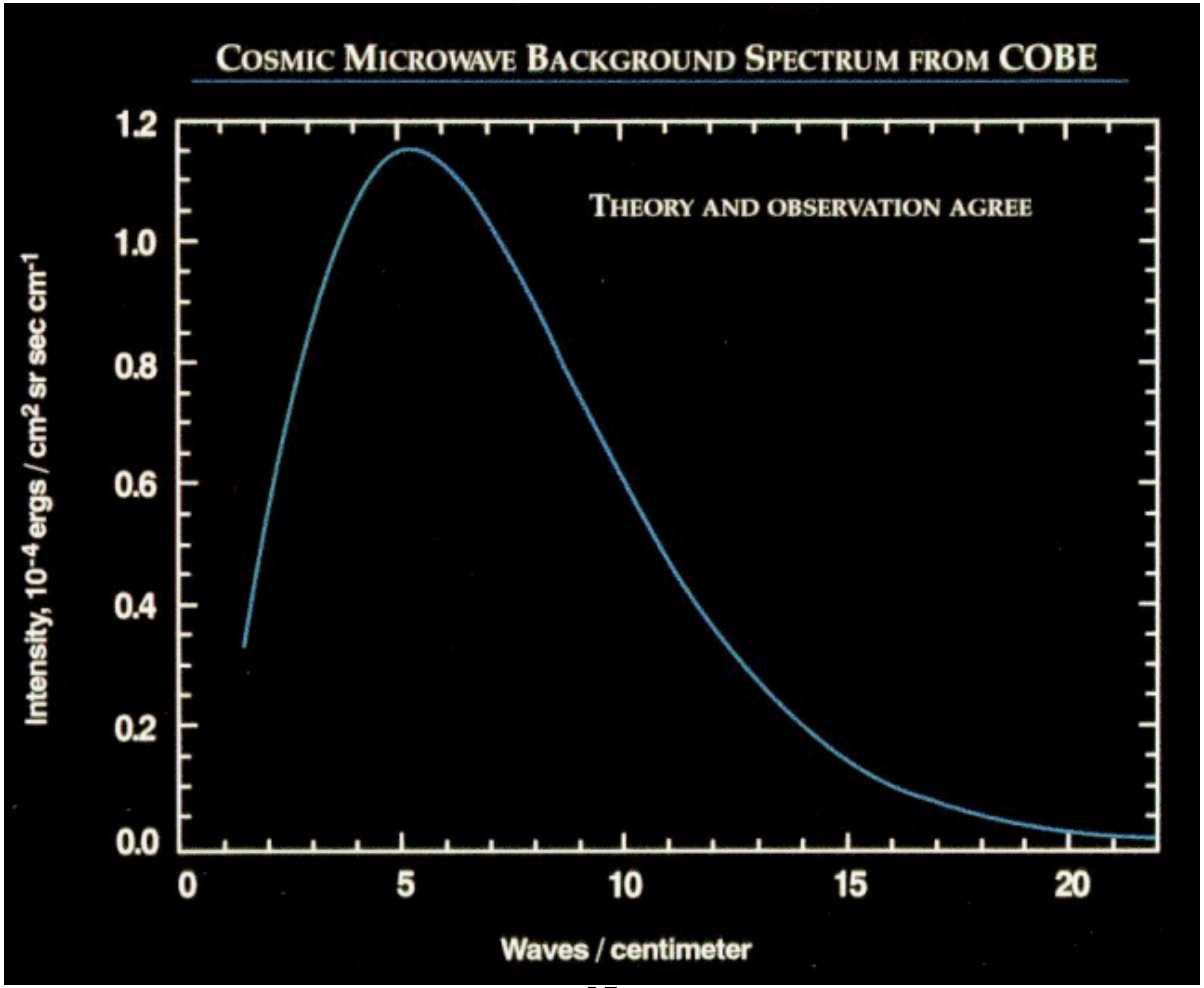
COBE-FIRAS

CMB spectrum is blackbody to 50 ppm precision

$|\langle y \rangle| < 1.5 \times 10^{-5}$ at 95% CL

specific intensity



wavenumber

Fixsen+ (1996); Fixsen (2009)

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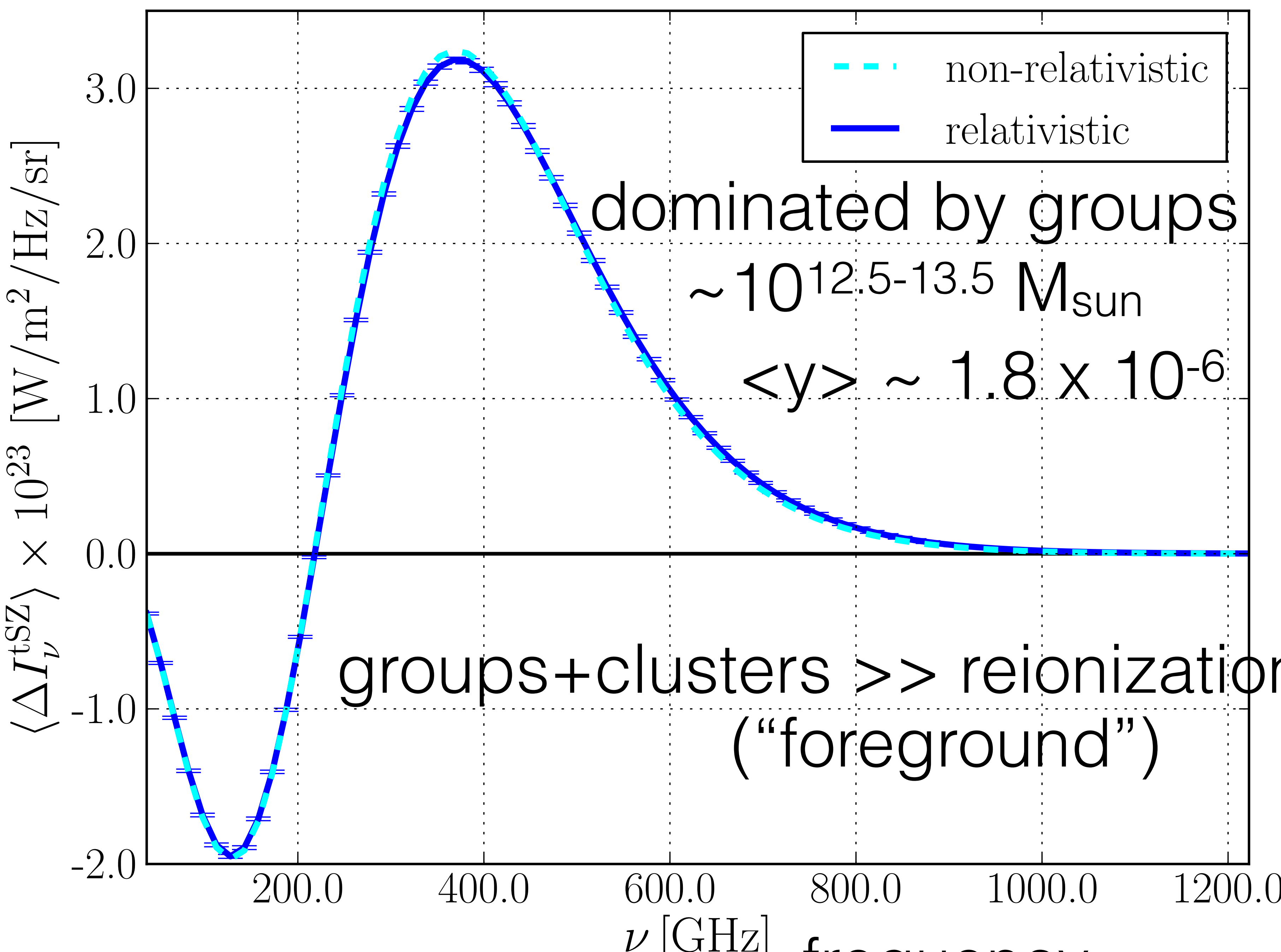
<y> and *PIXIE*

>1000σ detection of mean tSZ signal of the universe

specific intensity



dominated by groups $\sim 10^{12.5\text{-}13.5}$ M_{sun}

<y> ~ 1.8 x 10^{-6}

groups+clusters >> reionization/primordial
("foreground")

frequency

JCH+ (2015)

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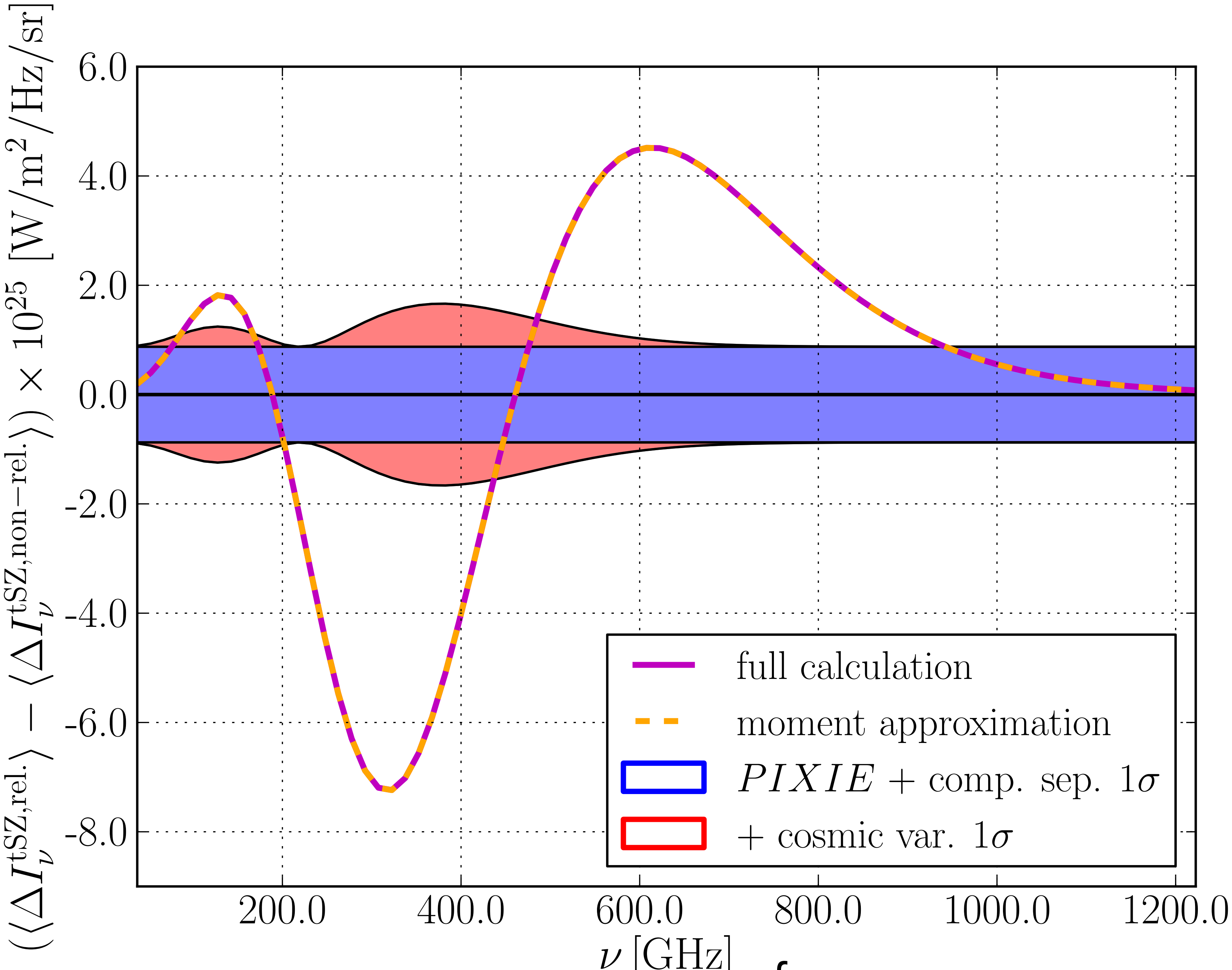
<y> and *PIXIE*

30σ detection of relativistic effects in mean tSZ signal

specific intensity



frequency

JCH+ (2015)

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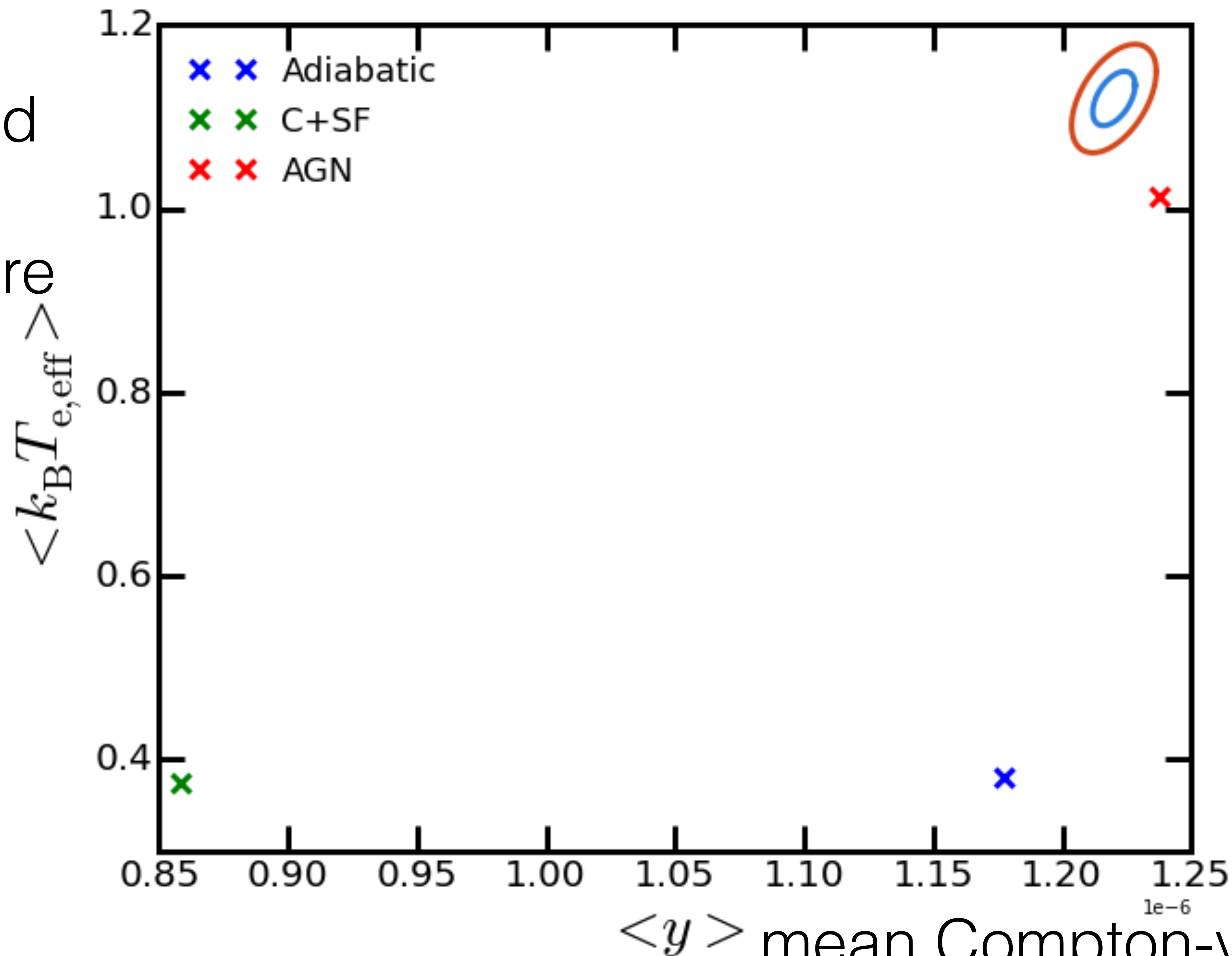
<y> and *PIXIE*

sub-percent constraints on gastrophysical models

mean τ-weighted electron temperature



mean Compton-y

Battaglia, JCH+ (in prep.)

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Outlook

- tSZ x CMB lensing and tSZ x CFHTLenS measurements are fit by a consistent gastrophysical model; both prefer σ_8 values somewhat lower than Planck CMB.

- Current measurements probe gas pressure profile over wide ranges in mass/redshift, but not “missing baryons”.

- tSZ statistics beyond the power spectrum (e.g., PDF) show great promise for cosmological constraints.

- Self-similarity (or not) of Y-M remains an open question.

- *PIXIE* measurement of tSZ monopole will yield sub-percent constraints on gastrophysics.

Extra Slides

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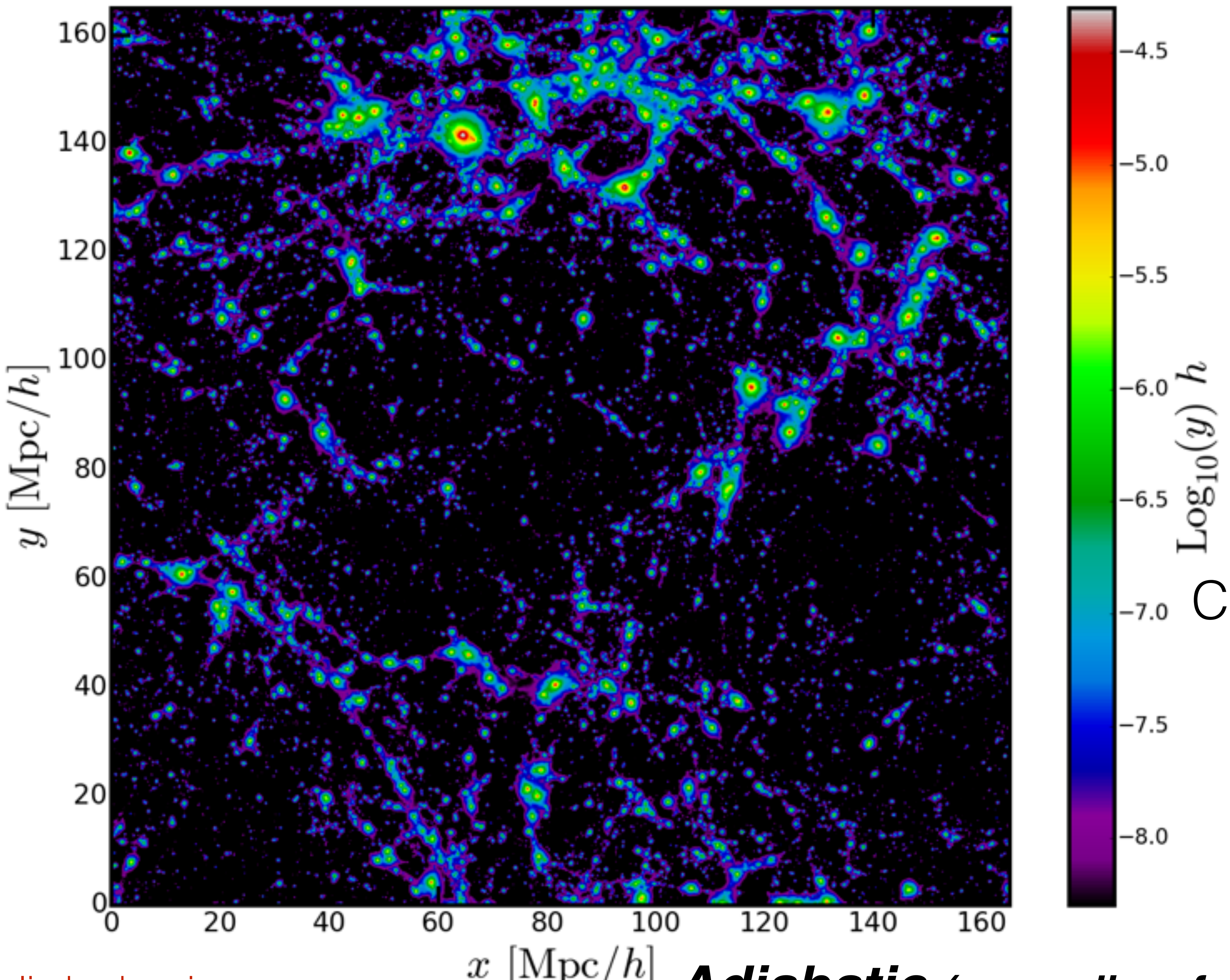
Probing Large-Scale Structure

dependence on intracluster medium “gastrophysics”



Compton-y

from N. Battaglia hydro sim.

***Adiabatic** (no cooling, feedback, …)*

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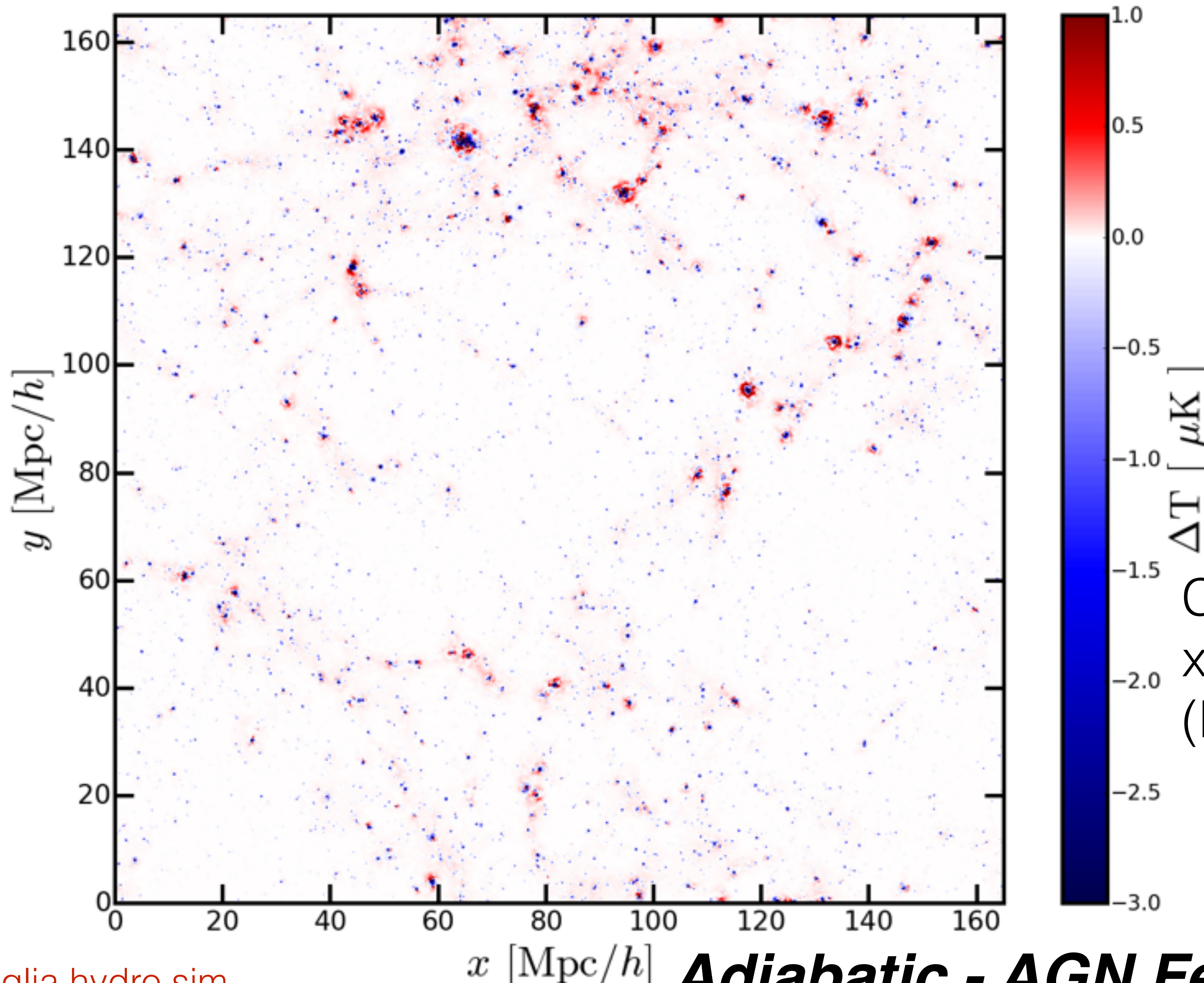
Probing Large-Scale Structure

dependence on intracluster medium "gastrophysics"



Compton-y x T_{CMB} x -2 (R-J limit)

from N. Battaglia hydro sim.

Adiabatic - AGN Feedback

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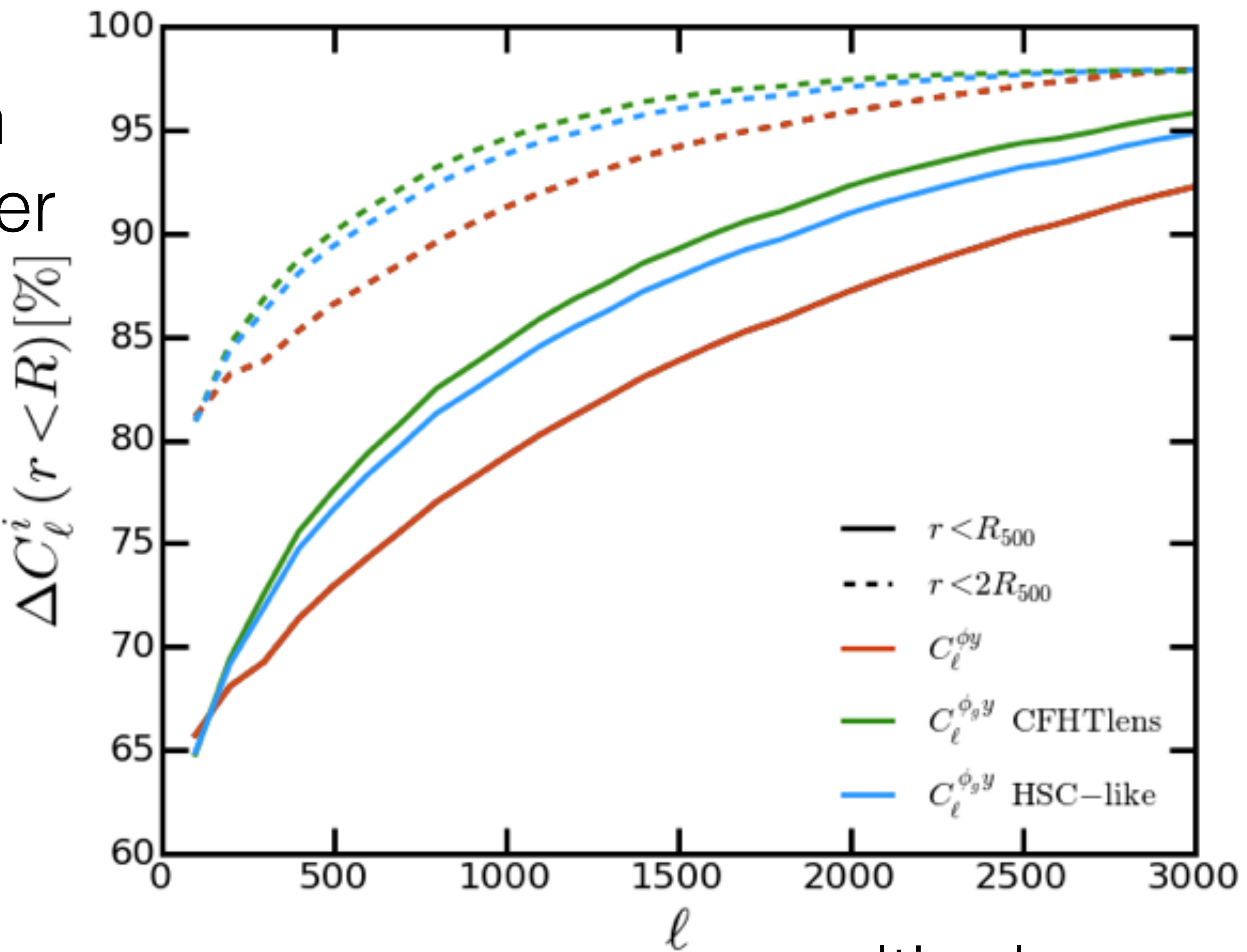
tSZ x Lensing: Takeaway

- It is extremely difficult to probe “missing baryons” with tSZ measurements, including tSZ x lensing.

fractional contribution to cross-power



multipole

Battaglia, JCH, & Murray (2014)

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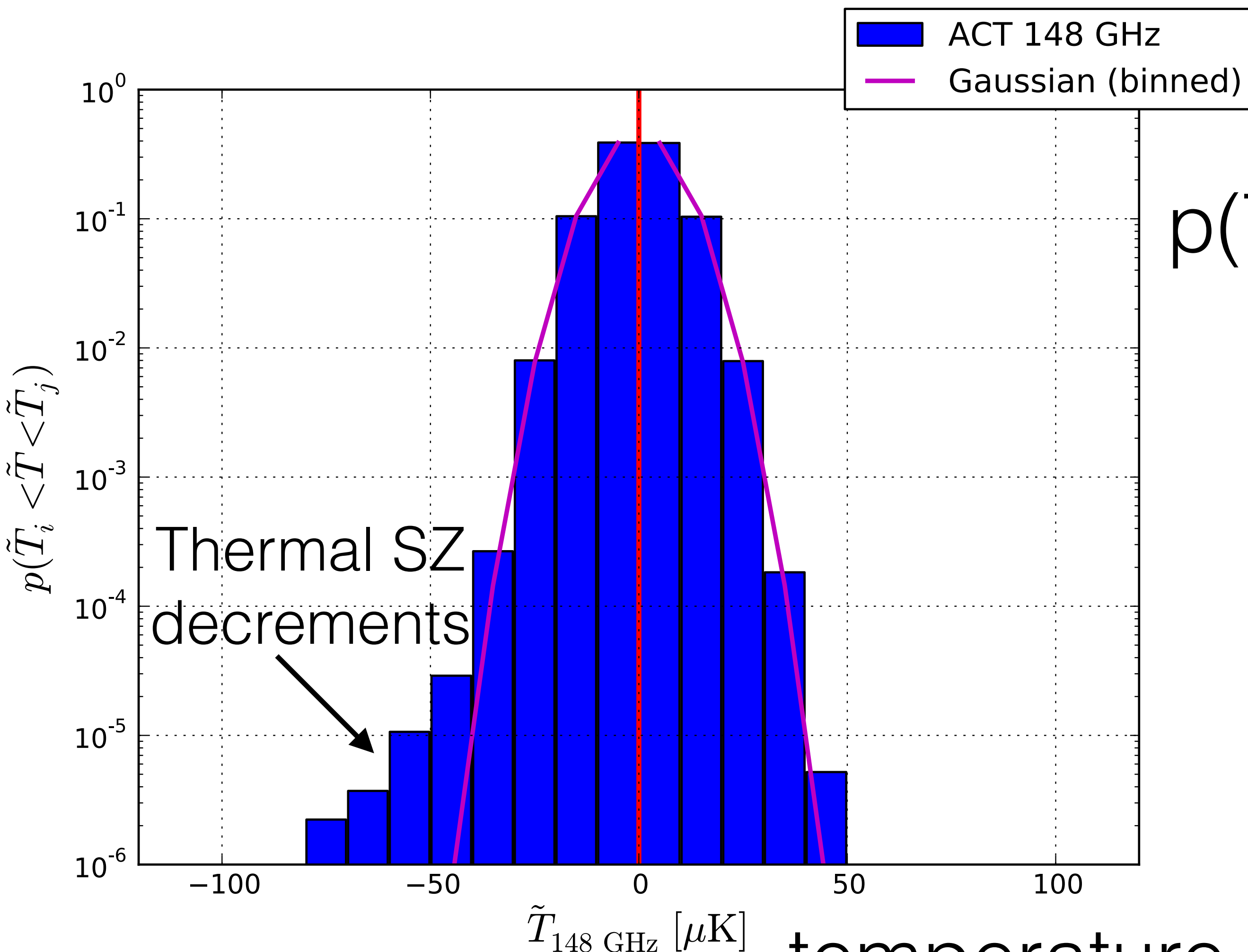
Data

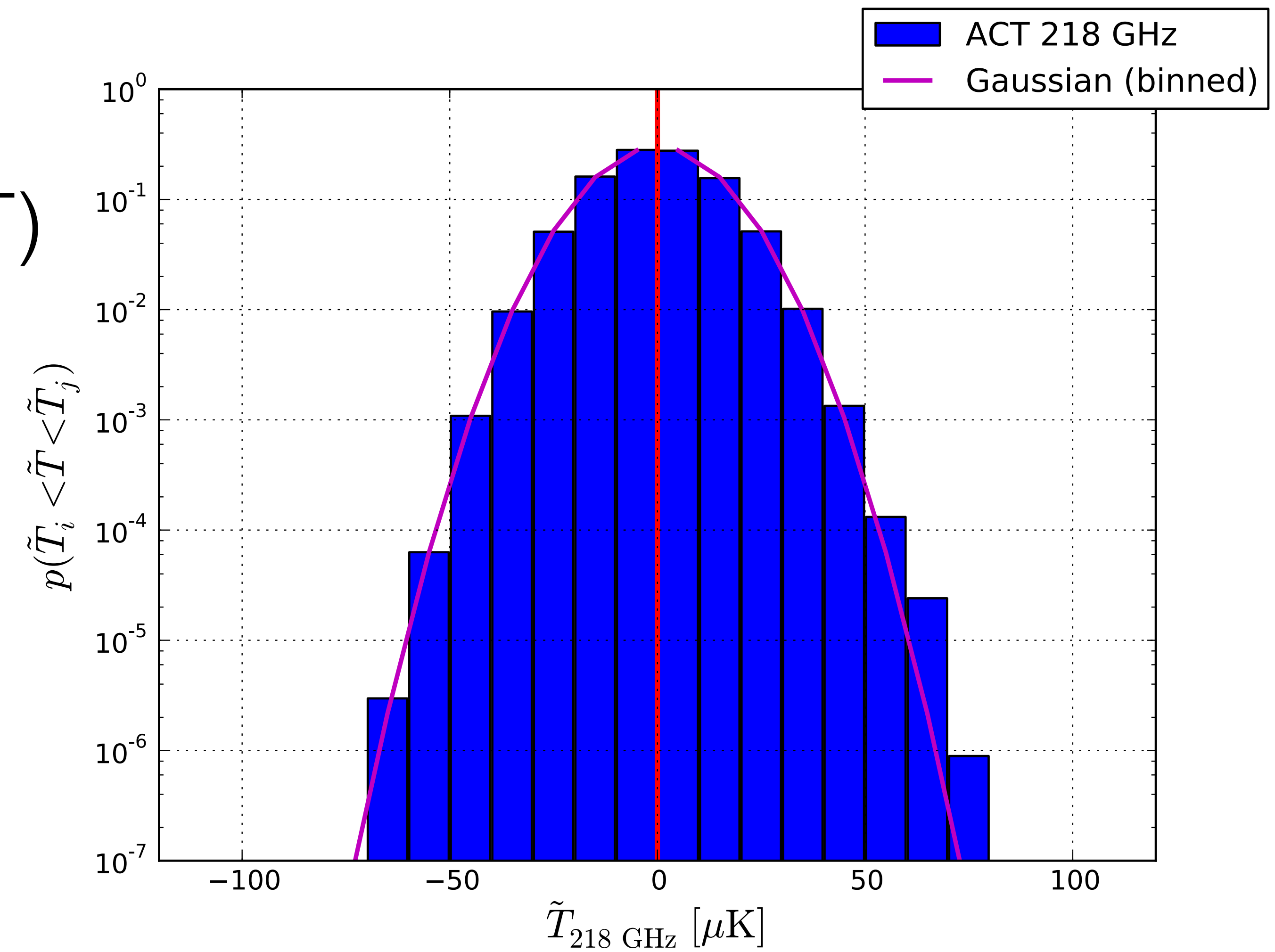
148 GHz



p(T)

temperature

218 GHz



- Wiener-filter ACT Equatorial 148 GHz map — clear non-gaussian tail
- No similar feature seen in identically-processed 218 GHz map

JCH+ (2014)

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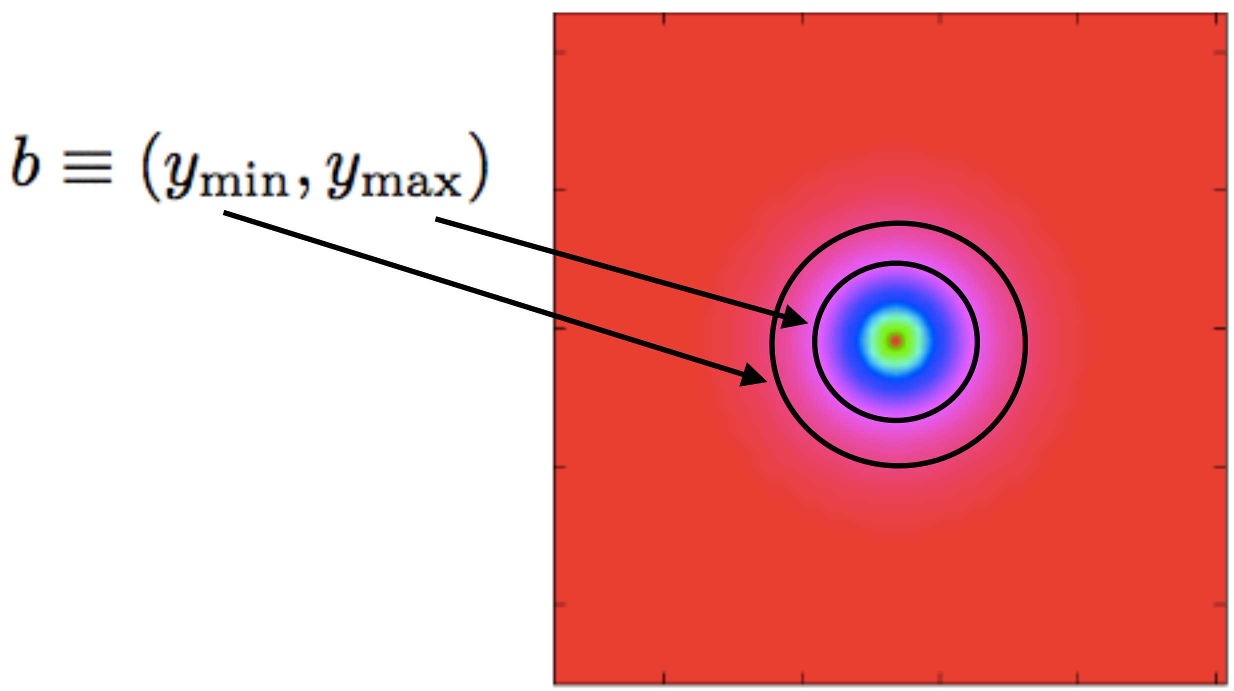
Model

- Thermal SZ PDF: how much sky area is subtended by tSZ (Compton-*y*) values in a given range?
- Simple for a spherical cluster: area between two circles



- Then add up such areas for all clusters:

$$\langle P_b \rangle_{\text{noiseless}} = \int dz \frac{d^2V}{dz d\Omega} \int dM \frac{dn}{dM} \pi \left(\theta^2(y_{min}, M, z) - \theta^2(y_{max}, M, z) \right)$$

volume element   mass function   area of annulus

JCH+ (2014)

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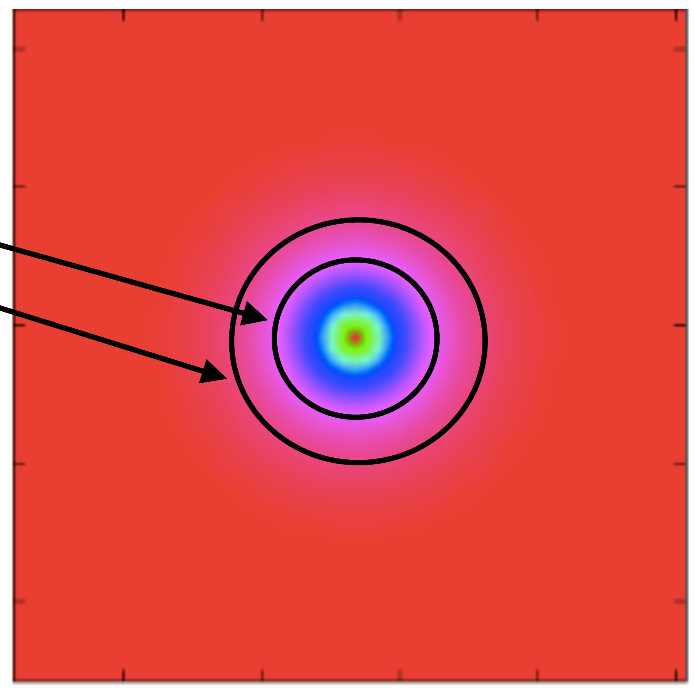
Model

- Thermal SZ PDF: how much sky area is subtended by tSZ (Compton-*y*) values in a given range?
- Simple for a spherical cluster: area between two circles

$$b \equiv (y_{\rm min}, y_{\rm max})$$



Complications:
- non-tSZ contributions in CMB map
- inhomogeneous/correlated noise
~~- cluster overlaps along line-of-sight~~

- Then add up such areas for all clusters:

$$\langle P_b \rangle_{\rm noiseless} = \int dz \frac{d^2V}{dz d\Omega} \int dM \frac{dn}{dM} \pi \left(\theta^2(y_{min}, M, z) - \theta^2(y_{max}, M, z)\right)$$

volume element — mass function — area of annulus

JCH+ (2014)

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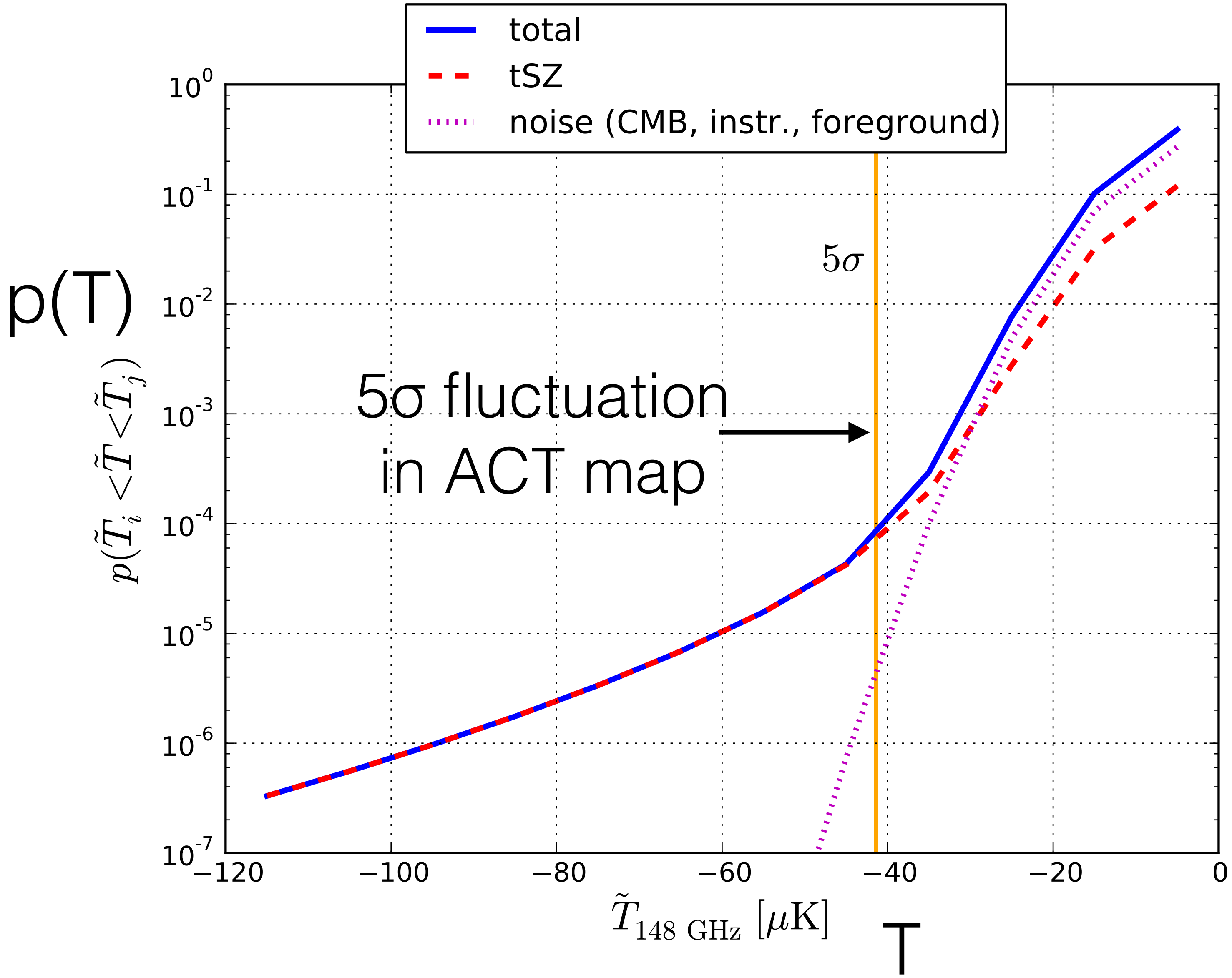
Model + Noise

- Observable tSZ PDF:
  - Convolve with noise PDF (measured from splits of data)
  - Convolve with other components (CMB, foregrounds)
  - Account for contributions from zero-tSZ pixels (pure noise)

- Fiducial model: WMAP9 cosmology + Tinker mass function + Battaglia pressure profile

- Noise PDF, Wiener filter, and beam specified to match ACT Equ 148 GHz data analysis



JCH+ (2014)

Parameter Sensitivity

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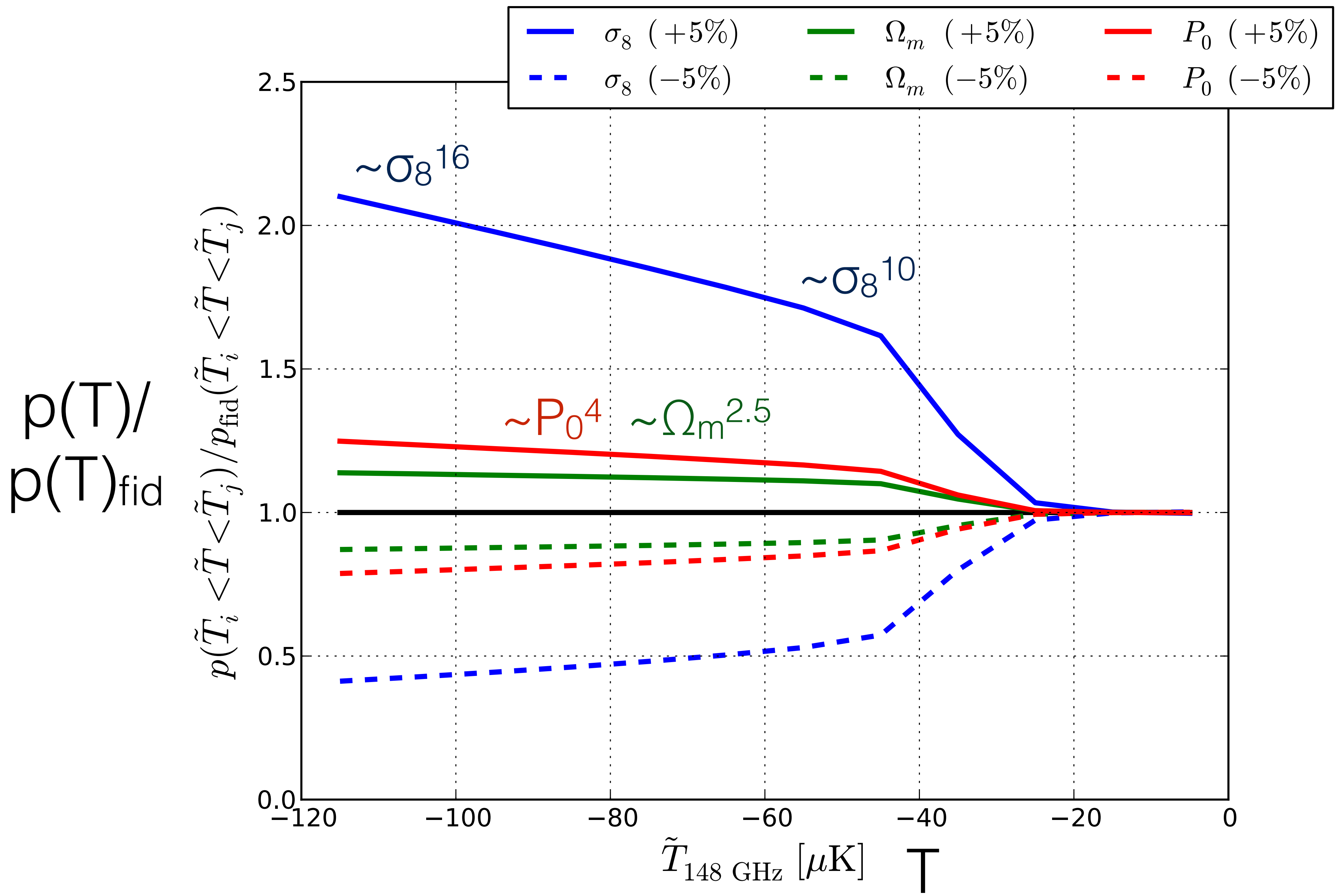

P_0 = overall normalized amplitude of $P_e(M,z)$ relation

JCH+ (2014)

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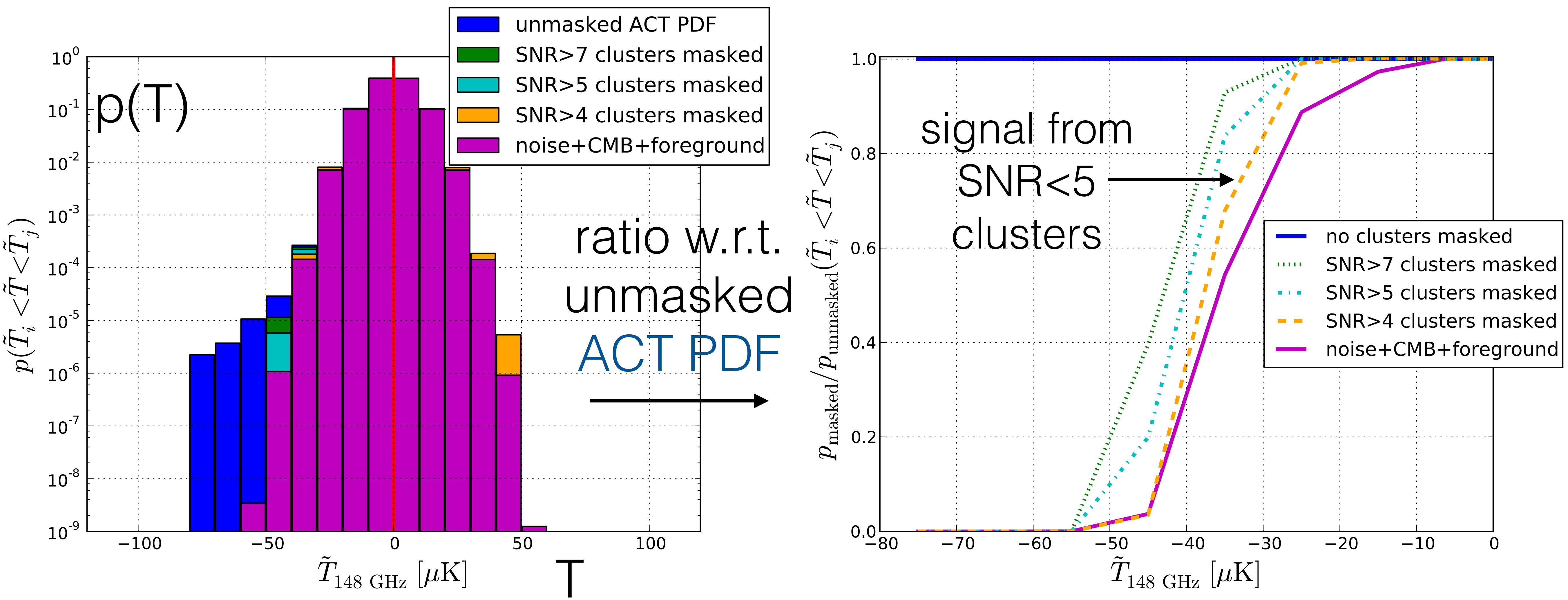
Contributions

How does the 148 GHz negative tail change as we mask individually detected clusters as a function of their SNR?



JCH+ (2014)

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Analysis

- Focus on σ_8 (most sensitive parameter)
- Fit only T<0 148 GHz PDF (avoids nearly all non-tSZ signals)
- Marginalize over non-tSZ foreground contribution
- Marginalize over parameterized ICM gas physics via P_0
- Correct for IR sources "filling in" tSZ decrements at 148 GHz
- Monte Carlo to compute covariance matrix (highly correlated) and validate pipeline

JCH+ (2014)