New Constraints on the Amplitude of Cosmic Density Fluctuations and Intracluster Gas from the Thermal SZ Signal Measured by Planck and ACT

Colin Hill

Princeton Astrophysics

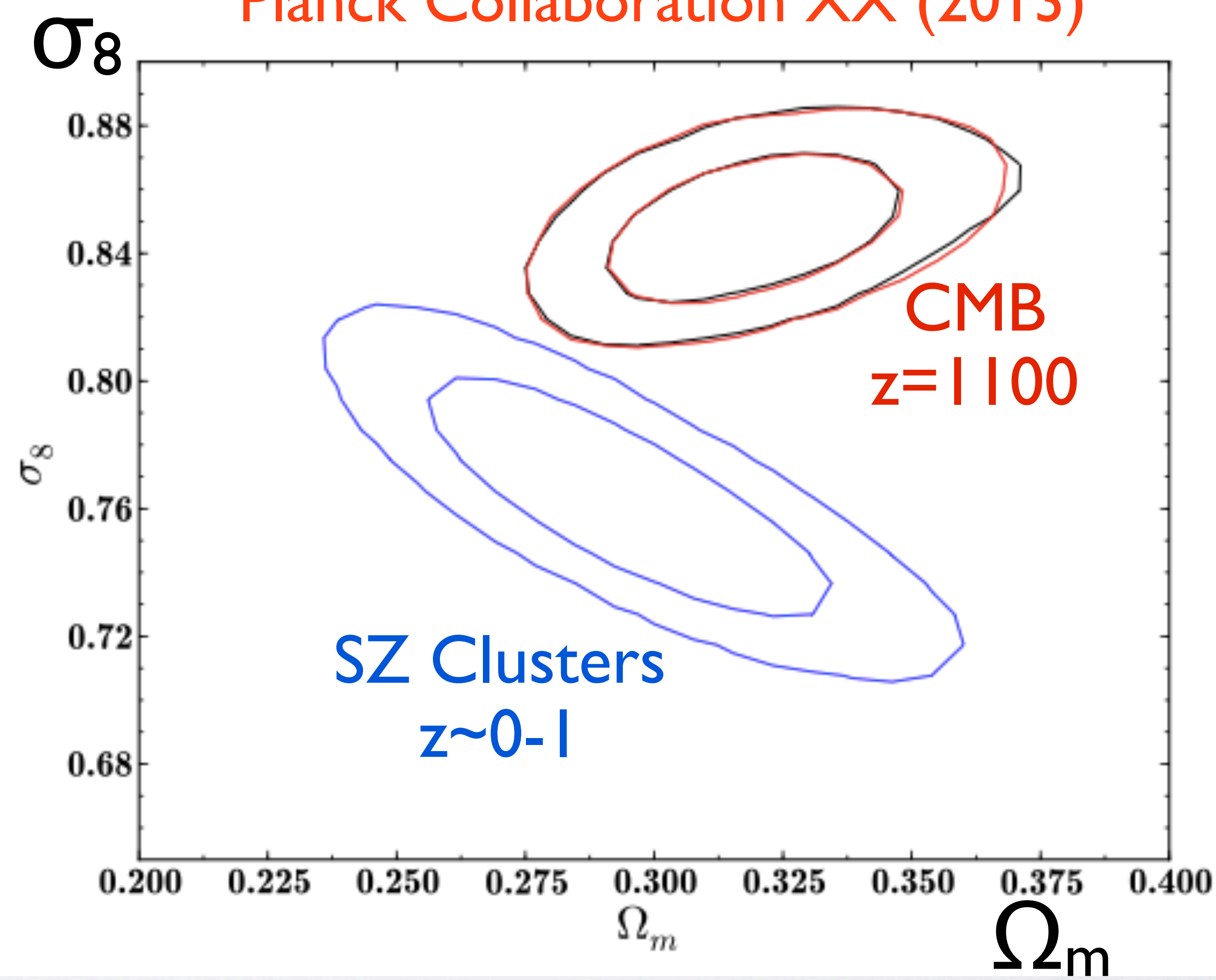
19 November 2013

1203.6633
1205.5794
1303.4726
1311.soon

Work with:
David Spergel, Enrico Pajer, Blake Sherwin, Kendrick Smith, ACT

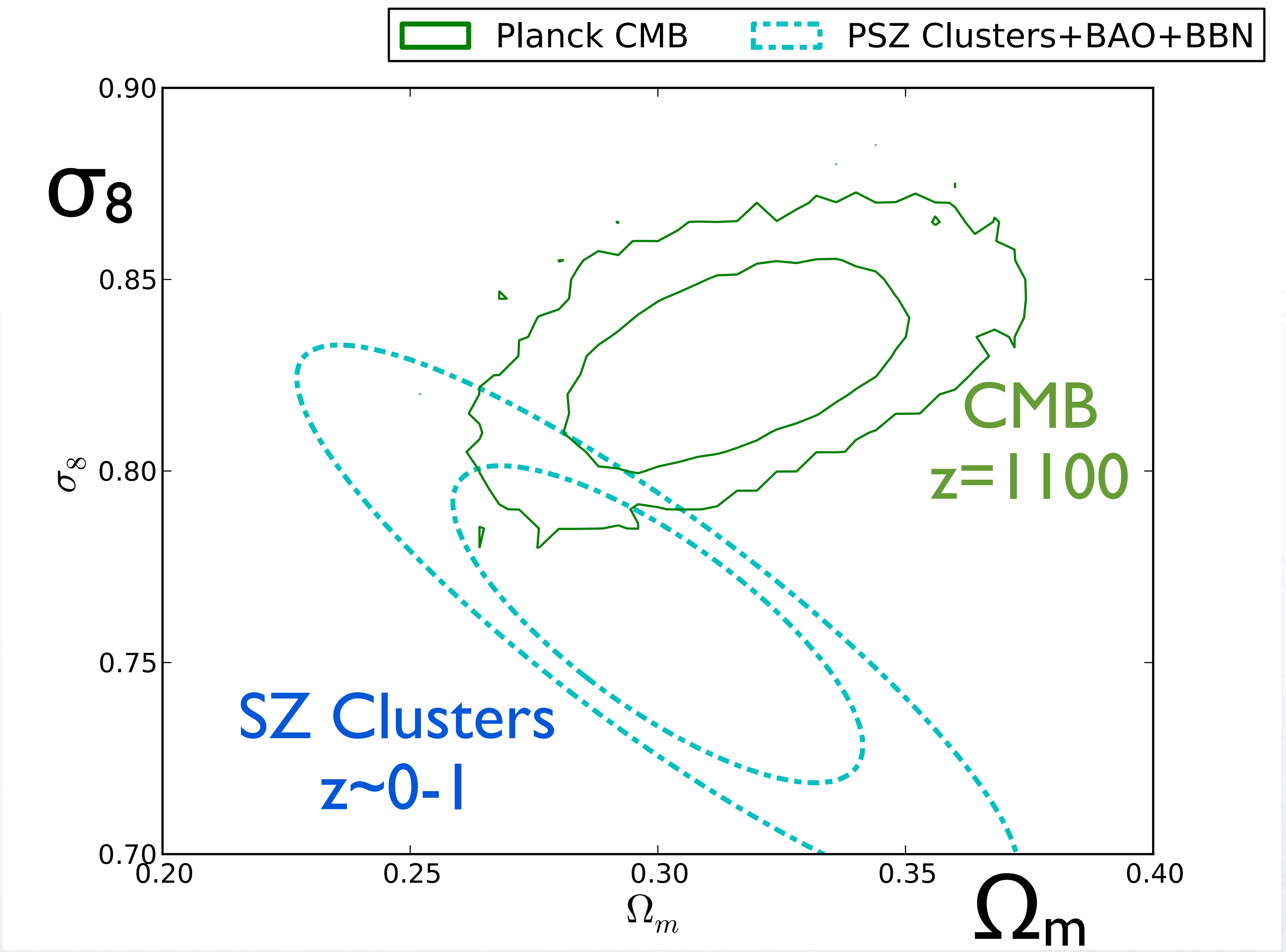
Outline

Planck Collaboration XX (2013)

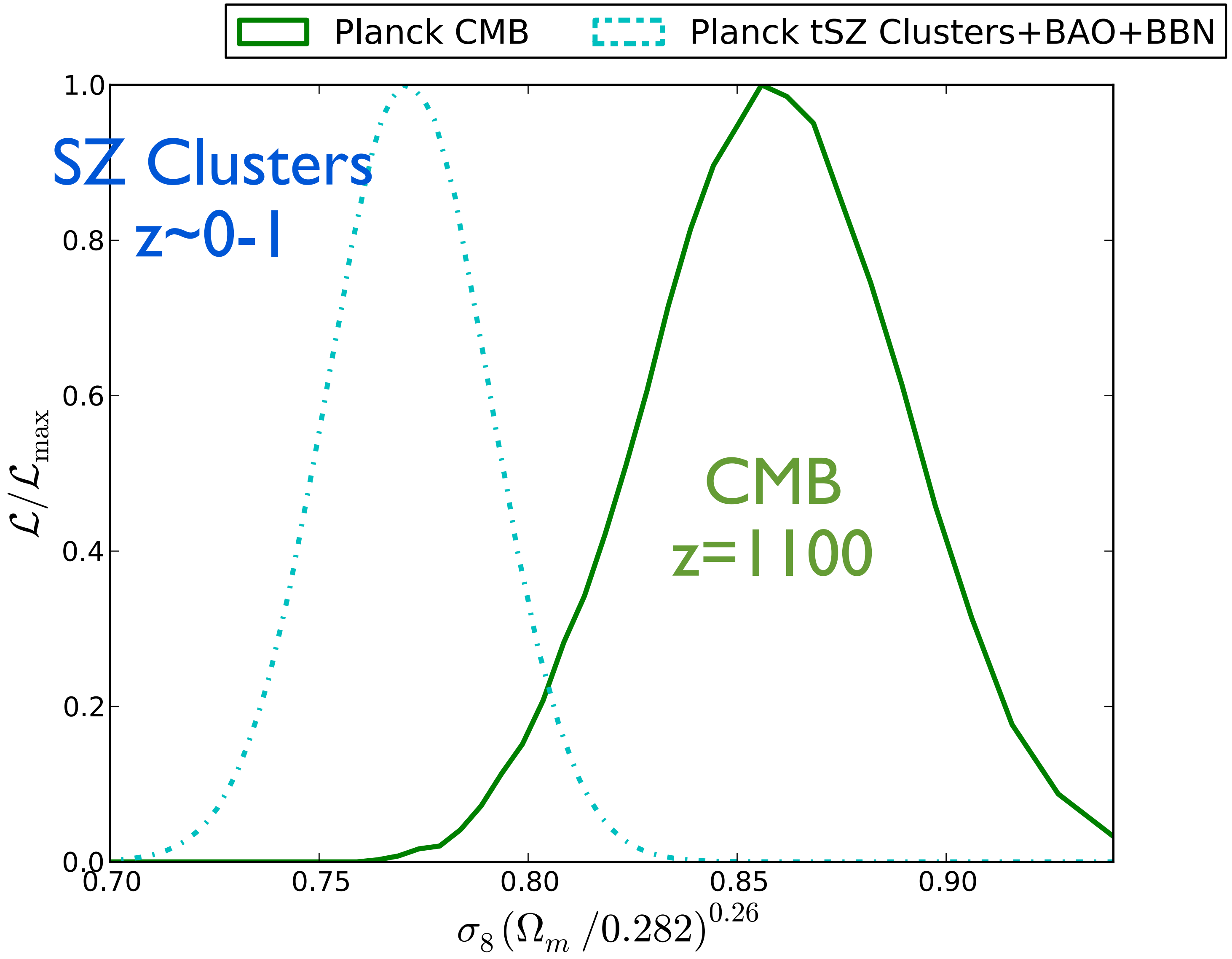


Outline

actually



Outline



$\sigma_8\,\Omega_m^{0.26}$

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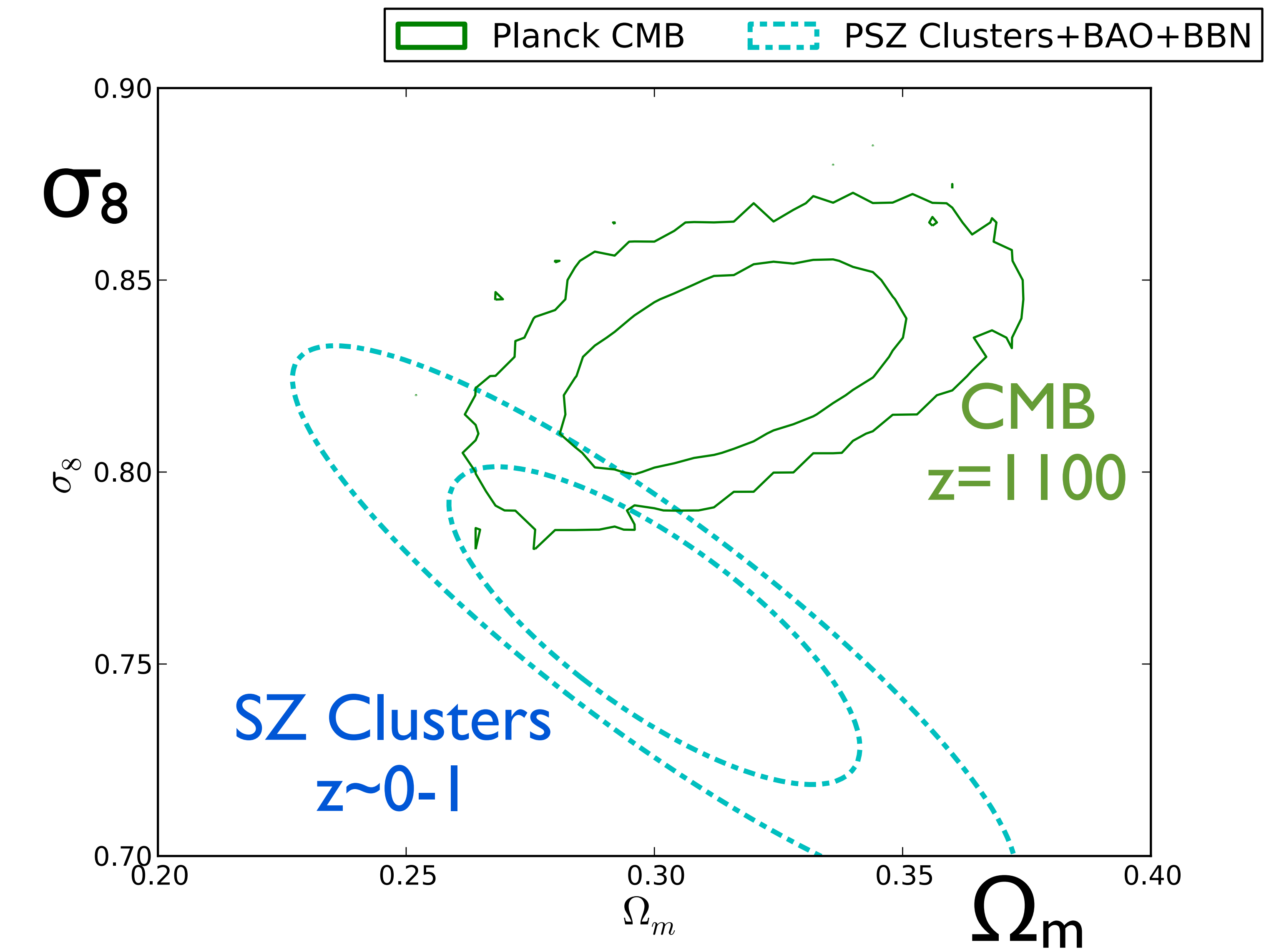
Wrong modeling of cluster gas physics? (or obs. systematics?)

Systematics in CMB analysis (e.g., foregrounds)?

New physics (e.g., massive neutrinos)?

$\Sigma m_\nu \sim$ 0.2-0.3 eV



Planck Collaboration XX (2013)

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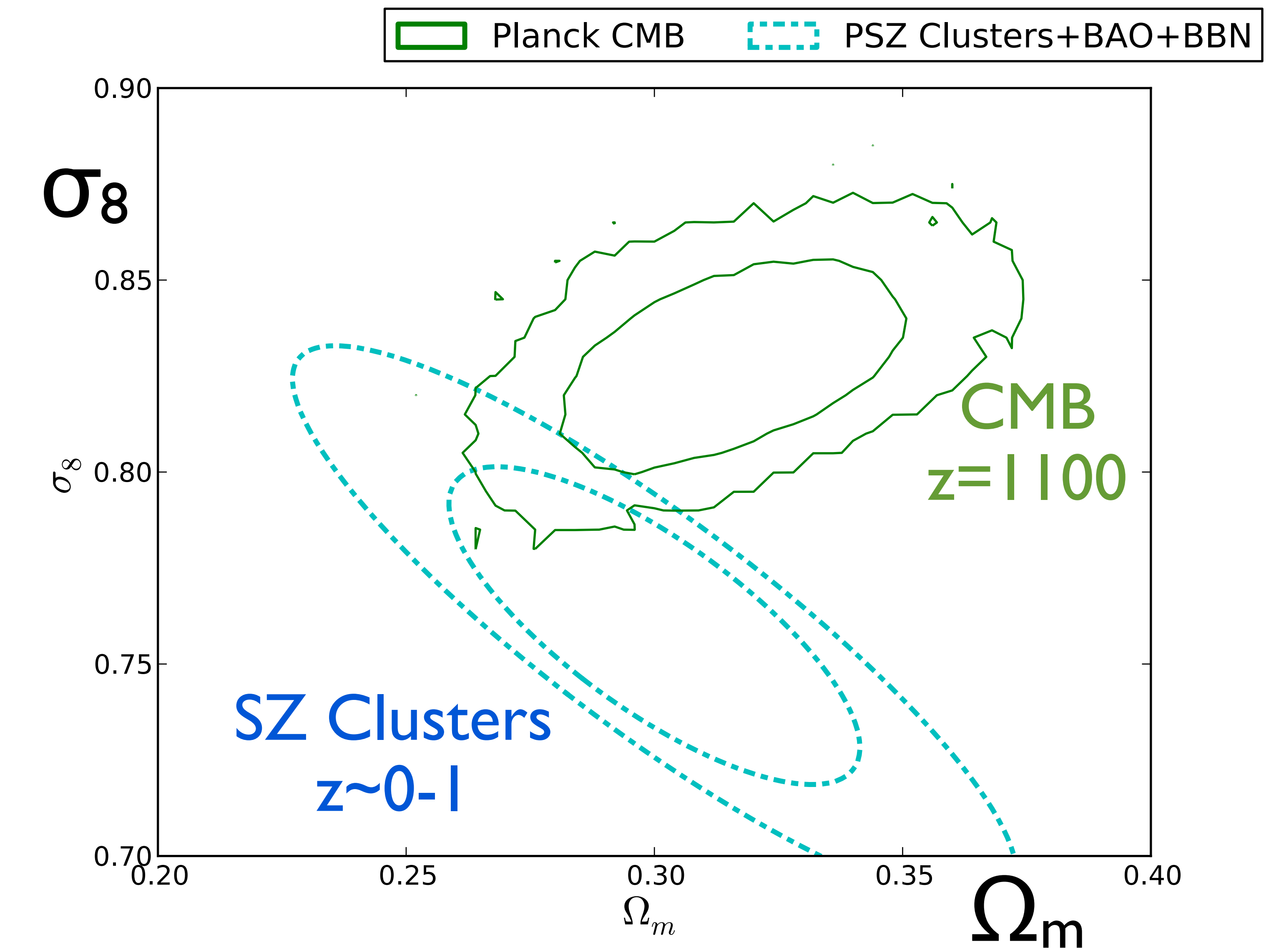
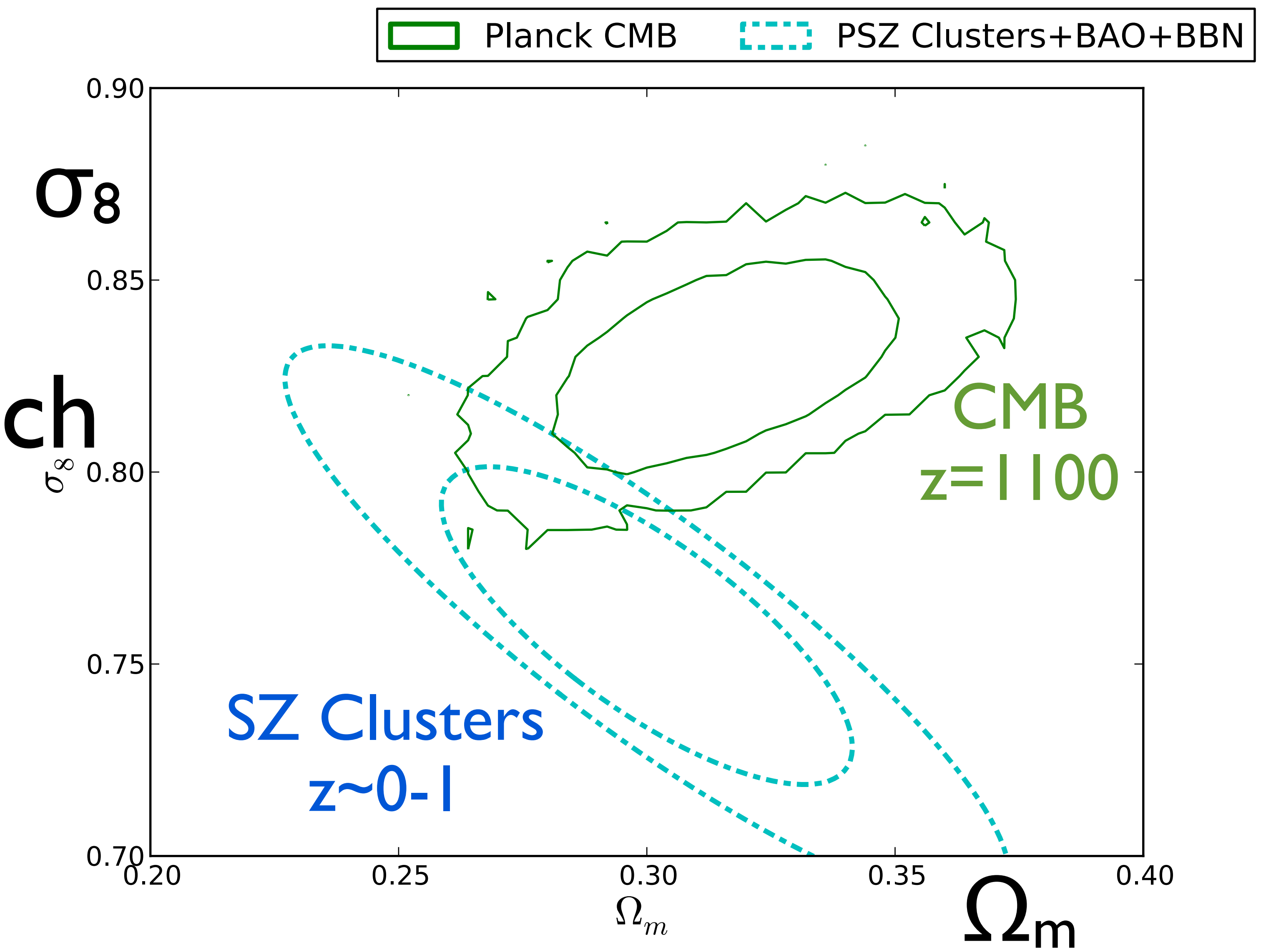
The Sunyaev-Zel'dovich (SZ) Effect

Planck:
- Thermal SZ Power Spectrum
- Thermal SZ x CMB Lensing

ACT:
- Thermal SZ 1-pt PDF



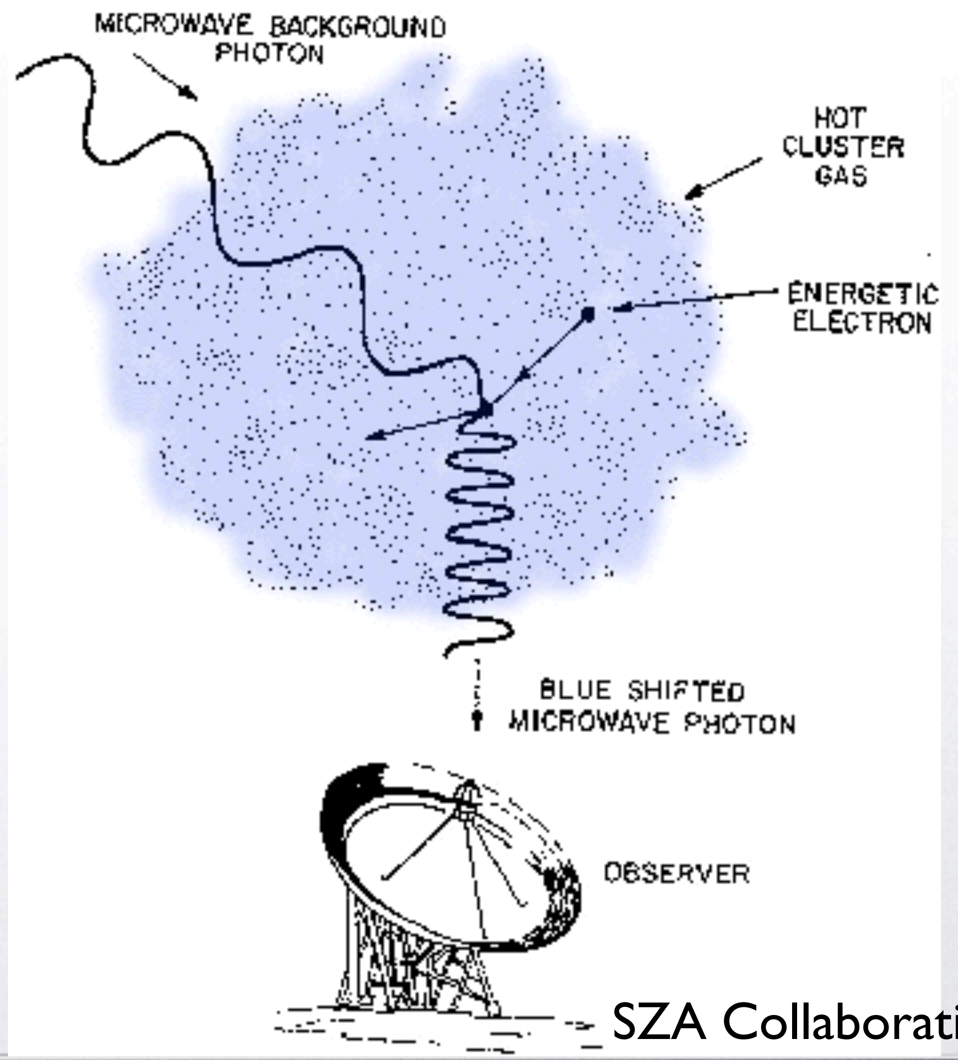
The Sunyaev-Zel'dovich Effect



The Sunyaev-Zel'dovich Effect

- Change in brightness of CMB photons due to inverse Compton scattering off hot electrons in intracluster medium (ICM)
  - Thermal (tSZ): caused by thermal motion of ICM electrons
  - Kinematic (kSZ): caused by bulk velocity of ICM electrons

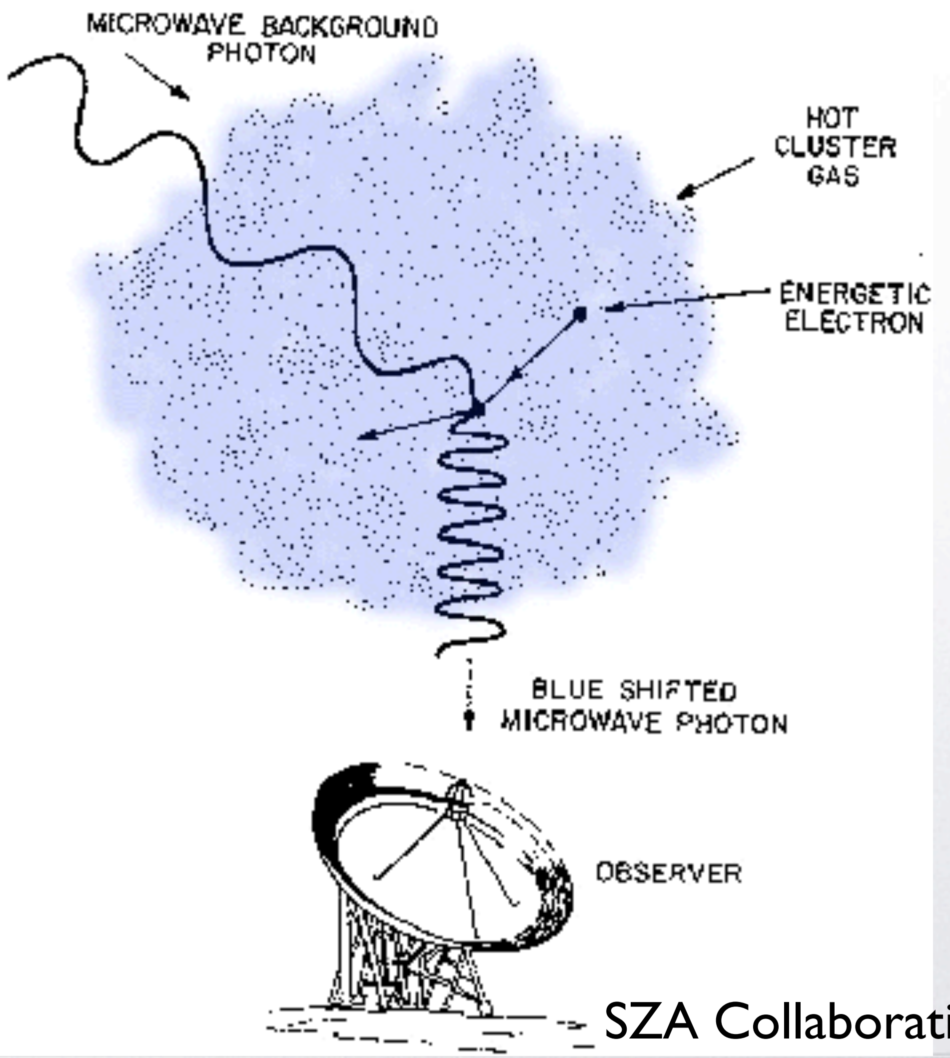
- tSZ: -ΔT below ~218 GHz
  +ΔT above ~218 GHz



SZA Collaboration

The Sunyaev-Zel'dovich Effect

- Change in brightness of CMB photons due to inverse Compton scattering off hot electrons in intracluster medium (ICM)
  - Thermal (tSZ): caused by thermal motion of ICM electrons
  - Kinematic (kSZ): caused by bulk velocity of ICM electrons
- tSZ: $-\Delta T$ below ~218 GHz
  $+\Delta T$ above ~218 GHz
- $\Delta T_{148\ \mathrm{GHz}}$ ~ 100s μK for massive clusters
- Nearly redshift-independent
- Integrated signal probes LOS integral of temperature-weighted mass (total thermal energy)
- Found on arcminute angular scales in CMB



SZA Collaboration

Zel'dovich & Sunyaev (1969)
Sunyaev & Zel'dovich (1970)

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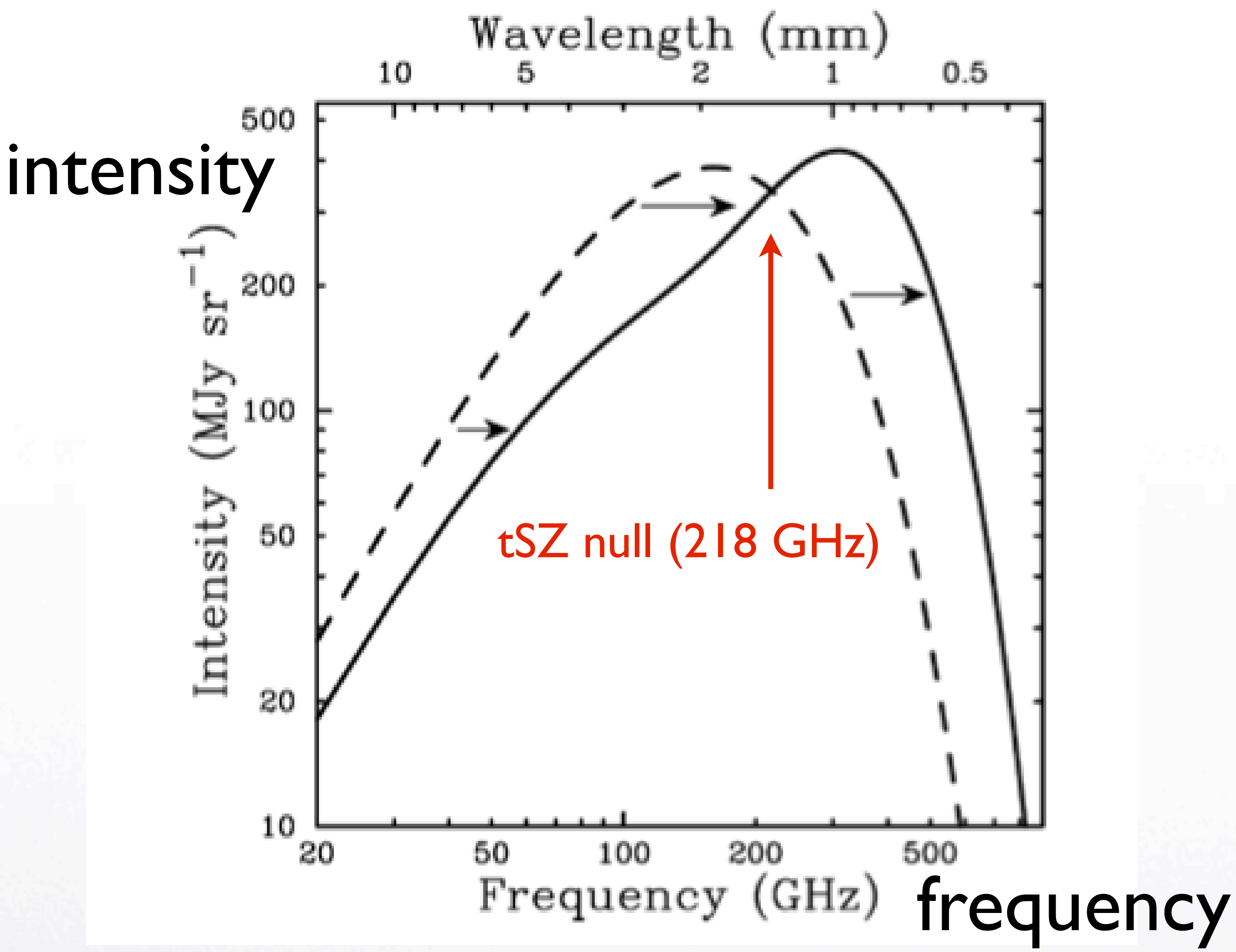

Unique Spectral Signature

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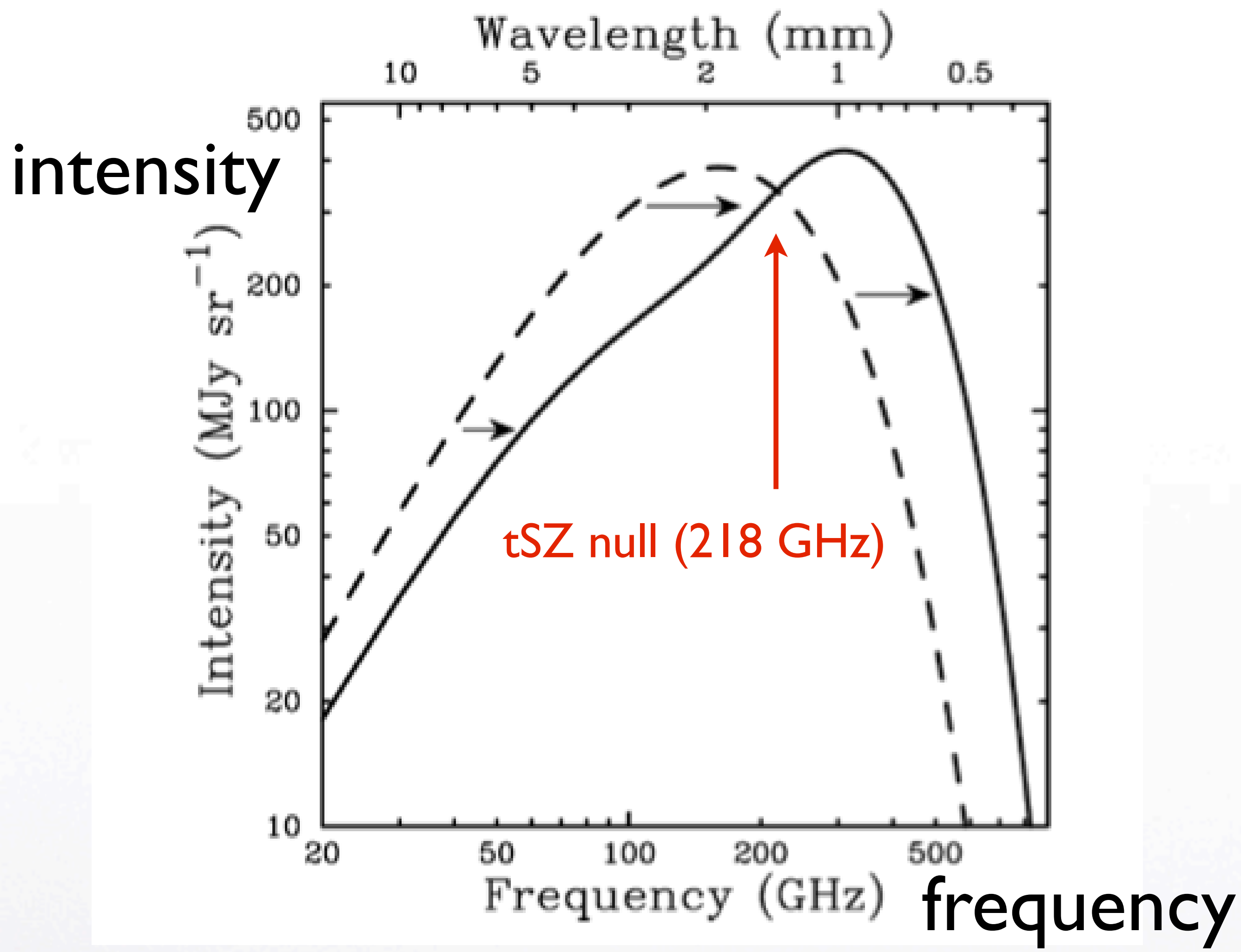
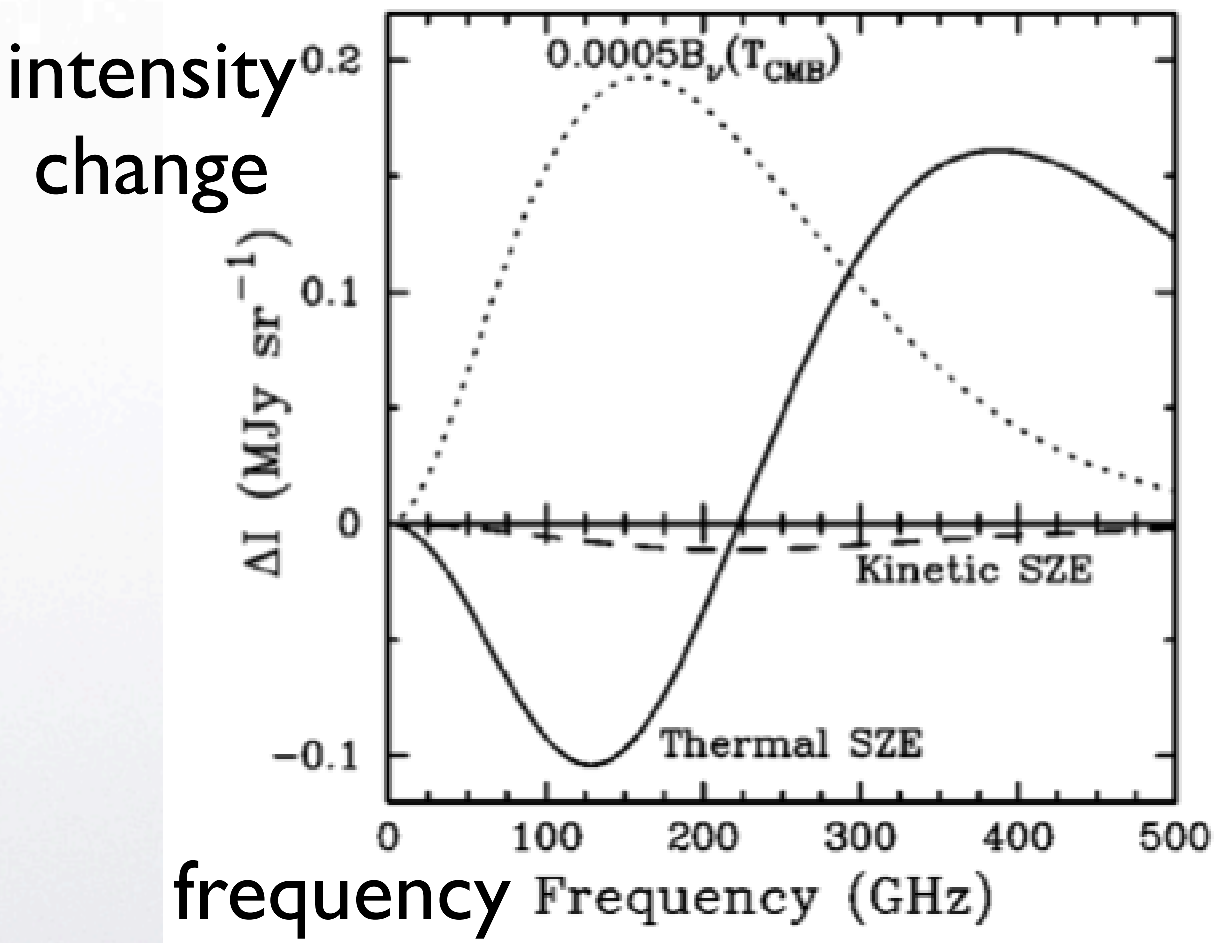
Unique Spectral Signature





Carlstrom et al. (2002)

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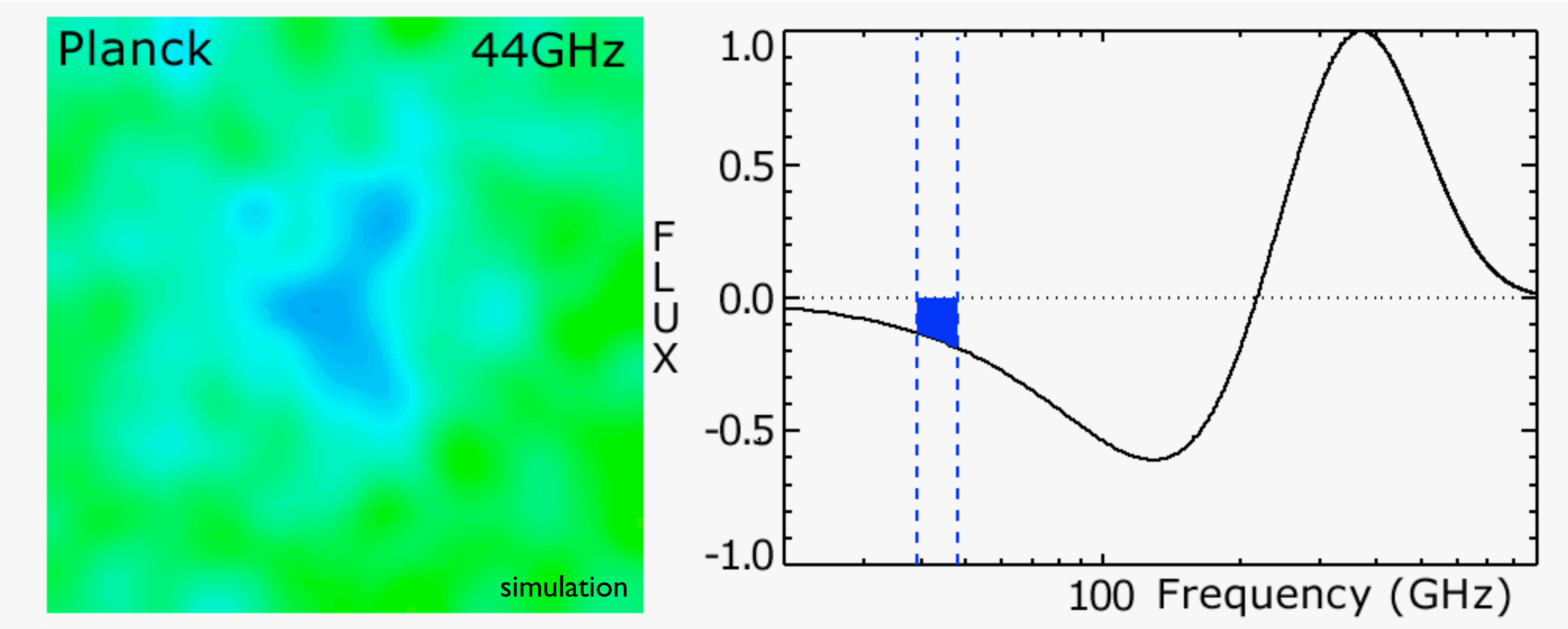
The Sunyaev-Zel’dovich Effect



ESA/Planck Collaboration

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The Sunyaev-Zel'dovich Effect

- Thermal SZ temperature shift at position $\vec{\theta}$ on the sky with respect to the center of a cluster of mass *M* at redshift *z*:

"Compton-y"

$$\frac{\Delta T(\vec{\theta}; M, z)}{T_{\rm CMB}} = g(\nu) y(\vec{\theta}; M, z)$$

tSZ spectral function

Sunyaev & Zel'dovich (1970)

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- Thermal SZ temperature shift at position $\vec{\theta}$ on the sky with respect to the center of a cluster of mass *M* at redshift *z*:

"Compton-y"

$$\frac{\Delta T(\vec{\theta}; M, z)}{T_{\rm CMB}} = g(\nu) y(\vec{\theta}; M, z)$$

$$= g(\nu) \frac{\sigma_T}{m_e c^2} \int P_e \left(\sqrt{l^2 + d_A^2(z)|\vec{\theta}|^2}; M, z \right) dl$$

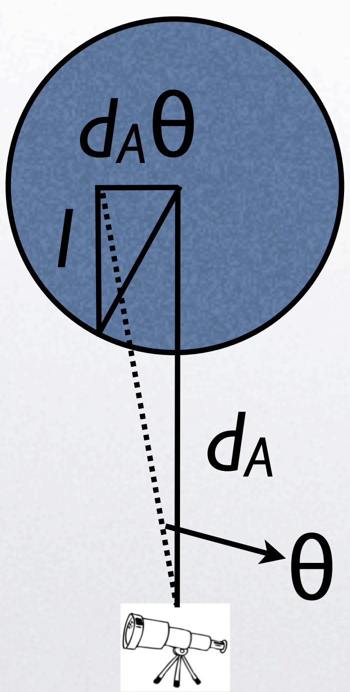
tSZ spectral function

Thomson cross-section

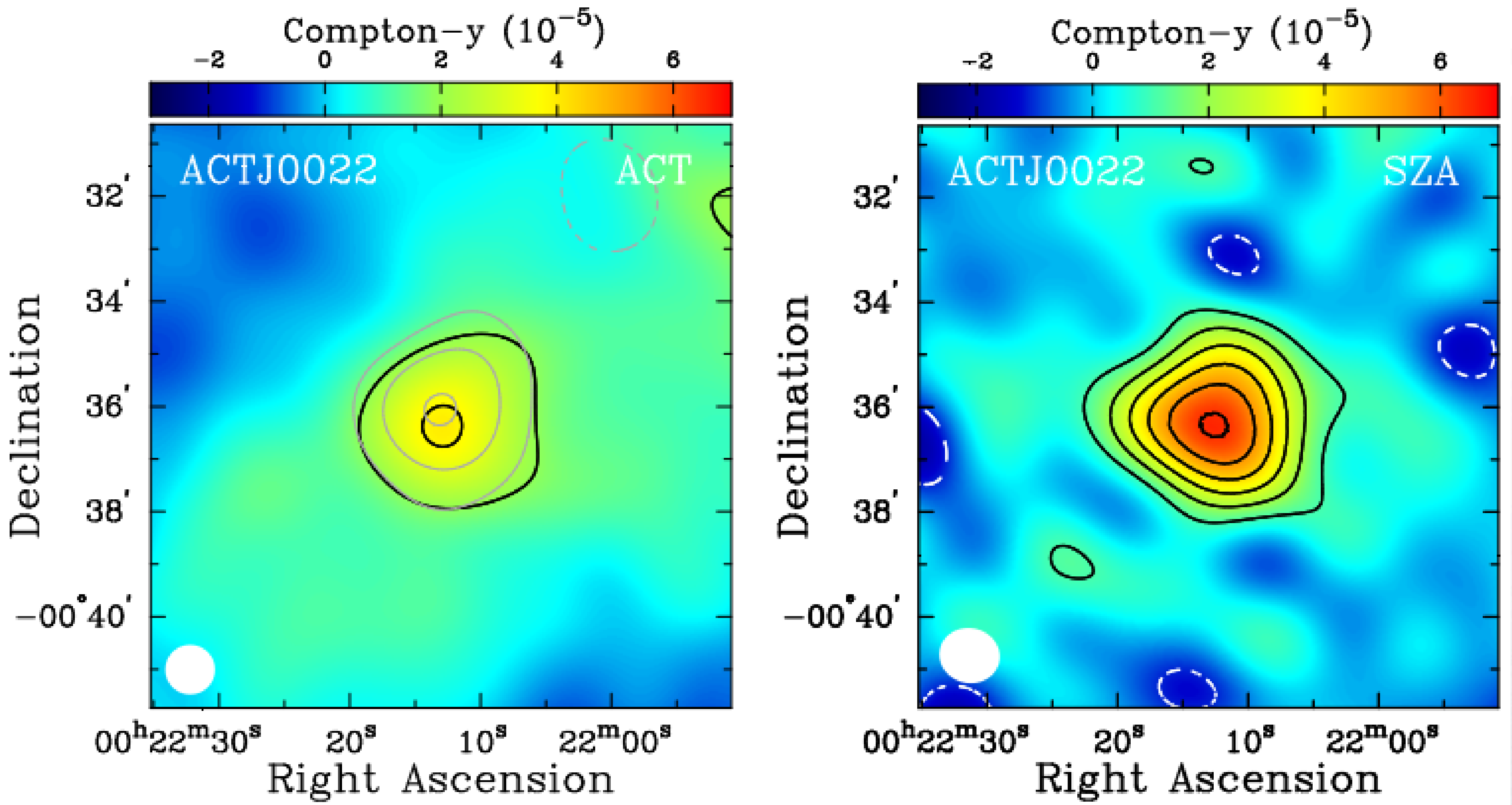
ICM electron pressure profile integrated over LOS

↓

Gastrophysics



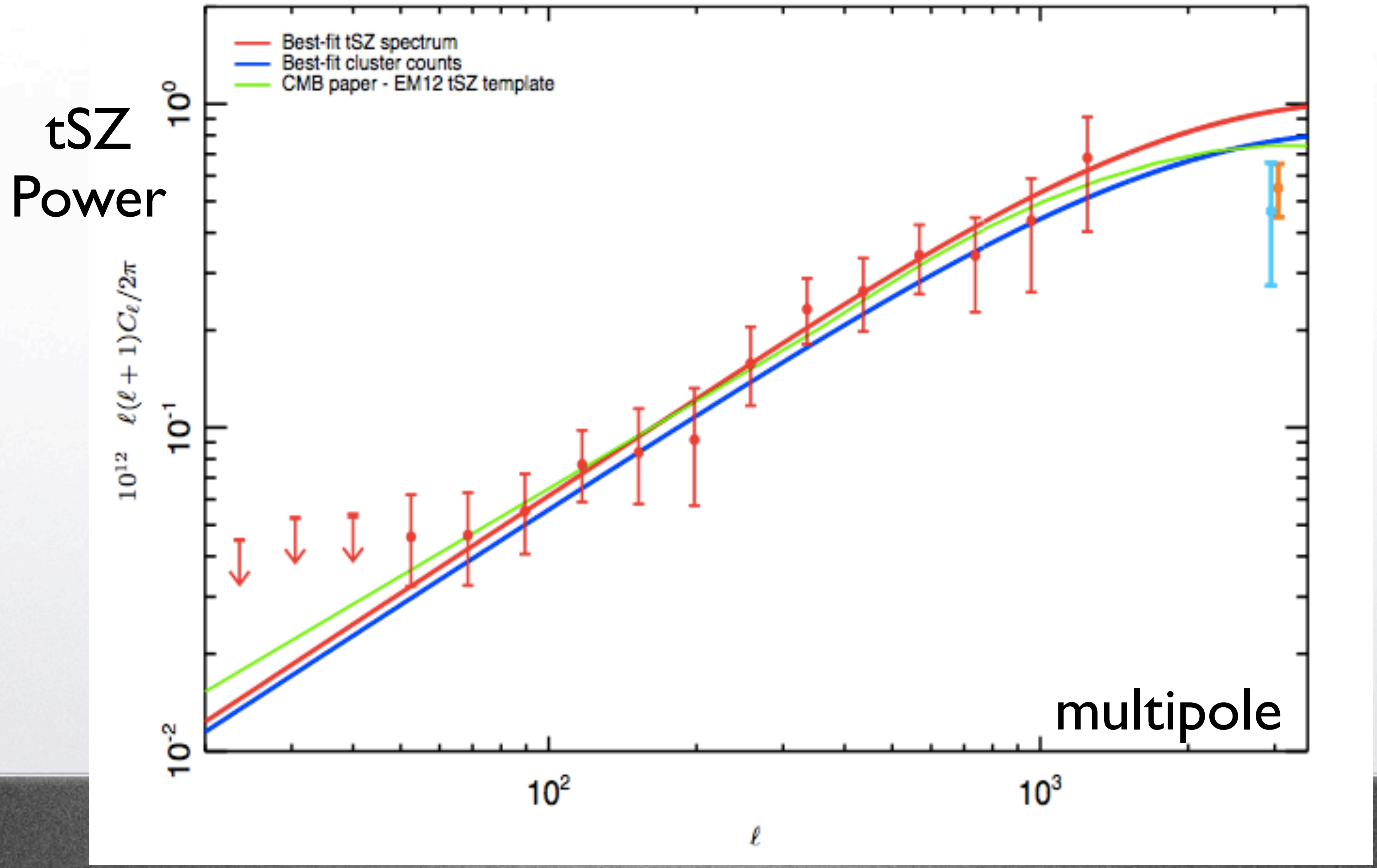
- Method 1: find and count clusters
  - Goal: masses and redshifts (requires optical/IR follow-up)
  - Cosmological analysis: directly reconstruct halo mass function
  - Difficulties: obtaining accurate masses + understanding selection function



z = 0.81
M ~ 10^{15} M_{sun}

Cosmology from Compton-y

- Method II: statistical approaches (power spectrum, bispectrum, ...)
  - Goal: amplitude of temp. fluctuations due to tSZ as a function of angular scale
  - Cosmological analysis: compare to halo model calculations or full simulations
  - Difficulties: ICM electron pressure profile (theory); must separate signal from other sources of CMB power (observation)



Cosmology from Compton-y

- Why adopt a statistical approach?
  - no selection effect-related systematics (Malmquist or Eddington bias)
  - no choice of "aperture" within which mass is measured
  - no need to apply an averaged/universal pressure profile to individual objects
  - signal is very sensitive to σ_8: rms amplitude of fluctuations on 8 h^{-1} Mpc scale
  - signal is very non-gaussian*, hence many statistics to measure
  - precise individual cluster masses are expensive to obtain and subject to many systematics

$$\frac{l(l+1)C_l}{2\pi} \simeq 330\,\mu\mathrm{K}^2 \boxed{\sigma_8^7} \left(\frac{\Omega_b h}{0.035}\right)^2$$

$$\langle T^3 \rangle \propto \boxed{\sigma_8^{10-11.5}}$$

Komatsu & Seljak (2002)
JCH & Sherwin (2013)

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Cosmology from Compton-y

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$$\langle T^3 \rangle \propto \sigma_8^{10-11.5}$$

- Difficulties:
  - need pressure profile model for wide range of masses/redshifts
  - must separate tSZ signal from other microwave sky components

- Why *y*?
  - Cosmology: σ_8 (and M_ν), Ω_m, *w*
  - ICM gastrophysics

Komatsu & Seljak (2002)
JCH & Sherwin (2013), JCH & Pajer (2013)

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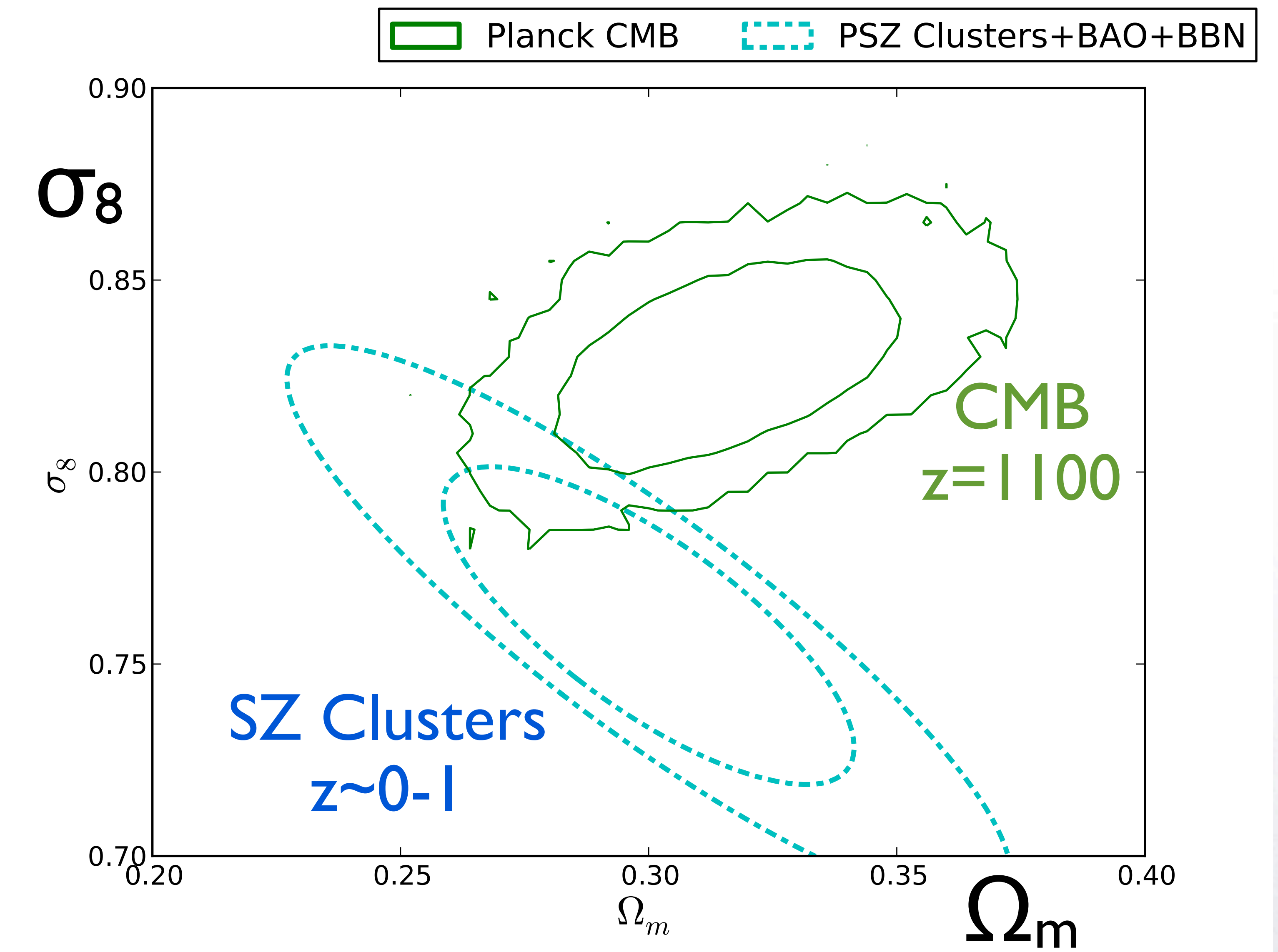
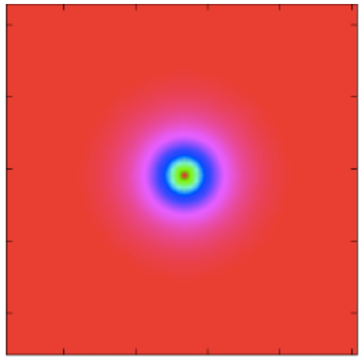
Planck:
Thermal SZ Power Spectrum



Thermal SZ Power Spectrum

- First: compute the Fourier transform of the *y*-profile of each cluster

Gastrophysics



$$y(\vec{\theta}; M, z) \xrightarrow{\text{F.T.}} \tilde{y}_\ell(M, z)$$

Komatsu & Seljak (2002)
JCH & Pajer (2013)

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Thermal SZ Power Spectrum

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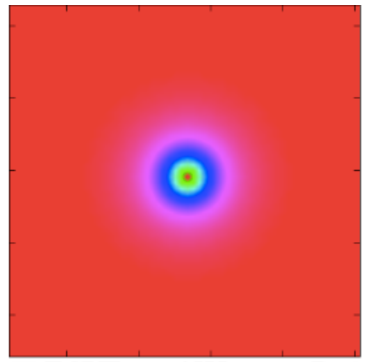
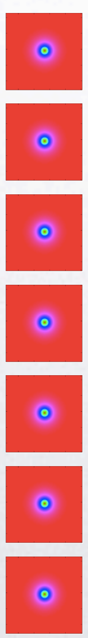
Gastrophysics



$$y(\vec{\theta}; M, z) \xrightarrow{\text{F.T.}} \tilde{y}_\ell(M, z)$$

- Then: add up the contributions from all clusters in the universe



$$C_\ell^{y,1h} = \int dz \frac{d^2V}{dz d\Omega} \int dM \frac{dn}{dM} |\tilde{y}_\ell(M, z)|^2$$

("one-halo" term)

comoving volume per steradian → **Cosmology** ← halo mass function

("two-halo" term also included in results)

ICM Gastrophysics

- ICM to lowest order: hydrostatic equilibrium between gas pressure and DM potential; gas traces DM; polytropic EOS (Komatsu-Seljak)

$$\frac{dP_{gas}(r)}{dr} = -\rho_{gas}(r)\frac{d\Phi_{DM}(r)}{dr}$$

- Problems: central cooling catastrophe, non-convergent profile at edge

Komatsu & Seljak (2001,02)
Battaglia et al. (2010,12), Shaw et al. (2010)

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$$\frac{dP_{gas}(r)}{dr} = -\rho_{gas}(r)\frac{d\Phi_{DM}(r)}{dr}$$

- Problems: central cooling catastrophe, non-convergent profile at edge
- Additional physics needed:
  - Formation shock heating
  - Star formation, supernova feedback, cosmic rays
  - Active galactic nucleus (AGN) feedback: can heat gas or expel it from cluster
  - Turbulent (non-thermal) pressure support: suppresses tSZ signal
  - Magnetic fields, plasma instabilities

Komatsu & Seljak (2001,02)
Battaglia et al. (2010,12), Shaw et al. (2010)

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ICM Gastrophysics

- Model adopted in this work/talk: parametrized "GNFW" fit from Battaglia et al. simulations (GADGET SPH + sub-grid AGN feedback)

$$\frac{P_{th}(x)}{P_{200,c}} = \frac{P_0\,(x/x_c)^{\gamma}}{[1+(x/x_c)^{\alpha}]^{\beta}} \quad , x \equiv r/r_{200,c}$$

$\alpha = 1.0$
$\gamma = -0.3$
$\beta \sim 4\text{-}5$

self-similar pressure at r_{200}
(radius within which avg density is $200\rho_c$)

- P_0, x_c, β are fit to power-laws in M and (1+z) -- capture deviations from self-similar profile (energy injection, nonthermal pressure support, etc.)

Battaglia et al. (2010, 2012)
Planck Collaboration V (2012)

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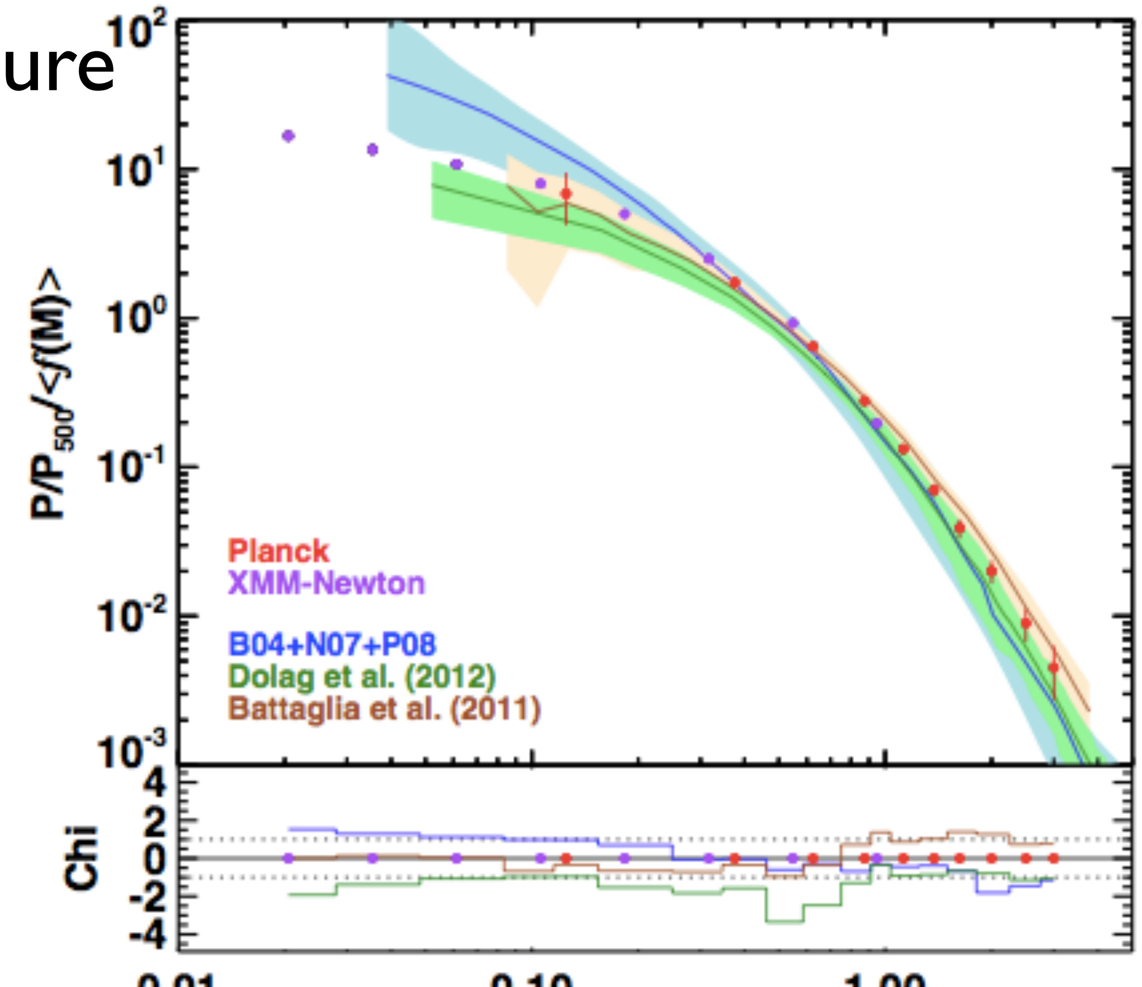
(radius within which avg density is $200\rho_c$)

- P_0, x_c, β are fit to power-laws in M and (1+z) -- capture deviations from self-similar profile (energy injection, nonthermal pressure support, etc.)

- Agrees well with all existing pressure profile observations (no tuning required) -- REXCESS (Arnaud), Planck stacked profile, Planck Coma

pressure



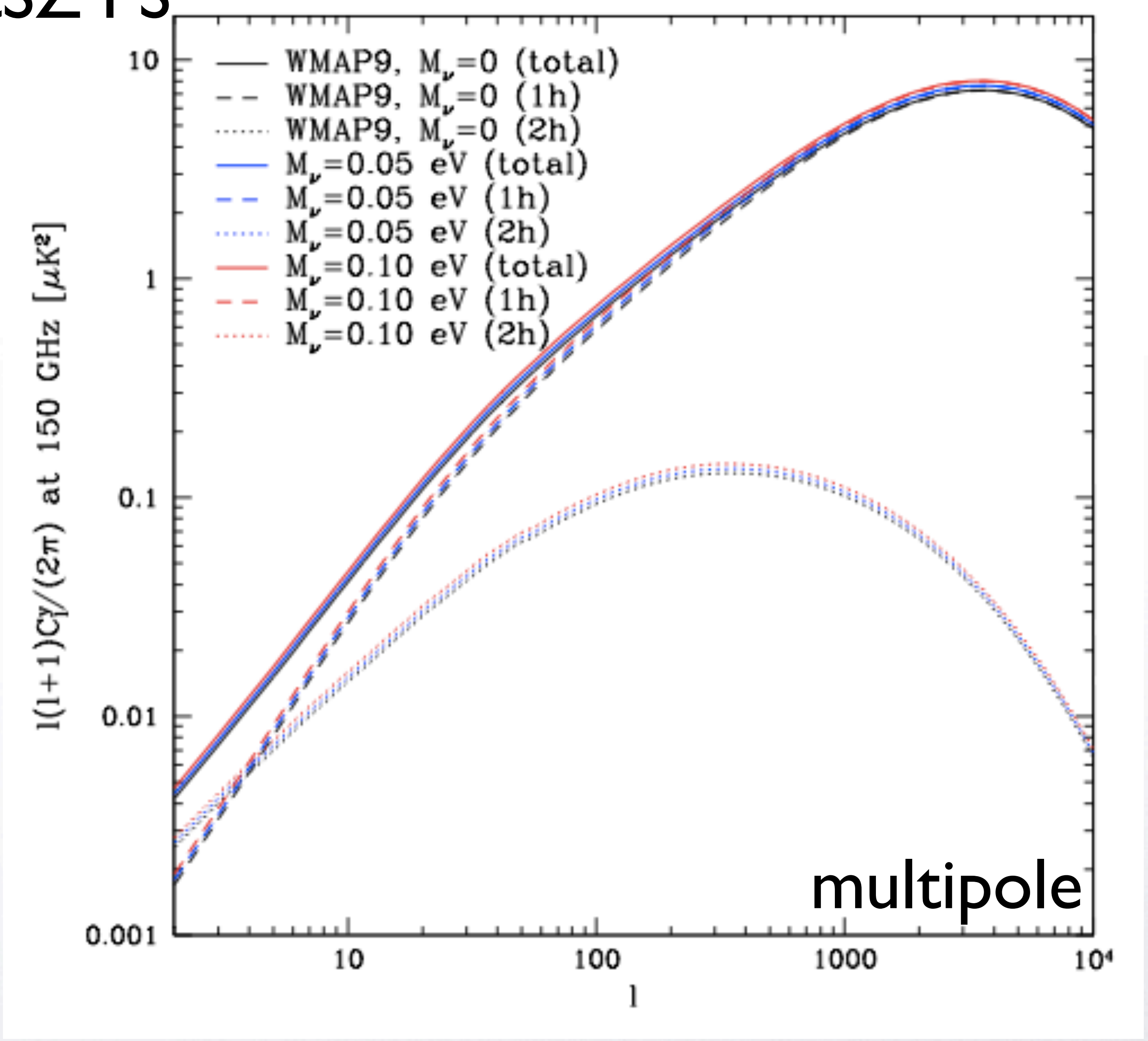
radius

Thermal SZ Power Spectrum

- Planck: >5' beams ⟶ PS likely contains most of tSZ information
- Prior to release: forecasting using halo model + parametrized pressure profile; motivation: primordial NG and neutrino masses

tSZ PS

effect of M_ν

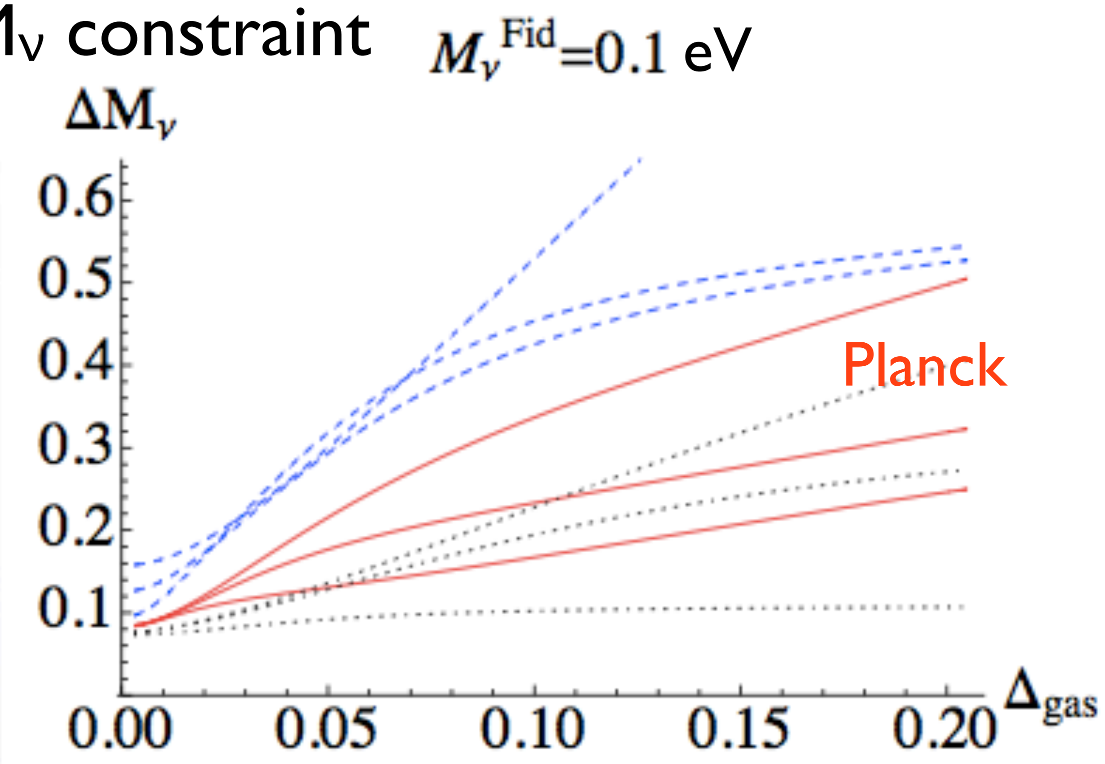


Thermal SZ Power Spectrum

- Punchline: need to constrain gastrophysics and cosmology simultaneously

- Planck:
  - Forecast: signal over 50<ell<1200
  - SNR ~ 30 if foregrounds can be controlled
  - Only cosmological parameters that tSZ is useful for: σ_8, Ω_m, (+M_ν, w, DE params)
  - Also: ~10% constraint on outer logarithmic slope of pressure profile

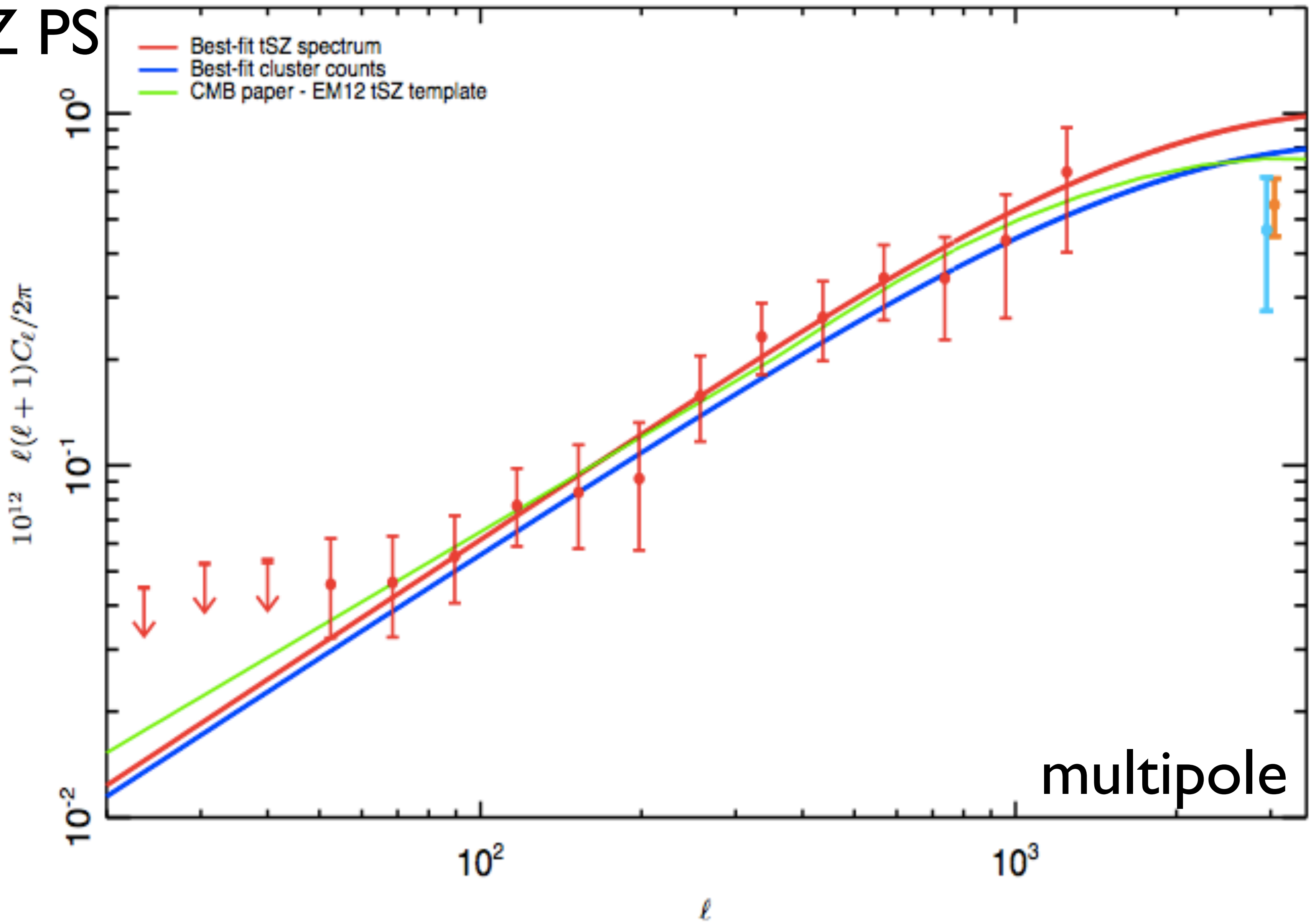
M_ν constraint



frac. prior on gastrophysics parameters

Thermal SZ Power Spectrum

tSZ PS



gastrophysics model is fixed (Arnaud); no variations considered

$$\sigma_8 \left(\Omega_m/0.28\right)^{3.2/8.1} = 0.784 \pm 0.016$$

12.3σ detection

foreground uncertainties dominate the errors

Planck+WP CMB:
0.868 ± 0.013

Planck Collaboration XXI (2013)

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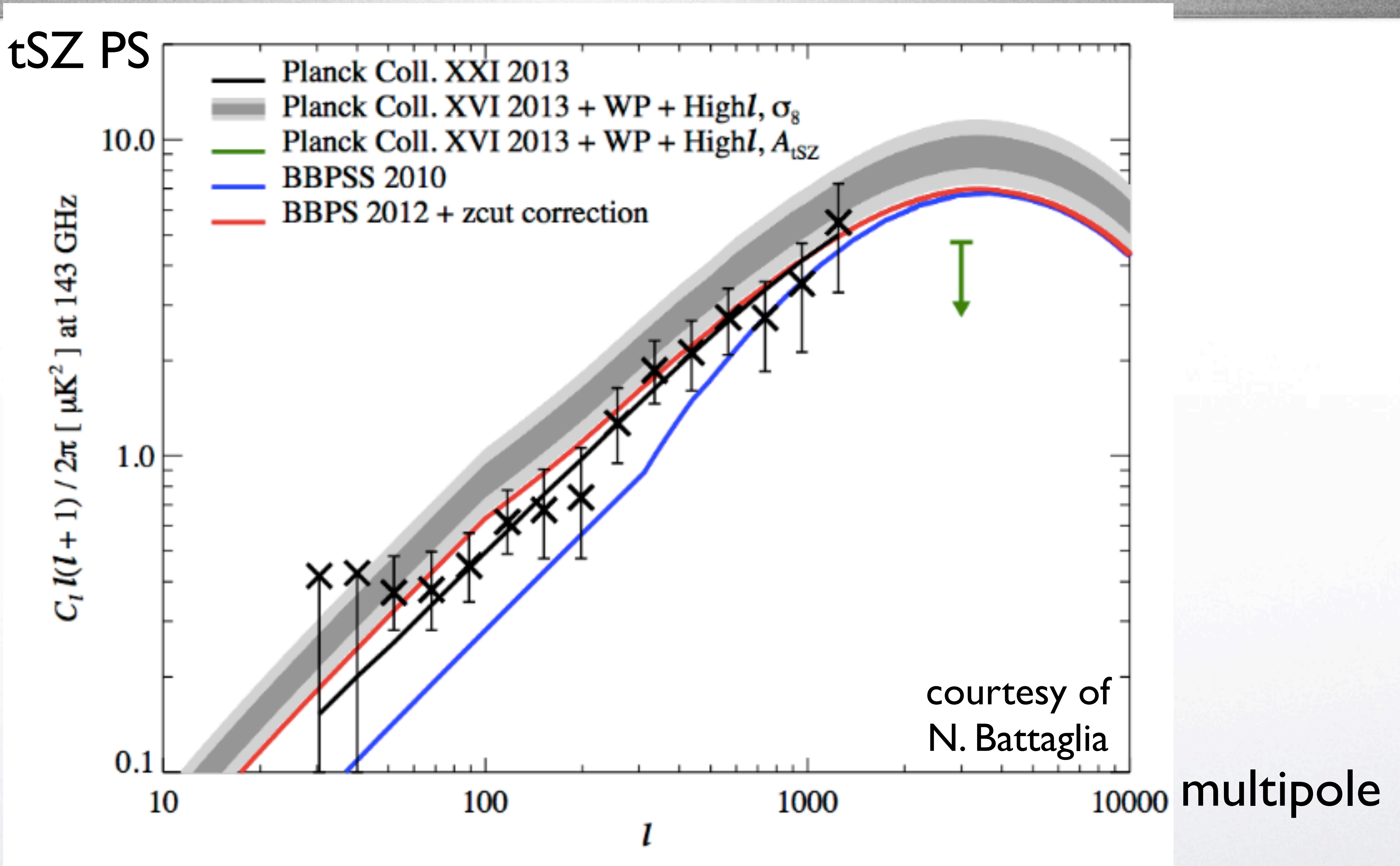
Thermal SZ Power Spectrum



What is the origin of the discrepancy between the measured tSZ signal and predictions based on primordial CMB constraints?

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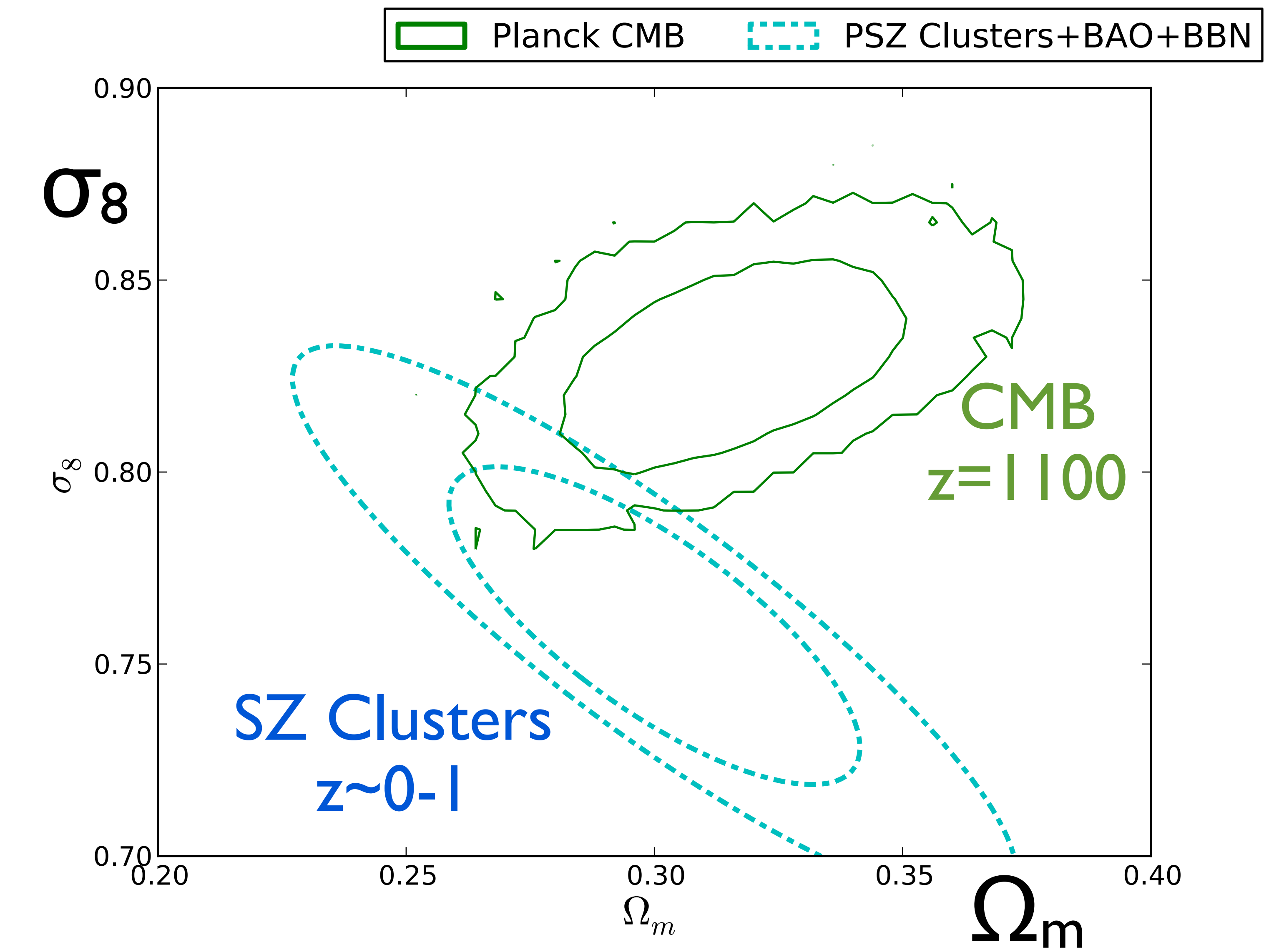
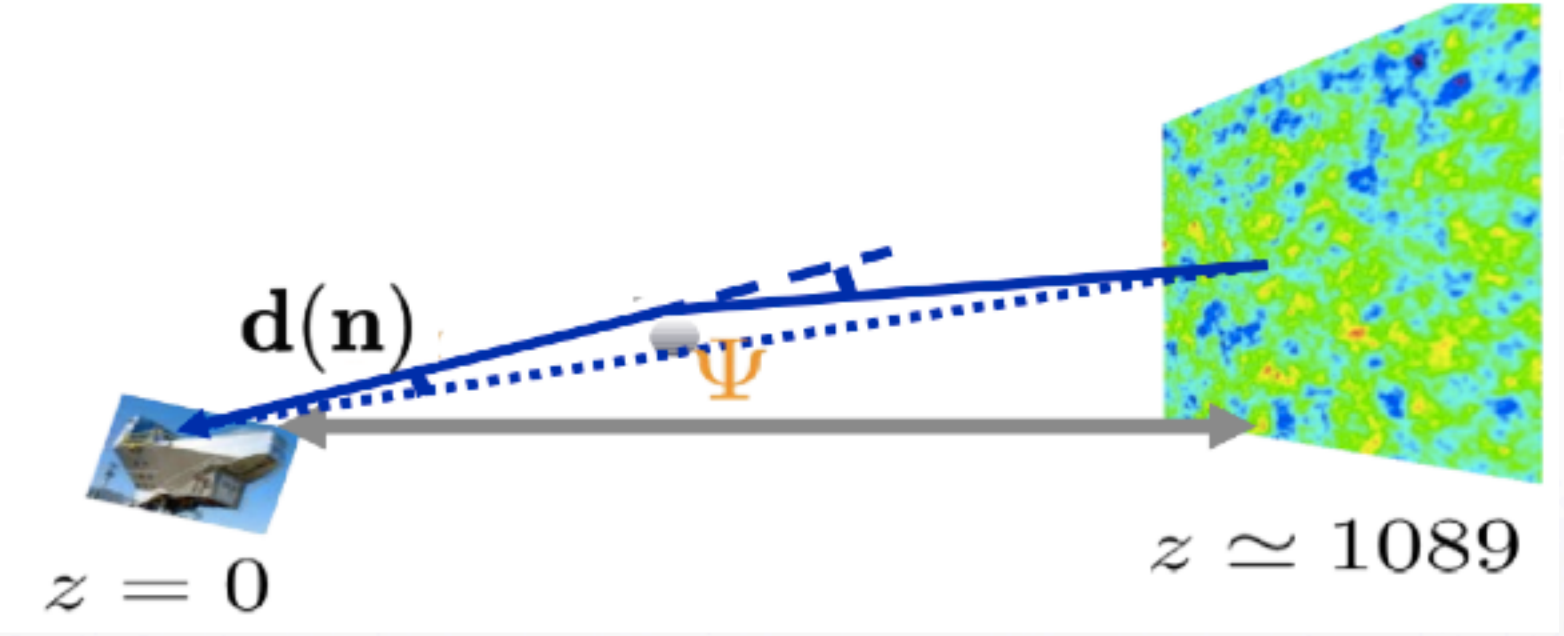
Planck:
Thermal SZ
x
CMB Lensing



CMB Lensing

- CMB photons are gravitationally deflected by large-scale structure along the LOS
- Many (~50) small random deflections lead to a net deflection (~3 arcmin), coherent on ~deg scales, which remaps the CMB:



$$T(\hat{\mathbf{n}})_{\text{lensed}} = T(\hat{\mathbf{n}} + \mathbf{d}(\hat{\mathbf{n}}))_{\text{unlensed}}$$

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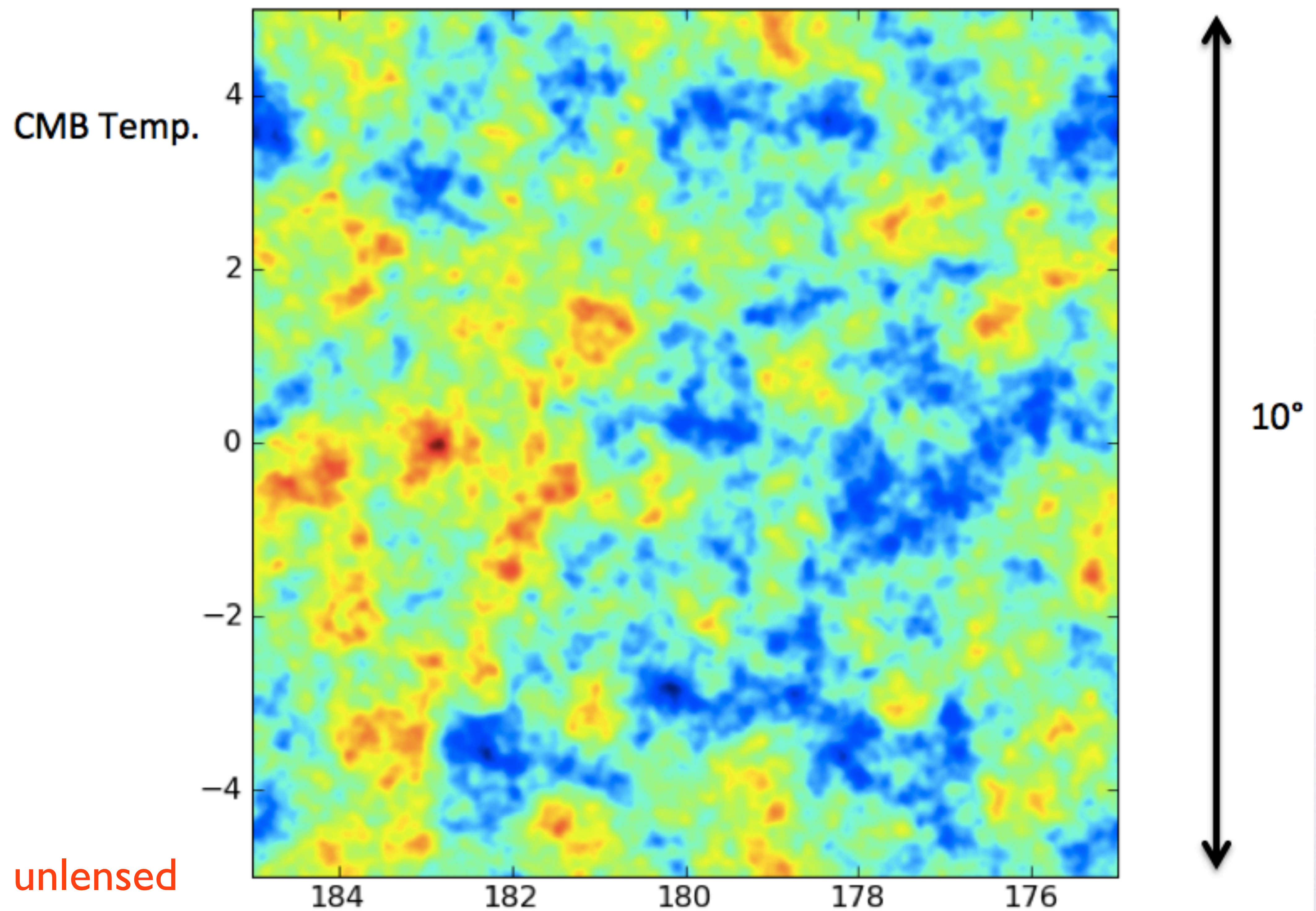
CMB Lensing



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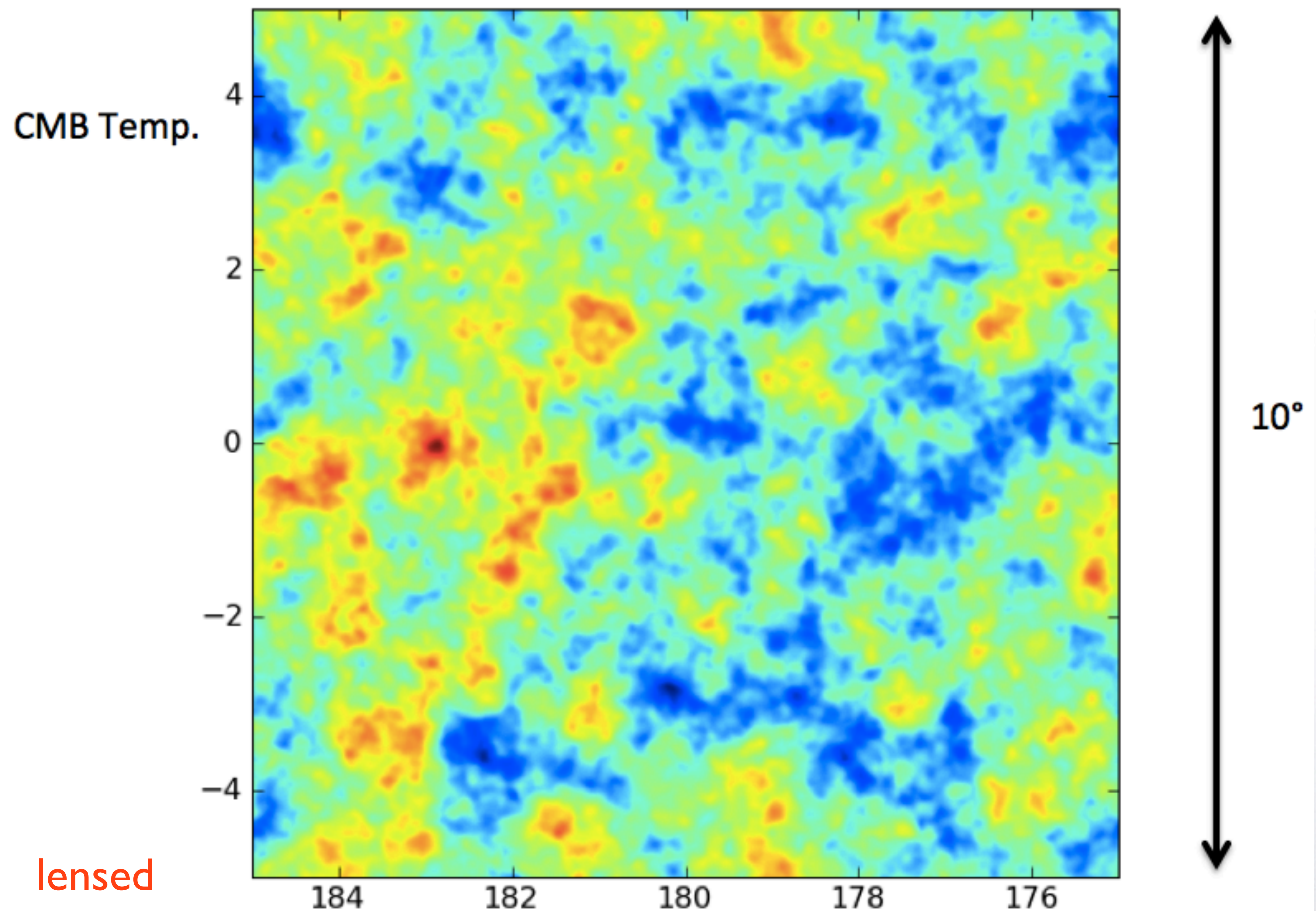
CMB Lensing



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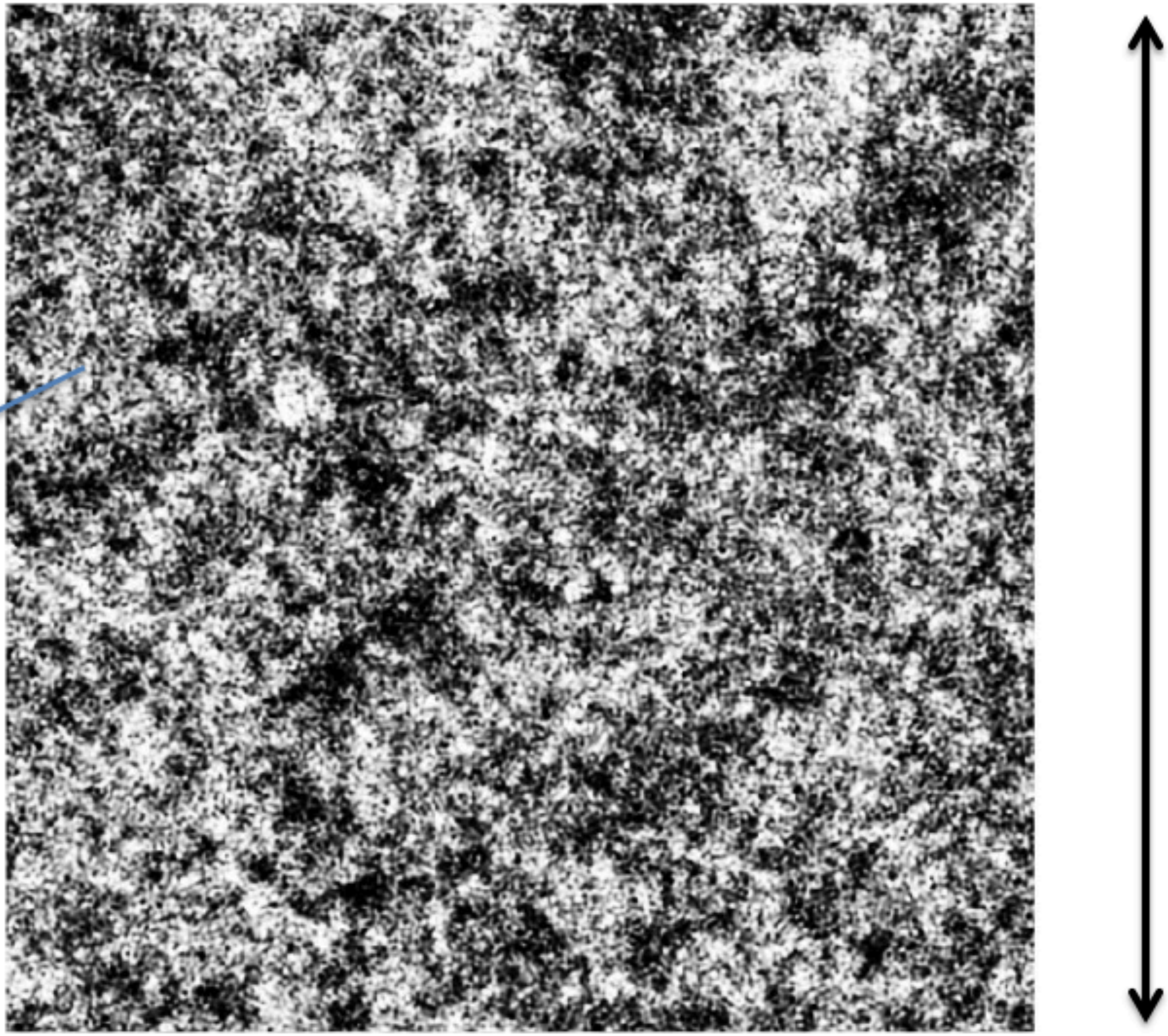
CMB Lensing

$$|\mathbf{d}(\hat{\mathbf{n}})|_{\mathrm{filt}}$$

small
arcminute-
scale
deflections,
coherent on
degree scales



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Thermal SZ x CMB Lensing

- Cross-spectrum can be derived similarly to tSZ auto-spectrum
- Need the Fourier transform of both the *y*-profile and φ- (lensing potential) profile (e.g., computed from NFW) for each halo

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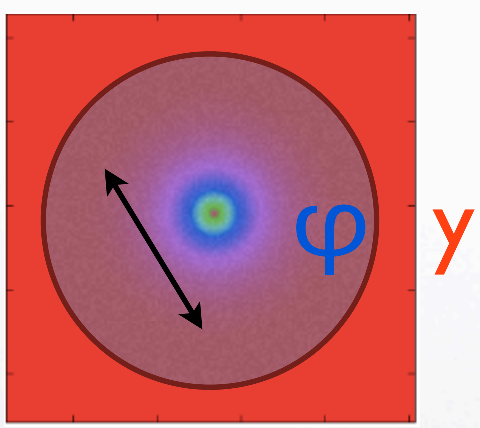
Thermal SZ x CMB Lensing

- Cross-spectrum can be derived similarly to tSZ auto-spectrum
- Need the Fourier transform of both the *y*-profile and φ- (lensing potential) profile (e.g., computed from NFW) for each halo
- Contributions from both "one-halo" and "two-halo" terms:

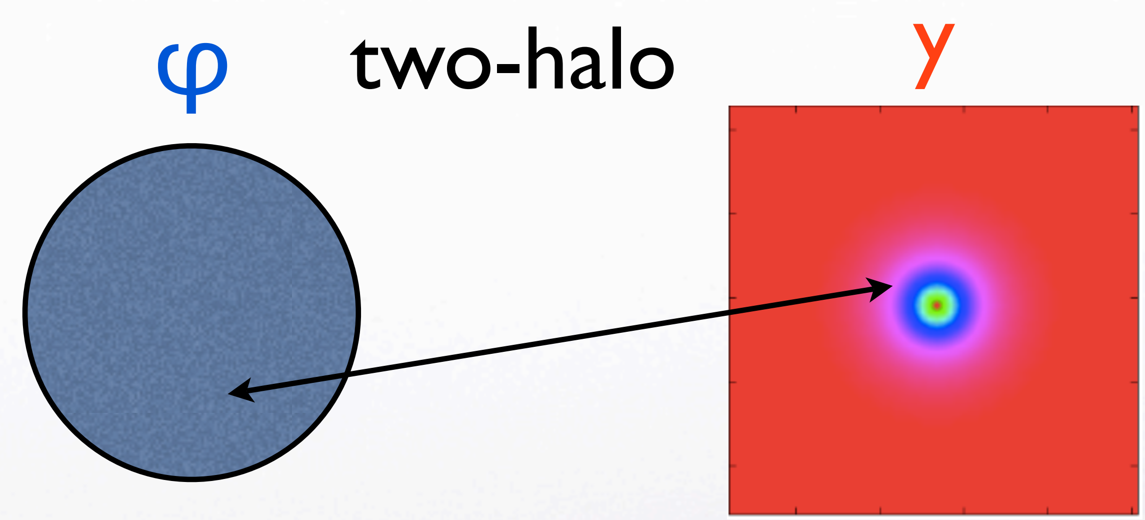
one-halo



dominates on small scales

sensitive to number of clusters and how gas traces DM in clusters

two-halo



dominates on large scales

sensitive to how gas traces DM on large scales (amongst many things)

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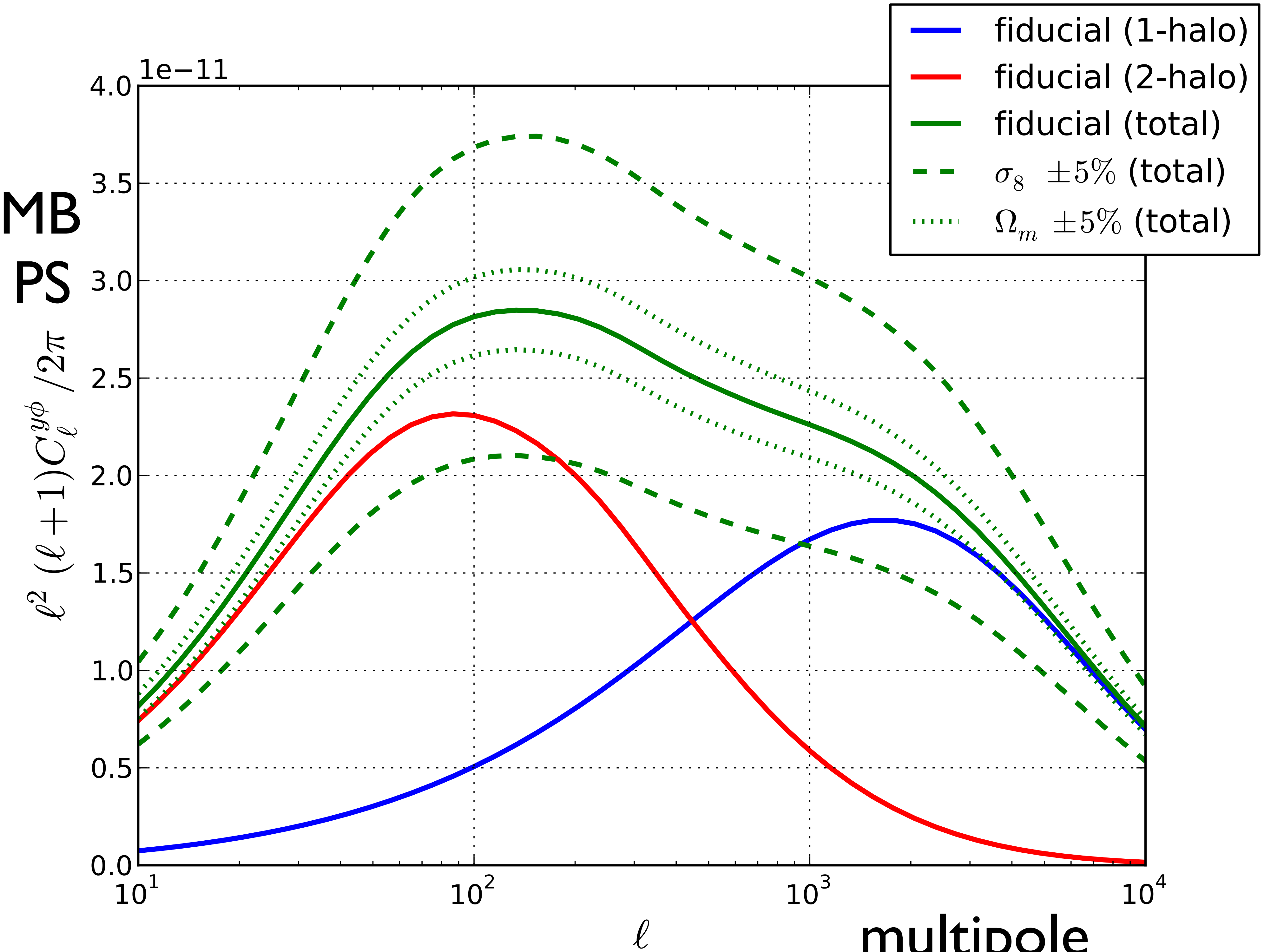
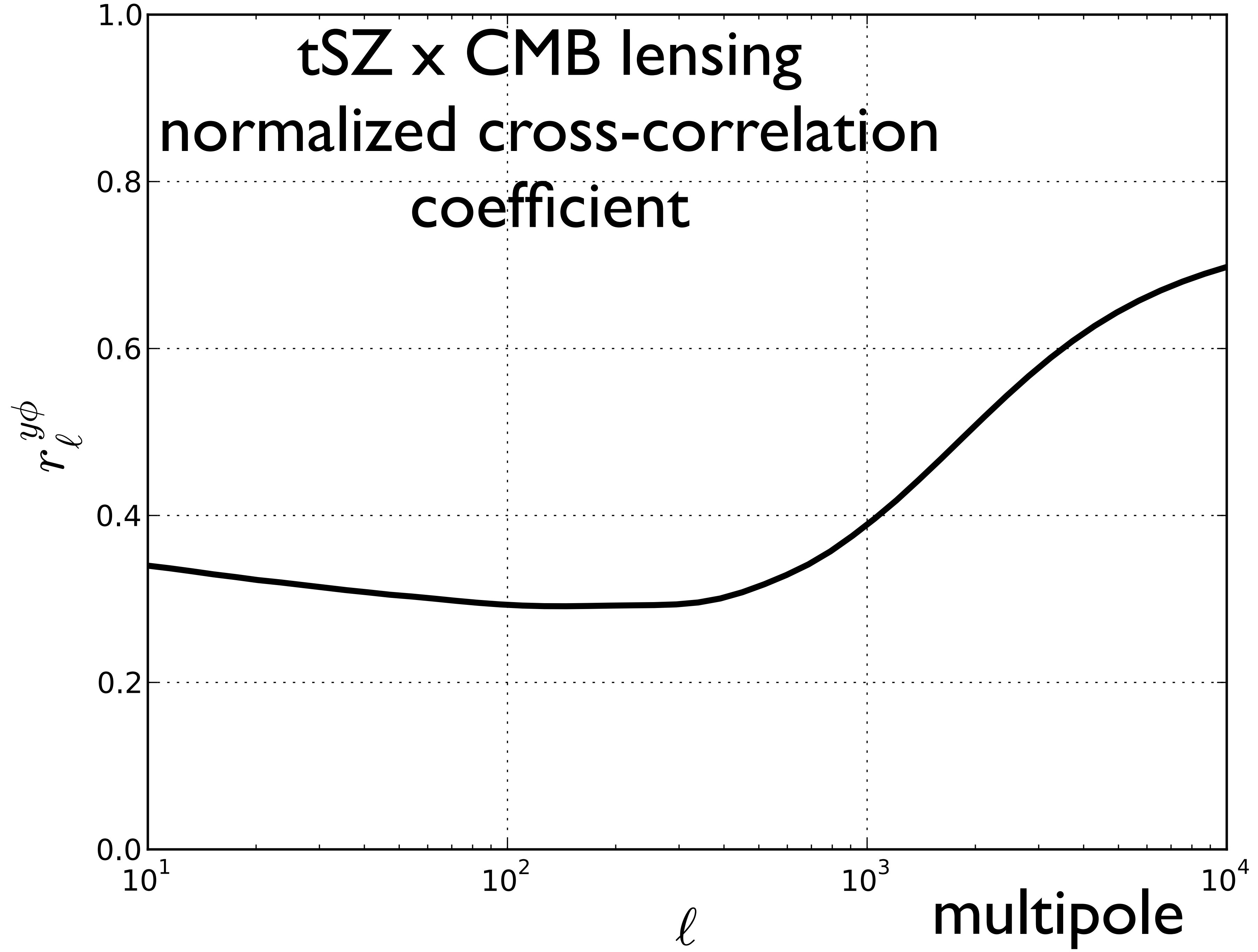
Thermal SZ x CMB Lensing

tSZ x CMB Lensing PS



multipole

Thermal SZ x CMB Lensing



JCH & Spergel (in prep.)

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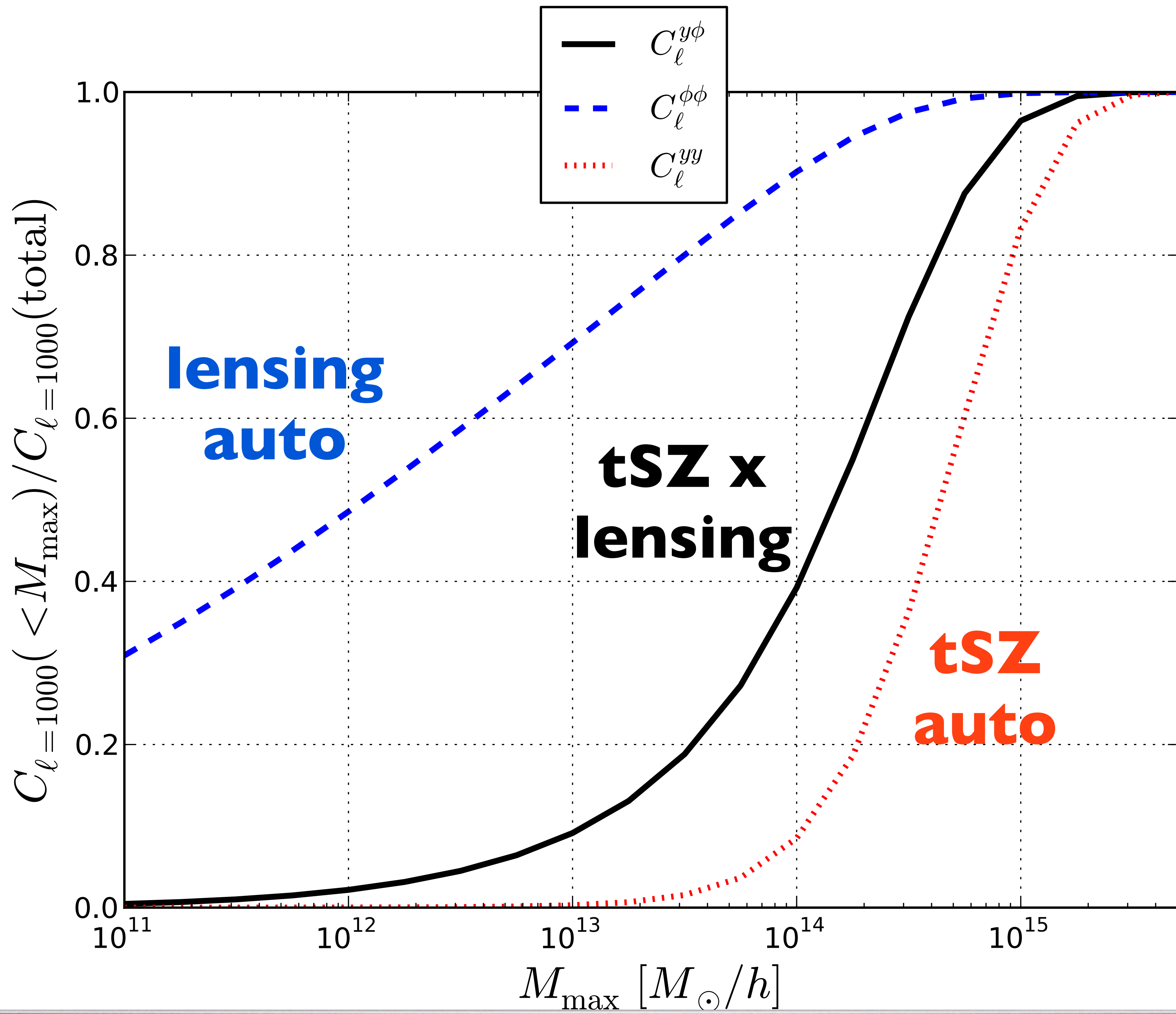
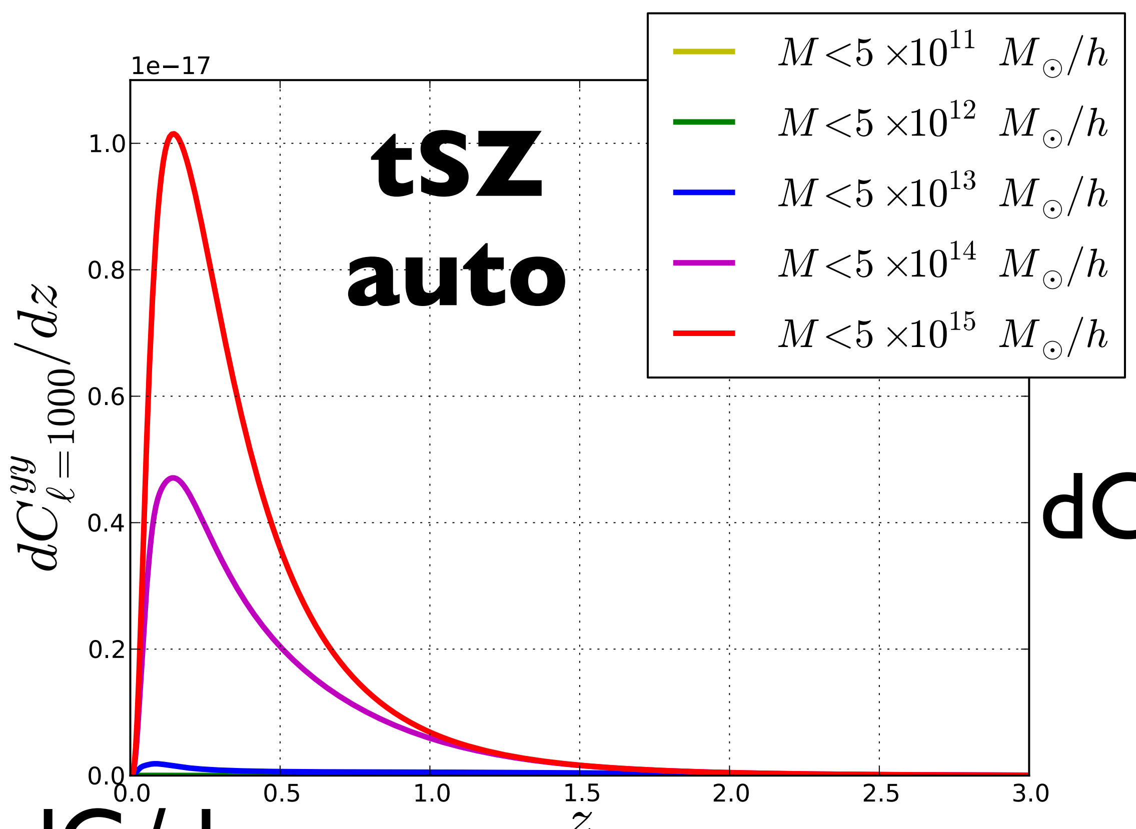
Mass/Redshift Contributions



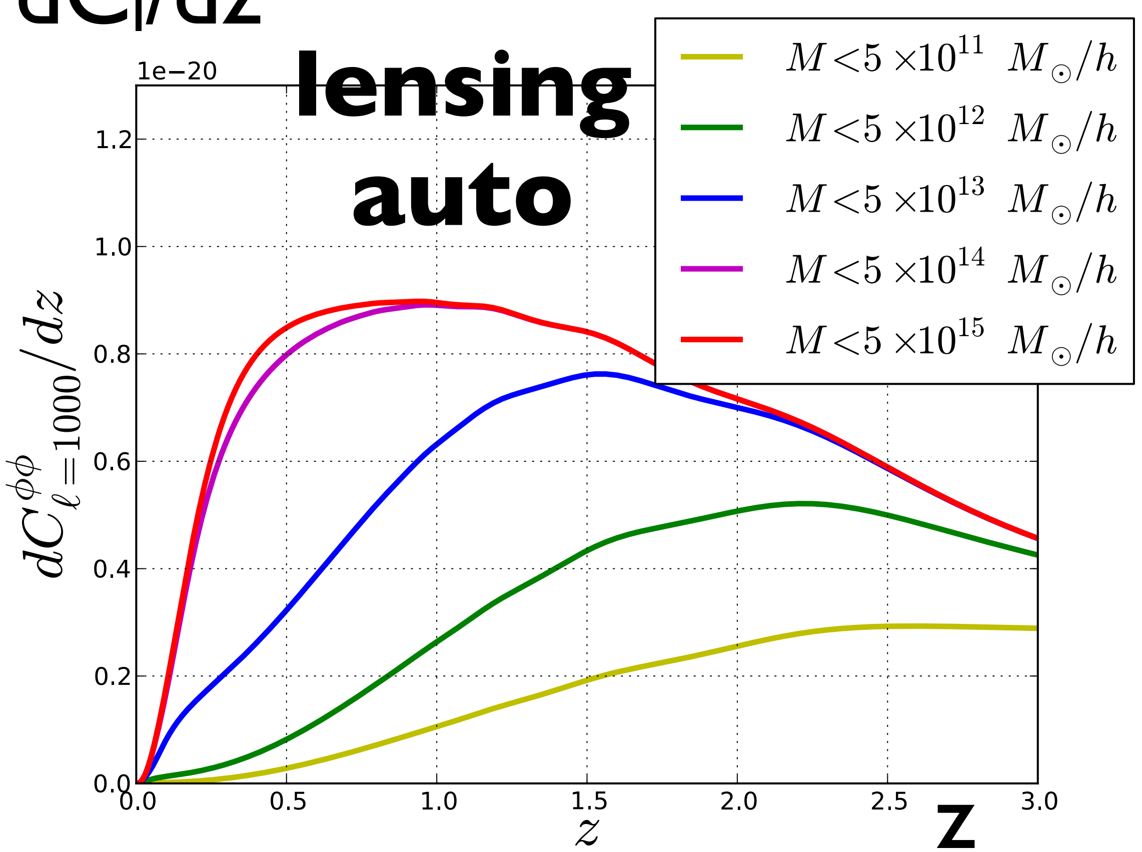
computed at *l*=1000 (one-halo-dominated regime in cross-spec)

Mass/Redshift Contributions

computed at l=1000 (one-halo-dominated regime in cross-spec)



dC$_l$/dz



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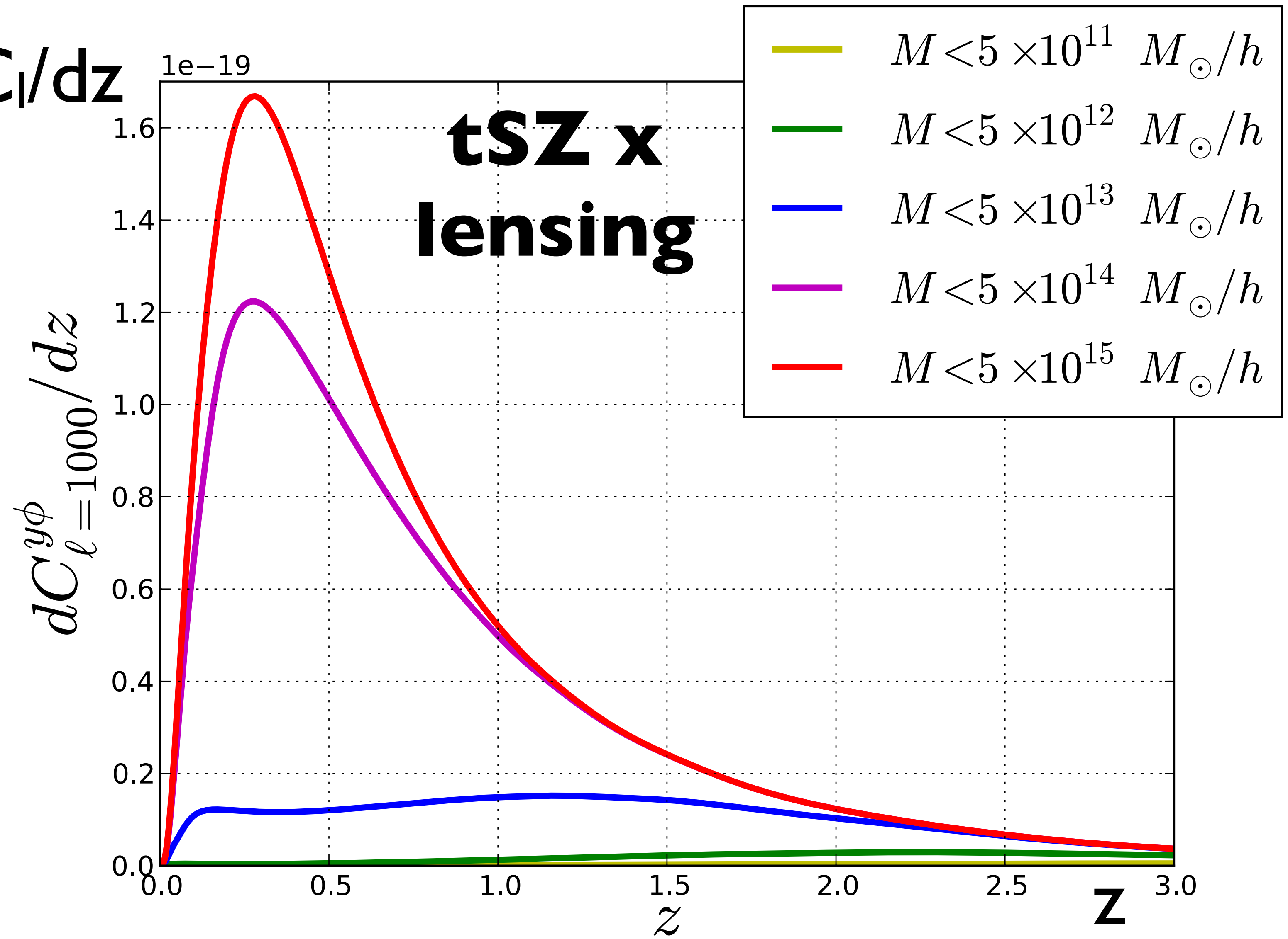

JCH & Spergel (in prep.)

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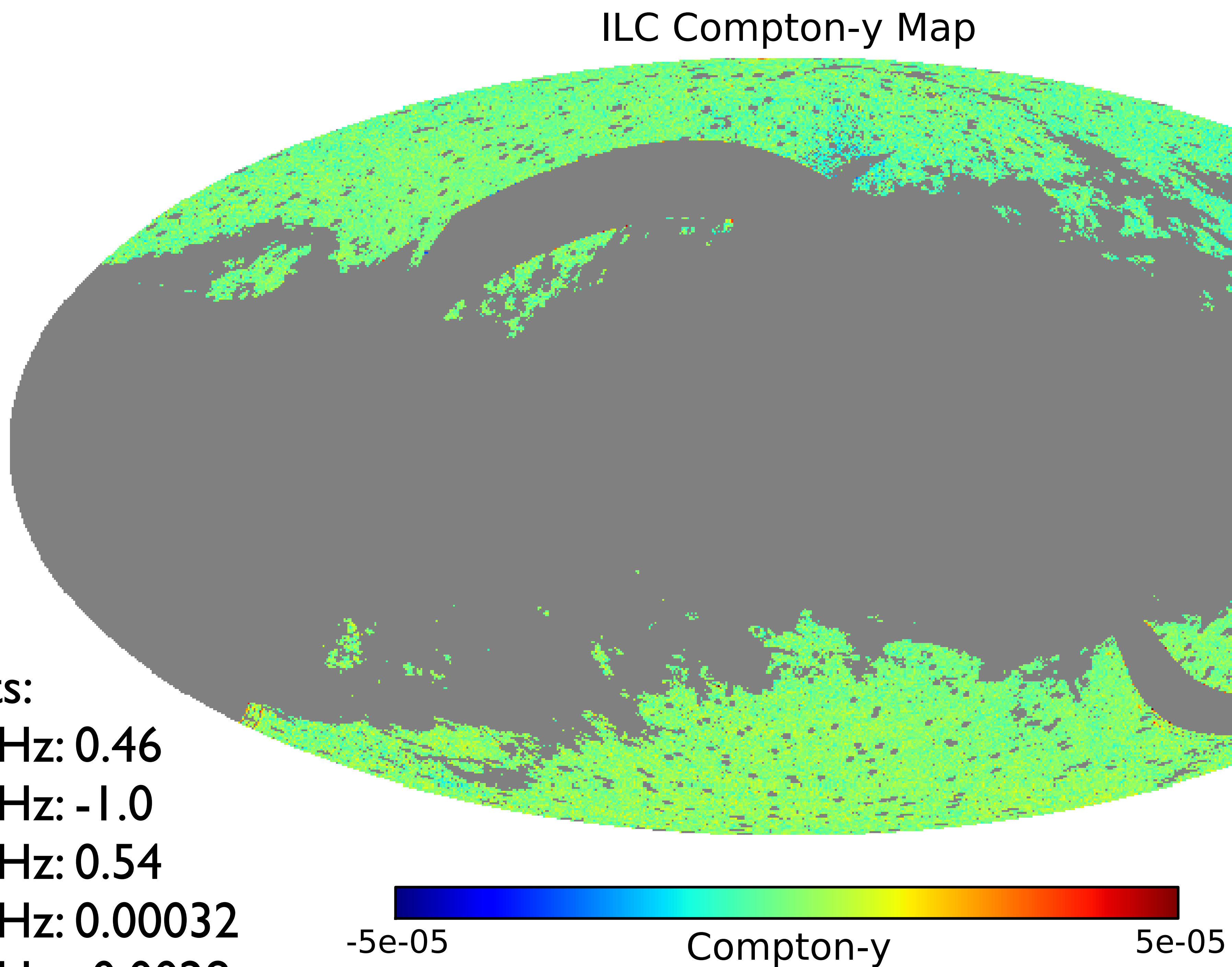
Measurement

Cross-correlate a Compton-y map with a CMB lensing potential map.

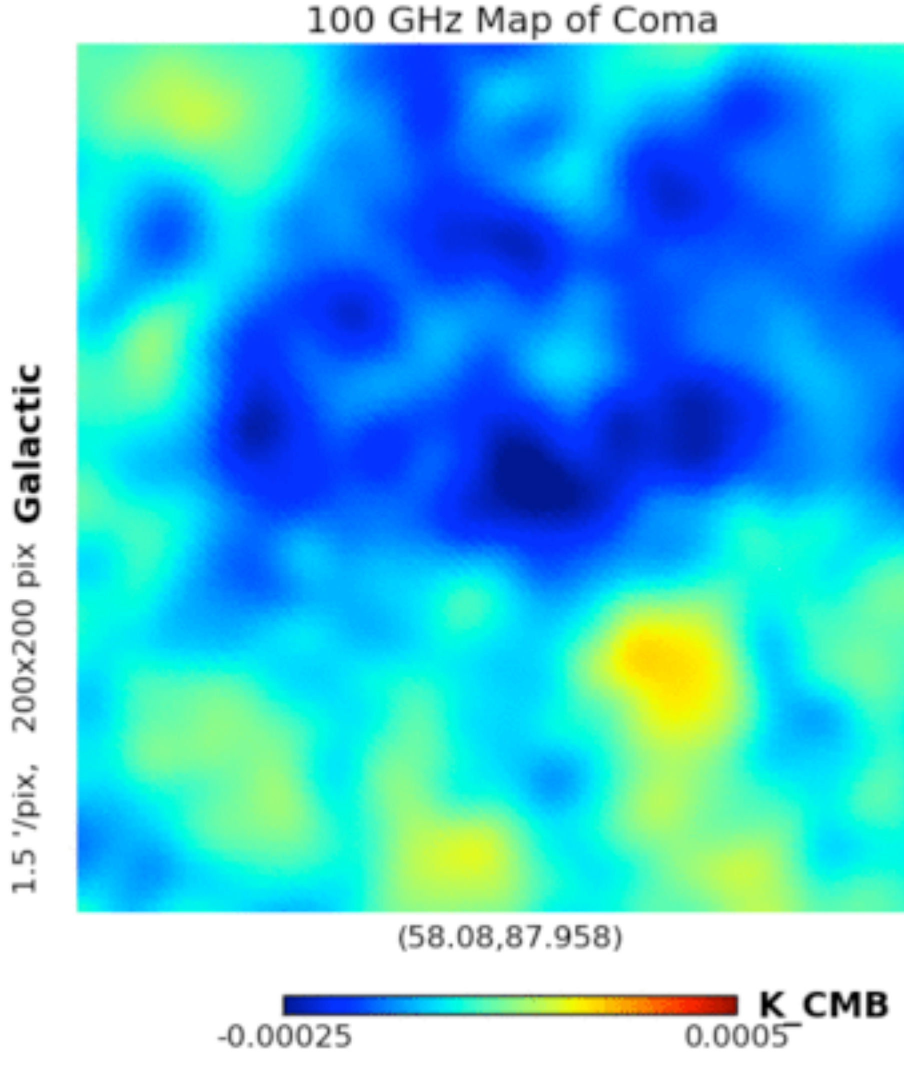
D.I.y-Map

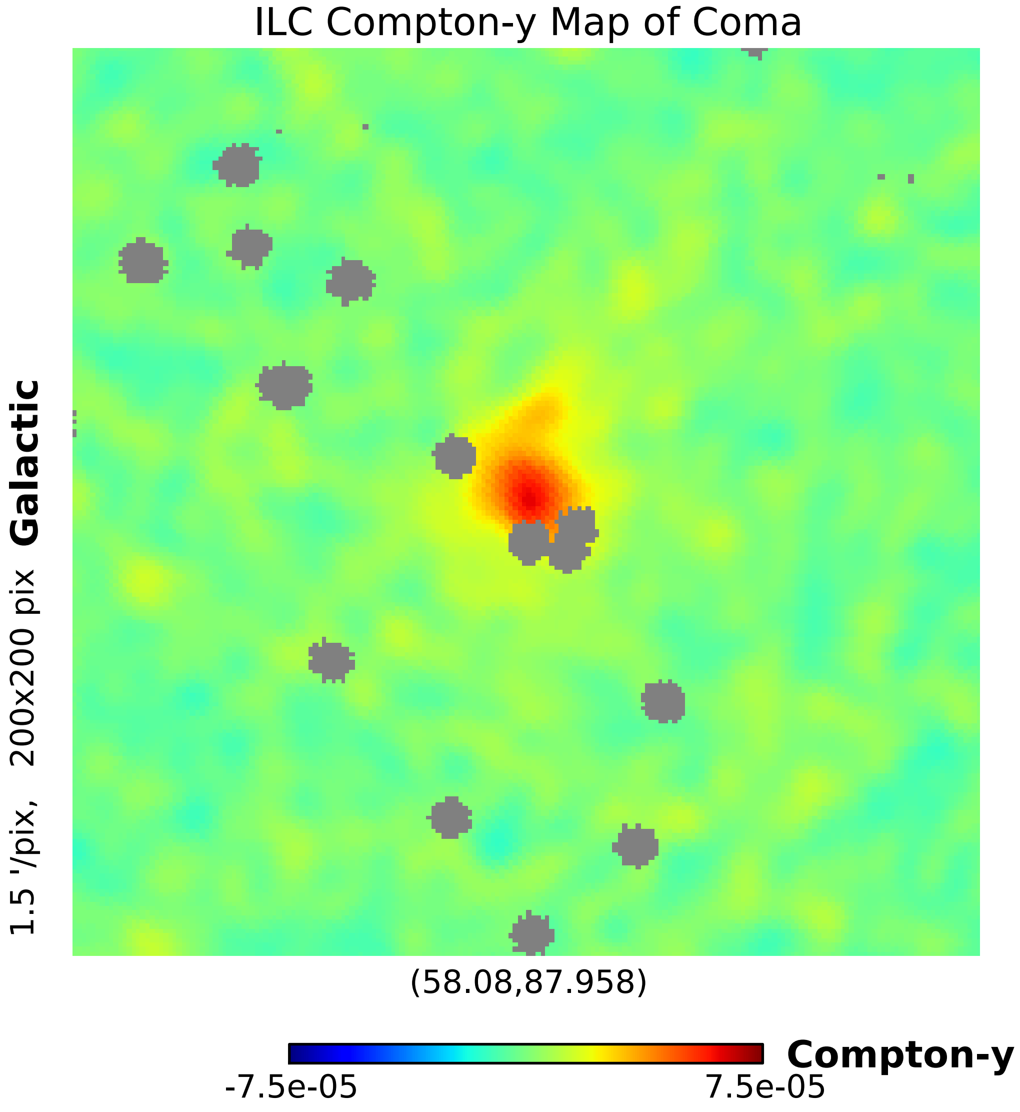


weights:
100 GHz: 0.46
143 GHz: -1.0
217 GHz: 0.54
353 GHz: 0.00032
545 GHz: -0.0028

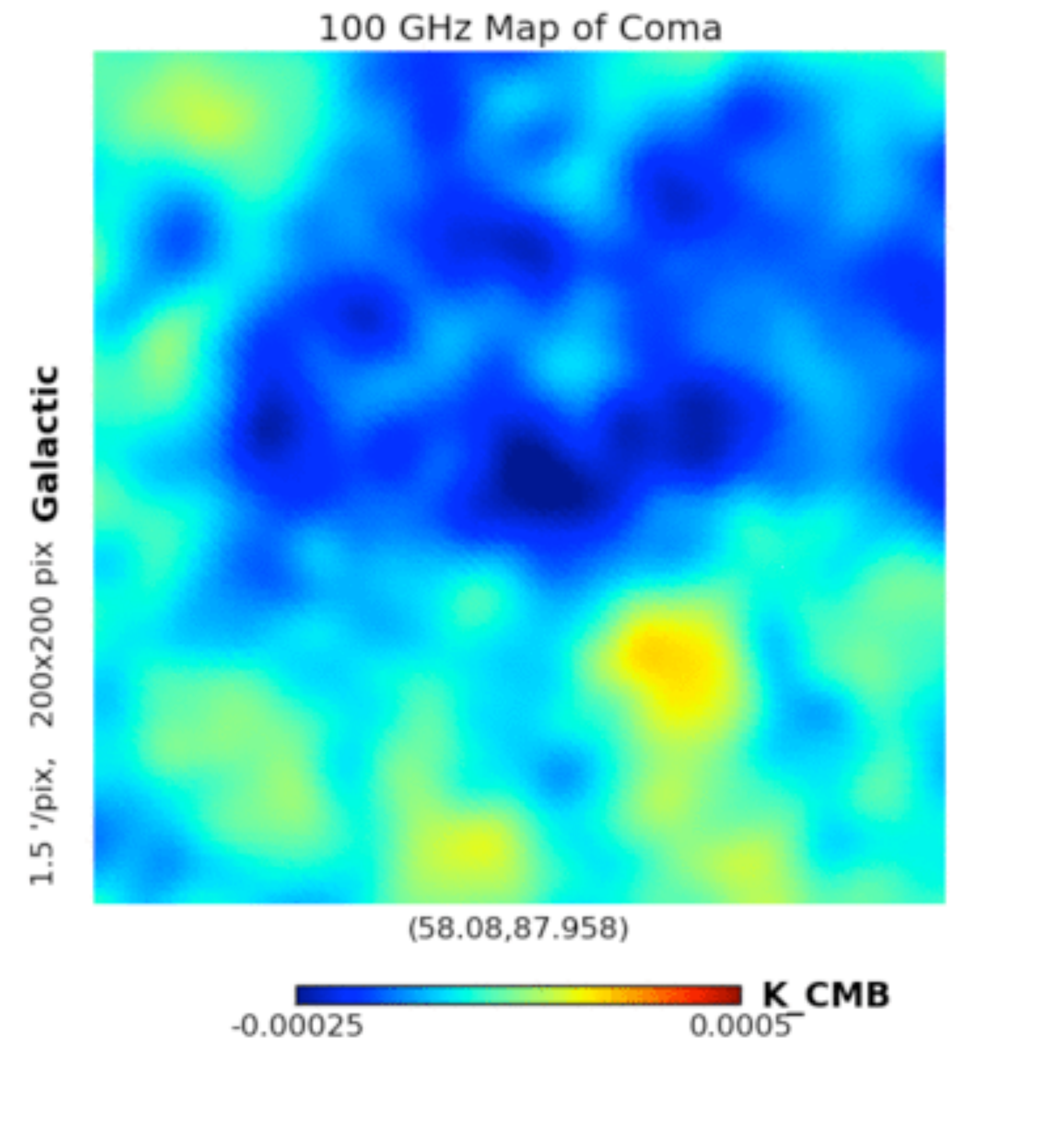
$f_{sky} \sim 0.25$

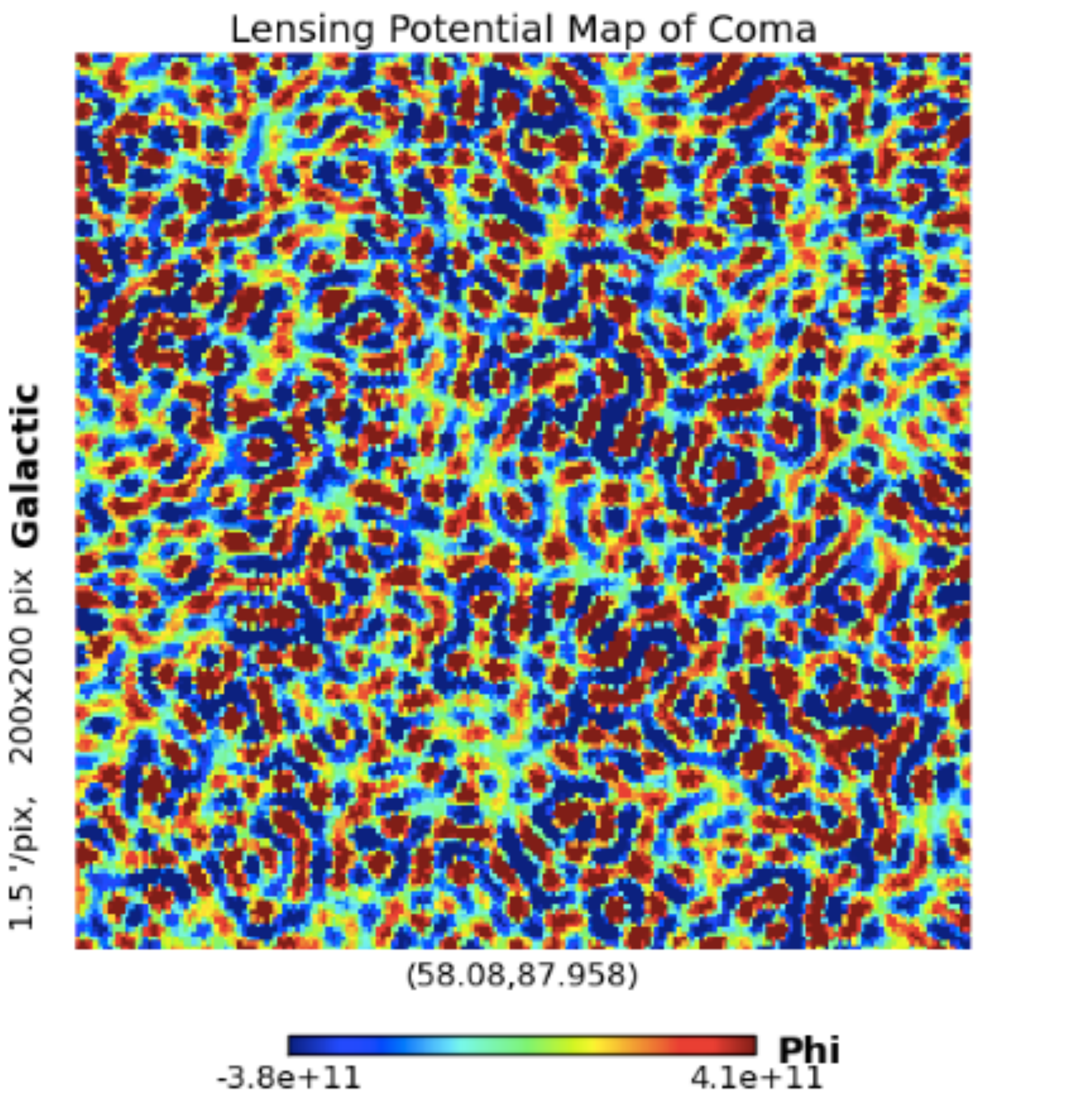
D.I.y-Map


100 GHz Map of Coma
1.5 '/pix, 200x200 pix Galactic
(58.08,87.958)
-0.00025
0.0005
K_CMB

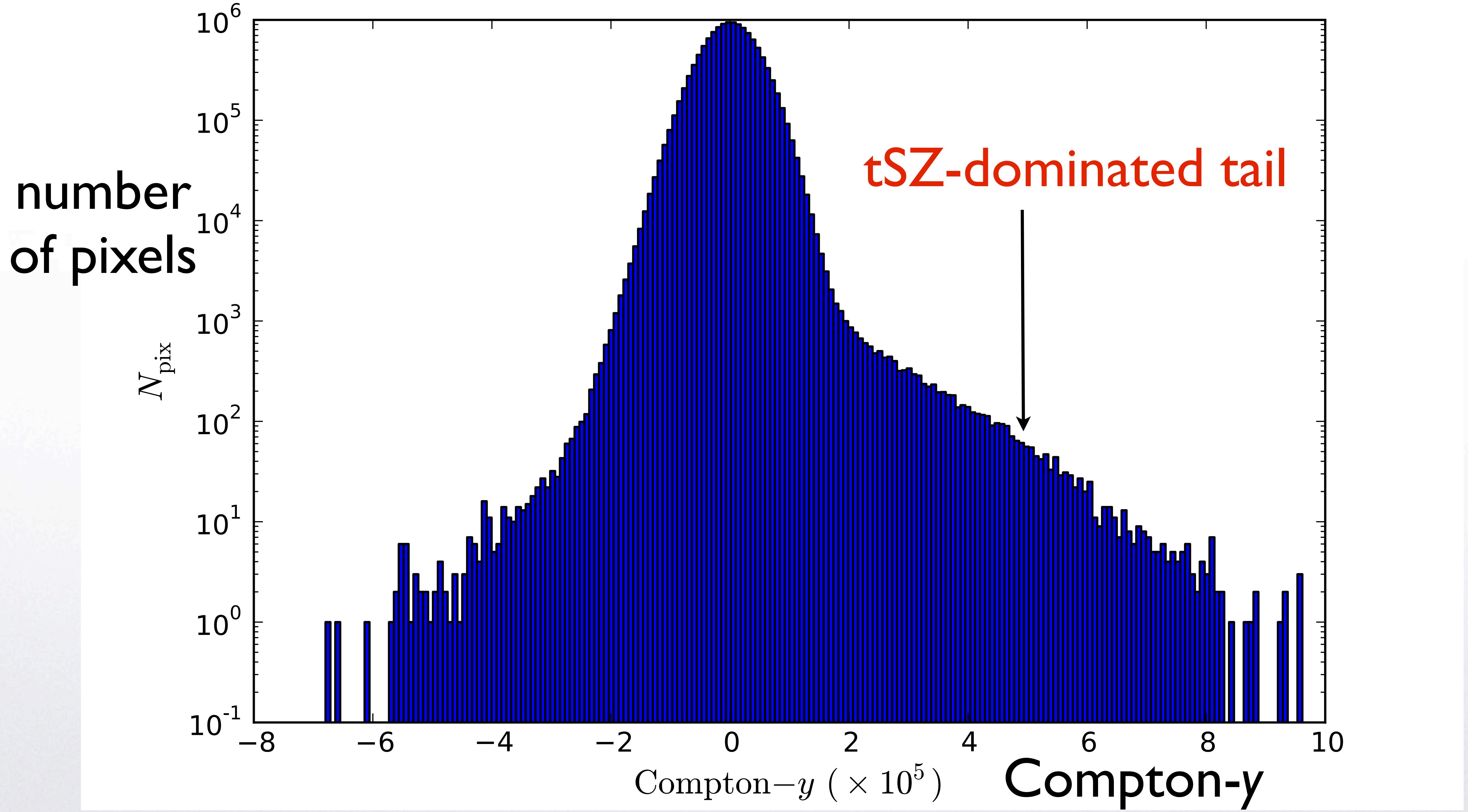

ILC Compton-y Map of Coma
1.5 '/pix, 200x200 pix Galactic
(58.08,87.958)
-7.5e-05
7.5e-05
Compton-y

D.I.y-Map


100 GHz Map of Coma
1.5 '/pix, 200x200 pix Galactic
(58.08,87.958)
K_CMB
-0.00025
0.0005

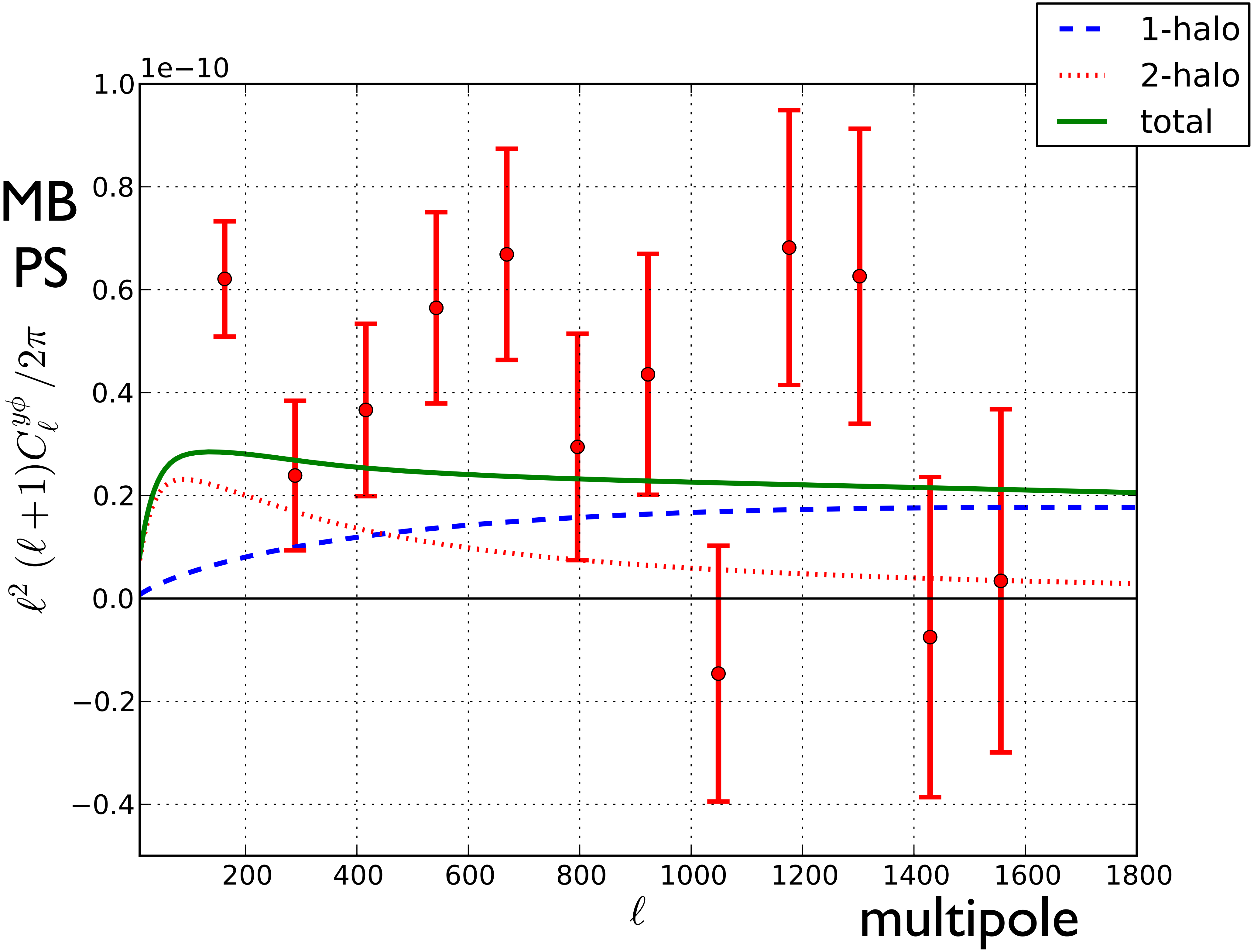

Lensing Potential Map of Coma
1.5 '/pix, 200x200 pix Galactic
(58.08,87.958)
Phi
-3.8e+11
4.1e+11

D.I.y-Map: Histogram



D.I.y x CMB Lensing

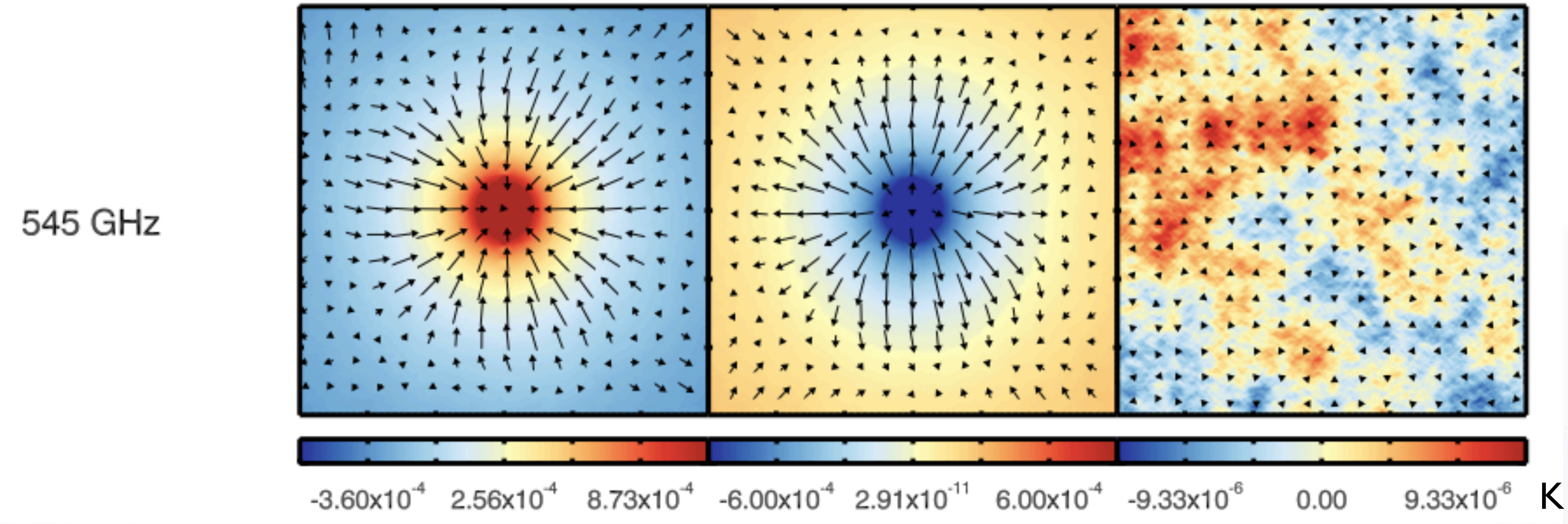
tSZ x CMB Lensing PS



8.7σ

D.I.y x CMB Lensing

- Main contamination worry: cosmic infrared background (CIB)
- Correlates very strongly with CMB lensing



D.I.y x CMB Lensing

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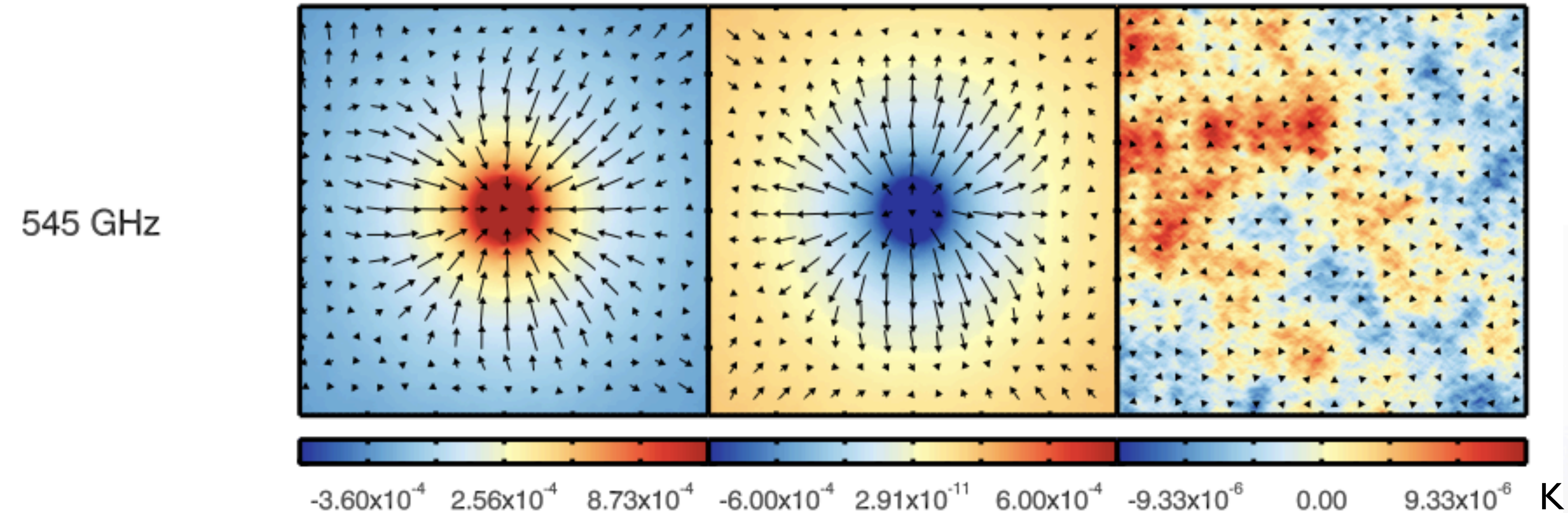
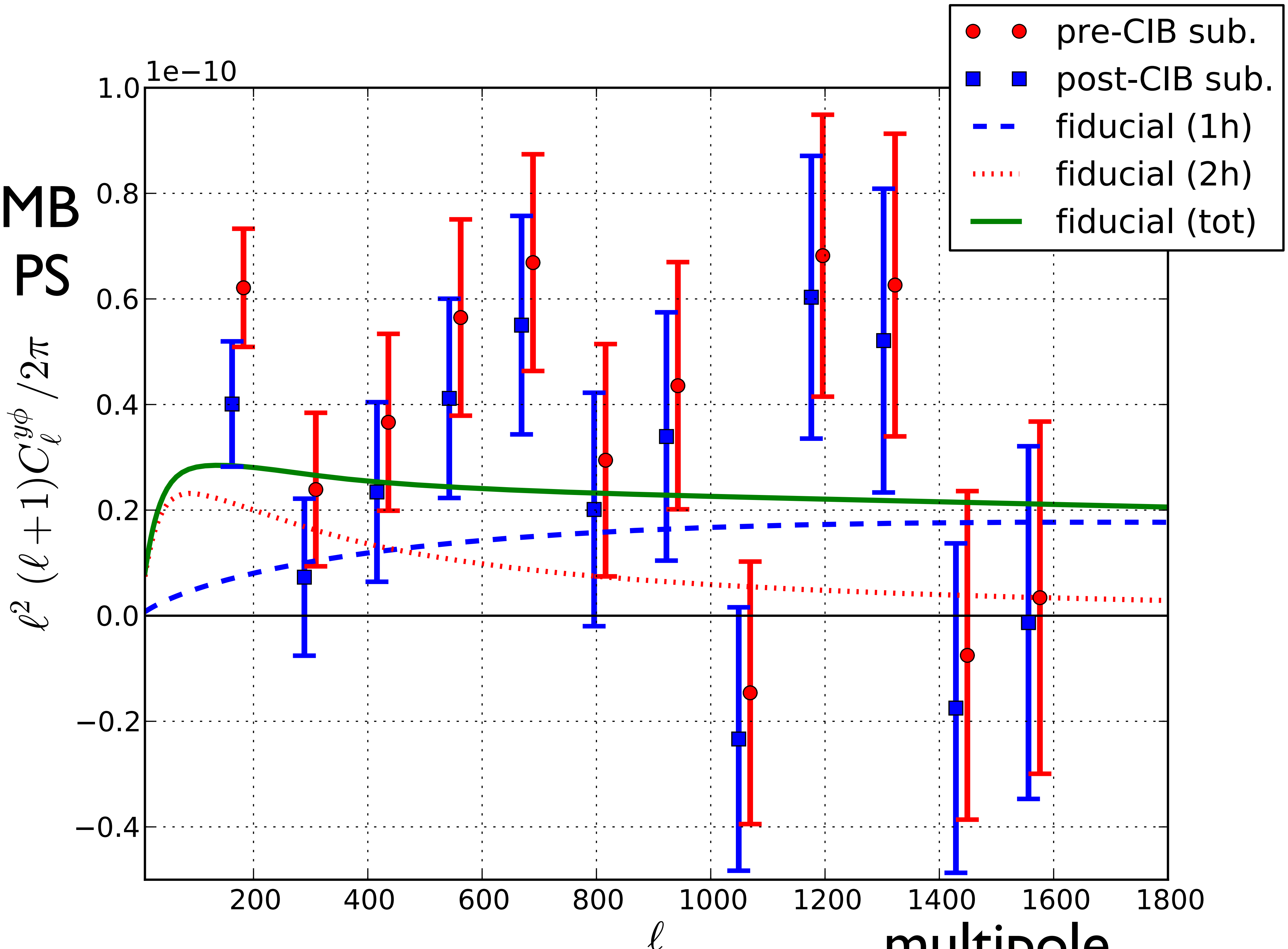


- Assess leakage of CIB into *y*-map as follows:
  - Cross-correlate with 857 GHz map
  - Separate contribution due to galactic dust from that due to CIB
  - Obtain coefficient describing *y* x CIB amplitude
  - Scale Planck CIB x lensing results by this coefficient and subtract the result from the *y* x lensing measurement

Planck Collaboration XVIII (2013)

Colin Hill
Princeton

tSZ x CMB Lensing PS



multipole

6.2σ

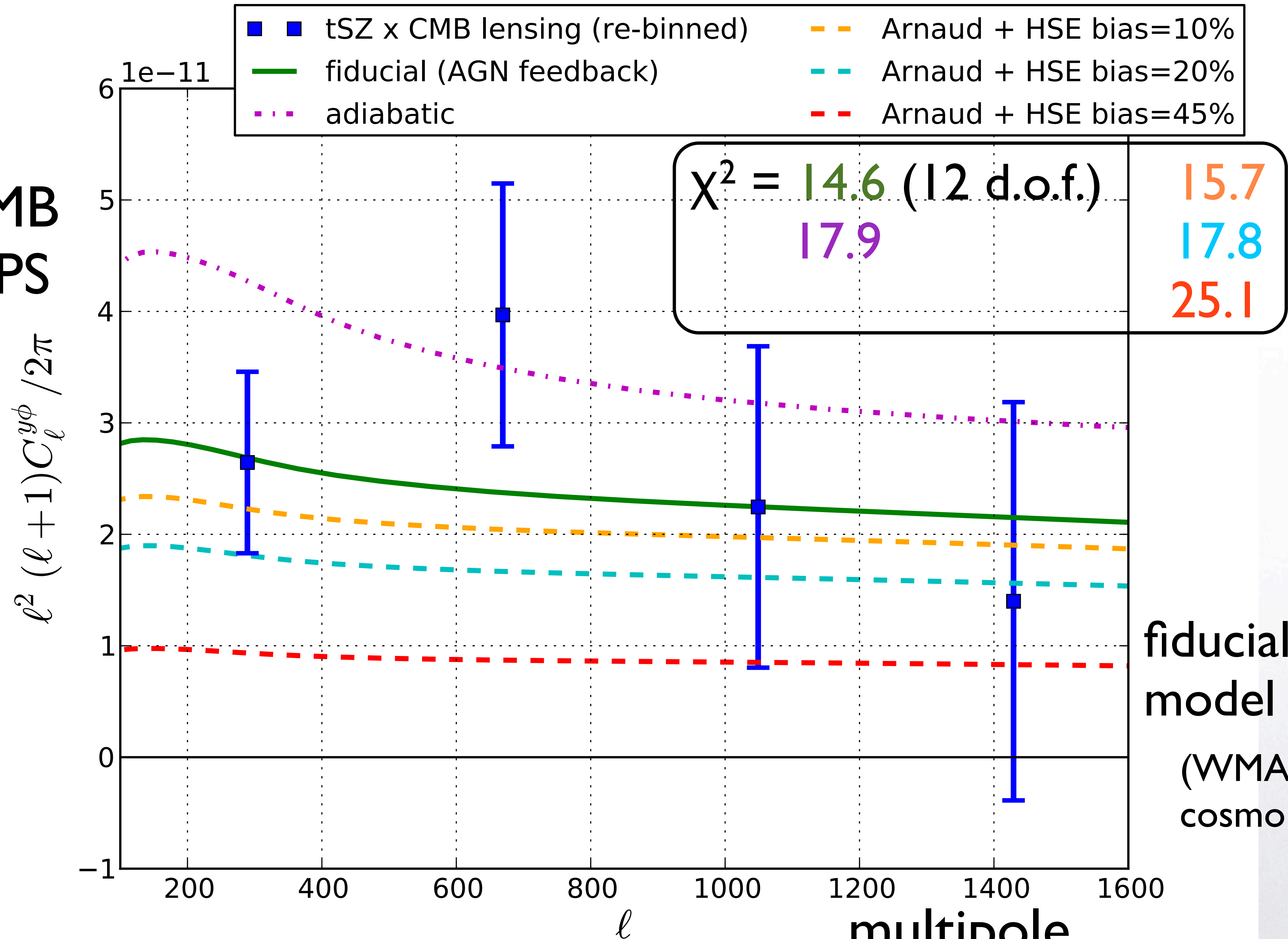
JCH & Spergel (in prep.)

Colin Hill
Princeton

Interpretation: Gastrophysics

Interpretation: Gastrophysics

tSZ x CMB Lensing PS



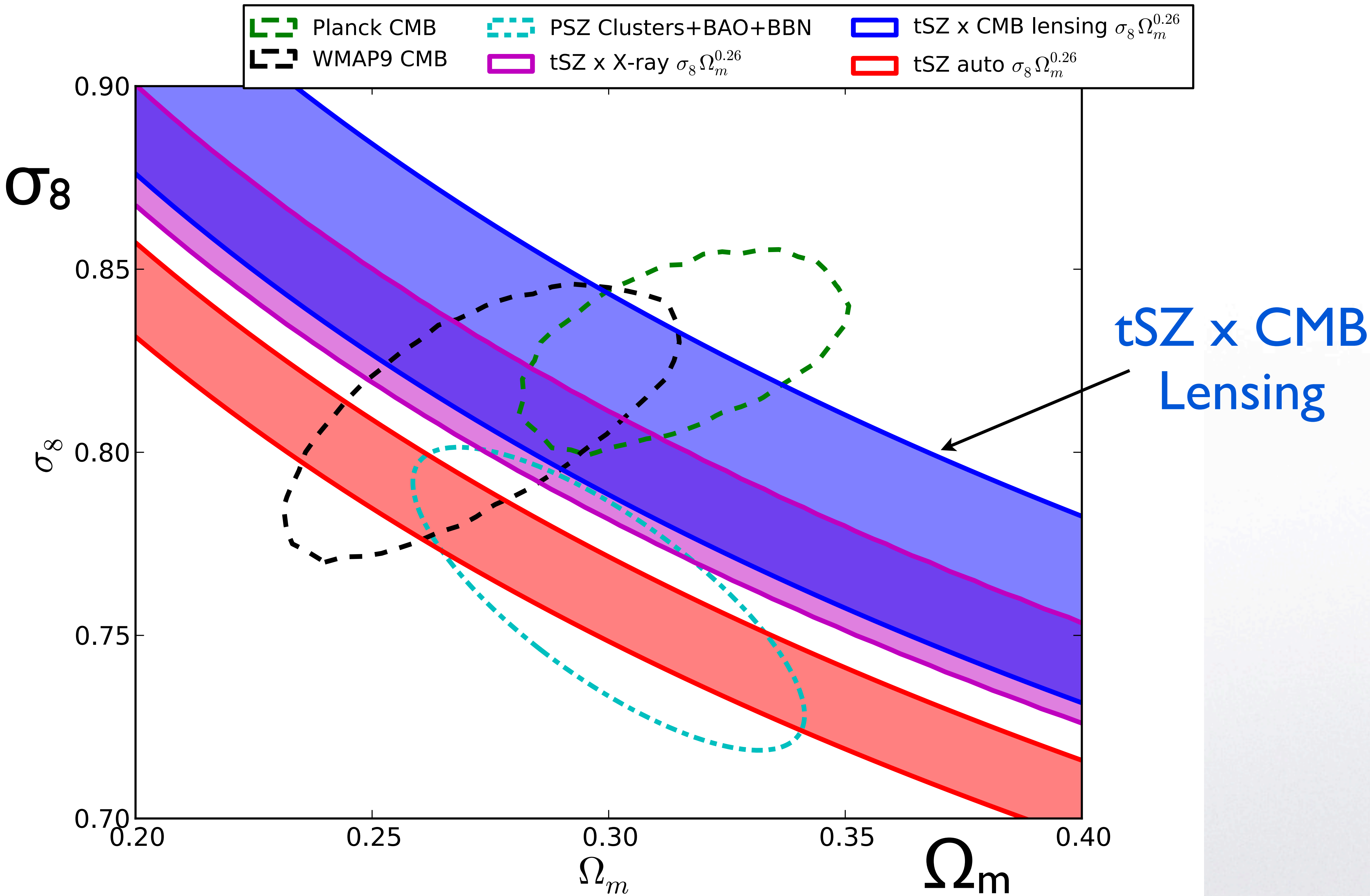
fiducial ICM model favored

(WMAP9 cosmology)

JCH & Spergel (in prep.)

Colin Hill
Princeton

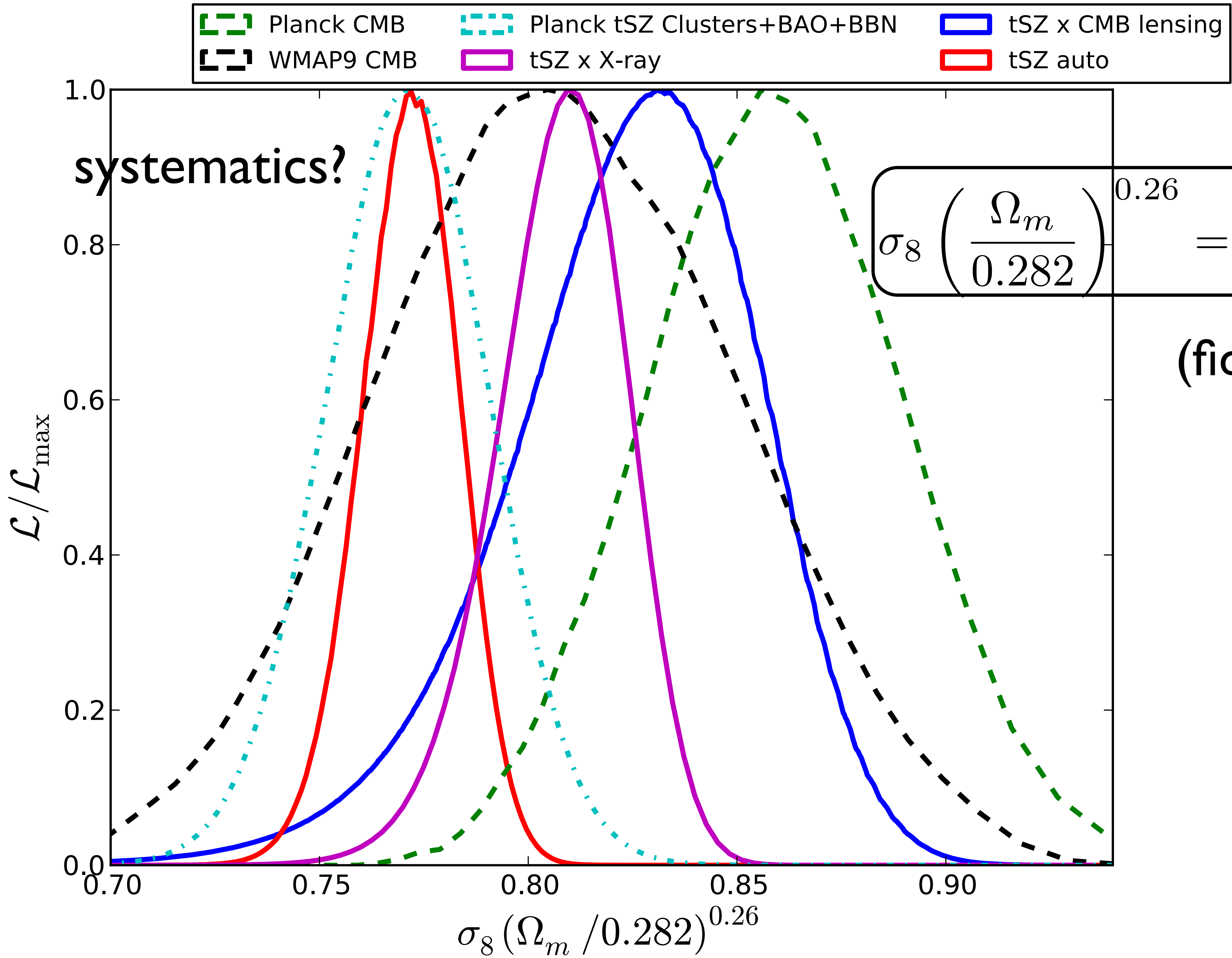
Interpretation: Cosmology



JCH & Spergel (in prep.)
Hajian, Battaglia, et al. (2013)

Colin Hill
Princeton

Interpretation: Cosmology



$$\sigma_8 \left(\frac{\Omega_m}{0.282}\right)^{0.26} = 0.831^{+0.026}_{-0.030}$$

(fiducial ICM)

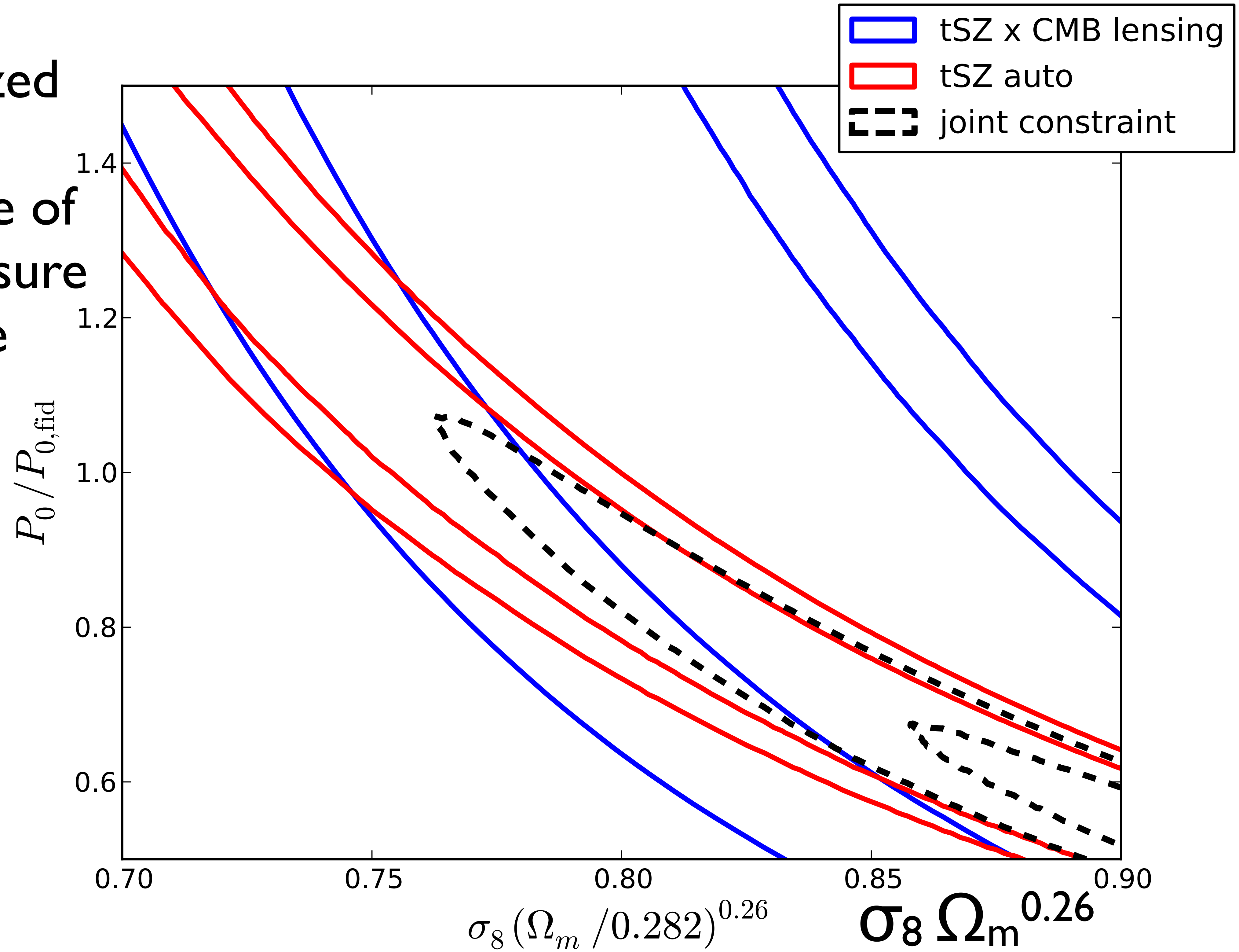
JCH & Spergel (in prep.)

Hajian, Battaglia, et al. (2013)

Colin Hill
Princeton

Interpretation: ICM + Cosmology

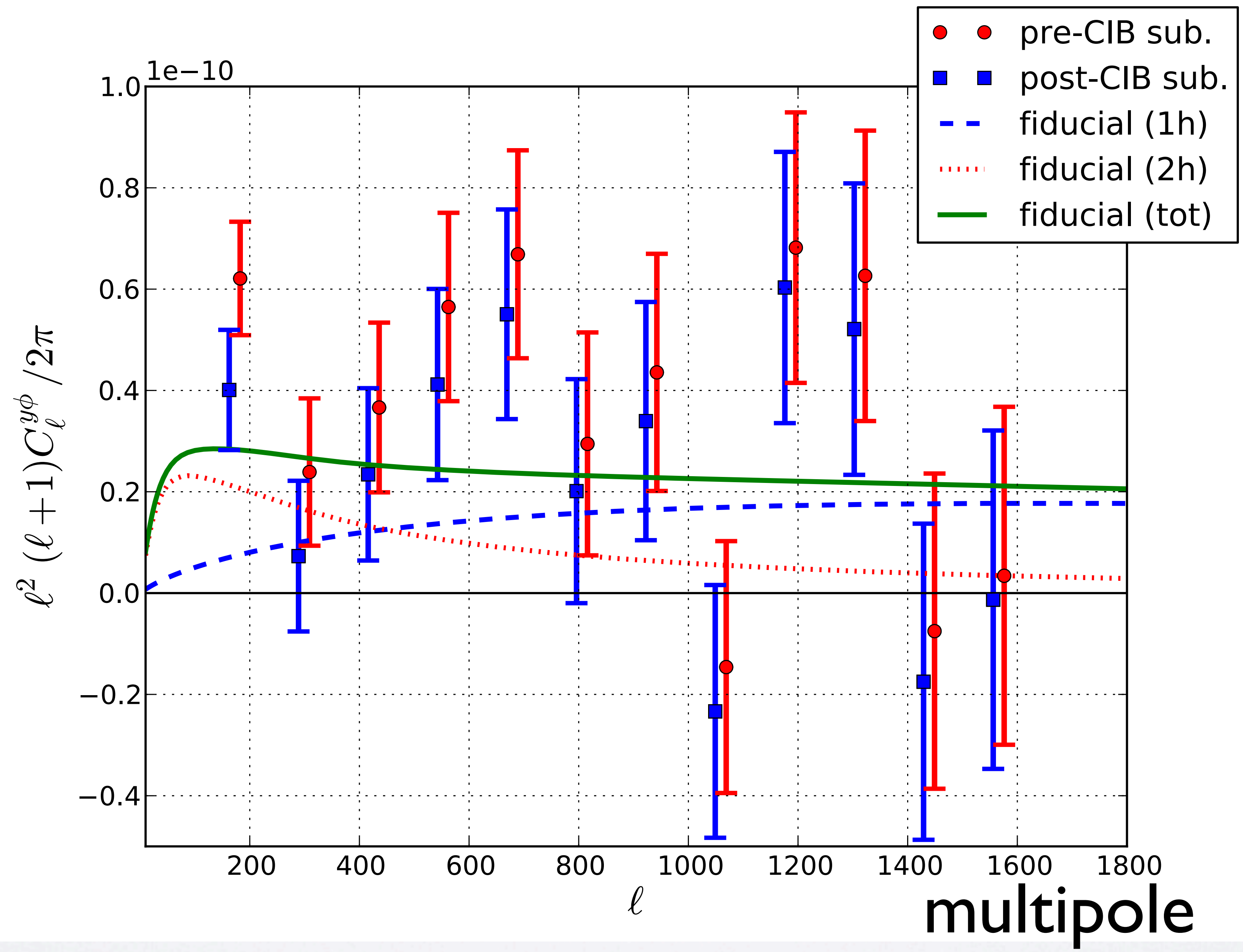
normalized mean amplitude of ICM pressure profile



$\sigma_8 \, \Omega_m^{0.26}$

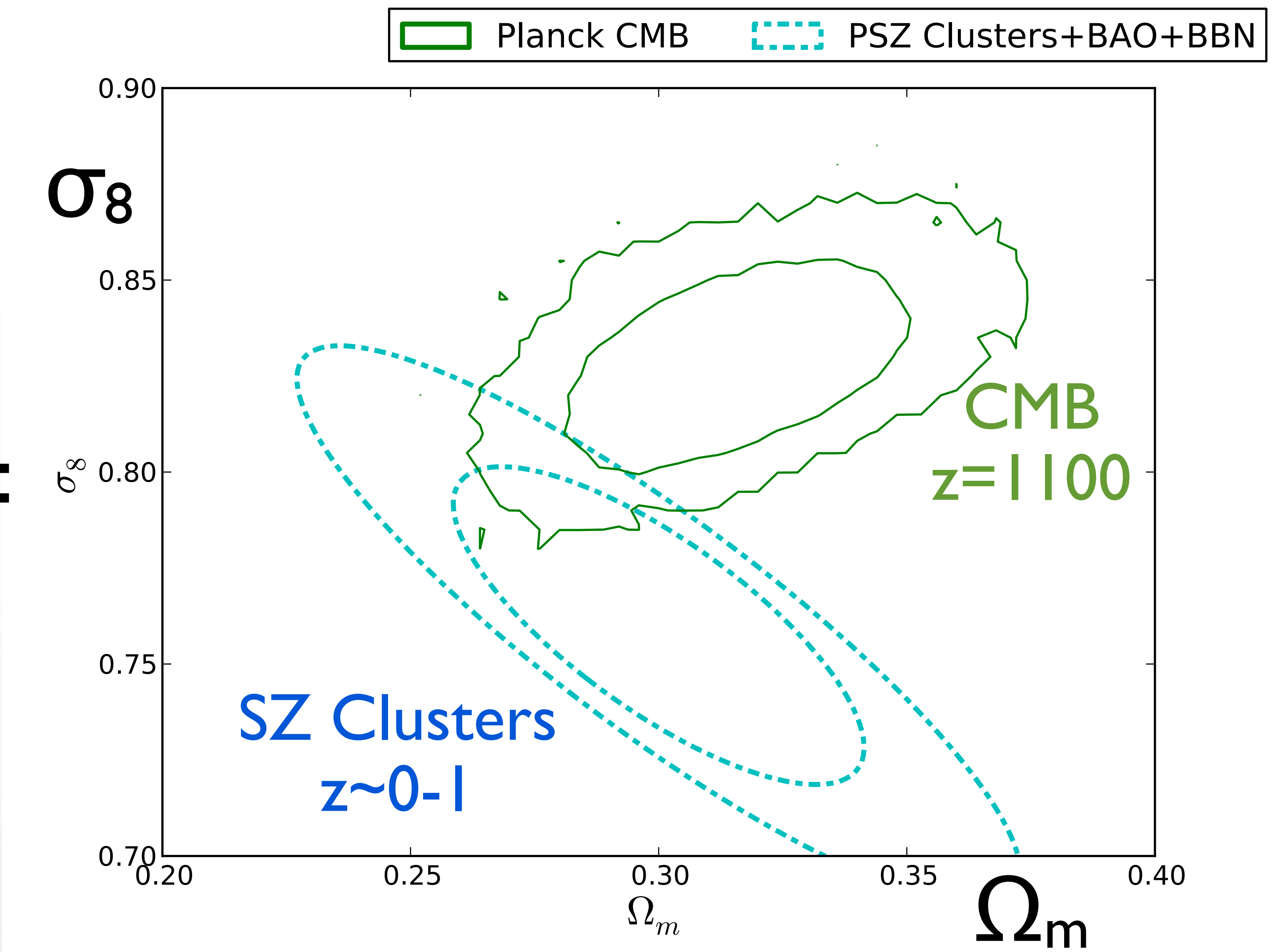
Interpretation

tSZ x CMB Lensing PS



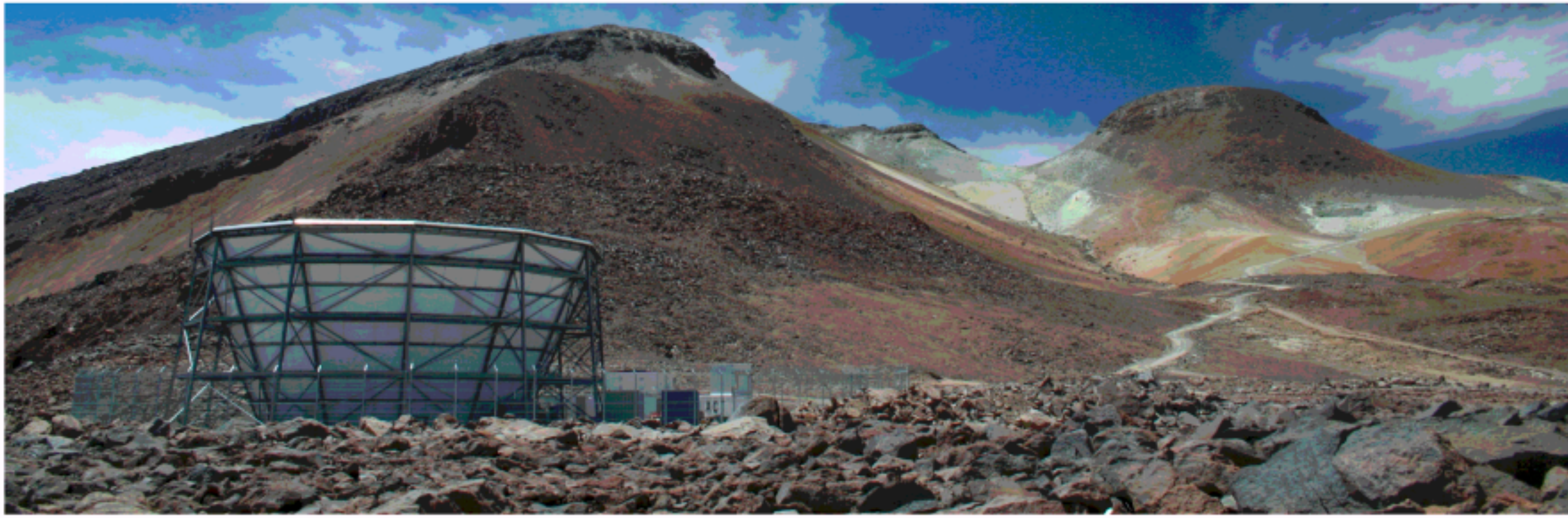
Direct confirmation that hot, ionized gas traces dark matter over a wide range of scales.

ACT:
Thermal SZ 1-pt PDF



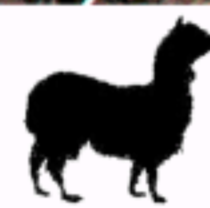
The Atacama Cosmology Telescope

http://www.princeton.edu/atacama/



ATACAMA
COSMOLOGY
TELESCOPE

148, 218,
277 GHz



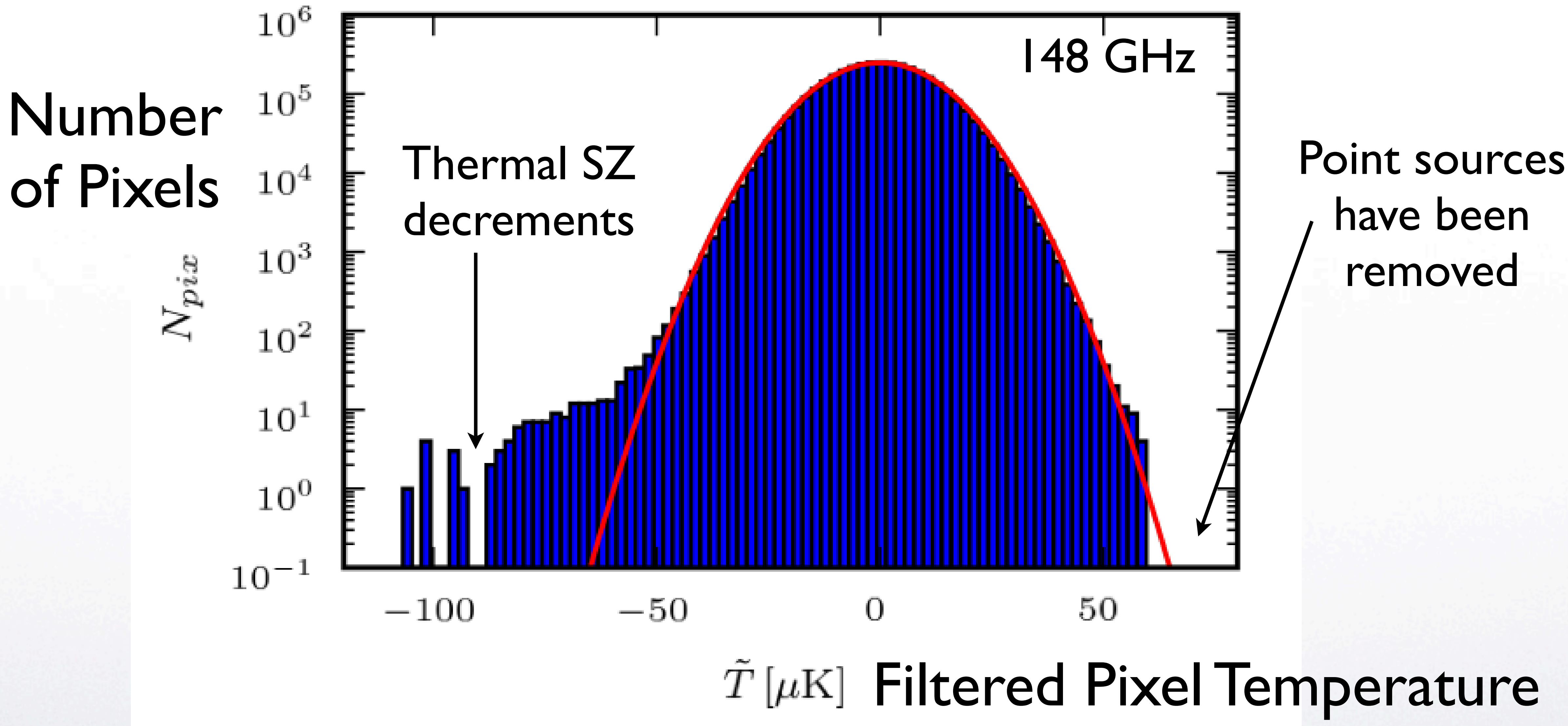
~1 arcmin
resolution

The Atacama Cosmology Telescope (ACT) is a six-meter telescope on Cerro Toco in the Atacama Desert in the north of Chile, near the Llano de Chajnantor Observatory. It is designed to make high-resolution, microwave-wavelength surveys of the sky in order to study the cosmic microwave background radiation (CMB). At an altitude of 5190 meters (17,030 feet), it is one of the highest permanent, ground-based telescopes in the world.

Colin Hill
Princeton

Higher-order tSZ Statistics

- ACT/SPT: small beams+low noise, hence significant detection of *y* NG



Wilson, Sherwin, JCH++ (2012)

Colin Hill
Princeton

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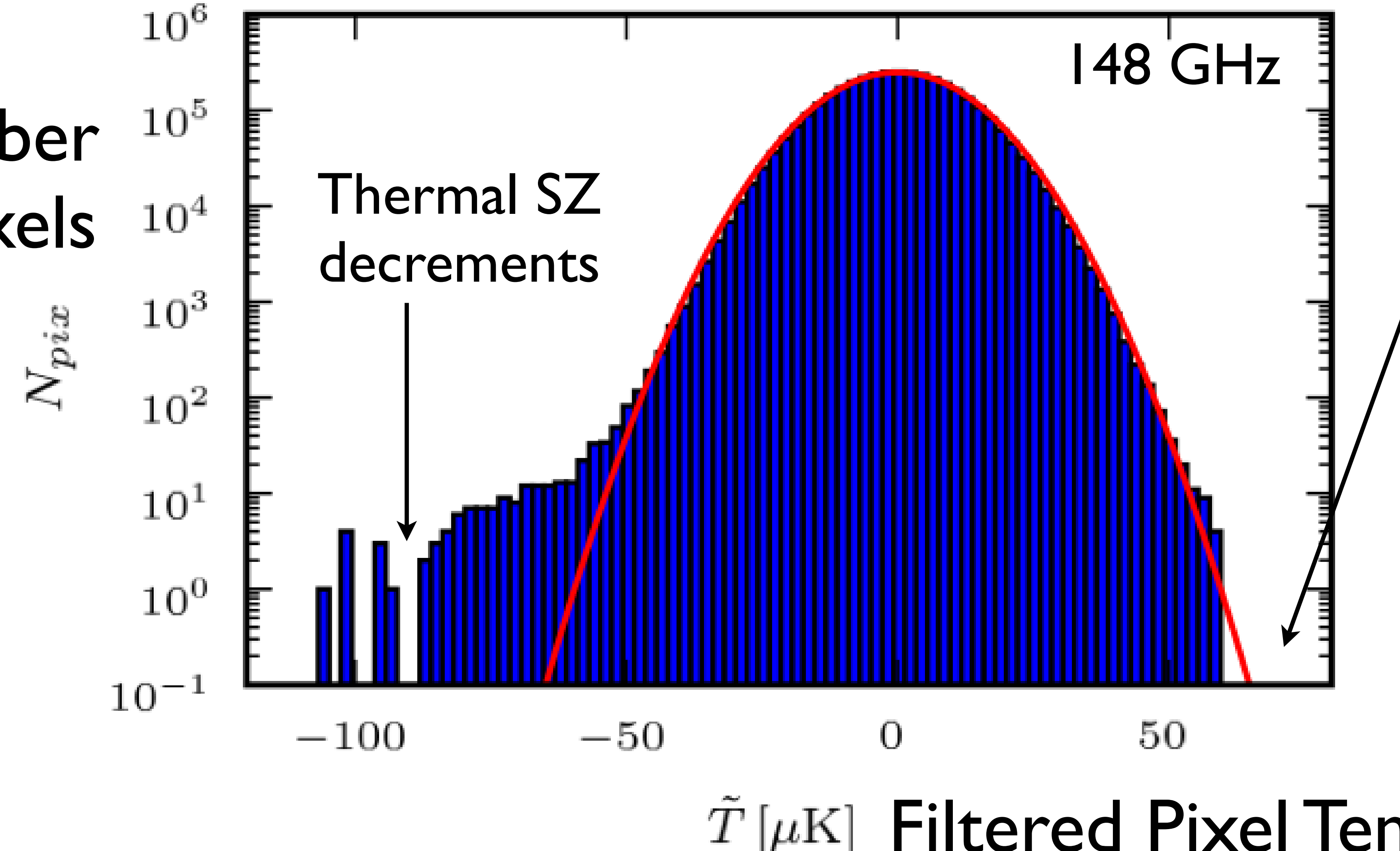


$$\left\langle \tilde{T}^3 \right\rangle = -31 \pm 6\,\mu\mathrm{K}^3 \quad \text{(Gaussian errors only)}$$
$$\pm 14\,\mu\mathrm{K}^3 \quad \text{(with non-Gaussian error, i.e., CV)}$$

$$\sigma_8 = 0.79^{+0.03}_{-0.03}\ (68\%\ \mathrm{C.L.})\ {}^{+0.06}_{-0.06}\ (95\%\ \mathrm{C.L.})$$

Wilson, Sherwin, JCH++ (2012)

Colin Hill
Princeton

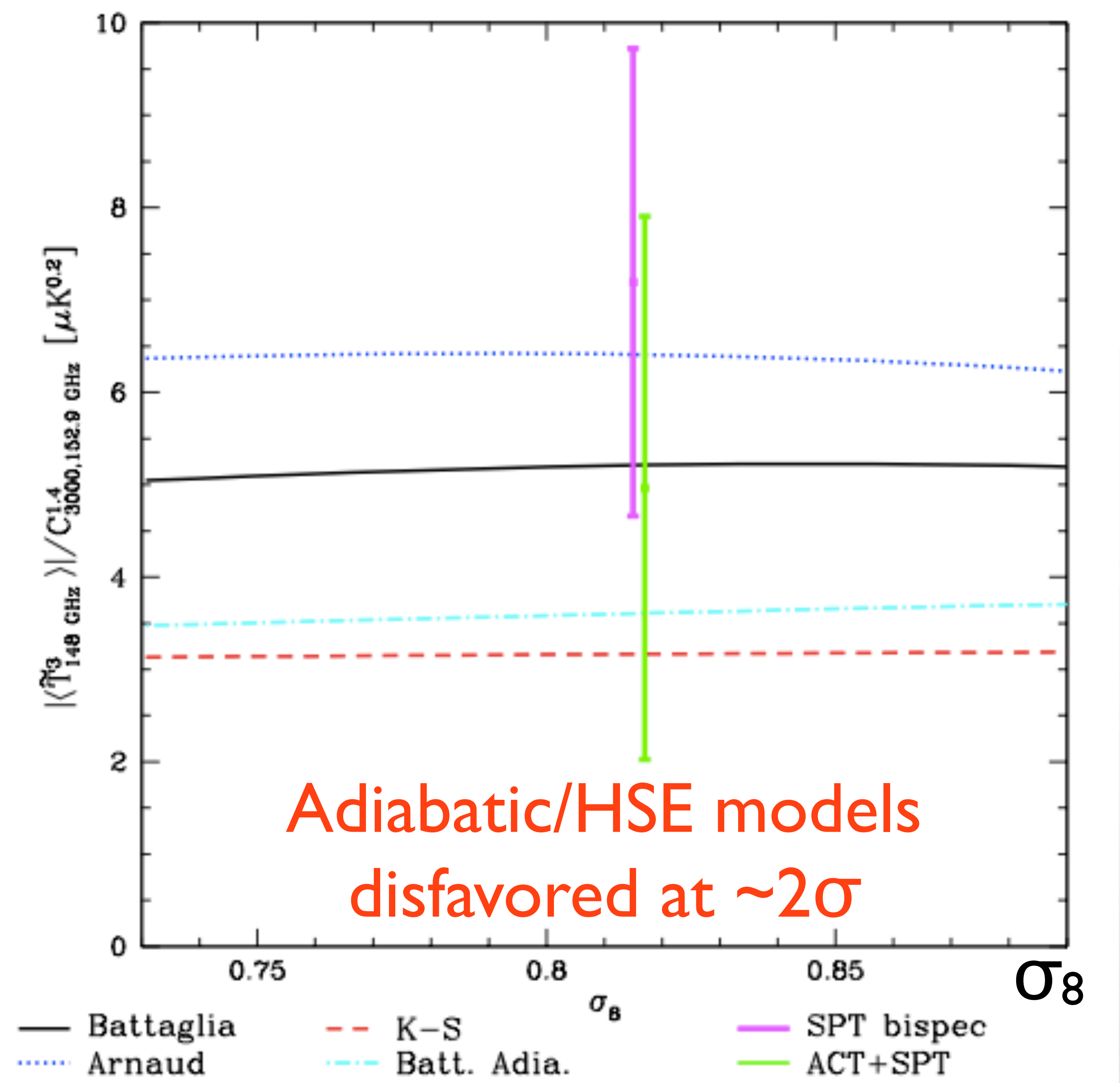
Higher-order tSZ Statistics

Different statistics depend differently on cosmology and ICM

$C_\ell \propto \sigma_8^7$ | $\langle T^3 \rangle \propto \sigma_8^{11}$

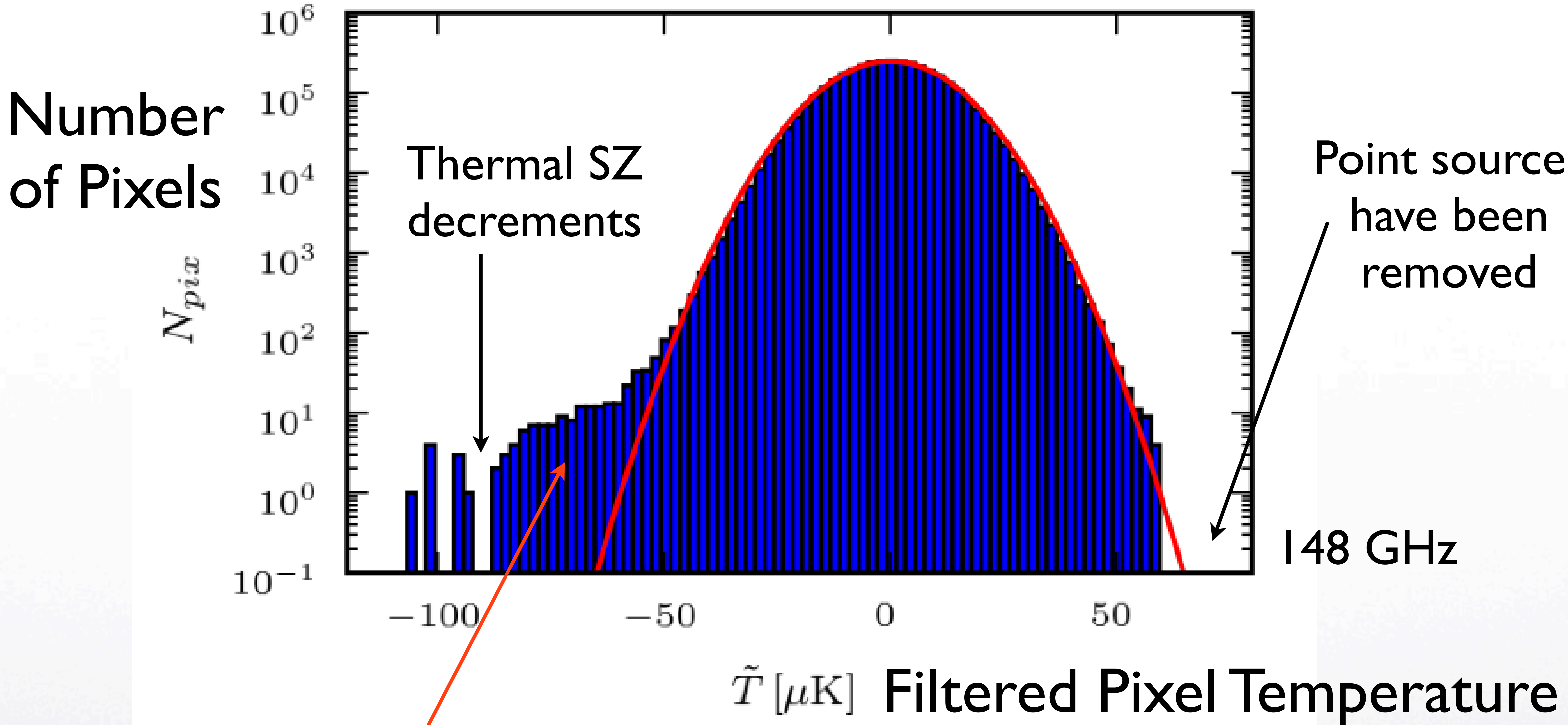
Can combine statistics to break ICM-cosmology degeneracy

'rescaled skewness'



(updated with new SPT results)

Beyond the Skewness



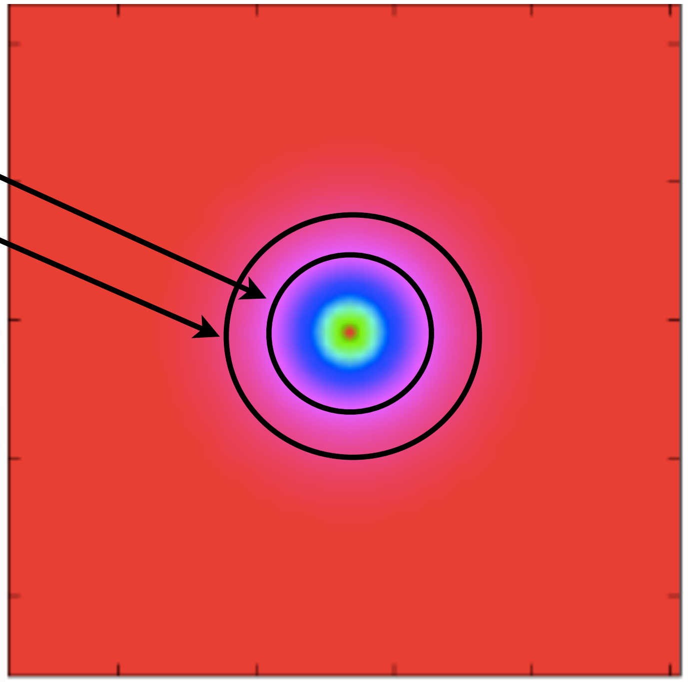
Why not compute the PDF itself? Have we used all of the information?

Colin Hill
Princeton

Thermal SZ PDF

- Useful re-phrasing: how much sky area is subtended by Compton-y values in a given range?

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



- Simple for a spherical cluster: area between two circles
- Then add up such areas for all clusters:

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

Thermal SZ PDF

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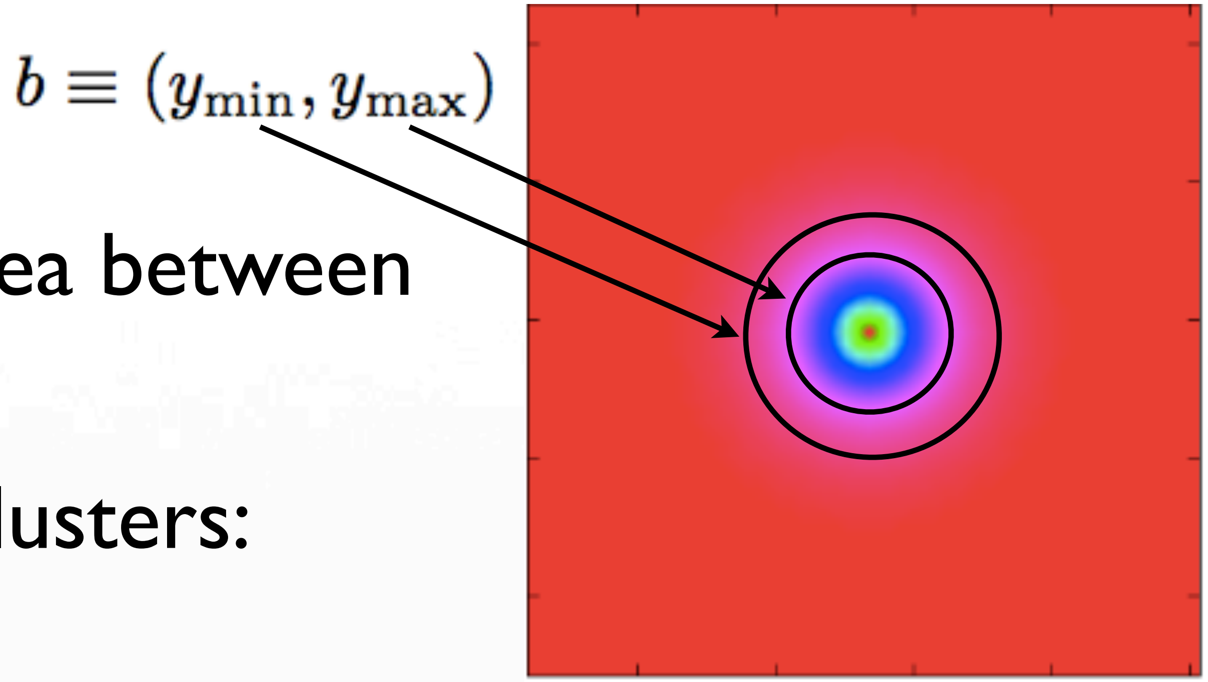

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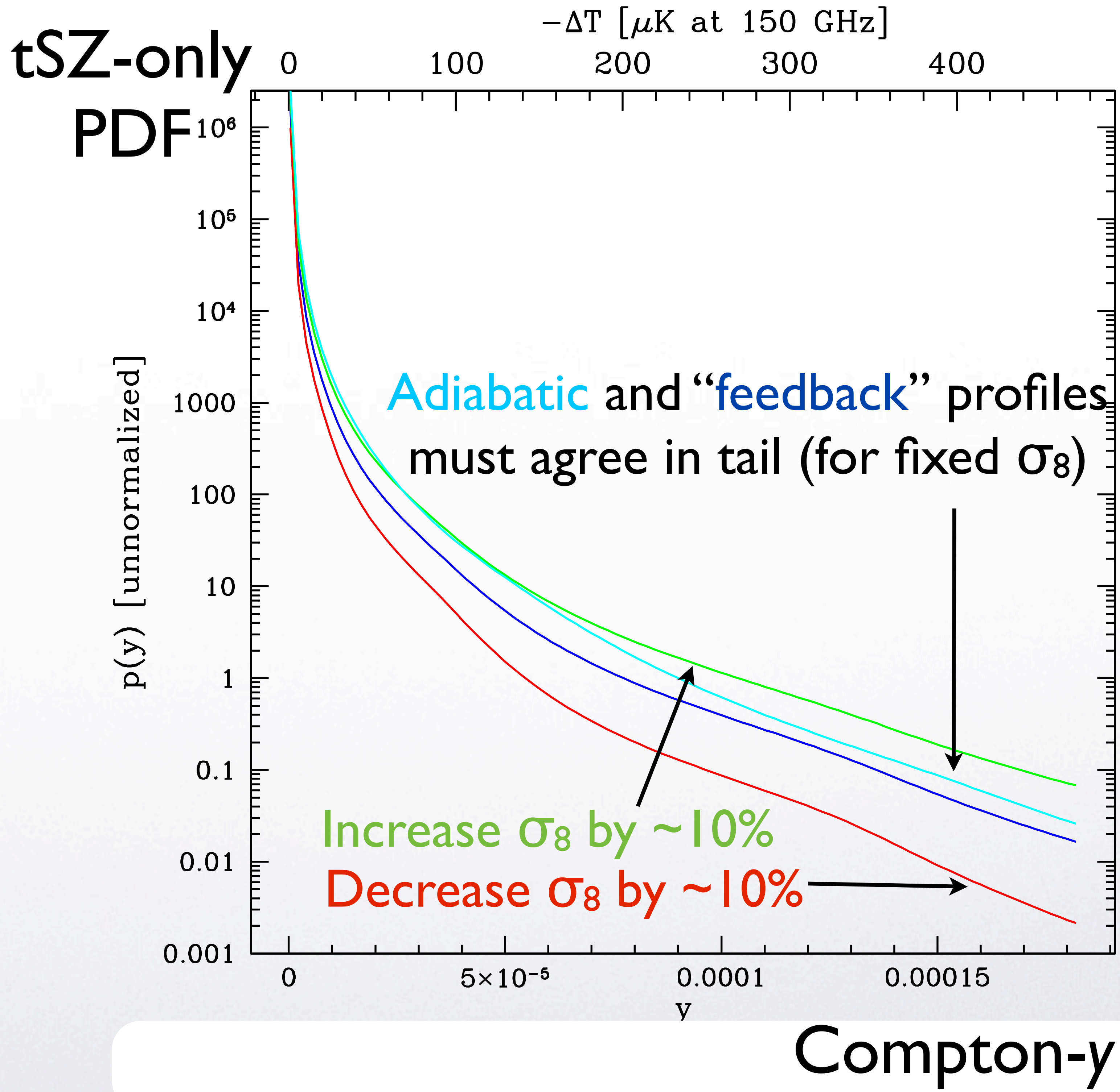
- Complications: non-tSZ contributions in CMB map
  inhomogeneous atmospheric/instrumental noise
  cluster overlaps along LOS

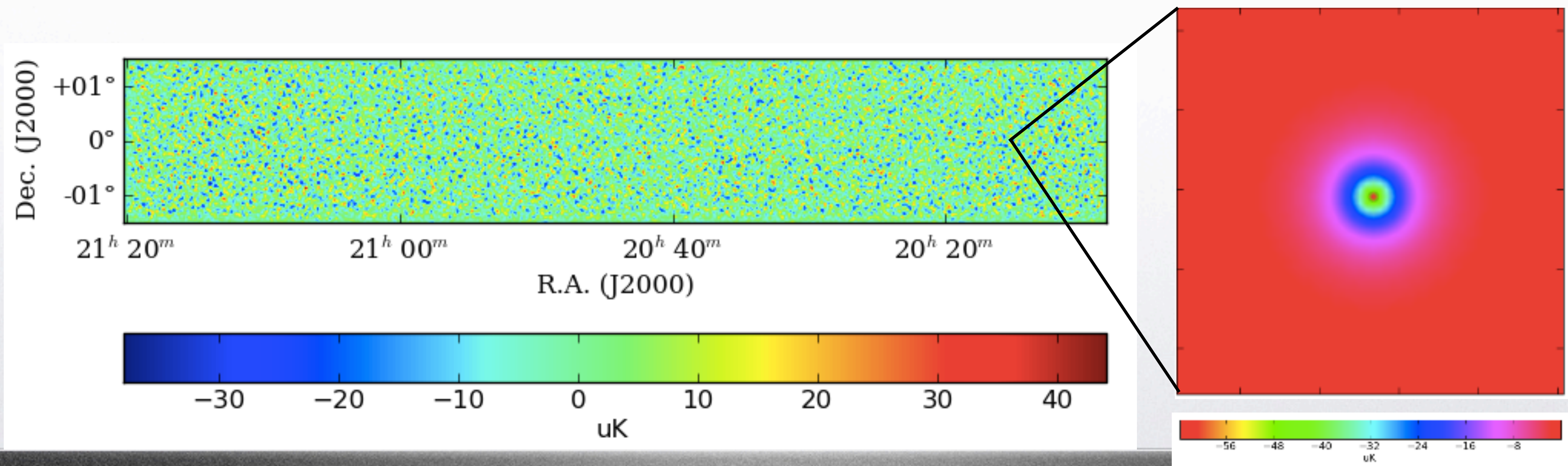
Thermal SZ PDF

- PDF includes cosmological power of all tSZ moments
- *y* PDF provides natural generalization of "rescaled moments"
  - Cosmology (σ_8) sets the amplitude of the PDF tail (where profiles agree)
  - Gastrophysics determines the shape of the PDF at lower *y*
- Caveat: PDF discards (most of the) angular information which polyspectra contain



Thermal SZ PDF

- Forecast: factor of ~3 decrease in σ_8 error compared to skewness alone if making same analysis assumptions (e.g., fixed gastrophysics model)
- PDF shape breaks degeneracy: forecast ~10-20% constraint on normalization of ICM pressure profile (P_0), with only small increase in $\Delta\sigma_8$
- In progress: robust determination of covariance matrix using a new simulation pipeline



- Thermal SZ measurements are a sensitive probe of both cosmology and the gastrophysics of the ICM.

- Questions remain:
  - Can we understand the ICM well enough to use tSZ for cosmology?
  - How to best parametrize ICM?
  - What is the best tSZ statistic for a given experiment or desired parameter?

- Using cross-correlations and higher-order statistics we can clarify the origin of the current tension between tSZ and primordial CMB constraints.