Cosmological Constraints from Moments of the Thermal SZ Effect

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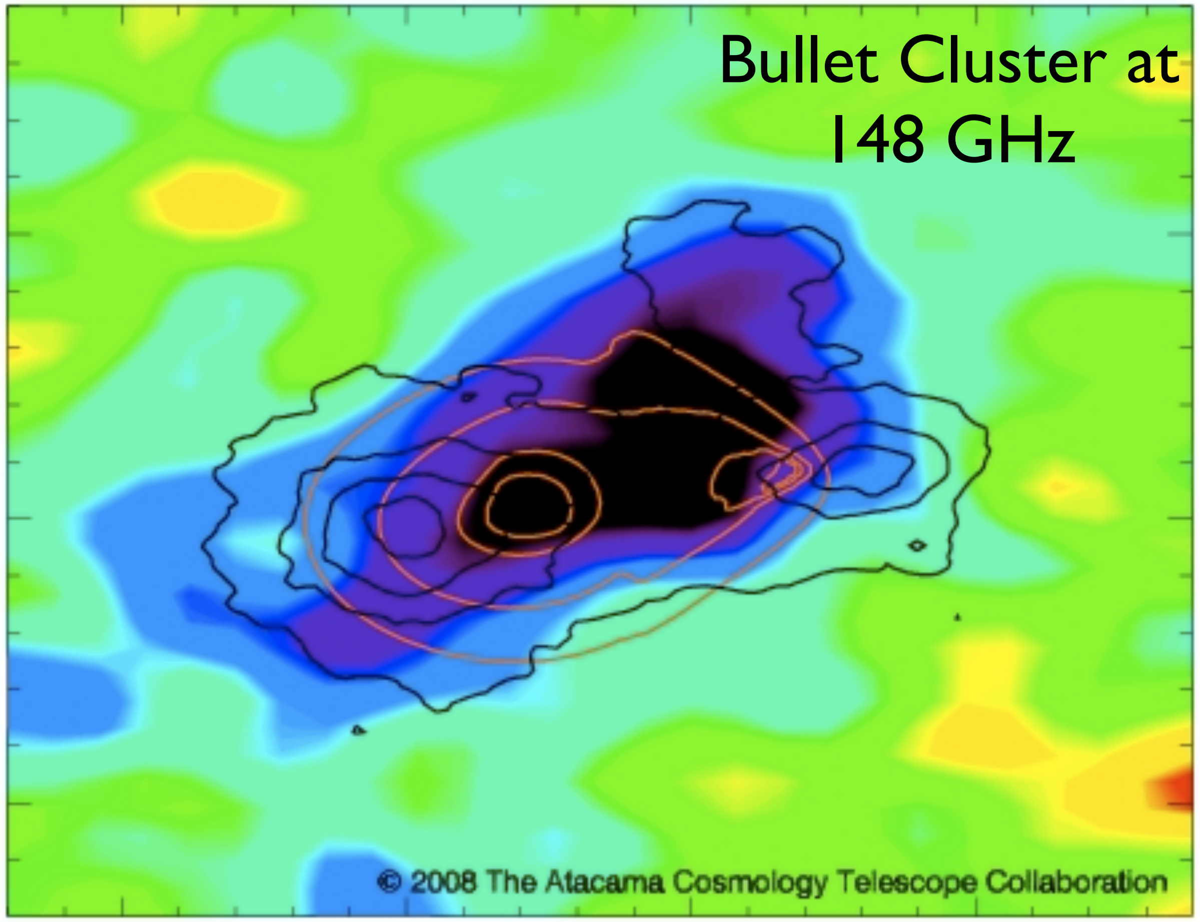
Work with:
Blake Sherwin, David Spergel, Michael Wilson, Atacama Cosmology Telescope Collaboration

Outline

- The Sunyaev-Zel'dovich (SZ) Effect
- Thermal SZ Moments: $\langle T^N \rangle$
- ACT Measurement: $\langle T^3 \rangle$
- Cosmological Constraints



- 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

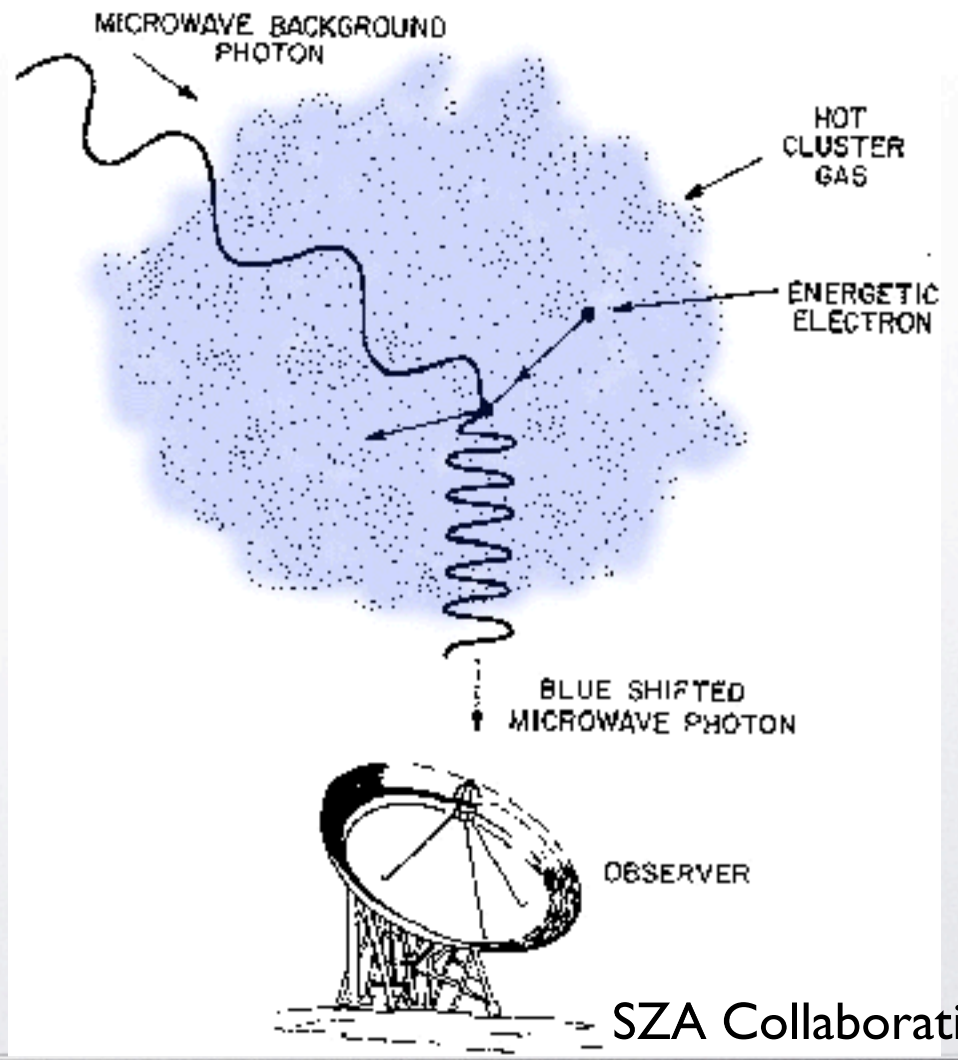
- tSZ: decrement below 218 GHz
  increment above 218 GHz

- $\Delta T \sim 100$-$1000\ \mu K$ for massive clusters

- Nearly redshift-independent

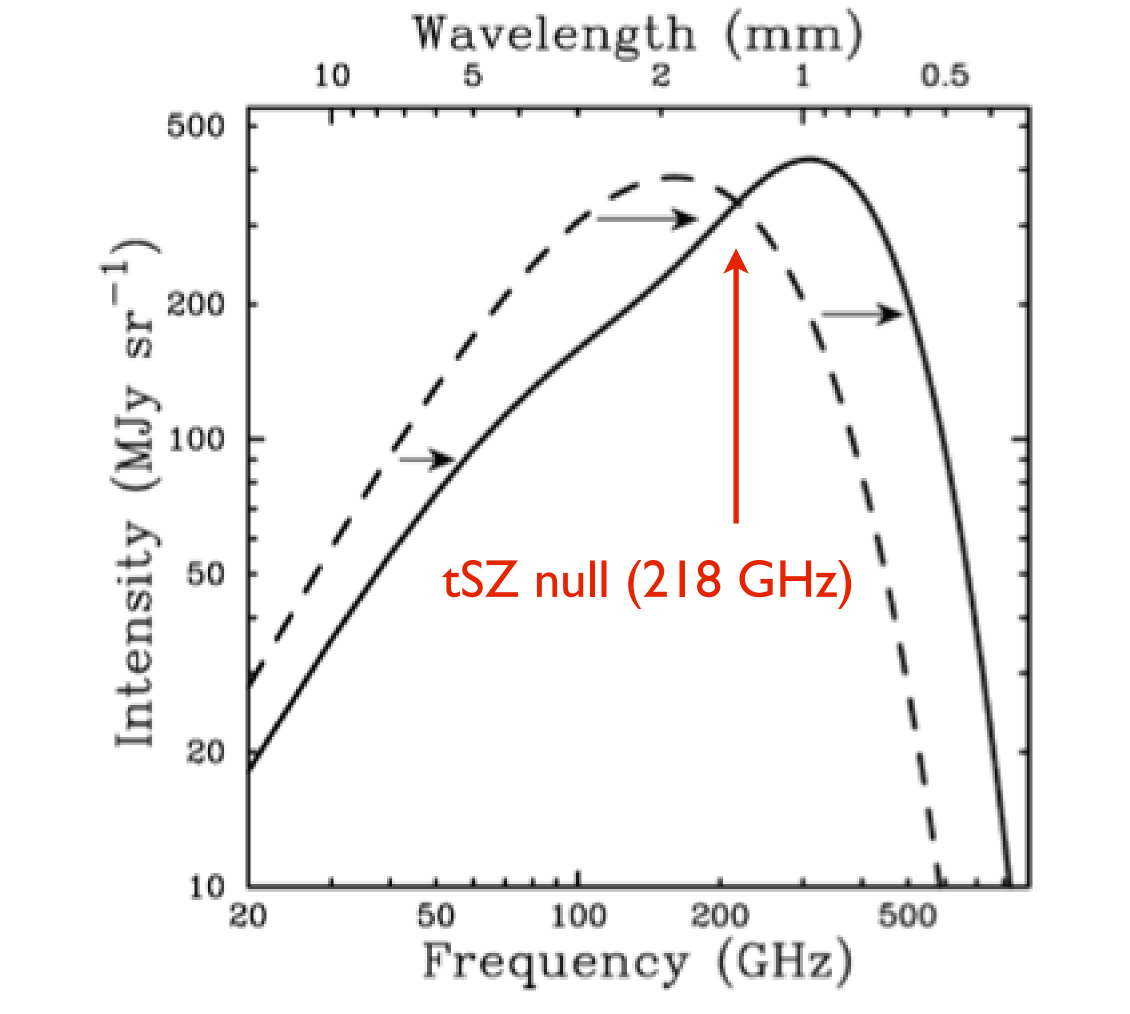
- Integrated signal probes LOS integral of temperature-weighted mass (total thermal energy)

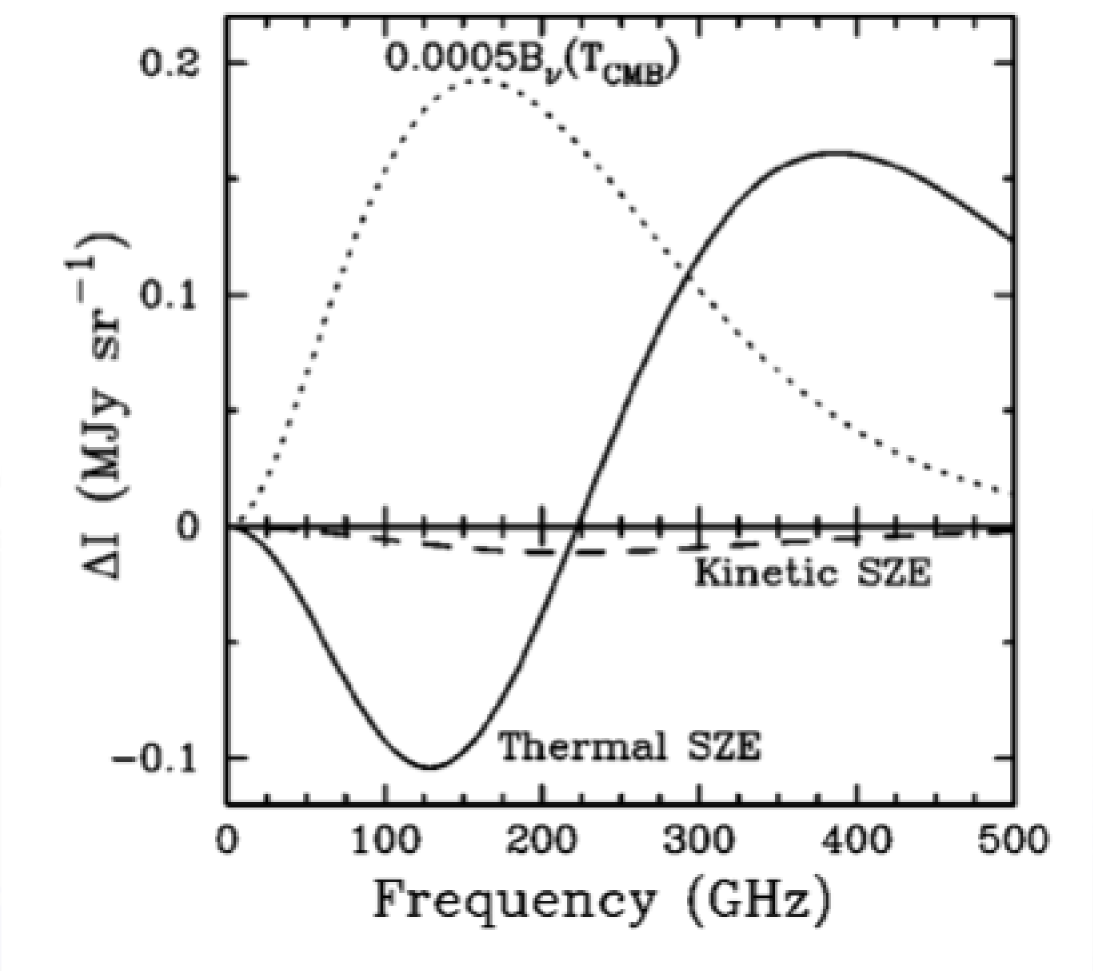
- Found on arcminute angular scales in CMB



SZA Collaboration

The Sunyaev-Zel'dovich Effect





Carlstrom et al. (2002)

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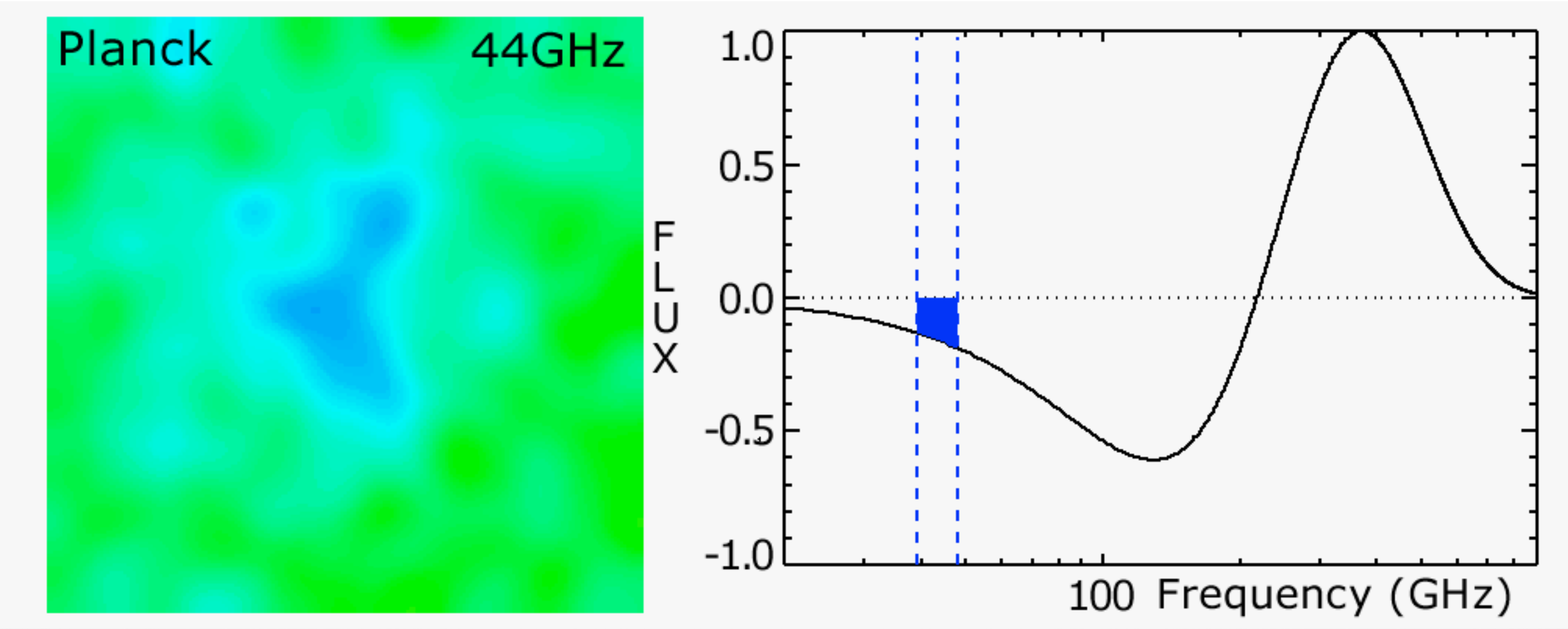
The Sunyaev-Zel'dovich Effect



ESA/Planck Collaboration

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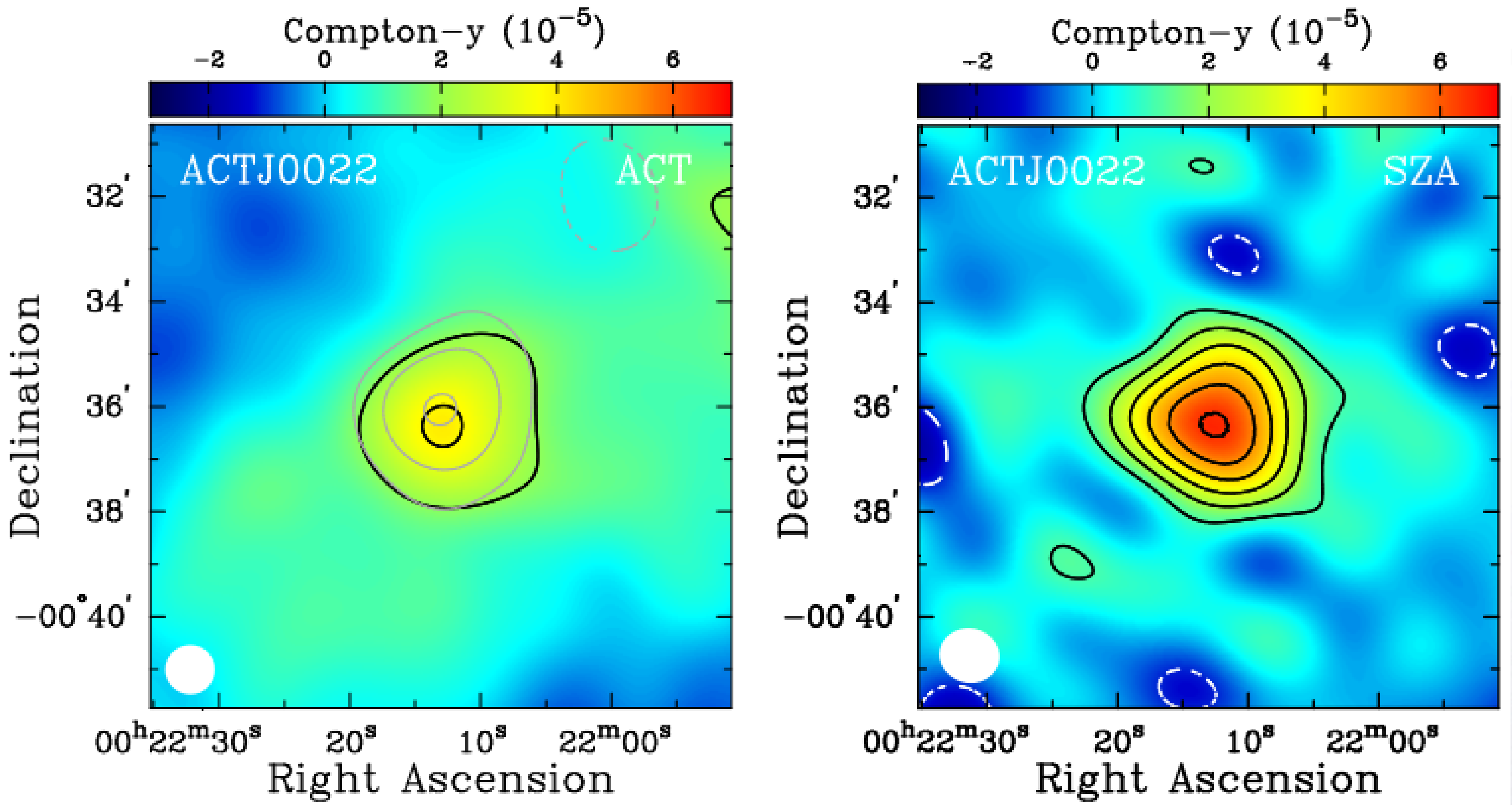
Thermal SZ Measurements

- Method 1: individual cluster observations
  - Goal: measure masses, redshifts, (peculiar velocities?), gas properties
  - Cosmological analysis: directly reconstruct halo mass function
  - Difficulties: selection function; measuring masses sufficiently accurately is hard



$z = 0.81$
$M \sim 10^{15}\ M_{sun}$

Reese, ..., JCH, et al. (2012)

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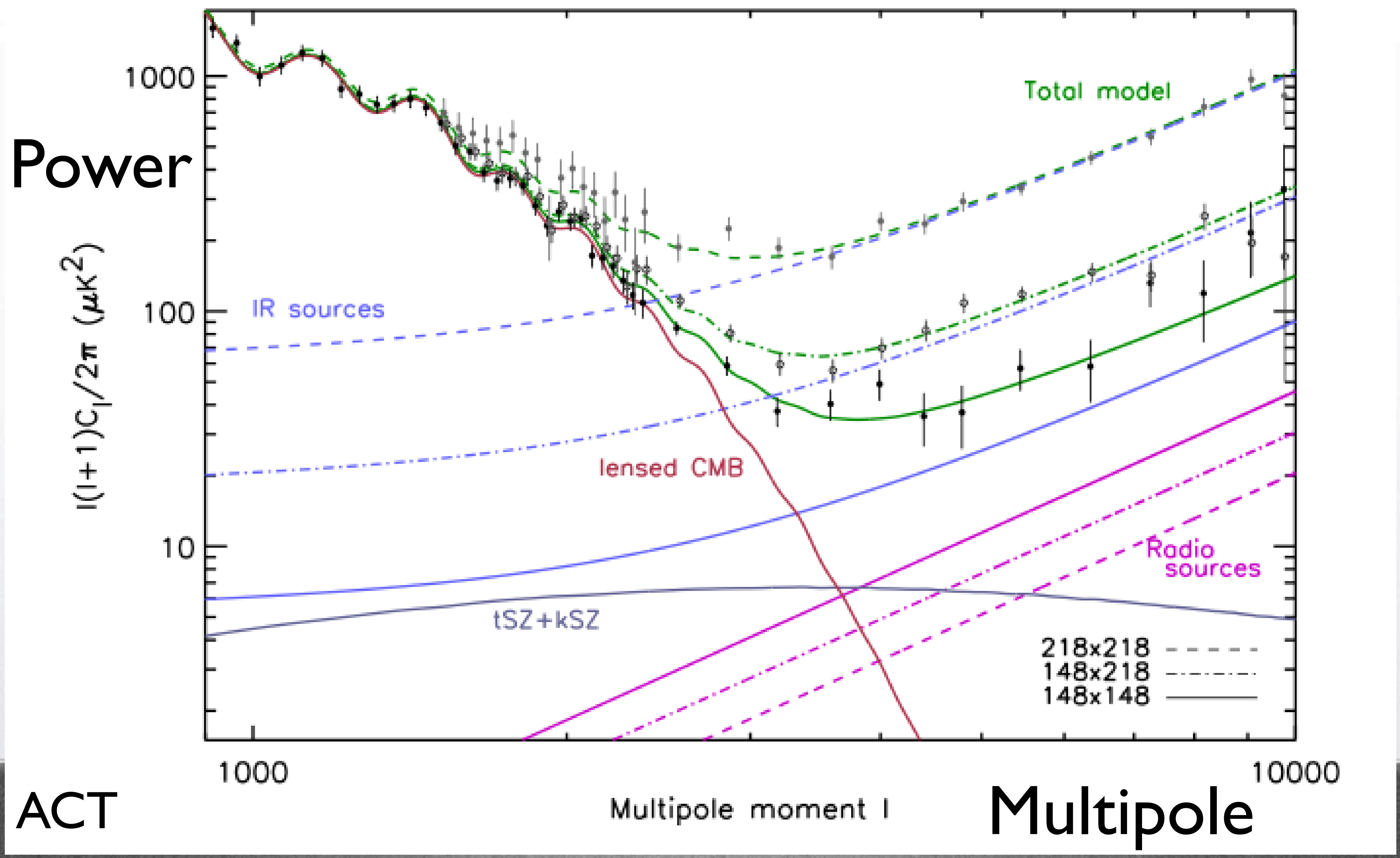
- Method II: power spectrum of tSZ signal in entire map
  - Goal: amplitude of temp. fluctuations due to tSZ as a function of angular scale
  - Cosmological analysis: compare to halo model calculations or full simulations
  - Difficulties: need ICM electron pressure profile for halos over wide mass and redshift ranges; must separate signal from other sources of CMB power



Dunkley et al. (2011)

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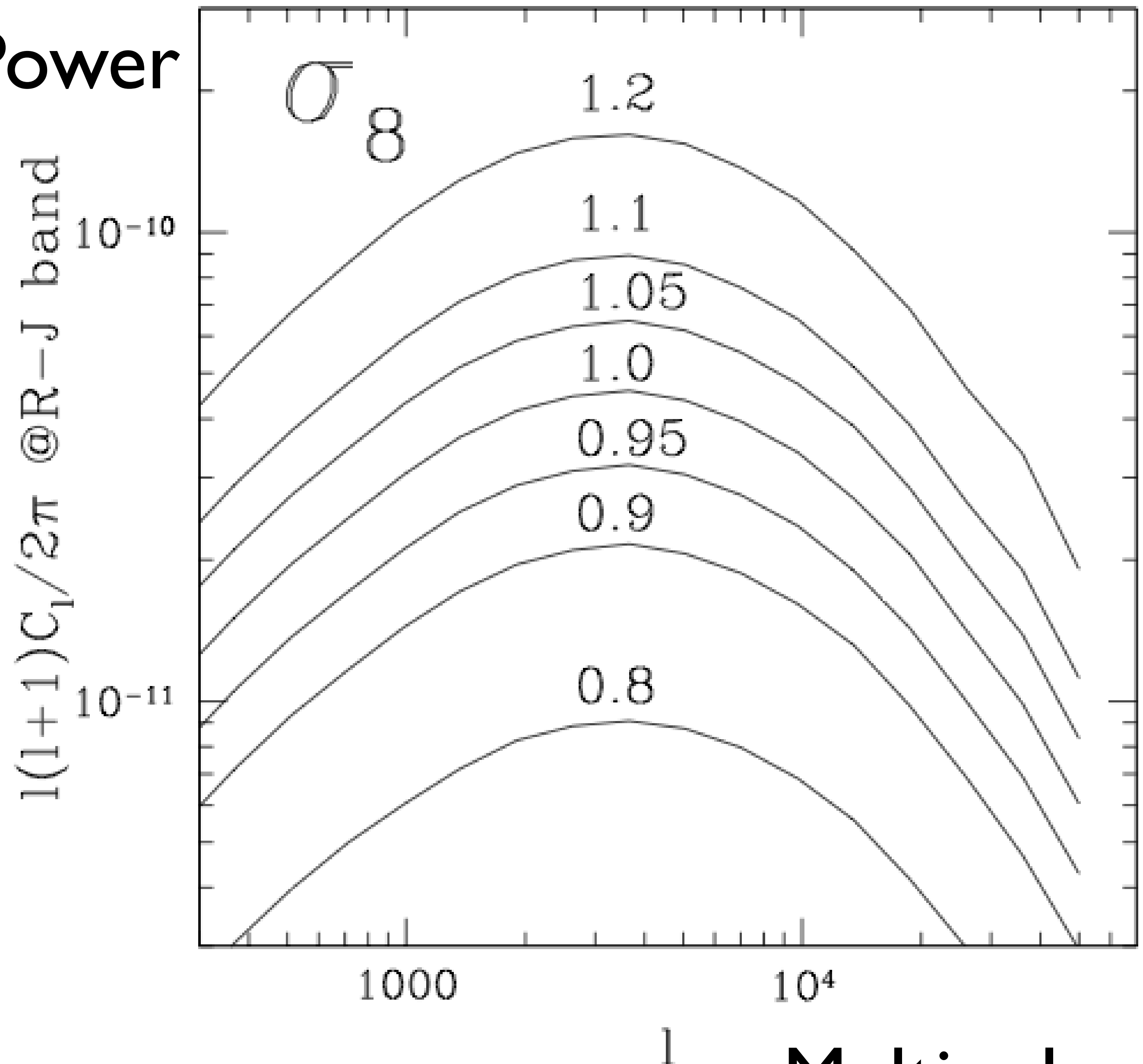
- Why use the tSZ power spectrum for cosmology?
  - Insensitive to selection effects
  - No mass-observable calibration
  - Very sensitive to σ_8: rms amplitude of density fluctuations on 8 h^{-1} Mpc scales
  - Initial hope: fairly insensitive to ICM gastrophysics around l~3000

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

Power



Multipole

Thermal SZ Power Spectrum

- It all changed in ~2009-10 when ACT+SPT measured tSZ power
- Lower than predicted! Would require lowering of σ_8

  ACT (tSZ+kSZ at l=3000): $6.8 \pm 2.9\ \mu\mathrm{K}^2$
  SPT (tSZ+0.5kSZ at l=3000): $4.71 \pm 0.64\ \mu\mathrm{K}^2$

  Naive interpretation: $\sigma_8 \sim 0.75$ rather than 0.8-0.82 (WMAP5/7)

- Or: the ICM is more complicated than we thought
- Error bars dominated by systematic uncertainty due to gastrophysics!
- What can we learn with data we already have?

Dunkley et al. (2011)
Reichardt et al. (2011)

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Thermal SZ Moments

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

$$T(\vec{\theta}; M, z) = \underbrace{g(\nu)}_{\text{tSZ spectral function}} \underbrace{T_{\mathrm{CMB}}}_{\text{CMB temp. today}} \frac{\underbrace{\sigma_T}_{\text{Thomson cross-section}}}{m_e c^2} \int \underbrace{P_e}_{\text{ICM electron pressure profile integrated over LOS}} \left(\sqrt{l^2 + d_A^2(z)|\vec{\theta}|^2}; M, z \right) dl$$

↓

Gastrophysics

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Thermal SZ Moments

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

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tSZ spectral function

CMB temp. today

Thomson cross-section

ICM electron pressure profile integrated over LOS

↓

Gastrophysics

- N^{th} thermal SZ moment:

$$\langle T^N \rangle = \int \frac{dV}{dz} dz \int \frac{dn(M,z)}{dM} dM \int d^2\vec{\theta}\, T(\vec{\theta}; M, z)^N$$

comoving volume per steradian →

halo mass function

↓

Cosmology

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Intracluster Medium Gastrophysics

- ICM to lowest order: hydrostatic equilbrium 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

- Additional physics needed:
  - Formation shock heating
  - Star formation, supernova feedback, cosmic rays
  - Active galactic nucleus feedback
  - Magnetic fields, plasma instabilities
  - Turbulent pressure support

- Non-thermal pressure support (from feedback, turbulence, ...) suppresses tSZ signal

Komatsu & Seljak (2001,02)
Battaglia et al. (2010,11), Shaw et al. (2010)

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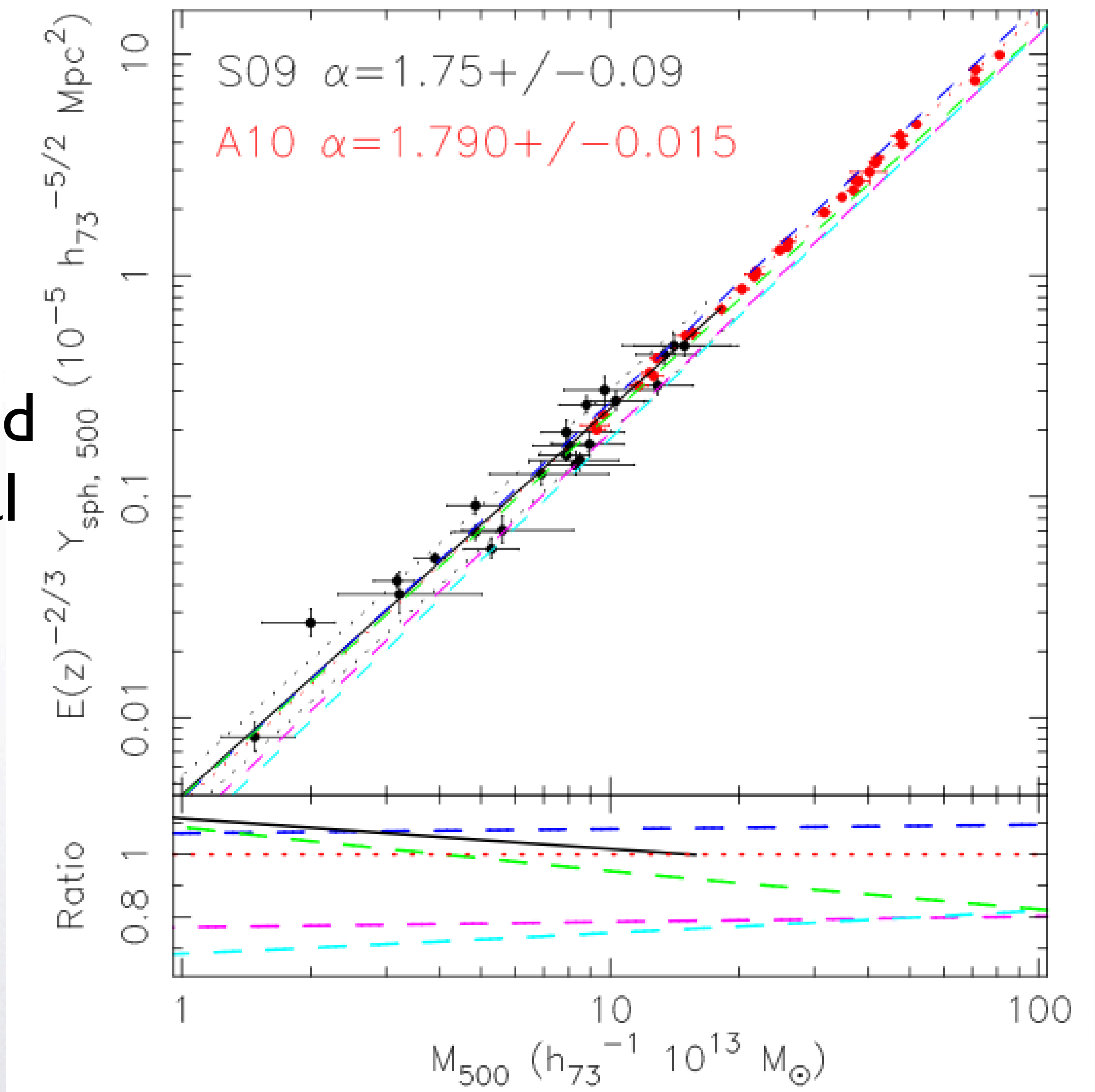
Intracluster Medium Gastrophysics

Integrated SZ Signal



Cluster Mass

>30% scatter over wide range in mass

order unity uncertainty in tSZ power spectrum (or variance)

Sun et al. (2011)

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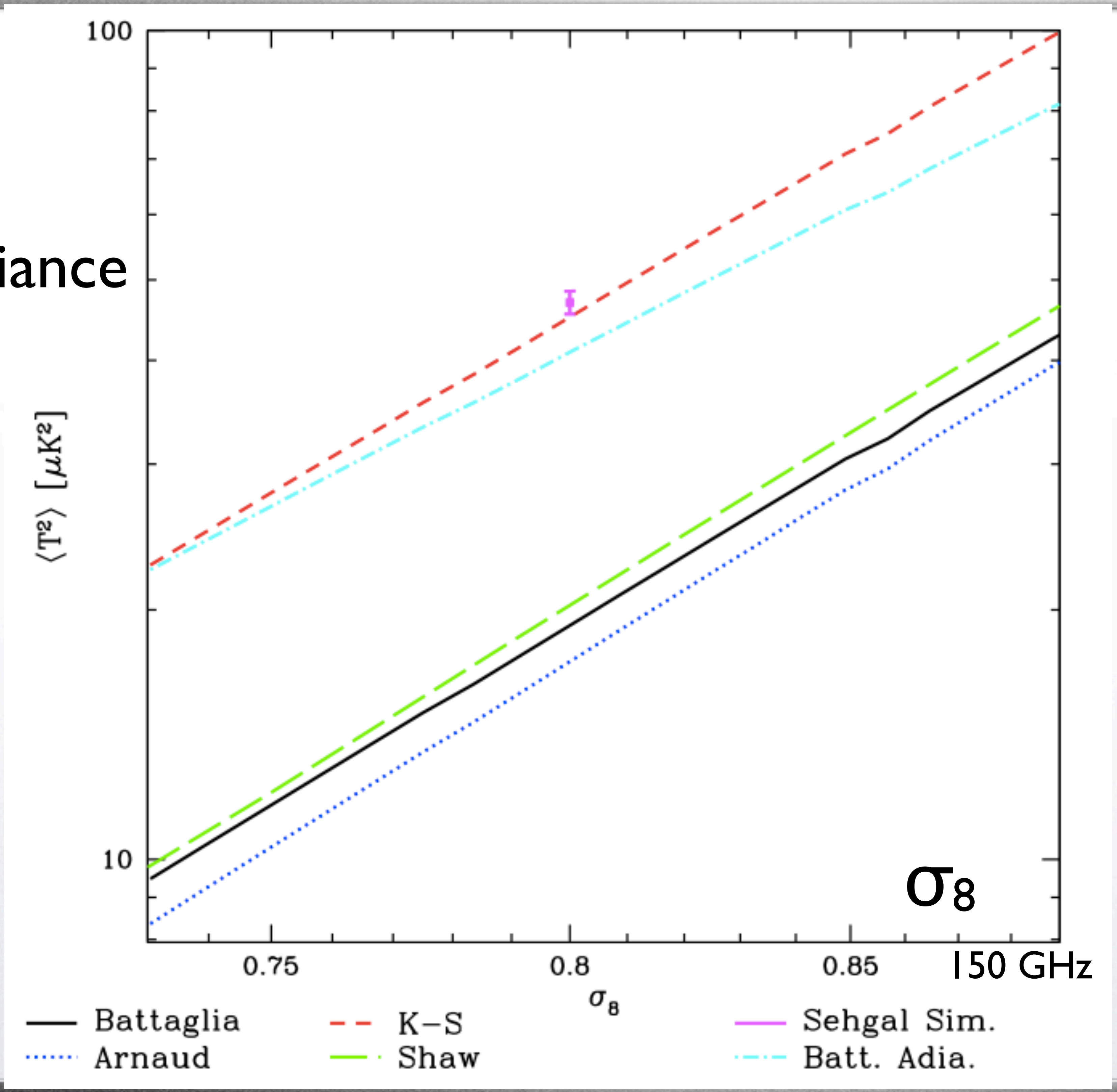
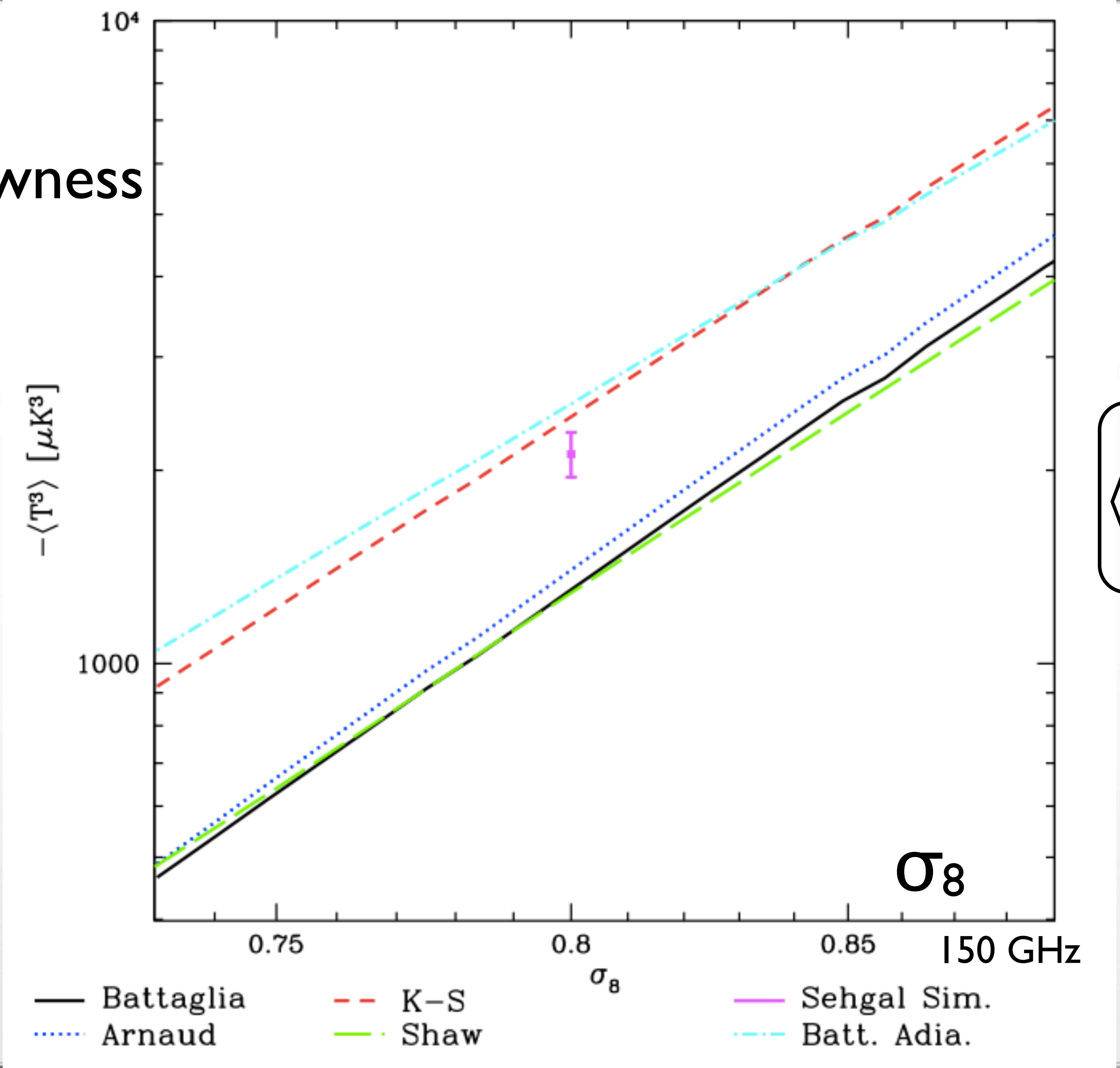
Variance



$$\boxed{\langle T^2 \rangle \propto \sigma_8^{7-8}}$$

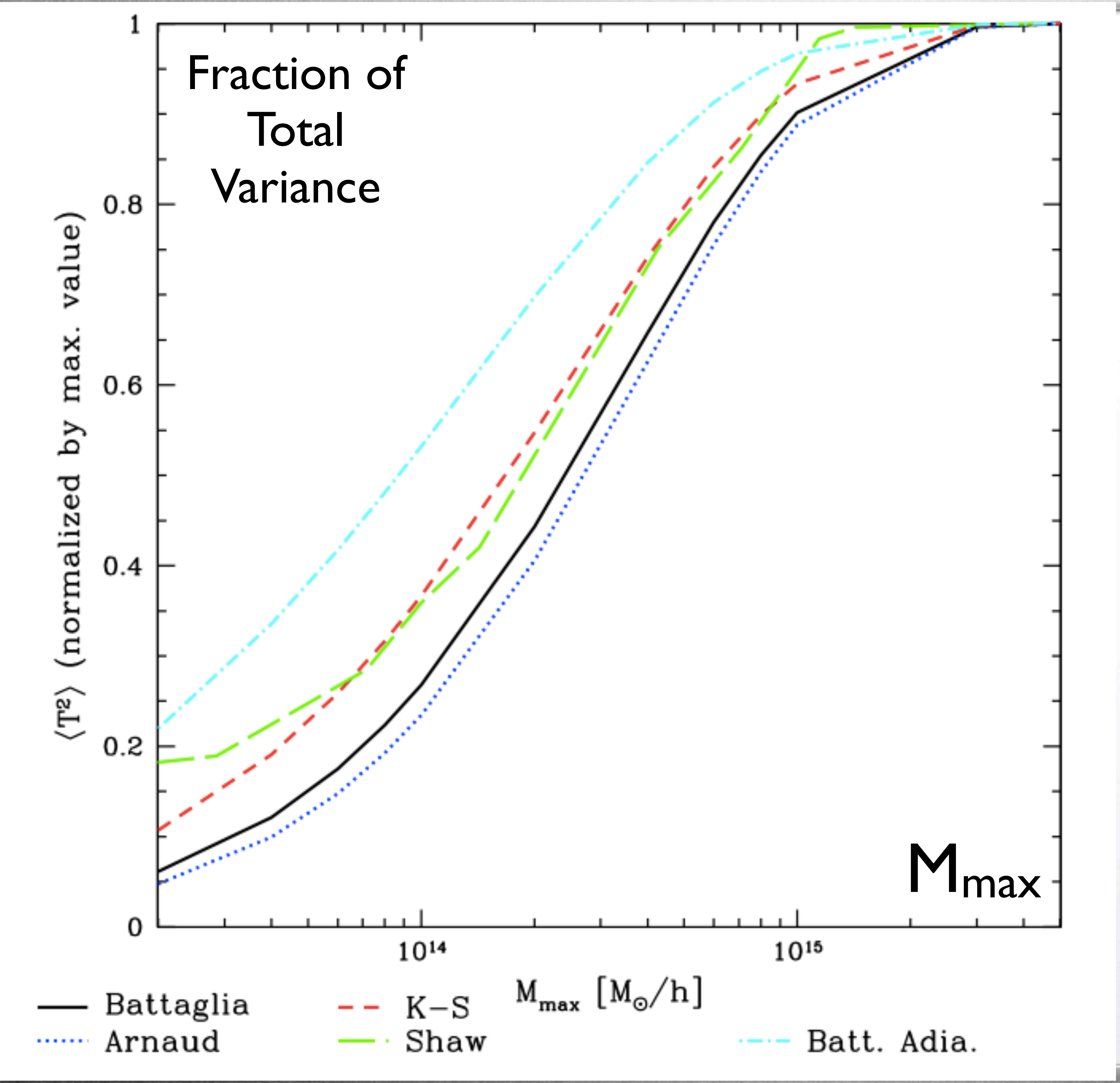
$$\langle T^2 \rangle = \sum_\ell \frac{2\ell+1}{4\pi} C_\ell$$

Skewness



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

Which Clusters Contribute?



~40-60% of tSZ variance signal comes from clusters with $M < 2 \times 10^{14} M_{\odot}/h$

JCH & Sherwin (2012)
Bhattacharya et al. (2012)

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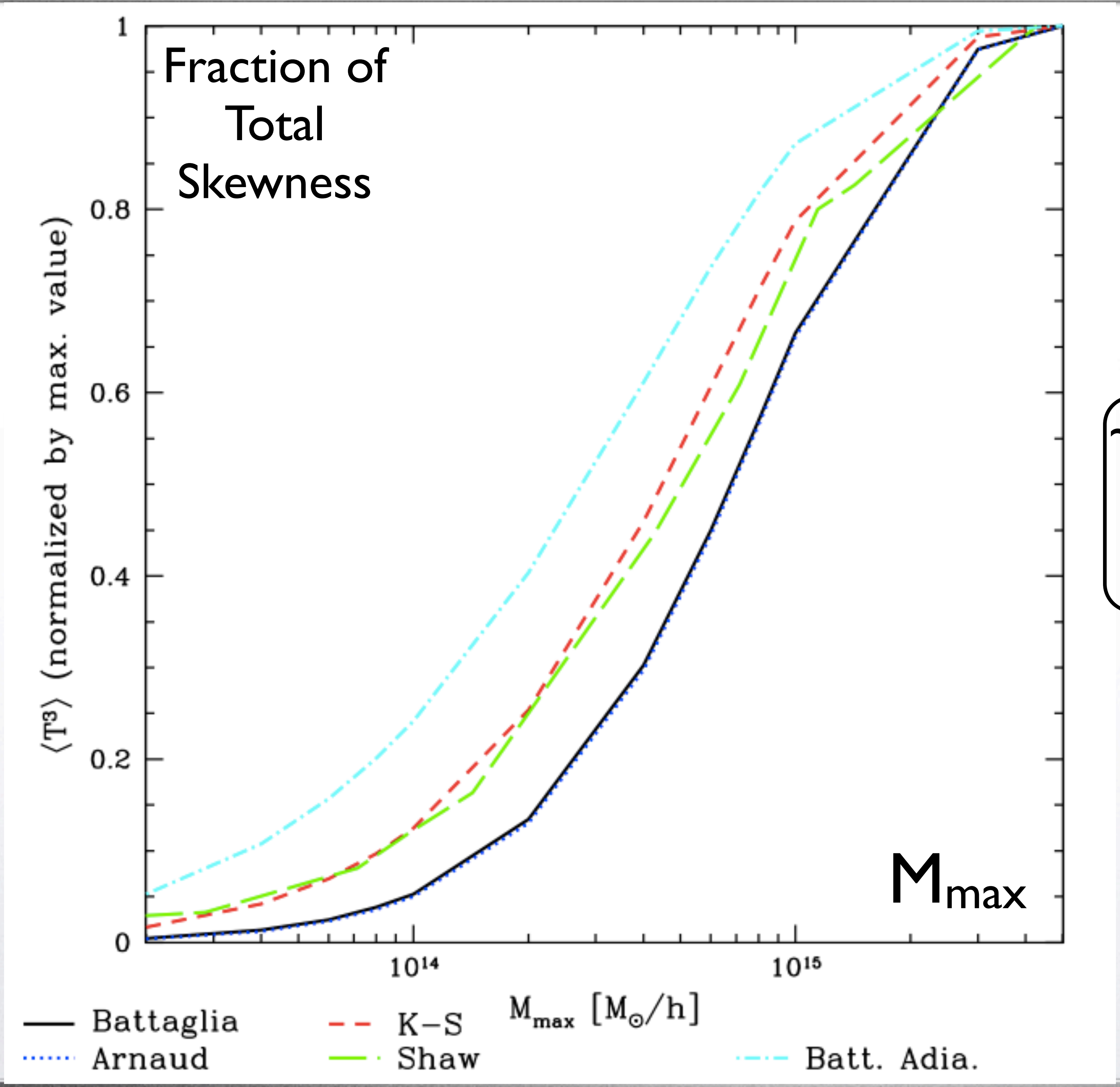
Which Clusters Contribute?



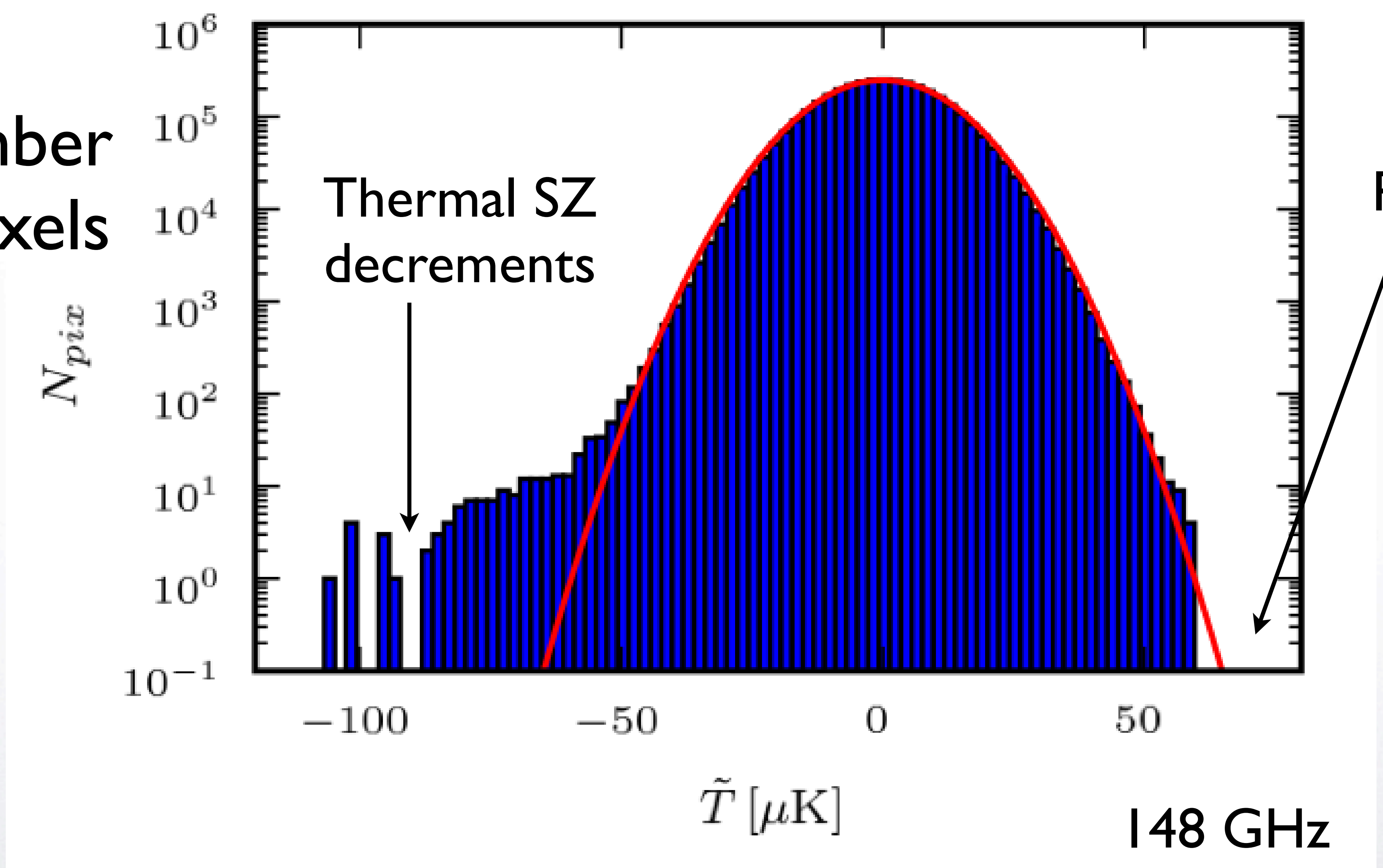
~10-30% of tSZ skewness signal comes from clusters with $M < 2 \times 10^{14} M_\odot/h$

How to Measure the Skewness

- Atacama Cosmology Telescope (ACT) maps at 148 GHz and 218 GHz covering ~300 sq. deg. on the equatorial strip (2008-10)
- Includes: primordial (lensed) CMB, thermal and kinetic SZ, dusty star-forming galaxies, radio sources, atmospheric and instrumental noise
- Only tSZ and point sources contribute to skewness
- Map processing:
  - Filter to upweight cluster scales ($l \sim 3000$)
  - Remove identified point sources via template subtraction
  - Construct mask using 218 GHz (tSZ-null) channel to remove any additional point source emission

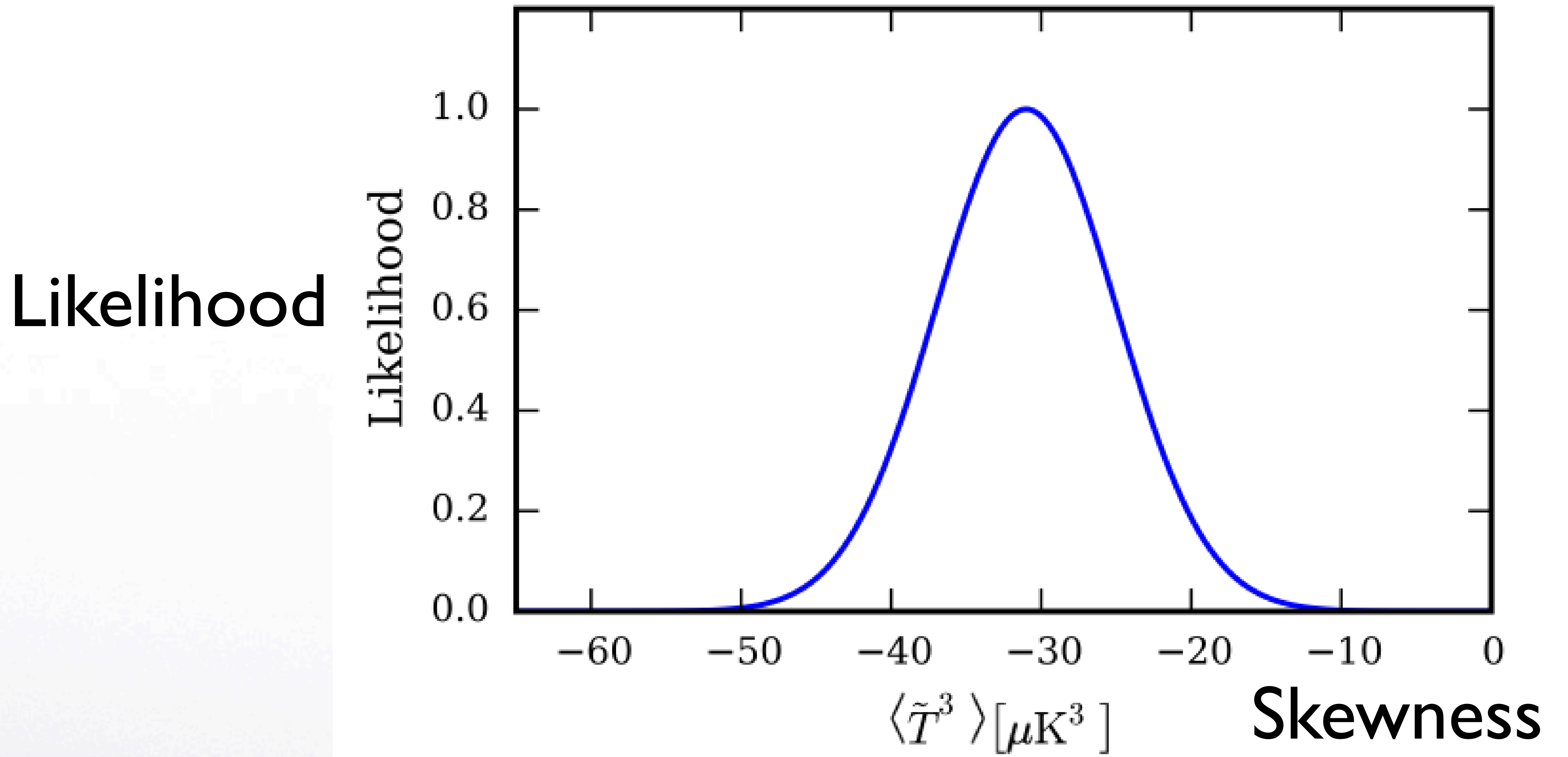
Filtered Temperature PDF

Number of Pixels



Filtered Pixel Temperature

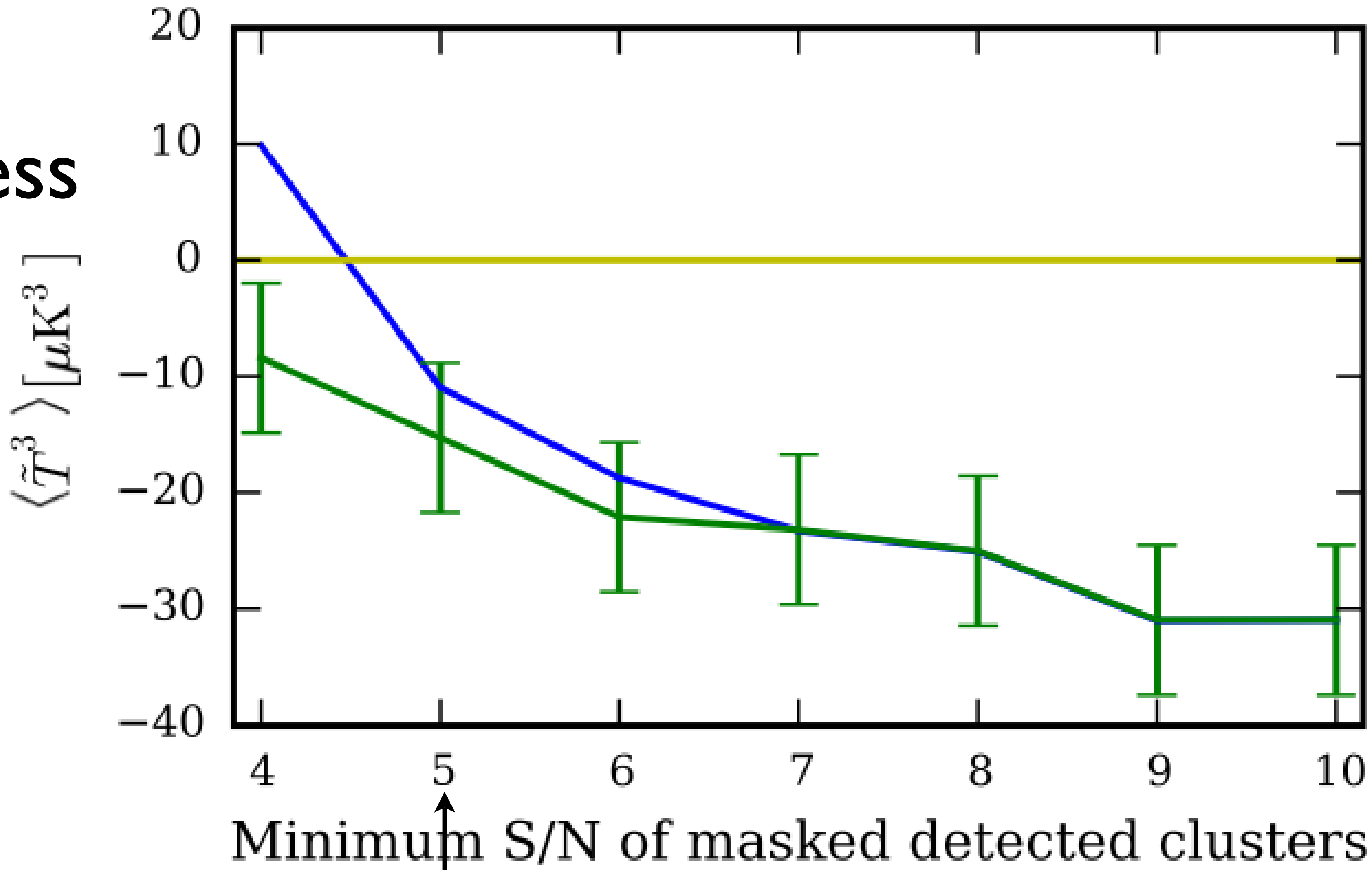
The Skewness Measurement



$$\boxed{\left\langle \tilde{T}^3 \right\rangle = -31 \pm 6\,\mu\mathrm{K}^3 \quad \text{(Gaussian errors only)} \\ \pm 14\,\mu\mathrm{K}^3 \quad \text{(including cosmic variance)}}$$

The Origin of the Signal: tSZ?

Skewness



using entire candidate catalog

using optically confirmed catalog

Cluster Mass Proxy

$$M \approx 9 \times 10^{14} M_{\odot}/h$$

Derived Cosmological Constraints

- Simple constraint: $$\sigma_8^D = \sigma_8^S \left[\frac{\left\langle \tilde{T}^3 \right\rangle^D}{\left\langle \tilde{T}^3 \right\rangle^S} \right]^{1/10.5}$$

sims from Battaglia, Sehgal

$$\longrightarrow \boxed{\sigma_8 = 0.78^{+0.03}_{-0.04}\ (68\%\,\mathrm{CL})\ ^{+0.05}_{-0.16}\ (95\%\,\mathrm{CL})}$$

- Forecast for South Pole Telescope: 15σ detection, 1-2% σ_8 constraint
- Systematic uncertainty due to ICM gastrophysics is comparable to but slightly less than statistical uncertainty -- much better than tSZ PS
- We have neglected any degeneracy with other cosmological parameters; most are irrelevant (Bhattacharya et al. 2012)
- Exception: $\langle T^3 \rangle \propto (\Omega_b h)^{3-4}$

Wilson, Sherwin, JCH, et al. (2012)
Bhattacharya et al. (2012)

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Overcoming Gastrophysics

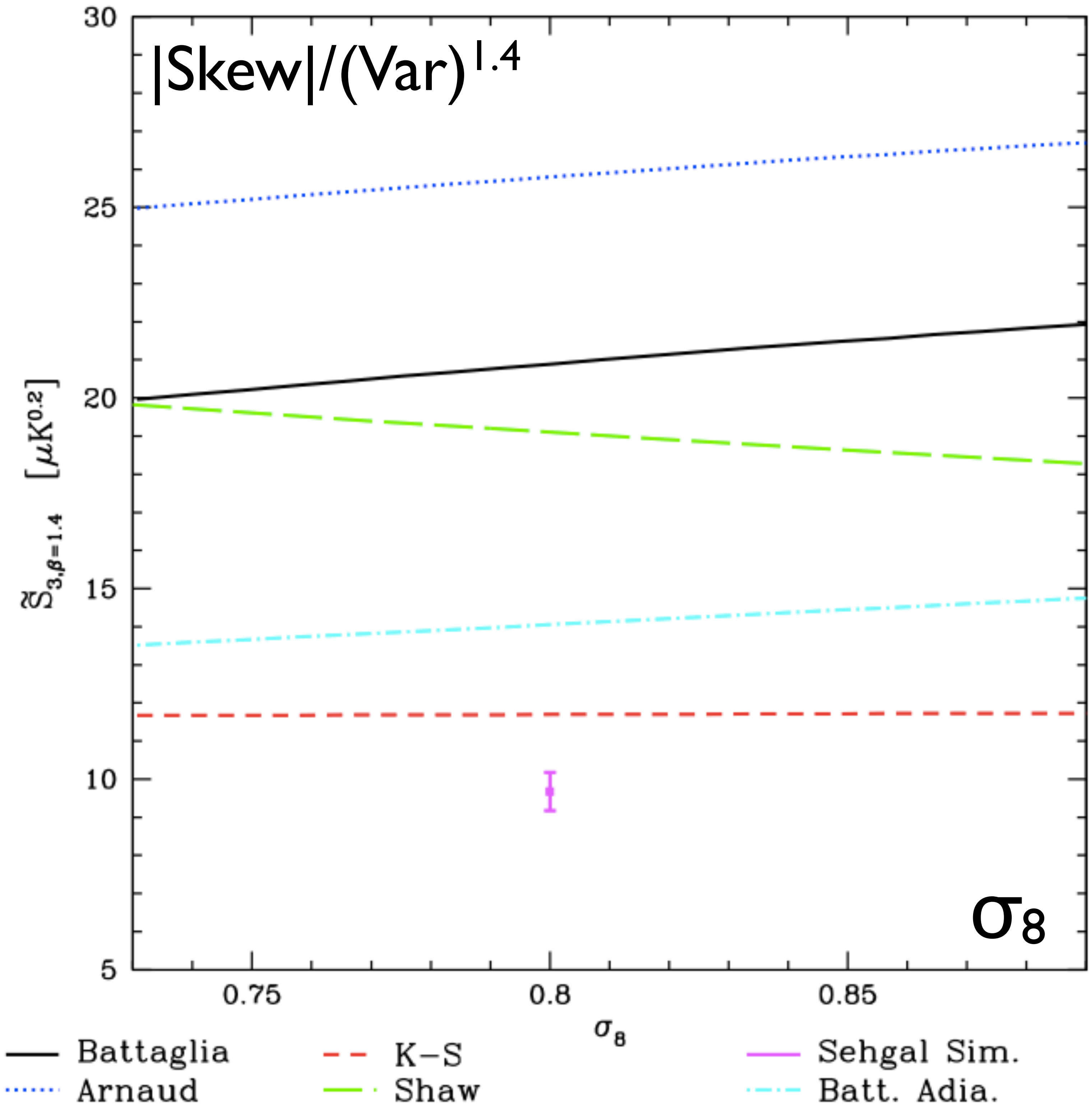
- Idea: tSZ variance and skewness depend differently on cosmological parameters and ICM gastrophysics
  $\longrightarrow$ construct combinations that 'cancel' one or the other

- Possibility 1: statistic that cancels gastrophysics
  $\longrightarrow$ surprisingly, may be possible

- Possibility 2: statistic that cancels cosmological dependence
  $\longrightarrow$ easy to find after determining scalings with σ_8

$$\langle T^2 \rangle \propto \sigma_8^{7-8}$$
$$\langle T^3 \rangle \propto \sigma_8^{10-11.5}$$
$$\longrightarrow \langle T^3 \rangle \propto \langle T^2 \rangle^{1.4}$$

Overcoming Gastrophysics



"Rescaled Skewness"

- As expected, statistic is nearly independent of cosmology, but sensitive to gastrophysics
- Measurement constrains ICM gastrophysics (in an averaged sense)
- Can then use the constrained model to achieve sub-percent constraint on σ_8
- Only significant degeneracy: scales linearly with Ω_b

JCH & Sherwin (2012)

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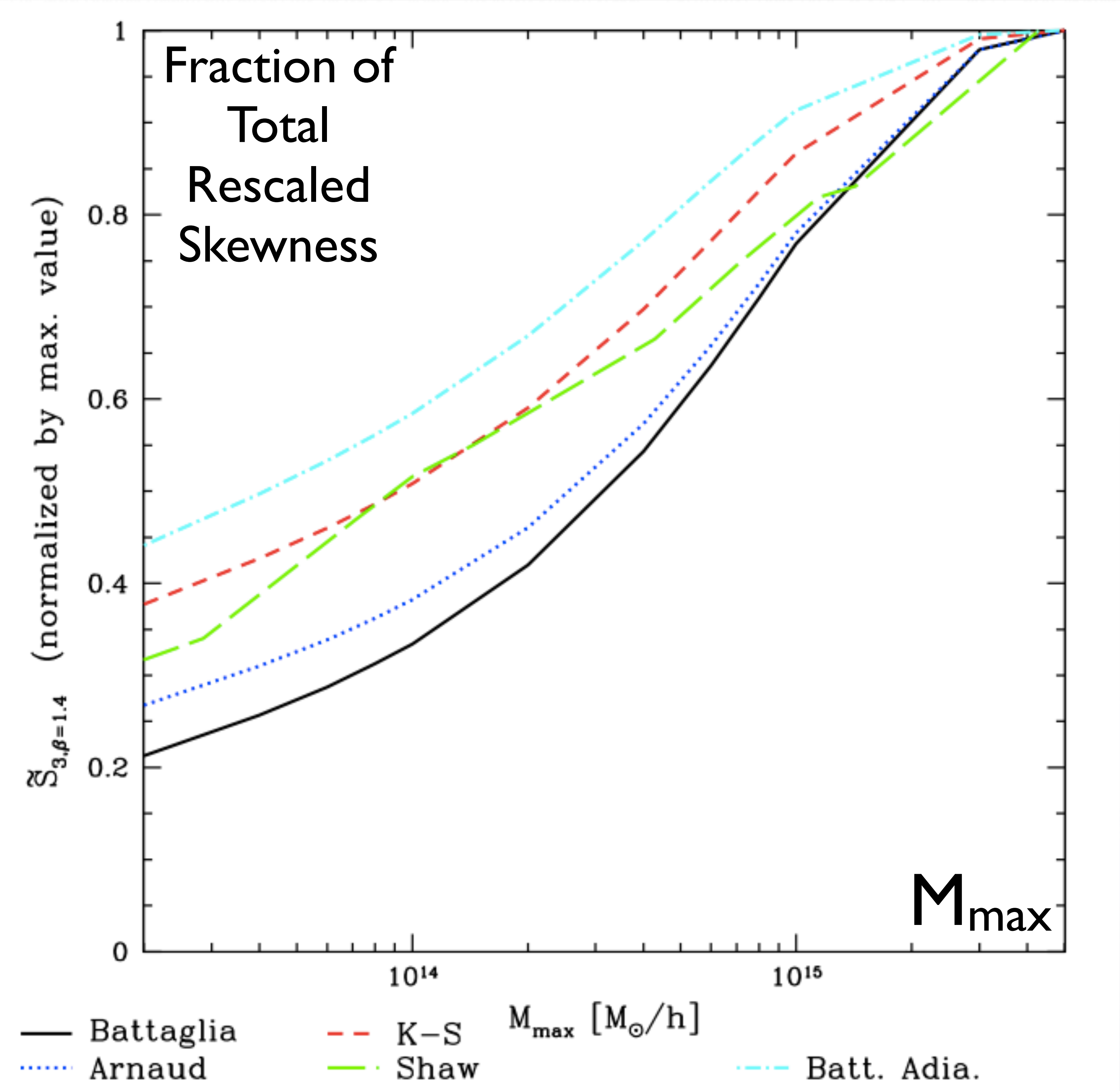
Which Clusters Contribute?

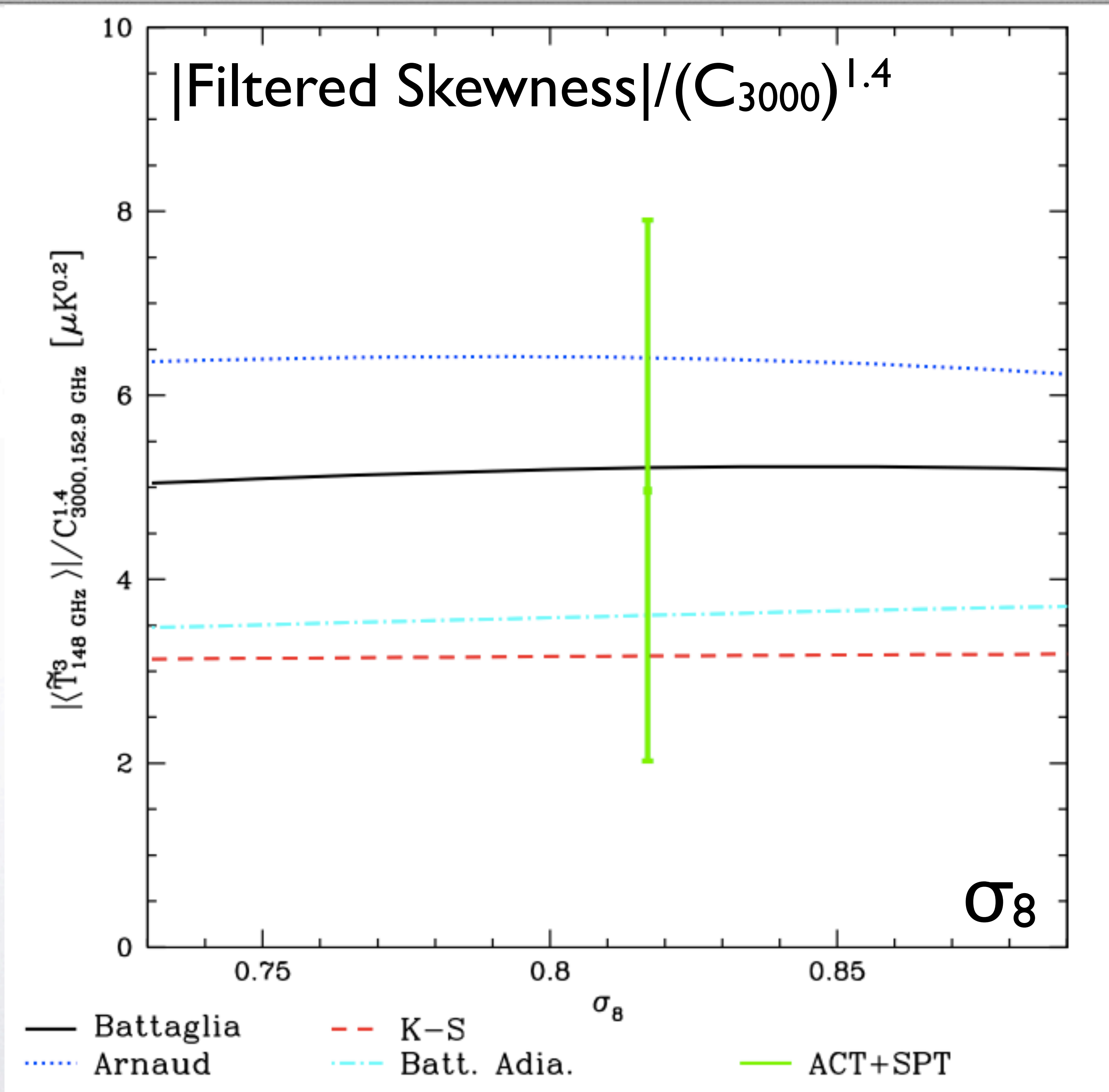


~40-60% of tSZ rescaled skewness signal comes from clusters with

$$M < 2 \times 10^{14} M_\odot/h$$

effectively a probe of f_{gas} in low-mass clusters

ACT+SPT Result



Future Constraints: Beyond σ_8

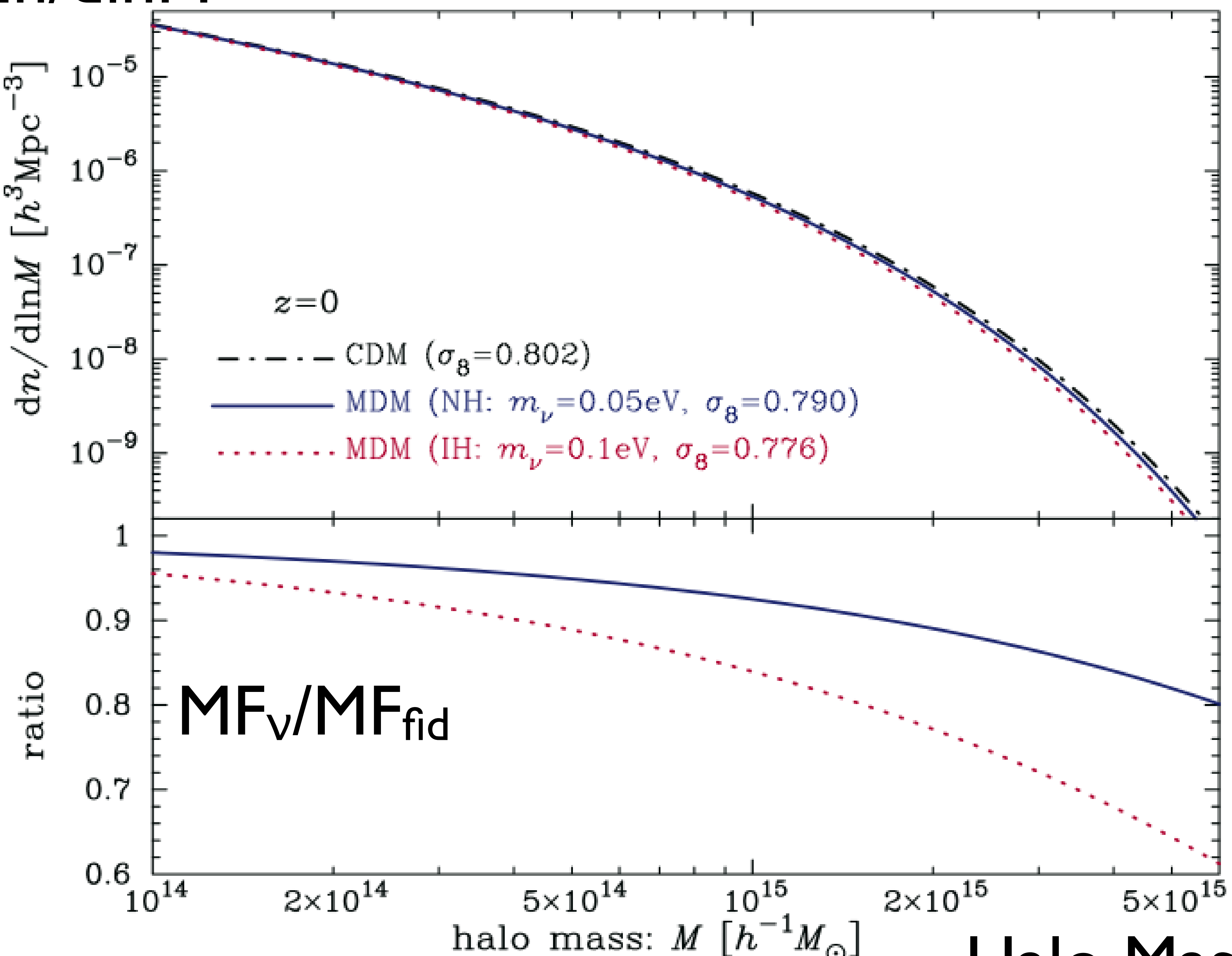
- In principle, thermal SZ signal is sensitive to any parameter that affects mass function
- Problem has been degeneracy of such effects with uncertainties in ICM gastrophysics

$$\langle T^N \rangle = \int \frac{dV}{dz} dz \int \frac{dn(M,z)}{dM} dM \int d^2\vec{\theta}\, T(\vec{\theta}; M, z)^N$$

- Neutrino masses
- Primordial non-Gaussianity
- Dark energy EOS

Neutrino Masses

dn/dlnM

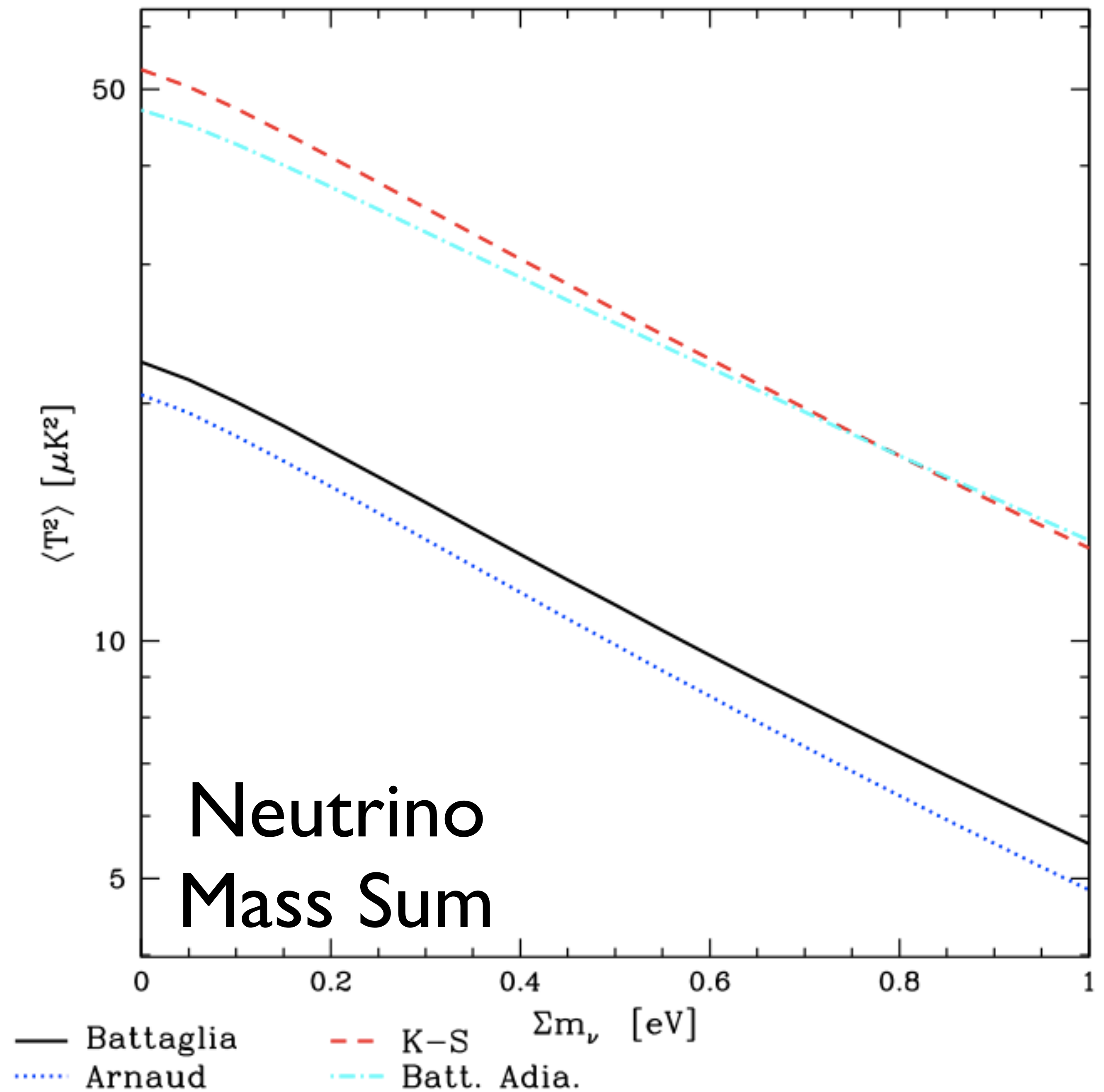


Halo Mass

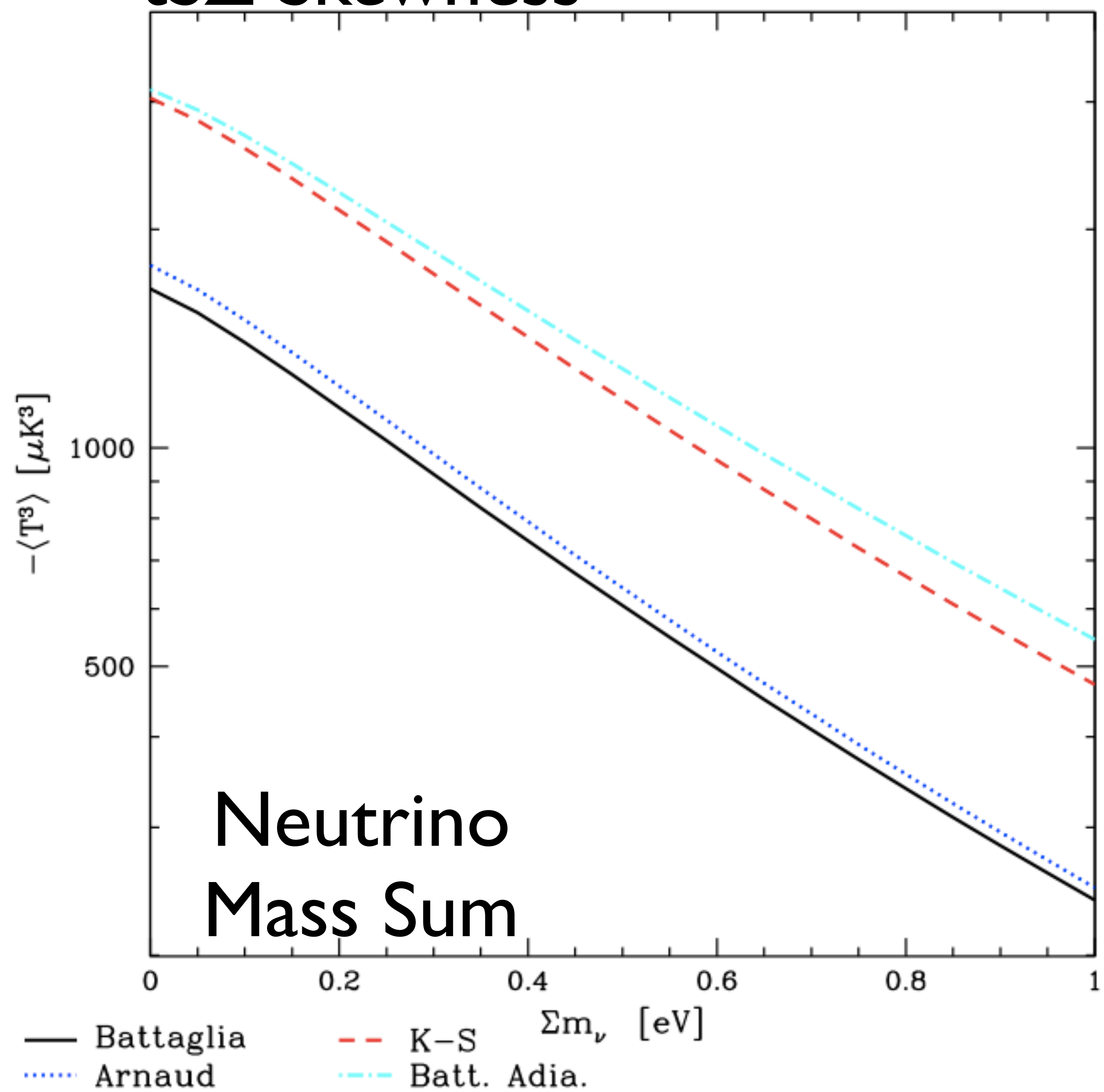
- Massive neutrinos suppress linear theory matter power spectrum
- Leads to decreased abundance of massive halos at late times

Neutrino Masses

tSZ Variance



tSZ Skewness



~quadratic-cubic dependence

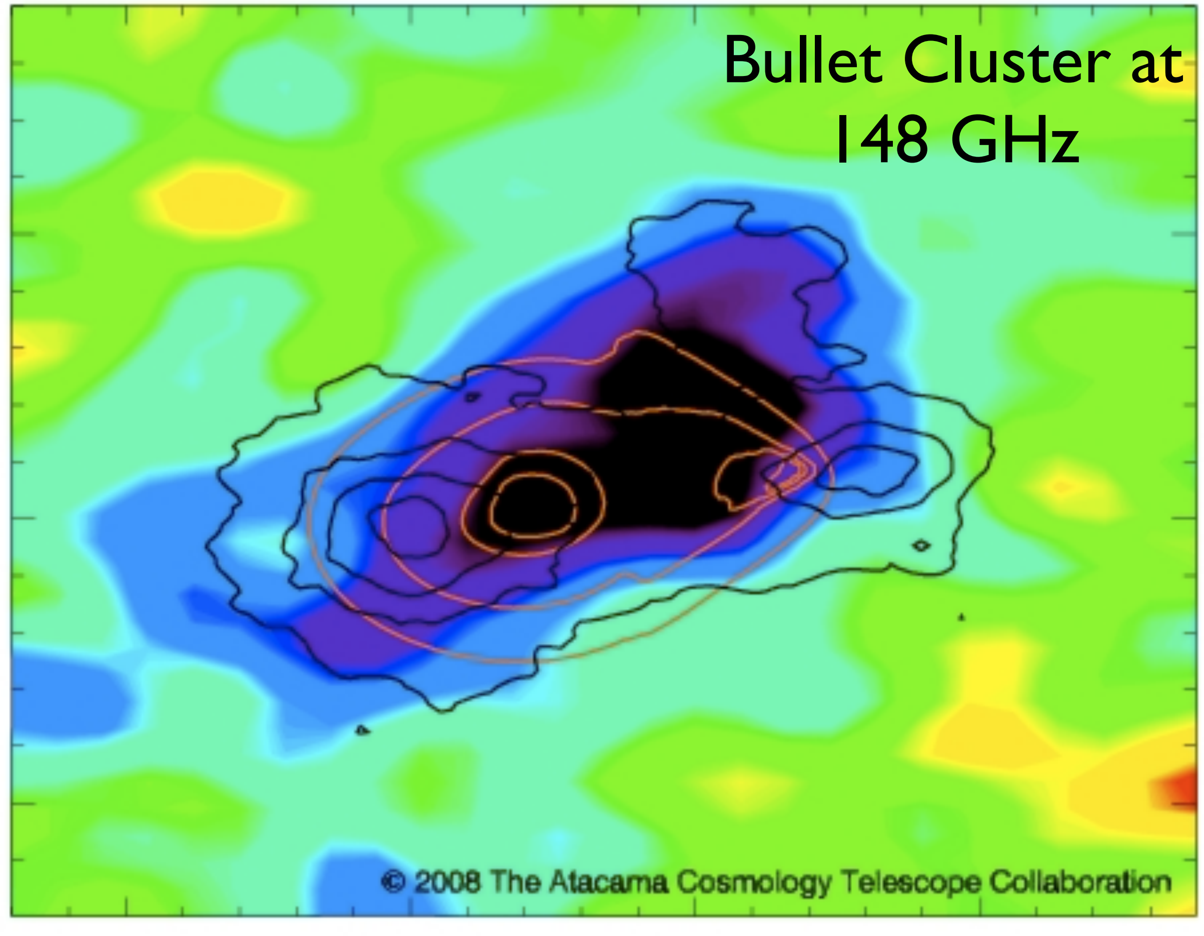
Prospects

- Planck forecast: difficult given bandpass uncertainties and CO contamination
- CV-limited, full-sky forecast:
  - 90σ detection of variance
  - 35σ detection of skewness
  - 55σ detection of 'rescaled skewness'

  $\longrightarrow$ 'solve' gastrophysics model to <2%
  - <1% error on σ_8 after constraining gastrophysics to 5% (more realistic)

Summary

- Thermal SZ measurements are a sensitive probe of both cosmology and the gastrophysics of the ICM.
- Using higher-order statistics we may be able to learn something about both.



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