Cosmological Constraints from Moments of the Thermal SZ Effect

Colin Hill
Princeton Astrophysics
14 August 2012

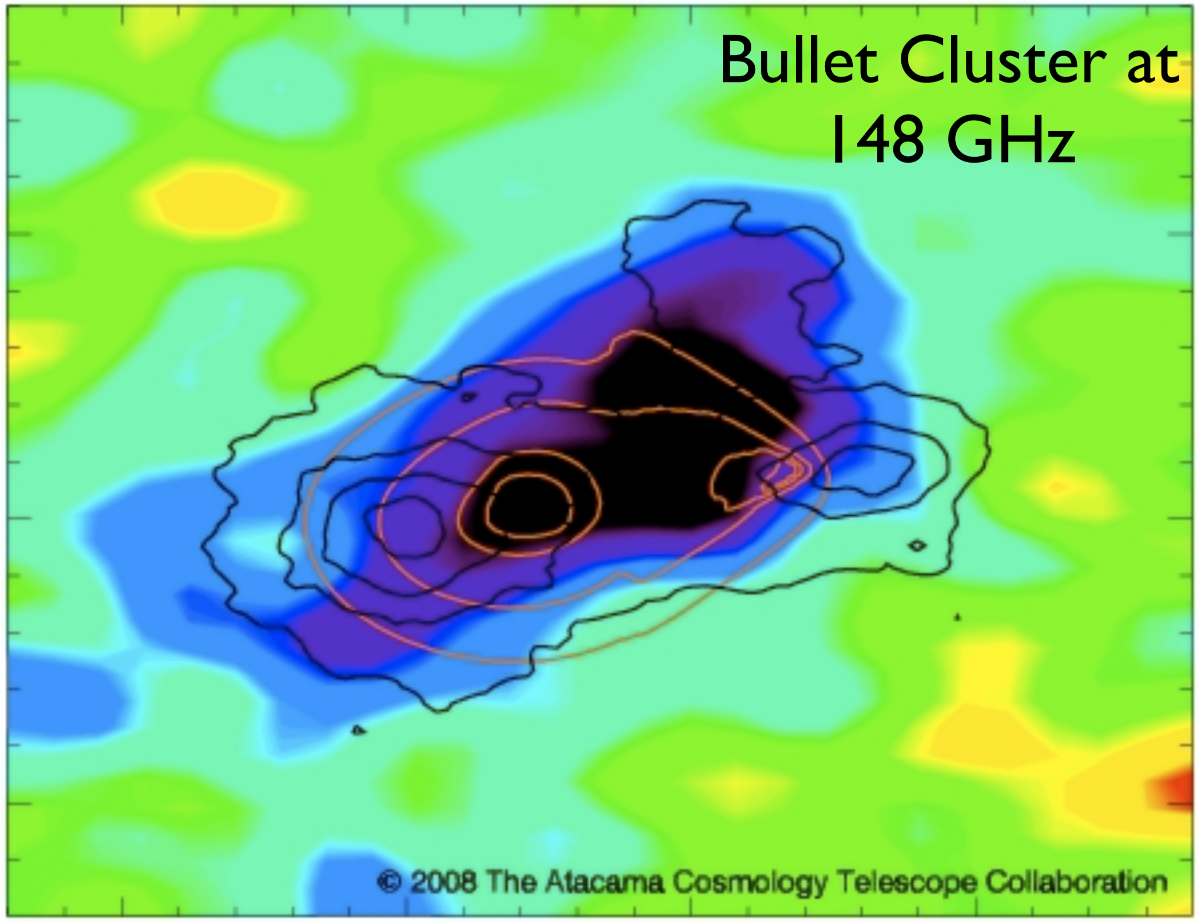
arXiv:1203.6633
arXiv:1205.5794

ACT

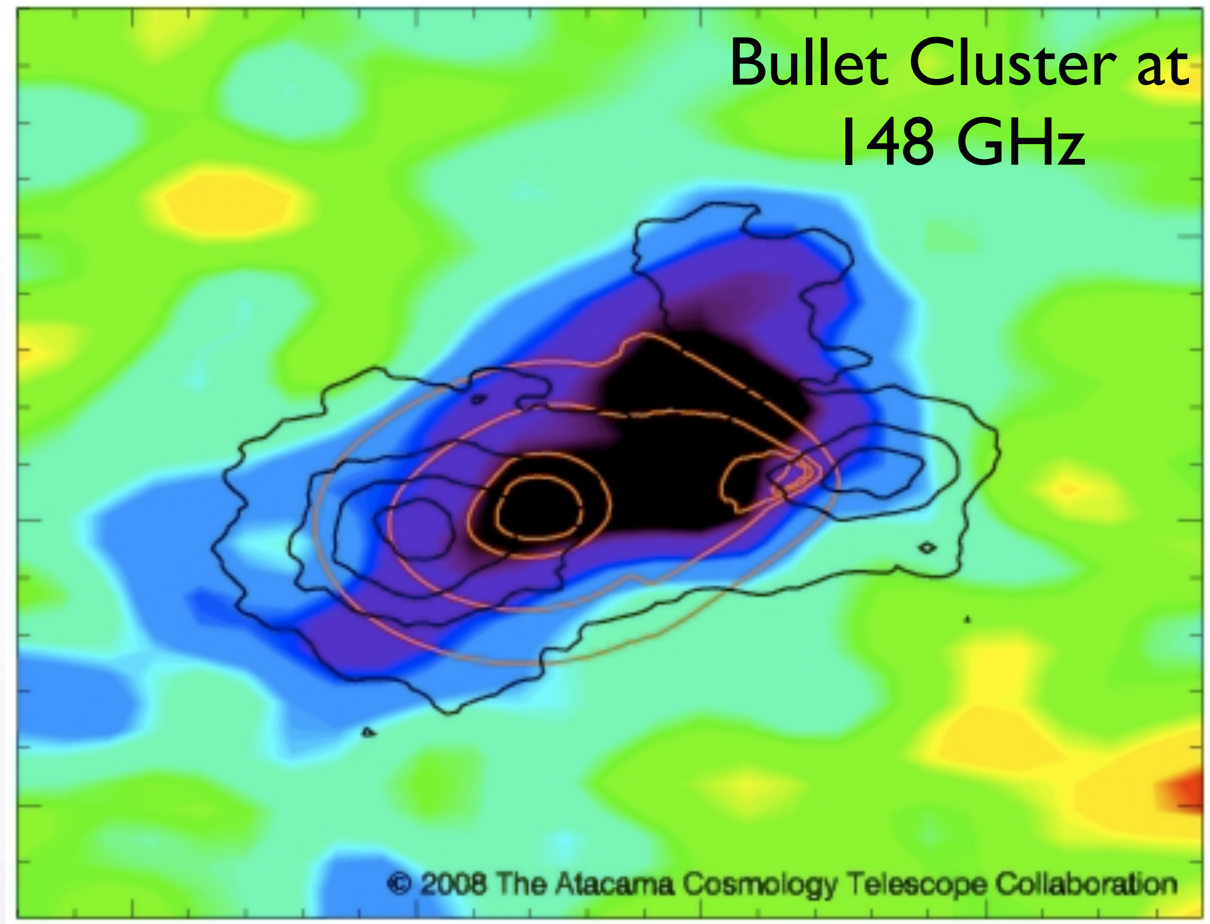
Work with:
Blake Sherwin, David Spergel, Michael Wilson, Atacama Cosmology Telescope Collaboration

Outline

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



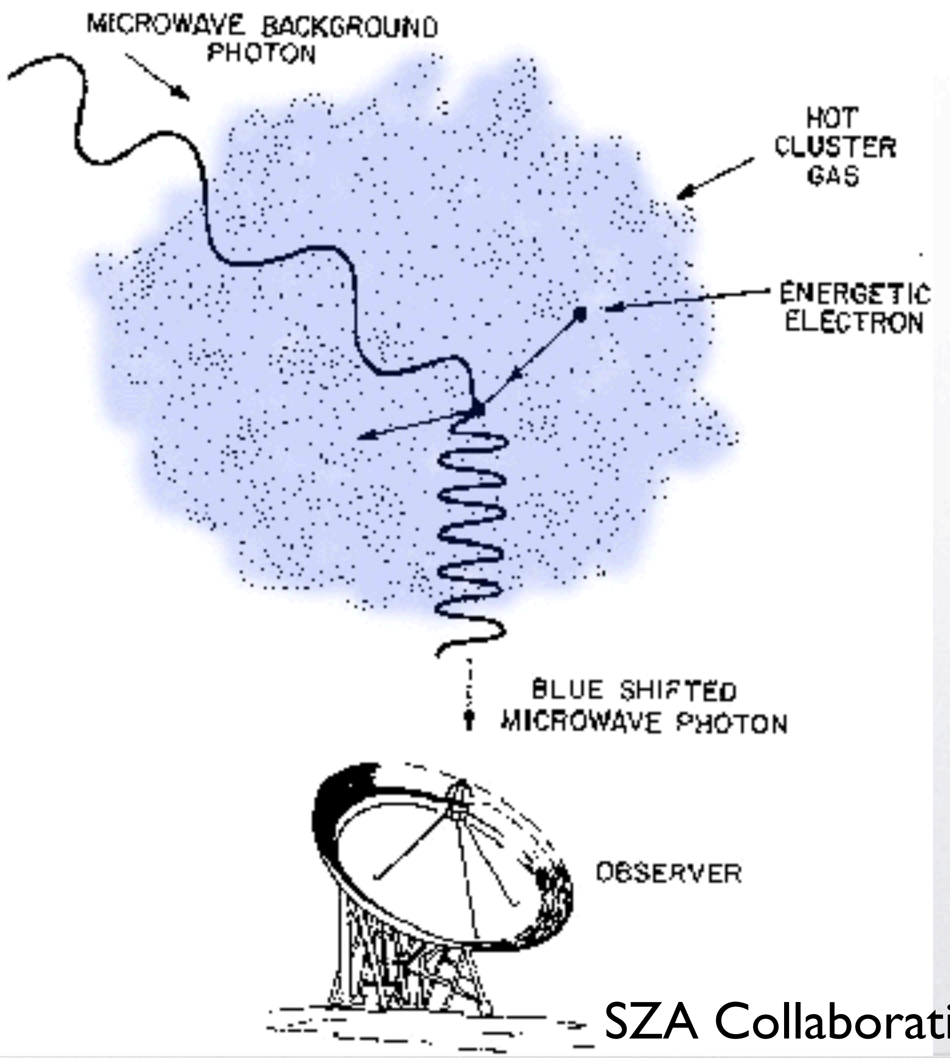
The Sunyaev-Zel'dovich Effect



The Sunyaev-Zel'dovich Effect

- 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

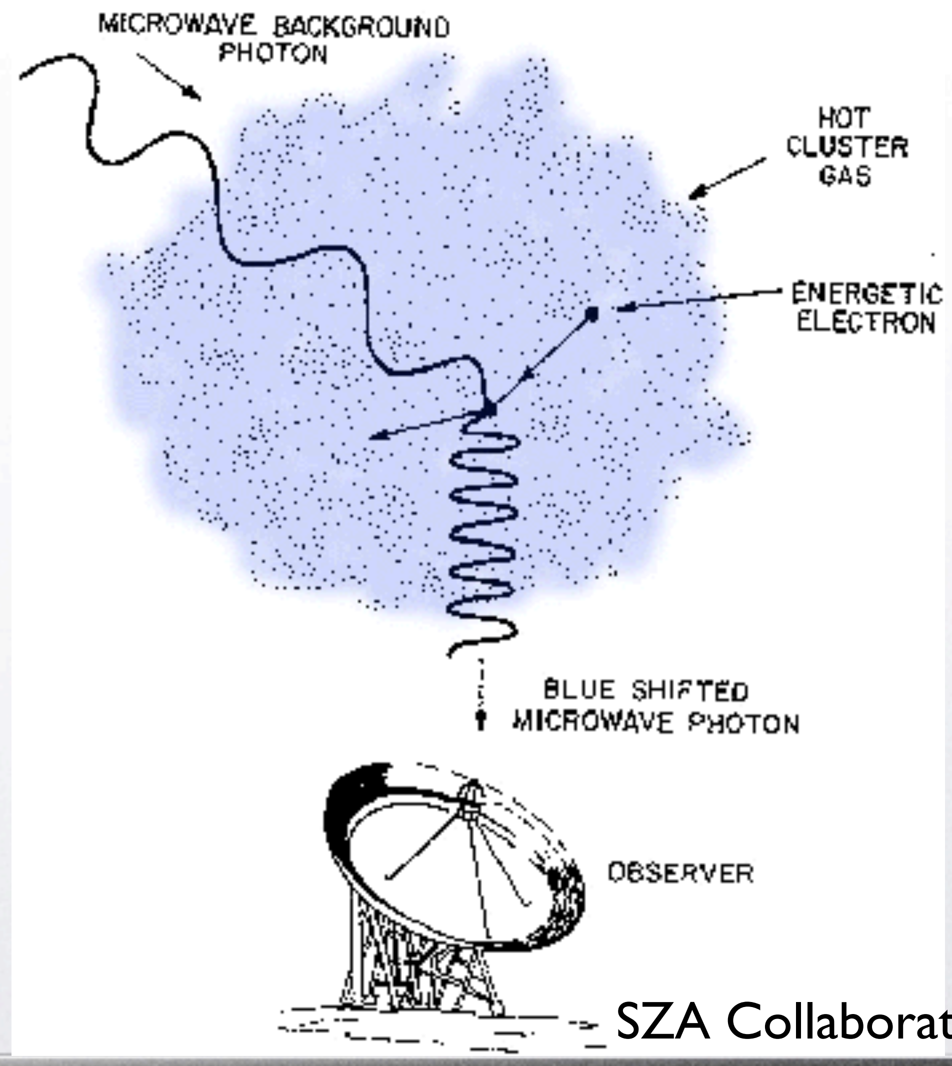
- tSZ: decrement below 218 GHz
  increment above 218 GHz



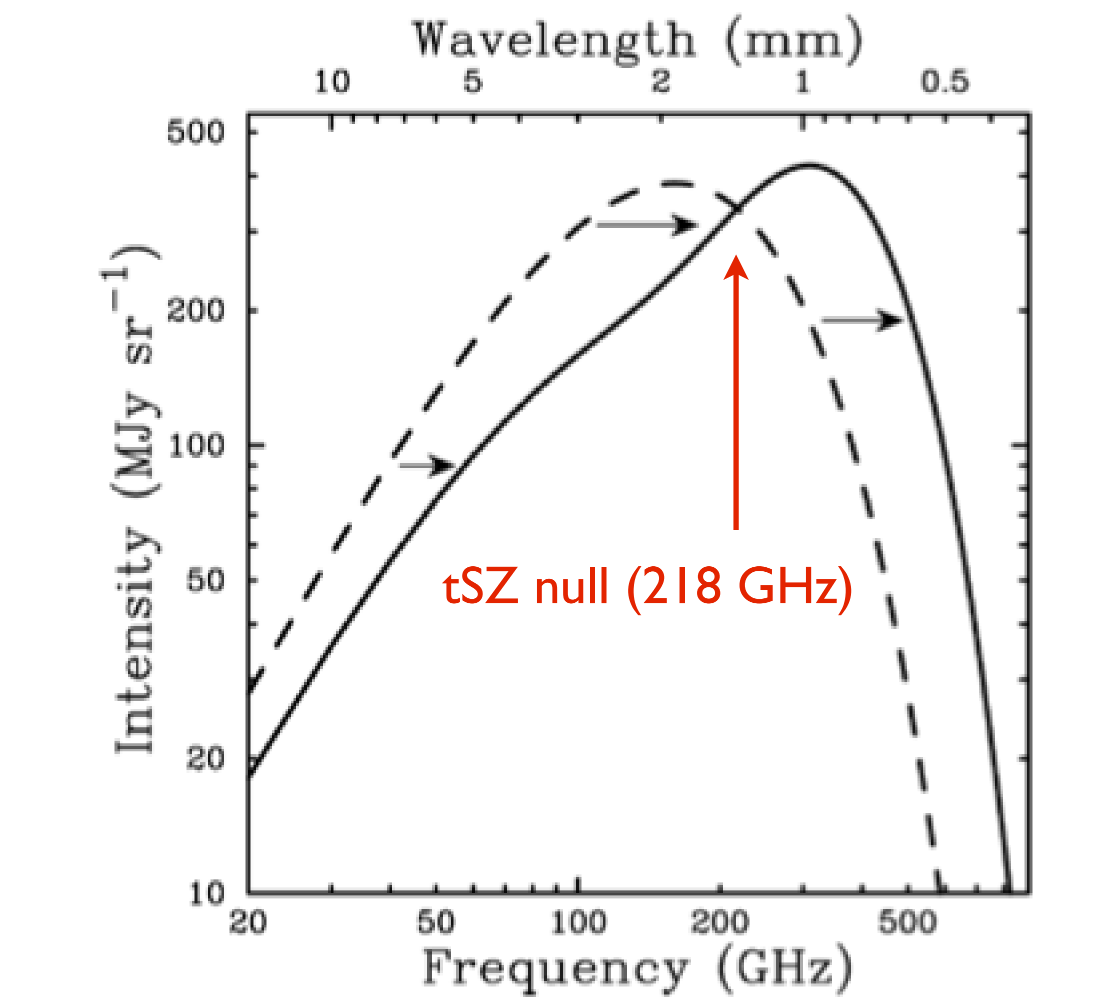
SZA Collaboration

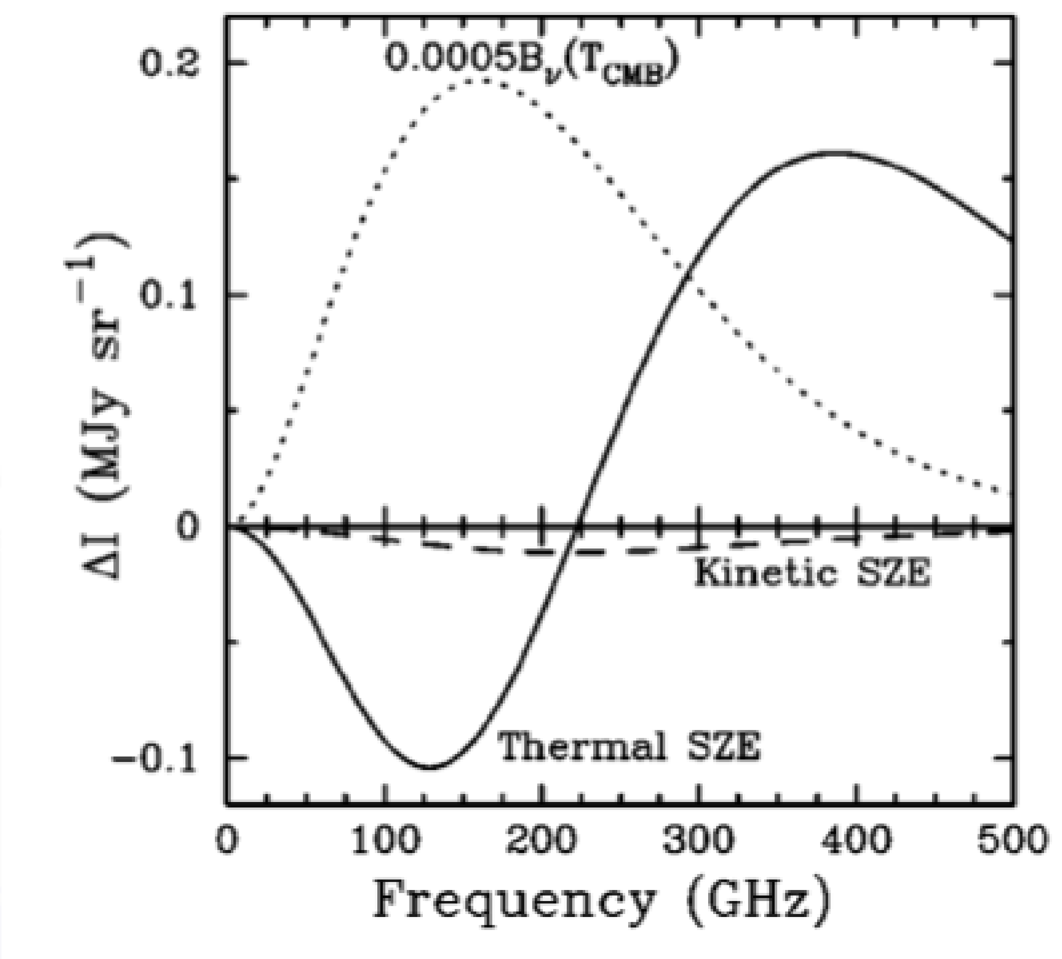
The Sunyaev-Zel'dovich Effect

- 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
- $\Delta T \sim 100\text{-}1000\ \mu K$ 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

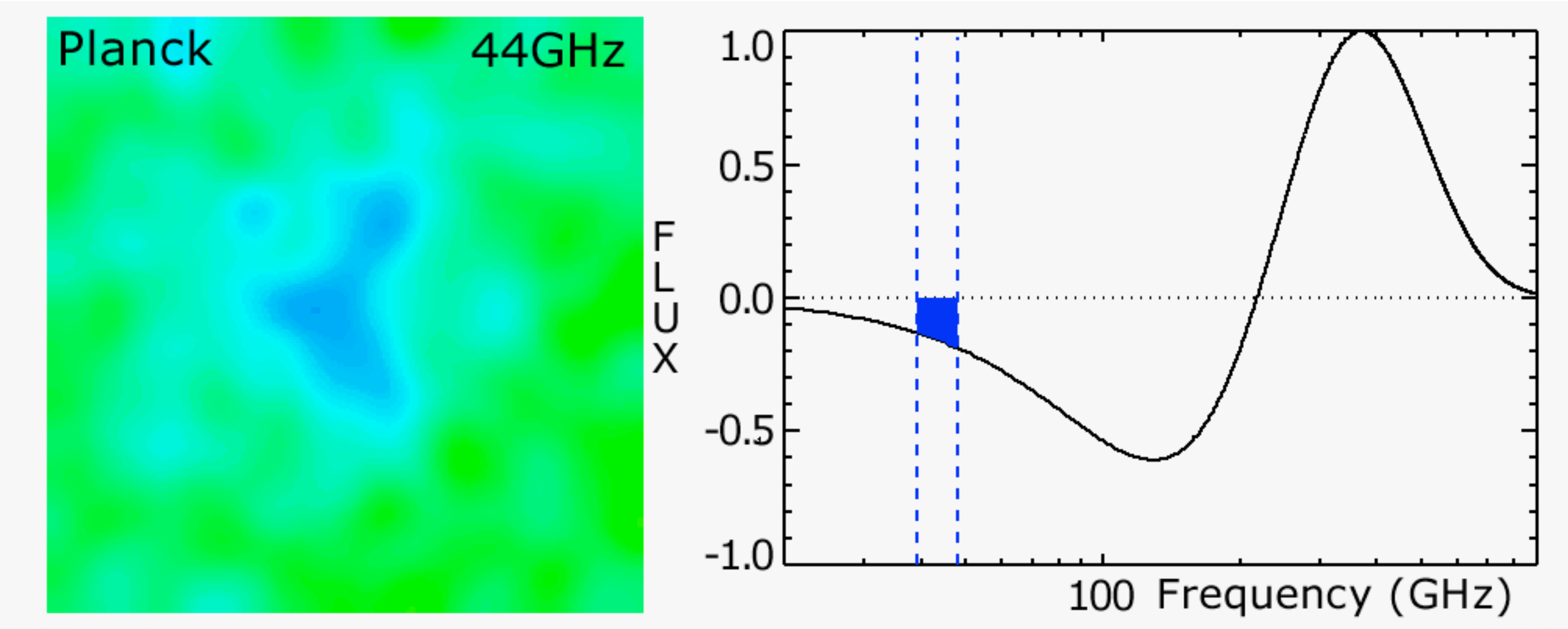




Carlstrom et al. (2002)

Colin Hill
Princeton

The Sunyaev-Zel'dovich Effect

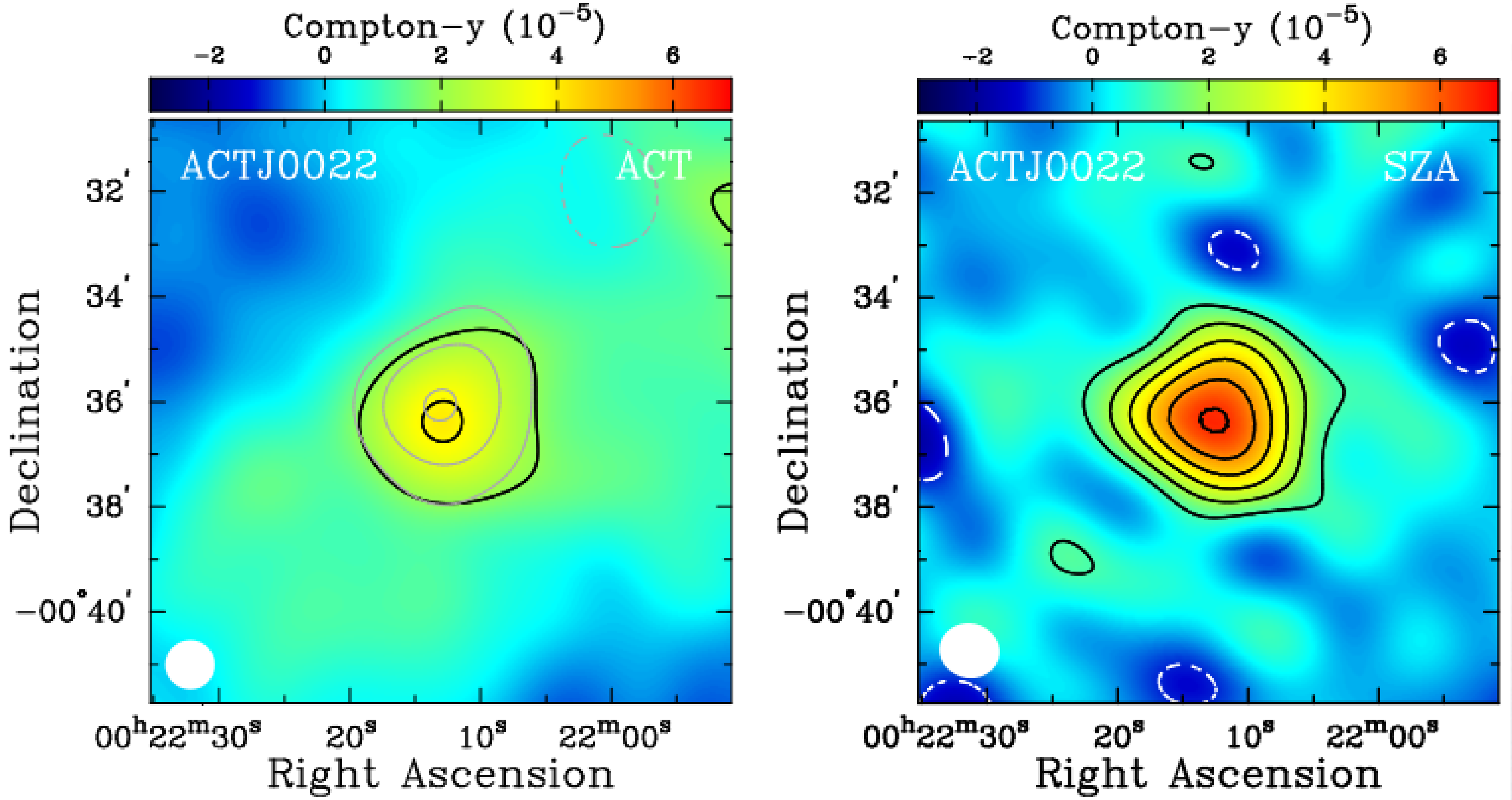


ESA/Planck Collaboration

Colin Hill
Princeton

Thermal SZ Measurements

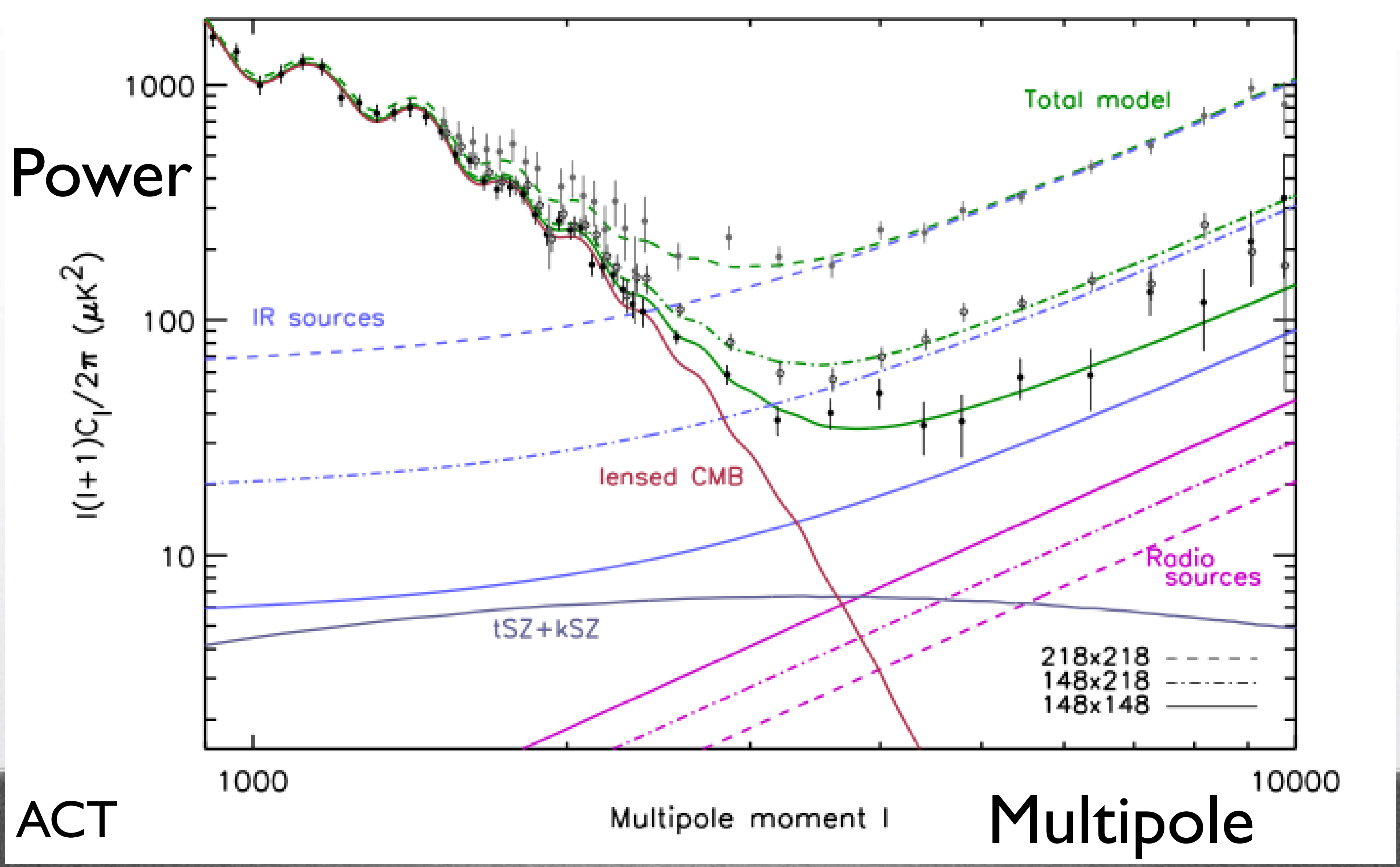
- Method 1: individual cluster observations
  - Goal: measure masses, redshifts, (peculiar velocities?), gas properties
  - Cosmological analysis: directly reconstruct halo mass function
  - Difficulties: selection function; measuring masses sufficiently accurately is hard



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

Thermal SZ Measurements

- 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



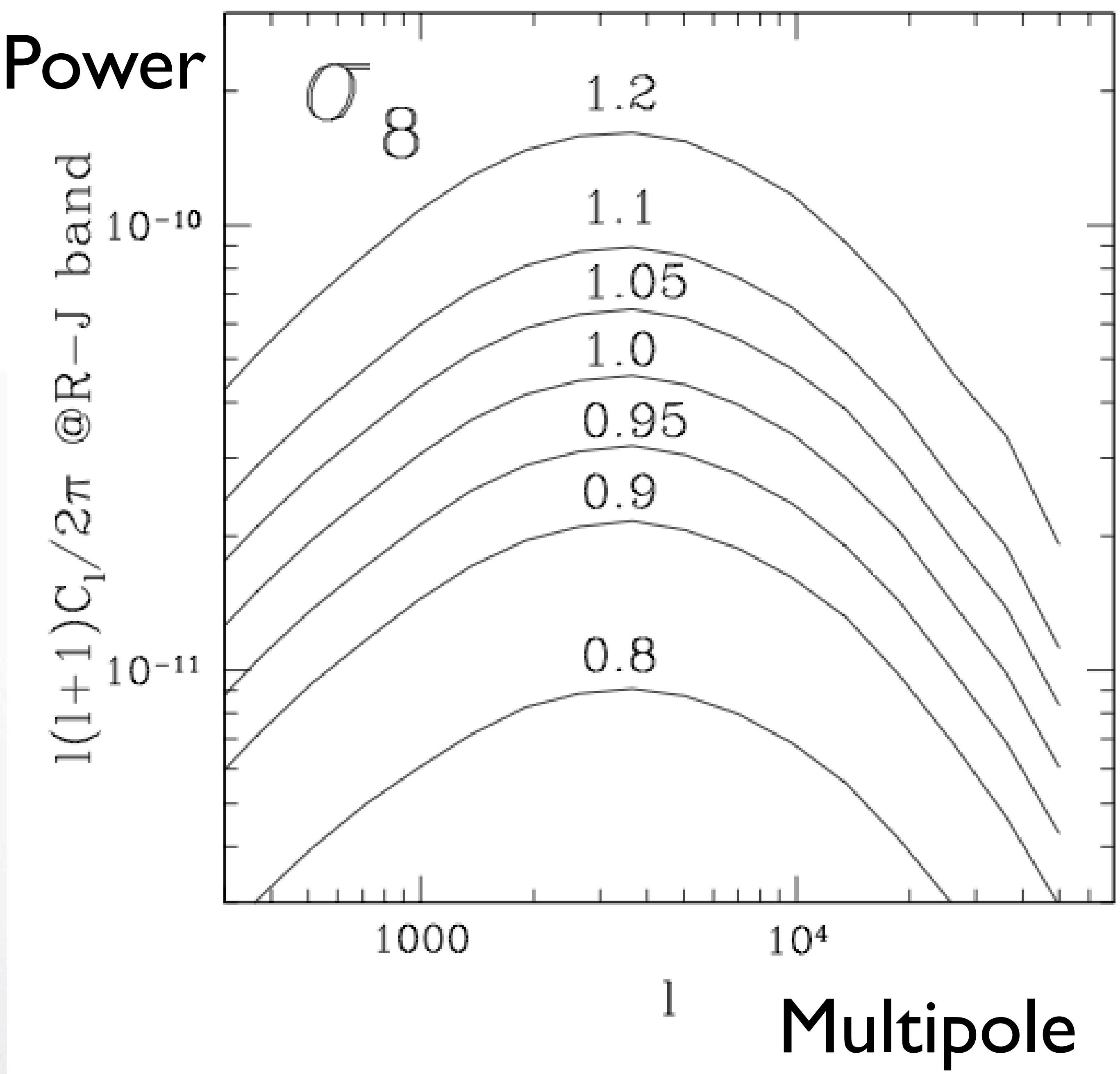
Dunkley et al. (2011)

Colin Hill
Princeton

Thermal SZ Power Spectrum

- 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

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



Komatsu & Seljak (2001,02)

Colin Hill
Princeton

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)

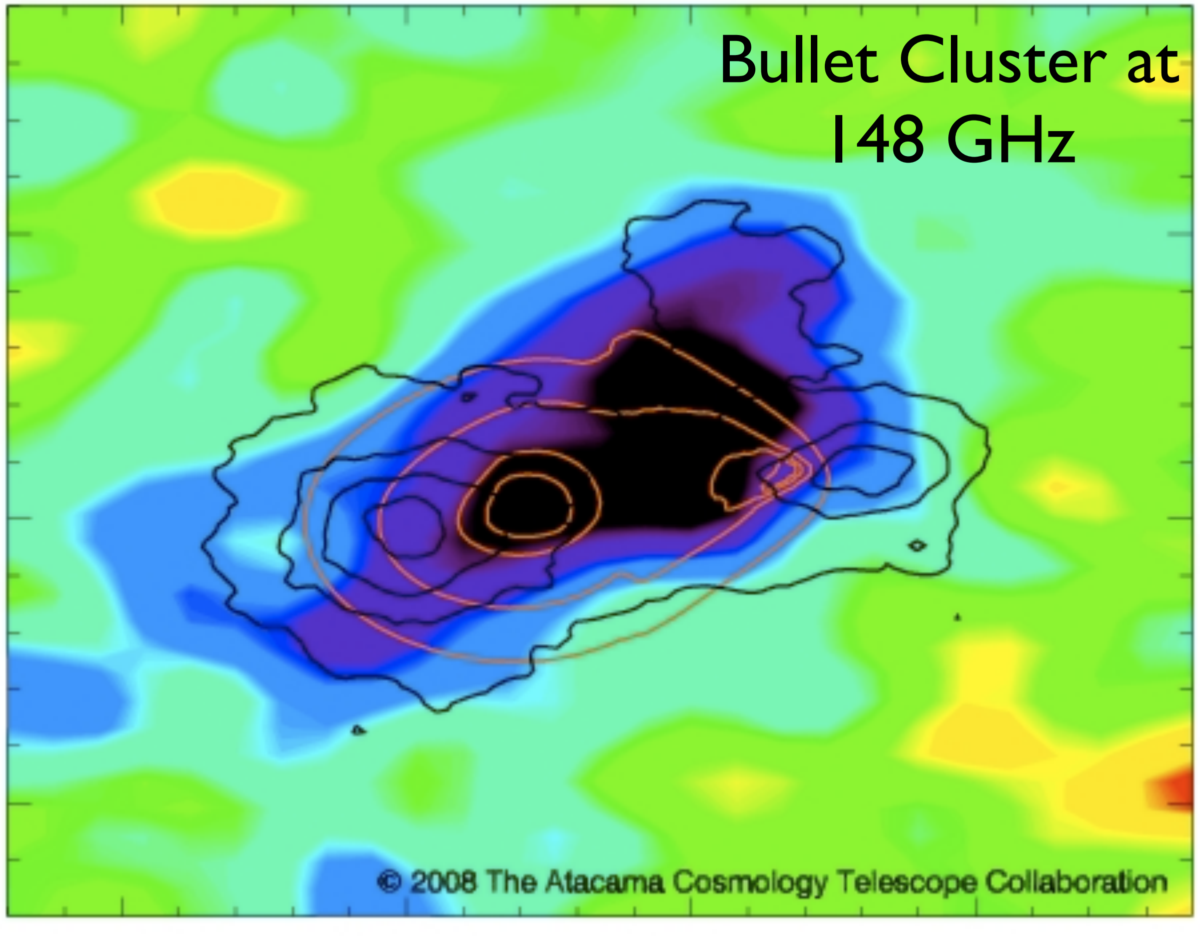
- Or: the ICM is more complicated than we thought
- Error bars dominated by systematic uncertainty due to gastrophysics!
- What can we learn with data we already have?

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

Colin Hill
Princeton

Thermal SZ Moments:

$$\langle T^N \rangle$$



Colin Hill
Princeton

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*:

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

tSZ spectral function — CMB temp. today — Thomson cross-section — ICM electron pressure profile integrated over LOS

↓

Gastrophysics

Colin Hill
Princeton

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*:

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

tSZ spectral function — CMB temp. today — Thomson cross-section — ICM electron pressure profile integrated over LOS

↓

Gastrophysics

- $N^{\rm th}$ thermal SZ moment:

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

comoving volume per steradian — halo mass function

↓

Cosmology

Colin Hill
Princeton

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

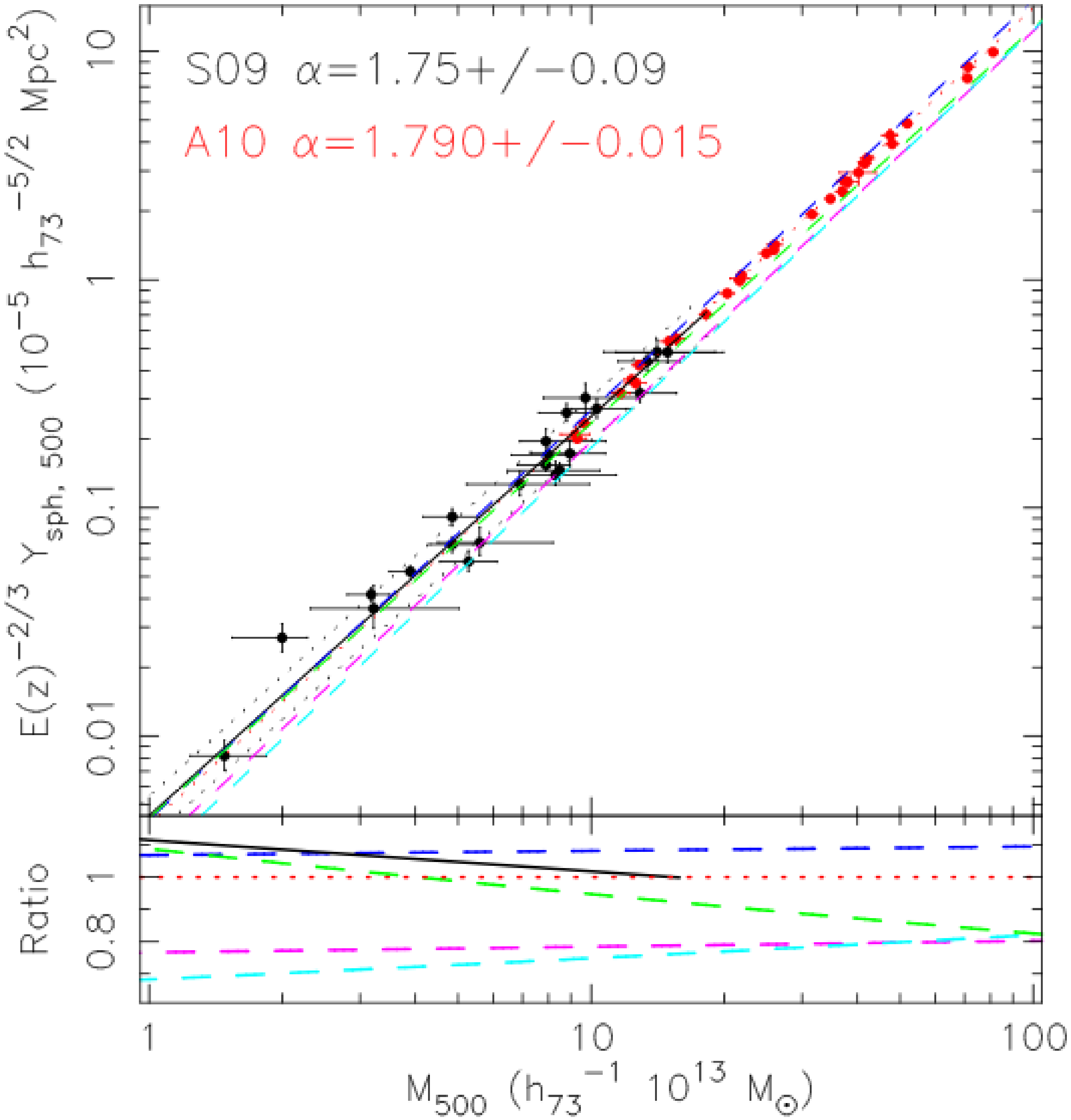
- Additional physics needed:
  - Formation shock heating
  - Star formation, supernova feedback, cosmic rays
  - Active galactic nucleus feedback
  - Magnetic fields, plasma instabilities
  - Turbulent pressure support

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

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

Colin Hill
Princeton

Integrated SZ Signal



Cluster Mass

>30% scatter over wide range in mass

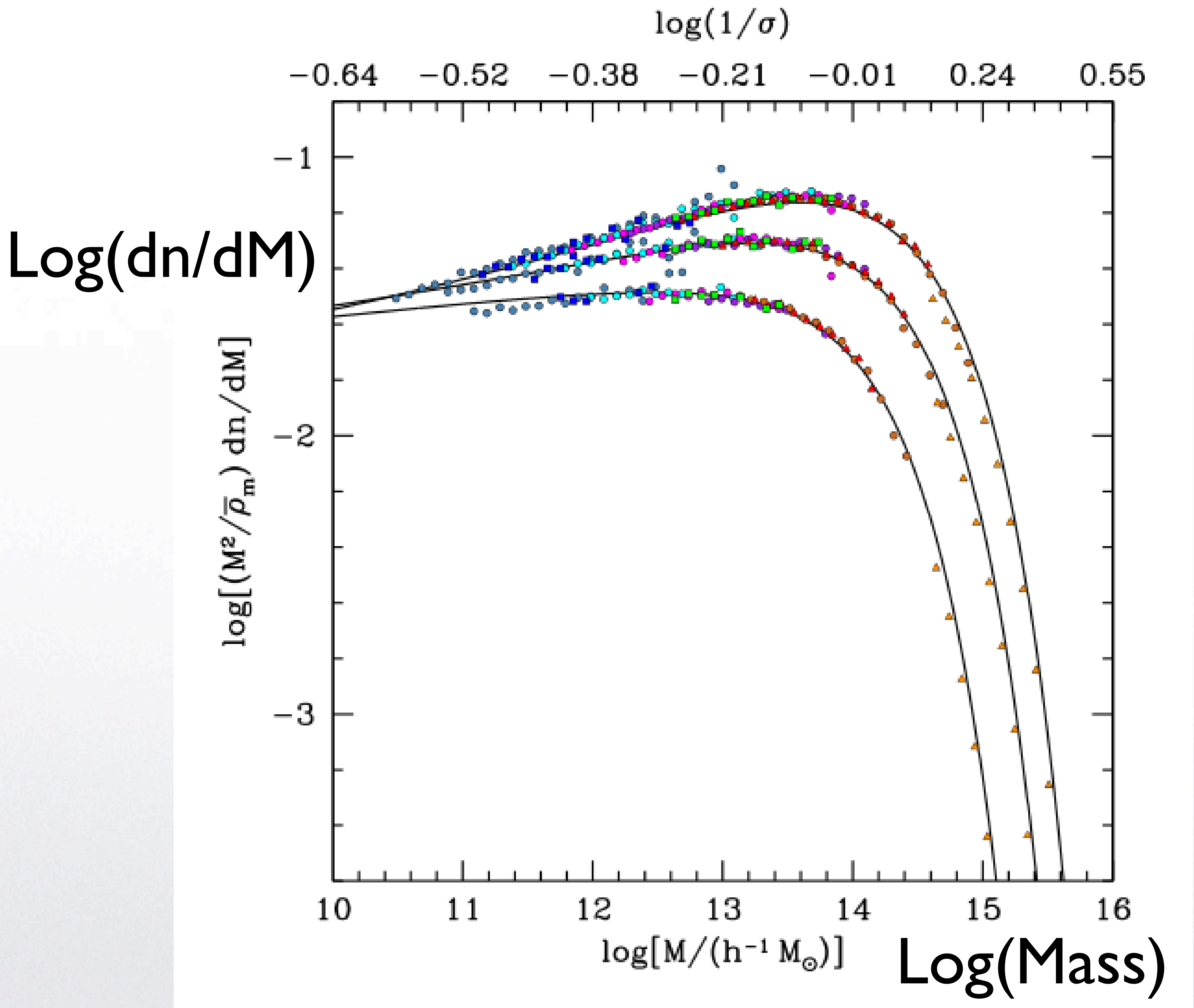
↓

order unity uncertainty in tSZ power spectrum (or variance)

Sun et al. (2011)

Colin Hill
Princeton

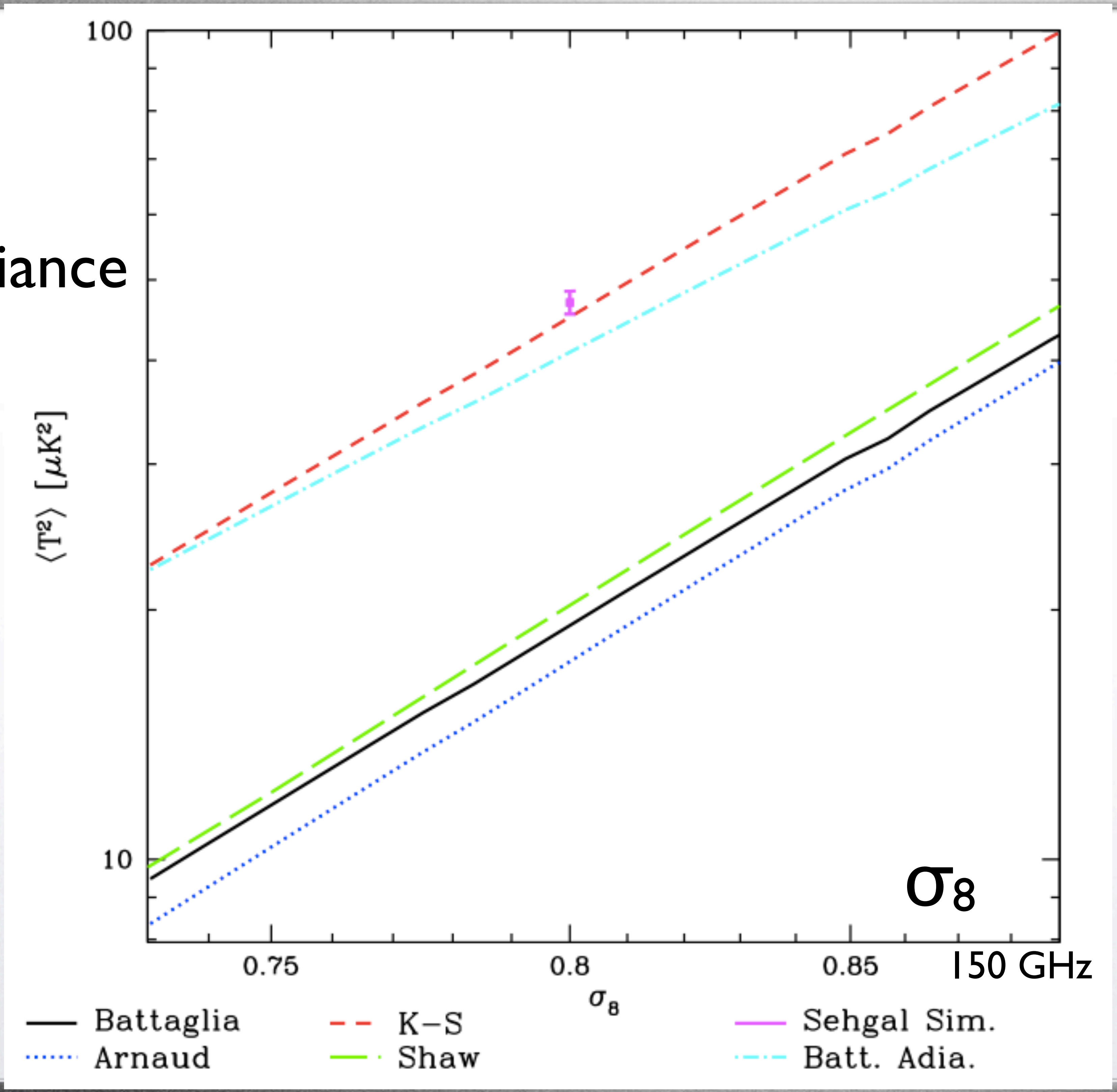
Cosmology: Mass Function



- Claim: ΛCDM mass function known to 5-10% accuracy or better
- Possible issues:
  - mass definitions
  - halo finders
  - baryonic physics
  - simulation initial conditions

Thermal SZ Moments: Variance

Variance

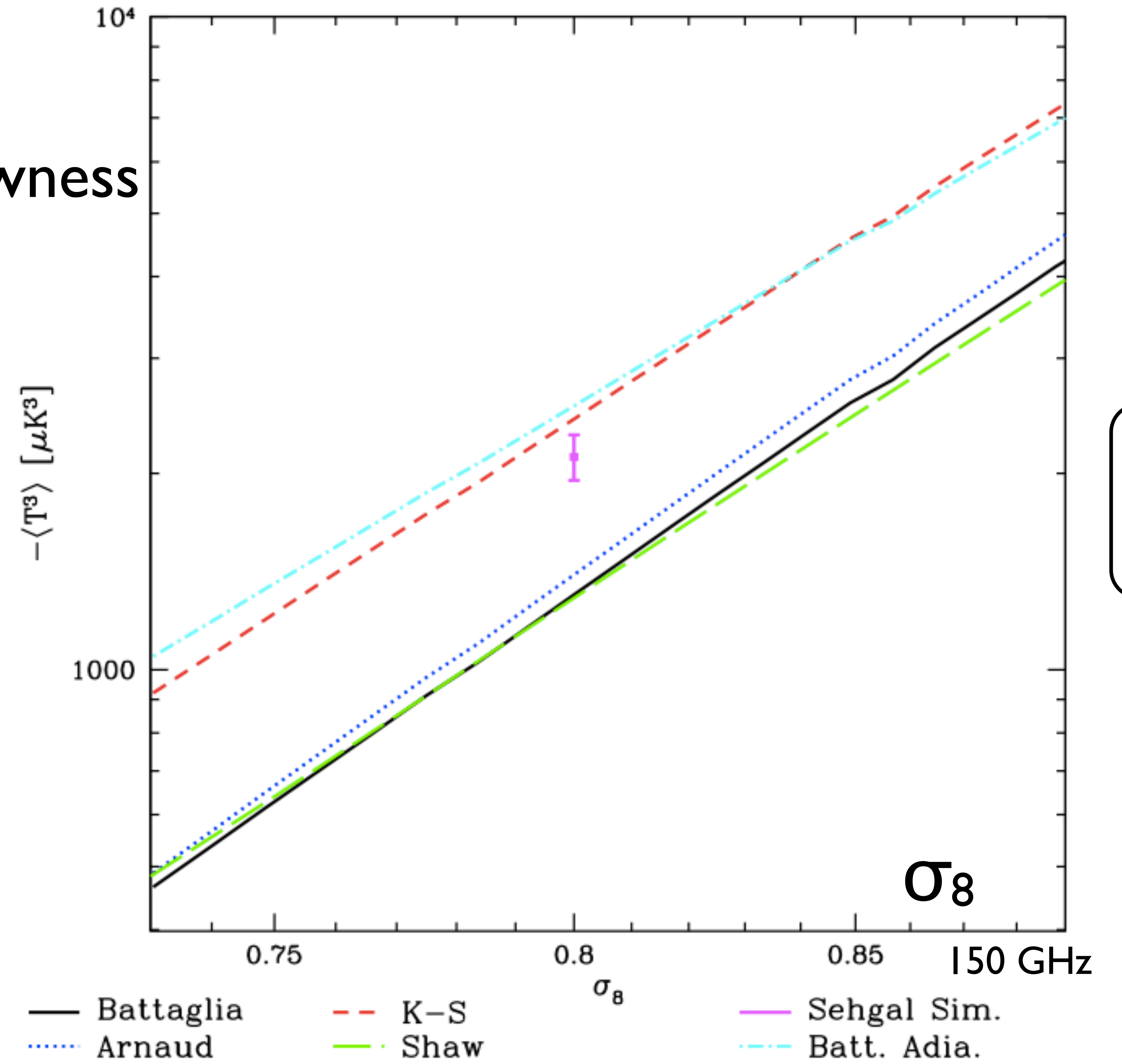


$$\langle T^2 \rangle \propto \sigma_8^{7-8}$$

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

Thermal SZ Moments: Skewness

Skewness

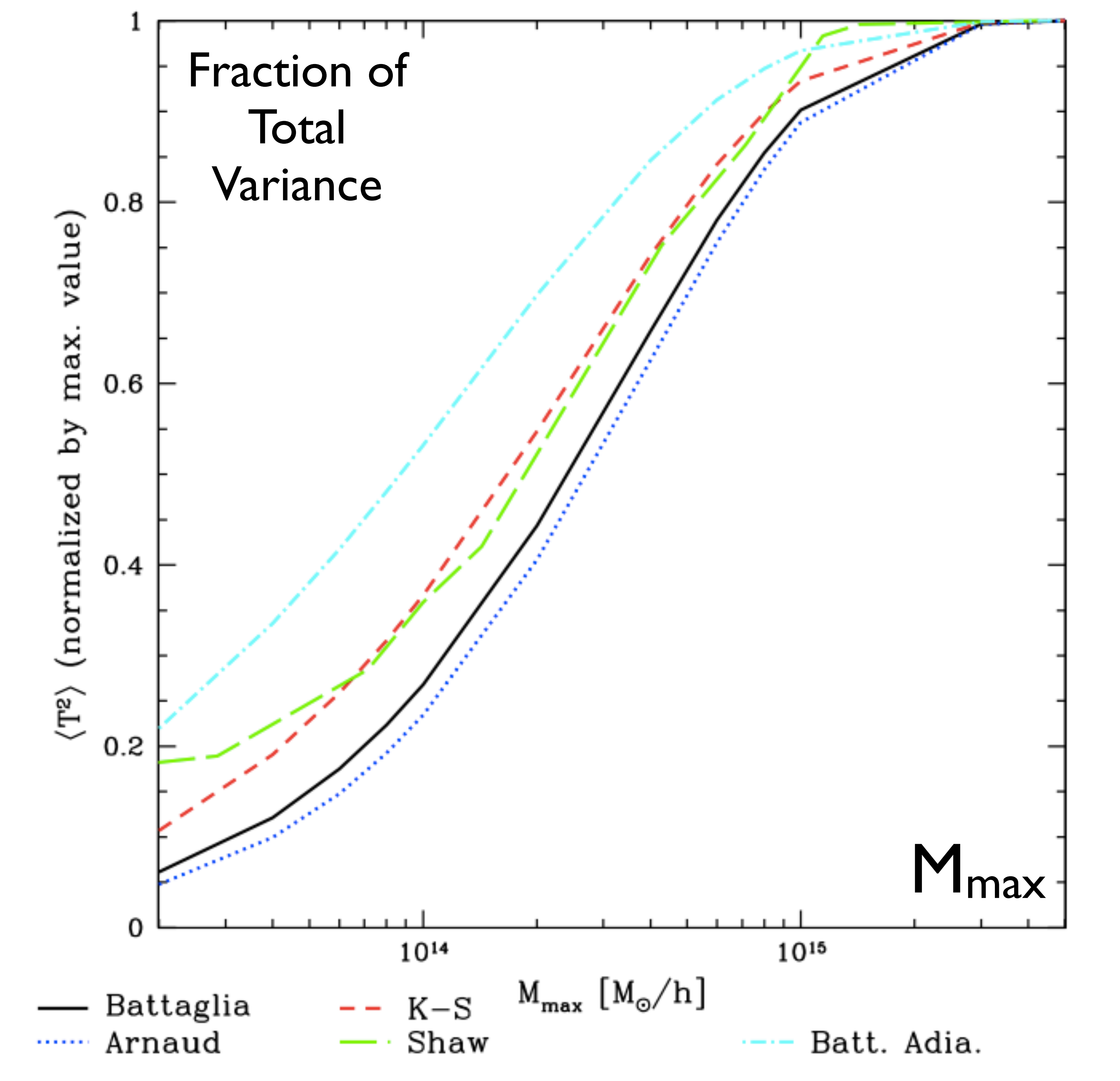


$$\langle T^3 \rangle \propto \sigma_8^{10-11.5}$$

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

Colin Hill
Princeton

Which Clusters Contribute?



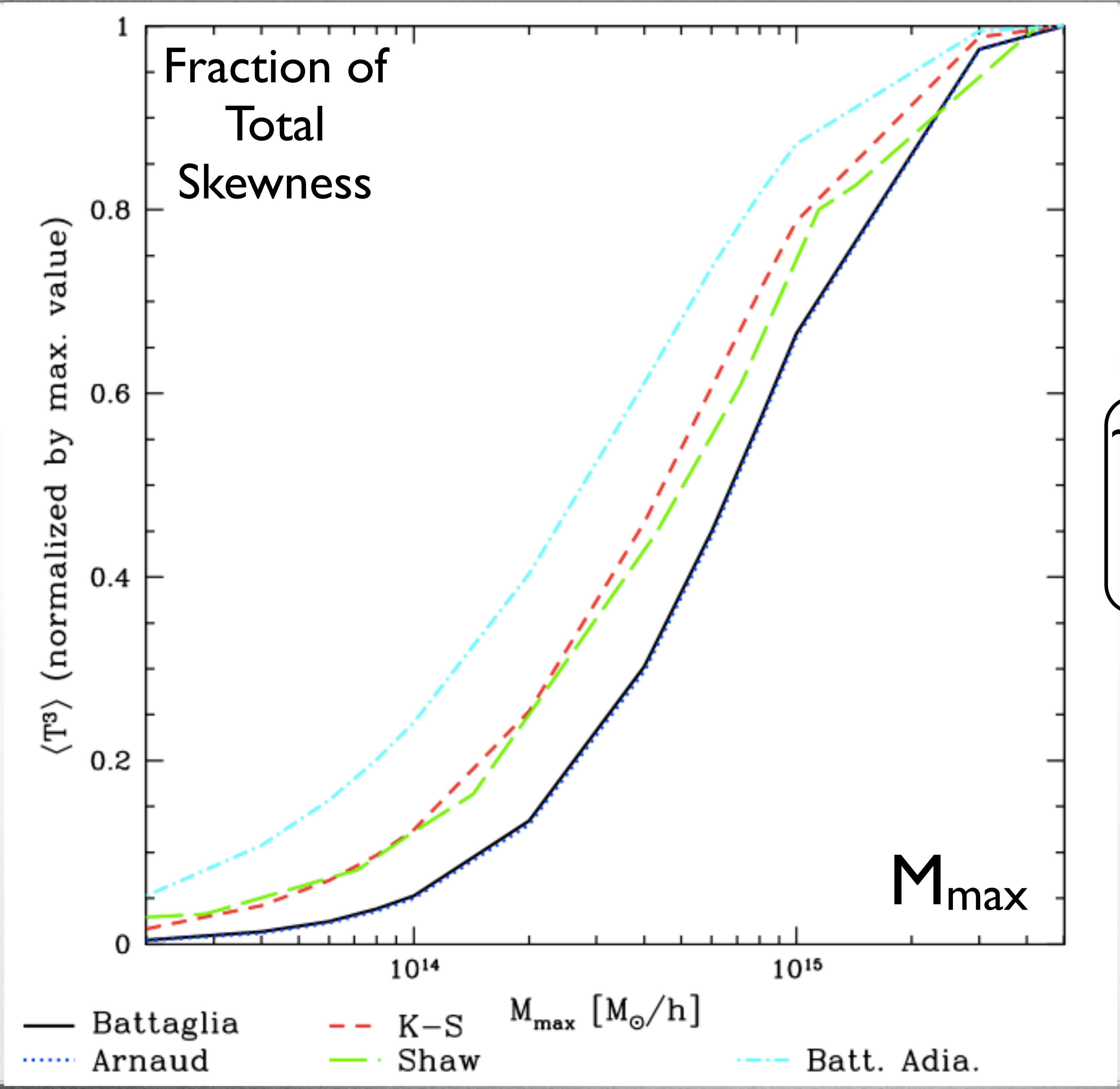
~40-60% of tSZ variance signal comes from clusters with

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

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

Colin Hill
Princeton

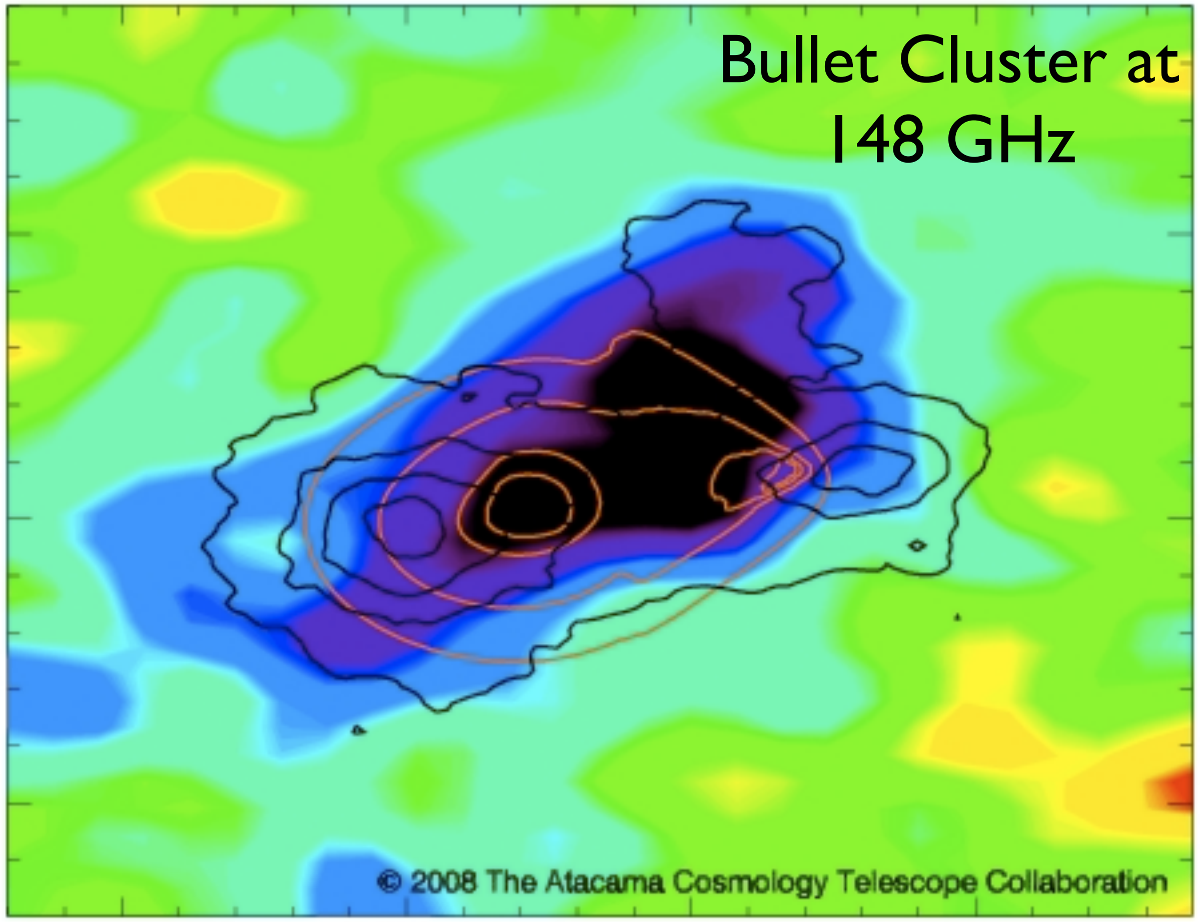
Which Clusters Contribute?



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

ACT Measurement:

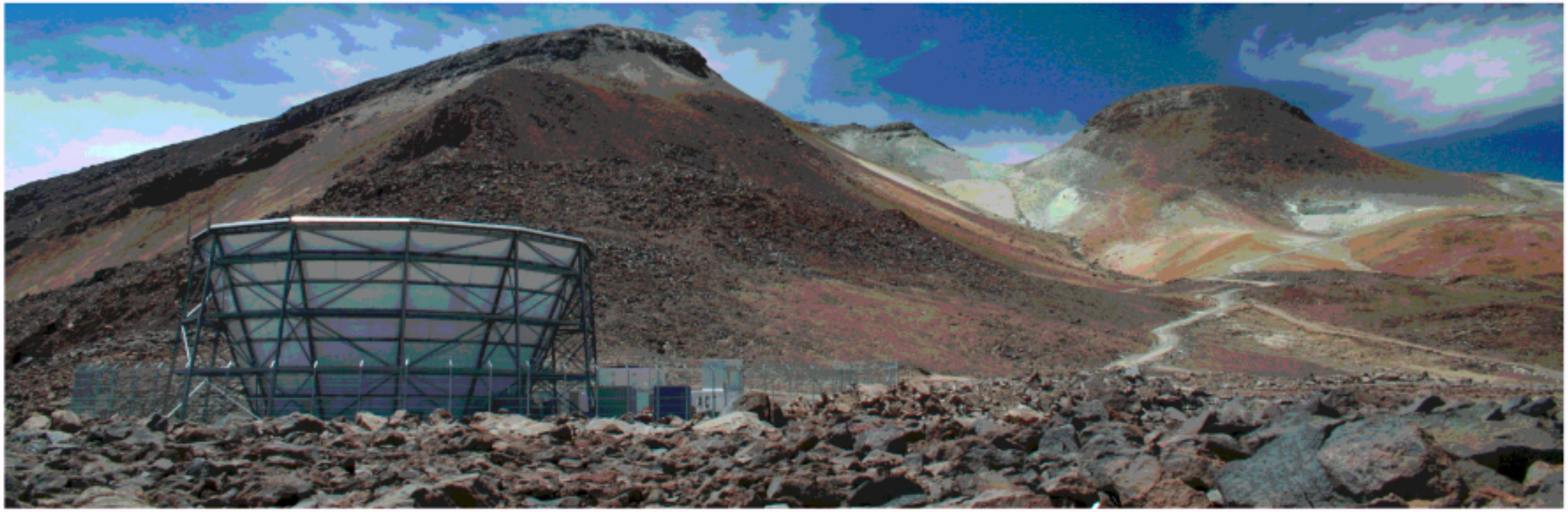
$$\langle T^3 \rangle$$



Colin Hill
Princeton

The Atacama Cosmology Telescope

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



ATACAMA COSMOLOGY TELESCOPE

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.

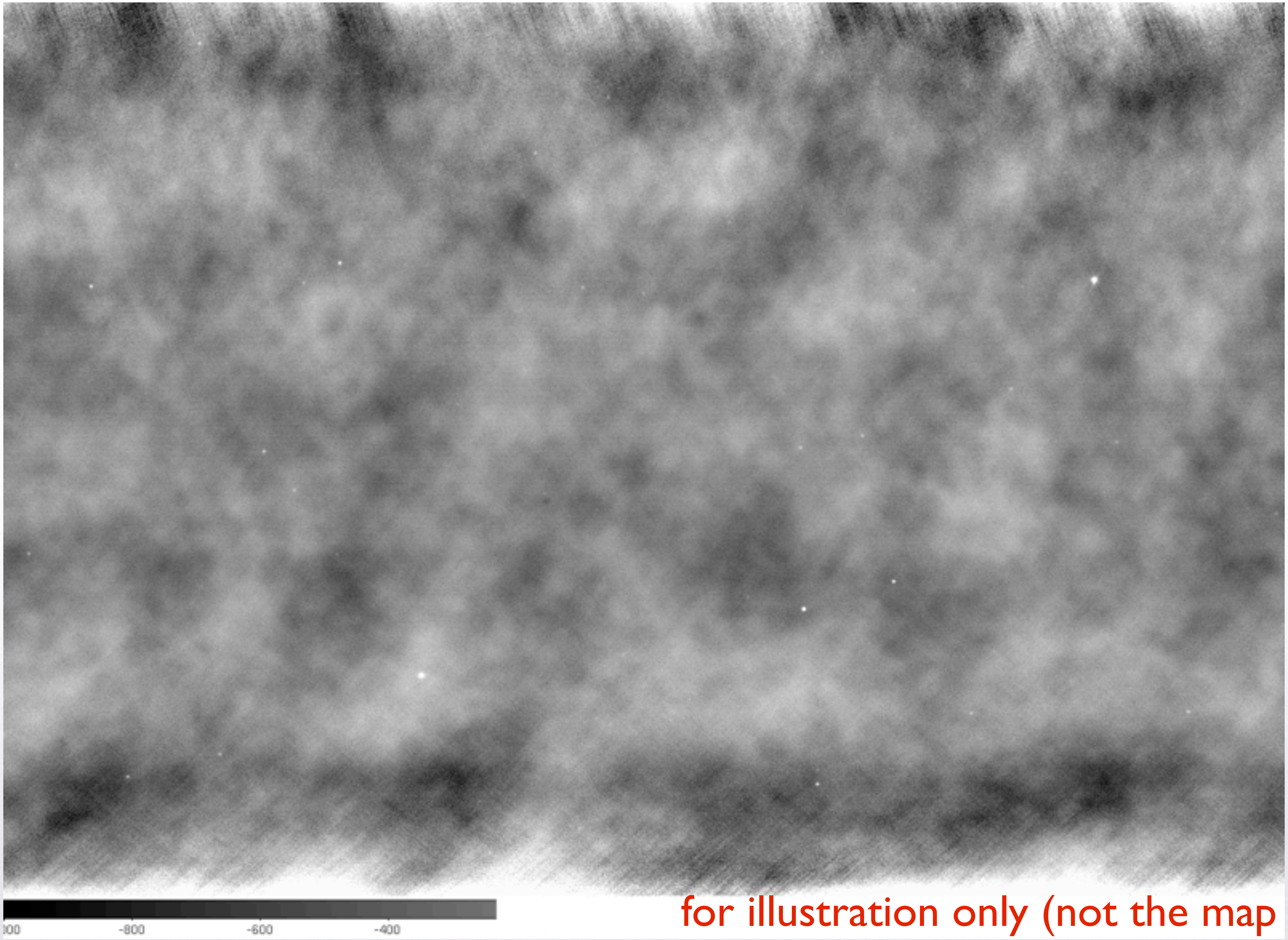
Colin Hill
Princeton

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
- Theoretical advantages:
  - Dominated by more massive clusters (less uncertainty in ICM modeling)
  - Scales with higher power of σ_8
  - Fewer DSFGs in massive, low-z clusters than in high-z groups that contribute much of the power spectrum signal

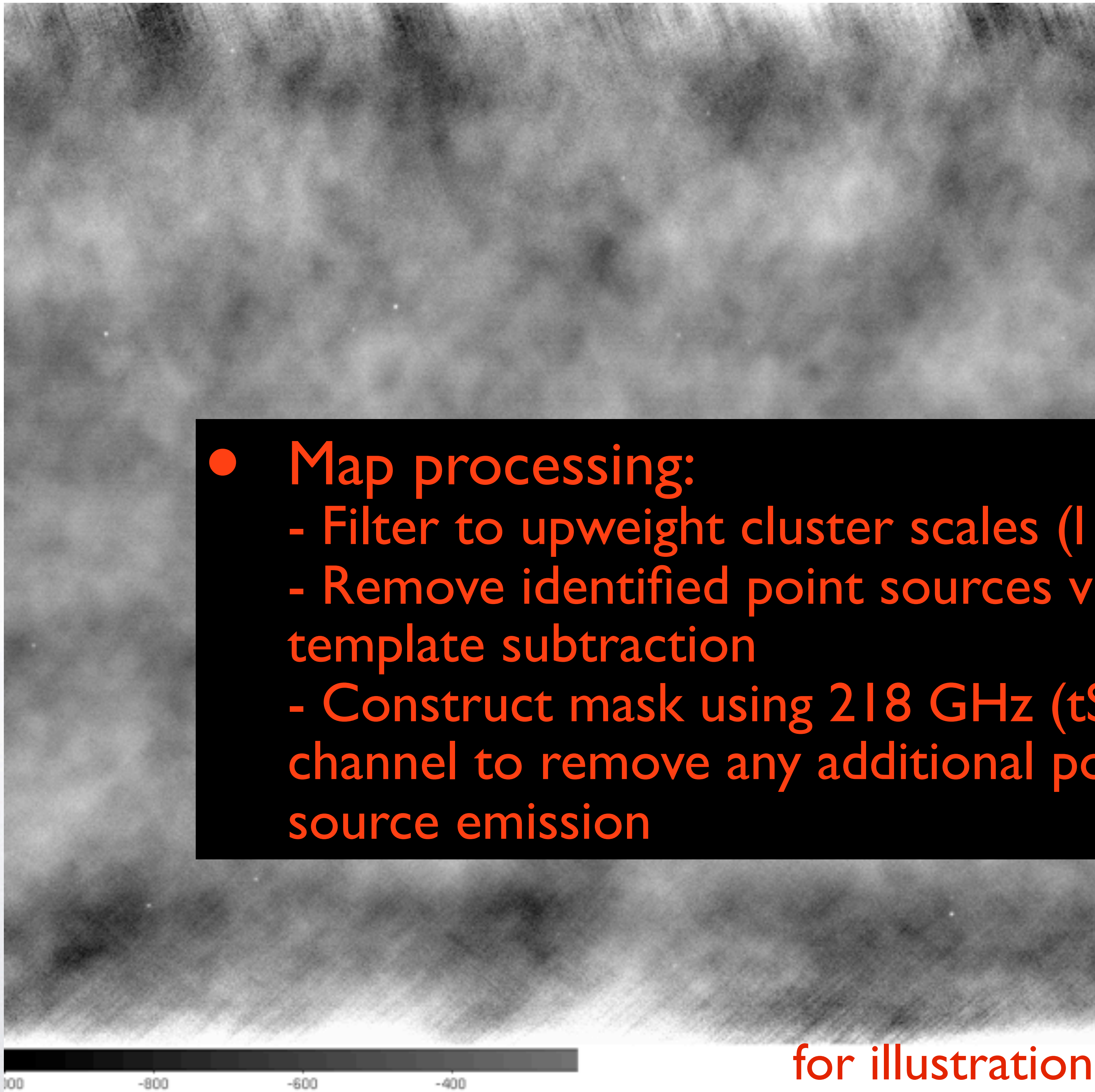
Wilson, Sherwin, JCH, et al. (2012)

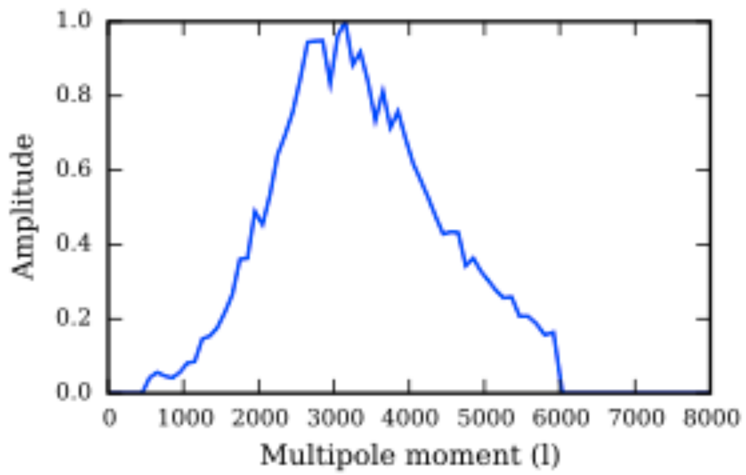
How to Measure the Skewness



for illustration only (not the map we used)

Colin Hill
Princeton





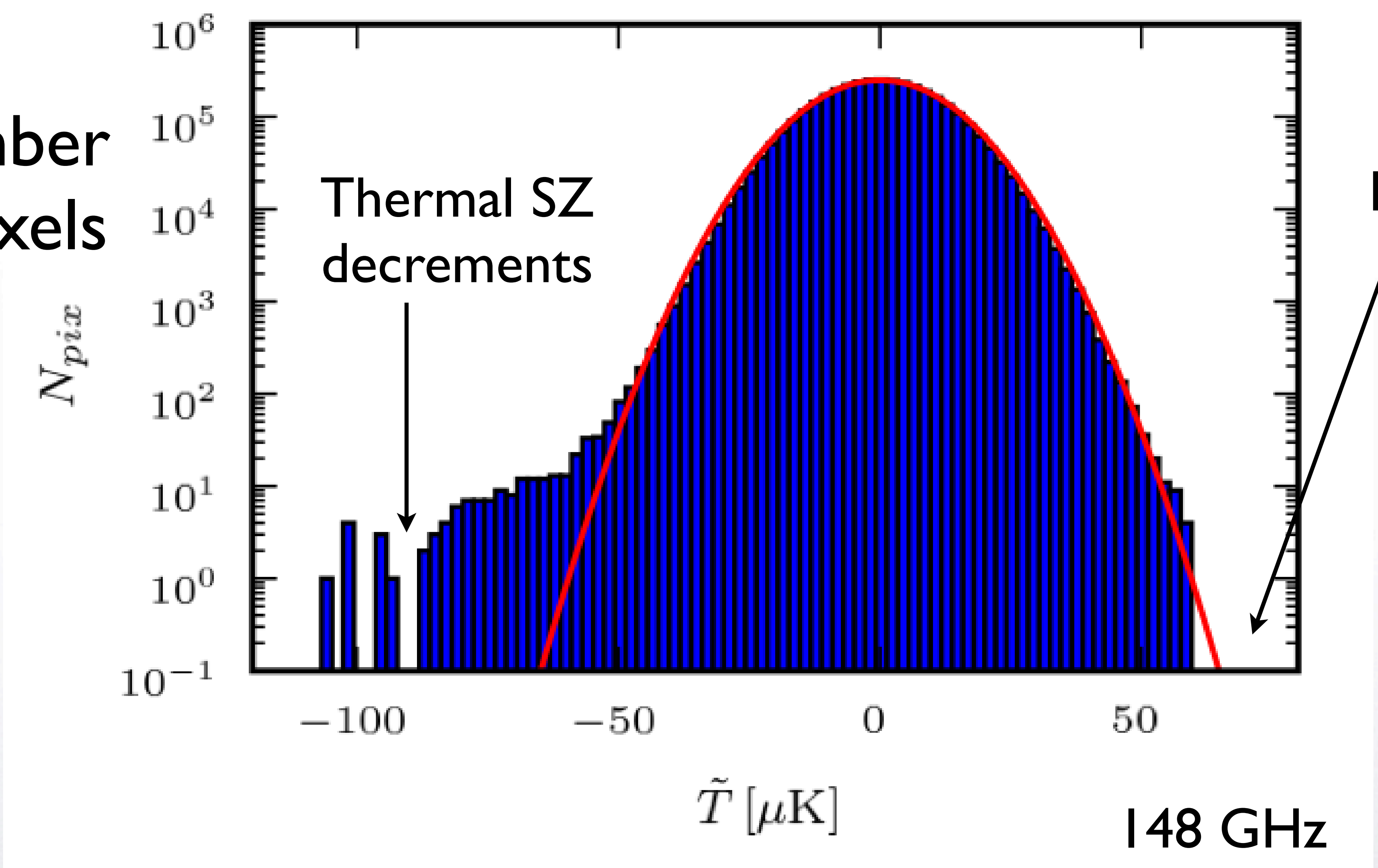
- Map processing:
  - Filter to upweight cluster scales (l ~ 3000)
  - Remove identified point sources via template subtraction
  - Construct mask using 218 GHz (tSZ-null) channel to remove any additional point source emission

for illustration only (not the map we used)

Colin Hill
Princeton

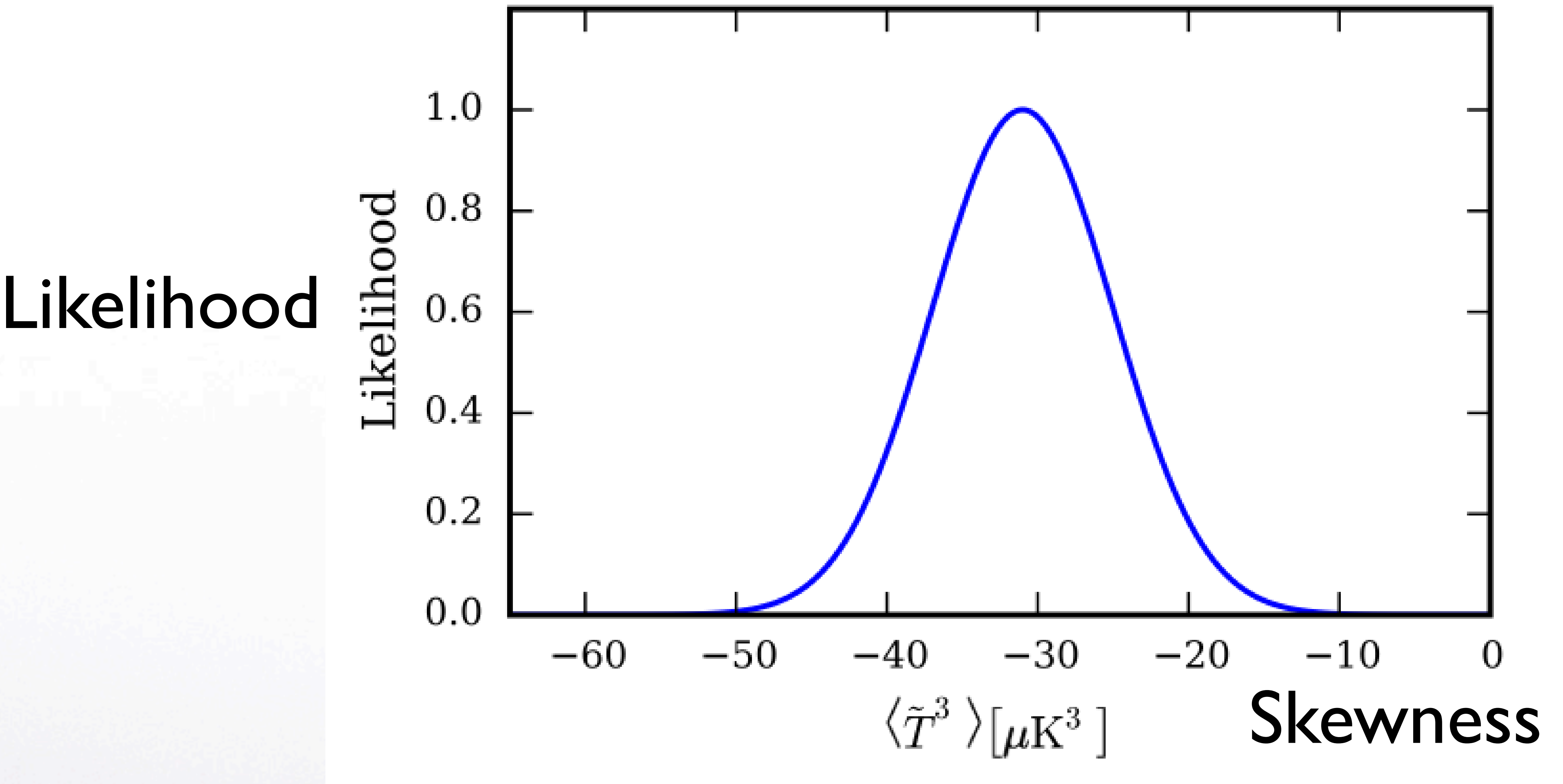
Filtered Temperature PDF

Number of Pixels



Filtered Pixel Temperature

The Skewness Measurement

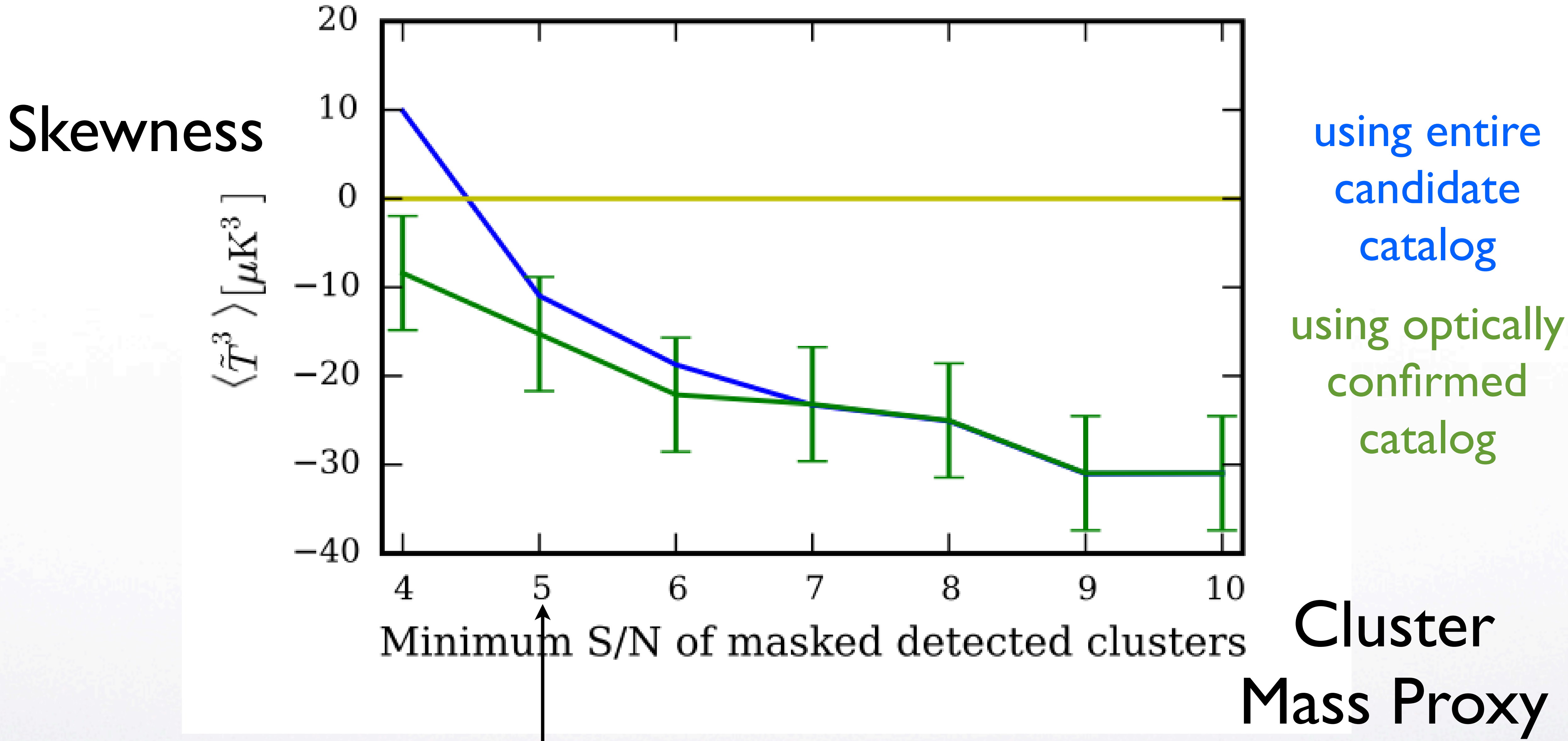


$$\left\langle \tilde{T}^3 \right\rangle = -31 \pm 6\,\mu K^3 \quad \text{(Gaussian errors only)}$$
$$\pm 14\,\mu K^3 \quad \text{(with non-Gaussian error, i.e., cosmic variance)}$$

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

Colin Hill
Princeton

The Origin of the Signal: tSZ?



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

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

Colin Hill
Princeton

Derived Cosmological Constraints

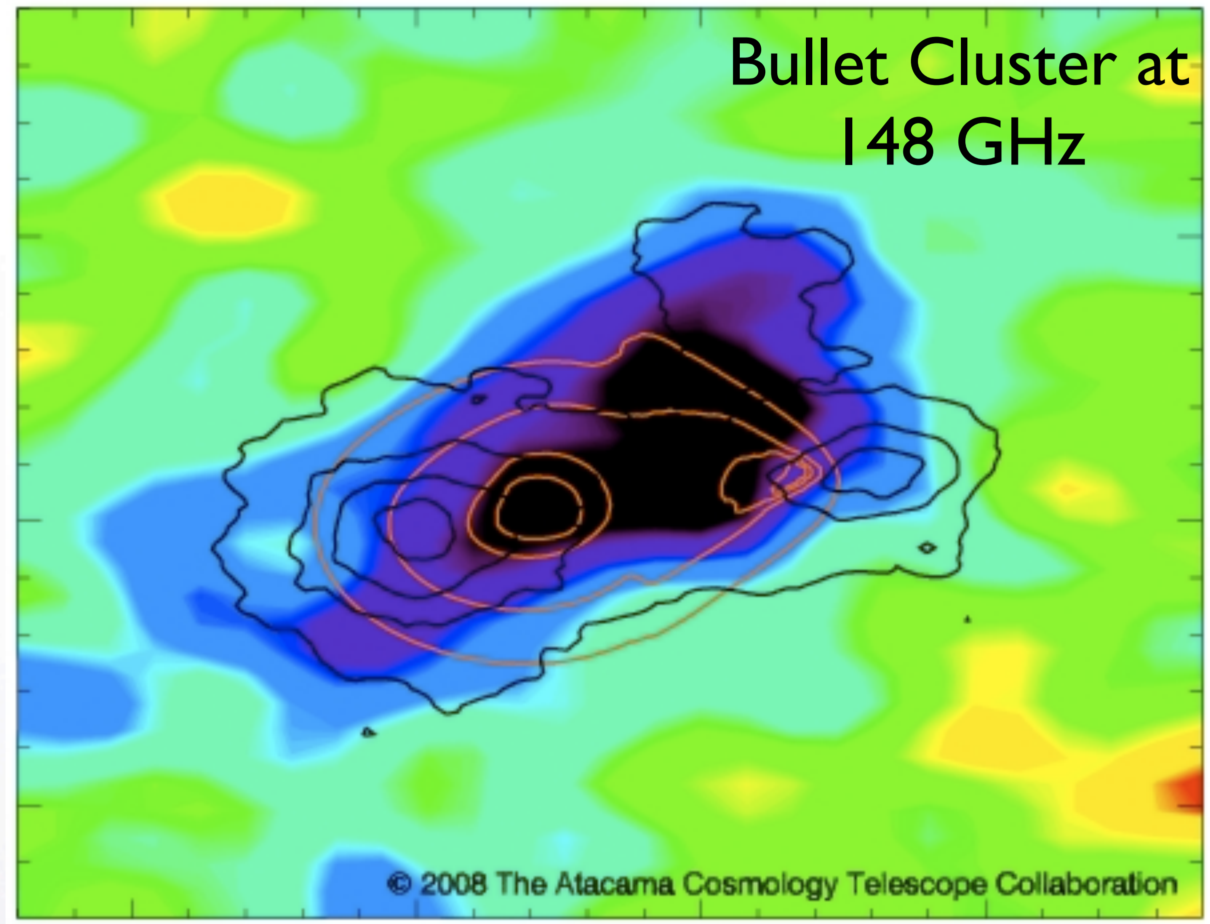
- Simple constraint: $\sigma_8^D = \sigma_8^S \left[\frac{\left\langle \tilde{T}^3 \right\rangle^D}{\left\langle \tilde{T}^3 \right\rangle^S} \right]^{1/10.5}$

sims from Battaglia, Sehgal

$$\longrightarrow \boxed{\sigma_8 = 0.78^{+0.03}_{-0.03}\ (68\%\,\mathrm{C.L.})\ ^{+0.06}_{-0.05}\ (95\%\,\mathrm{C.L.})}$$

- 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 -- better than tSZ PS
- We have neglected any degeneracy with other cosmological parameters; most are irrelevant (Bhattacharya et al. 2012)
- Exception: $\langle T^3 \rangle \propto (\Omega_b h)^{3-4}$

Cosmological Constraints



Overcoming Gastrophysics

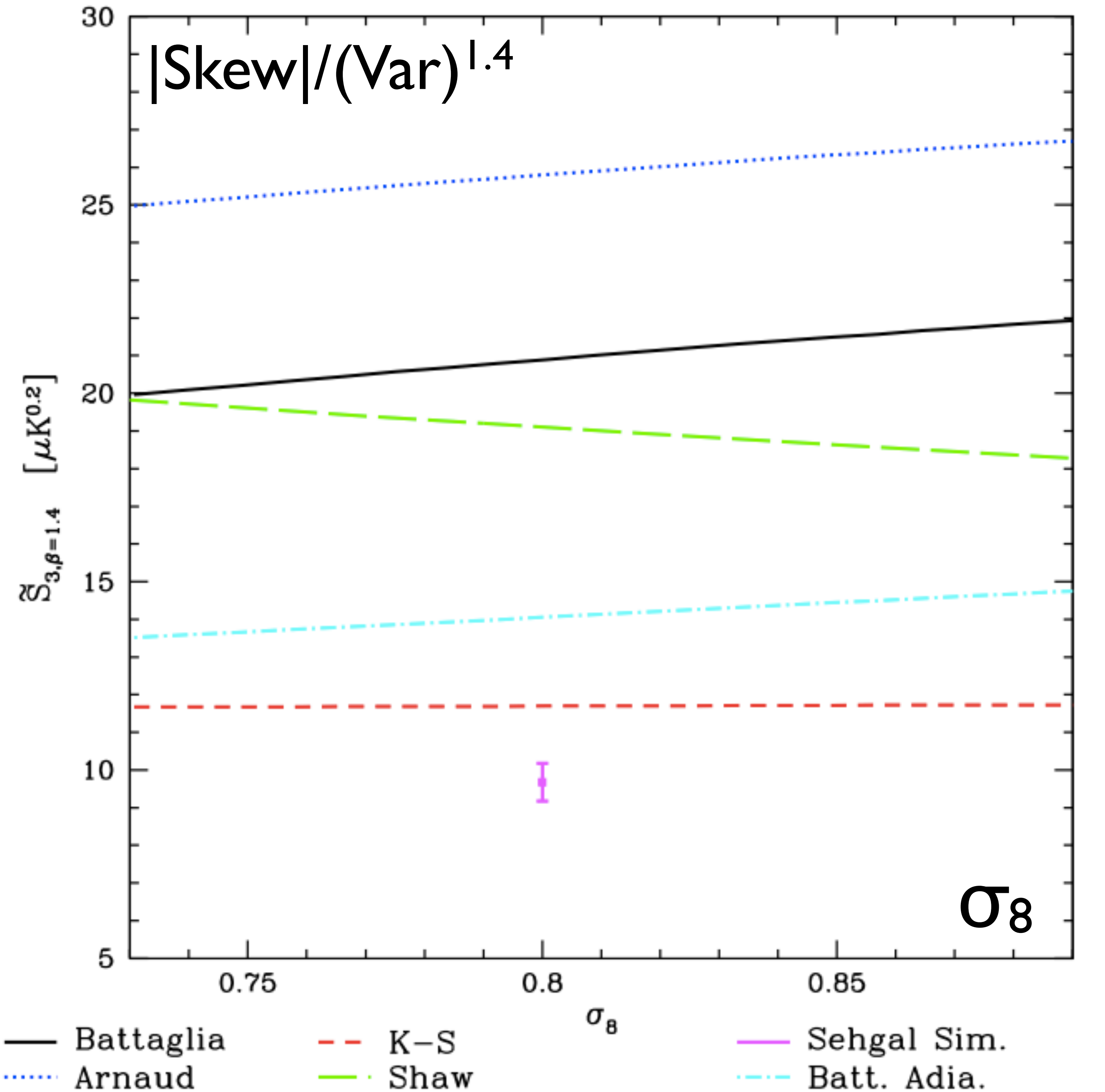
- Idea: tSZ variance and skewness depend differently on cosmological parameters and ICM gastrophysics
  $\longrightarrow$ construct combinations that 'cancel' one or the other

- 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

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

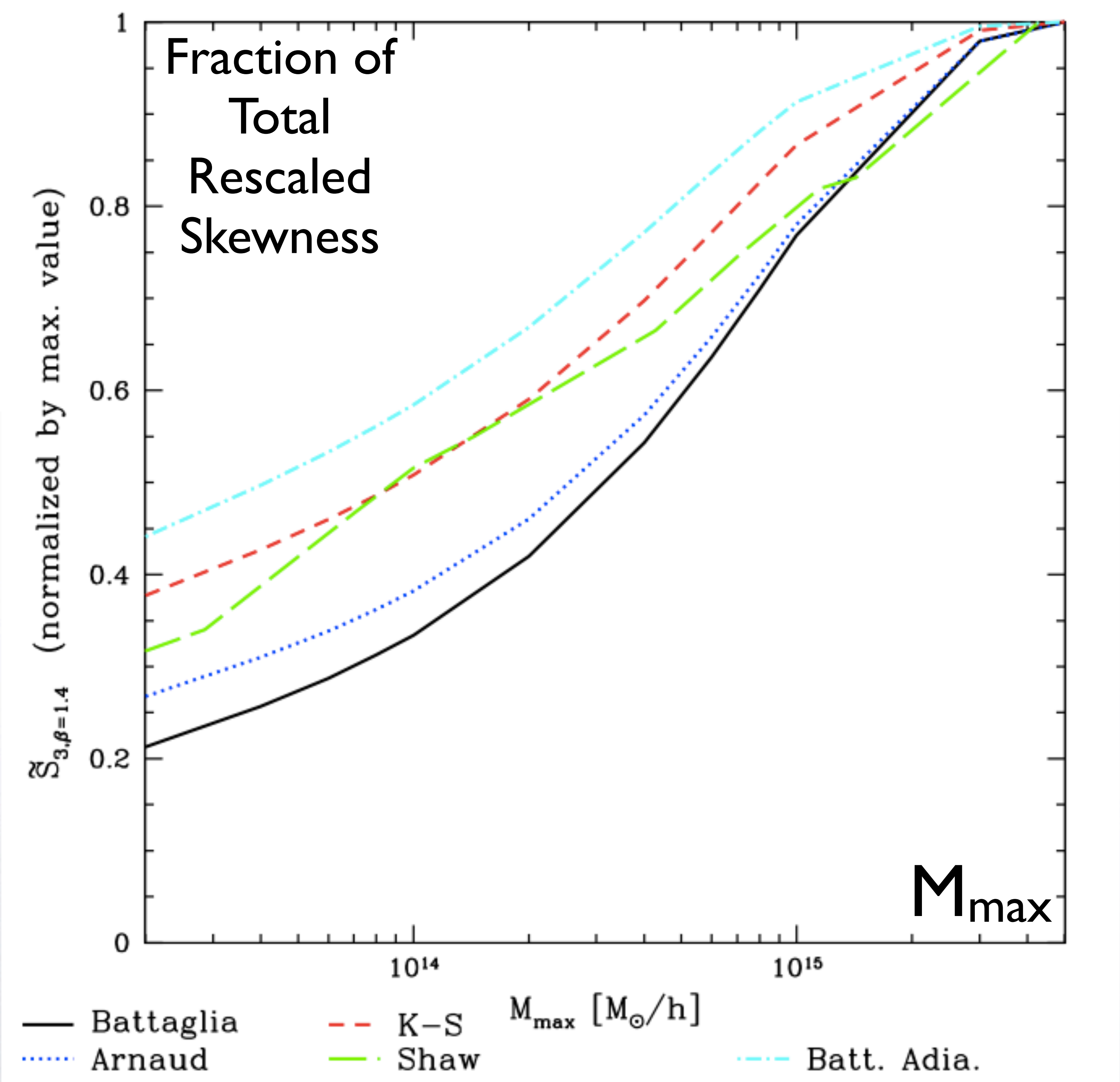
$$\longrightarrow \quad \langle T^3 \rangle \propto \langle T^2 \rangle^{1.4}$$



"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

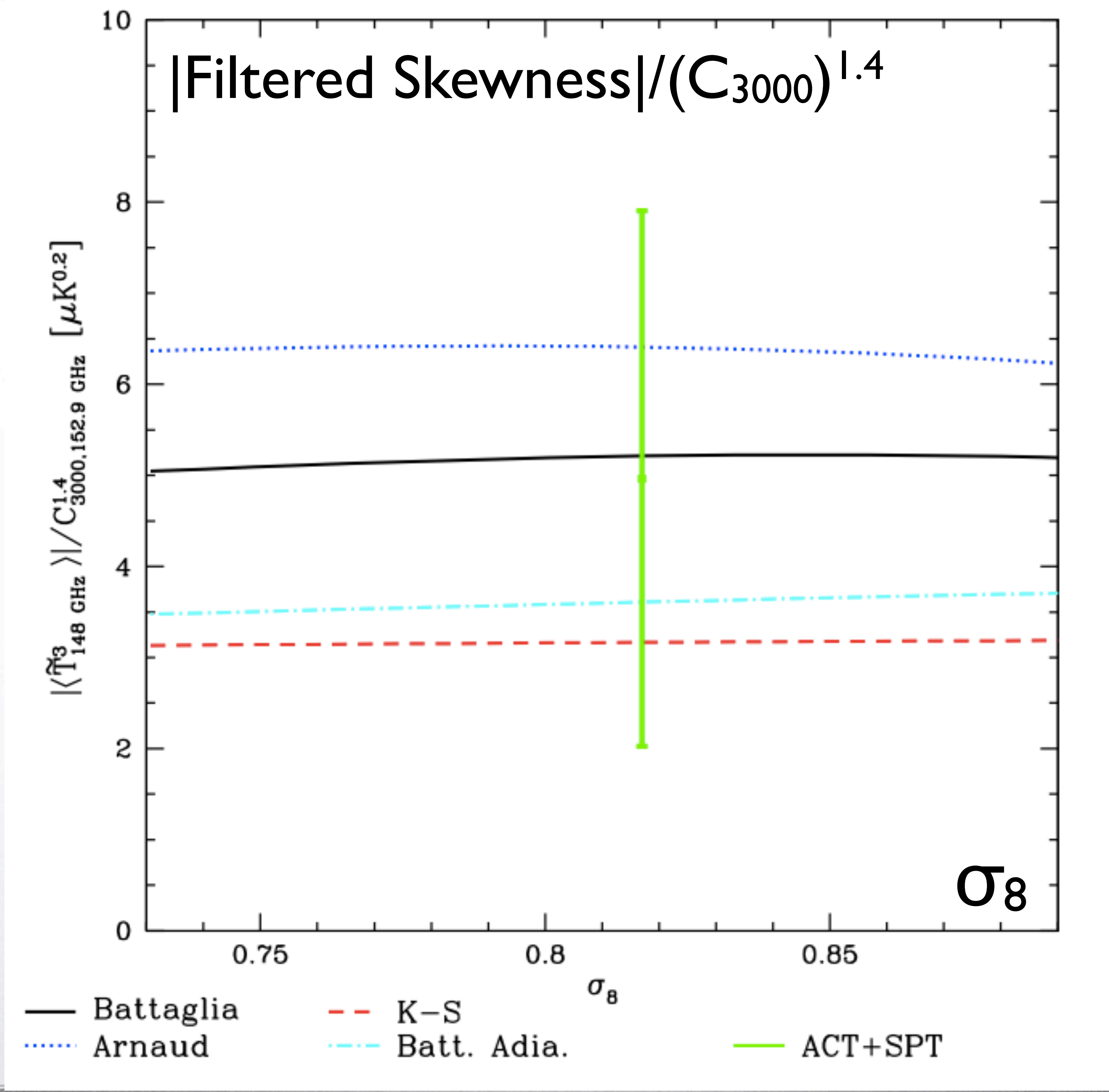
Which Clusters Contribute?



~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

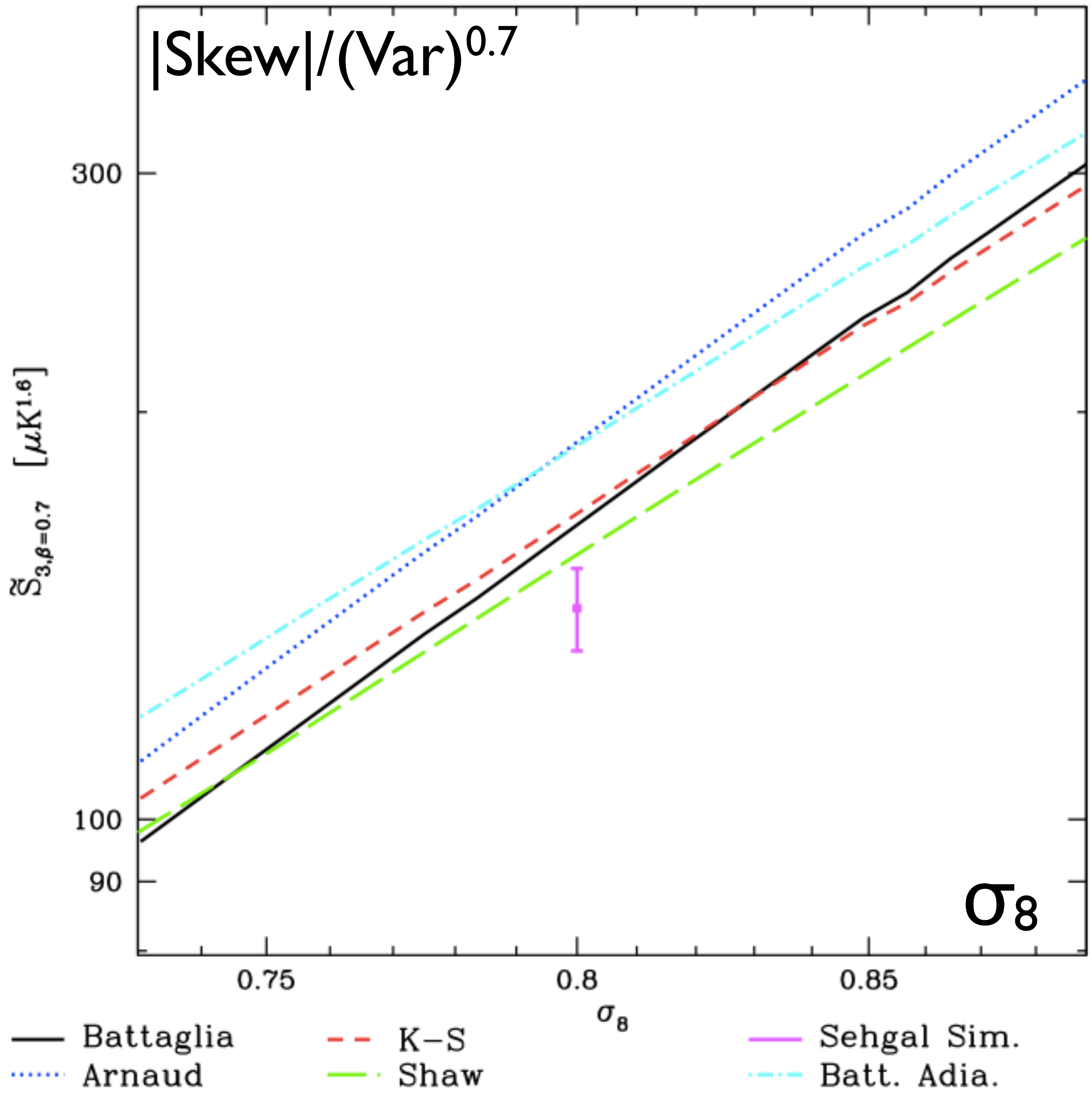
ACT+SPT Result



JCH & Sherwin (2012)

Colin Hill
Princeton

An Alternative Approach



JCH & Sherwin (2012)

Colin Hill
Princeton

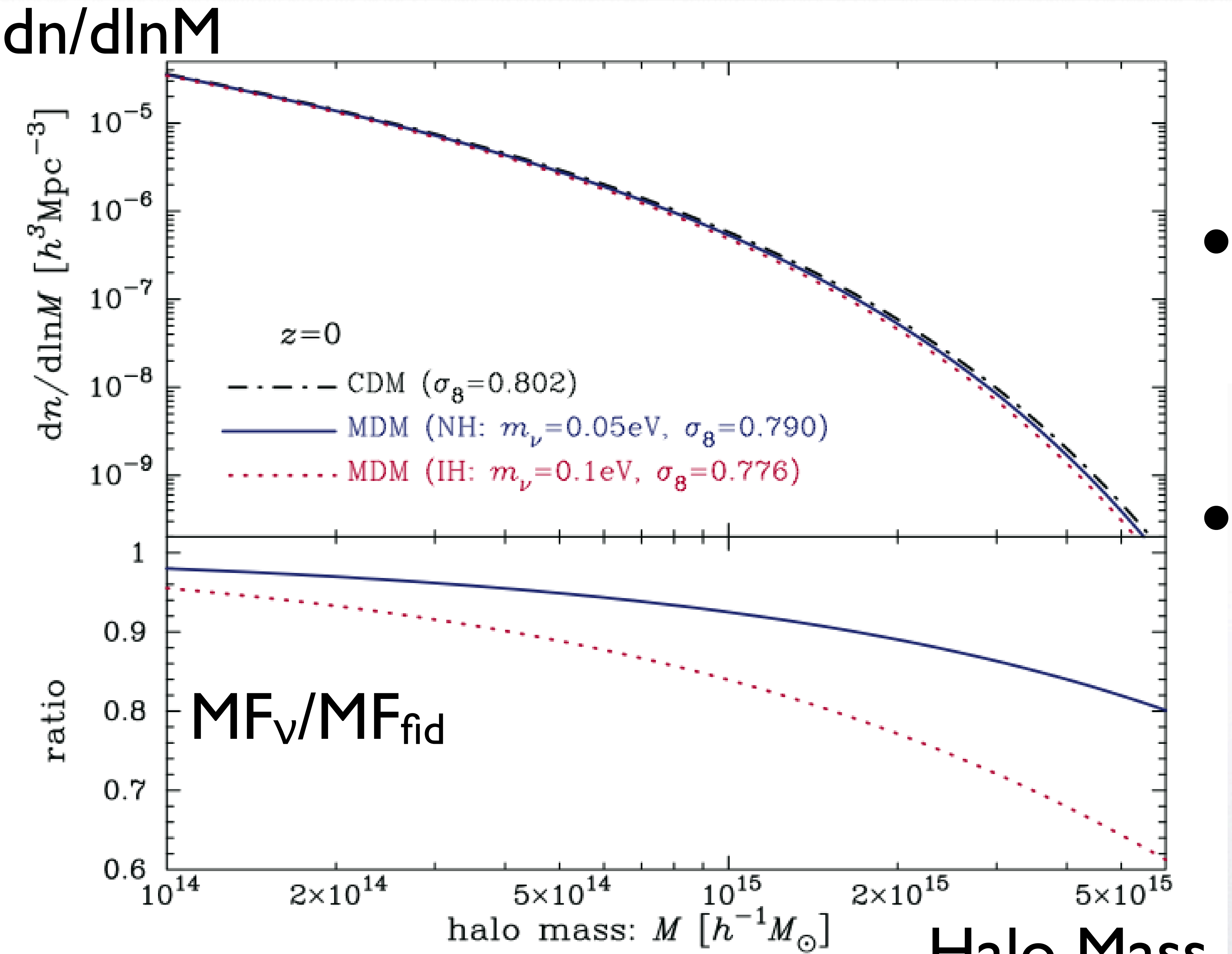
Future Constraints: Beyond σ_8

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

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

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

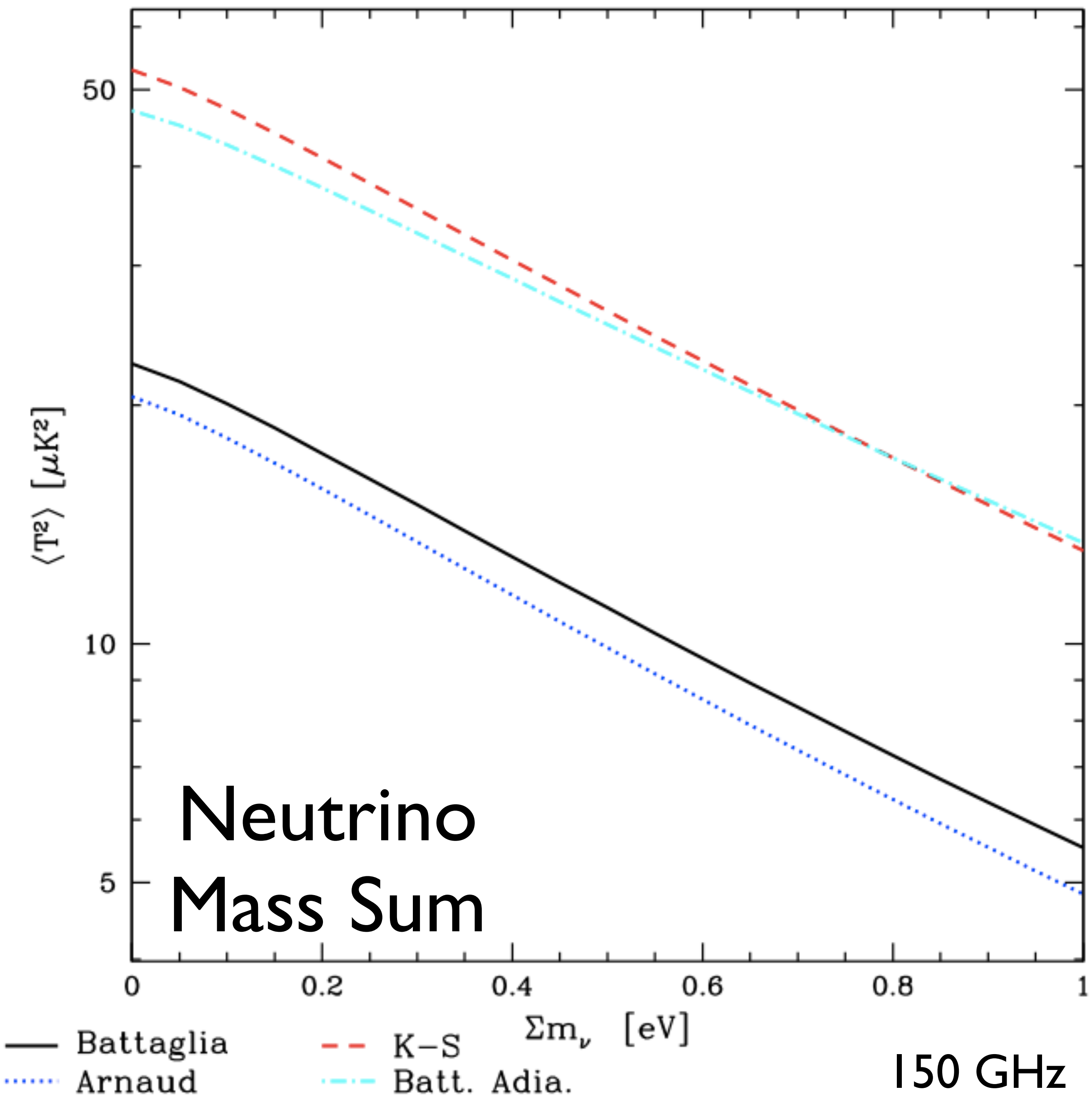
Neutrino Masses



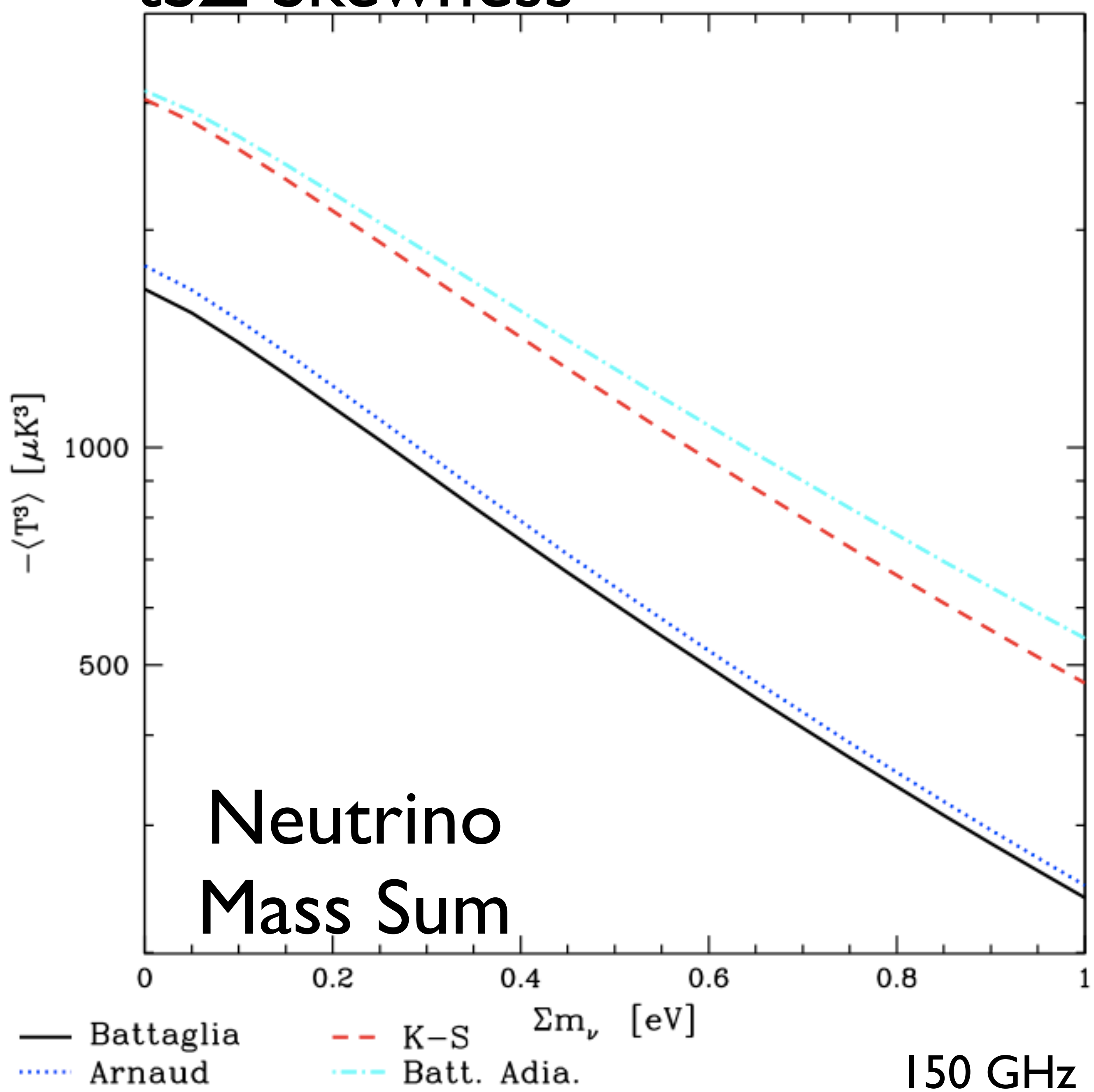
- Massive neutrinos suppress linear theory matter power spectrum
- Leads to decreased abundance of massive halos at late times

Neutrino Masses

tSZ Variance



tSZ Skewness

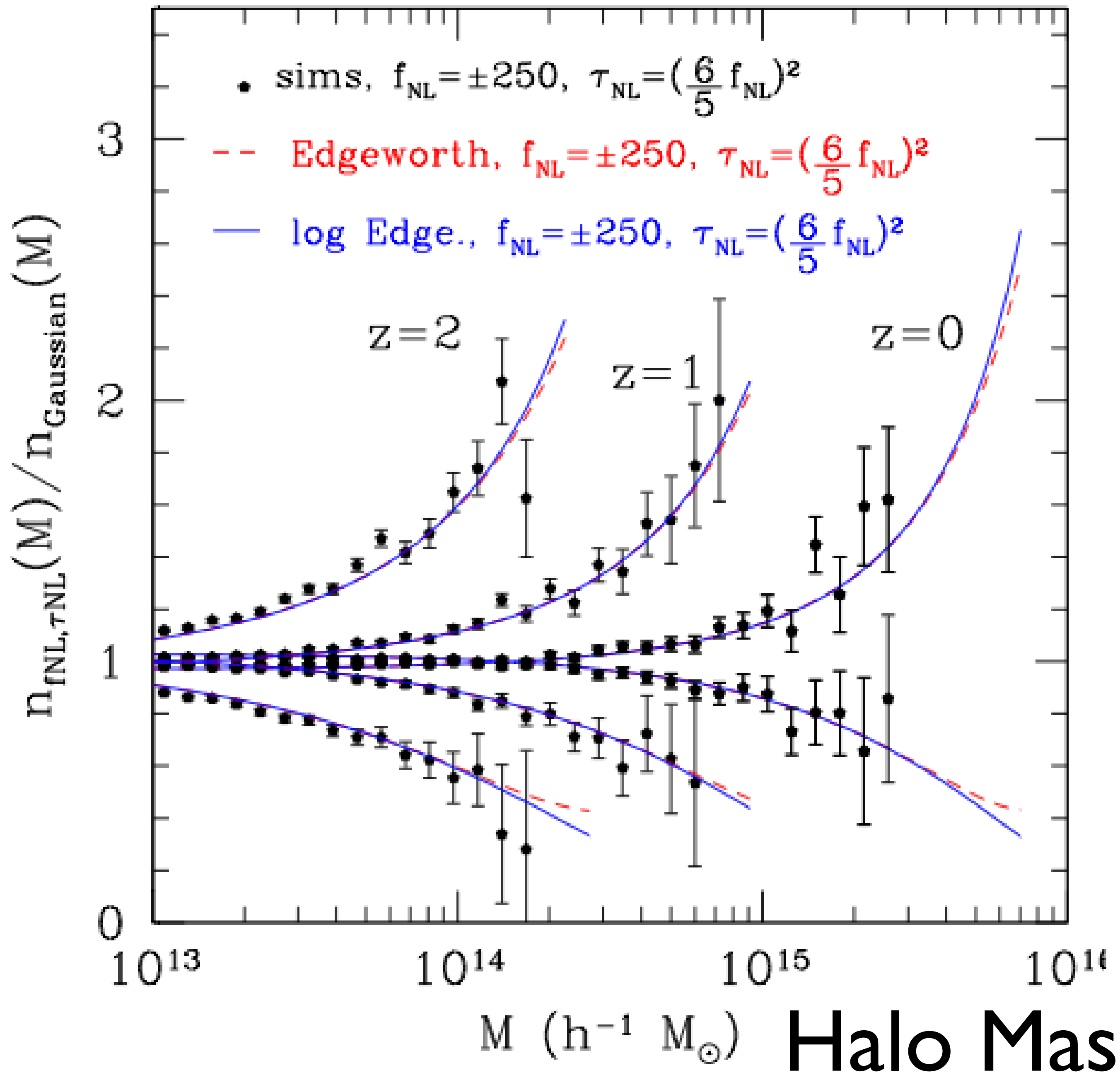


~quadratic-cubic dependence

JCH & Sherwin (2012)

Colin Hill
Princeton

MF$_{f_{NL}}$/MF$_{fid}$

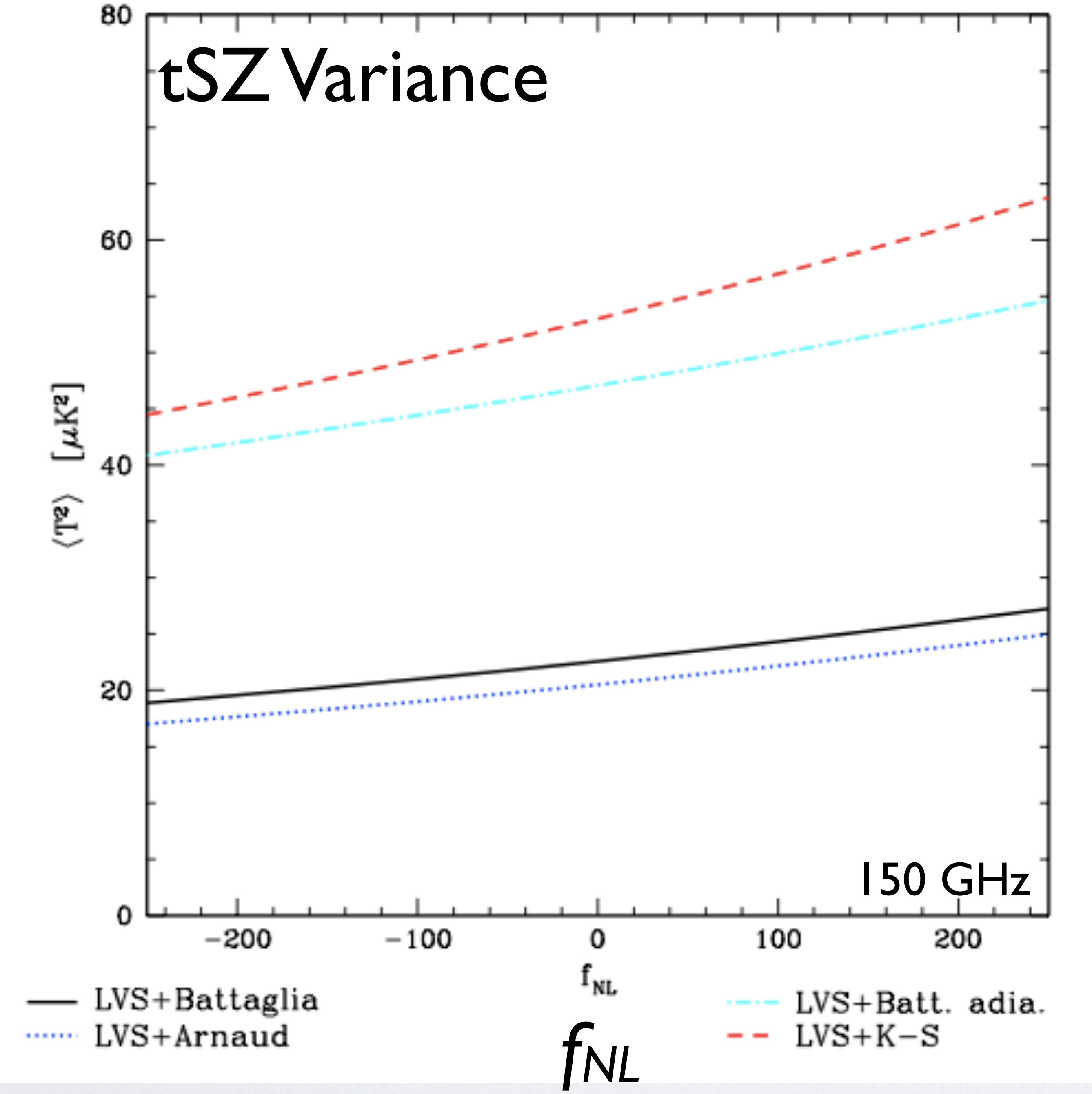


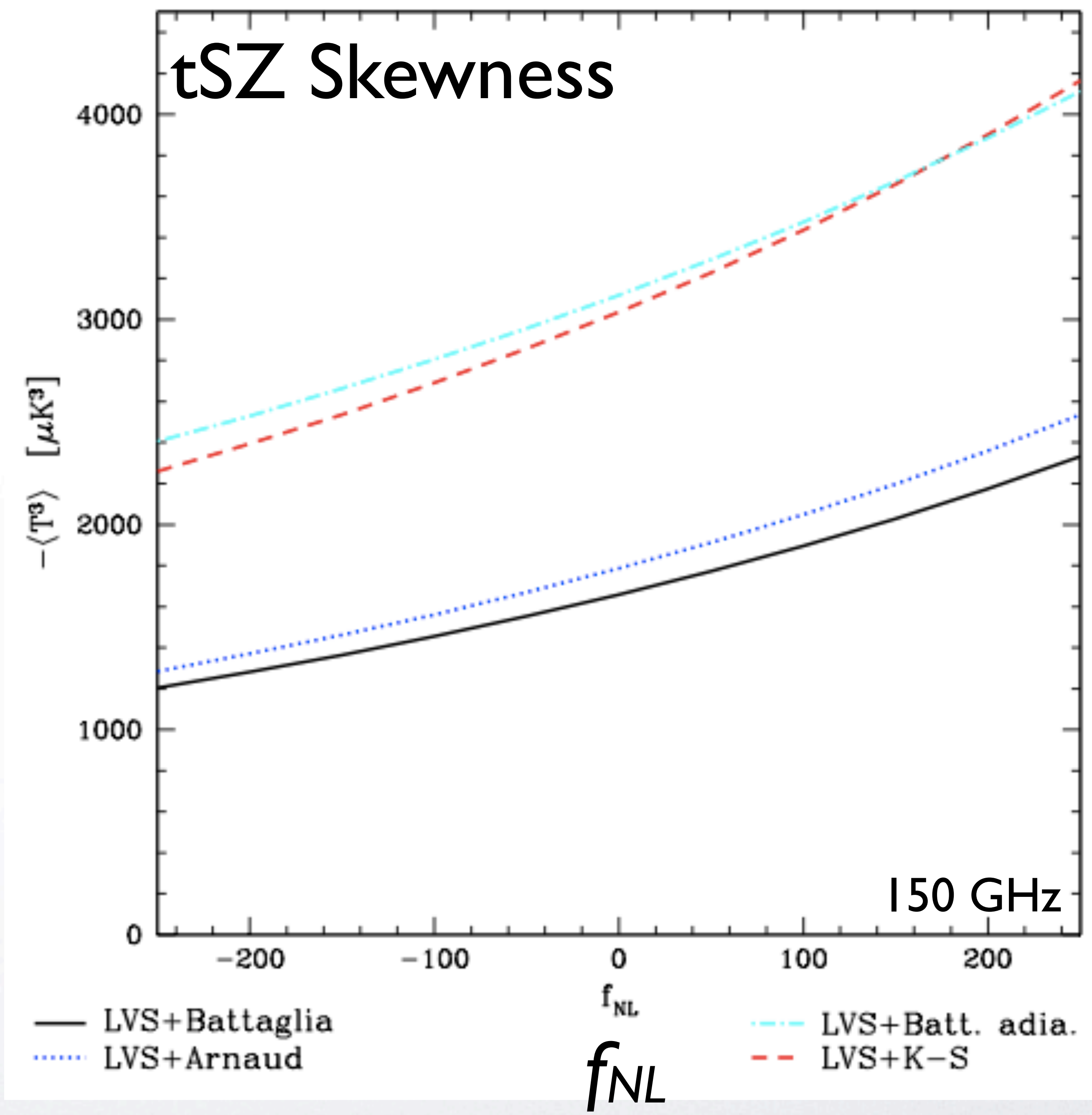
Halo Mass

- Positive (negative) f_{NL} corresponds to positive (negative) skewness in density field PDF
- Leads to more (fewer) massive halos at late times
- Sensitive to all types of NG (f_{NL}, g_{NL}, ...)
- Sensitive to much smaller scales than CMB or large-scale halo bias (so not automatically ruled out by other constraints)

LoVerde & Smith (2011)

Primordial non-Gaussianity





~quadratic dependence

JCH & LoVerde (in prep.)

Colin Hill
Princeton

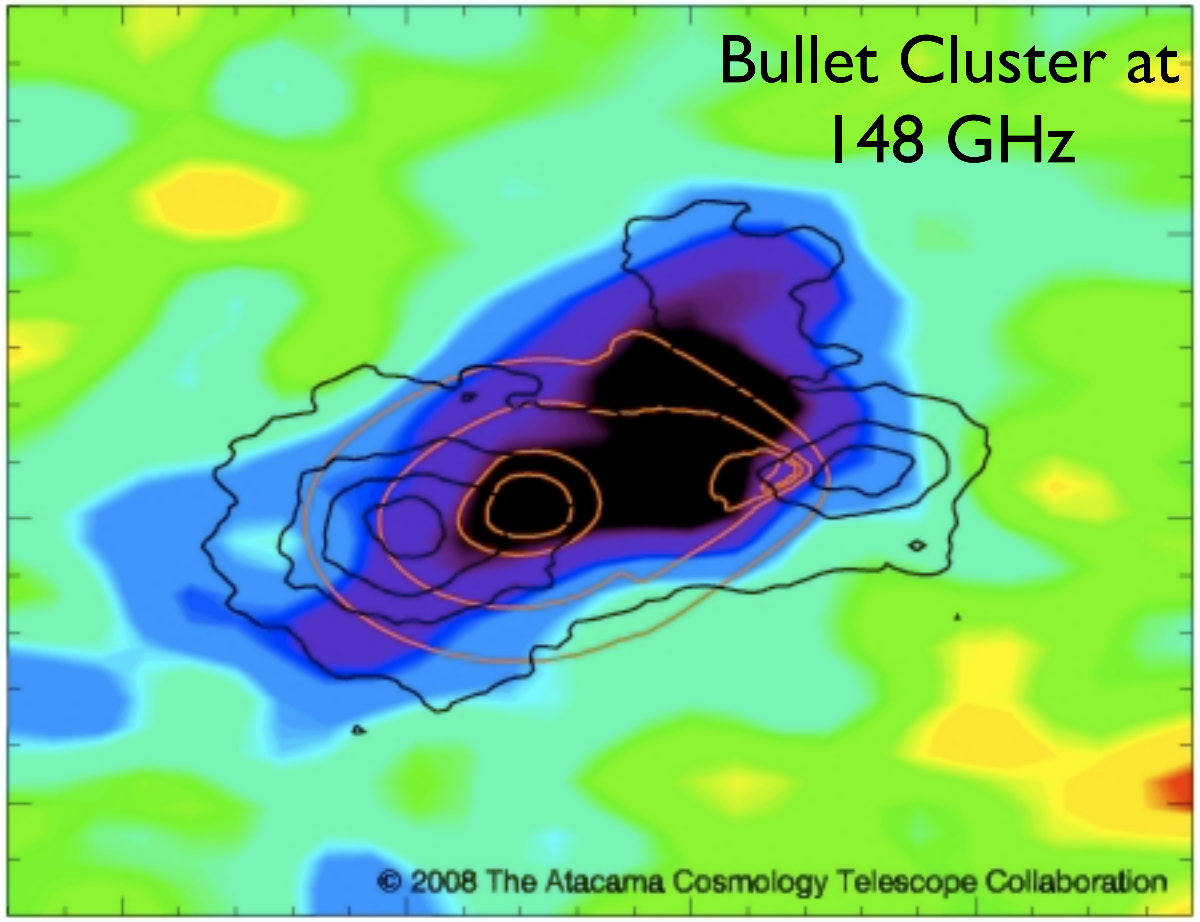
Prospects

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

  ⟶ constrain gastrophysics model to <5%
  - <1% error on σ_8 after constraining gastrophysics to 5%

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.



Colin Hill
Princeton