Clusters Detected by WMAP

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SZX Huntsville, September 21, 2011

Outline

- Coma
  - *Coma is sitting on a -100uK CMB fluctuation*
- A good agreement between SZ and X-ray data on **individual** clusters
- Effects of dynamical state (more precisely cool-core vs non-cool-core) on SZ
  - *Also seen by Planck*
- Lessons learned from the stacking analysis
  - *Scaling relations...*

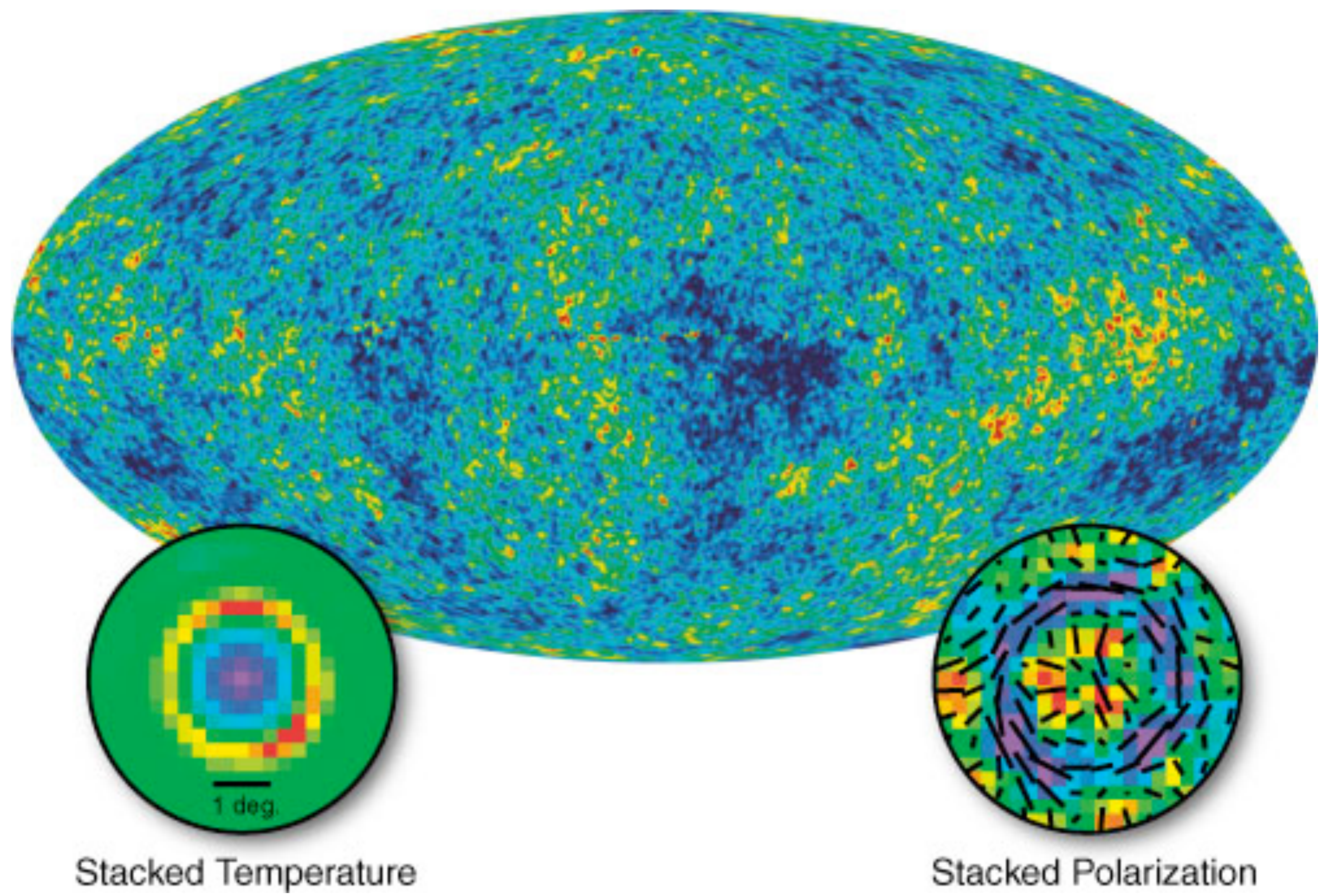
WMAP has collected 9 years of data, and left L2.

June 2001:
WMAP launched!

February 2003:
The first-year data release

March 2006:
The three-year data release

March 2008:
The five-year data release



- **January 2010: The seven-year data release**

WMAP 7-Year Science Team

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- G. Hinshaw
- N. Jarosik
- S.S. Meyer
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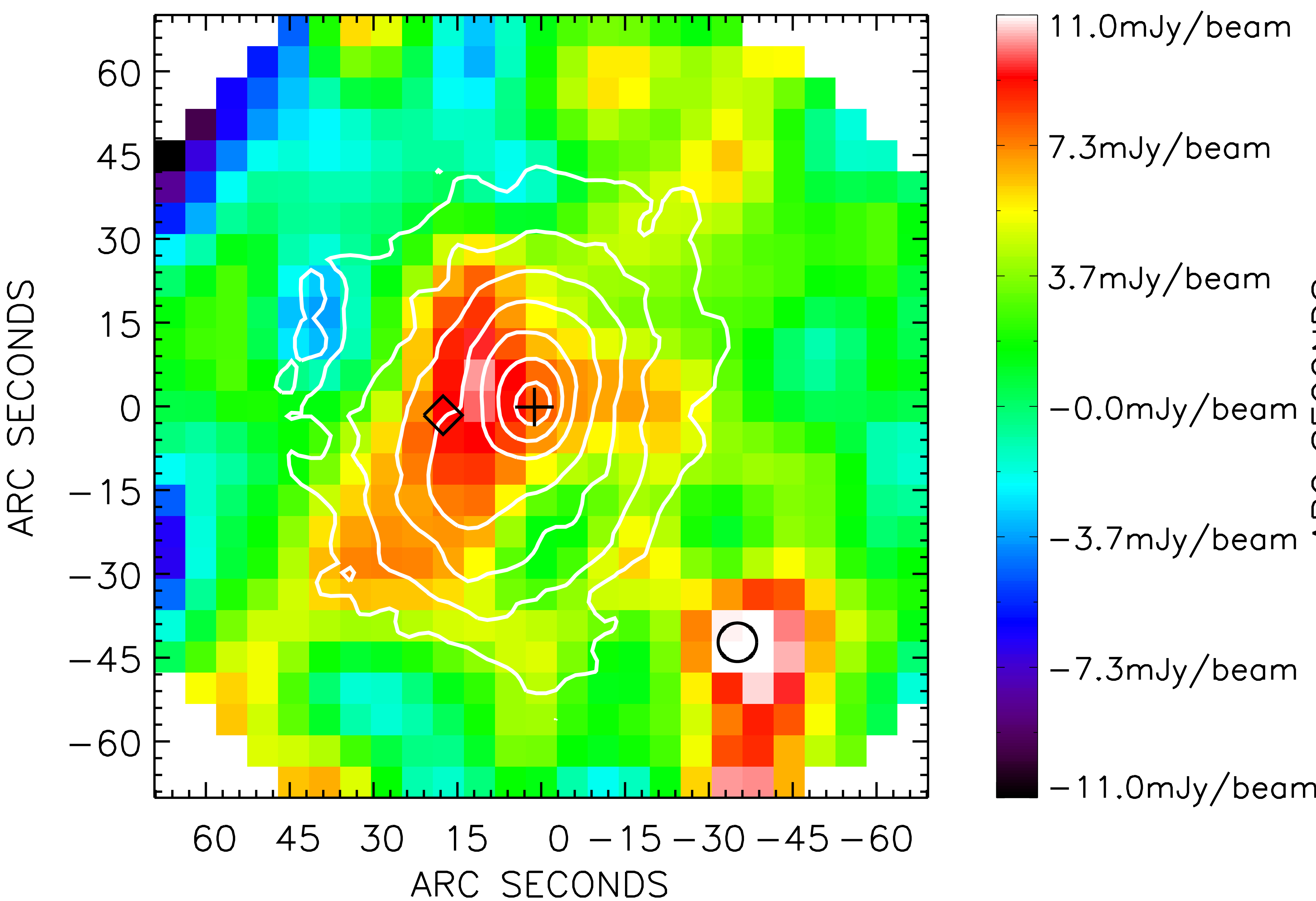
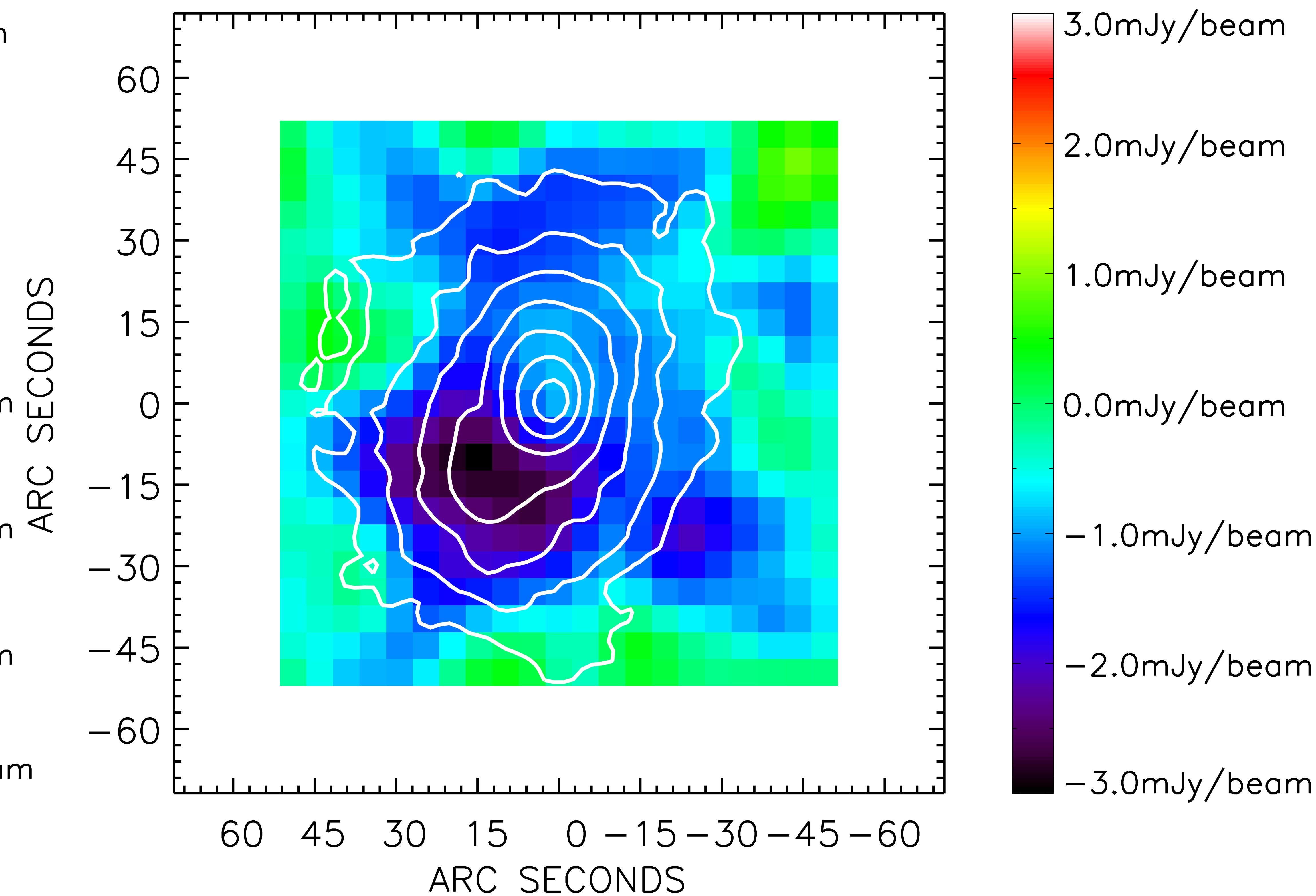
- L. Verde

WMAP 7-Year Papers

- **Jarosik et al.**, "*Sky Maps, Systematic Errors, and Basic Results*" Astrophysical Journal Supplement Series (ApJS), 192, 14 (2011)
- **Gold et al.**, "*Galactic Foreground Emission*" ApJS, 192, 15 (2011)
- **Weiland et al.**, "*Planets and Celestial Calibration Sources*" ApJS, 192, 19 (2011)
- **Bennett et al.**, "*Are There CMB Anomalies?*" ApJS, 192, 17 (2011)
- **Larson et al.**, "*Power Spectra and WMAP-Derived Parameters*" ApJS, 192, 16 (2011)
- **Komatsu et al**., "*Cosmological Interpretation*" ApJS, 192, 18 (2011)

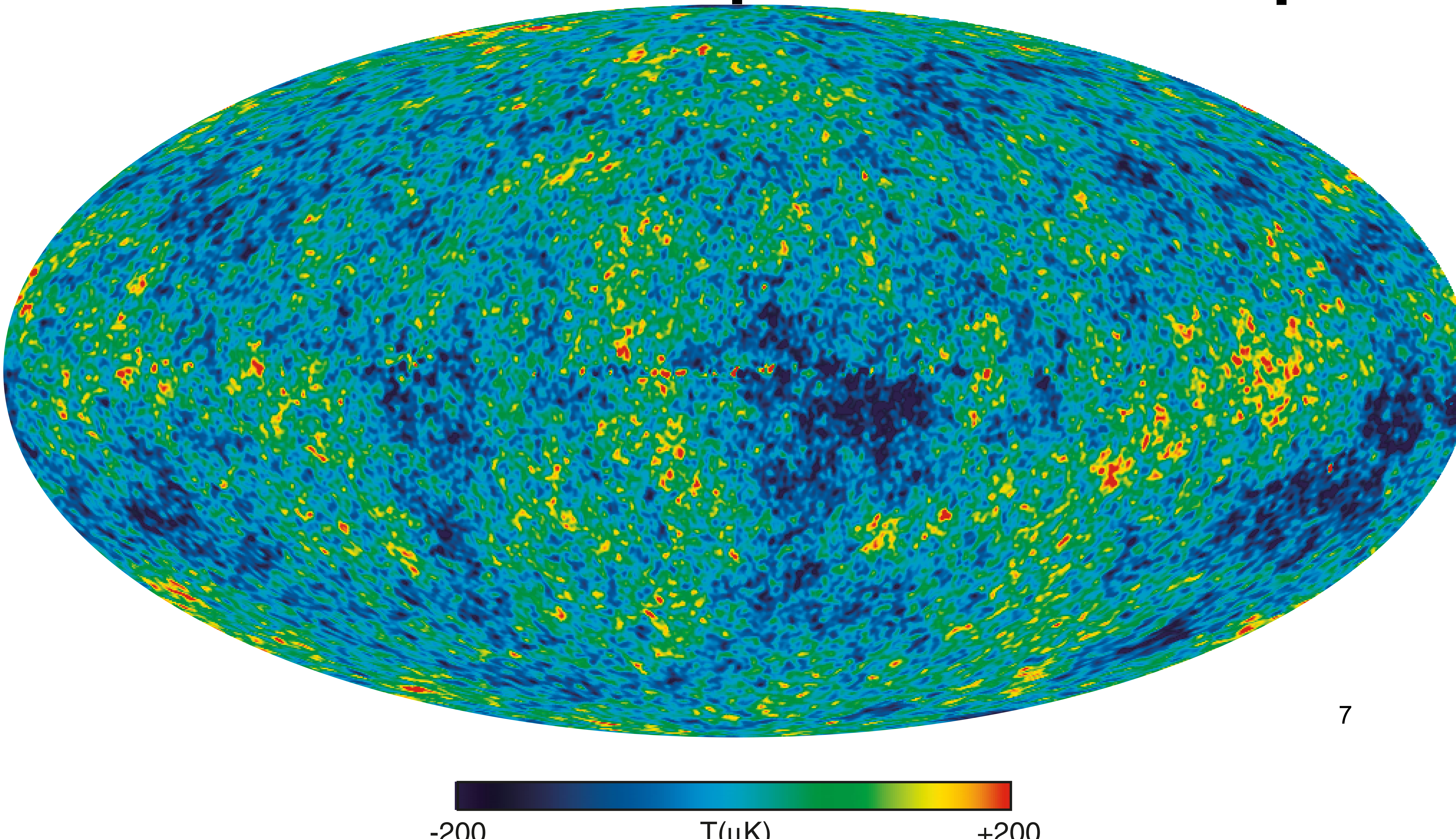
The SZ Effect: Decrement and Increment



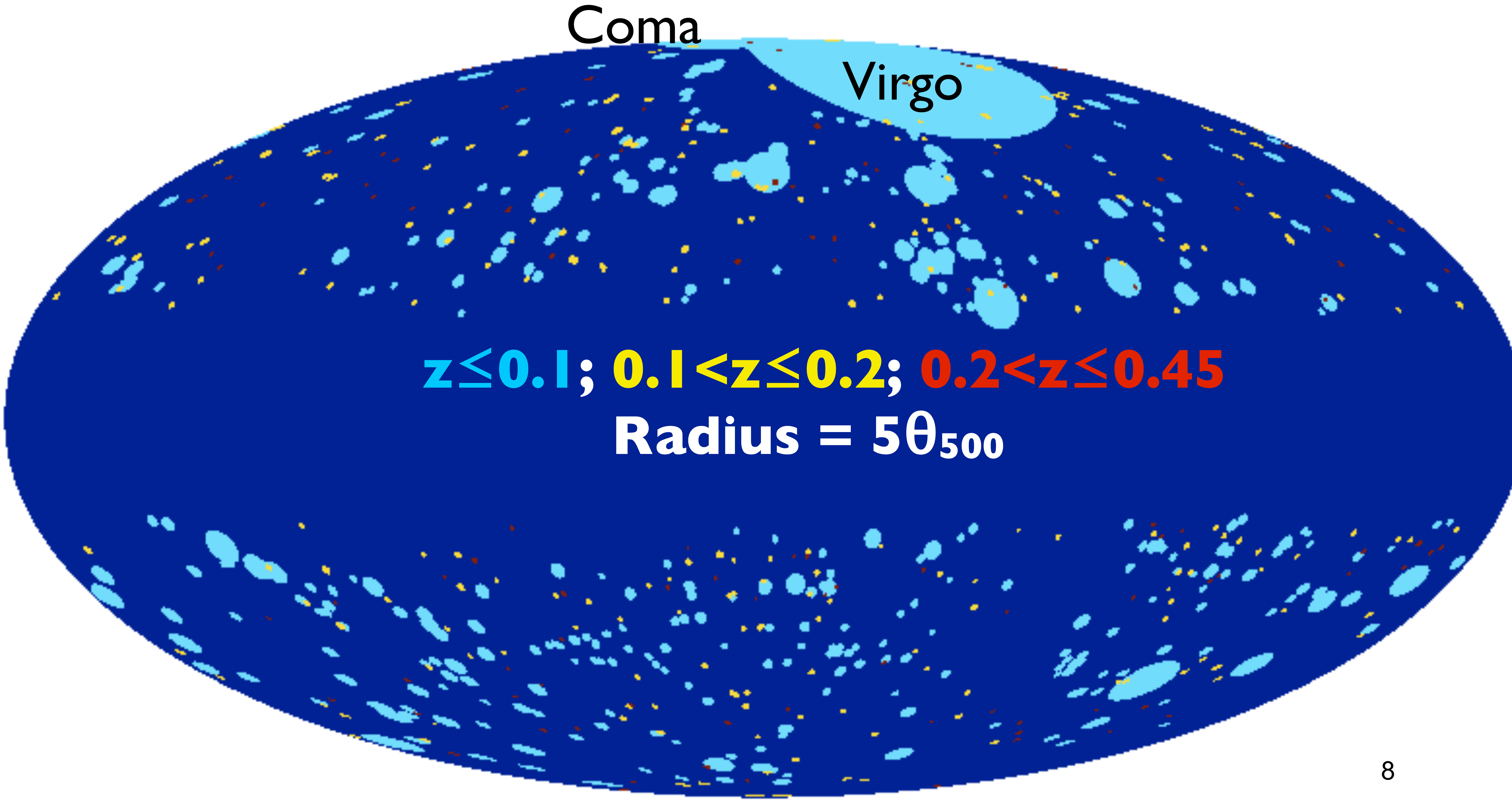


- RXJ1347-1145 (high-resolution SZ maps)
  - –Left, SZ increment (350GHz, 15” FWHM, Komatsu et al. 1999)
  - –Right, SZ decrement (150GHz, 12” FWHM, Komatsu et al. 2001)

WMAP Temperature Map



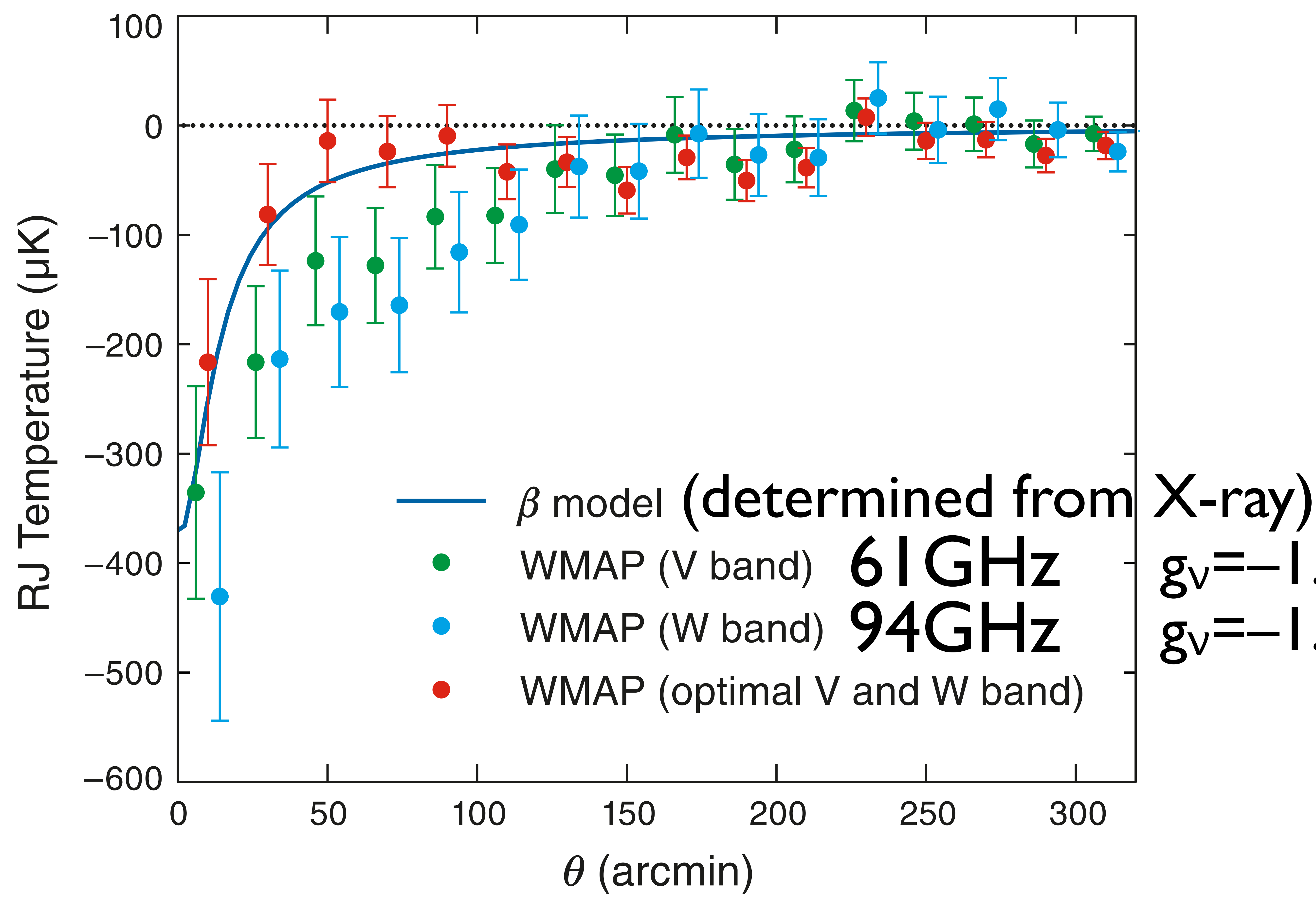
Where are clusters?



Coma Cluster (z=0.023)

We find that the CMB fluctuation in the direction of Coma is ≈ −100uK. (**This is a new result!**)

$y_{coma}(0)=(7\pm2)\times10^{-5}$ (68%CL)



$g_\nu=-1.81$

$g_\nu=-1.56$

- "Optimal V and W band" analysis can separate SZ and CMB. The SZ effect toward Coma is detected at **3.6σ**.

A Question

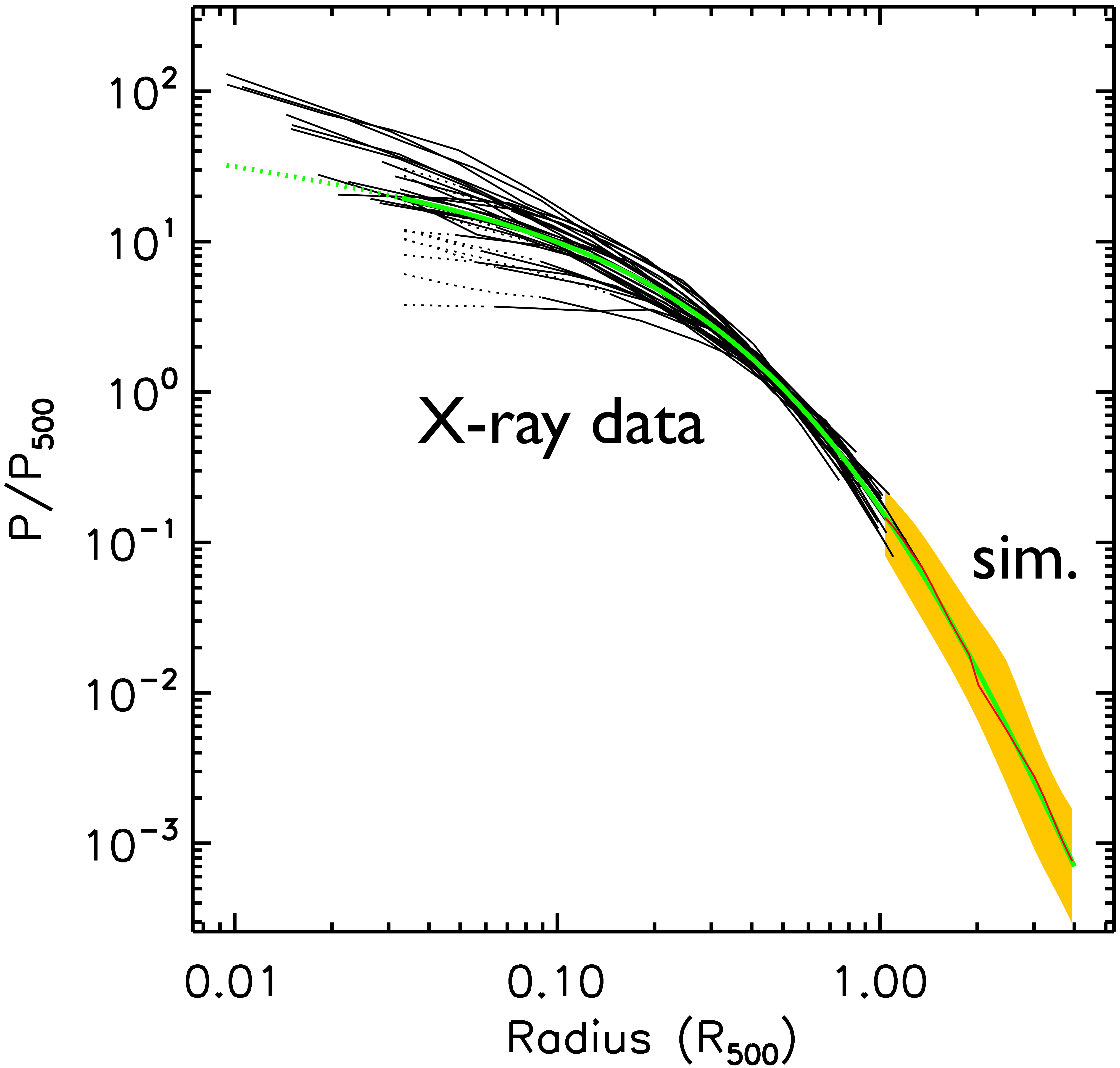
- Are we detecting the ***expected*** amount of electron pressure, P_e, in the SZ effect?
  - Expected from X-ray observations?
  - Expected from theory?

Arnaud et al. Profile

- A fitting formula for the average electron pressure profile as a function of the cluster mass (M_{500}), derived from 33 nearby ($z<0.2$) clusters (REXCESS sample).

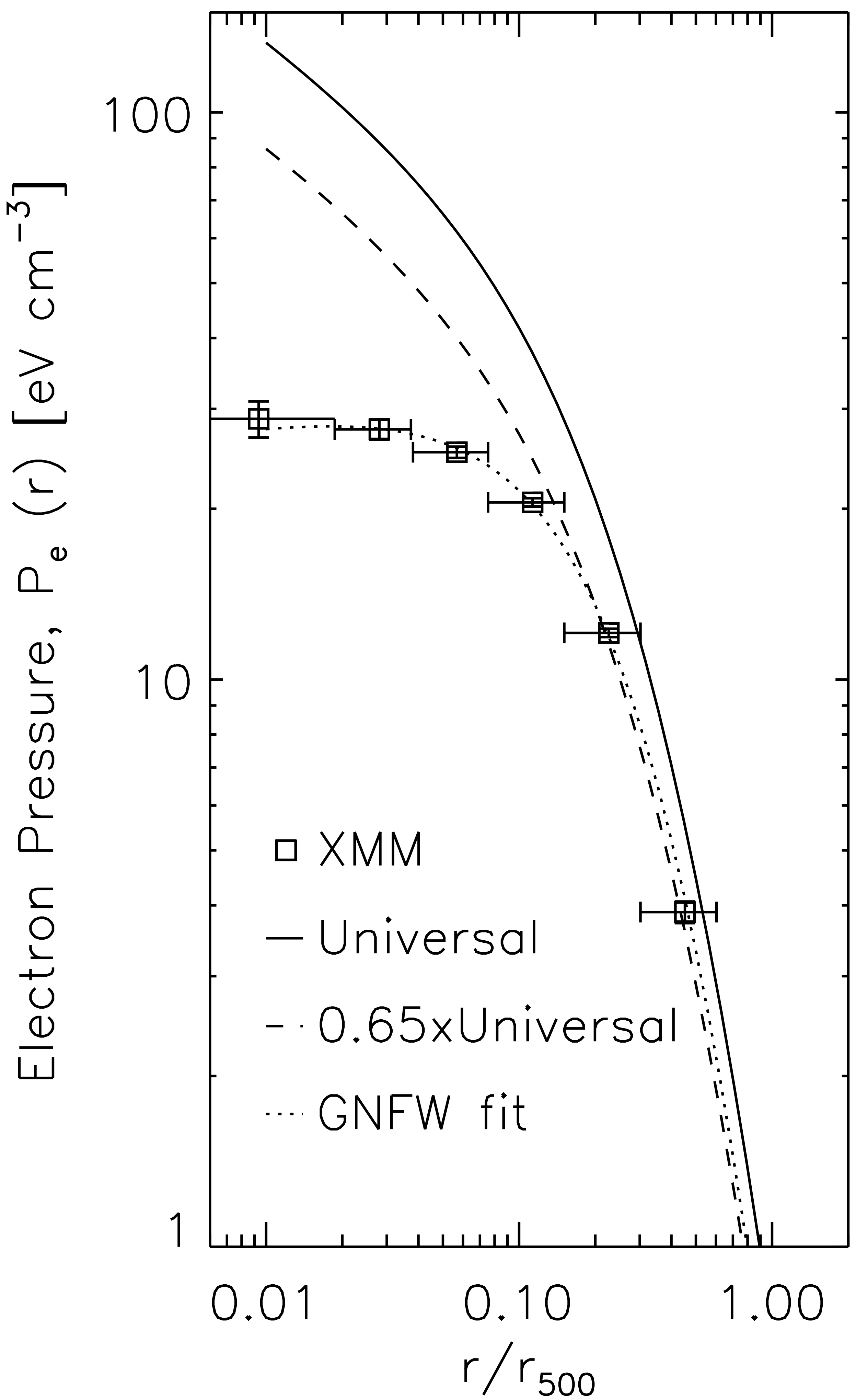
Arnaud et al., A&A, 517, A92 (2010)

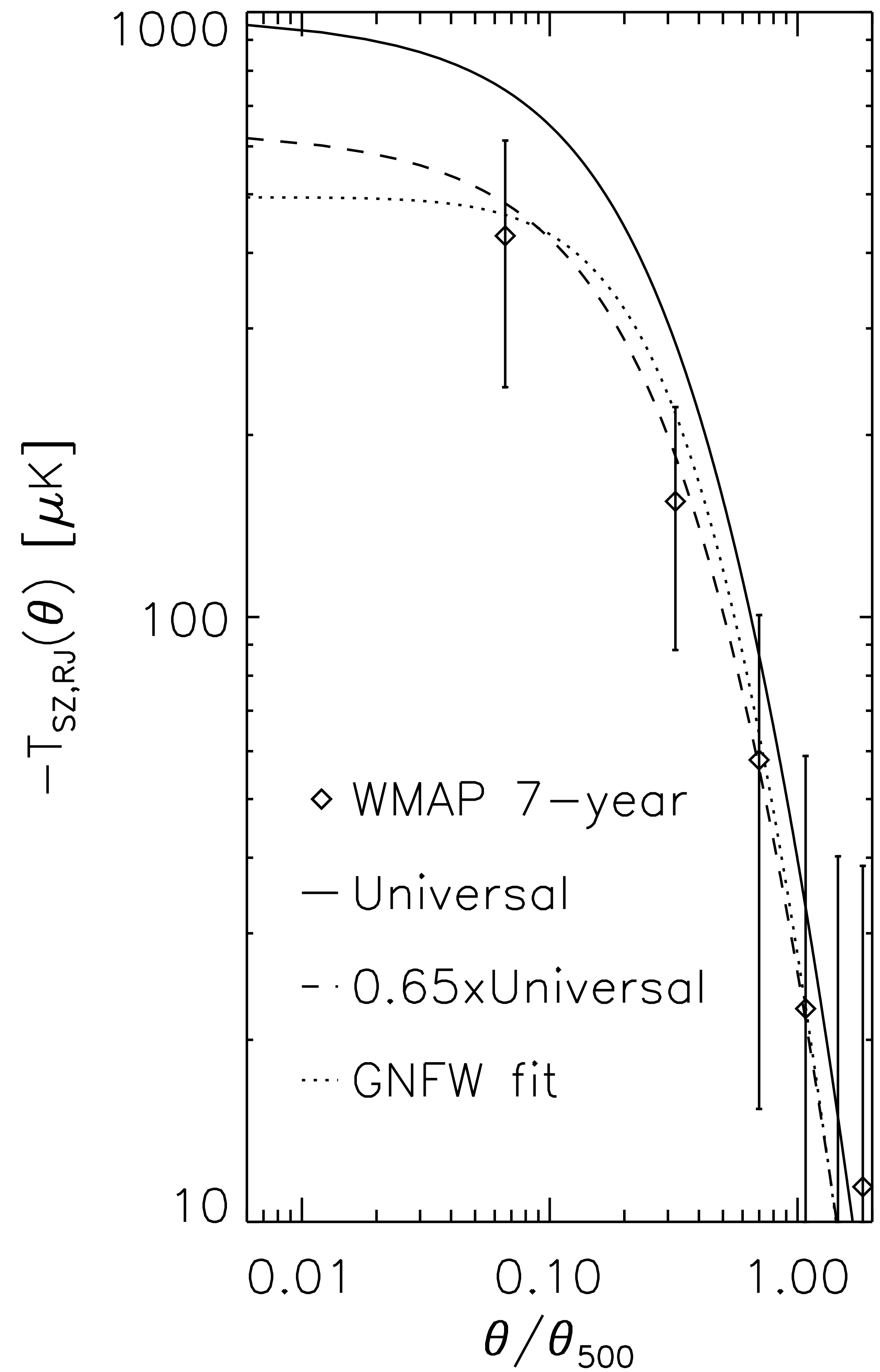
Arnaud et al. Profile



- A significant scatter exists at $R<0.2R_{500}$, but a good convergence in the outer part.

Coma Data vs $P_{universal}$





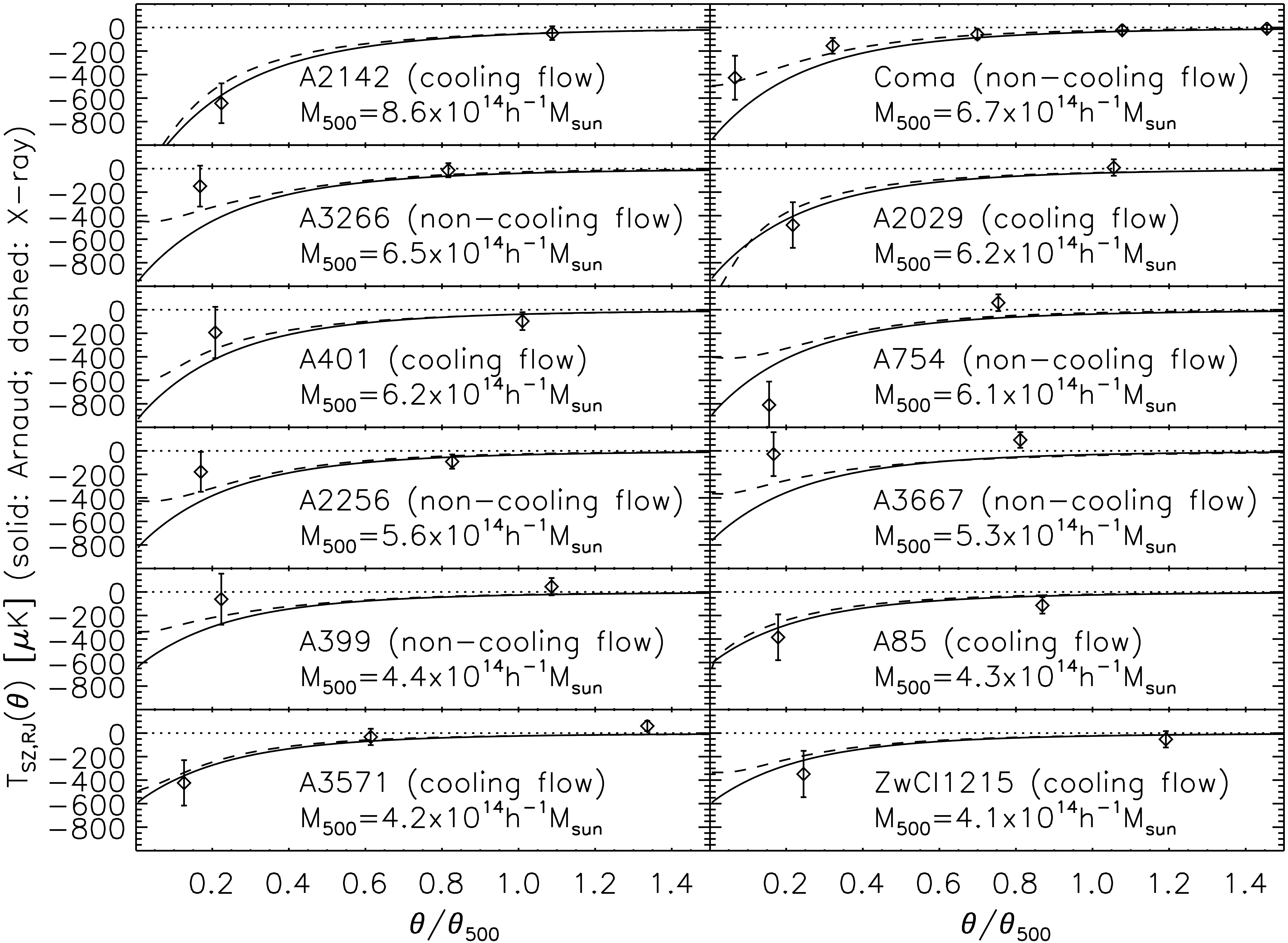
The X-ray data (XMM) are provided by A. Finoguenov.

- M_{500}=6.6x$10^{14}h^{-1}M_{sun}$ is estimated from the mass-temperature relation (Vikhlinin et al.)
  - T_X^{coma} =8.4keV.
- Arnaud et al.'s profile overestimates both the direct X-ray data and WMAP data by the same factor (0.65)!
  - To reconcile them, Tx^{coma}=6.5keV is required, but that is way too low.

Well...

- That's just one cluster. What about the other clusters?
  - We measure the SZ effect of a sample of well-studied nearby clusters compiled by Vikhlinin et al.

WMAP 7-year Measurements (Komatsu et al. 2011)



SZ seen in the WMAP

Mass Range[a]	# of clusters	X-ray Data	$P_{universal}$
$6 \le M_{500} < 9$	5	0.90 ± 0.16	0.73 ± 0.13
$4 \le M_{500} < 6$	6	0.73 ± 0.21	0.60 ± 0.17
$2 \le M_{500} < 4$	9	0.71 ± 0.31	0.53 ± 0.25
$1 \le M_{500} < 2$	9	-0.15 ± 0.55	-0.12 ± 0.47
$4 \le M_{500} < 9$	11	0.84 ± 0.13	0.68 ± 0.10
$1 \le M_{500} < 4$	18	0.50 ± 0.27	0.39 ± 0.22
$4 \le M_{500} < 9$			
cooling flow[d]	5	1.06 ± 0.18	0.89 ± 0.15
non-cooling flow[e]	6	0.61 ± 0.18	0.48 ± 0.15
$2 \le M_{500} < 9$	20	0.82 ± 0.12	0.660 ± 0.095
$1 \le M_{500} < 9$	29	0.78 ± 0.12	0.629 ± 0.094

[a] In units of $10^{14}\ h^{-1}\ M_{\odot}$. Coma is not included.

d: ALL of "cooling flow clusters" are relaxed clusters.

e: ALL of "non-cooling flow clusters" are non-relaxed clusters.

Signature of mergers?

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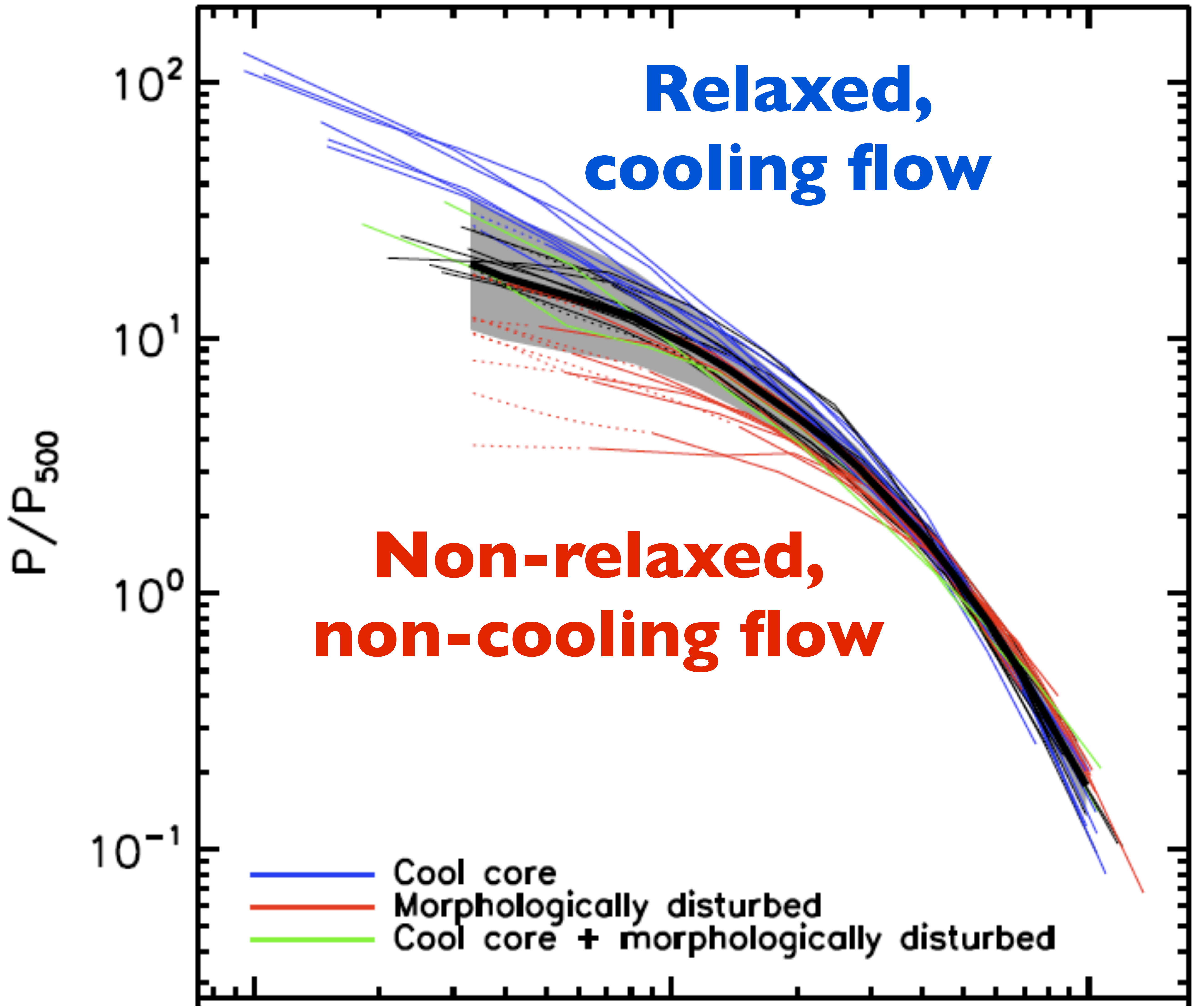
SZ: Main Results

- The X-ray data on the *individual* clusters agree well with the SZ measured by WMAP.
- Distinguishing between relaxed (CF) and non-relaxed (non-CF) clusters is important, even for SZ.
- This is confirmed by Planck (with a LOT more signal-to-noise!)

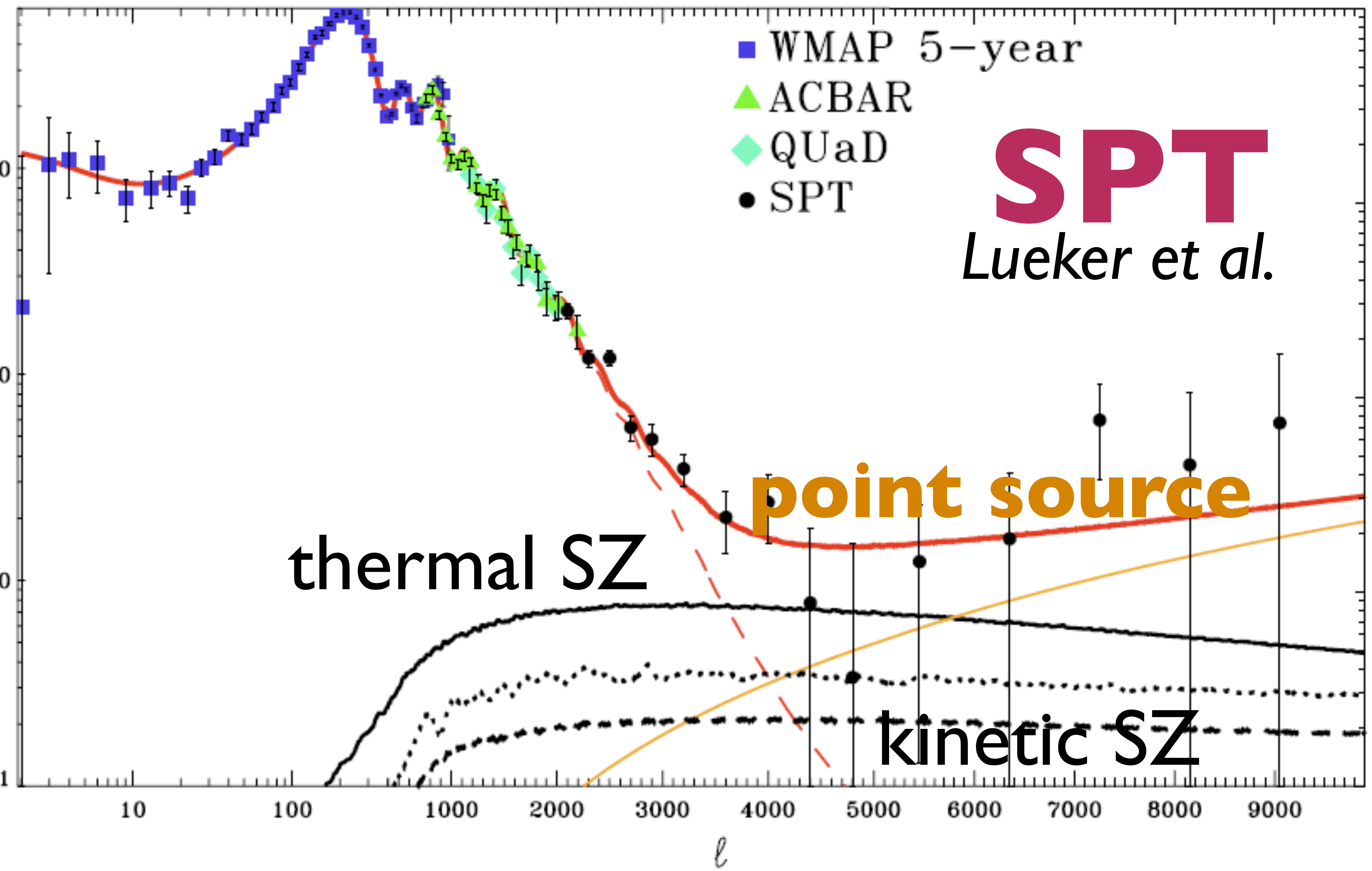
Arnaud et al., A&A, 517, A92 (2010)

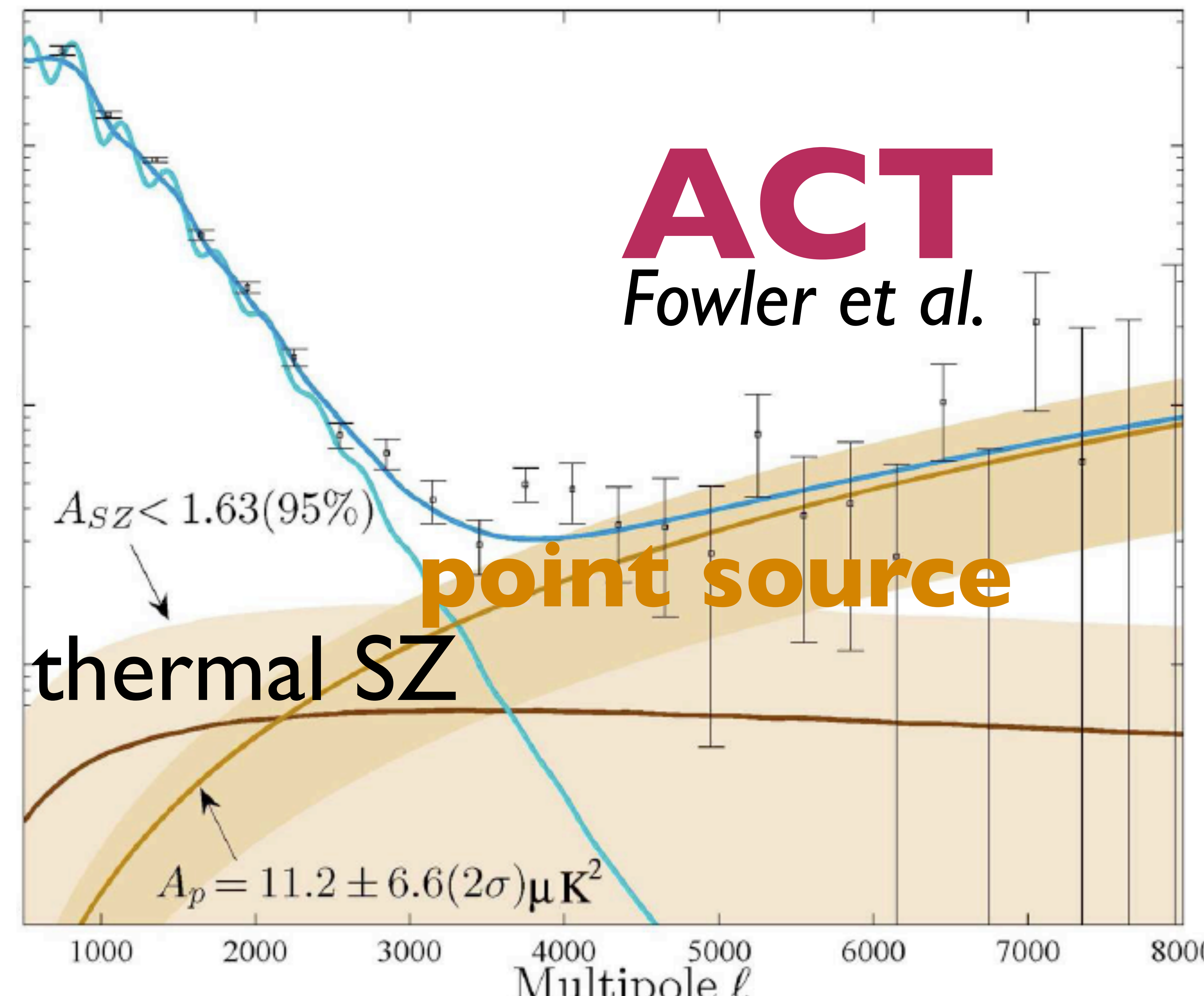
Cooling Flow vs Non-CF



- In Arnaud et al., they reported that the cooling flow clusters have much steeper pressure profiles in the inner part.

"World" Power Spectrum





- The SPT measured the secondary anisotropy from (possibly) SZ. **The power spectrum amplitude is A_{SZ}=0.4–0.6 times the expectations.** Why?

Lower ASZ: **Two** Possibilities

$$C_l = g_\nu^2 \int_0^{z_{\max}} dz \frac{dV}{dz} \int_{M_{\min}}^{M_{\max}} dM \frac{dn(M,z)}{dM} |\tilde{y}_l(M,z)|^2$$

- **[1] The number of clusters is less than expected.**
  - In cosmology, this is parameterized by the so-called "σ_8" parameter.

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

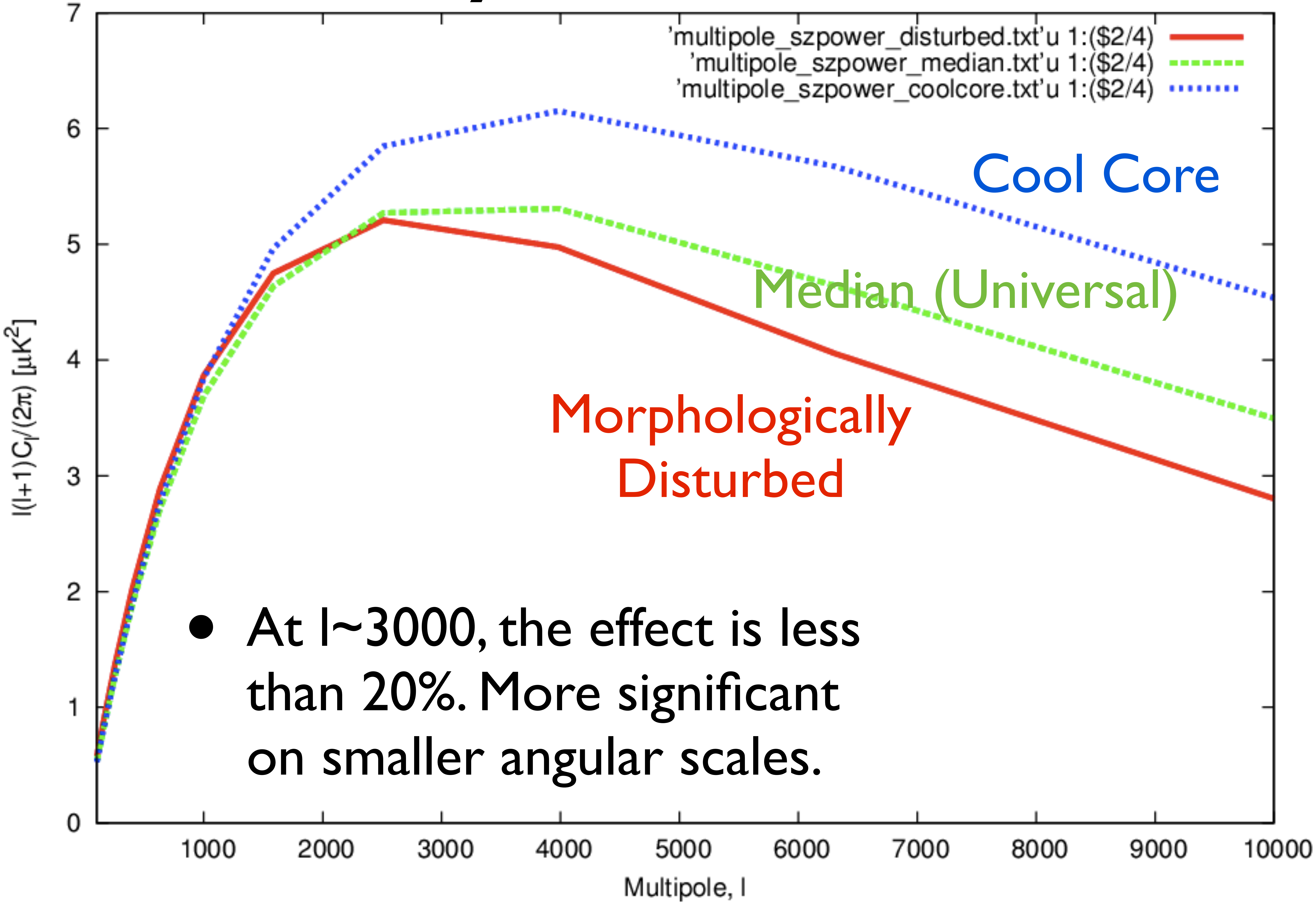
- σ_8 is 0.77 (rather than 0.81): $\sum m_\nu \sim 0.2$eV?

Lower A_{SZ}: **Two** Possibilities

$$C_l = g_\nu^2 \int_0^{z_{\max}} dz \frac{dV}{dz} \int_{M_{\min}}^{M_{\max}} dM \frac{dn(M,z)}{dM} \boxed{|\tilde{y}_l(M,z)|^2}$$

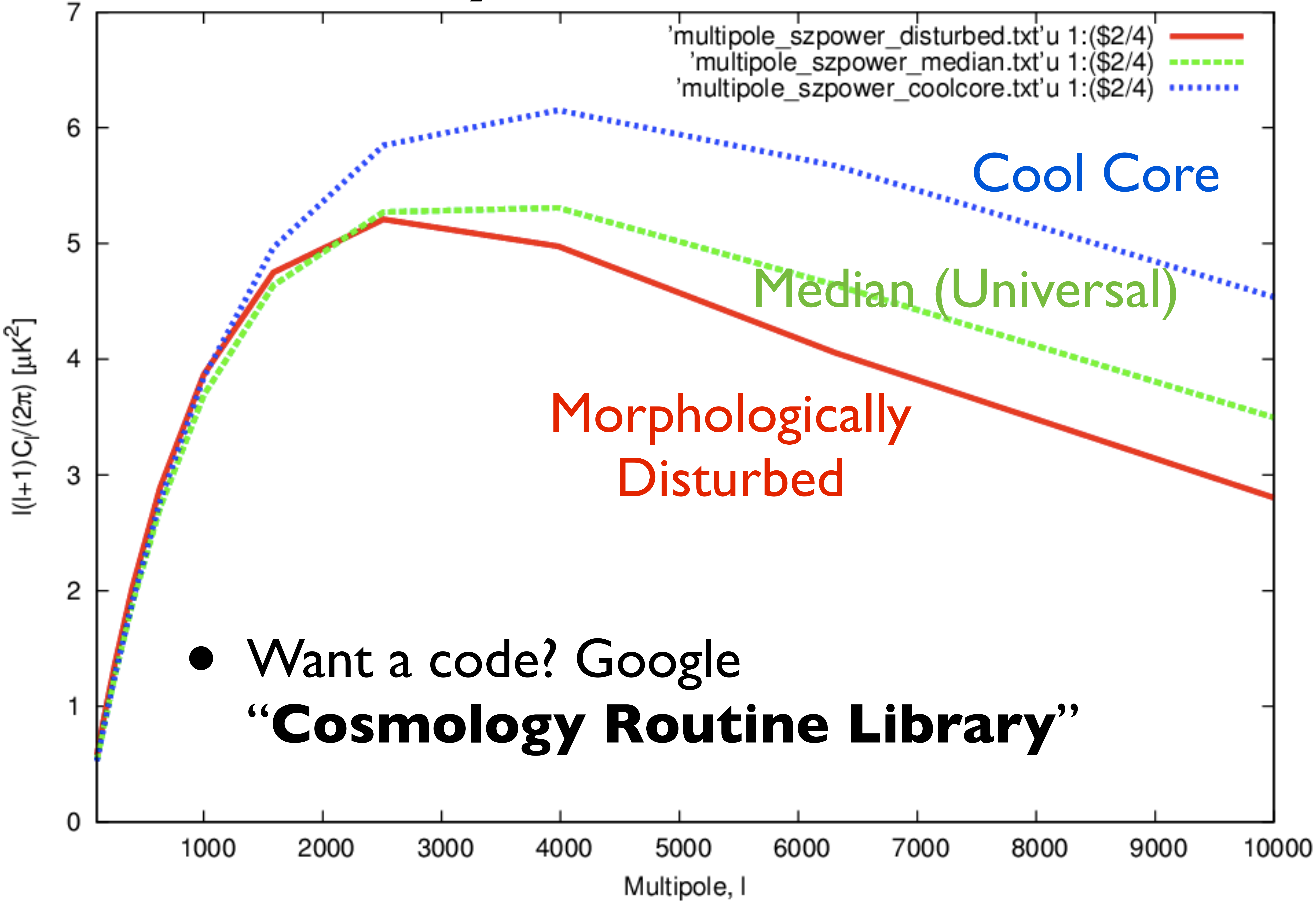
- **[2] Gas pressure per cluster is less than expected.**
  - The power spectrum is [gas pressure]^2.
  - A_{SZ}=0.4–0.6 means that the gas pressure is less than expected by ~0.6–0.7.
- *What would a dynamical state (more precisely, cool-core vs non-cool-core) do?*

Effects of Dynamical State on C_l



- At l~3000, the effect is less than 20%. More significant on smaller angular scales.

Effects of Dynamical State on C_l



- Want a code? Google "**Cosmology Routine Library**"

Conclusion 1

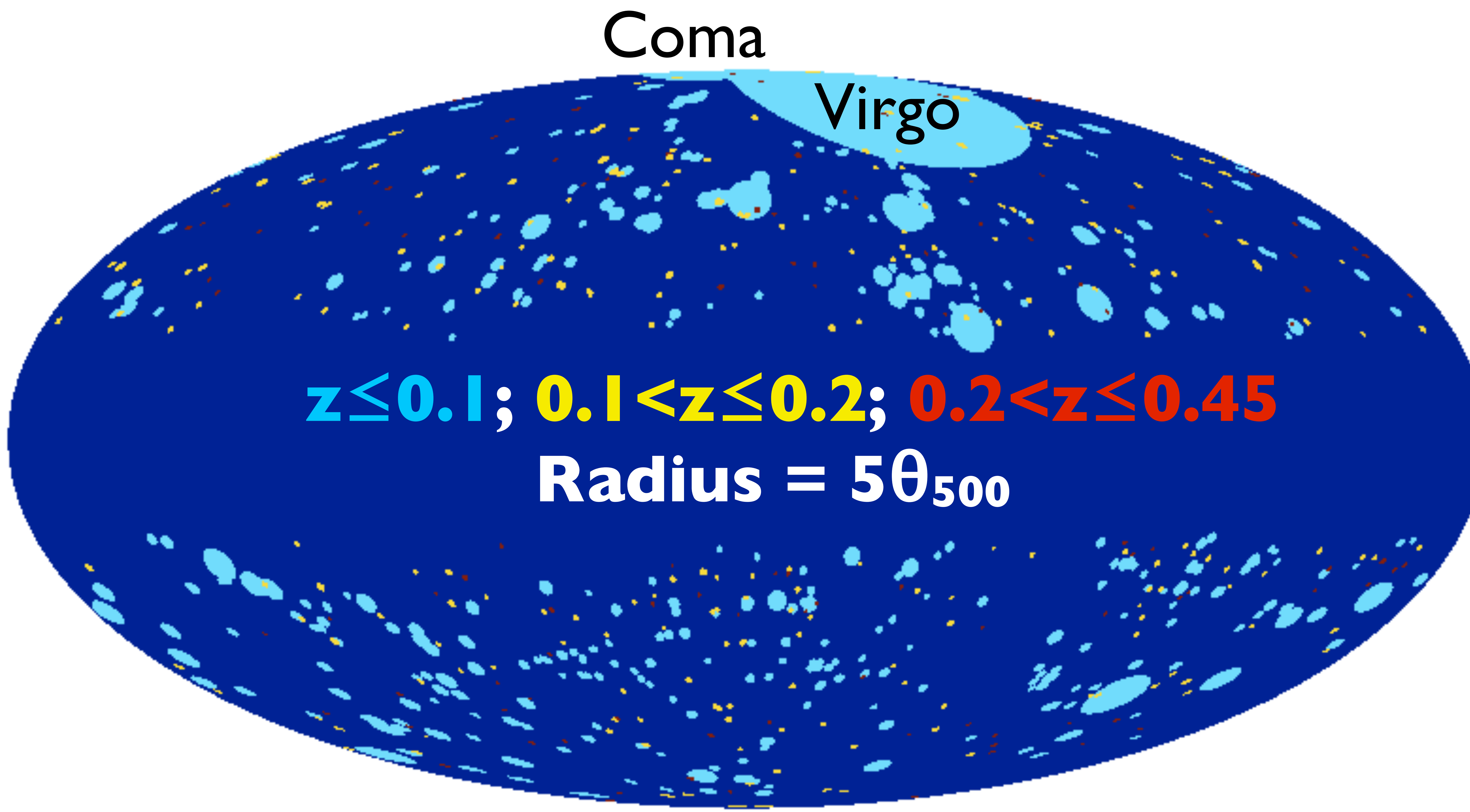
- Coma is sitting on top of a –100uK CMB fluctuation
- WMAP could detect SZ toward a few other massive clusters, even seeing the difference between cool-core and non-cool-core
    - Distinguishing relaxed and non-relaxed clusters is important, if you can resolve the profile of clusters

Statistical Detection of SZ

- Coma is bright enough to be detected by WMAP.
- Some clusters are bright enough to be detected individually by WMAP, but the number is still limited.
- By stacking the pixels at the locations of known clusters of galaxies (detected in X-ray), we detected the SZ effect at 8σ.
  - Many statistical detections reported in the literature:

    (Fosalba et al. 2003; Hernández-Monteagudo & Rubiño-Martín 2004; Hernández-Monteagudo et al. 2004; Myers et al. 2004; Afshordi et al. 2005; Lieu et al. 2006; Bielby & Shanks 2007; Afshordi et al. 2007; Atrio-Barandela et al. 2008; Kashlinsky et al. 2008; Diego & Partridge 2009; Melin et al. 2010).

ROSAT Cluster Catalog



- 742 clusters in |b|>20 deg (before Galaxy mask)
- 400, 228 & 114 clusters in $z \leq 0.1$, $0.1 < z \leq 0.2$ & $0.2 < z \leq 0.45$.

Size-Luminosity Relations

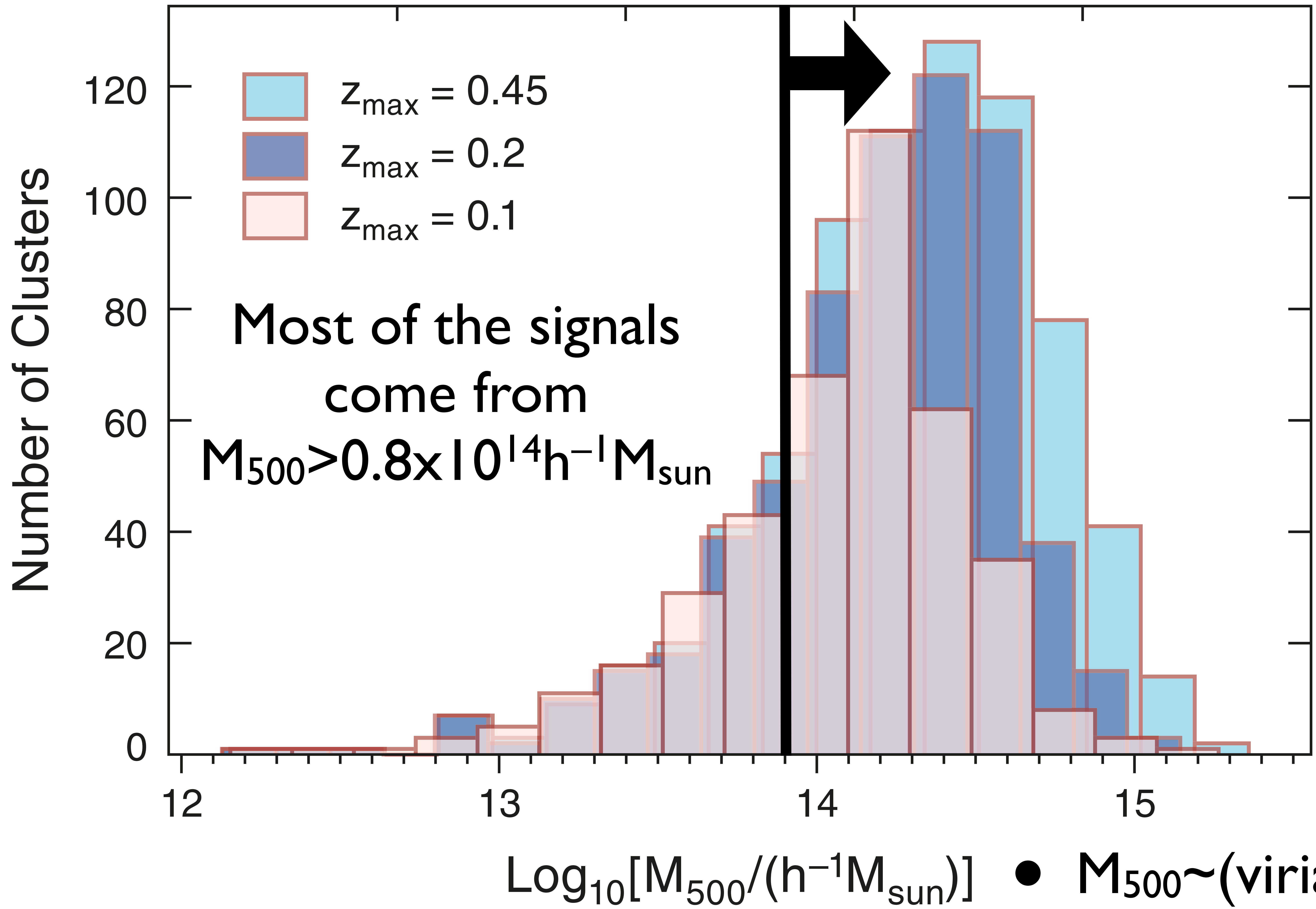
- To calculate the expected pressure profile for each cluster, we need to know the size of the cluster, r_{500}.
- This needs to be derived from the observed properties of X-ray clusters.
  - The best quantity is the gas mass times temperature, but this is available only for a small subset of clusters.
  - We use r_{500}–L_X relation (Boehringer et al.):

$$r_{500} = \frac{(0.753 \pm 0.063)\ h^{-1}\ \mathrm{Mpc}}{E(z)} \times \left(\frac{L_X}{10^{44}\ h^{-2}\ \mathrm{erg\ s^{-1}}}\right)^{0.228 \pm 0.015}$$

Uncertainty in this relation is the major source of sys. error.

$$E(z) \equiv H(z)/H_0 = \left[\Omega_m (1+z)^3 + \Omega_\Lambda\right]^{1/2}$$

Mass Distribution



- M_{500}~(virial mass)/1.6

Scaling Relations...

Gas Pressure Profile	Type	$z_{max} = 0.1$	$z_{max} = 0.2$	High L_X [b]	Low L_X [c]
Arnaud et al. (2009)	X-ray Obs. (Fid.)[d]	0.64 ± 0.09	$0.59 \pm 0.07^{+0.38}_{-0.23}$	0.67 ± 0.09	0.43 ± 0.12
Arnaud et al. (2009)	REXCESS scaling[e]	N/A	0.78 ± 0.09	0.90 ± 0.12	0.55 ± 0.16
Arnaud et al. (2009)	intrinsic scaling[f]	N/A	0.69 ± 0.08	0.84 ± 0.11	0.46 ± 0.13
Arnaud et al. (2009)	$r_{out} = 2r_{500}$[g]	N/A	0.59 ± 0.07	0.67 ± 0.09	0.43 ± 0.12
Arnaud et al. (2009)	$r_{out} = r_{500}$[h]	N/A	0.65 ± 0.08	0.74 ± 0.09	0.44 ± 0.14
Komatsu & Seljak (2001)	equation (C16)	0.59 ± 0.09	$0.46 \pm 0.06^{+0.31}_{-0.18}$	0.49 ± 0.08	0.40 ± 0.11
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Nagai et al. (2007)	Non-radiative	N/A	$0.50 \pm 0.06^{+0.28}_{-0.18}$	0.60 ± 0.08	0.33 ± 0.10
Nagai et al. (2007)	Cooling+SF	N/A	$0.67 \pm 0.08^{+0.37}_{-0.23}$	0.79 ± 0.10	0.45 ± 0.14

- Different scaling relations can give you a variety of results
  - Need for a "consistent scaling relation" (Melin), but it is not so trivial to find one
  - This limits accuracy of the stacking method

Missing P in Low Mass Clusters?

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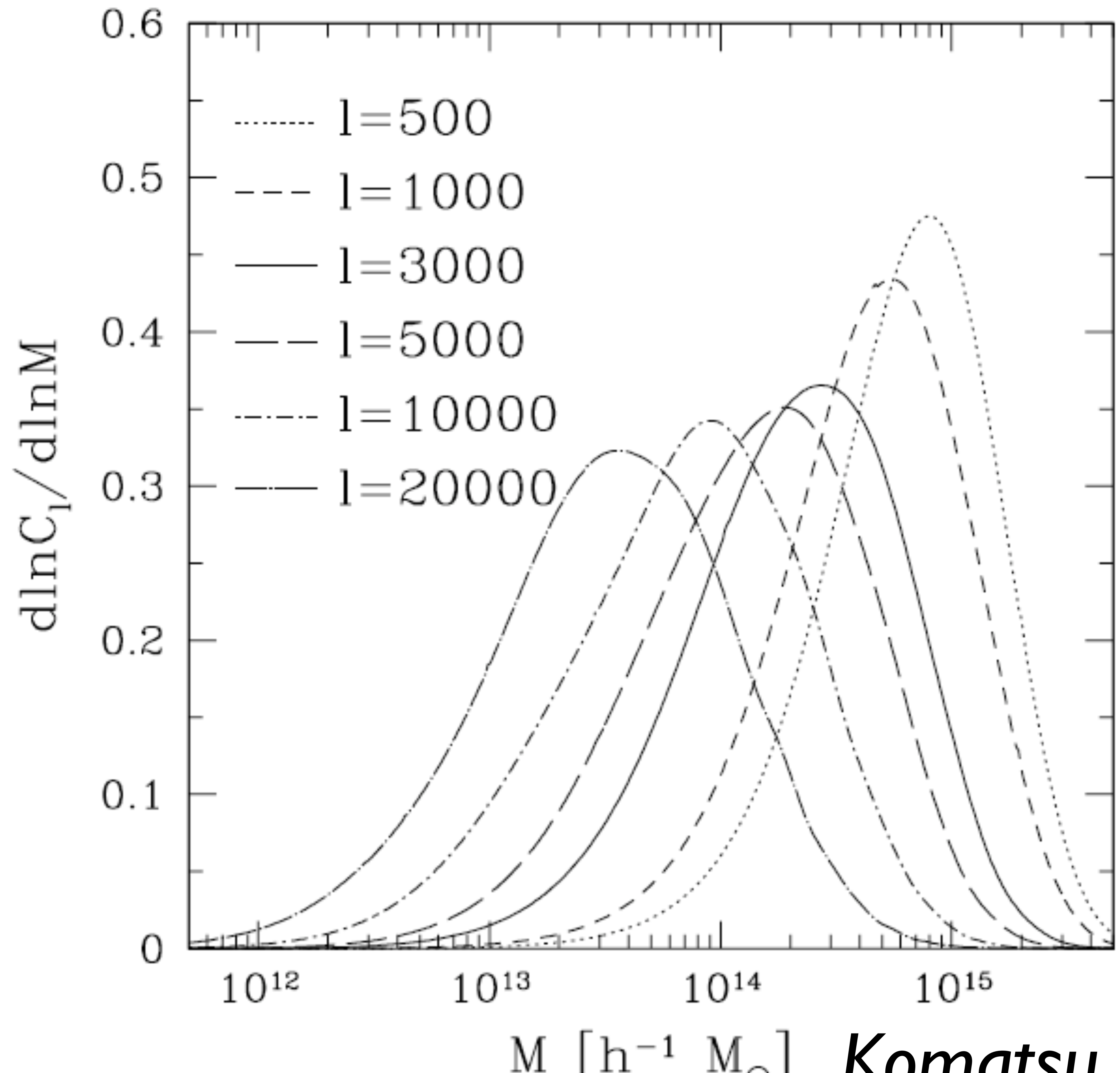
- "Low L_X" has $0.45 < L_X/(10^{44}\,\mathrm{erg\,s^{-1}}) < 4.5$
  - M_{500} < a few x $10^{14}\,h^{-1}\,M_{\rm sun}$

This is consistent with the lower-than-expected C_l^{SZ}



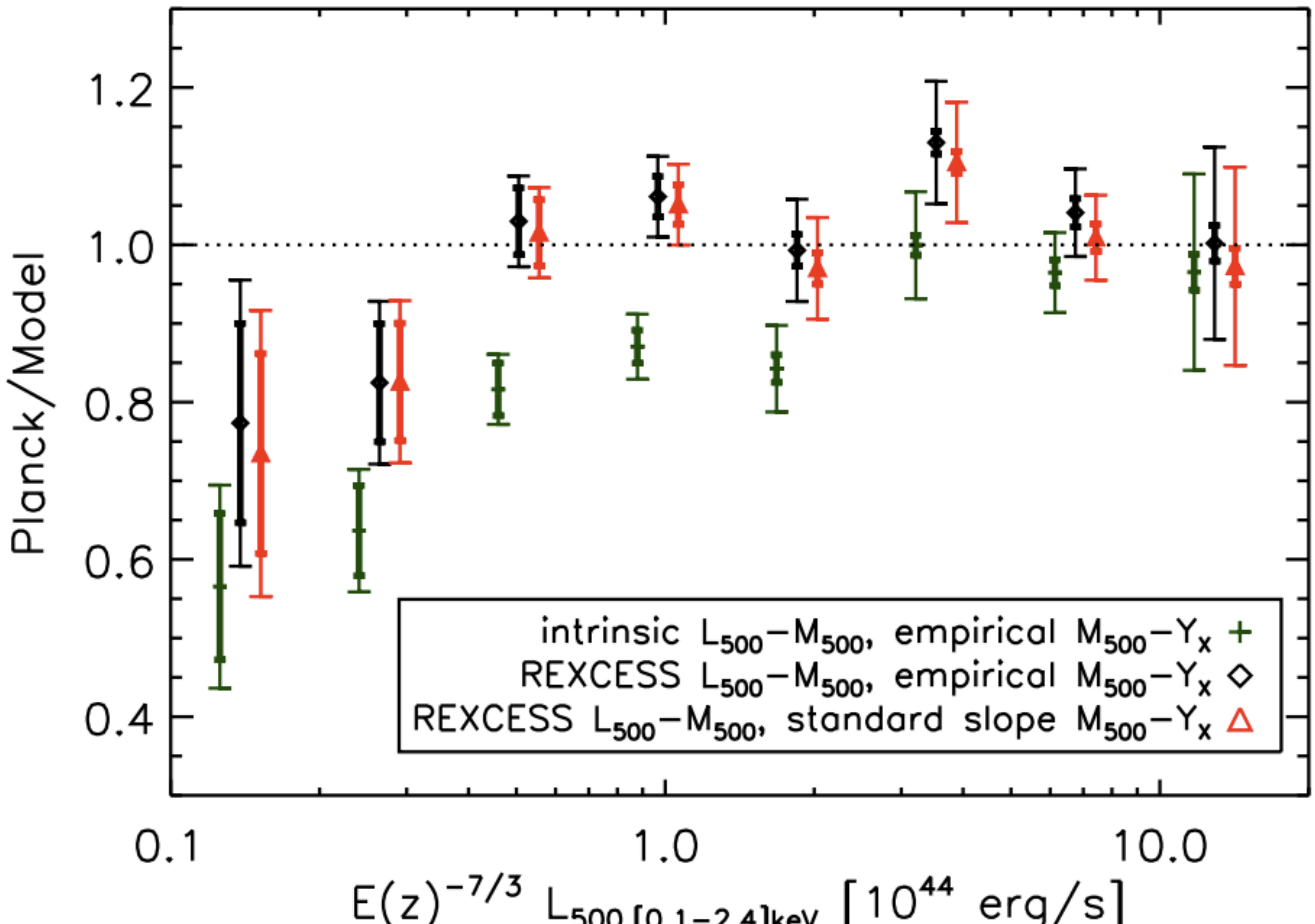
Komatsu and Seljak (2002)

- At l>3000, the dominant contributions to the SZ power spectrum come from low-mass clusters ($M_{500}<4\times10^{14}h^{-1}M_{sun}$).

However...

- This deficit of the pressure on low-mass clusters has not really been seen by Planck, for one of the scaling relations.
  - And they have MUCH more signal-to-noise.
- However, they also do see that the results change significantly depending on the L_X-M_{500} scaling relation adopted.
  - For another scaling relation they used, they see the deficit.

Scaling Relations...



A lesson [we] learned from the stacking analysis

- The stacking analysis is a potentially powerful technique for discovering unexpected phenomena
  - Optical vs SZ is very intriguing (Planck Paper XII)
- The scaling relation limits accuracy and complicates the interpretation of the results
- Once something is found, it is good to go back to individual clusters (the first part of the talk) and understand what is going on (CC vs NCC, for example)