WMAP 7-year Results: Sunyaev–Zel'dovich Effect

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A New Result!

We find, *for the first time in the Sunyaev-Zel'dovich (SZ) effect*, a significant difference between relaxed and non-relaxed clusters.

- Important when using the SZ effect of clusters of galaxies as a cosmological probe.

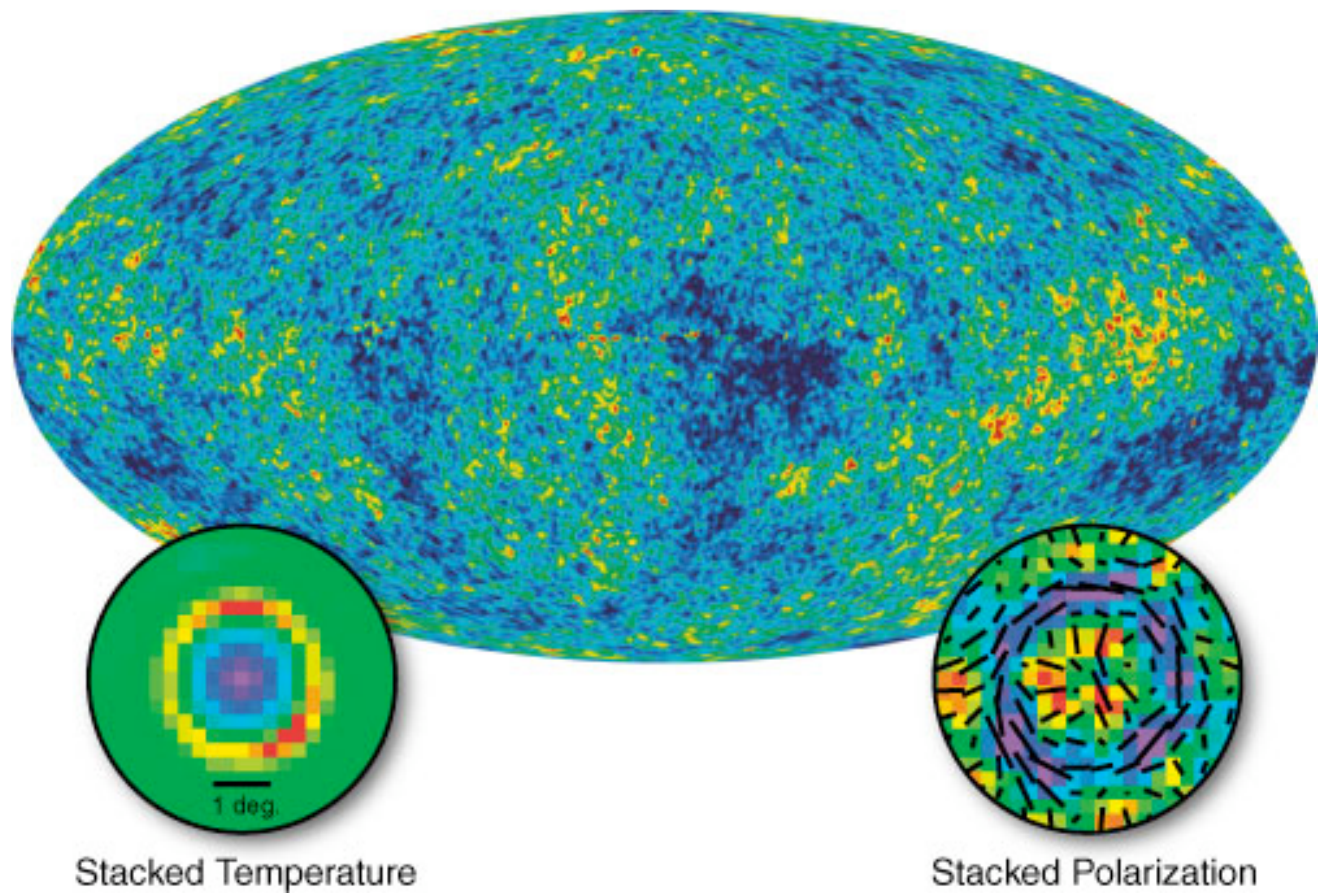
WMAP will have collected 9 years of data by August

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



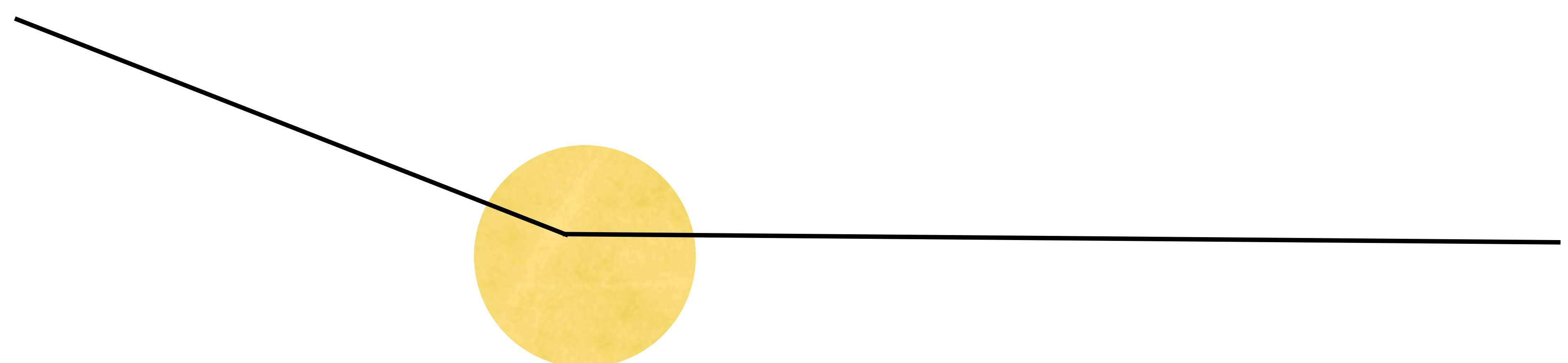
- **January 2010: The seven-year data release**

WMAP 7-Year Papers

- **Jarosik et al.**, "*Sky Maps, Systematic Errors, and Basic Results*" arXiv:1001.4744
- **Gold et al.**, "*Galactic Foreground Emission*" arXiv:1001.4555
- **Weiland et al.**, "*Planets and Celestial Calibration Sources*" arXiv:1001.4731
- **Bennett et al.**, "*Are There CMB Anomalies?*" arXiv:1001.4758
- **Larson et al.**, "*Power Spectra and WMAP-Derived Parameters*" arXiv:1001.4635
- **Komatsu et al.**, "*Cosmological Interpretation*" arXiv:1001.4538

Zel'dovich & Sunyaev (1969); Sunyaev & Zel'dovich (1972)

Sunyaev–Zel'dovich Effect



observer

- $\Delta T/T_{cmb} = g_\nu$ **y**

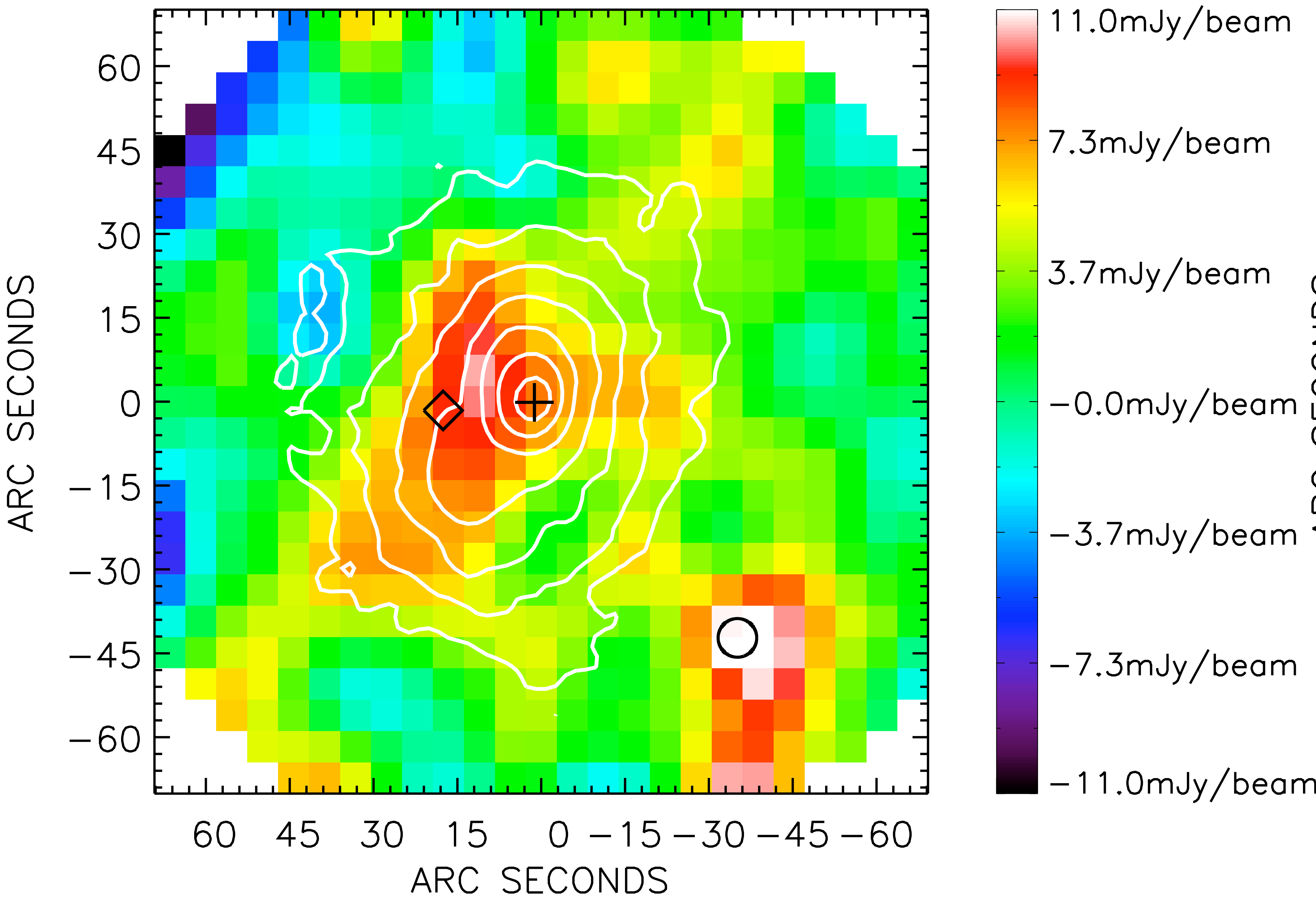
Hot gas with the
electron temperature of $T_e >> T_{cmb}$

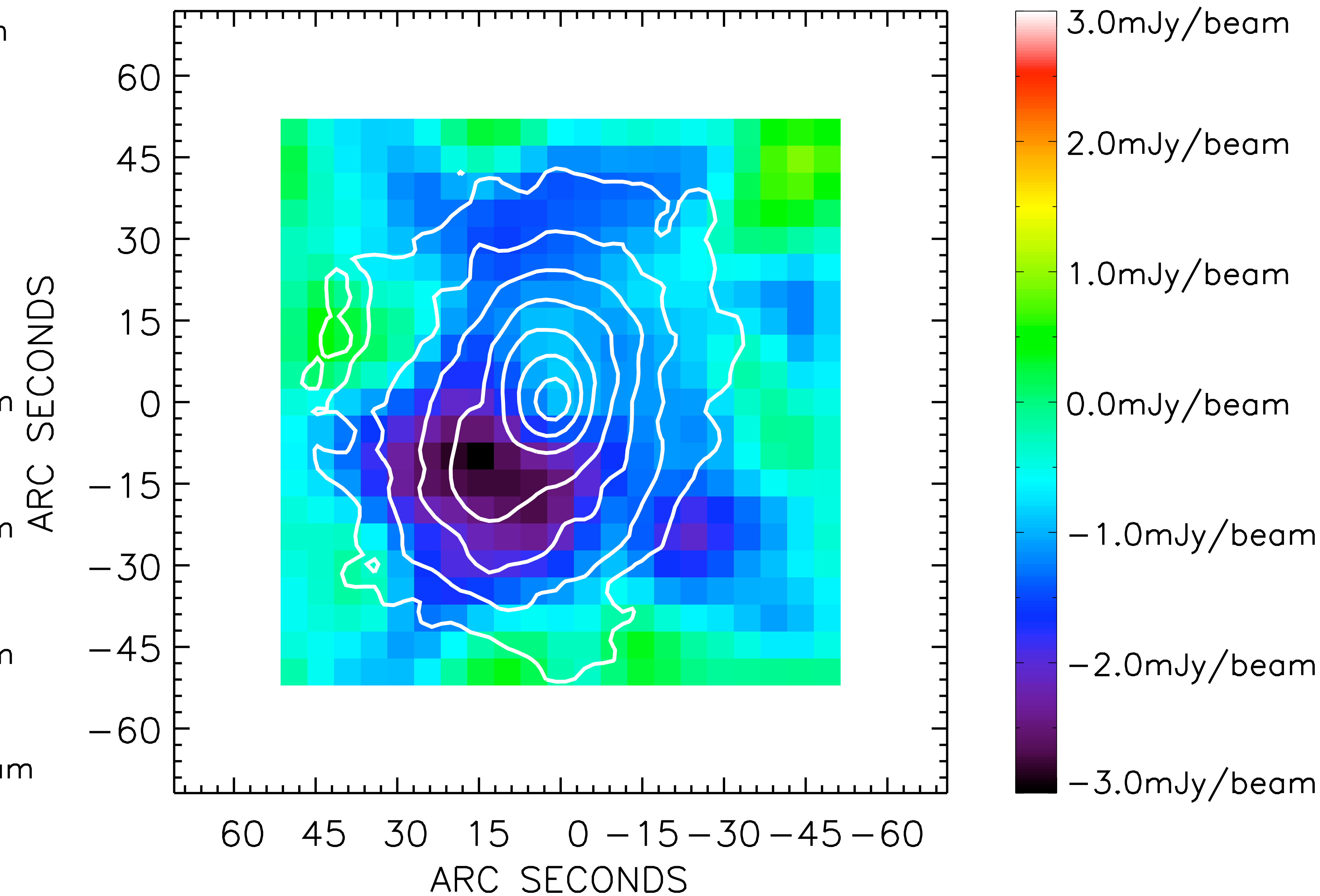
$$y = (\text{optical depth of gas})\ k_B T_e/(m_e c^2)$$
$$= [\sigma_T/(m_e c^2)] \int n_e k_B T_e \, d(\text{los})$$
$$= [\sigma_T/(m_e c^2)] \int (\textbf{electron pressure}) d(\text{los})$$

- Decrement: **$\Delta T<0$** (ν<217 GHz)
- Increment: **$\Delta T>0$** (ν>217 GHz)

$g_\nu = -2$ (ν=0); -1.91, -1.81 and -1.56 at ν=41, 61 and 94 GHz

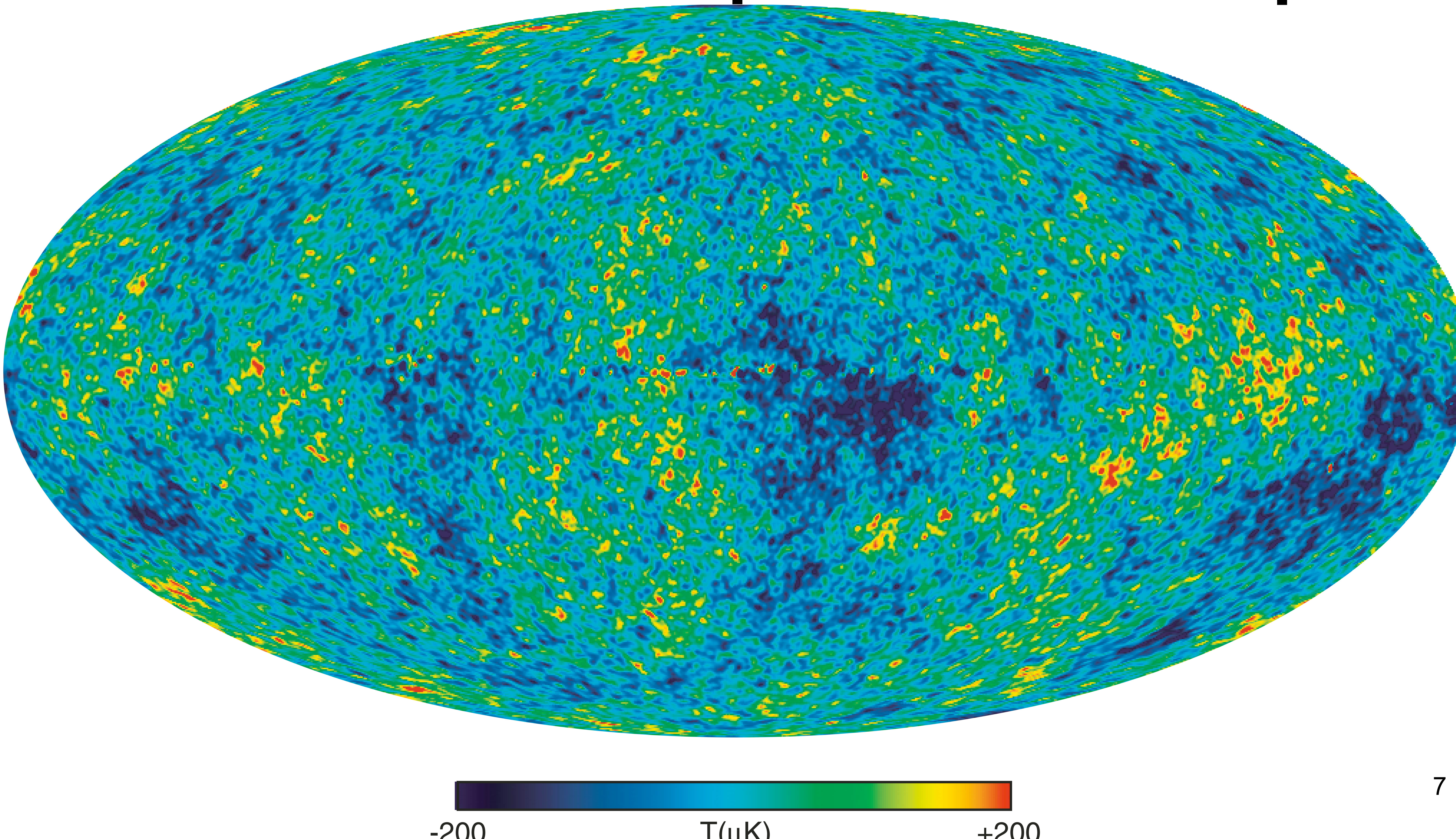
The SZ Effect: Decrement and Increment



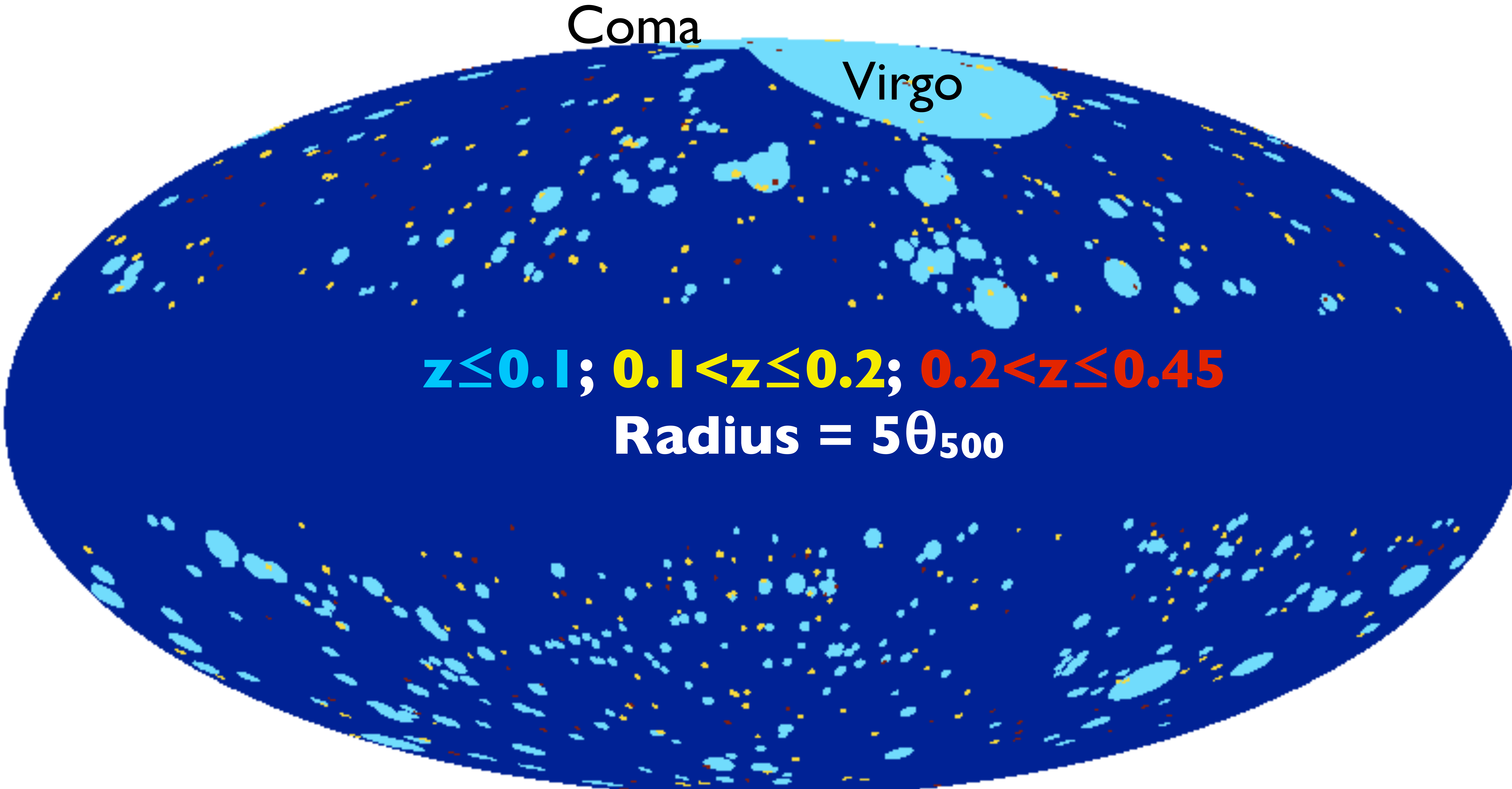


- RXJ1347-1145
  - –Left, SZ increment (350GHz, Komatsu et al. 1999)
  - –Right, SZ decrement (150GHz, Komatsu et al. 2001)

WMAP Temperature Map



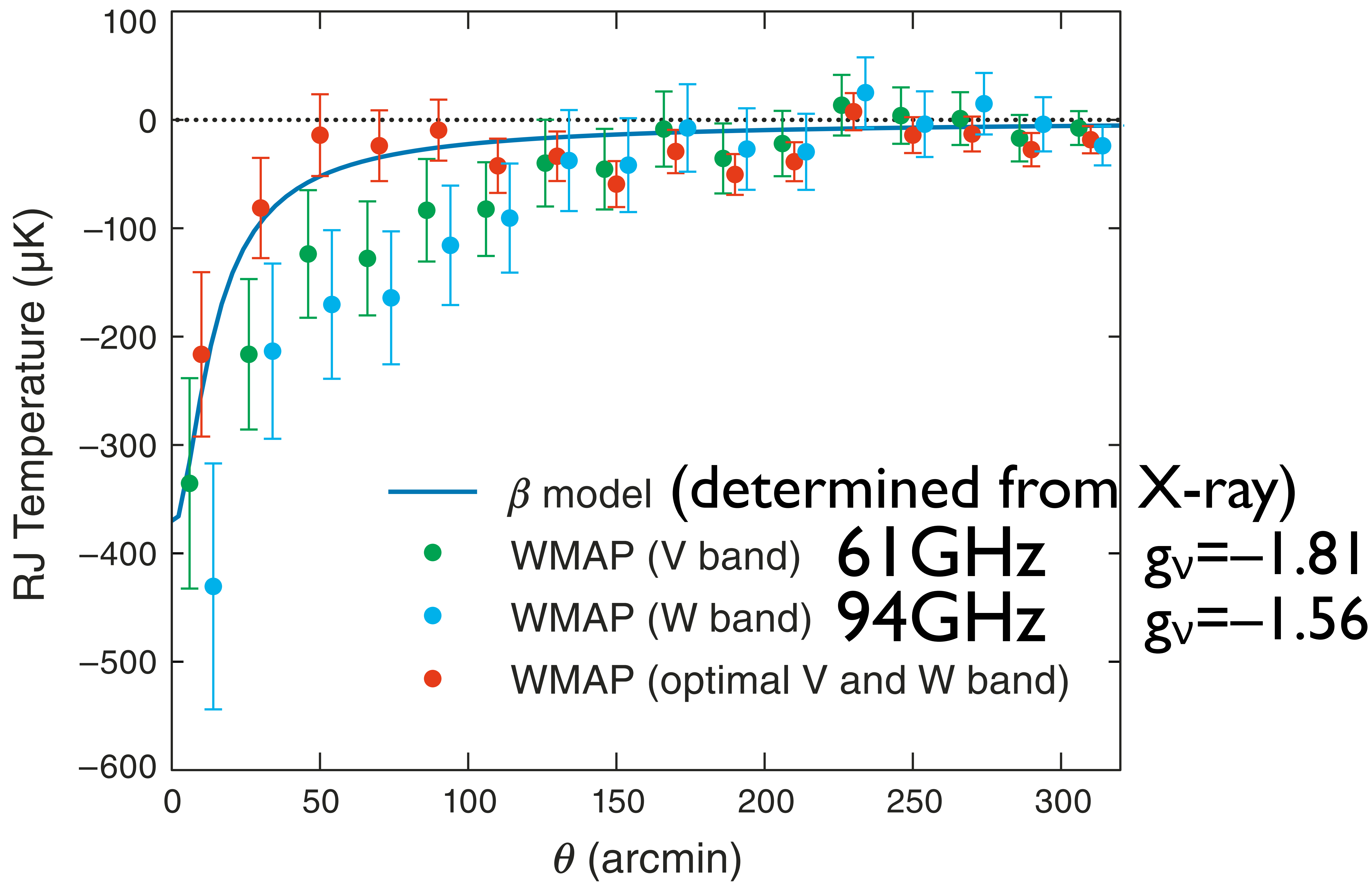
Where are clusters?



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)



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

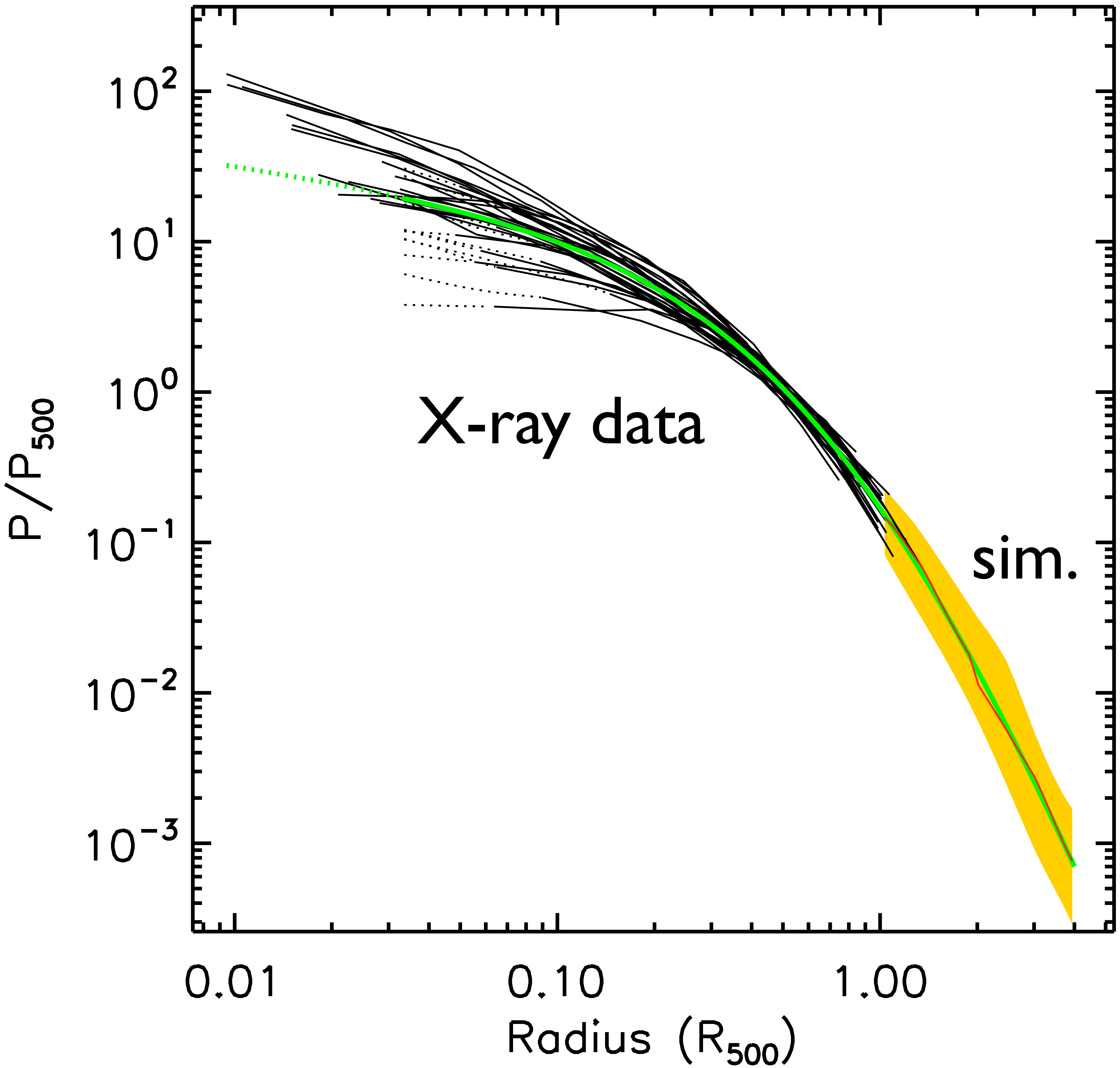
A Question

- 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

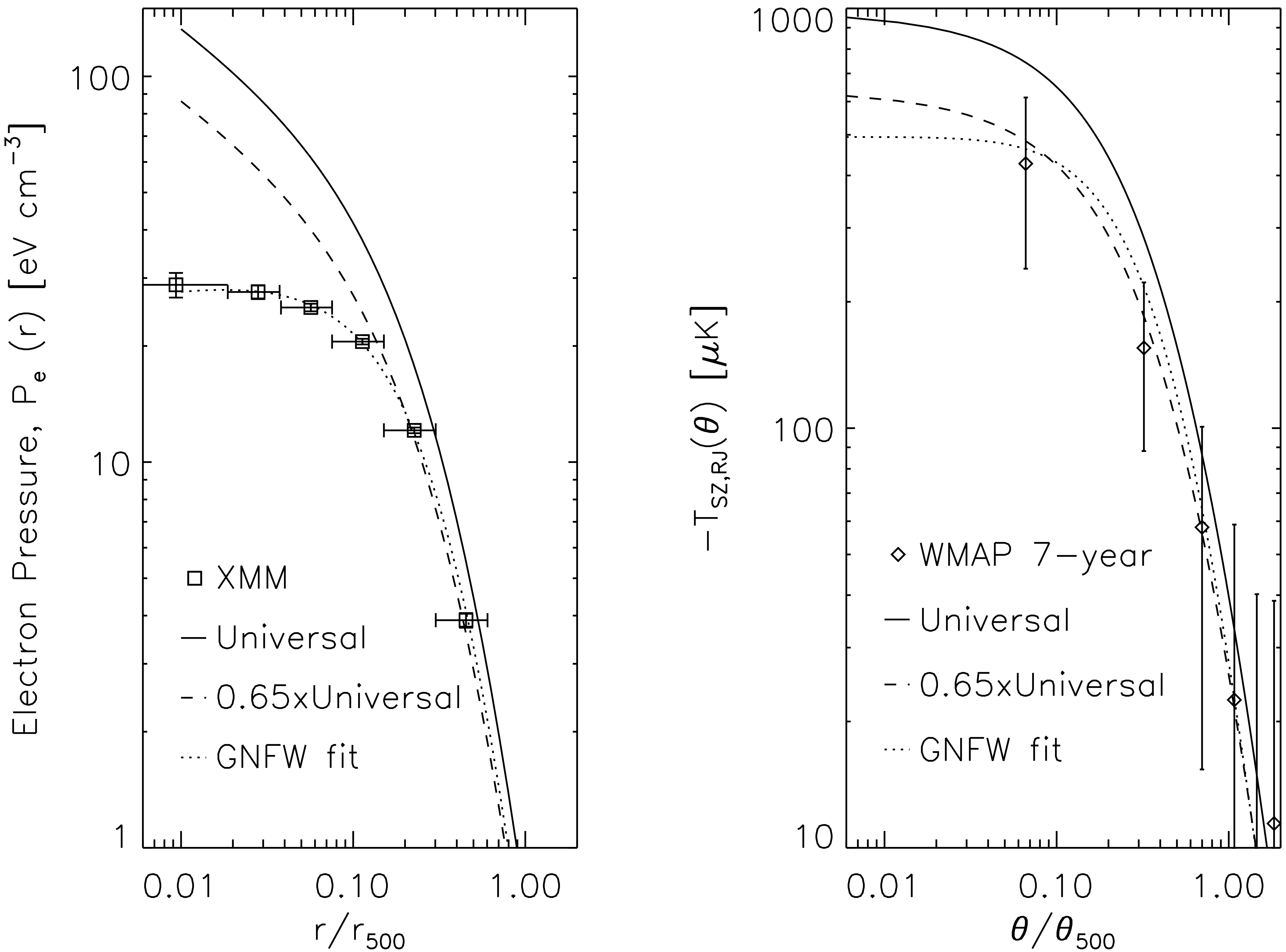
- A fitting formula for the average electron pressure profile as a function of the cluster mass (M_{500}), derived from 33 nearby ($z<0.2$) clusters (REXCESS sample).

Arnaud et al. Profile



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

Coma Data vs Arnaud



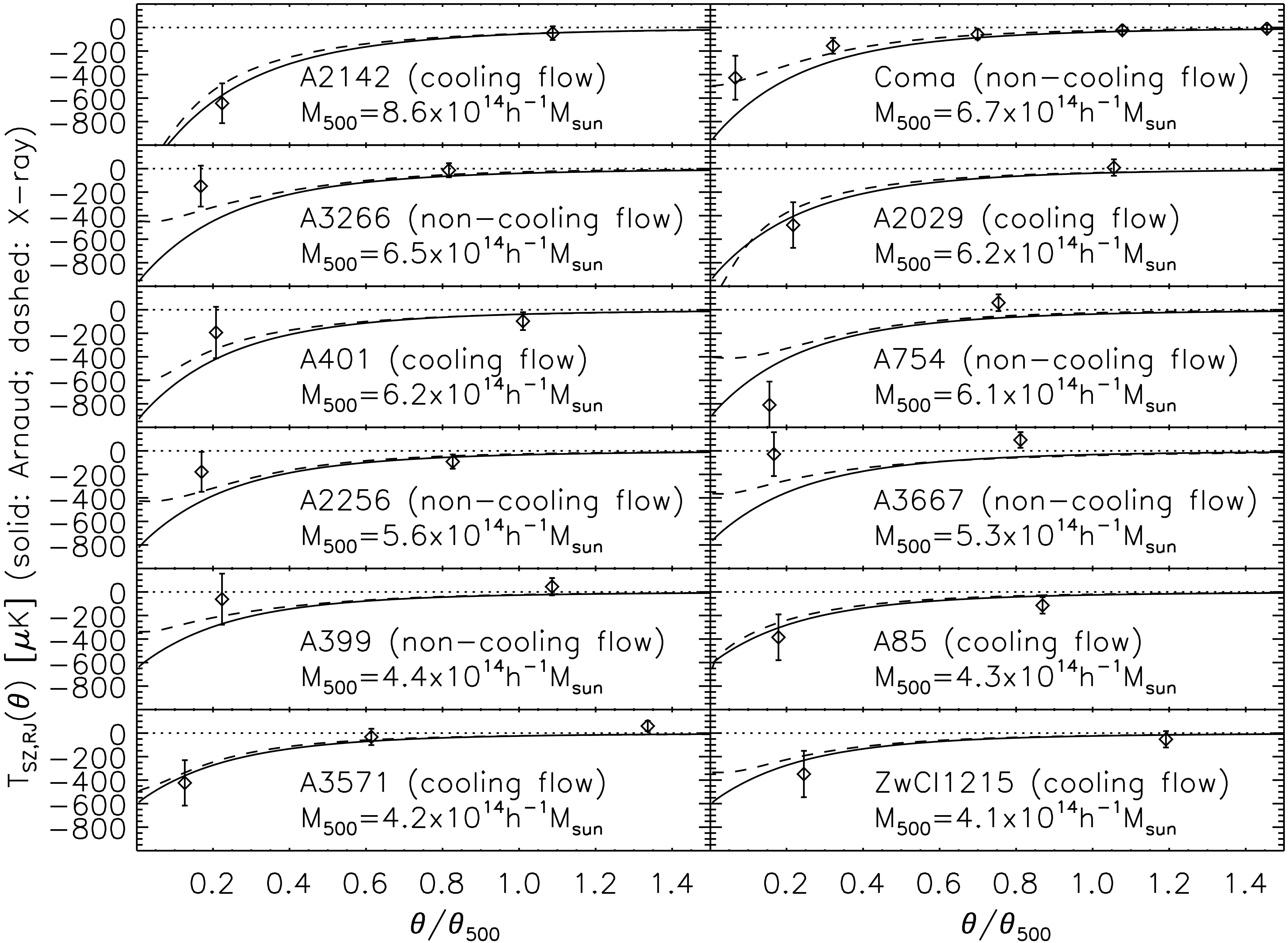
The X-ray data (XMM) are provided by A. Finoguenov.

- $M_{500}=6.6\times10^{14}h^{-1}M_{sun}$ 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. 2010)



Low-SZ is seen in the WMAP

Mass Range[a]	# of clusters	X-ray Data	Model
$6 \le M_{500} < 9$	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
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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.

Low-SZ: Signature of mergers?

Mass Range[a]	# of clusters	X-ray Data	Model
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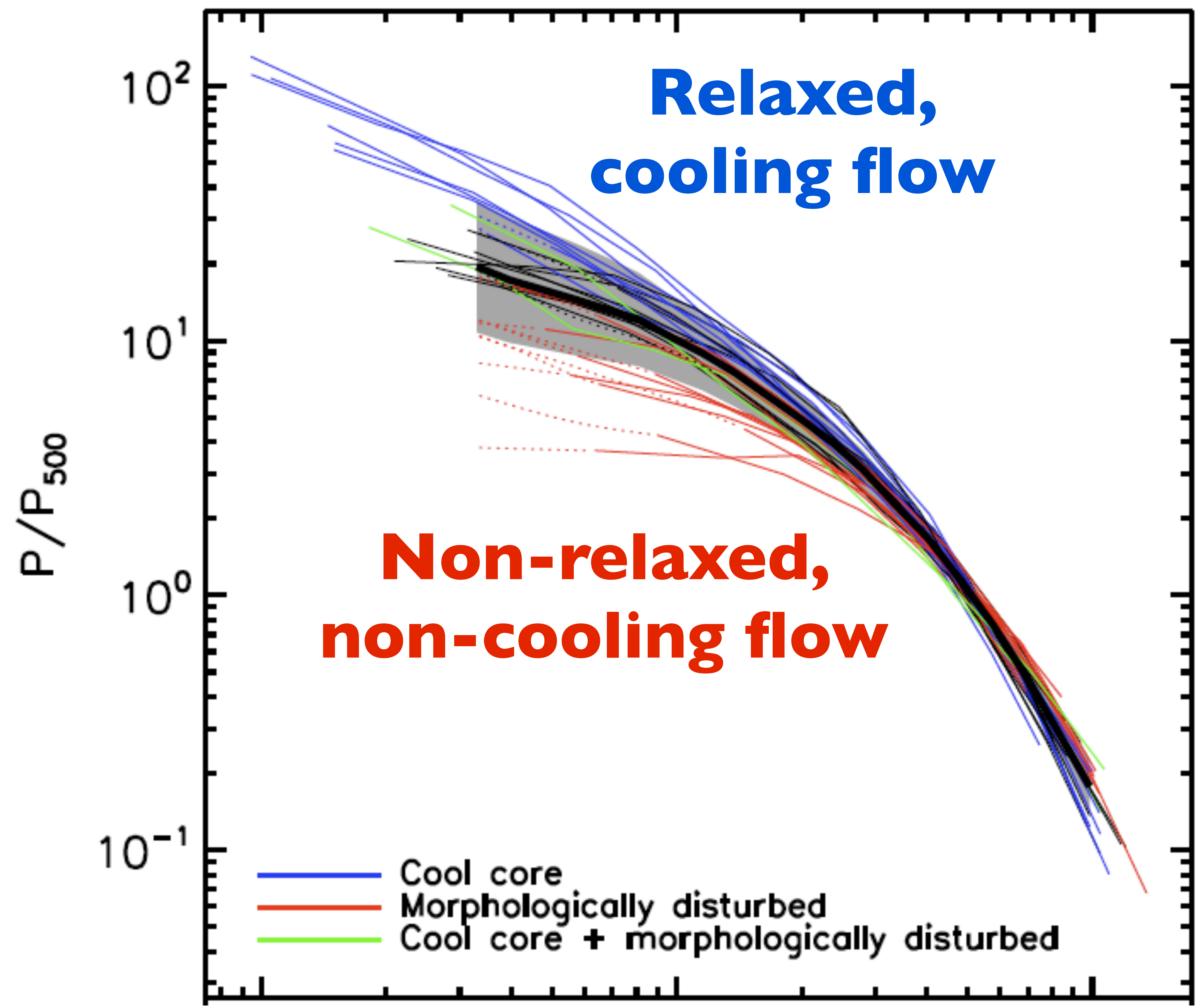
SZ: Main Results

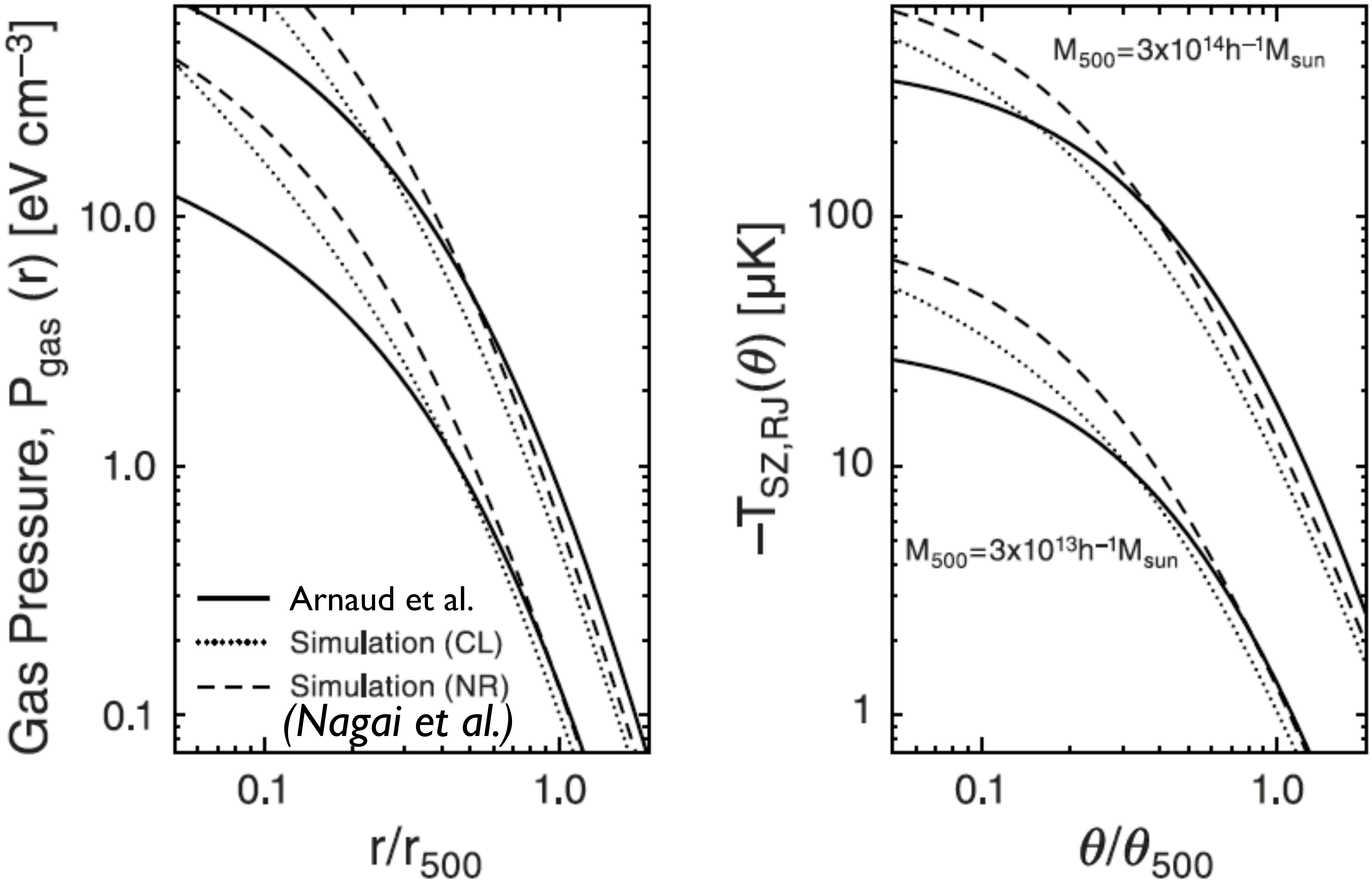
- Arnaud et al. profile systematically overestimates the electron pressure! (Arnaud et al. profile is **ruled out** at 3.2σ).
- But, the X-ray data on the *individual* clusters agree well with the SZ measured by WMAP.
- Reason: Arnaud et al. did not distinguish between relaxed (CF) and non-relaxed (non-CF) clusters.
  - This will be important for the proper interpretation of the SZ effect when doing cosmology with it.

Cooling Flow vs Non-CF

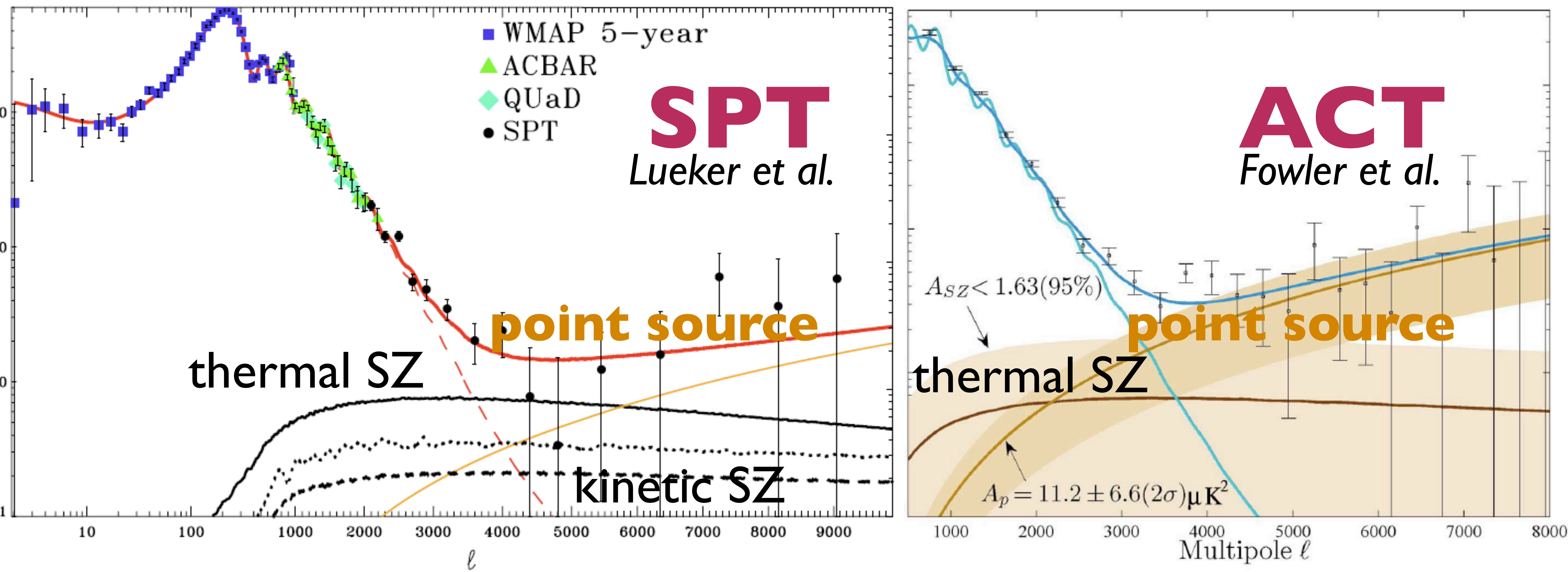


- In Arnaud et al., they reported that the cooling flow clusters have much steeper pressure profiles in the inner part.
- Taking a simple median gave a biased "universal" profile.

Theoretical Models



"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 A$_{SZ}$: **Two** Possibilities

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

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

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

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

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

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

- **[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.
- *And, our measurement shows that this is what is going on!*

Conclusion

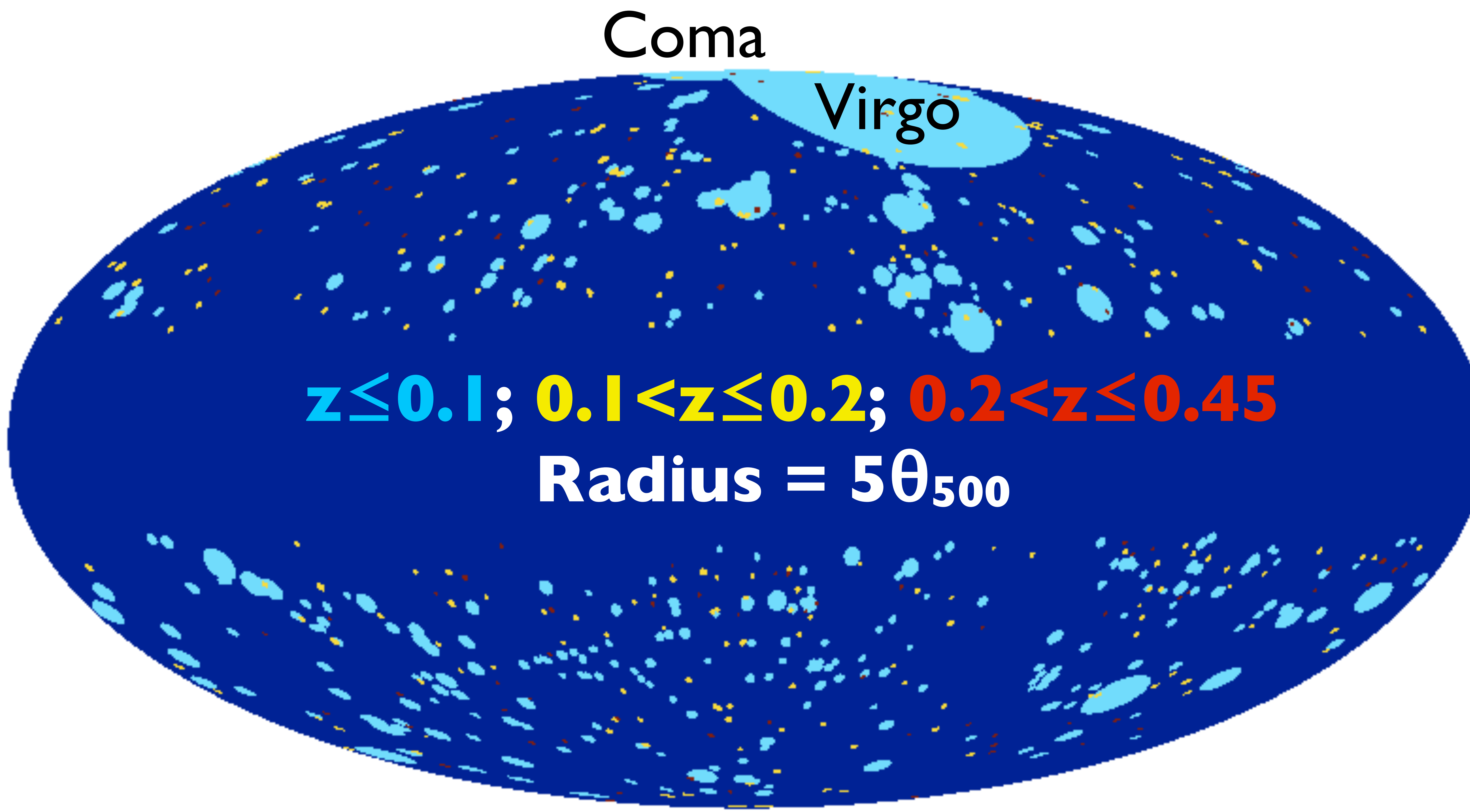
- SZ effect: Coma's radial profile is measured, several massive clusters are detected, and the statistical detection reaches 6.5σ.
  - Evidence for lower-than-theoretically-expected gas pressure.
- The X-ray data are fine: we need to revise the existing models of the intracluster medium.
  - ***Distinguishing relaxed and non-relaxed clusters is very important!***

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:

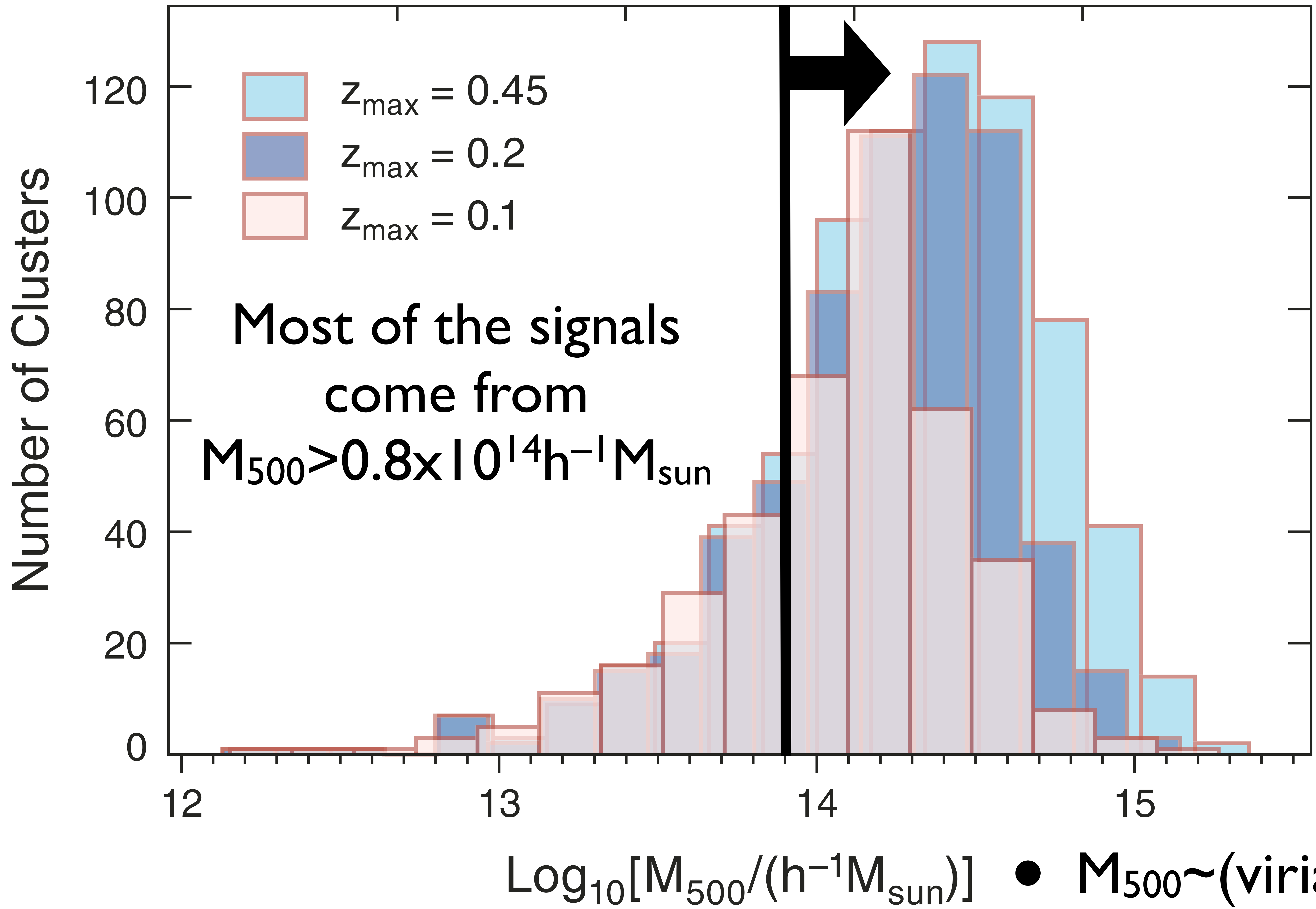
    (Fosalba et al. 2003; Hernández-Monteagudo & Rubiño-Martín 2004; Hernández-Monteagudo et al. 2004; Myers et al. 2004; Afshordi et al. 2005; Lieu et al. 2006; Bielby & Shanks 2007; Afshordi et al. 2007; Atrio-Barandela et al. 2008; Kashlinsky et al. 2008; Diego & Partridge 2009; Melin et al. 2010).

ROSAT Cluster Catalog



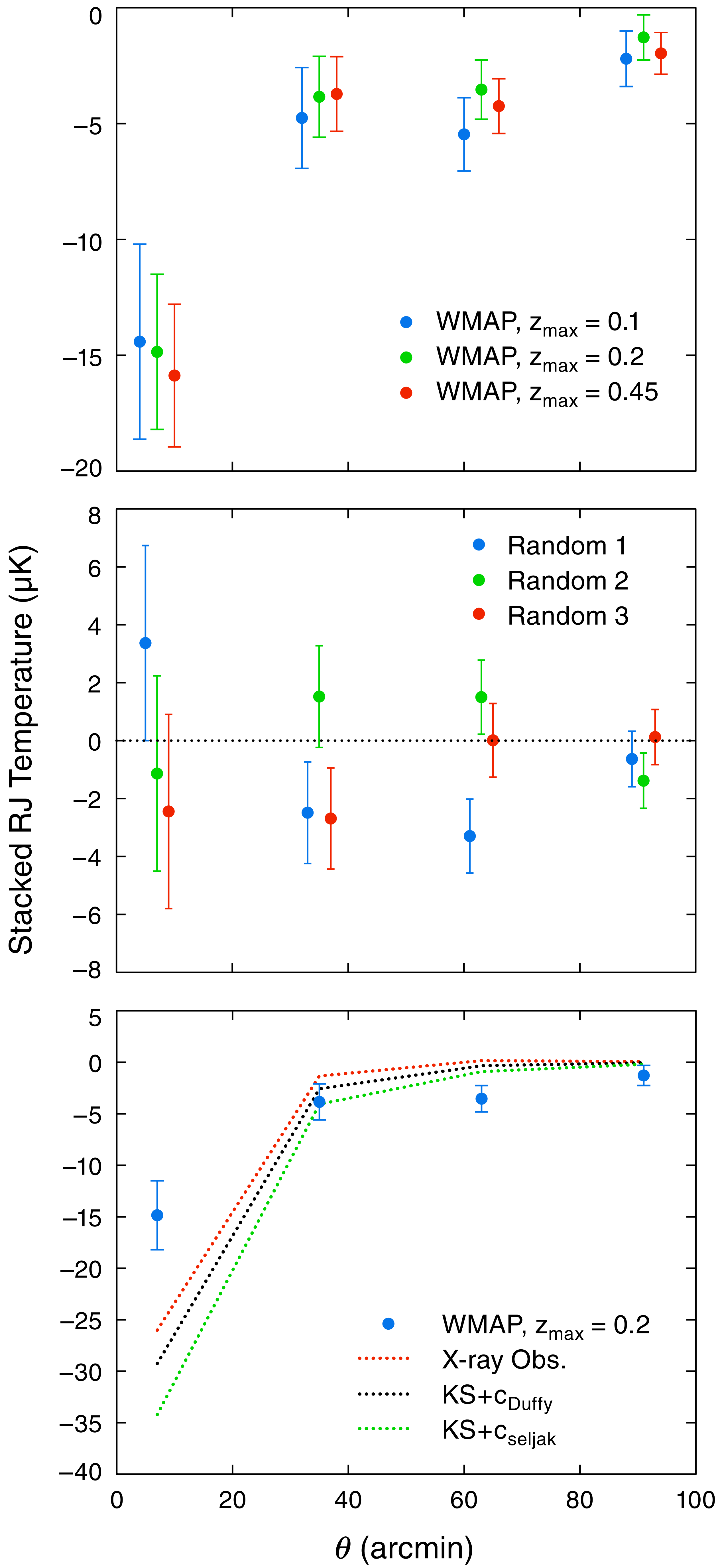
- 742 clusters in |b|>20 deg (before Galaxy mask)
- 400, 228 & 114 clusters in $z \le 0.1$, $0.1 < z \le 0.2$ & $0.2 < z \le 0.45$.

Mass Distribution



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

Angular Profiles



- (Top) Significant detection of the SZ effect.
- (Middle) Repeating the same analysis on the random locations on the sky does not reveal any noticeable bias.
- (Bottom) Comparison to the expectations. **The observed SZ ~ 0.5–0.7 times the expectations.**

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.

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

Missing P in Low Mass Clusters?

Gas Pressure Profile	Type	$z_{\rm max} = 0.1$	$z_{\rm max} = 0.2$	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)	$r_{\rm out} = 2r_{500}$[g]	N/A	0.59 ± 0.07	0.67 ± 0.09	0.43 ± 0.12
Arnaud et al. (2009)	$r_{\rm out} = r_{500}$[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

- One picture has emerged:
  - The results with the Fiducial scaling relation (Boehringer et al.) are fully consistent with the individual cluster analysis.
  - "Low L_X" clusters reveal a significant *missing pressure*.

But, be aware of "Junk Cosmology"

- "*Junk Cosmology*" = Average many many (hundreds, thousands...) uncertain data to extract ~3σ result.
  - Problem: you believe the result only when you get the expected result, but you don't believe it when you get an unexpected result. Therefore, in the end, you don't learn anything new.
- For our analysis, stacking hundreds of clusters was an example of junk cosmology. We had to do the "gem cosmology" (the first part of the talk) to make sure that what we got the right answer.

Are these results consistent with the gem cosmology?

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Compare to the individual analysis

Mass Range[a]	# of clusters	X-ray Data	Arnaud et al.[c]
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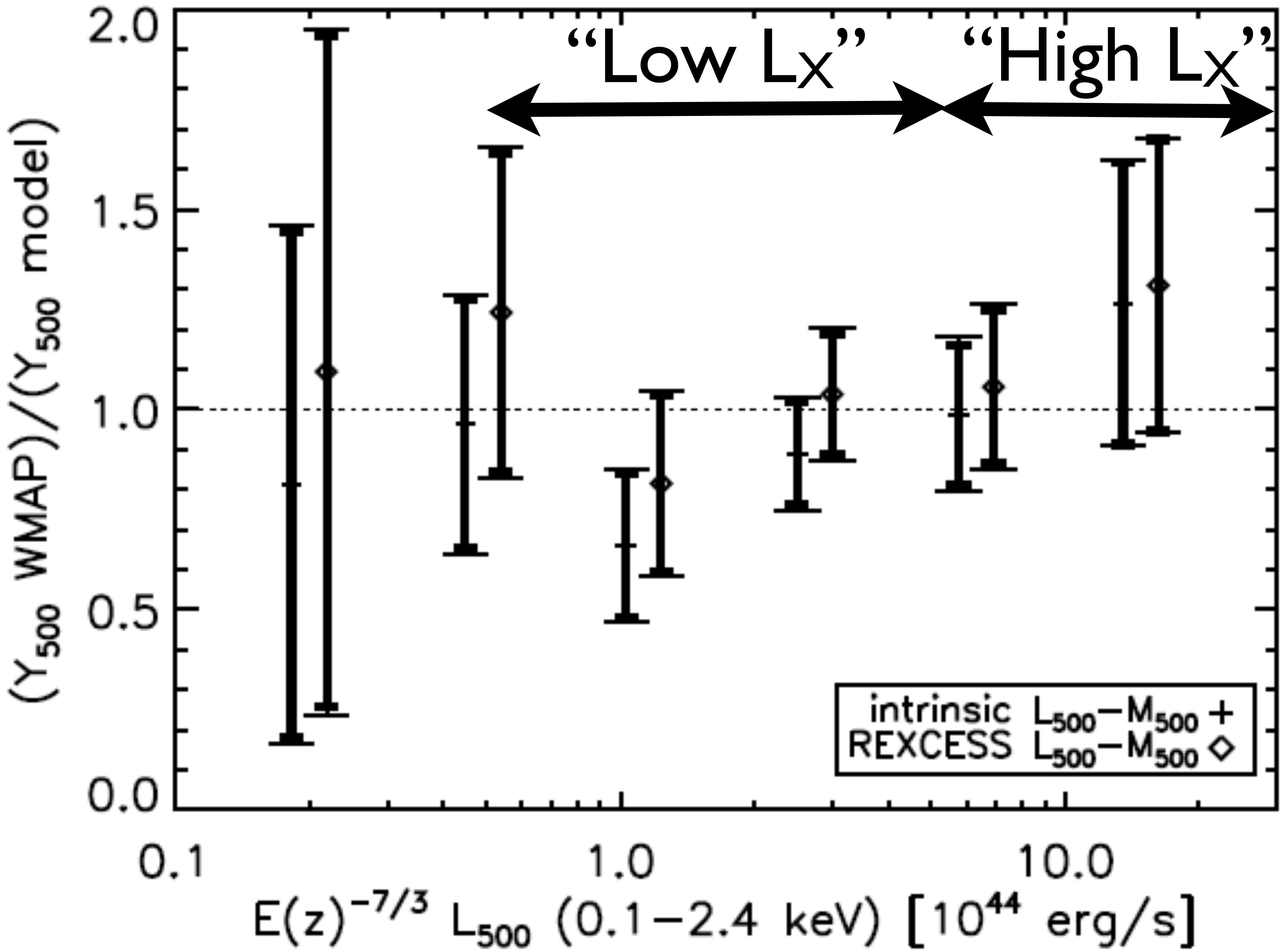
[a] In units of $10^{14}\ h^{-1}\ M_\odot$. Coma is not included.

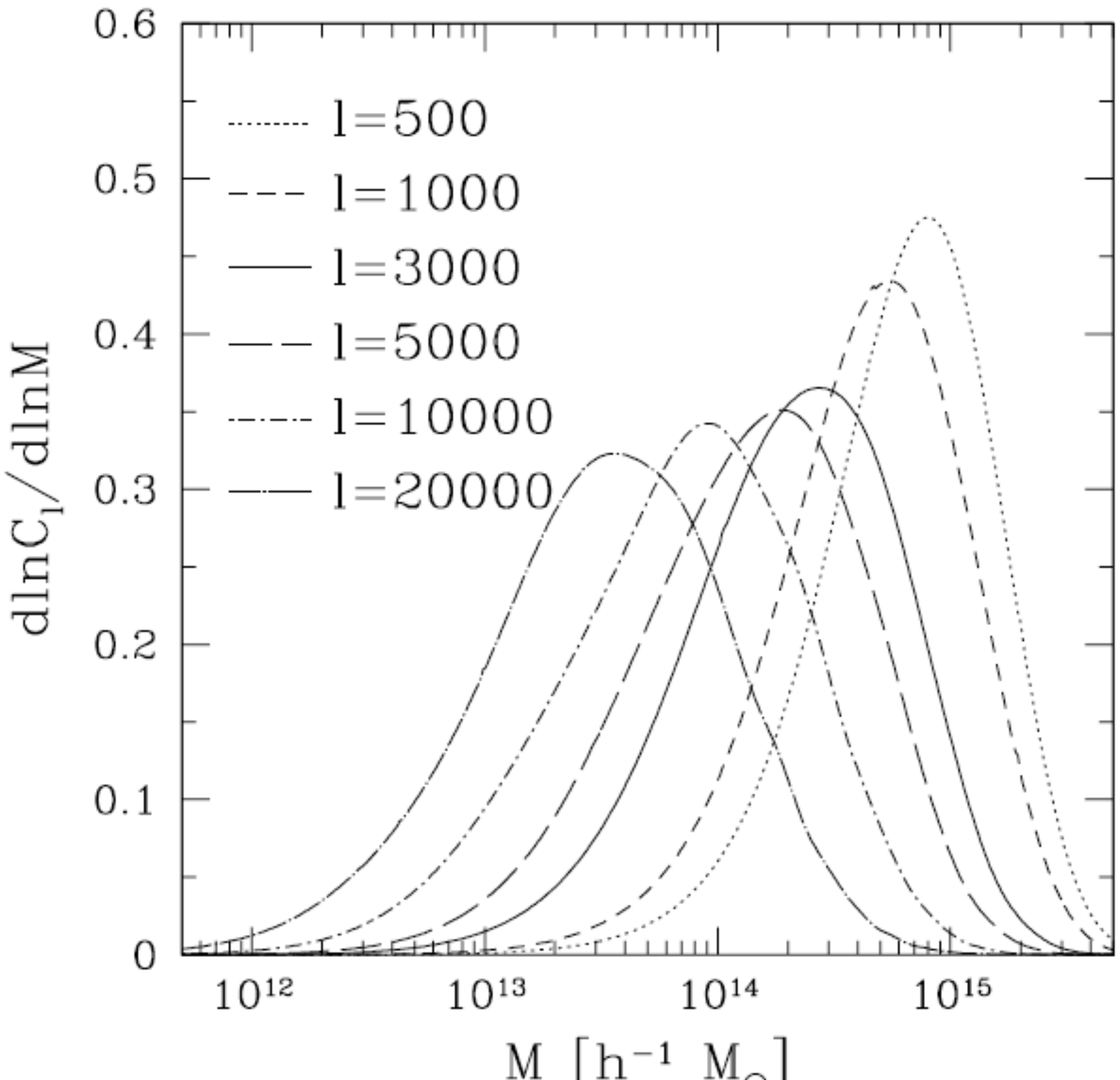
In a complete agreement (a miracle!)

Comparison with Melin et al.



- That low-mass clusters have lower normalization than high-mass clusters is also seen by a different group using a different method.
- While our overall normalization is much lower than theirs, the *relative* normalization is in an agreement.

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



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