Latest Results from CMB Experiments (Overview)

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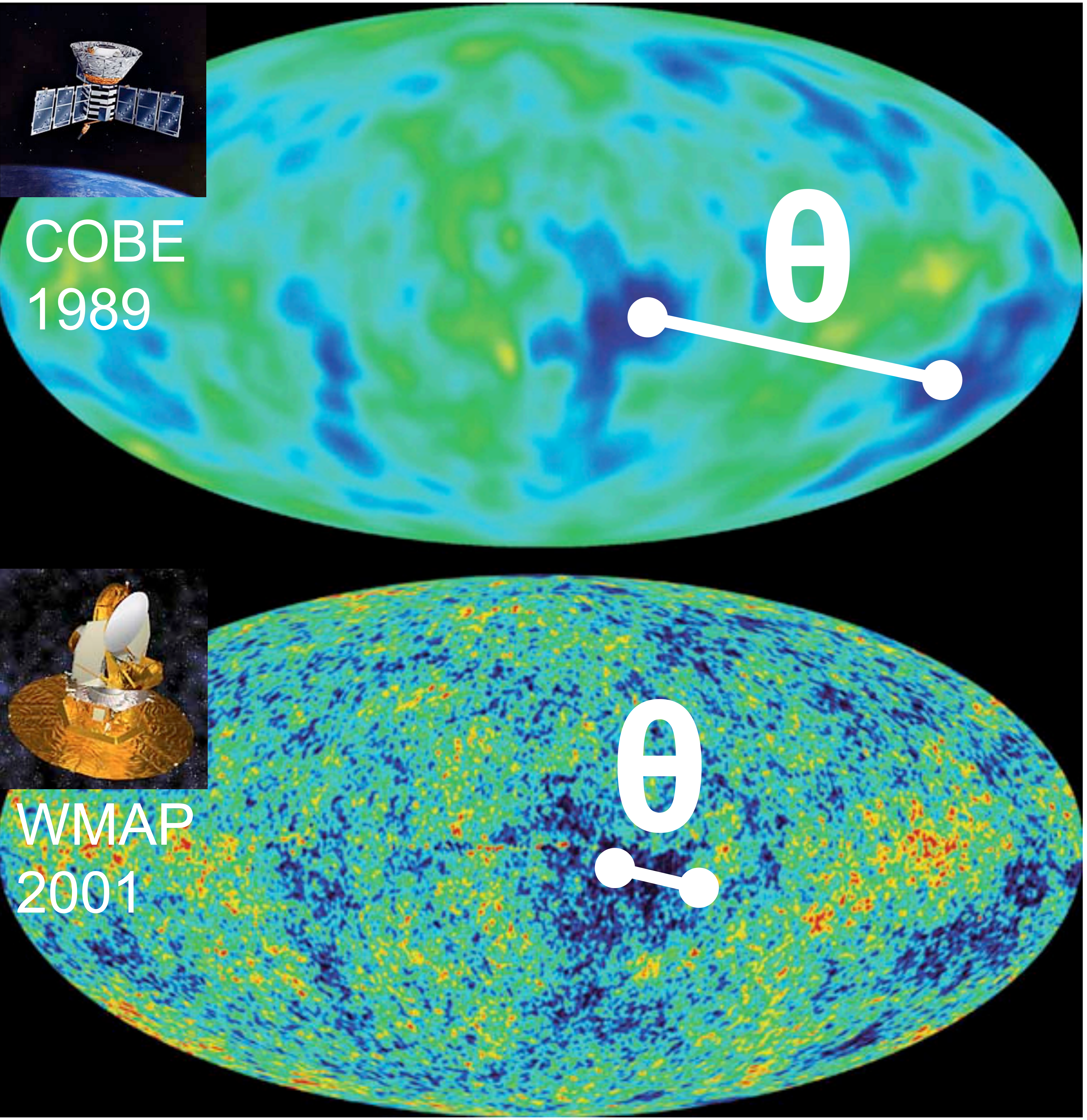
CMBワークショップ2010, 国立天文台, 6月7日

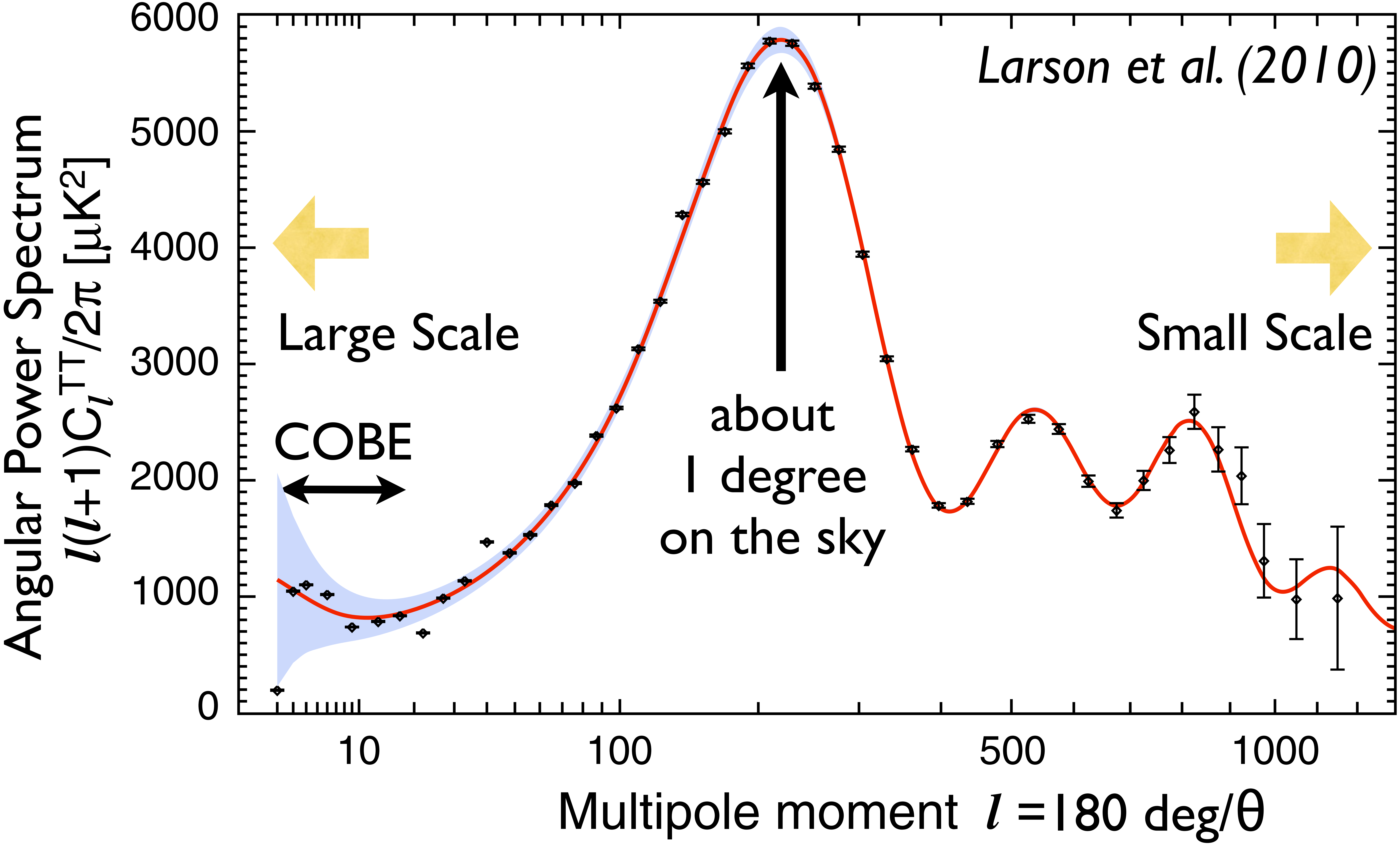
1. Temperature Anisotropy

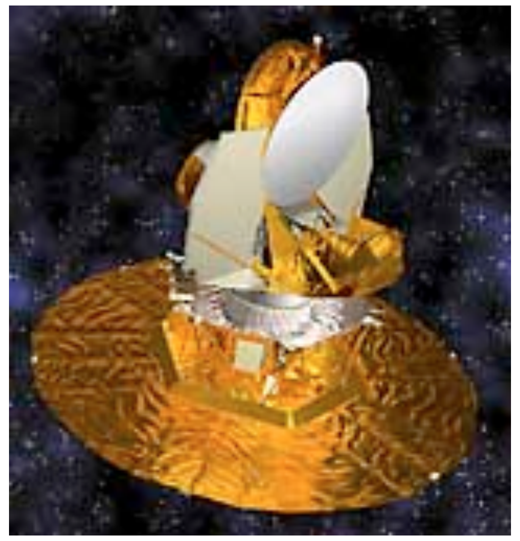


揺らぎの解析：
２点相関関数

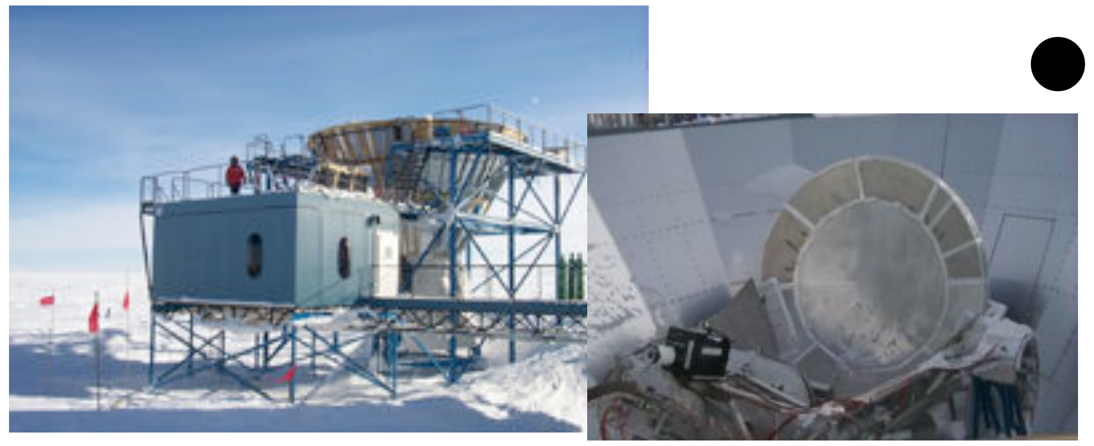
- $C(\theta)=(1/4\pi)\sum(2l+1)\mathbf{C_l}P_l(\cos\theta)$
- “パワースペクトル” C_l
  - $l \sim 180$度 / θ

WMAP 7-year Power Spectrum

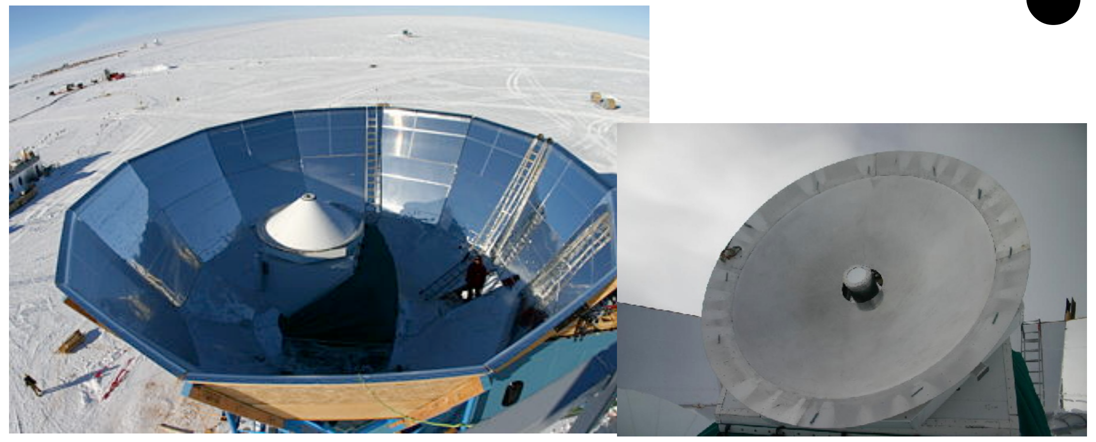




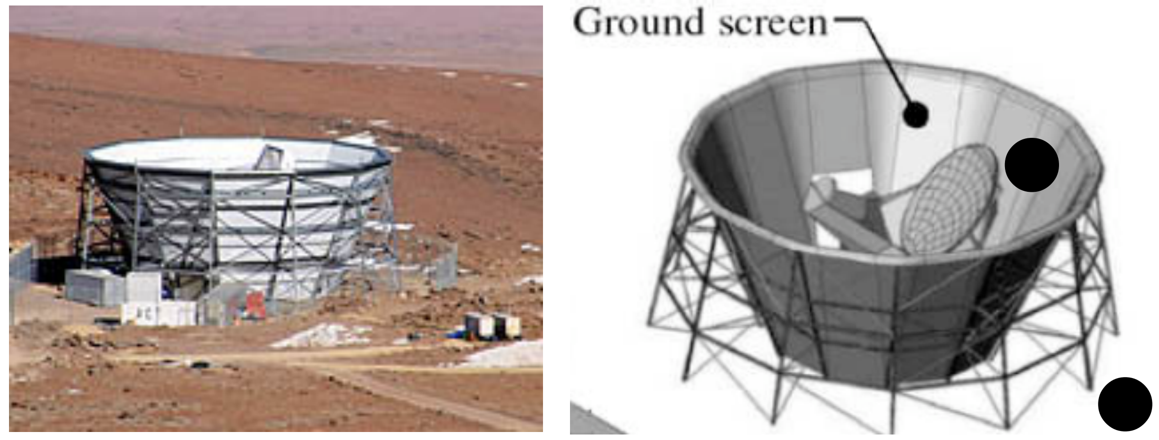
- **WMAP** (2001–2010), *Space, D=1.5m, ν=23, 33, 41, 61, 94GHz*
  - l=2–1000; Temp &Pol, 10 detectors (*HEMT*)



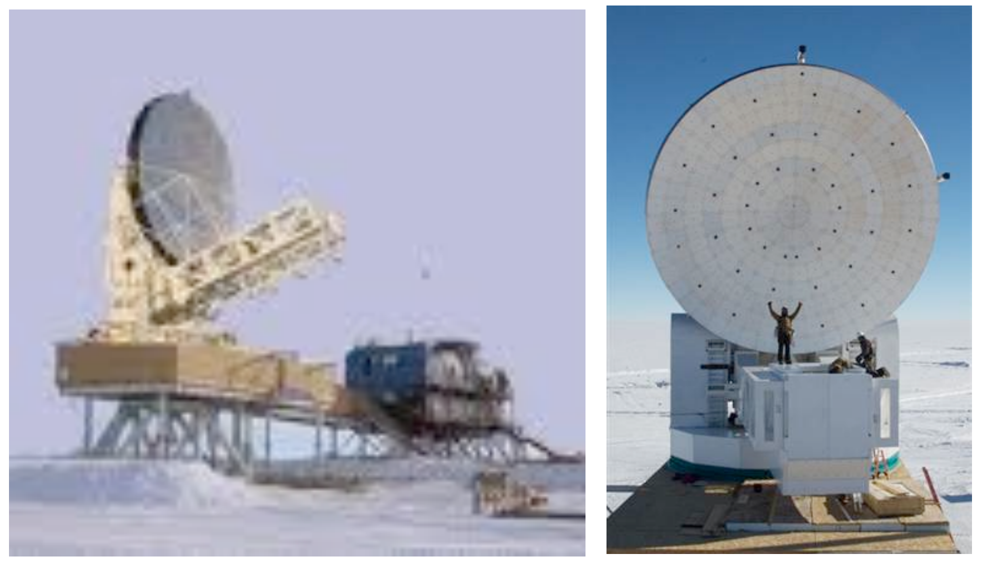
- **ACBAR** (2001–2005), *South Pole, D=2.1m, ν=150GHz*
  - l=470–2600; Temp only, 16 detectors (*bolo*)



- **QUaD** (2005–2007), *South Pole, D=2.6m, ν=100, 150GHz*
  - l=200–3000; Temp & Pol, 31 detectors (*bolo*)

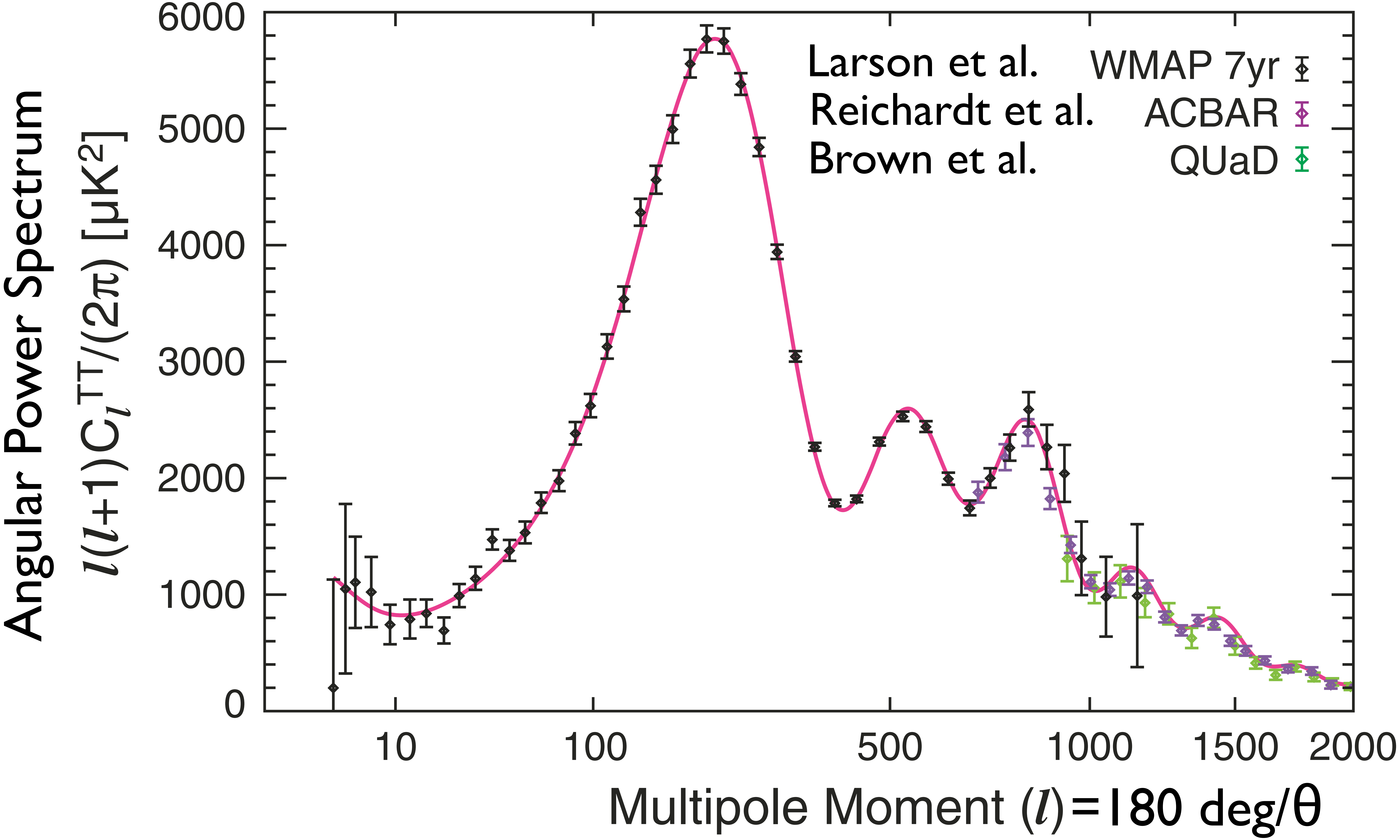


- **ACT** (2007–), *Chile, D=6m, ν=148, 218, 277GHz*
  - l=200–8000; Temp only, 3072 detectors (*bolo*)

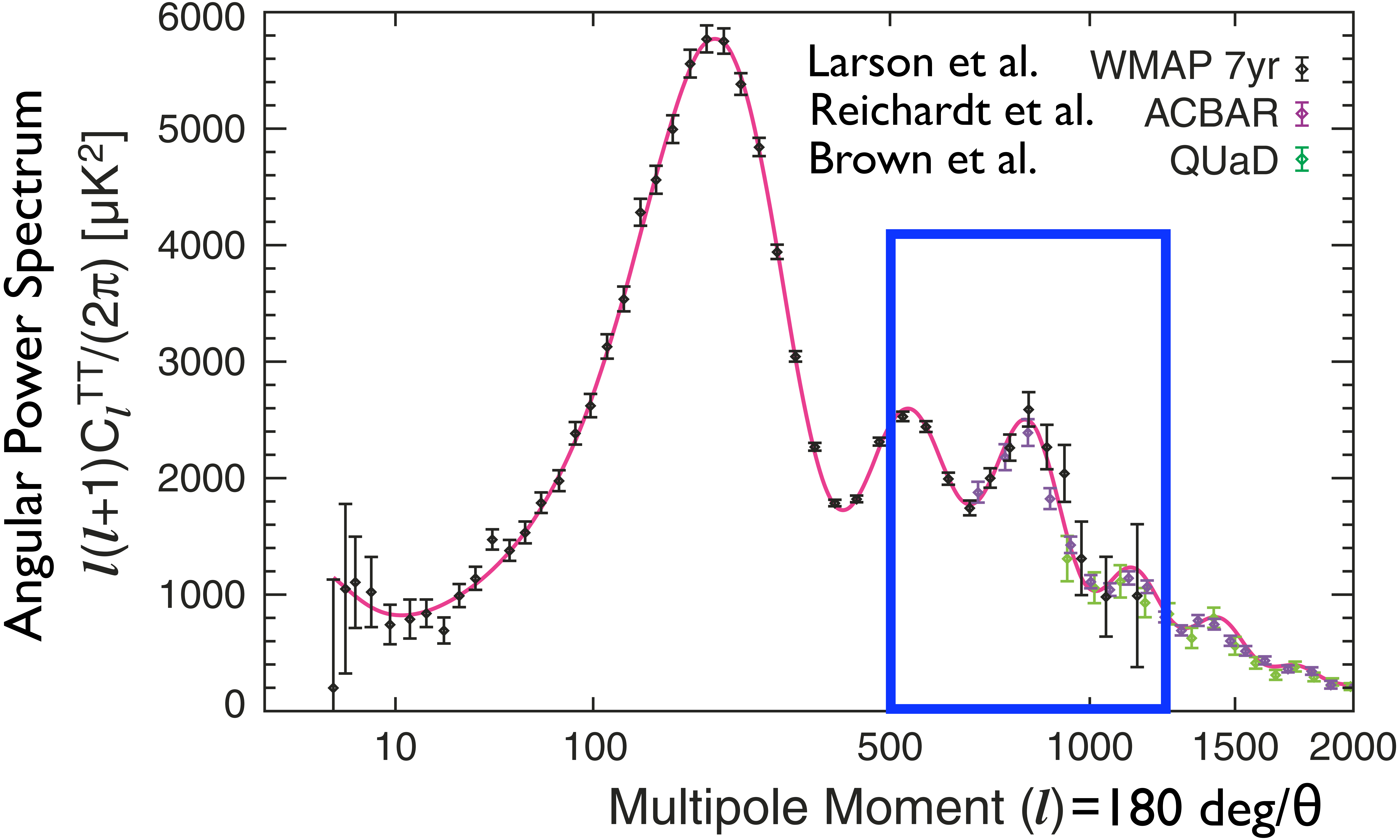


- **SPT** (2007–), *South Pole, D=10m, ν=95, 150, 220GHz*
  - l=2000–9000; Temp only, 960 detectors (*bolo*)

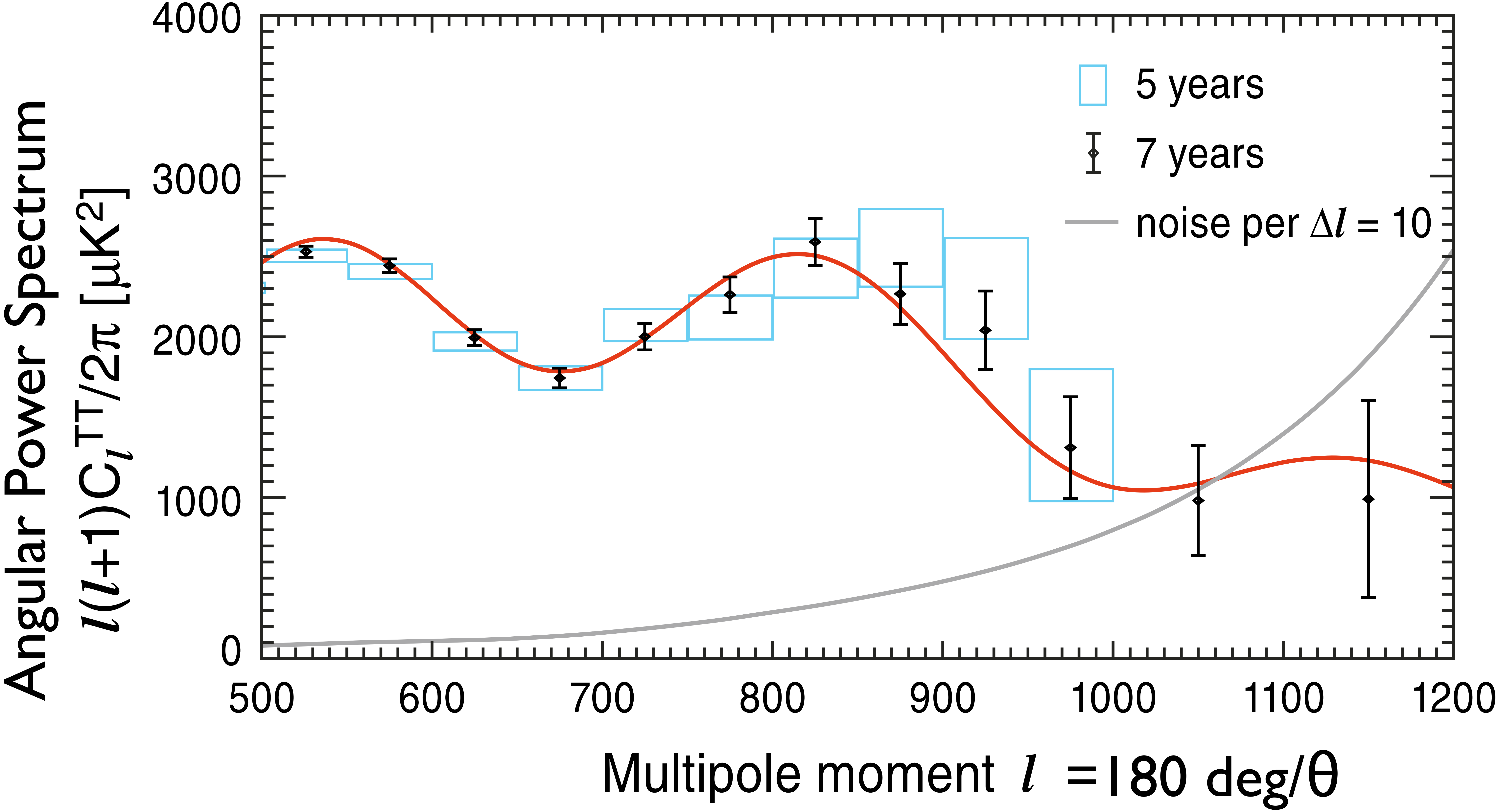
WMAP7 + ACBAR + QUaD



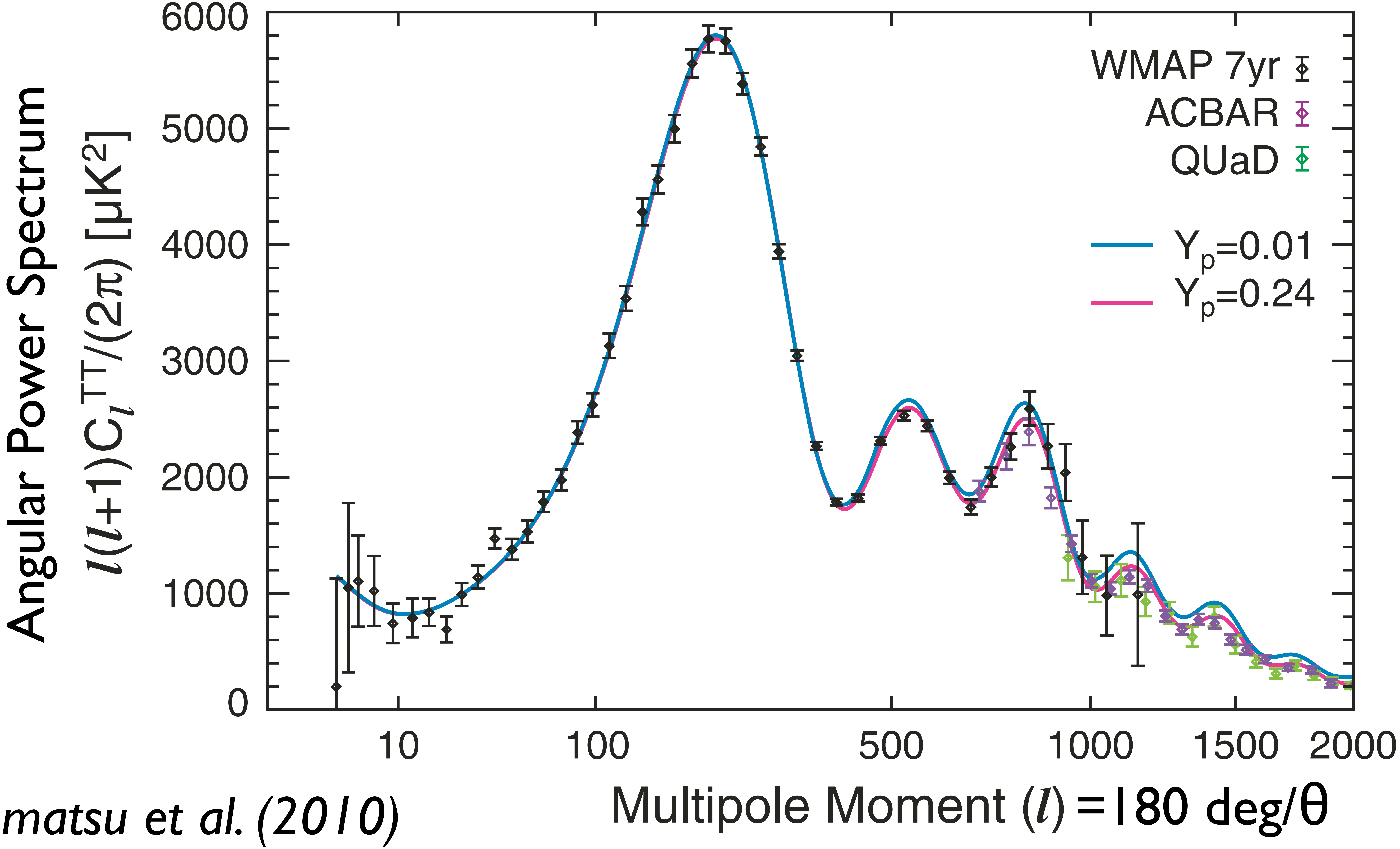
WMAP7 + ACBAR + QUaD



High-l Temperature C_l: Improvement from 5-year



Detection of Primordial Helium

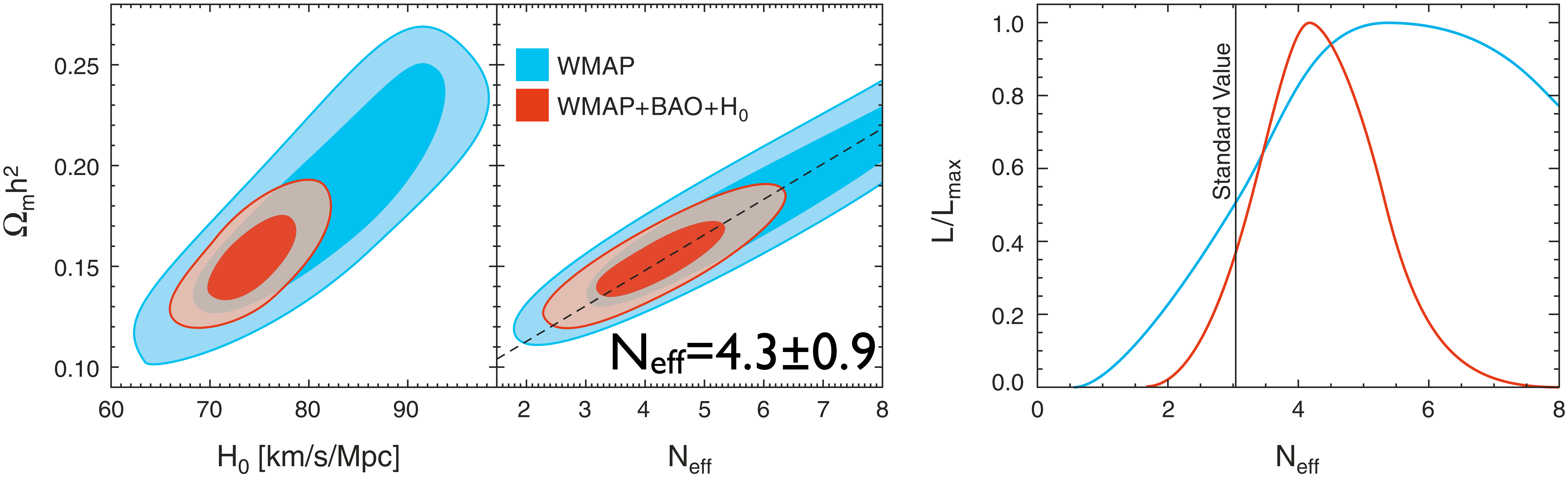


Komatsu et al. (2010)

Effect of helium on C_l^{TT}

- We measure the baryon number density, n_b, from the 1st-to-2nd peak ratio.
- As helium recombined at z~1800, there were fewer electrons at the decoupling epoch (z=1090): $n_e=(1-Y_p)n_b$.
- **More helium** = Fewer electrons = Longer photon mean free path $1/(\sigma_T n_e)$ = **Enhanced damping**
- **$Y_p = 0.33 \pm 0.08$** (68%CL)
  - Consistent with the standard value from the Big Bang nucleosynthesis theory: $Y_P=0.24$.
- Planck should be able to reduce the error bar to **0.01**.

Another "3rd peak science": Number of Relativistic Species



from external data

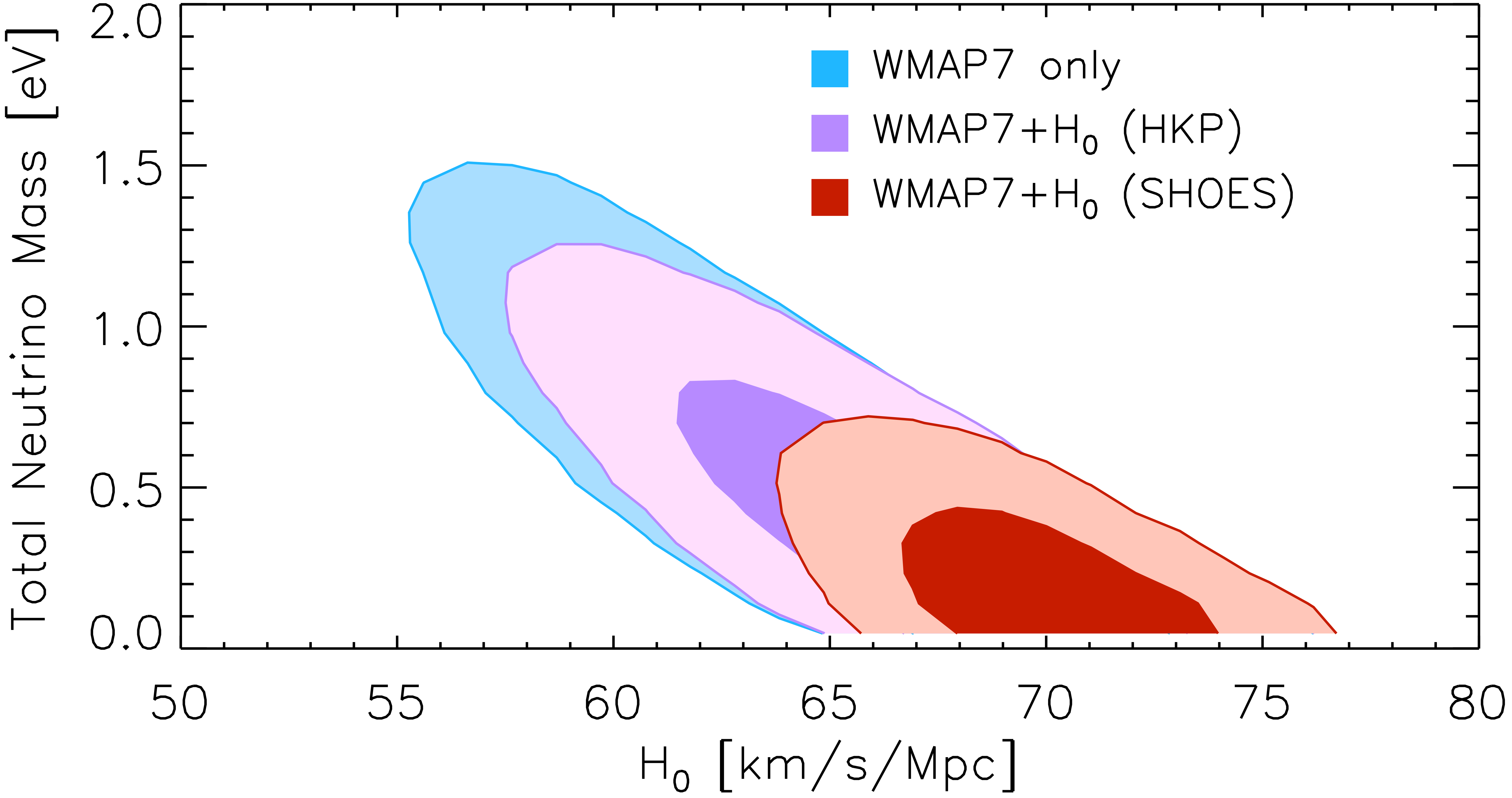
$$N_{\rm eff} = 3.04 + 7.44\left(\frac{\Omega_m h^2}{0.1308}\frac{3139}{1+z_{\rm eq}} - 1\right)$$

from 3rd peak

Komatsu et al. (2010)

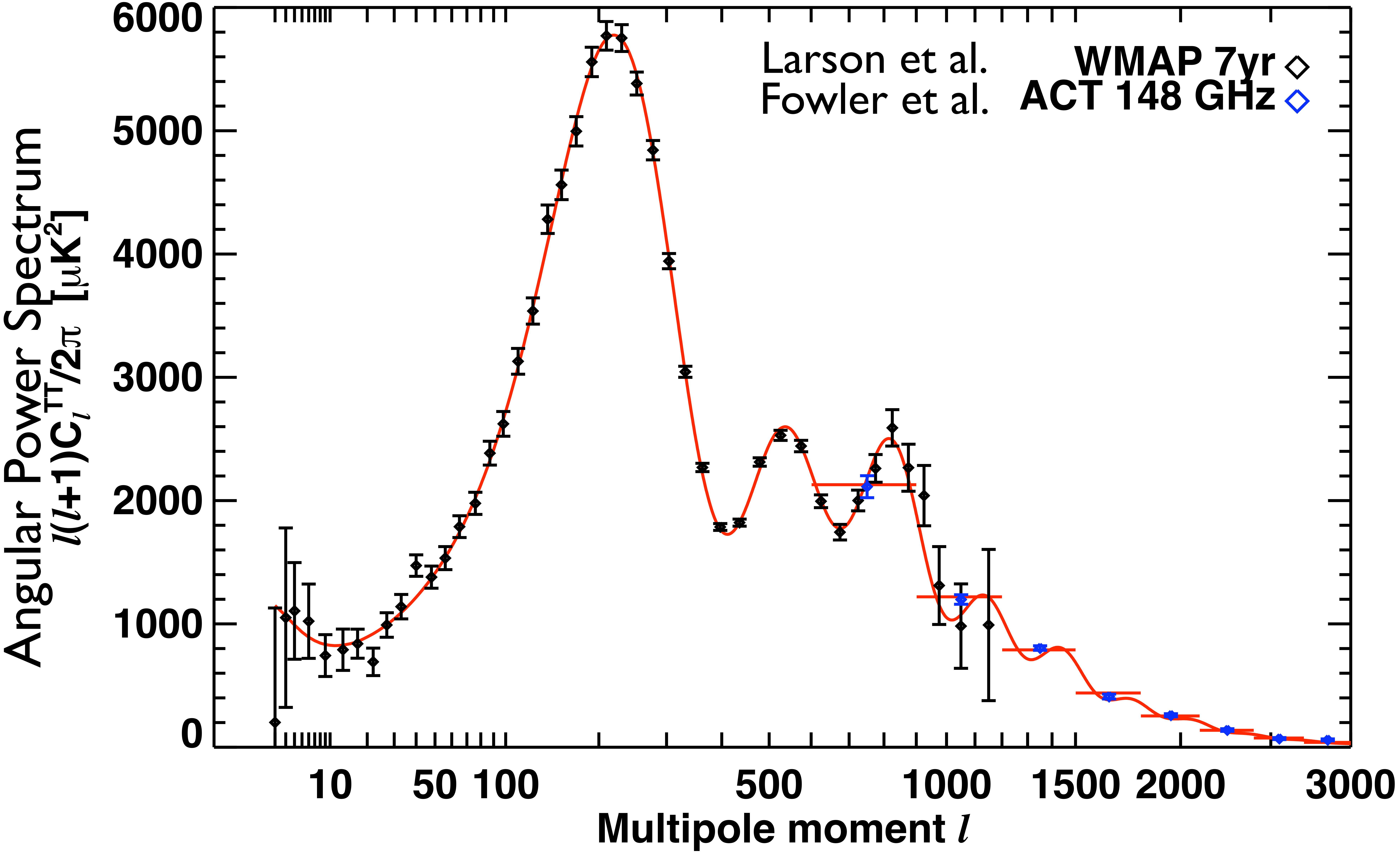
Komatsu et al. (2010)

And, the mass of neutrinos

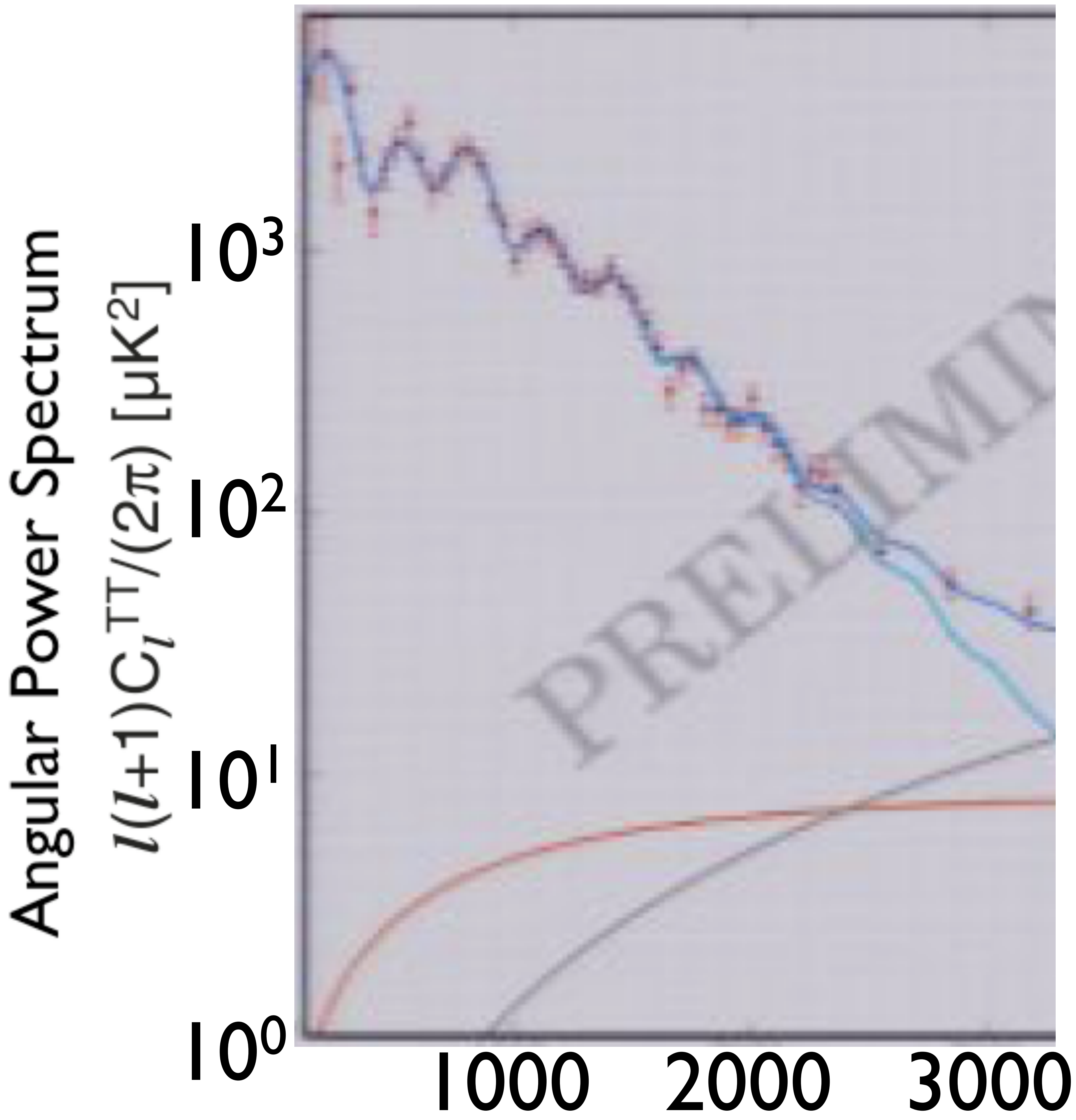


- WMAP data combined with the local measurement of the expansion rate (H_0), we get $\sum m_\nu < 0.6$ eV (95%CL)

WMAP7 + ACT


Larson et al.
Fowler et al.
WMAP 7yr ◇
ACT 148 GHz ◇
Angular Power Spectrum
$l(l+1)C_l^{TT}/2\pi$ [μK^2]
6000
5000
4000
3000
2000
1000
0
10
50
100
500
1000
1500
2000
3000
Multipole moment l

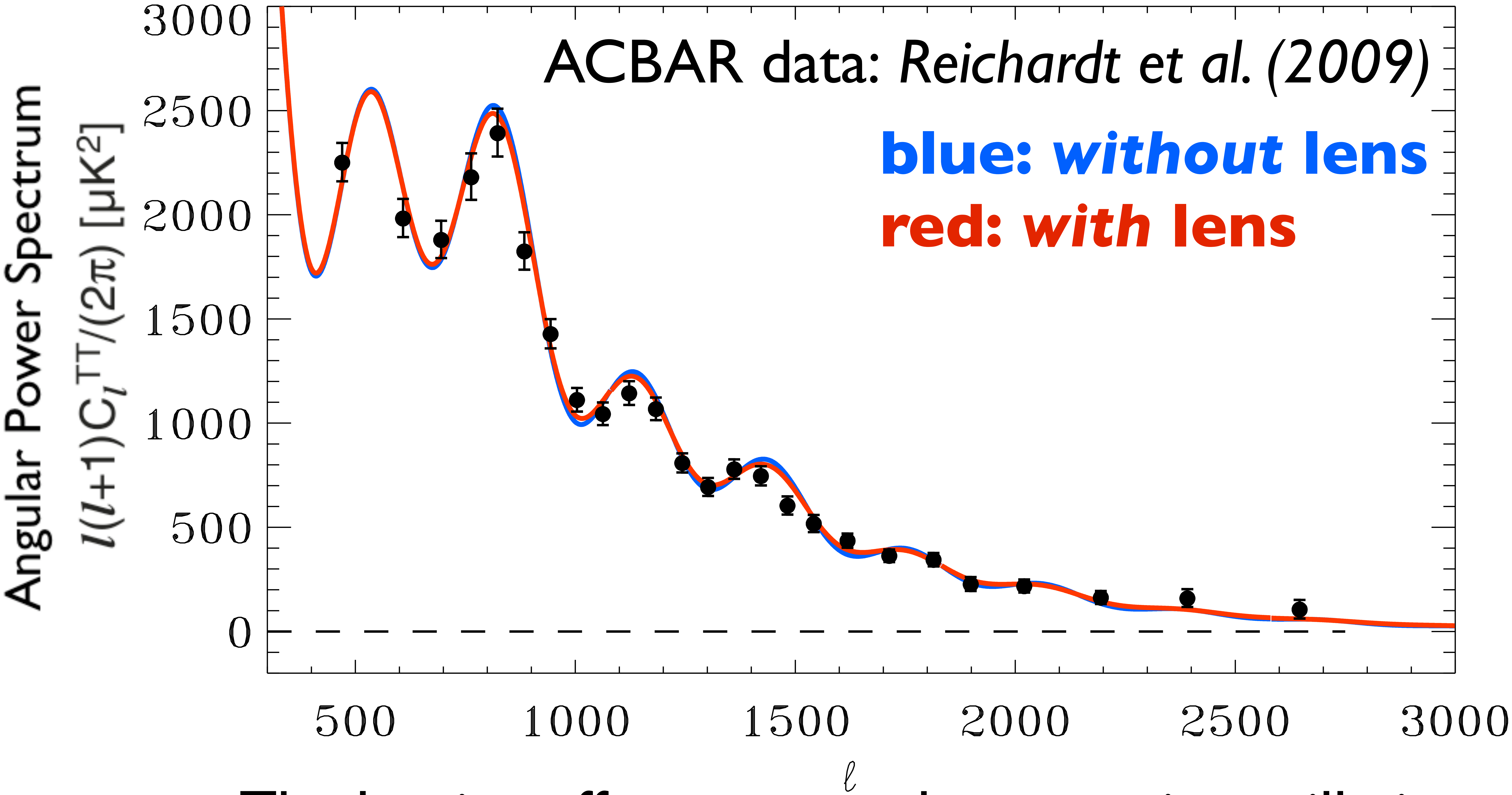
ACT: Sneak Peek



From Das et al. (2010) in preparation

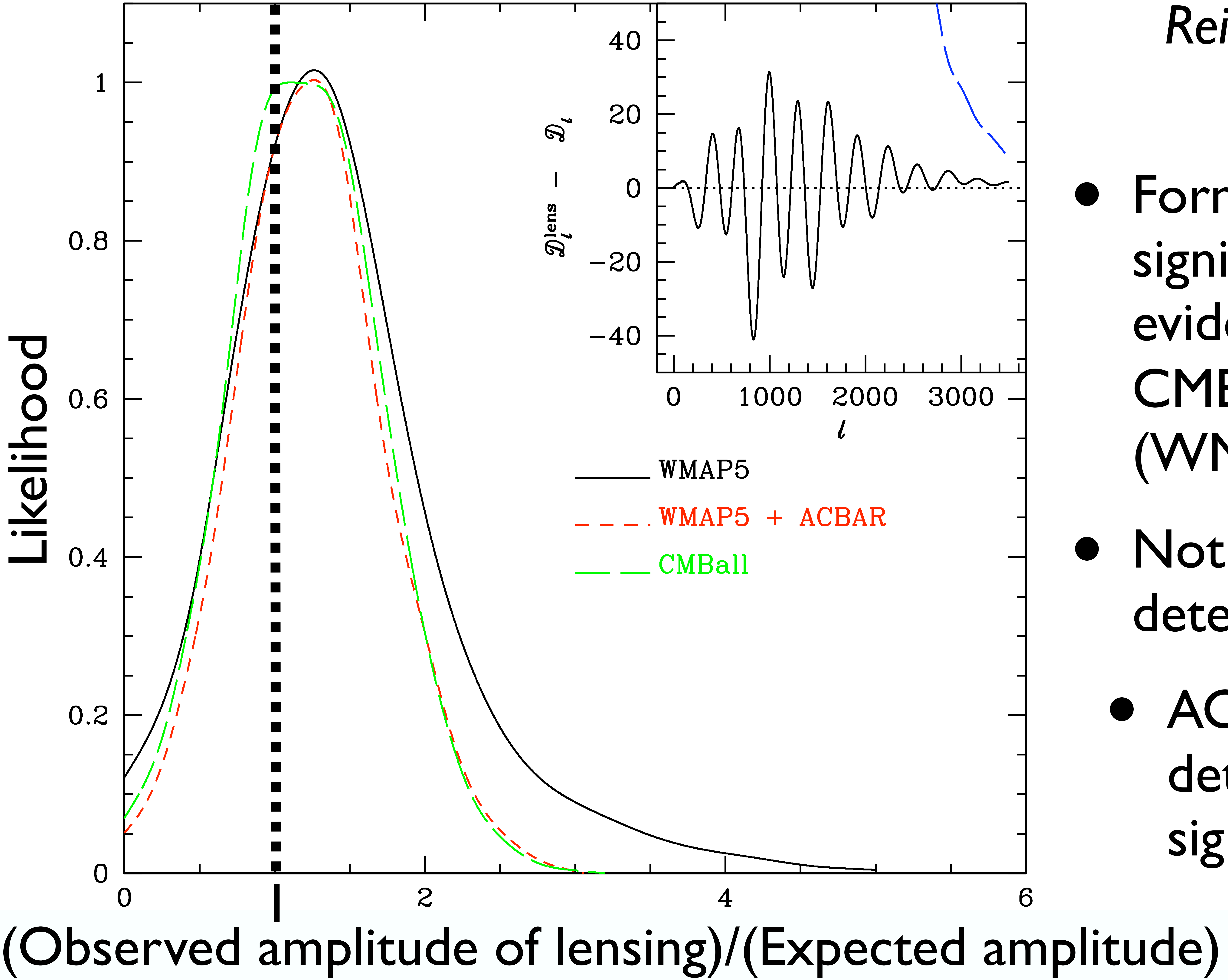
- From Szanne Staggs' talk at Perimeter (publicly available)

Has the CMB lensing been detected by ACBAR?



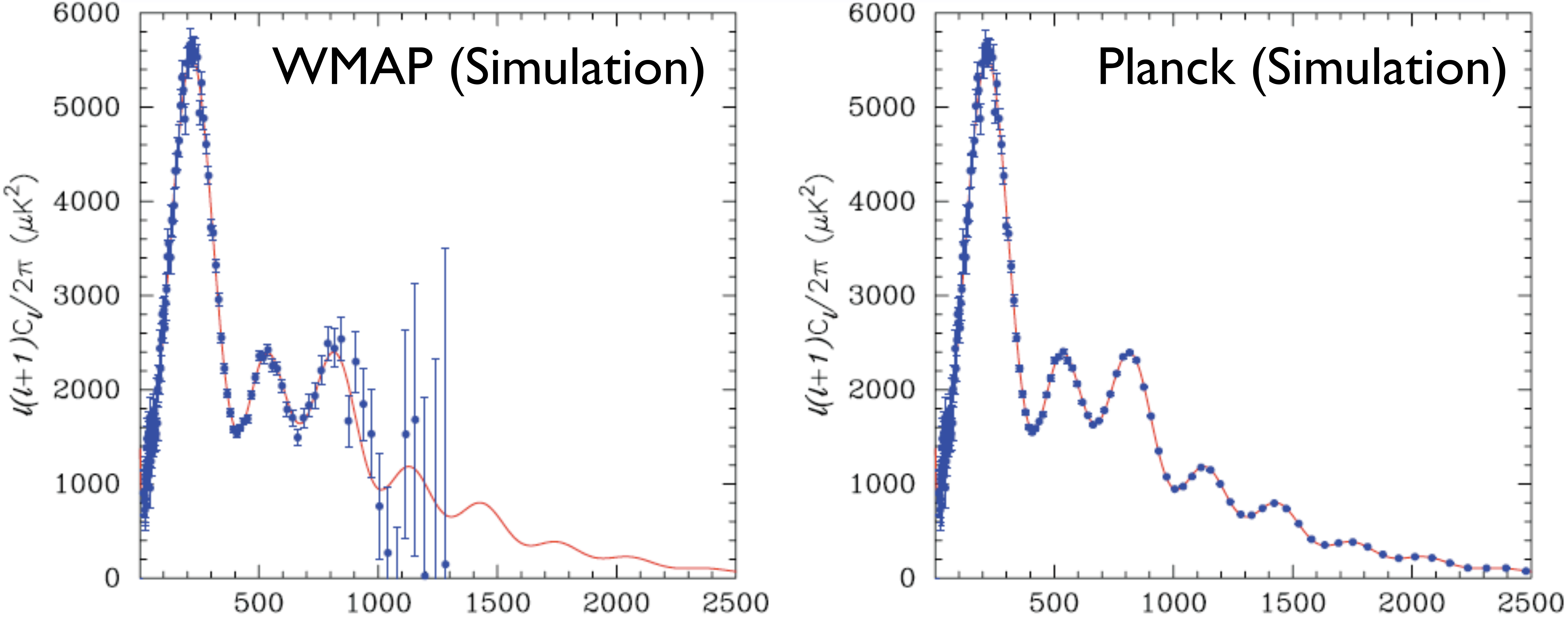
- The lensing effect smears the acoustic oscillation.

Reichardt et al. (2009)



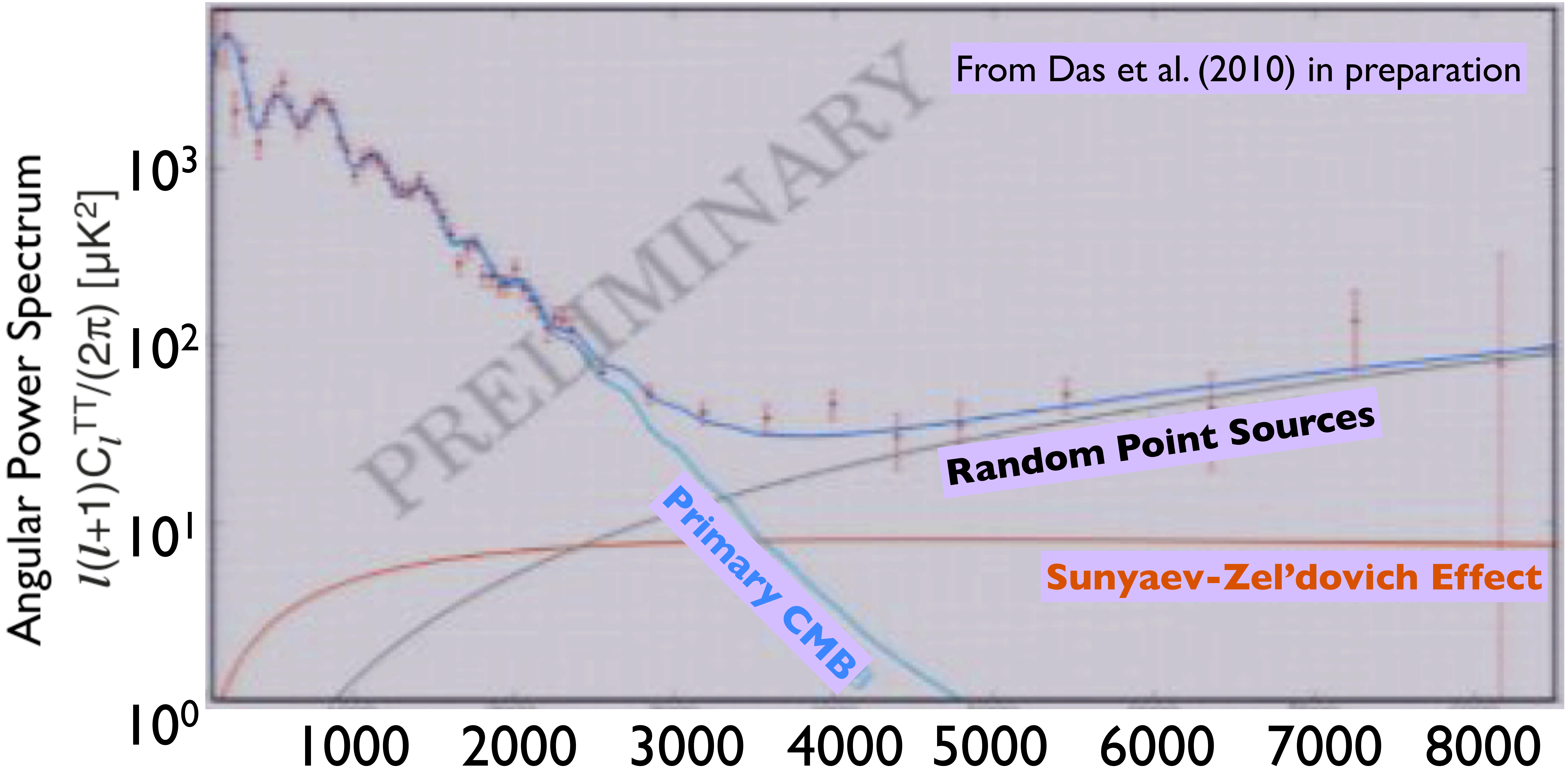
- Formal statistical significance of evidence for the CMB lensing is **2.3σ** (WMAP5+ACBAR)
- Not enough for detection.
  - ACT will probably detect it with high significance!

Planck: Expected $C_l^{\text{Temperature}}$



- WMAP: l~1000 => Planck: l~3000
- They will definitely detect lensing & helium, and perhaps Neff–3.

ACT: Sneak Peek



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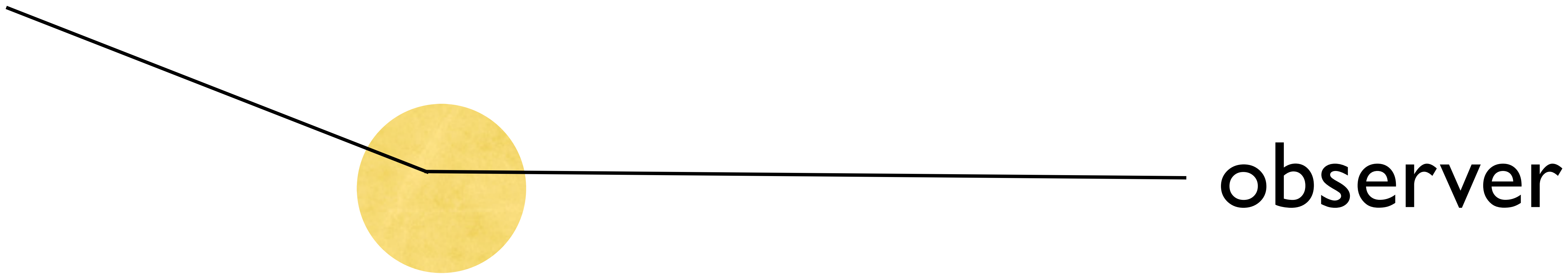
Zel’dovich & Sunyaev (1969); Sunyaev & Zel’dovich (1972)

Sunyaev–Zel’dovich Effect



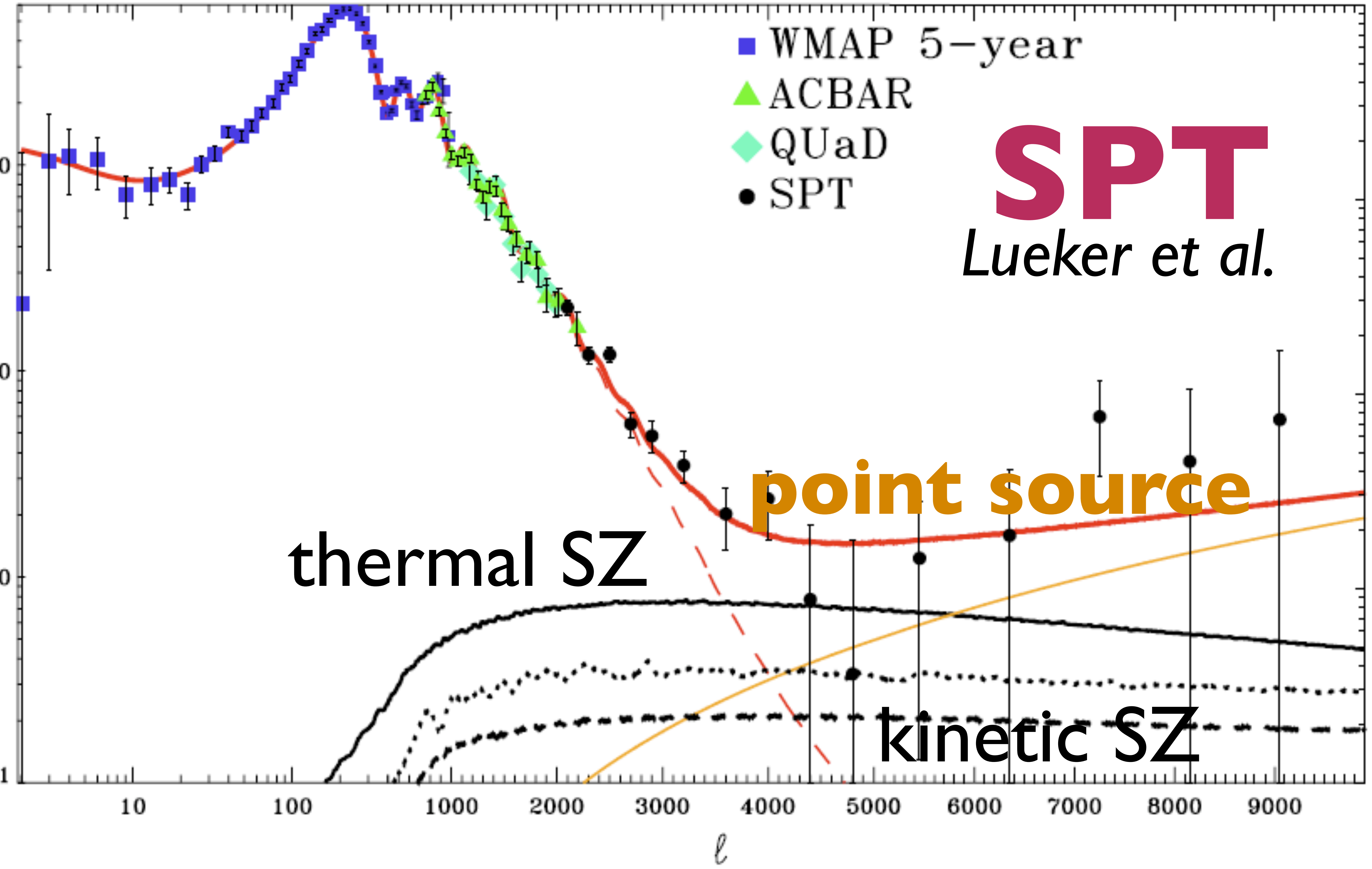
Hot gas with the
electron temperature of $T_e >> T_{cmb}$

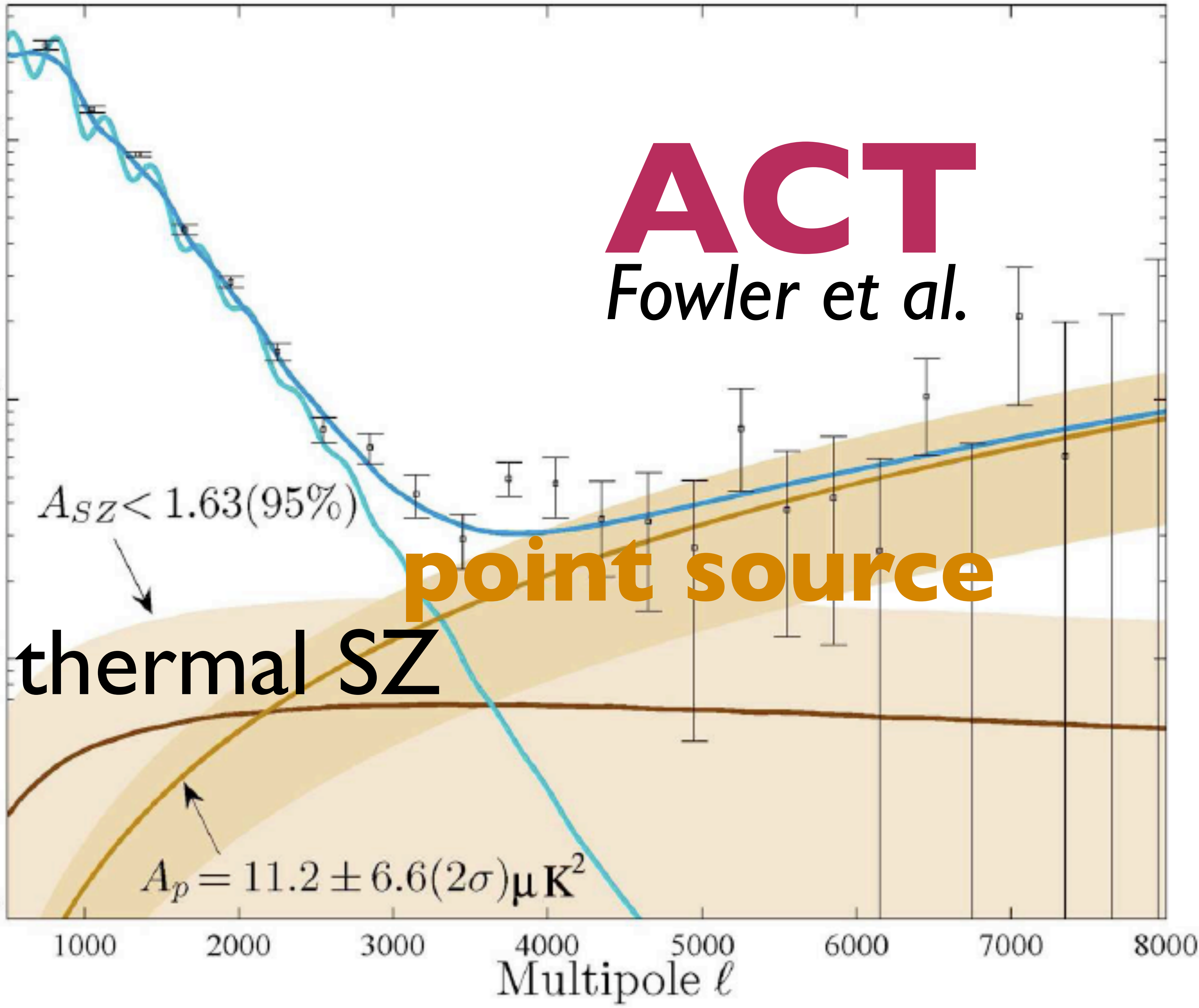
- $\Delta T/T_{cmb} = g_\nu \mathbf{y}$

$$\mathbf{y} = (\text{optical depth of gas})\ k_BT_e/(m_ec^2)$$
$$= [\sigma_T/(m_ec^2)] \int n_ek_BT_e\, d(\text{los})$$
$$= [\sigma_T/(m_ec^2)] \int (\textbf{electron pressure})\, d(\text{los})$$

g_ν=–2 (ν=0); –1.91, –1.81 and –1.56 at ν=41, 61 and 94 GHz

“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.

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

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

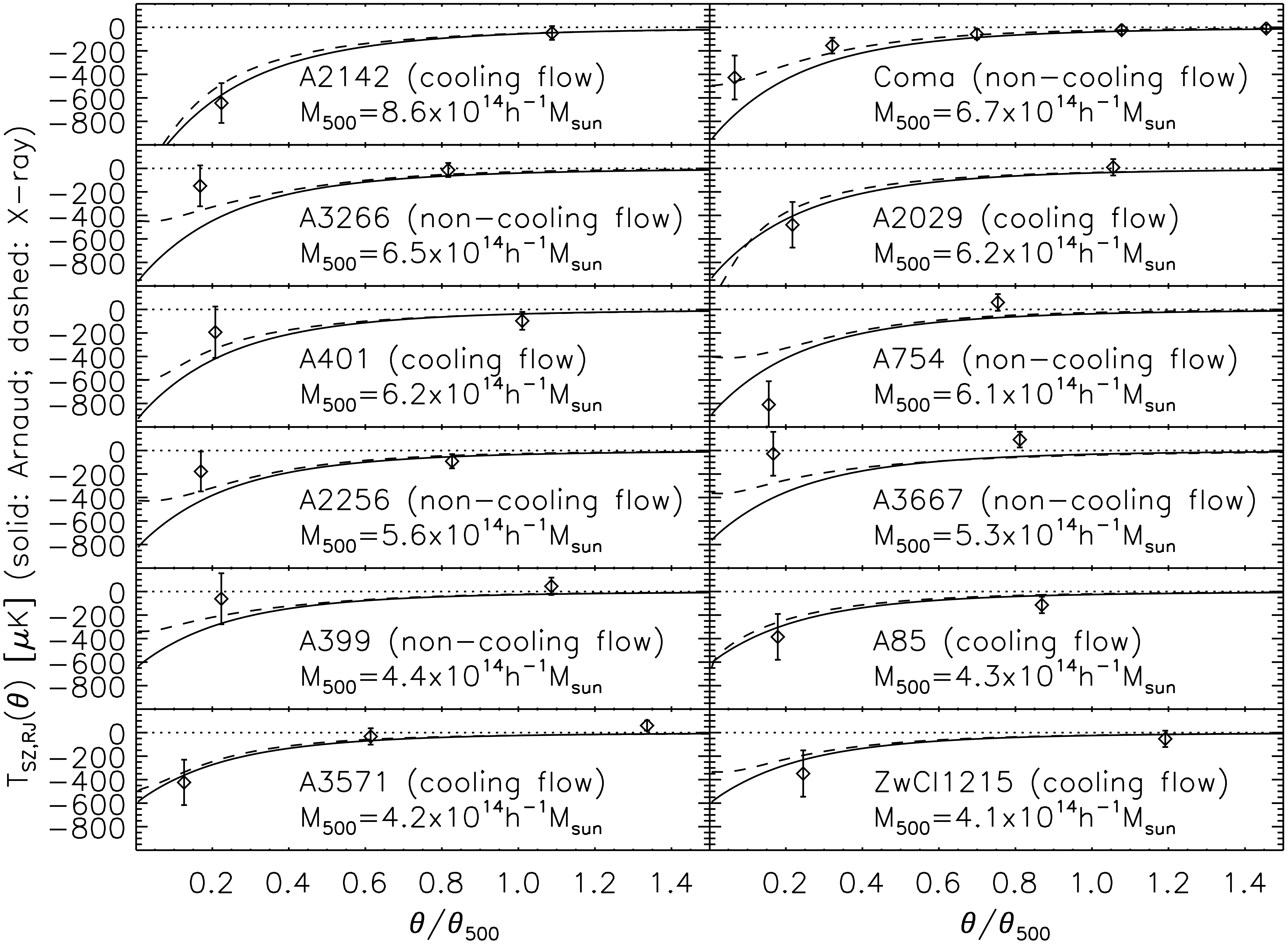
Lower A_{SZ}: **Two** Possibilities

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

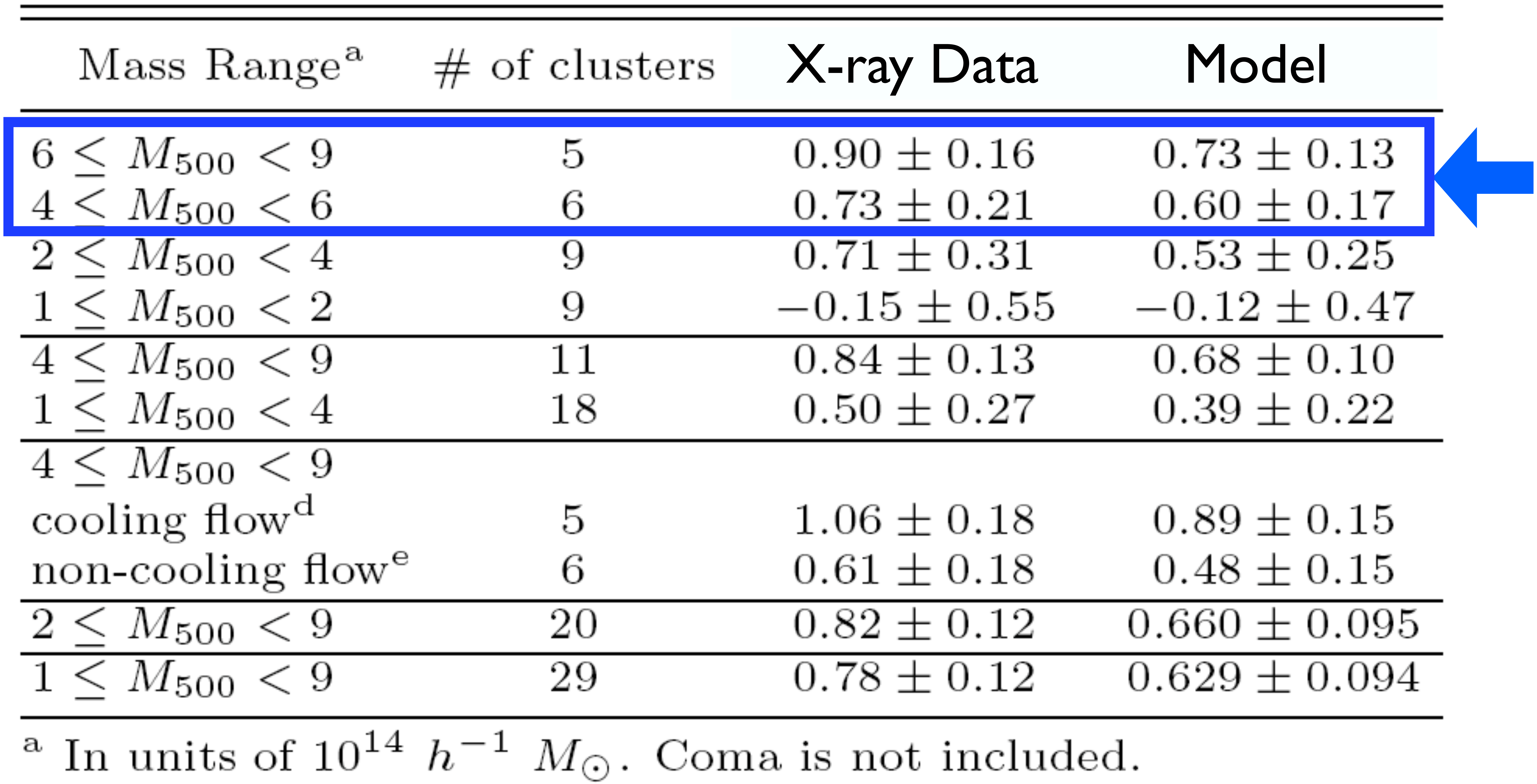
- **[2] Gas pressure per cluster is less than expected.**
  - The power spectrum is [gas pressure]^2.
  - A_{SZ}=0.4–0.6 means that the gas pressure is less than expected by ~0.6–0.7.
- We can test this by looking at the SZ effect of the *individual* clusters!

WMAP 7-year Measurements!

(Komatsu et al. 2010)



Low-SZ is seen in the WMAP



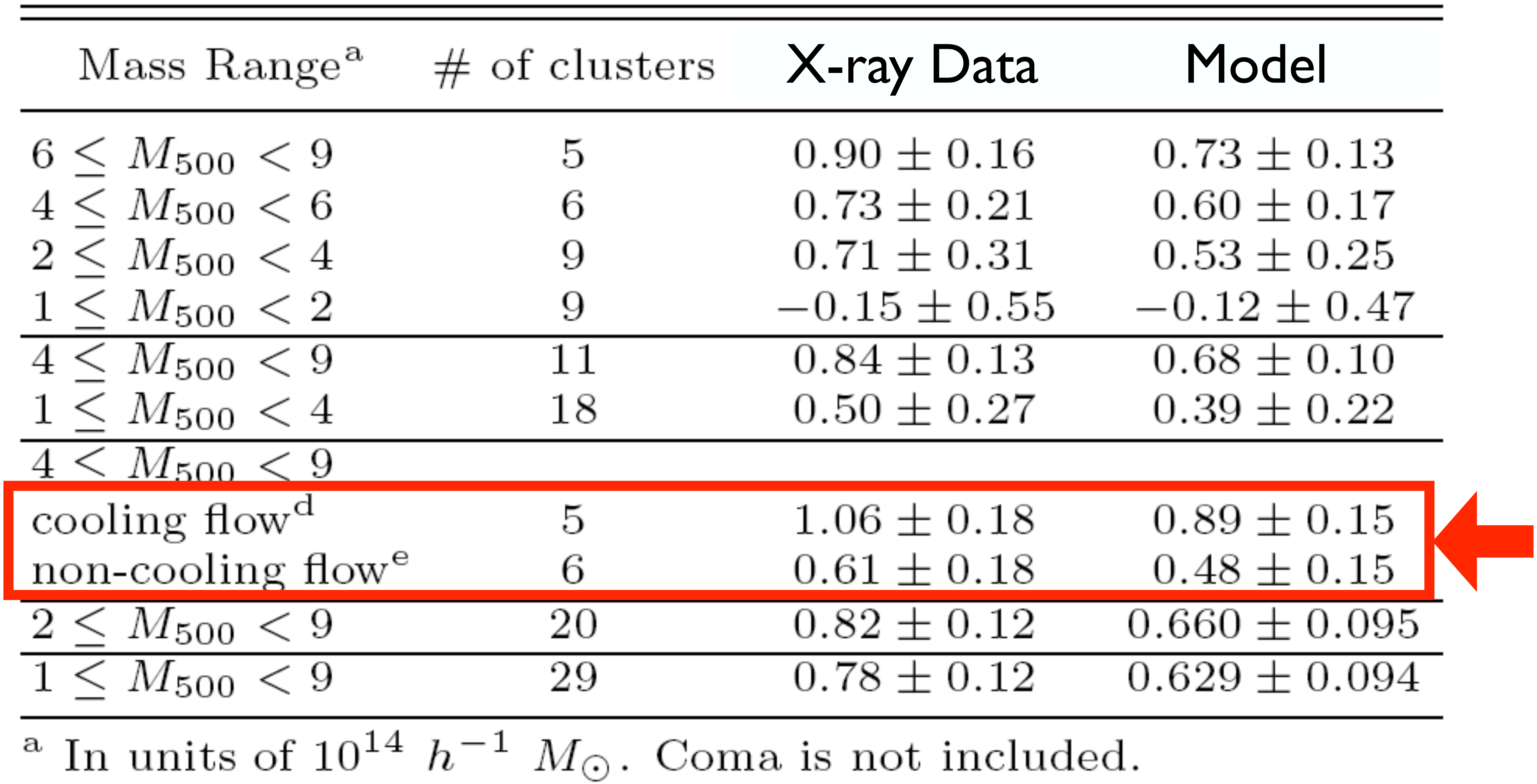
Mass Range[a]	# of clusters	X-ray Data	Model
$6 \leq M_{500} < 9$	5	0.90 ± 0.16	0.73 ± 0.13
$4 \leq M_{500} < 6$	6	0.73 ± 0.21	0.60 ± 0.17
$2 \leq M_{500} < 4$	9	0.71 ± 0.31	0.53 ± 0.25
$1 \leq M_{500} < 2$	9	-0.15 ± 0.55	-0.12 ± 0.47
$4 \leq M_{500} < 9$	11	0.84 ± 0.13	0.68 ± 0.10
$1 \leq M_{500} < 4$	18	0.50 ± 0.27	0.39 ± 0.22
$4 \leq M_{500} < 9$			
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
$2 \leq M_{500} < 9$	20	0.82 ± 0.12	0.660 ± 0.095
$1 \leq M_{500} < 9$	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?



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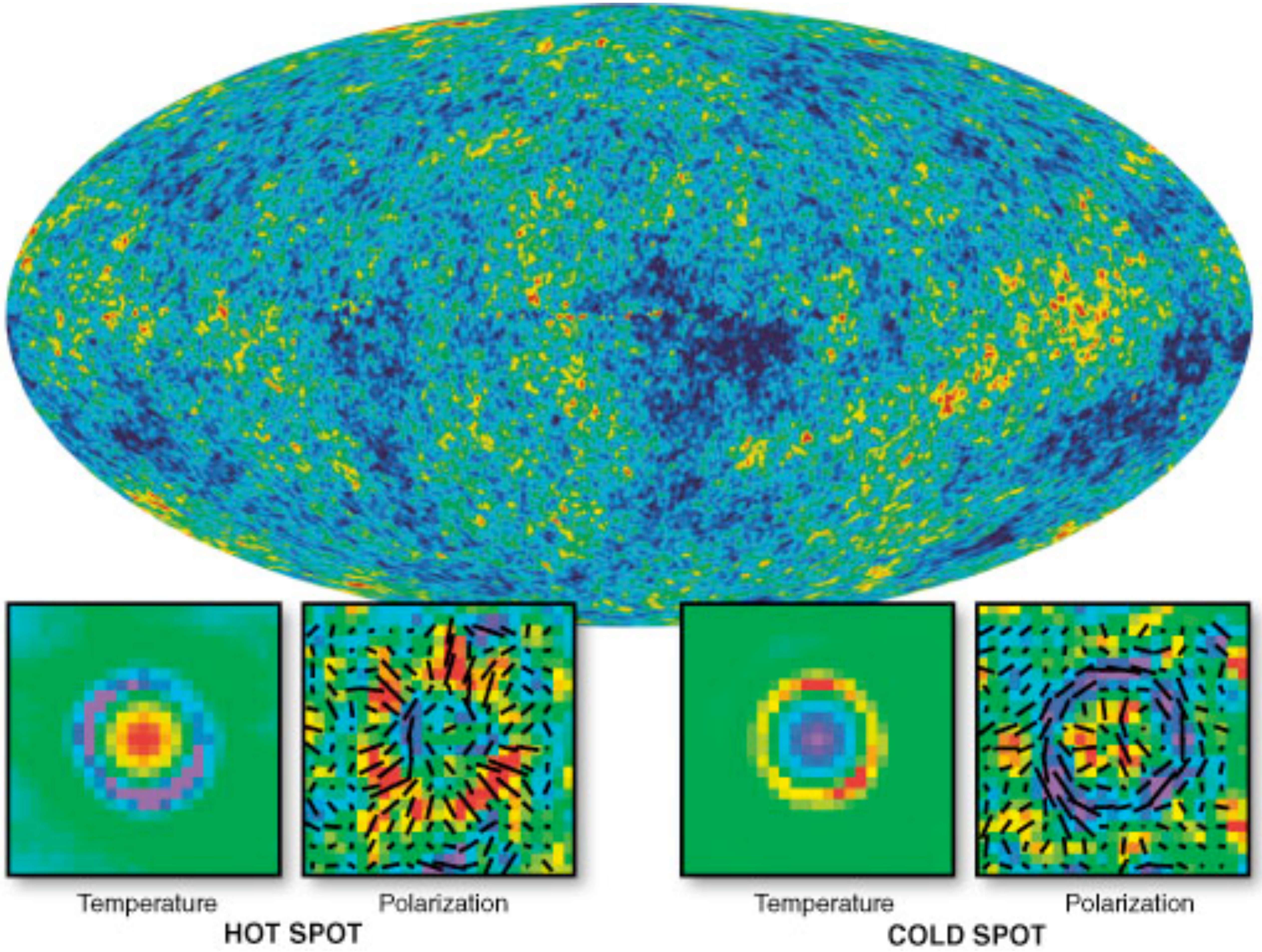
Recap: Temperature C_l

- 6 acoustic peaks (up to l=2000) have been measured.
  - Baryon density, dark matter density, helium abundance, and N_{eff} have been constrained.
  - The primordial tilt: $n_s=0.967\pm0.013$ (68%CL)
- Detection of lensing is yet to be made. (ACT, Planck)
- Missing SZ: the next frontier?

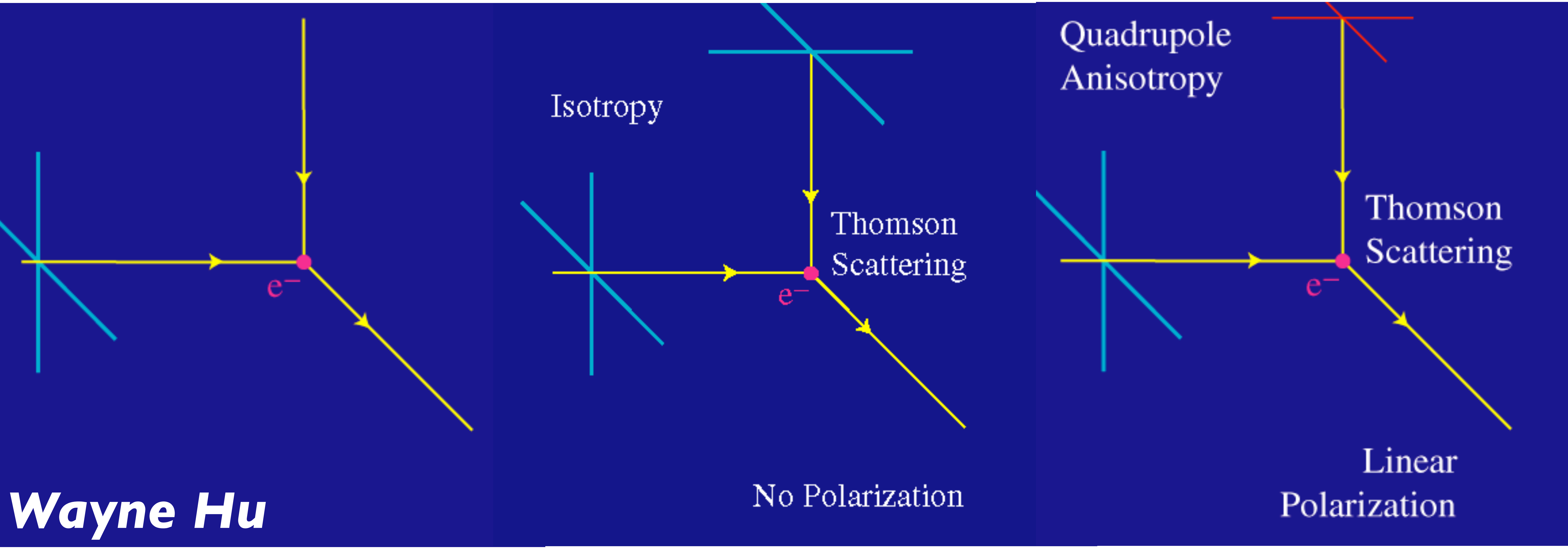
2. CMB Polarization

CMB Polarization



- *CMB is (very weakly) polarized!*

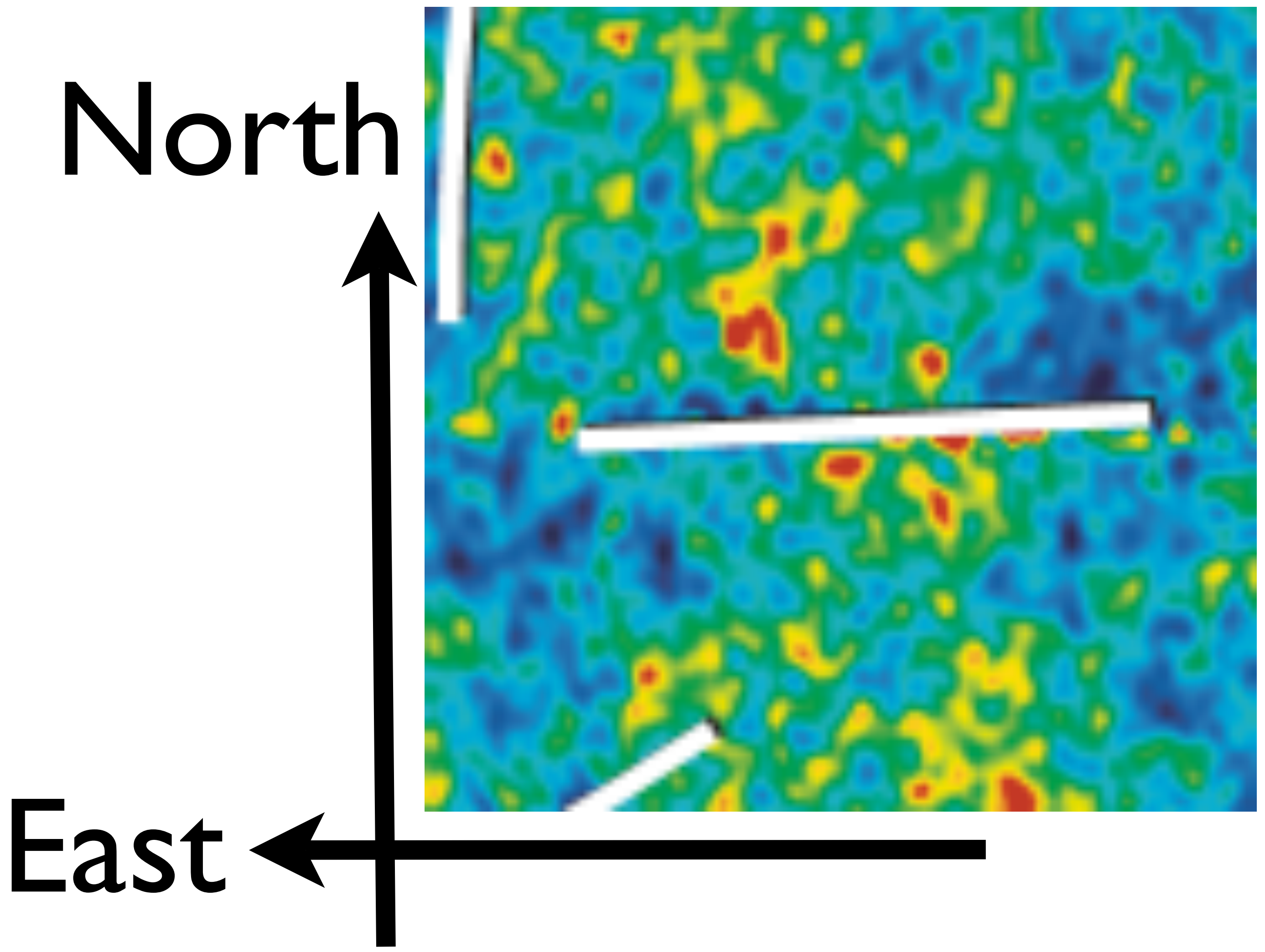
Physics of CMB Polarization

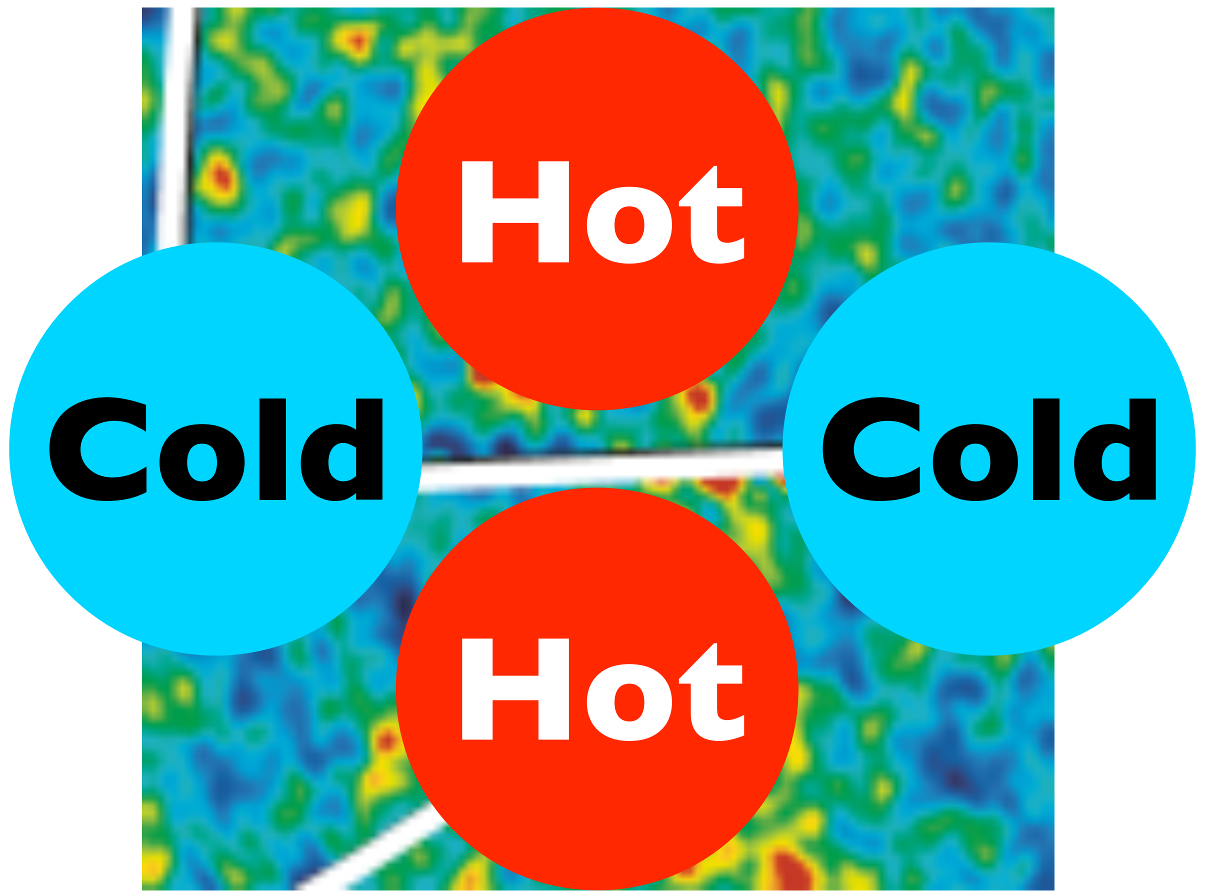


Wayne Hu

- CMB Polarization is created by a local temperature **quadrupole** anisotropy.

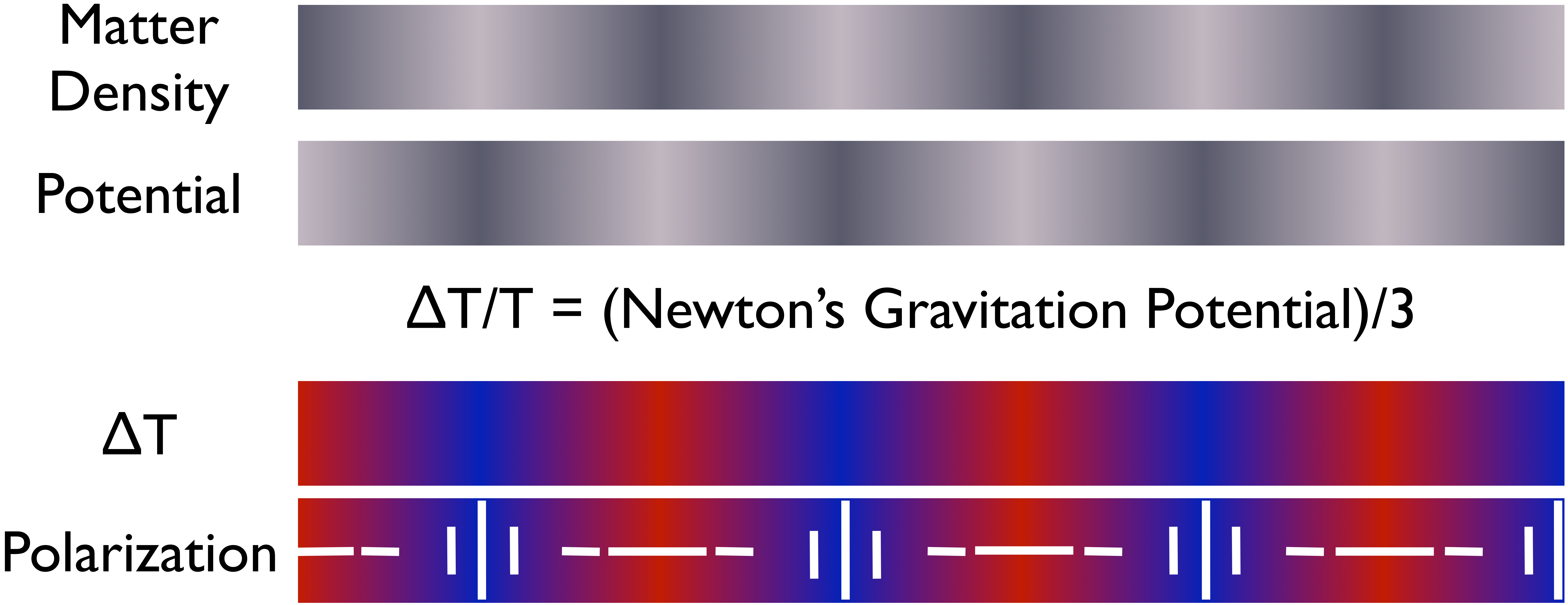
Principle





- **Polarization direction is parallel to “hot.”**

CMB Polarization on Large Angular Scales (>2 deg)

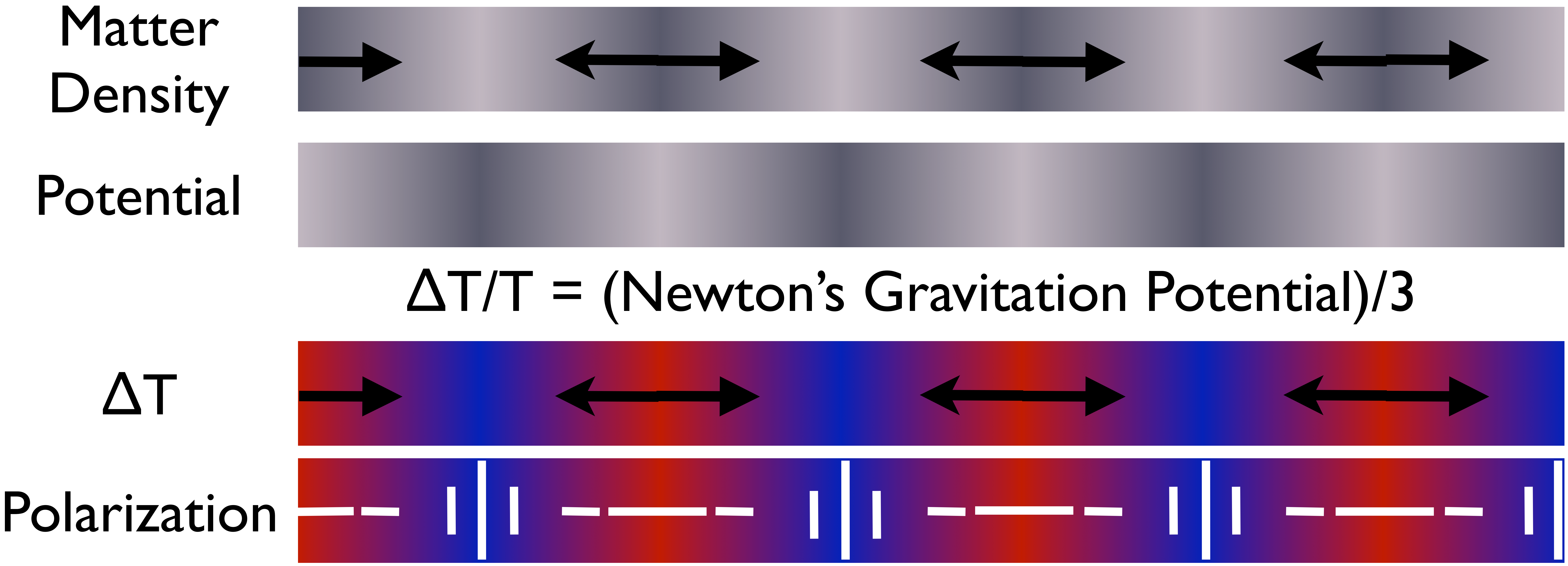


ΔT/T = (Newton's Gravitation Potential)/3

- How does the photon-baryon plasma move?

CMB Polarization Tells Us How Plasma Moves at z=1090

Zaldarriaga & Harari (1995)



Matter Density

Potential

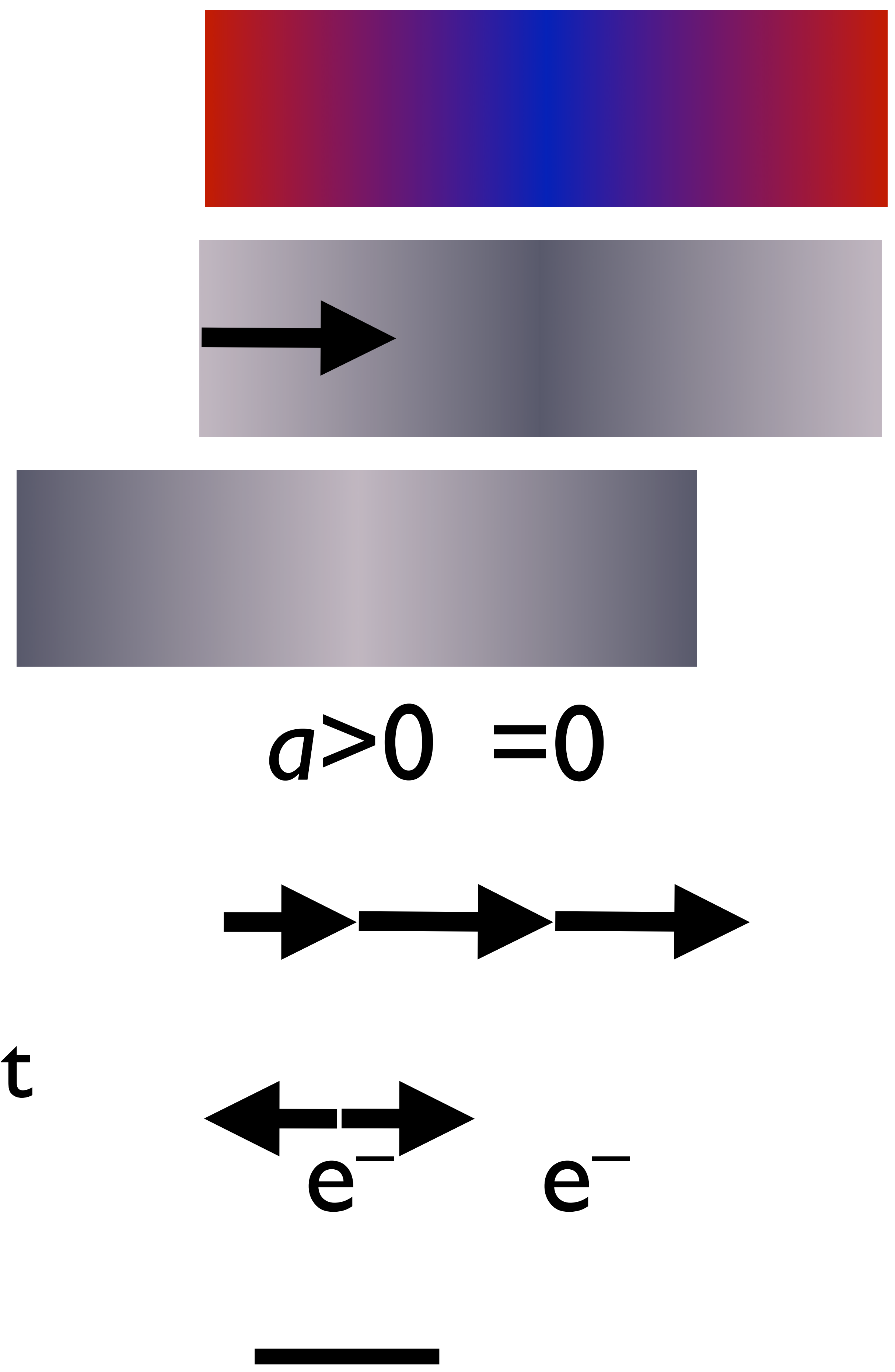
$\Delta T/T$ = (Newton's Gravitation Potential)/3

ΔT

Polarization

- Plasma **falling into** the gravitational potential well = **Radial** polarization pattern

Quadrupole From Velocity Gradient (Large Scale)



ΔT

Sachs-Wolfe: $\Delta T/T=\Phi/3$

Potential Φ

Stuff flowing *in*

Acceleration

$a=-\partial\Phi$

$a>0$ $=0$

Velocity

Velocity gradient

Velocity in the rest frame of electron

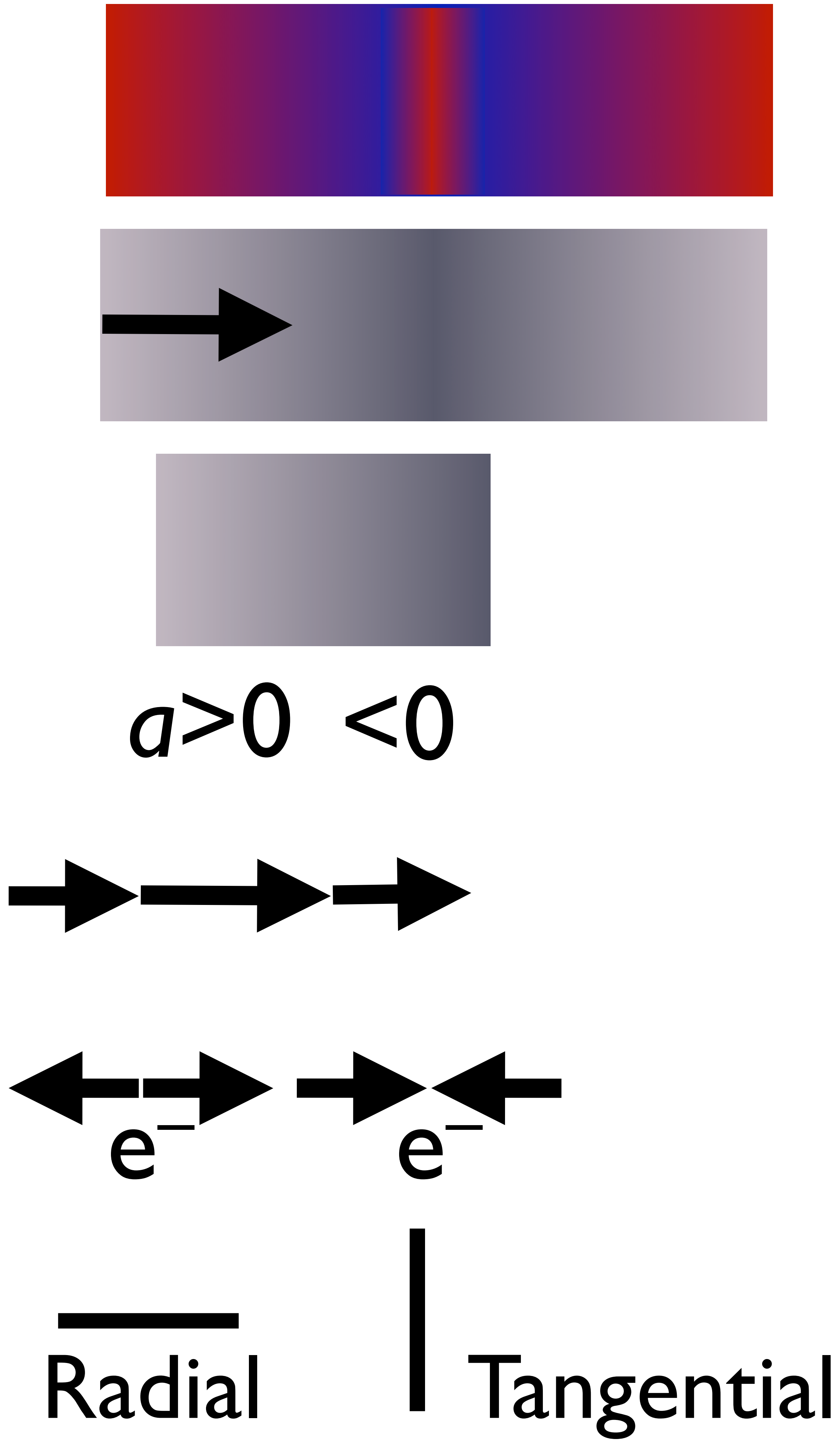
e^- e^-

The left electron sees colder photons along the plane wave

Polarization

Radial None

Quadrupole From Velocity Gradient (Small Scale)



ΔT

Compression increases temperature

Potential Φ

Stuff flowing *in*

Acceleration $a = -\partial\Phi - \partial P$

Pressure gradient slows down the flow

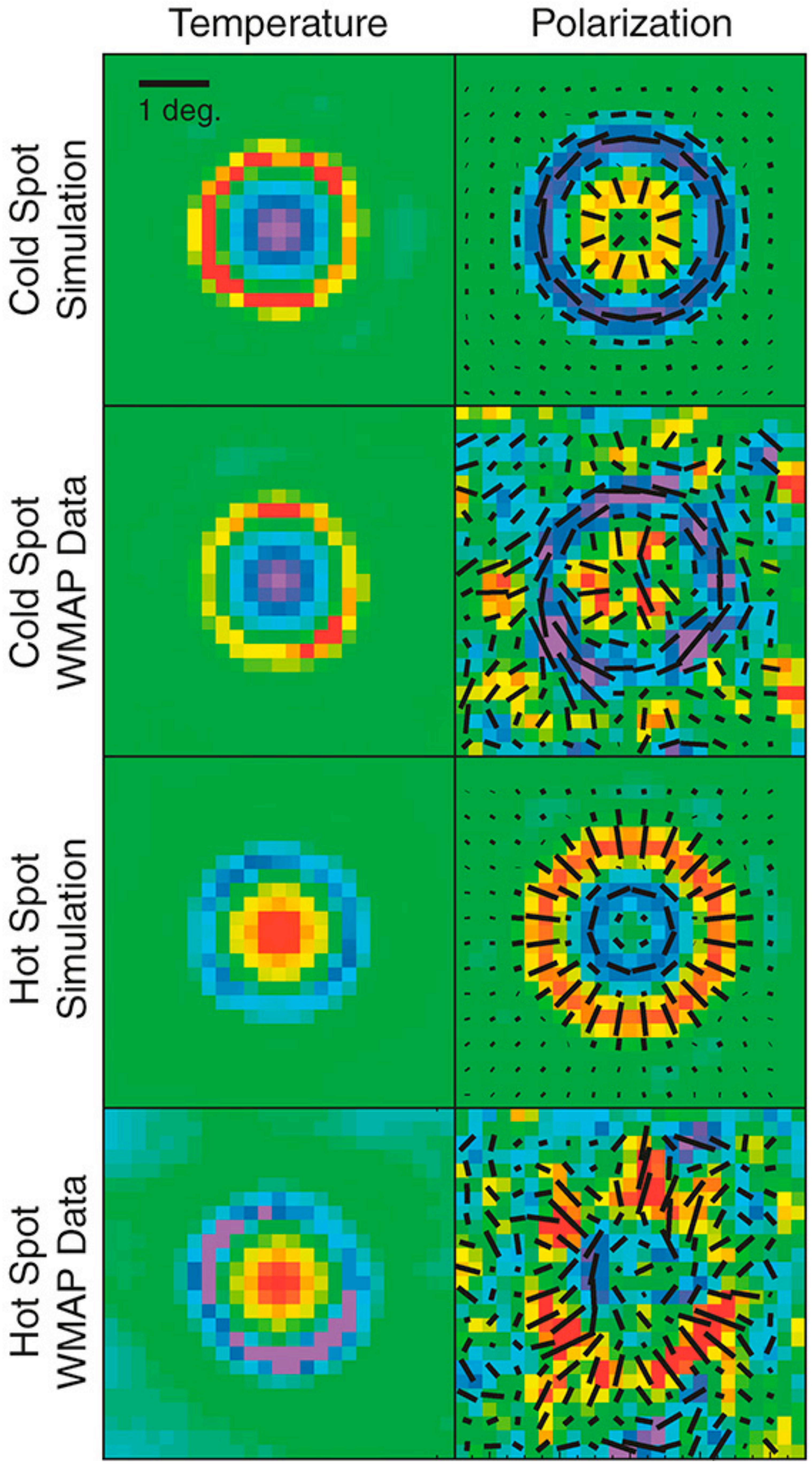
Velocity

Velocity gradient

Velocity in the rest frame of electron

Polarization

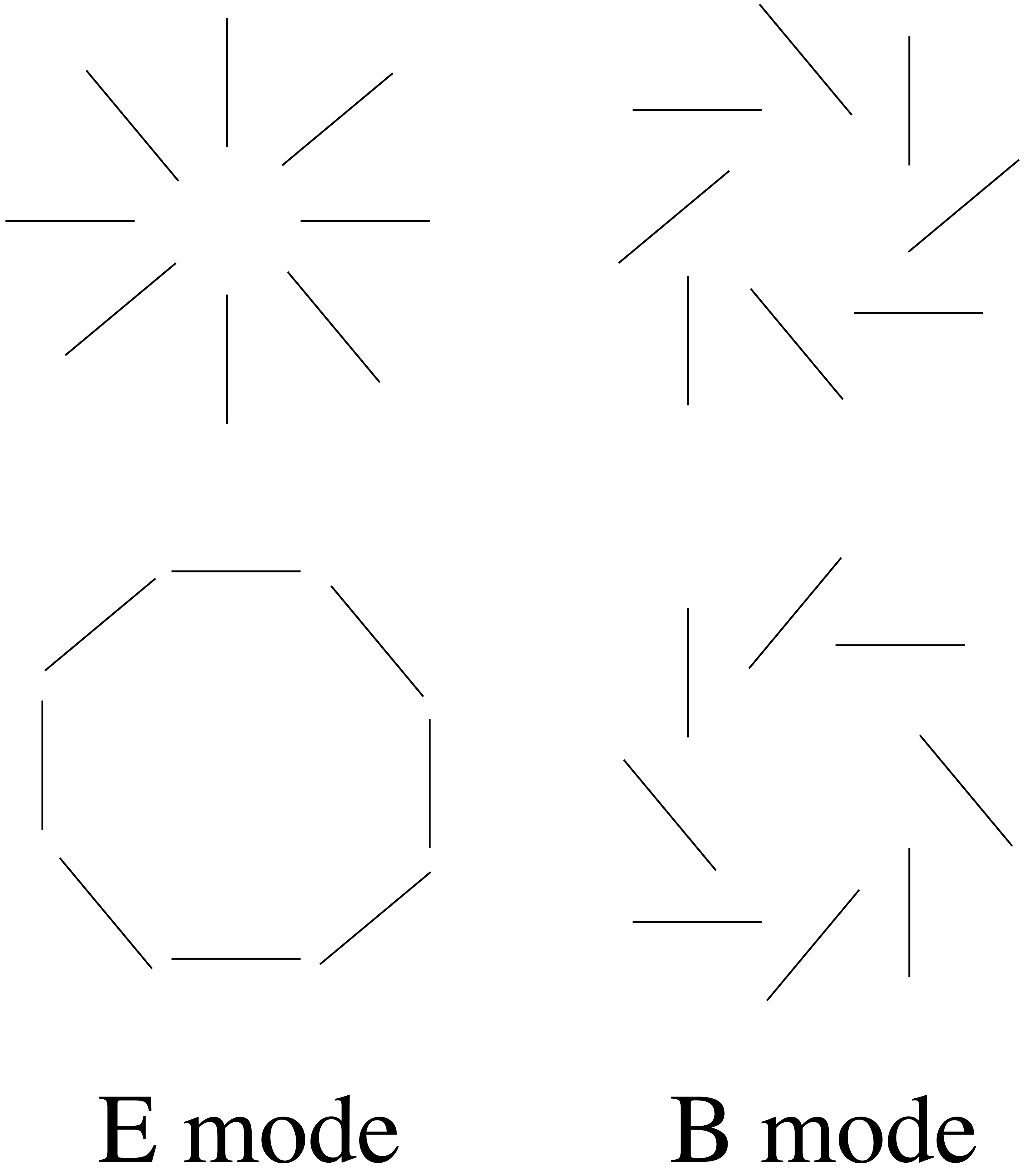
Komatsu et al. (2010)



Two-dimensional View

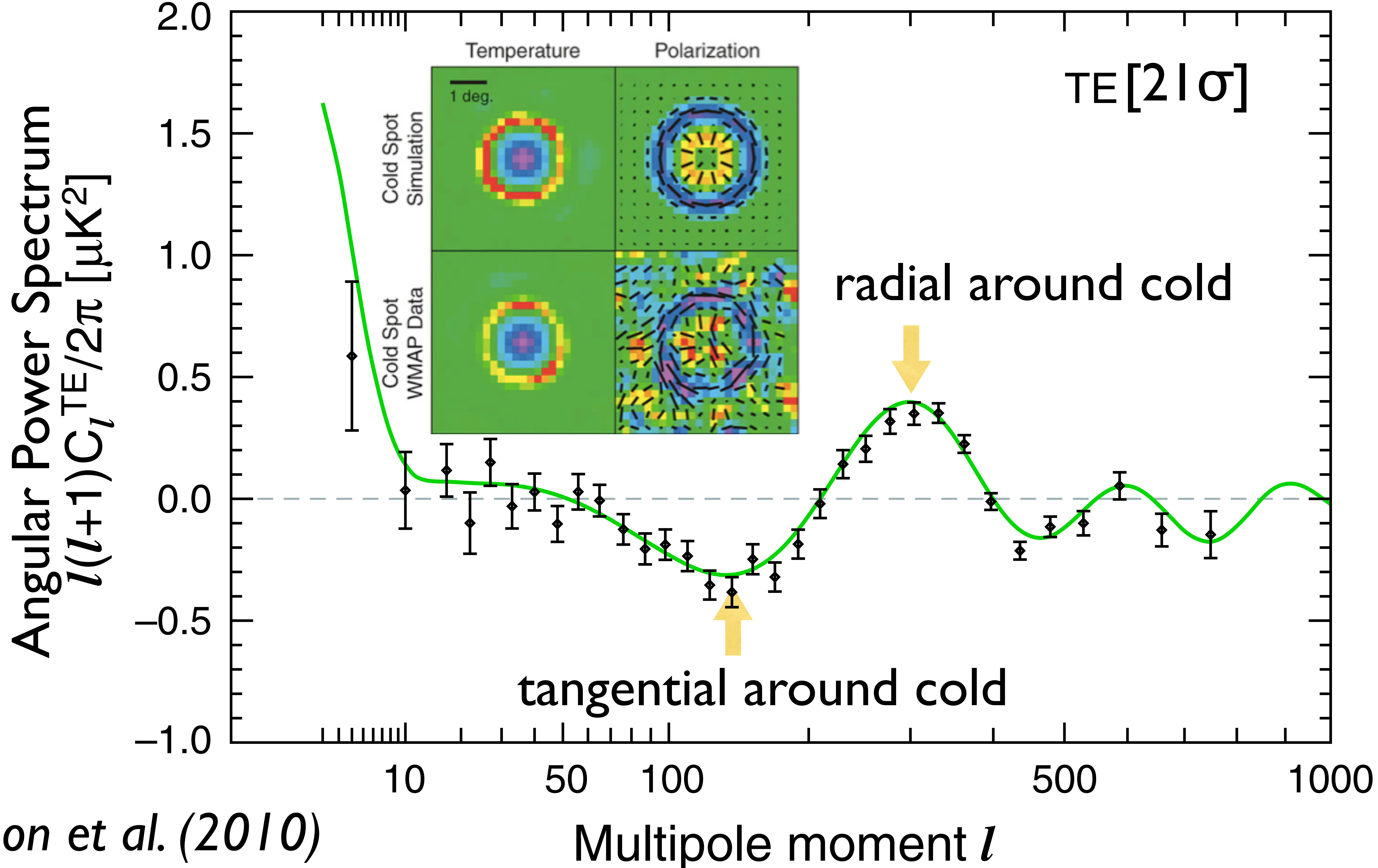
- Expected polarization pattern around cold and hot spots have been detected!
    - The overall significance level: 8σ
- This is the so-called “E-mode” polarization.

E-mode and B-mode



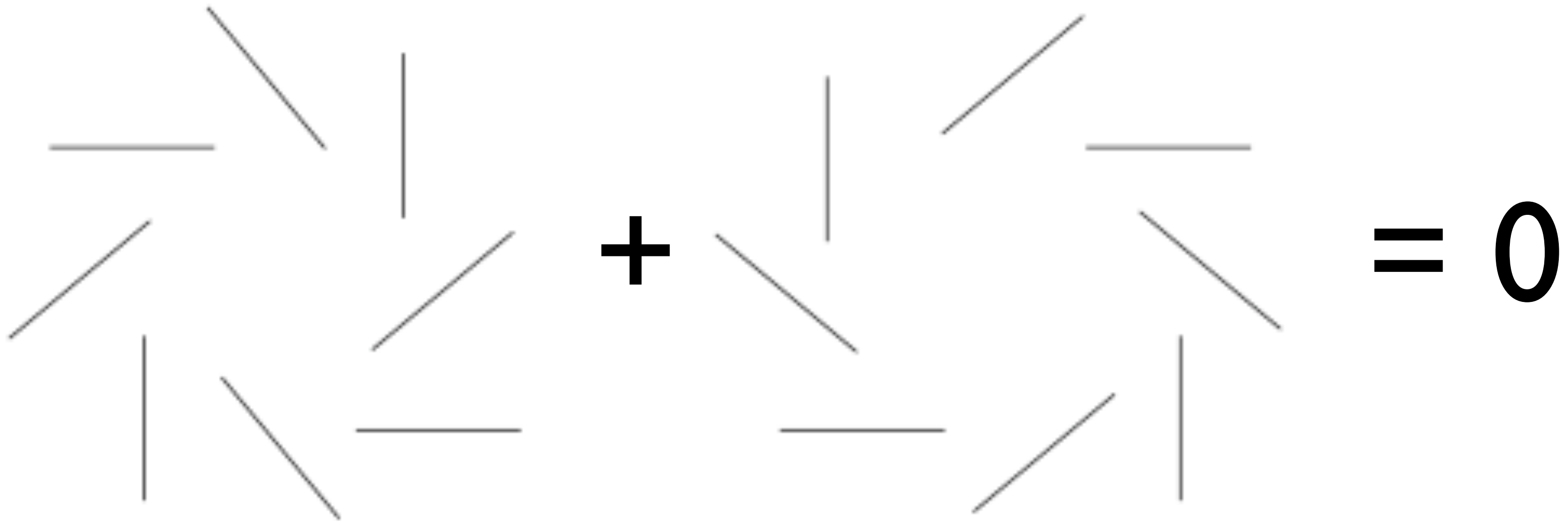
- Gravitational potential can generate the E-mode polarization, but not B-modes.
- **Gravitational waves** can generate both E- and B-modes!

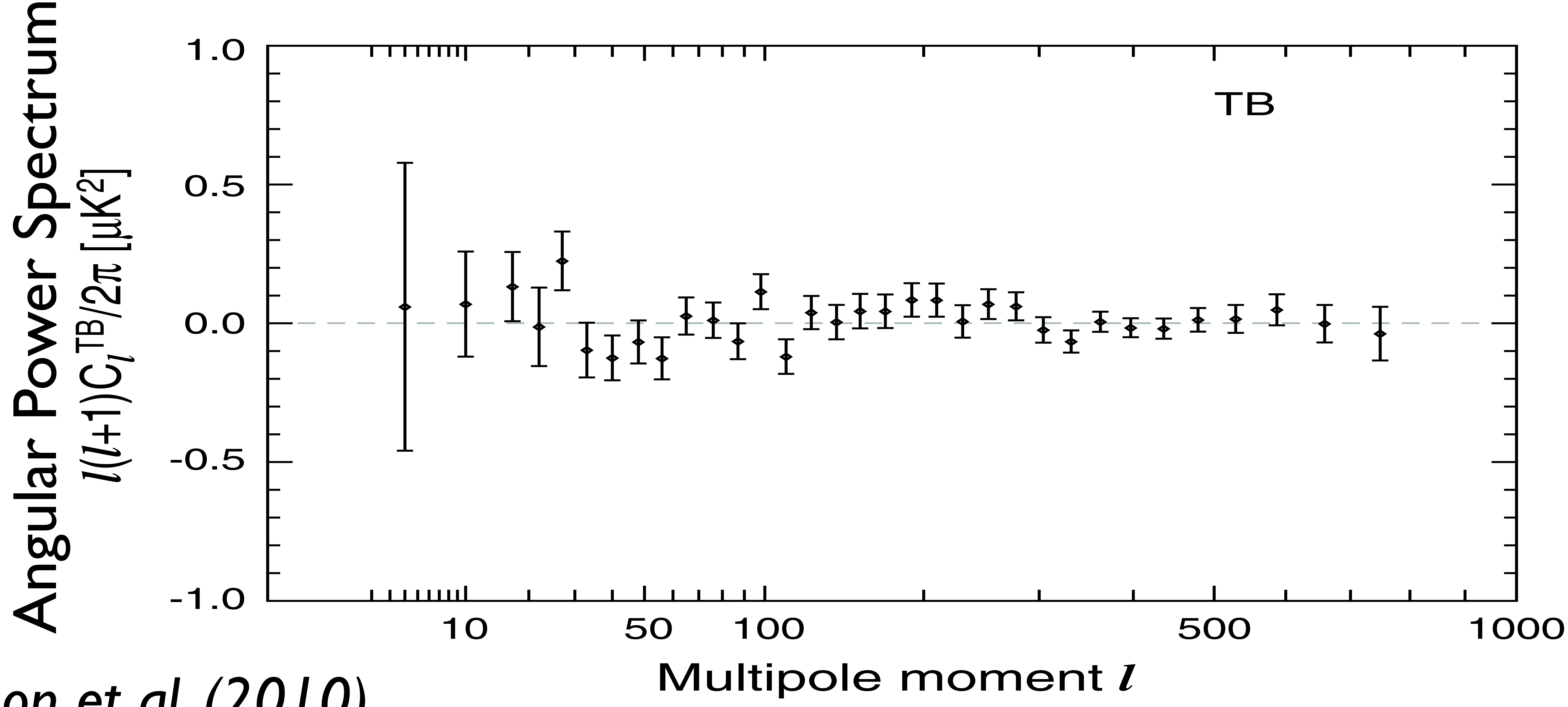
WMAP 7-year TE Correlation



Larson et al. (2010)

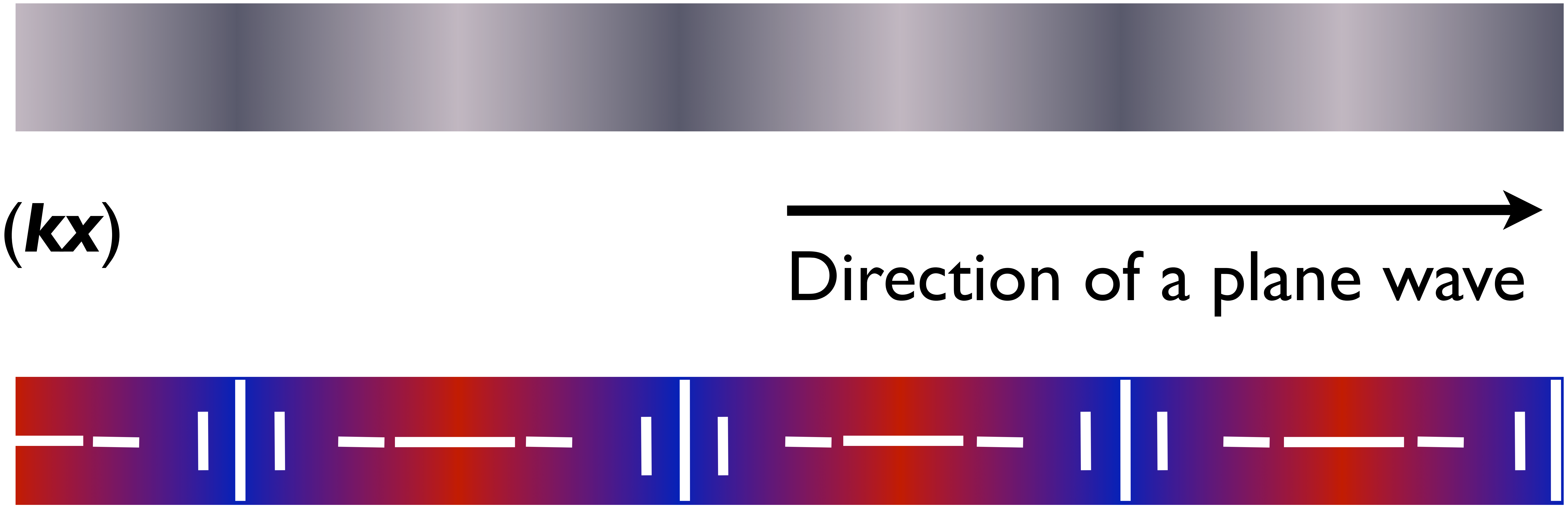
No TB Correlation





Larson et al. (2010)

E-mode



Potential

$\Phi(\boldsymbol{k},\boldsymbol{x})=\cos(\boldsymbol{kx})$

Direction of a plane wave

Polarization Direction

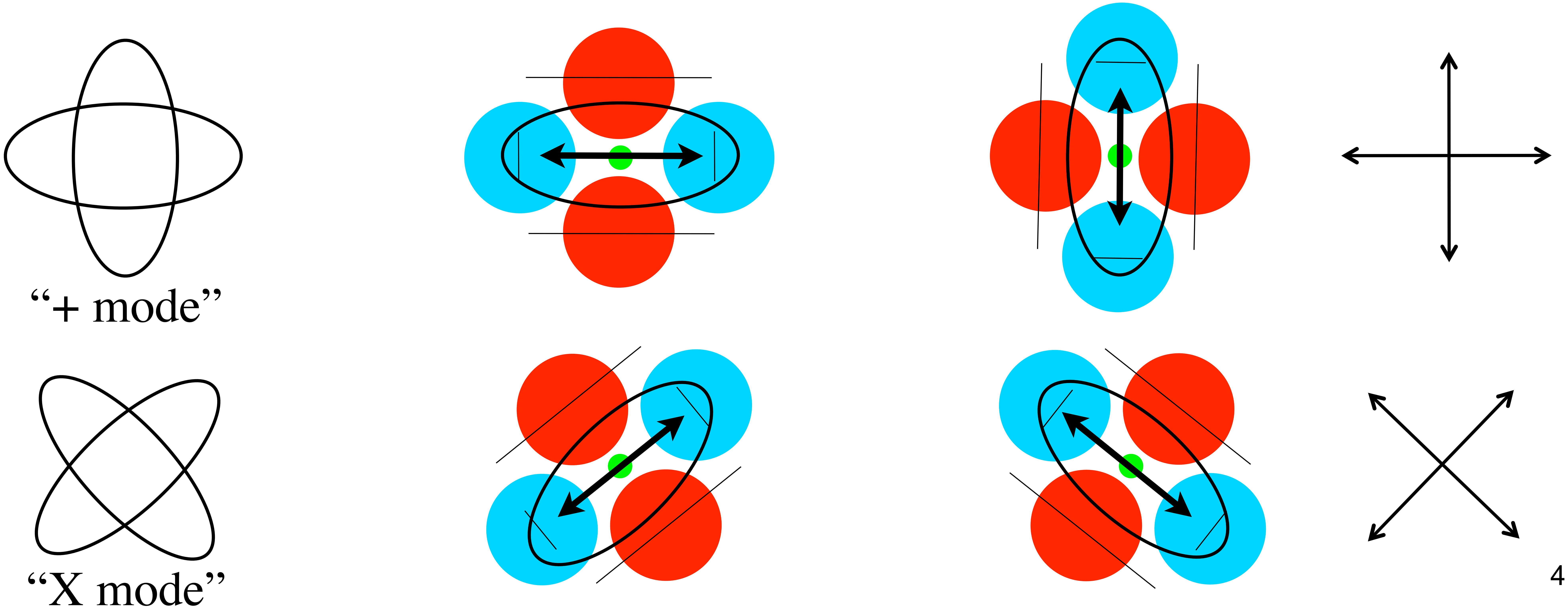
- **E-mode**: the polarization directions are either parallel or tangential to the direction of the plane wave perturbation.

B-mode

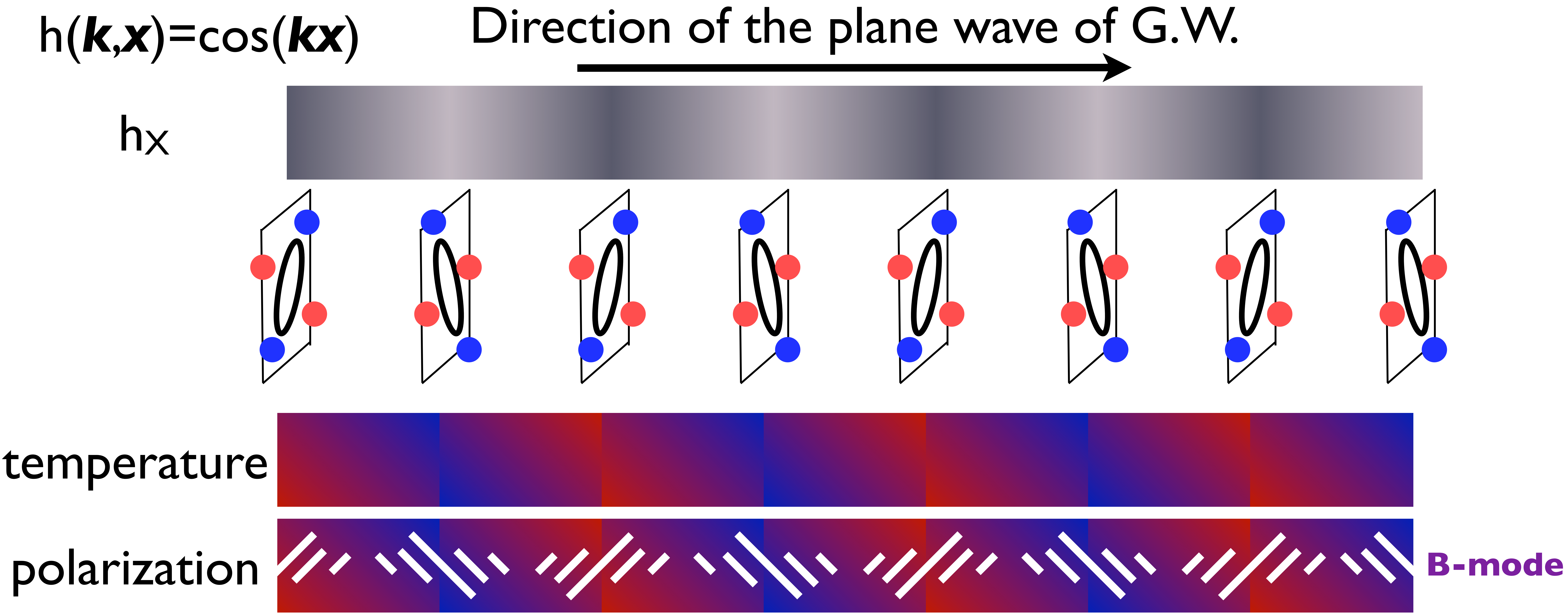
- **B-mode**: the polarization directions are tilted by 45 degrees relative to the direction of the plane wave perturbation.

Gravitational Waves and Quadrupole

- Gravitational waves stretch space with a quadrupole pattern.



Quadrupole from G.W.



$h(\boldsymbol{k},\boldsymbol{x})=\cos(\boldsymbol{k}\boldsymbol{x})$

Direction of the plane wave of G.W.

$h_\times$

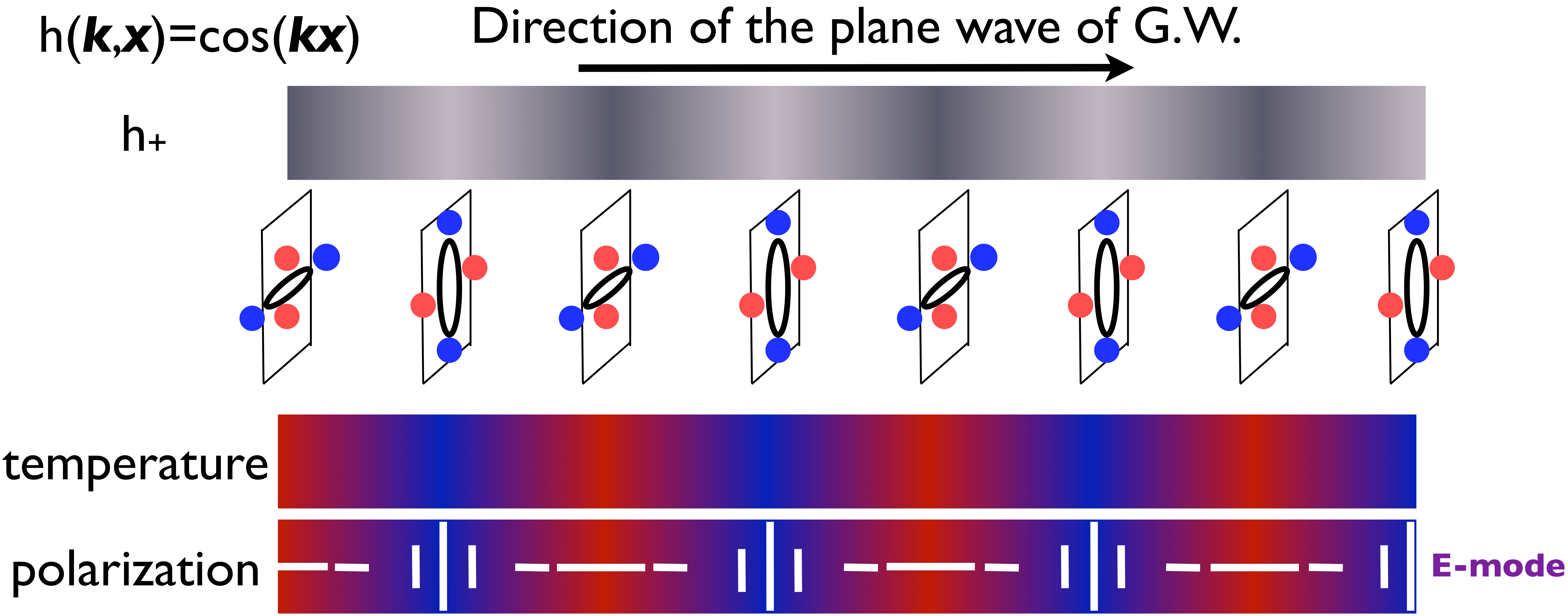
temperature

polarization

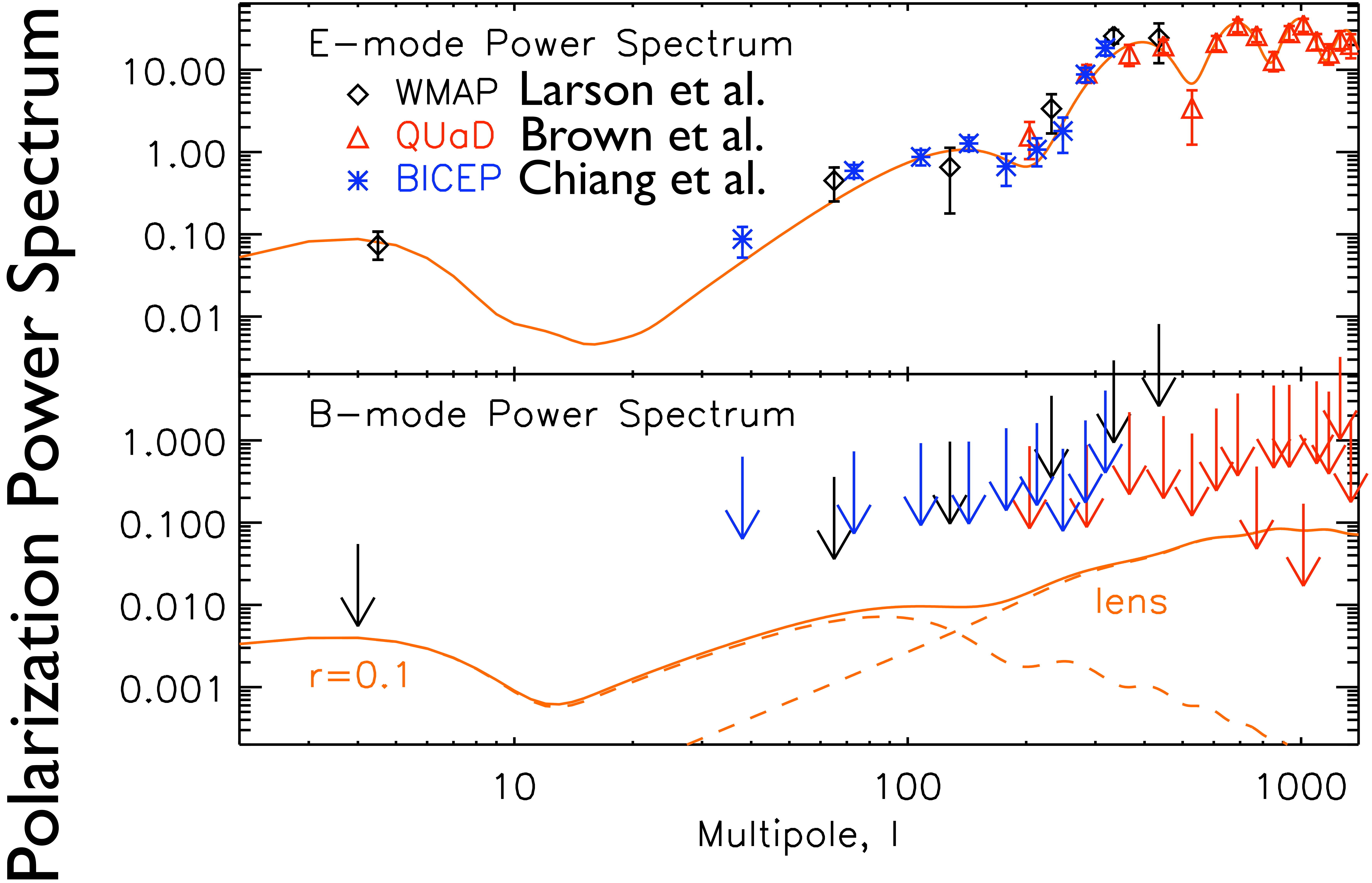
B-mode

- B-mode polarization generated by $h_\times$

Quadrupole from G.W.

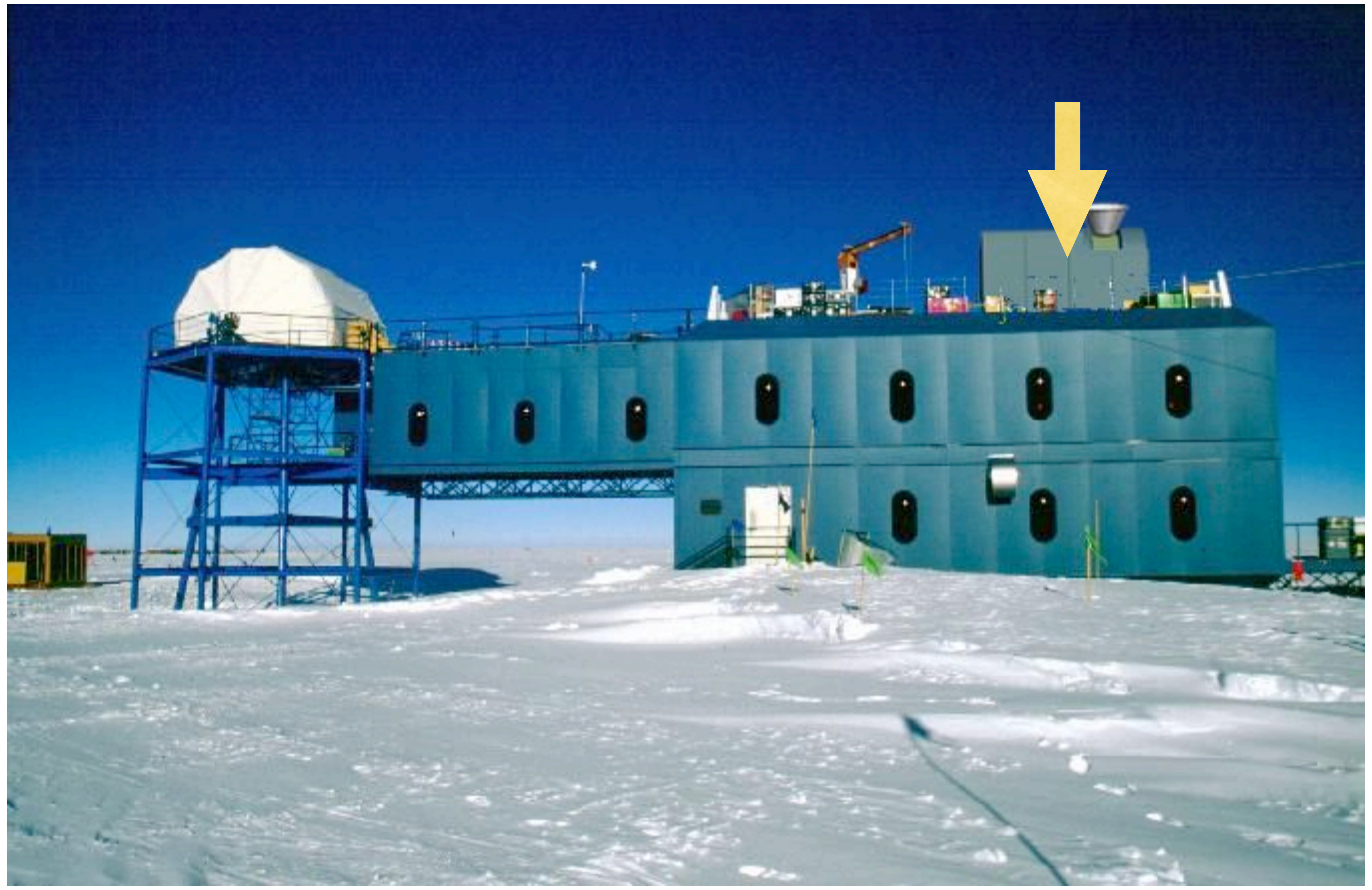


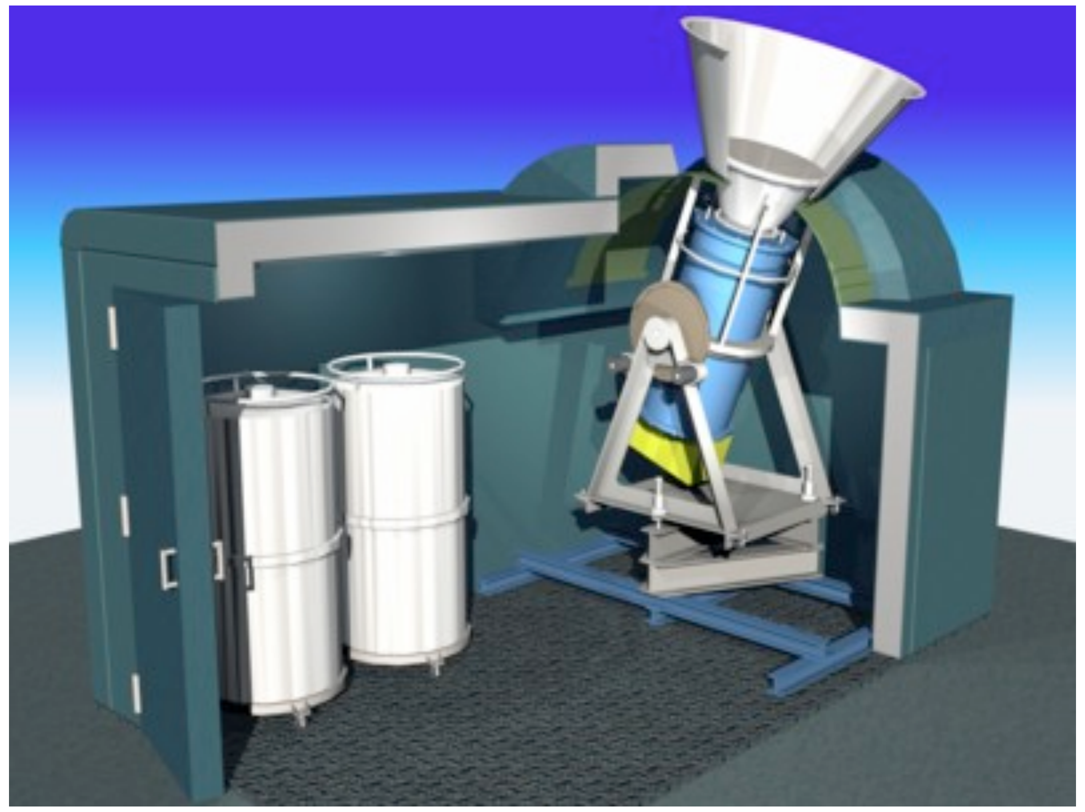
- E-mode polarization generated by h_+



- No detection of B-mode polarization yet. **B-mode is the next holy grail!**

BICEP (2006–)

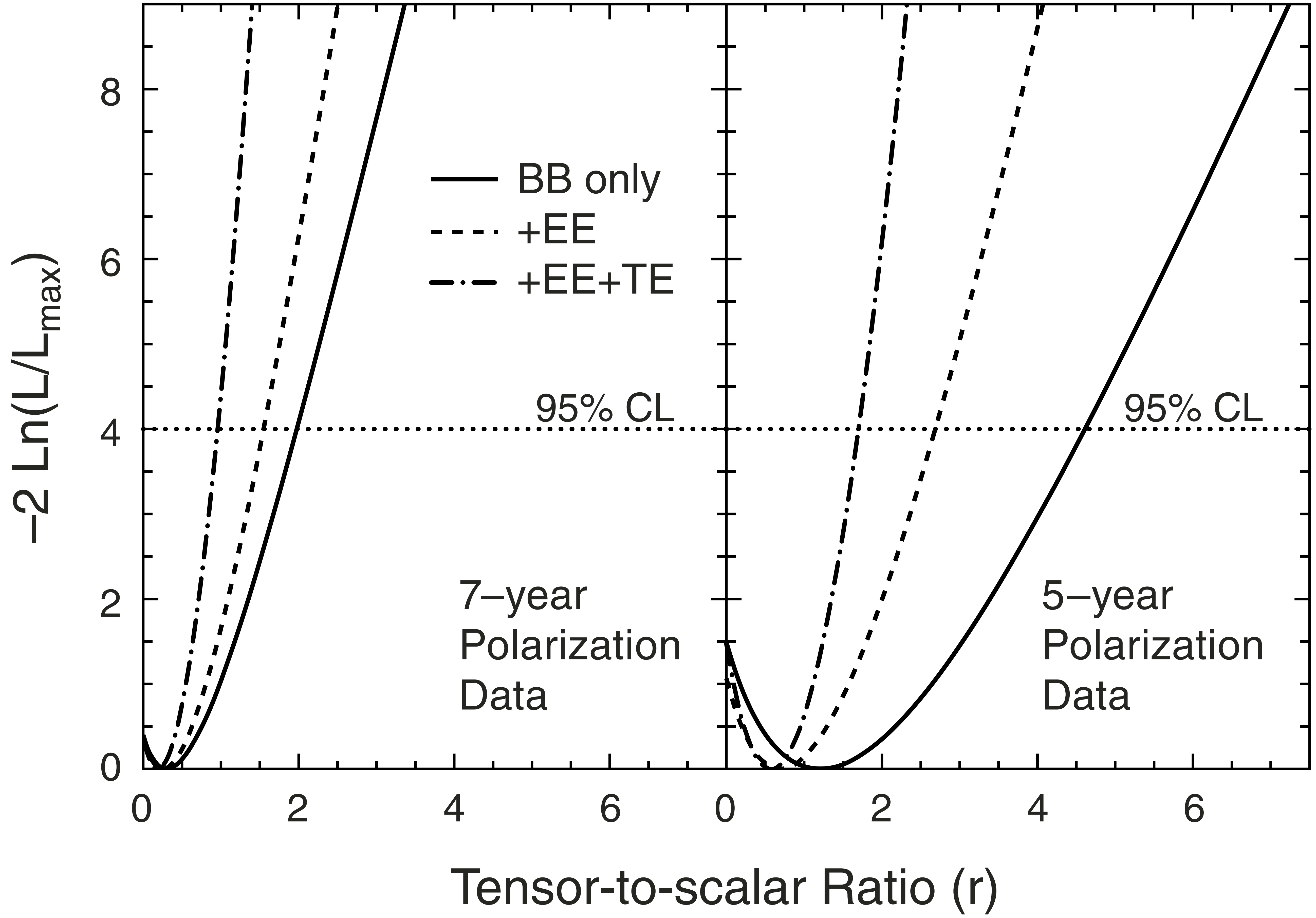




•D=**25cm**, ν=100 & 150GHz
•49 detectors (*bolometer*)
•Refracting telescope, with the optical system put in a cryostat (250mK).

- A good design, solely focused on detecting the primordial gravitational waves. The B-mode only limit is *r<0.72* (Chiang et al.)

WMAP's polarization data-only limits on tensor-to-scalar ration

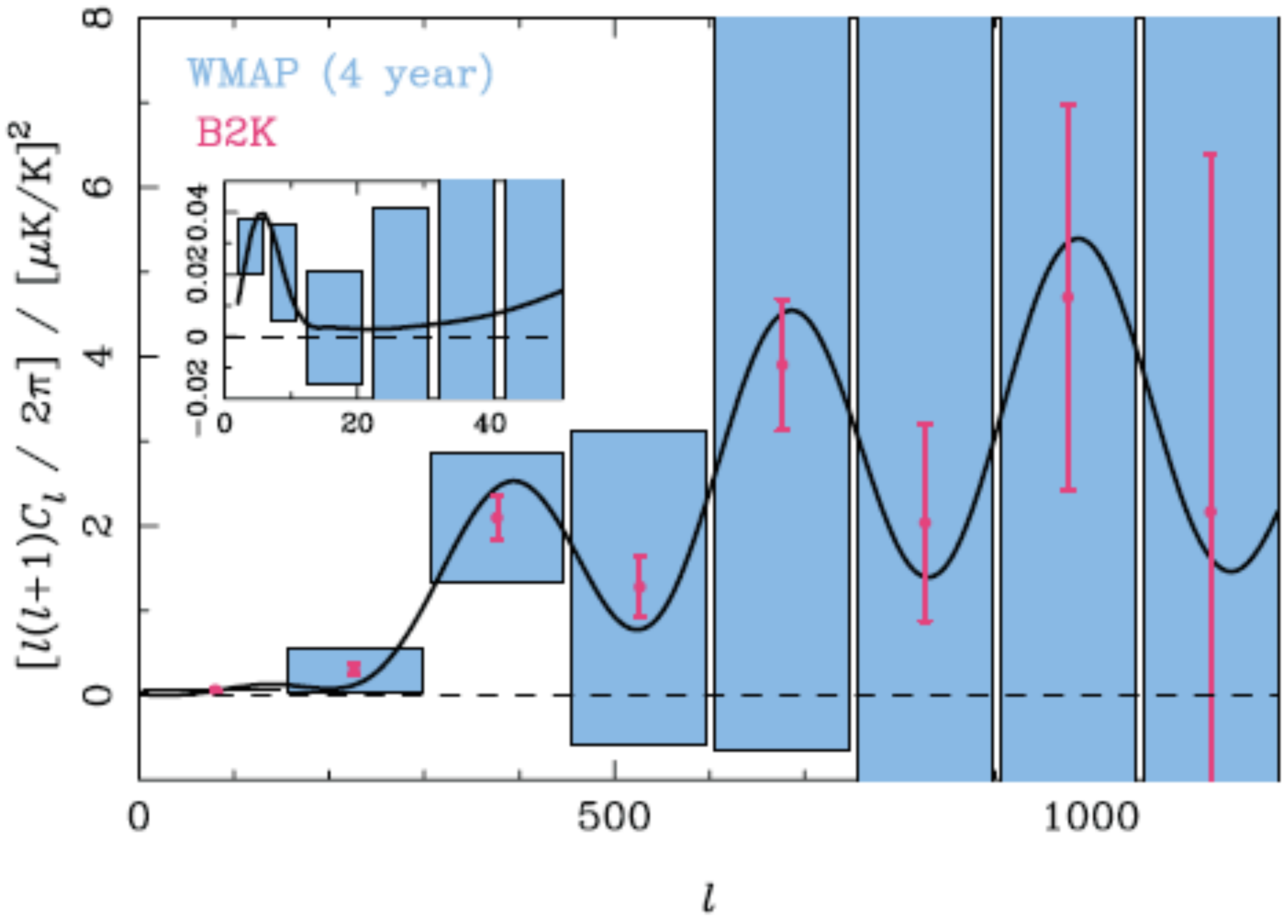


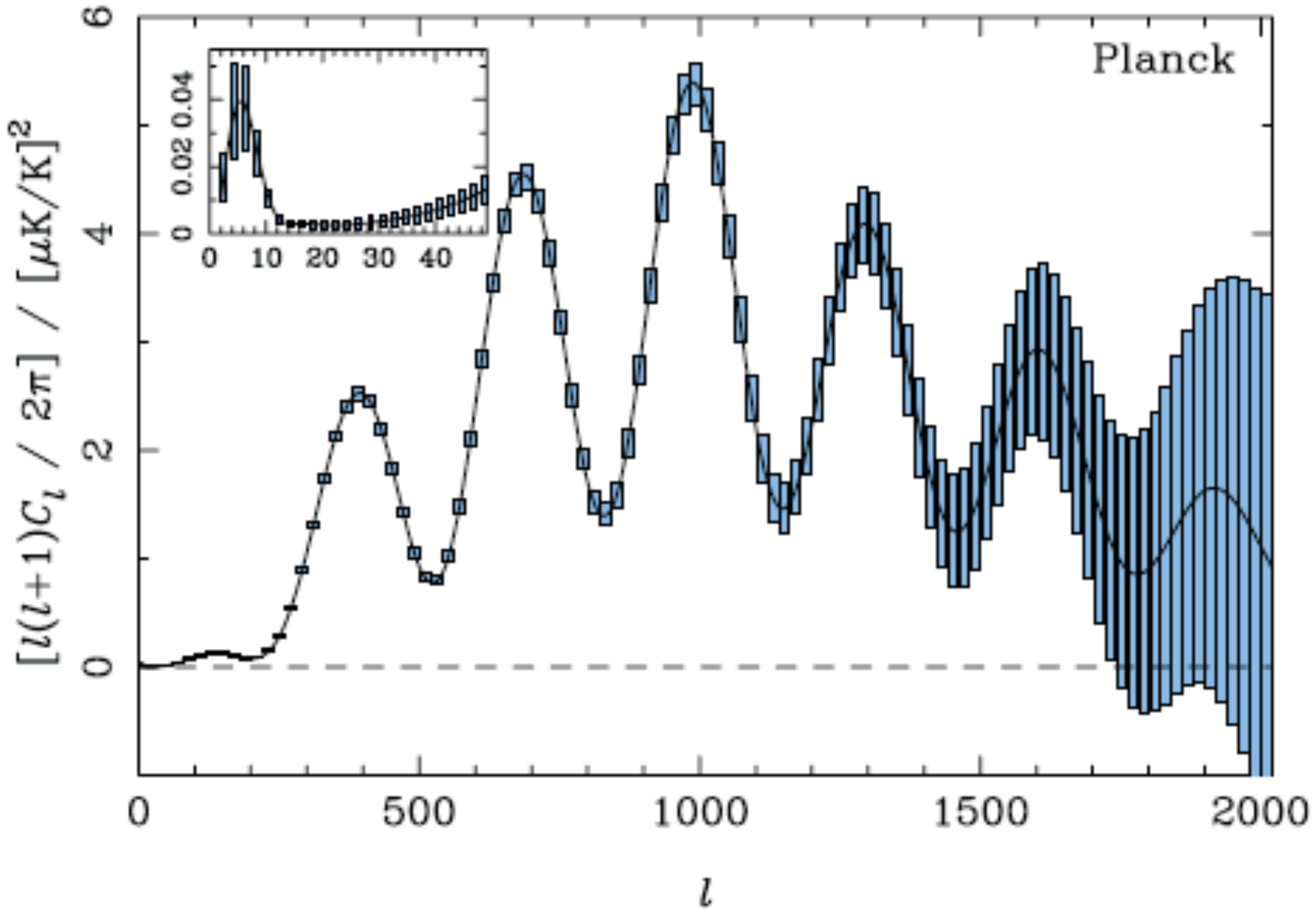
- *BB*: r<2.1
- *EE*/*BB*: r<1.6
- *TE*/*EE*/*BB*: r<0.93

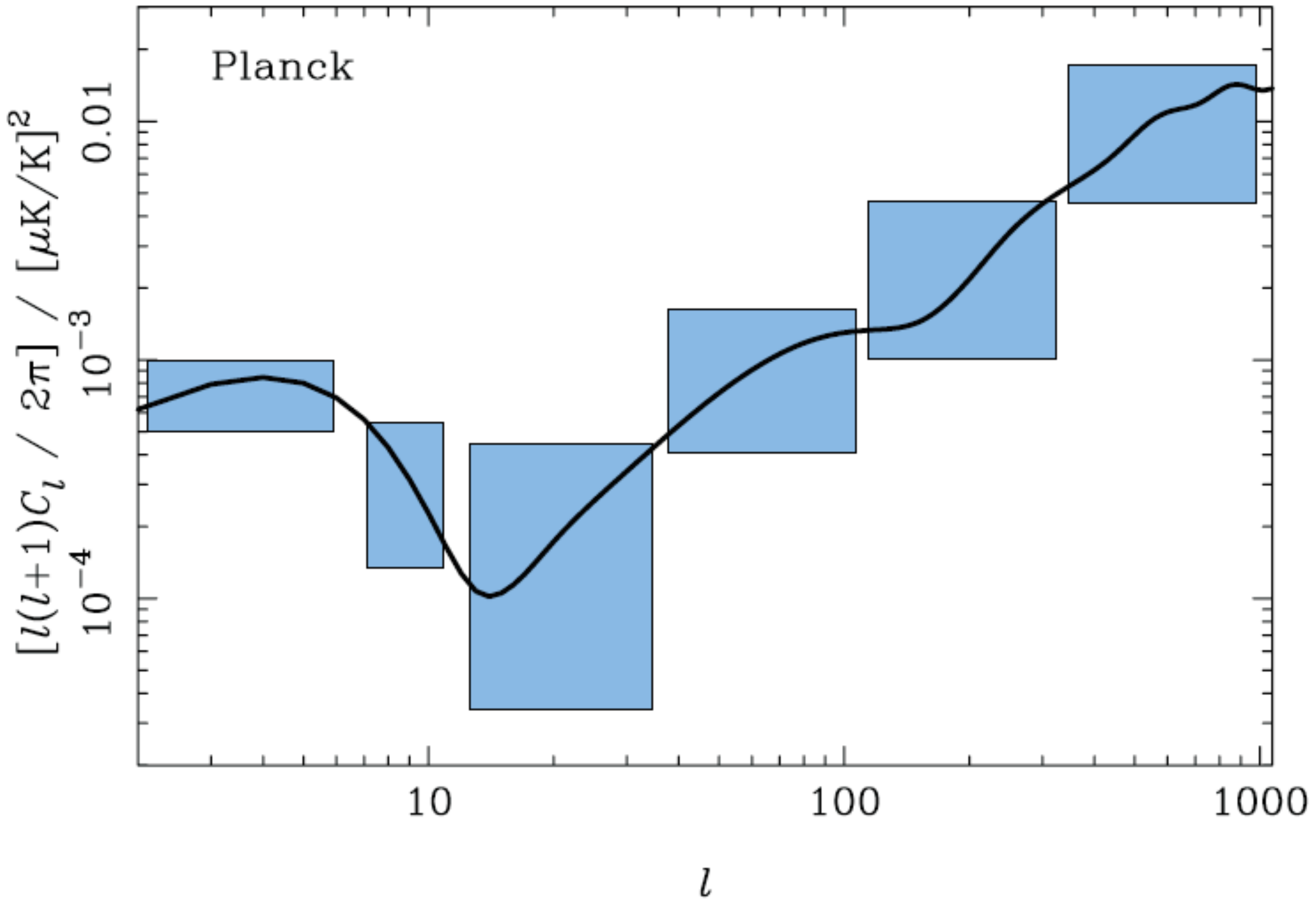
- *TT*/*TE*/*EE*/*BB*: r<0.36

Komatsu et al. (2010)

Planck: Expected $C_l^{Polarization}$

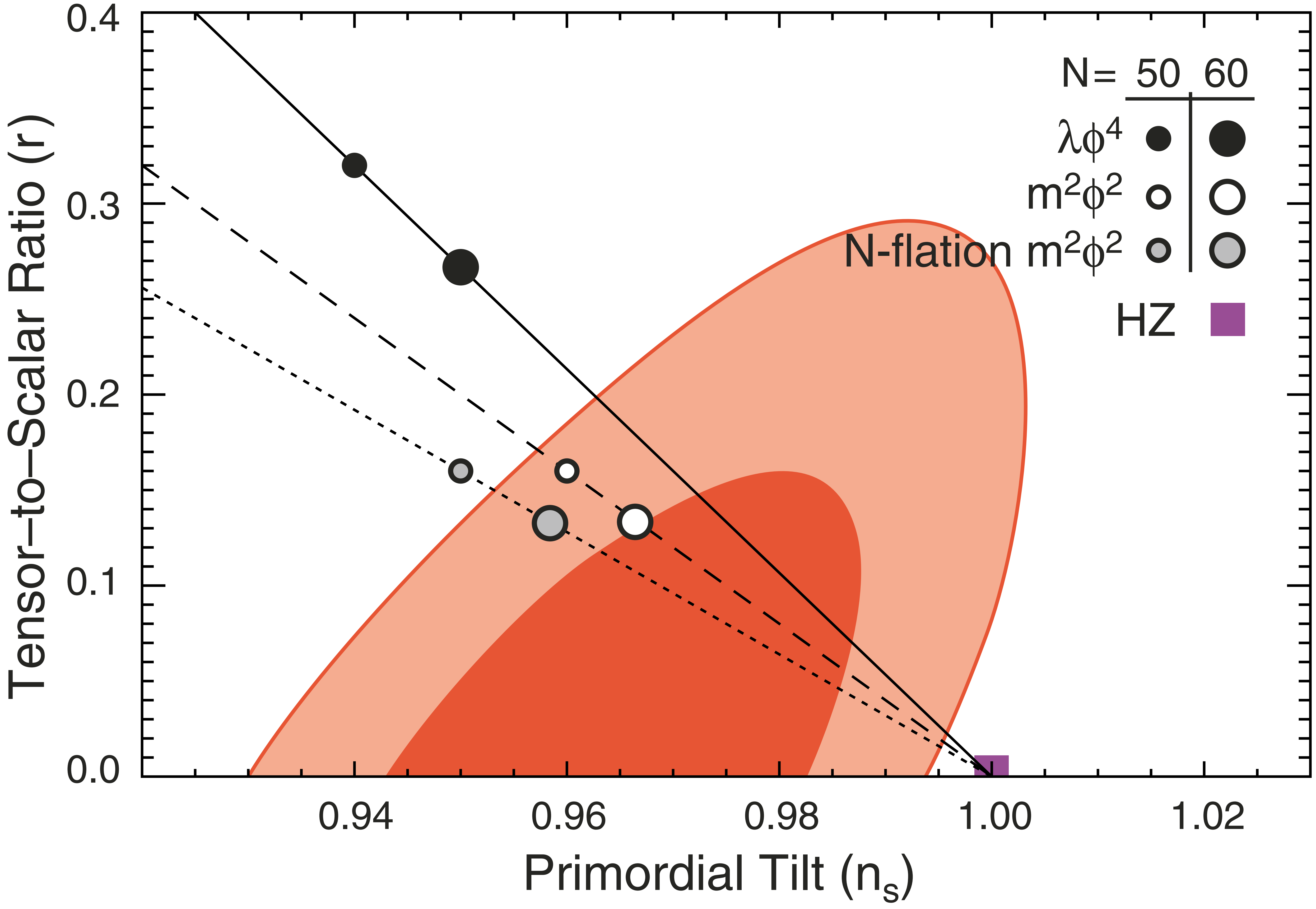






- (Above) E-modes
- (Left) B-modes (r=0.3)

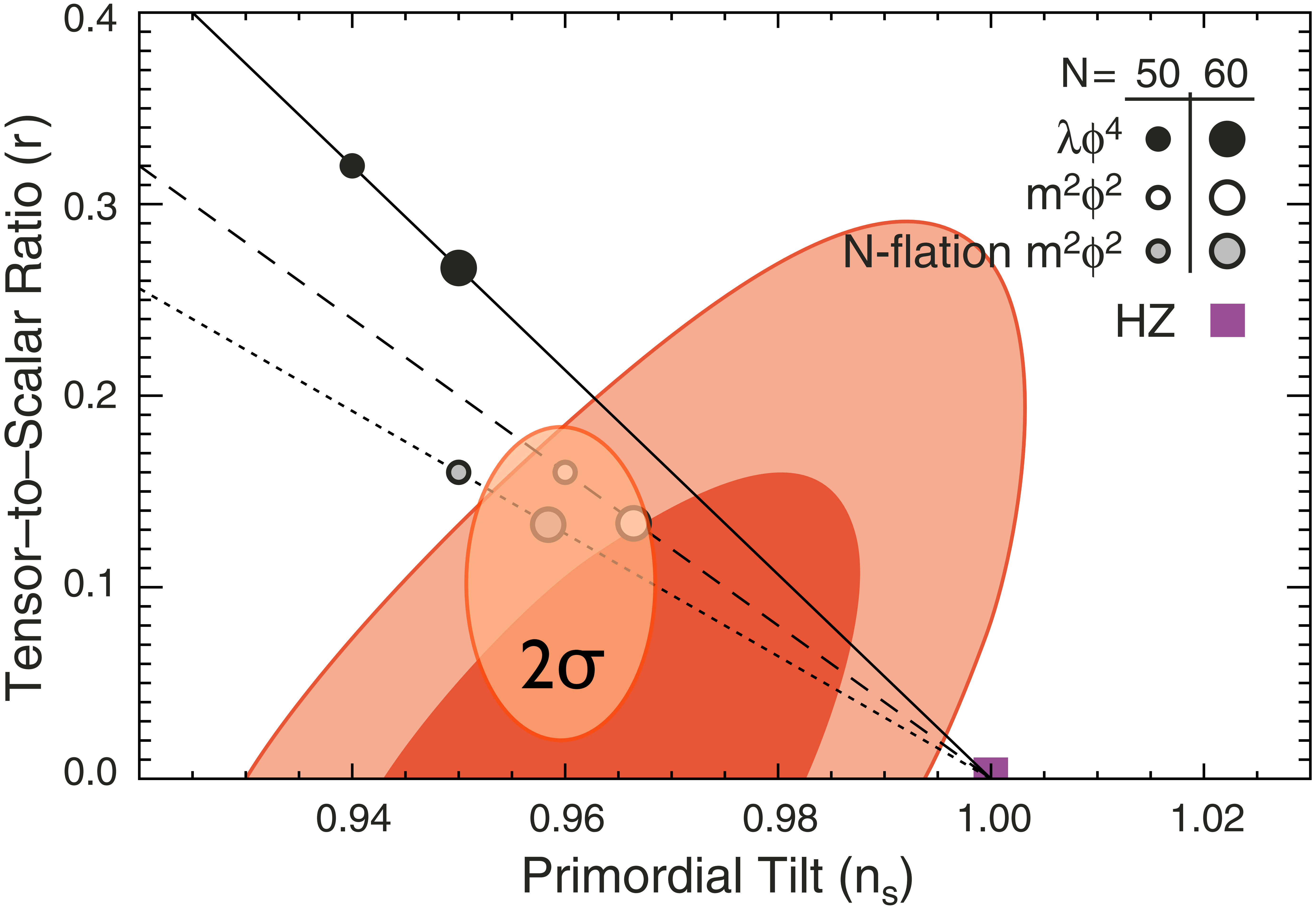
Probing Inflation by Power Spectrum



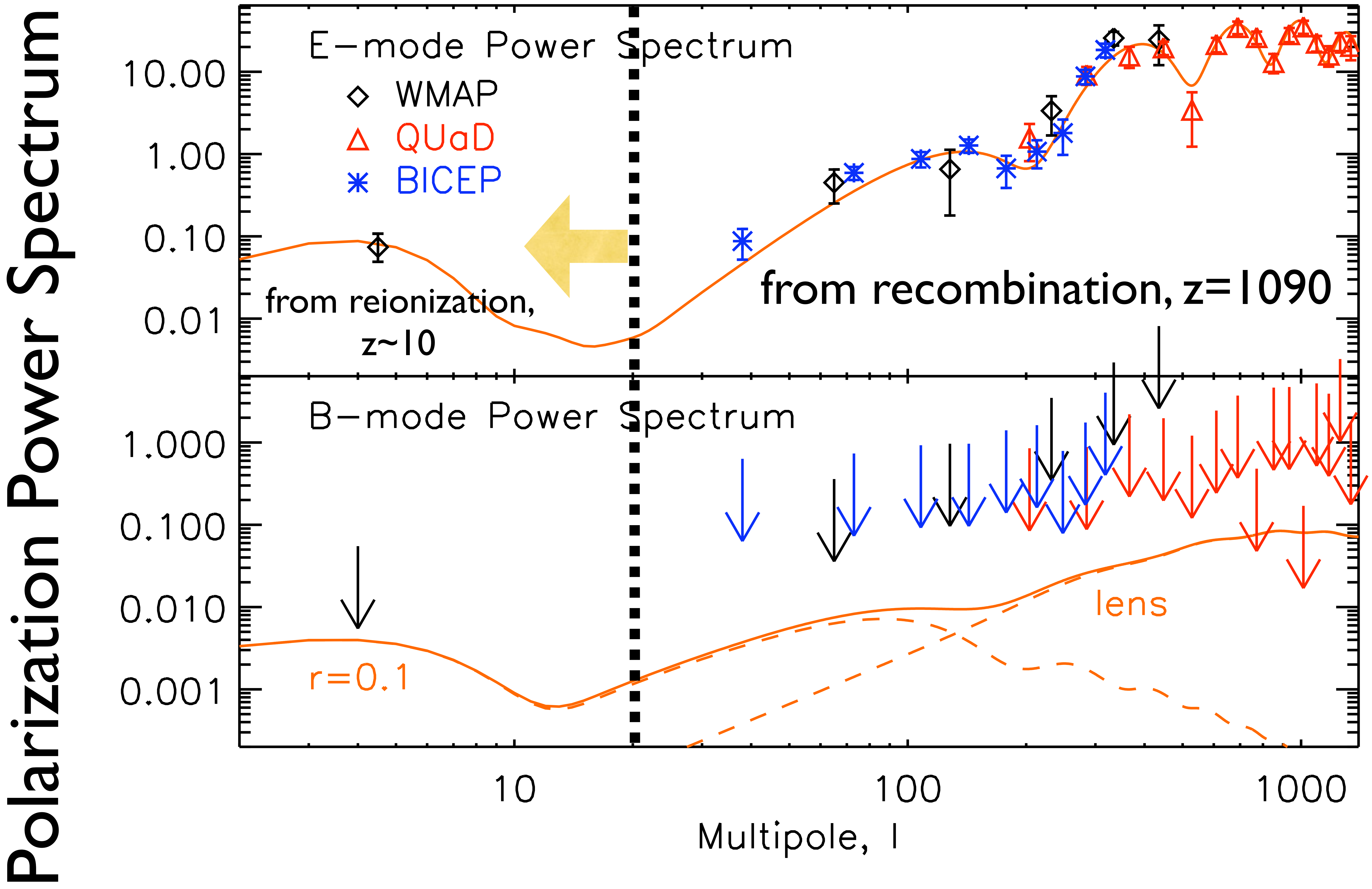
Komatsu et al. (2010)

- Joint constraint on the primordial tilt, n_s, and the tensor-to-scalar ratio, r.
  - Not so different from the 5-year limit.
  - $r < 0.24$ (95%CL)

Planck?



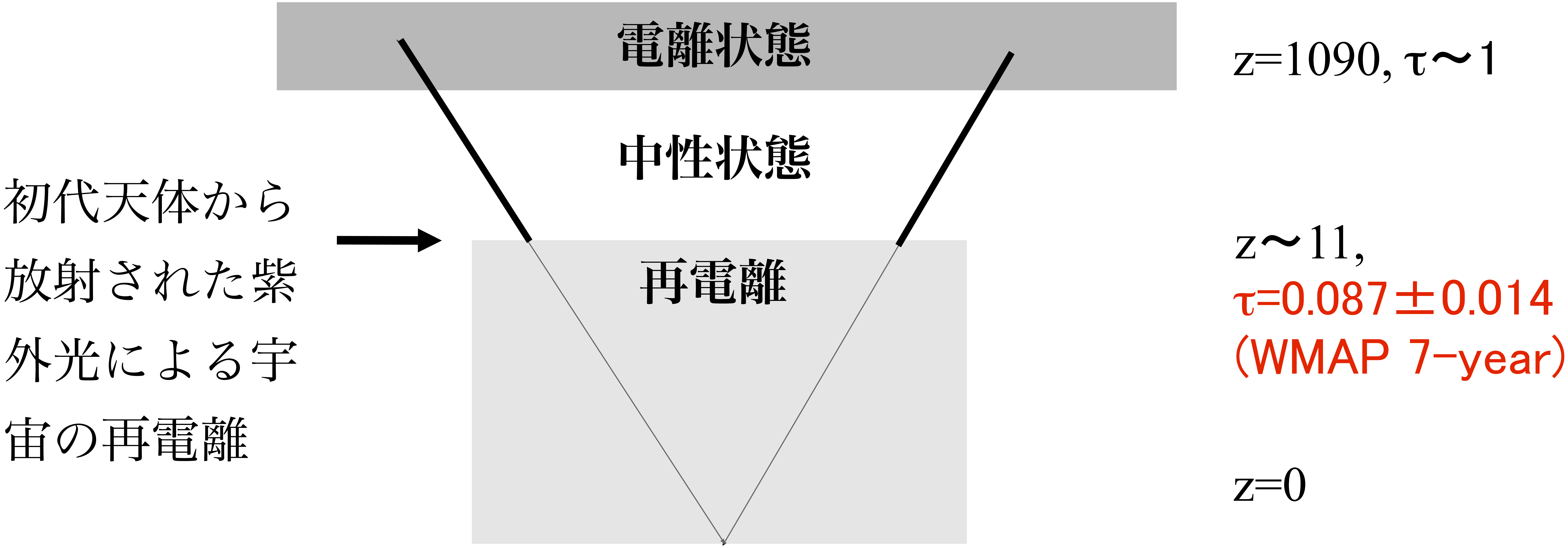
0.4
0.3
0.2
0.1
0.0
0.94
0.96
0.98
1.00
1.02
Tensor-to-Scalar Ratio (r)
Primordial Tilt (n_s)
N= 50 60
$\lambda\phi^4$
$m^2\phi^2$
N-flation $m^2\phi^2$
HZ
2σ



- The E-mode polarization from the cosmic reionization has been detected unambiguously.

宇宙の再電離と偏光の生成

- 現在観測される宇宙マイクロ波背景輻射はz=1090で散乱された光。
- そのうち、いくらか(~9%)は再電離時に放出された自由電子で散乱されてどこかへ行ってしまう。
- 一方で、どこかへ行くはずだった光子のうちいくらか(~9%)は我々の方向に散乱される。そして、**その散乱光は偏光している！**



Recap: Polarization C_l

- Scalar E-modes have been detected with high statistical significance.
  - The cosmic reionization has been detected unambiguously: τ=0.087±0.014 (68%CL)
  - Expected radial and tangential patterns confirmed.
    - Triumph of the standard model of the universe!
- No detection of B modes yet: *the next frontier*.

Summary

- Temperature power spectrum: go to high multipoles!
  - *Lensing and SZ effects*
- Polarization power spectrum: detect B modes!
  - *Lensing and gravitational waves*
- Beyond the power spectrum: no detection of 3-point function yet. That's another story (*arXiv:1003.6097*)