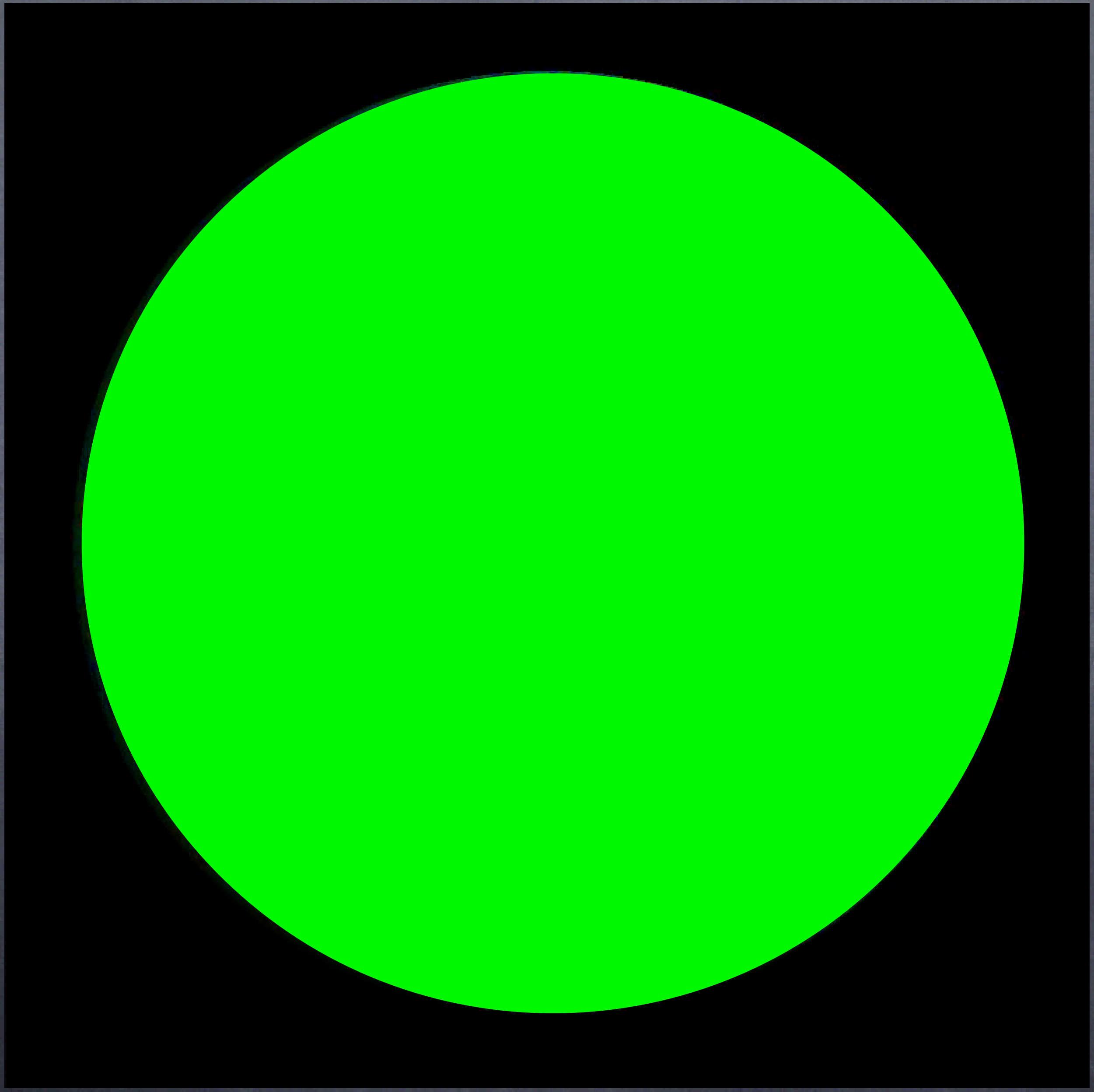
Cosmic Microwave Background

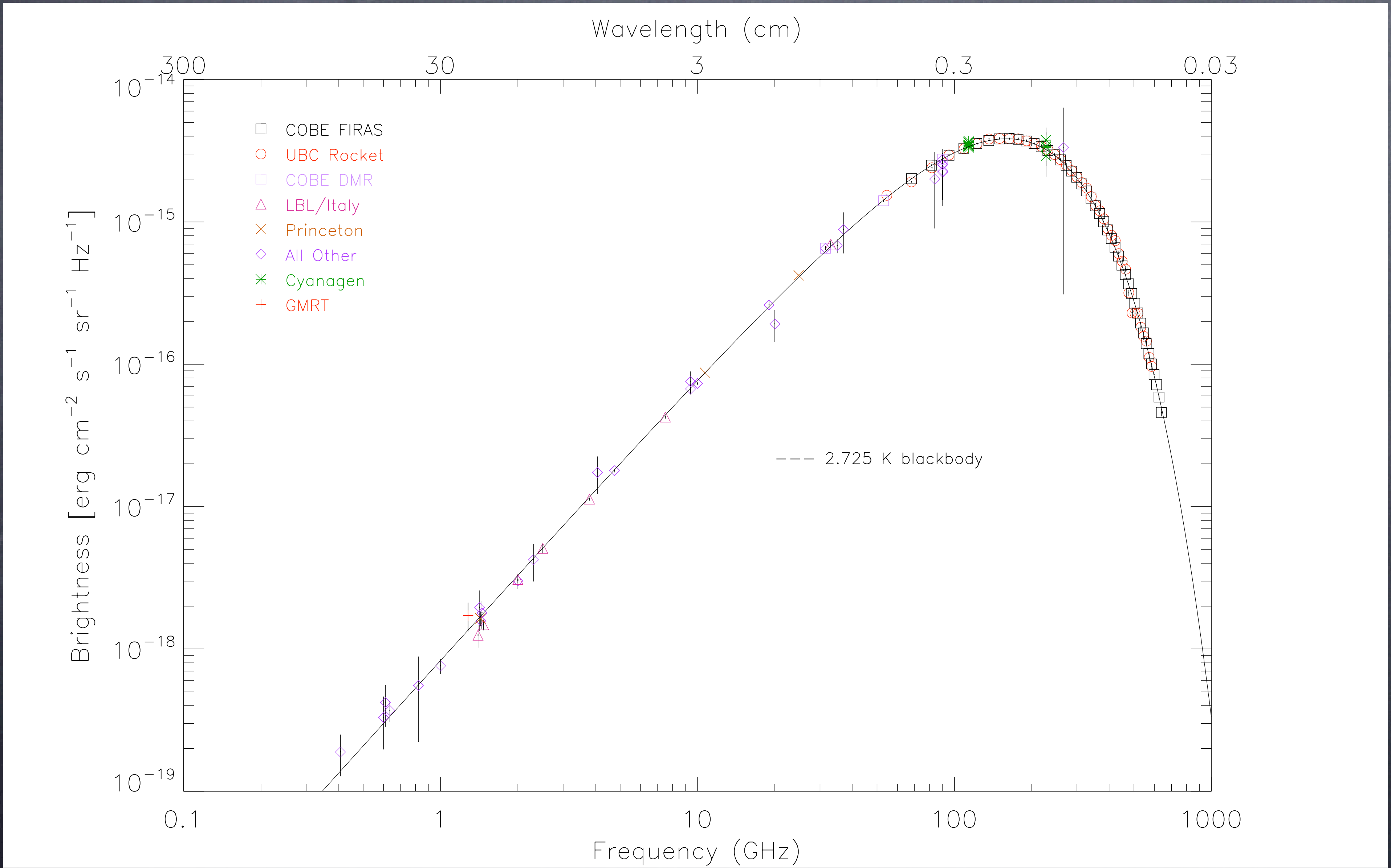
Douglas Scott

McGill, March 2008

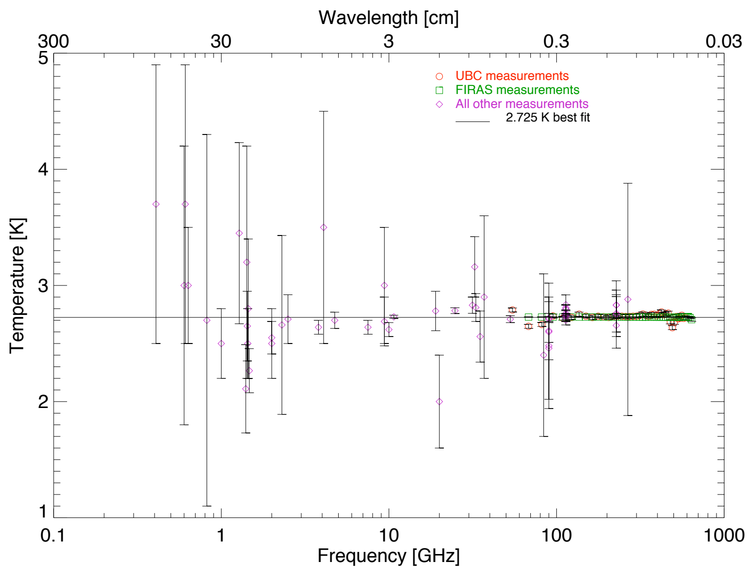
CMB Sky



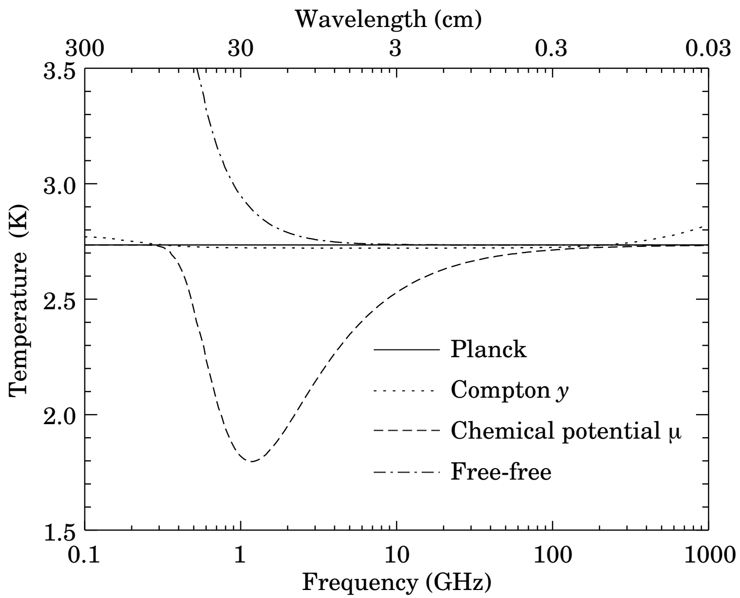
CMB Spectrum



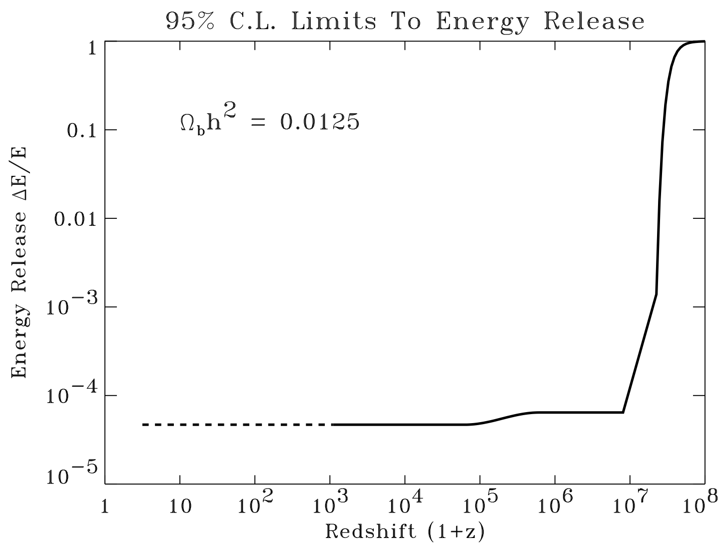
CMB Spectrum



+



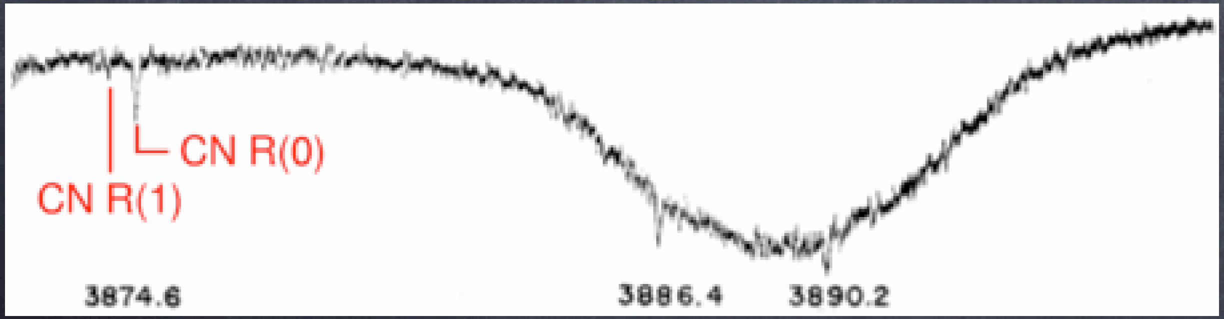
→



CMB history (eh)

Andrew McKellar

CN measurements at DAO (1940, 1941) ⇒ rotational temp ≈ 2.3K



Herzberg (1950): "...only a very restricted meaning"

Now the serious part

NOT!

Where did the CMB come from anyway?

Where did the CMB temperature come from?

T_0=2.725±0.001K

(Mather et al. 1999)

$$e\,\mathrm{Kelvin} (= 2.728\,\mathrm{K})$$

$$\sqrt{15/2}\,\mathrm{Kelvin} (= 2.739\,\mathrm{K})$$

$$30/11\,\mathrm{Kelvin} (= 2.727\,\mathrm{K})$$

$$-\ln(9\alpha)\,\mathrm{Kelvin} (= 2.723\,\mathrm{K})$$

$$\text{Triple point of water} \div 100 (= 2.7315\,\mathrm{K})$$

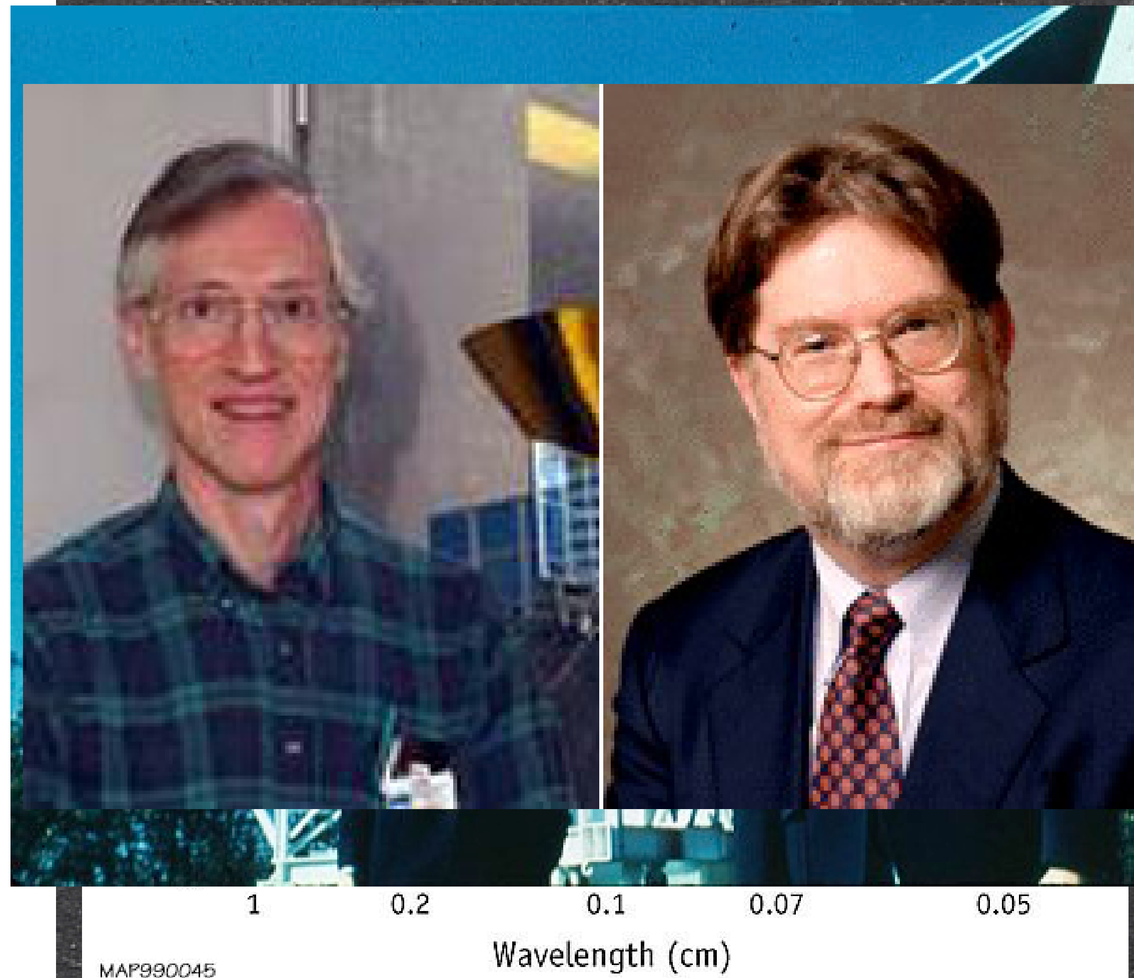
$$(2\alpha/\pi)^4 m_e c^2/k\ (= 2.762\,\mathrm{K})$$

$$(2/5)(\alpha_{\mathrm{G}} m_e/2\pi m_p)^{1/4} m_p c^2/k\ (= 2.719\,\mathrm{K})$$

$$[\alpha_{\mathrm{G}} \equiv G m_e^2/c\hbar] \qquad 16\sqrt{2}\pi\alpha_{\mathrm{G}}^{1/4} m_e c^2/k\ (= 2.727\,\mathrm{K})$$

$$hc/k\ \mu\mathrm{Leagues}\ (= 2.98\,\mathrm{K})$$

$$[\pi \mathrm{e}^{\pi} \simeq 73] \qquad \mathrm{e}^{-73} T_{\mathrm{Pl}}\ (= 2.805\,\mathrm{K})$$



Expansion 1920s

CMB 1960s

Hot Big Bang picture

GR
(easiest soln)
+ expansion
+ CMB
+ simple ICs
+ few components
→ Big Bang
(with spots)

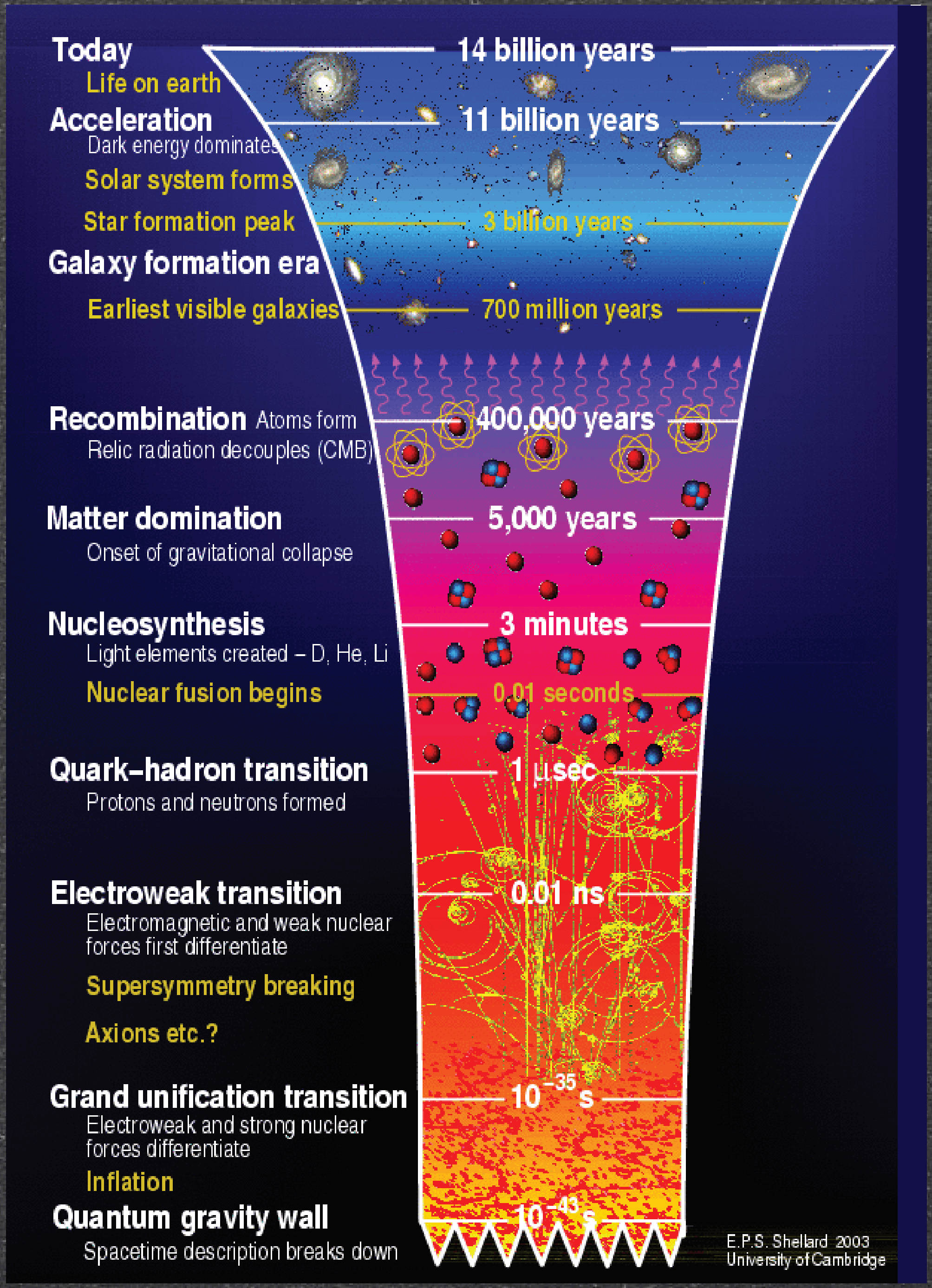


Table 2. The 12 Parameters of the Standard Model of Cosmology.

1 temperature:	T_0		
1 timescale:	H_0		
4 densities:	Ω_Λ	$\Omega_{\rm CDM}$	$\Omega_{\rm B}$
1 pressure:	$w \equiv p/\rho$		
1 mean free path:	$\tau_{\rm reion}$		
4 fluctuation descriptors:	A	n	$n' \equiv dn/d\ln$
12 total parameters			

A, E, H, I, K, L, M, N, O, P, U, W

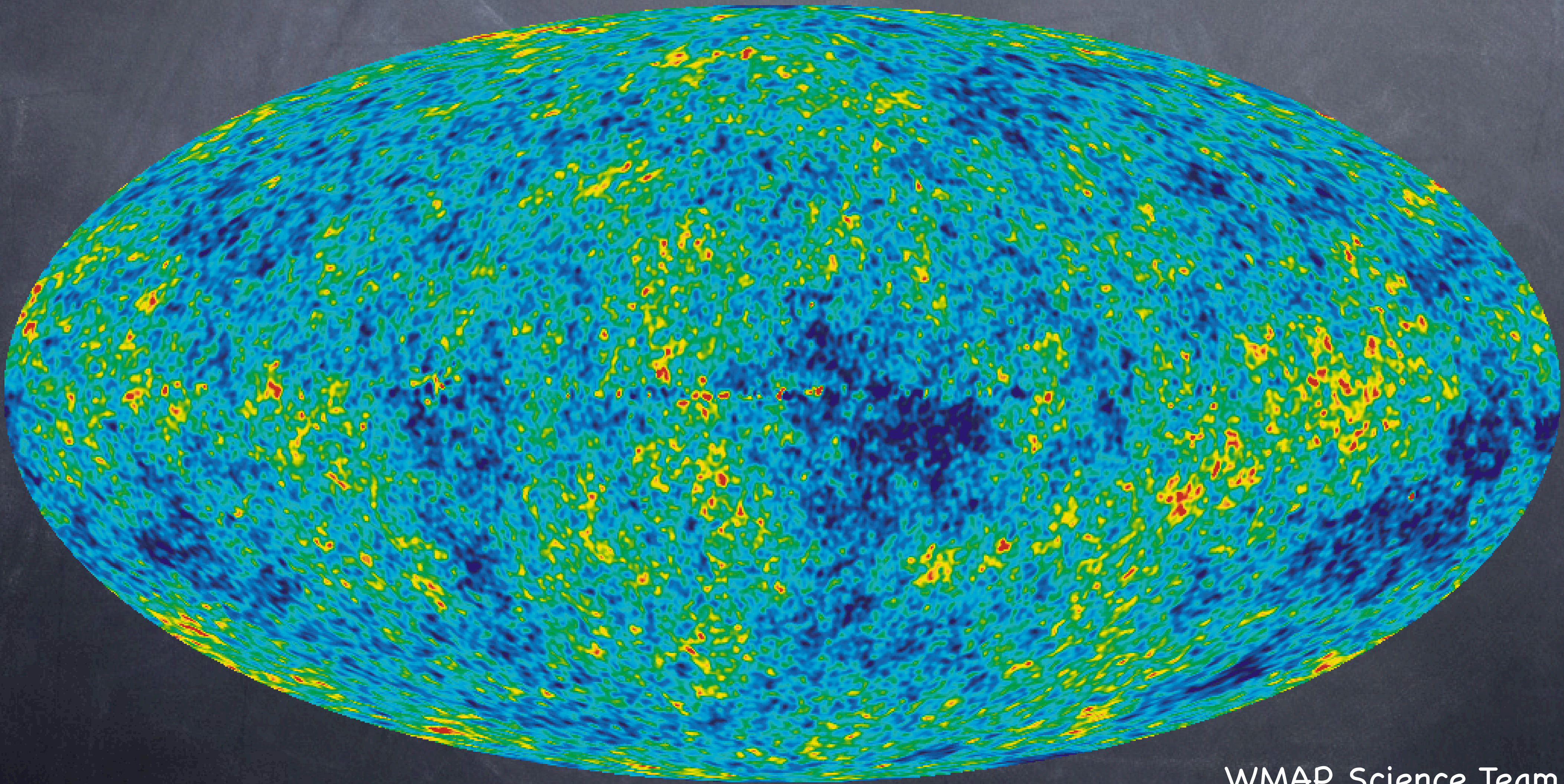
Table 1. The 26 Parameters of the Standard Model of Particle Physics.

6 quark masses:	m_u
4 quark mixing angles:	θ_{12}
6 lepton masses:	[illegible]
4 lepton mixing angles:	θ'_{12}
3 electroweak parameters:	α
1 Higgs mass:	$m_{\rm H}$
1 strong CP violating phase:	$\bar{\theta}$
1 QCD coupling constant:	$\alpha_{\rm S}(M_Z)$
26 total parameters	

A, B, C, D, E, F, G, H, I, J, K, L, M, N, O, P, Q, R, S, T, U, V, W, X, Y, Z

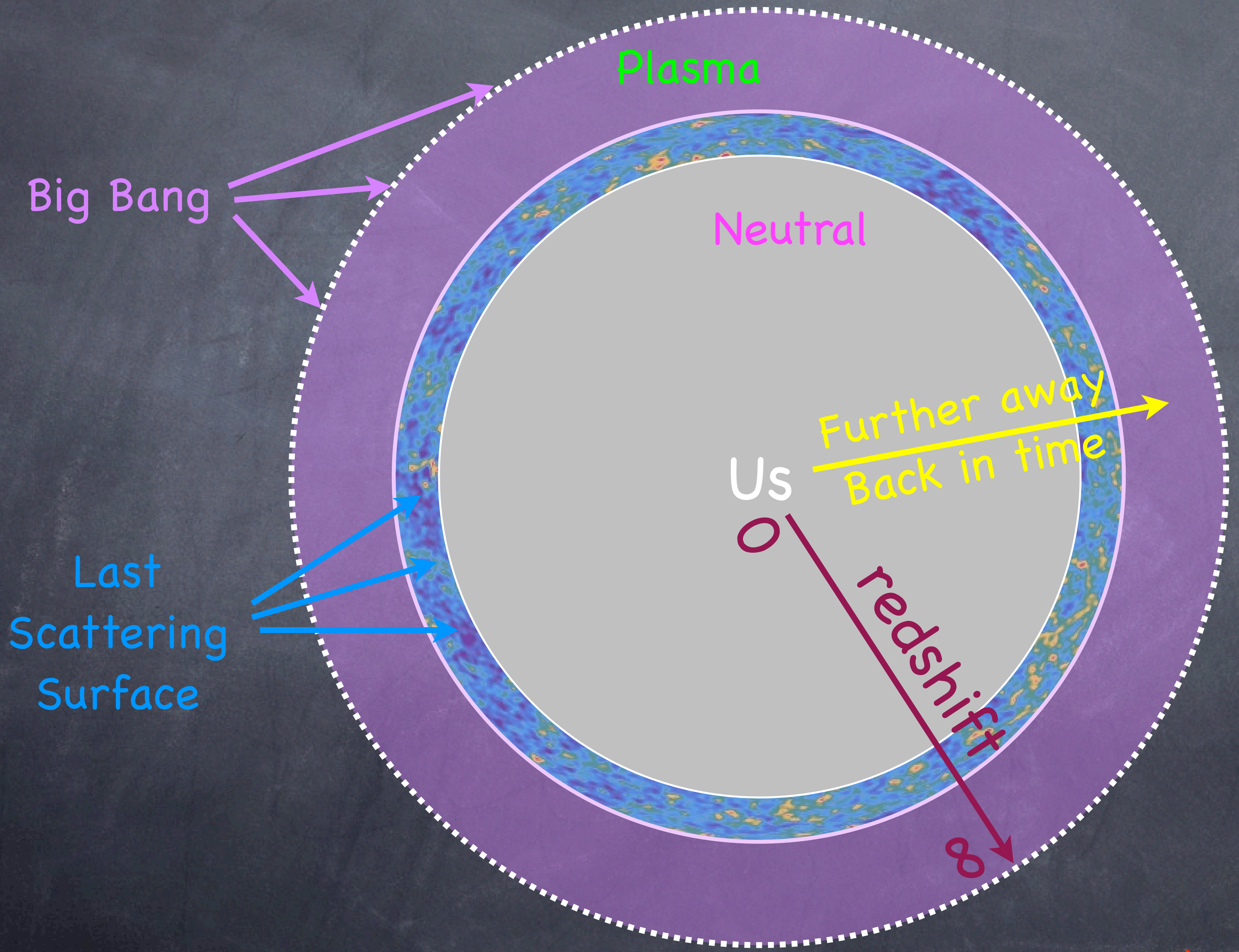
The CMB Sky

Temperature anisotropies at ~400,000 years



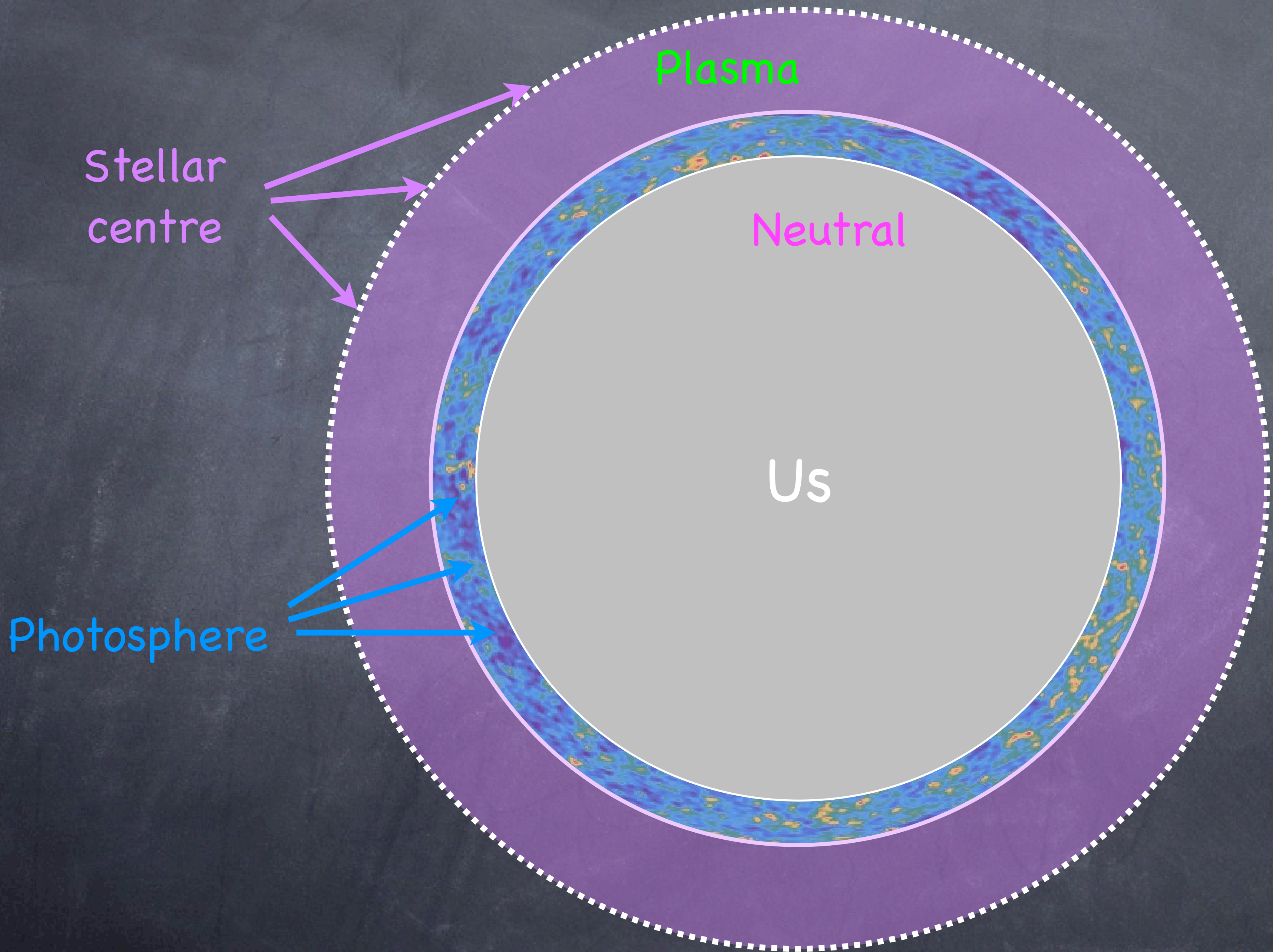
WMAP Science Team

The Universe is an inside-out star!



Crowe, Moss & Scott (in preparation)

The Universe is an inside-out star!



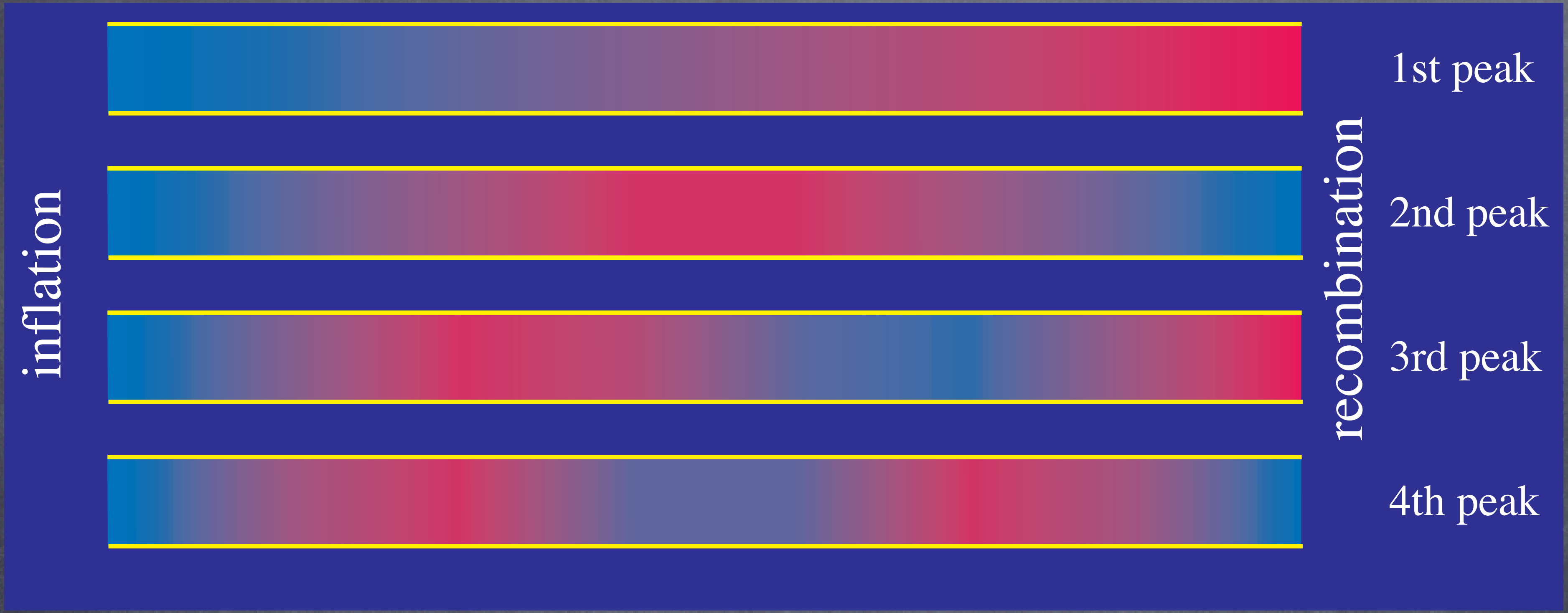
Crowe, Moss & Scott (in preparation)

The Universe is an inside-out star!

The Sun	The Universe
6000K	3000K
Photosphere 0.1% thick	Photosphere 10% thick
Complicated opacity	Thomson scattering
Helioseismology	CMBology
Rotation defines m=0	No special directions
Info from frequencies	Info from power spectra
Stochastic excitation	Synchronized init. conds.
Variability ~5mins	Variability ~Gyrs

Crowe, Moss & Scott (in preparation)

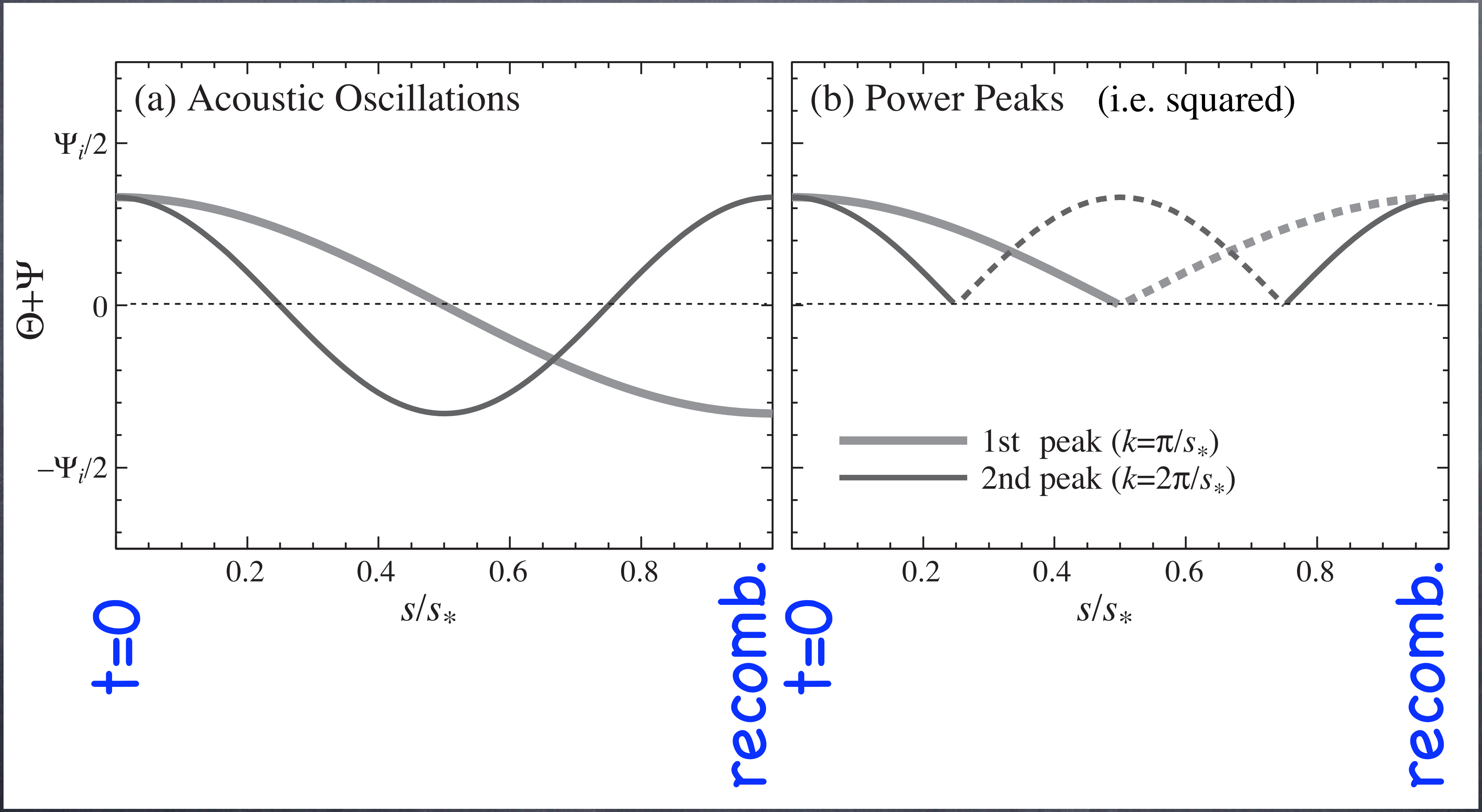
Acoustics



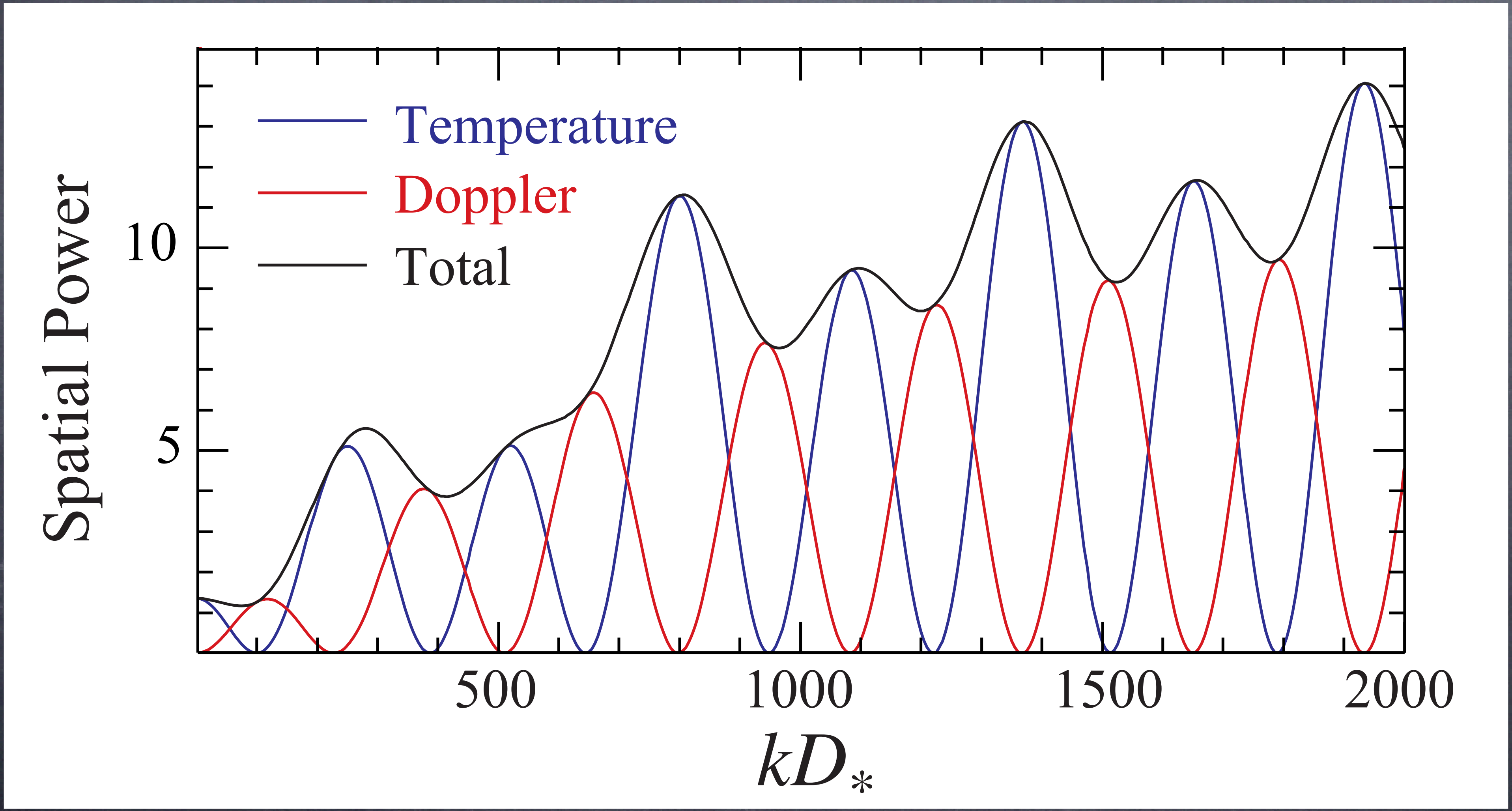
Cosmological perturbations are like standing waves, with a node at t=0, and observed as a snapshot at recombination

Wayne Hu

Origin of acoustic peaks



Temperature effect plus sub-dominant out-of-phase Doppler effect



Multiplied by damping envelope

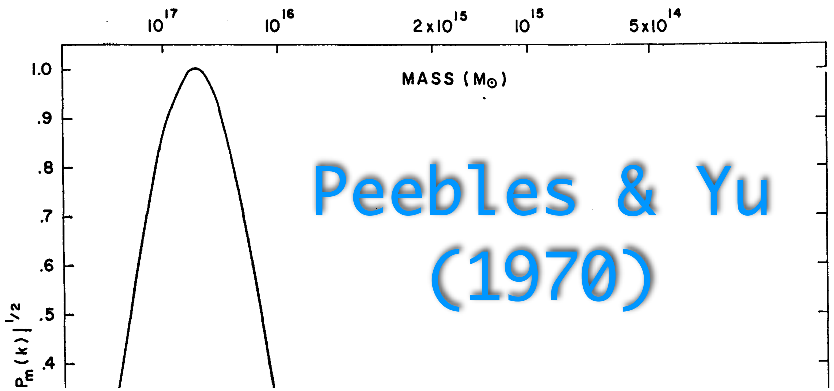
A bit more technical...

- Write distribution function for each fluid:
- $f(p,\theta,\varphi,x)$
- Boltzmann equations: Df/Dt = collisions
- Perform linear perturbations
- Expand in k-modes (for space)
- + l-modes (for angles)
- → coupled hierarchy of Boltzmann equations
- Solve numerically for any (independent) k
- Evolve to obtain P(k) today
- Integrate (carefully) over k and integrate through line-of-sight for power spectra

see Adam Moss' talk

Acoustic

Peebles & Yu (1970)



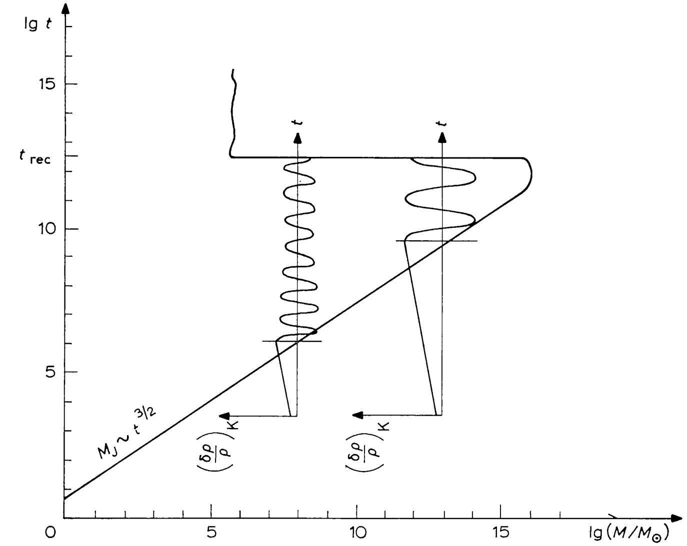


Fig. 1a. Diagram of gravitational instability in the 'big-bang' model. The region of instability is located to the right of the line $M_J(t)$; the region of stability to the left. The two additional lines of the graph demonstrate the temporal evolution of density perturbations of matter: growth until the … is smaller than the Jeans mass and oscillations thereafter. It is … recombination perturbations corresponding to different masses … correspond to different phases.

Wilson & Silk (1981)

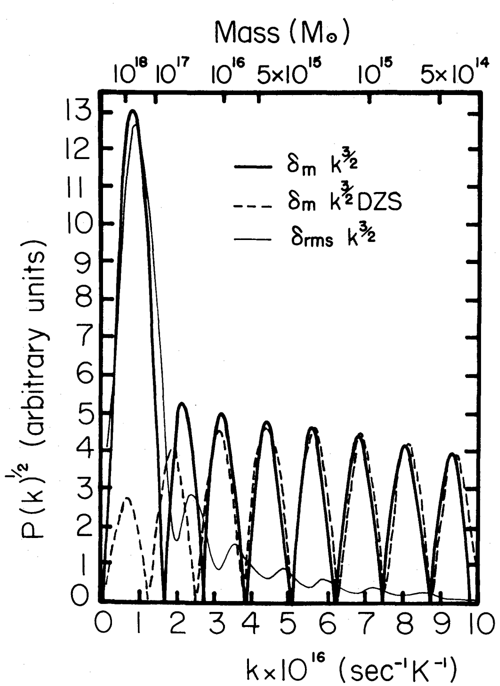
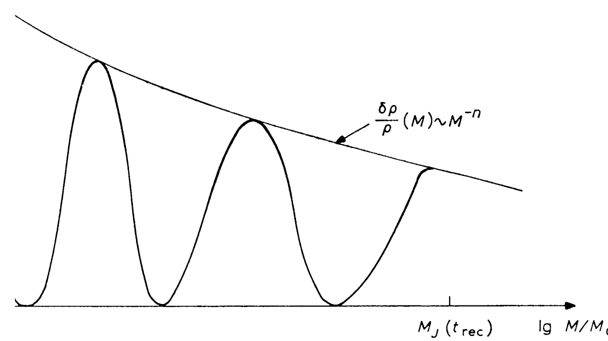
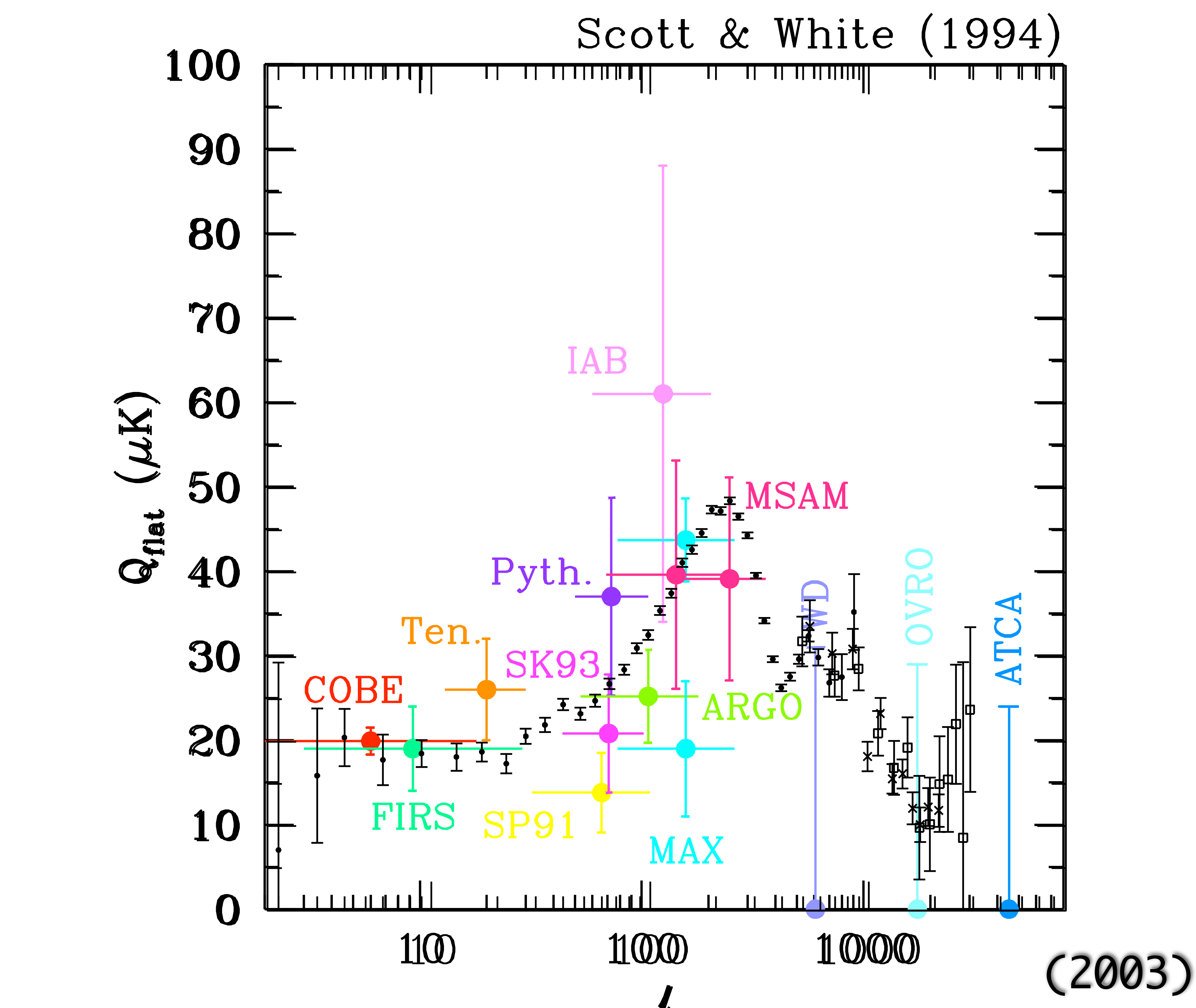


FIG. 1.—Residual matter and radiation adiabatic fluctuation spectra $P(k)=k^3|\delta_m|^2$ for $n=0$. Normalization is arbitrary, but relative normalization is that for $T = 2000$ K. Note that $\delta_m \propto T^{-1}$, whereas δ_{rms} is constant in time. Also shown for comparison is the analytic fit of the residual matter spectrum adopted by Doroshkevich *et al.* (1978), denoted by DZS.

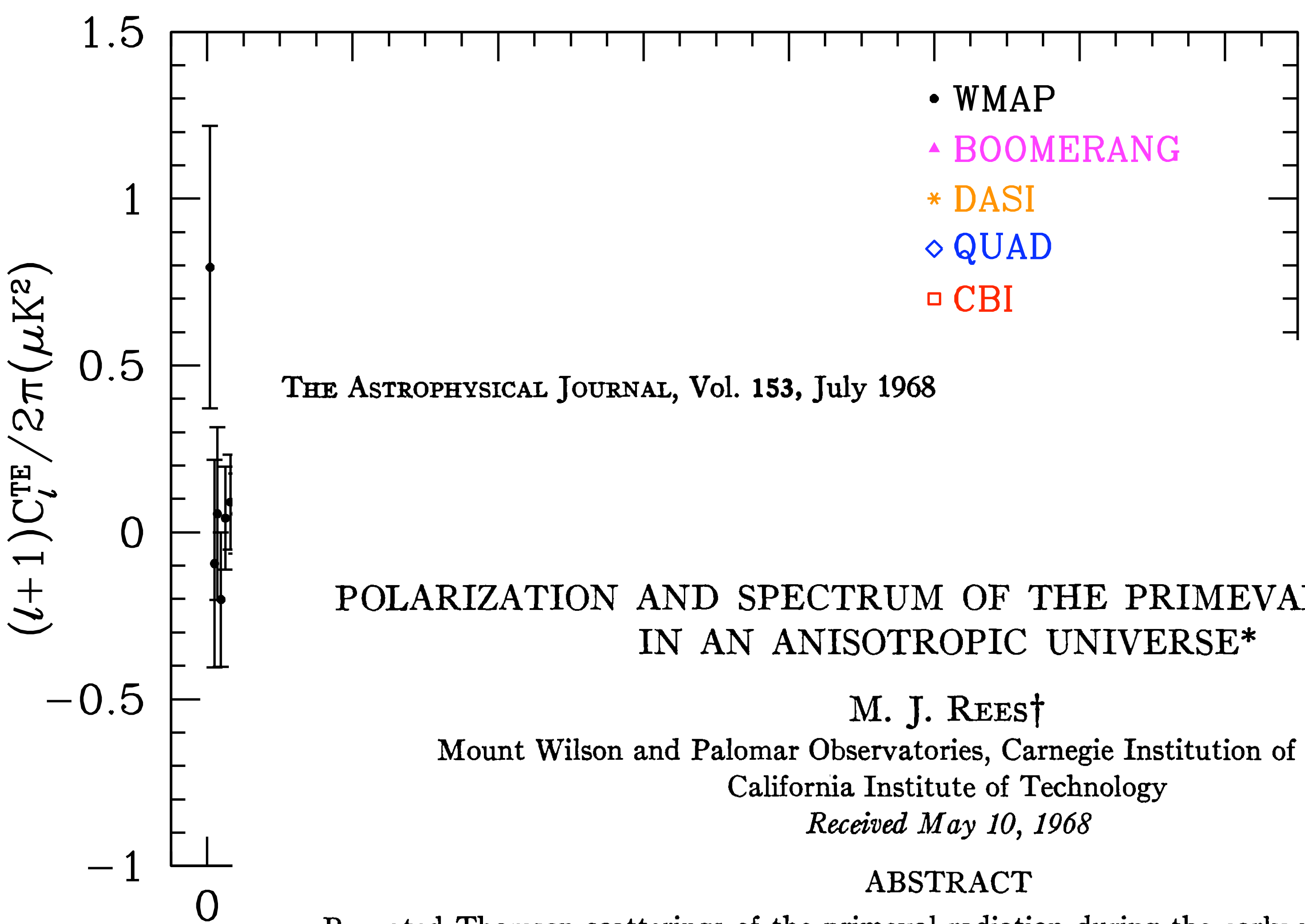
Sunyaev & Zel'dovich (1970)



…uare of the amplitude of density perturbations of matter on scale. … assumed dependence $(\delta\varrho/\varrho)_M \sim M^{-n}$. It is apparent that fluctuation should depend on scale in a similar manner.


Scott & White (1994)
100
90
80
70
60
50
40
30
20
10
0
Q_{flat} (μK)
IAB
MSAM
Pyth.
Ten.
SK93
COBE
ARGO
FIRS
SP91
MAX
WD
OVRO
ATCA
10
100
1000
ℓ
(2003)

CMB Polarization



The Astrophysical Journal, Vol. 153, July 1968

POLARIZATION AND SPECTRUM OF THE PRIMEVAL RADIATION IN AN ANISOTROPIC UNIVERSE*

M. J. Rees†
Mount Wilson and Palomar Observatories, Carnegie Institution of Washington
California Institute of Technology
Received May 10, 1968

ABSTRACT

Repeated Thomson scatterings of the primeval radiation during the early phases of an anisotropic universe would modify the black-body spectrum and produce linear polarization. Calculations are presented for a simple axisymmetric universe, and results for more general cosmological models are summarized. These effects are potentially observable.

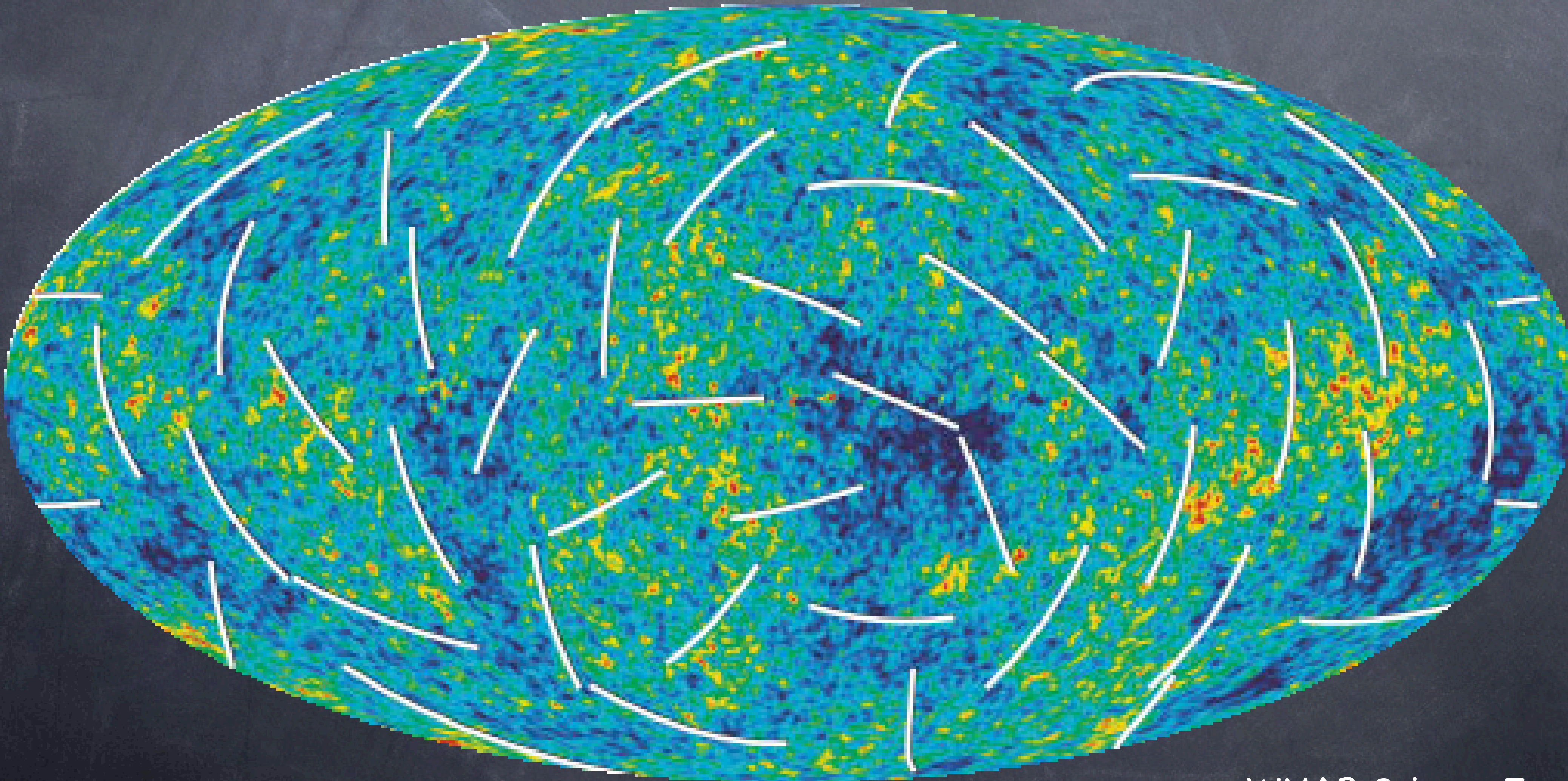
Information in the CMB

- CMB partially polarized
- 2 numbers for each pixel (as well as T)

  ⇨ call these "E" and "B"
- 4 correlations to measure: TT, TE, EE, BB

  ⇨ 4 different power spectra
- (TB and EB are zero)
- plus "non-Gaussian" signatures

All-sky Cosmic Polarization

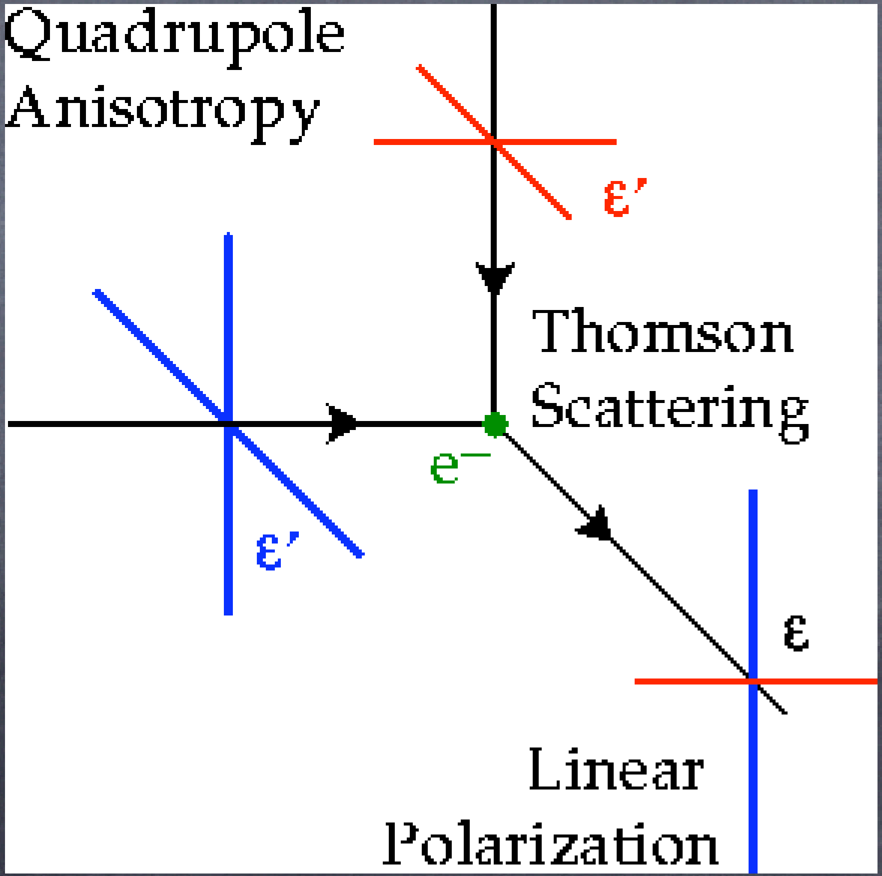


WMAP Science Team

Polarization Observables

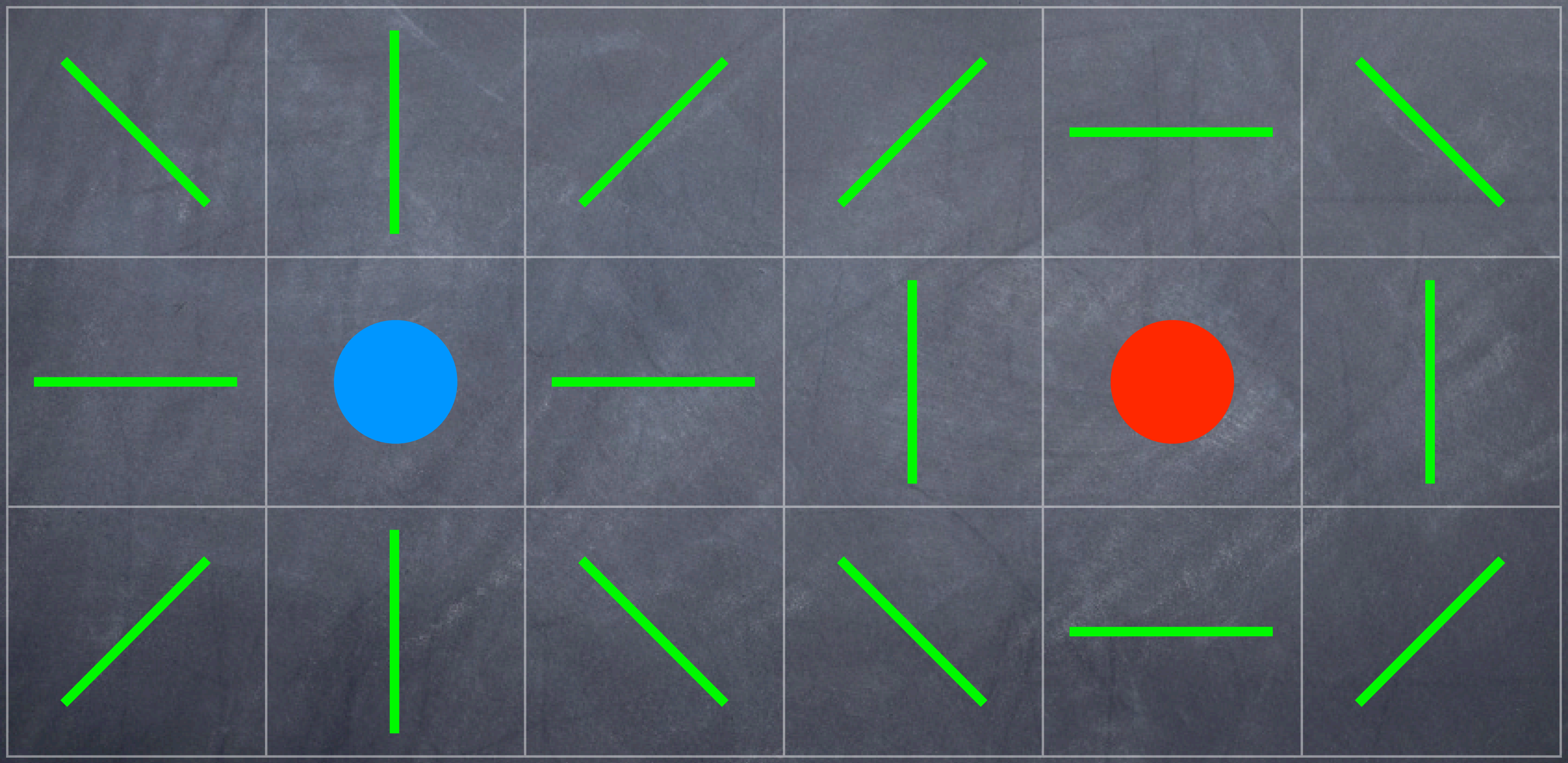
- Linear polarization expected only
- Measure x and y E-fields
- Convert to Q and U Stokes parameters
- Or use pseudo-vectors with $P^2=(Q^2+U^2)$ and $\tan 2\theta = U/Q$
- Or use coordinate-free geometric pair, "E" and "B"

Scattering of anisotropies generates polarization



Hu & White 1997

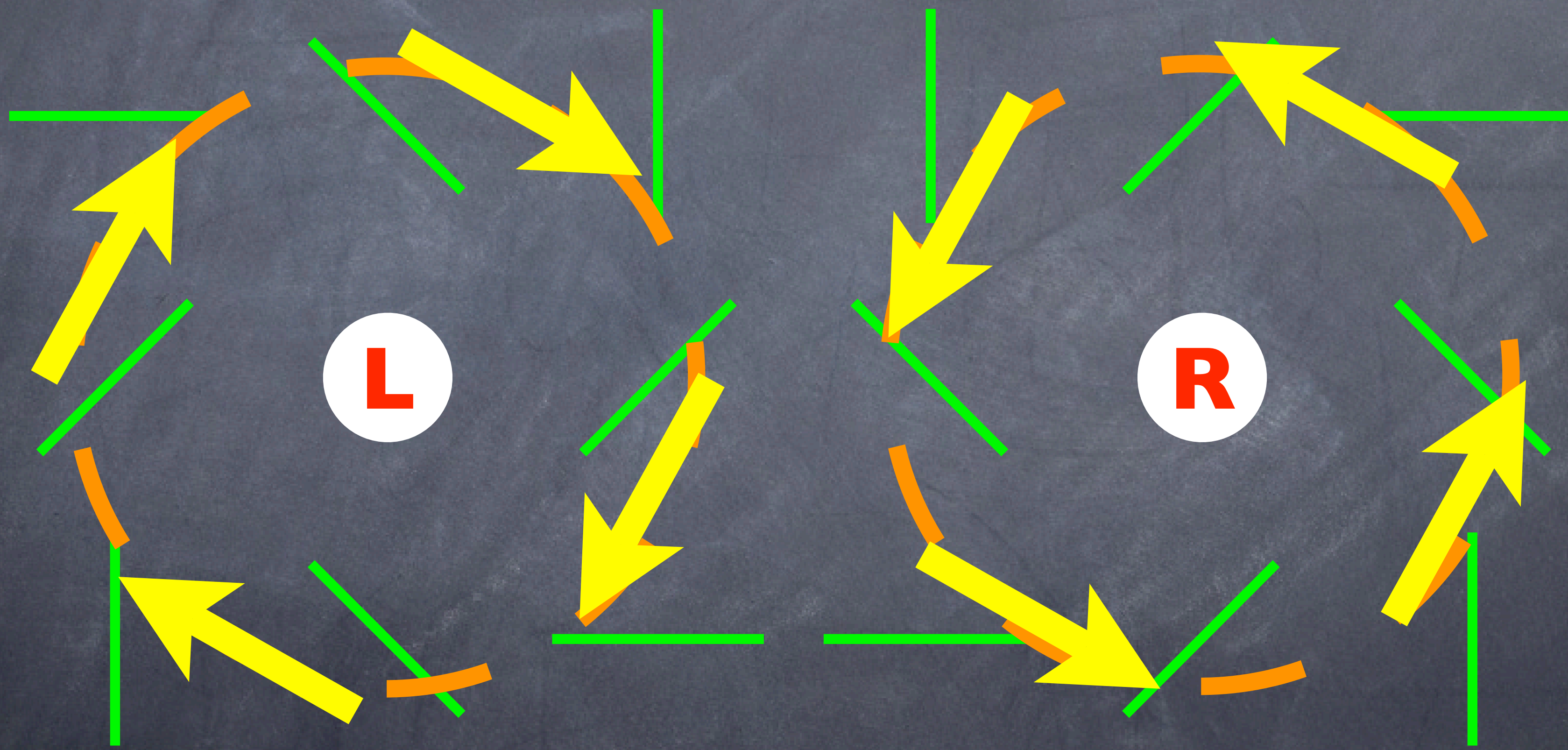
Polarization patterns



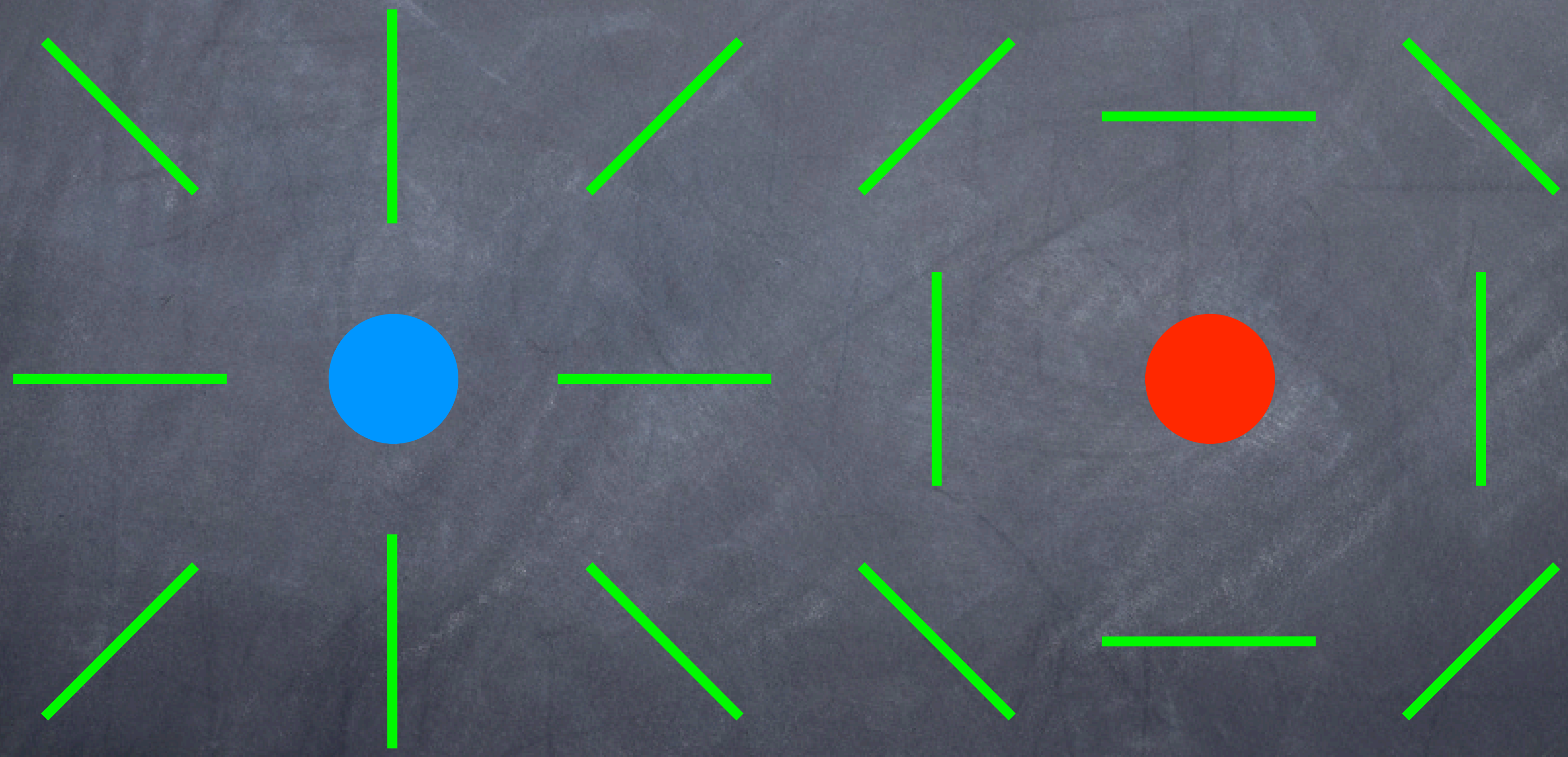
Cold spot

Hot spot

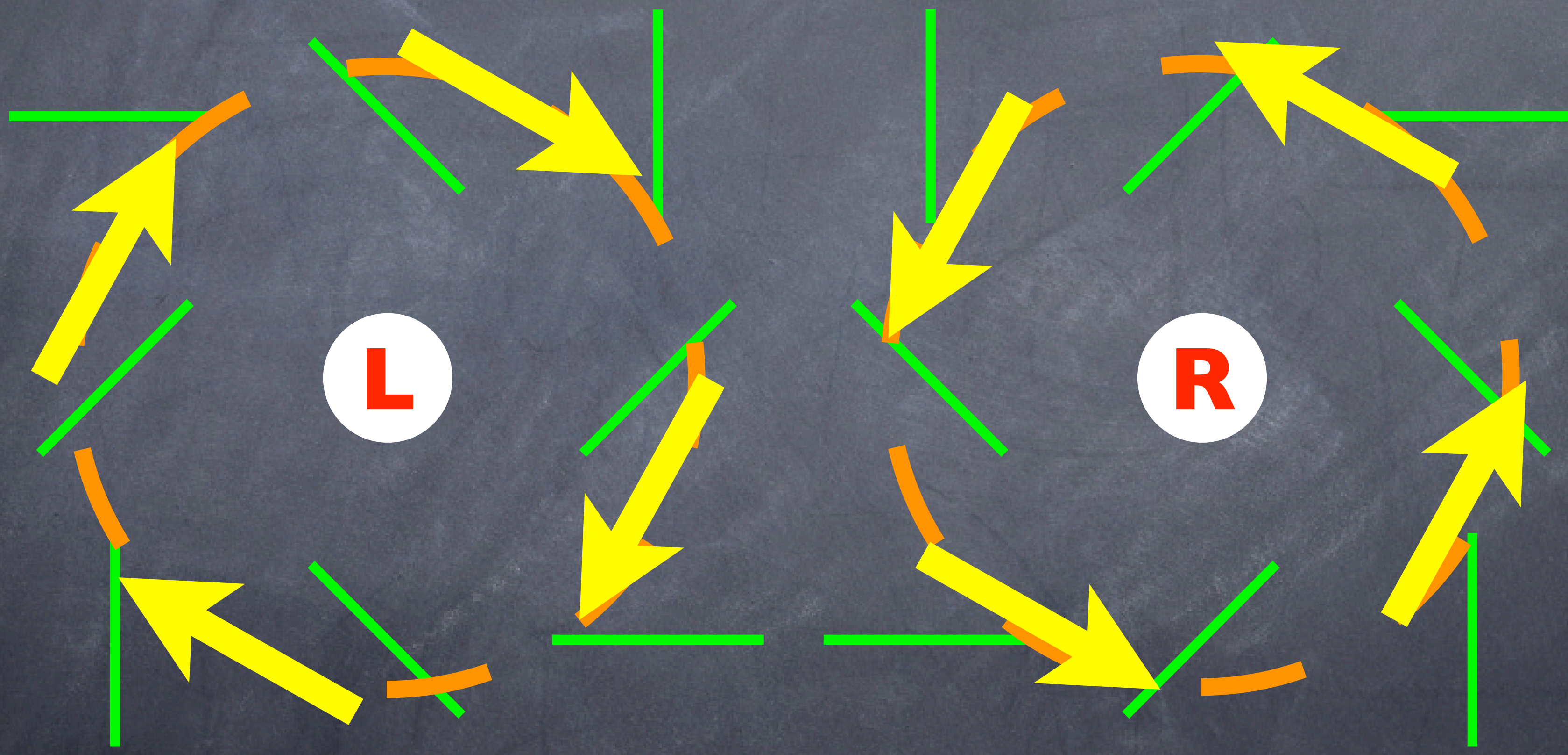
Rotate by 45°



“E modes”



“B modes”



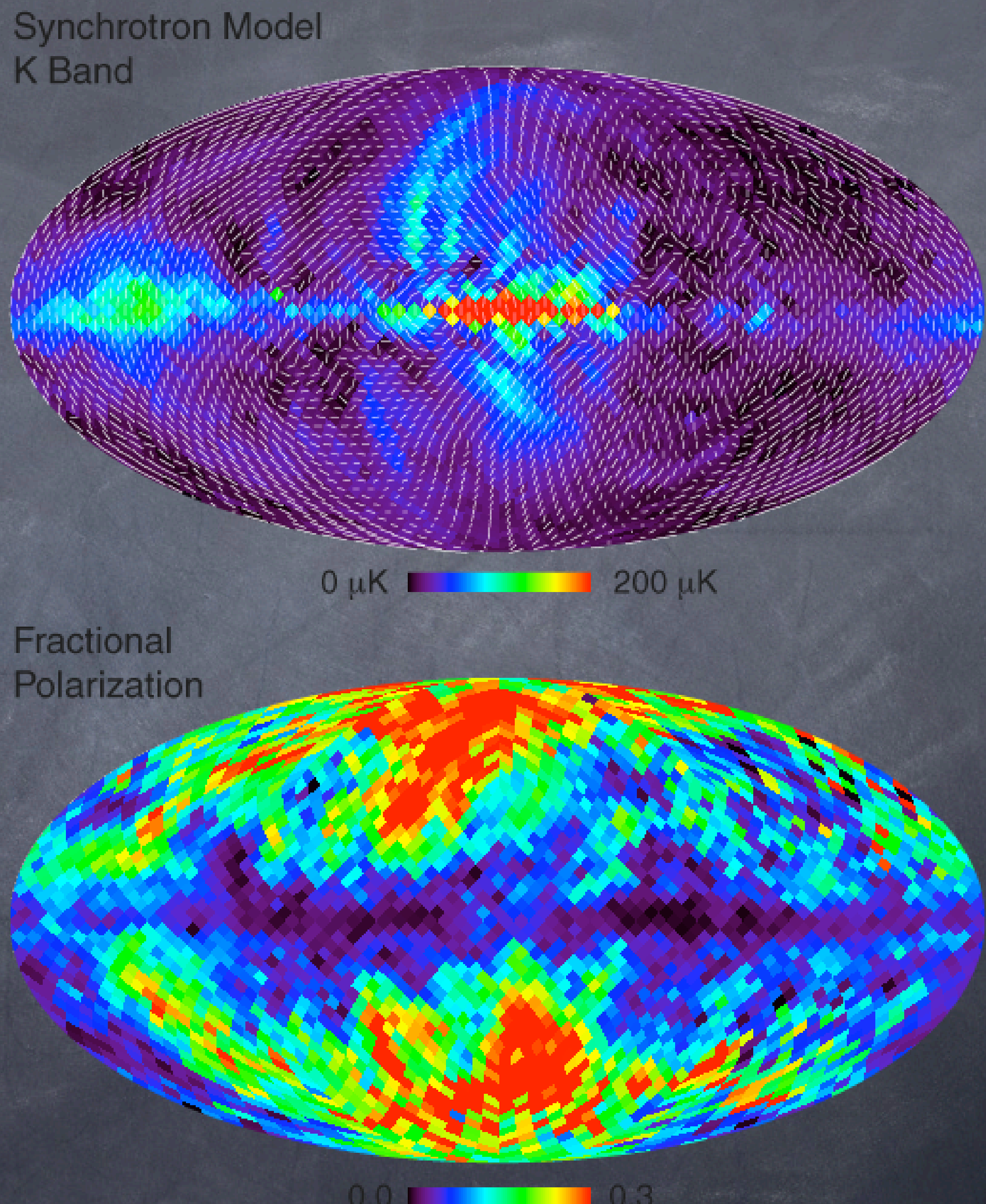
B-modes

- Require source with handedness
  $\Rightarrow$ Gravity waves (not density perts.)
- Gravity waves generated during inflation
  Amplitude $\propto$ inflationary energy scale

  $\Rightarrow$probe of 10^{16} GeV physics!
- Lots of experiments planned -
  Hard!

But...

polarized foregrounds are complicated and MUCH brighter!



Kogut et al. 2007

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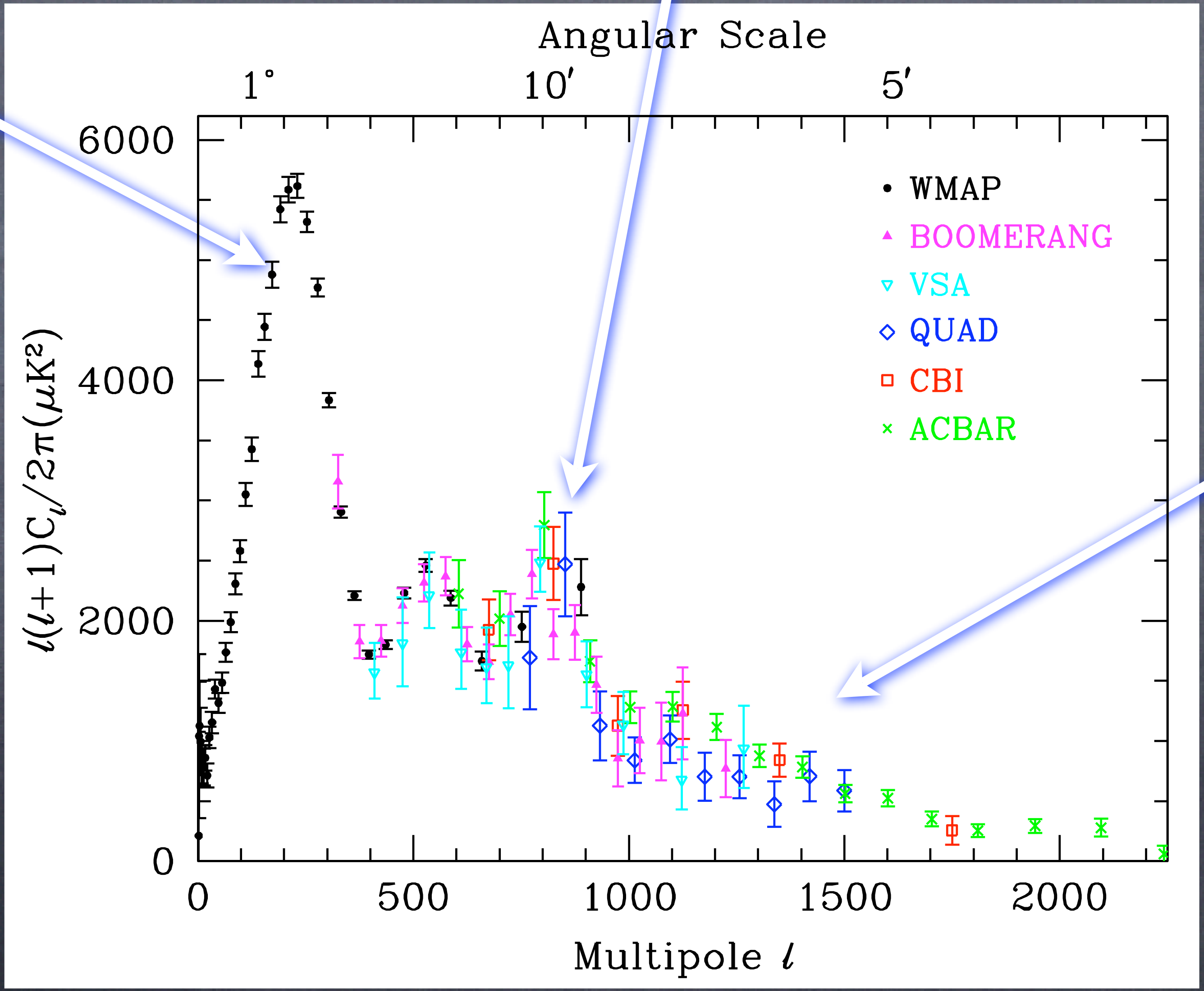
Current CMB anisotropy power spectrum

Main acoustic peak

3rd peak

Damping tail

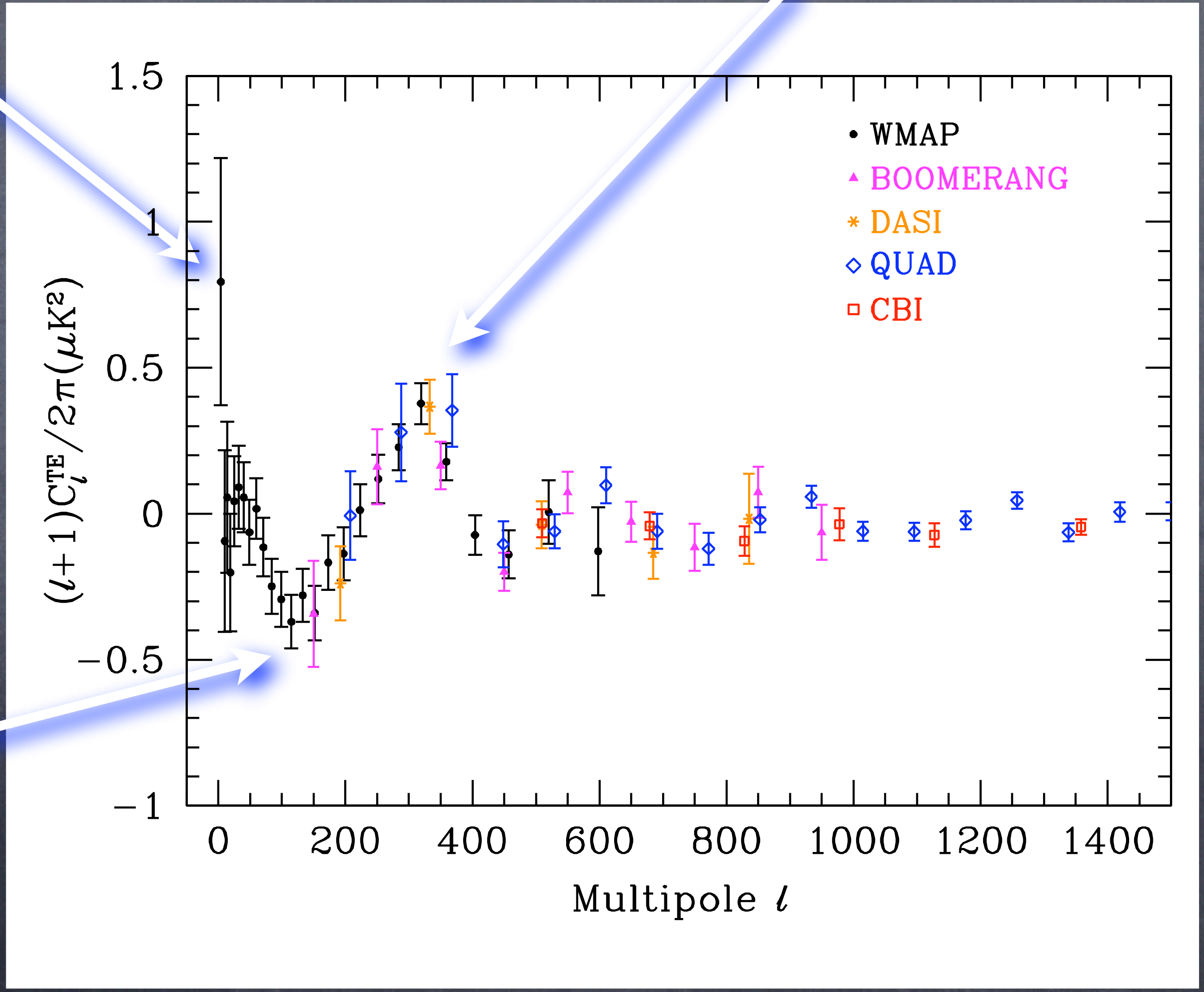


Temperature-Polarization cross spectrum

Reionization

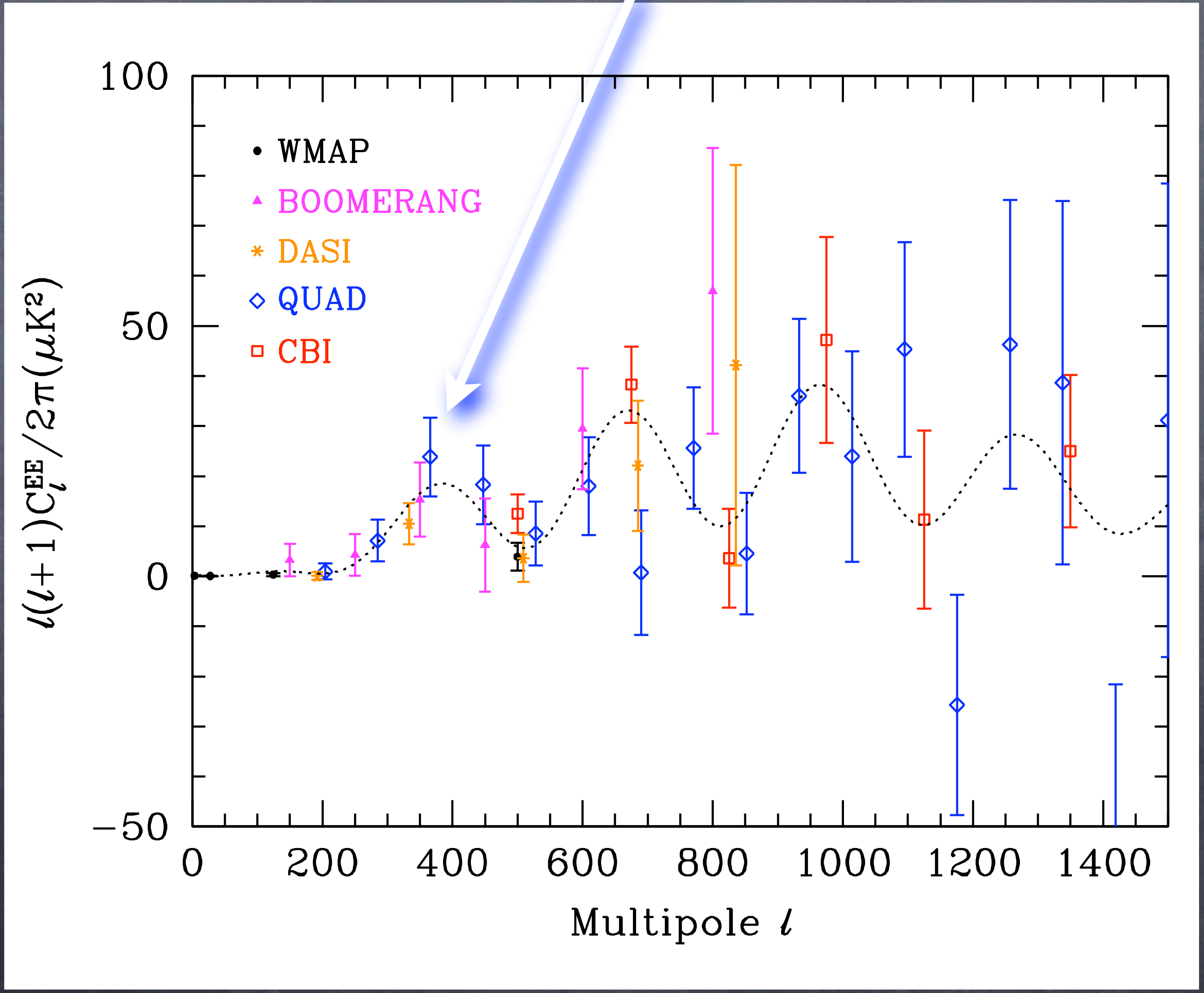
1st peak in TE spectrum

Super-Hubble Anti-correln.



Polarization E-mode spectrum

1st peak corresponds to trough in TT spectrum



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- Lots of experiments planned -
  But HARD!

- If $V=m^2\varphi^2$ and $n\approx0.95$, then $r\equiv T/S\approx0.15$
  $\Rightarrow$ straw-man target exists

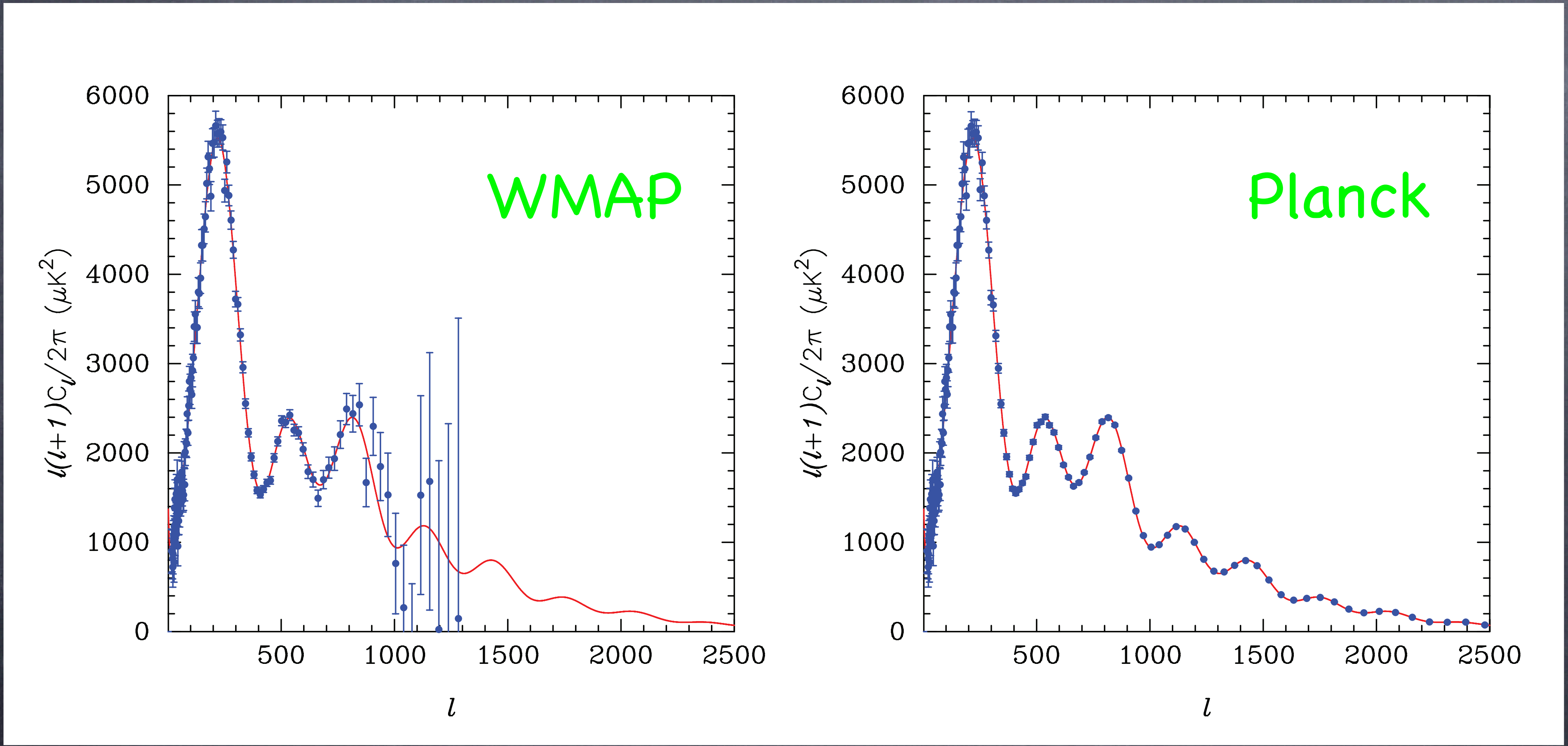
3rd CMB satellite

All sky
5′ resoln.

9 bands:
30-860GHz
(LFI & HFI)

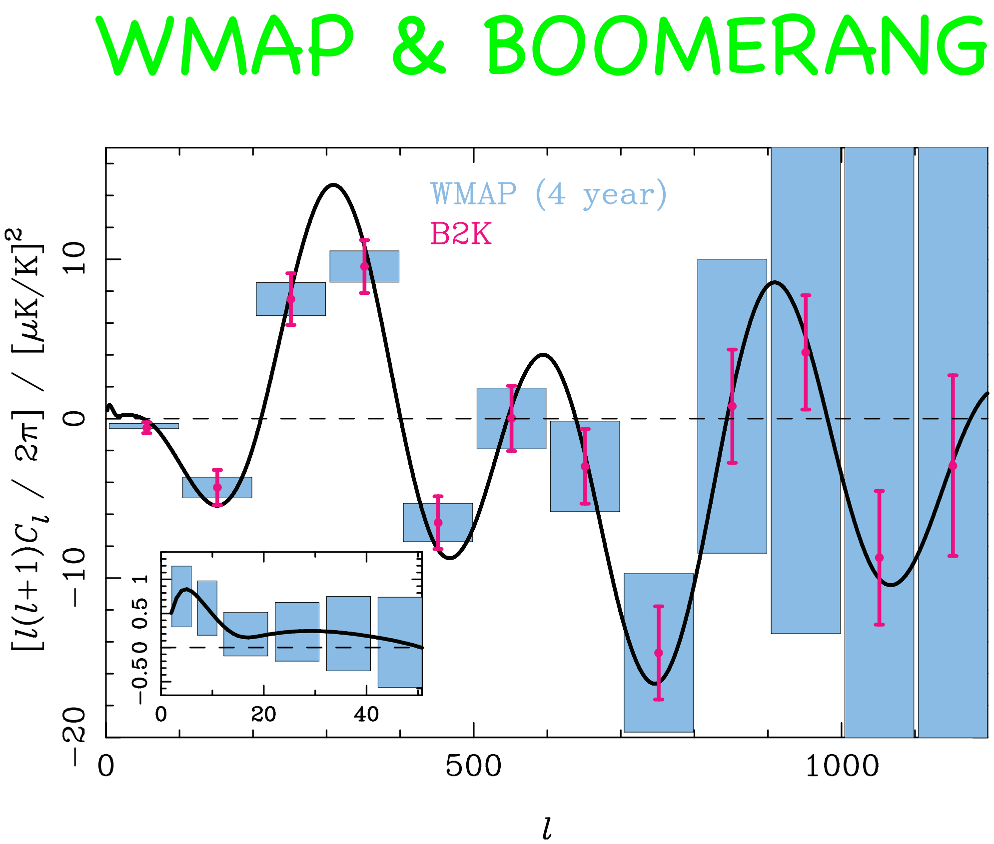
Launch
August
2008

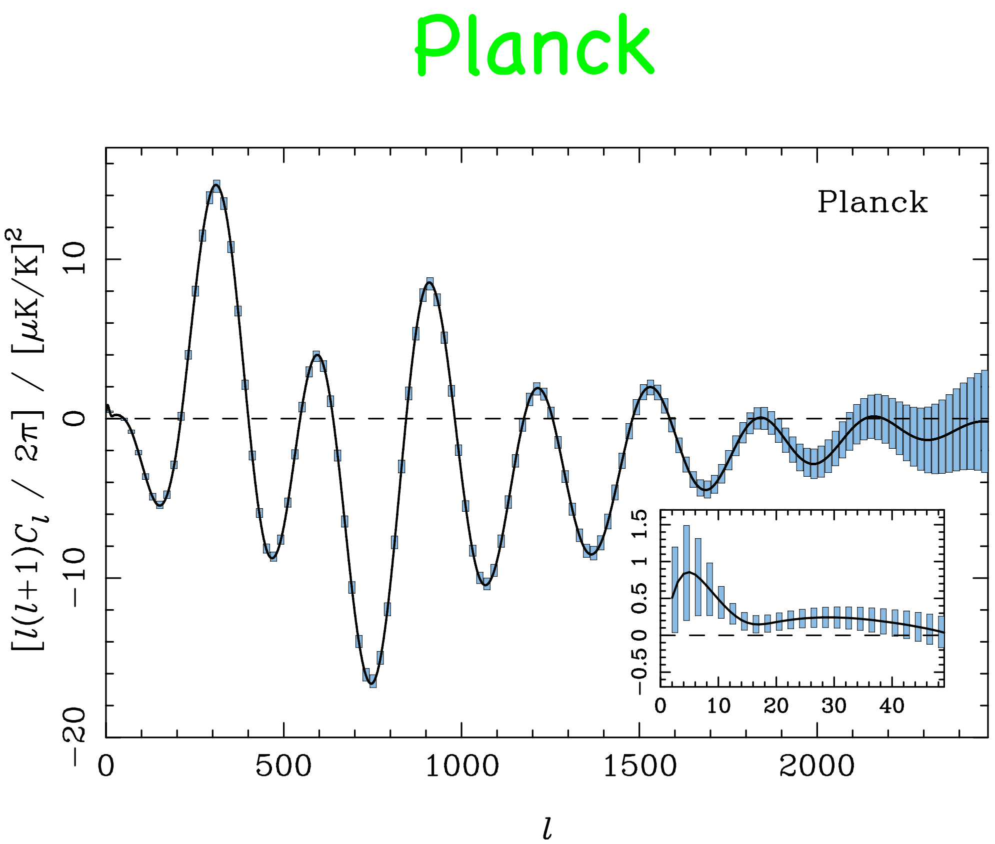
C_ℓ^{TT} forecast



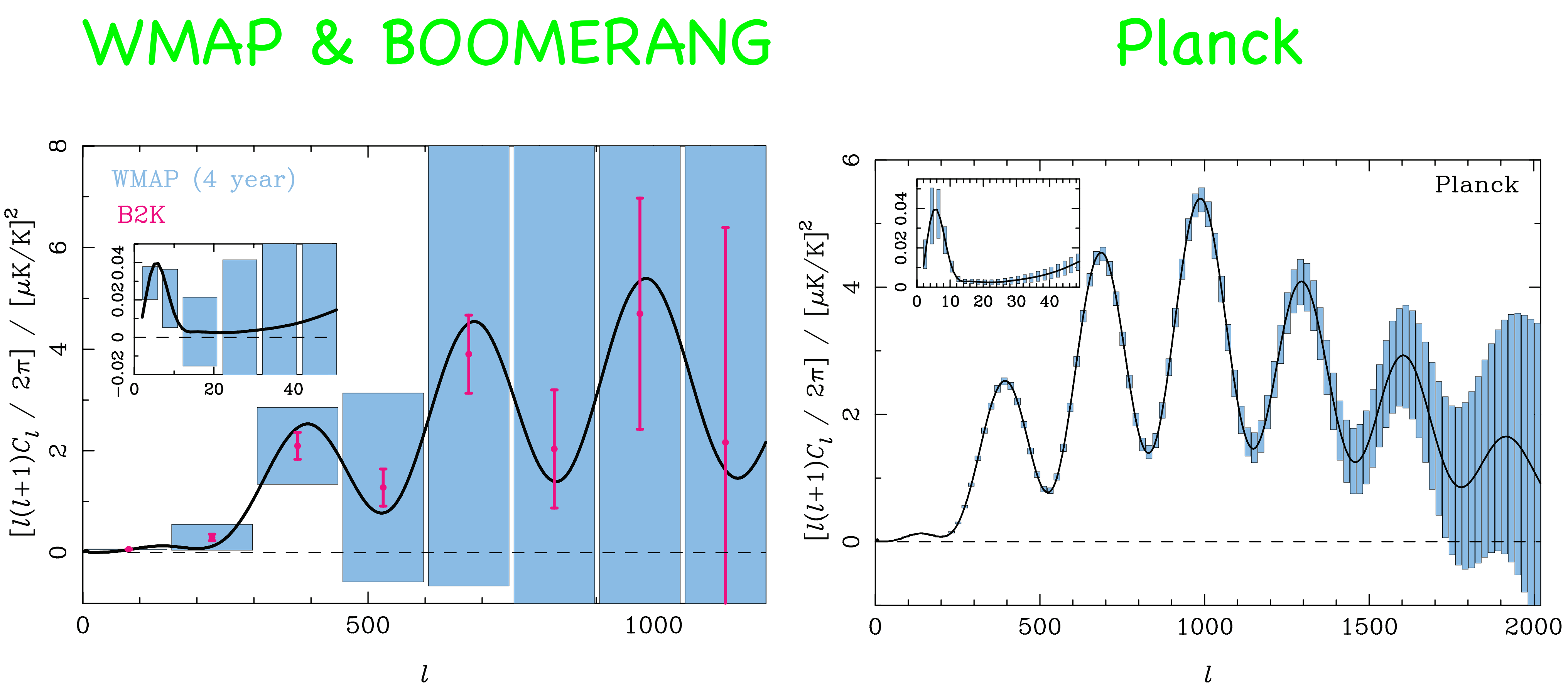
Roughly 16 times more information measured

C_ℓ^{TE} forecast

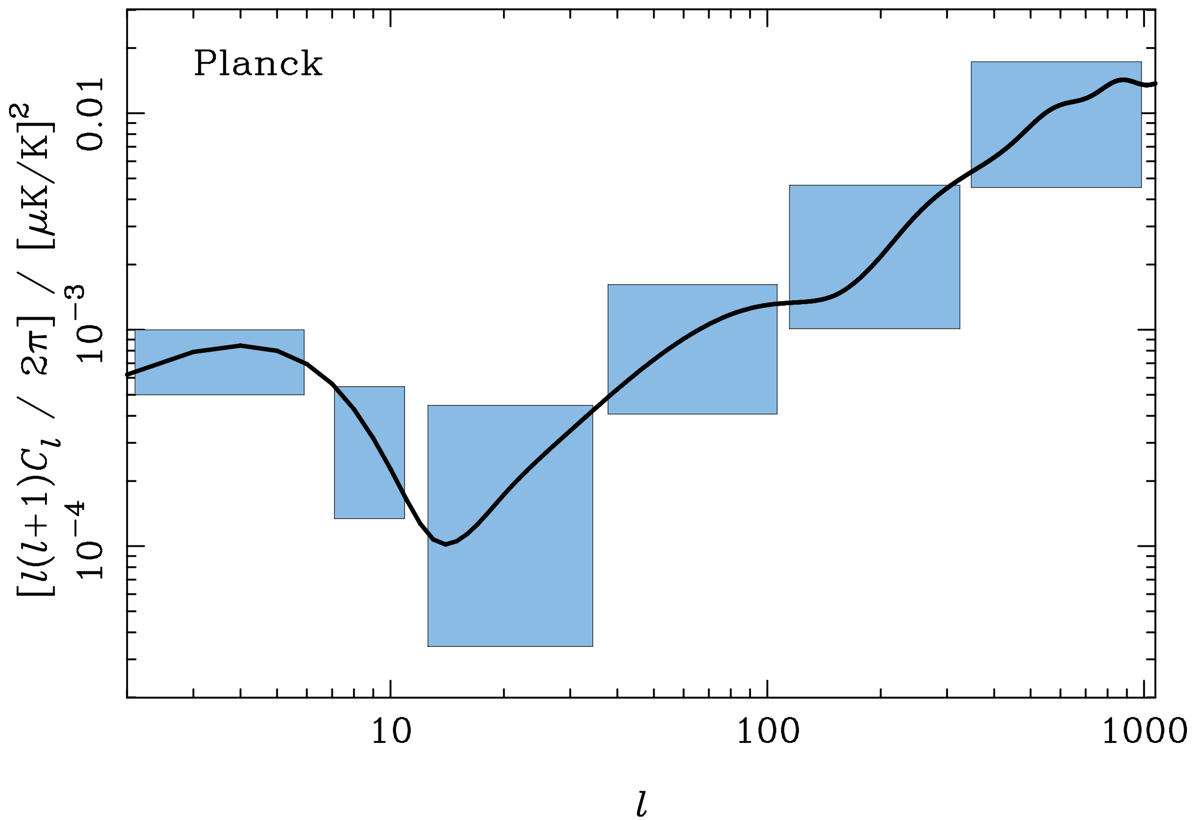




C_ℓ^{EE} forecast



C_ℓ^{BB} forecast



(Assumes
r=0.1
τ=0.17)

Inflationary B-modes **may** be in Planck's reach

Polarization: why bother?

- CMB is polarized as expected
- Confirms Thomson scattering at z=1100
- Out of phase with Temp., confirming adiabatic modes
- Signature of super-horizon fluctuations at large angles
- Reionization signature at largest angles
- Breaks some parameter degeneracies
- Can we detect inflationary B-modes?

Conclusions

- CMB theory in very good shape (linear perturbations + simple physics)
- All will be explained by Adam Moss!
- Clean measurement of details of ICs + cosmic evolution
- Potential for constraining physics at the highest energies
- "Secondary" anisotropies add complexity
- CMB/LSS correlations etc. etc.
- See talk by Gil Holder!

Planck's "Bluebook"

The updated science programme

(astro-ph/0604069)

http://www.rssd.esa.int/SA/PLANCK/docs/Bluebook-ESA-SCI(2005)1_V2.pdf

Low Frequency Instrument

High Frequency Instrument

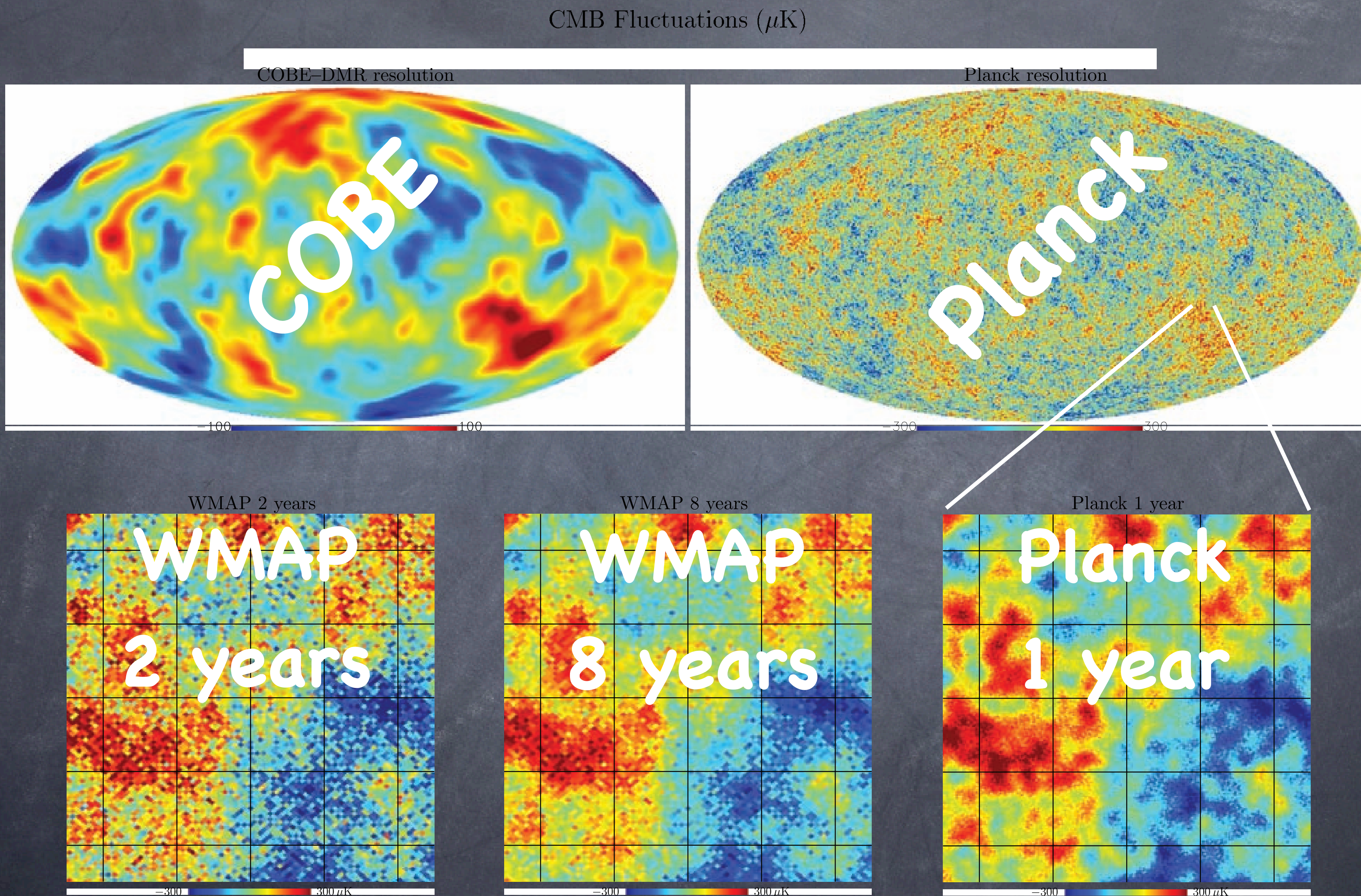
SUMMARY OF PLANCK INSTRUMENT CHARACTERISTICS

INSTRUMENT CHARACTERISTIC	LFI			HFI					
Detector Technology	HEMT arrays			Bolometer arrays					
Center Frequency [GHz]	30	44	70	100	143	217	353	545	857
Bandwidth ($\Delta\nu/\nu$)	0.2	0.2	0.2	0.33	0.33	0.33	0.33	0.33	0.33
Angular Resolution (arcmin)	33	24	14	10	7.1	5.0	5.0	5.0	5.0
$\Delta T/T$ per pixel (Stokes I)[a]	2.0	2.7	4.7	2.5	2.2	4.8	14.7	147	6700
$\Delta T/T$ per pixel (Stokes Q &U)[a]	2.8	3.9	6.7	4.0	4.2	9.8	29.8	...	...

[a] Goal (in μK/K) for 14 months integration, 1σ, for square pixels whose sides are given in the row "Angular Resolution".

Planck specifications

Instrument tests meet the specs!


CMB Fluctuations (μK)
COBE–DMR resolution
Planck resolution
COBE
Planck
−100
100
−300
300
WMAP 2 years
WMAP 8 years
Planck 1 year
WMAP
2 years
WMAP
8 years
Planck
1 year
−300
300 μK
−300
300 μK
−300
300 μK

Planck probes the origin of structure

- If n=0.95 Planck's lever-arm will nail it
  - Large angle polarization helps indirectly
  - Better cluster "SZ" estimate also helps
- Simplest inflationary models imply r~0.1
  - Inflationary B-modes may be in Planck's reach:
  - energy scale of inflation may be measurable!

- The Universe deserves to have its parameters measured well
- More parameter degeneracies broken
- Tighter reionization optical depth measurement
- Precise last-scattering distance for Dark Energy probes
- Better primordial non-Gaussianity limits
- Improved isocurvature constraints
- Wide frequency measurement of lowest multipoles
- Cleaner large-angle polarized foreground discrimination
- Large cluster survey through Sunyaev-Zel'dovich signature
- Measurement of large-scale structure SZ signal
- Correlation between large and small scales through lensing
- Detection of small-scale lensing B-mode signature
- Integrated Sachs-Wolfe effect correlations with structure
- Extragalactic point source catalogue at 9 frequencies
- All sky, complete picture of the Galaxy at large scales
- Investigation of "anomalous" dust
- Galactic magnetic field studies
- Plan for full-blown B-mode mission
- Search for unexpected things!
- More computer presentations