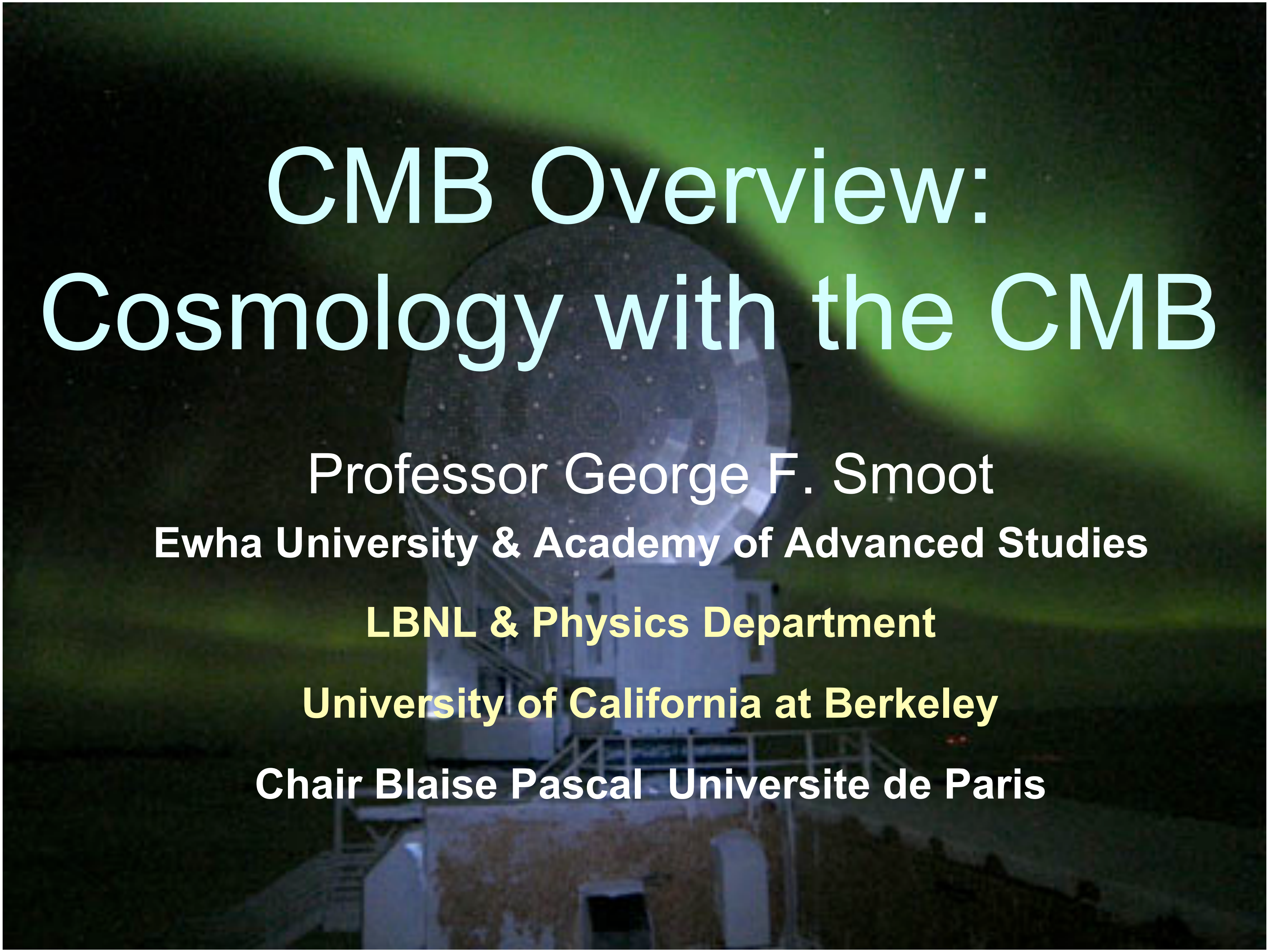


CMB Overview: Cosmology with the CMB

Professor George F. Smoot

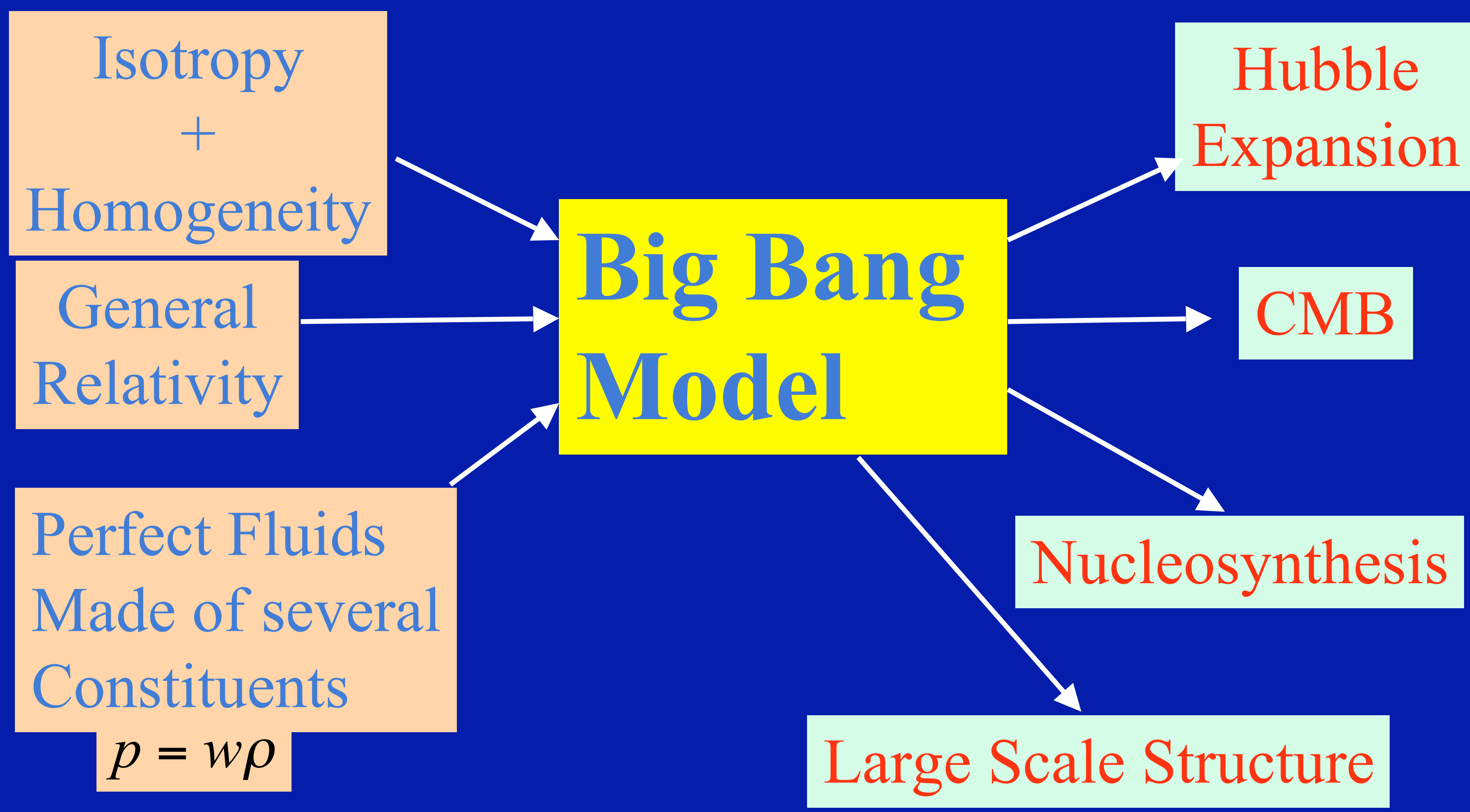
Ewha University & Academy of Advanced Studies

LBNL & Physics Department

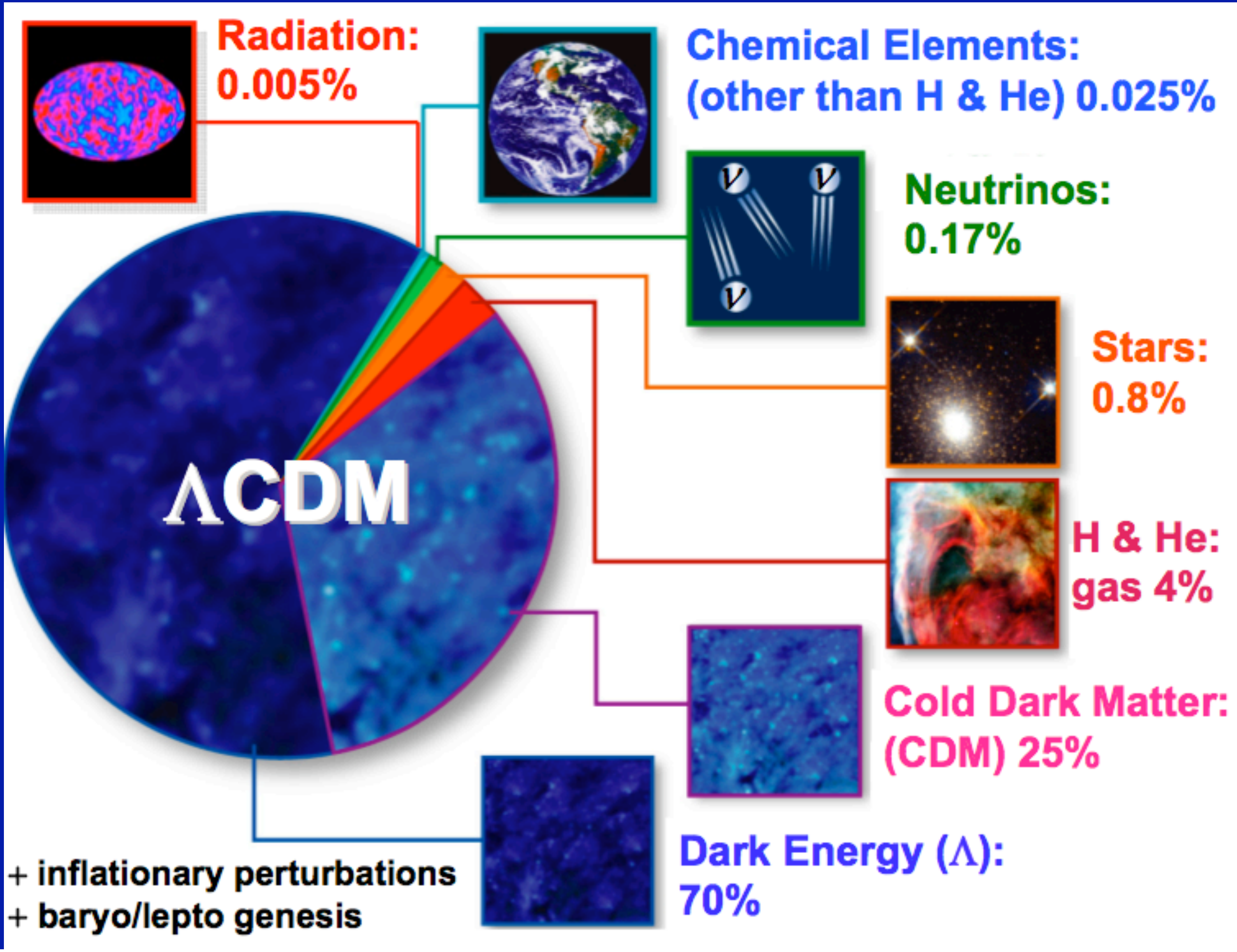
University of California at Berkeley

Chair Blaise Pascal Universite de Paris

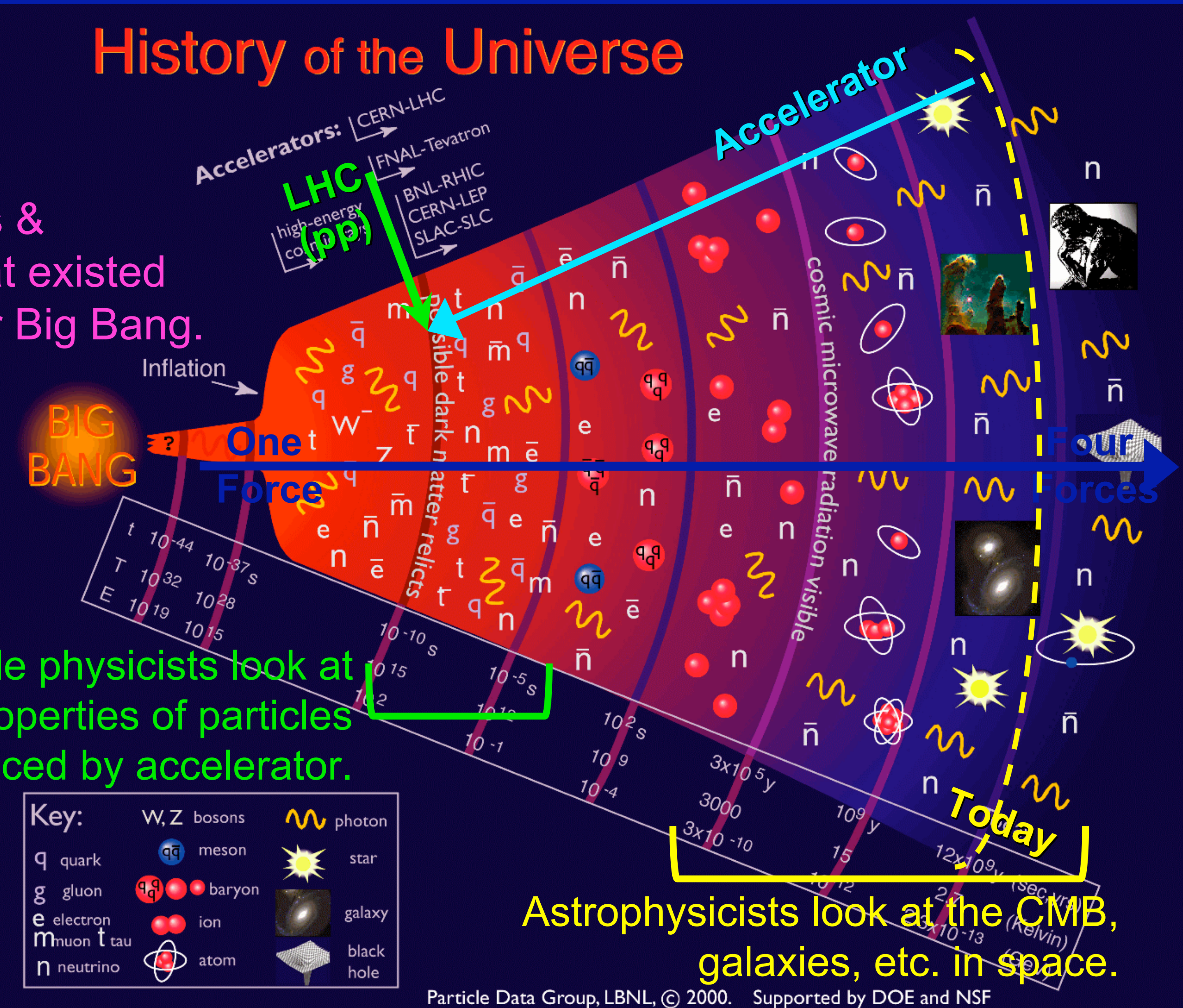
The Standard Big Bang Model: The Basic Framework



Dark Energy, Dark Matter & other Constituents Along with their equations of state (Lagrangian)



Create particles & antiparticles that existed ~ 0.001 ns after Big Bang.

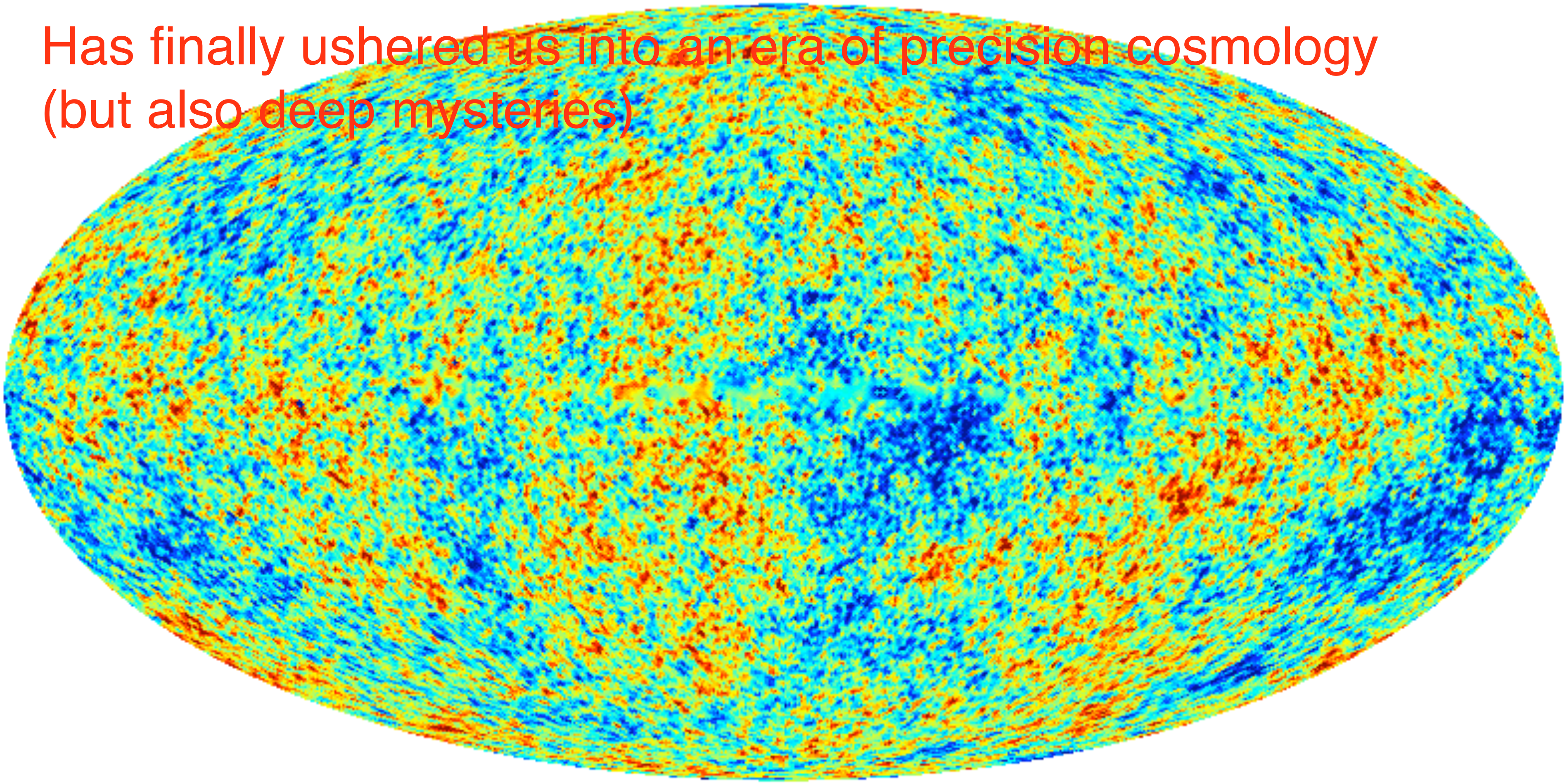


Particle physicists look at the properties of particles produced by accelerator.

Astrophysicists look at the CMB, galaxies, etc. in space.

The Cosmic Microwave Background

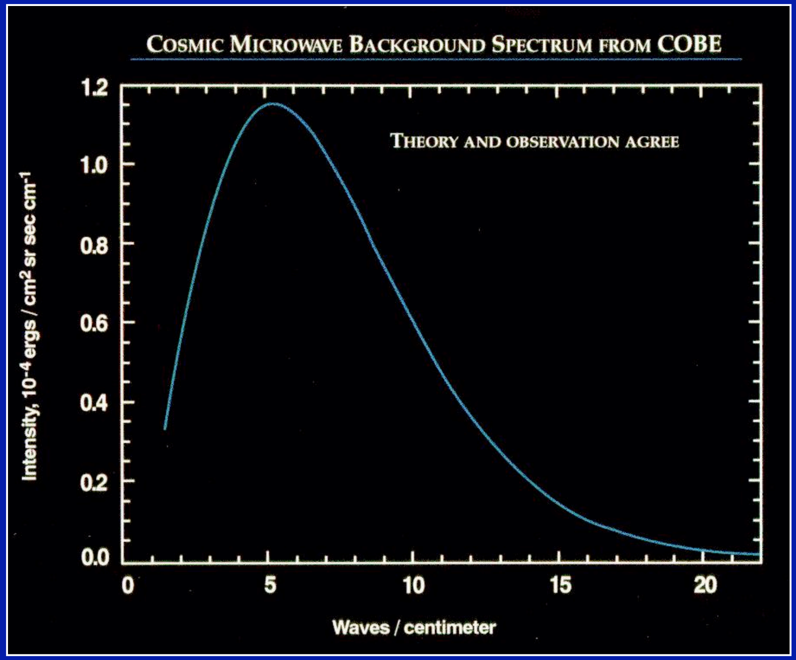
- The Cosmic Microwave Background (CMB) is a wonderful and critical tool in modern cosmology
- A very significant fraction of all the information in cosmology over the last 10 to 15 years has come from it
- Has finally ushered us into an era of precision cosmology (but also deep mysteries)

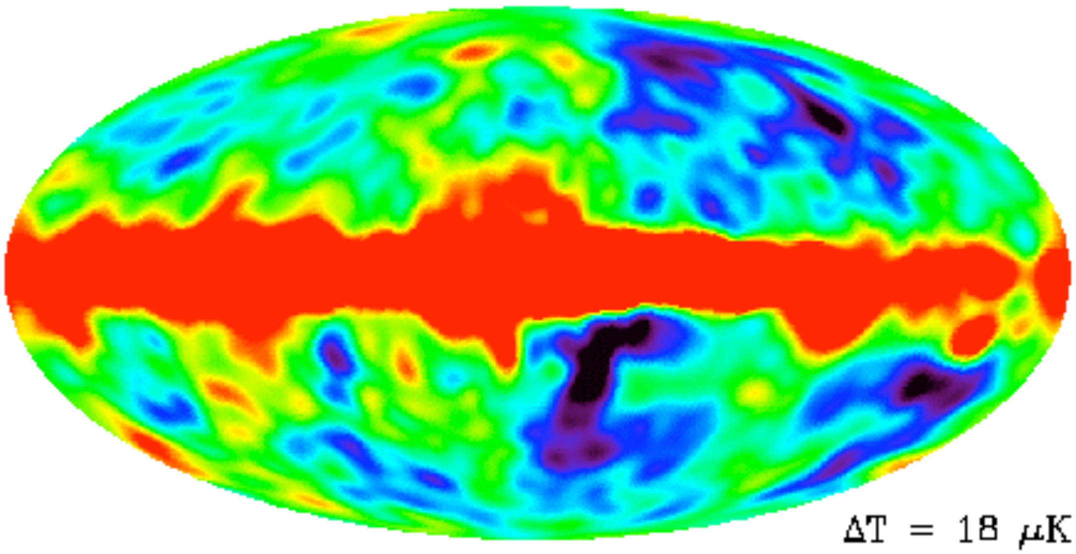


The Cosmic Microwave Background

Discovered 1965 (Penzias & Wilson)
- 2.7 K blackbody
- Isotropic (<1%)
- Relic of hot "big bang"

1970's and 1980's
- 3 mK dipole (local Doppler)
- $\delta T/T < 10^{-5}$ on arcminute scales



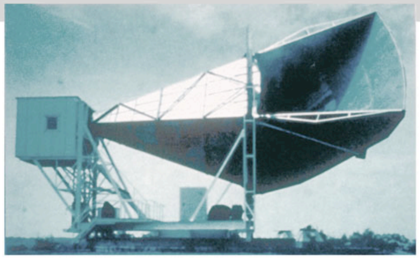


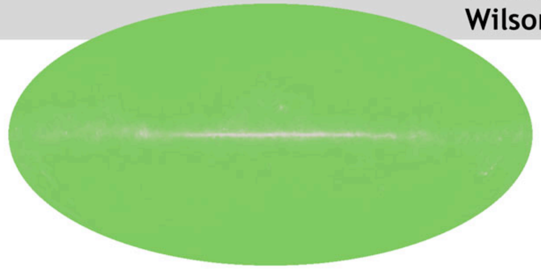
- COBE 1992
  - Blackbody 2.728 K
  - $\ell < 30$: $\delta T/T \approx 10^{-5}$

Cosmic Microwave Background Radiation Overview

The oldest light in universe

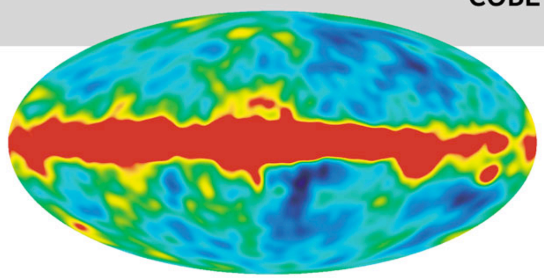
1965 — Penzias and Wilson





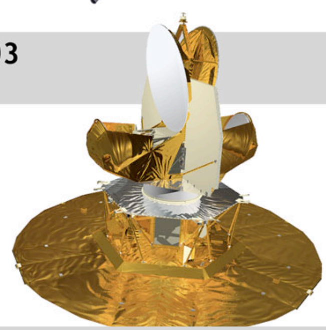
Discovered the remnant afterglow from the **Big Bang**.
→ **2.7 K**

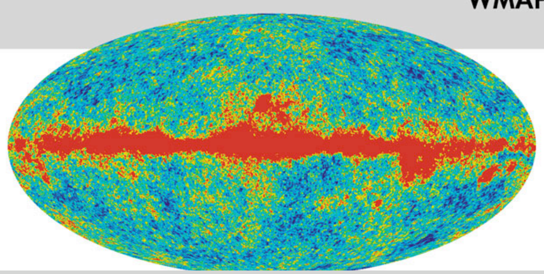
1992 — COBE



Blackbody radiation, Discovered the patterns (**anisotropy**) in the afterglow.
→ **angular scale ~ 7°** at a level $\Delta T/T$ of 10^{-5}

2003 — WMAP

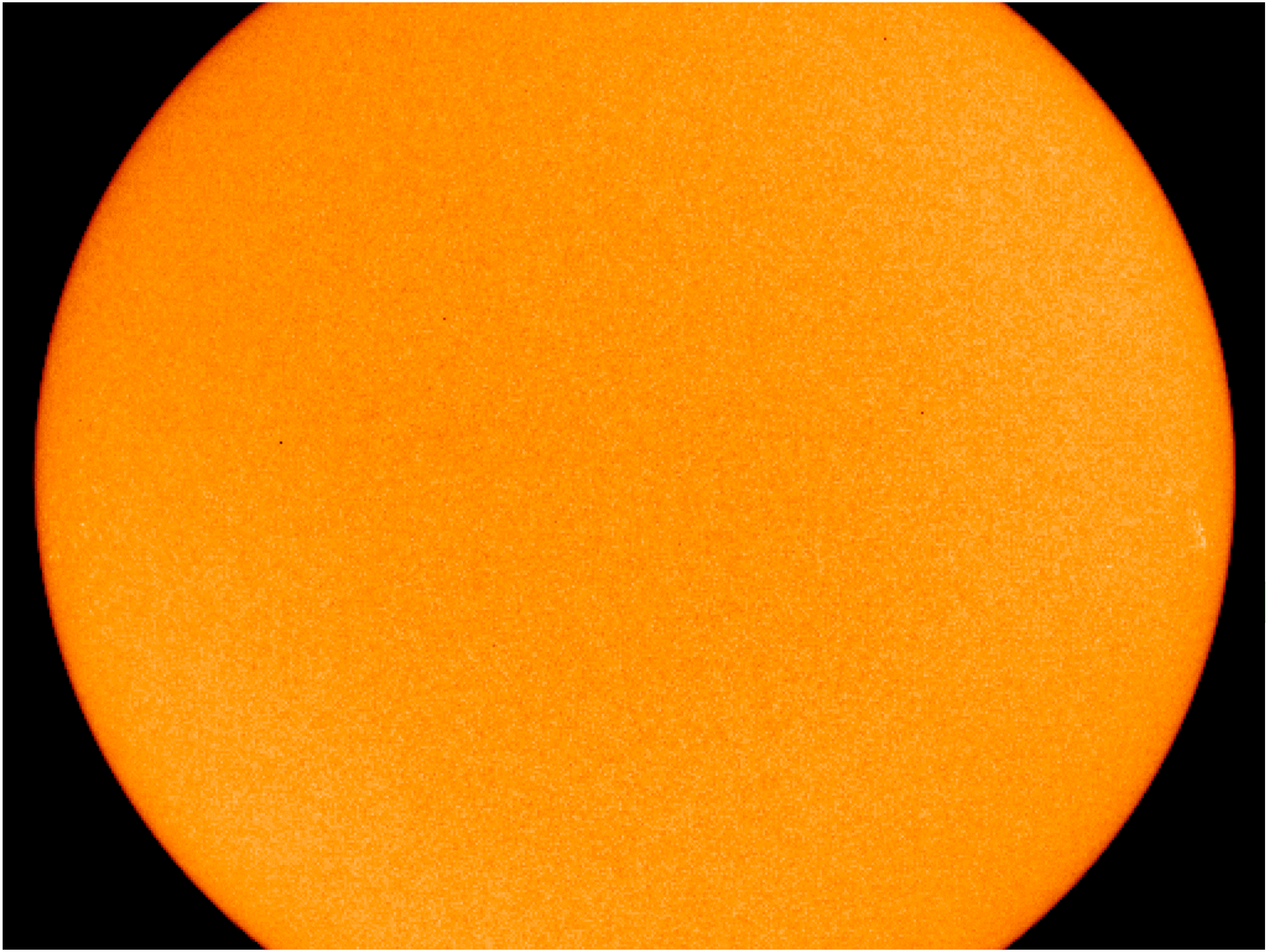




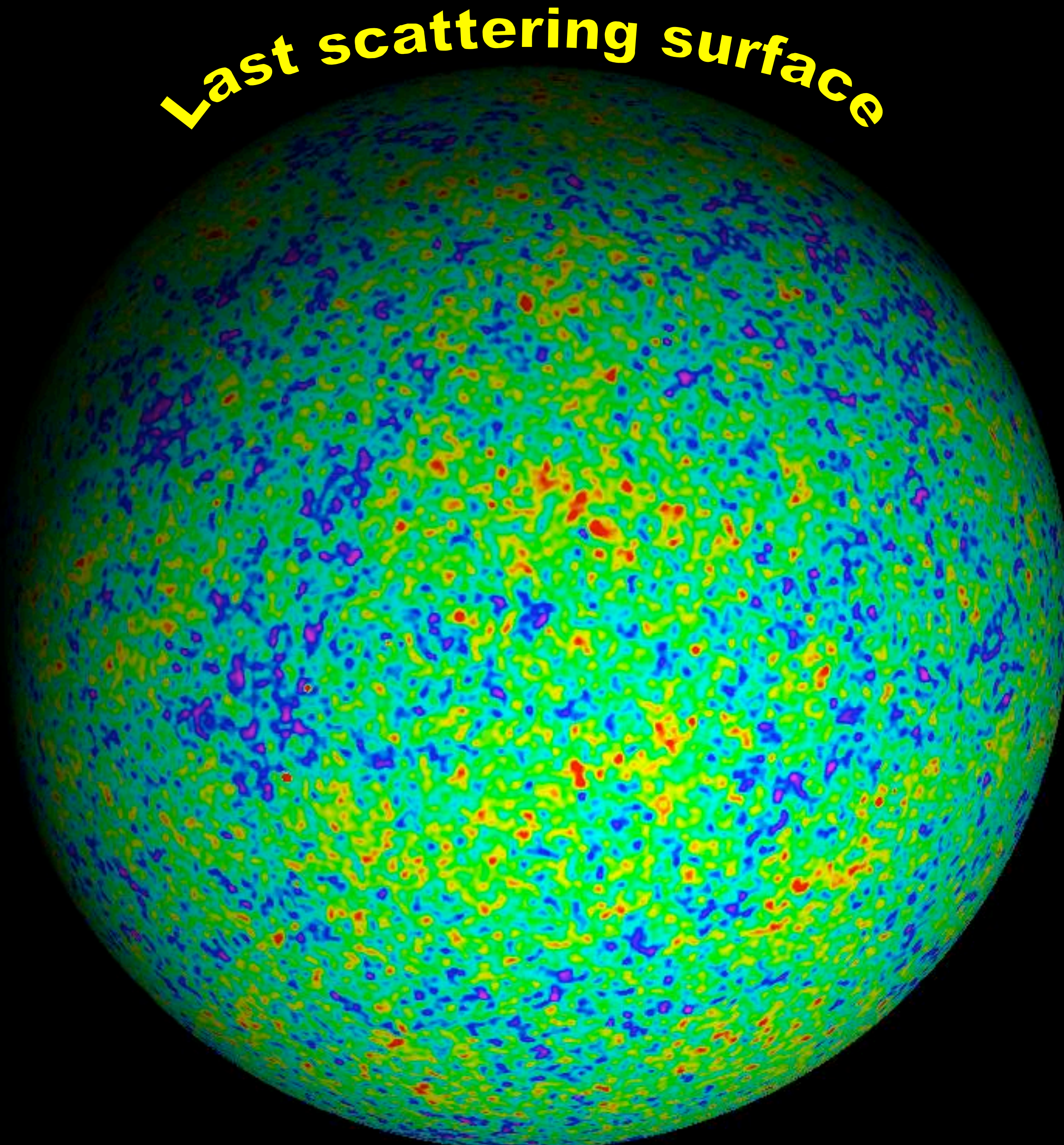
(Wilkinson Microwave Anisotropy Probe):
→ **angular scale ~ 15'**

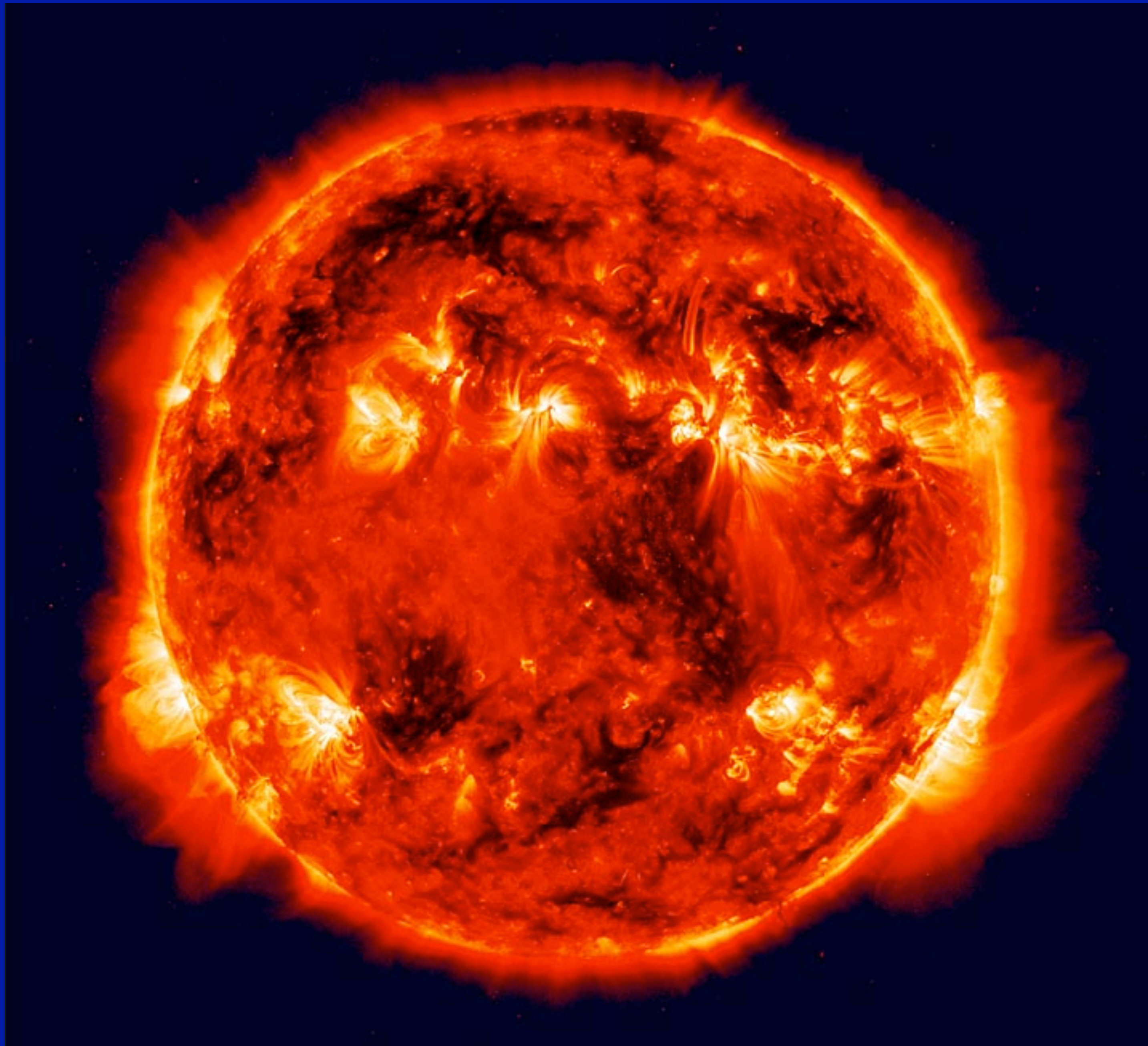
2009 — Planck

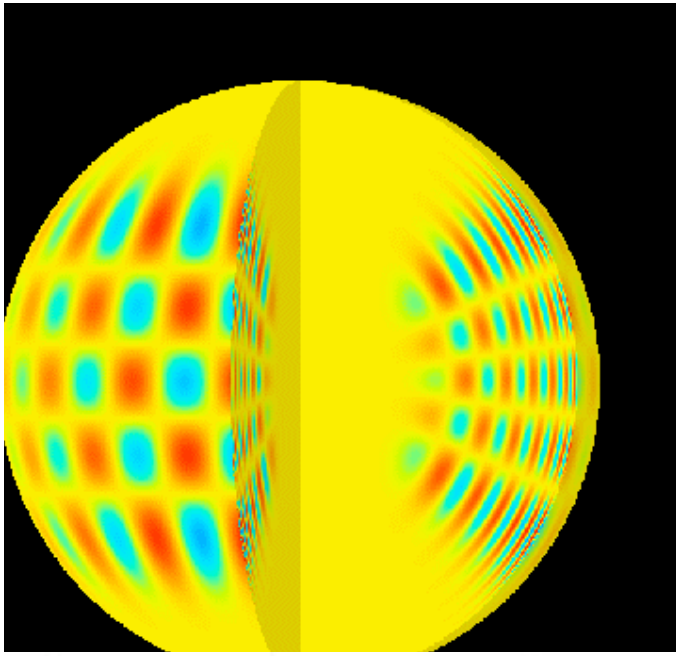
→ **angular scale ~ 5',**
$\Delta T/T \sim 2\times10^{-6}$, 30~867 Hz



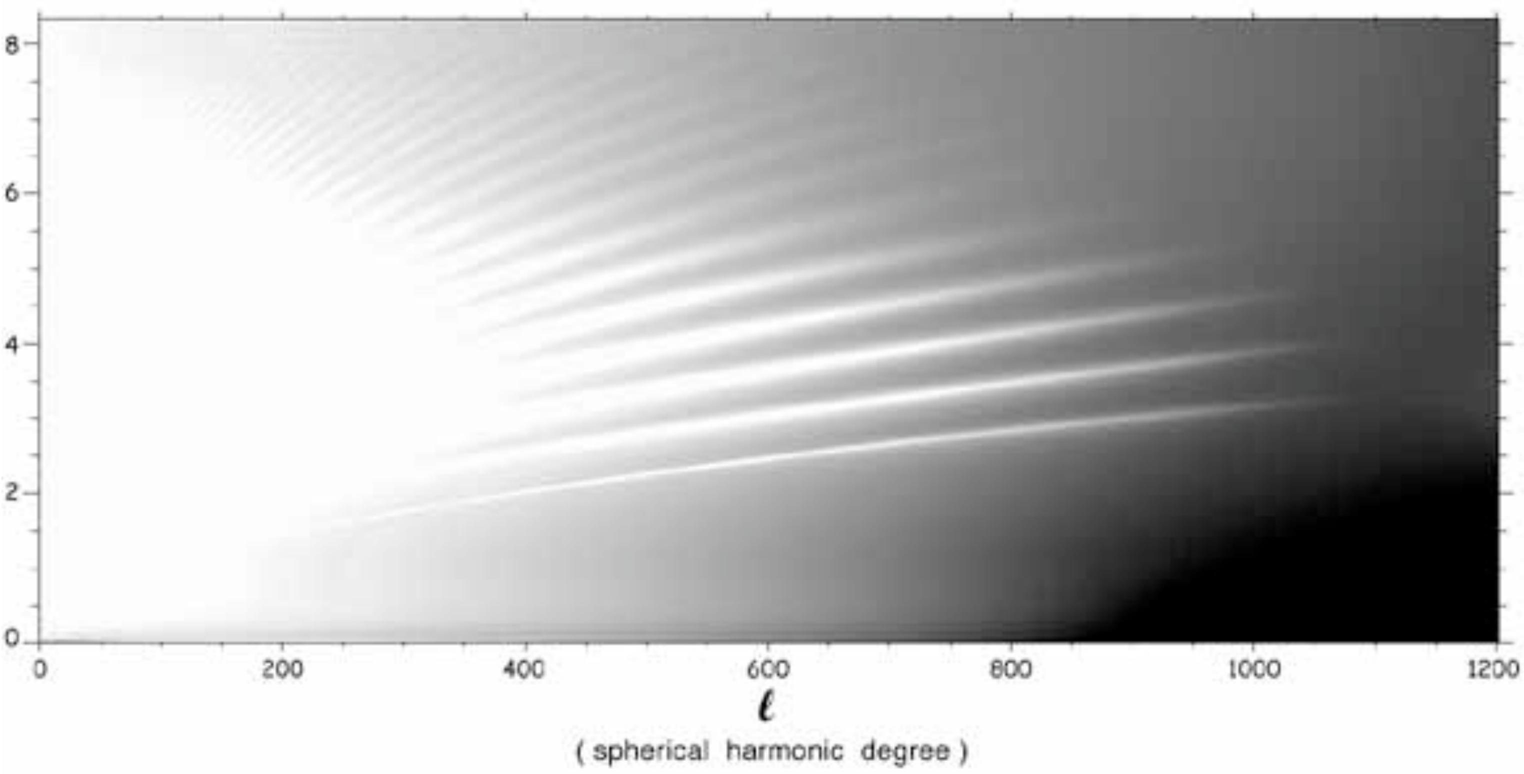
Foreground-cleaned WMAP map from Tegmark, de Oliveira-Costa & Hamilton, astro-ph/0302496

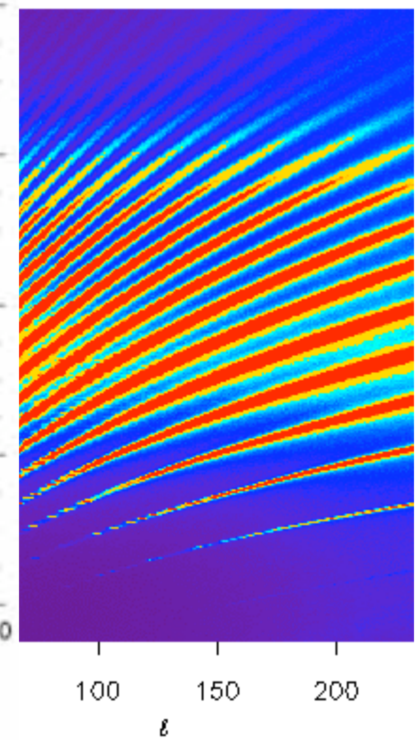






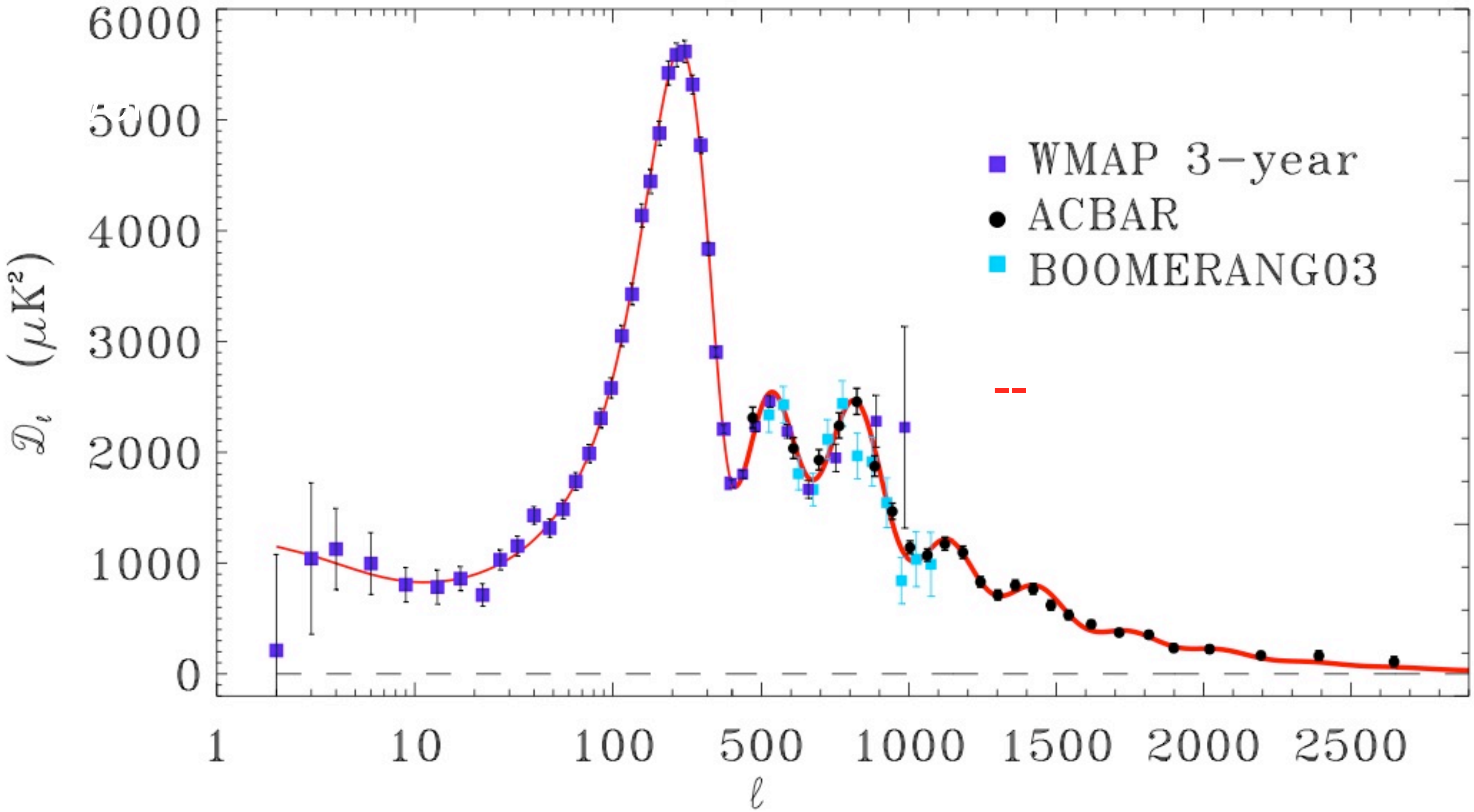
Helio-seismology power spectrum





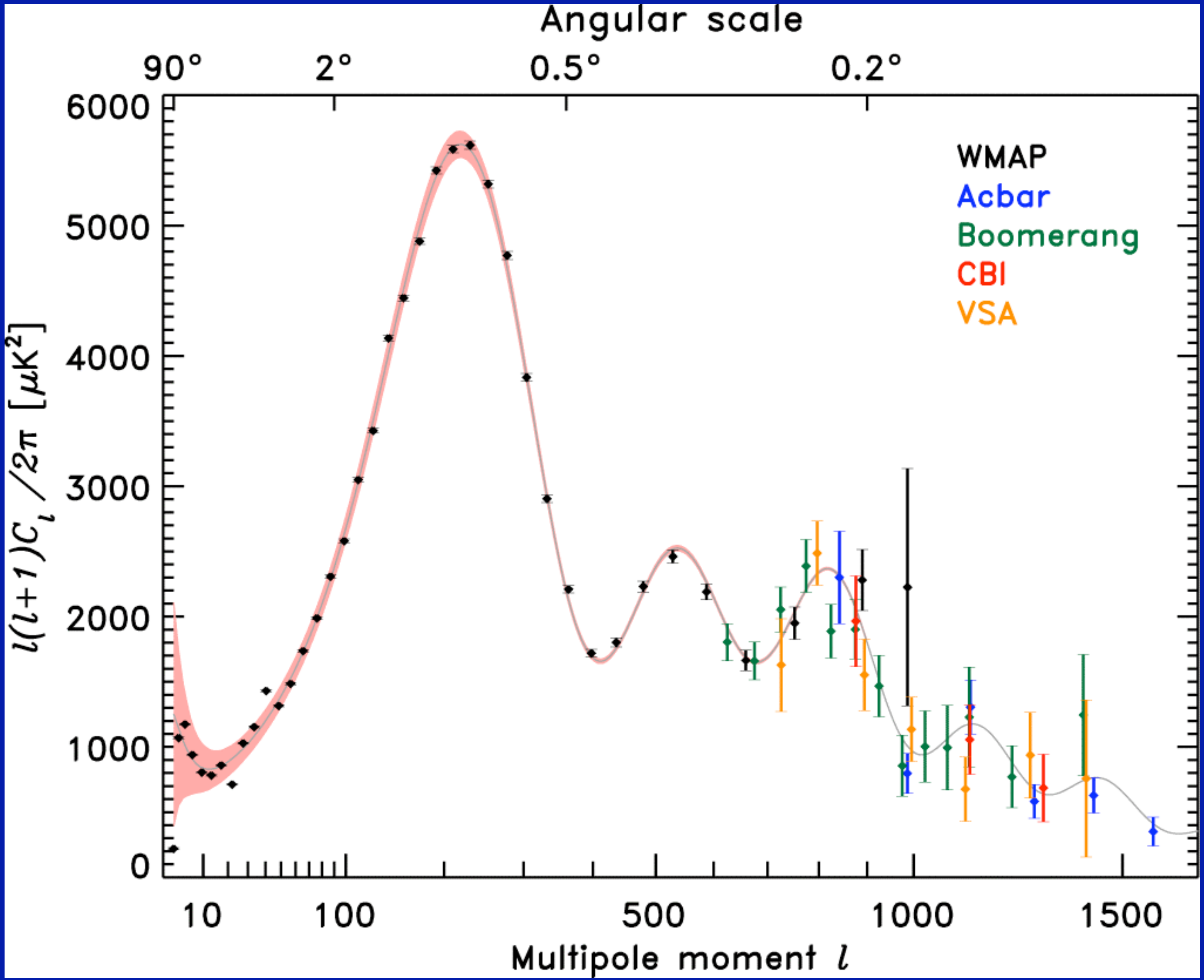
Spectral Analysis of CMB fluctuations

Angle 10° 1° 0.1° 0.05°



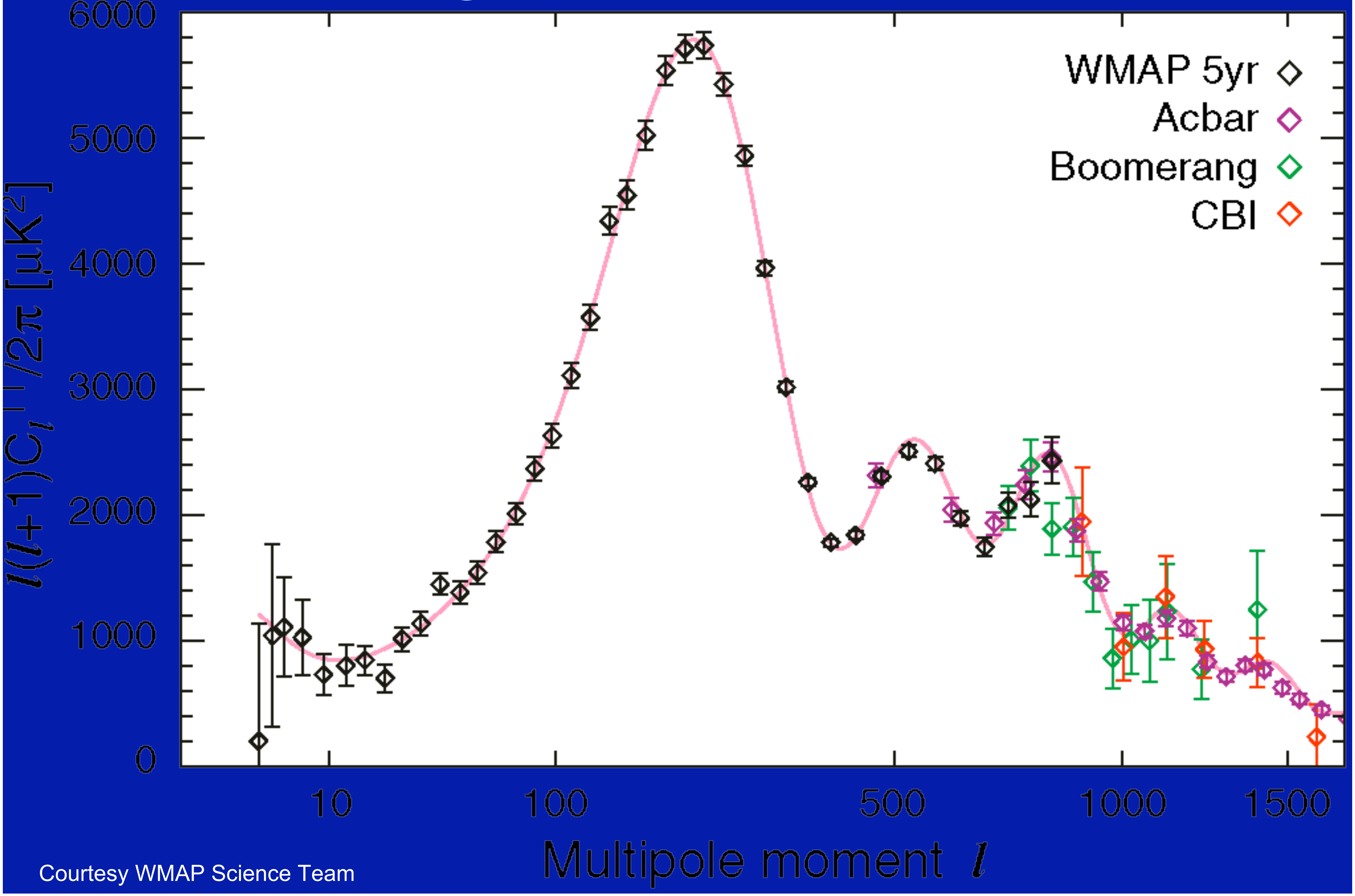
Angular frequency

CMB Angular Power Spectrum



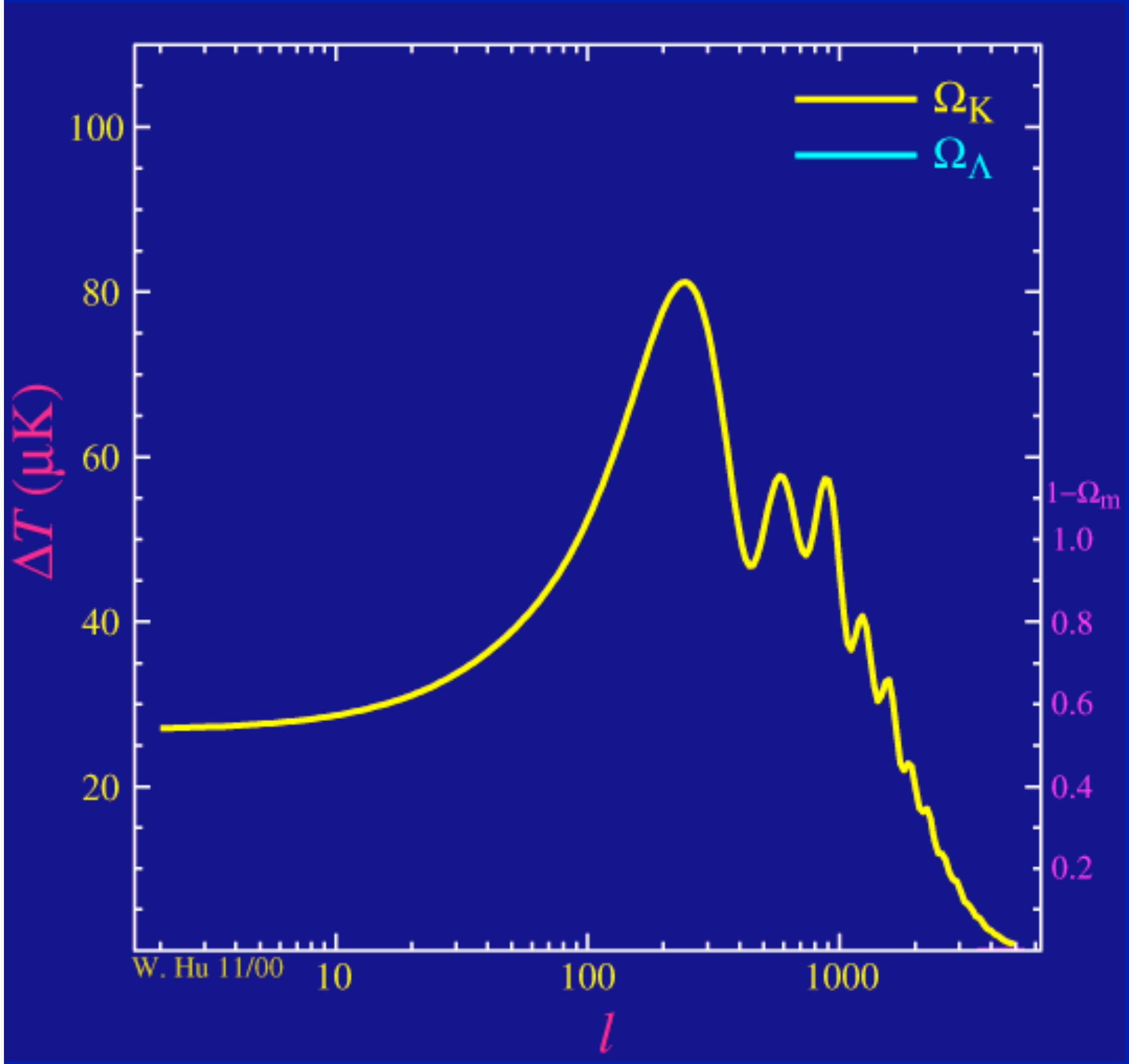
WMAP+ 3yr TT power spectrum (Hinshaw et al. 2006)

CMB Angular Power Spectrum



Courtesy WMAP Science Team

Peaks and Curvature

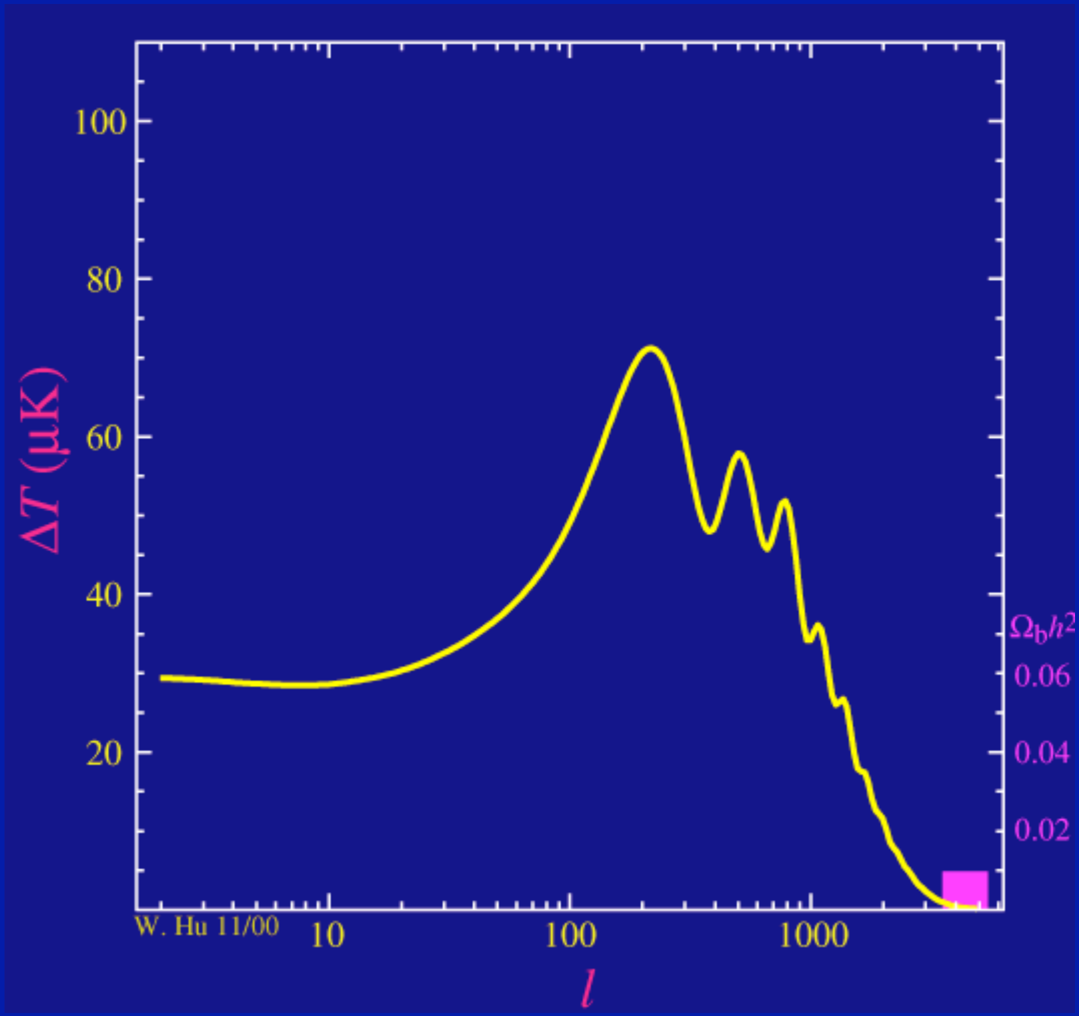


Courtesy Wayne Hu – *http://background.uchicago.edu*

Changing distance to z =1100 shifts peak pattern

- Location and height of acoustic peaks
  - determine values of cosmological parameters
- Relevant parameters
  - curvature of Universe (e.g. open, flat, closed)
  - dark energy (e.g. cosmological constant)
  - amount of baryons (e.g. electrons & nucleons)
  - amount of matter (e.g. dark matter)

Peaks and Baryons

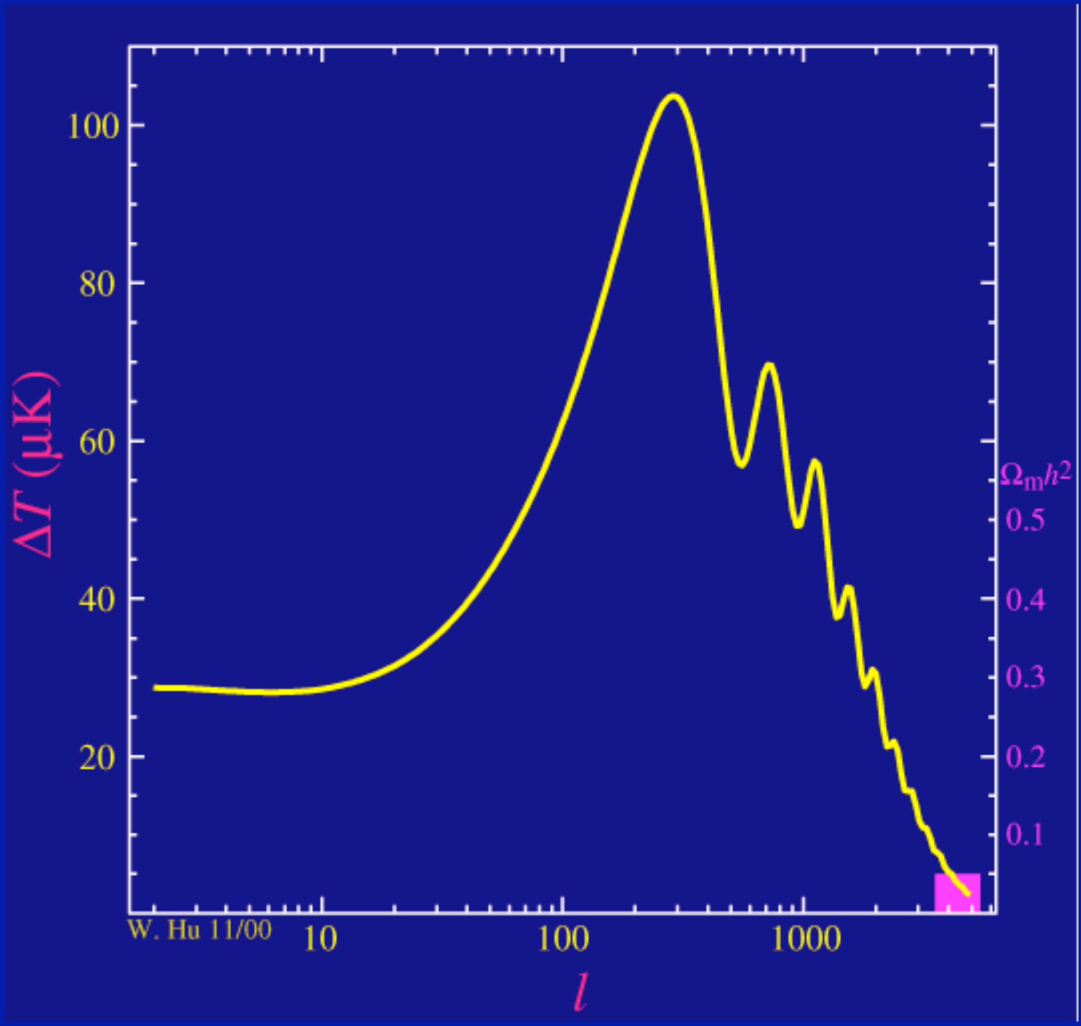


Changing baryon loading changes odd/even peaks

- Location and height of acoustic peaks
  - determine values of cosmological parameters
- Relevant parameters
  - curvature of Universe (e.g. open, flat, closed)
  - dark energy (e.g. cosmological constant)
  - amount of baryons (e.g. electrons & nucleons)
  - amount of matter (e.g. dark matter)

Courtesy Wayne Hu – *http://background.uchicago.edu*

Peaks and Matter

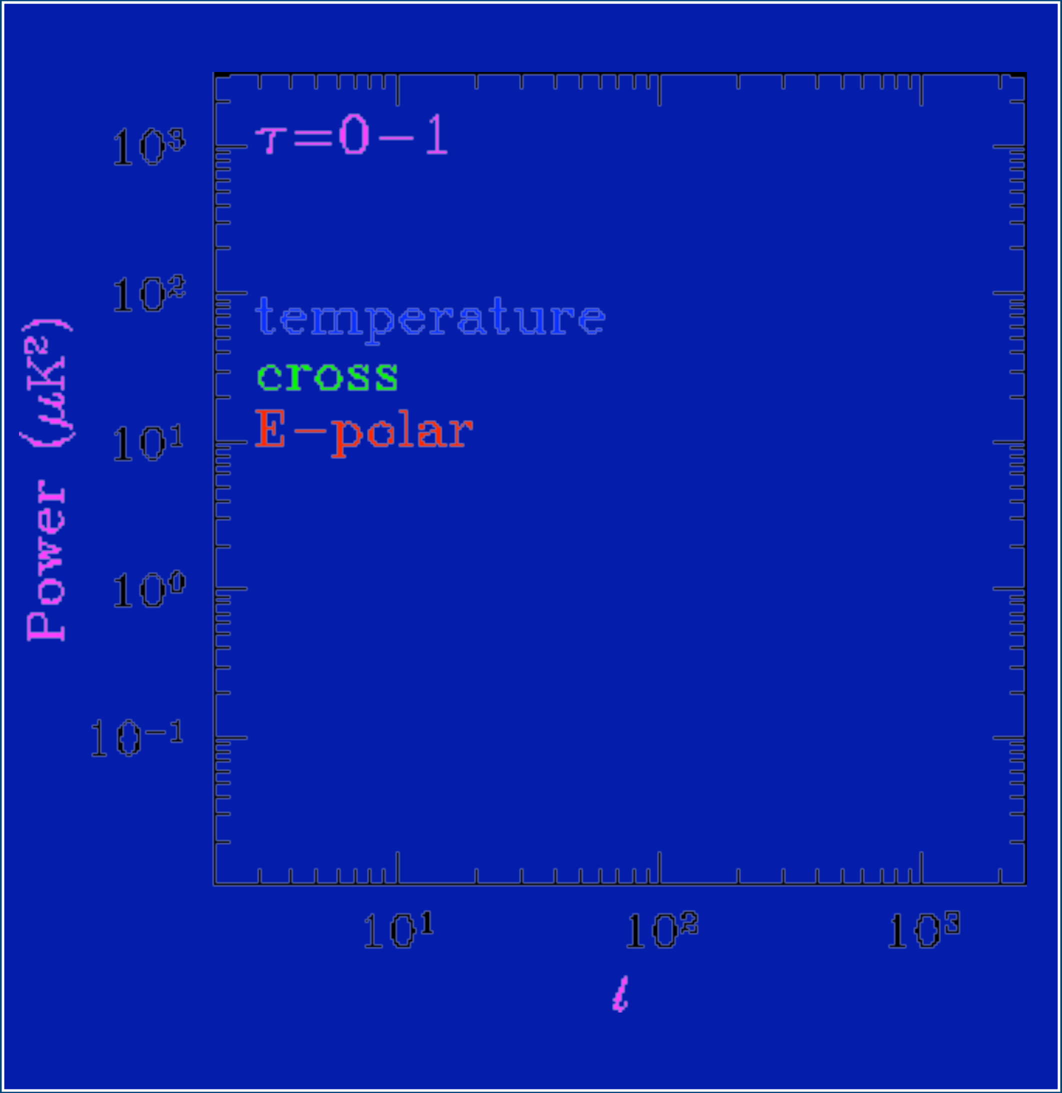


Courtesy Wayne Hu – *http://background.uchicago.edu*

Changing dark matter density also changes peaks…

- Location and height of acoustic peaks
  - determine values of cosmological parameters
- Relevant parameters
  - curvature of Universe (e.g. open, flat, closed)
  - dark energy (e.g. cosmological constant)
  - amount of baryons (e.g. electrons & nucleons)
  - amount of matter (e.g. dark matter)

Reionization



Late reionization reprocesses CMB photons

- Suppression of primary temperature anisotropies
  - as exp(-τ)
  - degenerate with amplitude and tilt of spectrum
- Enhancement of polarization
  - low ℓ modes E & B increased
- Second-order conversion of T into secondary anisotropy
  - not shown here
  - velocity modulated effects
  - high ℓ modes

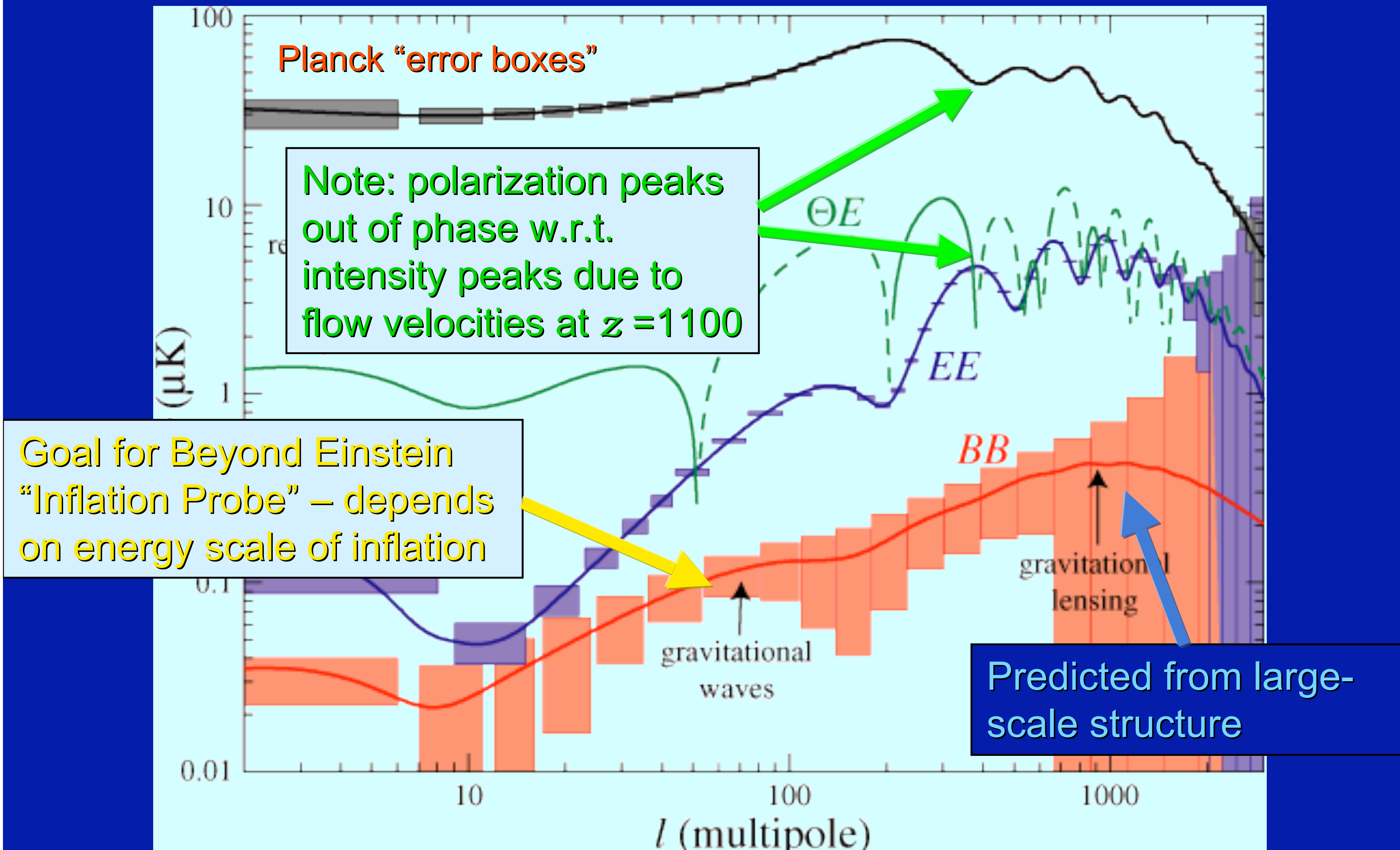
Courtesy Wayne Hu – *http://background.uchicago.edu*

CMB Checklist

Primary predictions from inflation-inspired models:

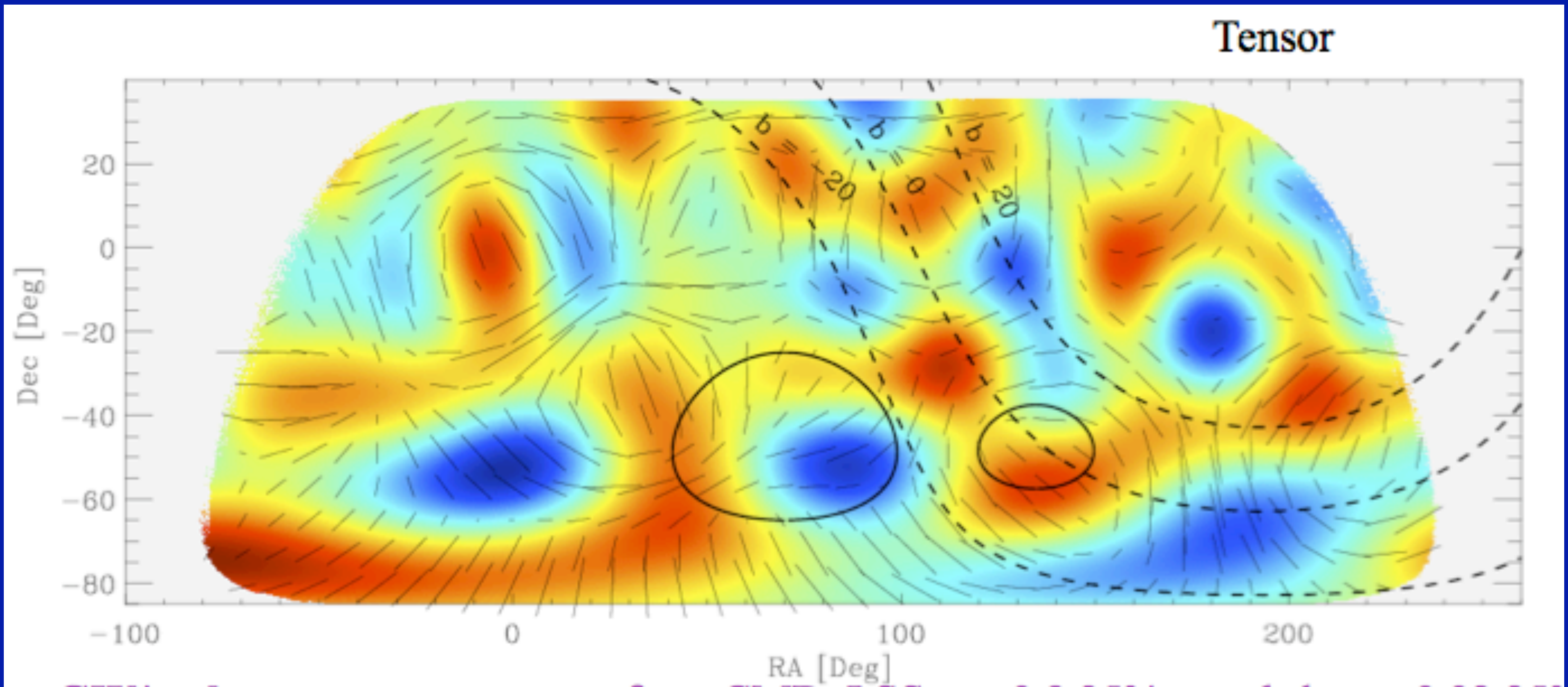
- acoustic oscillations below horizon scale
  - ✓ nearly harmonic series in sound horizon scale
  - ✓ signature of super-horizon fluctuations (horizon crossing starts clock)
  - ✓ even-odd peak heights baryon density controlled
  - ✓ a high third peak signature of dark matter at recombination
- nearly flat geometry
  - ✓ peak scales given by comoving distance to last scattering
- primordial plateau above horizon scale
  - ✓ signature of super-horizon potential fluctuations (Sachs-Wolfe)
  - ✓ nearly scale invariant with slight red tilt (n≈0.96) and small running
- damping of small-scale fluctuations
  - ✓ baryon-photon coupling plus delayed recombination (& reionization)

Planck: Predicted Power Spectrum



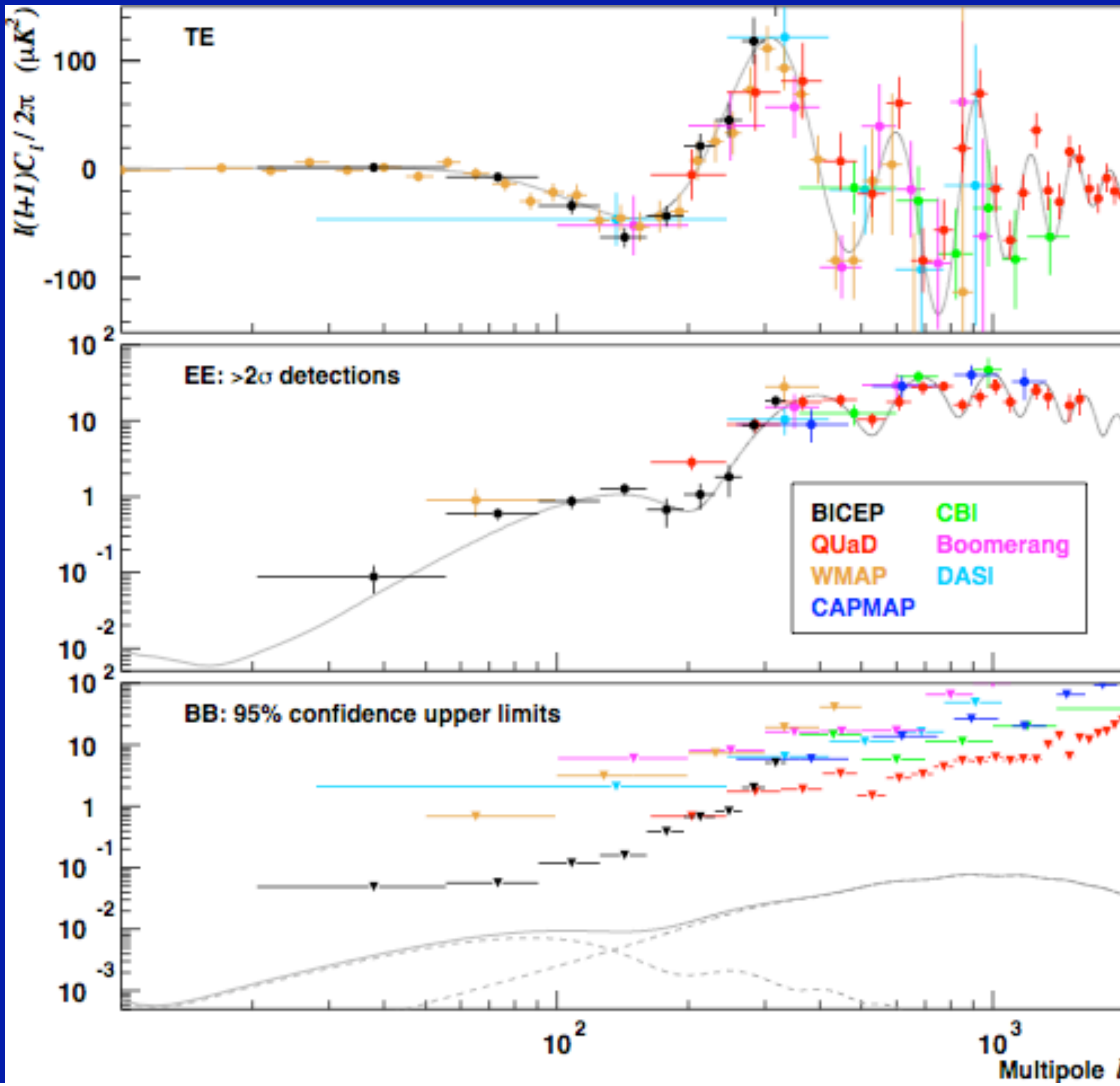
Hu & Dodelson *ARAA 2002*

Polarization E/B No-Tensor/Tensor Sky with and without Tensor Modes



http://www.astro.caltech.edu/~lgg/spider_front.htm

Current Status - 6/2009



CMB Checklist Continued

Polarization predictions from inflation-inspired models:

CMB is polarized

- ✓ acoustic peaks in E-mode spectrum from velocity perturbations
- ✓ E-mode peaks 90° out-of-phase for adiabatic perturbations
- ✓ vanishing small-scale B-modes
- ✓ reionization enhanced low ℓ polarization

Gravitational Waves from Inflation

- – B-modes from gravity wave tensor fluctuations
- – very nearly scale invariant with extremely small red tilt ($n \approx 0.98$)
- – decay within horizon ($\ell \approx 100$)
- – tensor/scalar ratio r from energy scale of inflation ~ $(E_{inf}/10^{16}\ \mathrm{GeV})^4$

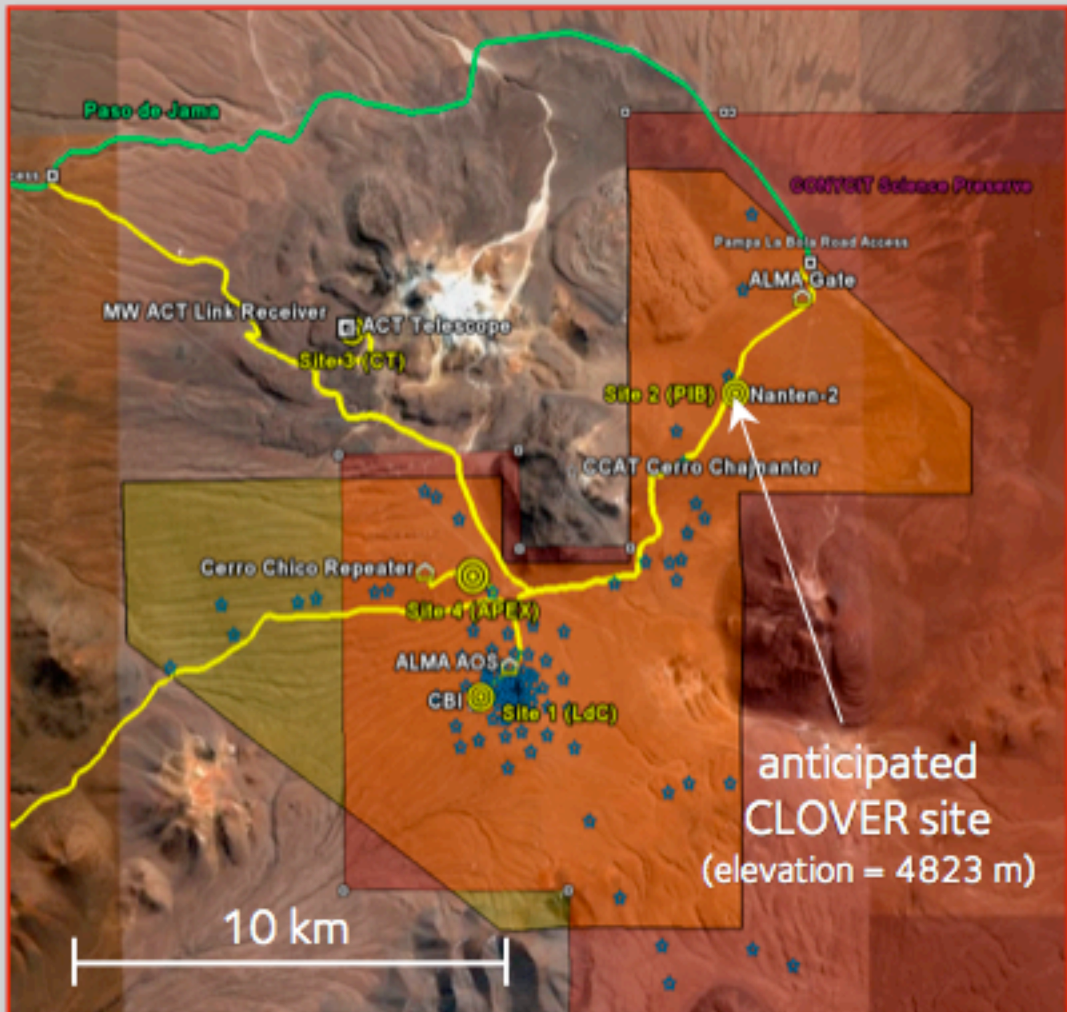
Our inflationary hot Big-Bang theory is standing up well to the observations so far! Now for those gravity waves…

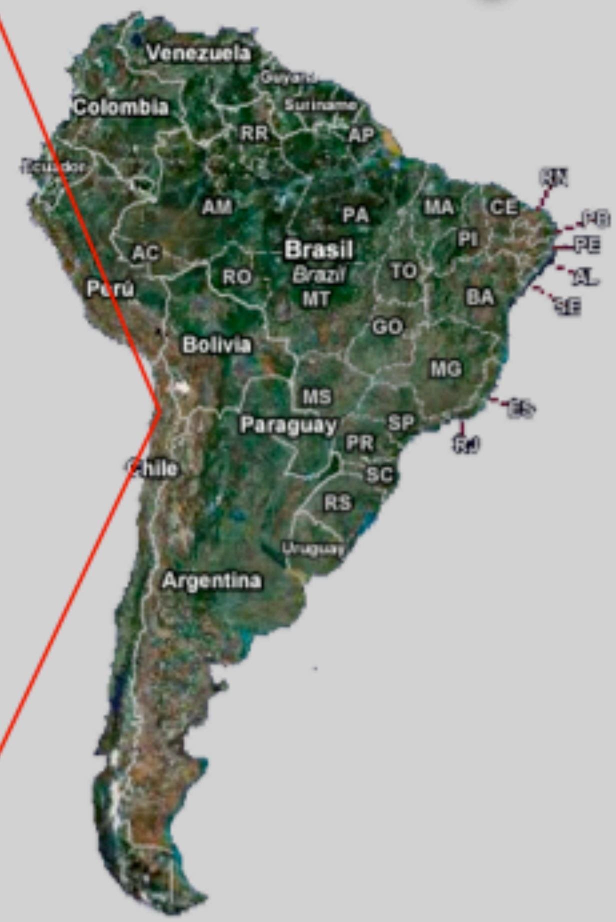
CMB Experiments at the South Pole

Club Med for CMB Experimentalists

Power, LHe, LN2, 80 GB/day, 3 square meals, and Wednesday Bingo Night.

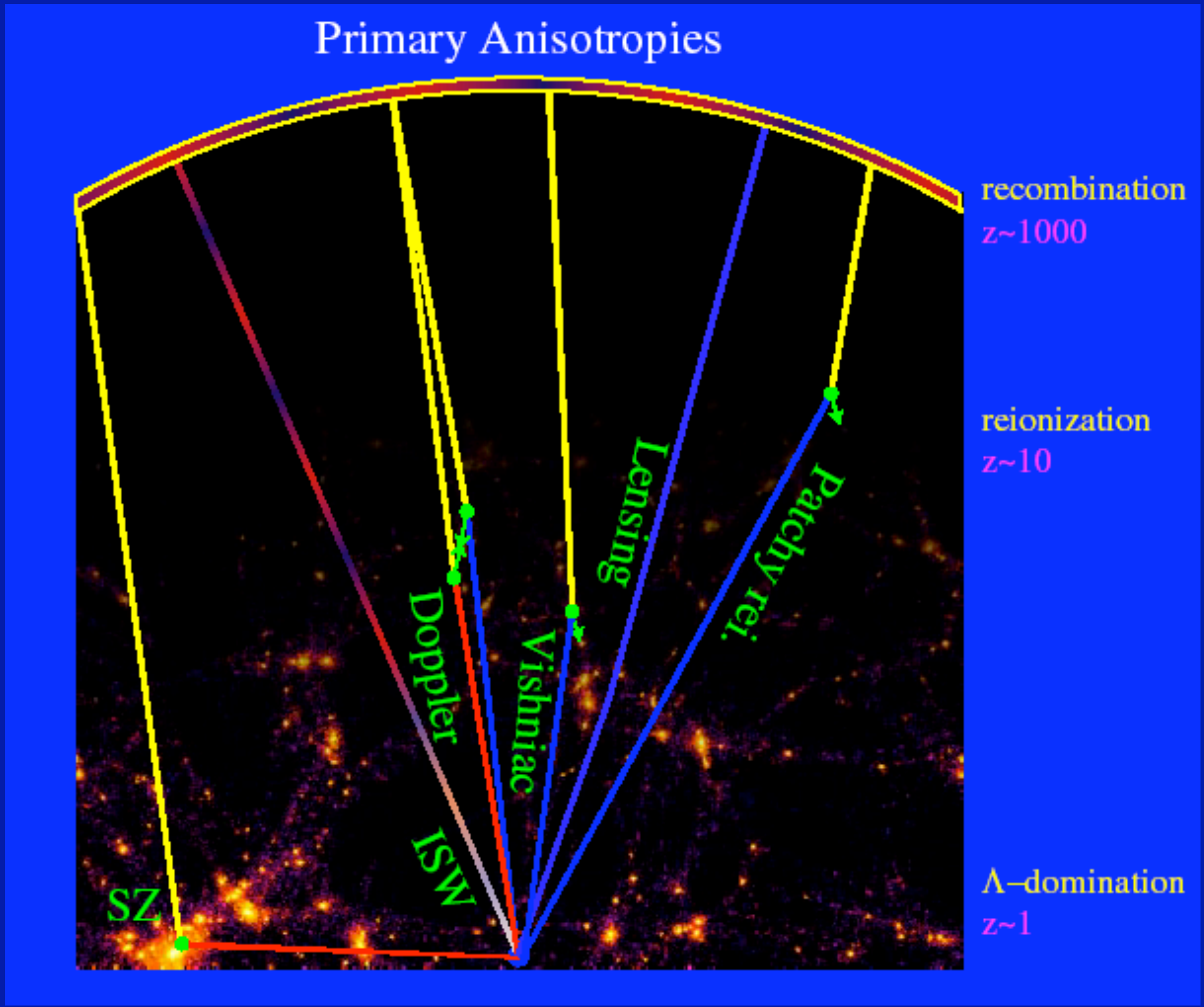
CLOVER Site: Atacama, Chile





Secondary Anisotropies

The CMB After Last Scattering…



Secondary Anisotropies from propagation and late-time effects

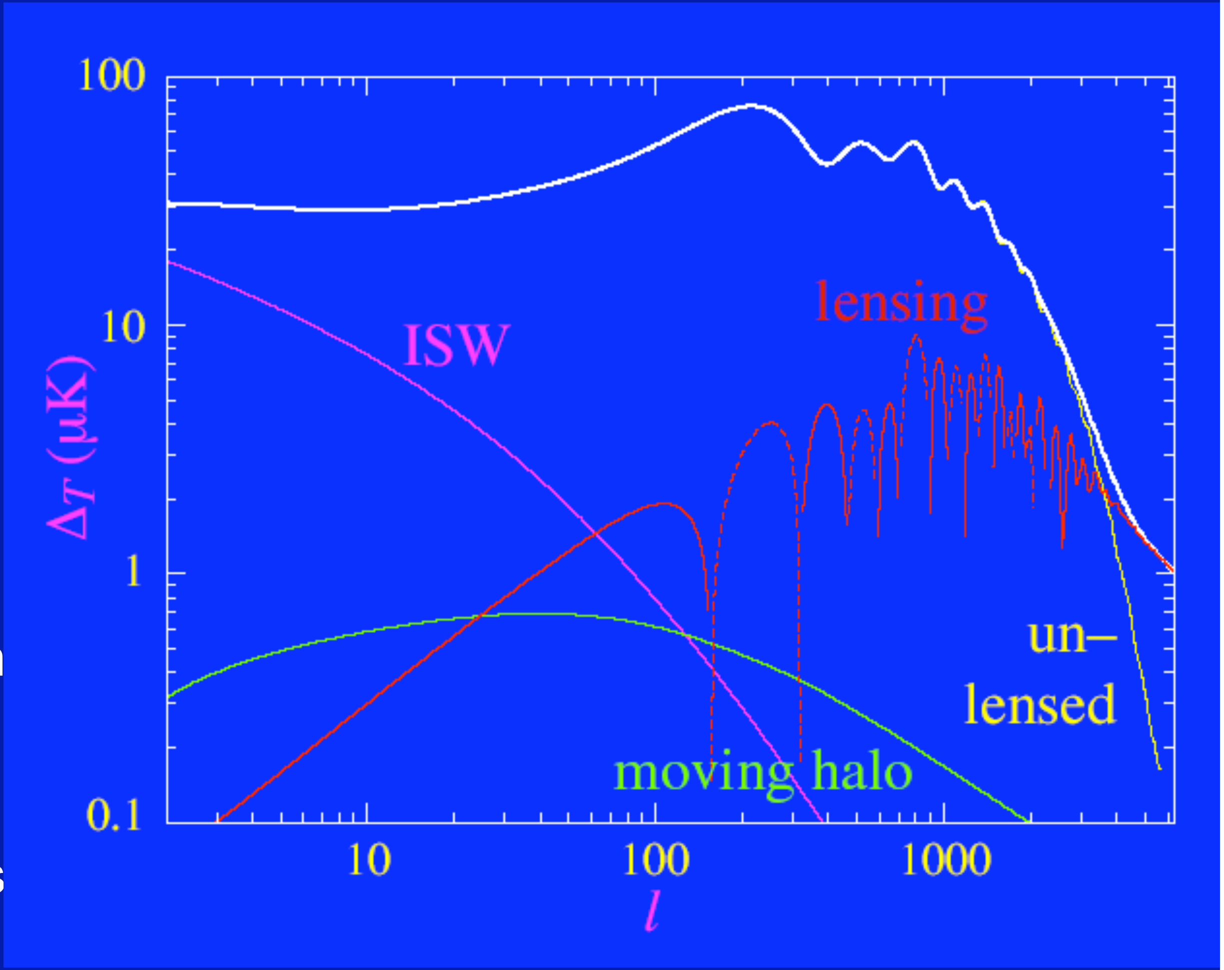
Courtesy Wayne Hu – *http://background.uchicago.edu*

Gravitational Secondaries

Due to CMB photons passing through potential fluctuations (spatial and temporal)

Includes:

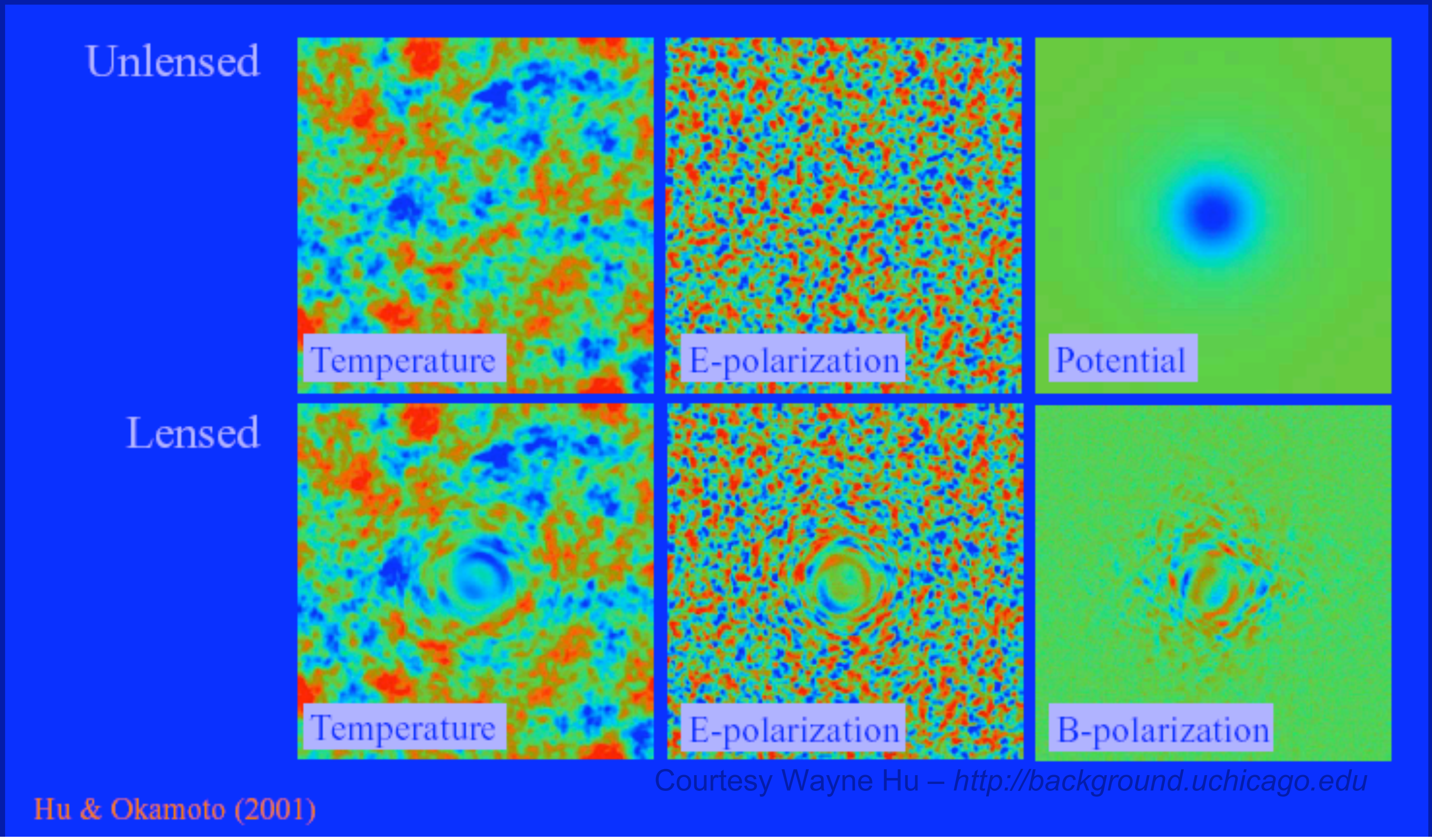
- Early ISW (decay, matter-radiation transition at last scattering)
- Late ISW (decay, in open or lambda models)
- Rees-Sciama (growth, non linear structures)
- Tensors (gravity waves)
- Lensing (spatial distortions



Courtesy Wayne Hu – *http://background.uchicago.edu*

CMB Lensing

- Distorts the background temperature and polarization
- Converts E to B polarization
- Can reconstruct from T,E,B on arcminute scales
- Can probe clusters



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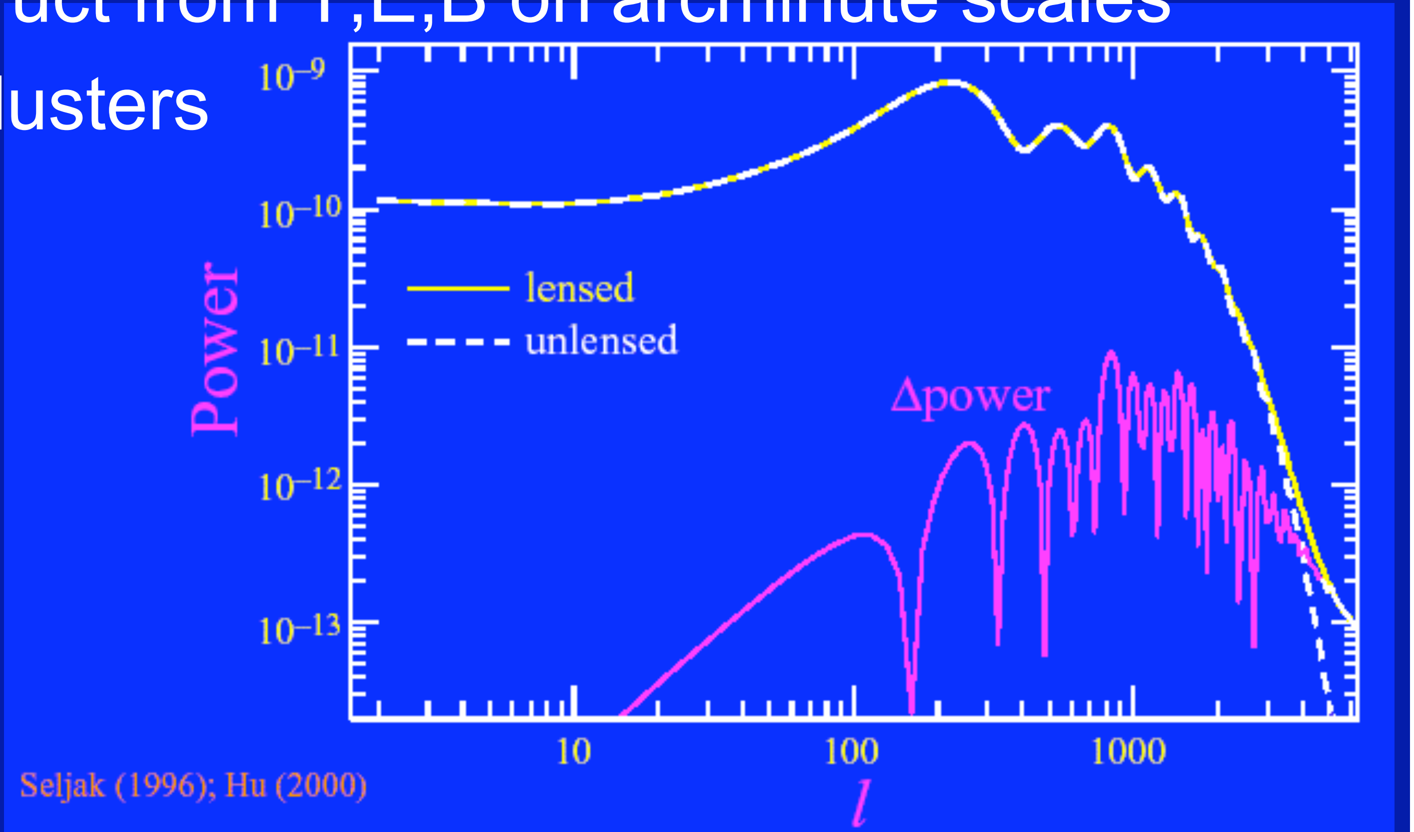
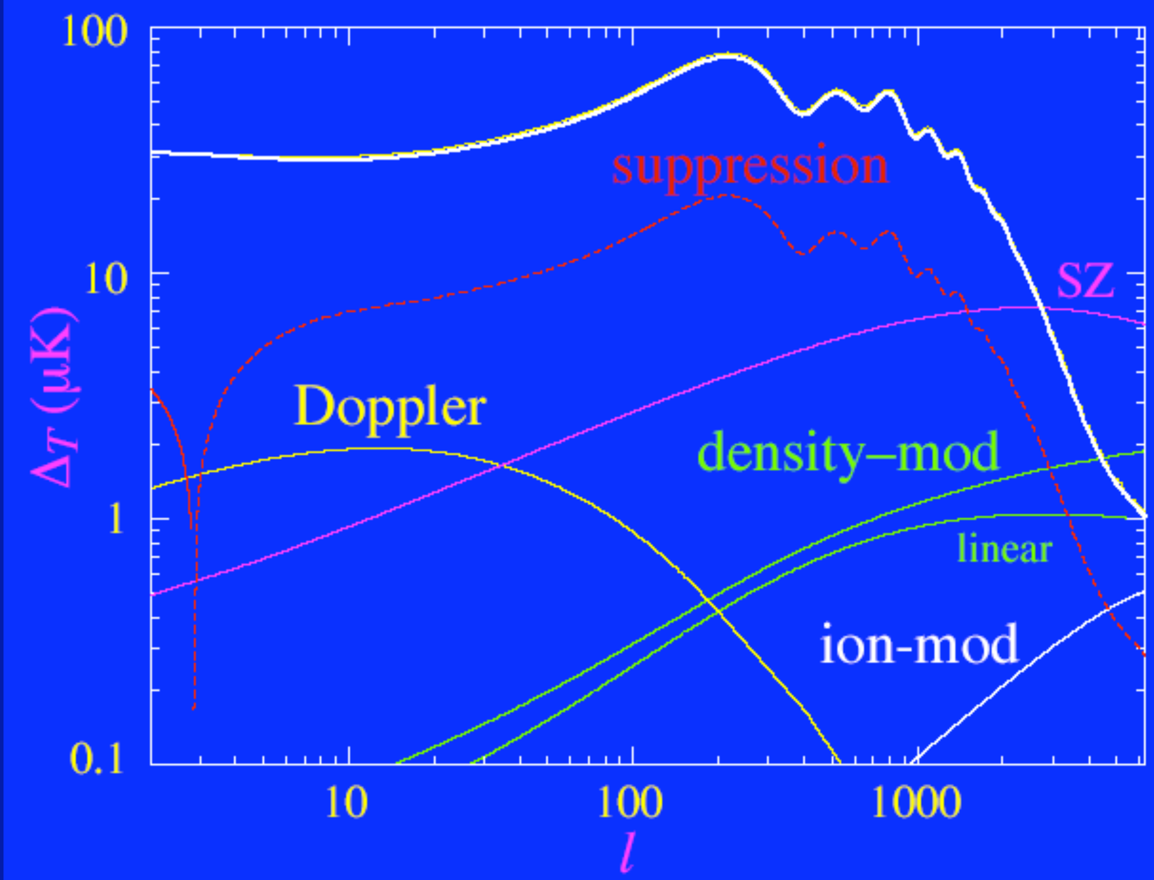


Courtesy Wayne Hu – *http://background.uchicago.edu*

Scattering Secondaries

Due to variations in:

- Density
  - Linear = Vishniac effect
  - Clusters = thermal Sunyaev-Zeldovich effect
- Velocity (Doppler)
  - Clusters = kinetic SZE
- Ionization fraction
  - Coherent reionization suppression
  - “Patchy” reionization



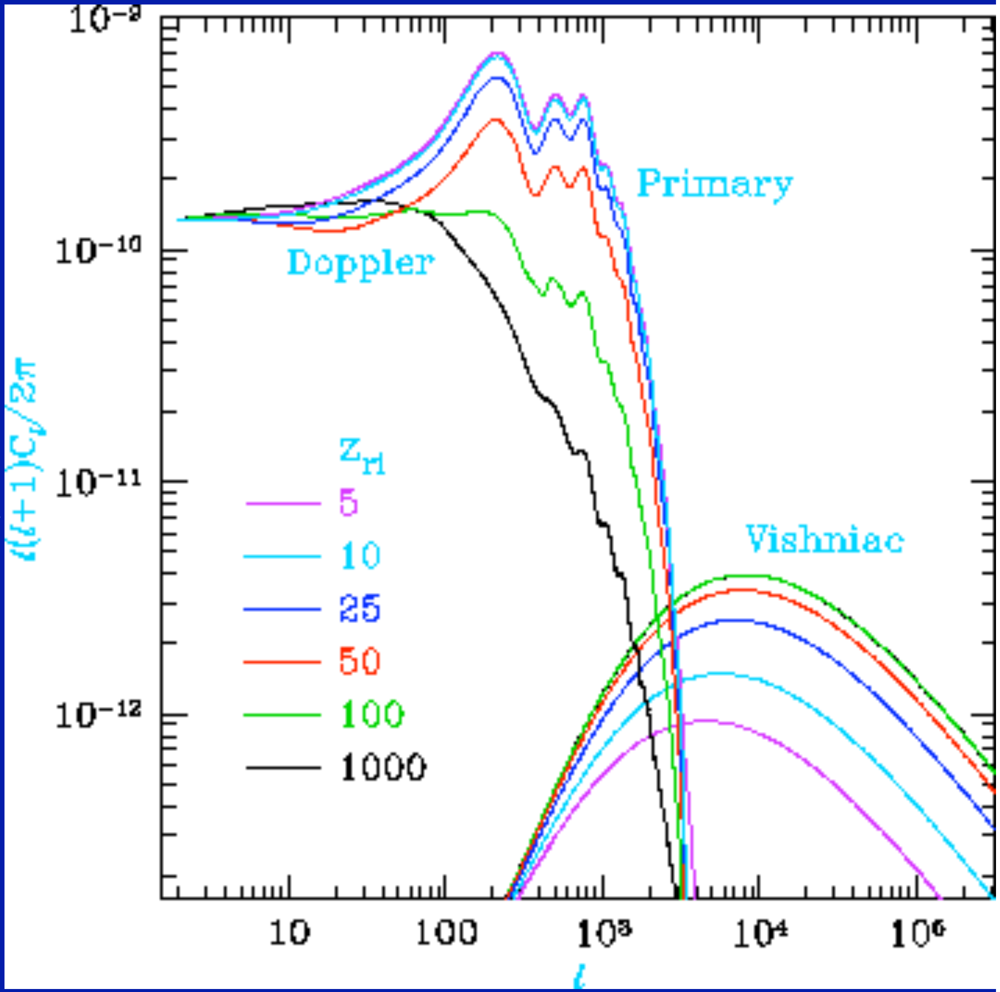
$$\frac{\Delta T}{T}(\hat{n}) = \int dx\,(n_e \sigma_T e^{-\tau})\,\hat{n}\cdot\mathbf{v}(\mathbf{x}, z)$$

$$n_e = X_e n_p = \bar{X}_e \bar{n}_p (1 + \delta_x + \delta_b)$$

Courtesy Wayne Hu – *http://background.uchicago.edu*

Ostriker-Vishniac Effect

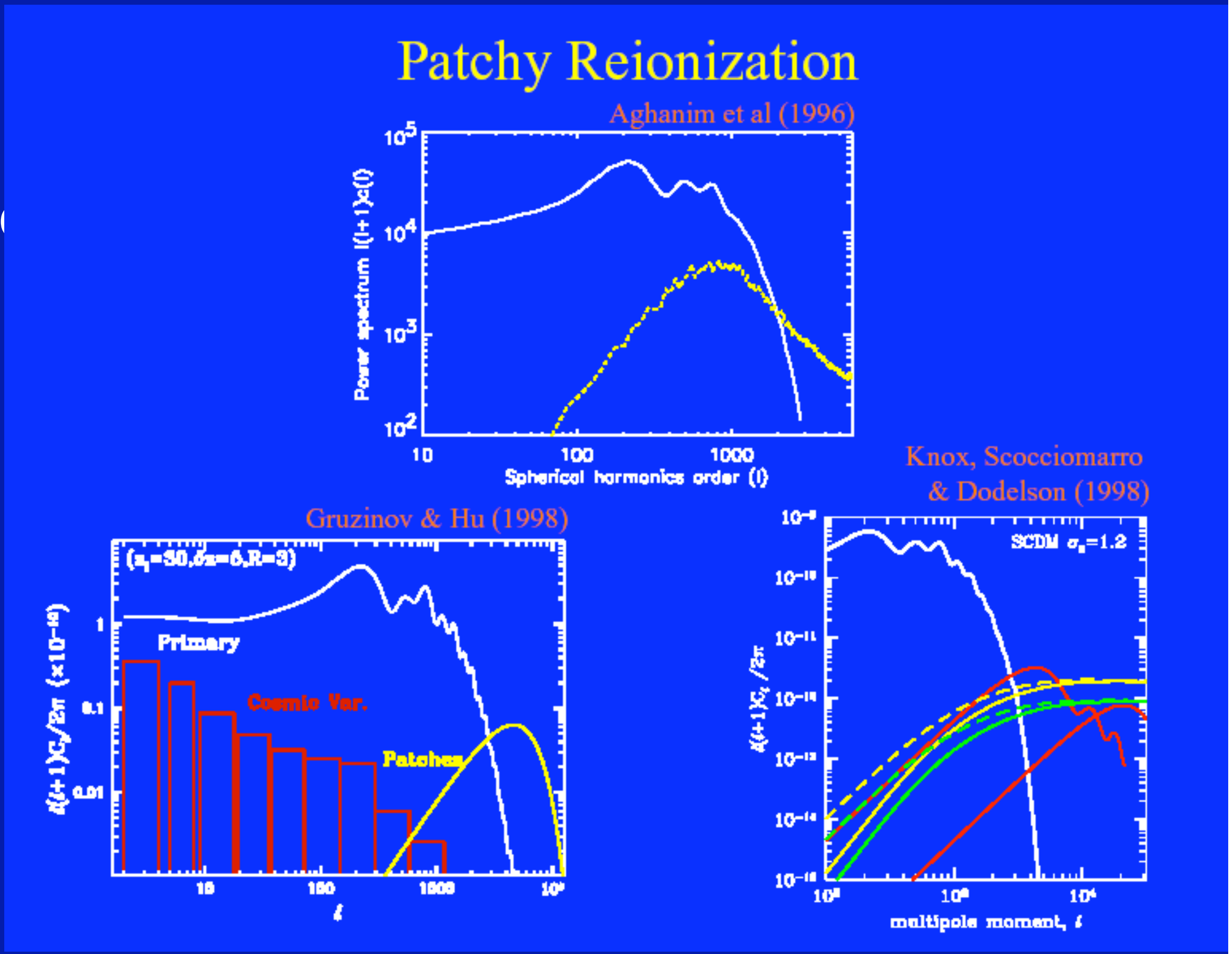
- Reionization + Structure
  - Linear regime
  - Second order (not cancelled)
  - Reionization supresses large angle fluctuations but generates small angle anisotropies



Courtesy Wayne Hu – *http://background.uchicago.edu*

Patchy Reionization

- Structure in ionization
  - Can distinguish between ionizati histories
  - Confusion, e.g. kSZ effect
  - e.g. Santos et al (0305471)
- Effects similar
  - kSZ, OV, PReI
  - Different z's, use lensing?



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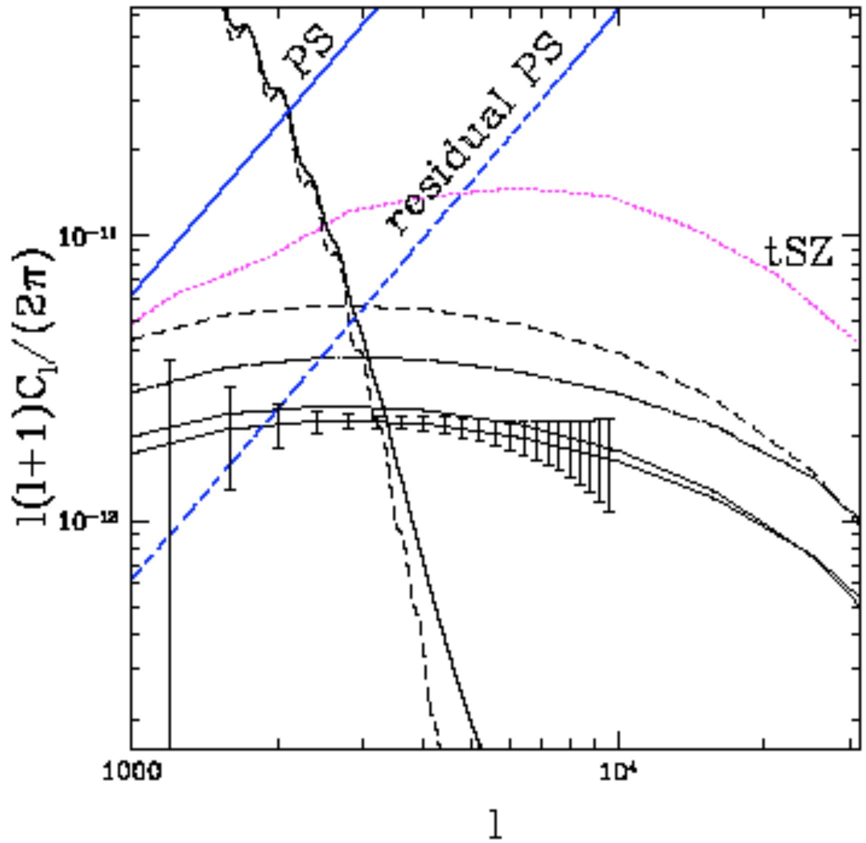
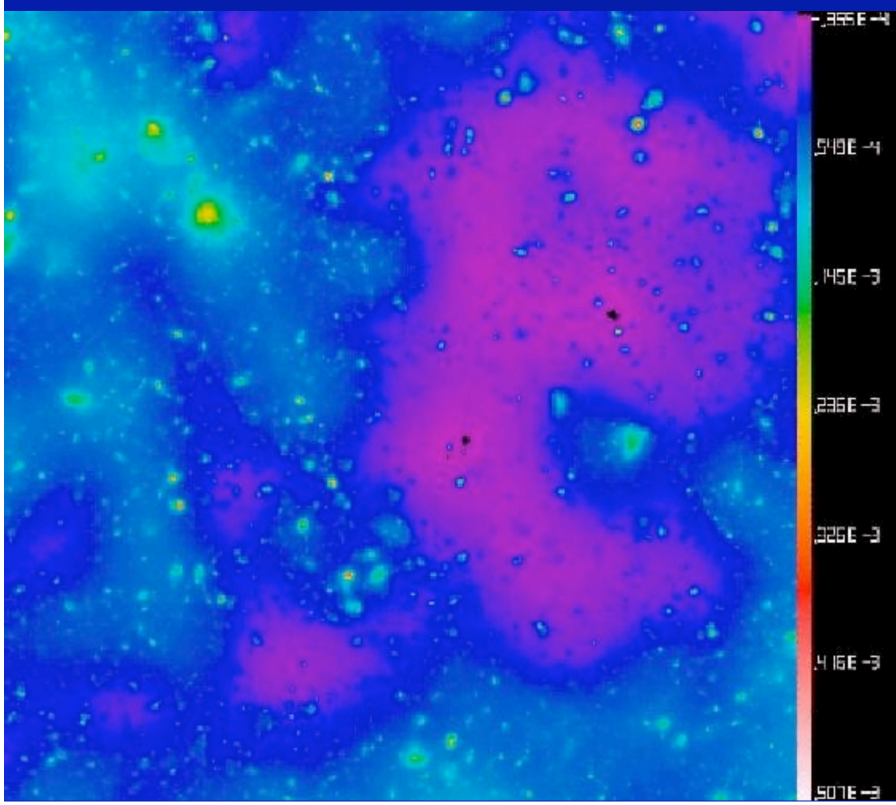
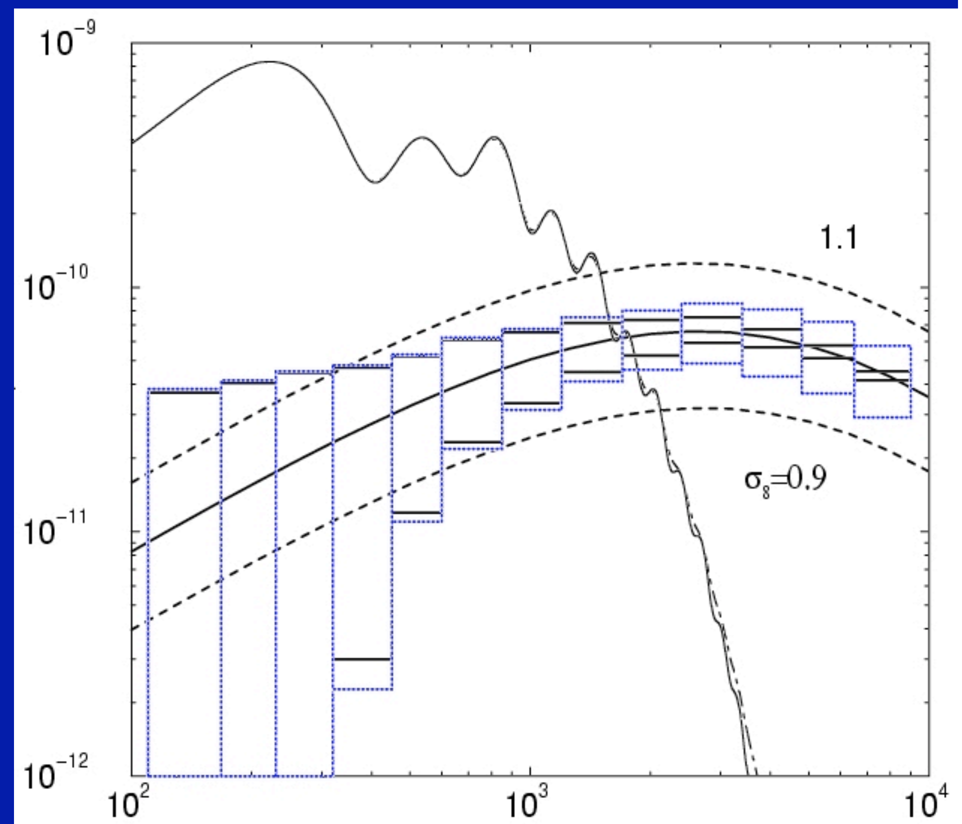


FIG. 5.— Patchy power spectra for the reionization models in Figure 3 (same line styles), together with other astrophysical contributions and expected measurement errors (see text). The solid (dashed) straight line is the the point source contribution at 217 GHz before (after) multi-frequency cleaning. The primary unlensed (dashed) and lensed (solid) CMB power spectra are also shown as is the thermal SZ power spectrum from White et al. (2002) (dotted) with its expected amplitude at lower frequencies. The thin line close to the solid one shows the patchy power spectrum for a model with $\tau = 0.11$ but large bias.

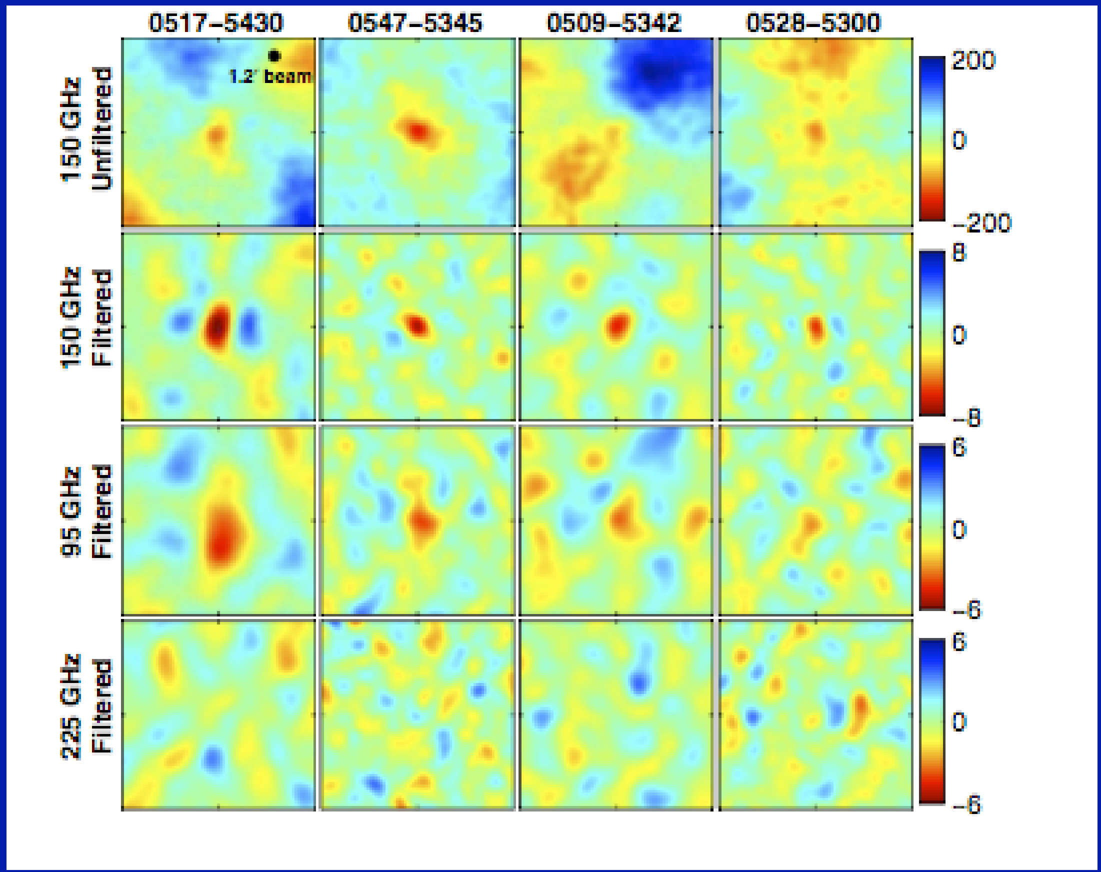
Sunyaev-Zeldovich Effect (SZE)





A. Cooray (astro-ph/0203048)

South Pole Telescope
Blank Field Detections

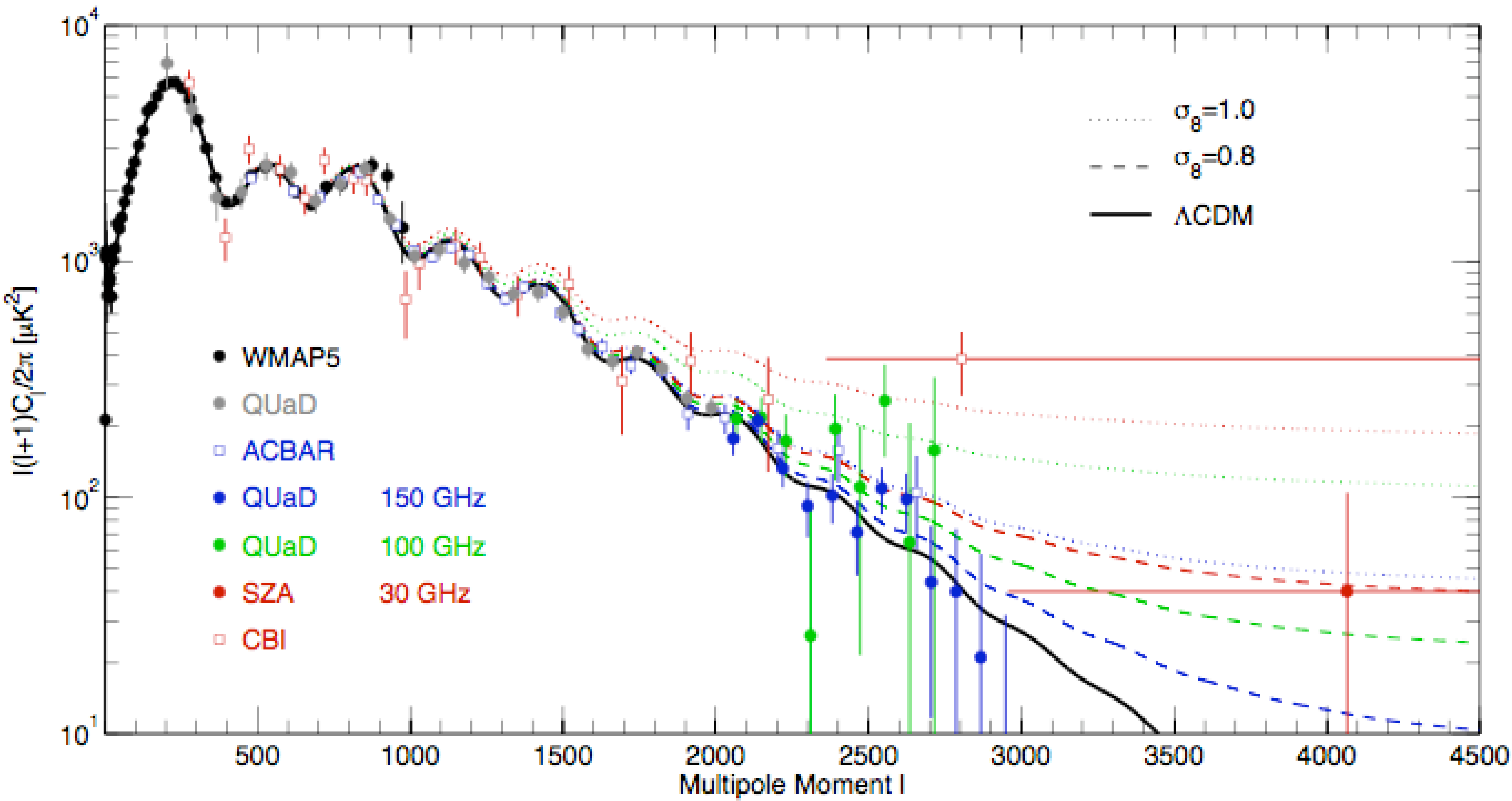


- 4 detections published so far (Staniszewski etal.,astro-ph/0810.1578)
- Rumours that maybe~100morecandidatesbynow
- SZA does not seem to have found any as yet
- Currently believe SPT mass cut-off will be about 6×10^{14} $M_\odot$ — AMI much smaller fields,but could go to ~2×10^{14} $M_\odot$

Damping Tail and CBI Excess

- Photon diffusion suppresses photon density fluctuations below ~ 3 Mpc at last scattering; 80 Mpc width of last scattering surface further washes out projection to ΔT
- Predicted exponential decline seen by CBI (30 GHz) and ACBAR (150 GHz) but ...
  - CBI and BIMA see excess emission at l > 2000: interpreted as SZ gives $\sigma_8 \approx 1.0$

Damping Tail and CBI Excess - QUAD Results



- QUAD now disagrees with CBI Consistent with σ_8=0.8 rather than 1
- Is CBI estimated source correction underestimated?

CMB Checklist (continued)

Secondary predictions from inflation-inspired models:

- late-time dark energy domination
  - ✓ low ℓ ISW bump correlated with large scale structure (potentials)
- late-time non-linear structure formation
  - ✓ gravitational lensing of CMB
  - ✓ Sunyaev-Zeldovich effect from deep potential wells (clusters)
- late-time reionization
  - – overall supression and tilt of primary CMB spectrum
  - – doppler and ionization modulation produces small-scale anisotropies
  - ✓ EE & TE low ℓ bump

CMB Checklist (finale)

Structure predictions from inflation-inspired models:

- late-time non-linear structure formation (revisited)
  - ✓ gravitational lensing of CMB
  - ✓ Sunyaev-Zeldovich effect from deep potential wells (clusters)
- growth of matter power spectrum
  - ✓ primordial power-law above current sound horizon
  - ✓ CMB acoustic peaks as baryon oscillations
- dark energy domination at late times
  - ✓ correlation of galaxies with Late ISW in CMB
  - – cluster counts (SZ) reflect LCDM growth and volume factors

<u>It appears our current Universe is dominated in energy density by a Dark Energy (Lambda) component!</u>

Primordial Non-Gaussianity

- Over two years has become clear to the wider CMB community that primordial non-Gaussianity is a powerful discriminant among competing theories of inflation - including 3=pt geometry
- Current focus is on the quantity f_{NL} defined for a curvature pertubations $\Phi(r)$ by

$$\Phi(r) = \Phi_L(r) + f_{NL} (\Phi^2_L(r) - <\Phi^2_L(r)>)$$

- So gives the non-linear correction to an underlying linear field
- In single-field, slow roll inflation, expect $f_{NL} \sim 1$
- This is very low (remember basic $\Phi(r)$ value $\sim 10^{-5}$) and corresponds to expectation that initial quantum states are like the ground state of a harmonic oscillator
- The claims that caught everyones' attention were from Yadav & Wandelt (astro-ph/0712.1148v3) and gave $27 < fNL < 147$ (95% confidence interval)
- Thus would exclude the hypothesis of Gaussian fluctuations at 99.5% confidence level

The quadratic NG model

✓ Many primordial (inflationary) models of non-Gaussianity can be represented in configuration space by the general formula

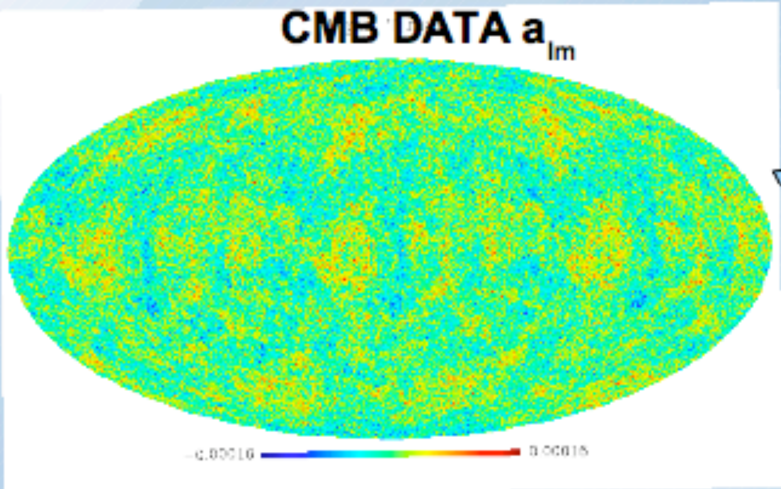
$$\Phi = \phi_L + f_{NL} * (\phi_L^2 - \langle\phi_L^2\rangle)$$

where Φ is the large-scale gravitational potential, ϕ_L its linear Gaussian contribution and f_{NL} is the dimensionless *non-linearity parameter* (or more generally *non-linearity function*). The percent of non-Gaussianity in CMB data implied by this model is

$$\text{NG \%} \sim 10^{-5} |f_{NL}|$$

$< 10^{-3}$ from *WMAP*

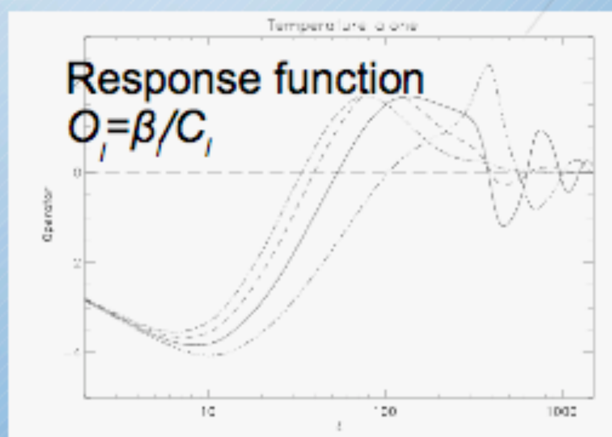
Reconstructed Primordial Perturbations

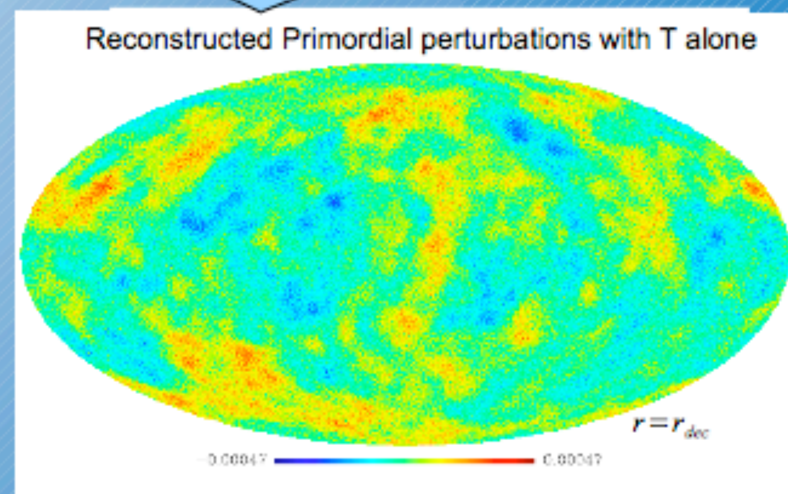


$\Phi_{lm} = O_l \, a_{lm}$

SW limit

$$\frac{\delta \phi}{\phi} = \frac{-1}{3} \frac{\delta T}{T}$$

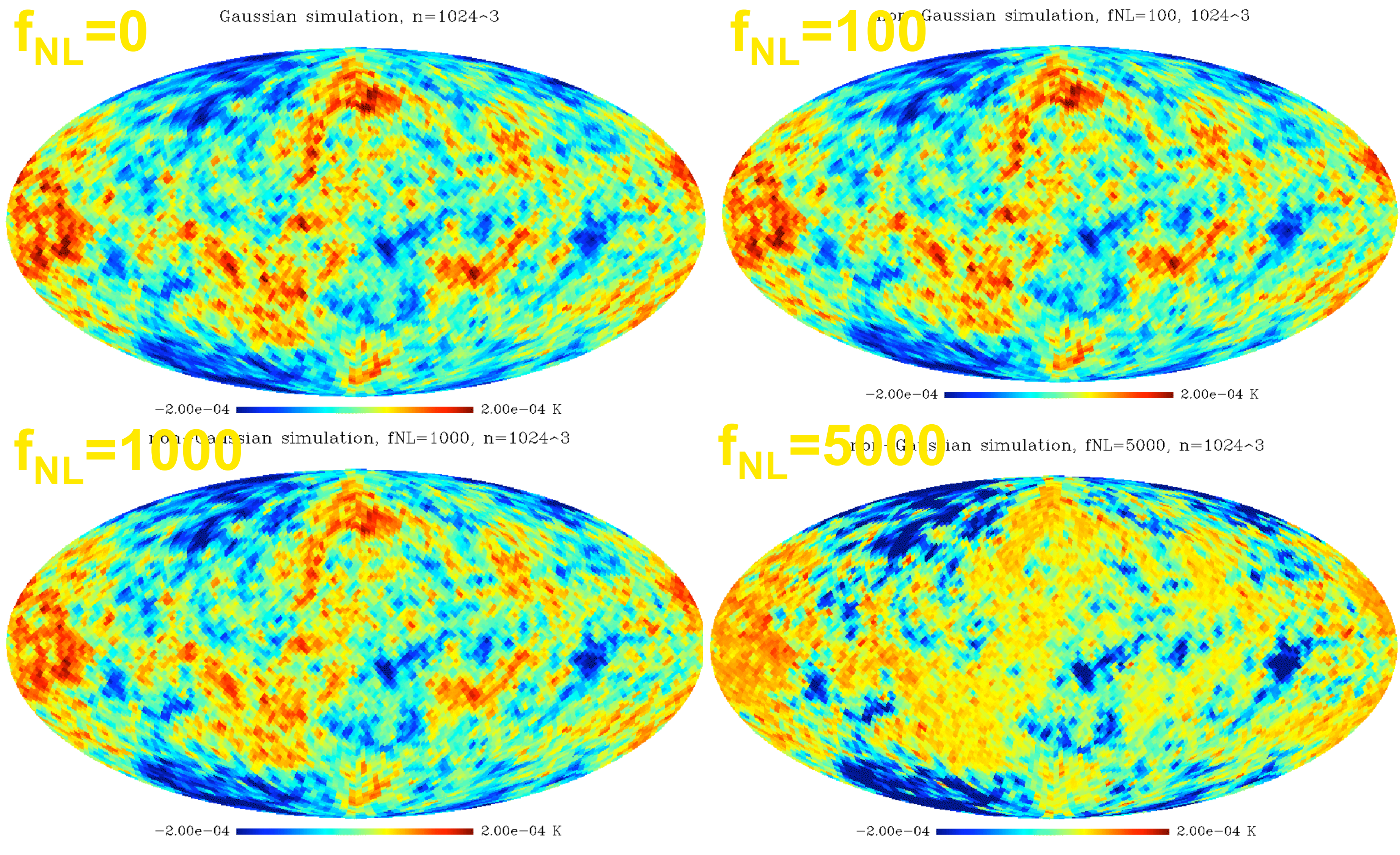




$$\beta^i_\ell(r) = \frac{2b^i_\ell}{\pi} \int k^2 dk P_\phi(k) g^i_\ell(k) \, j_\ell(kr),$$

Positive f_{NL} - more cold spots

Simulated temperature maps from $\Phi(x) = \Phi_G(x) + f_{NL}\Phi_G^2(x)$



Primordial Non-Gaussianty continued

- If real, this would be extremely significant, and favour non-standard forms of inflation, e.g. DBI (Dirac-Born-Infield), for which one expects $f_{NL} \sim 50$ or ekpyrotic scenarios
- However foregrounds are an issue!

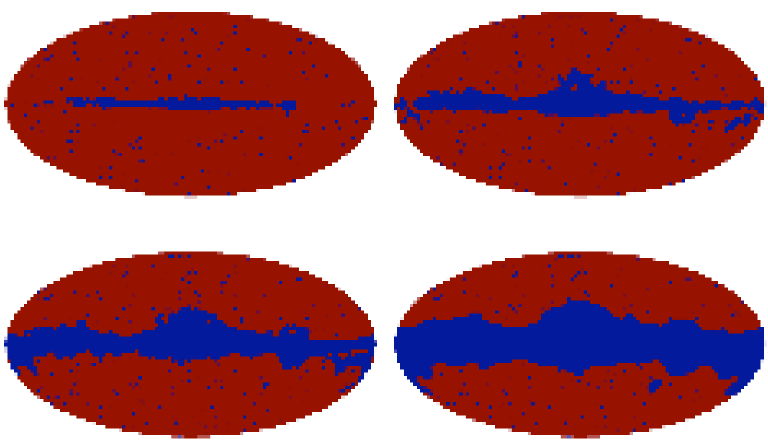


FIG. 2: The various masks used for computing the $f_{\rm NL}$ in Table I . From left to right, and top to bottom we show Kp12, Kp2, Kp0, and Kp0+. The point source exclusion regions are identical to those in the WMAP. Enlarging the point source exclusions does not change our results appreciably.

$\ell_{\rm max}$	VW				Q	QVW			
	Kp12	Kp2	Kp0	Kp0+	Kp0	Kp12	Kp2	Kp0	Kp0+
350	-1290	-27	35	19	1	-2384	-75	25	8
450	-1425	-16	68	65	-6	-2792	-80	55	65
550	-1510	-13	80	84	-11	-3136	-94	66	80
650	-1560	-22	79	81	-14	-3307	-94	63	77
750	-1575	-23	87	87	-20	-3368	-108	65	78
750*	$-1105\pm^{19}_{19}$	$-42\pm^{5}_{5}$	$-6\pm^{4}_{4}$	$-0.3\pm^{4}_{4}$				$-13\pm^{5}_{5}$	$1\pm^{6}_{6}$

TABLE I: Non-linear coupling parameter $f_{\rm NL}$ using the V+W, Q, and Q+V+W WMAP 3-year raw maps, as a function of maximum multipole used in the analysis ℓ_{max} and mask Kp12, Kp2, Kp0, and Kp0+ (corresponding f_{sky} is stated in the text and the masks are shown in Fig 2). The last row (750*) shows the mean $f_{\rm NL}$ estimated from Gaussian simulations including the WMAP foreground model. Foreground contamination biases $f_{\rm NL}$ negatively by similar amounts in both the data and the model.

How to search for f_{NL} – a specific parameterization of non-Gaussianity

$$\Phi(x) = \Phi_G(x) + f_{NL}\Phi_G^2(x)$$

Salopek & Bond 1990
Komatsu & Spergel 2001

Characterizes the amplitude of non-Gaussianity

Non-Gaussianity from Inflation

f_{NL} ~ 0.05 canonical inflation (single field, couple of derivatives) (Maldacena 2003, Acquaviva etal 2003)

f_{NL} ~ 0.1--100 higher order derivatives

DBI inflation (Alishahiha, Silverstein and Tong 2004)

UV cutoff (Creminelli and Cosmol, 2003)

f_{NL} >10 curvaton models (Lyth, Ungarelli and Wands, 2003)

f_{NL} ~100 ghost inflation (Arkani-Hamed et al., Cosmol, 2004)

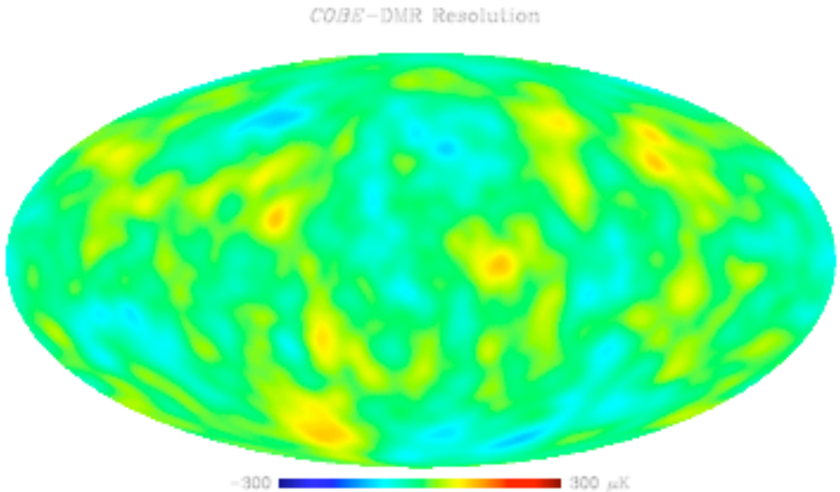
f_{NL} Complication

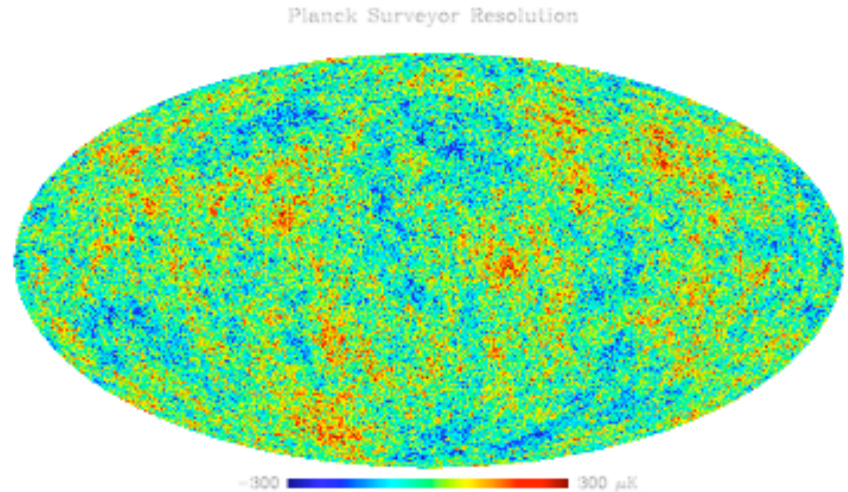
Constraints on f_{nl}

Constraints (95%CL)	Method	Experiment	Paper
$-18 < f_{nl} < +80$	Wavelets	WMAP-5	AC et al. (2009)
$-4 < f_{nl} < +80$	Bispectrum	WMAP-5	Smith et al. (2009)
$-65 < f_{nl} < +70$	LSS	SDSS and others	Slosar et al. (2008)
$-8 < f_{nl} < +111$	Wavelets	WMAP-5	AC et al. (2008)
$-9 < f_{nl} < +111$	Bispectrum	WMAP-5	Komatsu et al.(2008)
$-36 < f_{nl} < +100$	Bispectrum	WMAP-3	Creminelli et al (2003)
$+27 < f_{nl} < +147$	Bispectrum	WMAP-3	Yadav & Wandelt (2008)
$-180 < f_{nl} < +170$	Local curvature & wavelets	WMAP-1	Cabella et al. (2005)
$-178 < f_{nl} < +64$	Minkowski	WMAP-5	Komatsu et al. (2008)
$-101 < f_{nl} < +107$	Minkowski	WMAP-3	Gott et al. (2007)
$-800 < f_{nl} < +1050$	Minkowski	BOOMERANG	De Troia et al. (2007)
$-920 < f_{nl} < +1075$	Minkowski	Archeops	AC et al. (2008)

Andrés Curto

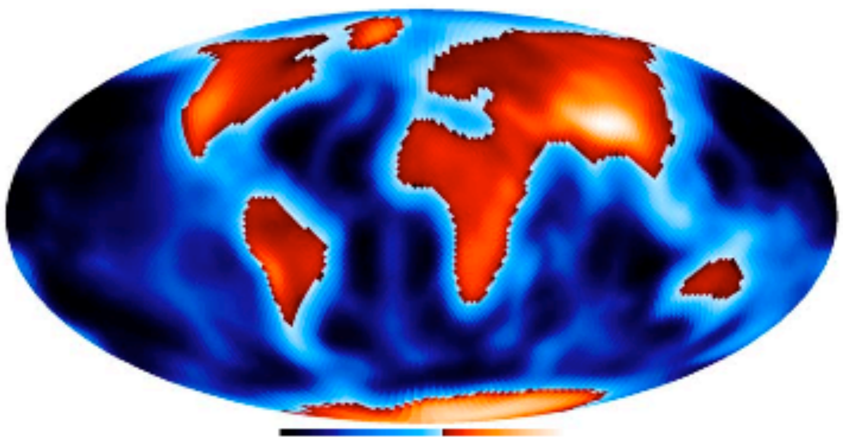
Great Discovery Era Unfolds …

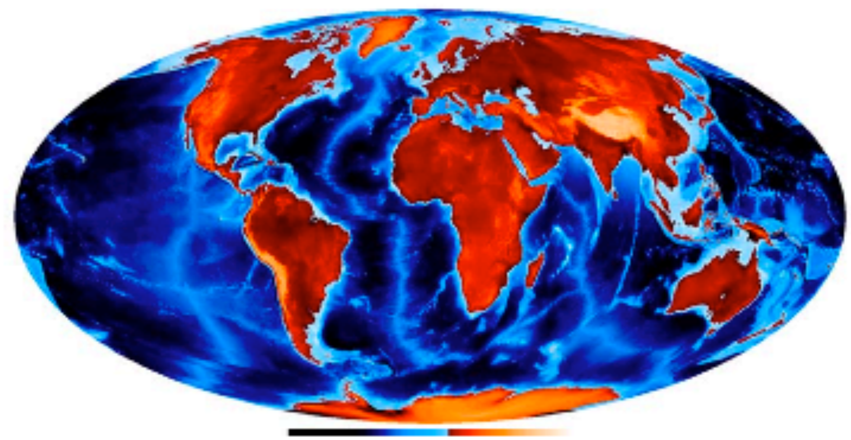




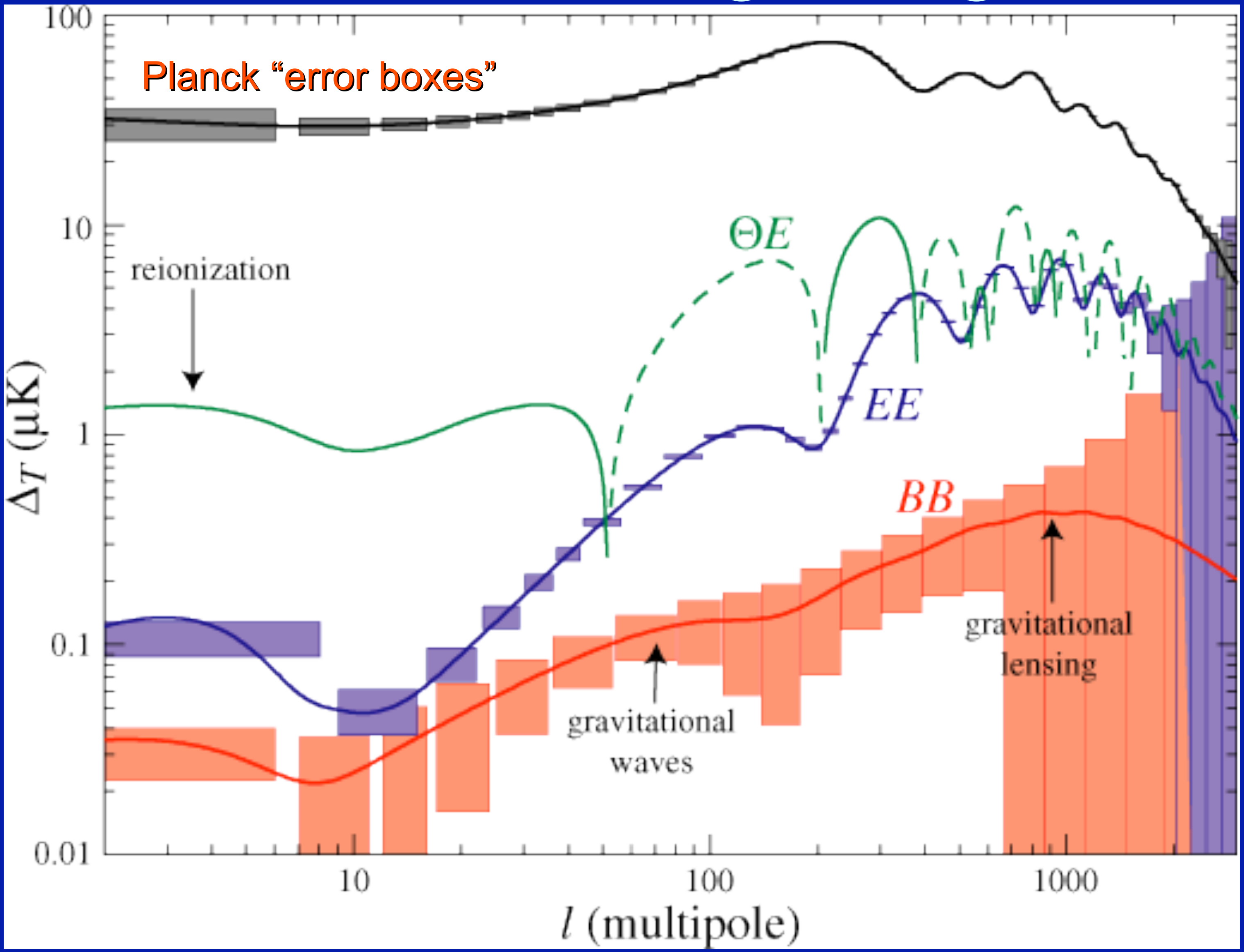
COBE DMR

WMAP & Planck





Planck: The next big thing in CMB!



Hu & Dodelson *ARAA 2002*

But much else also coming!