Une vie de cuisine exceptionnelle est seulement un chuchotement dans l' éternité du cosmos.

CMB Overview: Cosmology with the CMB

Professor George F. Smoot

Berkeley Center for Cosmological Physics

Ewha University & Academy of Advanced Studies

LBNL & Physics Department

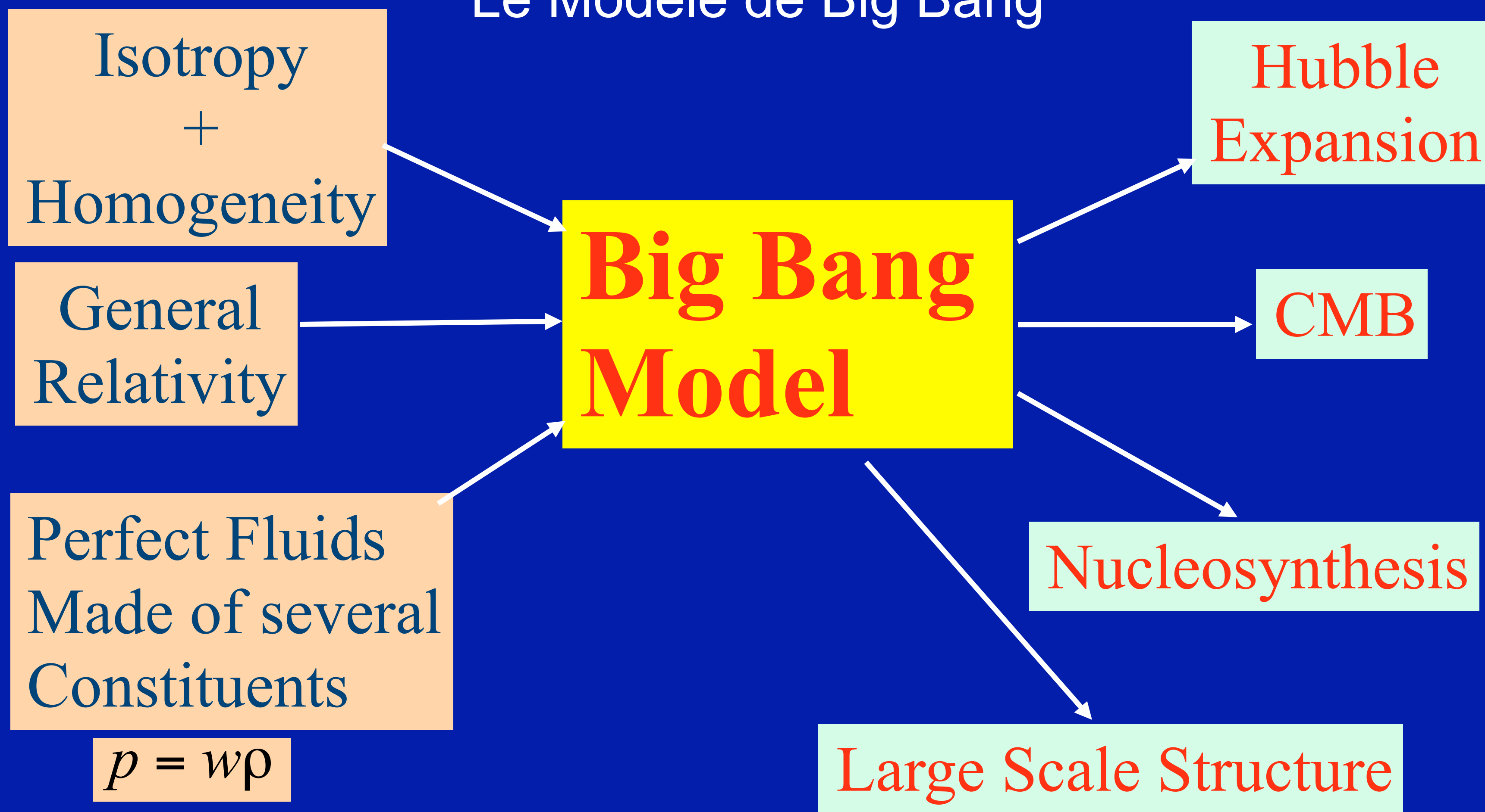
University of California at Berkeley

Chaire Blaise Pascal Université de Paris

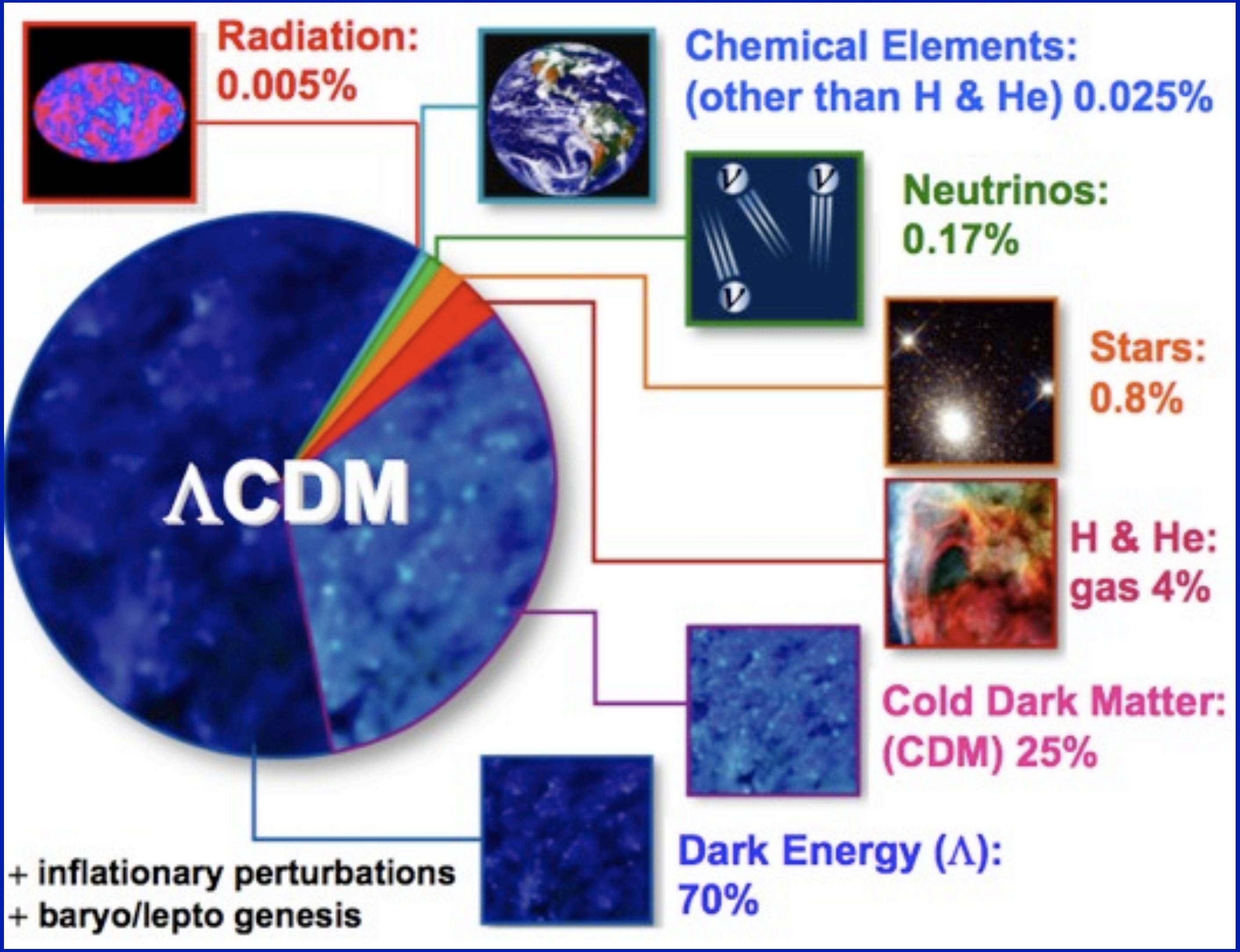
1st Paris-Berkeley Dark Energy Cosmology Workshop

The Standard Big Bang Model:

Le Modèle de Big Bang



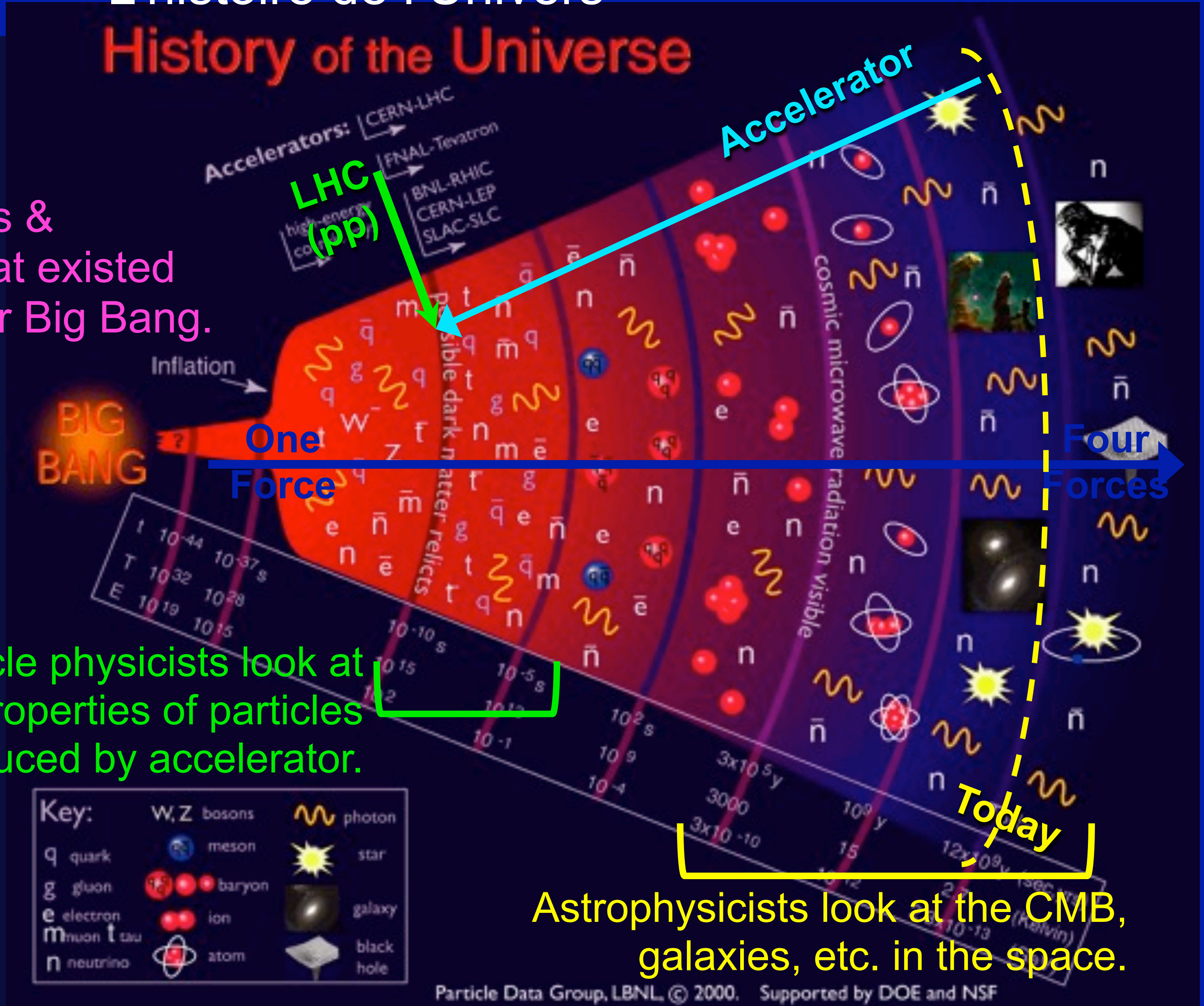
Dark Matter & Dark Energy



Matière Noire et Energie Noire

L'histoire de l'Univers

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 the space.

The Cosmic Microwave Background

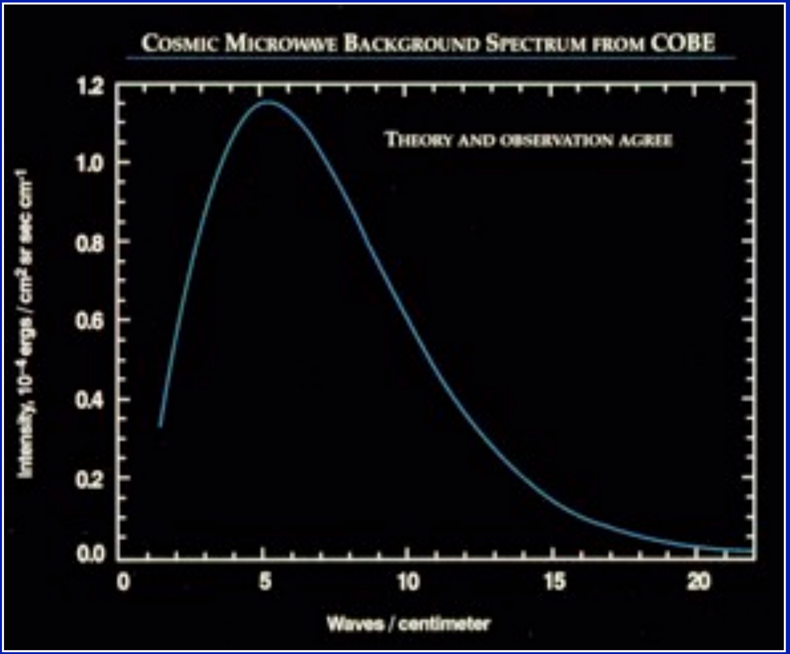
Le rayonnement de fond cosmique micro-onde

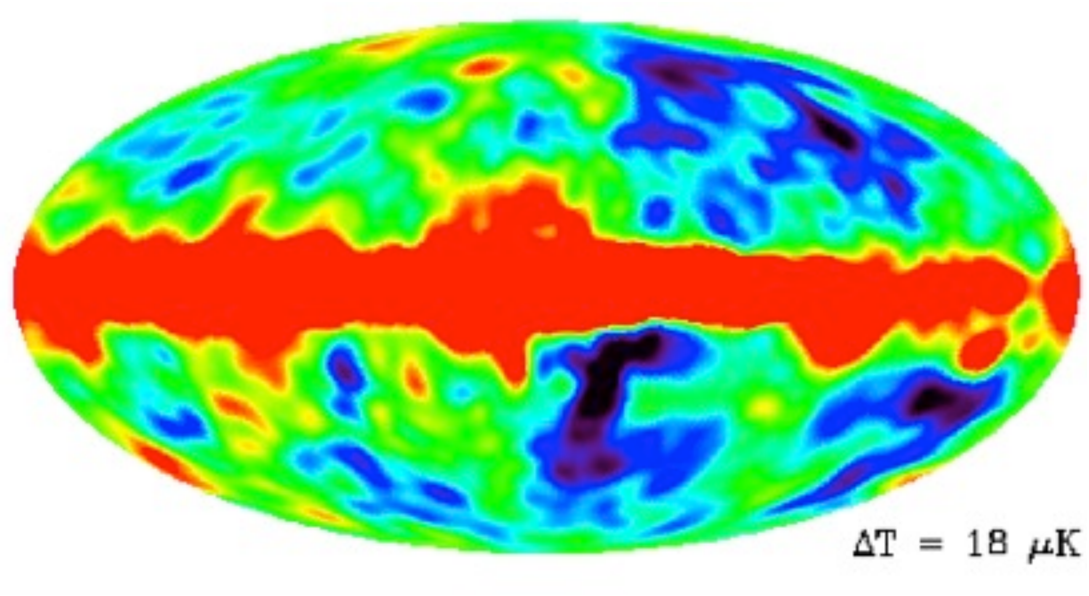
Discovered 1965 (Penzias & Wilson)

- 2.7 K blackbody
- Isotropic (<1%)
- Relic of hot "big bang"

1970's and 1980's

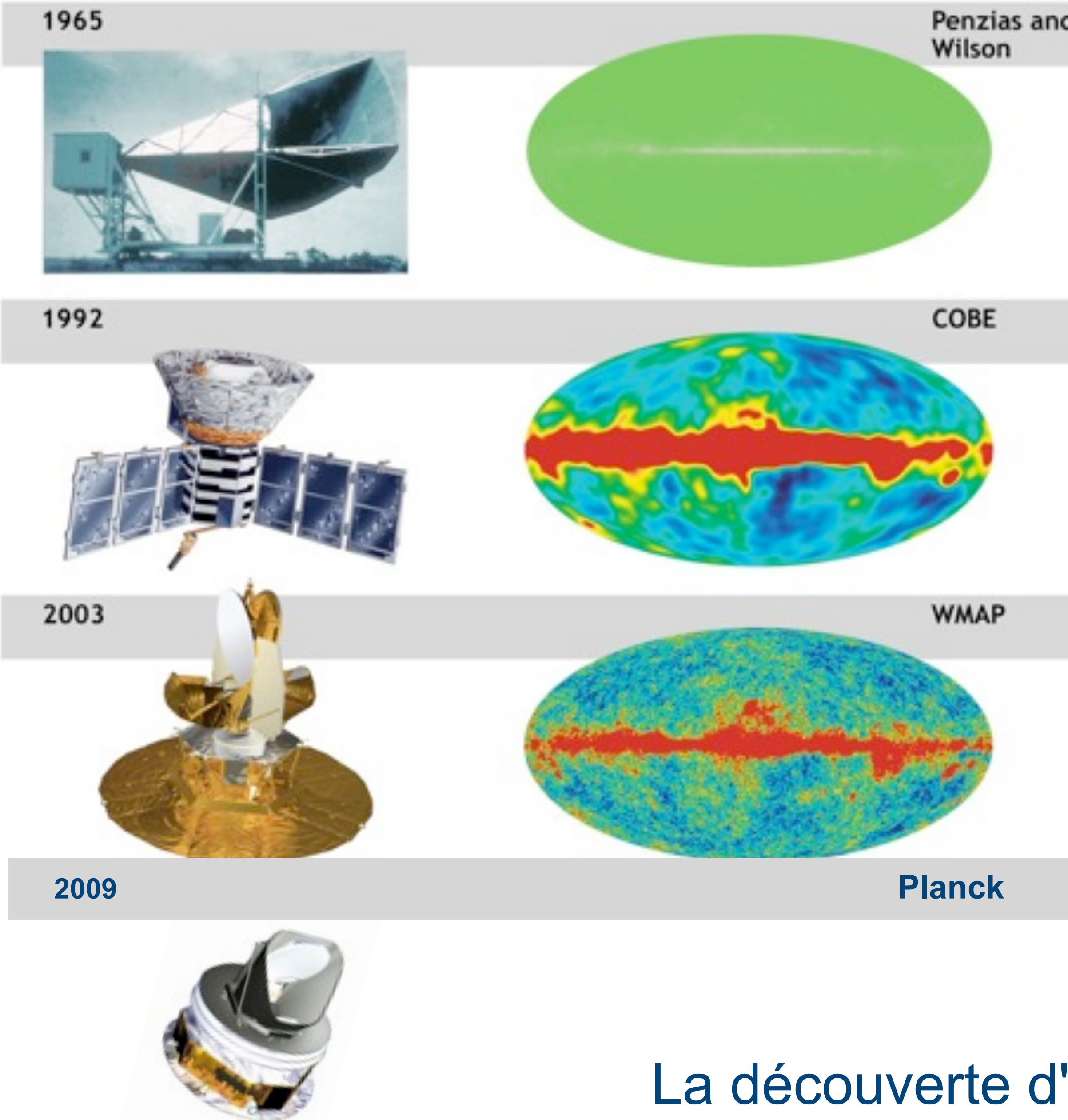
- 3 mK dipole (local Doppler)
- $\delta T/T < 10^{-5}$ on arcminute scales





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

Cosmic Microwave Background Radiation Overview



The oldest light in universe

La lumiére la plus ancienne en univers

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

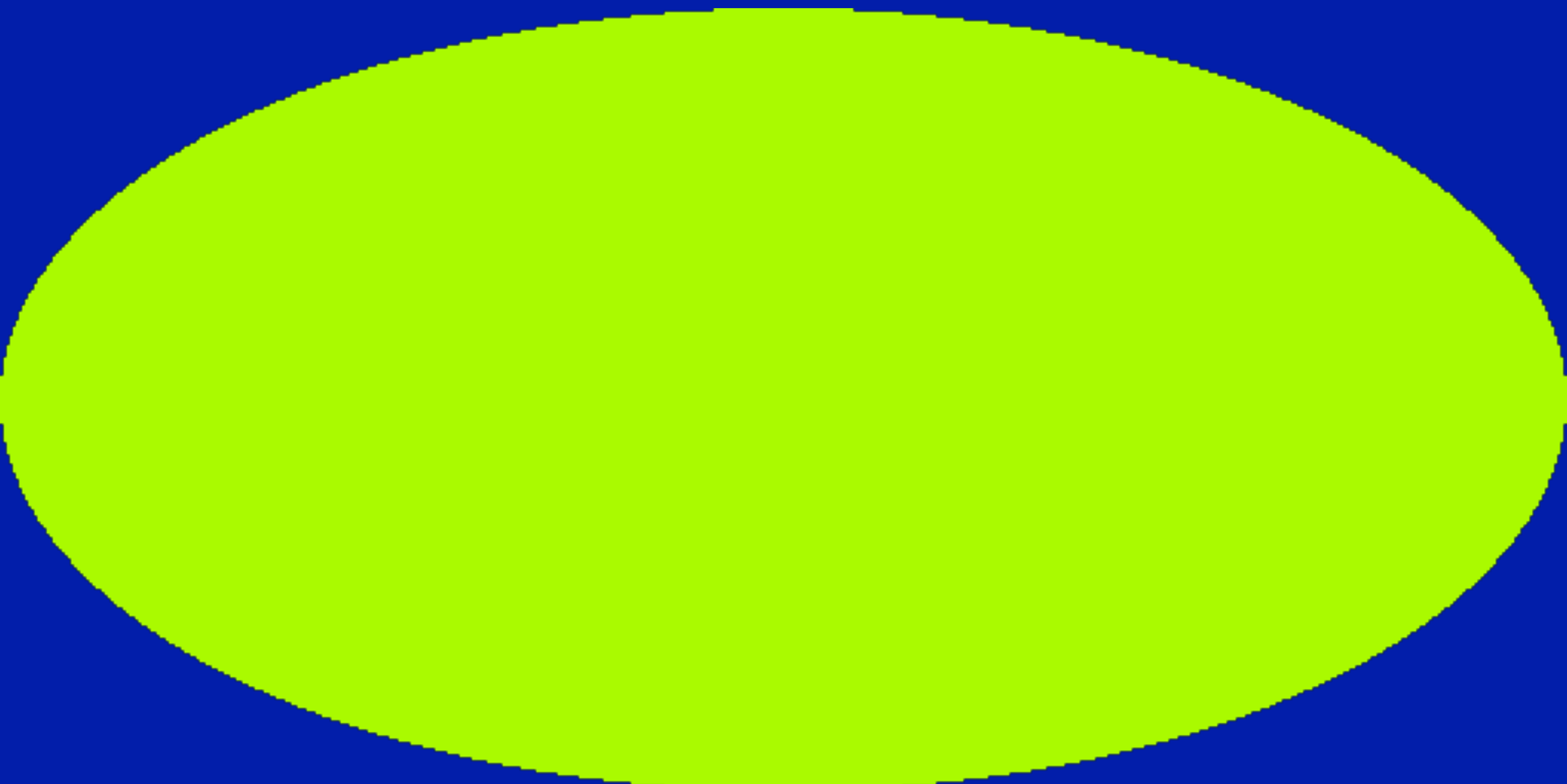
Blackbody radiation,
Discovered the patterns (**anisotropy**) in the afterglow.
→ **angular scale ~ 7°** at a level $\Delta T/T$ of 10^{-5}

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

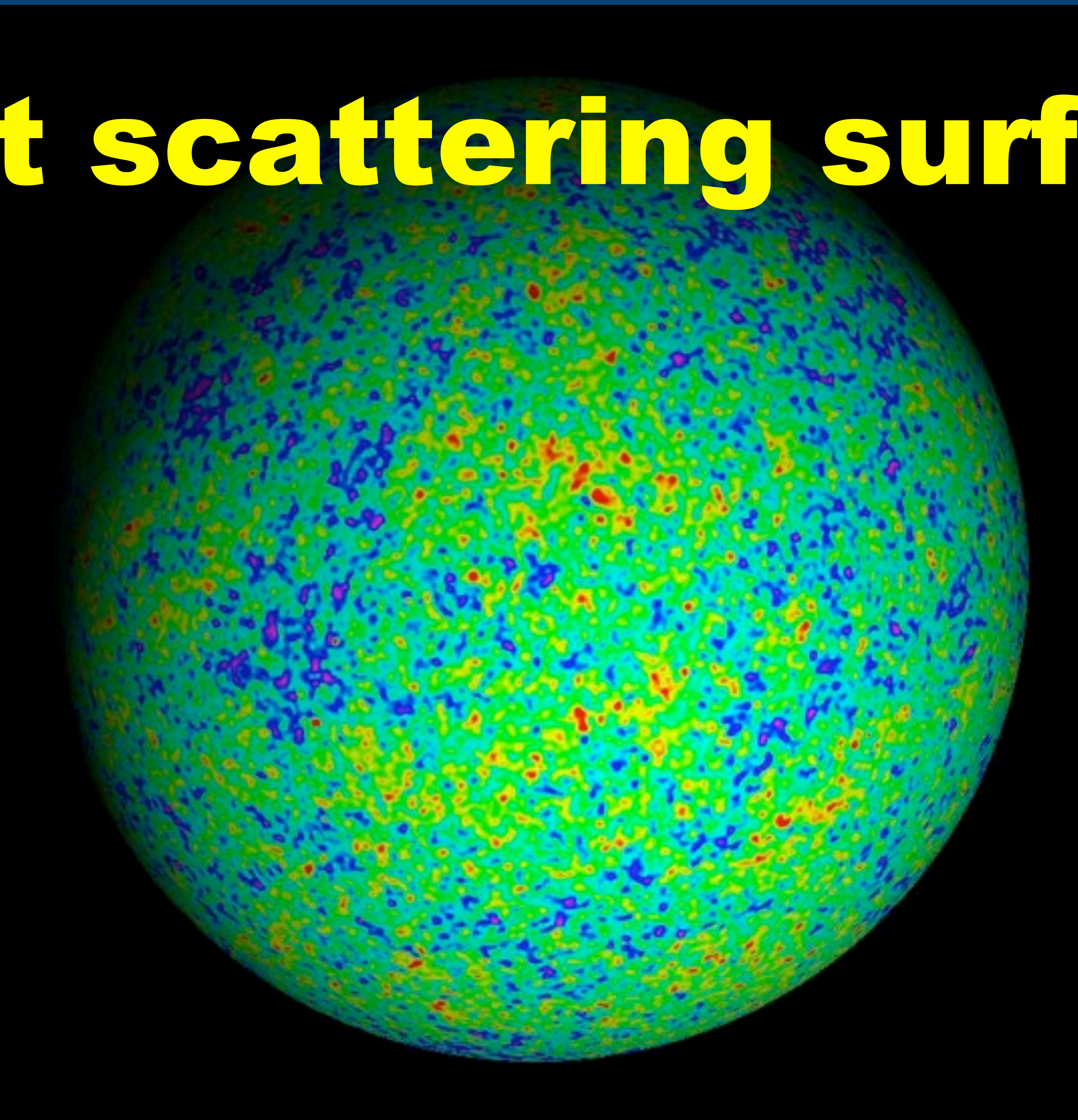
→ **angular scale ~ 5',**
$\Delta T/T \sim 2\times10^{-6}$, 30~867 Hz

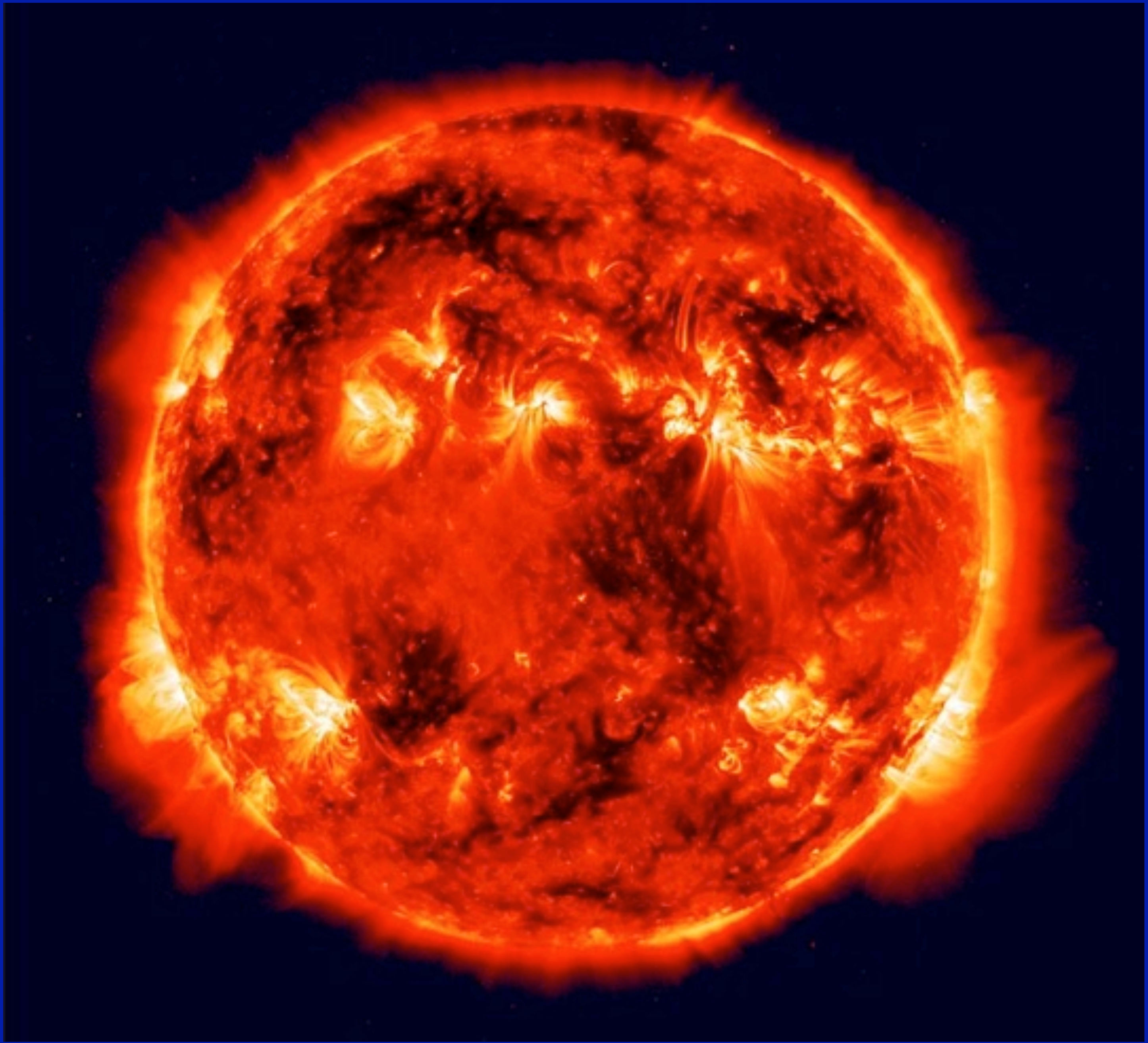
La découverte d'or la plus passionnante

Photosphere of Universe



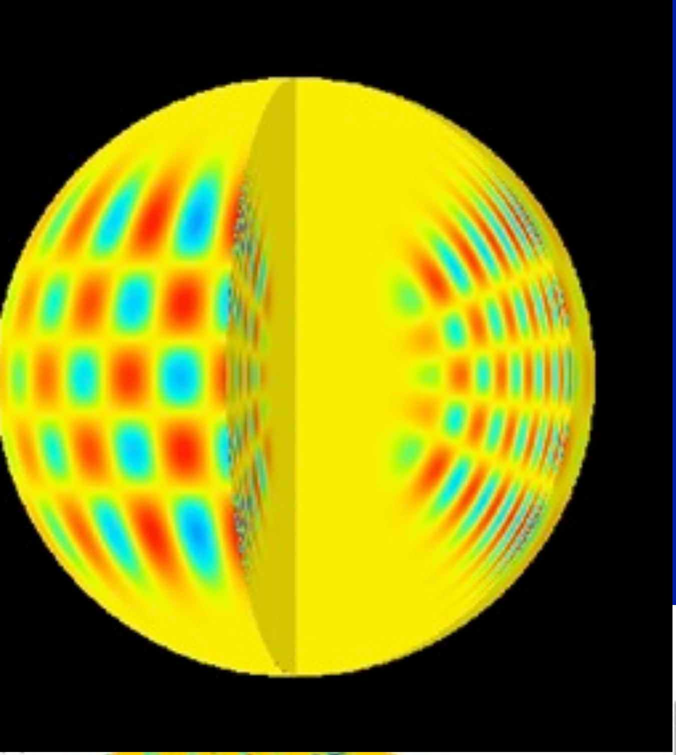
Foreground-cleaned WMAP map from Tegmark, de Oliveira-Costa & Hamilton, astro-ph/0302496

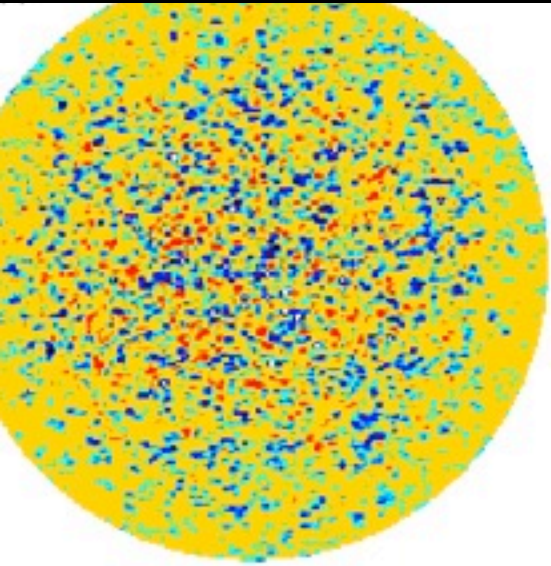


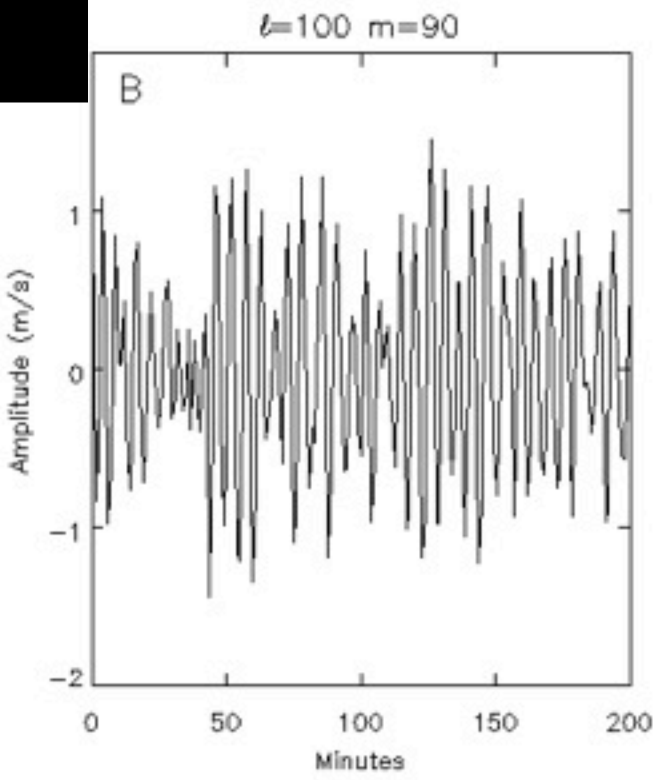


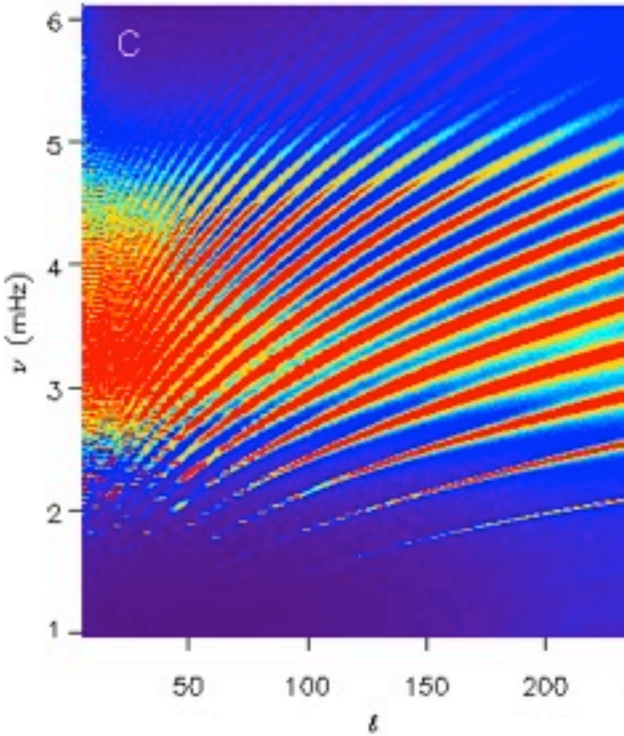
Helio-seismology power spectrum

$$T(\theta,\phi) = \sum_{lm} a_{lm} Y_{lm}(\theta,\phi)$$









Helio-seismology power spectrum

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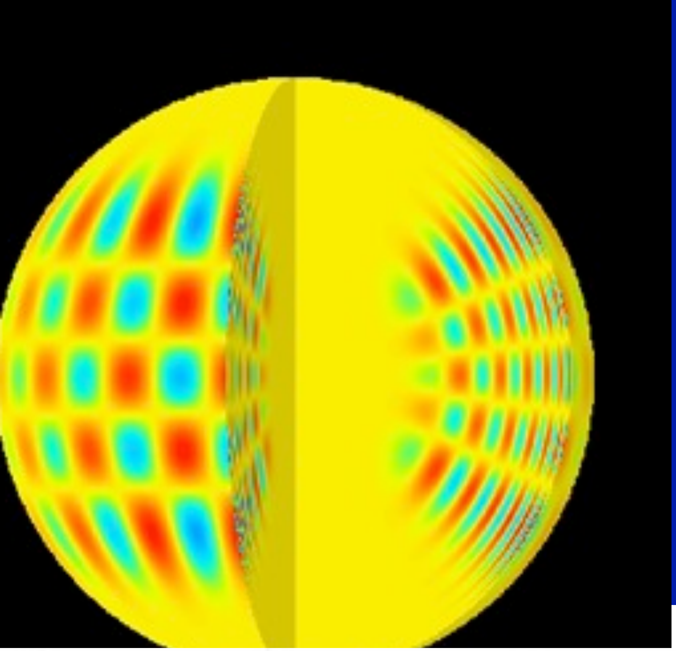
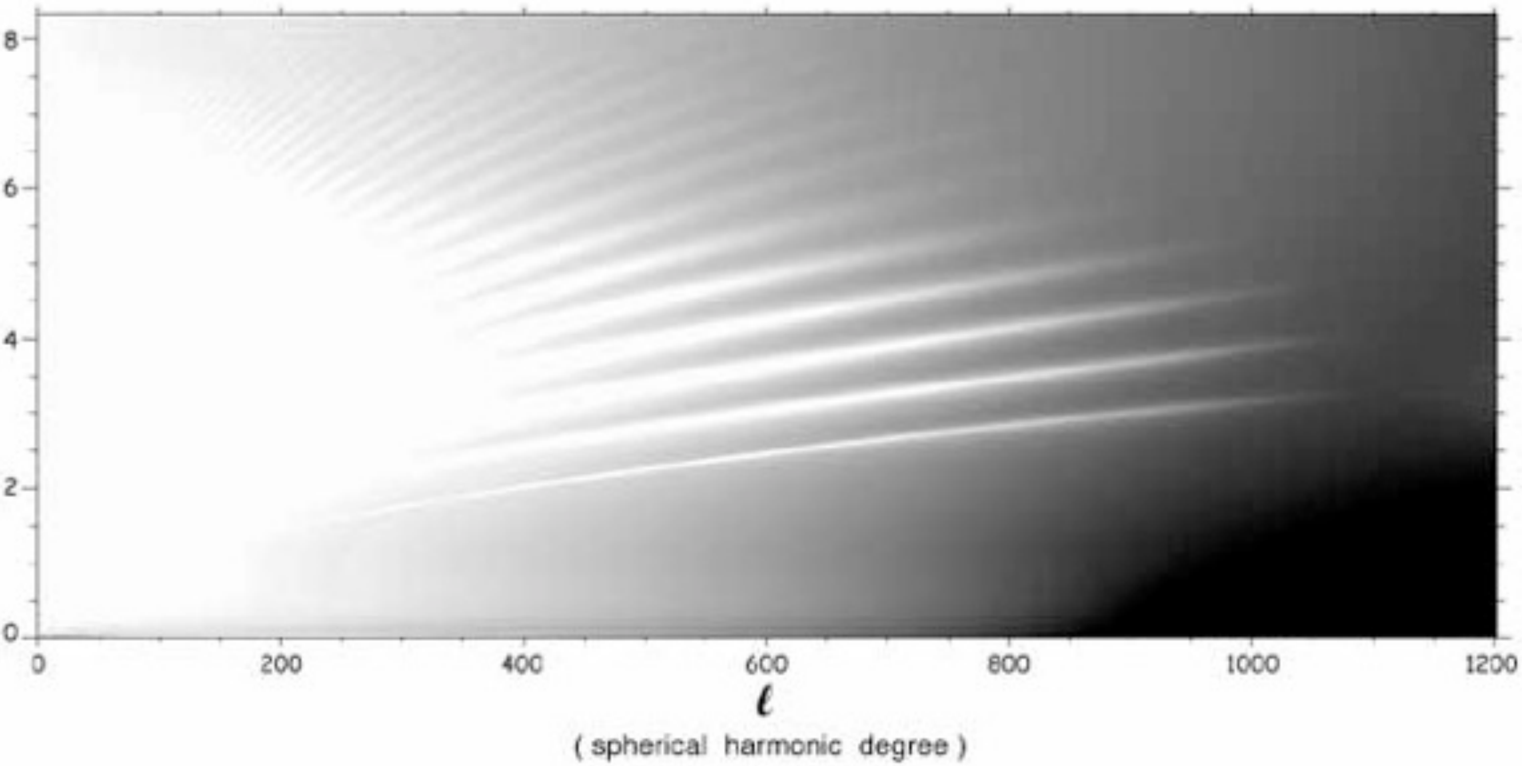
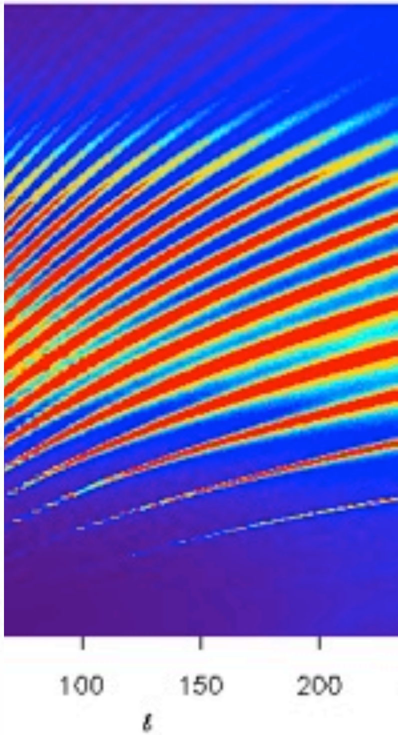
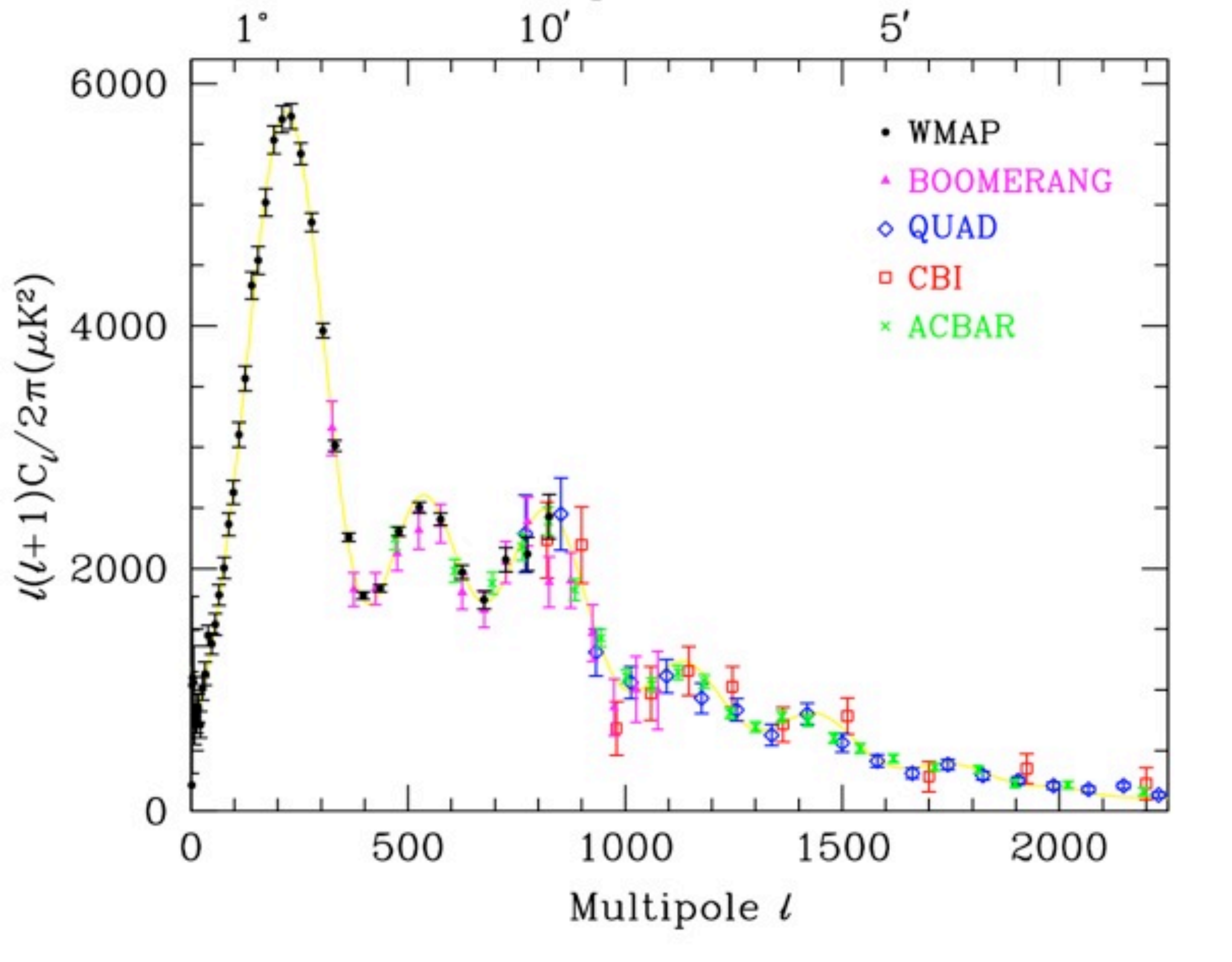






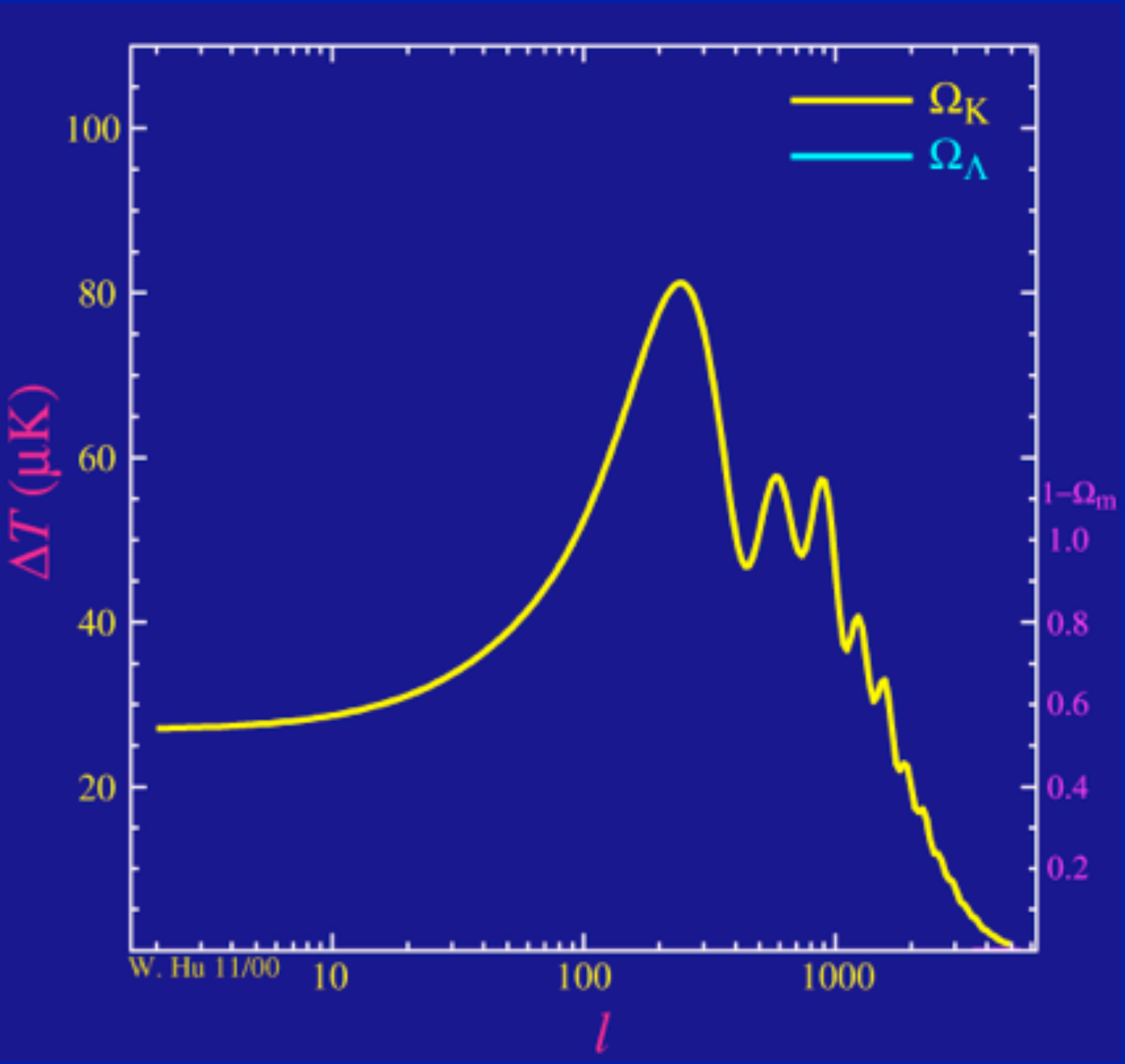
CMB Angular Power Spectrum



No preferred direction means we can average over m's to get power for each ℓ

$C_\ell \equiv \Sigma_m |a_{\ell m}|^2$

Peaks and Curvature or Dark Energy

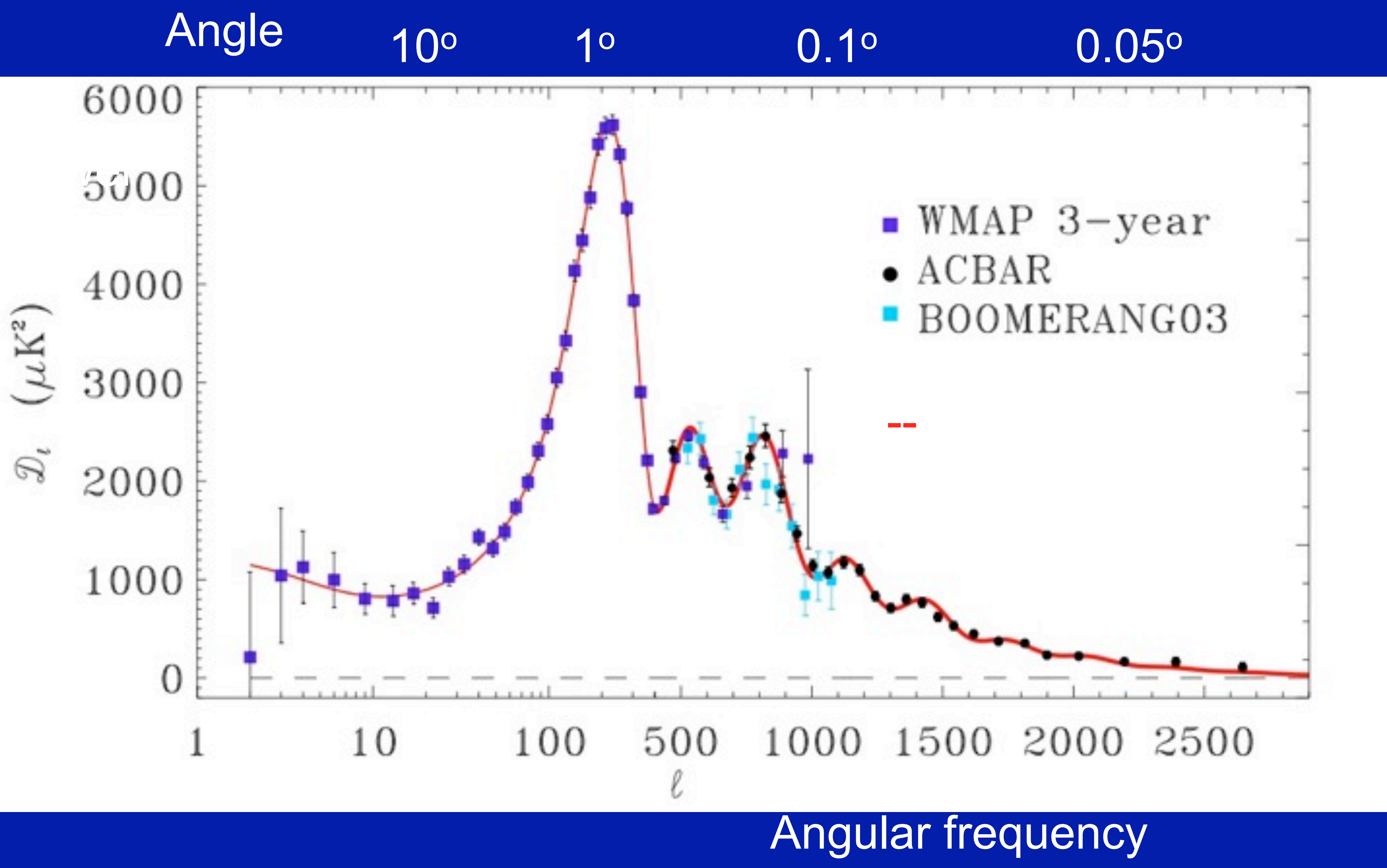


Courtesy Wayne Hu – *http://background.uchicago.edu*

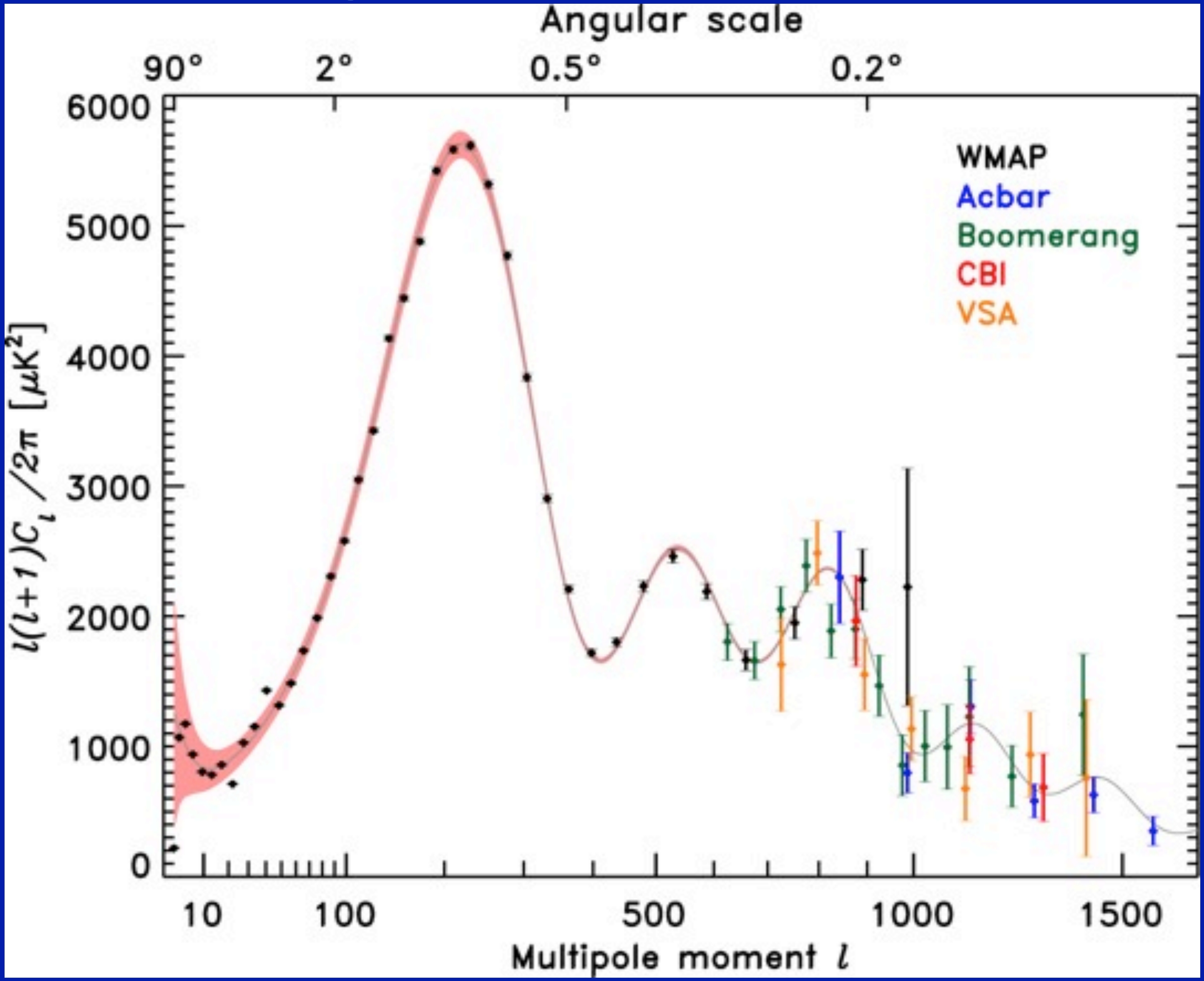
Changing distance to z =1100 shifts peak pattern

- 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)

Spectral Analysis of CMB fluctuations

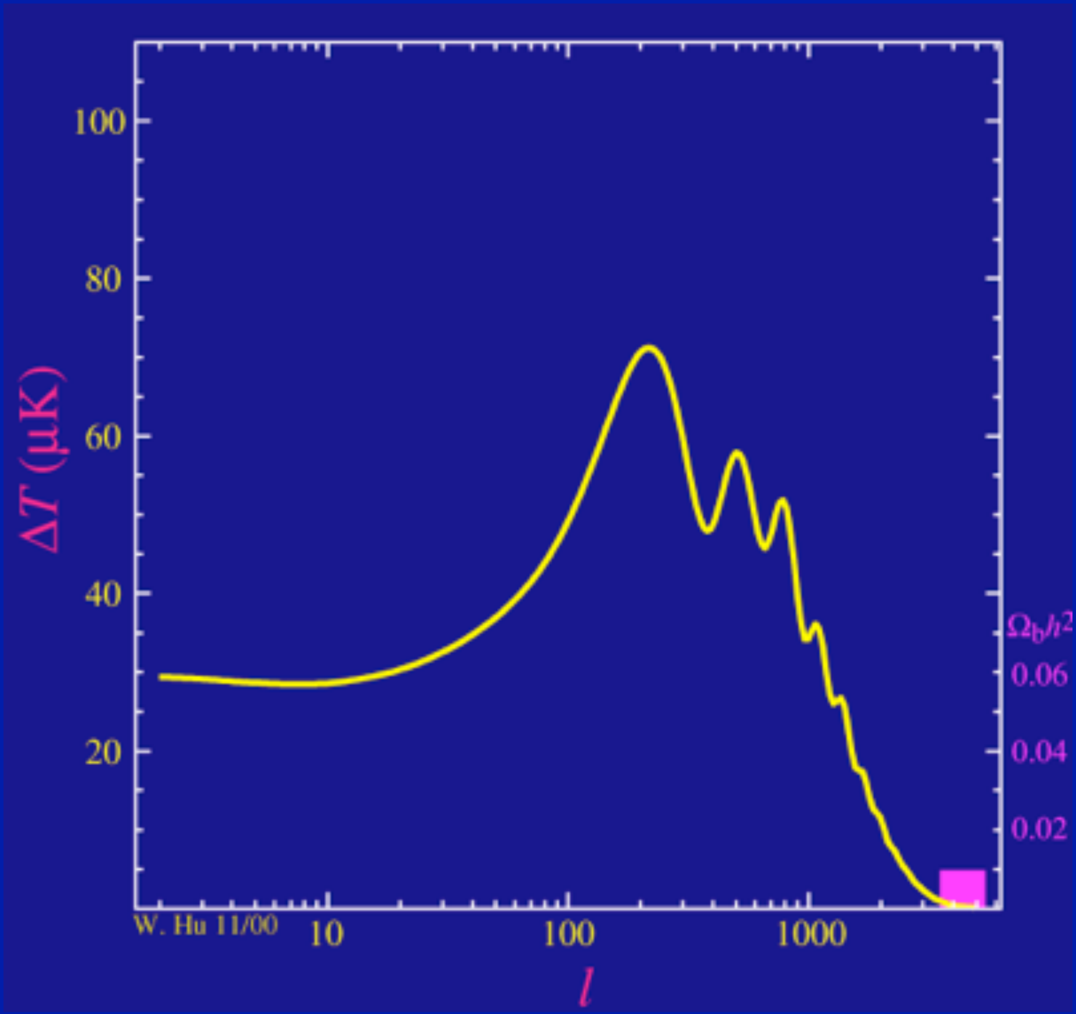


CMB Angular Power Spectrum



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

Peaks and Baryons

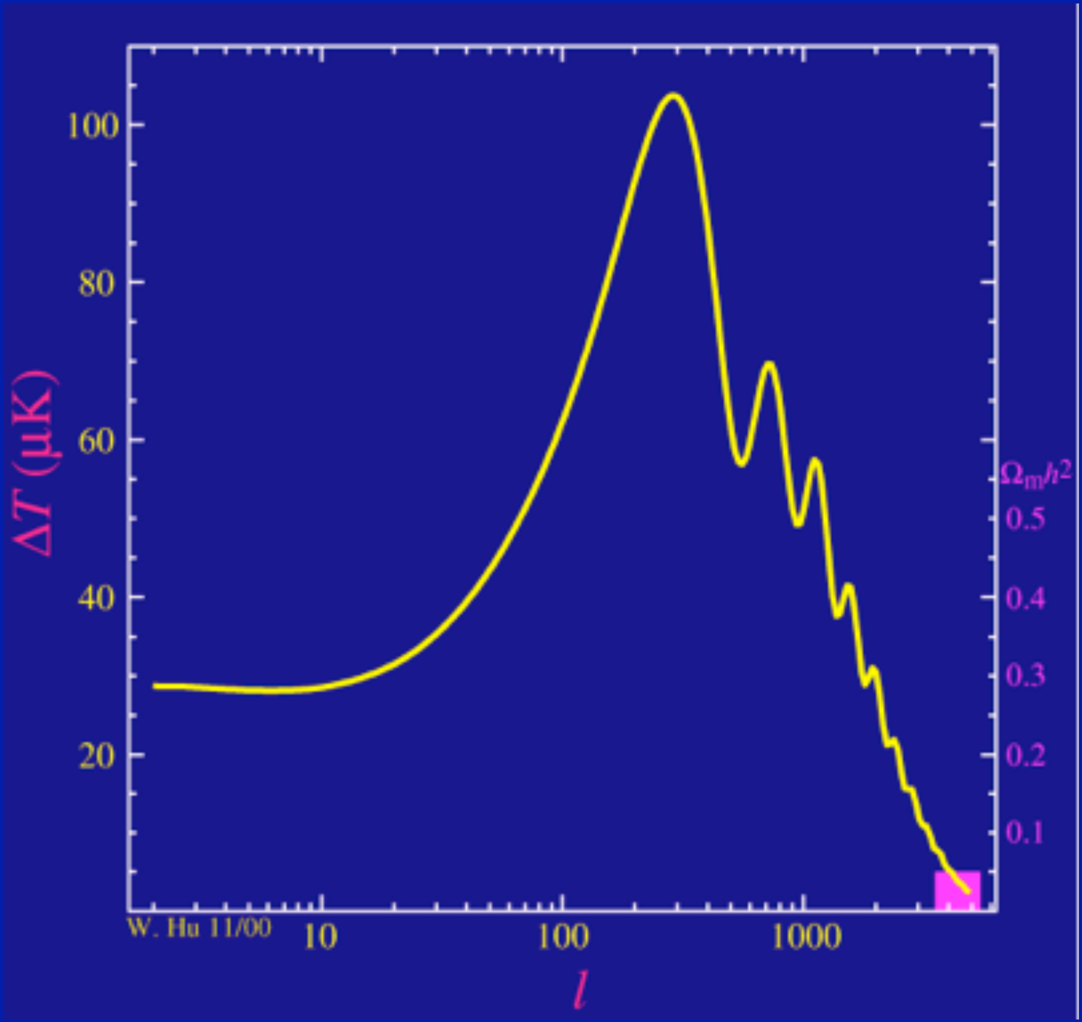


Courtesy Wayne Hu – *http://background.uchicago.edu*

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)

Peaks and Matter

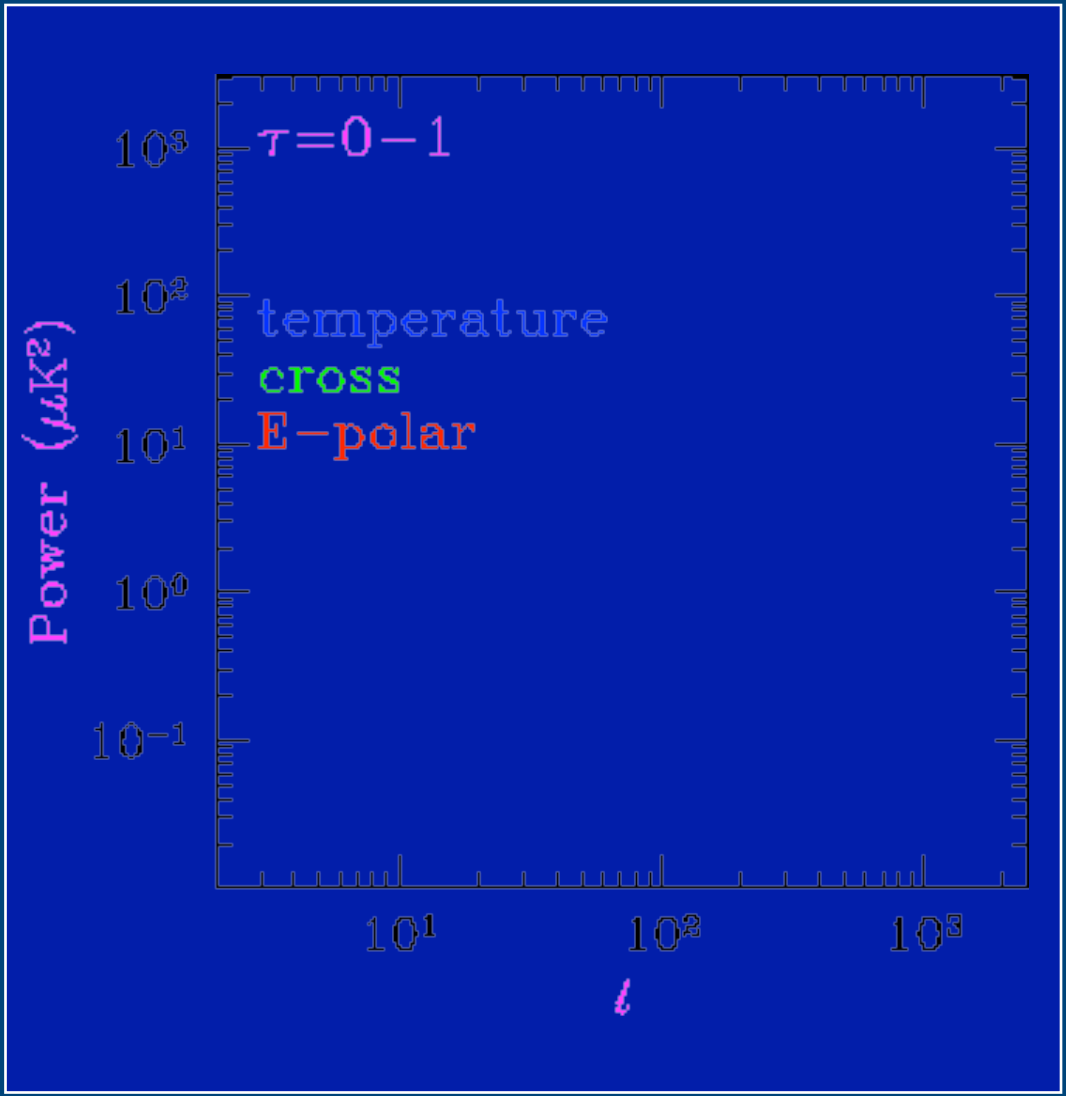


Courtesy Wayne Hu – *http://background.uchicago.edu*

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



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

Late reionization reprocesses CMB photons

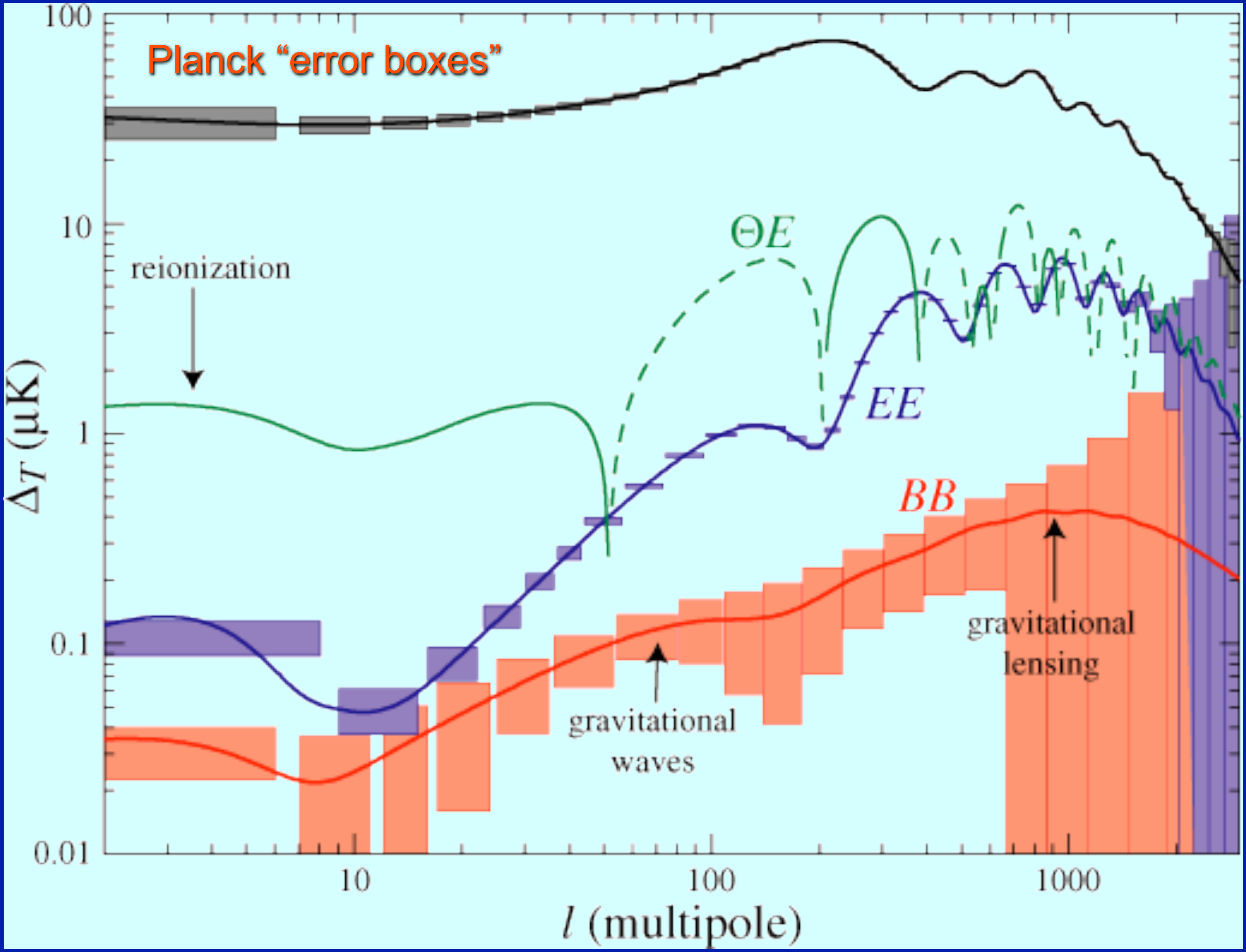
- Suppression of primary temperature anisotropies
  - as exp(-τ)
  - degenerate with amplitude and tilt of spectrum
- Enhancement of polarization
  - low ℓ modes E & B increased
- Second-order conversion of T into secondary anisotropy
  - not shown here
  - velocity modulated effects
  - high ℓ modes

CMB Checklist

Primary predictions from inflation-inspired models:

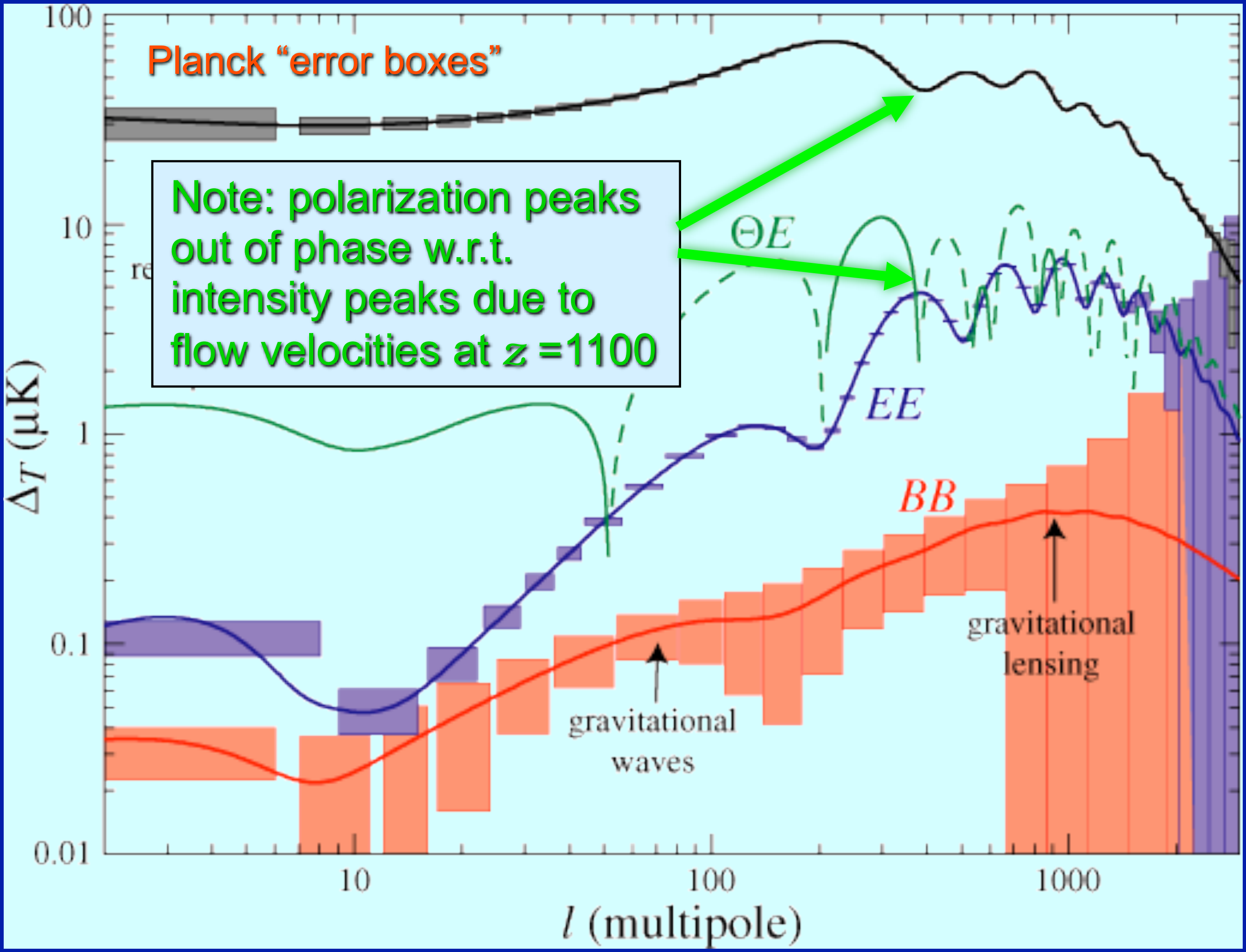
- acoustic oscillations below horizon scale
  - ✓ nearly harmonic series in sound horizon scale
  - ✓ signature of super-horizon fluctuations (horizon crossing starts clock)
  - ✓ even-odd peak heights baryon density controlled
  - ✓ a high third peak signature of dark matter at recombination
- nearly 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 ($n \approx 0.96$) and small running
- damping of small-scale fluctuations
  - ✓ baryon-photon coupling plus delayed recombination (& reionization)

Planck: Predicted Power Spectrum



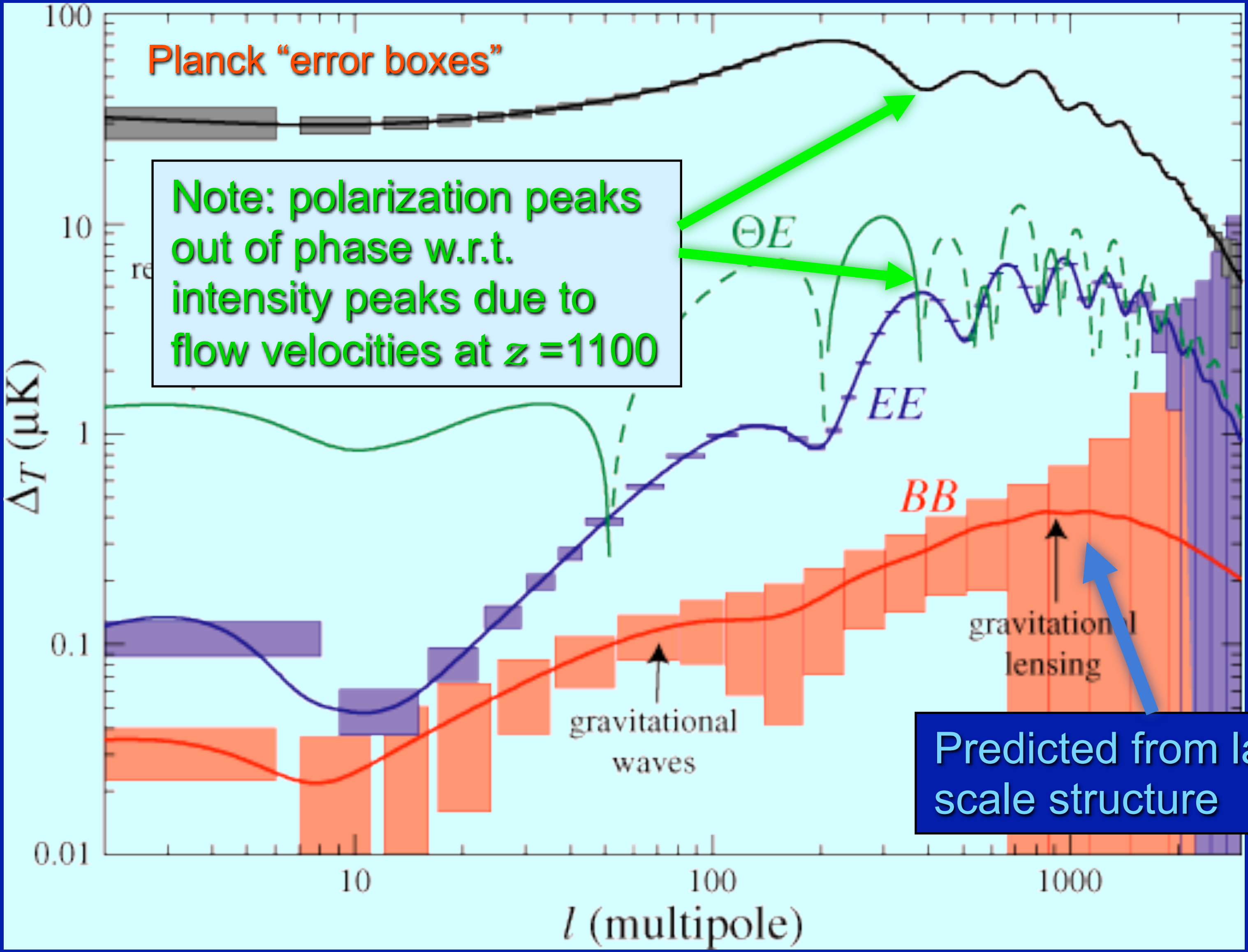
Hu & Dodelson *ARAA 2002*

Planck: Predicted Power Spectrum



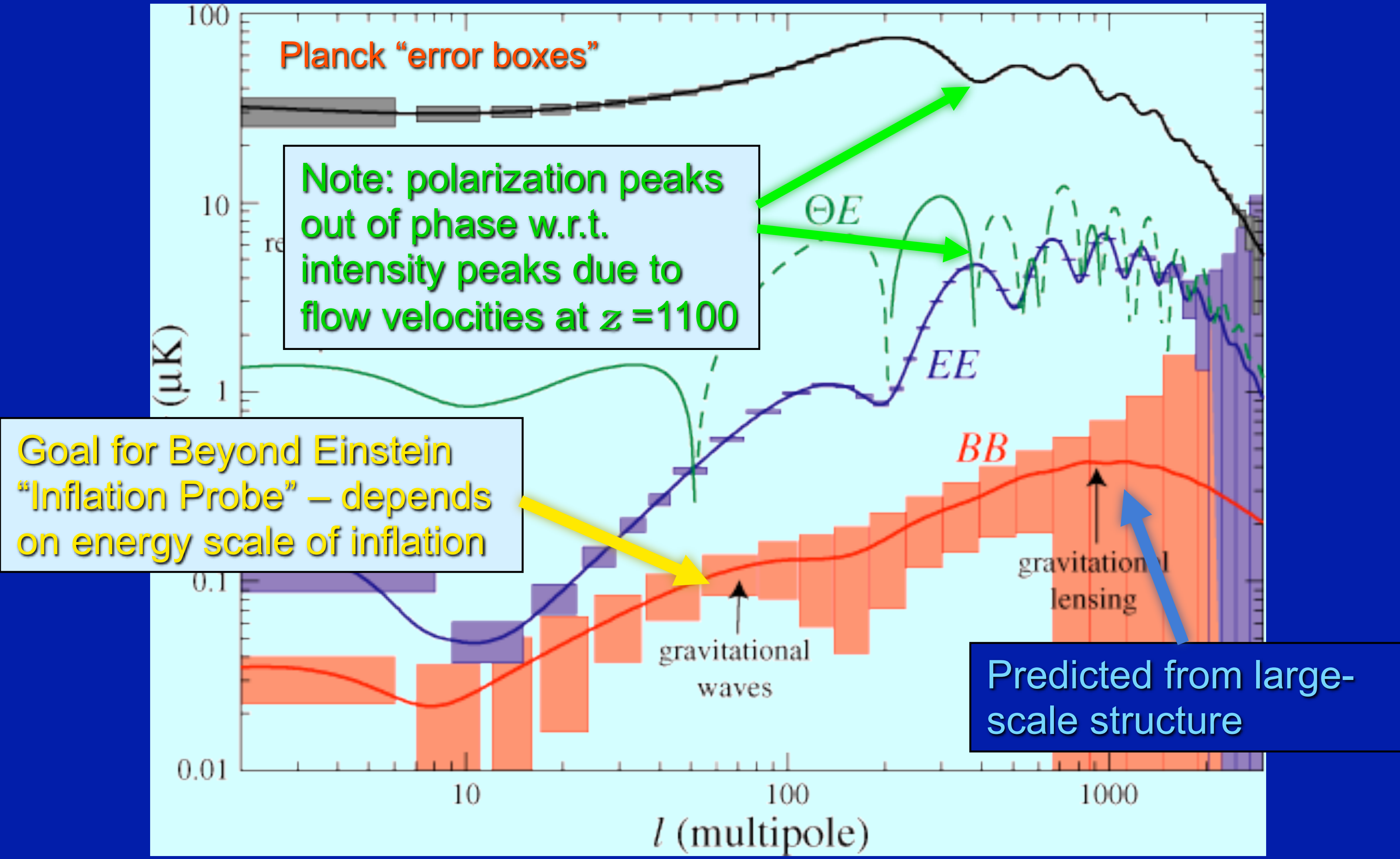
Hu & Dodelson *ARAA 2002*

Planck: Predicted Power Spectrum



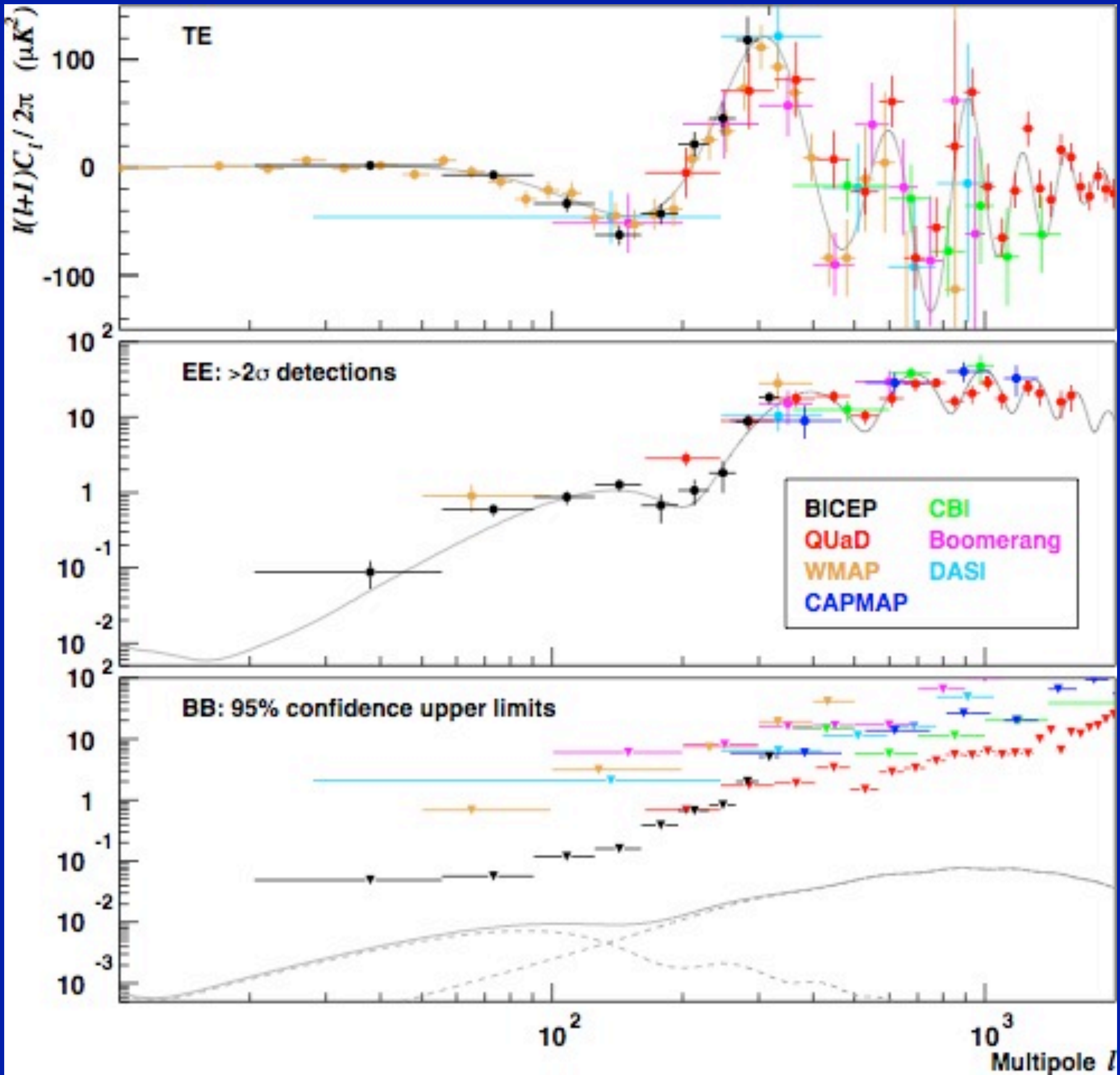
Hu & Dodelson *ARAA 2002*

Planck: Predicted Power Spectrum

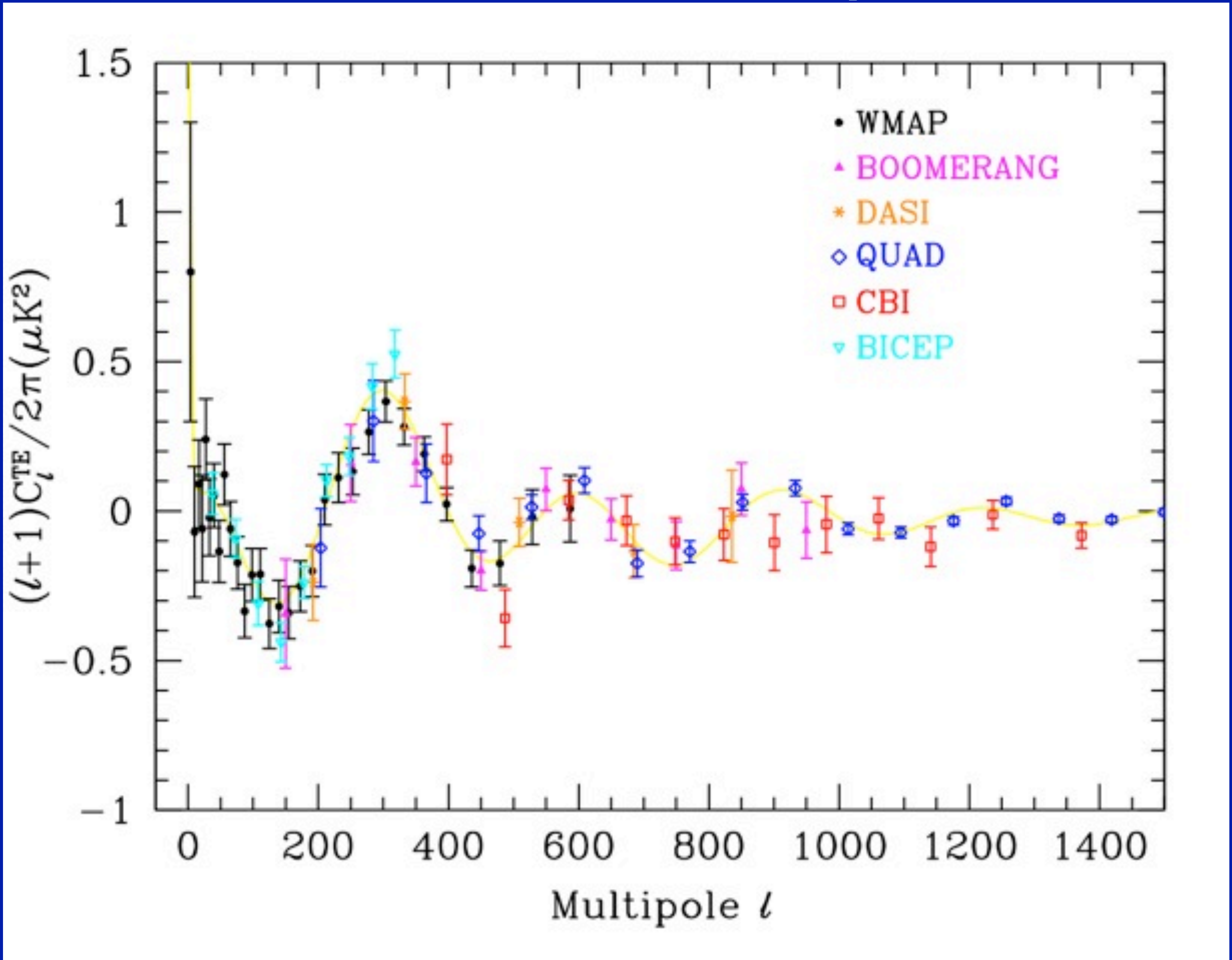


Hu & Dodelson *ARAA 2002*

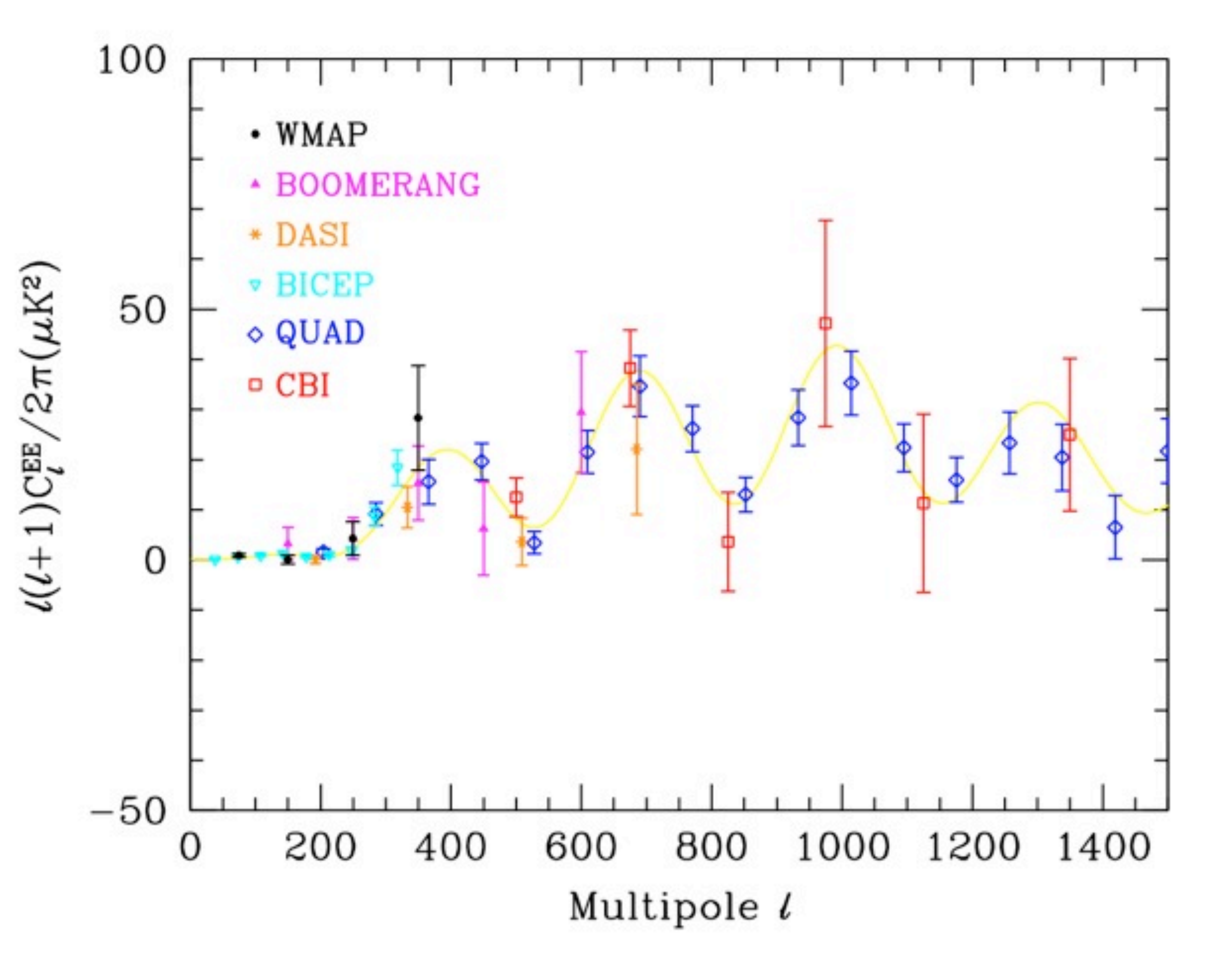
Current Status - 6/2009



T-E Cross Power Spectrum



EE Angular Power Spectrum



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≈0.98)
- – decay within horizon ($\ell \approx 100$)
- – tensor/scalar ratio r from energy scale of inflation ~ $(E_{inf}/10^{16}$ GeV
  4

Our inflationary hot Big-Bang theory is standing up well to

CMB Experiments at the South Pole

Club Med for CMB Experimentalists

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

Atacama: ACT Site

5200 meters near peak of Cerro Toco,
in the Atacama Desert in the Andes of Northern Chile
23º south latitude.
ACT, APEX, ALMA, CBI, Clover, Polar Bear

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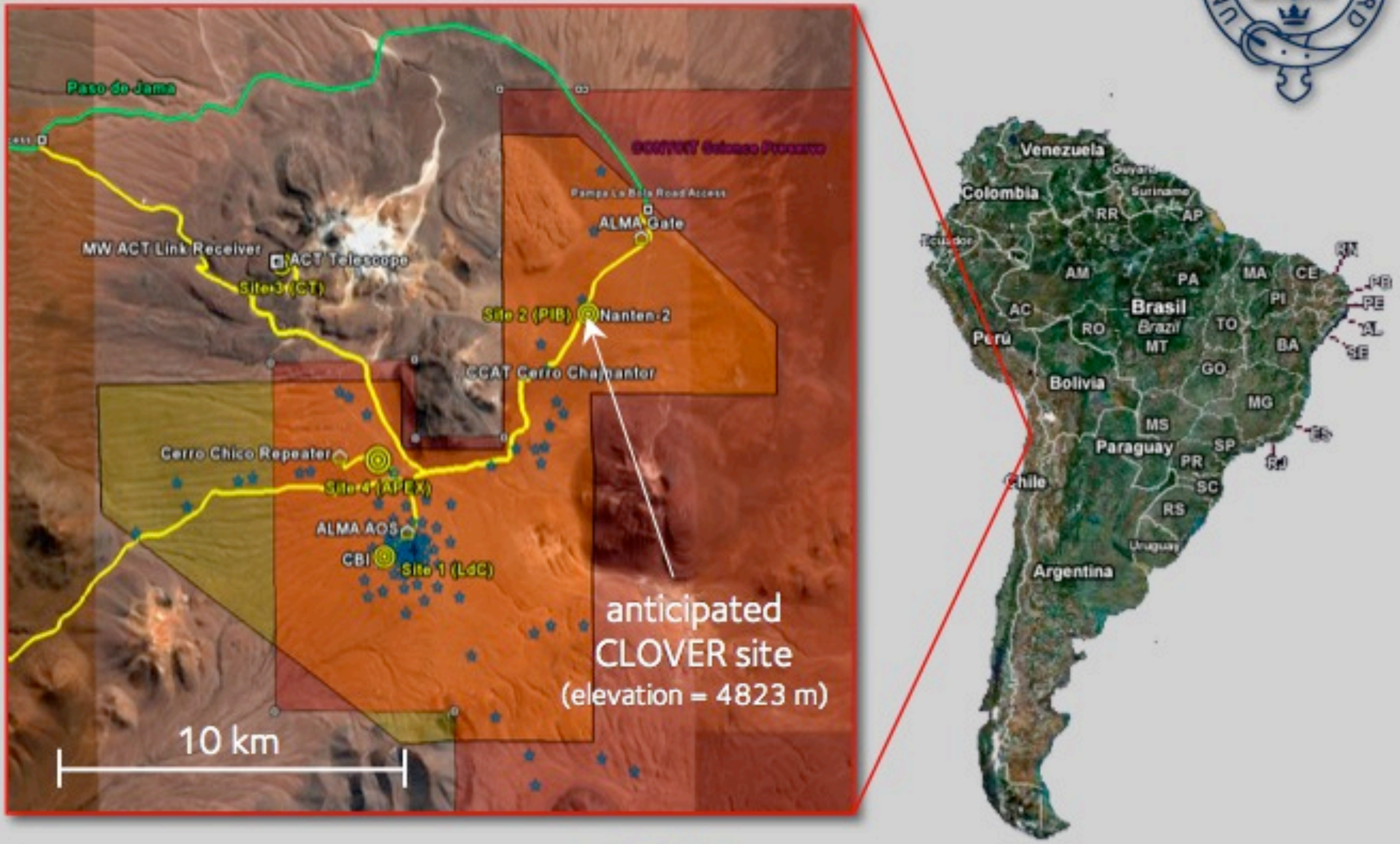
CLOVER Site: Atacama, Chile

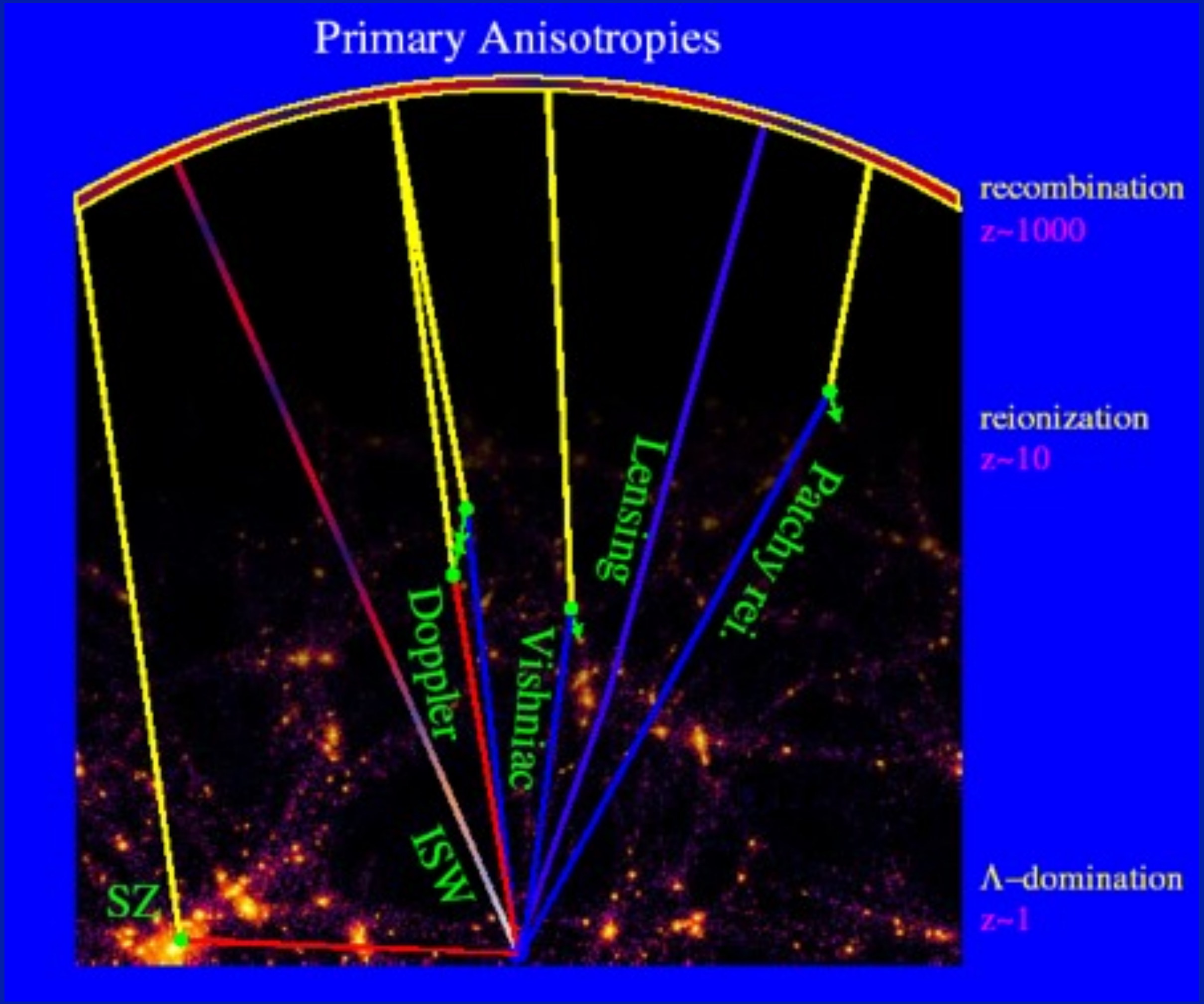


Bradley R Johnson

January 29, 2008

Secondary Anisotropies

The CMB After Last Scattering…



Secondary Anisotropies from propagation and late-time effects

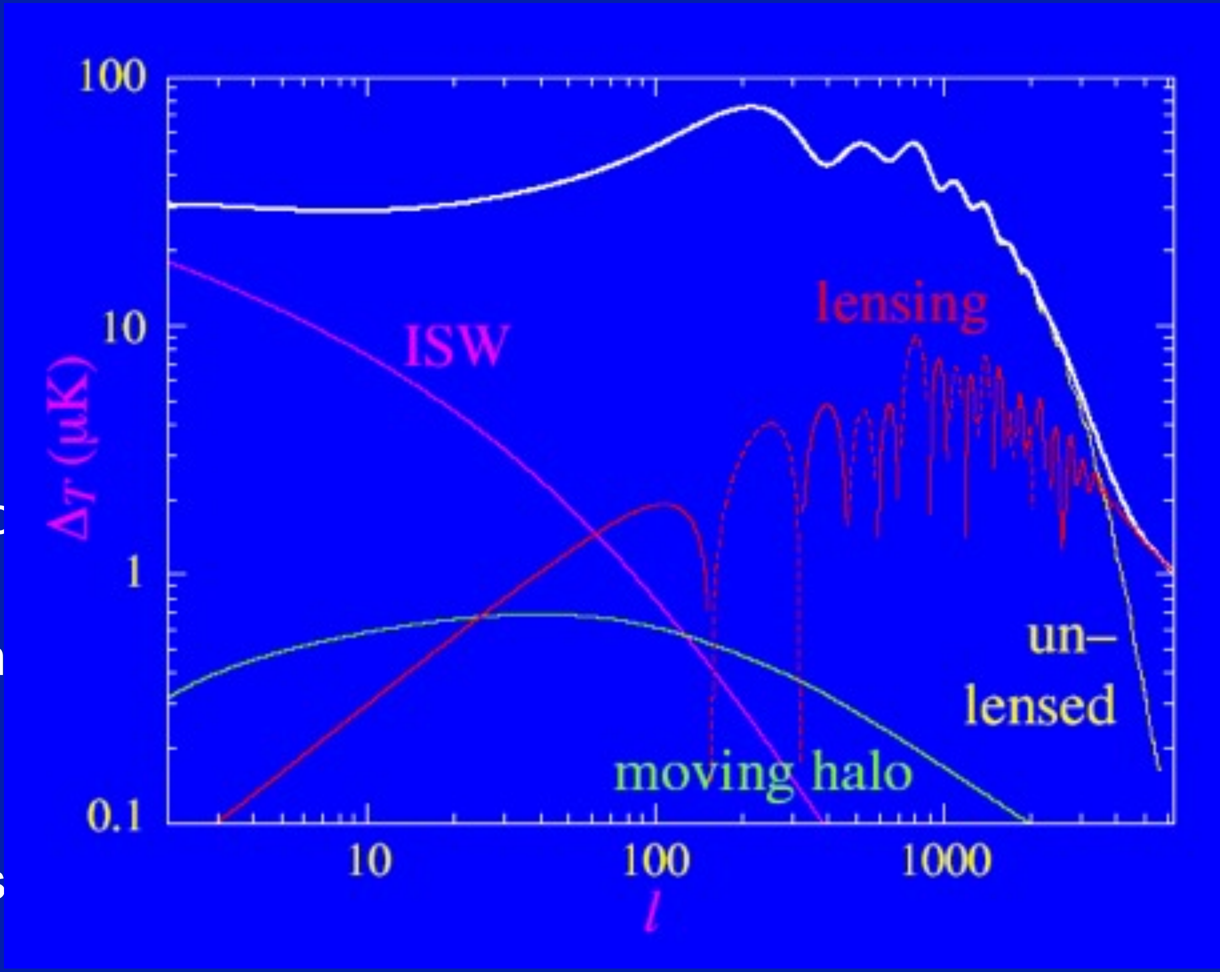
Courtesy Wayne Hu – *http://background.uchicago.edu*

Gravitational Secondaries

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

Includes:

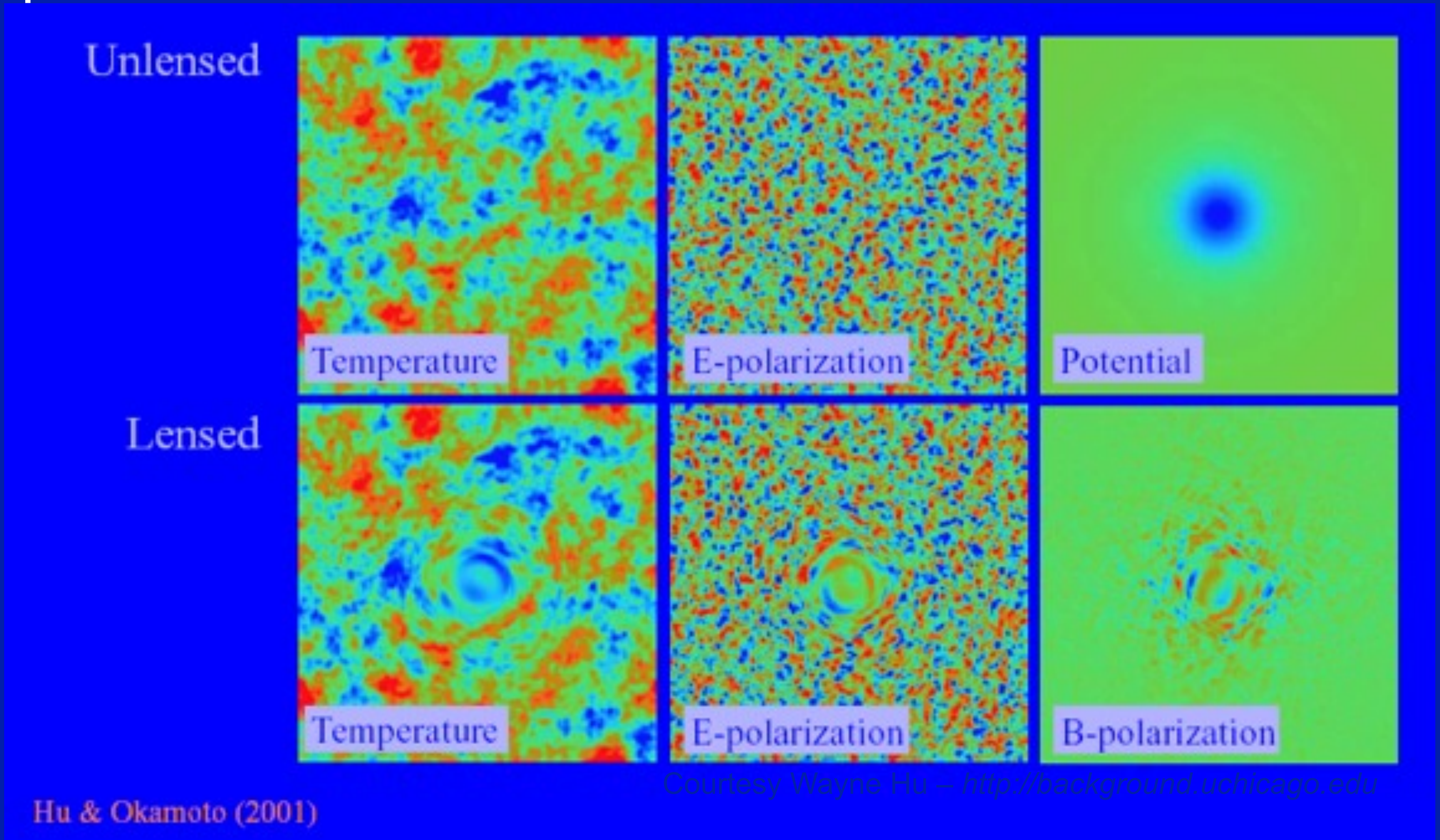
- Early ISW (decay, matter-radiation transition at last scattering)
- Late ISW (decay, in open o
- lambda models)
- Rees-Sciama (growth, non linear structures)
- Tensors (gravity waves)
- Lensing (spatial distortions



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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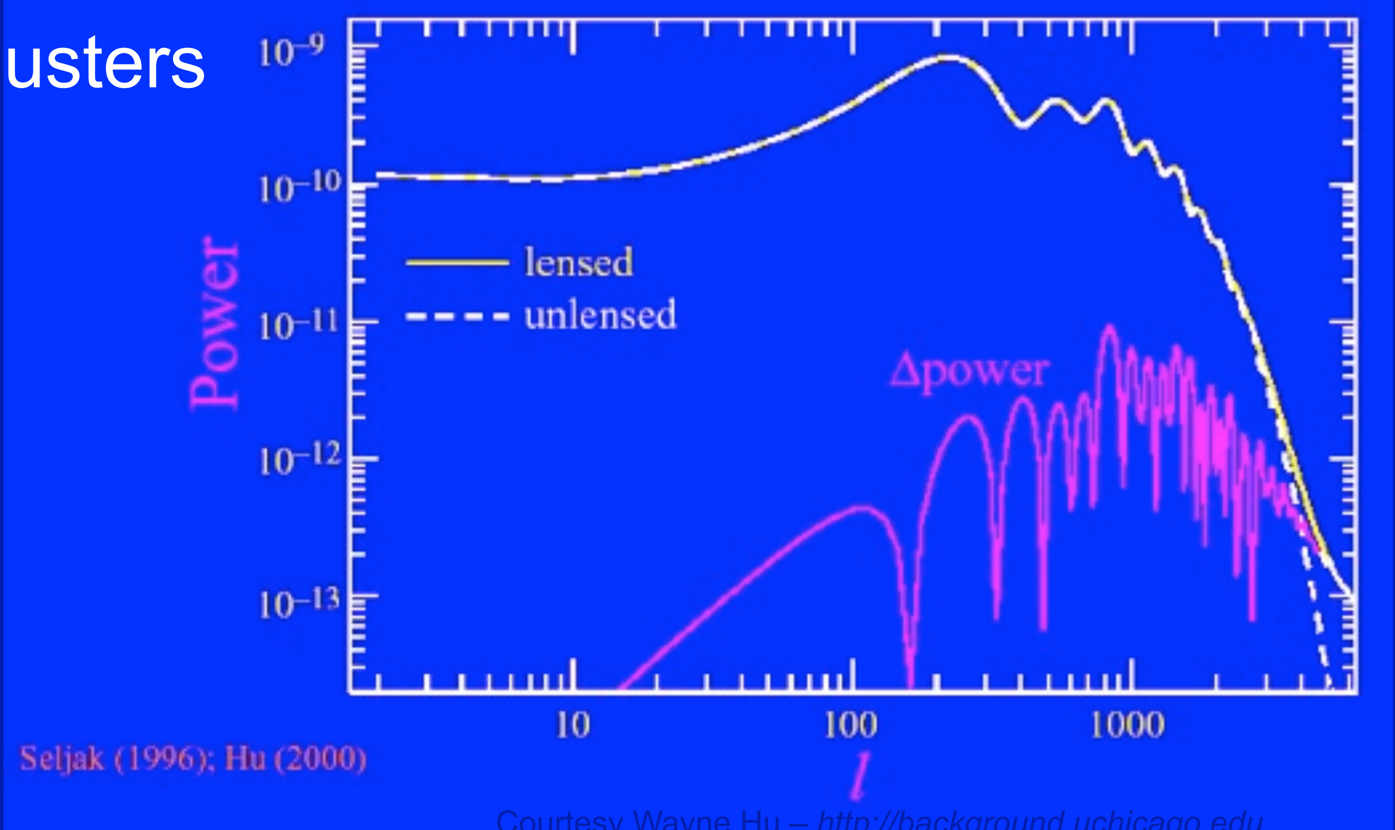
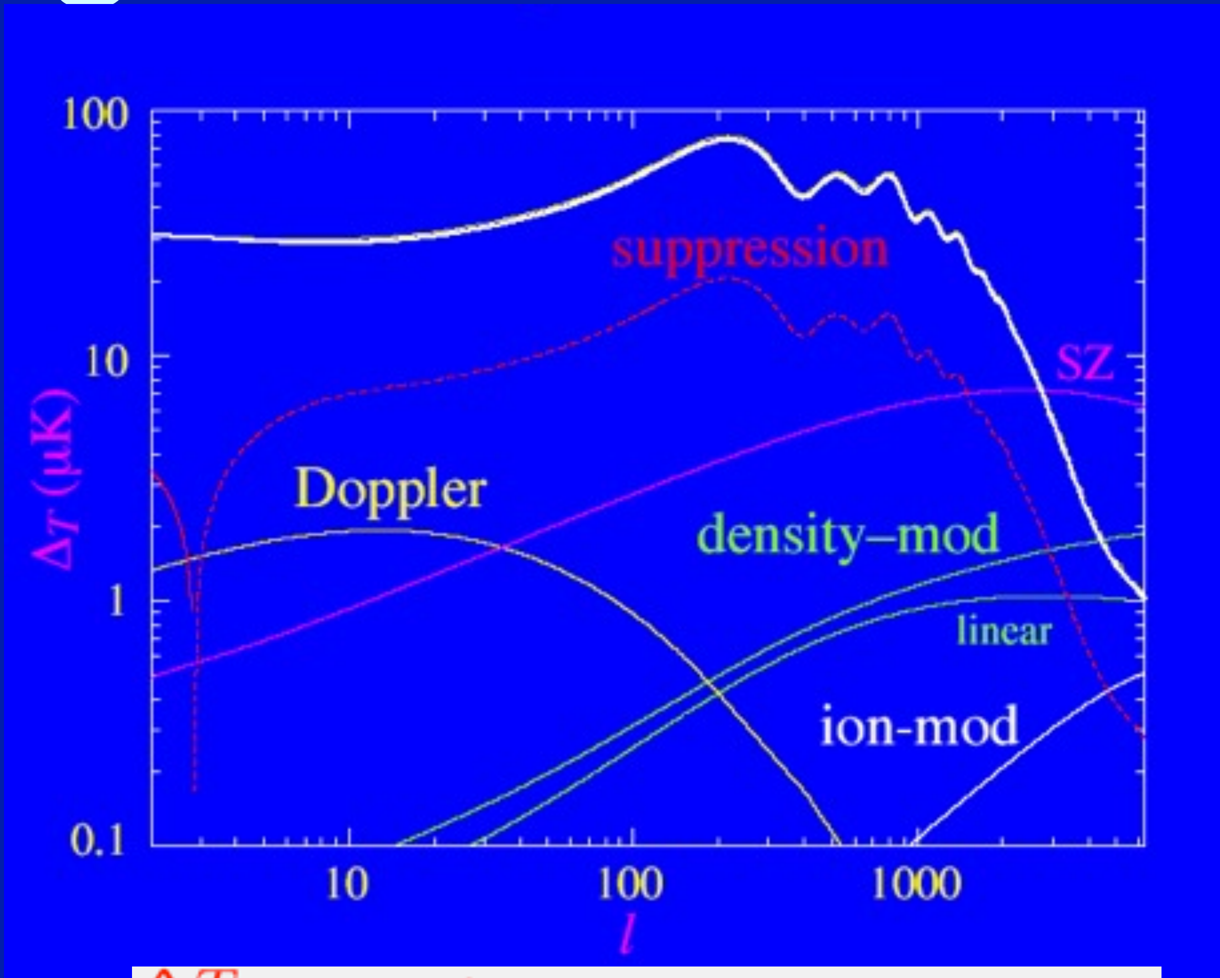


Courtesy Wayne Hu – *http://background.uchicago.edu*

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



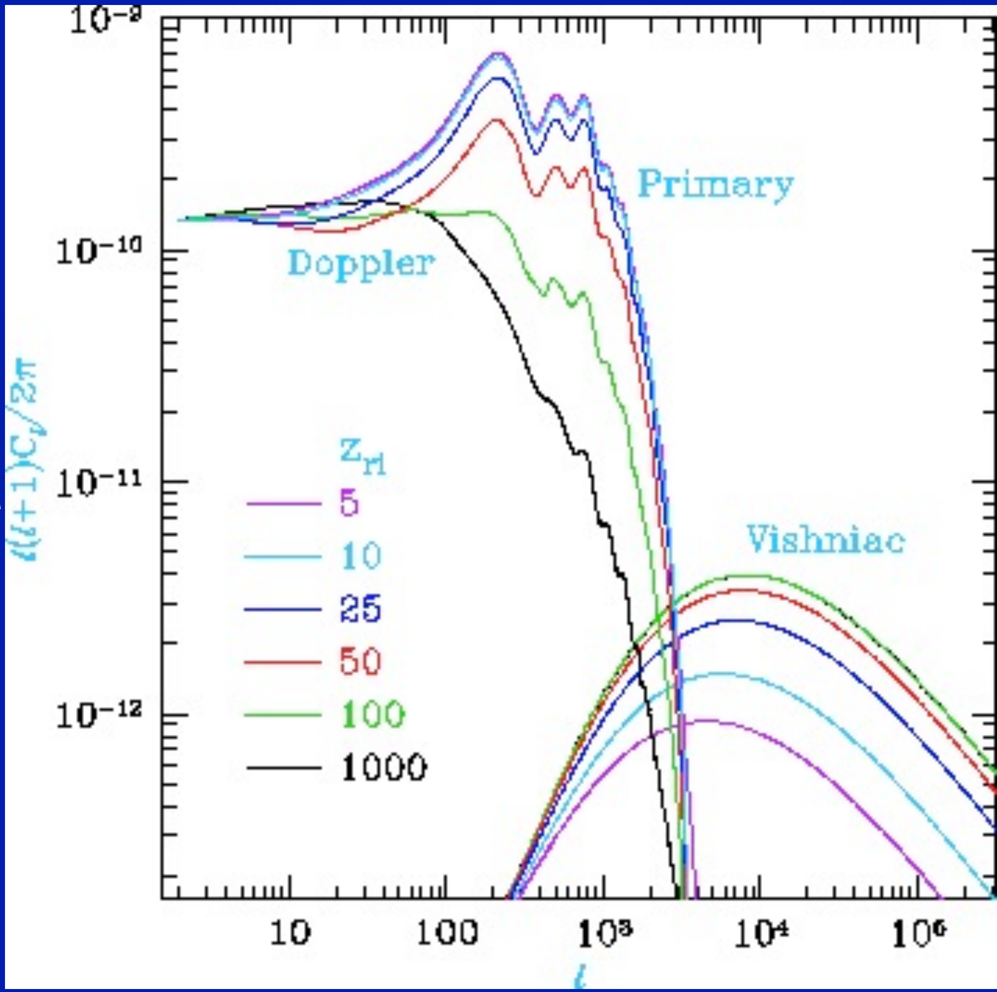
$$\frac{\Delta T}{T}(\hat{n}) = \int dx\,(n_e\,\sigma_T\,e^{-\tau})\,\hat{n}\cdot\mathbf{v}(\mathbf{x},z)$$

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

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

Ostriker-Vishniac Effect

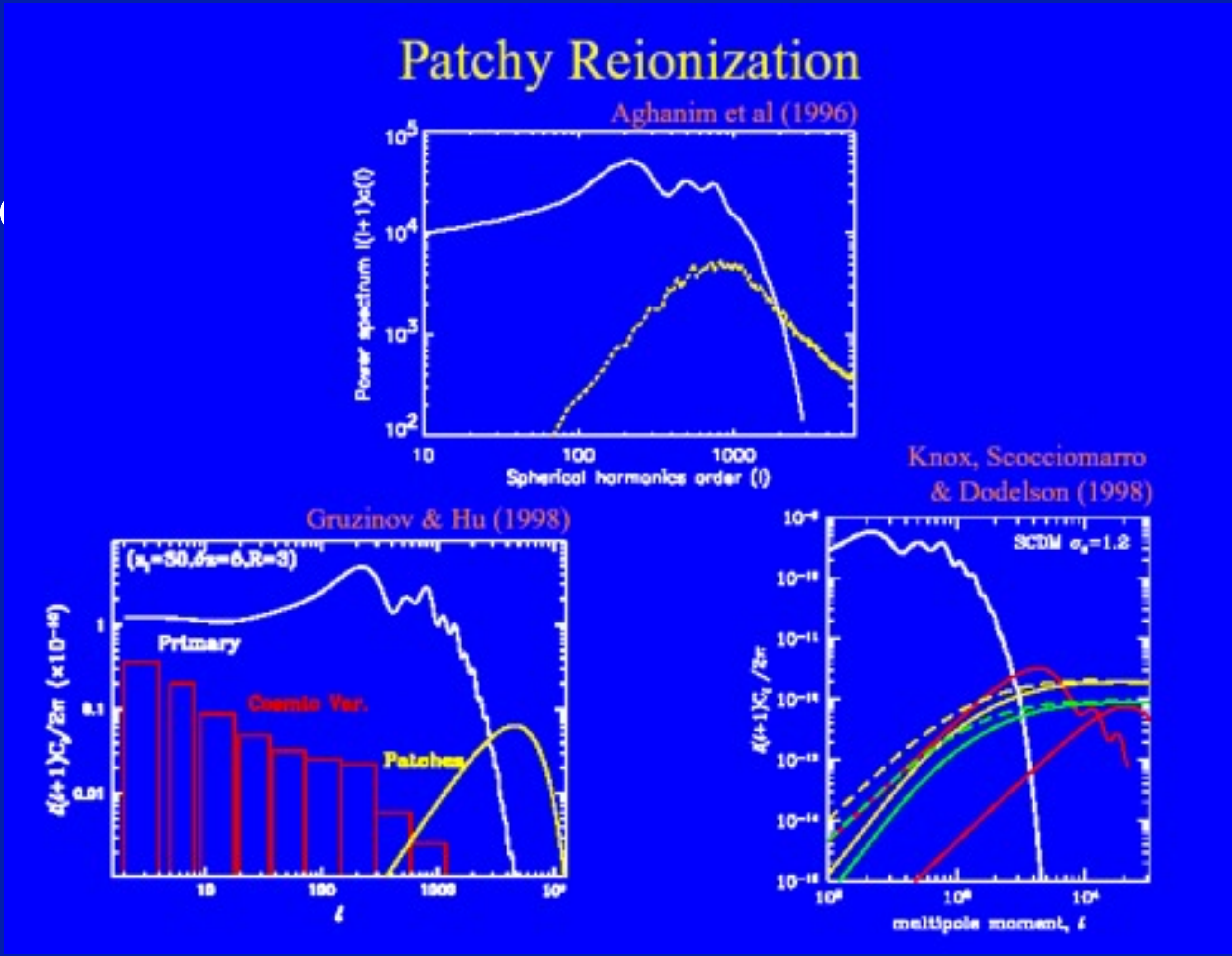
- Reionization + Structure
  - Linear regime
  - Second order (not cancelled)
  - Reionization supresses large angle fluctuations but generates small angle anisotropies



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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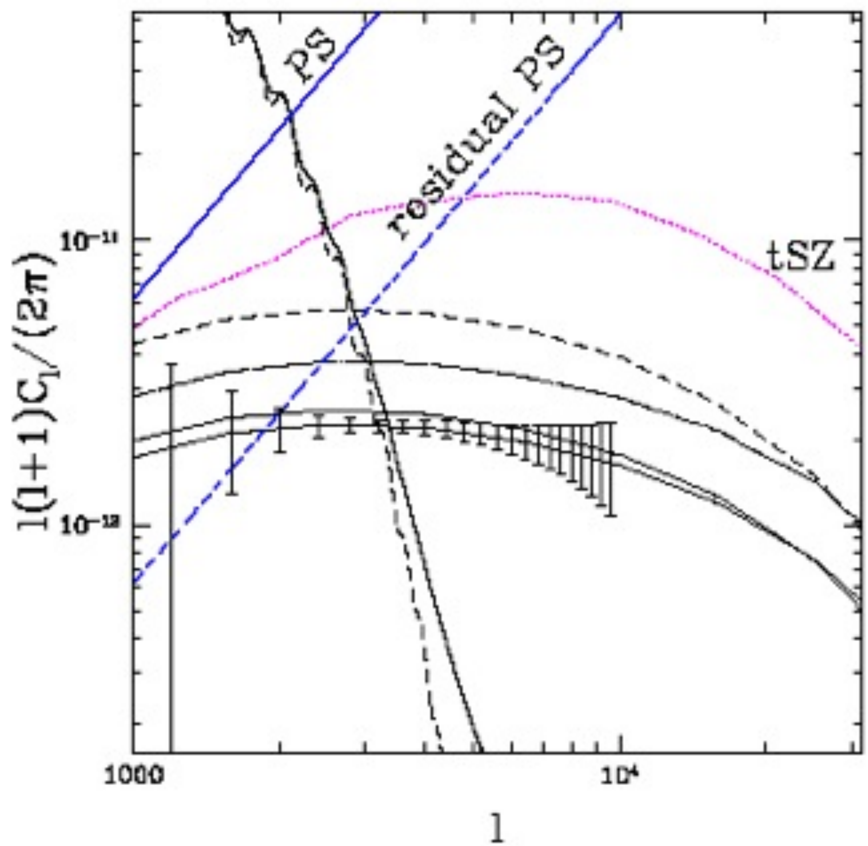
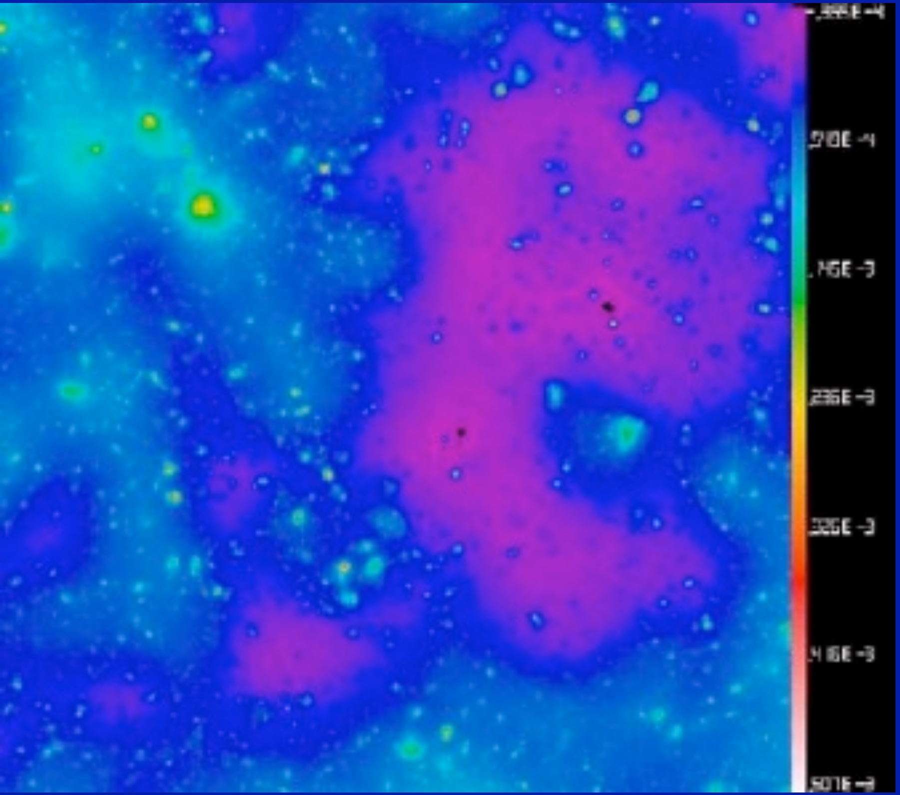
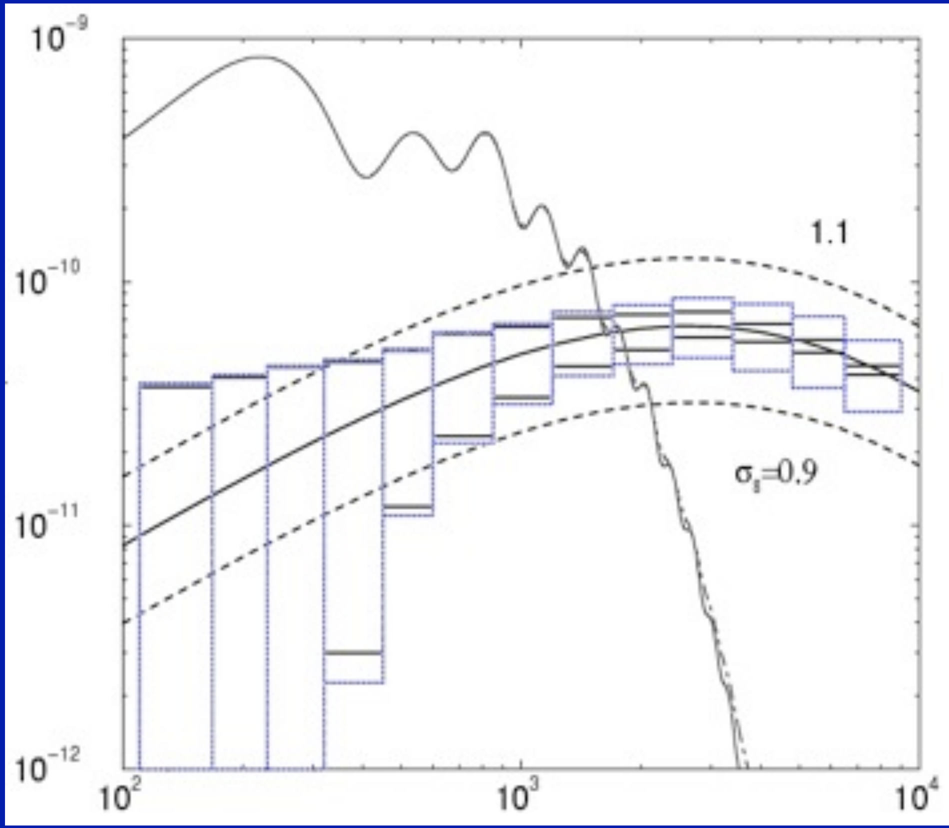


FIG. 5.— Patchy power spectra for the reionization models in Figure 3 (same line styles), together with other astrophysical contributions and expected measurement errors (see text). The solid (dashed) straight line is the the point source contribution at 217 GHz before (after) multi-frequency cleaning. 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





A. Cooray (astro-ph/0203048)

CMB Lensing Constraints on Dark Energy and Modified Gravity Scenarios arXiv:0908.1585

Erminia Calabrese, Asantha Cooray, Matteo Martinelli, Alessandro Melchiorri, Luca Pagano, Anze Slosar, George F. Smoot

Weak gravitational lensing leaves a characteristic imprint on the cosmic microwave background temperature and polarization angular power spectra. Here we investigate the possible constraints on the integrated lensing potential from future CMB angular spectra measurements expected from Planck and EPIC. We find that Planck and EPIC will constrain the amplitude of the integrated projected potential responsible for lensing at 6% and 1% level, respectively with very little sensitivity to the shape of the lensing potential. We discuss the implications of such a measurement in constraining dark energy and modified gravity scalar-tensor theories. We then discuss the impact of a wrong assumption on the weak lensing potential amplitude on cosmological parameter inference

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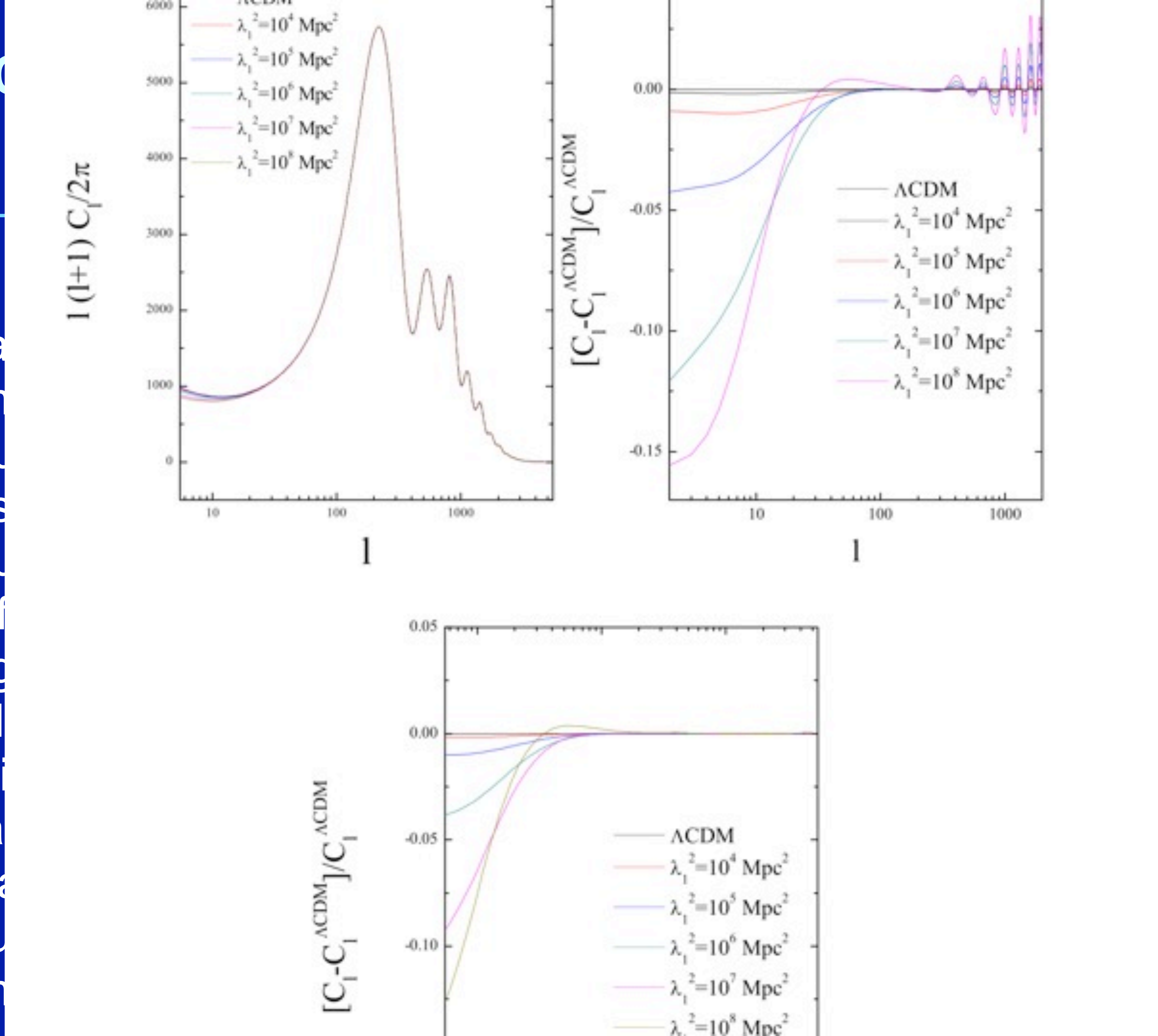

From Cavendish to PLANCK: Constraining Newton's Gravitational Constant with CMB Temperature and Polarization Anisotropy

Silvia Galli, Alessandro Melchiorri, George F. Smoot, Oliver Zahn

We present new constraints on cosmic variations of Newton's gravitational constant by making use of the latest CMB data from WMAP, BOOMERANG, CBI and ACBAR experiments and independent constraints coming from Big Bang Nucleosynthesis. We found that current CMB data provide constraints at the ~10% level, that can be improved to ~ 3% by including BBN data. We show that future data expected from the Planck satellite could constrain G at the ~ 1.5% level while an ultimate, cosmic variance limited, CMB experiment could reach a precision of about 0.4%, competitive with current laboratory measurements.

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Silvia Zahn

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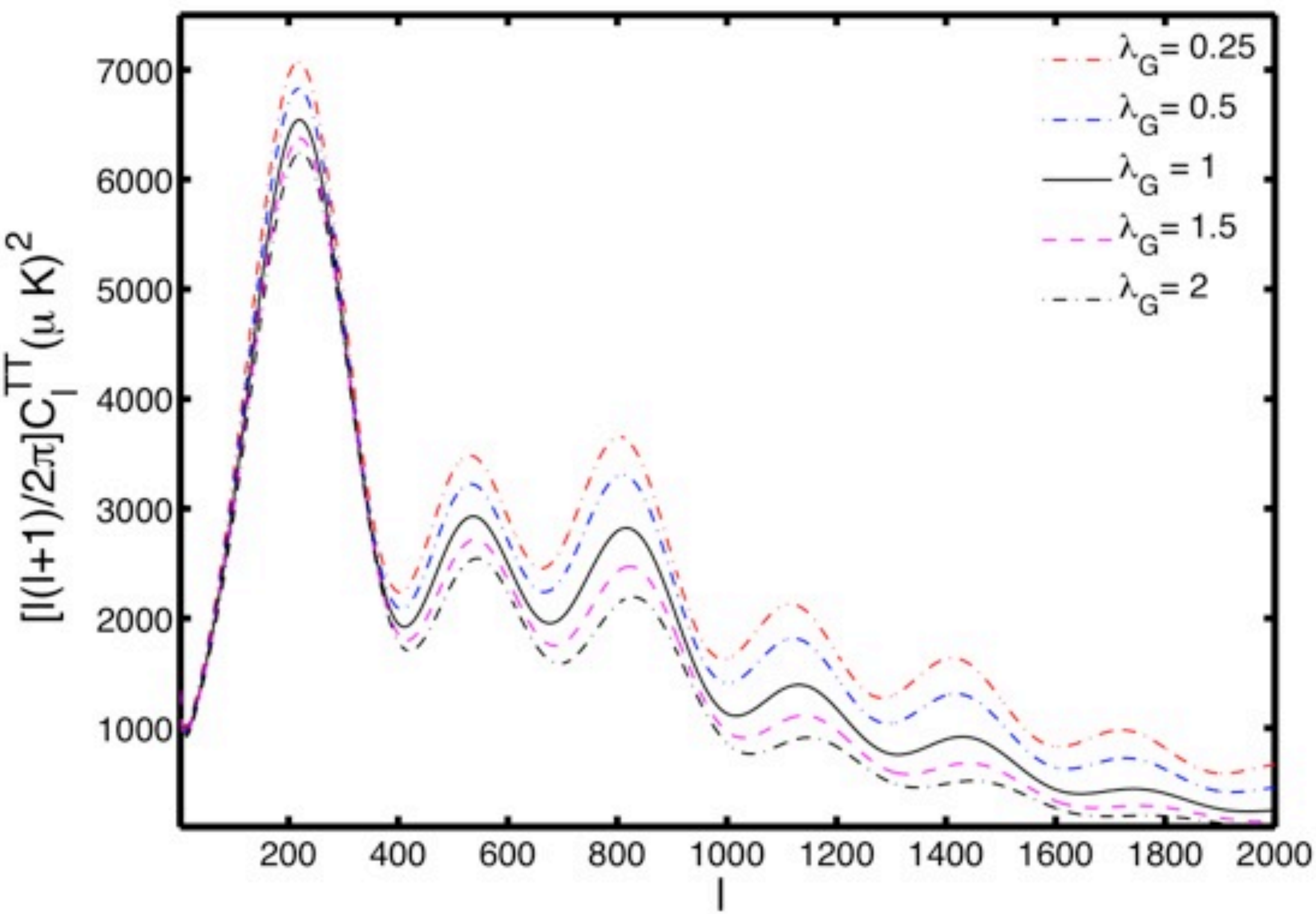

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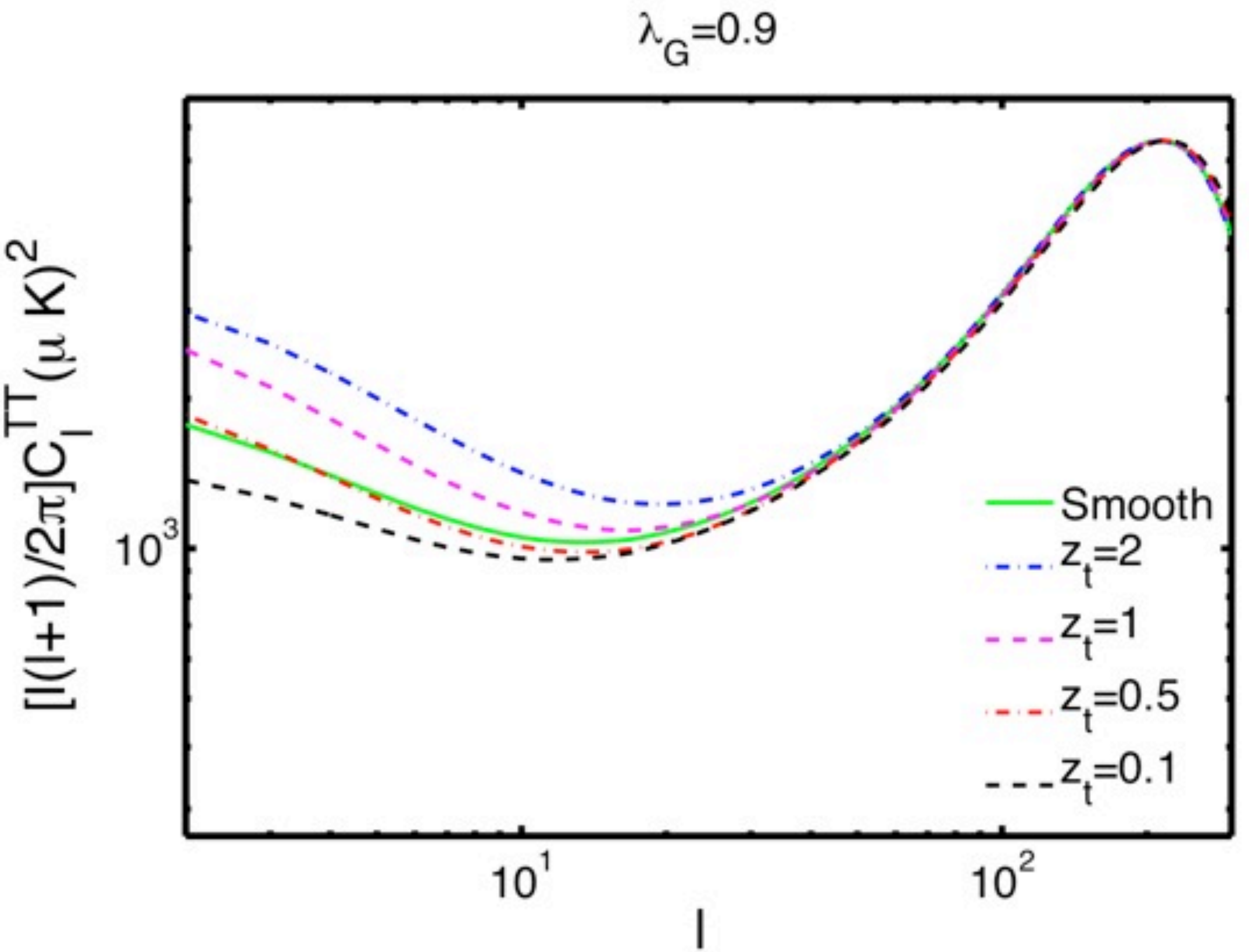

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CMB Checklist (continued)

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

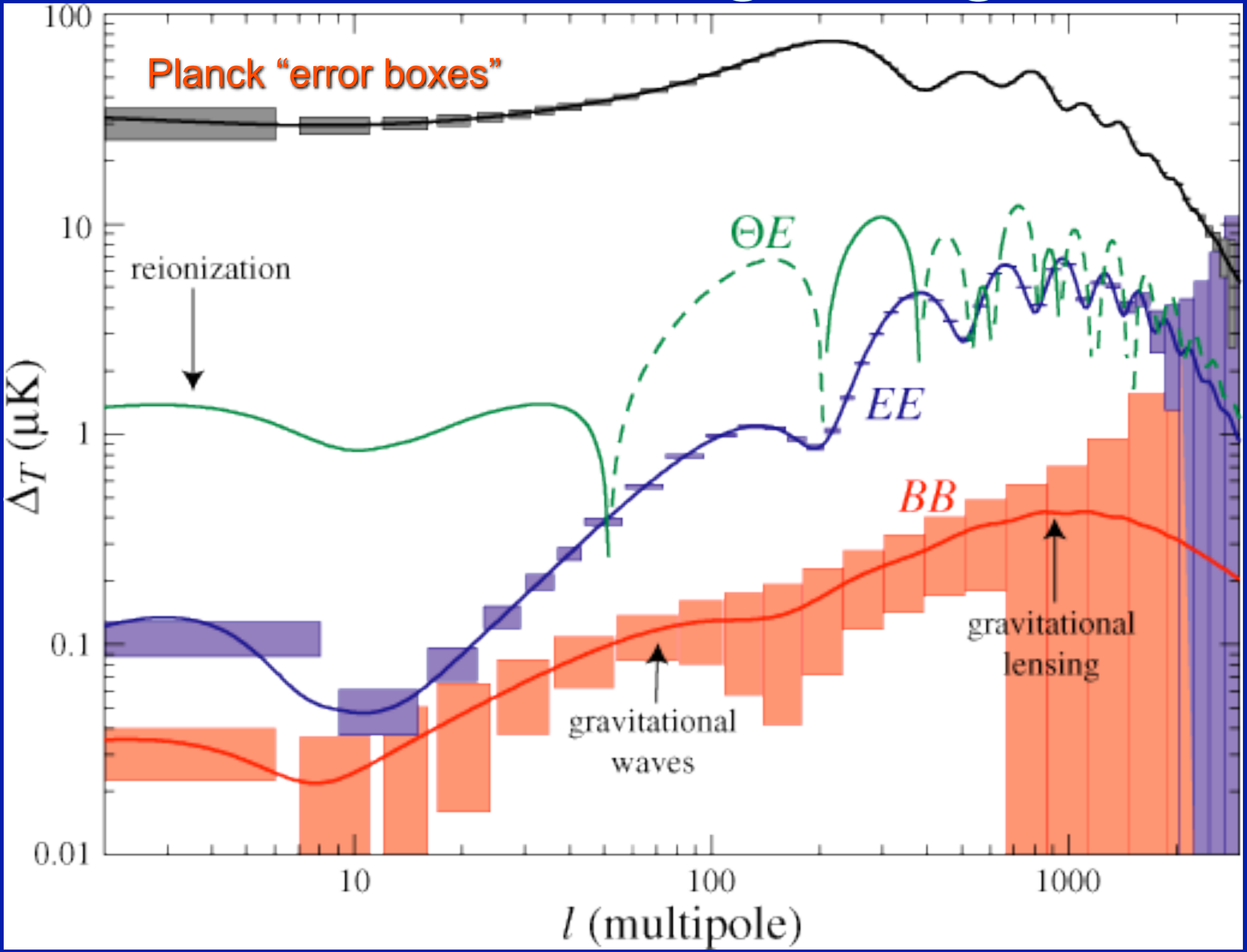
CMB Checklist (finale)

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
  - ✓ changing gravitation partially limited

It appears our current Universe is dominated in energy

Planck: The next big thing in CMB!



Hu & Dodelson *ARAA 2002*

But much else also coming!