Title: Cosmology â€“ Observations: CMB temperature and polarization

Date: Jul 14, 2015 11:45 AM

URL: http://pirsa.org/15070044

Abstract:

Excellent Reviews

- Wayne Hu tutorials:
  - http://background.uchicago.edu/index.html
- Kosowsky:
  - http://ned.ipac.caltech.edu/level5/Kosowsky/Kosowsky_contents.html
  - http://arxiv.org/abs/astro-ph/9904102
- Zaldarriaga
  - http://arxiv.org/abs/astro-ph/0305272
- Weiss report:
  - http://arxiv.org/abs/astro-ph/0604101
- CMBPol white papers:
  - http://arxiv.org/abs/0811.3919
  - http://arxiv.org/abs/0811.3916

Cosmic Microwave Background

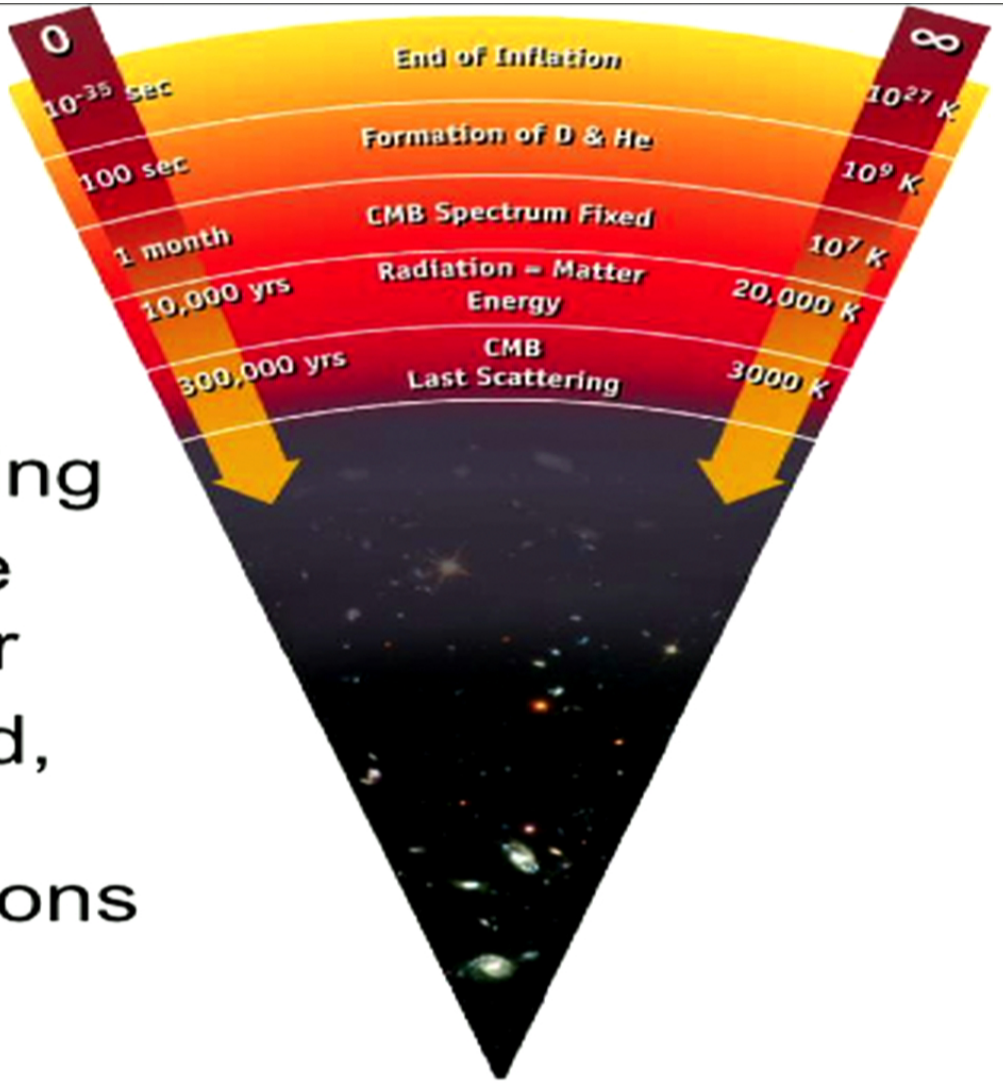
Gil Holder

McGill

CIFAR
CANADIAN INSTITUTE for ADVANCED RESEARCH

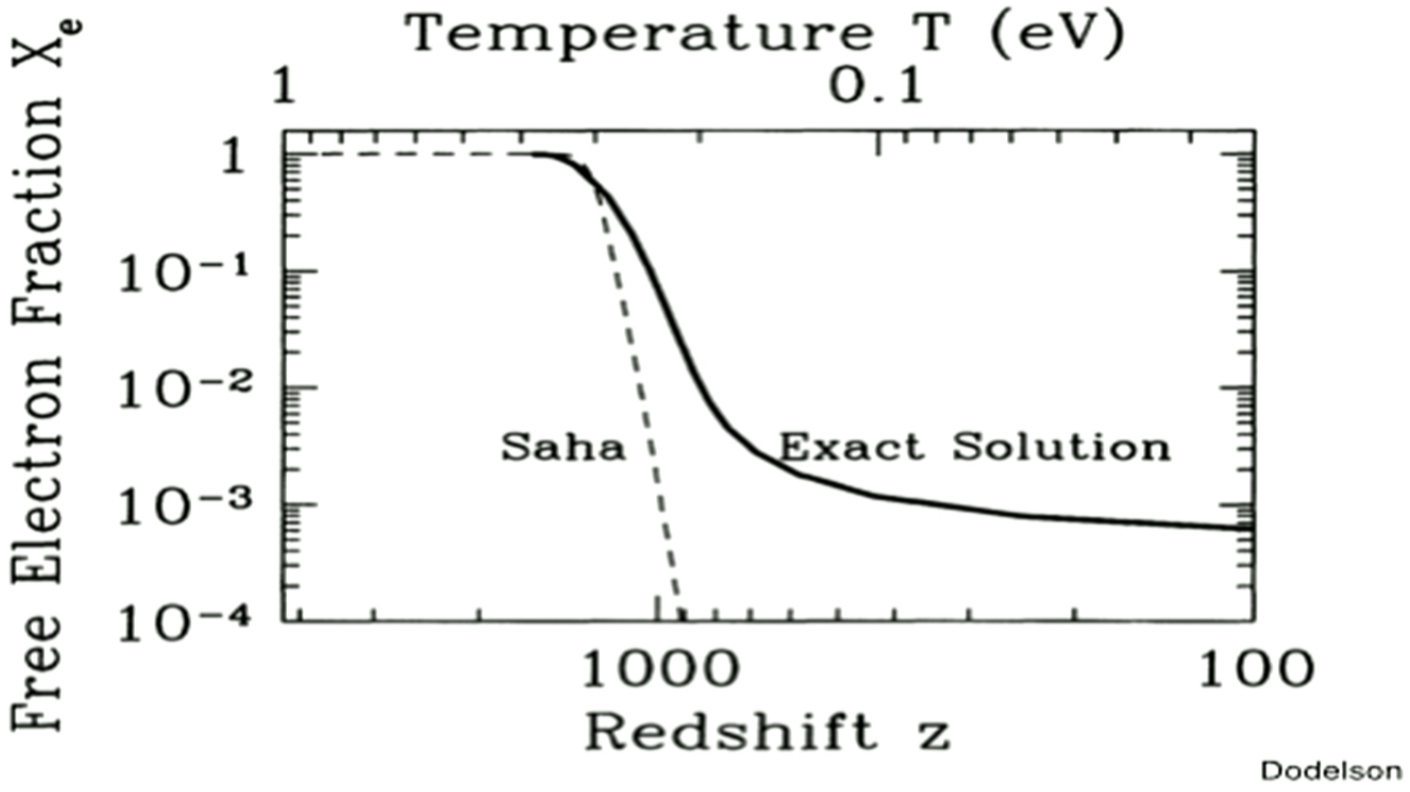
Hot Big Bang

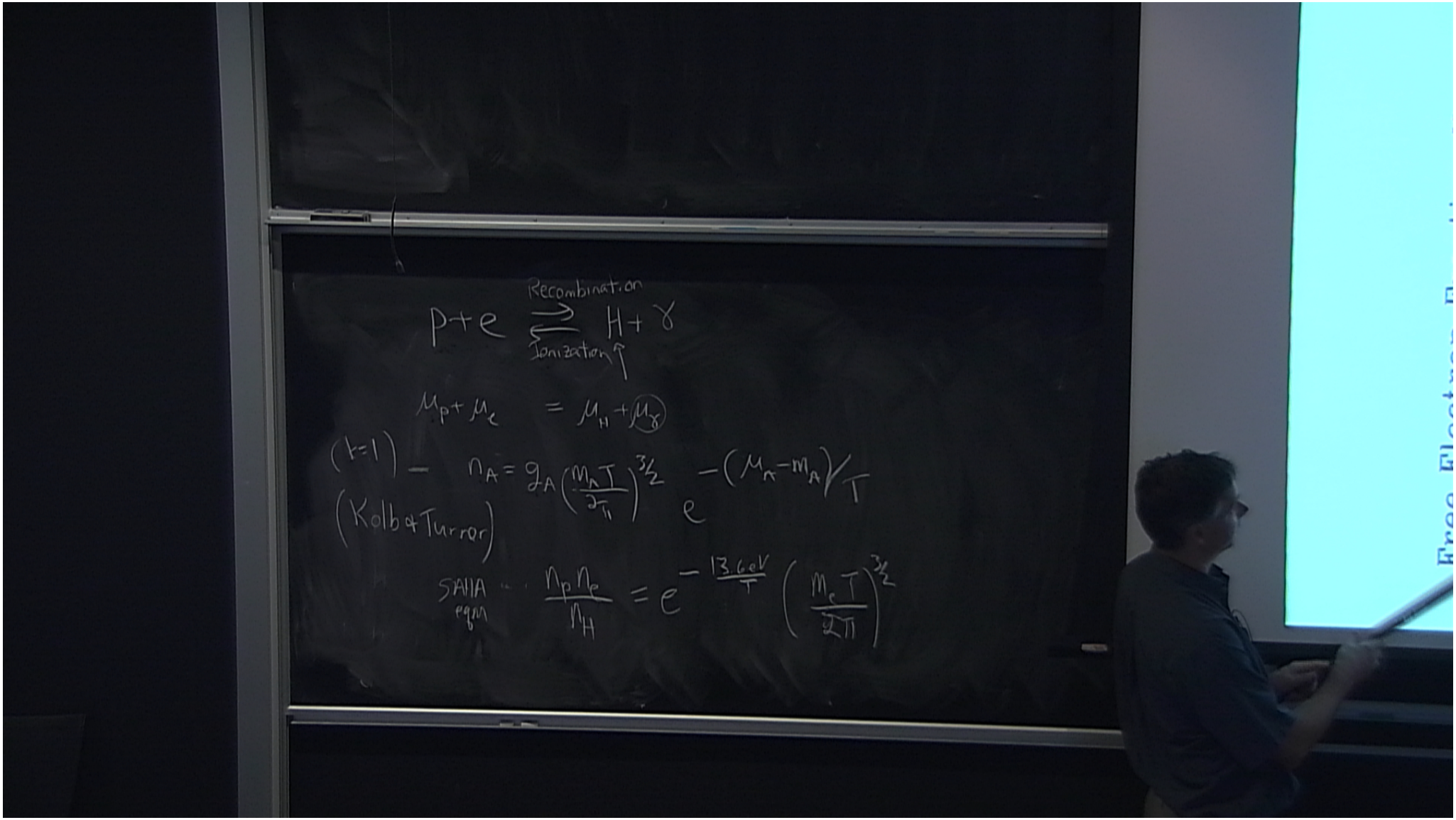
- Expanding => cooling
- At earlier times, the universe was hotter
- when atoms formed, universe became transparent to photons
  - *special timescale in the universe for photons*



http://www.astro.ucla.edu/~wright/BBhistory.html

“Recombination”




Recombination
Ionization
$p + e \rightleftharpoons H + \gamma$
$\mu_p + \mu_e = \mu_H + \mu_\gamma$
$(t=1)$
$n_A = g_A \left(\frac{m_A T}{2\pi}\right)^{3/2} e^{-(m_A - \mu_A)/T}$
(Kolb & Turner)
SAHA eqn
$\frac{n_p n_e}{n_H} = e^{-\frac{13.6\,eV}{T}} \left(\frac{m_e T}{2\pi}\right)^{3/2}$

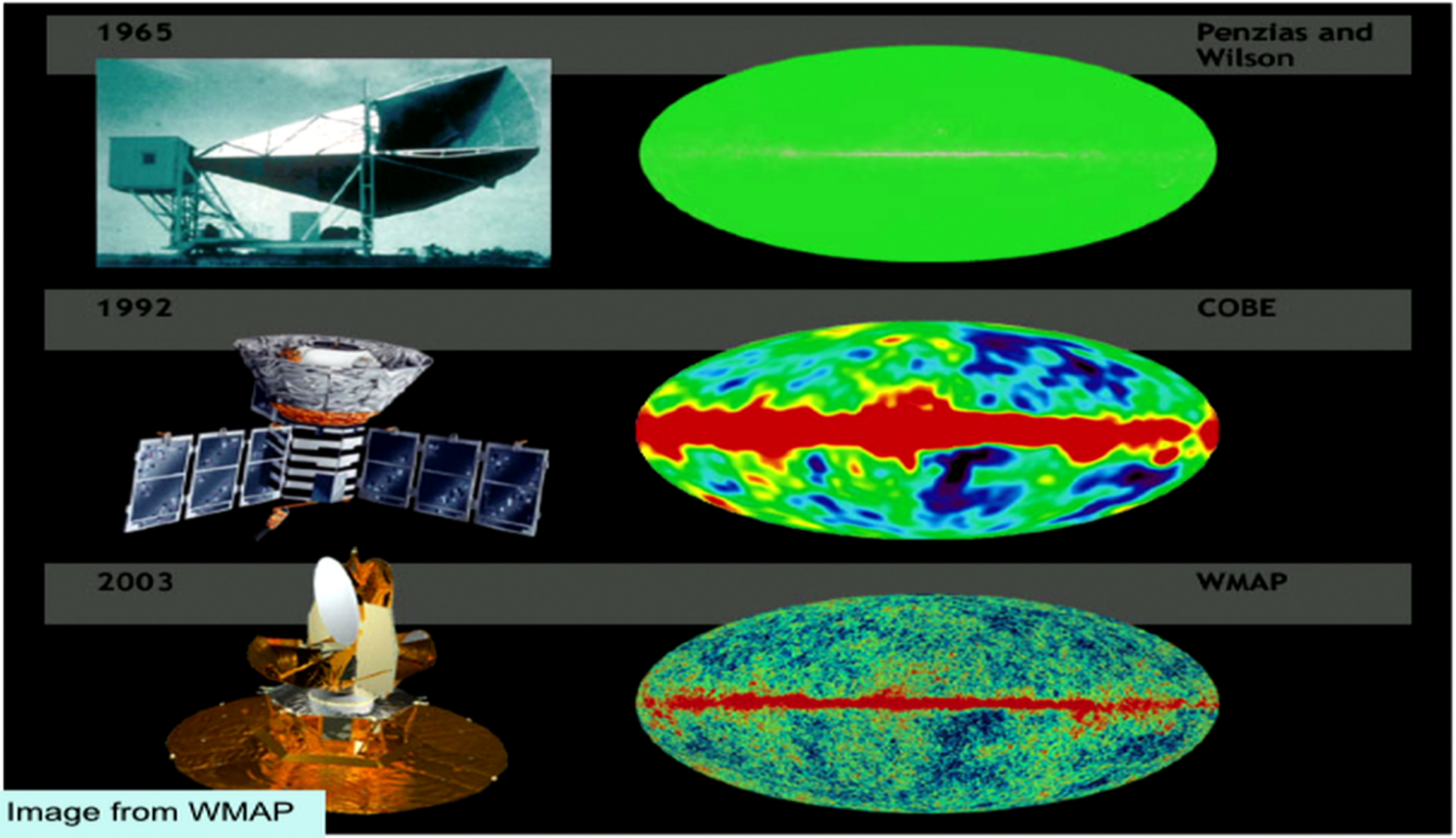
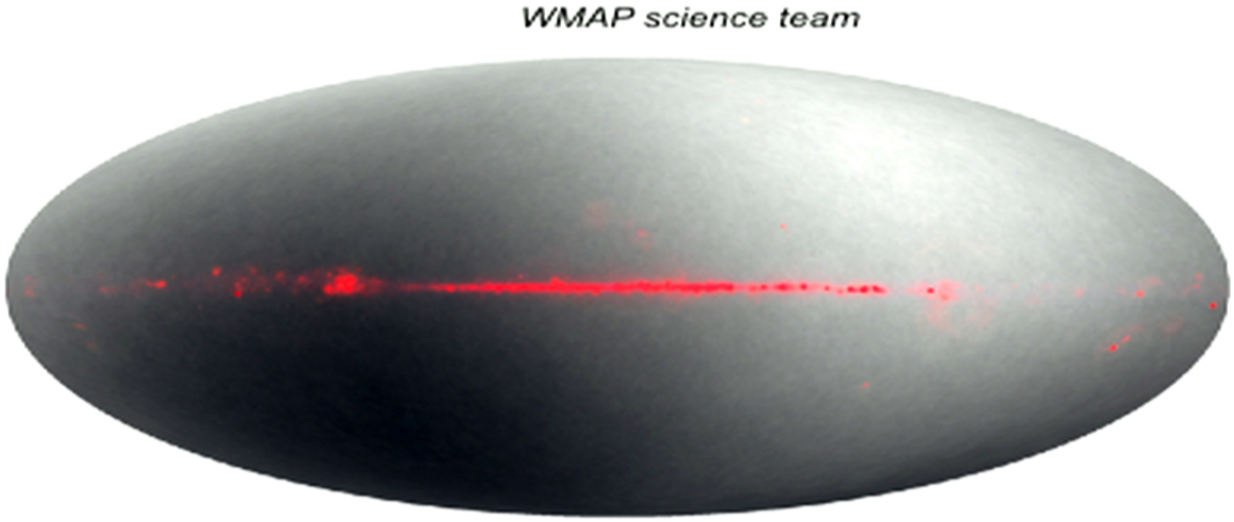


Image from WMAP

Isotropy

- Cosmic microwave background is remarkably isotropic
- Unnaturally isotropic!



+-3.5 mK scale, no monopole

The Cosmic Microwave Background

CMB according to COBE

(Bennett et al 1996)

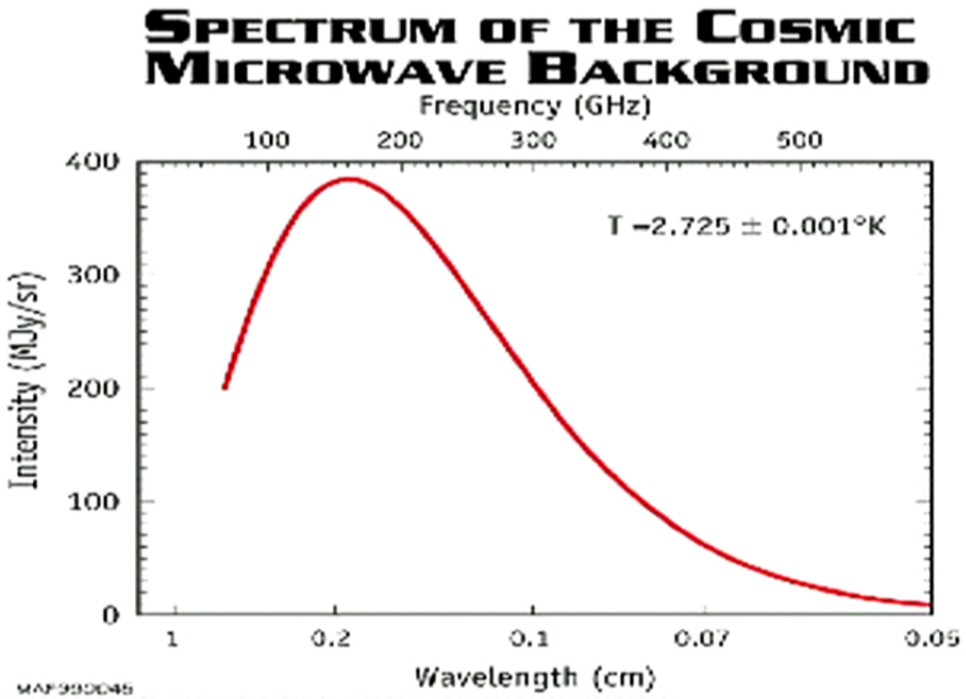


Image from COBE science team: http://lambda.gsfc.nasa.gov/product/cobe/

Isotropy

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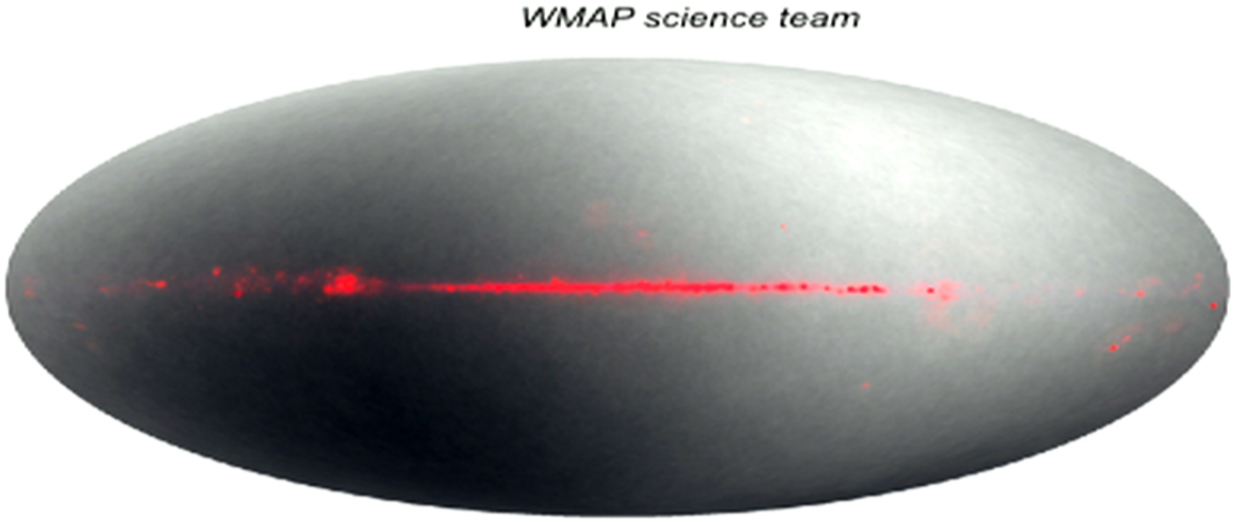

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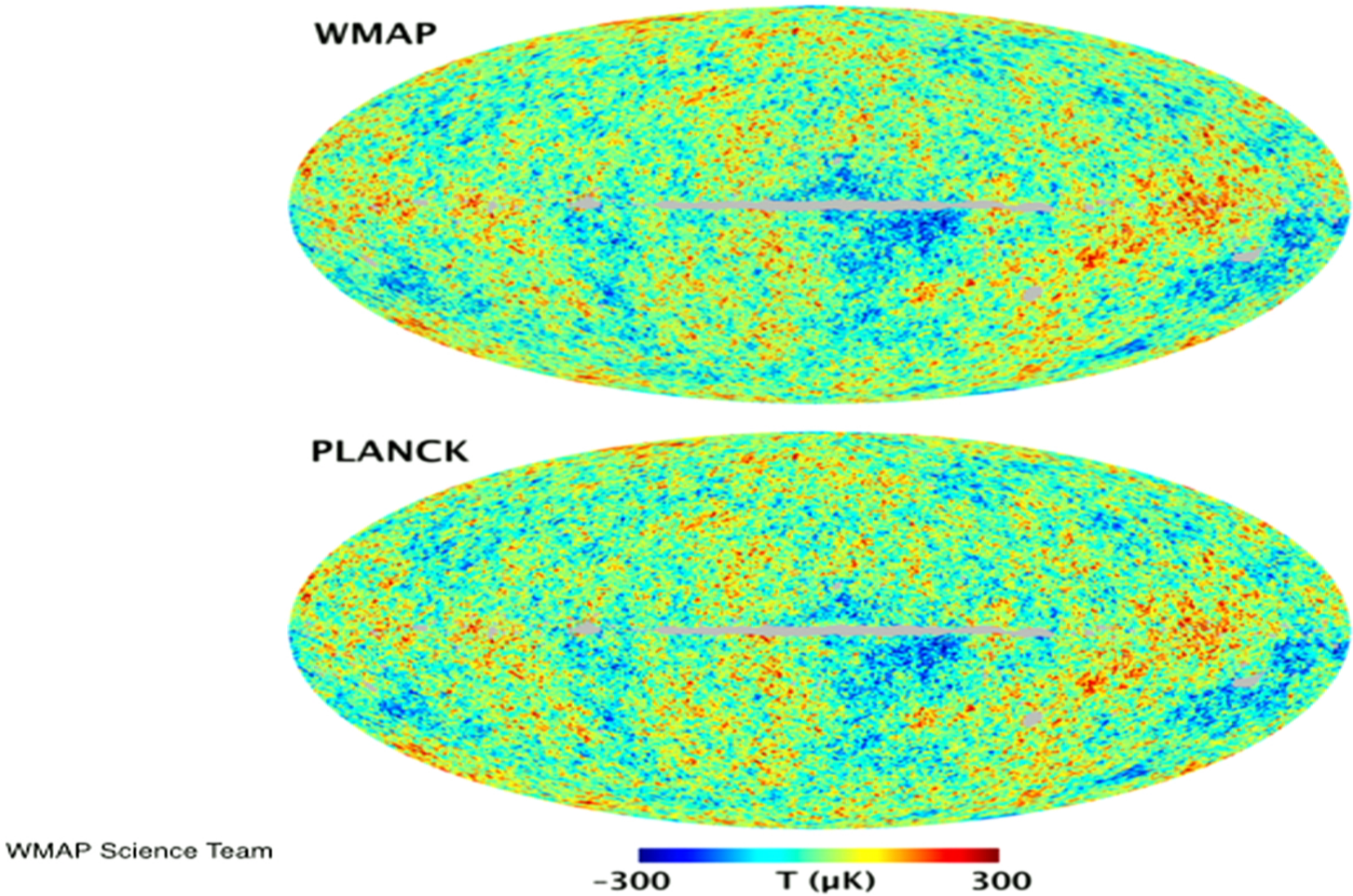
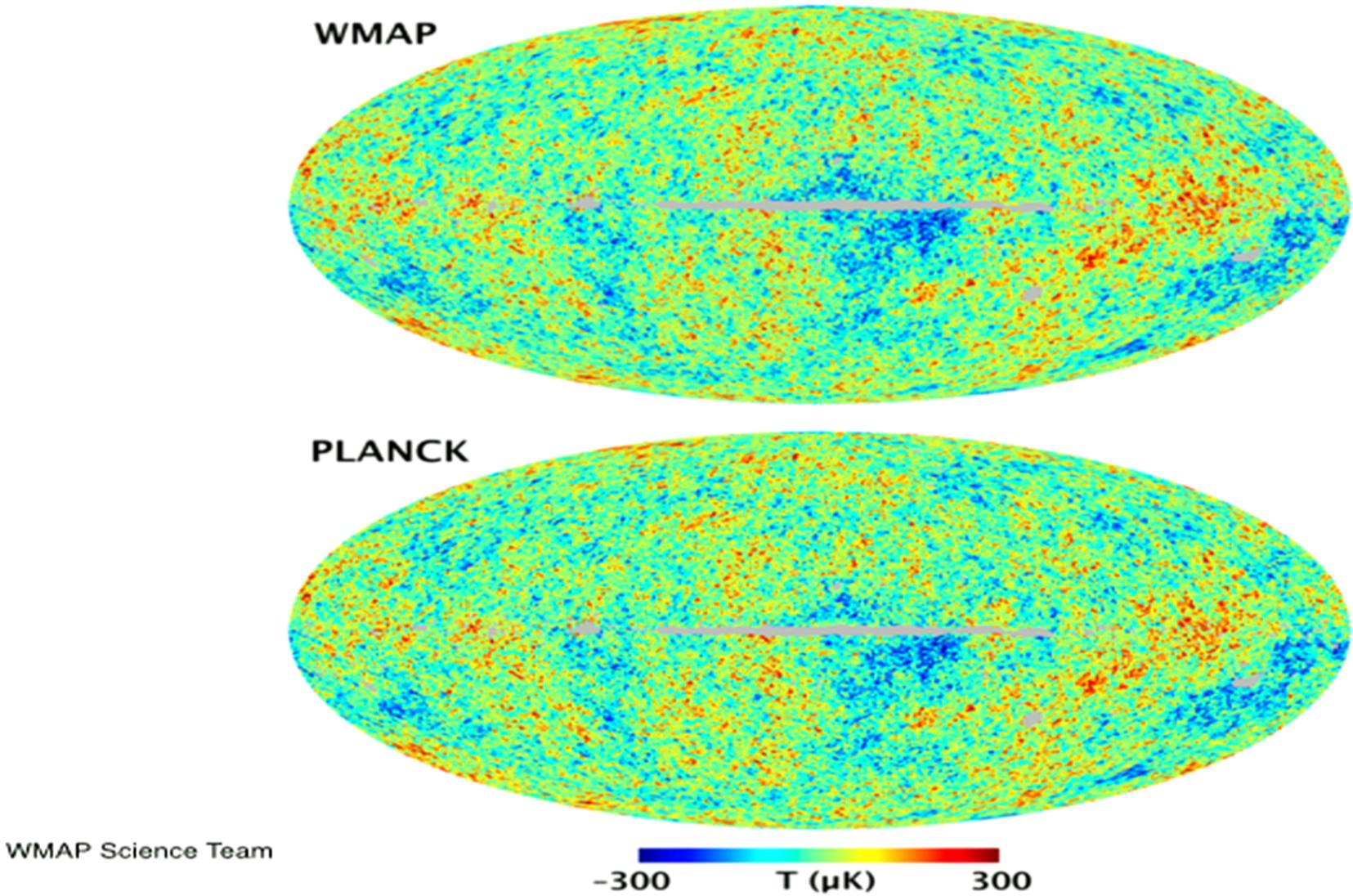
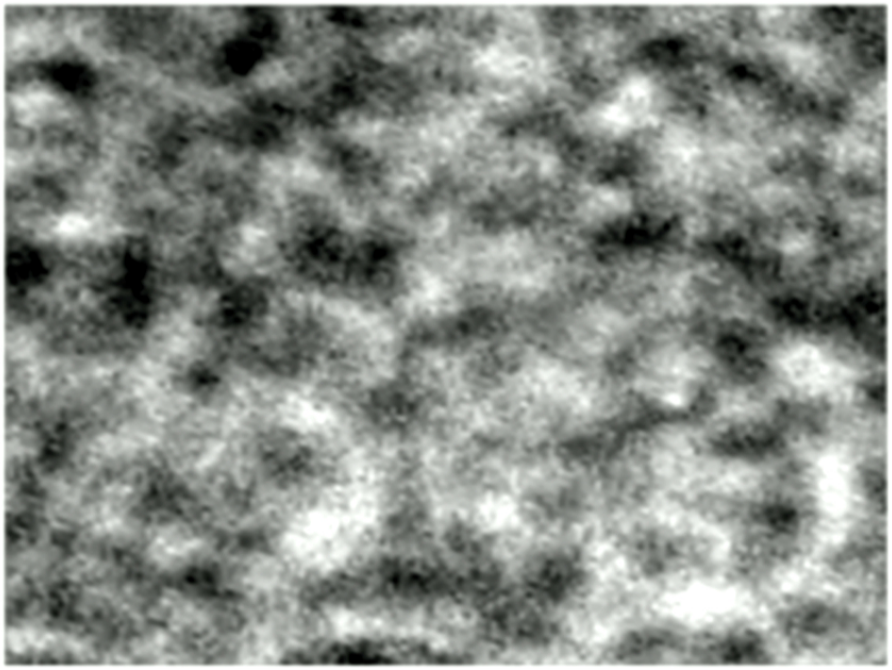

WMAP
PLANCK
WMAP Science Team
−300
T (μK)
300


WMAP
PLANCK
WMAP Science Team
−300
T (μK)
300

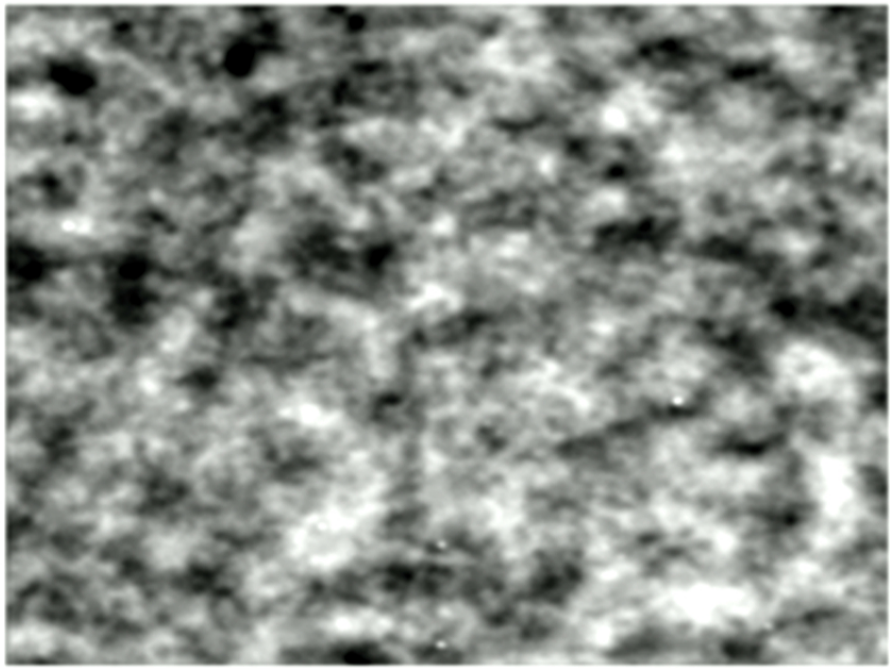
Planck has higher resolution than WMAP

WMAP 60 GHz



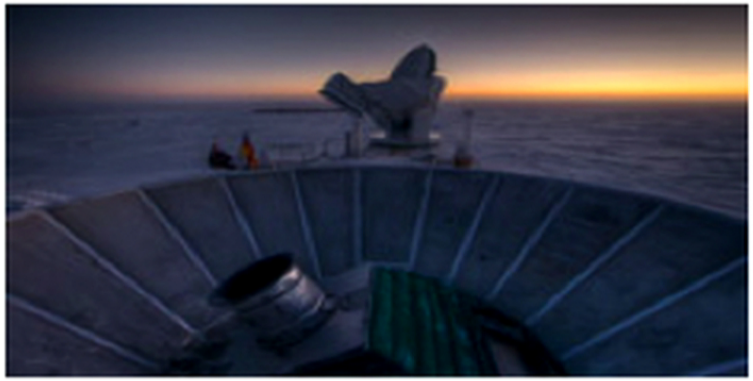
16°

Planck 143 GHz



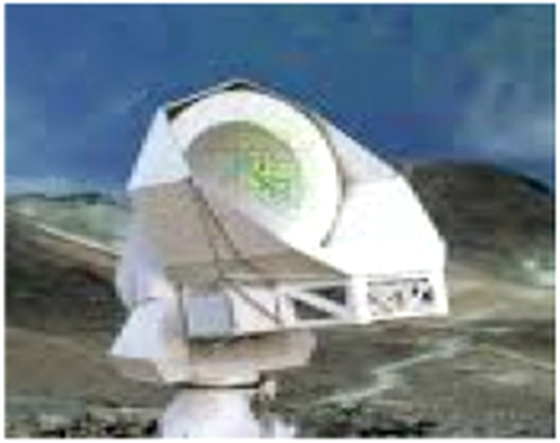
A Selection of Ground-Based CMB Probes

SPTpol

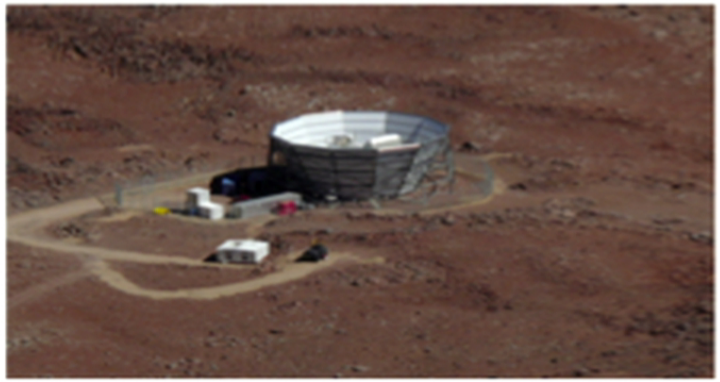


BICEP2

+KECK



Polarbear



ACTpol

+ABS

11

The South Pole Telescope (SPT)

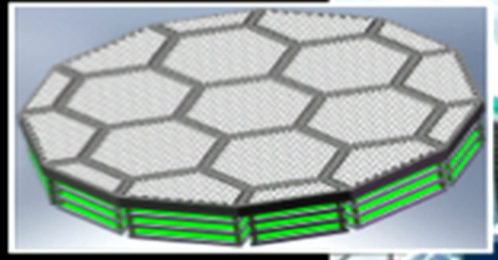
10-meter sub-mm quality wavelength telescope

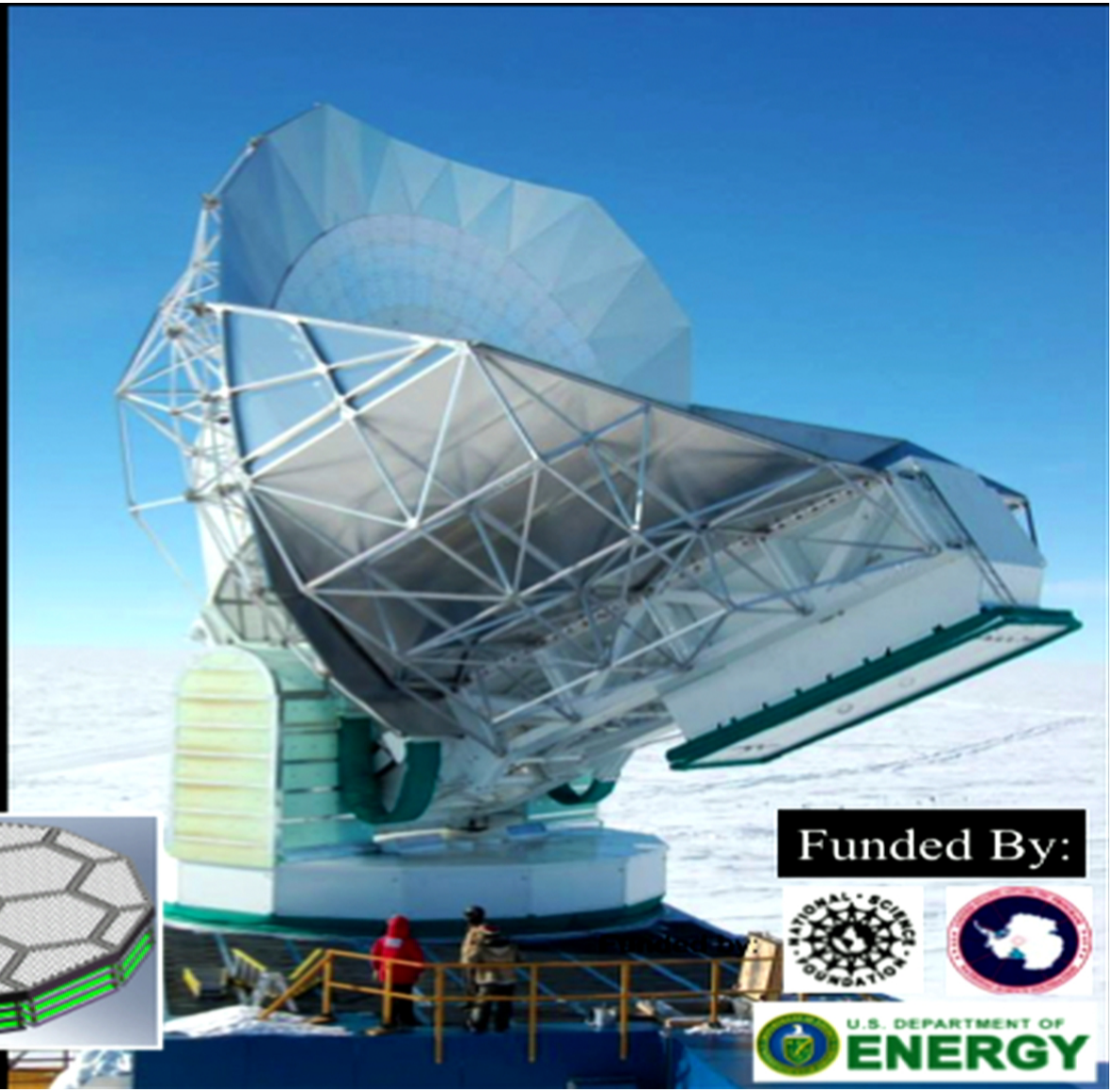
100, 150, 220 GHz and
1.6, 1.2, 1.0 arcmin resolution

2007: SPT-SZ
960 detectors
100,150,220 GHz

2012: SPTpol
1600 detectors
100,150 GHz
+Polarization

2016: SPT-3G
~15,200 detectors
100,150,220 GHz
+Polarization





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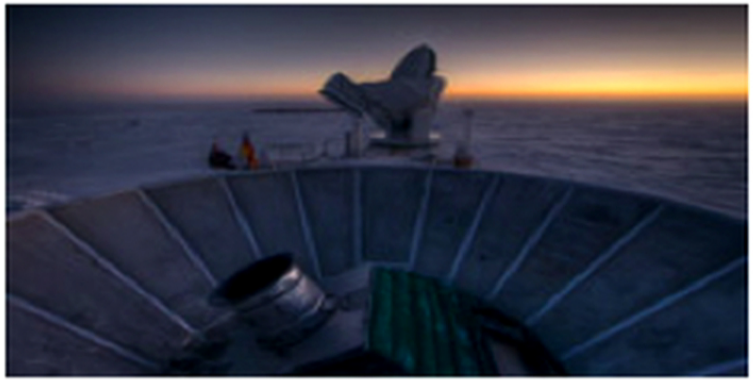

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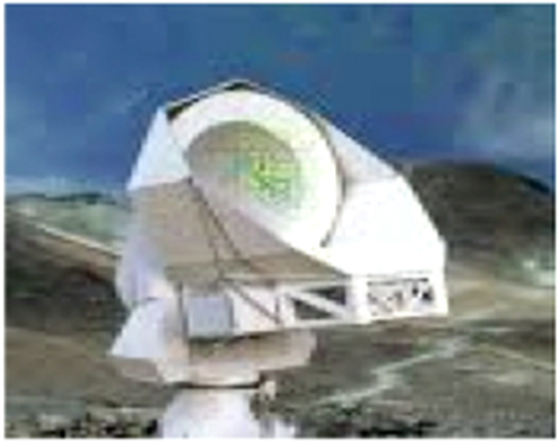
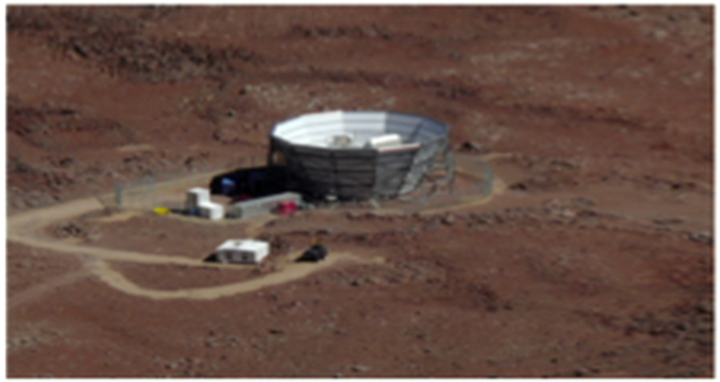


Polarbear

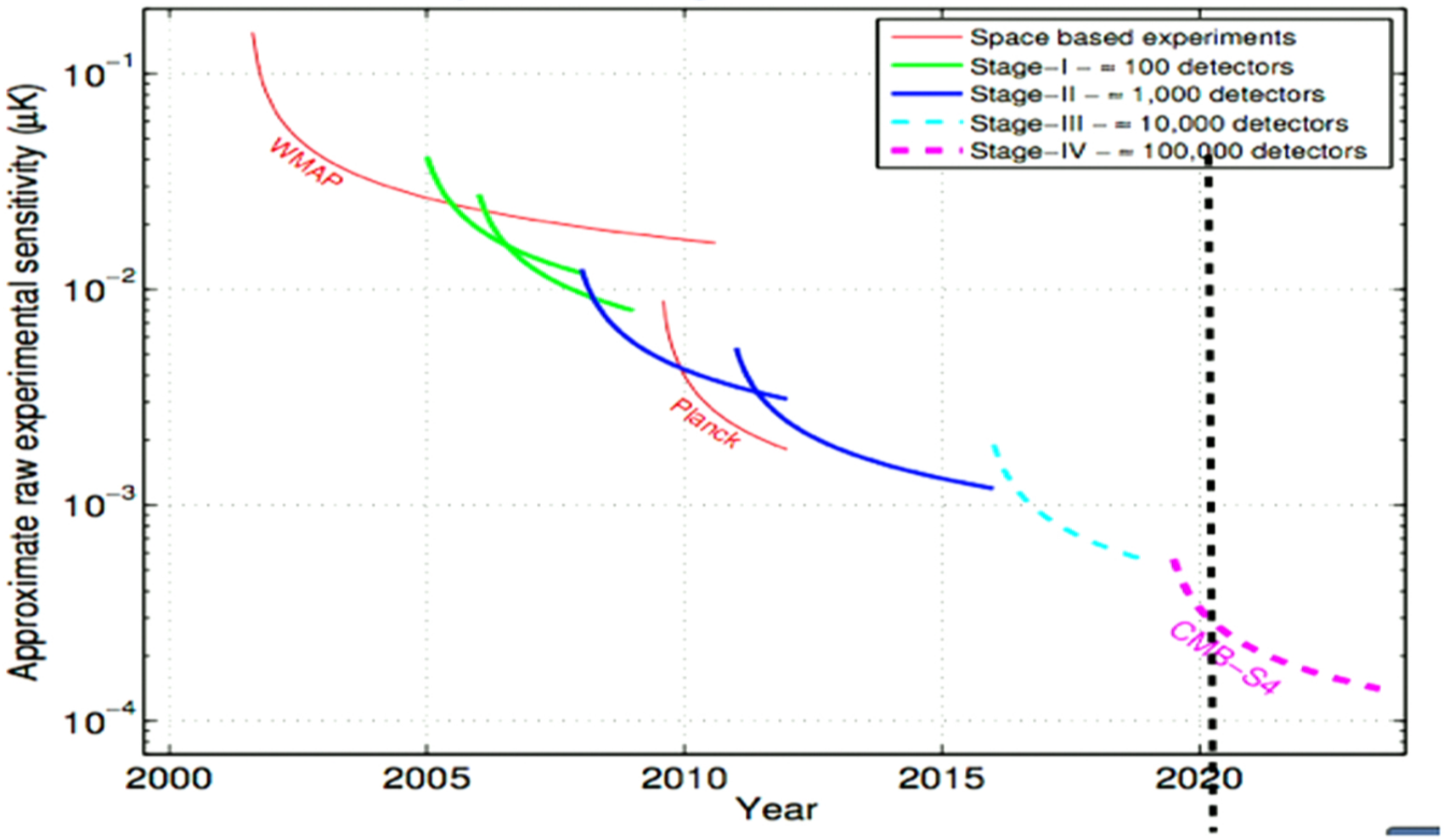


ACTpol

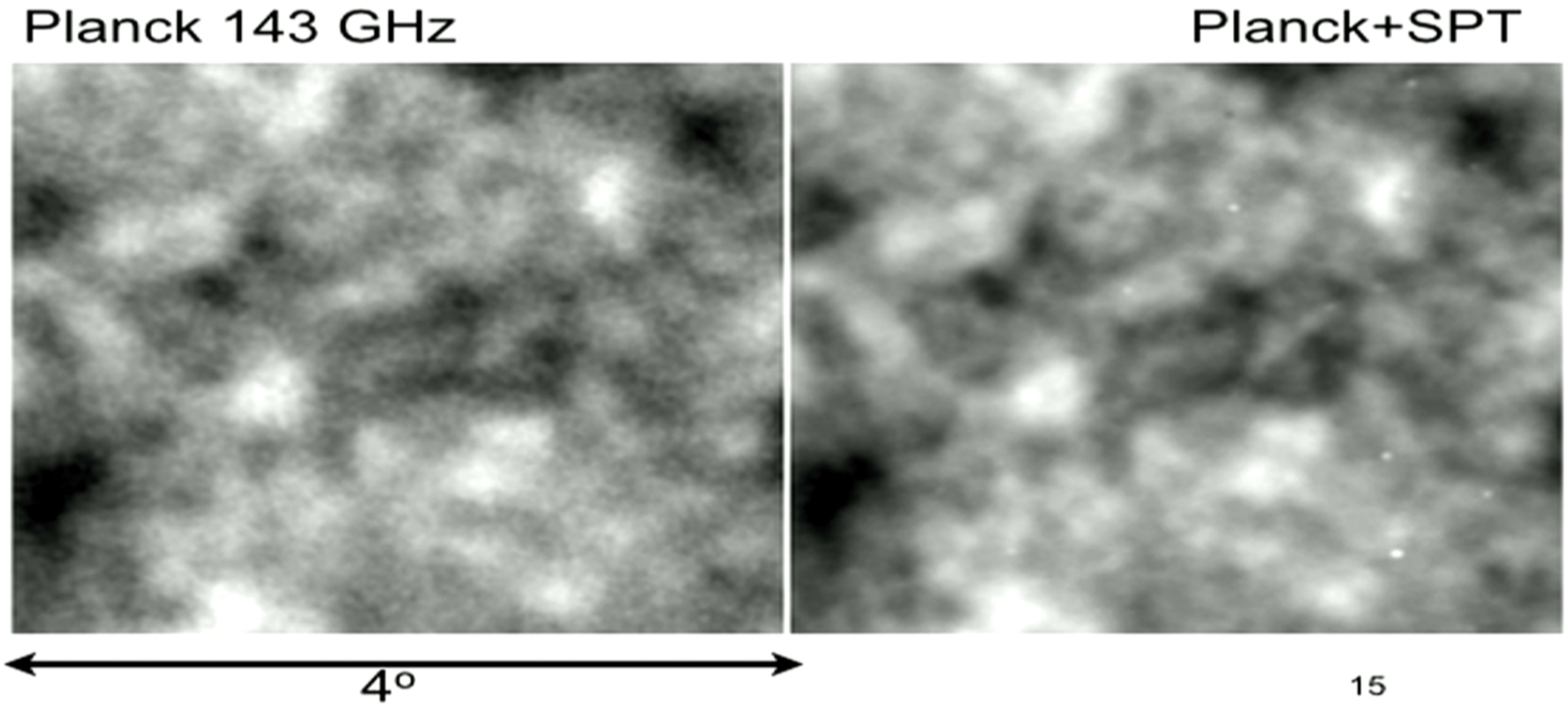
+ABS

11

Steady progress in CMB



SPT or ACT have higher resolution than Planck



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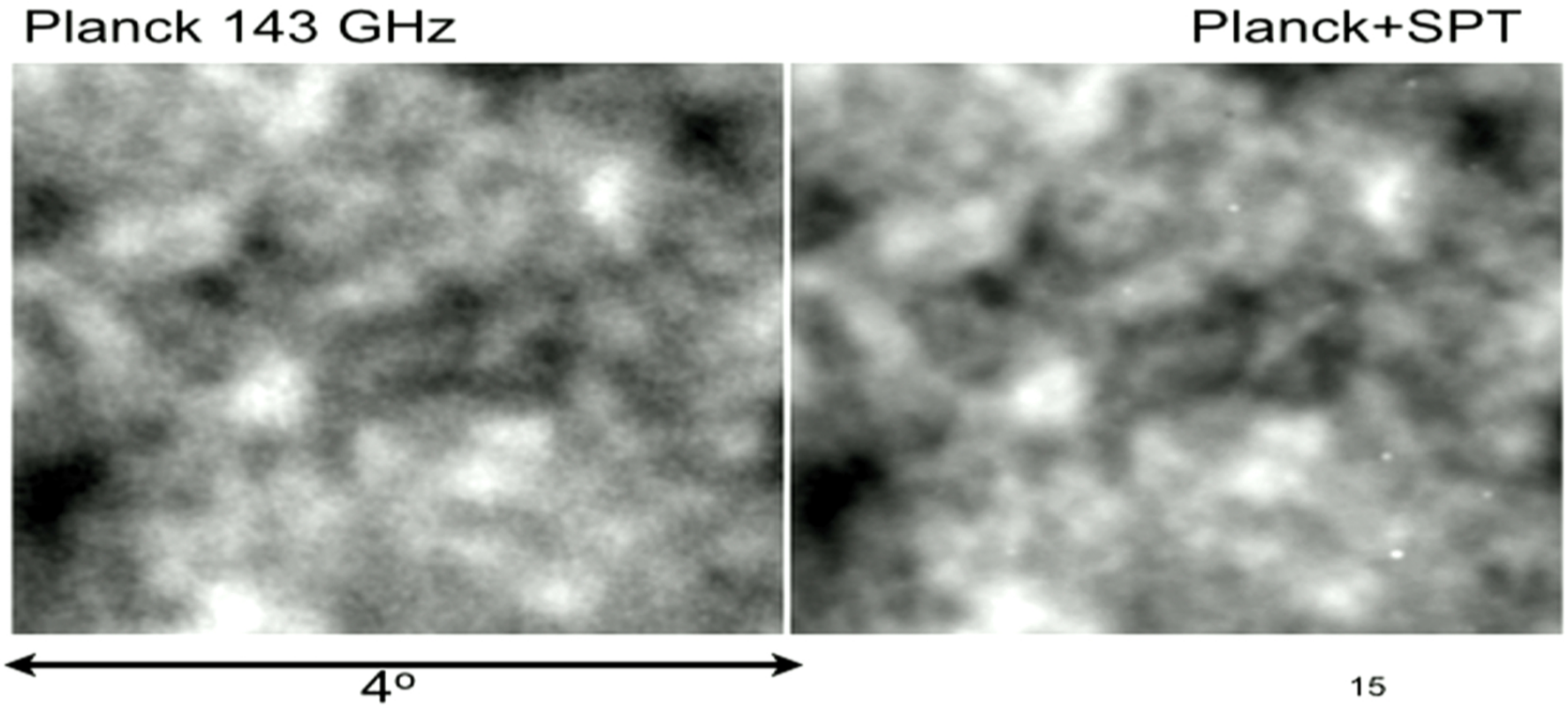
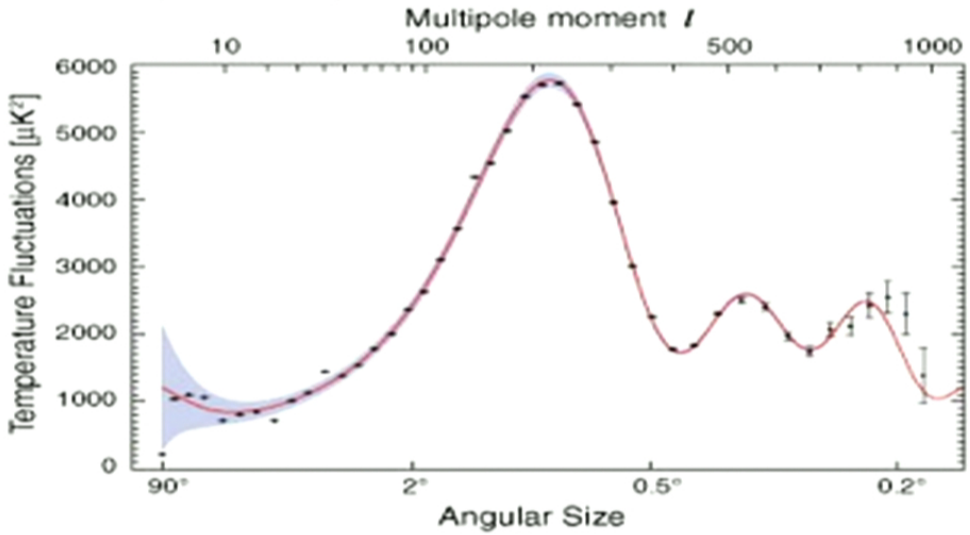


Spherical Harmonics

$$T(\theta, \phi) = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\theta, \phi).$$

$$Y_\ell^m(\theta, \varphi) = \sqrt{\frac{(2\ell+1)}{4\pi}\frac{(\ell-m)!}{(\ell+m)!}}\, P_\ell^m(\cos\theta)\, e^{im\varphi}$$

$$\hat{C}_l = \frac{1}{2l+1}\sum_m |\hat{a}_{lm}|^2.$$



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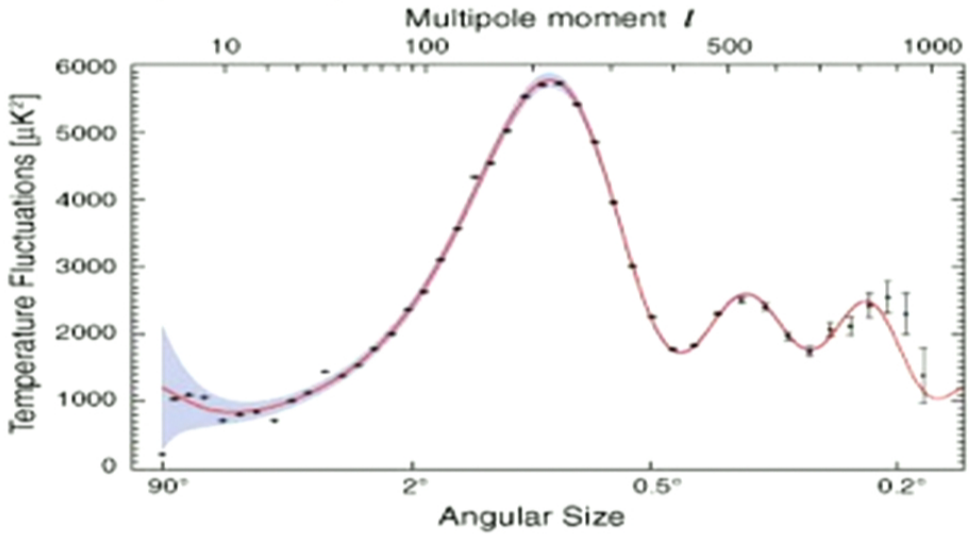
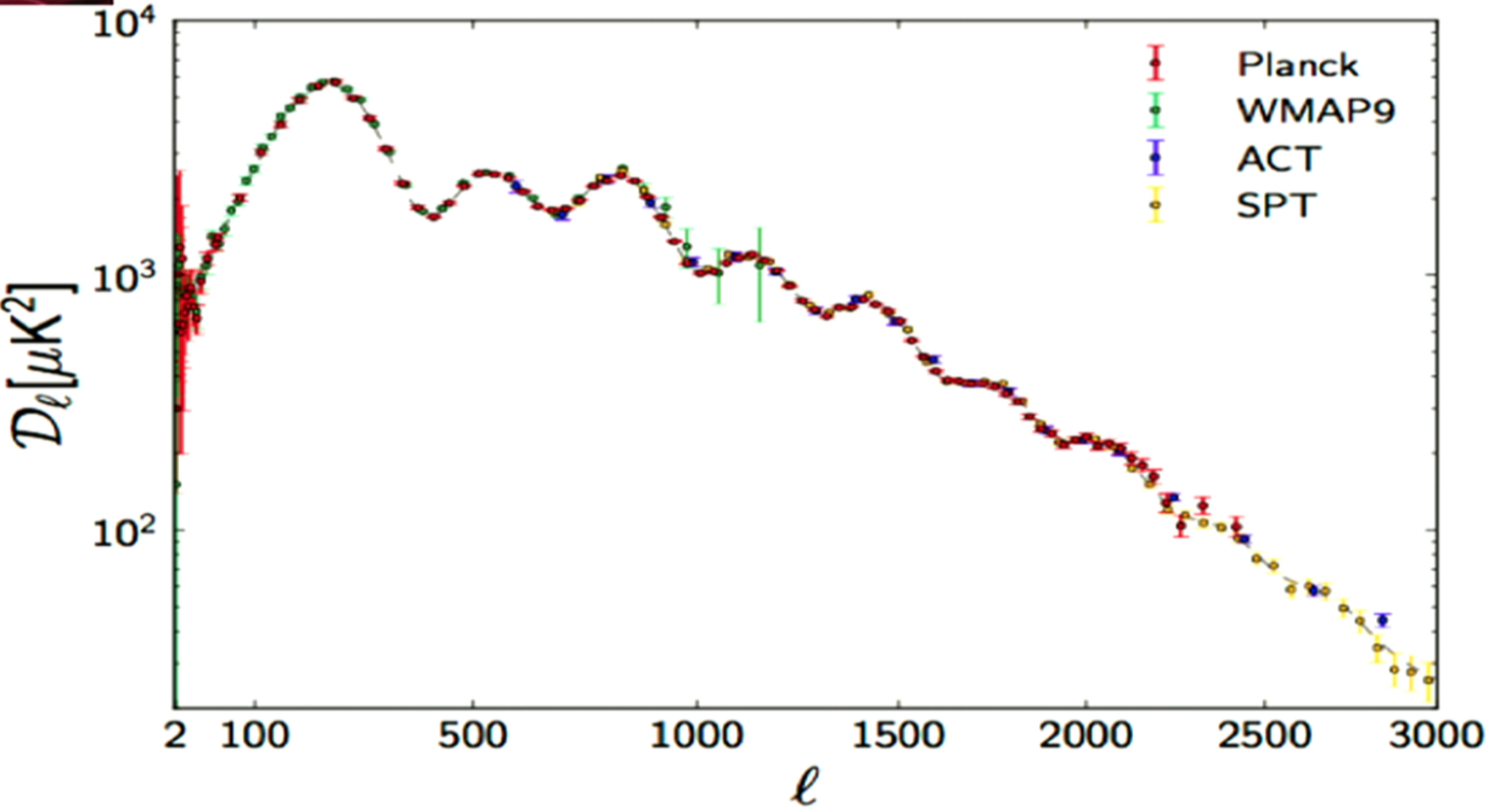
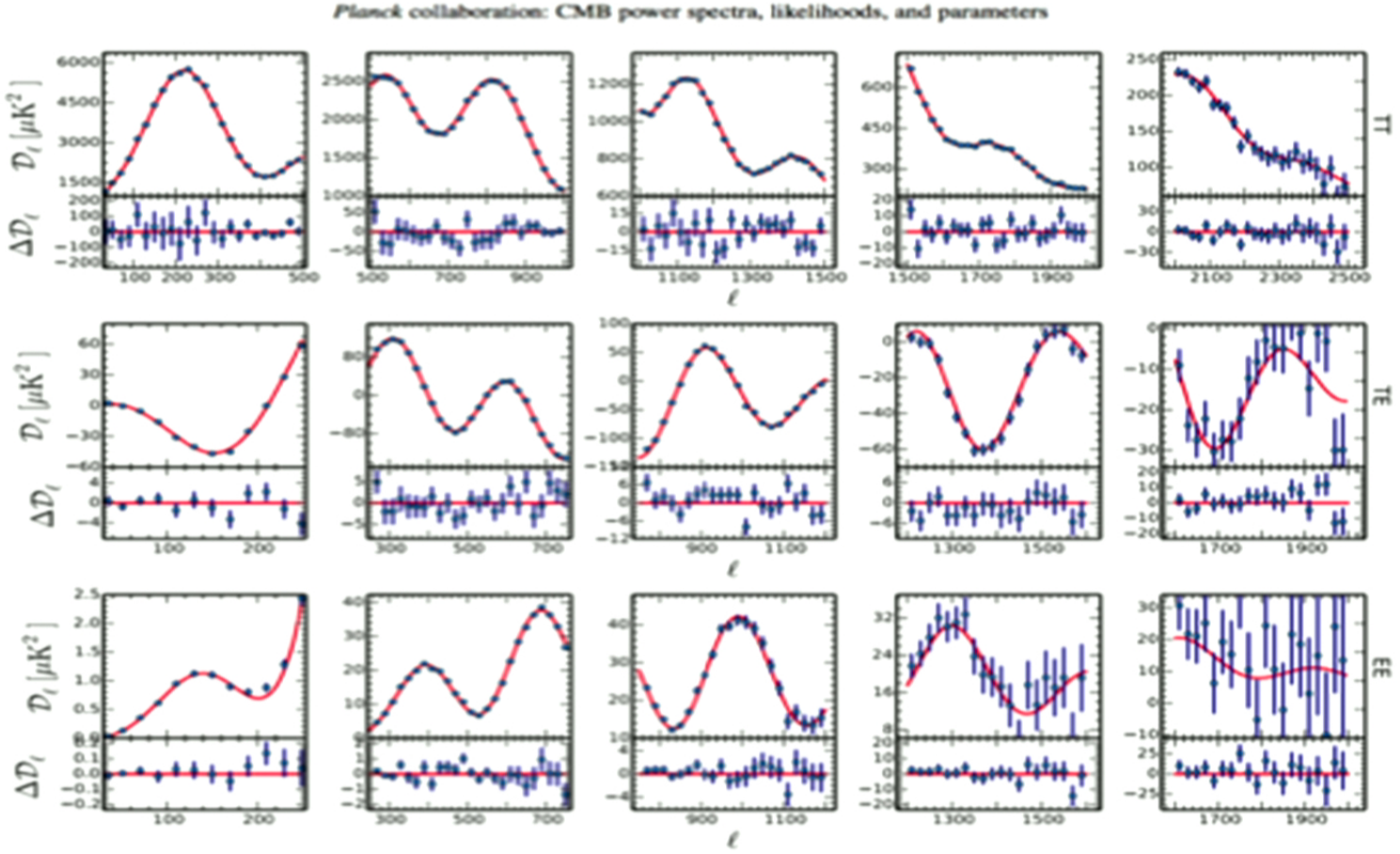


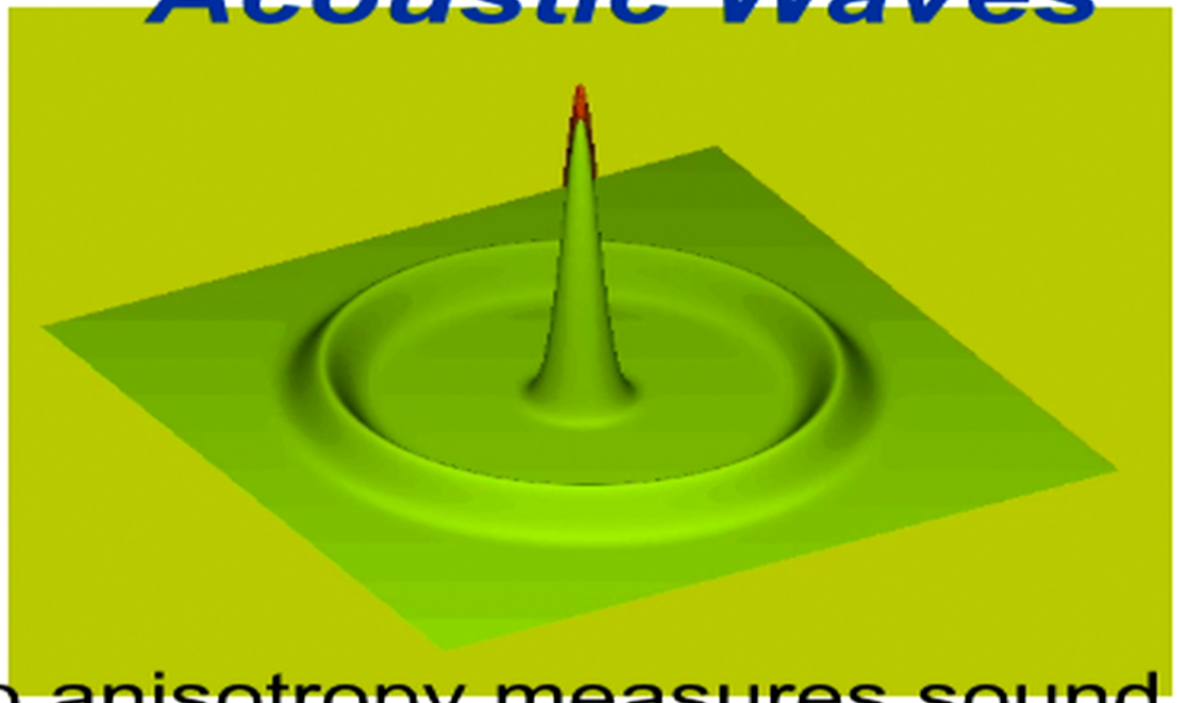
CMB Angular Power Spectrum



Zoom in on data

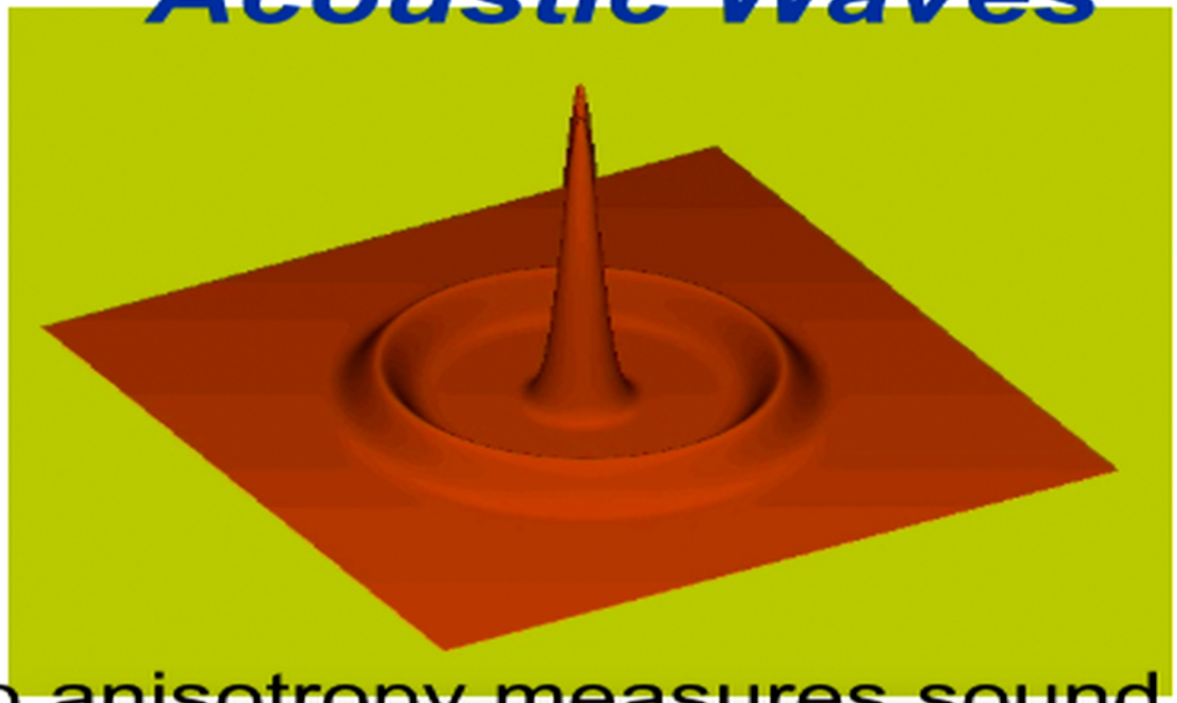


Acoustic Waves



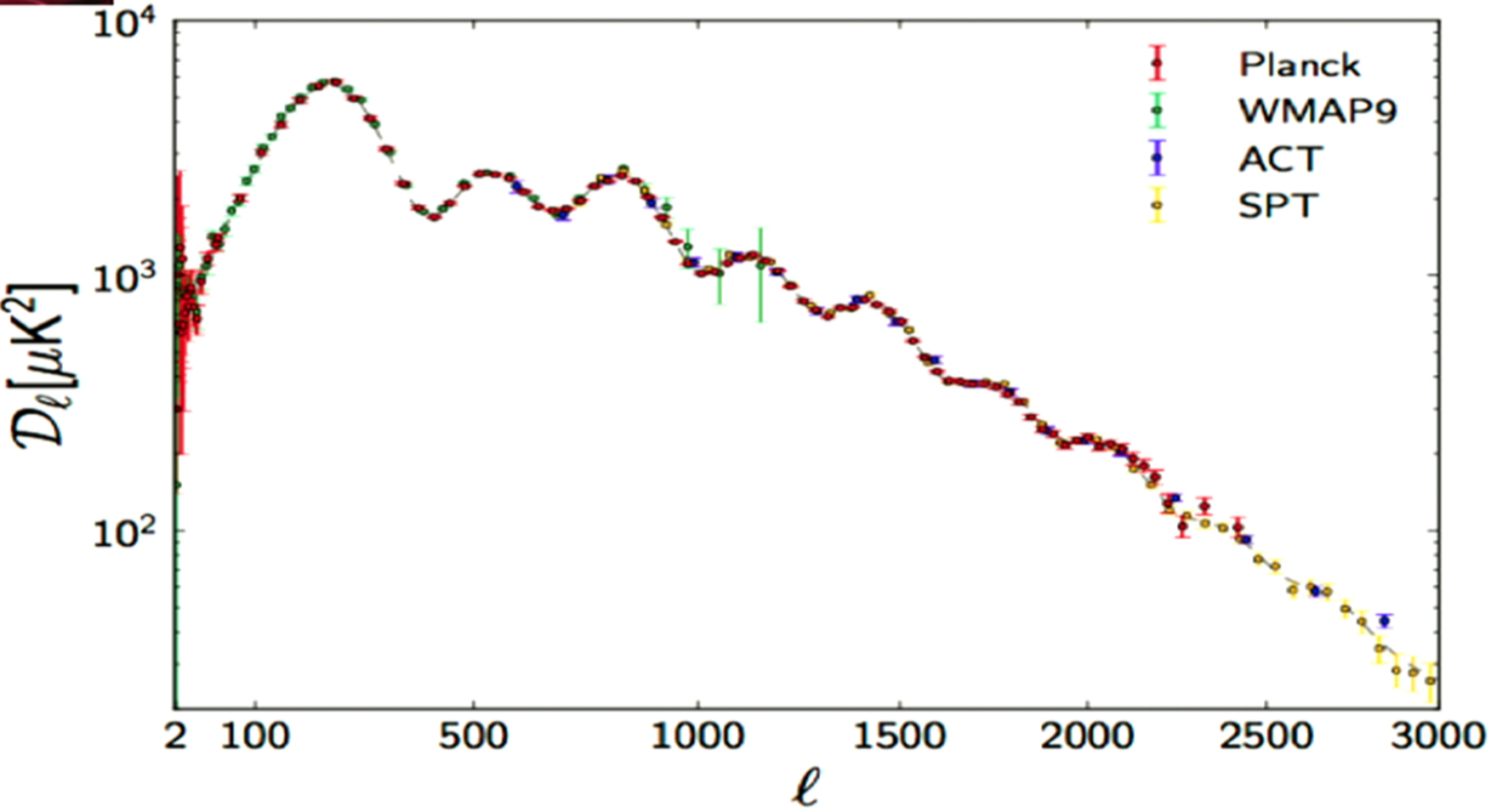
- cmb anisotropy measures sound waves, gravitational redshifts, intrinsic photon overdensities, diffusion

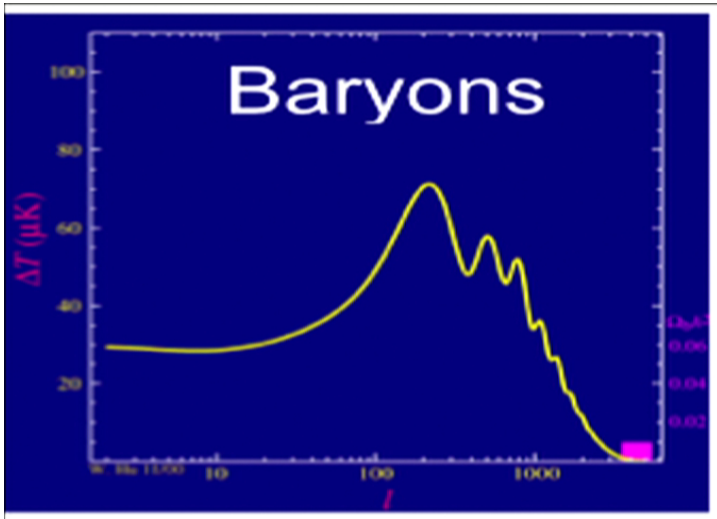
Acoustic Waves

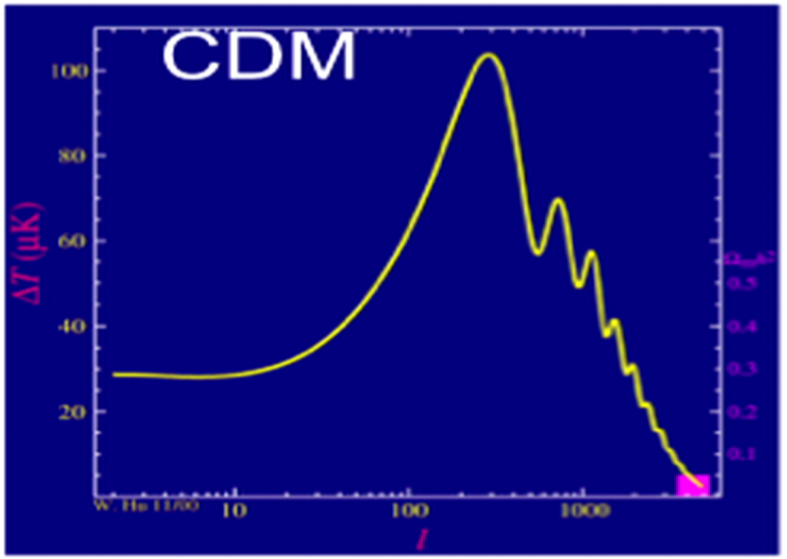


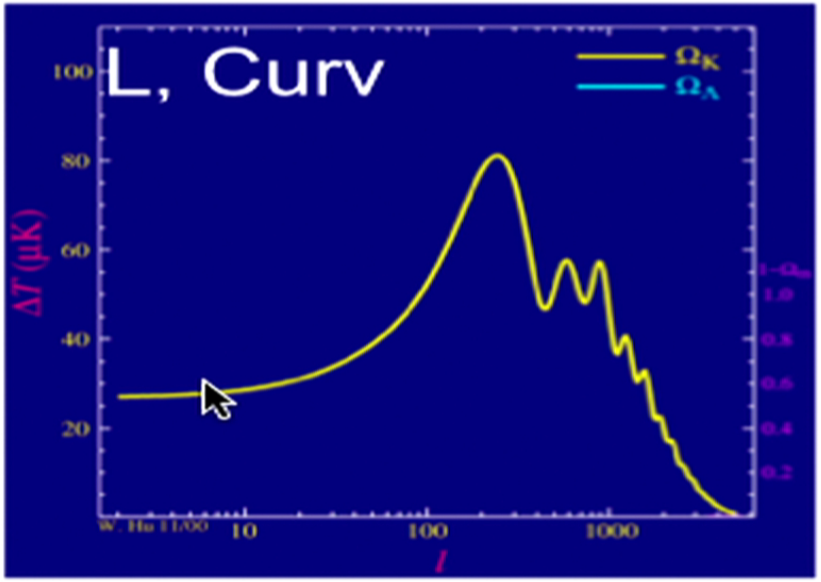
- cmb anisotropy measures sound wave[illegible]trinsic photon overdensities, diffusion

CMB Angular Power Spectrum









Wayne Hu tutorials

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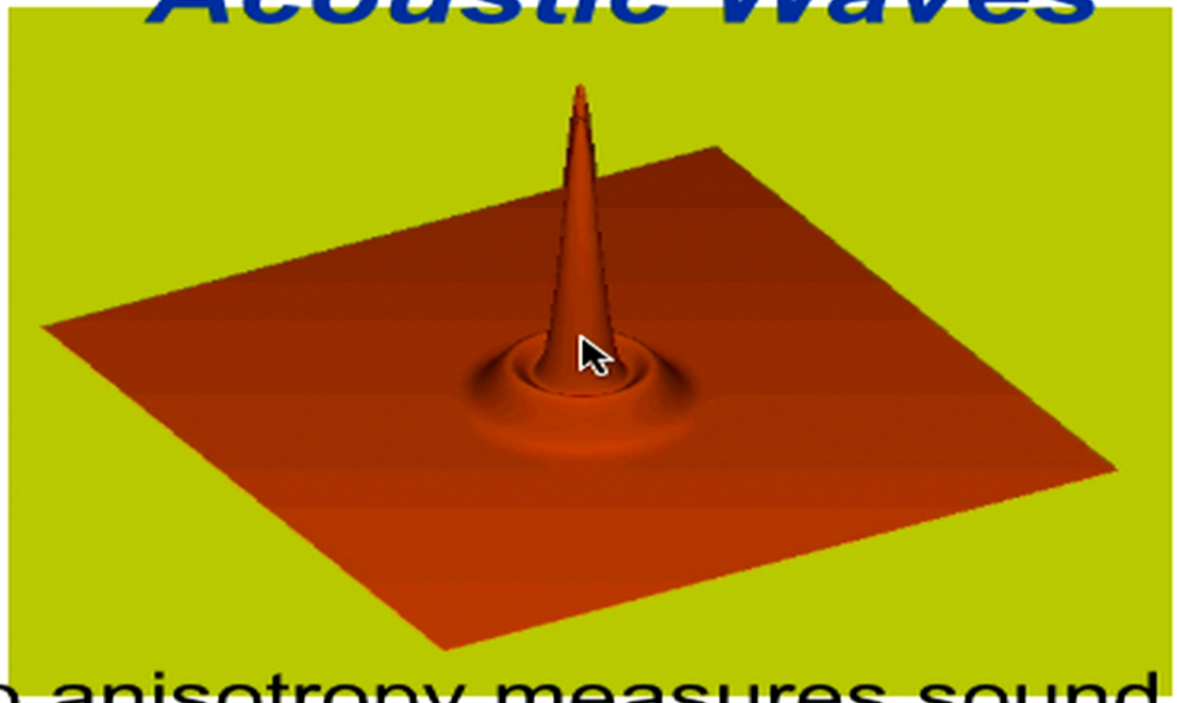
Acoustic Waves



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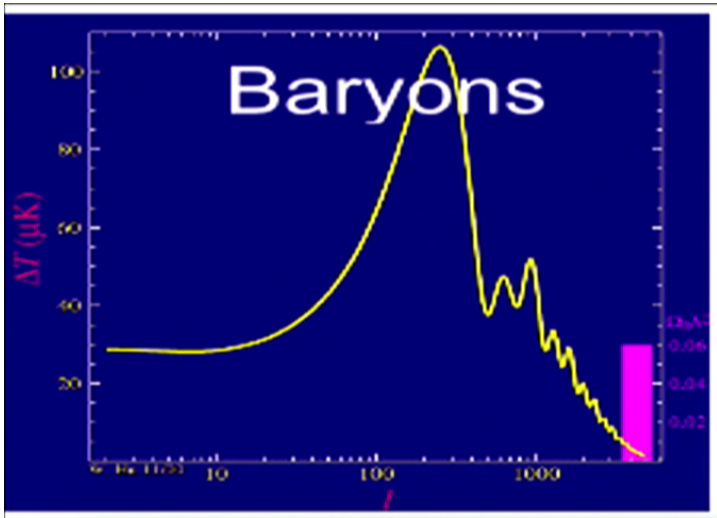

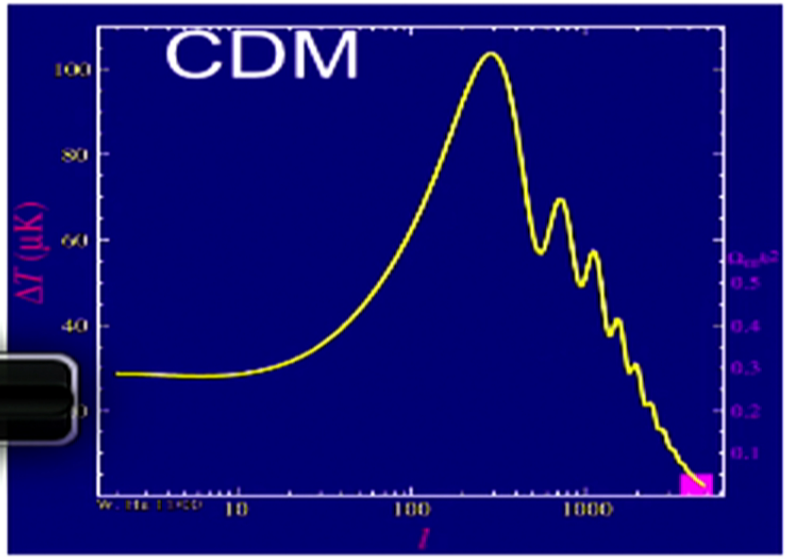

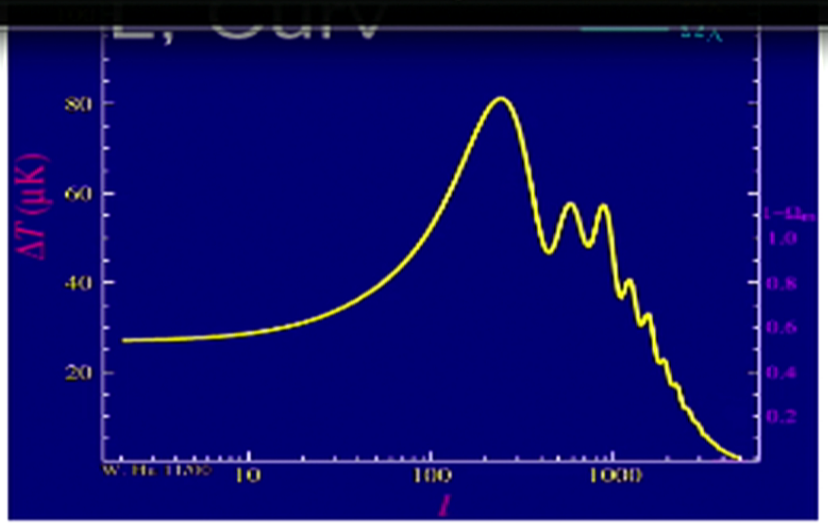

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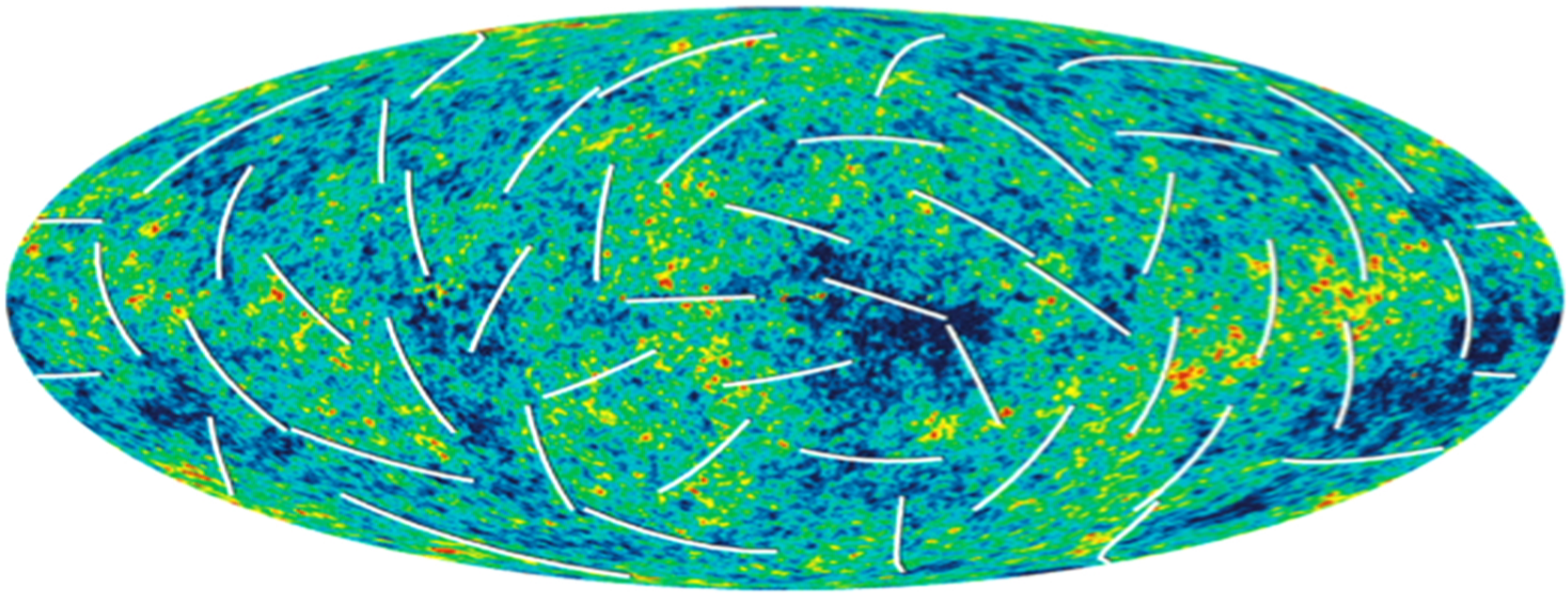
CMB Polarization



- CMB fluctuations are relatively strongly polarized (~10%)

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Scattering causes Polarization

- Bouncing light picks out one polarization
- Polarized sunglasses reduce glare by blocking horizontal polarization (more likely to be scattered!)

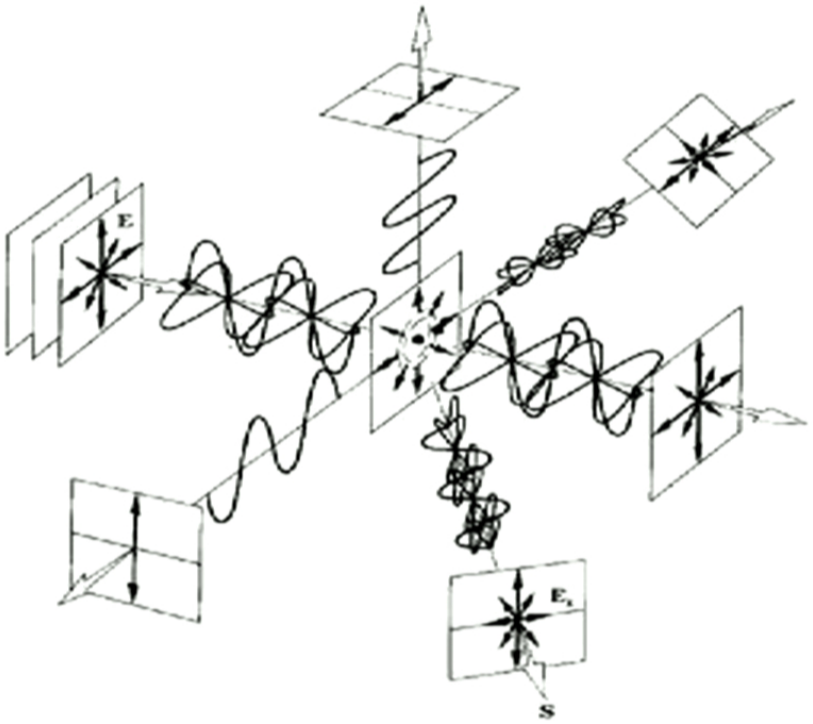


FIGURE 8.36 Scattering of unpolarized light by a molecule.

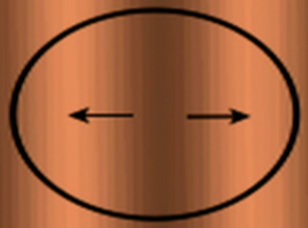
From Hecht, Optics

Polarization from Anisotropy

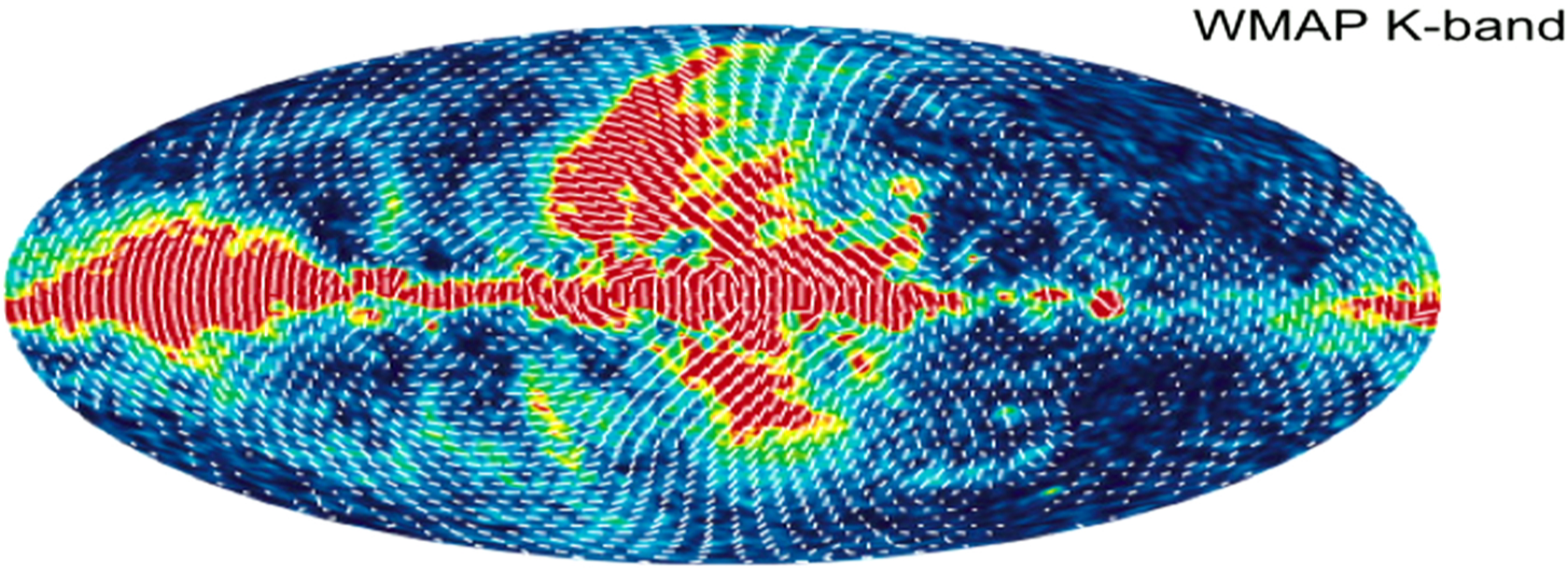
photon mean free path
increases as recombination occurs

Two reasons for local photon quadrupole anisotropy

1. quadrupole in local Temperature
2. shear in Doppler shift from velocities



Polarized Maps



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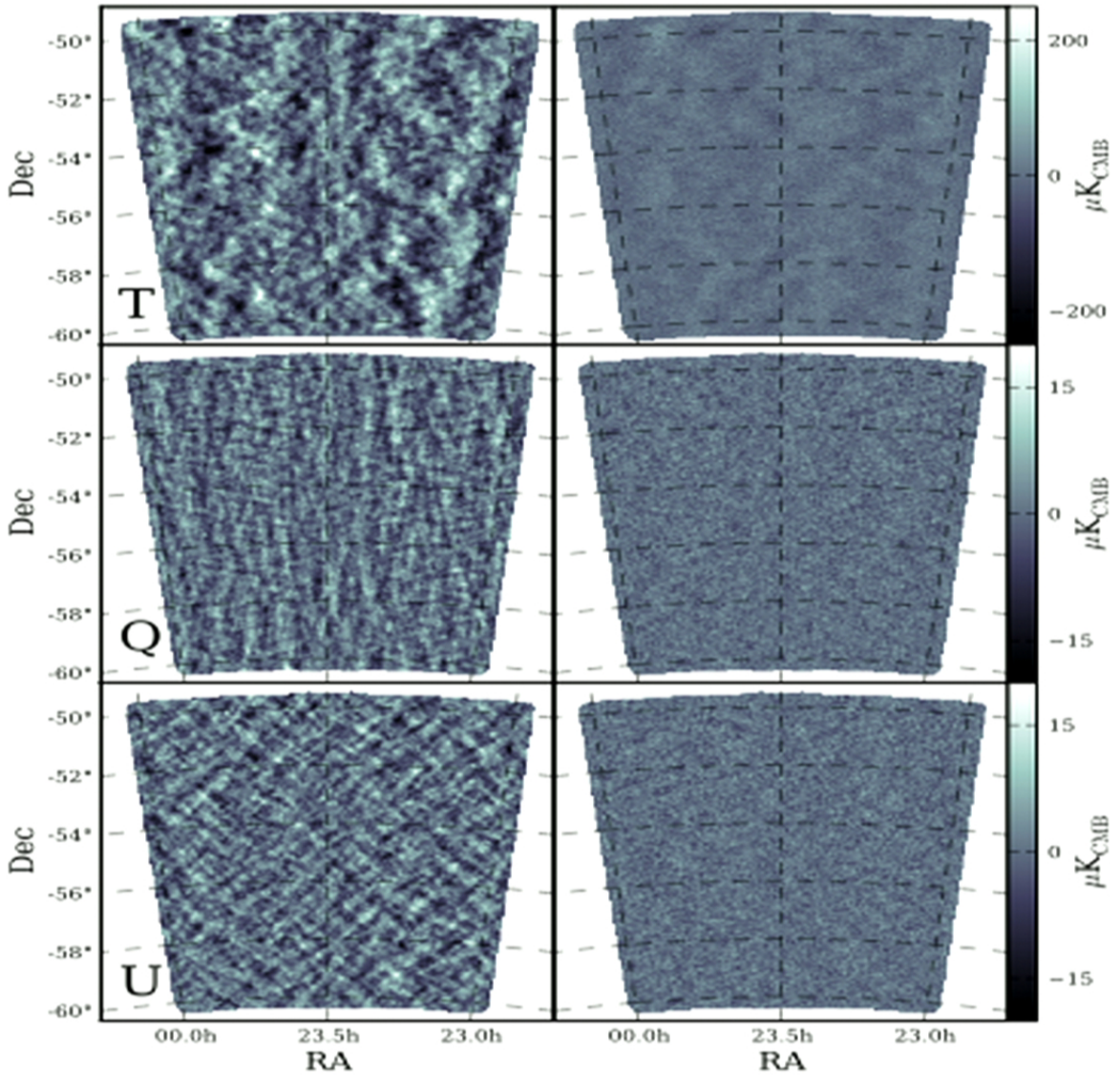
SPTpol Maps



Crites et al 2015

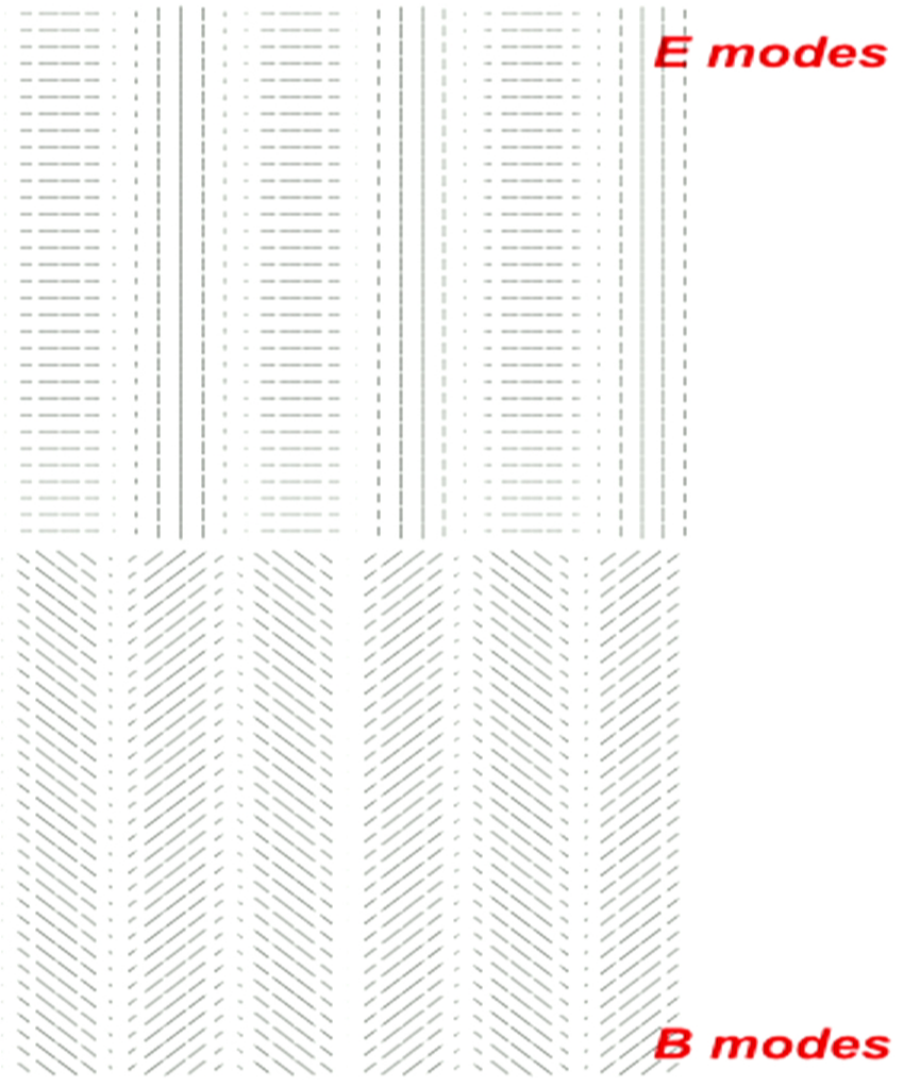
E-modes and B-modes

$$Q(\boldsymbol{l}) = [E(\boldsymbol{l})\cos(2\phi_{\boldsymbol{l}}) - B(\boldsymbol{l})\sin(2\phi_{\boldsymbol{l}})]$$
$$U(\boldsymbol{l}) = [E(\boldsymbol{l})\sin(2\phi_{\boldsymbol{l}}) + B(\boldsymbol{l})\cos(2\phi_{\boldsymbol{l}})].$$

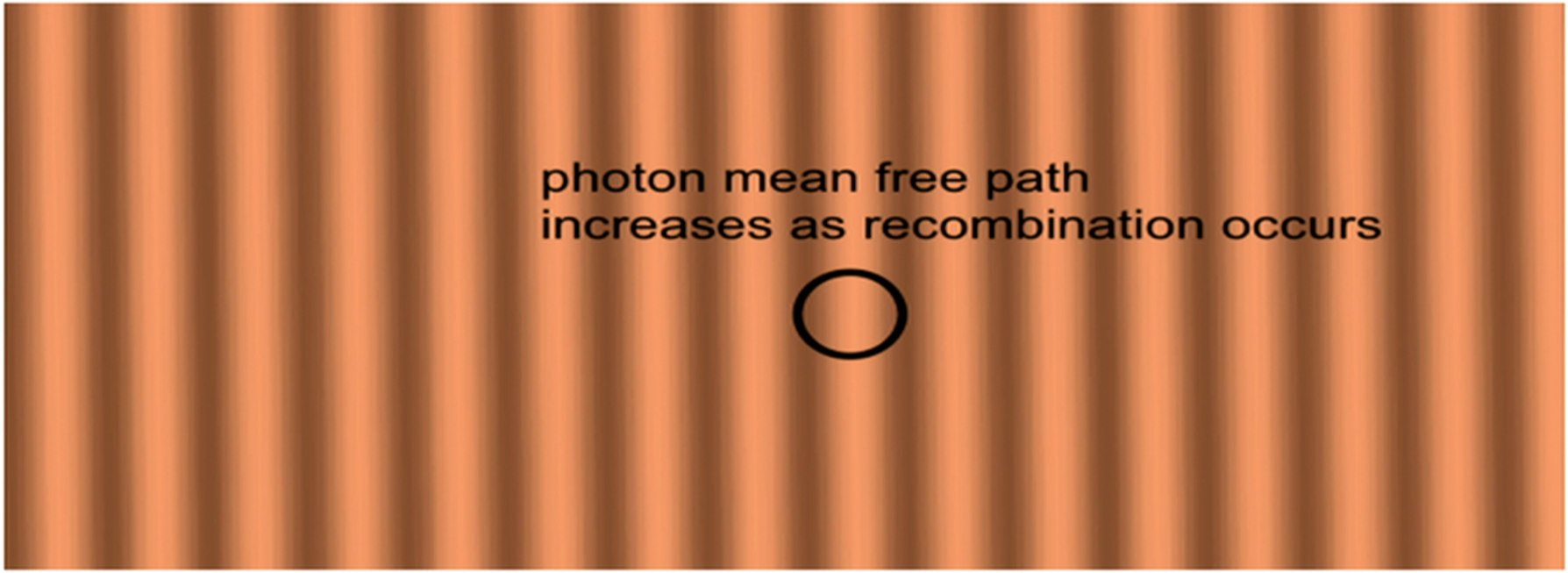
- E/B is a different way to express polarization field
- easy to understand in flat-sky limit (i.e. Fourier modes)

E-modes/B-modes

- E-modes vary spatially parallel or perpedicular to polarization direction
- B-modes vary spatially at 45 degrees
- CMB
    - scalar perturbations only generate *only* E



Density fluctuations generate pure E mode



- E-modes <=> polarization
- lensing convergence <=> shear

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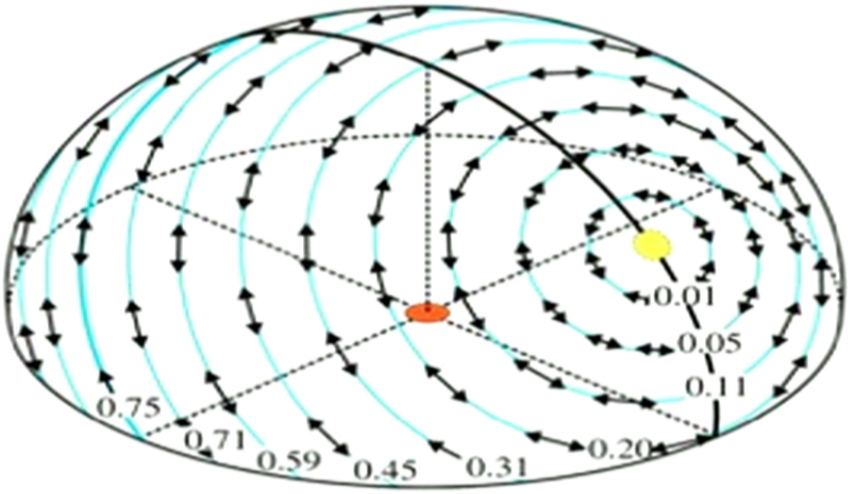
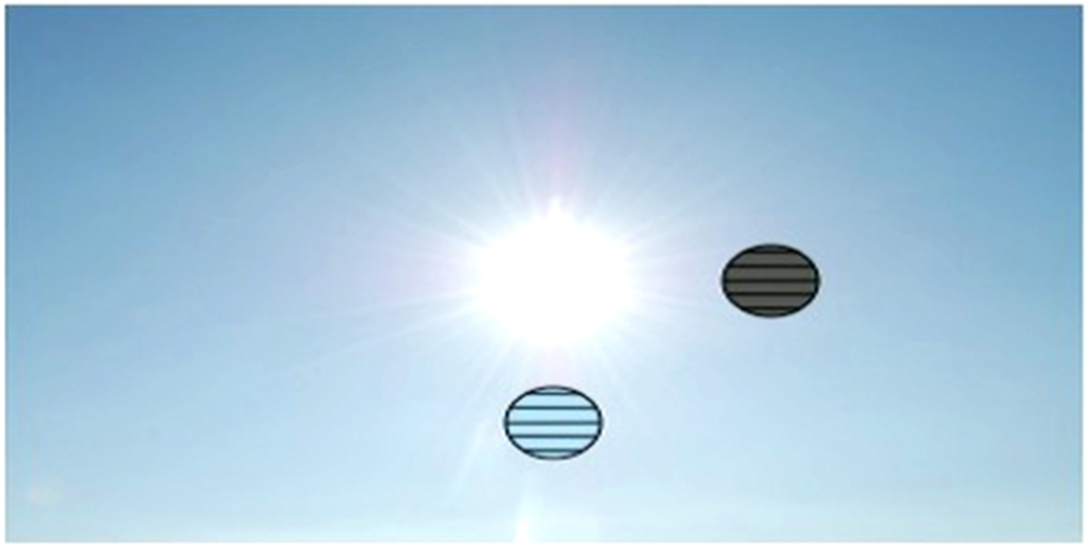
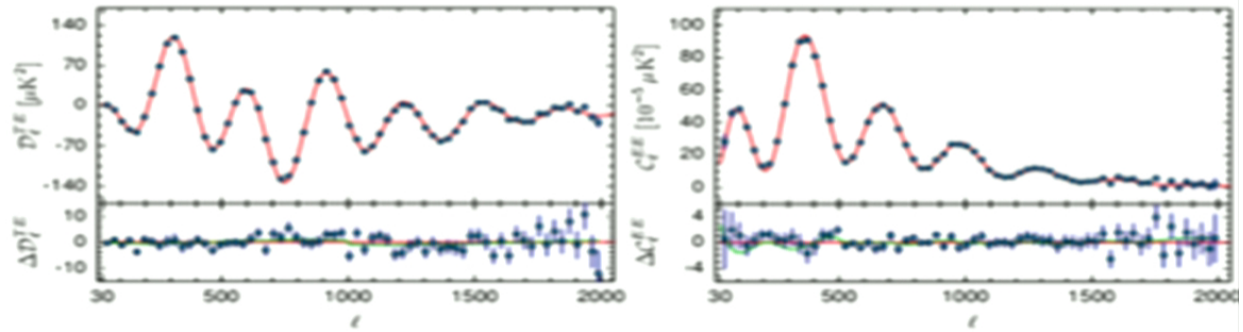
Blue sky is “E-mode”



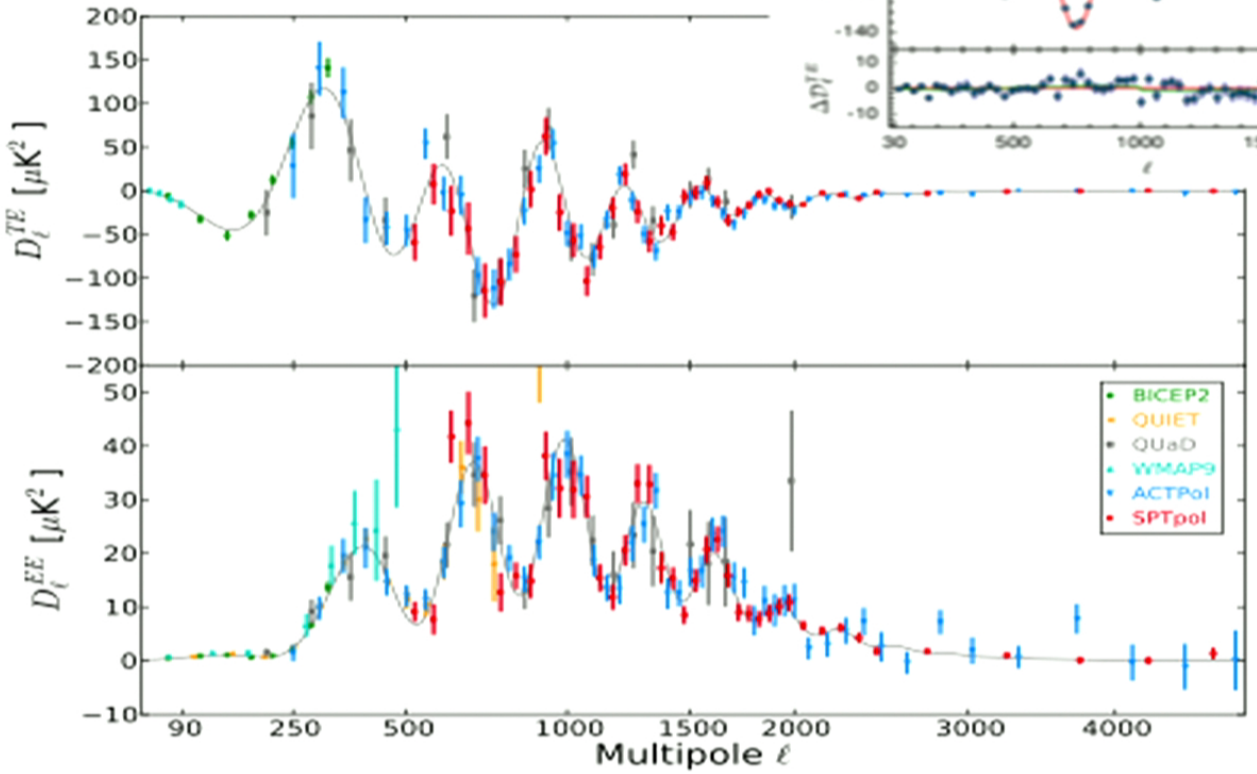


4

E-mode Power Spectrum

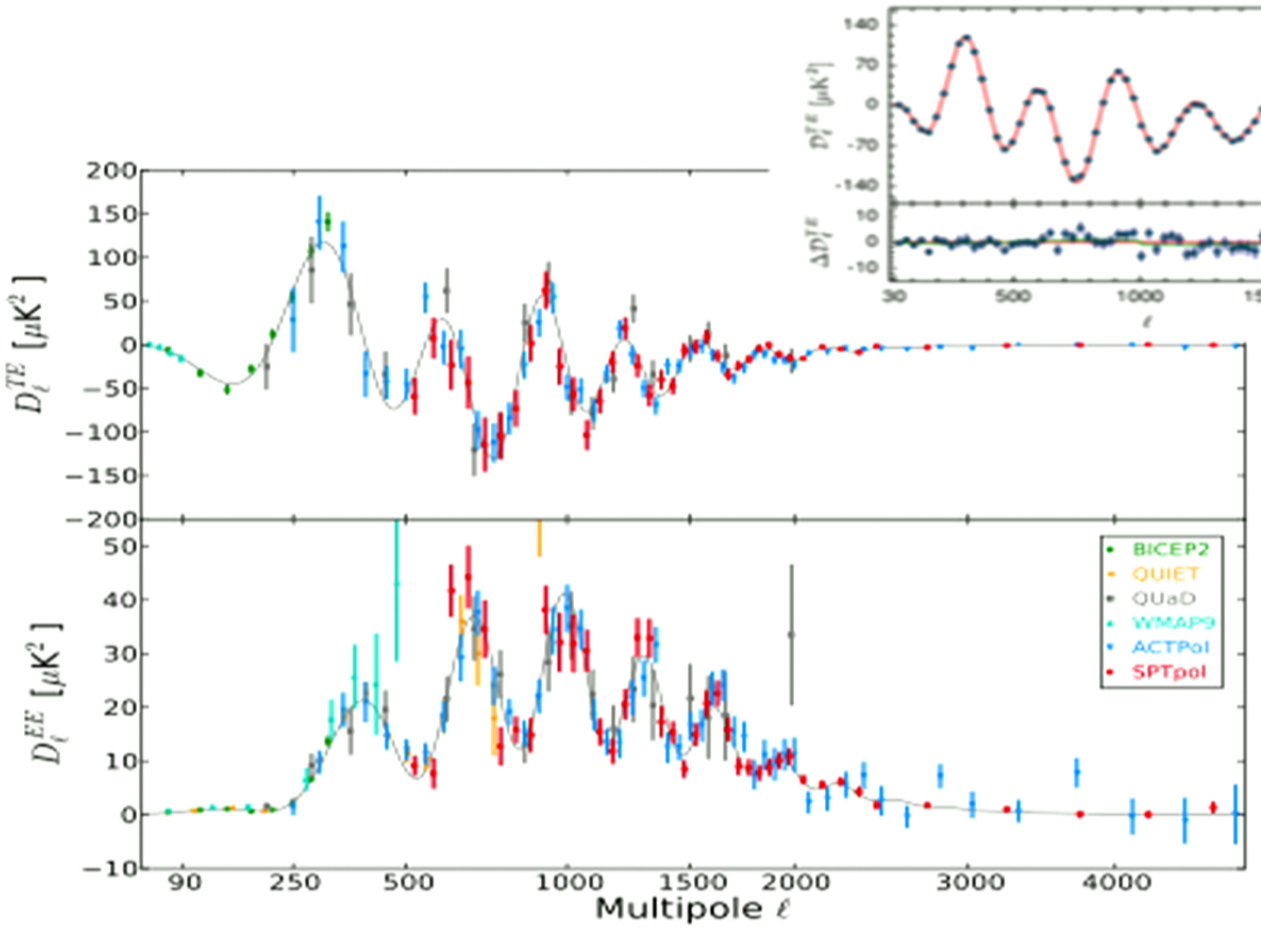


Planck 2015

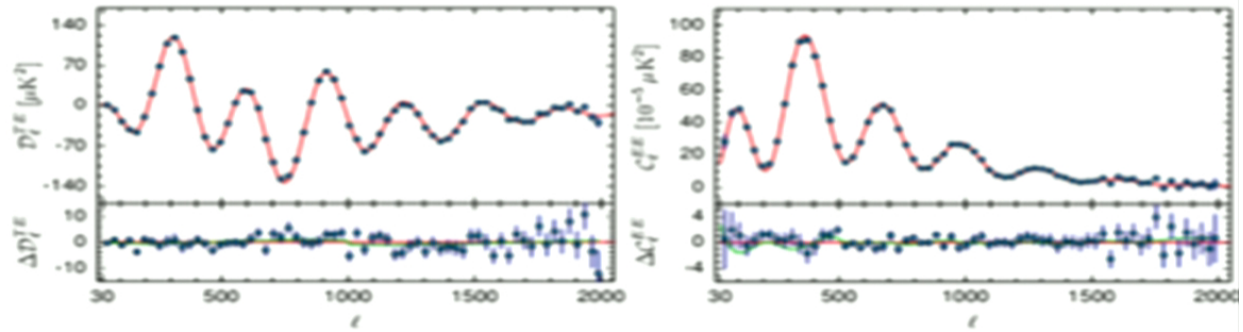


Crites et al 2015

E-mode Power Spectrum



Crites et al 2015



Planck 2015