CMB Anisotropy and Polarization

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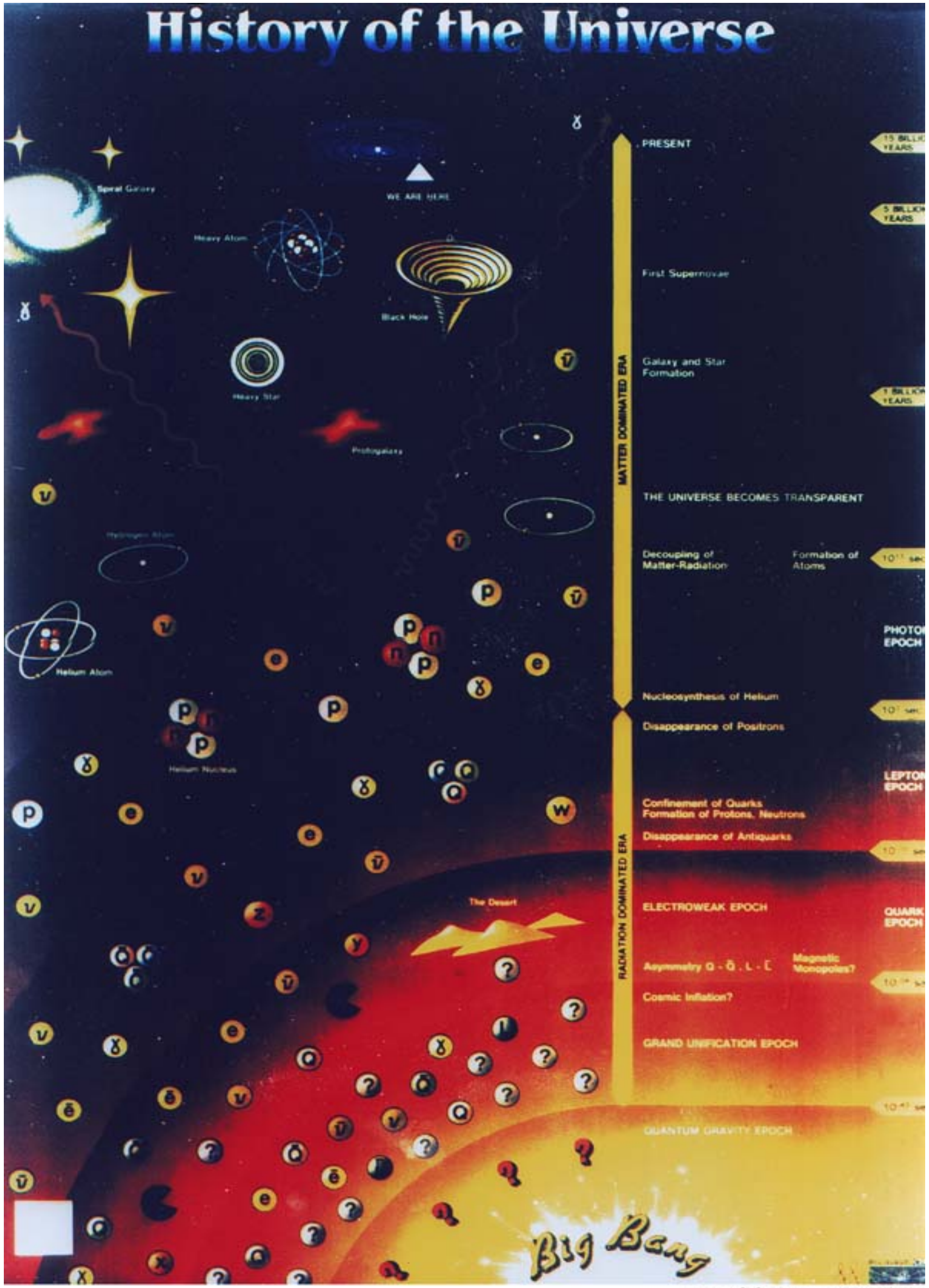
Outline

- The 3K cosmic microwave background
  - the relic photons of Hot Big Bang
- CMB anisotropy and polarization
- How to probe the early Universe and measure the cosmological parameters
- Current status and future directions



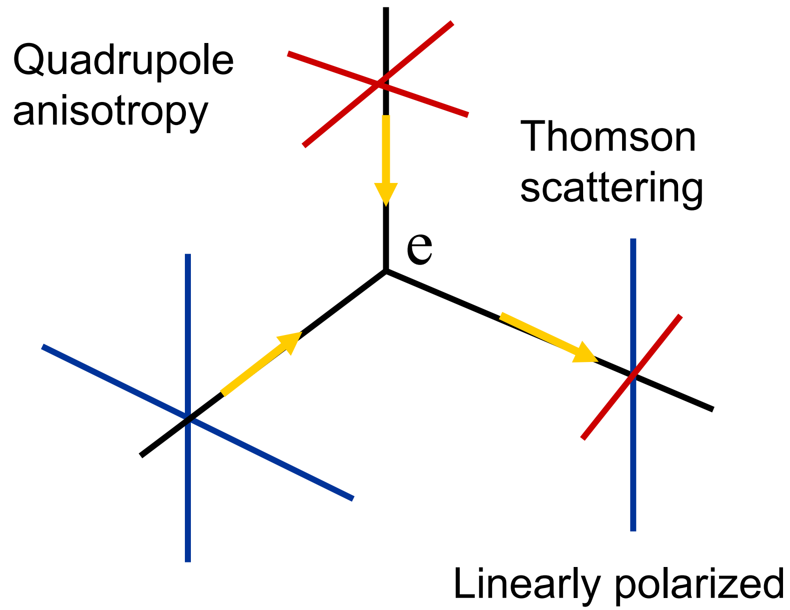
Fermilab Image 01-582D

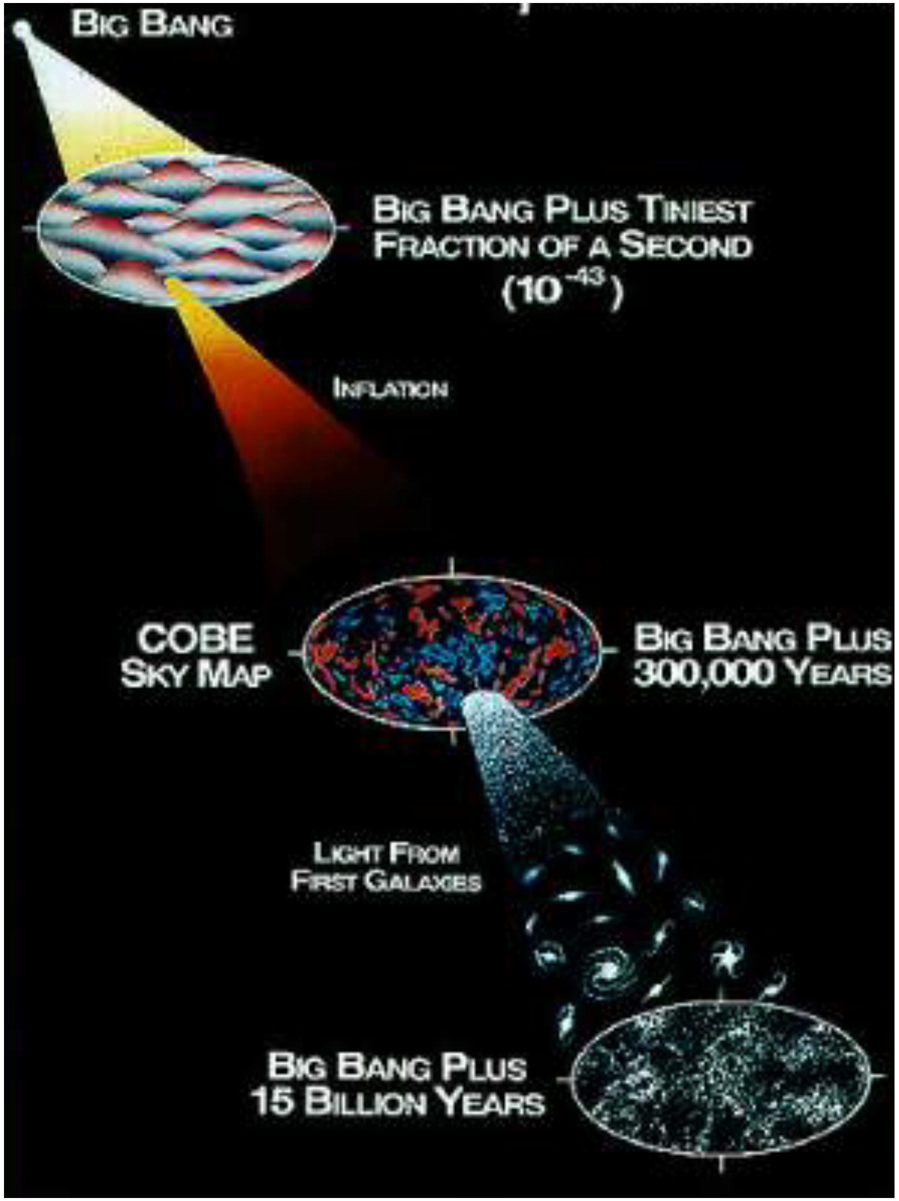
Cosmic Microwave Background

- Relic photons of hot big bang
- First observed in 1965
- Black body radiation of temperature about 3K
- Coming from last scatterings with electrons at redshift of about 1100 or 400,000 yrs after the big bang (age of the Universe is about 14 Gyrs)
- Slightly anisotropic (10**μ**K) and linearly polarized (**μ**K)

CMB Anisotropy and Polarization

- On large angular scales, matter imhomogeneities or primordial gravitational waves generate gravitational redshifts
- On small angular scales, acoustic oscillations in plasma on last scattering surface generate Doppler shifts
- Thomson scatterings with electrons generate polarization



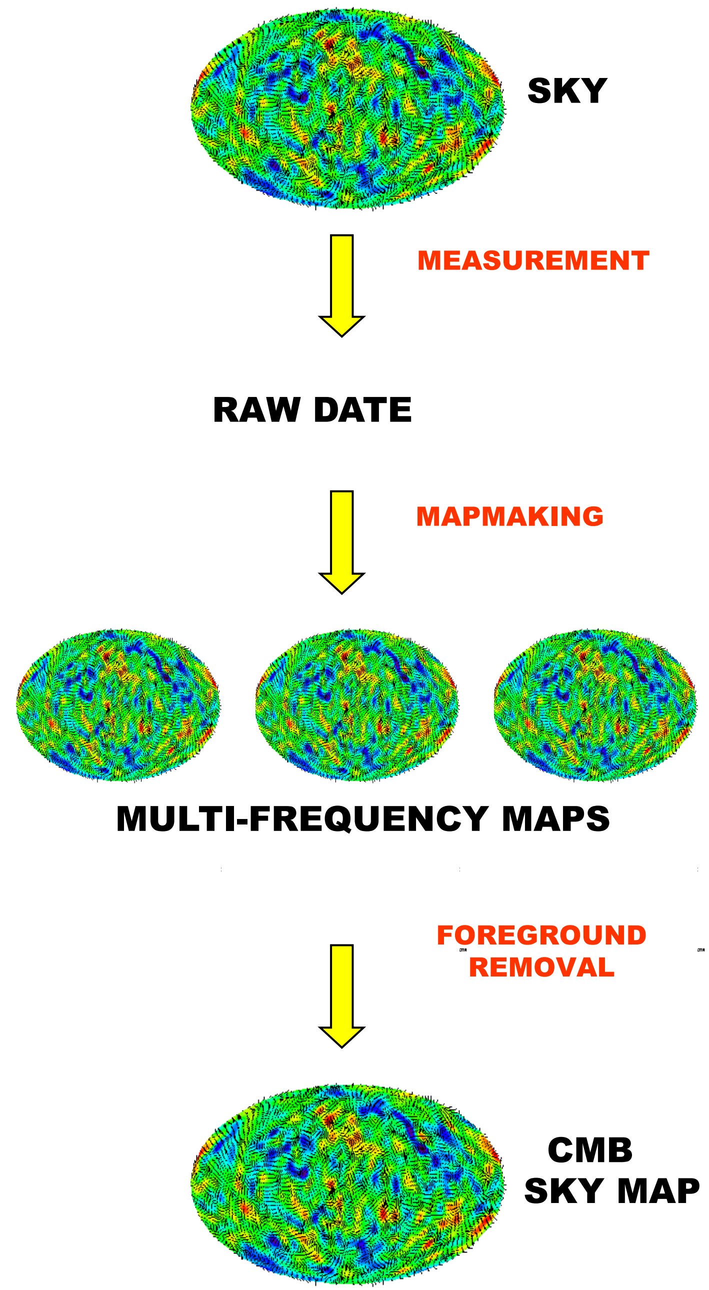


CMB Measurements

- Point the telescope to the sky
- Measure CMB Stokes parameters:

  $T = T_{CMB} - T_{mean}$,

  $Q = T_{EW} - T_{NS}$, $U = T_{SE\text{-}NW} - T_{SW\text{-}NE}$
- Scan the sky and make a sky map
- Sky map contains CMB signal, system noise, and foreground contamination including polarized galactic and extra-galactic emissions
- Remove foreground contamination by multi-frequency subtraction scheme
- Obtain the CMB sky map



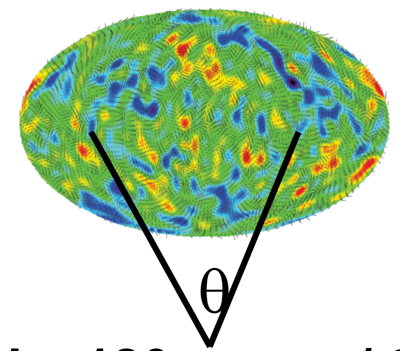
CMB Anisotropy and Polarization Angular Power Spectra

Decompose the CMB sky into a sum of spherical harmonics:

$T(\theta,\varphi) = \Sigma_{lm}\ a_{lm}\ Y_{lm}\ (\theta,\varphi)$

$(Q - iU)\ (\theta,\varphi) = \Sigma_{lm}\ a_{2,lm}\ {}_{2}Y_{lm}\ (\theta,\varphi)$

$(Q + iU)\ (\theta,\varphi) = \Sigma_{lm}\ a_{-2,lm}\ {}_{-2}Y_{lm}\ (\theta,\varphi)$



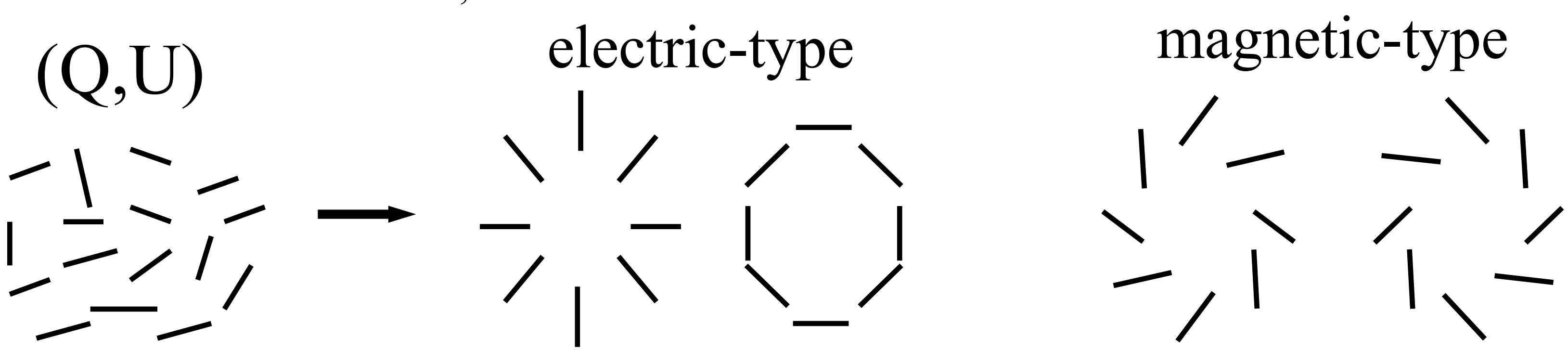
l = 180 degrees/ θ

$C^{T}_{l} = \Sigma_m (a^*_{lm}\ a_{lm})$ anisotropy power spectrum

$C^{E}_{l} = \Sigma_m (a^*_{2,lm}\ a_{2,lm} + a^*_{2,lm}\ a_{-2,lm})$ E-polarization power spectrum

$C^{B}_{l} = \Sigma_m (a^*_{2,lm}\ a_{2,lm} - a^*_{2,lm}\ a_{-2,lm})$ B-polarization power spectrum

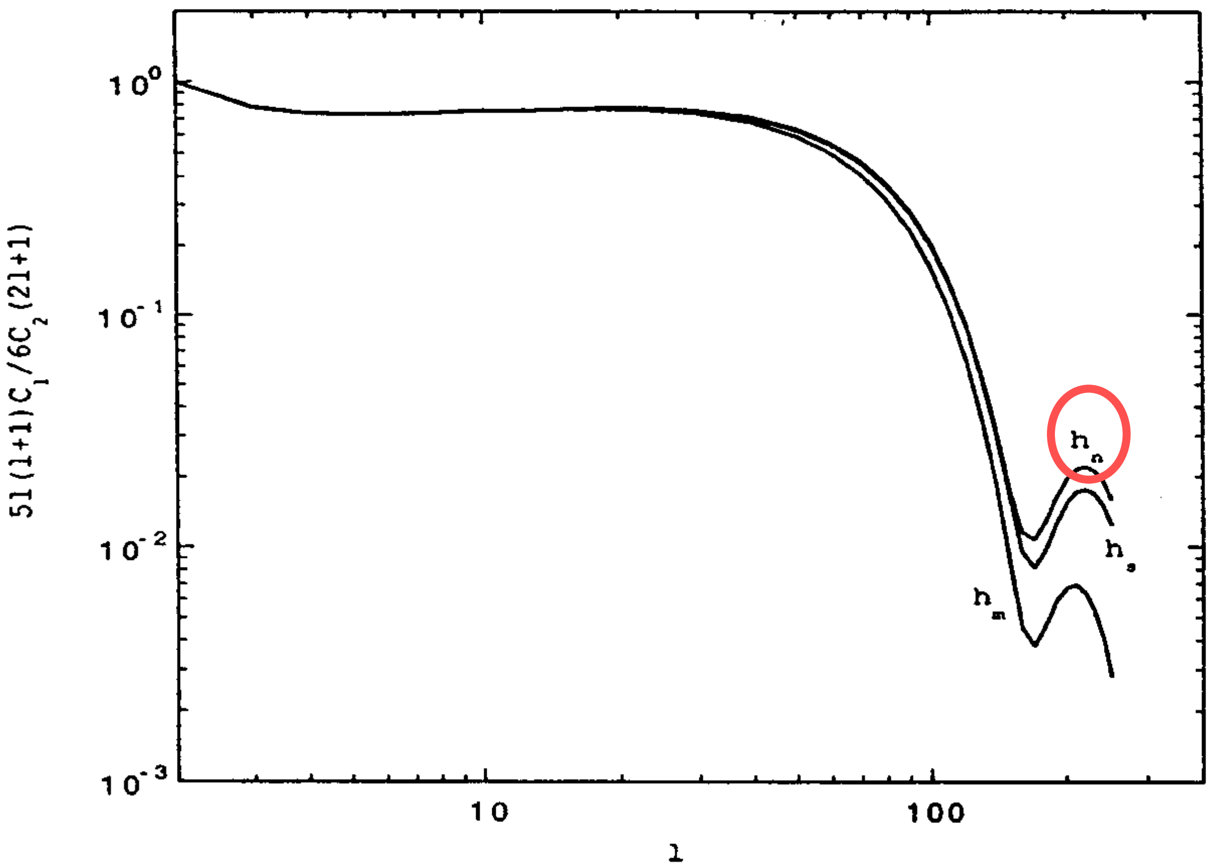
$C^{TE}_{l} = -\Sigma_m (a^*_{lm}\ a_{2,lm})$ TE correlation power spectrum



PGWs and CMB temperature anisotropy

Sachs–Wolfe effect: $$\frac{\delta T}{T}(\mathbf{e}) = -\frac{1}{2}\int_e^r d\Lambda e^i e^j \frac{\partial}{\partial \eta'} h_{ij}(\eta', \mathbf{x})$$

$$C_l = \frac{32\pi v}{3}(2l+1)(l+2)(l+1)l(l-1)\int_0^\infty \frac{dk'}{k'}\left[\int_{\eta'_{\rm dec}}^{\eta'_0} d\eta' \frac{dh(\eta')}{d\eta'} \frac{j_l[k'(\eta'_0-\eta')]}{k'^2(\eta'_0-\eta')^2}\right]^2$$



Collisional Boltzmann Equation

Ng&Ng 96

$$\left(\frac{\partial}{\partial \eta} + \boldsymbol{e} \cdot \frac{\partial}{\partial \boldsymbol{x}}\right)\boldsymbol{n} = -\frac{1}{2}\frac{\partial \boldsymbol{n}}{\partial \ln \nu}\frac{\partial h_{ij}}{\partial \eta}e^i e^j - \sigma_T N_e a \times \left[\boldsymbol{n} - \frac{1}{4\pi}\int_{-1}^{1}\int_0^{2\pi} P(\mu, \phi, \mu', \phi')\boldsymbol{n}\, d\mu'\, d\phi'\right], \quad (1)$$

where σ_T is the Thomson scattering cross section, N_e is the number of free electrons per unit volume, ($\mu = \cos\theta, \phi$) are the polar angles of the propagation direction $\boldsymbol{e}$ of the photon with a comoving frequency ν, and P is the phase matrix for Thomson scattering.

scalar modes/ density perturbations

The solution $\boldsymbol{n}$ for the equation of transfer assumes the form $\boldsymbol{n} = \boldsymbol{n}_0 + (n_0\, \delta\boldsymbol{n}/2)$, where $\boldsymbol{n}_0$ and $\delta\boldsymbol{n}$ are the unperturbed solution and perturbation, respectively. We expand $\delta\boldsymbol{n} = \int d\boldsymbol{k}\, \boldsymbol{n}' e^{i\boldsymbol{k}\cdot\boldsymbol{x}}$, where $\boldsymbol{n}' = \alpha\boldsymbol{a} + \beta\boldsymbol{b}$. For the scalar-mode solution, the Stokes components n_u and n_v both decouple from n_l and n_r, and it suffices to consider only the first two components of $\boldsymbol{n}$ with $\boldsymbol{a} = (1, 1)$ and $\boldsymbol{b} = (1, -1)$. Substituting the solution $\boldsymbol{n}$ and the Fourier expansion for h_{ij} into equation (1), and expanding α and β in terms of Legendre polynomials,

$$\alpha(\mu) = \sum_l (2l+1)\alpha_l P_l(\mu)\,,$$

$$\beta(\mu) = \sum_l (2l+1)\beta_l P_l(\mu)\,, \quad (3)$$

$$\dot{\alpha} + ik\mu\alpha = \tfrac{1}{3}[T(k)]^{1/2}k^2\eta(1 + 2P_2) - q \times [\alpha - \alpha_0 - \tfrac{1}{2}P_2(\alpha_2 - \beta_0 + \beta_2)] ,$$

$$\dot{\beta} + ik\mu\beta = -q[\beta - \tfrac{1}{2}(1 - P_2)(\beta_0 - \alpha_2 - \beta_2)] ,$$

$$h_{ij} = \int d\mathbf{k}\, \delta_k e^{i\mathbf{k}\cdot\mathbf{x}} k_i k_j \qquad \delta_k \propto k^2\eta^2$$

T(k) CDM transfer function

$$q = \sigma_T N_e a.$$

$$\dot{\alpha}_0 = -ik\alpha_1 + \frac{1}{3}[T(k)]^{1/2}k^2\eta ,$$

$$\dot{\alpha}_1 = -\frac{i}{3}k(\alpha_0 + 2\alpha_2) - q\alpha_1 ,$$

$$\dot{\alpha}_2 = -\frac{i}{5}k(2\alpha_1 + 3\alpha_3) + \frac{2}{15}[T(k)]^{1/2}k^2\eta - \frac{q}{10}(9\alpha_2 + \beta_0 - \beta_2) ,$$

$$\dot{\beta}_0 = -ik\beta_1 - \frac{q}{2}(\beta_0 + \beta_2 + \alpha_2) ,$$

$$\dot{\beta}_1 = -\frac{i}{3}k(\beta_0 + 2\beta_2) - q\beta_1 ,$$

$$\dot{\beta}_2 = -\frac{i}{5}k(2\beta_1 + 3\beta_3) - \frac{q}{10}(9\beta_2 + \beta_0 - \alpha_2) ,$$

$$\left.\begin{aligned} \dot{\alpha}_l &= -q\alpha_l - \frac{ik}{2l+1}[l\alpha_{l-1} + (l+1)\alpha_{l+1}] \\ \dot{\beta}_l &= -q\beta_l - \frac{ik}{2l+1}[l\beta_{l-1} + (l+1)\beta_{l+1}] \end{aligned}\right\} l \geq 3$$

tensor modes/ GWs

In the case of the tensor mode, only n_v decouples, and we thus choose the basis (Polnarev 1985) $\boldsymbol{a} = [\frac{1}{2}(1-\mu^2)\cos 2\phi](1, 1, 0)$ and $\boldsymbol{b} = \frac{1}{2}[(1+\mu^2)\cos 2\phi, -(1+\mu^2)\cos 2\phi, 4\mu \sin 2\phi]$ for the + mode solution. The × mode solution is given by the same expressions with cos 2ϕ and sin 2ϕ interchanged, and an additional minus sign in the last component of the basis vector b. Defining $\xi = \alpha + \beta$, we obtain a system of coupled differential equations in a similar way:

$$h_{ij}^{\lambda} = \int d\boldsymbol{k}\, h_k e^{i\boldsymbol{k}\cdot\boldsymbol{x}} \epsilon_{ij}^{\lambda}$$

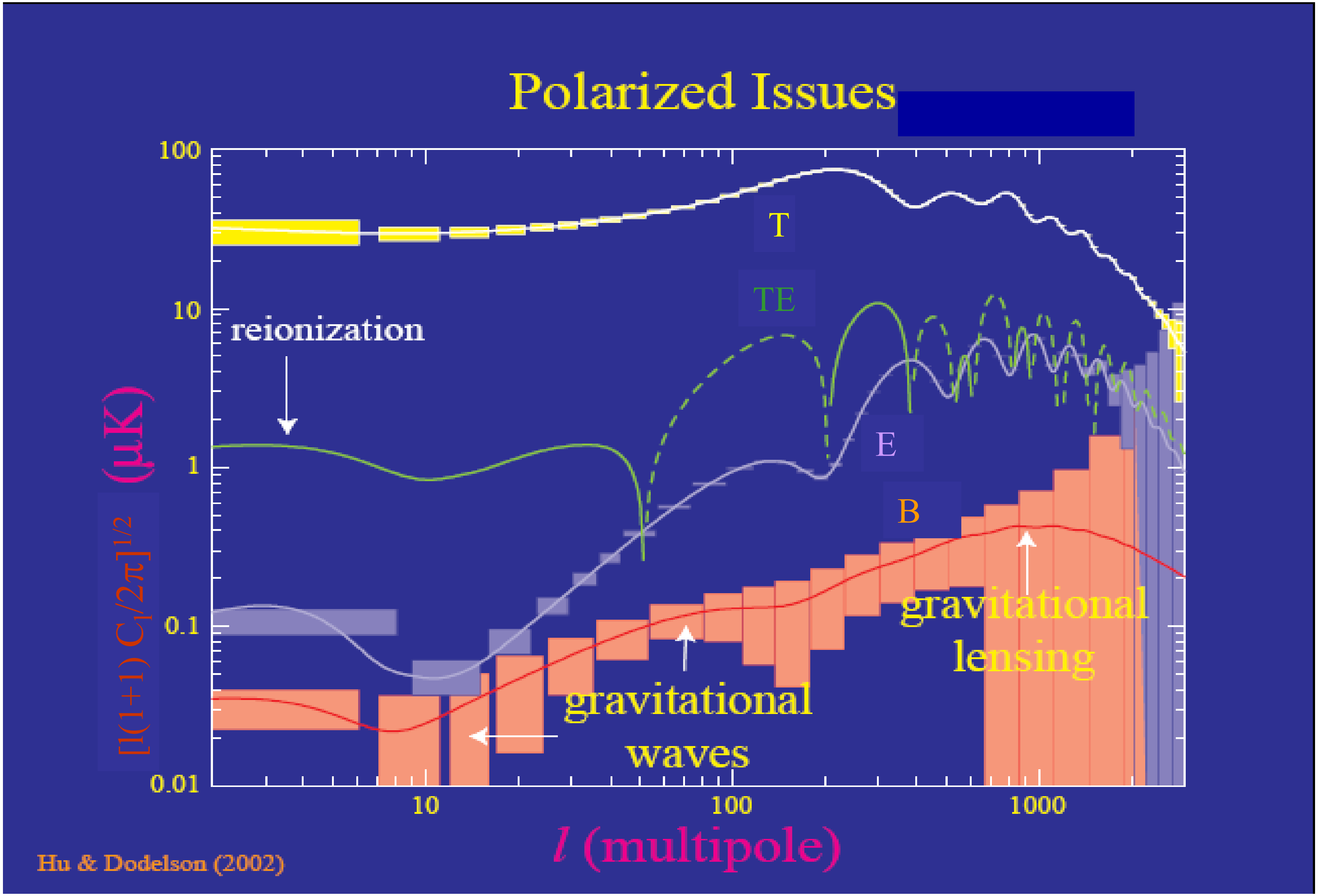
$$\ddot{h}_k + (2\dot{a}\dot{h}_k/a) + k^2 h_k = 0,$$

$$\begin{aligned}
\dot{\xi}_0 &= -q\xi_0 - ik\xi_1 + \dot{h}_k\,, \\
\dot{\beta}_0 &= -\tfrac{3}{10} q\beta_0 - ik\beta_1 + q \\
&\quad \times\left(\tfrac{5}{7}\beta_2 + \tfrac{3}{35}\beta_4 - \tfrac{1}{10}\xi_0 + \tfrac{1}{7}\xi_2 - \tfrac{3}{70}\xi_4\right),
\end{aligned} \tag{7}$$

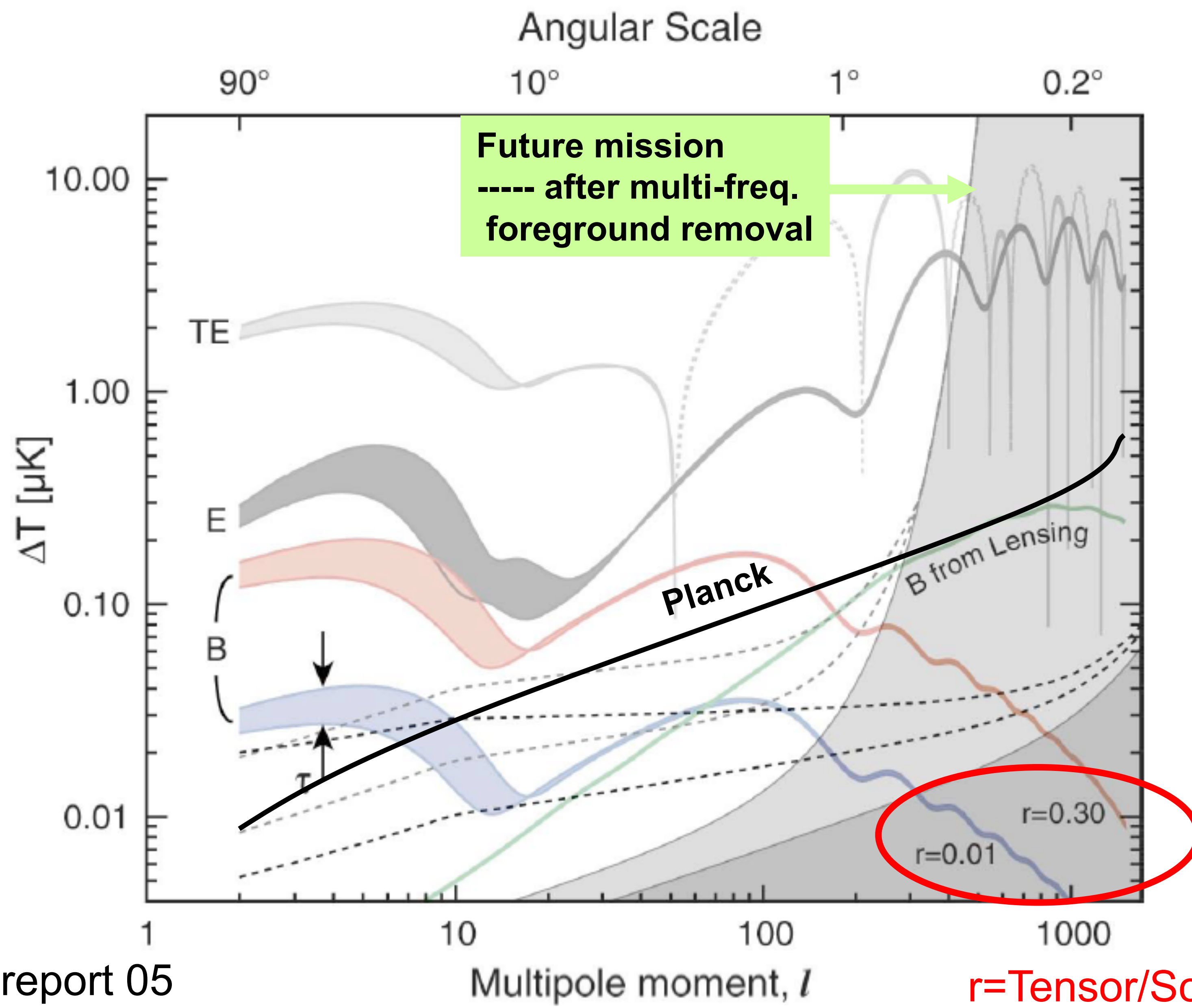
$$\left.\begin{aligned}
\dot{\xi}_l &= -q\xi_l - \frac{ik}{2l+1}[l\xi_{l-1} + (l+1)\xi_{l+1}] \\
\dot{\beta}_l &= -q\beta_l - \frac{ik}{2l+1}[l\beta_{l-1} + (l+1)\beta_{l+1}]
\end{aligned}\right\} l \geq 1\,,$$

+ multi-component fluid perturbation evolution → CMB numerical codes : COSMICS Ma+Bertschinger, CMBFAST Seljak+Zaldarriaga, CAMB,…

Theoretical Predictions for CMB Power Spectra



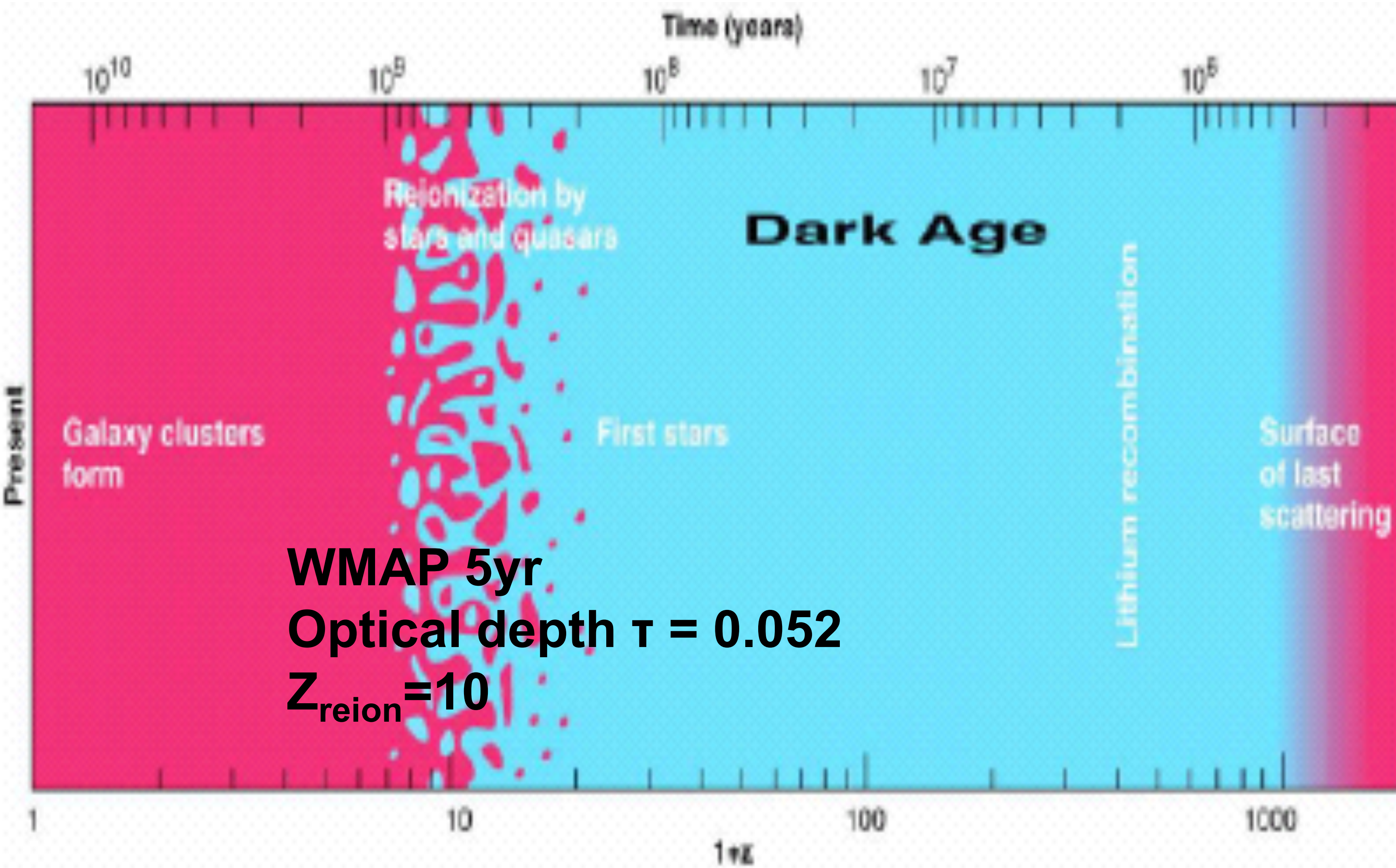
Gravity-wave induced B-mode



Weiss report 05

r=Tensor/Scalar

Large-scale CMB Polarization and Reionization of the Universe

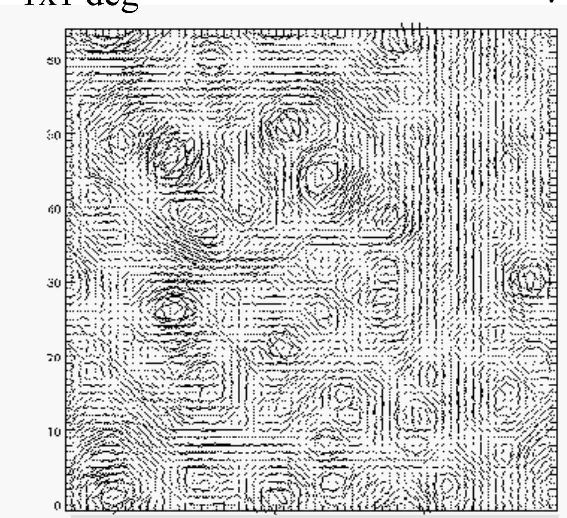


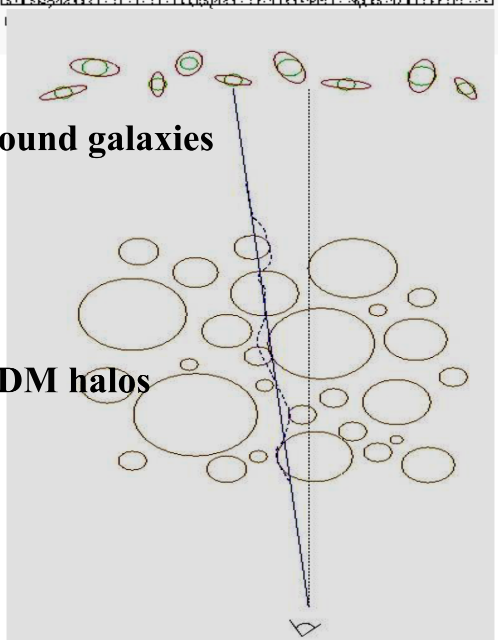
WMAP 5yr
Optical depth $\tau = 0.052$
$Z_{reion}=10$

Weak Lensing by Large-Scale Structure

Jain et al. 1997
1x1 deg

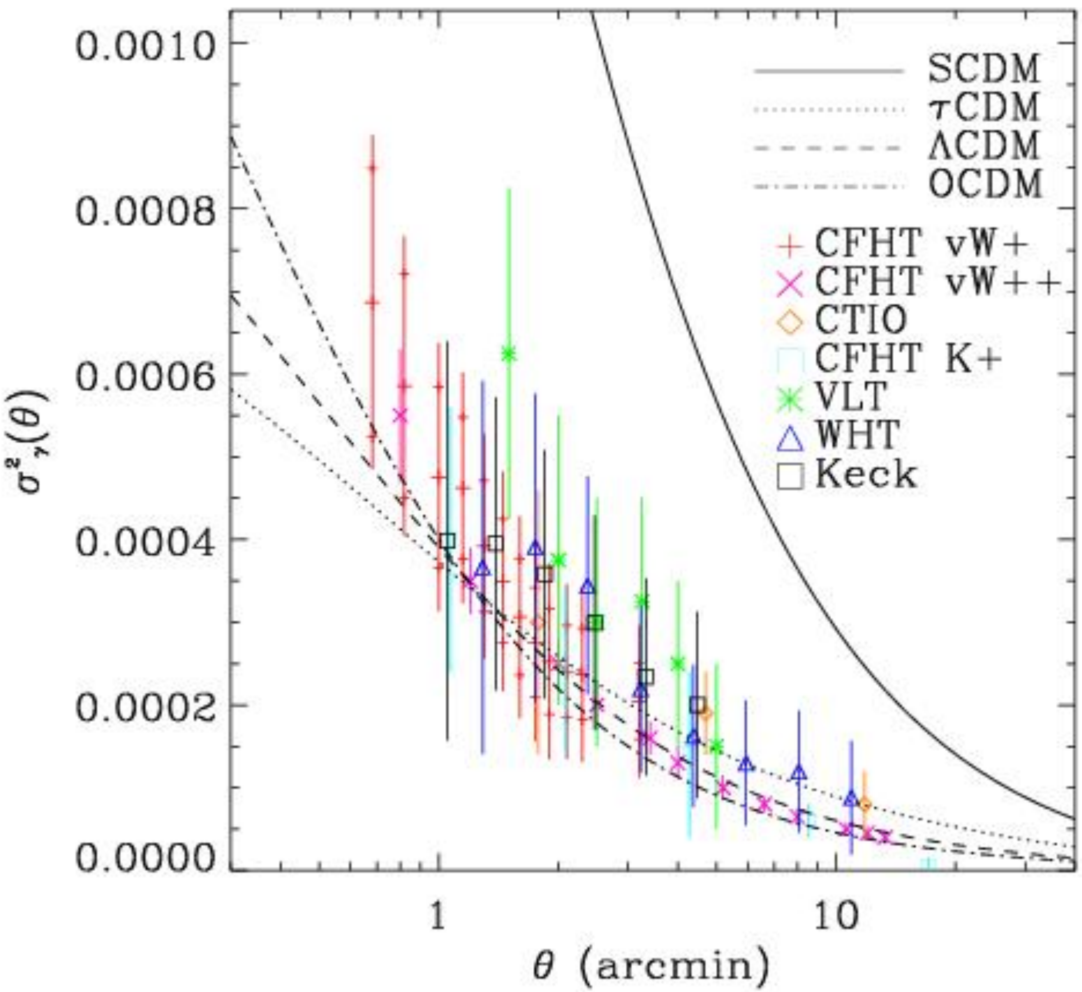
Cosmic Shear γ





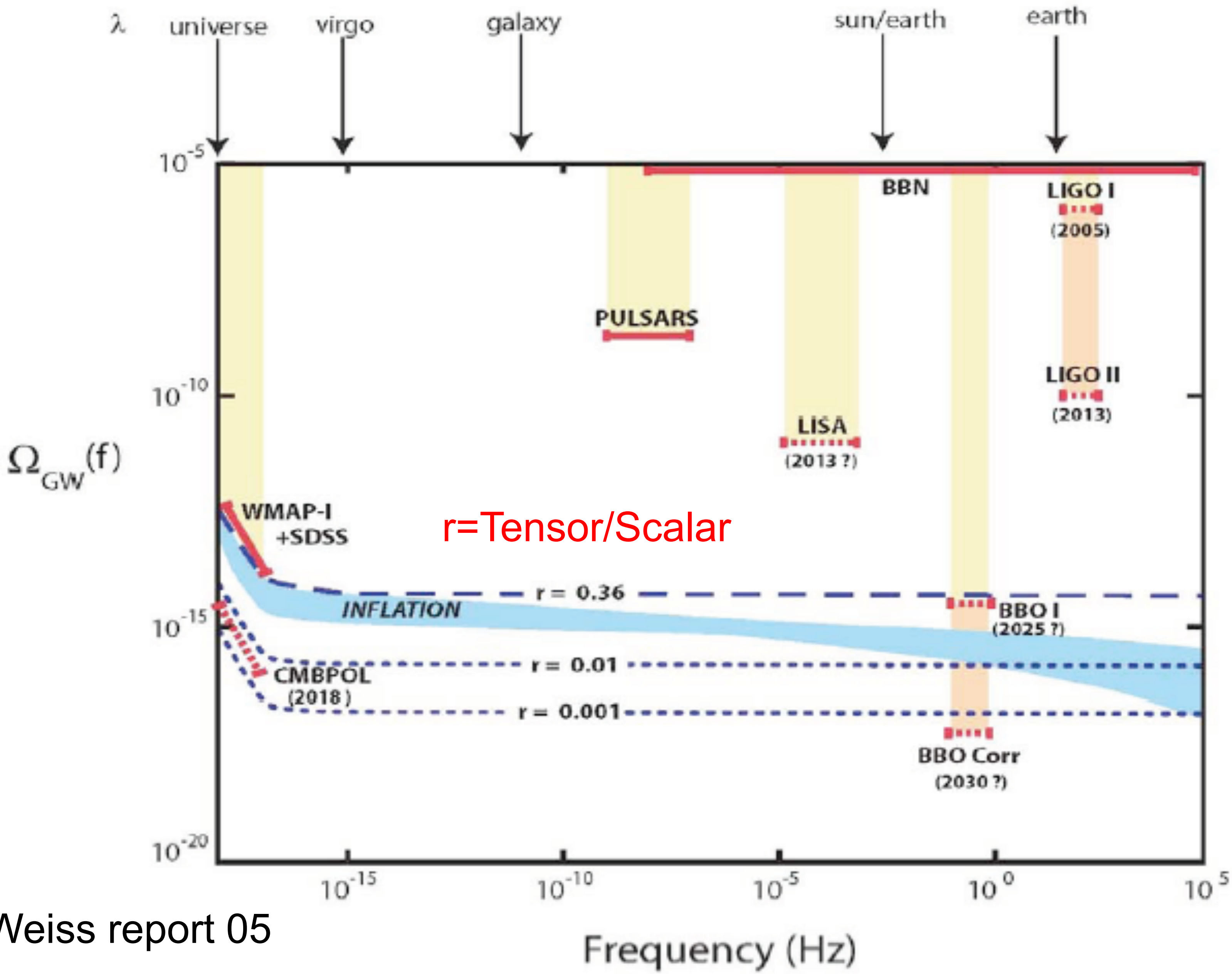
Shear Variance in circular cells with size θ

$$\sigma^2_\gamma(\theta) = \langle\gamma^2\rangle$$



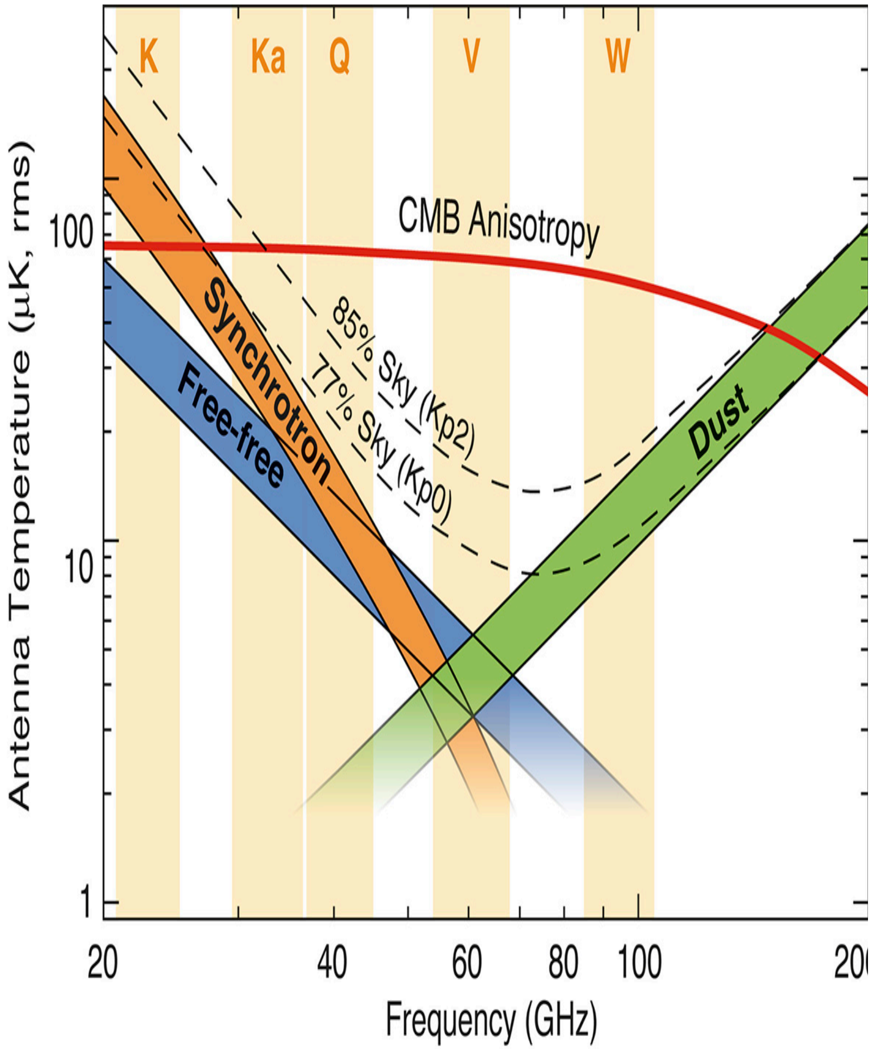
Ellis et al. 02

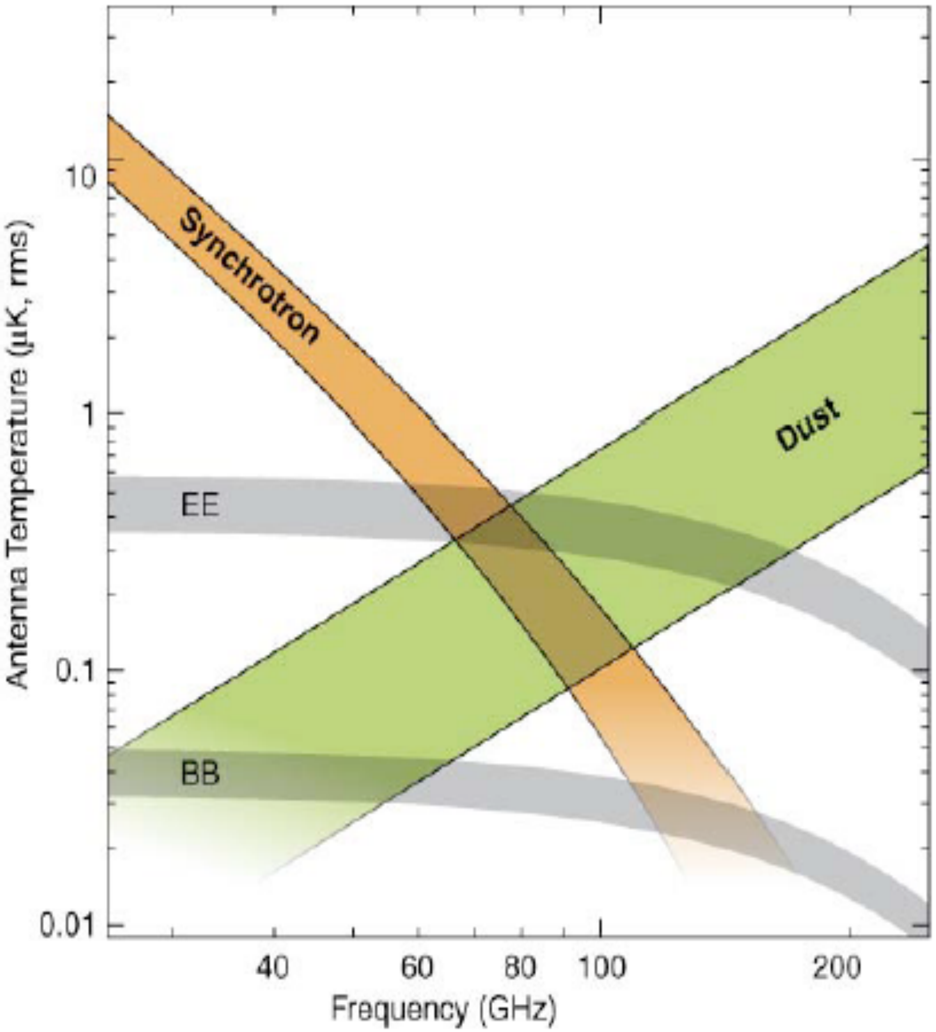
Primordial gravitational waves



Weiss report 05

CMB Foreground



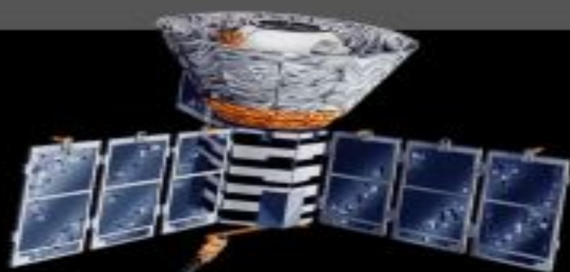


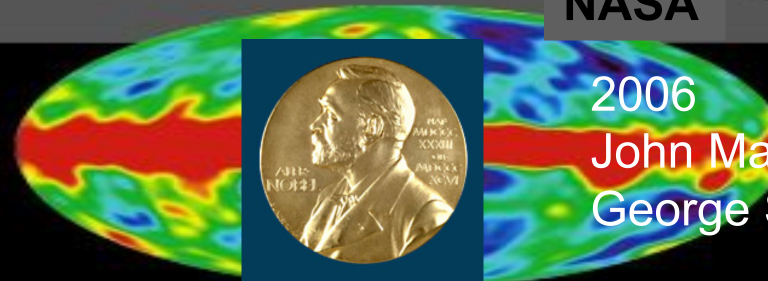
CMB Milestones

1965 — AT&T Bell — Penzias and Wilson

1978
Arno Penzias
Robert Wilson

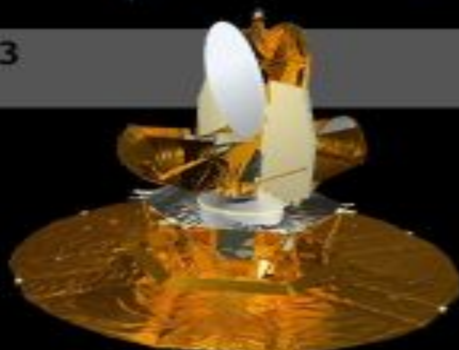
1992 — NASA — COBE

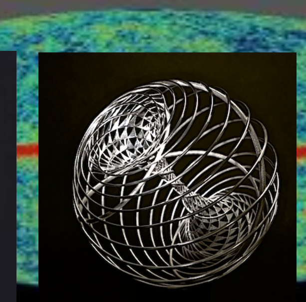




2006
John Mather
George Smoot

2003 — NASA — WMAP

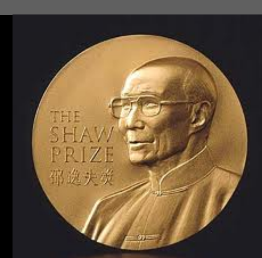


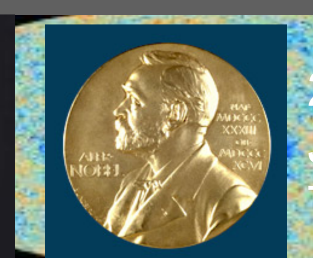


2010, 2018
Charles Bennett
Lyman Page
David Spergel

2013 — ESA — Planck

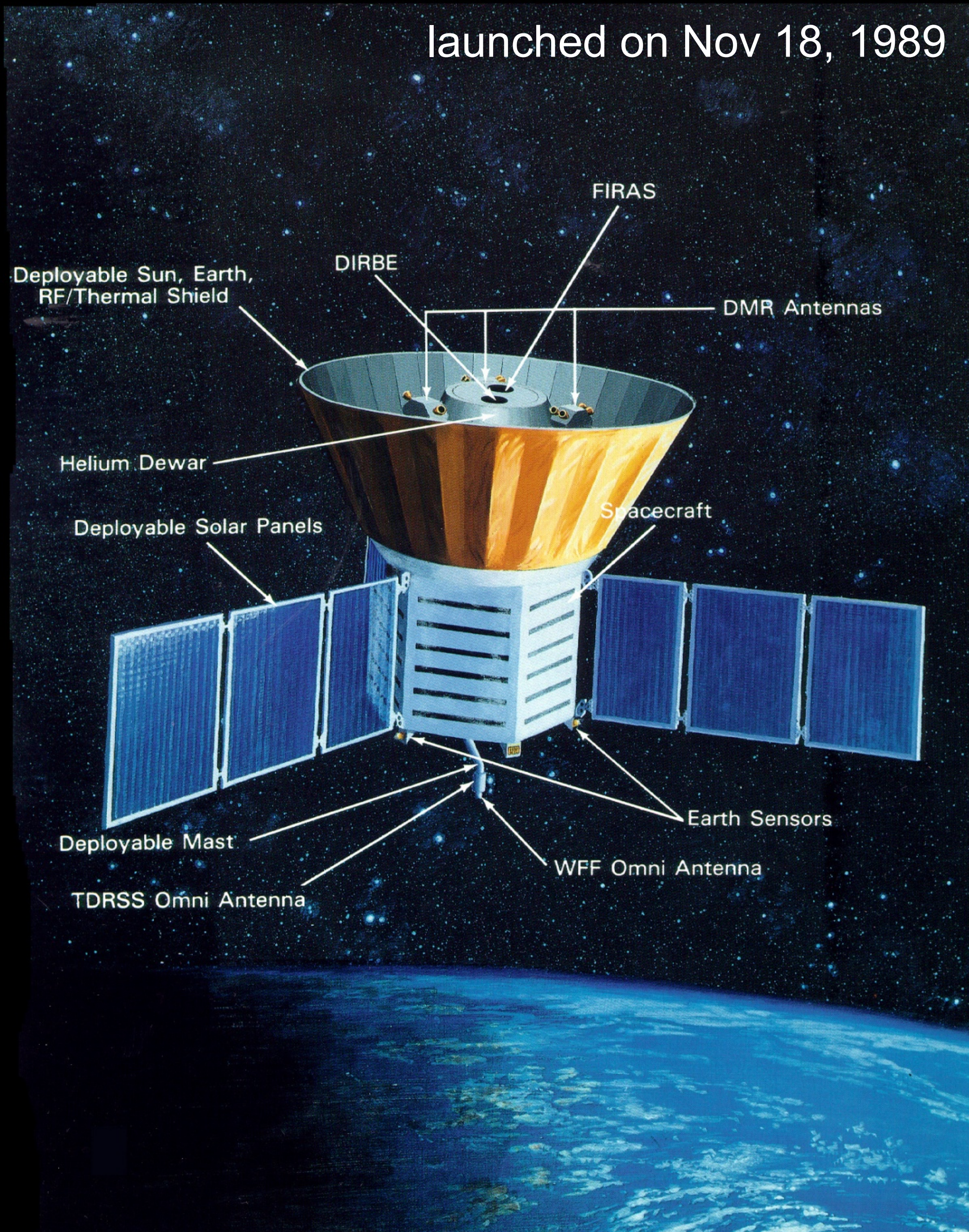
Plus many ground-based experiments

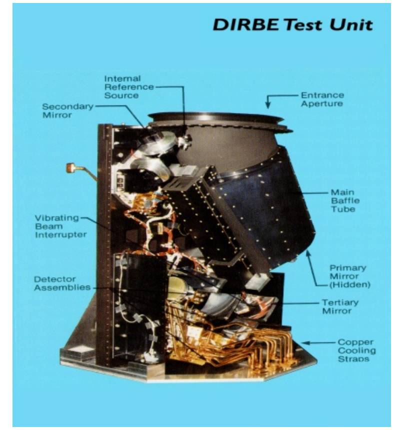




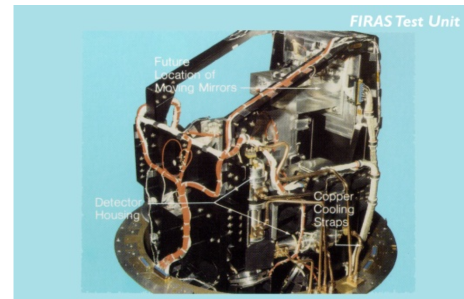
2004, 2019
James Peebles
Theoretical Cosmologist

The COBE Satellite

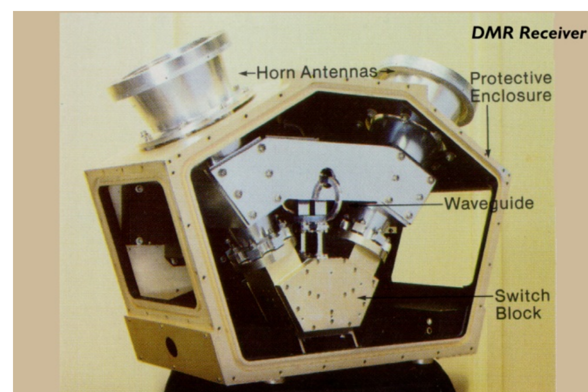




Diffuse InfraRed Background Experiment

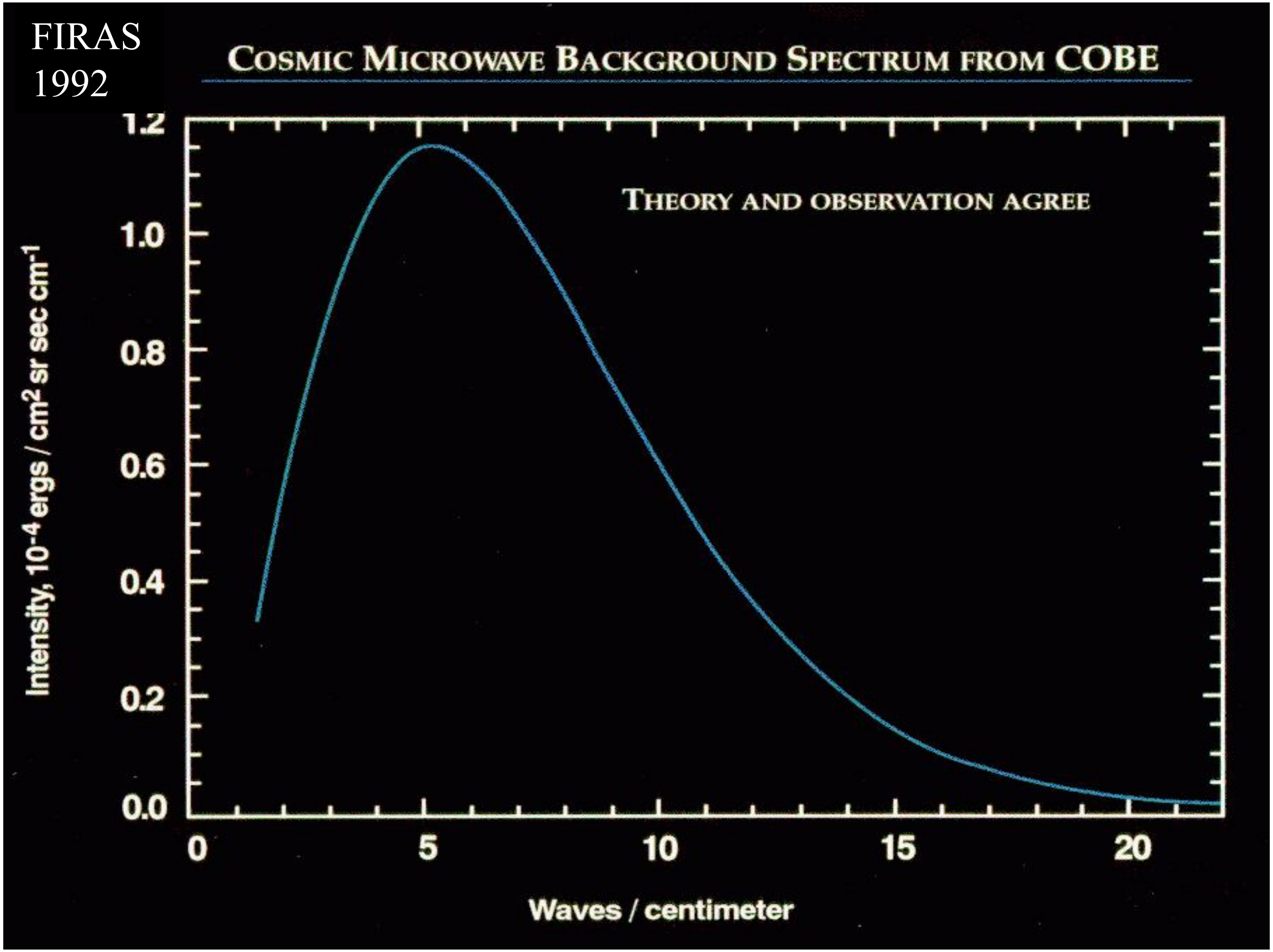


Far InfraRed Absolute Spectrophotometer

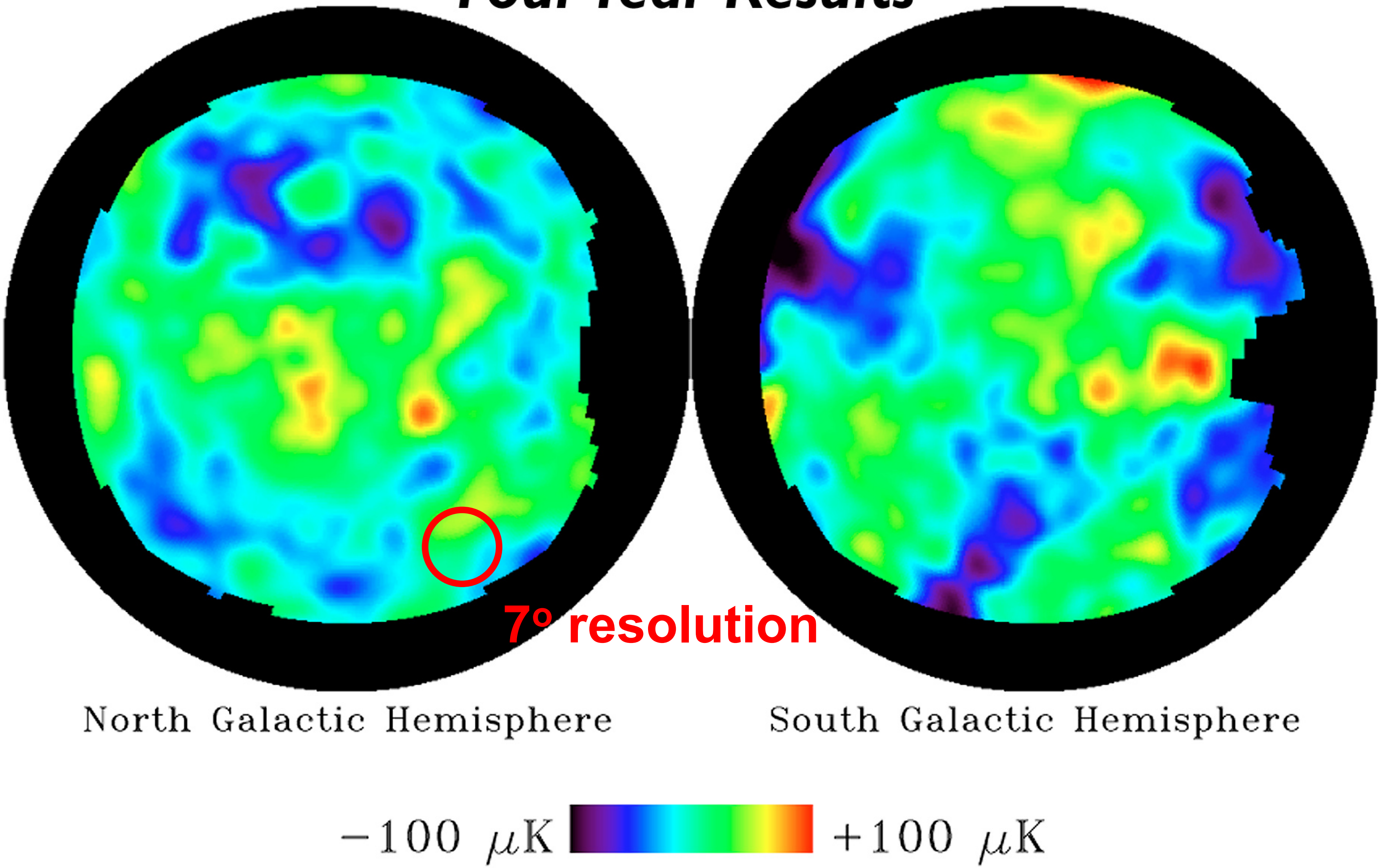


Differential Microwave Radiometer

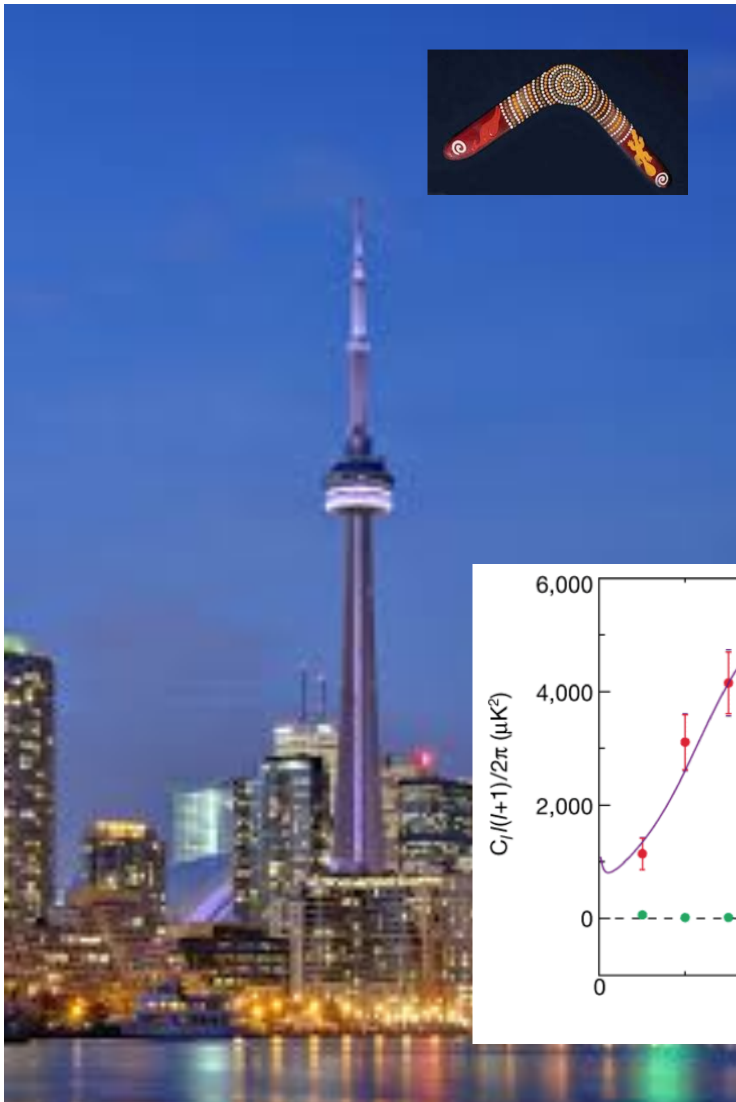
CMB Spectrum T=2.725 ± 0.002



COBE - DMR Map of CMB Anisotropy
Four Year Results

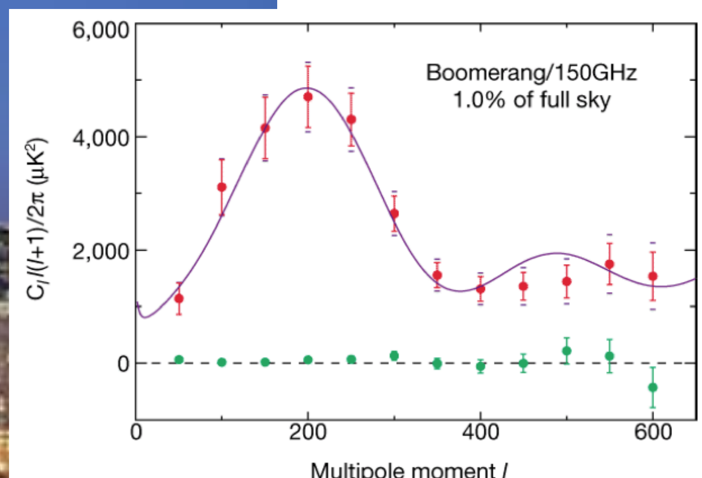


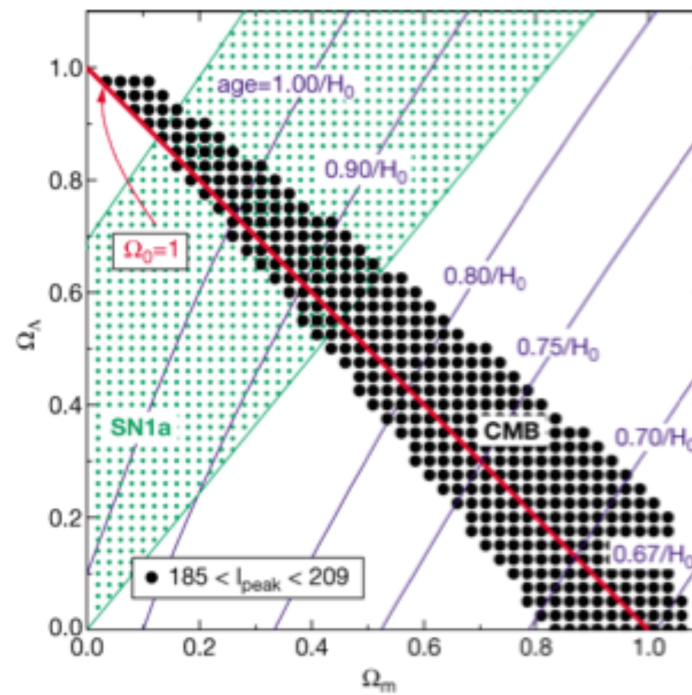
Location of first Doppler peak determining the curvature of the Universe (2000)



BOOMERANG
(pipeline headquarter@CITA)

MAXIMA
(headquarter@Berkeley
with Proty Wu)

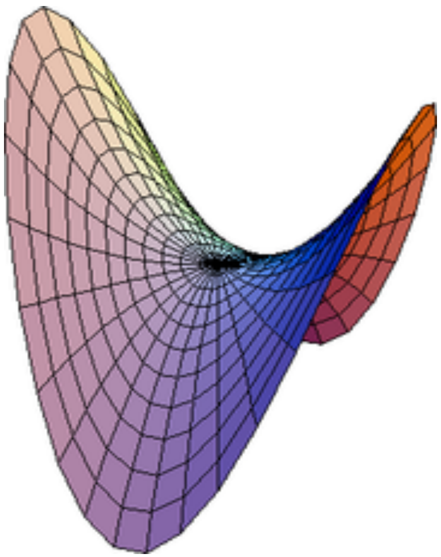


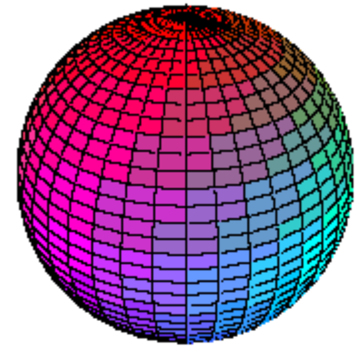


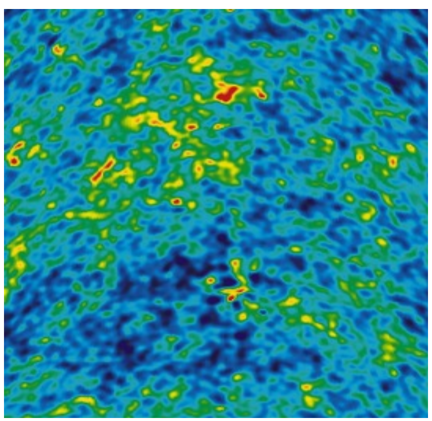
k=-1

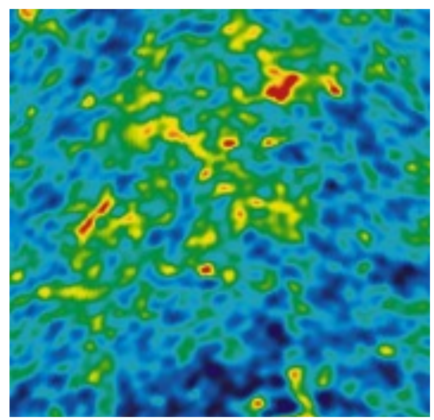
k=0

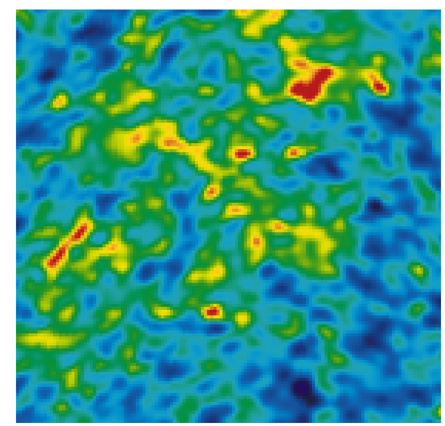
k=1







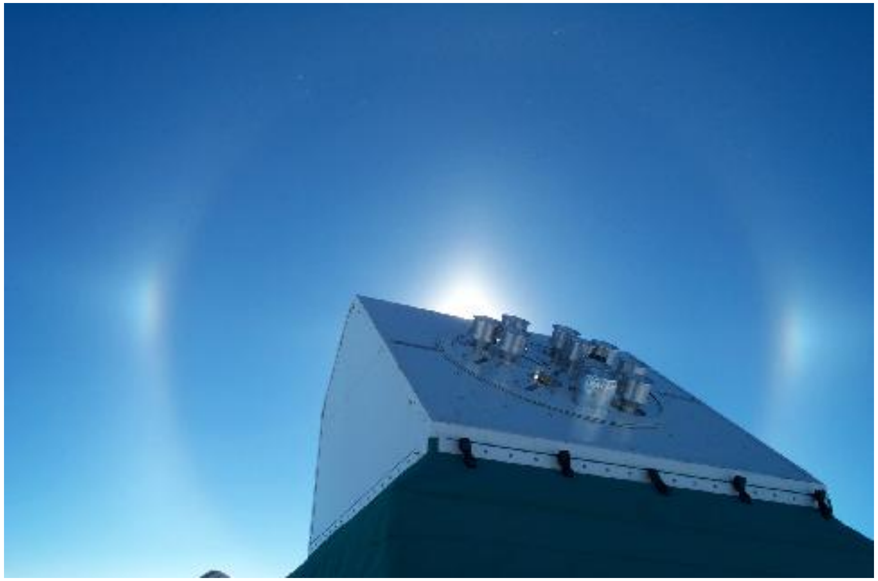




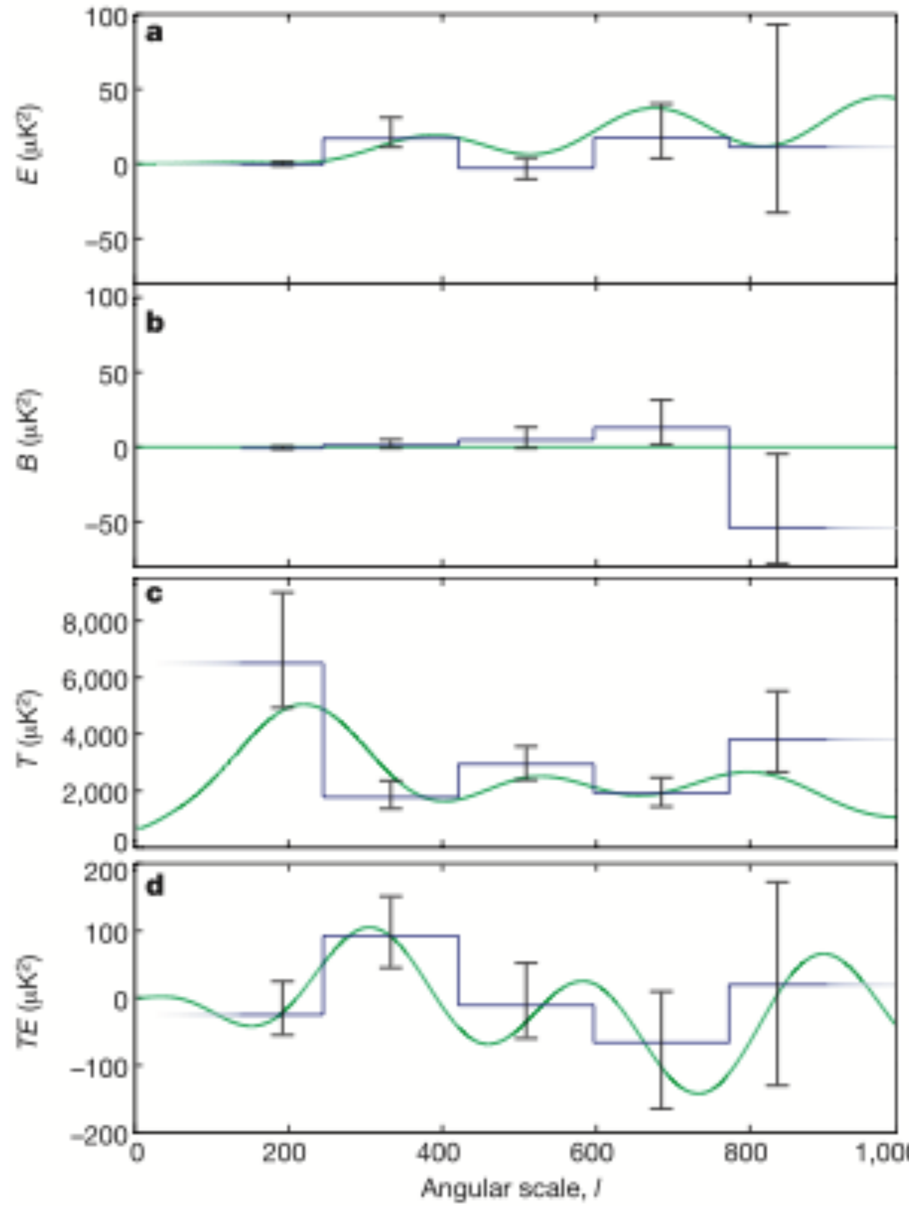
$$1 = \Omega_M + \Omega_{DE} - k / (R^2H^2)$$

$$\Omega_M + \Omega_{DE} = 1.099 ^{+0.100}_{-0.085}$$

First detection of polarization by DASI (2002)



DASI@South Pole
Interferometry



FIRST-YEAR *WILKINSON MICROWAVE ANISOTROPY PROBE* (*WMAP*)[1] OBSERVATIONS: TEMPERATURE-POLARIZATION CORRELATION

A. Kogut,[2] D. N. Spergel,[3] C. Barnes,[4] C. L. Bennett,[2] M. Halpern,[5] G. Hinshaw,[2] N. Jarosik,[4] M. Limon,[2,4,6] S. S. Meyer,[7] L. Page,[3] G. S. Tucker,[2,6,8] E. Wollack,[2] and E. L. Wright[9]

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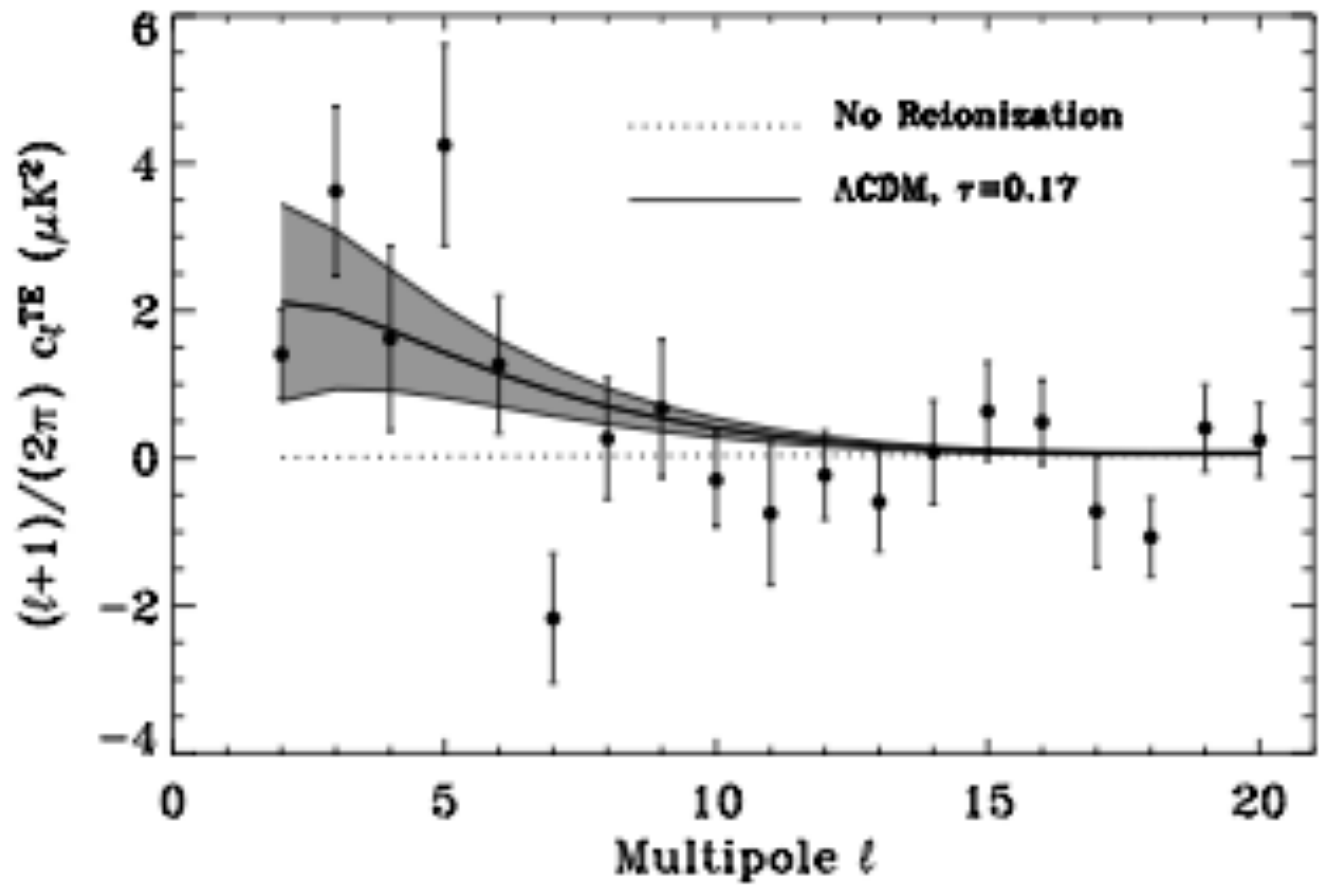
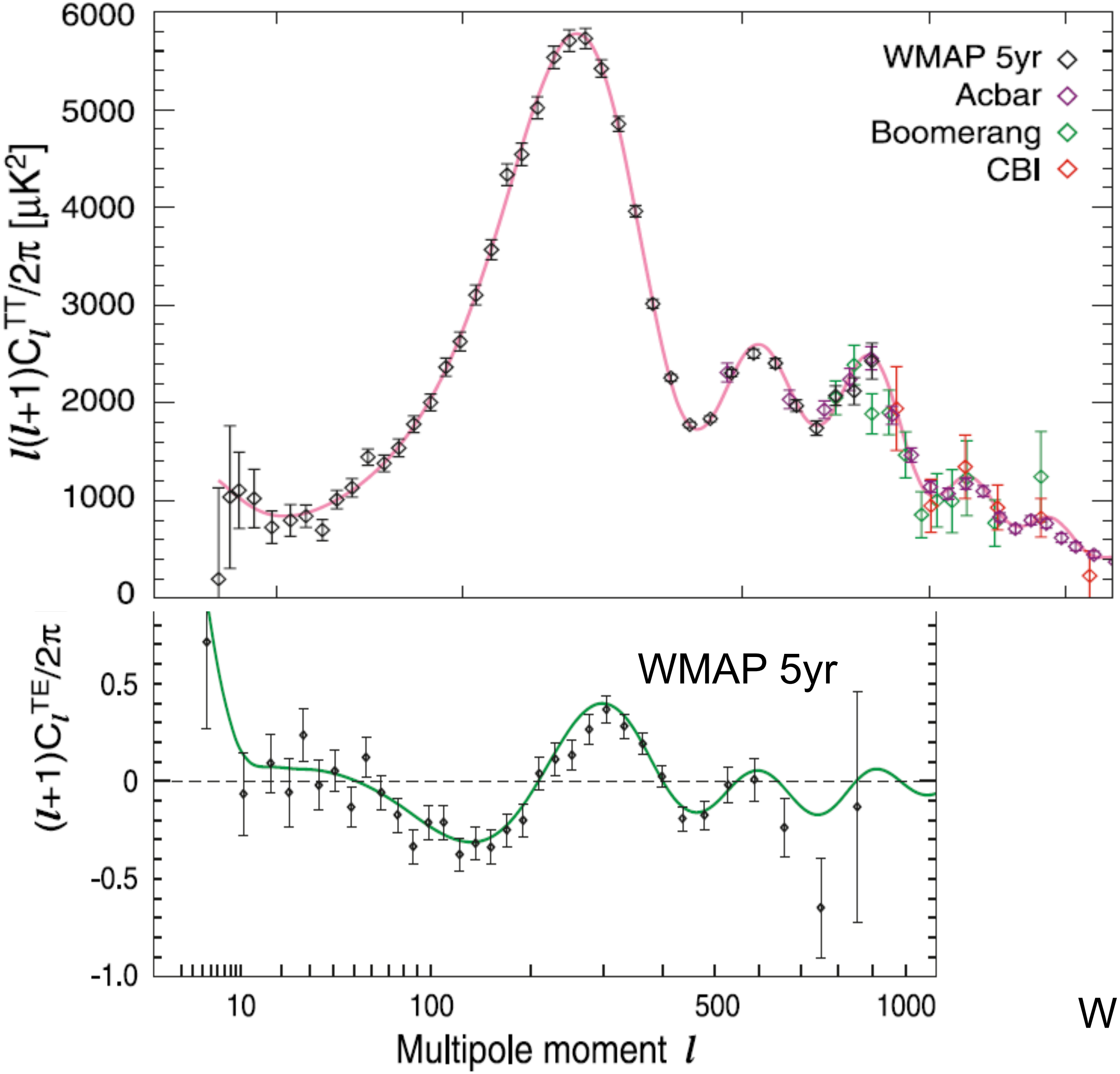


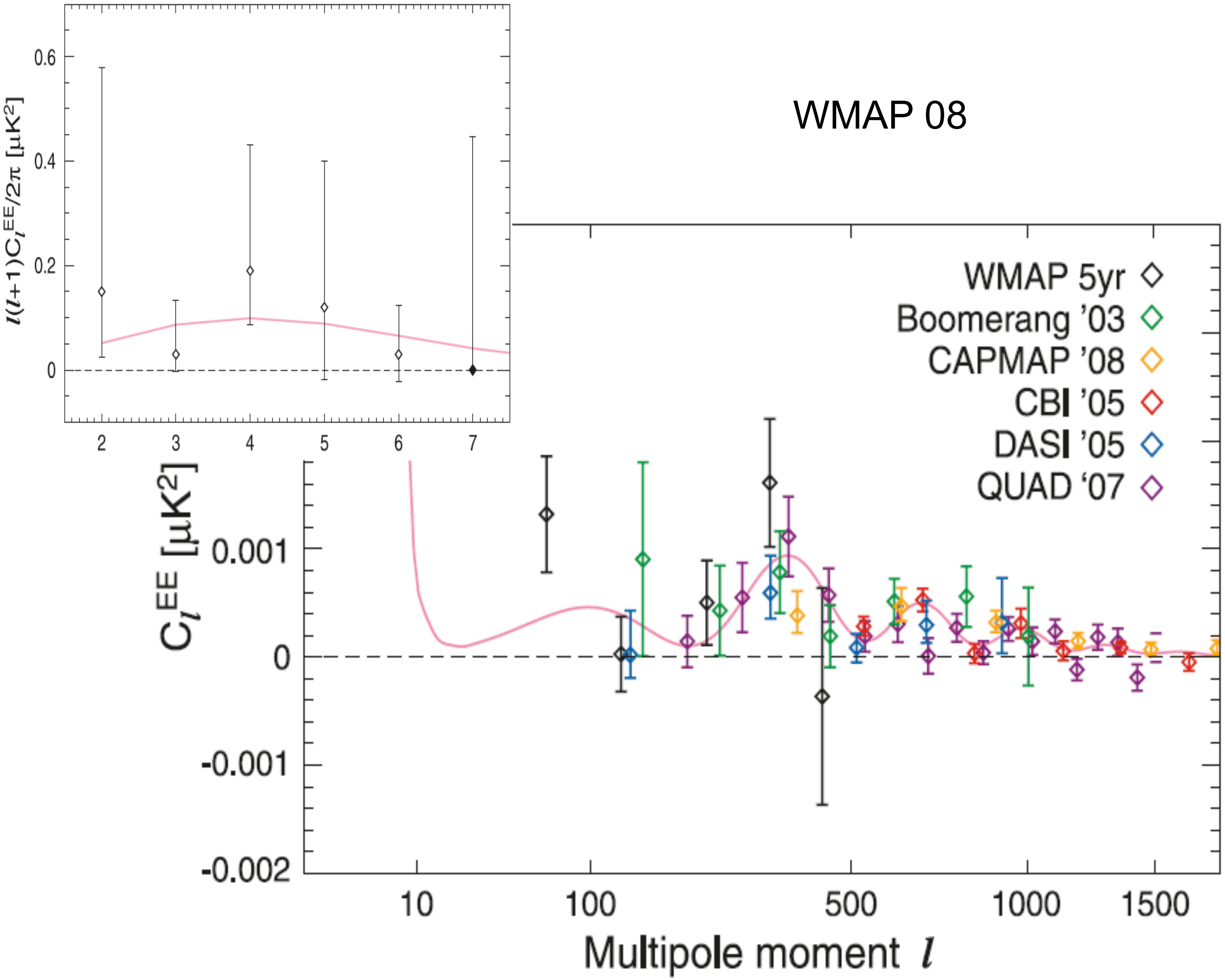
$Z_{reionization} \sim$ 20 (too big to be true?)



6000
5000
4000
3000
2000
1000
0
$l(l+1)C_l^{TT}/2\pi$ [μK²]
WMAP 5yr
Acbar
Boomerang
CBI
0.5
0
-0.5
-1.0
$(l+1)C_l^{TE}/2\pi$
WMAP 5yr
10
100
500
1000
Multipole moment l

WMAP 08

WMAP 08



WMAP 5yr
Boomerang '03
CAPMAP '08
CBI '05
DASI '05
QUAD '07
C_l^{EE} [μK^2]
Multipole moment l
$l(l+1)C_l^{EE}/2\pi$ [μK^2]
0.6
0.4
0.2
0
2
3
4
5
6
7
0.001
0
-0.001
-0.002
10
100
500
1000
1500

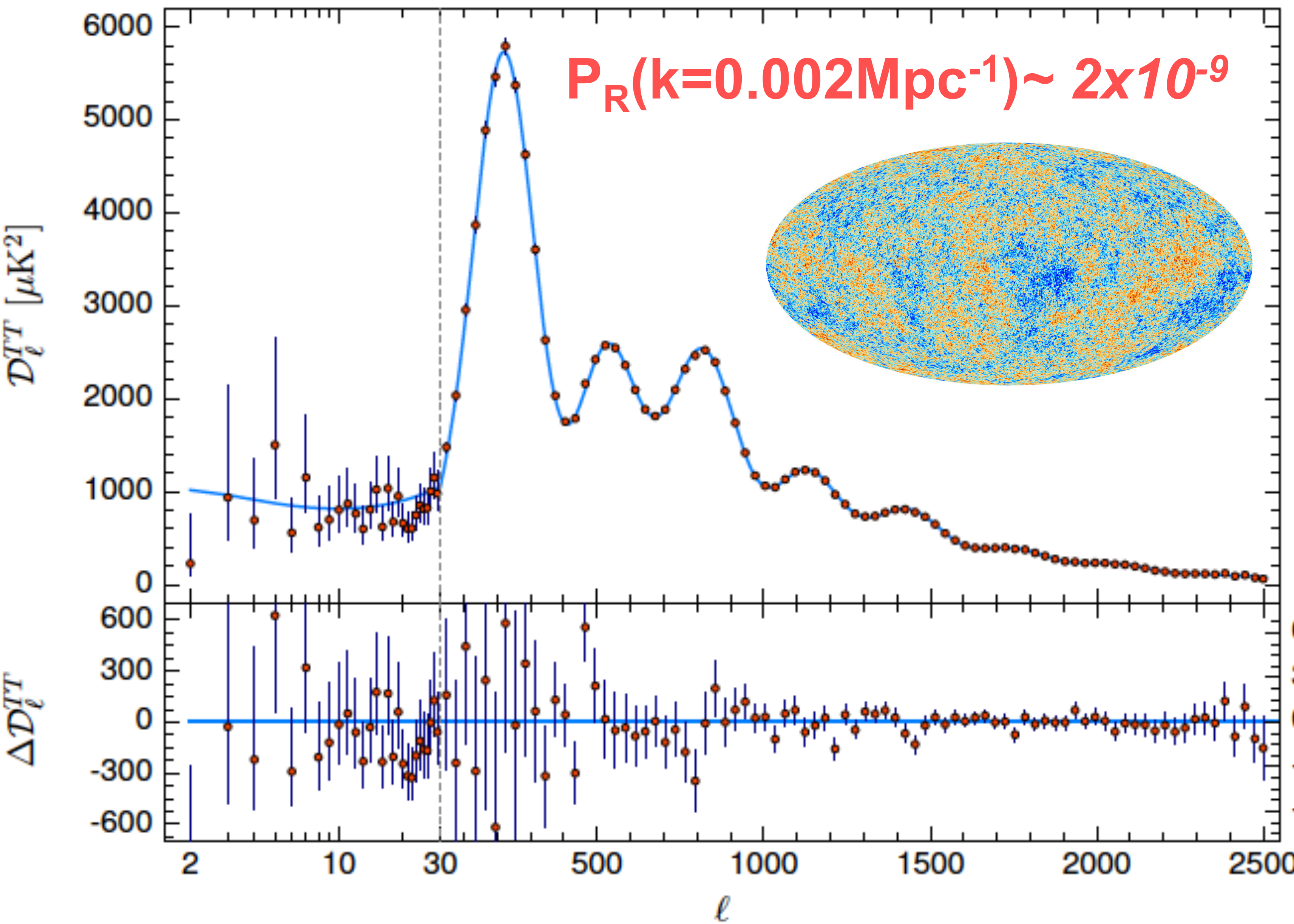
WMAP Cosmological Parameters

Model: lcdm+sz+lens

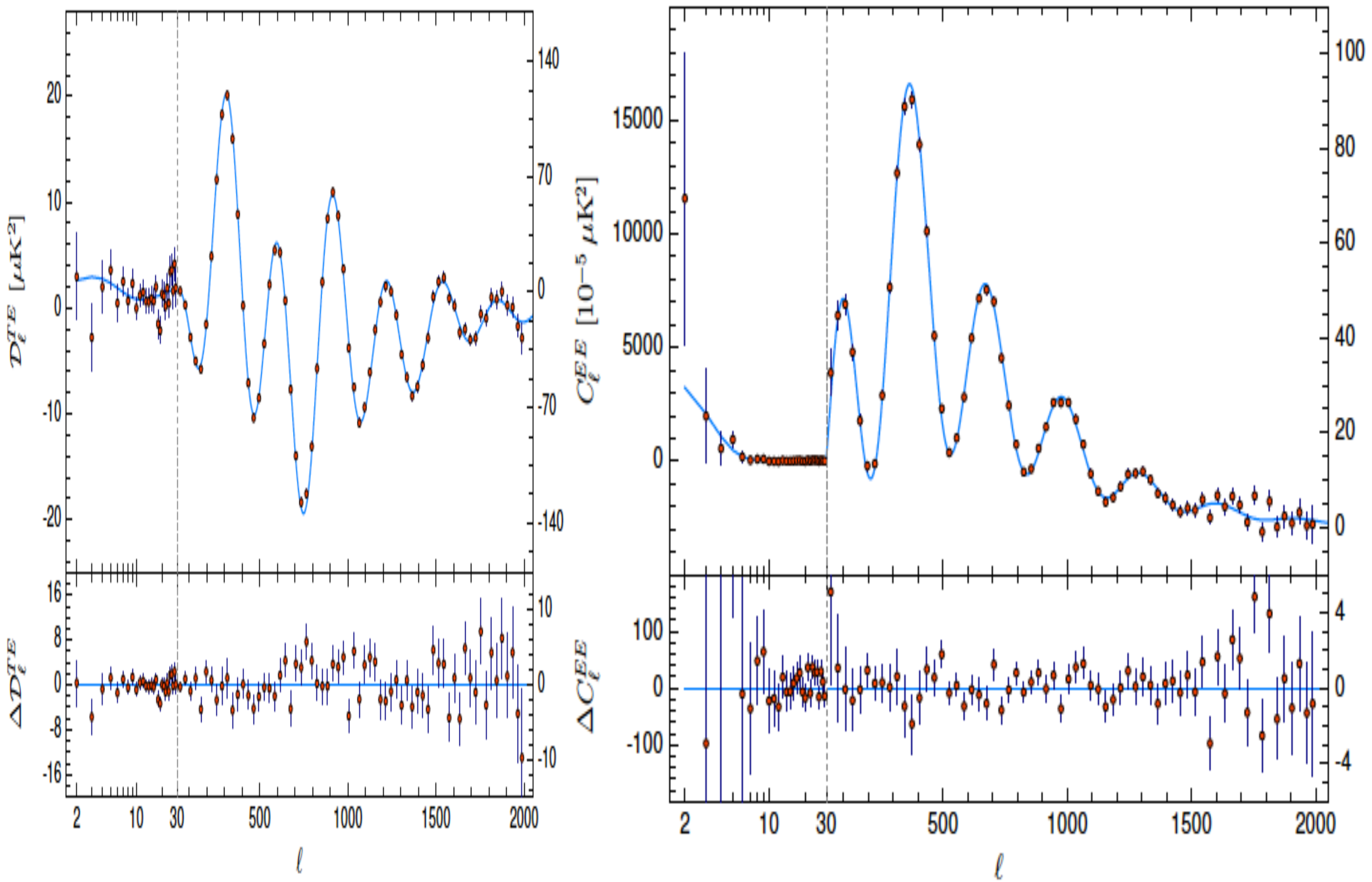
Data: wmap5+cmb

$10^2\Omega_b h^2$	2.250 ± 0.061	$1 - n_s$	0.040 ± 0.014
$1 - n_s$	$0.013 < 1 - n_s < 0.067$ (95% CL)	$A_{\rm BAO}(z = 0.35)$	0.451 ± 0.021
C_{220}	5753^{+42}_{-44}	$d_A(z_{\rm eq})$	14351^{+186}_{-181} Mpc
$d_A(z_*)$	14188^{+188}_{-183} Mpc	$\Delta^2_{\mathcal{R}}$	$(2.41 \pm 0.11) \times 10^{-9}$
h	$0.725^{+0.026}_{-0.027}$	H_0	$72.5^{+2.6}_{-2.7}$ km/s/Mpc
$k_{\rm eq}$	0.00952 ± 0.00045	$\ell_{\rm eq}$	135.0 ± 4.7
ℓ_*	$302.14^{+0.84}_{-0.83}$	n_s	0.960 ± 0.014
Ω_b	$0.0430^{+0.0028}_{-0.0029}$	$\Omega_b h^2$	0.02250 ± 0.00061
Ω_c	$0.207^{+0.025}_{-0.026}$	$\Omega_c h^2$	$0.1079^{+0.0061}_{-0.0060}$
Ω_Λ	$0.750^{+0.029}_{-0.028}$	Ω_m	$0.250^{+0.028}_{-0.029}$
$\Omega_m h^2$	0.1304 ± 0.0061	$r_{\rm hor}(z_{\rm dec})$	287.2 ± 3.4 Mpc
$r_s(z_d)$	$154.2^{+2.0}_{-1.9}$ Mpc	$r_s(z_d)/D_v(z = 0.2)$	$0.1969^{+0.0079}_{-0.0078}$
$r_s(z_d)/D_v(z = 0.35)$	0.1178 ± 0.0042	$r_s(z_*)$	$147.5^{+1.8}_{-1.7}$ Mpc
R	1.708 ± 0.020	σ_8	0.783 ± 0.035
$A_{\rm SZ}$	$0.66^{+0.57}_{-0.66}$	t_0	$13.70^{+0.14}_{-0.13}$ Gyr
τ	$0.086^{+0.017}_{-0.016}$	θ_*	0.010398 ± 0.000029
θ_*	$0.5958^{+0.0016}_{-0.0017}$ $^\circ$	t_*	382028^{+5752}_{-5791} yr
$z_{\rm dec}$	1087.9 ± 1.2	z_d	1019.8 ± 1.5
$z_{\rm eq}$	3122 ± 147	$z_{\rm reion}$	10.9 ± 1.4
z_*	1090.62 ± 0.95		

Planck CMB Anisotropy $D^{TT}_l = l(l+1)\, C^T_l$ 2018



Planck CMB Polarization Power Spectra 2018



Best-fit 6-parameter
ΛCDM model 2018

Density perturbation (scalar)

Spectral index $\mathcal{P}_{\mathcal{R}}(k) = A_s \left(\frac{k}{k_0}\right)^{n_s-1}$

k_0=0.05Mpc^{-1}

Parameter	TT+lowE 68% limits	TE+lowE 68% limits	EE+lowE 68% limits	TT,TE,EE+lowE 68% limits	TT,TE,EE+lowE+lensing 68% limits	TT,TE,EE+lowE+lensing+BAO 68% limits
$\Omega_b h^2$	0.02212 ± 0.00022	0.02249 ± 0.00025	0.0240 ± 0.0012	0.02236 ± 0.00015	0.02237 ± 0.00015	0.02242 ± 0.00014
$\Omega_c h^2$	0.1206 ± 0.0021	0.1177 ± 0.0020	0.1158 ± 0.0046	0.1202 ± 0.0014	0.1200 ± 0.0012	0.11933 ± 0.00091
$100\theta_{MC}$	1.04077 ± 0.00047	1.04139 ± 0.00049	1.03999 ± 0.00089	1.04090 ± 0.00031	1.04092 ± 0.00031	1.04101 ± 0.00029
τ	0.0522 ± 0.0080	0.0496 ± 0.0085	0.0527 ± 0.0090	$0.0544^{+0.0070}_{-0.0081}$	0.0544 ± 0.0073	0.0561 ± 0.0071
$\ln(10^{10} A_s)$	3.040 ± 0.016	$3.018^{+0.020}_{-0.018}$	3.052 ± 0.022	3.045 ± 0.016	3.044 ± 0.014	3.047 ± 0.014
n_s	0.9626 ± 0.0057	0.967 ± 0.011	0.980 ± 0.015	0.9649 ± 0.0044	0.9649 ± 0.0042	0.9665 ± 0.0038
z_{re}	7.50 ± 0.82	$7.11^{+0.91}_{-0.75}$	$7.10^{+0.87}_{-0.73}$	7.68 ± 0.79	7.67 ± 0.73	7.82 ± 0.71

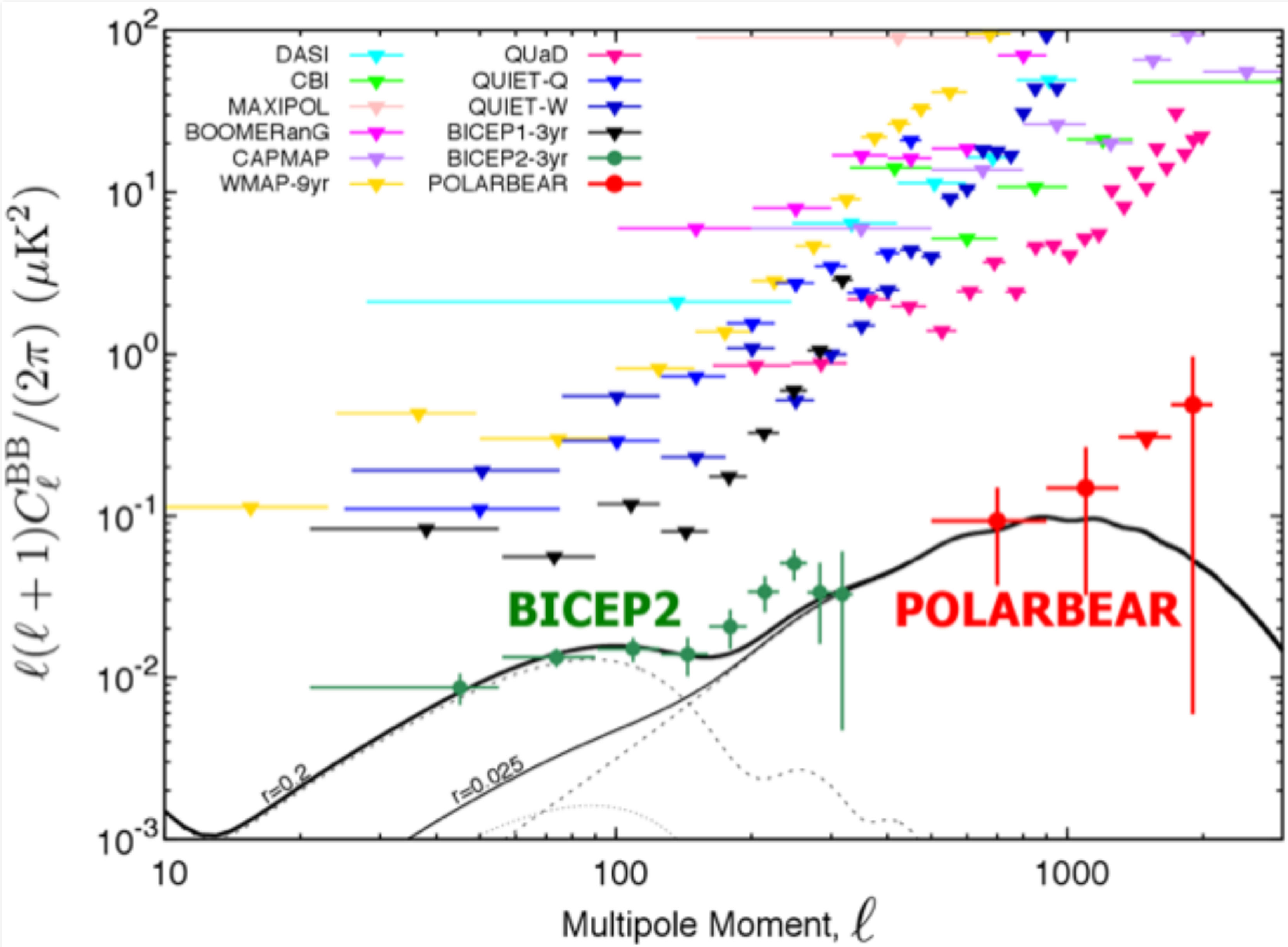
ΛCDM model + 1-parameter extension

Spectral index $\mathcal{P}_{\mathcal{R}}(k) = A_s \left(\frac{k}{k_0}\right)^{n_s - 1}$

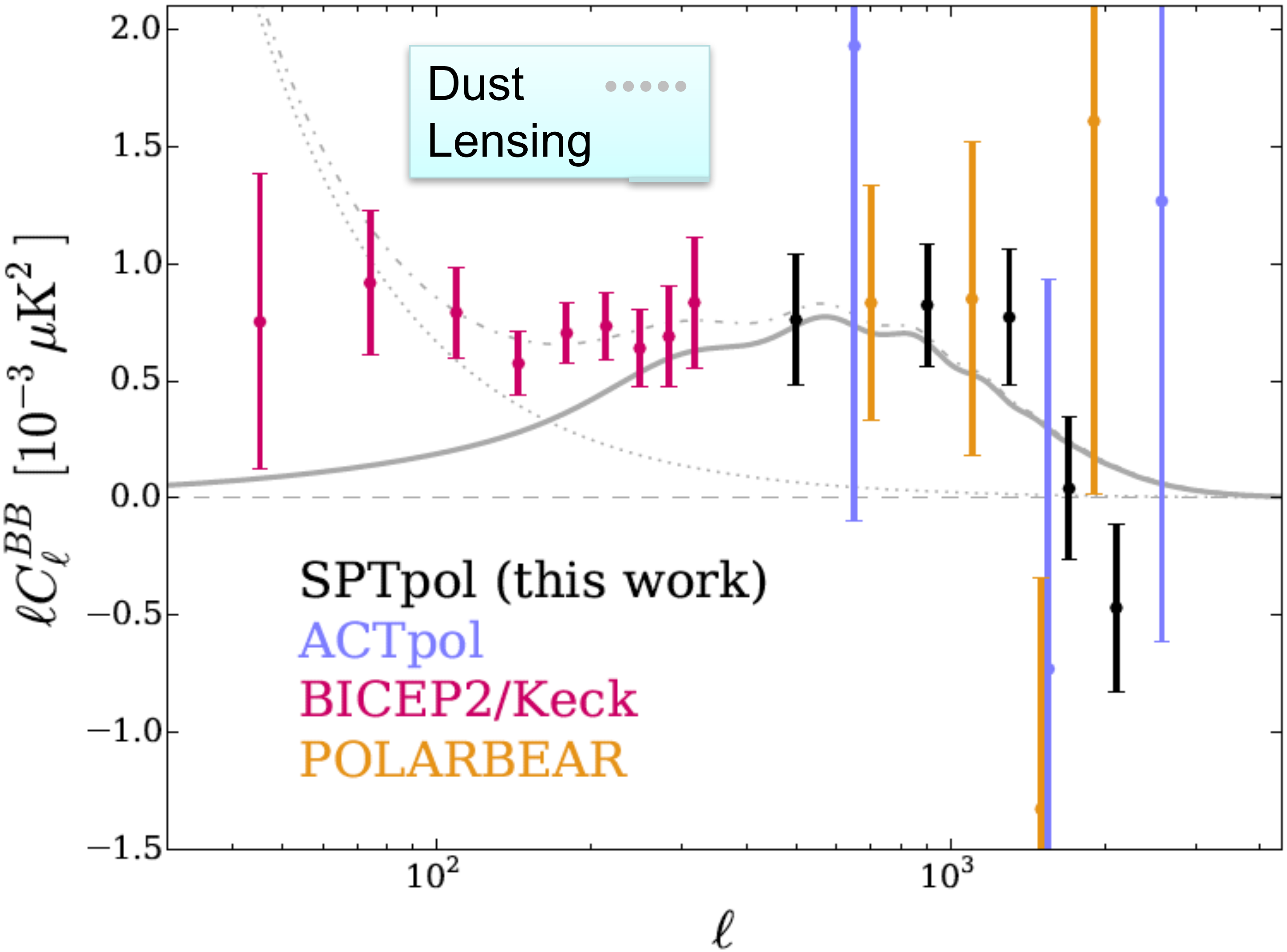
r = Tensor/Scalar
= $P_h(k)/P_R(k)$ at k=0.002 Mpc^{-1}

Parameter	TT+lowE	TT, TE, EE+lowE	TT, TE, EE+lowE+lensing	TT, TE, EE+lowE+lensing+BAO
Ω_K	$-0.056^{+0.044}_{-0.050}$	$-0.044^{+0.033}_{-0.034}$	$-0.011^{+0.013}_{-0.012}$	$0.0007^{+0.0037}_{-0.0037}$
Σm_ν [eV]	< 0.537	< 0.257	< 0.241	< 0.120
$N_{\rm eff}$	$3.00^{+0.57}_{-0.53}$	$2.92^{+0.36}_{-0.37}$	$2.89^{+0.36}_{-0.38}$	$2.99^{+0.34}_{-0.33}$
$Y_{\rm P}$	$0.246^{+0.039}_{-0.041}$	$0.240^{+0.024}_{-0.025}$	$0.239^{+0.024}_{-0.025}$	$0.242^{+0.023}_{-0.024}$
$dn_s/d\ln k$	$-0.004^{+0.015}_{-0.015}$	$-0.006^{+0.013}_{-0.013}$	$-0.005^{+0.013}_{-0.013}$	$-0.004^{+0.013}_{-0.013}$
$r_{0.002}$	< 0.102	< 0.107	< 0.101	< 0.106
w_0	$-1.56^{+0.60}_{-0.48}$	$-1.58^{+0.52}_{-0.41}$	$-1.57^{+0.50}_{-0.40}$	$-1.04^{+0.10}_{-0.10}$

POLARBEAR+BICEP2 B-mode Detection



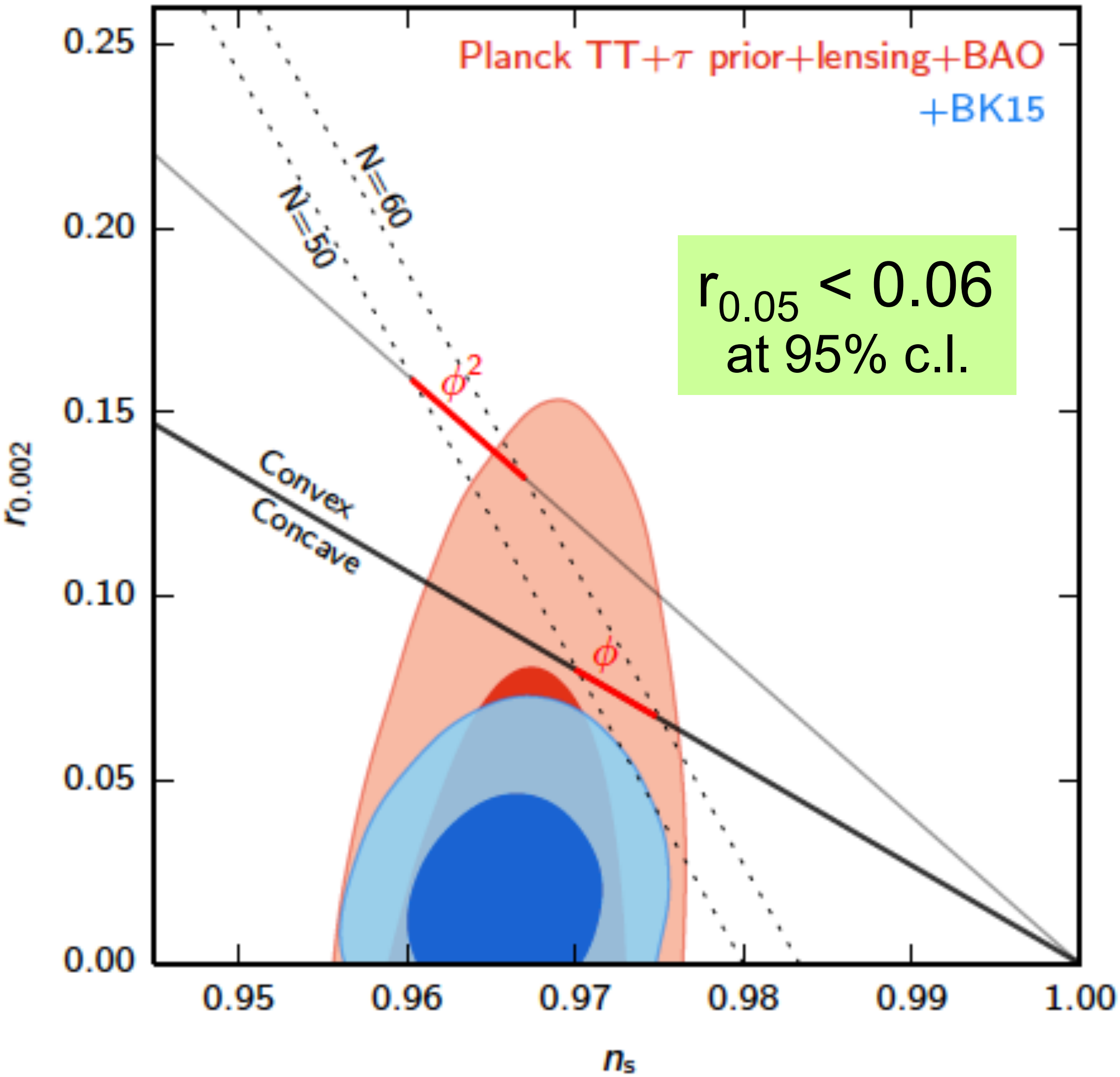
Current B-mode measurements



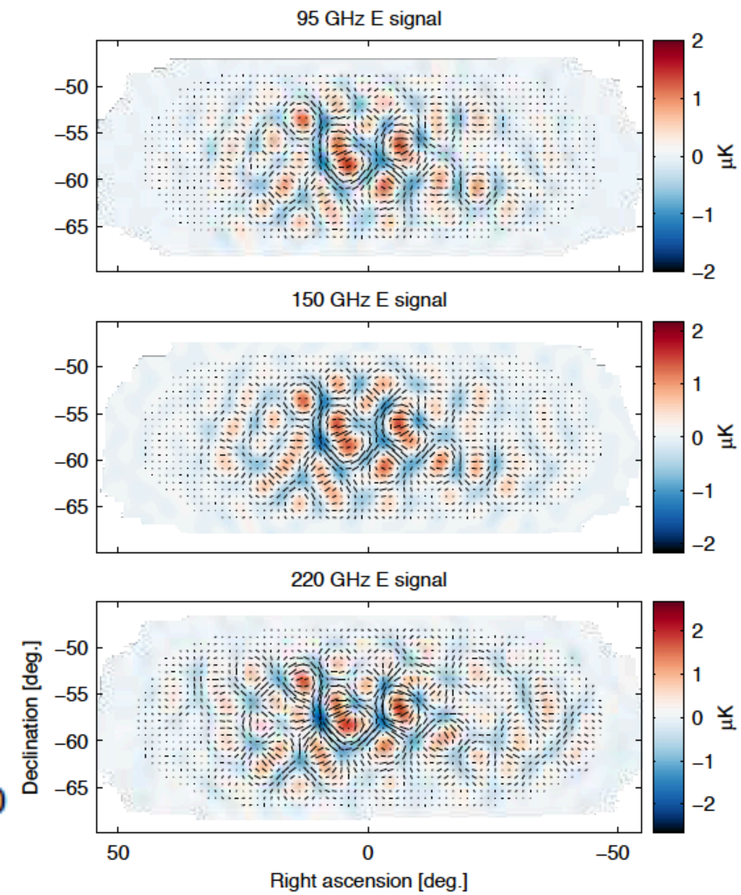
Galactic polarized dust emission
B-mode power spectrum at 150 GHz

$$\frac{l(l+1)}{2\pi} C_{l\,\mathrm{dust}}^{BB} = 0.0118 \left(\frac{l}{80}\right)^{-0.42} \mu K^2.$$

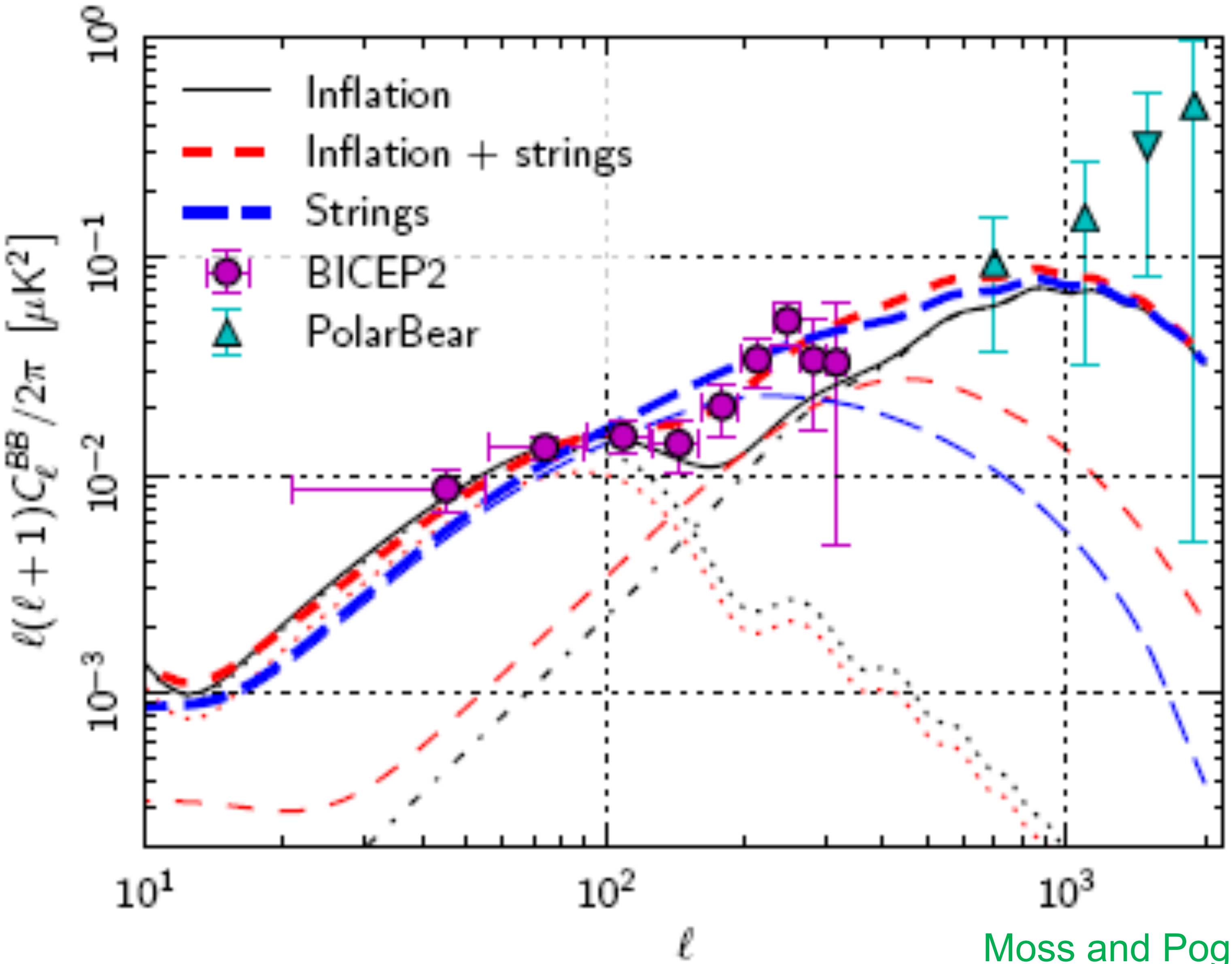
Joint Planck+BICEP2/Keck Array constraint on r by removal of dust contamination (2018)



Keck Array 2015
E-polarization data



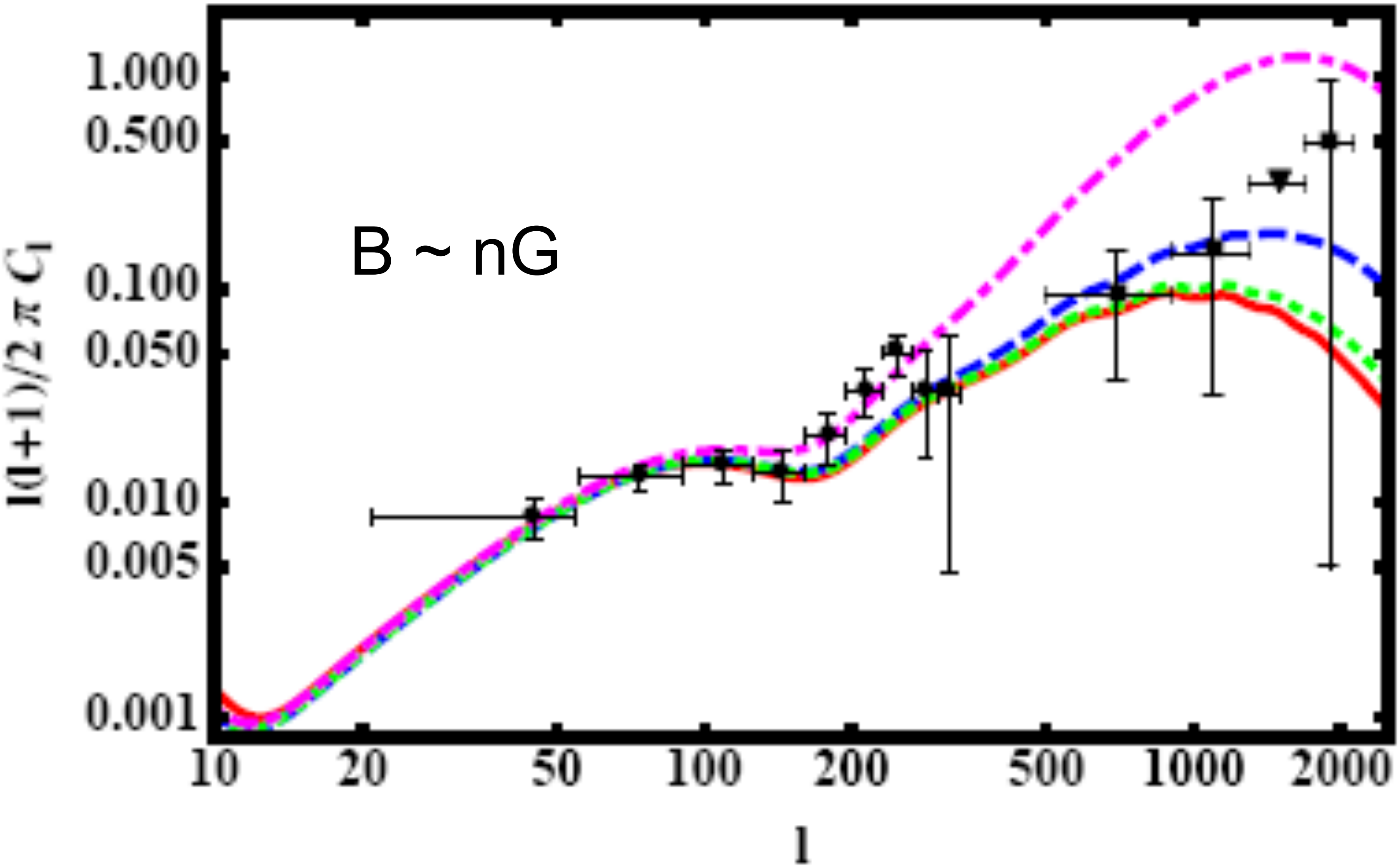
Alternative sources?



Moss and Pogosian 14

Can primordial magnetic fields be the origin of the BICEP2 data?

Camille Bonvin[1], Ruth Durrer[2] and Roy Maartens[3,4]



Search for Cosmic Parity Violation

- T. D. Lee and C. N. Yang, C. S. Wu

  Parity symmetry is broken in sub -atomic world - weak interaction is left-handed

- Is there any parity violation in the cosmos on the sky?

  CMB polarization, polarized radio galaxies,…

- BICEP to AliCPT@China

CMB power spectra

- <TT>, <EE>, <BB>, and <TE> correlations exist in standard ΛCDM model
- Since B is odd under parity symmetry, we expect that <TB> = <EB> = 0
- Any trace of <TB> ≠ <EB> ≠ 0 may indicate parity violation

DE/DM Coupling to Electromagnetism

$$\mathcal{L}_N = -\frac{1}{4}\sqrt{-g}B_{F\tilde{F}}(\phi)F_{\mu\nu}\tilde{F}^{\mu\nu}\,, \quad \text{where} \quad \phi \equiv \frac{\Phi}{M}\,, \qquad M = M_{Pl}/\sqrt{8\pi}$$

This leads to photon dispersion relation

Carroll, Field, Jackiw 90

$$n_\pm = \varepsilon \mp \frac{1}{2}\frac{\partial B_{F\tilde{F}}}{\partial\phi}\left(\frac{\partial\phi}{\partial\eta} + \vec{\nabla}\phi\cdot\hat{n}\right)$$

$(\varepsilon, \vec{n})$ is the photon four-momentum

$\pm$ left/right handed η conformal time

vacuum birefringence

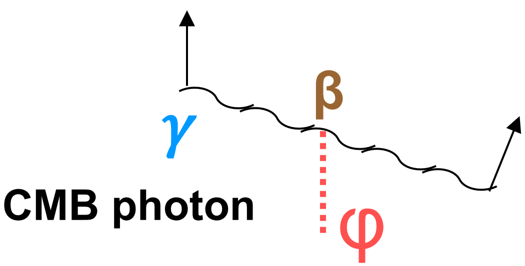
then, a rotational speed of polarization plane

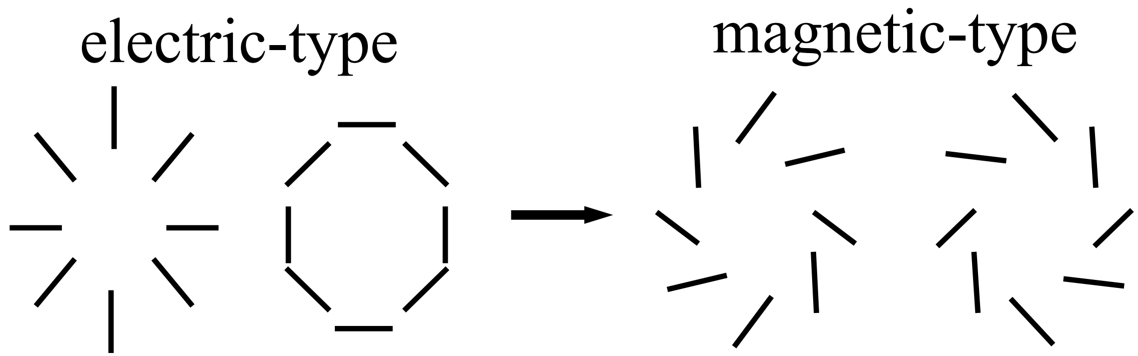
$$\omega = \frac{1}{2}(n_+ - n_-) = -\frac{1}{2}\frac{\partial B_{F\tilde{F}}}{\partial\phi}\left(\frac{\partial\phi}{\partial\eta} + \vec{\nabla}\phi\cdot\hat{n}\right)$$

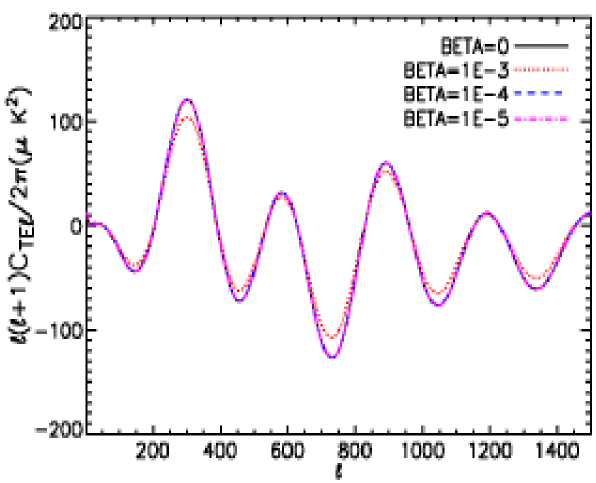
If B=βφ, cooling of horizontal branch stars would imply $\beta < 10^7$

DE mean field induced vacuum birefringence – cosmic rotation of CMB polarization

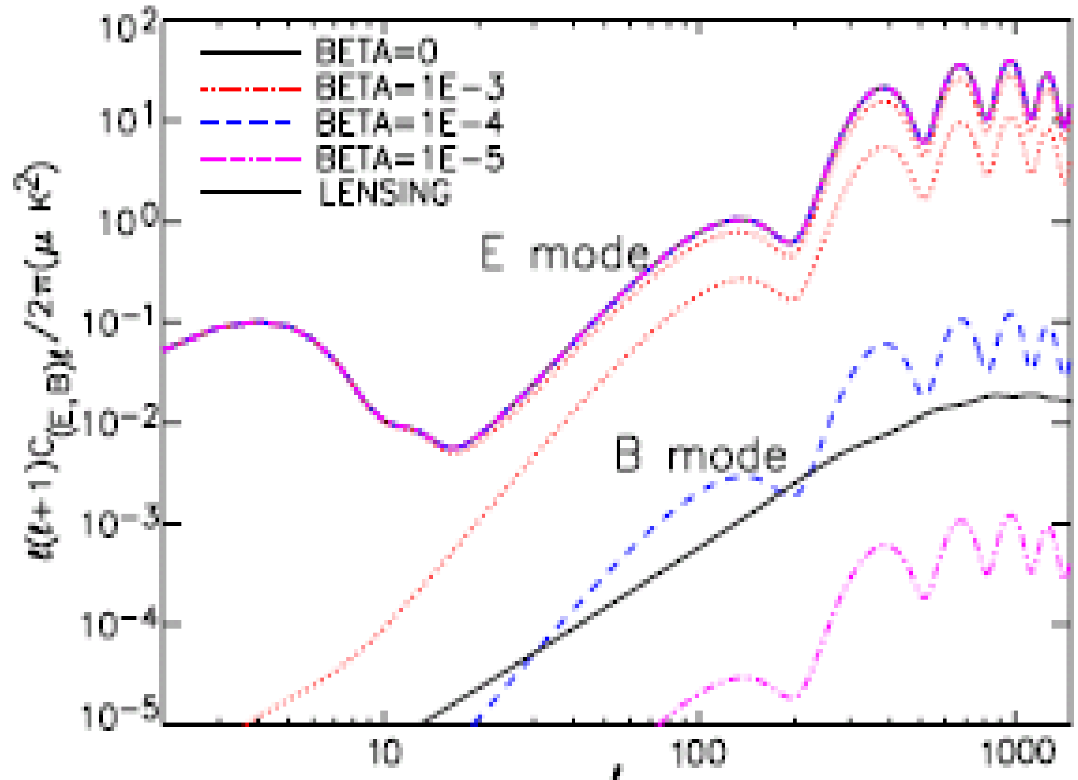
Zhang et al 06
Liu,Lee,Ng 06



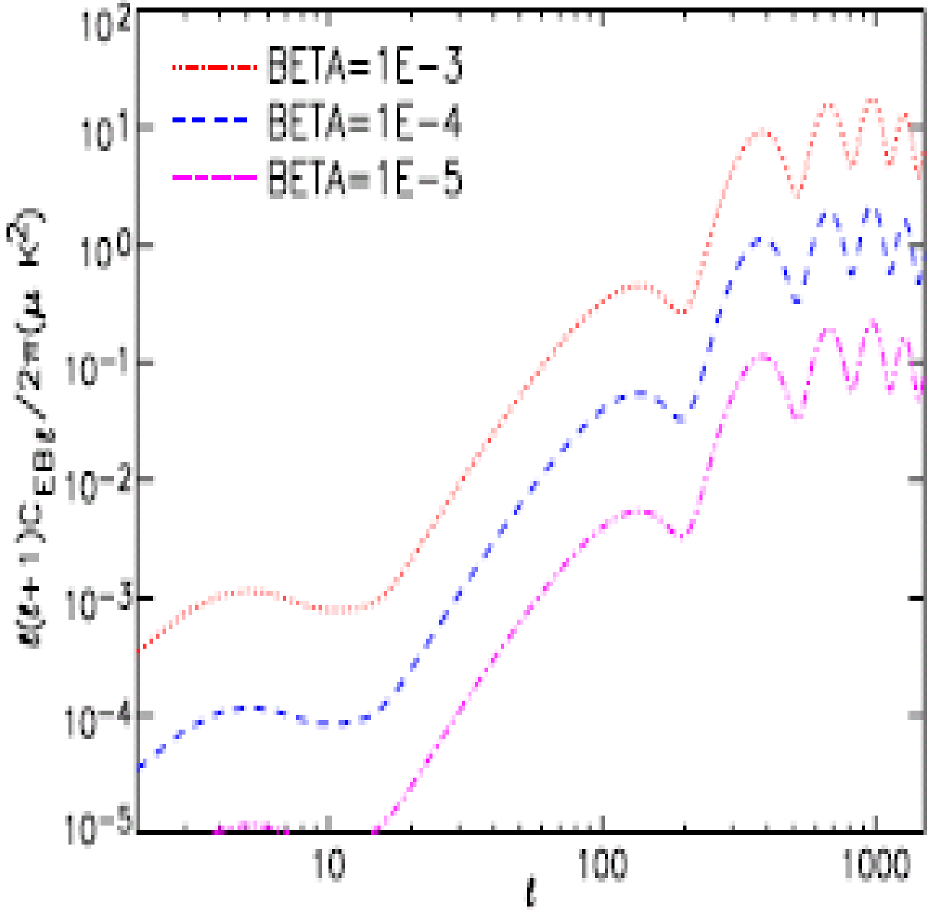


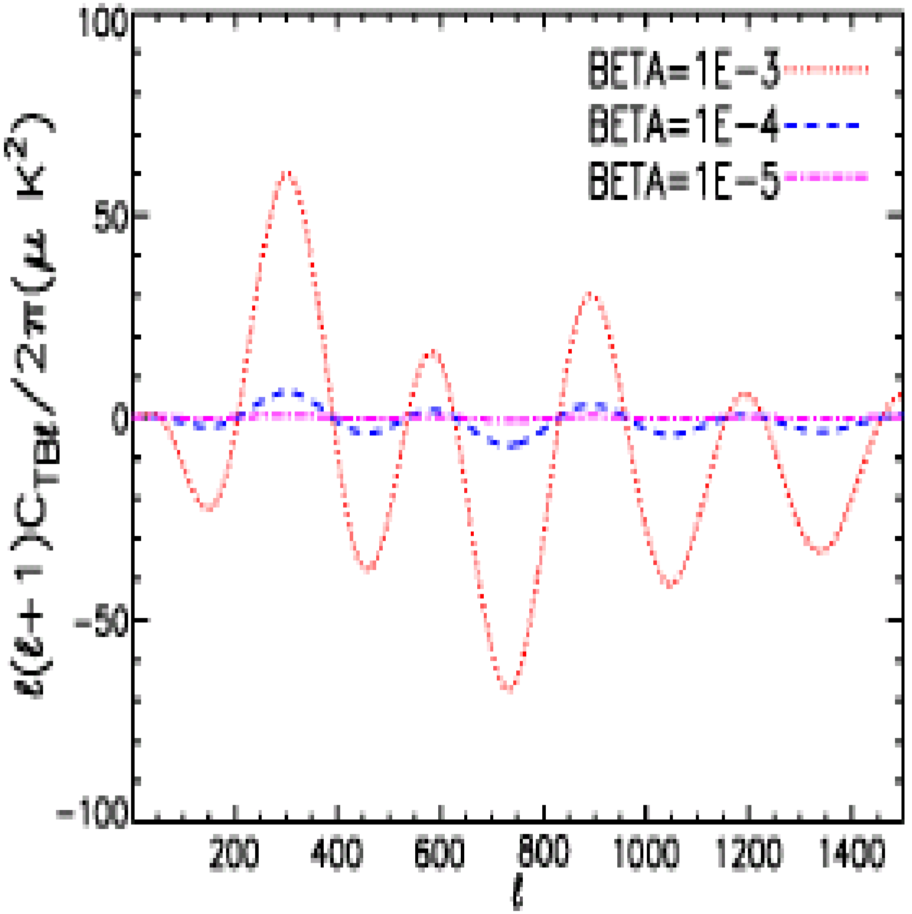


TE spectrum



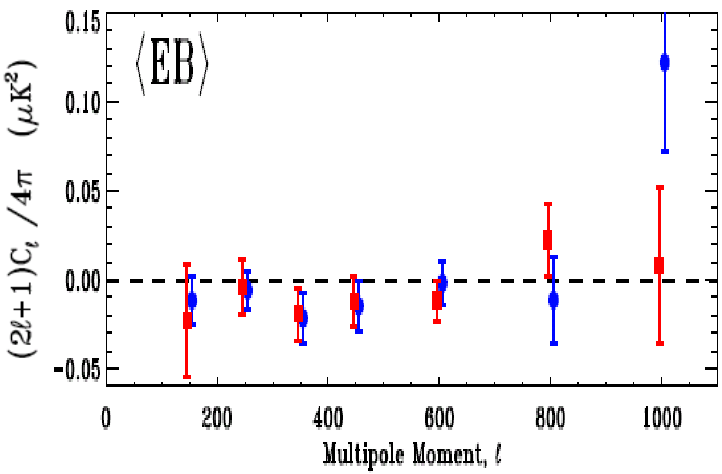
Parity violating EB,TB cross power spectra – cosmic parity violation

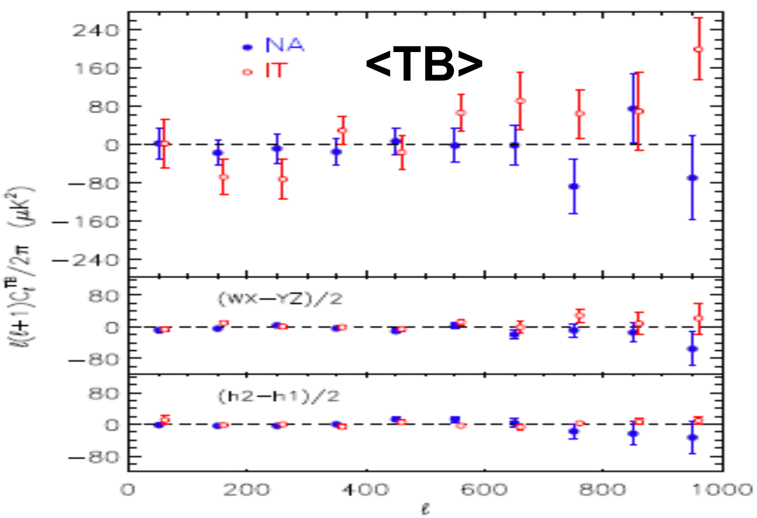




Constraining β by CMB polarization data

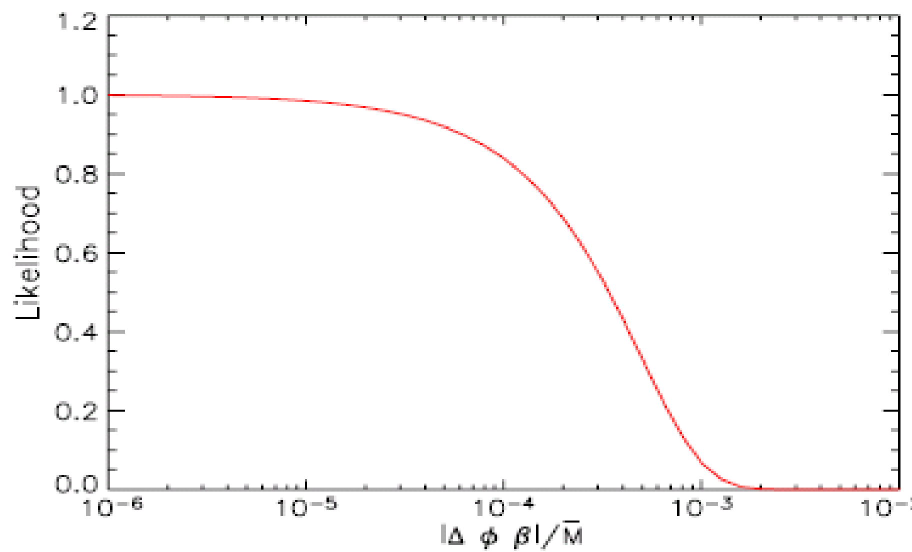
2003 Flight of BOOMERANG





Likelihood analysis assuming reasonable quintessence models

$V(\phi) = V_0 \exp(\lambda\phi^2/2\bar{M}^2)$ $\quad V(\phi) = V_0 \cosh(\lambda\phi/\bar{M})$



$|\beta_{FF}\Delta\phi|/\bar{M} < 8.32 \times 10^{-4}$ at 95% **c.l.**

where $\Delta\phi$ is the total change of ϕ until today.

$\bar{M}$ reduced Planck mass

More stringent limits from…WMAP…to Planck

Including Dark Energy Perturbation

Dark energy perturbation $\phi(\eta,\vec{x}) = \bar{\phi}(\eta) + \delta\phi(\eta,\vec{x}) \qquad \delta\phi(\eta,\vec{x}) = \frac{1}{\sqrt{(2\pi)^3}}\int \delta\phi(\vec{k}',\eta)e^{i\vec{k}'\cdot\vec{x}}d^3k'$

time and space dependent rotation $\omega = -\frac{1}{2}\frac{\partial B_{F\tilde{F}}}{\partial\phi}\left(\frac{\partial\phi}{\partial\eta} + \vec{\nabla}\phi\cdot\hat{n}\right)$

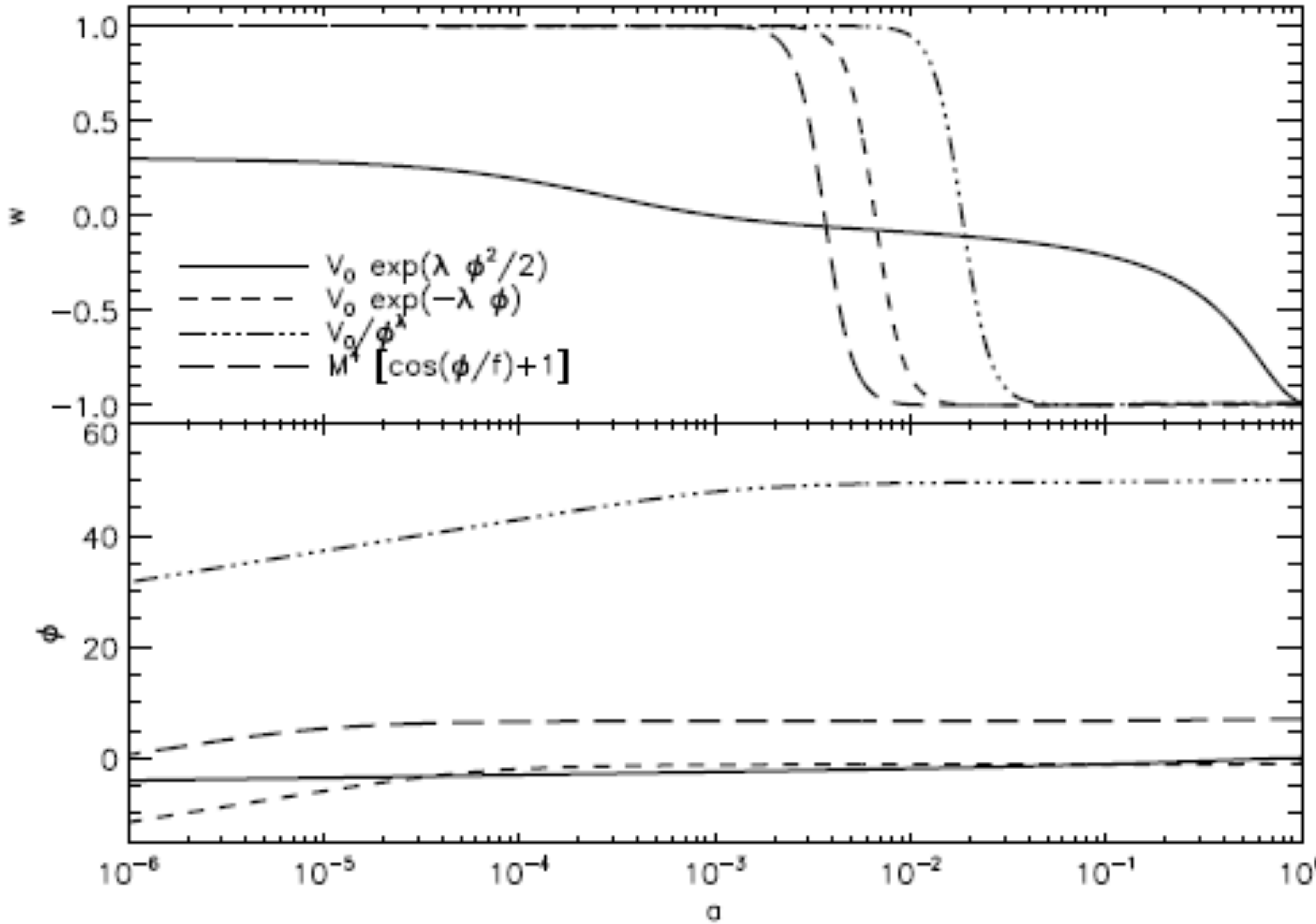
$$\dot{\Delta}_{Q\pm iU}(\vec{k},\eta) + ik\mu\Delta_{Q\pm iU}(\vec{k},\eta) = n_e\sigma_T a(\eta)\Big[-\Delta_{Q\pm iU}(\vec{k},\eta)\times$$

$$\sum_m \sqrt{\frac{6\pi}{5}}\,{}_{\pm 2}Y_2^m(\hat{n})S_P^{(m)}(\vec{k},\eta)\Big] \mp i2\frac{1}{\sqrt{(2\pi)^3}}\int d\vec{k}'\,\tilde{\omega}(\vec{k}-\vec{k}',\eta)\Delta_{Q\pm iU}(\vec{k}',\eta)$$

$$\tilde{\omega}(\vec{k},\eta) = -\frac{1}{2}\frac{\partial B_{F\tilde{F}}}{\partial\bar{\phi}}\left[\dot{\delta\phi}_{\vec{k}}(\eta) + i\vec{k}\cdot\hat{n}\,\delta\phi_{\vec{k}}(\eta)\right]$$

- Perturbation induced polarization power spectra in general quintessence models are small
- Interestingly, in nearly ΛCDM models (no time evolution of the mean field), birefringence generates <BB> while <TB>=<EB>=0

We Tried Many Scalar Dark Energy Models



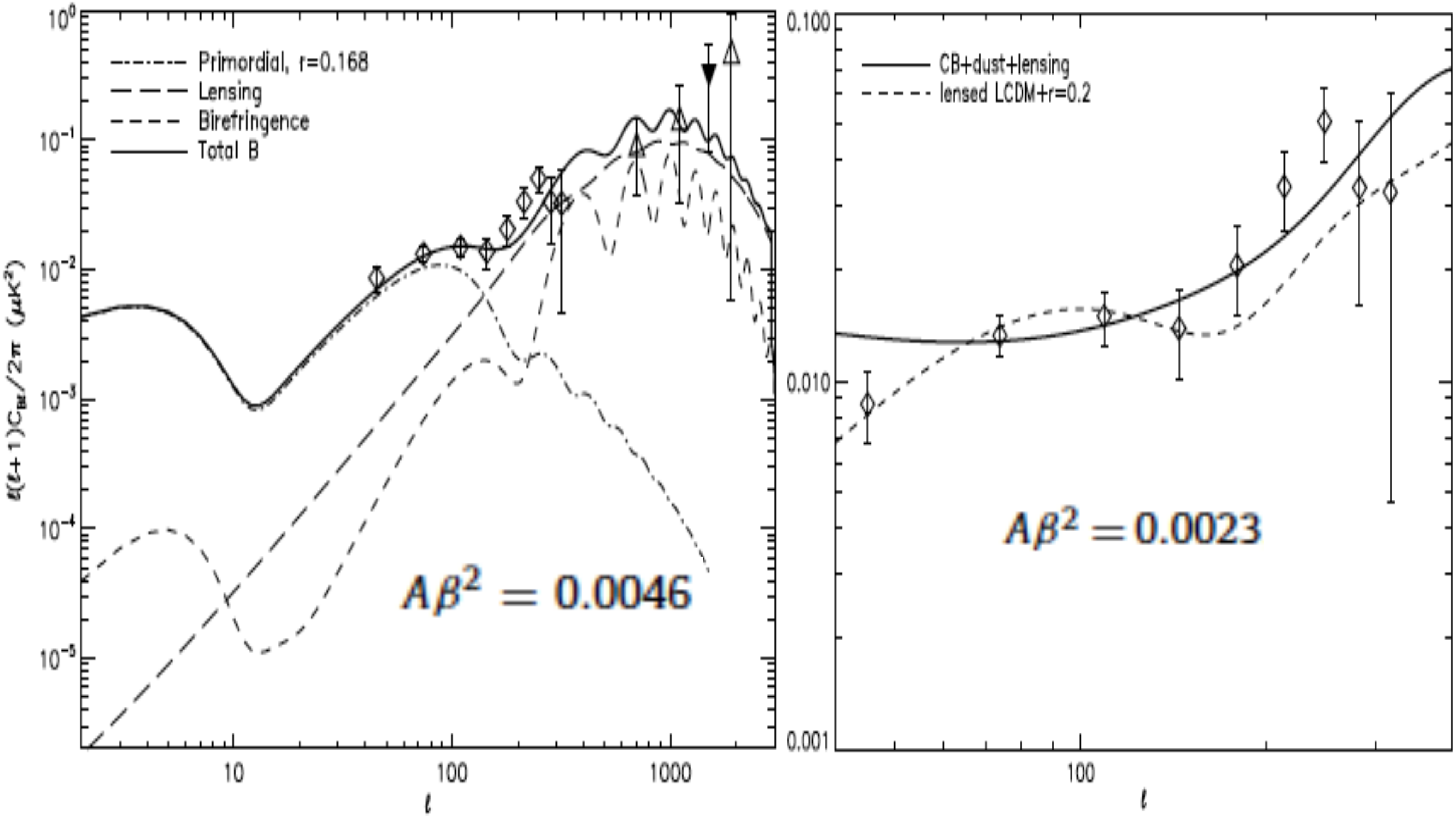
Cosmic Birefringence (CB) Fluctuations

Nearly massless pseudo scalar

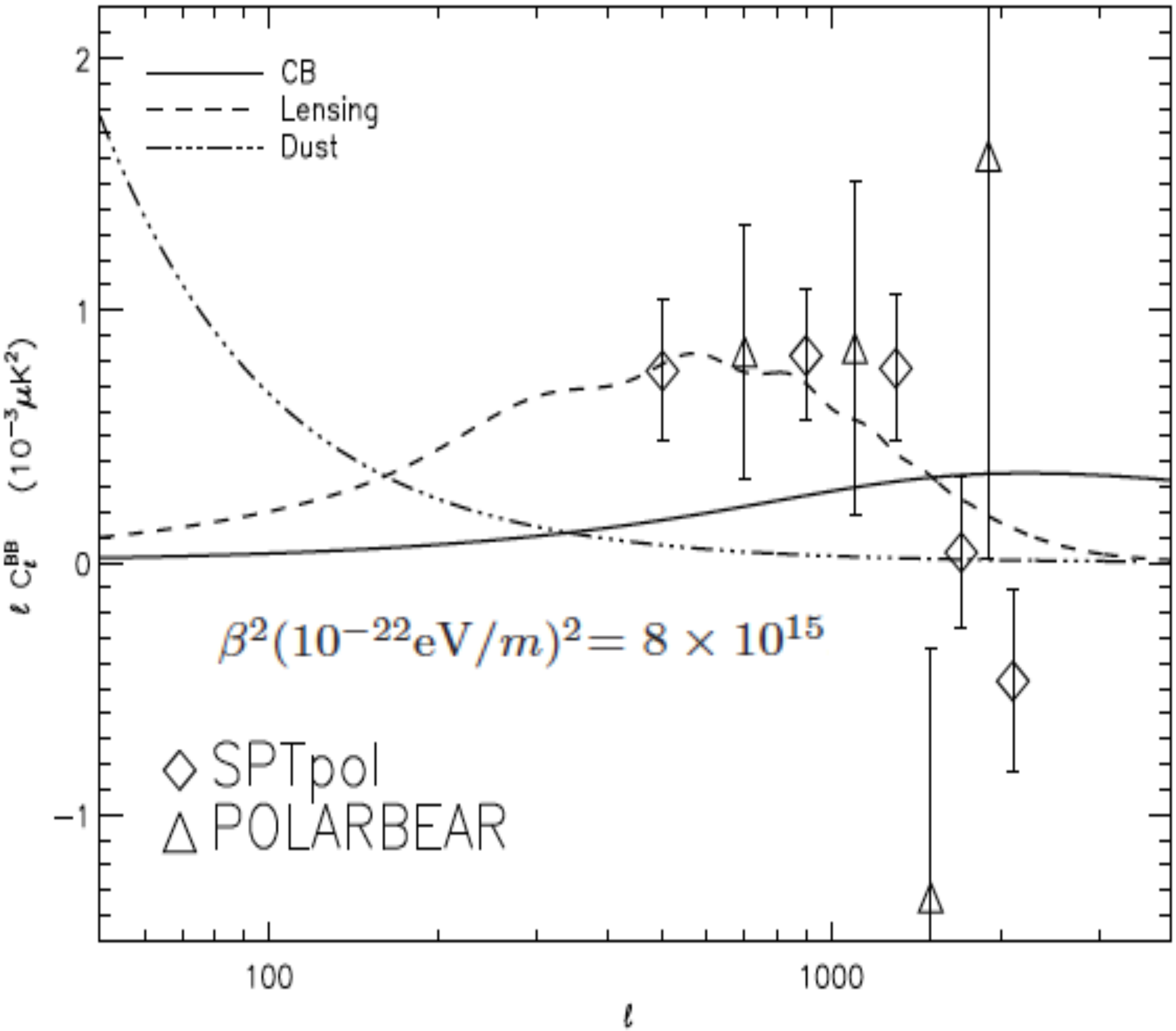
$$\left\langle \delta\phi_{\vec{k},i}\delta\phi_{\vec{k}',i}\right\rangle = (2\pi^2/k^3)P_{\delta\phi}(k)\,\delta(\vec{k}-\vec{k}')$$

$$P_{\delta\phi}(k) = Ak^{n-1}$$

Pospelov et al. 08
Lee, Liu, Ng14



Axion ($m \sim 10^{-22}$eV) CDM curvature perturbation



$\delta\rho_\phi/\rho_\phi = \delta\rho/\rho$

$$\rho_\phi = m_\phi^2\phi^2$$

$$\frac{\delta\rho_\phi}{\rho_\phi} = 2\frac{\delta\phi}{\phi}$$

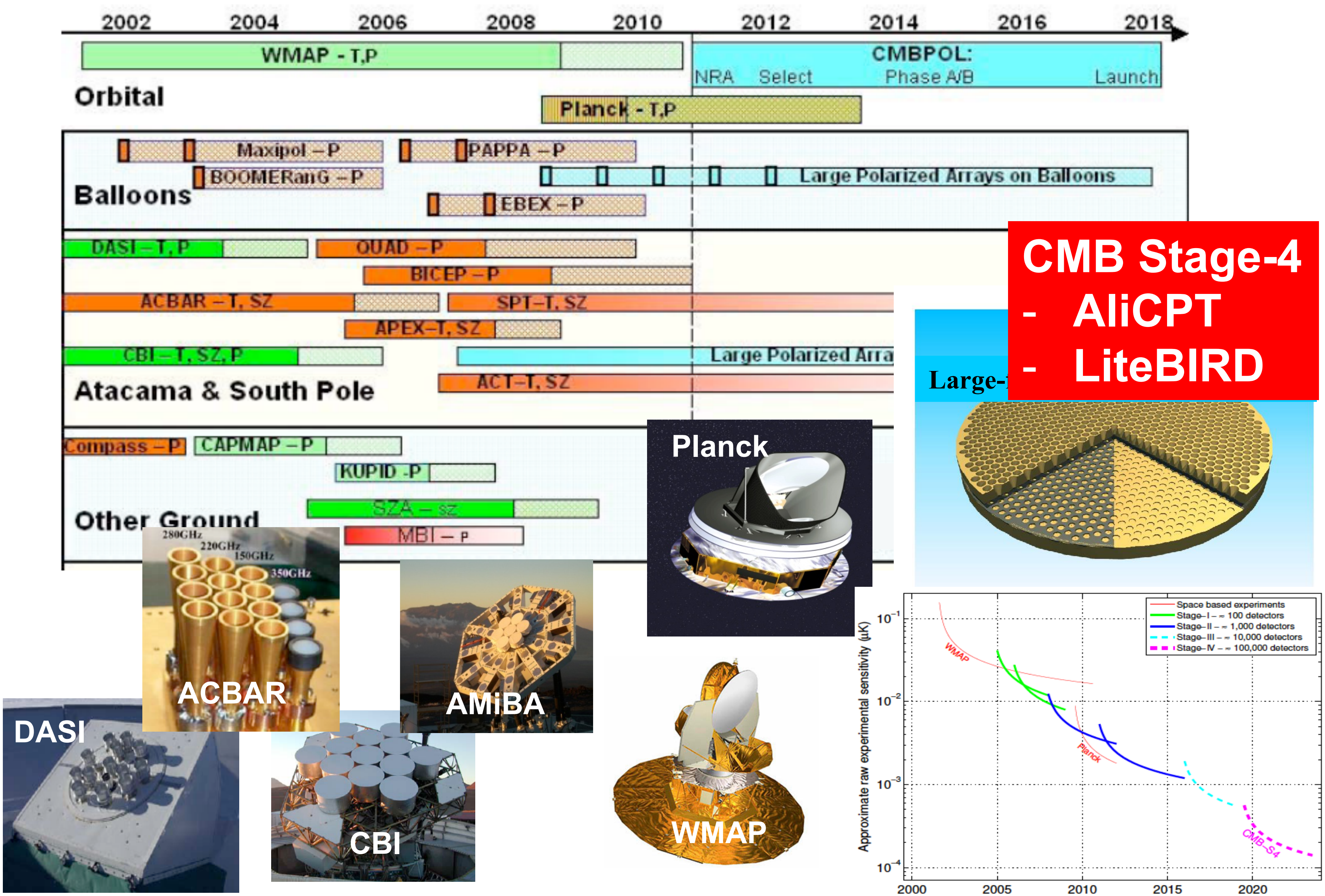
$$\frac{\delta\phi}{M} = \frac{\delta\phi}{\phi}\frac{\phi}{M}$$

$$\phi = \phi_m\left(\frac{a_m}{a}\right)^{\frac{3}{2}}$$

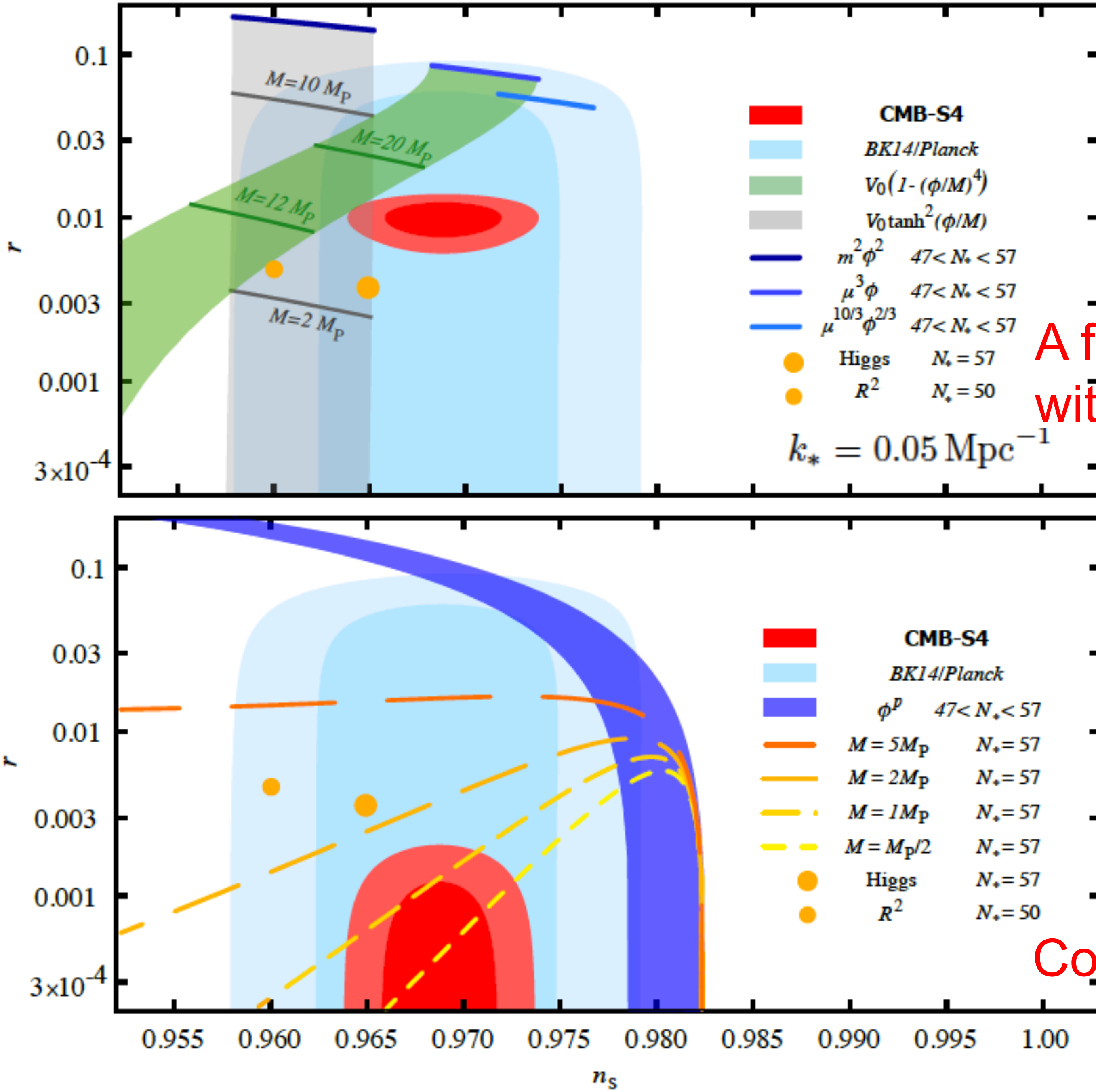
$$H(a_m) = m$$

Liu, Ng 17

Recent, On-going, and Future CMB Space Missions and Experiments



CMB-S4 forecasts on inflation models



A fiducial model with r=0.01

Constraints on r

Summary

- Cosmic microwave background is a powerful tool for unveiling the initial conditions of the early Universe
- Anisotropy power spectrum has been well measured
- Combined with other observations such as supernova, large-scale structure formation, gravitational lensing, cosmological parameters have been measured at ~1% accuracy
- Polarization signal is a sensitive probe of the formation of first stars and reionization history
- B-mode polarization is a clean signal of primordial gravitational waves and inflation
- Future and next-generation observations will lead us to an era of high-precision cosmology