Birefringent DE/DM and CMB B-modes

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KEK-PH2018 and
3rd KIAS-NCTS-KEK Joint workshop
KEK, Tsukuba, Dec 4-7, 2018

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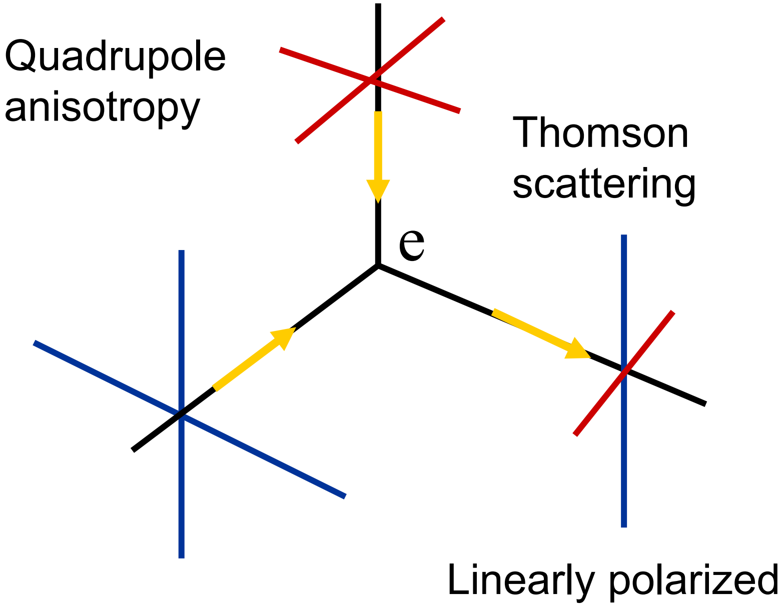
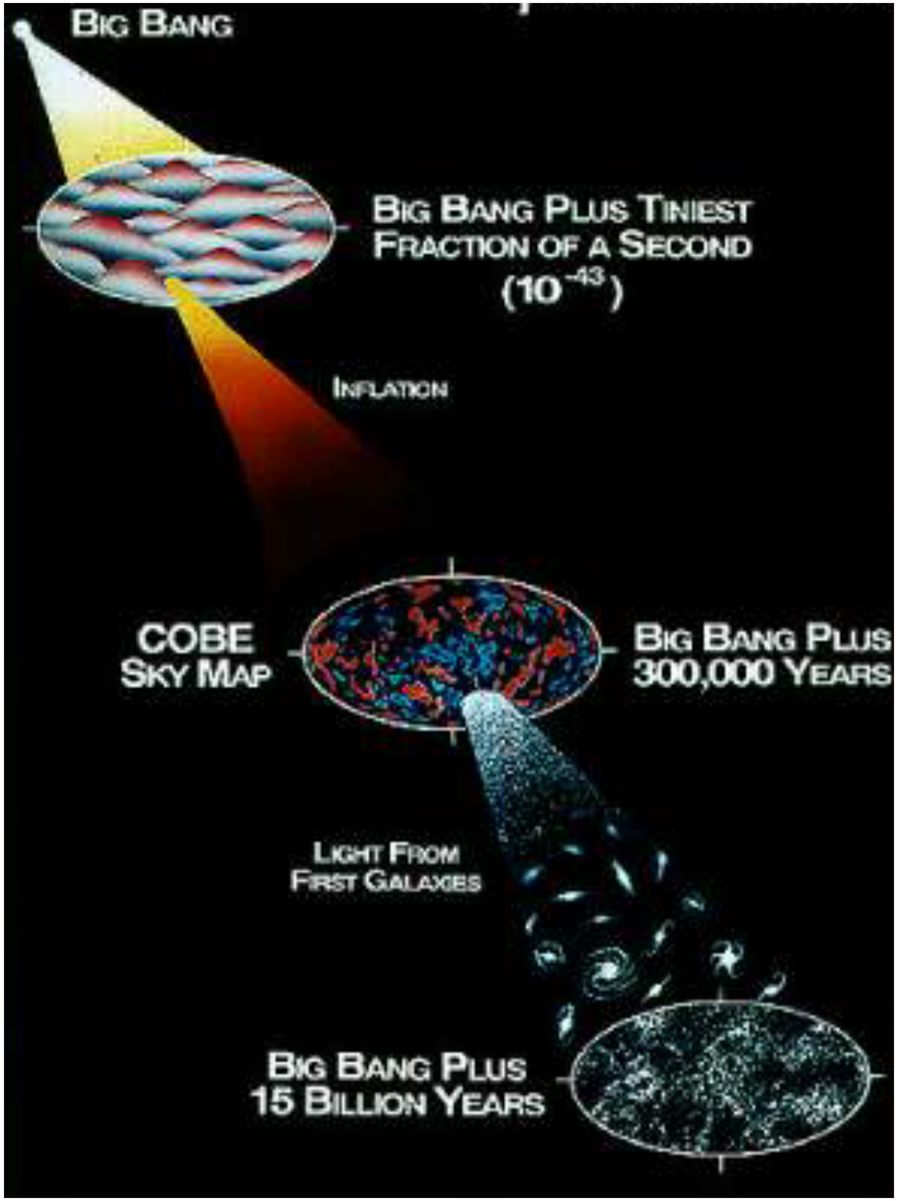
CMB Anisotropy and Polarization

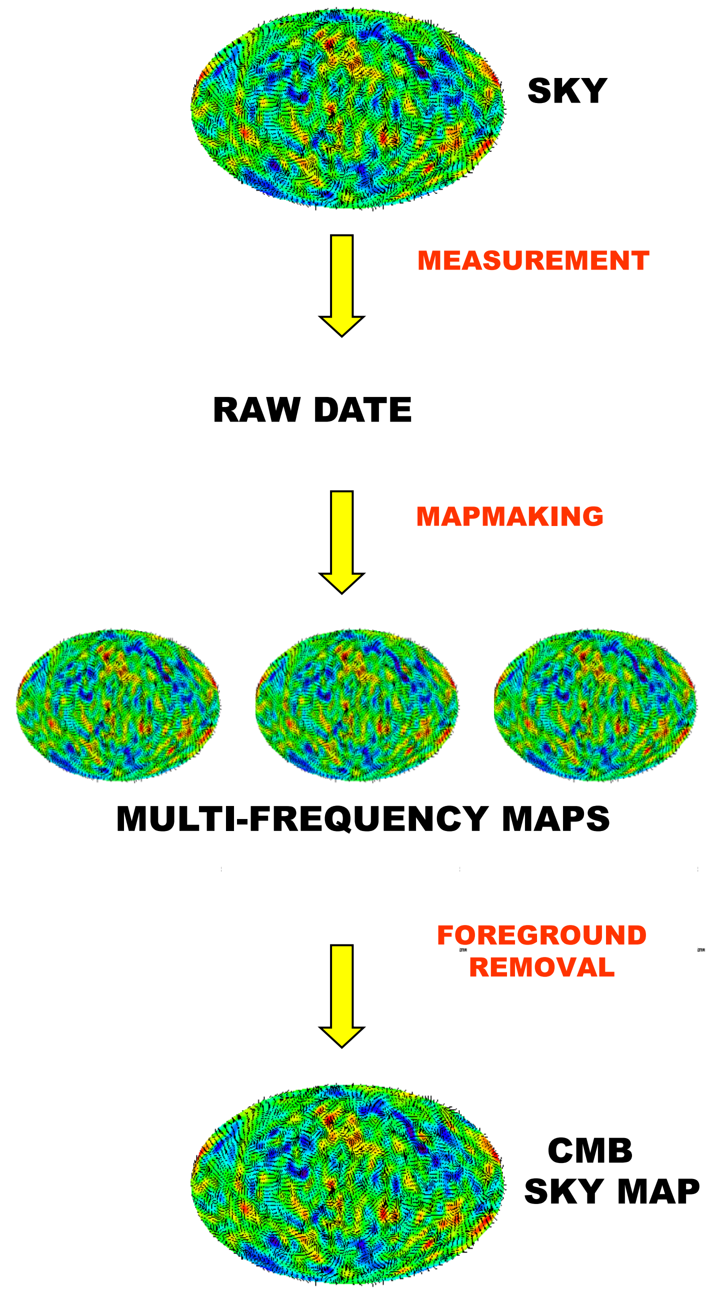
- On large angular scales, matter imhomogeneities generate gravitational redshifts
- On small angular scales, acoustic oscillations in plasma on last scattering surface generate Doppler shifts
- Thomson scatterings with electrons generate polarization





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



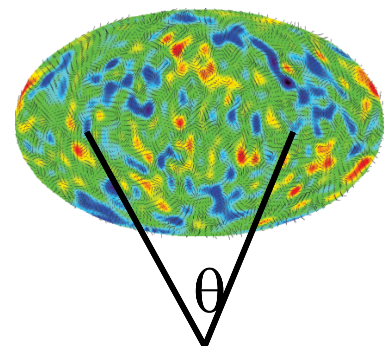
CMB Anisotropy and Polarization Angular Power Spectra

Decompose the CMB sky into a sum of spherical harmonics:

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

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

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



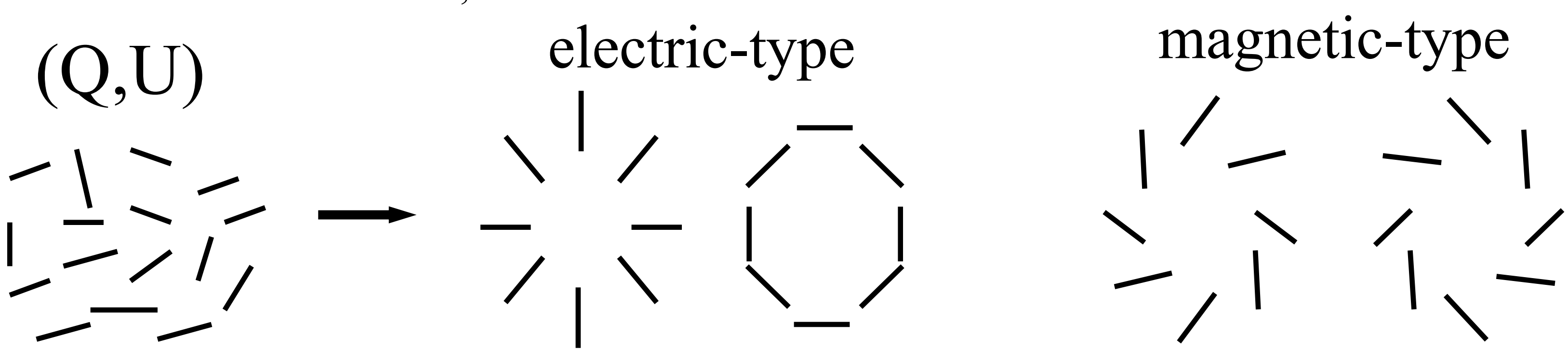
l = 180 degrees/ θ

$C^{TT}_{l} = \Sigma_m (a^*_{lm}\, a_{lm})$ Anisotropy power spectrum

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

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

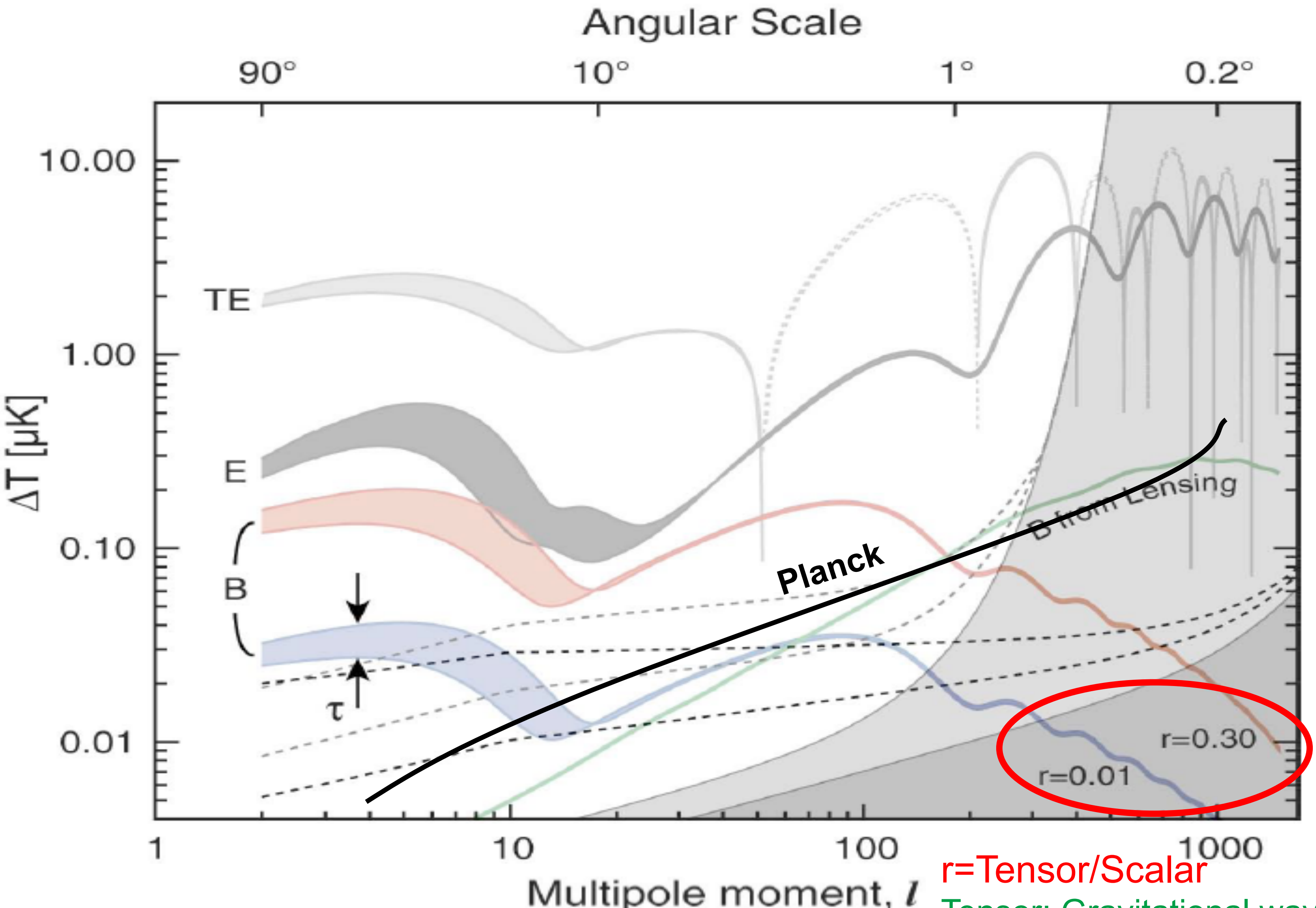
$C^{TE}_{l} = -\Sigma_m (a^*_{lm}\, a_{2,lm})$ TE correlation power spectrum



Standard Lore

- <TT>, <EE>, <BB>, and <TE> correlations exist in standard Lamda cold dark matter cosmological model
- Since B is odd under parity symmetry, <TB> = <EB> = 0

Theoretical Predictions for CMB Power Spectra



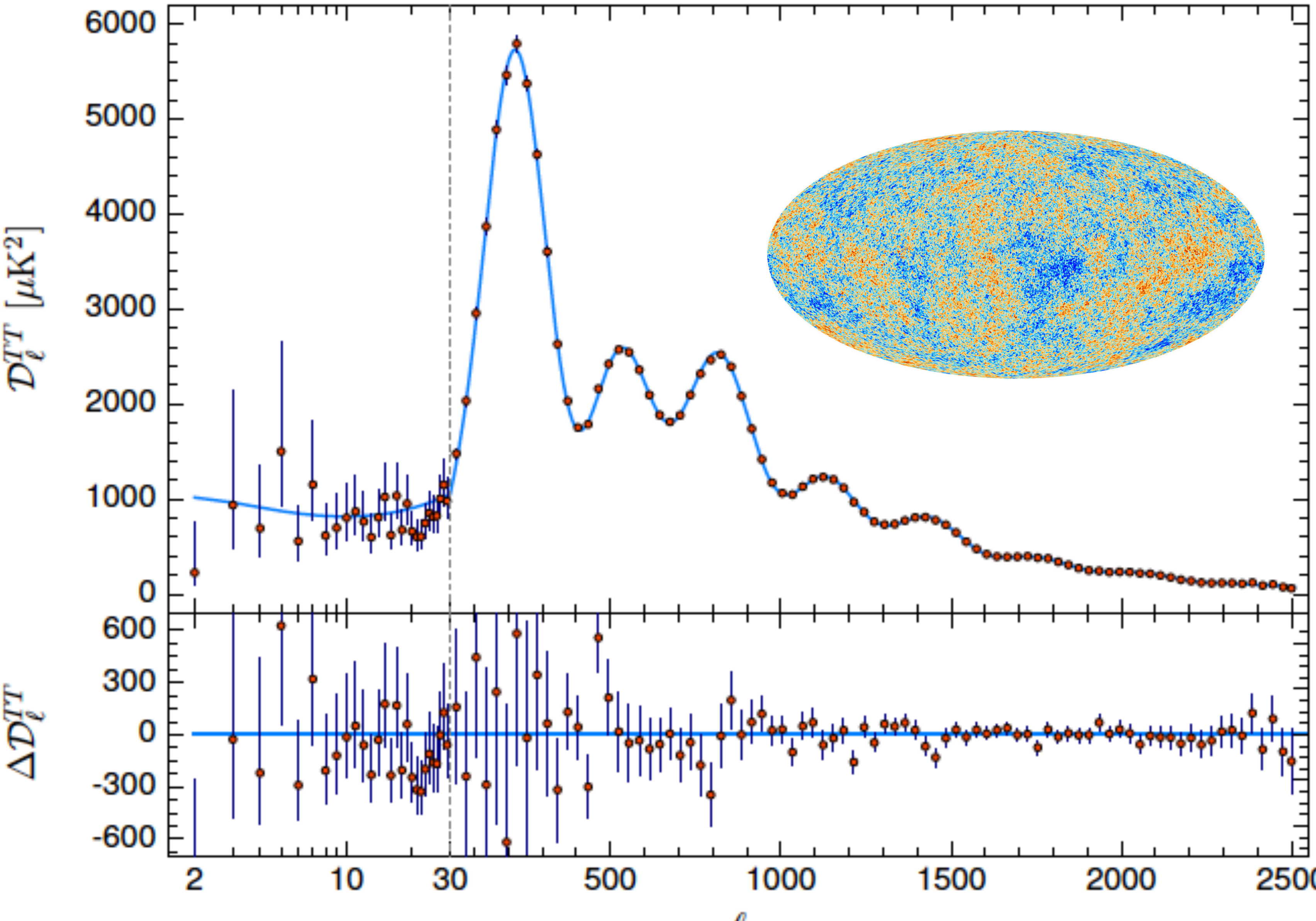
r=Tensor/Scalar

Tensor: Gravitational waves

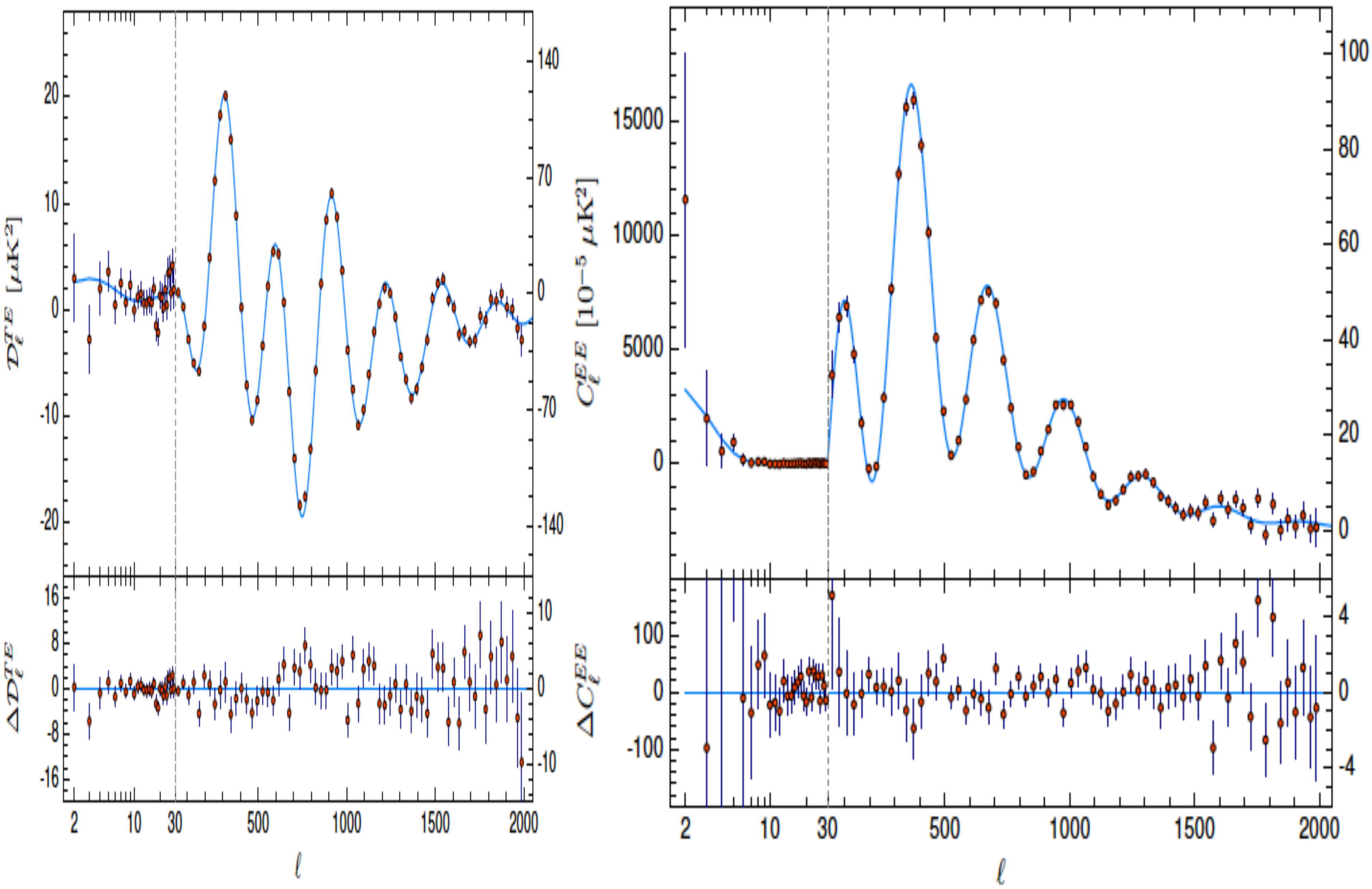
Scalar: Density fluctuations

Weiss report 05

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

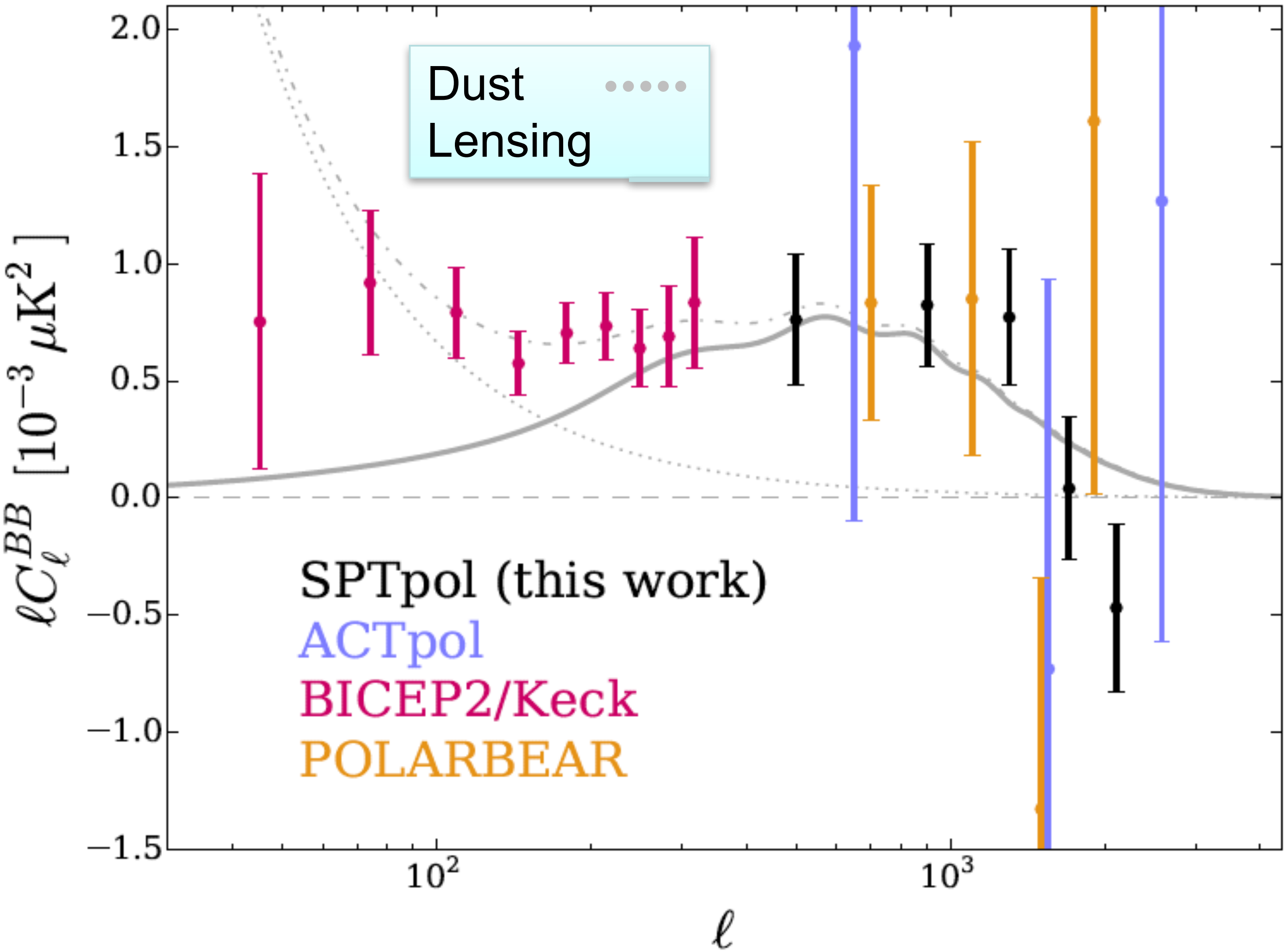
Spectral index $\mathcal{P}_{\mathcal{R}}(k) = A_s \left(\frac{k}{k_0}\right)^{n_s-1}$

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	$-1.56^{+0.60}_{-0.48}$	$-1.58^{+0.52}_{-0.41}$	$-1.57^{+0.50}_{-0.40}$	$-1.04^{+0.10}_{-0.10}$

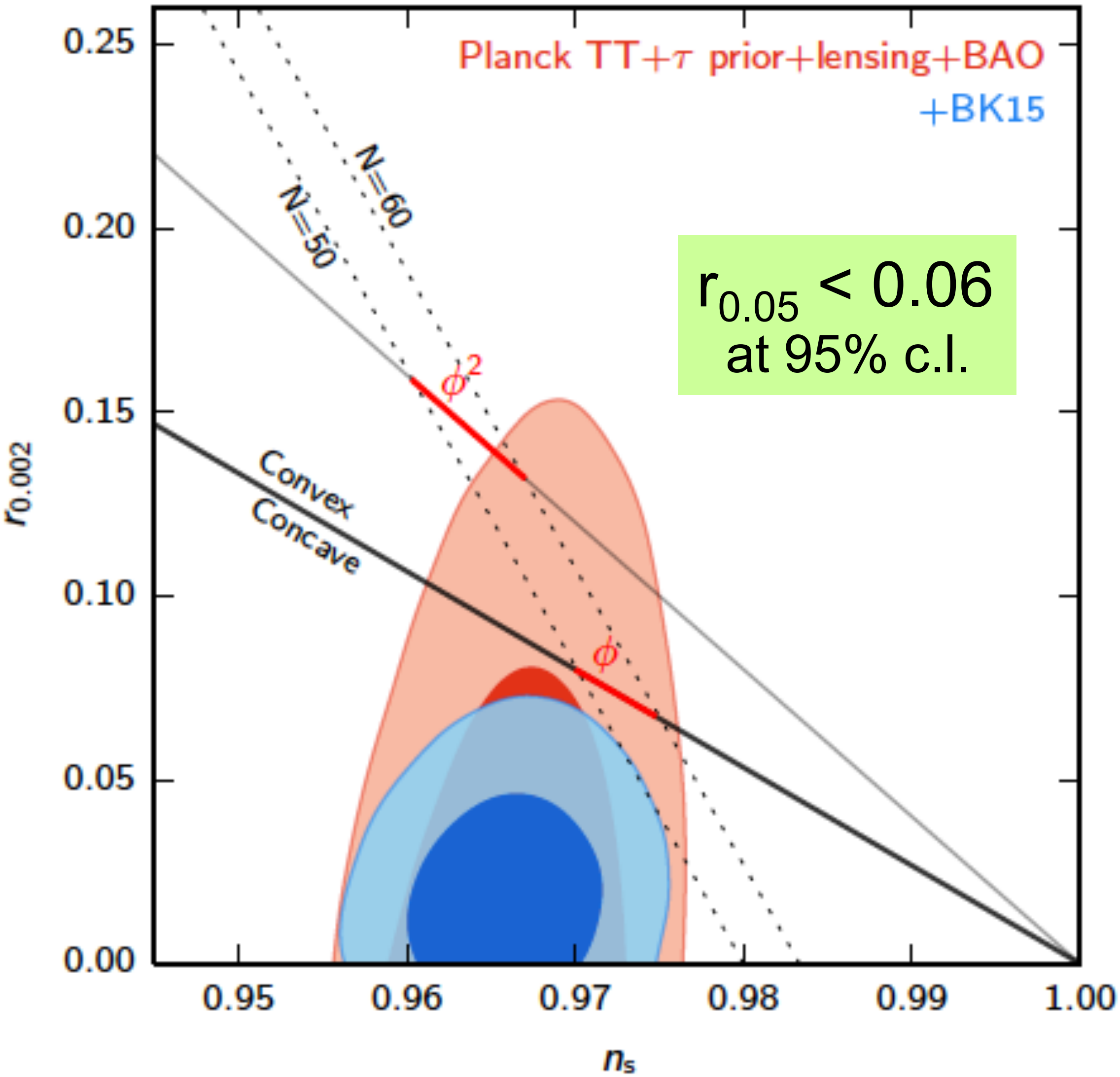
Current B-mode measurements



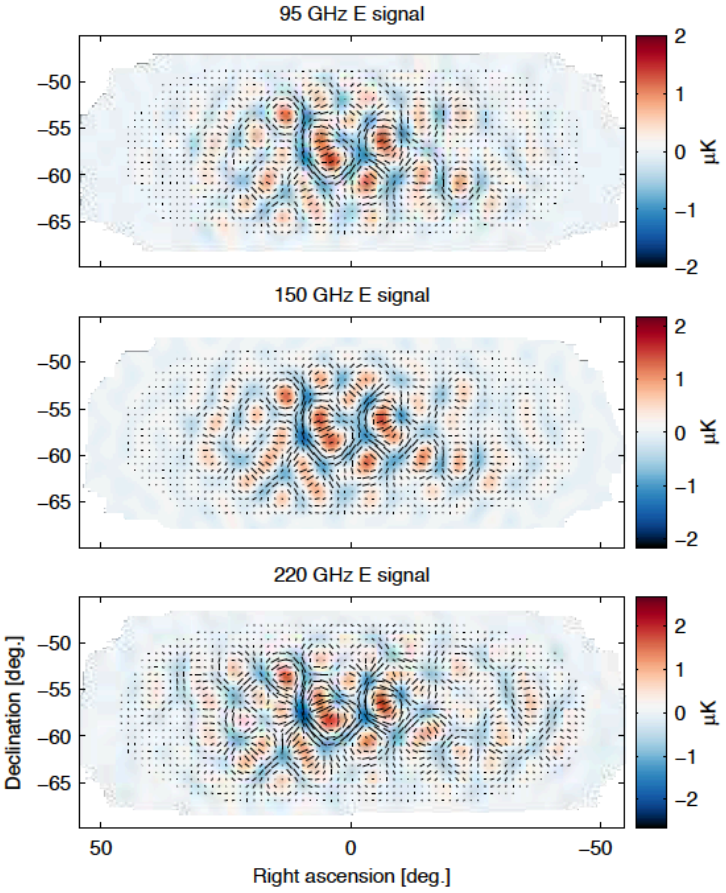
Galactic polarized dust emission
B-mode power spectrum at 150 GHz

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

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



Keck Array 2015
E-polarization data



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

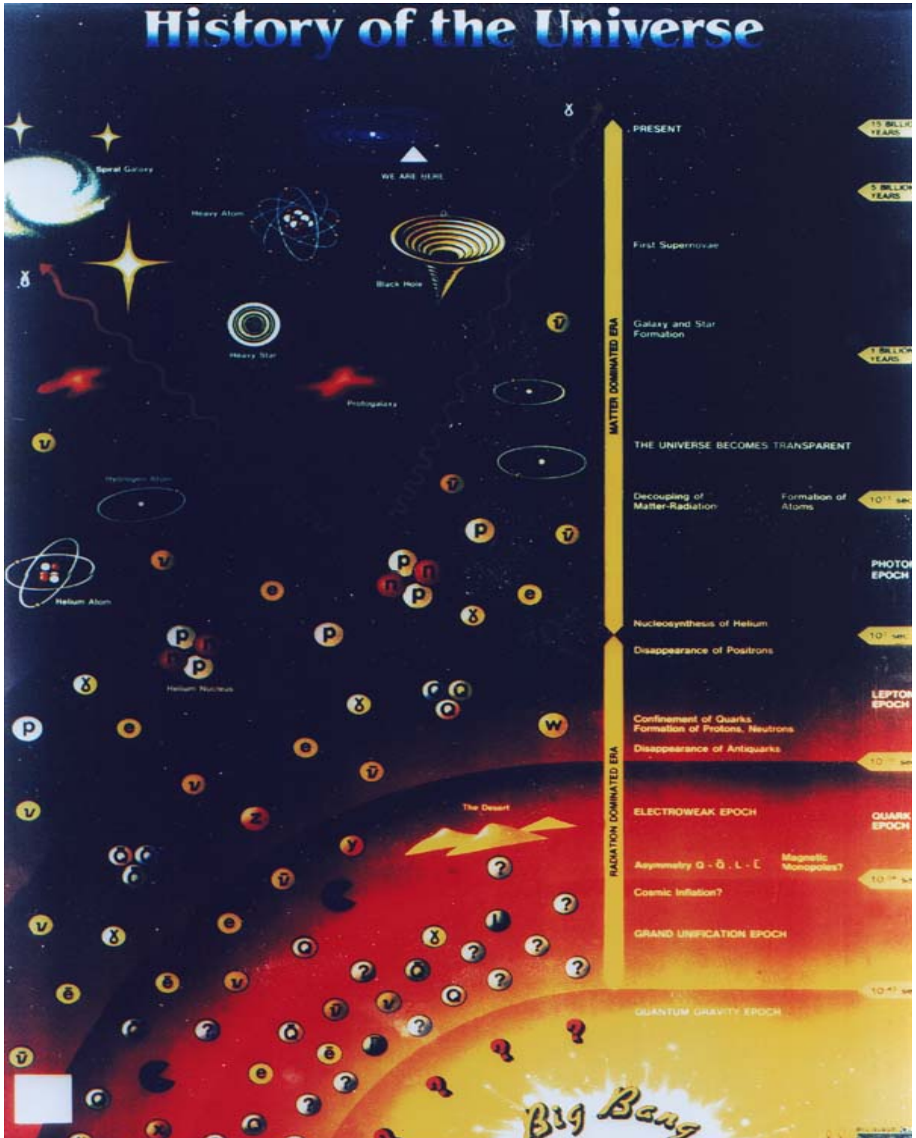
- Is there any parity violation in the cosmos on the sky?

  CMB polarization, polarized radio galaxies,…

CMB power spectra

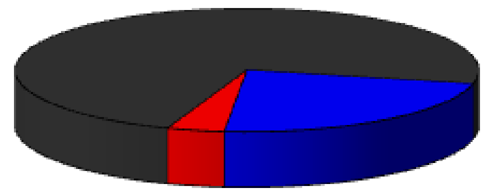
- <TT>, <EE>, <BB>, and <TE> correlations exist in standard ΛCDM model
- Since B is odd under parity symmetry, we expect that <TB> = <EB> = 0
- Any trace of <TB> ≠ <EB> ≠ 0 may indicate parity violation

The Hot Big Bang Model



Fermilab Image 01-582D

Cosmic Budget



What is CDM?
Weakly interacting but can gravitationally clump into halos

What is DE??
Inert, smooth, anti-gravity!!

Axion-like DE and CDM

(too many references to list)

- Weak equivalence principle plus spin dictates a universal pseudoscalar (Ni 77)
- There exists at least one fundamental scalar – the Higgs boson !
- Axion monodromy – large-field inflation
- Peccei-Quinn symmetry breaking – QCD axion CDM
- Problems in small-scale structures – 10^{-22} eV scalar (maybe pseudoscalar) fuzzy CDM
- String axiverse – a plentitude of axions with a vast mass range 10^{-33} eV - 10^{-10} eV
- Extended string axiverse – axions as DE

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 $\quad$ η conformal time

vacuum birefringence

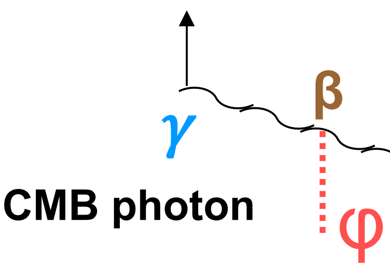
then, a rotational speed of polarization plane

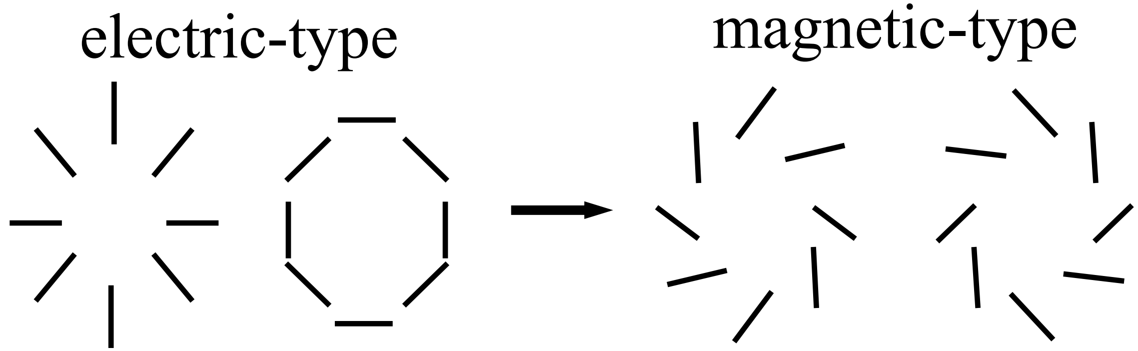
$$\omega = \frac{1}{2}(n_+ - n_-) = -\frac{1}{2}\frac{\partial B_{F\tilde{F}}}{\partial \phi}\left(\frac{\partial \phi}{\partial \eta} + \vec{\nabla}\phi \cdot \hat{n}\right)$$

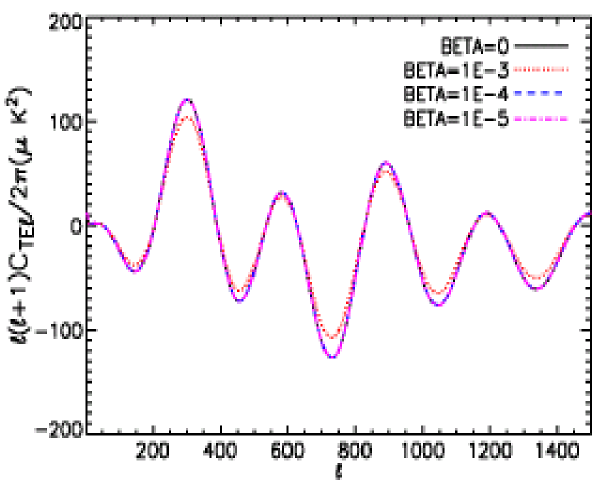
If $B=\beta\varphi$, cooling of horizontal branch stars would imply $\beta<10^7$

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

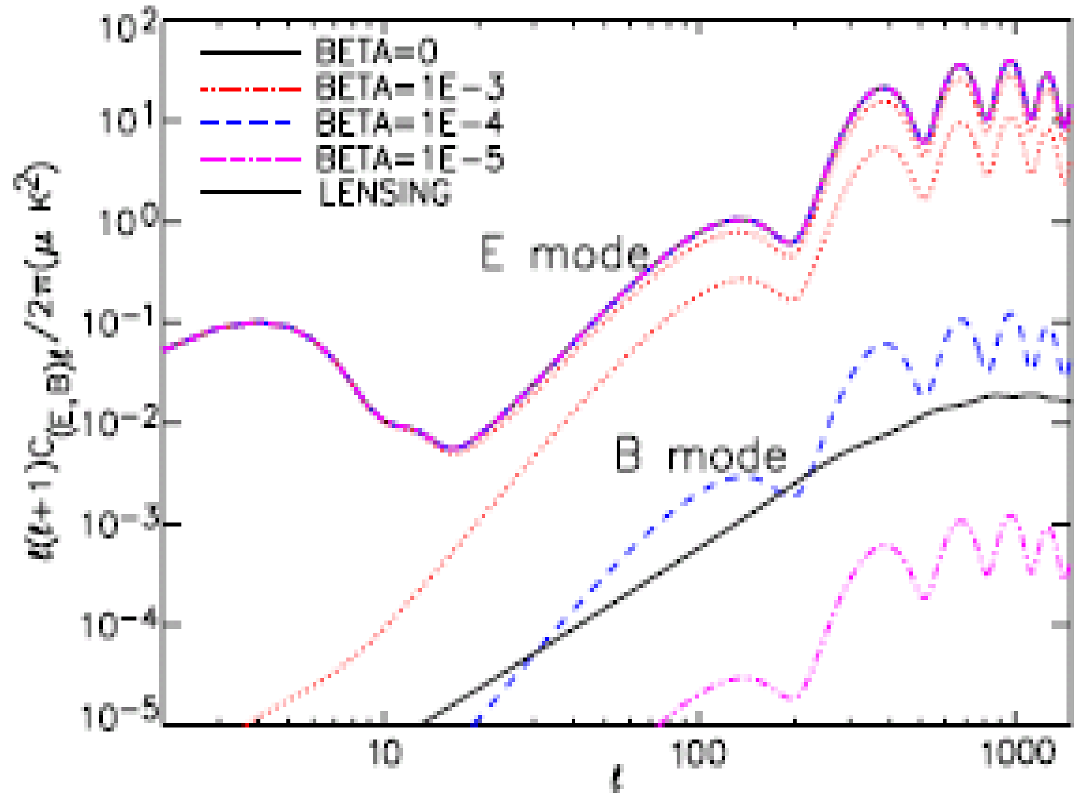
Zhang et al 06
Liu,Lee,Ng 06



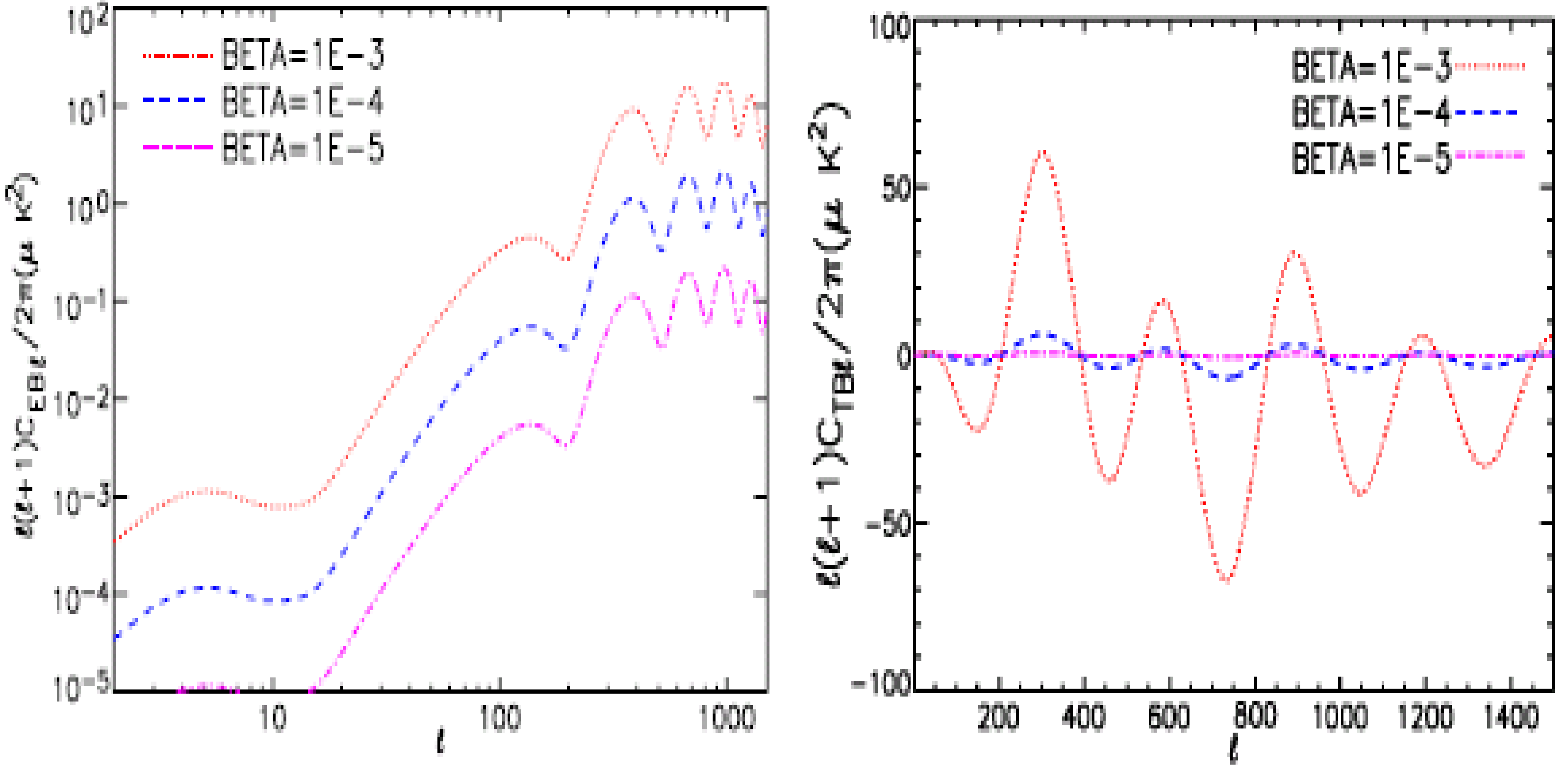




TE spectrum

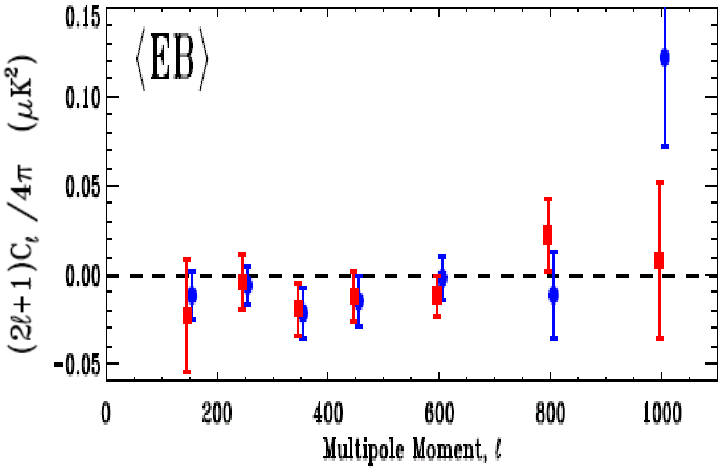


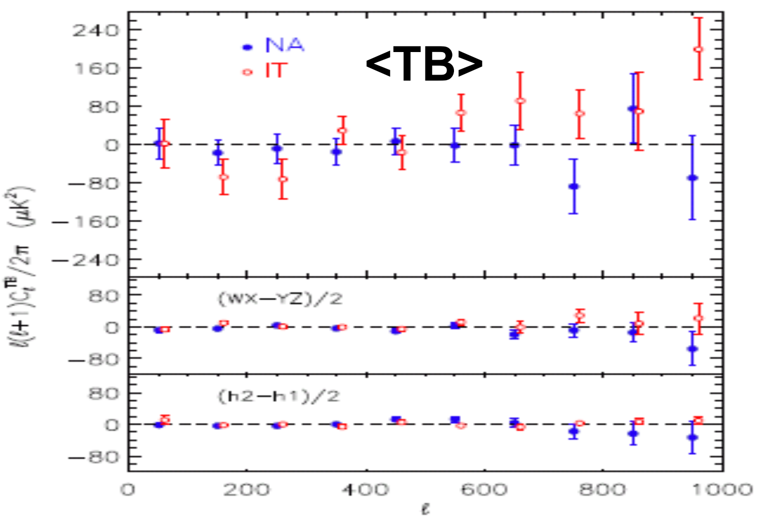
Parity violating EB,TB cross power spectra – cosmic parity violation



Constraining β by CMB polarization data

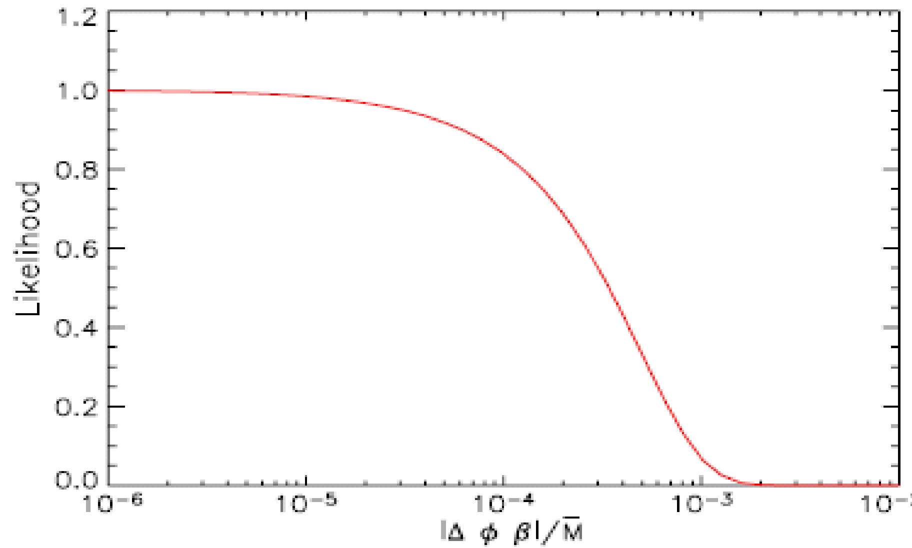
2003 Flight of BOOMERANG





Likelihood analysis assuming reasonable quintessence models

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



$|\beta_{FF}\Delta\phi|/\bar{M} < 8.32 \times 10^{-4}$ 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

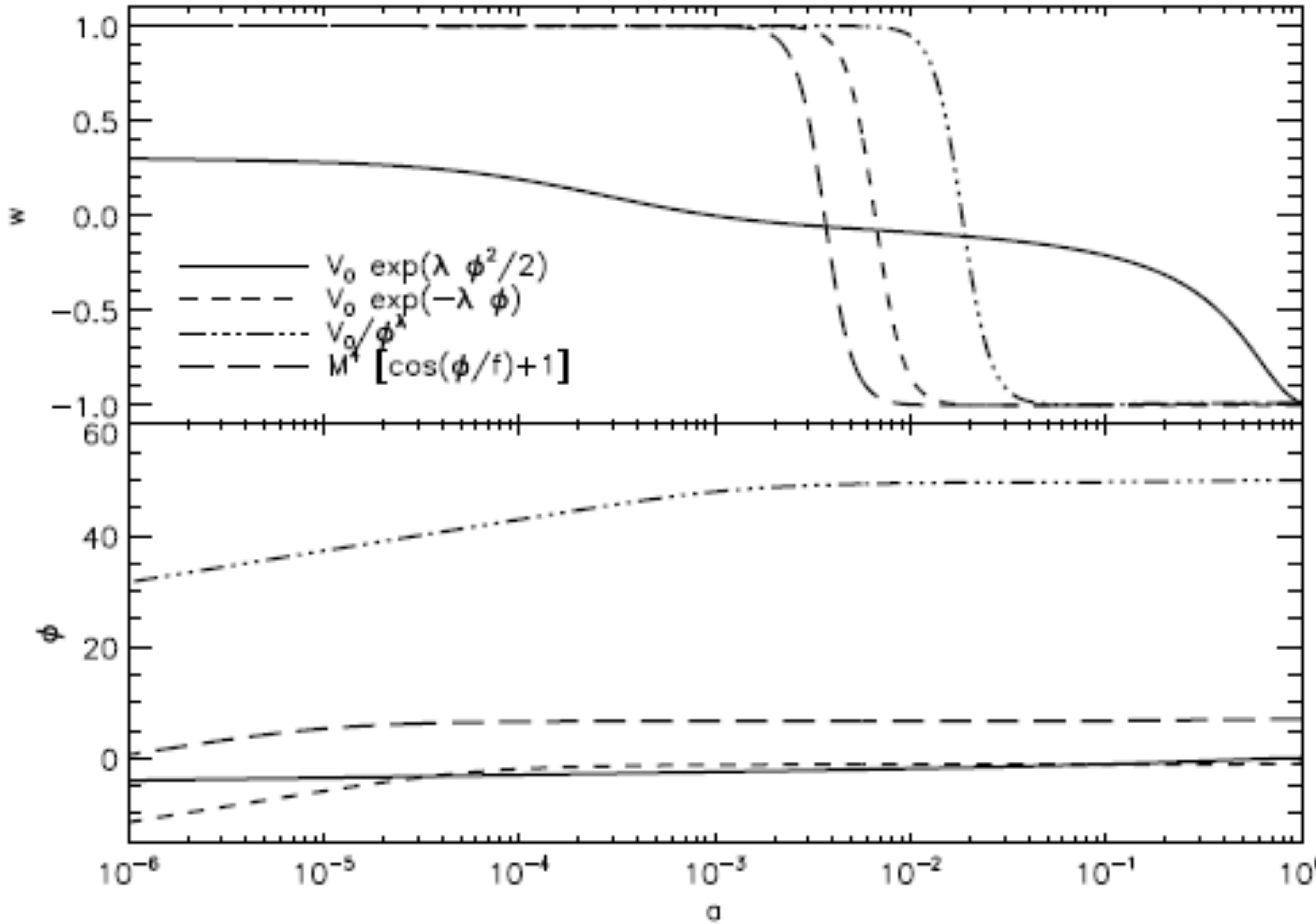
$$\omega = -\frac{1}{2}\frac{\partial B_{F\tilde{F}}}{\partial\phi}\left(\frac{\partial\phi}{\partial\eta} + \vec{\nabla}\phi\cdot\hat{n}\right)$$

$$\dot{\Delta}_{Q\pm iU}(\vec{k},\eta) + ik\mu\Delta_{Q\pm iU}(\vec{k},\eta) = n_e\sigma_T a(\eta)\Big[-\Delta_{Q\pm iU}(\vec{k},\eta) \times \sum_m \sqrt{\frac{6\pi}{5}}\,{}_{\pm 2}Y_2^m(\hat{n}) S_P^{(m)}(\vec{k},\eta)\Big] \mp i2\frac{1}{\sqrt{(2\pi)^3}}\int d\vec{k}'\,\tilde{\omega}(\vec{k}-\vec{k}',\eta)\Delta_{Q\pm iU}(\vec{k}',\eta)$$

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

- 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



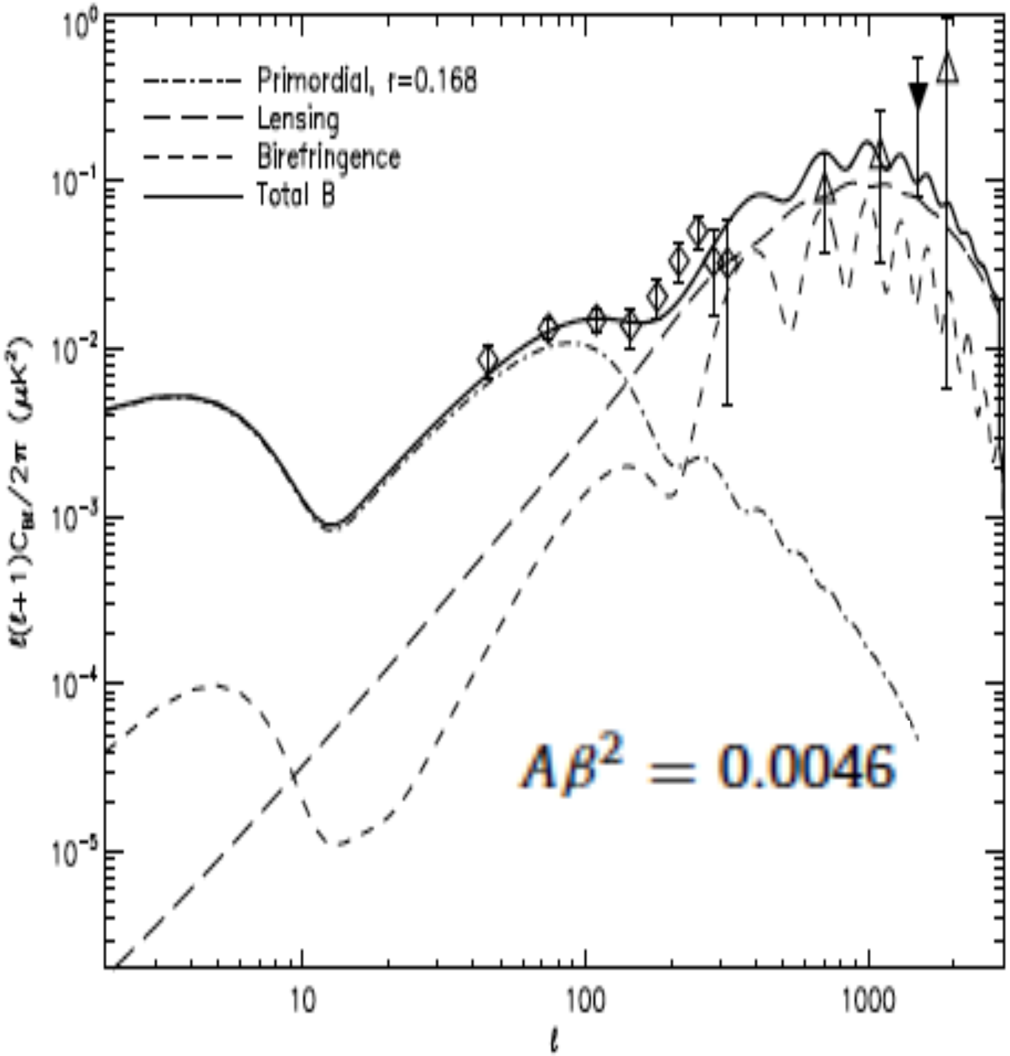
Cosmic Birefringence (CB) Fluctuations

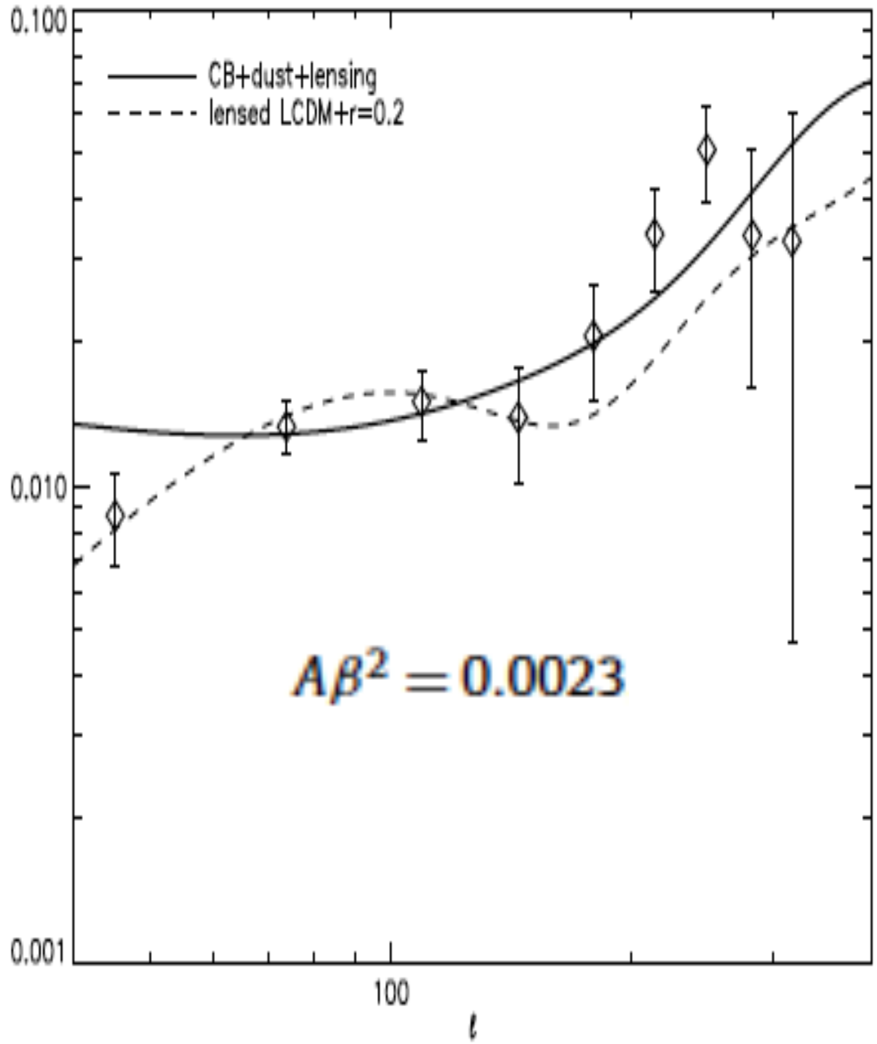
Nearly massless pseudo scalar

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

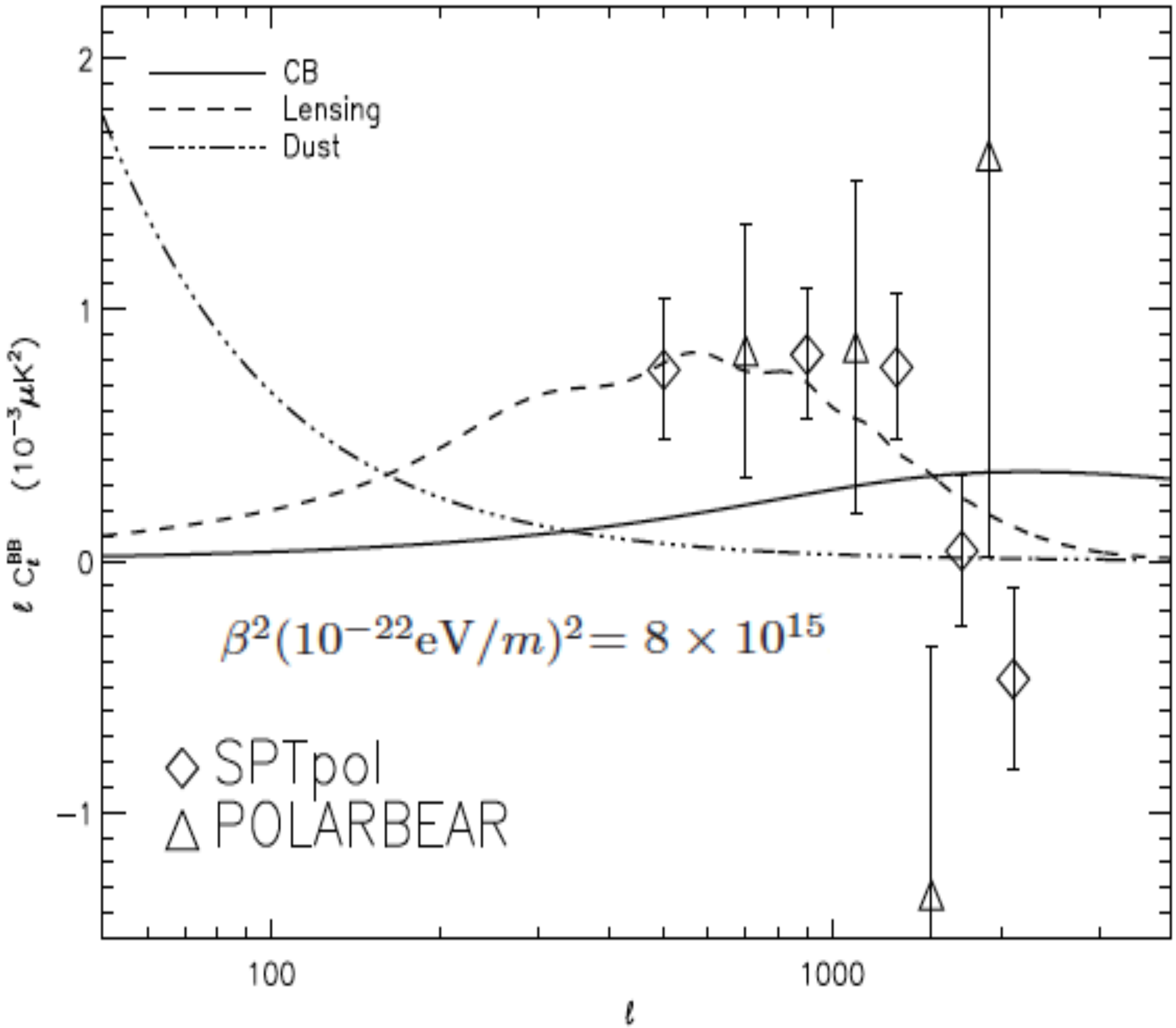
$$P_{\delta\phi}(k) = Ak^{n-1}$$

Pospelov et al. 08
Lee, Liu, Ng14





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



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

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

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

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

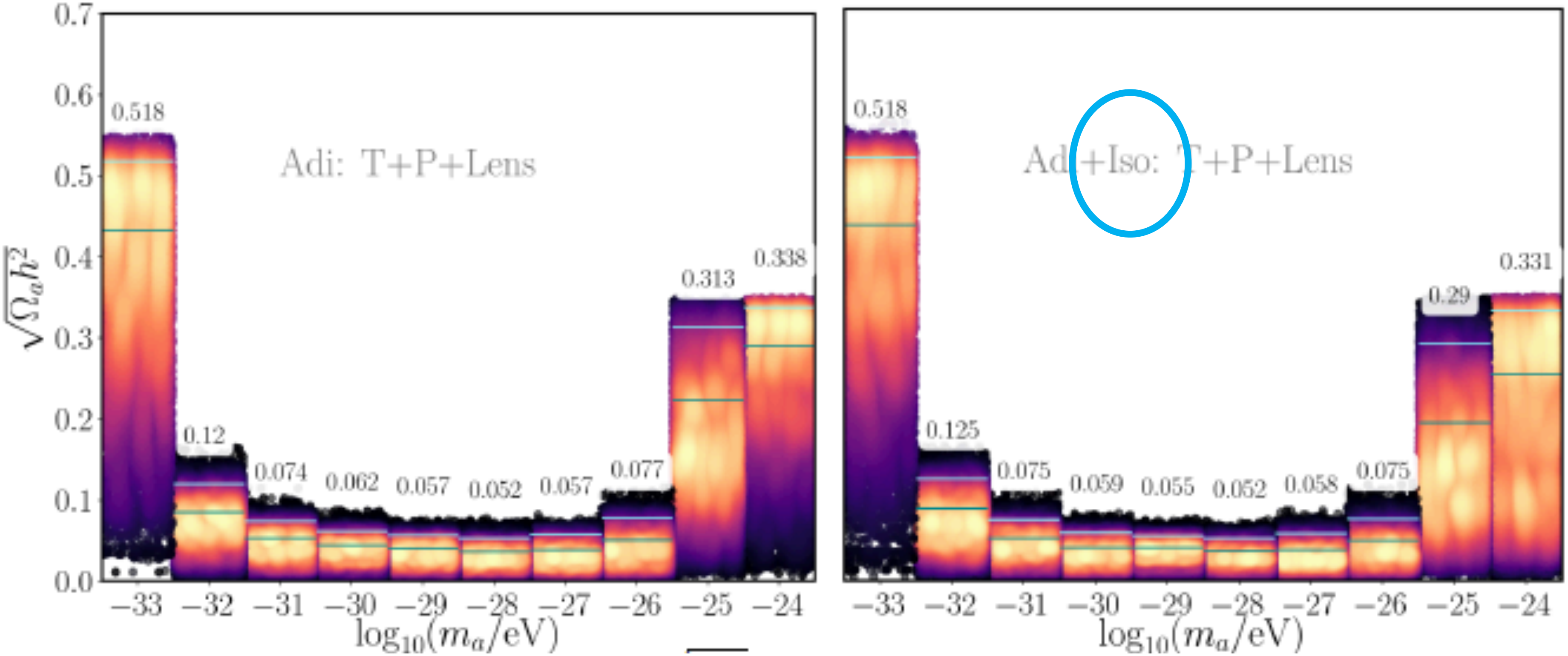
$$\phi = \phi_m\left(\frac{a_m}{a}\right)^{\frac{3}{2}}$$

$$H(a_m) = m$$

Liu, Ng 17

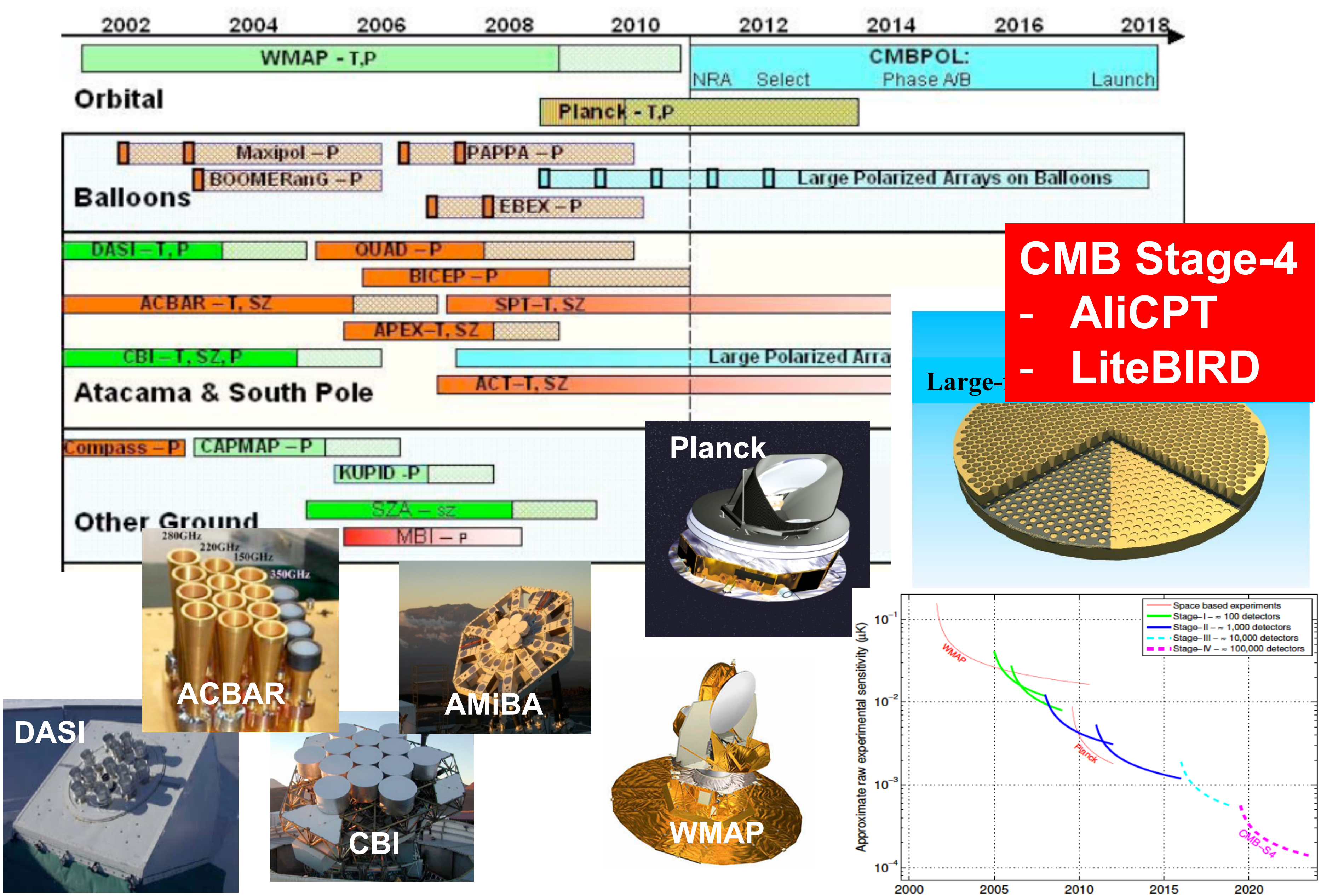
Axion isocurvature perturbation

R. Hložek, D. J. E. Marsh, D. Grin 18



We precisely identify a "window of co-existence" for 10^{-25} eV $\leq m_a \leq 10^{-24}$ eV where the data allow, simultaneously, a $\sim 10\%$ contribution of ULAs to the DM, and $\sim 1\%$ contributions of isocurvature and tensor modes to the CMB power. ULAs in this window (and *all* lighter ULAs) are shown to be consistent with a large inflationary Hubble parameter, $H_I \sim 10^{14}$ GeV. The window of co-existence will be fully probed

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



Summary

- Future observations such as SNe, lensing, galaxy survey, CMB, etc. to measure dark energy w(z) at high-z

- Using CMB B-mode polarization to search for dark energy induced vacuum birefringence
  - Mean field time evolution → <BB>, <TB>, <EB>
  - Include DE perturbation → <BB>, <TB>=<EB>=0

- Axion cold matter matter curvature perturbation → <BB>, <TB>=<EB>=0; isocurvature perturbation?

- This may confuse the searching for genuine B modes induced by gravitational lensing or primordial gravitational waves, so de-rotation is needed to remove vacuum birefringence effects Kamionkowski 09, Ng 10