

Search for Axion-Like Particles Using CMB Polarization



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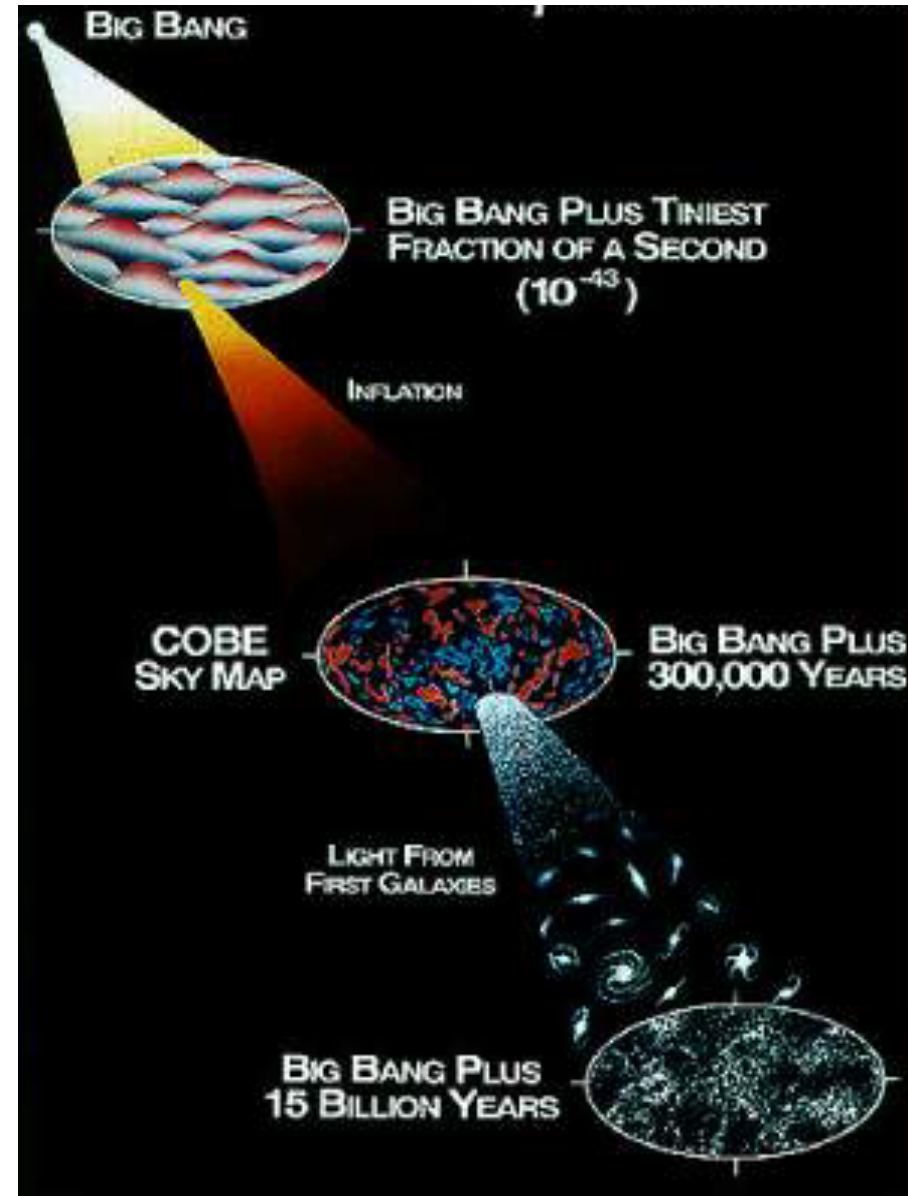
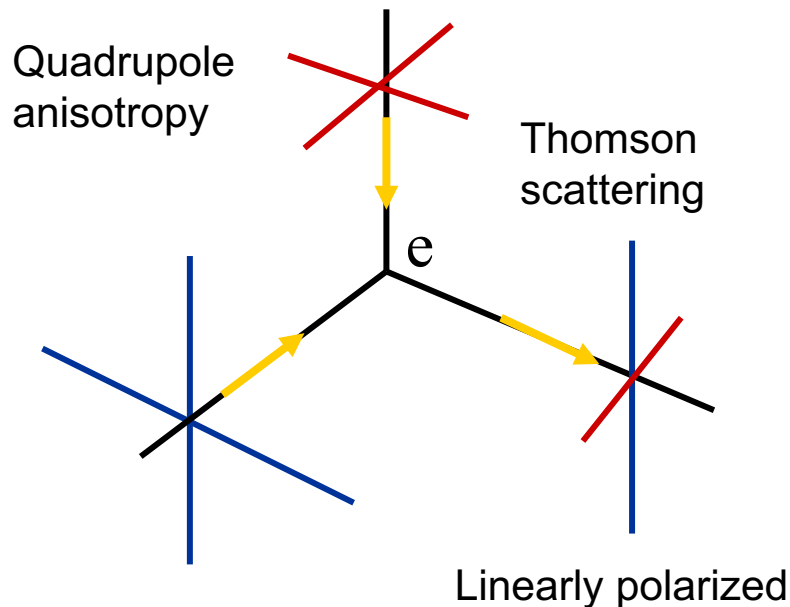
**Institute of Physics &
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**Mini-workshop: Theory - Future Prospects for
Particle Physics, Astro-particle Physics
and Cosmology, Jan 9-10, 2020
IAS HEP Program, HKUST**

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Seokcheon Lee (Sungkyunkwan U)**

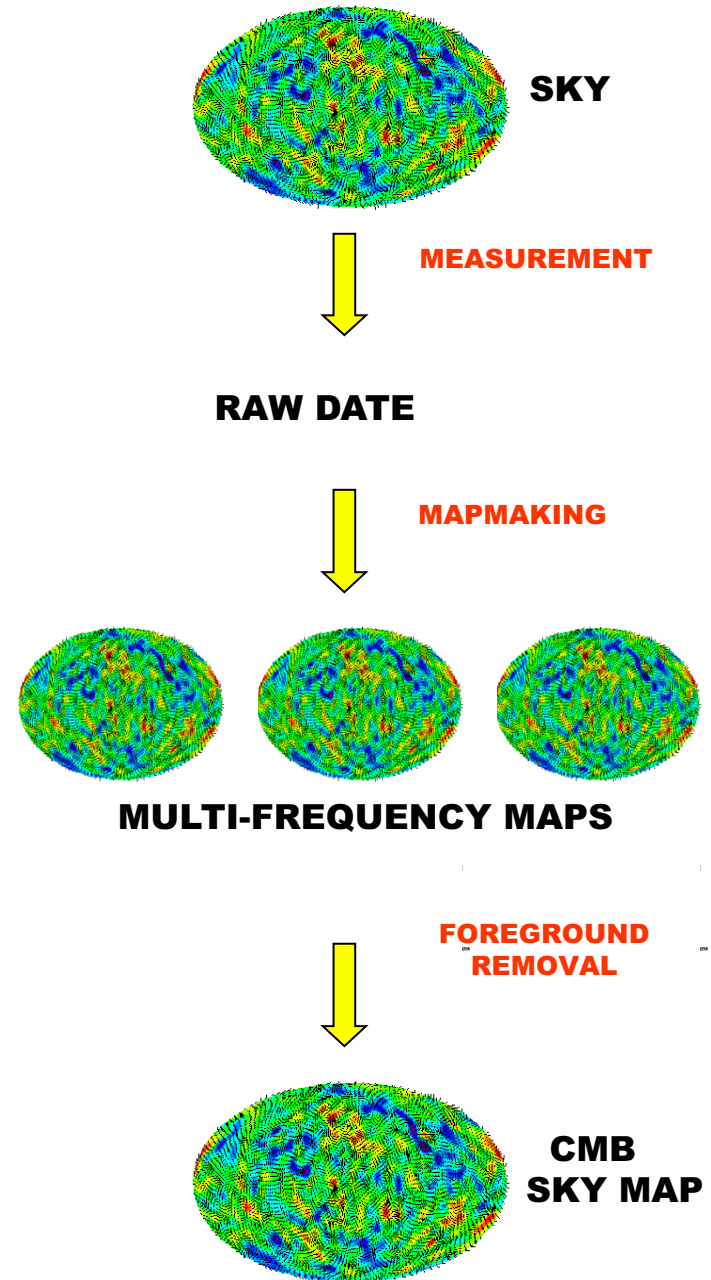
CMB Anisotropy and Polarization

- On large angular scales, matter inhomogeneities 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:
 $T = T_{\text{CMB}} - T_{\text{mean}}$
 $Q = T_{\text{EW}} - T_{\text{NS}}, U = T_{\text{SE-NW}} - T_{\text{SW-NE}}$
- 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



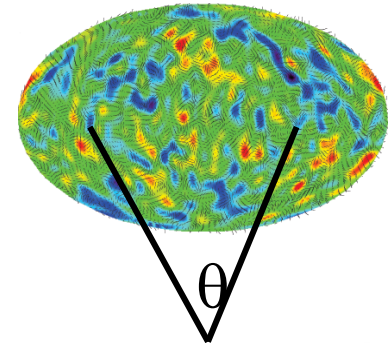
CMB Anisotropy and Polarization Angular Power Spectra

Decompose the CMB sky into a sum of spherical harmonics:

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

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

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

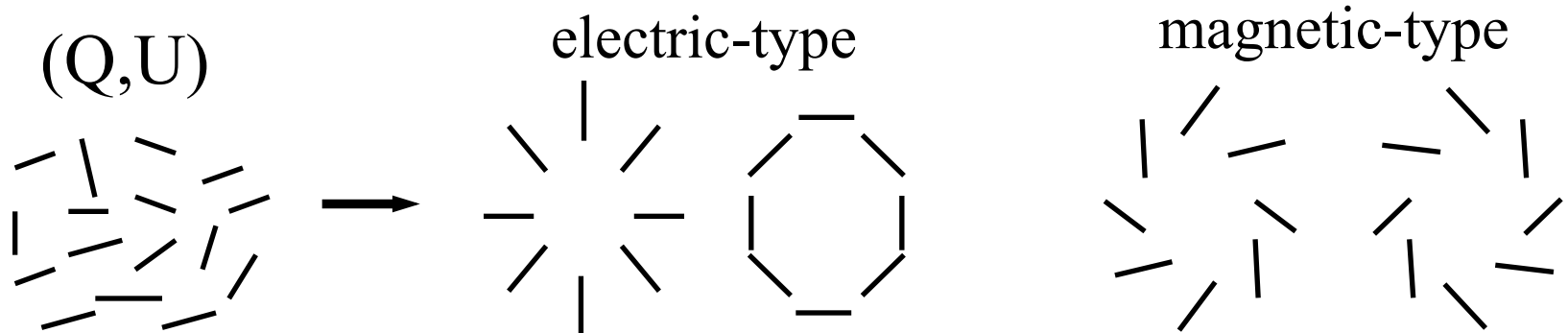


$$C_{l}^{TT} = \sum_m (a_{lm}^* a_{lm}) \text{ Anisotropy power spectrum } l = 180 \text{ degrees} / \theta$$

$$C_{l}^{EE} = \sum_m (a_{2,lm}^* a_{2,lm} + a_{-2,lm}^* a_{-2,lm}) \text{ E-polarization power spectrum}$$

$$C_{l}^{BB} = \sum_m (a_{2,lm}^* a_{2,lm} - a_{-2,lm}^* a_{-2,lm}) \text{ B-polarization power}$$

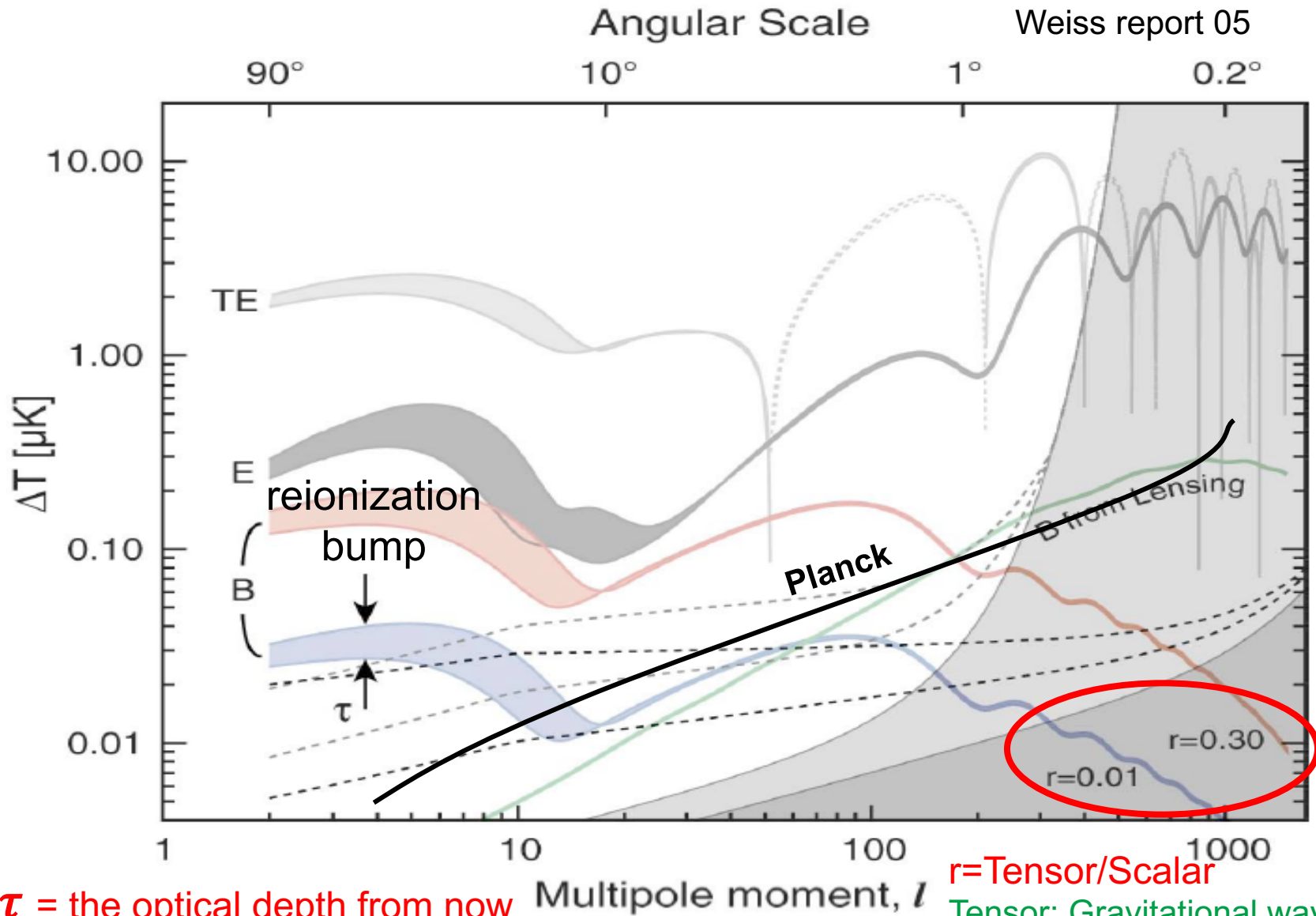
$$C_{l}^{TE} = - \sum_m (a_{lm}^* a_{2,lm}) \text{ TE correlation power spectrum}$$



Standard Lore

- $\langle TT \rangle$, $\langle EE \rangle$, $\langle BB \rangle$, and $\langle TE \rangle$ correlations exist in standard Λ cold dark matter cosmological model
- Since B is odd under parity symmetry, $\langle TB \rangle = \langle EB \rangle = 0$

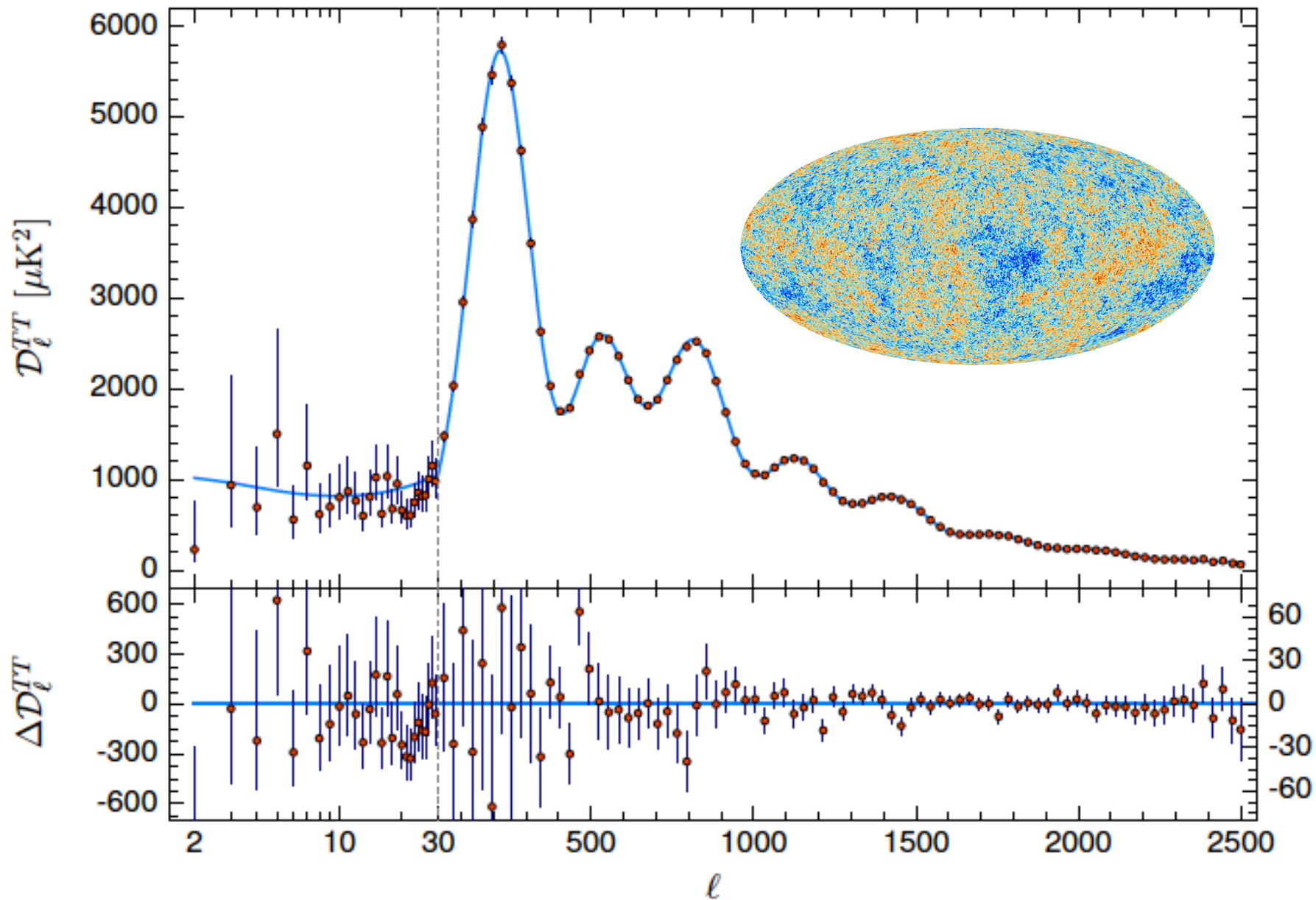
Theoretical Predictions for CMB Power Spectra



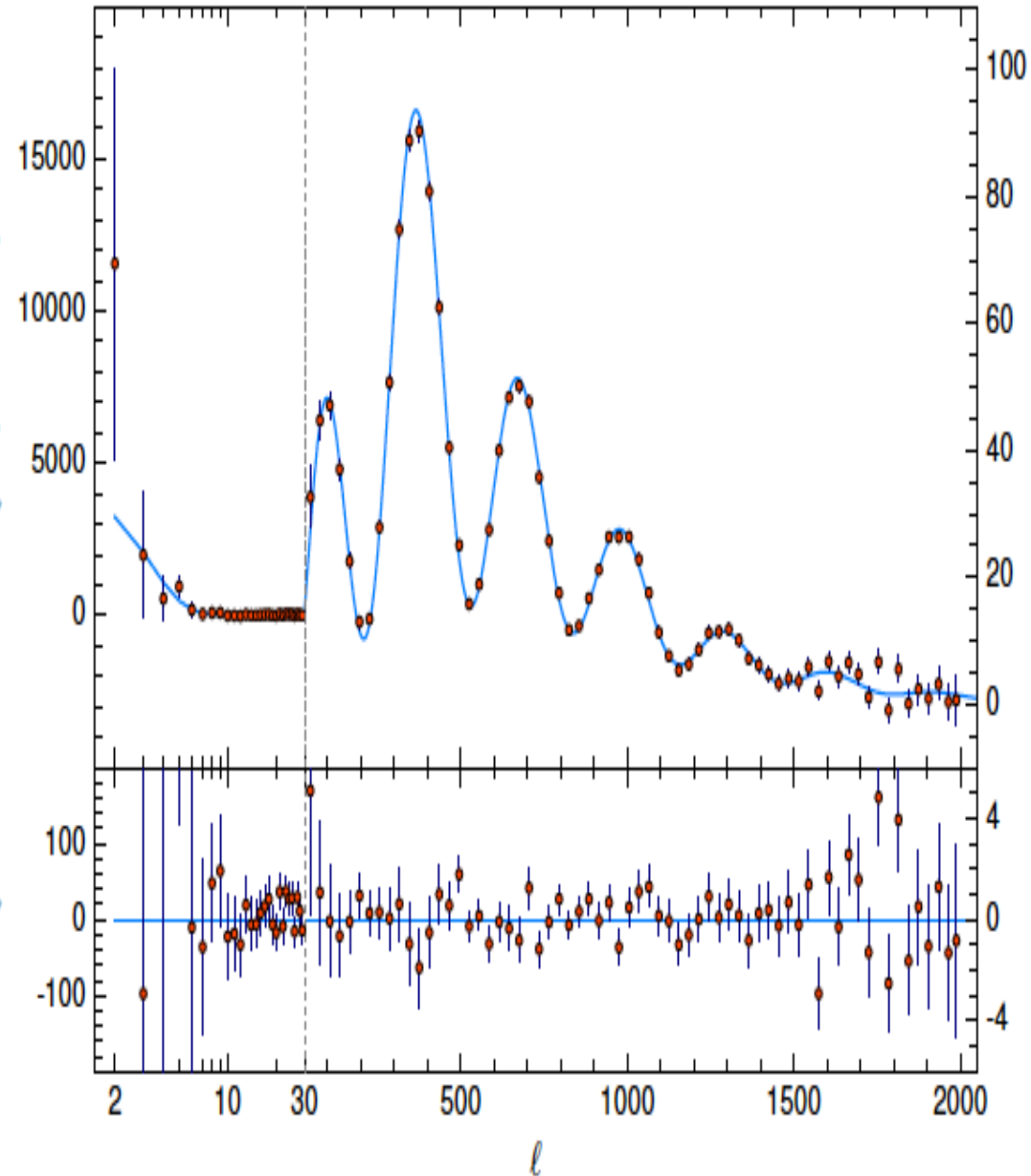
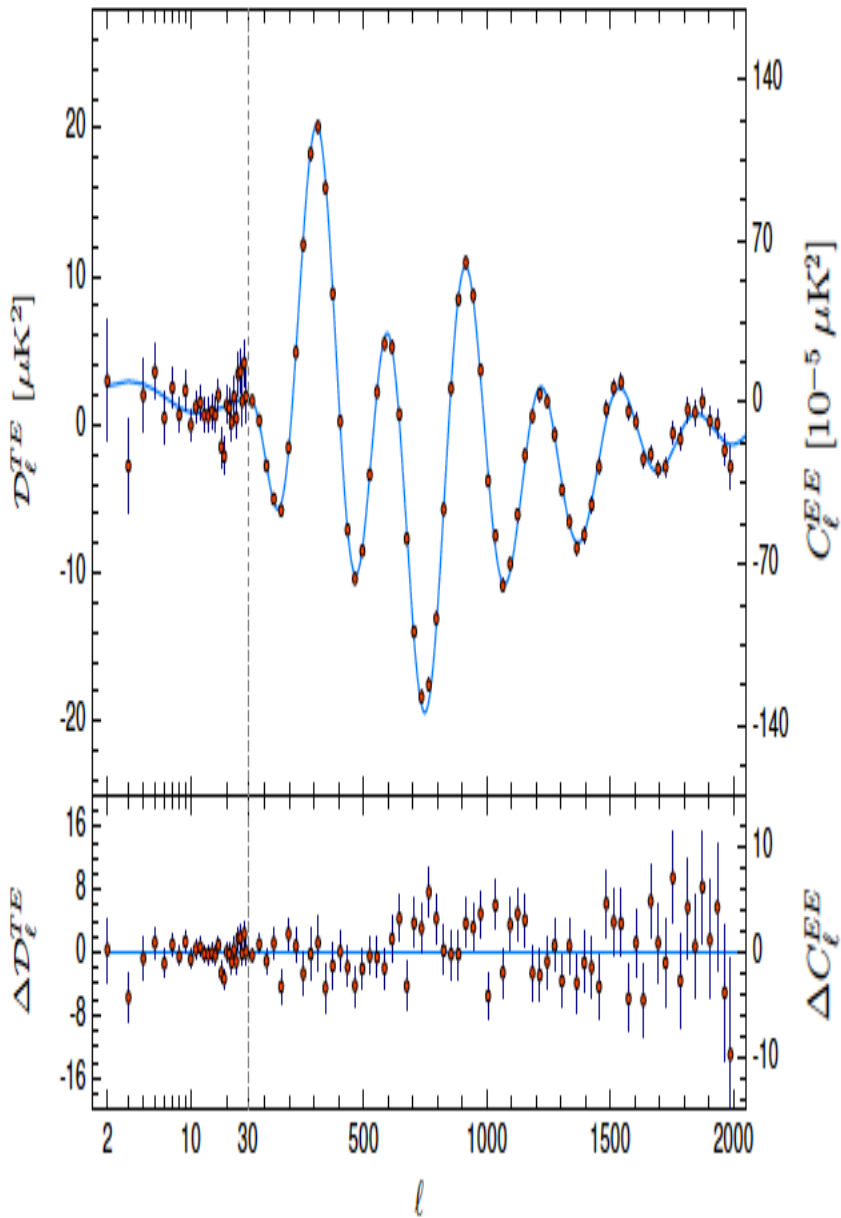
τ = the optical depth from now to the last scattering surface

$r = \text{Tensor} / \text{Scalar}$
 Tensor: Gravitational waves
 Scalar: Density fluctuations

Planck CMB Anisotropy $D_{\ell}^{TT} = 1(l+1) C_{\ell}^T$ 2018



Planck CMB Polarization Power Spectra 2018



Best-fit 6-parameter Λ CDM model 2018

Density perturbation (scalar)

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

$$k_0 = 0.05 \text{Mpc}^{-1}$$

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
$100\theta_{\text{MC}}$	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

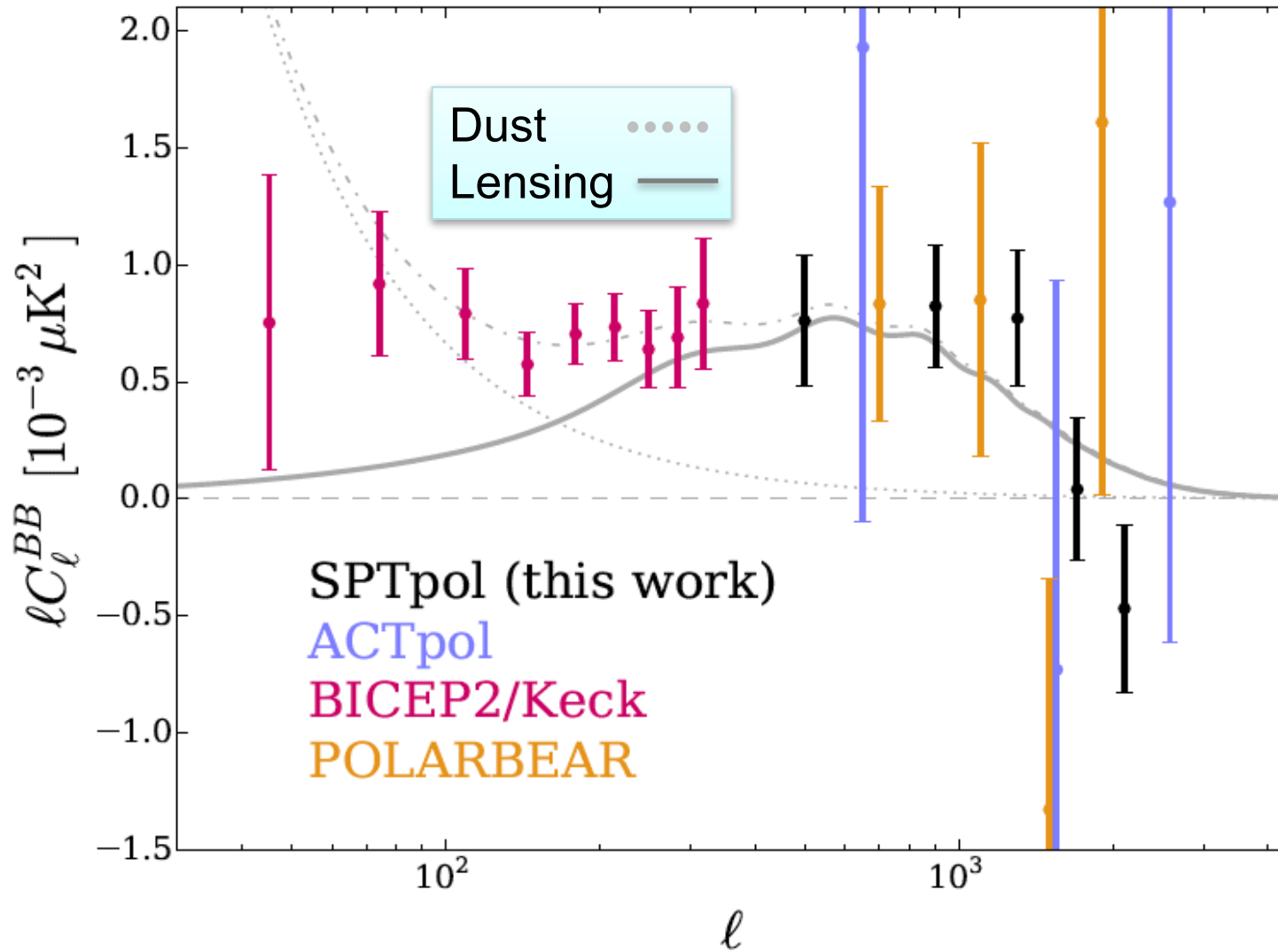
Λ CDM model + 1-parameter extension

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

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

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

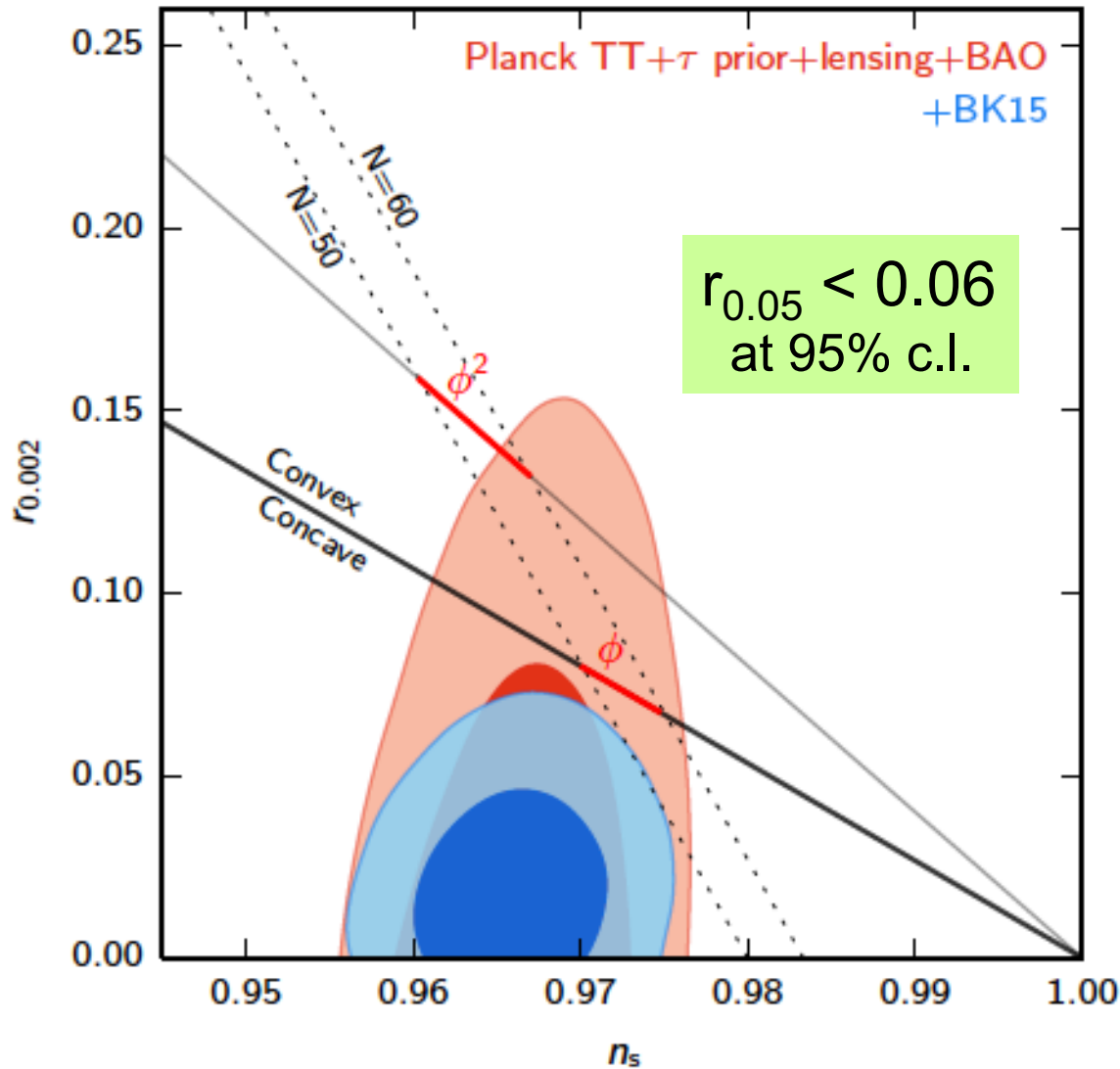
Current B-mode measurements



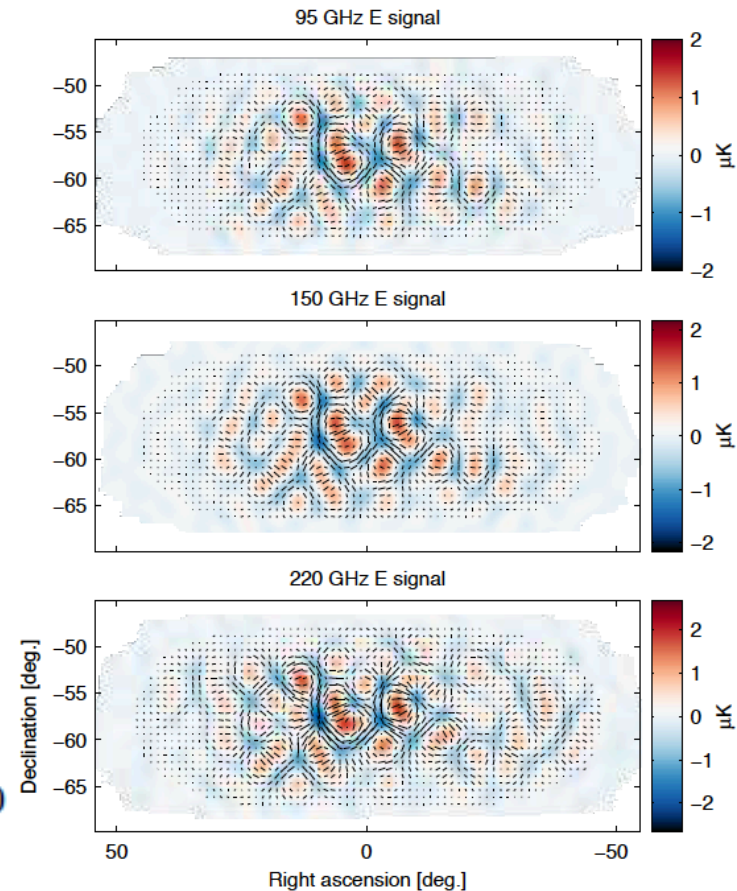
Galactic polarized dust emission
B-mode power spectrum at 150 GHz

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

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



Keck Array 2015 E-polarization data



Search for Cosmic Parity Violation

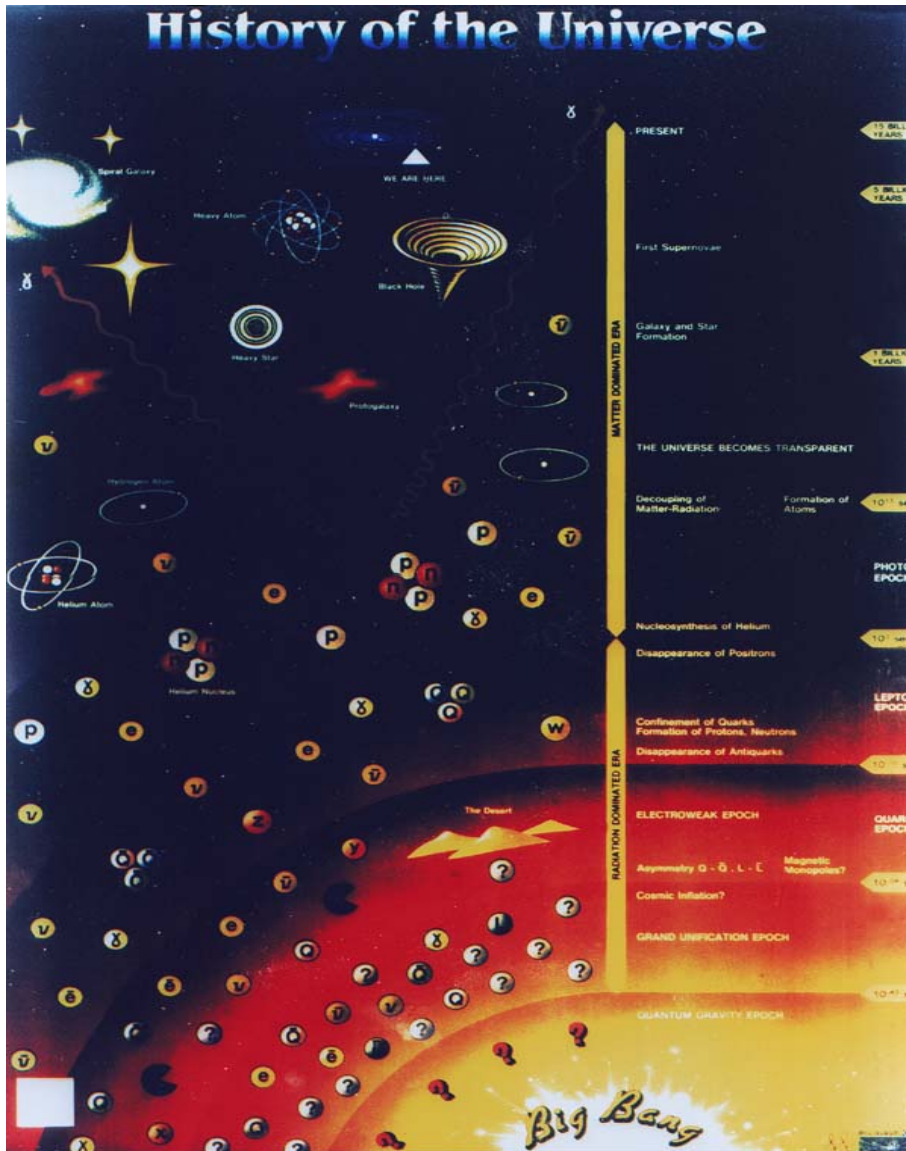
- T. D. Lee and C. N. Yang, C. S. Wu
Parity symmetry is broken in sub-atomic world - weak interaction is left-handed
- Is there any parity violation in the cosmos on the sky?
CMB polarization, polarized radio galaxies,....

CMB power spectra

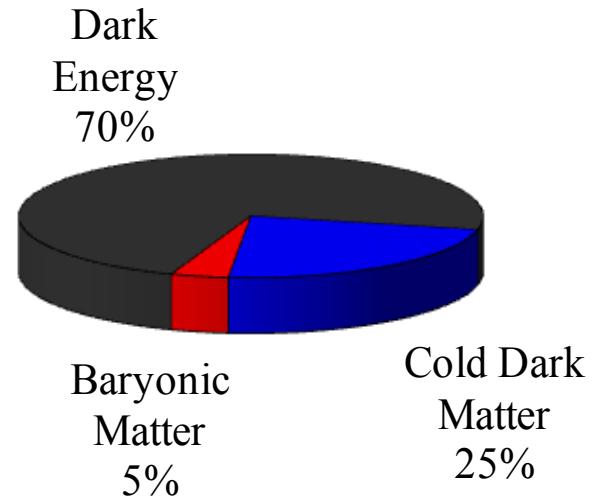
- $\langle TT \rangle$, $\langle EE \rangle$, $\langle BB \rangle$, and $\langle TE \rangle$ correlations exist in standard Λ CDM model
- Since B is odd under parity symmetry, we expect that $\langle TB \rangle = \langle EB \rangle = 0$
- Any trace of $\langle TB \rangle \neq \langle EB \rangle \neq 0$ may indicate parity violation

The Hot Big Bang Model

Cosmic Budget



Fermilab Image 01-582D



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

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

This leads to photon dispersion relation Carroll, Field, Jackiw 90

$$n_{\pm} = \varepsilon \mp \frac{1}{2} \frac{\partial B_{F\tilde{F}}}{\partial \phi} \left(\frac{\partial \phi}{\partial \eta} + \vec{\nabla} \phi \cdot \hat{n} \right) \quad (\varepsilon, \vec{n}) \text{ is the photon four-momentum}$$

± left/right handed η conformal time

vacuum birefringence

then, a rotational speed of polarization plane

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

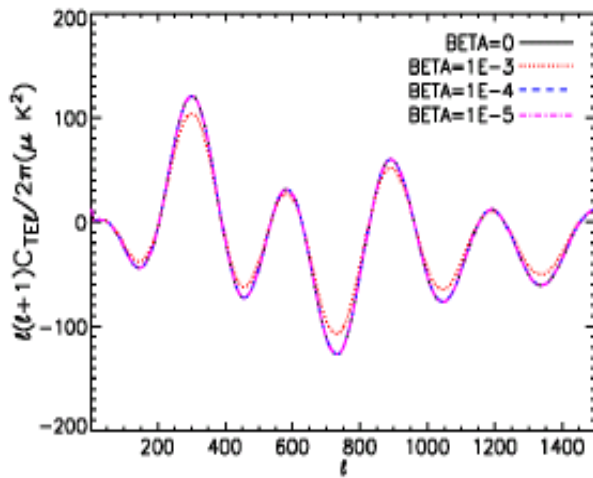
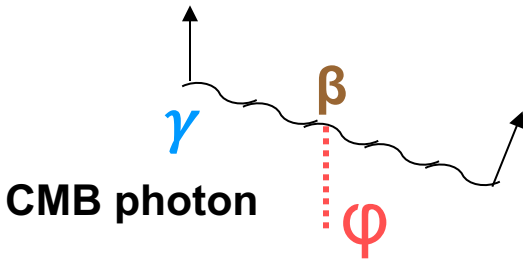
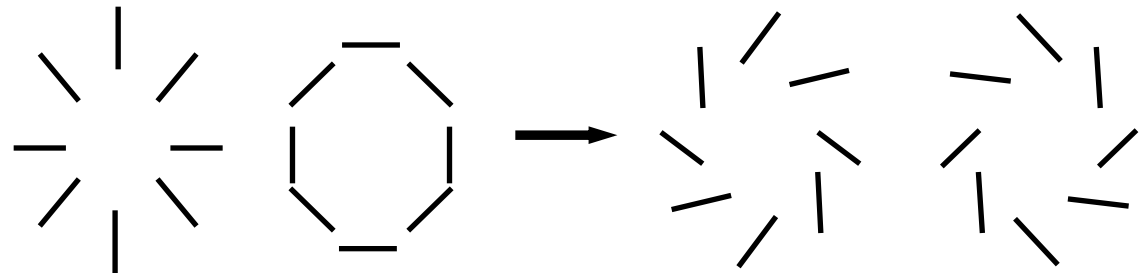
If $B=\beta\phi$, cooling of horizontal branch stars would imply $\beta < 10^7$

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

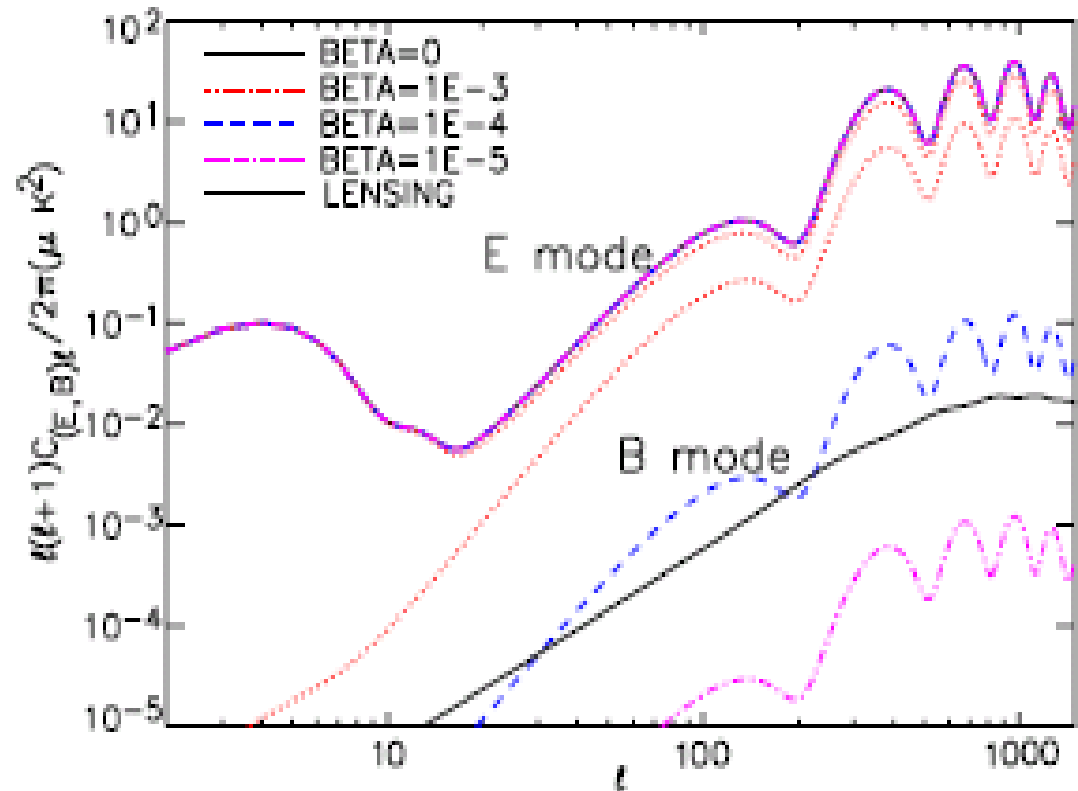
Zhang et al 06
Liu, Lee, Ng 06

electric-type

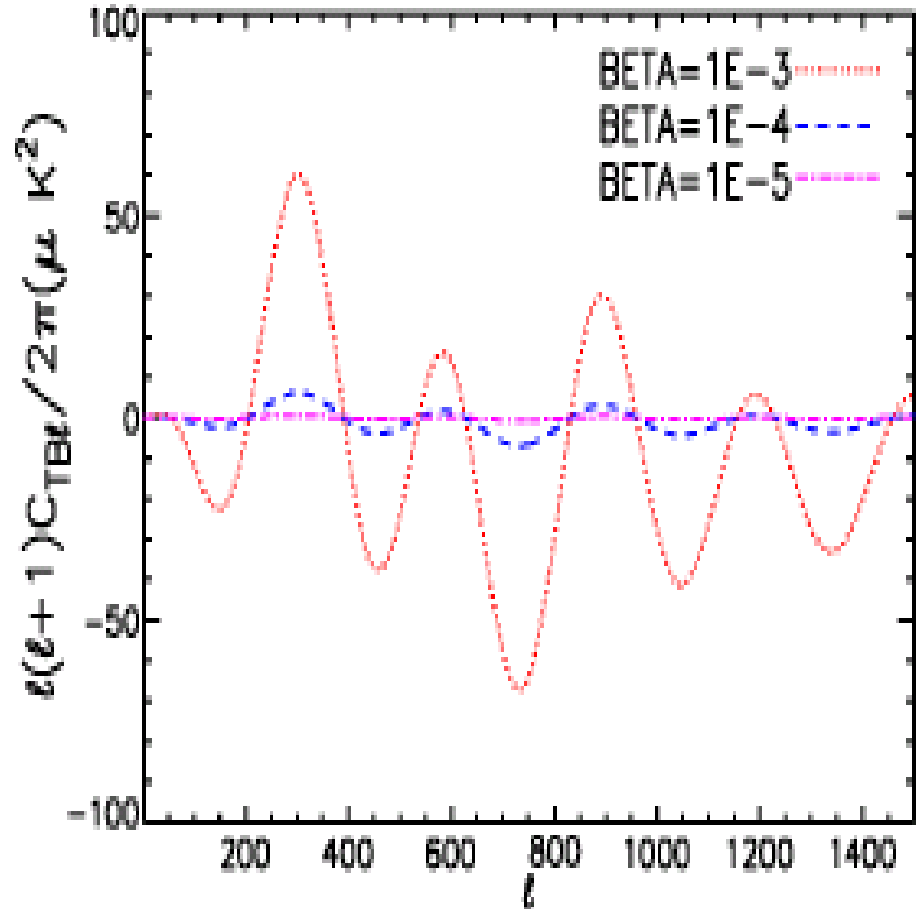
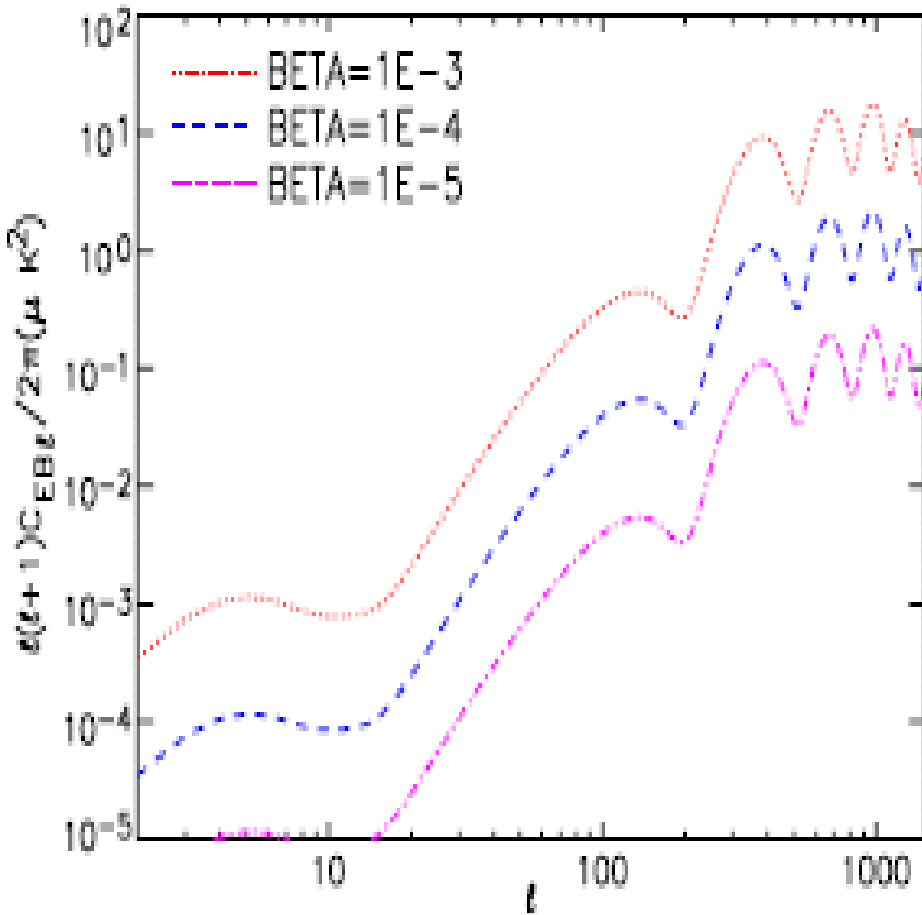
magnetic-type



TE spectrum

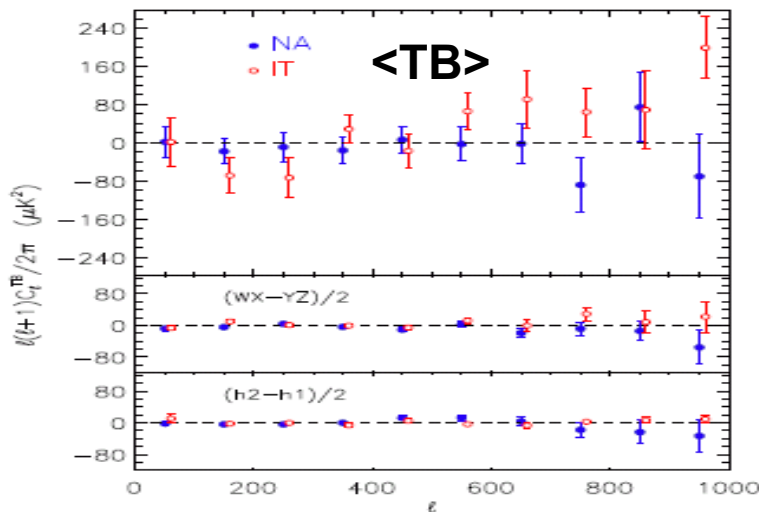
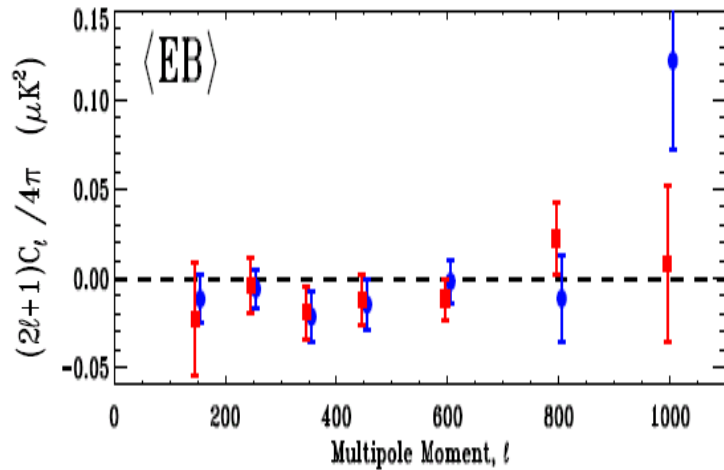


Parity violating EB, TB cross power spectra – cosmic parity violation



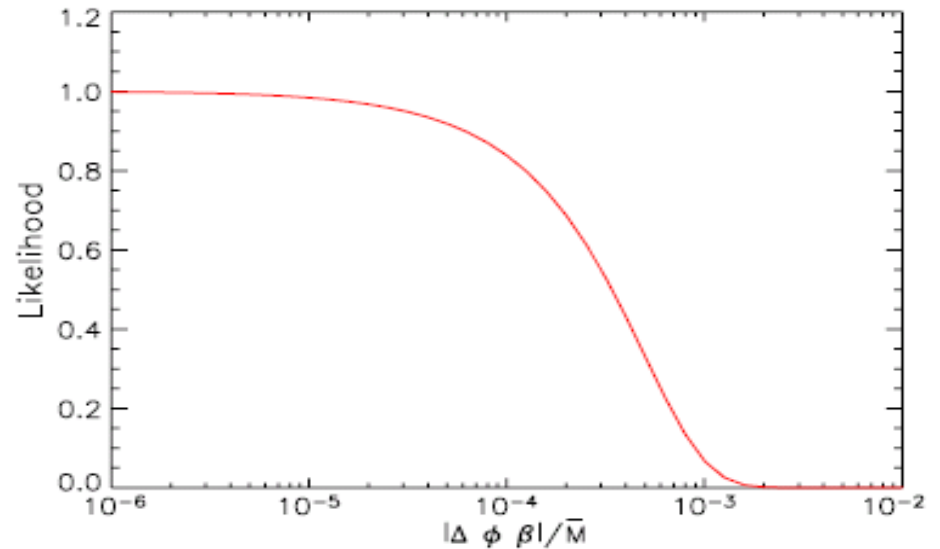
Constraining β by CMB polarization data

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

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

time and space
dependent rotation

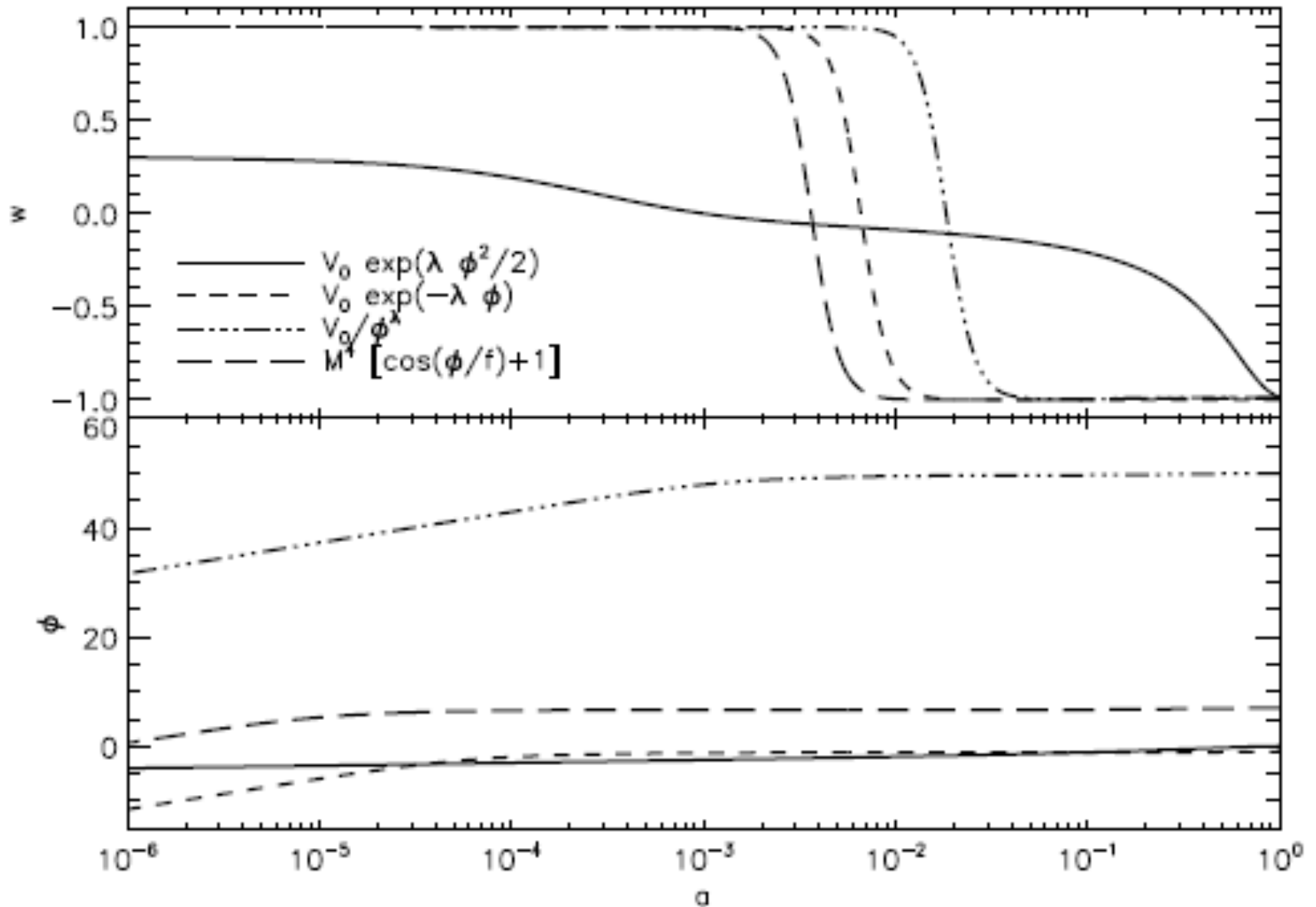
$$\omega = -\frac{1}{2} \frac{\partial B_{F\bar{F}}}{\partial \phi} \left(\frac{\partial \phi}{\partial \eta} + \vec{\nabla} \phi \cdot \hat{n} \right)$$

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

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

- Perturbation induced polarization power spectra in general quintessence models are small
- Interestingly, in nearly Λ CDM models (no time evolution of the mean field), birefringence generates $\langle BB \rangle$ while $\langle TB \rangle = \langle EB \rangle = 0$

We Tried Many Scalar Dark Energy Models



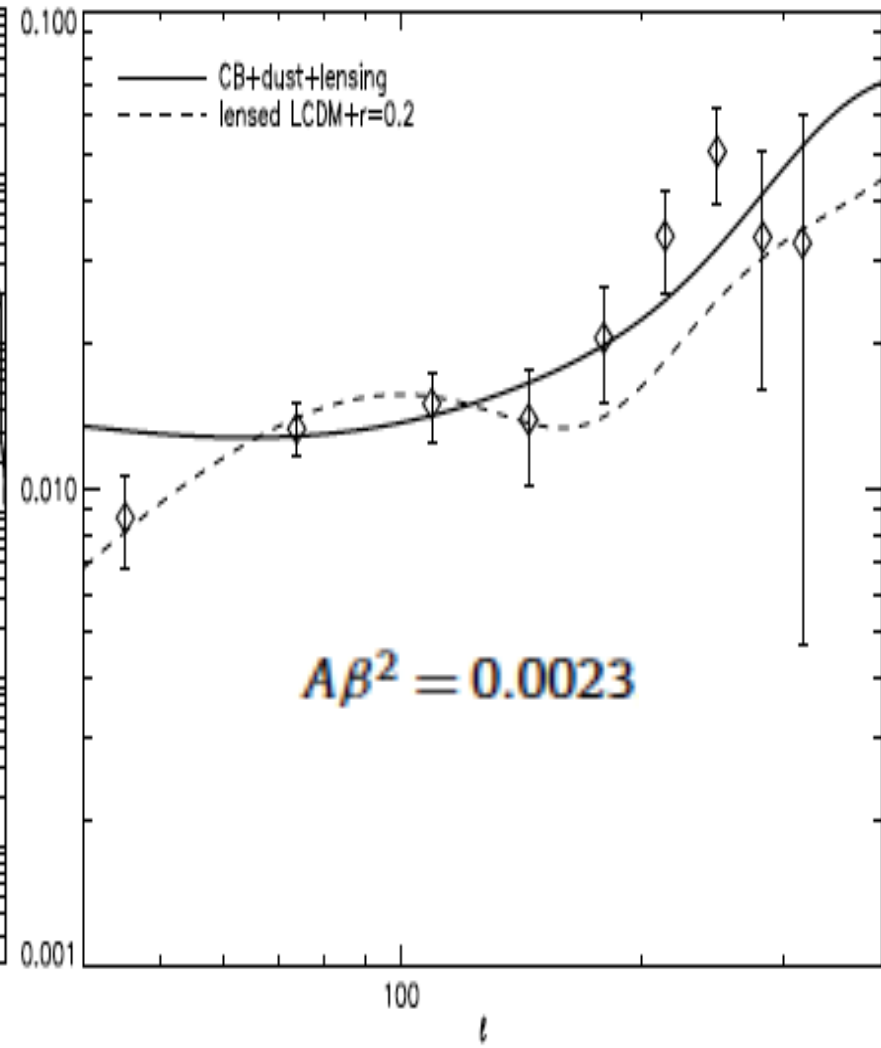
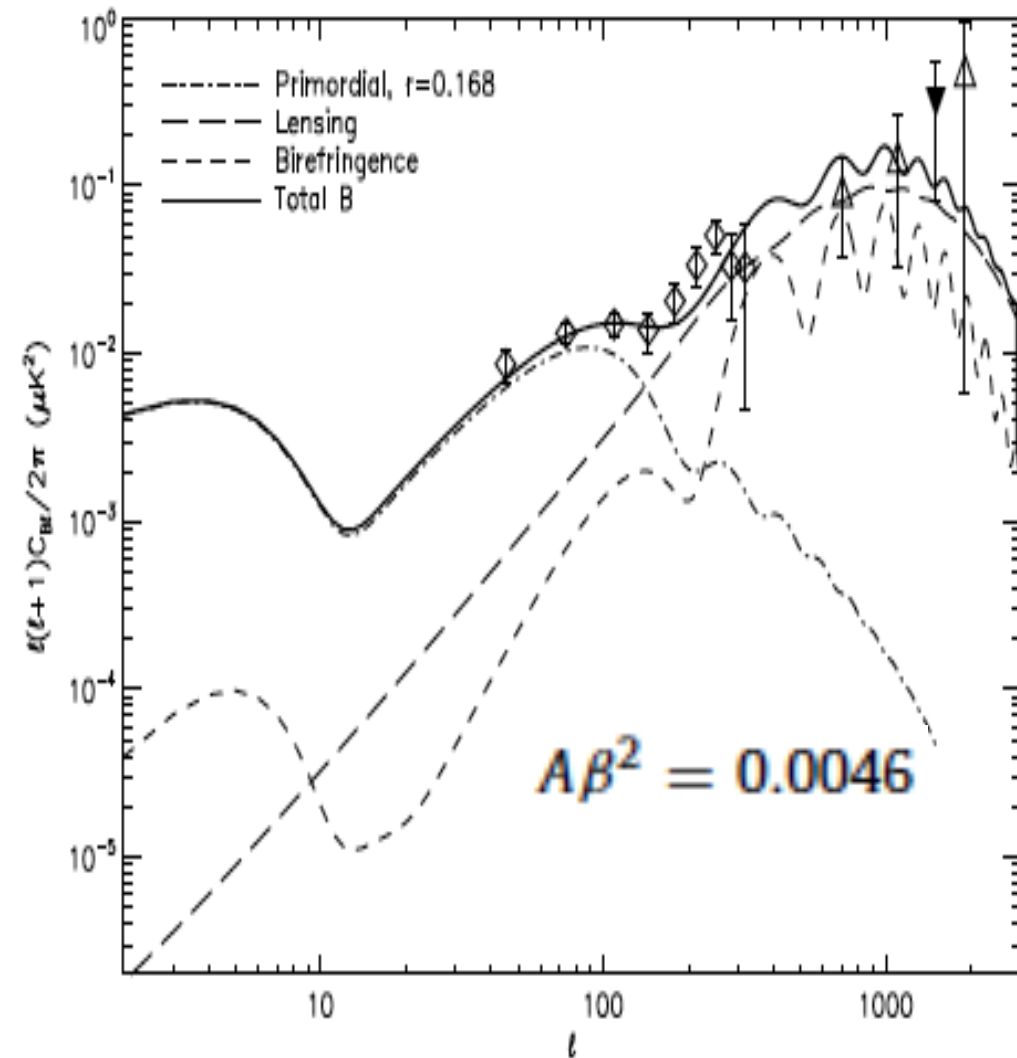
Cosmic Birefringence (CB) Fluctuations

Nearly massless
pseudo scalar

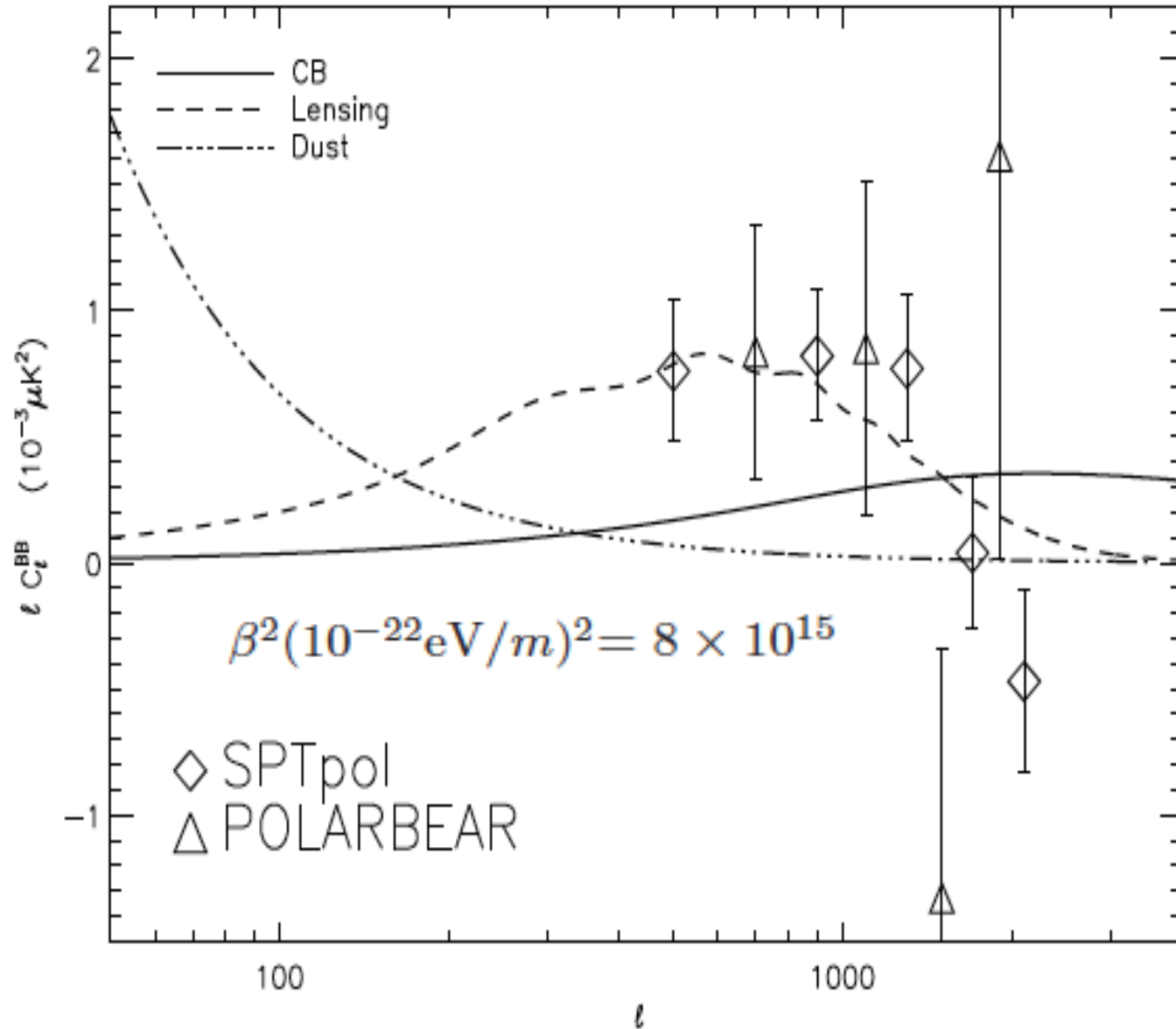
$$\langle \delta\phi_{\vec{k},i} \delta\phi_{\vec{k}',i} \rangle = (2\pi^2/k^3) P_{\delta\phi}(k) \delta(\vec{k} - \vec{k}')$$

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

Pospelov et al. 08
Lee, Liu, Ng14



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



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

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

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

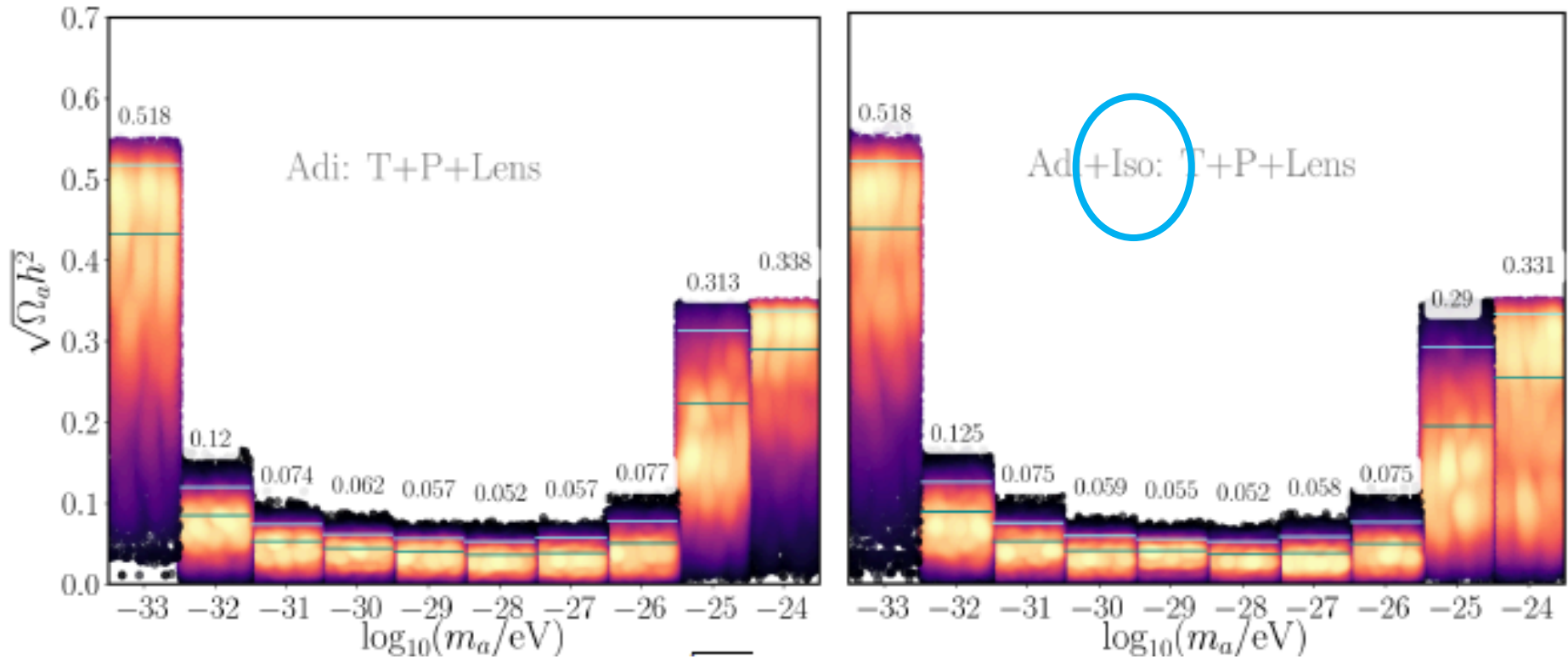
$$\frac{\delta \phi}{M} = \frac{\delta \phi}{\phi} \frac{\phi}{M}$$

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

$$H(a_m) = m$$

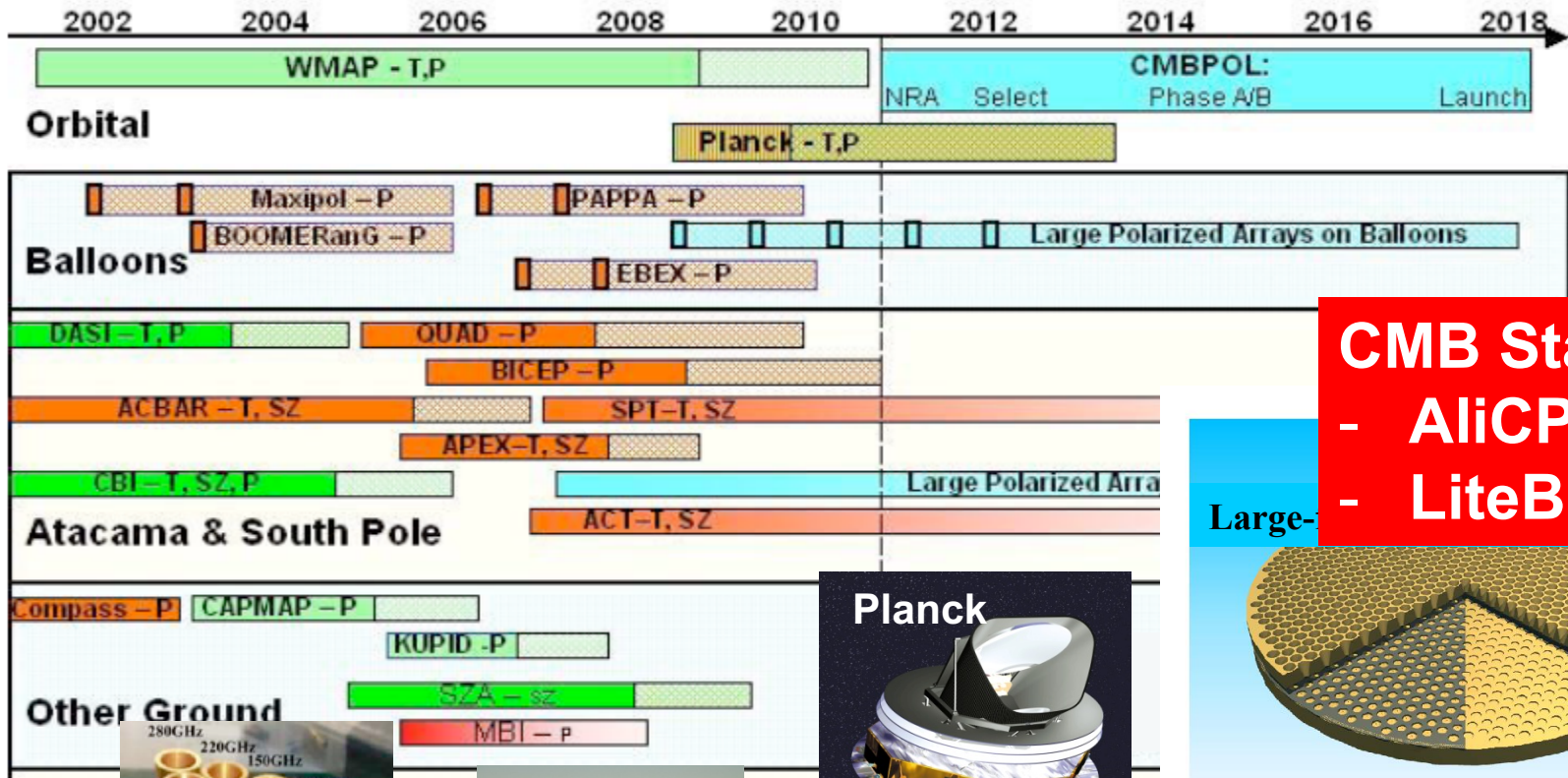
Axion isocurvature perturbation

R. Hložek, D. J. E. Marsh, D. Grin 18

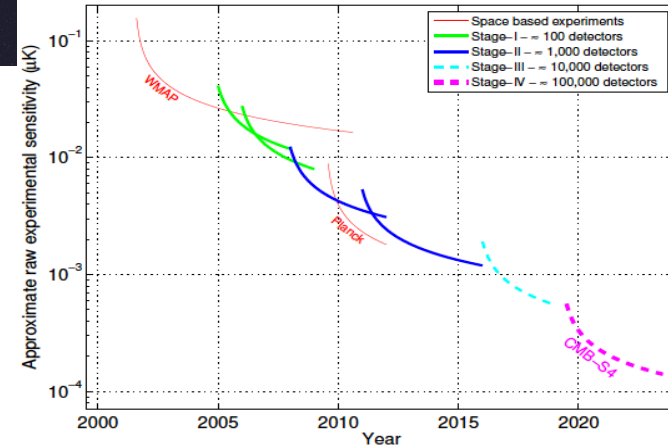
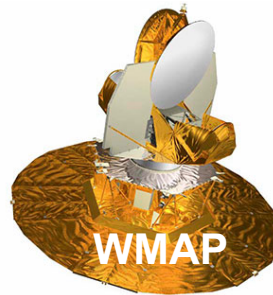
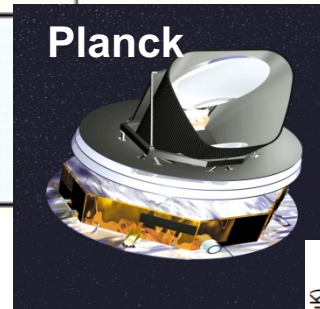
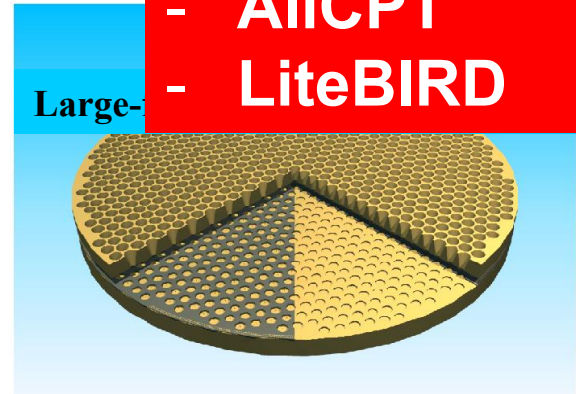


We precisely identify a “window of co-existence” for $10^{-25} \text{ eV} \leq m_a \leq 10^{-24} \text{ eV}$ where the data allow, simultaneously, a $\sim 10\%$ contribution of ULAs to the DM, and $\sim 1\%$ contributions of isocurvature and tensor modes to the CMB power. ULAs in this window (and *all*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

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



CMB Stage-4
 - AliCPT
 - LiteBIRD



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 $\rightarrow \langle BB \rangle, \langle TB \rangle, \langle EB \rangle$
 - Include DE perturbation $\rightarrow \langle BB \rangle, \langle TB \rangle = \langle EB \rangle = 0$
- Axion cold matter matter curvature perturbation $\rightarrow \langle BB \rangle, \langle TB \rangle = \langle EB \rangle = 0$; 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](#)