Axion-induced CMB B modes

Kin-Wang Ng (吳建宏)

Institute of Physics &
Institute of Astronomy and Astrophysics,
Academia Sinica, Taiwan

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Collaborators: Guo-Chin Liu (TKU)
Seokcheon Lee (KIAS)

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

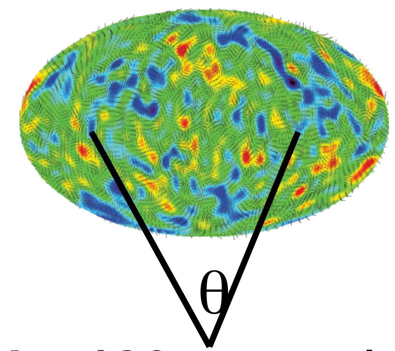
CMB Anisotropy and Polarization Angular Power Spectra

Decompose the CMB sky into a sum of spherical harmonics:

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

$$(Q - iU)(\theta,\varphi) = \Sigma_{lm}\ a_{2,lm}\ {}_2Y_{lm}(\theta,\varphi)$$

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



l = 180 degrees/ θ

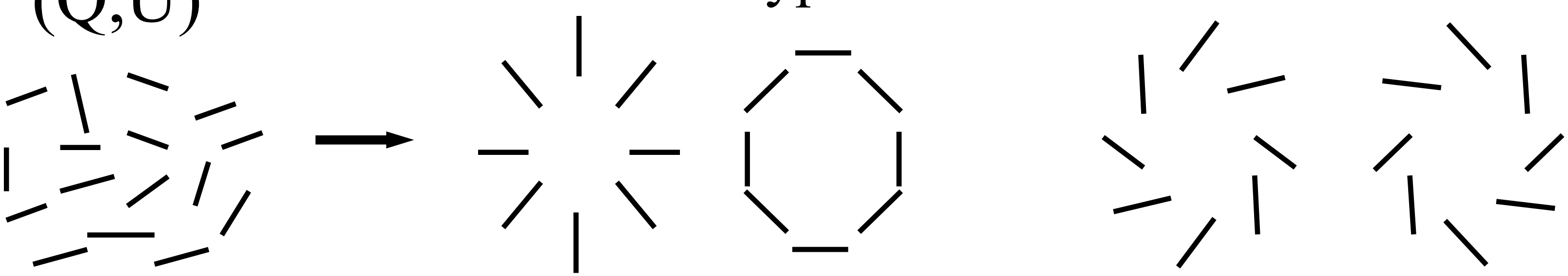
$C^{TT}_l = \Sigma_m (a^*_{lm}\, a_{lm})$ Anisotropy power spectrum

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

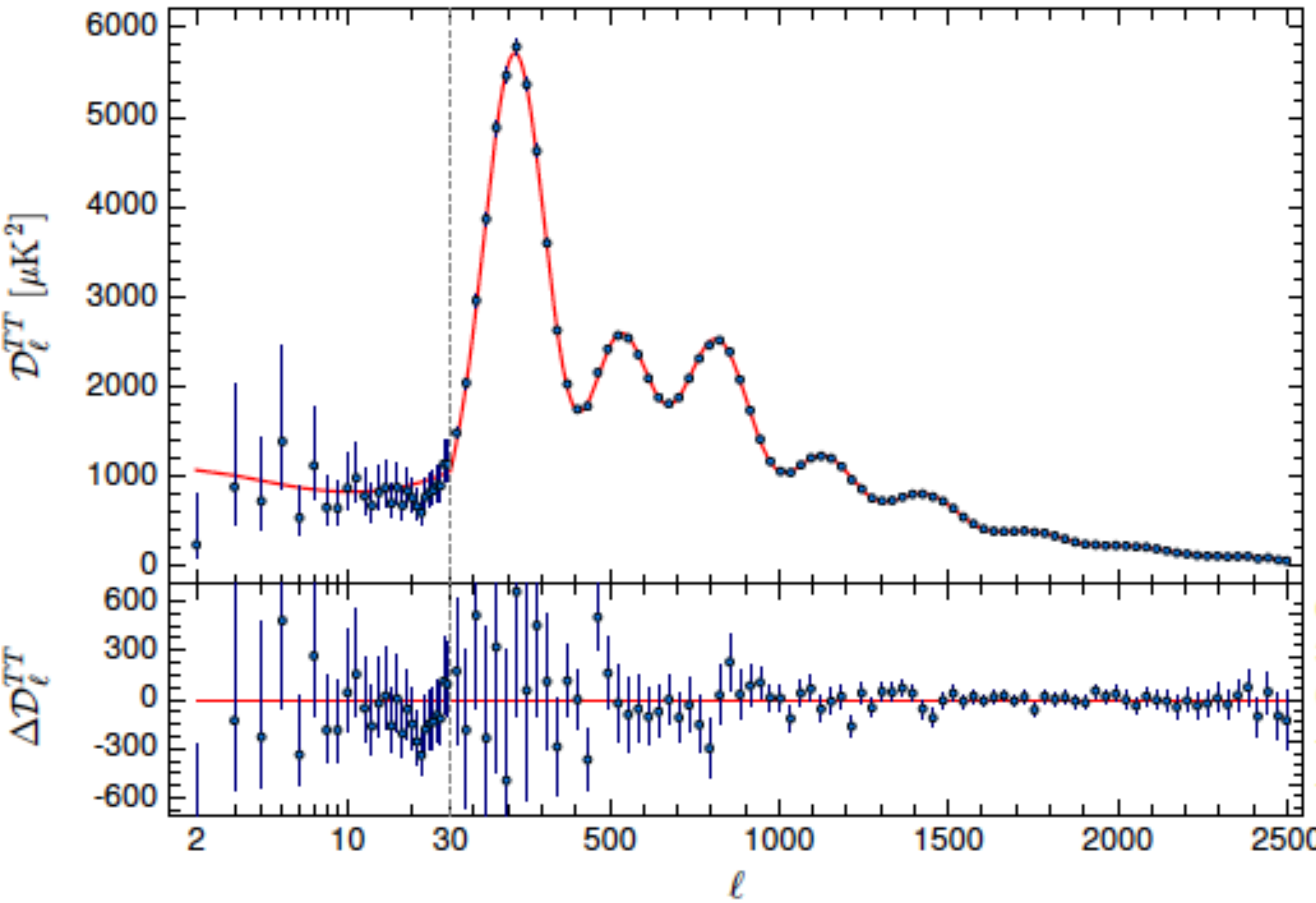
$C^{BB}_l = \Sigma_m (a^*_{2,lm}\, a_{2,lm} - a^*_{2,lm}\, a_{-2,lm})$ B-polarization power

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

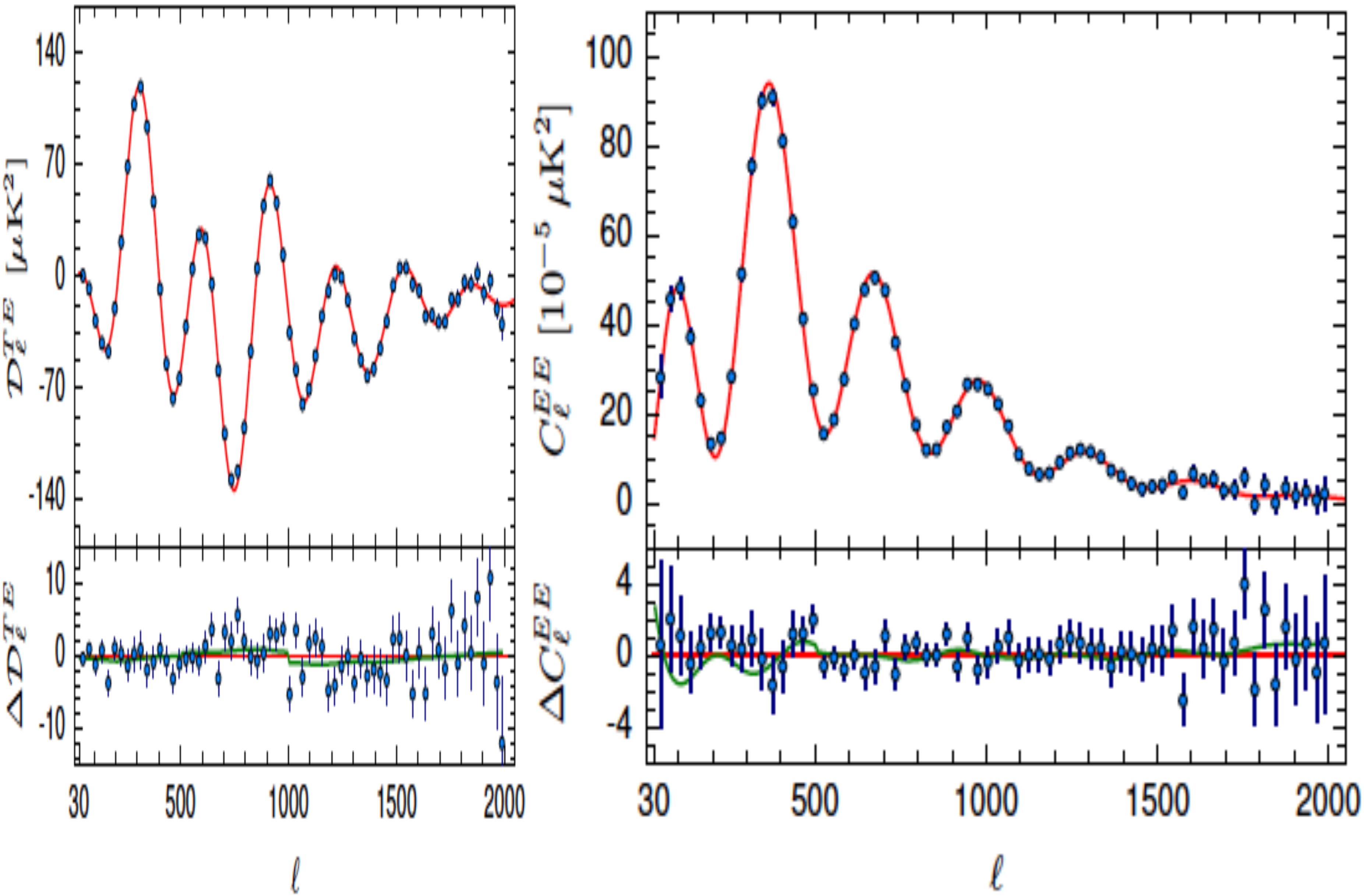
(Q,U) electric-type magnetic-type



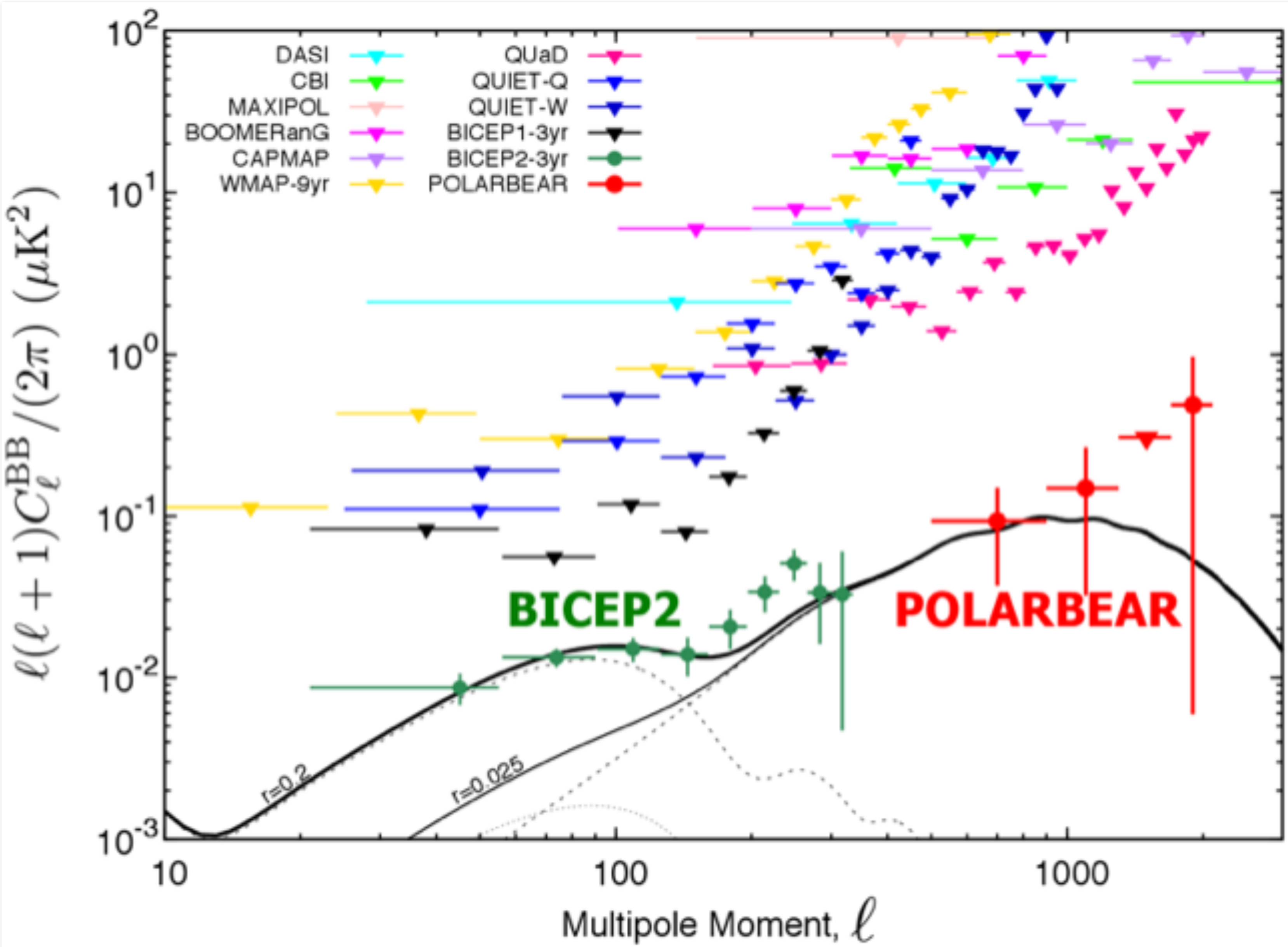
Planck CMB Anisotropy $D^{TT}_l = l(l+1)\ C^T_l$ 2015



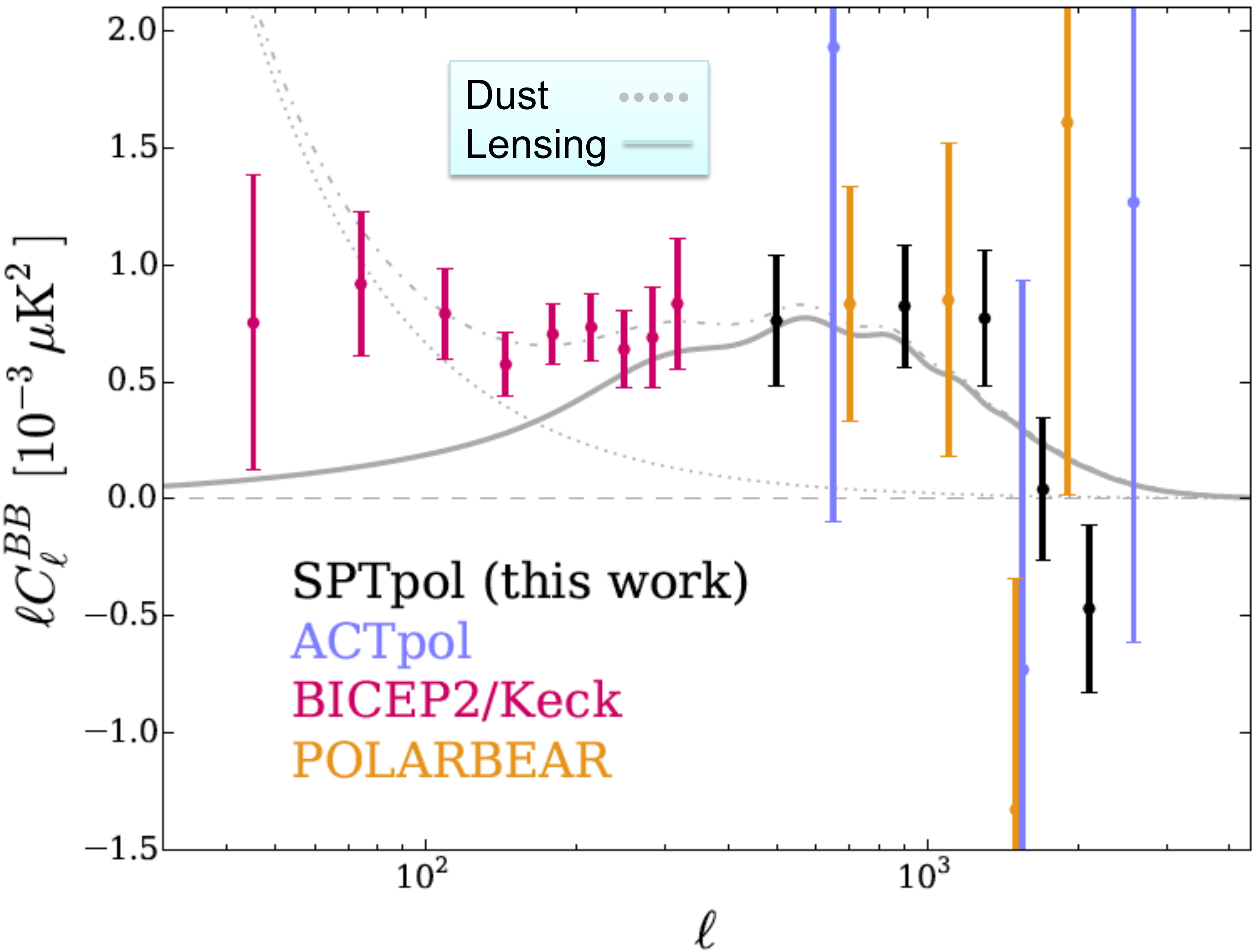
Planck CMB Polarization Power Spectra 2015



POLARBEAR+BICEP2 B-mode Detection



More B-mode detection



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 $\quad \eta$ conformal time

vacuum birefringence

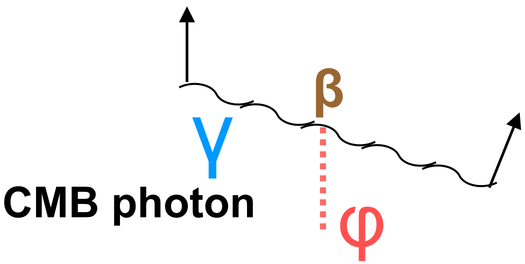
then, a rotational speed of polarization plane

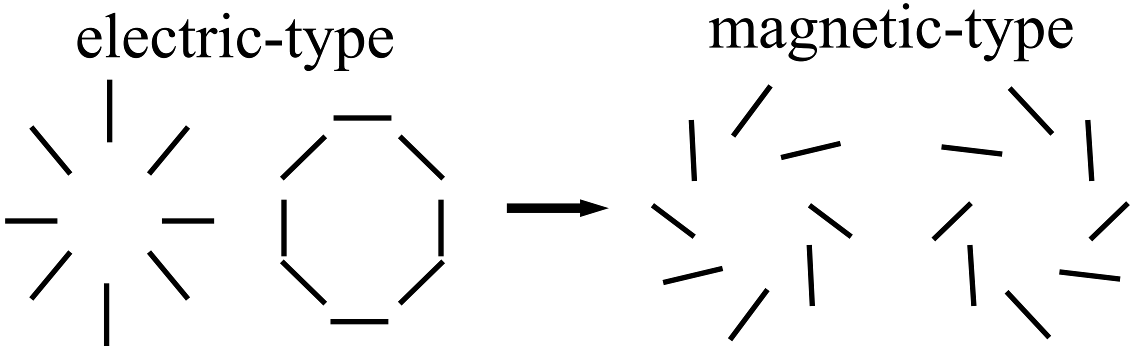
$$\omega = \frac{1}{2}(n_+ - n_-) = -\frac{1}{2}\frac{\partial B_{F\tilde{F}}}{\partial\phi}\left(\frac{\partial\phi}{\partial\eta} + \vec{\nabla}\phi\cdot\hat{n}\right)$$

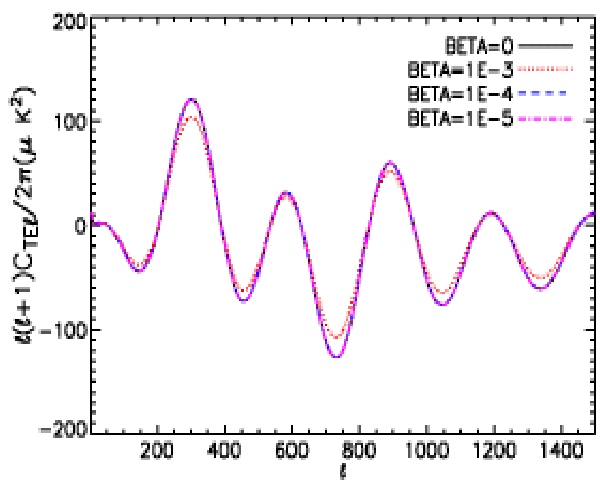
If $B=\beta\varphi$, cooling of horizontal branch stars would imply $\beta<10^7$

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

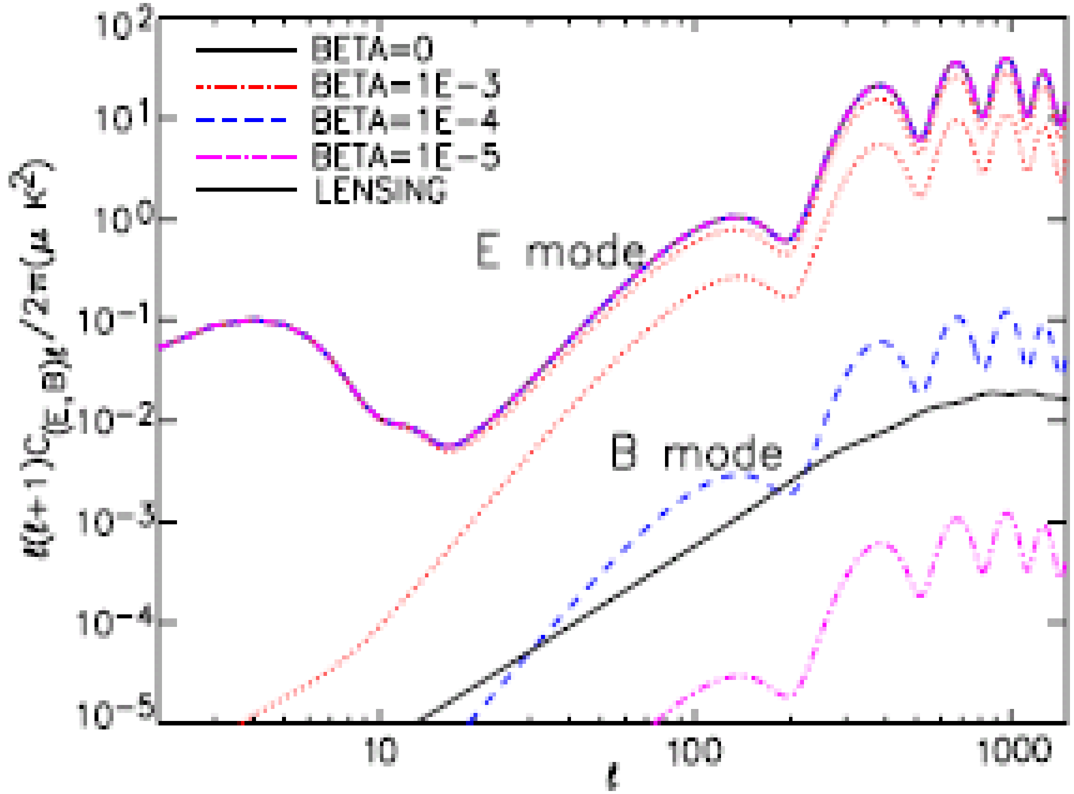
Liu,Lee,Ng 06







TE spectrum



Radiative transfer equation

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

$$\sum_m \sqrt{\frac{6\pi}{5}}\, {}_{\pm 2}Y_2^m(\hat{n}) S_P^{(m)}(\vec{k},\eta)\Bigg] \mp i2\omega\Delta_{Q\mp iU}(\vec{k},\eta),$$

μ=n·k,
η: conformal time
a: scale factor
n_e: e density
σ_T: Thomson cross section

Source term for polarization $$S_P^{(m)}(\vec{k},\eta) \equiv \Delta_{T2}^{(m)}(\vec{k},\eta) + 12\sqrt{6}\Delta_{+,2}^{(m)}(\vec{k},\eta) + 12\sqrt{6}\Delta_{-,2}^{(m)}(\vec{k},\eta)$$

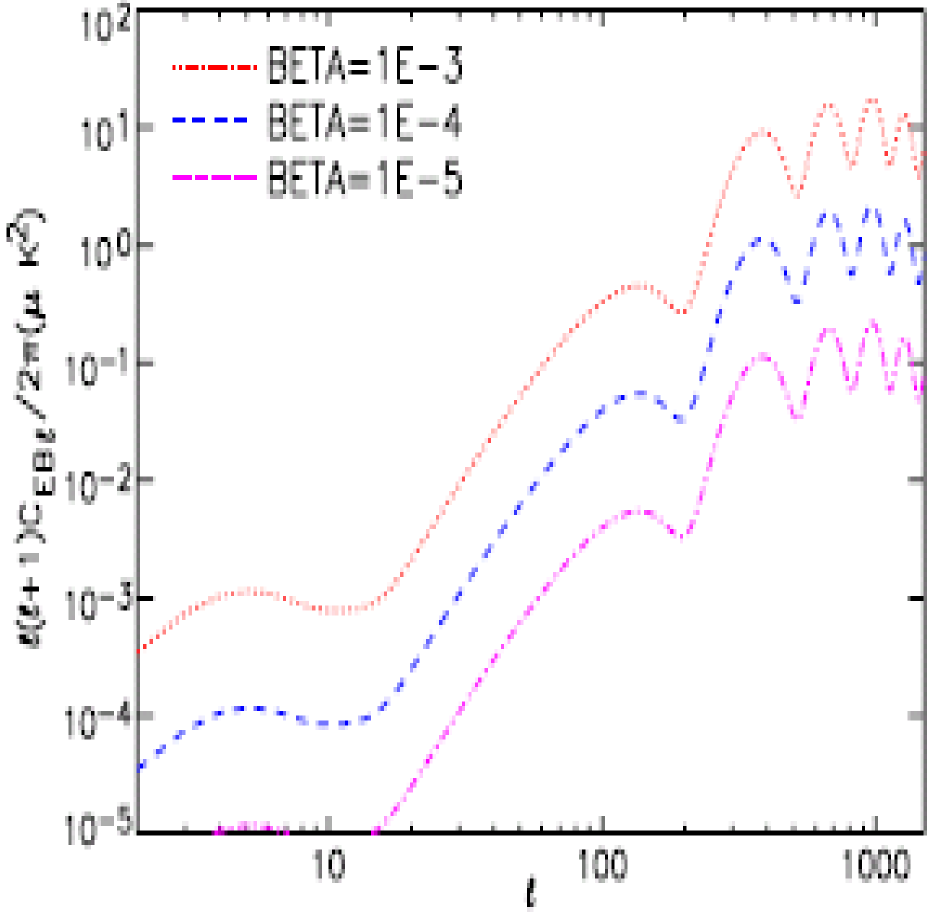
Cosmic rotation $$\bar{\omega}(\eta) = -\frac{1}{2}\beta_{F\tilde{F}}\frac{d\bar{\phi}}{d\eta}.$$

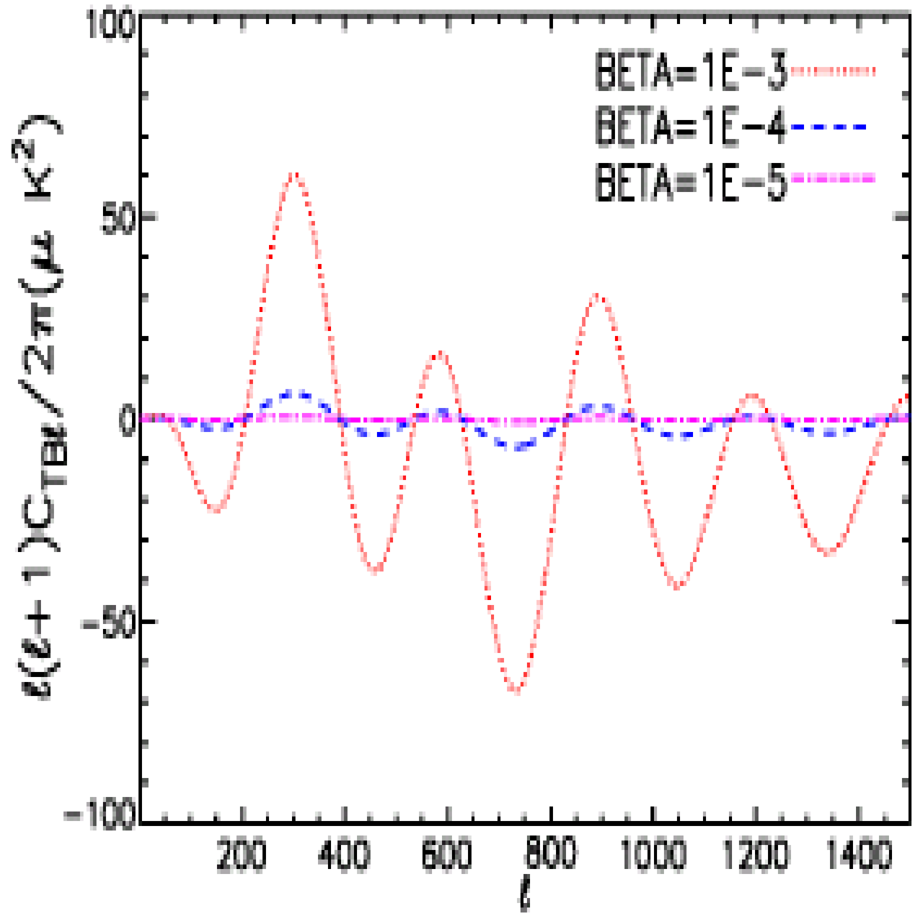
$$\mathcal{L}_N = -\frac{1}{4}\sqrt{-g}B_{F\tilde{F}}(\phi)F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$B_{F\tilde{F}} = \beta_{F\tilde{F}}\phi \quad \phi \equiv \frac{\Phi}{M}$$

Rotation angle $$\alpha(\eta) = \int_\eta^{\eta 0} d\eta' \omega(\eta')$$

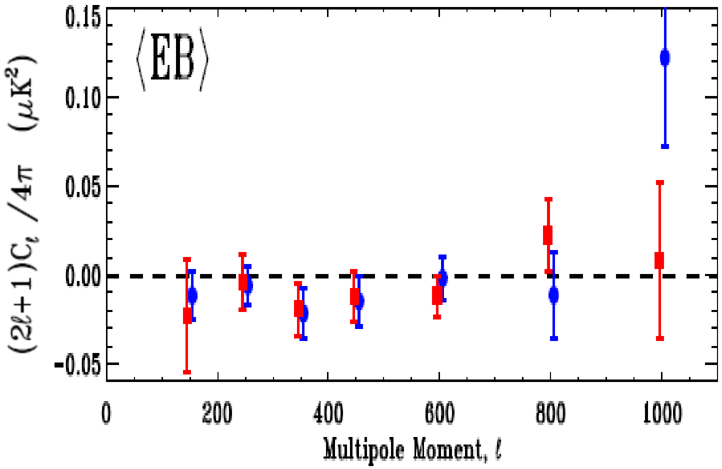
Parity violating EB,TB cross power spectra – cosmic parity violation

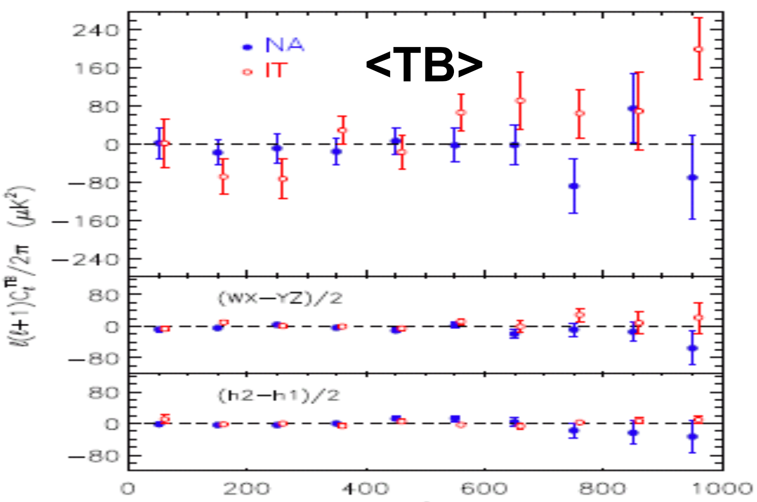




Constraining β by CMB polarization data

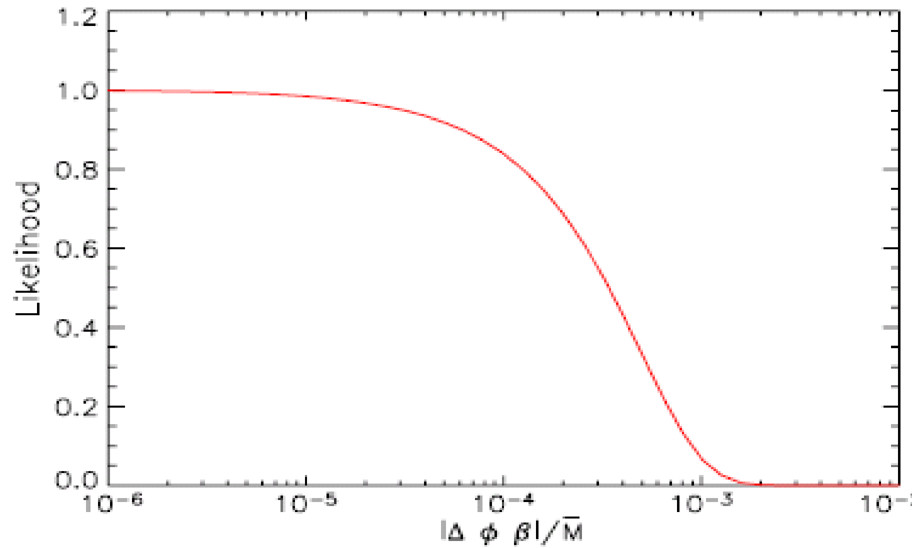
2003 Flight of BOOMERANG





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 ……….
….Ni et al.

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

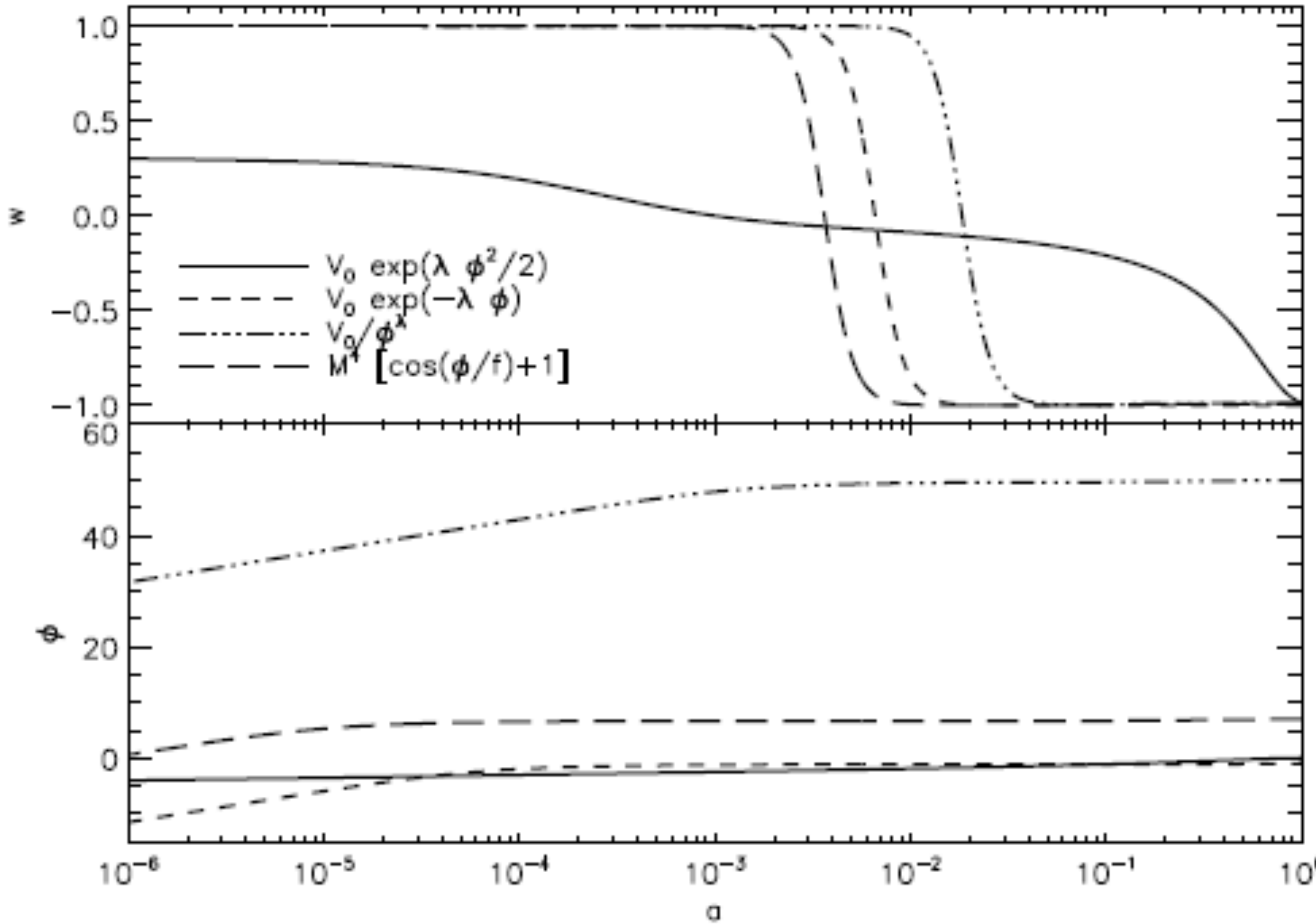
$$\omega = -\frac{1}{2}\frac{\partial B_{F\tilde{F}}}{\partial\phi}\left(\frac{\partial\phi}{\partial\eta} + \vec{\nabla}\phi\cdot\hat{n}\right)$$

$$\dot{\Delta}_{Q\pm iU}(\vec{k},\eta) + ik\mu\Delta_{Q\pm iU}(\vec{k},\eta) = n_e\sigma_T a(\eta)\Big[-\Delta_{Q\pm iU}(\vec{k},\eta)\times \sum_m\sqrt{\frac{6\pi}{5}}\,{}_{\pm2}Y_2^m(\hat{n})S_P^{(m)}(\vec{k},\eta)\Big] \mp i2\frac{1}{\sqrt{(2\pi)^3}}\int d\vec{k}'\,\tilde{\omega}(\vec{k}-\vec{k}',\eta)\Delta_{Q\pm iU}(\vec{k}',\eta)$$

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

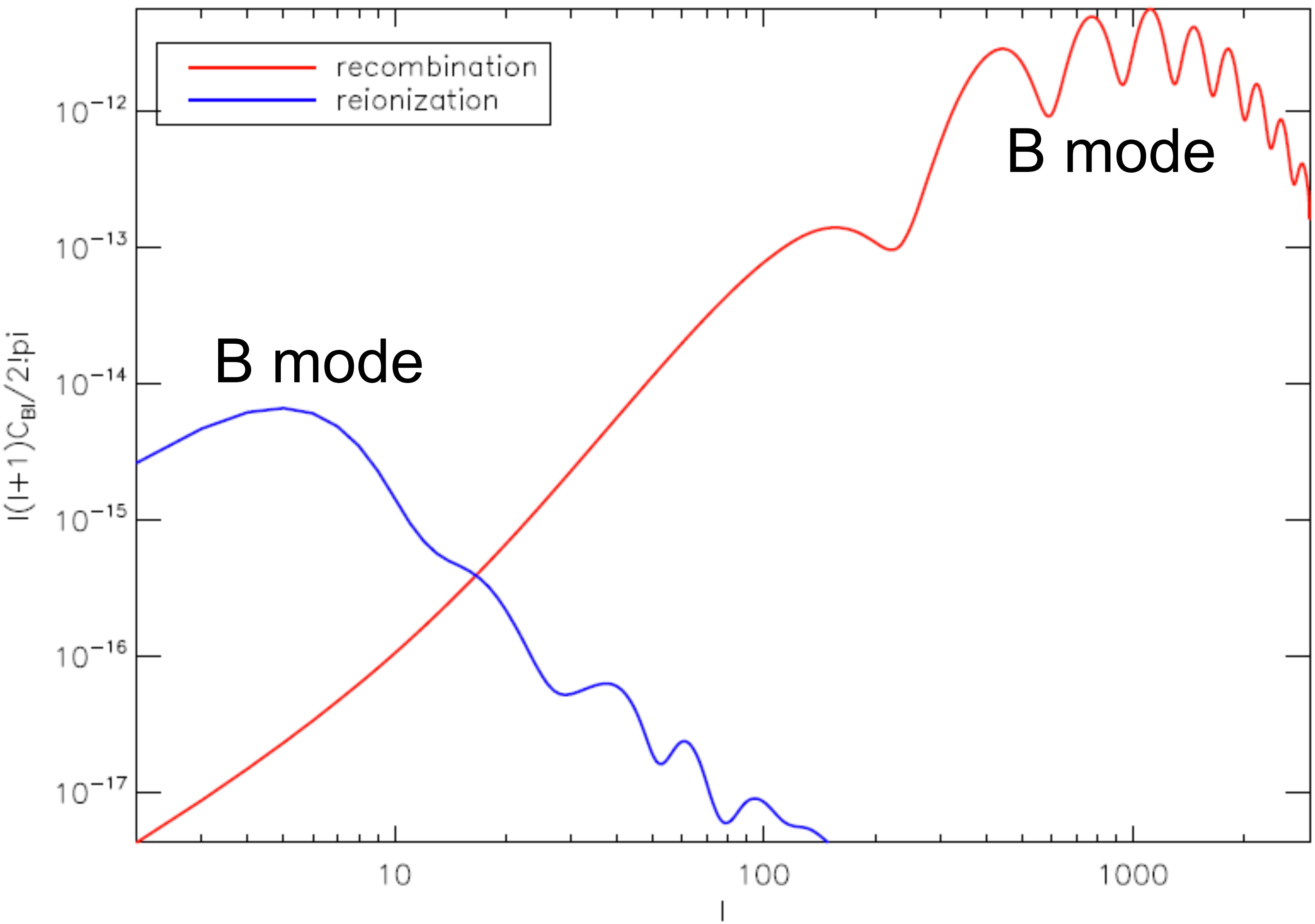
- Perturbation induced polarization power spectra in general quintessence models are small
- Interestingly, in nearly ΛCDM models (no time evolution of the mean field), birefringence generates <BB> while <TB>=<EB>=0

We Tried Many Scalar Dark Energy Models



Dark energy perturbation with w=-1 Lee,Liu,Ng 14

Birefringence generates <BB> while <TB>=<EB>=0



Cosmic Birefringence Fluctuations

Lee, Liu, Ng14

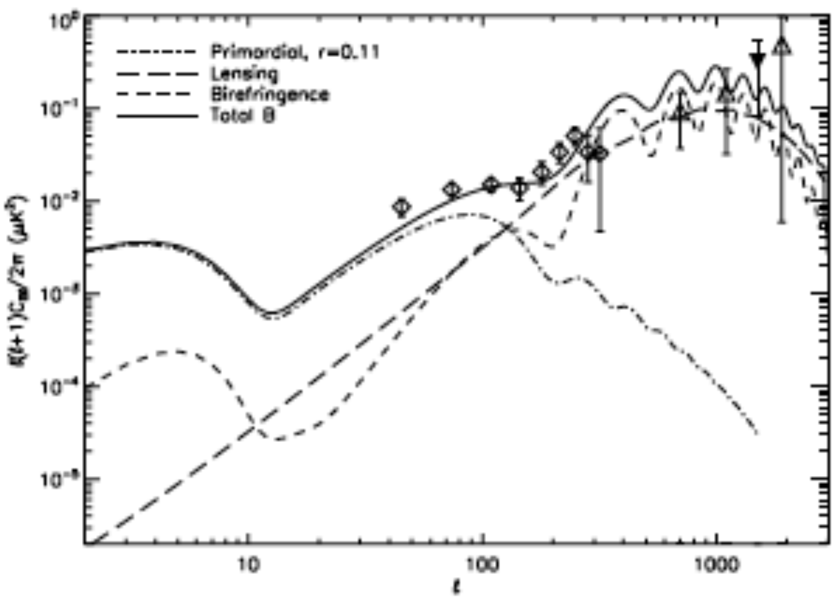
Nearly massless pseudo scalar

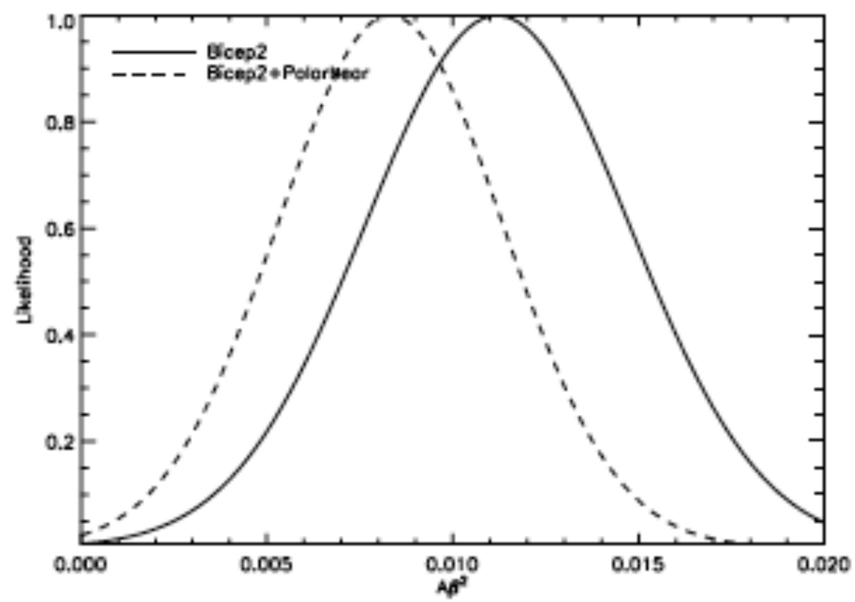
$$\left\langle \delta\phi_{\vec{k},i}\delta\phi_{\vec{k}',i}\right\rangle = (2\pi^2/k^3)P_{\delta\phi}(k)\,\delta(\vec{k}-\vec{k}')$$

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

Lensed-LCDM+r=0.11+CB

Lee, Liu & Ng arXiv:1403.5585





$A\beta^2 = 0.0112 \pm 0.032$ BICEP2

$A\beta^2 = 0.0084 \pm 0.029$ BICEP2+POLARBEAR

Planck mission has put an upper limit on $A < 3.4 \times 10^{-11}$

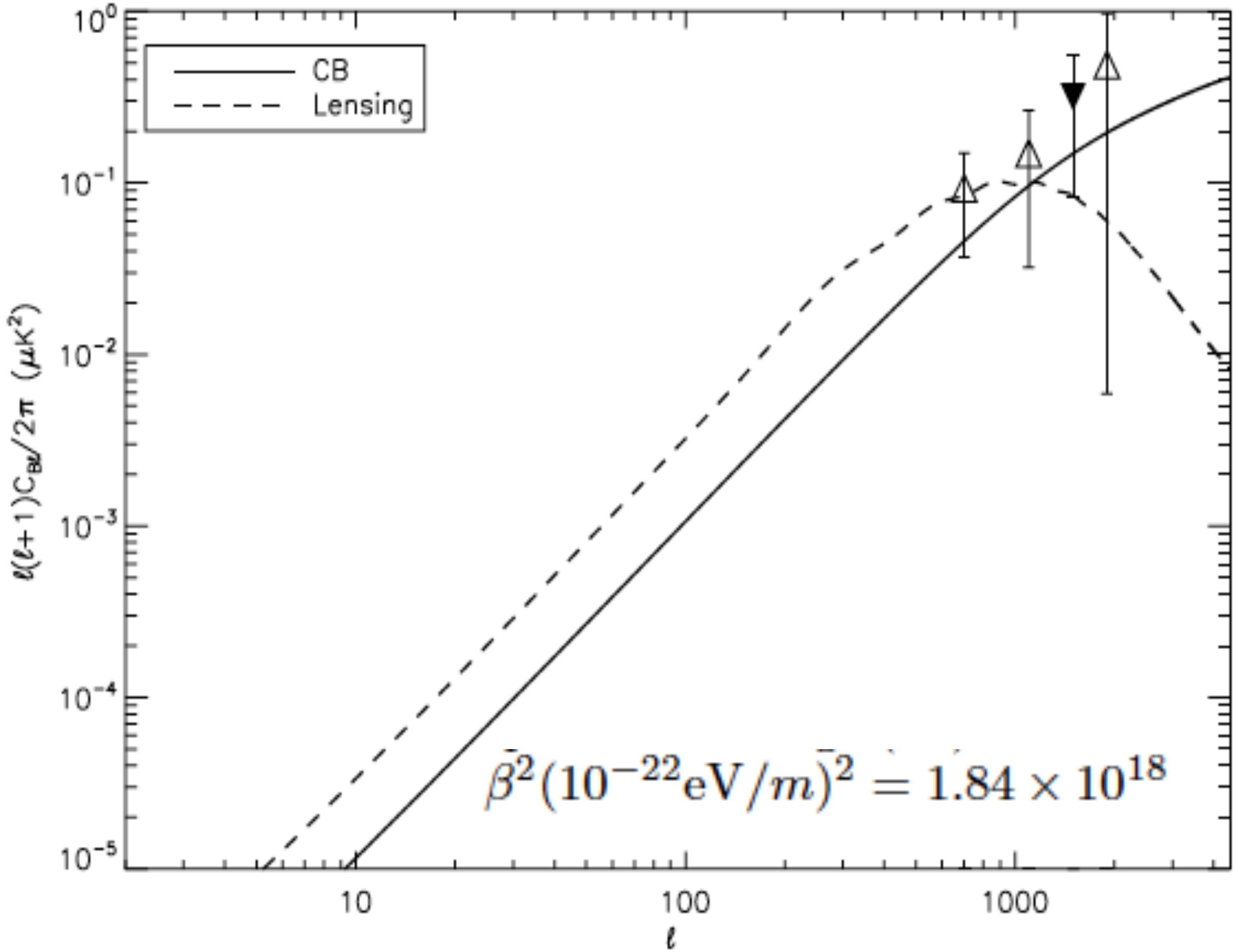
$\chi^2(r=0.2+\text{lensing}) - \chi^2(\text{CB}+r=0.11+\text{lensing}) = -3.01$

Only use BICEP2+Polarbear data

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

(preliminary !)

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



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

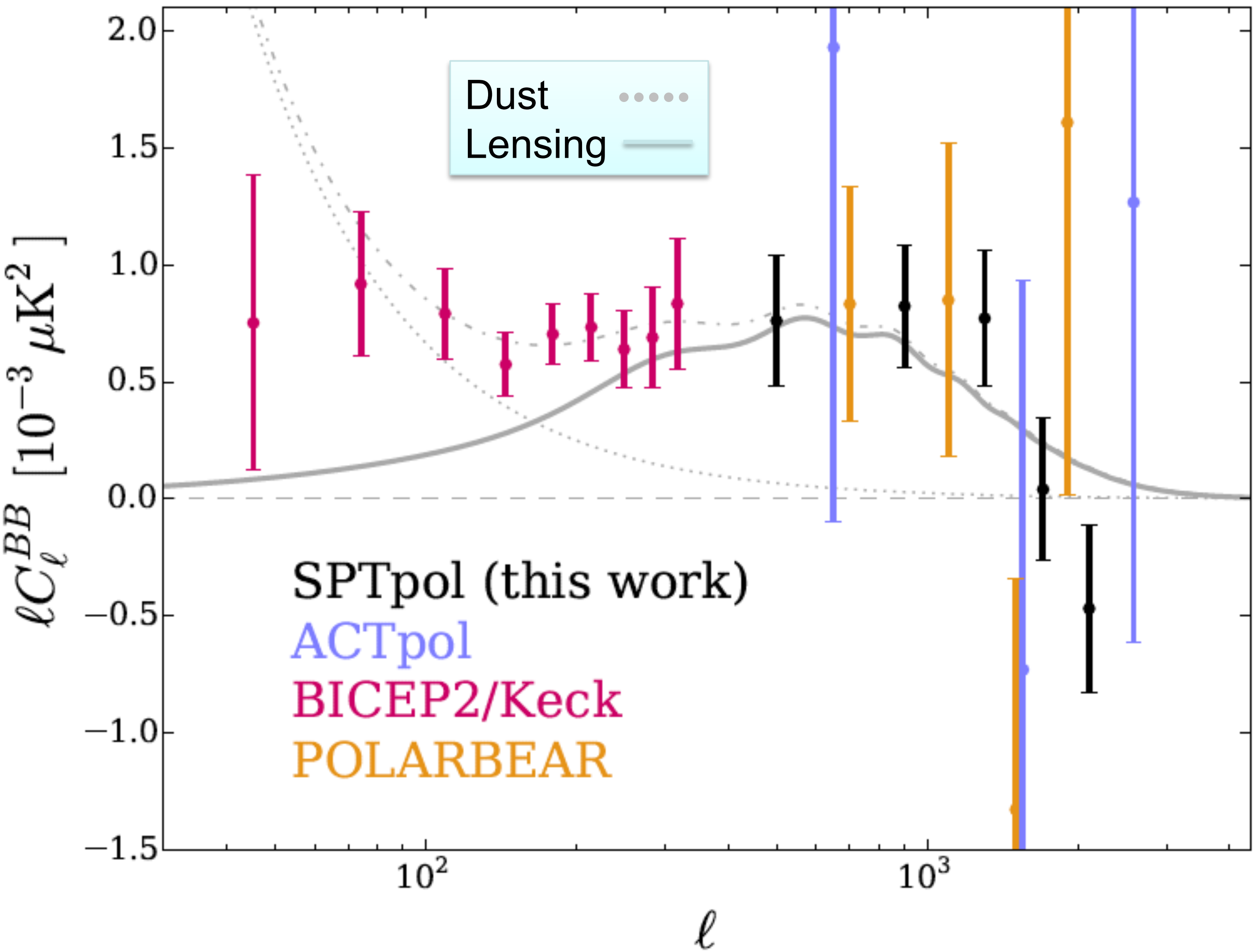
$$\frac{\delta\rho_\phi}{\rho_\phi} = 2\frac{\delta\phi}{\phi}$$

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

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

$$H(a_m) = m$$

More B-mode detection



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