Axion-like Field in Cosmology

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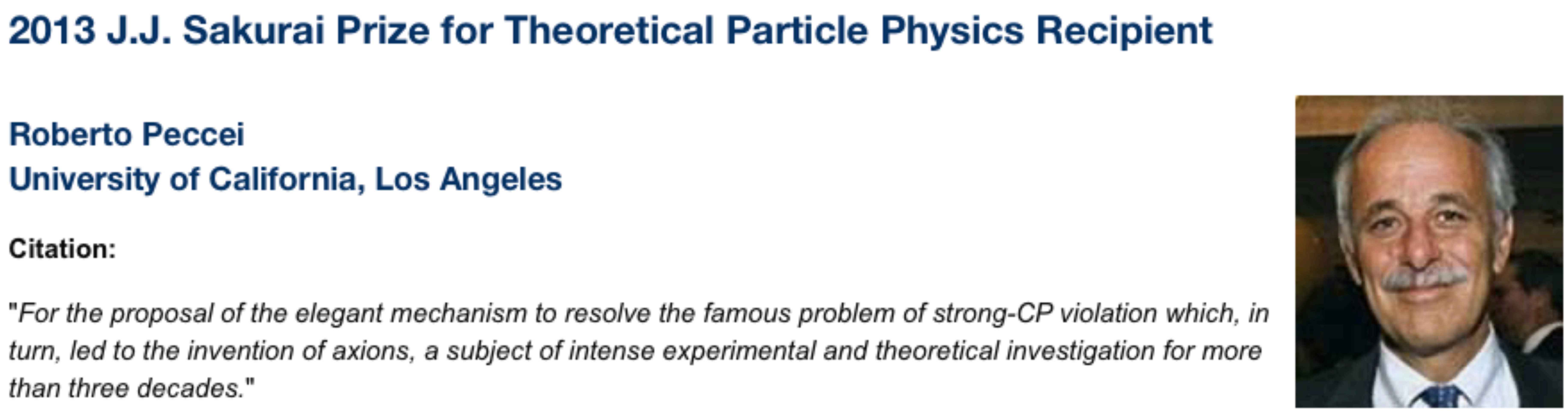
中国科学技术大学

轴子物理研讨会 2020年6月29日

In Memory of Professor Roberto Peccei



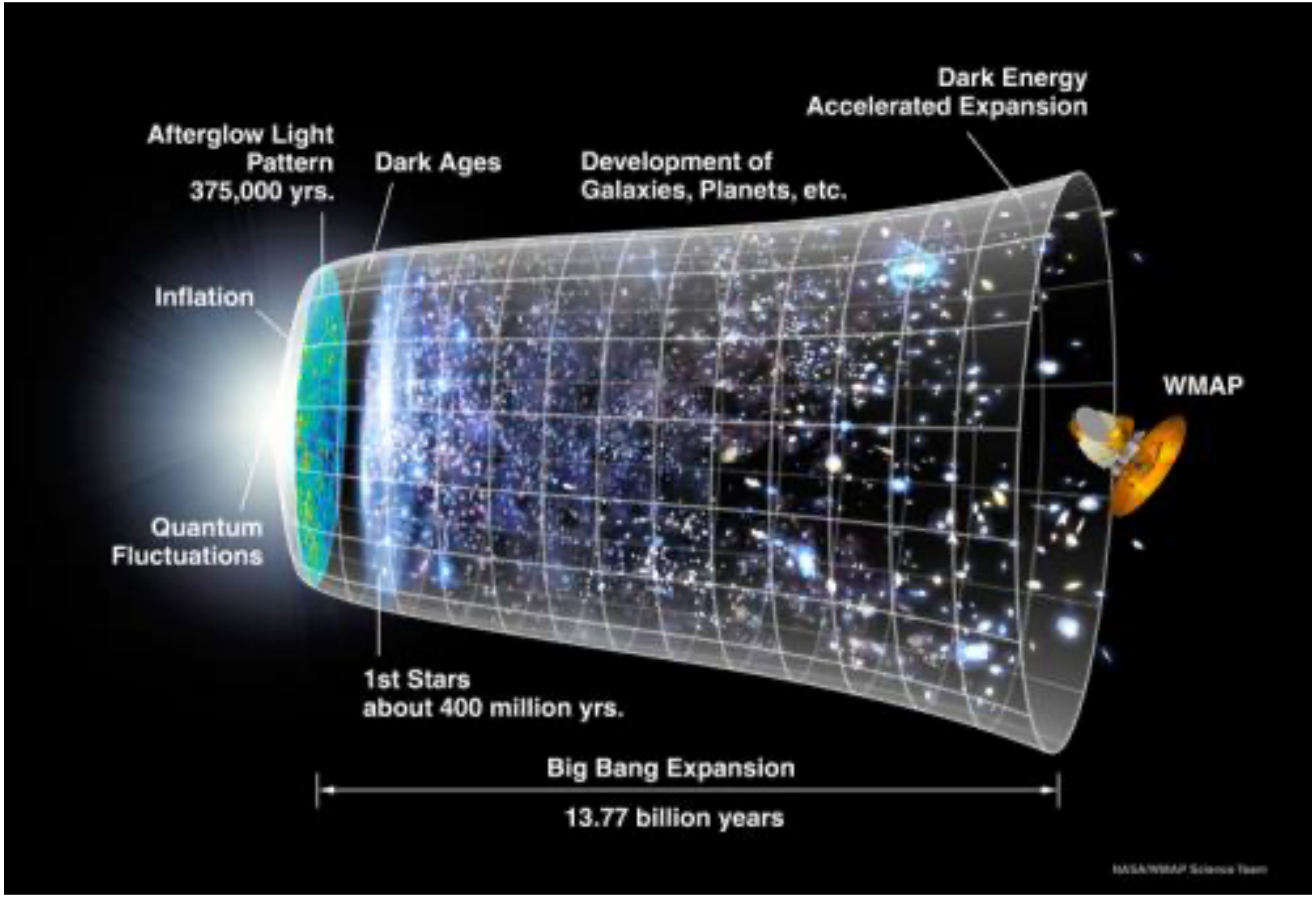
2013 J.J. Sakurai Prize for Theoretical Particle Physics Recipient

Roberto Peccei
University of California, Los Angeles

Citation:

"For the proposal of the elegant mechanism to resolve the famous problem of strong-CP violation which, in turn, led to the invention of axions, a subject of intense experimental and theoretical investigation for more than three decades."

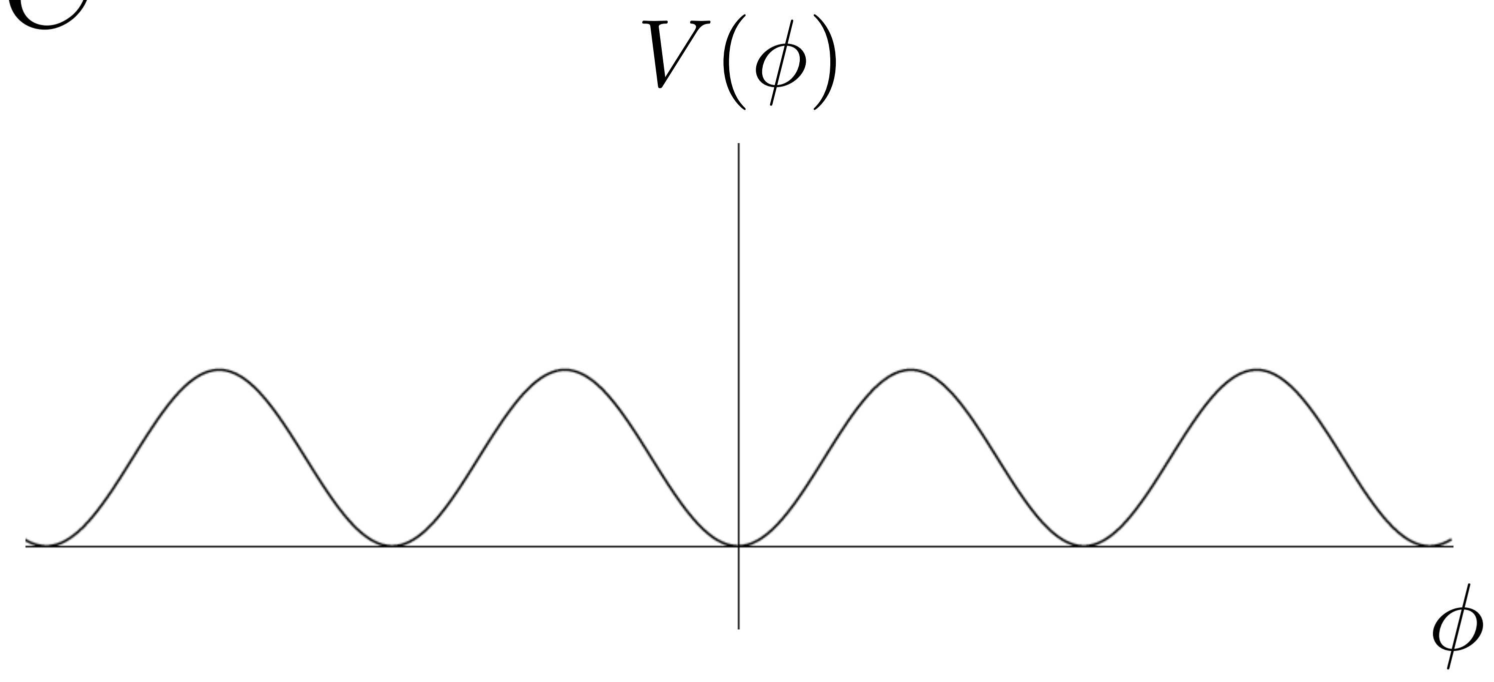
History of the universe



Axion-like field: pseudo Nambu-Goldstone Boson (pNGB)

(approximate) shift symmetry $\phi \to \phi + C$

$$\mathcal{L} = \frac{1}{2}\partial_\mu \phi \partial^\mu \phi - \Lambda^4 (1 - \cos\frac{\phi}{f})$$



Two scales

f —— decay constant, scale for global symmetry breaking

Λ —— scale for explicit symmetry breaking

Small mass $m = \frac{\Lambda^2}{f}, \ \Lambda << f$

Derivative couplings $\mathcal{L}_{int} \sim \partial_\mu \phi J^\mu$

EOM in expanding universe $\ddot{\phi} + 3H\dot{\phi} \boxed{- \frac{1}{a^2}\nabla^2 \phi} + V_\phi = 0$

dropped out

Condensation

$$\ddot{\phi} + 3H\dot{\phi} + m^2\phi = 0$$

$$\rho_\phi = \frac{\dot{\phi}^2}{2} + \frac{m^2\phi^2}{2} \ , \ p_\phi = \frac{\dot{\phi}^2}{2} - \frac{m^2\phi^2}{2}$$

(1) $m << H$ $$\ddot{\phi} + 3H\dot{\phi} \boxed{+ m^2\phi} = 0$$

negligible

$\dot{\phi} = 0$ or $\dot{\phi} \propto a^{-3} \to 0$ $\quad \frac{\dot{\phi}^2}{2} << V(\phi) \ , \ w_\phi = p_\phi/\rho_\phi \simeq -1$ slow roll

(2) $m >> H$ $$\ddot{\phi} + 3H\dot{\phi} + m^2\phi = 0 \xrightarrow[u = a^{3/2}\phi]{} \ddot{u} + m^2 u \boxed{- (\frac{3}{2}\dot{H} + \frac{9}{4}H^2)u} = 0$$

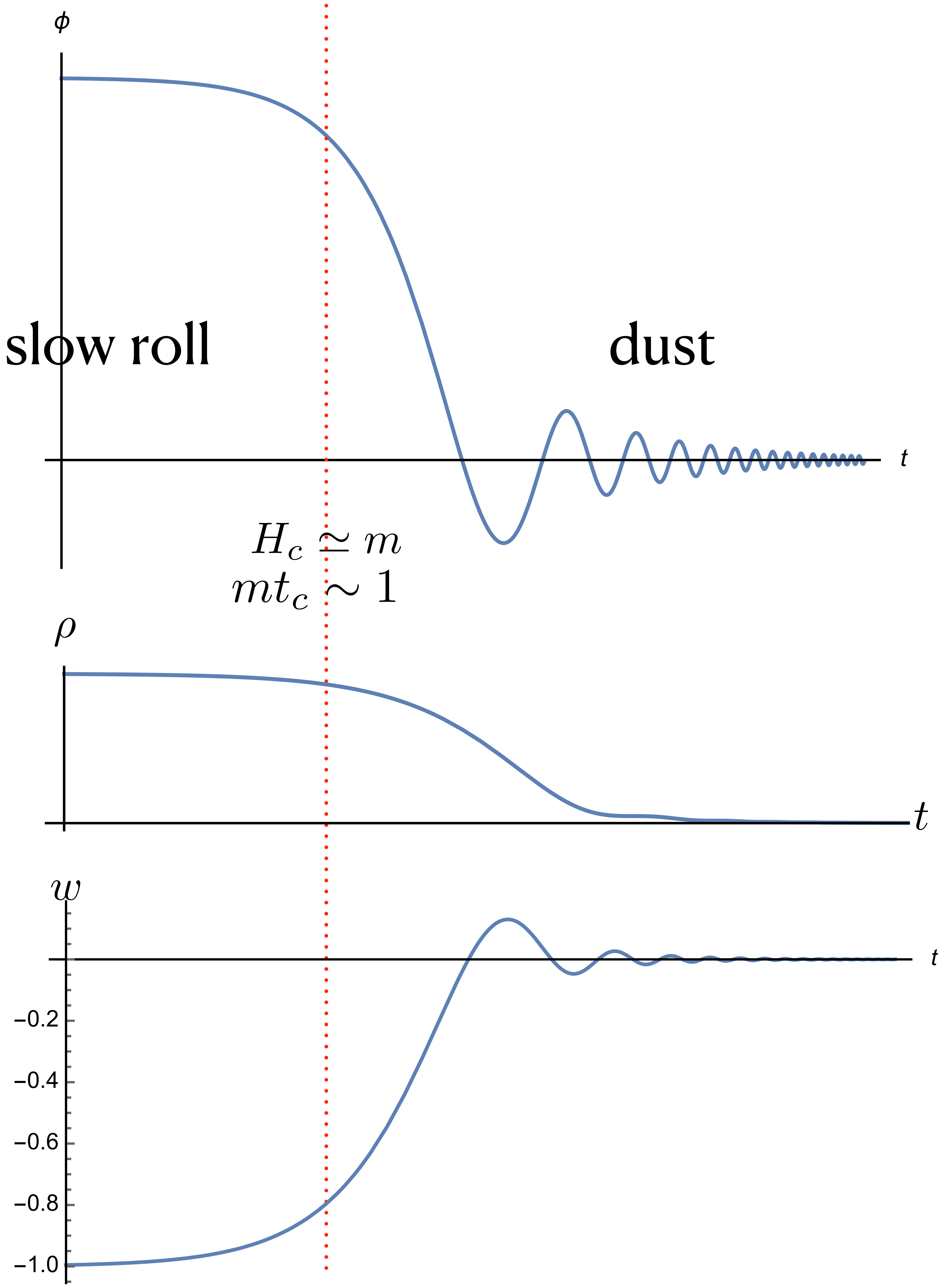
negligible

$$u = A\cos(mt + \theta_0)$$

$$\phi = Aa^{-3/2}\cos(mt + \theta_0)$$

$$< \rho_\phi >= \frac{1}{2} < \dot{\phi}^2 + m^2\phi^2 > \simeq a^{-3}\frac{m^2A^2}{2} \qquad < p_\phi >= \frac{1}{2} < \dot{\phi}^2 - m^2\phi^2 > \simeq 0$$

dust-like



slow roll

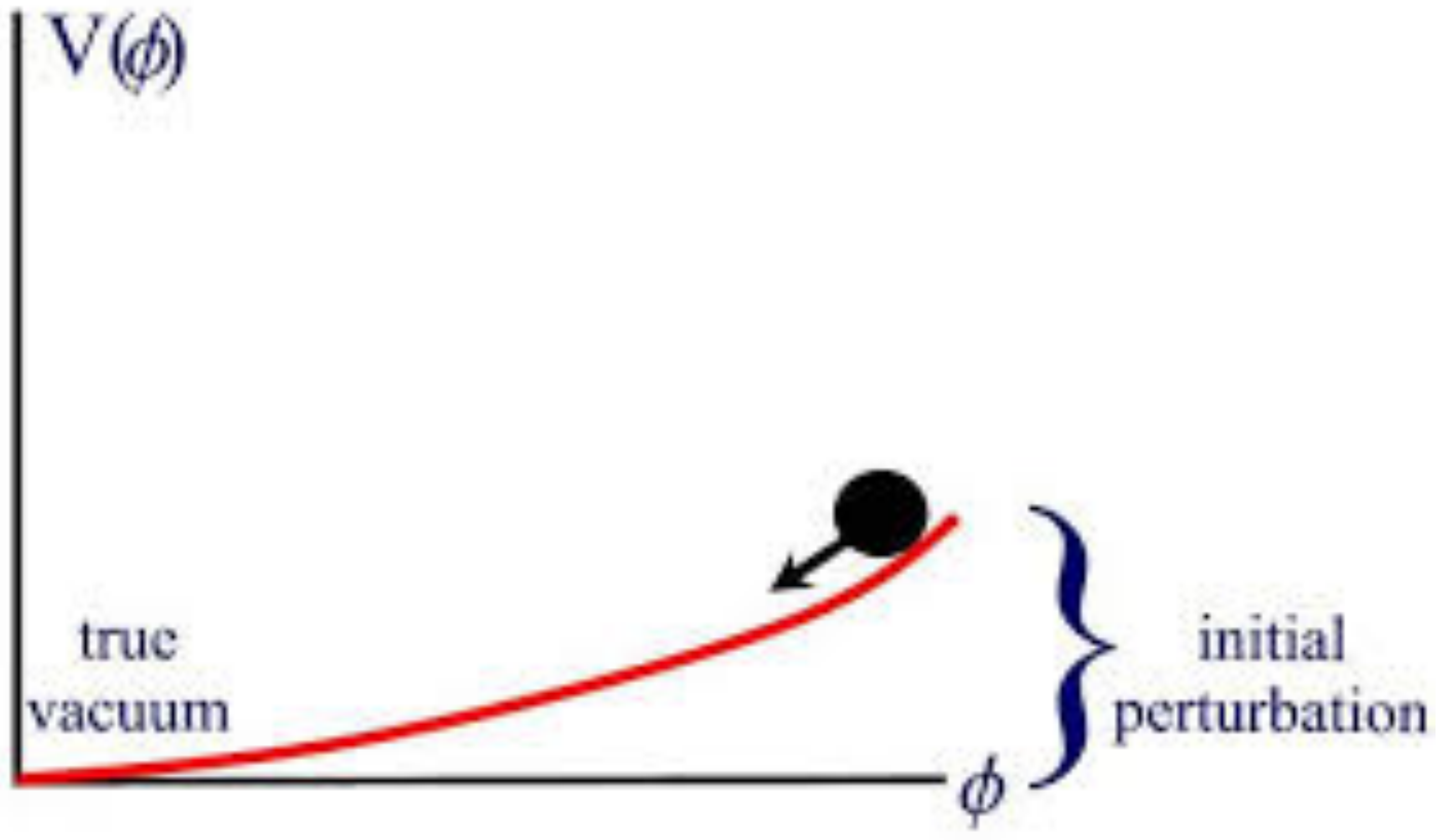
dust

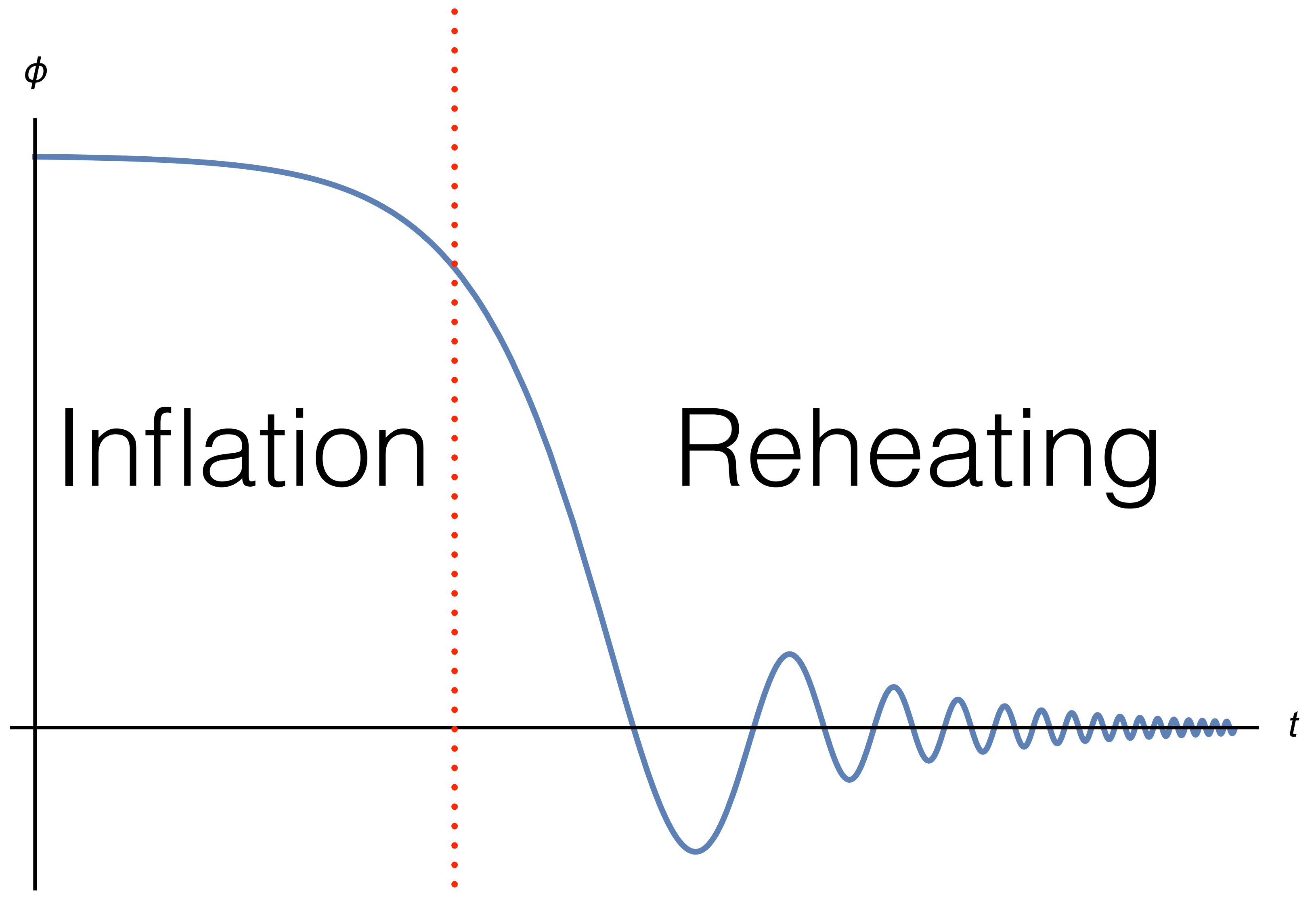
$H_c \simeq m$

$mt_c \sim 1$

$$H \sim \frac{1}{t}$$

Inflation Driven by Axion-like Field





$$m = H_c \leq H_{in}$$

Slow roll during inflation

$$H^2 = \frac{1}{3M_p^2}(\frac{\dot{\phi}^2}{2} + V) \simeq \frac{V}{3M_p^2} \qquad \ddot{\phi} + 3H\dot{\phi} + V_\phi = 0,\ 3H\dot{\phi} + V_\phi \simeq 0 \qquad M_p^2 = \frac{1}{8\pi G}$$

$$\epsilon \simeq \frac{M_p^2}{2}\left(\frac{V_\phi}{V}\right)^2,\ \eta \simeq M_p^2\frac{V_{\phi\phi}}{V} \qquad \epsilon\ ,\ |\eta| < 1$$

Axion-like field as inflaton

Natural inflation model

Freese, Frieman and Olinto, PRL (1990)

$$V = \Lambda^4 (1 - \cos\frac{\phi}{f})$$

Difficulties

$$\epsilon = \frac{M_p^2}{2f^2}\frac{1+\cos\frac{\phi}{f}}{1-\cos\frac{\phi}{f}} \qquad \eta = \frac{M_p^2}{f^2}\frac{\cos\frac{\phi}{f}}{1-\cos\frac{\phi}{f}} \qquad \delta = \epsilon - \eta = \frac{M_p^2}{2f^2}$$

$|\delta| \ll 1,\ f \gg M_p/\sqrt{2}$ Outside the range of validity of EFT

Quantum gravity effects, e.g., virtual black holes, break global symmetries.

They are proportional to $(\frac{f}{M_p})^n$, unsuppressed.

Extranatural inflation, extra dimensional version of natural inflation

Arkani-Hamed, Cheng, Creminelli and Randall, PRL(2003)

5d model, 5th dimension compactified on a circle R
Abelian field A_a

No local potential, and non-local potential for Wilson loop in the presence of charged fields in the bulk $e^{i\theta} = e^{i\oint A_5 dx^5}$

With massless charged fields, one-loop

$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 - \frac{3}{64\pi^6 R^4}(1 - \cos\frac{\phi}{f_{\text{eff}}}) \qquad \phi = f_{\text{eff}}\theta = \frac{\theta}{2\pi g_4 R} \qquad g_4^2 = g_5^2/(2\pi R)$$

For sufficiently small $g_4,\ f_{\text{eff}} \gg M_p$

Quantum gravity corrections are negligible as long as $R^{-1} < M_5$

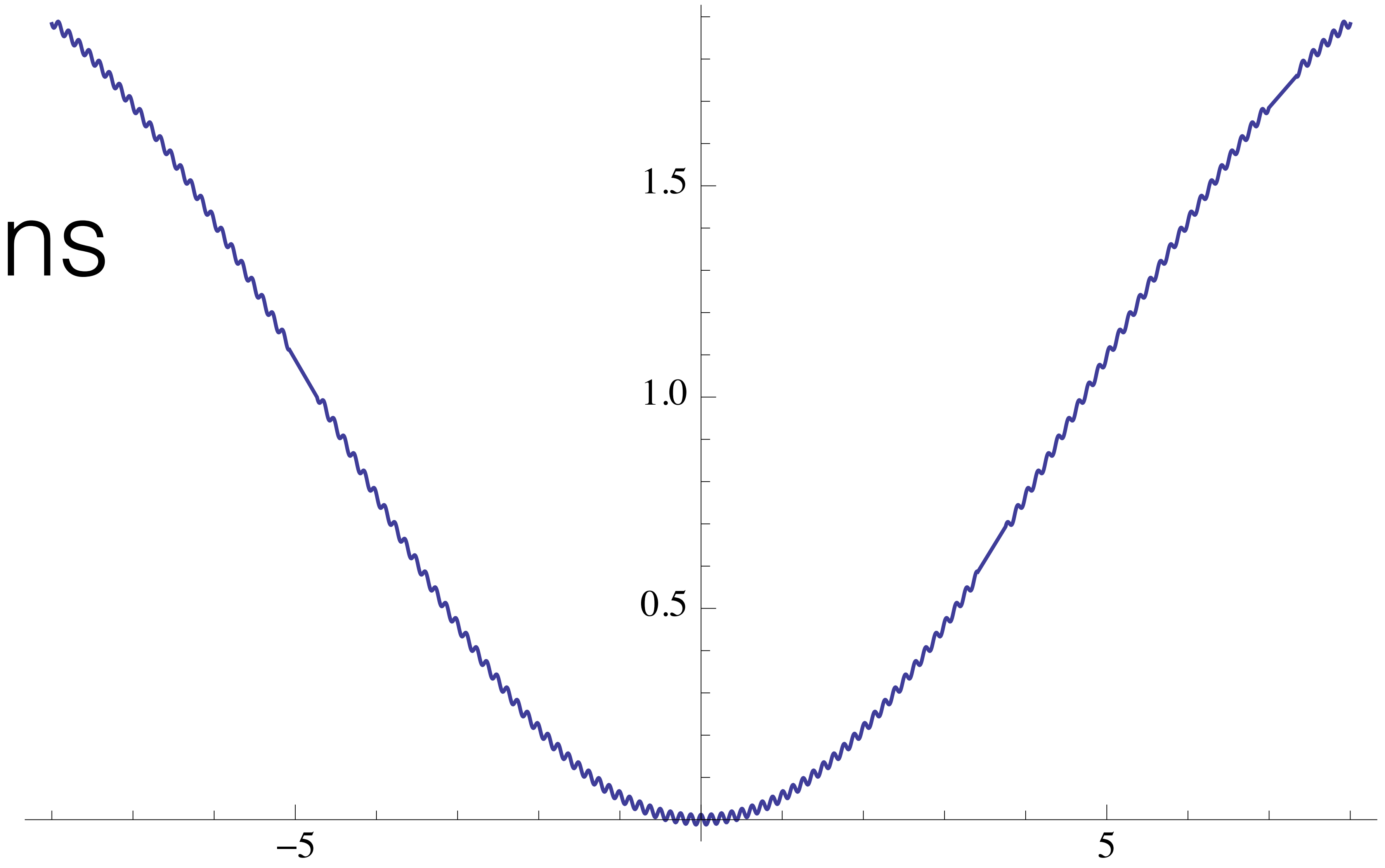
Virtual black holes cannot spoil gauge symmetry, non-local effects suppressed by $e^{-2\pi M_5 R}$

Consider two fields coupling to A_5 $\quad M_1 = 0,\ M_2 > R^{-1}$

$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 - V_0\left[1 - \cos\left(\frac{q_1\phi}{f_{\rm eff}}\right) - \sigma\cos\left(\frac{q_2\phi}{f_{\rm eff}}\right)\right]$$

where

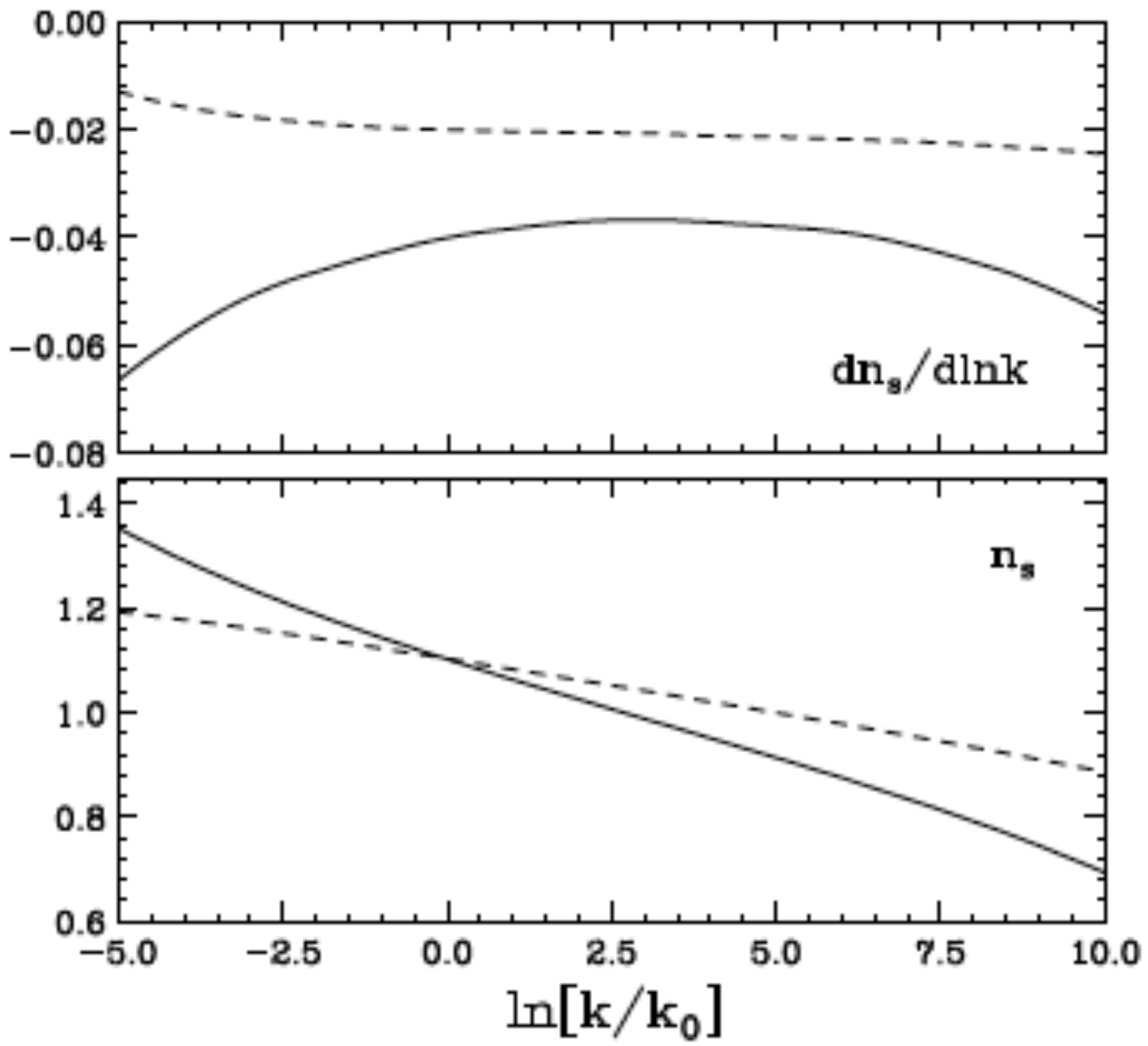
$$\sigma = (-)^{F_2+1}e^{-x_2}\left(\frac{x_2^2}{3} + x_2 + 1\right),\ \ V_0 = \frac{3}{64\pi^6 R^4} \qquad x_a = 2\pi R M_a$$



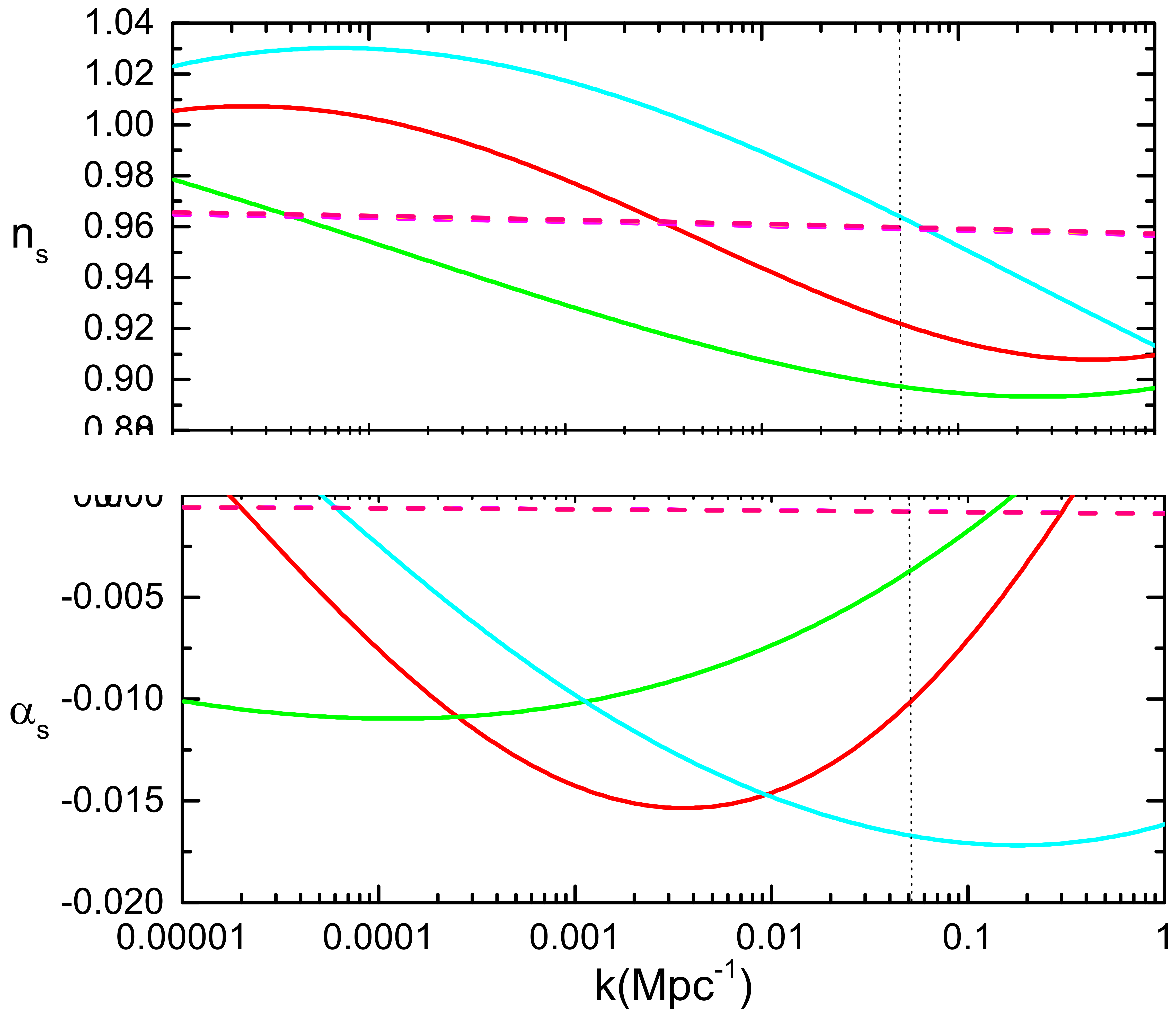
Extranatural inflation modulated by rapid oscillations
Slow-rolling is mildly broken
Overall picture of inflation is unchanged

Feng, ML, Zhang & Zhang, PRD(2003)

Power spectrum with large running



Feng, ML, Zhang & Zhang astro-ph/0302479, PRD(2003)



Wan, Li, ML, Qiu, Cai & Zhang, arXiv:1405.2784, PRD(2014)

$$\mathrm{Slow-roll}: \frac{dn_s}{d\ln k} \sim 10^{-3}$$

Axion-like Field as Cold Dark Matter

$$m = H_c > H_{eq} \sim 10^{-28}\mathrm{eV}$$

KeV axion dark matter

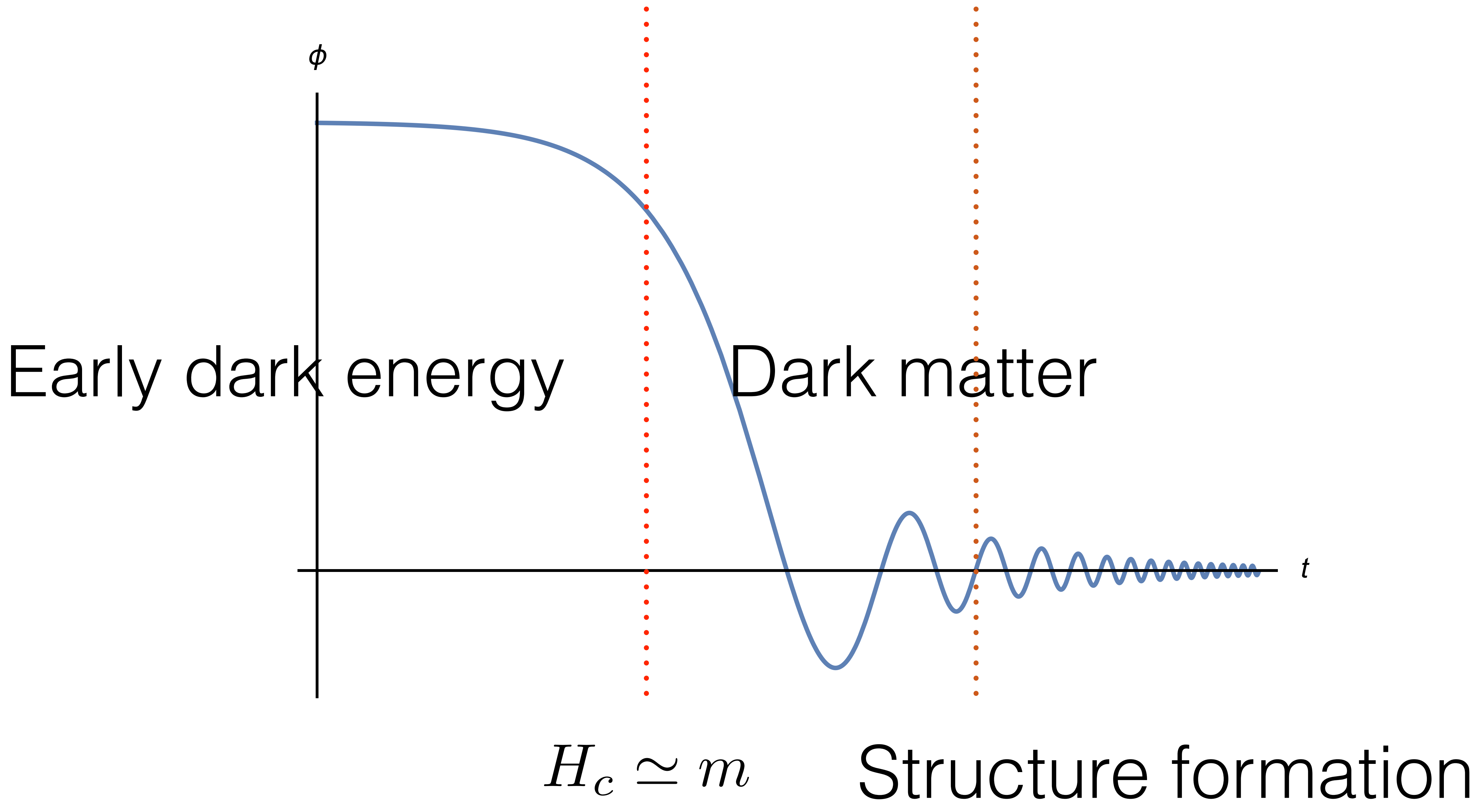
$$\Lambda \sim 1\mathrm{TeV},\ \ f \sim 10^{12}\mathrm{GeV},\ \ m \sim 1\mathrm{KeV}$$

$$H_c = m \sim \frac{T_c^2}{M_{pl}} \quad T_c \sim 10^6\mathrm{GeV}$$

Fuzzy dark matter

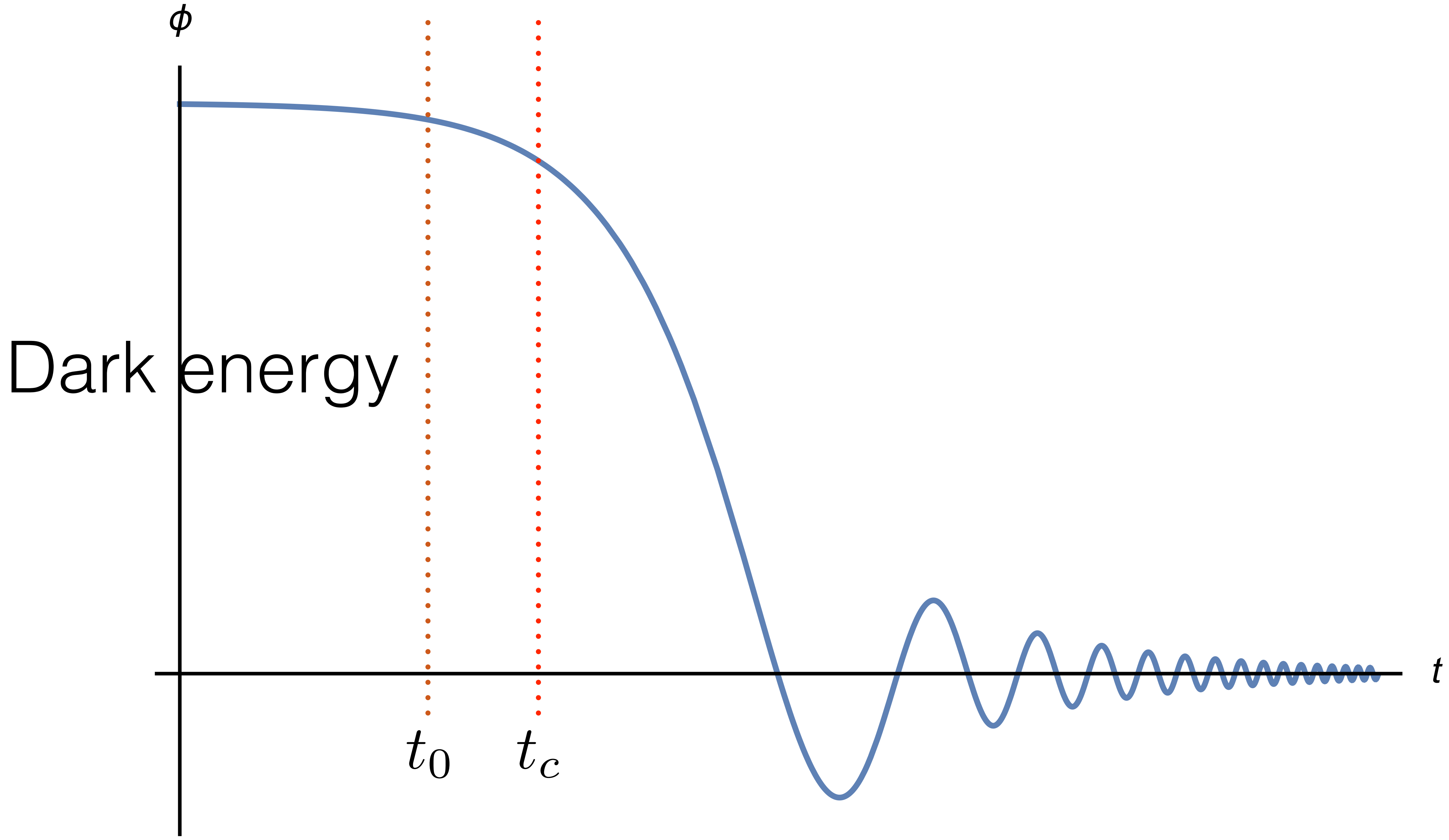
$$m = \frac{\Lambda^2}{f} \sim 10^{-22}\mathrm{eV}$$

$$T_c \sim 500\mathrm{eV},\ \ f \sim 10^{17}\mathrm{GeV},\ \ \Lambda \sim 100\mathrm{eV}$$



Hui, Ostriker, Tremaine, Witten, arXiv: 1610.08297

Axion-like Field as Dark Energy



Slow rolling up to now

$$m = H_c \leq H_0 \sim 10^{-33}\mathrm{eV}$$

Shift symmetry guarantees the flat potential

Derivative couplings with other matter $\partial_\mu \phi \bar{\psi} \gamma^\mu \gamma^5 \psi$

Propagates spin-dependent force

No long range force superimposed between unpolarized objects

Coupling to photons via the Chern-Simons term

$$\mathcal{L} = \frac{\beta}{M}\partial_\mu \phi K^\mu \to -\frac{\beta\phi}{2M} F_{\mu\nu}\widetilde{F}^{\mu\nu} \qquad K^\mu = A_\nu \widetilde{F}^{\mu\nu},\ \partial_\mu K^\mu = \frac{1}{2}F_{\mu\nu}\widetilde{F}^{\mu\nu} \qquad \widetilde{F}^{\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\rho\sigma}F_{\rho\sigma}$$

The rolling of dark energy picks out a preferred time direction

Lorentz and time reversal symmetries are broken, leading to CPT violation in photons

EOM $\nabla_\mu F^{\mu\nu} = -\frac{2\beta}{M}\partial_\mu \phi \widetilde{F}^{\mu\nu} \qquad \nabla_\mu \widetilde{F}^{\mu\nu} = 0$

Polarization direction of light gets a rotation

$$(Q \pm iU)' = e^{\pm 2i\alpha}(Q \pm iU)$$

Rotation angle

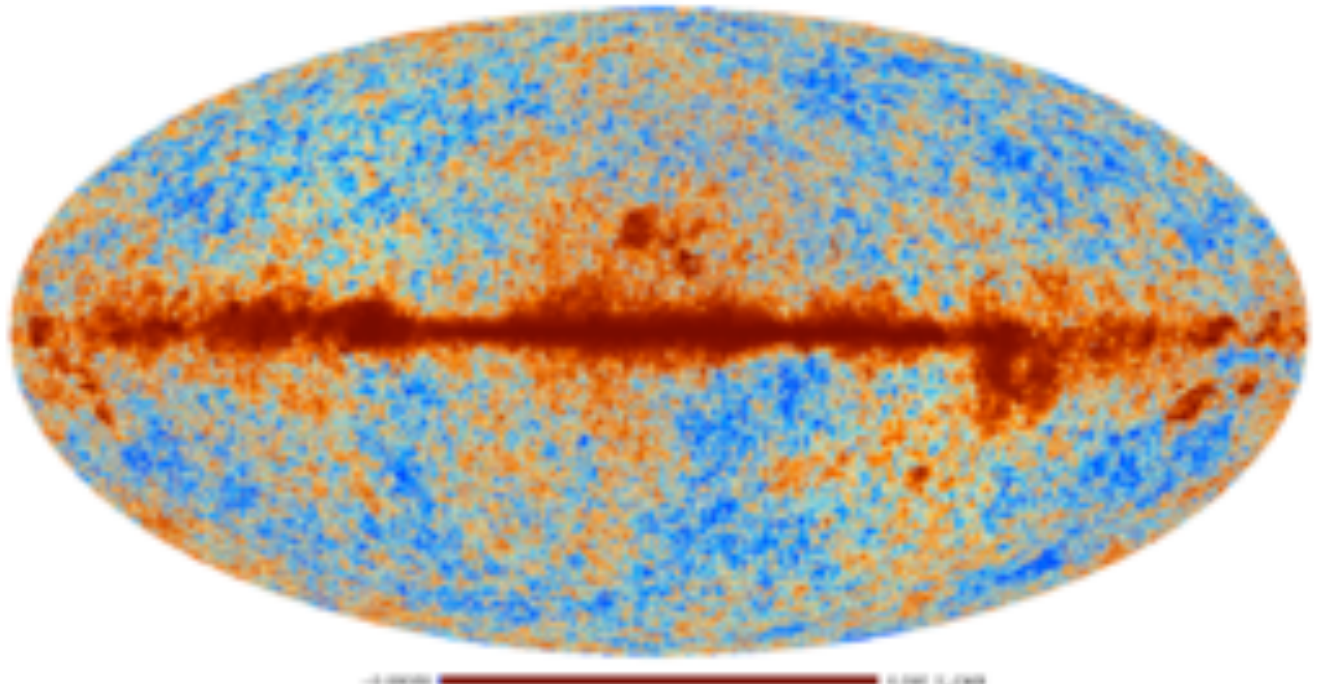
$$\alpha = \int \frac{\beta}{M}\partial_\mu \phi dx^\mu(\lambda) = \frac{\beta}{M}\Delta\phi$$

frequency-independent

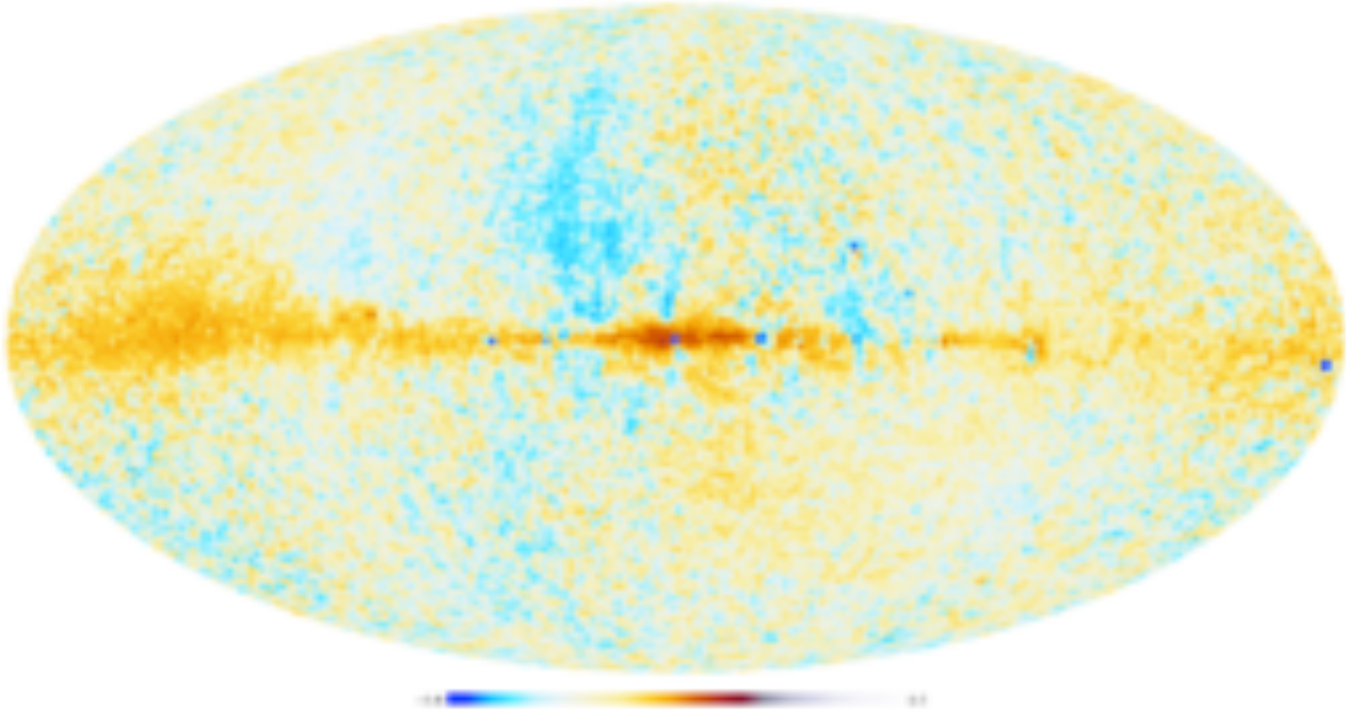
CMB anisotropies

CMB Maps
Planck2015

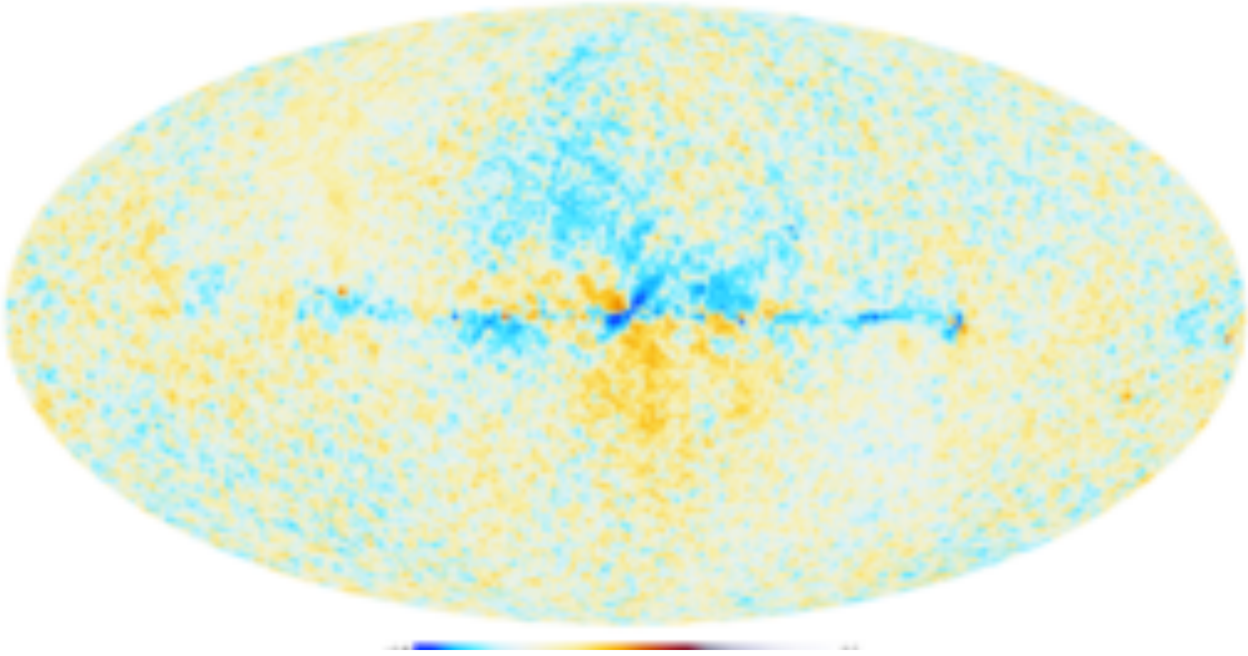
Stokes I



Stokes Q



Stokes U



E/B Decomposition of CMB Polarization

Seljak & Zaldarriaga, PRD (1997);
Kamionkowski, Kosowsky & Stebbins, PRD (1997)

$$T(\hat{n}) = \sum_{lm} a_{T,lm} Y_{lm}(\hat{n}) \qquad l \geq 0$$

$$(Q \pm iU)(\hat{n}) = \sum (E_{lm} \pm iB_{lm})\ {}_{\pm 2}Y_{lm}(\hat{n}) \quad l \geq 2$$

Power spectra

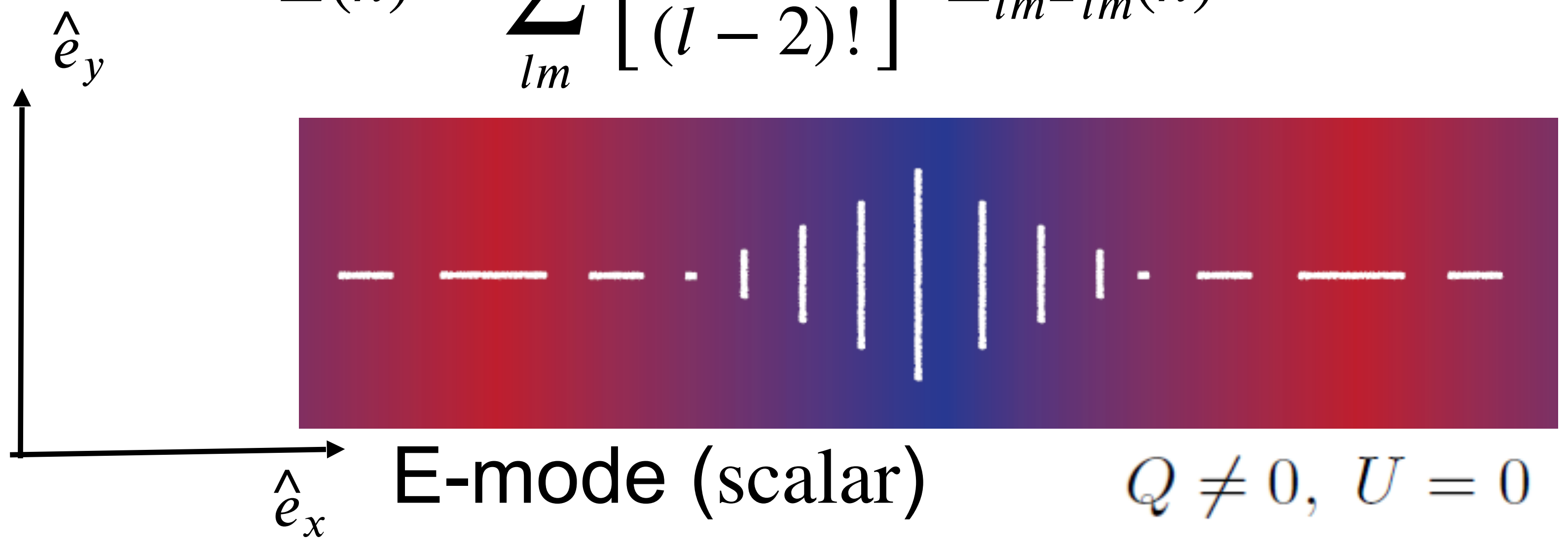
$$< a^*_{T,l'm'} a_{T,lm} >= C_l^{TT} \delta_{ll'} \delta_{mm'} \qquad < E^*_{l'm'} E_{lm} >= C_l^{EE} \delta_{ll'} \delta_{mm'}$$

$$< B^*_{l'm'} B_{lm} >= C_l^{BB} \delta_{ll'} \delta_{mm'} \qquad < a^*_{T,l'm'} E_{lm} >= C_l^{TE} \delta_{ll'} \delta_{mm'}$$

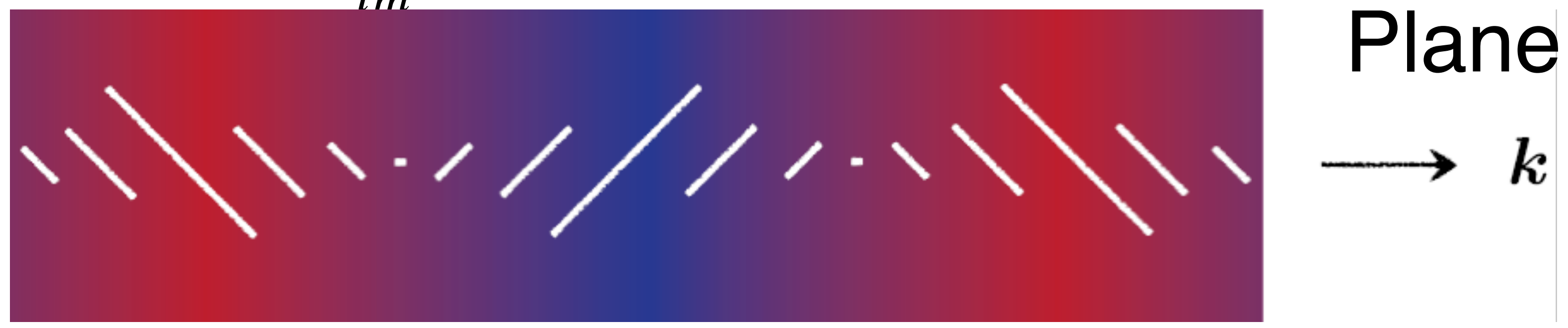
$$< a^*_{T,l'm'} B_{lm} >= C_l^{TB} \delta_{ll'} \delta_{mm'} \qquad < E^*_{l'm'} B_{lm} >= C_l^{EB} \delta_{ll'} \delta_{mm'}$$

$$E(\hat{n}) \equiv \sum_{lm} \left[\frac{(l+2)!}{(l-2)!} \right]^{\frac{1}{2}} E_{lm} Y_{lm}(\hat{n})$$

$$B(\hat{n}) \equiv \sum_{lm} \left[\frac{(l+2)!}{(l-2)!} \right]^{\frac{1}{2}} B_{lm} Y_{lm}(\hat{n})$$

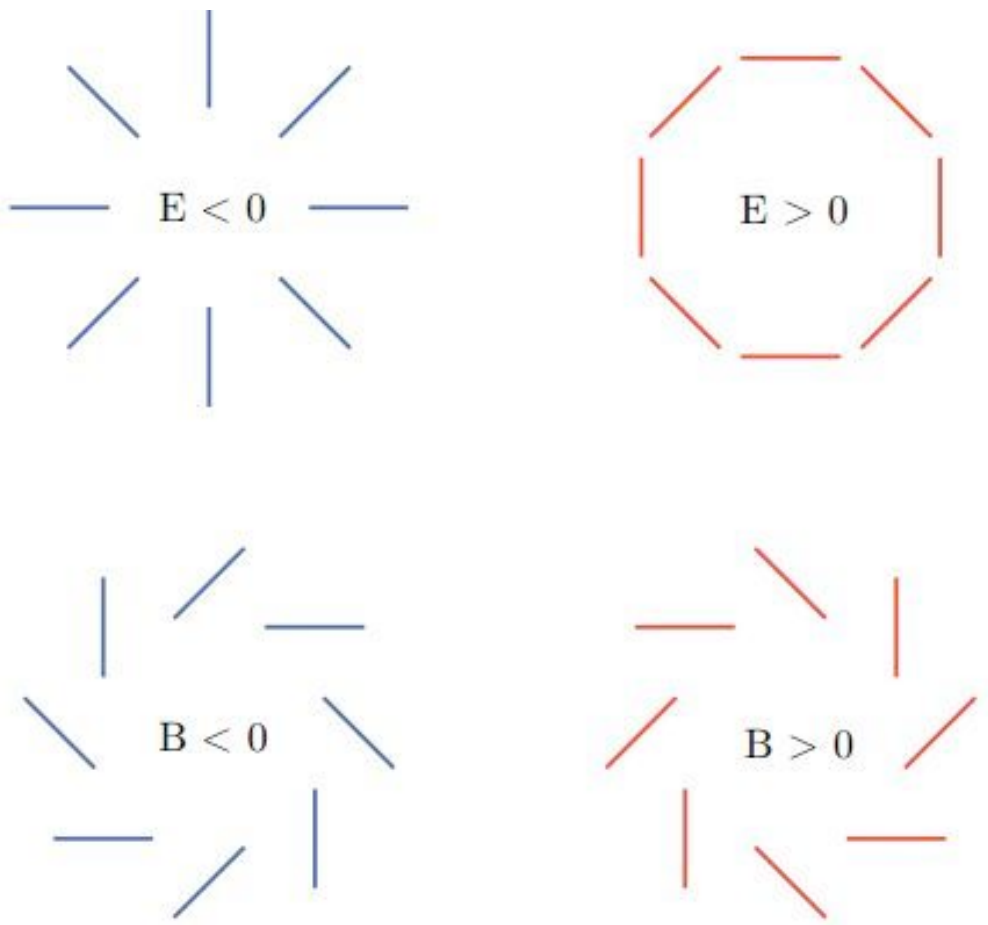


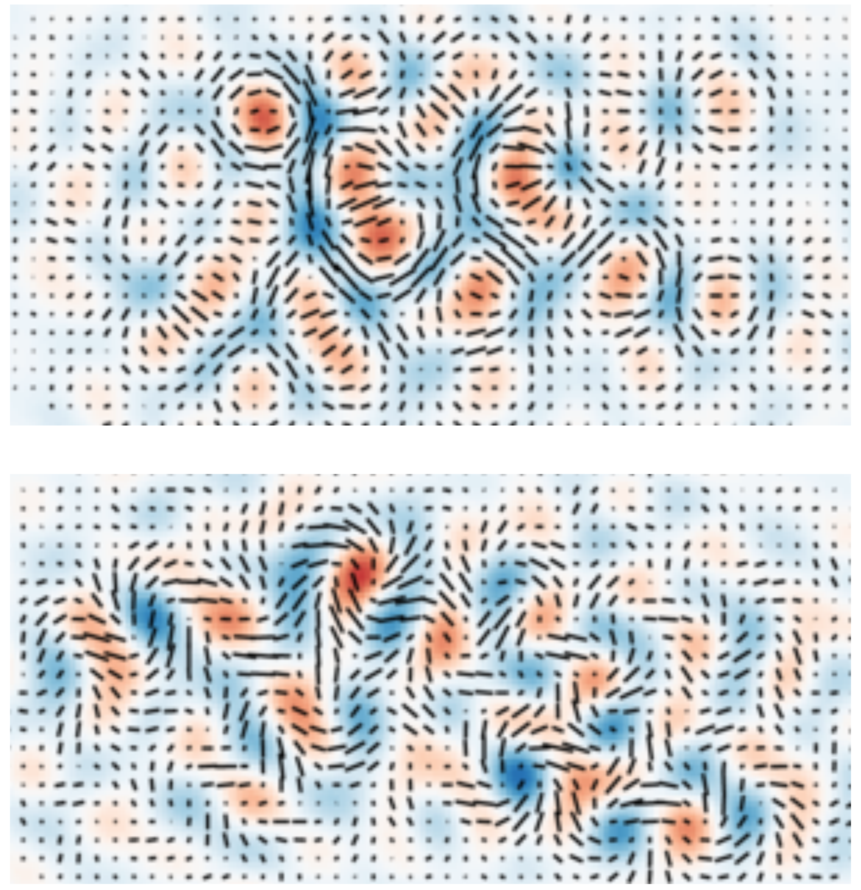
E-mode (scalar) $Q \neq 0,\ U = 0$



Plane wave

B-mode (pseudo scalar) $Q = 0,\ U \neq 0$

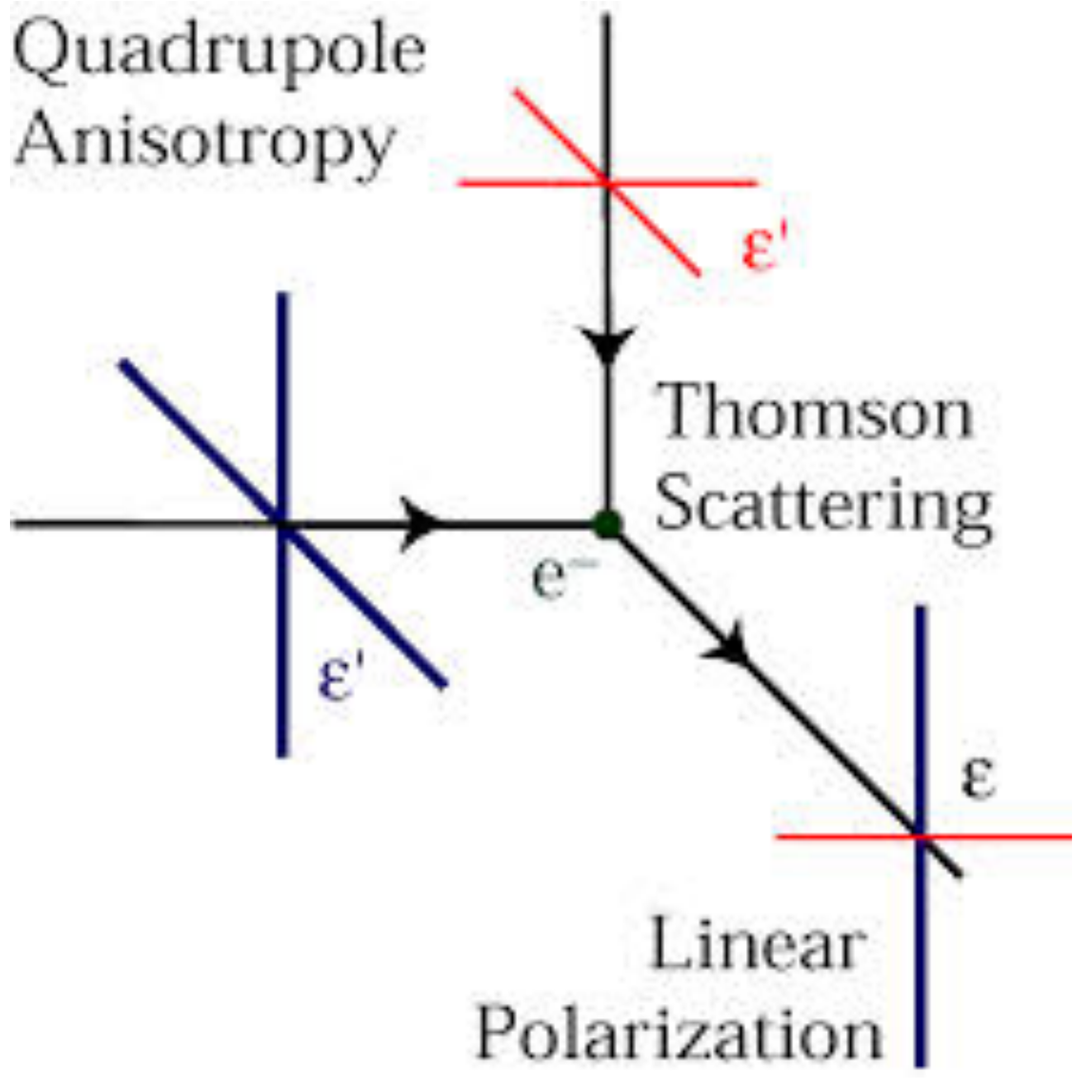




Without CPT violation:

$$C_\ell^{\mathrm{TB}} \equiv 0 \qquad C_\ell^{\mathrm{EB}} \equiv 0$$

CMB偏振的产生



时空的非均匀性，散射

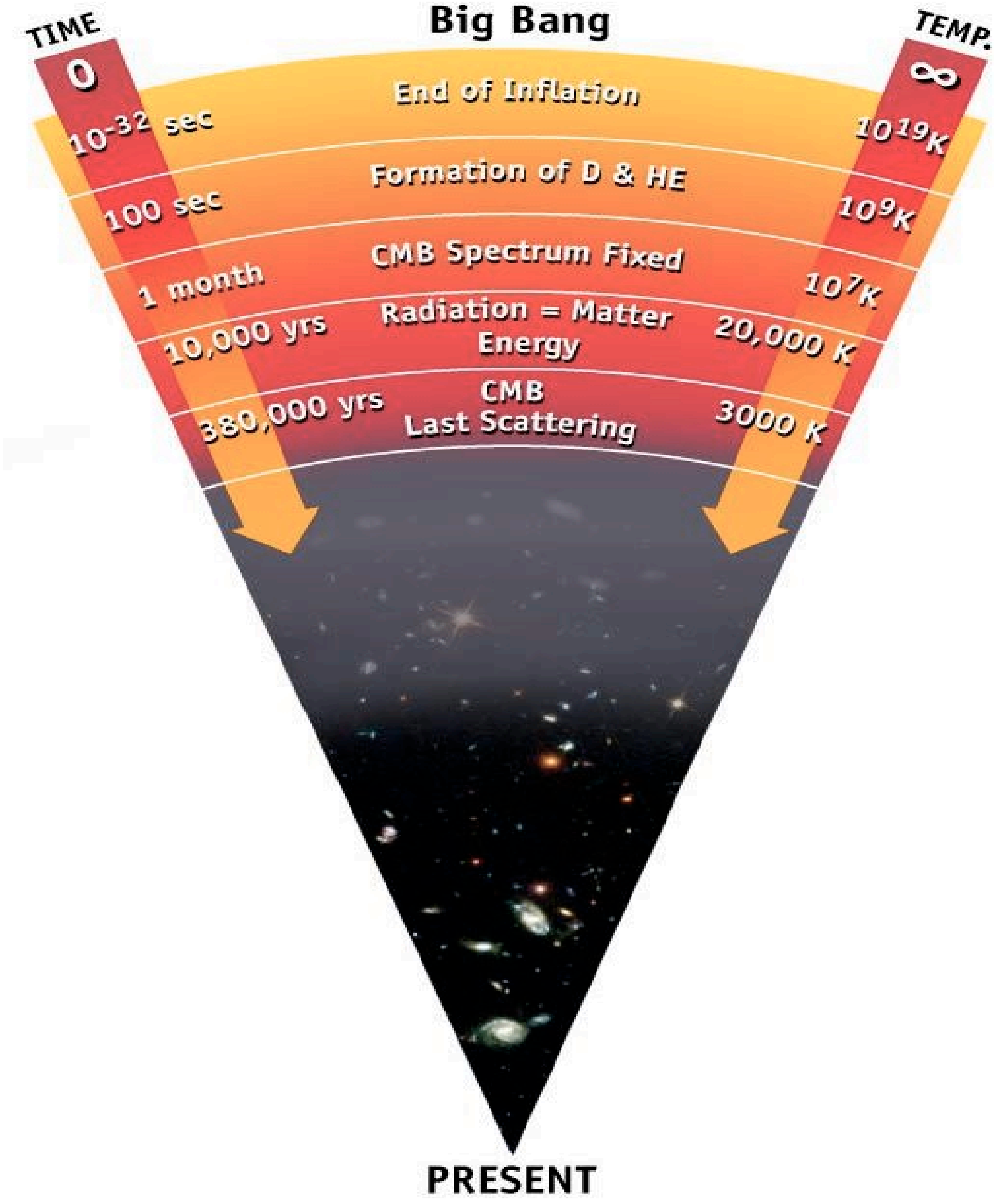
Thomson散射

$$\frac{d\sigma_T}{d\Omega} \propto |\varepsilon \cdot \varepsilon'|$$

需要有入射光的四极矩

复合期以前，宇宙中的光为自然光，因为频繁的随机散射：（1）破坏四极矩；（2）退极化

CMB的偏振图像形成于最后一次散射



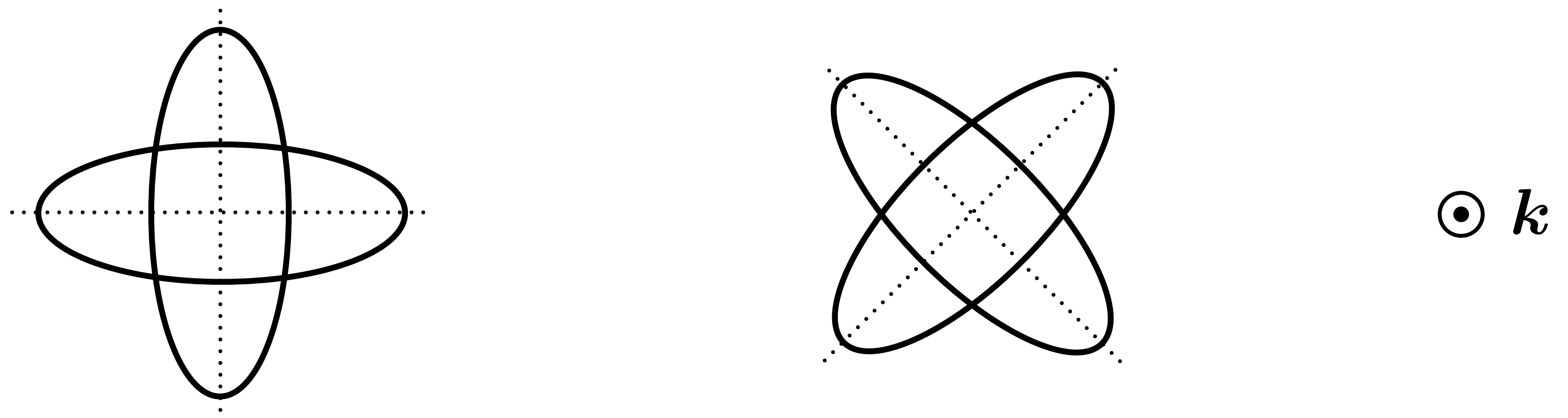
时空非均匀性导致辐射场温度的四极矩

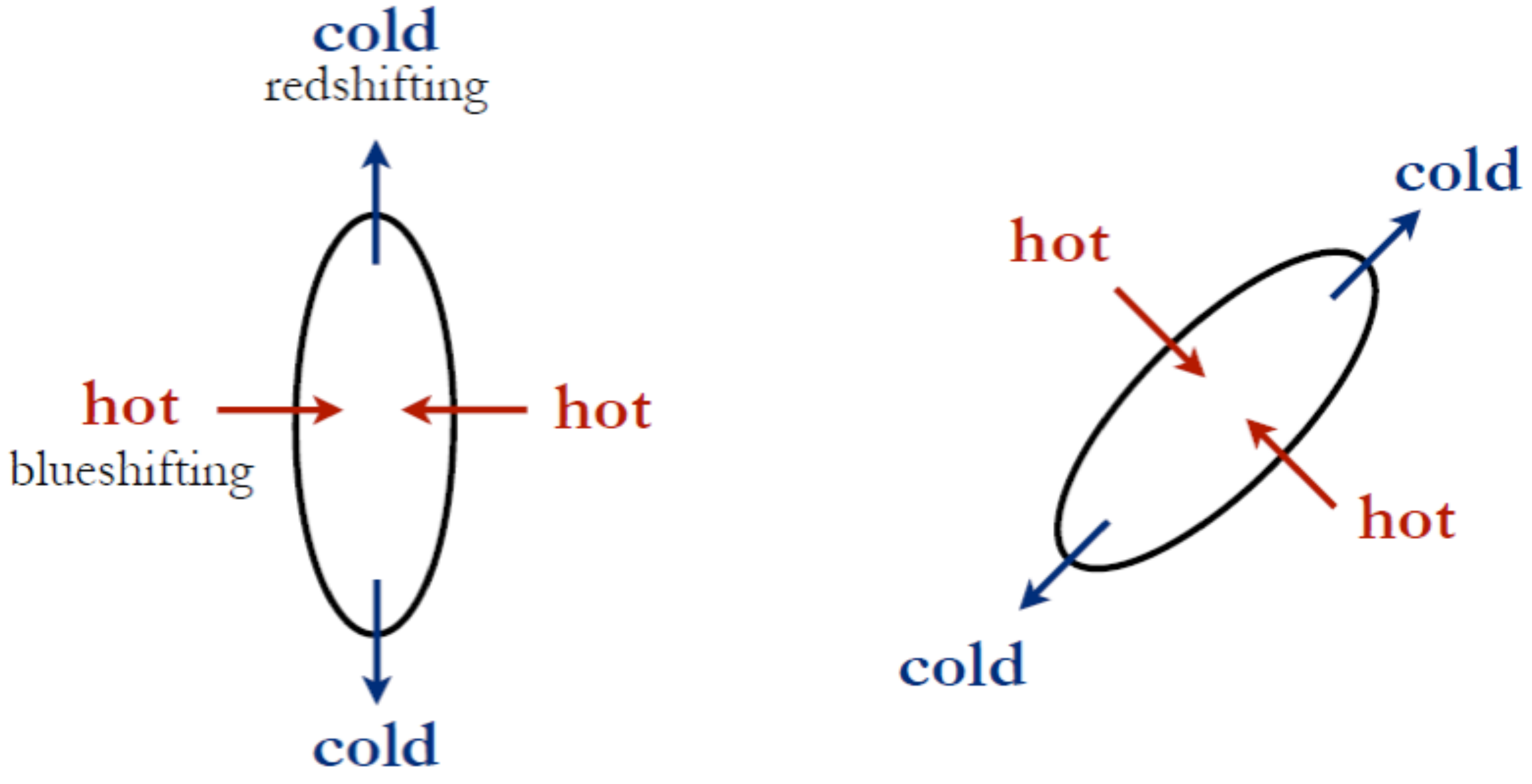
$$ds^2 = a^2(\eta)(1+2\psi)d\eta^2 - a^2(\eta)[(1-2\phi)\delta_{ij} + h_{ij}]dx^i dx^j$$

标量扰动（密度扰动）：　$\psi, \ \phi$

张量扰动（引力波）：　h_{ij}　　$h_{ij} = h_{ji}, \ h^i_i = 0, \ \partial^i h_{ij} = 0$

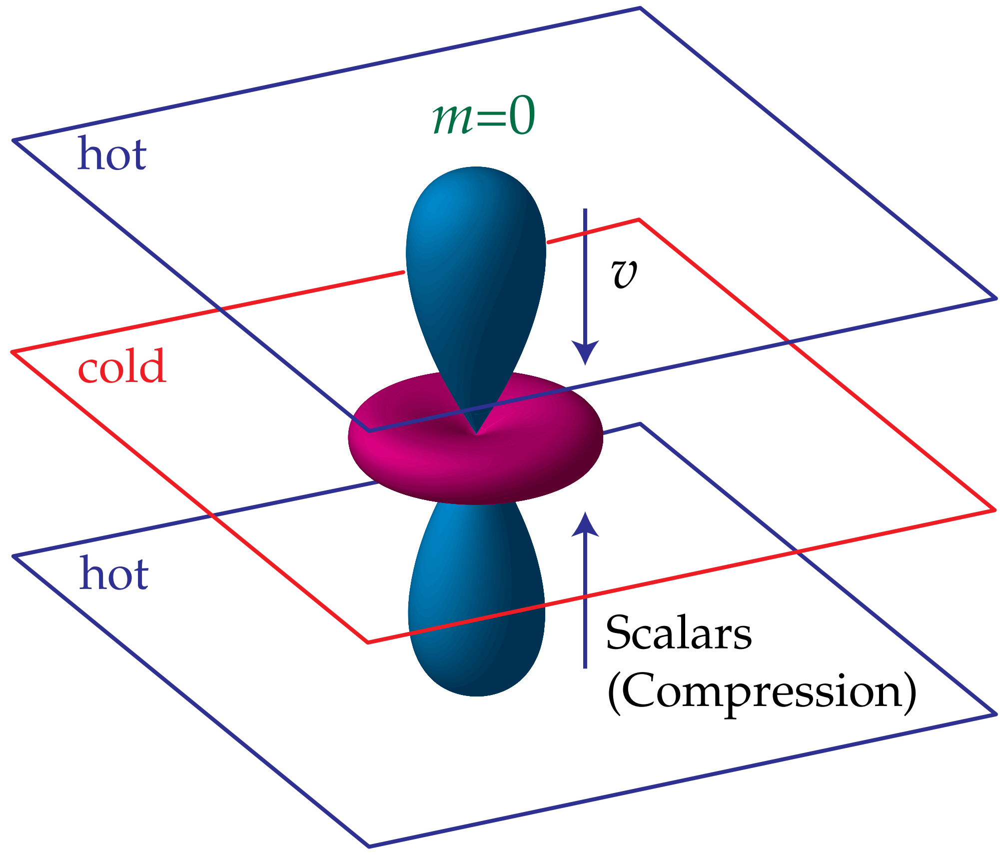
GW的两个偏振分量



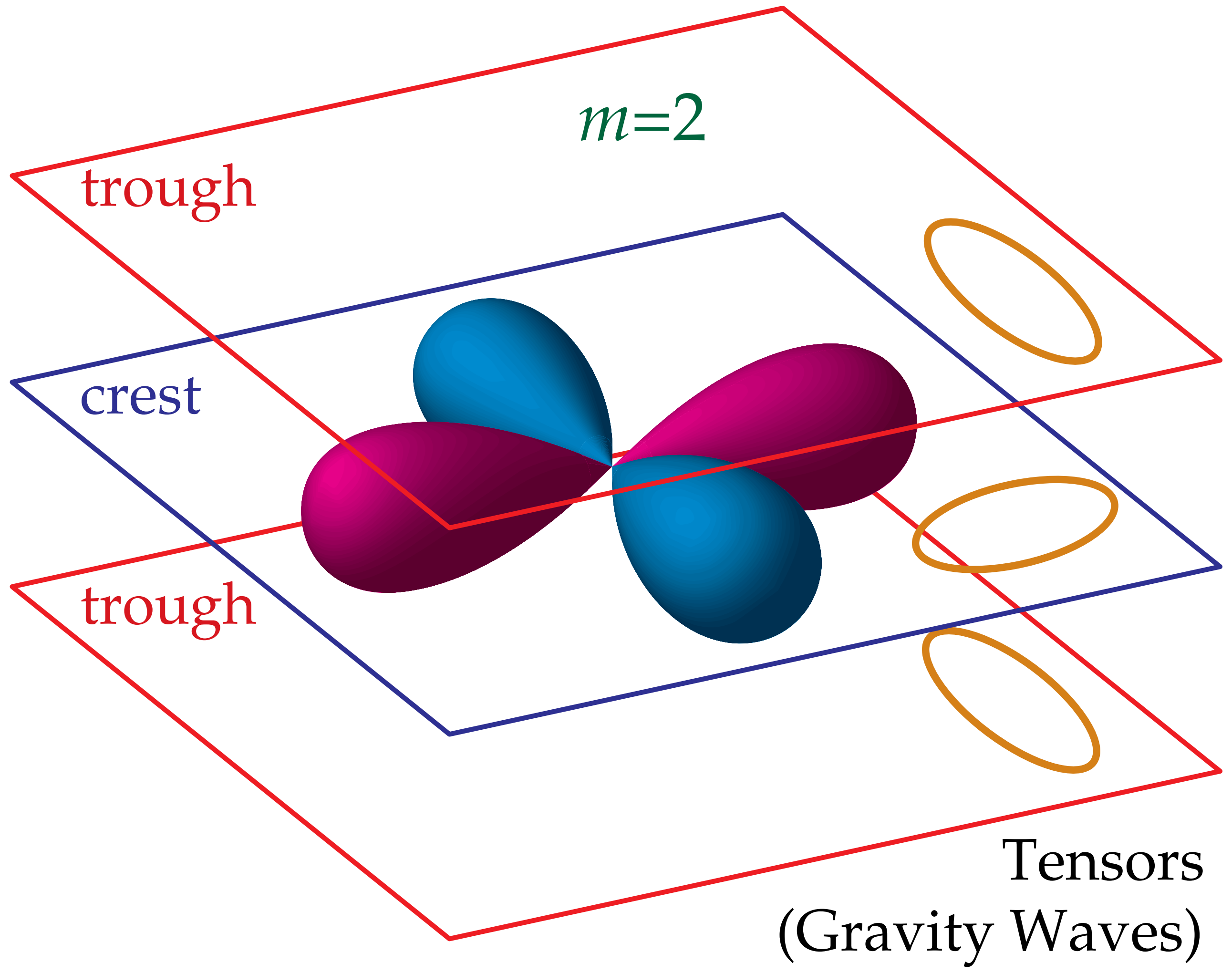


Scalar quadrupole,
azimuthal symmetric
generates T and E

Tensor quadrupole,
without azimuthal symmetry,
generates T, E and B



$$\vec{\mathbf{k}}||\hat{\mathbf{z}}$$



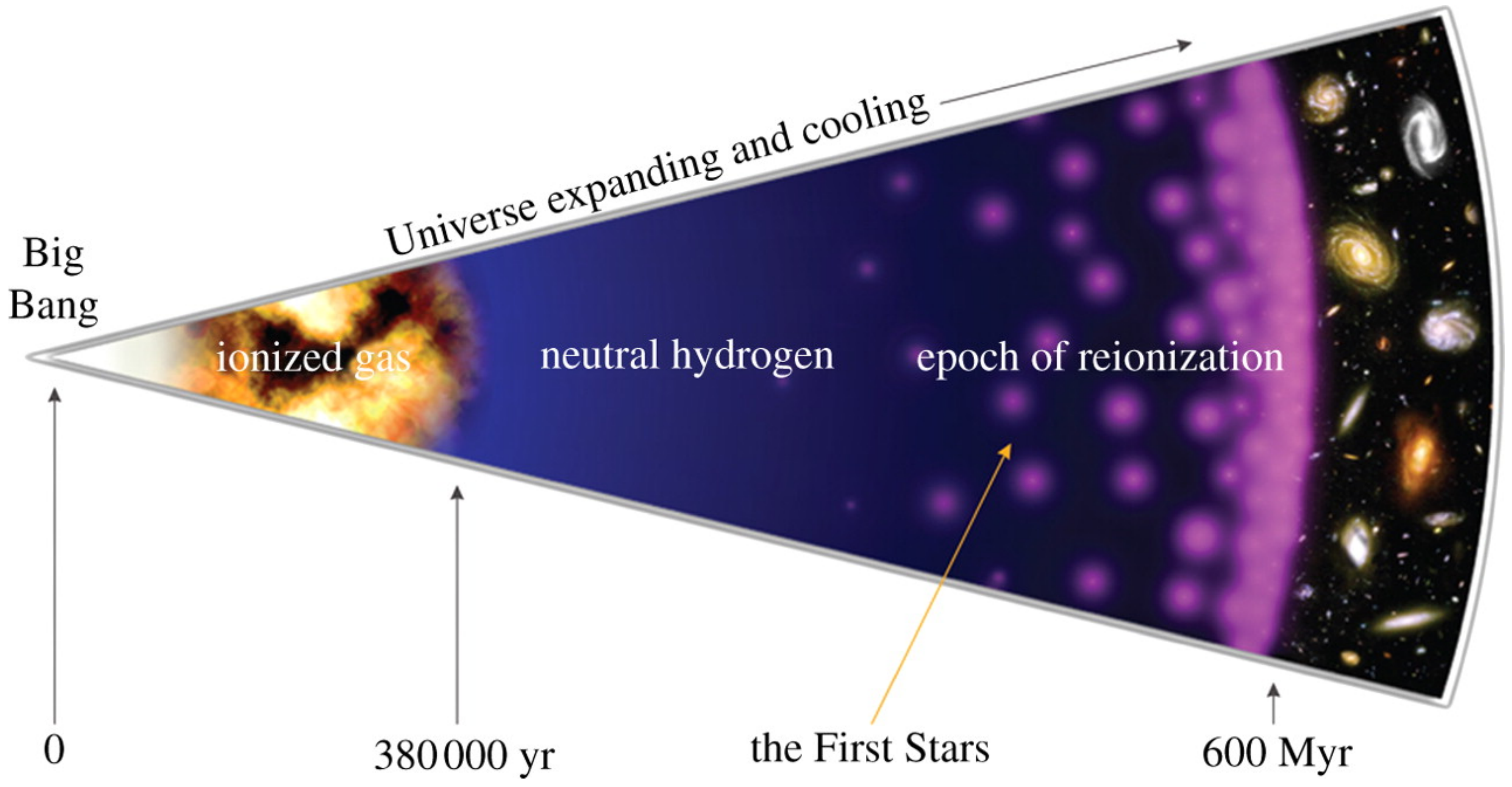
Hu & White, astro-ph/9706147

$$C_l^{XX'\ (i)} = 2(4\pi^2)^2 \int d\ln k\ P_i(k)\Delta^i_{Xl}(k)\Delta^i_{X'l}(k)$$

$$X, X' = T, E, B \quad i = s, t$$

Boltzmann code: CMBFAST, CAMB,…

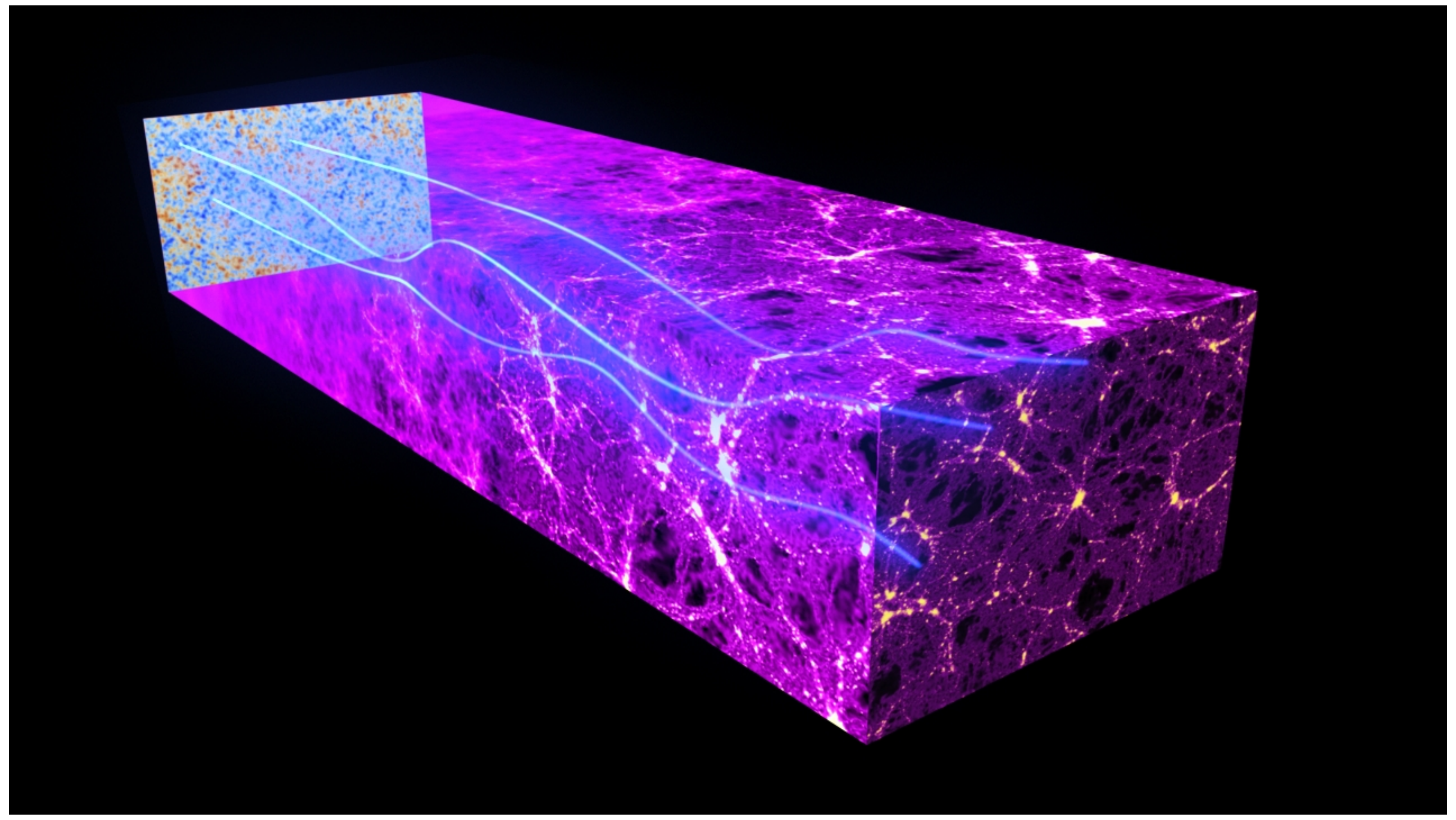
复合期以后的变化



重电离

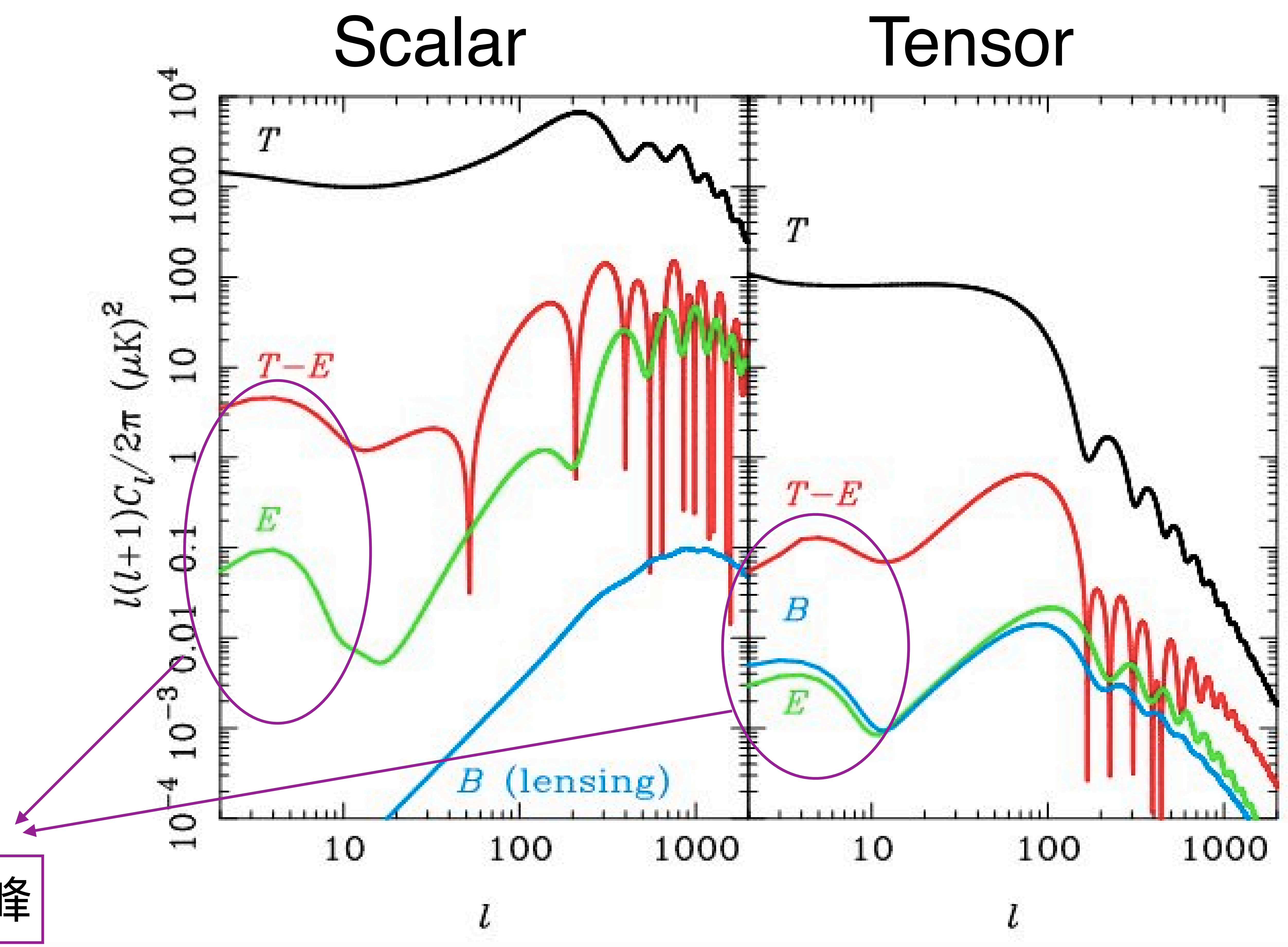
压低复合期产生的偏振，

又产生大尺度上新的偏振



弱引力透镜

Lensed B-mode peaked around $l \sim 1000$



重电离峰

Challinor & Peiris, arXiv:0903.5158 r=0.22

大尺度上的CMB B模式偏振主要是由原初引力波产生，

成为寻找原初引力波的最佳窗口.

CMB power spectra changed by Chern-Simons coupling of axion-like field
CPT test with CMB

$$(Q \pm iU)' = e^{\pm 2i\alpha}(Q \pm iU)$$

$$\begin{aligned}(E_{lm} \pm iB_{lm})' &= \int d\Omega \; {}_{\pm 2}Y^*_{lm}(\hat{\mathbf{n}})(Q \pm iU)'(\hat{\mathbf{n}}) = \int d\Omega \; {}_{\pm 2}Y^*_{lm}(\hat{\mathbf{n}}) \exp(\pm i2\alpha(\hat{\mathbf{n}}))(Q \pm iU)(\hat{\mathbf{n}}) \\ &= \sum_{l_1 m_1} (E_{l_1 m_1} \pm iB_{l_1 m_1}) \int d\Omega \; {}_{\pm 2}Y^*_{lm}(\hat{\mathbf{n}}) \exp(\pm i2\alpha(\hat{\mathbf{n}})) \; {}_{\pm 2}Y_{l_1 m_1}(\hat{\mathbf{n}}) \\ &\equiv \sum_{l_1 m_1} (E_{l_1 m_1} \pm iB_{l_1 m_1}) F^{\pm}_{l m l_1 m_1} \; .\end{aligned}$$

Isotropic rotation

$$C_\ell^{\prime TB} = C_\ell^{TE} \sin(2\alpha)$$

Lue, Wang & Kamionkowski, 1999

$$C_\ell^{\prime EB} = \frac{1}{2}\left(C_\ell^{EE} - C_\ell^{BB}\right) \sin(4\alpha)$$

Feng, Li, ML & Zhang, 2005

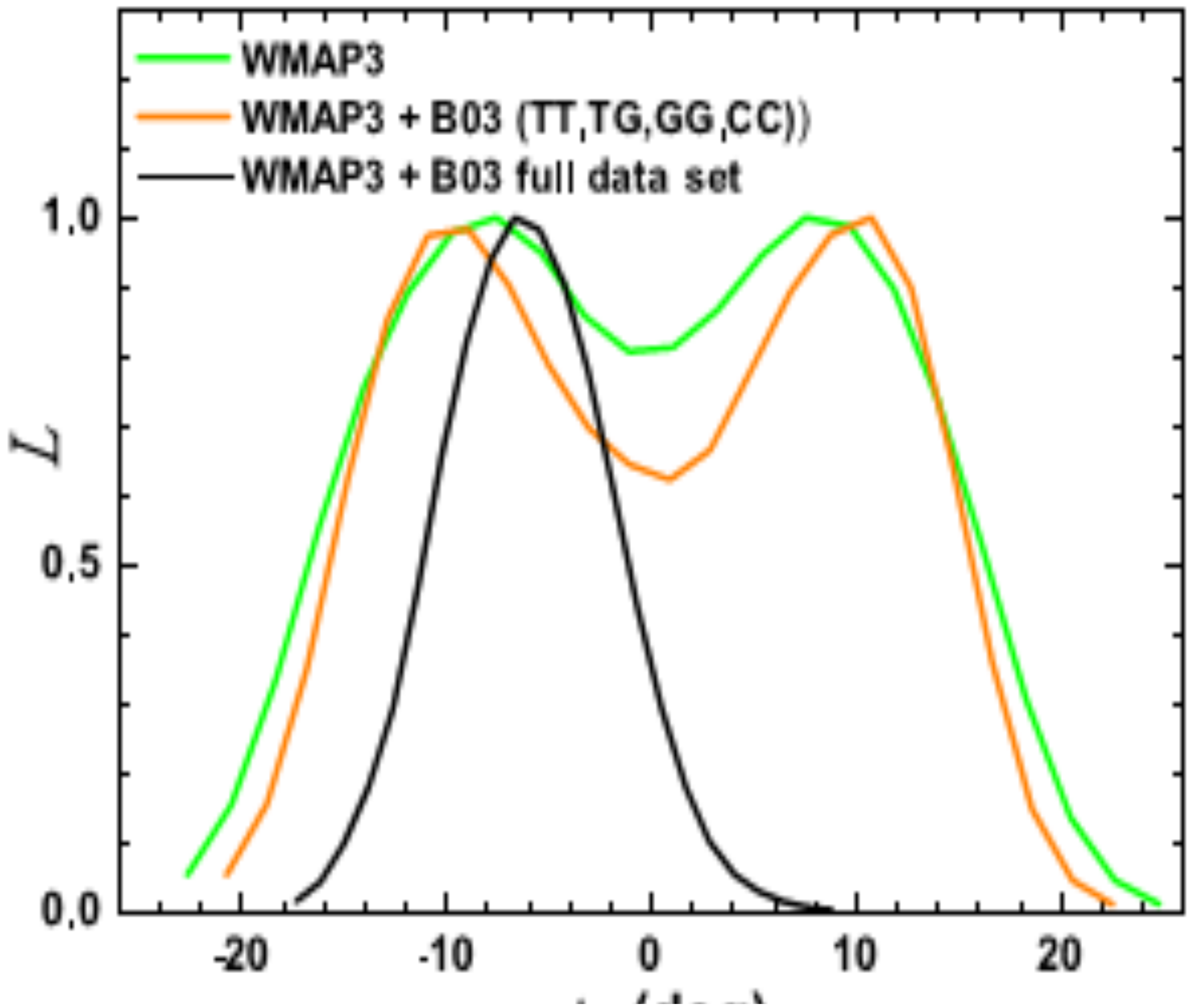
$$C_\ell^{\prime TE} = C_\ell^{TE} \cos(2\alpha)$$

$$C_\ell^{\prime EE} = C_\ell^{EE} \cos^2(2\alpha) + C_\ell^{BB} \sin^2(2\alpha)$$

Feng et al, 2006

$$C_\ell^{\prime BB} = C_\ell^{EE} \sin^2(2\alpha) + C_\ell^{BB} \cos^2(2\alpha)$$

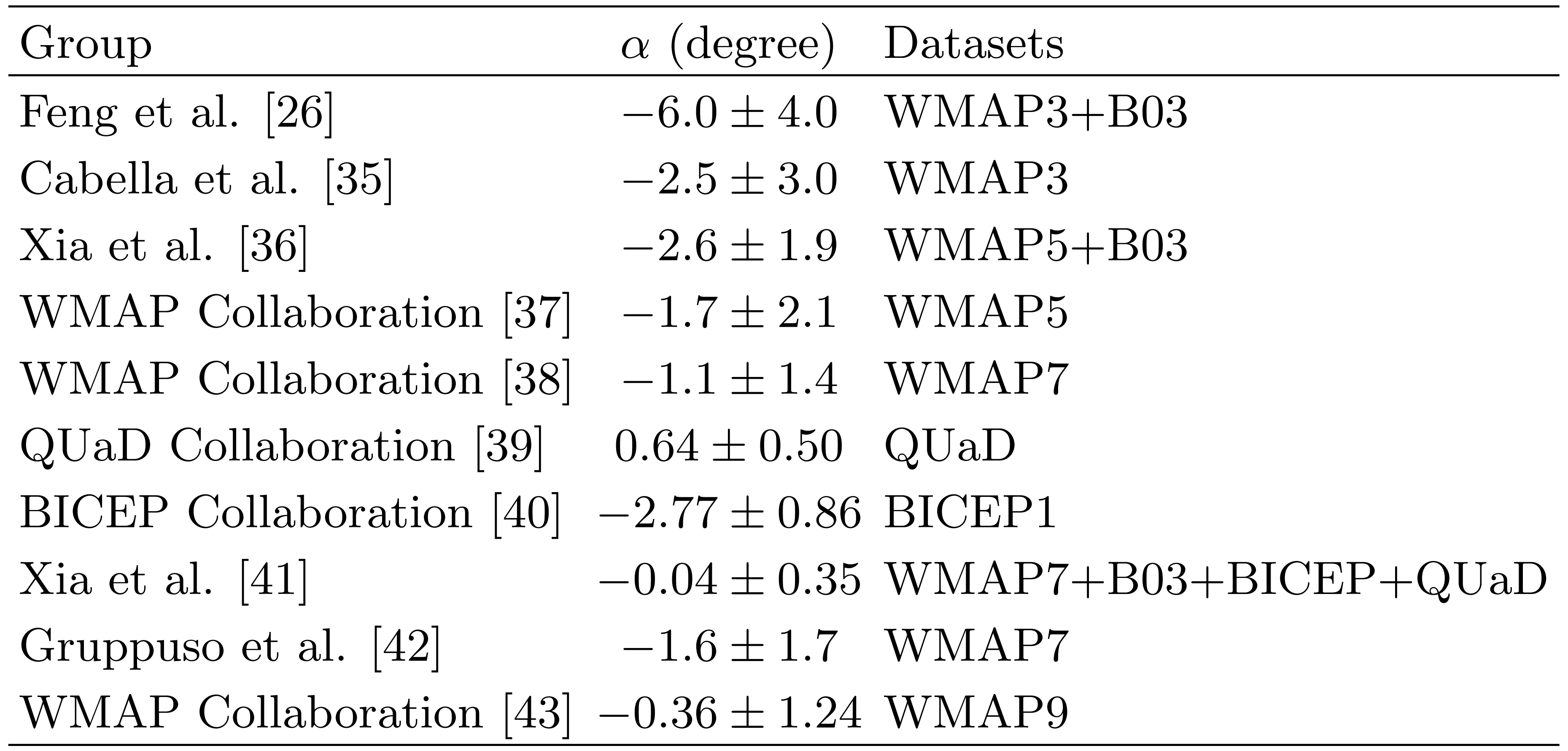
Produces TB and EB correlations
A new source for B-mode



WMAP3+BOOMERanG03 $\alpha = -6.0 \pm 4.0 \mathrm{deg}$

Feng, ML, Xia, Chen, Zhang, PRL (2006)

TABLE I: Summary of some measurements on the rotation angle



Group	α (degree)	Datasets
Feng et al. [26]	-6.0 ± 4.0	WMAP3+B03
Cabella et al. [35]	-2.5 ± 3.0	WMAP3
Xia et al. [36]	-2.6 ± 1.9	WMAP5+B03
WMAP Collaboration [37]	-1.7 ± 2.1	WMAP5
WMAP Collaboration [38]	-1.1 ± 1.4	WMAP7
QUaD Collaboration [39]	0.64 ± 0.50	QUaD
BICEP Collaboration [40]	-2.77 ± 0.86	BICEP1
Xia et al. [41]	-0.04 ± 0.35	WMAP7+B03+BICEP+QUaD
Gruppuso et al. [42]	-1.6 ± 1.7	WMAP7
WMAP Collaboration [43]	-0.36 ± 1.24	WMAP9

$\alpha = -1.08^\circ \pm 0.20^\circ$ POLARBEAR, 2014

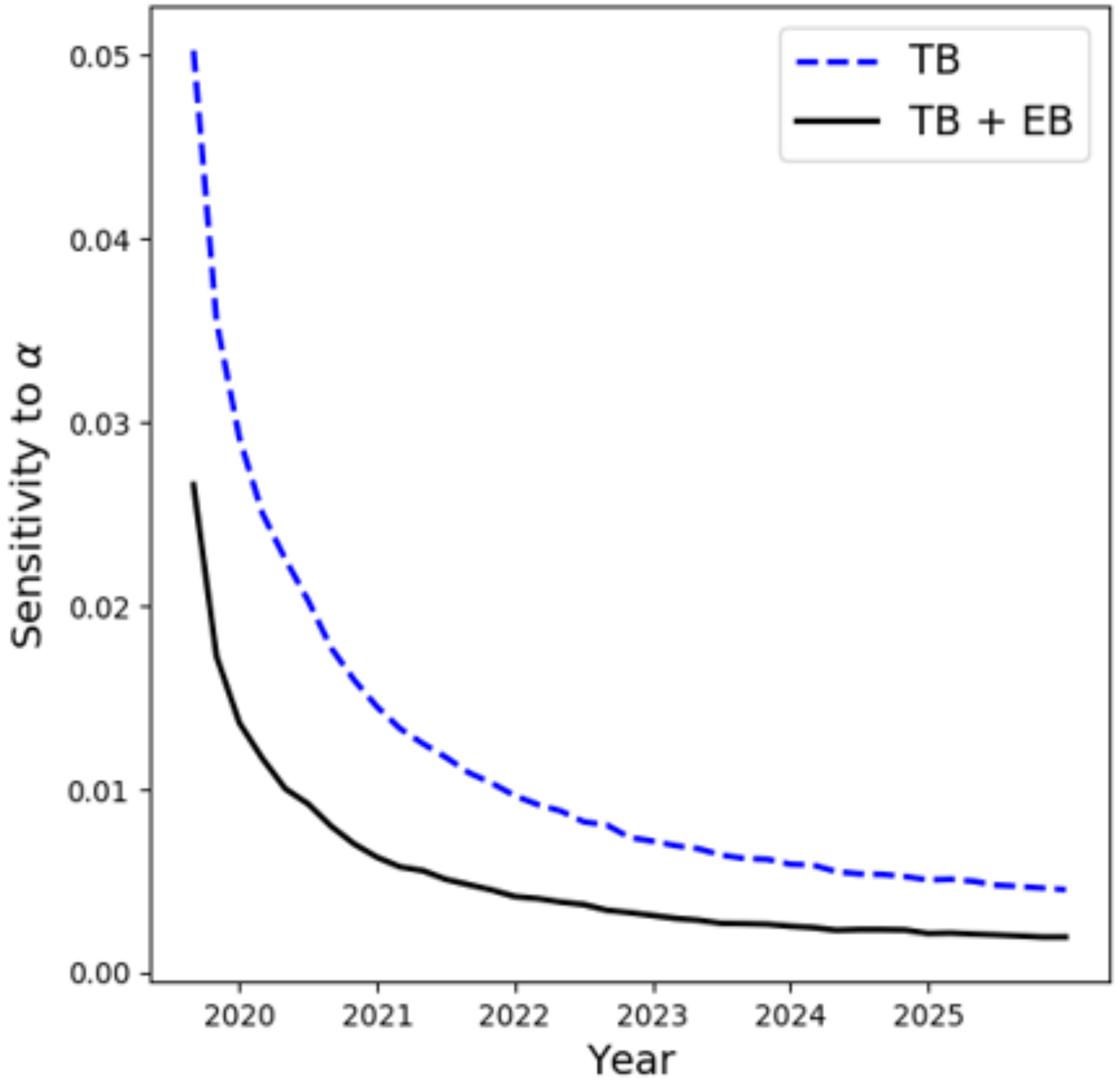
$\alpha = -1^\circ \pm 0.2^\circ$ BICEP2, 2014

$\alpha = -0.2^\circ \pm 0.5^\circ$ ACTPol, 2014

$\alpha = 0.31^\circ \pm 0.05^\circ$ Planck, 2016

AliCPT

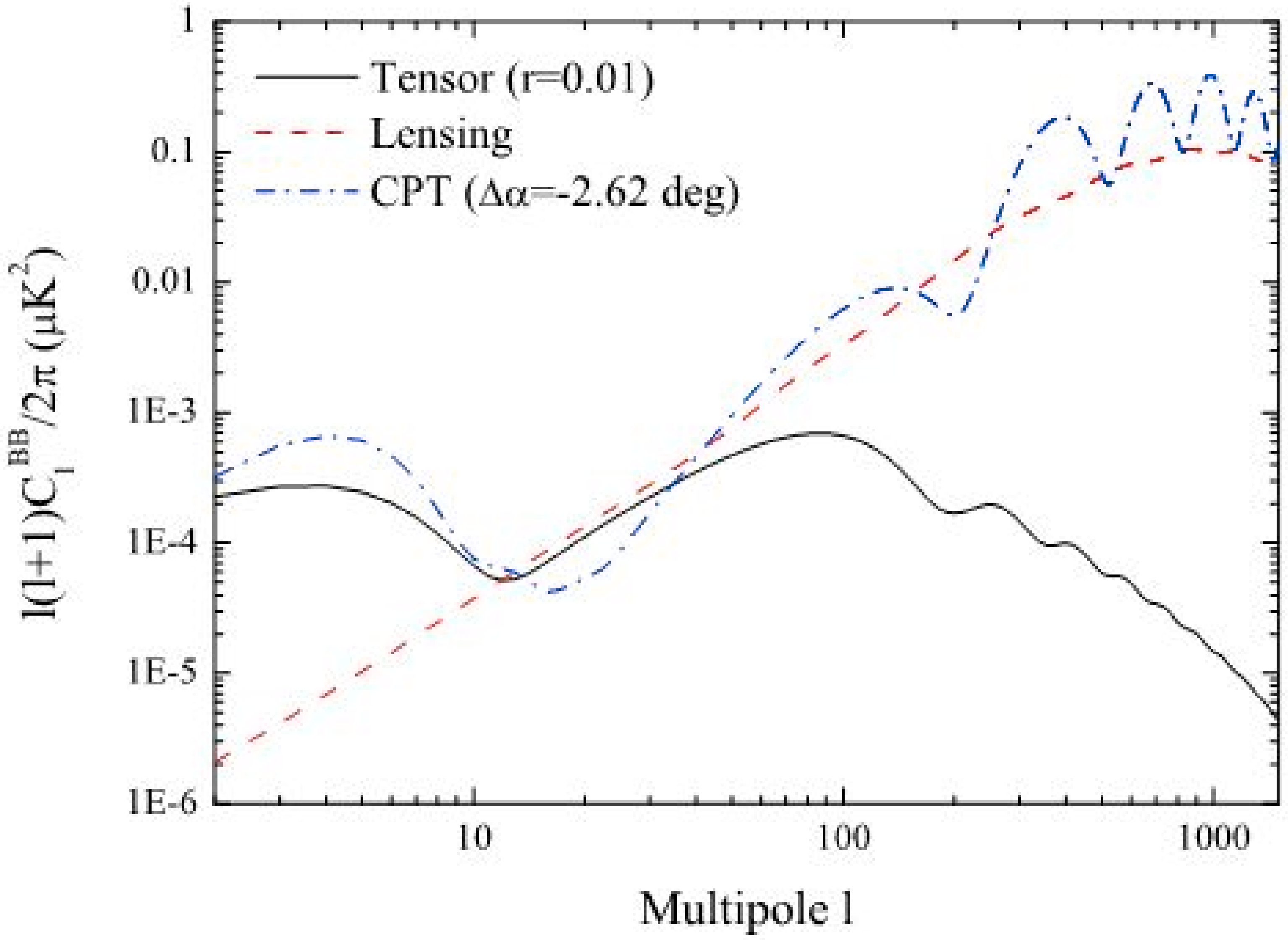
Credit: Siyu Li



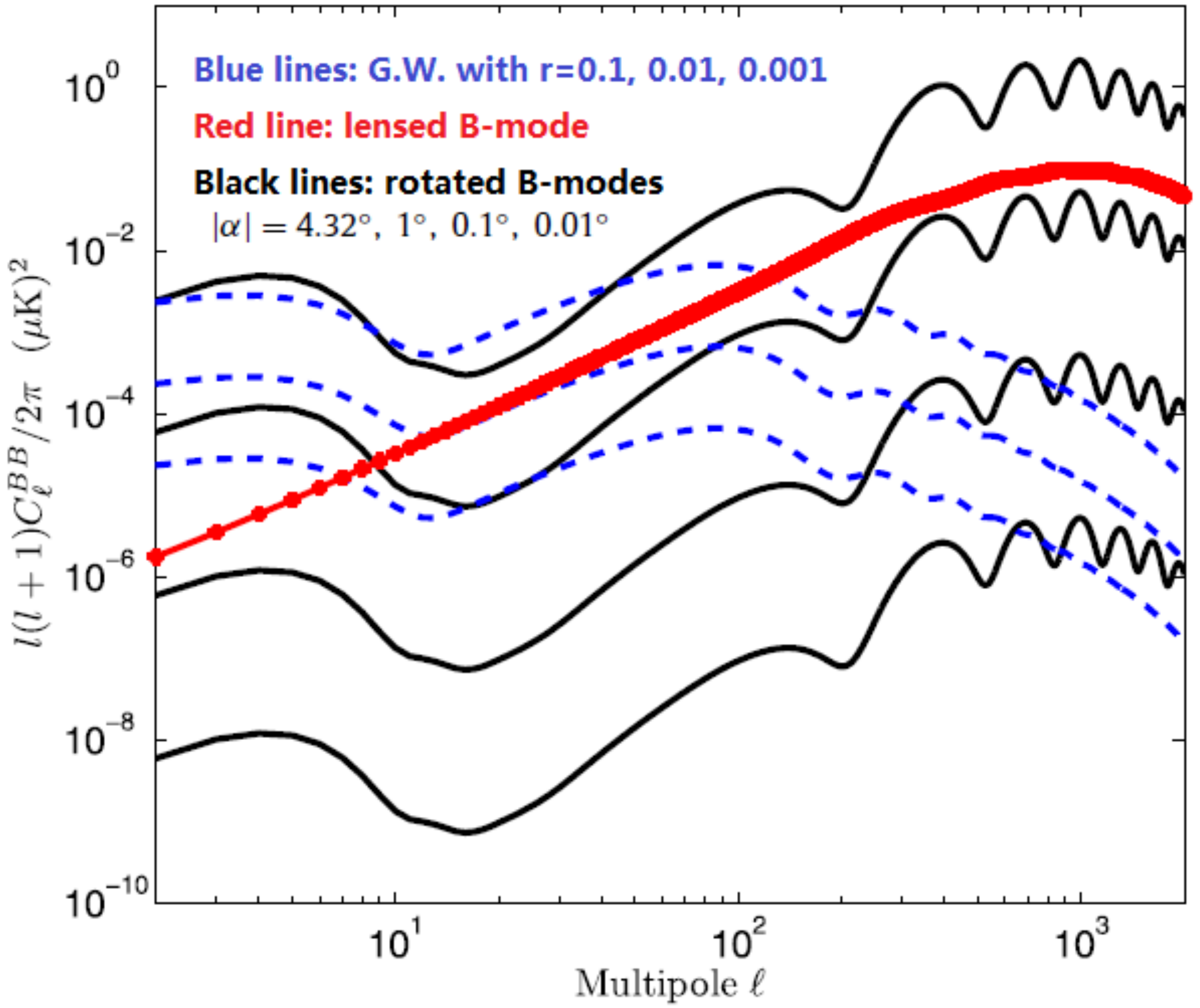
New source of B-mode

$$C_\ell^{\prime BB} = C_\ell^{EE} \sin^2(2\alpha) + C_\ell^{BB} \cos^2(2\alpha)$$

Same structure with EE spectrum



J.Q. Xia, H. Li, X. Zhang, Phys.Lett. B687 (2010) 129-132



Needs de-rotation for primordial GWs detection

Zhao & ML, PLB (2014)

Anisotropic CMB Rotation

In general, the rotation angle is anisotropic ML&Zhang, 2008

$$\alpha = \frac{\phi(x_{LSS}) - \phi(x_0)}{M}$$

$$\alpha(\hat{\mathbf{n}}) \equiv \bar{\alpha} + \Delta\alpha(\hat{\mathbf{n}}) \qquad \Delta\alpha(\hat{\mathbf{n}}) = \sum_{lm} b_{lm} Y_{lm}(\hat{\mathbf{n}})$$

Power spectrum of anisotropic rotation angle

$$\langle b_{lm} b^*_{l'm'} \rangle = C_l^{\alpha\alpha} \delta_{ll'} \delta_{mm'}$$

$$C^\alpha(\beta) \equiv \langle \Delta\alpha(\hat{\mathbf{n}}) \Delta\alpha(\hat{\mathbf{n}}') \rangle = \sum_l \frac{2l+1}{4\pi} C_l^{\alpha\alpha} P_l(\cos\beta)$$

Rotated spectra

$$C_l'^{EE} + C_l'^{BB} = \exp\left[-4C^{\alpha}(0)\right] \sum_{l'} \frac{2l'+1}{2} (C_{l'}^{EE} + C_{l'}^{BB}) \int_{-1}^{1} d_{22}^{l'}(\beta) d_{22}^{l}(\beta) e^{4C^{\alpha}(\beta)} d\cos(\beta)$$

$$C_l'^{EE} - C_l'^{BB} = \cos(4\bar{\alpha}) \exp\left[-4C^{\alpha}(0)\right] \sum_{l'} \frac{2l'+1}{2} (C_{l'}^{EE} - C_{l'}^{BB}) \int_{-1}^{1} d_{-22}^{l'}(\beta) d_{-22}^{l}(\beta) e^{-4C^{\alpha}(\beta)} d\cos(\beta)$$

$$C_l'^{EB} = \sin(4\bar{\alpha}) \exp\left[-4C^{\alpha}(0)\right] \sum_{l'} \frac{2l'+1}{4} (C_{l'}^{EE} - C_{l'}^{BB}) \int_{-1}^{1} d_{-22}^{l'}(\beta) d_{-22}^{l}(\beta) e^{-4C^{\alpha}(\beta)} d\cos(\beta)$$

$$C_l'^{TE} = C_l^{TE} \cos(2\bar{\alpha}) e^{-2C^{\alpha}(0)}$$

$$C_l'^{TB} = C_l^{TE} \sin(2\bar{\alpha}) e^{-2C^{\alpha}(0)} \; .$$

ML&Zhang, 2008; ML & Yu, 2013

Similar to Weak Lensing

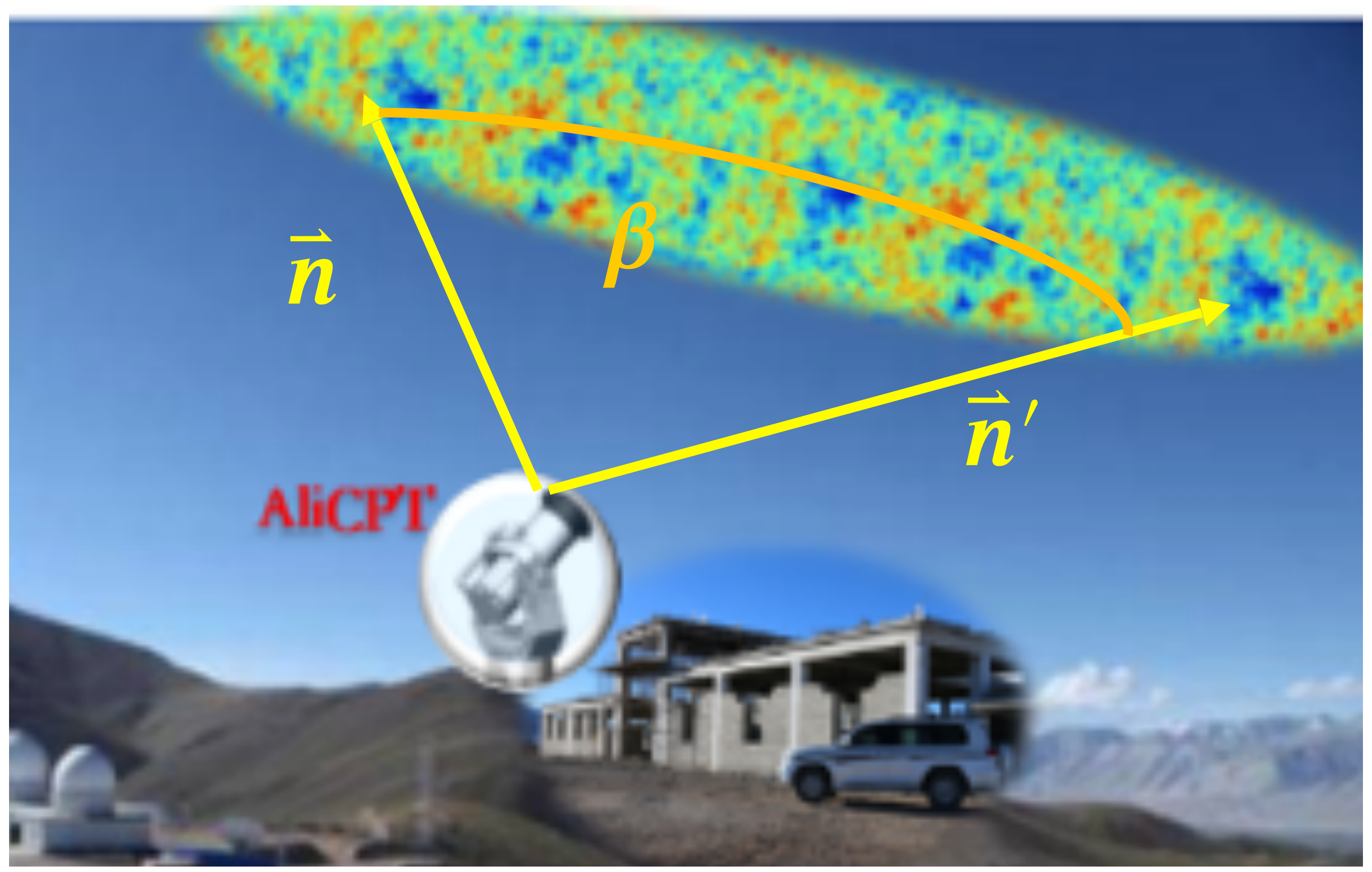
Measurements or constraints on anisotropic rotation angle

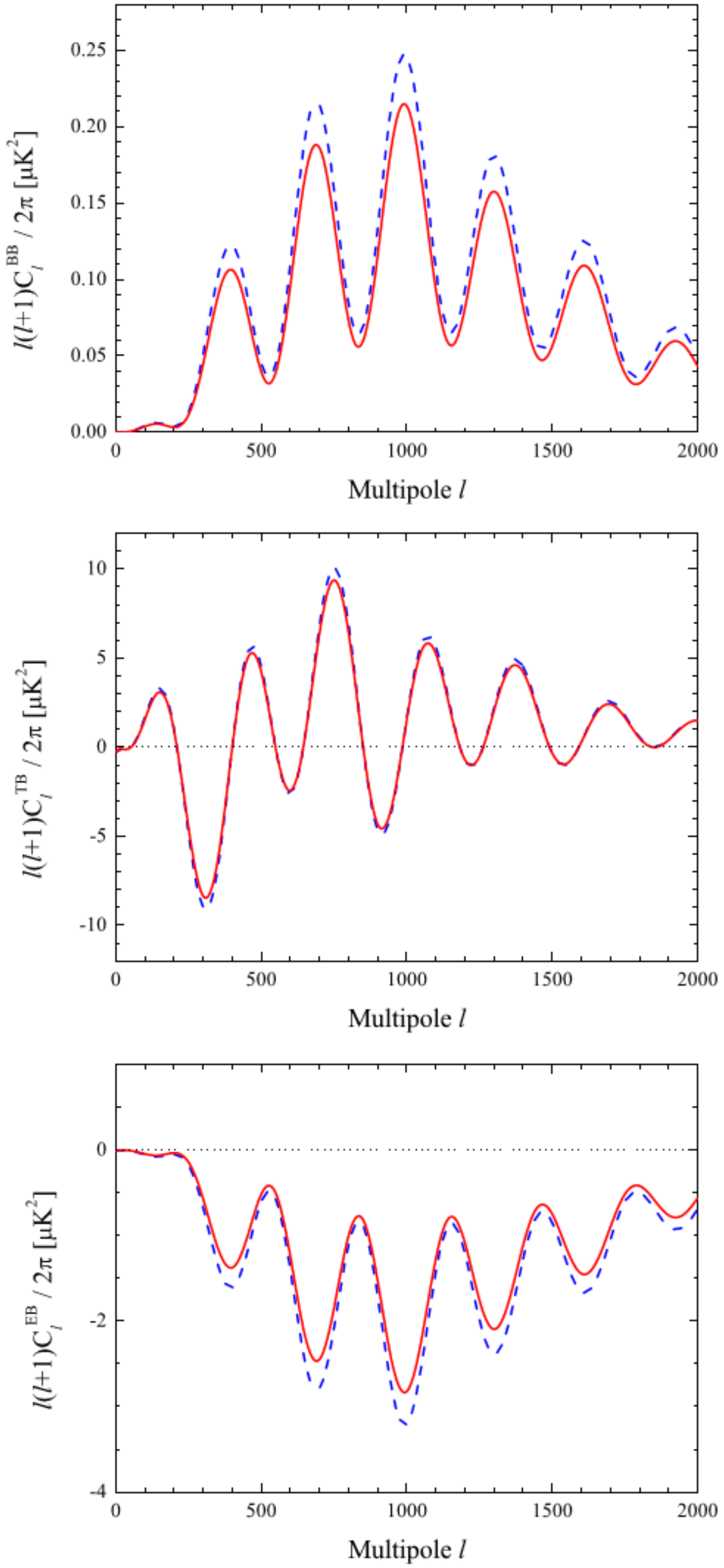
method: binned power $C_l^{\alpha\alpha}$ spectrum of

data： WMAP9+B03+BICEP1

$$C^\alpha(\beta) \equiv \langle \Delta\alpha(\hat{\mathbf{n}})\Delta\alpha(\hat{\mathbf{n}}')\rangle = \sum_l \frac{2l+1}{4\pi} C_l^{\alpha\alpha} P_l(\cos\beta)$$

$$\cos\beta = \vec{n} \bullet \vec{n}$$





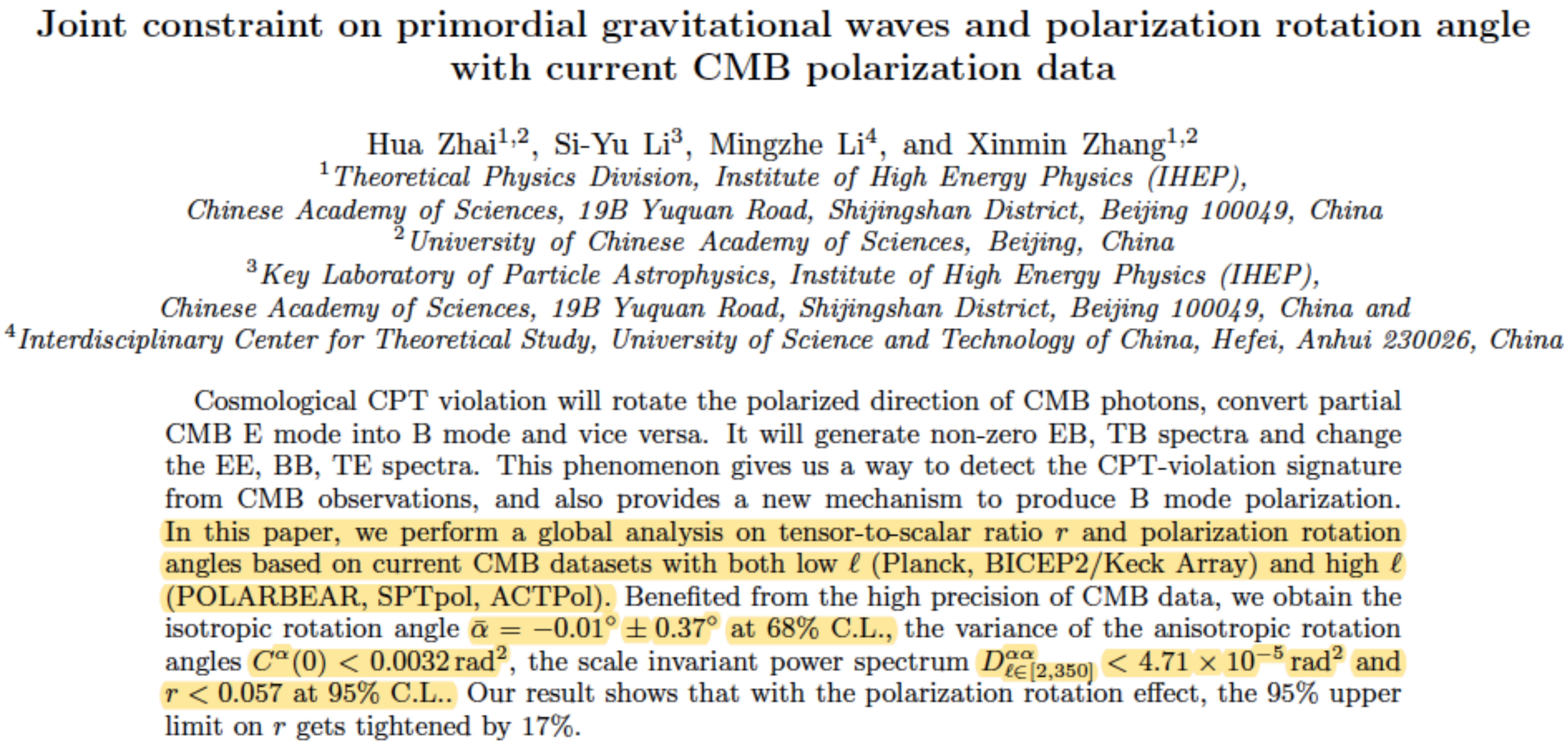
S. Li, J. Xia, M. Li, H. Li, X. Zhang, ApJ. 799 (2015) 211

Constraints on anisotropic rotation

$\sqrt{C_2^{\alpha\alpha}/(4\pi)} \leq 1^\circ$	WMAP7	Gluscevic et al, 2012
$C^\alpha(0) = \sum_l \frac{2l+1}{4\pi} C_l^{\alpha\alpha} < 0.014$	WMAP9+QUaD+BICEP1	ML & Yu, 2013
$C^\alpha(0) < 0.035$	WMAP9+B03+BICEP1	Siyu Li et al, 2015

By assumption of scale invariant spectrum, no sum over l

$\frac{l(l+1)}{2\pi} C_l^{\alpha\alpha} < 3.1 \times 10^{-4}$	POLARBEAR	Ade et al, 2015
$\frac{l(l+1)}{2\pi} C_l^{\alpha\alpha} \leq 0.33 \times 10^{-4}$	BICEP2/Keck Array	Ade et al, 2017



Joint constraint on primordial gravitational waves and polarization rotation angle with current CMB polarization data

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Cosmological CPT violation will rotate the polarized direction of CMB photons, convert partial CMB E mode into B mode and vice versa. It will generate non-zero EB, TB spectra and change the EE, BB, TE spectra. This phenomenon gives us a way to detect the CPT-violation signature from CMB observations, and also provides a new mechanism to produce B mode polarization. In this paper, we perform a global analysis on tensor-to-scalar ratio r and polarization rotation angles based on current CMB datasets with both low ℓ (Planck, BICEP2/Keck Array) and high ℓ (POLARBEAR, SPTpol, ACTPol). Benefited from the high precision of CMB data, we obtain the isotropic rotation angle $\bar{\alpha} = -0.01^\circ \pm 0.37^\circ$ at 68% C.L., the variance of the anisotropic rotation angles $C^\alpha(0) < 0.0032\,\mathrm{rad}^2$, the scale invariant power spectrum $D^{\alpha\alpha}_{\ell\in[2,350]} < 4.71 \times 10^{-5}\,\mathrm{rad}^2$ and $r < 0.057$ at 95% C.L.. Our result shows that with the polarization rotation effect, the 95% upper limit on r gets tightened by 17%.

arXiv:1910.02395, PLB(2020)

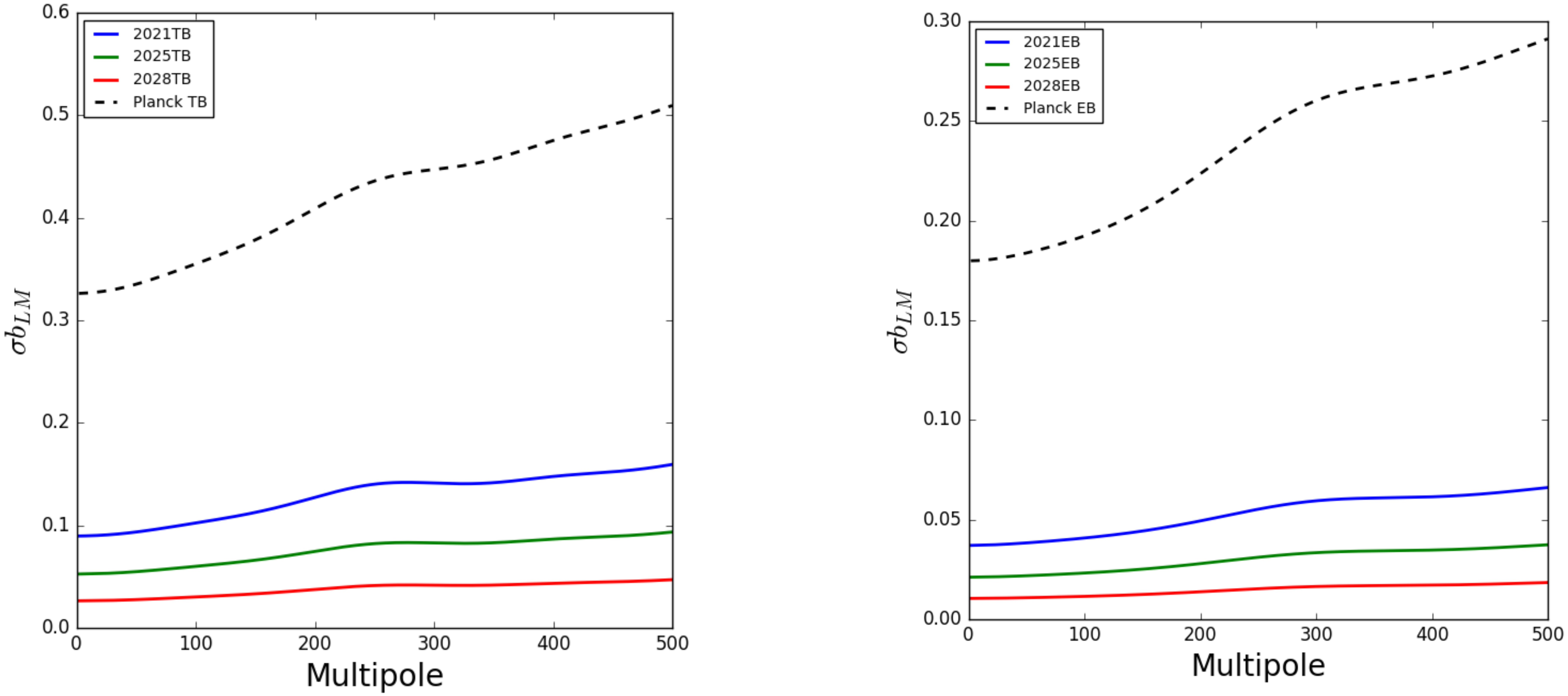
Binned power spectrum for $D_l^{\alpha\alpha} = \frac{l(l+1)}{2\pi} C_l^{\alpha\alpha}$

$D_l^{\alpha\alpha}(i),\ i = 1 \sim 6$ [2, 350), [350, 700), [700, 1100), [1100, 1500), [1500, 2000), [2000, 2500]

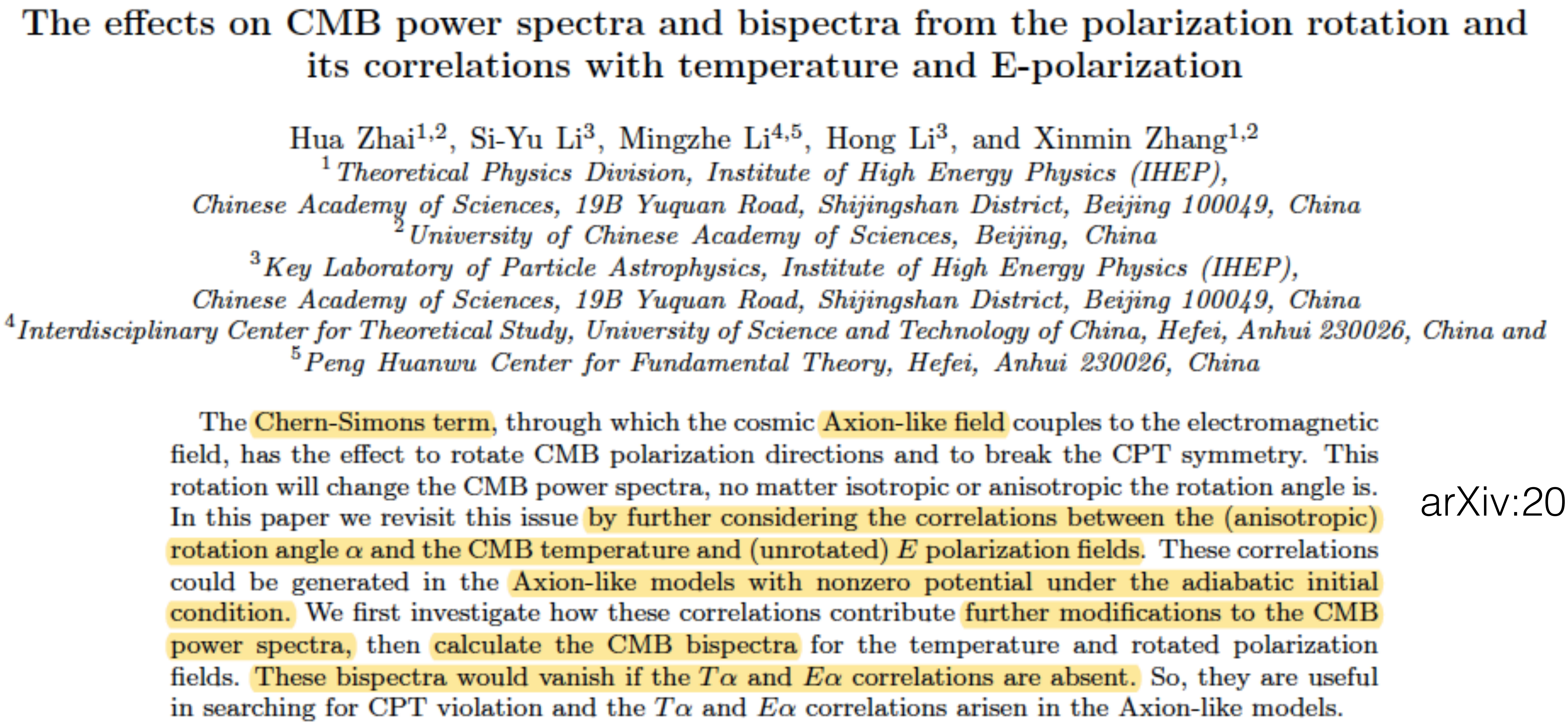
TABLE I: 2σ Constraints on r and polarization rotation angles.

-	$P_{\Lambda\mathrm{CDM}} + r$	$P_{\Lambda\mathrm{CDM}} + r + \bar{\alpha}$	$P_{\Lambda\mathrm{CDM}} + r + \bar{\alpha} + D_\ell^{\alpha\alpha}(\mathrm{rad}^2)$
r	< 0.069	< 0.067	< 0.057
$\bar{\alpha}$	-	$-0.1^\circ \pm 1.0^\circ$	$-0.01^\circ \pm 0.70^\circ$
$D_\ell^{\alpha\alpha}(1)$	-	-	$< 4.71 \times 10^{-5}$
$D_\ell^{\alpha\alpha}(2)$	-	-	$< 7.13 \times 10^{-4}$
$D_\ell^{\alpha\alpha}(3)$	-	-	$< 1.35 \times 10^{-3}$
$D_\ell^{\alpha\alpha}(4)$	-	-	$< 1.85 \times 10^{-3}$
$D_\ell^{\alpha\alpha}(5)$	-	-	$< 1.83 \times 10^{-3}$
$D_\ell^{\alpha\alpha}(6)$	-	-	$< 2.08 \times 10^{-3}$
$C^\alpha(0)$	-	-	< 0.0032

Sensitivity of AliCPT to anisotropic rotation



Credit: Siyu Li



The effects on CMB power spectra and bispectra from the polarization rotation and its correlations with temperature and E-polarization

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The Chern-Simons term, through which the cosmic Axion-like field couples to the electromagnetic field, has the effect to rotate CMB polarization directions and to break the CPT symmetry. This rotation will change the CMB power spectra, no matter isotropic or anisotropic the rotation angle is. In this paper we revisit this issue by further considering the correlations between the (anisotropic) rotation angle α and the CMB temperature and (unrotated) E polarization fields. These correlations could be generated in the Axion-like models with nonzero potential under the adiabatic initial condition. We first investigate how these correlations contribute further modifications to the CMB power spectra, then calculate the CMB bispectra for the temperature and rotated polarization fields. These bispectra would vanish if the $T\alpha$ and $E\alpha$ correlations are absent. So, they are useful in searching for CPT violation and the $T\alpha$ and $E\alpha$ correlations arisen in the Axion-like models.

arXiv:2006.01811

CMB power spectra and bispectra by Tα and Eα correlations

$$\delta\ddot{\phi} + 2\mathcal{H}\delta\dot{\phi} + a^2V''\delta\phi + k^2\delta\phi = \dot{\phi}(3\dot{\Phi} + \dot{\Psi}) - 2a^2V'\Psi$$

generated T and E maps on LSS

Further modifications to the power spectra

$$\widetilde{C}_l^{EE} + \widetilde{C}_l^{BB} = \frac{1}{2} e^{-4C^\alpha(0)} \int d\cos\beta \; e^{4C^\alpha(\beta)} d_{22}^l(\beta) \left[\sum_L (2L+1) d_{22}^L(\beta) \left(C_L^{EE} + C_L^{BB} \right) + W_{E\alpha}^2(\beta) \right],$$

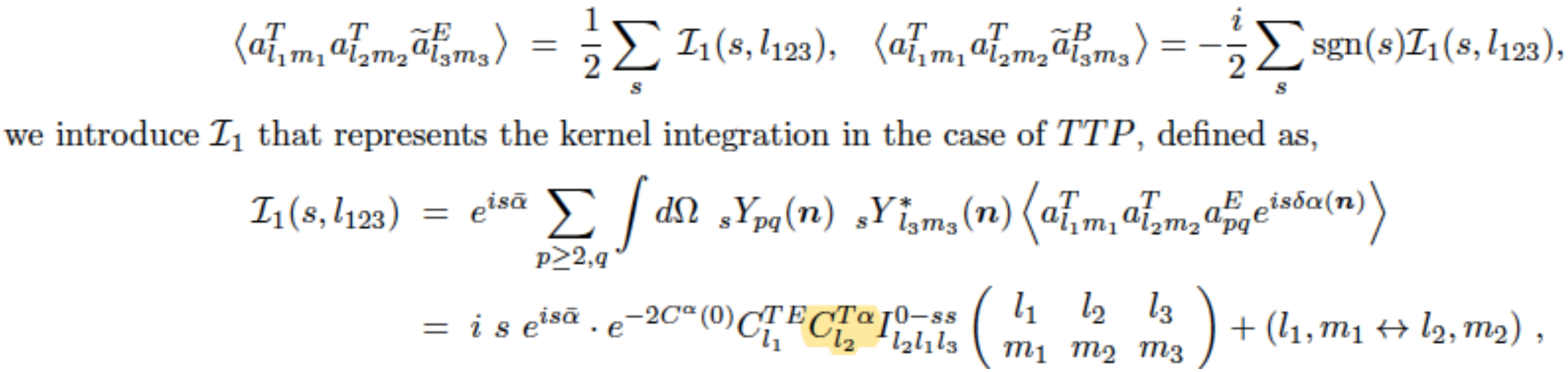
$$\widetilde{C}_l^{EE} - \widetilde{C}_l^{BB} = \frac{1}{2} e^{-4C^\alpha(0)} \cos(4\bar{\alpha}) \int d\cos\beta \; e^{-4C^\alpha(\beta)} d_{-22}^l(\beta) \left[\sum_L (2L+1) d_{-22}^L(\beta) \left(C_L^{EE} - C_L^{BB} \right) - W_{E\alpha}^2(\beta) \right],$$

$$\widetilde{C}_l^{EB} = \frac{1}{4} e^{-4C^\alpha(0)} \sin(4\bar{\alpha}) \int d\cos\beta \; e^{-4C^\alpha(\beta)} d_{-22}^l(\beta) \left[\sum_L (2L+1) d_{-22}^L(\beta) \left(C_L^{EE} - C_L^{BB} \right) - W_{E\alpha}^2(\beta) \right]$$

$$W_{E\alpha}(\beta) = \frac{1}{\sqrt{\pi}} \sum_L (2L+1) \, d_{02}^L(\beta) C_L^{E\alpha}$$

T\alpha correlation has no contribution
Rotated TE and TB spectra are unaffected

Bispectra of the rotated CMB fields generated with non-vanishing T\alpha and E\alpha correlations



$$\langle a^T_{l_1m_1} a^T_{l_2m_2} \tilde{a}^E_{l_3m_3} \rangle = \frac{1}{2}\sum_s \mathcal{I}_1(s,l_{123}), \quad \langle a^T_{l_1m_1} a^T_{l_2m_2} \tilde{a}^B_{l_3m_3} \rangle = -\frac{i}{2}\sum_s \mathrm{sgn}(s)\mathcal{I}_1(s,l_{123}),$$

we introduce $\mathcal{I}_1$ that represents the kernel integration in the case of TTP, defined as,

$$\begin{aligned}\mathcal{I}_1(s,l_{123}) &= e^{is\bar{\alpha}} \sum_{p\geq 2,q} \int d\Omega \;\; {}_sY_{pq}(\boldsymbol{n}) \;\; {}_sY^*_{l_3m_3}(\boldsymbol{n}) \left\langle a^T_{l_1m_1} a^T_{l_2m_2} a^E_{pq} e^{is\delta\alpha(\boldsymbol{n})} \right\rangle \\ &= i\ s\ e^{is\bar{\alpha}} \cdot e^{-2C^{\alpha}(0)} C^{TE}_{l_1} C^{T\alpha}_{l_2} I^{0-ss}_{l_2l_1l_3} \begin{pmatrix} l_1 & l_2 & l_3 \\ m_1 & m_2 & m_3 \end{pmatrix} + (l_1, m_1 \leftrightarrow l_2, m_2)\ ,\end{aligned}$$

Details of other bispectra, TEE, TEB, TBB, EEE, EEB, EBB, BBB, can be found in arXiv:2006.01811

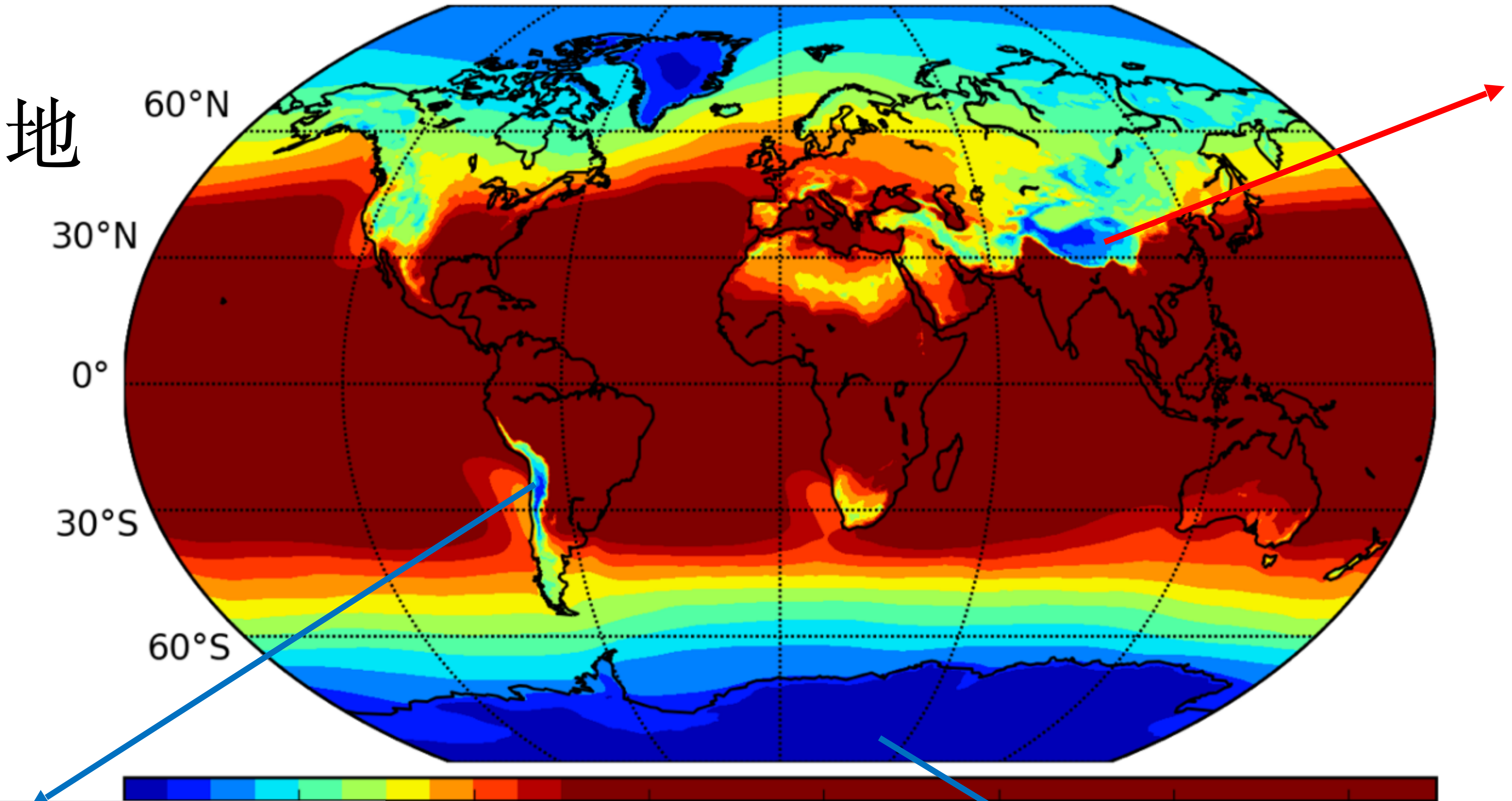
Useful in searching for CPT violation and the T\alpha and E\alpha correlations in the axion-like models

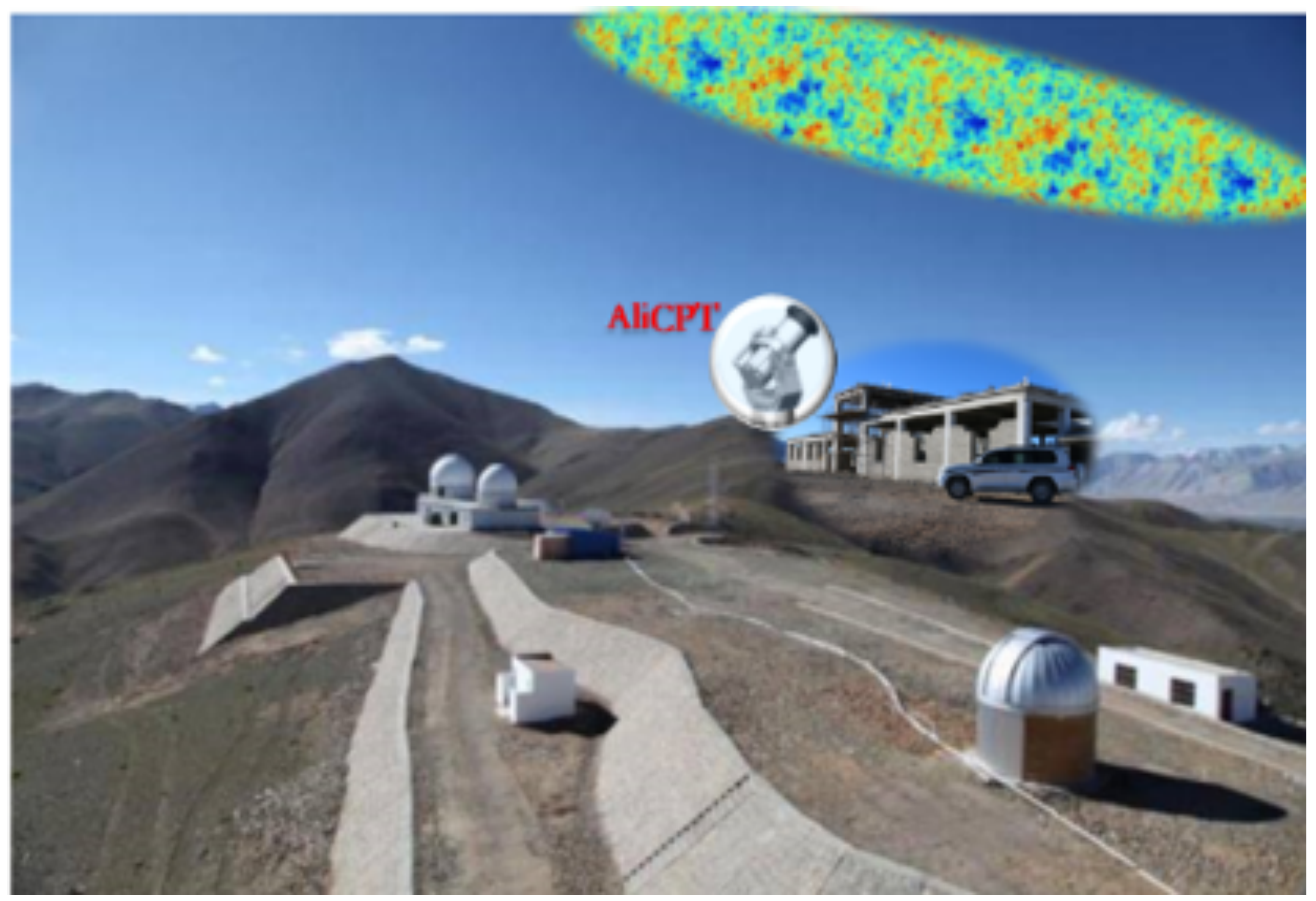
类轴子宇宙学实验探测

CMB实验计划:

目前无空间项目

地面项目分布于三大基地





西藏阿里地区：AliCPT

智利Atacama沙漠：

ACTPol, POLARBEAR等

南极极点：BICEP, SPTpol等

Conclusions

- In the context of 4d theories, inflation model with single axion-like field suffers from theoretical difficulties. These may be circumvented in higher dimension theories.
- Axion-like fields serve as good candidates for dark matter.
- Axion-like field is a natural candidate for dark energy, which has a very flat potential. Shift symmetry, derivative couplings.
- Derivative coupling to photon, CPT violation, photon's polarization rotation, can be tested by CMB.

Thanks for your attentions!