# Searching for cosmological parity violation

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**Seokcheon Lee (Sungkyunkwan U.)**
**Hing Tong Cho (TKU)**
**Changbom Park, Zahra Davari (KIAS)**

# Parity or left-right symmetry

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

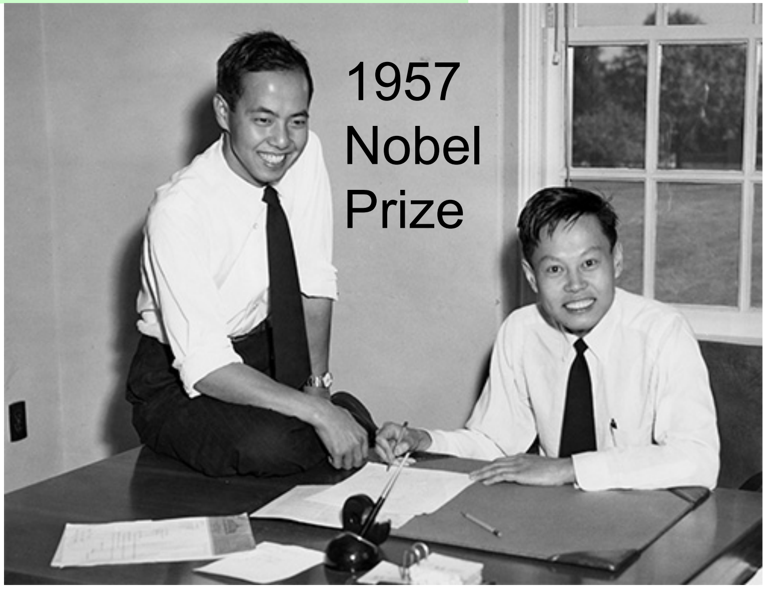
  Parity symmetry is broken in sub-atomic world - weak interaction is left-handed

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

  Chiral gravitational wave background

  CMB polarization

  CMB/galaxy four-point functions




1978 inaugural Wolf Prize

# Outline

- Axion with mass and breaking scale
  ($m_\varphi$, $f_\varphi$) as free parameters
- Assume an axion-photon coupling via a Chern-Simons term $\varphi E \cdot B$
- Axion inflation – primordial black hole (PBH) seeds and chiral gravitational waves (GWs)
- Cosmic birefringence due to axion dark matter / dark energy / string-wall networks and CMB B-mode polarization
- Conclusion

# Axion Inflation

We consider a version of the trapped inflation driven by a pseudoscalar $\varphi$ that couples to a $U(1)$ gauge field $A_\mu$:

$$\mathcal{S} = \int d^4x\sqrt{-g}\left[\frac{M_p^2}{2}R - \frac{1}{2}\partial_\mu\varphi\partial^\mu\varphi - V(\varphi)\right.$$
$$\left. -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{\alpha}{4f}\varphi\tilde{F}^{\mu\nu}F_{\mu\nu}\right], \qquad (3)$$

Sorbo, Barnaby, Namba, Peloso, Meerburg, Pager, Unal,….

$$\varphi = \phi(\eta) + \delta\varphi(\eta,\vec{x})$$

$d\eta = dt/a$

Under the temporal gauge, $A_\mu = (0,\vec{A})$, we decompose $\vec{A}(\eta,\vec{x})$ into its right and left circularly polarized Fourier modes, $A_\pm(\eta,\vec{k})$, whose equation of motion is then given by

$$\left[\frac{d^2}{d\eta^2} + k^2 \mp 2aHk\xi\right]A_\pm(\eta,k) = 0, \quad \xi \equiv \frac{\alpha}{2fH}\frac{d\phi}{dt}. \quad (5)$$

$k/(aH) < 2|\xi|$

Spinoidal instability

## Background

$$\frac{d^2\phi}{dt^2} + 3H\frac{d\phi}{dt} + \frac{dV}{d\phi} = \frac{\alpha}{f}\langle \vec{E}\cdot\vec{B}\rangle,$$

$$3H^2 = \frac{1}{M_p^2}\left[\frac{1}{2}\left(\frac{d\phi}{dt}\right)^2 + V(\phi) + \frac{1}{2}\langle \vec{E}^2 + \vec{B}^2\rangle\right]$$

$$\langle \vec{E}\cdot\vec{B}\rangle \simeq -2.4\cdot 10^{-4}\frac{H^4}{\xi^4}\,\mathrm{e}^{2\pi\xi},$$

$$\left\langle\frac{\vec{E}^2+\vec{B}^2}{2}\right\rangle \simeq 1.4\cdot 10^{-4}\frac{H^4}{\xi^3}\,\mathrm{e}^{2\pi\xi}.$$

$$\frac{1}{2}\langle \vec{E}^2 + \vec{B}^2\rangle = \int \frac{dk\,k^2}{4\pi^2 a^4}\sum_{\lambda=\pm}\left(\left|\frac{dA_\lambda}{d\eta}\right|^2 + k^2|A_\lambda|^2\right),$$

$$\langle \vec{E}\cdot\vec{B}\rangle = -\int \frac{dk\,k^3}{4\pi^2 a^4}\frac{d}{d\eta}\left(|A_+|^2 - |A_-|^2\right).$$

## Perturbation

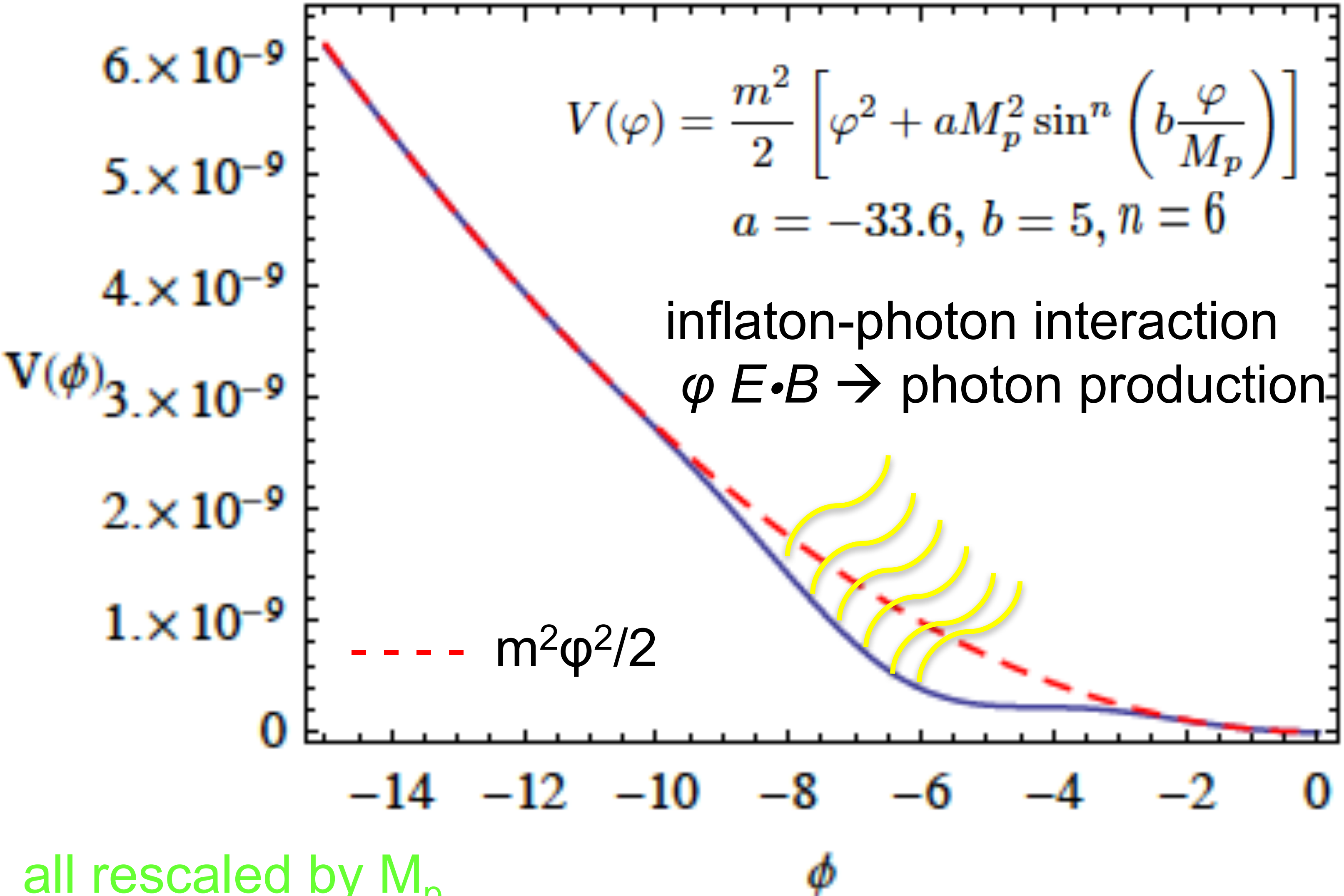
$$\left[\frac{\partial^2}{\partial t^2} + 3\beta H\frac{\partial}{\partial t} - \frac{\vec{\nabla}^2}{a^2} + \frac{d^2V}{d\phi^2}\right]\delta\varphi(t,\vec{x}) = \frac{\alpha}{f}\left(\vec{E}\cdot\vec{B} - \langle\vec{E}\cdot\vec{B}\rangle\right)$$

$$\delta\varphi = \frac{\alpha}{3\beta f H^2}\left(\vec{E}\cdot\vec{B} - \langle\vec{E}\cdot\vec{B}\rangle\right)$$

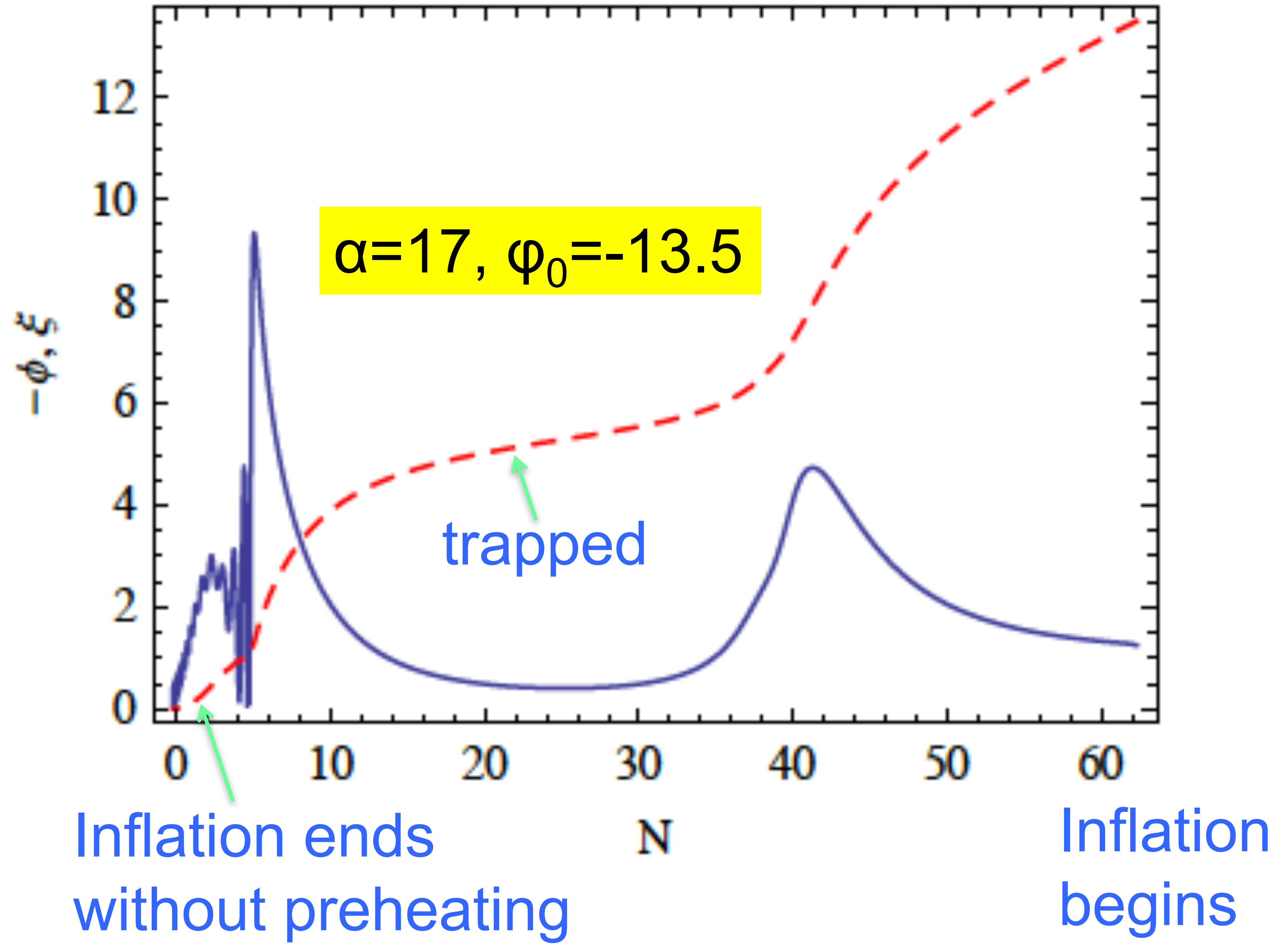
$$\beta \equiv 1 - 2\pi\xi\frac{\alpha}{f}\frac{\langle\vec{E}\cdot\vec{B}\rangle}{3H(d\phi/dt)}$$

$$\Delta_\zeta^2(k) = \langle\zeta(x)^2\rangle = \frac{H^2\langle\delta\varphi^2\rangle}{(d\phi/dt)^2} = \left[\frac{\alpha\langle\vec{E}\cdot\vec{B}\rangle}{3\beta f H(d\phi/dt)}\right]^2$$

# e.g. Axion inflation with a steep potential Cheng, Lee, Ng 16

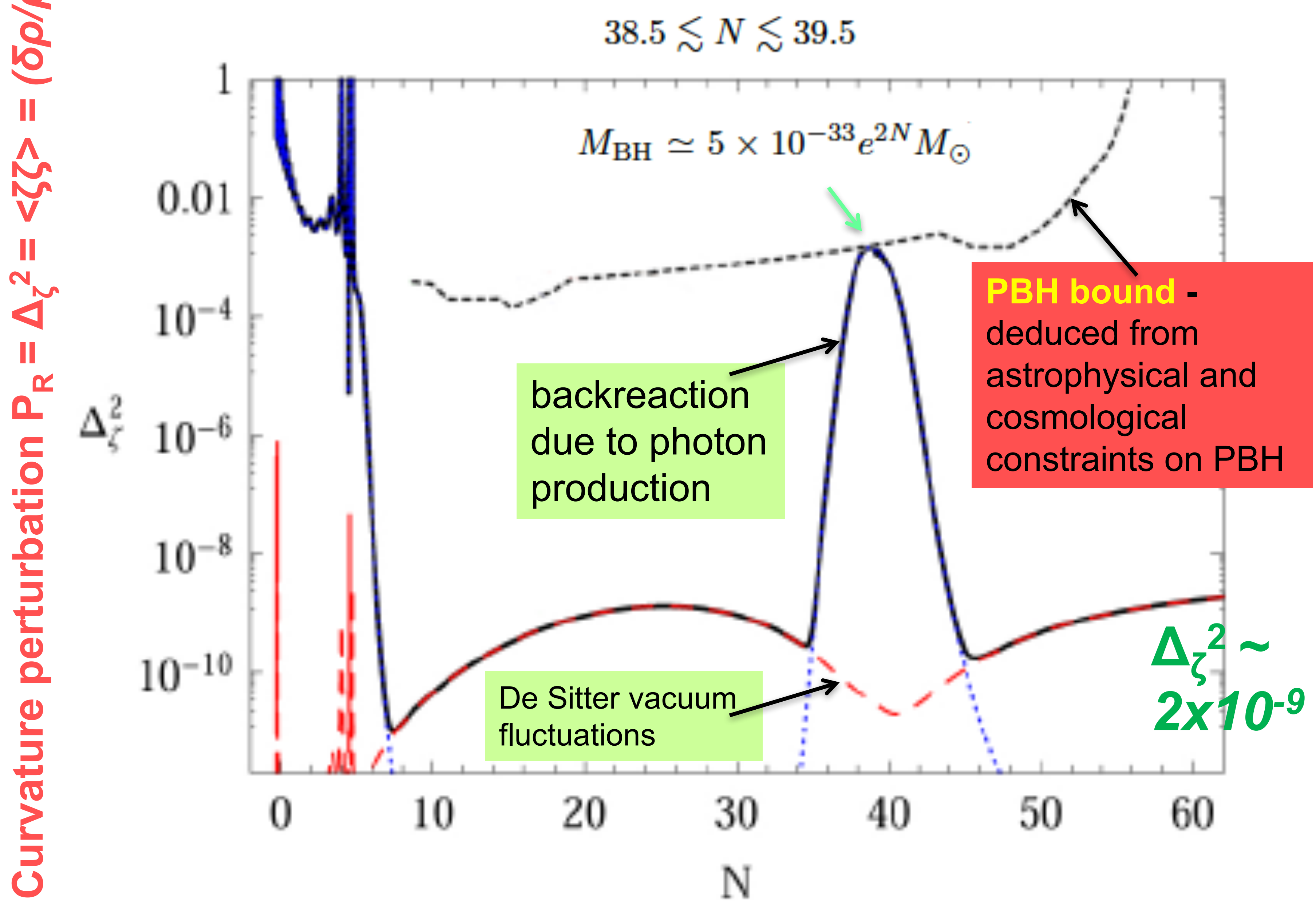



all rescaled by $M_p$

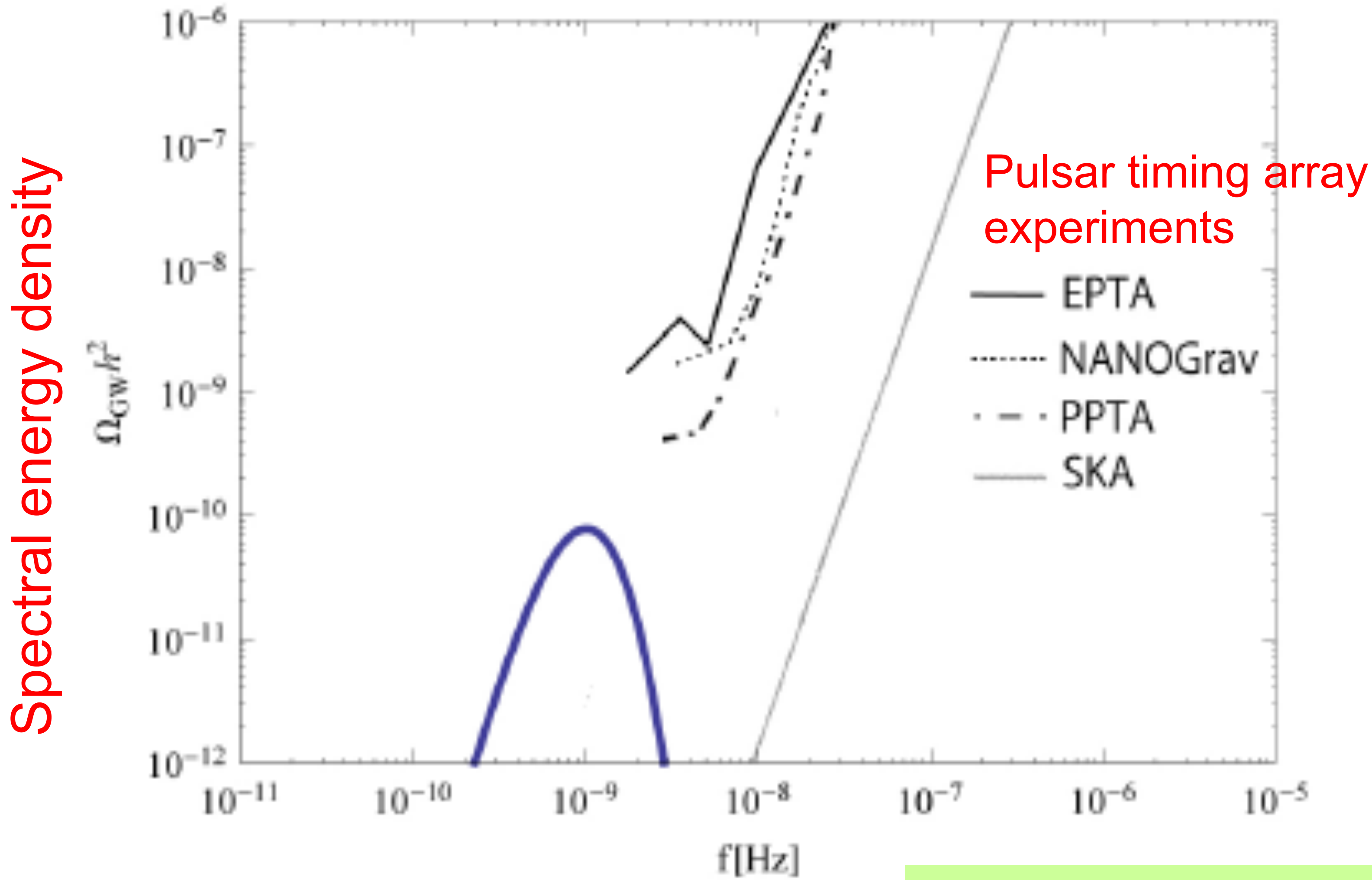


α=17, φ0=-13.5
trapped
Inflation ends without preheating
Inflation begins
−φ, ξ
N
0
2
4
6
8
10
12
0
10
20
30
40
50
60

# Production of 10-100$M_\odot$ PBHs



# Associated Chiral Gravitational Waves in Axion Inflation




$$\left[\frac{\partial^2}{\partial\eta^2} + \frac{2}{a}\frac{da}{d\eta}\frac{\partial}{\partial\eta} - \vec{\nabla}^2\right] h_{ij} = \frac{2a^2}{M_p^2}\left(-E_iE_j - B_iB_j\right)^{TT}$$

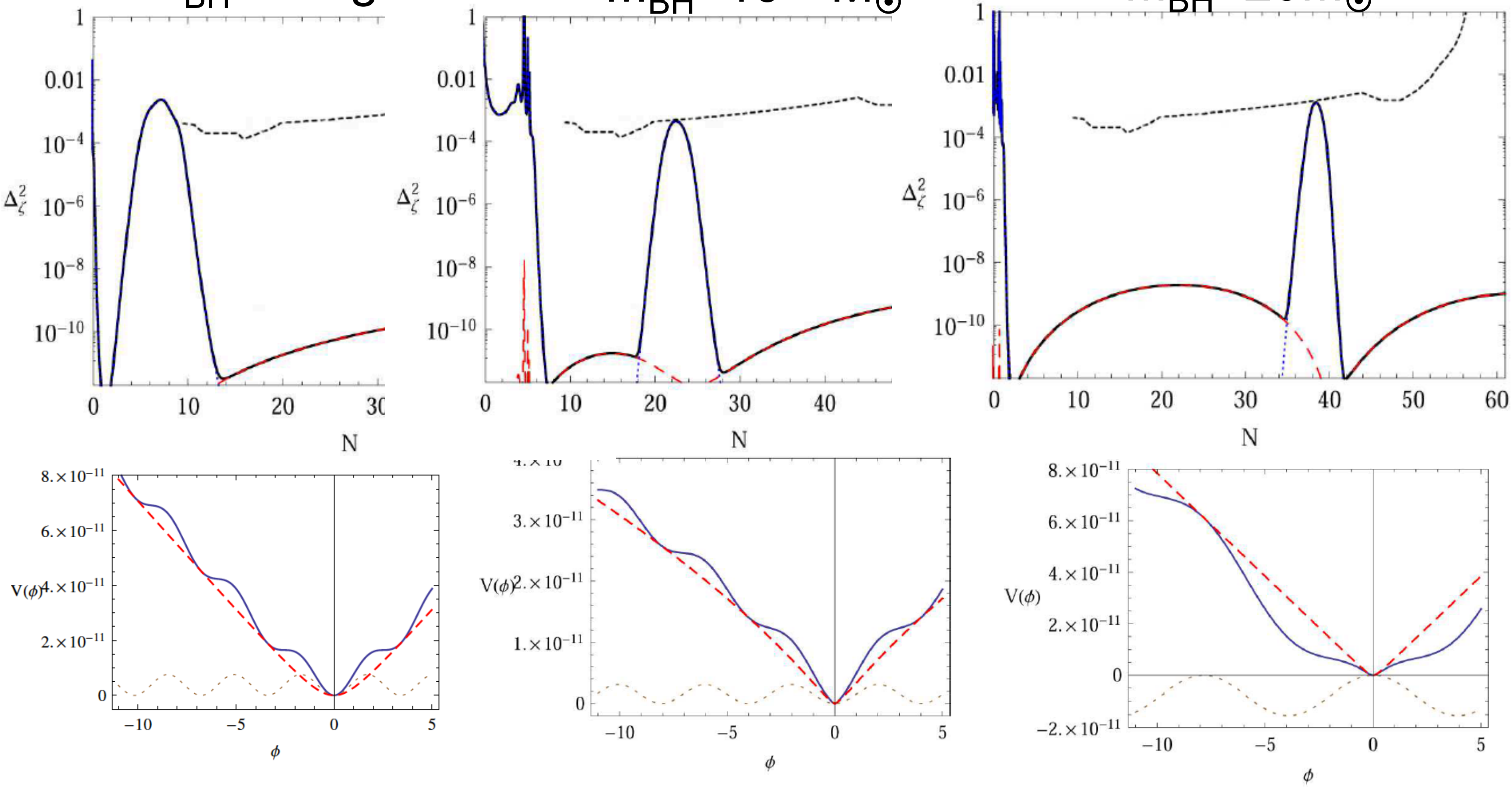
Chiral GWs　Sorbo 11　Chiral photons

Transverse traceless part of photon energy-momentum

**<E·E> ~ <E·B> ~ ζ**

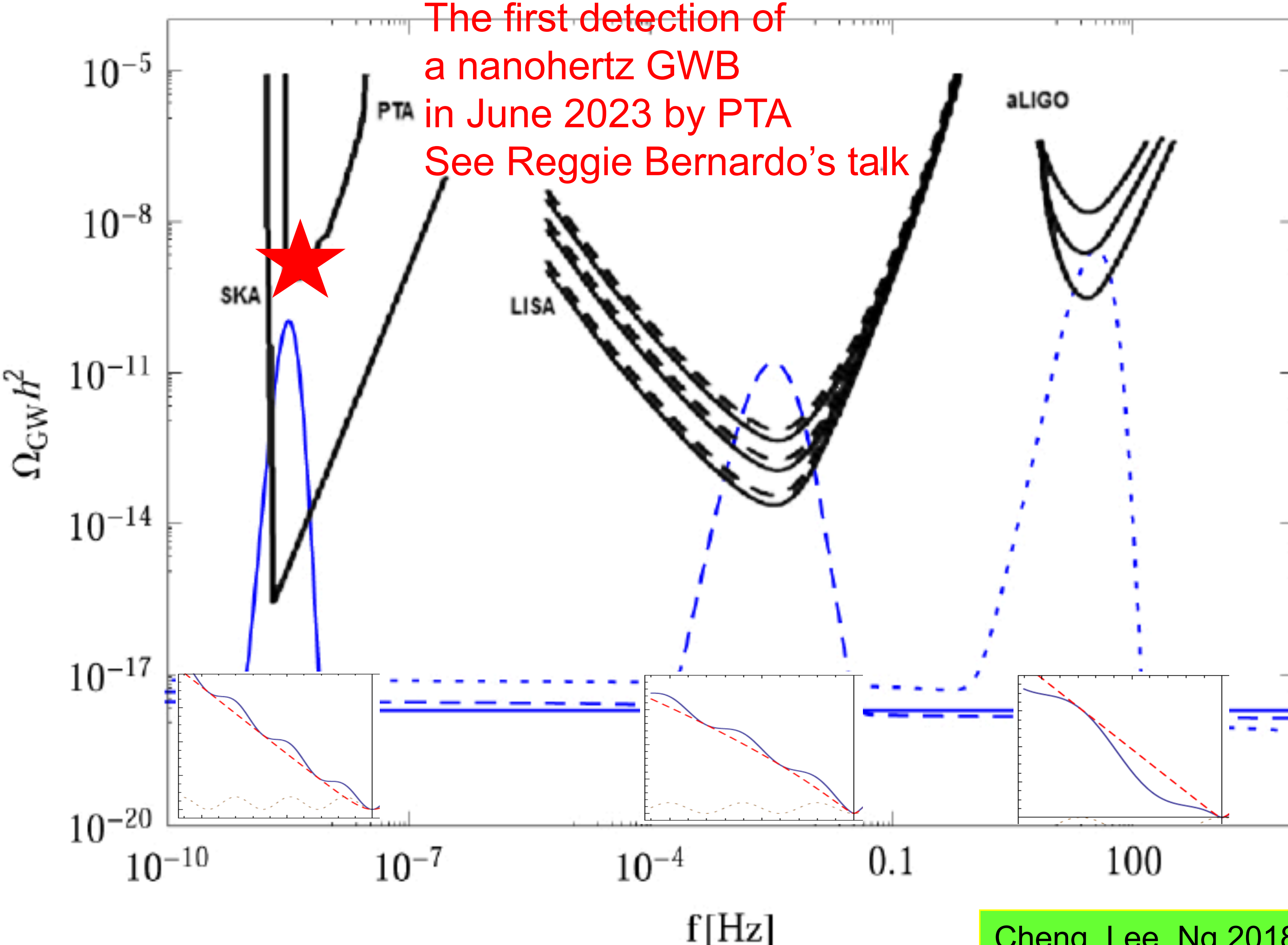
# Production of PBHs realized in axion monodromy inflation with sinusoidal modulations

$M_{BH} \sim 10^8$ g $\quad$ $M_{BH} \sim 10^{-13} M_\odot$ $\quad$ $M_{BH} \sim 20 M_\odot$



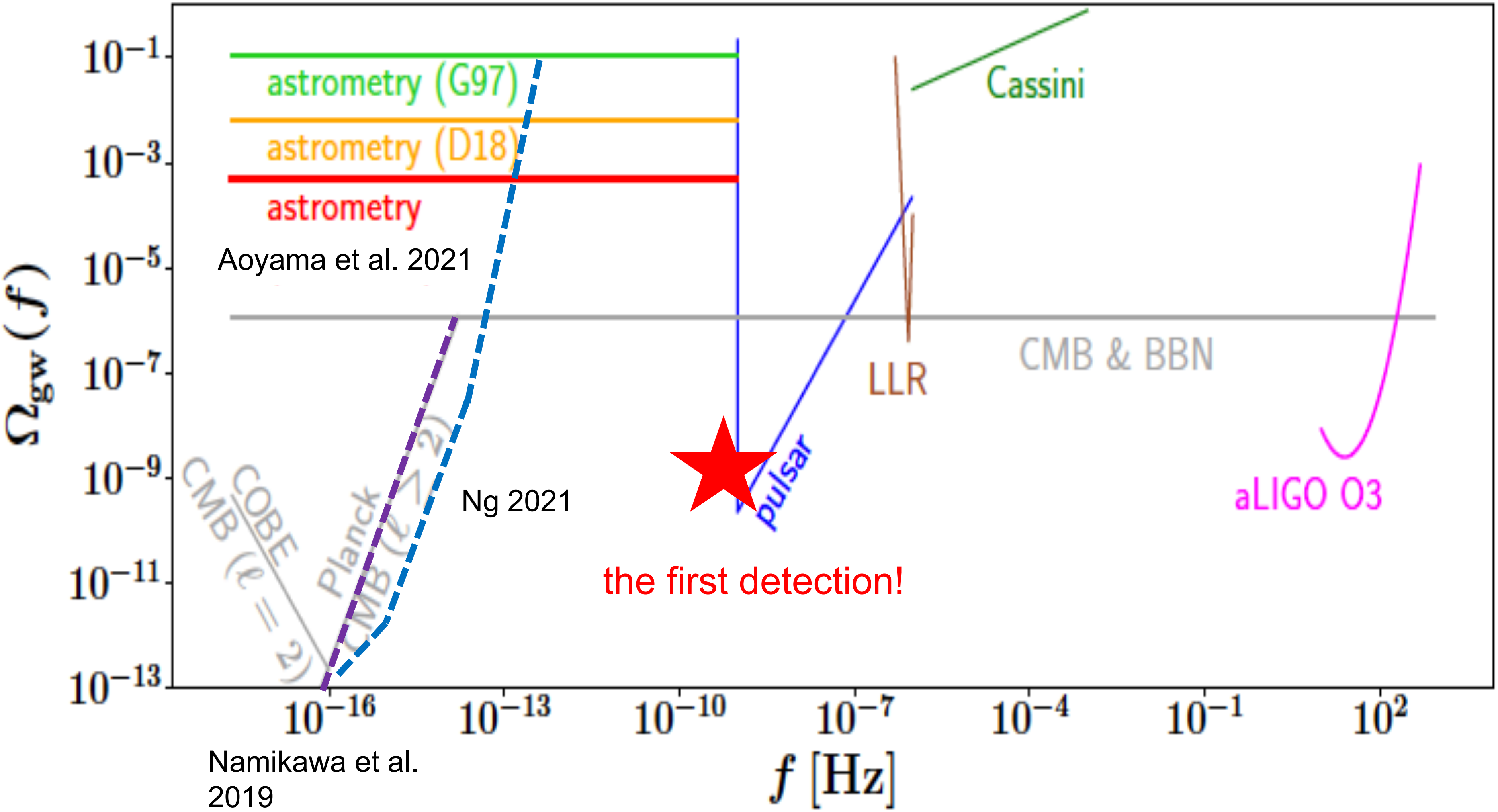
# Chiral GWs associated with PBHs in modulated axion inflation

The first detection of
a nanohertz GWB
in June 2023 by PTA
See Reggie Bernardo's talk




Cheng, Lee, Ng 2018

# Current Upper Bounds

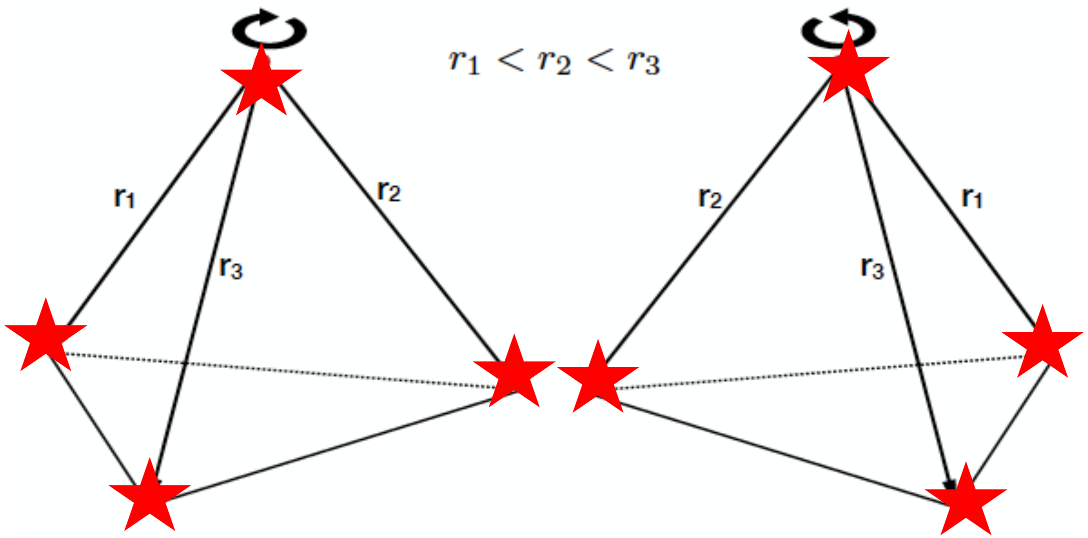



CMB&BBN – extra degrees of freedom
Cassini+LLR – radar launching

CMB – anisotropy + B-mode polarization
aLIGO – direct detection of wave strain
Pulsar – Shapiro time delay
Astrometry – gravitational lensing effect

# Four-point Correlation Function of Density Perturbation in Axion Inflation

## 4-point correlation functions of galaxies




$\boldsymbol{\delta}$(x) is galaxy number density

$$\hat{\zeta}(\mathbf{r}_1, \mathbf{r}_2, \mathbf{r}_3) \equiv \langle \delta(\mathbf{s})\delta(\mathbf{s}+\mathbf{r}_1)\delta(\mathbf{s}+\mathbf{r}_2)\delta(\mathbf{s}+\mathbf{r}_3)\rangle$$

Gravitational interactions are inherently parity symmetric, so gravitational evolution does not produce parity-breaking in LSS. If cosmological in origin, it must stem from the epoch of inflation.

**Probing parity violation with the four-point correlation function of BOSS galaxies**

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PHYSICAL REVIEW D **106,** 063501 (2022)

**Measurement of parity-odd modes in the large-scale 4-point correlation function of Sloan Digital Sky Survey Baryon Oscillation Spectroscopic Survey twelfth data release CMASS and LOWZ galaxies**

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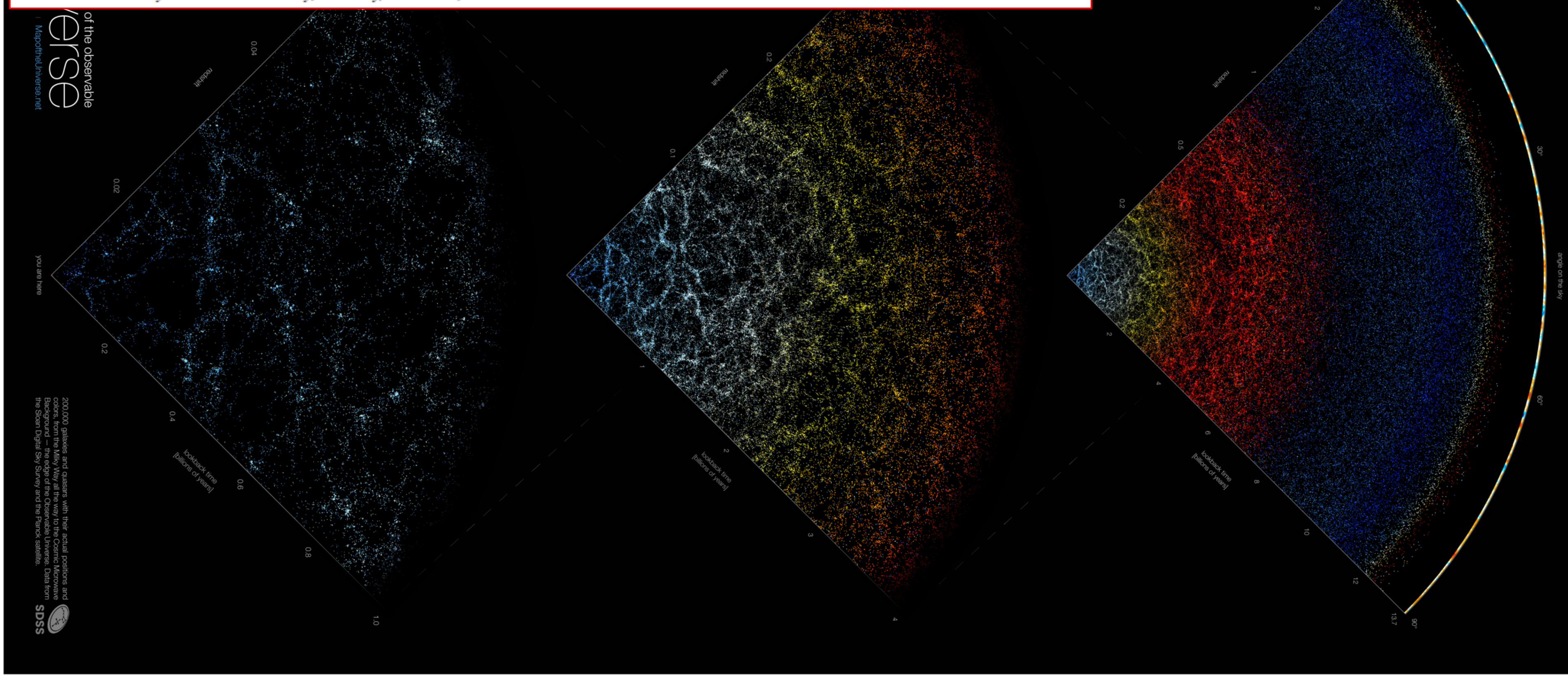
[3]*Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*

Monthly Notices *of the* ROYAL ASTRONOMICAL SOCIETY
MNRAS **522,** 5701–5739 (2023)



arXiv:2502.06931

# Searching for Inflationary Physics with the CMB Trispectrum: 3. Constraints from *Planck*

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Is there new physics hidden in the four-point function of the cosmic microwave background (CMB)? We conduct a detailed analysis of the *Planck* PR4 temperature and polarization trispectrum for $\ell \in [2, 2048]$. Using the theoretical and computational tools developed in Paper 1 and Paper 2, we search for 33 template amplitudes, encoding a variety of effects from inflationary self-interactions to particle exchange. We find no evidence for primordial non-Gaussianity and set stringent constraints on both phenomenological amplitudes and couplings in the inflationary Lagrangian. Due to the use of optimal estimators and polarization data, our constraints are highly competitive. For example, we find $\sigma(g_{\rm NL}^{\rm loc}) = 4.8 \times 10^4$ and $\tau_{\rm NL}^{\rm loc} < 1500$ (95% CL), a factor of two improvement on Effective Field Theory amplitudes, and a $43\sigma$ detection of gravitational lensing. Many templates are analyzed for the first time, such as direction-dependent trispectra and the collapsed limit of the 'cosmological collider', across a range of masses and spins. We perform a variety of validation tests; whilst our results are stable, the most relevant systematics are found to be lensing bias, residual foregrounds, and mismatch between simulations and data. The techniques discussed in this series can be extended to future datasets, allowing the primordial Universe to be probed at even higher sensitivity.

CMB 4-point functions e.g. $\langle T(x_1)\, T(x_2)\, T(x_3)\, T(x_4) \rangle$

We have computed 4-point functions generated in axion inflation

$\langle\zeta(x_1)\ \zeta(x_2)\ \zeta(x_3)\ \zeta(x_4)\rangle$

# Four-point correlation functions in axion inflation

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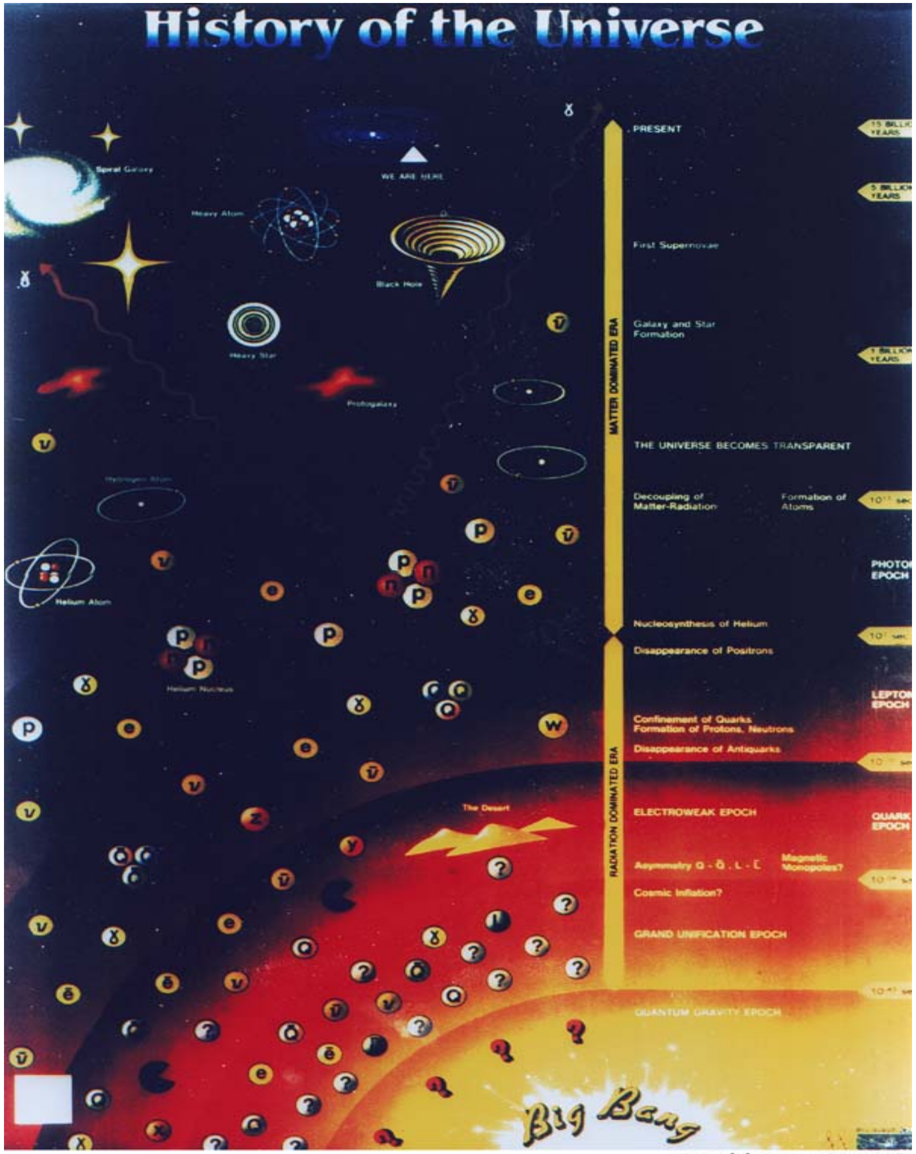
(Dated: June 13, 2025)

## Abstract

We study parity violation in the early universe by examining the four-point correlation function within the axion inflation model. Using an open quantum system formalism from our previous work, we calculate the influence functional to fourth order, from which we then derive the inflaton four-point correlation function. When we decompose this function using isotropic basis functions, the expansion coefficients $\zeta_{\ell',\ell'',\ell'''}$ naturally split into parity-even and parity-odd components. In the large $\xi$ approximation, which enhances the production of right-handed photons in the model, the derivation of these coefficients simplifies. We work out the lowest-order nonvanishing parity-odd $\zeta_{234}$ term which clearly indicates the presence of parity violation. Moreover, our derived values of the coefficients are consistent with recent observational data from galaxy surveys

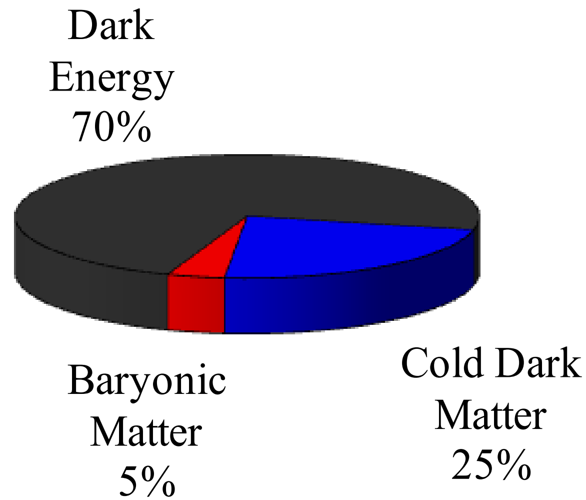
arXiv:2506.02331

# 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

# Scalar field model for DE/DM

kinetic energy X

potential energy

$S = \int d^4x \, [f(\varphi)\, \partial_\mu\varphi\partial^\mu\varphi/2 - V(\varphi)]$

Equation of State $w = p/\varepsilon = (X-V)/(X+V)$

Sound speed $c_s^{\,2} = 1$

Assume a spatially homogeneous scalar field $\varphi(t)$

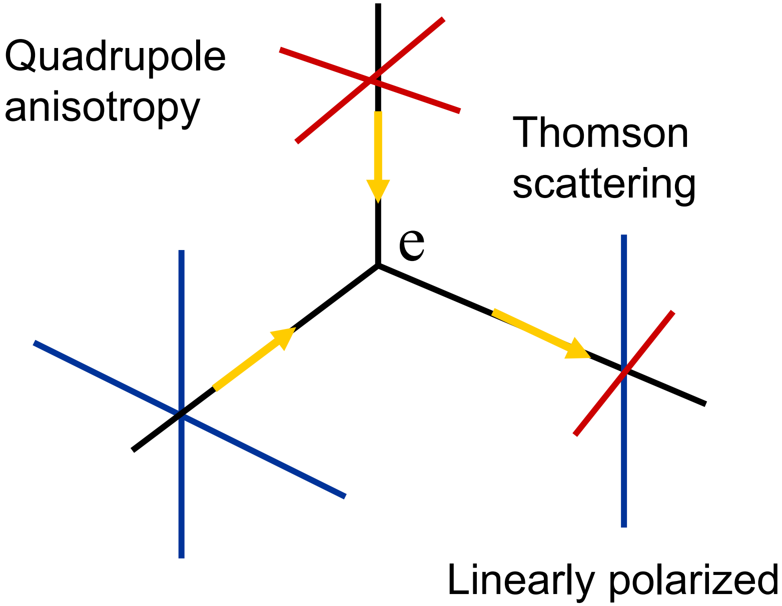
- $f(\varphi)=1 \rightarrow X=\dot\varphi^2/2 \rightarrow \quad -1 < w < 1$ *quintessence*
- any $f(\varphi) \rightarrow$ negative $X \rightarrow \quad w < -1$ ***phantom***
- $V(\varphi) = m^2\varphi^2/2,\ m >> H_{eq}$ cold dark matter

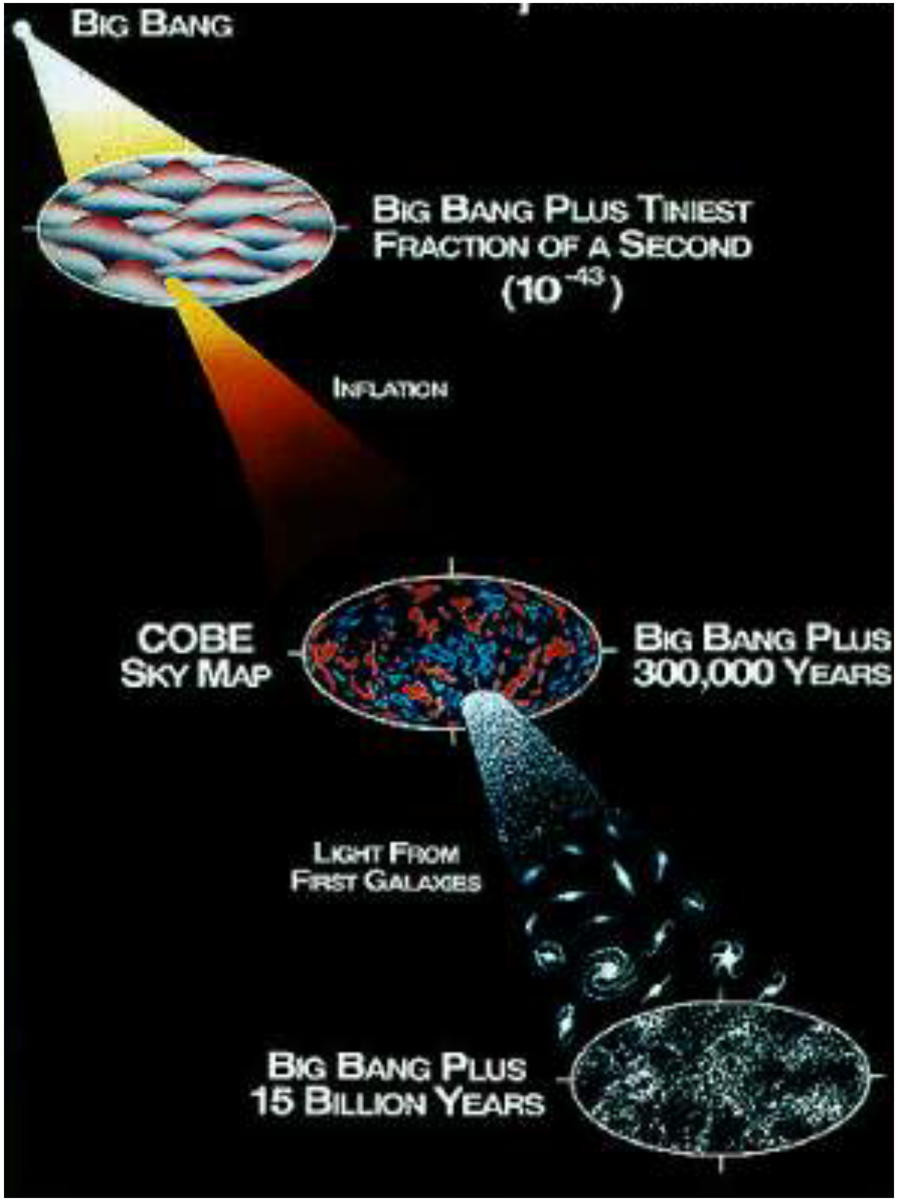
$V(\varphi) \rightarrow$

| | |
|---|---|
| $m^2\phi^2, \lambda\phi^4$ | Frieman et al (1995) |
| $V_0/\phi^\alpha, \alpha > 0$ | Ratra & Peebles (1988) |
| $V_0 \exp(\lambda\phi^2)/\phi^\alpha$ | Brax & Martin (1999,2000) |
| $V_0(\cosh\lambda\phi - 1)^p$ | Sahni & Wang (2000) |
| $V_0 \sinh^{-\alpha}(\lambda\phi)$ | Sahni & Starobinsky (2000), Ureña-López & Matos (2000) |
| $V_0(e^{\alpha\kappa\phi} + e^{\beta\kappa\phi})$ | Barreiro, Copeland & Nunes ( 2000) |
| $V_0(\exp M_p/\phi - 1)$ | Zlatev, Wang & Steinhardt (1999) |
| $V_0[(\phi - B)^\alpha + A]e^{-\lambda\phi}$ | Albrecht & Skordis (2000) |

# 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



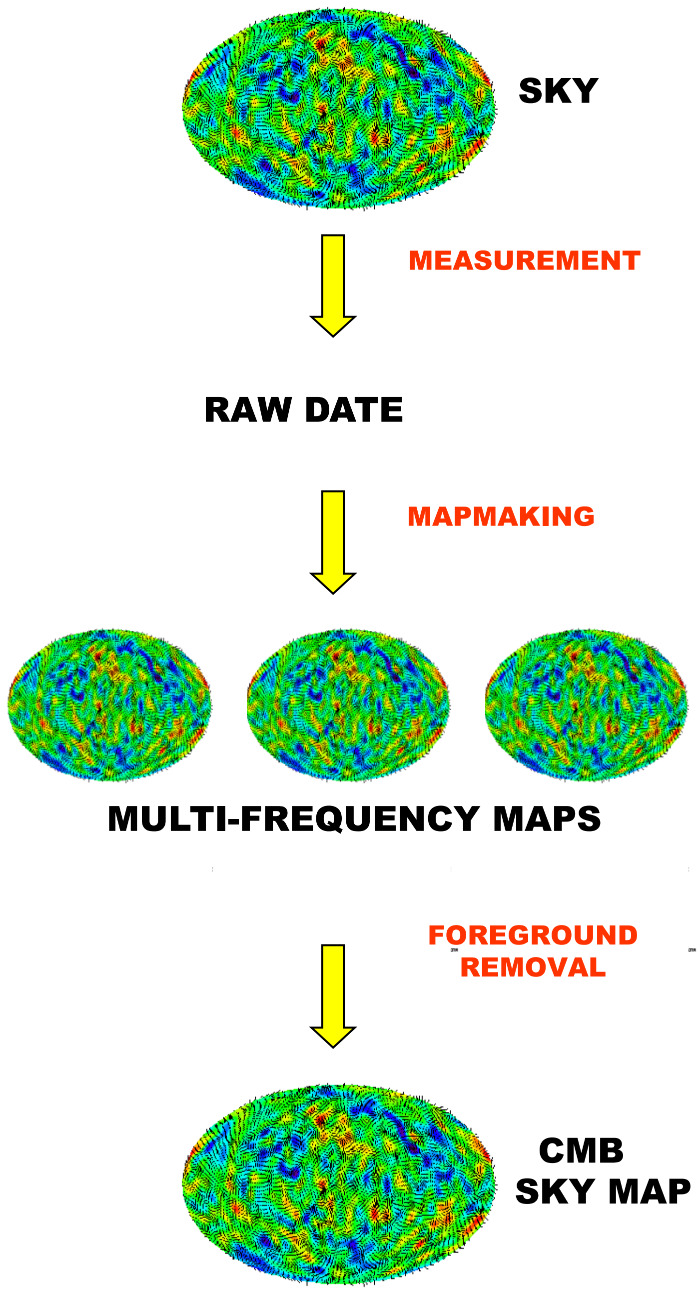



# CMB Measurements

- 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



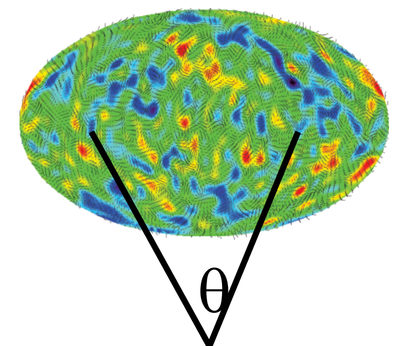
# CMB Anisotropy and Polarization Angular Power Spectra

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**

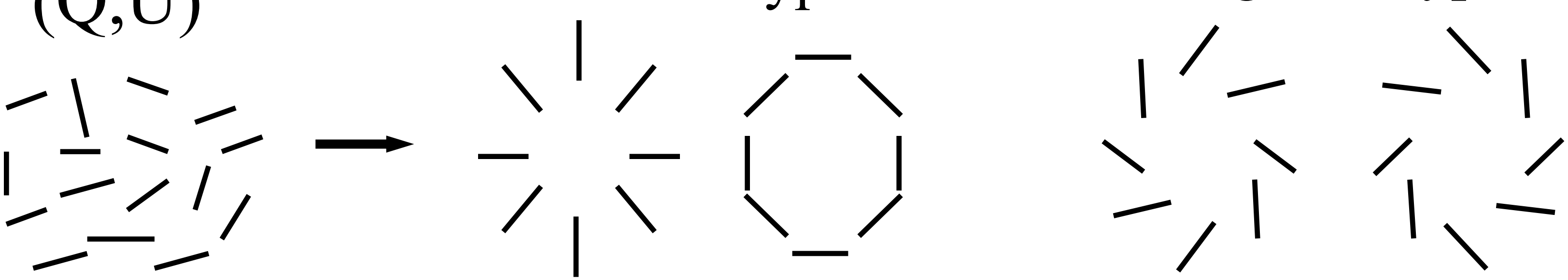
$C^{TT}_{l} = \Sigma_m (a^*_{lm}\, a_{lm})$ Anisotropy power spectrum

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

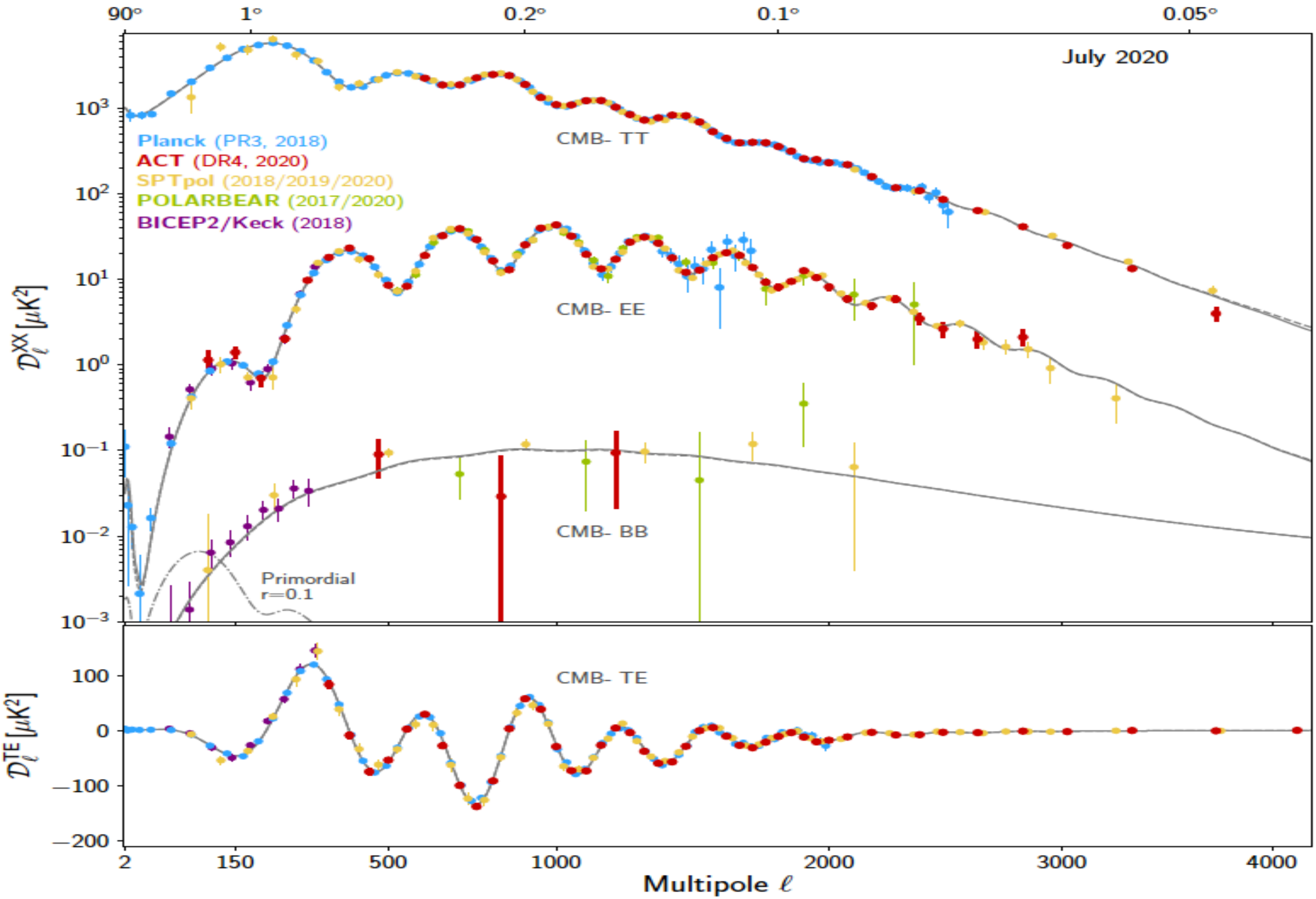
(Q,U) electric-type magnetic-type



# 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

# Latest report on CMB measurements



# 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 $\beta<10^7$

# For homogenous field $\phi$(t), cosmic birefringence induces a constant rotation angle $\alpha$

ical birefringence". The rotated angle of the polarization direction for an observed source would then be given by

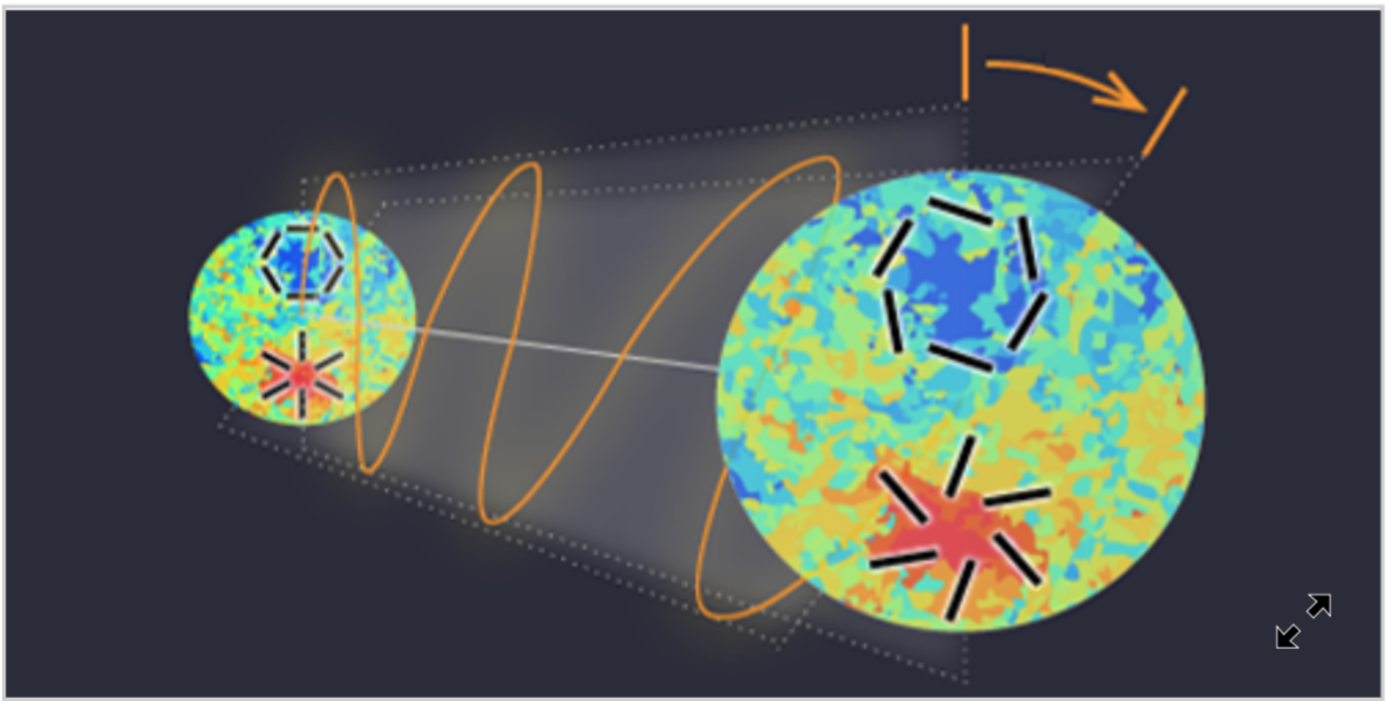
$$\bar{\alpha} = \int_z^0 \bar{\omega}(\eta) d\eta = -\frac{1}{2}\beta_{F\tilde{F}}\Delta\bar{\phi}, \qquad (25)$$

where $\Delta\bar{\phi}$ is the change in $\bar{\phi}$ between the redshift $z$ of the source and today. Measure-

# Hints of Cosmic Birefringence?

November 23, 2020 • *Physics* 13, s149

**A new analysis of the cosmic microwave background shows that its polarization may be rotated by exotic effects indicating beyond-standard-model physics.**



Y. Minami/KEK

Rotation angle

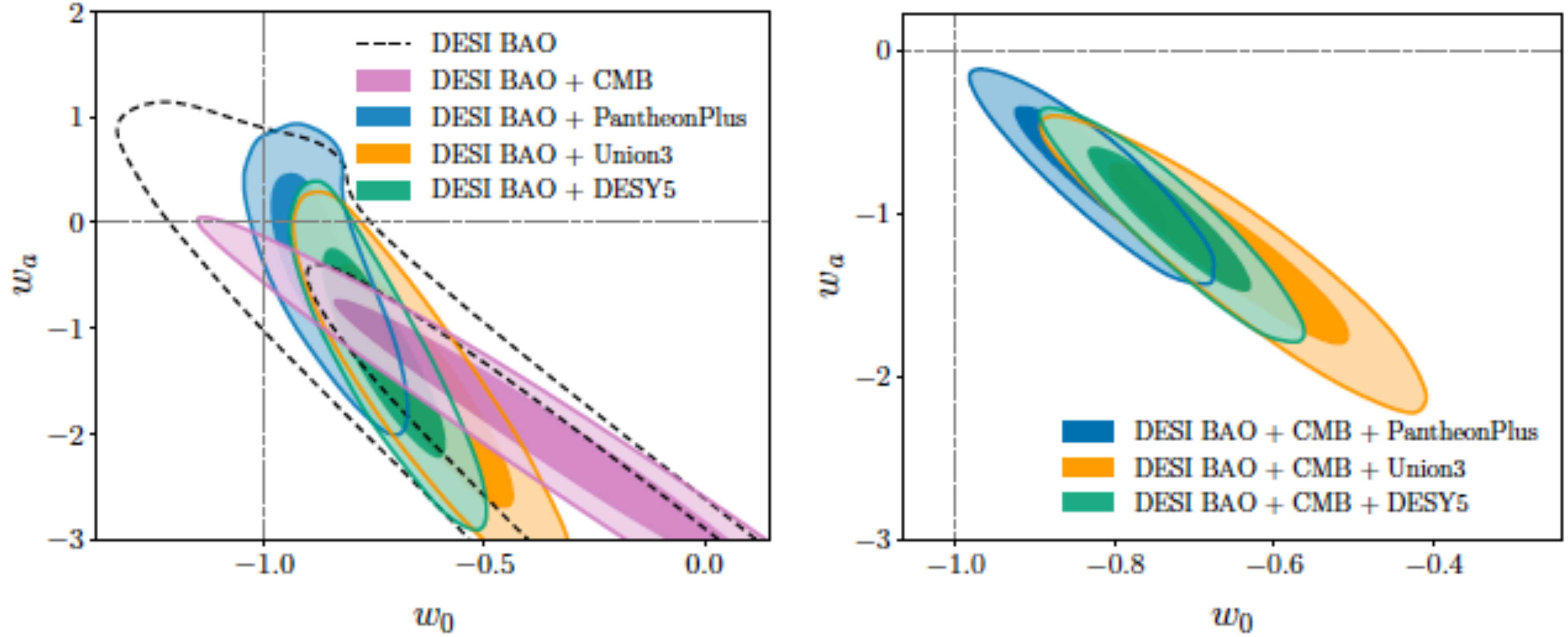
$$\alpha = -0.342^{\circ}{}^{+0.094^{\circ}}_{-0.091^{\circ}} \ (68\% \ \mathrm{CL})$$

Y. Minami and E. Komatsu, "New extraction of the cosmic birefringence from the Planck 2018 polarization data," **Phys. Rev. Lett. 125, 221301 (2020)**.

B. Feng, M. Li, J.-Q. Xia, X. Chen, and X. Zhang, Phys. Rev. Lett. **96**, 221302 (2006).

Systematics?

# The 2024 DESI galaxy survey measurement of $w(z) = w_0 + w_a\, z/(1+z)$




$$
(z_\mathrm{p}, w_\mathrm{p}) = \begin{cases} (0.57, -1.094 \pm 0.070) & \text{(DESI+CMB)} \\ (0.26, -0.982 \pm 0.028) & \text{(DESI+CMB+PantheonPlus)} \\ (0.33, -0.960 \pm 0.038) & \text{(DESI+CMB+Union3)} \\ (0.26, -0.946 \pm 0.026) & \text{(DESI+CMB+DESY5).} \end{cases}
$$

Time-evolving Dark Energy !!

## V. ALCOCK-PACZYNSKI TEST 1979

Alcock and Paczyński (AP) [5] studied the behaviour of the ratio $\Delta z/(z\Delta\theta)$ for an astrophysical object subtending some narrow redshift interval $\Delta z$ along the light of sight and some circle of angular radius $\Delta\theta$ across the line of sight. This is now referred as the AP test which measures cosmological parameters through the relation,

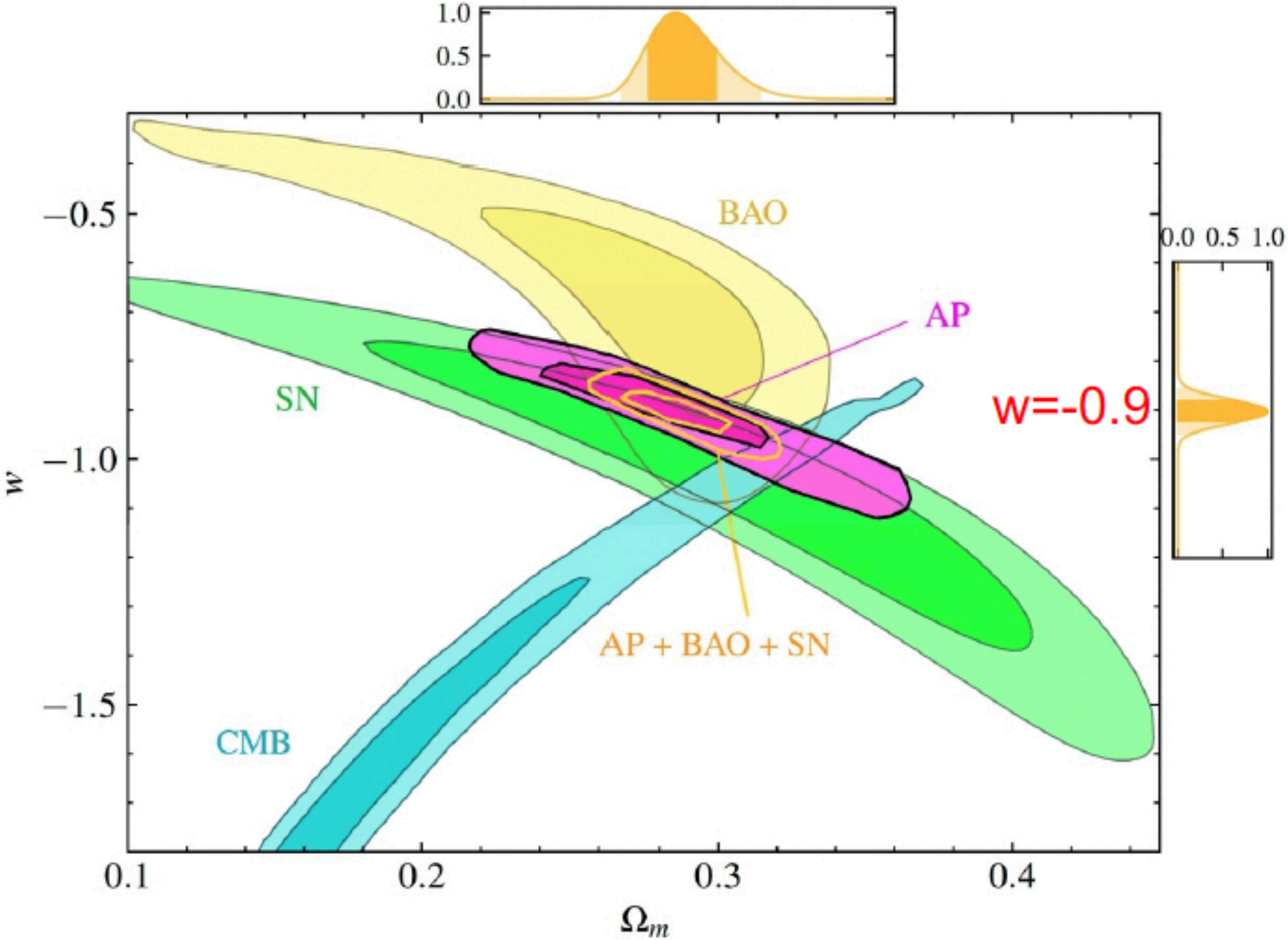
$$\frac{\Delta z}{z\Delta\theta} = \frac{1+z}{z} H(z) D_A(z) \frac{r_\parallel}{r_\perp}, \tag{26}$$

where $r_\parallel$ and $r_\perp$ are the comoving sizes of the object along and across the light of sight, respectively. The redshift $z$ and the angular diameter distance $D_A$ of the object are given by

$$1+z = \frac{1}{a}, \quad D_A(z) = \frac{\eta_0 - \eta}{H_0(1+z)}. \tag{27}$$

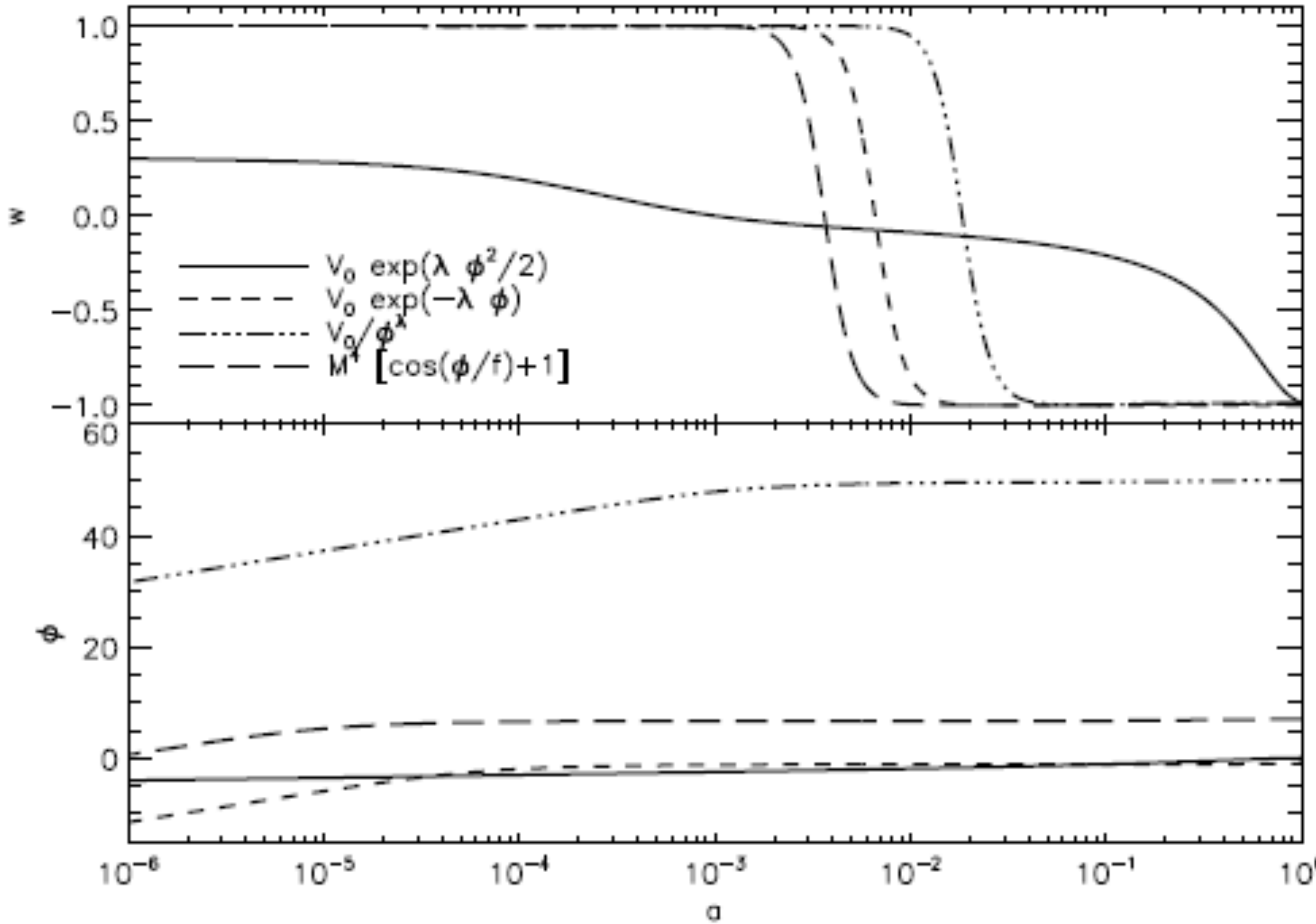
AP test is sensitive to DE equation of state w

# First AP test results Dong+ Changbom Park et al. 2024



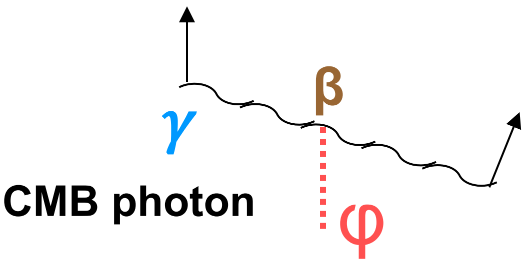

We are now reconstructing axion V(φ) for late dark energy

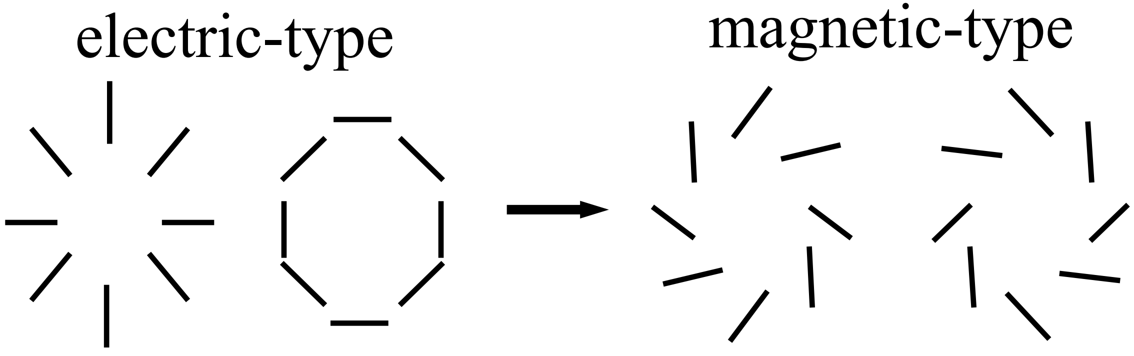
# We Tried Many Scalar Dark Energy Models

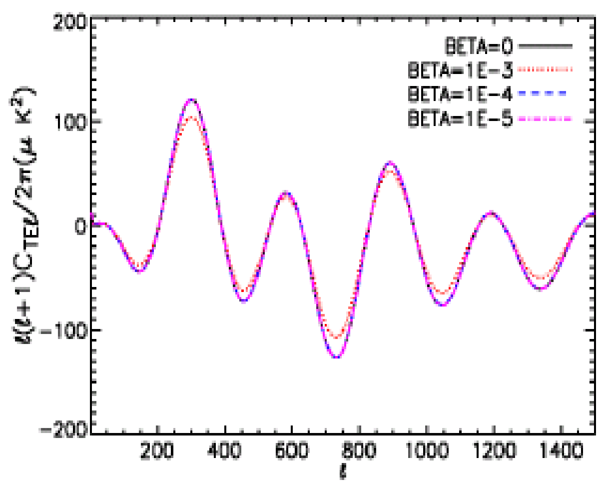


# DE mean field induced vacuum birefringence – cosmic rotation of CMB polarization

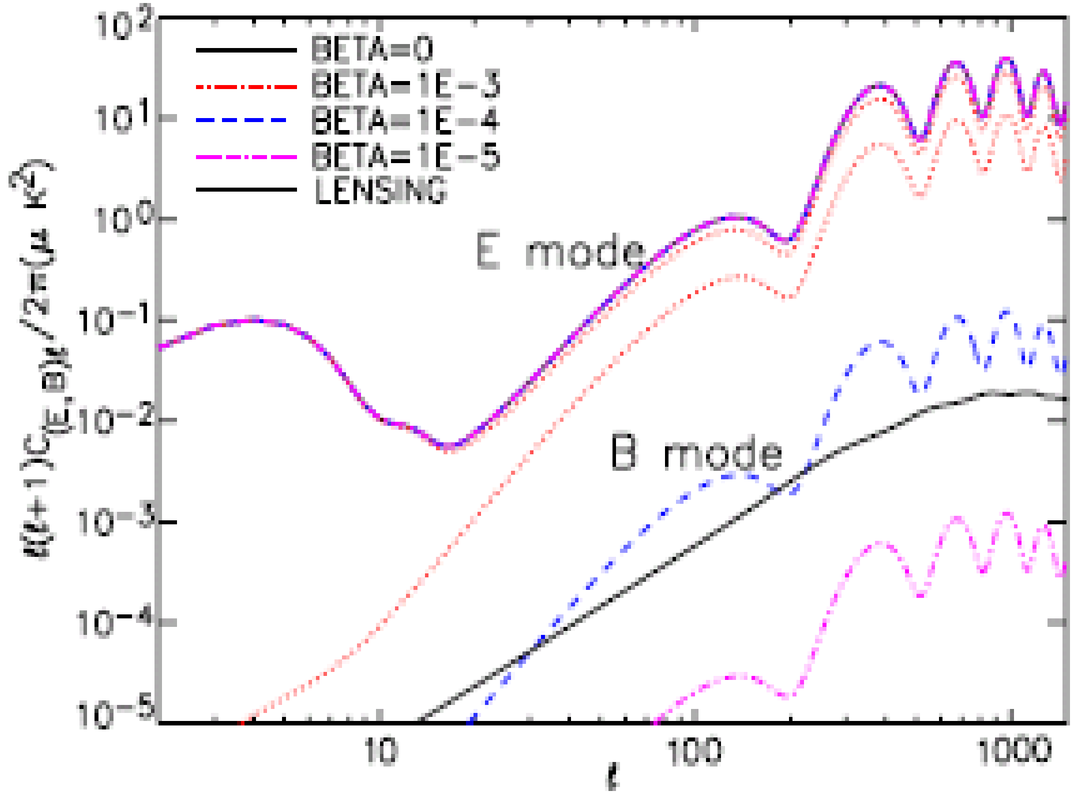
Liu,Lee,Ng 06



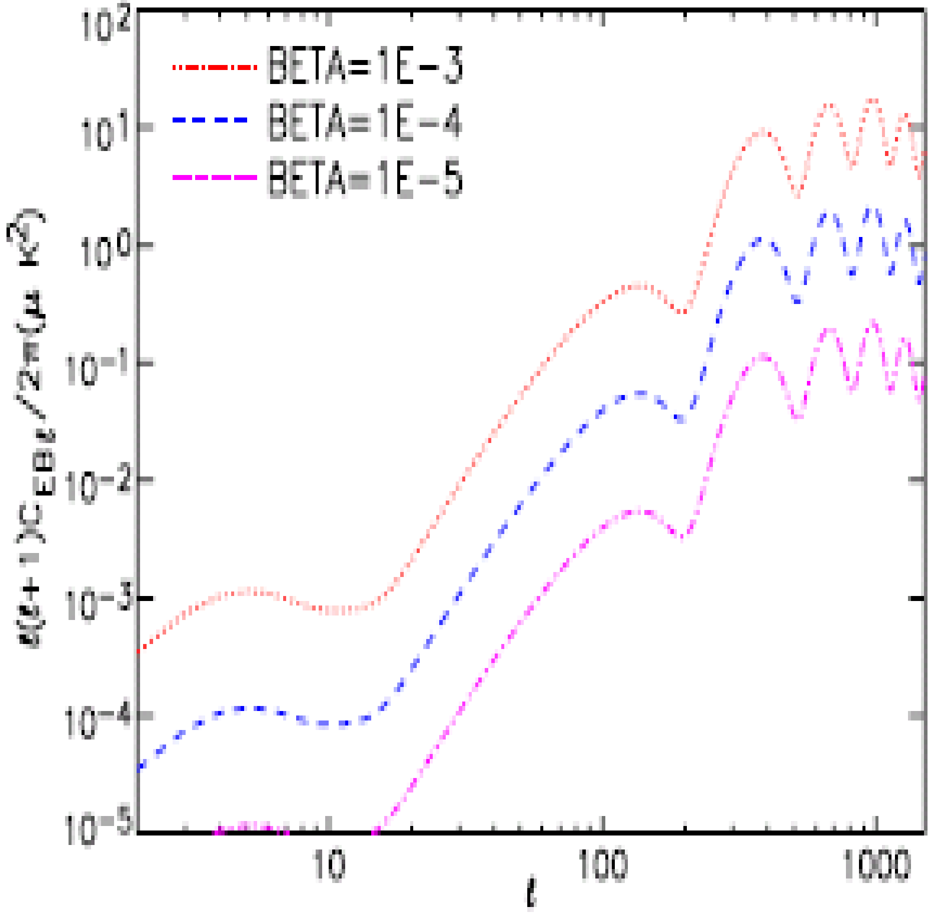



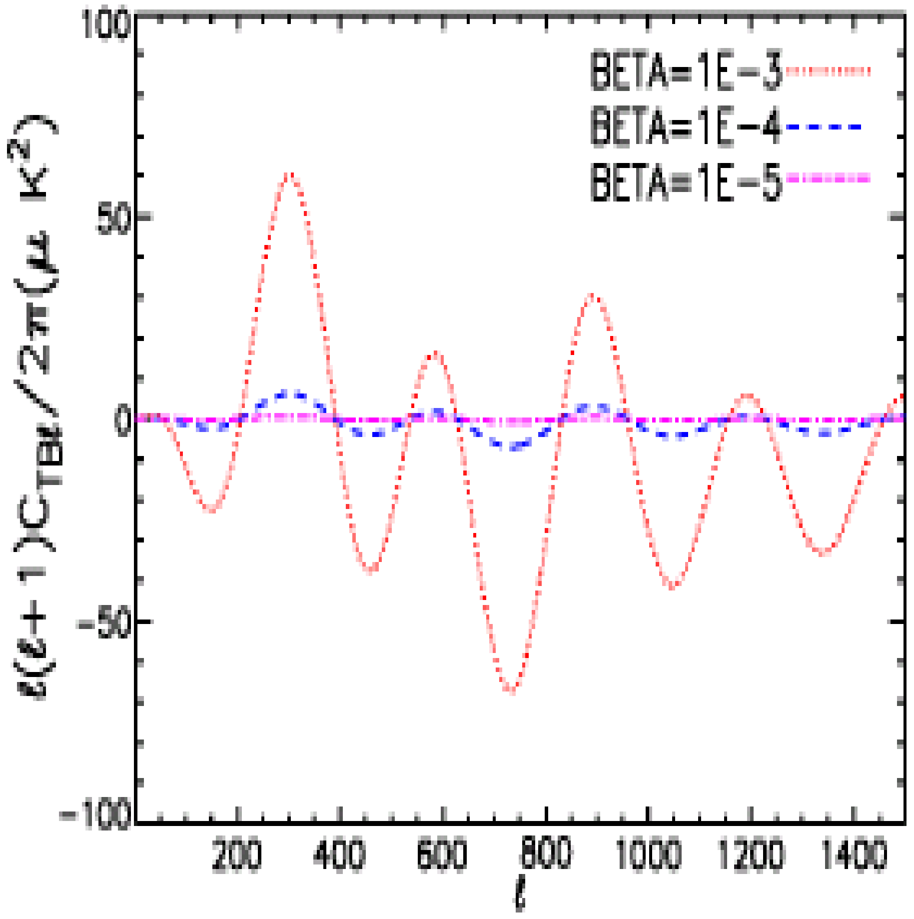




TE spectrum



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



# 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

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

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

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

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

- 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

# Cosmic Birefringence (CB) Fluctuations

Nearly massless pseudo scalar

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

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

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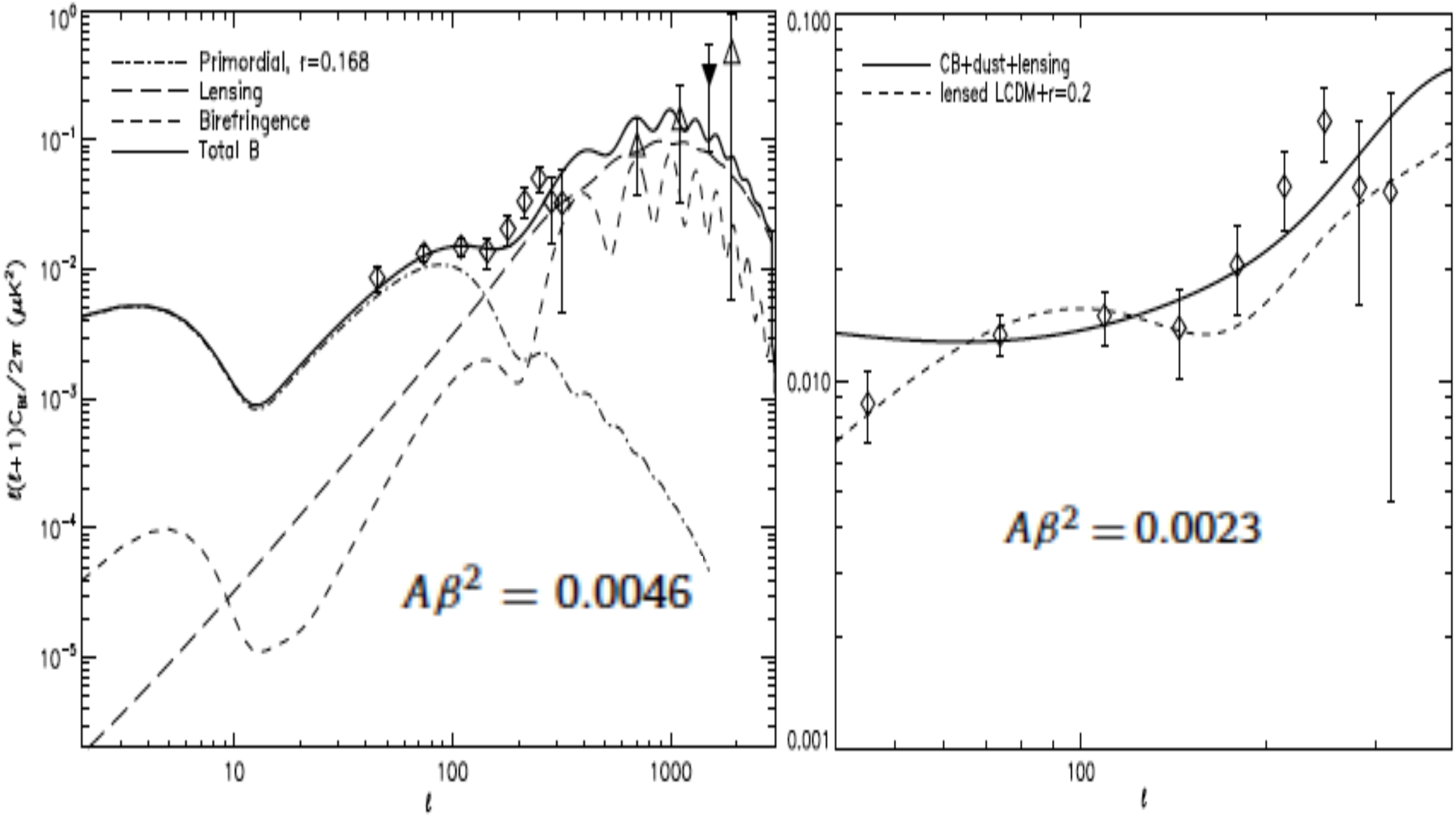
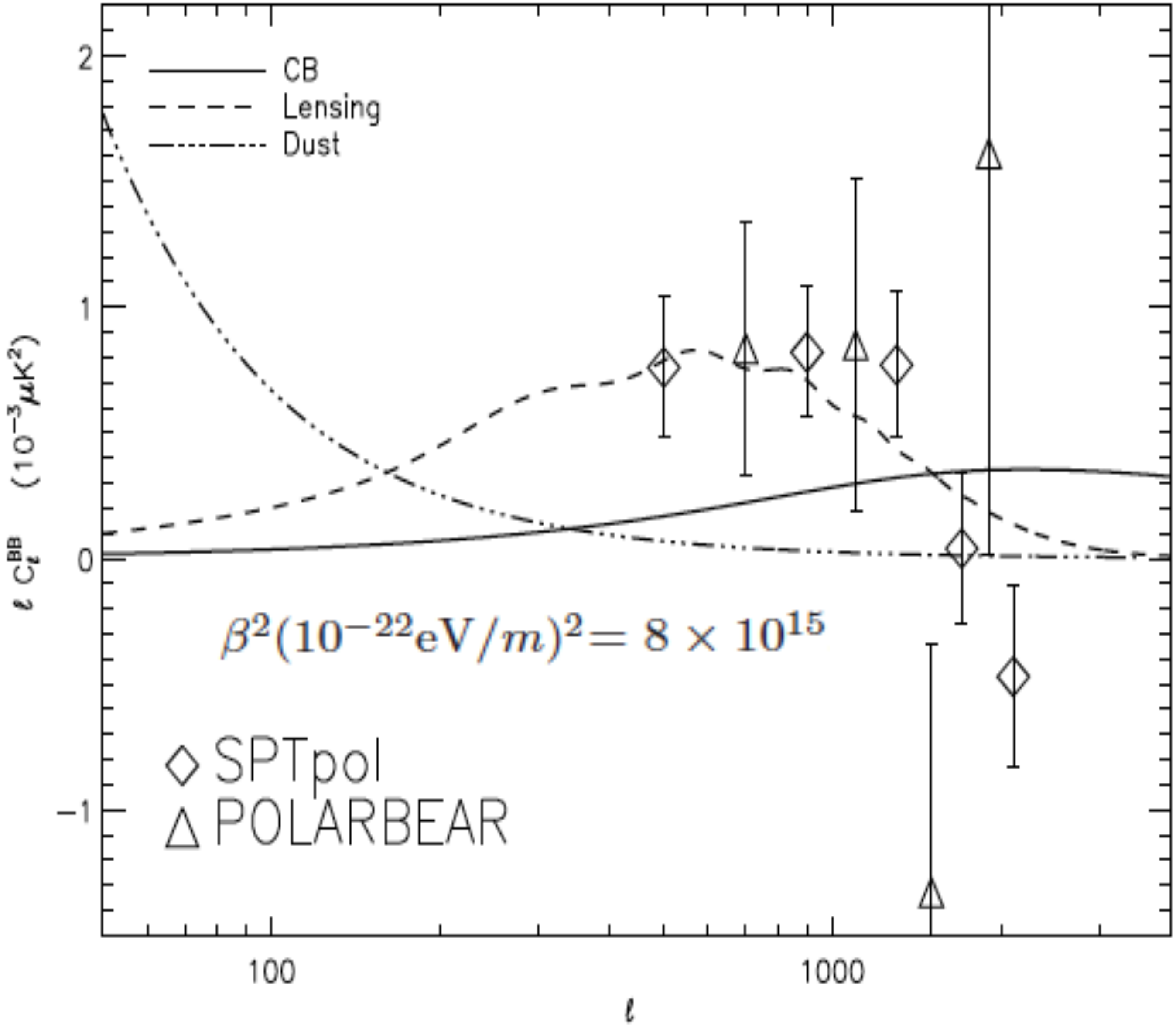


# Axion (m~$10^{-22}$eV) CDM curvature perturbation




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

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

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

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

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

$$H(a_m) = m$$

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# Ultra-light Axionic string-wall networks


[55] P. Agrawal, A. Hook, and J. Huang, JHEP **07**, 138 (2020), arXiv:1912.02823 [astro-ph.CO].

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[57] W. W. Yin, L. Dai, and S. Ferraro, (2021), arXiv:2111.12741 [astro-ph.CO].

[58] M. Jain, R. Hagimoto, A. J. Long, and M. A. Amin, JCAP **10**, 090 (2022), arXiv:2208.08391 [astro-ph.CO].

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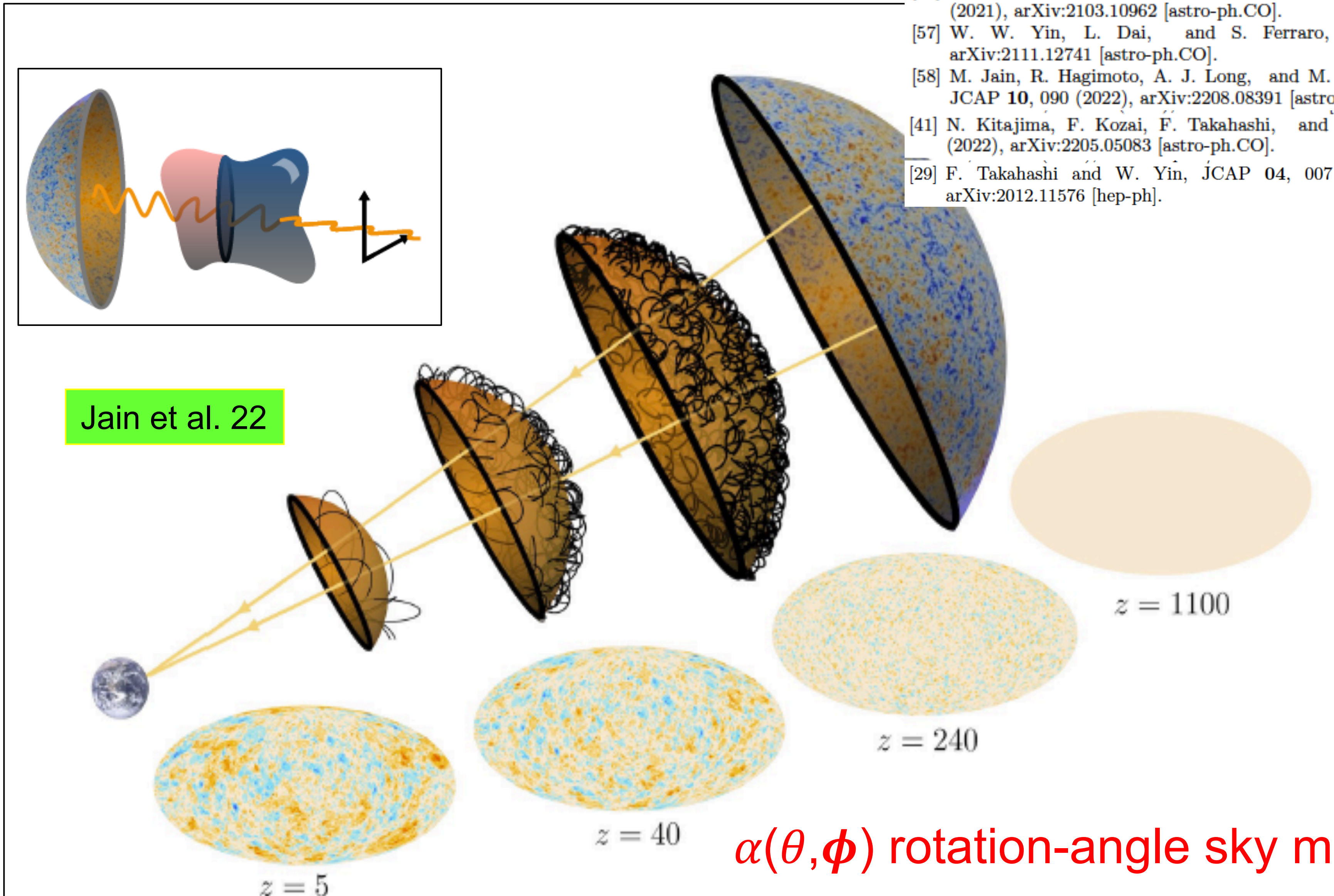
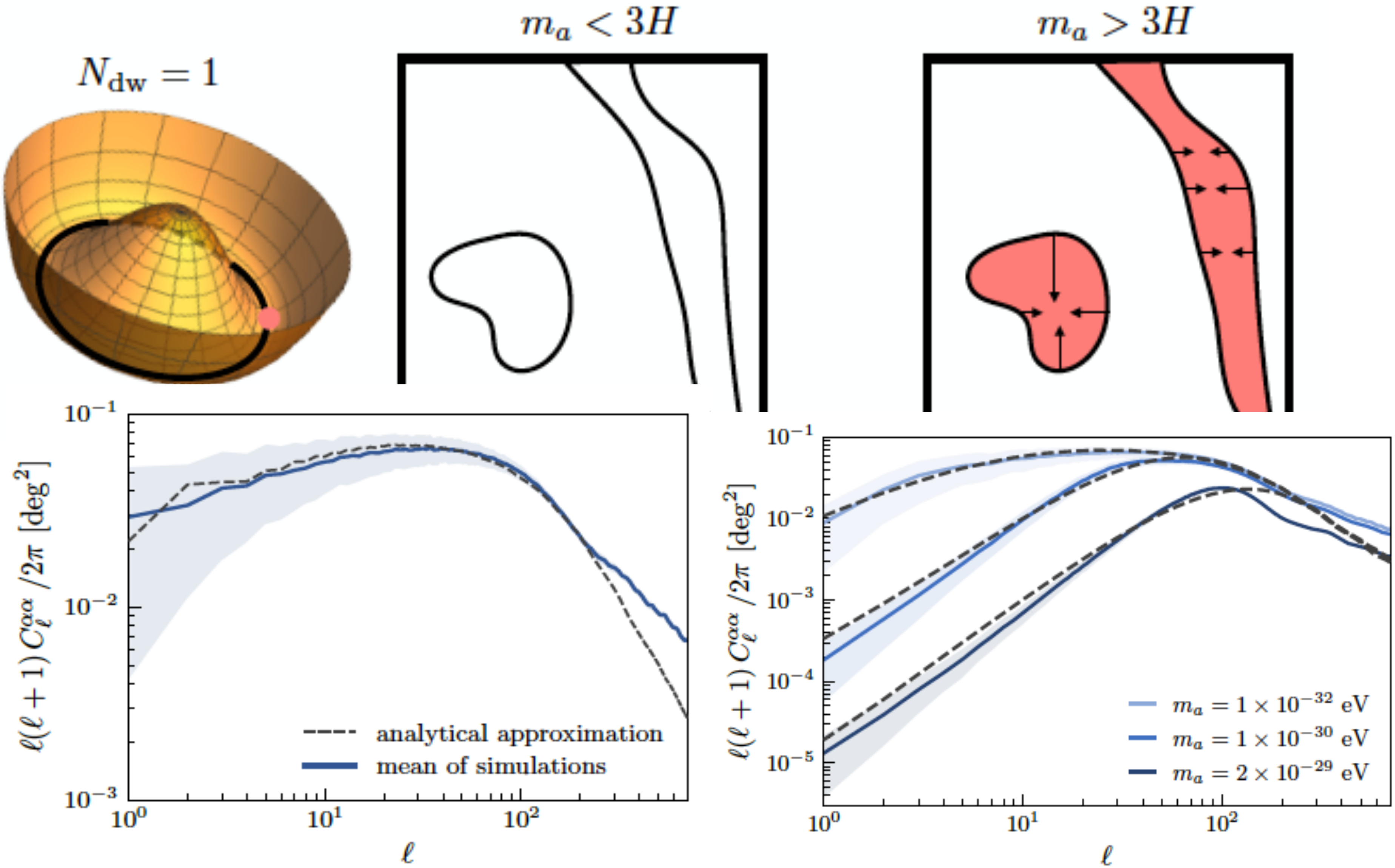



$\alpha(\theta,\boldsymbol{\phi})$ rotation-angle sky map




Anisotropic cosmic birefringence

$\alpha(\hat{n}) = \sum_{lm} \alpha_l^m Y_l^m(\hat{n})$

$C_l^{\alpha\alpha} = \left\langle |\alpha_l^m|^2 \right\rangle$

# 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 late axion dark energy induced vacuum birefringence
  - Mean field time evolution → <BB>, <TB>, <EB>
  - Include DE perturbation → <BB>, <TB>=<EB>=0

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

- Axion inflation gives rise to chiral gravitational waves and parity-violating 4-point correlation function or trispectrum

- Cosmic Parity Violation to unveil nature's handedness