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Early Dark Energy as a common ground for Cosmic Birefringence and the Hubble tension"

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Based on
2408.09521 [astro-ph.CO]

CONTENTS

I. Motivation

Is Einstein Gravity and Standard Model of Cosmology (Λ CDM) satisfactory?

1. Theoretical Aspect

- GR is an **effective theory** valid below UV cut-off, $M_{Pl} \sim 10^{19} GeV$

Ex) String theory $\xrightarrow[\text{Low Energy}]{}$ Einstein Gravity ($\sim R$) + higher curvatures ($\sim R^n, n \geq 2$) (α'-expansion)

- **Extreme fine-tuning ($\Lambda = 2,9\text{x}10^{-122} \ell_P^{-2}$) needed** for Present accelerating Expansion (c.c. or DE)

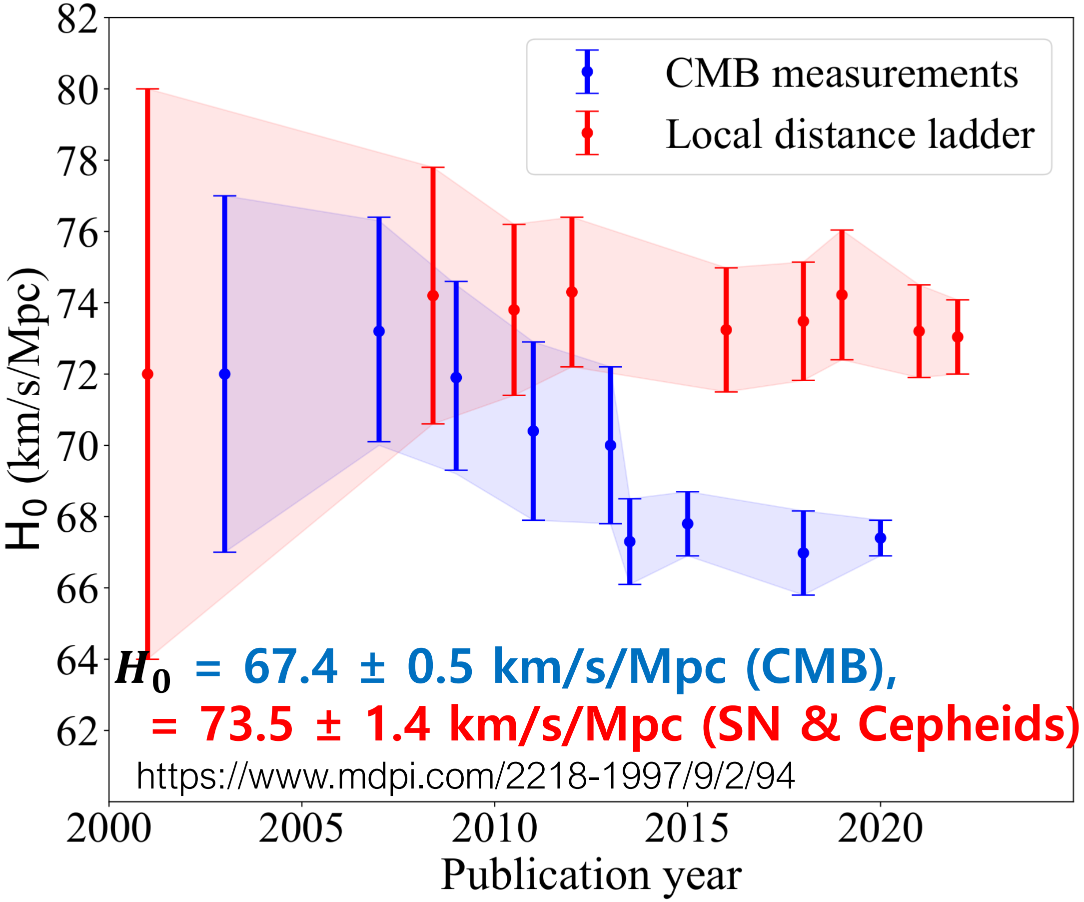
2. Observational Aspect:

The ΛCDM model has received strong observational support in the last few decades, but it still faces a few noteworthy challenges.

1)Hubble (H_0) tension (≈ 5σ discrepancy)

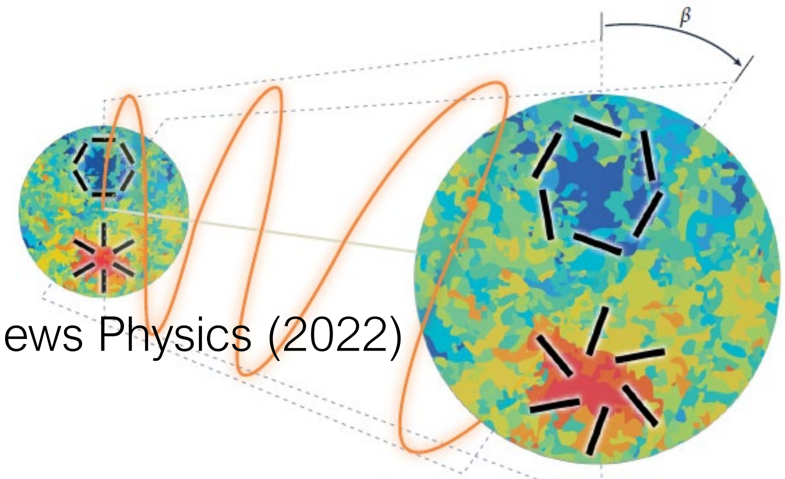
$\boldsymbol{H_0}$ = **67.4 ± 0.5 km/s/Mpc (CMB),** inferred from early universe measurements of the Cosmic Microwave Background (CMB) radiation,

= **73.5 ± 1.4 km/s/Mpc (SN & Cepheids)** direct measurements from the local distance ladder.



2) Cosmic Birefringence(~3σ)

Cosmic birefringence : the rotation of the plane of linear polarization of the CMB photons during their travel from the last scattering surface to the observer.



Komatsu, Nature Reviews Physics (2022)

Recently, this rotation angle was measured,

$$\beta = 0.342^{+0.094}_{-0.091} \text{ deg } (1\sigma)$$

which excludes β =0 at 3.6σ level.

Minami and Komatsu, New Extraction of the Cosmic Birefringence from the Planck 2018 Polarization Data, PRL (2020).

Eskilt and Komatsu, Improved constraints on cosmic birefringence from the WMAP and Planck cosmic microwave background polarization data, PRD (2022).

3)$\sigma_8(S_8)$ etc.

3. How to resolve?

Beyond the Standard Model of Cosmology and/or Particle Physics by introducing the additional degree of freedom ex) higher curvature terms, scalar fields, etc.

We focus on Early Dark Energy (EDE) models

II. Models of the EDE by a scalar field

1) an ultralight axion (ULA)
2) with α-attractor
3) and Rock ‘n’ Roll potentials

Cf) We compared the α-attractor and Rock ‘n’ Roll models with the CMB data.

M. Braglia, W. Emond, F. Finelli, A. E. Gumrukcuoglu, K. Koyama, Unified framework for early dark energy from α-attractors, PRD, (2020).

P. Agrawal, Cyr-Racine, Pinner, Lisa Randall, Rock ‘n’ roll solutions to the Hubble tension, Physics of the Dark Universe, 42, 101347 (2023).

L. Yin, J. Kochappan, T. Ghosh, B-HL, Is cosmic birefringence model-dependent?, JCAP, 10, 007 (2023).

Want to show that the EDE + ΛCDM model may resolve

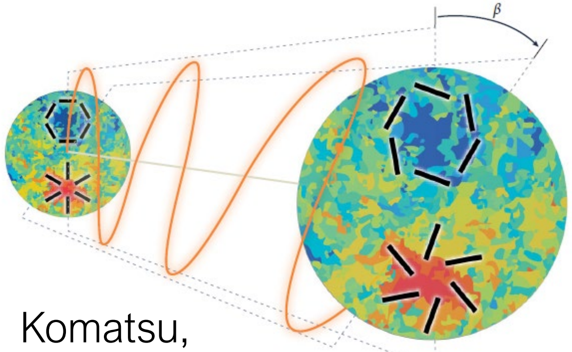
1) the Hubble tension

$$\mathcal{L} = -\frac{1}{2}(\partial\phi)^2 - V_n(\phi) \qquad V_n(\phi) = V_0\left(1 - \cos\frac{\phi}{f}\right)^n$$

and

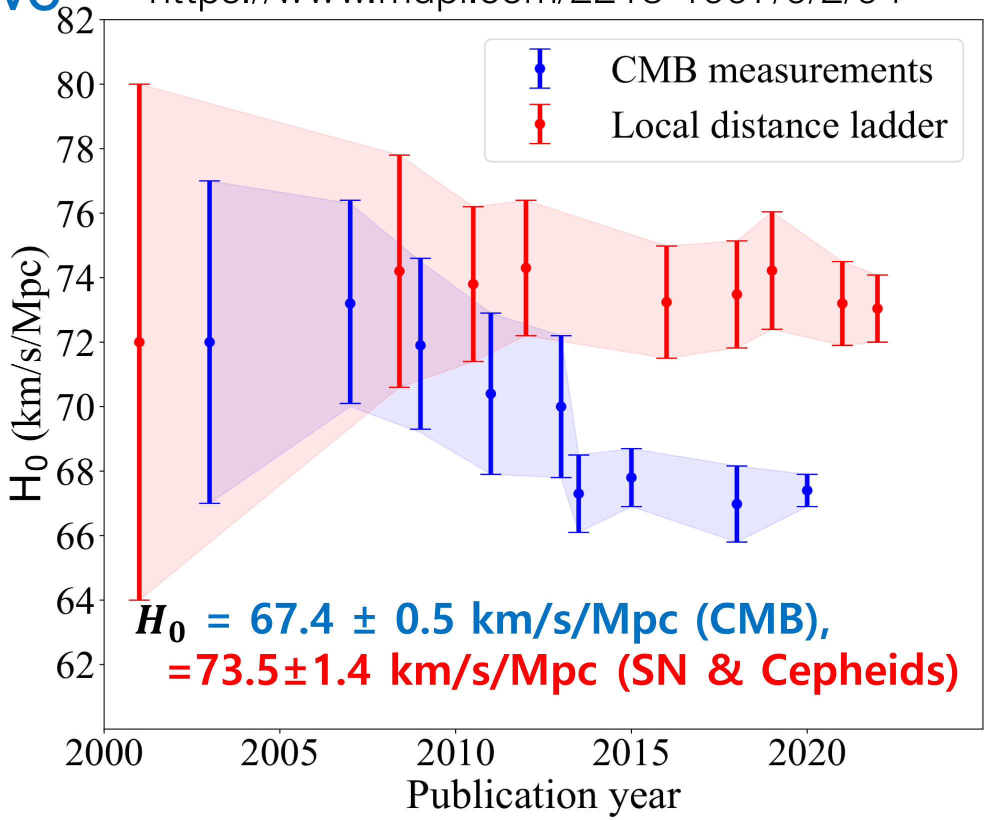
2) cosmic birefringence

$$\mathcal{L} = -\frac{1}{2}(\partial\phi)^2 - V_n(\phi) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}g\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$$



Komatsu, Nature Reviews Physics (2022)

https://www.mdpi.com/2218-1997/9/2/94

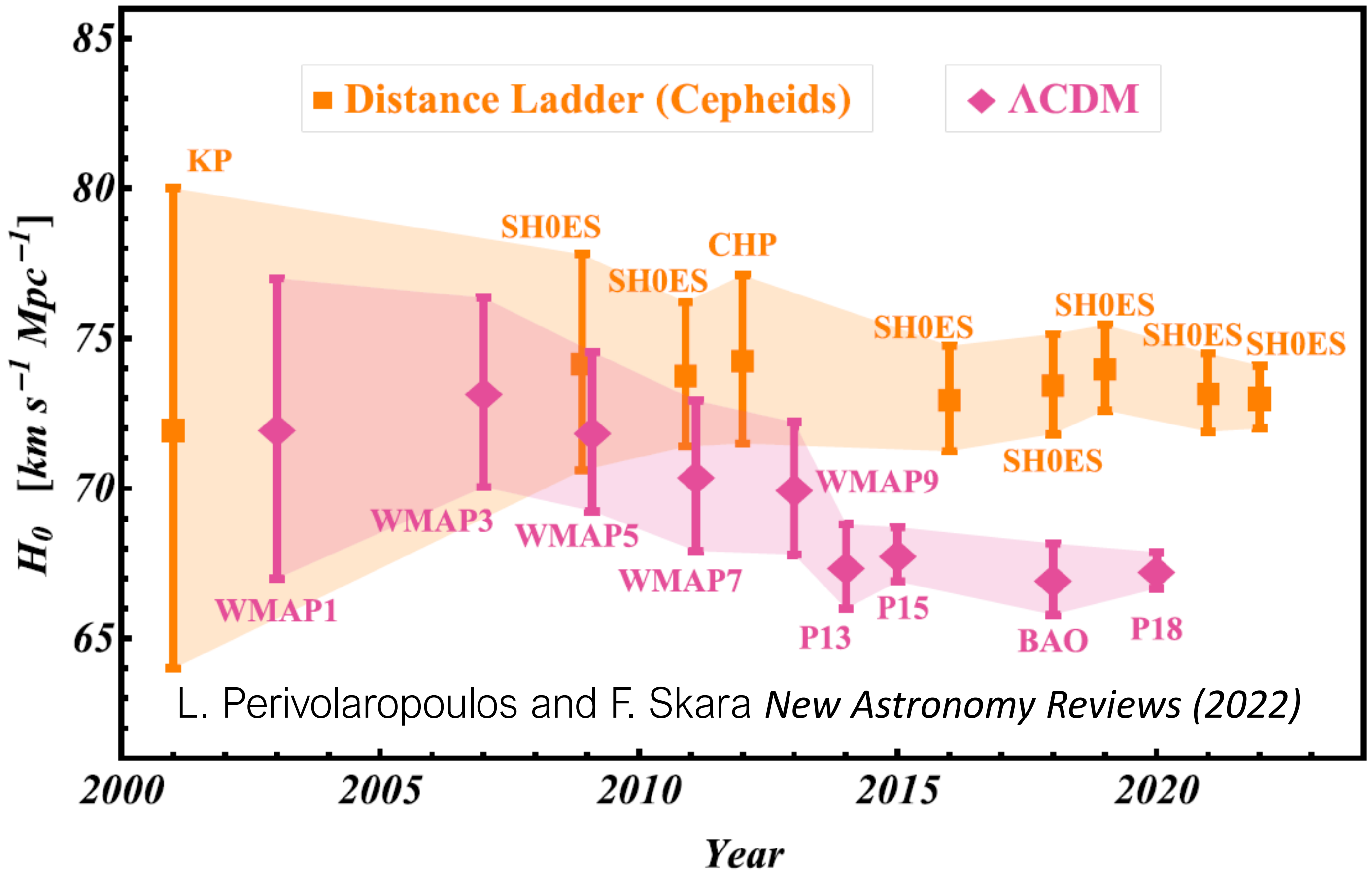


II-1) EDE to resolve H_0 tension

Ultra-light axion-like (ULA) scalar field ϕ with a potential

$$V_n(\phi) = V_0 \left(1 - \cos\frac{\phi}{f}\right)^n$$

f: the spontaneous breaking scale of the global U(1) symm.



L. Perivolaropoulos and F. Skara *New Astronomy Reviews (2022)*

The field equations of motion

The Hubble eqn

$$H = H_0\sqrt{\Omega_m(a) + \Omega_r(a) + \Omega_\Lambda + \Omega_\phi(a)}$$

$$\Omega_i = \rho_i/\rho_{crit},\ \rho_{crit} = 3H_0^2/8\pi G$$

The scalar field eom

$$\ddot{\phi} + 3H\dot{\phi} + \frac{dV_n(\phi)}{d\phi} = 0$$

$c_a^2 \equiv \frac{\dot{p}_\phi}{\dot{\rho}_\phi}$ the adiabatic sound speed

$c_s^2 \equiv \frac{\delta p_\phi}{\delta \rho_\phi}$ the effective sound speed

Ω_ϕ modifies the expansion history at $z > z_c$,
but decays quickly post recombination so as not to affect the late Universe.

V.Poulin, T.Smith, T.Karwal M.Kamionkowski, Early Dark Energy can Resolve the Hubble Tension, PRL(2019).

Smith, Poulin. Amin PRD (2020)

Solution

$$\Omega_\phi(a) = \frac{2\Omega_\phi(a_c)}{1+\left(\frac{a_c}{a}\right)^{3(1+w_n)}},\ w_n = \frac{n-1}{n+1}$$

$$w_\phi(z) = \frac{1+w_n}{1+\left(\frac{a_c}{a}\right)^{3(1+w_n)}} - 1,$$

For $a \to 0$ (at early times)

$w_\phi(z) \to -1$

$\rho_\phi(z)$ ≈constant

$w_n \nearrow$ as $n \nearrow$

$-1 \leq w_n \leq 1$

For $a \gg a_c$, (at later times)

$w_\phi(z) \to w_n$

$\rho_\phi(z) \propto a^{-3(1+w_n)}$ dilution

for n=1, $w_n = 0$ like matter
for n=2, $w_n = 1/3$ like radiation
for n≥3, $w_n > 1/3$ faster than radiation
for $n = \infty$, $w_n = 1$ $\rho_\phi(z) \propto a^{-6}$

`Early Dark Energy (EDE)' (slow roll phase) at early times (z ≳ 3000),

Hubble friction dominates,
the field is frozen (slowly rolling), behaves like a cosmol const

$$w_\phi(z) \simeq -1 \ c_a^2 \equiv \frac{\dot{p}_\phi}{\dot{\rho}_\phi} \simeq -\frac{7}{3} \ c_s^2 \equiv \frac{\delta p_\phi}{\delta \rho_\phi} = 1$$

Requires a ~5% EDE to the total energy density at z ≃ 5000

'Oscillating Phase' : (dilution at later times)

The homogeneous EDE energy density dilutes away

c_s^2 depends on the the potential.

an EDE that begins to dilute faster than radiation (n≥3) afterwards at a redshift $z_c \gtrsim 3000$

The behavior of the EDE field
- behaves like a cosmological constant before a critical redshift z_c
- and then decays rapidly without making changes to the late time evolution of the Universe.

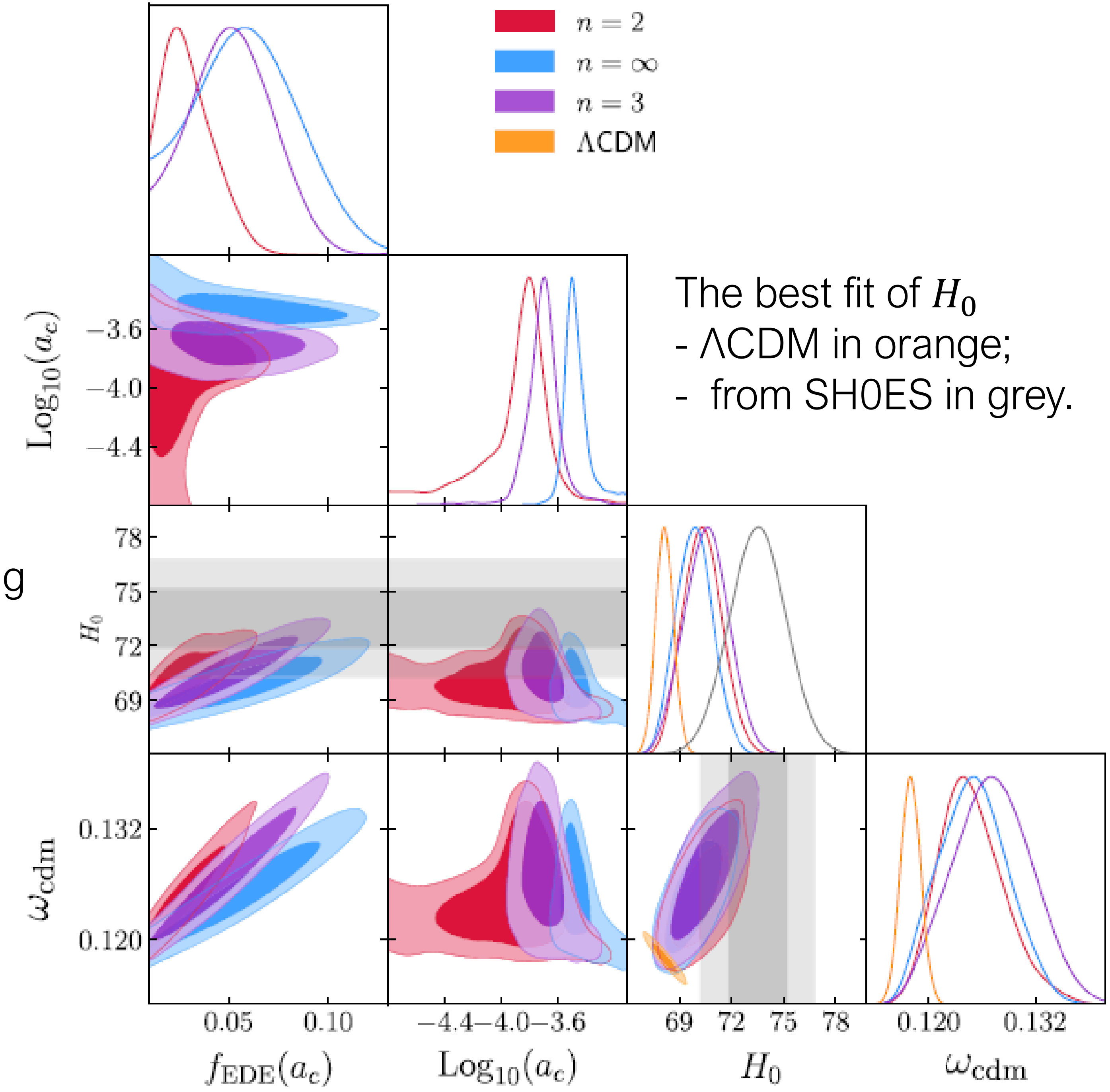
the sound horizon at decoupling is reduced resulting in a larger value of the Hubble parameter H_0 inferred from the cosmic microwave background (CMB).

can solve the Hubble tension

The best-fit χ^2 in the EDE cosmology is reduced by −9 to −14 (with a slight preference for n=3) compared to ΛCDM using the same datasets.

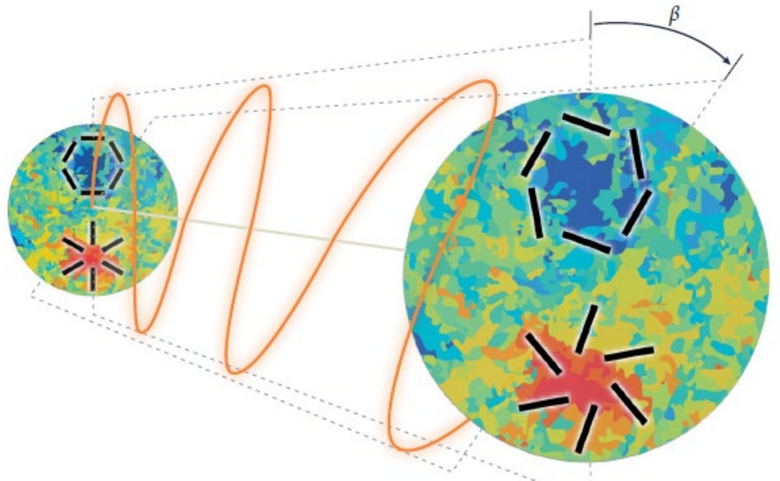
The EDE resolution of the Hubble tension, along with the current accelerated expansion and early-Universe inflation may suggest that the periods of anomalous expansion of Universe.

A future could probe the specific residual oscillations in the CMB power spectra associated with the EDE dynamics, while the shifts in A_s, n_s, r_s, and k_{eq} will be probed by future LSS surveys.



The best fit of H_0
- ΛCDM in orange;
- from SH0ES in grey.

II-2) EDE to resolve cosmic birefringence



Komatsu, Nature Reviews Physics (2022)

Needs Parity violating interaction

A Chern-Simons term (coupling between the EDE field ϕ and the CMB photons) generates a signal of cosmic birefringence in the CMB.

Consider axion-like pseudo-scalar field EDE models

$$\mathcal{L} = -\frac{1}{2}(\partial\phi)^2 - V(\phi) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}g\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$$

with potentials given by

$$V(\phi) = V_0\left(1 - \cos\frac{\phi}{f}\right)^n$$

We focus on n=3.

ϕ : the axion-like pseudo-scalar field,
f : the axion decay constant,
$n > 1$ (to ensure that the EDE density dissipates rapidly after recombination)
$g \equiv g_{EDE}$: the coupling constant
use $\theta = \frac{\phi}{f}$ for simplicity

CMB Polarization is sensitive to the parity violating Chern-Simons term
- rotate the plane of linear polarization and
- produce a non-zero cross-correlation power spectrum of E- & B-mode pol w/ opposite parities.

the coupling term induces a difference between the phase velocities of the left and right hand circularly polarised waves, leading to a rotation of the plane of polarization by an angle β.

$$\beta(\hat{\boldsymbol{n}}) = \frac{g}{2}\left(\phi(\eta_o) - \phi(\eta_e, r\hat{\boldsymbol{n}})\right)$$

As the field, ϕ, evolves with time, it changes the rotation angle,
The net rotation angle is given by

$$\beta(t_1, t_2) = \frac{g_{EDE}}{2}\int_{t_{LSS}}^{t_o} \frac{d\phi}{dt} dt = \frac{g_{EDE}}{2}\left(\phi(t_o) - \phi(t_{LSS})\right) = \frac{g_{EDE}}{2}\left(\phi(\eta_o) - \phi\left(\eta_{e,} r = c(\eta_o - \eta_{e,})\right)\right)$$

Leading to nonzero parity-odd power spectra, TB, and EB correlations.

a cross-correlation power spectrum of E- & B-mode pol fields with opposite parities.

The CMB polarisation power spectra

the Stokes parameters

$$Q = |E_x|^2 - |E_y|^2 = 2Re\,(E_+^* E_-)$$
$$U = 2Re\,(E_x^* E_y) = 2Im\,(E_+^* E_-)$$

$$Q \pm iU = Pe^{\pm 2i\beta} = Pe^{\mp 2i\psi} \quad (\psi > 0)$$

$$E_\pm = \frac{1}{\sqrt{2}}(E_x \mp iE_y)$$

decompose the observed Stokes parameters into E and B modes of of parity eigenstates

$$Q(\hat{\boldsymbol{n}}) \pm iU(\hat{\boldsymbol{n}}) = -\sum_{\ell=2}^{\infty} \sum_{m=-\ell}^{\ell} (E_{\ell m} \pm iB_{\ell m})\ {}_{\pm 2}Y_\ell^m(\hat{\boldsymbol{n}})$$

$\hat{\boldsymbol{n}}$: the direction of an observer's line of sight,
$E_{\ell m}, B_{\ell m}$: spherical harmonics coeffs of E & B modes
${}_{\pm 2}Y_\ell^m(\hat{\boldsymbol{n}})$: the spin-2 spherical harmonics, and
ℓ_{max}: the maximum multipole used for the analysis.

The coefficients transform under inversion of spatial coordinates,

$$\hat{\boldsymbol{n}} \rightarrow -\hat{\boldsymbol{n}}$$
$$E_{\ell m} \rightarrow (-)^{\ell} E_{\ell m}$$
$$B_{\ell m} \rightarrow (-)^{\ell+1} B_{\ell m}$$

$$\mathcal{C}_\ell^{XY} = 4\pi \int \mathrm{d}(\ln \mathrm{q}) \mathcal{P}_s(\mathrm{q}) \Delta_{X,\ell}(\mathrm{q}) \Delta_{Y,\ell}(\mathrm{q}),$$

$\mathcal{P}_s$: the primordial scalar perturb power spectrum,
X, Y : labels for the E- & B-modes of the CMB pol,
Δ_s : the Fourier transforms of the Stokes parameters of linear polarisation

the angular power spectrum

$$\mathcal{C}_\ell^{EE} \equiv \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} |E_{\ell m}|^2 \qquad \mathcal{C}_\ell^{BB} \equiv \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} |B_{\ell m}|^2$$

parity even

$$\mathcal{C}_\ell^{EB} \equiv \frac{1}{2\ell+1} \sum_{m} \boldsymbol{Re}(E_{\ell m} B_{\ell m}^*) \qquad \mathcal{C}_\ell^{TB} \equiv \frac{1}{2\ell+1} \sum_{m} \boldsymbol{Re}(T_{\ell m} B_{\ell m}^*)$$

parity odd — can be used to probe new physics that violates parity symmetry

Whereas $\mathcal{C}_{TB}$ used to be the most sensitive probe of parity violation in the WMAP era
$\mathcal{C}_{EB}$ has become the most sensitive one in the current era of CMB experiments with low polarization noise.

The $\mathcal{C}_{EE}$ data are dominated by sound waves excited by density fluctuations in the fireball Universe. Density fluctuations excited sound waves in the cosmic plasma of a single fluid, a 'cosmic hot soup have been observed clearly as peaks and troughs in $\mathcal{C}_{TT}$ and $\mathcal{C}_{TE}$ as well as in $\mathcal{C}_{EE}$.

Nonlinear effects, such as the grav lensing effect of the CMB by the intervening matter distribution in the Universe, mix the E and B modes at different multipoles and produce non-zero $\mathcal{C}_{BB}$.
This lensing- induced $\mathcal{C}_{BB}$ has been measured.

No $\mathcal{C}_{EB}$ is generated in this process unless parity symmetry is violated by other new physics.

$\mathcal{C}_{EE}$ and $\mathcal{C}_{BB}$ we find that the map is consistent with no B modes from primordial GWs.

the CMB polarisation power spectra under the simplifying assumption of a constant β

If ϕ =const during the epoch of recombination & evolved only later,
the observed E & B modes (denoted by the superscript "o") would be given by

$$E^0_{\ell m} = E_{\ell m}\cos(2\beta) - B_{\ell m}\sin(2\beta)$$

$$B^0_{\ell m} = E_{\ell m}\sin(2\beta) + B_{\ell m}\cos(2\beta)$$

$$\mathcal{C}_\ell^{EB,0} \equiv \frac{\sin(4\beta)}{2}\left(\mathcal{C}_\ell^{EE} - \mathcal{C}_\ell^{BB}\right) + \cos(4\beta)\,\mathcal{C}_\ell^{EB}$$

the power spectra can be reduced to,

$$\mathcal{C}_\ell^{EE,0} \equiv \cos^2(2\beta)\mathcal{C}_\ell^{EE} + \sin^2(2\beta)\mathcal{C}_\ell^{BB}$$

$$\mathcal{C}_\ell^{BB,0} \equiv \sin^2(2\beta)\mathcal{C}_\ell^{EE} + \cos^2(2\beta)\mathcal{C}_\ell^{BB}$$

where,
$\mathcal{C}_\ell$ denote the power spectra for $g_{EDE} = 0$.

Eskilt, Herold, Komatsu, Murai, Namikawa, Naokawa, Constraints on Early Dark Energy from Isotropic Cosmic Birefringence, PRL (2023).

	Base	Base + SH0ES
f_{EDE}	0.0872	0.1271
$\log_{10} z_c$	3.560	3.563
θ_i	2.749	2.768
$100\omega_{\mathrm{b}}$	2.265	2.278
ω_{CDM}	0.1282	0.1324
$100\theta_s$	1.041	1.041
$\ln(10^{10} A_s)$	3.063	3.071
n_s	0.983	0.992
τ	0.0562	0.0568

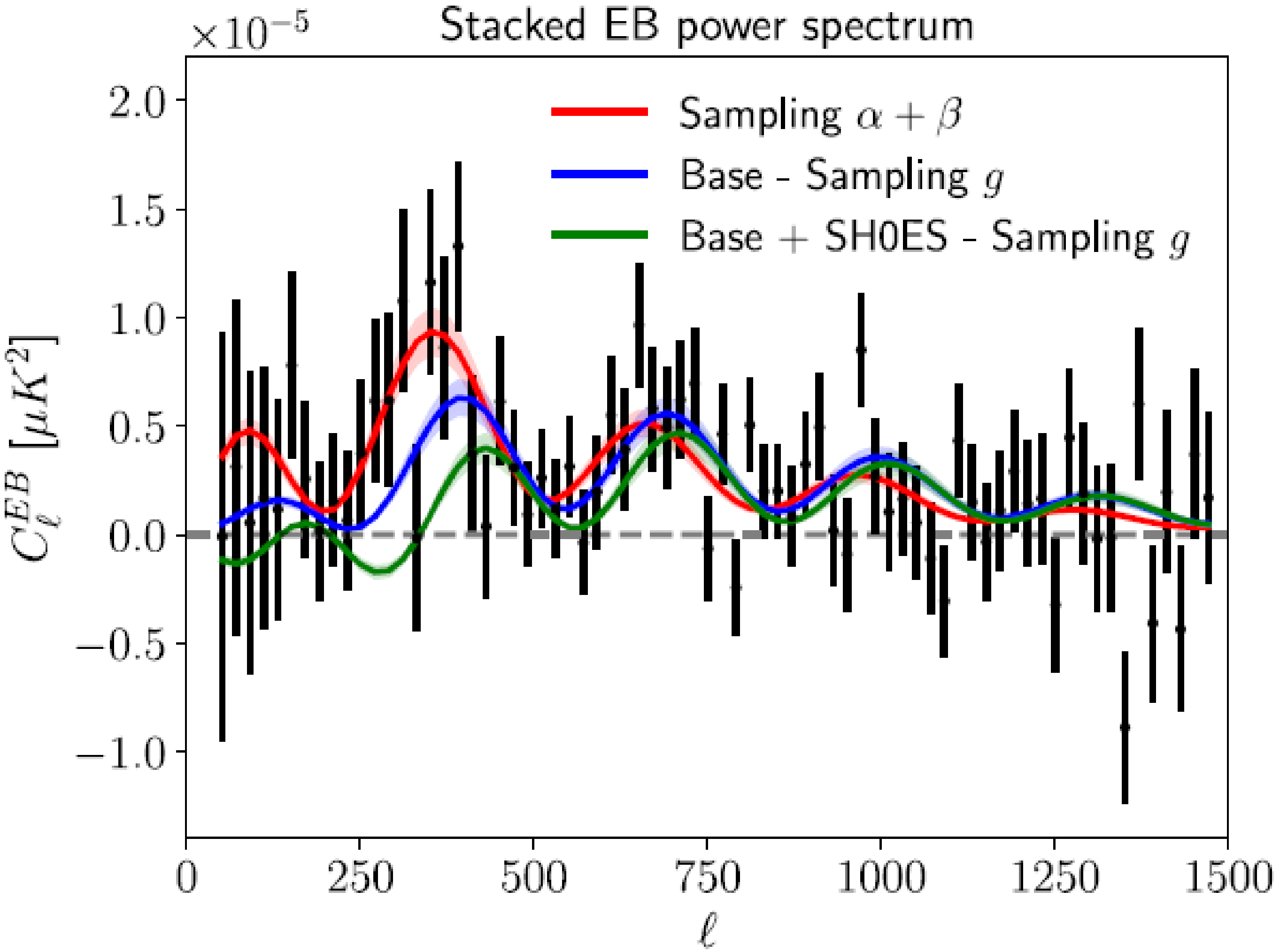
Best-fitting cosmological parameters under the Planck + BOSS (base) and base + SH0ES data sets.

The EDE parameters in Table yield

$f = 0.15\ M_{Pl}$(base) and

$= 0.18\ M_{Pl}$(base + SH0ES).

The EDE model has three more parameters than ΛCDM: f_{EDE}, z_c, and θ_i. f_{EDE} is the maximum energy density fraction of the EDE field reached at a z_c, while $\theta_i = \phi_i/f$.



(black) (pts w/ error bars) : Observed EB power spectrum

(red) :the best-fitting models of α + β

(blue & green). two EDE models w/ parameters in Table

$\chi^2 =$ 65.8,

77.5, and

103.5 for 71 degrees of freedom

Conclusions of Eskilt, Herold, Komatsu, Murai, Namikawa, Naokawa, Constraints on Early Dark Energy from Isotropic Cosmic Birefringence, PRL (2023)

constraint on γ-ϕ coupling constant g

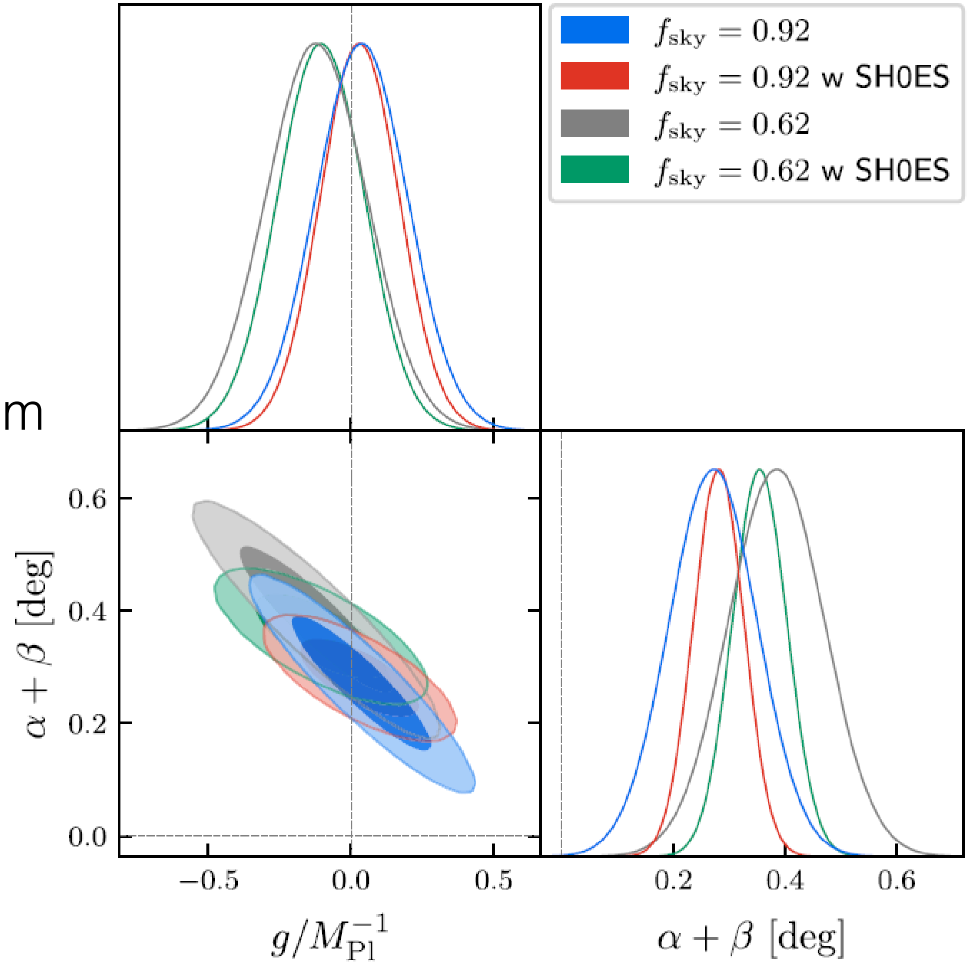
$$gM_{Pl} = 0.04 \pm 0.16$$

$|g| \ll M_{Pl}^{-1}$ much weaker than grav. indep of miscalibration ∡ or Galactic foreground emission.

the Planck data do not favor cosmic birefringence by a pre-recom but favor that occurred after the epoch of recombination, β, (or a miscalibration of pol angles of the Planck detectors, α.)

$g = c_{\phi\gamma}\alpha_{em}/(2\pi f)$ yields $c_{\phi\gamma} = 5.2$, contradicting the weak gravy conjecture $|g| \gtrsim M_{Pl}^{-1}$ demanding $c_{\phi\gamma} \gtrsim 130$,

The EDE model w/ n = 3, are not supported by the CMB obser. Fitting the n = 3 model to the Planck 2018 pol. data, varying the Chern-Simons coupling constant, g_{EDE}, and fixing all the other EDE parameters, the shape of the resulting EB power spectra does not agree with the data.



Posterior distributions of g=M-1 Pl and α þ β for the bestfitting EDE parameters under the base and base þ SH0ES data sets, and two Galactic masks.

III. Fitting with the CMB EB angular power spectrum

This implores us to investigate the effect of varying the EDE parameters instead of fixing them, on the process of fitting the model to the data, which is a key result of this work.

We focus on the ultralight axion field models of with n = 3.
We study the dependence of the CMB EB spectra on the EDE parameters, energy density f_{EDE}, critical redshift z_c, coupling constant g_{EDE} and initial value θ_i, and simultaneously fit the EDE+ΛCDM model parameters to the CMB, BAO and H_0 data.

Eskilt, Herold, Komatsu, Murai, Namikawa, Naokawa, Constraints on Early Dark Energy from Isotropic Cosmic Birefringence, PRL (2023).

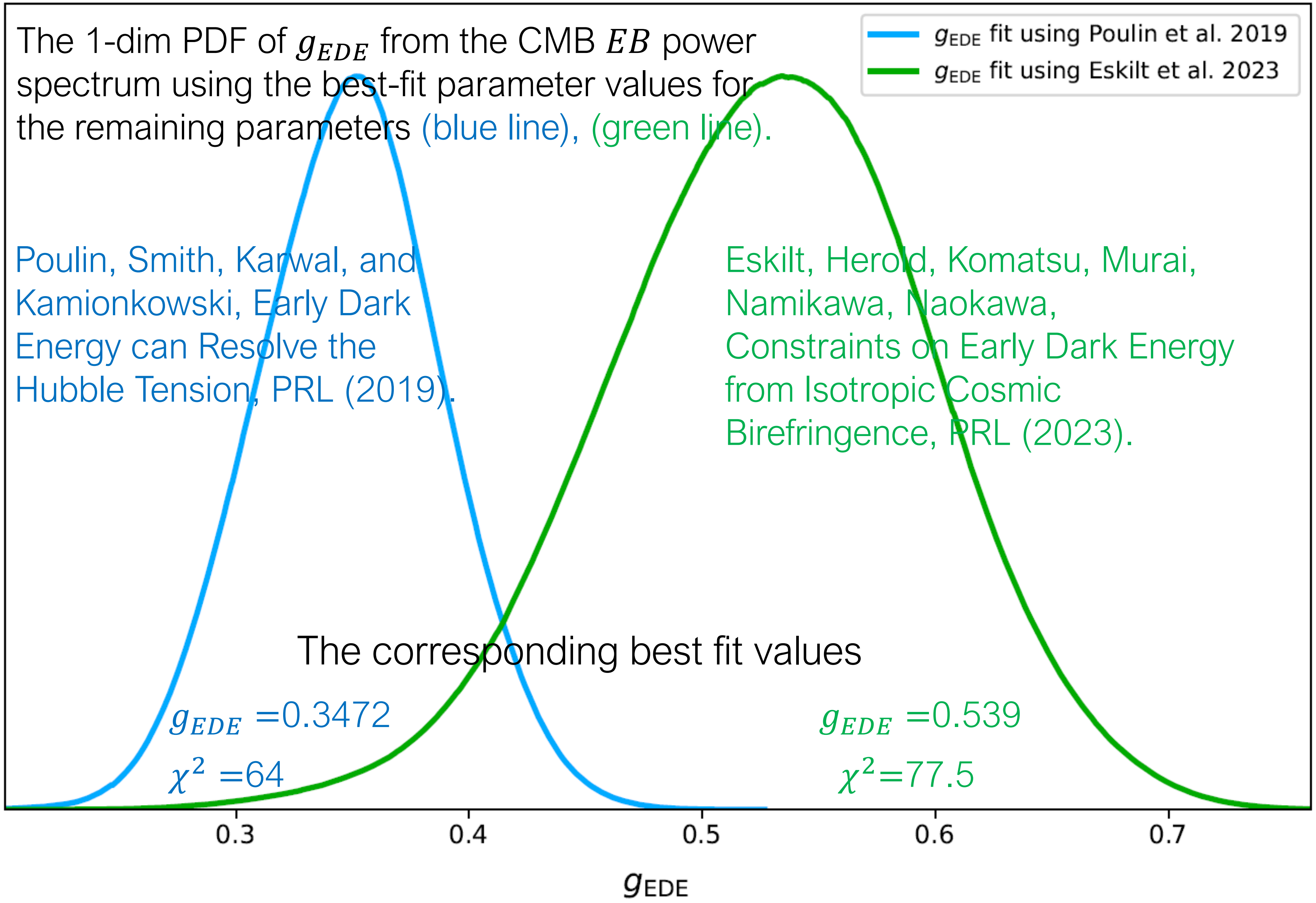
Observational evidence for Early Dark Energy as a unified explanation for Cosmic Birefringence and the Hubble tension Joby Kochappan, Lu Yin, B.-H L. and Tuhin Ghoshf e-Print: 2408.09521 [astro-ph.CO]

There is a shift in g_{EDE} when the other cosmol parameters are changed.

This result suggests that the fitting the CMB EB angular power spectrum with the EDE model to the data depends on the background cosmological parameters,.

the 4 EDE+ 6 ΛCDM=10 parameters: f_{EDE}, g_{EDE}, $\log_{10} z_c$,θ_i, $100 * \theta_s$, A_s, n_s, ω_b, ω_{CDM} and τ

The 1-dim PDF of g_{EDE} from the CMB EB power spectrum using the best-fit parameter values for the remaining parameters (blue line), (green line).



Poulin, Smith, Karwal, and Kamionkowski, Early Dark Energy can Resolve the Hubble Tension, PRL (2019).

Eskilt, Herold, Komatsu, Murai, Namikawa, Naokawa, Constraints on Early Dark Energy from Isotropic Cosmic Birefringence, PRL (2023).

The corresponding best fit values

g_{EDE} =0.3472

χ^2 =64

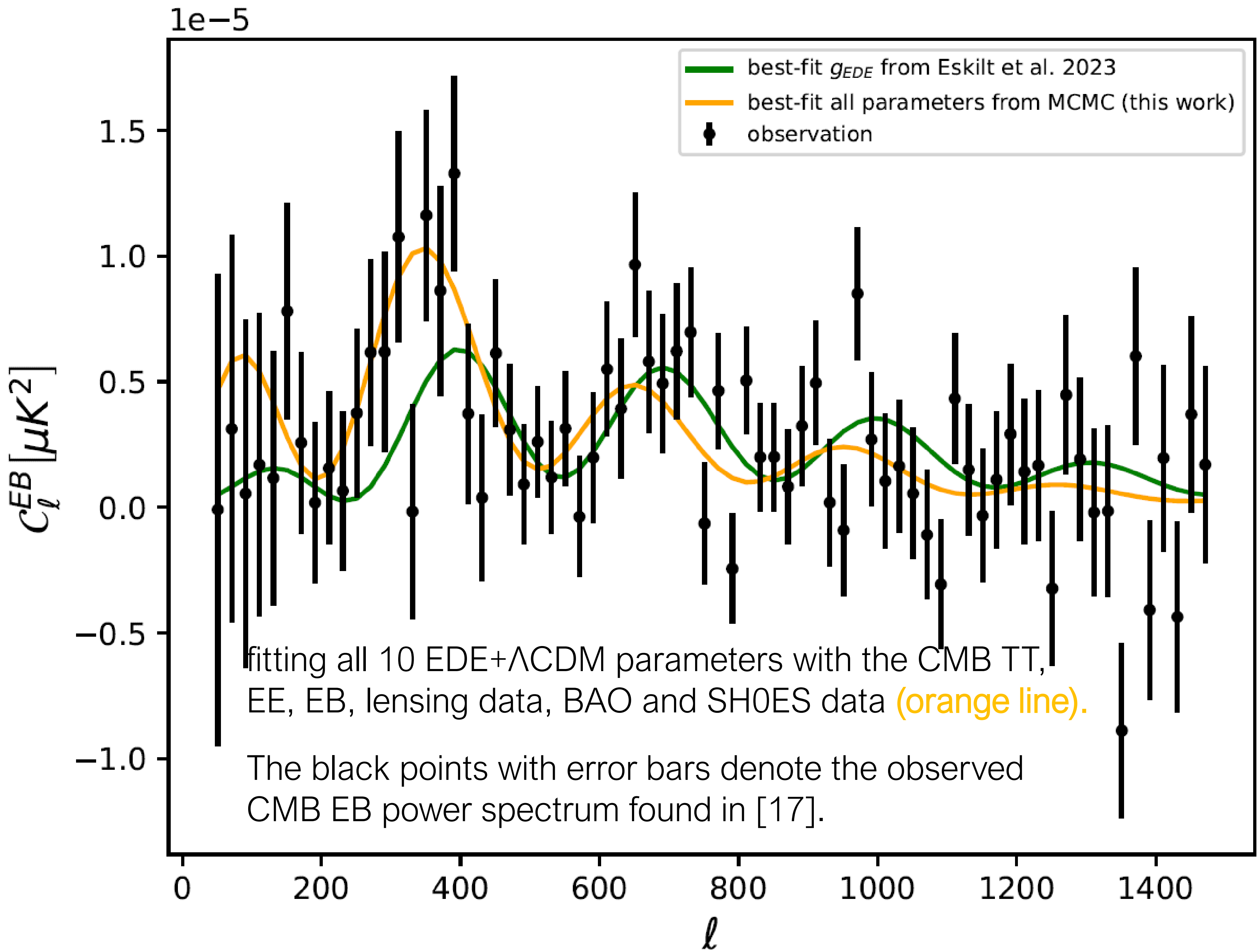
g_{EDE} =0.539

χ^2=77.5

There is a shift in g_{EDE} when the other cosmol parameters are changed.

Parameter	Best-fit
$f_{\rm EDE}$	0.058
$\log_{10}(a_c)$	3.696
θ_i	3.0
$100\theta_s$	1.0414
$100\omega_b$	2.258
$\omega_{\rm cdm}$	0.1299
$10^9 A_s$	2.177
n_s	0.988
$\tau_{\rm reio}$	0.068

	Base
$f_{\rm EDE}$	0.0872
$\log_{10} z_c$	3.560
θ_i	2.749
$100\omega_{\rm b}$	2.265
$\omega_{\rm CDM}$	0.1282
$100\theta_s$	1.041
$\ln(10^{10}A_s)$	3.063
n_s	0.983
τ	0.0562



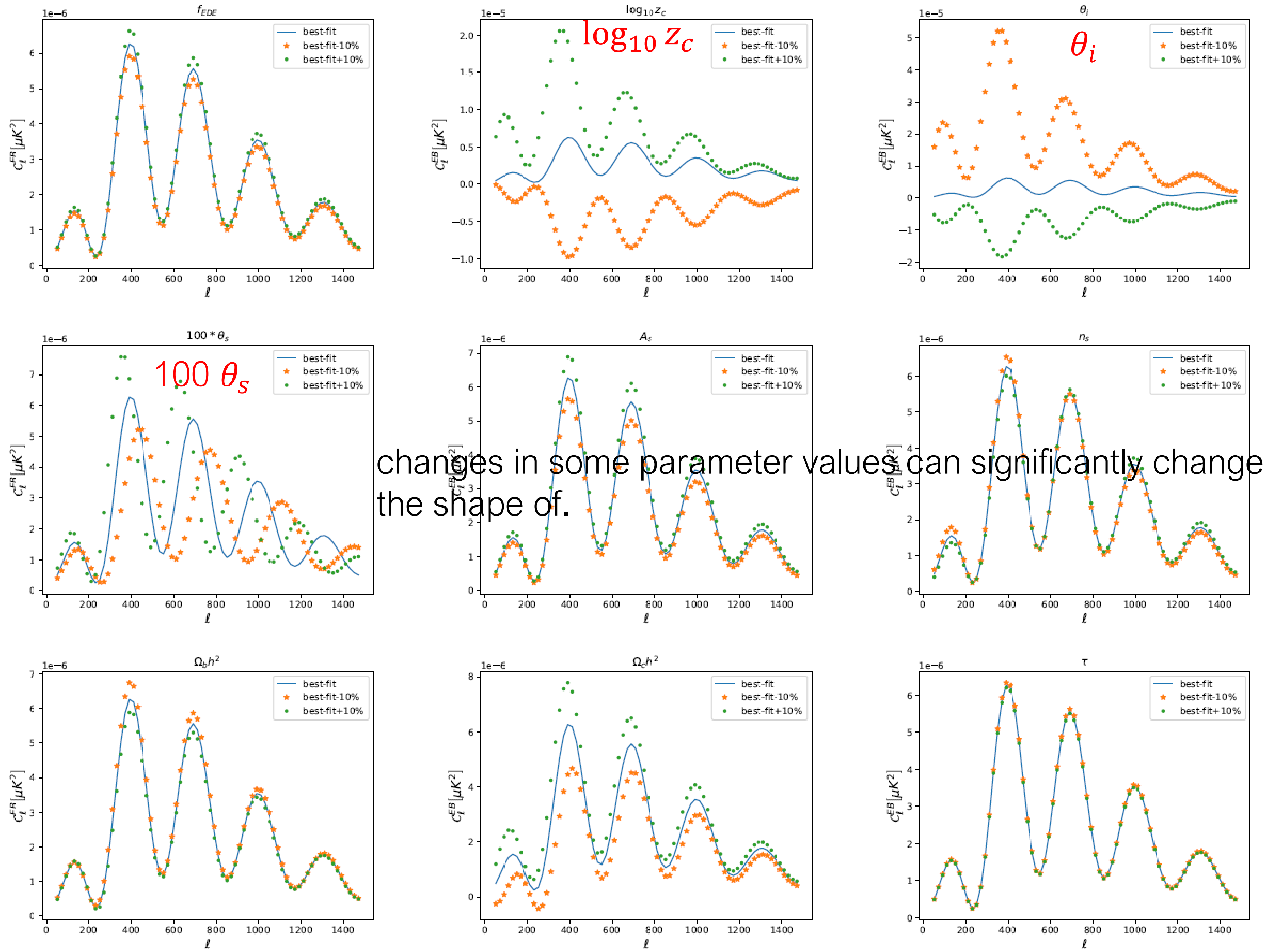
Comparison of the theoretical CMB EB power spectrum

The black points with error bars denote the observed CMB EB power spectrum.

(green line) fitting only g_{EDE} keeping all other parameters fixed to the best-fit results; Eskilt etal PRL (2023).
The shape of the predicted C_ℓ^{EB} is in clear disagreement with the observed power spectrum.

(orange line) Varying and fitting all 10 EDE+ΛCDM parameters with the CMB TT, EE, EB, lensing data, BAO and SH0ES data.
the predicted C_ℓ^{EB} is in good agreement with the observations, with a χ^2 of 68

Parameter dependance of the CMB EB power spectrum



changes in some parameter values can significantly change the shape of.

Vary one parameter at a time, keeping all others fixed (except for $g_{EDE} = 0.539$ among nine of the EDE + ΛCDM).

For each parameter, we use three values,

The blue lines : the best-fit value of the parameters (Base)

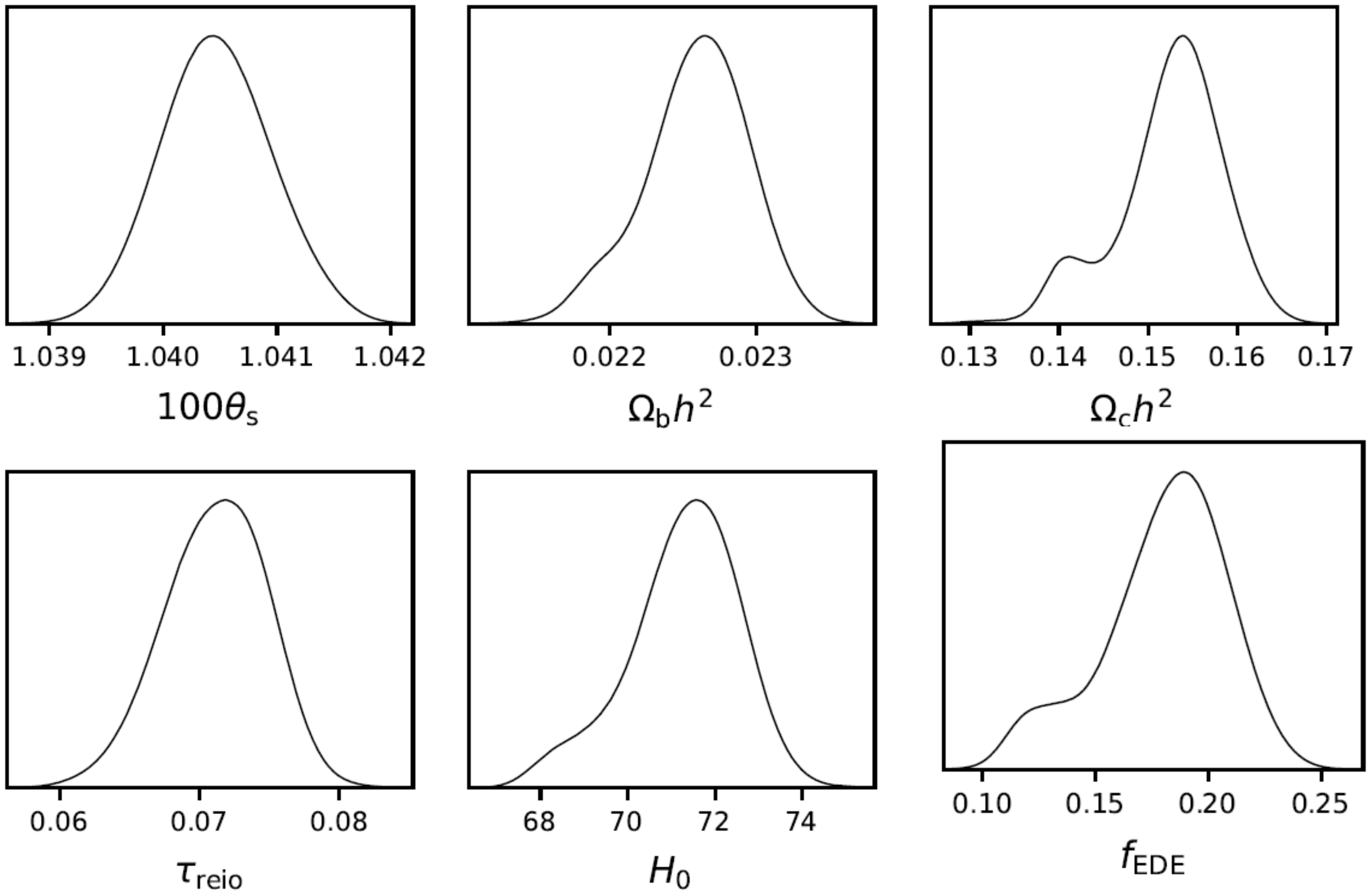
the green and orange lines : the best-fit +10% and best-fit −10% values, respectively.

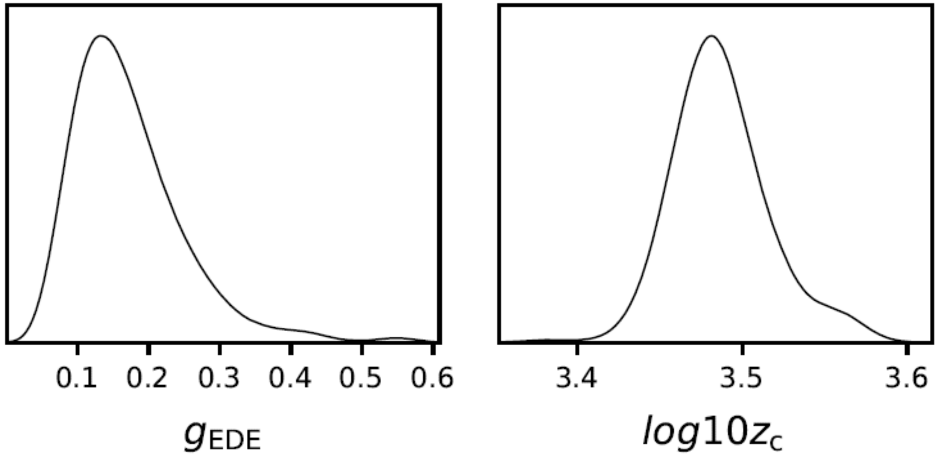
X-axis : the multipoles ℓ,

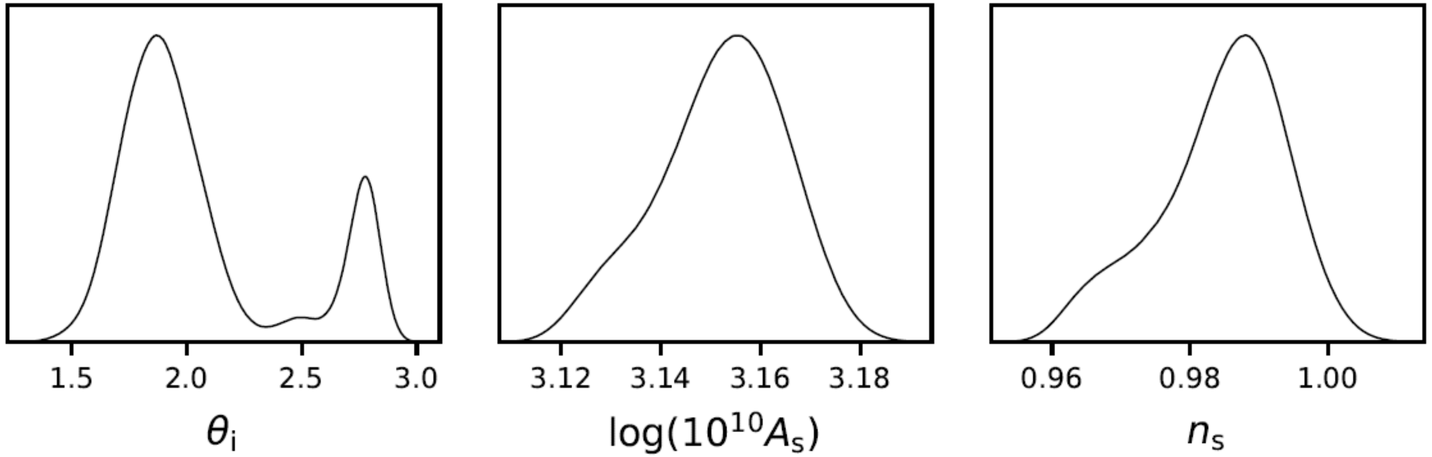
Y-axis : $\mathcal{C}_\ell^{EB}$ (μK^2)

Changes to values of $\log_{10} z_c$, θ_i, 100 θ_s and ω_{CDM} significantly alter the shape of the $\mathcal{C}_\ell^{EB}$, while the remaining parameters at most change only the amplitude.

Fitting EDE + ΛCDM model parameters to the CMB data

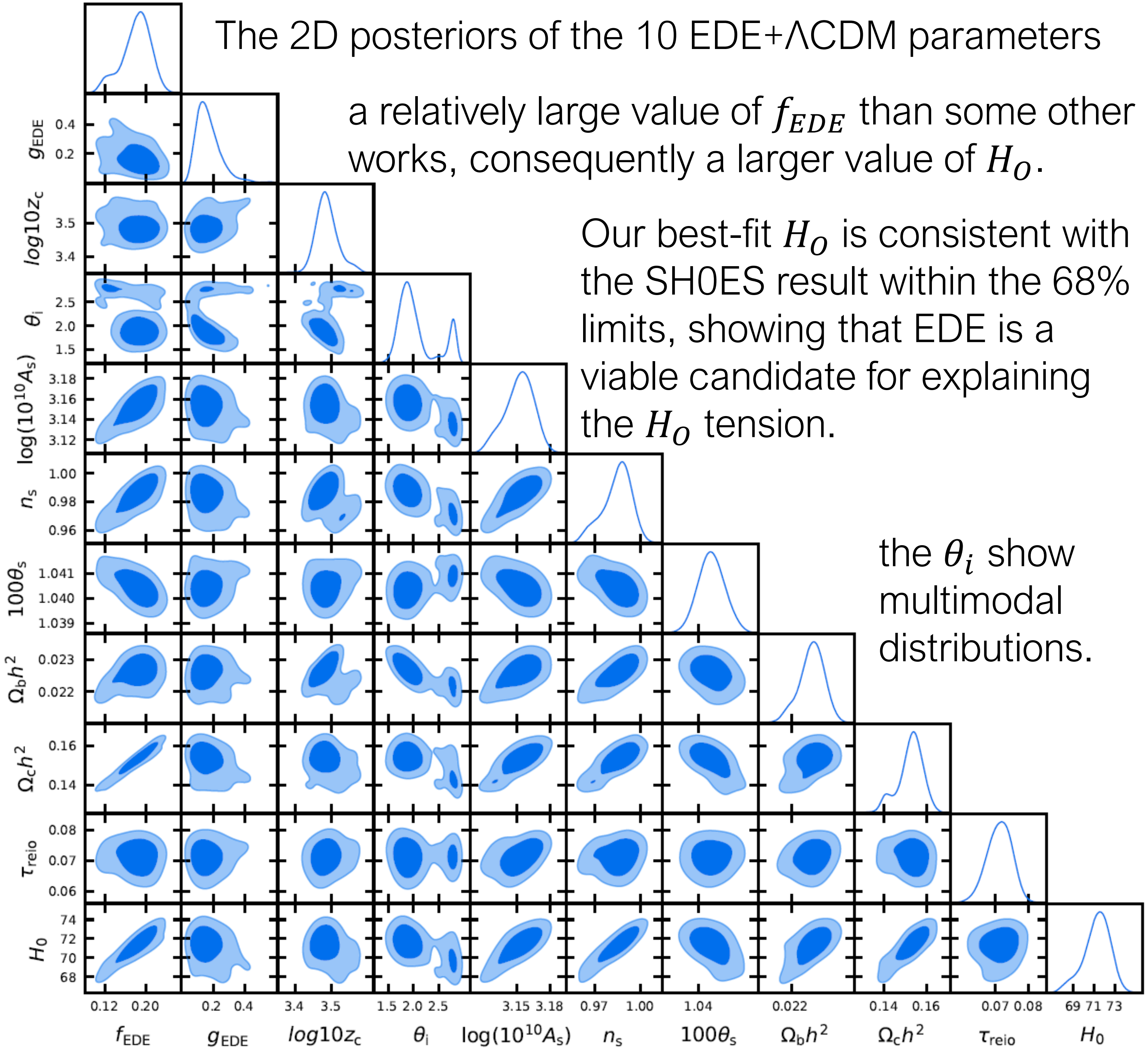






The 1D marginalised PDFs of the 4 EDE+ 6 ΛCDM= 10 parameters from the MCMC fitting of CMB, BAO & SNIa.

f_{EDE}, g_{EDE}, $\log_{10} z_c$, θ_i, $100 * \theta_s$, A_s, n_s, ω_b, ω_{CDM} and τ



The 2D posteriors of the 10 EDE+ΛCDM parameters

a relatively large value of f_{EDE} than some other works, consequently a larger value of H_O.

Our best-fit H_O is consistent with the SH0ES result within the 68% limits, showing that EDE is a viable candidate for explaining the H_O tension.

the θ_i show multimodal distributions.

Parameter	Best-fit	Marginalised
$f_{\rm EDE}$	$0.1950^{+0.0579}_{-0.0774}$	0.1801
$g_{\rm EDE}$	$0.1483^{+0.2942}_{-0.1021}$	0.1701
$\log_{10}(z_c)$	$3.4752^{+0.0853}_{-0.0606}$	3.4869
θ_i	$1.89^{+0.8703}_{-0.5302}$	2.0733
$100\theta_s$	$1.0404^{+0.0014}_{-0.0017}$	1.0405
$100\omega_b$	$2.272^{+0.09}_{-0.102}$	2.259
$\omega_{\rm cdm}$	$0.1558^{+0.0131}_{0.0157}$	0.1523
$10^9 A_s$	$2.3414^{+0.0933}_{-0.068}$	2.339
n_s	$0.9887^{+0.0213}_{-0.0213}$	0.9845
$\tau_{\rm reio}$	$0.0679^{+0.0139}_{-0.0097}$	0.0711
H_0	$72.03^{+2.73}_{-3.41}$	71.26

IV. Summary

We have revisited the axion-like Early Dark Energy model with n=3 with the coupling btw the EDE field & the CMB photons $-\frac{1}{4}g\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$ which gives rise to a non-vanishing EB power spectrum.

While recent results suggest that the axion-like EDE model with n=3 is not favored for the origin of cosmic birefringence, we have shown that this is not necessarily true depending on one's choice of cosmological parameters.

We explore the full 10-dimensional parameter space of the n=3 EDE +ΛCDM model. We use CMB temperature data, E mode polarisation data, EB cross-correlation data and lensing data from Planck, BAO data from SDSS dr12, and H_0 measurements from the SH0ES team.

We obtain best-fit values for model parameters that are in agreement with the observations of cosmic birefringence, and are also consistent with the late Universe measurements of the Hubble constant.

Our results show that the n=3 EDE model can simultaneously explain the observation of cosmic birefringence, as well as resolve the Hubble tension, hitting two birds with one stone.

Thank you!