On the potential of pseudo-scalar dark energy

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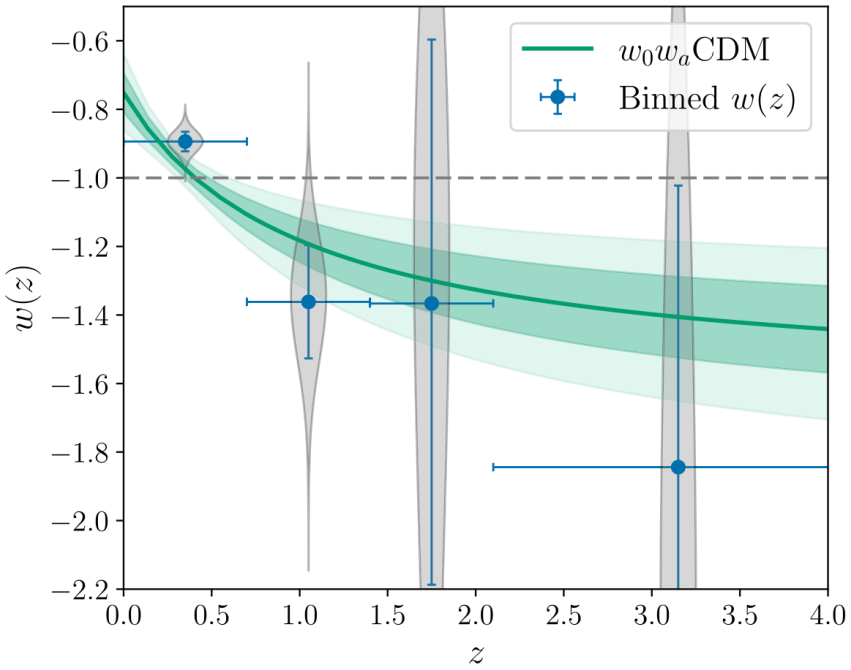
arXiv: 2606.09994

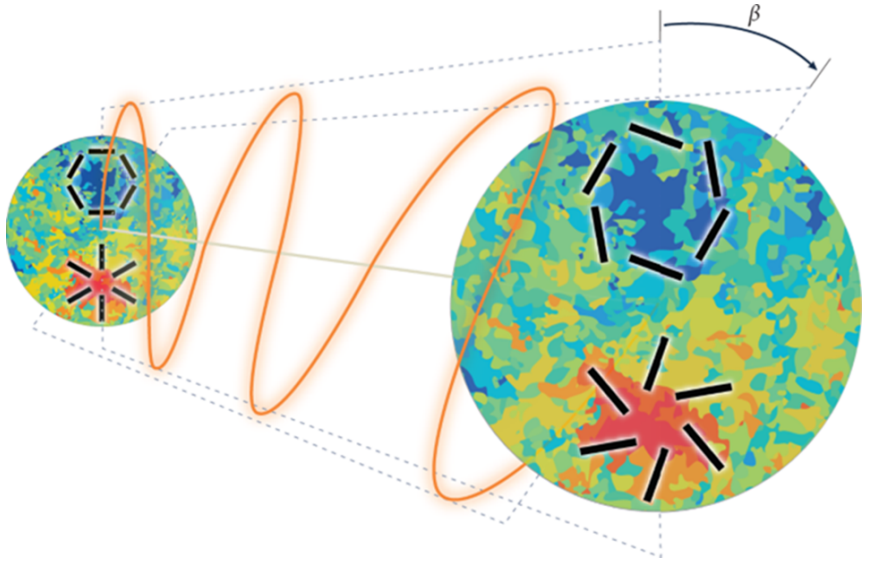
GGI 20th Anniversary

Motivations

Credit: DESI DR2 Results II



Credit: Y.Minami



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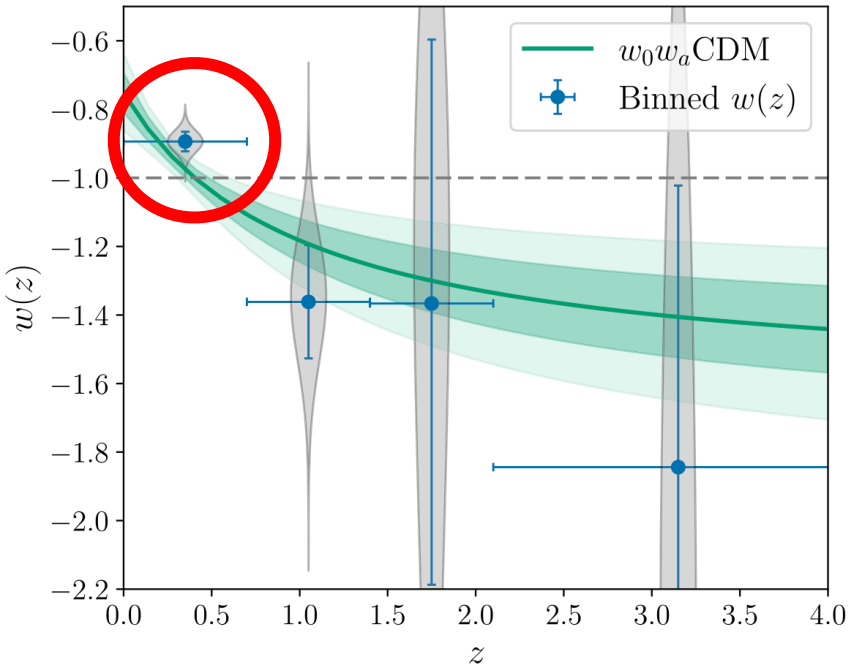

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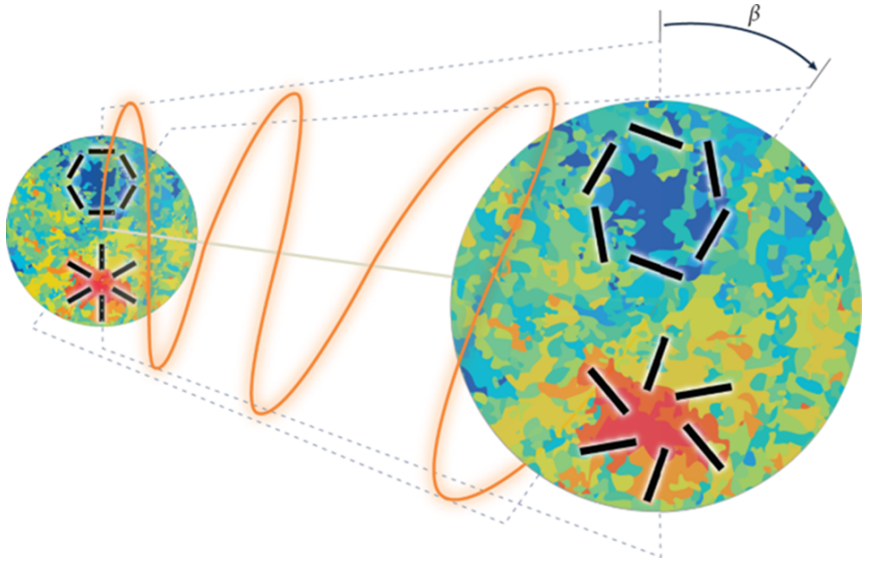

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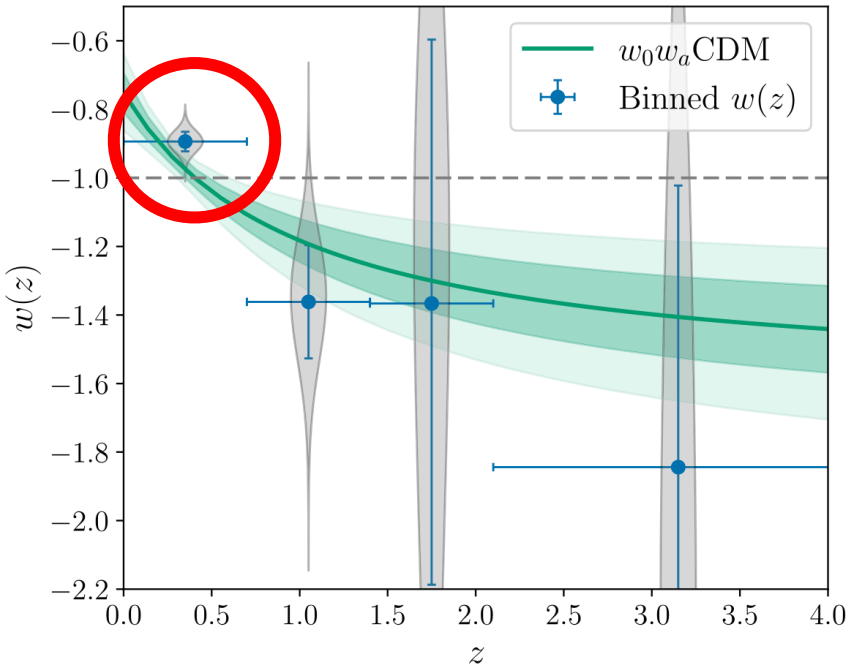

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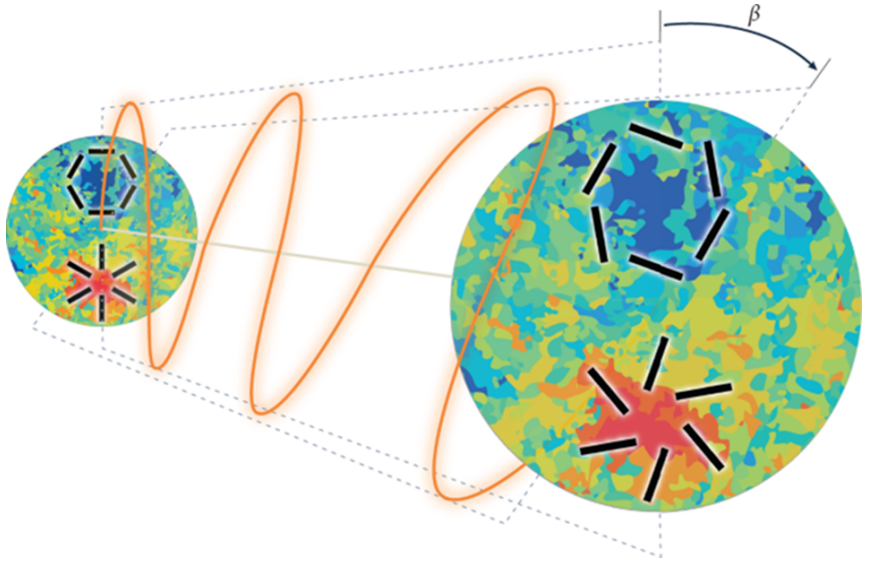


A pseudo-scalar field with a potential and Chern-Simons coupling to photons **can reproduce both!**

Model

$$\mathcal{L}_\phi = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi) - \frac{\alpha}{8\pi f}c_{\phi\gamma}\phi F_{\mu\nu}\widetilde{F}^{\mu\nu}$$

$$\beta = \frac{g_{\phi\gamma}}{2}(\phi_0 - \phi_*) = \left(\frac{\alpha c_{\phi\gamma}}{4\pi f}\right)(\phi_0 - \phi_*) \simeq 0.03^\circ c_{\phi\gamma}\frac{\Delta\phi}{f}$$

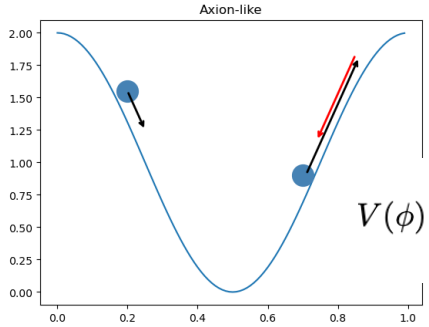
$$H_0, A_s, n_s, \omega_b, \omega_{\rm cdm}, \tau_{\rm reio}$$

Axion-like:	f, μ, $\phi'_{\rm kick}$, $\phi_{\rm ini}$, $c_{\phi\gamma}$
Linear +:	f, μ, $\phi'_{\rm kick}$, $\phi_{\rm ini}$
Linear −:	f, μ, $\phi_{\rm ini}$
Quadratic:	f, μ, $\phi_{\rm ini}$
Ratra-Peebles:	f, μ , $\phi_{\rm ini}$

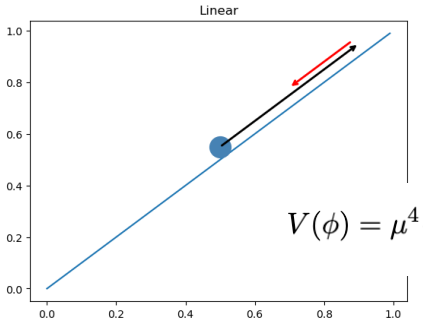
COSMOLOGY

SCALAR FIELD

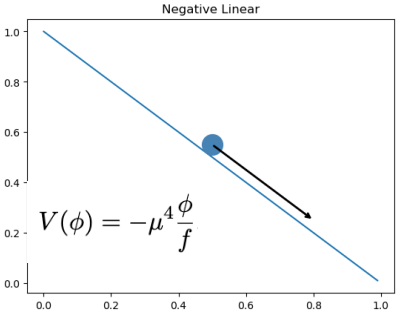
Model



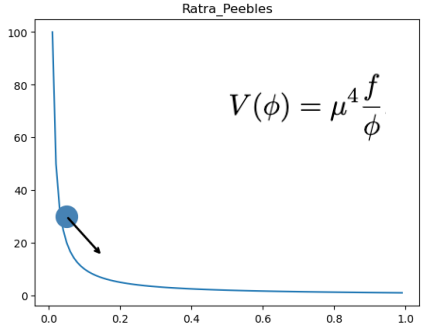
$$V(\phi) = m^2 f^2 \left[1 - \cos\left(\frac{\phi}{f}\right)\right]$$



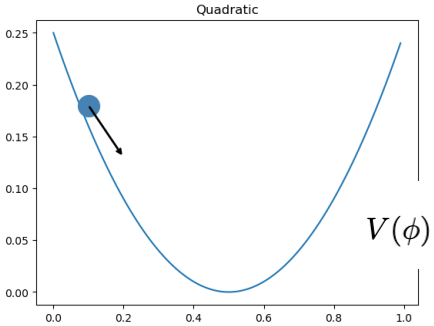
$$V(\phi) = \mu^4 \frac{\phi}{f}$$



$$V(\phi) = -\mu^4 \frac{\phi}{f}$$



$$V(\phi) = \mu^4 \frac{f}{\phi}$$



$$V(\phi) = \frac{1}{2} m^2 \phi^2$$

Change:
w(z)

$\Delta\phi \rightarrow \beta$

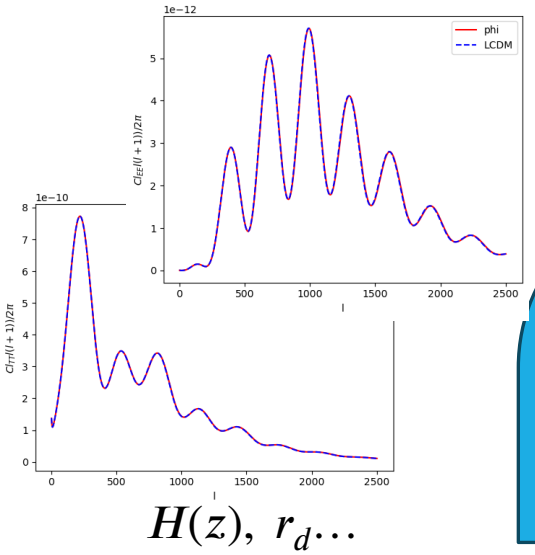
Data

- **CMB:** **Planck NPIPE (PR4)** CamSpec high-ℓ TTTEEE + **Planck 2018** low-ℓ TT and EE (9915 + 56 data-points). *distance to last scattering, ISW effect*
- **SNe:** Pantheon$^+$ (1701 light curves from 1550 Sne Ia in $z \in [0.001,2.26]$). *expansion rate at low redshift*
- **BAO:** **DESI DR2** (13 data-points in $z \in [0.295,2.33]$ from galaxies, quasars, and the Lyman-α forest).
- **CB:** **ACT DR6** $\beta = 0.215 \pm 0.074$ deg.

$$\log \mathcal{L}_\beta = -\frac{(\beta_{\rm model} - \beta_{\rm data})^2}{2\sigma^2}$$

Methods

Cosmology Data:
Planck CMB, DESI BAO,
Patheon SN
+
ACT Birefringence β



$H(z),\ r_d \ldots$

Power Spectra TTTEEE
Expansion history

Cobaya
MCMC

likelihoods

Sample

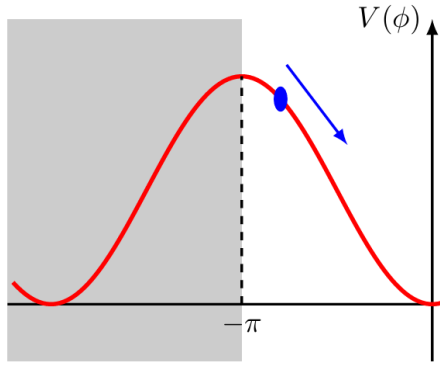
Cosmology Parameters:
$\mathrm{H0}, A_s,\ n_s,\ \omega_b,\ \omega_{cdm},\ \tau_{reio}$ + nuisance

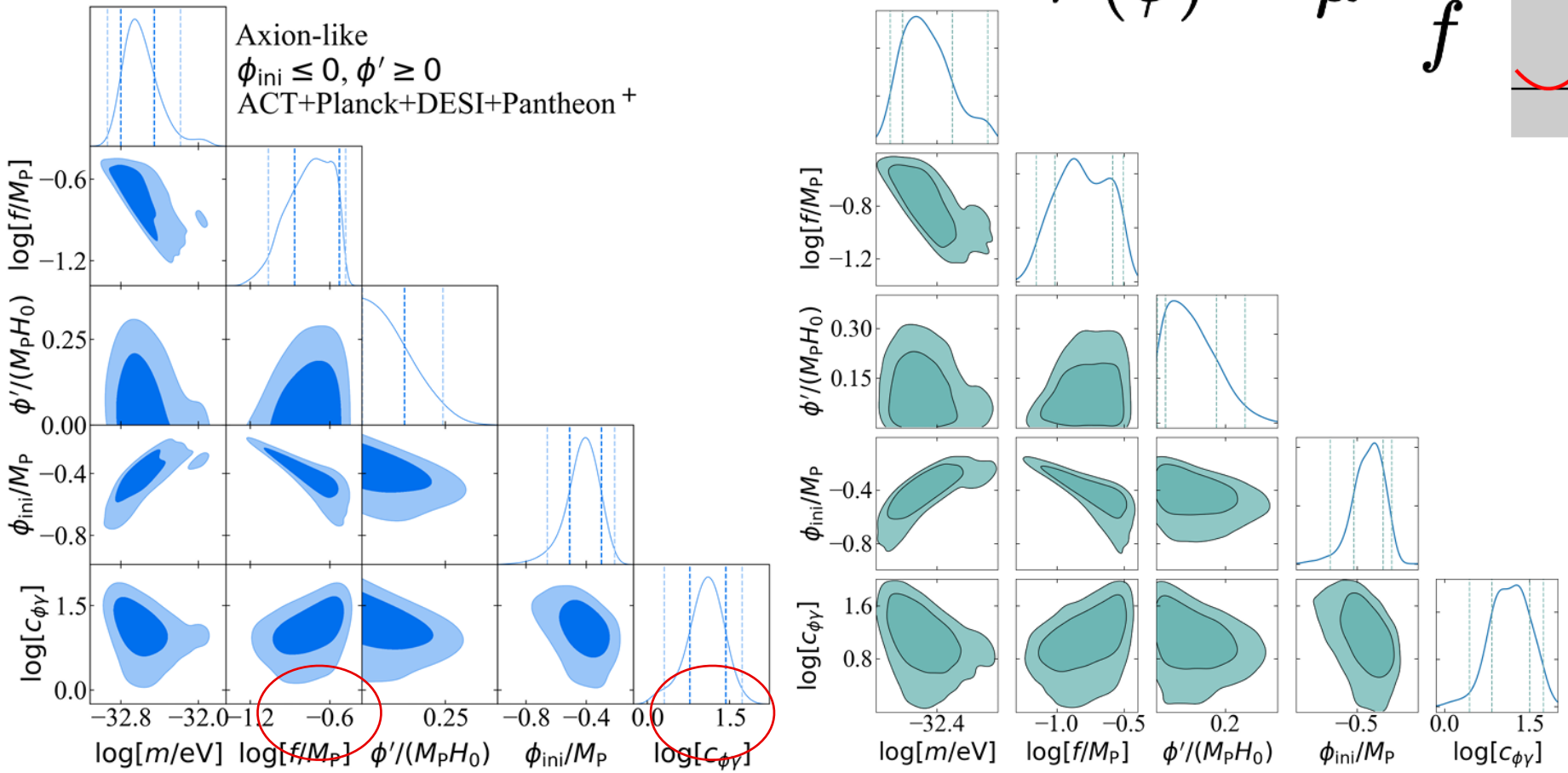
BSM parameters:
$f,\ \mu(m)\ \phi', \phi_{ini},\ c_{\phi\gamma}$

CLASS DDE ver.

Axion-like potential

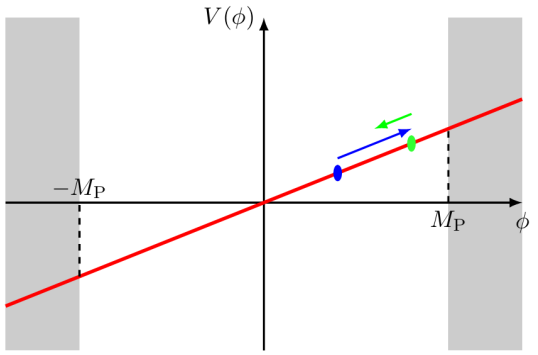
$$V(\phi) = \mu^4 \frac{\phi}{f}$$

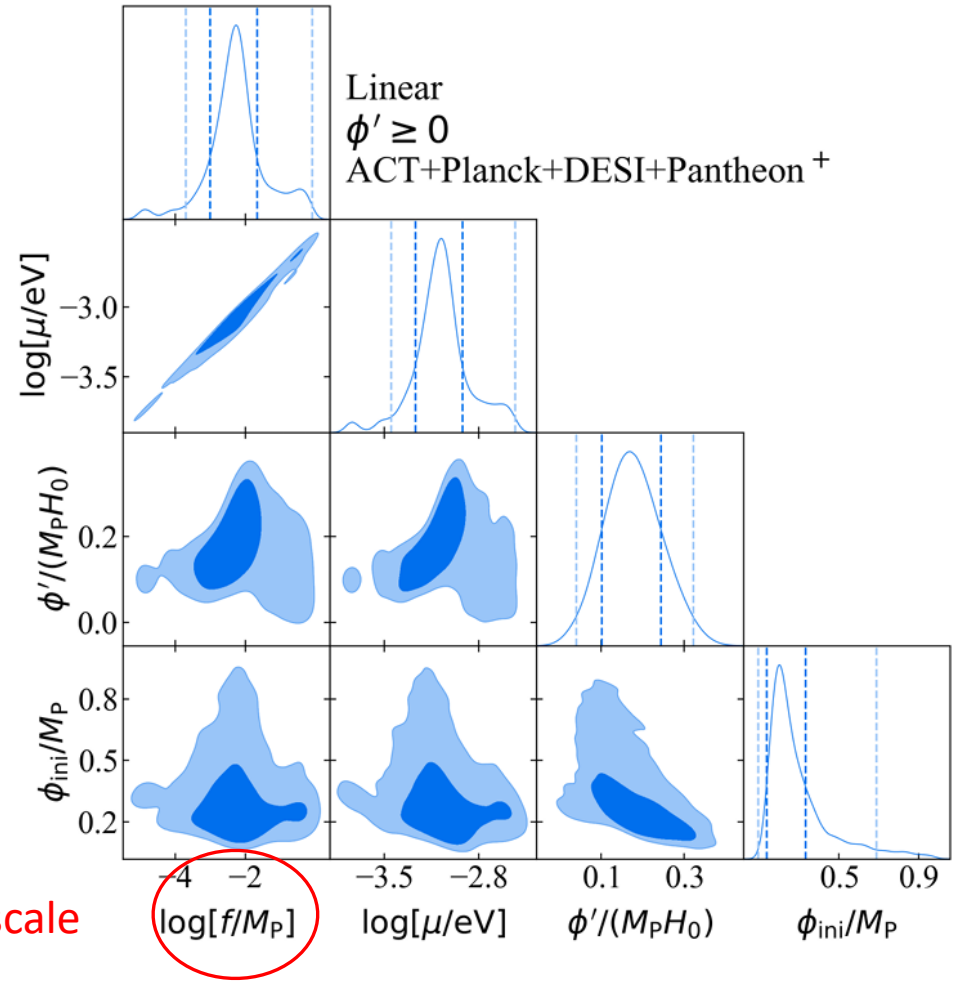




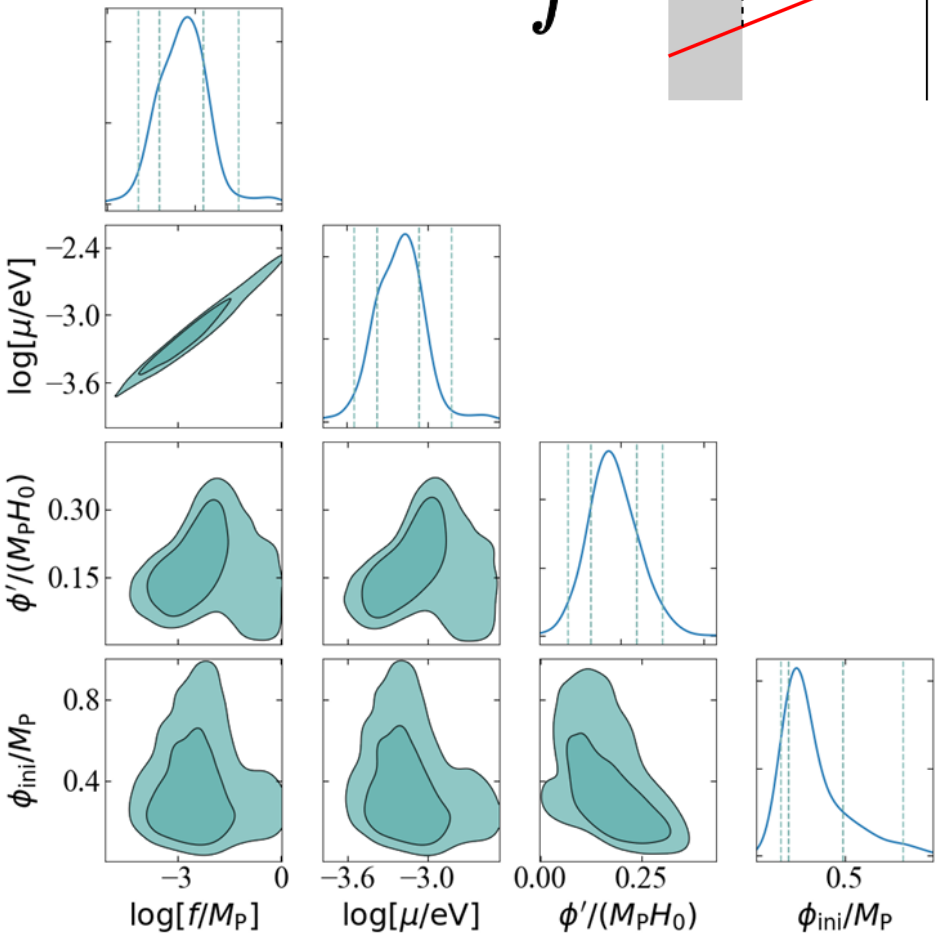
Linear potential

$$V(\phi) = \mu^4 \frac{\phi}{f}$$





GUT scale



Constraints

ΛCDM:

$$\chi^2_{\rm cosmo,\Lambda} = 3861$$

$$\Delta {\rm AIK_C} = \chi^2_{\rm cosmo,\Lambda} - \chi^2_{\rm cosmo,\phi DE} - 2{\rm k_d}$$

$$+\chi^2_{\beta,\Lambda} = 8.4$$

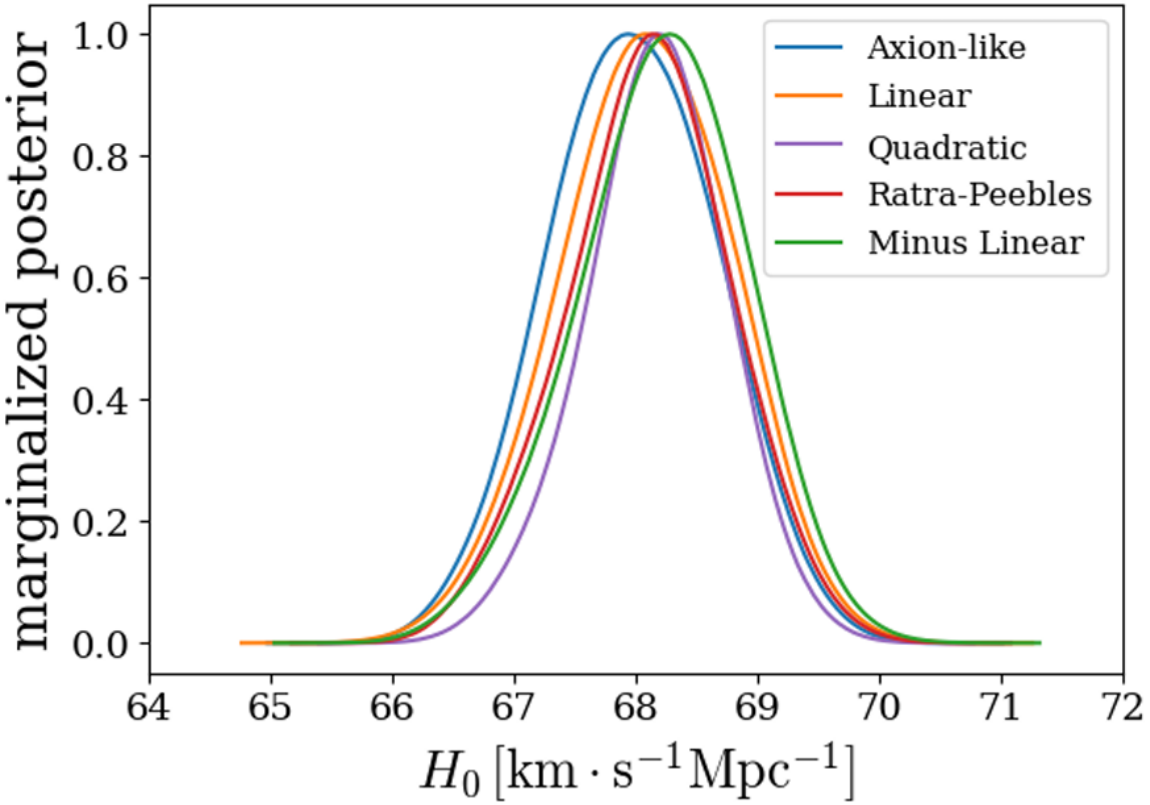
3σ

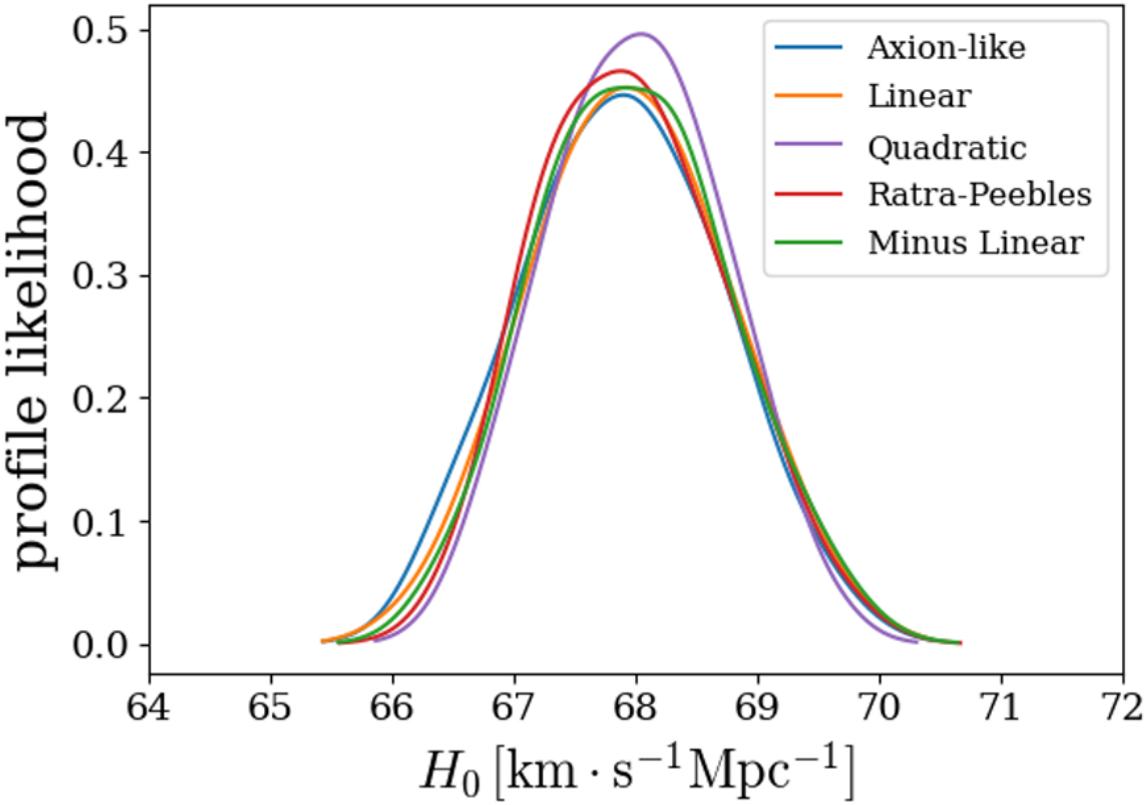
4σ

	Axion-like	Linear	Minus Linear	Quadratic	Ratra-Peebles
$\log[f/M_{\rm P}]$	$-0.75^{+0.23}_{-0.11}$ $-0.88^{+0.29}_{-0.13}$	$-2.19^{+0.54}_{-0.83}$ $-2.99^{+0.74}_{-0.51}$	$-2.02^{+0.19}_{-0.46}$ $-2.22^{+0.30}_{-0.12}$	$-2.06^{+0.15}_{-0.34}$ $-2.13^{+0.20}_{-0.15}$	$-1.93^{+0.18}_{-0.50}$ $-2.12^{+0.25}_{-0.17}$
$\log[\mu/{\rm eV}]$	/	$-3.06^{+0.14}_{-0.21}$ $-3.24^{+0.18}_{-0.13}$	$-3.03^{+0.10}_{-0.12}$ $-3.05^{+0.08}_{-0.07}$	/	$-2.28^{+0.14}_{-0.09}$ $-2.27^{+0.09}_{-0.07}$
$\log[m/{\rm eV}]$	$-32.58^{+0.13}_{-0.22}$ $-32.59^{+0.34}_{-0.15}$	/	/	$-33.00^{+0.13}_{-0.09}$ $-32.95^{+0.06}_{-0.13}$	/
$\phi'_{\rm kick}$ $[M_{\rm P}H_0]$	$0.102^{+0.026}_{-0.102}$ $0.113^{+0.061}_{-0.085}$	$0.177^{+0.073}_{-0.073}$ $0.154^{+0.085}_{-0.027}$	/	/	
$\phi_{\rm ini}$ $[M_{\rm P}]$	$-0.43^{+0.13}_{-0.09}$ $-0.35^{+0.07}_{-0.17}$	$0.30^{+0.03}_{-0.16}$ $0.23^{+0.26}_{-0.04}$	$-0.38^{+0.16}_{-0.02}$ $-0.28^{+0.02}_{-0.21}$	$-0.65^{+0.19}_{-0.09}$ $-0.56^{+0.05}_{-0.20}$	$0.32^{+0.02}_{-0.15}$ $0.22^{+0.22}_{-0.01}$
$\log c_{\phi\gamma}$	$1.06^{+0.37}_{-0.28}$ $0.88^{+0.63}_{-0.04}$	/	/	/	/
β [deg]	$0.18^{+0.09}_{-0.09}$ $0.16^{+0.12}_{-0.02}$	$0.15^{+0.11}_{-0.13}$ $0.24^{+0.04}_{-0.11}$	$0.17^{+0.10}_{-0.10}$ $0.26^{+0.01}_{-0.12}$	$0.18^{+0.09}_{-0.09}$ $0.20^{+0.08}_{-0.06}$	$0.16^{+0.09}_{-0.16}$ $0.23^{+0.04}_{-0.09}$
H_0 [km/s/Mpc]	$67.93^{+0.73}_{-0.71}$ $67.90^{+0.59}_{-0.63}$	$68.09^{+0.73}_{-0.72}$ $68.05^{+0.47}_{-0.72}$	$68.17^{+0.70}_{-0.70}$ $67.60^{+0.86}_{-0.39}$	$68.14^{+0.70}_{-0.61}$ $67.86^{+0.70}_{-0.38}$	$68.09^{+0.72}_{-0.66}$ $67.65^{+0.80}_{-0.37}$
$\chi^2_{\rm total}$	3848.7	3848.3	3848.0	3848.3	3847.5
$\Delta{\rm AIK_c}$	6.9	8.7	11.1	10.7	11.5

4.9σ

Models comparison





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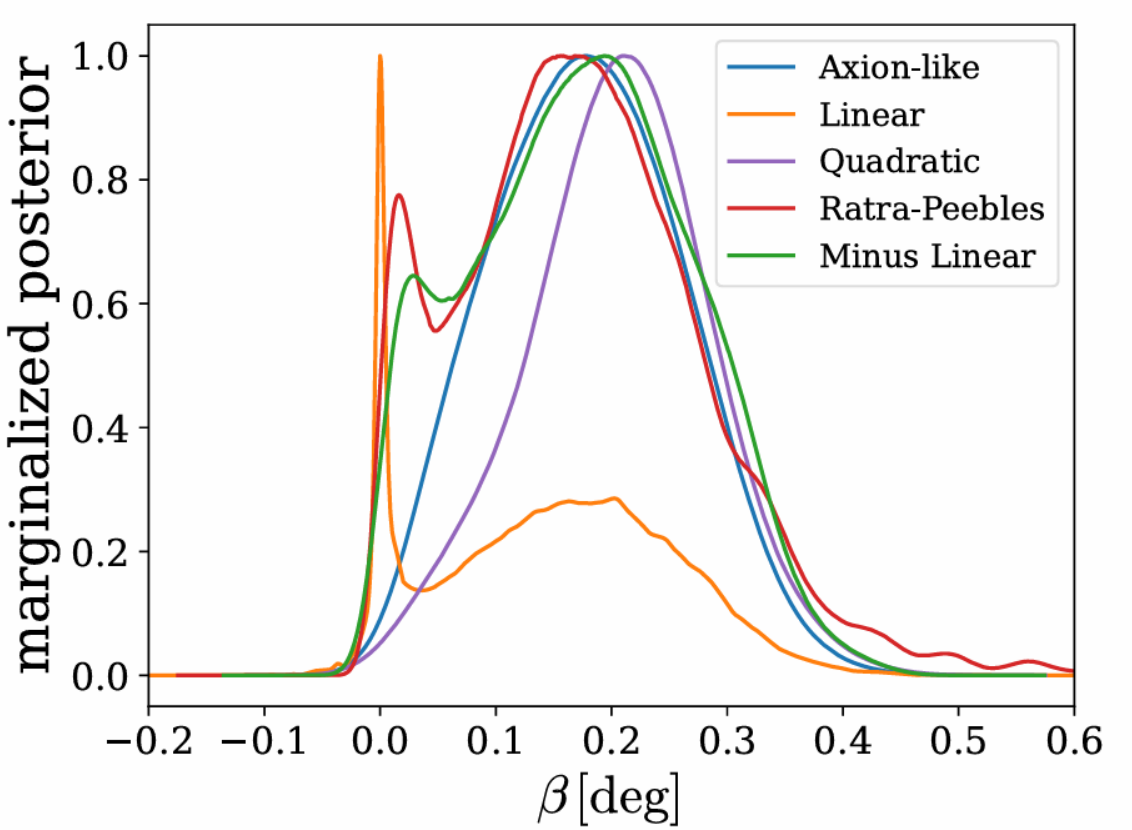
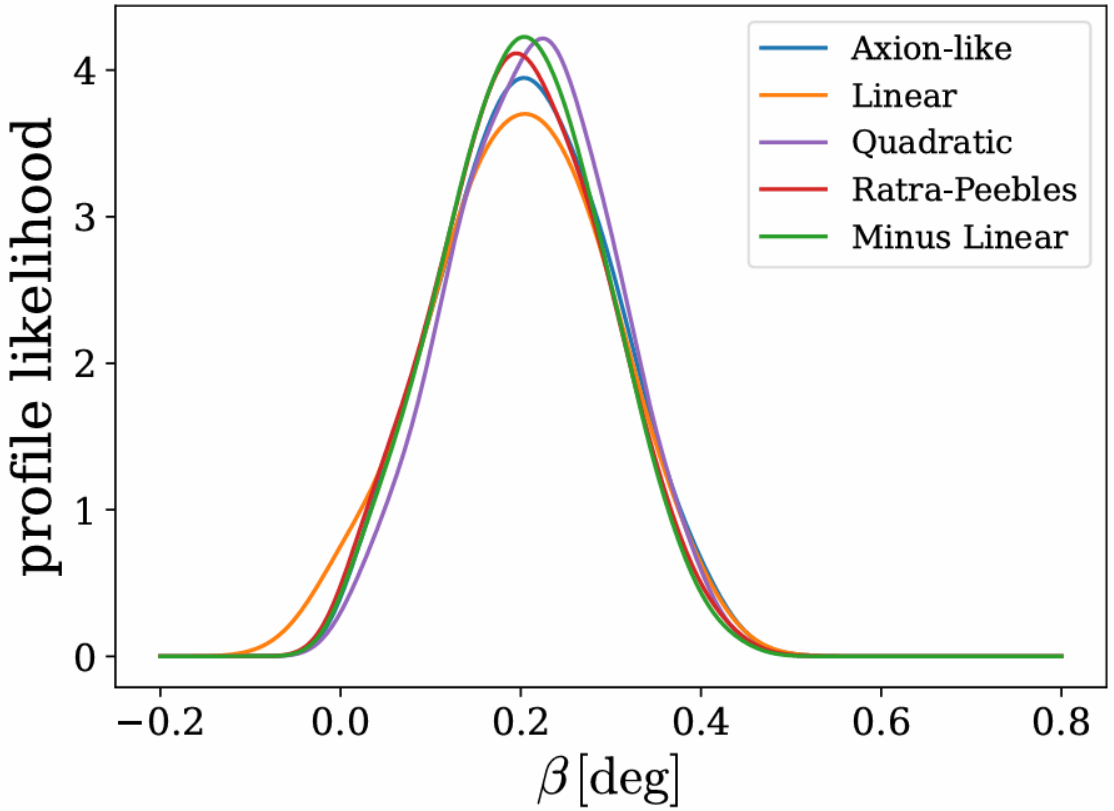
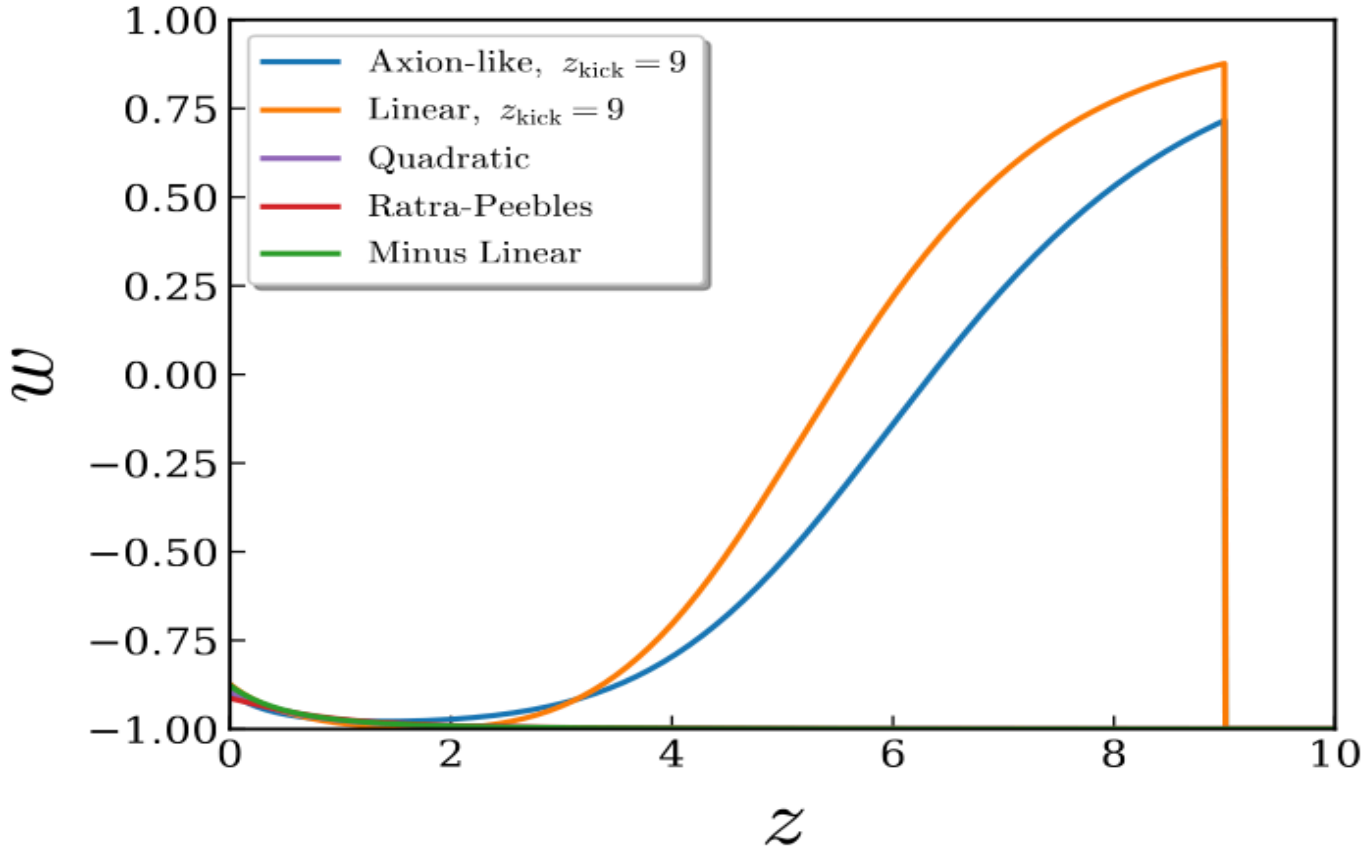
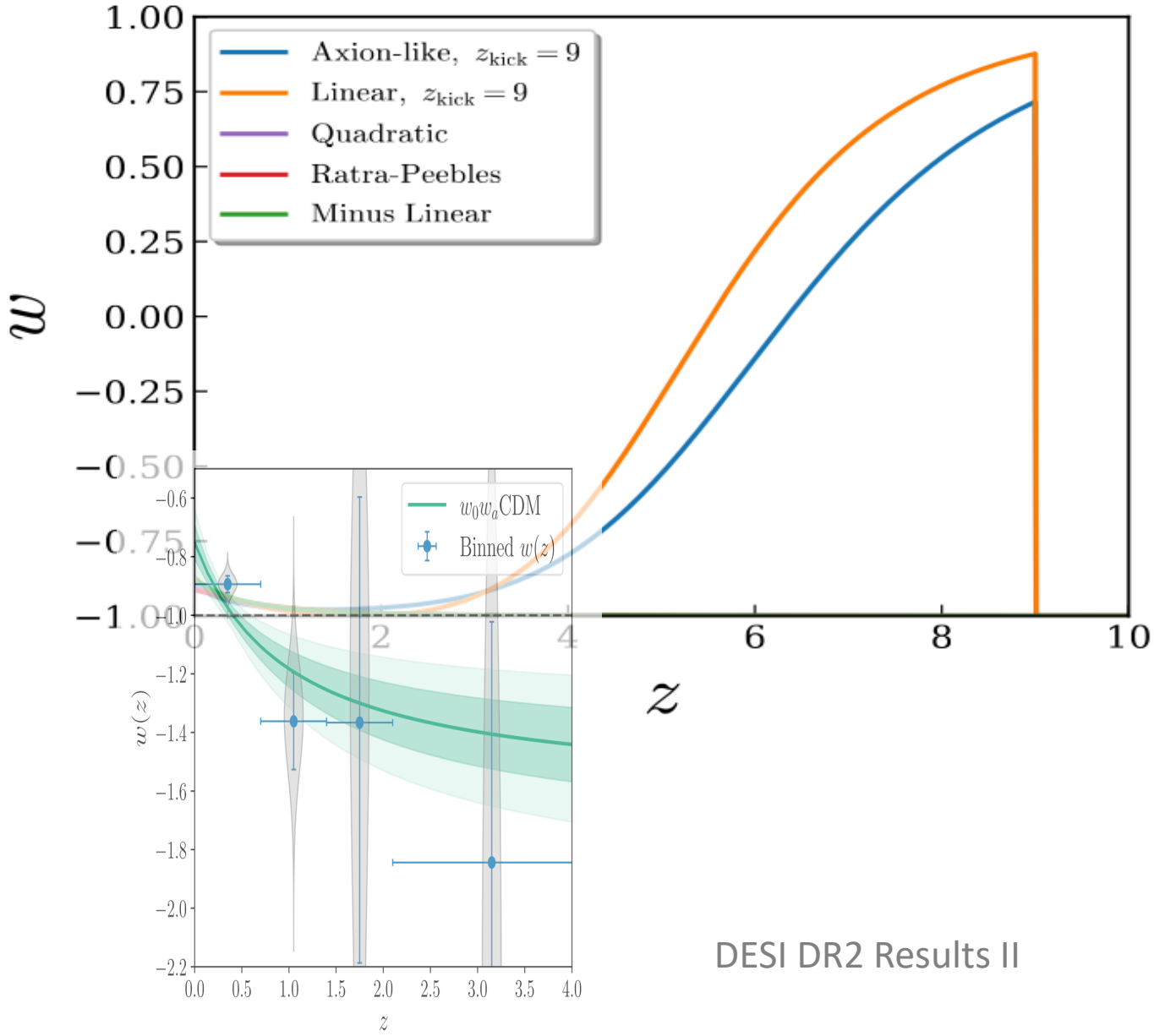




w(z)

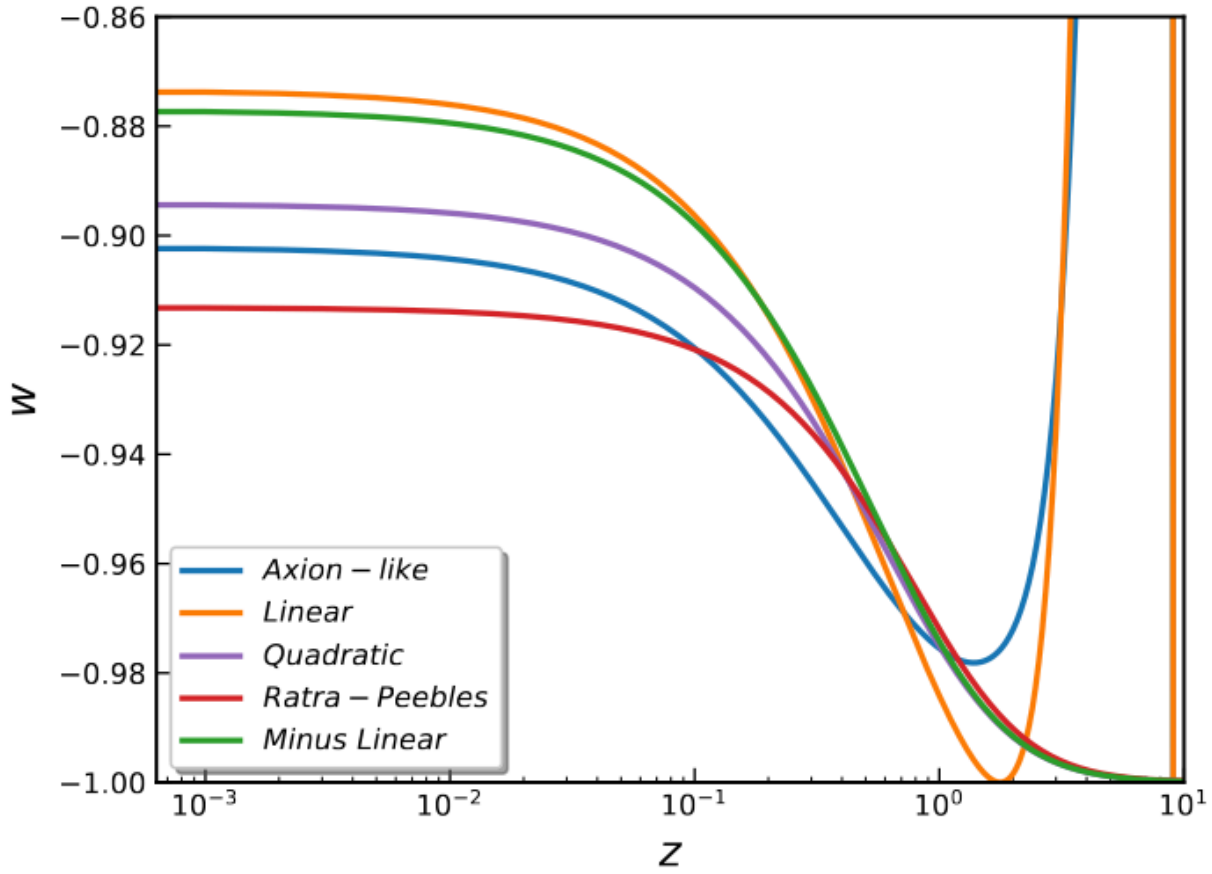

Axion-like, $z_{\rm kick} = 9$
Linear, $z_{\rm kick} = 9$
Quadratic
Ratra-Peebles
Minus Linear
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
−1.00
w
0
2
4
6
8
10
z

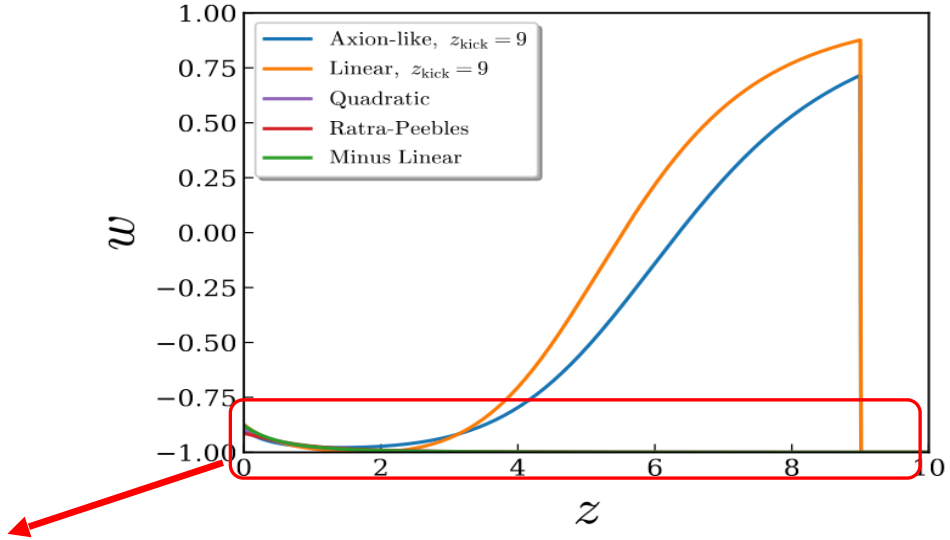
w(z)



DESI DR2 Results II

w(z)


−0.86
−0.88
−0.90
−0.92
−0.94
−0.96
−0.98
−1.00
w
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
z
Axion − like
Linear
Quadratic
Ratra − Peebles
Minus Linear


1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
−1.00
w
0
2
4
6
8
10
z
Axion-like, $z_{\rm kick} = 9$
Linear, $z_{\rm kick} = 9$
Quadratic
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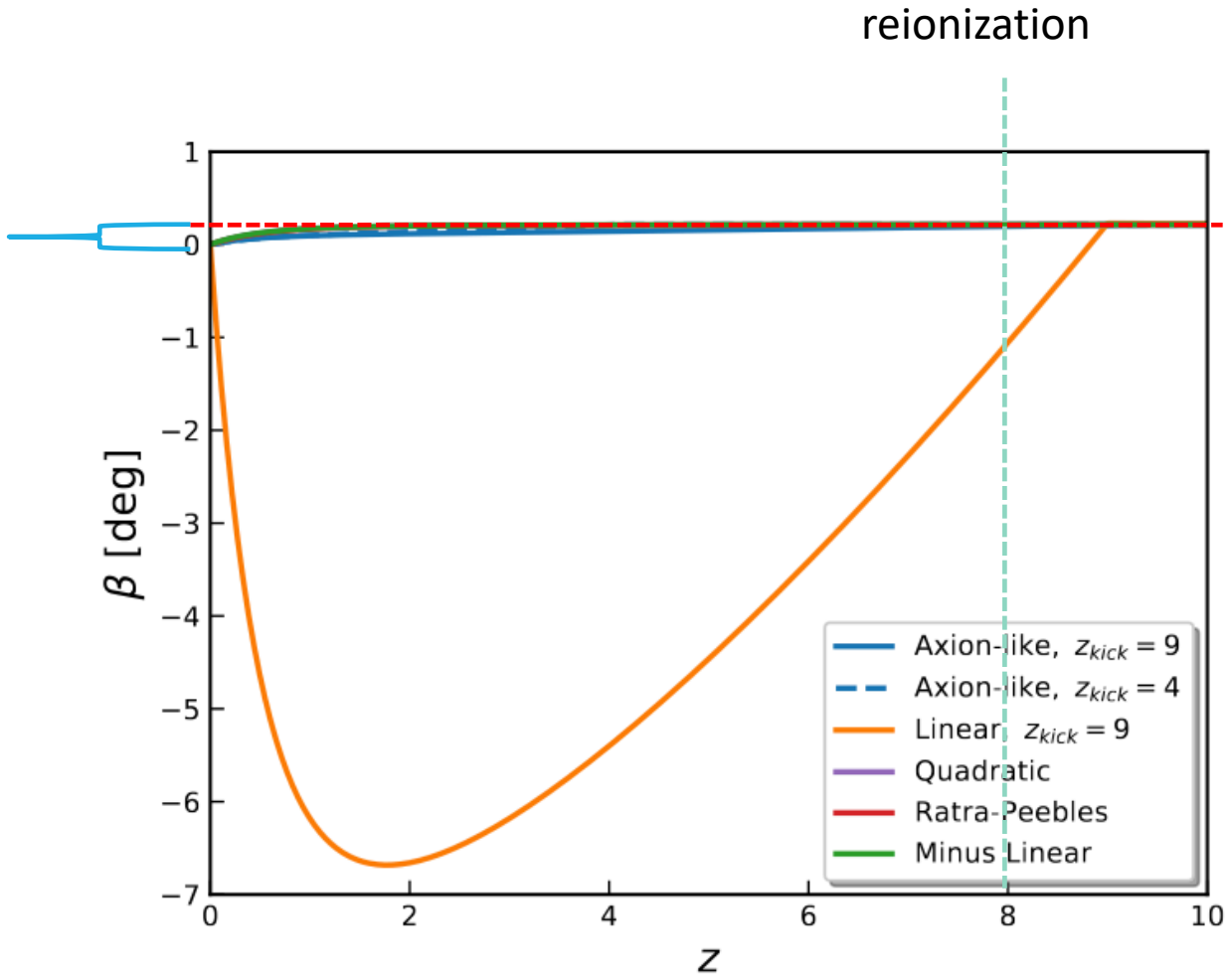
β(z)

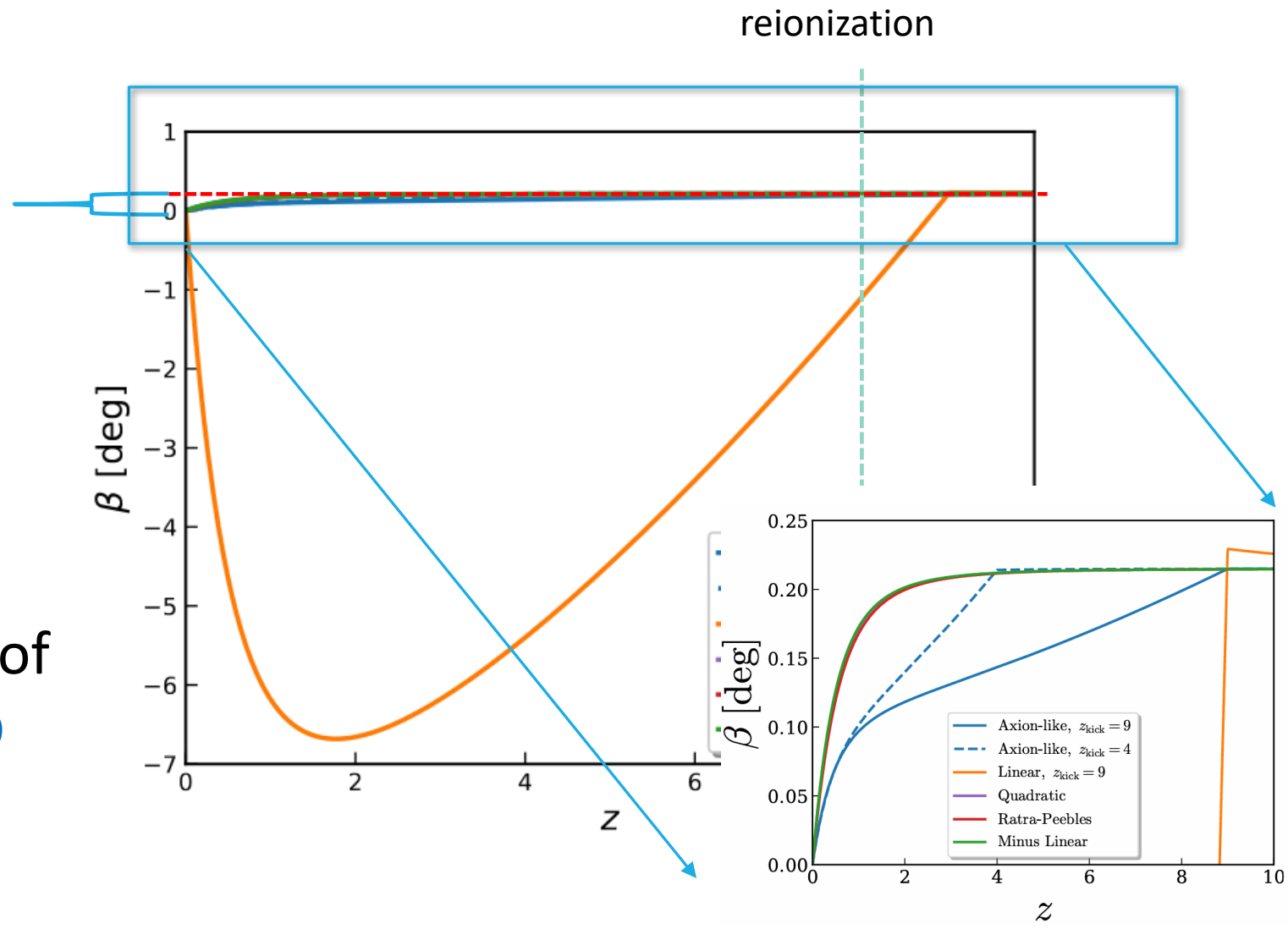
CMB: β = 0.215 ± 0.074 deg



Too fine-tuned?

β(z)

CMB: β = 0.215 ± 0.074 deg



Too fine-tuned?

Check the birefringence angle of reionization photons: **LiteBIRD**

SKA radio

Conclusions

- **Evidence for Dynamical Dark Energy** over a cosmological constant at about **3σ** level (cosmology data only).
- **4σ** level **when cosmic birefringence is included.**
- An axion-like potential is a viable model only for large values of the anomaly coefficient!
- Scenarios in which the pseudo-scalar field rolls down a potential with quadratic, linear, or Ratra–Peebles forms can provide a good fit, with a symmetry-breaking scale close to the GUT scale.

Discussion

- Future experiments as
  - LiteBIRD (CMB)
  - SKA (radio)

  can rule out/constrain these models through birefringence tomography
- Gravitational effects in non-linear scale (galaxy clusters, or even smaller)?
- w(z)<-1 (phantom crossing)

THANK YOU!