Quintessence with Sharp Transitional Feature and Late-Time Cosmological Signals

with Kiyotomo Ichiki, Yuichiro Tada, and Shun Yoshioka, arXiv:2602.14389 [astro-ph.CO]

Takahiro Terada (KMI, Nagoya U.), GW and the Earky Universe, KMI, Mar. 13, 2026

# Dark Energy Spectroscopic Instrument

- 4m-aperture telescope in Arizona
- First cosmic observation at Stage 4
- 8 yr observations since 2021 (extended)
- Spectroscopy of 50+ million galaxies & quasars
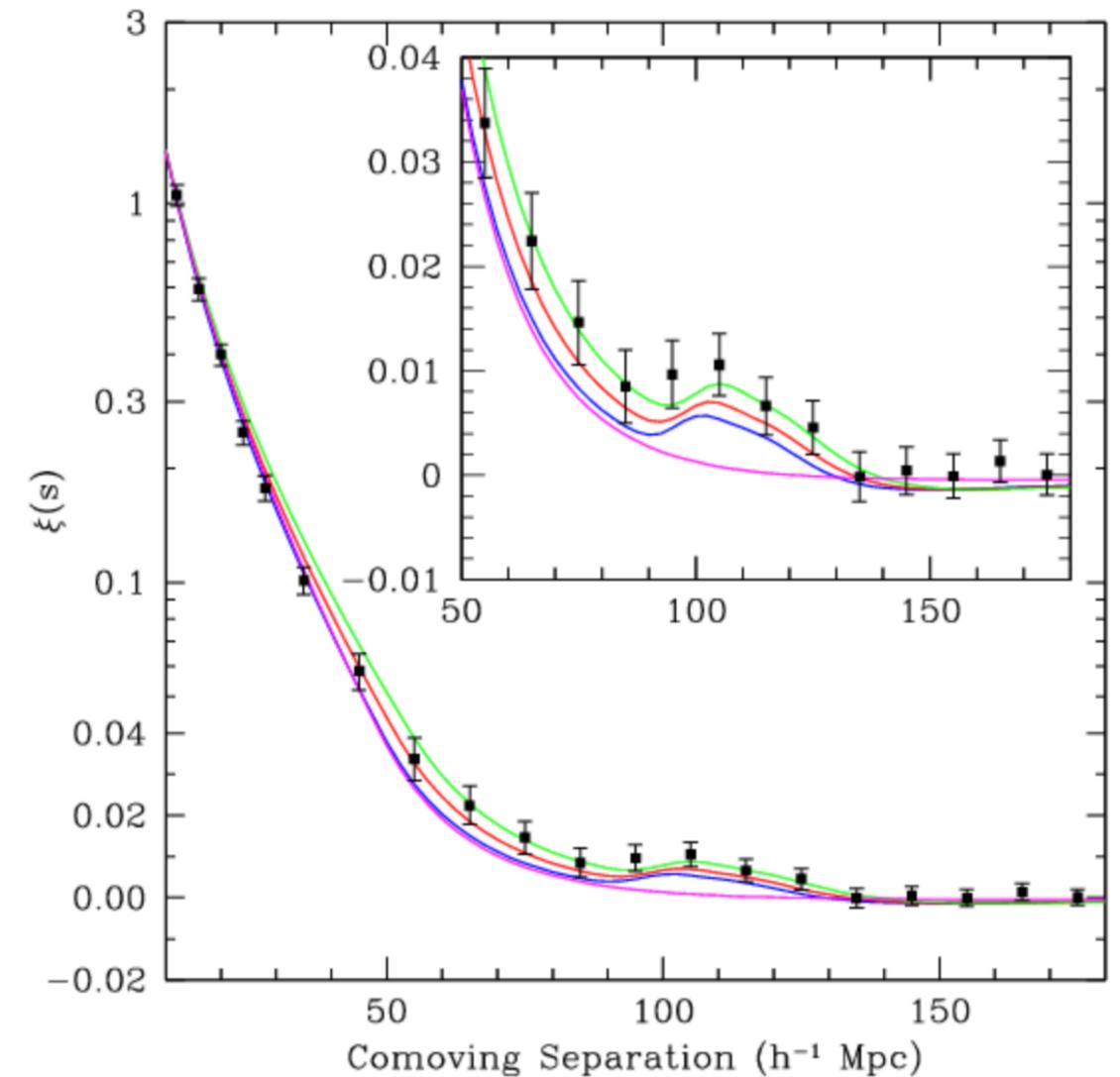- 5000 independent robotic optical fibers
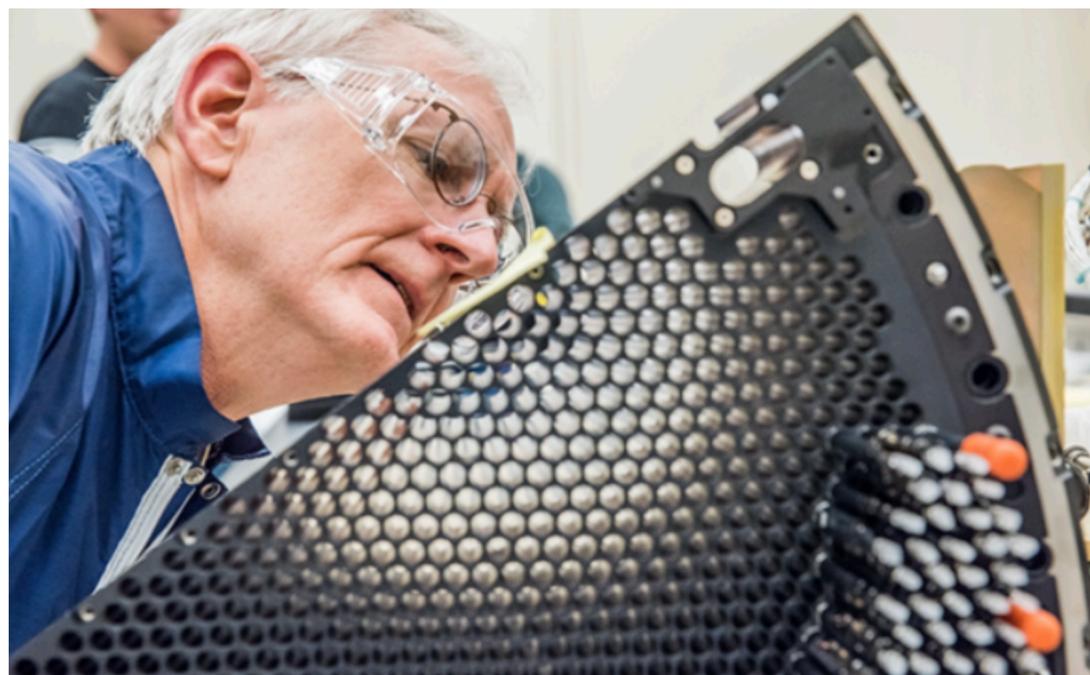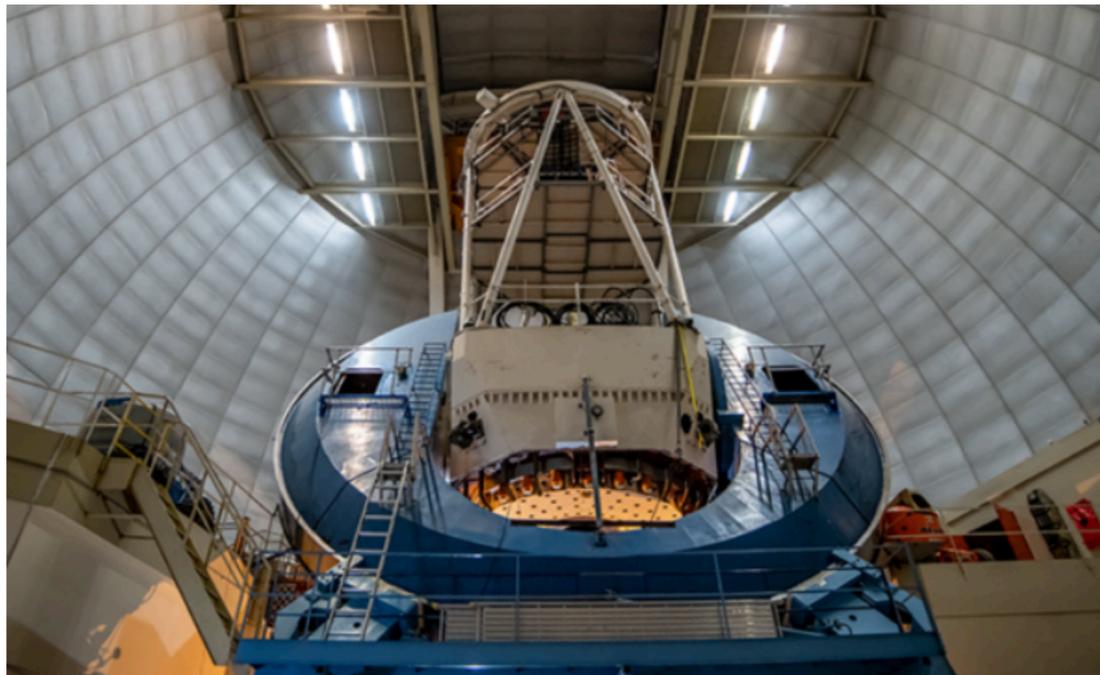
[Images from the web site of DESI]

Baryon Acoustic Oscillations (BAO)

Typical scale of perturbations in the mixed photon-baryon fluid → Typical scale between galaxies
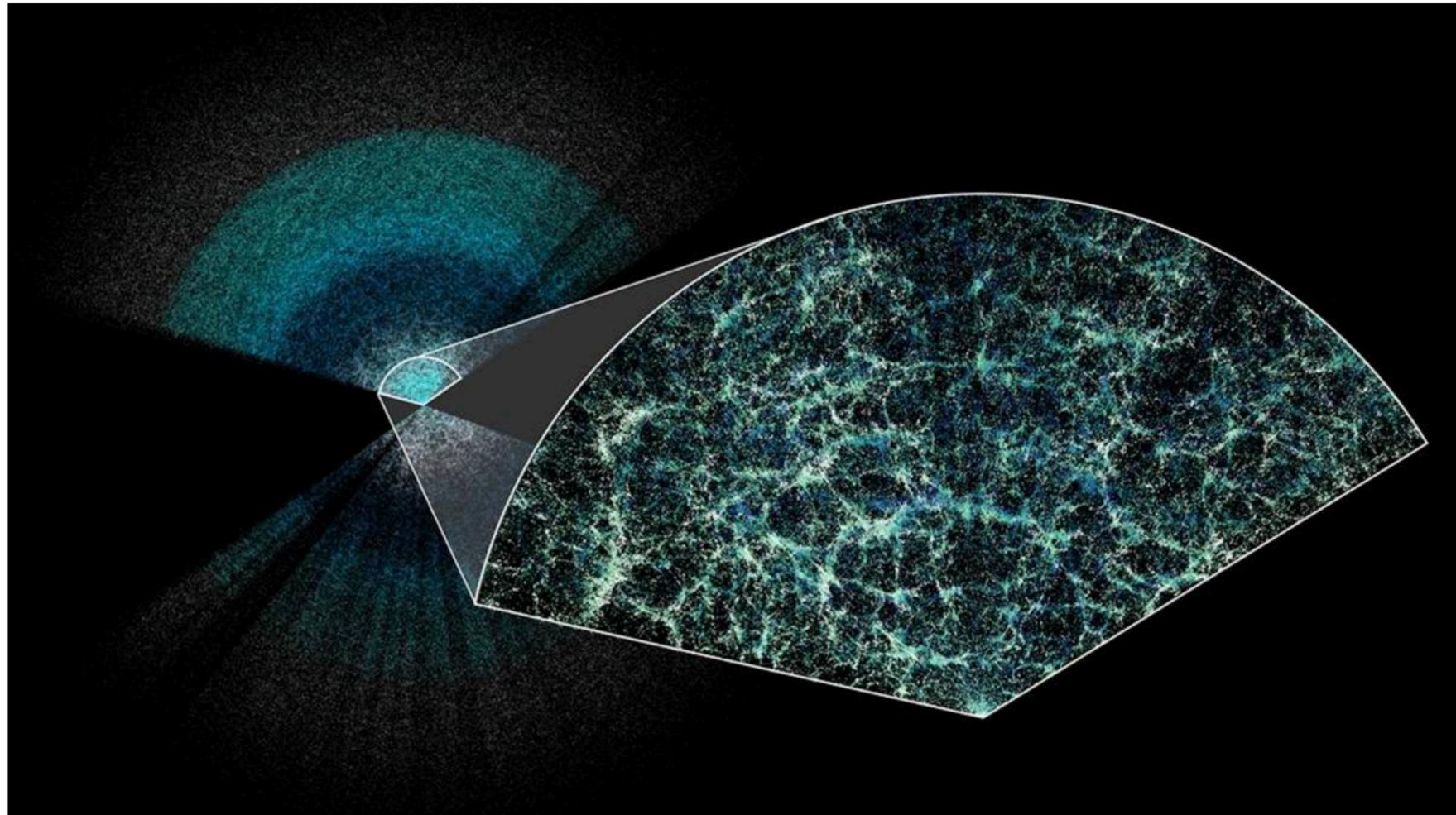
[Courtesy: Claire Lamman/DESI collaboration/custom colormap package by cmastro]

[Eisenstein et al. (SDSS), astro-ph/0501171]

Cosmic History from BAO

$$D_{\mathrm{M}}(z) = \frac{c}{H_0\sqrt{\Omega_K}} \sinh\left[\sqrt{\Omega_K}\int_0^\infty \frac{\mathrm{d}z'}{H(z')/H_0}\right] = \frac{r_{\mathrm{d}}}{\Delta\theta}$$
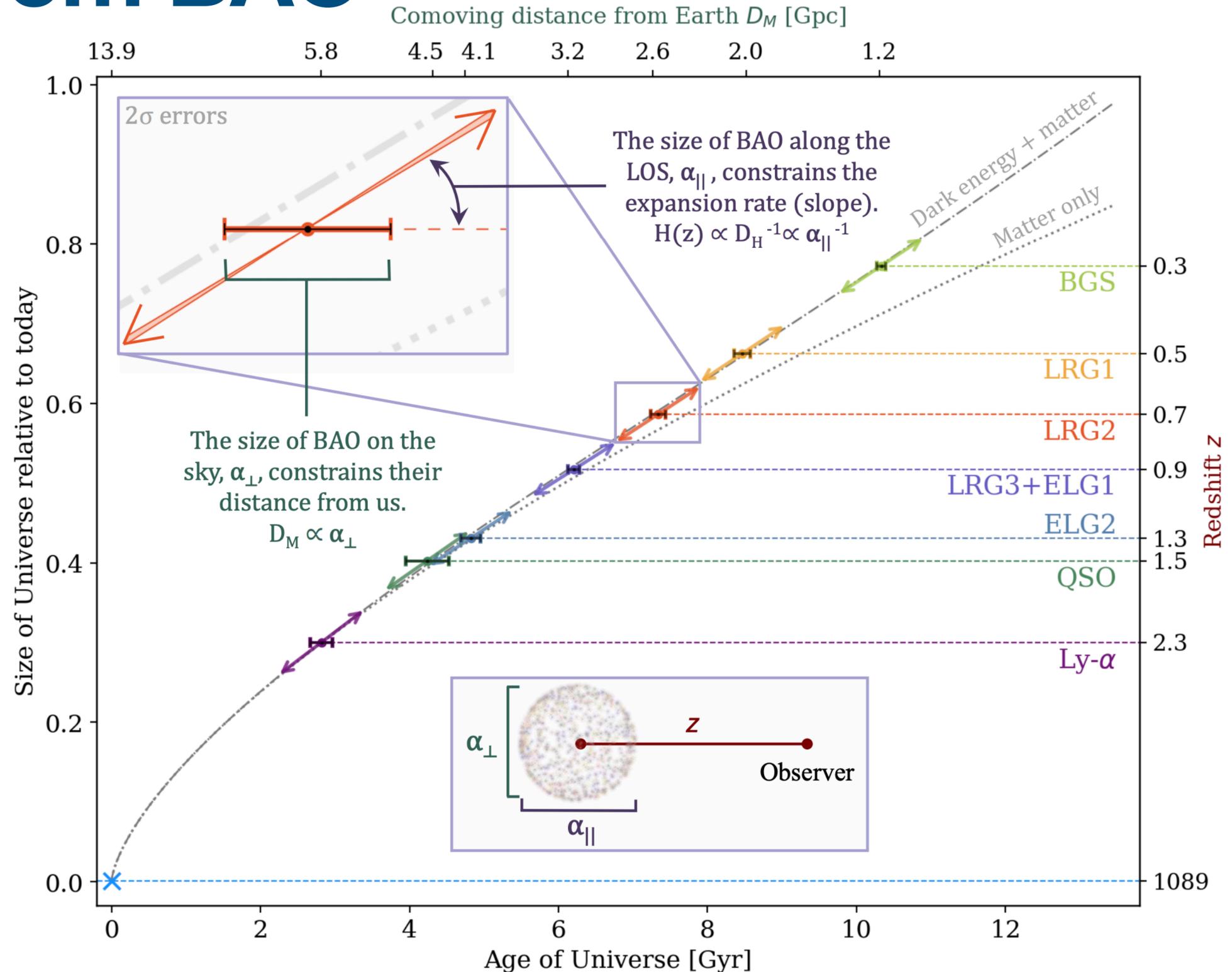
$$D_{\mathrm{H}}(z) = \frac{c}{H(z)} = \frac{r_{\mathrm{d}}}{\Delta z} \qquad r_{\mathrm{d}} = \int_{z_{\mathrm{d}}}^\infty \frac{c_{\mathrm{s}}(z)}{H(z)}\mathrm{d}z \approx 147\,\mathrm{Mpc}$$

$$D_{\mathrm{V}}(z) = \left(zD_{\mathrm{M}}(z)^2 D_{\mathrm{H}}(z)\right)^{1/3}$$

$$F_{\mathrm{AP}} = \frac{D_{\mathrm{M}}}{D_{\mathrm{H}}}$$

[Adame et al., DESI 2024 VI, 2404.03002]
[Karim et al., DESI DR2 Results II, 2503.14738]

Evidence of Dynamical Dark Energy

DESI+CMB+SNe showed an **evidence of dynamical dark energy** at ~3σ.

[Adame et al., DESI 2024 VI, 2404.03002] [Adame et al., DESI 2024 VII, 2411.12022] [Karim et al., DESI DR2 Results II, 2503.14738]

Eq.-of-state parameter: $w \equiv P/\rho$

ansatz: $w_0 w_a \mathrm{CDM}$ model (CPL parametrization)

[Chevallier, Polarski, gr-qc/0009008]
[Linder, astro-ph/0208512]

$$w(a) = w_0 + w_a(1 - a)$$

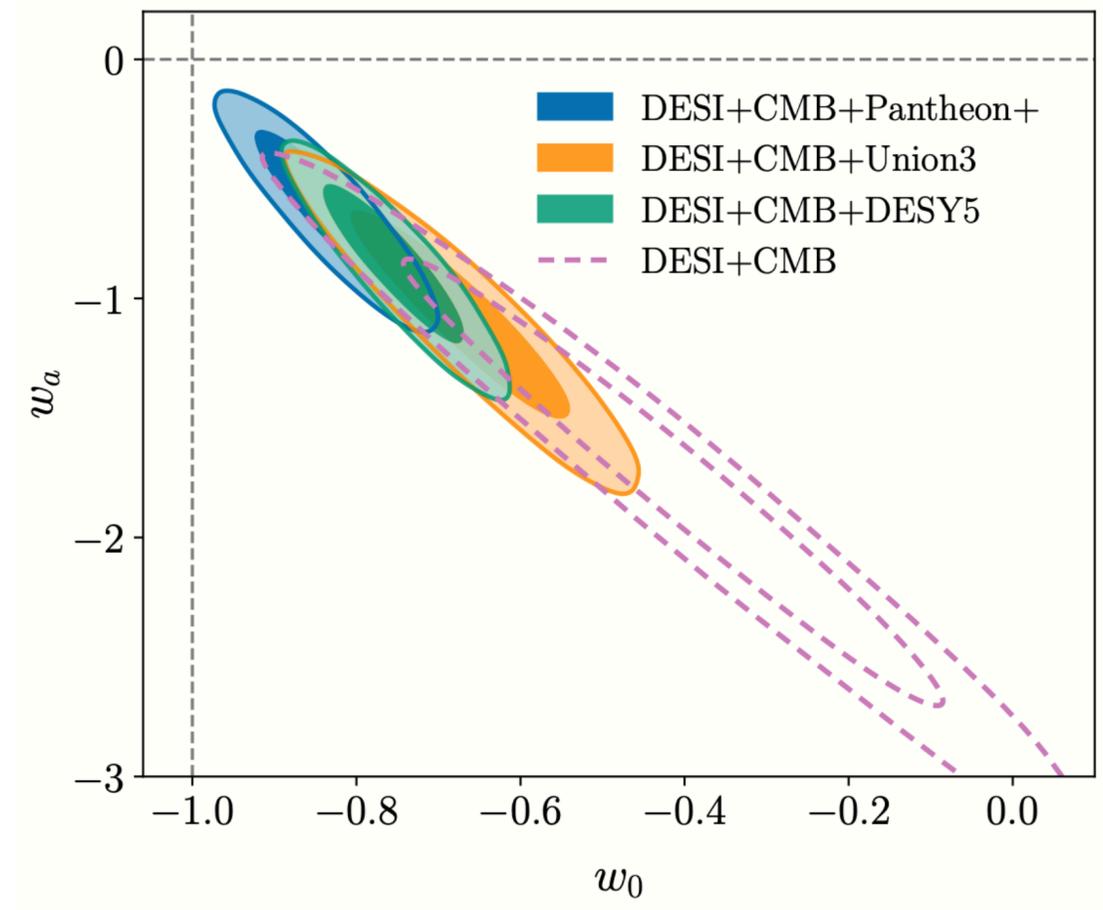without   SNe: 3.1σ with   Union3: 3.8σ

with Pantheon+: 2.8σ with   DES-Y5: 4.2σ

See [Popovic et al., 2511.07517]
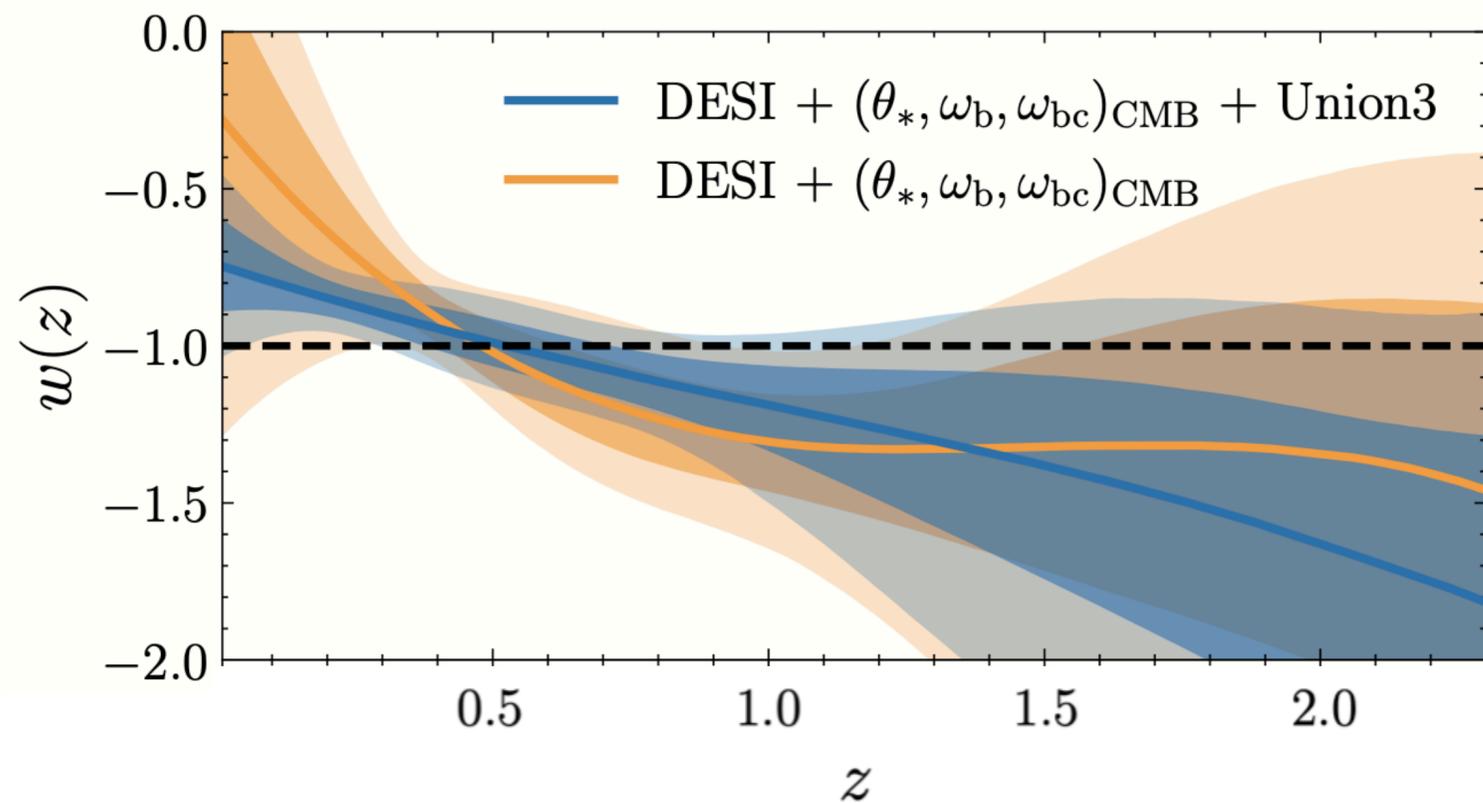for a reanalysis leading to 3.2σ.

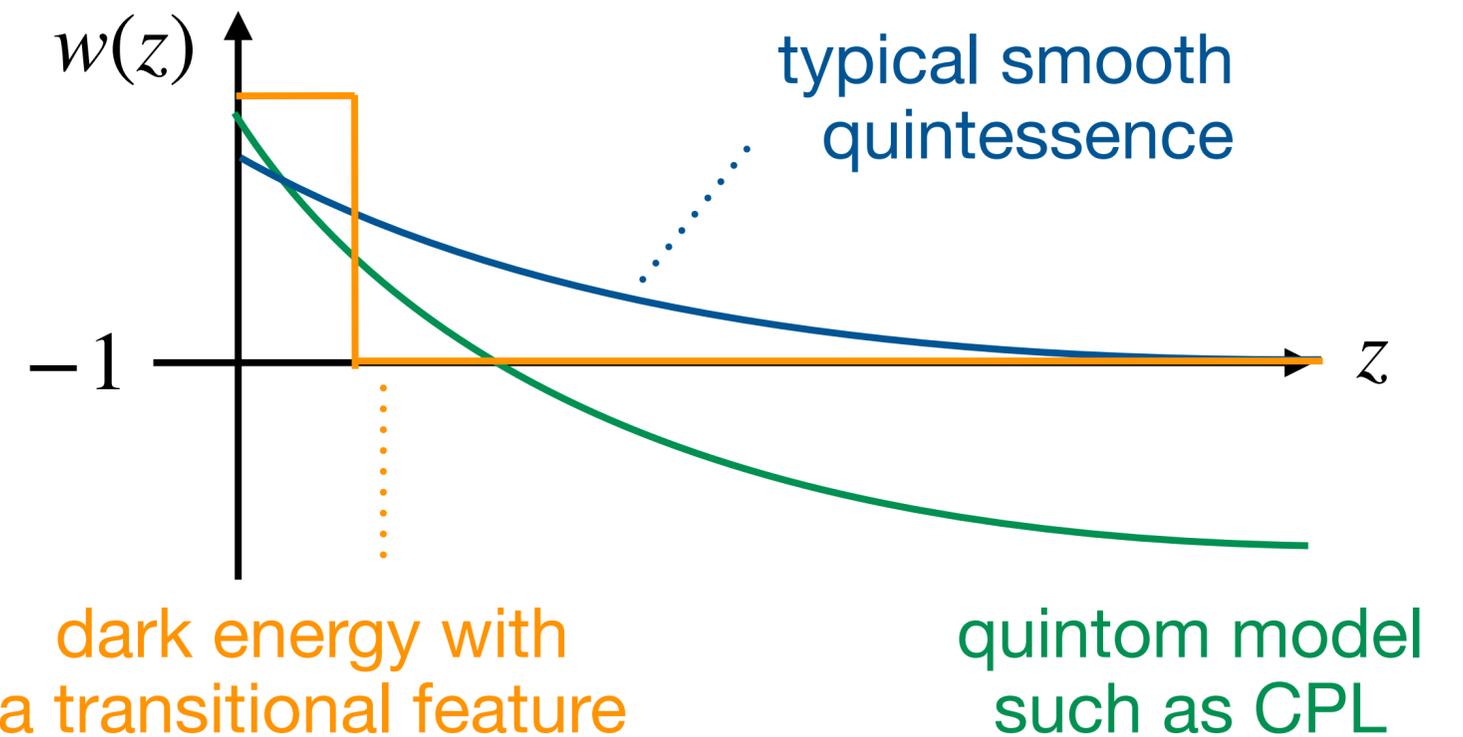What is the **physical mechanism** of the dynamical dark energy?

Phenomenological Possibilities

Observational constraints

modified version of
[Lodha et al., DESI DR2 dark energy, 2503.14743]

Phenomenological modeling

typical smooth quintessence

dark energy with a transitional feature

quintom model such as CPL

We consider **non-phantom** models in this talk.

Transitional VS Smooth Dark Energy

[Dutta, Scherrer, 0809.4441]
[Chiba, 0902.4037]

TABLE III. 68% CL posterior for each DE model

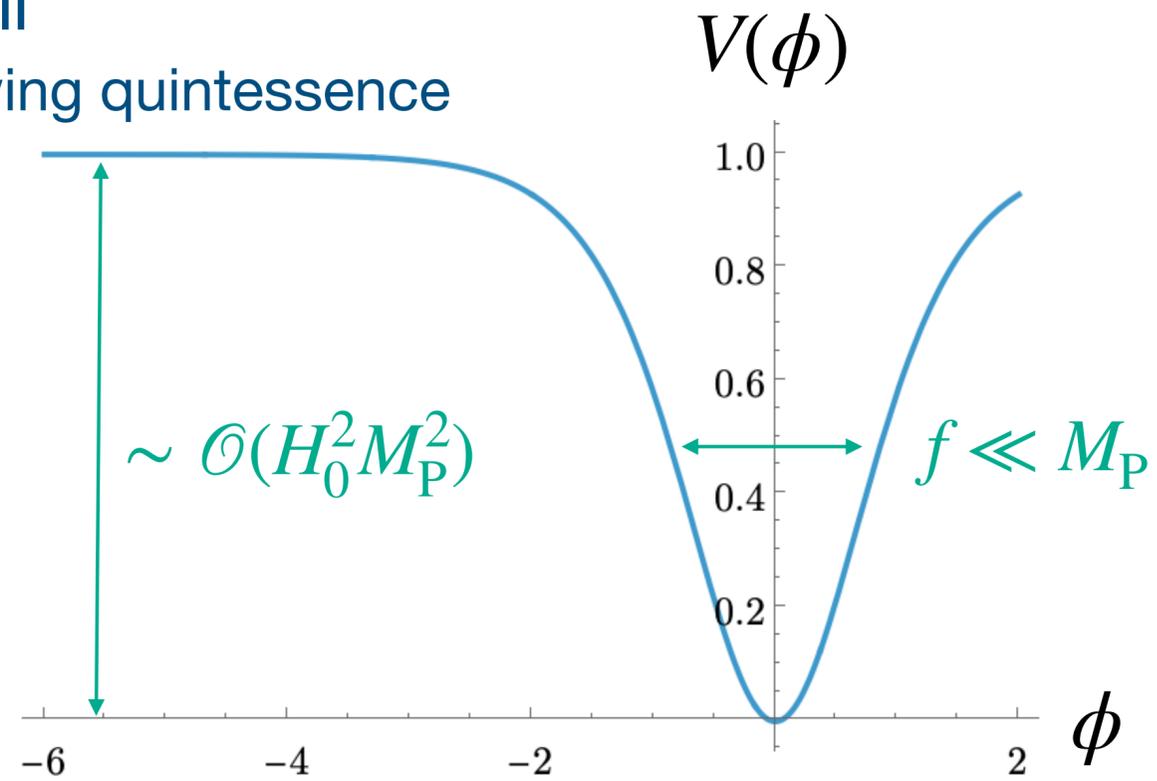| Parameters	TDE			DSCh		
	DESY5	PantheonPlus	Union3	DESY5	PantheonPlus	Union3
w_0	$-0.32^{+0.18}_{-0.61}$	$-0.54^{+0.21}_{-0.51}$	$-0.548^{+0.076}_{-0.40}$	> 0.00415	$-0.18^{+0.32}_{-0.71}$	$0.12^{+0.82}_{-0.34}$
a_{t} or K	$0.913^{+0.062}_{-0.0054}$	> 0.853	$0.861^{+0.10}_{-0.032}$	$14.8^{+5.5}_{-4.5}$	> 15.5	$12.0^{+3.1}_{-6.1}$
$\Omega_{\mathrm{b}}h^2$	0.02255 ± 0.00013	0.02255 ± 0.00013	0.02256 ± 0.00013	0.02255 ± 0.00013	0.02254 ± 0.00013	0.02255 ± 0.00013
$\Omega_{\mathrm{c}}h^2$	0.11760 ± 0.00066	0.11766 ± 0.00068	0.11752 ± 0.00068	0.11764 ± 0.00065	0.11767 ± 0.00064	0.11758 ± 0.00067
$100\theta_{\mathrm{MC}}$	1.04122 ± 0.00028	1.04121 ± 0.00028	1.04123 ± 0.00028	1.04121 ± 0.00028	1.04122 ± 0.00028	1.04122 ± 0.00028
$\log(10^{10}A_{\mathrm{s}})$	$3.054^{+0.014}_{-0.016}$	$3.054^{+0.014}_{-0.015}$	3.054 ± 0.015	3.054 ± 0.015	3.053 ± 0.015	$3.054^{+0.014}_{-0.016}$
n_{s}	0.9709 ± 0.0033	0.9708 ± 0.0034	0.9711 ± 0.0034	0.9708 ± 0.0034	0.9707 ± 0.0034	0.9710 ± 0.0034
τ	$0.0611^{+0.0067}_{-0.0078}$	$0.0611^{+0.0066}_{-0.0078}$	$0.0615^{+0.0070}_{-0.0079}$	0.0611 ± 0.0074	$0.0610^{+0.0068}_{-0.0078}$	$0.0614^{+0.0067}_{-0.0079}$
$H_0/(\mathrm{km/s/Mpc})$	$65.97^{+0.88}_{-0.71}$	67.36 ± 0.74	65.8 ± 1.2	$65.89^{+0.59}_{-0.73}$	67.06 ± 0.66	$65.5^{+1.1}_{-1.3}$
$\Delta\chi^2$	-14.8	-3.66	-8.68	-15.4	-4.59	-7.26

Their fitting qualities are comparable to each other.

Our Basic Idea

Our Basic Idea
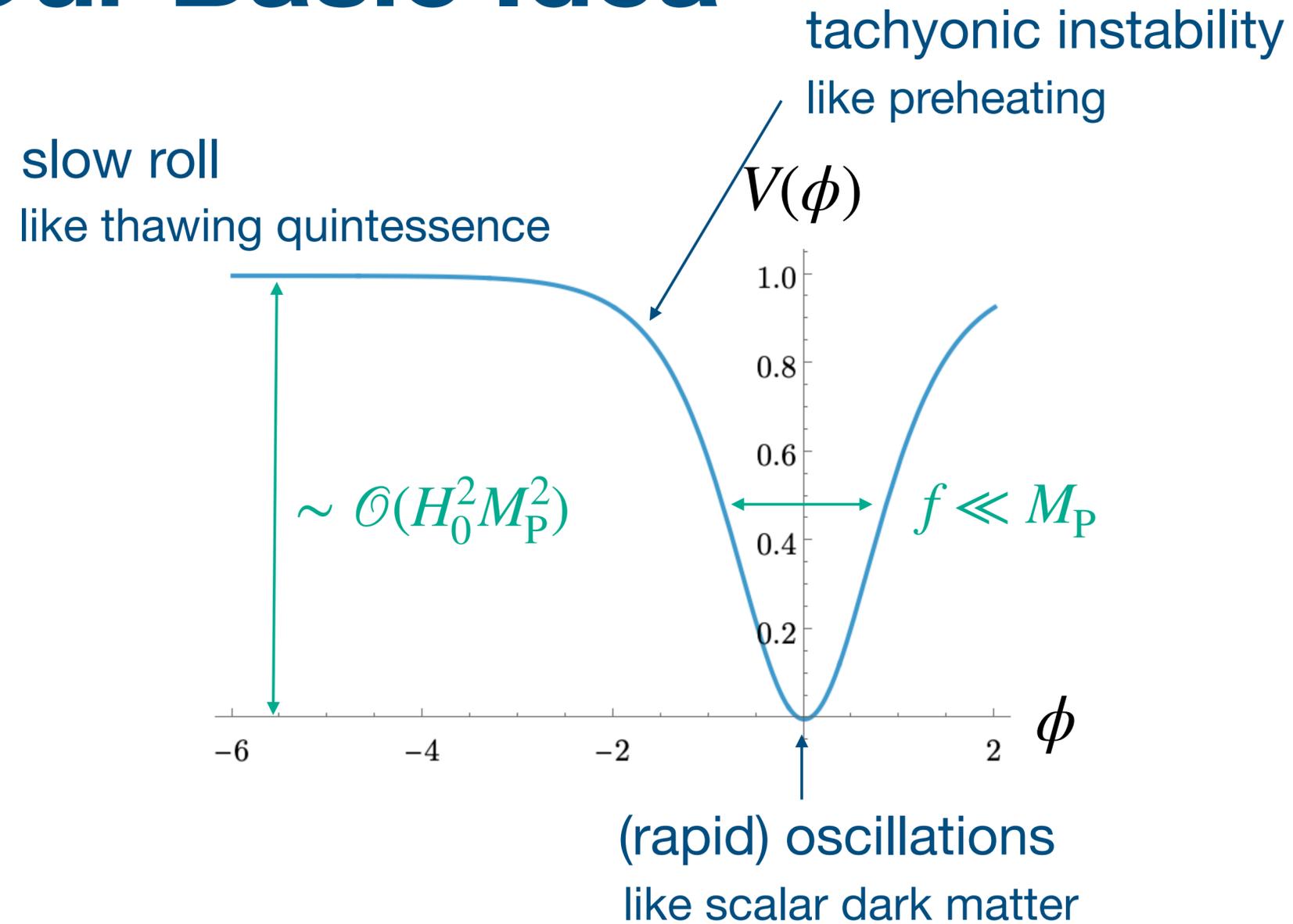
slow roll

like thawing quintessence

$V(\phi)$

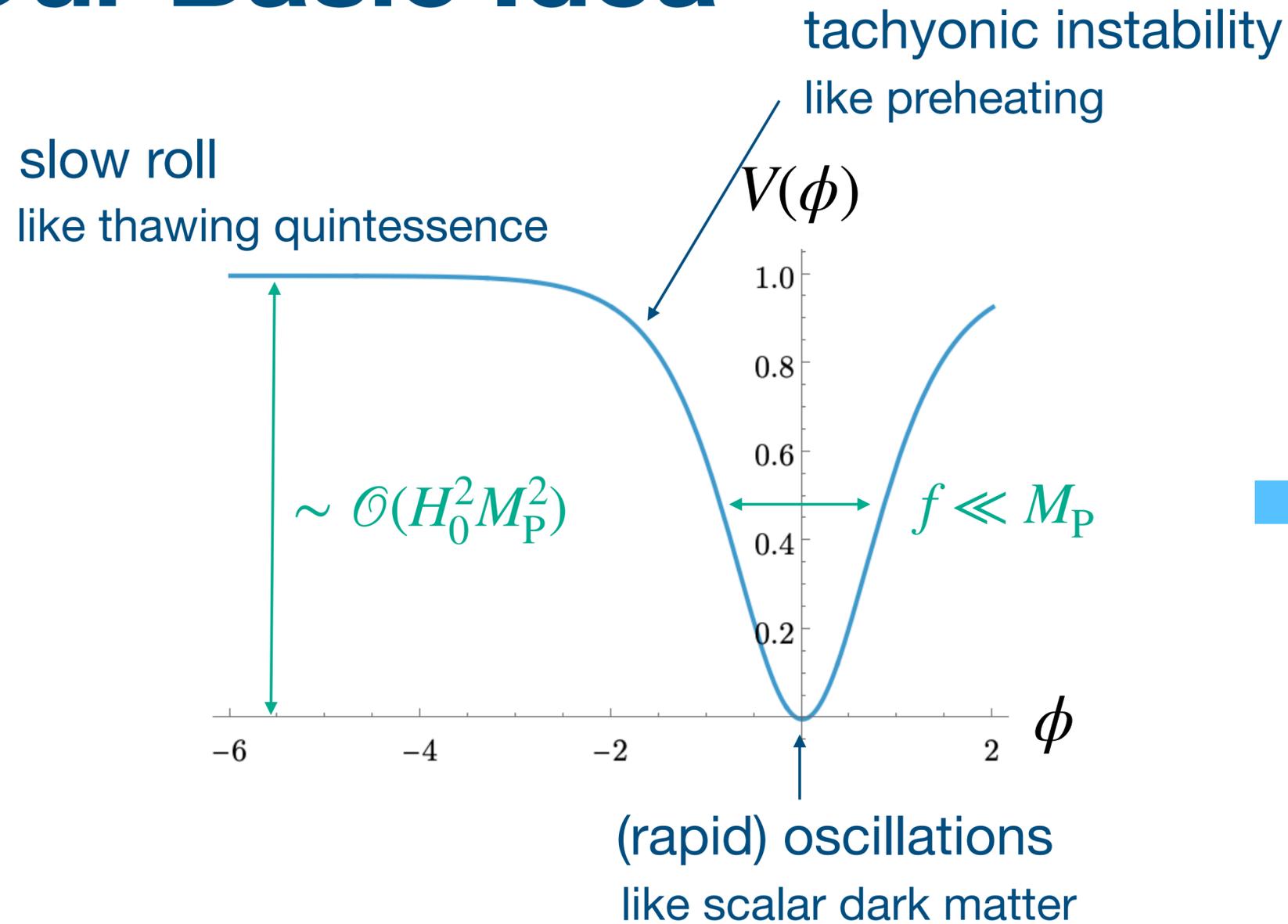$\sim \mathcal{O}(H_0^2 M_{\mathrm{P}}^2)$

$f \ll M_{\mathrm{P}}$

ϕ

Our Basic Idea

tachyonic instability
like preheating

slow roll
like thawing quintessence

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$\sim \mathcal{O}(H_0^2 M_\mathrm{P}^2)$

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(rapid) oscillations
like scalar dark matter

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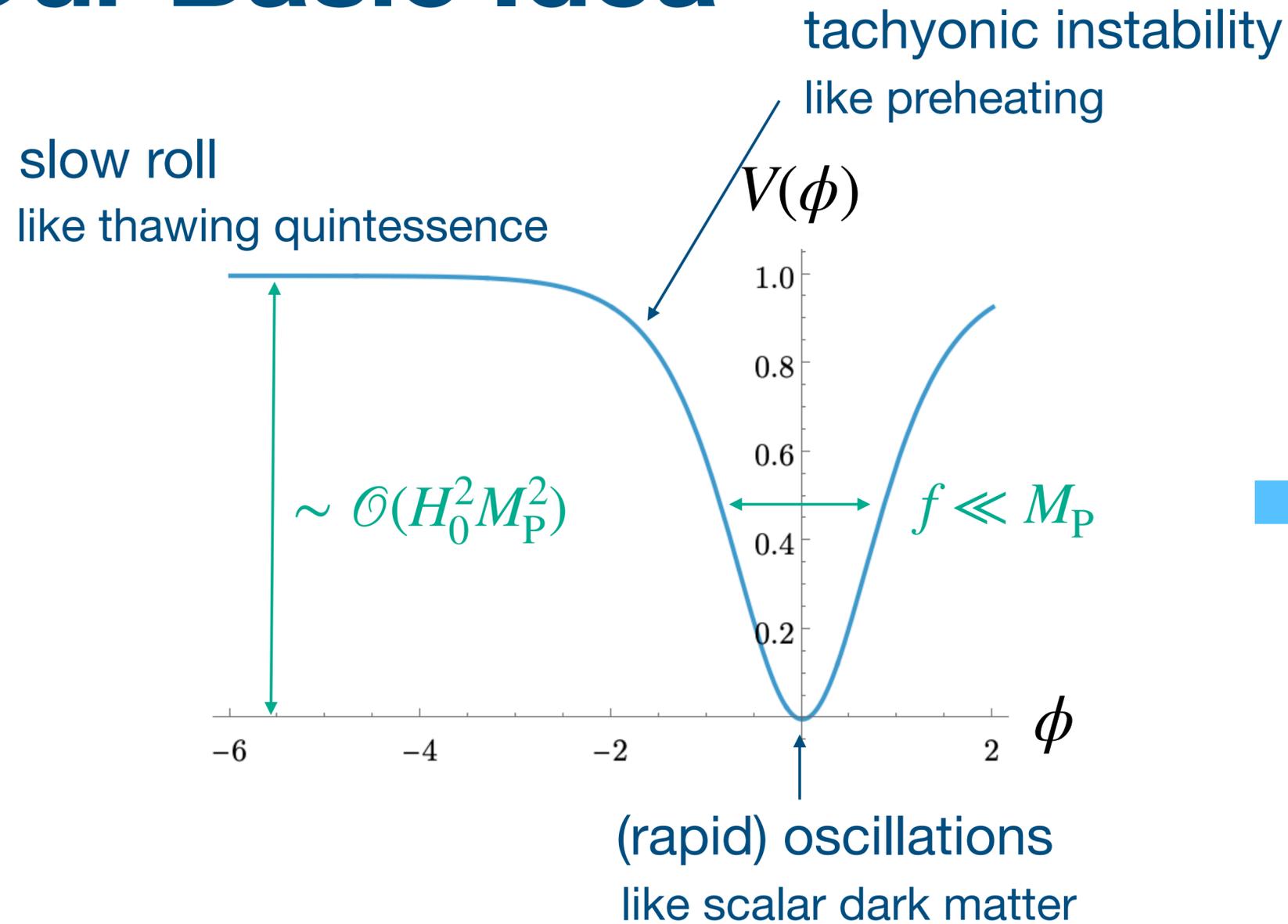
Multiple Implications

- Transmutation of dark energy into dark matter
- Curvature perturbations
- Gravitational waves
- and perhaps more

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Multiple Implications

- Transmutation of dark energy into dark matter
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- and perhaps more

As a concrete example, we consider the following potential, $V(\phi) = V_0 \tanh^2(\phi/f)$, which appears in **approximately scale-invariant models**.
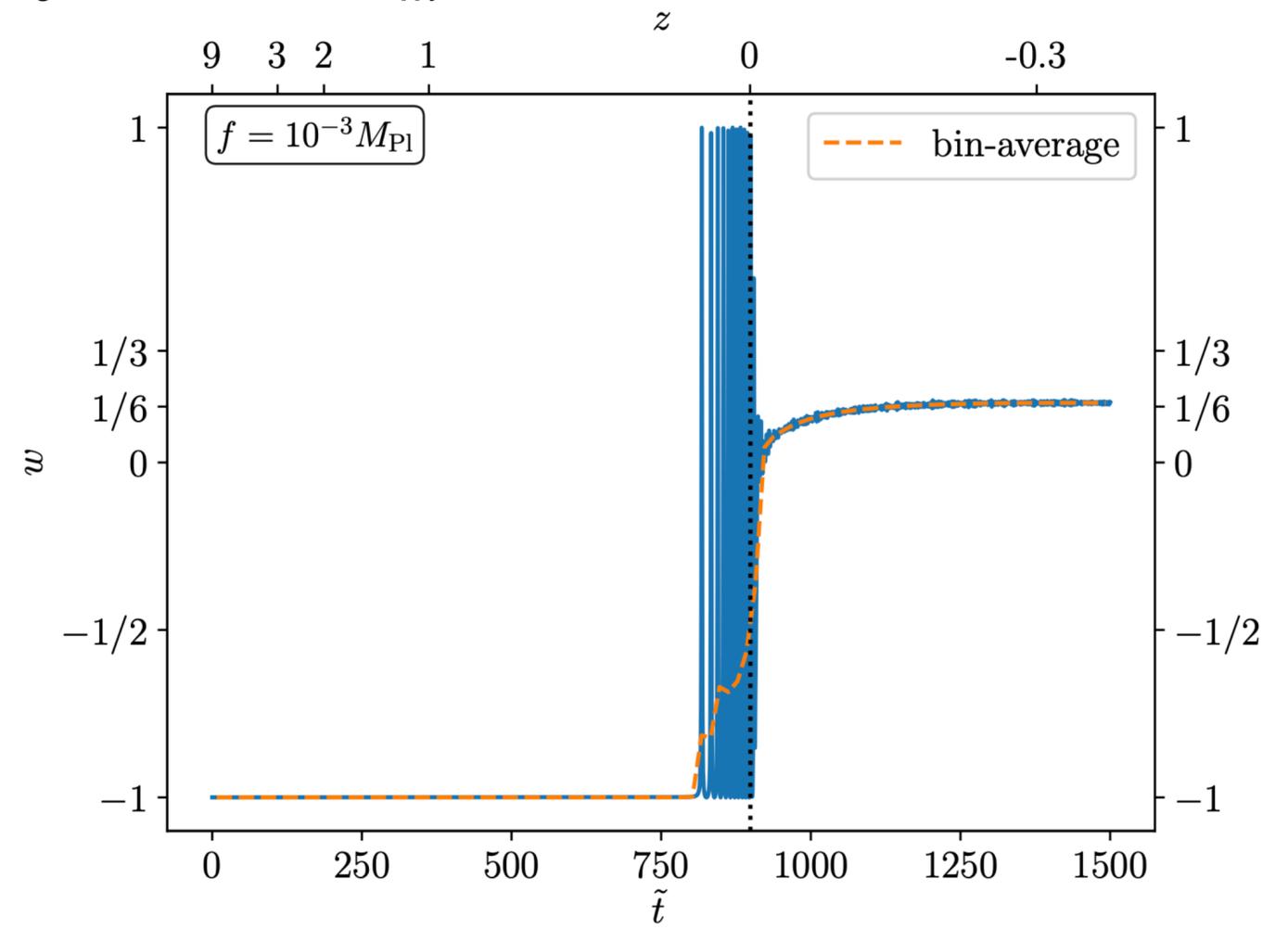
Approximate Realization of the Step Model

We use a classical lattice simulation program $\mathscr{C}osmo\mathscr{L}attice$ to compute the nonlinear dynamics.

[Figueroa, Florio, Torrenti, Valkenburg, 2006.15122; 2102.01031]

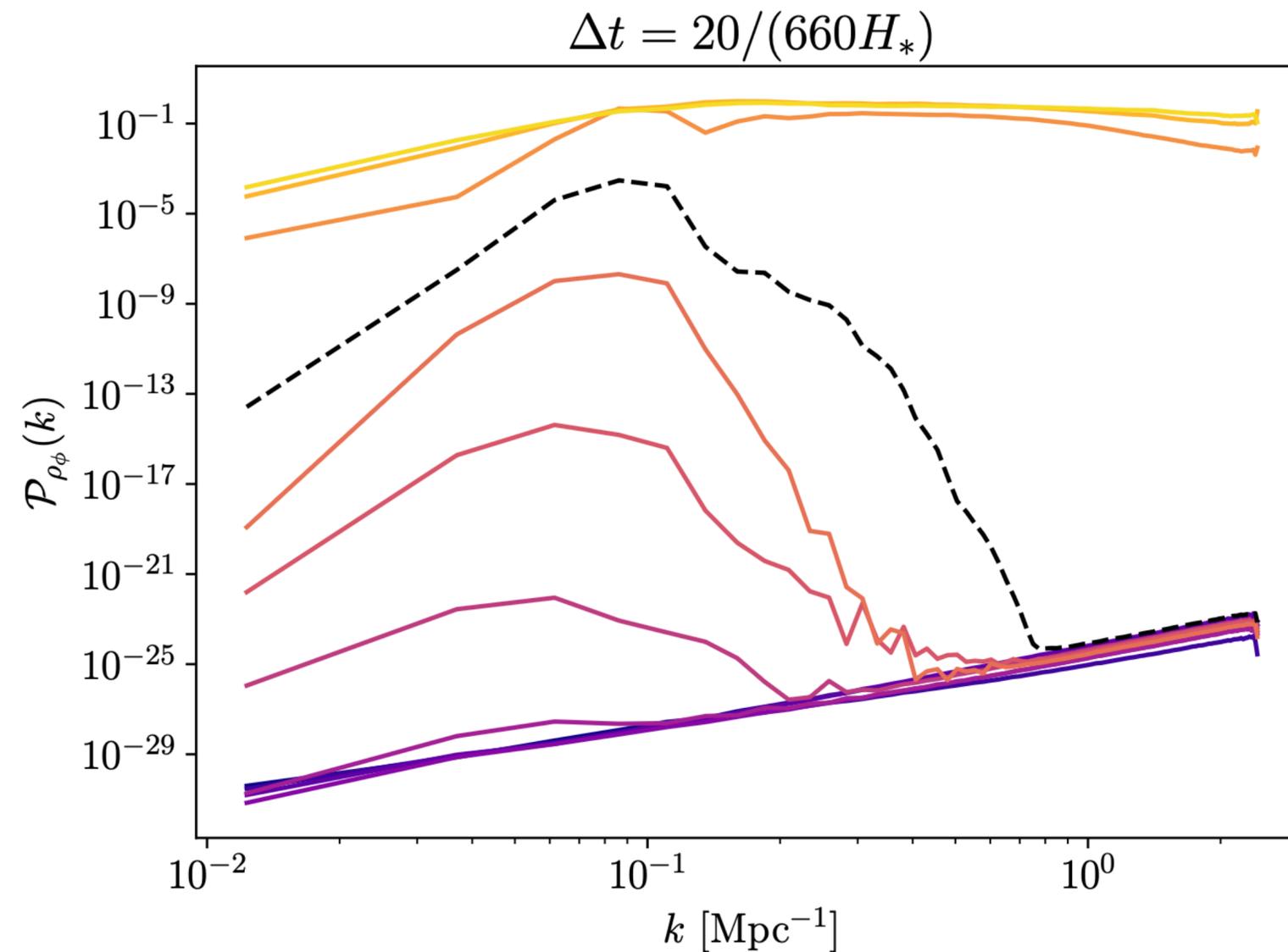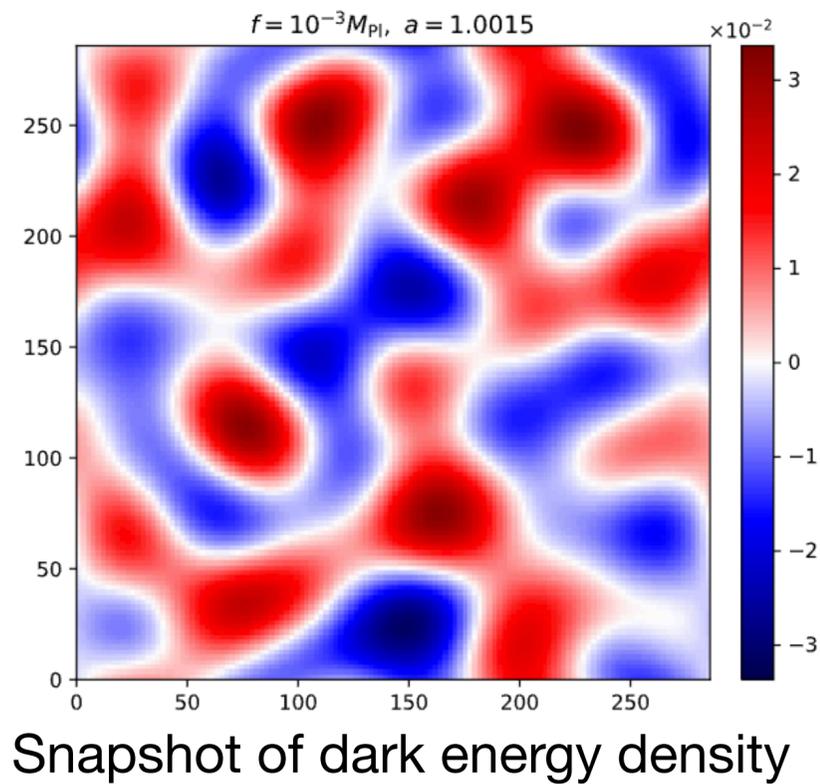$$f = 10^{-3}M_{\mathrm{P}},\ N = 256,\ h_0 = 0.66,\ \Omega_m = 0.32$$
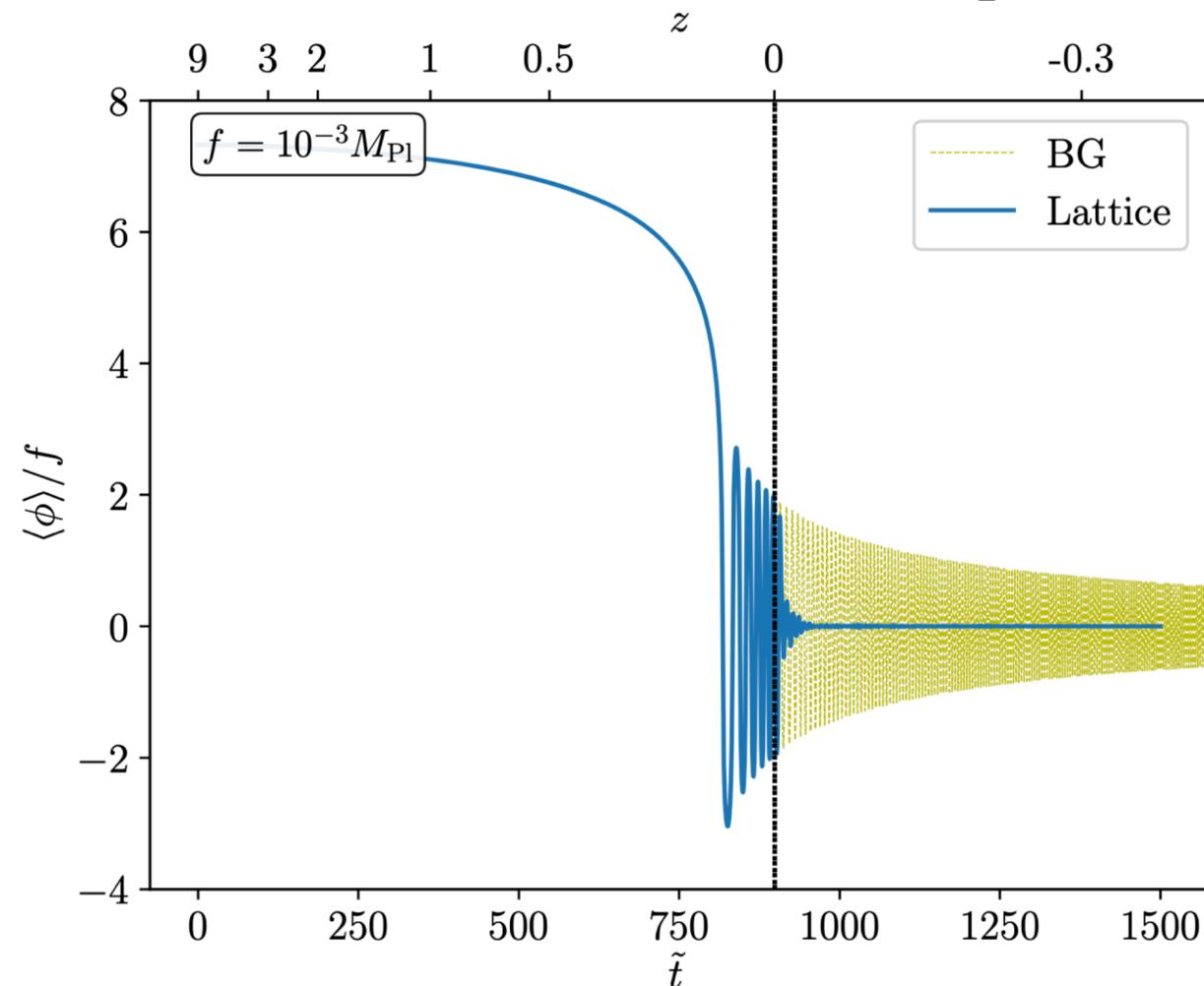
Time evolution of the spatial average of the dark energy field

Time evolution of the (time-averaged) equation-of-state (EoS) parameter

Dark Energy Density Perturbations

Snapshot of dark energy density

$$\Delta t = 20/(660 H_*)$$

$$f = 10^{-3} M_{\rm P}$$

peak wavenumber:

$$k_{\rm peak}/a \approx 3.54/T$$

half period:

$$T \approx \frac{\pi f}{\sqrt{2(V_0 - \rho)}}$$

[Tomberg, Veermäe, 2108.10767]

Growth of the power spectrum of the dark energy density

Dark Energy Perturbations Gravitationally Affect CMB

$$f = 10^{-3.25}M_{\mathrm{P}}$$

Multipole moment of the transfer function of the temperature perturbations due to the **ISW effect**
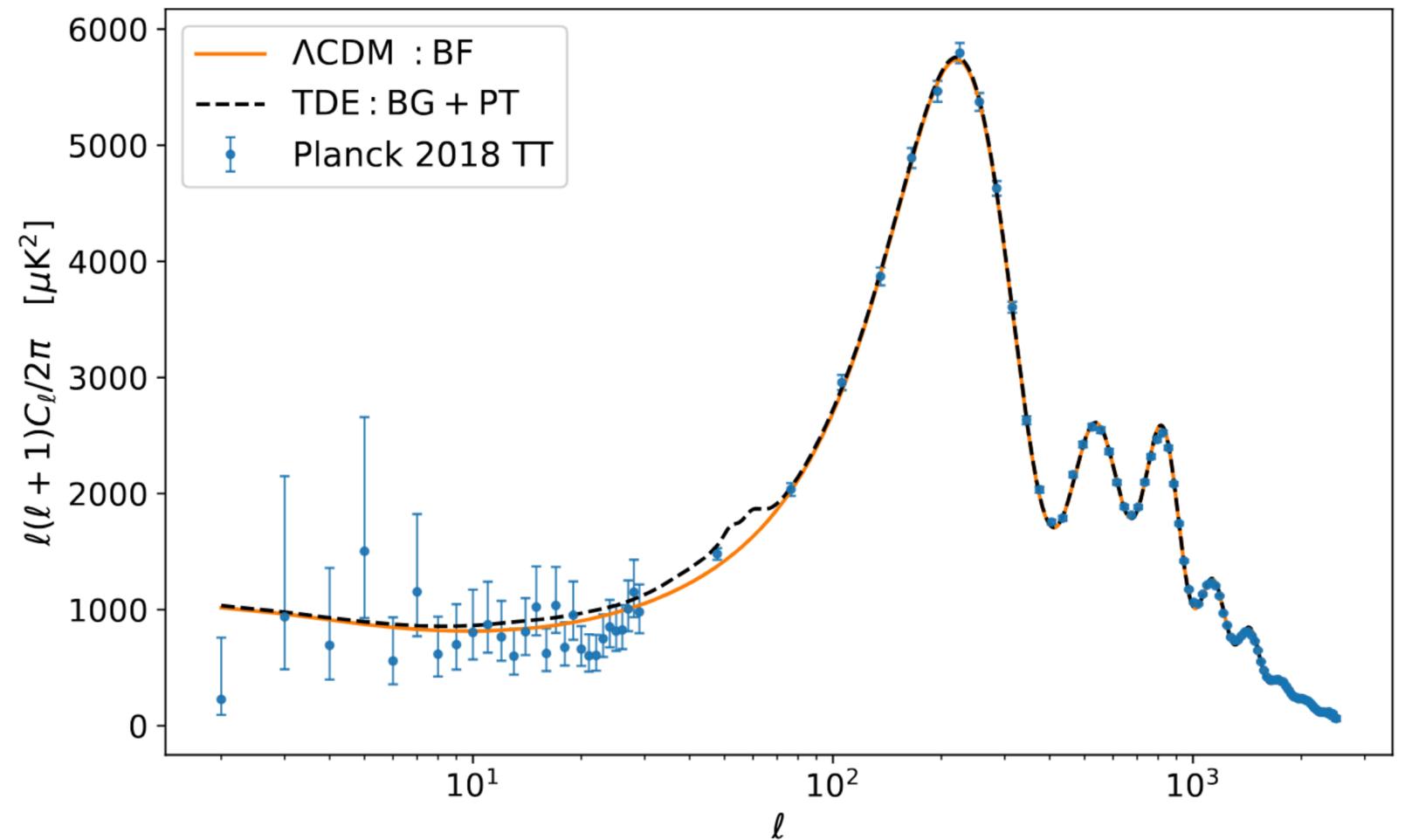
[Seljak, Zaldarriaga, astro-ph/9603033]

$$\Delta_{T,\ell}^{(\mathrm{S})}(k, \tau = \tau_0) \simeq \int_0^{\tau_0} \mathrm{d}\tau \, (\dot{\Phi} + \dot{\Psi}) j_\ell(k(\tau_0 - \tau))$$

Combining it with the primordial power spectrum $P_\psi(k)$,
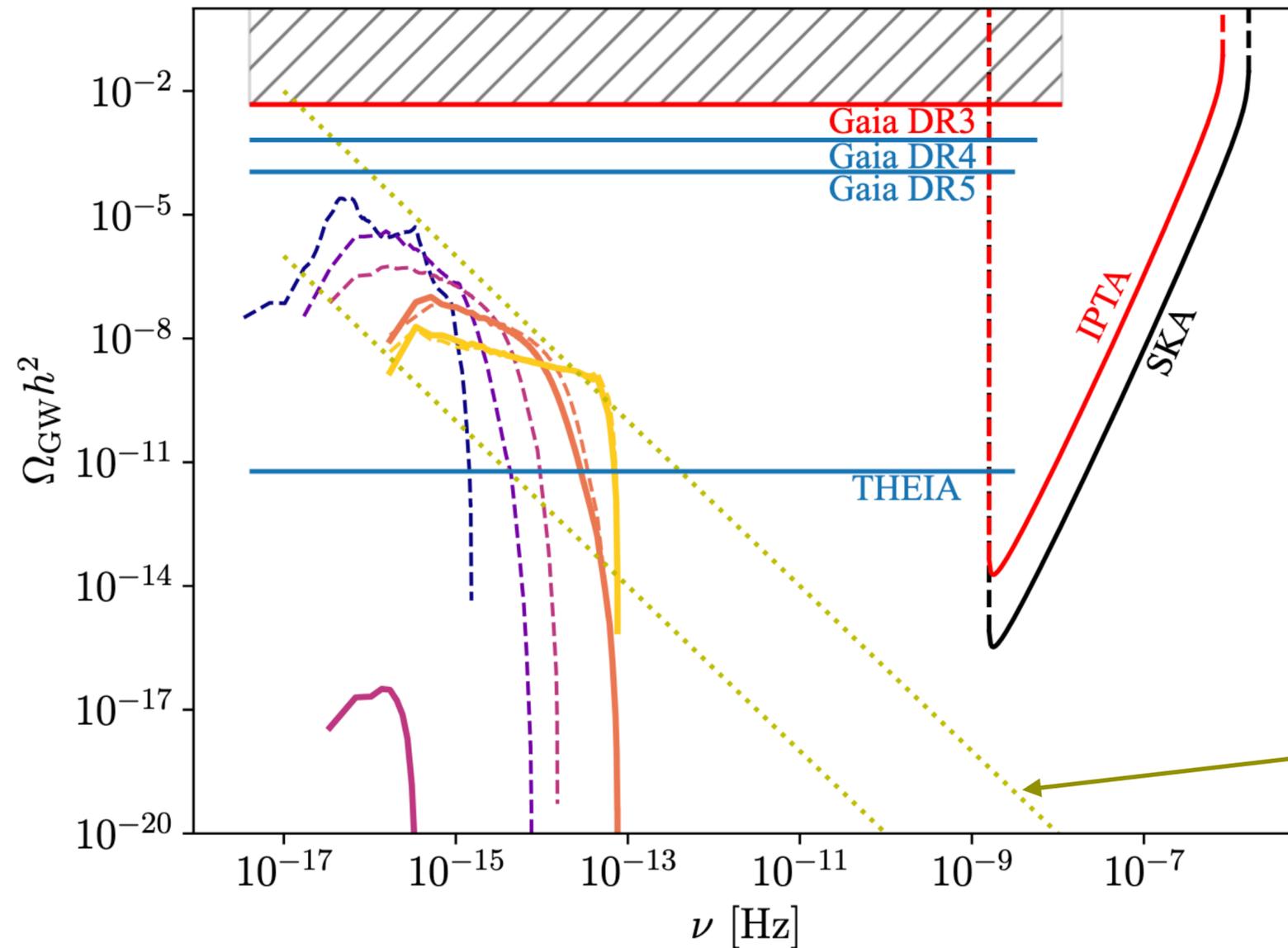
Multipole moment of the temperature perturbations is

$$C_\ell^{(\mathrm{S})} = (4\pi)^2 \int \mathrm{d}k \, k^2 P_\psi(k) \, | \Delta_{T,\ell}^{(\mathrm{S})}(k, \tau = \tau_0) |^2$$

Power spectrum of temperature perturbations

Observably large effects!

Dark Energy Particles Induce Gravitational Waves

Dimensional analysis for the peak position

$$h(\nu_{\text{peak}}) \sim \frac{\rho_{\text{DE}}}{\nu_{\text{peak}}^2 M_{\text{P}}^2} \sim \frac{H_0^2}{\nu_{\text{peak}}^2}$$

$$\Omega_{\text{GW}}(\nu_{\text{peak}}) \sim \frac{\nu_{\text{peak}}^2 h(\nu_{\text{peak}})^2}{H_0^2}$$

$$\sim \frac{H_0^2}{\nu_{\text{peak}}^2}$$

Quasar astrometry can constrain the scenario in the future!

Other Observational Implications

- Gravitational effects of DE oscillations. (PTA constraints on ultralight scalar)

- Gravitational effects of DE inhomogeneity. (oscillons)

- GW-induced curl mode in weak gravitational lensing. (CMB & LSS)

- Violation of the consistency relations for correlation functions. (LSS)

- Effects on black holes. (superradiance; modified BBH merger signals)

- Cosmic birefringence and astrophysical constraints in extended models.

- Any implications for cosmological tensions?

Summary

Summary

~3σ evidence of dynamical dark energy has been observed.

Models with *a sharp transitional feature* at $z \sim 0.1$ can also fit the observational data.

Preheating-like dynamics (tachyonic resonance) occur.

- Dark energy field behaves like (an additional component of) dark matter.
- Dark energy perturbations are explosively produced at very late time.
  - They gravitationally affect the CMB.
  - They produce the stochastic GW background.
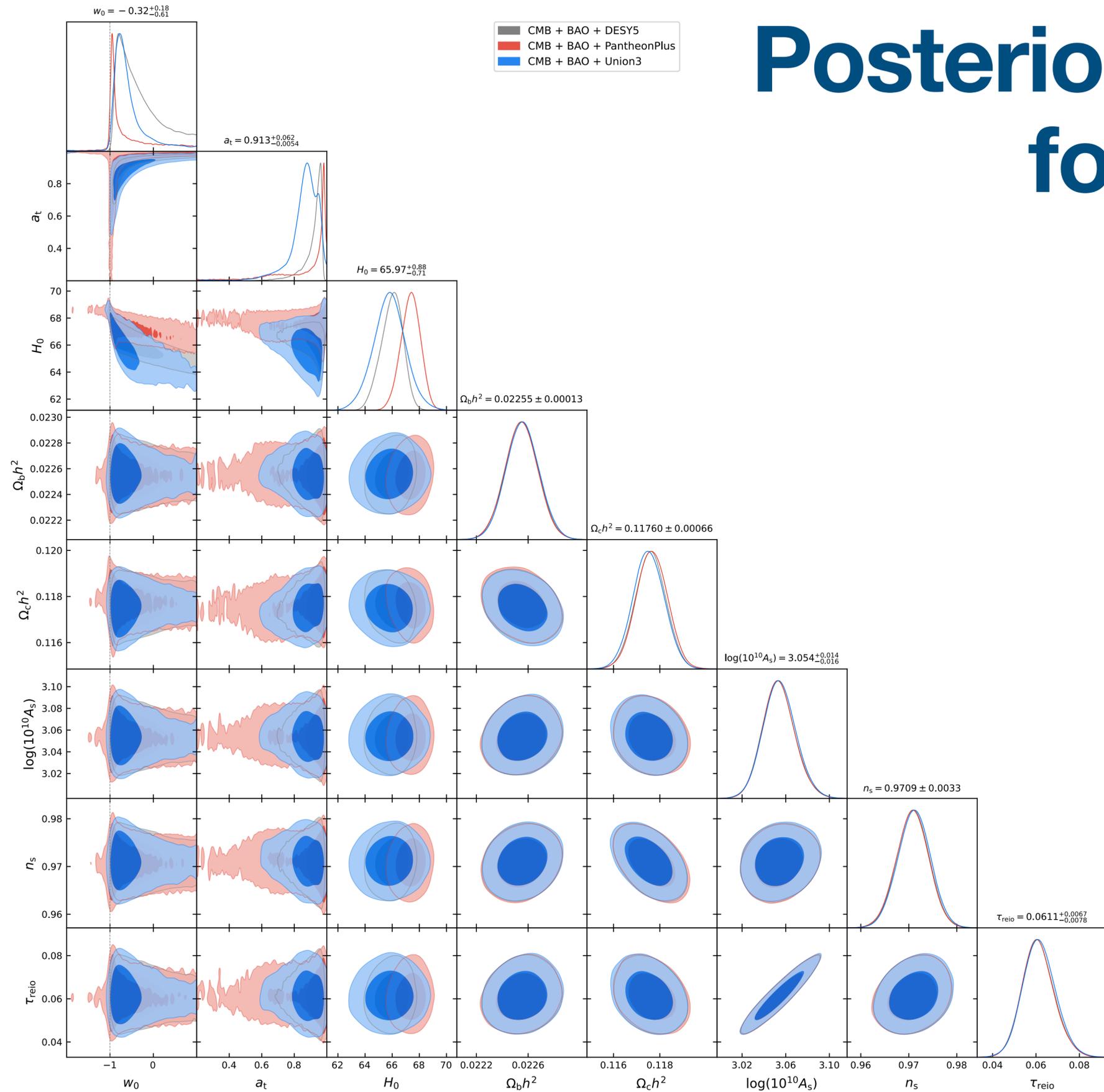- More cosmological signals to be explored.

Conclusion

Significant modification (e.g., O(1) inhomogeneity) of cosmology at very late time challenging the standard lore in an attempt to explain dynamical dark energy.
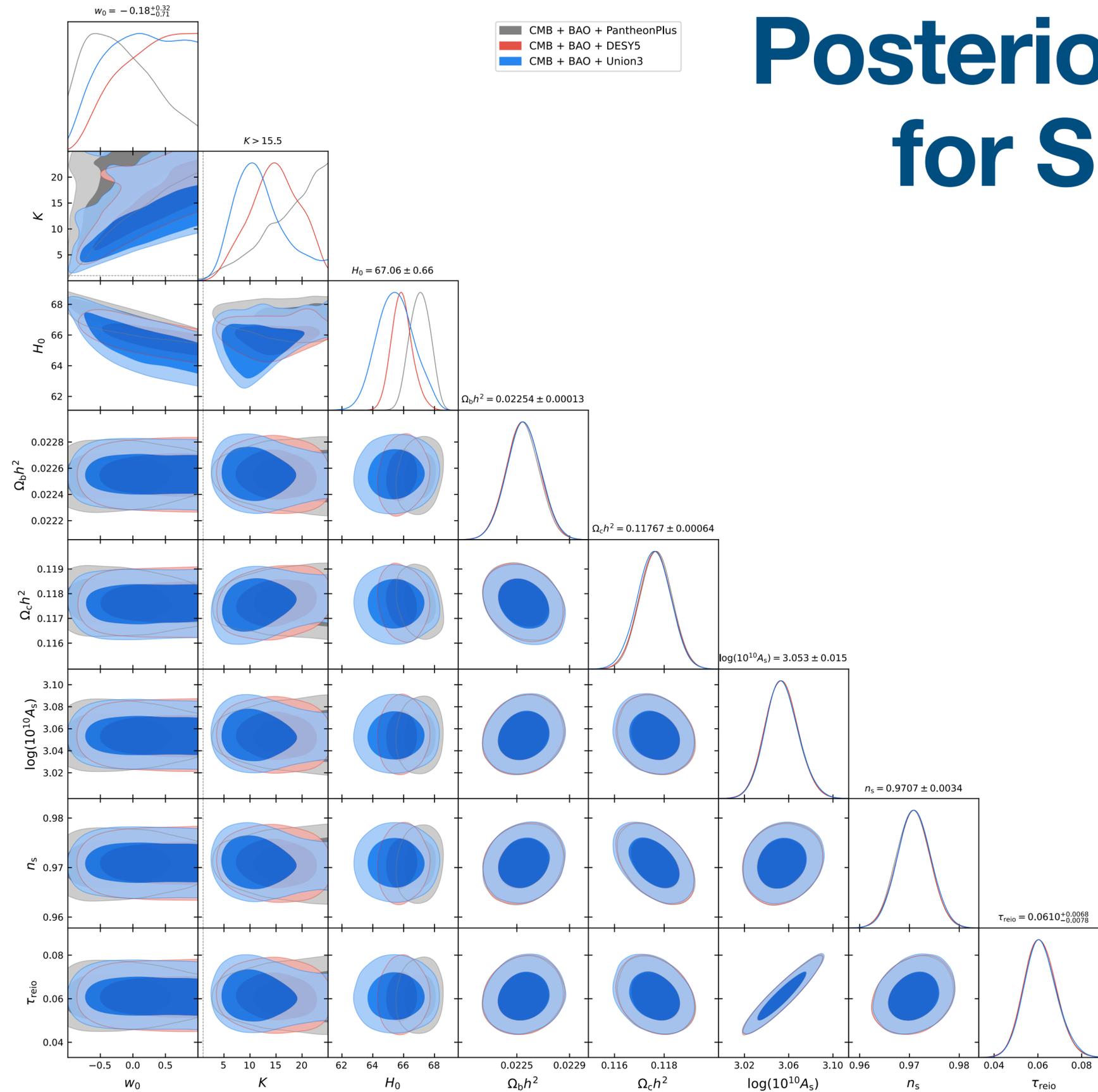
Such a novel possibility has not been throughly studied. Future observations will probe our scenario.

Appendix

Posterior Distribution for Step Model

Legend:
- CMB + BAO + DESY5
- CMB + BAO + PantheonPlus
- CMB + BAO + Union3

$w_0 = -0.32^{+0.18}_{-0.61}$

$a_t = 0.913^{+0.062}_{-0.0054}$

$H_0 = 65.97^{+0.88}_{-0.71}$

$\Omega_b h^2 = 0.02255 \pm 0.00013$

$\Omega_c h^2 = 0.11760 \pm 0.00066$

$\log(10^{10} A_s) = 3.054^{+0.014}_{-0.016}$

$n_s = 0.9709 \pm 0.0033$
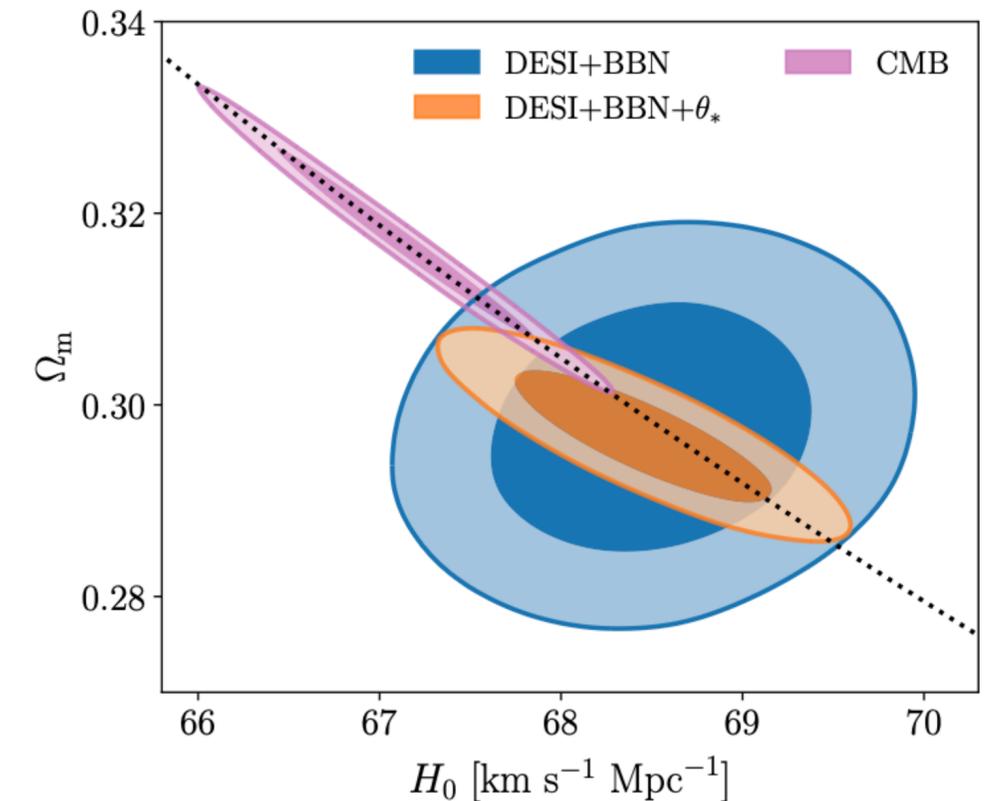
$\tau_{reio} = 0.0611^{+0.0067}_{-0.0078}$

Posterior Distribution for Smooth Model

DESI Results History

- **DR1 BAO:** reported **evidence of dynamical dark energy**   [Adame et al., DESI 2024 VI, 2404.03002]

- **DR1 full-shape:** similar results   [Adame et al., DESI 2024 VII, 2411.12022]

- **DR2 BAO:** similar tendency with smaller uncertainties; **larger tension with CMB.**

  [Karim et al., DESI DR2 Results II, 2503.14738]

  - Still dominated by statistical uncertainties.

  - An outliner at $z \approx 0.5$ in DR1 BAO is now closer to ΛCDM.

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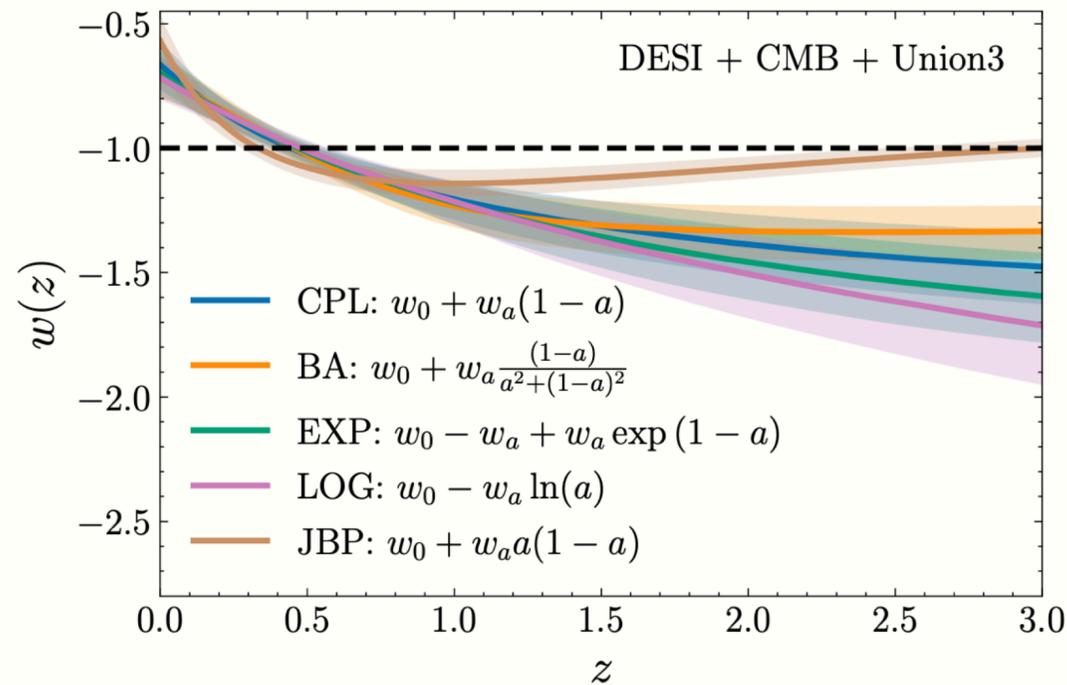 Analyses with $w_0 w_a \mathrm{CDM}$ model $(w(a) = w_0 + w_a(1-a))$

  - **DESI+CMB (w/o SNe) gives 3.1σ.**

  - With SNe,

    2.8σ (Pantheon+), 3.8σ (Union3), 4.2σ (DES-Y5)。

  - DESI+SNe fitting **automatically fits CMB** as well.
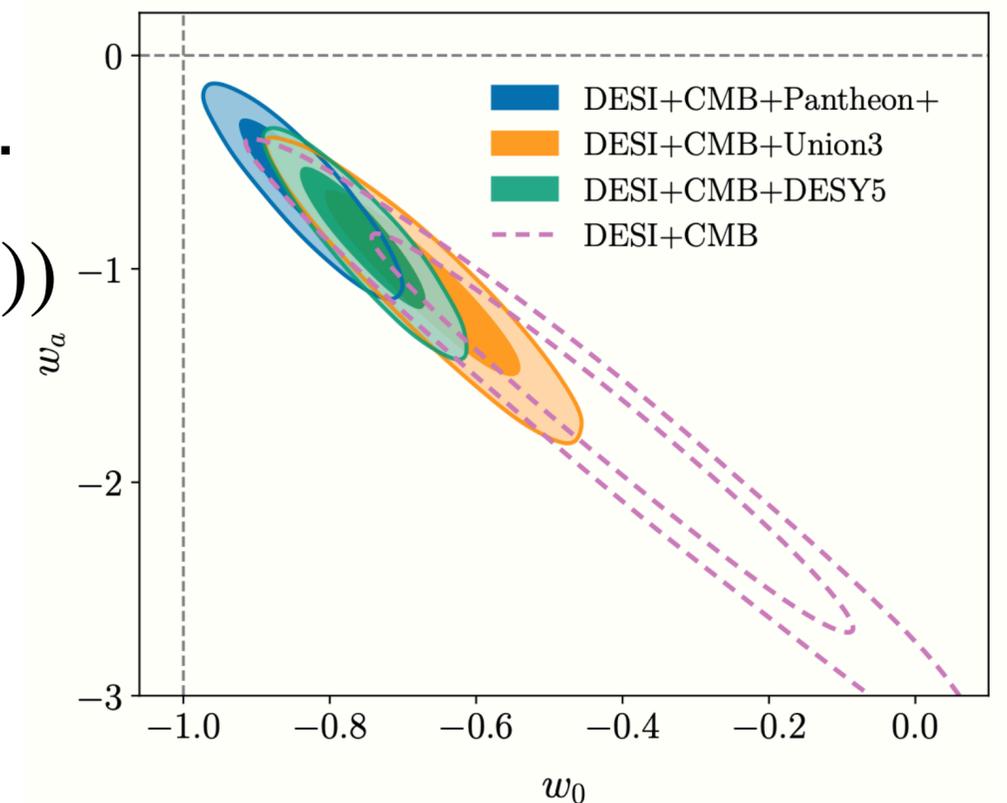
Dynamical Dark Energy
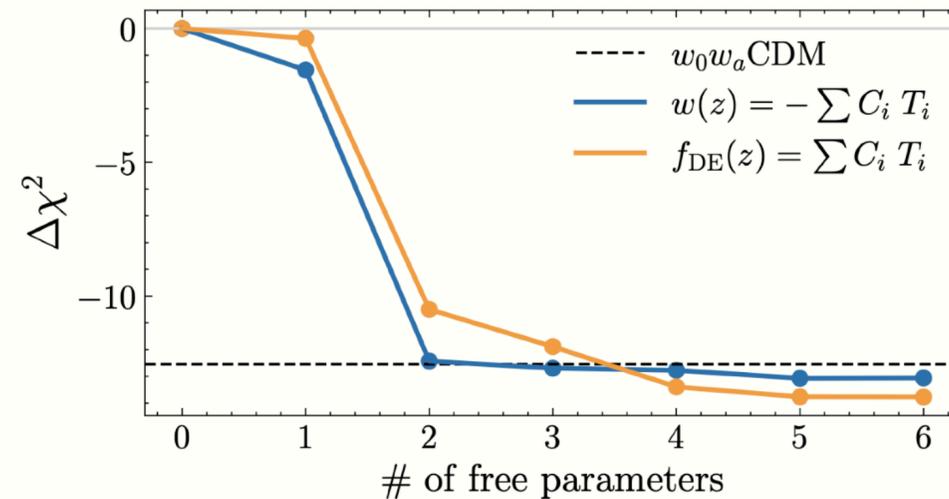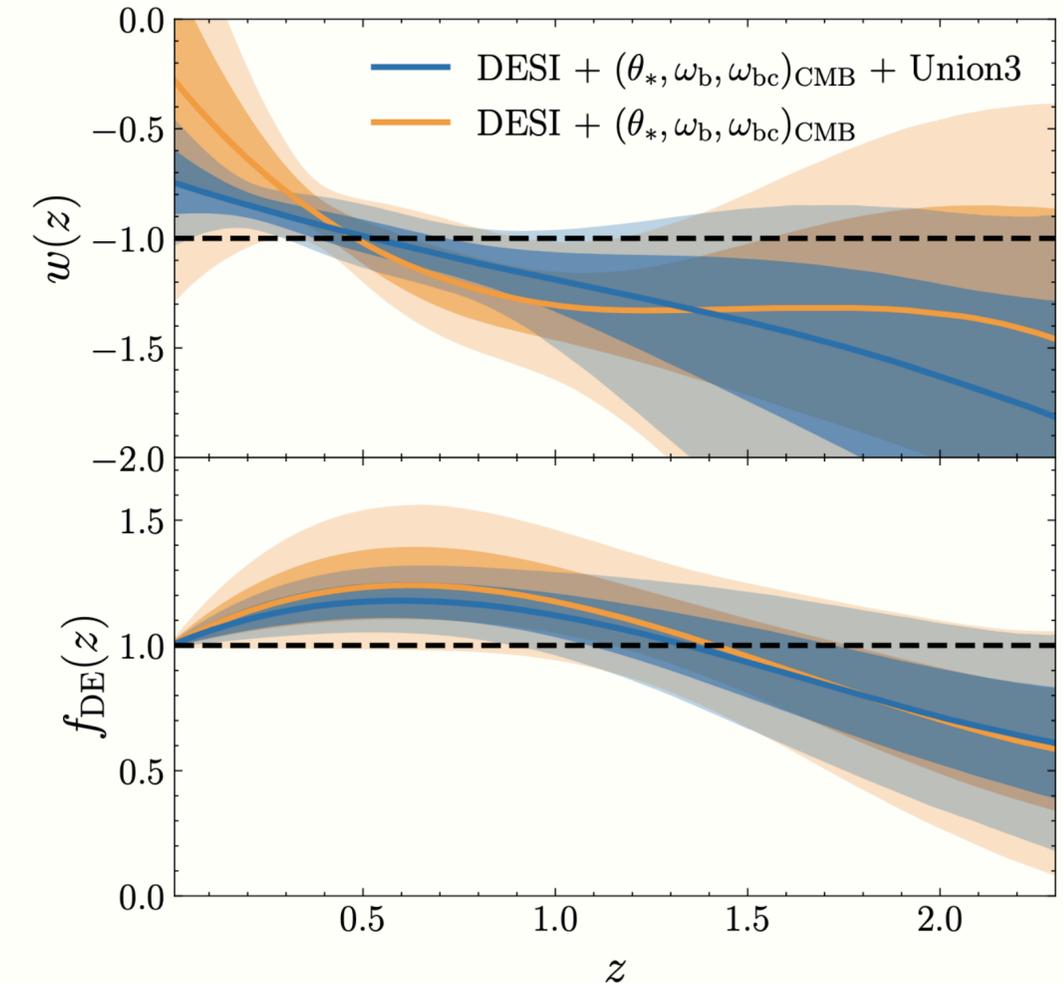
Equation of State $P = w\rho \rightarrow \rho \propto a^{-3(1+w)}$

Not only CPL ($w_0w_a\mathrm{CDM}$) but various 2-parameter models favor the phantom (w < -1) regime. **Large uncertainty at high-z.**

Fits are not significantly improved with more than 2 parameters.

Fit by cubic Chebyshev polynomials. **Large uncertainty at high-z.**

Phantom or Not?

$$w = \frac{\langle \frac{1}{2}\dot{\phi}^2 - \frac{1}{6}(\nabla\phi)^2 - V \rangle}{\langle \frac{1}{2}\dot{\phi}^2 + \frac{1}{2}(\nabla\phi)^2 + V \rangle} \geq -1$$

The standard scalar field (classically) satisfies the **Null Energy Condition (NEC)**.

A natural explanation is given by the **thawing quintessence**.

Smooth time evolution from smooth scalar potential ▶

DESI+CMB:	+PantheonPlus	+Union3	+DESY5
DE classes		ΔDIC ($\Delta\chi^2$)	
Thaw. (Cal.)	+0.4 (−1.6)	−0.6 (−2.5)	−5.8 (−7.1)
Thaw. (Alg.)	−1.0 (−2.9)	−4.6 (−6.9)	−10.1 (−13.2)
Emergent	+2.1 (−0.05)	+1.8 (−0.1)	+0.2 (−1.5)
Mirage	−9.1 (−10.5)	−13.8 (−16.2)	−18.7 (−20.7)
$w_0 w_a$	−6.8 (−10.7)	−13.5 (−17.4)	−17.2 (−21.0)

better than ΛCDM, but worse than $w_0 w_a$CDM

※ A more negative value is better.
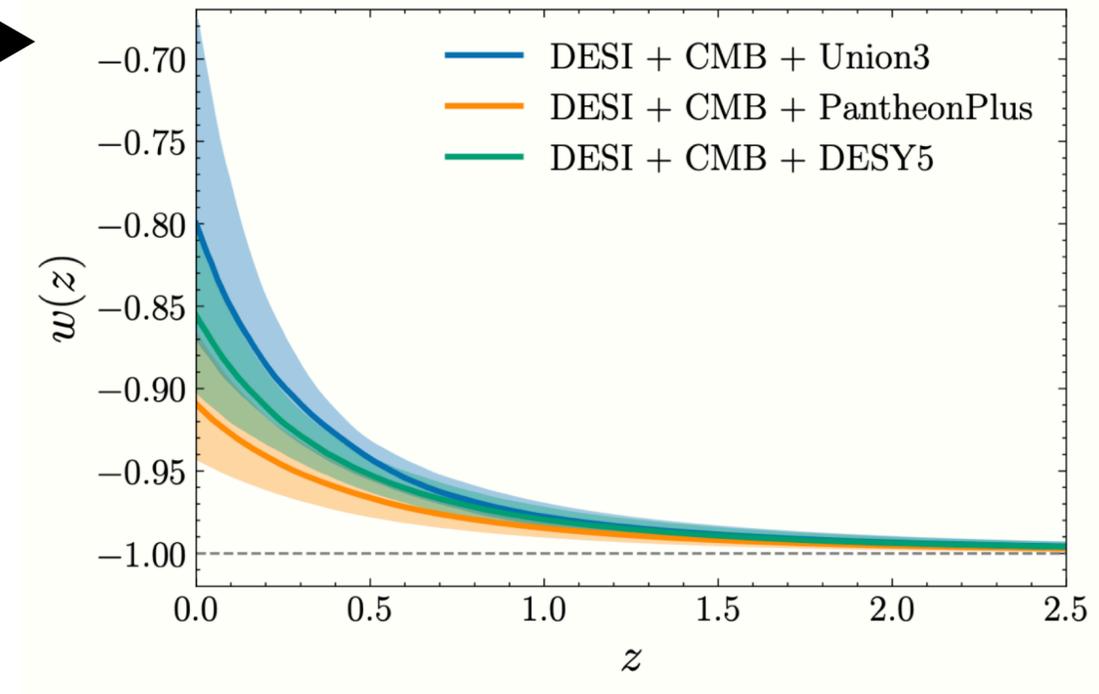
Marginalized constraints in the case of the axion-like potential

$$V = m_a^2 f_a^2 \left[1 + \cos(\varphi/f_a) \right]$$

[Lodha et al., DESI DR2 dark energy, 2503.14743]

Dark Energy with Transitional Feature

step model (our main focus)

$$w(a) = \begin{cases} -1 & (a < a_{\mathrm{t}}) \\ w_0 & (a \geq a_{\mathrm{t}}) \end{cases}$$

broken-linear model

$$w(a) = \begin{cases} -1 & (a < a_{\mathrm{t}}) \\ -1 + (w_0 + 1)\frac{a - a_{\mathrm{t}}}{1 - a_{\mathrm{t}}} & (a \geq a_{\mathrm{t}}) \end{cases}$$

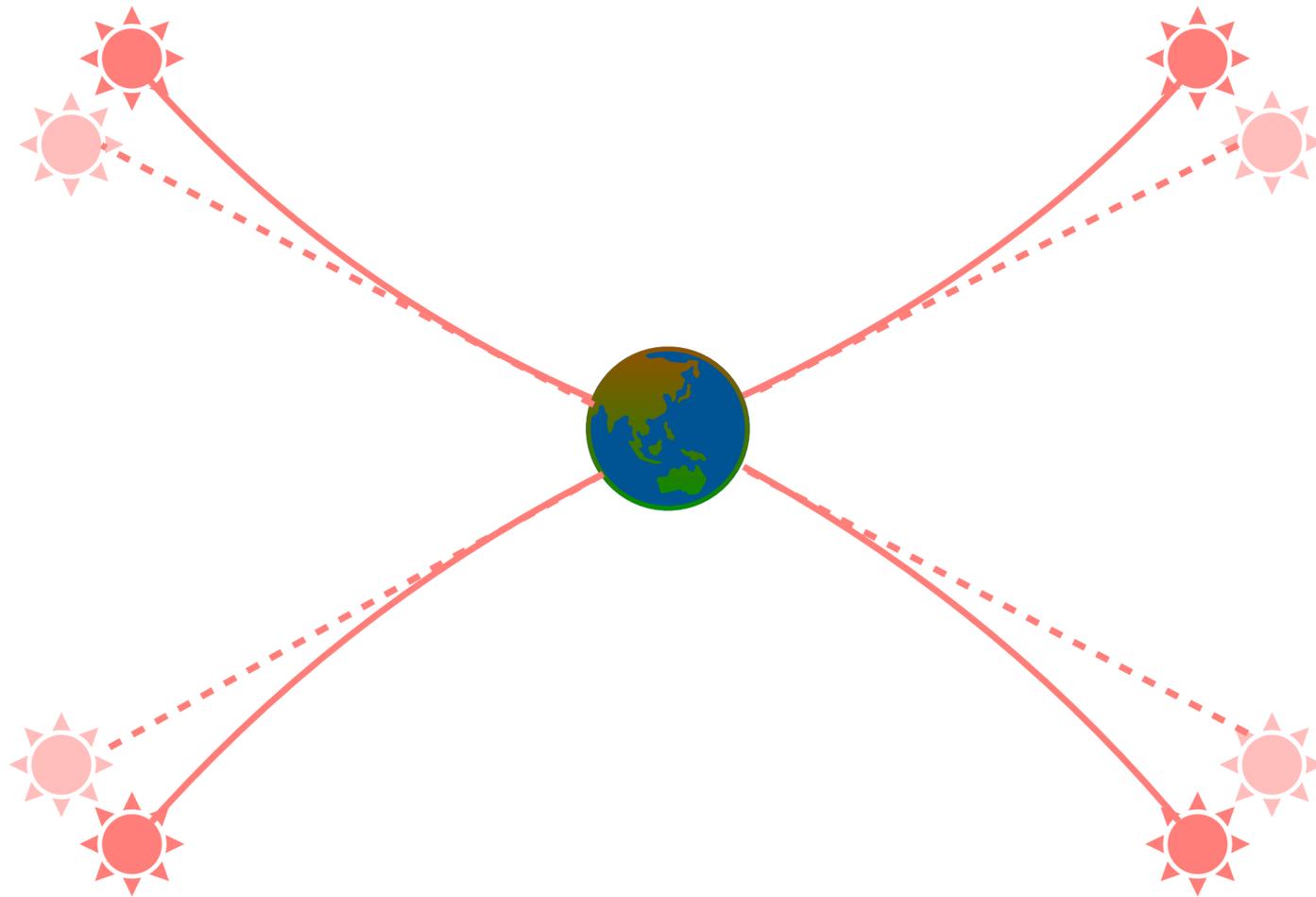[Gialamas, Hütsi, Kannike, et al., 2406.07533]

[Keeley, Joudaki, Kaplinghat, Kirkby, 1905.10198]
[Keeley, Abazajian, Kaplinghat, Shafieloo, 2502.12667]

cf. [Notari, Redi, Tesi, 2406.08459]

Quasar Astrometry

quasar (so bright and visible at a distance)

$$\Delta\theta \sim h$$

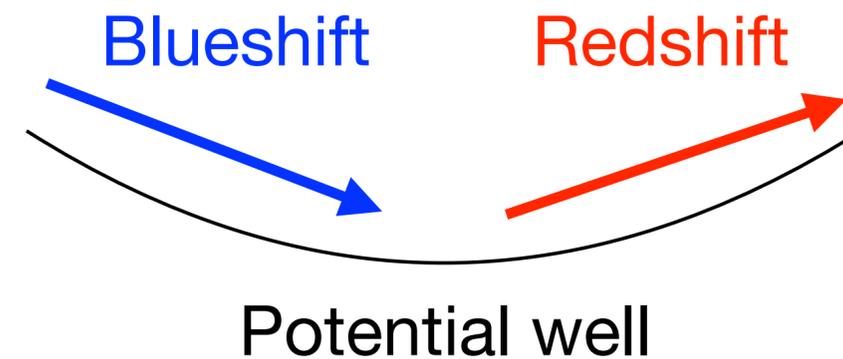$$\frac{\mathrm{d}\Delta\theta}{\mathrm{d}t} \sim hf$$

Expand it by spherical harmonics.

Extract the quadrupole component.

(Similar to the principles of PTA)

Search for the global-sky correlation due to GWs; each quasar has peculiar motion.

Integrated Sachs-Wolfe (ISW) Effect

Energy of the CMB photon changes as it passes through gravitational potential.
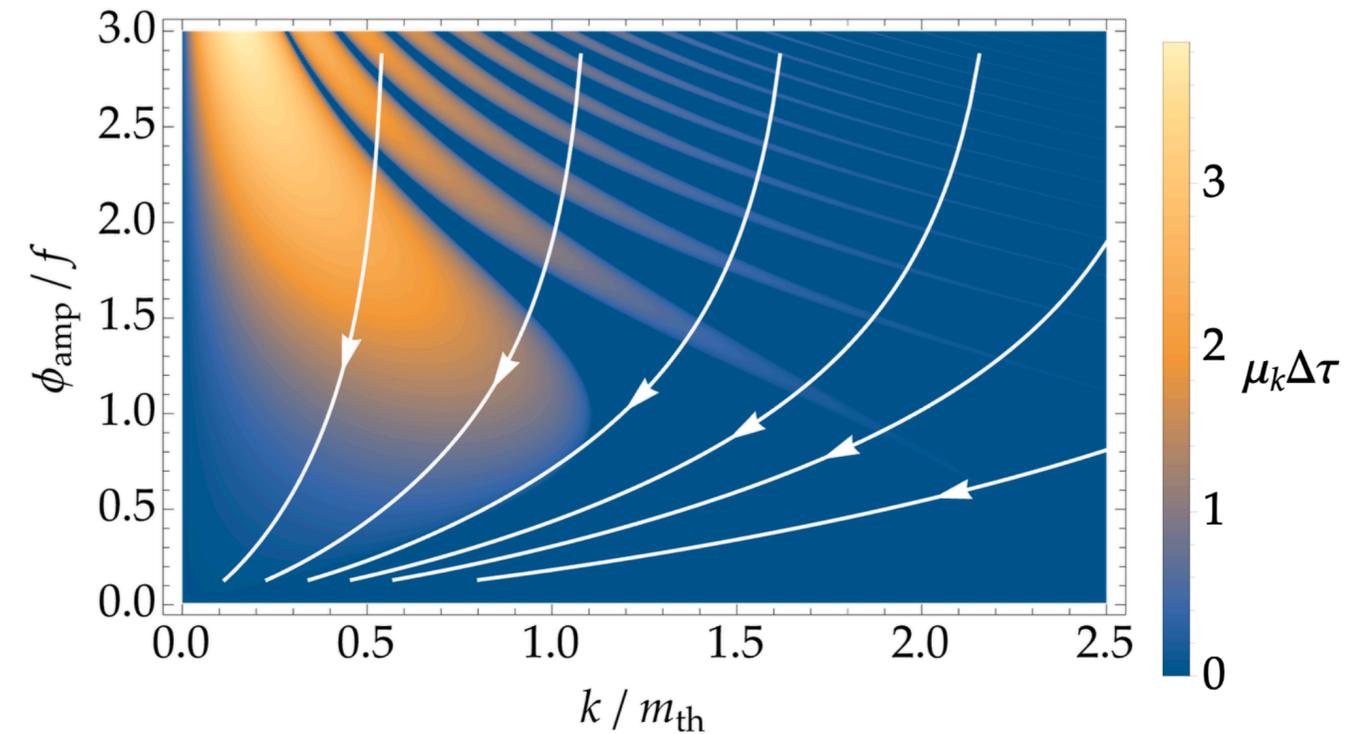
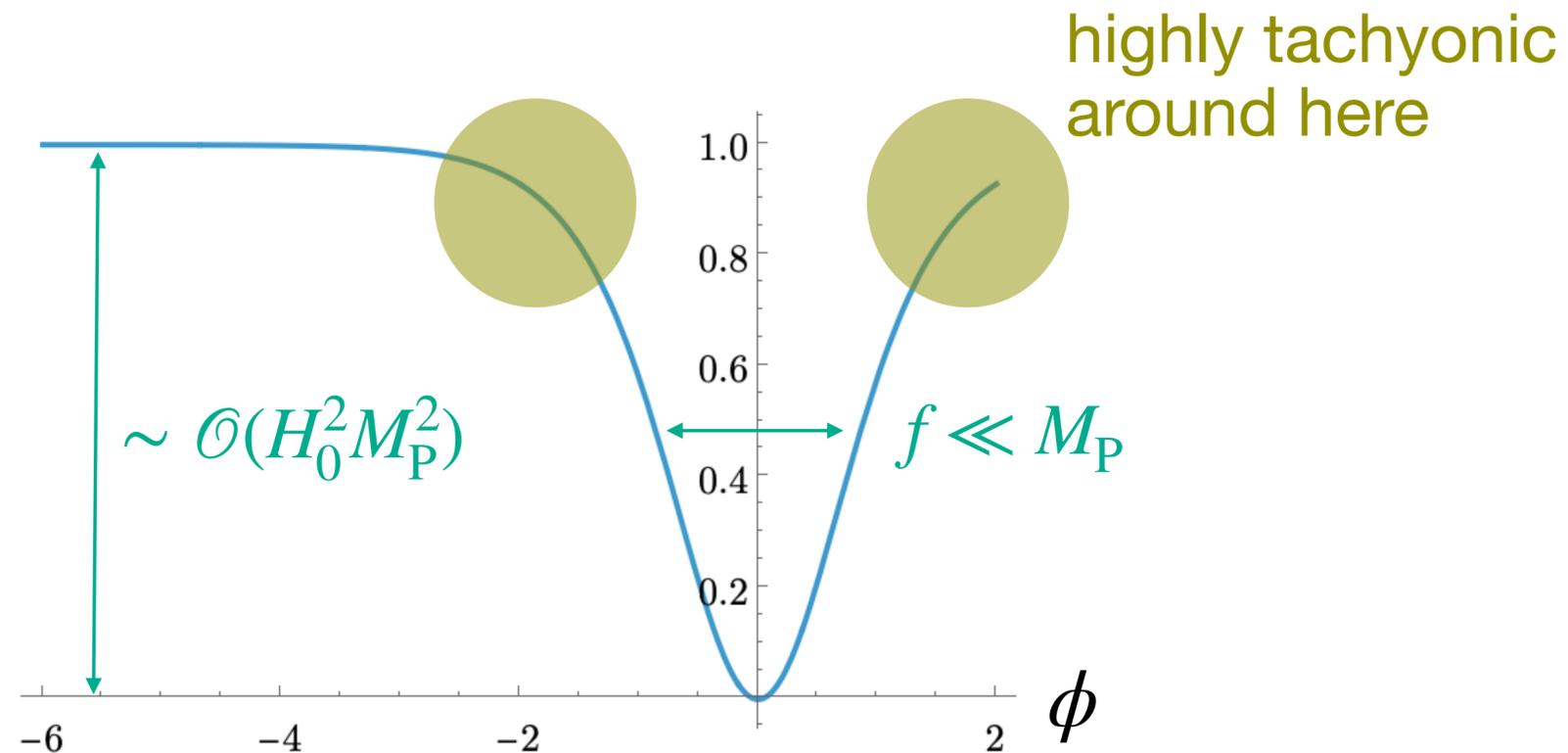For static potential, there is no effect.

With time evolution, the effect remains.

Blueshift   Redshift

Potential well

$$\frac{\Delta T}{T} \sim \int \mathrm{d}\tau \, (\dot{\Phi} + \dot{\Psi})$$

Tachyonic Resonance

highly tachyonic
around here

$\sim \mathcal{O}(H_0^2 M_{\mathrm{P}}^2)$

$f \ll M_{\mathrm{P}}$

ϕ

ϕ_{amp}/f

k/m_{th}

$\mu_k \Delta\tau$

Floquet chart

Repeated tachyonic instability
leads to a resonance structure.

UV Cutoff Scale

$$V(\phi) = V_0 \tanh^2(\phi/f) \quad \longrightarrow \quad \text{higher dimensional ops. of the form } \exp(-2m\bar{\phi}/f)(\delta\phi/f)^n$$

The strongest bounds come from $m = 1$ and $n \to \infty$.

Neglecting $\mathcal{O}(1)$ numerical coefficients, the tree-level perturbative unitarity bound is $\Lambda \sim f$.

The typical energy scale (for sufficiently small f), $H_0 M_{\rm Pl}/f$, should not exceed the cutoff scale Λ.

$\to$ We obtain an absolute lower bound, $f \gtrsim f_{\rm min} := \sqrt{H_0 M_{\rm Pl}} \approx 10^{-3} \, {\rm eV} \approx 10^{-30} M_{\rm Pl}$.