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Constraining Spatial Curvature with Priors from Swampland Conjectures

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Collaboration with : Hun Jang and Shinji Mukohyama, arxiv:2605.22362 (2026)

Dark Energy: a discovery

Three approaches to dark energy

Theory: What is the Lagrangian of Dark Energy?

Phenomenology: How can dark energy affect other constituents of the universe?

Observations: What are the observational constraints on it?



- Inflation Theory:
The very early Universe, primordial density fluctuations
- Cold Dark Matter (CDM):
Formation of galaxies and large-scale structure
- Standard Model (SM):
Elementary particles and fundamental interactions
- General Relativity (GR):
Governs gravity, predicts the expansion of the Universe
- Dark Energy:
The observed late-time accelerated expansion
- Λ CDM Model:
The current standard model of cosmology, Excellent observational agreement



But the nature of dark energy remains unresolved

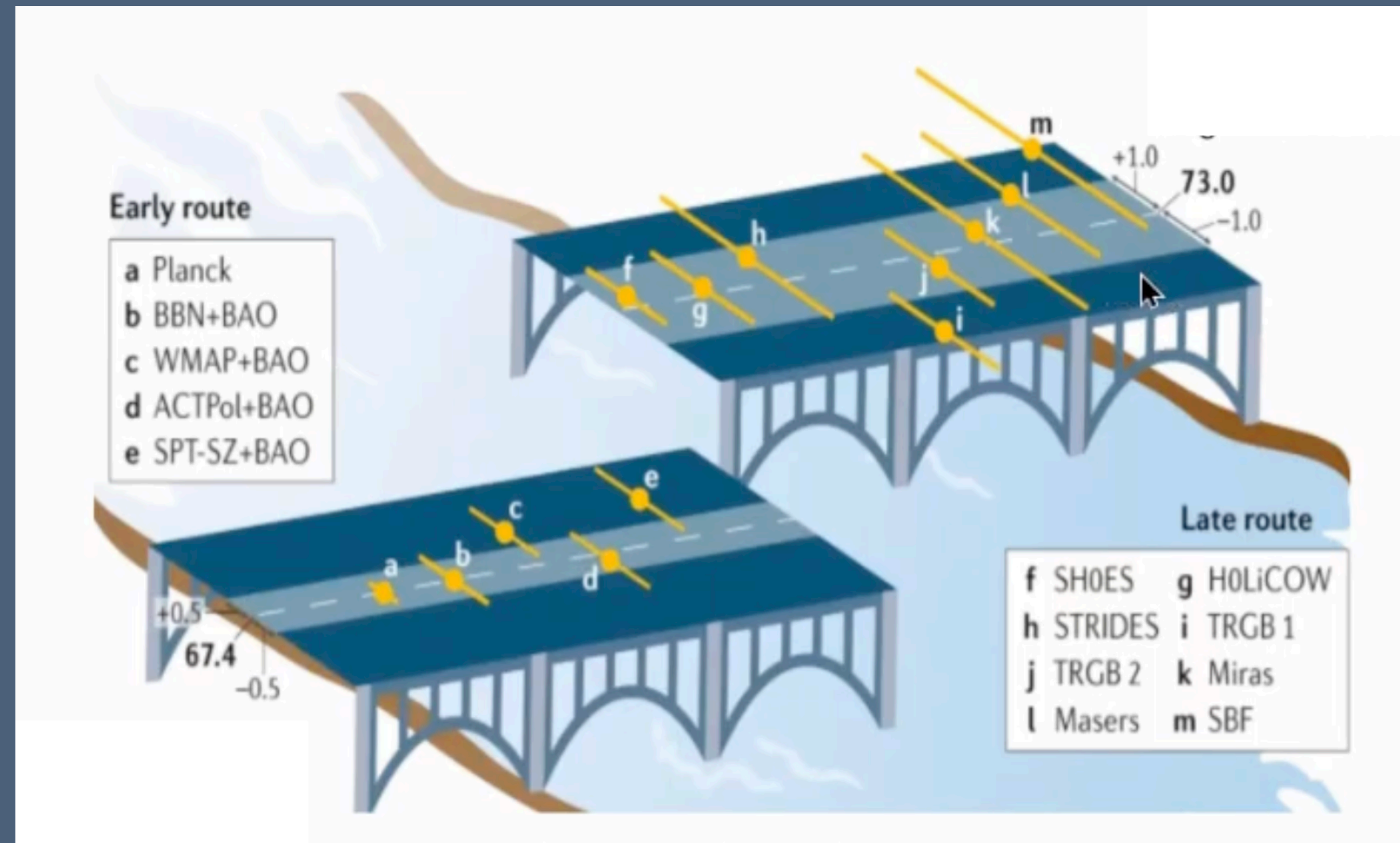
The Hubble Tension

A discrepancy between early time and late-time measurements of H_0

Calibrated by CMB (Planck 2018)

$$H_0 = 67.4 \pm 0.5 \text{ Km/s/Mpc}$$

Local distance ladder calibrated by Cepheids $H_0 = 73.5 \pm 1.1 \text{ Km/s/Mpc}$



Valentino et al 2021 Class. Quantum Grav. 38 153001

M. Kamionkowski, Adam G. Riess, Annu. Rev. Nucl. Part. Sci. 2023. 73:153–80

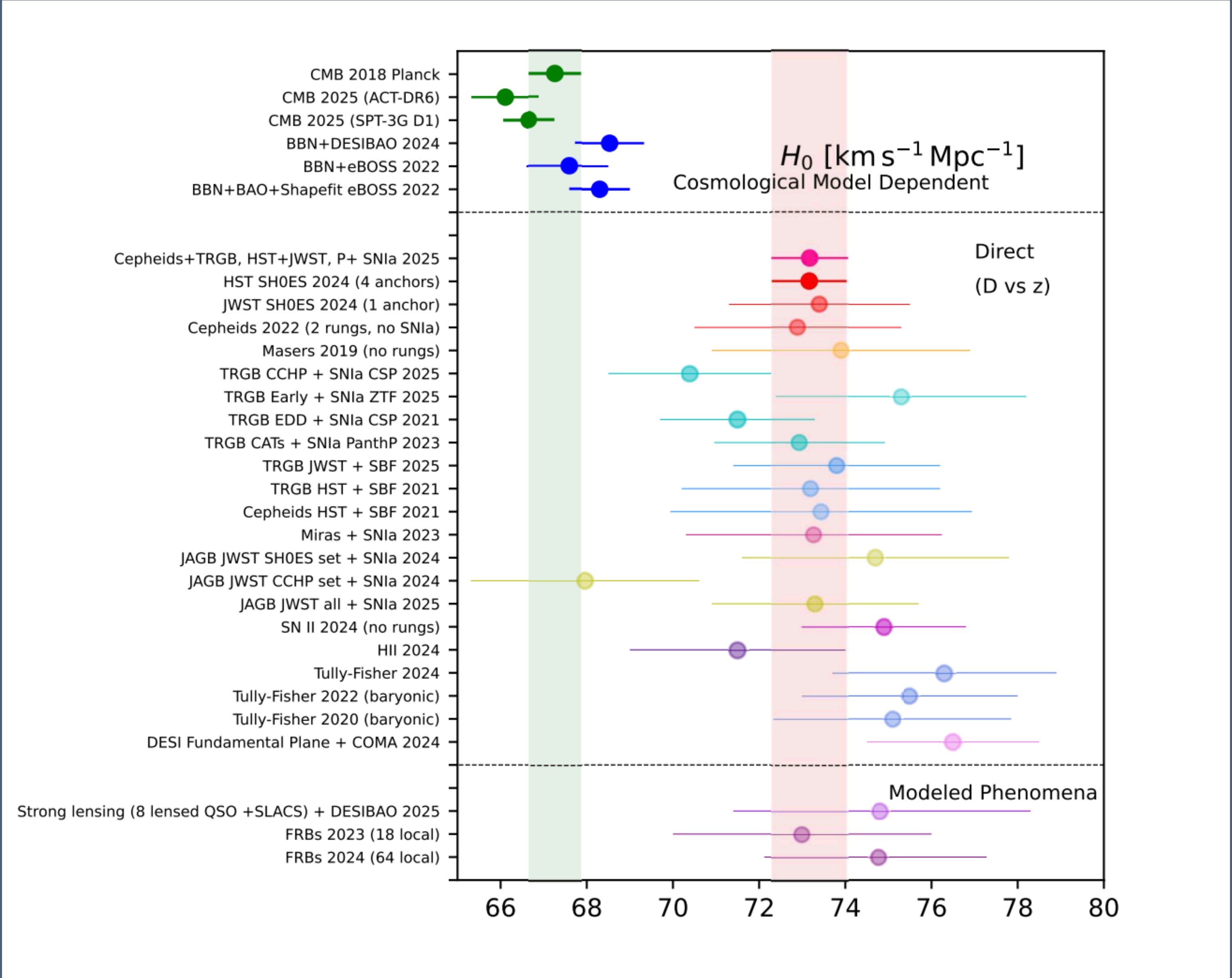
Recent determinations of H_0

Indirect measurements: Cosmic Microwave Background (CMB), Baryon acoustic oscillations (BAO), galaxy clustering...

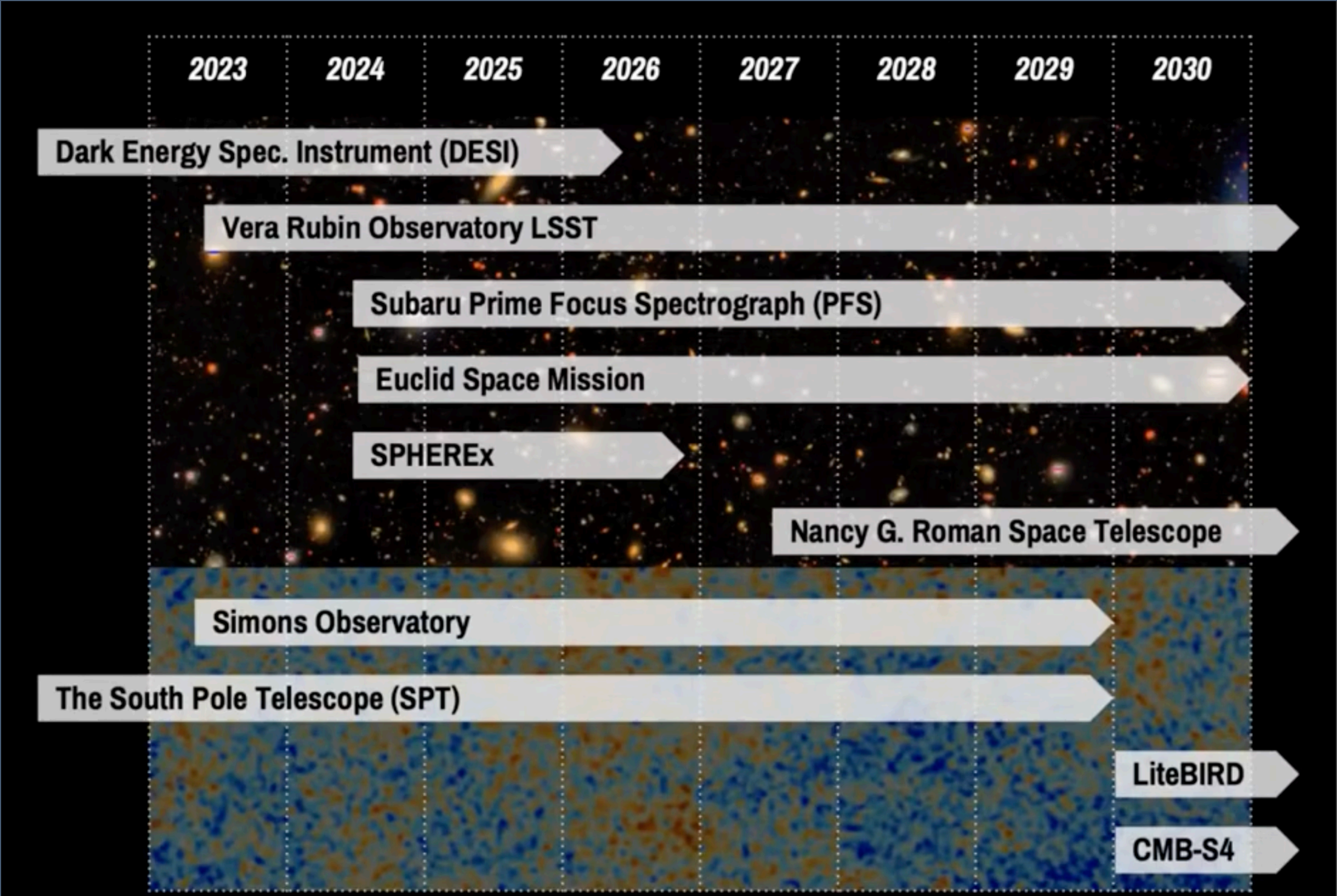
(model dependent)

Direct measurements: distance ladder (Cepheids, TRGB, SNe), gravitational lensing...
(model independent)

arxiv.2509.25288



Amount of Observations we have now



Parameters to measure:

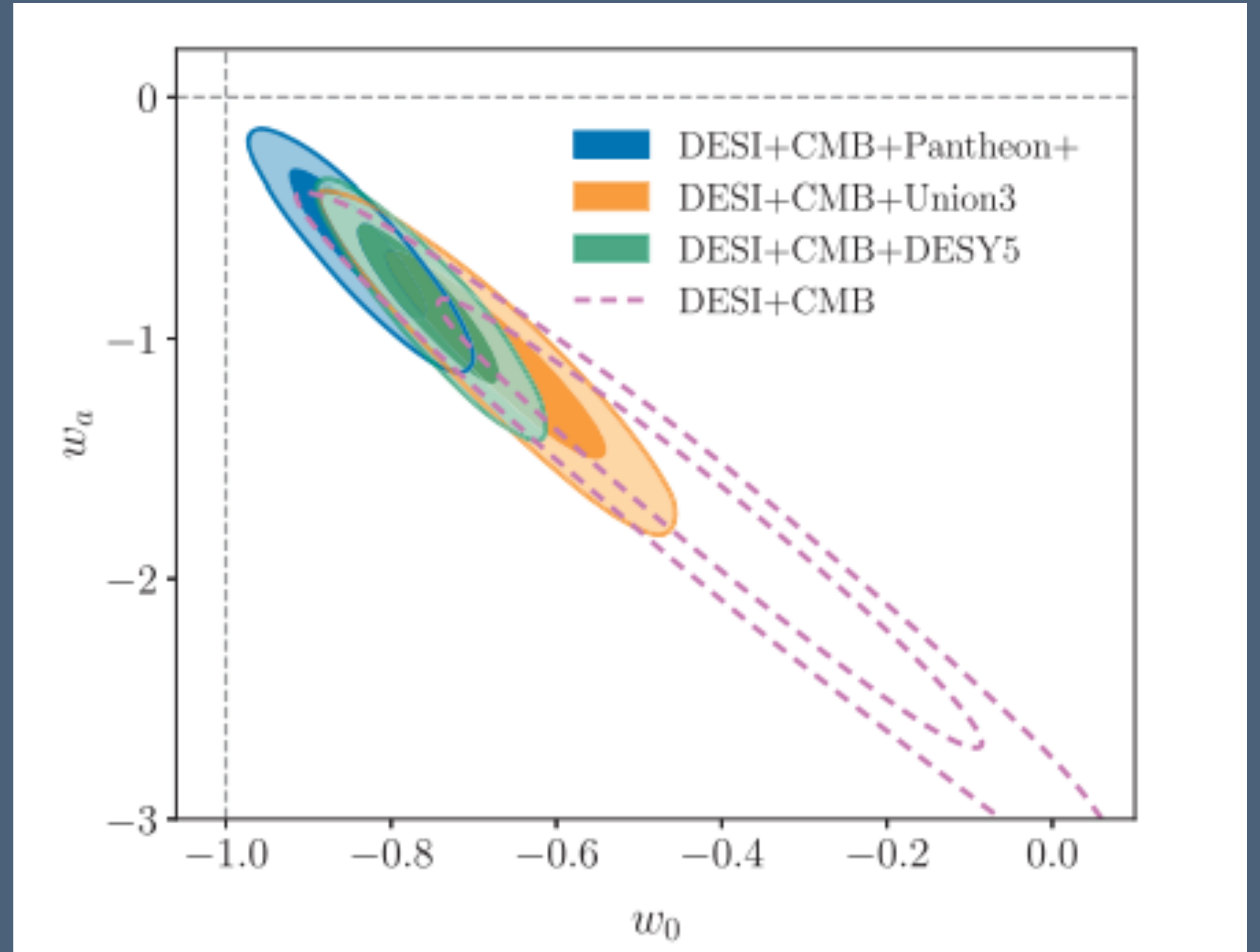
- Equation of state $w = w_0 + w_a z/(1 + z) + \dots$
- Amplitude of clustering of galaxies S_8 or σ_8
- Rate of comoving expansion today H_0
- Energy density today Ω_m

Tests for consistency:

- Models that predict the same expansion history may predict different clustering growth rates
- Early and late universe analyses should yield consistent results.

Evidence for dynamical dark energy by DESI

- Dynamical dark energy:
 $w(z) = w_0 + w_a(1 - a)$
- w_0 :present day value
- Λ CDM : $w_0 = -1, w_a = 0$
- Disfavors Λ by 2.8σ to 4.2σ



Dark Sector?



1. Explain Data

Equally well or better
than Λ CDM



2. Increase H_0

Help alleviate
the Hubble tension



3. Not Induce Tensions Elsewhere

Consistent with $(S_8, \sum m_\nu, \dots)$



4. Be Well Motivated Theoretically

Rooted in fundamental physics
and compelling theory

Can theoretically motivated priors from quantum gravity influence cosmological parameter estimation?

Quantum Gravity —————> Swampland Conjectures —————> Theory Prior on λ

Curved Exponential Quintessence —————> Constraints on Ω_k and λ

From Quantum Gravity to Cosmology

Quantum gravity suggests that a Universe with a perfectly constant dark energy may be difficult to realize.

Swampland: Effective field theories that appear consistent at low energies but cannot arise from a consistent theory of quantum gravity.

This motivates the swampland conjectures, which distinguishes effective field theories consistent with quantum gravity.

Scalar-field potentials are no longer arbitrary but must satisfy theoretical consistency conditions.

de Sitter Swampland Conjecture

$$\frac{|\nabla V|}{V} \geq \frac{s_1}{M_P}$$

Requires a minimum slope for positive scalar potentials.

$s_1 = \mathcal{O}(1)$: Measures the strength of the theoretical constraint.

Motivated by: Higher-dimensional supergravity and string compactifications.

Larger s_1 : steeper potentials, making cosmic acceleration more difficult.

Lectures on the string Landscape and the Swampland, (2022) arXiv:2212.06187

S. Sun and Y. L. Zhang. Notes on quantum corrections of swampland and trans-planckian censorship conjectures. Phys. Lett. B, 816:136245, 2021.

S. Laliberte and R. Brandenberger. String gases and the swampland. JCAP, 07:046, 2020.

Representative Theoretical Predictions for s_1 arising from different quantum-gravity scenarios.

Scenario	$D=10, d=4$	$D=11, d=4$
(S1) Compactification of D -dimensional supergravity to d dimensions (strong energy)	$s_1 = 2\sqrt{\frac{2}{3}}$	$s_1 = 2\sqrt{\frac{9}{14}}$
(S2) Compactification of D -dimensional supergravity to d dimensions (null energy)	$s_1 = \sqrt{\frac{3}{2}}$	$s_1 = 2\sqrt{\frac{7}{18}}$
(S3) Quantum correction to strong energy condition ($D \rightarrow 4$)	$s_1 = \sqrt{\frac{8}{3}} \left(1 + \frac{\beta}{3\pi}\right)$	$s_1 = \sqrt{\frac{18}{7}} \left(1 + \frac{\beta}{3\pi}\right)$
(S4) Quantum correction to null energy condition ($D \rightarrow 4$)	$s_1 = \sqrt{\frac{3}{2}} \left(1 + \frac{C\beta}{3\pi}\right)$	$s_1 = \sqrt{\frac{14}{9}} \left(1 + \frac{C\beta}{3\pi}\right)$
(S5) TCC (tower lighter than Hubble)	$s_1 = \sqrt{\frac{2}{3}}$	$s_1 = \sqrt{\frac{2}{3}}$
(S6) TCC (tower heavier than Hubble)	$s_1 = \sqrt{2}$	$s_1 = \sqrt{2}$
(S7) Sharpened distance and strong de Sitter conjectures	$s_1 = \frac{1}{\alpha}, \alpha \geq \frac{1}{\sqrt{2}}$	$s_1 = \frac{1}{\alpha}, \alpha \geq \frac{1}{\sqrt{2}}$
(S8) String gas setting	$s_1 = \frac{1}{\sqrt{6}}$	$s_1 = \frac{1}{\sqrt{7}}$
(S9) Combined dSC	$s_1^c + p_2(1 + s_2) \geq 1$	$s_1^c + p_2(1 + s_2) \geq 1$

Benchmark adopted

G. Obied et al. De sitter space and the swampland. 2018.

D. Andriot, C. Roupec, Further refining the de sitter swampland conjecture, Fortsch. Phys., 67(1-2), 1800105, 2019

D: higher-dimensional spacetime
d: effective spacetime dimension (here d=4).

Cosmological Framework

Canonical quintessence in a curved FLRW universe

Canonical scalar-field action:

$$S = \int d^4x \sqrt{-g} \left[\frac{1}{2} M_p^2 R - \frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - V(\phi) + \mathcal{L}_m \right]$$

Einstein–Klein–Gordon equations:

$$\begin{aligned} H^2 &= \frac{1}{3} \sum_i \rho_i, \quad \text{where } i = r, m, k, \phi \\ \dot{H} &= -\frac{1}{2} \sum_i (\rho_i + p_i), \\ \ddot{\phi} + 3H\dot{\phi} + V_{,\phi} &= 0. \end{aligned}$$

Density parameters:

$$\Omega_i \equiv \frac{\rho_i}{3H^2}$$

$$1 - \Omega_k = \Omega_m + \Omega_r + \Omega_\phi = \Omega_T$$

$$\Omega_k \equiv -\frac{k}{a^2 H^2}$$

Dynamical System Formulation

Dimensionless Variables

$$x = \frac{\dot{\phi}}{\sqrt{6}H}, \quad y = \frac{\sqrt{V}}{\sqrt{3}H}, \quad z = \frac{\sqrt{-k}}{aH}, \quad u = \frac{\sqrt{\rho_r}}{\sqrt{3}H}.$$

Exponential Potential

$$V(\phi) = V_0 e^{-\lambda\phi},$$

$$\lambda > 0$$

Autonomous System

$$\Omega_\phi = x^2 + y^2, \quad w_\phi = \frac{x^2 - y^2}{x^2 + y^2},$$

$$\Omega_k = z^2, \quad \Omega_r = u^2, \quad w_{eff} = x^2 - y^2 - \frac{z^2}{3} + \frac{u^2}{3}$$

$$\begin{aligned} x' &= \sqrt{\frac{3}{2}} y^2 \lambda + x \left[3(x^2 - 1) + z^2 + \frac{3}{2} \Omega_m + 2u^2 \right], \\ y' &= y \left[-\sqrt{\frac{3}{2}} x \lambda + 3x^2 + z^2 + \frac{3}{2} \Omega_m + 2u^2 \right], \\ z' &= z \left[z^2 - 1 + 3x^2 + \frac{3}{2} \Omega_m + 2u^2 \right], \\ u' &= u \left[z^2 - 2 + 3x^2 + \frac{3}{2} \Omega_m + 2u^2 \right]. \end{aligned}$$

Numerically solved to study the complete cosmological evolution.

Motivation from Previous Work

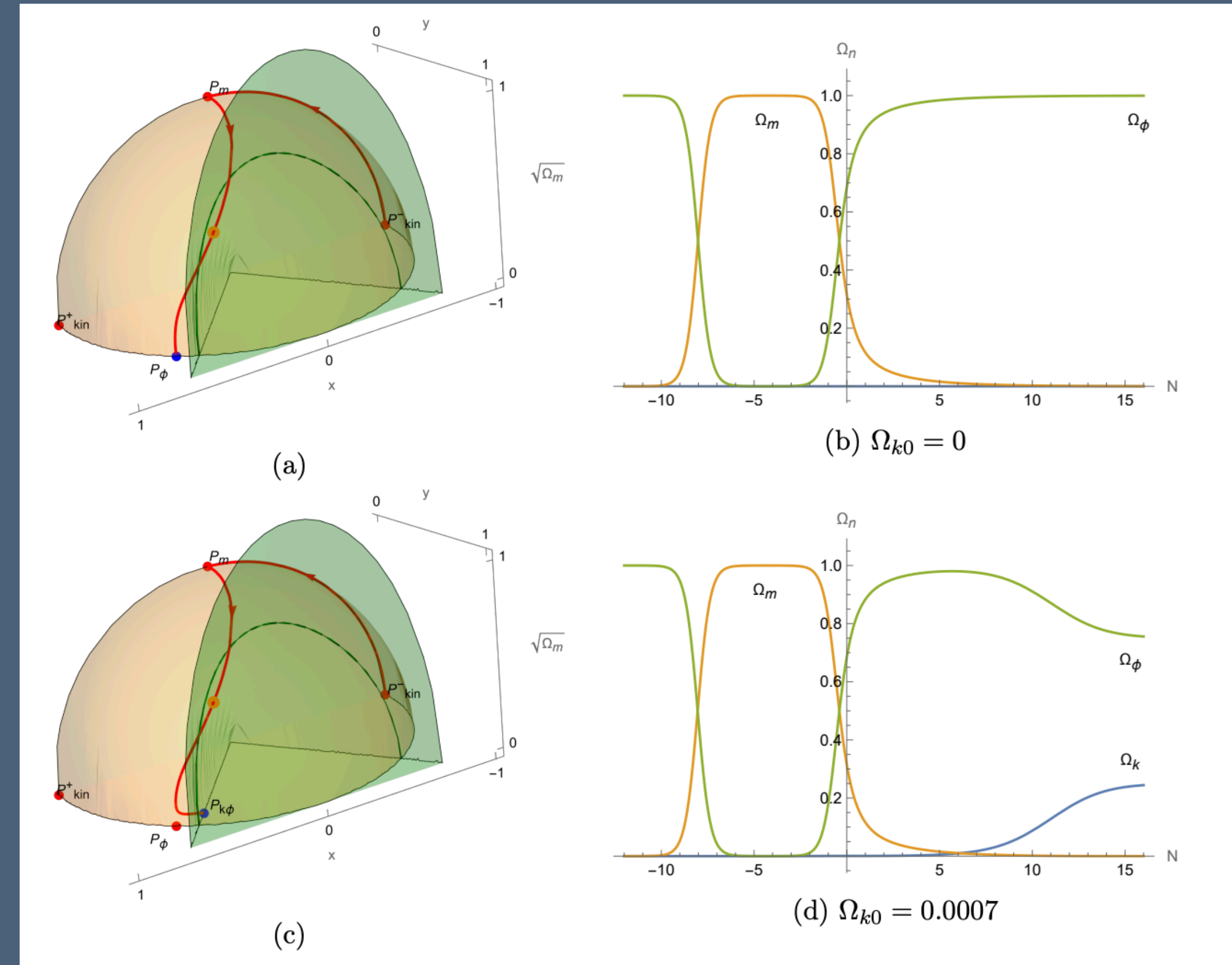
Flat universe: Acceleration requires $\lambda \leq \sqrt{2}$

Open universe: New curvature-assisted attractor

Viable solutions for $\sqrt{2} < \lambda \lesssim \sqrt{3}$

Are these results consistent with the
Swampland Distance Conjecture
and current cosmological observations?

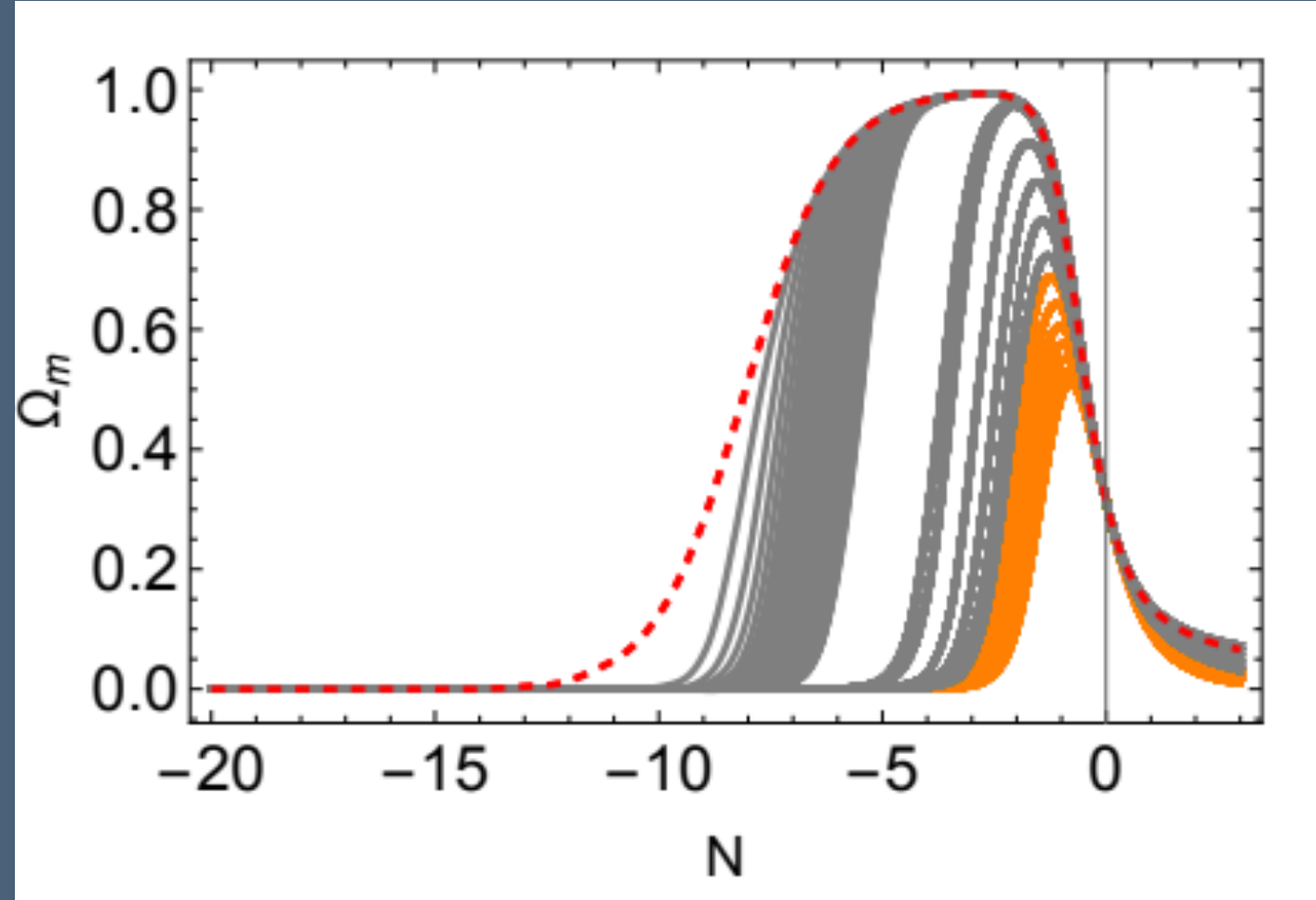
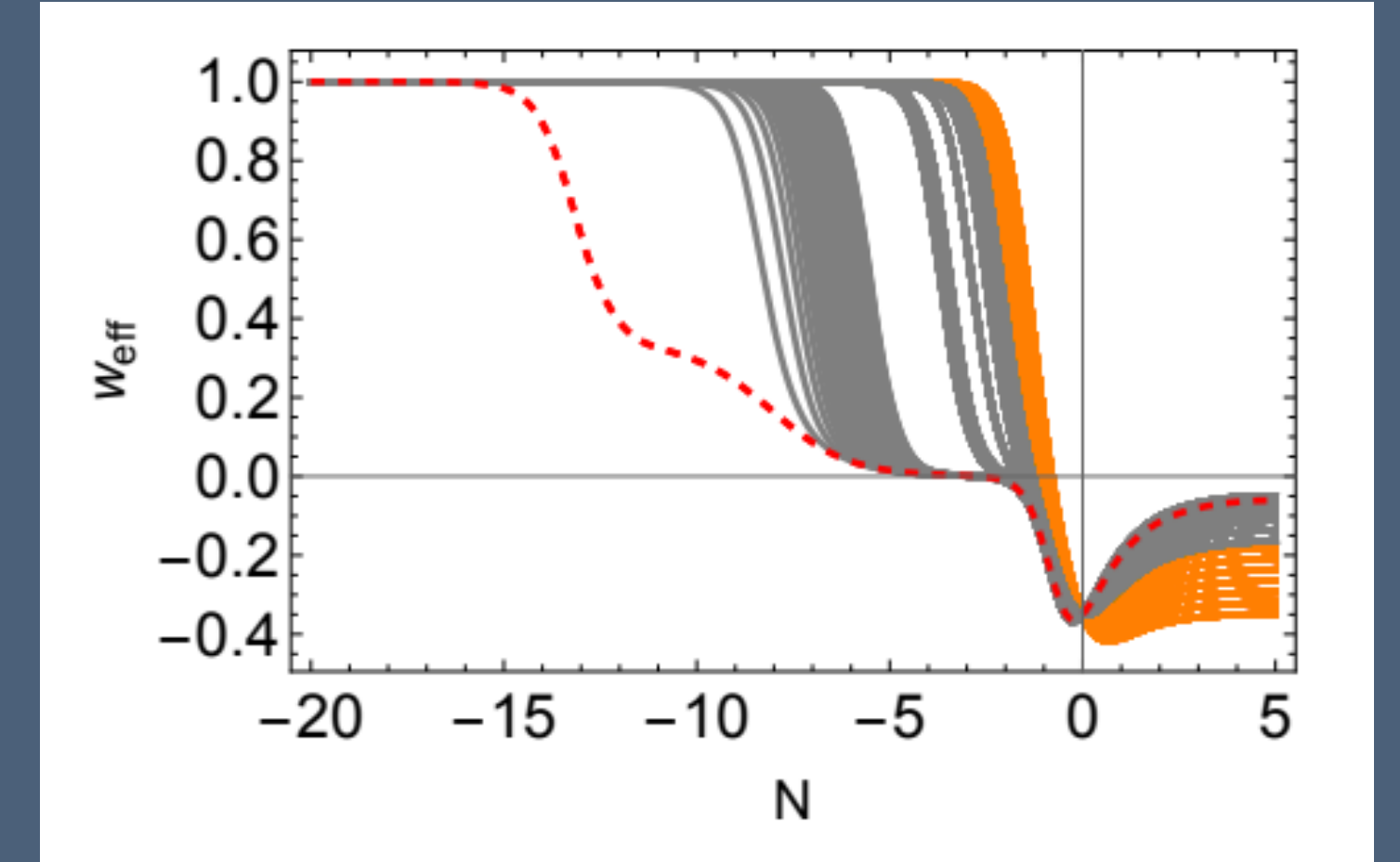
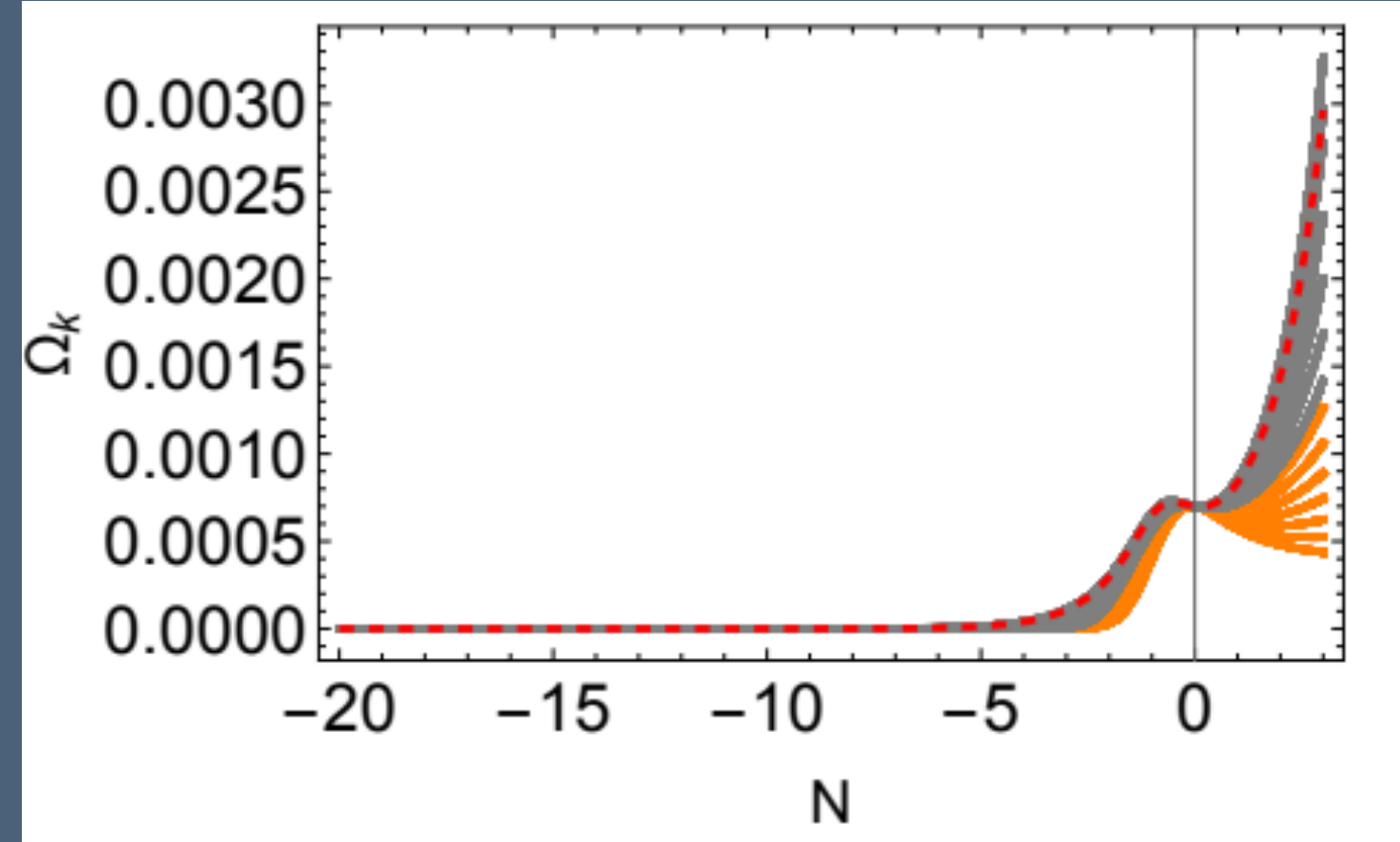
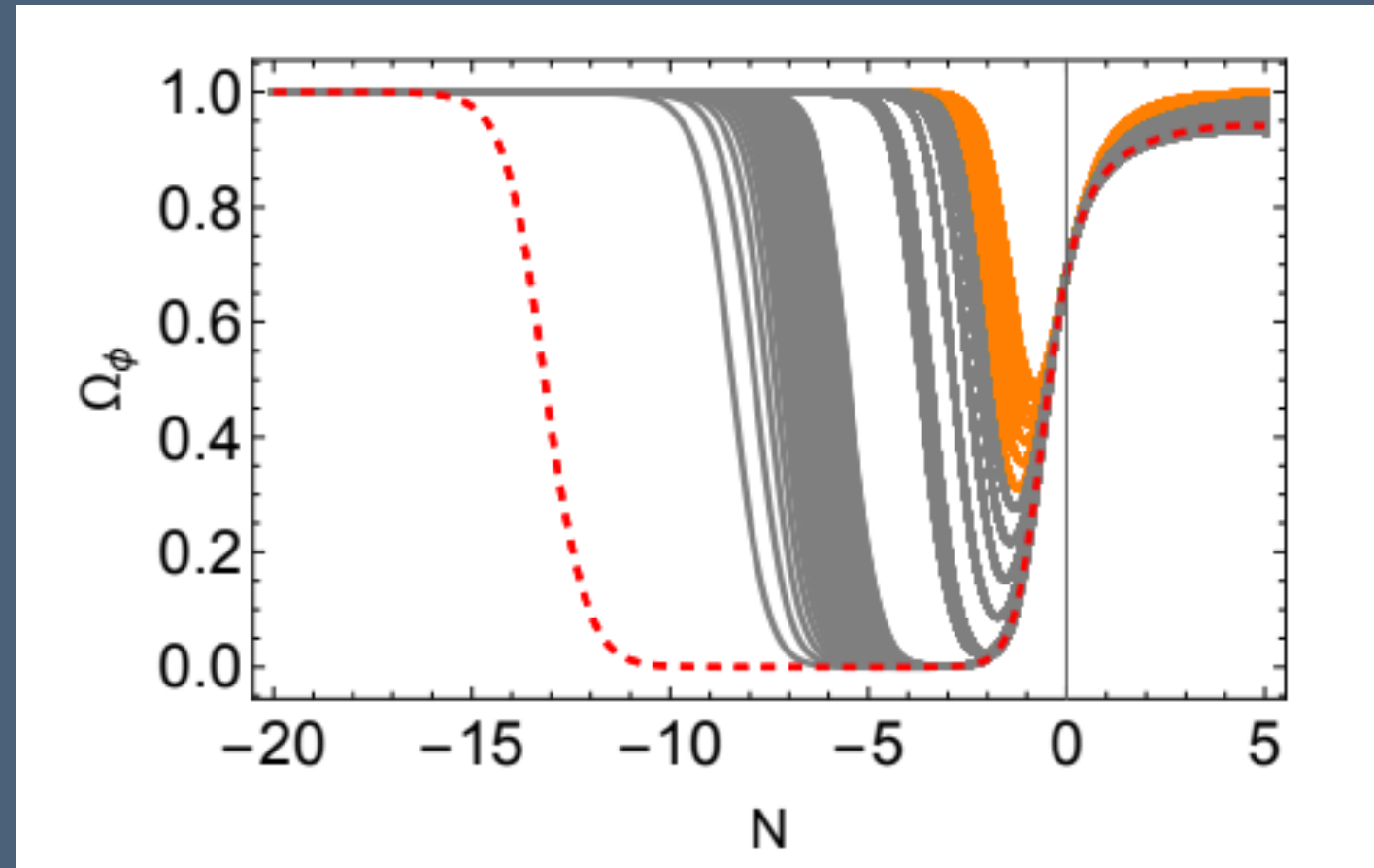
Spatial curvature modifies the late-time attractor
while leaving the standard radiation and matter
eras largely unchanged.



David Andriot et al., Exponential Quintessence: curved, steep and stringy?
J. High Energ. Phys. 2024, 117 (2024).

$$\lambda = \sqrt{\frac{8}{3}}$$

Background Cosmological Evolution



- Standard cosmic evolution is successfully reproduced.
- Evolution is highly sensitive to the slope parameter λ .
- Larger values of λ delay scalar-field domination and weaken late-time acceleration.
- Negative spatial curvature helps maintain a viable thermal history.

- Gray: $1.6 < \lambda < 1.75$
- Orange: $1.4 < \lambda < 1.6$
- Red dashed: $\lambda = \sqrt{3}$

$$N = 0, \quad \Omega_{\phi 0} = 0.685, \quad \Omega_{r 0} = 10^{-4}, \quad \Omega_{k 0} = 7 \times 10^{-4}$$

Consistency with the Swampland Distance Conjecture

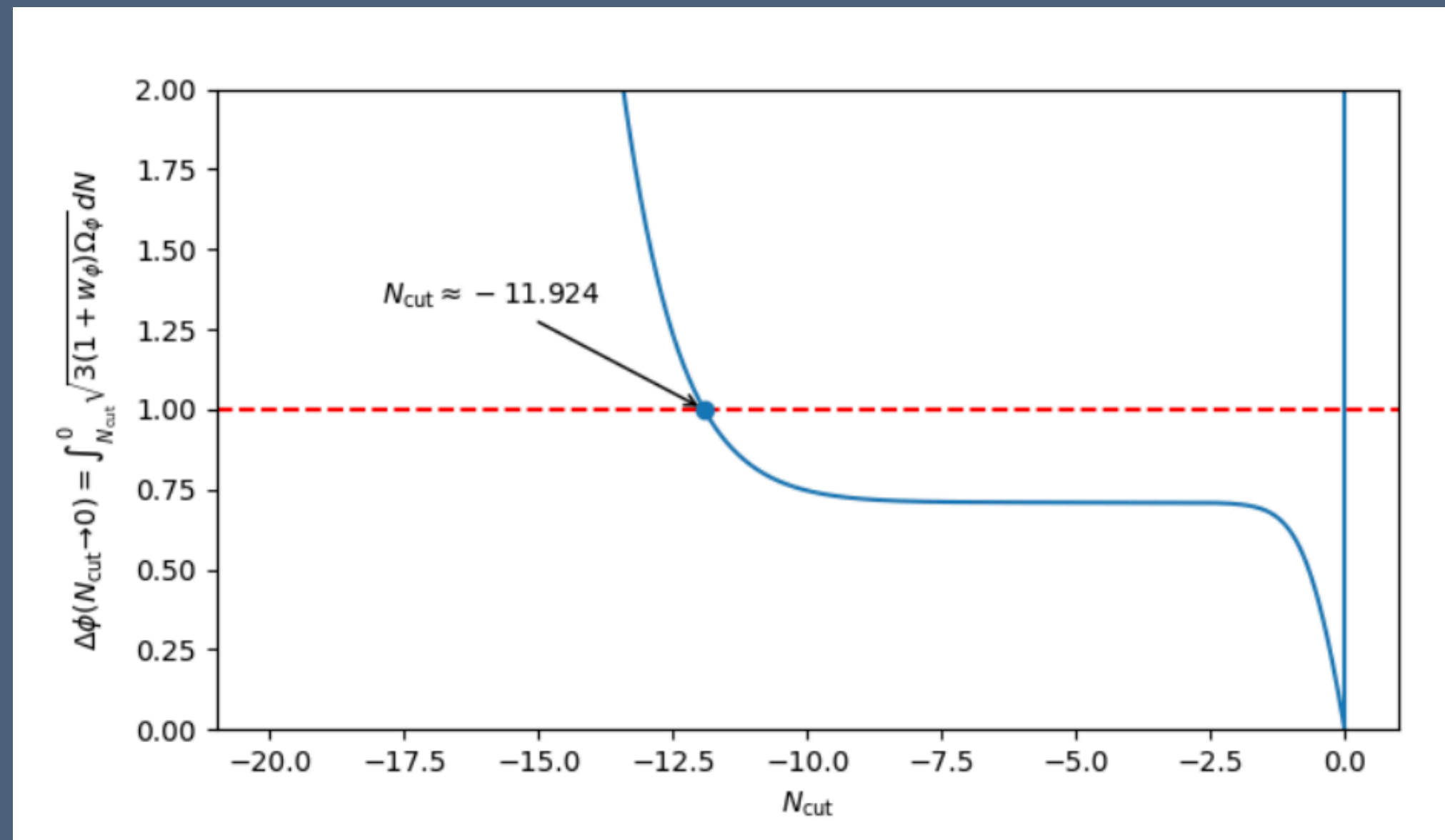
- Large scalar-field excursions trigger an infinite tower of light states.
- Beyond this point, the single-field effective theory is no longer reliable.
- Therefore, the scalar-field excursion must satisfy

$$\Delta\phi \lesssim \mathcal{O}(1)$$

SDC Consistency Condition

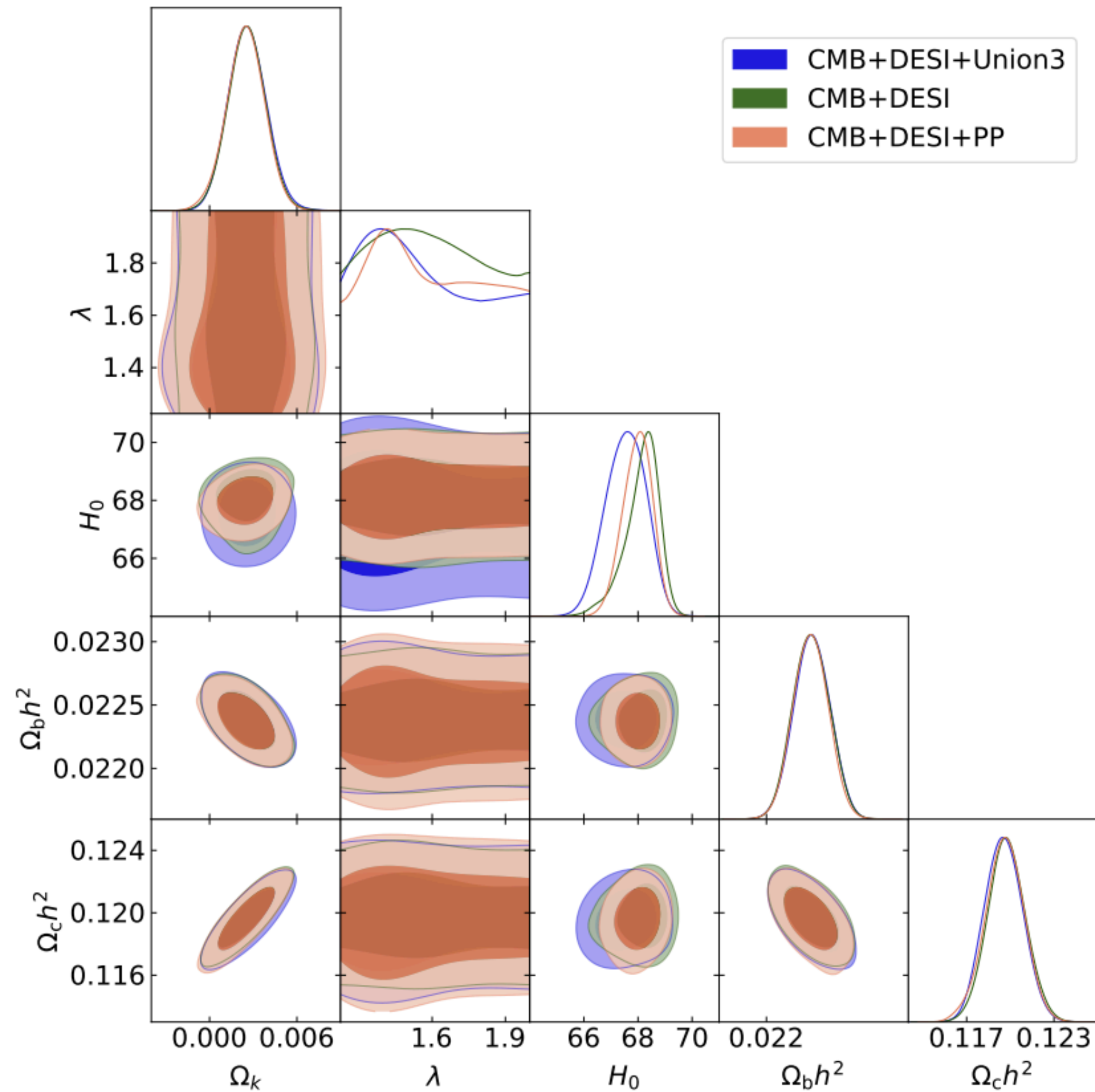
$$\Delta\phi(N_{\text{cut}} \rightarrow 0) = \int_{N_{\text{cut}}}^0 \sqrt{3(1+w_\phi)\Omega_\phi} dN \lesssim \mathcal{O}(1)$$

The integral determines the earliest EFT-valid epoch



This defines an effective cutoff, beyond which the single-field effective description is expected to break down.

Cosmological Constraints on Curved Quintessence



Current observations have limited constraining power on λ .

Parameter	Prior range
Ω_k	$[-0.05, 0.05]$
$\Omega_b h^2$	$[0.005, 0.1]$
$\Omega_c h^2$	$[0.001, 0.99]$
λ	$[1.225, 2]$
H_0	$[50, 100]$

The posterior distributions are sampled using a Markov Chain Monte Carlo (MCMC) approach implemented within the COBAYA

Posterior distributions

Key Results

Parameter	CMB+DESI	CMB+DESI+PP	CMB+DESI+Union3
$\Omega_b h^2$	0.02238 ± 0.00015	0.02237 ± 0.00015	0.02238 ± 0.00015
$\Omega_c h^2$	0.1197 ± 0.0013	0.1196 ± 0.0013	0.1195 ± 0.0013
$\ln(10^{10} A_s)$	3.053 ± 0.015	$3.055^{+0.014}_{-0.015}$	3.054 ± 0.015
n_s	0.9652 ± 0.0043	$0.9651^{+0.0041}_{-0.0047}$	0.9656 ± 0.0044
τ_{reio}	$0.0588^{+0.0071}_{-0.0079}$	$0.0599^{+0.0070}_{-0.0096}$	0.0590 ± 0.0076
$H_0 \text{ (km s}^{-1}\text{Mpc}^{-1}\text{)}$	$68.14^{+0.74}_{-0.42}$	$67.98^{+0.59}_{-0.50}$	$67.55^{+0.81}_{-0.69}$
λ	< 1.60	$1.60^{+0.23}_{-0.31}$	< 1.58
Ω_k	0.0025 ± 0.0013	0.0025 ± 0.0013	0.0026 ± 0.0013
r_d	147.17 ± 0.28	147.20 ± 0.30	147.20 ± 0.28

A mild preference is found for a small positive spatial curvature

λ is weakly constrained within the swampland prior.

$$\Omega_k \simeq 0.0025 \pm 0.0013.$$

(mild preference for positive curvature)

Conclusions

- Curved exponential quintessence provides a viable cosmological evolution consistent with current observations.
- Current cosmological data place weak constraints on the swampland slope parameter allowing values beyond $\sqrt{3/2}$.
- A mild preference is found for positive spatial curvature.
- Future surveys will provide stronger tests.

Thank you so much for your attention!



