To curve, or not to curve

Is curvature-assisted quintessence observationally viable?

Based on
arXiv:2406.09212

George Alestas, Matilda Delgado, Ignacio Ruiz, Y.A. Miguel Montero, Savvas Nesseris

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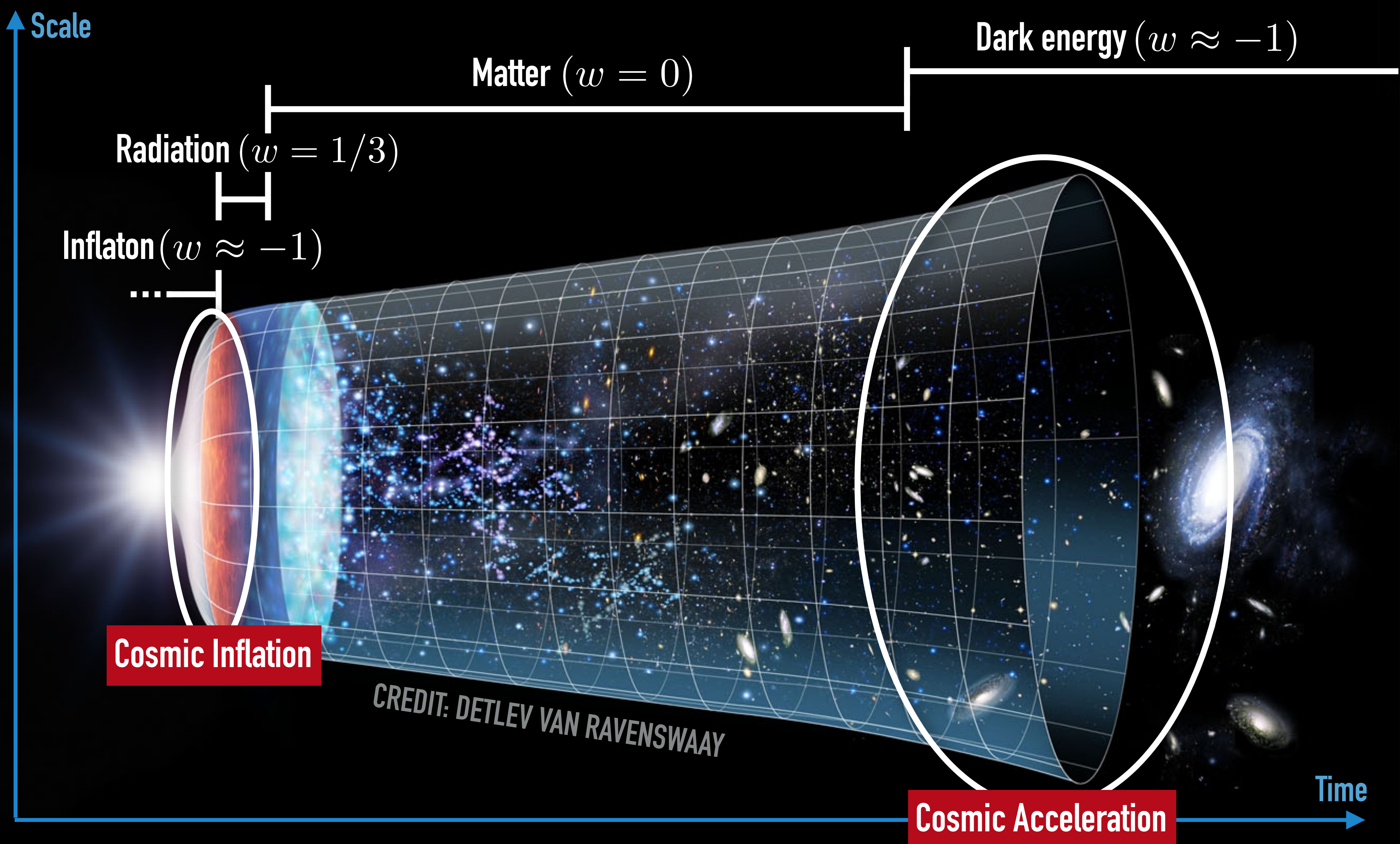
Case Western Reserve University, Cleveland, Ohio, USA
Imperial College London, UK

String Phenomenology
Padova, June 27, 2024

FROM COSMIC INFLATION TO COSMIC ACCELERATION

$$w = P/\rho$$



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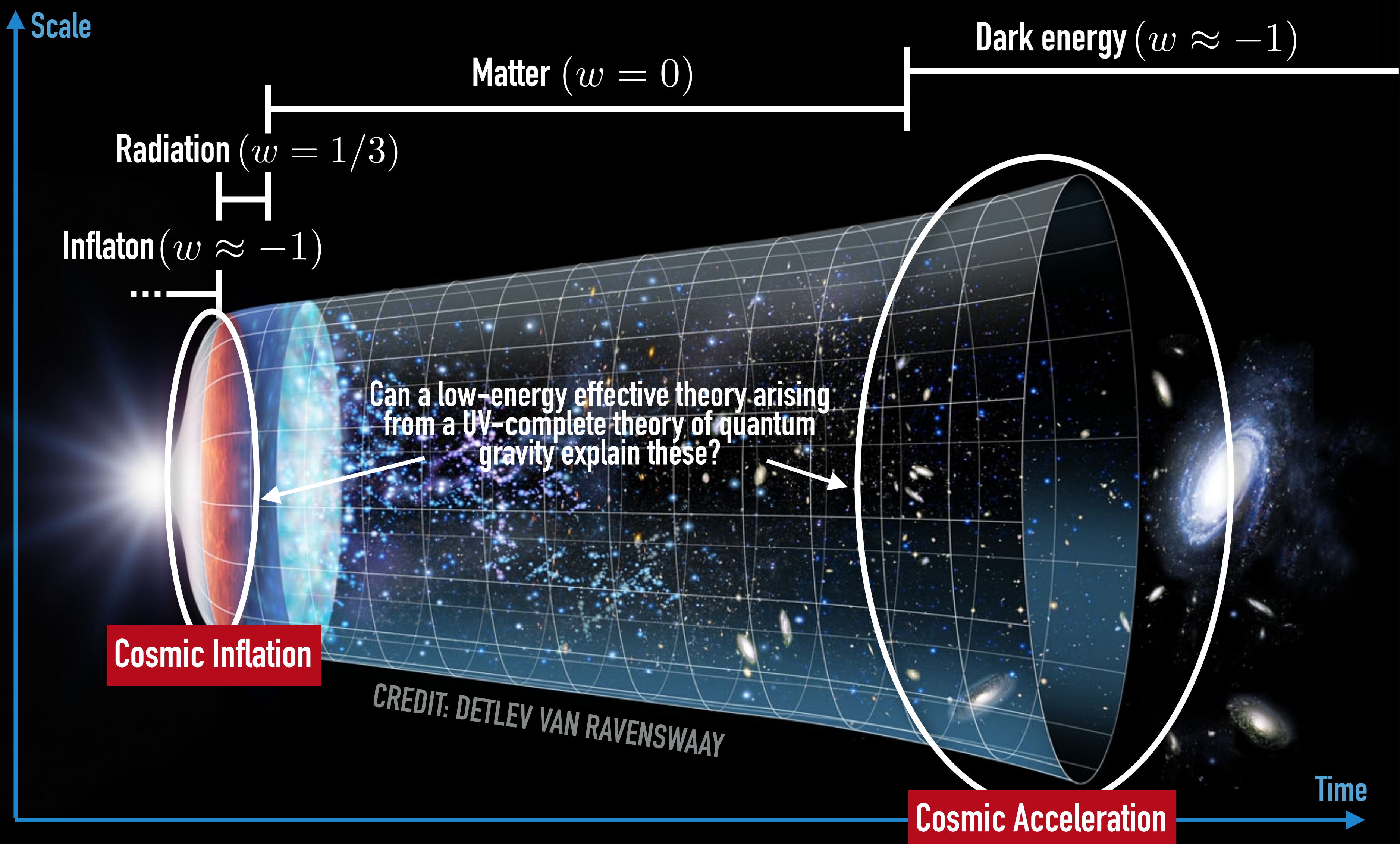


WE HAVE MEASURED THE CONTENTS OF THE UNIVERSE:

Baryons: 5%

Massive neutrinos: 0.1%

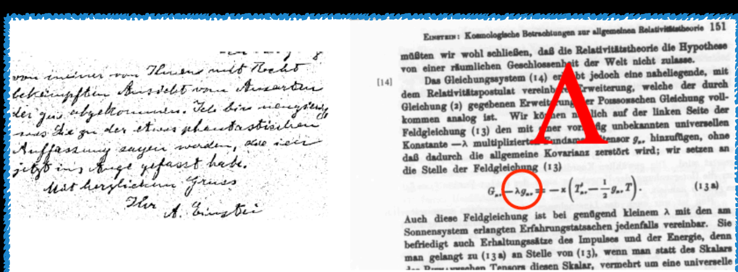
Photons: 0.01%

CDM: ~25%

Λ: ~70%

Λ AND BEYOND

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = T_{\mu\nu}$$


EINSTEIN: Kosmologische Betrachtungen zur allgemeinen Relativitätstheorie 151

müßten wir wohl schließen, daß die Relativitätstheorie die Hypothese von einer räumlichen Geschlossenheit der Welt nicht zulasse.

[14] Das Gleichungssystem (14) er[illegible]bt jedoch eine naheliegende, mit dem Relativitätspostulat vereinb[illegible] Erweiterung, welche der durch Gleichung (2) gegebenen Erweit[illegible] der Poissonschen Gleichung vollkommen analog ist. Wir kö[illegible]en n[illegible]lich auf der linken Seite der Feldgleichung (13) den mit [illegible]ner vor[illegible]fig unbekannten universellen Konstante —λ multipliziert[illegible] Fundame[illegible]tensor $g_{\mu\nu}$ hinzufügen, ohne daß dadurch die allgemeine Kovarianz zerstört wird; wir setzen an die Stelle der Feldgleichung (13)

$$G_{\mu\nu} - \lambda g_{\mu\nu} = -\kappa\left(T_{\mu\nu} - \frac{1}{2} g_{\mu\nu} T\right). \quad (13a)$$

Auch diese Feldgleichung ist bei genügend kleinem λ mit den am Sonnensystem erlangten Erfahrungstatsachen jedenfalls vereinbar. Sie befriedigt auch Erhaltungssätze des Impulses und der Energie, denn man gelangt zu (13a) an Stelle von (13), wenn man statt des Skalars

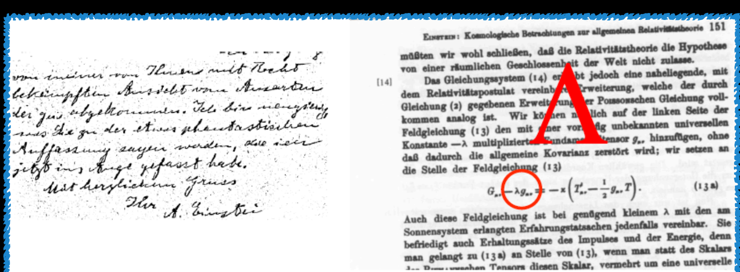
Einstein 1917

Λ

Cosmological Constant

Λ AND BEYOND

$$\underbrace{G_{\mu\nu} + \Lambda g_{\mu\nu}}_{\text{Gravity is something else}} = T_{\mu\nu}$$



Einstein: Kosmologische Betrachtungen zur allgemeinen Relativitätstheorie 151

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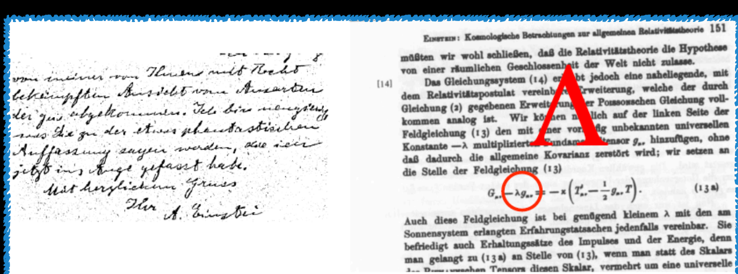

Einstein 1917

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Λ AND BEYOND

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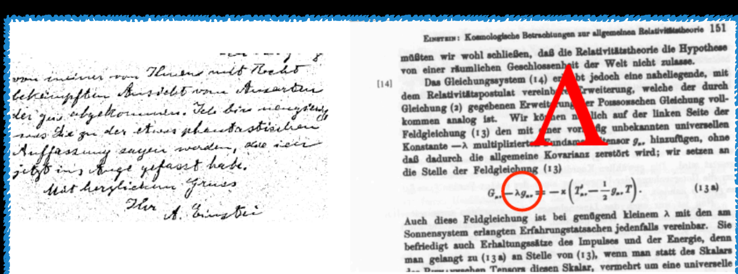
Simplest option: dynamical scalar field or quintessence

$$\frac{1}{2}\partial_\mu\phi\partial^\mu\phi + V(\phi)$$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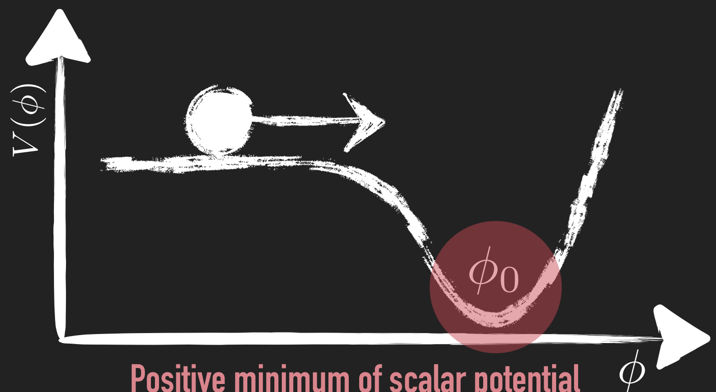
Einstein 1917

MODULI SPACE, Λ, AND QUINTESSENCE

In string theory, we have moduli $\vec{\phi}$ in moduli space with potential $V(\vec{\phi})$.



Positive minimum of scalar potential

$$\Lambda = 8\pi G_{\rm N}\, V(\phi_0)$$

Effective positive cosmological constant

String landscape

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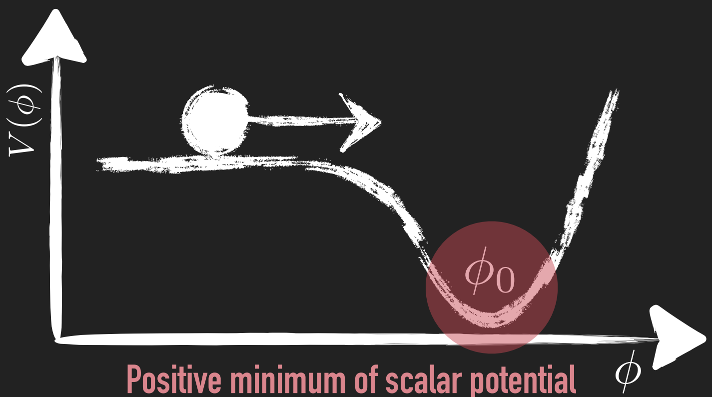

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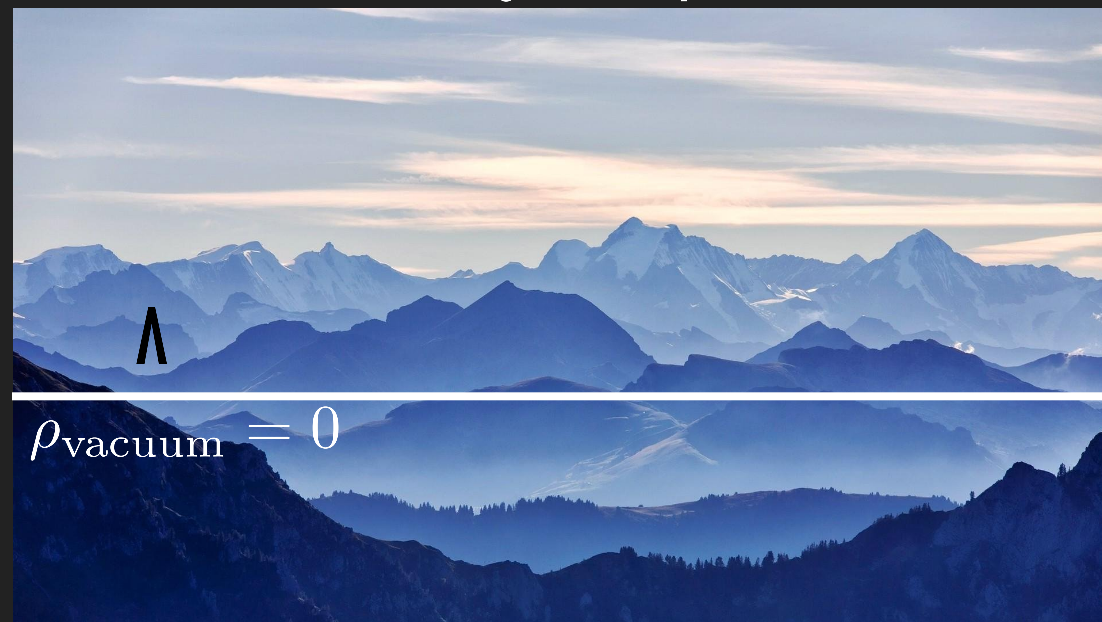
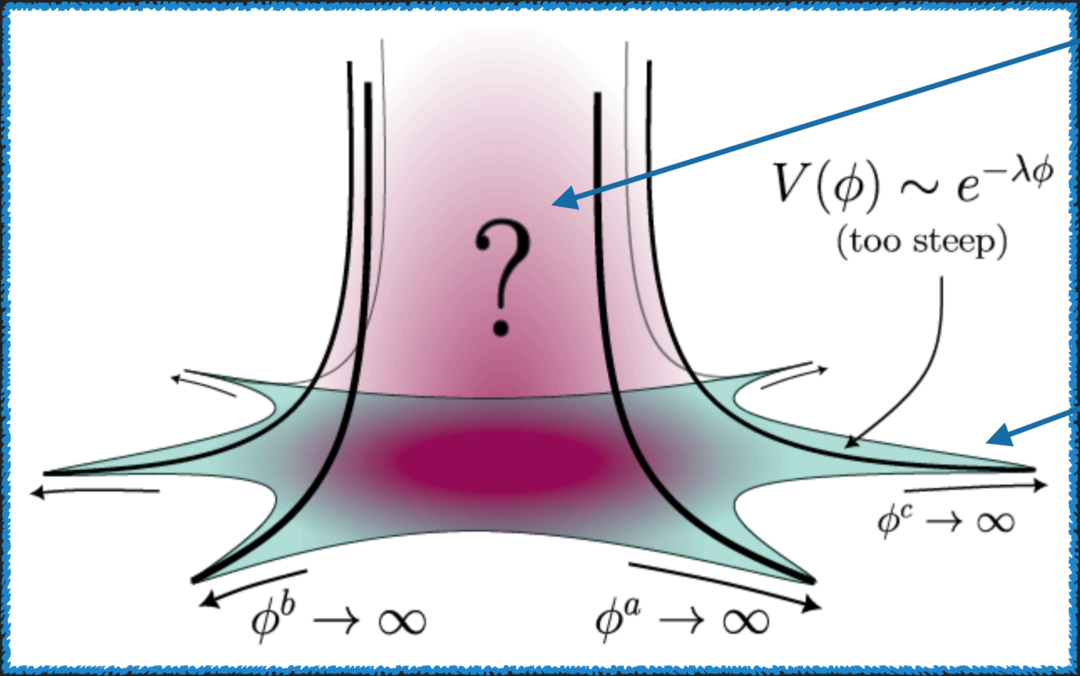


What about quintessence? Can we get it from string theory?

MODULI SPACE, Λ, AND QUINTESSENCE

CREDIT: MATILDA DELGADO



Moduli space of a string theoretic EFT

Bulk region

[theory is strongly coupled and we lose computational control]

very little is known about $V(\vec{\phi})$

Asymptotic regions

[theory is under perturbative control]

$V(\vec{\phi})$ can be reliably computed

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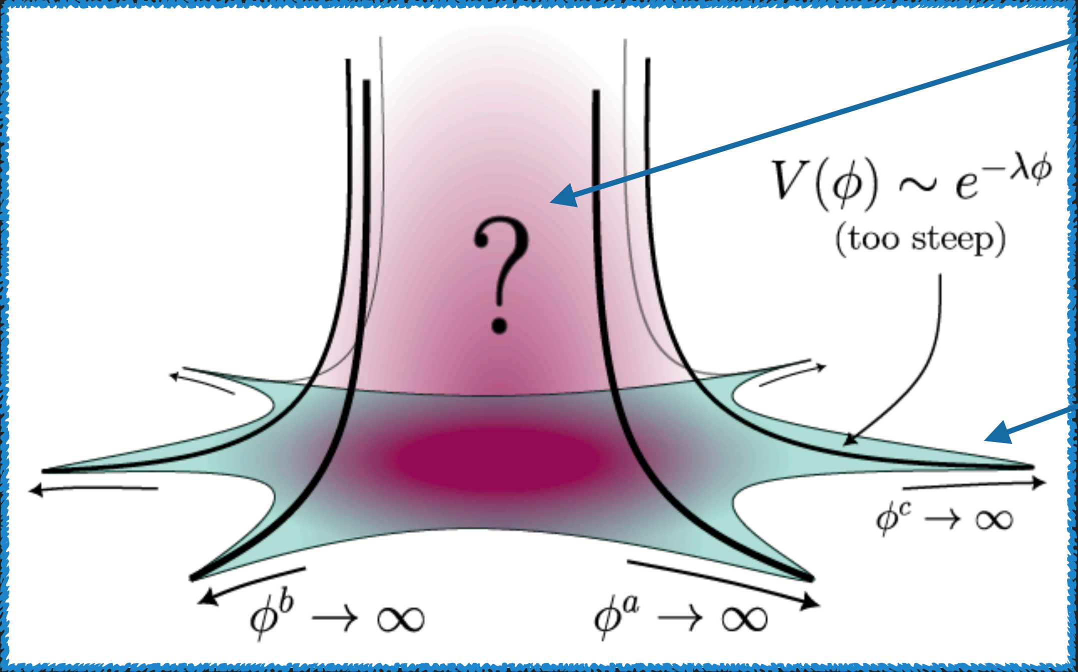

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Despite decades of effort

- realizing a de Sitter minimum in asymptotic regions remains an open question,
- every time we compute an asymptotic potential in string theory, it is a sum of exponentials $V(\vec{\phi}) = V_0 e^{-\vec{\lambda}\cdot\vec{\phi}}$

  ➔ no minimum.

  [Grimm, Li, Valenzuela 20; McAllister, Quevedo 23; Van Riet, Zoccarato 23; Castellano, Herráez, Ibáñez 22, 23]

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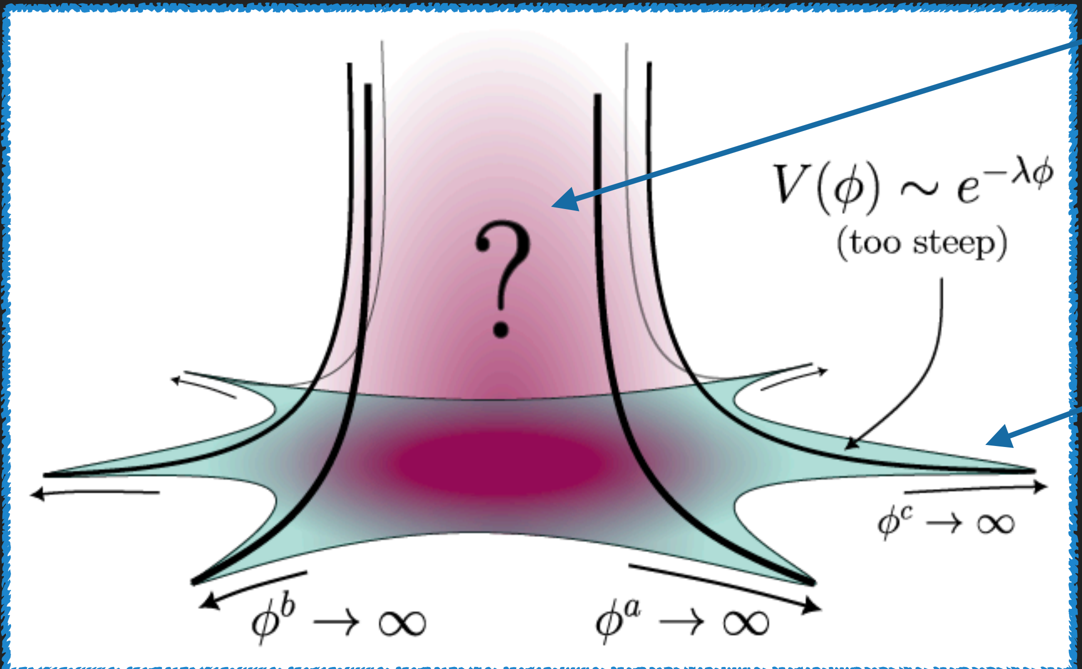

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The situation is worse:

In all known asymptotic string theory examples: [Maldacena, Nunez 01; Hertzberg, Kachru, Taylor, Tegmark 07; Obied, Ooguri, Spodyneiko, Vafa 18; Andrio 19; Andriot, Cribiori, Erkinger 20; Calderón-Infante, Ruiz, Valenzuela 22; Shiu, Tonioni, Tran 23; Cremonini, Gonzalo, Rajaguru, Tang, Wrase 23; Hebecker, Schreyer, Venken 23; Van Riet 23; Seo 24]

$$\frac{\|\nabla V\|}{V} \geq \frac{2}{\sqrt{d-2}} \quad \text{as} \quad |\phi| \to \infty$$

$$S = \int d^d x \sqrt{-g} \left\{ \frac{1}{16\pi G_N} R - \frac{1}{2} G_{ab} \partial_\mu \phi^a \partial^\mu \phi^b - V(\vec{\phi}) \right\}$$

Metric in moduli space

MODULI SPACE, Λ, AND QUINTESSENCE

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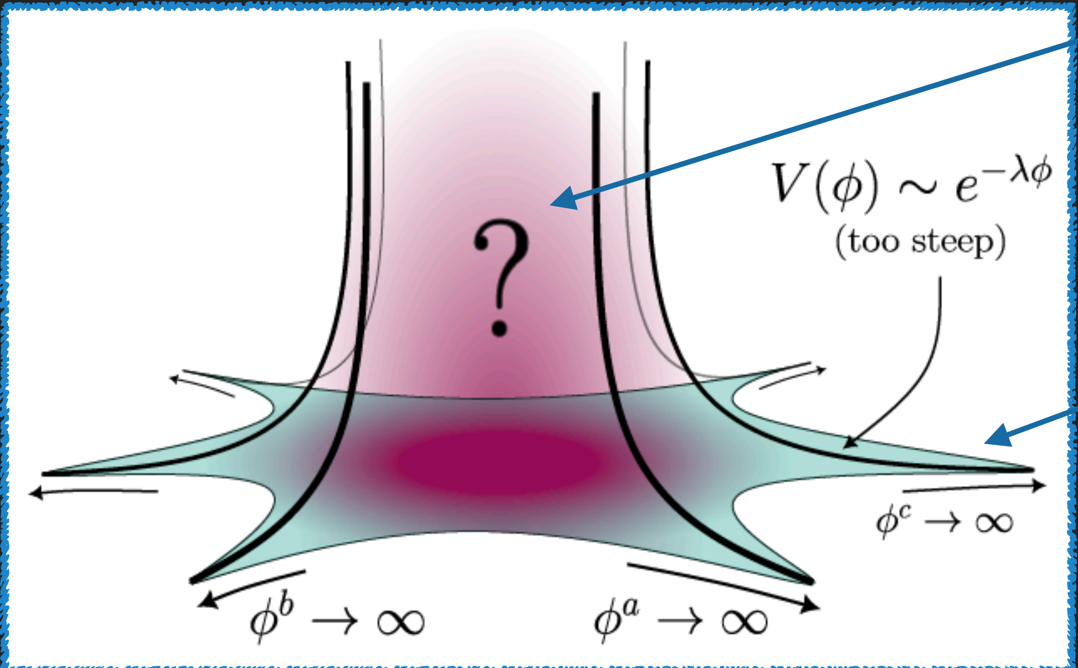

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It is conjectured to hold universally [Rudelius 21]

"Strong de Sitter conjecture"

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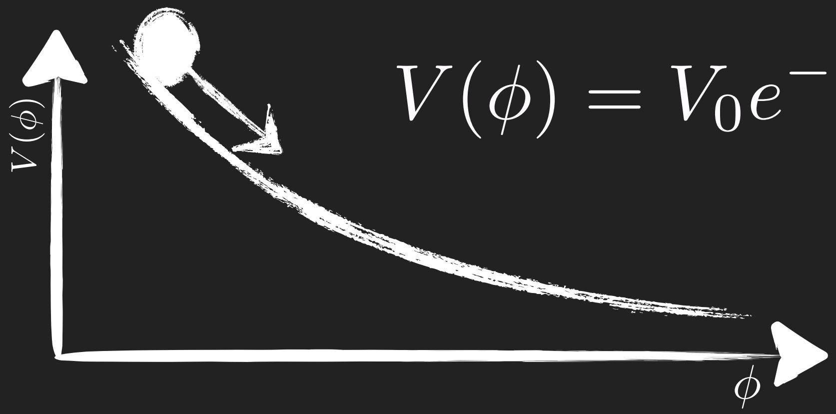
Metric in moduli space

SINGLE-FIELD QUINTESSENCE WITH EXPONENTIAL POTENTIAL



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In 4 dimensions:

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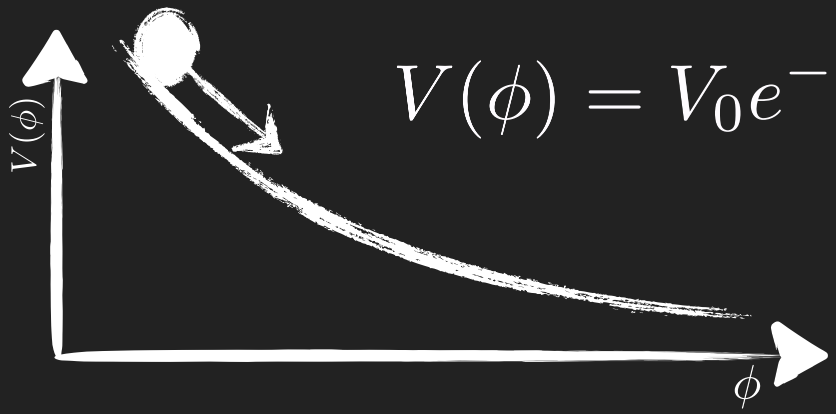

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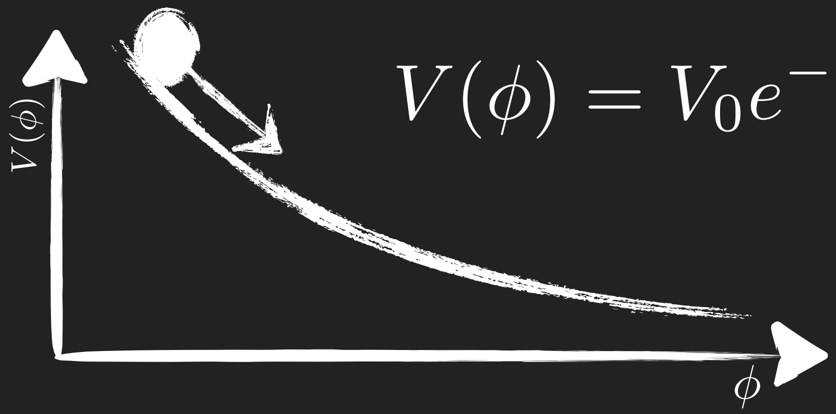

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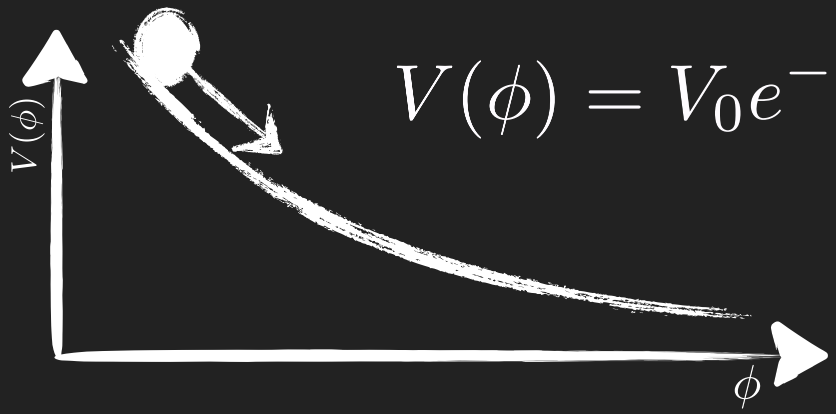

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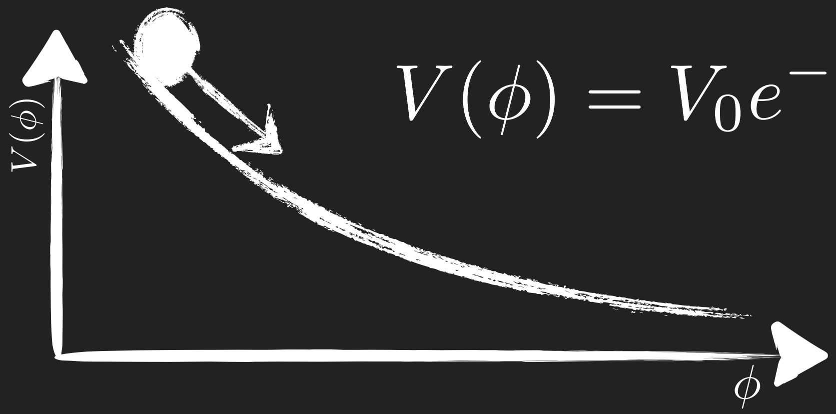

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Susha's Talk tomorrow

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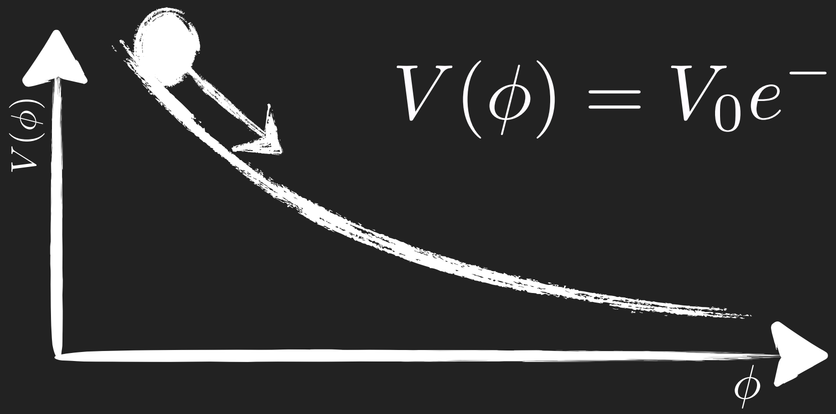

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$$2M_{\mathrm{Pl}}^2 \dot{H} = -\dot{\phi}^2 - \rho_{\mathrm{m}} + 2M_{\mathrm{Pl}}^2 \frac{k}{a^2}$$

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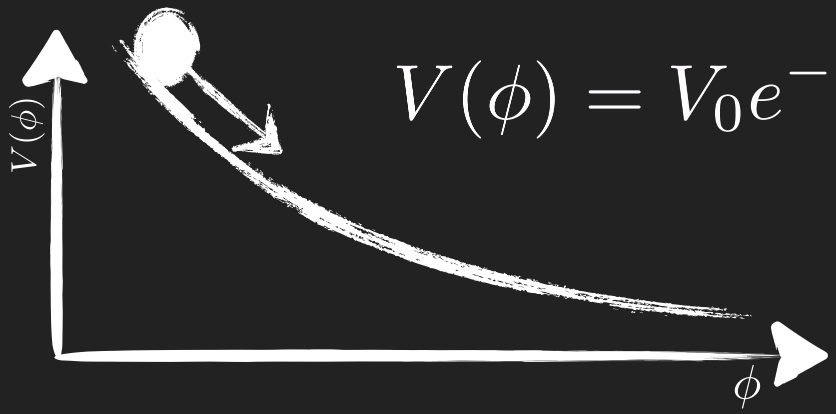

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$$\rho_\phi = \dot{\phi}^2/2 + V(\phi)$$

$$P_\phi = \dot{\phi}^2/2 - V(\phi)$$

$$w_\phi = \frac{P_\phi}{\rho_\phi} = \frac{\dot{\phi}^2/2 - V(\phi)}{\dot{\phi}^2/2 + V(\phi)}$$

Equation of state parameter for scalar field

DYNAMICAL SYSTEM

$$x \equiv \frac{\dot{\phi}}{\sqrt{6} M_{\mathrm{Pl}} H}\,, \quad y \equiv \frac{\sqrt{V(\phi)}}{\sqrt{3} M_{\mathrm{Pl}} H}\,, \quad z \equiv -\Omega_k \equiv \frac{k}{a^2 H^2}$$

$$\Omega_{\mathrm{m}} \equiv \frac{\rho_{\mathrm{m}}}{3 M_{\mathrm{Pl}}^2 H^2}$$

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$$\begin{cases} 1 = x^2 + y^2 - z + \Omega_{\rm m} \\ \dfrac{{\rm d}x}{{\rm d}N} = \sqrt{\dfrac{3}{2}}\lambda y^2 - \dfrac{1}{2}x\left(-3x^2 + 3y^2 - z + 3\right) \\ \dfrac{{\rm d}y}{{\rm d}N} = \dfrac{1}{2}y\left(3x^2 - \sqrt{6}\lambda x - 3y^2 + z + 3\right) \\ \dfrac{{\rm d}z}{{\rm d}N} = z\left(3x^2 - 3y^2 + z + 1\right) \\ N \equiv \ln a \end{cases}$$

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$$w_{\mathrm{eff}} \equiv \frac{P_\phi + P_{\mathrm{m}} + P_z}{\rho_\phi + \rho_{\mathrm{m}} + \rho_z}$$

Effective equation of state parameter

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Effective equation of state parameter

$$\epsilon \equiv -\frac{\dot{H}}{H^2} = \frac{3}{2}\left(x^2 - y^2 + 1\right) + \frac{1}{2}z \quad \Longrightarrow \quad w_{\rm eff} = \frac{2}{3}\epsilon - 1 = x^2 - y^2 + \frac{1}{3}z$$

Slow-roll parameter

DYNAMICAL SYSTEM

$$x \equiv \frac{\dot{\phi}}{\sqrt{6}M_{\mathrm{Pl}}H}\,, \quad y \equiv \frac{\sqrt{V(\phi)}}{\sqrt{3}M_{\mathrm{Pl}}H}\,, \quad z \equiv -\Omega_k \equiv \frac{k}{a^2H^2}$$

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$$\begin{cases} 1 = x^2 + y^2 - z + \Omega_{\mathrm{m}} \\ \frac{\mathrm{d}x}{\mathrm{d}N} = \sqrt{\frac{3}{2}}\lambda y^2 - \frac{1}{2}x\left(-3x^2 + 3y^2 - z + 3\right) \\ \frac{\mathrm{d}y}{\mathrm{d}N} = \frac{1}{2}y\left(3x^2 - \sqrt{6}\lambda x - 3y^2 + z + 3\right) \\ \frac{\mathrm{d}z}{\mathrm{d}N} = z\left(3x^2 - 3y^2 + z + 1\right) \\ N \equiv \ln a \end{cases}$$

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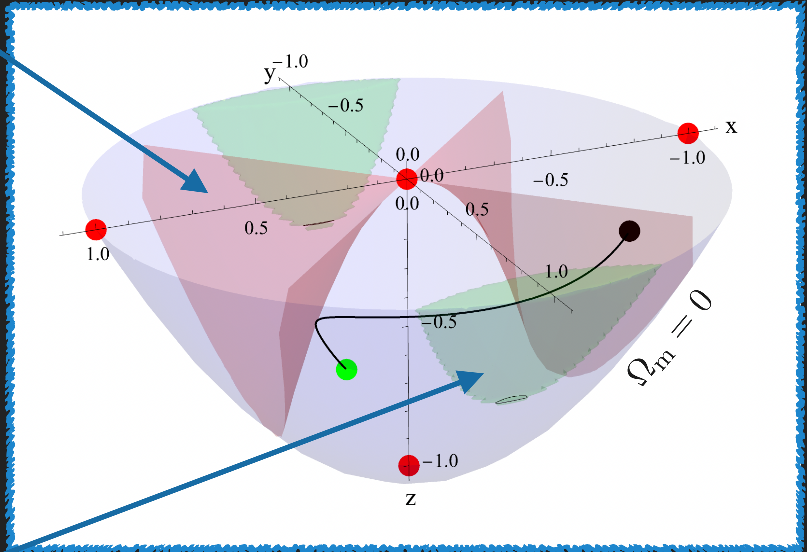
Matter domination $w_{\rm eff} = 0$

Red dots: unstable fixed points — Green dots: attractor fixed points



Phase space of the dynamical system

$$w_{\rm eff} \equiv \frac{P_\phi + P_{\rm m} + P_z}{\rho_\phi + \rho_{\rm m} + \rho_z}$$

Effective equation of state parameter

Accelerating expansion with $w_{\rm eff} \in [-1, -0.7]$

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NUMERICAL GRID ANALYSIS OF PHASE SPACE

A viable dark energy model must simultaneously:

- contain an extended period of matter domination before the onset of late-time cosmic acceleration,
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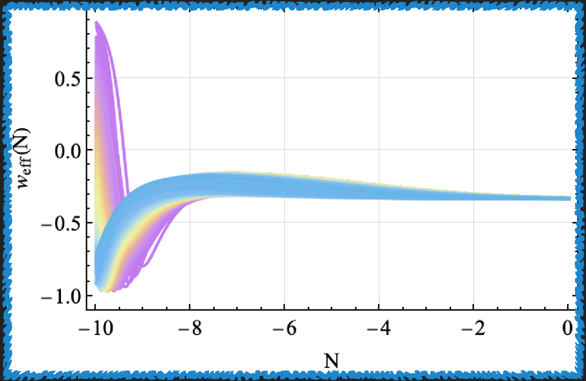

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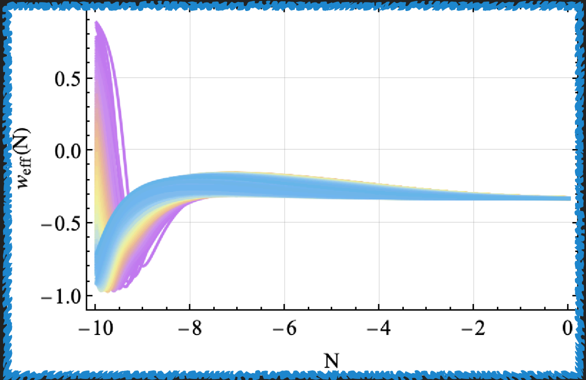

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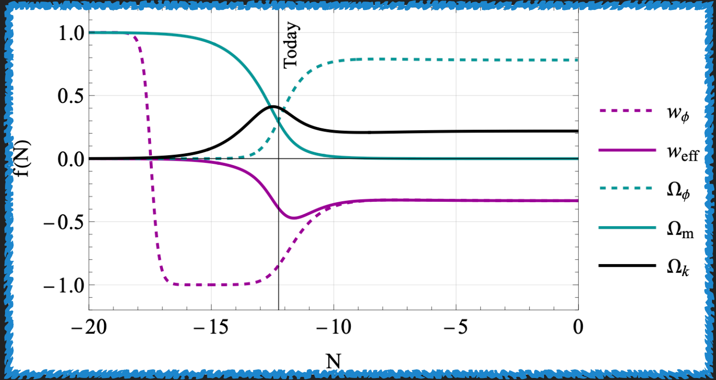
Extended matter domination



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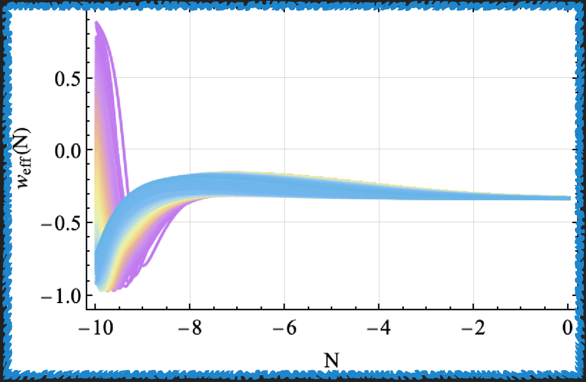

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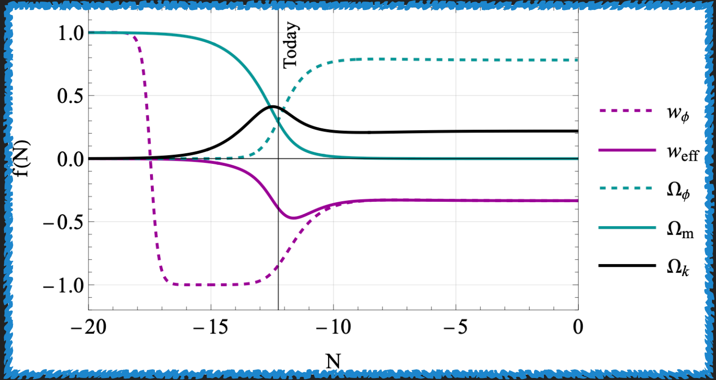

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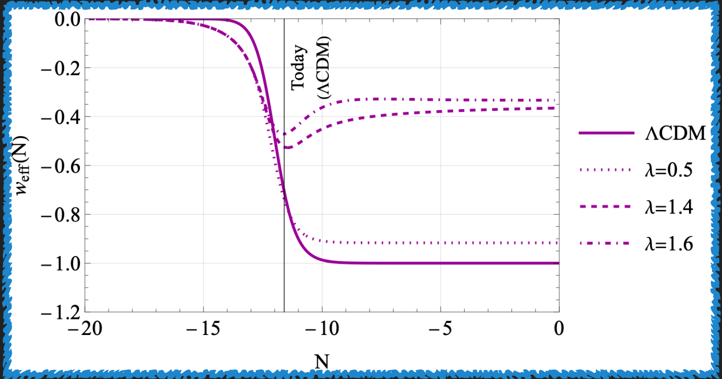

BAYESIAN ANALYSIS AND PARAMETER ESTIMATION

We perform a full MCMC analysis of the parameter space using:

- cosmic microwave background (CMB) distance priors provided by Planck
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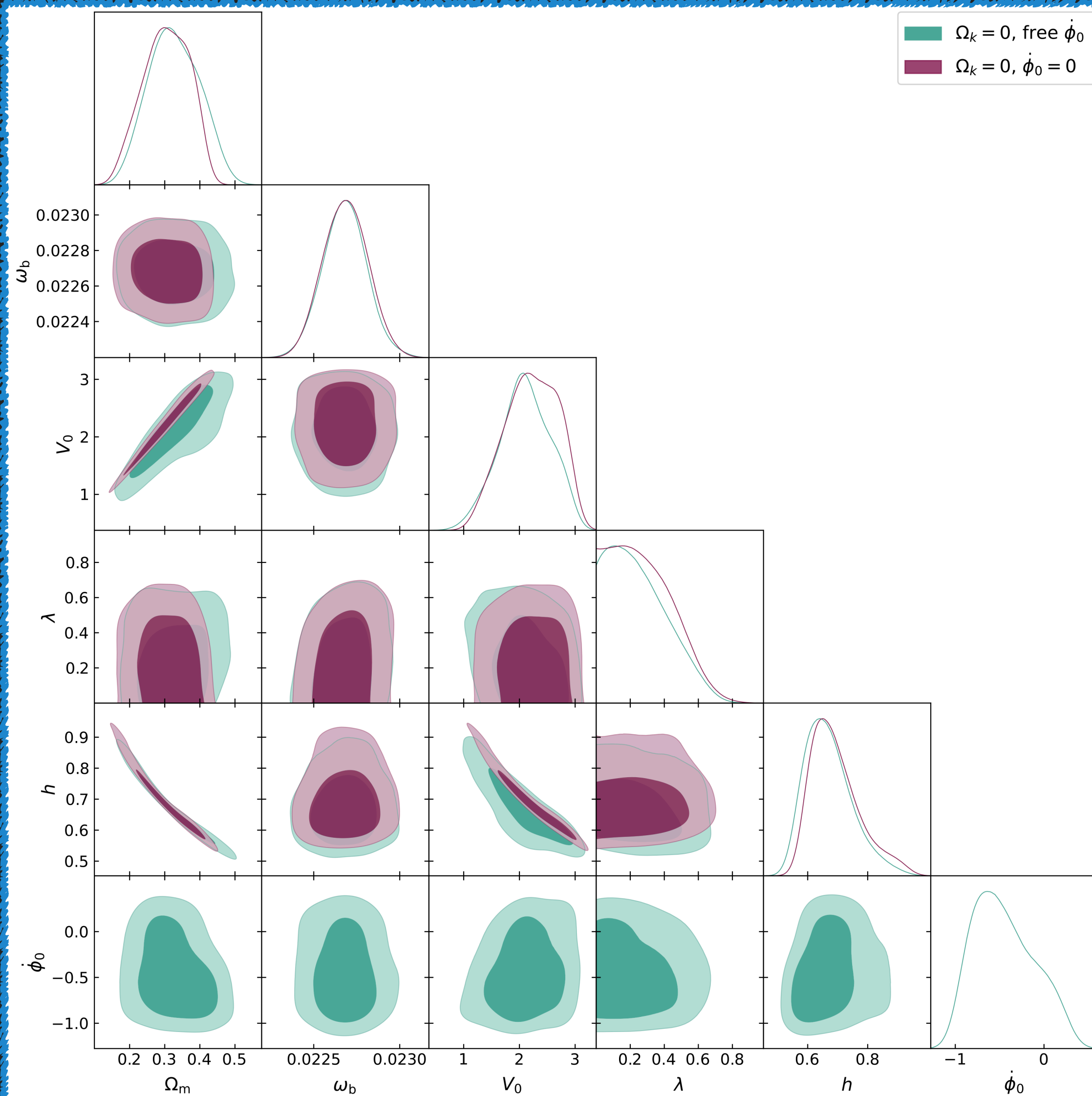

Flat universe

$$\lambda \lesssim 0.6$$

(1σ C.L.)

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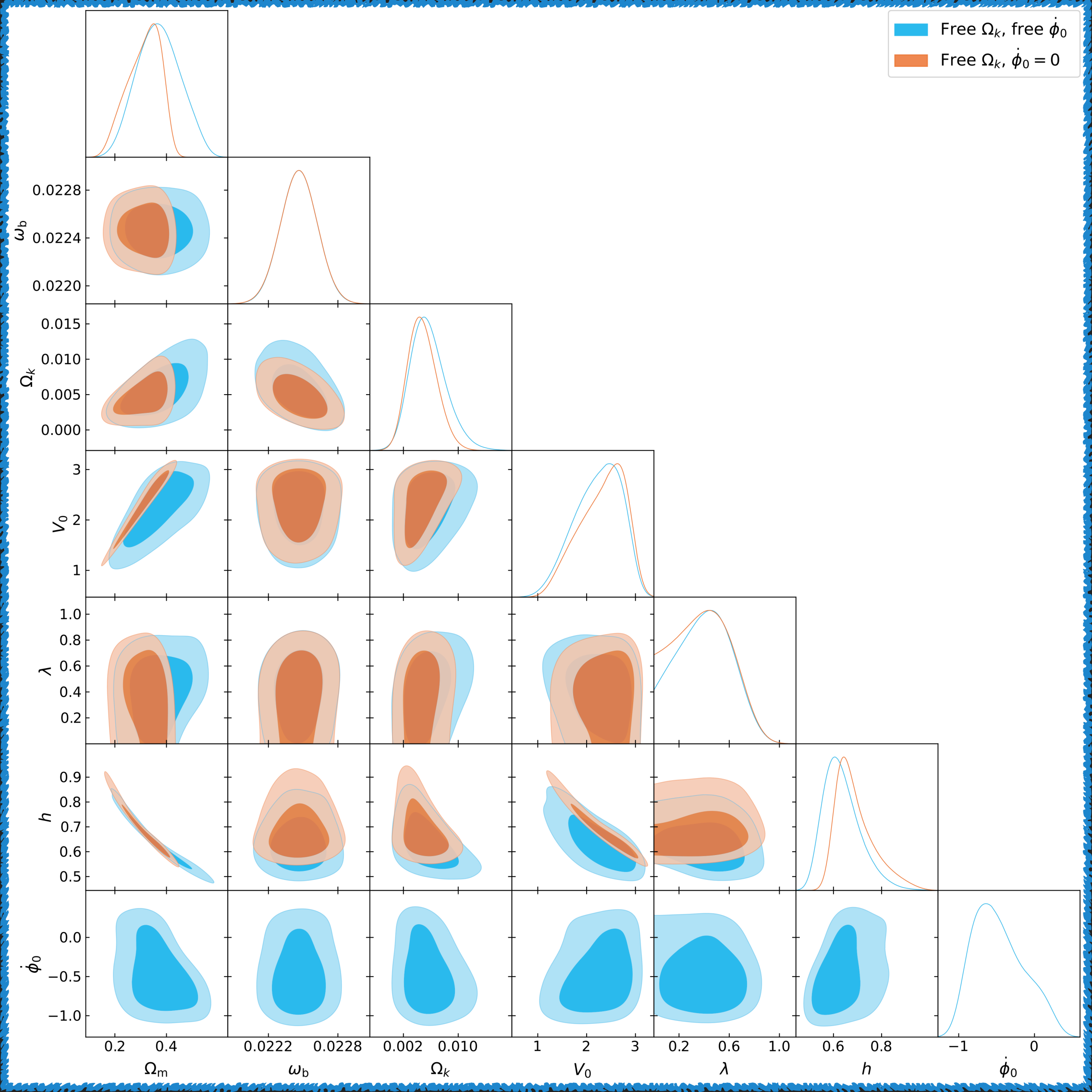

Free curvature

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SUMMARY

- Single-field models of accelerated expansion with nearly flat potentials are able to provide observationally viable explanations for the early-time cosmic inflation and the late-time cosmic acceleration
- They are in strong tension with string theory evidence and the associated de Sitter swampland constraints.
- It has recently been argued that in an open universe a new stable fixed point arises, which may lead to viable single-field-based accelerated expansion with an arbitrarily steep potential.
- We have shown, through dynamical systems analysis and a Bayesian statistical inference of cosmological parameters, that the new cosmological solutions do not render steep-potential, single-field, accelerated expansion observationally viable.
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OUTLOOK

- If the strong de Sitter conjecture is true and a universal feature of the asymptotic regions of string theory, then there seem to be two avenues to explore:
    1. construct accelerating solutions through the bulk of moduli space,
    2. construct models with more than one scalar field, although this too may be challenging in asymptotic corners of string theory due to universal features of the moduli space metric.