Dark energy and string theory: an update

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Introduction

Our universe is currently expanding + expansion is **accelerating**

⟶ What is the energy responsible for this acceleration? ⟶ **Dark energy**

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$\longrightarrow$ 4d theory of scalar fields φ^i minimally coupled to gravity:

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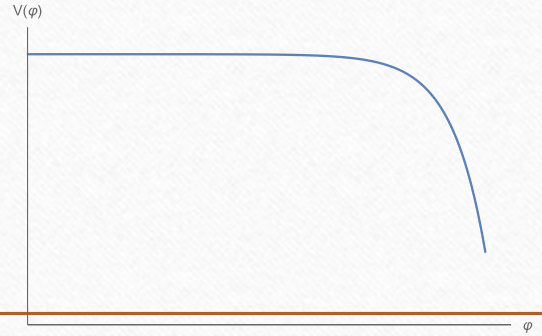
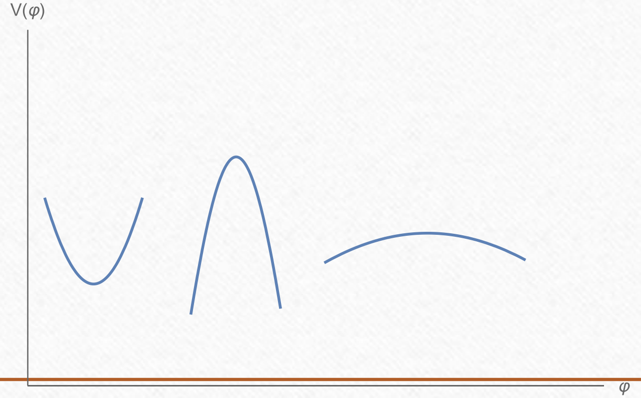
Prime example: cosmological constant $\Lambda = \frac{V}{M_p^2} =$ constant, ✓ in agreement with current observations

$\longrightarrow$ several ways to have an (almost) constant V

almost flat,
plateau V



critical point,
de Sitter solution
$V' \equiv \partial_\varphi V = 0$



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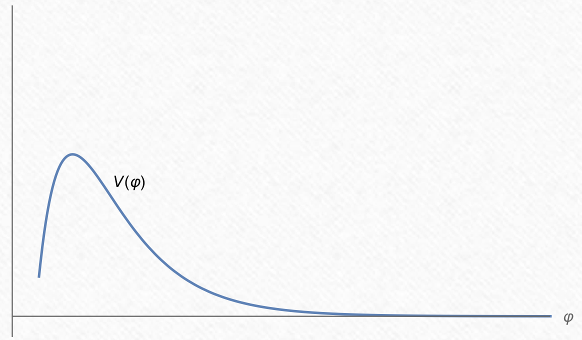

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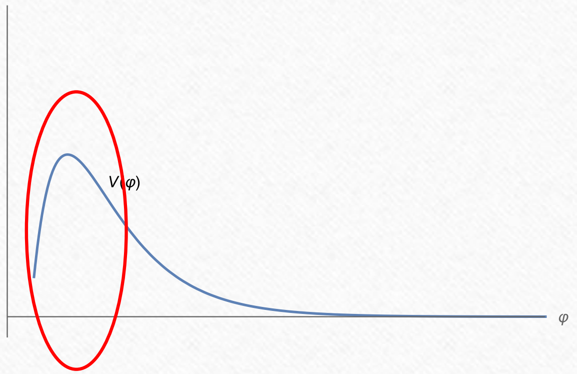

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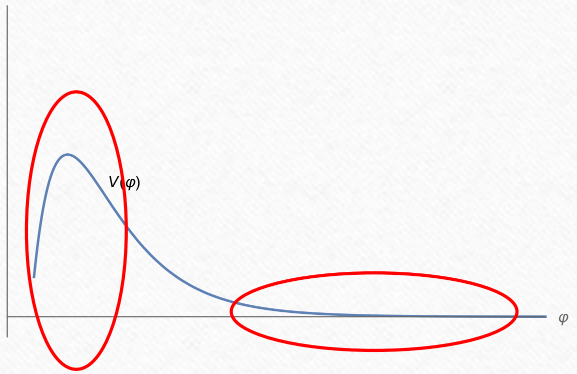

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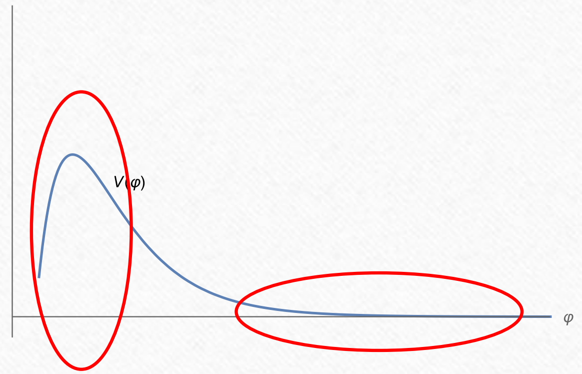
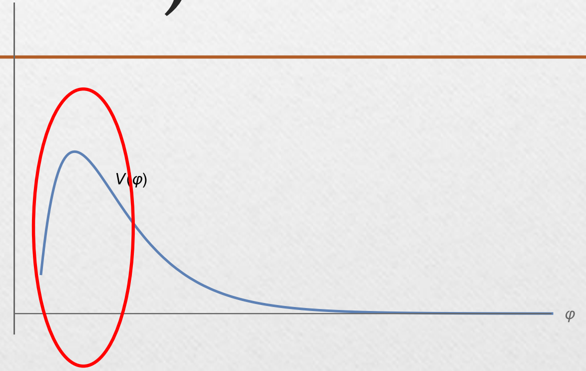


Role played by **space curvature**, captured by k (FLRW)
or Ω_k (observations)
$k = -1$ offers ✓ options for high $\frac{|V'|}{V}$ and string models

$\longrightarrow$ (leave aside **transient** scenarios)

I. (Classical) de Sitter solutions



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KKLT, LVS

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⟶ debate on validity of approximations/regimes/control

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2. verify that solution obeys class. approx.: $g_s \sim e^{\phi} < 1,\ r > l_s,\ \ldots$ Difficult to check

typically not well realised / boundary of validity / grey zone (no parametric control)

No known good classical de Sitter solution;

still instructive to study 10d supergravity candidate solutions

⟶ find common **properties**

All de Sitter solutions only found with at least 3 (intersecting) sets of O_p/D_p.

Examples: s_{6666} : O_6 along 123, 145, 256, (346)

s_{55} : O_5 along 12, 34, D_5 along 56

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Previously: **Conjecture 1**: *no de Sitter solution with 1 set (i.e. parallel O_p/D_p).* Andriot ’19

Here: **Conjecture 4**: *no de Sitter solution with 2 (intersecting) sets of O_p/D_p.*

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Great news for phenomenology! $\mathcal{N} \leq 1$ better for particle physics (chirality).
Here a common stringy framework for (viable) cosmology and particle physics *naturally* appears.

+ important role for dS_d , $d > 4$ ($\longrightarrow$ no solution?) Andriot, Horer '22

From 10d supergravity solution (database IIA/B) $dS_4 \times$ 6d group manifold

$\longrightarrow$ dimensional reduction / consistent truncation to 4d theory with V

Automatized into code `MSSV.nb` : 10d solutions $\longrightarrow g_{ij}(\varphi^k),\ V(\varphi^k)$

Andriot, Marconnet, Rajaguru, Wrase '22

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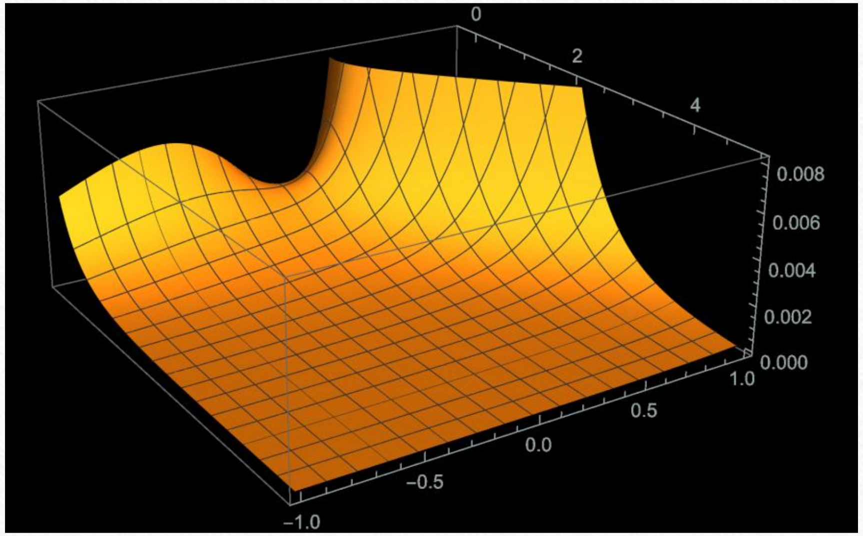

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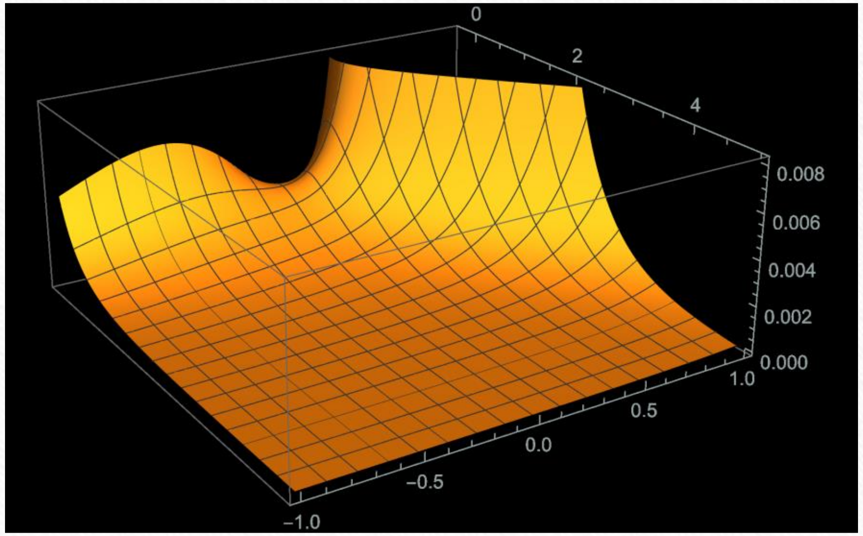

$$V^{\rm IIB}(\varphi^i) = \frac{M_p^2}{2}\frac{e^{2\phi}}{vol_6}\Bigg(-R_6 + \frac{1}{2}|H_3|^2_{\rm int} - e^{\phi} \sum_{p=3,5,7,9} \frac{T_{10}^{(p)}}{p+1} + \frac{e^{2\phi}}{2}\bigg[|F_1|^2_{\rm int} + \big|F_3 - C_0 \wedge H_3 + F_1 \wedge B_2\big|^2_{\rm int} + \Big|F_5 - C_2 \wedge H_3 + F_3 \wedge B_2 - C_0 \wedge H_3 \wedge B_2 + \frac{1}{2} F_1 \wedge B_2 \wedge B_2\Big|^2_{\rm int} \bigg]\Bigg)$$

(also for Mink., AdS sol.)

For $\varphi \sim e^{-\phi},\, r/l_s$, **bulk** of field space: strong coupling, stringy regime

asymptotics: weak coupling, low energy ⟶ classical

But **classical regime** starts away from asymptotics / grey zone in the bulk at $e^{\phi} \lesssim 1,\ r/l_s \gtrsim 1$

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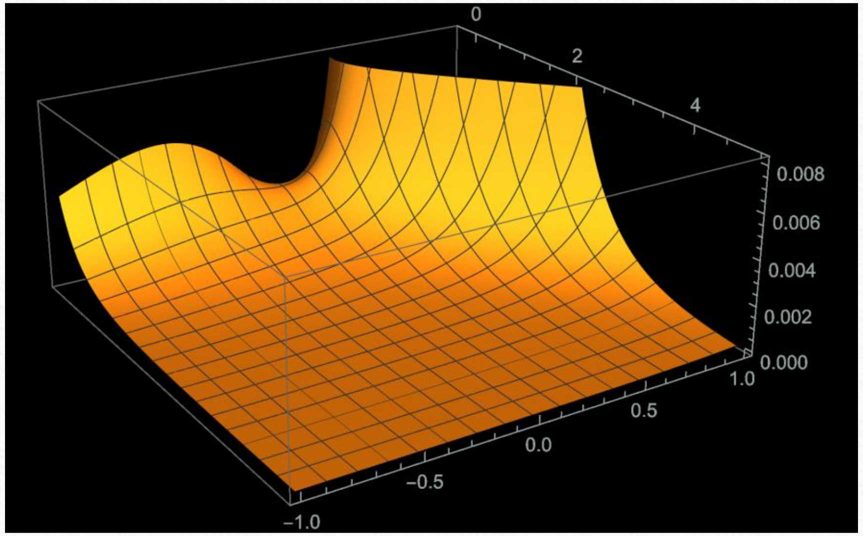
A whole region (towards asymptotics) where classical regime / **trustable** V

⟶ of interest to further applications



All dS solutions found are **perturbatively unstable**:
at least one tachyonic field/maximum

$$\longrightarrow \eta_V < 0 \quad \text{with} \quad \eta_V = M_p^2 \, \frac{\mathrm{Min}\left(g^{ik}\nabla_k \partial_j V\right)}{V}$$

Is this bad for cosmology? No dS vacuum but ok with inflation or quintessence…

Single-field slow-roll inflation: data: $\eta_V \sim -0.01$ Planck '18

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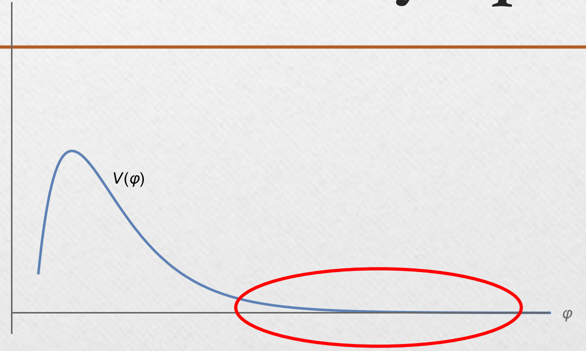
Summary: « classical » dS solutions: in the bulk, grey zone; unstable
At hand many examples of $g_{ij}(\varphi^k), \; V(\varphi^k)$ away from dS critical point.

Probably no dS_d solution with $d > 4$ (related to susy)

II. Rolling fields and asymptotic slopes



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Cosmology with potential slopes and rolling fields: inflation, quintessence

Can we get $\frac{|V'|}{V} \ll 1$: quasi de Sitter / almost flat V ? $\longrightarrow$ Very unlikely!

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Discussions, refinements: this cannot be true everywhere in field space
⟶ only true in the **asymptotics** of field space: $\varphi \to \infty$

Trans-Planckian Censorship Conjecture Bedroya, Vafa '19
(**TCC**):

$$\varphi \to \infty, \quad \frac{|V'|}{V} \geq \sqrt{\frac{2}{3}} \approx 0.82$$

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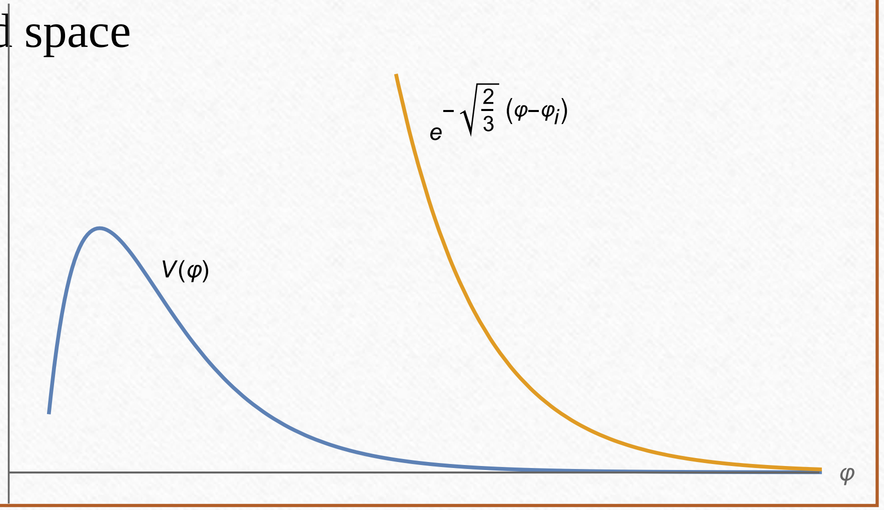

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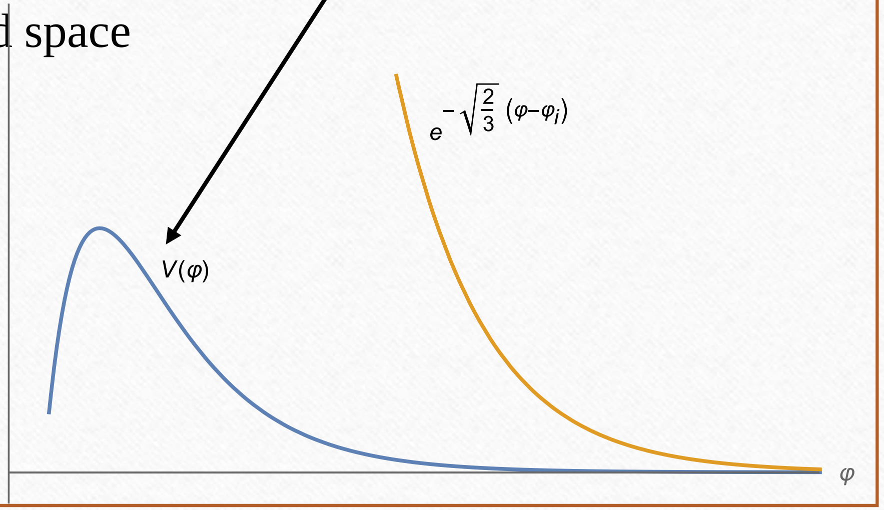
Bulk of field space: dS solution or slow-roll inflation



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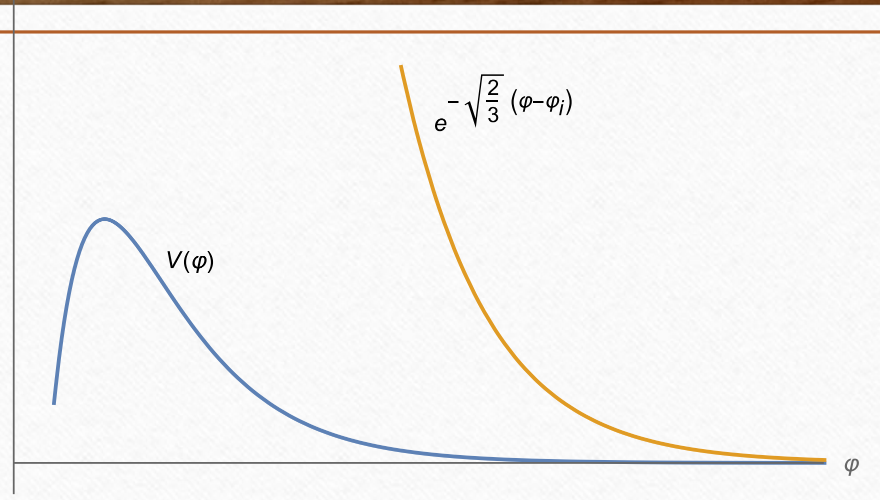

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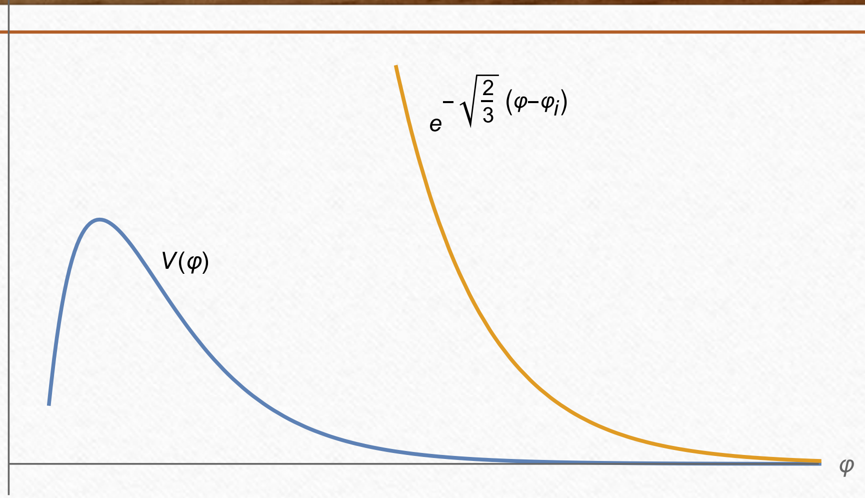

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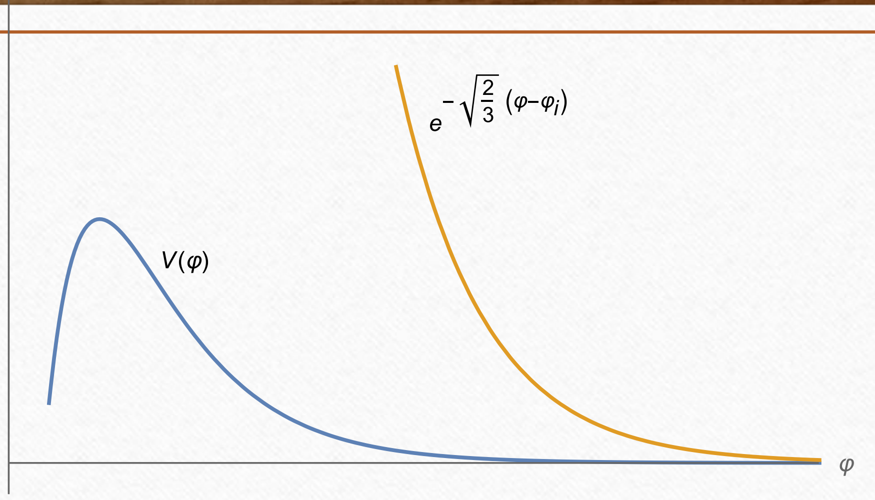

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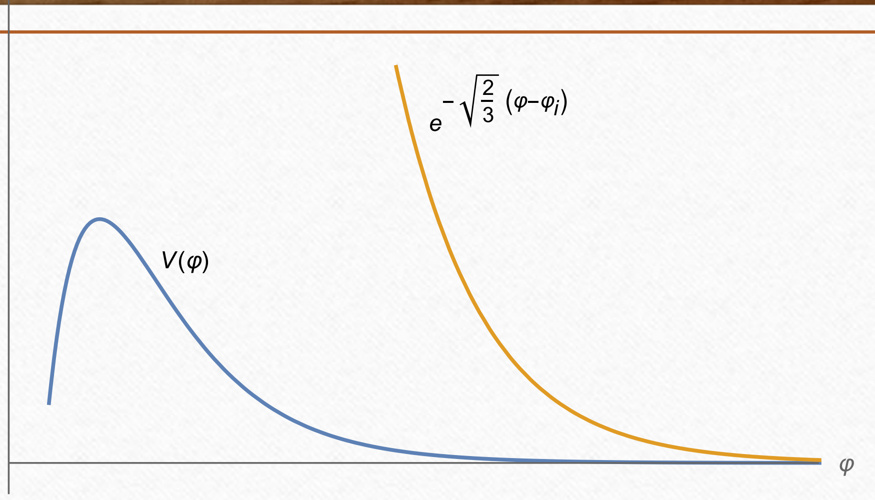

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  Result: $c \geq \sqrt{\frac{2}{3}}$ Andriot, Cribiori, Erkinger '20

Impressive/surprising matching because TCC based on bottom-up/effective cosmology argument

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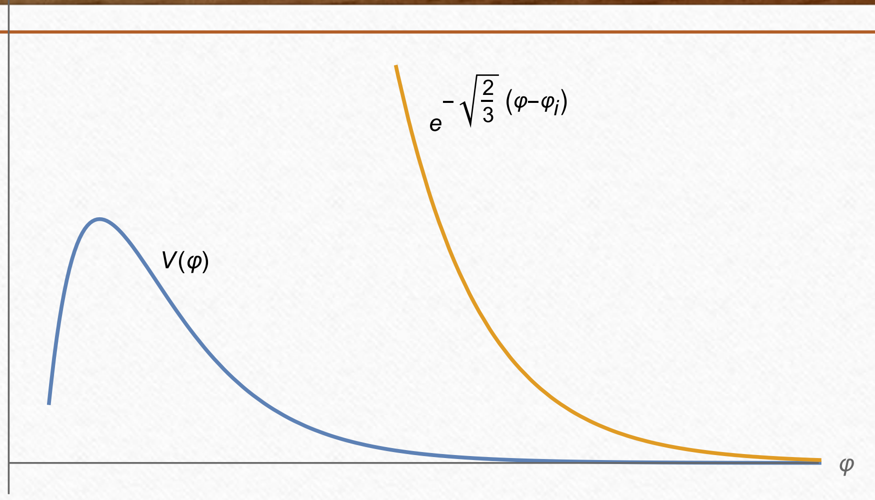
$$\varphi \to \infty, \ \frac{|V'|}{V} \geq \sqrt{\frac{2}{3}} \approx 0.82 \qquad \left(d \geq 4 : \frac{|V'|}{V} \geq \frac{2}{\sqrt{(d-1)(d-2)}} \right)$$



Asymptotics of field space ~ string classical regime

$$g_s \ll 1, \ r \gg l_s$$

Obstruction to dS in the asymptotics ⟷ difficulties with classical dS

This link made precise with **supergravity no-go theorems**:

- in $d = 4$: 10 no-go theorems against classical dS_4 reformulated in the form $\frac{|V'|}{V} \geq c$

  Result: $c \geq \sqrt{\frac{2}{3}}$ Andriot, Cribiori, Erkinger '20

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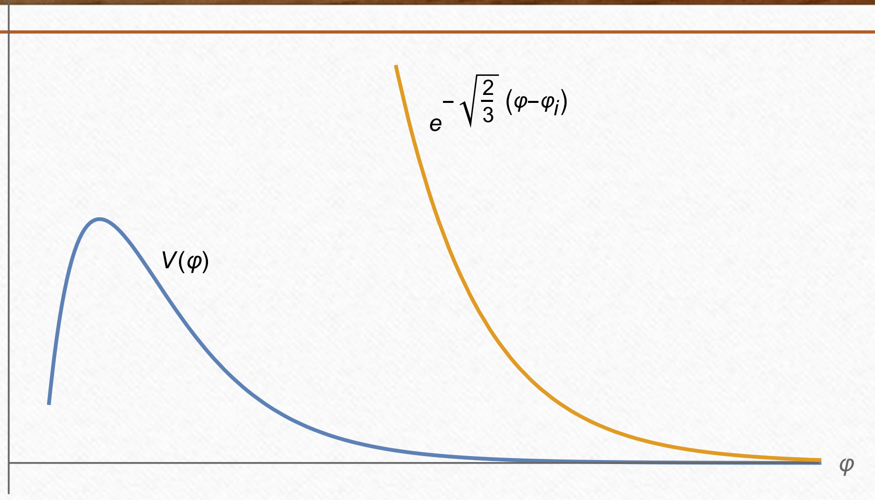

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Many supergravity compactification potentials obey TCC asymptotic bound

4d multifield: **Strong de Sitter conjecture** (asymptotics in field and time): $\frac{\nabla V}{V} \geq \sqrt{2}$ Rudelius ’21, ’22

No known counter example from string models potentials

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More dramatic: theoretical bound on **asymptotic accelerated expansion**: $\gamma \leq \sqrt{2}$

Halliwell '86, Copeland, Liddle, Wands '97
Shiu, Tonioni, Tran '23

⟶ explain and extend this

Andriot, Tsimpis, Wrase, '23

Take a single (canonically normalized) field and $V = V_0\, e^{-\gamma\, \varphi}$

Take FLRW metric with arbitrary space curvature, $k = 0, \pm 1$

(observations: very small Ω_k , compatible with $k = 0$ or diluted (expansion) $k \neq 0$)

Write down 3 equations of motion

$\longrightarrow$ can be rewritten as a dynamical system $\longrightarrow$ **study the fixed points**

$\longrightarrow$ **relevant for asymptotics!!**

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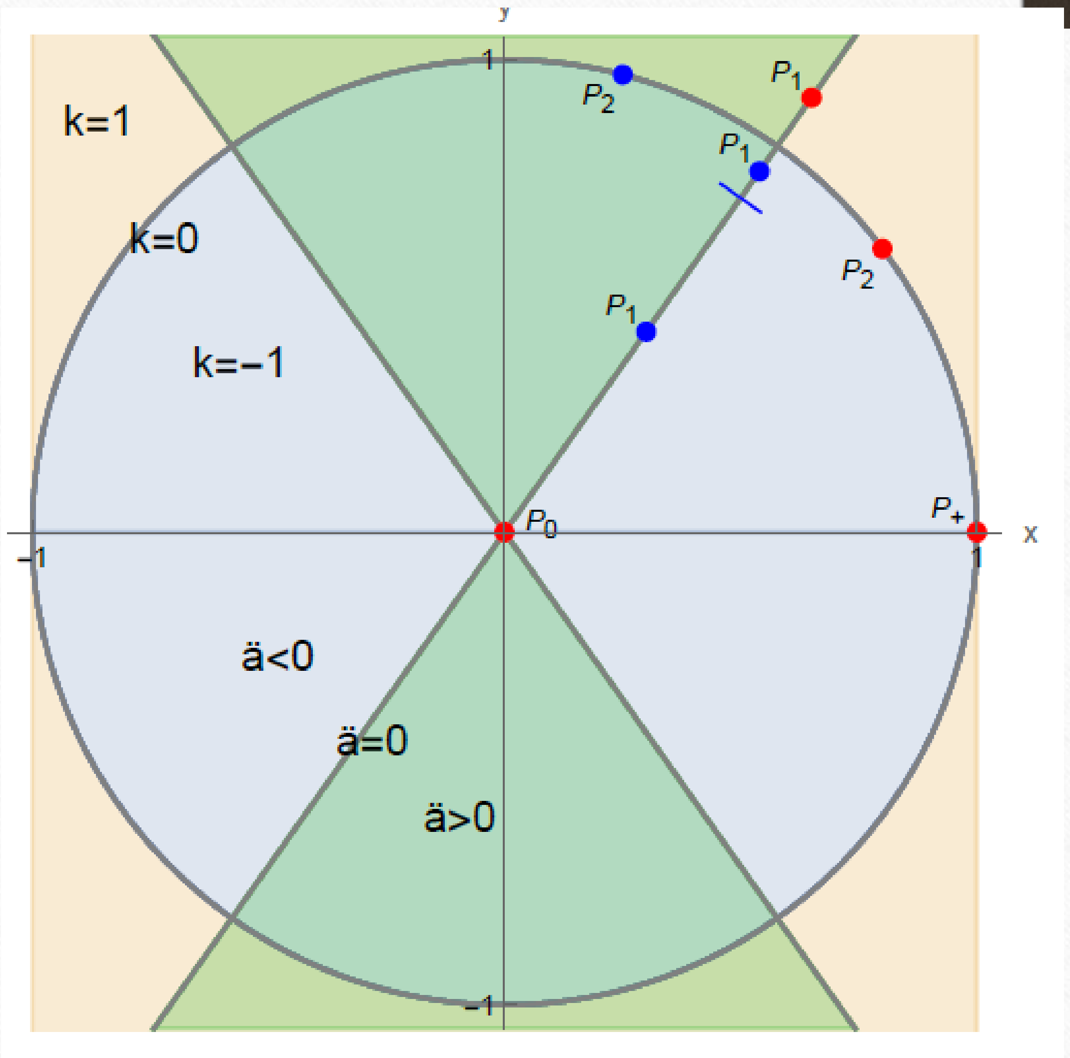
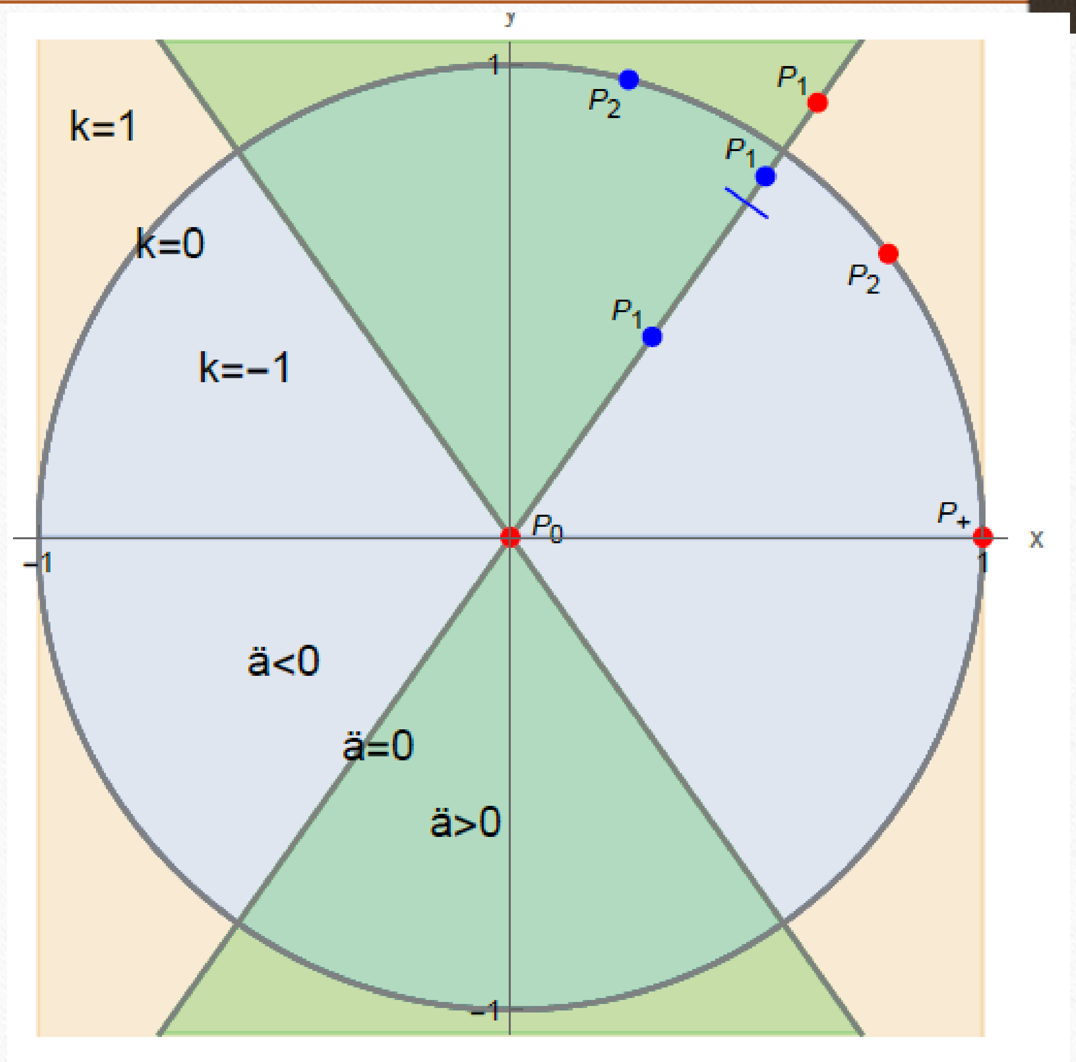
Acceleration at P_1 : no! $\ddot{a} = 0$

But solutions in its **vicinity** exhibit (eternal) acceleration!

$\longrightarrow$ « **asymptotic acceleration** »!



Phase space $(x, y) = \left(\frac{\dot{\varphi}}{H\sqrt{6}}, \frac{\sqrt{V}}{H\sqrt{3}}\right)$



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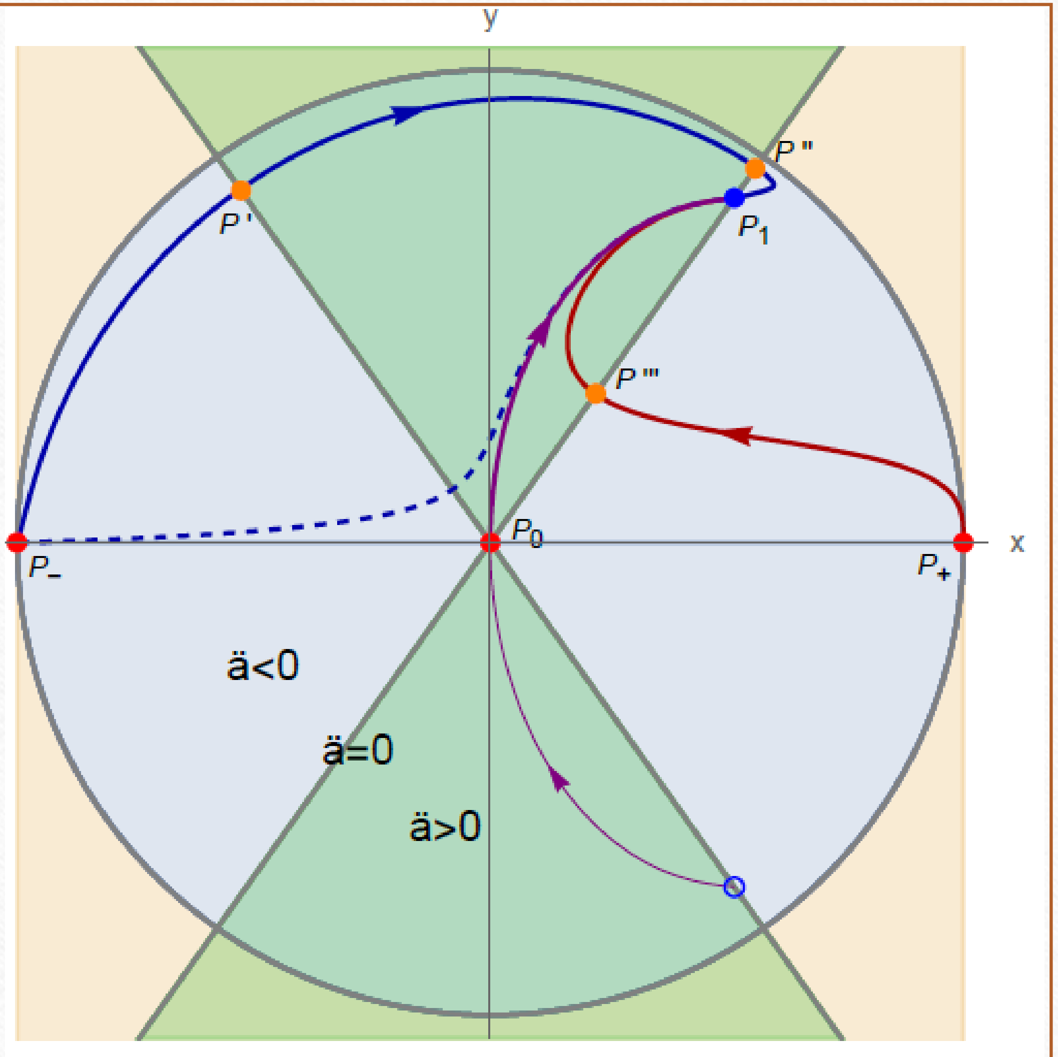
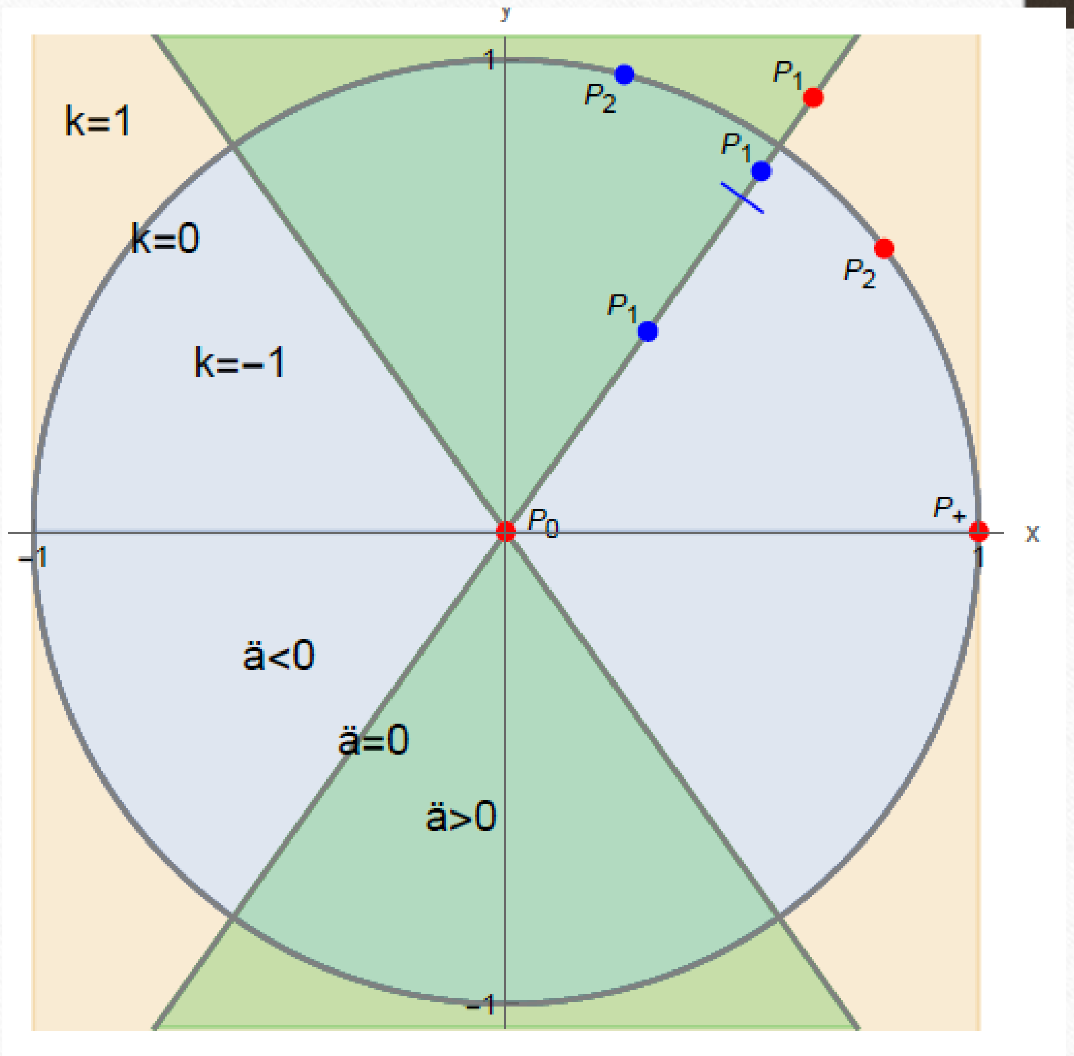


Cosmological solutions asymptoting to P_1



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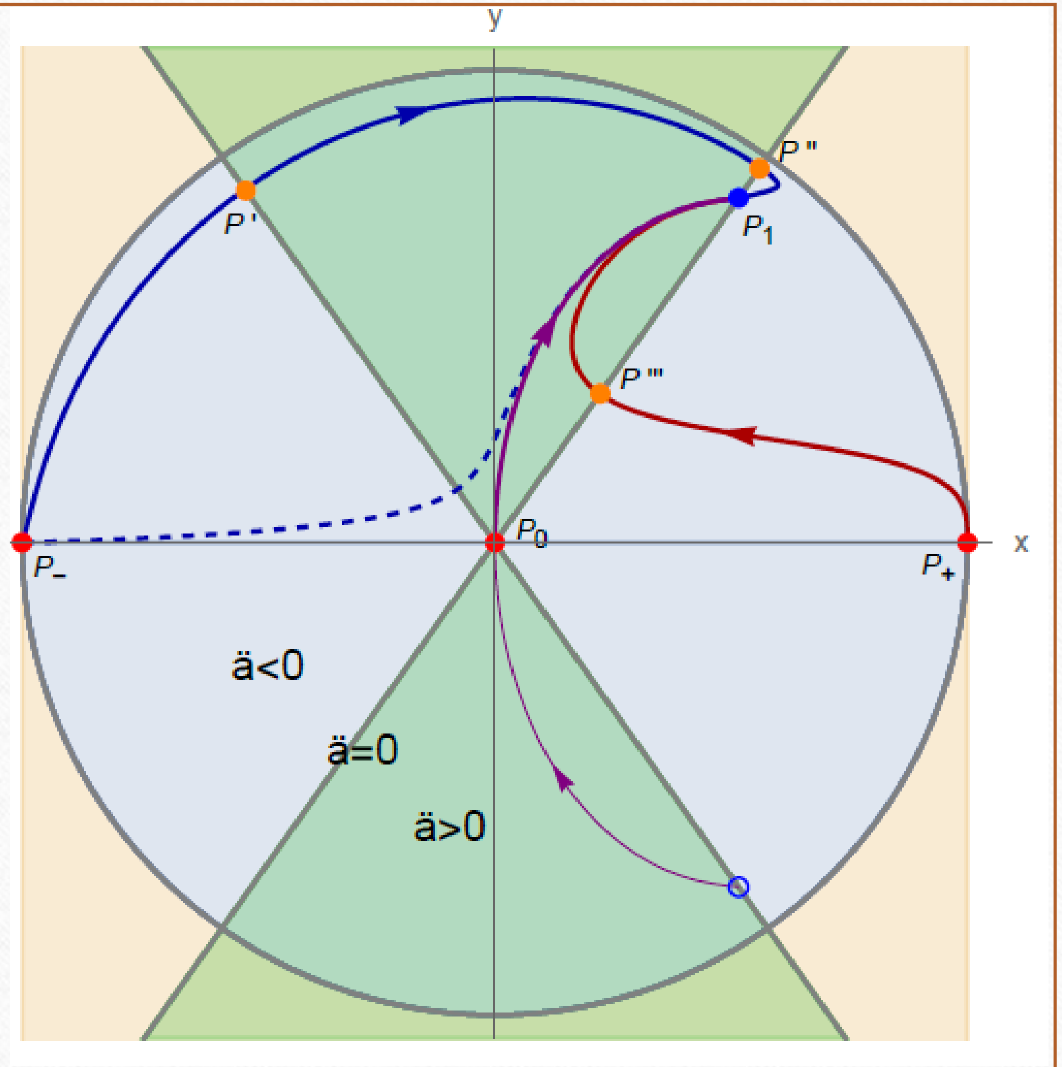
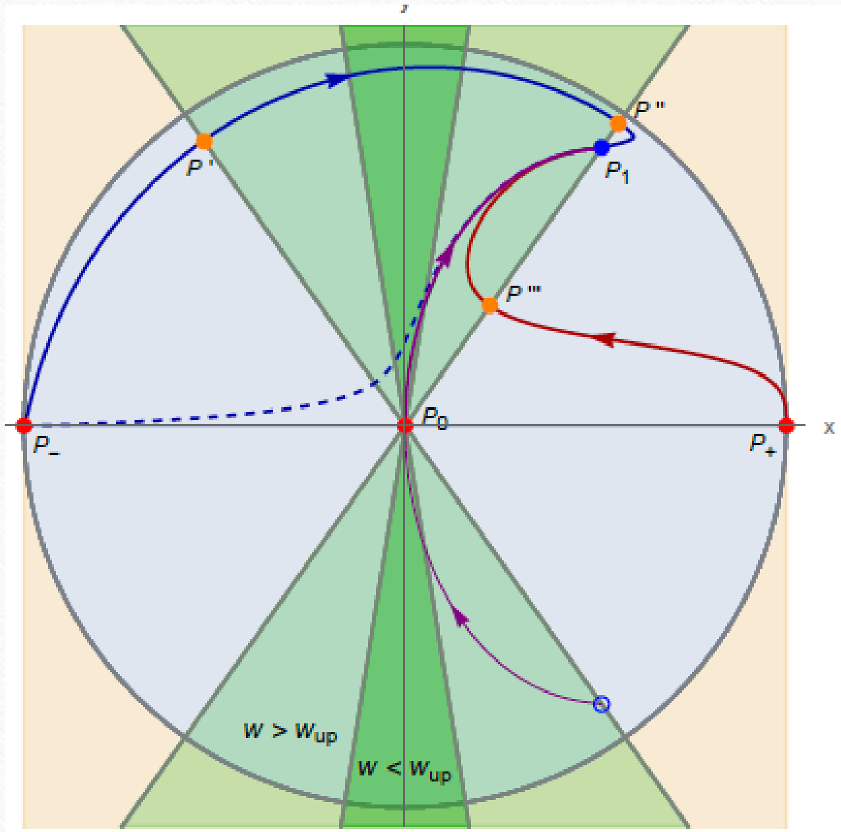
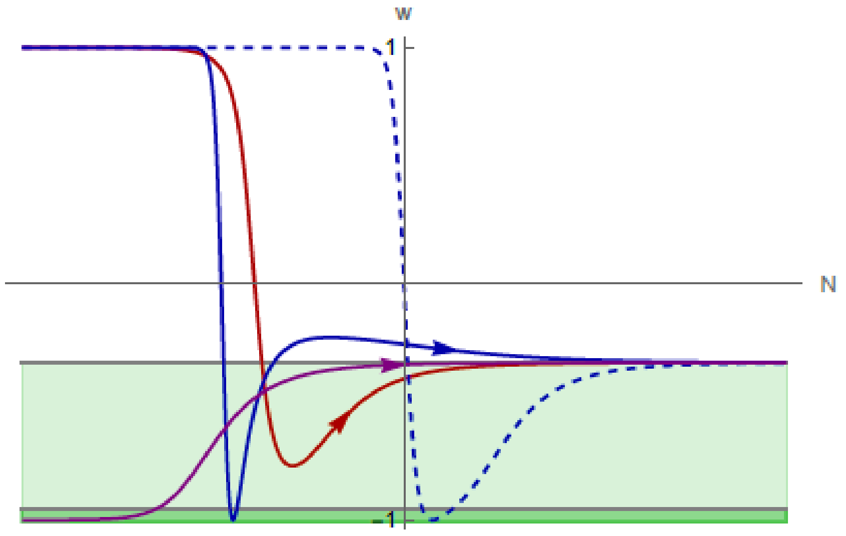


Cosmological solutions asymptoting to P_1

Acceleration: eternal, semi-eternal, transient

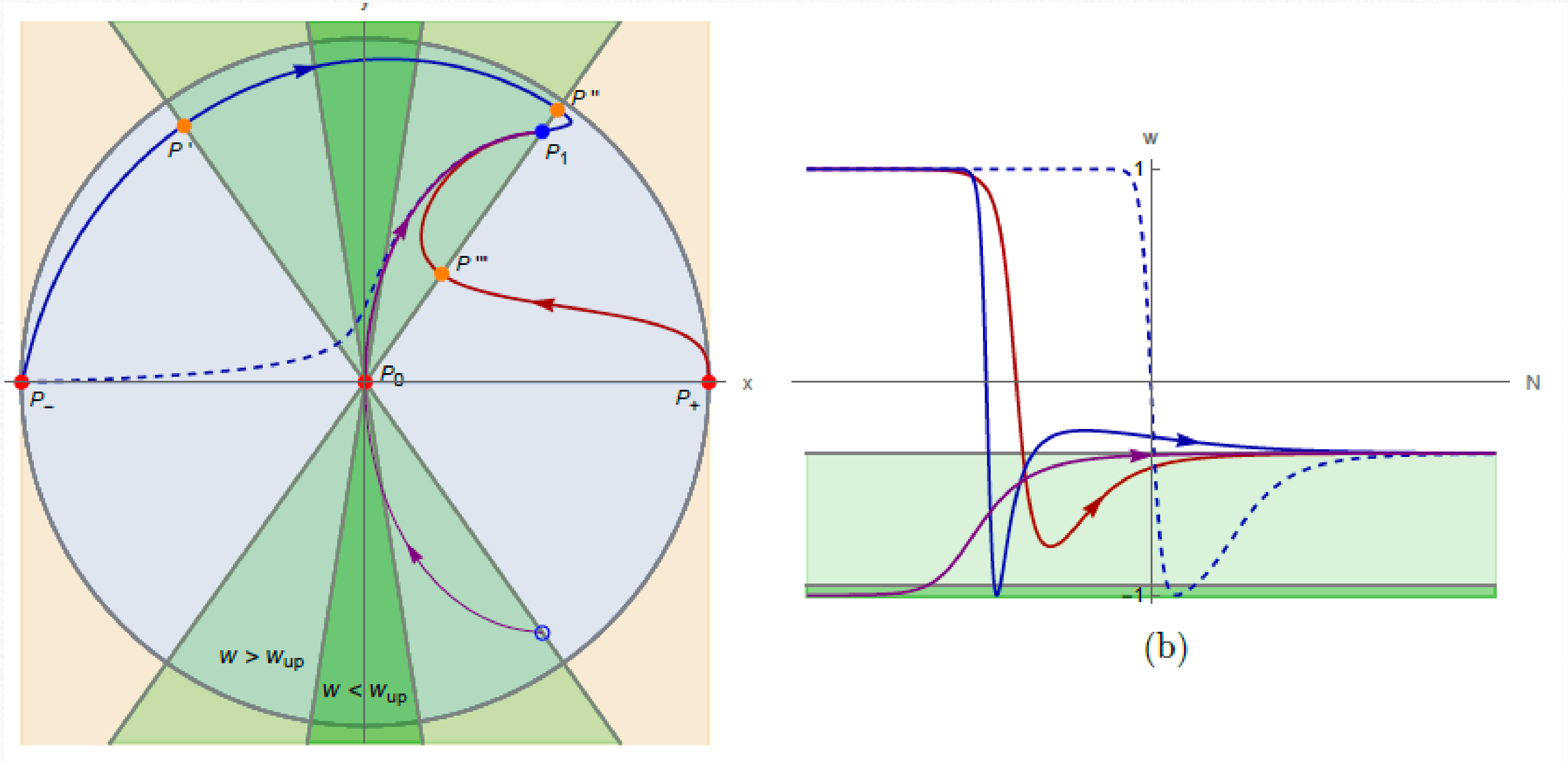


(a)



(b)

How **realistic**? $w < -0.95 = w_{\text{up}}$



(a) (b)

How **realistic**? $w < -0.95 = w_{\rm up}$

Transient acceleration solution: tunable **number of e-folds** ⟶ Possible solutions for dark energy and inflation….

String theory realisations? $\gamma > \sqrt{2}$ makes it much easier

Consistent truncation from 10d to 4d, giving a single field with exponential potential

Marconnet, Tsimpis ’22

Field: volume, or volume and dilaton $\longrightarrow$ dynamical compactifications

Advantage: no O-plane, no smearing discussion, and classical regime easily reached

Deserves more investigation (other fields?)

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Event horizon, of size $d_e = a(t_i) \int_{t_i}^{\infty} \frac{\mathrm{d}t}{a(t)}$ for solutions asymptoting to P_1

Determined by fixed point $P_1 : a(t) \sim t \longrightarrow d_e = \infty$, **no horizon**

Instead of ``no asymptotic acceleration’’ claim (for string theory/quantum gravity), rather ``**no cosmological/event horizon**’’…?!

(in particular no pure de Sitter solution)

Conclusion

- De Sitter solutions: difficult to obtain from string theory; no fully controlled example (for now)
- Accelerated expansion via rolling fields: in the asymptotics? Not with $k = 0$
- Possible / realized with $k = -1$; how realistic are the solutions?
- General claim on the absence of event horizon from string theory?
- Transient scenarios: a lot to explore

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Thank you for your attention!