Quintessence: from string theory to observations, and back

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2403.07065 (with F. Ruehle)

2405.09323 (with S. Parameswaran, D. Tsimpis, T. Wrase, I. Zavala)

+ work in progress

The landscape
vs. the Swampland

07/24
ESI, Vienna

Introduction

Topic: **Dark Energy**

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

Accelerated expansion due to dark energy (~ 70%)

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Characterised by **equation of state parameter** w

- Radiation (relativistic matter): $w = \frac{1}{3}$
- (Non-relativistic) matter: $w = 0$
- Dark energy (from theory): $w < -\frac{1}{3} \times \frac{1}{\text{“}70\%\text{”}} \approx -0.49$

$\longrightarrow$ Cosmological constant $\Lambda > 0:\ w = -1$

$\longrightarrow$ Dynamical dark energy / quintessence: $-1 < w < 1$, varies!

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Settled very soon!!

Very timely question because of **observations**!!

DES, DESI, (Euclid, LSST/Vera Rubin)

’24

ΛCDM: $w = -1$ ✓

Dyn. dark energy: ✓

$w_0 w_a$CDM: $w_0 \approx -0.75$

Consider **cosmological model**: $\int \mathrm{d}^4x \sqrt{|g_4|} \left(\frac{M_p^2}{2} \mathcal{R}_4 - \frac{1}{2} \partial_\mu \varphi \partial^\mu \varphi - V(\varphi) \right)$ (+ matter)

(for most of this talk: single, canonically normalized scalar field φ)

+ solutions with FLRW metric: $\mathrm{d}s_4^2 = -\mathrm{d}t^2 + a^2(t) \left(\frac{\mathrm{d}r^2}{1-kr^2} + r^2 \mathrm{d}\Omega_2^2 \right)$ $+ \varphi(t)$ $(\dot{\varphi} \equiv \partial_t \varphi)$

$\longrightarrow$ $w = \frac{\frac{1}{2}\dot{\varphi}^2 - V}{\frac{1}{2}\dot{\varphi}^2 + V}$ $\quad -1 \leq w \leq 1$

Solve 2 Friedmann equations + scalar equation of motion $\longrightarrow$ Solution, cosmological evolution of w

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- **De Sitter solution**: $\partial_\varphi V = 0,\ \dot{\varphi} = 0,\ V(\varphi) = \text{constant} = \Lambda \times M_p^2$ $\longrightarrow$ $w = -1$

  (minimum or maximum of V)

- **Quintessence**: $\partial_\varphi V \neq 0,\ \dot{\varphi} \neq 0,\ V(\varphi) = \text{non} - \text{constant}$ $\longrightarrow$ w varying

  (slope of V)

  (actually not arbitrarily)

$\longrightarrow$ compare to observations

String theory realisation?

Easily obtain: $\int \mathrm{d}^4x \sqrt{|g_4|} \left(\frac{M_p^2}{2} \mathcal{R}_4 - \frac{1}{2} \partial_\mu \varphi \partial^\mu \varphi - V(\varphi) \right)$ (+ matter?) (multifield?)

$\longrightarrow$ origin of dark energy: physical content in extra dimensions!

However: require an appropriate V to agree with observational constraints

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  Attempts, constraints, conjectures

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- **De Sitter maximum**: cosmological constant *for some time* / quintessence

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- **Appropriate** V : quintessence

  $\longrightarrow$ controlled example from string theory: field space asymptotics (e.g. classical, pert. regime)

  $V = V_0\, e^{-\lambda\, \varphi}$ $\longrightarrow$ ok with observations?

Plan:

- Qualitative features of quintessence, and observations
- Exponential quintessence and string theory
- Classical de Sitter solution with parametric control?

I. Quintessence and observations

$$\int \mathrm{d}^4x \sqrt{|g_4|} \left(\frac{M_p^2}{2} \mathcal{R}_4 - \frac{1}{2} \partial_\mu \varphi \partial^\mu \varphi - V(\varphi) \right)$$ (+ matter + radiation)

+ FLRW metric, $H = \frac{\dot{a}}{a} > 0$

1st Friedmann equation: $3H^2 = \sum_n \rho_n$

Radiation: $\rho_r = \rho_{r0} \left(\frac{a}{a_0} \right)^{-4}$

Matter: $\rho_m = \rho_{m0} \left(\frac{a}{a_0} \right)^{-3}$

Dark energy: $\rho_\varphi = \frac{1}{2} \dot{\varphi}^2 + V(\varphi)$

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Today (~ model independent): $\Omega_{r0} \approx 0.0001$

$a = a_0$

$\Omega_{m0} \approx 0.3149$

$\Omega_{\varphi 0} \approx 0.6815$

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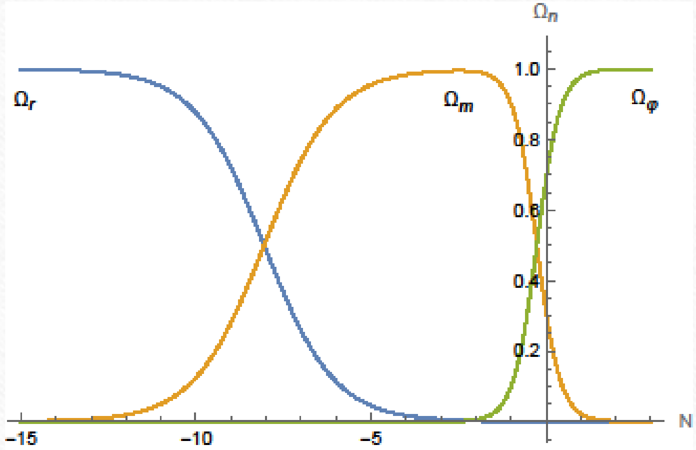
→ ΛCDM: evolution is fixed:

$(\dot{\varphi} = 0, \partial_\varphi V = 0)$

(solution is fully determined)



Successive phases of :

- Radiation domination
- Matter domination
- Rise of dark energy

in agreement with observations!

Quintessence: $\dot{\varphi} \neq 0, \partial_\varphi V \neq 0$

Solution is determined when fixing further initial condition: $\dot{\varphi}(t_0) \;\leftrightarrow\; w_0$

$\longrightarrow$ **Different possible solutions and evolutions**

$\longrightarrow$ Fine tune to get successive phases!

Example: exponential quintessence: $V = V_0\, e^{-\lambda\,\varphi},\; \lambda = \sqrt{3},\; w_0 = -0.51073604885$

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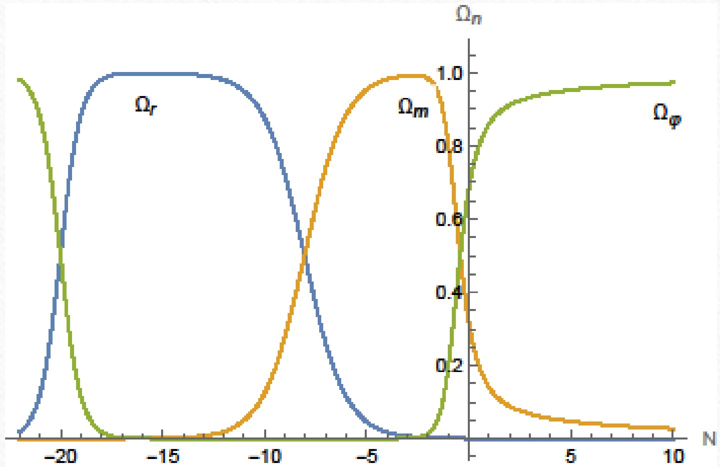


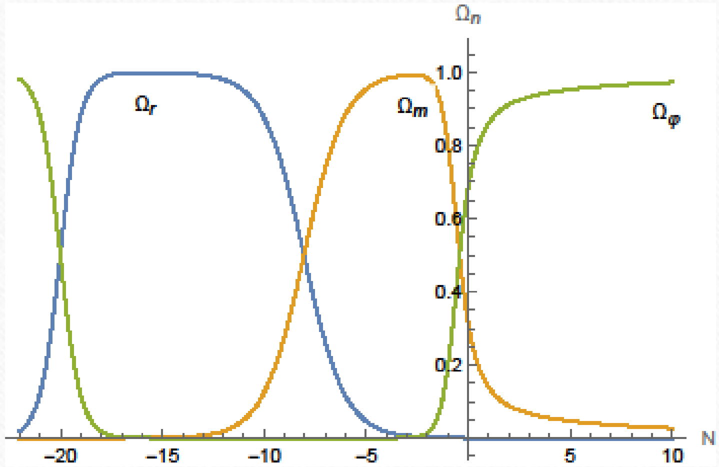
$\longrightarrow$ For such a solution, what is the evolution of w ?

One difference with ΛCDM:

initial kination phase…

For ΛCDM, $w = -1$

But for quintessence? $w = \frac{\frac{1}{2}\dot{\varphi}^2 - V}{\frac{1}{2}\dot{\varphi}^2 + V}$ (in terms of e-folds, $N = \ln \frac{a}{a_0}$, where today $N = 0$)



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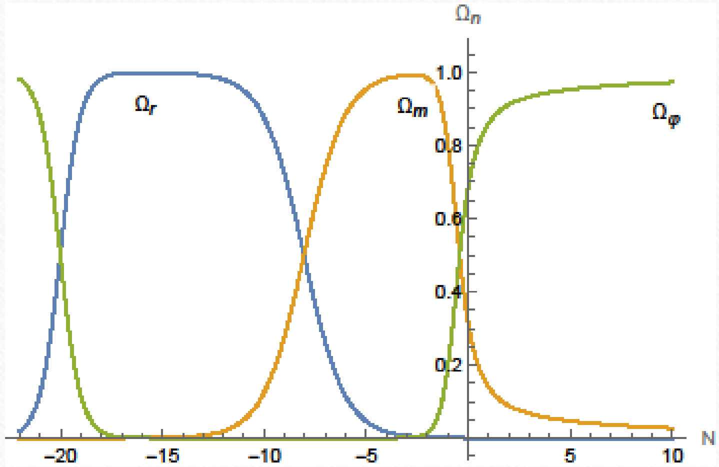
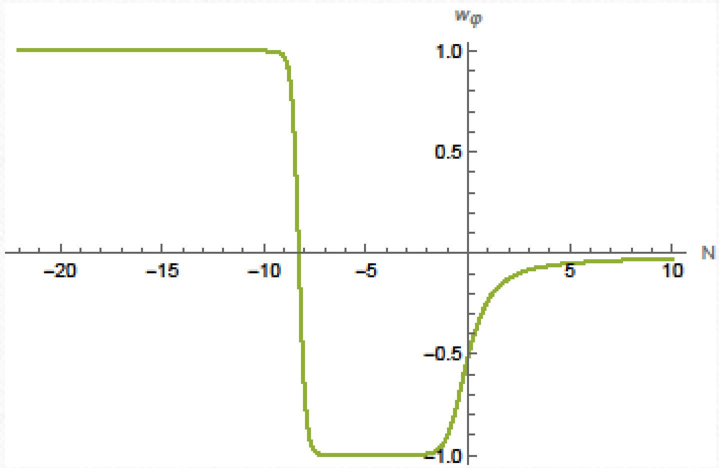


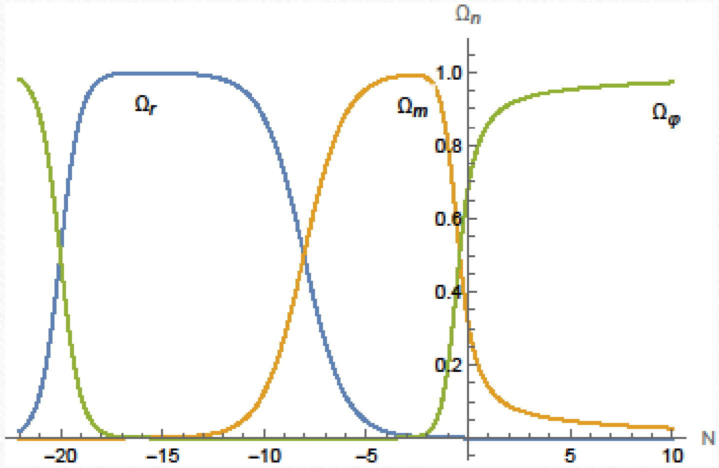


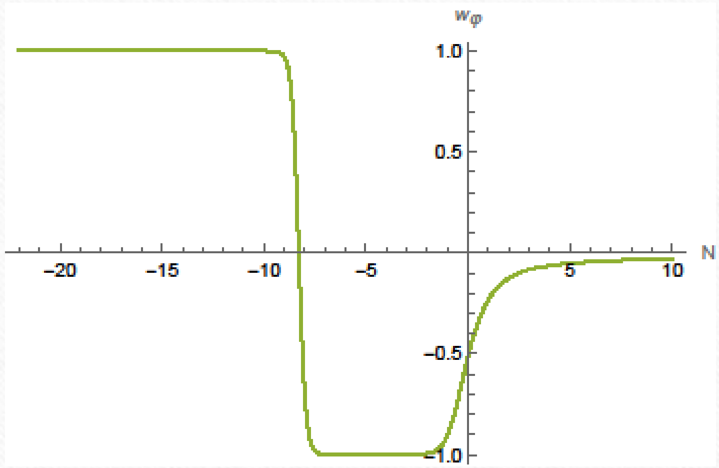
Initial kination phase: $w = 1$

During matter domination, $w = -1$

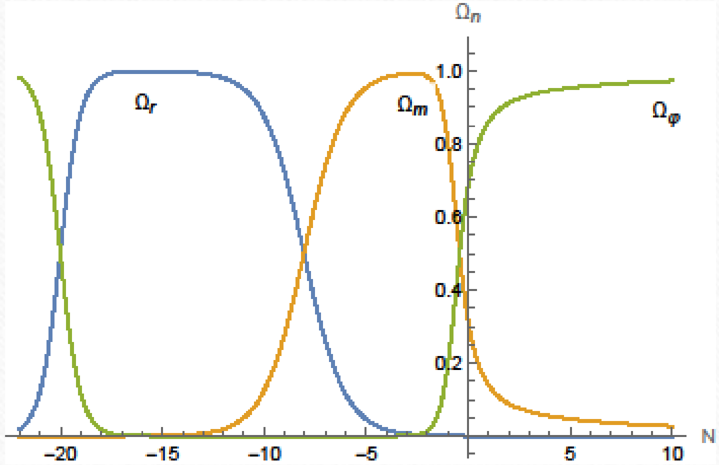
Then recent variation.

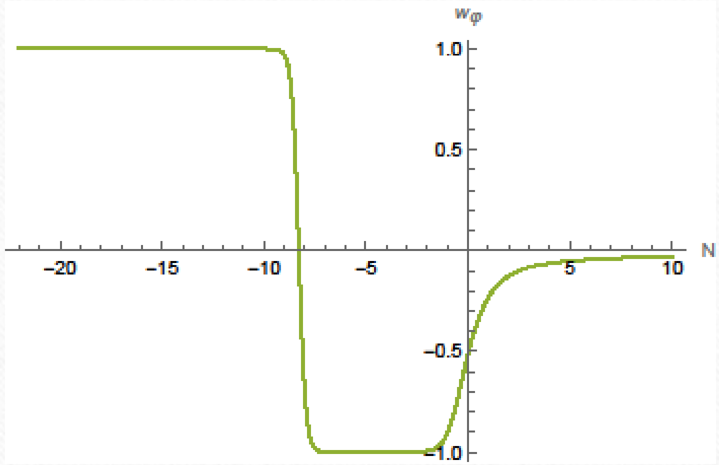
Very similar to ΛCDM between $-8 \leq N \leq 0$!





$w = -1$ possible thanks to freezing of the field, $\dot{\varphi} \approx 0$: due to **high Hubble friction**!





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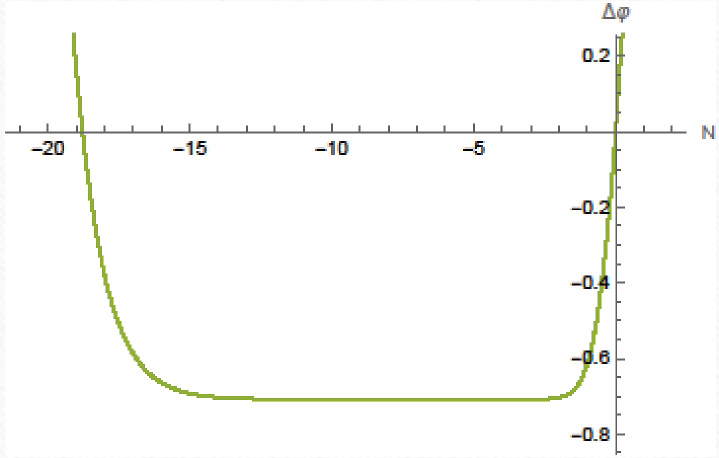
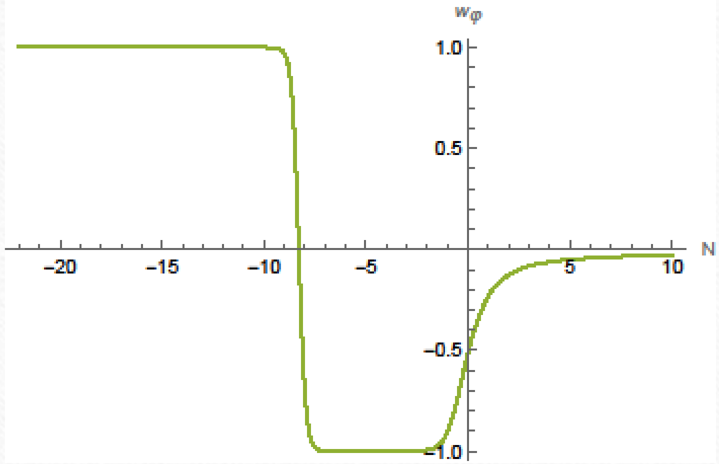


Initial and recent variation of the field

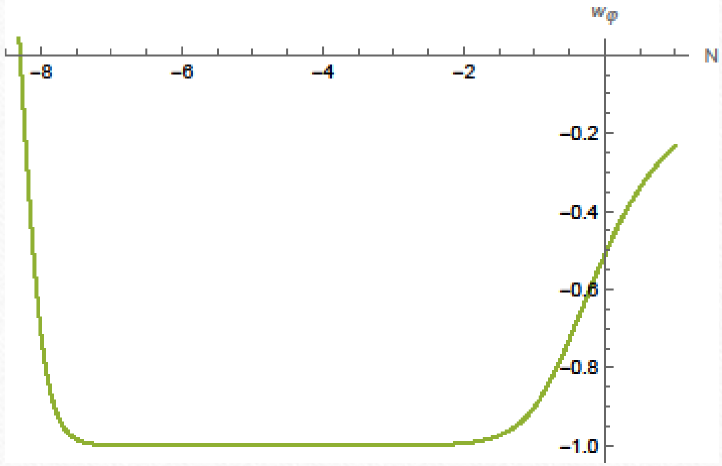
in between: frozen!

This **questions the need of moduli stabilisation**…!

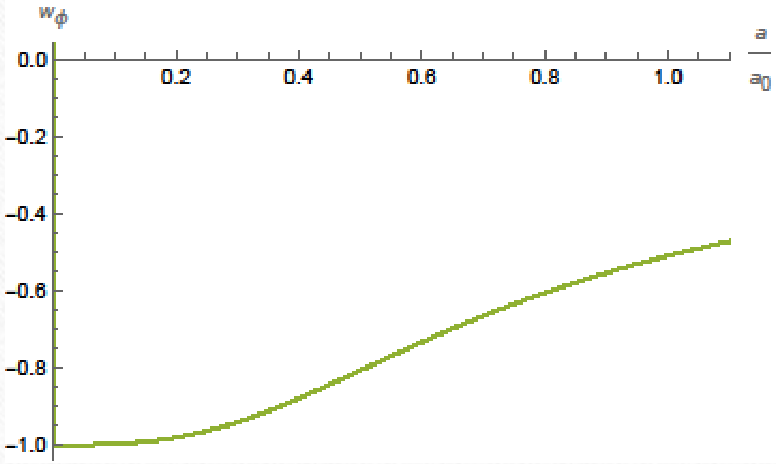
Observations: $w(a)$



$w(N)$

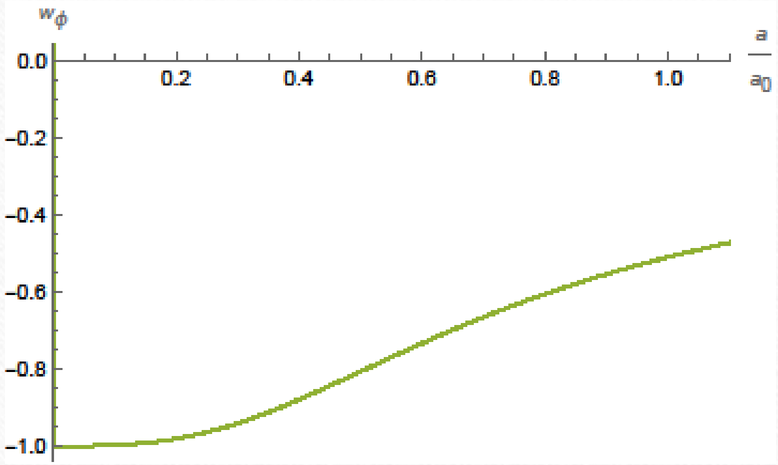


$w(N)$ zoomed in



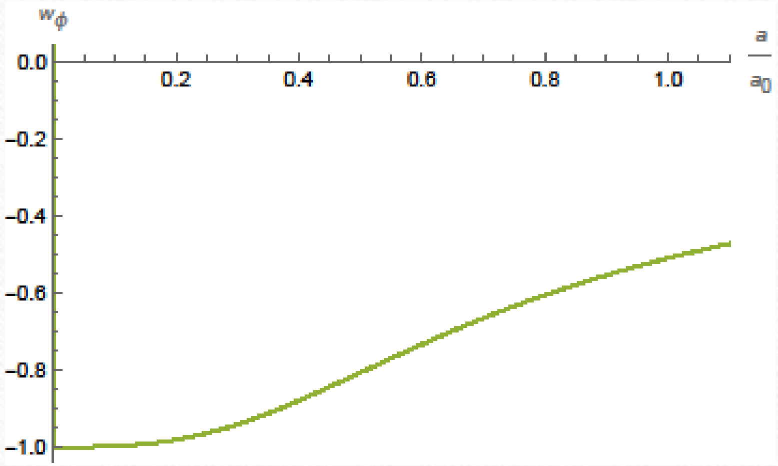
$w(a)$

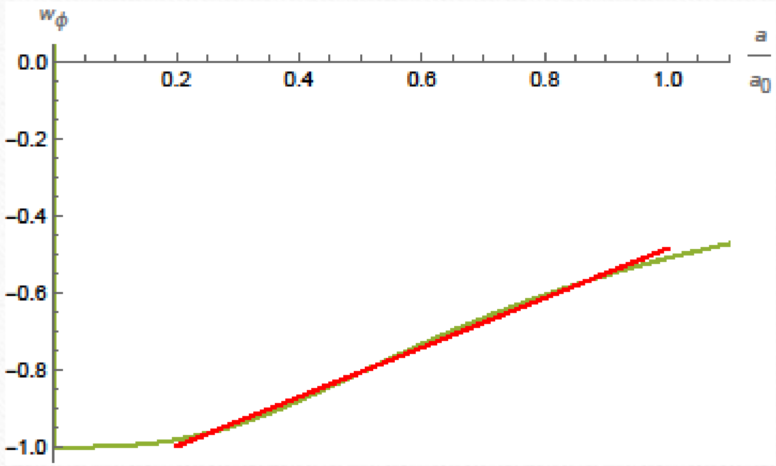
Observations: $w(a)$ CPL or $w_0 w_a$ parametrisation: linear approximation:



$$w(a) = w_0 + w_a \left(1 - \frac{a}{a_0}\right)$$

Observations: $w(a) = w_0 + w_a\left(1 - \frac{a}{a_0}\right)$ $0.2 \leq \frac{a}{a_0} \leq 1$ (redshift $z = 4$)





$w_0 = -0.49$

$w_a = -0.64$

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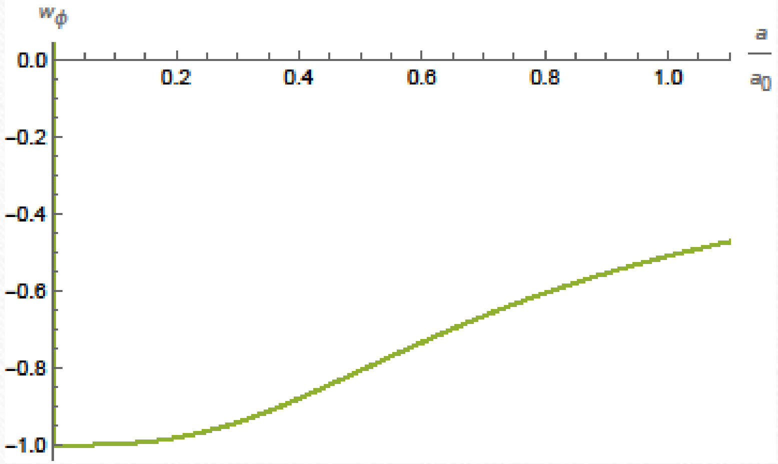

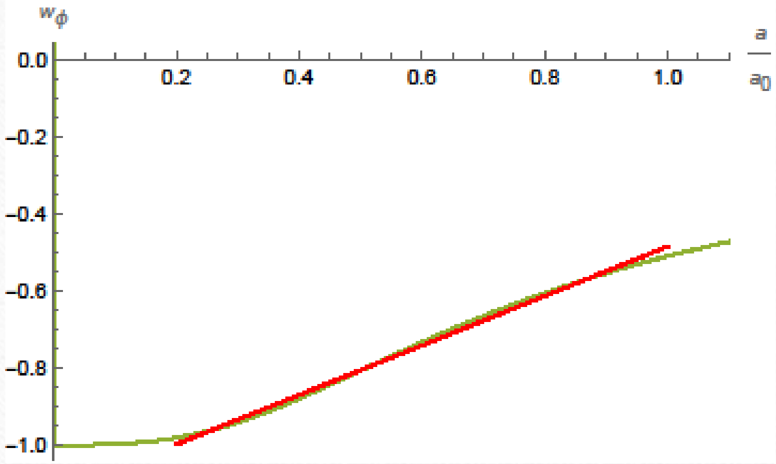

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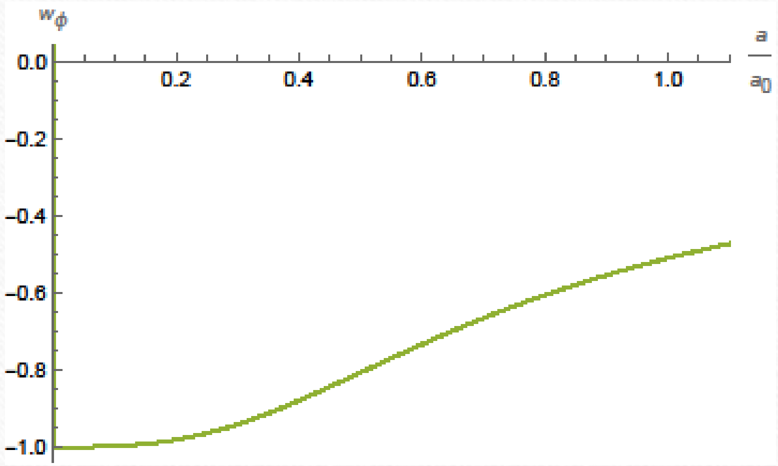
Exponential quint.:

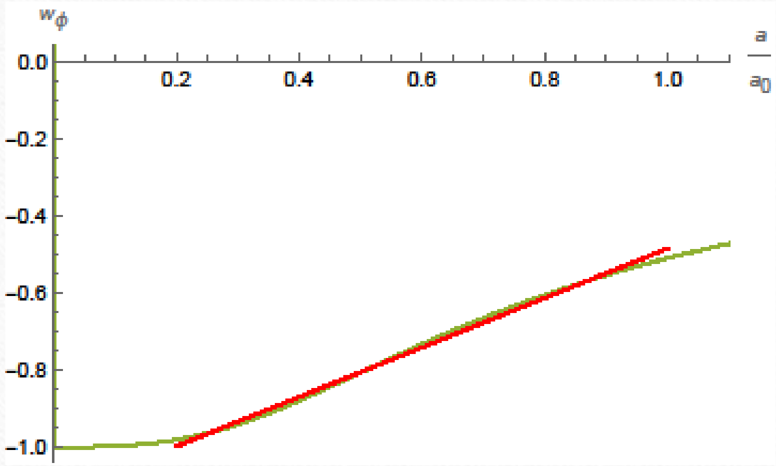
$$V = V_0\, e^{-\lambda\varphi}$$

λ	Best Fit w_0	w_a
0	-1.0000	0
1	-0.8559	-0.1914
$\sqrt{2}$	-0.6885	-0.4034
$\sqrt{8/3}$	-0.5584	-0.5586
$\sqrt{3}$	-0.4859	-0.6402
2	-0.2217	-0.8932

D.A., S. Parameswaran, D. Tsimpis, T. Wrase, I. Zavala, '24

Observations: $w(a) = w_0 + w_a\left(1 - \frac{a}{a_0}\right)$ $\quad 0.2 \leq \frac{a}{a_0} \leq 1$ $\quad$ (redshift $z = 4$)





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DESI '24

$$w_0 = -0.83,\; w_a = -0.75$$

$$w_0 = -0.65,\; w_a = -1.27$$

$$w_0 = -0.73,\; w_a = -1.05$$

Not ok with exp. quint., steeper $w(a)$!

But observational constraints to be refined…

II. Exponential quintessence

2405.09323 (with S. Parameswaran, D. Tsimpis, T. Wrase, I. Zavala)

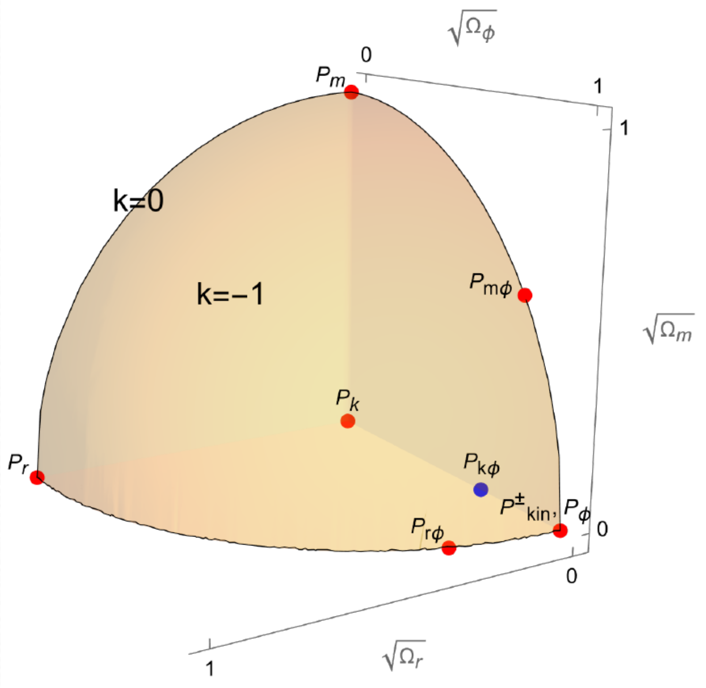
Exponential quintessence: special: $\frac{\partial_\varphi V}{V} = -\lambda = \text{constant}$

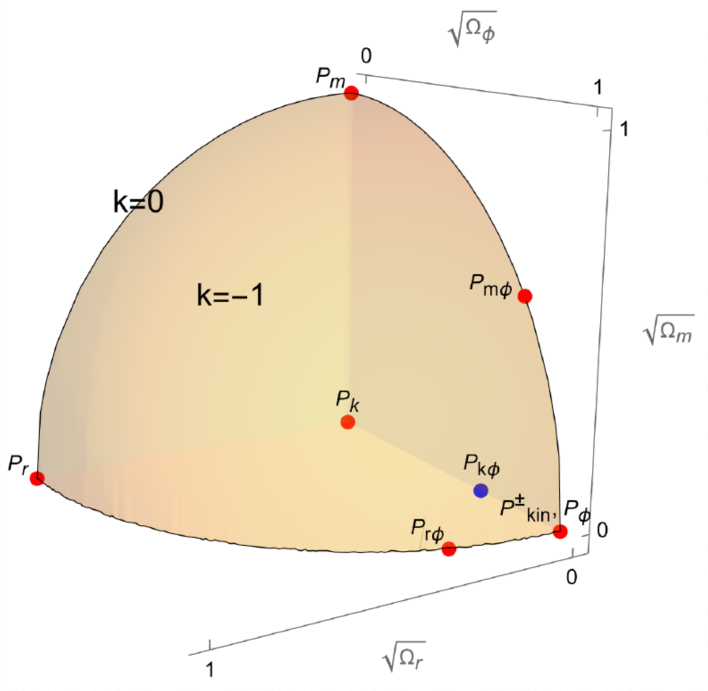
$\longrightarrow$ allows to write the equations of motion in the form of an autonomous **dynamical system**

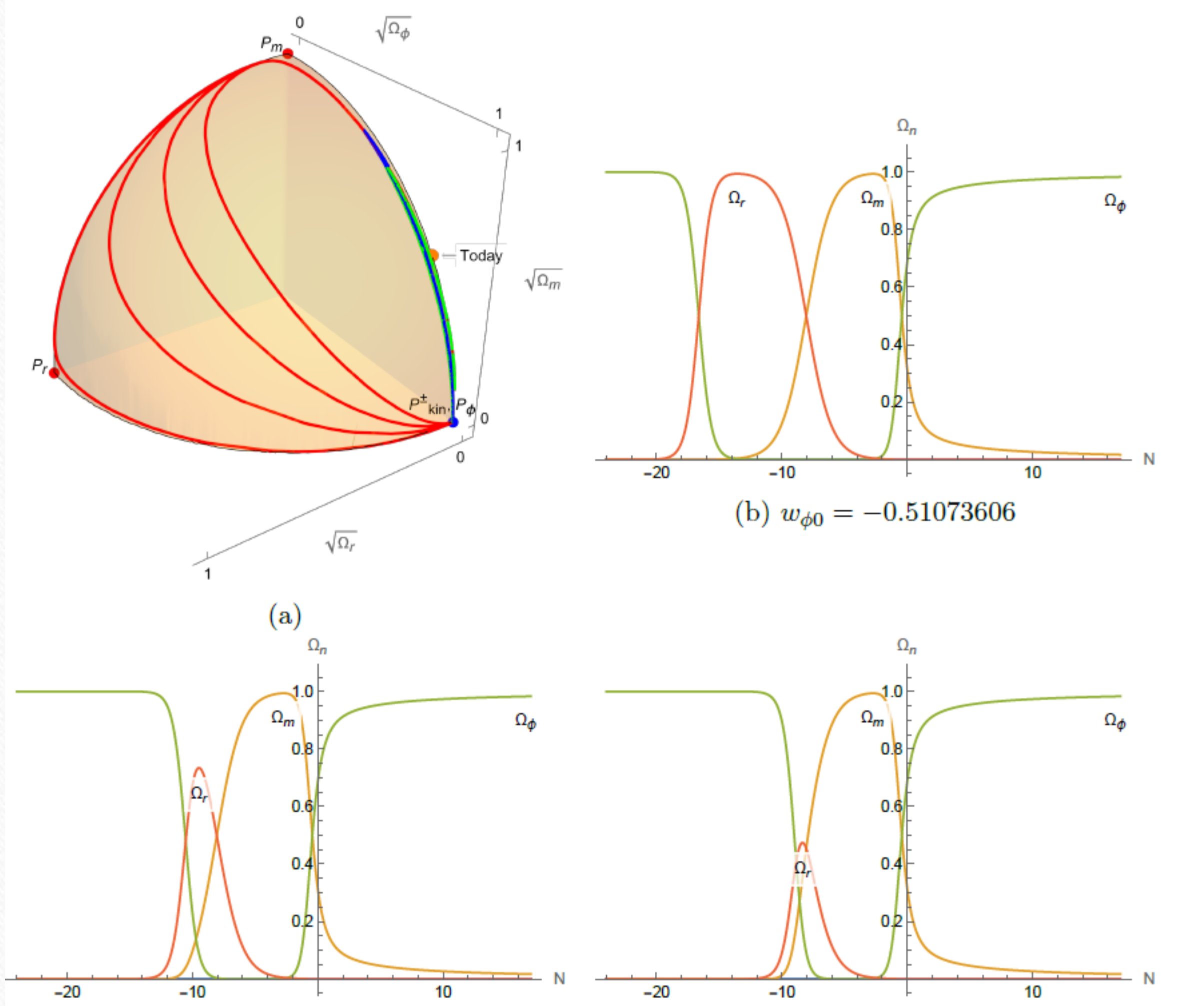
Use known methods to find **fixed points**, study their stability

Old story, but **comprehensive analysis**

including $\Omega_\varphi, \Omega_m, \Omega_r, \Omega_k$, study of **phase space** and **different solutions** (numerical, analytical)…





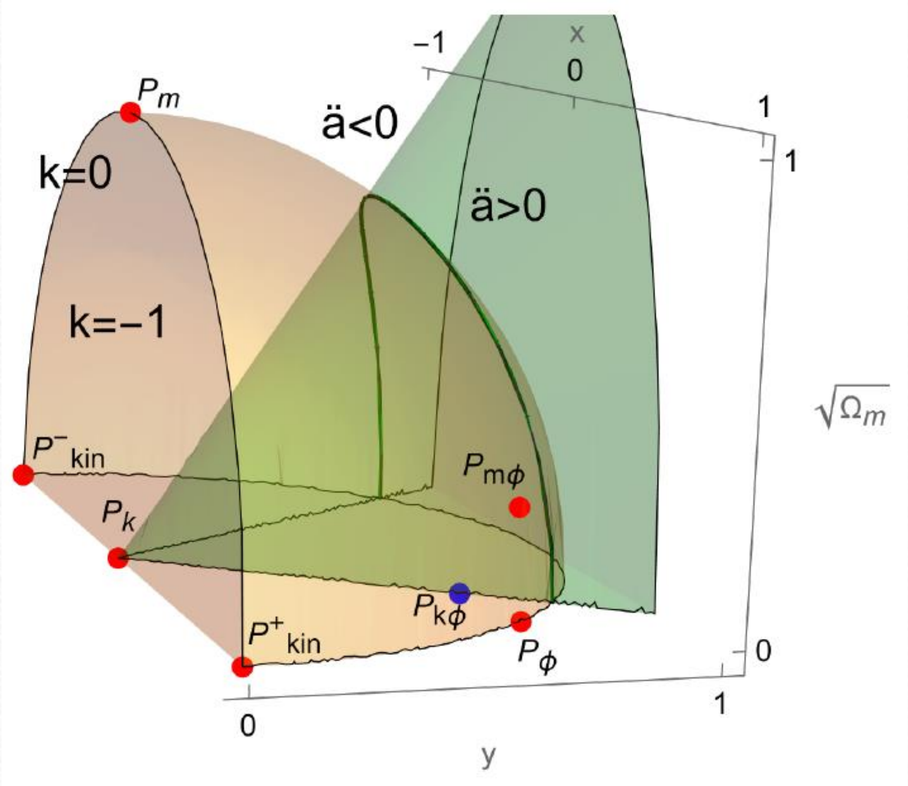


(a)

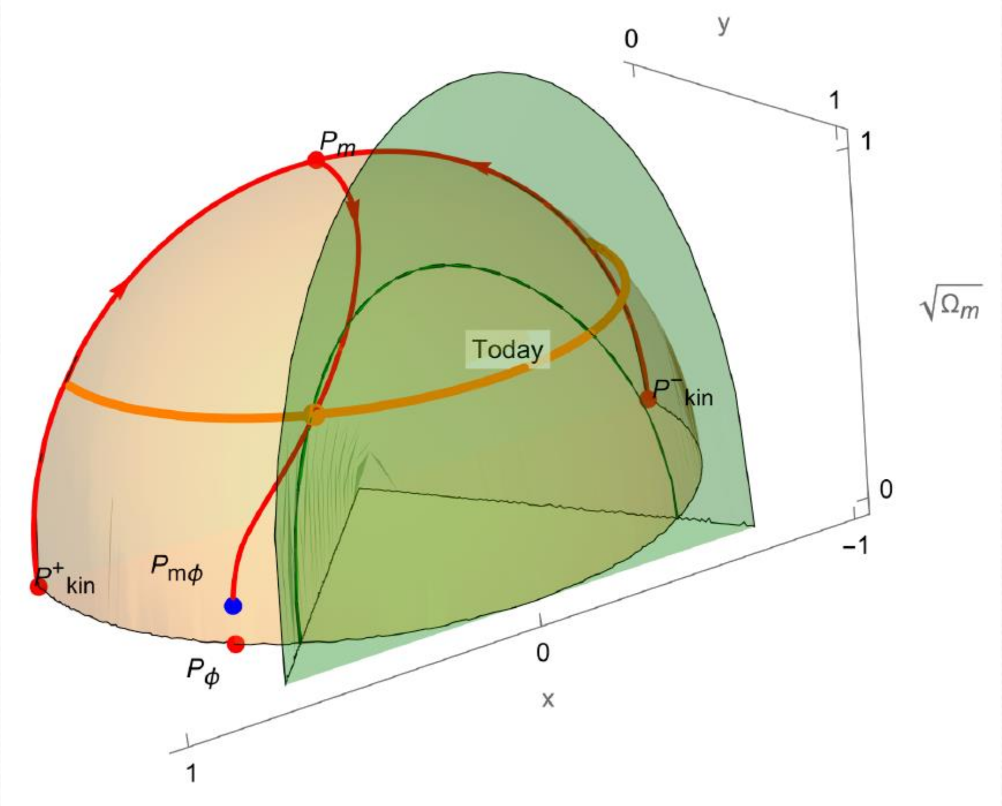
(b) $w_{\phi 0} = -0.51073606$

(c) $w_{\phi 0} = -0.510737$

(d) $w_{\phi 0} = -0.510731$



P_m
k=0
k=−1
ä<0
ä>0
P^-_{kin}
P_k
$P_{m\phi}$
$P_{k\phi}$
P^+_{kin}
P_ϕ
x
−1
0
1
1
0
y
0
1
$\sqrt{\Omega_m}$



y
0
1
1
0
P_m
Today
P^-_{kin}
P^+_{kin}
$P_{m\phi}$
P_ϕ
$\sqrt{\Omega_m}$
−1
0
x
1

For string theory origin: $\lambda \geq \sqrt{2}$ Strong de Sitter conjecture, constraints on asymptotics of V suffers no counter-example Bedroya, Vafa '19, Rudelius '21

$\longrightarrow$ **Lessons learnt on exponential quintessence**:

- acceleration phase (today) is **transient**!
- **past radiation domination + acceleration today**: $\lambda \lesssim \sqrt{3}$
- $w_0 w_a$ parametrisation
- impact of **spatial curvature**, solutions which are **horizonless**…

Observations seem however to disfavor such a realisation: $\lambda < 0.5 - 1$

without curvature: Agrawal et al, Akrami et al, Raveri et al, '18, Schöneberg et al '23
with curvature: Bhattacharya et al, Alestas et al, '24

Exponential quintessence remains an interesting « testbed example », for quintessence phenomena and string theory realisation

String realisation: pure NSNS example:

Andersson, Heinzle ’06, Marconnet, Tsimpis ’22, Andriot, Tsimpis, Wrase ’23

6d curved Einstein manifold, constant dilaton, no flux, no orientifold (!)

Only one field rolling: volume. Gives $V = V_0\, e^{-\lambda\,\varphi}\,,\ \lambda = \sqrt{\frac{8}{3}} \quad \left(\sqrt{2} < \lambda < \sqrt{3}\right),\ k = -1$

$\alpha' -$ and loop corrections under control

6d volume grows, but 4d one grows faster: scale separation!

Find an appropriate cosmological solution

Field ~ constant during radiation and matter domination

Recent evolution: $\Delta\varphi \approx 0.5\, M_p$, sub-Planckian

Good control! How realistic w.r.t. matter and couplings?

III. Classical de Sitter example?

2403.07065 (with F. Ruehle)

Briefly present one example of **de Sitter solution** from string theory, possibly well-controlled

Motivated cosmological applications, not evaluated here

(no associated cosmological solution and $w(a)$)

D.A., P. Marconnet, T. Wrase '20
D.A., L. Horer, P. Marconnet, '22
D.A., P. Marconnet, M. Rajaguru, T. Wrase, '22
D.A., F. Ruehle, '24

10d type IIB supergravity (no corr. or non-pert. contrib.), solution:

4d de Sitter $\times$ 6d group manifold (compact curved solvmanifold) $\longrightarrow$ 3d $\times$ 3d

$H,\ F_1,\ F_3$

$O_5\ (12),\ O_5/D_5\ (34),\ D_5\ (56)$ (smeared)

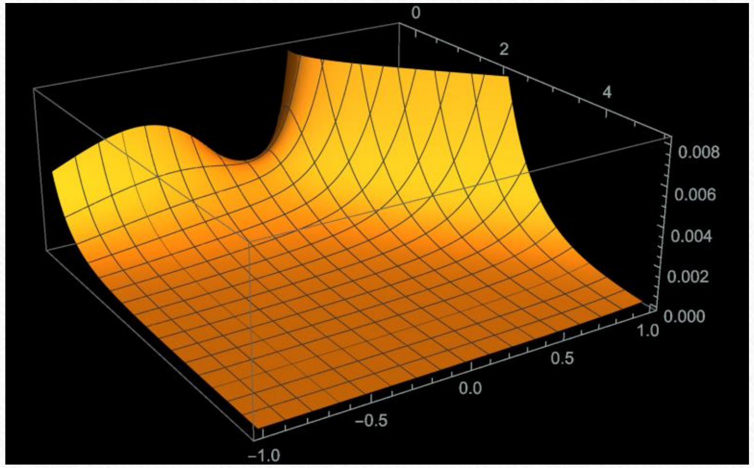
Consistent truncation to 4d: get V with 22 fields

4 flat directions, 1 tachyon, 17 (meta)stable

$\eta_V \approx -4$

Cosmological constant/quintessence scenario?

Agrawal, Obied '18



Two main problems: 10d supergravity solution $\longrightarrow$ **classical** string background?

smeared sources $\longrightarrow$ **backreaction**? (around orientifold)?

Here: hopeful on classicality thanks to **parametric control / scaling** (novelty!)

< 2020: only known 10d supergravity dS$_4$ solutions: type IIA with O_6 (+ 1 T-dual)

2018: not classical! (no scaling that makes volume large, string coupling small)

+ no-go theorems… Wrase et al ’18, Junghans ’18, Grimm et al ’19, Andriot ’19,’20, Cicoli et al ’21

Here: new solutions: exhibit a γ scaling: circumvents previous no-go theorems:

6 characteristic lengths in geometry: $r_{a=1\dots 6}$

$r_4, r_5 \to \gamma\ r_4, r_5,\quad r_1, r_2 \to \gamma^{\frac{1}{2}}\ r_1, r_2,\quad r_3, r_6, g_s$ invariant $\quad 4\ r_a\ \nearrow$ (6d volume $\nearrow$)

(+ scaling of flux numbers and structure constants)

If r_3, r_6, g_s appropriate values $\longrightarrow$ **classical** with parametric control...

$r_4, r_5 \to \gamma\ r_4, r_5, \quad r_1, r_2 \to \gamma^{\frac{1}{2}}\ r_1, r_2, \quad r_3, r_6, g_s$ invariant

(+ scaling of flux numbers and structure constants)

Effect on supergravity variables:

$\longrightarrow\ T_{10}^I \ \to\ \frac{1}{\gamma^2}\, T_{10}^I\ , \qquad F_{1\,.}, F_{3\,\dots}, H_{\dots}, f^a{}_{bc} \ \to\ \frac{1}{\gamma}\, F_{1\,.}, F_{3\,\dots}, H_{\dots}, f^a{}_{bc}$

$\longrightarrow\ \text{Eq. of motion} \ \to\ \frac{1}{\gamma^2}\ \text{Eq. of motion}\ ,\ \ \text{Solution} \ \to\ \text{Solution}'\ ,\ \ \mathcal{R}_4^S \ \to\ \frac{1}{\gamma^2}\, \mathcal{R}_4^S\ ,$

(analogous to DGKT)

+ Crucial for α'-corrections: involve higher powers of supergravity variables!

$\longrightarrow$ reduced with higher powers of $\frac{1}{\gamma}$ $\longrightarrow$ **Parametric control!**

Remaining doubts:

- $g_s < 1\ ,\ r_1, r_2, r_4, r_5 > l_s\ ,$ but $\ r_3, r_6 < l_s$ Those are not radii, no winding mode associated? Cycle volumes?
- Open string d.o.f. from D-branes…
- Orientifold backreaction…

Summary

- Equation of state parameter w + evolution $w(a)$: crucial! Soon observationally constrained.
- Role of (high) Hubble friction: underestimated in string pheno / swampland

- String theory realisations?

  - Exponential quintessence or other $V(\varphi)$?
  - De Sitter maximum (a classical one?)
  - Include matter!

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Thanks for your attention!