Dynamical Dark Energy:
from String Theory to Observations

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Strings 2024
CERN

based on
2405.09323 [hep-th] w/ Andriot, Tsimpis, Wrase & Zavala
2405.17396 [astro-ph.CO] w/ Battacharya, Borghetto, Malhotra, Tasinato & Zavala
see also Physics Report on ‘String Cosmology: from the Early Universe to Today’
w/ Cicoli, Conlon, Maharana, Quevedo & Zavala

Dark Energy, Λ and the String Landscape

- Concordance model of cosmology suggests that Dark Energy is a tiny vacuum energy sourcing a de Sitter Universe:

$$\Lambda \approx 7 \times 10^{-121} M_{pl}^4 \quad \text{and} \quad w_{\mathrm{D}E} \equiv \frac{p_{\mathrm{D}E}}{\rho_{\mathrm{D}E}} = -1$$

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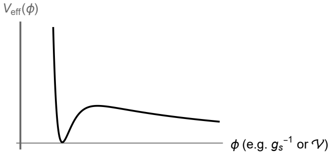

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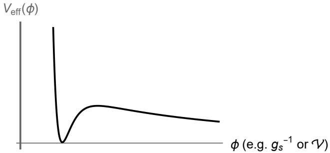

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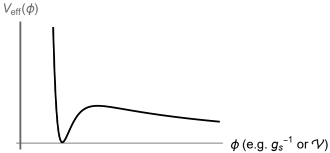

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- String landscape + eternal inflation + anthropic principle arguably best explanation so far for Dark Energy and cosmological constant problem, despite conceptual issues e.g. event horizon...

Banks '00, Banks & Fischler '01, Witten '01, . . . , Banks '19

Observational hints beyond ΛCDM?

- As cosmological data grows in variety and precision, emerging tensions when fitting ΛCDM, e.g. $3 - 6\sigma$ H_0 tension:

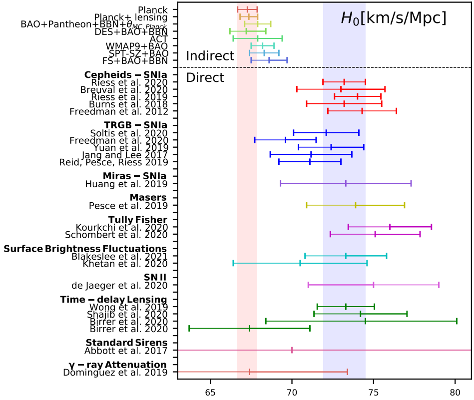

Figure reproduced from Di Valentino '20

Systematic error or new physics?

Observational hints beyond ΛCDM?

- Recent Dark Energy surveys aimed at measuring $w_{DE}(a)$ are finding intriguing hints of deviations from Λ.

  DESI, assuming parametrisation $w_{DE}(a) = w_0 + w_a(1 - a)$, finds:

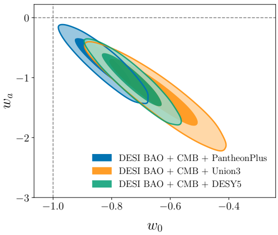

Figure reproduced from DESI '24

and preference over ΛCDM at 2.5σ, 3.5σ or 3.9σ depending on SN 1a data set used.

Statistics or new physics?

See e.g. Cortês & Liddle '24; Ó Colgain, Dainotti, Capozziello, Pourojaghi, Sheikh-Jabbari & Stojkovic '24; Shlivko & Steinhardt for some debate

Early days w/ first year of data analysed out of planned 5 years...

eBOSS 2014-20, SuMIRe 2014-29, DESI 2021-26, Euclid 2023-29, VRO/LSST 2025-35, Roman Telescope 2027-32

Plan

Are there simple, controlled, stringy candidates for Dynamical Dark Energy with observational signatures?

What can we learn about string theory and the landscape while looking for such models?

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What can we learn about string theory and the landscape while looking for such models?

Focus today on a class of ‘quintessence’ models with a runaway string modulus.

- Asymptotic acceleration, event horizons and the swampland
- Runaway quintessence in an open universe
- Constraints from observational data
- Outlook

Important questions I won't discuss...

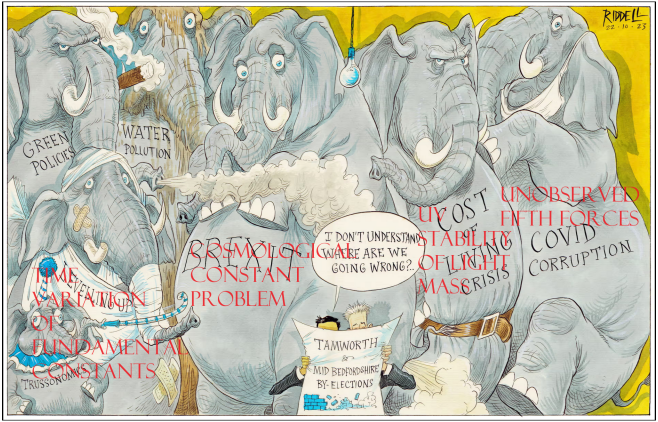

Figure adapted from The Guardian

Acceleration at large volume and weak coupling?

- In 4d string models, we have most control at the asymptotics of moduli space (g_s and α' corrections small).
- Moduli potentials there are typically runaway w/ $V(\phi) \sim e^{-\lambda\phi}$ for canonically normalised fields: can this source acceleration?
- Widely believed that dS vacua do not exist *at the asymptotics*:

  Dine & Seiberg '85; Obied, Ooguri, Spodyneiko & Vafa '18; H. Ooguri, E. Palti, G. Shiu & C. Vafa '18; Rudelius '21

  $$\frac{|\nabla V|}{V} \geq \sqrt{\frac{4}{d-2}} = \sqrt{2} \text{ for } d = 4 \quad (*)$$

  No known counter-example.

  For some interesting attempts see e.g. Calderón-Infante, Ruiz & Valenzuela '22; Cremoini, Gonzalo, Rajaguru, Tang & Wrase '23
- Precludes asymptotic, eternal acceleration, which needs $\frac{|\nabla V|}{V} < \sqrt{2}$ (though transient acceleration is possible).

  Townsend & Wohlfarth '03, . . . , Russo & Townsend '19
- Consistent with early insights that quintessence has same conceptual challenges as de Sitter, including event horizons.

  Hellerman, Kaloper & Susskind '01
  Fischler, Kashani-Poor, McNees & Paban '01
- Fitting exponential quintessence $V(\phi) \sim e^{-\lambda\phi}$ to the cosmological data bounds $\lambda \lesssim 0.6$, outside stringy bounds (*).

  Agrawal, Obied, Steinhardt & Vafa '18; Akrami, Kallosh, Linde & Vardanyan '18; Raveri, Hu & Sethi '18; Schöneberg, Vacher, Dias, Carvalho & Martin '23

Loop hole - quintessence in an open universe

- There do exist 10/11D solutions with eternal acceleration – they are time-dependent and have negatively curved 3D spatial slices.

Chen, Ho, Neupane, Ohta & Wang ’03; Andersson & Heinzle ’06; Marconnet & Tsimpis ’23

$$ds_{10}^2 = e^{2A(t)}\left(g_{\mu\nu}^{FRW,k=-1}dx^\mu dx^\nu + g_{mn}dy^m dy^n\right)$$

- Corresponding 4D EFTs with potentials such as: Marconnet & Tsimpis ’23

$$V = \begin{cases} 72\, c_3^2\, e^{-\phi-12A} + \frac{3}{2}\, c_4^2\, e^{\frac{\phi}{2}-14A} & \text{CY with internal 3- and 4-form fluxes} \\ \frac{1}{2}\, c_{4,\mathrm{ext}}^2\, e^{-\frac{\phi}{2}-18A} + \frac{1}{2}\, m_0^2\, e^{\frac{5\phi}{2}-6A} - 6\, k_6\, e^{-8A} & \text{Einstein with external 4-form flux} \\ \frac{3}{2}\, c_4^2\, e^{\frac{\phi}{2}-14A} + \frac{1}{2}\, m_0^2\, e^{\frac{5\phi}{2}-6A} - 6\, k_6\, e^{-8A} & \text{EK with internal 4-form flux} \\ \frac{1}{2}\, c_{4,\mathrm{ext}}^2\, e^{-\frac{\phi}{2}-18A} + \frac{3}{2}\, c_2^2\, e^{\frac{3\phi}{2}-10A} - 6\, k_6\, e^{-8A} & \text{EK with internal 2-form, external 4-form} \end{cases}$$

E.g. IIA on compact hyperbolic manifold with only one geometric modulus – volume – and no fluxes, after fixing dilaton:

$$V \sim e^{-\sqrt{\frac{8}{3}}\varphi} \text{ for canonically normalised } \varphi$$

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Andriot, Tsimpis, Wrase '23

- Open universes produced by CDL tunnelling in landscape.

Freivogel, Kleban, Rodriguez Martinez & Susskin '05; but see Buniy, Hsu, Zee '06; Horn '17; Cespedes, de Alwis, Muia & Quevedo '20, '23 for alternatives

4D cosmology - quintessence in an open universe

Andriot, SLP, Tsimpis, Wrase & Zavala '24

Can 'stringy' curved, steep ($\lambda > \sqrt{2}$), exponential quintessence lead to a realistic cosmology?

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Can 'stringy' curved, steep ($\lambda > \sqrt{2}$), exponential quintessence lead to a realistic cosmology? We need to include matter and radiation!

Consider the full 4d cosmology in an open FRW universe ($k = -1$):

$$\mathrm{d}s^2 = -\mathrm{d}t^2 + a^2(t)\left(\frac{\mathrm{d}r^2}{1-kr^2} + r^2\mathrm{d}\Omega_2^2\right) .$$

Contributions to energy-momentum:

n	component	ρ_n	p_n	$w_n \equiv \frac{p_n}{\rho_n}$
r	radiation	$\propto a^{-4}$	$\propto a^{-4}$	$\frac{1}{3}$
m	matter	$\propto a^{-3}$	$\propto a^{-3}$	0
k	curvature	$-\frac{3k}{a^2}$	$\frac{k}{a^2}$	$-\frac{1}{3}$
ϕ	scalar field	$\frac{\dot\phi^2}{2} + V(\phi)$	$\frac{\dot\phi^2}{2} - V(\phi)$	w_ϕ

*Recall: $\rho_n \sim a^{-3(1+w_n)}$ and we also use 'density parameters' $\Omega_n \equiv \frac{\rho_n}{3H^2}$ ($H \equiv \frac{\dot a}{a}$). For a universe dominated by single fluid $a(t) \sim t^{\frac{2}{3(1+w_n)}}$ and we have accelerated expansion when $w_{\rm eff} < -\frac{1}{3}$.

Dynamical Systems Analysis

The eoms can be expressed as an autonomous system defining:

$$x = \sqrt{\Omega_\phi \frac{(1+w_\phi)}{2}}\,, \quad y = \sqrt{\Omega_\phi - x^2}\,, \quad z = \sqrt{\Omega_k}\,, \quad u = \sqrt{\Omega_r}$$

with $\Omega_m = 1 - x^2 - y^2 - z^2 - u^2$ and $' = \frac{d}{dN}$ where $N = \ln a$:

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

Analysis of fixed points $(x'(N), y'(N), z'(N), u'(N)) = (0, 0, 0, 0)$ gives insight into global cosmology – cosmological solutions correspond to orbits in the phase space (x, y, z, u) passing between fixed points.

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Fixed points – for $\lambda > \sqrt{2}$, $P_{k\,\phi}$ is the global attractor with $w_{\rm eff} = -\frac{1}{3}$.

(x, y, z, u)	Ω_m	Existence	$w_{\rm eff}$	Stability
$P^{\pm}_{\rm kin} = (\pm 1, 0, 0, 0)$	0	$\forall\,\lambda$	1	unstable/saddle
$P_k = (0, 0, \pm 1, 0)$	0	$\forall\,\lambda$	$-\frac{1}{3}$	saddle
$P_{k\,\phi} = \left(\frac{1}{\lambda}\sqrt{\frac{2}{3}}, \pm\frac{2}{\lambda\sqrt{3}}, \pm\sqrt{1-\frac{2}{\lambda^2}}, 0\right)$	0	$\lambda > \sqrt{2}$	$-\frac{1}{3}$	stable
$P_\phi = \left(\frac{\lambda}{\sqrt{6}}, \pm\frac{\sqrt{6-\lambda^2}}{\sqrt{6}}, 0, 0\right)$	0	$\lambda < \sqrt{6}$	$\frac{\lambda^2}{3} - 1$	stable for $\lambda \leq \sqrt{2}$/saddle for $\lambda > \sqrt{2}$
$P_{m\,\phi} = \left(\frac{1}{\lambda}\sqrt{\frac{3}{2}}, \pm\frac{1}{\lambda}\sqrt{\frac{3}{2}}, 0, 0\right)$	$1 - \frac{3}{\lambda^2}$	$\lambda > \sqrt{3}$	0	saddle
$P_m = (0, 0, 0, 0)$	1	$\forall\,\lambda$	0	saddle
$P_r = (0, 0, 0, \pm 1)$	0	$\forall\,\lambda$	$\frac{1}{3}$	saddle
$P_{r\,\phi} = \left(\frac{1}{\lambda}\sqrt{\frac{8}{3}}, \pm\frac{2}{\lambda\sqrt{3}}, 0, \pm\sqrt{1-\frac{4}{\lambda^2}}\right)$	0	$\lambda > 2$	$\frac{1}{3}$	saddle

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Flat case ($z = 0$) is an invariant subspace - without curvature the stable fixed point becomes P_ϕ for $\lambda \leq \sqrt{3}$ or $P_{m\,\phi}$ for $\lambda > \sqrt{3}$:

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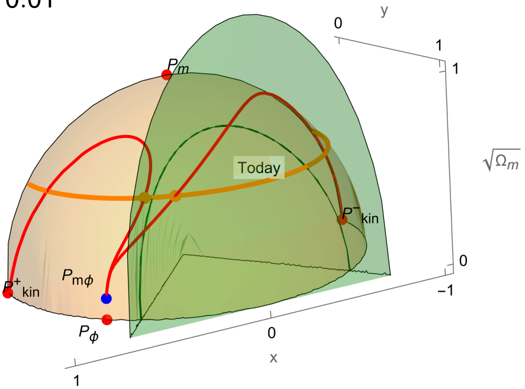
Phase space and orbits - flat case

For illustration, consider first $u = 0 = z$ (so $\Omega_m = 1 - x^2 - y^2$).

For $\lambda = \sqrt{3} + 0.01$



Orbits go from $P^{\pm}_{\text{kin}}$ to $P_{m\,\phi}$ on the sphere. Determined by initial conditions, which we may set by today's values for $(\Omega_{m0}, \Omega_{\phi 0}, w_{\phi 0})^*$. Through green region there is accelerated expansion. *Orbits do not generally pass by matter domination, P_m, so cannot be realistic.*

* for which we need to fits to the data.

Some orbits for $k = 0$ - matter domination

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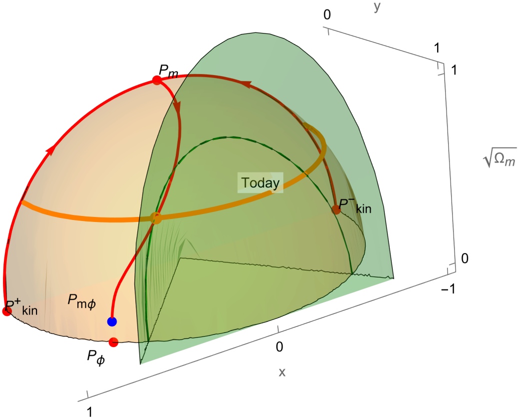
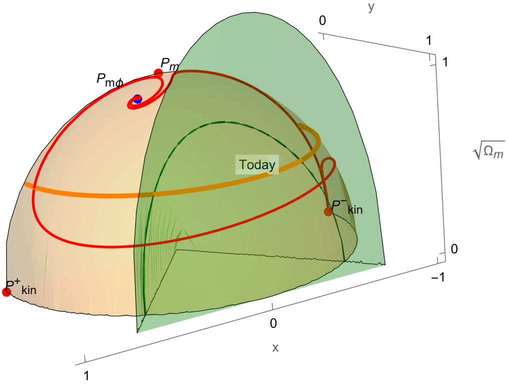


For given Ω_{m0}, $\Omega_{\phi 0}$, by tuning $w_{\phi 0}$ we pass through past matter domination (and – after restoring u – radiation domination).

Some orbits for $k = 0$ - upper bound on λ

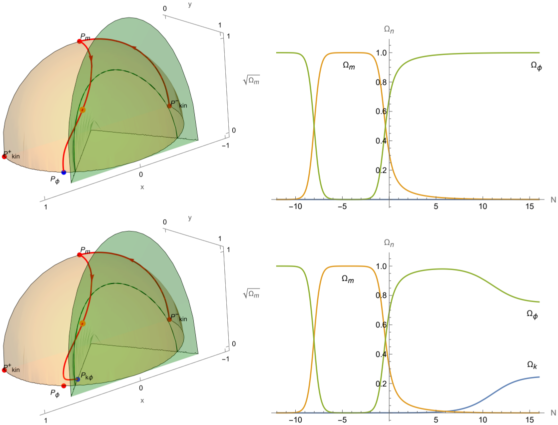
Now consider a larger value for $\lambda = 5$:



As λ increases, $P_{m\phi}$ approaches P_m; it crosses circle $x^2 + y^2 = \Omega_{\phi 0}$ when $\lambda \approx \sqrt{\frac{3}{\Omega_{\phi 0}}}$. For higher λ, matter domination in future (if at all). Requiring moreover acceleration today $\Rightarrow$ upper bound $\lambda \lesssim \sqrt{3}$.

Impact of curvature on past and future

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



With curvature universe ends at $P_{k\,\phi} \Rightarrow w_{\text{eff}} = -\frac{1}{3}$, $\ddot{a} = 0$.
Small curvature today $\Rightarrow$ even smaller in past $\Rightarrow$ pasts are similar.
Past matter domination $\Rightarrow$ only a transient acceleration epoch.

Impact of curvature on present day

Present universe has quantitative differences with curvature:

λ	$w_{\phi 0}$ for $\Omega_{k0} = 0$	$w_{\phi 0}$ for $\Omega_{k0} = 0.085$
0	-1.0000	-1.0000
1	-0.8486	-0.8720
$\sqrt{2}$	-0.6874	-0.7363
$\sqrt{8/3}$	-0.5719	-0.6400
$\sqrt{3}$	-0.5107	-0.5894
2	-0.3028	-0.4231

Minimal requirements of (1) past radiation domination and (2) acceleration today leads to upper bound $\lambda \lesssim \sqrt{3}$, sensitive to parameters $\Omega_{\phi 0}$ and Ω_{k0}, but pushed slightly up with curvature.

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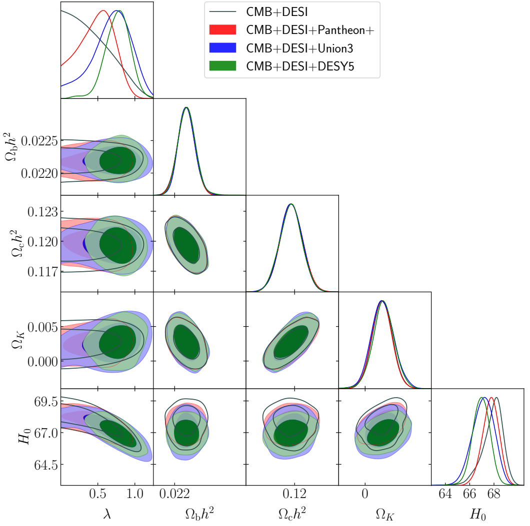
How high can λ be in the presence of curvature when confronted with cosmological data?

Use Einstein-Boltzmann codes to solve for evolution of background and perturbations to compute observables and Markov Chain Monte Carlo sampling codes for parameter estimations.

Cosmological Constraints

Bhattacharya, Borghetto, Malhotra, SLP, Tasinato, Zavala '24;
Alestas, Delgado, Ruiz, Akrami, Montero, Nesseris '24;
see also Ramadan, Sakstein, Rubin '24 for flat case

Data would suggest $\lambda < \sqrt{2}$, eternal acceleration and event horizon.



Parameter	CMB+DESI	+Pantheon+	+Union3+	+DESY5
$\boldsymbol{\lambda}$	< 0.537	$0.48^{+0.28}_{-0.21}$	$0.68^{+0.31}_{-0.20}$	$0.77^{+0.18}_{-0.15}$
$\Omega_{\boldsymbol{k}}$	0.0026 ± 0.0015	0.0025 ± 0.0015	$0.0028^{+0.0016}_{-0.0019}$	0.0027 ± 0.0016

Summary and Outlook

- Pure quintessence in an curved Universe allows for eternal acceleration at the asymptotics of moduli space – control and no event horizon – for string-allowed values $\frac{|\nabla V|}{V} = \lambda > \sqrt{2}$.
- Adding phenomenological requirement of past radiation domination makes acceleration epoch only transient.
- Adding moreover phenomenological requirement of current acceleration puts upper bound on $\lambda \lesssim \sqrt{3}$.
- The cosmological data indicates no preference (yet) for non-zero curvature and a 2-4σ preference for $\lambda \neq 0$ but with $\lambda < \sqrt{2}$ – away from string models and back to eternal acceleration.
- Data shows no preference (yet) between ΛCDM and qCDM and mild preference for $w_0 w_a$ parameterisation.
- Alternative string-inspired models, like hilltop (including axions) or interacting dark sectors with transient de Sitter, may well fit the data better.
- More cosmological data to come - we can hope to know much more about Dark Energy in the near future and begin to rule out models and have favoured ones!