Dark Energy
With a Little Help from its Friends

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based on
JHEP 12 (2021) 124, JHEP 09 (2022) 208 and 2306.07332 with
Bruno Bento, Dibya Chakraborty and Ivonne Zavala
PRD 101, 023503 (2020) and work to appear with Joaquim Gomes and Ed Hardy

Motivation

- Observations to date are consistent with Dark Energy being a tiny vacuum energy sourcing a de Sitter Universe: Planck '18

$$\langle V \rangle = 7 \times 10^{-121} M_{pl}^4 \quad \text{and} \quad w \equiv \frac{p}{\rho} = -1.028 \pm 0.032$$

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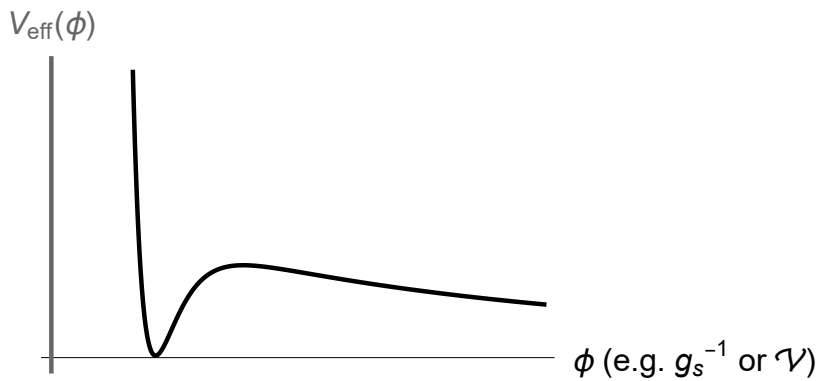

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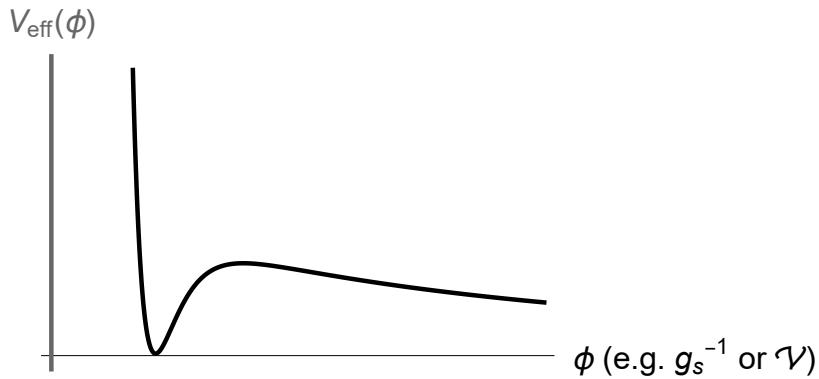

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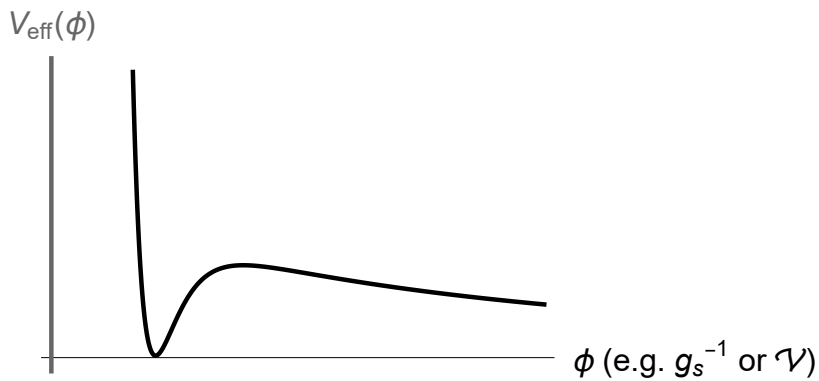

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- Much progress towards explicit de Sitter string solutions but they are always near the boundaries of control. Dine & Seiberg '85 and vast literature
- Together with conceptual issues – the absence of an S-matrix formulation in dS – has lead to speculation that long-lived dS may be inconsistent with quantum gravity – on going fruitful debate...

Witten '01; Banks '12; Danielsson & van Riet '18; Obied, Ooguri, Spodyneiko, Vafa '18; Cicoli et al '18

Plan

Are their simple, alternative, string-inspired candidates for Dark Energy with observational signatures?

eBOSS 2014-2020, SuMIRE 2014-2024, DESI 2019-2024, LSST 2020-2030, Euclid 2020-2026, WFIRST 2024-2030

- Challenges in building dS vacua and quintessence in string theory – *control issues for dS, need for large field distances and/or fine-tuning in potential and/or initial conditions for quintessence, ...* .
- How interacting Dark Sector can source a transient dS with small field displacements and no fine-tuning in potential or initial conditions, consistently with string swampland conjectures.

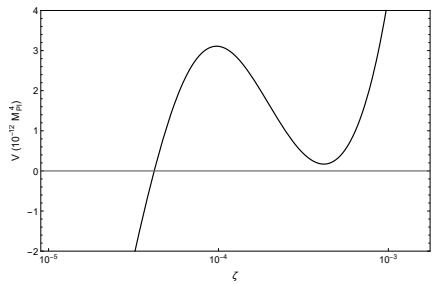
Challenges in building de Sitter string vacua

Bento, Chakraborty, SLP, Zavala '23 – see upcoming talk at String Pheno 2023 for more details!

Case study – *'weakly-warped LVS dS solution'*

(c.f. KKLT Kachru et al '03 & strongly-warped LVS, Balasubramanian et al '05)

- String compactification on CY manifold with fluxes containing a 'weakly-warped deformed conifold'.
- Leading perturbative and non-perturbative corrections, and susy breaking antibrane, leads to a metastable de Sitter vacuum:



  provided $\frac{g_s^2 W_0^2}{\mathcal{V}^{2/3}} \gg 1$ with W_0 superpotential from fluxes.
- $\exists$ various 'sub-leading' corrections – *curvature corrections, KK modes, backreactions* – compute their parametric dependence.
- Curvature and warping corrections are parametrically suppressed, but 'higher F-terms' $\Rightarrow$:

Cicoli, Conlon, Maharana & Quevedo '13
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$$\delta V \sim \frac{m_{3/2}^2}{m_{kk}^2} \sim \frac{g_s^2 W_0^2}{\mathcal{V}^{2/3}}.$$

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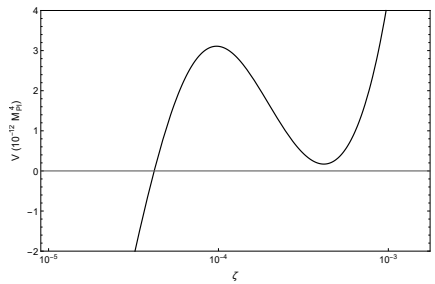

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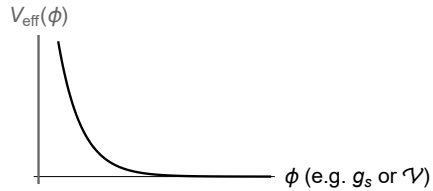
- dS solution consistent only if δV's numerical coefficient small.

Similar analysis done for strongly-warped LVS in Junghans '22

Challenges in building quintessence in string theory

- Slow-roll quintessence needs scalar field with flat potential $\epsilon_V \equiv (M_{\rm Pl} V'/V)^2 < 1$, similarly evasive in string theory:



- No-go theorems for single-field models from 4D N=1 sugra.
  Bento, Chakraborty, SLP, Zavala '20; Rudelius '21
- Some progress using multi-field, but conceptual problems similar to dS and more – $m_\phi \lesssim H_0$, fifth forces, time-variation of fundamental constants, ...
  e.g. Calderon-Infante, Ruiz, Valenzuela '22; Shiu, Tonioni & Tran '23
- Axions with $V(a) \sim e^{-\phi} \sin(a/f)$ would have protected light masses due to shift-symmetry and evade fifth forces.
- But slow-roll would require $f_{\rm eff} > M_{\rm Pl}$ via e.g. fine-tuned alignment mechanism or fine-tuned hilltop initial condition.
  Kim, Nilles & Peloso '04; see Cicoli et al '18 for a review
- Often encounter tensions with string theory swampland conjectures – large field distances bring down light towers and large corrections to EFT.
  but see e.g. Montero, Vafa & Valenzuela '22 for how this may lead to predictions

Interacting Dark Sectors

Elephant in the Room by Banksy

Claim: interacting Dark Sector can source a transient dS with small field displacements and no fine-tuning in potential or initial conditions, consistently with string swampland conjectures.

Interacting Dark Sectors

Gomes, Hardy & SLP, to appear

Toy model - two interacting dark scalar fields:

$$\mathcal{L} = \frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi + \frac{1}{2} g^{\mu\nu} \partial_\mu \psi \partial_\nu \psi + V(\phi, \psi) \ ,$$

with canonical kinetic terms and a scalar potential of the form:

$$V(\phi, \psi) = V(\phi) + \frac{1}{2} m_\psi^2 \psi^2 + \frac{1}{2} \frac{m_{\rm int}^2}{\Lambda^2} \phi^2 \psi^2 \ .$$

and Higgs-like hilltop or runaway potential for ϕ:

$$V(\phi) = \rho_{\rm de} \left(\left(\frac{\phi}{\Lambda} \right)^2 - 1 \right)^2 \quad \text{or} \quad V(\phi) = \rho_{\rm de} \, e^{-\frac{\phi}{\Lambda}}$$

With $m_{\rm int} = 0$ either ϕ or ψ could source slowly-rolling quintessence... but only with fine-tuning to hilltop or dangerous large field distances.

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With $m_{\rm int} \neq 0$ and ψ behaving as DM, DR or subdominant DE - can stabilise ϕ near $\phi = 0$ to source observed DE as transient dS!

How DM can help DE

Dvali & Kachru '03; Copeland & Rajantie '05; Axenides & Dimoloulos '04 'Locked Inflation/Dark Energy'; Gomes, Hardy & SLP to appear

- Suppose FRW background with energy density dominated by $V(\phi)$; assuming $m_\psi > m_{\rm int}\phi/\Lambda$:

$$\ddot{\psi} + 3H\dot{\psi} + m_\psi^2\psi = 0\,.$$

For $\psi_{init} \neq \psi_{min} = 0$ and $m_\psi > H_0 \Rightarrow$ classical oscillations:

$$\psi(t) = \psi_0 e^{-3H(t-t_0)/2}\cos(m_\psi t)$$

$\sim$ collection of scalar particles oscillating coherently with $\nu \sim m_\psi$.

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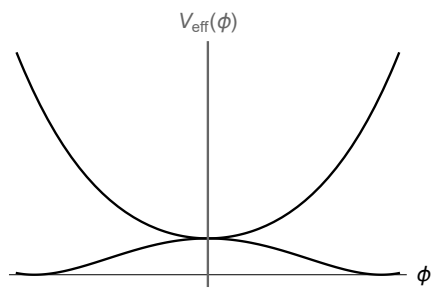
- For hilltop - ϕ can be held at $\phi = 0$ where it sources Dark Energy:



A transient de Sitter

- ψ's amplitude falls - eventually it will be unable to hold ϕ away from its minimum:

$$N = \frac{2}{3} \log \left(\frac{m_{\rm int} \psi_0}{\sqrt{\rho_{\rm de}}} \right)$$

- Time that ψ spends in instability region should be less than time-scale on which ϕ would roll:

$$N = \frac{2}{3} \log \left(\frac{\psi_0 \Lambda m_{\rm int} m_\psi}{\rho_{\rm de}} \right)$$

- Full dynamics for ϕ described by Matthieu equation with time-dependent coefficients – $\hat{\phi} = e^{3H_0 t/2}\phi$ and $\tau = m_\psi t$ leads to:

$$\hat{\phi}'' + (a(\tau) - 2q(\tau)\cos(2\tau))\hat{\phi} = 0$$

with solution given by Floquet's theorem:

$$\phi(t) \sim e^{(0.11 m_\psi - 3H_0/2)t} .$$

Parametric resonant instability in ϕ would end DE domination unless there is sufficient Hubble friction $m_\psi/H_0 \lesssim 15$.

DM Assisted DE – full cosmology

Gomes, Hardy & SLP to appear

- Parametric resonance must not end DE epoch too quickly $\Rightarrow m_\psi \lesssim 15 H_0 \Rightarrow \psi$ begins oscillations after $t_{eq} \Rightarrow \psi$ not all DM.

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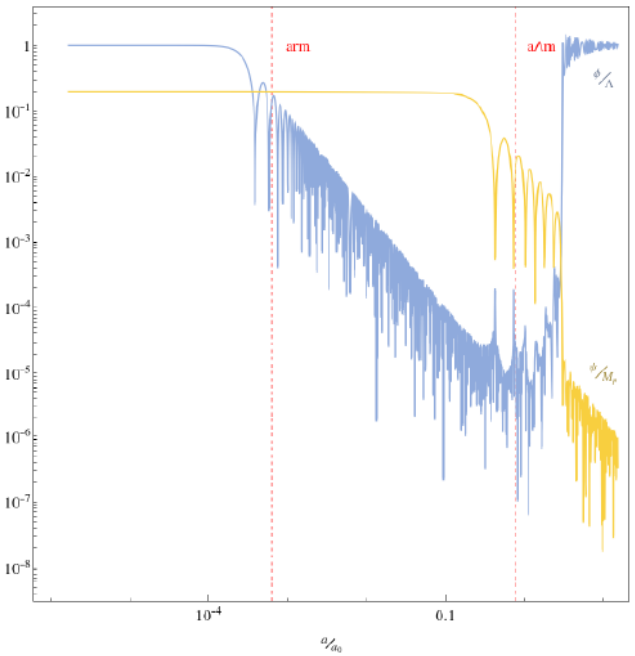
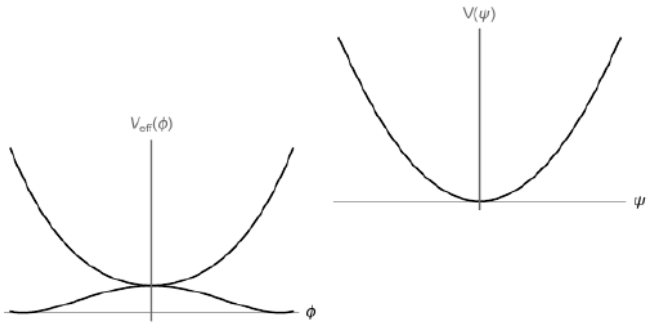
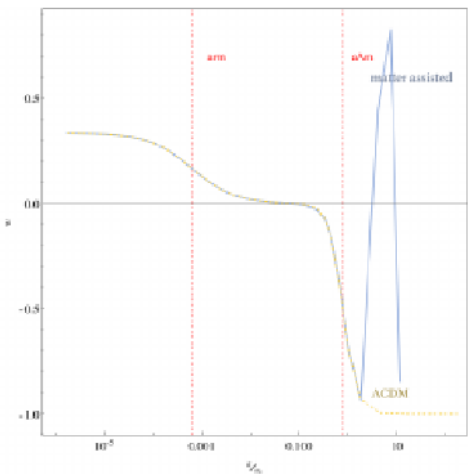
- Full cosmology can be solved numerically:





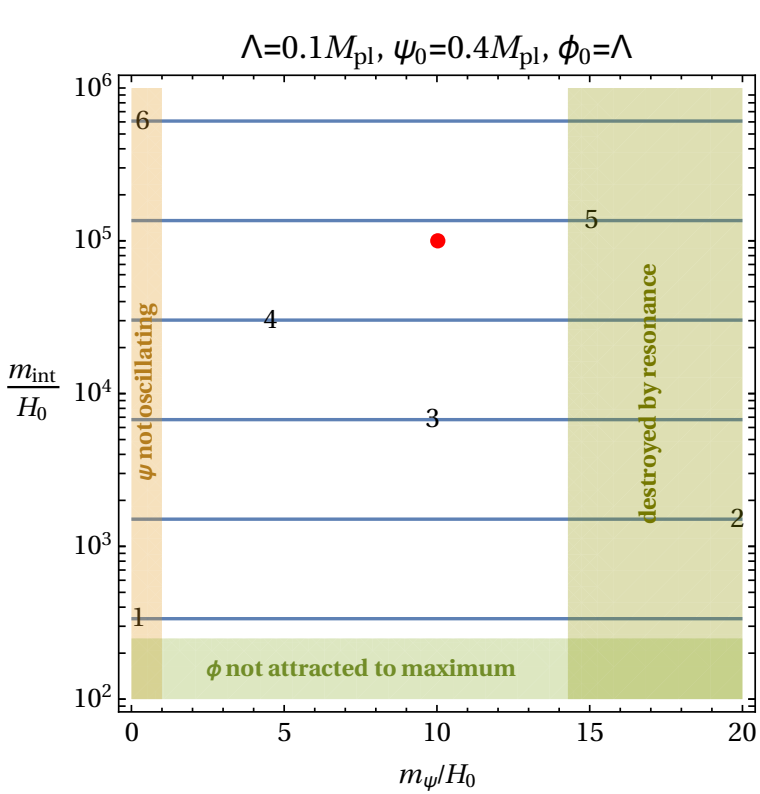


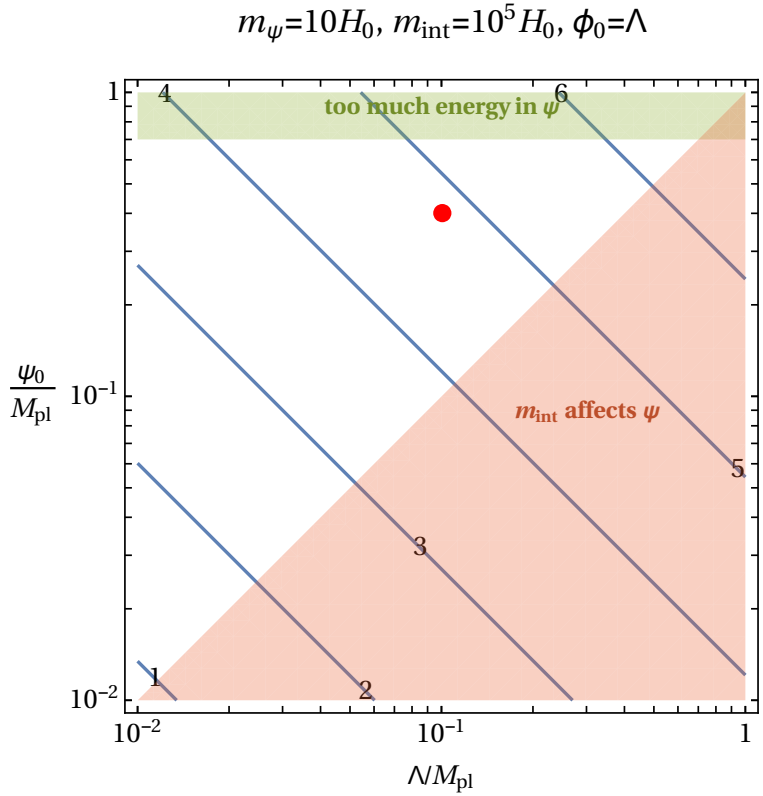
$$\frac{\Lambda}{M_{\rm pl}} = 0.1,\ \frac{m_{\rm int}}{H_0} = 10^5,\ \frac{m_\psi}{H_0} = 10,\ \frac{\dot\psi_0}{M_{\rm pl}} = 0.4,\ \frac{\dot\phi_0}{\Lambda} = 1.$$

- No tuning of initial conditions necessary, no super-Planckian distances, a transient dS with no fine-tuning in Lagrangian parameters!

DM Assisted DE – parameter space

Gomes, Hardy & SLP to appear





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- Realisation within string theory – and the cosmological constant problem :) – to be worked out.