Transient de Sitter Vacua from Interacting Dark Sectors

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Deconstructing the String Landscape (a.k.a landscapia)
31st November 2023, Saclay

based on 2311.08888 with Joaquim Gomes and Ed Hardy
and will also mention work to appear soon with Marco Serra

Motivation

- Runaway moduli ubiquitous in string compactifications, but seem always to be too steep to source quintessence.

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- Metastable dS vacua via quantum effects, numerically controlled – with anthropics – still be best explanation of Dark Energy.

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- Non-susy strings offer alternative place to search of accelerating solutions – more no-gos
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Type II on $M_{d-1,1} \times M_p \times T^{SS}_{10-d-p}$ with fluxes

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Aside – parametrically controlled non-susy, partially scale separated adS found...but (so far) tachyonic below BF bound.
SLP & Serra to appear soon; see de Luca, Silverstein & Torroba '21; Baykara, Robbins & Sethi '22; de Luca & Tomasiello 22 for related work

Plan

'String-inspired' mechanisms to dynamically stabilise steep runaway directions into transient dS vacua consistently with observations and swampland conjectures.

- Interacting Dark Sectors can lead to a transient dS vacuum despite Lagrangian potential having no dS vacuum.
- Observational constraints
- Fine-tuning
- Swampland conjectures
- Outlook – embedding into string theory...

Talk will focus on DM – DE scenarios – other parameter spaces also possible with DR – DE and multi-field quintessence.

We will not address the cosmological constant problem.

Interacting Dark Sectors

Gomes, Hardy & SLP '23

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:

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

and Higgs-like hilltop or runaway potential for ϕ:

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

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With $m_{\text{int}} = 0$ either ϕ or ψ could source slowly-rolling quintessence...
but only with fine-tuning i.c.s 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!

DM assisted DE

Dvali & Kachru '03; Copeland & Rajantie '05; Axenides & Dimoloulos '04 'Locked Inflation/Dark Energy'; Gomes, Hardy & SLP '23

- Suppose FRW background with energy density dominated by $V(\phi)$ [full cosmology below]; assuming $m_\psi > m_{\text{int}}\phi/\Lambda$:

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

  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 w/ $\nu \sim m_\psi$, evolving as matter $\rho_\psi \sim 1/a^3$.

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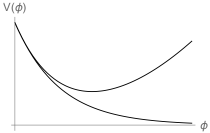
- Quartic interaction $\frac{m_{\rm int}^2}{\Lambda^2}\langle\psi^2\rangle\phi^2 \Rightarrow$ effective mass contribution for ϕ:

$$\frac{\partial V(\phi,\psi)}{\partial\phi} = 0 \Rightarrow \frac{\phi_{\rm min}}{\Lambda} = \mathrm{W}_0\left(\frac{\rho_{\rm de}}{m_{\rm int}^2\,\langle\psi^2\rangle}\right) \ll 1$$

ϕ held in dS minimum where it sources Dark Energy.



A transient de Sitter

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- Full dynamics for ϕ described by [inhomogeneous] Matthieu equation with time-dependent coefficients – $\hat{\phi} = e^{3H_0t/2}\phi$ 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:

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- At late-times – global attractor, non-accelerating, scaling solution, for which Ω_ϕ remains fixed, small, fraction of the total energy.

DM Assisted DE – full cosmology

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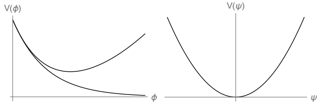
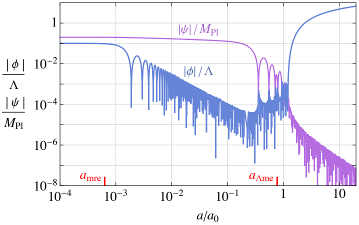
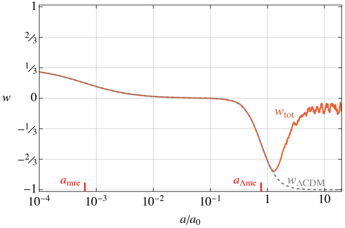
  $\Rightarrow m_\psi \lesssim 15H_0 \Rightarrow \psi$ begins oscillations after $t_{eq} \Rightarrow \psi$ not all DM.
- Full cosmology can be solved numerically giving e.g. $N_{\rm DE} \sim 0.5$:





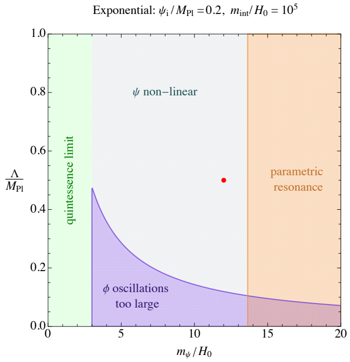


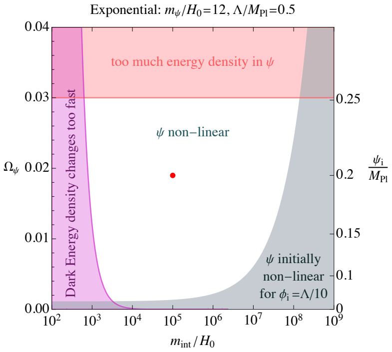
$m_\psi = 12H_0$, $m_{\rm int} = 10^5 H_0$, $\Lambda = M_{\rm Pl}/2$, $\phi_{\rm i} = 10^{-1}\Lambda$, $\psi_{\rm i} = M_{\rm Pl}/5$.

- No fine-tuning of initial conditions necessary, no super-Planckian distances, no fine-tuning between Lagrangian parameters, consistent with cosmological observations.

DM Assisted DE – parameter space

Potential observational signatures - Ω_ψ, $w(z)$, spatial variation in w due to fluctuations in ψ_i, fifth forces...





DM Assisted DE – fine-tuning

- Need light scalar fields $m_\psi \lesssim 15 H_0$, $m_\phi^{\text{eff}} \gtrsim H_0$, and small quartic coupling $\frac{m_{\text{int}}}{\Lambda} \lesssim \frac{H_0}{M_{pl}} \sim 10^{-60}$.
- Quartic interaction $\frac{1}{2}\frac{m_{\text{int}}^2}{\Lambda^2}\phi^2\psi^2 \Rightarrow$ radiative corrections:

$$\Delta m_\psi^2 \approx \frac{m_{\text{int}}^2}{32\pi^2\Lambda^2}\Lambda_{\text{UV}}^2 \qquad \text{and} \qquad \Delta m_\phi^2 \approx \frac{m_{\text{int}}^2}{32\pi^2\Lambda^2}\Lambda_{\text{UV}}^2$$

  sufficiently suppressed provided $\Lambda_{\text{UV}} \lesssim \Lambda, M_{pl}\frac{H_0}{m_{\text{int}}}$.
- Corrections from gravitational couplings to visible sector states with mass M:

$$\Delta m_\phi^2 \sim \frac{1}{(4\pi)^6}\frac{M^6}{M_{\text{Pl}}^4} \qquad \text{and} \qquad \Delta m_\psi^2 \sim \frac{1}{(4\pi)^6}\frac{M^6}{M_{\text{Pl}}^4}\,,$$

  sufficiently suppressed only for $M \lesssim$ GeV.
- Corrections from heavy string states as in quintessence scenarios...susy? sequestering?

Out of the Swampland

- All field ranges sub-Planckian – EFT under control.
- de Sitter swampland conjecture: Ooguri, Palti, Shiu & Vafa '18

$$\text{either } M_{\text{Pl}}\,|\nabla V| \geq \mathcal{O}(1)\,V \quad \text{(1a)}$$
$$\text{or } M_{\text{Pl}}^2 \min(\nabla_i \nabla_j V) \leq -\mathcal{O}(1)\,V \quad \text{(1b)}$$

  rules out metastable de Sitter and with observations requires $\Lambda \gtrsim 1.67 M_{pl}$ for quintessence sourced by $\rho_{\text{de}} e^{-\phi/\Lambda}$.
- (1a) satisfied at $\frac{\phi_{\text{min}}}{\Lambda}$ for all $\psi < \sqrt{2\langle\psi^2\rangle}$ provided:

$$\frac{H_0}{m_\psi} < \frac{m_\psi}{m_{\text{int}}}\,.$$

- Numerical analysis $\Rightarrow$ full cosmological trajectories satisfy (1).
- Just a few N_{DE} $\Rightarrow$ Transplanckian censorship conjecture satisfied.

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- Other parameter spaces are possible – with ψ playing role of Dark Radiation or a multi-field quintessence scenario that similarly supports ϕ in a false vacuum.
- Embedding into string theory in progress - fifth-forces $\Rightarrow$ both fields must be local moduli sequestered from visible sector.

Dark Energy from Interacting Dark Sectors

	DM assisted	DR assisted	Q assisted
m_ψ	$H_0 \lesssim m_\psi \lesssim 15 H_0$	$m_\psi \lesssim T_{\rm h} \lesssim \rho_{\rm de}^{1/4}$	$m_\psi \lesssim H_0$
$m_\phi^{\rm eff}$	$m_\phi^{\rm eff} \gtrsim H_0$	$T_{\rm v,0} \gg m_\phi^{\rm eff} \gtrsim H_0$	$m_\phi^{\rm eff} \gtrsim H_0$
$m_{\rm int}$	$m_{\rm int} \gtrsim \frac{M_{\rm Pl}}{\Lambda} \frac{M_{\rm Pl}}{\psi_{\rm i}} H_0$	$m_{\rm int} \gtrsim \rho_{\rm de}^{1/4}$	$m_{\rm int} > \frac{M_{\rm Pl}}{\psi_{\rm i}} H_0$
λ	$\lambda \ll m_\psi^2 / M_{\rm Pl}^2$	$\lambda \gtrsim (m_{\rm int}/(M_{\rm Pl}\xi_{\rm h}^2))^{1/4}$	$\lambda \ll m_\psi^2 / M_{\rm Pl}^2$
Parametric resonance?	yes	no	no
Bubble nucleation?	no	yes	no
No fine-tuning from quartic coupling?	$\Lambda_{\rm UV} \ll \Lambda, M_{\rm Pl} \frac{H_0}{m_{\rm int}}$	$\Lambda_{\rm UV} \lesssim \rho_{\rm de}^{1/4}$	$\Lambda_{\rm UV} \ll \Lambda, M_{\rm Pl} \frac{H_0}{m_{\rm int}}$
No fine-tuning from graviton exchange with other sectors?	$M < {\rm GeV}$	$M < (M_{\rm Pl}/\Lambda)^{1/3} {\rm GeV}$	$M < {\rm GeV}$
No fine-tuning from $\mathcal{O}(1)$ couplings to other sectors?	$m_{\rm soft\ hid} \ll H_0$	$m_{\rm soft\ hid} \ll \rho_{\rm de}^{1/4}$	$m_{\rm soft\ hid} \ll H_0$
Sequestering of portal couplings, e.g. $\kappa\phi\mathcal{O}_{\rm SM}$	$\kappa \lesssim 10^{-6} M_{\rm Pl}^{-1}$	$\kappa \lesssim M_{\rm Pl}^{-1}$	$\kappa \lesssim 10^{-6} M_{\rm Pl}^{-1}$
Other potential signals?	$w(z)$, Ω_ψ	$w(z)$, $N_{\rm eff}$	$w(z)$
dS swampland constraint?	satisfied for $\frac{H_0}{m_\psi} < \frac{m_\psi}{m_{\rm int}}$	satisfied	violated