Thermal Dark Energy
and Other String Candidates

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University of Liverpool

KITP Conference | UV Meets the IR: Effective Field Theory Bounds from QFT to String Theory
13th October 2020

based on work with:
Ed Hardy Phys.Rev. D101 (2020) no.2, 023503
Yessenia Olguín, Gianmassimo Tasinato & Ivonne Zavala JCAP 1901 (2019) no.01, 031
Bruno Bento, Dibya Chakraborty & Ivonne Zavala 2005.10168 [hep-th] and 2011.XXXX

Plan

Given the difficulties in obtaining controlled de Sitter vacua in string theory, are there simple Dark Energy alternatives?

- Quintessence from a runaway string modulus
- Thermal Dark Energy

What do they tell us about the String Landscape vs. Swampland?
What are their observational signatures?

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

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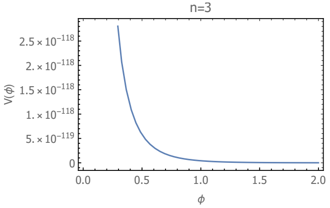

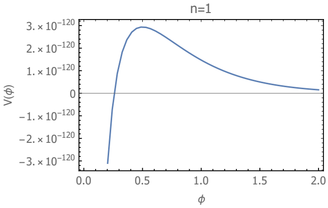

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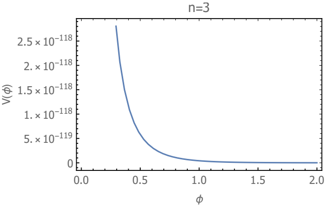

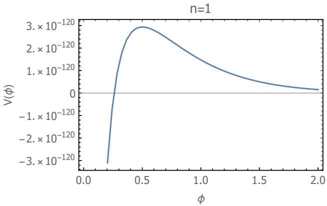

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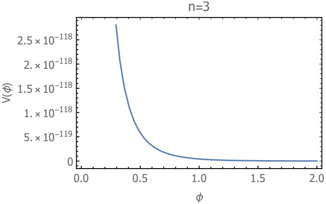

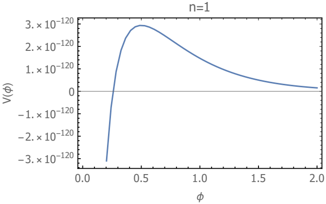

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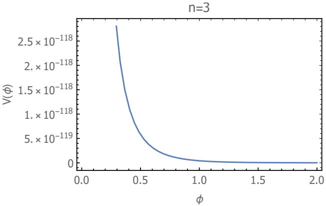

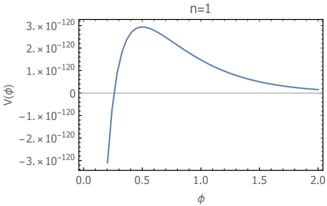

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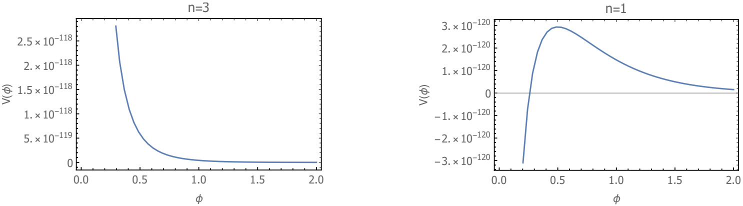

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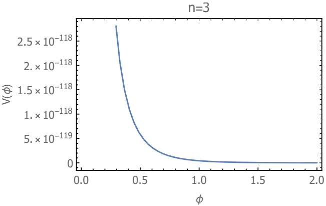

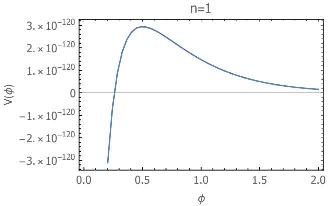

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- ϕ can be frozen by Hubble friction but not simultaneously dominate the energy density of Universe... unless initial conditions are fine-tuned to hilltop *(note unstable dS)*

Quintessence No-Gos in Supergravity

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$K = -n\log(\Phi + \bar{\Phi})$ and $V = V_0\phi^{-p}$ $\Rightarrow$ slow-roll for $p^2/n \lesssim 1$, but 4D sugra constrains V_0 in terms of p and n.

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Hardy & Parameswaran '20

Elephant in the Room by Banksy

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High T effects transform the Unstable dS in the Higg's Mexican Hat potential to a metastable dS.... no accelerated expansion as $V(H)$ dominated by ρ_{rad}... consider a light hidden sector where thermal effects generate a metastable dS that dominates Universe and drives accelerated expansion.

Light Hidden Sectors at Finite Temperature

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- Suppose light hidden d.o.f's, still in internal thermal equilibrium today, $\Gamma_I = n\langle\sigma v\rangle \gg H$ since reheating $\Rightarrow \xi_h \equiv \left(\frac{T_h}{T_v}\right) \gg \mathcal{O}(1)\frac{T_v}{M_{pl}}$

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- A light scalar field (matter or modulus) with non-zero vev, e.g.:

$$V(\phi) = \lambda\phi^4 - \frac{m_\phi^2}{2}\phi^2 + C$$

with $\phi_1 \equiv \langle\phi\rangle_{min} = m_\phi/(2\sqrt{\lambda})$ and $\langle V\rangle_{min} = 0$ for $C = m_\phi^4/(16\lambda)$.

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$$y_i\phi\bar{\psi}^i\psi^i \qquad \text{and} \qquad \lambda_a\phi^2\chi^a\chi^a$$

i.e. effective masses $m_{\psi^i}(\phi_c) = y_i\phi_c$ and $M_{\chi^a}(\phi_c) = \sqrt{\lambda_a}\phi_c$.

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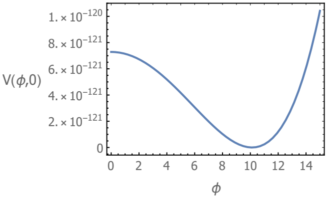
- At finite temperature, plasma interacts with homogeneous scalar field background – which itself determines the masses and interactions of particles $\Rightarrow$ thermal potential for ϕ.

Thermal Dark Energy

cf. Thermal Inflation, Lyth & Stewart '95



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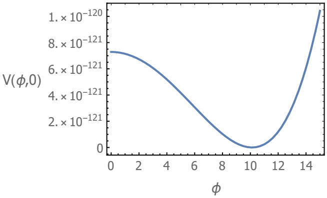

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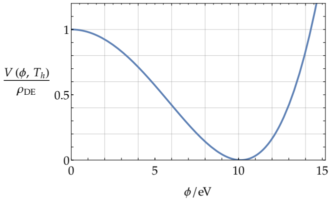

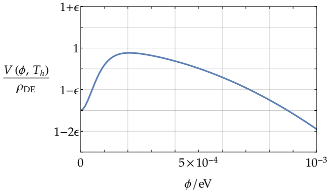

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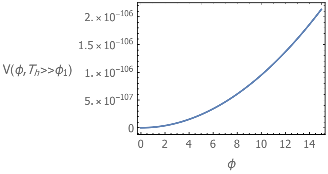

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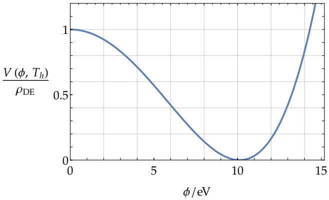

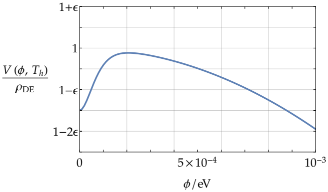

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- Shift from $\phi = \phi_1$ to $\phi = 0$ induces vacuum energy:

$$V(0, T_h) = \frac{m_\phi^4}{16\lambda}$$

see also Chung & Long '11

Dark Radiation and Dark Energy

Hidden sector contributes to Einstein's equations in two ways:

- Dark radiation:

$$\rho_{r\ hid} = \frac{\pi^2 g_h {T_h^0}^4}{30} \quad \text{with} \quad T_h^0 < T_v^0$$

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For Thermal Dark Energy we need:

- potential energy ($\rho_{DE} \approx (2.3meV)^4$) larger than radiation energy ($T_v^0 \approx 0.24meV$) today:

$$\frac{m_\phi^4}{16\lambda} > \frac{\pi^2 g_v {T_v^0}^4}{30}$$

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E.g. for $T_h \sim 3 \times 10^{-5} eV$, $m_\phi \sim 1 \times 10^{-6} eV$ and $\lambda \sim 2 \times 10^{-15}$ we would have $V_{vac} \sim (2meV)^4$ and $w = -1$ today.

Other phenomenological constraints

- ΔN_{eff} constrains temperature of hidden sector:

$$N_{eff} \approx 3 + \frac{4}{7} g_*^h \left(\frac{T_h}{T_v} \right)^4$$

then $N_{eff} \lesssim 3.18$ from BBN $\Rightarrow T_h^0 \lesssim 0.3 T_v^0$ for $g_*^h = 1 + \frac{7}{8}4$.

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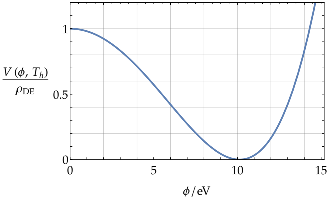
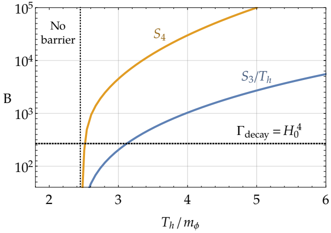
- Metastable dS decays through nucleation of bubbles of true vacuum: need $\Gamma_{nucl} \ll H_0^4$, where:

$$\Gamma_3 = T_h^4 \left(\frac{S_3}{2\pi T_h} \right)^{3/2} e^{-S_3/T_h} \quad \text{or} \quad \Gamma_4 = v^4 \left(\frac{S_4}{2\pi} \right)^2 e^{-S_4}$$

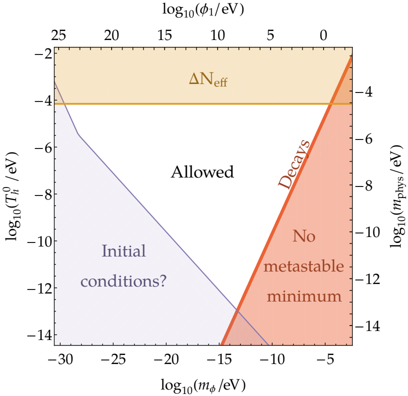




For $m_\phi = 10^{-6} eV$ vacuum decay is negligible until T_h close to when metastable minimum disappears at $N_E \sim 4$.

A Viable, Robust Parameter Space

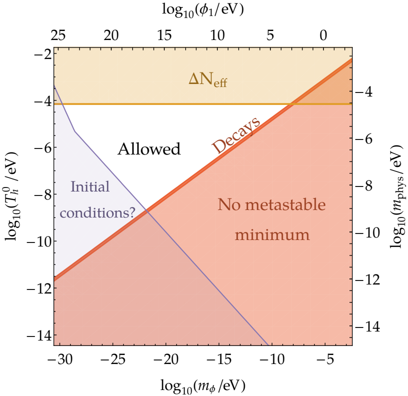
For $V(\phi, 0) = \lambda\phi^4 - \frac{1}{2}m_\phi^2\phi^2 + \frac{m_\phi^4}{16\lambda}$



Note $m_{phys}^2 = 2bT_h^{0\,2}$, $\rho_{DE} = \frac{m_\phi^4}{16\lambda}$ and $\phi_1 = \frac{m_\phi}{2\sqrt{\lambda}}$

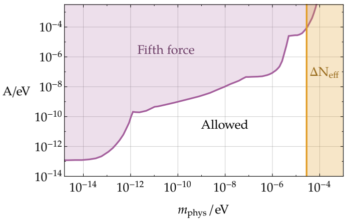
A Viable, Robust Parameter Space

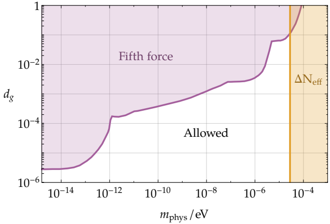
For $V(\phi, 0) = \frac{1}{2} m_\phi^2 (\phi - \phi_1)^2$



Note $m_{phys}^2 = 2b{T_h^0}^2$ and $\frac{1}{2} m_\phi^2 \phi_1^2 = \rho_{DE}$

Observational Signals





Portal interactions between visible and thermal dark energy sectors, e.g.

$$-(A\phi + g\phi^2)|H|^2 \qquad \text{and} \qquad d_g \frac{\beta_3}{\sqrt{2} g_3 M_{pl}} \phi F^a_{\mu\nu} F^{a\,\mu\nu}$$

- A, d_g constrained mainly by fifth forces.
- g mainly constrained by requirement that hidden sector stays cool to keep ΔN_{eff} small $\Rightarrow g < 10^{-10}\xi_h$.

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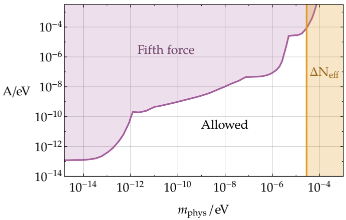

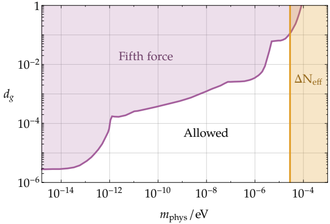

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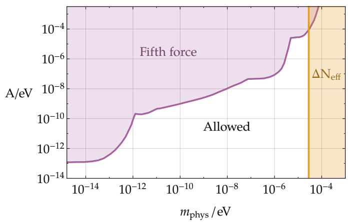

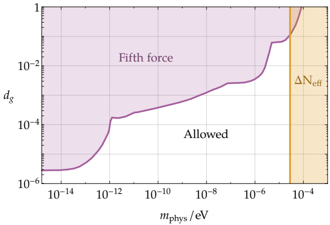

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Visible sector loops $\Rightarrow m_\phi^2 \sim g\Lambda_{UV}^2$ and ϕ tadpoles $\mathcal{L} \sim A\Lambda_{UV}^2\phi$, $d_g\Lambda_{UV}^4\phi/M_{pl}$ – couplings accessible to fifth forces require fine-tuning.

Fine-tuning

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$$W = (m_\psi - \Phi)\Psi^2 \quad \text{and} \quad V_{soft} = m_\phi^2|\phi|^2 + m_\chi^2|\chi|^2$$

with $m_\phi, m_\chi \ll m_\psi$ gives:

$$V = |\chi|^4 + |2m_\psi\chi - 2\phi\chi|^2 + m_\phi^2|\phi|^2 + m_\chi^2|\chi|^2 \quad \text{and}$$

$$\mathcal{L}_f \supset -(m_\psi - \langle\phi\rangle)\psi^2 + 2\langle\chi\rangle\eta\psi$$

suppressed hidden susy breaking scale $\Rightarrow$ superpotential and mass hierarchy protected by susy.

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- Stability against loops from visible sector states and string states – sequestering of susy breaking via extra dimensions? e.g. for $m_{3/2} \gtrsim 10^{-8} GeV$ from low-scale gauge mediation, need $m_{soft} \lesssim 10^{-7} m_{3/2}$ – much easier than for quintessence.

Summary and Outlook

- Existence or not of metastable dS vacua and/or quintessence in string theory remains an open question.
- Light hidden dark sector with finite temperature effects explains Dark Energy with $w = -1$ consistently with Swampland conjectures.
- Hidden sector susy can help with fine-tuning, and much less sequestering needed than for quintessence: $m \sim 10^{-6}$eV vs. $m \sim 10^{-33}$eV
- Potentially observable via ΔN_{eff} and fifth forces.
- DE epoch will end when $T_h \sim m_\phi$ with first order phase transition towards true vacuum, and conversion to hidden sector radiation, matter and gravitational waves.
- Multiple Thermal DE eras may realise the EDE scenario to explain the H_0 tension, leaving gravitational wave signatures as each TDE sector transitions to global minimum...PBHs?
- Embed in explicit string constructions and understand finite temperature effects vs swampland?