Thermal Dark Energy

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Corfu Summer Institute
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based on
JCAP 1901 (2019) no.01, 031 with
Yessenia Olguín-Trejo, Gianmassimo Tasinato and Ivonne Zavala
and 1907.10141 with Ed Hardy

Dark Energy

- Diverse observational probes point to Dark Energy consistent with a tiny Cosmological Constant:

$$\langle V \rangle_0 = 7 \times 10^{-121} M_{pl}^4 \quad \text{and} \quad w_0 = -1.028 \pm 0.032$$

Planck '18

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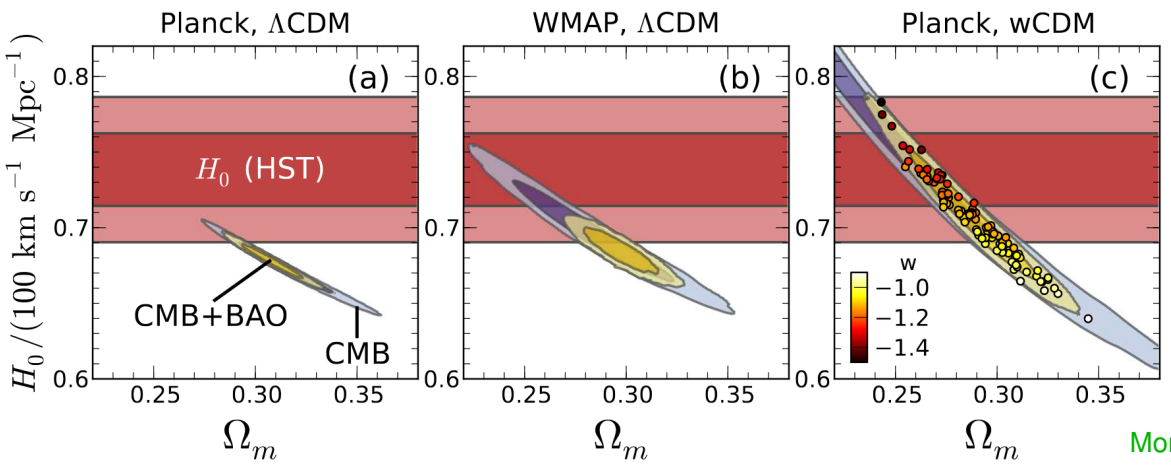
- Growing tension between direct measurements of H_0 and CMB fit using ΛCDM:



Mortonson et al '14

5.3 σ discrepancy...

Reiss et al '19, H0LiCOW XIII '19

early dark energy, N_{eff}, phantom DE, fading dark matter...?

Karwal & Kamionkowski '16; Calabrese, Huterer, Linde, Melchiorri & Pagano '11; Planck '15; Agrawal, Obied & Vafa '19; ...

Plan

- dS string vacua and the dS swampland conjecture
- No-go for simplest dS alternative:
  quintessence from a runaway string modulus
- An alternative to dS and quintessence – Thermal Dark Energy

dS vacua in String Theory

see also talks by Russo, Tsimpis, Nakajima, Cribiori

- In string models of DE, we typically look for 4D compactification to metastable dS with moduli potential $\langle V(\phi^i)\rangle_{min} > 0$.

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- We have long known that this would be hard:
  - string coupling moduli are runaways in perturbative regime unless there are parameters to fine tune Dine & Seiberg '85
  - two-derivative sugra with positive tension objects does not admit dS Maldacena & Nuñez '00
  - extensions e.g. classical iia on CY orientifolds with geometric fluxes: $\frac{|\nabla V|}{V} \geq \sqrt{\frac{54}{13}}$ Hertzberg, Kachru & Taylor '07

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- Over the last two decades technical progress in string compactifications and moduli stabilisation has brought us close to concrete de Sitter vacua from string theory

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- No consensus yet on these constructions.

dS Swampland Conjecture

"What if string theory has no dS vacua?" *even if metastable dS prove to be robust, question may inspire interesting alternatives...*

Danielsson & Van Riet '18

Conjecture: The scalar potential in the LEEFT of any consistent quantum gravity must satisfy either:

Obied, Ooguri, Spodyneiko & Vafa '18
Garg & Krishnan '18
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for possible generalisation see Gautason, Van Hemelryck & Van Riet '18 and Lüst, Palti & Vafa '19

$$\sqrt{\nabla^j V \nabla_j V} \geq \frac{c}{M_{pl}} V$$

or:

$$\min(\nabla^i \nabla_j) V \leq -\frac{c'}{M_{pl}^2} V$$

for some universal constants $c, c' > 0$ of order 1.

Rules out metastable dS, allows sufficiently unstable dS.

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E.g. top-down heterotic dS vacua satisfy conjecture with $c, c' = 1$.

Parameswaran, Ramos-Sanchez & Zavala '10; Olguín-Trejo, Parameswaran, Tasinato & Zavala '18

Implications for Dark Energy

Dark energy may be quintessence field:

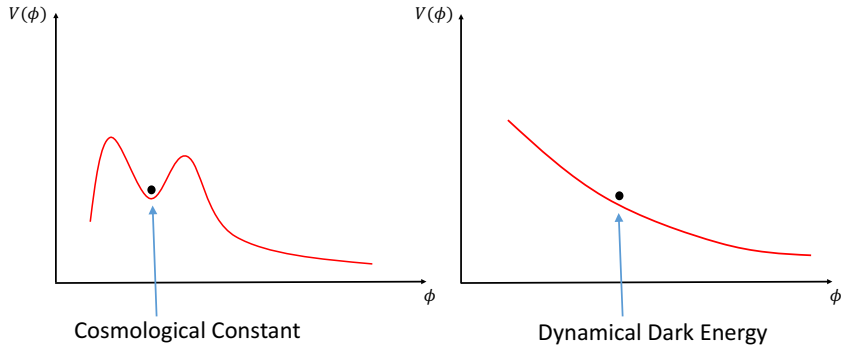

Figure from Palti's recent review

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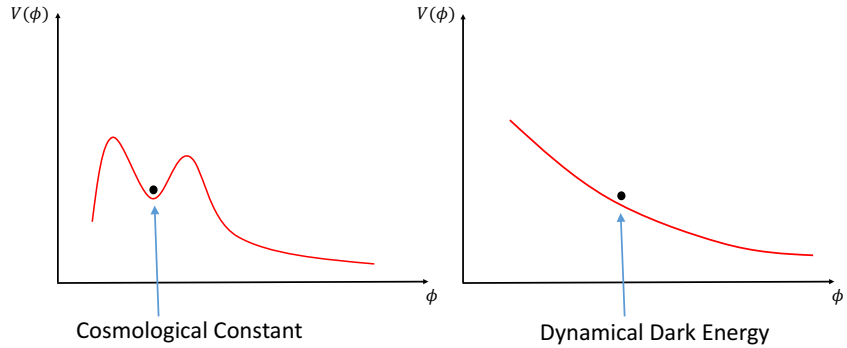

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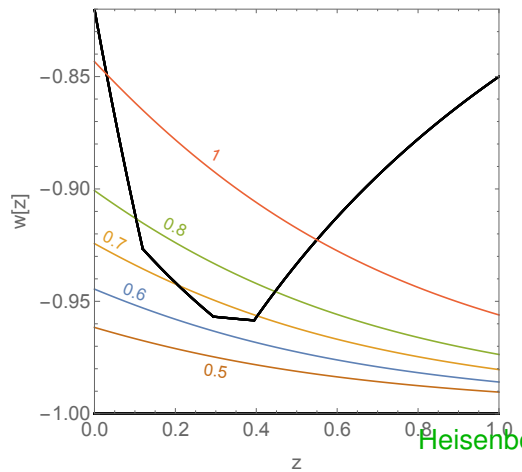
Assuming convex potential, e.g. $V = V_0 e^{\lambda(\phi)\phi}$, current observations on $w(z)$ constrain c in $|\nabla V| M_{pl} > cV$ to $c \lesssim 0.6$



Agrawal, Obied, Steinhardt & Vafa '18
Akrami, Kallosh, Linde & Vardanyan '18
Heisenberg, Bartelmann, Brandenberger & Refregier '19
Raveri, Hu & Sethi '19

Can string theory provide a simple model of slow roll quintessence?

String Models of Quintessence

Choi ’99 *"String or M theory axion as quintessence"*
Albrecht, Burgess, Ravndal & Skordis ’01 *"Natural quintessence and LEDs"*
Hellerman, Kaloper & Susskind ’01 *"String theory and quintessence"*
Kaloper & Sorbo ’08 *"Where in the string landscape is quintessence"*
Panda, Sumitomo & Trivedi ’10 *"Axions as quintessence in string theory"*
Cicoli, Pedro & Tasinato ’12 *"Natural quintessence in string theory"*
Blabäck, Danielsson & Dibitetto ’14 *"Accelerated Universes from type IIA"*
Cicoli, de Alwis, Maharana Muia & Quevedo ’18 *"dS vs quintessence in string theory"*
Acharya, Maharana, Muia ’18 *"Hidden sectors, kinetic mixings, 5th forces and quintessence"*
Emelin & Tatar ’18 *"Axion hilltops, Kahler modulus quintessence and the swampland criteria"*
D’Amico, Kaloper & Lawrence ’18 *"Strongly coupled quintessence"*
Hertzberg, Sandora & Trodden ’19 *"Quantum fine-tuning in stringy quintessence models"*
Heckman, Lawrie, Lin & Zoccarato ’19 *"Pixelated Dark Energy"*
van de Bruck & Thomas ’19 *"Dark Energy, the Swampland and the Equivalence Principle"*
Dimopoulos & Donaldson-Wood ’19 *"Warm quintessential inflation"*

Shout if I missed your favourite model!

String Models of Quintessence

see Cicoli, de Alwis, Maharan, Muia & Quevedo '18 for a review

Quintessence – a slowly-rolling ultra-light string modulus with:

$$\langle V \rangle \approx 10^{-120} M_{pl}^4 \quad \text{and} \quad m \lesssim 10^{-32} eV$$

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- axion - need large f_a or hilltop fine-tuning of initial conditions
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- local string modulus - $\Delta\phi \gtrsim M_{pl}$? sequestering?
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Most constructions have similar ingredients and challenges to dS constructions.

Quintessence from a Runaway String Modulus?

Olguin-Trejo, Parameswaran, Tasinato & Zavala '18

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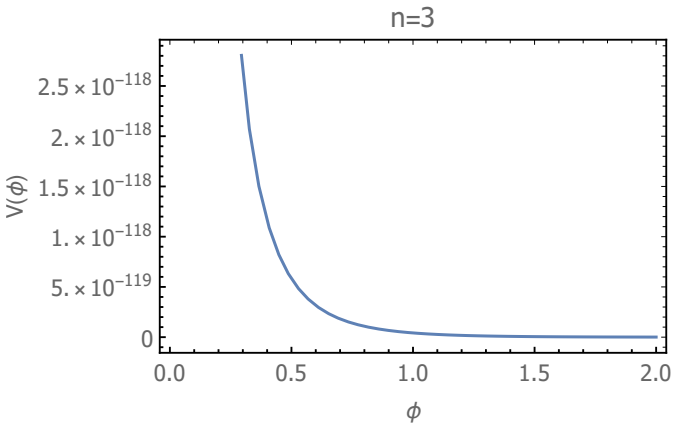

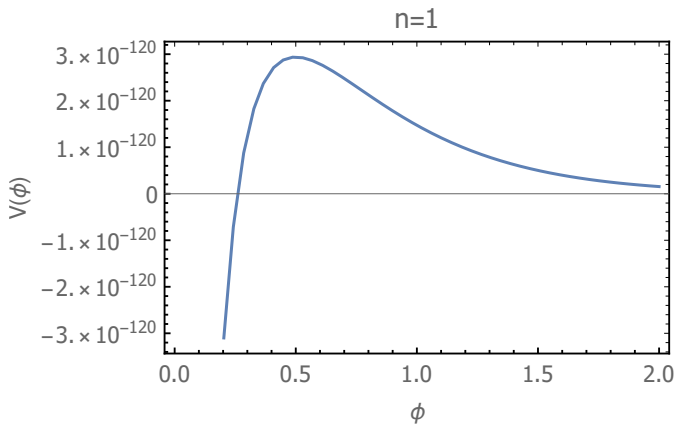

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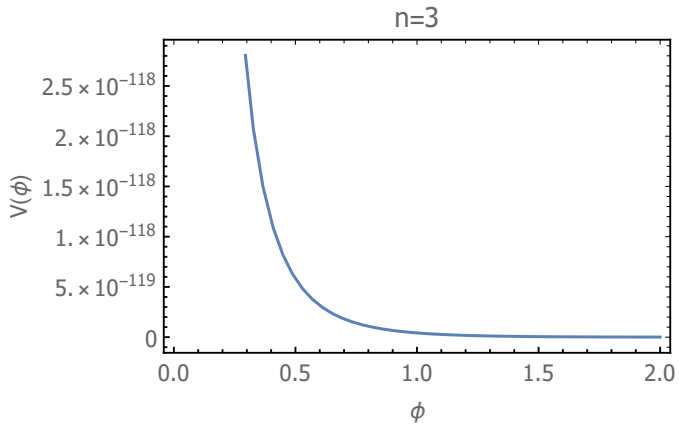

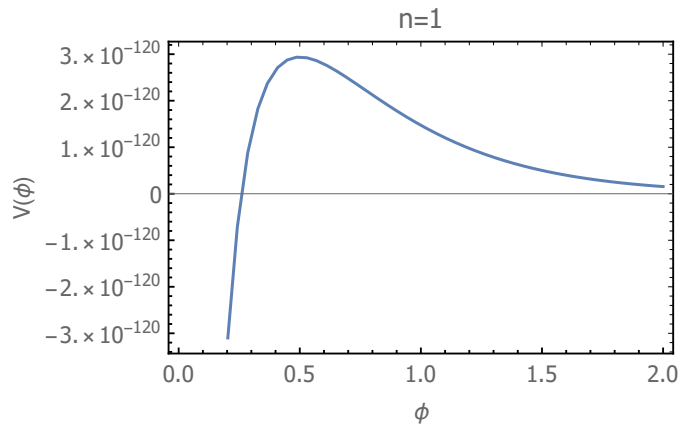

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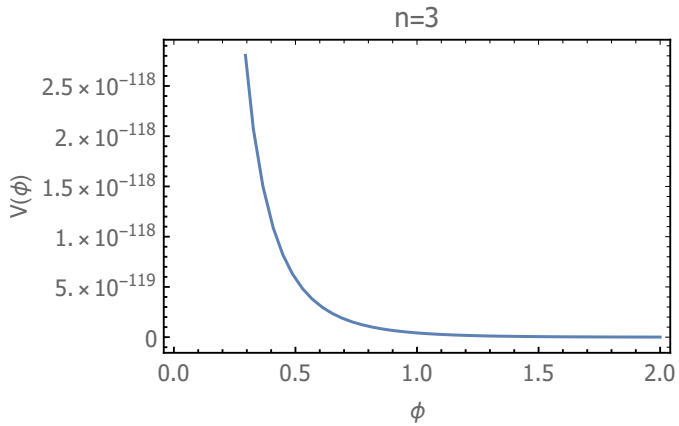

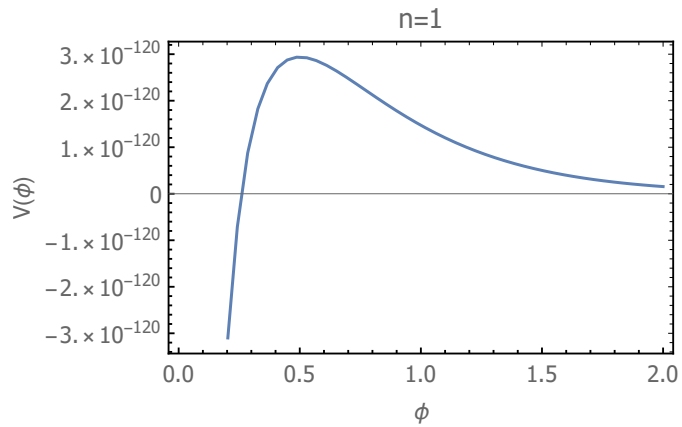

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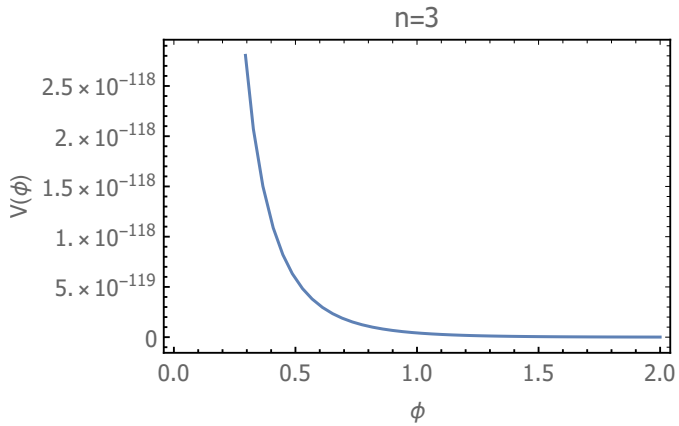

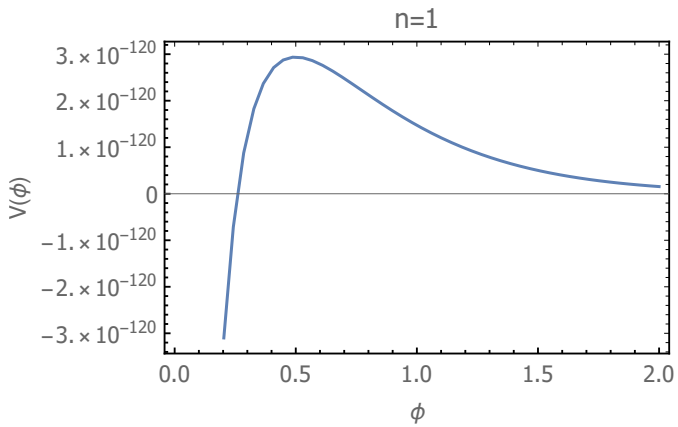

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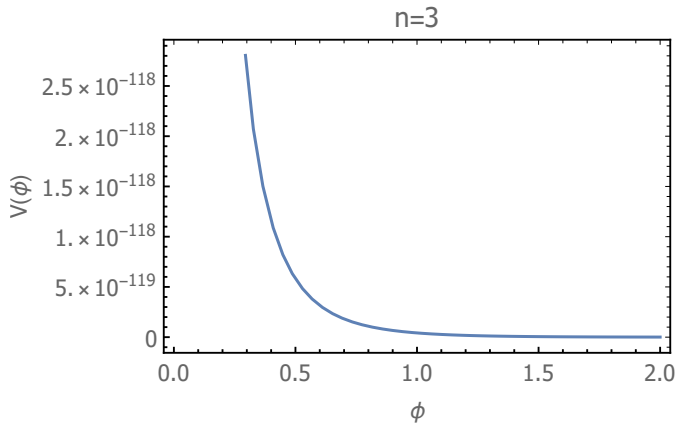

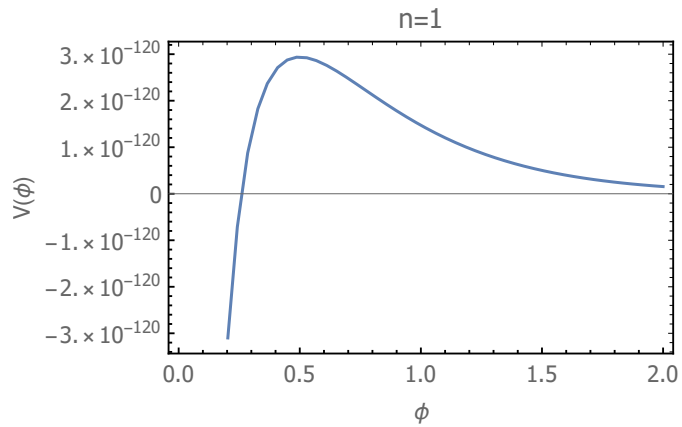

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Light Hidden Sectors at Finite Temperature

- String models can have abundance of hidden sectors, with rich internal dynamics but only weakly coupled to visible sector.

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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 $\langle\phi\rangle_{min} = m_\phi/(2\sqrt{\lambda})$ 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. $m_{\psi^i}(\phi_c) = y_i\phi_c$ and $M_{\chi^a}(\phi_c) = \sqrt{\lambda_a}\phi_c$.

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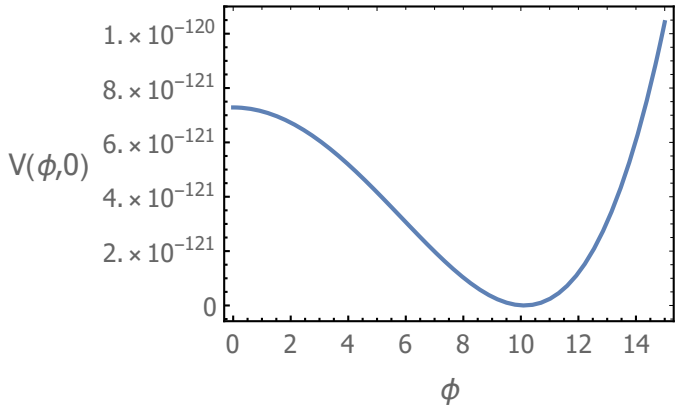
- At finite temperature, plasma interacts with homogeneous scalar field background – which itself determines the masses and interactions of particles – $\Rightarrow$ thermal potential for ϕ.

Thermal Dark Energy

cf. Thermal Inflation, Lyth & Stewart '95



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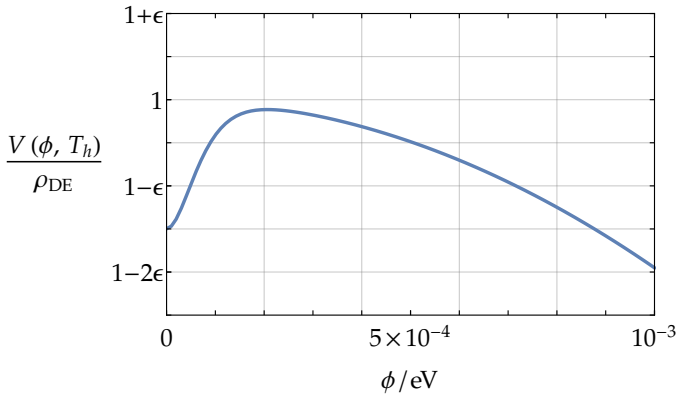

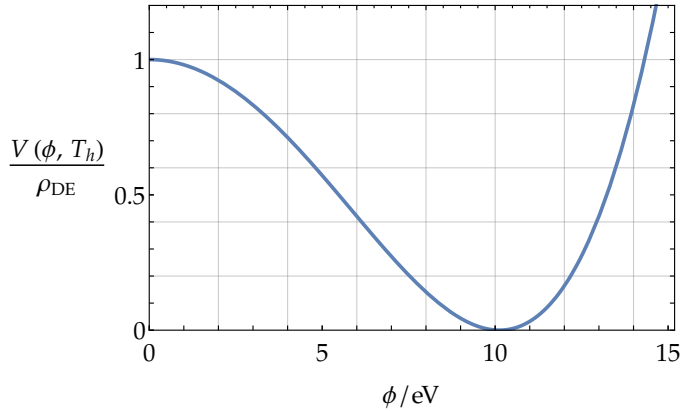

- For $T \gg m_{\psi^i}(\phi_c), M_{\chi^a}(\phi_c)$ finite temperature effects contribute to potential:

$$V_{tot}(\phi, T_h) = \lambda\phi^4 - \frac{m_\phi^2}{2}\phi^2 + \frac{m_\phi^4}{16\lambda} + bT_h^2\phi^2$$

e.g. $b = 1/12$ for single hidden Dirac fermion with $y = 1$.

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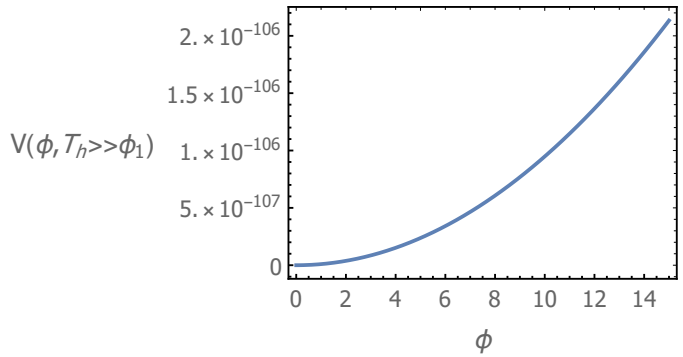

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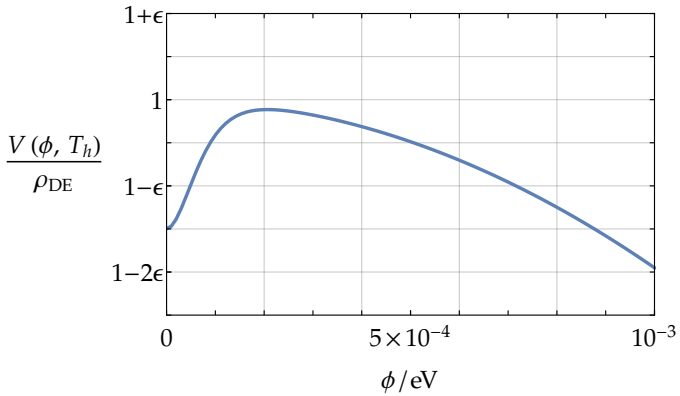

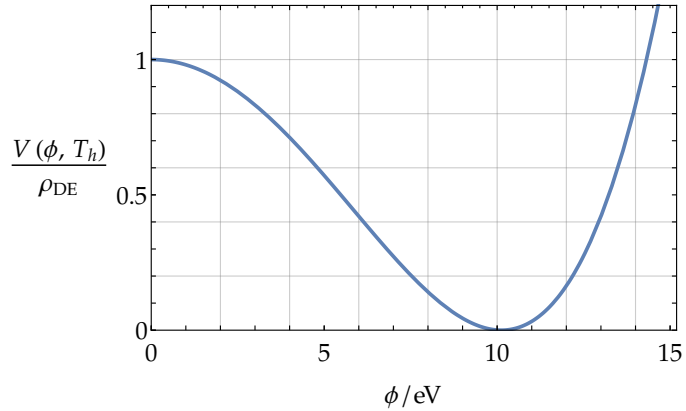

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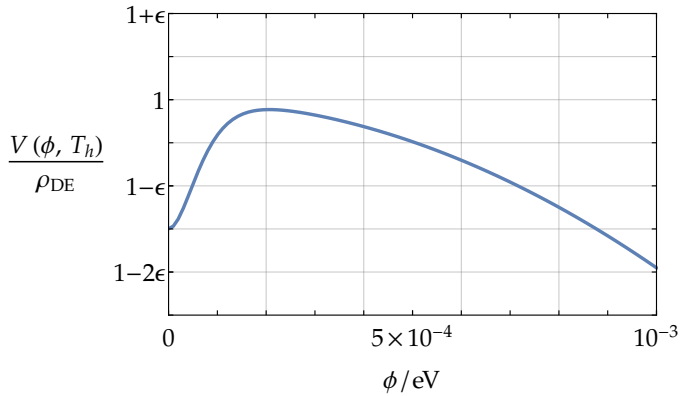

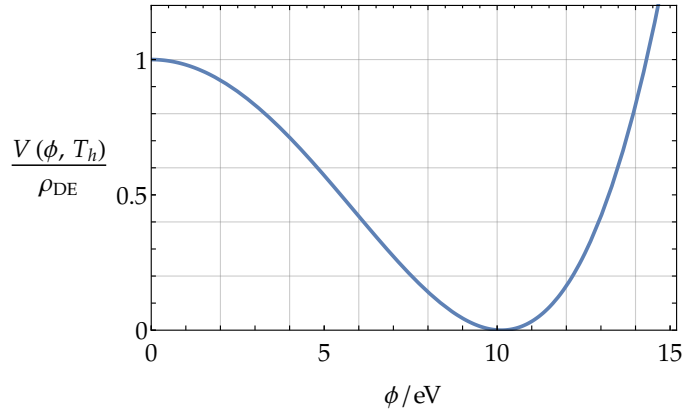

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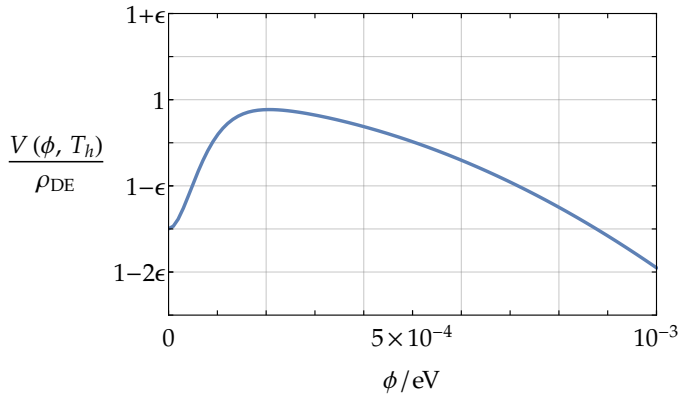

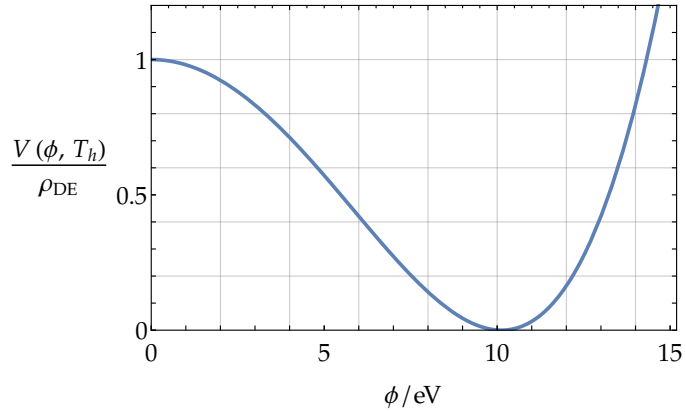

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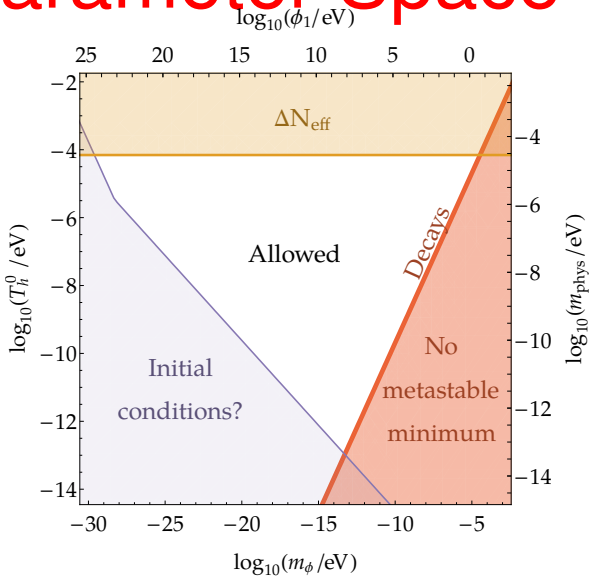
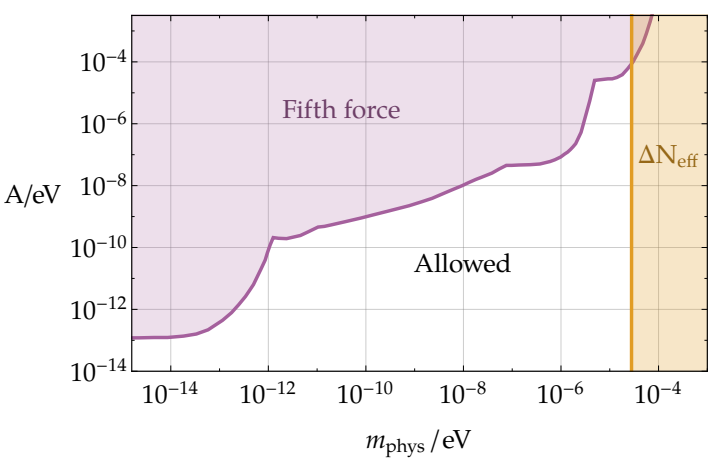
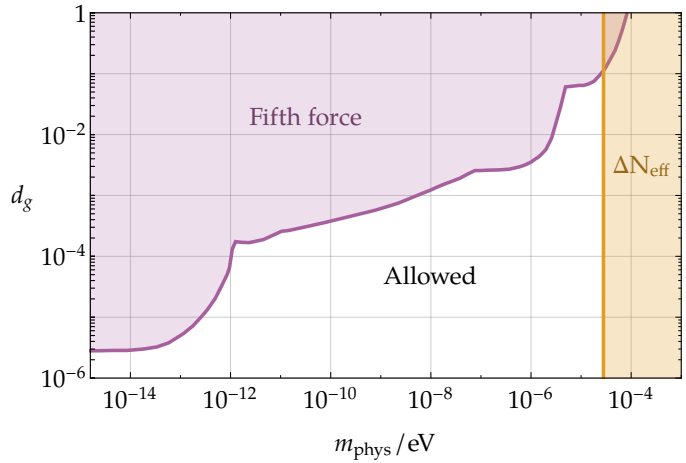
A Viable, Robust Parameter Space



- Finite temperature effects induce metastable dS minimum, which is sufficiently long-lived, $\Gamma_{nucl} \ll H_0^4$.
- Vacuum energy dominates over hidden sector radiation energy density today, $\rho_r^h = \frac{\pi^2 g_h T_h^{0\,4}}{30}$.
- Hidden sector temperature sufficiently low to evade constraints on $N_{eff} \approx 3 + \frac{4}{7} g_*^h \left(\frac{T_h}{T_v}\right)^4 \rightarrow T_h^0 \lesssim 0.3\, T_v^0$.
- A global minimum at $\phi = 0$ for reheating temperatures would explain initial conditions.
- Observed DE for e.g. $m_\phi \lesssim 10^{-6}$eV and $\lambda \lesssim 2 \times 10^{-15}$ - embed in (mildly) sequestered susy hidden sector to avoid fine-tuning.

Observational Signals





- Time dependence of DE negligible for simplest models.
- Portal interactions between visible and hidden sectors, e.g.

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

constrained by:

  - fifth forces
  - requirement that hidden sector stays cool to keep ΔN_{eff} small

- ΔN_{eff} and multiple Thermal DE epochs could help alleviate H_0 tension à la early DE - with gw signals at phase xsns.

Summary

- Existence or not of metastable dS vacuum in string theory remains an open question, though we've long known it would be hard and progress has been made.
- Very few candidates for quintessence in string theory - usually in tension with Swampland conjectures and/or have control issues.
- The simplest non-perturbative string runaways do not source quintessence.
- Light hidden dark sector with finite temperature effects explains Dark Energy with $w = -1$ consistently with Swampland conjectures and plausibly without fine-tuning.
- Potentially observable via fifth forces and ΔN_{eff}.
- DE epoch ends in the future when $T_h \sim m_\phi$ with first order phase transition towards true vev, and conversion to hidden sector radiation, matter and gravitational waves.
- Multiple Thermal DE eras may explain the H_0 tension, leaving gravitational wave signatures.