Thermal Dark Energy

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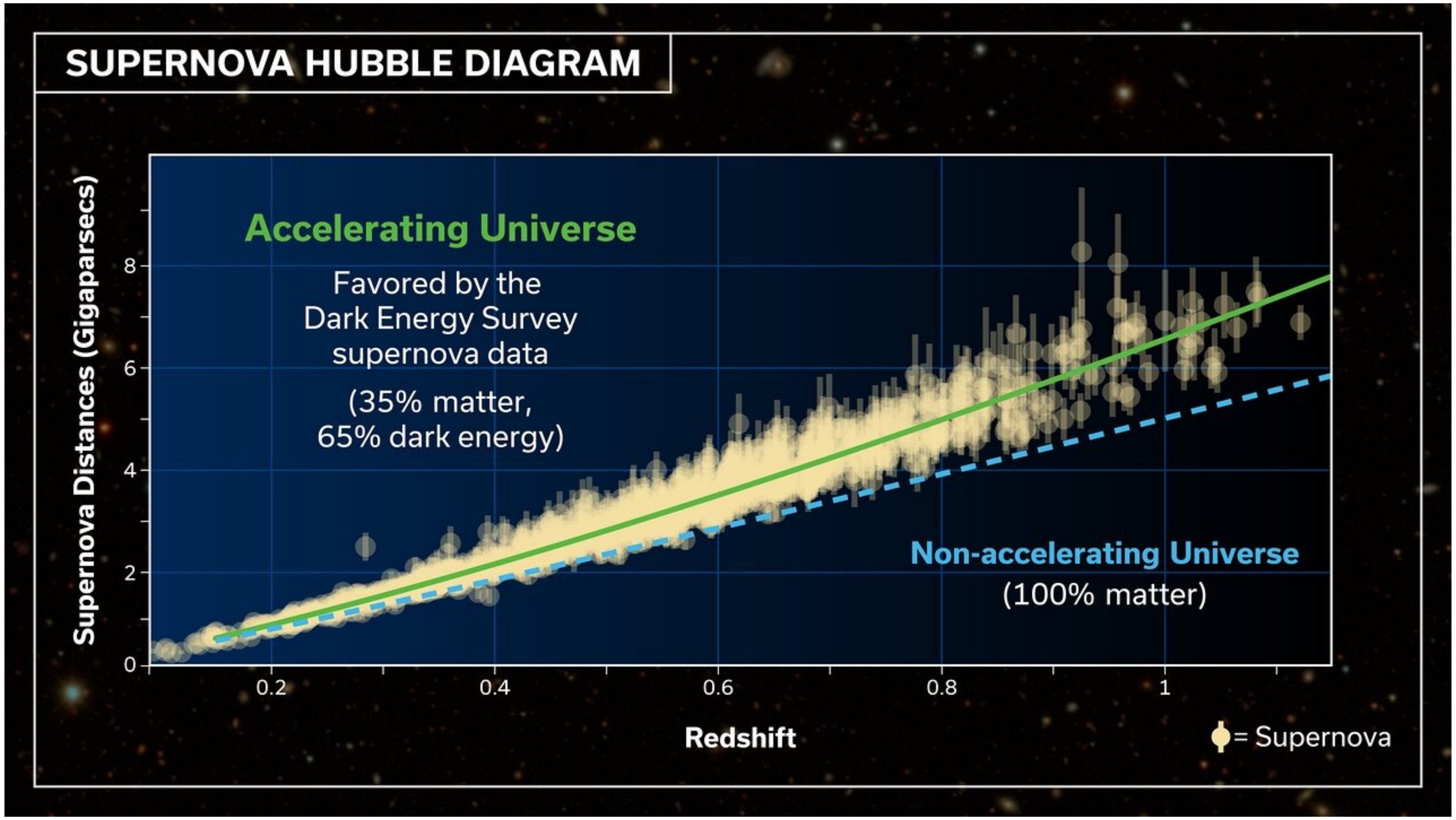
- 1907.10141, PRD with Susha Parameswaran
- 2311.08888, PRD, with Joaquim Gomes & Susha Parameswaran

Cosmological constants



From DES collaboration

Also, CMB/BAO/structure formation

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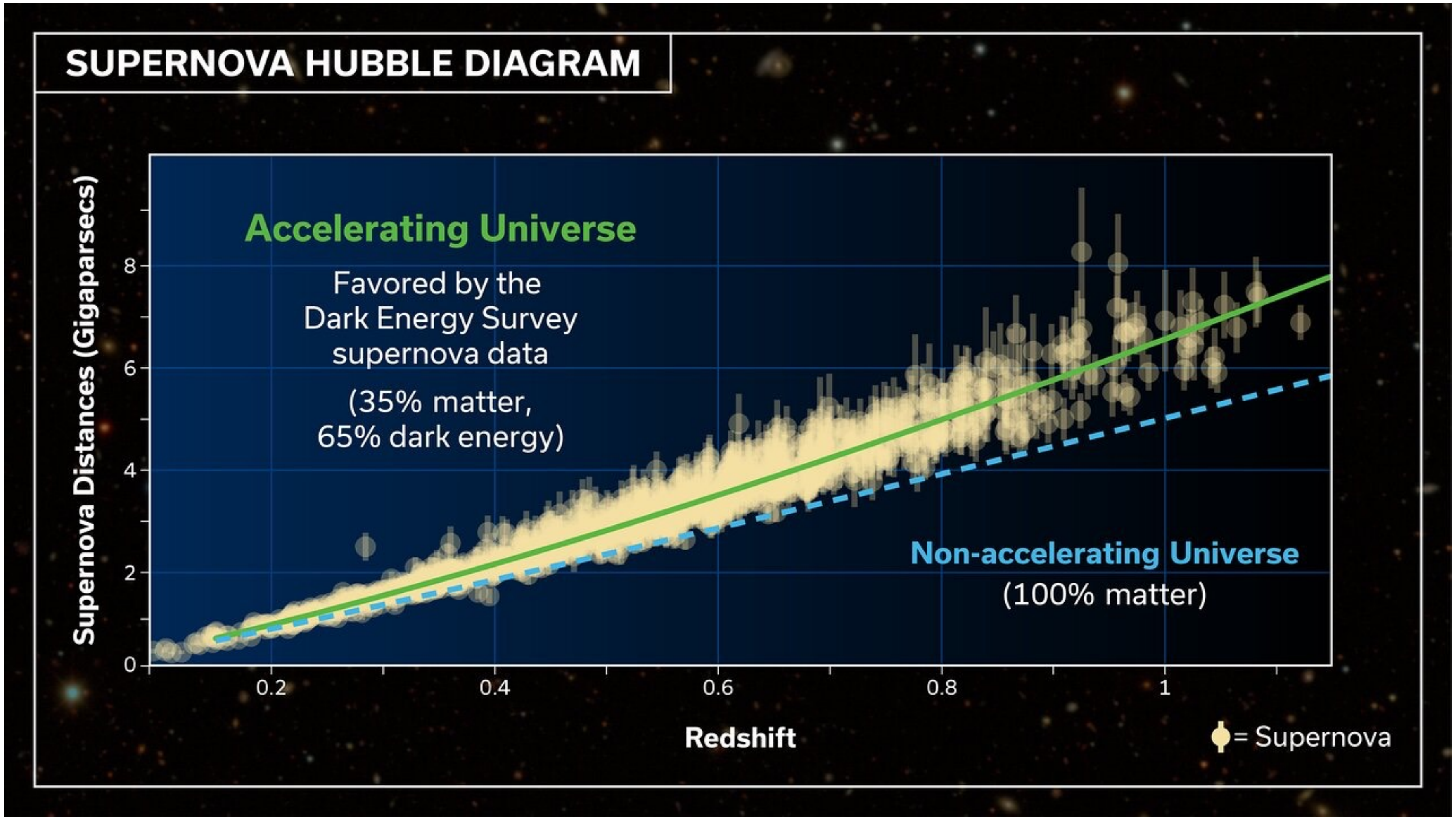

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See however, e.g. *Is the evidence for dark energy secure?* S. Sarkar *Gen.Rel.Grav.* 40 (2008)

Dark energy in string theory

$$\rho_{\mathrm{de}} \sim 10^{-120} M_{\mathrm{Pl}}^4 \ll \langle h \rangle^4$$

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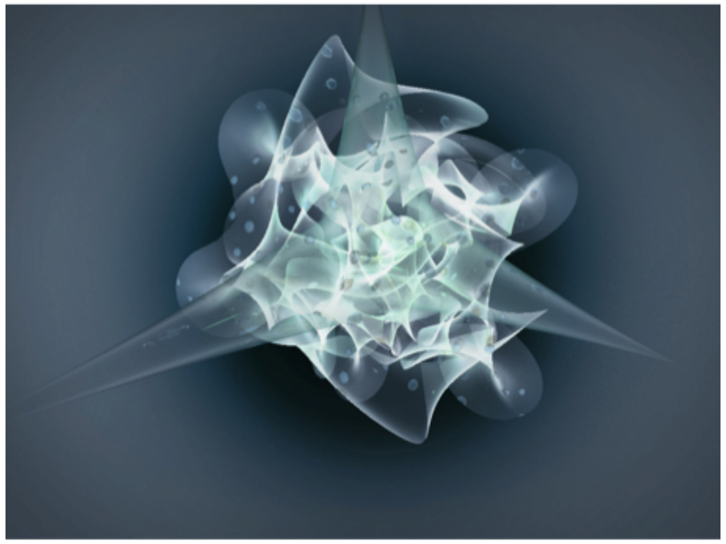

Aim: 4d compactification with stabilised moduli with

$$\langle V \rangle_{\rm min} > 0$$

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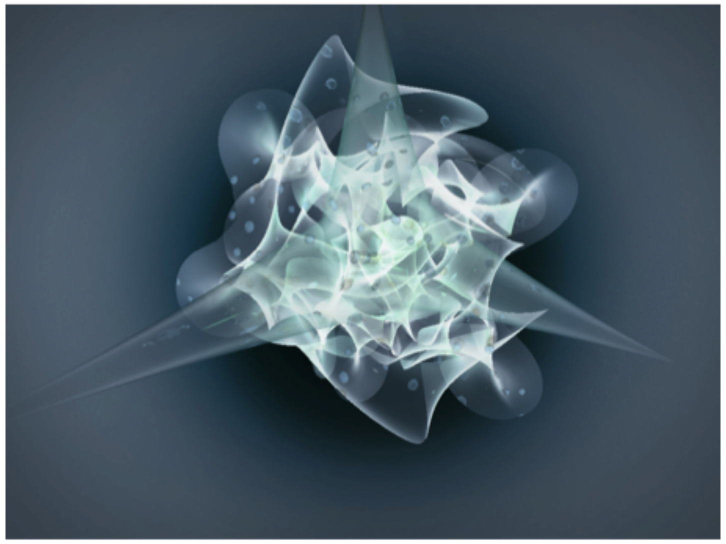

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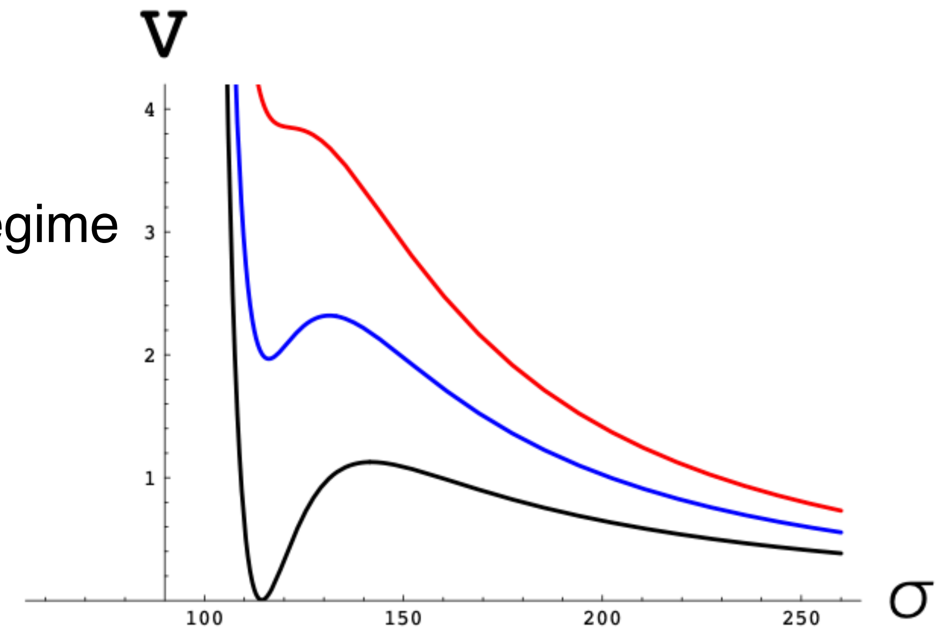
Long known to be hard:

Dine & Seiberg,1985: string coupling moduli runaway in perturbative regime

Maldacena & Nuñez, 2000: two-derivative SUGA does not admit dS



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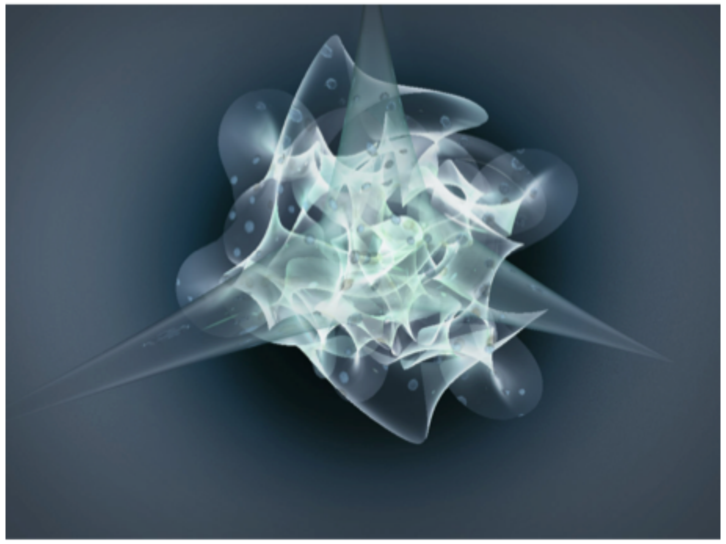

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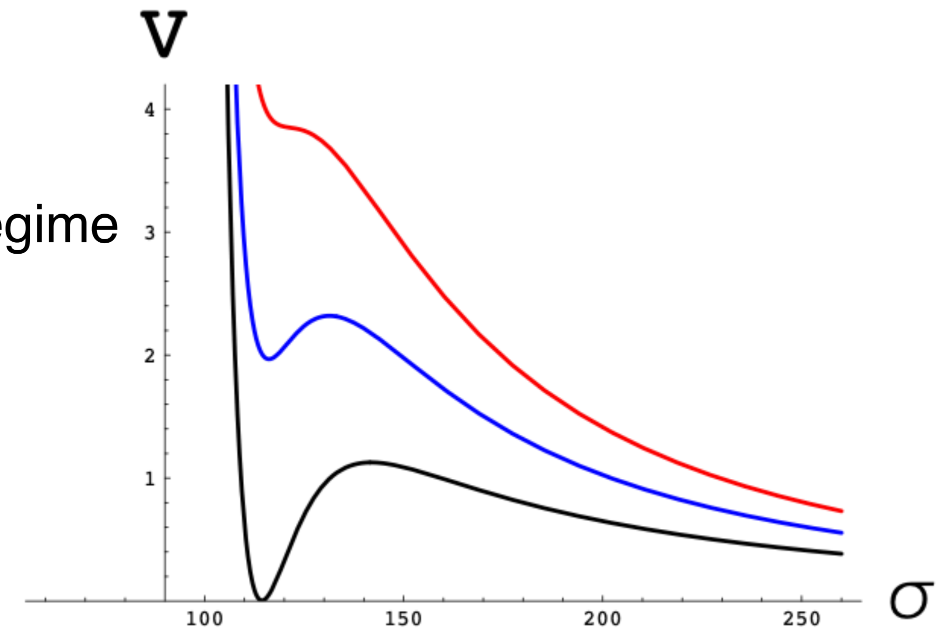

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Constructions, e.g. KKLT, LVS but challenges

- Fluxes only under control in 10d SUSY? trust 4d EFT? Higher corrections in LVS? etc

What if there are no dS vacua?

Conjecture (Obied, Ooguri, Spodyneiko & Vafa 2018):

The scalar potential in the low-energy EFT of any consistent quantum gravity must satisfy either:

$$\sqrt{\nabla^i V \, \nabla_i V} \geq \frac{c}{M_{\rm Pl}} V$$

or

$$\min \left(\nabla^i \nabla_j V \right) \leq - \frac{c'}{M_{\rm Pl}^2} V$$

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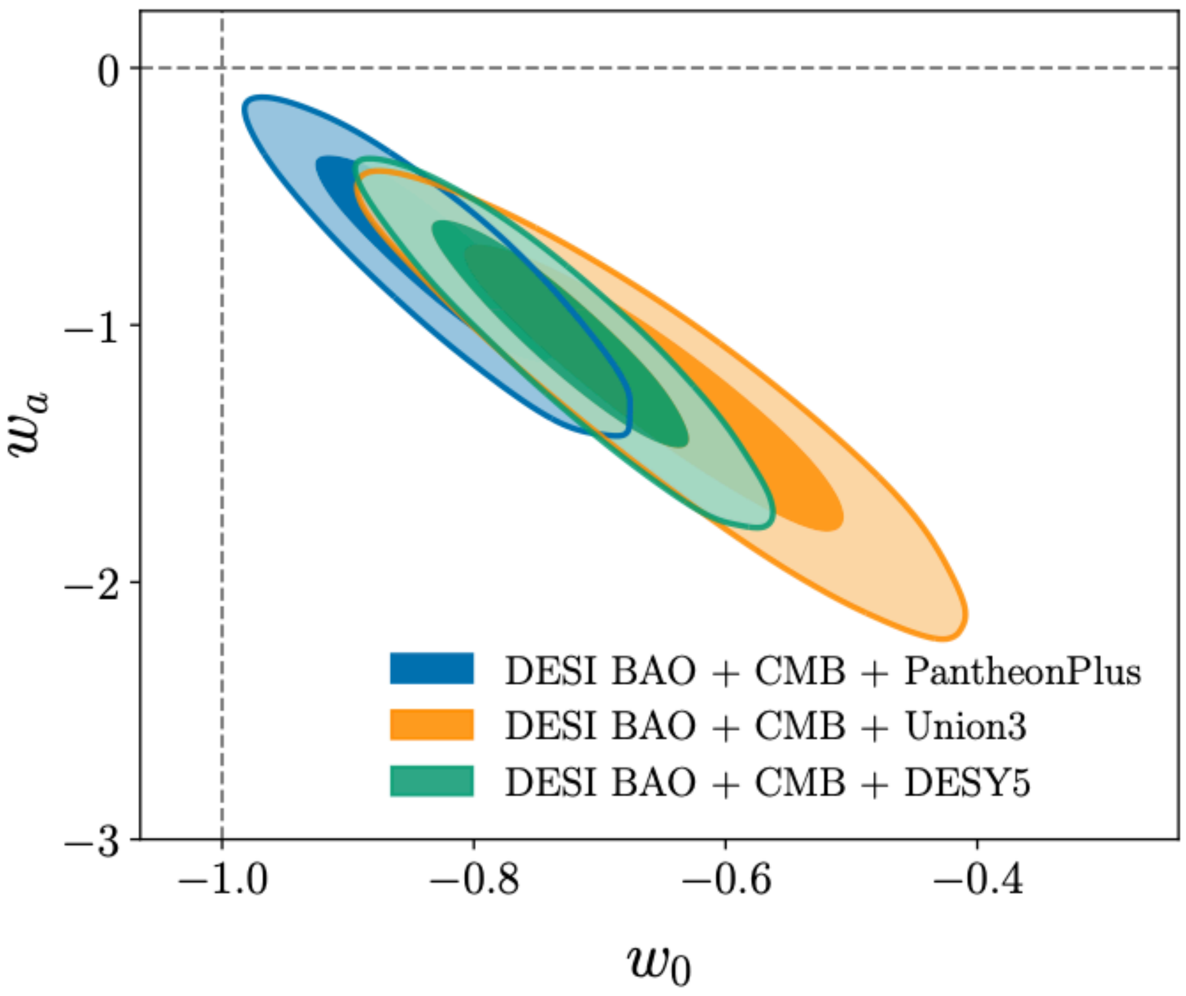
Even if metastable dS constructions prove robust, the question may inspire interesting alternatives

Possible hints for evolution

$$w(a) = w_0 + w_a(1 - a)$$



DESI collaboration, *JCAP* 02 (2025) 021

Quintessence

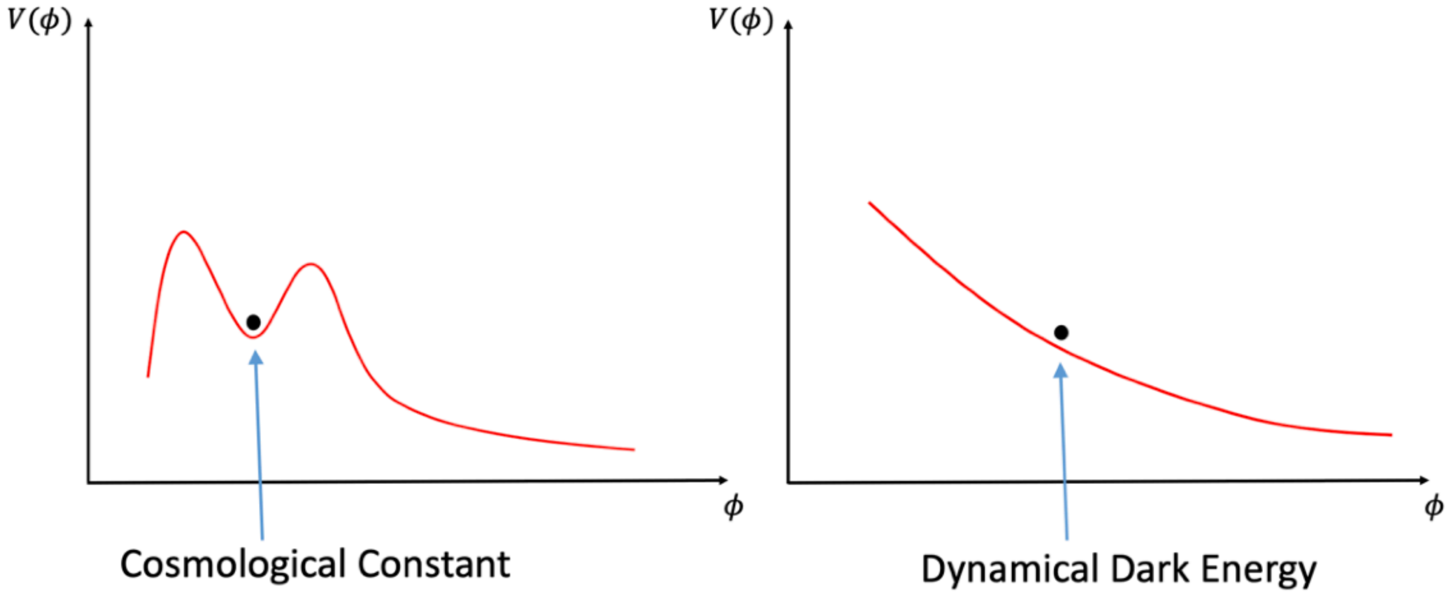


Figure from review by E. Palti

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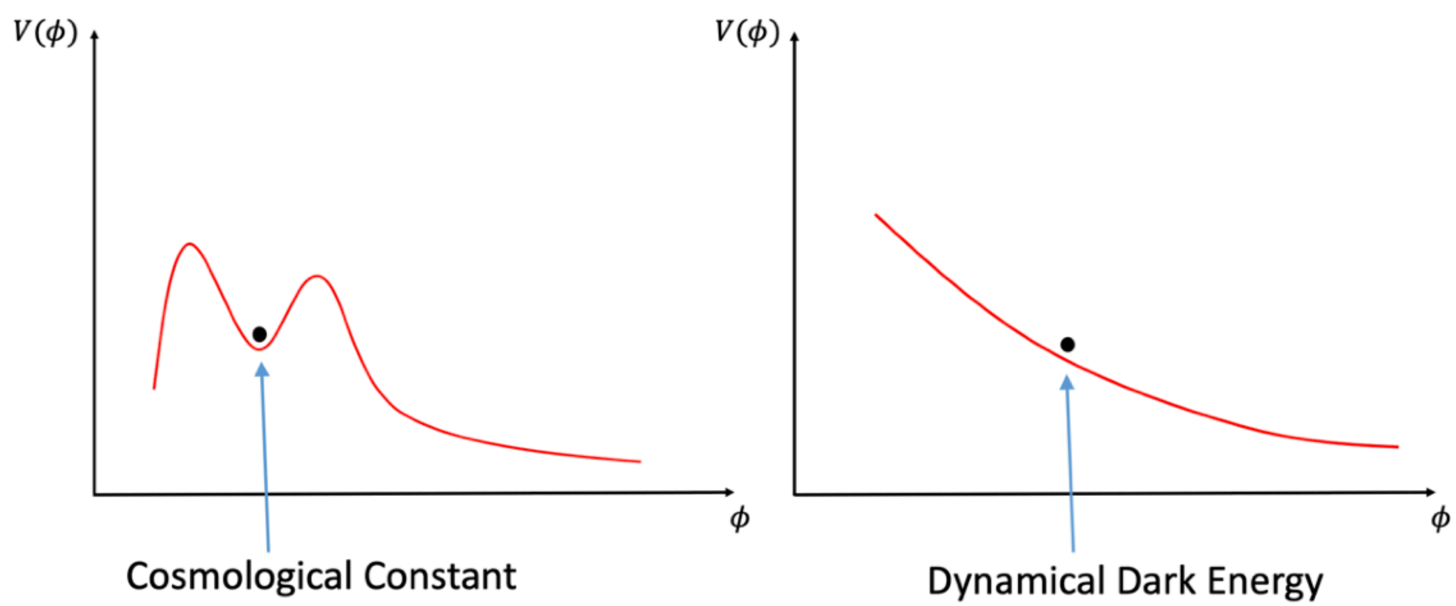

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- Must stabilise all except one modulus with $m_\phi \lesssim H_0 \sim 10^{-33}\,\mathrm{eV}$

→ two fine-tuning problems

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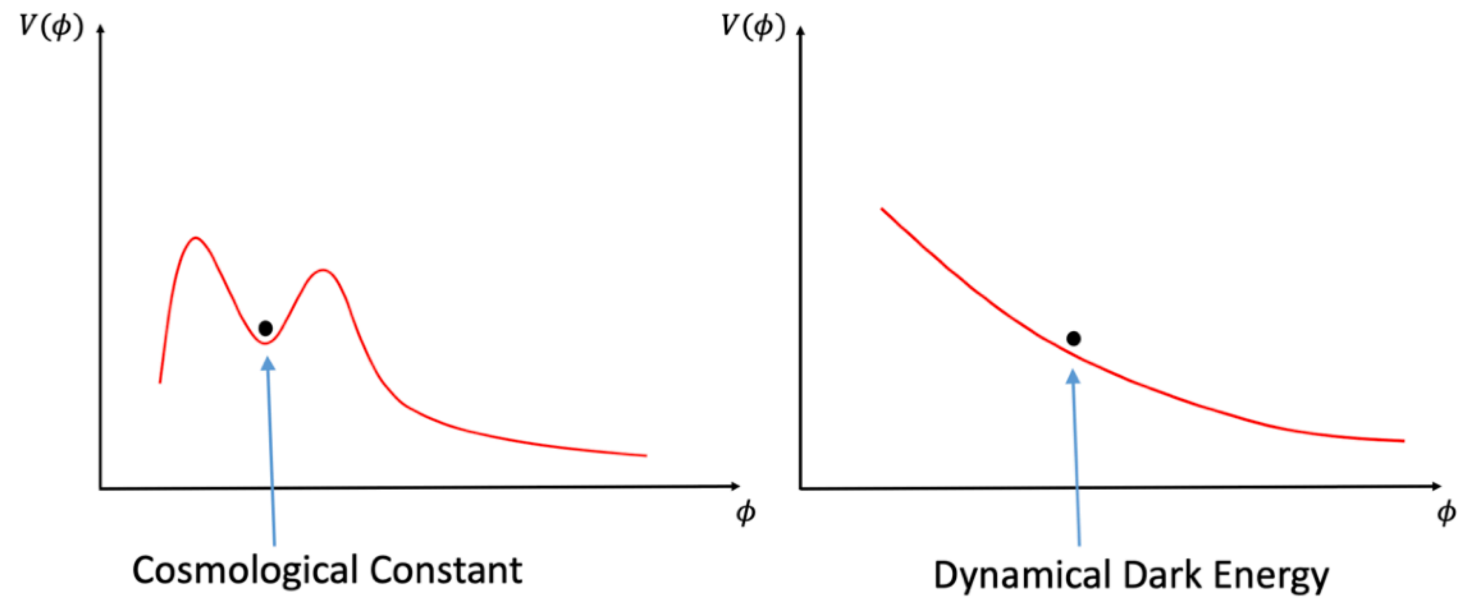


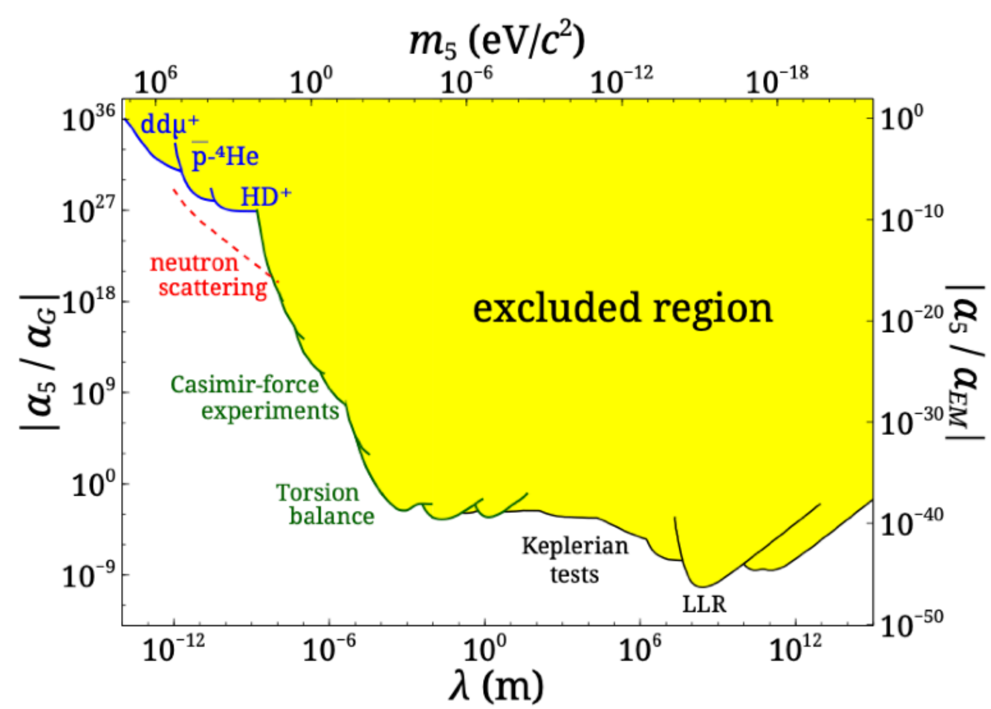
Figure from review by E. Palti

- Must stabilise all except one modulus with $m_\phi \lesssim H_0 \sim 10^{-33}\,\mathrm{eV}$

→ two fine-tuning problems

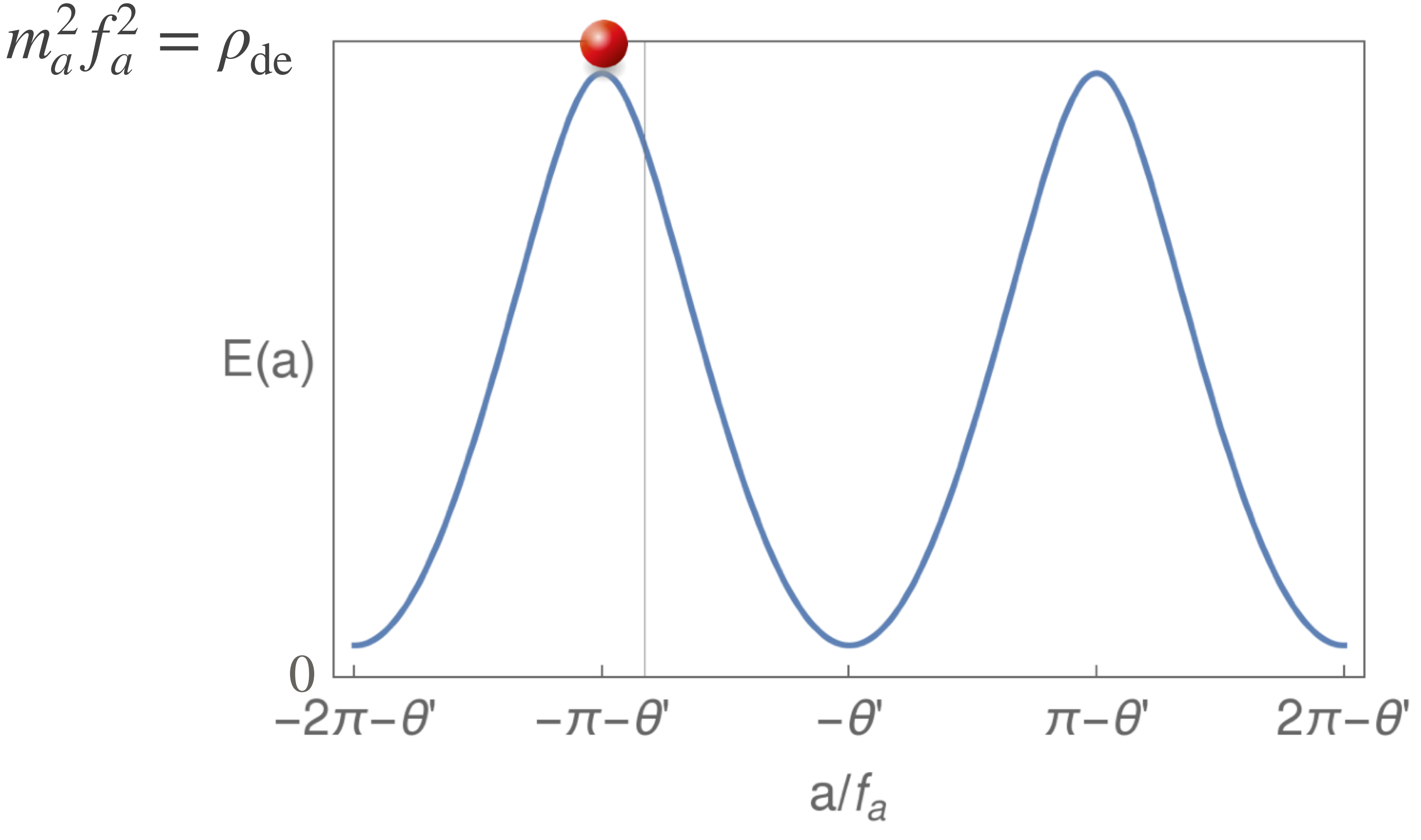
- 5th force constraints

- Time-variation of constants



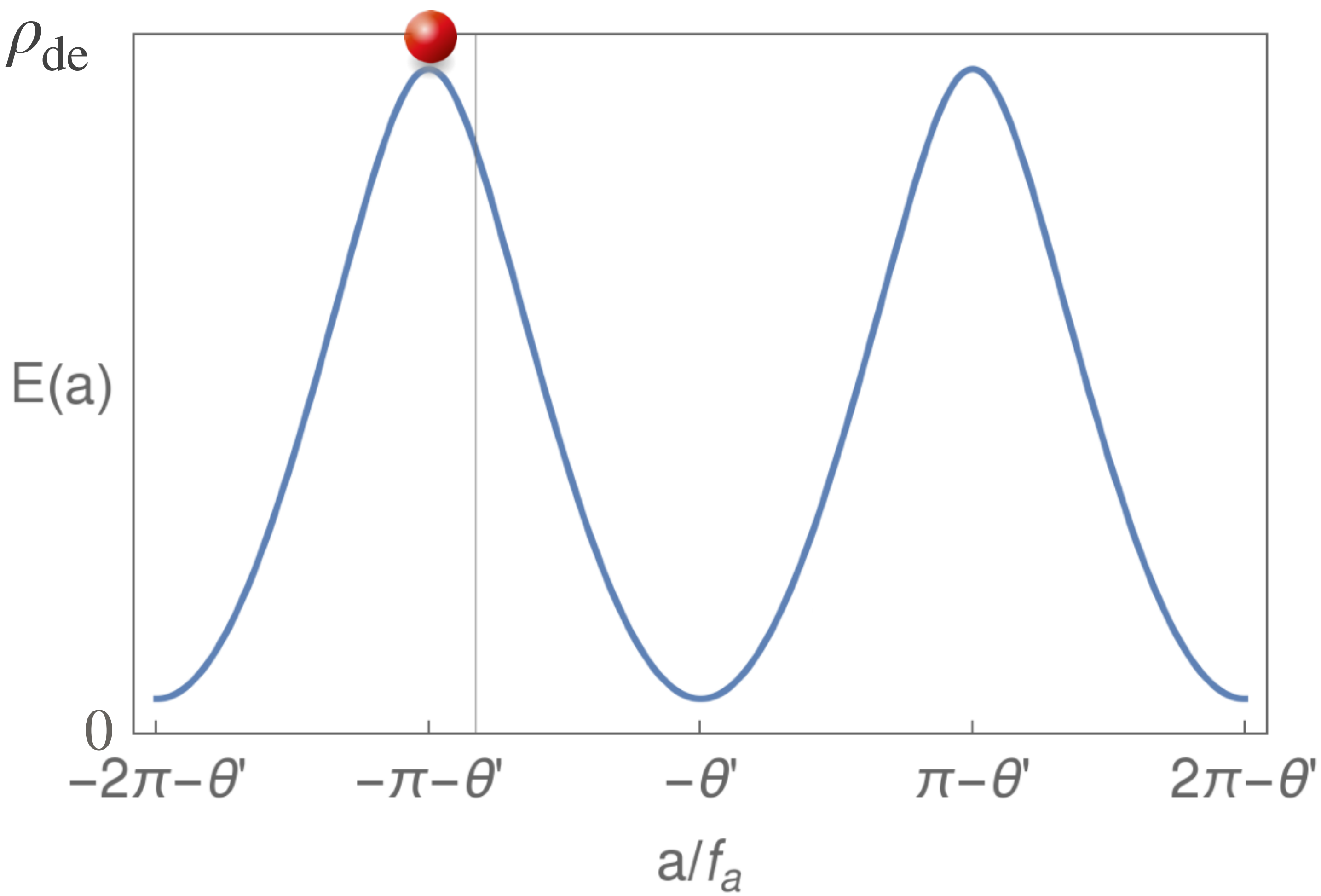
from [1308.1711]

Hilltop axion



Hilltop axion

$m_a^2 f_a^2 = \rho_{\rm de}$



$f_a < M_{\rm Pl} \implies m_a \gtrsim H_0$ which requires exponential fine-tuning

Also $m_a \sim M_{\rm pl} e^{-\alpha M_{\rm Pl}/f_a}$

Thermal dark energy

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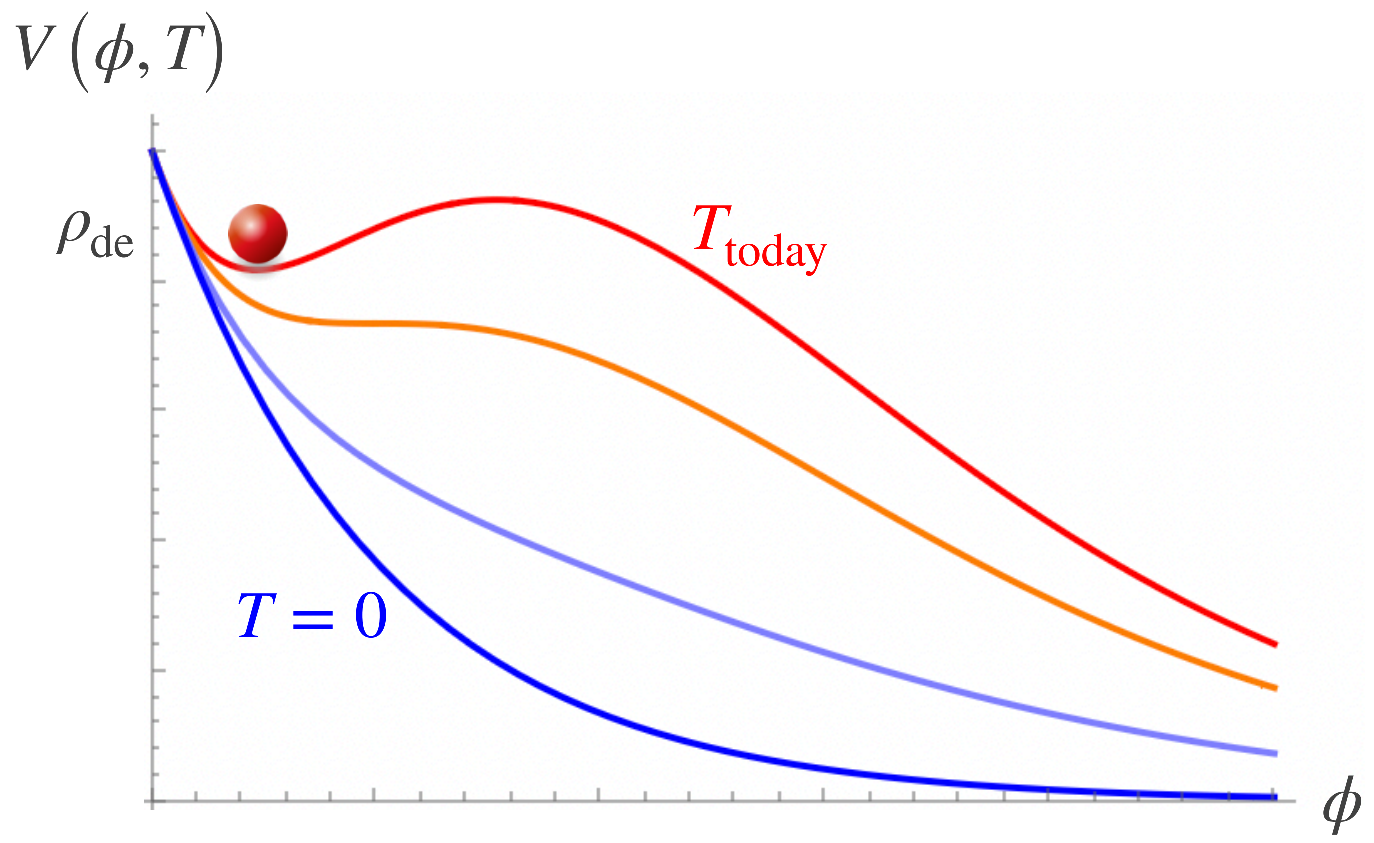

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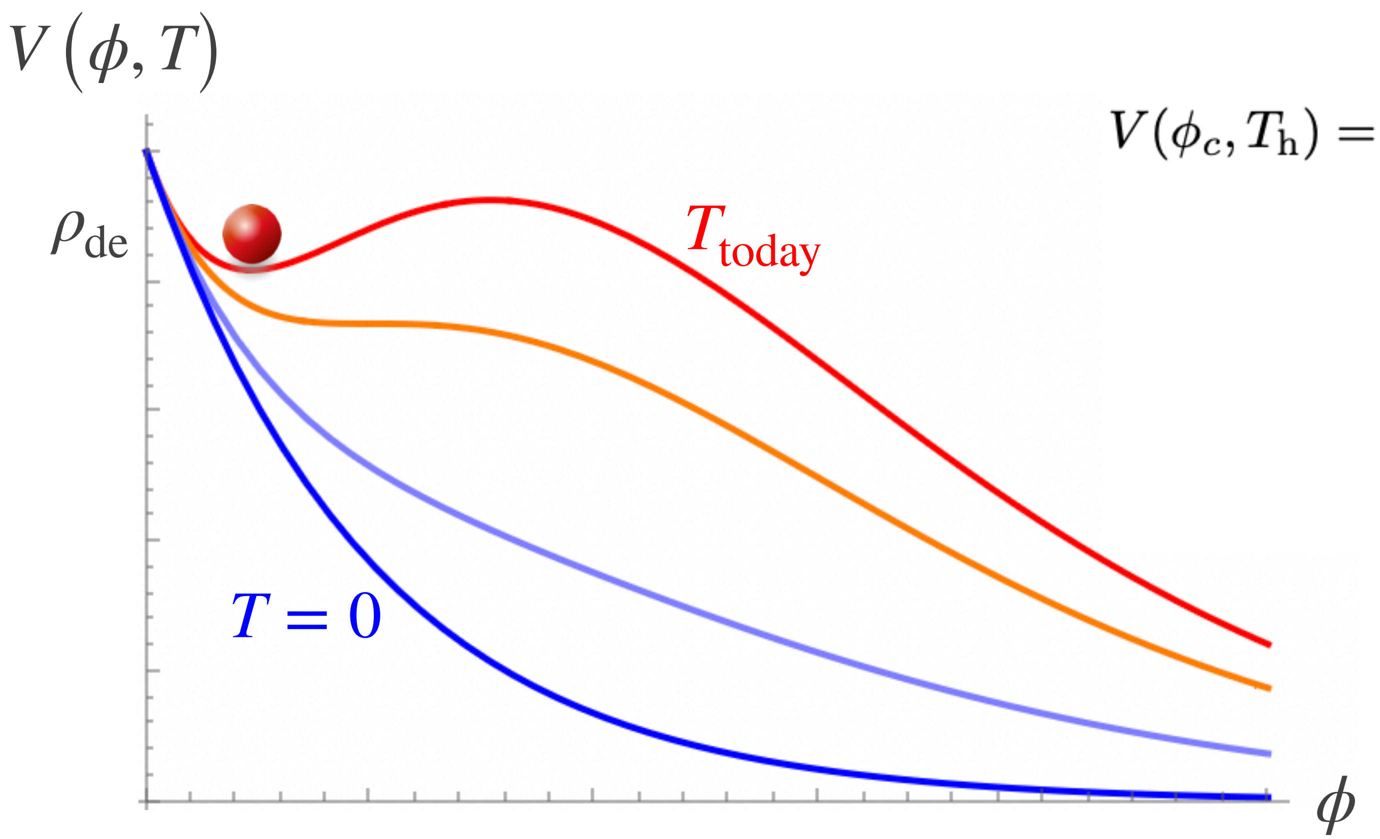

$$V(\phi_c, T_{\rm h}) = V_0(\phi_c) + \frac{T_{\rm h}^4}{2\pi^2}\left(-\sum_{\psi^i} n_{\psi^i}\, J_F\left(\frac{m^2_{\psi^i}(\phi_c)}{T_{\rm h}^2}\right) + \sum_{\chi_a} n_{\chi^a}\, J_B\left(\frac{M^2_{\chi_a}(\phi_c)}{T_{\rm h}^2}\right)\right)$$

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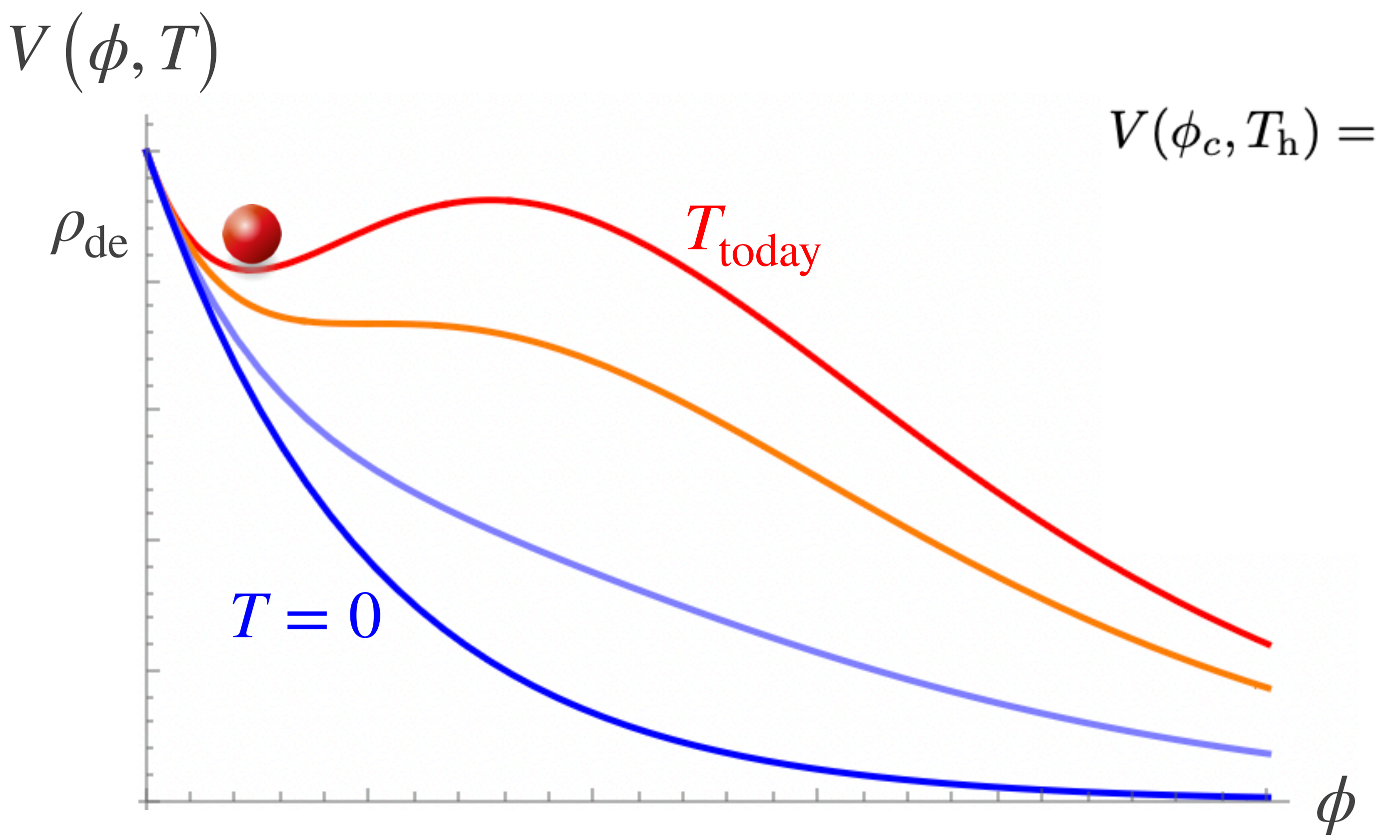

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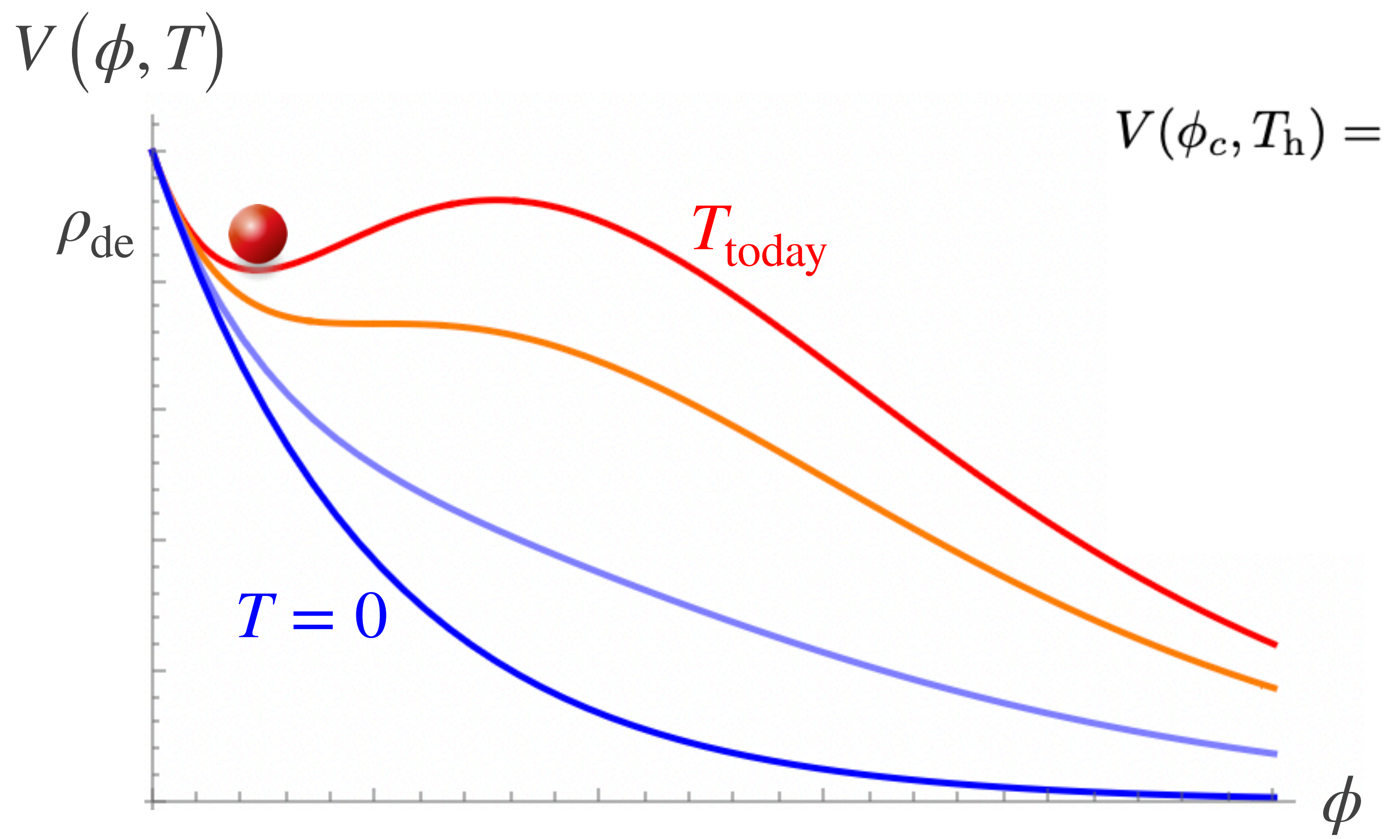
Hidden sectors generic in string theory

Thermal dark energy



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$T^4_{\rm visible}/\rho_{\rm de} \simeq 10^{-5}$

Hidden sectors generic in string theory

$\Delta N_{\rm eff}$ constraints require $T_{\rm h} \lesssim T_{\rm visible}$

$\rho_{\rm de} \gg T_{\rm h}^4 \implies$ extremely super-cooled phase transition

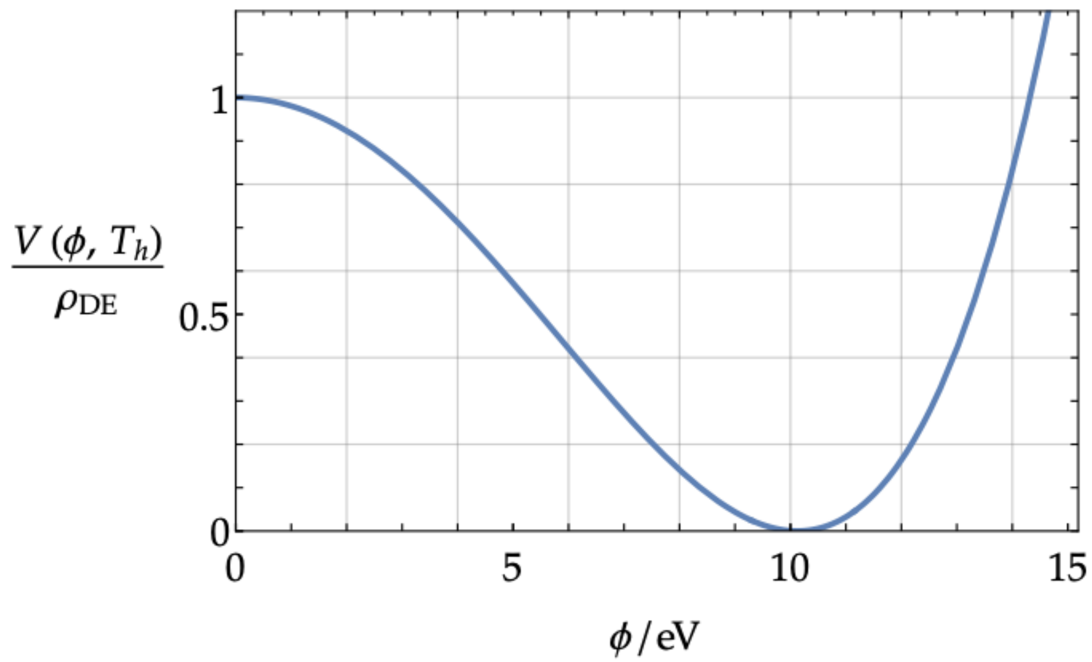
Proof of principle model

Scalar with potential

$\sim m_\phi^4/\lambda$

$$V_0(\phi) = \lambda\phi^4 - \frac{m_\phi^2}{2}\phi^2 + C$$

Gives mass to fermions: $y_i \phi \bar{\psi}^i \psi^i$



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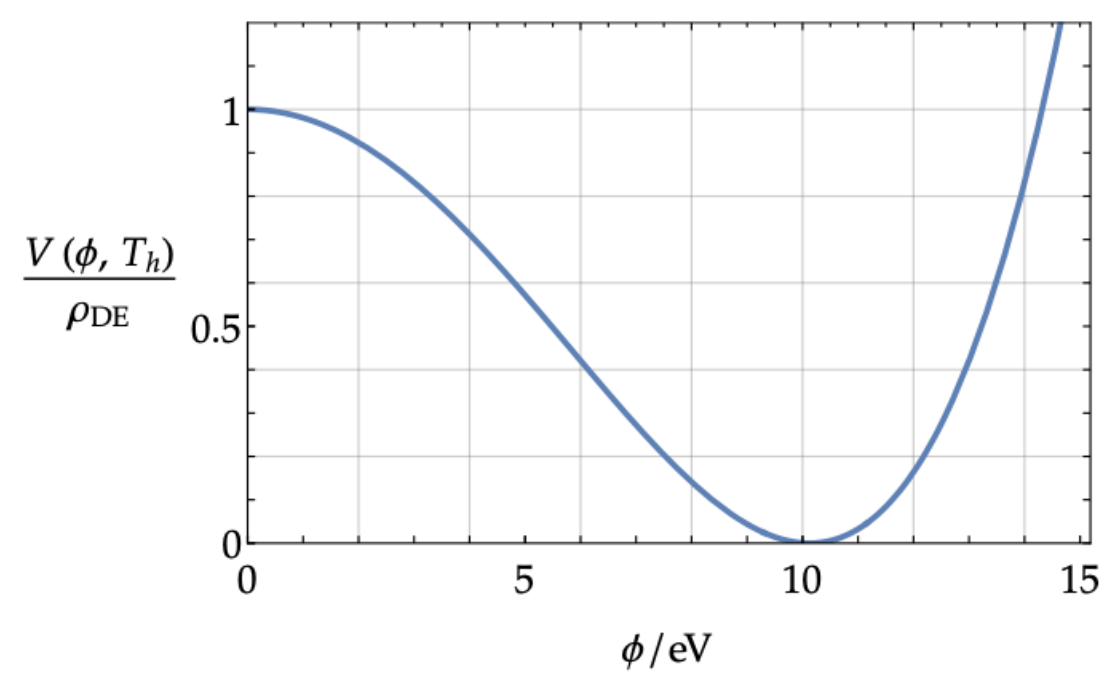

For $T_{\rm h} \gg m_{\psi^i}(\phi_c) \implies T_{\rm h} \gg y_i \phi_c$

$$V(\phi, T_{\rm h}) = \lambda\phi^4 - \frac{m_\phi^2}{2}\phi^2 + \frac{m_\phi^4}{16\lambda} - aT_{\rm h}^4 + bT_{\rm h}^2\phi^2$$

with $b \sim 1$ for $y_i \sim 1$

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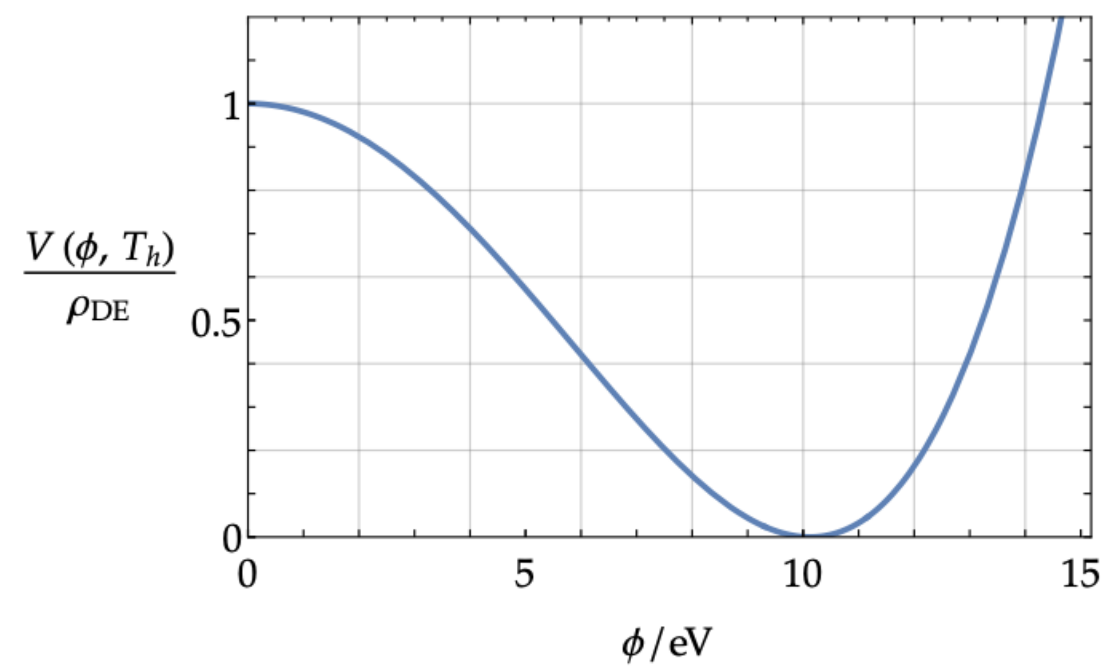

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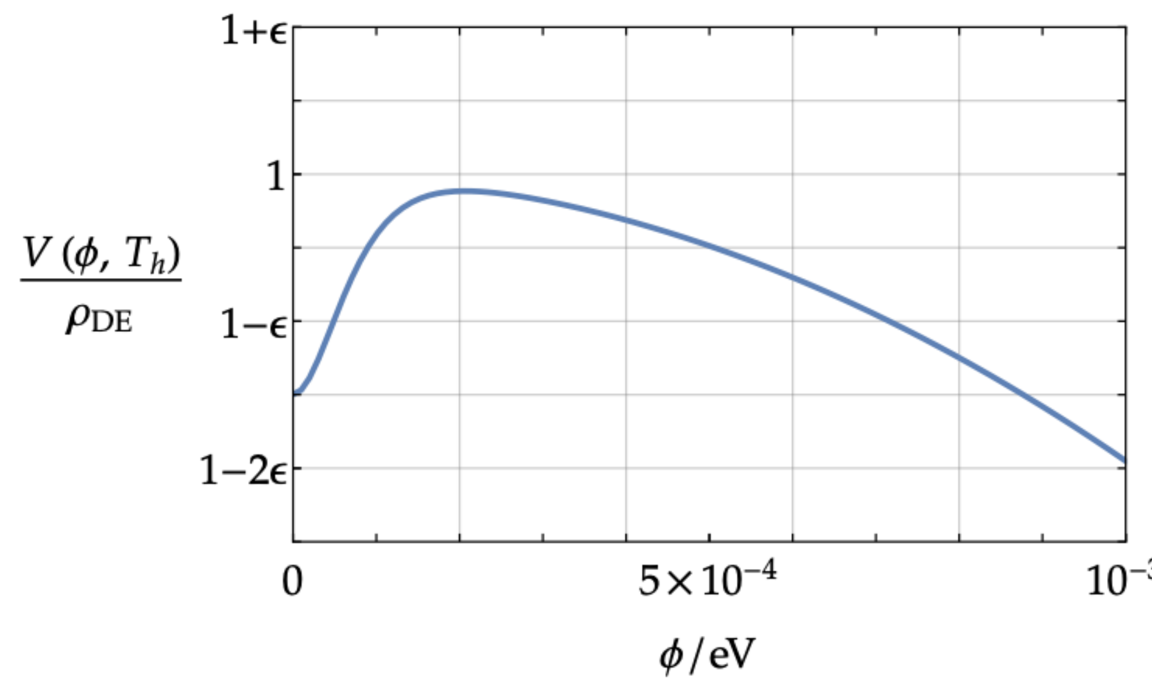

with $b \sim 1$ for $y_i \sim 1$

Meta-stable minimum for $T_\mathrm{h} > \frac{m_\phi}{\sqrt{2b}}$

Parameter space

Fix $m_\phi^4/\lambda = \rho_{\rm de}$

Require $\rho_{\rm de} = m_\phi^4/\lambda \gg T_h^4 \gtrsim m_\phi^4$

$\implies \lambda \ll 1$

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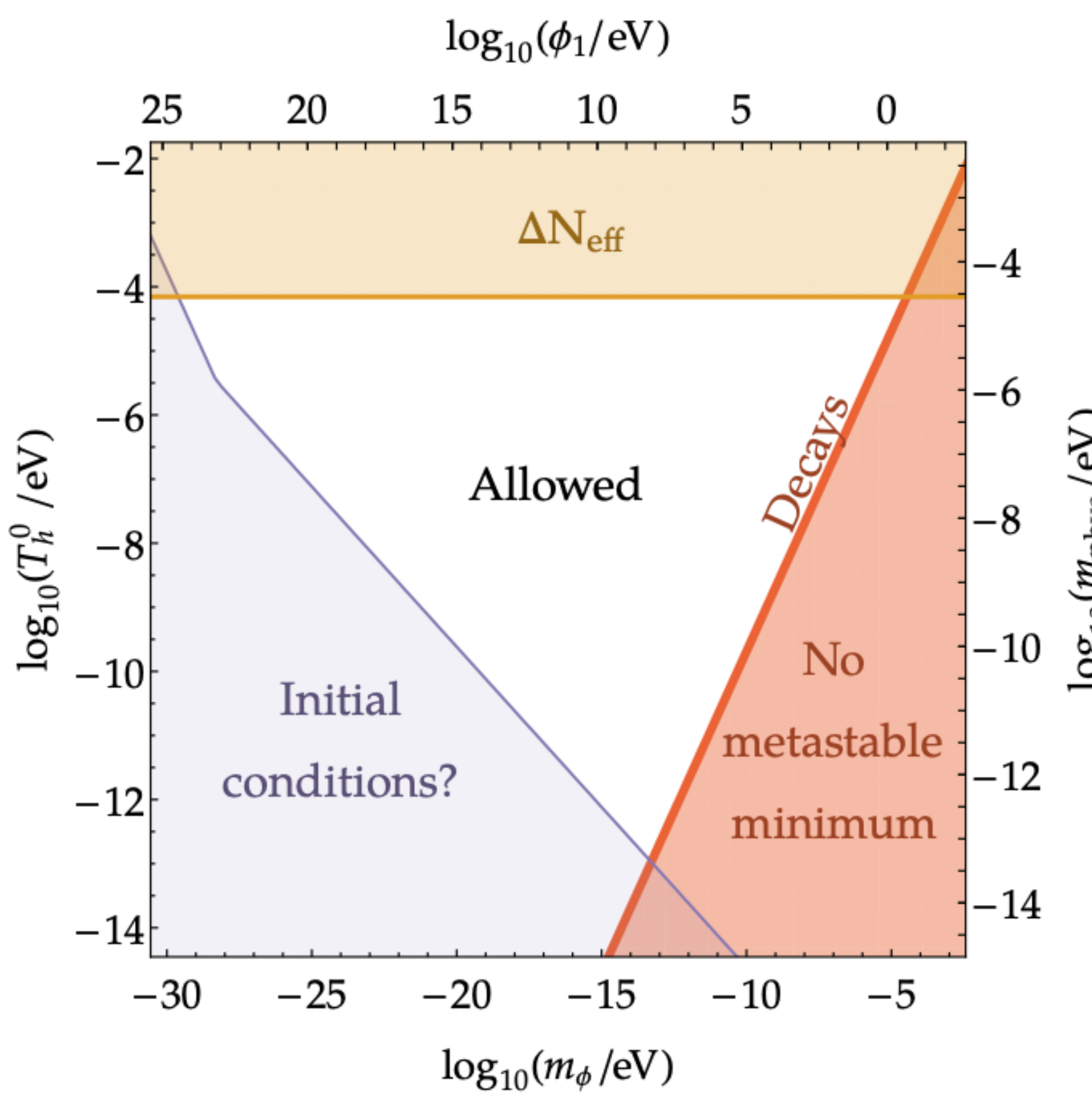

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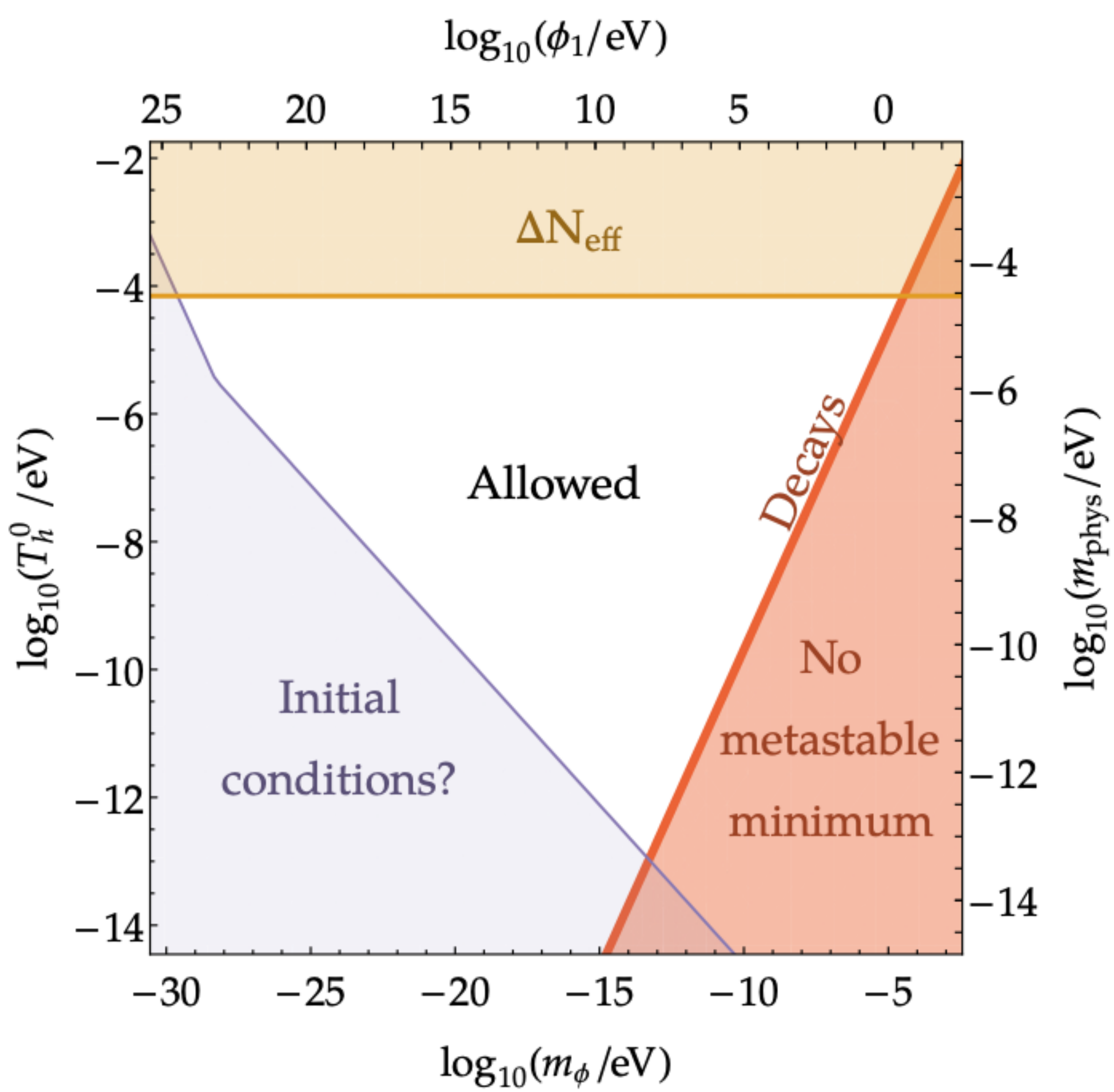
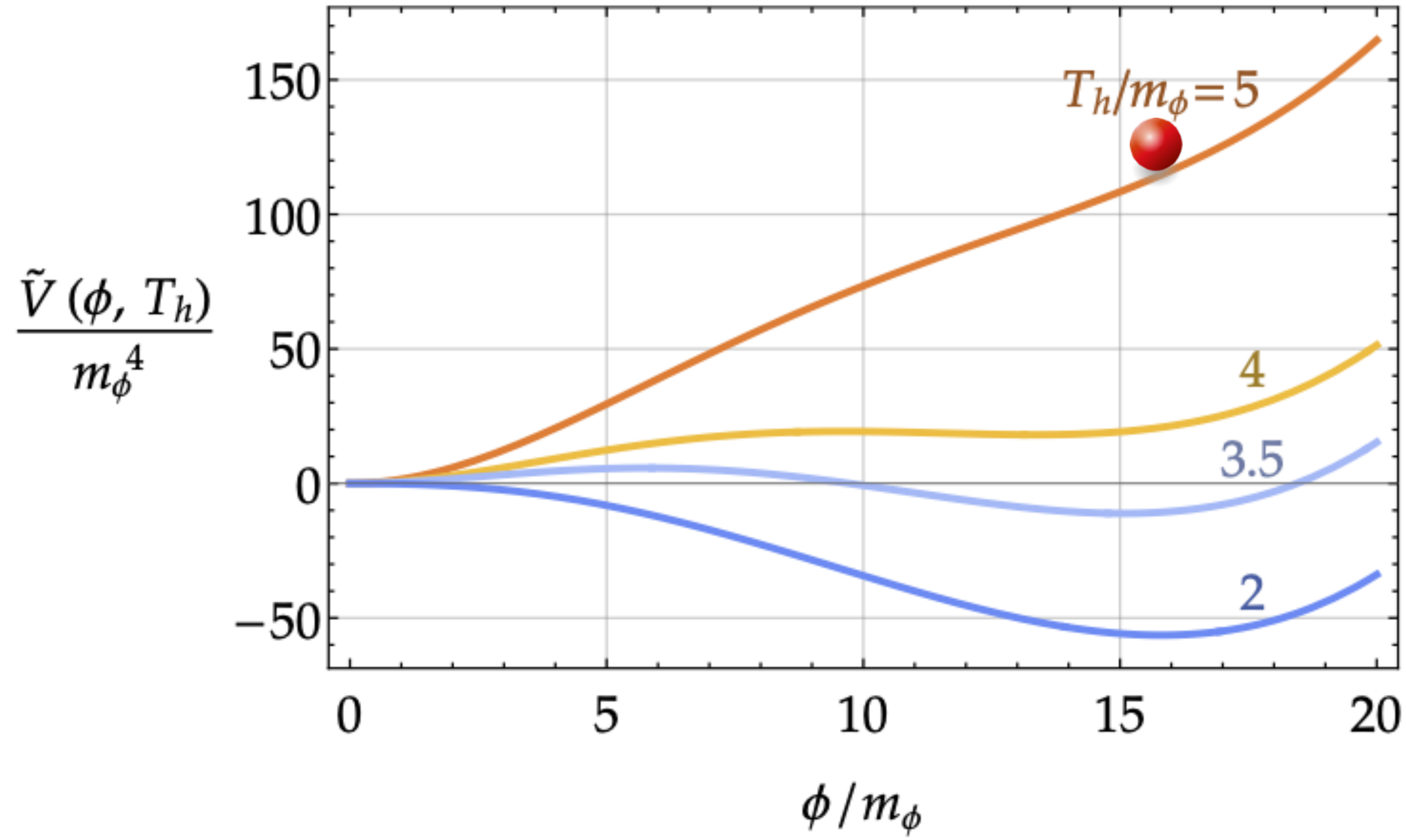
dS conjecture is satisfied throughout parameter space



Early universe evolution

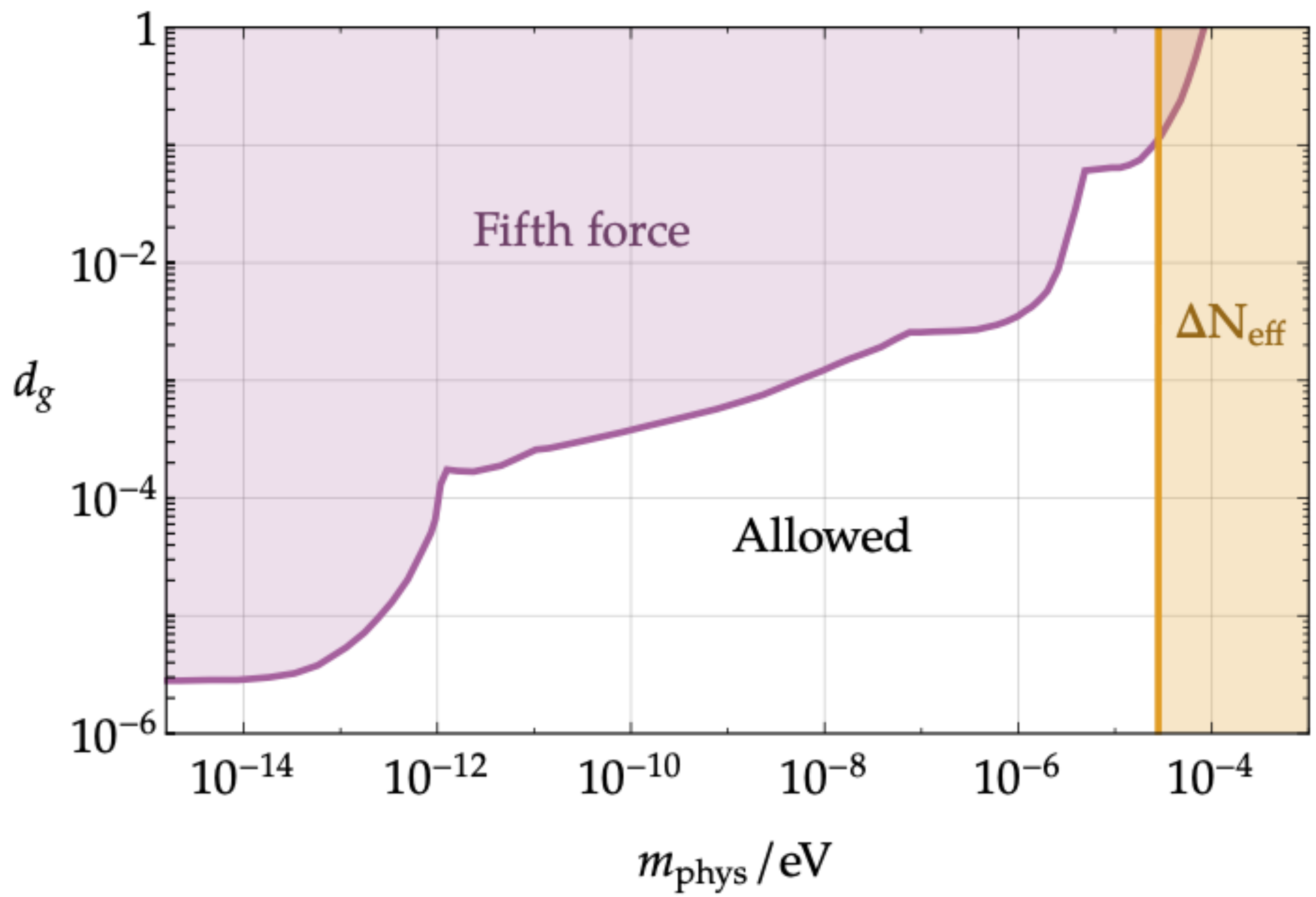
If initial $T_h \gtrsim \phi_1$, field is driven to the metastable minimum



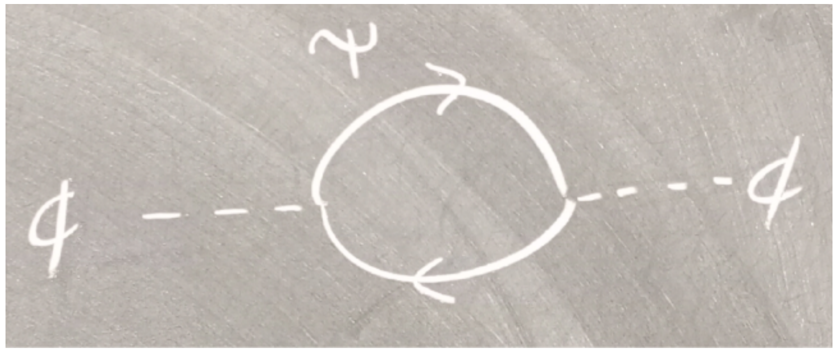
5th forces

E.g.

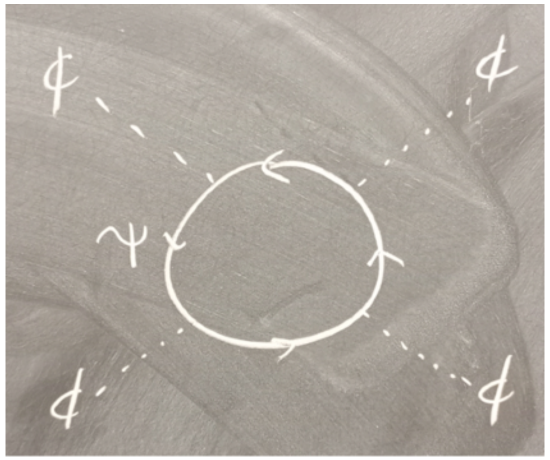
$$\mathcal{L} \supset d_g \frac{\beta_3}{\sqrt{2} g_3 M_{\rm Pl}} \phi \, G_{\mu\nu} G^{\mu\nu}$$



Fine tuning



$$m_\phi^2 \sim \frac{y_i^2}{4\pi}\Lambda_{\mathrm{UV}}^2$$



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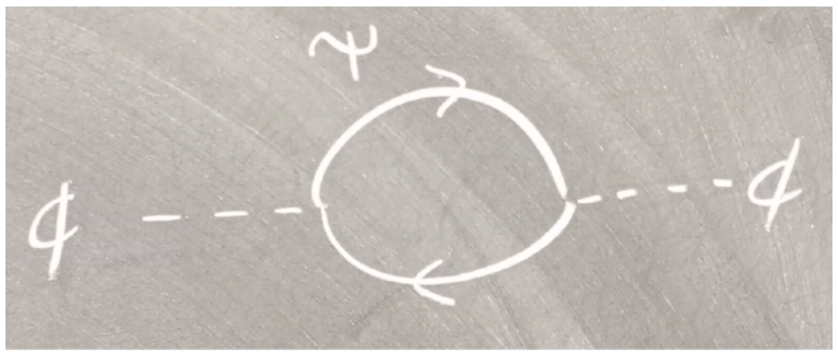

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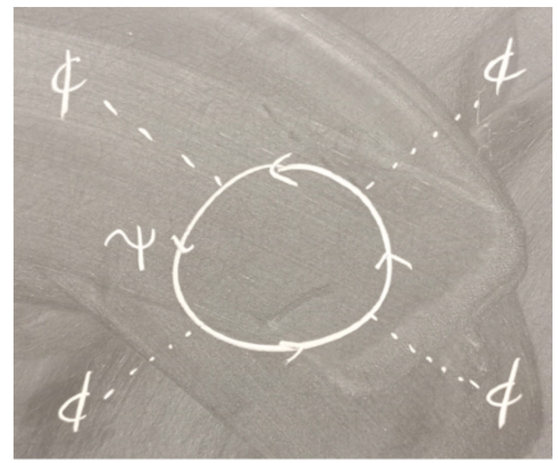

$$\lambda \sim \frac{y_i^4}{4\pi}$$

~~SUSY~~

$$F \sim \left(10^5\,\mathrm{GeV}\right)^2$$

$m_{\mathrm{mess}} \sim \mathrm{TeV}$

M_{Pl}

SM

$$m_{\mathrm{soft}} \sim \frac{F}{m_{\mathrm{mess}}} \sim 10^3\,\mathrm{GeV}$$

Hidden

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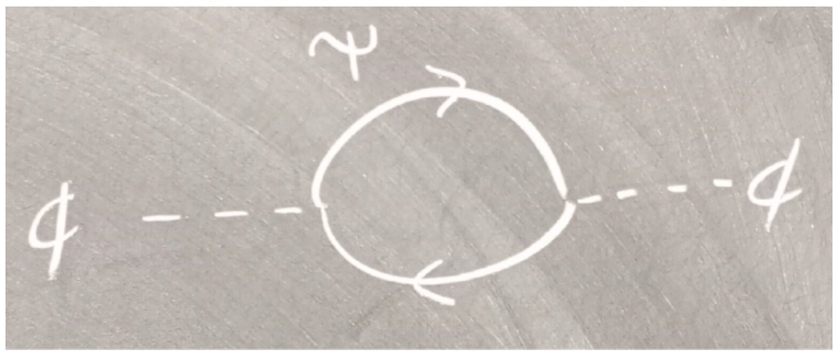

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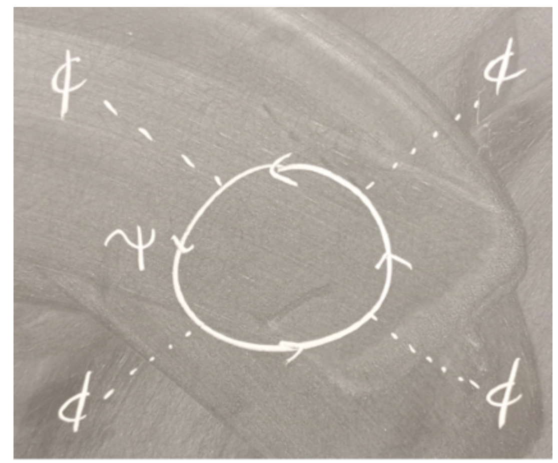

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$$W = (m_\psi - \Phi)\,\Psi^2$$

$$V_{\rm soft} = m_\phi^2\,|\phi|^2 + m_\chi^2\,|\chi|^2$$

$$V = |\chi|^4 + |2m_\psi\chi - 2\phi\chi|^2 + m_\phi^2\,|\phi|^2 + m_\chi^2\,|\chi|^2$$

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$M_{\rm Pl}$

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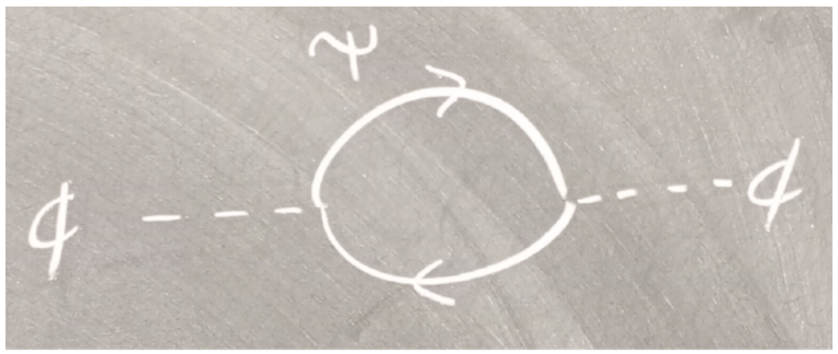

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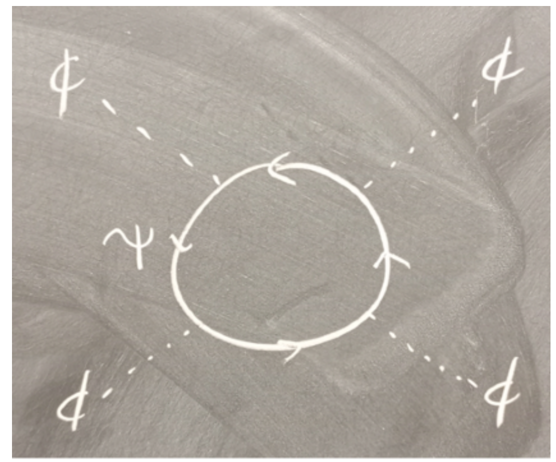

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Gauge sector alternatives?

Signals

- Transition taking place now?

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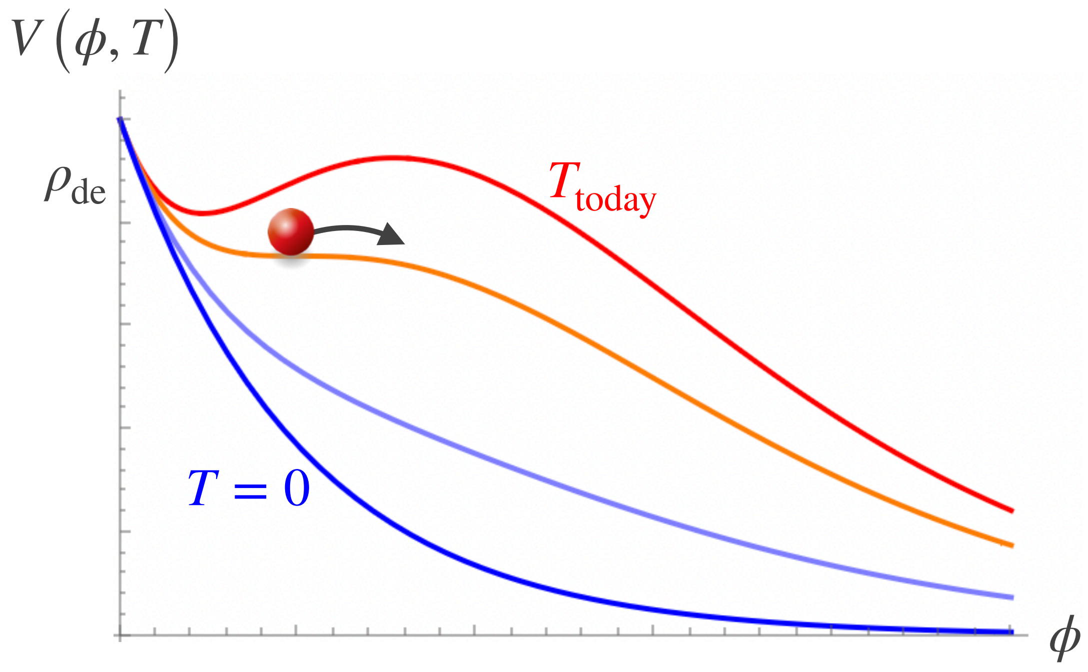

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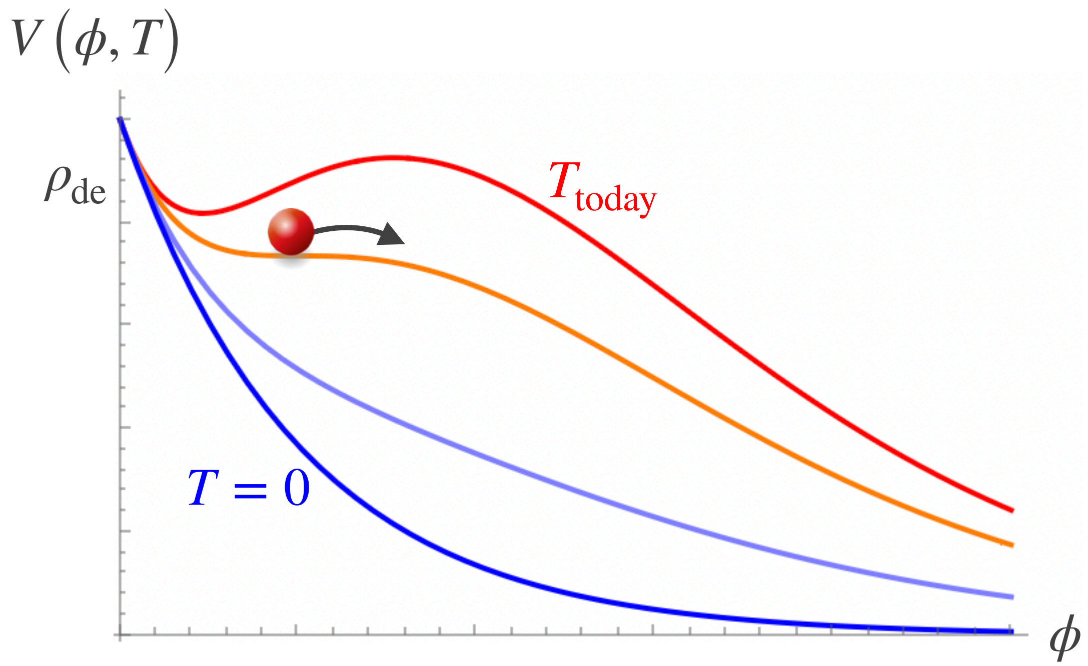

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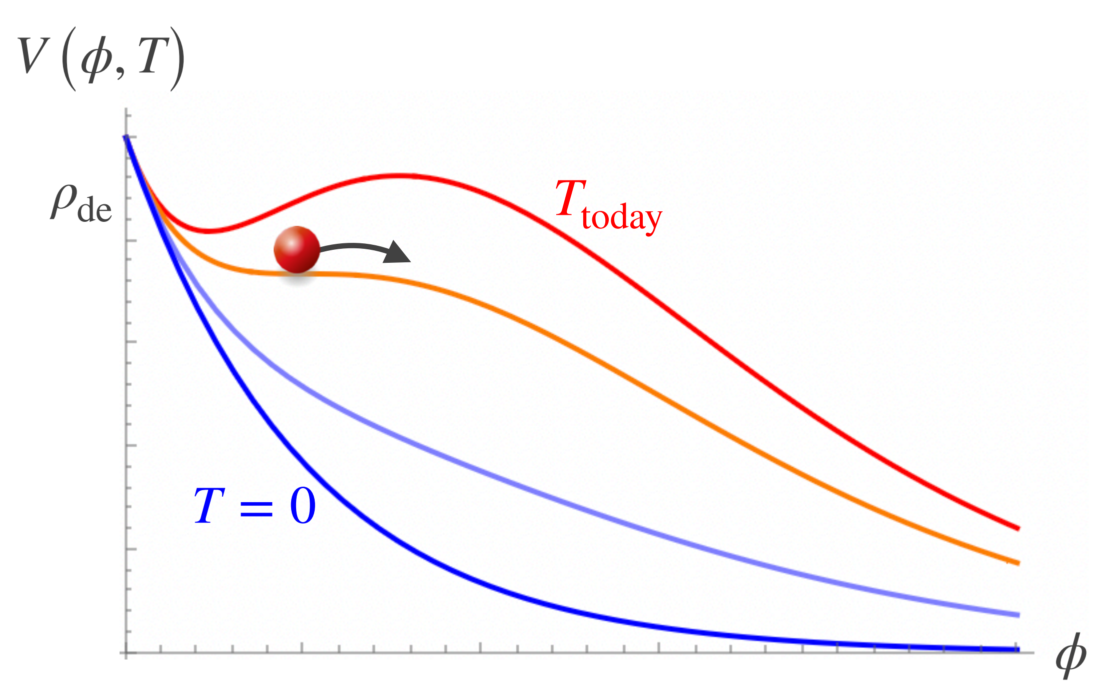
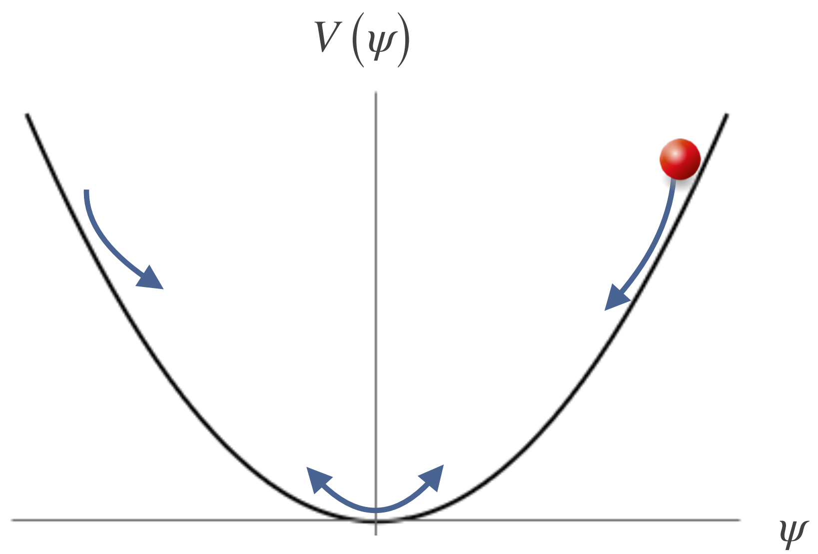
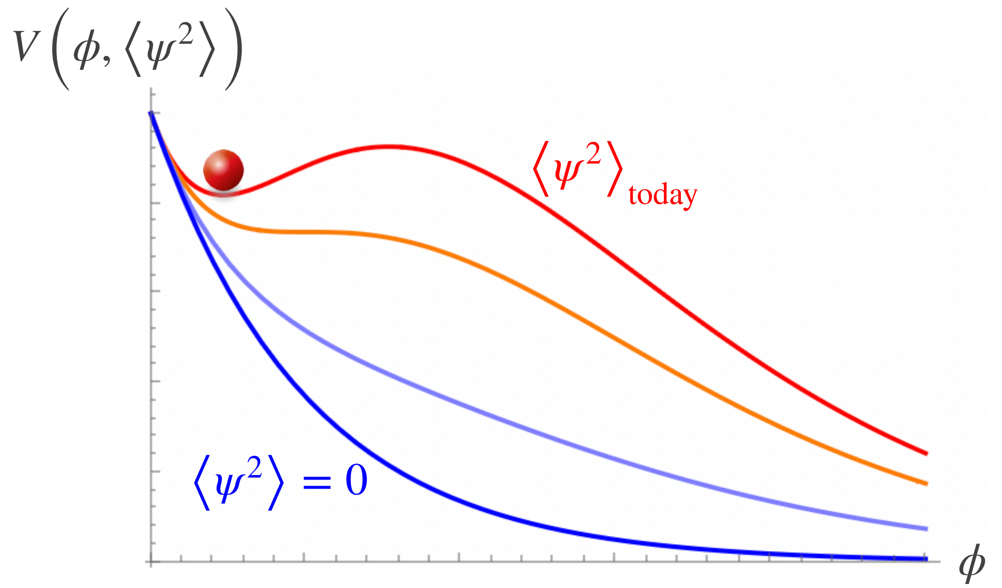


- Analogous dynamics in the early universe?
  → Early dark energy, black holes, etc.

Dark matter assisted dark energy





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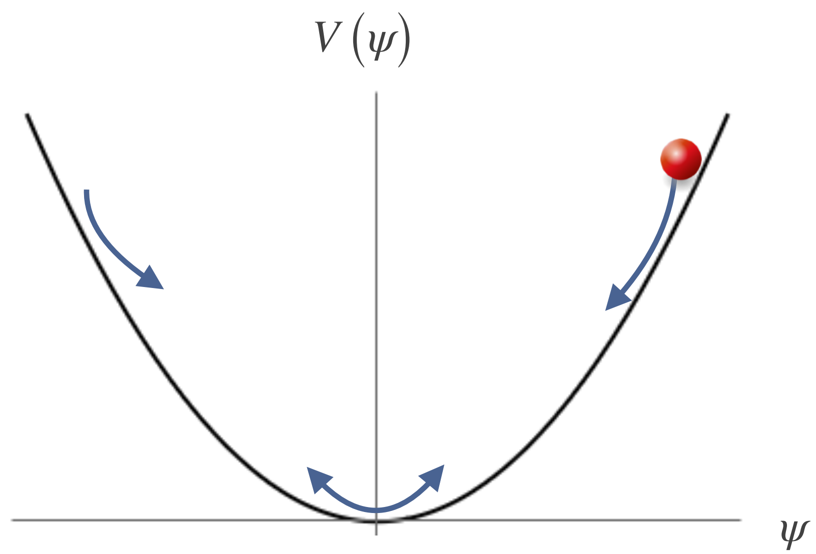
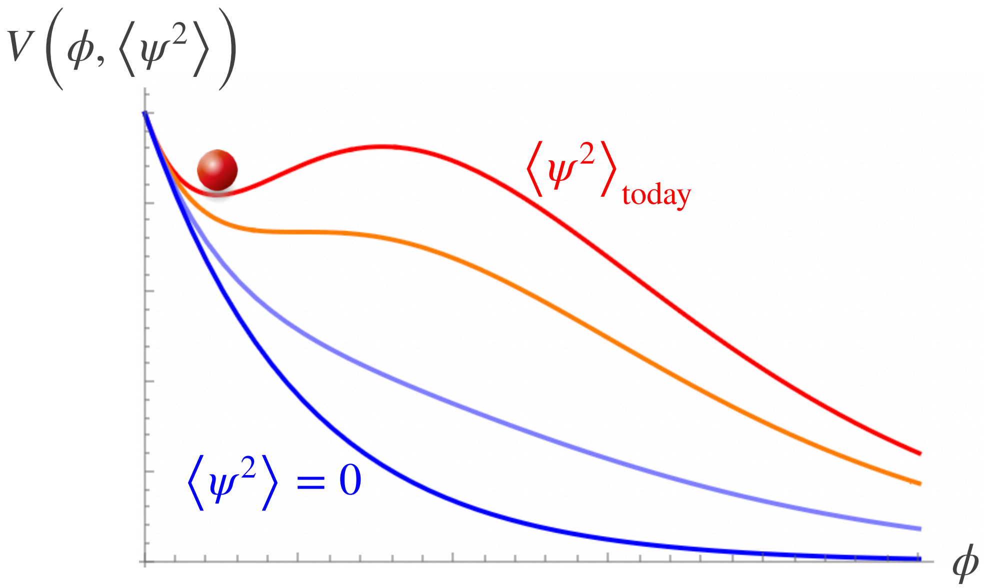
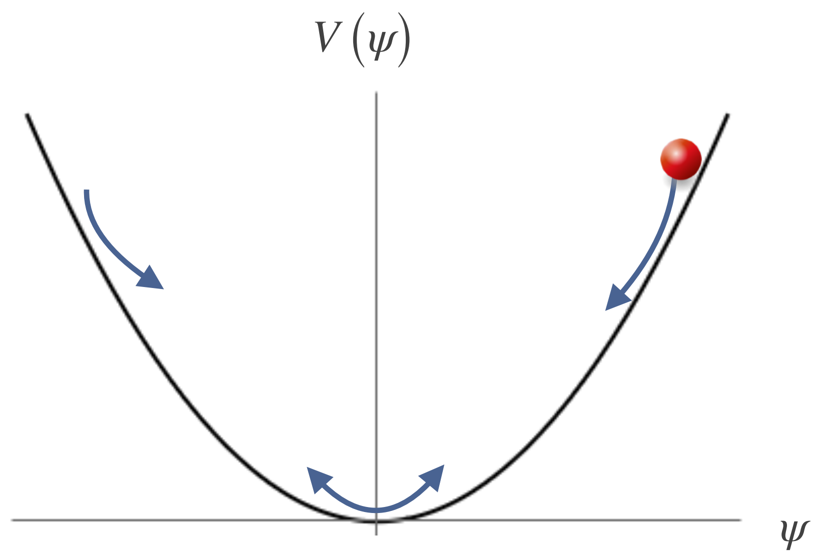


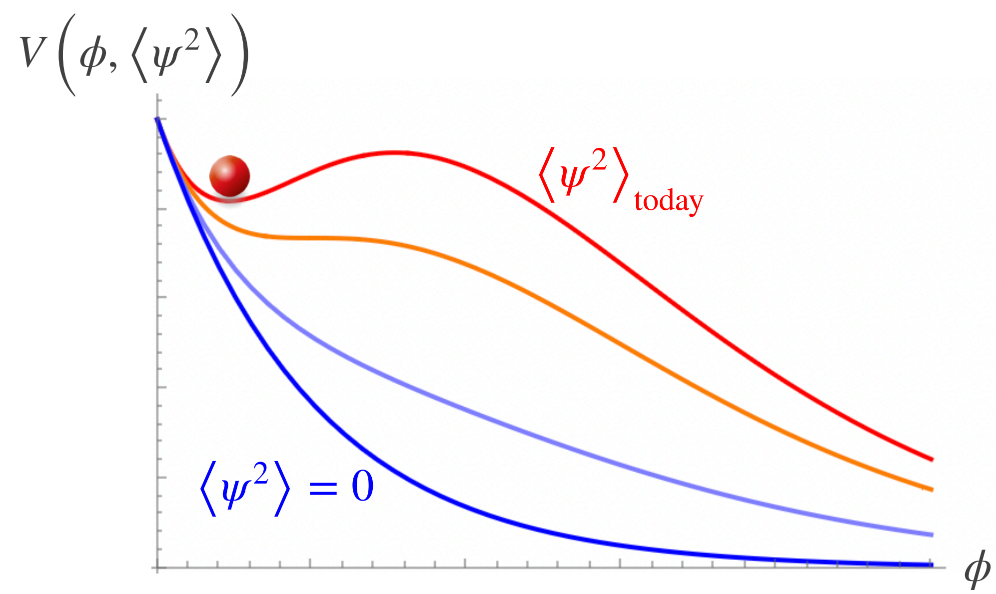


$$V(\phi,\psi) = V(\phi) + \frac{1}{2}m_\psi^2\psi^2 + \frac{1}{2}\frac{m_{\rm int}^2}{\Lambda^2}\phi^2\psi^2$$

$$V_{\rm exp}(\phi) \equiv \rho_{\rm de}\, e^{-\phi/\Lambda}$$

Dark matter assisted dark energy





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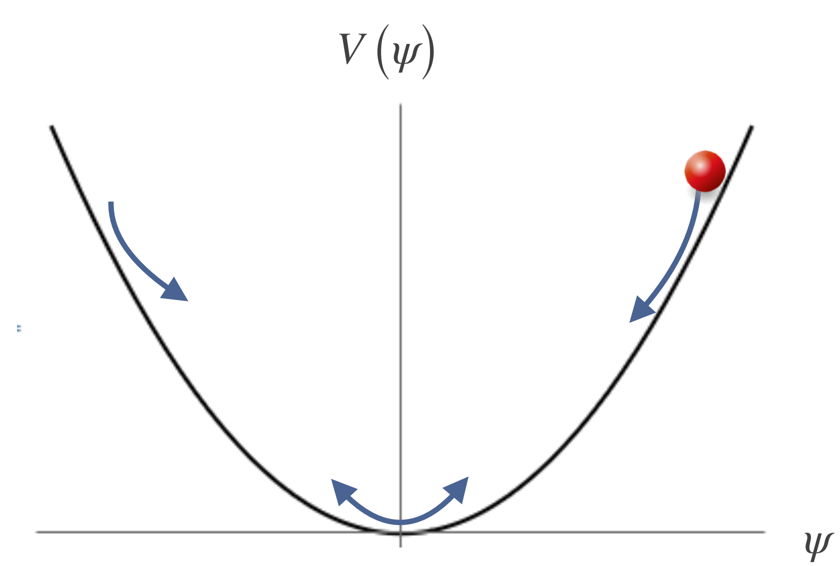
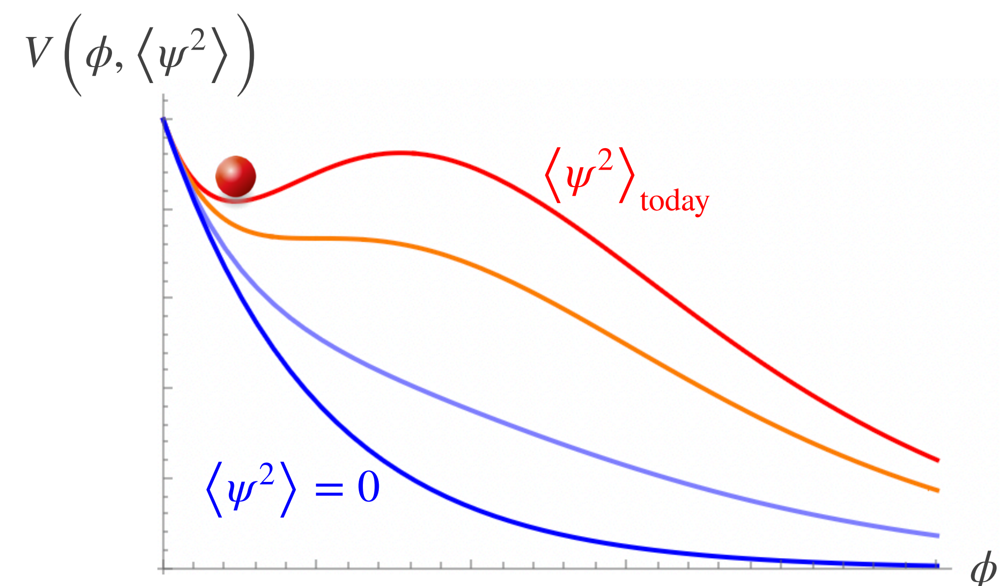
So $V\left(\phi, \langle\psi^2\rangle\right) = \rho_{\rm de}e^{-\phi/\Lambda} + \frac{1}{2}\langle\psi^2\rangle\frac{m_{\rm int}^2}{\Lambda^2}\phi^2$ minimised at $\phi/\Lambda \simeq \dfrac{\rho_{\rm de}}{m_{\rm int}^2\langle\psi^2\rangle}$

Dark matter assisted dark energy





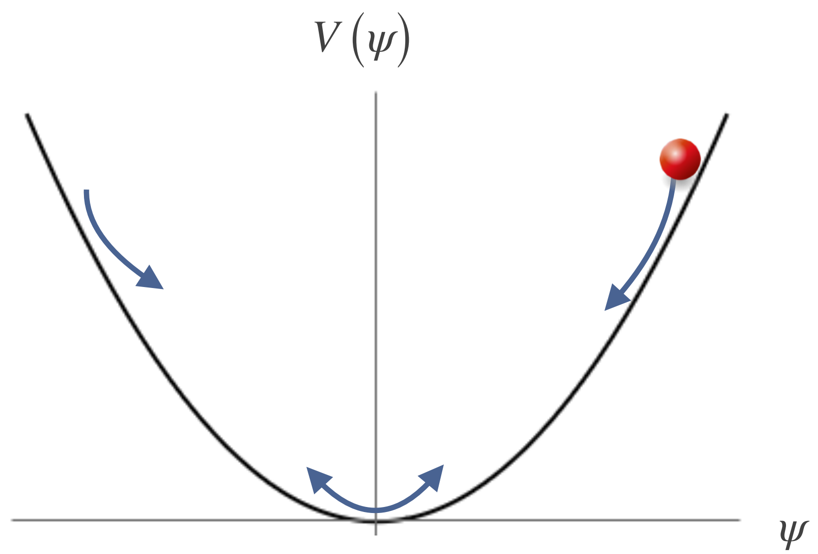
$$V(\phi,\psi) = V(\phi) + \frac{1}{2}m_\psi^2\psi^2 + \frac{1}{2}\frac{m_{\text{int}}^2}{\Lambda^2}\phi^2\psi^2$$

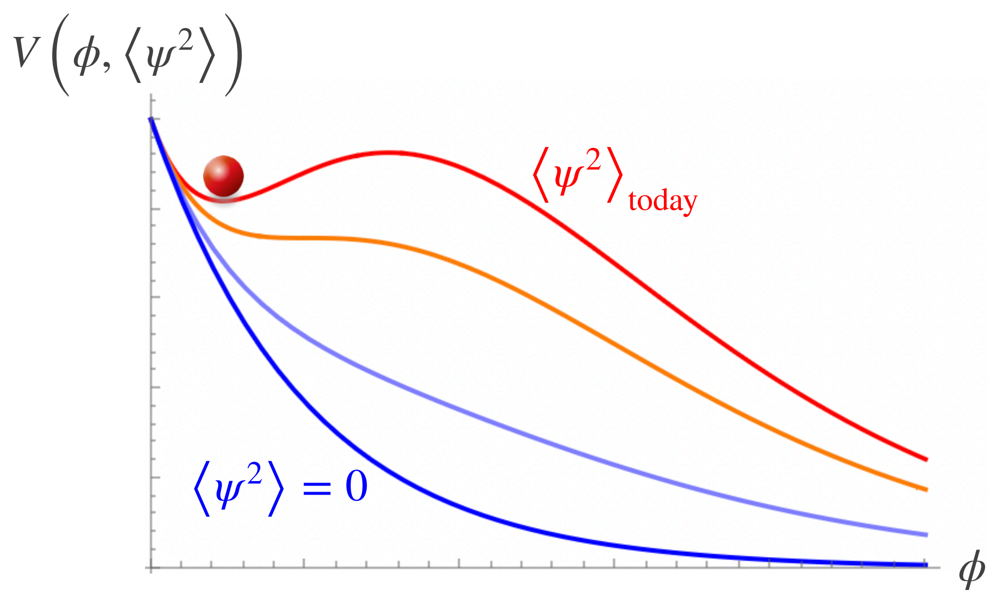
$$V_{\exp}(\phi) \equiv \rho_{\text{de}}\, e^{-\phi/\Lambda}$$

So $V\left(\phi, \langle\psi^2\rangle\right) = \rho_{\text{de}}e^{-\phi/\Lambda} + \frac{1}{2}\langle\psi^2\rangle\frac{m_{\text{int}}^2}{\Lambda^2}\phi^2$ minimised at $\phi/\Lambda \simeq \frac{\rho_{\text{de}}}{m_{\text{int}}^2\langle\psi^2\rangle}$

Vacuum energy dominates if $\rho_{\text{de}} \gg m_\psi^2\langle\psi^2\rangle$ No back-reaction provided $m_\psi^2 \gg m_{\text{int}}^2\frac{\phi^2}{\Lambda^2}$

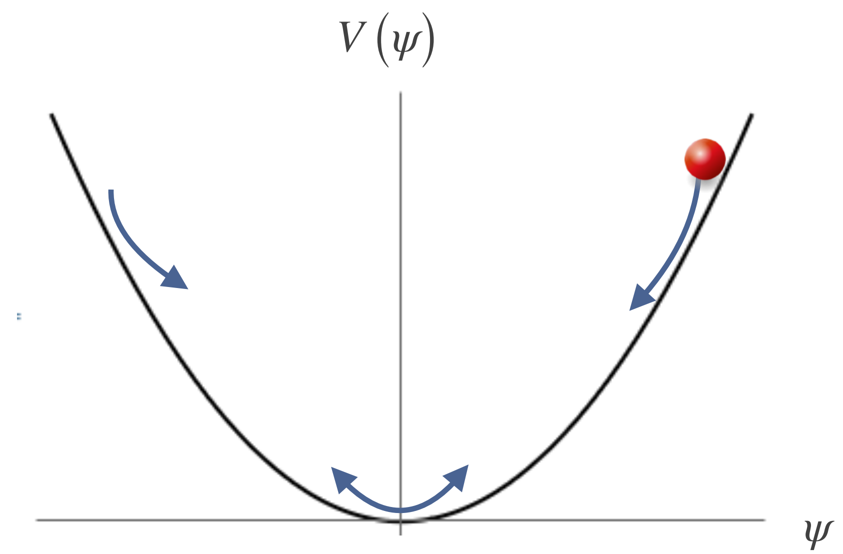
Complication

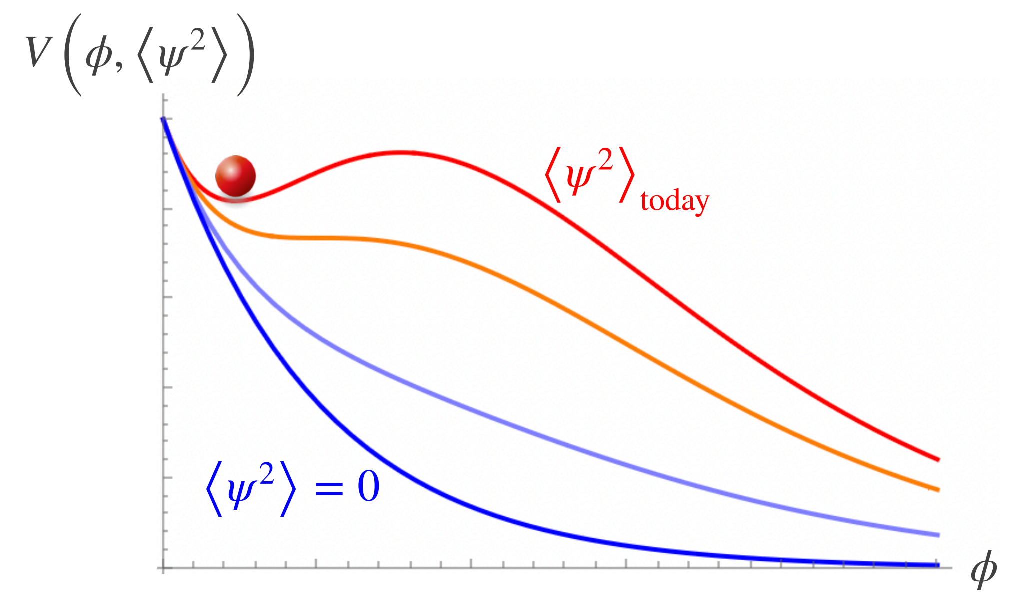




$$\ddot{\phi} + 3H_0\dot{\phi} + \left(m_{\text{int}}^2\psi_{\text{i}}^2 e^{-3H_0 t}\cos^2(m_\psi t) + \rho_{\text{de}}\right)\frac{\phi}{\Lambda^2} \approx \frac{\rho_{\text{de}}}{\Lambda},$$

Complication





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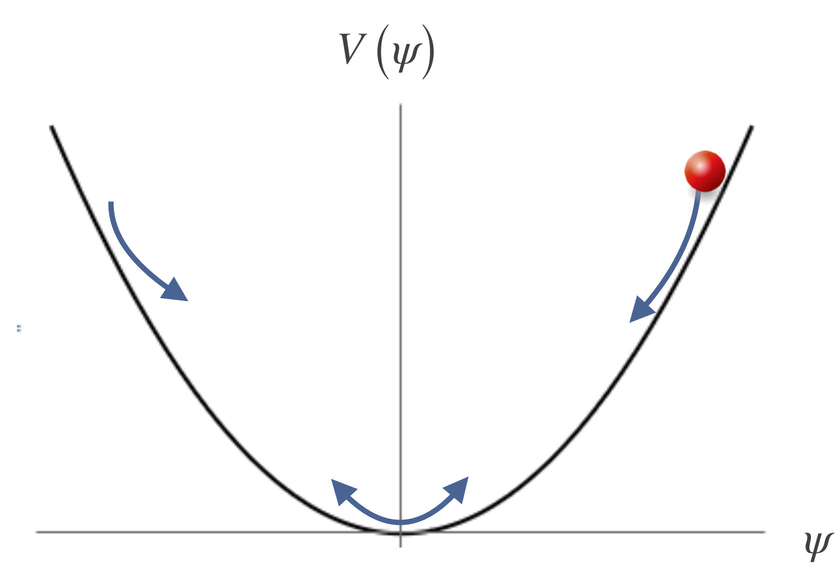
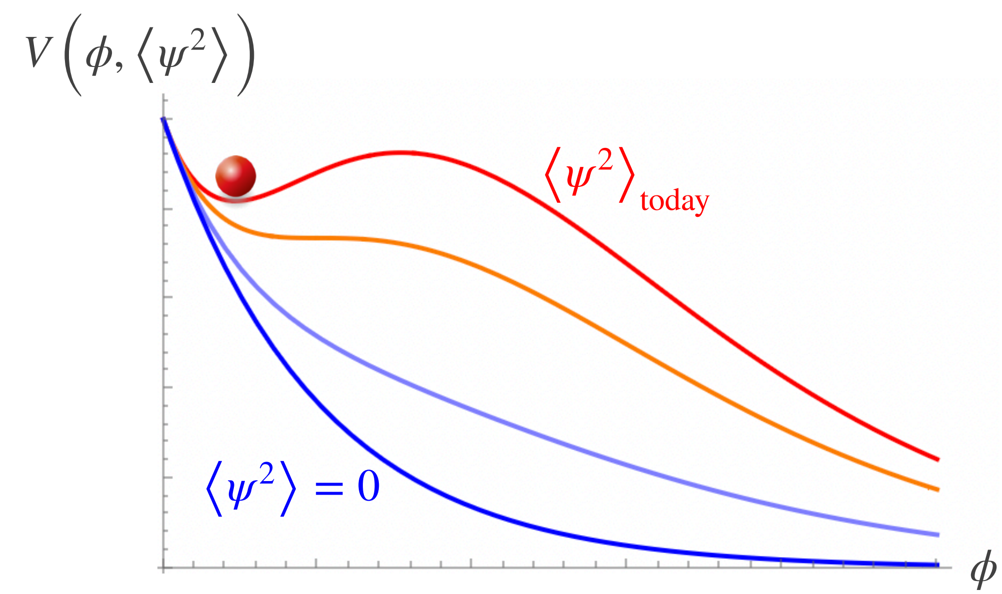
Homogeneous part: $\hat{\phi}'' + \left(c(\tau) + 2q(\tau)\cos(2\tau)\right)\hat{\phi} = 0$ where $\hat{\phi} = e^{3H_0 t/2}\phi$ $\tau = m_\psi t$

Mathieu equation $\hat{\phi}(\tau) = e^{s\tau} f(\tau)$ with periodic $f(\tau + \pi) = f(\tau)$

Complication





$$\ddot{\phi} + 3H_0\dot{\phi} + \left(m_{\text{int}}^2 \psi_{\text{i}}^2 e^{-3H_0 t}\cos^2(m_\psi t) + \rho_{\text{de}}\right)\frac{\phi}{\Lambda^2} \approx \frac{\rho_{\text{de}}}{\Lambda},$$

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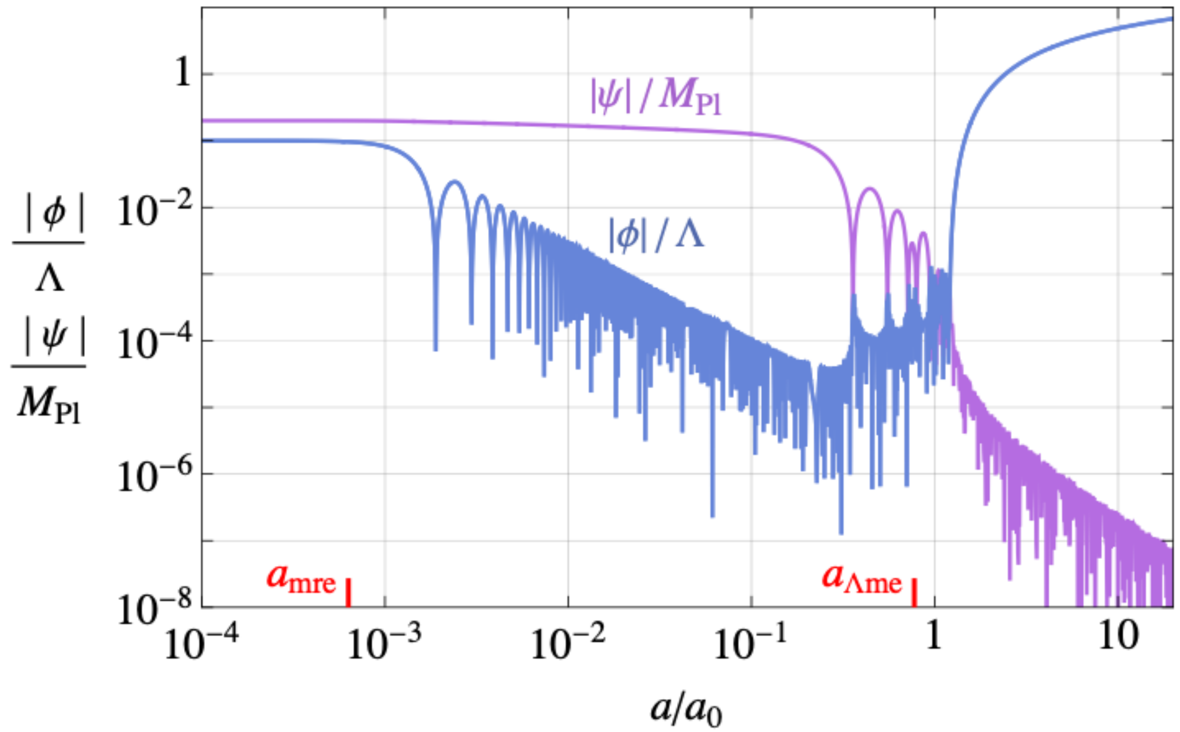
→ Mathieu equation $\quad \hat{\phi}(\tau) = e^{s\tau} f(\tau)$ with periodic $f(\tau + \pi) = f(\tau)$

$\phi(t) \propto e^{(\bar{s}m_\psi - 3H_0/2)t}$ where $\bar{s} \approx 0.11$ $\quad$ so $\quad m_\psi/H_0 \lesssim 15$

to avoid resonant instability

Example model



$$m_\psi = 12H_0$$

$$m_{\rm int} = 10^5 H_0$$

$$\Lambda = M_{\rm Pl}/2$$

Initial conditions

$$\phi_{\rm i} = 10^{-1}\Lambda,\ \psi_{\rm i} = M_{\rm Pl}/5$$

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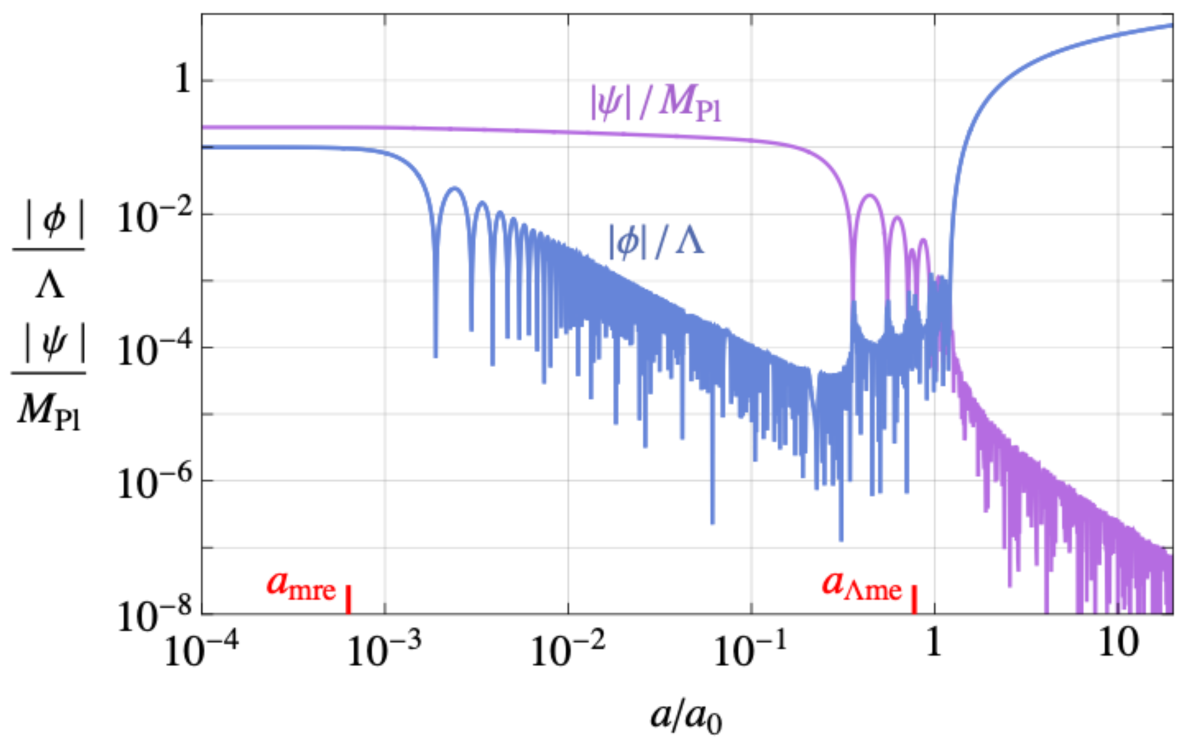

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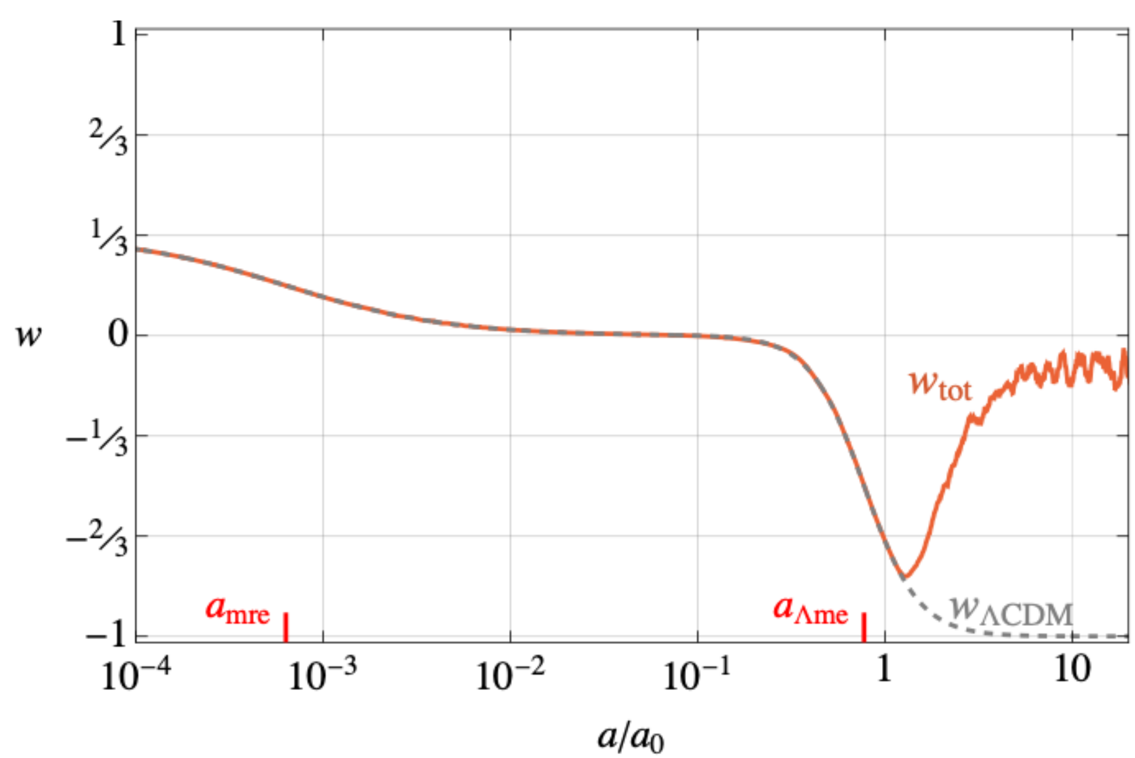
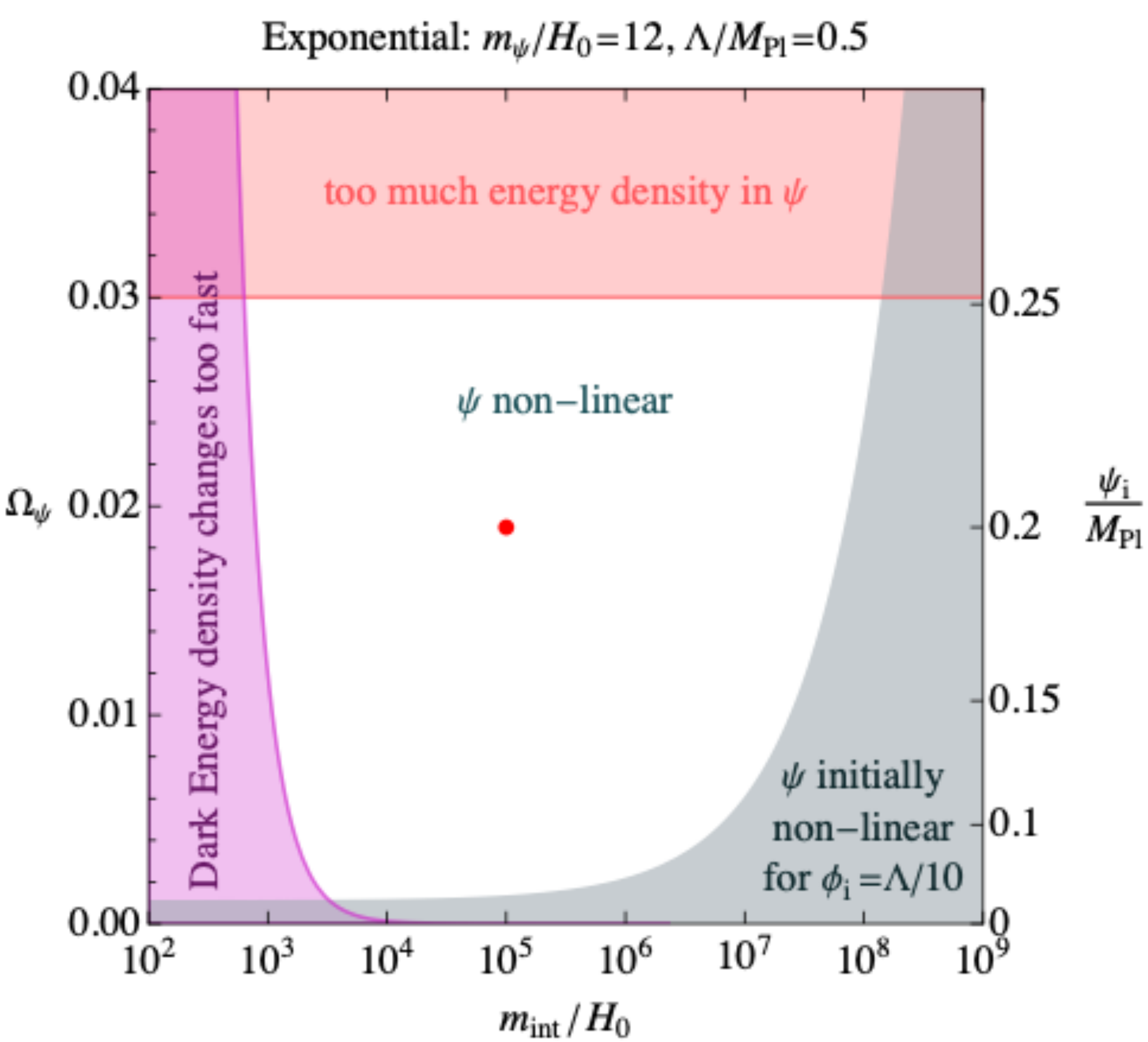
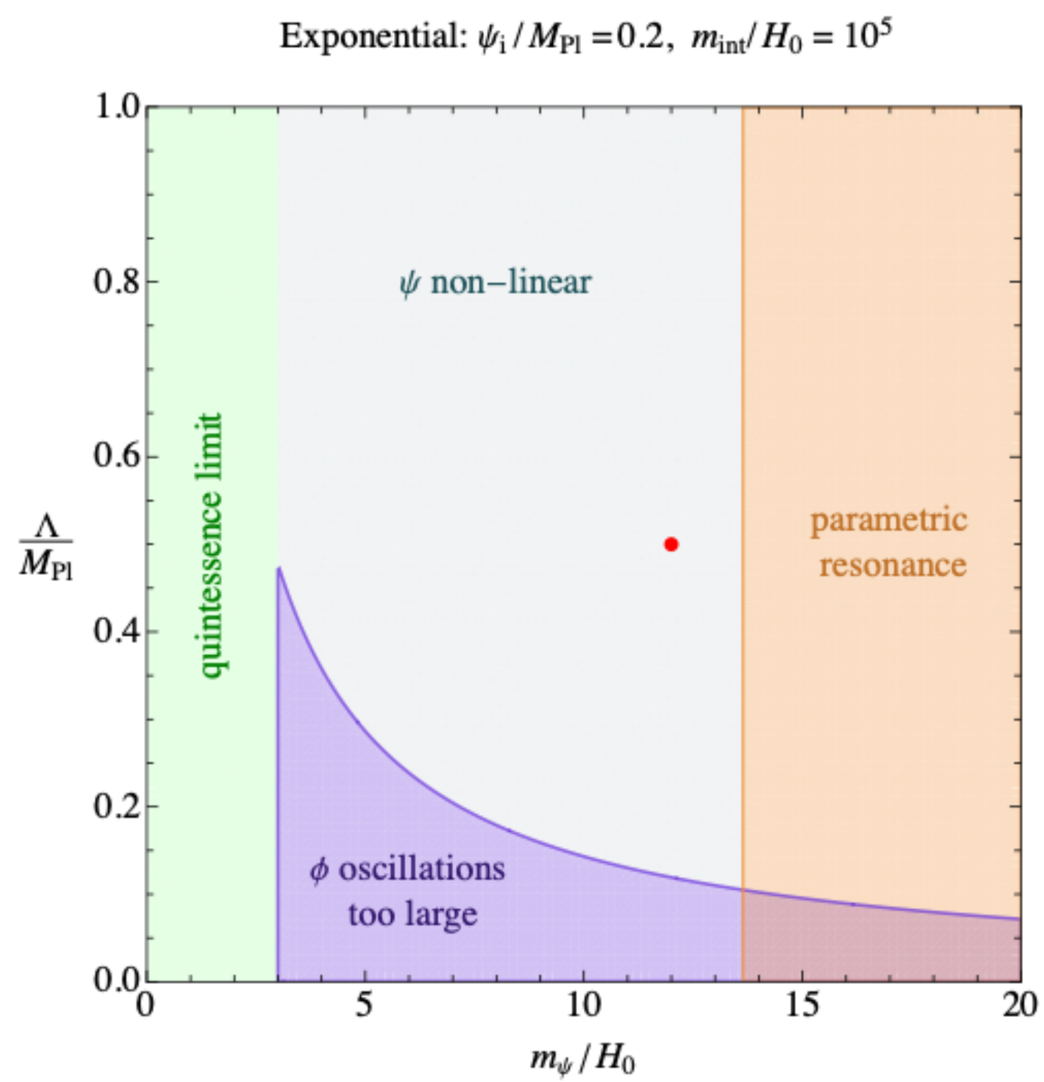


Consistent with observations

Constraints





Conclusions

- New possibilities for transient dark energy
- Must still tune CC at true minimum, but can otherwise be natural
- Typically hard to get many e-folds of accelerated expansion

To do:

- Embed in more realistic SUGRA/ string theory motivated models, or strongly coupled gauge theory sector
- Study observational signals
- How do the arguments against dS change at finite T?

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Thanks