Daniele Teresi

Cosmological Naturalness

02 Aug 2022 - PASCOS, Heidelberg

Naturalness, 2022?

- The EFT “Standard Model” explains almost everything we see and we do not see
- Naturalness = dimensional analysis works. Already from G. Galilei $t \sim \sqrt{l/g}$. But:

$$m_{\text{Higgs}}, \rho_{\text{vacuum}}, \theta_{\text{QCD}} \lll \text{dimensional analysis}$$

- Concrete problem, not aesthetic, if SM as an EFT, with calculable parameters
- LHC has basically made 2.5 discoveries:

A. Higgs boson B. unnaturalness of m_{Higgs} C. quasi-criticality (if SM extrapolated)

Naturalness, 2022?

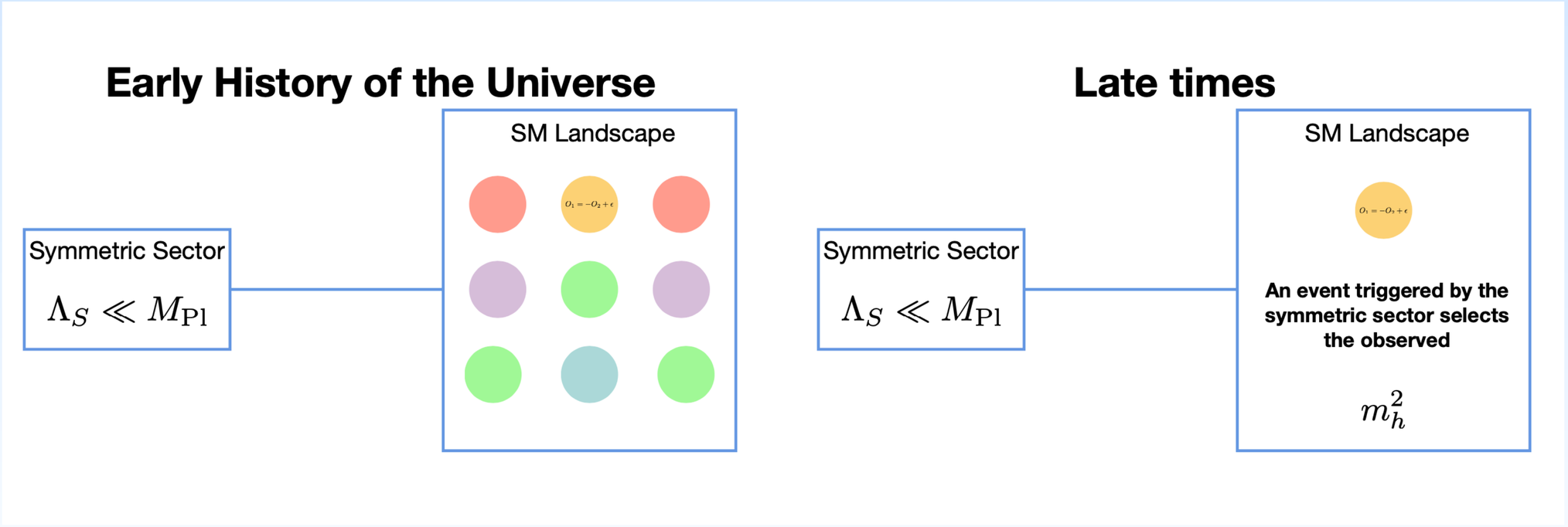
Essentially 3.5 possibilities:

- LHC will soon discover new physics related to $m_{\rm Higgs}$ (partial solution/non-solution)
- epicycles of low-scale SUSY or compositeness
- new frameworks in which $m_{\rm Higgs}$ is natural (ideally, not currently known)
- Nature is unnatural, but unnaturalness is selected dynamically (= cosmologically)

[…, Strumia, DT 2002.02463; D'Agnolo, DT 2106.04591; 2109.13249]

Cosmological Naturalness

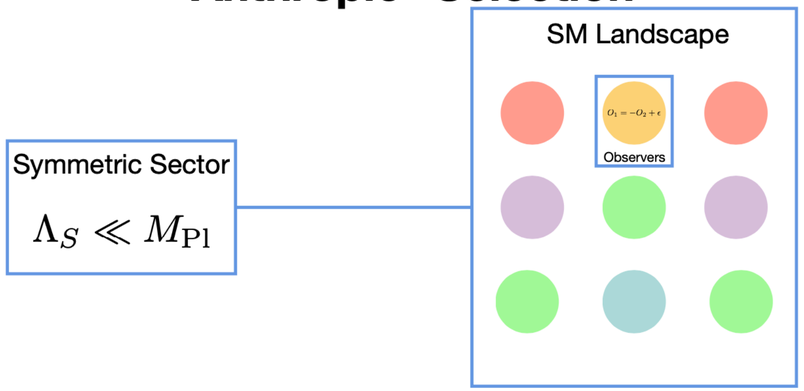
i.e. how cosmology can select a small Higgs mass



Cosmological Naturalness

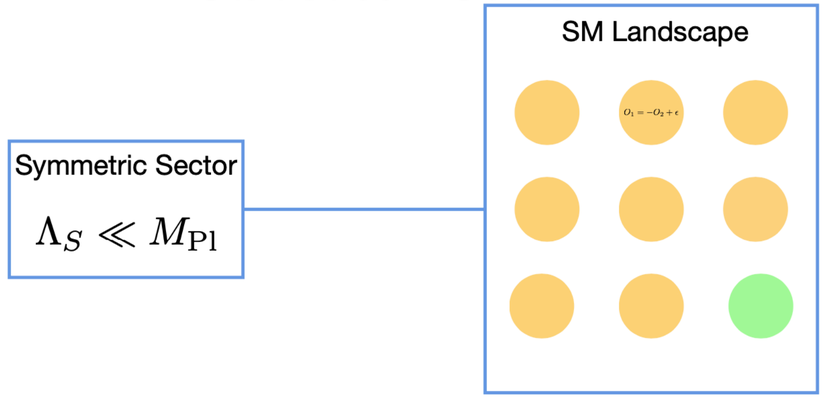
i.e. how cosmology can select a small Higgs mass

"Anthropic" Selection



light Higgs from small CC
[Arvanitaki, Dimopoulos, Gorbenko, Huang, Van Tilburg]

"Statistical" Selection

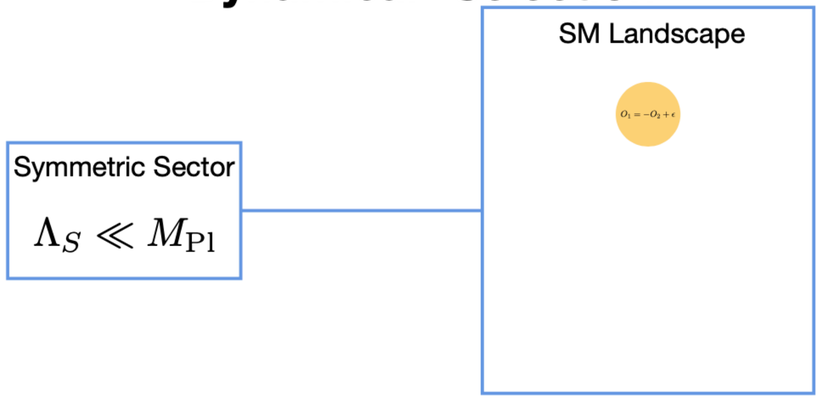


vacuum accumulation
[Dvali, Vilenkin]

light Higgs inflates most
[Geller, Hochberg, Kuflik; Cheung, Saraswat]

Self-Organized Localization
[Giudice, McCullough, You]

"Dynamical" Selection



relaxion
[Graham, Kaplan, Rajendran]

NNaturalness
[Arkani-Hamed, Cohen, D'Agnolo, Hook, Kim, Pinner]

Selfish Higgs
[Giudice, Kehagias, Riotto]

Precarious Naturalness
[Strumia, DT]

crunching dilaton
[Csáki, D'Agnolo, Geller, Ismail]

Sliding Naturalness
[D'Agnolo, DT, 2106.04591, 2109.13249]

Sliding Naturalness

A novel way to select $0 < \langle h \rangle \lesssim O(100)$ GeV
and solve jointly the strong-CP problem,
explain DM, …

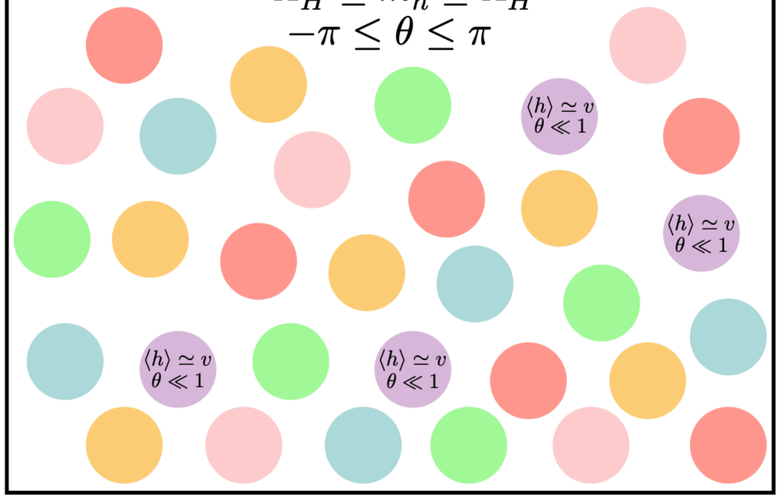
R. T. D'Agnolo, D. Teresi, 2106.04591 PRL, 2109.13249 JHEP

Sliding Naturalness

sketch of the mechanism

Landscape of Higgs mass, θ and CC values

$$-\Lambda_H^2 \leq m_h^2 \leq \Lambda_H^2$$
$$-\pi \leq \theta \leq \pi$$



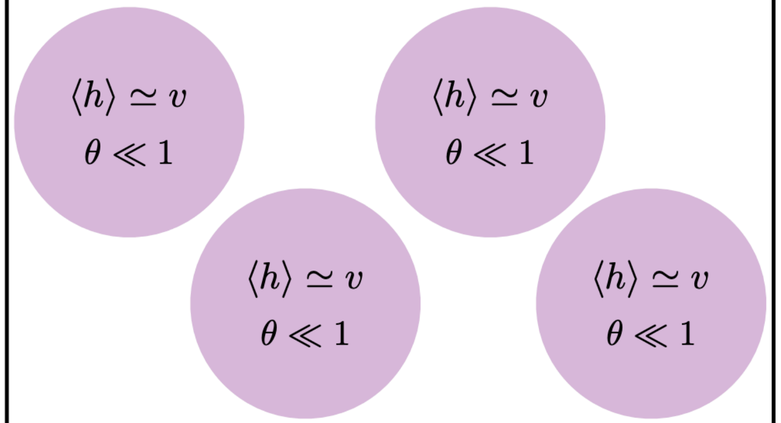
After reheating and a time

$$t_c \sim 10^{-5}\ \mathrm{s}$$

All patches where the Higgs vev is far from the weak scale or the QCD θ-angle is large **crunch**

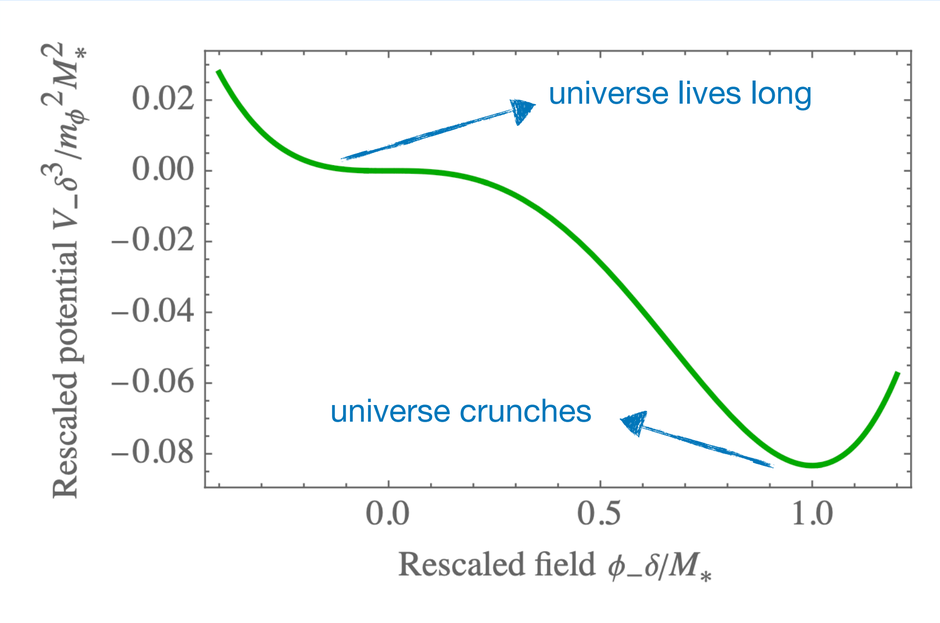
Only universes with the observed value of the weak scale and θ can live for cosmologically long times.

Today the multiverse looks like:



Sliding Naturalness

Two Scalars to Rule Them All

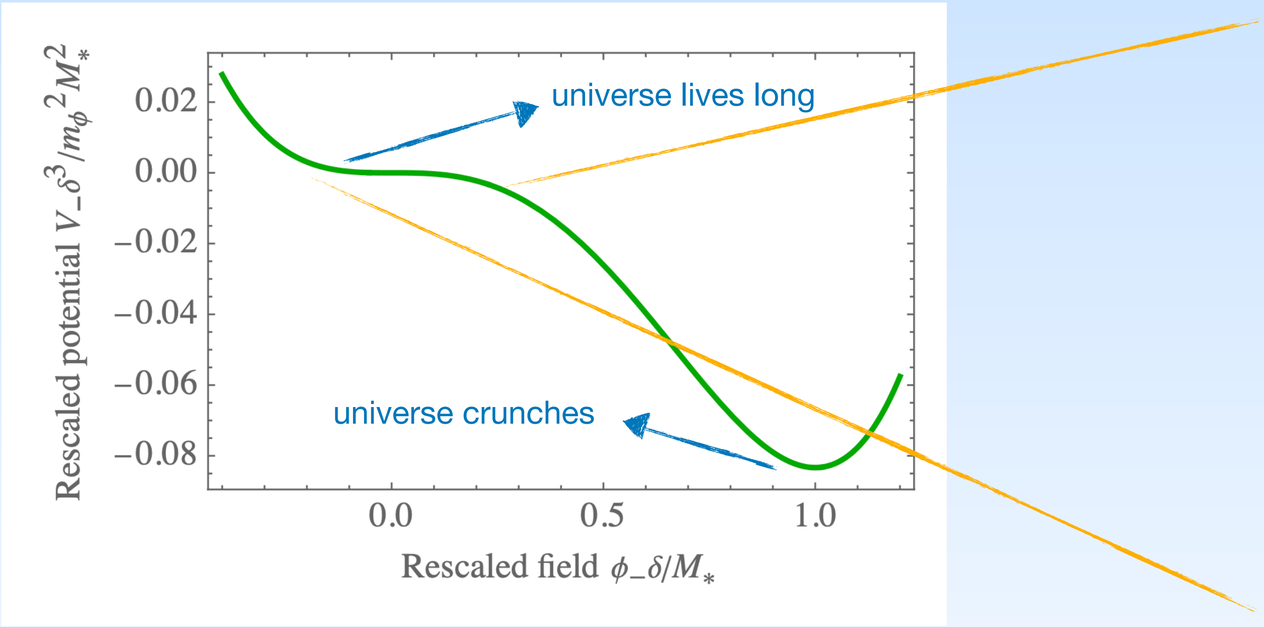


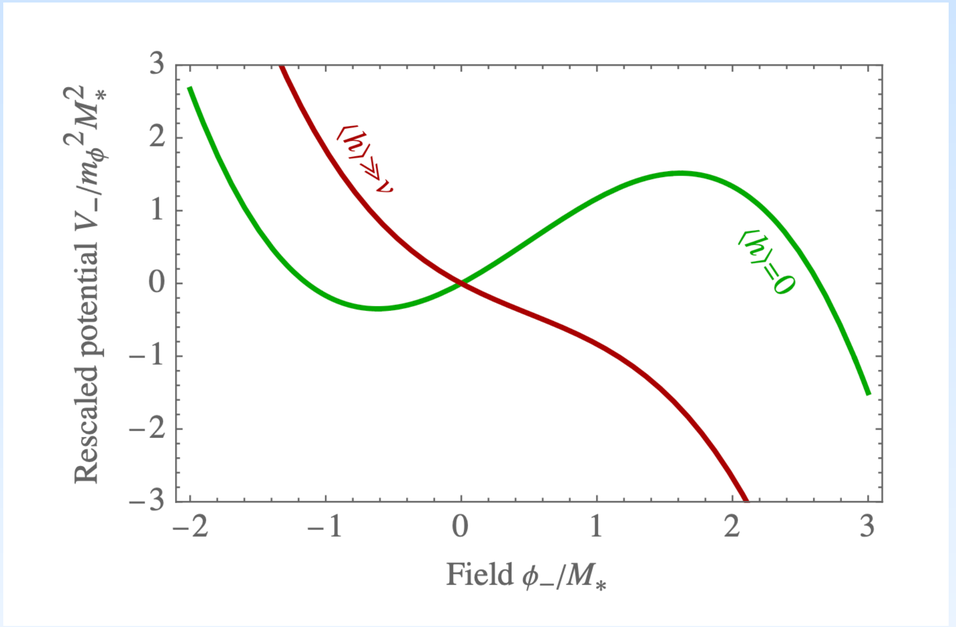
- At global minimum $V \sim -M_*^4$ too big to be compensated by a CC in the landscape
- At local minimum CC in the landscape can be tuned $V \approx 0$

Sliding Naturalness

Two Scalars to Rule Them All

universe crunches if $\langle h \rangle \gg v$





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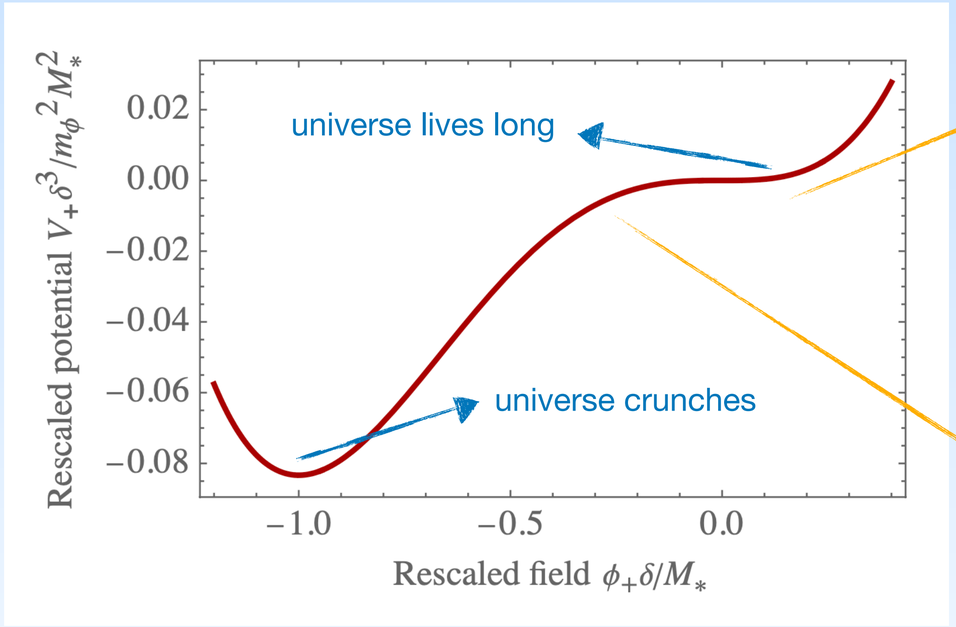
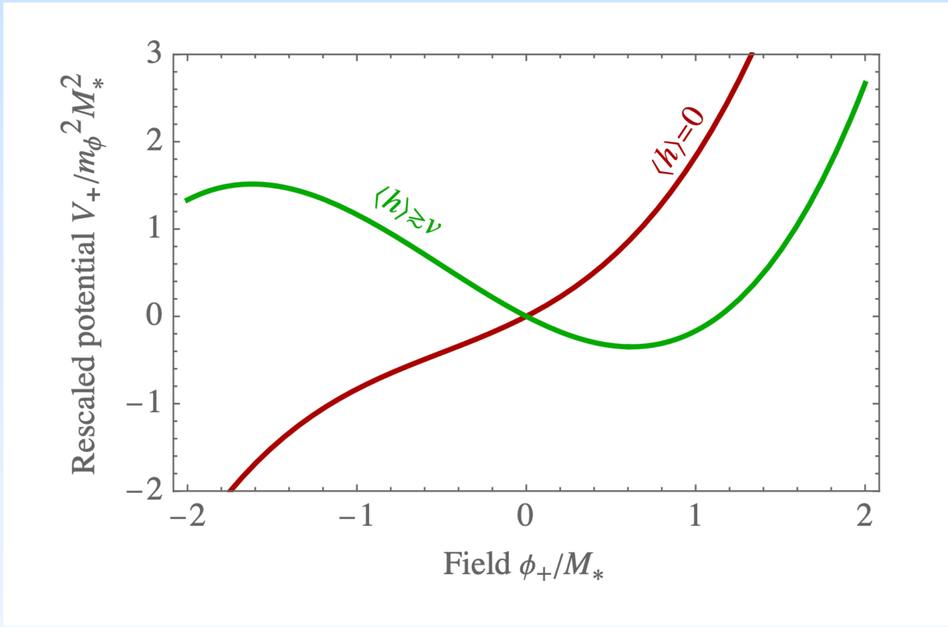
Sliding Naturalness

Two Scalars to Rule Them All

universe crunches if $\langle h \rangle \lesssim v$





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Sliding Naturalness

Two Scalars to Rule Them All

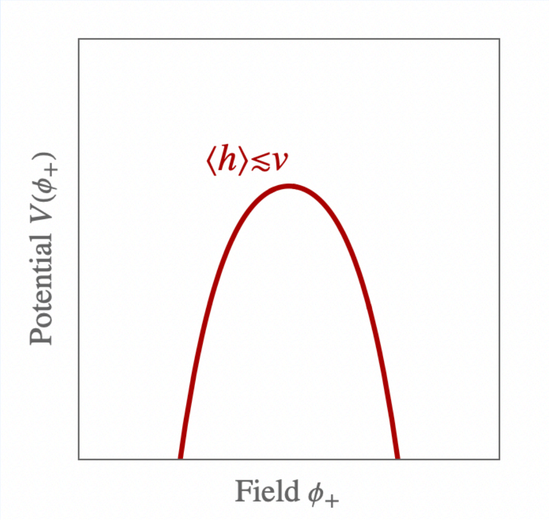
the only universes that live long
are those where

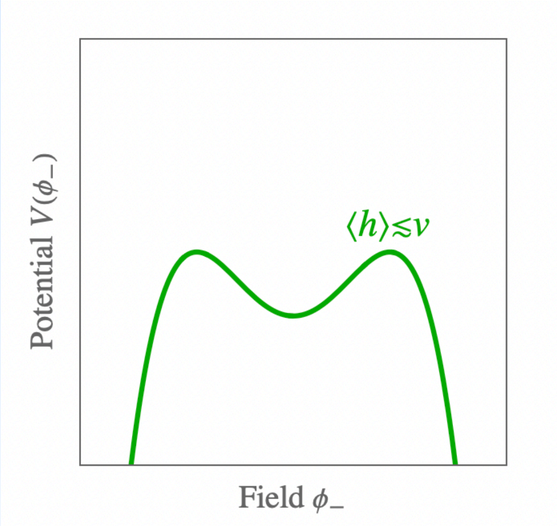
$$v \lesssim \langle h \rangle \lesssim v$$

The Lagrangian

$$V_+ = -\frac{m_+^2}{2}\phi_+^2 - \frac{m_+^2}{M_+^2}\phi_+^4$$

$$V_- = +\frac{m_-^2}{2}\phi_-^2 - \frac{m_-^2}{M_-^2}\phi_-^4$$





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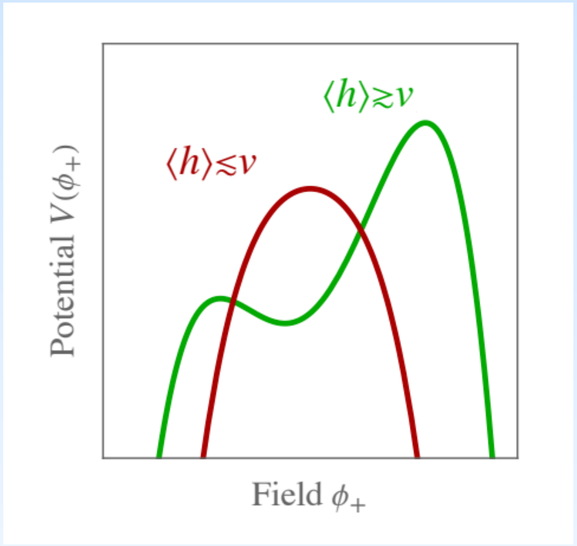
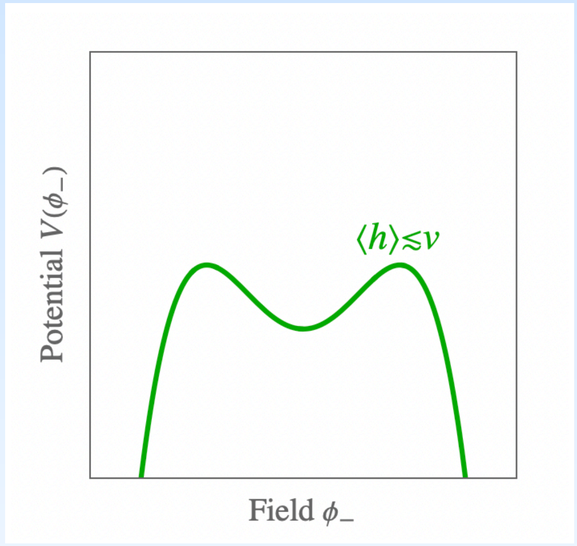




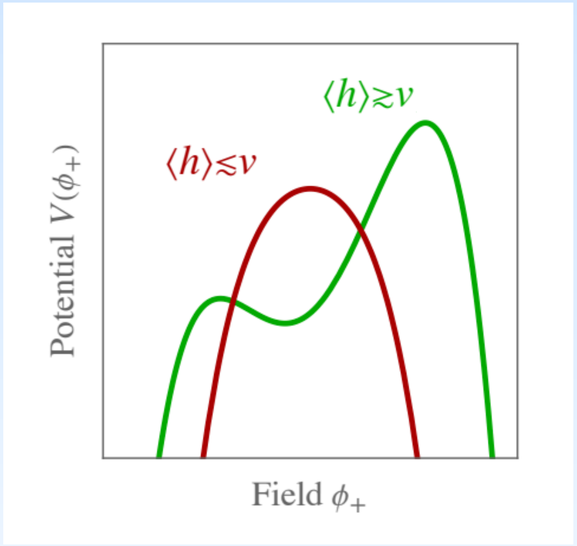
$$V_{\phi H} = -\frac{\alpha_s}{8\pi}\left(\frac{\phi_+}{F_+} + \frac{\phi_-}{F_-} + \theta\right) G\tilde{G}$$

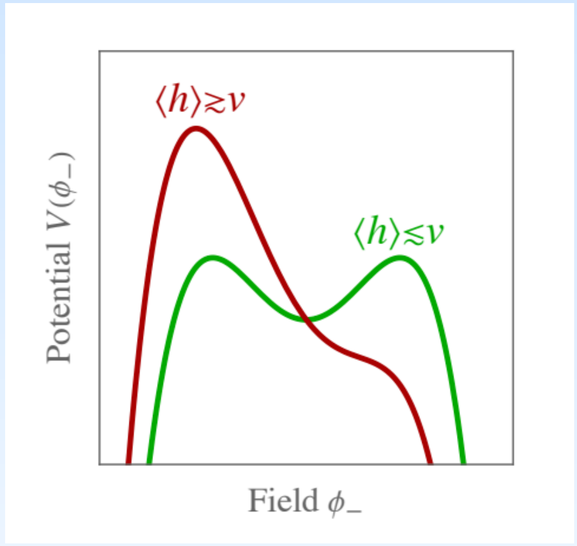
$$\longrightarrow -m_\pi^2 f_\pi^2 \cos(\ldots)$$

$$\sim \frac{\Lambda(\langle h \rangle)^4}{2}\left(\frac{\phi_+}{F_+} + \frac{\phi_-}{F_-} + \theta\right)^2$$

The Lagrangian

$$V_+ = -\frac{m_+^2}{2}\phi_+^2 - \frac{m_+^2}{M_+^2}\phi_+^4 \qquad V_- = +\frac{m_-^2}{2}\phi_-^2 - \frac{m_-^2}{M_-^2}\phi_-^4$$





$$V_{\phi H} = -\frac{\alpha_s}{8\pi}\left(\frac{\phi_+}{F_+} + \frac{\phi_-}{F_-} + \theta\right) G\tilde{G}$$

$$\longrightarrow -m_\pi^2 f_\pi^2 \cos(\ldots)$$

$$\sim \frac{\Lambda(\langle h\rangle)^4}{2}\left(\frac{\phi_+}{F_+} + \frac{\phi_-}{F_-} + \theta\right)^2$$

this selects a small and non-zero EW scale:

$$m_+^2 F_+^2 \lesssim \Lambda(\langle h\rangle)^4 \lesssim \frac{m_-^2 F_- M_-}{\theta}$$

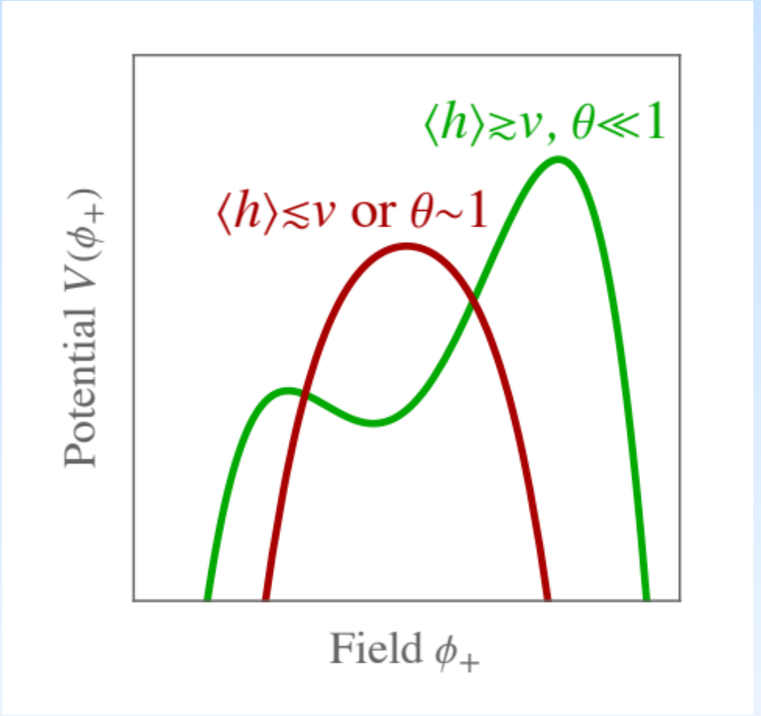
A novel solution to the strong-CP problem

$$V_{\phi H} \sim \frac{\Lambda(\langle h \rangle)^4}{2}\left(\frac{\phi_+}{F_+} + \frac{\phi_-}{F_-} + \theta\right)^2$$

θ shifts the stabilizing effect for ϕ_+

metastable minimum possible only if $\theta \ll 1$

(otherwise negative quartic wins)



the same dynamics selects jointly: $v \lesssim \langle h \rangle \lesssim v$ and $\theta \ll 1$

Dark matter

- "wrong" universes crunch in $t \sim 1/m_{\pm}$
- $m_+ \lesssim 1/t_{\rm QCD} \sim 10^{-11}$ eV otherwise ϕ_+ is doomed to crunch, before $\Lambda(\langle h \rangle) \neq 0$
- the two scalars are stable over cosmological scales, because very light
- nice scenario: ϕ_+ or ϕ_- dark matter
- relic density from oscillations:

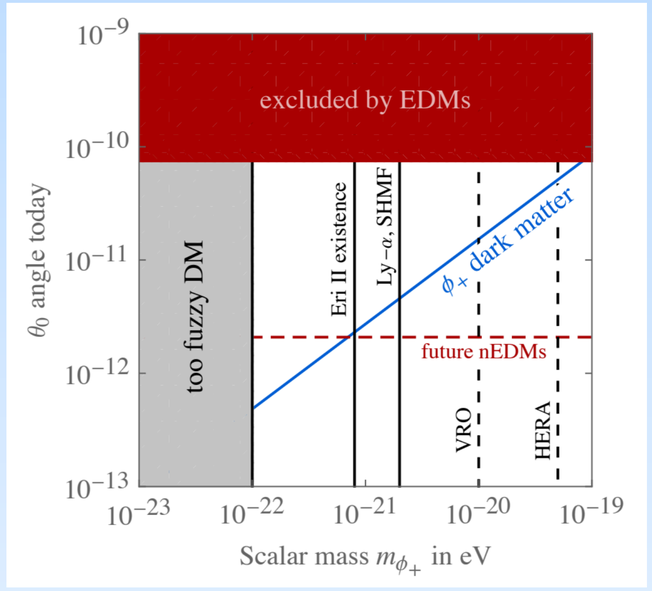
for instance: $$\frac{\rho_{\phi_+}}{\rho_{\rm DM}} \simeq \frac{\theta_0^2 \Lambda_{\rm QCD}^4}{T_{\rm eq} M_{\rm Pl}^{3/2} m_{\phi_+}^{3/2}} \simeq \left(\frac{\theta_0}{10^{-10}}\right)^2 \left(\frac{10^{-19}\ {\rm eV}}{m_{\phi_+}}\right)^{3/2}$$

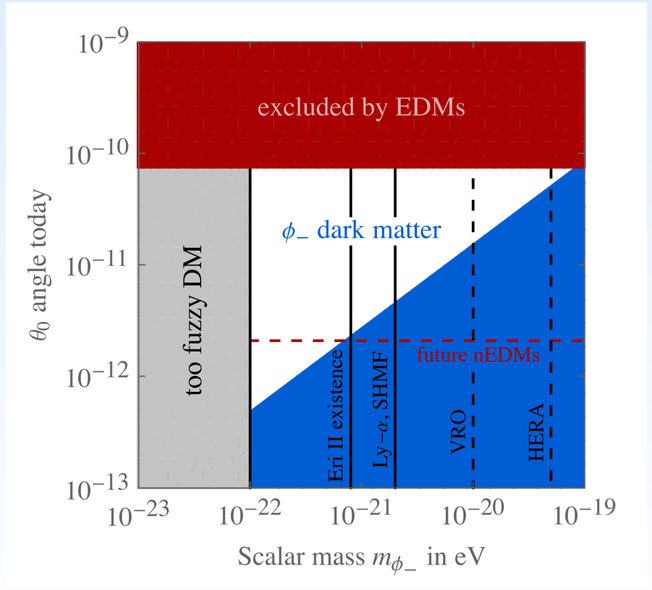
Smoking-gun pattern

- ϕ_+ is a light scalar $m_{\phi_+} \lesssim 10^{-11}$ eV
  with mass-couplings on the QCD line:
  $$m_{\phi_+}^2 \sim \frac{\Lambda_{\rm QCD}^4}{F_+^2}$$

- ϕ_- can be heavier, with mass larger than the QCD line:
  $$m_{\phi_-}^2 \sim \theta \frac{\Lambda_{\rm QCD}^4}{F_- M_-} \gtrsim \frac{\Lambda_{\rm QCD}^4}{F_-^2}$$
  since $M_-/F_- \lesssim M_+/F_+ \sim \theta$

- if DM, smoking-gun relation with EDMs





Virtues of the mechanism

Why, in a totally unbiased way, I would buy this story

- described by a simple potential and quite general (UV does not look painful)
- compatible with standard inflation (it does not need 10^{many} e-folds, or low H…)
- it can explain $v = 246\,\text{GeV}$ even if Higgs coupled at $\mathcal{O}(1)$ with particles at M_{Pl}
- it is not directly affected by the measure problem of eternal inflation
- compatible with swampland (dS and distance conjectures)
- bonuses: DM for free, strong-CP for free, smoking-gun pheno, …

Conclusions

The hierarchy problem is still out there, more pressing than ever.

Traditional solutions have been failing, but new ideas are being developed. They involve cosmological dynamics.

The way to probe these ideas is different from traditional frameworks.

Sliding Naturalness seems to be a good option.

Backup slides

The ingredients of the game

general features of dynamical selection

- A landscape for the Higgs mass (many vacua from string theory [Bousso, Polchinski] or O(10-100) scalars [Arkani-Hamed, Dimopoulos, Kachru; Ghorbani, Strumia, DT, 1911.01441]). Difficult to observe.

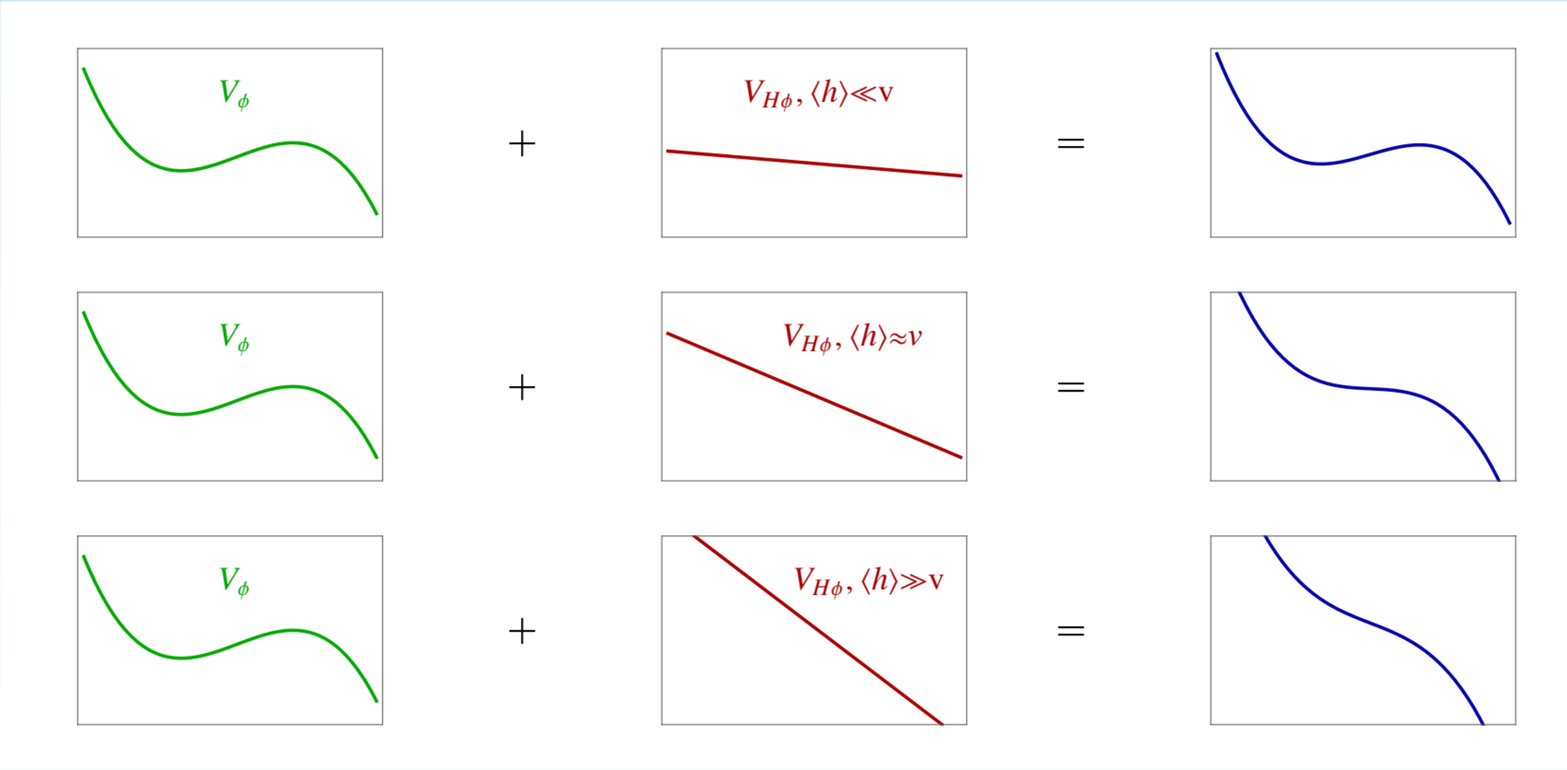
- light scalars ϕ (more in next slide)

- trigger operator [Arkani-Hamed, D'Agnolo, Kim] $\mathcal{O}(\langle h \rangle)$: $\phi G\tilde{G}, \quad \phi F\tilde{F}, \quad \phi H_1 H_2$.
  Pheno signatures!

Why light scalars?

An NDA argument [D'Agnolo, DT, 2109.13249]

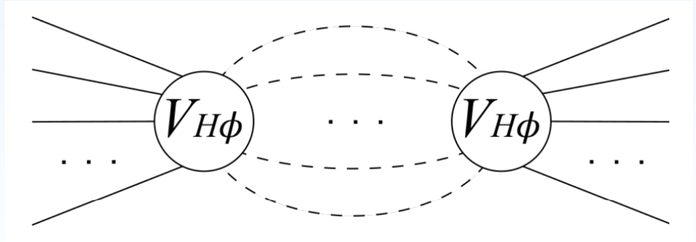
- <Higgs>-dependent "just-so" to compete with *H*-independent potential



Why light scalars?

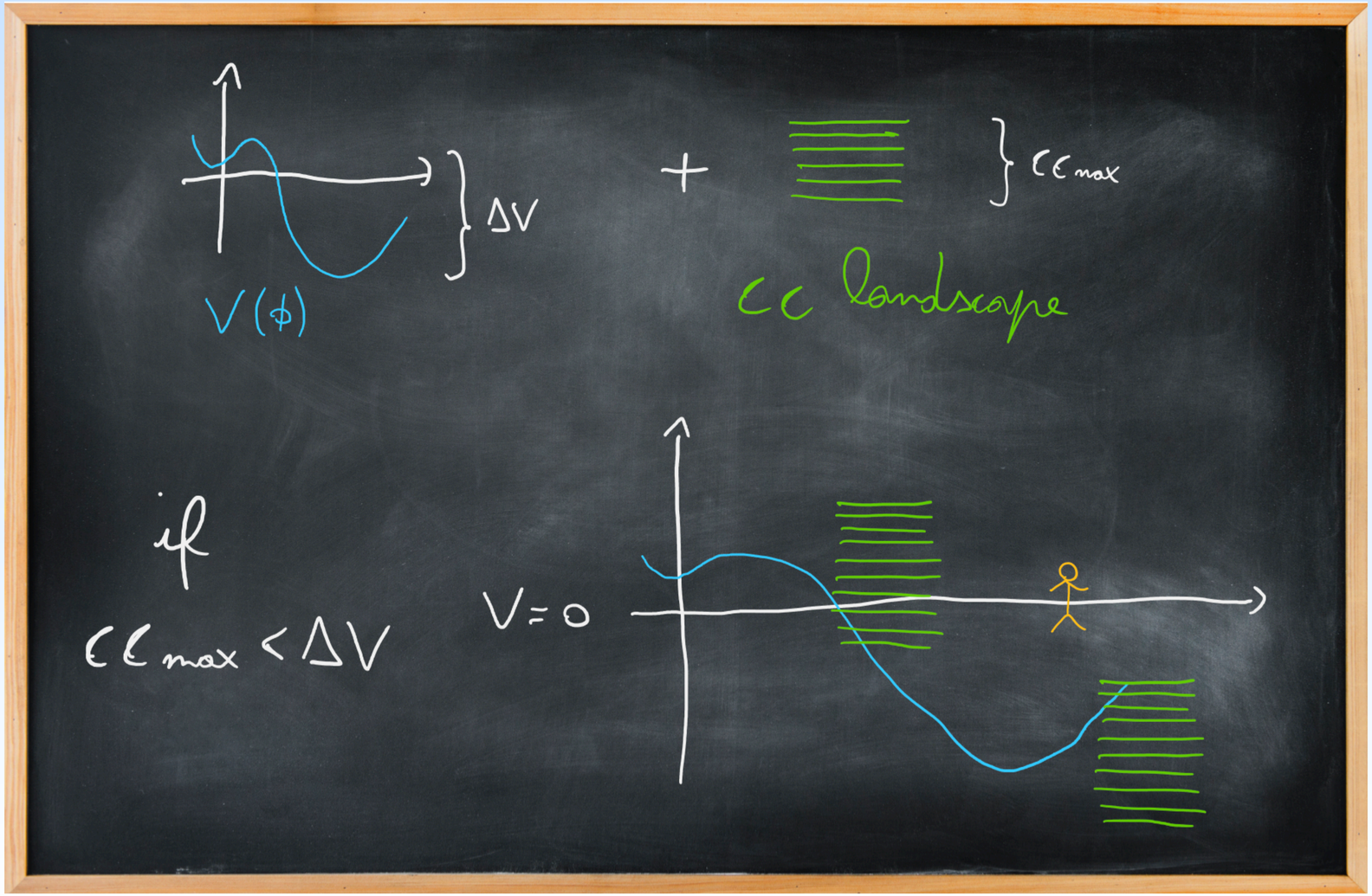
An NDA argument [D'Agnolo, DT, 2109.13249]

- <Higgs>-dependent "just-so" to compete with *H*-independent potential
- NDA: $V_\phi \sim m_\phi^2 M_*^2 \left(\frac{\phi}{M_*}\right)^n \qquad V_{\langle H\rangle\phi} \sim g^2 M_*^4 \left(\frac{\phi}{M_*}\right)^m \left(\frac{\langle h\rangle}{\Lambda_H}\right)^{2q}$
- light scalars $\leftrightarrow$ cutoff $\gg v$: $m_\phi^2 \sim g^2 M_*^2 \left(\frac{v}{\Lambda_H}\right)^{2q}$
- g bound from pheno or naturalness:



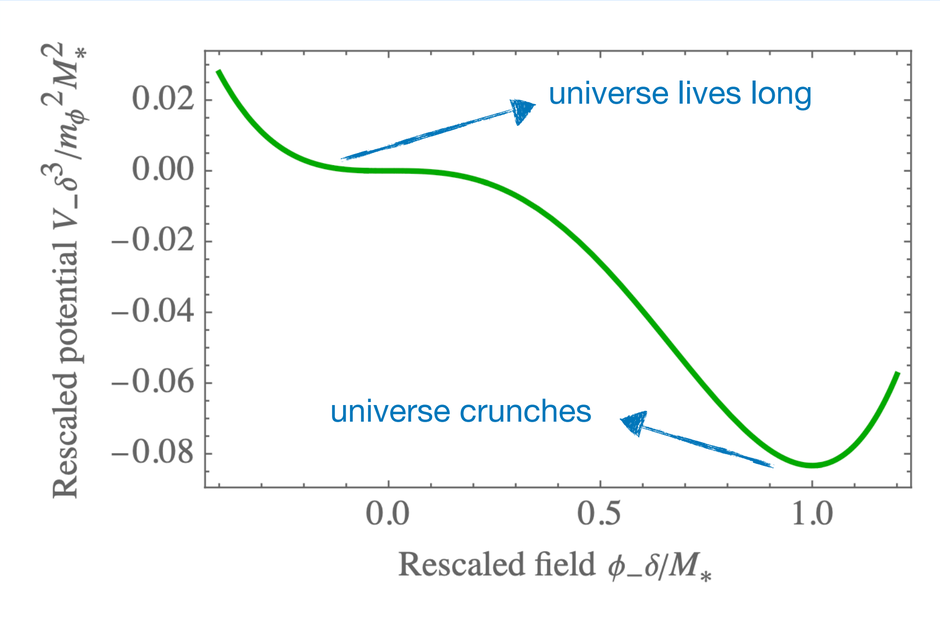
$$m_\phi \lesssim \frac{4\pi v^2}{M_*}$$

The global minimum crunches



Sliding Naturalness

Two Scalars to Rule Them All



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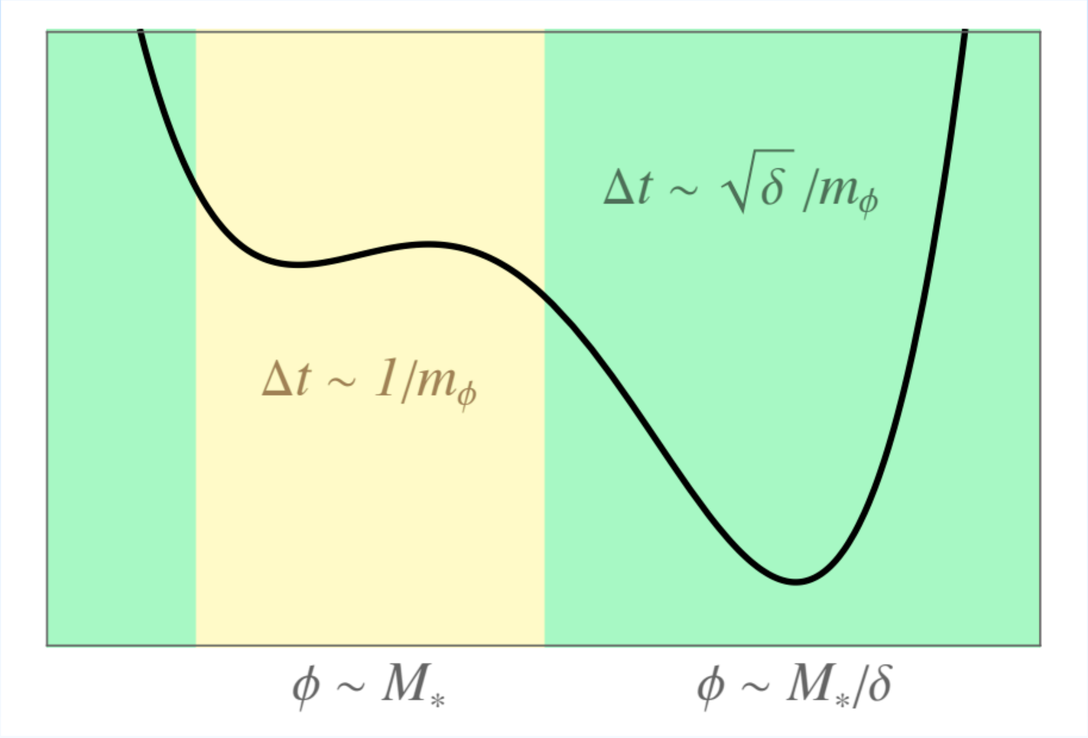
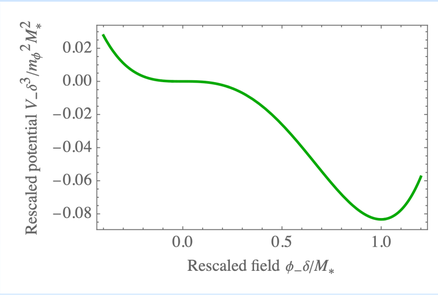


More in general

- Many different potentials will do the job (two widely split minima),
  for instance $V_{\phi_-} = m_{\phi_-}^2 M_*^2 \left(\frac{\phi_-}{M_*} + \frac{\phi_-^2}{2M_*^2} - \frac{\phi_-^3}{3M_*^3} + \frac{\delta}{4} \frac{\phi_-^4}{M_*^4} \right) + \dots$ with $\delta \ll 1$



- Hierarchy between minima needs to be stabilized by a symmetry,
  for instance $W_{\phi_-} = L\Phi_- + \mu\Phi_-^2 + \lambda\Phi_-^3$ and $V_B = \epsilon\mu\phi_-^3$

- Hierarchy problem → stabilizing symmetry for $V_{\phi_\pm}$ (secluded from SM!)

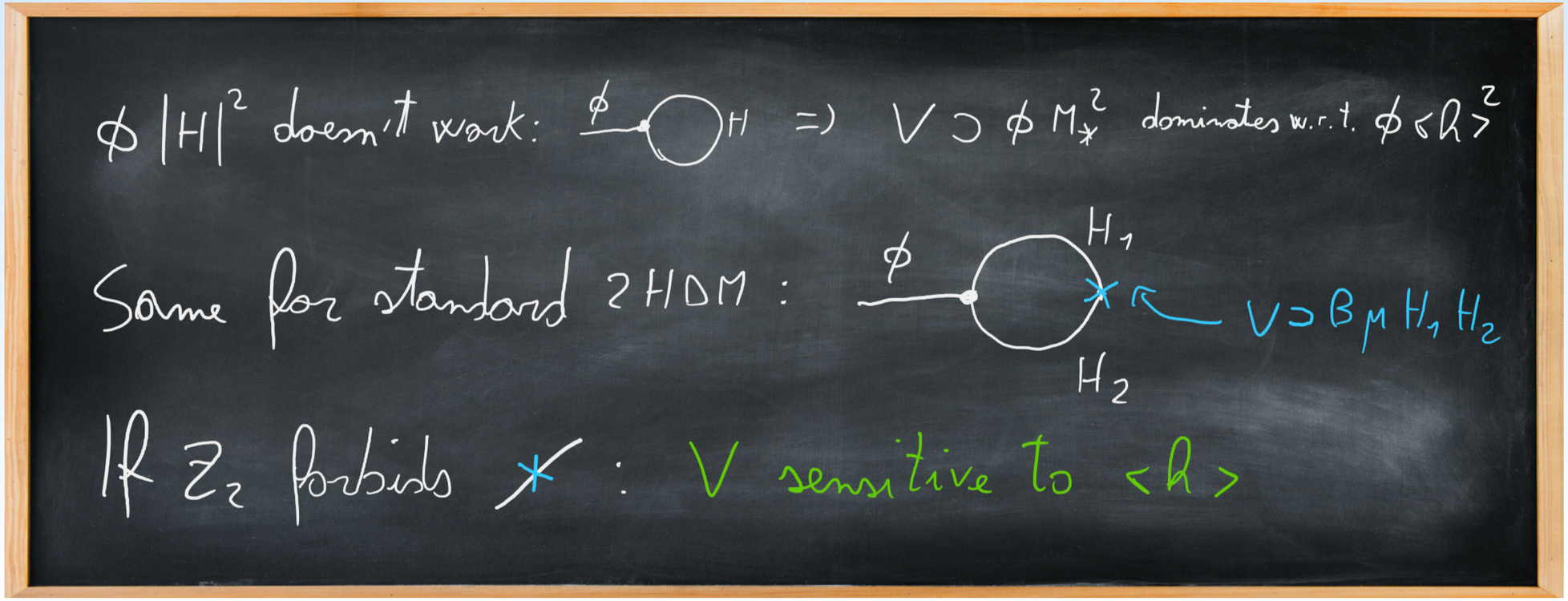
- $\phi_\pm$ coupled to any “trigger operator” $V \supset \phi_\pm \mathcal{O}(\langle h \rangle)$

The H_1H_2 trigger
just a few words

[Arkani-Hamed, D'Agnolo, Kim, '20]

marginally alive, fully tested at HL-LHC

2HDM becomes a trigger if a $\mathbb{Z}_2$ forbids "H_1H_2" operators $\longrightarrow$ $V \supset \kappa \phi_\pm H_1 H_2$ but $V \not\supset \kappa \phi_\pm \times \text{cutoff}^2$



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