Daniele Teresi

Sliding Naturalness

HiDDeN webinar, 30/11/21

Naturalness, 2021?

- 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, 2021?

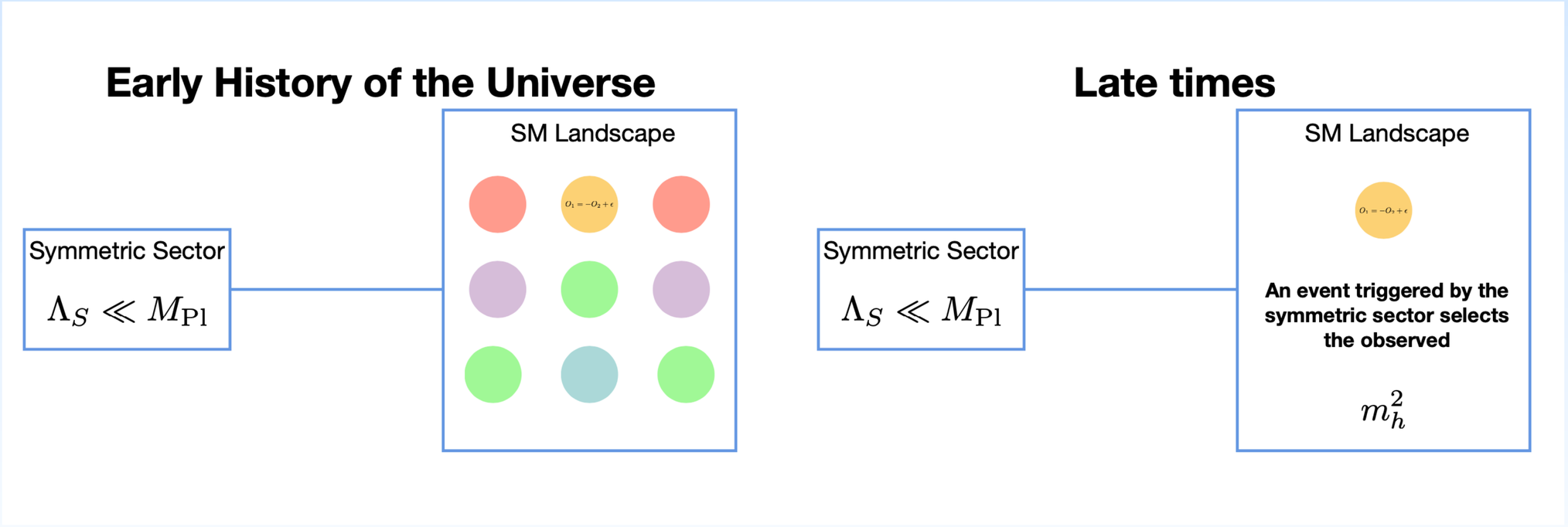
Essentially 3.5 possibilities:

- 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

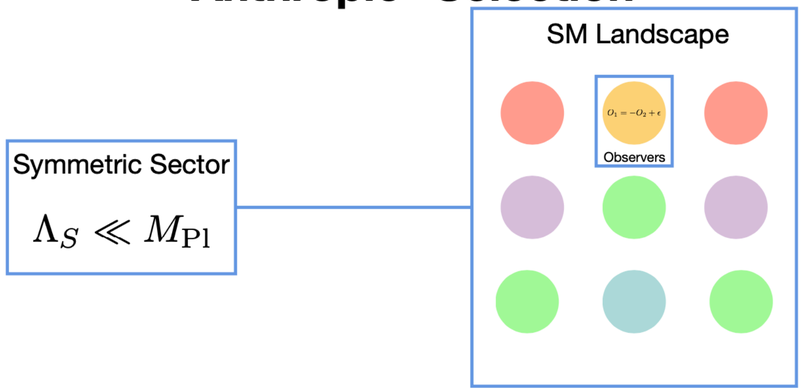
i.e. how cosmology can select a small Higgs mass



Cosmological Naturalness

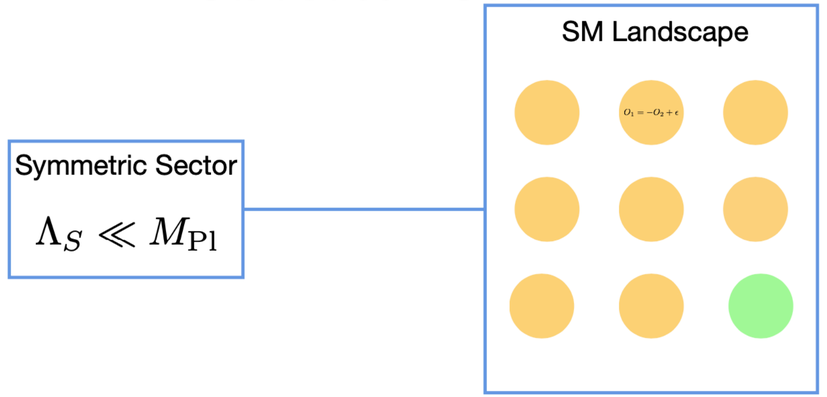
i.e. how cosmology can select a small Higgs mass

"Anthropic" Selection



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

"Statistical" Selection

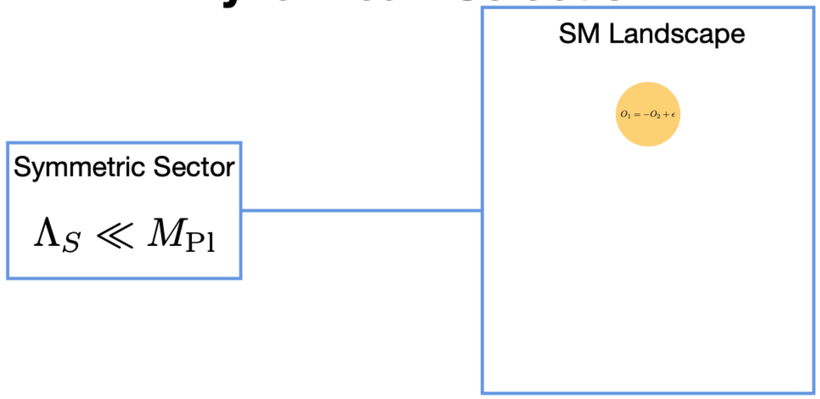


vacuum accumulation
[Dvali, Vilenkin]

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]

The ingredients of the game

general features of Cosmological Naturalness

- 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 [D'Agnolo, DT, 2109.13249]: NDA potential $V_\phi \sim m_\phi^2 M_*^2 \left(\frac{\phi}{M_*}\right)^n$ has to be affected by $V_{H\phi} \sim g^2 M_*^4 \left(\frac{\phi}{M_*}\right)^m \left(\frac{\langle h\rangle}{M_*}\right)^q \implies \boxed{m_\phi^2 \sim g^2 M_*^2 \left(\frac{v}{M_*}\right)^q}$

- 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!

Sliding Naturalness

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

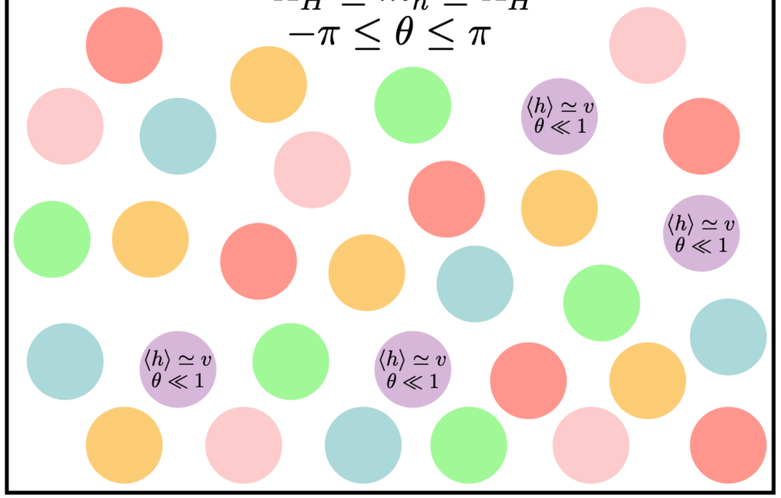
R. T. D'Agnolo, D. Teresi, 2106.04591 (accepted for PRL), 2109.13249

Sliding Naturalness

sketch of the mechanism

Landscape of Higgs mass, θ and CC values

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



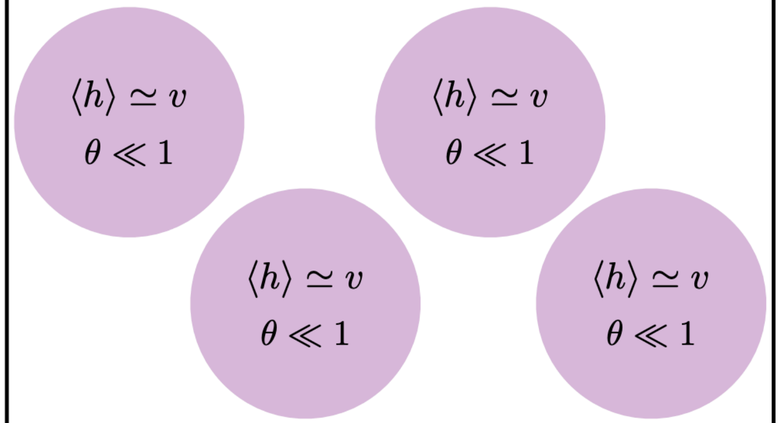
After reheating and a time

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

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:



Crunching solutions to the hierarchy problem

short history of last couple of years (apart from Covid19)

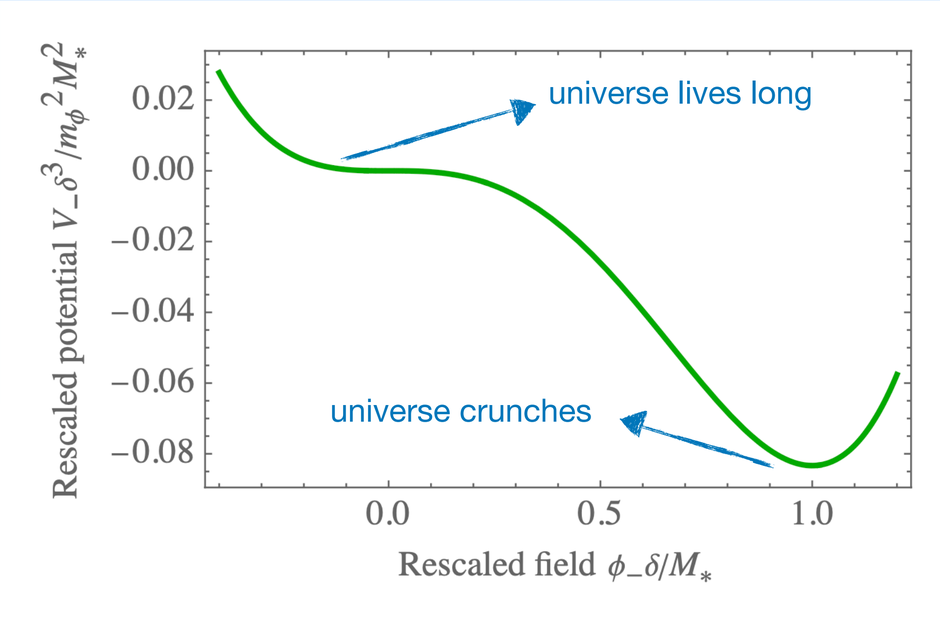
- Crunching “unwanted” patches first thought in the context of CC:
  [Bloch, Csáki, Geller, Volansky, 1912.08840]

- In the context of the hierarchy problem first appeared in
  Precarious Naturalness: [Strumia, DT, 2002.02463]

- Then, idea used in different mechanisms:
  - crunching dilaton [Csáki, D’Agnolo, Geller, Ismail, 2007.14396]
  - Sliding Naturalness [D’Agnolo, DT, 2106.04591, 2109.13249]

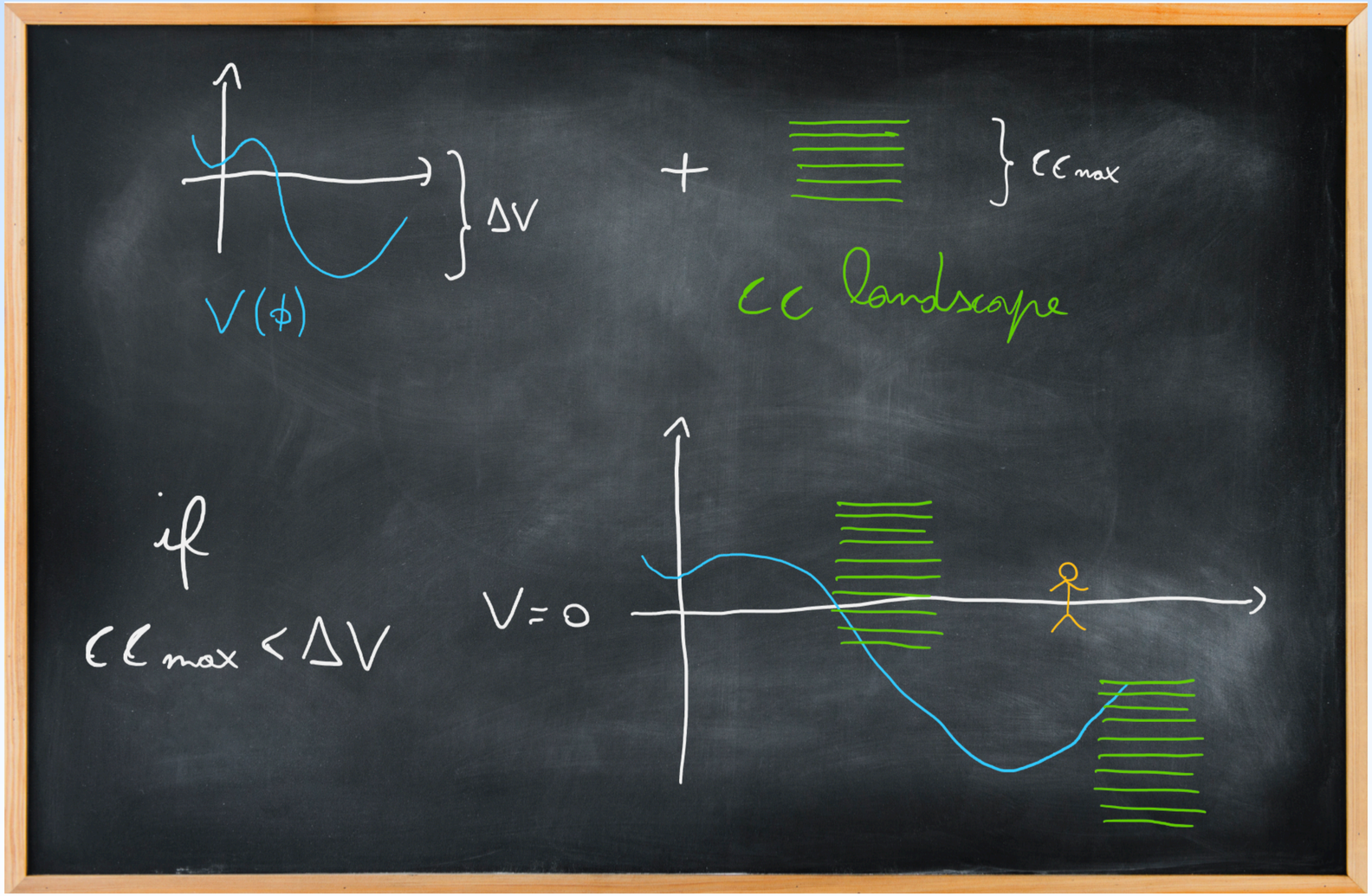
Sliding Naturalness

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 $V \approx 0$

The global minimum crunches



Sliding Naturalness

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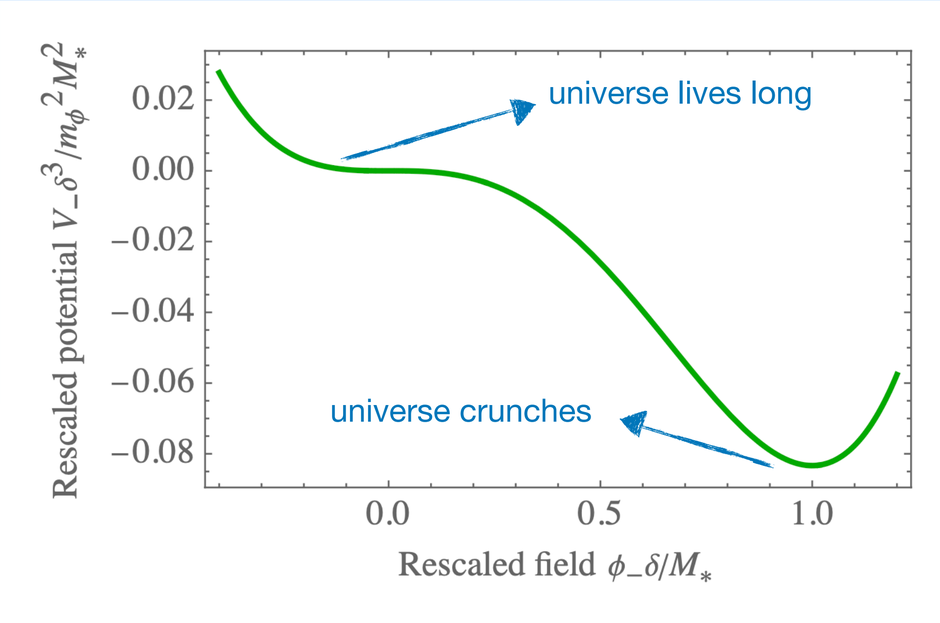

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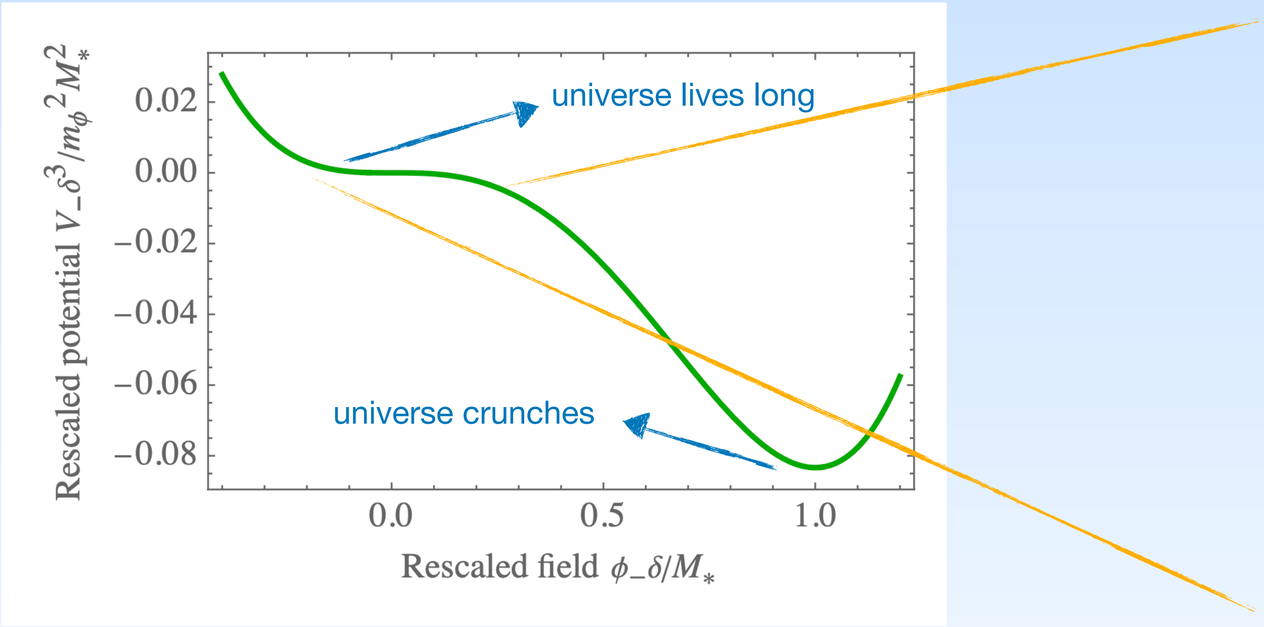
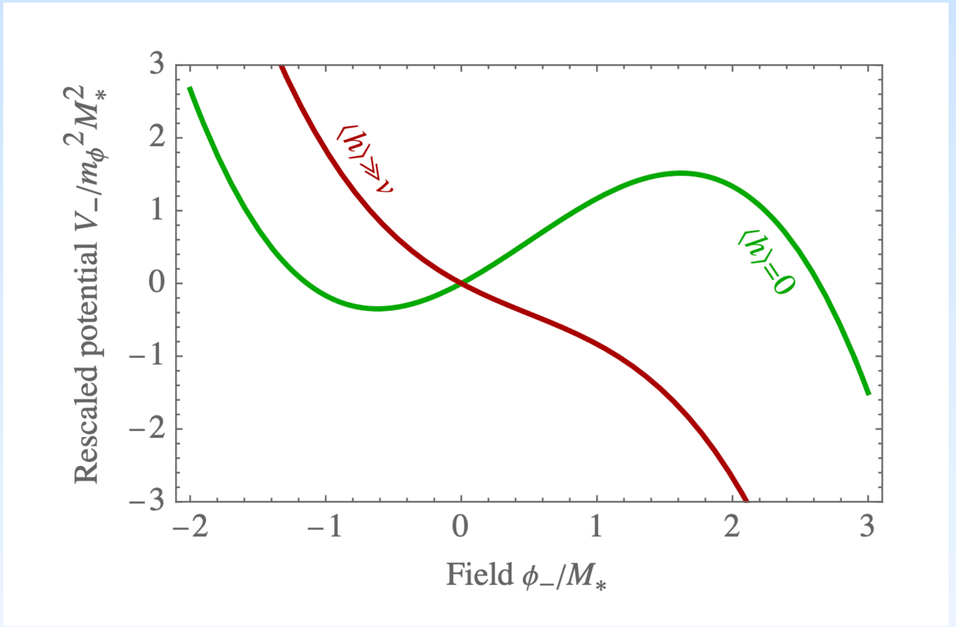
Sliding Naturalness

Two Scalars to Rule Them All

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





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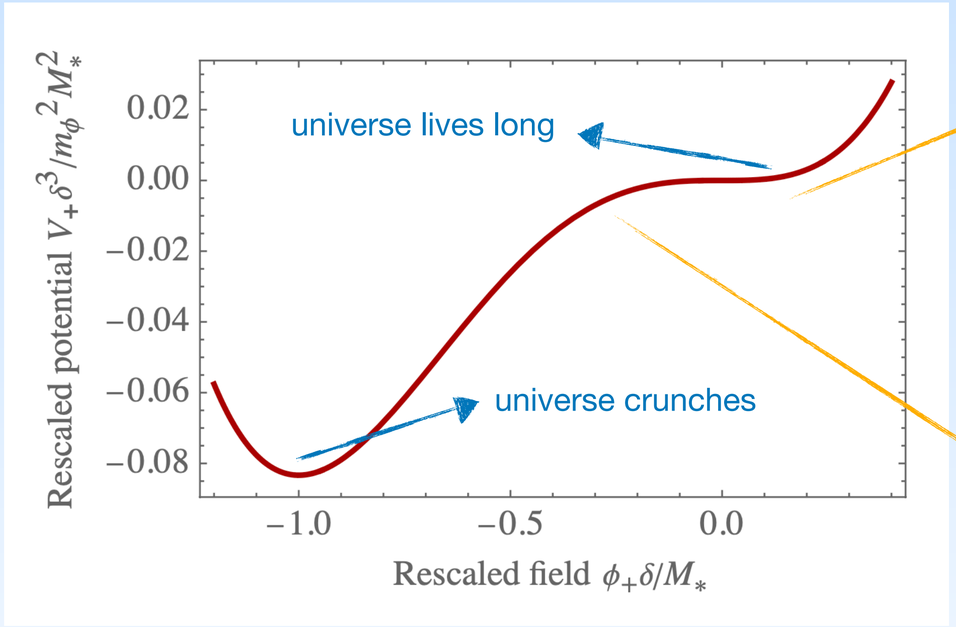
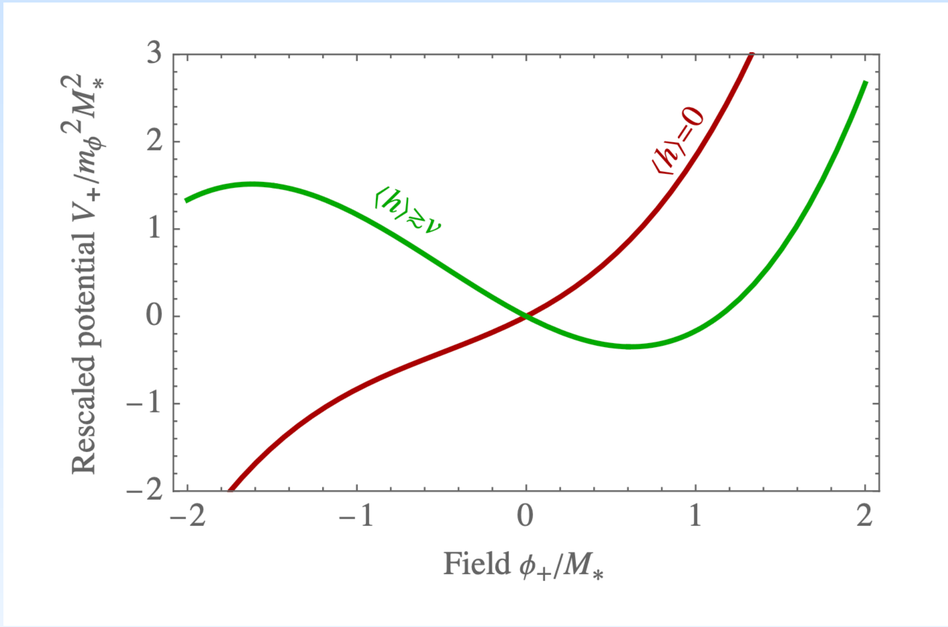
Sliding Naturalness

Two Scalars to Rule Them All

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





- At global minimum $V \sim -M_*^4$ too big to be compensated by a CC in the landscape
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Sliding Naturalness

Two Scalars to Rule Them All

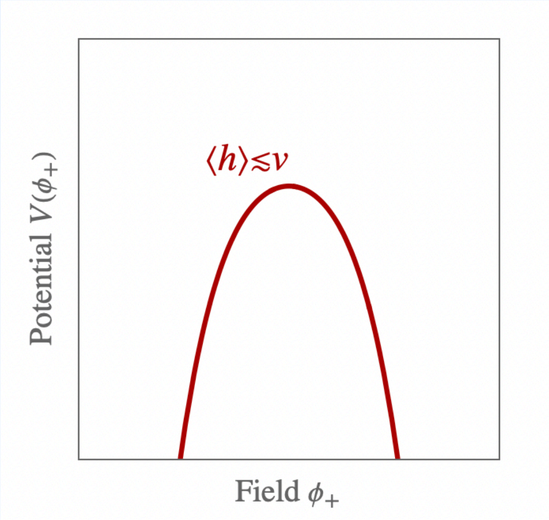
the only universes that live long
are those where

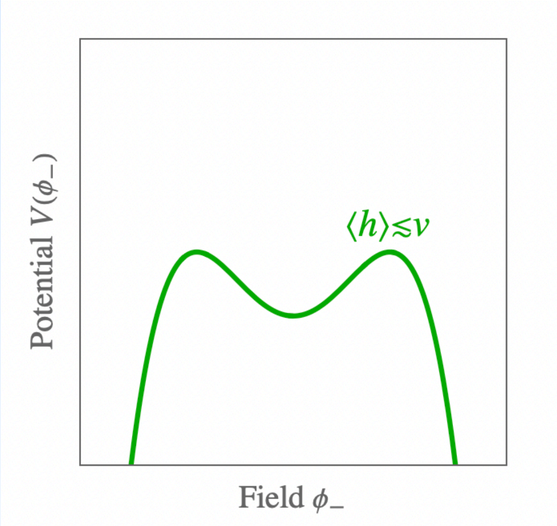
$$v \lesssim \langle h \rangle \lesssim v$$

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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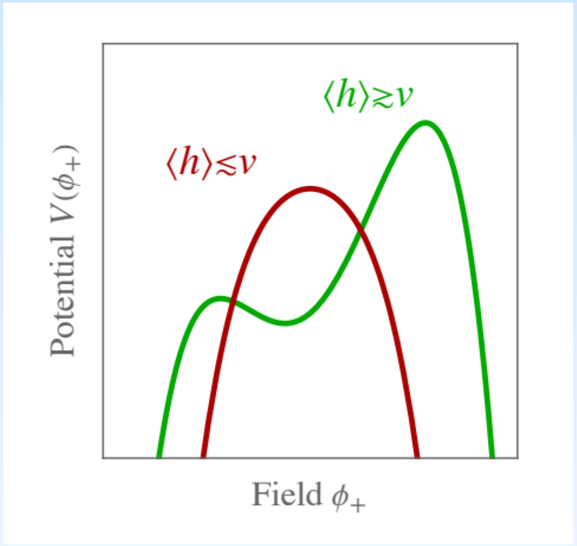
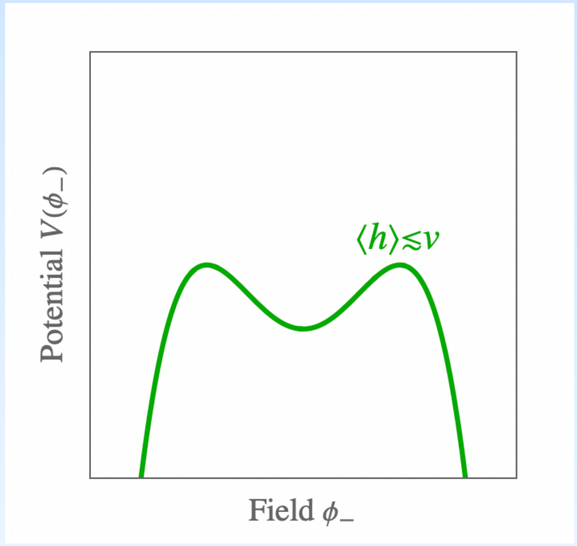




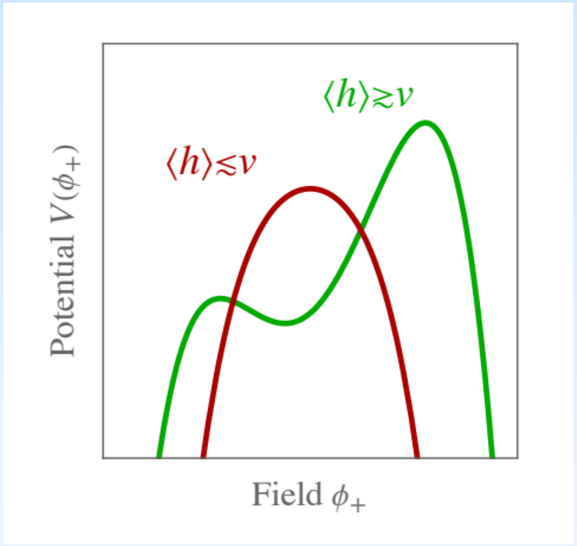
$$V_{\phi H} = -\frac{\alpha_s}{8\pi}\left(\frac{\phi_+}{F_+} + \frac{\phi_-}{F_-} + \theta\right) G\tilde{G}$$

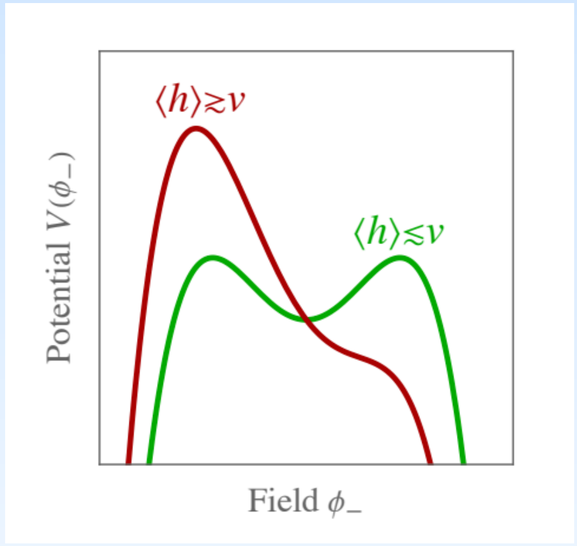
$$\longrightarrow -m_\pi^2 f_\pi^2 \cos(\ldots)$$

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

The Lagrangian

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





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

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

this selects a small and non-zero EW scale:

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

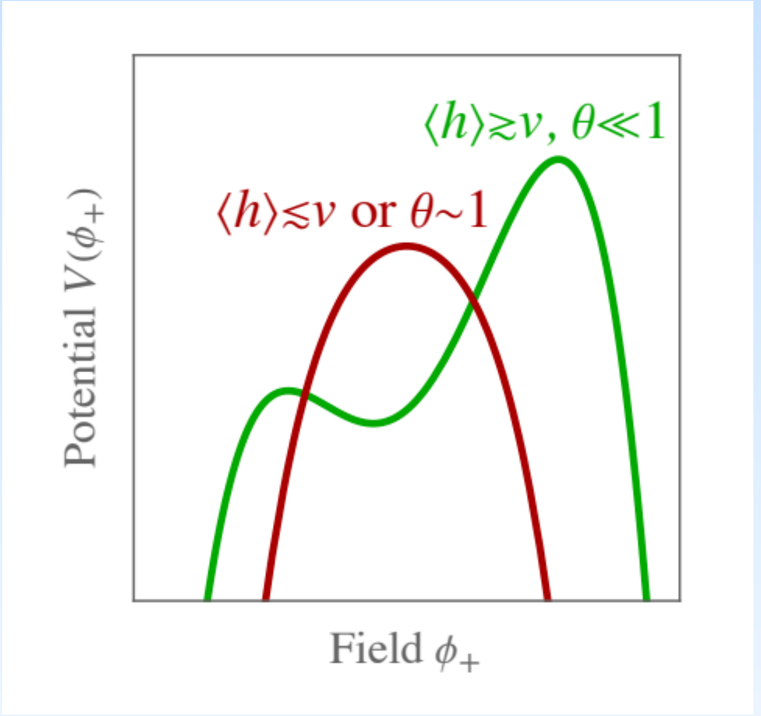
A novel solution to the strong-CP problem

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

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

not sensitive to initial conditions
(unlike misalignment mechanism)

- relic density from oscillations due to kick at $t_{\rm QCD}$:

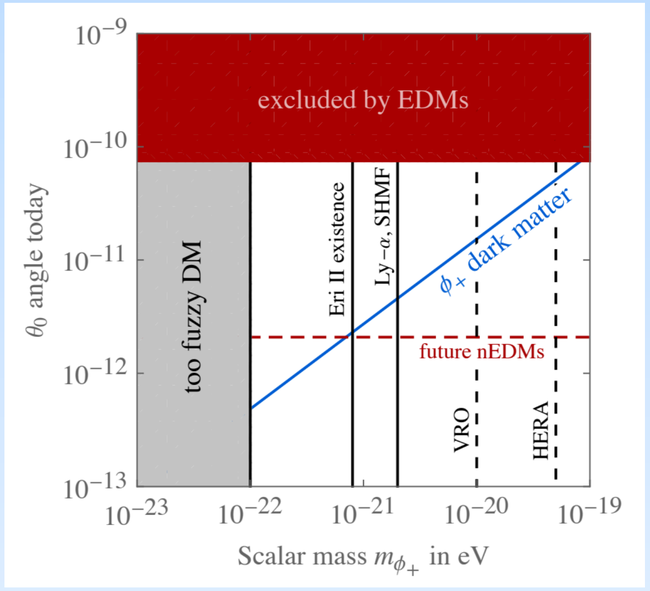
for instance: $$\frac{\rho_{\phi_+}}{\rho_{\rm DM}} \simeq \frac{\theta_0^2 \Lambda_{\rm QCD}^4}{T_{\rm eq} M_{\rm Pl}^{3/2} m_{\phi_+}^{3/2}} \simeq \left(\frac{\theta_0}{10^{-10}}\right)^2 \left(\frac{10^{-19}\ {\rm eV}}{m_{\phi_+}}\right)^{3/2}$$

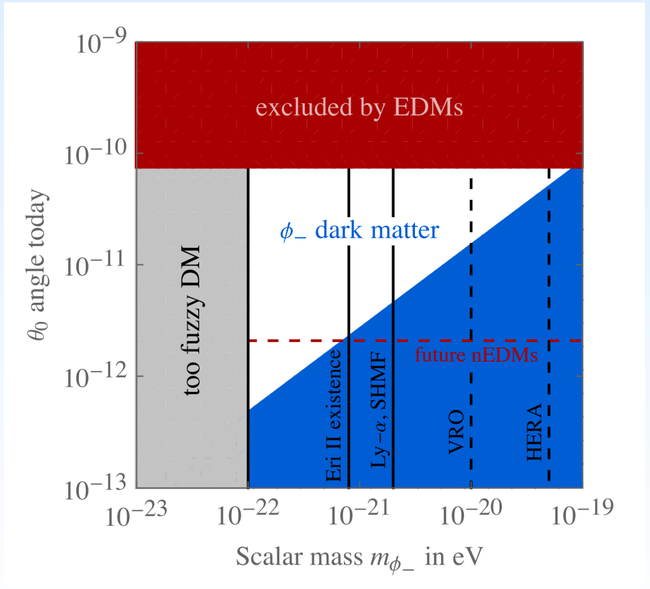
Smoking-gun pattern

- 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 $M_-/F_- \lesssim M_+/F_+ \sim \theta$

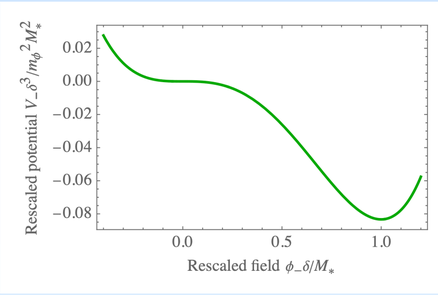
- if DM, smoking-gun relation with EDM





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!)

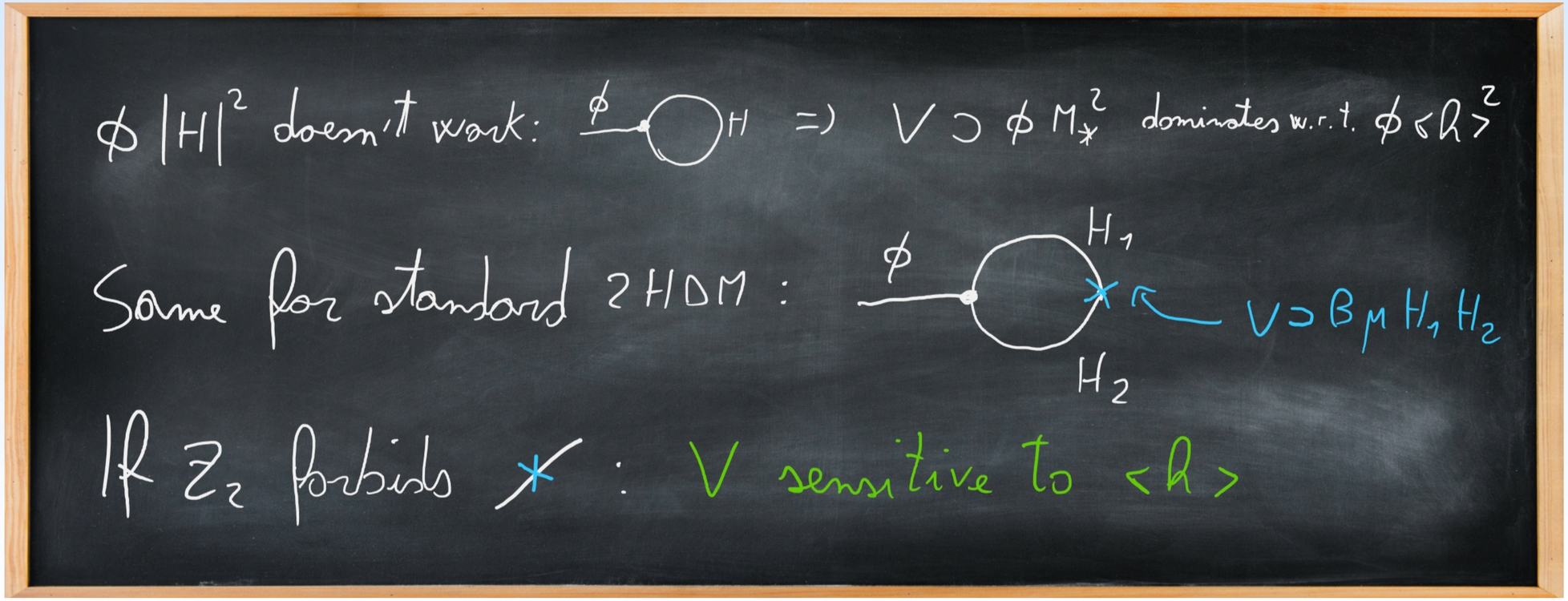
- $\phi_\pm$ coupled to any “trigger operator” $V \supset \phi_\pm \mathcal{O}(\langle h \rangle)$

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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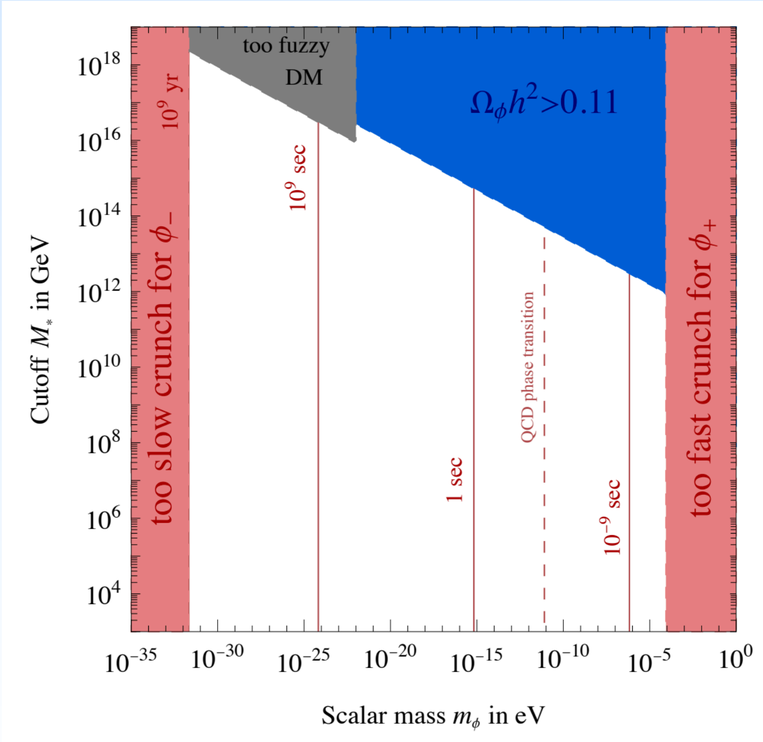

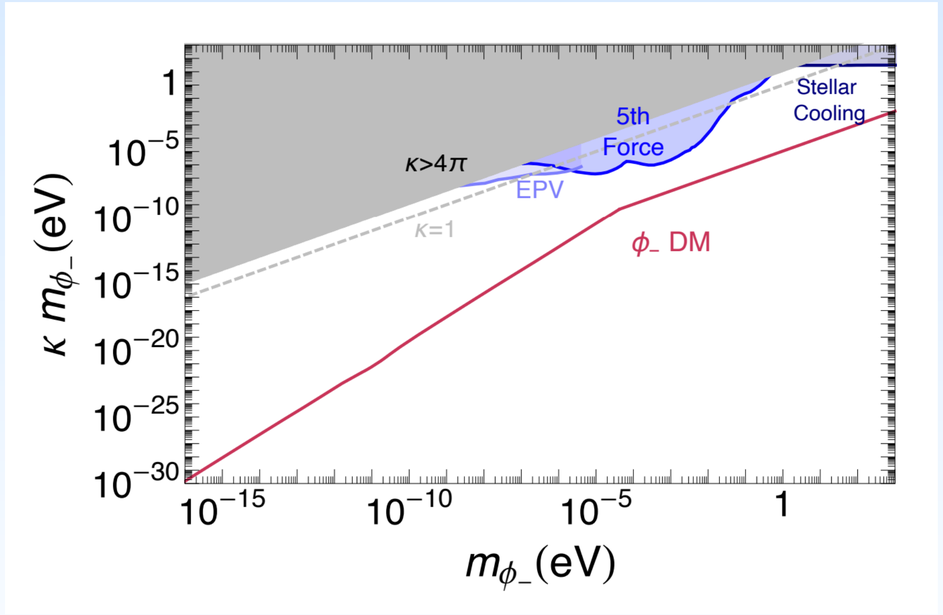

Virtues of the mechanism

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…)
- it can explain $v = 246\,\text{GeV}$ even if Higgs coupled at $\mathcal{O}(1)$ with particles at M_{Pl}
- it is not 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.