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Cosmological Approaches to the Higgs Hierarchy Problem

22nd PANIC 2021 - Lisbon, on zoom - 08/09/21

Naturalness, 2021?

(ideas stolen from G. Giudice, *The Dawn of the Post-Naturalness Era*, 2017; R. Rattazzi, *BSM for Millennials*, 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
- LHC has basically made 2.5 discoveries:
 - A. Higgs boson
 - B. unnaturalness of m_{Higgs}
 - C. quasi-criticality (if SM extrapolated)

Naturalness, 2021?

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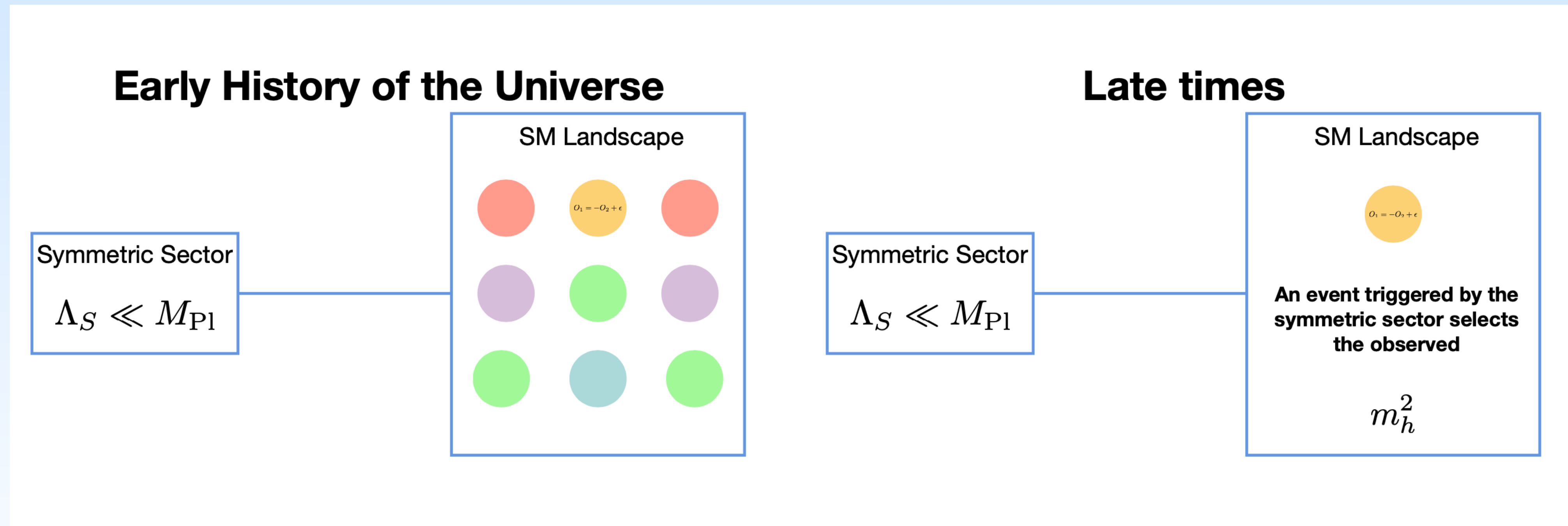
Essentially 3.5 possibilities:

- LHC will soon discover new physics related to m_{Higgs} (partial solution/non-solution)
- epicycles of low-scale SUSY or compositeness
- new frameworks in which m_{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.XXXXX](#)]

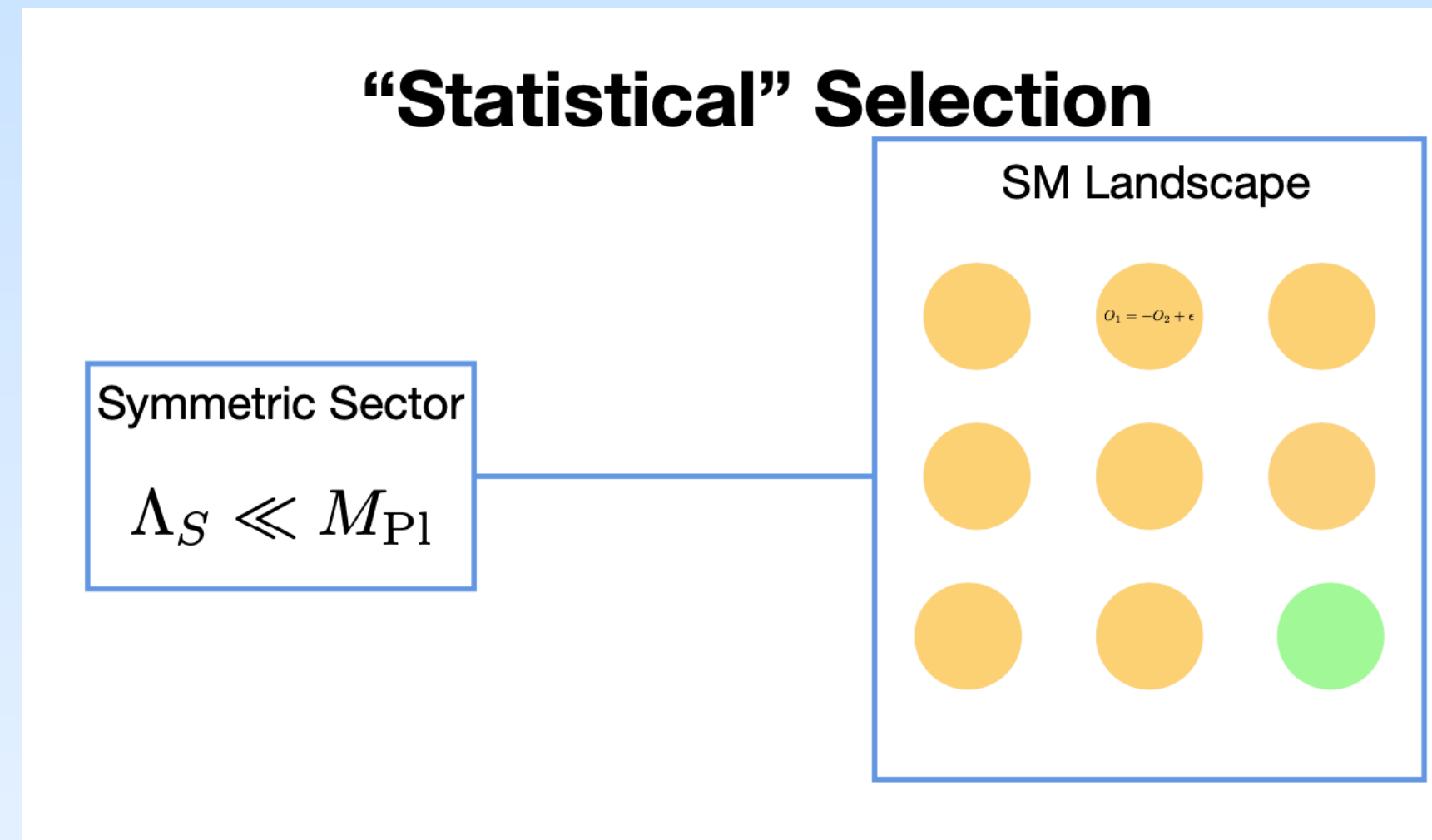
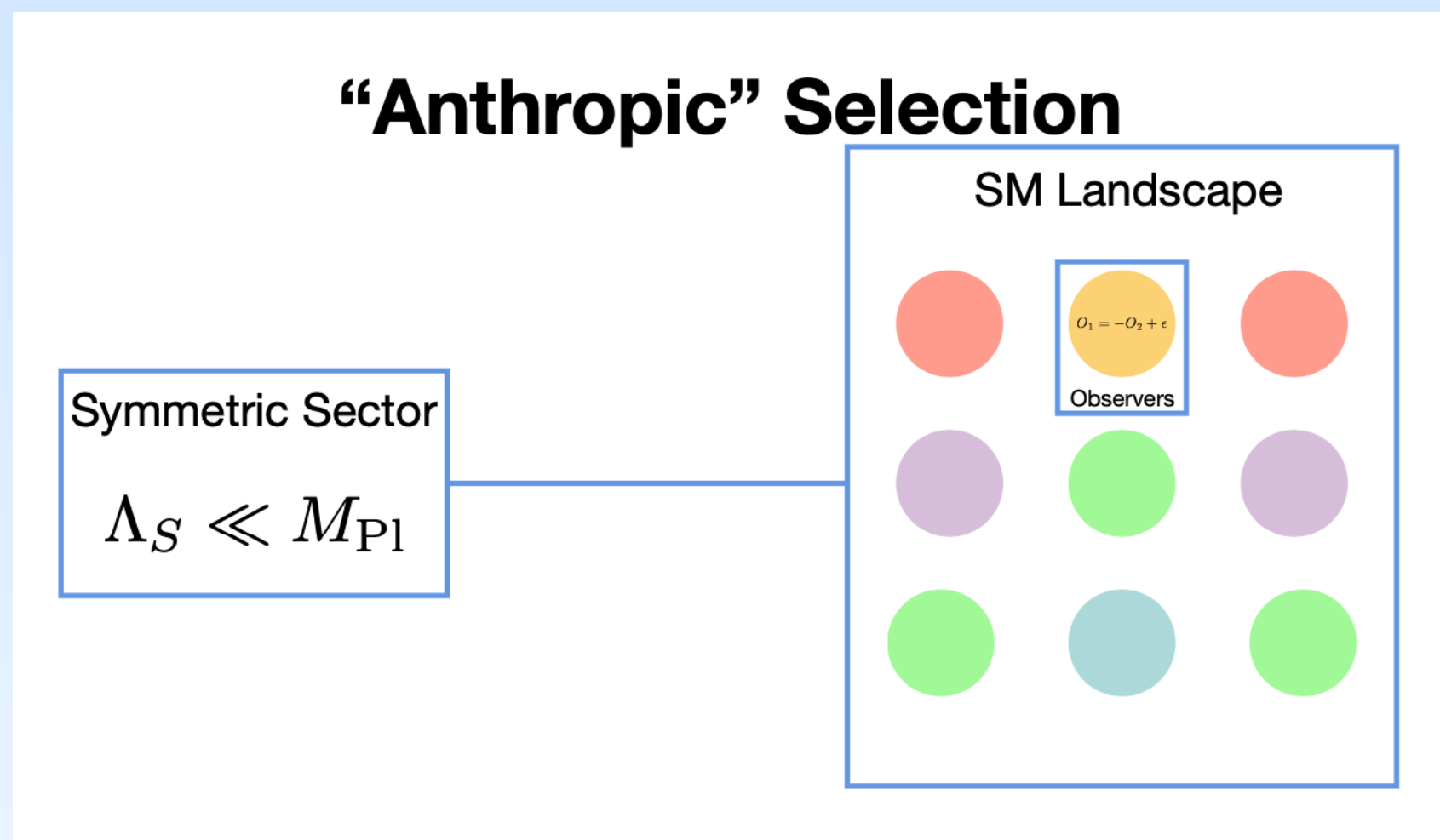
Cosmological Naturalness

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

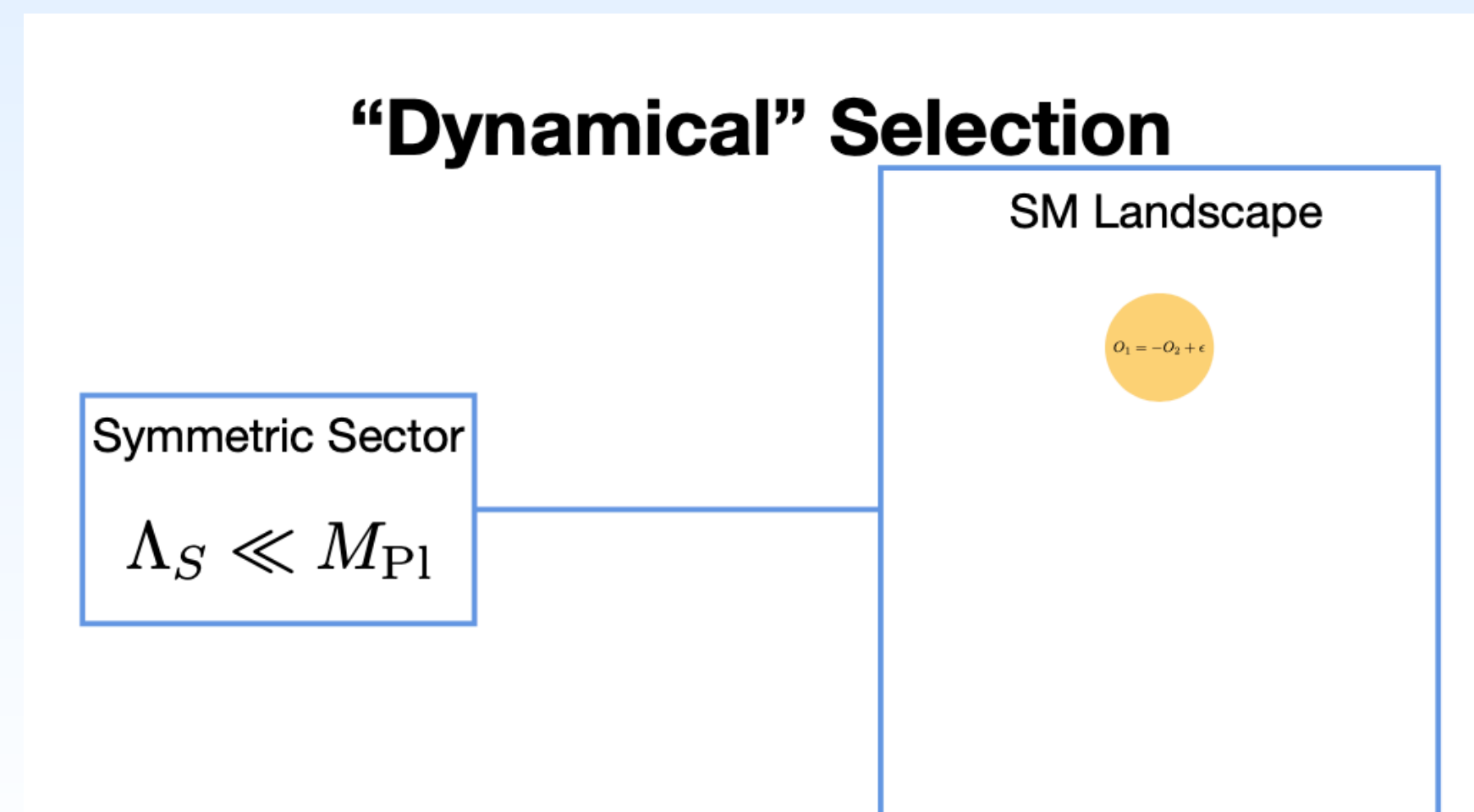


Cosmological Naturalness

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



- vacuum accumulation [Dvali, Vilenkin]
- light Higgs inflates most [Geller, Hochberg, Kuflik; Cheung, Saraswat]
- Self-Organized Localization [Giudice, McCullough, You]



- Precarious Naturalness [Strumia, DT]
- crunching dilaton [Csáki, D’Agnolo, Geller, Ismail]
- Sliding Naturalness** [D’Agnolo, DT, 2106.04591, 2109.XXXXX]

relaxion [Graham, Kaplan, Rajendran]

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

Selfish Higgs [Giudice, Kehagias, Riotto]

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.XXXXX]: NDA potential $V_\phi \sim m_\phi^2 M_*^2 \left(\frac{\phi}{M_*}\right)^n$ has to be

affected by $V_{H\phi} \sim g^2 M_*^4 \left(\frac{\phi}{M_*}\right)^m \left(\frac{\langle h \rangle}{M_*}\right)^q \implies m_\phi^2 \sim g^2 M_*^2 \left(\frac{v}{M_*}\right)^q$

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

Pheno signatures!

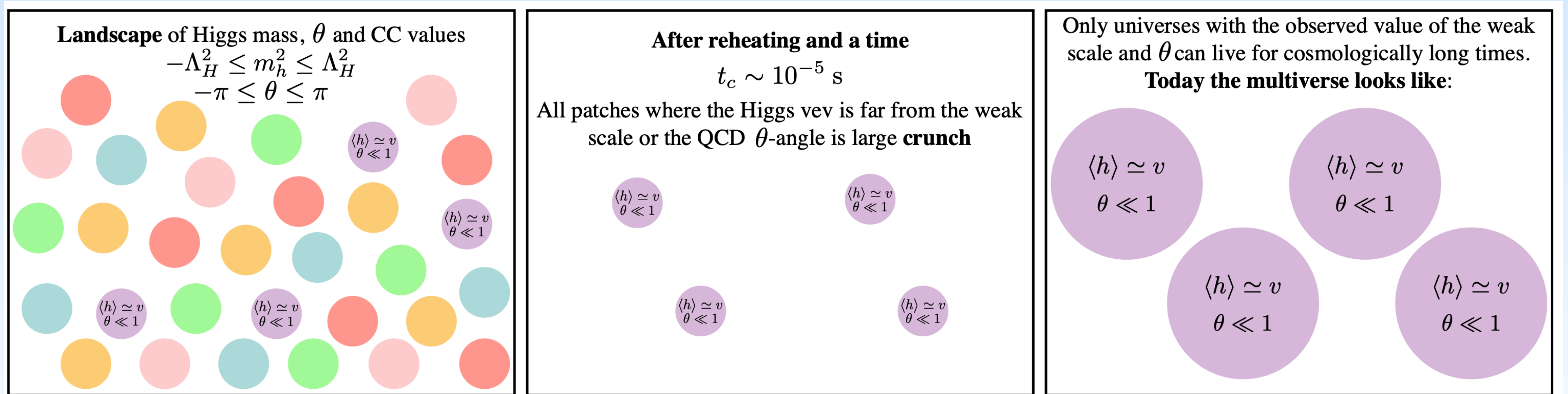
Sliding Naturalness

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

R. T. D'Agnolo, D. Teresi, "Sliding Naturalness", 2106.04591

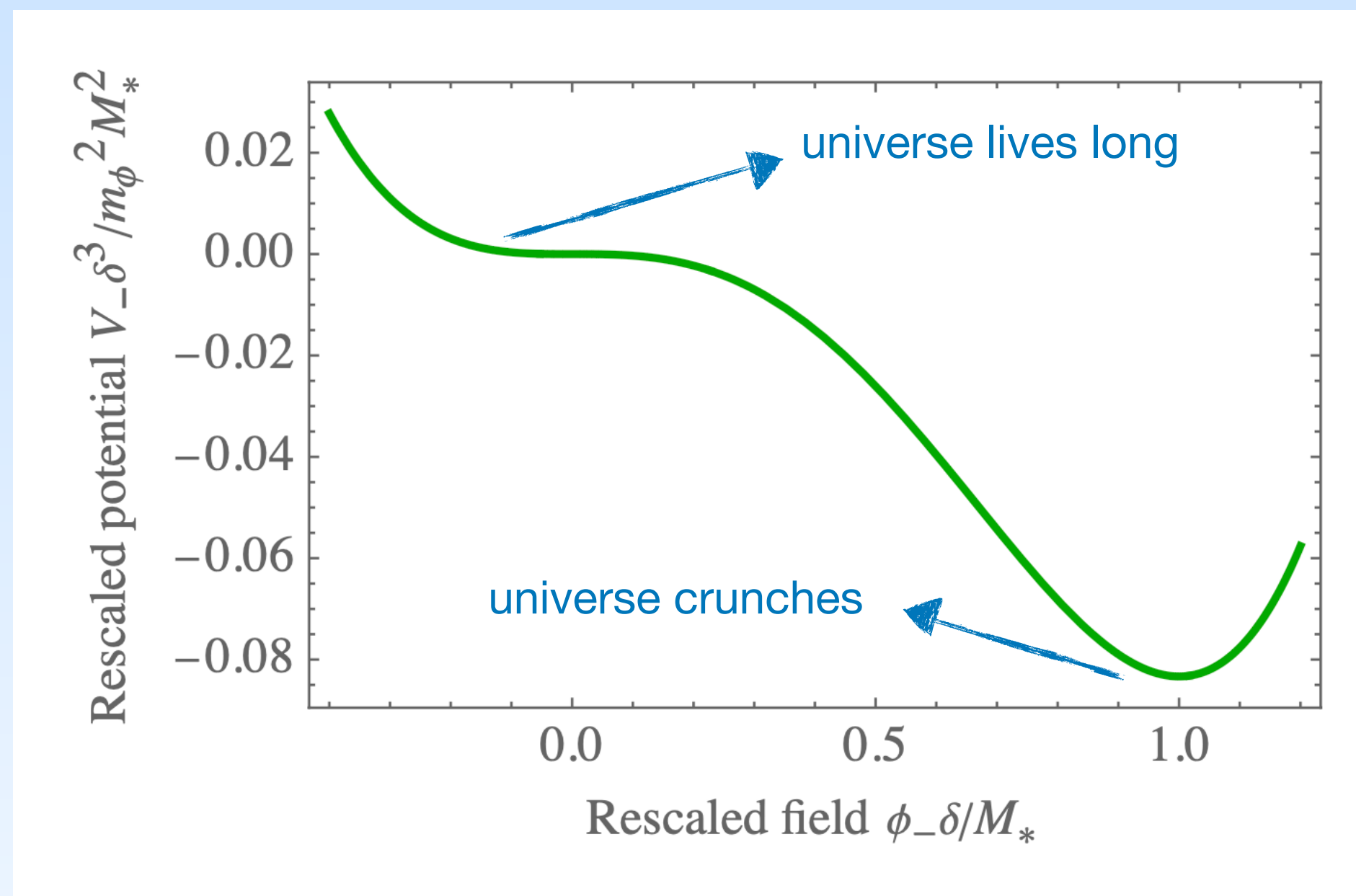
Sliding Naturalness

sketch of the mechanism



Sliding Naturalness

Two Scalars to Rule Them All

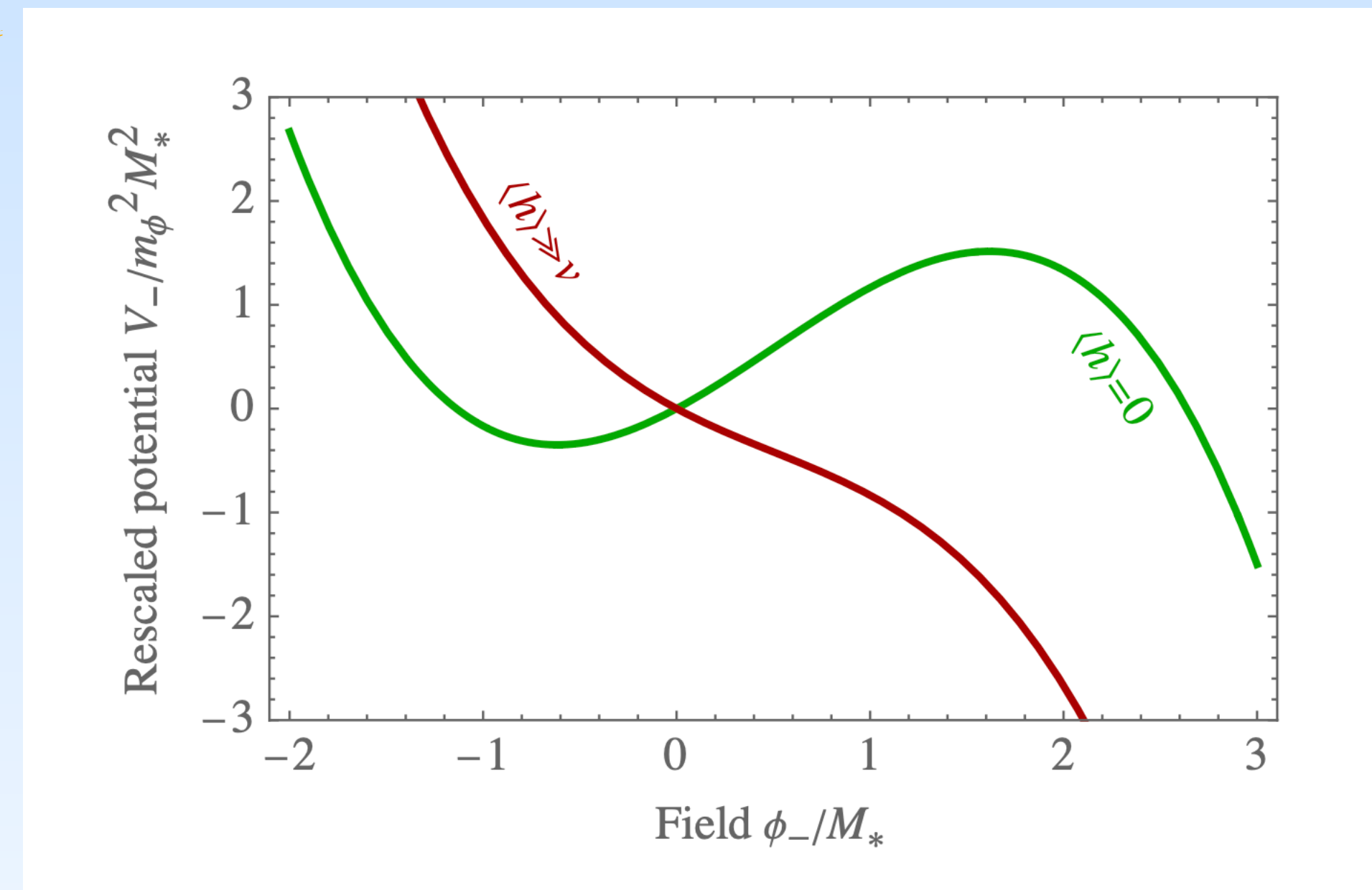
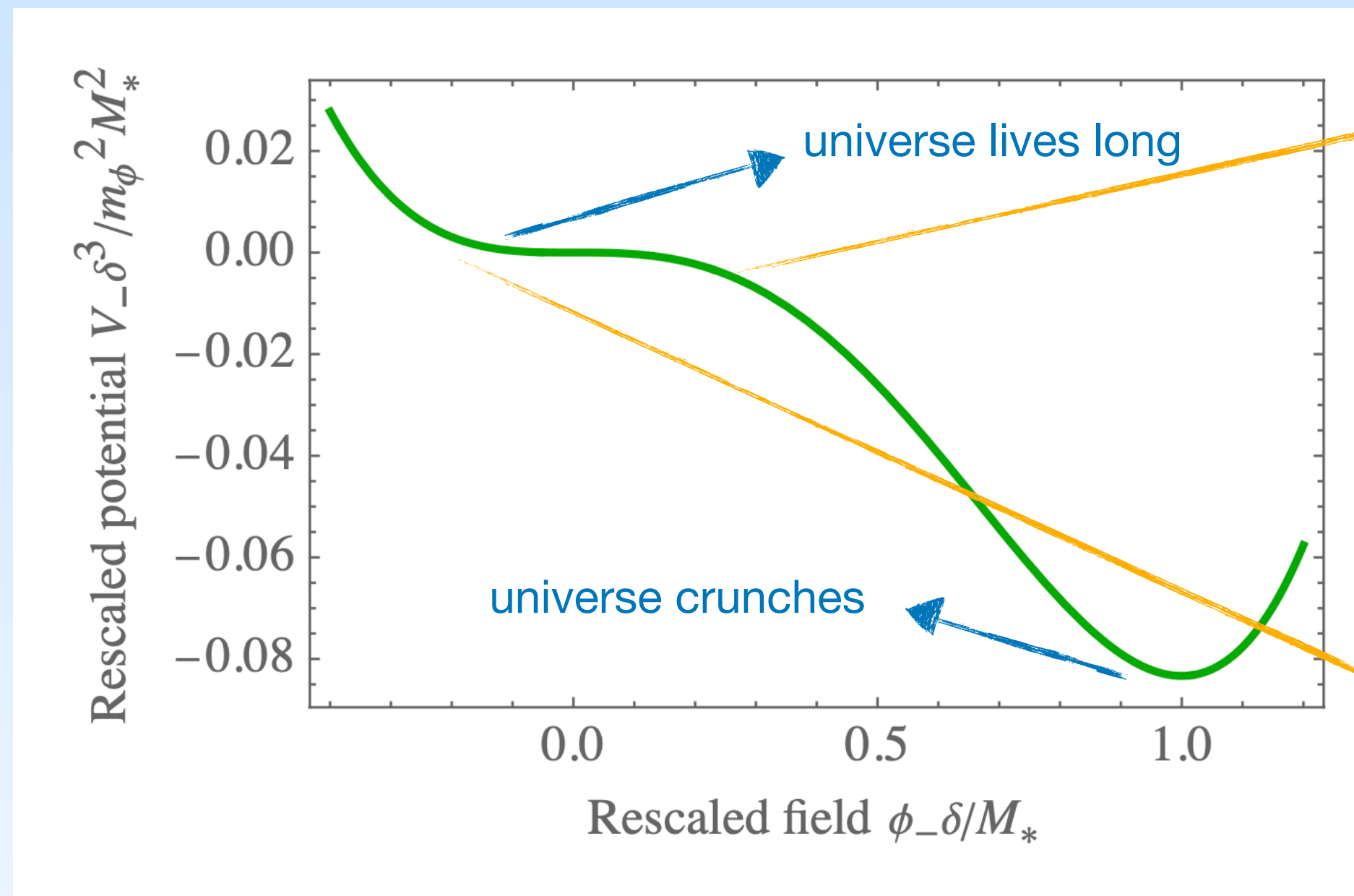


- At global minimum $V \sim -M_*^4$ too big to be compensated by a CC in the landscape
- At local minimum CC in the landscape can be tuned $V \approx 0$

Sliding Naturalness

Two Scalars to Rule Them All

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

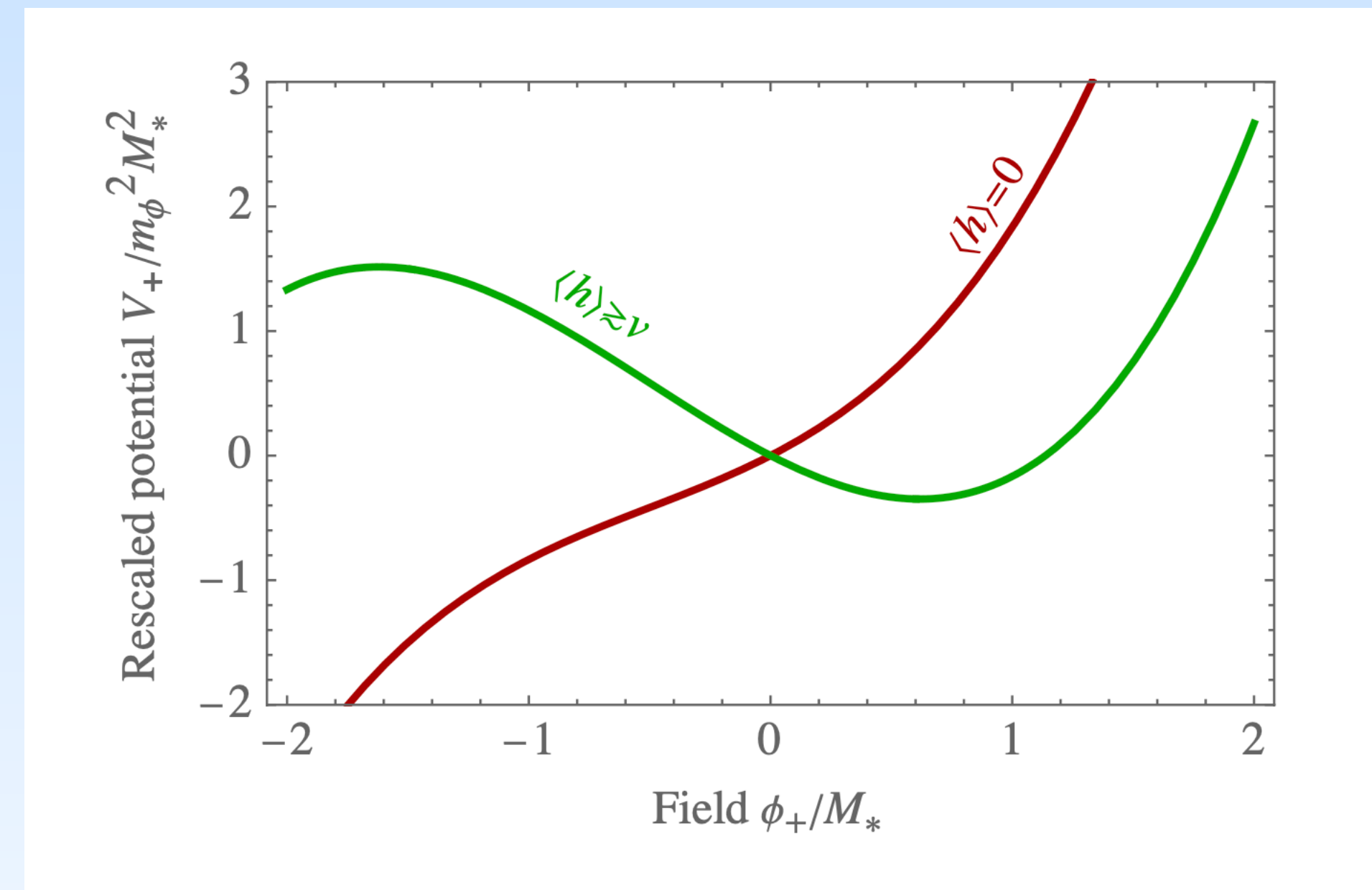
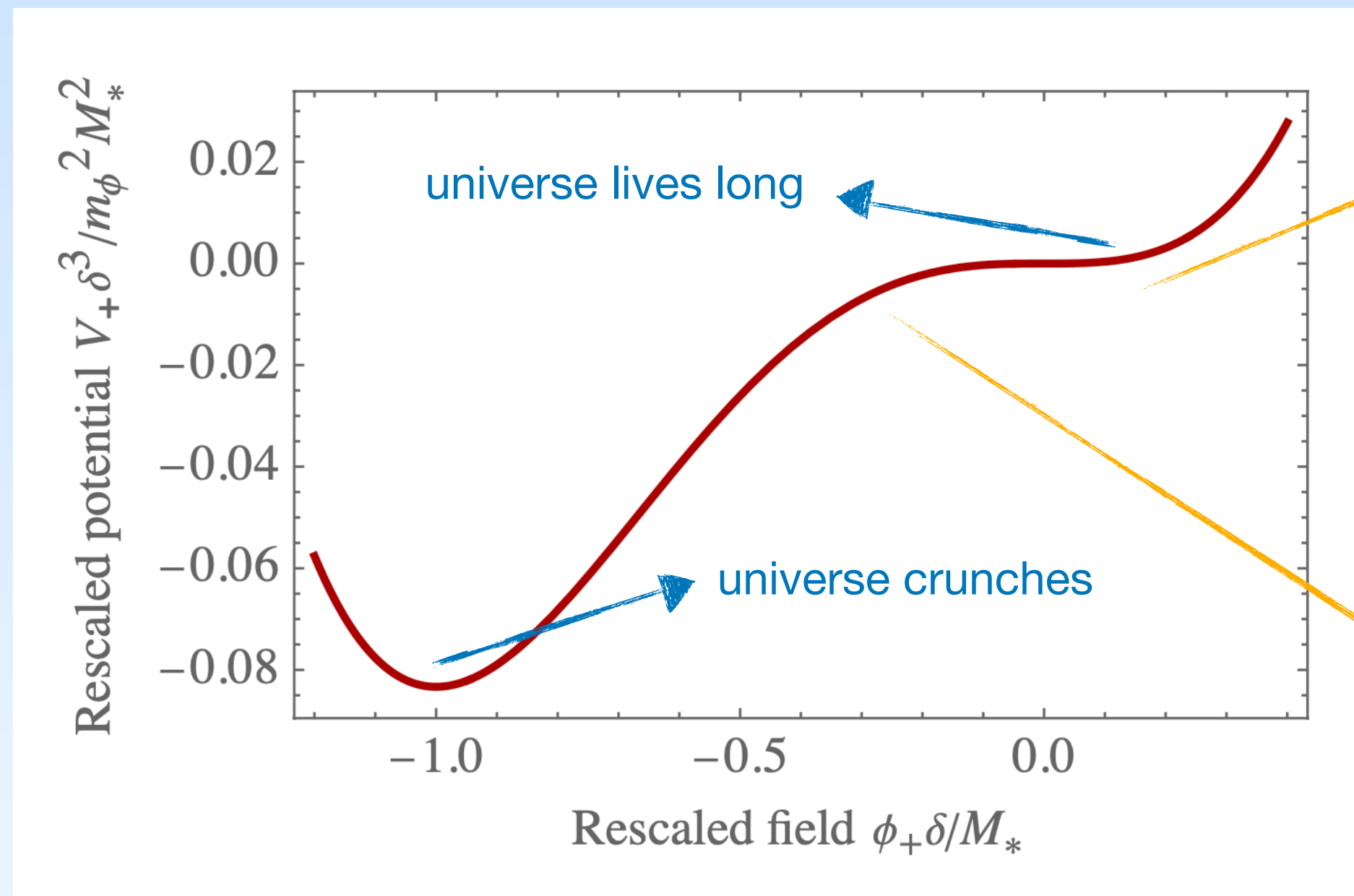


- At global minimum $V \sim -M_*^4$ too big to be compensated by a CC in the landscape
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Sliding Naturalness

Two Scalars to Rule Them All

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

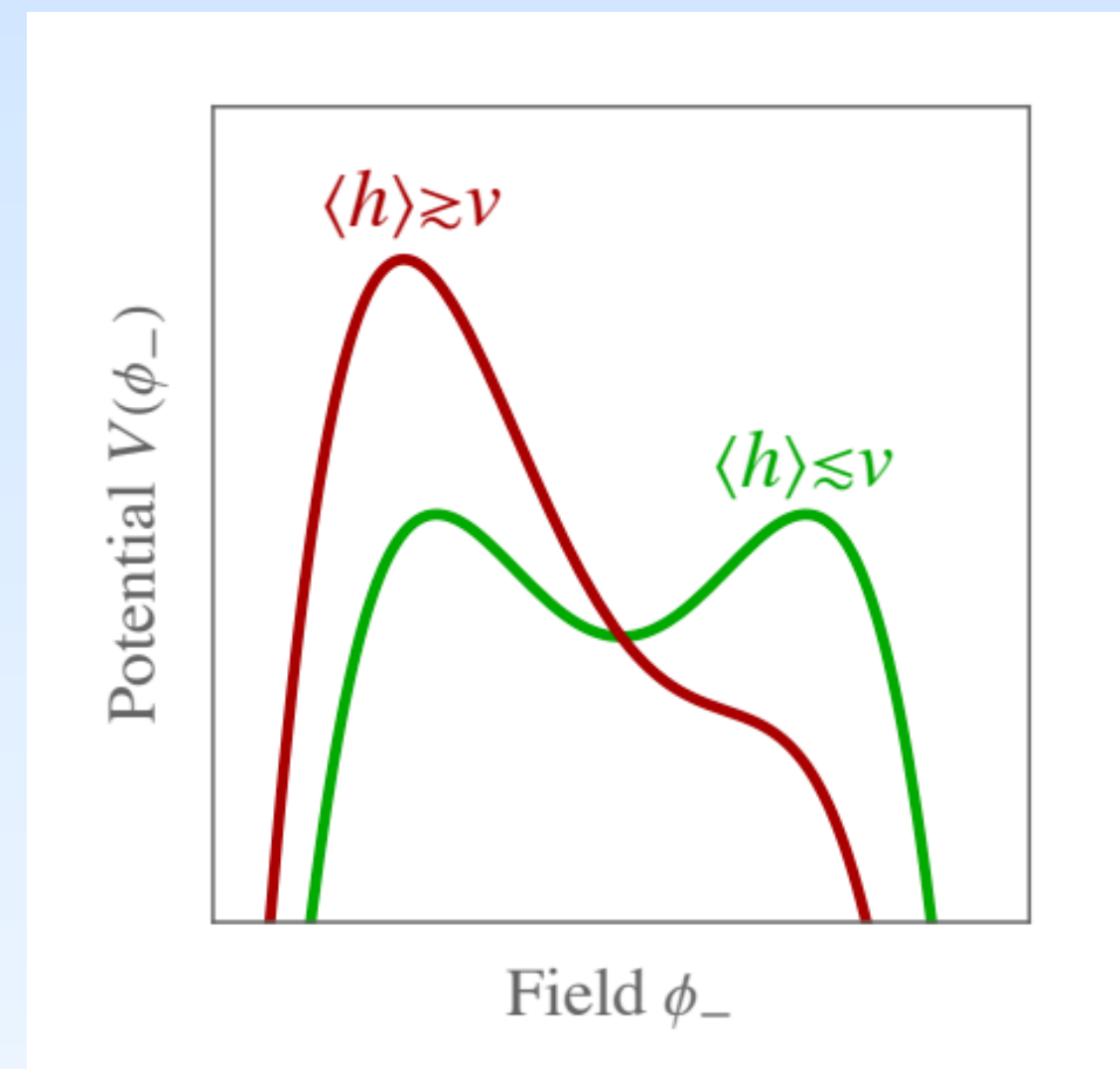
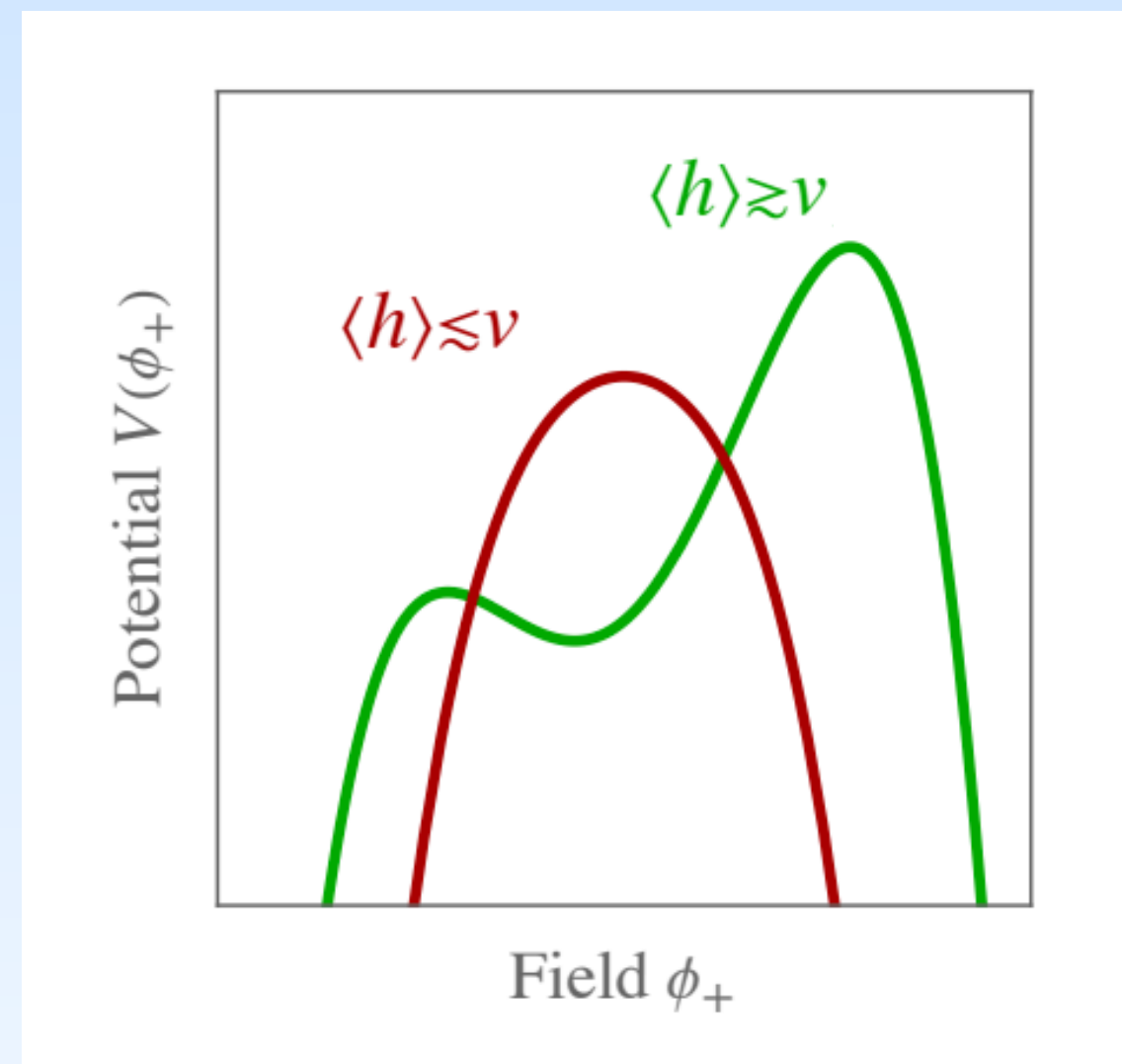
the only universes that live long
are those where

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

The Lagrangian

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

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



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

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

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

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

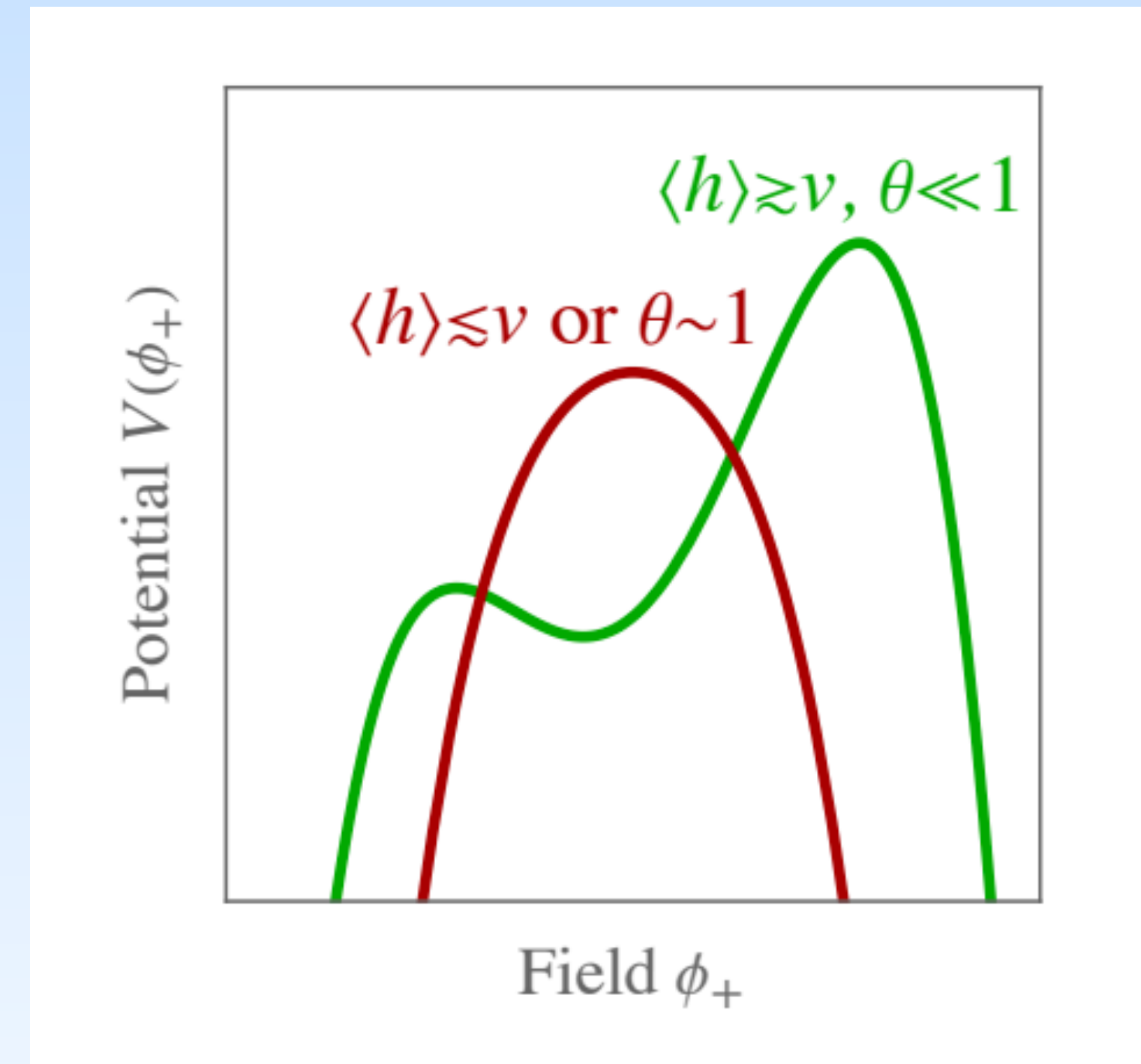
$$V_{\phi H} \sim \frac{\Lambda(\langle h \rangle)^4}{2} \left(\frac{\phi_+}{F_+} + \frac{\phi_-}{F_-} + \theta \right)^2$$

θ shifts stabilizing effect for ϕ_+

metastable minimum possible only if $\theta \ll 1$
(otherwise negative quartic wins)

the same dynamics selects jointly:

$$v \lesssim \langle h \rangle \lesssim v \quad \text{and} \quad \theta \ll 1$$



Dark matter

- “wrong” universes crunch in $t \sim 1/m_{\pm}$
- $m_{+} \lesssim 1/t_{\text{QCD}} \sim 10^{-11}$ 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
- scenario: ϕ_{+} dark matter
- relic density from oscillations due to kick at t_{QCD} :

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

Smoking-gun pattern

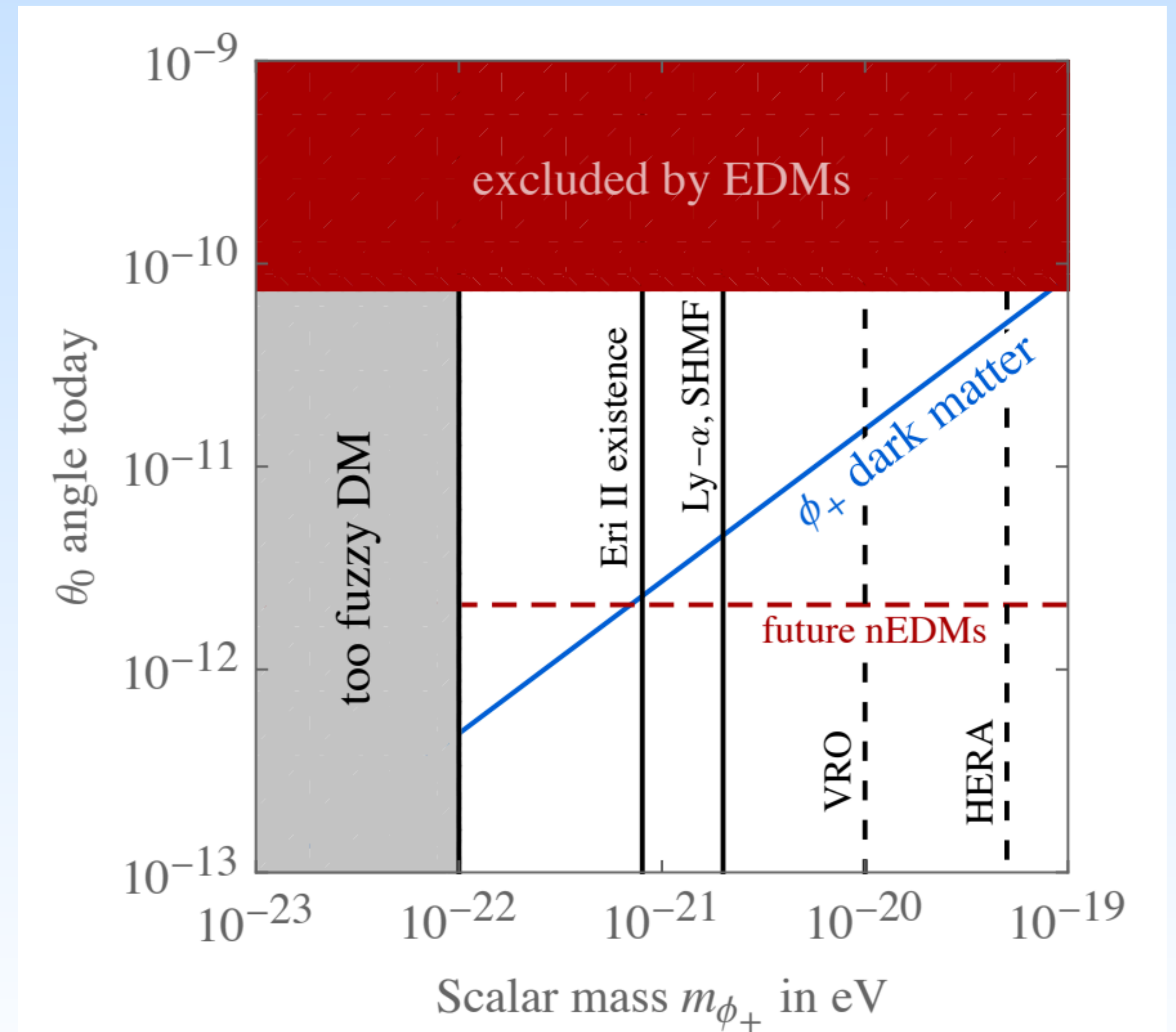
- ϕ_+ is a light scalar $m_{\phi_+} \lesssim 10^{-11}$ eV
with mass-couplings on the QCD line:

$$m_{\phi_+}^2 \sim \frac{\Lambda_{\text{QCD}}^4}{F_+^2}$$

- if DM, smoking-gun relation with EDM

- ϕ_- can be heavier, with mass larger than the QCD line:

$$m_{\phi_-}^2 \sim \theta \frac{\Lambda_{\text{QCD}}^4}{F_- M_-} \gtrsim \frac{\Lambda_{\text{QCD}}^4}{F_-^2} \quad \text{since } M_-/F_- \lesssim M_+/F_+ \sim \theta$$



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.