Sliding Naturalness

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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Motivation and summary

- m_h^2, θ_{QCD} and Λ_{CC} are much smaller than their expected value.
- Novel framework to simultaneously explain the small values of m_h^2 and θ_{QCD} via dynamical selection in the early Universe.
- It gives two ALPs in the low-energy spectrum, one of them might be DM.
- Compatible with any inflation mechanism and with swampland conjectures.

Basic Idea

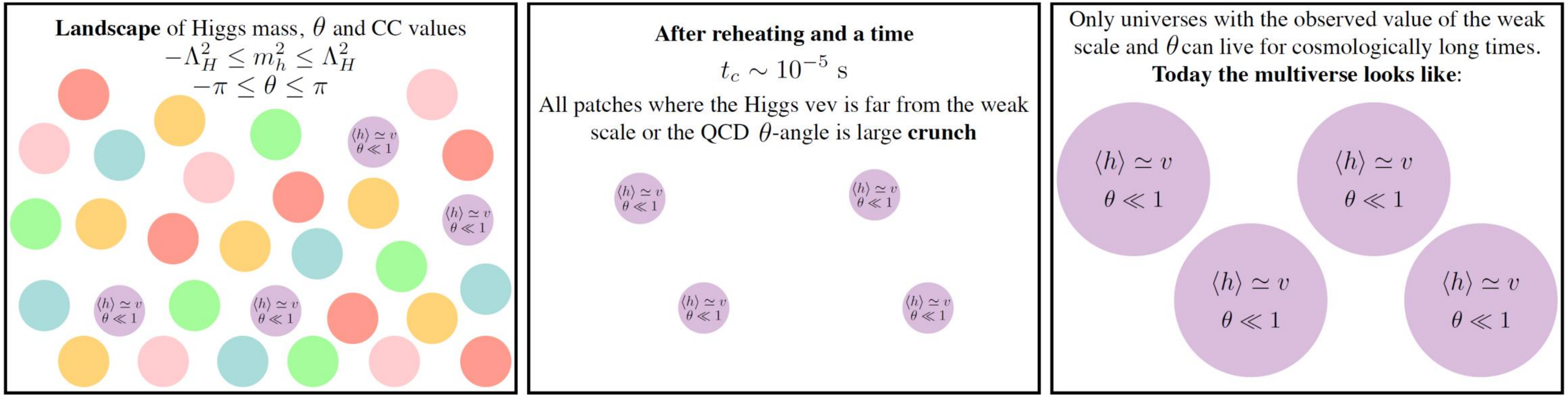


FIG. 1. Cartoon of the basic mechanism: a landscape of Higgs masses and QCD θ-angles is populated early in the history of the Universe. All patches with Higgs vev and θ far from the observed ones crunch after the QCD phase transition. The only universes that survive until today and grow to cosmological sizes are those with $\langle h \rangle \simeq v$ and $\theta \lesssim 10^{-10}$.

$$-\Lambda_{max}^4 \leqslant \Lambda_{CC}^4 \leqslant \Lambda_{max}^4 \qquad \Lambda_{max}^4 \sim \Lambda_H^4 \sim M_{Pl}^4$$

Assumptions

$$\mu_S \leqslant \langle h \rangle \leqslant \mu_B\,, \quad \theta \leqslant \theta_{max} \ll 1$$

Dynamically generated bounds

Basic Idea

- Consider 2 scalars $\phi_{\pm}$
- Their potential has a deep global min. with energy density $\lesssim -\Lambda_{max}^4 \sim O(M_{Pl}^4)$
- When $\phi_{\pm}$ roll to the global min., the Universe crunches quickly.
- The surviving Universes are in a metastable minimum

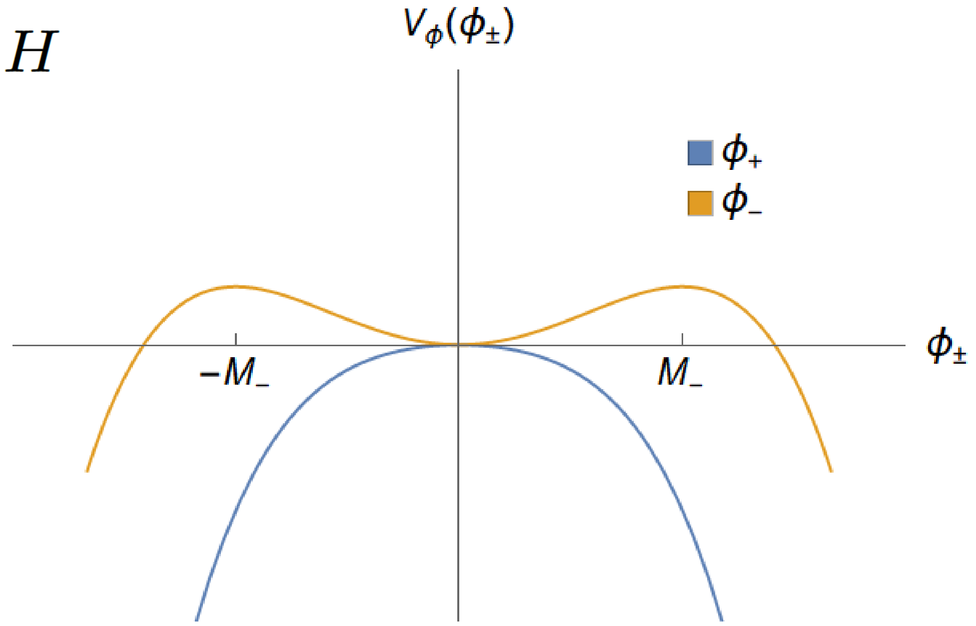
Weak scale and θ selection

> 0

$$V = V_\phi + V_{\phi H}$$

$$V_\phi = \mp \frac{m_{\phi_\pm}^2}{2}\phi_\pm^2 - \frac{m_{\phi_\pm}^2}{4M_\pm^2}\phi_\pm^4$$

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



$$m_{\phi_\pm}, \Lambda_{QCD} \ll F_\pm, M_\pm$$

Higgs-vev sensitive

Achieves selection

Shift-sym. breaking

EFT validity region: $|\phi_\pm| \lesssim M_\pm$

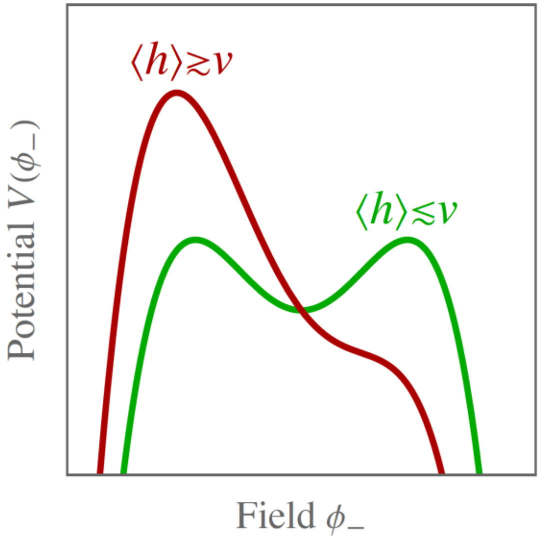
Weak scale and θ selection

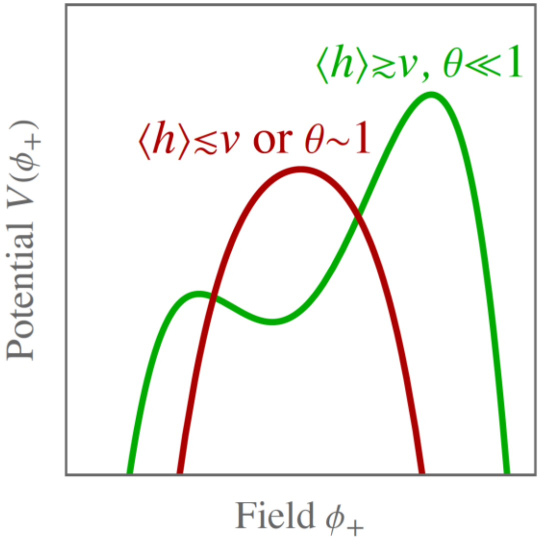
At low energies, below QCD condensation scale, match to χ Lag.

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

$$m_{u,d} \lesssim 4\pi f_\pi$$

$$\Lambda^4(\langle h \rangle) = m_\pi^2 f_\pi^2 \frac{m_u m_d}{(m_u + m_d)^2}$$





$$M_\pm \ll F_\pm$$

$$m_{\phi_+} \ll m_{\phi_-}$$

$$\theta \ll 1$$

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

Minimum for ϕ_-

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

Minimum for ϕ_+

$$\frac{M_+}{F_+} \gtrsim \theta + \frac{\langle \phi_- \rangle}{F_-} \quad \text{and} \quad \Lambda^4(\langle h \rangle) \gtrsim m_{\phi_+}^2 F_+^2$$

Weak scale and θ selection

Additional results from the minimization

$$M_-/F_- \lesssim M_+/F_+ \simeq \theta_0 \lesssim \theta_{\rm exp} \simeq 10^{-10}$$

$$m^2_{\phi_+} \simeq \frac{\Lambda^4_{\rm QCD}}{F^2_+}, \qquad m^2_{\phi_-} \simeq \left(\theta + \frac{M_+}{F_+}\right)\frac{\Lambda^4_{\rm QCD}}{F_- M_-} \gtrsim \frac{\Lambda^4_{\rm QCD}}{F^2_-}$$

$$\Lambda^4_{\rm QCD} \equiv \Lambda^4(v) \simeq (80 \text{ MeV})^4$$

Physical masses of $\phi_\pm$ in the limit $\mu_S \simeq \mu_B \simeq v$

The mass of ϕ_- could be higher for $v < \mu_B$

- **ϕ_+: “axion”, QCD axion-like relation between mass and coupling. Solves strong CP problem.**
- **ϕ_-: ALP, heavier than QCD axion with same couplings.**

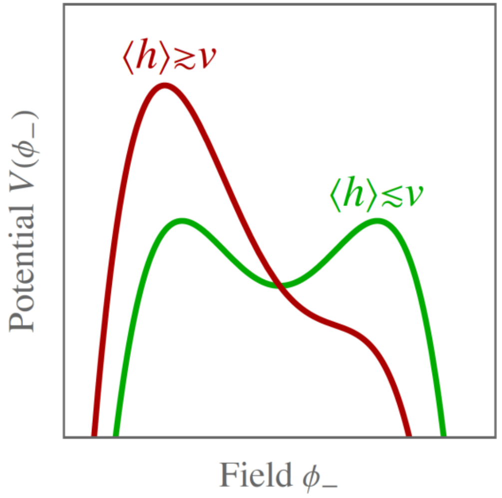
Cosmology: Inflation and crunching

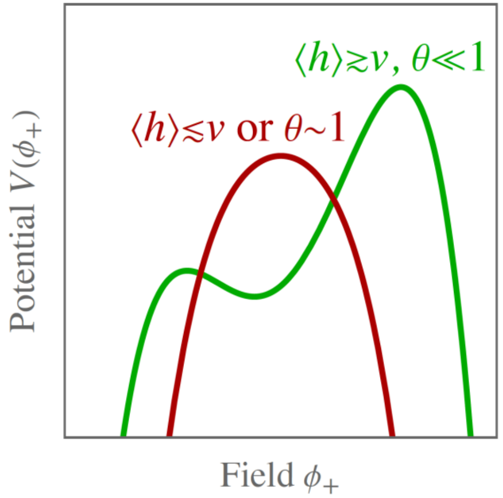
- **No assumption on Univ. before reheating nor on reheating temperature.**
- **$\phi_\pm$ couple to the reheating sector only via QCD anomaly.**
- **Three cases for the crunching time:**

  1. **$\langle h \rangle$ or θ outside the stability range: No $\phi_\pm$ inflation, radiation domination, reheating temperature compatible with BBN bounds.**
  2. **$\langle h \rangle \cong \mu_S$ or $\langle h \rangle \cong \mu_B$: Longest crunching time dominated by the region** $|\phi_\pm| \lesssim M_\pm$

$$t_c \simeq \max[1/m_{\phi_+}, 1/m_{\phi_-}] \simeq 1/m_{\phi_+}$$

  3. **If $|\phi_\pm| \gtrsim M_\pm$, the Univ. always crunches in a short time.**





- **A subtlety:**

  1. **If $v \cong \mu_S$, then we need** $m_{\phi_+} \lesssim H(\Lambda_{QCD}) \simeq 10^{-11}\ \text{eV} \simeq (0.1\ \text{ms})^{-1}$

  This constraint is lifted for $\mu_S \ll v$

Cosmology: Dark Matter

- The additional scalars are stable for cosmo scales $\tau_{\phi_\pm} \simeq 10^{24}\ \mathrm{s}\ (\mathrm{eV}/m_{\phi_\pm})^5$
- They could constitute all the DM
- ϕ_- is subdominant for the case

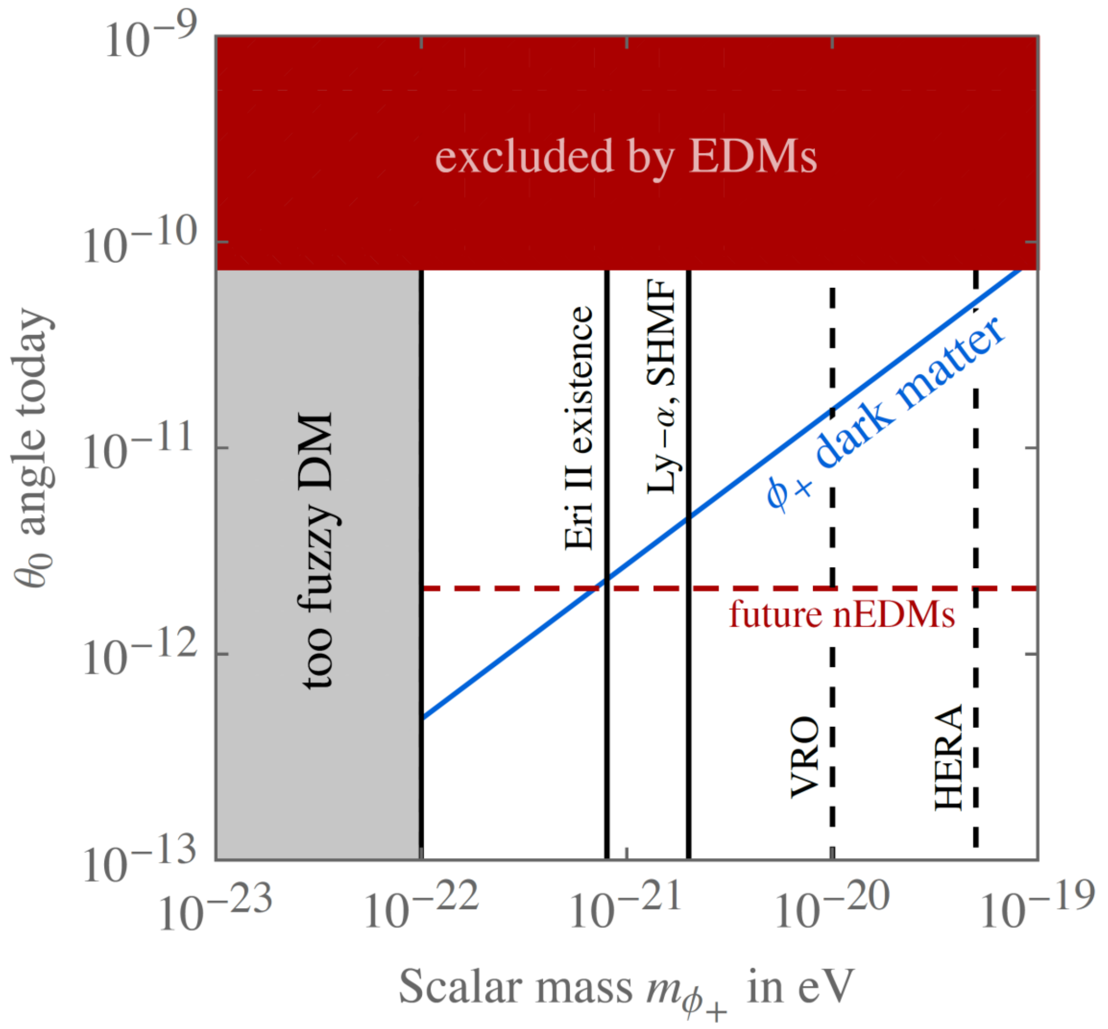
$$m_{\phi_-} \gg m_{\phi_+}$$

- ϕ_+ has a relic density:

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

Suppression w.r.t. PQ-QCD axion.

$$\theta_0 \lesssim \theta_{\rm exp} \simeq 10^{-10}$$



Cosmology: CC and the Swampland

- **So far, the CC was supposed to be selected by anthropics.**
- **This mechanism is compatible with modern swampland conjectures.**
- **De Sitter and distance conjectures are satisfied for:**

$$M_{\pm} < M_{\rm Pl}$$

- **Accounting for DM requires**

$$F_{+} > M_{\rm Pl}$$

- **Maximal CC that doesn't require super-planckian field excursions:**

$$\Lambda_{\rm sub}^4 \simeq \frac{\Lambda_{\rm QCD}^4}{\theta_0^2}\frac{M_{\rm Pl}^4}{F_+^4} \lesssim (10^{14}\ {\rm GeV})^4 \left(\frac{10^{-10}}{\theta_0}\right)^2 \qquad (\mu_S \ll v,\ F_+ \gtrsim 10^8\ {\rm GeV})$$

- **Mechanism compatible with standard inflation.**

Smoking-gun signals and conclusions

- ϕ_+ could be found in searches for QCD axions. But it doesn't have superradiance due to its self-coupling.
- The ϕ_+ DM hypothesis can be probed by the combination of fuzzy DM and EDM experiments.
- ϕ_- can be found in ALP experiments as a heavy QCD axion (for its couplings).
- There is a peculiar pattern that should appear in a variety of experiments.
- Paper in preparation by the authors exploring general implementations of the idea.

Appendix A: a possible UV completion with scale invariance

$V_\phi + \frac{\lambda''_\pm}{M_\pm^\epsilon}\phi_\pm^{4+\epsilon}$ → **Deep minimum at:** $\lambda''_\pm \phi_\pm^{4+\epsilon}/M_\pm^\epsilon$

Λ_{UV}

$V_\phi = \lambda'_\pm S_\pm^2 \phi_\pm^2 + \lambda_\pm \phi_\pm^4$

($S_\pm$) → **Field**

$F_\pm$

$V_\phi + \mathcal{O}\left(\partial\phi_\pm\right)$ → **Scale inv. broken by shift-sym. derivative couplings.**

$M_\pm$

$\langle S_\pm \rangle \neq 0$ → **SSB of scale and shift invariance due to the S field**

$V_\phi = \mp \frac{m_{\phi_\pm}^2}{2}\phi_\pm^2 - \frac{m_{\phi_\pm}^2}{4M_\pm^2}\phi_\pm^4$ **Here is where the EFT potential is generated.**

$\Lambda(\langle h \rangle)$

$V_{\phi H}$ **Breaks shift sym.** $\phi_\pm \to \phi_\pm + c_\pm$ → $\phi_\pm \to \phi_\pm + 2\pi F_\pm n$

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