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Exploring Post-Naturalness Scenarios of BSM at FCC

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Naturalness, 2022?

- The EFT “Standard Model” explains almost everything we see and we do not see
- Naturalness = dimensional analysis (+ selection rules) works.

Already from G. Galilei $t \sim \sqrt{l/g}$. But:

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

- LHC has discovered unnaturalness of m_{Higgs}
- Concrete problem, not aesthetic, if SM as an EFT, with calculable parameters:
if dimensional analysis fails only here, we want to understand why

Post-Naturalness

see, e.g., G. Giudice, *The Dawn of the Post-Naturalness Era*

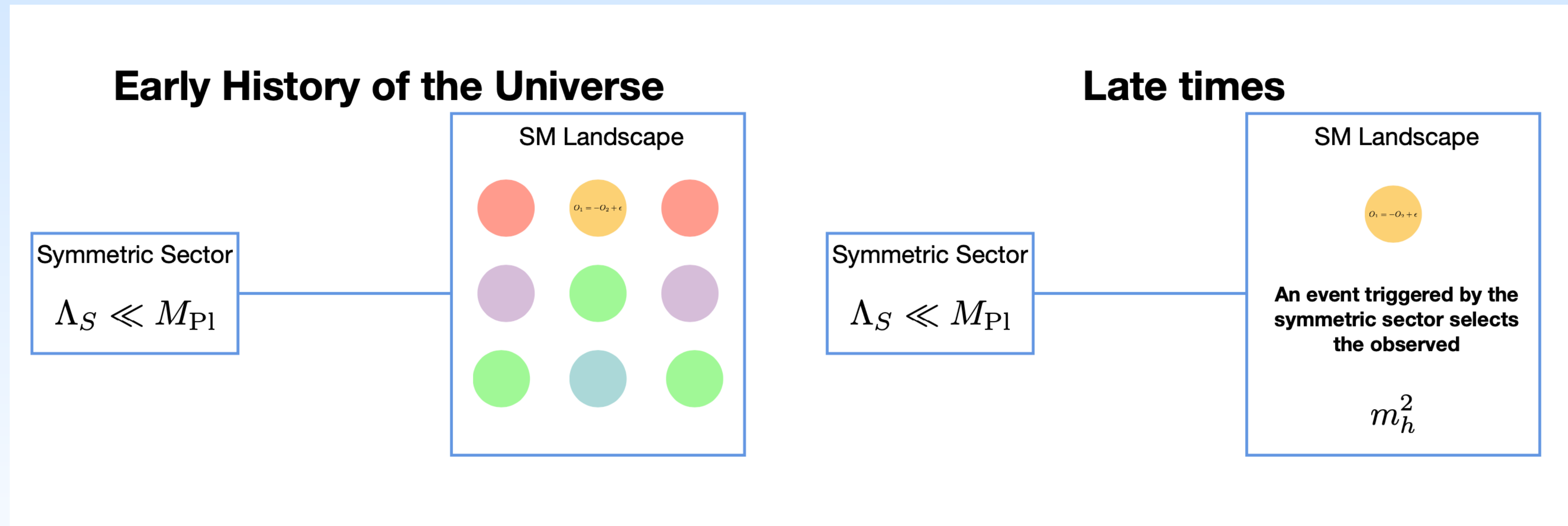
Several attitudes are possible:

- 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 (ideal, but not currently known). Swampland? UV/IR?
- **Nature is unnatural**, but unnaturalness is selected dynamically (= cosmologically)

What are the implications of this idea for FCC?

Cosmological Naturalness

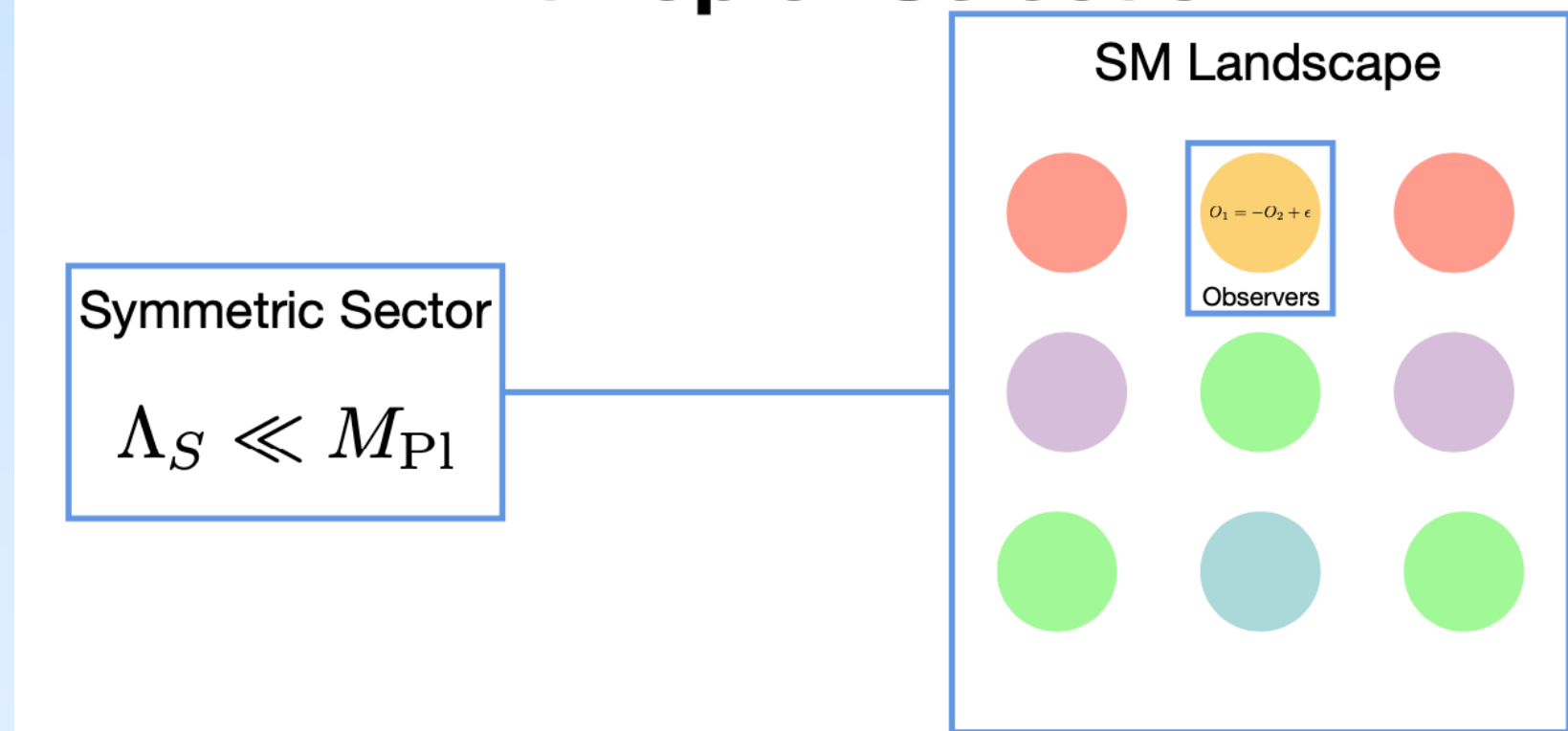
i.e. how cosmology can select a small Higgs mass



Cosmological Naturalness

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

“Anthropic” Selection



“Statistical” Selection



vacuum accumulation
[Dvali, Vilenkin]

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

Self-Organized Localization
[Giudice, McCullough, You]

light Higgs from small CC

[Arvanitaki, Dimopoulos, Gorbenko, Huang, Van Tilburg]

relaxion

[Graham, Kaplan, Rajendran]

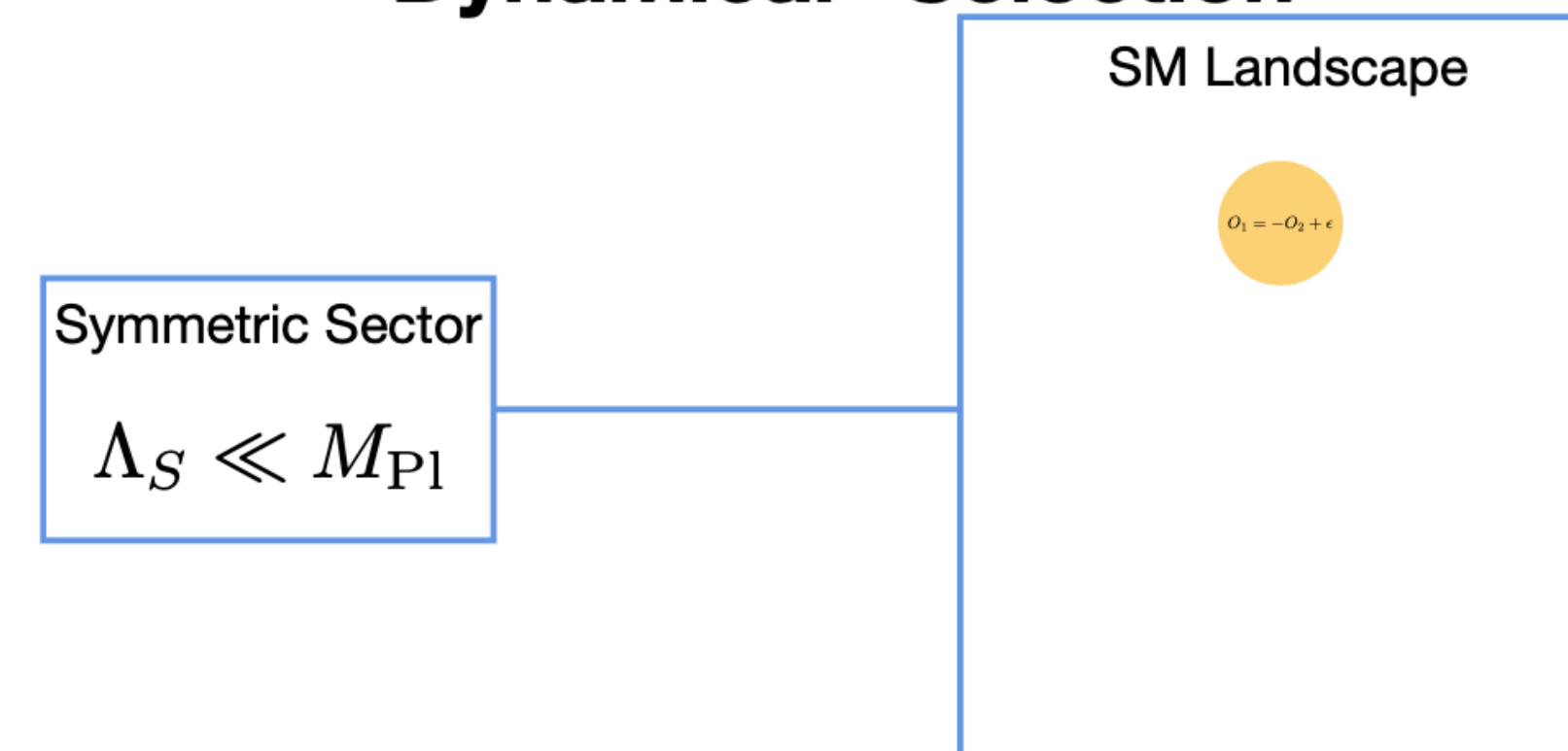
NNaturalness

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

Selfish Higgs

[Giudice, Kehagias, Riotto]

“Dynamical” Selection



Precarious Naturalness
[Strumia, DT]

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

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

Dynamical Selection

Three model scenarios for FCC

A biased example selection, to not make anybody unhappy



The Bad

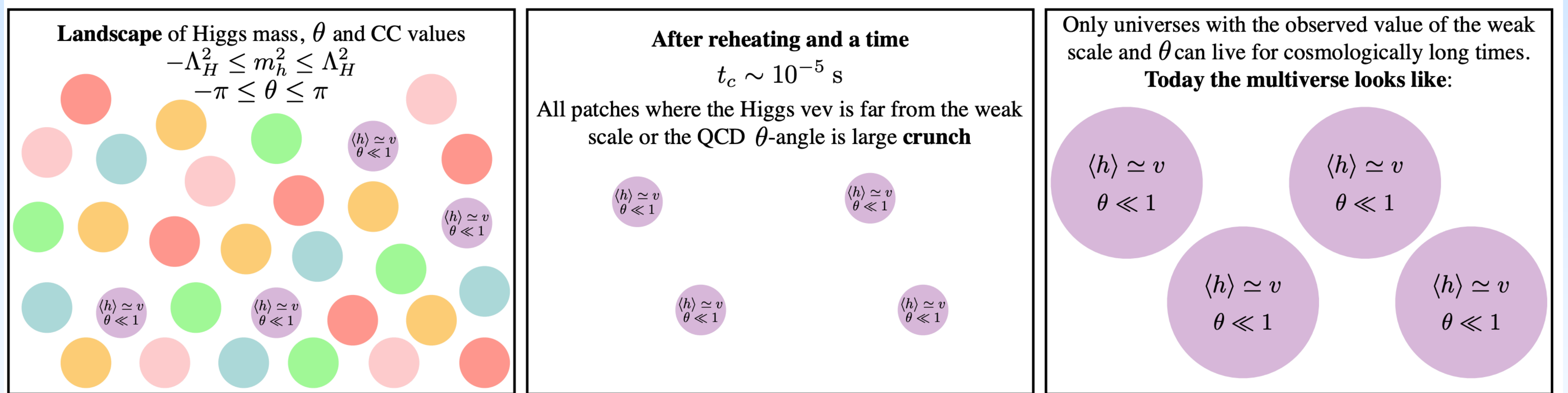
Naturalness up to high scales, decoupled from collider physics

example: R.T. D'Agnolo, DT, *Sliding Naturalness*, 2106.04591, 2109.13249



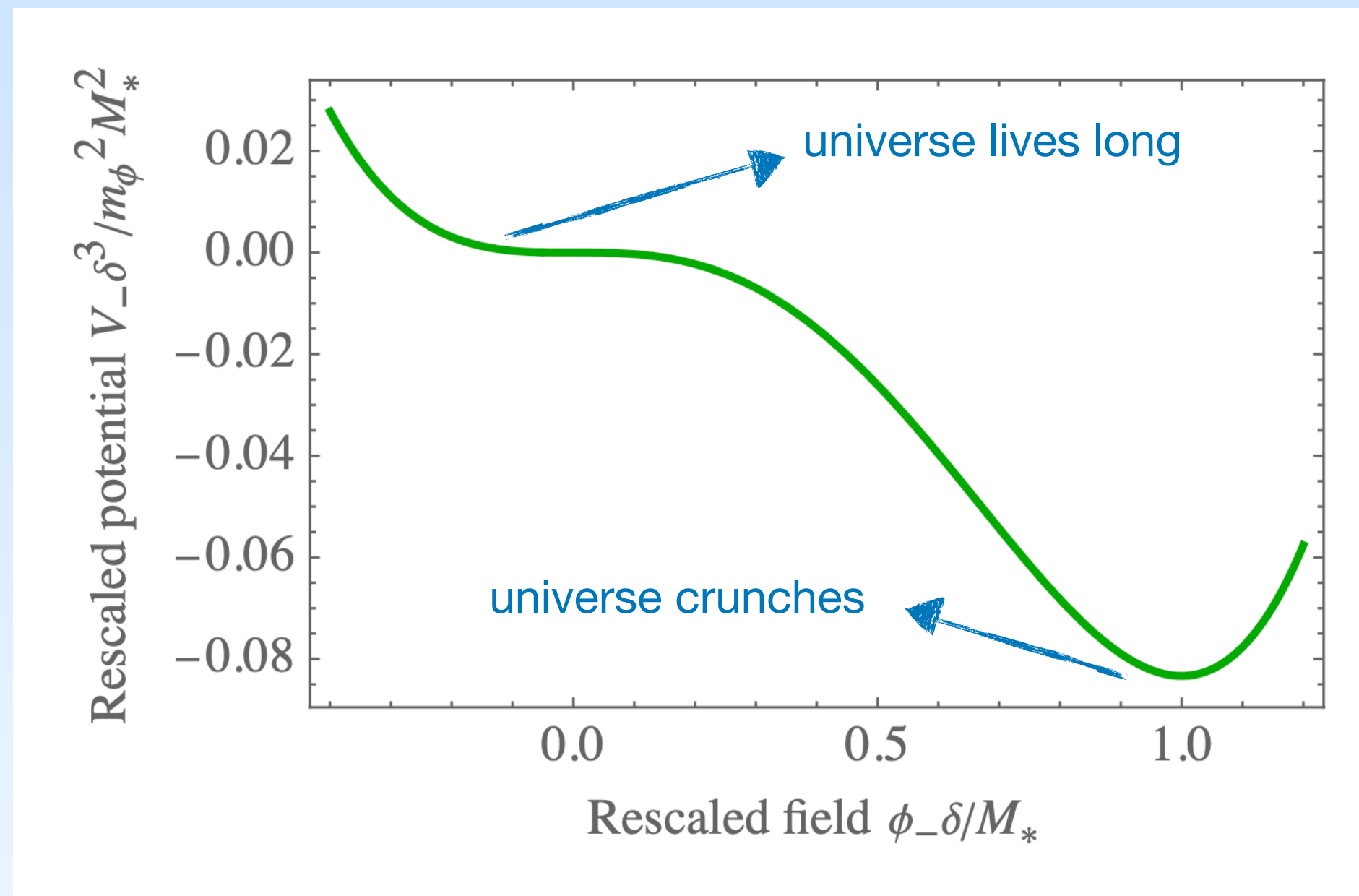
Sliding Naturalness

sketch of the mechanism



Sliding Naturalness

selecting a small Higgs vev

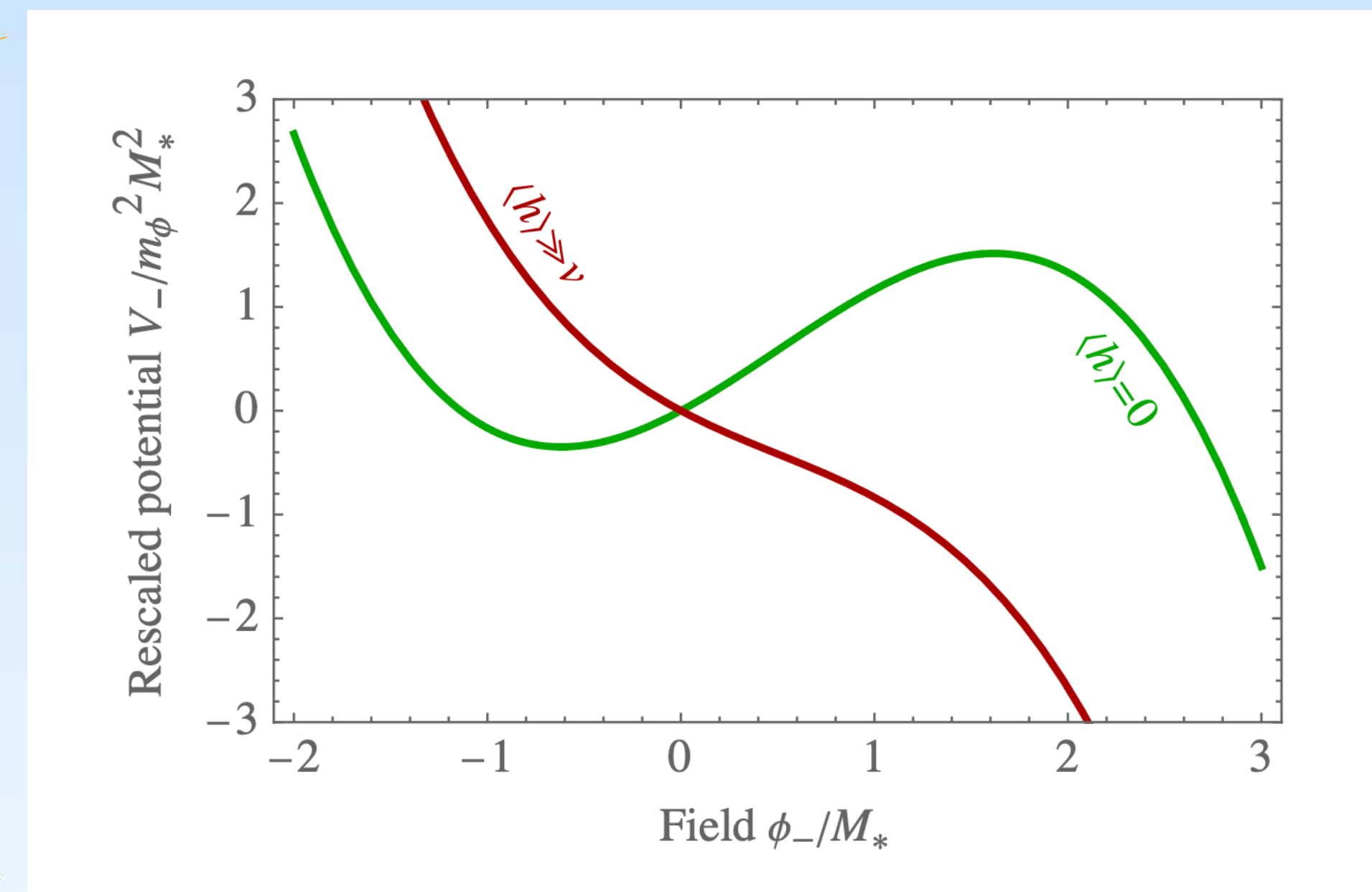
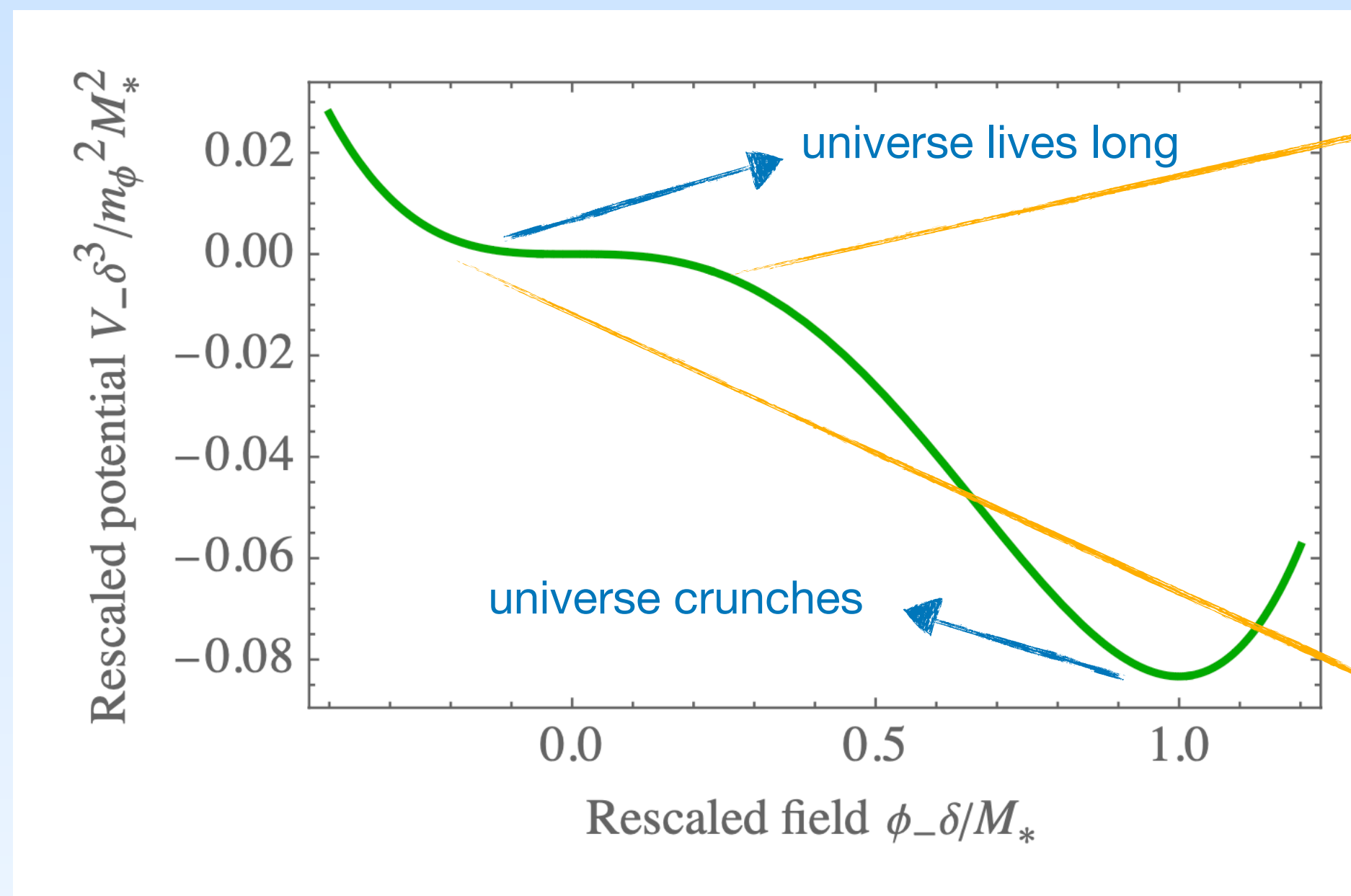


- At global minimum $V \sim -M_*^4$ too big to be compensated by a CC in the landscape
- At local minimum CC in the landscape can be tuned $V \approx 0$

Sliding Naturalness

selecting a small Higgs vev

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

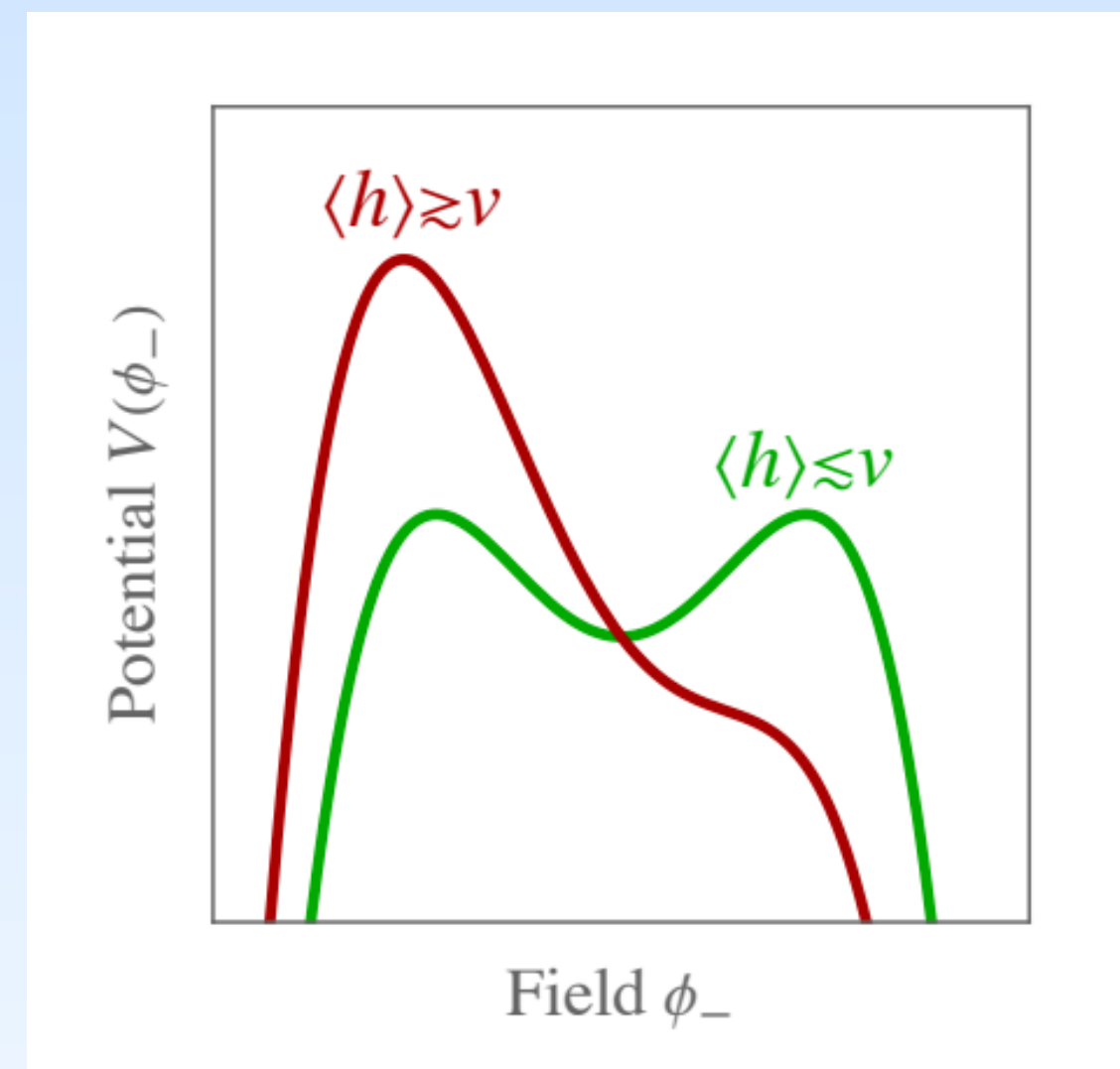
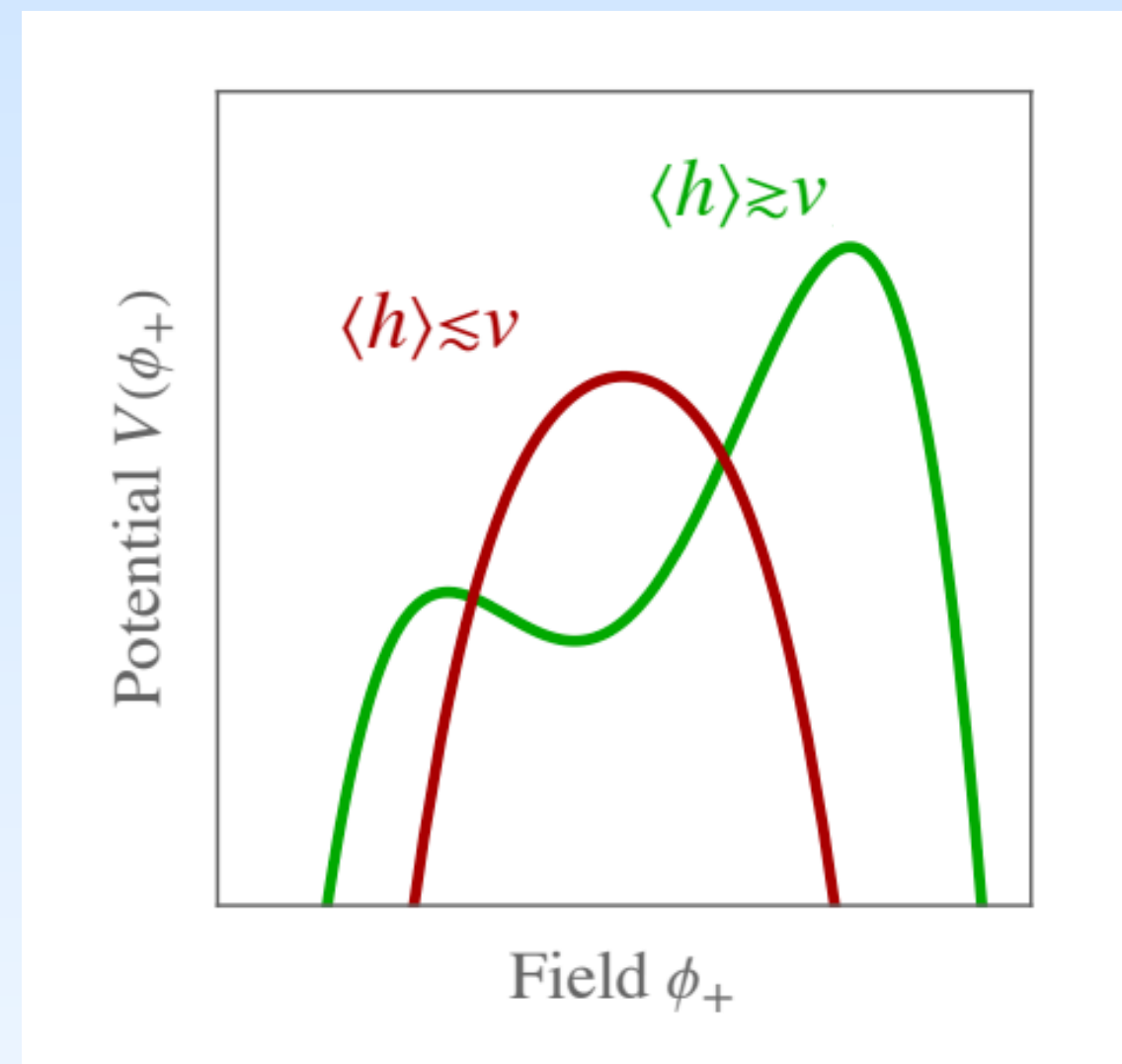


- At global minimum $V \sim -M_*^4$ too big to be compensated by a CC in the landscape
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The Lagrangian

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

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



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

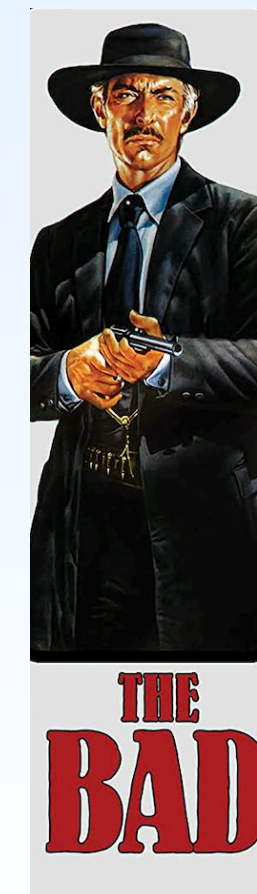
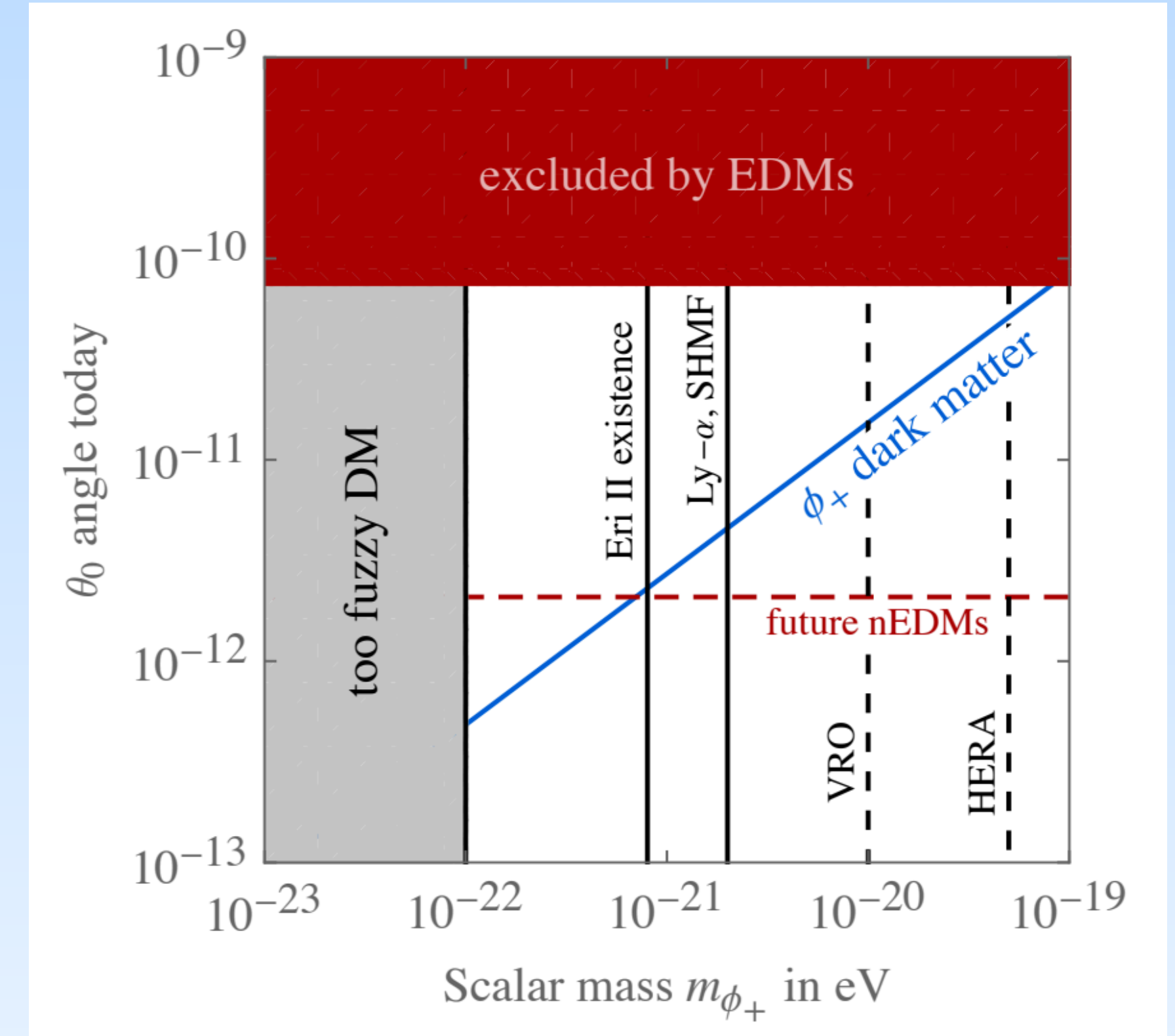
$$\longrightarrow -m_\pi^2 f_\pi^2 \cos(\dots)$$

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

This selects a small and non-zero Higgs vev and solves the strong-CP problem in a new way

Phenomenology

- The hierarchy problem is solved up to arbitrarily high scales
- The only BSM ingredients are two ultra-light scalars with ALP pheno
- They can be DM, if so smoking-gun relation with EDMs
- Nothing at colliders up to unknown high scales



The Good

Naturalness up to high scales, but some collider “remnants”

example: R.T. D’Agnolo, DT, *Sliding Naturalness* with $H_1 H_2$ trigger, 2109.13249



Sliding Naturalness with H_1H_2 trigger

changing the trigger changes pheno

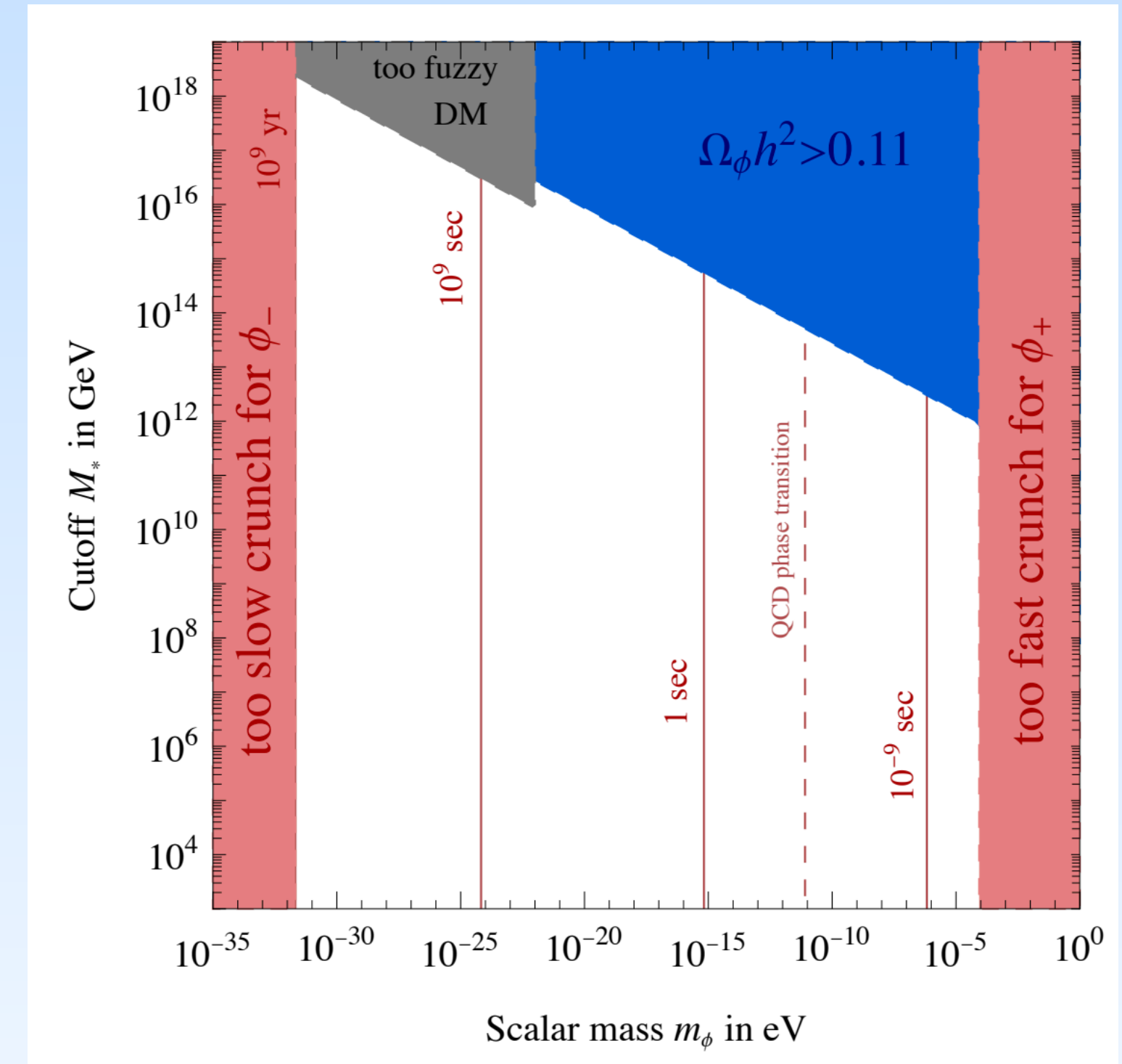
- Pheno largely determined by interaction with SM
- What matters is ϕ potential dependent on $\langle h \rangle$, not on the cutoff \longrightarrow trigger operators

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

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

- Naturalness up to high scales, but H_1H_2 pheno at colliders

talk by R. D'Agnolo



The Ugly (but ideal for FCC)

1-loop gain in the
Naturalness scale

“A tank to shoot a fly”, undisclosed physicist

example: A. Strumia, DT, *Precarious Naturalness*,
2002.02463



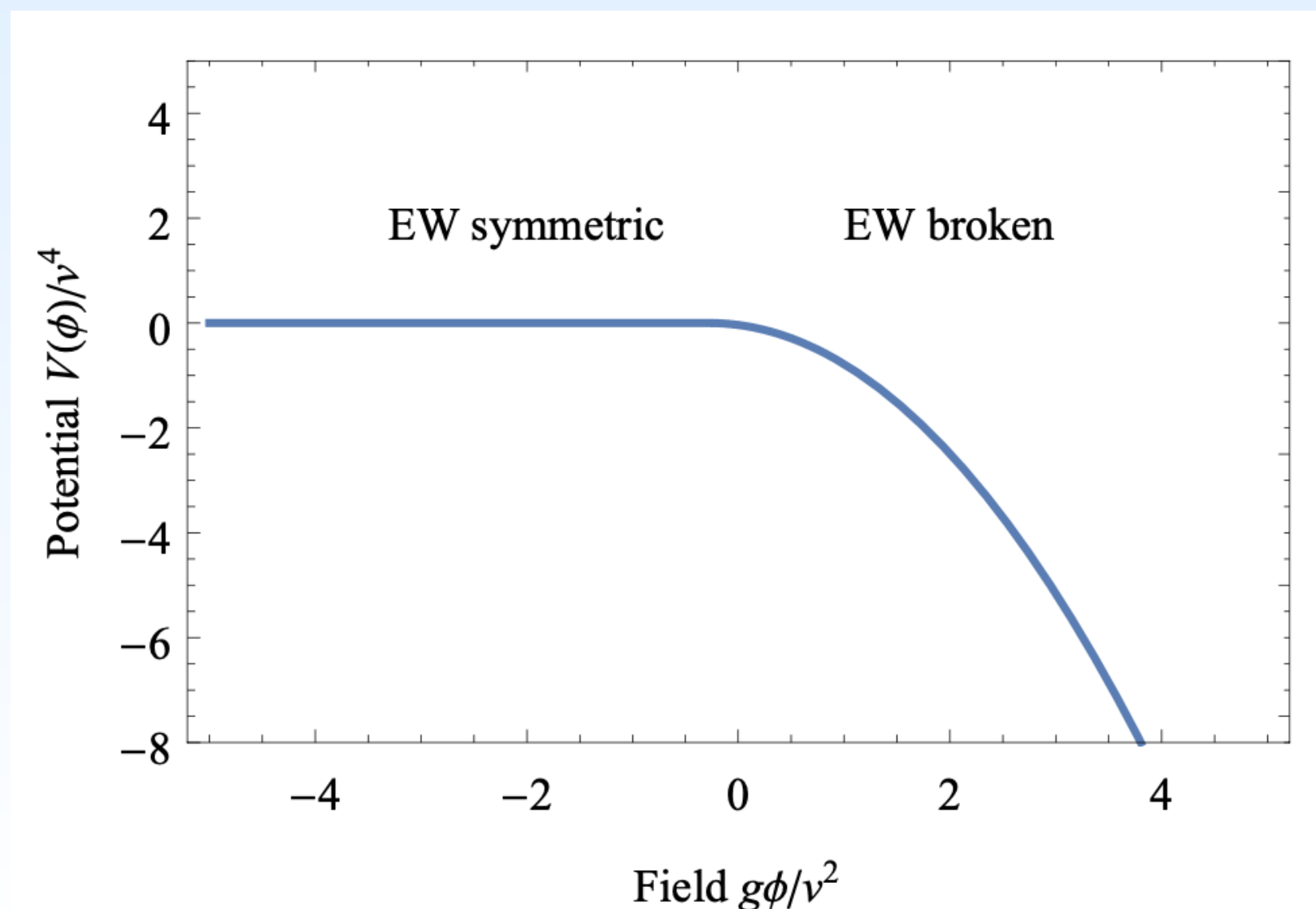
Precarious Naturalness

- we consider an ultra-light scalar $\phi \simeq$ shift-symmetric, up to tiny coupling g scanning the Higgs mass:

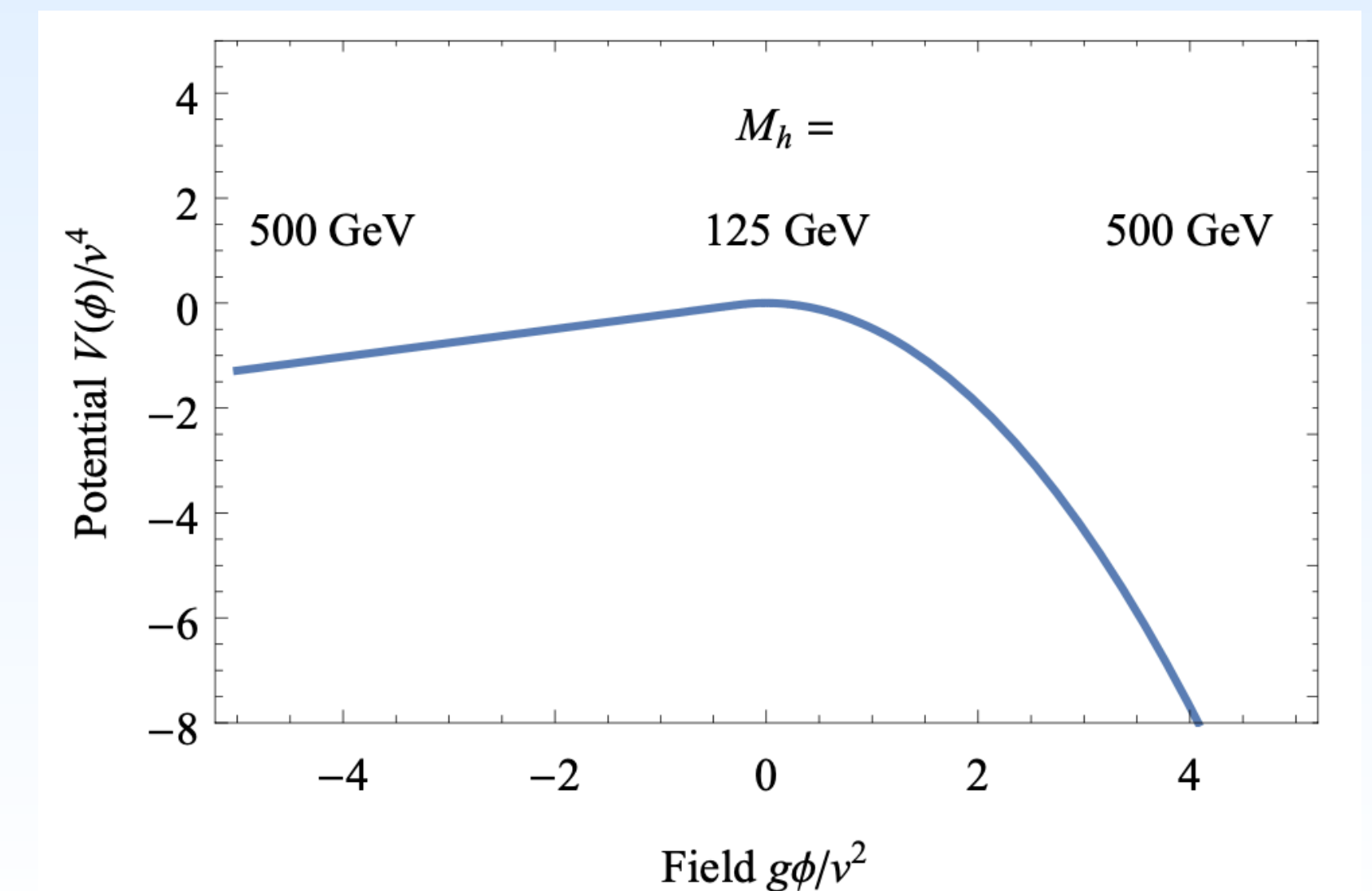
$$V(H, \phi) = V_0 - m_h^2(\phi) |H|^2 + \lambda |H|^4 \quad \text{with} \quad m_h^2(\phi) \simeq M^2 + gM\phi$$

- integrating out the Higgs: $V_{\text{eff}}(\phi) \simeq V_0 - \frac{m_h^4(\phi)}{4\lambda} \theta(m_h^2)$

new-physics scale

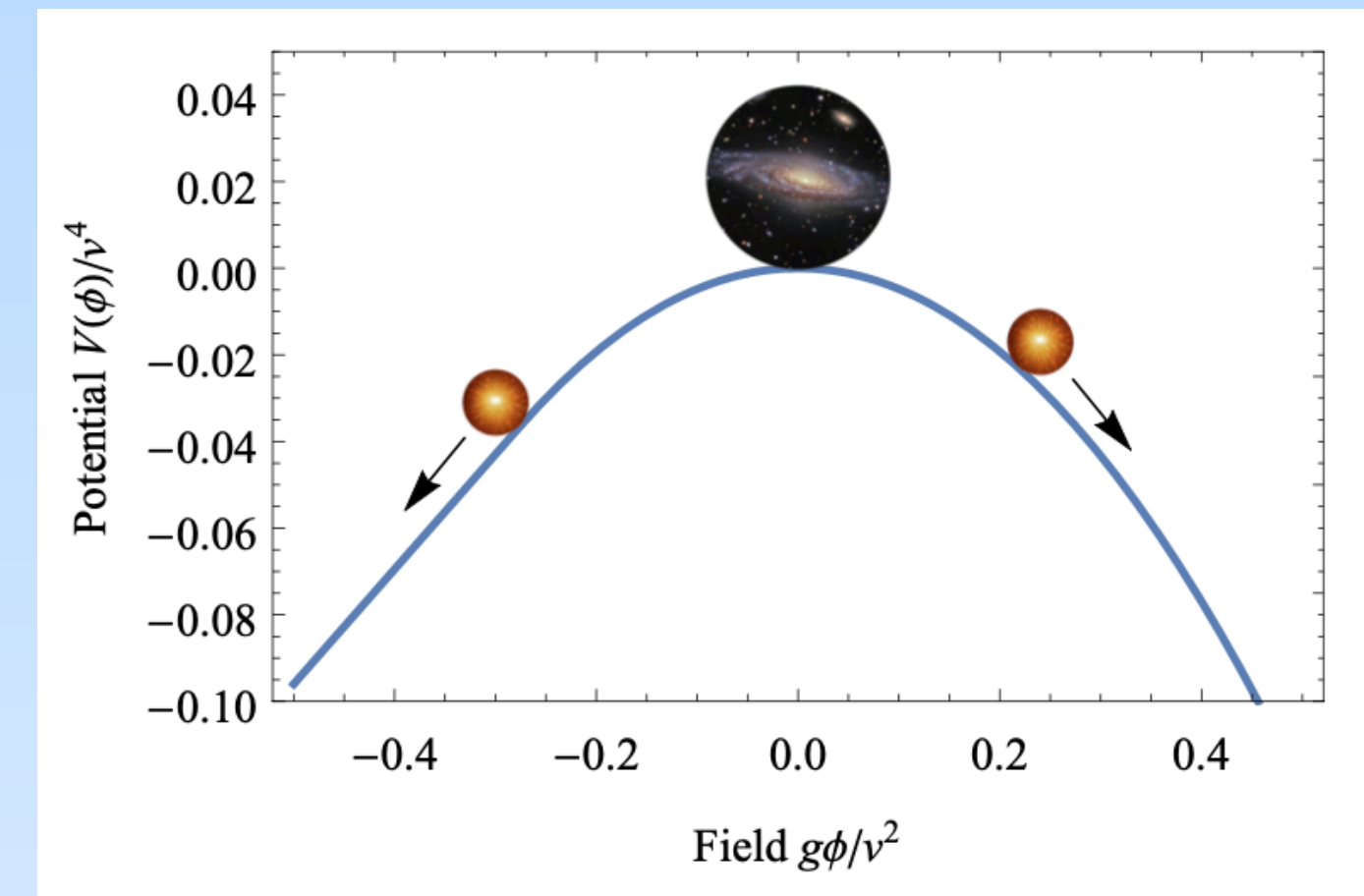


loops from new physics at M



Precarious Naturalness

living at the top



- we showed that for tiny $g \lesssim H_0$ we can actually be living at the top, only those patches survive, the remaining ones crunch

- EFT expectation: $V_{\text{eff}} \approx -\frac{m_h^4(\phi)}{4\lambda} + \frac{\hbar M^2}{16\pi^2} gM\phi$

- at the top the Higgs mass is suppressed: $m_h^2 \approx \frac{\hbar M^2}{16\pi^2} \lambda$

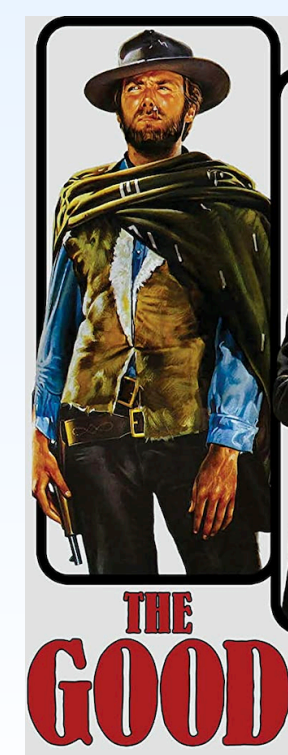
crucially,
no top or gauge

- naturalness scale $M \approx 4\pi v \sim 3 \text{ TeV}$

- natural new-physics sector (SUSY, compositeness,...)
in the multi-TeV range



but



for FCC

Statistical Selection

Just a few words

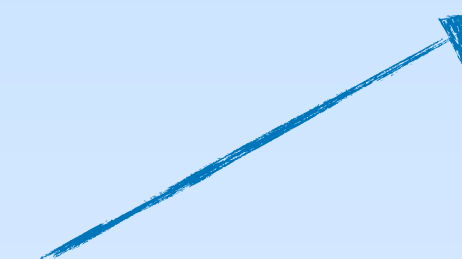
example: G. Giudice, M. McCullough, T. You,
Self-Organized Localization, 2105.08617

SOL approach to light Higgs

the volume of the multiverse dominated by criticality

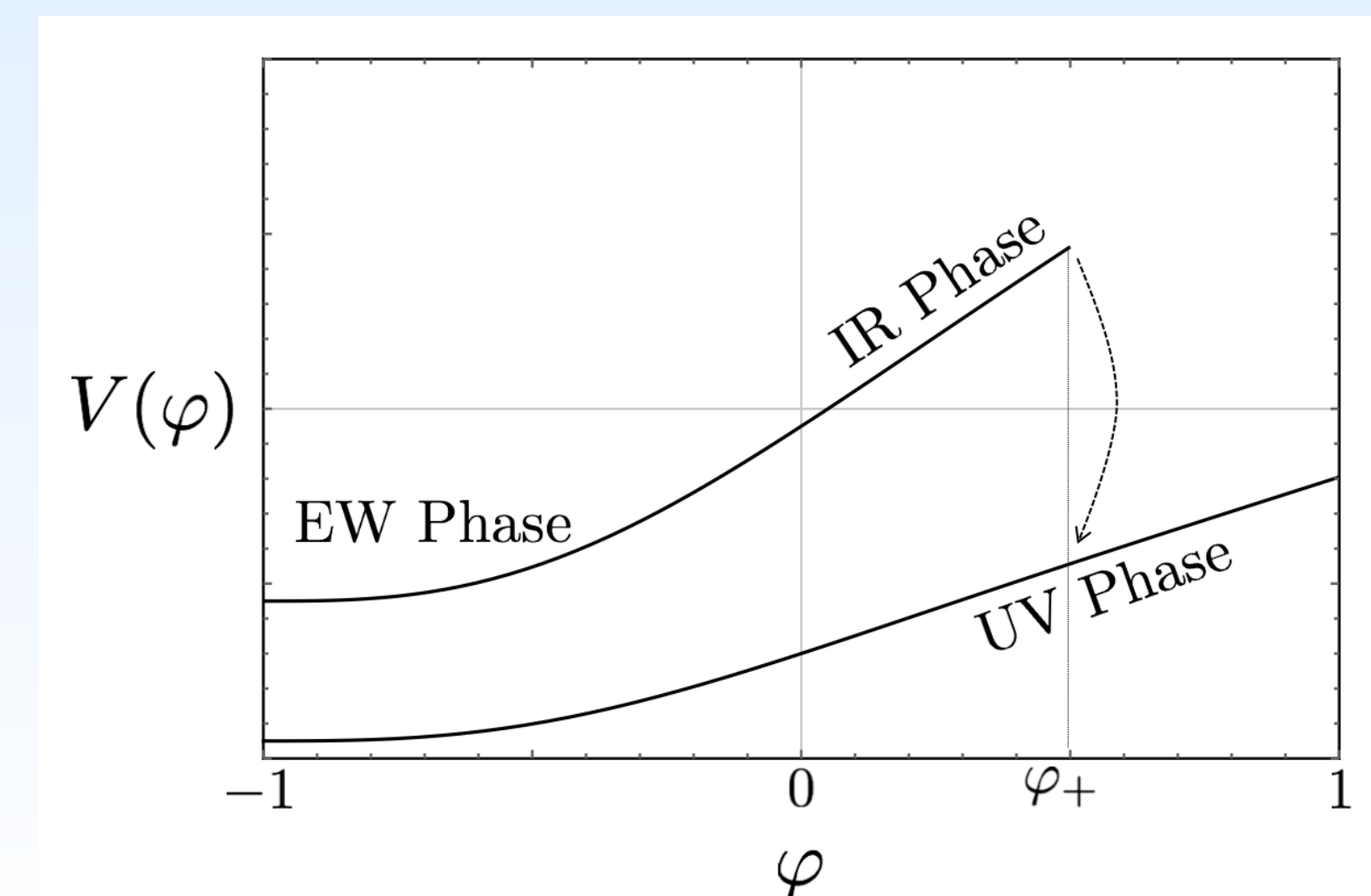
- Precarious Naturalness selects criticality **dynamically**
- Criticality can also be selected **statistically**, in the presence of (eternal) inflation the top inflates most and dominates the volume of the multiverse

caveat:
measure problem



[Geller, Hochberg, Kuflik; Cheung, Saraswat; Giudice, McCullough, You]

- If phase transition is second-order, selection is de-powered (φ potential distorted by loops)
- Self-Organized Localization: selection is powerful if first-order phase transition
- Higgs metastability: SM has an IR and an UV phase, where $\langle h \rangle$ is at low or high energy
- If φ scans m_H , IR phase at the verge of UV can be selected

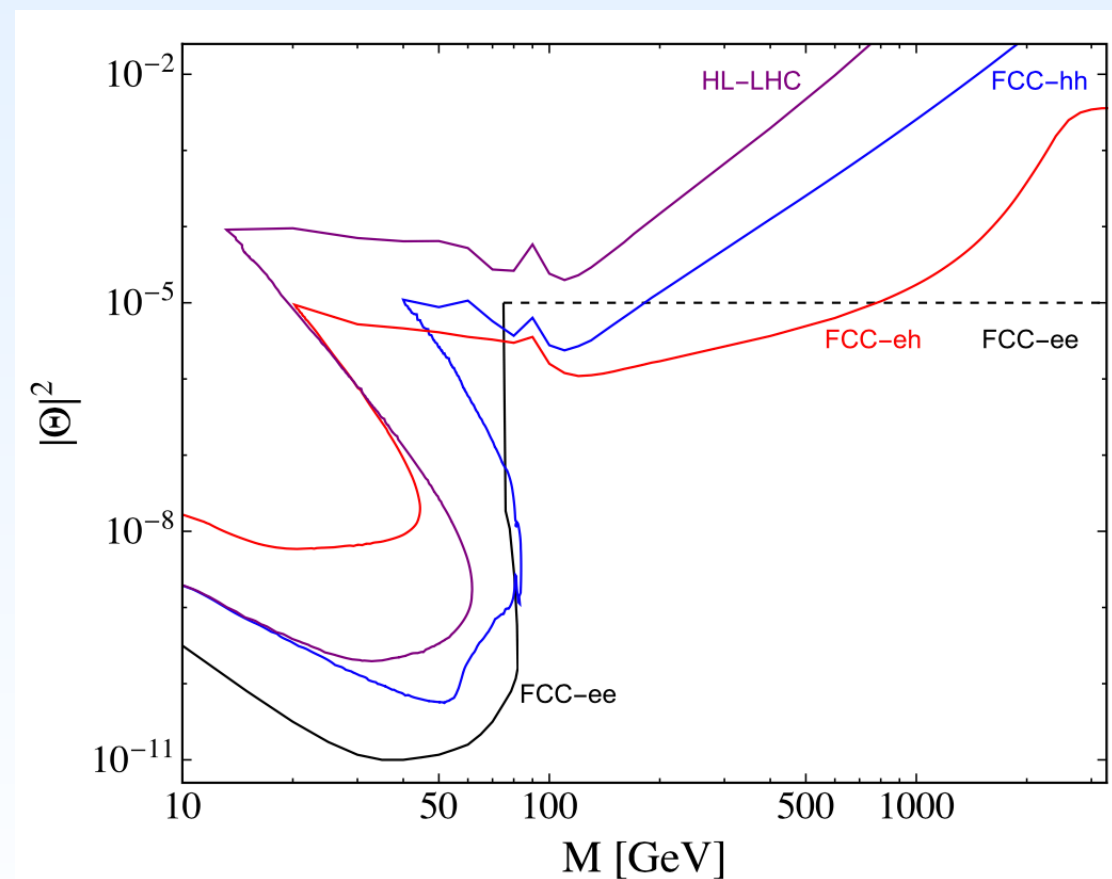


Pushing criticality down to the TeV scale

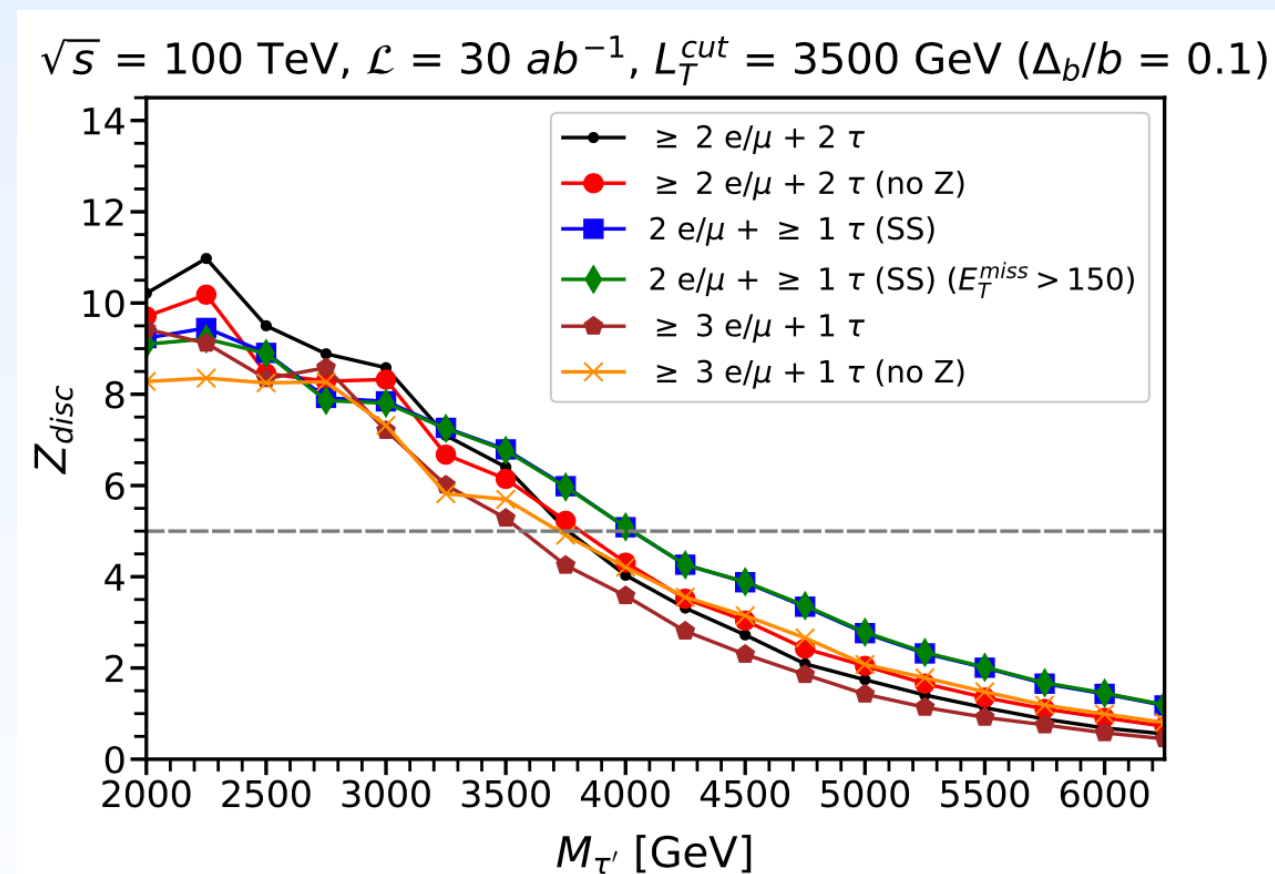
- in the SM criticality at $\sim 10^{11}$ GeV
- to address the hierarchy problem, one needs to lower it to \sim TeV, e.g. by adding vectorlike leptons:

$$(a) \quad \mathcal{L} = -y_{VL}\bar{\psi}\chi H_h + \text{h.c.} , \quad (b) \quad \mathcal{L} = -y_{VL}\bar{\psi}LH_h + \text{h.c.}$$

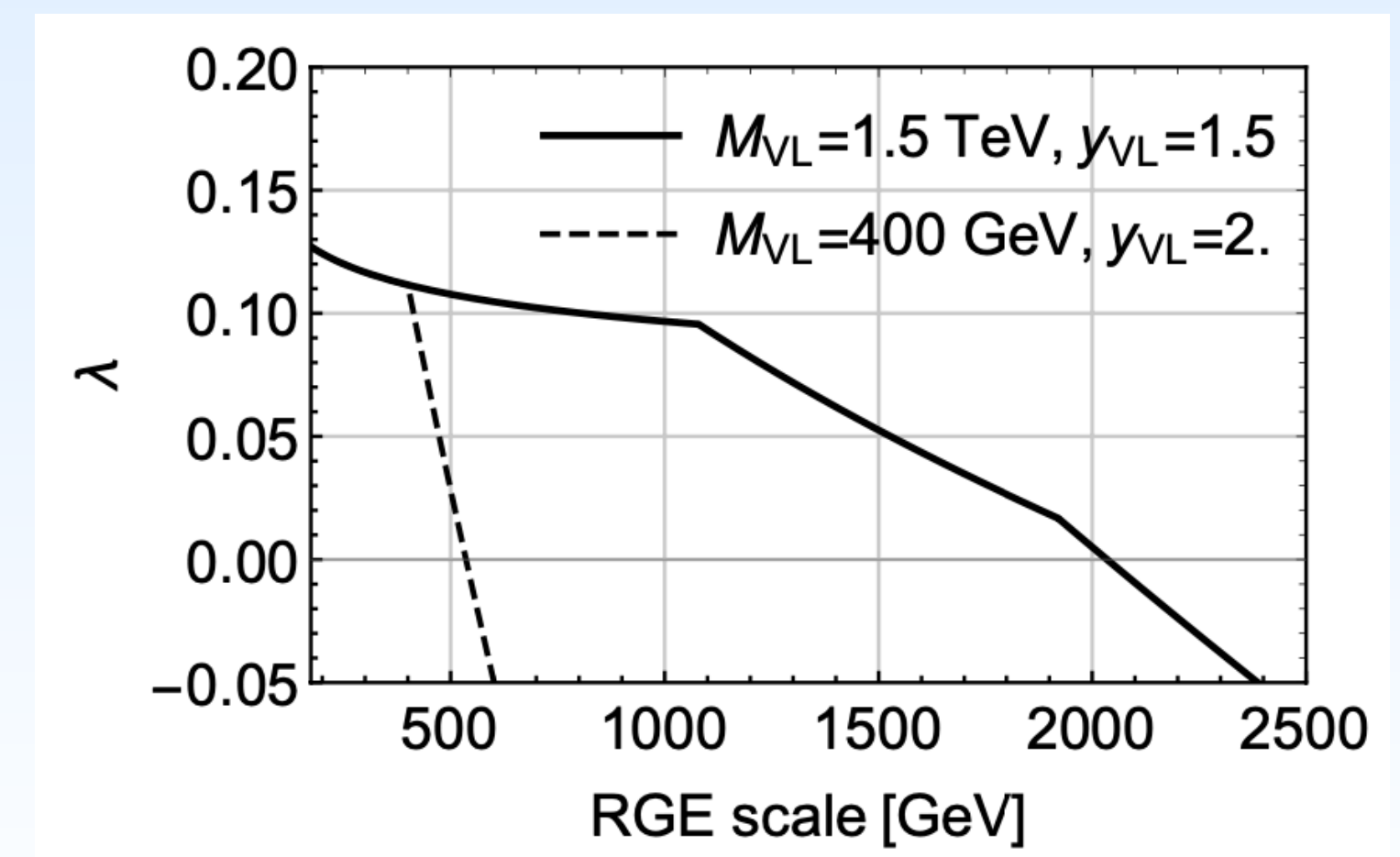
- they are target for FCC:



[singlet; FCC Physics Opportunities]



[different doublet; Bhattachipolu, Martin]



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.

FCC could observe new physics related to Post-Naturalness, but no strong prior for/against it.