A Minimal model for Cosmological Selection of the Electroweak scale

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The Hierarchy Problem

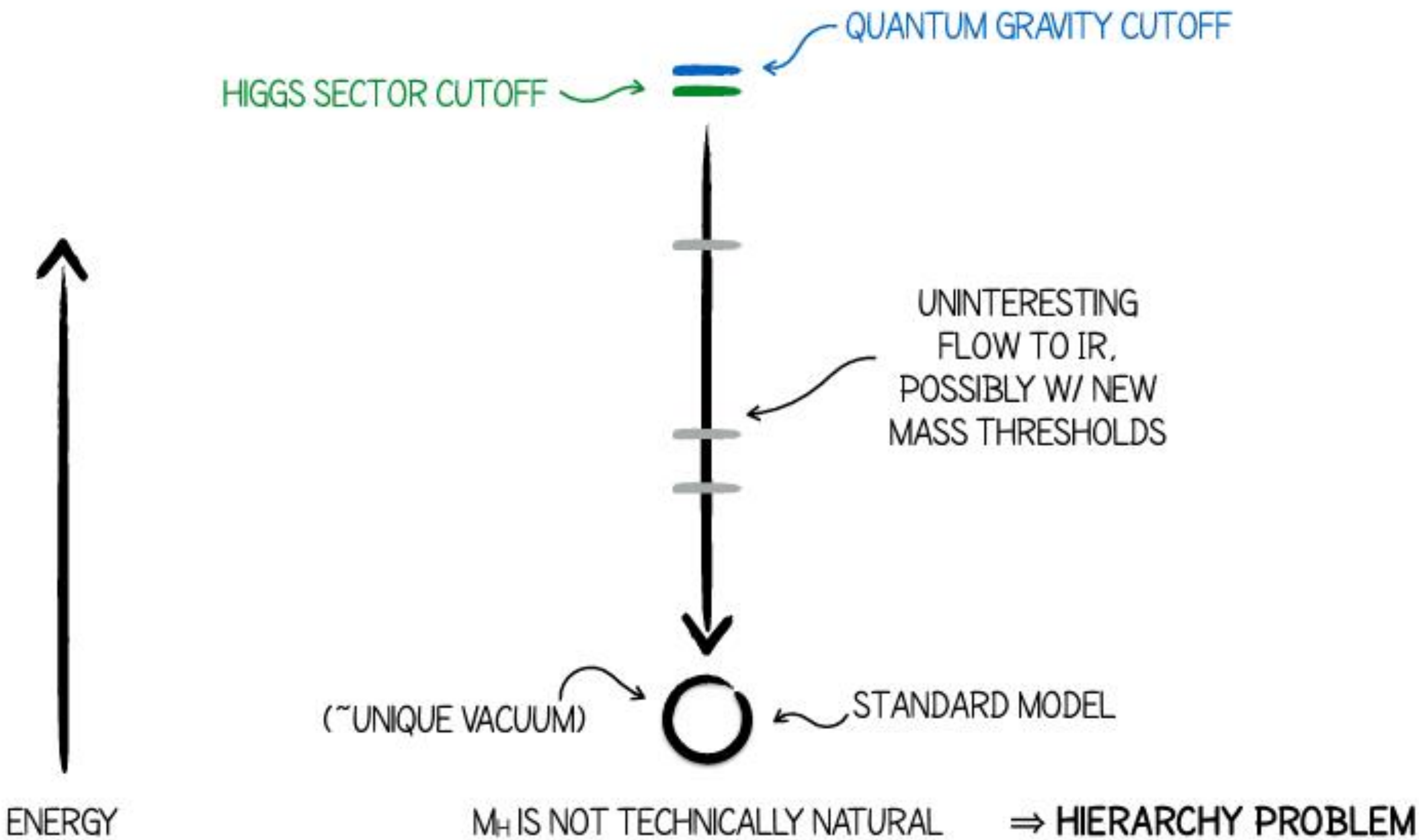
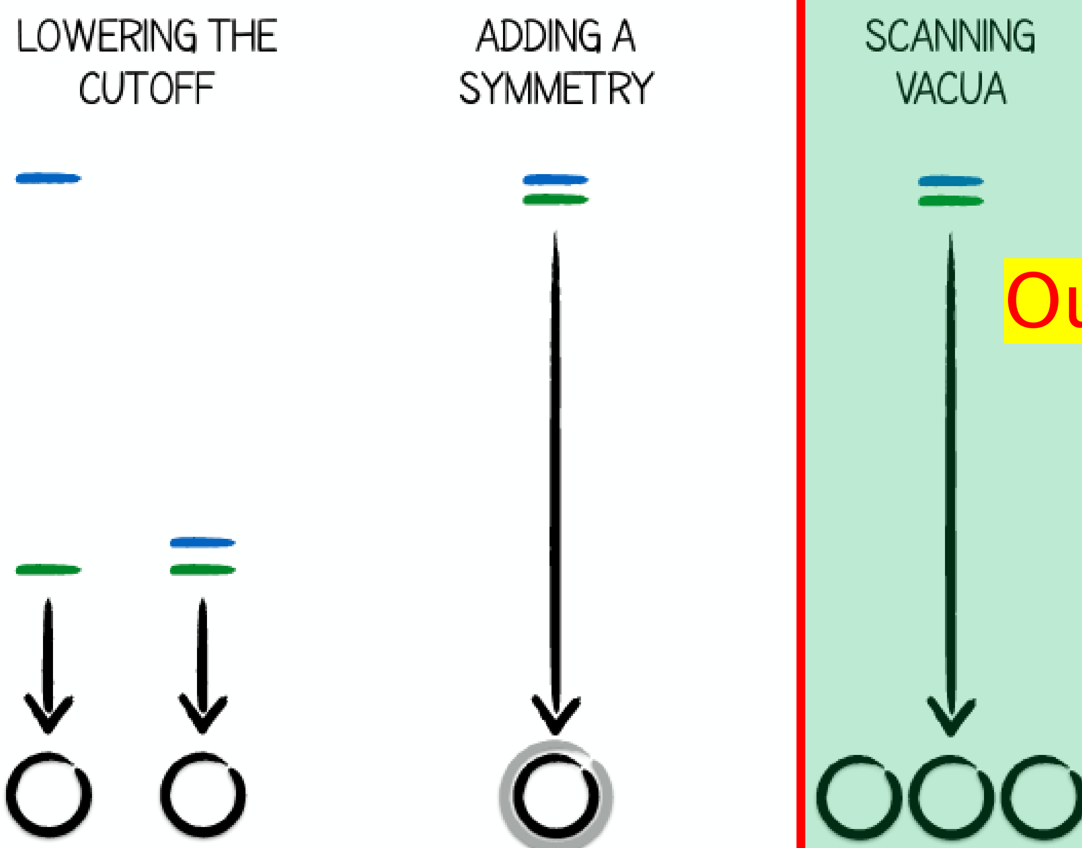


Image Credit: N. Craig, PiTP 2017 Lect.Notes.

The Hierarchy Problem: Solutions

Image Credit: N. Craig, PiTP 2017 Lect.Notes.

Clean Ideas. But Null Results at LHC!!!

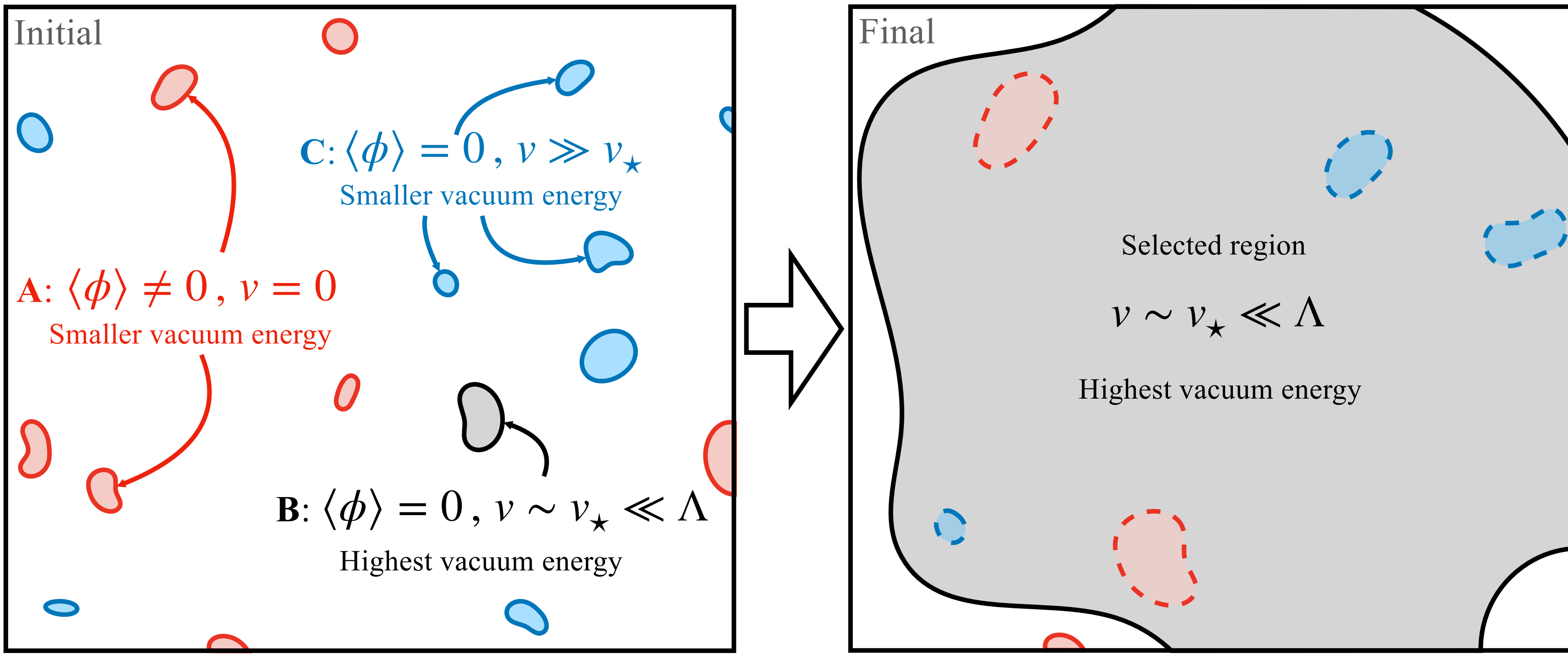


Eg: Technicolor, Extra-dimensions

Eg: SUSY, Composite Higgs

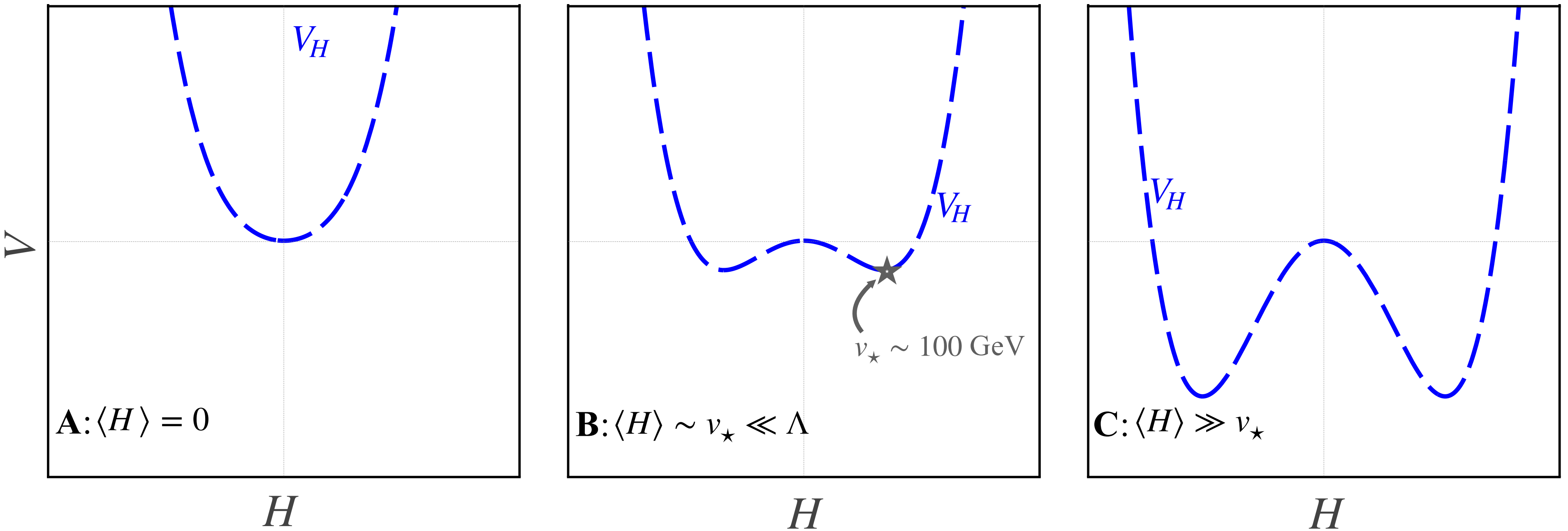
Eg: Relaxion, Sliding Naturalness, Nnaturalness, Anthropics, etc.

The Main idea



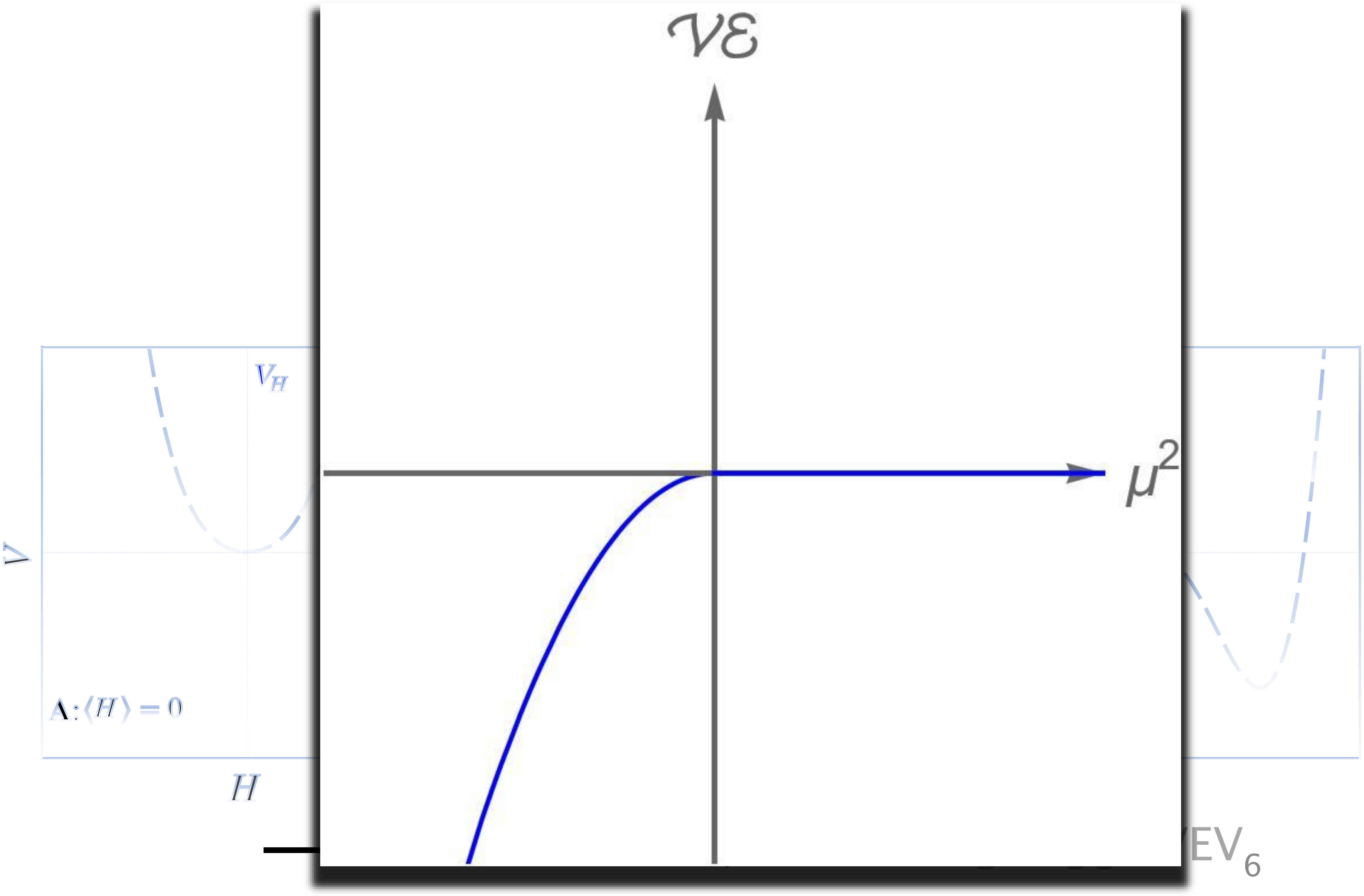
Selection Mechanism

$$V_H(H) = \mu^2|H|^2 + \lambda|H|^4$$



Increasing Higgs VEV

Selection Mechanism



Selection Mechanism

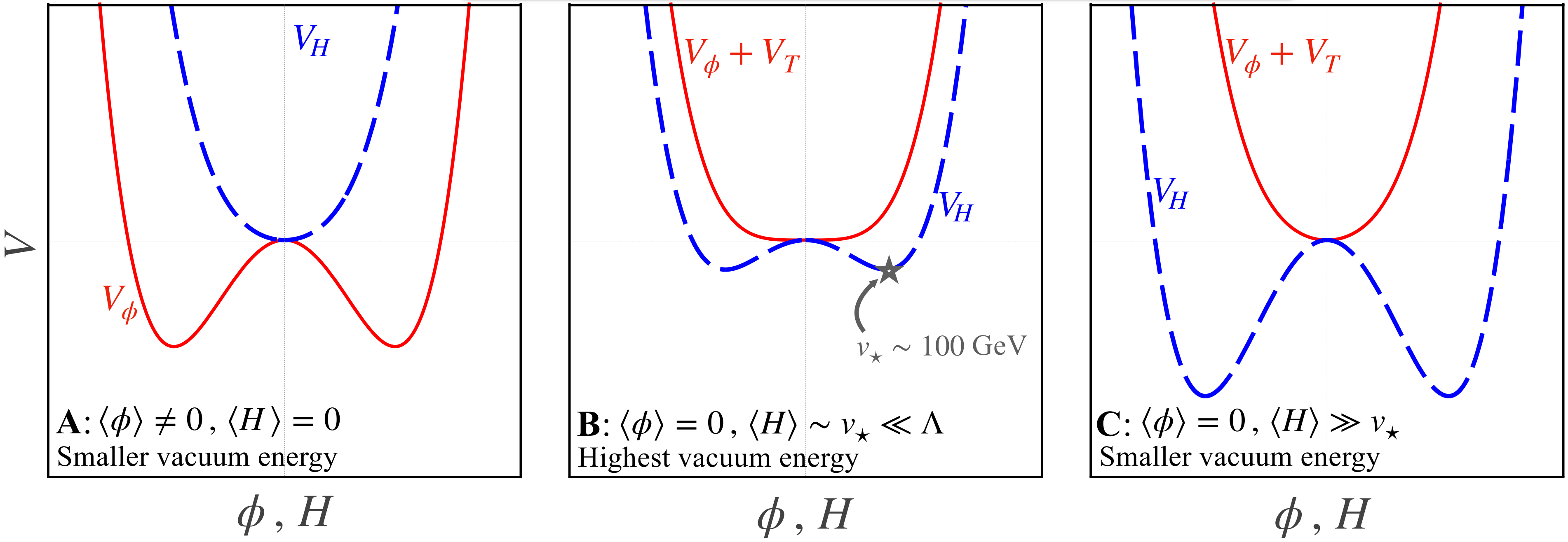
ϕ : A PNGB like light pseudoscalar

$$V(\phi, H) = V_H + V_\phi + V_T$$

$$V_H(H) = \mu^2|H|^2 + \lambda|H|^4$$

$$V_\phi(\phi) = \mu_\phi^2 f^2 \left(-\frac{1}{2}\left(\frac{\phi}{f}\right)^2 + \lambda_\phi \left(\frac{\phi}{f}\right)^4 + \ldots \right)$$

$$V_T(\phi, H) = \frac{\mu_\phi^2 f^2}{2} \kappa \left(\frac{|H|^2}{\mu_\phi f}\right) \left(\frac{\phi}{f}\right)^2$$



Increasing Higgs VEV

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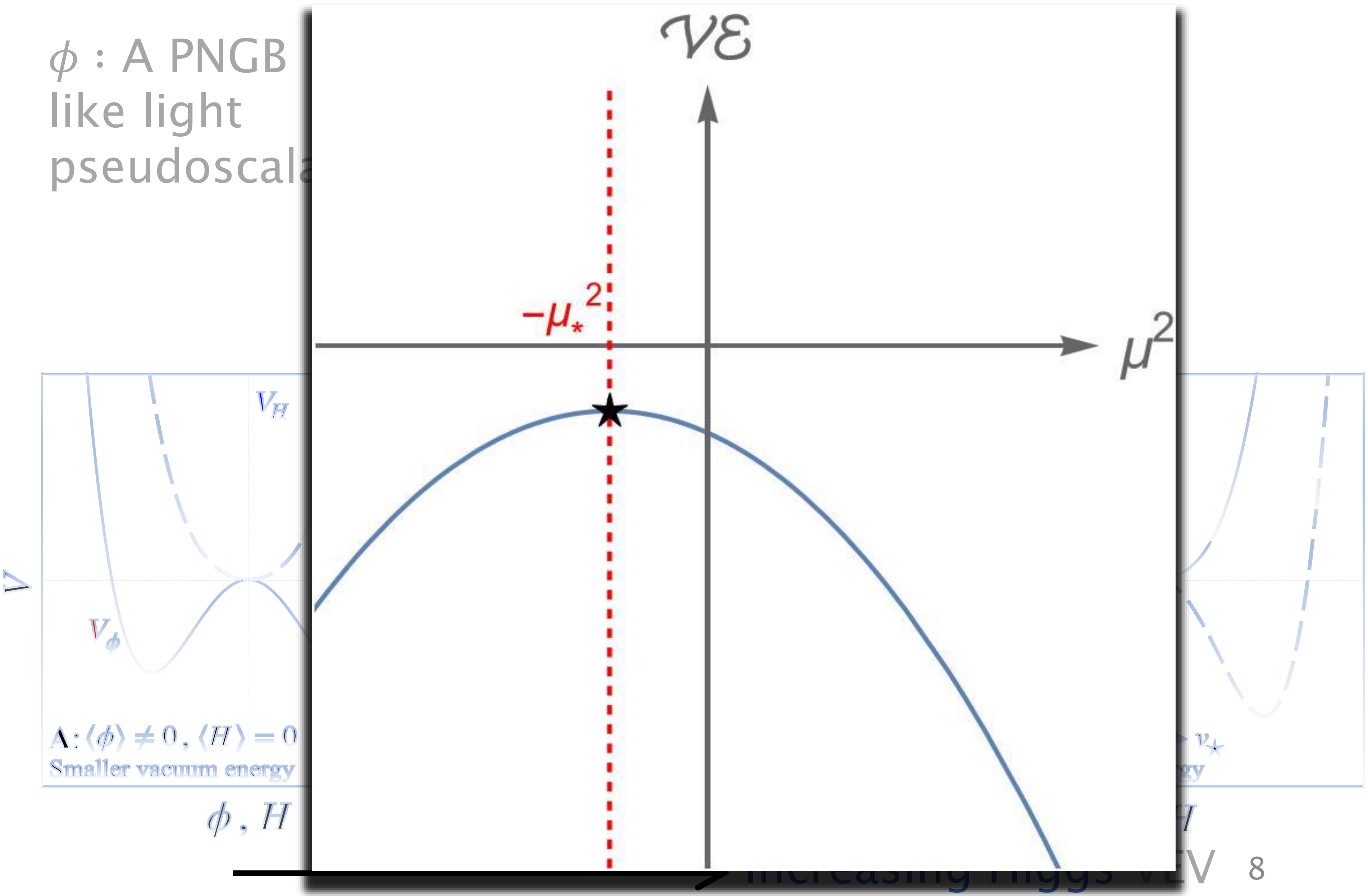
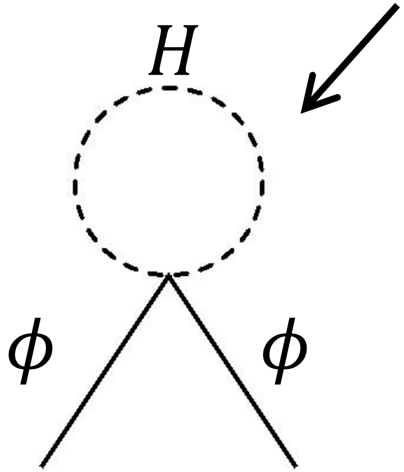


Selection Mechanism

Problem with 1 Higgs and 1 ϕ :

$$V_T(\phi, H) = \frac{\mu_\phi^2 f^2}{2} \kappa \left(\frac{|H|^2}{\mu_\phi f} \right) \left(\frac{\phi}{f} \right)^2$$



$$V_{1-\text{loop}} \sim \frac{\kappa \mu_\phi}{f} \frac{\Lambda^2}{16\pi^2} \phi^2$$

Spoils the Triggering mechanism!

Solution: Add another Higgs doublet.

The Model

$$V_{\rm 2HDM}(H_1,H_2) = \mu_1^2 H_1^\dagger H_1 + \mu_2^2 H_2^\dagger H_2 + \lambda_1 (H_1^\dagger H_1)^2 + \lambda_2 (H_2^\dagger H_2)^2 + \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 (H_2^\dagger H_1)(H_1^\dagger H_2) + \frac{1}{2}\left(\lambda_5 (H_1^\dagger H_2)^2 + \lambda_5^* (H_2^\dagger H_1)^2\right)$$

$$V_\phi(\phi) = \mu_\phi^2 f^2 \left(-\frac{1}{2}\left(\frac{\phi}{f}\right)^2 + \lambda_\phi \left(\frac{\phi}{f}\right)^4 + \dots \right)$$

$$V_T(\phi,H_1,H_2) = \frac{\mu_\phi^2 f^2}{2}\left(\kappa\left(\frac{H_1^\dagger H_2}{\mu_\phi f}\right) + h.c.\right)\left(\frac{\phi}{f}\right)^2$$

$$V(\phi,H_1,H_2) = V_{\rm 2HDM} + V_\phi + V_T$$

$$\text{Approximate } \mathbb{Z}_2 : H_1 \to -H_1 \Longrightarrow \Delta V_\phi^{2-loop} \sim \kappa^2 \frac{\mu_\phi^2}{f^2}\frac{\mu_\phi^2}{(16\pi^2)^2}\phi^2$$

Effective Triggering possible now!

The Cosmological Set-up

$$\mathcal{VE}^{(ijk)} = \mathcal{VE}_{\mathcal{H}}(\{\alpha_H^{(i)}\}, P(\phi, H_1, H_2)) + \mathcal{VE}_{\chi}(\{\beta_\chi^{(j)}\}, P(\chi))) + (\Lambda_{cc}^{(k)})^4$$

Higgs sector

Inflaton sector

Cosmological Constant

$$\{\alpha_H^{(i)}\} = \{\mu_1^2, \mu_2^2, \lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5, \kappa, |\mu_\phi^2|, \lambda_\phi\}$$

Inflationary Hubble

For $P(\phi, H_1, H_2)$ to sharply peak at the classical minima:

$$\frac{H_I^4}{v_\star^4} \ll 1, \qquad \frac{H_I^4}{\mu_\phi^2 f^2} \ll 1, \qquad \frac{f^2}{M_{pl}^2} \ll 1$$

The Cosmological Set-up

$$\mathcal{VE}^{(ijk)} = \mathcal{VE}_{\mathcal{H}}(\{\alpha_H^{(i)}\}, P(\phi, H_1, H_2)) + \mathcal{VE}_{\chi}(\{\beta_\chi^{(j)}\}, P(\chi))) + (\Lambda_{cc}^{(k)})^4$$

Inflationary dynamics would result in the multiverse being dominated by the vacuum state where each of the above terms—and in particular the Higgs contribution is maximized.

$$\Lambda_{\text{cutoff}} \sim \sqrt{H_I M_{pl}} \sim 10^{10}\ \text{GeV} \sqrt{H_I/v_\star}$$

For $P(\phi, H_1, H_2)$ to sharply peak at the classical minima: $\frac{H_I^4}{v_\star^4} \ll 1,\quad \frac{H_I^4}{\mu_\phi^2 f^2} \ll 1,\quad \frac{f^2}{M_{pl}^2} \ll 1$

Maximizing Vacuum Energy: Varying μ_1^2 and μ_2^2

Class-I	Class-II	Class-III
EW symmetry preserved: $\langle H_1 \rangle = \langle H_2 \rangle = 0$ $\langle \phi \rangle \neq 0$	EW symmetry broken and $\langle \phi \rangle \neq 0$	EW symmetry broken and $\langle \phi \rangle = 0$

Maximizing Vacuum Energy: Varying μ_1^2 and μ_2^2

Desired class of minima is selected if the quartics satisfy the following conditions:

Potential bounded from below: $\lambda_3 + \lambda_4 - |\lambda_5| + 2\sqrt{\lambda_1\lambda_2} \geq 0$

Class-III minima exist: $\lambda_4 - |\lambda_5| < 0$

Class-II minima do not co-exist with class-III: $\lambda_3 + \lambda_4 - \frac{\kappa^2}{8\lambda_\phi} - \left|\lambda_5 - \frac{\kappa^2}{8\lambda_\phi}\right| \leq -2\sqrt{\lambda_1\lambda_2}$

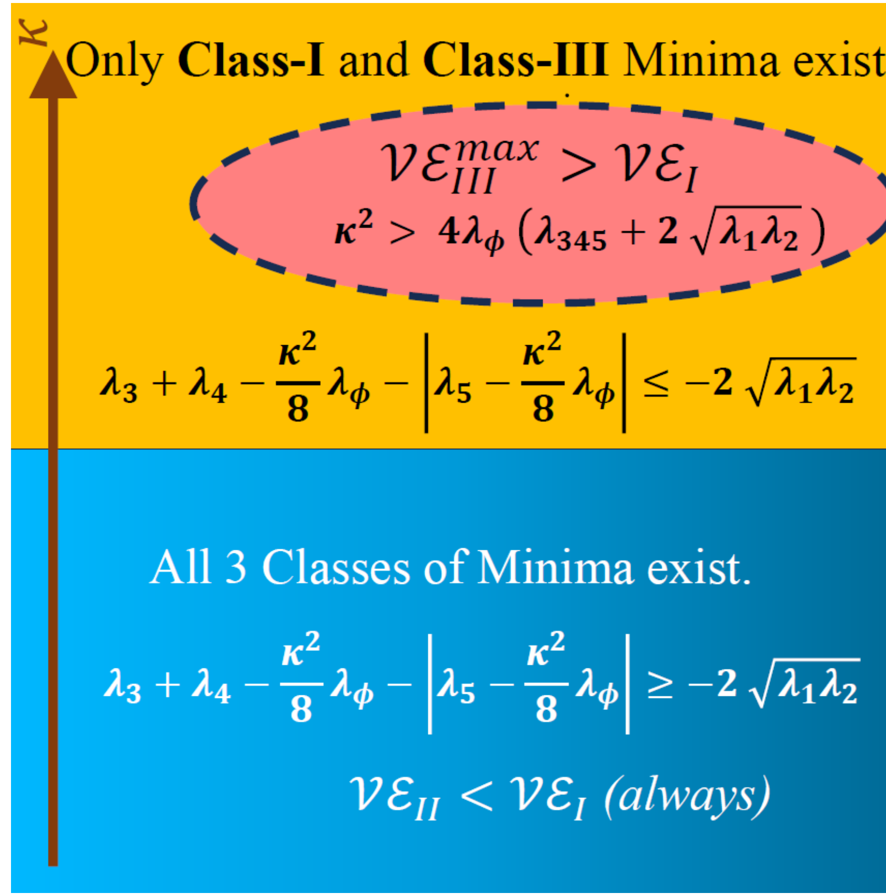
Vacuum energy of class-III > class-I: $\kappa^2 > 4\lambda_\phi(\lambda_{345} + 2\sqrt{\lambda_1\lambda_2})$

where $\lambda_{345} = \lambda_3 + \lambda_4 - |\lambda_5|$

Maximizing Vacuum Energy: Interplay of the Quartics

By varying the quartics, Class-III minima is always "SELECTED" during inflation.

Thus, ALL the previous conditions are automatically satisfied by requiring the maximal Vacuum energy!



$$v_\star^2 = \frac{\mu_\phi f}{\kappa s_{\beta_\star} c_{\beta_\star}} \quad \& \quad \tan^2\beta_\star = \sqrt{\frac{\lambda_1}{\lambda_2}}$$

Predictions: 2HDM Pheno

$$\tan^2 \beta_* = \sqrt{\frac{\lambda_1}{\lambda_2}}$$

125 GeV

$$\cos \alpha = \sqrt{\frac{m_h^2 - m_H^2 \tan^2 \beta}{(m_h^2 - m_H^2)(1 + \tan^2 \beta)}}$$

Decays of CP-even Higgs bosons

Can be directly measured at the LHC

Charged Higgs/Pseudoscalar decays

Requiring maximal vacuum energy gives **a precise, falsifiable prediction.**

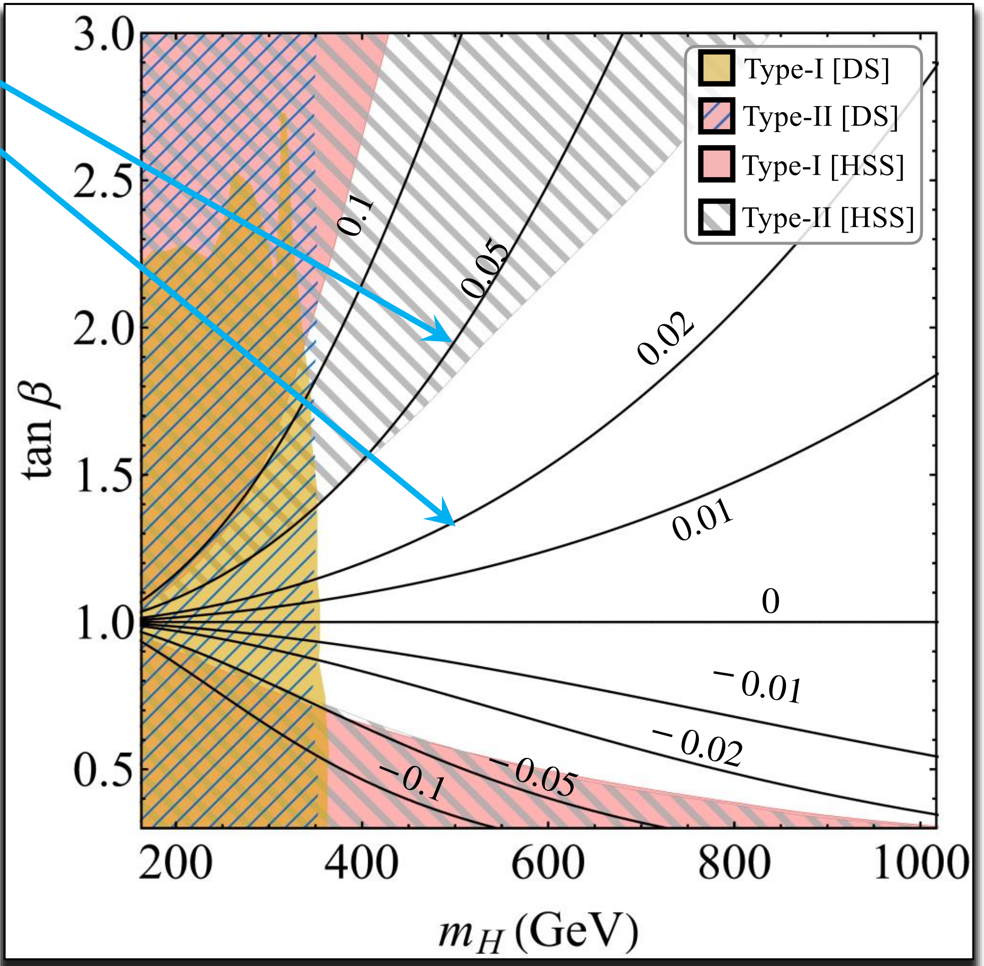
Predictions: 2HDM Pheno

Precise, falsifiable prediction: $\cos\alpha = \sqrt{\dfrac{m_h^2 - m_H^2 \tan^2\beta}{(m_h^2 - m_H^2)(1+\tan^2\beta)}}$

Contours of $\cos(\alpha - \beta)$

⇕

Deviations in couplings of the lighter Higgs from SM values. (HSS)



DS bounds: $H \to \gamma\gamma$

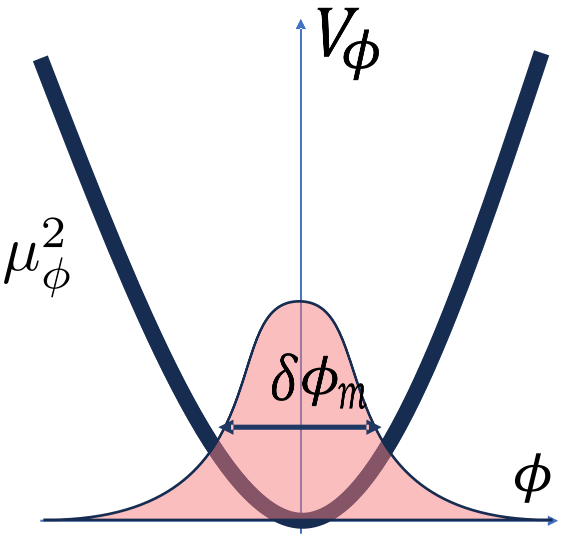
$H/A \to \tau\tau$

Charged Higgs bounds come mainly from $b \to s\,\gamma$ processes and can always be evaded by choosing $m_{H^+} \gtrsim 650$ GeV.

Pheno of ϕ: The 2 regimes

$$V_\phi = m_\phi^2 \phi^2 + \lambda_\phi \frac{\mu_\phi^2}{f^2} \phi^4$$

$$\text{where} \quad m_\phi^2 = \left(-\mu_\phi^2 + \kappa \frac{\mu_\phi}{f} v_\star^2 s_{\beta_\star} c_{\beta_\star}\right) \equiv \epsilon^2 \mu_\phi^2$$



To obtain $P(\phi)$, we solve the modified FPV equation:

$$\frac{\partial P}{\partial t} = \frac{\partial}{\partial \phi}\left[\frac{H_I^3(\phi)}{8\pi^2}\frac{\partial P}{\partial \phi} + \frac{V'(\phi)}{3H_I(\phi)} P\right] + 3H_I(\phi) P \;\Rightarrow\; \delta\phi_m$$

The 2 scales: $\delta\phi_m \quad \& \quad \delta\phi_q \sim \frac{\epsilon f}{\sqrt{\lambda_\phi}}$

Quadratic Regime ($\rho_\phi \sim a^{-3}$): $\delta\phi_m \sim \frac{H_I^2}{m_\phi} \quad (\text{for} \;\; \delta\phi_m \ll \delta\phi_q)$

Quartic Regime ($\rho_\phi \sim a^{-4}$): $\delta\phi_m \sim \frac{H_I}{\lambda_\phi^{1/4}}\sqrt{\frac{f}{\mu_\phi}} \quad (\text{for} \;\; \delta\phi_m \gg \delta\phi_q)$

Pheno of ϕ: The 2 regimes

$$\mathcal{L}_{\phi^2 SM} = -c_e \frac{\phi^2}{f^2} m_e \bar{e} e - c_q \frac{\phi^2}{f^2} m_q \bar{q} q + c_\gamma \frac{\phi^2}{f^2} \frac{\alpha_{em}}{4\pi} F_{\mu\nu} F^{\mu\nu} + c_g \frac{\phi^2}{f^2} \frac{\alpha_s}{4\pi} G^a_{\mu\nu} G^{a,\mu\nu}$$

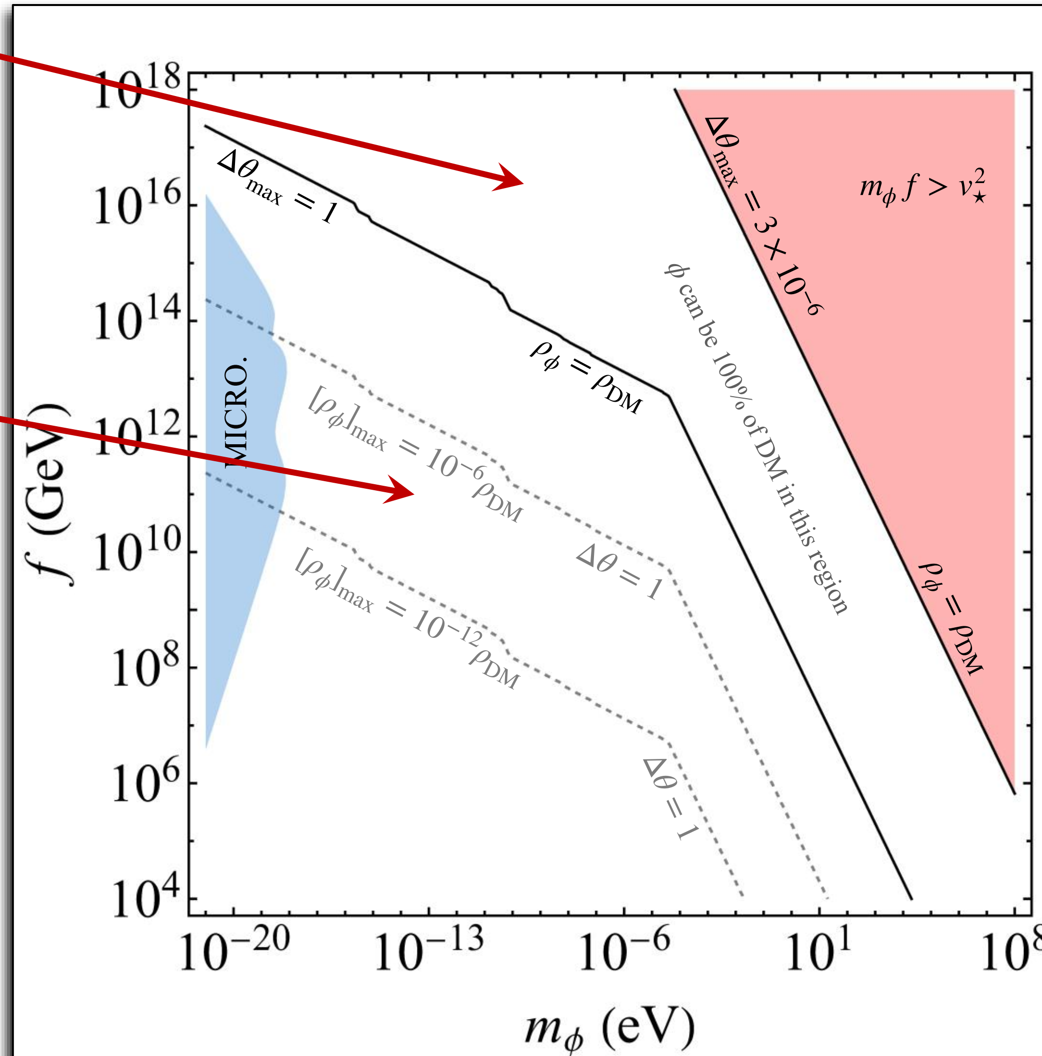
"Dark Matter" band: ϕ can explain the obs. dark matter density here.

ϕ can explain only a fraction of obs. dark matter density here.

Experiments:

1. Violation of eq. principle (eg: MICROSCOPE)

2. Time variation of fundamental constants in atomic physics exps.



Plethora of recent works

1. G. Dvali and A. Vilenkin, “Cosmic attractors and gauge hierarchy,” (2004)
2. G. Dvali, “Large hierarchies from attractor vacua,” (2006)
3. P. W. Graham, D. E. Kaplan, and S. Rajendran, “Cosmological Relaxation of the Electroweak Scale,” (2015)
4. N. Arkani-Hamed, T. Cohen, R. T. D'Agnolo, A. Hook, H. D. Kim, and D. Pinner, “Solving the Hierarchy Problem at Reheating with a Large Number of Degrees of Freedom,” (2016)
5. C. Cheung and P. Saraswat, “Mass Hierarchy and Vacuum Energy,”(2018)
6. G. F. Giudice, A. Kehagias, and A. Riotto, “The Selfish Higgs,”(2019)
7. A. Strumia and D. Teresi, “Relaxing the Higgs mass and its vacuum energy by living at the top of the potential,” (2020)
8. C. Csaki, R. T. D'Agnolo, M. Geller, and A. Ismail, “Crunching Dilaton, Hidden Naturalness,” (2020)
9. M. Geller, Y. Hochberg, and E. Kuflik, “Inflating to the Weak Scale,” (2019)
10. N. Arkani-Hamed, R. T. D'Agnolo, and H. D. Kim, “The Weak Scale as a Trigger,” (2020)
11. G. F. Giudice, M. McCullough, and T. You, “Self-Organised Localisation,” (2021)
12. R. Tito D'Agnolo and D. Teresi, “Sliding Naturalness,” (2021)
13. R. Tito D'Agnolo and D. Teresi, “Sliding Naturalness: Cosmological selection of the weak scale” (2022)

Mostly from the last decade

Key Features of our model

- A **generic PNGB potential** for ϕ; NO clockwork needed.
- ϕ-field value **never exceeds the cutoff f**,let alone the Planck scale.
- Unlike the anthropic principle for weak scale, our mechanism **doesn't restrict the variation of other model parameters** as the Higgs VEV is varied.
- Maximizing the vacuum energy **automatically selects** regions with desirable properties.
- **Precise, falsifiable 2HDM prediction** that can be tested in present and future colliders.
- ϕ can account for the **observed DM density** and can be probed in exps. looking for **violation of equivalence principle** and **variation of fundamental constants**.
- Compatible with the "**stationary measure**" during eternal inflation. Also, compatible with **Weinberg's anthropic argument for Λ_{cc}**. (described in details in our paper.)

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Thank You !!!