Crunchy, critical, natural Higgs

(on the hierarchy problem, vacuum selection, and metastability)

Ameen Ismail

MI Seminar

2502.07876 + WIP w/ S. Benevedes and T. Steingasser
(also 2007.143976, 2210.02456)

Eight years ago!

(my first time visiting Kingston)

(only picture I could find from that trip)

(no, I don't know why I'm posing like that, ask 18-year old Ameen)

THE UNIVERSITY OF CHICAGO

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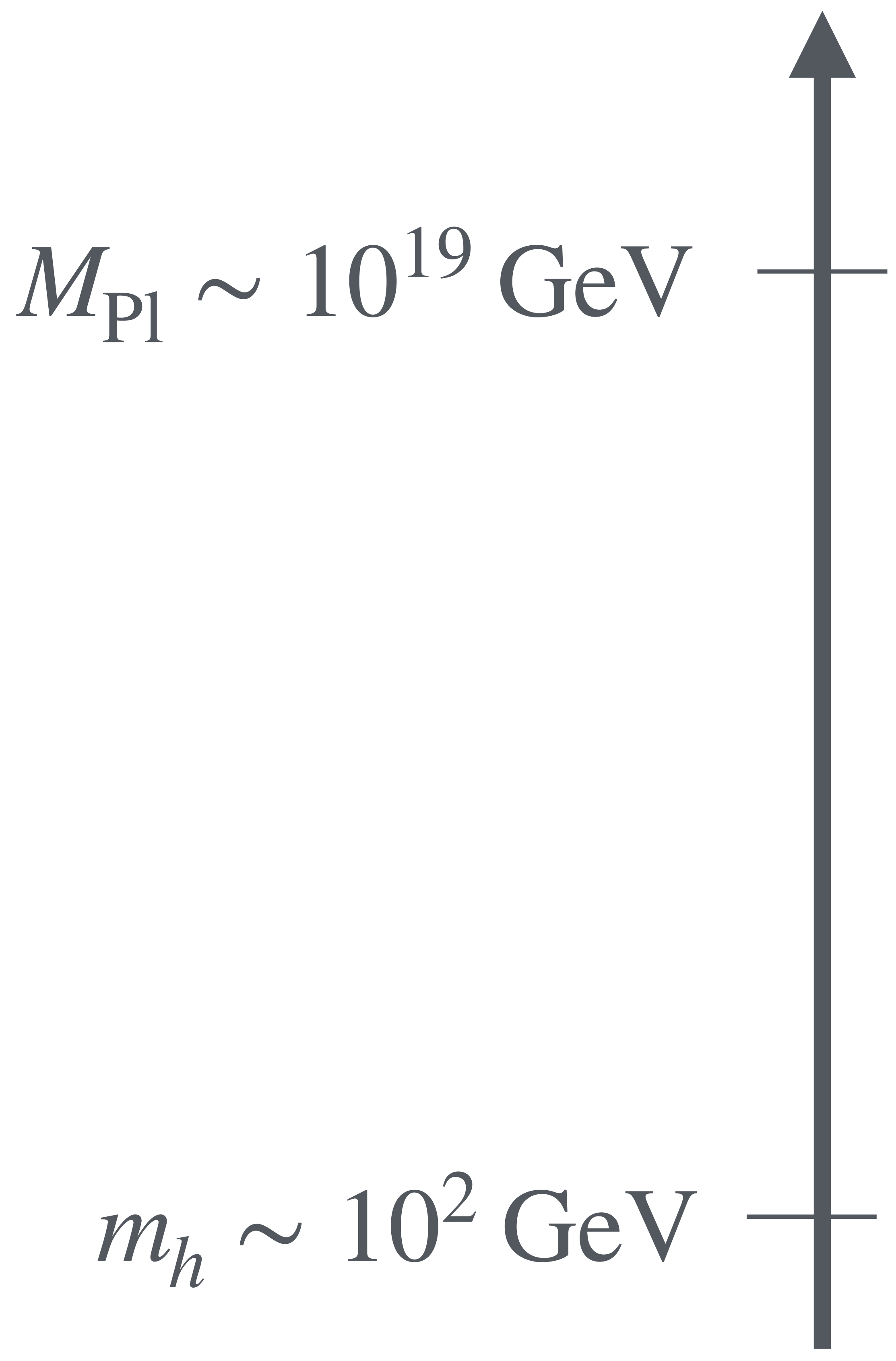
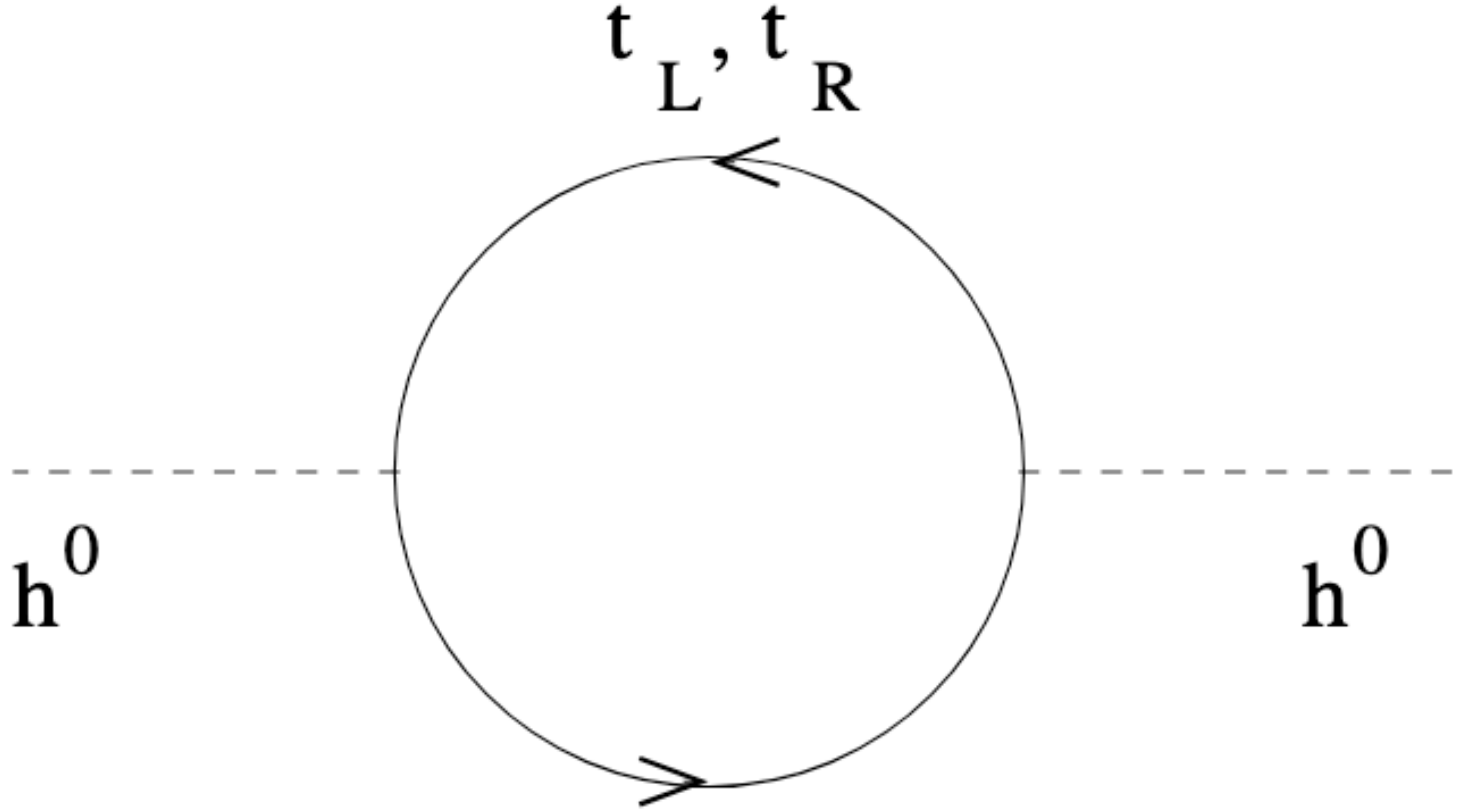
The hierarchy problem

- The Higgs mass is a relevant operator unprotected by symmetry
  - so we expect mass gets Planck-scale quantum corrections
  - implies Higgs mass is finely tuned without new physics
- Traditional solutions protect m_h^2 with a symmetry:
  - e.g. weak-scale SUSY, compositeness, RS
  - typically predict new coloured states (top partners)



Not the hierarchy problem

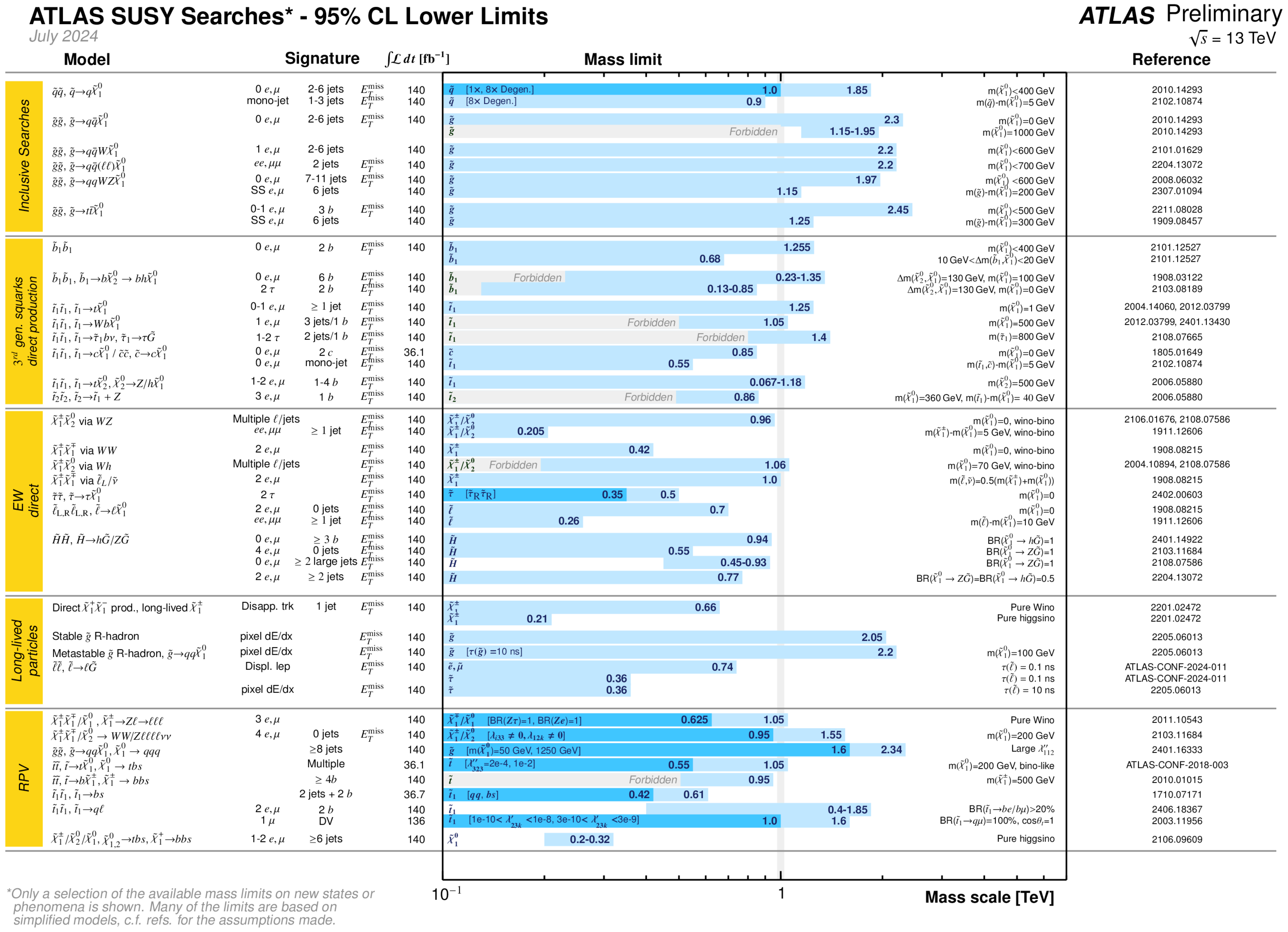
- I know how to regularize a loop diagram, I promise
- Fundamental issue is the **origin** of the weak scale, and **IR sensitivity** to UV parameters
- The loop diagram is shorthand to illustrate this sensitivity when we're too lazy to do better



$$\delta m_h^2 \sim \frac{y_t^2}{16\pi^2}\Lambda_{\mathrm{UV}}^2$$

Why bother with the Higgs hierarchy?

- Symmetry-based solutions are increasingly constrained by the LHC
- By no means am I saying they are dead!
- But it's natural to speculate of other approaches that could have different phenomenology



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Some great ideas I won't talk about

(beyond this slide, anyway)

- Neutral naturalness / twin Higgs
- Relaxion and similar models
- NNaturalness
- I will focus on **vacuum selection**

The Twin Higgs: Natural Electroweak Breaking from Mirror Symmetry

Z. Chacko,[1] Hock-Seng Goh,[1] and Roni Harnik[2]

[1] *Department of Physics, University of Arizona, Tucson, AZ 85721*
[2] *Department of Physics, University of California, Berkeley, CA 94720*
Theoretical Physics Group, Lawrence Berkeley National Laboratory, Berkeley, CA 94720

Cosmological Relaxation of the Electroweak Scale

Peter W. Graham,[1] David E. Kaplan,[1,2,3,4] and Surjeet Rajendran[3]

[1] *Stanford Institute for Theoretical Physics, Department of Physics, Stanford University, Stanford, CA 94305*
[2] *Department of Physics & Astronomy, The Johns Hopkins University, Baltimore, MD 21218*
[3] *Berkeley Center for Theoretical Physics, Department of Physics, University of California, Berkeley, CA 94720*
[4] *Kavli Institute for the Physics and Mathematics of the Universe (WPI), Todai Institutes for Advanced Study, University of Tokyo, Kashiwa 277-8583, Japan*

(Dated: June 24, 2015)

***N*naturalness**

***N*ima Arkani-Hamed,[1] Timothy Cohe*N*,[2] Raffaele Tito D'Ag*N*olo,[1]
A*N*son Hook,[3] HyuNg Do Kim,[4] and David Pi*N*ner[5]

[1] *School of Natural Sciences, Institute for Advanced Study, Princeton, New Jersey 08540, USA*
[2] *Institute of Theoretical Science, University of Oregon, Eugene, OR 97403, USA*
[3] *Stanford Institute for Theoretical Physics, Stanford University, Stanford, CA 94305, USA*
[4] *Department of Physics and Astronomy and Center for Theoretical Physics, Seoul National University, Seoul 151-747, Korea*
[5] *Princeton Center for Theoretical Science, Princeton University, Princeton, NJ 08544, USA*

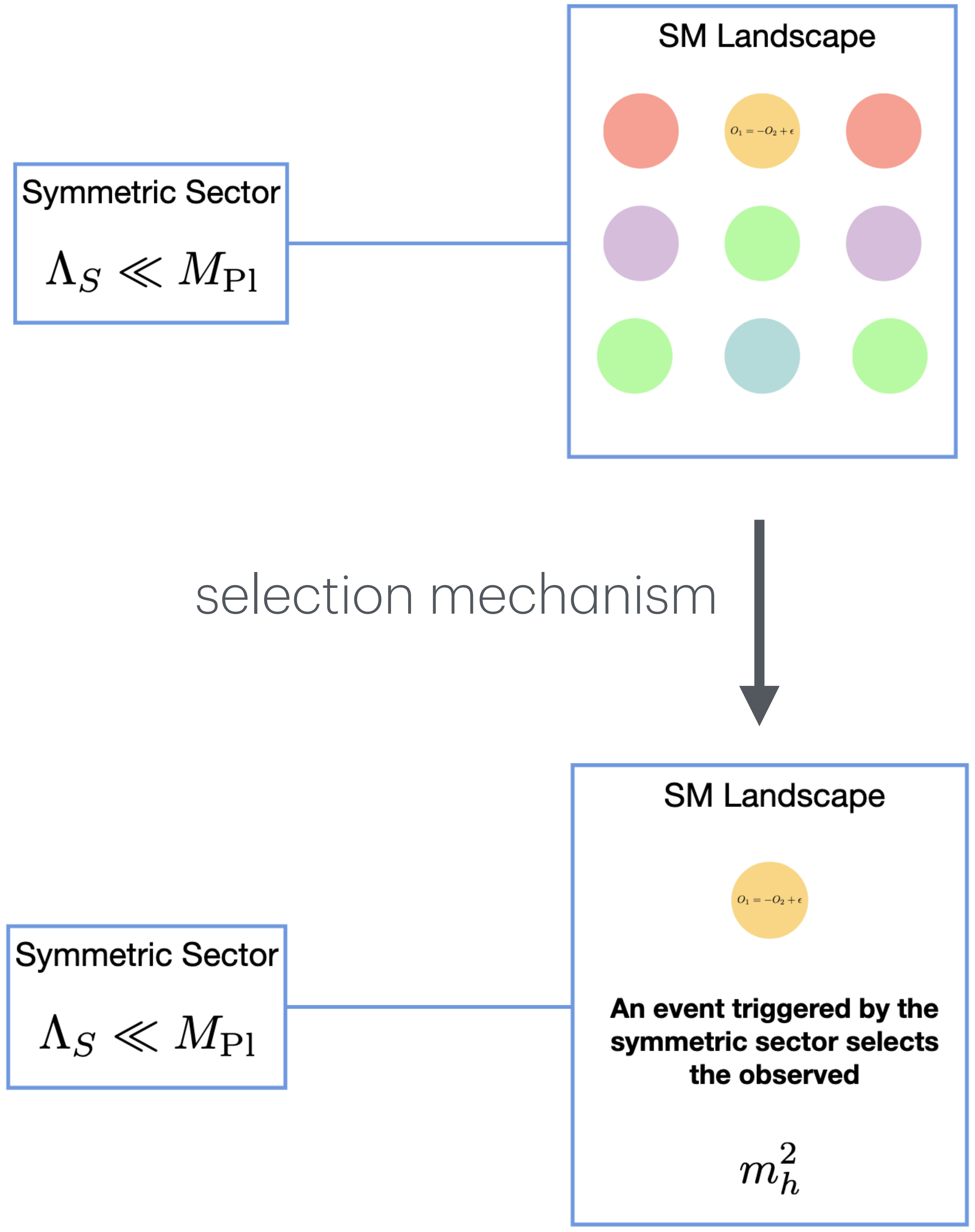
Outline

- **Cosmological naturalness / dynamical vacuum selection**
- How a metastable Higgs can select the EW scale
- Two explicit models and their phenomenology
- Tying up loose ends, and future work (time permitting)

Cosmological naturalness

(vacuum selection)

- Landscape scans the Higgs mass: $m_h^2 \in (-\Lambda^2, \Lambda^2)$
- New physics removes all patches **except** those with a fine-tuned EW scale
- e.g. scalar field triggers cosmo. **crunch**
- Typical pheno: light, weakly-coupled scalar mixing with Higgs



modified from 2109.13249

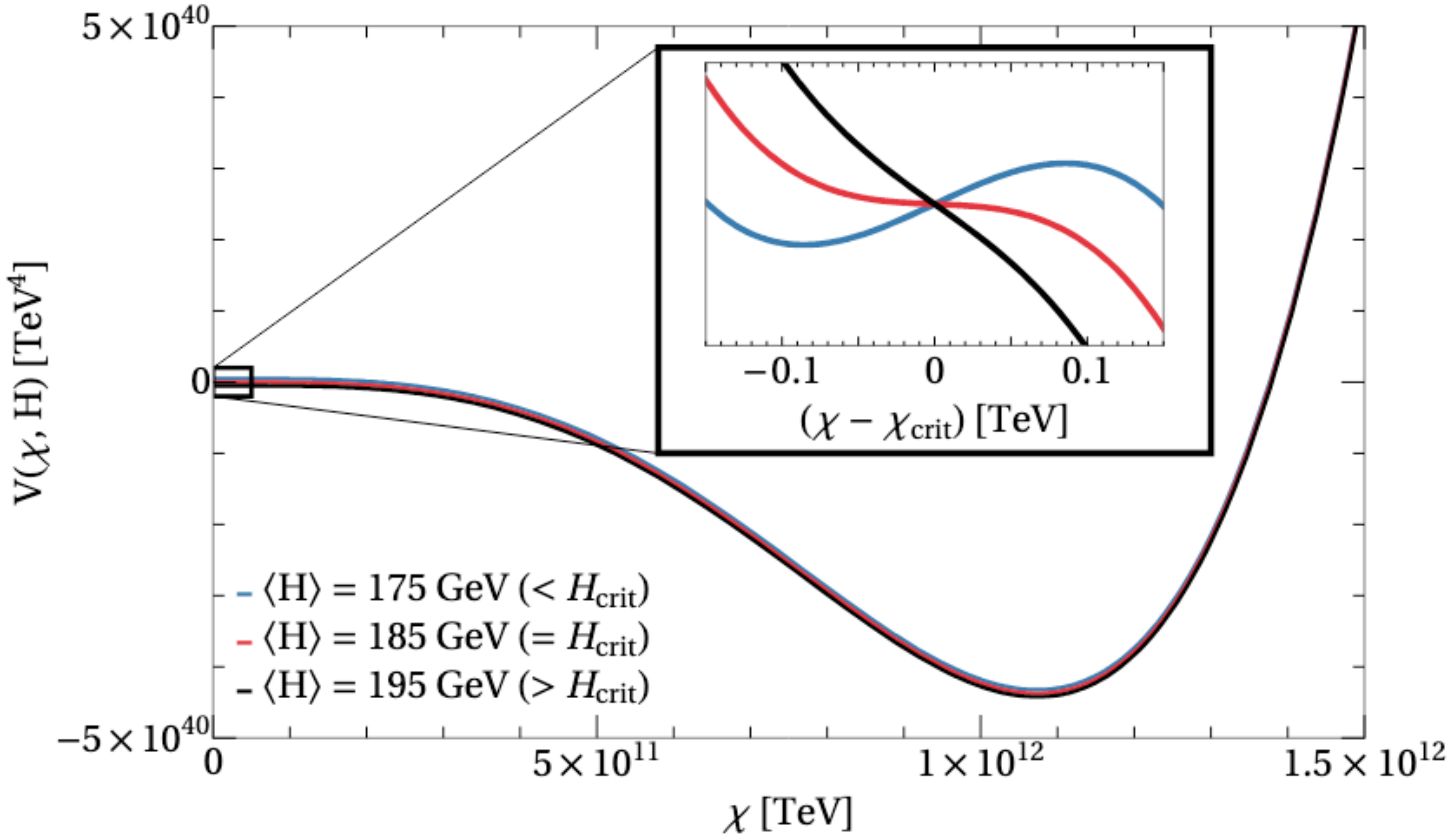
Cosmological naturalness pheno

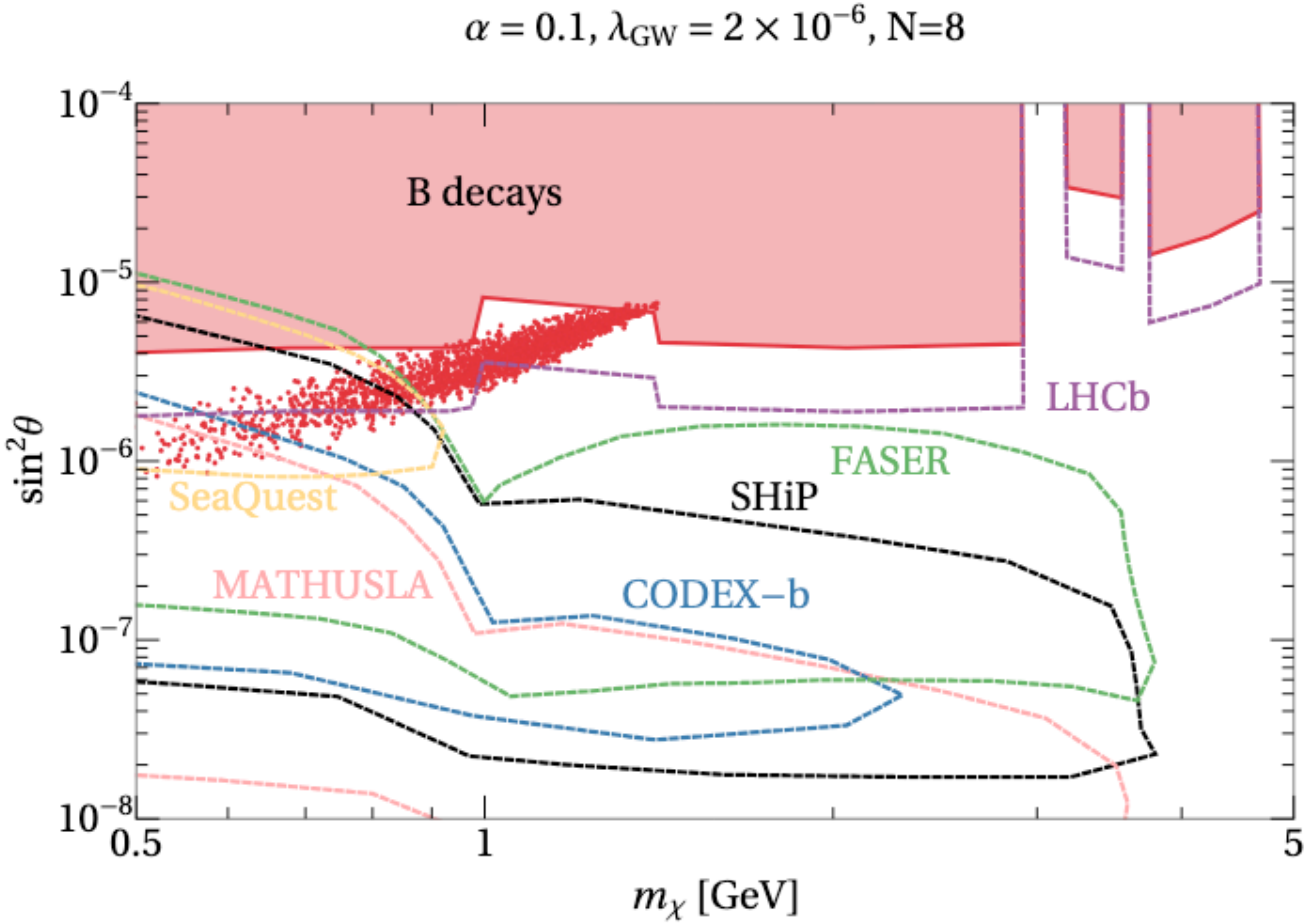
- Potential must be **sensitive** to EW-scale Higgs VEVs
- SM Higgs no good: nothing "special" about EW scale, nothing happens when m^2 crosses 0!
- So, need* a new scalar ϕ
  - Should couple to a good "trigger operator" like $G\tilde{G}$ (c.f. relaxion) (see 2012.04652)
  - Should be light compared to observed EW scale

*or we can change the Higgs potential; see the rest of this talk.

An example

Crunching dilaton, hidden naturalness (2007.14396)





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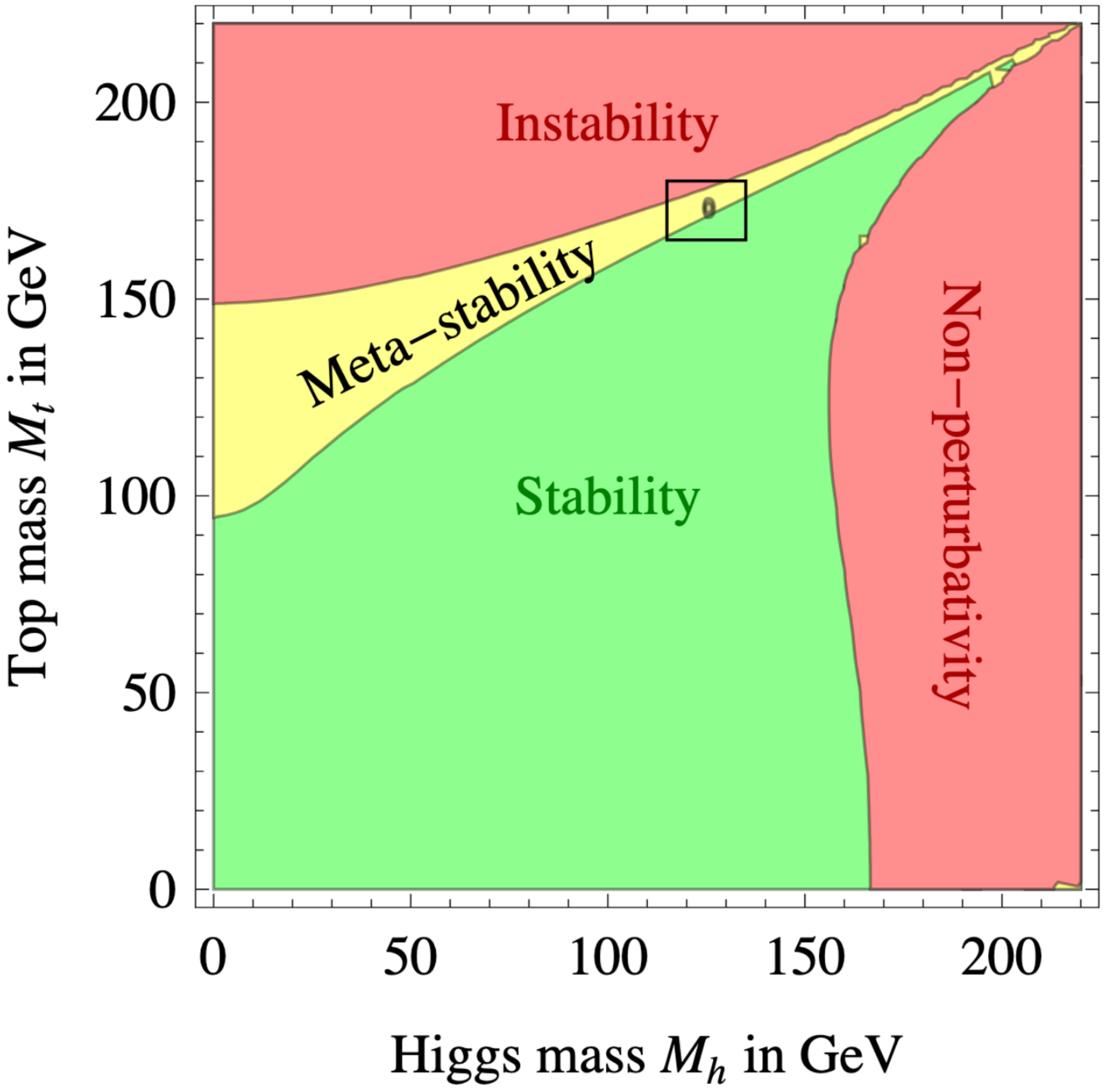
Electroweak metastability

- In the SM, EW vacuum seems to be metastable
- Quartic runs negative at **instability scale**:
  $\lambda(\mu_I) = 0, \ \mu_I \sim 10^{10}\,\mathrm{GeV}$
- Possible connections to EW hierarchy?
  - self-organized criticality (e.g. 2003.12594, 2105.08617)
  - metastability bounds (e.g. 2108.09315, 2408.10297)



1205.6497

The big picture

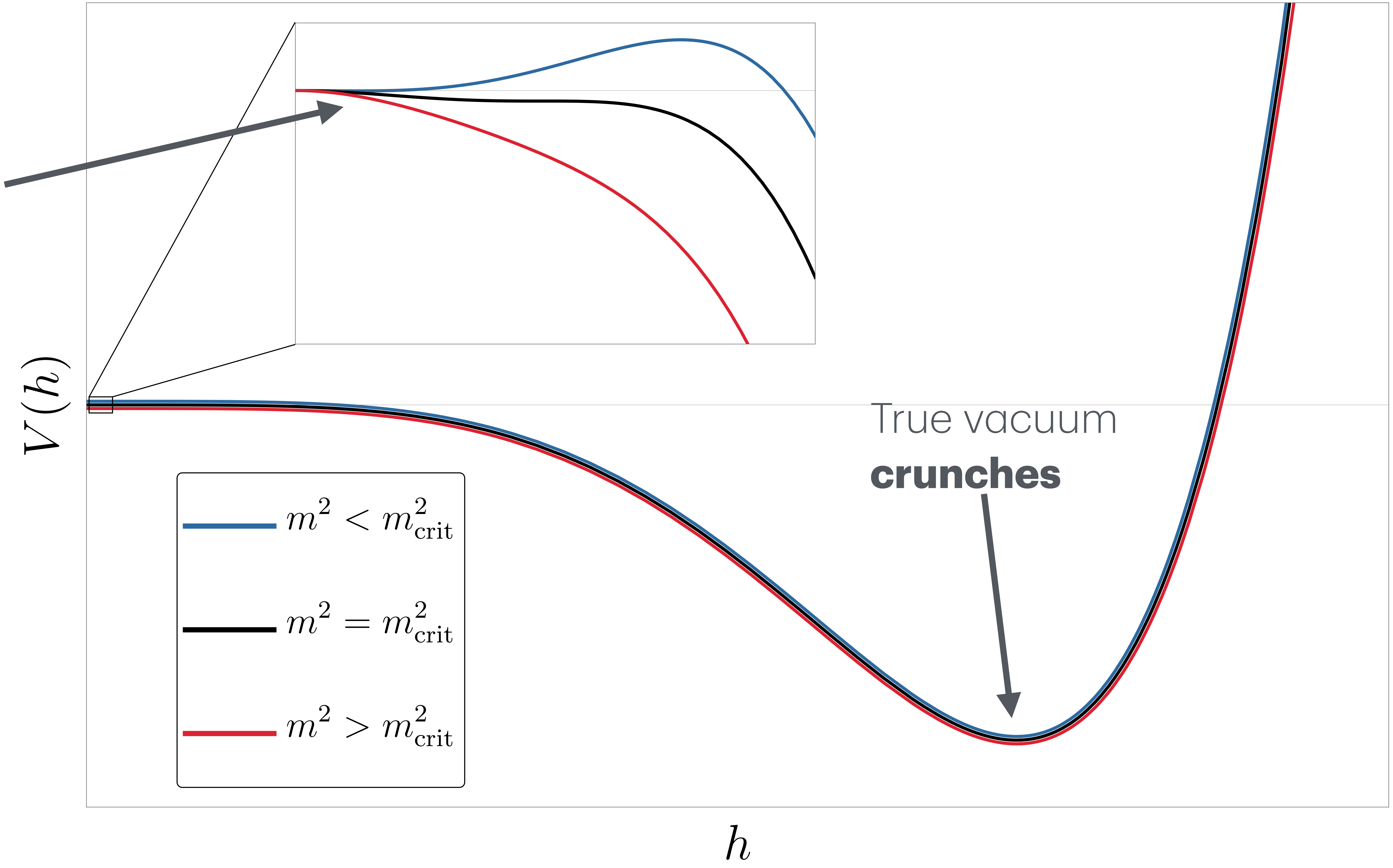
Vacuum selection via Higgs metastability

- Suppose the following:
  - There is a **landscape** that scans the Higgs mass: $V_i(h) = -m_i^2 h^2 + \lambda(h) h^4$
  - The Higgs quartic runs negative at a scale μ_I; the EW vacuum is **metastable**
  - The true vacuum, generated by UV physics, has a **large and negative** energy density
- Claim: this is sufficient to **dynamically select the EW scale** if $\mu_I \sim \mathrm{TeV}$

Potential sketch

False vacuum exists **only** when m^2 is fine-tuned:

$$m^2 < m^2_{\text{crit}} \sim \mu_I^2$$



The big picture

What patches survive until today?

- If $m^2 < m^2_{\text{crit}}$, the Higgs sits in a metastable minimum — standard cosmological history
- If $m^2 > m^2_{\text{crit}}$ there is only the true minimum — the Higgs rolls down and triggers a **crunch**

The only patches that avoid a crunch have a fine-tuned Higgs.

- But we need $m_{\text{crit}} \sim \mu_I \sim \text{TeV}$ to select the observed EW scale — requires **new physics**

Three objections

- Patches that preserve EW symmetry (positive m^2)
  - These are not crunched away, so we need another way to excise such patches
  - Several ways to accomplish this; not my main focus (see Csáki, D'Agnolo, Geller, **AI** '20; D'Agnolo, Teresi '21)
- Lifetime of the false vacuum
  - Lowering μ_I destabilizes vacuum — need to ensure our patch is long-lived
  - Later, we'll use this to bound the scale of a UV completion
- CC problem: I'll assume anthropics, but dynamical mechanisms also possible (see 1912.08840)
- **More on all of these things later!**

One-loop estimate

- Potential: $V_{\text{eff}}(h) = -\frac{1}{4}m^2h^2 + \frac{1}{4}\lambda(h)h^4, \quad \lambda(h) = -b\log\frac{h}{\mu_I}$

instability scale

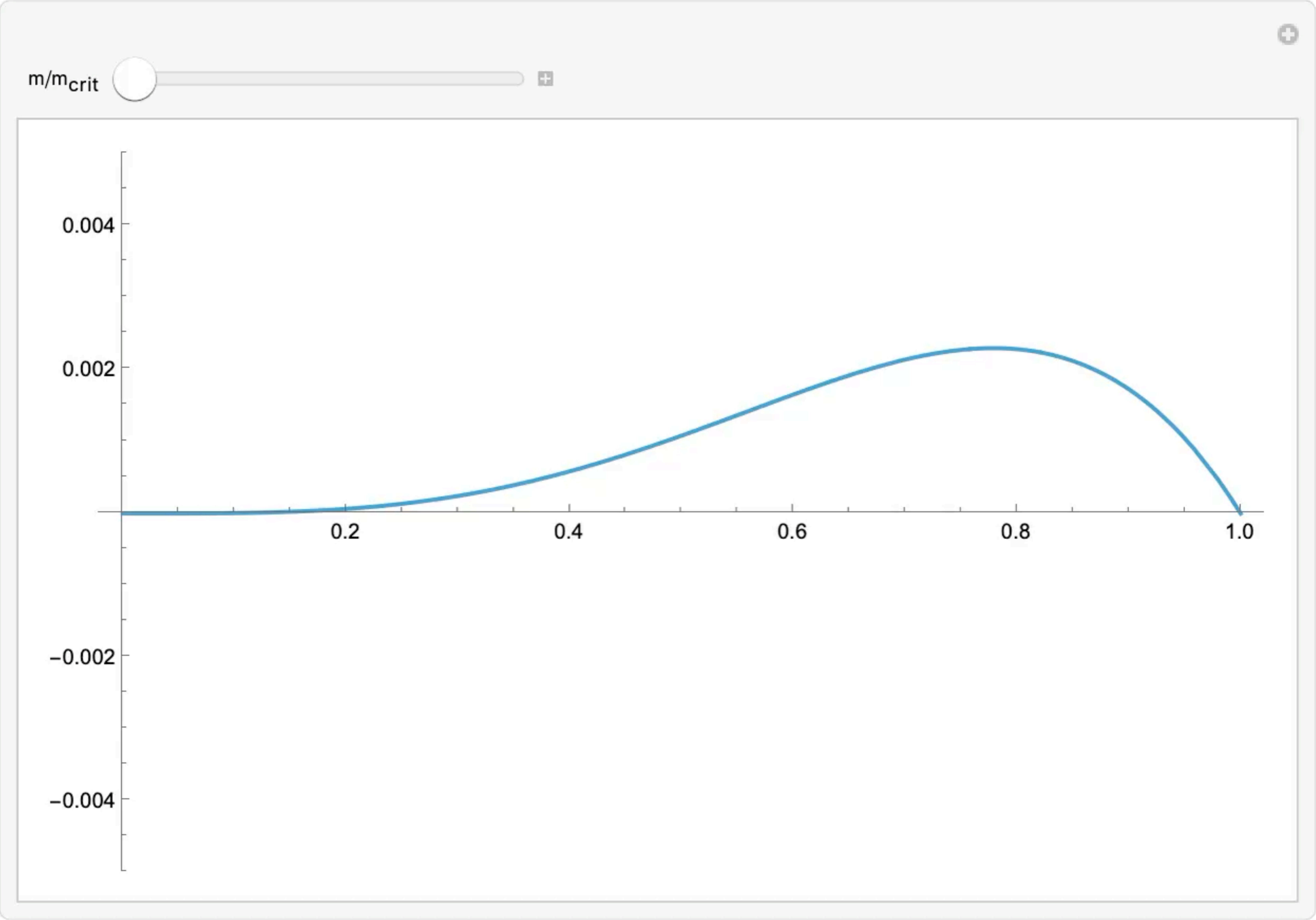
negative β-function

- VEV satisfies $\frac{1}{2}|b|\,v^2\left(1 + 4\log\frac{v}{\mu_I}\right) = m^2$

- Maximized at

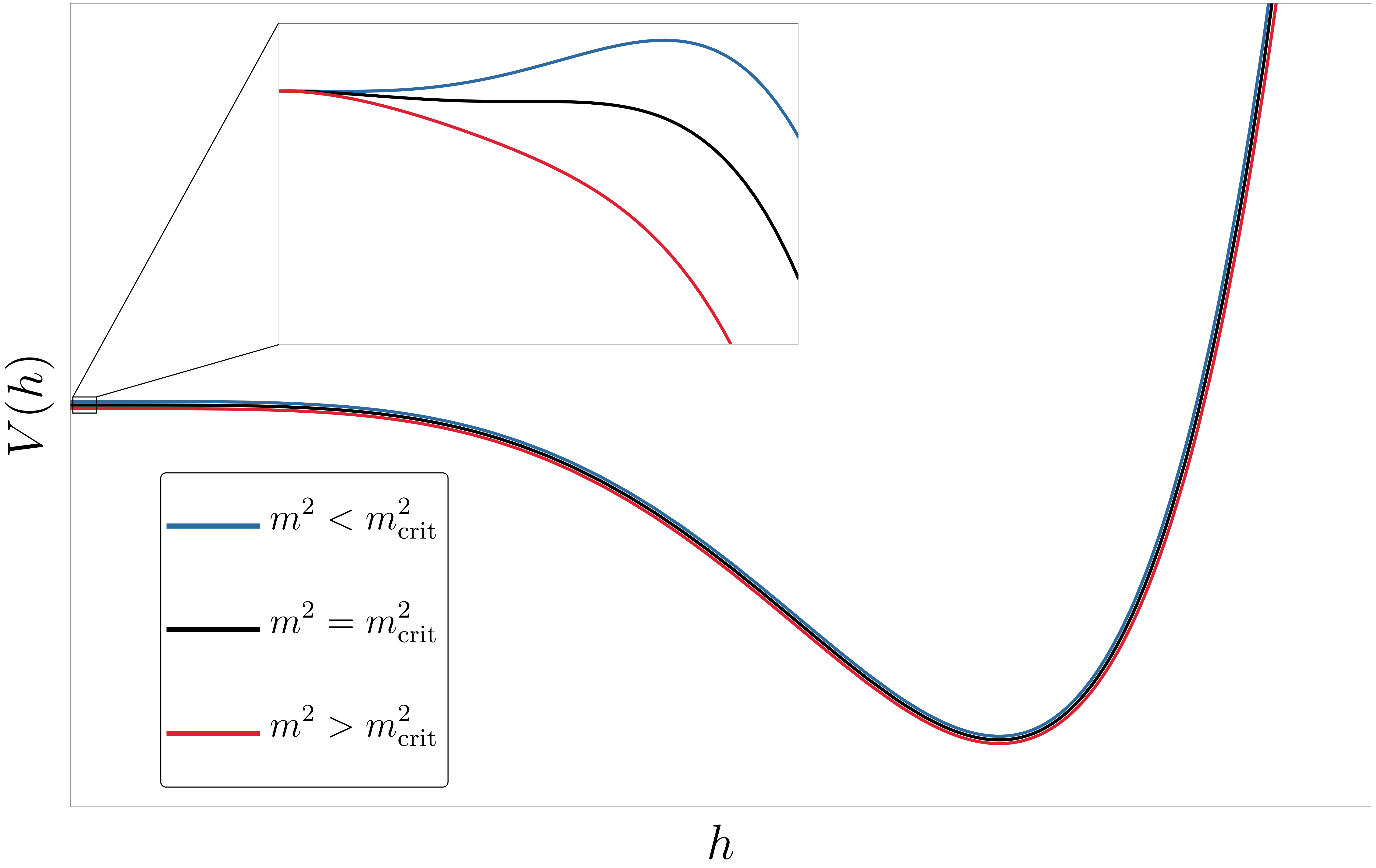
$$\boxed{v_{\text{crit}} = e^{-3/4}\mu_I,\ m^2_{\text{crit}} = e^{-3/2}\,|b|\,\mu_I^2}$$

One-loop estimate



Vacua

False vacuum exists only when $m < m_{\text{crit}}$, typical energy density $V_{\text{eff}}(v) \sim b\mu_I^4$



Can have $\mu_I \ll \Lambda_{\text{UV}}$; instability scale generated by dim'l transmutation

True vacuum presumably generated by higher-dim operators, typical energy density $-\Lambda_{\text{UV}}^4$

Beyond one loop?

- We can be more careful, e.g. by including dim-6 term $C_6 \left|H\right|^6/\Lambda_{\mathrm{UV}}^2$:

$$\frac{m^2}{|\beta_\lambda(\mu_I)|\,\mu_I^2} = 2\frac{h^2}{\mu_I^2}\left[6\frac{C_6}{|\beta_\lambda(\mu_I)|}\frac{\mu_I^2}{\Lambda^2}\frac{h^2}{\mu_I^2} - \ln\left(\frac{h}{\mu_I}e^{1/4}\right)\right]$$

(existence of false vacuum)

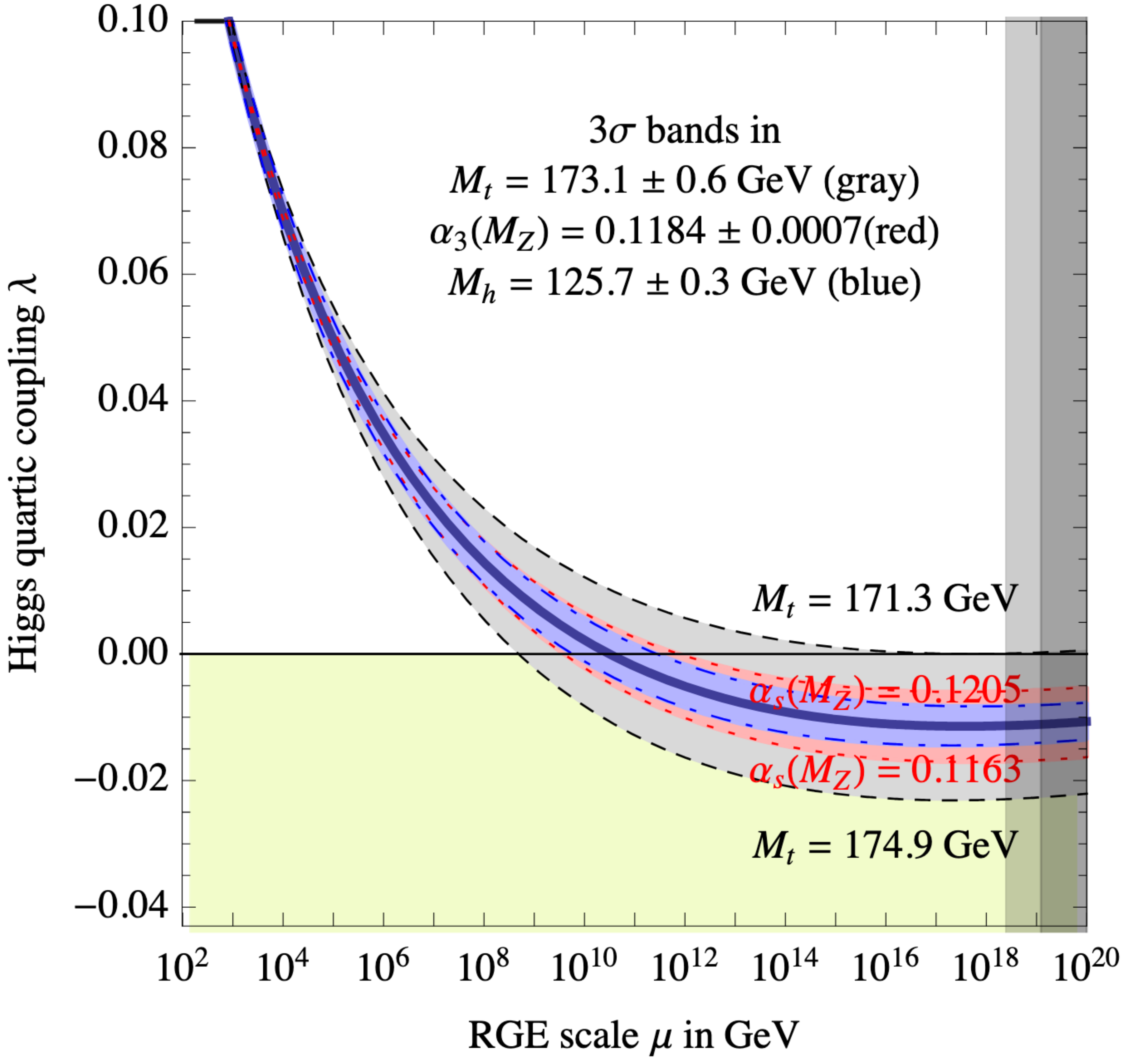
- **Qualitative story unchanged** as long as $\mu_I \ll \Lambda_{\mathrm{UV}}$:
  - metastable minimum when $m^2 \lesssim \mu_I^2$
  - large separation in vacuum energy b/w false and true vacua

Outline

- Cosmological naturalness / dynamical vacuum selection
- How a metastable Higgs can select the EW scale
- **Two explicit models and their phenomenology**
- Tying up loose ends, and future work (time permitting)

μ_I in the SM and beyond

- Recall $\mu_I \sim 10^{10}\,\mathrm{GeV}$ in the SM
- To address EW hierarchy, we want $\mu_I \sim \mathrm{TeV}$
- Our approach: add **vector-like fermions** at a TeV!



1205.6497

TeV-scale vector-like fermions

- Distinct phenomenology from existing approaches (both symmetry-based solutions and other vacuum selection mechanisms)
- We’ll focus on two simple models: **HNL** and **singlet-doublet** models
- Upshot: probe directly and indirectly at future lepton colliders

Two simple models

i) heavy neutral lepton

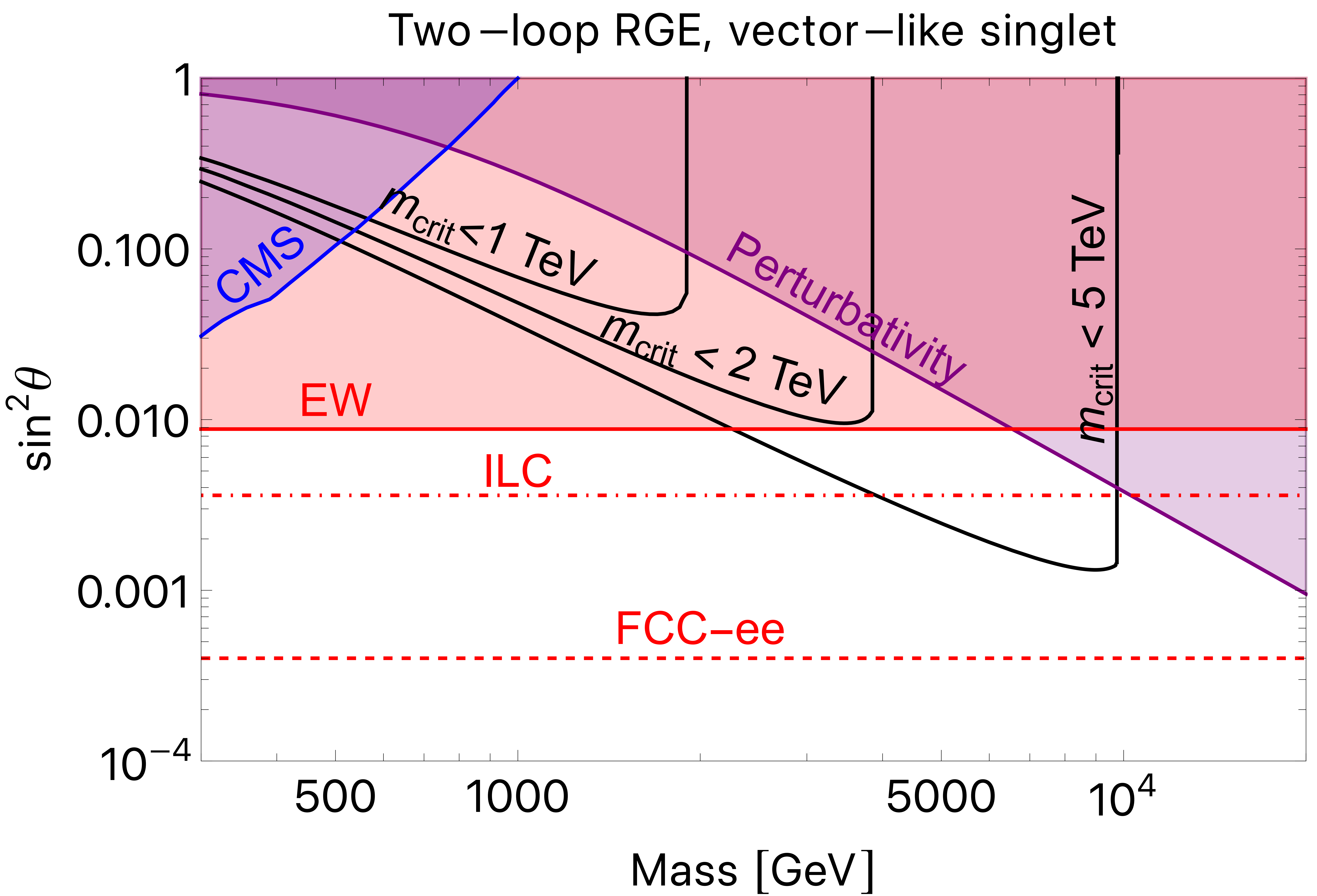
- Minimal model: vector-like pair of singlets ψ_L, ψ_R

$$-\mathscr{L}_\psi \supset M\overline{\psi_L}\psi_R + y_i\overline{L_i}\tilde{H}\psi_R + \mathrm{h.c.}$$

- Take $y_{1,2} = 0,\ y_3 = y$ — after EWSB, ψ mixes with ν_τ through an angle

$$\sin^2\theta = \frac{y^2v^2/2}{y^2v^2/2 + M^2}$$

- Drives down instability scale: $16\pi^2\Delta\beta = -\,2y^4 + 4\lambda y^2$



Two−loop RGE, vector−like singlet
1
0.100
0.010
0.001
10^{-4}
$\sin^2\theta$
500
1000
5000
10^4
Mass [GeV]
CMS
m_{crit}<1 TeV
m_{crit} < 2 TeV
m_{crit} < 5 TeV
Perturbativity
EW
ILC
FCC−ee

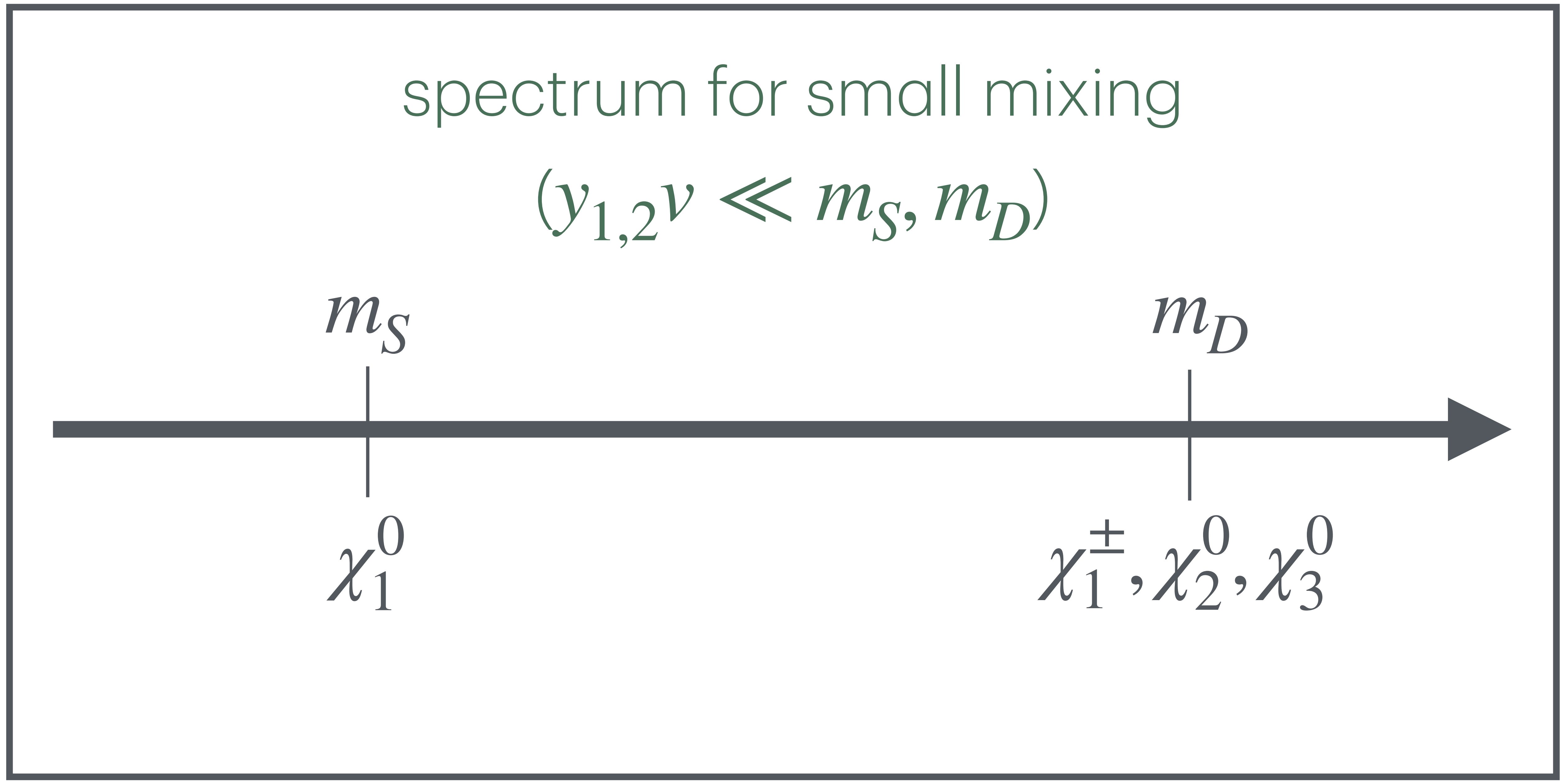
Two simple models

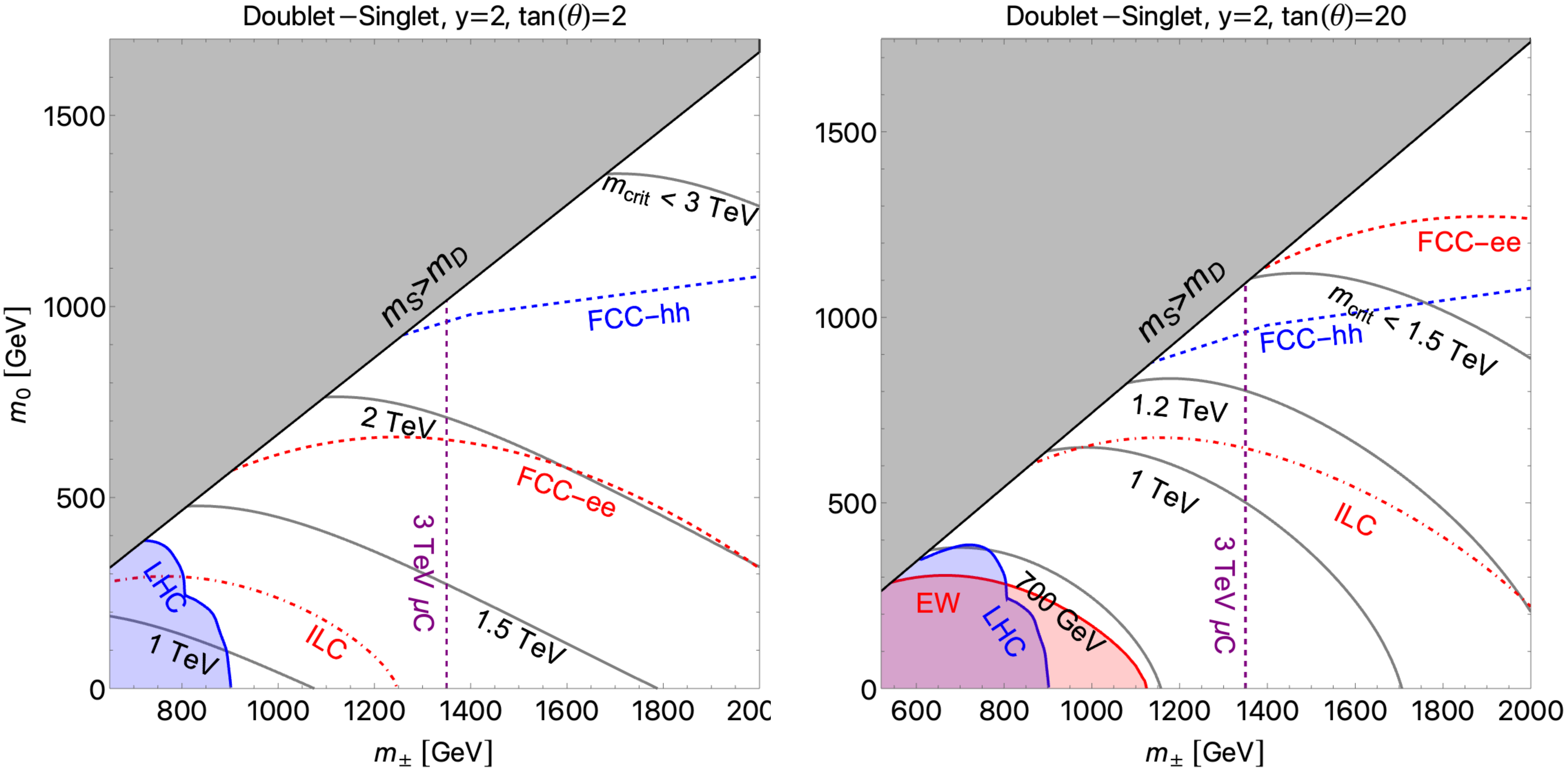
ii) singlet-doublet

- Singlet ψ_L, pair of SU(2) doublets $\chi_{L,R}$ with $Y = 1/2$

$$-\mathscr{L} \supset \frac{1}{2} m_S \overline{\psi_L} \psi_L + m_D \overline{\chi_R} \chi_L - y_1 \chi_L \tilde{H} \psi_L - y_2 \overline{\chi_R} H \psi_L$$

- Mimics Higgsino-bino system in the MSSM:
  - charged Dirac fermion with $m_\pm = m_D$
  - three neutral Majorana fermions
- Assume $m_S < m_D$ (analogy: bino-like LSP)





Doublet − Singlet, y=2, tan(θ)=2
Doublet − Singlet, y=2, tan(θ)=20
m_0 [GeV]
$m_\pm$ [GeV]
$m_S > m_D$
m_{crit} < 3 TeV
m_{crit} < 1.5 TeV
FCC−hh
FCC−ee
ILC
LHC
EW
3 TeV μC
2 TeV
1.5 TeV
1.2 TeV
1 TeV
700 GeV

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Loose end 1: vacuum lifetime

- Requiring EW vacuum lifetime to exceed age of universe:

$$\boxed{\lambda \gtrsim -0.06}$$

(Isidori, Ridolfi, Strumia '01)

- Now we can bound the new physics scale
  - For HNL model with $M = 3\ \mathrm{TeV}, m_{\mathrm{crit}} = 5\ \mathrm{TeV}$, find $\Lambda_{\mathrm{stab}} \sim 10^3\ \mathrm{TeV}$
  - New physics could modify either the running or the tree-level potential
- Scale Λ_{stab} does **not** need to be the same as scale of true vacuum

Possible UV completions?

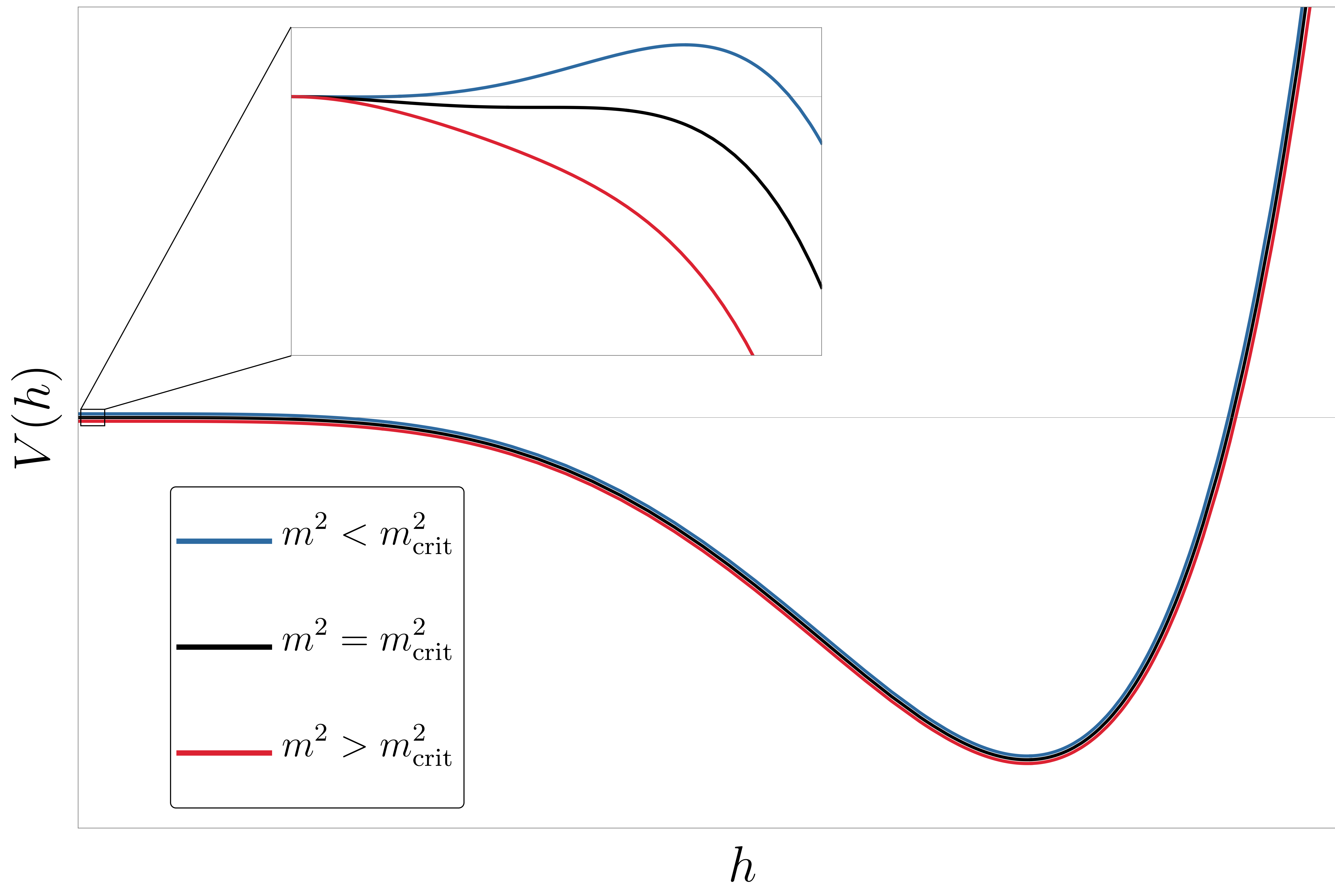
- Majoron model of neutrino masses (see 2503.22787)
  - Stabilizes via tree-level modification of potential (dim-6 term)
  - Without fine-tuning, $\Lambda_{\rm stab} \sim \Lambda_{\rm UV}$
- Near-conformal UV fixed point
  - Quartic approaches a constant $\lambda_{\rm UV} \gtrsim -0.06$ at high scales
  - Can naturally have $\Lambda_{\rm stab} \ll \Lambda_{\rm UV}$

Loose end 2: positive m^2

- Key point: patches where the Higgs VEV is too large crunch

- Generically expect patches with positive mass-squared, which will **always** have a metastable minimum at the origin!

- Let's see an explicit way to deal with them (likely not the only one)



One way out

(adapted from 2106.04591)

- Ultralight scalar ϕ w/ approximate shift symmetry:

$$V_\phi = -\frac{1}{2}m_\phi^2\phi^2 - \frac{1}{4}\lambda_\phi\phi^4 - \frac{\alpha_s}{8\pi f}\phi G\tilde{G}$$

- Some comments:
  - Expect $\lambda_\phi \sim m_\phi^2/M^2 \ll 1$, w/ shift symmetry broken at M
  - (Rel)axion-like coupling generated at UV scale f

One way out
(adapted from 2106.04591)

- Potential below the QCD scale:

$$V_\phi = -\frac{1}{2}m_\phi^2\phi^2 - \frac{1}{4}\lambda_\phi\phi^4 - \Lambda^4\cos\phi/f = \frac{1}{2}\left(-m_\phi^2 + \frac{\Lambda^4}{f^2}\right)\phi^2 - \frac{1}{4}\left(\lambda + \frac{\Lambda^4}{f^4}\right)\phi^4 + \ldots$$

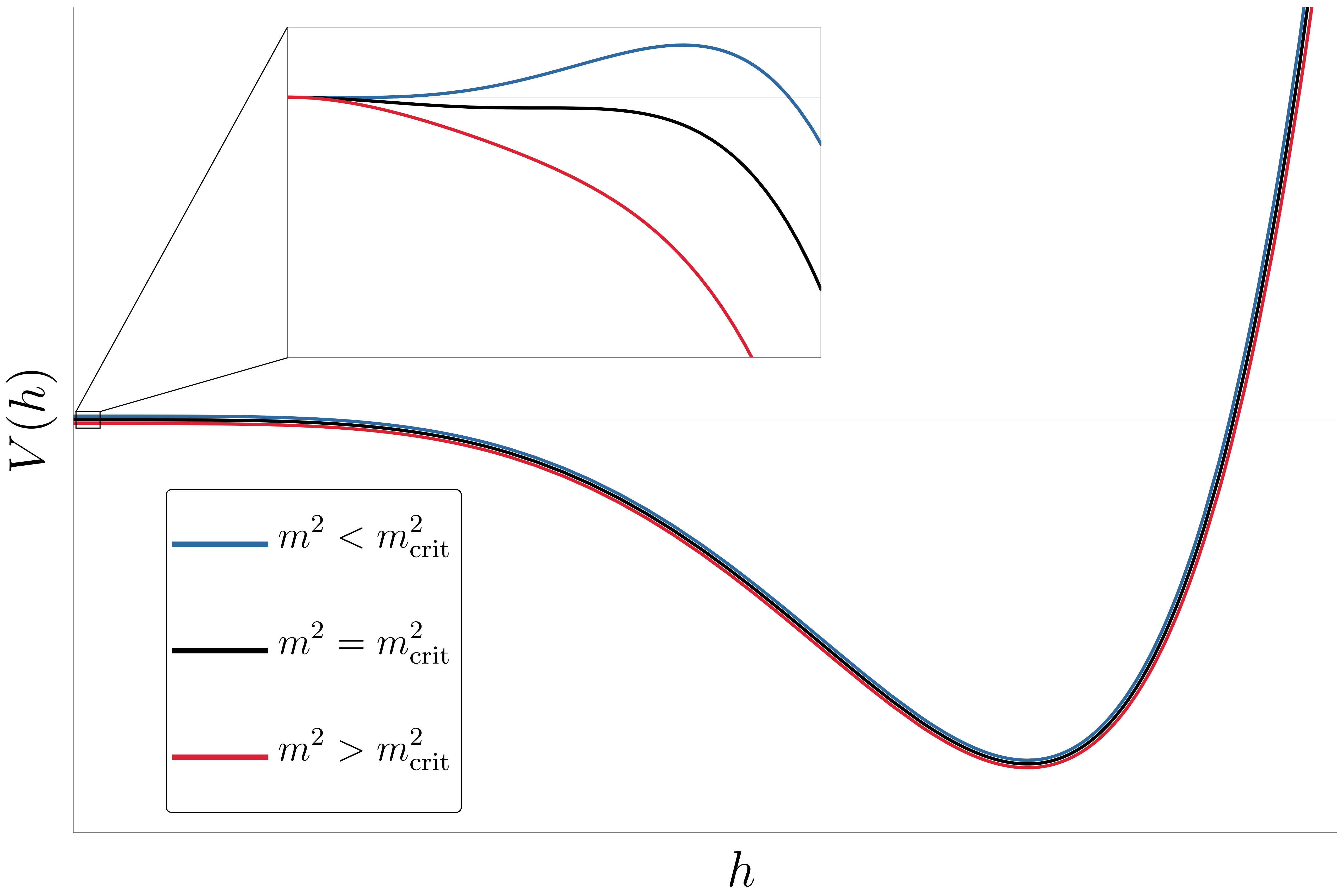
- Stable minimum for ϕ iff $\Lambda^4 \gtrsim m_\phi^2 f^2$

- But recall $\Lambda^4 \propto v$ (GOR relation), hence:

$\boxed{\text{Patches with small or vanishing Higgs VEV will crunch.}}$

Loose end 3: the CC problem

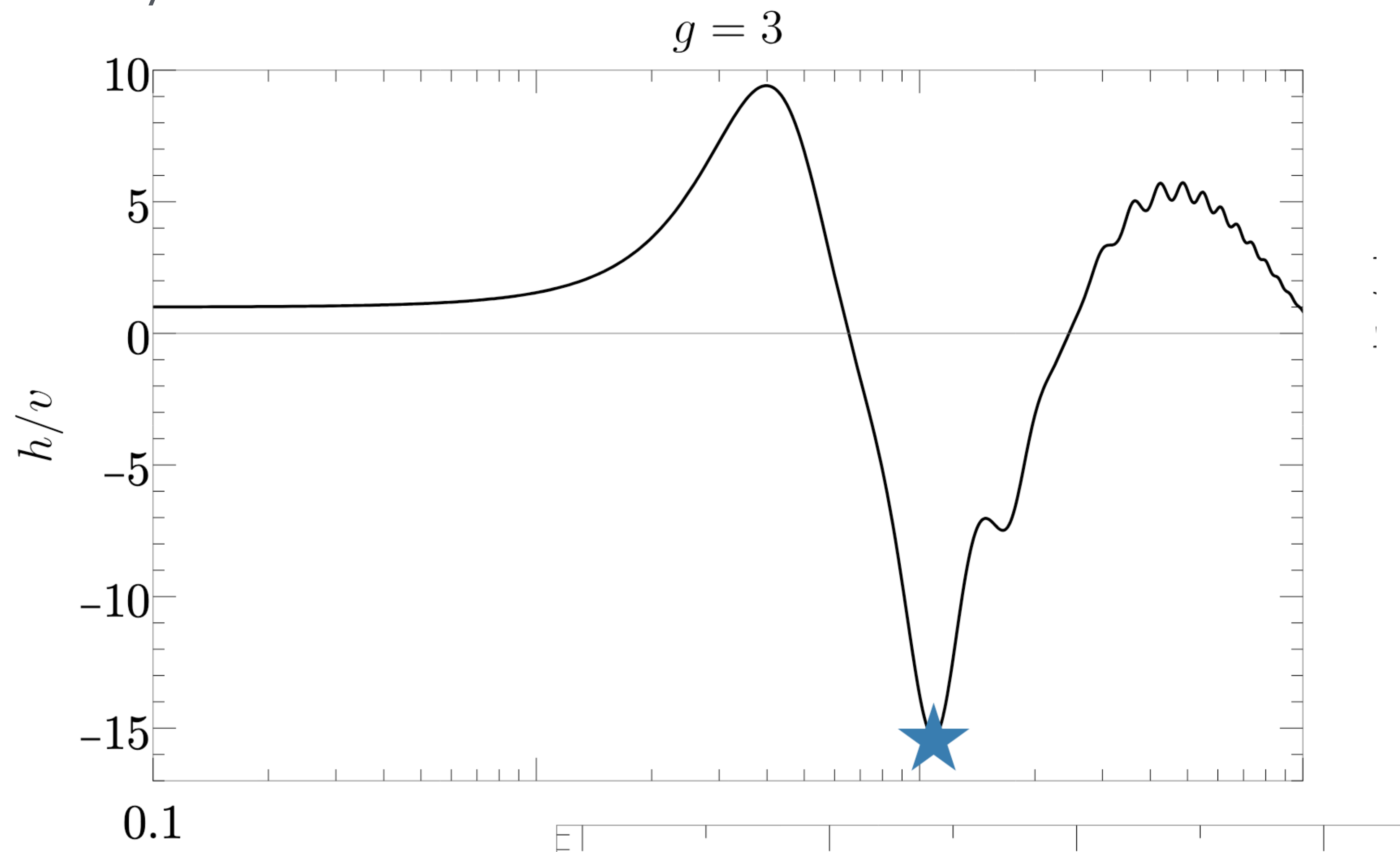
- Energy density of false vacuum: $\sim \mu_I^4$
- Energy density of true vacuum: $\sim \Lambda_{\mathrm{UV}}^4$
- Assume landscape for CC up to a cutoff scale Λ_{CC}
- Need $\mu_I \lesssim \Lambda_{\mathrm{CC}} \lesssim \Lambda_{\mathrm{UV}}$, so we can solve CC problem in false vacuum but true vacuum still crunches

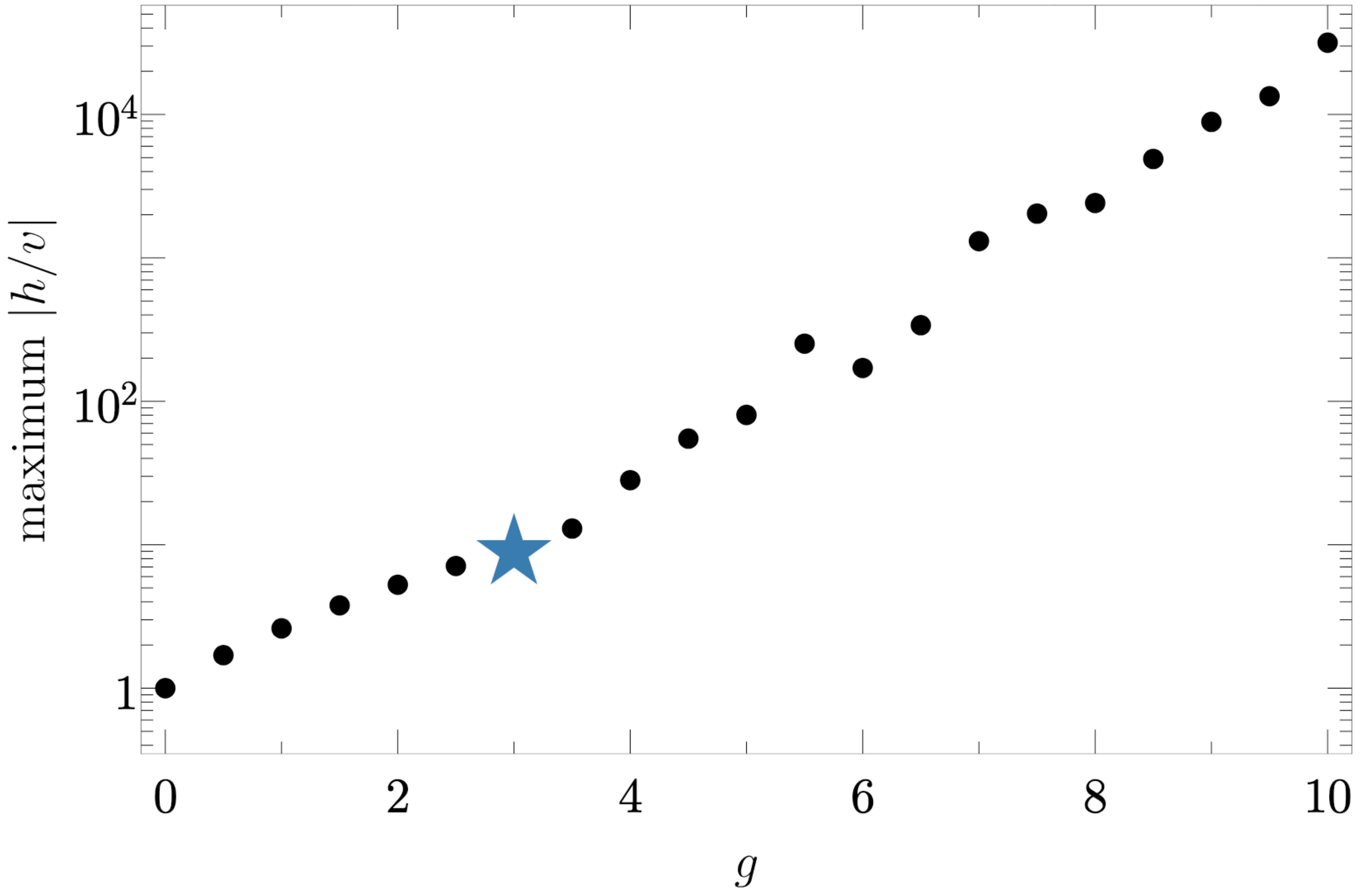


Resonance during preheating

An alternative to lowering the instability scale?

- Consider an inflaton-Higgs coupling $\phi\,|H|^2$
- Inflaton oscillates, leading to **tachyonic resonance** effect
- Exponentially large fluctuations of Higgs field (which could push it over the potential barrier and into the true vacuum!)





Resonance during preheating

An alternative to lowering the instability scale?

- To avoid a crunch, Higgs needs to lie near origin after inflation
- Assuming $H_I \lesssim v$, after inflation Higgs sits in its VEV $h = v/\sqrt{2}$
- N.B. this is very preliminary!

Summary and outlook

- This is a new take on the hierarchy problem, in which metastability helps select the EW scale
- Differences from existing ideas:
  - Symmetry-based solutions — sure, we need new particles at a TeV, but they have nothing to do with cancelling quadratic divergences
  - Other dynamical selection mechanisms — the Higgs potential itself is responsible for the vacuum selection, instead of a new scalar sector
- These differences are reflected in the pheno of our explicit models
- These models can be probed at future lepton colliders: FCC-ee, muon collider, etc.

Thank you!

Crunchy, critical, natural Higgs

- more info:
  - https://arxiv.org/abs/2502.07876
  - https://ameenismail.github.io/
  - ameenismail@uchicago.edu