Higgs ~~BSM~~ physics in light of LHC8

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What is the 5th force?

- Is it weak or strong?
- Is it a gauge force?
- Is it associated with a fundamental scalar?

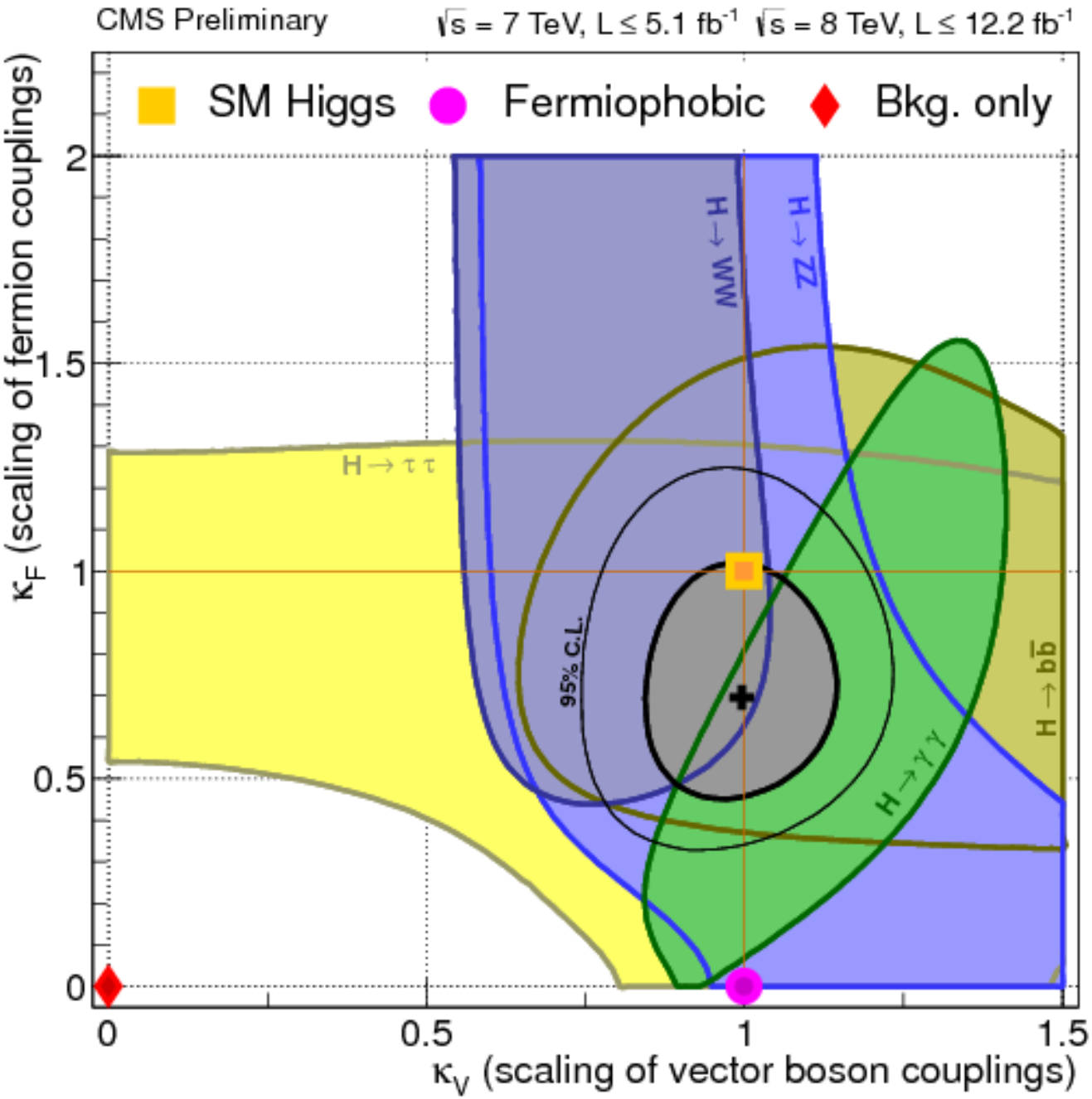
Test the Higgs structure

$$L = \frac{1}{2}\partial_\mu h\,\partial^\mu h - \frac{1}{2}m_h^2 h^2$$

$$-\left(M_W^2\,W_\mu^+ W^{-\mu} + \frac{1}{2}M_Z^2\,Z_\mu Z^\mu\right)\left(1 + 2a\frac{h}{v}\right)$$

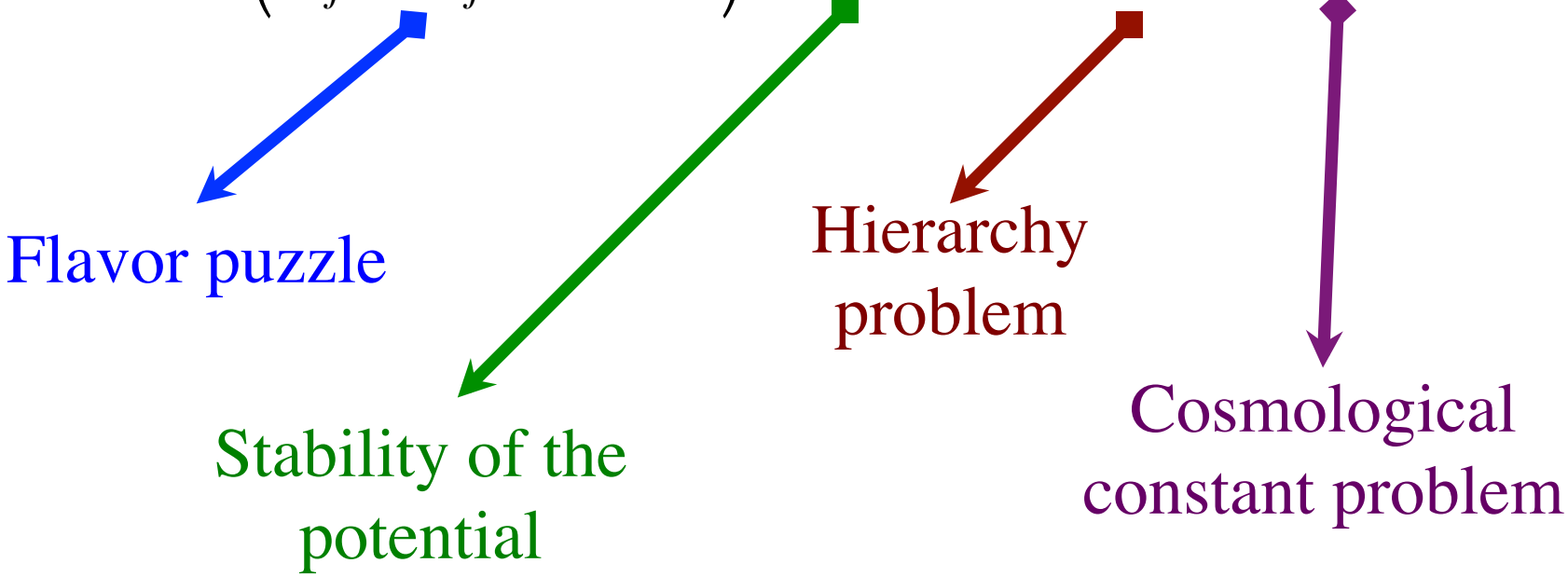
$$-m_f\bar{f}\,f\left(1 + c\frac{h}{v}\right)$$

$$+\left(c_{WW}W_{\mu\nu}^+ W^{-\mu\nu} + c_{ZZ}Z_{\mu\nu}Z^{\mu\nu} + c_{Z\gamma}Z_{\mu\nu}F^{\mu\nu} + c_{\gamma\gamma}F_{\mu\nu}F^{\mu\nu} + c_{gg}G_{\mu\nu}^a G^{a\mu\nu}\right)\frac{h}{v}$$


CMS Preliminary
√s = 7 TeV, L ≤ 5.1 fb-1 √s = 8 TeV, L ≤ 12.2 fb-1
SM Higgs
Fermiophobic
Bkg. only
κF (scaling of fermion couplings)
κV (scaling of vector boson couplings)
H → ττ
H → WW
H → ZZ
H → γγ
H → bb̄
95% C.L.
0
0.5
1
1.5
2

Almost all the problems of the SM originate from Higgs interactions

$$L = \left(h_{ij}\overline{\psi}_i\psi_j H + \text{h.c.}\right) - \lambda|H|^4 + \mu^2|H|^2 - \Lambda^4$$



Just because the 5th force is not a gauge force...

Stability of the potential

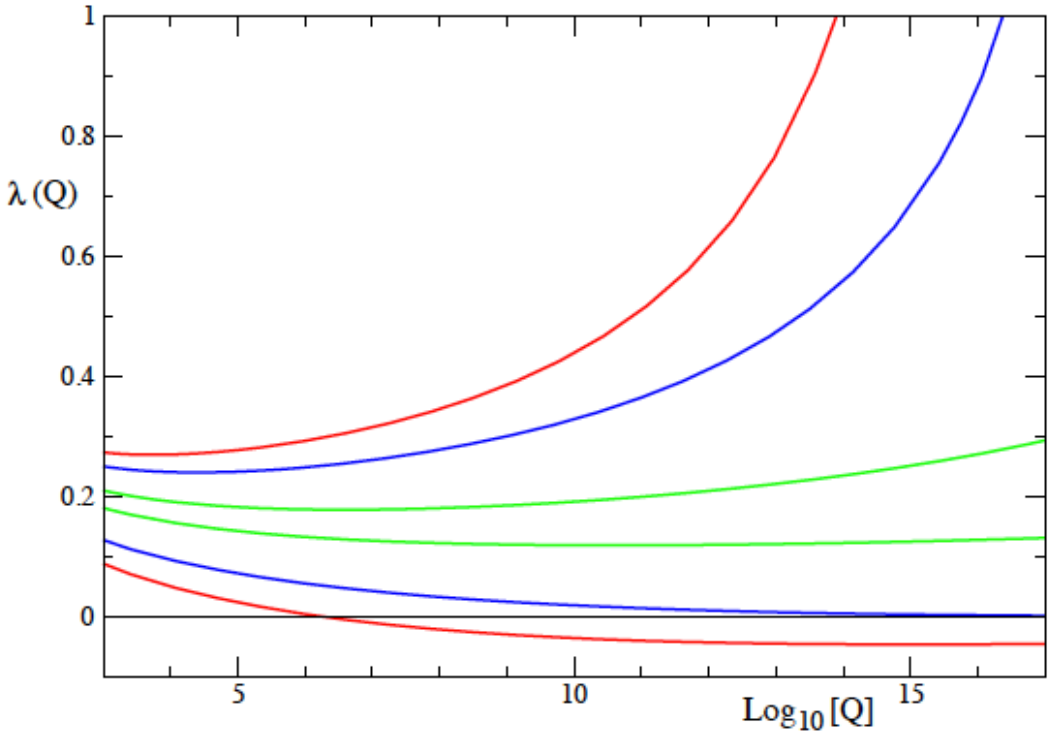
$$V = \frac{\lambda}{4}\left(h^2 - v^2\right)^2 \approx \frac{\lambda h^4}{4} \quad \Rightarrow \quad V \approx \frac{\lambda(h)\, h^4}{4}$$

$$16\pi^2 \mu \frac{d\lambda}{d\mu} = 24\lambda^2 - 6y_t^4 + 12\lambda y_t^2$$

$$-3\lambda\left(3g^2 + g'^2\right) + \frac{3}{8}\left(3g^4 + 2g^2 g'^2 + g'^4\right)$$

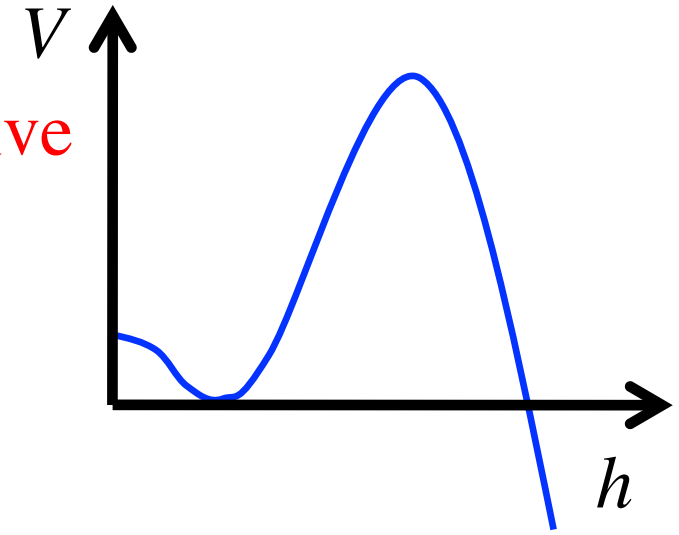
⬆Higgs mass

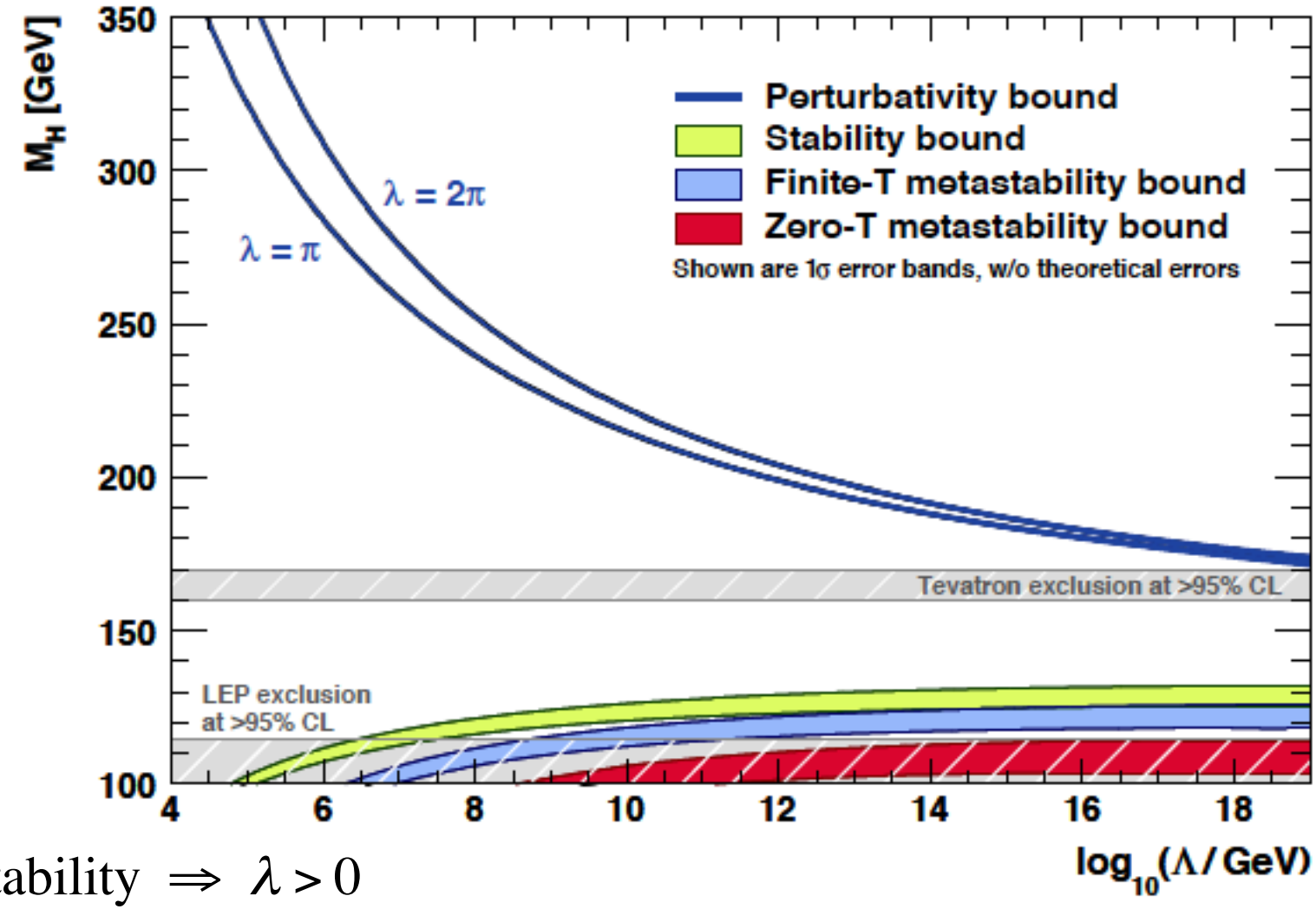
⬇Top quark mass



↑Higgs mass

- Heavy Higgs ➔ λ non-perturbative
- Light Higgs ➔ λ < 0

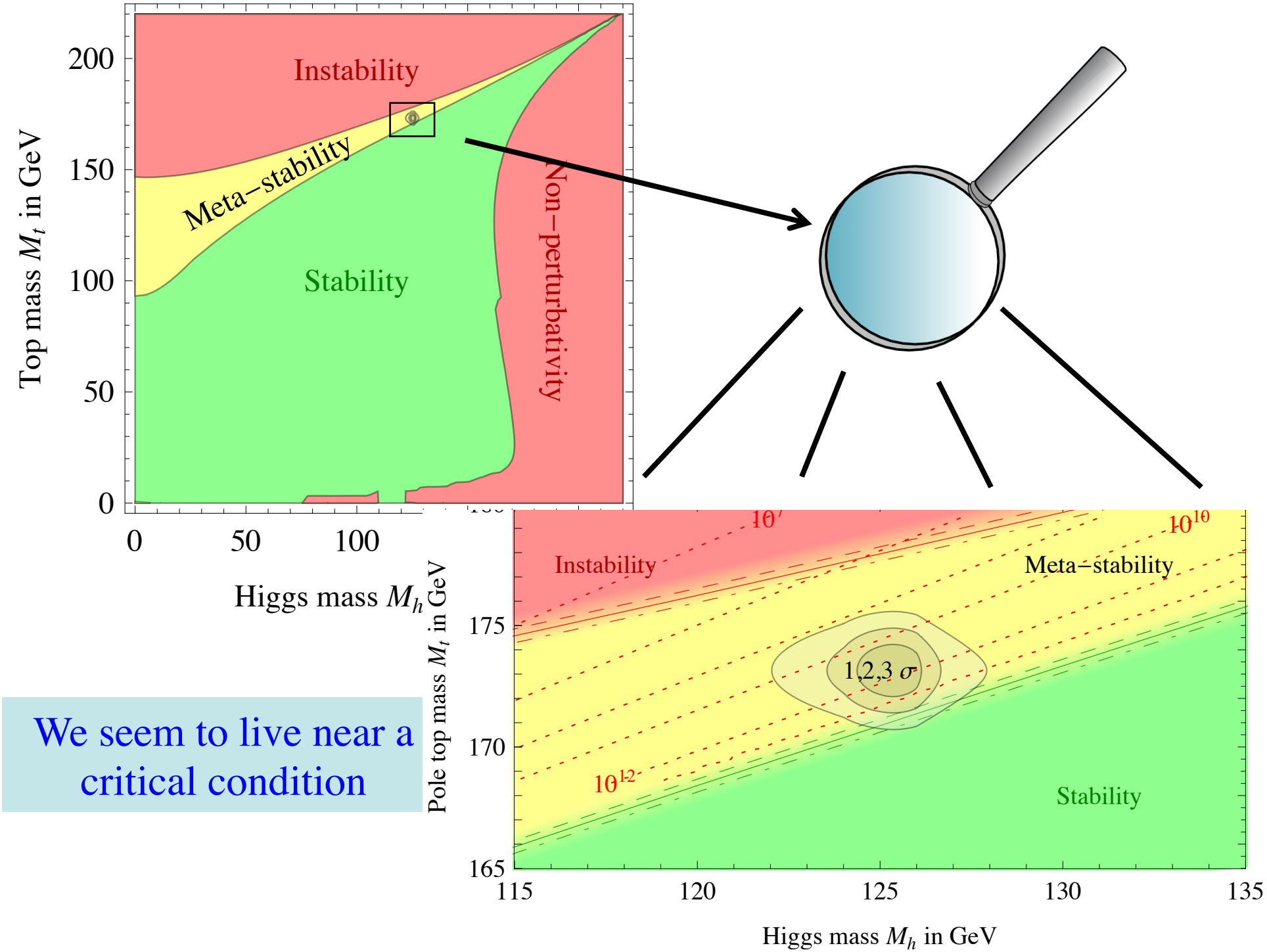




Stability $\Rightarrow$ $\lambda > 0$

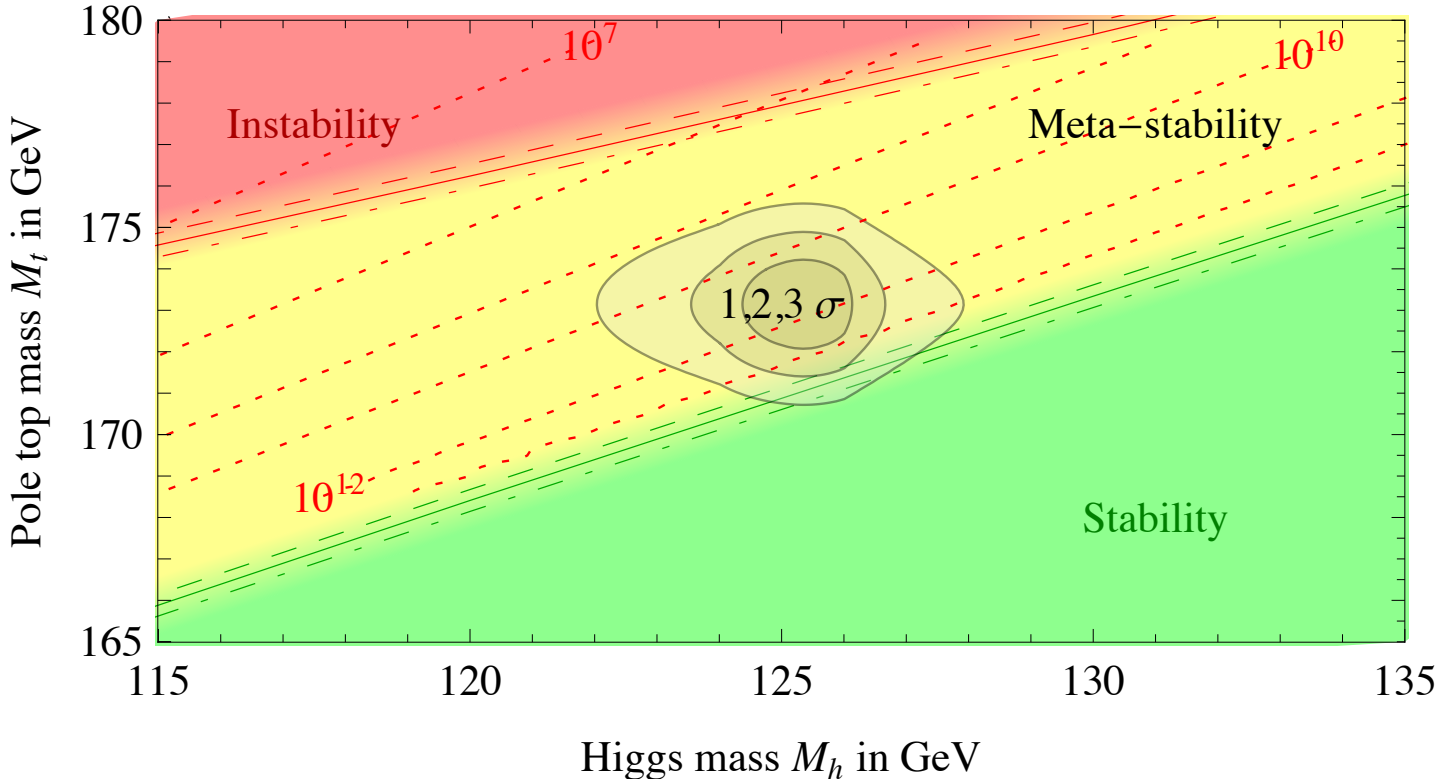
Quantum metastability $\Rightarrow$ Tunneling probability $\propto$ $\exp\left(-\dfrac{8\pi^2}{3|\lambda(\Lambda)|}\right)$

Thermal metastability $\Rightarrow$ For $T \approx \Lambda$



We seem to live near a critical condition

Precise determinations of M_h and M_t are necessary to establish the fate of our universe

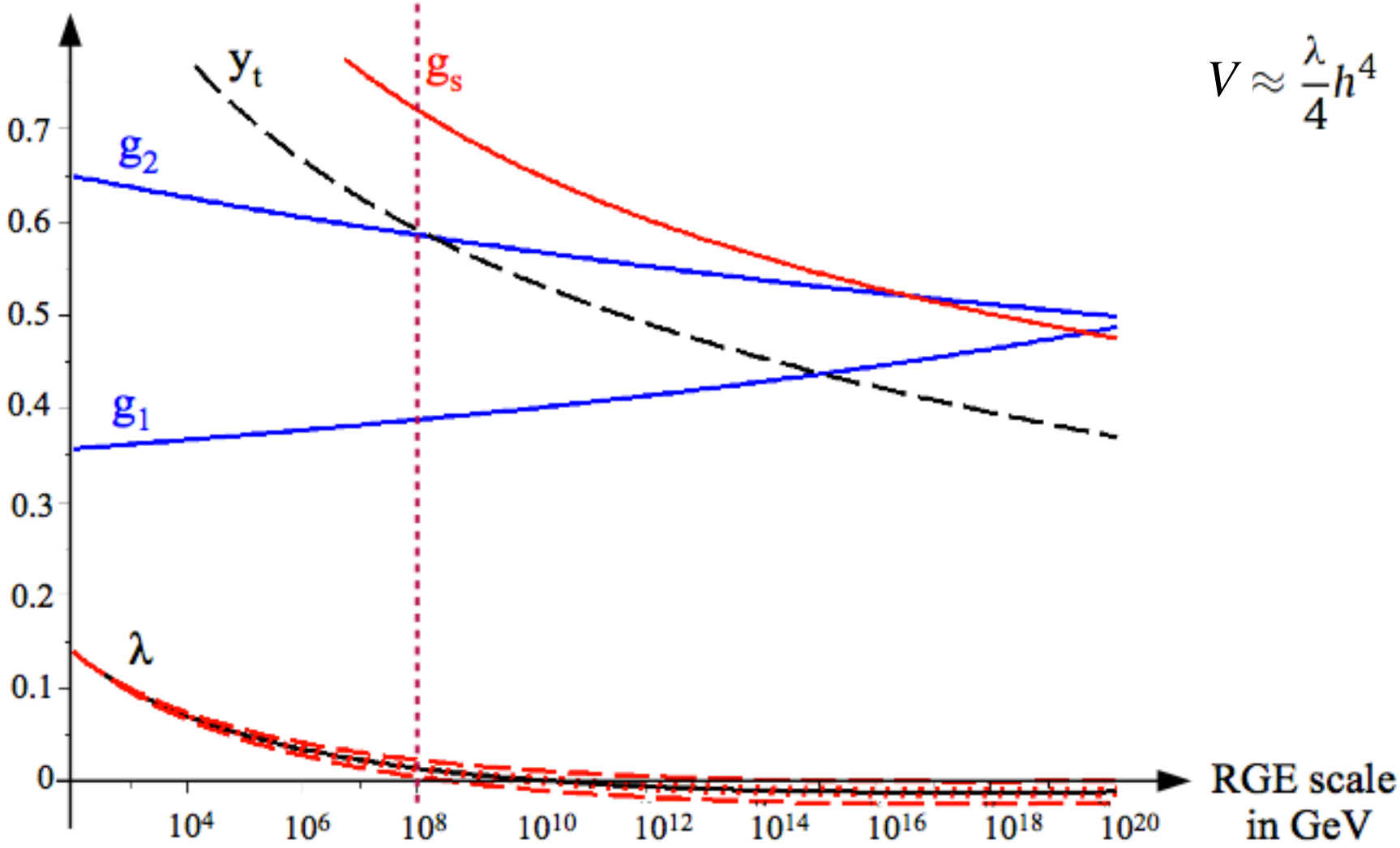


Stability condition:

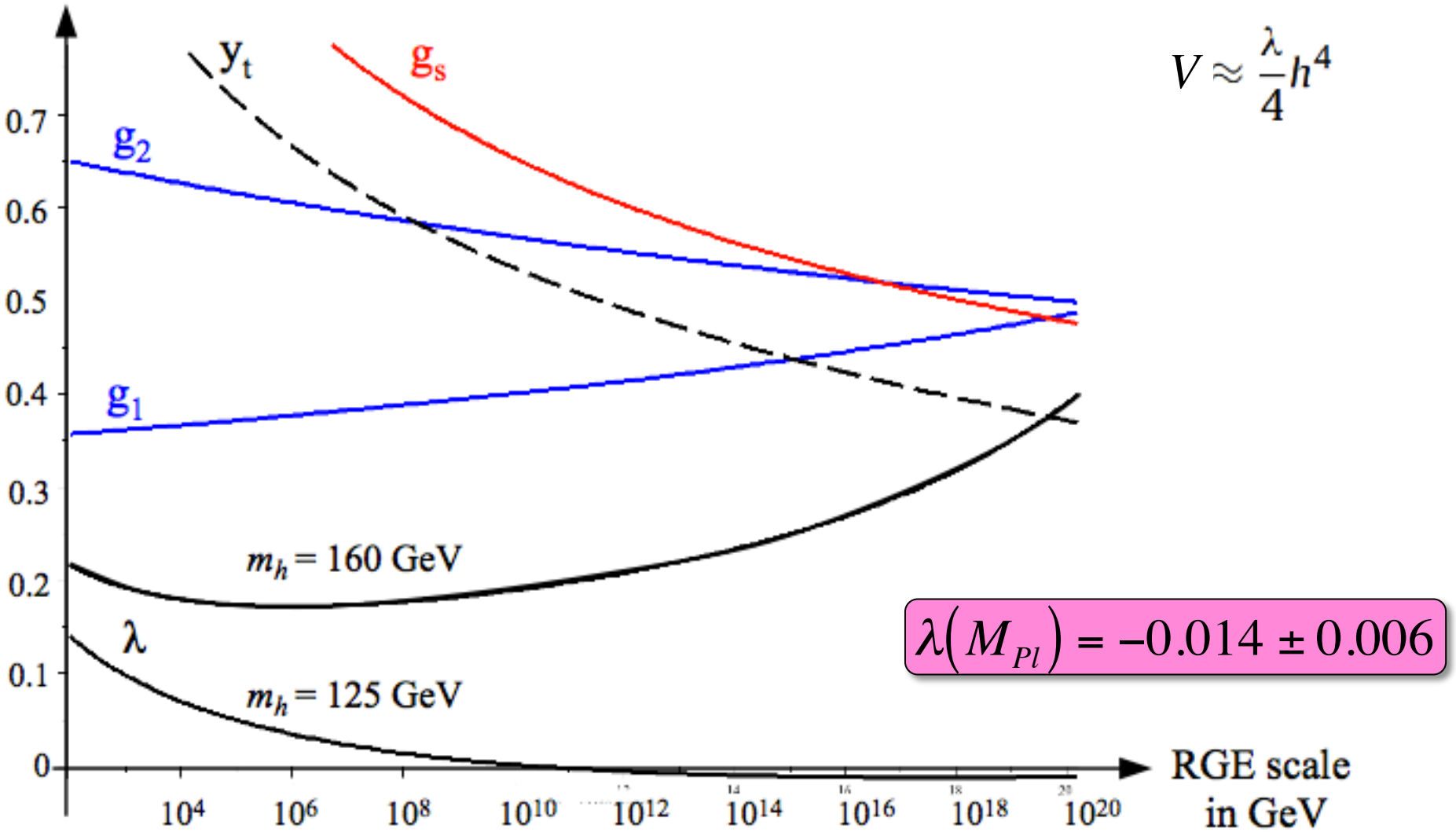
$$M_h\ [\mathrm{GeV}] > 129.4 + 1.4\left(\frac{M_t\ [\mathrm{GeV}] - 173.1}{0.7}\right) - 0.5\left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right) \pm 1.0_{\mathrm{th}}$$

Thermal metastability for any $T < M_P$:

$$m_h \ [\text{GeV}] > 122 + 1.6\left(\frac{m_t \ [\text{GeV}] - 173.1}{0.7}\right) - 0.6\left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right) \pm 3.0_{th}$$



λ and β_λ nearly vanish at high energies?



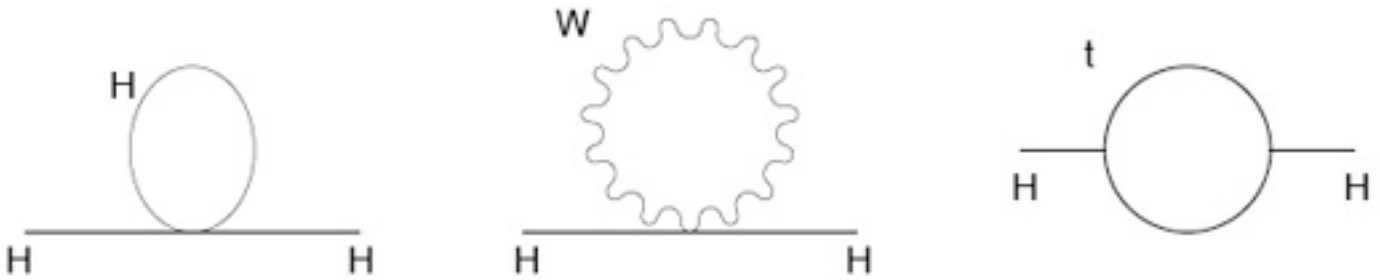
$$V \approx \frac{\lambda}{4} h^4$$

$$\lambda(M_{Pl}) = -0.014 \pm 0.006$$

Naturalness

Let us consider $V(H) = -\mu_H^2 |H|^2 + \lambda |H|^4$

$\mu_H^2 = \lambda\, v^2 = m_h^2 / 2$ very sensitive to high-energy corrections



$$\delta m_h^2 = \frac{3G_F}{4\sqrt{2}\pi^2}\left(4m_t^2 - 2m_W^2 - m_Z^2 - m_h^2\right)\Lambda^2 = \left(0.2\,\Lambda\right)^2$$

$$\frac{\delta m_h^2}{m_h^2} < \Delta \quad \Rightarrow \quad \Lambda_{\max} \approx 500\ \text{GeV}\left(\frac{m_h}{125\ \text{GeV}}\right)\Delta^{1/2}$$

No large tuning $\Rightarrow \Lambda <$ TeV

• Naturalness is not an idle theoretical concept

• Its importance goes beyond ~~EW~~, and it will influence the strategy for future directions in particle physics

- Naturalness is linked to the use of EFT
- EFT is the tool to implement the intuitive notion of separation of scales
- At each stage we have discovered simpler laws and larger symmetries
- We can use the naturalness criterion to infer the energy scale of the next layer

Naturalness at work:
1. classical electron self-energy

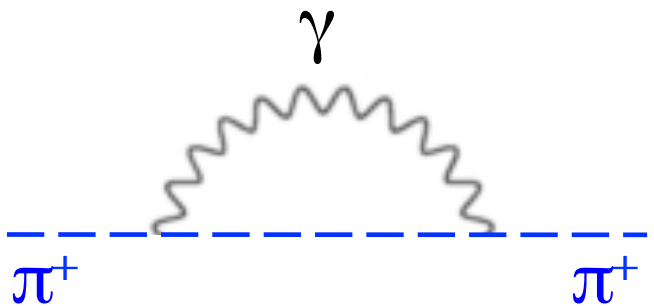
electrostatic energy: $E \approx \frac{\alpha}{r} < m_e c^2 \Rightarrow \Lambda < \frac{m_e}{\alpha} \approx 70$ MeV

magnetic energy: $E \approx \frac{\mu^2}{r^3}, \mu = \frac{e\hbar}{2m_e c} < m_e c^2 \Rightarrow \Lambda < \frac{m_e}{\alpha^{1/3}} \approx 3$ MeV

(spinning sphere)

New physics (positron) at $m_e < \Lambda$

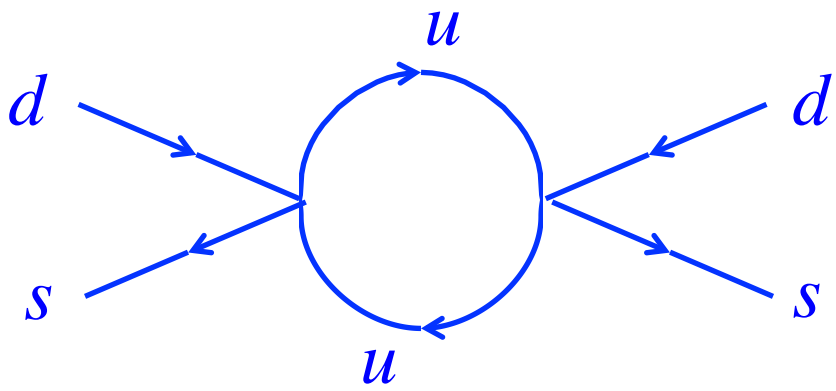
Naturalness at work:
2. QED contribution to pion mass difference



$$\frac{3\alpha}{4\pi}\Lambda^2 < M^2_{\pi^+} - M^2_{\pi^0} \;\Rightarrow\; \Lambda < 850\ \text{MeV}$$

New physics (hadrons) at $M_\rho < \Lambda$ ($M_\rho = 770$ MeV)

Naturalness at work:
3. Neutral kaon mass difference

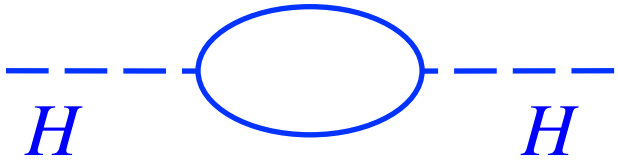


Effective theory at M_K:

$$\frac{G_F^2 f_K^2}{6\pi^2}\sin^2\theta_c \Lambda^2 < \frac{M_{K_L^0} - M_{K_S^0}}{M_{K_L^0}} \Rightarrow \Lambda < 2\ \text{GeV}$$

New physics (charm) at $m_c < \Lambda$ ($m_c = 1.2$ GeV)

Naturalness at work ?
The weak scale



$$\delta m_h^2 = \frac{3G_F}{4\sqrt{2}\pi^2}\left(4m_t^2 - 2m_W^2 - m_Z^2 - m_h^2\right)\Lambda^2 < m_h^2 \Rightarrow \Lambda < 500\ \text{GeV}$$

Where is new physics?

- Around the corner?
- Mild tuning?
- Failure of effective theory approach?

Indications for a failure of EFT?

- Dark energy
  Where is new physics? $\Lambda_{CC} = 2.4 \times 10^{-3}\ \mathrm{eV}$

- Holography, gauge-gravity duality, AdS-CFT correspondence: a single Lagrangian cannot encompass the physical content of the theory?

- IR/UV connection

Connection between smallest and largest distances?

Largest scale = Hubble length H^{-1} = 10^{26} m

Smallest scale = Planck length M_P^{-1} = 10^{-35} m

$$\Lambda_{CC} = \sqrt{H\, M_P} = 5 \times 10^{-3} \text{ eV}$$

$$\Lambda_{Weak} = \sqrt{\Lambda_{CC}\, M_P} = 5 \text{ TeV}$$

An effective theory will never be able to catch an IR/UV connection

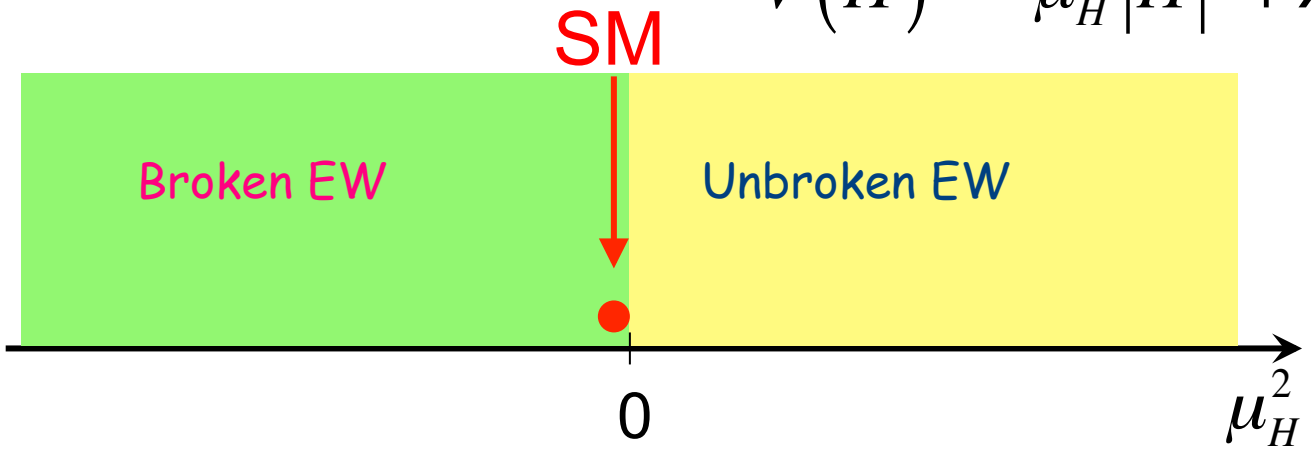
Another possibility: the multiverse

- Anthropic arguments may play a role in selecting the PDF of the universes
- This is the most convincing explanation of the CC so far
- If true, some questions that we thought as fundamental are just the result of environmental conditions

- Physics is confronting a crossroad: naturalness of unnaturalness?
- Far-reaching consequences for physics

Naturalness: a problem of criticality

$$V(H) = -\mu_H^2 |H|^2 + \lambda |H|^4$$



Why is nature so close to the critical line?

Symmetry?
- Supersymmetry: $\mu_H{}^2 = 0$ ($\lambda = 0$ at $\tan\beta = 1$)
- Goldstone boson: $\lambda = 0$

Do we live near a critical condition because of dynamics or because of statistics in the multiverse?

Naturalness: a problem of symmetry

Difficulty to keep fundamental scalar particle much lighter than the scale of validity of the theory

FERMION

QED $L = \bar{\psi}\left[\left(i\partial^{\mu} - eA^{\mu}\right)\gamma_{\mu} - m\right]\psi - \frac{1}{4}F^{\mu\nu}F_{\mu\nu}$

Mass renormalization

$$\delta m \approx \frac{\alpha}{4\pi} m \log\frac{\Lambda^2}{m^2}$$

- δm proportional to m
- only *log* divergent

It can be "naturally" small (*i.e.* $m<<\Lambda$) [Setting it to zero enhances the symmetry of the theory. *'t Hooft*]

m is protected by a symmetry

Chiral symmetry $\psi_L \to e^{i\alpha}\ \psi_L, \psi_R \to e^{i\beta}\ \psi_R, \alpha \neq \beta \Rightarrow m$ not invariant

$\delta m \quad \propto \quad$ "symmetry breaking" $\quad \approx m$

GAUGE BOSON

Gauge symmetry $A_\mu \rightarrow A_\mu + \partial_\mu \Lambda$

forbids $m^2 A_\mu A^\mu$

GOLDSTONE BOSON

Shift symmetry $\varphi \rightarrow \varphi + \xi$

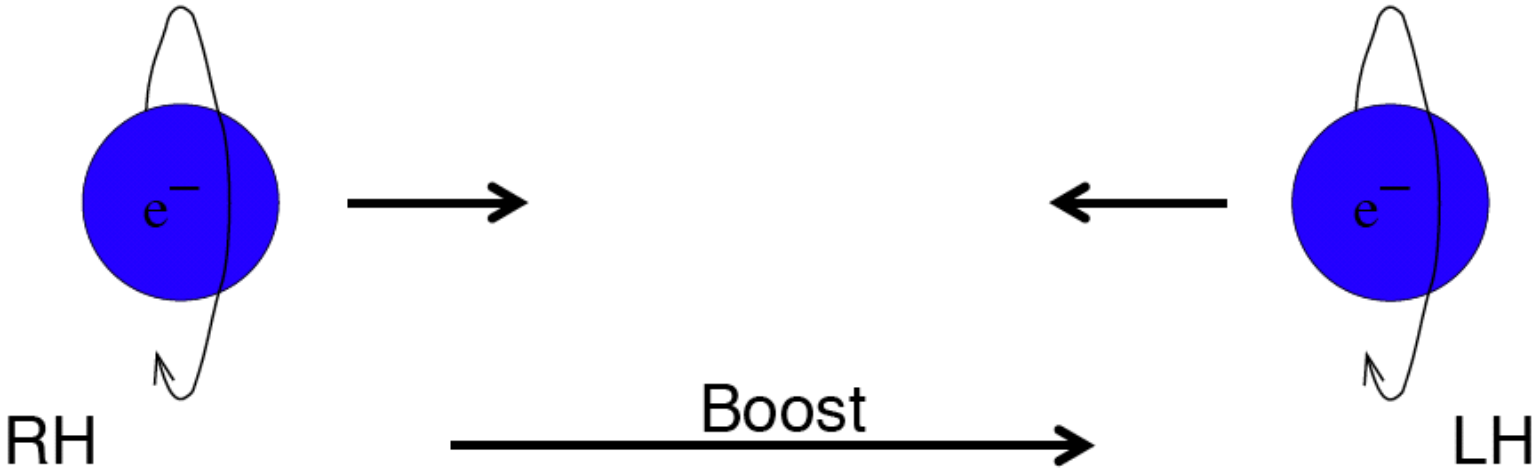
forbids $m^2 \varphi^2$

What protects μ_H^2 ? $V(H) = -\mu_H^2 |H|^2 + \lambda |H|^4$

Setting $\mu_H^2 = 0$ does not increase the symmetry

Physical interpretation: For spin-1/2 and spin-1, mass is related to existence of new helicity states

A massless spin-1/2 fermion has one helicity state



If e^- is massive, a new helicity state exists

Quantum corrections to mass are multiplicative

Possible strategies

Relate scalars to fermions + chiral symmetry ➔ supersymmetry

Higgs as a pseudo-Goldstone bosons ➔ composite models

Relate scalars to vectors + gauge symmetry ➔ gauge-Higgs unification

Eliminate scalars ➔ technicolor

Eliminate hierarchy ➔ extra dimensions