Symmetries and their origin

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- Local gauge symmetries associated with forces and dynamics
  - » QED, QCD, Weak interactions …
- Global symmetries associated with conservation laws
  - » Energy momentum conservation, selection rules …

- Where do these symmetries come from ?
  - » Fundamental or Emergent ?

- Hints (?) from experimental data and interpretation for future physics searches

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The Standard Model works very well

Particle physics

•Nice thing (QED, QCD, Higgs, ... LHC, LEP ...)

Standard Model works very well,

no sign yet of BSM also in dark matter searches (CRESST, Xenon100, LUX...), precision measurements: eEDM..., CPT and Lorentz invariance ...

meets

General relativity

•Nice thing (Gravitational waves, Binary pulsars, lensing, black holes, Lab tests of Inverse Square Law to 56 μm...)

→ Plug classical Higgs potential into Einstein‘s equations

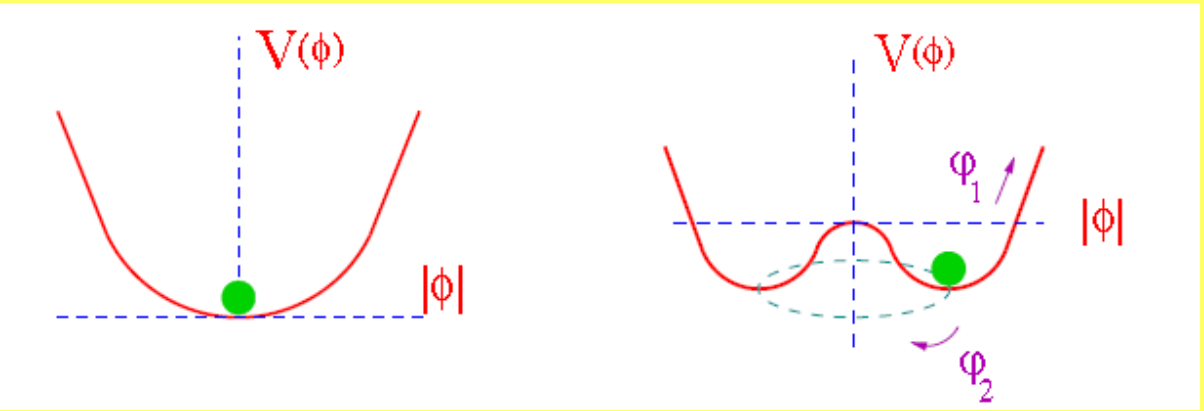
Cosmological constant „discrepancy“ of 10^{56} (!) + wrong sign (!)

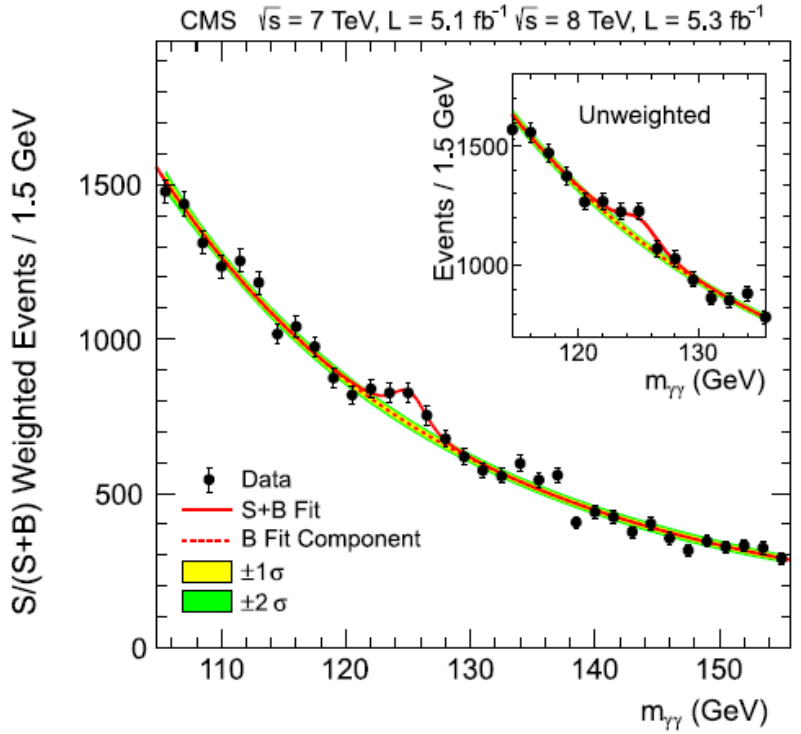
Open questions: Dark matter, neutrino masses, baryon asymmetry ...

Phases of gauge theories

- Particle physics is built from
  - QED in the Coulomb Phase
  - QCD in the Confining Phase
    - » QCD condensates ~ - (200 MeV)^4 from DChSB
  - Electroweak Interactions in the Higgs Phase
    - » Higgs condensate ~ - (250 GeV)^4

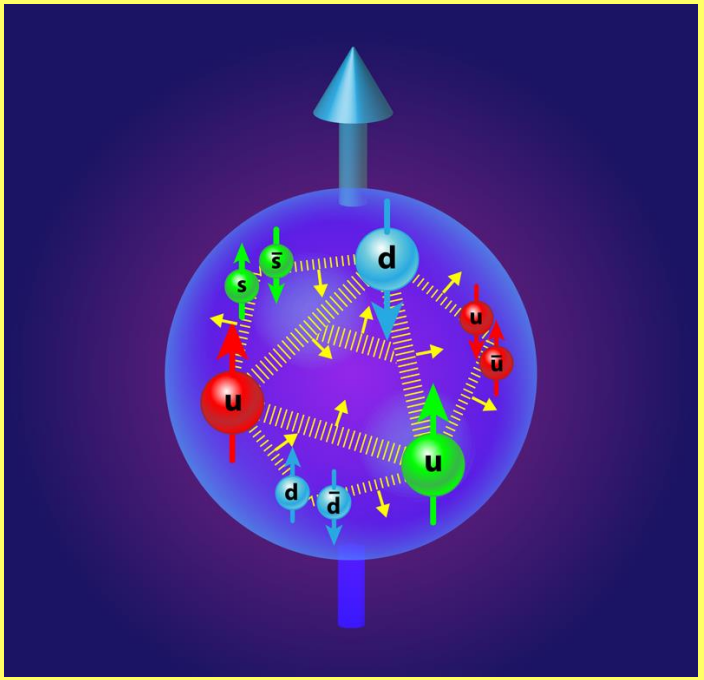
$$V(\phi) = \mu^2 \phi\phi^* + \lambda(\phi\phi^*)^2$$





Emergent forces I

In QCD all hadron physics is emergent from more fundamental quarks and gluons



- Protons including their mass, spin ...
- Pions as messengers (exchange particles) of nuclear forces
- Pions are special because of chiral symmetry
- Confinement and DChSB in the infrared
- What about DSB and critical phenomena (phase transtions) in the ultraviolet ?

Emergent forces II

- Particle Physics in the ultraviolet: more symmetry or less ?

  Standard Model ← SM + SUSY ← GUTs ← Strings

  or

  „Planck system" → Quantum Field Theory ~ SM (symmetric)
  → SM (Spontaneous Symmetry Breaking)

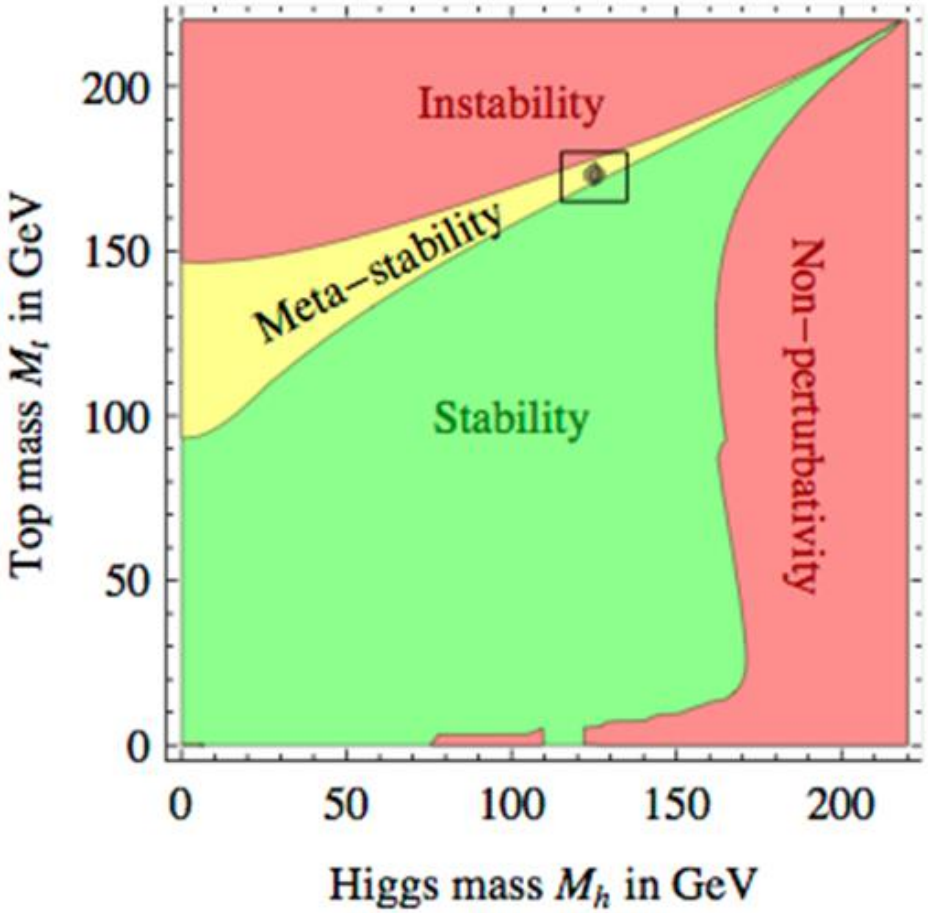
- Standard Model as long range tail of critical system which sits close to Planck scale (-- a bit like van der Waals forces)

- Phase transition in the UV
  - Long range tail renormalisable QFT (gauge symmetry for J=1 fields)
  - Non-trivial interactions for less than or equal to 4 dimensions
  - Long range modes have to cooperate to give this: simplest small gauge groups (most likely) preferred [Jegerlehner, Bjorken, Nielsen ...]

Results from LHC

- LHC: So far just Standard Model Higgs and no BSM, SUSY ...

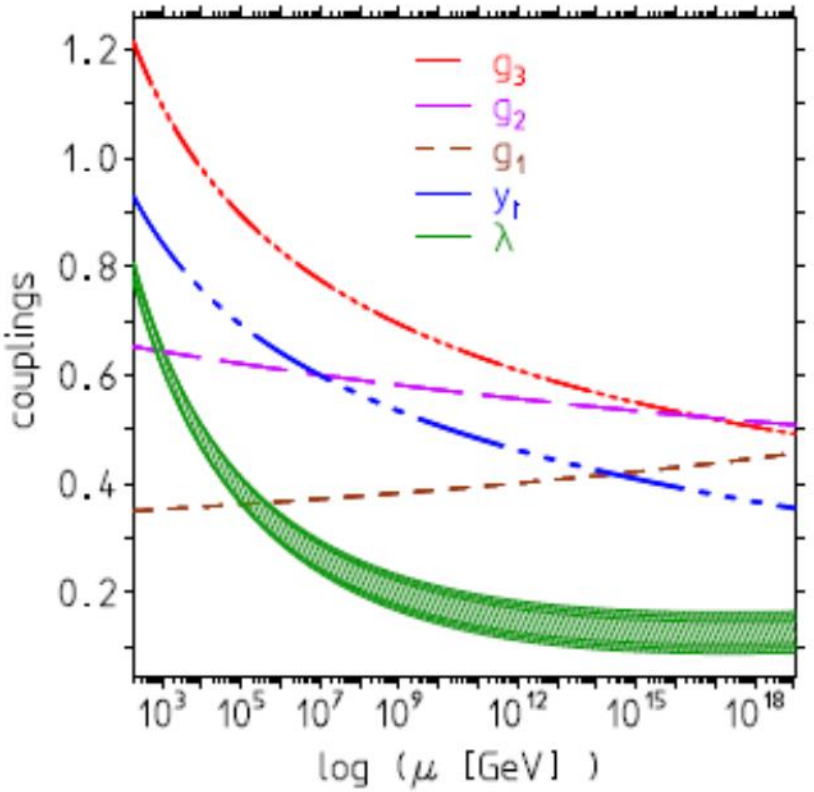
- Remarkable: the Higgs and top mass sit in window of possible parameter space where the Standard Model is a consistent theory up to the Planck mass close to the border of a stable and meta-stable vacuum.



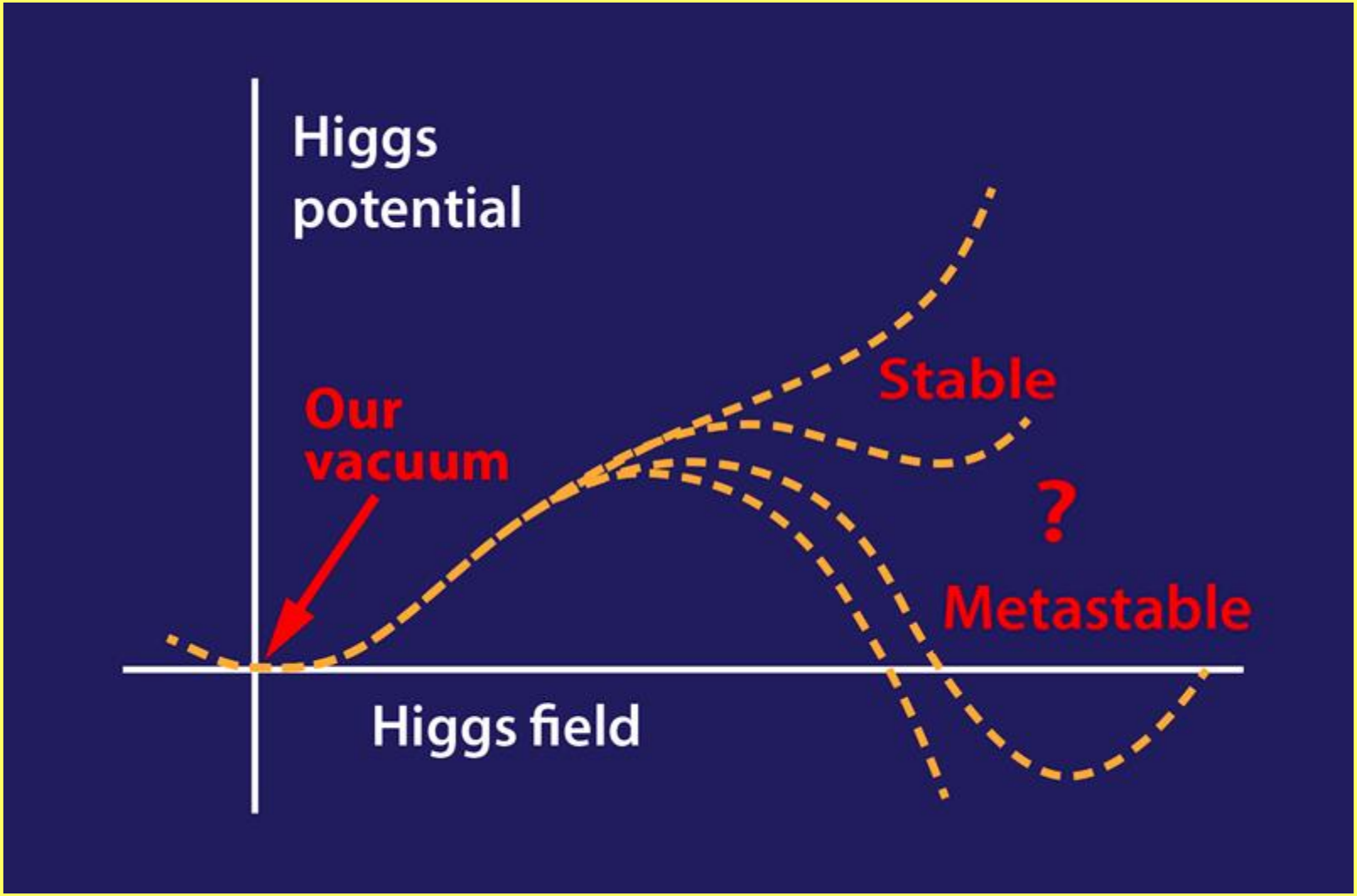
$$V(\phi) = \mu^2 \phi\phi^* + \lambda(\phi\phi^*)^2$$

Vacuum stability - Jegerlehner

The SM running parameters

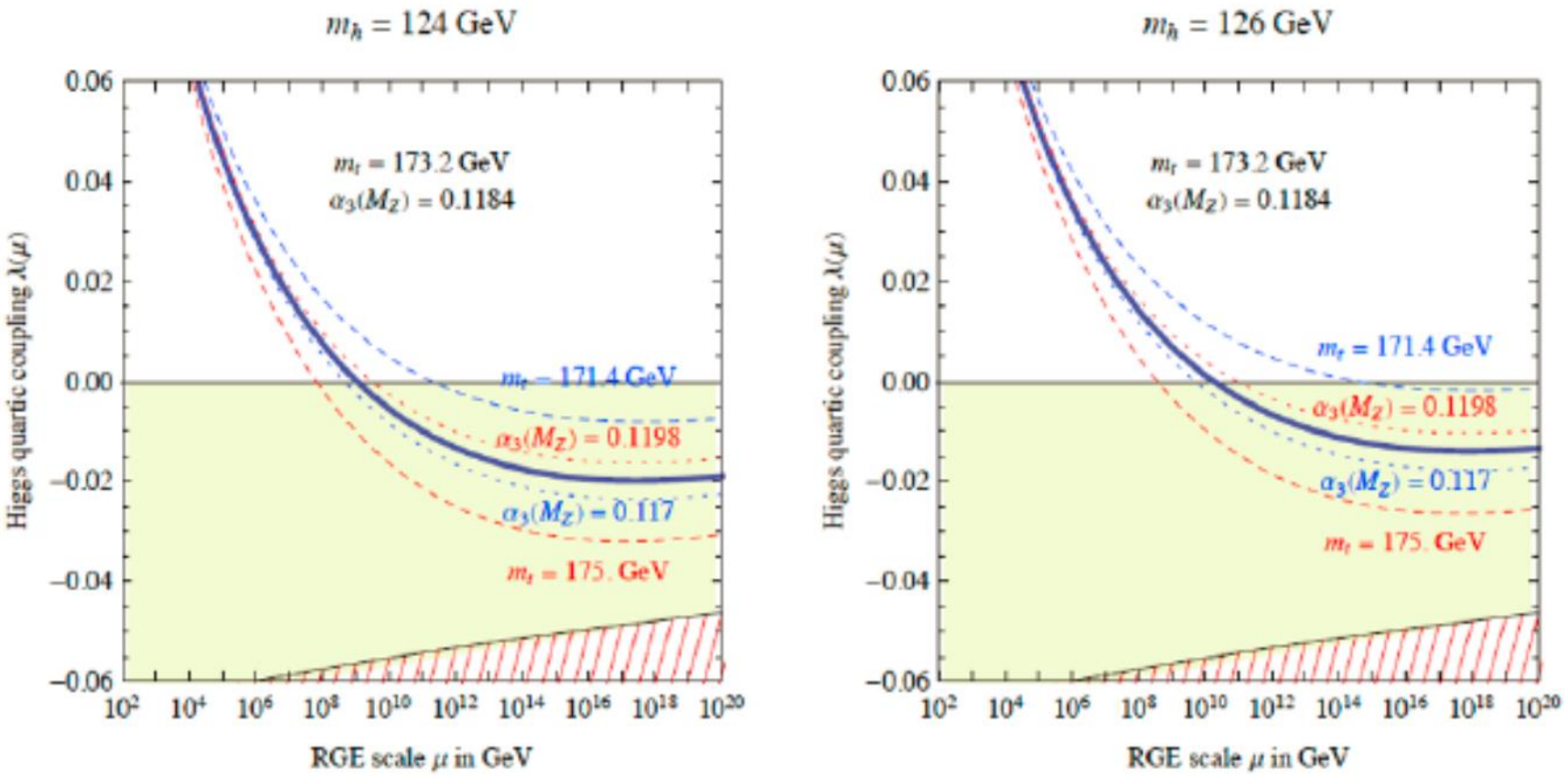


Vacuum stability

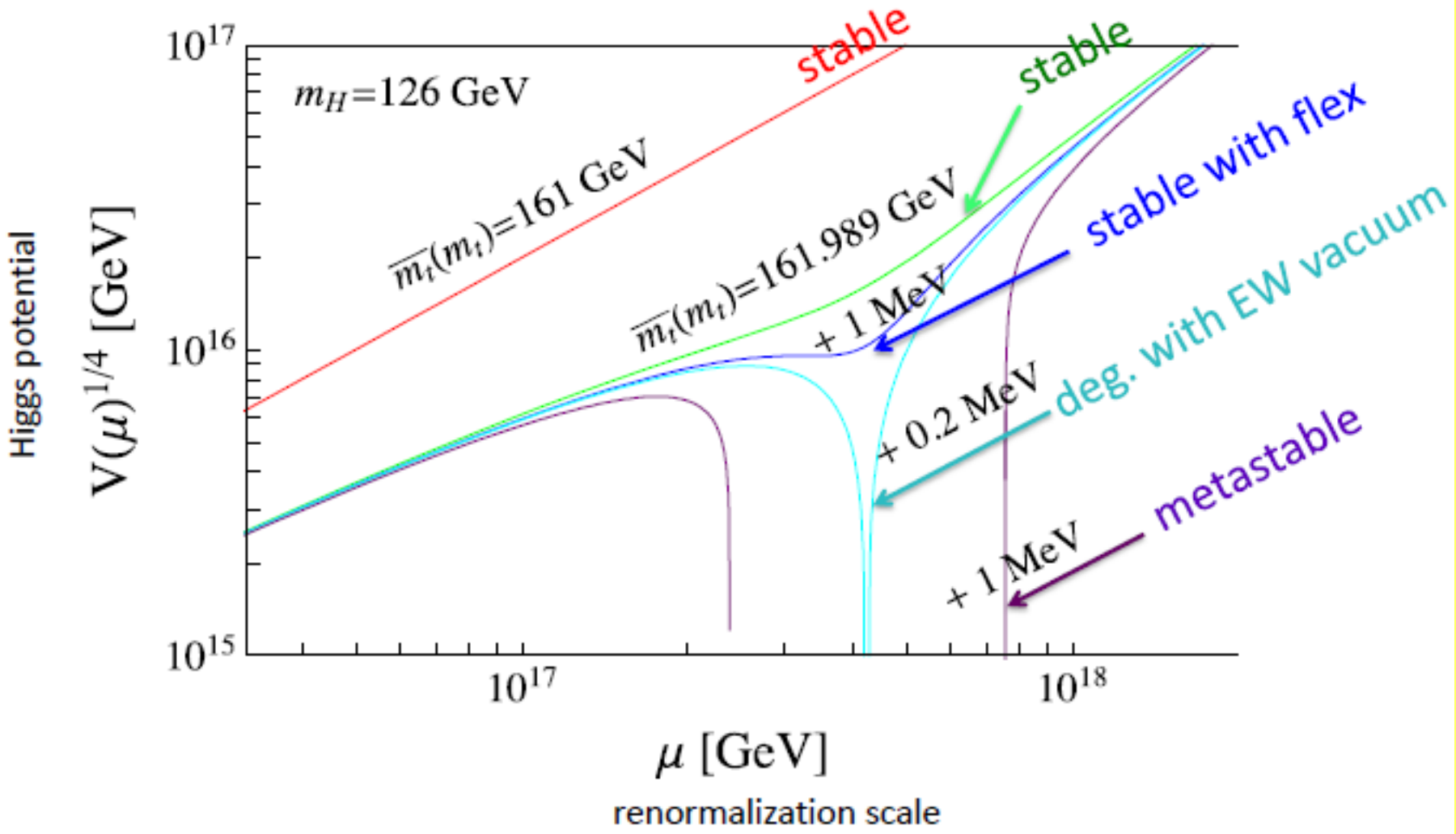


At the edge of a stable vacuum

Vacuum stability – Buttazzo et al

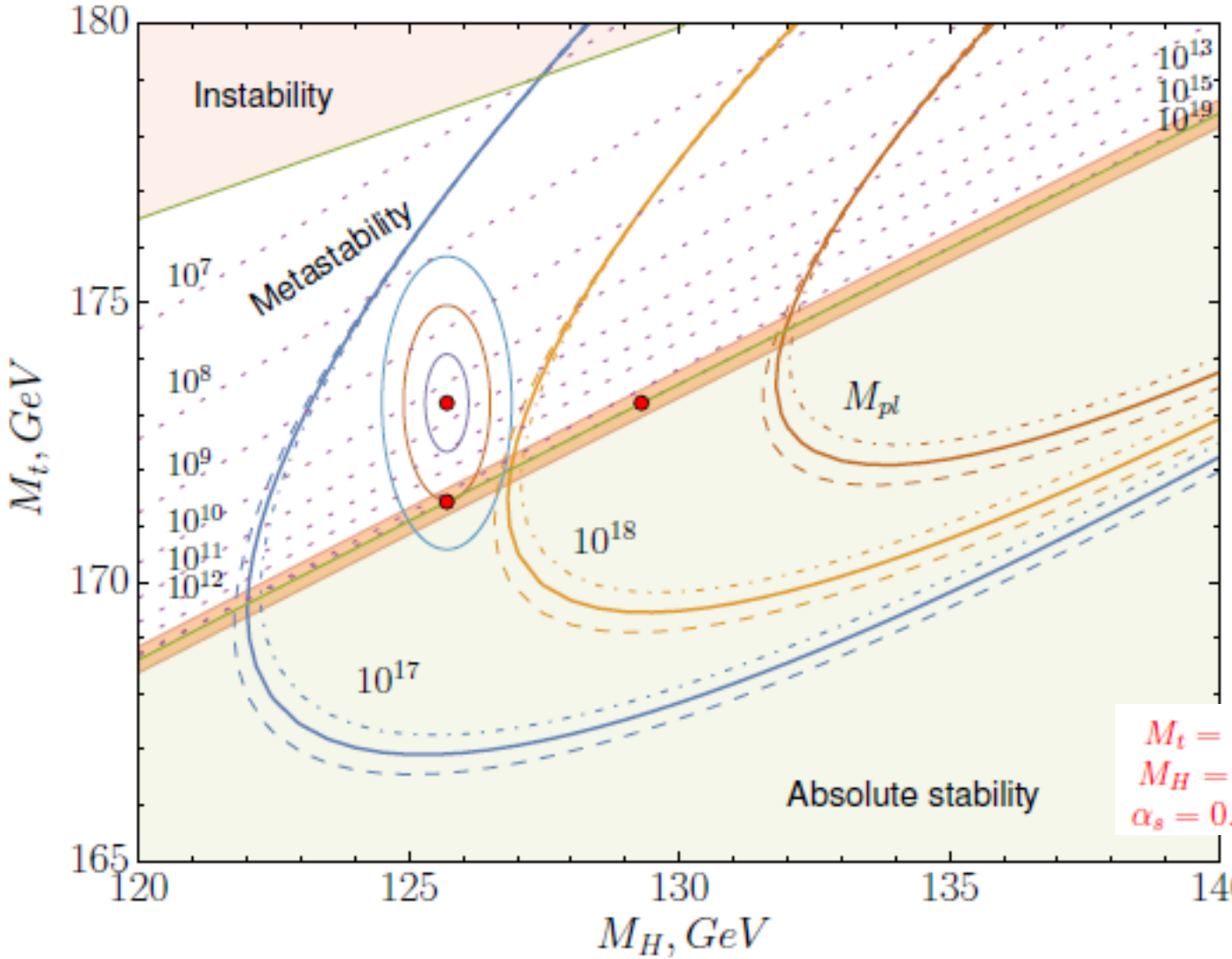


Vacuum stability - Masina



Bednyakov, Kniehl et al

Phase diagram



Gauge and Lorentz symmetries

- Local gauge invarionce and space-time Lorentz invariance closely connected
    - E.g. Gauge symmetry ←→ invariance of choice of phase of wavefunction at each point in space
- If gauge symmetries are emergent, then also expect Lorentz invariance to be (spontaneously) broken or emergent

  [Bjorken 1963: Photon as Goldstone boson associated with spontaneous breaking of Lorentz invariance]
- Lorentz invariance, locality, Hermitian Hamiltonian → CPT
- Emergent or broken Lorentz invariance implies small CPT violation
- How big ?

Electroweak Vacuum Stability

- Possible critical phenomena close to Planck mass with Standard Model as the long range tail of a critical Planck system
- Is the Standard Model „emergent" ?

$$\frac{1}{\alpha_{\text{gut}}} = \frac{4\pi}{g^2} \simeq \frac{c_g}{4\pi} \ln \frac{M^2}{\mu^2}.$$

(cf. Low energy part of GUT spontaneously broken by multiple Higgs fields and condensates)

[Bjorken, Jegerlehner, Nielsen et al, Volovik]

If yes, possible violations of Lorentz invariance, gauge invariance &tc at very high scales close to the Planck mass - perhaps vanishing with vanishing dark energy and suppressed in laboratory experiments by powers of μ/M [Bjorken 2001]

Emergent particle physics

The low energy expansion at a glance

	dimension	operator	scaling behavior
hidden world	·	∞–many	
	·	irrelevant	
↑	·	operators	
no data	$d = 6$	$(\Box\phi)^2, (\bar{\psi}\psi)^2, \cdots$	$(E/\Lambda_{\rm Pl})^2$
|	$d = 5$	$\bar{\psi}\sigma^{\mu\nu}F_{\mu\nu}\psi, \cdots$	$(E/\Lambda_{\rm Pl})$
|	$d = 4$	$(\partial\phi)^2, \phi^4, (F_{\mu\nu})^2, \cdots$	$\ln(E/\Lambda_{\rm Pl})$
experimental data	$d = 3$	$\phi^3, \bar{\psi}\psi$	$(\Lambda_{\rm Pl}/E)$
	$d = 2$	$\phi^2, (A_\mu)^2$	$(\Lambda_{\rm Pl}/E)^2$
↓	$d = 1$	ϕ	$(\Lambda_{\rm Pl}/E)^3$

world as seen — tamed by symmetries

Note: d=6 operators at LHC suppressed by $(E_{\rm LHC}/\Lambda_{\rm Pl})^2 \approx 10^{-30}$

⇒ require chiral symmetry, gauge symmetry, ··· ??? self-organized!

– just looks symmetric as we cannot see the details –

[Jegerlehner]

Coupling constants and masses fixed to get stable long-range vacuum

Particle physics and gravity

- Dark energy scale μ_{vac} ~ 0.002 eV

$$\rho_{\rm vac} = \mu^4, \quad \mu \sim 0.002 \text{ eV}$$

$$\mu_{\rm vac} \sim m_\nu \sim \Lambda_{\rm ew}^2/M$$

- If taken literally, this formula connects
  Dark Energy, neutrino physics and EWSB
  to a new high mass scale M ~ 3 x 10^{16} GeV which needs to be understood.

- Suggests perhaps the cosmological constant puzzle and electroweak hierarchy problems might be linked with a common origin at very high mass scale, close to the Planck mass (?)

Scales

- Dark energy scale ~ 0.002 eV

$$\mu_{\rm vac} \sim m_\nu \sim \Lambda_{\rm ew}^2/M$$

- Electroweak Higgs scale 250 GeV
- QCD Scale 1 GeV
- Planck mass (gravitation) 10^{19} GeV
- Light neutrino mass ~ 0.005 eV (normal hierachy)
- Inflation (fourth root of r, Bicep2+...) ~ 10^{16} GeV
- Jegerlehner (EWSB) 1.4 x 10^{16} GeV (sign change of c-term)

$$m_0^2 = m^2 + \delta m^2\,; \qquad \delta m^2 = \frac{\Lambda^2}{32\pi^2}\,C$$

$$C_1 = \frac{6}{v^2}\,(M_H^2 + M_Z^2 + 2M_W^2 - 4M_t^2) = 2\,\lambda + \frac{3}{2}\,g'^2 + \frac{9}{2}\,g^2 - 12\,y_t^2 \ldots$$

- GUTs 10^{15} GeV