Emergent particle physics and the cosmological constant puzzle

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- LHC surprise : the Standard Model works so well
  - Higgs vacuum close to the border of stable and metastable
  - Naturalness, GUTs or Emergence (anti-GUT)

- Cosmological constant
  - Accelerating Universe: believed to be driven by vacuum energy
  - Positive vacuum energy = negative vacuum pressure
  - Cosmological constant scale ~ 0.002 eV << EW and Planck scales
  - How to understand in connection with particle physics ?

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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

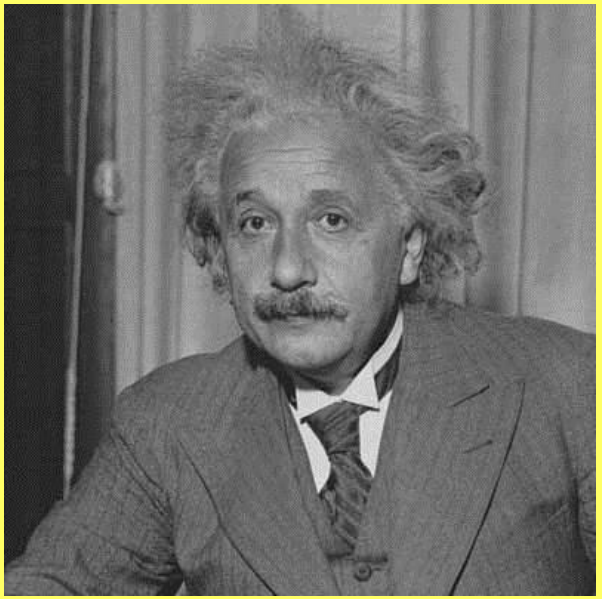
Cosmological constant „discrepancy“ of 10^{56} (!) + wrong sign (!)

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

General Relativity

- Einstein gravity couples to energy

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = -\frac{8\pi G}{c^2} T_{\mu\nu} + \Lambda g_{\mu\nu}$$



- Cosmological constant as integration constant

$$\Lambda = 8\pi G \rho_{\rm vac} + \Lambda_0$$

- Spontaneous symmetry breaking introduces finite energy scales

- If the vacuum has energy (e.g. Higgs and QCD condensates, zero-point energies) with coupling to gravitation, then the vacuum gravitates

- How big is the energy density of „nothing" ?

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

CC and Vacuum Energy

- Cosmological constant behaves like a vacuum energy density
- Quantum field theory: Zero point energies and condensates (SSB)

- Zero Point Energies done naively and with MSbar (Lorentz invariantly)
  - Usual particle physics: Normal-Order away, and define ρ_{vac} =0
    Measure differences, not absolute quantities

$$\rho_{\rm vac} = \frac{1}{2}\sum\{\hbar\omega\} = \frac{1}{2}\hbar \sum_{\rm particles} g_i \int_0^{k_{\rm max}} \frac{d^3k}{(2\pi)^3}\sqrt{k^2+m^2}\,.$$

$$\rho_{\rm vac} = -p_{\rm vac} \simeq -\frac{1}{2}\hbar g_i \frac{m^4}{64\pi^2}\left[\frac{2}{\epsilon}+\frac{3}{2}-\gamma-\ln\left(\frac{m^2}{4\pi\mu^2}\right)\right]+\cdots,$$

- Note here massless photon gives zero, biggest contribution from the top

- Question: Are zero point energies physical ? If yes, do they gravitate ?
  » Casimir without ZPEs (Jaffe), Light-front (Brodsky), …
  Time dependent counterterm ? (condensates in early Universe)

Fundamental symmetries

- Gauge symmetries guiding principle of modern particle physics theory: Determine interactions of QED, QCD, e-weak (before Higgs sector)

- Are (gauge) symmetries always present ?

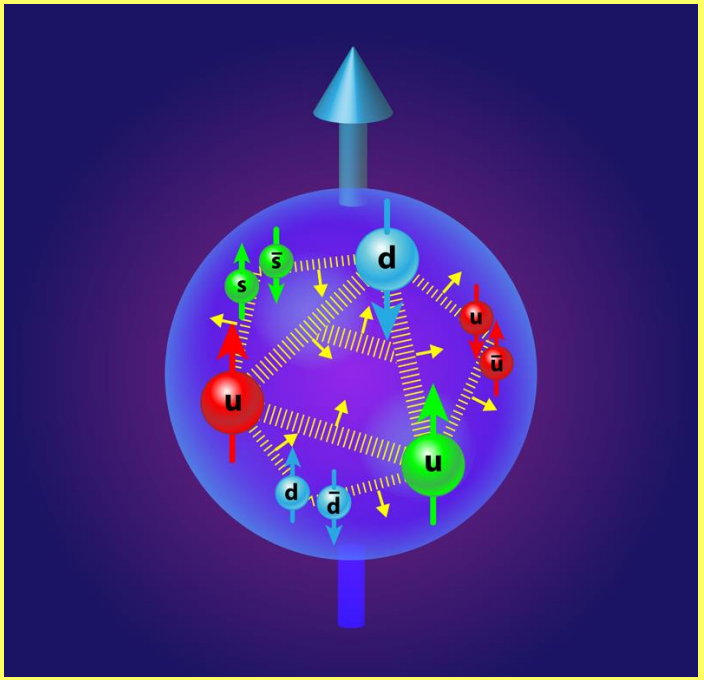
Making symmetry as well as breaking it

Emergent space time and Planck scale

- Examples from quantum systems: High T_c superconductors, Quantum Hall effect, collective excitations in A-phase of low temperature ^3He ...

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
- Proton spin as delicate interplay of confinement, DChSB, gluon spin and topology
- What about DSB and critical phenomena 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)

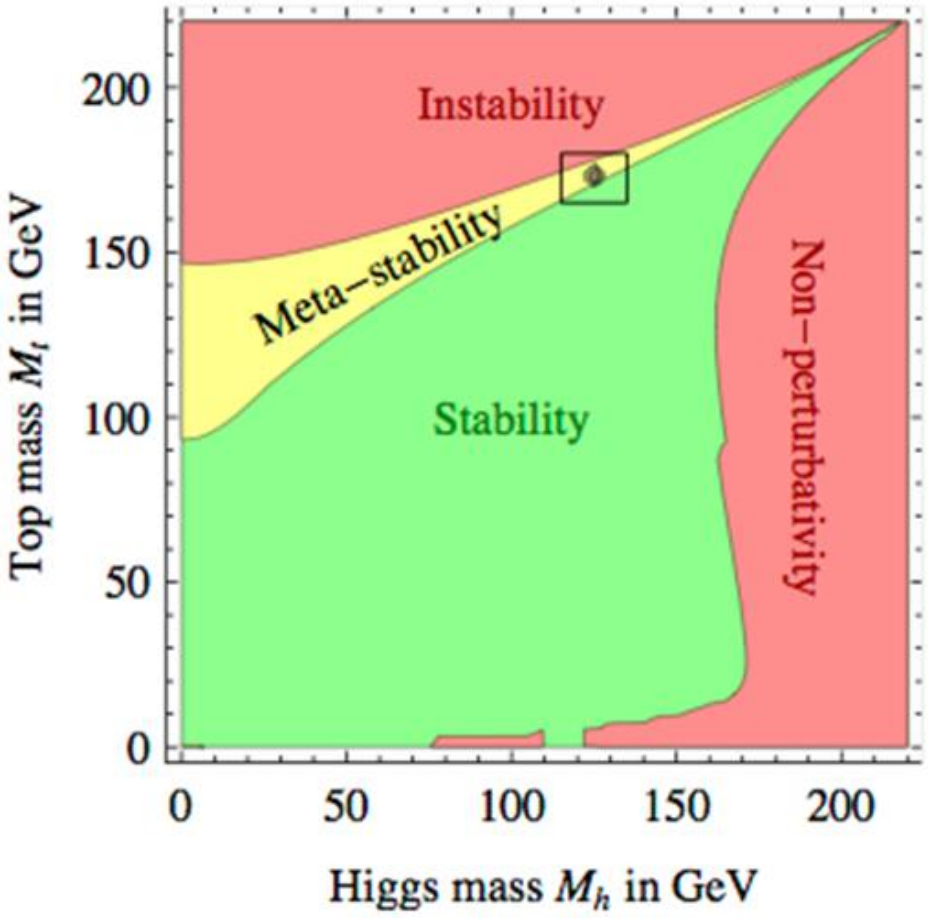
- Standard Model as long range tail of critical system which sits close to Planck scale [Jegerlehner, Bjorken, Nielsen ...]

- Phase transition in the UV
  - Long range tail renormalisable QFT (gauge symmetry for J=1 YM 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 (perhaps likely) preferred

Results from LHC: Critical physics in UV ?

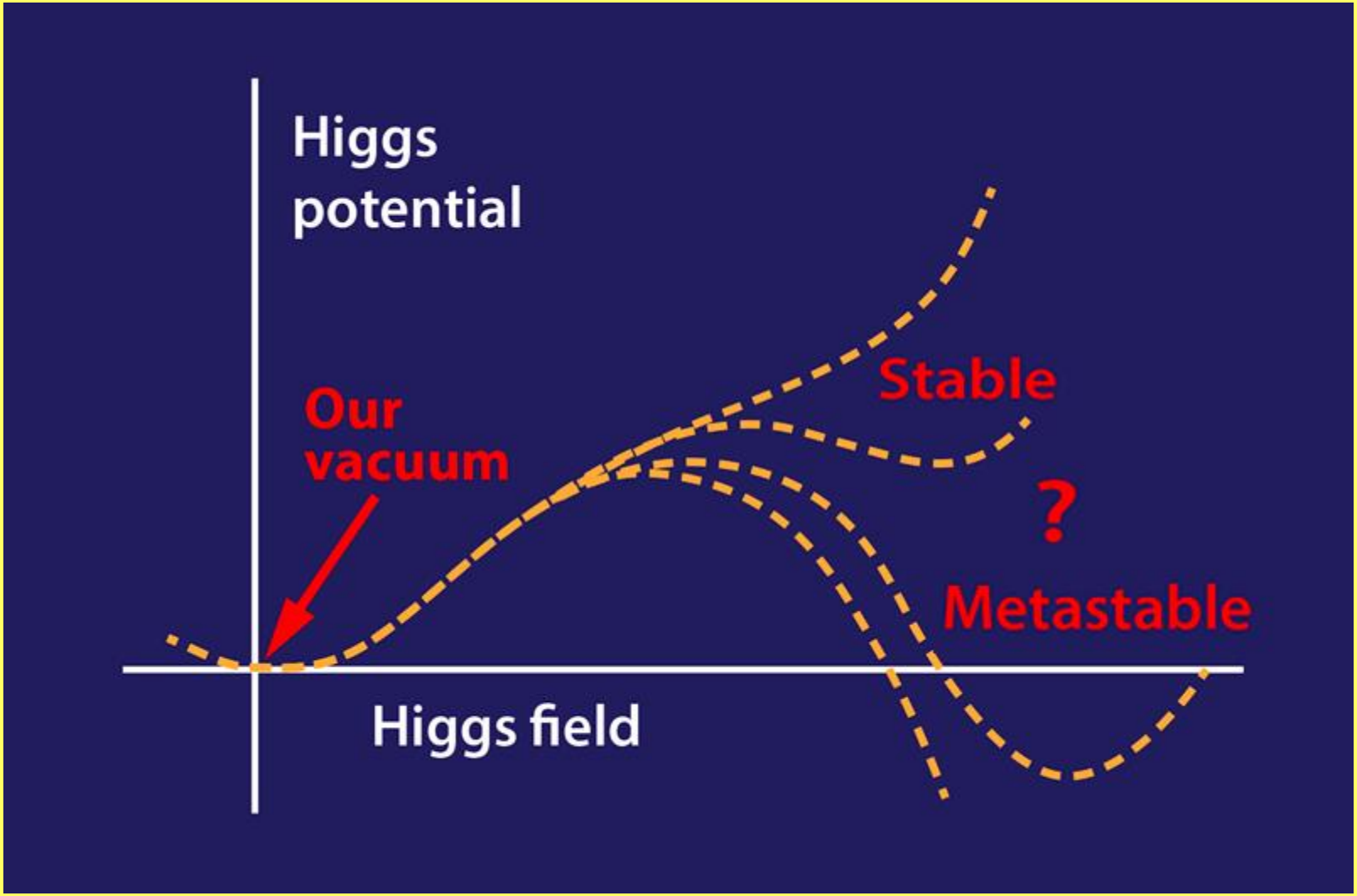
- LHC: So far just Standard Model Higgs and no BSM, SUSY ...

- 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.



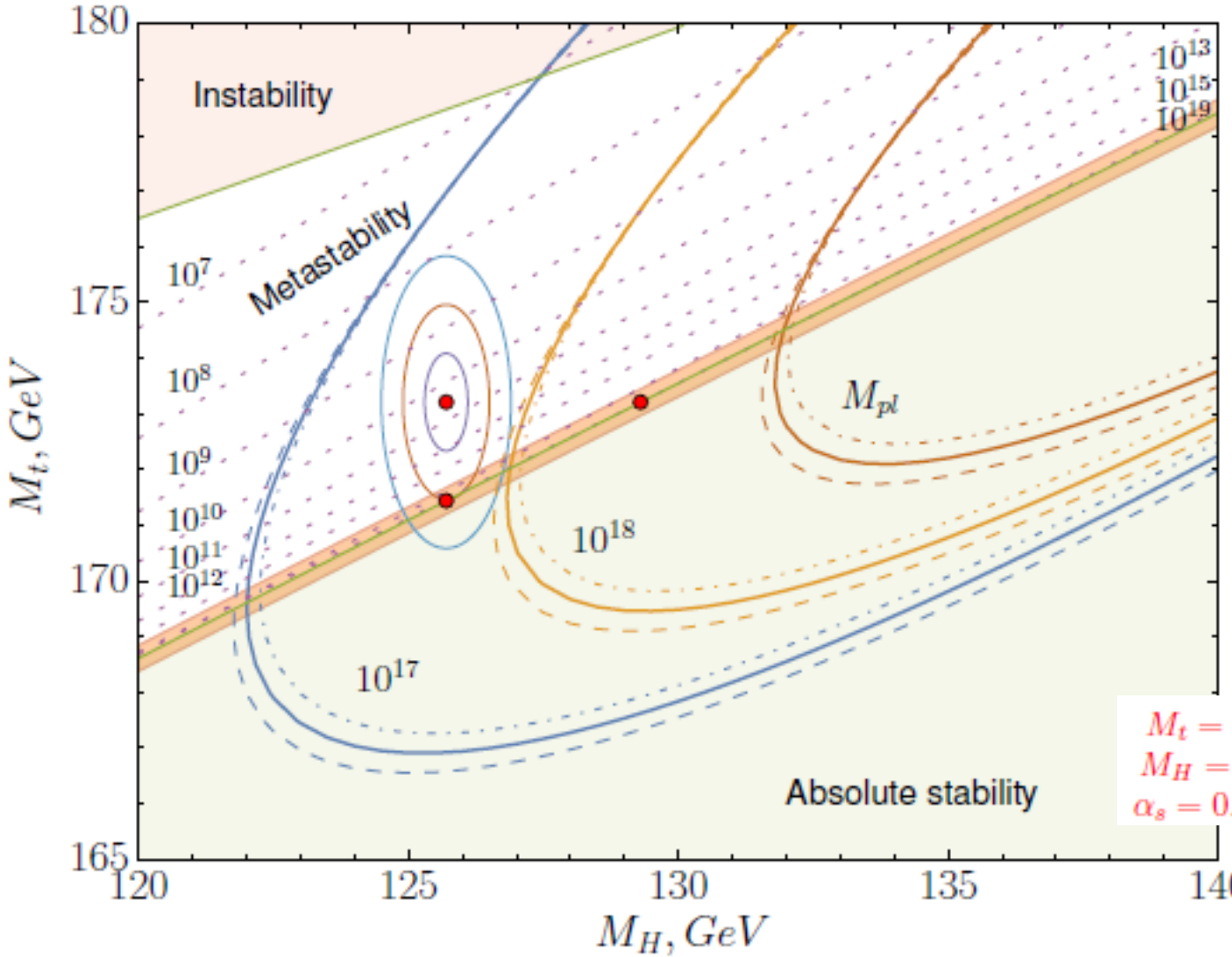
$$V(\phi) = \mu^2 \phi\phi^* + \lambda(\phi\phi^*)^2$$

Vacuum stability



Bednyakov, Kniehl et al

Phase diagram



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" ?

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

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

$$Z_3 = \frac{g^2}{g_0^2} \to 0$$

[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]

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)
- Axion potential scale bigger than 10^9 GeV
- Jegerlehner (EWSB) 1.4 x 10^{16} GeV (sign change of Higgs c-term)

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

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

- GUTs 10^{15} GeV

Analogies: „Neutrinos" and Ising systems

- Analogy based on Ising model (spin system)

$$H = -J \sum_{i,j} \left(\sigma_{i,j}\sigma_{i+1,j} + \sigma_{i,j+1}\sigma_{i,j} \right) .$$

- In the ground state all the spins line up and the energy per spin and free energy density go to zero, corrections are suppressed by powers of $e^{--\beta J}$

- With no external field, pressure is equal to minus the free energy density
  (same equation of state as cosmological constant)

- Looks like neutrino vacuum

  Neutrinos so far observed are left handed

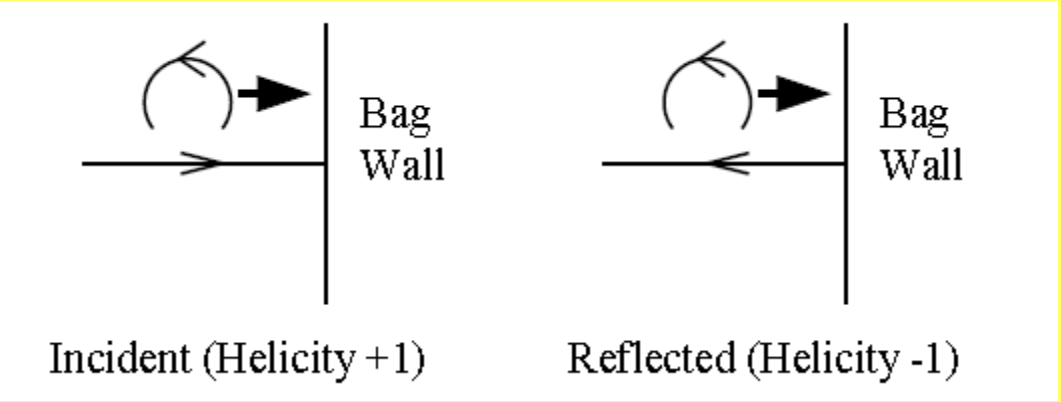
  Free energy density in Stat. Mech. ←→ vacuum energy density in QFT

- Postulate Ising like interaction in the UV: mass scales in the vacuum are J in the UV characterising „LH Ising neutrinos" and Higgs scale connecting L ←→ R

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

„Neutrinos“ and ground state

- Confining SU(2) with vector interactions
  - „Mesons“ made of electrons and neutrinos
  - Decouple RH neutrino: What happens to Confinement ?
- No RH neutrino → no scalar condensate → usual confining solution disappears!



- Change in non-perturbative propagator, DSB to Higgs (or Coulomb) phase, or is the confinement radically re-organized ?

Small QCD correction ~ 30 MeV

Summary and Open Questions

- Emergent particle physics as alternative to Unification

  - New non-pertubative dynamics in the extreme UV (?)

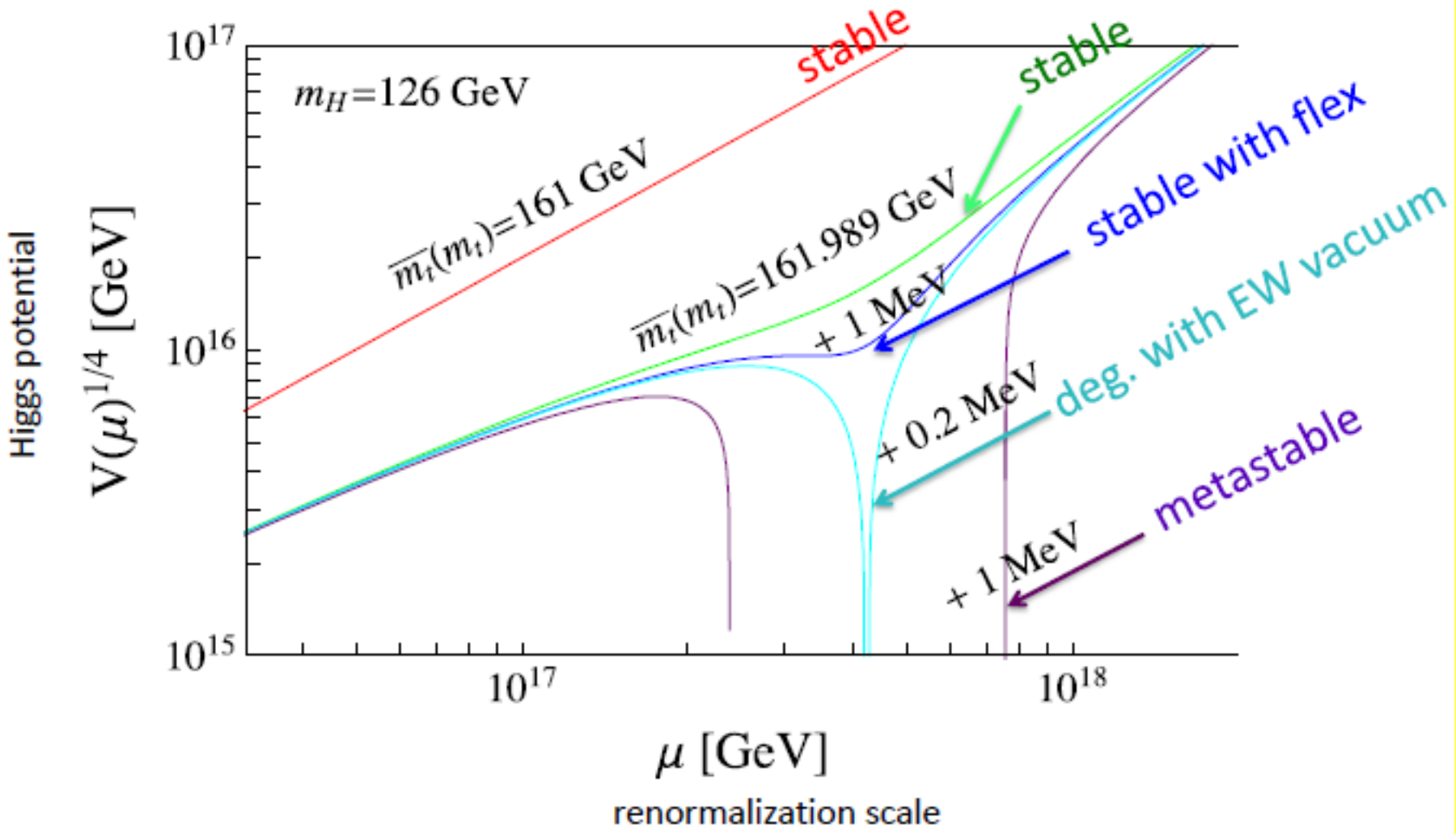
- Choice of particle physics gauge group

- If phase transition in the UV, then
  - » Are „neutrinos" (chirality) important ?
  - » Limits of perturbative extrapolation ?
  - » Flatness important ? (e.g. Crystaline Gravity, ´t Hooft)

- Matter as impurity in space-time/„spin" system ?

- Gauge and Lorentz invariance tighty constrained by experiments

Vacuum stability - Masina



Our evolving Universe