The Cosmological Constant Puzzle - Symmetries of Quantum Fluctuations

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based on work with Janina Krzysiak, PLB 803 (2020) 135351

- Scale hierarchies in particle physics
  - Cosmological constant scale ≪ QCD, Higgs and Planck masses
  - Higgs mass ≪ Planck scale

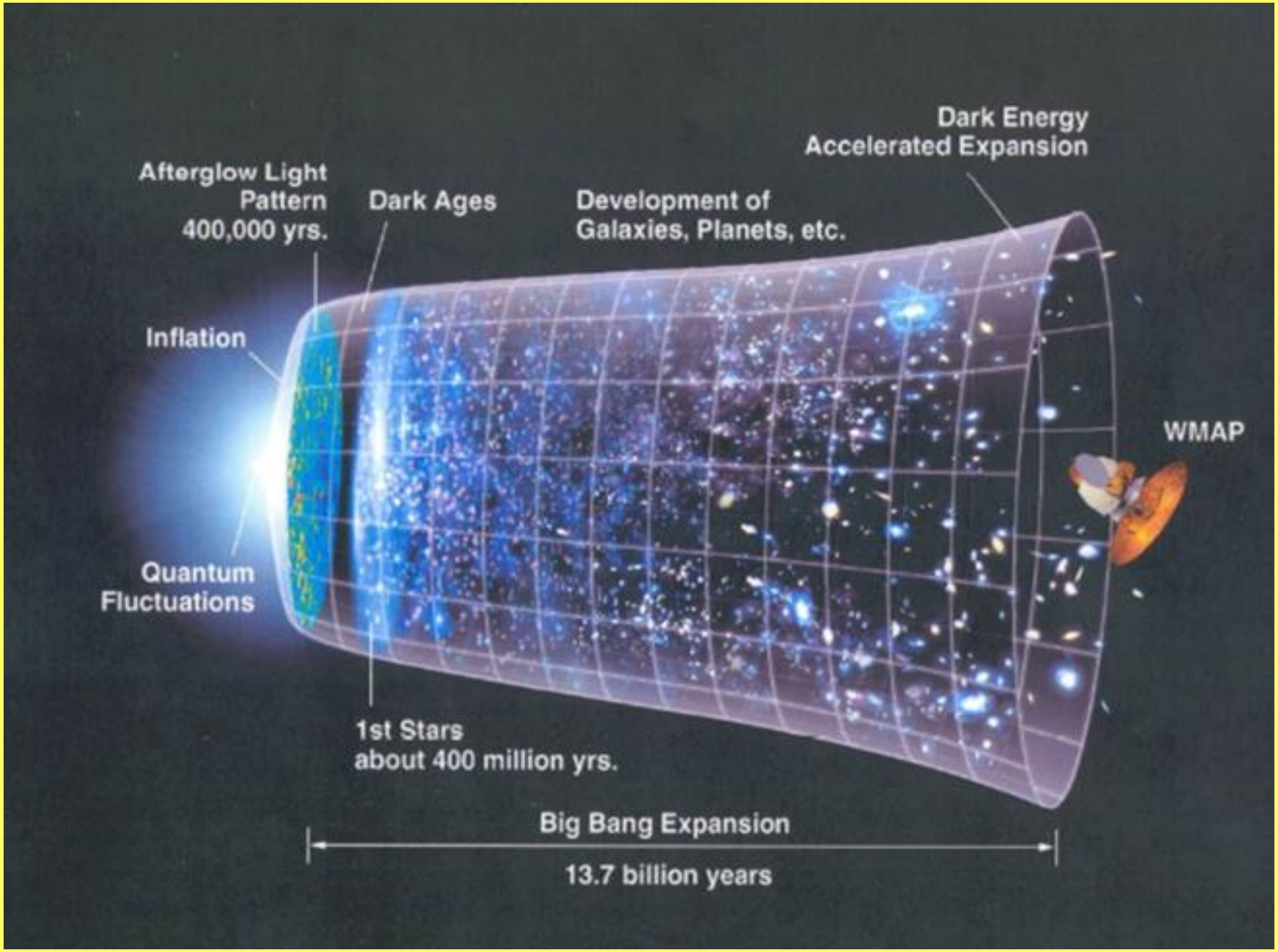
- Hints for new particles or something deeper?
- Subtleties with Poincare and RG invariance and mass generation

- Gauge symmetries determine our interactions: Where do they come from?
  - Connecting the cosmological constant and neutrino masses

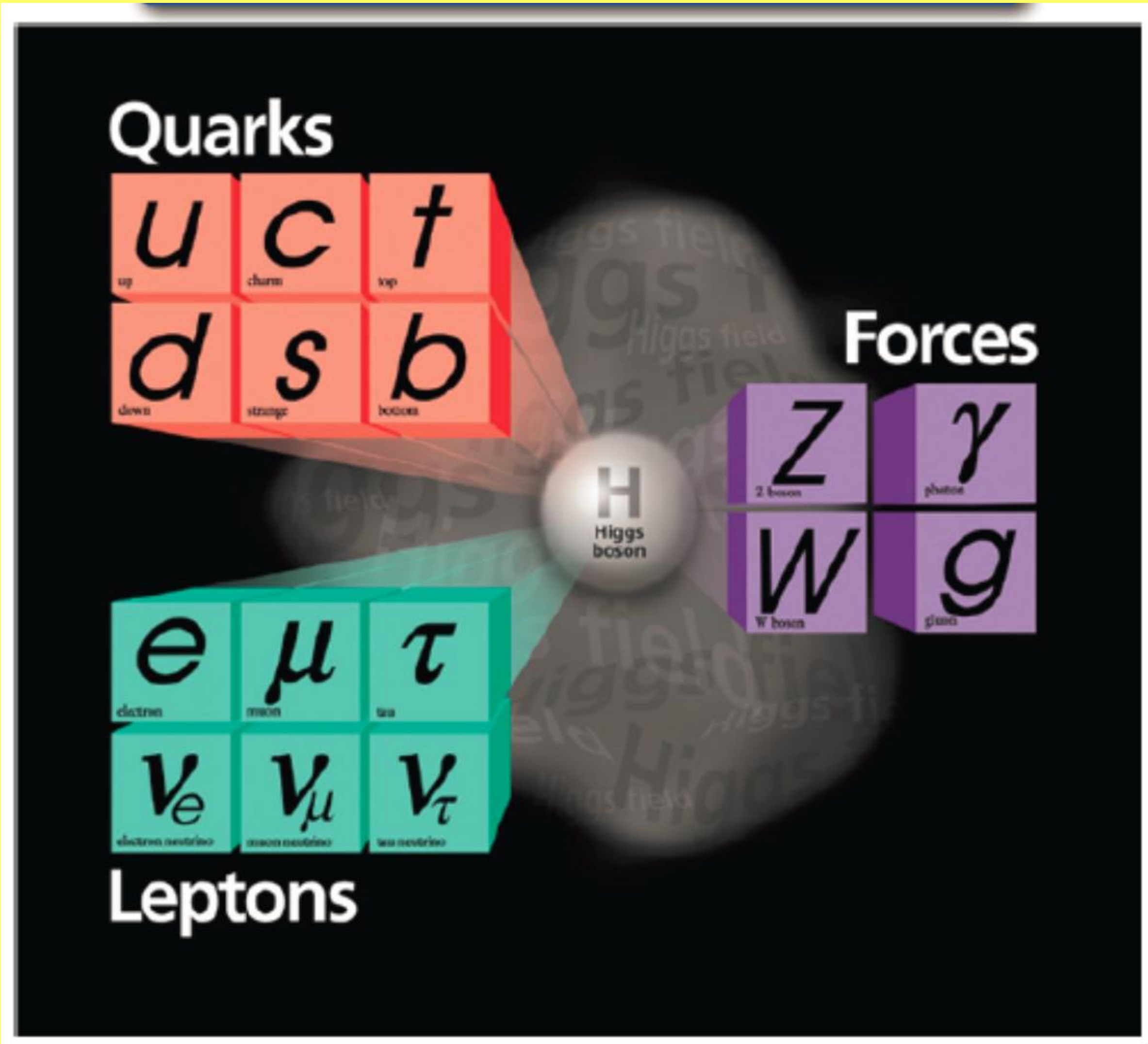
UJ Seminar, April 19th 2021

JAGIELLONIAN UNIVERSITY IN KRAKOW

Accelerating expansion of the Universe



Particle physics –
Quarks, leptons and gauge bosons

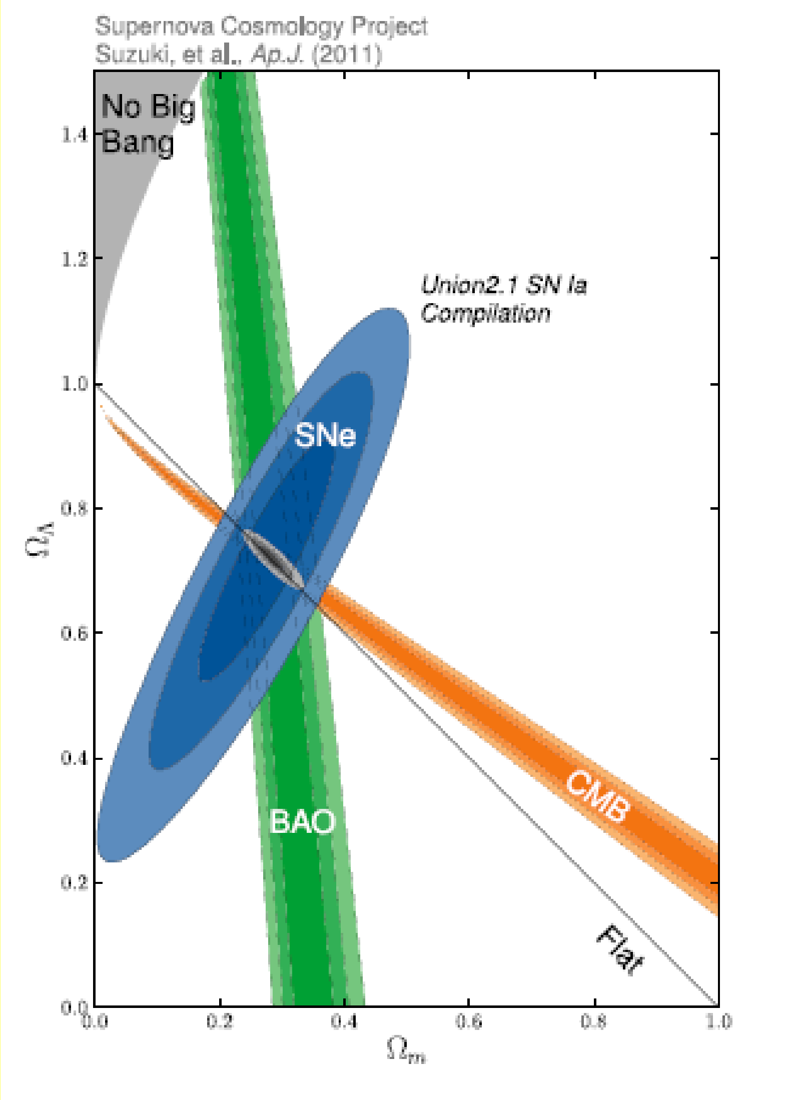


Fundamental Interactions

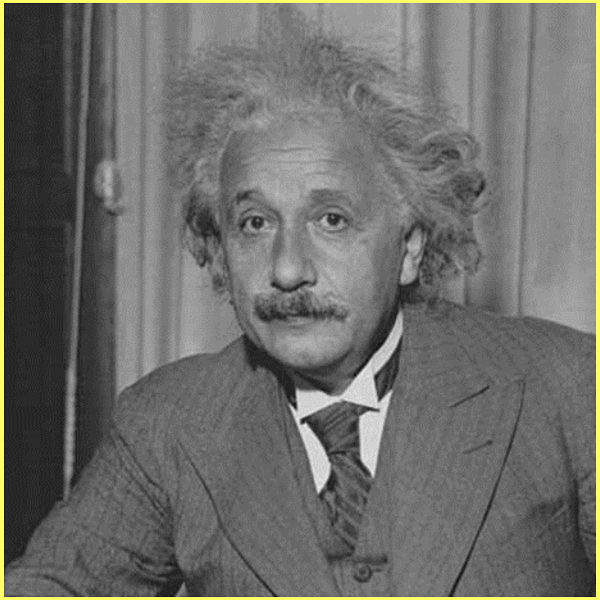
	Strength
Strong	$\alpha_s = \frac{g_s^2}{4\pi\hbar c} \sim 1^{\dagger}$
Electromagnetic	$\alpha_{em} = \frac{e^2}{4\pi\hbar c} \sim \frac{1}{137}$
Weak	$G_F m_p^2 \sim 10^{-5\dagger}$
Gravitational	$G_N m_p^2 \sim 10^{-36}$

Dark Energy Measurements

- 70% of the energy budget of the Universe is dark energy.
- Consistency between different types of measurements: Supernovae 1a, CMB and Distribution of galaxies in space (that evolved from CMB fluctuations).
- Time independent within present measurement uncertainities.

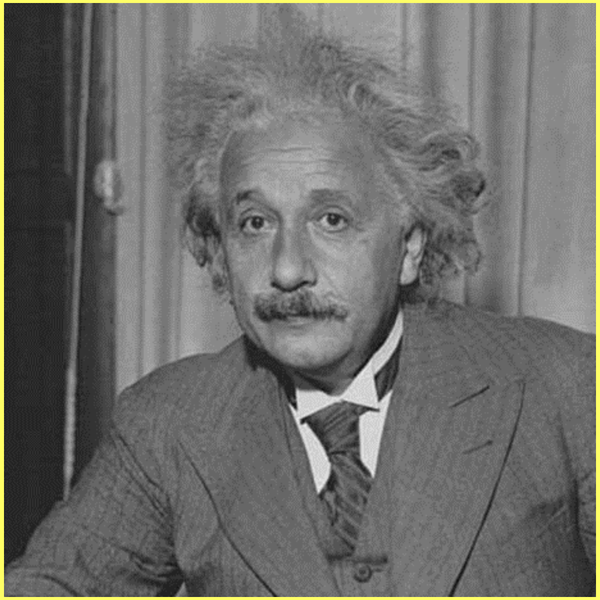


General Relativity



- Energy and mass connected
   - » $E = m c^2$
- Newton gravity couples to mass
- Einstein gravity couples to energy
- „Spacetime tells matter how to move; matter tells space how to curve.“
- If „nothing“ (the vacuum) has energy (e.g. Vacuum condensates), then the vacuum gravitates
- „Nothing“ also tells space how to curve.
   - » How big is the energy of „nothing“ ?

The Cosmological Constant



- Vacuum energy is measured just through the Cosmological Constant in General Relativity

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

- Energy density $\rho_{\rm vac} = \Lambda/(8\pi G)$

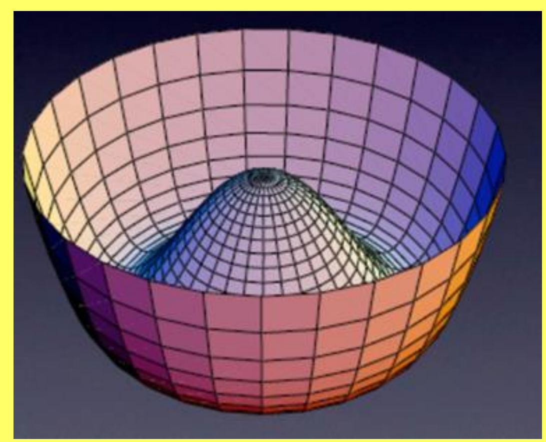
receives contributions from ZPEs, vacuum potentials (EWSB, QCD) plus gravitational term

$$\rho_{\rm vac} = \rho_{\rm zpe} + \rho_{\rm potential} + \rho_\Lambda ,$$

- In General Relativity the Cosmological Constant determines accelerating expansion of the Universe ← it is an observable and therefore RG scale invariant
  - Numerically, astrophysics (Planck) tells us $\rho_{vac} \sim (0.002 \text{ eV})^4$

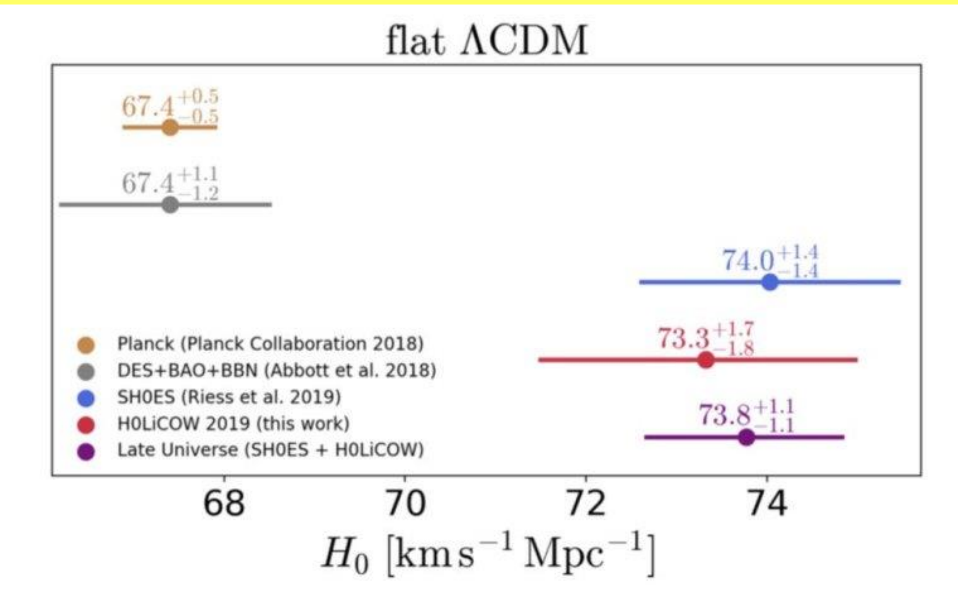
The Cosmological Constant and Particle Physics

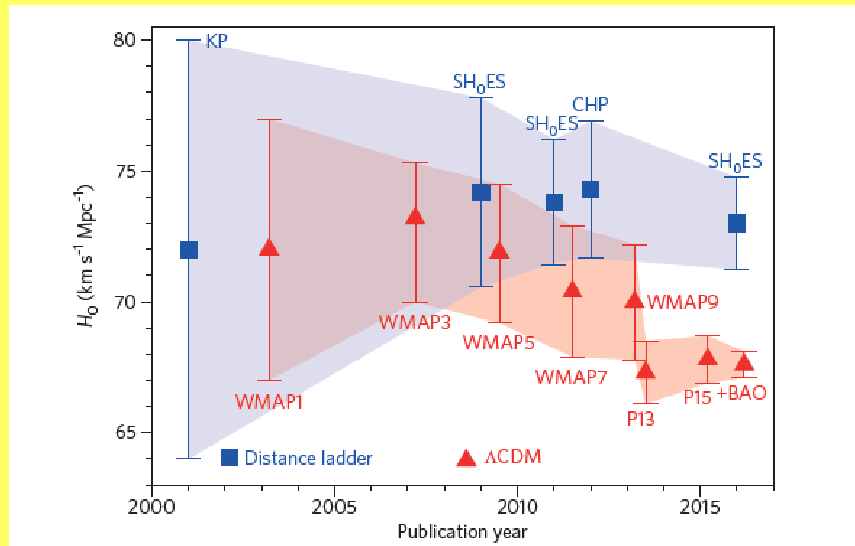
- Particle Physics Standard Model with gauge group SU(3) x $SU(2)_L$ x U(1).
  - Works very well!
  - Describes particle physics experiments from LHC to low energy precision.
  - No evidence (so far) for new particles or interactions in LHC data.
- Vacuum energy through
  - Quantization (Zero Point Energies)
  - Potentials in the vacuum from spontaneous symmetry breaking
    - Higgs and QCD condensates
- Scales in the vacuum: QCD, Higgs scale, Planck mass
- Need also Dark matter, matter-antimatter asymmetry.



Hubble tension

- ~5 sigma tension between recent and early time measurements of the Hubble constant
  - Planck, CMB $$H_0 = 67.4 \pm 0.5\ \mathrm{km s^{-1} Mpc^{-1}}$$
  - Recent time measurements $$H_0 \sim 73.0\ \mathrm{km s^{-1} Mpc^{-1}}$$



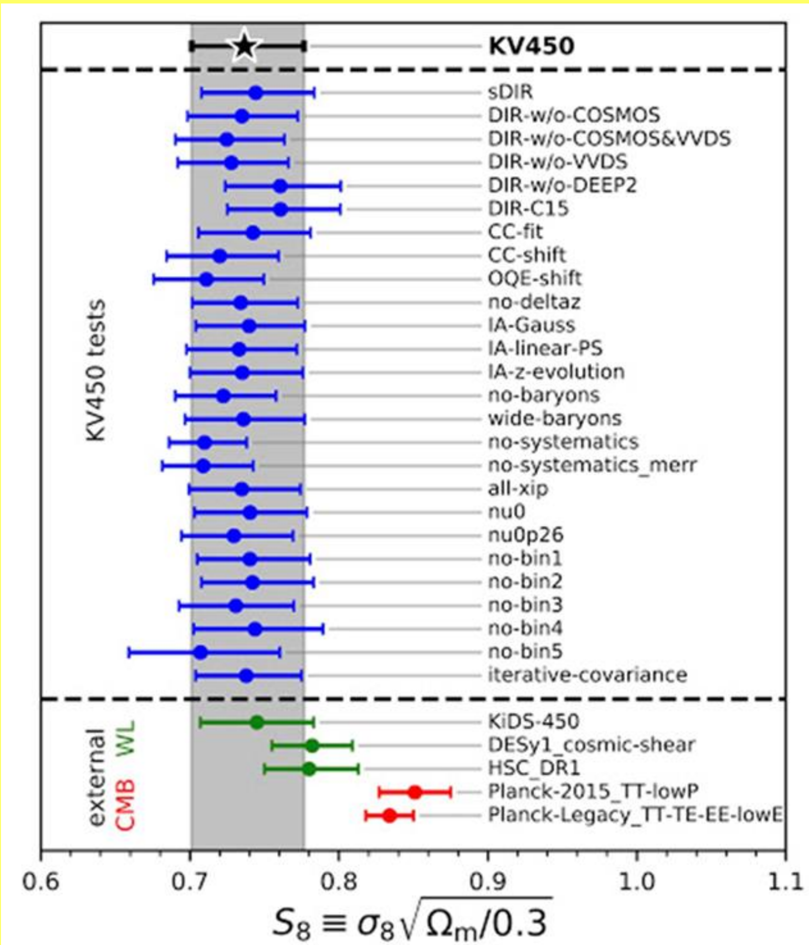


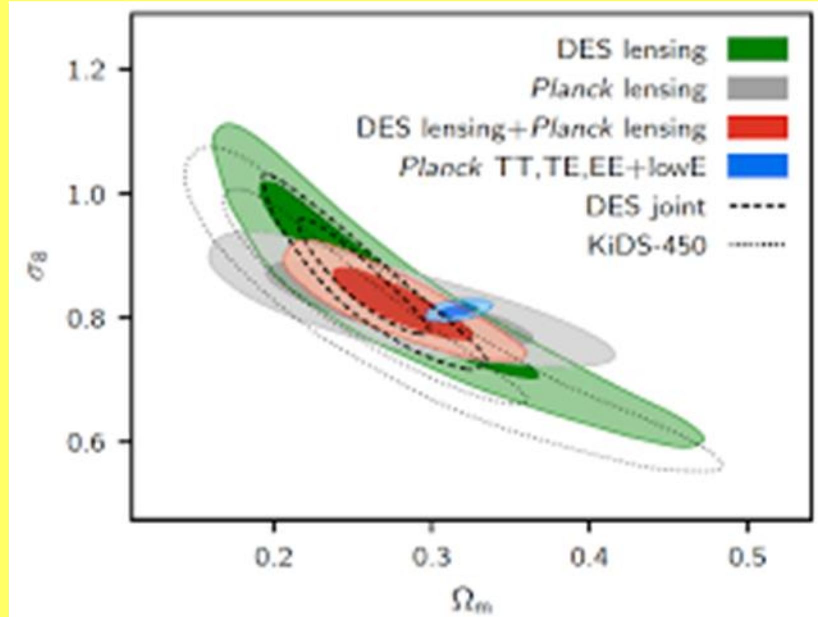
$$ds^2 = c^2 dt^2 - a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2\left(d\theta^2 + \sin^2\theta\, d\phi^2\right)\right]$$

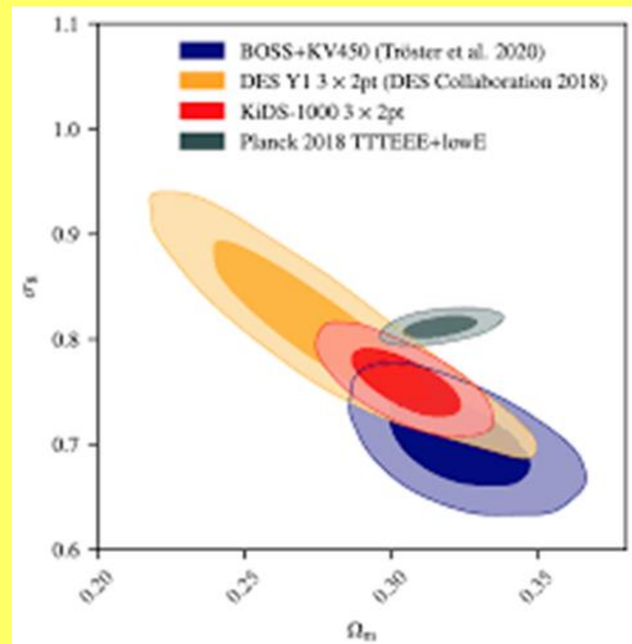
$$\left(\frac{H}{H_0}\right)^2 = \Omega_{R,0}(1+z)^4 + \Omega_{M,0}(1+z)^3 + \Omega_{K,0}(1+z)^2 + \Omega_{\Lambda,0}$$

Matter clumping tension

- ~ 3 sigma effect







Hierarchy Puzzles - Zero Point Energies

- Zero point energies (important through Cosmological Constant)

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

- Symmetries – Covariance - and the correct vacuum Equation of State

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

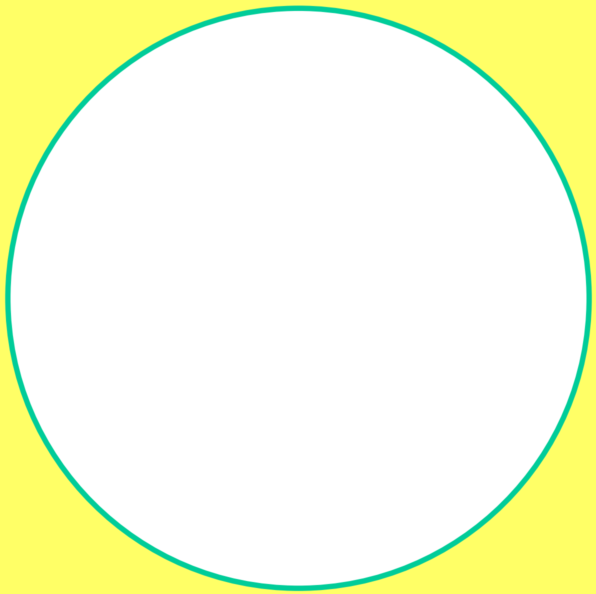
- For Standard Model particles, ρ_{zpe} comes from coupling to the Higgs
  – Proportional to particle masses, m^4

- (Using a brute force cut-off gives radiation EoS, $\rho=p/3$, for leading term)

Symmetries and anomalies

- Symmetries and UV regularization

- Need to define „infinite“ momentum consistent with how nature works



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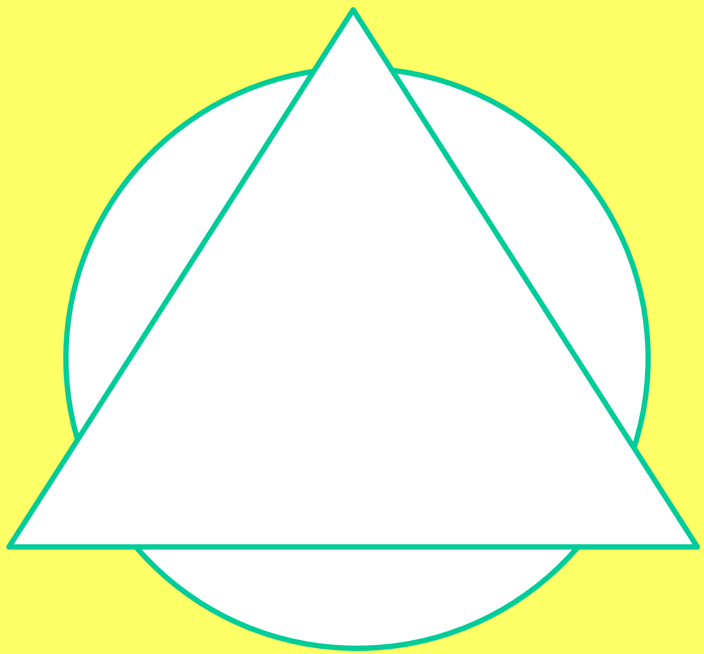


- Famous examples: $\pi^0 \rightarrow 2\gamma$, η' mass in QCD

Big numbers and Pauli constraints

- Pauli constraints and ZPEs
  - Collective cancellation between bosons and fermions

$$\sum_i g_i m_i^4 = 0$$

$$\sum_i g_i m_i^4 \ln m_i^2 = 0$$

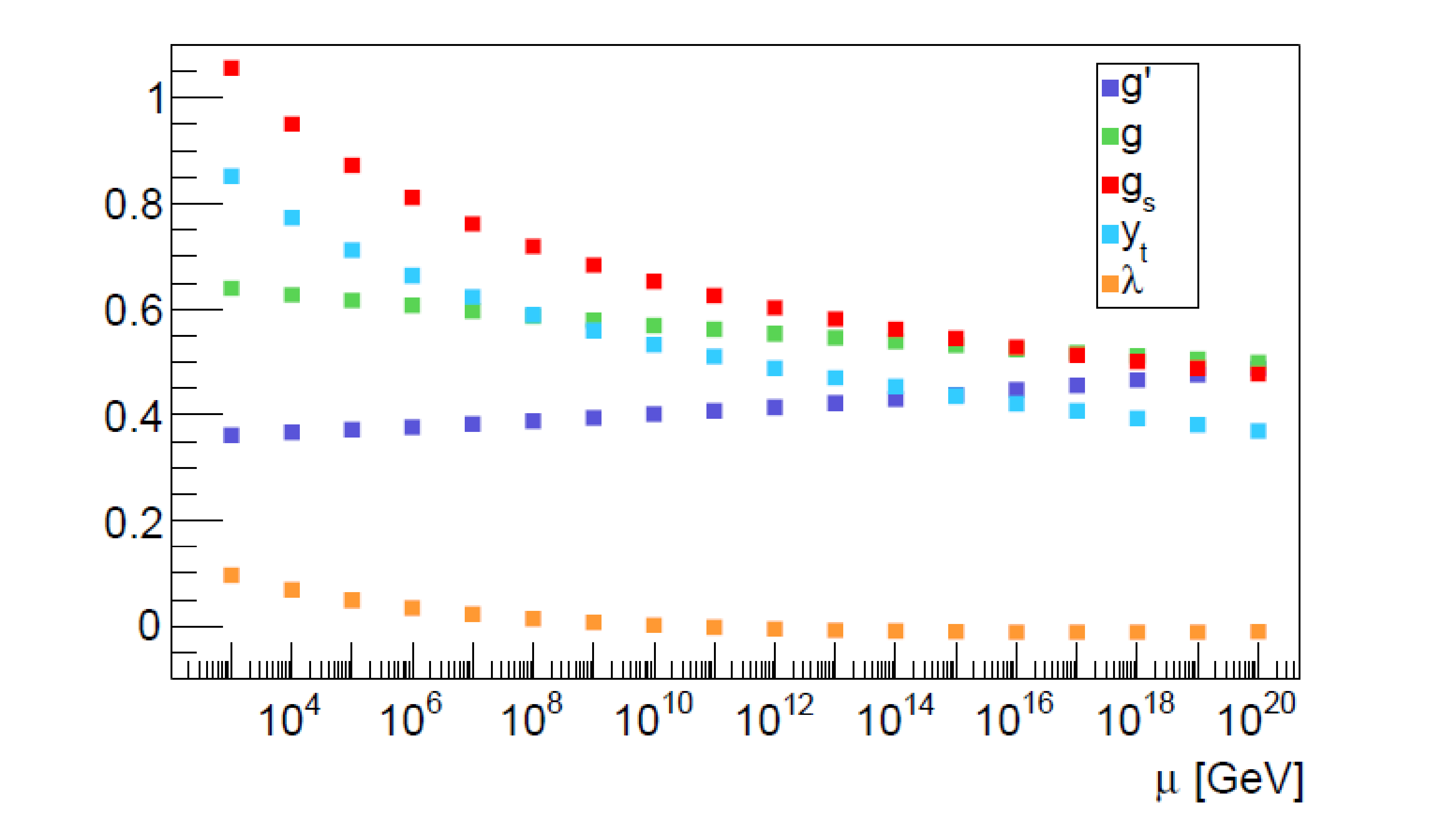
- Needs Higgs mass of 319 and 311 GeV to cancel with PDG top, W, Z masses to cancel – measured Higgs mass is 125 GeV.

- Pauli conditions involve cancellations between bosons and fermions (terms have different RG scale dependence)

- Need extra strength in the bosons
  - Consider SM extended to extra scalars and 2 Higgs Doublet Models
  - EP constraints on 2HDMs – would need extra fermions to get to work

Scale Dependence and Running Couplings

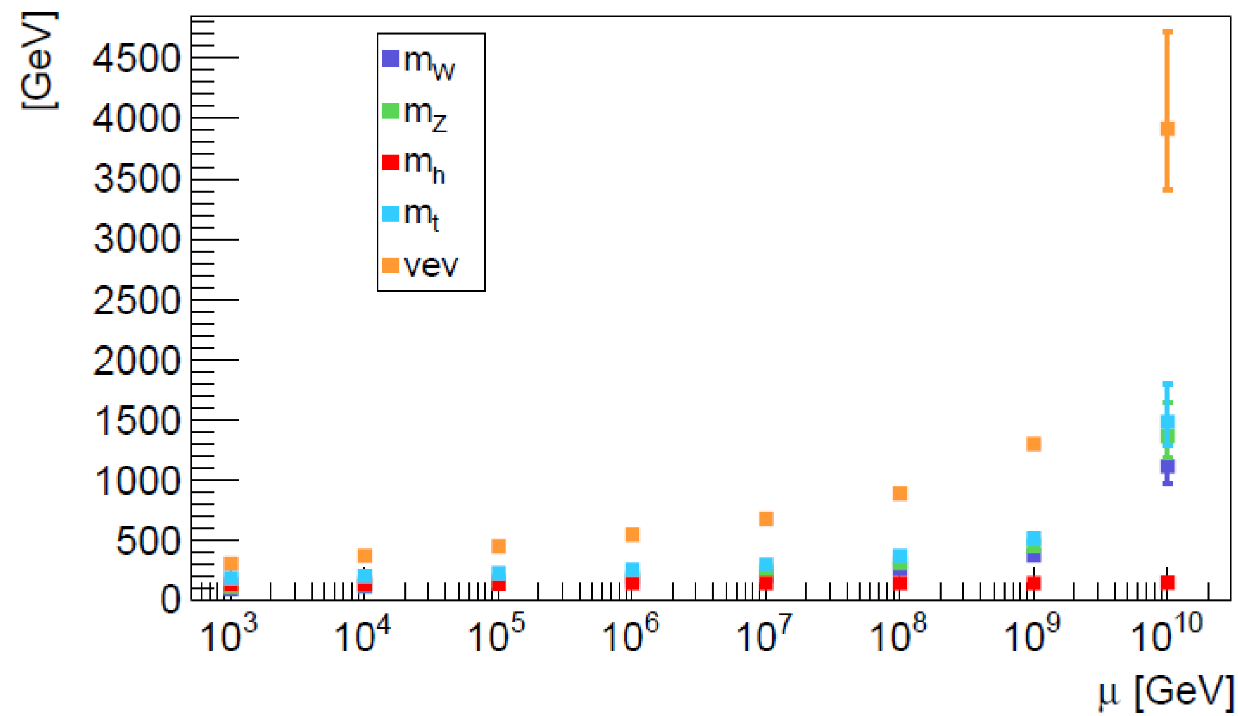
- Running Standard Model parameters [C++ code of Kniehl et al, 2016]
  Plots from SDB + J.Krzysiak, Acta Phys. Pol. B 51 (2020) 1251.



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

Running masses and Higgs vev

- Running Standard Model parameters [C++ code of Kniehl et al, 2016]
  - Running W, Z, top and Higgs masses and Higgs vev



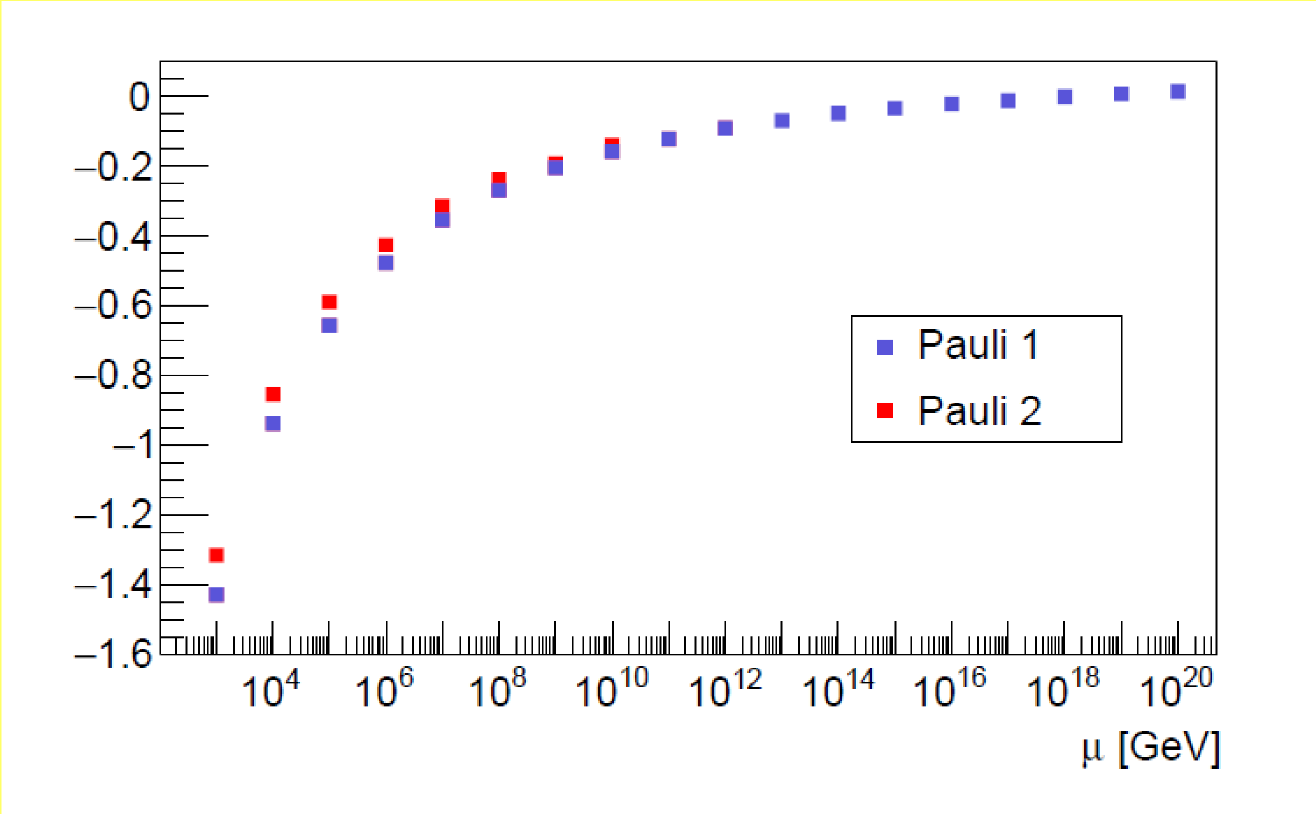
$$m_h^2 = 2\lambda v^2$$

$$m_W^2 = \frac{1}{4}g^2v^2, \quad m_Z^2 = \frac{1}{4}(g^2 + g'^2)v^2$$

$$m_f = y_f\frac{v}{\sqrt{2}} \qquad (f = \text{quarks and charged leptons})$$

Running Pauli Conditions

Running Pauli conditions (bosons – fermions)



$$6m_W^4 + 3m_Z^4 + m_h^4 = 12m_t^4$$

$$6m_W^4 \ln m_W^2 + 3m_Z^4 \ln m_Z^2 + m_h^4 \ln m_h^2 = 12m_t^4 \ln m_t^2$$

normalised to v^4 (Pauli 1) and $v^4 \ln v^2$ (Pauli 2)

Emergent Symmetries and Particle Physics

- Are (gauge) symmetries always present ?

(Gauge symmetries determine our particle interactions)

Making symmetry as well as breaking it

- Emergence: Symmetries dissolving in the UV instead of extra unification – question of resolution.

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

[SDB, Prog. Part. Nucl. Phys. 113 (2020) 103756]

Emergent Symmetries

- Standard Model as an effective theory with infinite tower of higher dimensional operators, suppressed by powers of the (large) emergence scale M

- Global symmetries tightly constrained by gauge invariance and renormalisability when restricted to dimension 4 operators, e.g. QED

$$\mathcal{L} = \bar{\psi} i \gamma^\mu D_\mu \psi - m \bar{\psi} \psi - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

- Can be broken in higher dimensional operators, suppressed by powers of M

- Examples, lepton and baryon number violation, Weinberg, PRL 1979

- E.g. Lepton number violation ← Majorana neutrino masses at mass dimension 5 (Weinberg)

$$O_5 = \frac{(\Phi L)_i^T \lambda_{ij} (\Phi L)_j}{M}$$

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

Cosmological Constant

- Is an observable and therefore RG scale invariant

$$\frac{d}{d\mu^2}\rho_{\rm vac} = 0.$$

$$\rho_{\rm vac} = \rho_{\rm zpe} + \rho_{\rm potential} + \rho_{\Lambda},$$

- Scale dependence (explicit μ, in masses and couplings) cancels:
  What is left over?

- Curious: With finite Cosmological Constant there is no solution of Einstein's equations of GR with constant Minkowski metric (Weinberg, RMP)
  - No longer global space-time translational invariant
  - Metric is dynamical with accelerating expansion of the Universe
  - Cf. Success of special relativity and usual particle physics in Lab
    [Also, QCD puzzle and current to constituent quarks]

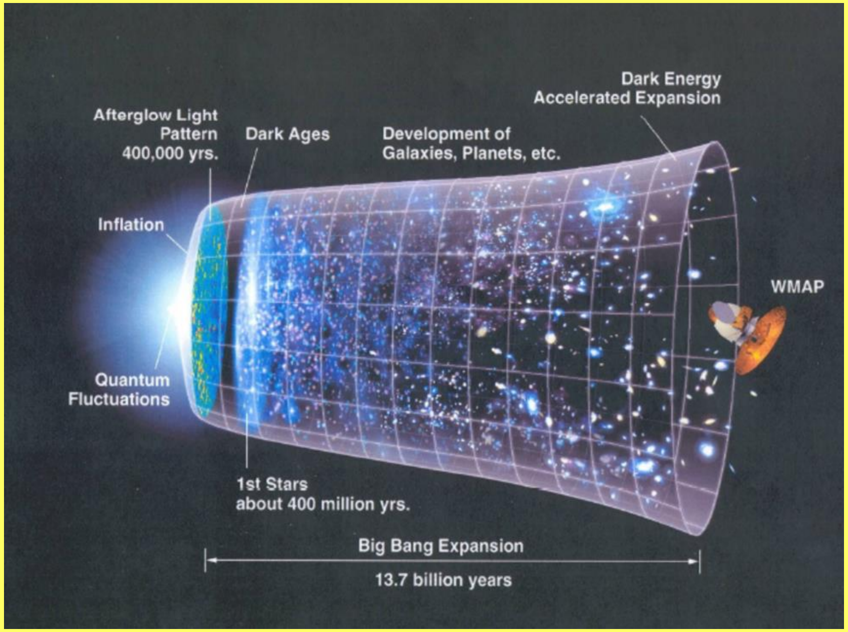
Metric with finite Cosmological Constant

- Minkowski metric → de Sitter metric with finite cosmological constant

$$ds^2 = d\hat{t}^2 - e^{2H_\infty \hat{t}}(d\hat{r}^2 + \hat{r}^2 d\theta^2 + \hat{r}^2 \sin^2\theta d\phi^2).$$

$$ds^2 = \left(1 - \frac{r^2}{R_\infty^2}\right) dt^2 - \left(1 - \frac{r^2}{R_\infty^2}\right)^{-1} dr^2 - r^2(d\theta^2 + \sin^2\theta d\phi^2)$$

$$\frac{1}{R_\infty^2} = H_\infty^2 = \frac{8\pi G}{3}\mu^4 = \frac{\Lambda}{3}.$$



Cosmological Constant Scale

- Zero cosmological constant makes sense at dimension 4
  - E.g. Global Minkowski metric works in laboratory experiments

- Cosmological constant scale then suppressed by power of M
  - » 4 dimensions of space-time, so to power of 4 in CC

- Then, scale of Cosmological Constant ~ scale of neutrino mass ~ 0.002 eV

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

  - Einstein's second guess and Feynman lectures ← works at dimension 4

  - Anthropic argument (Weinberg)
    - CC can be at most 10x bigger to allow galaxies to form
    - Higgs mass constrained to be at most 30% bigger with matter fixed

      [Also 30% is also ~ constraint from perturbative unitarity]

Summary

- LHC results do not *require* anything else at mass dimension 4
- Fine balance of Standard Model parameters and EW vacuum stability
  - Higgs mass correlated with Planck scale physics
- Subtle interplay of Poincare symmetry and mass generation
  - Vacuum EoS with ZPE coming from Higgs couplings for SM particles
  - With emergence,
    - Cosmological Constant zero at mass dimension 4
    - Einstein´s second guess, also Feynman gravitation lectures
    - Scale suppressed by power of emergence, just as neutrino masses [SDB+JK: Physics Letters B803 (2020) 135351]
      - » Why does Nature like the Minkowski metric?