The Cosmological Constant with Emergent Gauge Symmetries

Steven Bass

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

- Cosmological constant and accelerating expansion of the Universe
- Energy density of the vacuum perceived by gravitation
- Characterised by tiny scale ~0.002 eV << QCD, Higgs and Planck scales
- How to explain in terms of particle physics and subatomic vacuum?
- CC puzzle involves subtleties with Poincare and RG invariance and mass generation
- Possible explanation in terms of emergent symmetries.

BNL Forum, November 4th 2021

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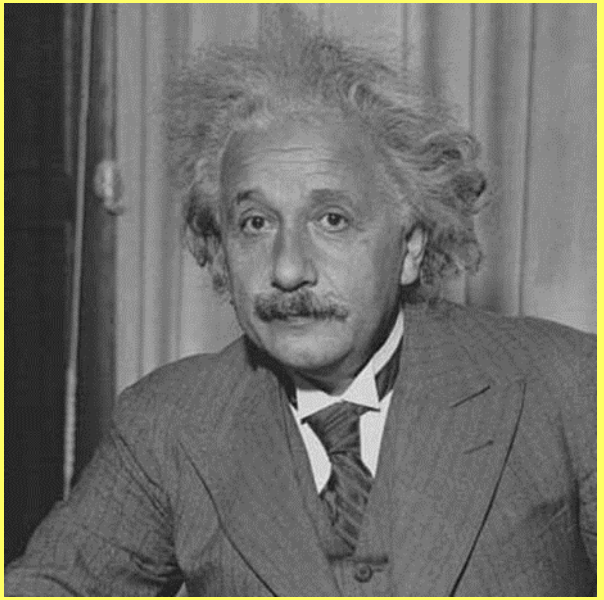
The Cosmological Constant



- 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 $\rho_{vac} \sim (0.002\ \text{eV})^4$

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

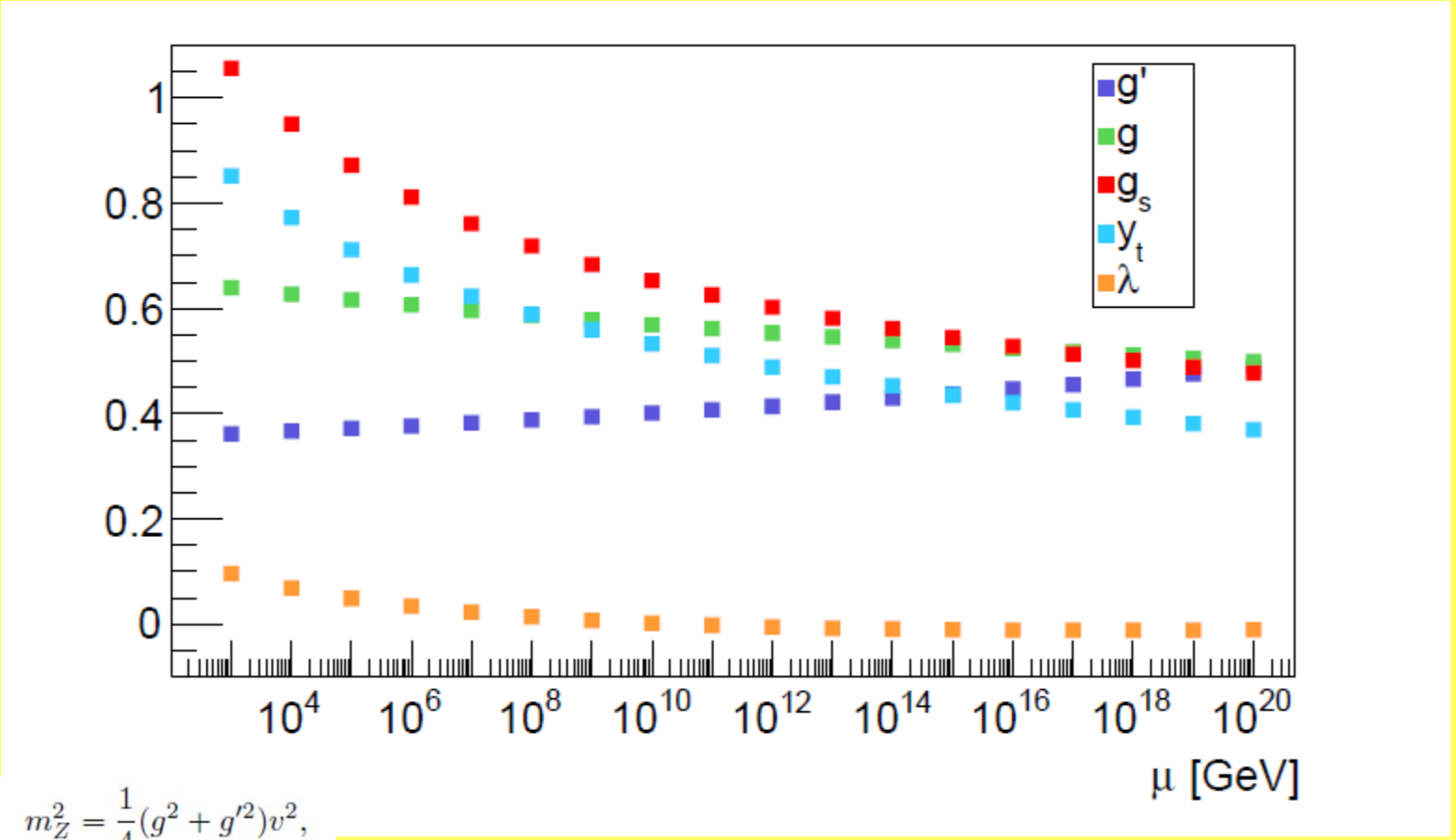
$$\rho_{\rm zpe} = -p_{\rm zpe} = -\hbar\, g_i\, \frac{m^4}{64\pi^2}\left[\frac{2}{\epsilon}+\frac{3}{2}-\gamma-\ln\left(\frac{m^2}{4\pi\mu^2}\right)\right]+\ldots$$

- 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)

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.



$$m_W^2 = \frac{1}{4}g^2v^2, \qquad m_Z^2 = \frac{1}{4}(g^2+g'^2)v^2,$$
$$m_f = y_f\frac{v}{\sqrt{2}},$$
$$m_H^2 = 2\lambda v^2.$$

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

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 ...].
- Examples in quantum many-body physics: String-nets, Superfluid ^{3}He-*A*

[SDB, Prog. Part. Nucl. Phys. 113 (2020) 103756; 2110.00241]

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

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

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

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?

Extra reading

- *SDB, e-Print: 2110.00241 [hep-ph], to appear in Phil. Trans. Royal Society A*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Research

Article submitted to journal

Emergent gauge symmetries - making symmetry as well as breaking it

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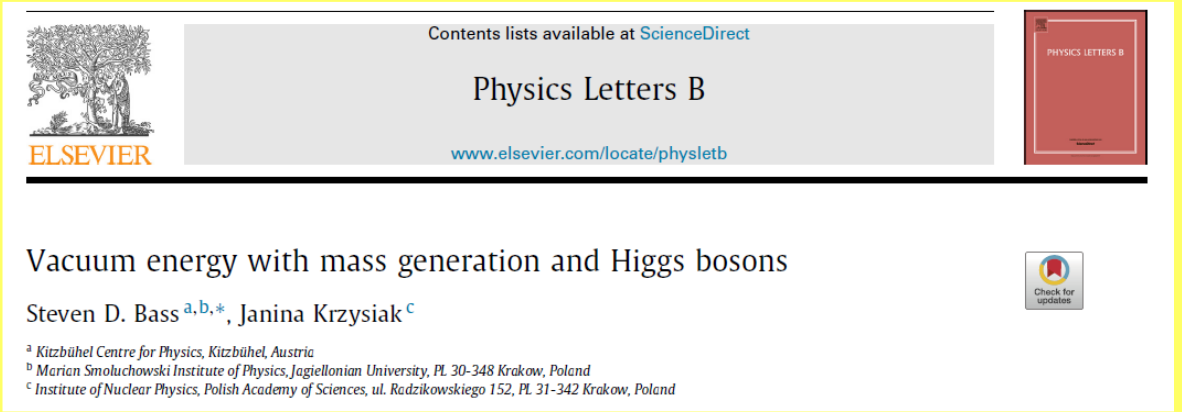
- *SDB, Prog. Part. Nucl. Phys. 113 (2020) 103756*

- *SDB + J Krzysiak, Phys. Lett. B 803 (2020) 135351*
- *SDB + J Krzysiak, Acta Phys. Polon. B 51 (2020) 1251*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Vacuum energy with mass generation and Higgs bosons

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