Vacuum Energy and the cosmological constant puzzle

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- Cosmological constant puzzle: (arXiv:1503.05483 [hep-ph], MPLA – in press)

- Accelerating Universe: believed to be driven by energy of „nothing“ (vacuum)

- Positive vacuum energy = negative vacuum pressure

- Vacuum energy density (cosmological constant or dark energy) is 10^{56} times less than what Standard Model particle physics expects, though curiously ~ (light neutrino mass)^4

- Coincidence puzzle: Very different time dependence of matter, radiation and vacuum energy densities since Big Bang. Today matter and vacuum energy densities are within order of magnitude of each other.

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Dark energy and its size

- Particle physics
  - Nice thing (QED, QCD, Higgs, ... LHC, LEP ...)

    Standard Model works very well,

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

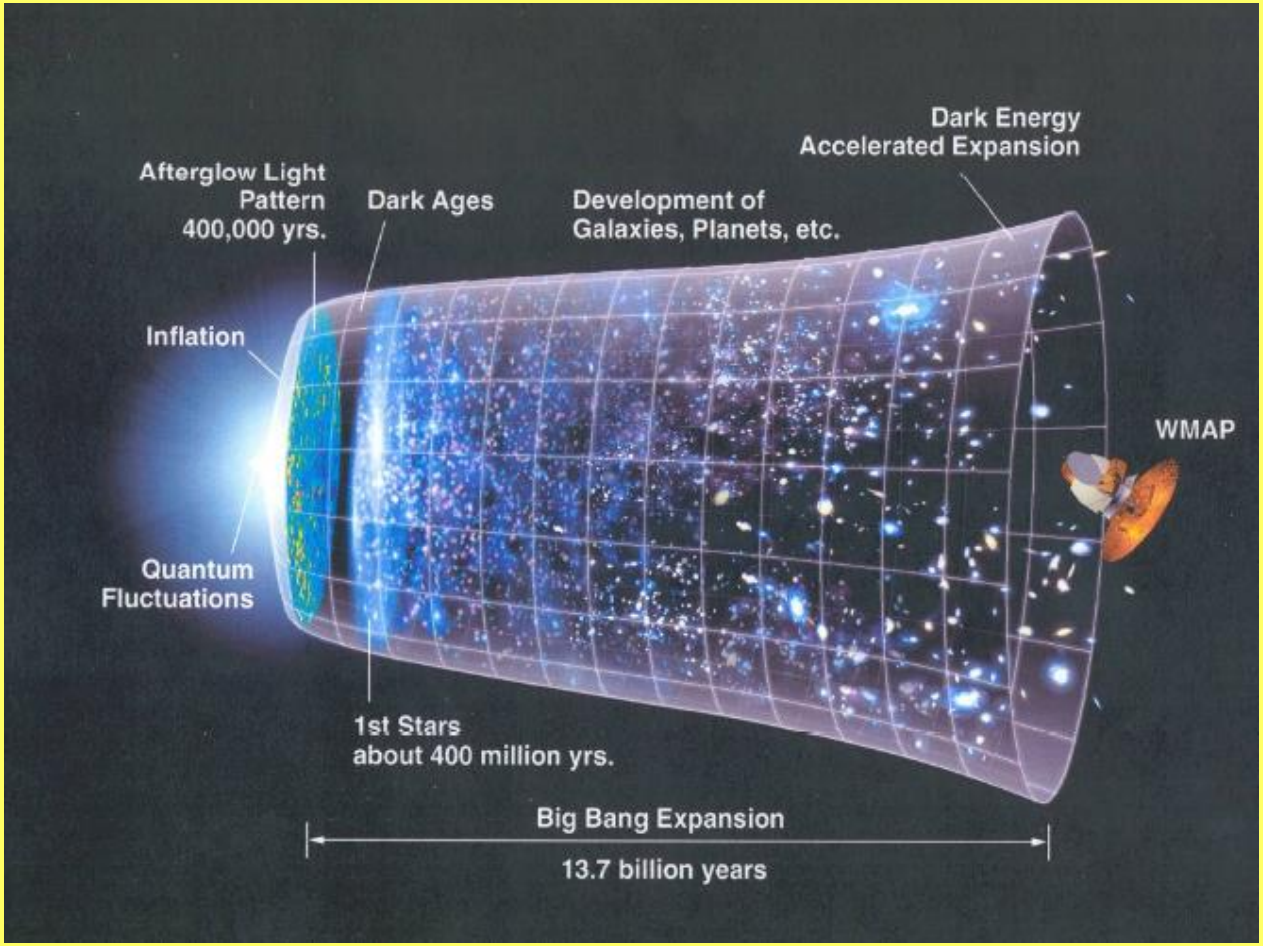
meets

- General relativity
  - Nice thing (Binary pulsars, lensing, black holes, Lab tests of Inverse Square Law to 56 μm...)

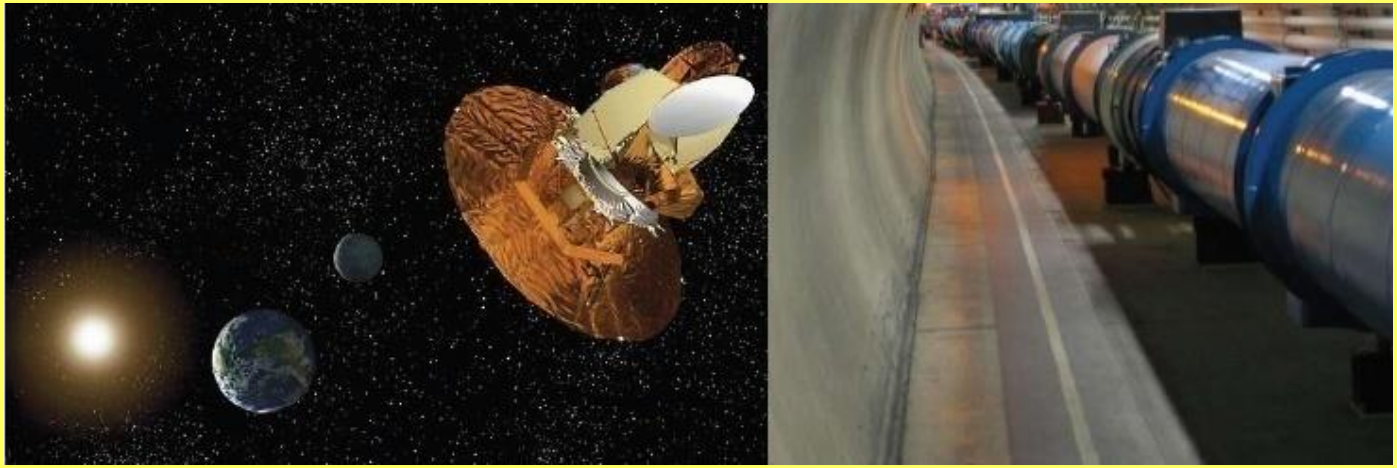
    → Curious result: discrepancy of 10^{56} (!) + wrong sign (!)

    Also, within present errors, couplings and masses are time independent

Our evolving Universe



Gravity and particle physics



Gravitation and the cosmological constant are fundamentally different from particle physics and other physics in that gravity couples to everything whereas other physics processes and experiments involve measuring the differences between quantities.

Absolute values of the zero-point vacuum energy only enters when coupling to gravity.

The Cosmological Constant Puzzle

- Cosmological constant behaves like a vacuum energy (plus counterterm)

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

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

- Quantum field theory (particle physics): zero point energies

$$\rho_{\rm vac} = E/V = \frac{1}{2}\sum\{\hbar\omega_0\} = \frac{1}{2}\hbar \sum_{particles} g_i \int_0^{k_{max}} \frac{d^3k}{(2\pi)^3}\sqrt{k^2+m^2} \sim \sum_i \frac{g_i k_{max}^4}{16\pi^2}$$

- „Normal ordering" → zero,
  but then Spontaneous Symmetry Breaking (Higgs) and condensates

$$\Lambda_{\rm vac} = 8\pi G \Lambda_{\rm ew}^4$$

$$\rho_{\rm vac} = \frac{1}{2}\sum \hbar\omega \sim (250\,{\rm GeV})^4,$$

- Accelerating Universe corresponds to

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

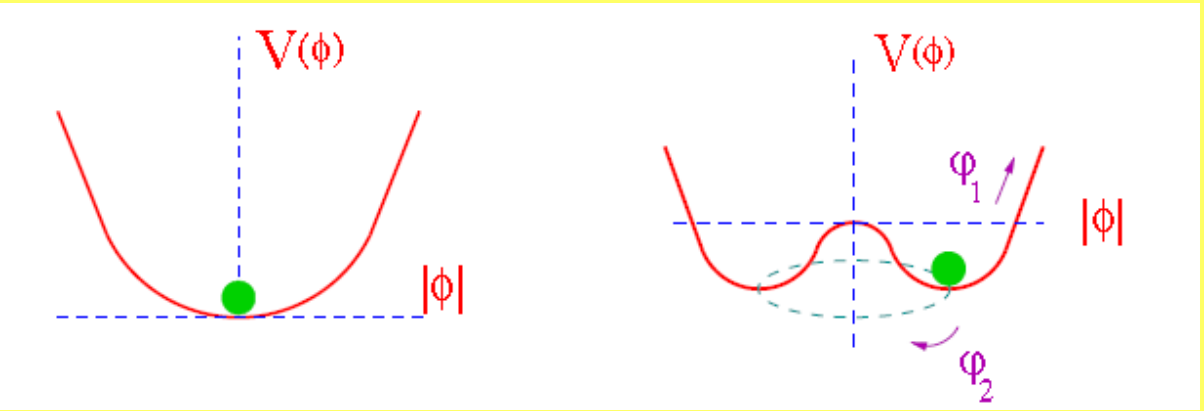
$$\mu_{\rm vac} \sim \Lambda_{\rm ew}^2/2M$$

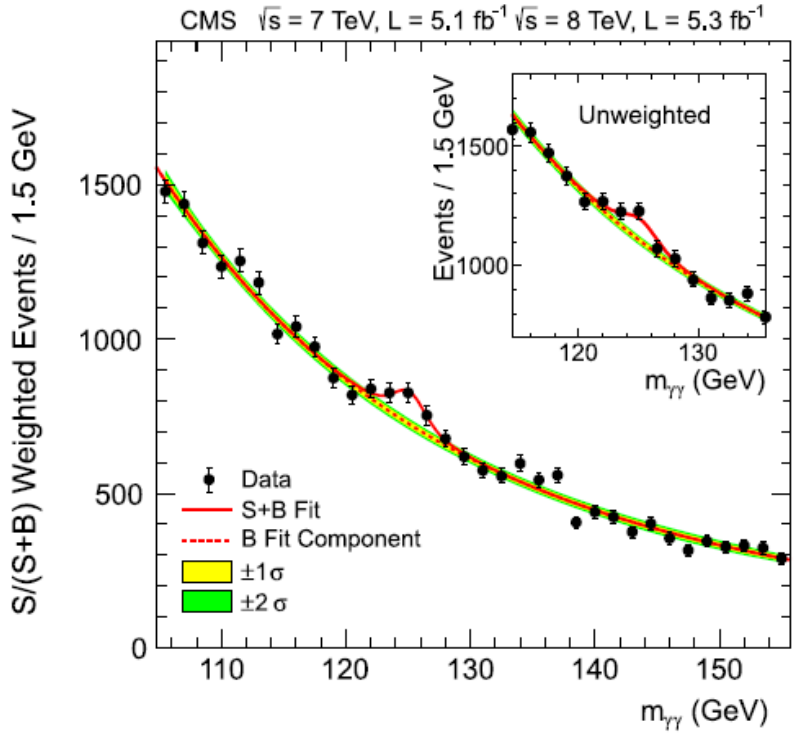
- Do zero-point energies and condensates gravitate ?

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

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





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)

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

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

- GUTs 10^{15} GeV

» How to reconcile the different scales ?

Input from experiments

- LHC
  So far just Standard Model Higgs and no BSM, SUSY …
- Remarkable: Higgs and top mass sit in window of possible parameter space where Standard Model might be stable up to Planck mass

- No confirmed dark matter sighting despite much experimental effort

- Couplings and masses seem time independent within present accuracy back to CMB (380 000 years after Big Bang)

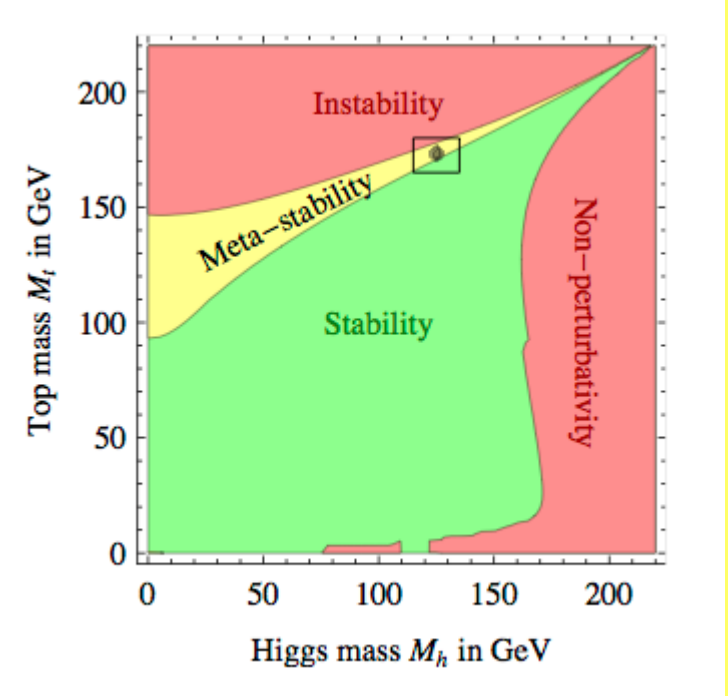
- Precision measurements, especially electron EDM
  - Probes possible extra sources of CP violation
  - Electron is round to current precision
    - » No SUSY &tc effects up to LHC energies unless special cancellation of phases
    - » Next generation of eEDM experiments will probe up to 100TeV scale

Electroweak Vacuum Stability

- Remarkable: Higgs and top mass sit in window of possible parameter space where Standard Model might be stable up to Planck mass

- Possible critical phenomena close to Planck mass with Standard Model as long range tail

- Is the Standard Model „emergent" ?
  (cf. Low energy part of GUT
  spontaneously broken by Higgs fields and condensates)
  If yes, possible violations of Lorentz invariance, gauge invariance &tc at very high scales close to the Planck mass
  - perhaps suppressed by powers of μ/M



Attempts to understand

- Analogy based on Ising model (spin magnet)

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

- 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 Statistical Mechanics
    ←→ vacuum energy in Quantum Field Theory

- Resultant picture: Standard Model like an „impurity" in a spin system which exists near the Planck scale, at about 3×10^{16} GeV . Phase transition involving the neutrino generates parity violation and Higgs phase for gauge bosons which couple to the neutrino. The Vacuum energy of the Higgs system diluted by same physics which generates parity violation

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

SDB, Acta Phys Pol B 45 (2014) 1269; arXiv:1210.3297 [hep-ph]

Where are we going ?