

Vacuum Energy and the cosmological constant puzzle

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- Cosmological constant puzzle: Mod. Phys. Lett. A 30 (2015) 1540033
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- 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 \sim (light neutrino mass)⁴
- Explore possible interface of dark energy and LHC results: Higgs vacuum (meta-)stability

Humboldt Kolleg Kitzbühel, June 29 2016

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 (CRESST, Xenon100, LUX...), precision measurements: eEDM..., CPT and Lorentz invariance ...

meets

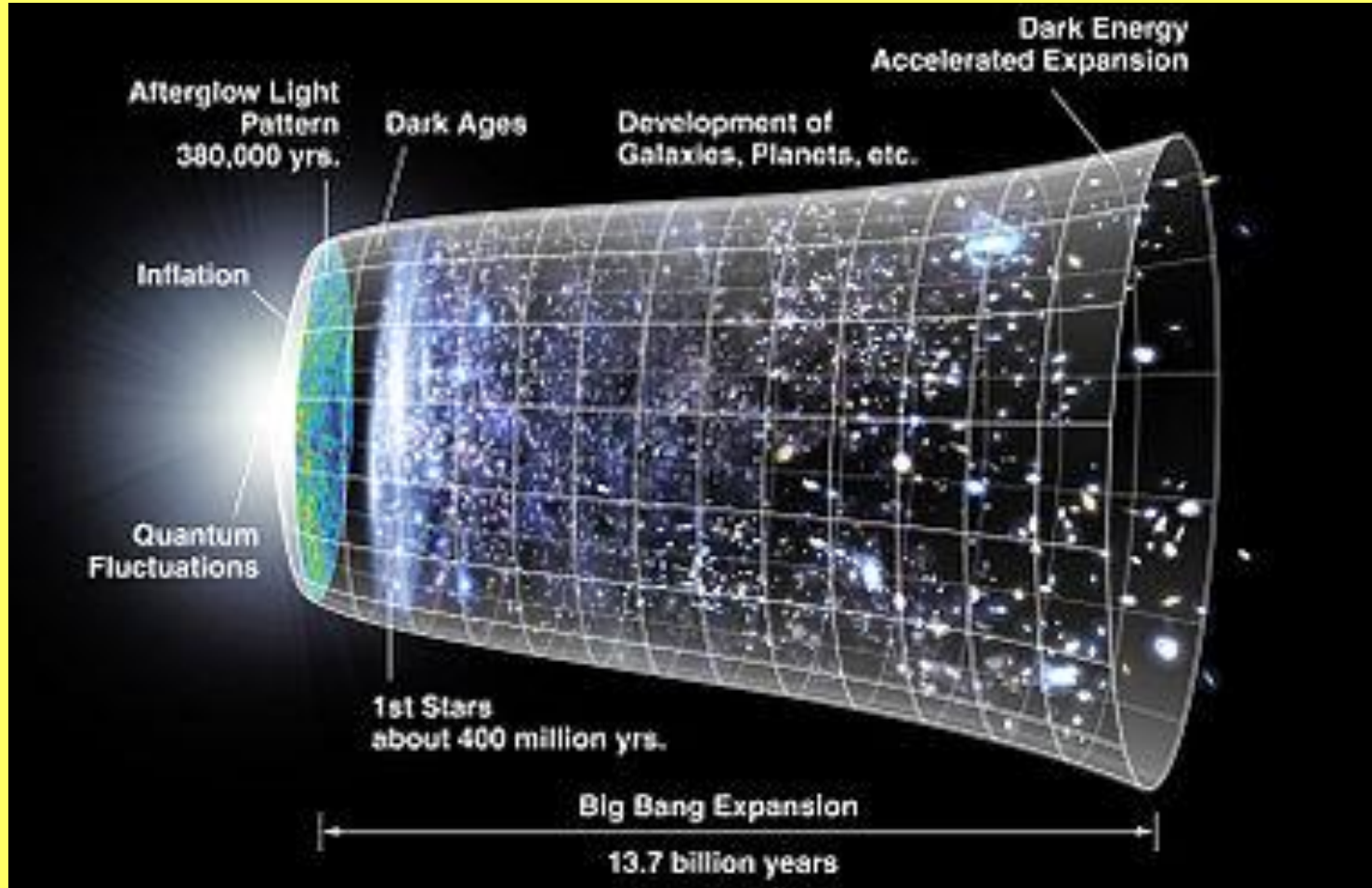
- General relativity

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

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

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

Our evolving Universe



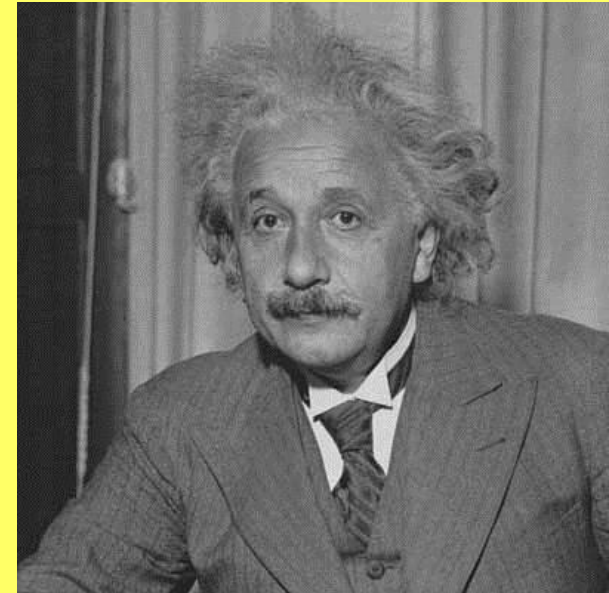
General relativity

- Energy and mass connected

$$\gg E = m c^2$$

- Newton gravity couples to mass
- Einstein gravity couples to energy

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



- „Matter tells space how to warp.
And warped space tells matter how to move“
- If „nothing“ (the vacuum) has energy (e.g. Vacuum condensates), then the vacuum gravitates
- „Nothing“ also tells space how to warp. How big is the energy of „nothing“ ?

The Cosmological Constant Puzzle

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

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

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

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

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

- „Normal ordering“ → zero,
but then

Spontaneous Symmetry Breaking and condensates (Higgs, QCD, GUTs ...)

$$\rho_{\text{vac}}^{\text{ew}} \sim -(250 \text{ GeV})^4$$

- Accelerating Universe corresponds to

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

Phenomenological observation

- Dark energy scale $\mu_{\text{vac}} \sim 0.002 \text{ eV}$

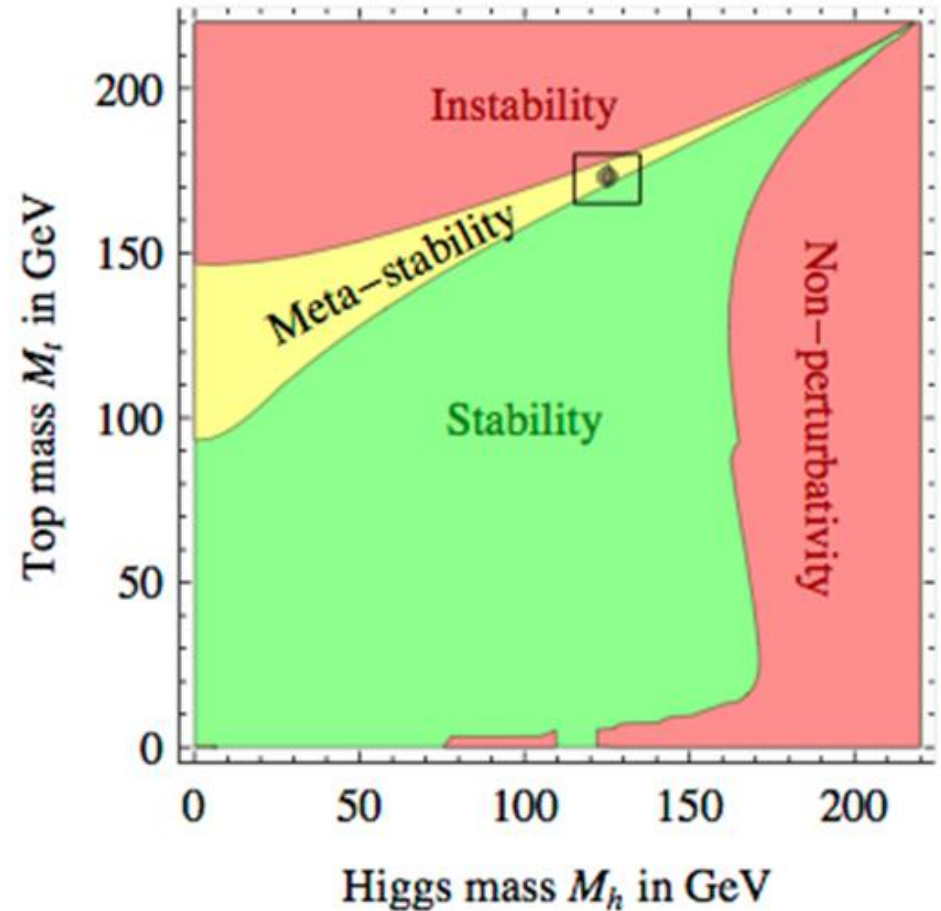
$$\rho_{\text{vac}} = \mu^4, \quad \mu \sim 0.002 \text{ eV}$$

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

- If taken literally, this formula connects
Dark Energy, neutrino physics and EWSB
to a new high mass scale $M \sim 3 \times 10^{16} \text{ GeV}$ 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 (?)

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.



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

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“ ?
(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]

Scales

- Dark energy scale $\sim 0.002 \text{ eV}$
- Electroweak Higgs scale 250 GeV
- QCD Scale 1 GeV
- Planck mass (gravitation) 10^{19} GeV
- Light neutrino mass $\sim 0.005 \text{ eV}$ (normal hierachy)
- Inflation (fourth root of r, Bicep2+...) $\sim 10^{16} \text{ GeV}$
- Jegerlehner (EWSB) $1.4 \times 10^{16} \text{ GeV}$ (sign change of c-term)
- GUTs 10^{15} GeV

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

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

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

Attempts to understand

- Analogy based on Ising model (spin magnet)

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

- 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
 \leftrightarrow vacuum energy density 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

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

Where are we going ?

