Vacuum Energy and the cosmological constant puzzle

Steven Bass

- Cosmological constant puzzle:

- 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.

Schladming, March 2 2015

Dark energy and its size

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

    Standard Model works very well,

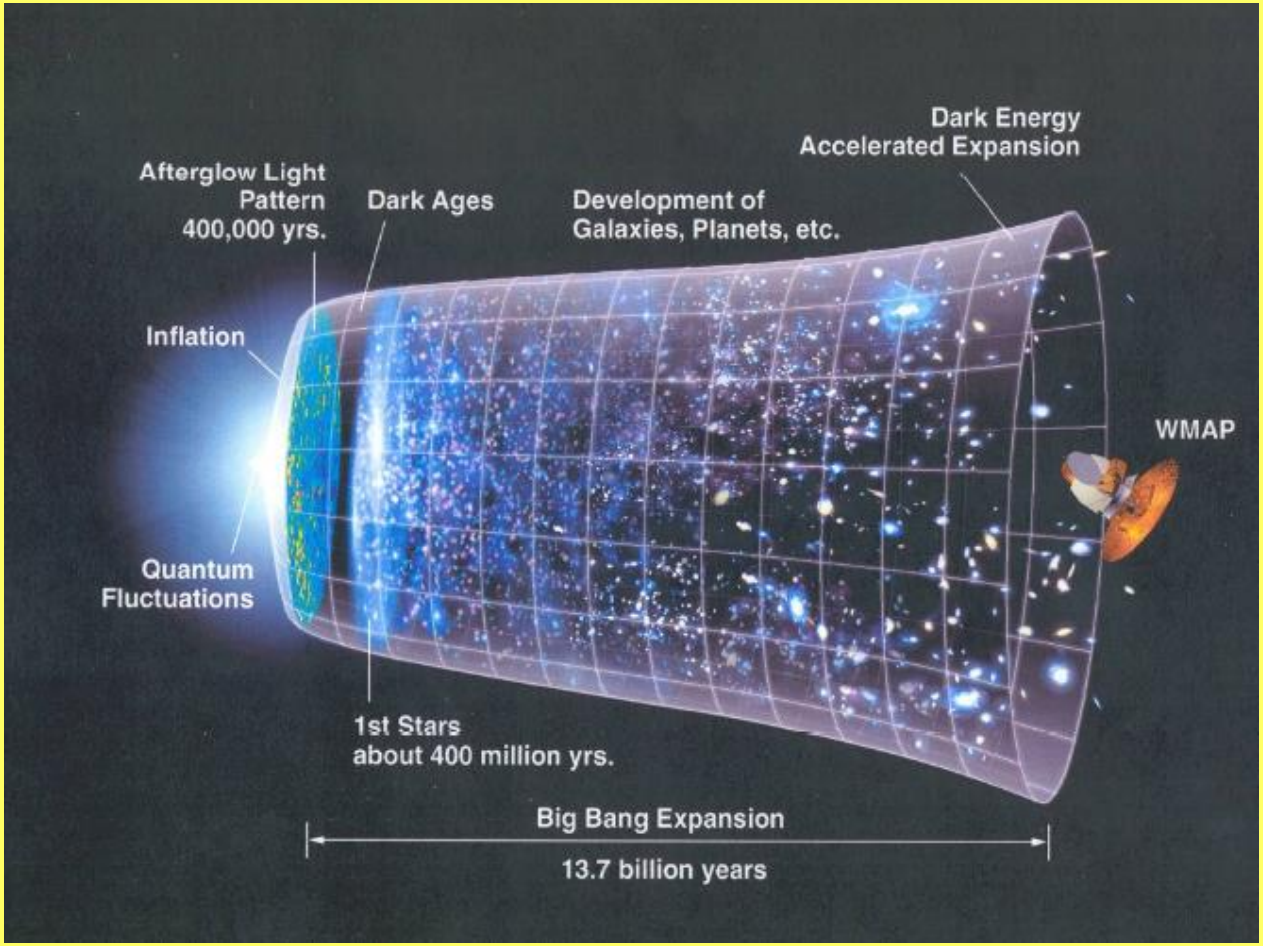
    no sign yet of BSM also in dark matter searches (Xenon100, LUX...), precision measurements: eEDM..., CPT and Lorentz invariance ...

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 (!)

Our evolving Universe



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

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

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

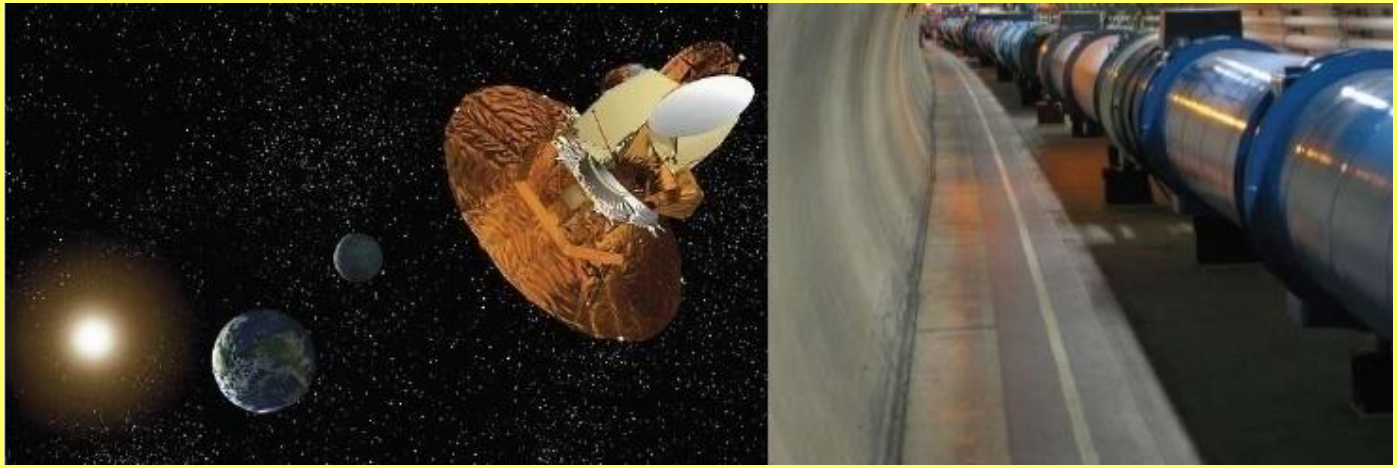
- Accelerating Universe corresponds to

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

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

- Do zero-point energies and condensates gravitate ?

Gravity and particle physics



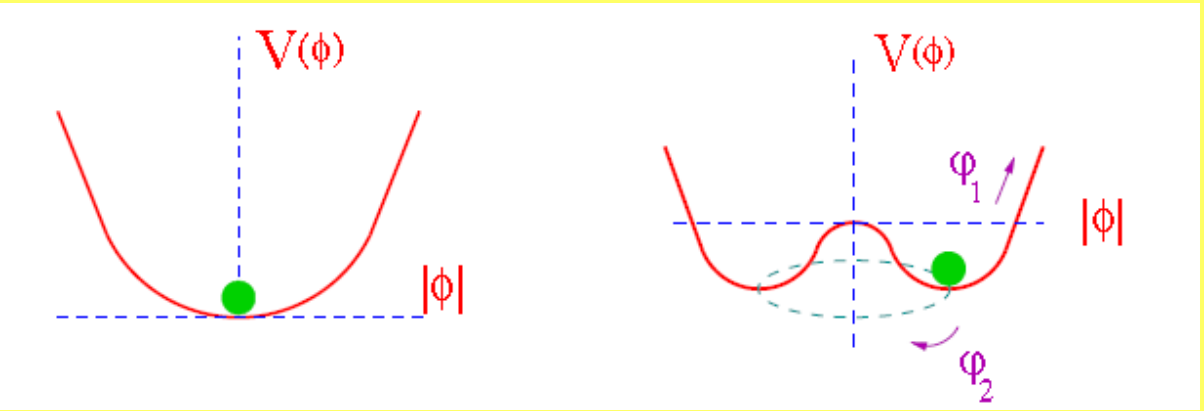
Gravitation and the cosmological constant are fundamentally different from particle physics and other physics in that gravity couples to everything whereas other physics processes and experiments involve measuring the differences between quantities.

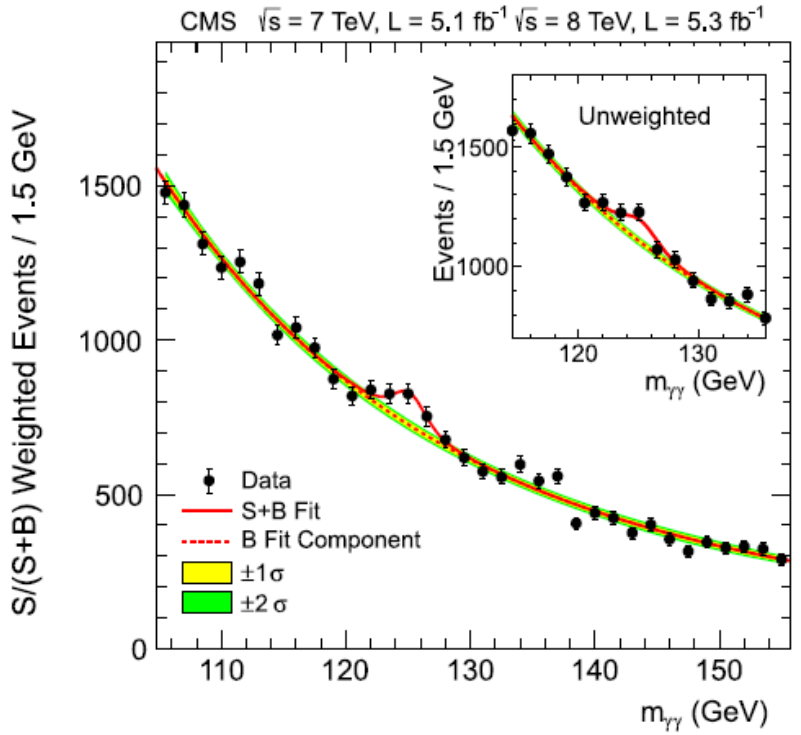
Absolute values of the zero-point vacuum energy only enters when coupling to gravity.

Phases of gauge theories

- Particle physics is built from
  - QED in the Coulomb Phase
  - QCD in the Confining Phase
    - » QCD condensates ~ - $(200\ \mathrm{MeV})^4$ from DChSB
  - Electroweak Interactions in the Higgs Phase
    - » Higgs condensate ~ - $(250\ \mathrm{GeV})^4$

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





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)

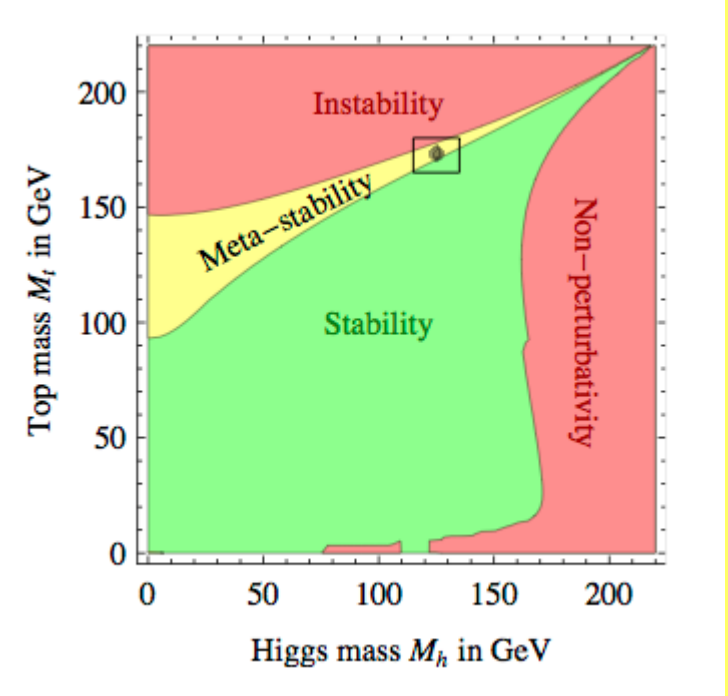
- Precision measurements, especially electron EDM
  - Probes possible extra sources of CP violation
  - Electron is round to current precision
    - » No SUSY &tc effects up to LHC energies unless special cancellation of phases
    - » Next generation of eEDM experiments will probe up to 100TeV scale

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

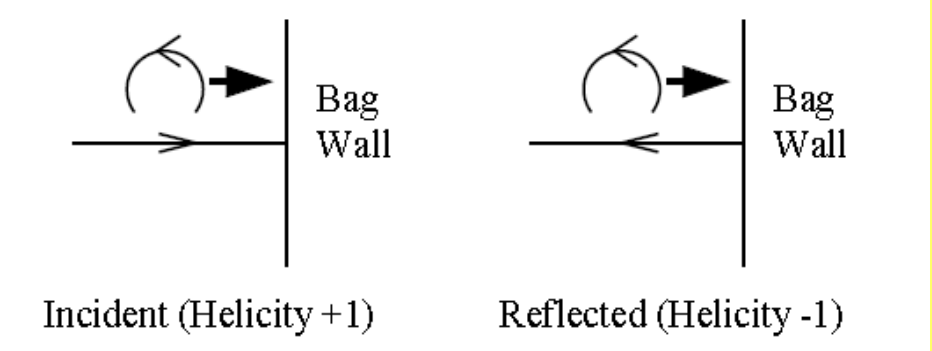
- Possible critical phenomena close to Planck mass with Standard Model as long range tail

- Is the Standard Model „emergent" ?
  (cf. Low energy part of GUT
  spontaneously broken by Higgs fields and
  condensates)



Ground state of chiral gauge theory

- Confining SU(2) with vector interactions:
  - „Mesons" made of electrons and neutrinos
  - Decouble RH neutrino: What happens to Confinement ?
- No RH neutrino → no scalar condensate → usual confining solution disappears!
  (in the Bag model, a LH quark would bounce off the confining wall as a RH quark)



- Change in non-perturbative propagator, DSB to Higgs (or Coulomb) phase, or confinement radically reorganised ?

Small QCD correction ~ 30 MeV

Look for analogous system: Spin model

- Consider Ising model for spin system with no external field

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

- Pressure is equal to minus the free energy density

$$P = -\left(\frac{\partial F}{\partial V} \right)_T$$

- Ground state: spins line up and energy per spin and free energy density go to zero.

- Corrections suppressed by powers of $\exp(-2\beta J)$

Spin model „neutrinos"

- Suppose we identify the chirality of the neutrino with the „spins" in an Ising model

  » phenomenological guess (toy model), see what happens

- Scale must be very large (so J does not appear in the ground state)

$$J \sim M \gg \alpha_s, \alpha_{\rm ew}, \alpha$$

- Turn on Ising interaction → generates parity violation (no RH neutrino)

- Anomaly cancelation wanted in UV, so DSB should be active there

- DSB scale should not appear smaller than any power of running coupling

$$\Lambda_{\rm ew} = M_{\rm cutoff}\ e^{-c/g(M^2_{\rm cutoff})^2} \ll M_{\rm cutoff}$$

DSB in „spin model + gauge theory“

- With mass scale in particle physics Lagrangian

$$\Lambda_{\rm ew} = M_{\rm cutoff}\ e^{-c/g(M^2_{\rm cutoff})^2} \ll M_{\rm cutoff}$$

- Higgs sector with finite mass gap gives non-zero ground state vacuum energy (behaves like an „impurity“ in the Ising system)

- Ground state energy in spin basis

$$\mu_{\rm vac} \sim \begin{bmatrix} 0 & -\Lambda_{ew} \\ -\Lambda_{ew} & -2M \end{bmatrix}$$

- Diagonalising gives

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

as scale characterising the ground state

Where are we going ?