LHC results and the cosmological constant puzzle

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•Cosmological constant puzzle:

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

•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.

Cracow Epiphany Conference, January 8 2014

Dark energy and its size

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

    Standard Model works very well,

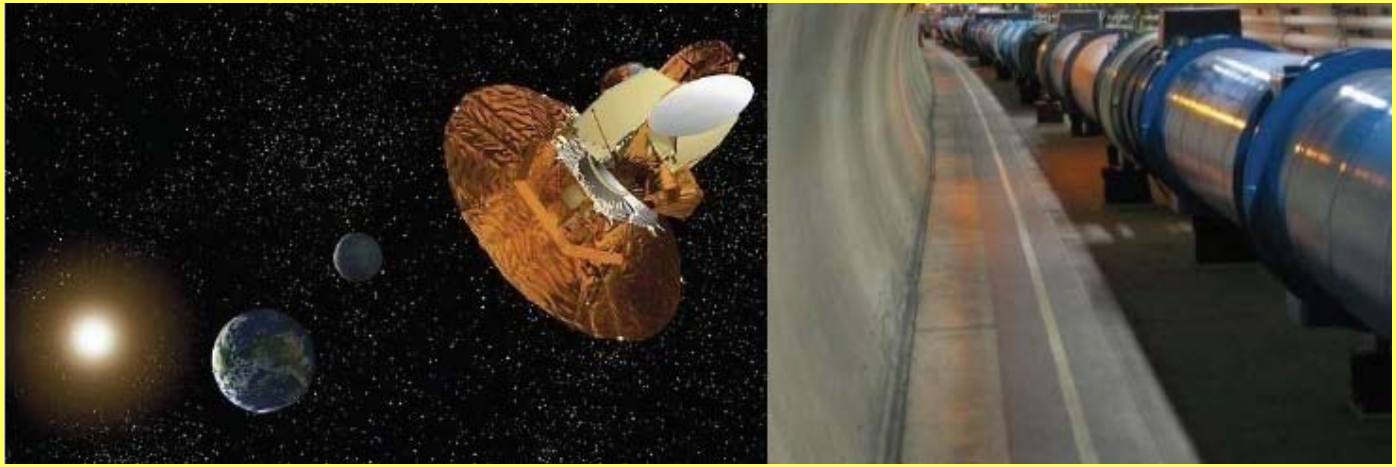
    no sign yet of BSM also in dark matter searches (Xenon100, LUX...), precision measurements: eEDM..., CPT and Lorentz invariance ...

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 (!)

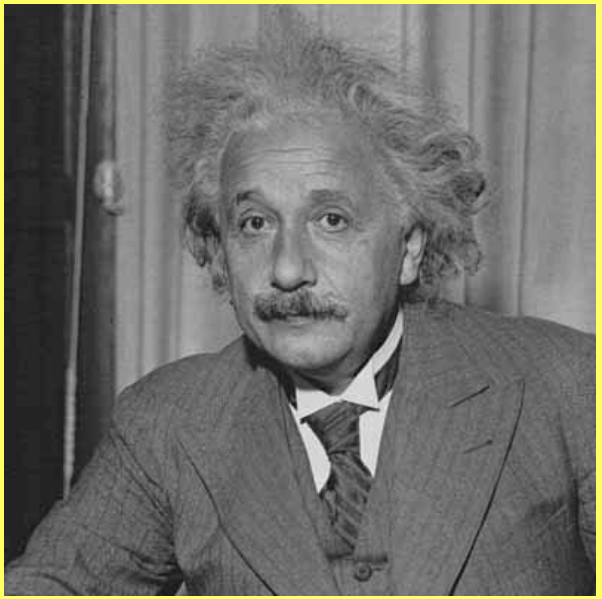
Gravity and particle physics



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.

General relativity



- Energy and mass connected

  » $E = m\,c^2$

- Newton gravity couples to mass

- Einstein gravity couples to energy

- „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" ?

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

Einstein´s equations and gravity

- General relativity: dynamical theory of gravity linking gravity with spacetime geometry

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

- „Matter tells space how to warp. And warped space tells matter to move"

- Cosmological principle: homogeneous and isotropic

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

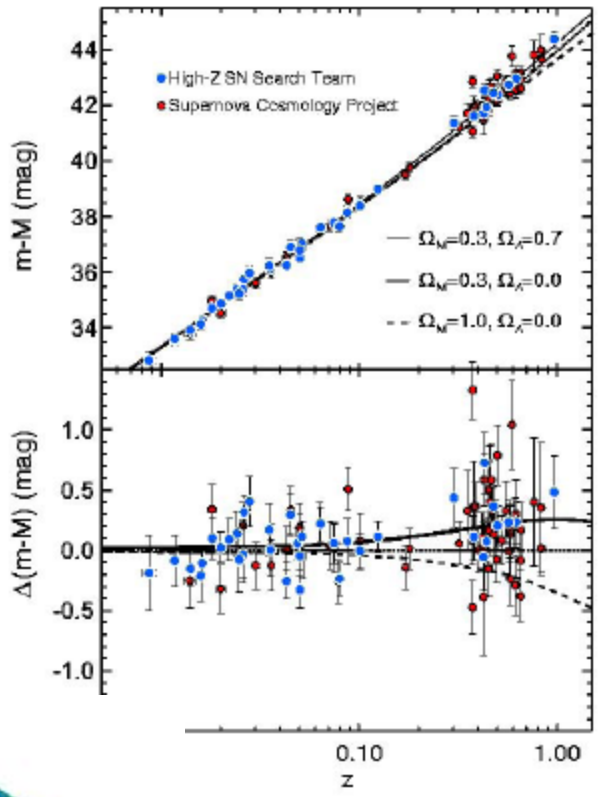
- Evaluate Einstein's equations for $T_{\mu\nu}$ for a perfect fluid, equal to $\mathrm{diag}[\rho, p, p, p]$

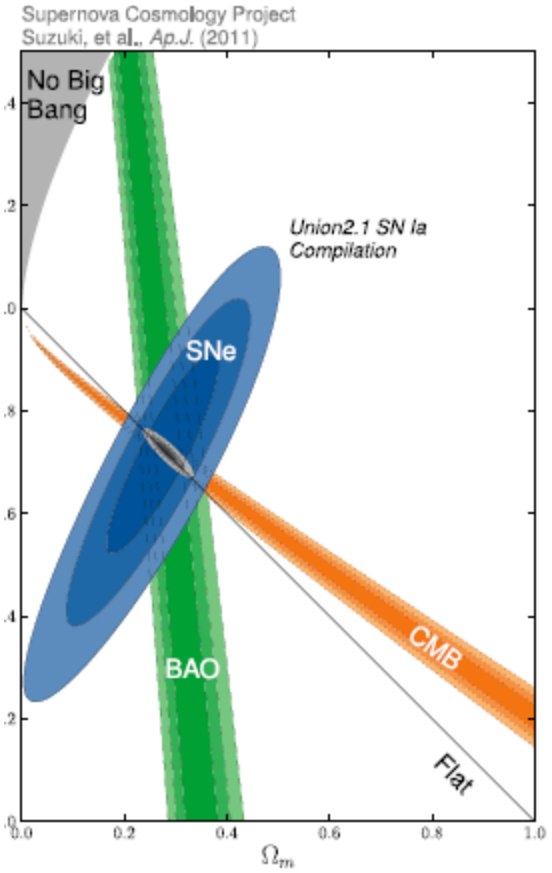
$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{k}{a^2} + \frac{1}{3}\Lambda$$

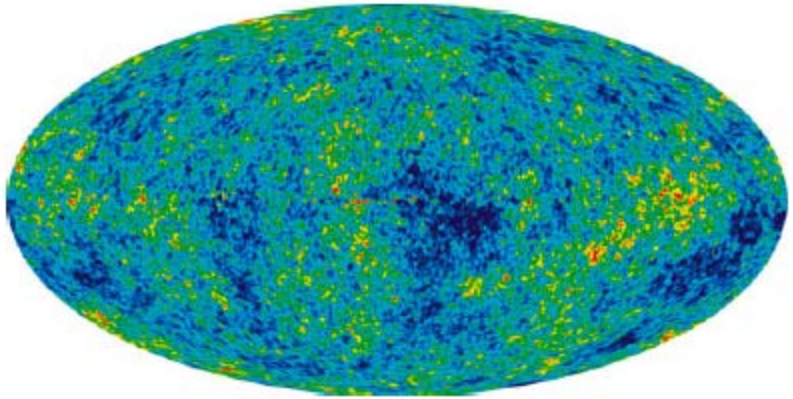
$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p) + \frac{1}{3}\Lambda$$

Convergence of measurements

- 70% of the energy budget of the Universe is vacuum energy





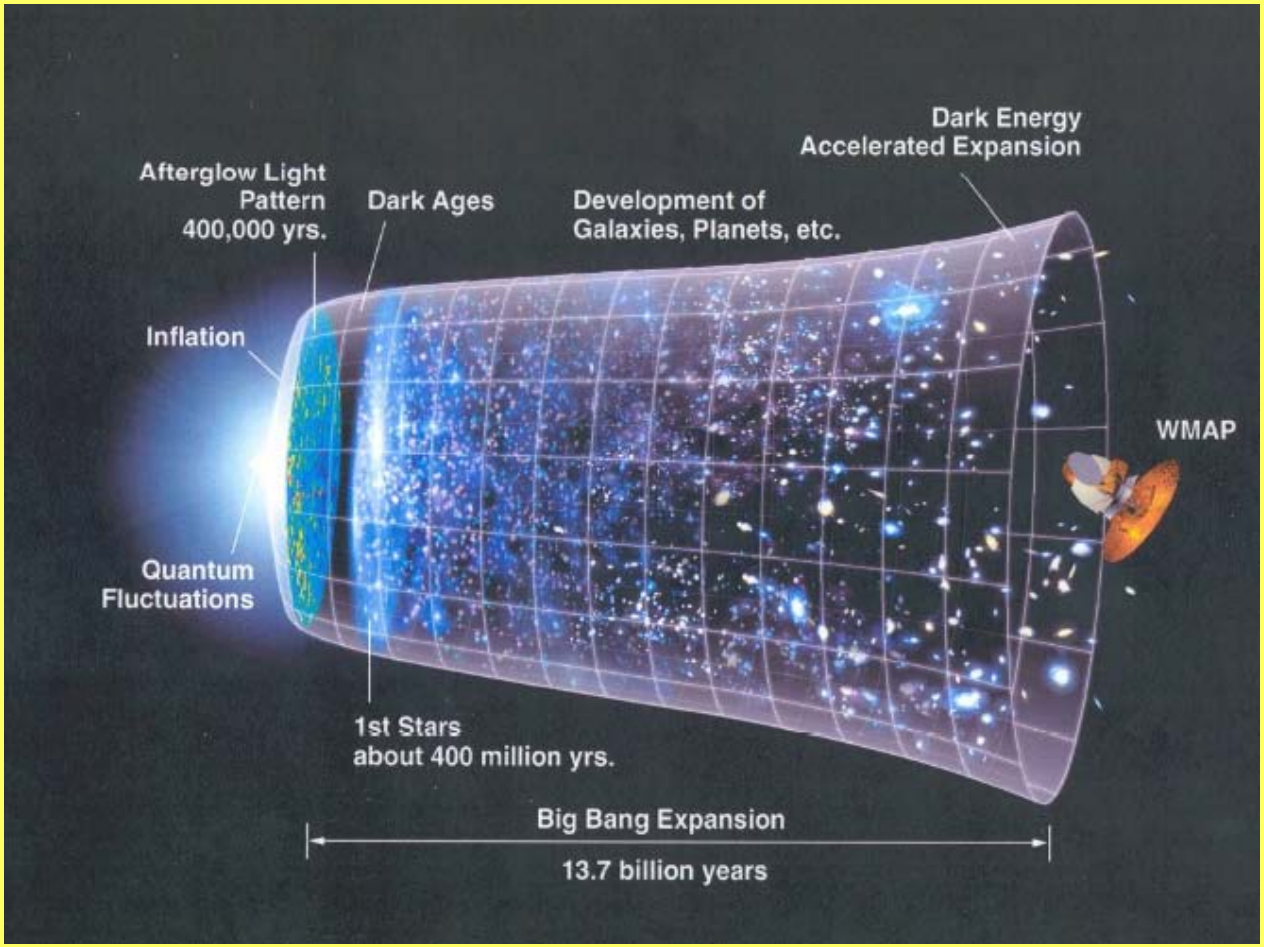


$$\Omega \equiv \frac{\rho}{\rho_{\rm crit}} = \frac{8\pi G\rho}{3H_0^2} = 1 + \frac{k}{\dot{a}^2}$$

$$\rho_{\rm crit} = \frac{3H_0^2}{8\pi G} = 1.88 \times 10^{-29} h_0^2 \ {\rm gcm}^{-3}$$

$$\rho = \rho_{\rm vac} + \rho_{\rm radiation} + \rho_{\rm matter}.$$

Our evolving Universe



The Cosmological Constant Puzzle

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

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

- 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

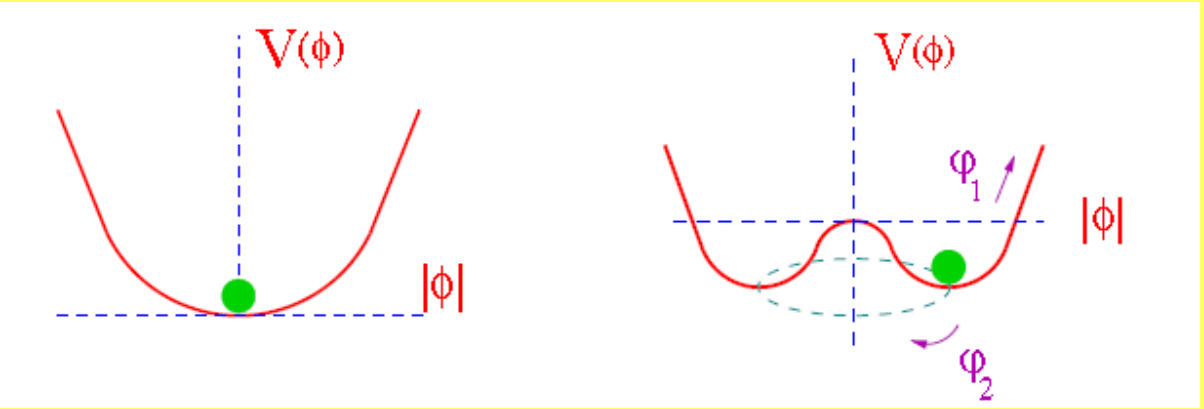
$$\rho_{\rm vac} = \mu^4, \quad \mu \sim 0.002 \text{ eV}$$

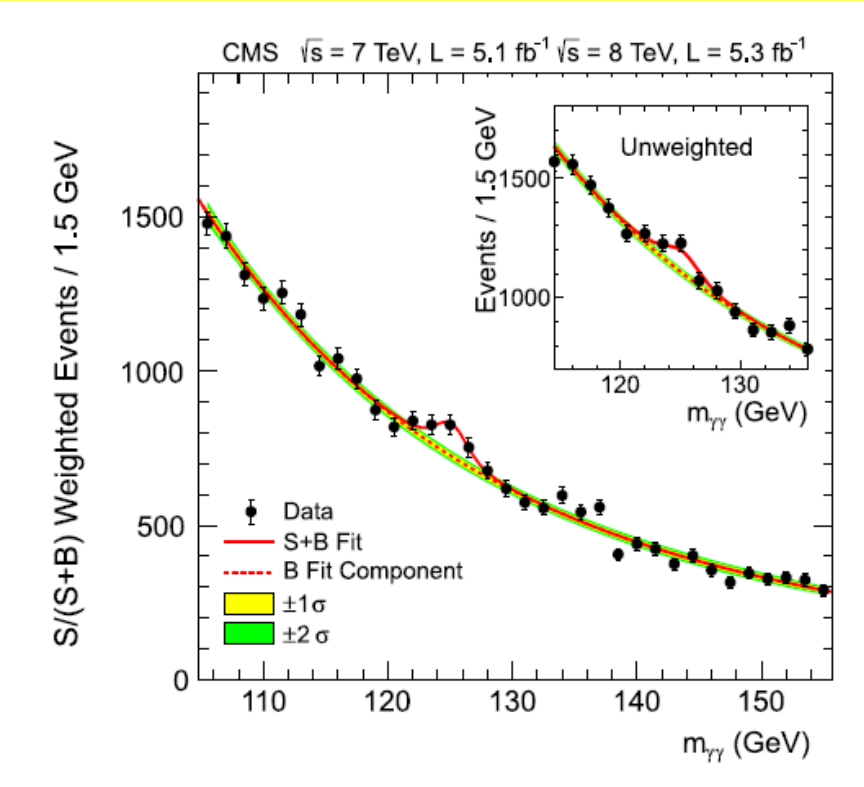
$$\mu_{\rm vac} \sim \Lambda_{\rm ew}^2/2M$$

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

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





Dark energy: Challenges for theory

- Why is it finite ?
- Why so very small << very large particle physics prediction ?
- Why the positive sign ?

- Do condensates gravitate ?
  - E.g. Freedom to define zero of energy in QFT, but time dependence
- Connection with inflation ?

- Sum of many big numbers (quantum fields and particle physics) add up to very small number

- Usual trick:
  - Assume solved by (gravity) counterterms or anthropic arguments
  - Introduce new (time dependent) scalar field (quintesence) or modified gravity
  - Can we understand the physics without elementary scalar fields ?

Phases of gauge theories

- Can change phases through changing external parameters
  - E.g. Electron mass = 0

    →3+1 dimensions Photon gets a mass (with no elementary Scalar)

    [Gribov, 1982]

    → In the Schwinger model (1+1 Dimensions), Confinement gives way to a Higgs Phase

    [Gross et al, 1996]

"The pure 4D Yang-Mills theory is expected to be confining.

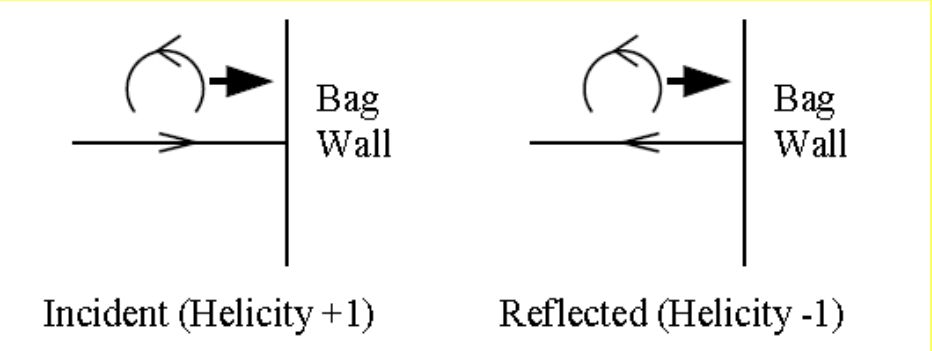
In view of what we learned from 1+1 dimensional examples we may wonder, however, whether instead it could be in the screening phase: certain gluonic excitations might be capable of screening fundamental test charges.

This possibility seems to be experimentally ruled out, however, since no states of fractional baryon number have been observed."

- What about turning off couplings of gauge bosons to RH neutrinos ?

„Neutrinos“

- 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

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

- The energy density of the combined „spin"-gauge system (e.g. whole thing that couples to gravity) is suppressed by the same physics which gives parity violation

Where are we going ?