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.

DESY Zeuthen, October 30 2014

ÖAW
Austrian Academy of Sciences

Dark energy and its size

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

  Standard Model works very well,

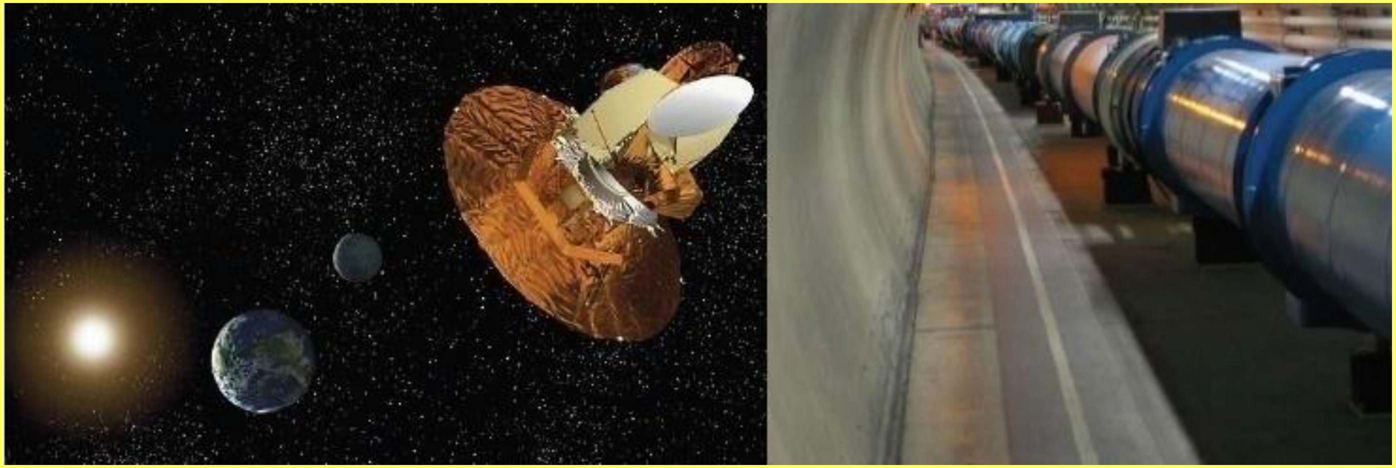
  no sign yet of BSM also in dark matter searches (Xenon100, LUX...), precision measurements: eEDM..., CPT and Lorentz invariance ...

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 (!)

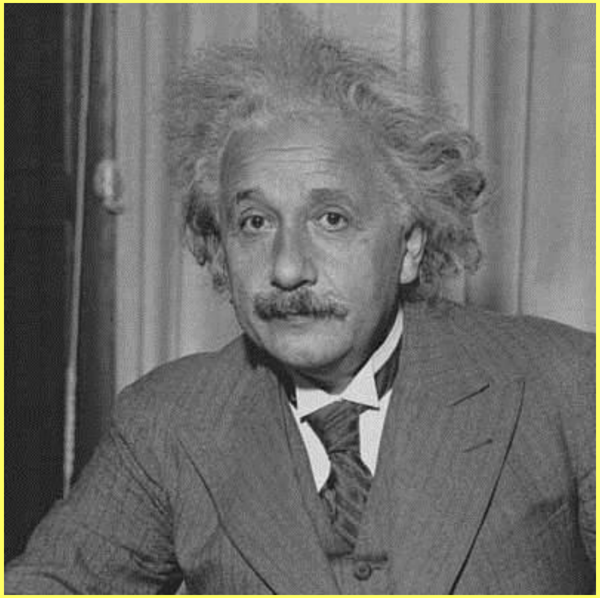
Gravity and particle physics



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" ?

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

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

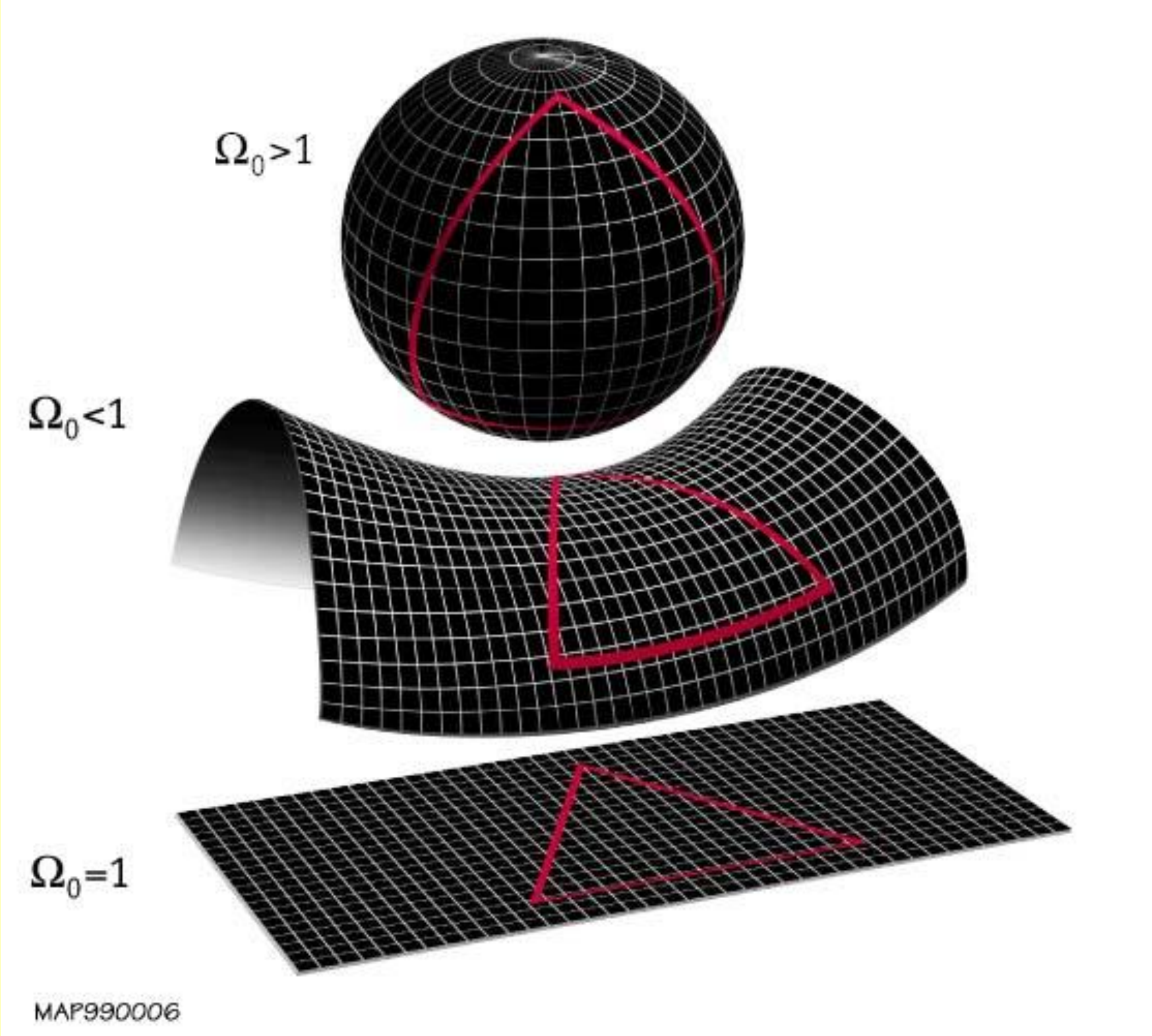
$$ds^2 = c^2 dt^2 - a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2(d\theta^2 + \sin^2\theta d\phi^2)\right]$$

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

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

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

The geometry of space



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

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

$$H = \frac{\dot{a}}{a}$$

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

Solutions of possible (flat) Universes

- Matter dominated, p=0

$$a(t) \propto t^{\frac{2}{3}}$$
$$\rho_{\text{matter}} \propto a^{-3}$$

- Radiation dominated,

$$p = \frac{1}{3}\rho$$

$$a(t) \propto t^{\frac{1}{2}}$$
$$\rho_{\text{radiation}} \propto a^{-4}$$

- Vacuum dominated

$$p = -\rho \ (\text{or } T_{\mu\nu} \propto g_{\mu\nu})$$

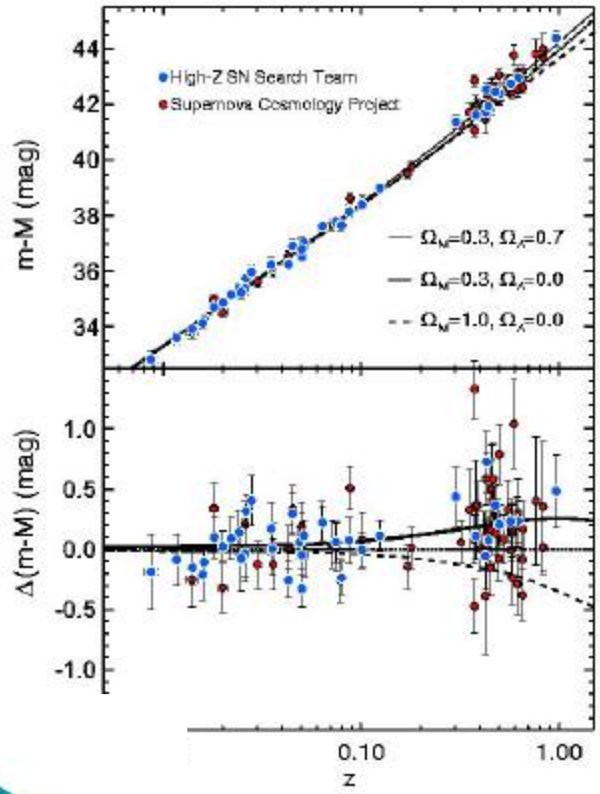
$$a(t) \propto e^{Ht}$$
$$\rho_{\text{vac}} = \text{constant} = \frac{\Lambda}{8\pi G}$$

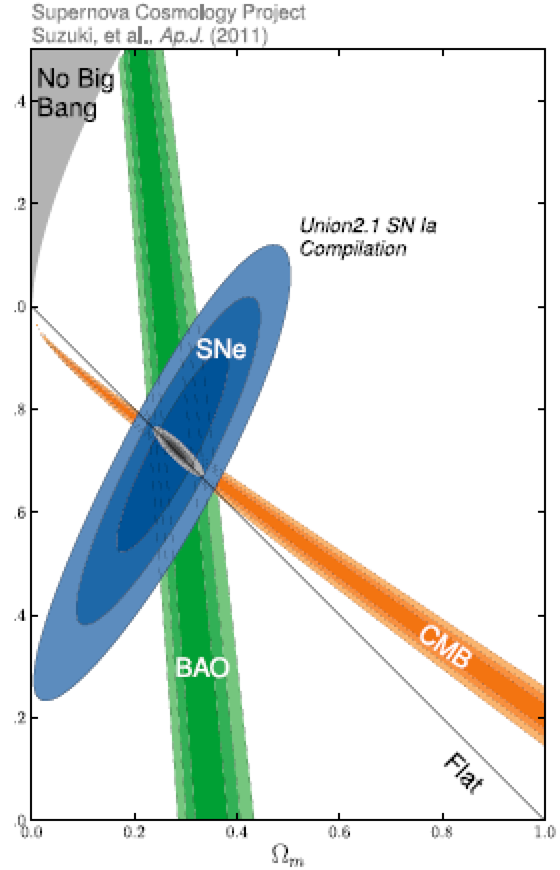
with Hubble constant

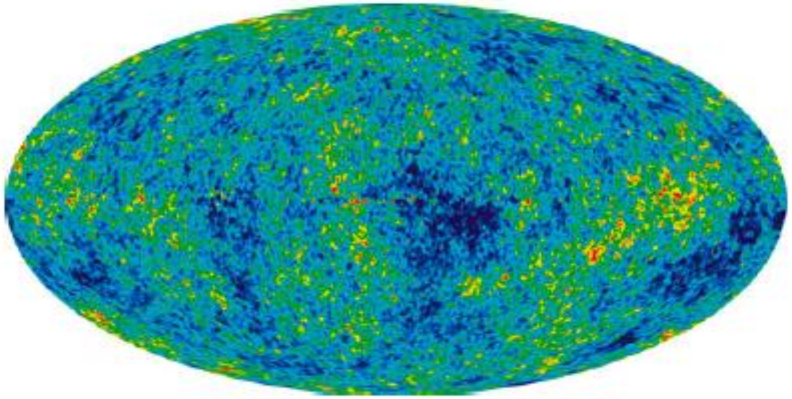
$$H = \sqrt{\frac{8\pi G \rho_{\text{vac}}}{3}} = \text{constant}.$$

Convergence of measurements

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







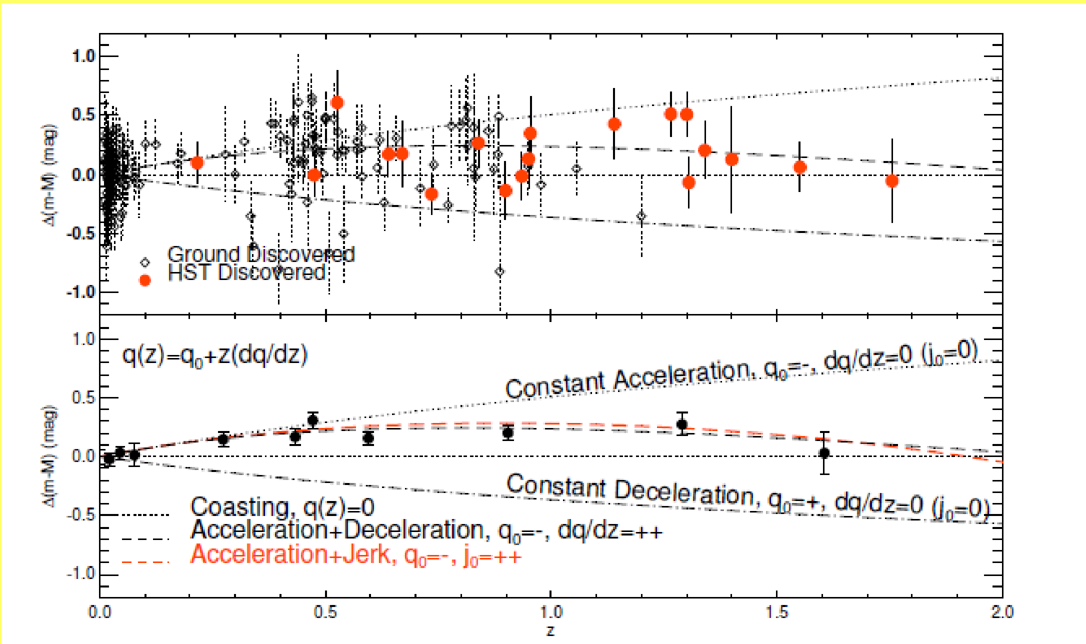
$$\Omega \equiv \frac{\rho}{\rho_{\rm crit}} = \frac{8\pi G \rho}{3H_0^2} = 1 + \frac{k}{\dot{a}^2}$$

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

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

Supernova 1a

- Redshift measures how much the space between the supernova and the observer has stretched
- Compare brightness to redshift for distant (type 1a) supernovae to see how the expansion rate has changed



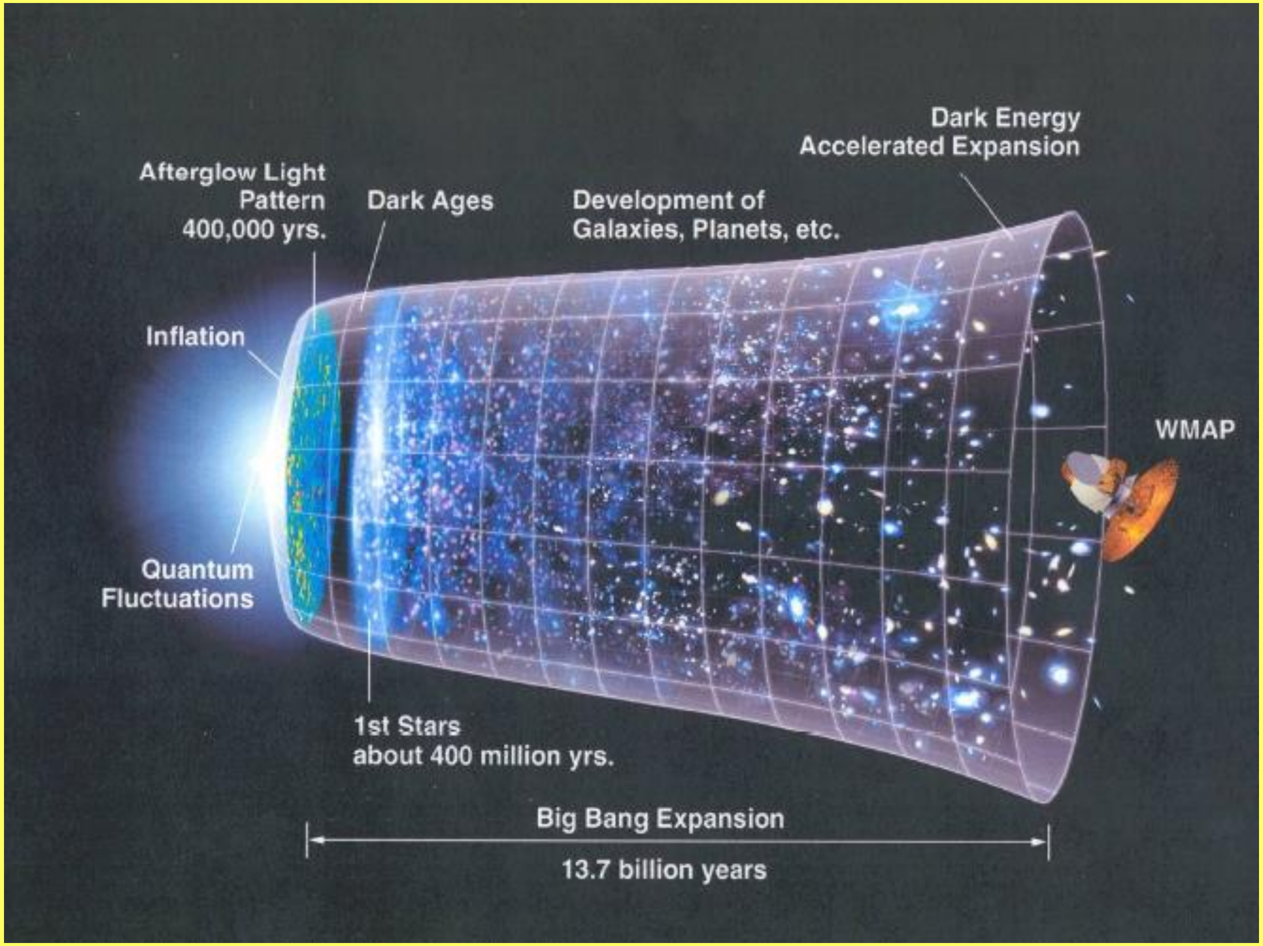
$$q \equiv -\frac{\ddot{a}a}{\dot{a}^2} = -\left(1 + \frac{\dot{H}}{H^2}\right).$$

- If just matter Universe, then the further away (back in time) a supernova is, the brighter (closer) it would appear relative to its redshift. The opposite is observed for $z < 1$.

Supernovae (type 1a)

- Star uses up its nuclear fuel, collapses under gravity and then recoils with explosion leaving black hole or neutron star remnant
- White dwarf star: size of earth, mass of the sun in binary star system
- Accretion onto carbon/oxygen white dwarf
- Standard candle, $^{56}\mathrm{Ni} \rightarrow ^{56}\mathrm{Co} \rightarrow ^{56}\mathrm{Fe}$
  uniform brightness, 5 billion times sun
- Time lasts about 20 days to reach maximum brightness
- 10^{43} watts, 3x in galaxy per millenium

Our evolving Universe



Planck results

- Probing the dark energy equation of state, w = p/rho
  - Assume Constant EoS

$$w = -1.13^{+0.24}_{-0.25} \quad (95\%; \textit{Planck}+\text{WP}+\text{BAO}),$$

$$w = -1.09 \pm 0.17 \quad (95\%; \textit{Planck}+\text{WP}+\text{Union2.1}),$$
$$w = -1.13^{+0.13}_{-0.14} \quad (95\%; \textit{Planck}+\text{WP}+\text{SNLS}),$$

  - Time dependent EoS $w(a) = w_0 + w_a(1-a)$

$$w_0 = -1.04^{+0.72}_{-0.69} \quad (95\%; \textit{Planck}+\text{WP}+\text{BAO}),$$
$$w_a < 1.32 \quad (95\%; \textit{Planck}+\text{WP}+\text{BAO}).$$

  - Euclid target: Measure the DE equation of state parameters w_0 and w_1 to a precision of 2% and 10% respectively, using both expansion history and structure growth (2019+)

Scales of dark energy

- Dark energy scale close to what we expect for light neutrino mass

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

- Relation to Hubble scale

$$\frac{1}{R_\infty^2} = H_\infty^2 = \frac{8\pi G}{3}\rho_{\mathrm{vac}} = \frac{\Lambda}{3}.$$

- Geometric mean of Hubble scale and Planck mass

$$\mu \sim \sqrt{H_\infty M_{\mathrm{Pl}}}$$

$$M_{\mathrm{Pl}} = \sqrt{\frac{\hbar c}{G}} = 1.3 \times 10^{19} m_{\mathrm{proton}} = 1.2 \times 10^{19} \text{ GeV}$$

- Alternative curvature scale

$$m^2 \sim \frac{\Lambda}{3} \sim \frac{1}{R^2}, \quad m \sim 10^{-33} \text{ eV}$$

Scales

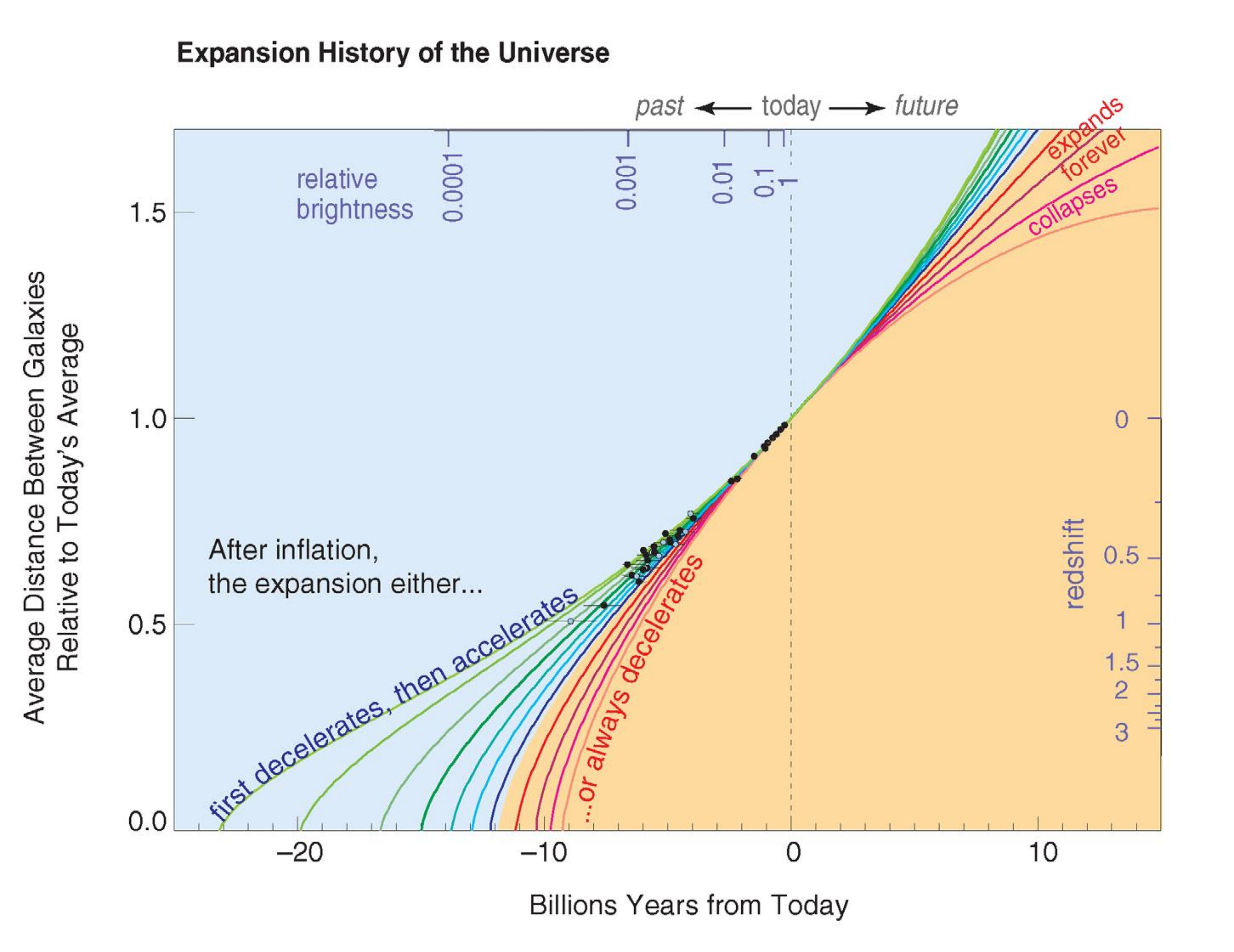
- Dark energy scale ~ 0.002 eV
- Electroweak Higgs scale 250 GeV
- QCD Scale 1 GeV
- Planck mass (gravitation) 10^{19} GeV
- Light neutrino mass ~ 0.005 eV (normal hierachy)
- Inflation (Bicep2) 2 x 10^{16} GeV (modulo possible dust)
- Jegerlehner (EWSB) 1.4 x 10^{16} GeV (sign change of c-term)

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

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

- GUTs 10^{15} GeV

Expansion History of the 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

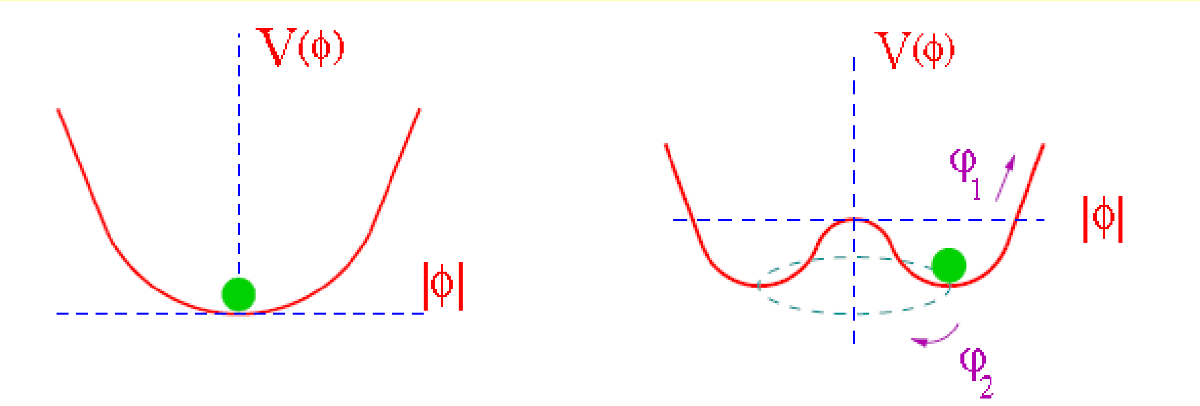
$$\rho_{\rm vac} = \mu^4, \quad \mu \sim 0.002\ {\rm eV}$$

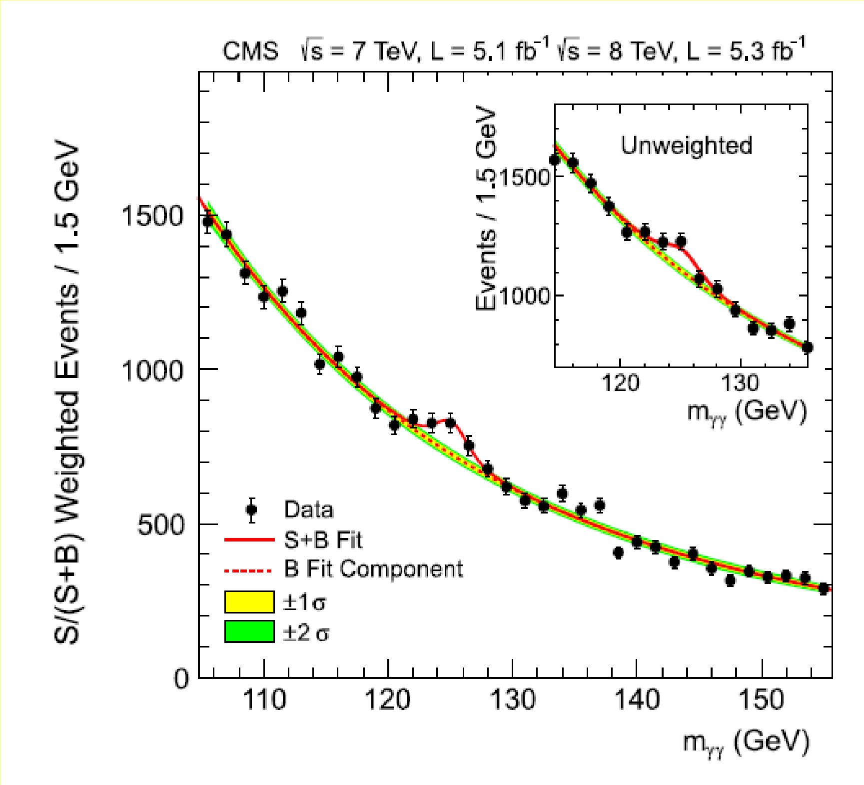
$$\mu_{\rm vac} \sim \Lambda_{\rm ew}^2/2M$$

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

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





Do zero point energies gravitate ?

- Zero point energies (e.g. QED)
- Mass generated through interactions (QCD, Yukawa couplings to Higgs fields) in the visible sector.
    - Without these interactions there is no Newton gravity.
    - Massless QED (modulo IR issues about consistency) does not generate mass perturbatively
    - Suggests (?) phenomenological hypothesis that (free field) zero point energies might also not gravitate.
    - Jaffe argument (2005) that Casimir effect does not need zero point energies

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, resum quantum gravity with asymptotic safety ...
  - Can we understand the physics without elementary scalar fields ?

Dark energy: driven by new scalar field

- Possible connection with inflation - first period of (rapid) acceleration
- Here equation of state different to w = p/rho = -1

$$\rho = \frac{1}{2}\dot{\phi}^2 + V(\phi)$$
$$p = \frac{1}{2}\dot{\phi}^2 - V(\phi)$$

- Same fine tuning puzzle for quantum fields.
- Scalar field should decay from large potential $\langle V \rangle \sim 10^{64}\ \mathrm{GeV}^4$
  - » Very small mass $\Lambda \sim m^2 \sim \frac{1}{R^2}$
- So far, Cosmological constant describes all data with no evidence for more
- Time dependent couplings ? Stability of scalar to quantum corrections ?

Time dependent fundamental constants (?)

$$\frac{d}{dt}\left[G\rho\right] + 3HG(\rho + \frac{p}{c^2}) = 0$$

- Time dependent couplings (?)
- Lagrangian with coupling to time dependent scalar
- Constraints from experiments on time dependence of fine structure constant from CMB (13 B years), Quantum Optical Clocks (today) ...
- M_p/m_e ratio (transitions in methanol in early Universe, 7B years and Quantum optical clocks today)

	Planck+WP	*Planck*+WP+BAO	*WMAP*-9
$\Omega_b h^2$	0.02206 ± 0.00028	0.02220 ± 0.00025	0.02309 ± 0.00130
$\Omega_c h^2$	0.1174 ± 0.0030	0.1161 ± 0.0028	0.1148 ± 0.0048
τ	0.095 ± 0.014	0.097 ± 0.014	0.089 ± 0.014
H_0	65.2 ± 1.8	66.7 ± 1.1	73.9 ± 10.9
n_s	0.975 ± 0.012	0.969 ± 0.012	0.973 ± 0.014
$\log(10^{10} A_s)$	3.106 ± 0.029	3.100 ± 0.029	3.090 ± 0.039
α/α_0	0.9936 ± 0.0043	0.9989 ± 0.0037	1.008 ± 0.020

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.

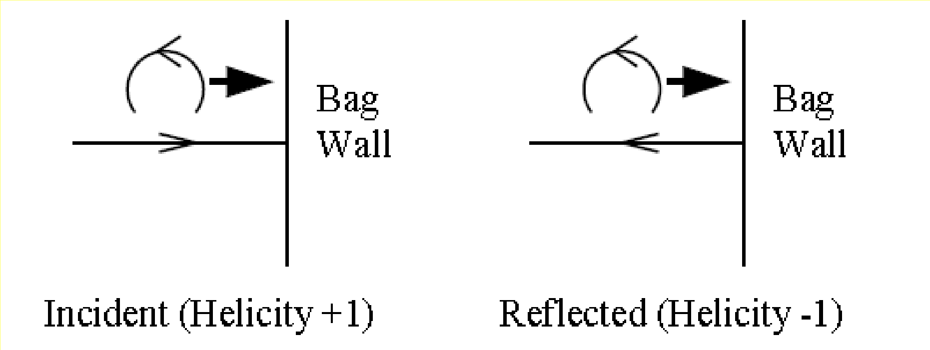
In view of what we learned from 1+1 dimensional examples we may wonder, however, whether instead it could be in the screening phase: certain gluonic excitations might be capable of screening fundamental test charges.

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

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

- 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

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

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 ?