The cosmological constant (non)-problem

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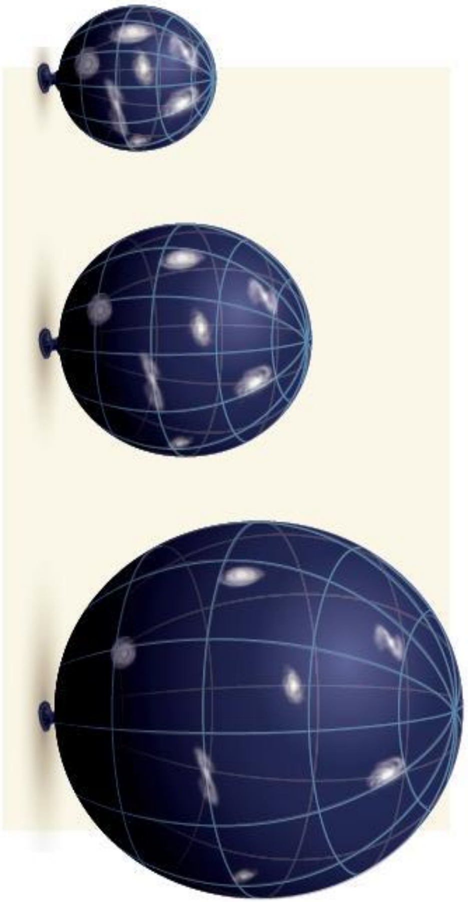
talk based on:

E.B., C. Rovelli, ``*Why all these prejudices against a constant?*'' arXiv:1002.3966 [astro-ph.CO]

E.B., C. Rovelli & R. Kolb, ``*Is dark energy really a mystery?*'' *Nature* **466**, 321-322 (2010)

Outline

- **The universe is expanding. Observations indicate that its expansion is speeding up.**
- To account for this acceleration, a mysterious substance – *dark energy* – is often invoked. The underlying physics is unknown. This is often presented as a great mystery, 75% of the content of the Universe.
- A simple explanation is to hand: the cosmic acceleration is predicted and simply described by General Relativity (GR) with a **positive *cosmological constant* Λ**.
- The standard model of cosmology (ΛCDM) assumes the presence of Λ and provides the best account of the present observational data [Lahav-Liddle, pdg 2010] .
- Three objections to Λ are commonly presented, and nourish the `mystery':
  - Einstein's greatest blunder
  - The problem of cosmic coincidence
  - The problem of QFT vacuum energy
- We argue that there is confusion, historical or conceptual, in each of these counter-arguments to Λ.



Part 1.

Λ, Einstein's greatest blunder ?

``Much later, when I was discussing cosmological problems with Einstein, he remarked that the introduction of the cosmological term was the biggest blunder he ever made in his life."

George Gamow, My World Line (Viking, 1970) p44.

Einstein's greatest blunder

- 1916, Einstein introduces Λ in GR eqs for generality
- 1917, Λ fine-tuned to have a *static Universe*
- 1929, Hubble, observational evidence of the expansion of the Universe

Story often told:

Einstein, and after him the relativity community, rejected Λ as it spoils the beauty of GR just to account for apparent staticity

[Einstein and Hubble at Mt.Wilson in 1931, Caltech Archives]

The true blunder:

Einstein missed the prediction of the cosmic expansion – before its discovery – failing to see that
- without Λ
- with a generic value of Λ
- even with fine-tuned Λ (because of instability)

the Universe is not static in GR

- Cosmological constant: integral part of GR

$$S[g] = \frac{1}{16\pi G_N}\int (R(g) - 2\Lambda)\,\sqrt{-g}\,d^4x$$

- Two fundamental constants

  G_N = strength of the gravitational interaction

  Λ = `zero-point' curvature of space-time

  to be determined experimentally

Cosmic acceleration: the discovery (1998)

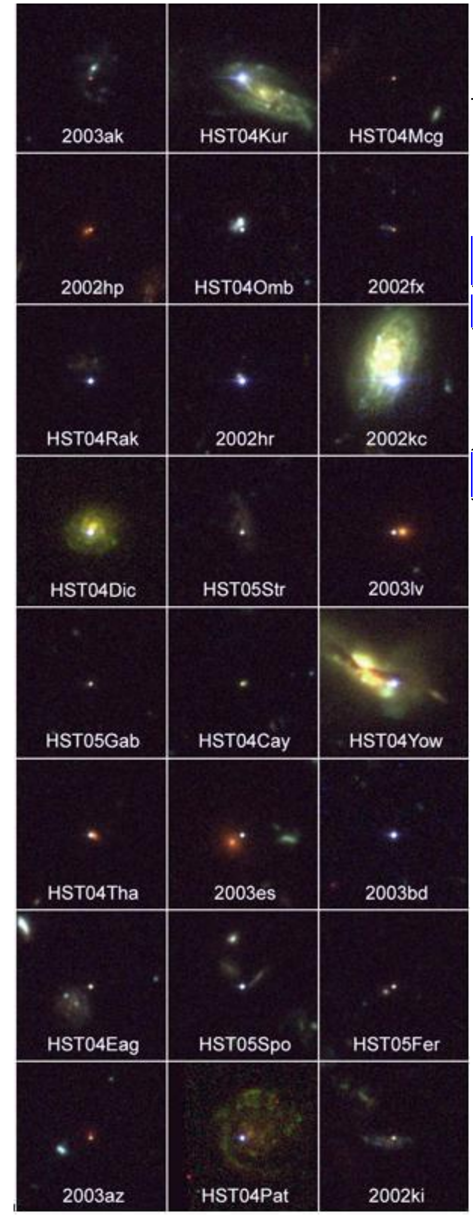
Two breakthroughs enabled discovery of cosmic acceleration:

i. the demonstration that type Ia supernovae (SNe Ia) are standardizable candles [Phillips 1993].

ii. the deployment of large mosaic CCD cameras on 4m class telescopes, enabling the systematic search of large areas of sky, containing ~ 1000 galaxies, for these rare events.

By comparing images taken weeks apart, the discovery of SNe at redshifts $z \sim 0.5$ could be `scheduled' on a statistical basis.

- In mid-1990s, two independent teams took advantage of these breakthroughs (the Supernova Cosmology Project and the High-z SN Search) to measure the SN Hubble diagram to much larger distances than was previously possible.
- Both teams found that distant SNe are ~ 0.25 mag dimmer than they would be in a decelerating Universe, indicating that **the expansion has been speeding up for the past 5 Gyr**
- When analyzed assuming a Universe with matter and cosmological constant Λ, their results provided evidence for $\Lambda > 0$ at greater than 99% confidence.



Distant Supernove Credit: NASA, ESA, and A. Riess (STScI)

Cosmic acceleration: theory

- Friedmann equation:

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

- Def. density parameters

$$\Omega_\Lambda = \frac{\Lambda}{3H^2} \quad , \qquad \Omega_{\rm matter} = \frac{8\pi G_N\, \rho}{3H^2}$$

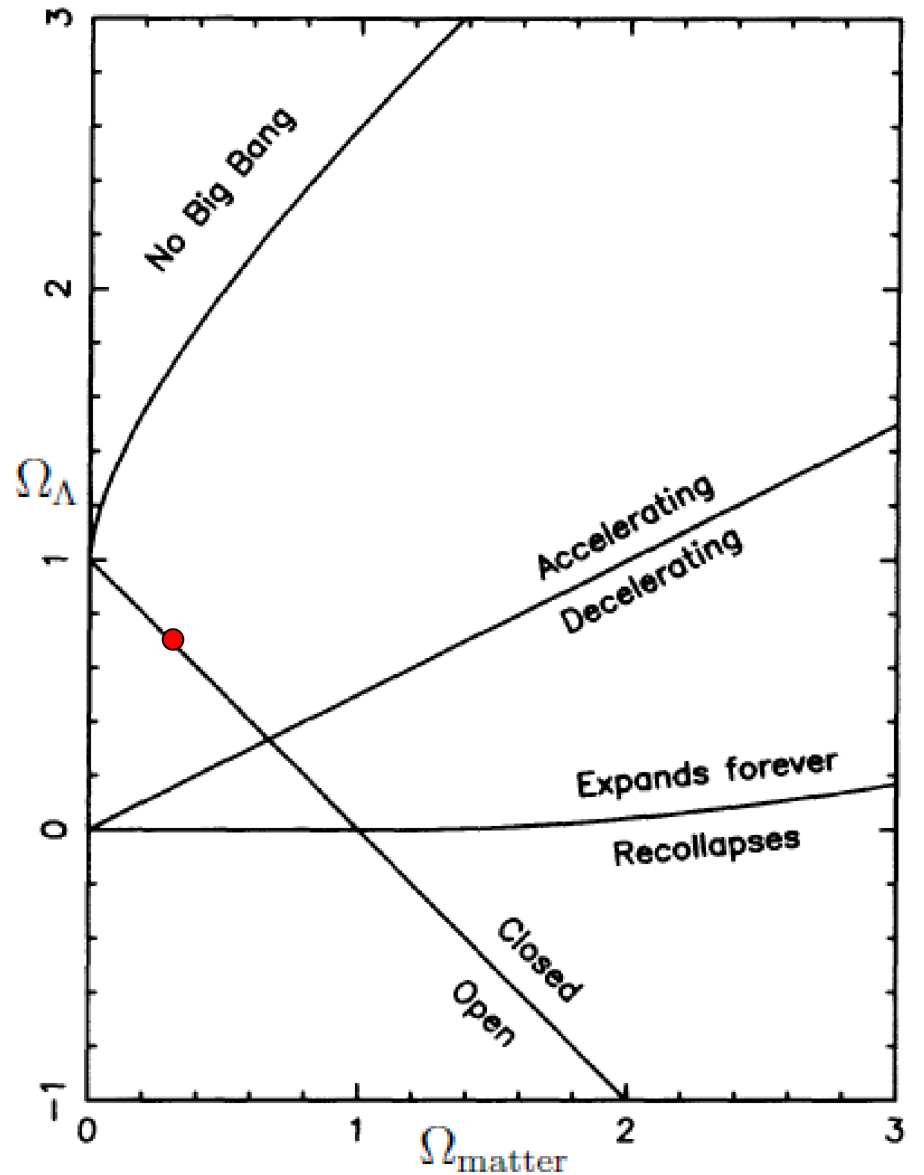
- Friedmann eqn again

$$\Omega_\Lambda + \Omega_{\rm matter} = 1 + \frac{k}{a^2 H^2}$$

- Acceleration equation

$$\frac{\ddot{a}}{a} = -\frac{4\pi G_N}{3}\left(\rho + 3P\right) + \frac{\Lambda}{3}$$

- To have cosmic acceleration $\ddot{a} > 0$
  - either positive Λ
  - or admit that matter today can have an exotic eqn of state $\rho + 3P < 0$



[in the diagram: pressureless matter today assumed, Liddle 2003]

Cosmic acceleration: observational status

- Standard model of cosmology (ΛCDM)
  Lambda-Cold Dark Matter model
- Observed values of density params today

$$\Omega_\Lambda \simeq 0.757 \pm 0.021 \quad , \quad \Omega_{\text{matter}} \simeq 0.246 \pm 0.028$$

- Hubble constant

$$H_0 \simeq 72 \pm 5 \ \text{km}\,\text{s}^{-1}\text{Mpc}^{-1} \approx (13.8\,\text{Gyr})^{-1}$$

- Deceleration parameter

$$q_0 \equiv -\frac{1}{H_0^2}\frac{\ddot{a}_0}{a_0} \simeq -0.64 \pm 0.03$$

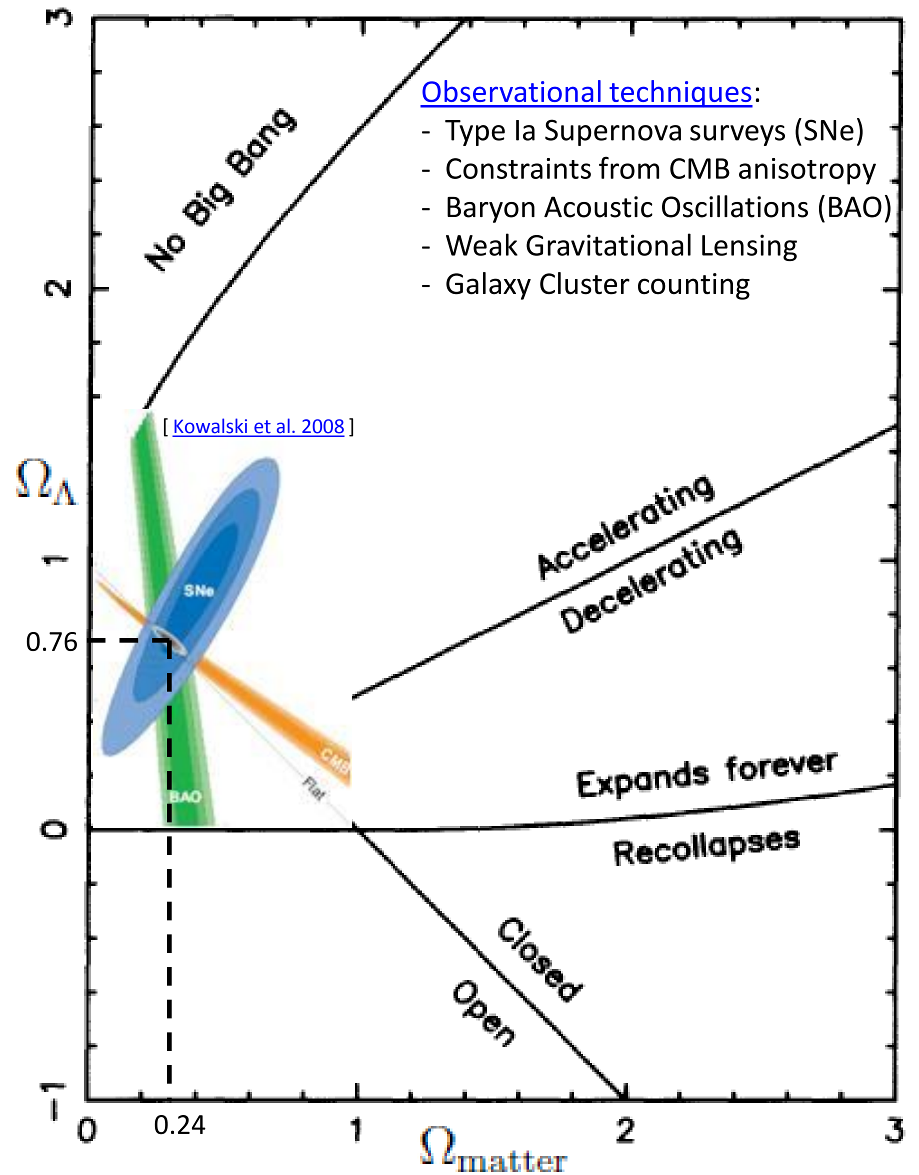
- Radius of curvature $\quad \frac{k}{a_0^2 H_0^2} \simeq 0.003 \pm 0.010$
  (much larger than Hubble radius)

- **Success of Einstein's General Relativity with** $\Lambda \approx (10^{26}\,\text{m})^{-2}$

- Exciting mystery in the matter sector

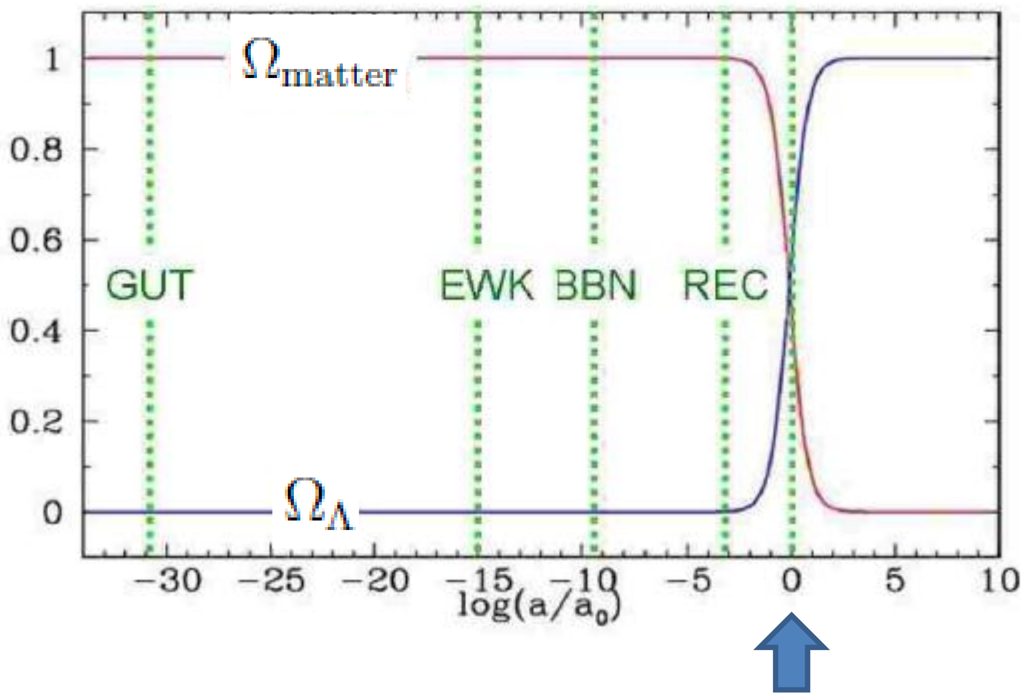
$$\Omega_{\text{matter}} = \Omega_{\text{known matter}} + \Omega_{\text{cold dark matter}}$$

$$\Omega_{\text{baryon}} \simeq 0.042 \pm 0.002 \quad , \quad \Omega_{\text{cold dark matter}} \simeq 0.204 \pm 0.028$$



Part 2.

Cosmic coincidence problem ?
Why $\Omega_{\mathrm{matter}} \sim \Omega_\Lambda$ now?



The cosmic coincidence problem

- Standard `coincidence' argument against the cosmological constant scenario :

data indicate that we happen to live in a very brief phase of cosmic history when $\Omega_{\rm matter} \sim \Omega_\Lambda$

  - unlikely coincidence
  - clashes with the cosmological principle

- Matter density *today*

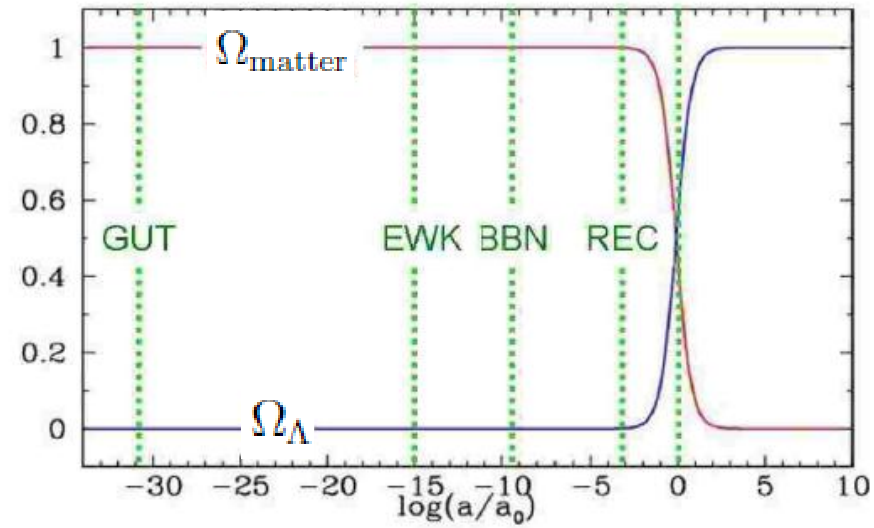
$$\rho_{\rm matter} \simeq 10^{11} M_\odot/{\rm Mpc}^3 \sim 10^{-23}\,{\rm g/m}^3$$

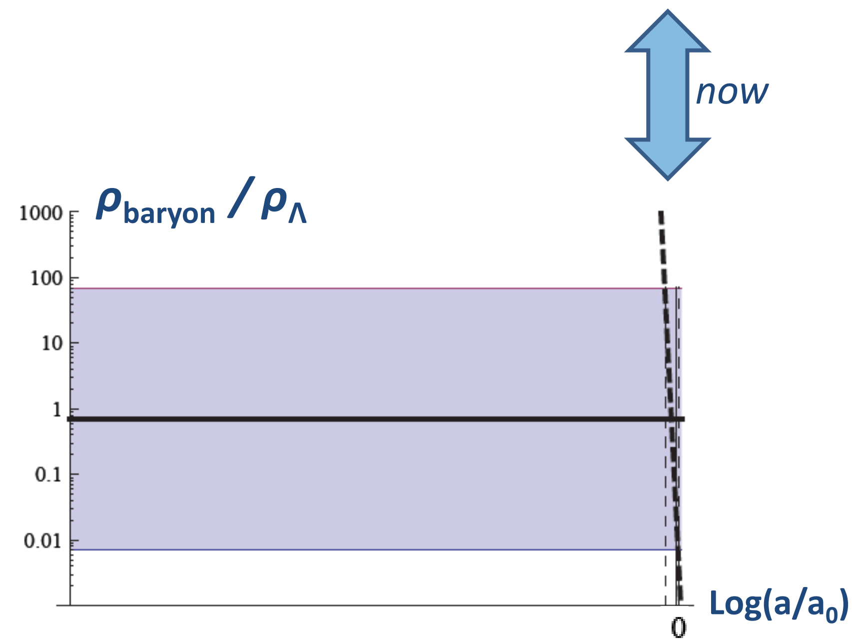
scales in time as a^{-3}

- Cosmological const. = *constant* energy-density

$$\rho_\Lambda \equiv \frac{\Lambda}{8\pi G_N} \simeq 10^{-23}\,{\rm g/m}^3$$

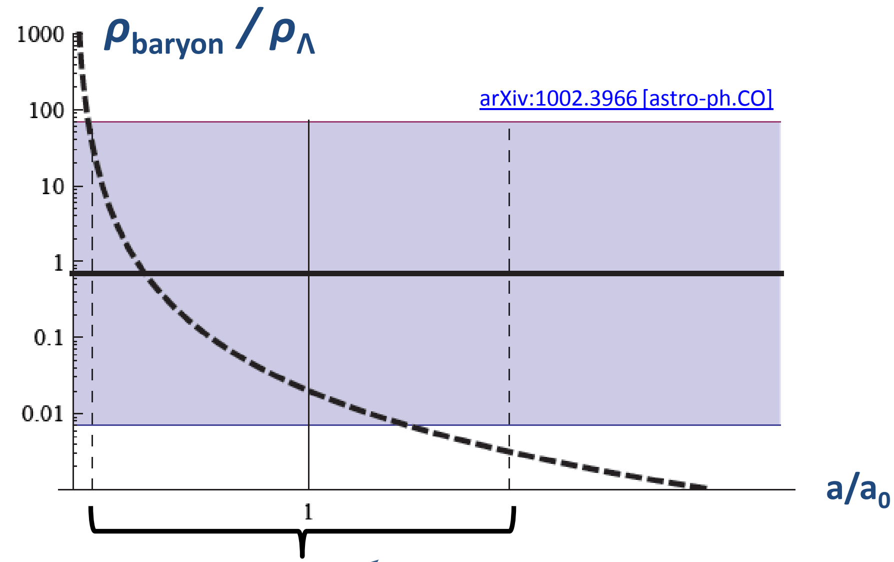
- Argument used to argue that the acceleration is in fact due to a fluid – *dark energy* – with density varying with time and with exotic eqn of state $P = w(a)\,\rho$, $w(a_0) < -1/3$

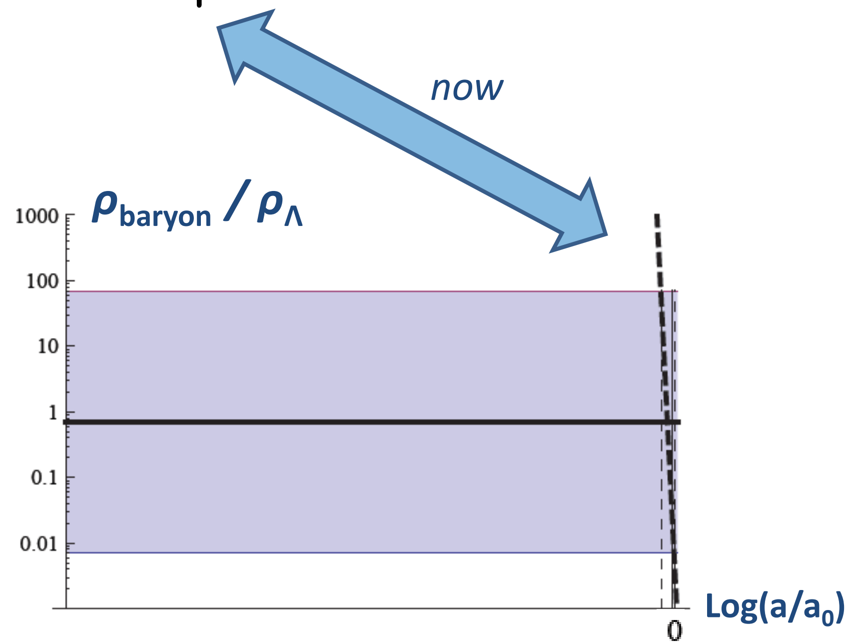




Cosmic coincidence problem ?

- Unlikely coincidence ? Very brief phase?
  Probability arguments are tricky
  and should be handled with care
- Why should we assume equiprobability on a logarithmic scale?
- *Equiprobability in proper-time* (or in the scale factor ***a***) is more reasonable
- When this is done, the short phase lasts for half the life of the Universe t_H
- Problem put back into perspective:
  - not a fine-tuned coincidence
  - issue of orders of magnitudes:
    why do we happen to live in an age of the Universe that is not many orders of magnitude smaller or larger?
- The cosmological principle cannot be applied uncritically: quite reasonable that we can live only during those few Gyr [Weinberg 1989 , sec. V]

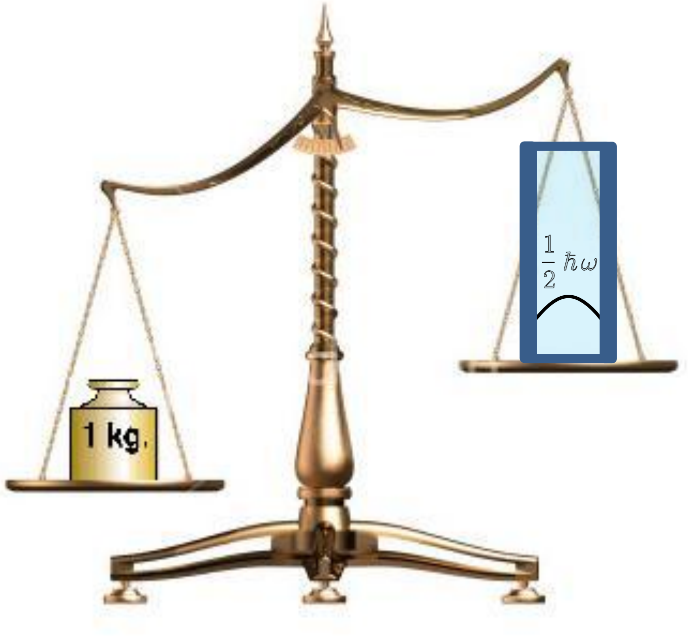




Part 3.

The problem of QFT vacuum energies.

Do vacuum energies gravitate?



QFT vacuum energy $\boldsymbol{\rho}_{\mathbf{vac}}$ and Λ

- In Quantum Field Theory (QFT), the **vacuum energy density** diverges quartically with the physical UV cut-off M_{UV}

$$\rho_{\rm vac} = \int_{|\vec{p}|<M_{UV}} \frac{d^3\vec{p}}{(2\pi\,\hbar)^3}\,\frac{1}{2}\,\hbar\,\omega(\vec{p}) \;\sim\; \hbar^{-3}\,M_{UV}^4 \quad , \qquad \langle 0|T_{\mu\nu}|0\rangle = -\rho_{\rm vac}\,g_{\mu\nu}$$

- **Severe problem if it contributes to the effective cosmological constant**:

$$\Lambda_{\rm eff} = \Lambda \;+\; 8\pi G_N\,\rho_{\rm vac}$$

  the hypothetical contribution is enormously larger than the observed value of Λ

$$\Lambda_{\rm obs} \approx \left(10^{26}\,{\rm m}\right)^{-2} \quad , \qquad 8\pi G_N\,\rho_{\rm Pl} \;\approx\; (10^{-35}\,{\rm m})^{-2}$$

- **Open puzzle of QFT in the presence of gravity.**
  The problem pertains to QFT, not to GR with Λ. It is a mistake to identify Λ with the vacuum energy. The problem does not affect the ΛCDM model.

- $\boldsymbol{\rho}_{\mathbf{vac}}$, is it real? can it be measured? does it gravitate?

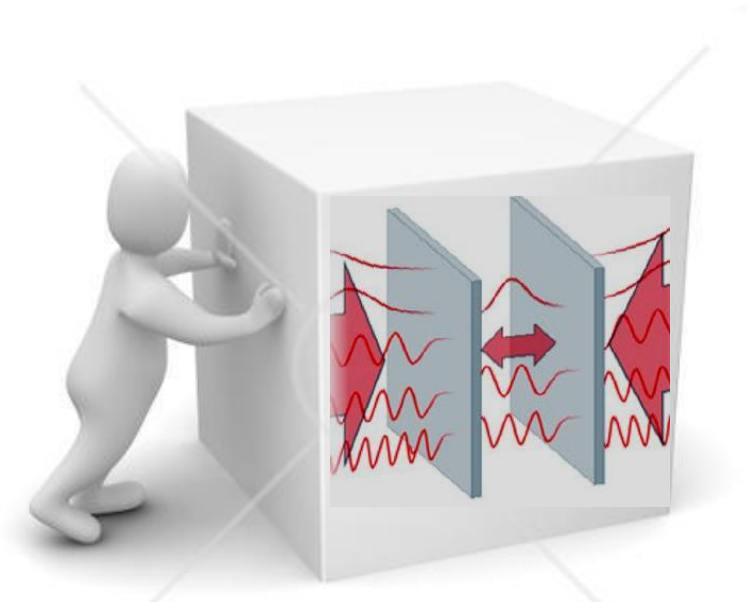
- Discussion 1: - Casimir effect
  - Vaporization heat in solids
  - Loop corrections to electrostatic energy in nuclei

- Discussion 2: Effective Field Theory, Naturalness, and subtraction

Casimir Effect and Vacuum energy ρ_{vac}

- Casimir effect: often presented as an argument for the reality of vacuum energies

$$E(a) = \hbar^{-3}\, M_{UV}^4\, V \;-\; \frac{\pi^2}{720}\frac{\hbar}{a^4}\, V$$
$$= \;E_0 \;+\; \Delta E$$



- In fact it probes only the dependence of ΔE on external parameters = boundary conditions

$$F = -\frac{d}{da}\Delta E$$

- Physical argument : the term $\hbar^{-3}\, M_{UV}^4\, V$ does not contribute to the inertial mass of the box, and therefore does not gravitate

- Massless scalar field is a S^3 Universe of radius *a* [Ford 1976] Static FRW background. Renormalized energy-momentum tensor, vacuum state, depends on *a*

$$\rho(a) = \frac{\hbar}{480\pi^2\, a^4} \qquad , \qquad P(a) = \frac{\hbar}{1440\pi^2\, a^4}$$

- It does not behave as a cosmological constant, ***P (a) = 1/3 ρ(a)***

$\frac{1}{2}\hbar\omega$ and the heat of vaporization in solids

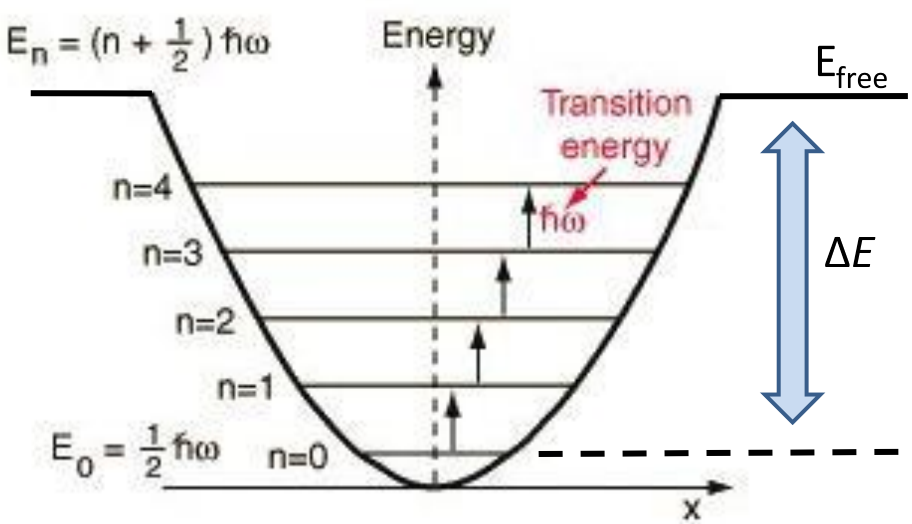
- 1911 , Nernst at 1st Solvay conference:
  do the zero-point energy really exist?
  is there a physical process that allows to measure the $\frac{1}{2}\hbar\omega$?

- 1913, Stern, Born- VonKarman,
  in order to explain experimental data on the heat of complete vaporization of monoatomic solids, zero-point energy needs to be taken into account

- Notice that the process is only sensitive to the ionization energy,

$$\Delta E = E_{\text{free}} - \frac{1}{2}\hbar\omega \quad ,$$

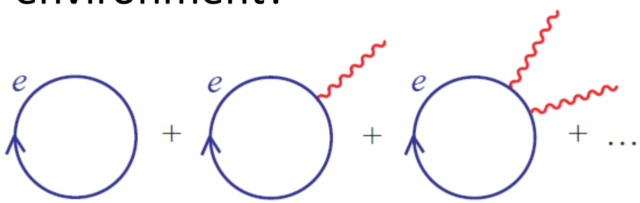
  not to the zero-point energy.

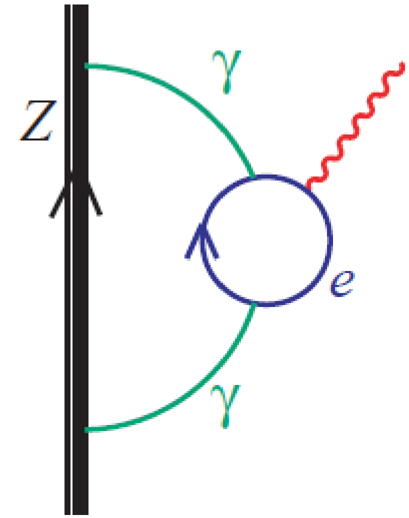


Loop corrections to the *mass* of a nucleus

- [Polchinski 2006]: we know that in some situations, loop corrections do gravitate. E.g., electrostatic contribution to the mass of a nucleus.

  Why the analogous loops should not gravitate in a vacuum environment?





- Electrostatic contribution to the mass of a nucleus: $\Delta E = \frac{\alpha}{4\pi} \ln(m_e R_{\rm nuc})\, M_{\rm nuc}$

  for Aluminium $\frac{\Delta E}{M_{\rm nuc}} \simeq 10^{-3}$, for Platinum $\frac{\Delta E}{M_{\rm nuc}} \simeq 3 \times 10^{-3}$

- From [Dicke et al. 1964], we know that Aluminium and Platinum have the same ratio of gravitational to inertial mass to one part in 10^{12}

- Notice: only the Log part of the loop correction contributes

A cosmological constant problem in QFT ?

- Why the mass of the electron is about 0.5 MeV and not much larger?

  why is $\rho_\Lambda \equiv \frac{\Lambda}{8\pi G_N} \simeq 10^{-23}\,\mathrm{g/m^3} \simeq \left(10^{-3}\mathrm{eV}\right)^4$ and not much larger?

- The statement often heard, that QFT gives the *wrong* prediction for Λ, is not correct. It simply gives no prediction.
- Standard QFT allows to describe how coupling constants renormalize with the scale, not to *predict* their value

- To be compared to the current paradigm in the hep-ph community :

  Effective Field Theory = QFT + naturalness principle

- Fruitful point of view:
  - *physical cut-off* = scale of new physics
  - low-energy dimensionful constants have the scale of the cut-off (unless they are protected by a symmetry)

- *Natural* value of the vacuum energy density (in flat space EFT)

  $\rho_\Lambda \sim M_{UV}^4$ unless a symmetry protects it to *0*

- *Does it gravitate?*

Ode to Effective Field Theory reasoning

[Burgess 1998]
[Polchinski 1992]

- **Quadratic (and quartic?) divergences in QFT are interesting as they can be used to extimate the scale of new physics**

  - [Das et al 1967] Electromagnetic pion mass difference, 1-loop QED quadratic divergence ⇨ *pre*diction of the mass of the ρ
  - [GIM1970] Quadratic divergent contribution to the mass difference of K_L and K_S ⇨ prediction of the *charm*
  - [201?] 1-loop quadratic divergence of the mass of the Higgs ⇨ new physics at the TeV
  - *Quartic divergence of vacuum energy ⇨ ???*

$$m_{\pi^0} \simeq 145\text{MeV}$$
$$m_{\pi^\pm} \simeq 150\text{MeV}$$

$$m^2_{\pi^\pm} - m^2_{\pi^0} = \frac{3}{16\pi^2}\,\alpha\, M^2_{UV}$$

$$M_{UV} \sim m_\rho \simeq 770\text{MeV}$$

- Dangerous to extend flat space arguments to curved space without the due care

- Notice that: for the EFT of gravitons + SM matter on flat Minkowski space, the term of dim 4 (cosmological constant) decouples from gravitons

- [Maggiore 2010]: EFT in FRW Universe. Vacuum energy with subtraction as for the ADM mass. Effect $M^2_{UV} H^2$ compatible with present constraints. It does not behave as a cosmological constant.

General Relativity with a cosmological constant Λ

- Empirical adequacy:

  The Lambda-Cold Dark Matter (ΛCDM) model is today the standard model in cosmology and is ``almost universally accepted by cosmologists as the best description of the present data" [Lahav-Liddle, `The particle data book' 2010]

- Theoretical consistency:
  - Λ is a completely natural part of General Relativity
  - It is no-more no-less mysterious than any of the other numerous constants in fundamental theories
  - There are open issues (e.g. why QFT vacuum energies do not contribute to Λ, what happens during phase transitions) but these pertain to other domains of physics, not to the problem of the *physical reason for the accelerated expansion of the Universe*

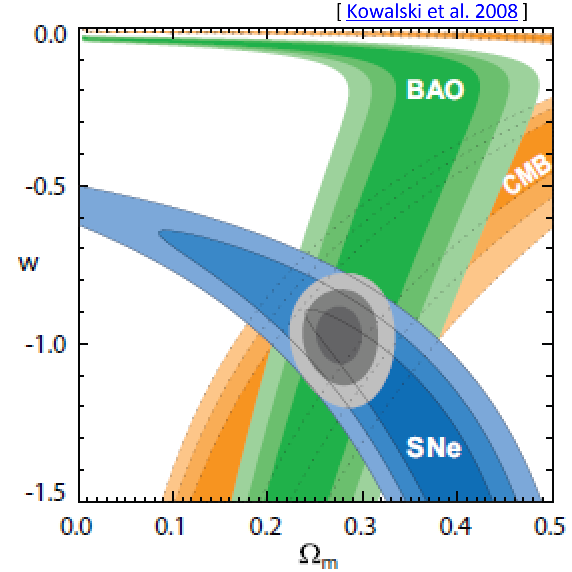
- It is important to **keep testing the Λ scenario** , and continue to explore alternative ideas. E.g. parameterizations

$$w(a) = w_0 + (1 \pm \tfrac{a}{a_0})\, w_1 \qquad\qquad P = w(a)\,\rho$$

$$w_0 \simeq -1 \pm 0.2 \quad , \quad w_1 \simeq 0 \pm 1$$

⇨ see [Kolb et al., The Dark Energy Task Force]

[Kowalski et al. 2008]



“Arguably the greatest mystery of humanity today is the prospect that 75% of the universe is made up of a substance known as dark energy about which we have almost no knowledge at all.”
L. Calder, O. Lahav, Physics World 23 (2010) 32-37

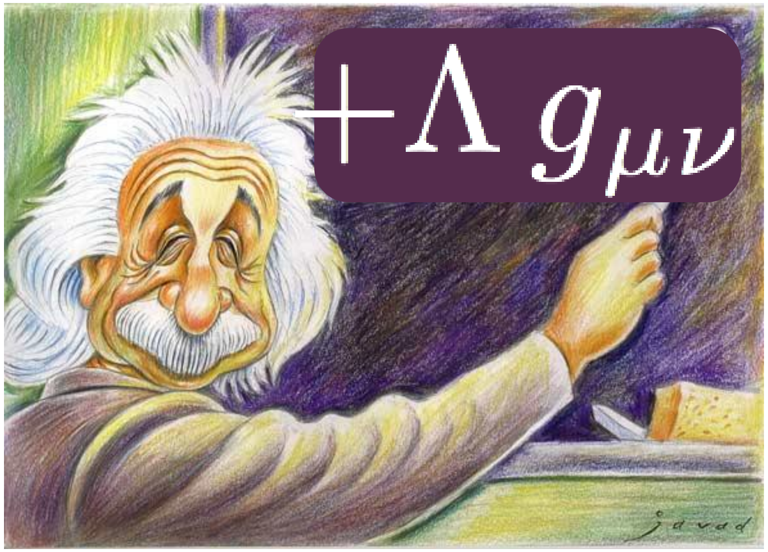
“Dark energy remains a mystery. [We are] frustrated by the lack of theoretical candidates for [it].”
J.A. Tyson, Nature 464, (2010) 172

This is exaggerated.

Summary

- We must keep testing the ΛCDM scenario and continue explore alternatives ideas.

- But to say ``lack of theoretical candidates'' or ``great mystery'' for the cosmic acceleration, is badly misleading.



- It is especially wrong to talk about

  `` a substance ''

  It is like saying that the centrifugal force that pushes out from a merry-go-round is the effect of a ``mysterious substance''.

- The acceleration in the cosmic expansion is **well-understood and well-accounted for, by current fundamental physical theory.**

- It is not due to a vacuum energy or a mysterious substance: it is a long distance repulsive force due to the **intrinsic dynamics of geometry .**

- *No great mystery here!*