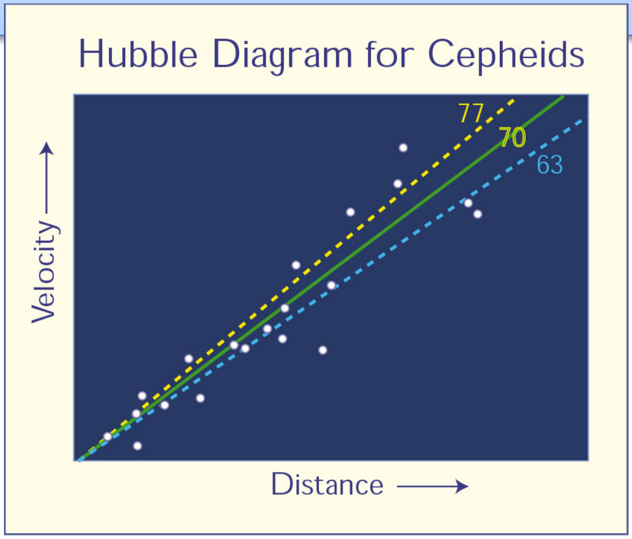
Current tension

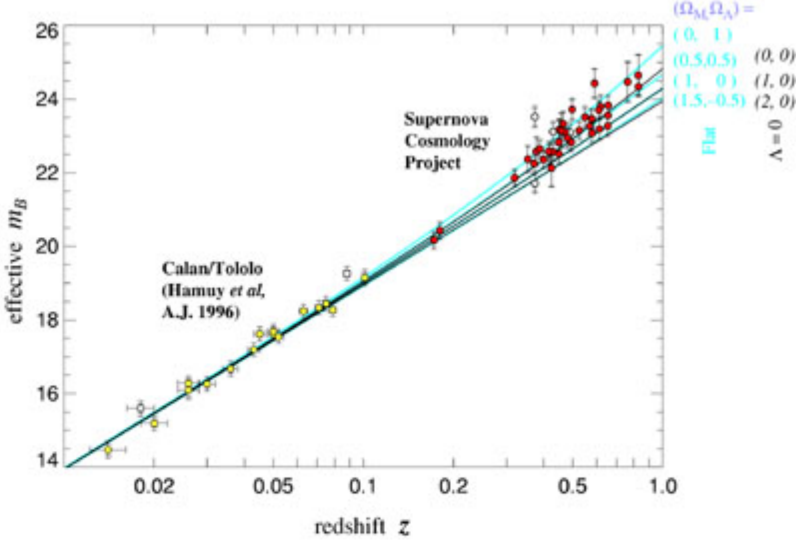
- The local distance ladder constrains the Hubble constant using data out to z ≤ 0.15 to H_0 =73.24 ± 1.7 (SH0ES program, Riess et al. 2016; Dhawan et al. 2018)

- Assuming ΛCDM, strong gravitational lensing probes the expansion out to z ≤ 1.7 giving H_0 = 72 ± 3 (H0LiCOW, Bonvin et al. 2017)

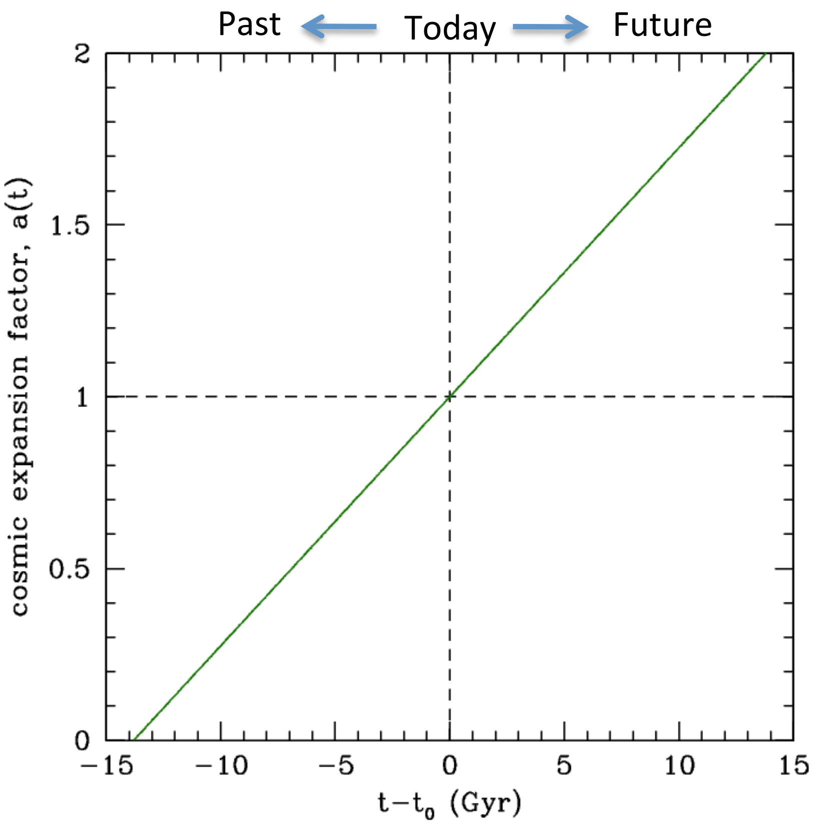
- Assuming ΛCDM, CMB probes distances out to to z ~ 1090 giving H_0 = 67.81 ± 0.92 (Planck collaboration 2016)

- Ongoing discussion whether the Hubble constant tension (3.4 σ) calls for new physics (e.g. early or late dynamical dark energy, violations of the cosmological principle)





The cosmic expansion history

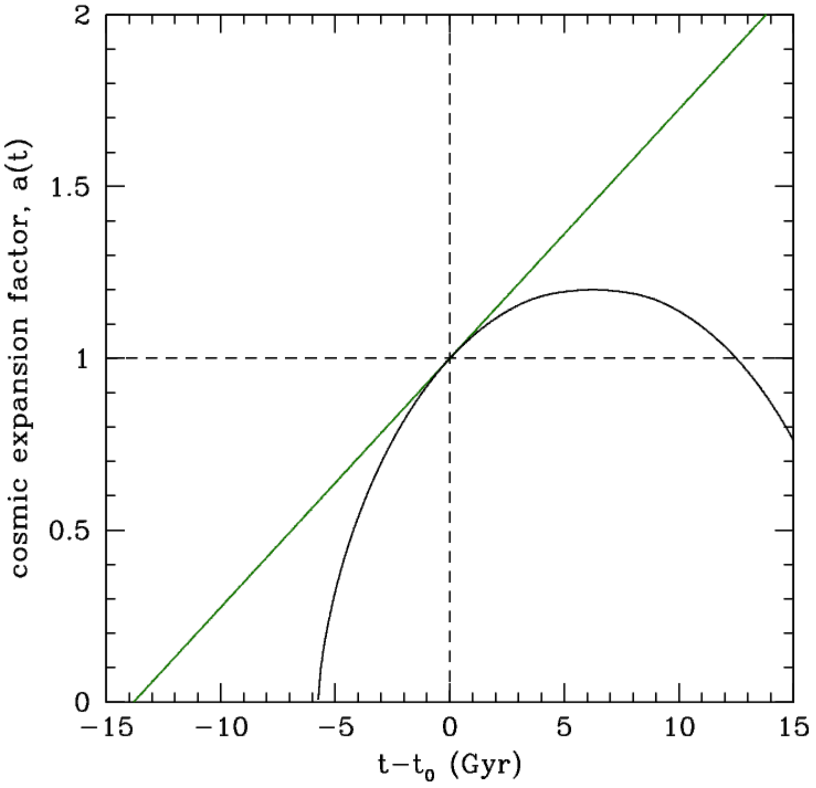


Friedmann equations state that, given the current expansion rate, the past and future expansion history depend on what the universe is made of.

Let us consider a few examples:

- Empty universe. The universe has always expanded at the current rate (no slowdown or acceleration): $a(t)=H_0 (t-t_0)$
- H_0= 100 h km/s/Mps, h=0.71 ± 0.02

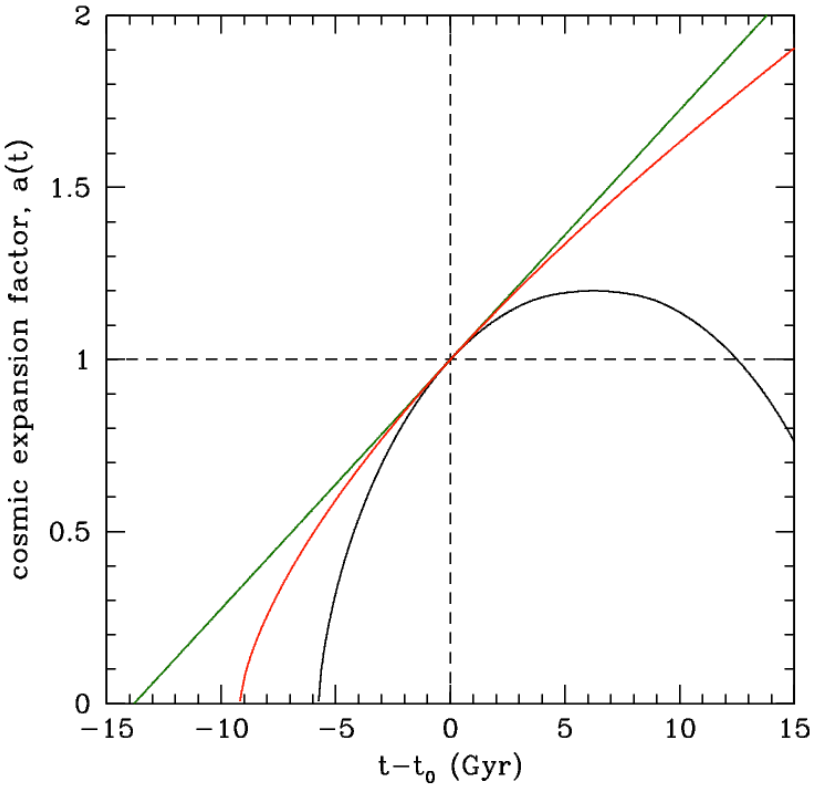
The cosmic expansion history



- The universe has always expanded at the current rate

- The universe contains a lot of matter (Ω_m= 6) and collapses in the future

The cosmic expansion history



- The universe has always expanded at the current rate

- The universe contains a lot of matter (Ω_m= 6)

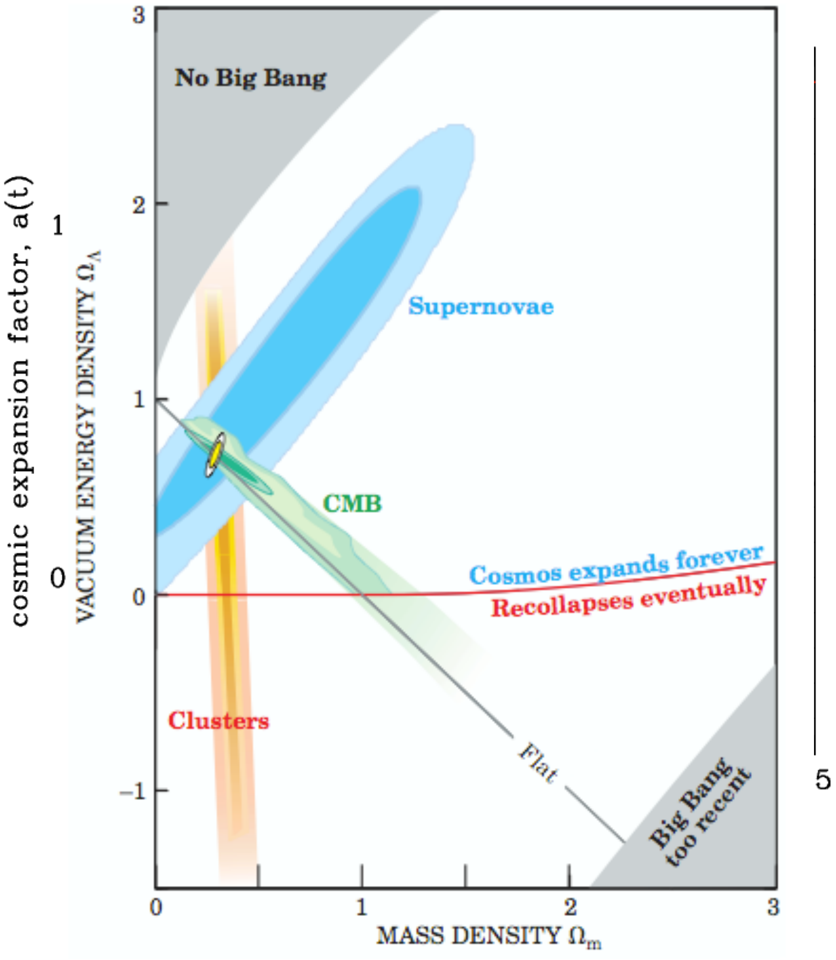
- The universe contains less matter (Ω_m= 1) and asymptotically stops expanding in the infinite future. We use this value of the matter density as a reference and call it "critical density".

$$\rho_{\mathrm{crit}} = \frac{3H_0^2}{8\pi G}, \qquad \Omega_{\mathrm{m}} = \frac{\rho_{\mathrm{m}}}{\rho_{\mathrm{crit}}}$$

Friedmann equations show that k=sign(Ω_{tot}-1) with Ω_{tot}= Ω_m+ Ω_r+ Ω_Λ

Standard candles and standard rulers

The accelerating universe



The Nobel Prize in Physics 2011

Saul Perlmutter, Brian P. Schmidt, Adam G. Riess

Photo: Lawrence Berkeley National Lab

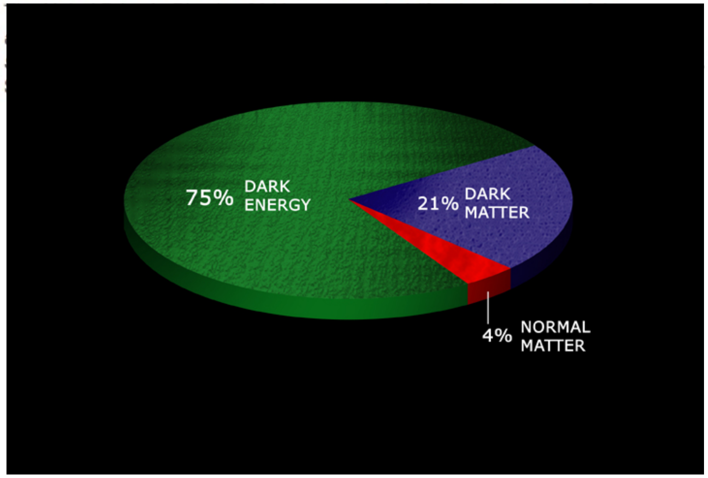
Saul Perlmutter

Photo: Belinda Pratten, Australian National University

Brian P. Schmidt

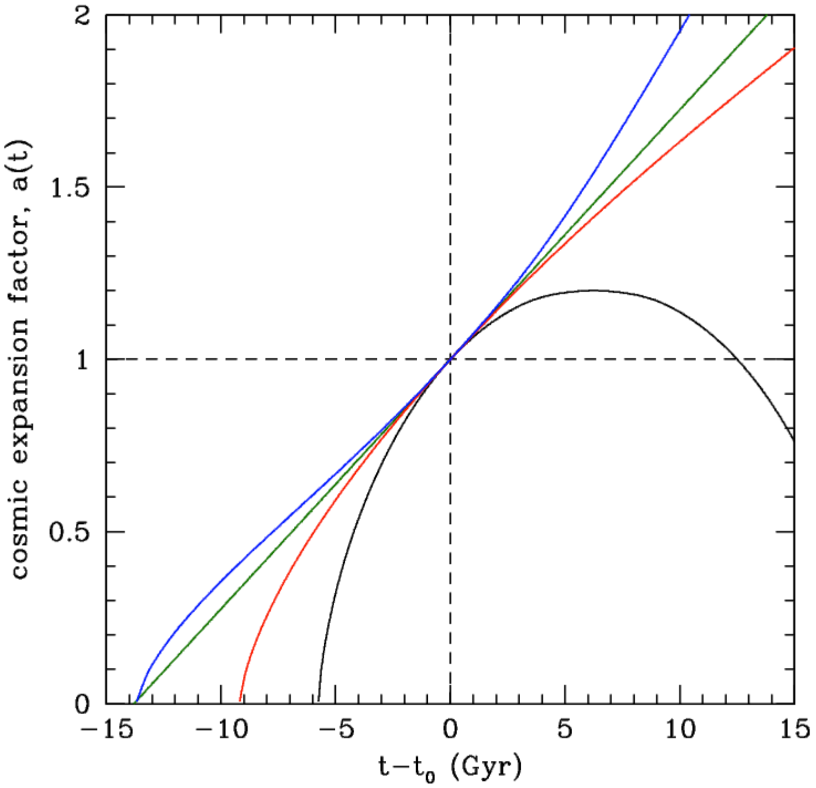
Photo: Scanpix/AFP

Adam G. Riess



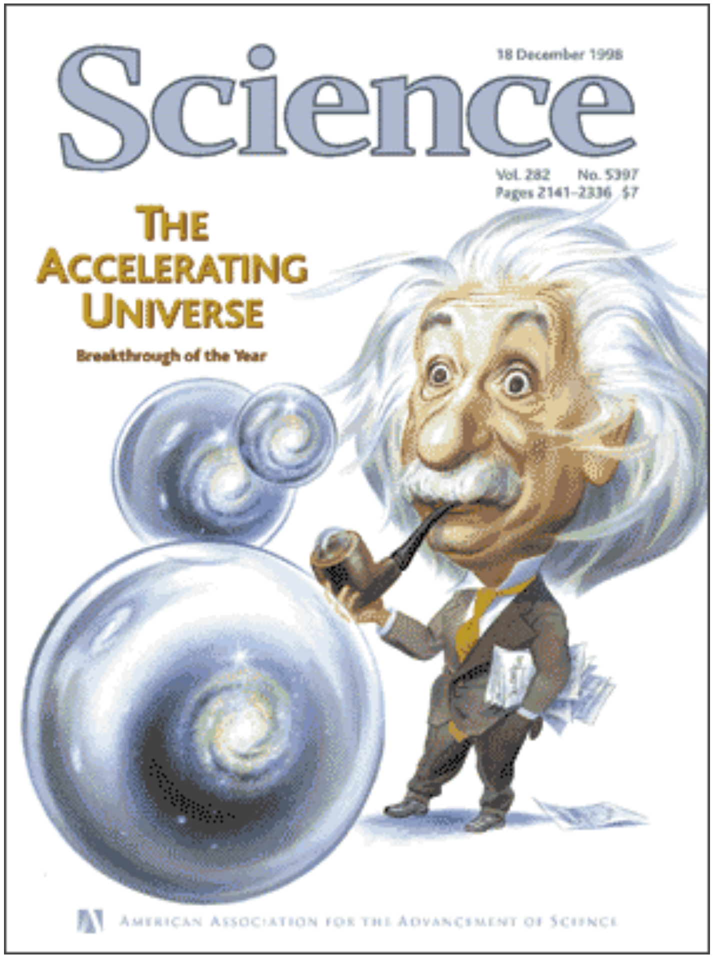
$\Omega_{tot} \approx 1$

The cosmic expansion history



- The universe has always expanded at the current rate
- The universe contains a lot of matter (Ω_m= 6)
- The universe contains less matter (Ω_m= 1)
- The universe contains a mix of matter and "dark energy" (Ω_m= 0.27, Ω_Λ= 0.73)

The accelerating universe



18 December 1998

Science

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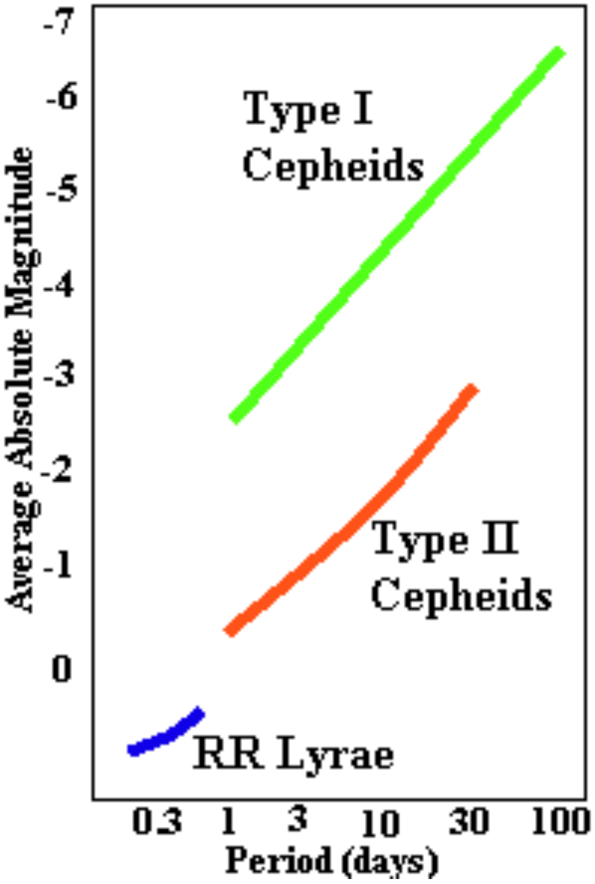
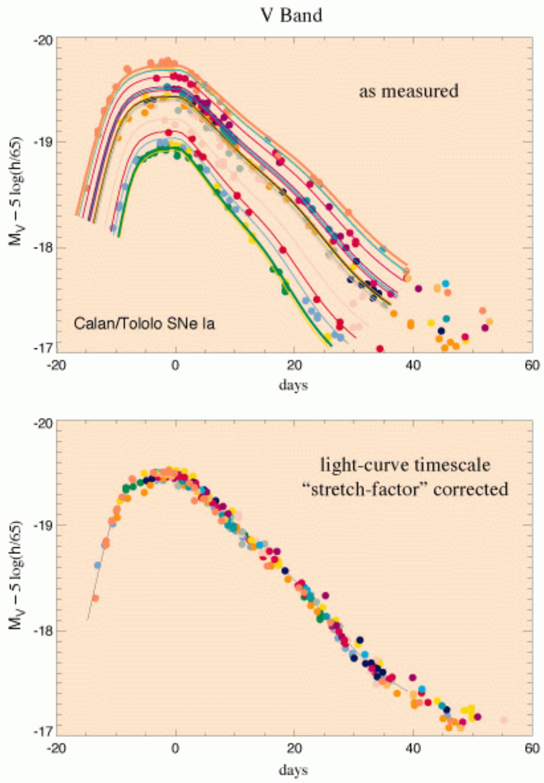
THE ACCELERATING UNIVERSE

Breakthrough of the Year

AMERICAN ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE

“Standardizable” candles

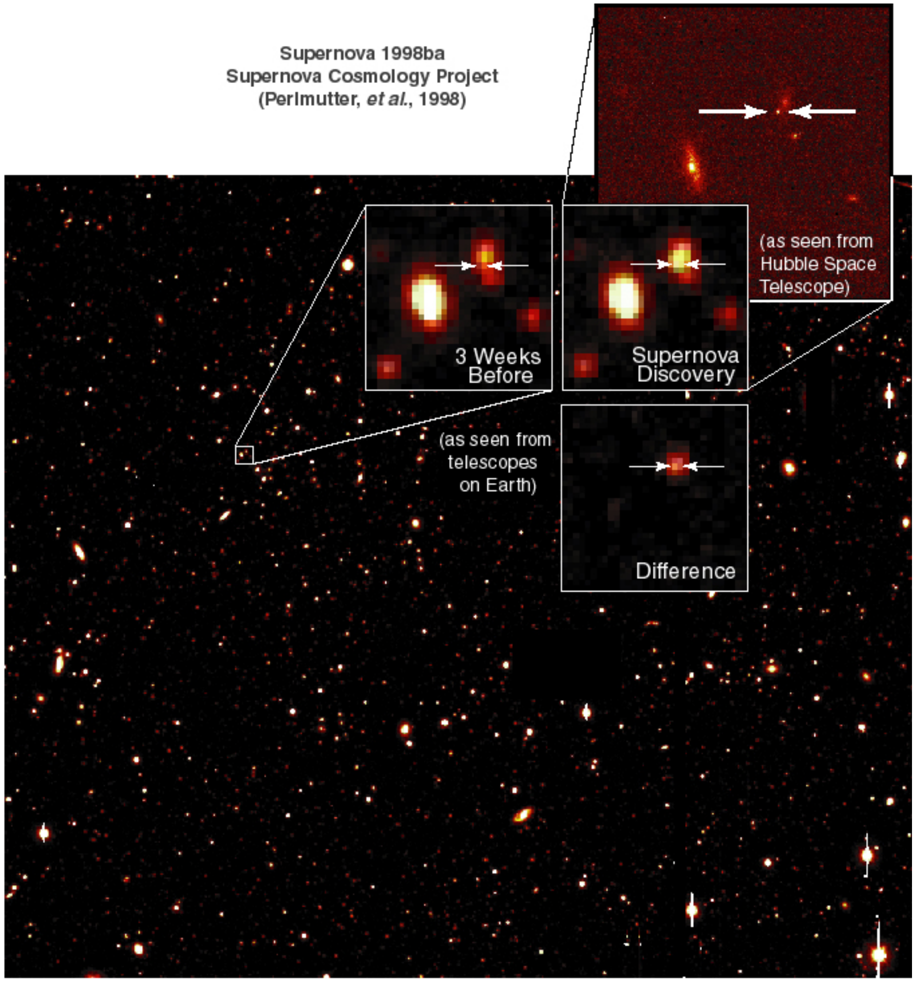


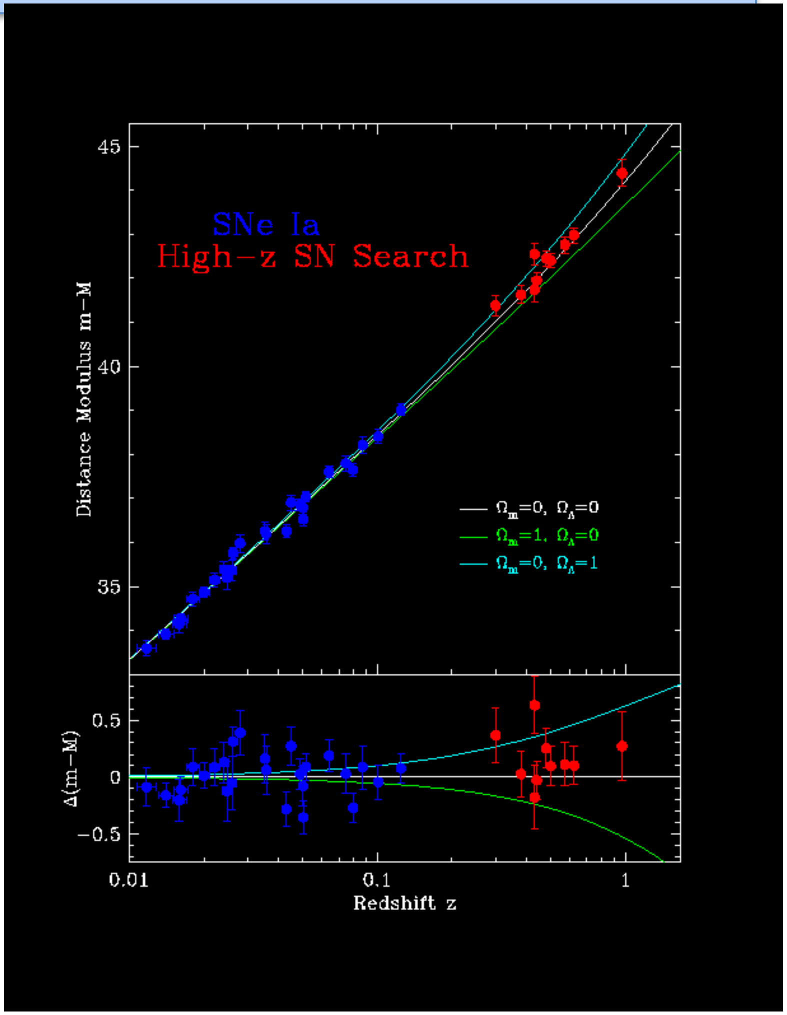


Low Redshift Type Ia Template Lightcurves

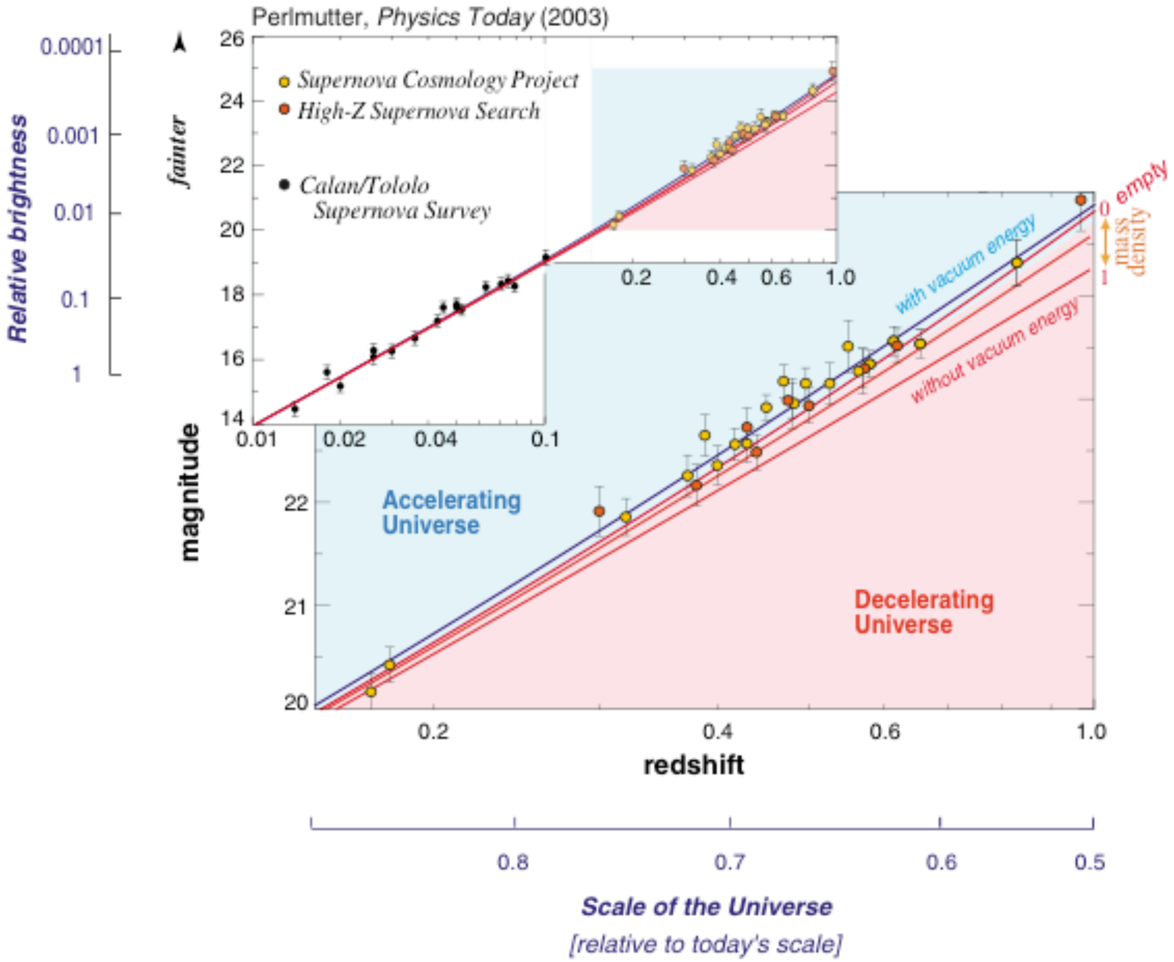
Hubble diagram from SNae Ia

Supernova 1998ba
Supernova Cosmology Project
(Perlmutter, *et al.*, 1998)





Accelerated expansion?

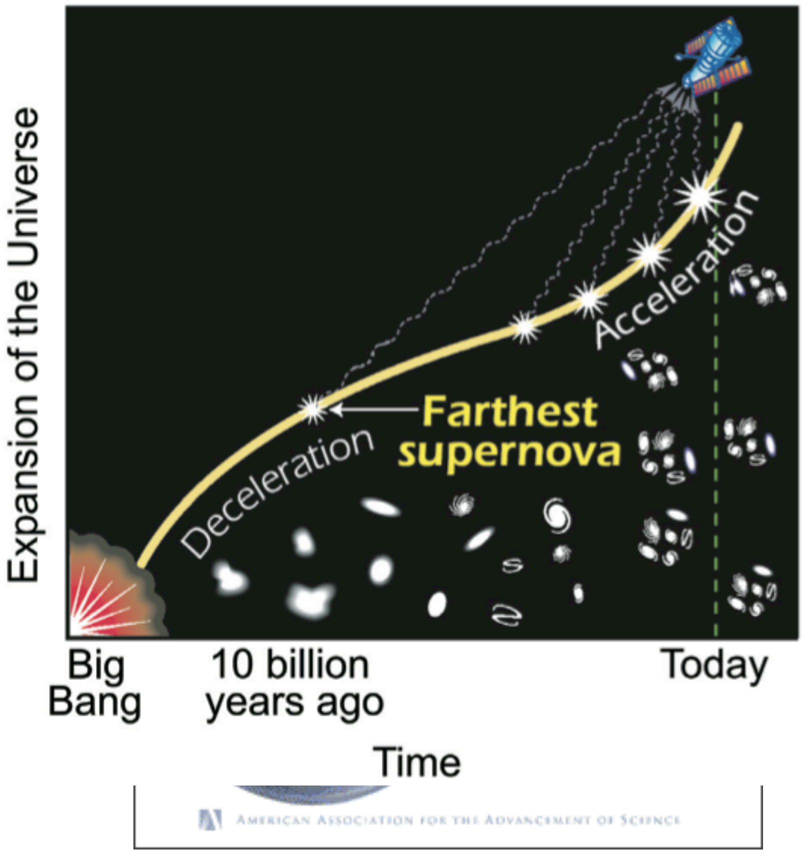

Perlmutter, *Physics Today* (2003)

- In 1998, two independent teams found that SNae Ia at $z \approx 0.5$ appear about 25% dimmer than they would in a decelerated universe

- This suggests an accelerated Hubble flow: acceleration increases the distance the light must travel to reach us

- Improved data collected in the last few years have confirmed the original results

Dark energy, a primer



American Association for the Advancement of Science

- Acceleration of cosmic expansion discovered in 1998 from observation of the distance-redshift relation of supernovae Ia

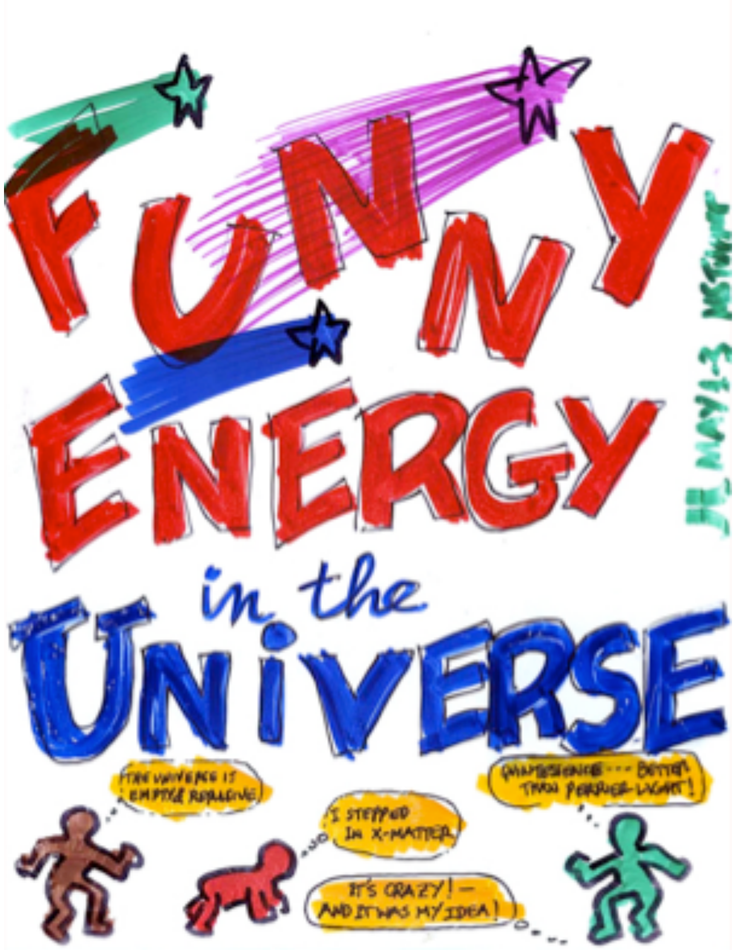
- Friedmann equation

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right)$$

then implies $p < -\rho c^2 / 3$ (i.e. a strongly negative pressure or tension)

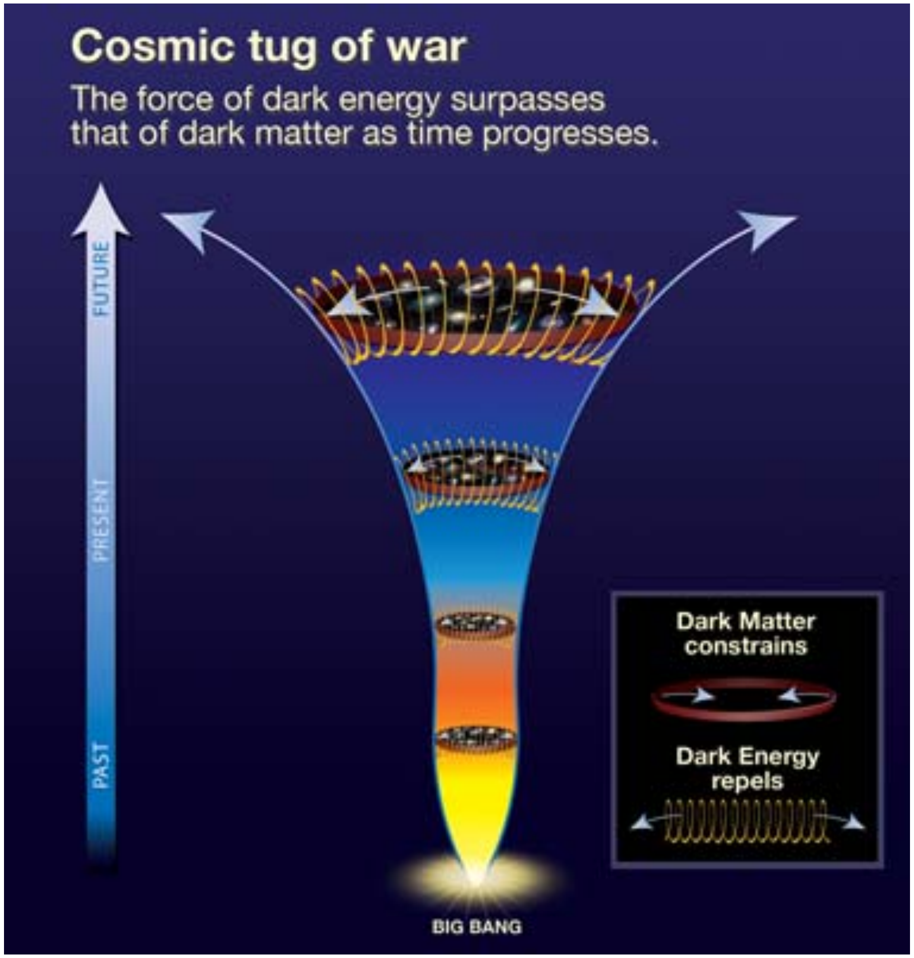
- The (hypothetical) dominant negative pressure component has been dubbed “dark energy” (name coined by M. Turner)

What counteracts gravity?



Michael Turner 1998

What counteracts gravity?



- The elegant universe (Brian Greene)
- The extravagant universe (Robert Kirshner)
- The preposterous universe (Sean Carroll)
- Maybe the most fundamentally mysterious thing in basic science (Frank Wilczek)
- Not only queerer than we suppose but queerer than we can suppose! (J.B.S. Haldane)

Why no one noticed it before?

- The measured value corresponds to a matter density of 0.000000000000000000000000006 kg per cubic meter (less than the mass of 4 protons)
- The best vacuum made in a physics laboratory has a density which is higher by a factor of a billion
- A cube stretching from Bonn to the Moon only contains 340 g of dark energy
- A cube stretching from Bonn to the Sun only contains 20 million Kg of dark energy, a fraction 0.00000000000000000000001 of the solar mass
- A cube enclosing the whole Galaxy contains nearly 1 trillion solar masses of dark matter but only 3 million solar masses of dark energy
- A cube as large as the visible universe contains 73% of the mass in dark energy

What could it be?

- The cosmological constant, Λ (Einstein 1917)

$$R_{\mu\nu} - \frac{1}{2}R\,g_{\mu\nu} + \Lambda\,g_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right) + \frac{\Lambda c^2}{3}$$

- Quantum-vacuum energy (Zel'dovich 1968)

$$T_{ab}^{(\mathrm{vac})} = \frac{\Lambda}{8\pi}g_{ab}$$

$$\rho_{\mathrm{vac}} = \frac{\Lambda}{8\pi}$$

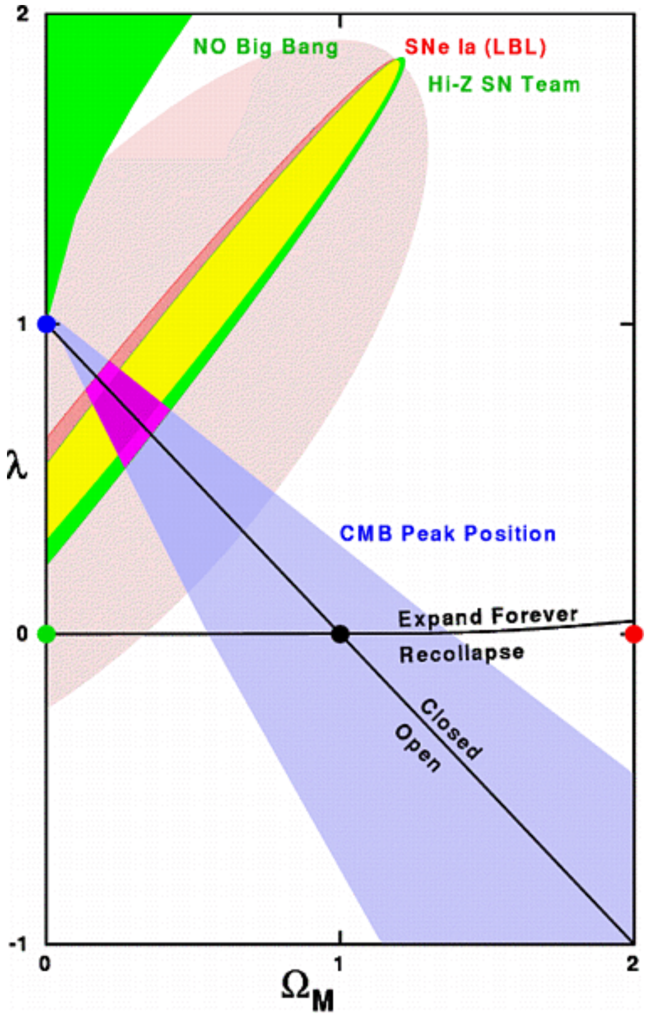
$$w = \frac{p}{\rho} = -1$$

- Quintessence - An unknown scalar field, ϕ

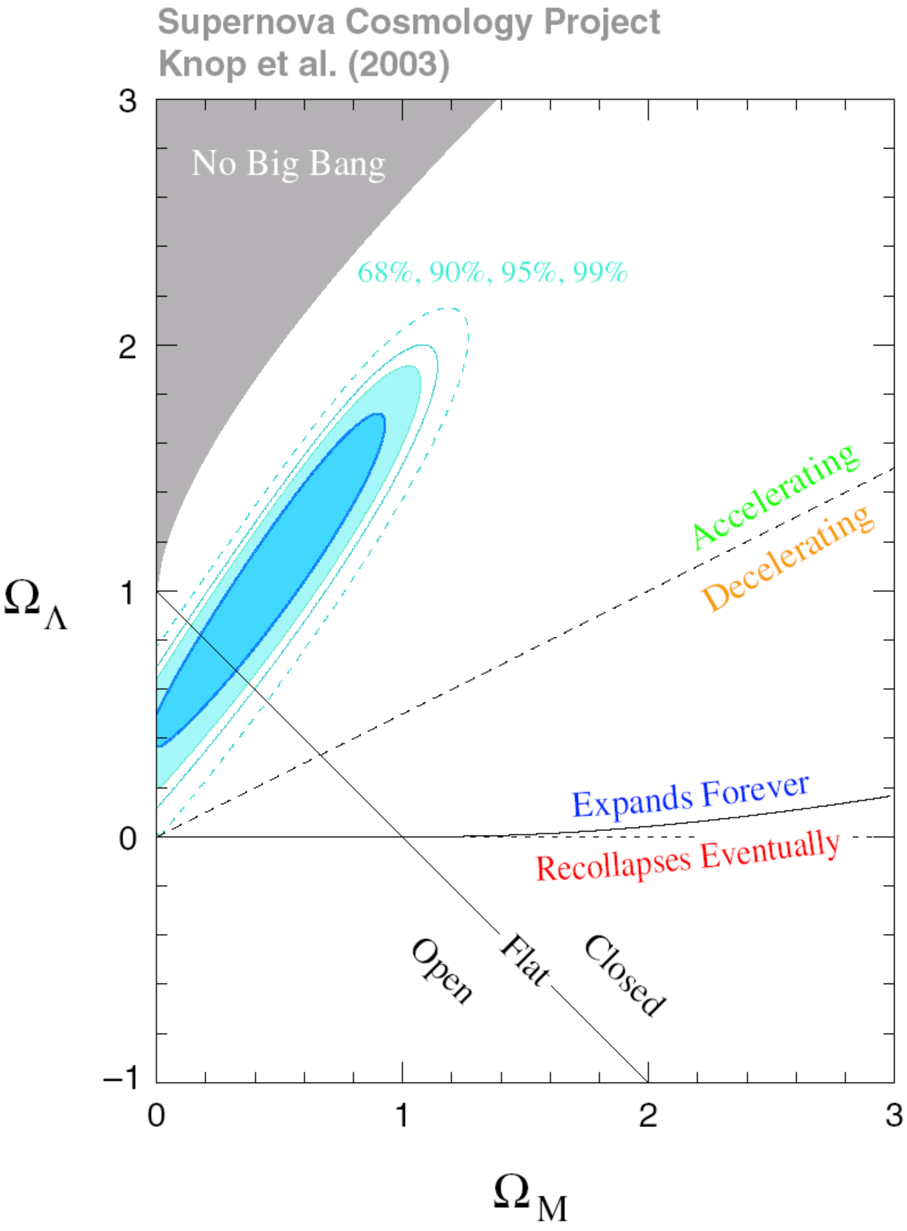
$$w = \frac{\frac{1}{2}\dot{\phi}^2 - V(\phi)}{\frac{1}{2}\dot{\phi}^2 + V(\phi)},$$

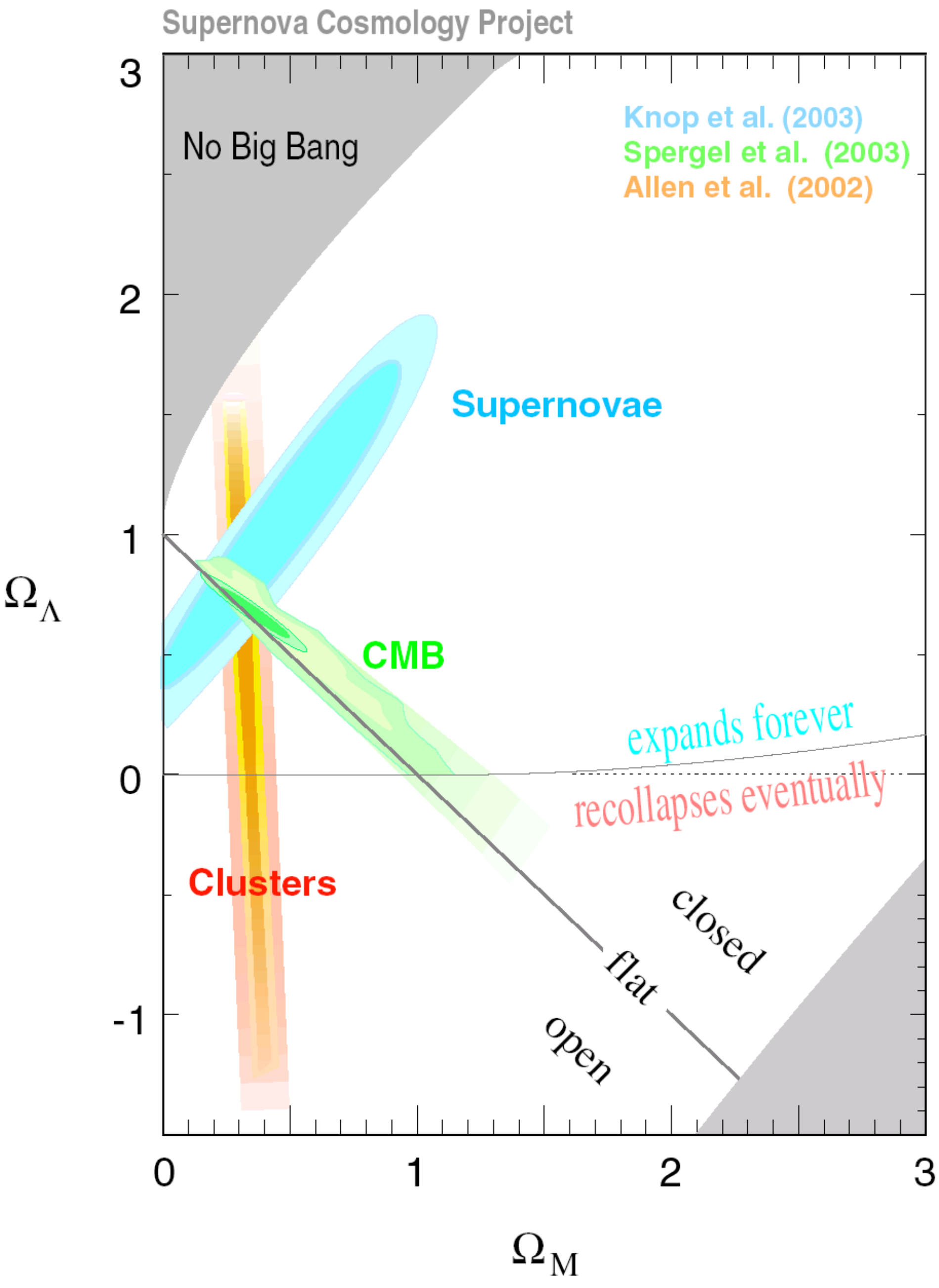
- A sign that Einstein's gravity is wrong on large scales

A non-vanishing cosmological constant



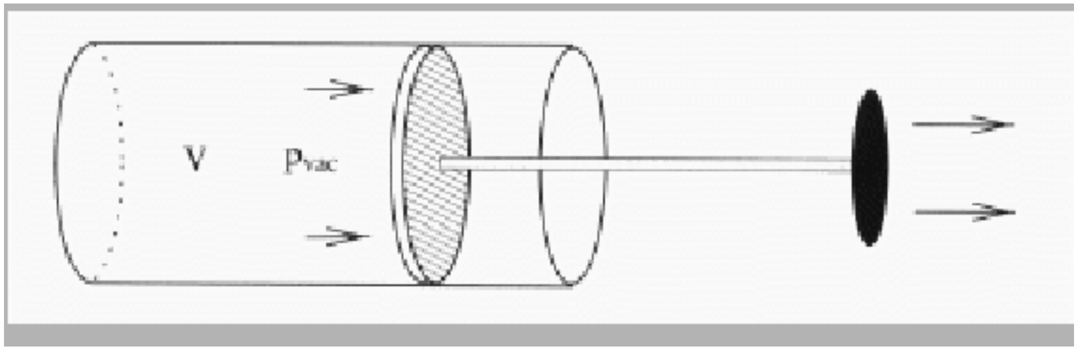
- The simplest explanation of cosmic acceleration is that Einstein's cosmological constant is small but positive
- In this case fitting the SNa Ia Hubble diagram gives $0.8\ \Omega_m - 0.6\ \Omega_\Lambda \approx -0.2 \pm 0.1$
- As we will see, CMB anisotropies suggest that $\Omega_m + \Omega_\Lambda \approx 1.0$
- Therefore, one finds
  $\Omega_m \approx 0.2 - 0.3$
  $\Omega_\Lambda \approx 0.7 - 0.8$
- Additional datasets give consistent answers


Supernova Cosmology Project
Knop et al. (2003)

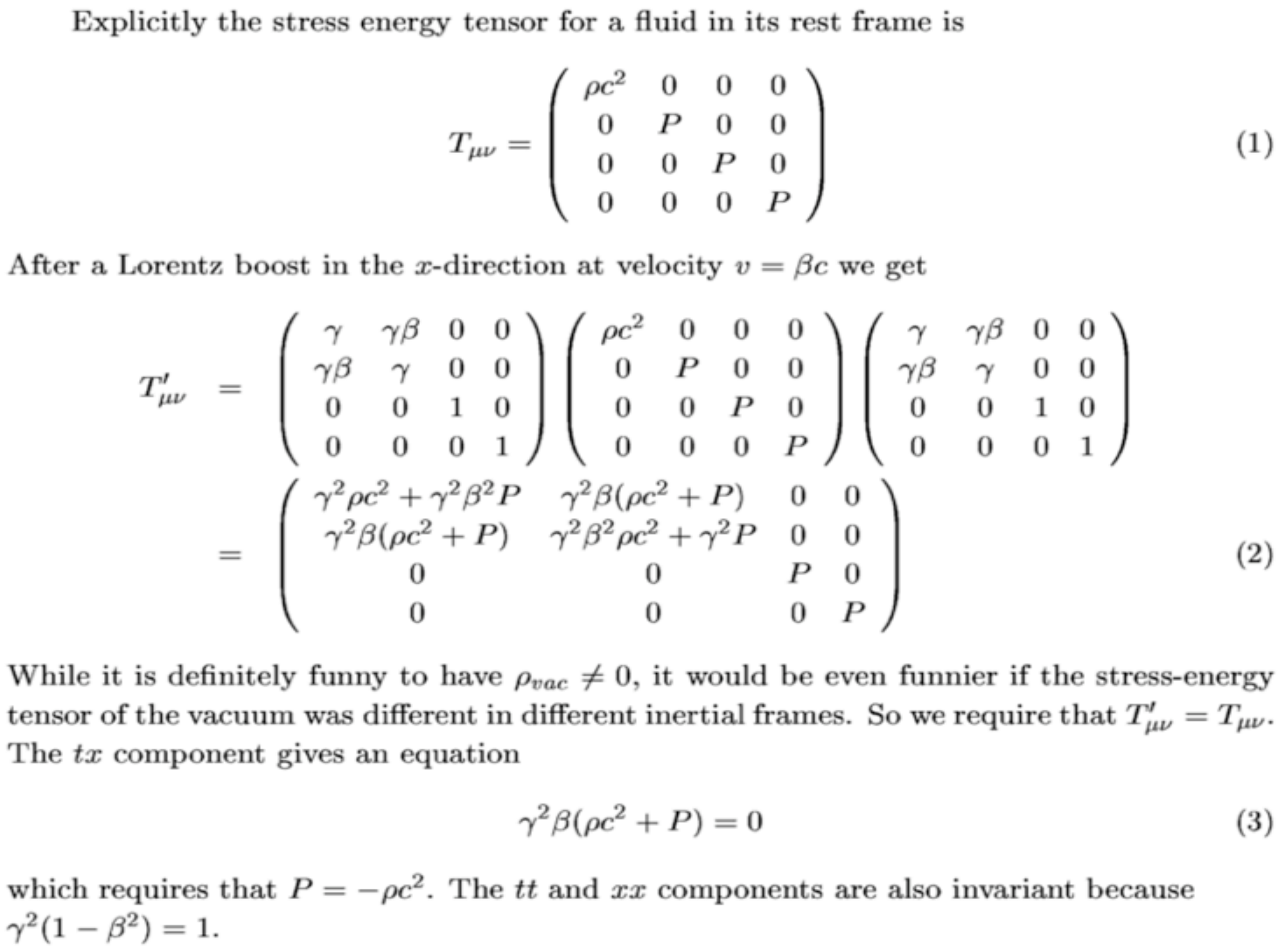

Supernova Cosmology Project

Modern interpretation of Λ

- Hermann Weyl attempted to link Λ to the quantum vacuum state
- In 1967, Yakov Zel'dovich noticed that if the vacuum state is a true ground state then all observers must agree on its form. But he realized that the only Lorentz invariant energy momentum tensor is the diagonal Minkowski tensor. Therefore, he proposed to move the Λ-term on the rhs of Einstein's field equations and to consider it as a source of energy-momentum which corresponds to a uniform sea of vacuum energy
- This corresponds to a fluid with $p=-\rho c^2$
- This can be seen from classical thermodynamics. The work done by a change in volume dV is equal to -pdV but the amount of energy in a box of vacuum energy increases when dV>0. Therefore p has to be negative.



Zel'dovich calculation



Explicitly the stress energy tensor for a fluid in its rest frame is

$$T_{\mu\nu} = \begin{pmatrix} \rho c^2 & 0 & 0 & 0 \\ 0 & P & 0 & 0 \\ 0 & 0 & P & 0 \\ 0 & 0 & 0 & P \end{pmatrix} \tag{1}$$

After a Lorentz boost in the x-direction at velocity $v = \beta c$ we get

$$\begin{aligned} T'_{\mu\nu} &= \begin{pmatrix} \gamma & \gamma\beta & 0 & 0 \\ \gamma\beta & \gamma & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \rho c^2 & 0 & 0 & 0 \\ 0 & P & 0 & 0 \\ 0 & 0 & P & 0 \\ 0 & 0 & 0 & P \end{pmatrix} \begin{pmatrix} \gamma & \gamma\beta & 0 & 0 \\ \gamma\beta & \gamma & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \\ &= \begin{pmatrix} \gamma^2\rho c^2 + \gamma^2\beta^2 P & \gamma^2\beta(\rho c^2 + P) & 0 & 0 \\ \gamma^2\beta(\rho c^2 + P) & \gamma^2\beta^2\rho c^2 + \gamma^2 P & 0 & 0 \\ 0 & 0 & P & 0 \\ 0 & 0 & 0 & P \end{pmatrix} \end{aligned} \tag{2}$$

While it is definitely funny to have $\rho_{vac} \neq 0$, it would be even funnier if the stress-energy tensor of the vacuum was different in different inertial frames. So we require that $T'_{\mu\nu} = T_{\mu\nu}$. The tx component gives an equation

$$\gamma^2\beta(\rho c^2 + P) = 0 \tag{3}$$

which requires that $P = -\rho c^2$. The tt and xx components are also invariant because $\gamma^2(1 - \beta^2) = 1$.

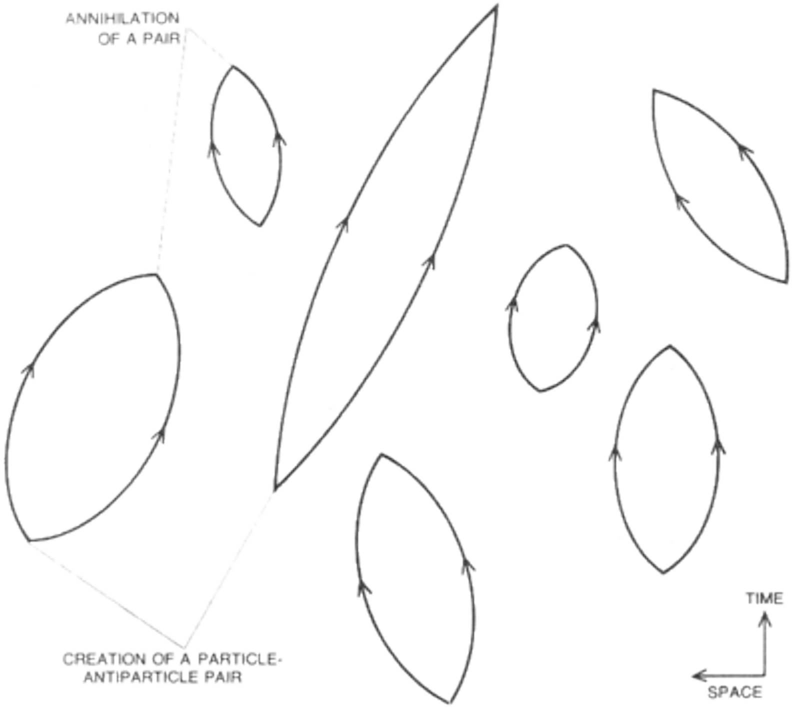
Dicke coincidence argument

(why the vacuum energy should be zero)

- If SNa and CMB data are correct, then then vacuum density is approximately 75% of the total energy density today.
- At redshift 2 (nearly 10 Gyr ago for H_0=73 km/s/Mpc), the vacuum energy density was only 9% of the total
- 10 Gyr in the future, the vacuum energy density will be 96% of the total
- Why are we alive at the time when the vacuum density is undergoing its fairly rapid transition from a negligible fraction to the dominant fraction?
- This is an example of Anthropic reasoning

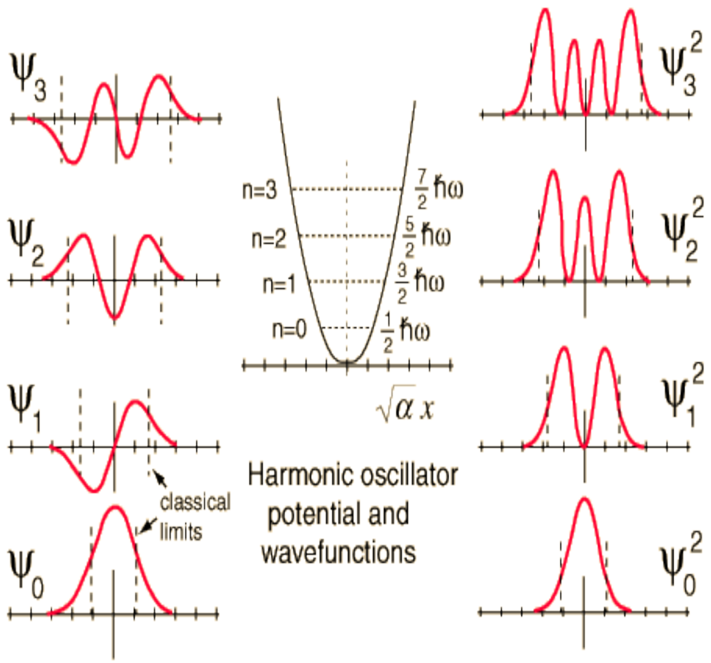
A dynamic vacuum state

- In the language of perturbative quantum field theory (Feynman diagrams), particle-antiparticle pairs ($\Delta E=2mc^2$) can be created from nothing as long as the energy is paid back in a time Δt which is short enough not to violate Heisenberg's uncertainty principle $\Delta E\ \Delta t > h/2\pi$
- This implies that the vacuum is not empty but it is teaming with virtual particles pairs
- Therefore empty space can have an energy density associated to it

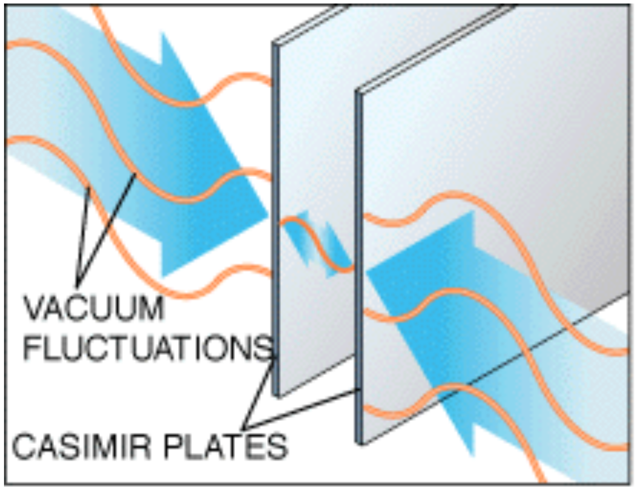


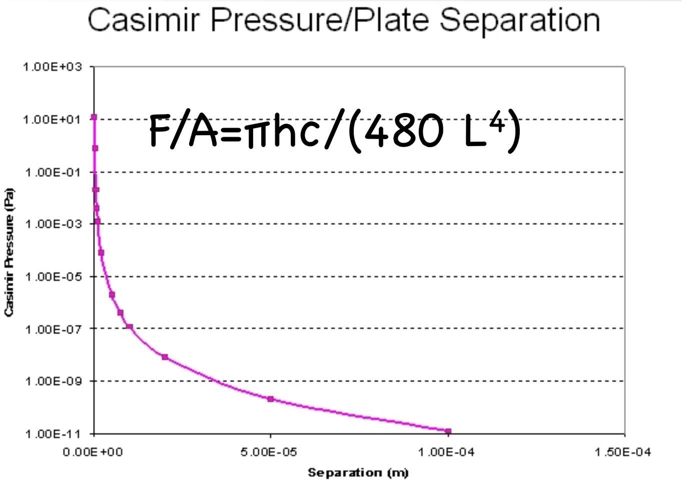
Zero-point energy (Nullpunktsenergie)

- Alternatively, vacuum energy can be seen as the sum of the zero-point energies of the quanta of the fields
- The minimum energy of an harmonic oscillator is $E_0=h\nu/2$, this is called the zero-point energy
- Quantum field theory can be regarded as a collection of infinitely many harmonic oscillators and therefore QFT predicts a non-zero vacuum energy
- Unfortunately we have no idea how to calculate it in a realistic way



Casimir effect



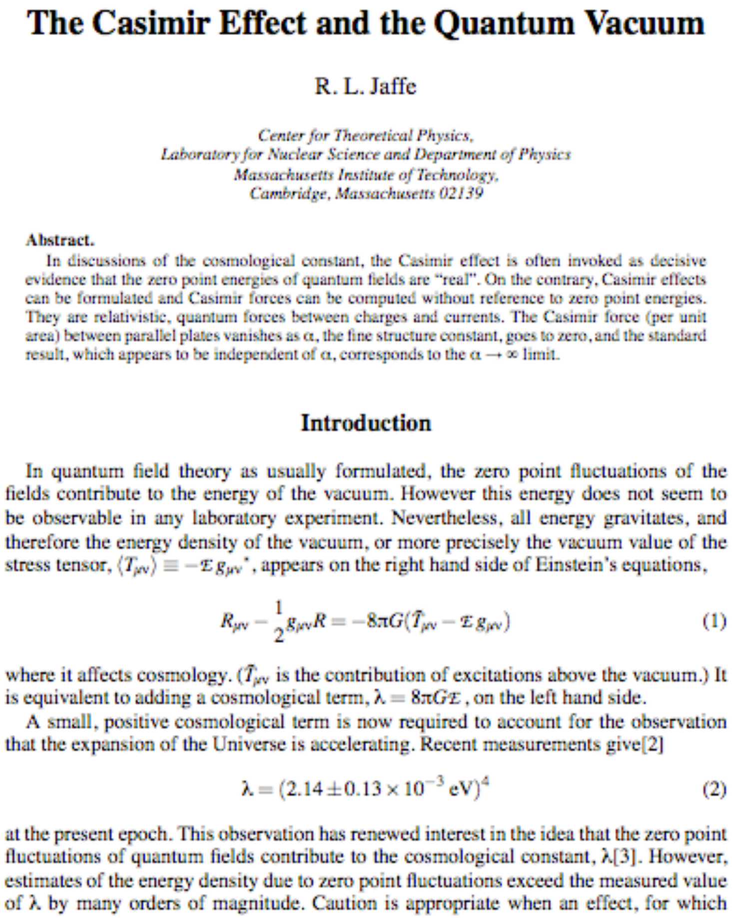

Casimir Pressure/Plate Separation

$$F/A=\pi hc/(480\ L^4)$$

In 1948, Hendrik Casimir predicted that two close, parallel, UNCHARGED conducting plates should experience a small attractive force due to quantum vacuum fluctuations of the electromagnetic field. The tiny force has been first measured in 1996 by Steven Lamoreaux and by many others afterwards.

…no general consensus…

- Does the Casimir effect provide evidence of the “reality” of quantum fluctuations and zero-point energies?
- In 2005 R. L. Jaffe (MIT) showed that the Casimir effect can be computed without reference to zero-point energies
- In his calculation the effect originates from relativistic quantum forces between charges and currents
- Are zero-point energies of quantum fields real? Do they contribute to the cosmological constant?



The Casimir Effect and the Quantum Vacuum

R. L. Jaffe

Center for Theoretical Physics,
Laboratory for Nuclear Science and Department of Physics
Massachusetts Institute of Technology,
Cambridge, Massachusetts 02139

Abstract.
In discussions of the cosmological constant, the Casimir effect is often invoked as decisive evidence that the zero point energies of quantum fields are “real”. On the contrary, Casimir effects can be formulated and Casimir forces can be computed without reference to zero point energies. They are relativistic, quantum forces between charges and currents. The Casimir force (per unit area) between parallel plates vanishes as α, the fine structure constant, goes to zero, and the standard result, which appears to be independent of α, corresponds to the α → ∞ limit.

Introduction

In quantum field theory as usually formulated, the zero point fluctuations of the fields contribute to the energy of the vacuum. However this energy does not seem to be observable in any laboratory experiment. Nevertheless, all energy gravitates, and therefore the energy density of the vacuum, or more precisely the vacuum value of the stress tensor, $\langle T_{\mu\nu}\rangle \equiv -\mathcal{E}\, g_{\mu\nu}{}^{*}$, appears on the right hand side of Einstein's equations,

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = -8\pi G(\tilde{T}_{\mu\nu} - \mathcal{E}\, g_{\mu\nu}) \qquad (1)$$

where it affects cosmology. ($\tilde{T}_{\mu\nu}$ is the contribution of excitations above the vacuum.) It is equivalent to adding a cosmological term, $\lambda = 8\pi G\mathcal{E}$, on the left hand side.

A small, positive cosmological term is now required to account for the observation that the expansion of the Universe is accelerating. Recent measurements give[2]

$$\lambda = (2.14 \pm 0.13 \times 10^{-3}\ \mathrm{eV})^4 \qquad (2)$$

at the present epoch. This observation has renewed interest in the idea that the zero point fluctuations of quantum fields contribute to the cosmological constant, λ[3]. However, estimates of the energy density due to zero point fluctuations exceed the measured value of λ by many orders of magnitude. Caution is appropriate when an effect, for which

The vacuum energy problem

- The measured value of Λ implies that the vacuum "mass" density is rather small ≈ 6×10^{-27} kg m^{-3} (the entire dark-energy content of the solar system equals the energy emitted by the Sun in 3 hours)
- If you naively sum up the zero-point energies of all the vibrational modes of a quantum field and assume that space-time is a continuum you get a divergent energy density (shorter wavelengths contribute more energy)
- If you admit that space-time might not be continuous at the Planck length and only consider modes with $\lambda > l_P$ you get an enormous but finite vacuum energy density ≈ 10^{96} kg m^{-3}
- If you also consider that fields are not free and that there are interactions between the modes you still find an answer which is tens of orders of magnitude away from the observed value
- For instance, if you adopt the minimal supersymmetric model and repeat the calculation you find that the vacuum energy is exactly zero. However, when the supersymmetry is broken (as it has to be today), you end up with a difference of nearly 60 orders of magnitudes.
- An unbearable amount of fine tuning is required to reconcile our present understanding in QFT with the observational data
- Note, however, that the naive QFT estimate agrees with observations if a cutoff at scales smaller than 1 mm is imposed

Vacuum energy

- In quantum field theory the vacuum has a non vanishing energy
- This is observable: Lamb shift, Casimir effect
- Does vacuum gravitate?

A little problem of fine tuning!

A bone in the throat!
(S. Weinberg)

Quantum theory overpredicts the observed value by a factor between
1,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000
and
1,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,
000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000, 000,000

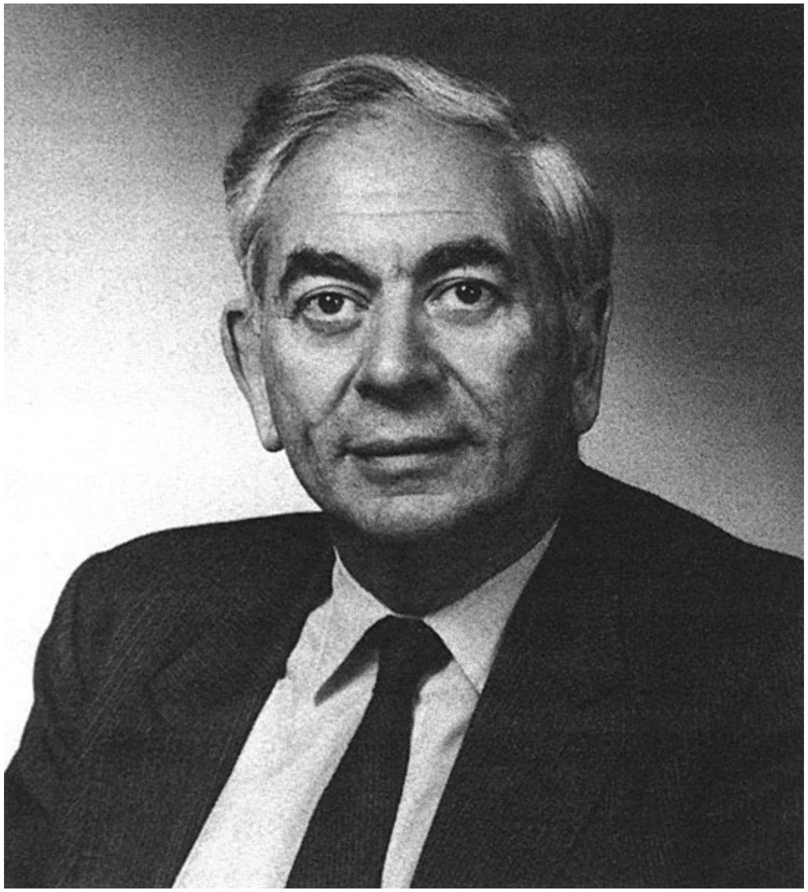
At the heart of the problem

- Physical phenomena in QFT are only determined by energy differences. Therefore diverging terms in the zero-point energy can be subtracted out. However, in general relativity is the total energy which gravitates and generates space-time curvature.
- Once again we need a unified treatment of gravity and quantum mechanics which is not available

Open questions

- Is the zero-point energy a physical quantity or just an artifact of our calculations?
- If it is physical, does it gravitate?

Dennis Sciama point of view

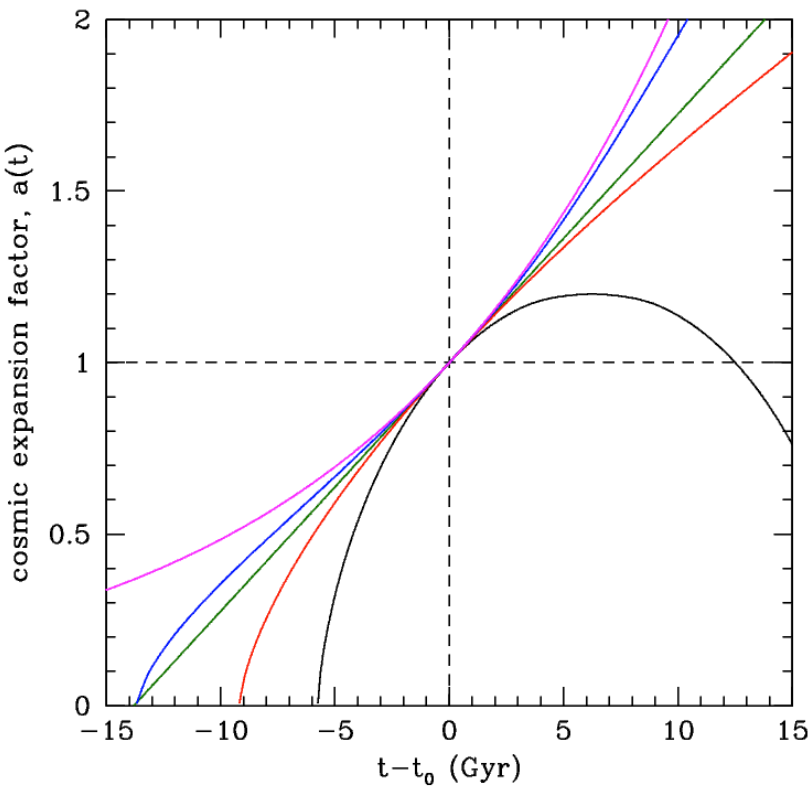


- "Even in its ground state, a quantum system possesses fluctuations and an associated zero-point energy, since otherwise the uncertainty principle would be violated. In particular the vacuum state of a quantum field has these properties. For example, the electric and magnetic fields in the electromagnetic vacuum are fluctuating quantities."
- "We now wish to comment on the unsolved problem of the relation between zero-point fluctuations and gravitation. If we ascribe an energy $h\nu\ /\ 2$ to each mode of the vacuum radiation field, then the total energy of the vacuum is infinite. It would clearly be inconsistent with the original assumption of a background Minkowski space-time to suppose that this energy produces gravitation in a manner controlled by Einstein's field equations of general relativity. It is also clear that the space-time of the real world approximates closely to the Minkowski state, at least on macroscopic scales. It thus appears that we must regularize the zero-point energy of the vacuum by subtracting it out according to some systematic prescription. At the same time, we would expect zero-point energy differences to gravitate. For example, the (negative) Casimir energy between two plane-parallel perfect conductors would be expected to gravitate; otherwise, the relativistic relation between a measured energy and gravitation would be lost."

Possible ways out

- Thanks to some unknown symmetry principle, the true vacuum energy is small but non-zero
- We live in a false vacuum but the true vacuum has zero energy
- A slowly varying dynamical component (a scalar field which varies in space and time, often called quintessence, with a particle mass ≈10^{-33} eV) is mimicking a vacuum energy density (useful to explain the "why now" problem). In this case the eq. of state has w(z).
- The anthropic solution (quantum probabilities)
- There is no dark energy and general relativity is wrong (extra-dimensions)
- There is no dark energy and the FRW metric is wrong (e.g. the fitting problem or backreaction, Ellis & Stoeger 1987)
- The data are wrong and the universal expansion is not accelerated

The cosmic expansion history

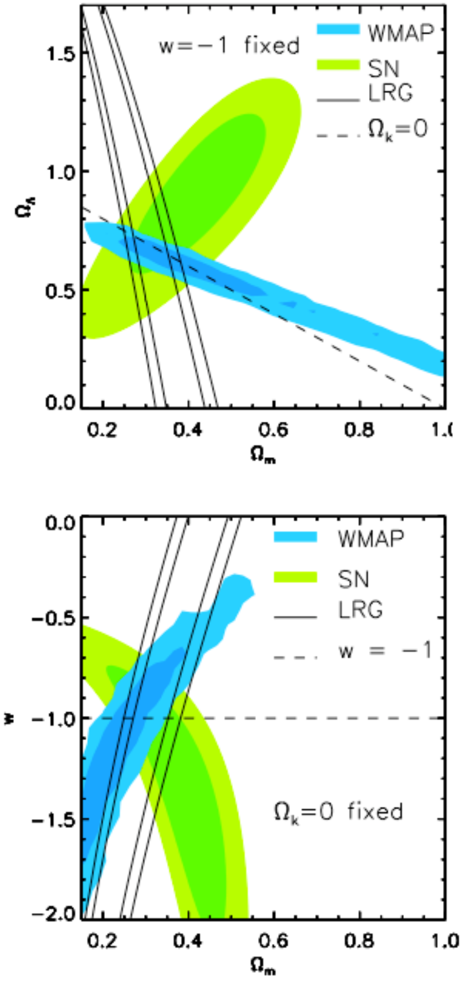


- The universe has always expanded at the current rate
- The universe contains a lot of matter ($\Omega_m = 6$)
- The universe contains less matter ($\Omega_m = 1$)
- The universe contains a mix of matter and “dark energy” ($\Omega_m = 0.27$, $\Omega_\Lambda = 0.73$)
- The universe just contains dark energy ($\Omega_\Lambda = 1$)

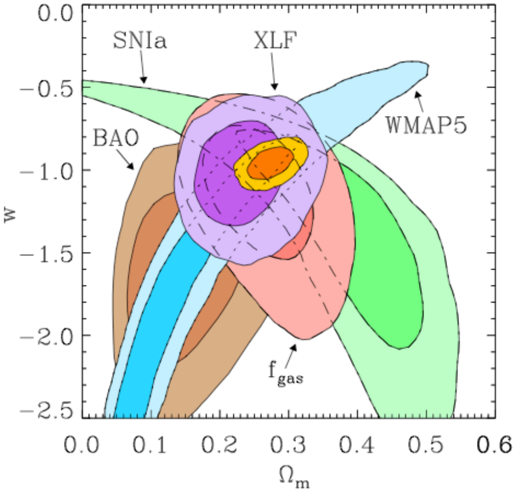
Cosmic concordance

- Statistics of temperature anisotropies in the microwave background
- Statistics of the galaxy distribution
- Abundance of galaxy clusters
- Hubble diagram of supernovae Ia

Reid et al. 2009



Mantz et al. 2009



What do we know of dark energy?

- Smoothly distributed through space, doesn’t fall into galaxies or clusters
- Constant density (or nearly constant) through time, not diluted by cosmic expansion
- Invisible to ordinary matter, only detected by gravity

Phenomenological parameterization

- Since we do not know what dark energy is and since there are too many models for it, from the observational point of view, the community has decided to use a phenomenological parameterization for the equation of state:

$$w(a)=w_0+(1-a)\ w_a$$

- Current and future surveys aim at setting tight constraints on w_0 and w_a to test whether deviations from -1 and 0 are measured
- If a deviation will be seen, then it will be re-mapped on to more physical parameters to discriminate between models

Our universe in six numbers

$$H_0 = 68.5 \pm 2.0 \text{ km/s/Mpc}$$

$$\Omega_m = 0.282 \pm 0.016$$

$$\Omega_b = 0.048 \pm 0.0028$$

$$\Omega_\Lambda = 0.723 \pm 0.016$$

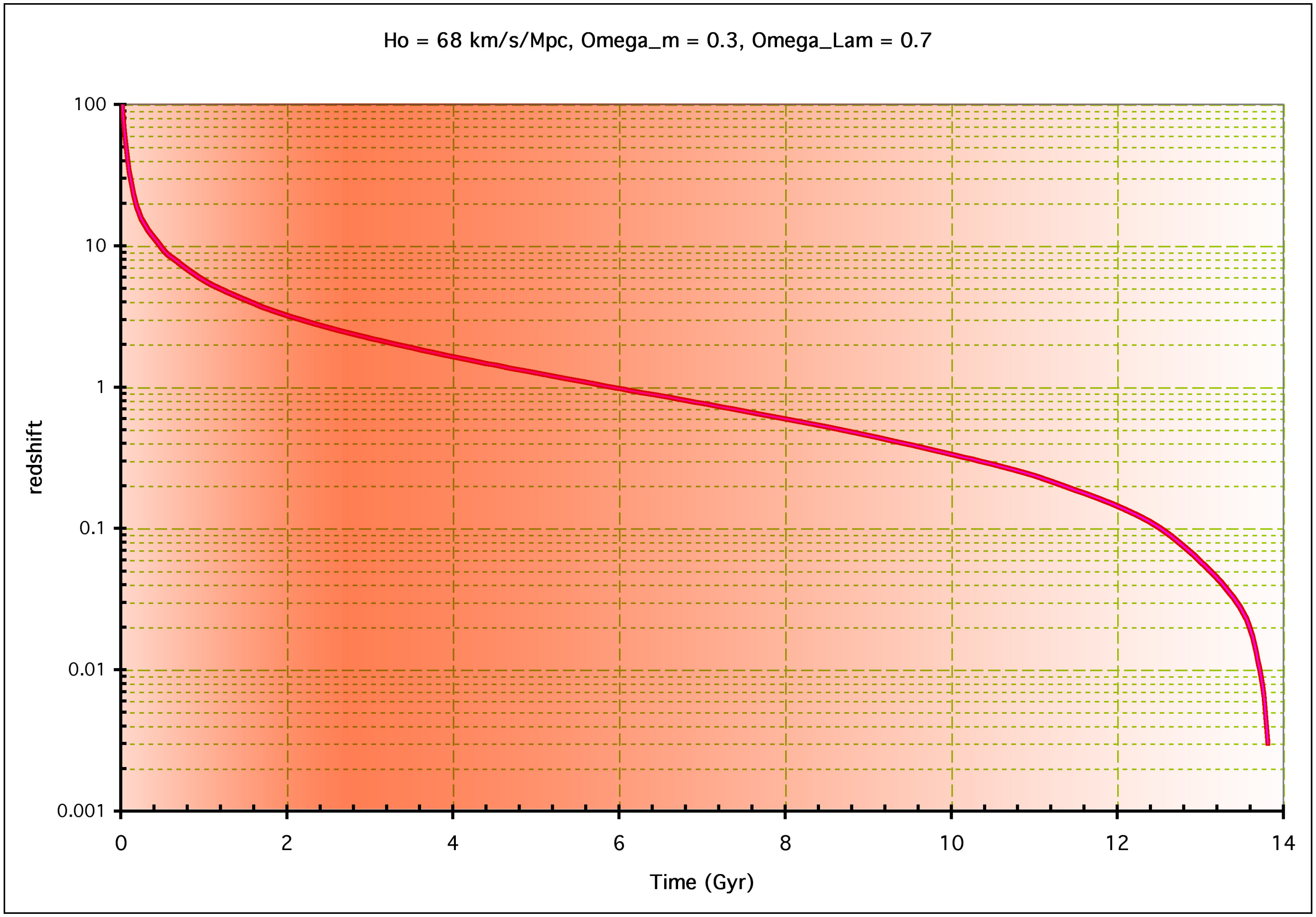
$$\Omega_r \approx 8.6 \cdot 10^{-5} \text{ (photons + 3 massless neutrino species)}$$

$$0.99 < \Omega_{tot} < 1.02 \text{ (95\% CL)}$$

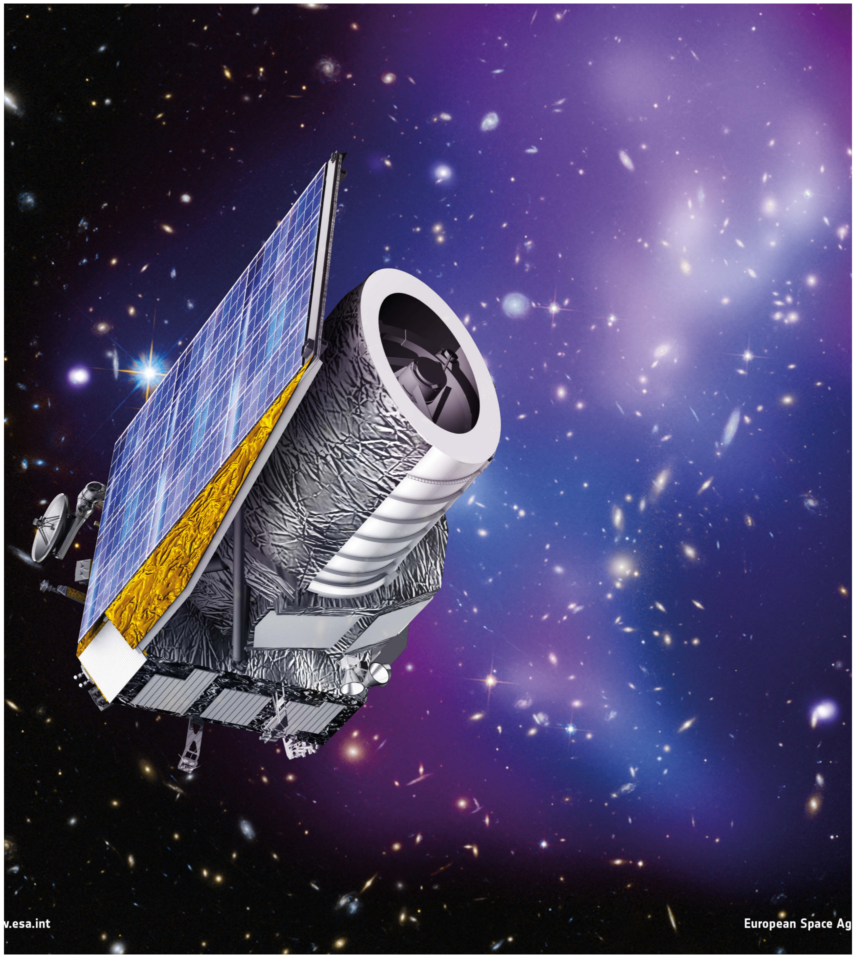
Komatsu et al. 2011 (WMAP7+LSS+SNae)

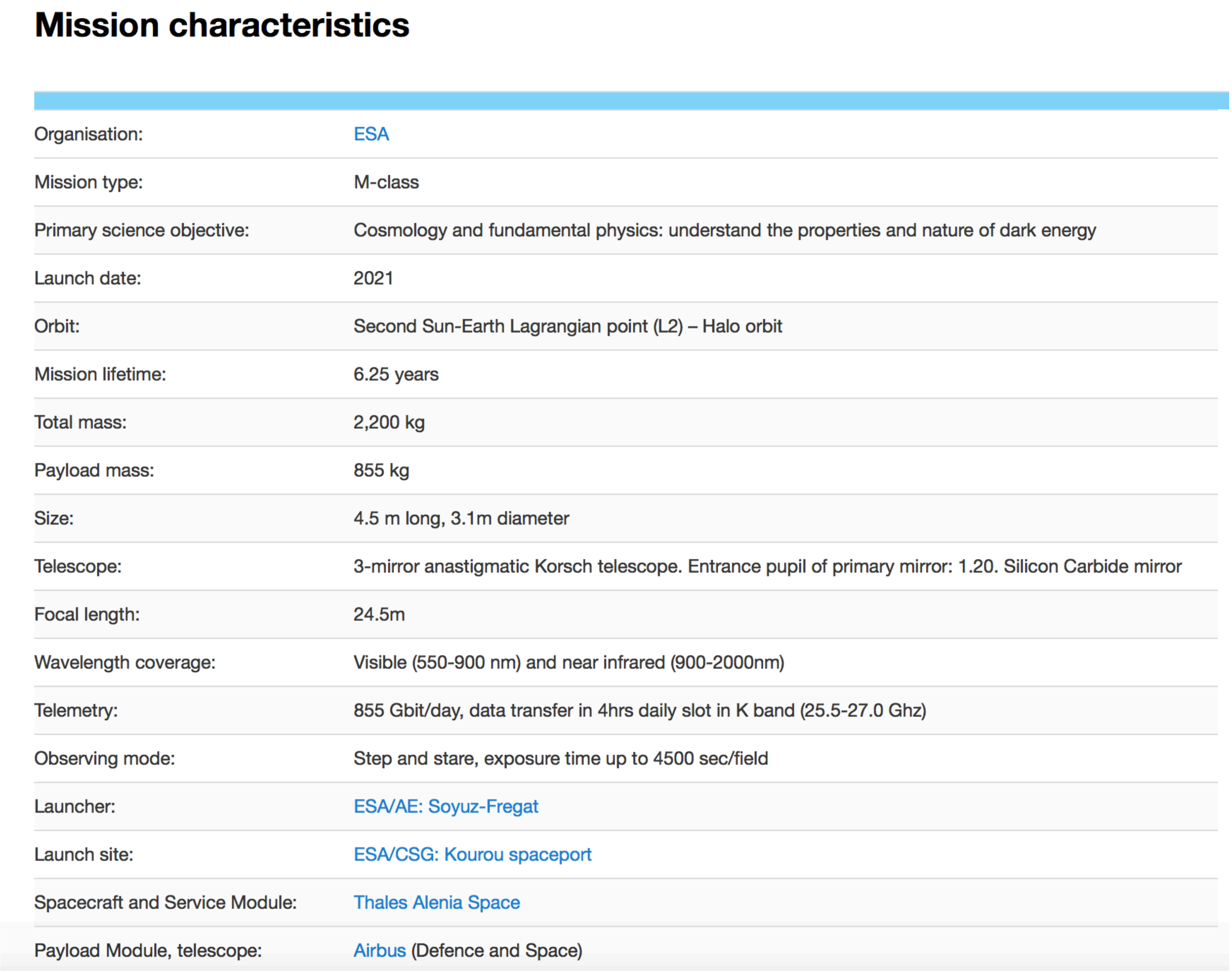
The challenge that EUCLID will take is moving from inventorying to understanding!

Redshift vs time



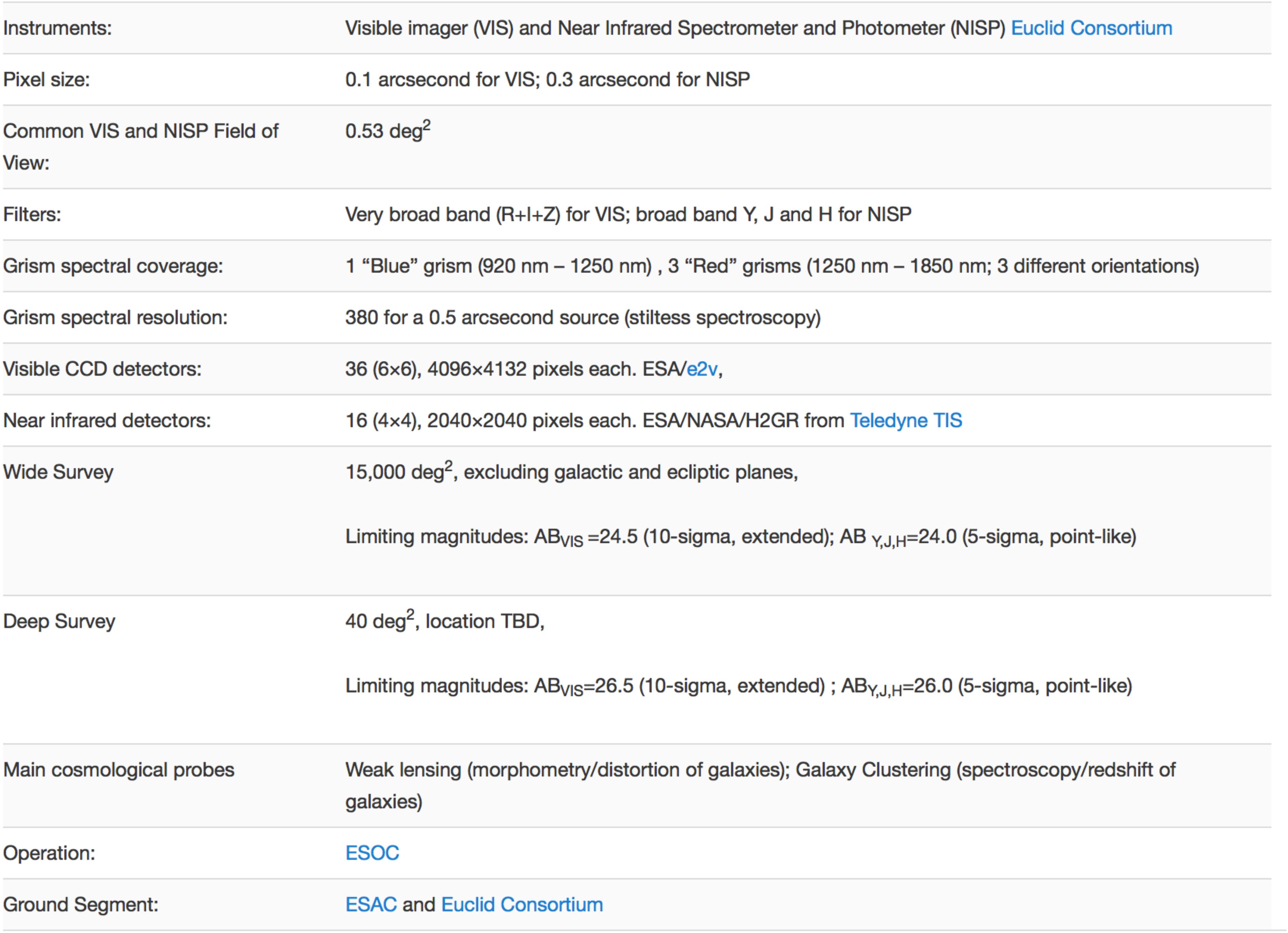
The Euclid mission





Mission characteristics

Organisation:	ESA
Mission type:	M-class
Primary science objective:	Cosmology and fundamental physics: understand the properties and nature of dark energy
Launch date:	2021
Orbit:	Second Sun-Earth Lagrangian point (L2) – Halo orbit
Mission lifetime:	6.25 years
Total mass:	2,200 kg
Payload mass:	855 kg
Size:	4.5 m long, 3.1m diameter
Telescope:	3-mirror anastigmatic Korsch telescope. Entrance pupil of primary mirror: 1.20. Silicon Carbide mirror
Focal length:	24.5m
Wavelength coverage:	Visible (550-900 nm) and near infrared (900-2000nm)
Telemetry:	855 Gbit/day, data transfer in 4hrs daily slot in K band (25.5-27.0 Ghz)
Observing mode:	Step and stare, exposure time up to 4500 sec/field
Launcher:	ESA/AE: Soyuz-Fregat
Launch site:	ESA/CSG: Kourou spaceport
Spacecraft and Service Module:	Thales Alenia Space
Payload Module, telescope:	Airbus (Defence and Space)



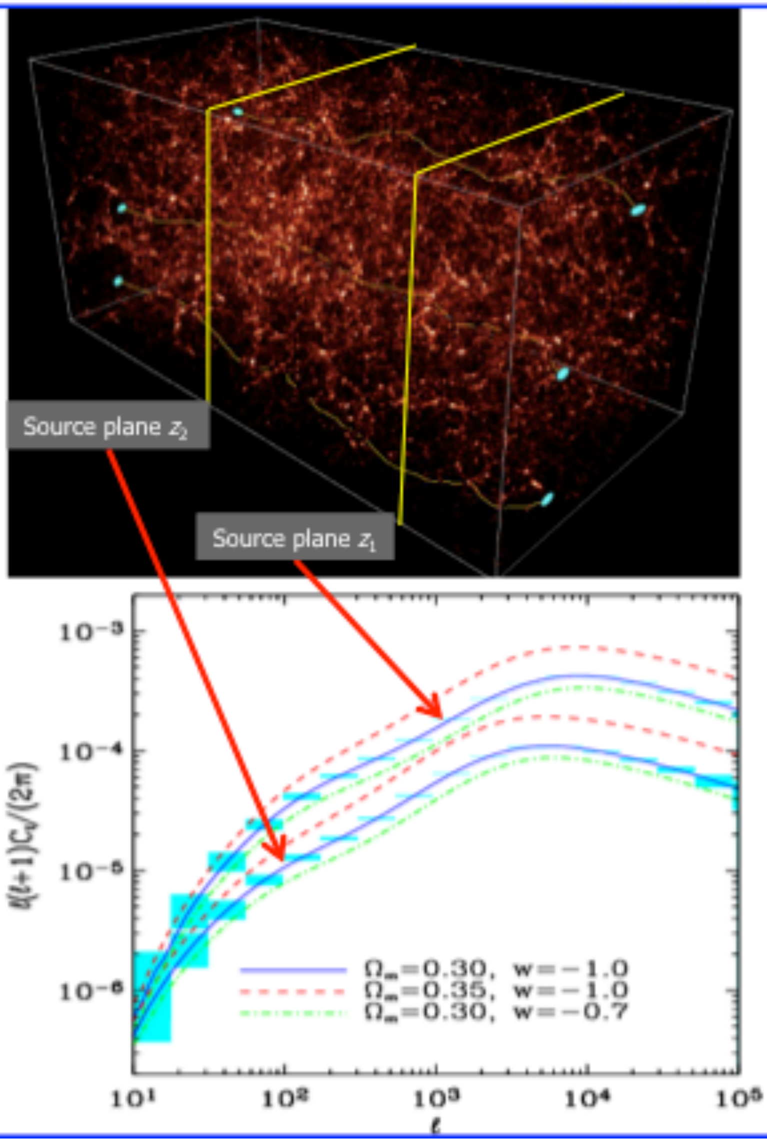
Instruments:	Visible imager (VIS) and Near Infrared Spectrometer and Photometer (NISP) Euclid Consortium
Pixel size:	0.1 arcsecond for VIS; 0.3 arcsecond for NISP
Common VIS and NISP Field of View:	0.53 deg^2
Filters:	Very broad band (R+I+Z) for VIS; broad band Y, J and H for NISP
Grism spectral coverage:	1 “Blue” grism (920 nm – 1250 nm) , 3 “Red” grisms (1250 nm – 1850 nm; 3 different orientations)
Grism spectral resolution:	380 for a 0.5 arcsecond source (stiltess spectroscopy)
Visible CCD detectors:	36 (6×6), 4096×4132 pixels each. ESA/e2v,
Near infrared detectors:	16 (4×4), 2040×2040 pixels each. ESA/NASA/H2GR from Teledyne TIS
Wide Survey	15,000 deg^2, excluding galactic and ecliptic planes, Limiting magnitudes: AB_{VIS} =24.5 (10-sigma, extended); $AB_{Y,J,H}$=24.0 (5-sigma, point-like)
Deep Survey	40 deg^2, location TBD, Limiting magnitudes: AB_{VIS}=26.5 (10-sigma, extended) ; $AB_{Y,J,H}$=26.0 (5-sigma, point-like)
Main cosmological probes	Weak lensing (morphometry/distortion of galaxies); Galaxy Clustering (spectroscopy/redshift of galaxies)
Operation:	ESOC
Ground Segment:	ESAC and Euclid Consortium

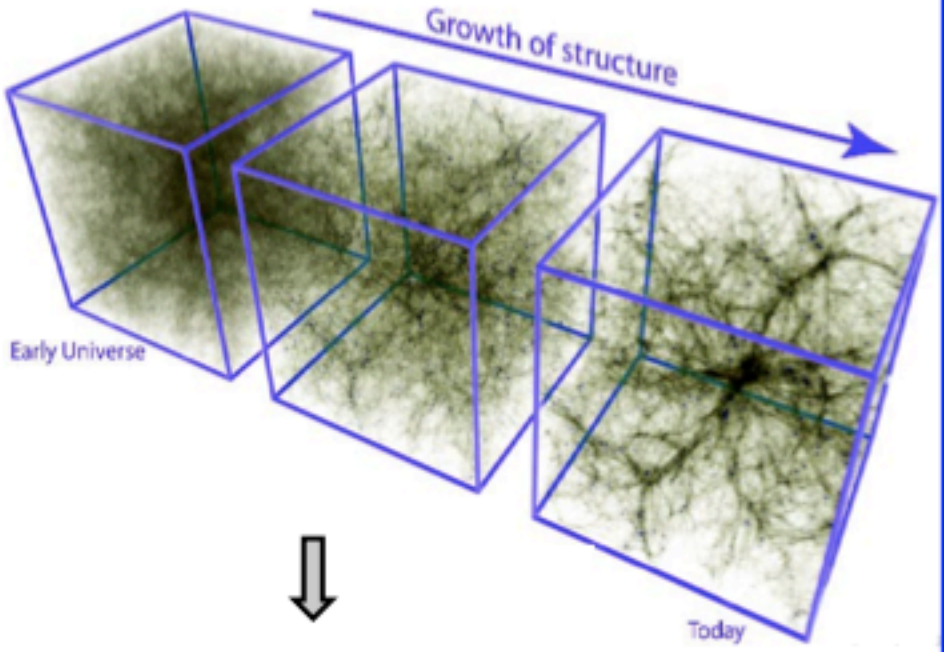
WL probe: Cosmic shear over 0<z<2 :

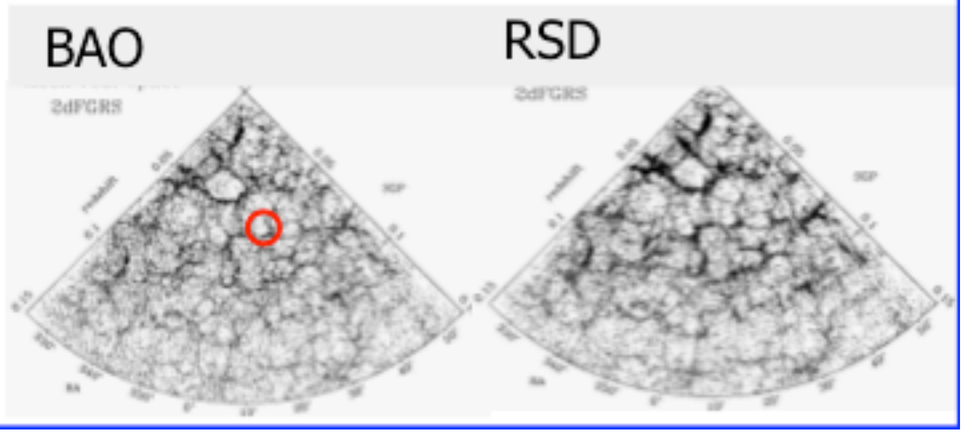
1.5 billion galaxies shapes, gravitational shear and photometric redshifts (u,g,r,i,z,Y,J,H) with 0.05 (1+z) accuracy over 15,000 deg^2

GC; BAO, RSD probes: 3-D positions of galaxies over 0.7<z<1.8 :

35 million spectroscopic redshifts with 0.001 (1+z) accuracy over 15,000 deg^2







Euclid is primarily a cosmology and fundamental physics mission. Its main scientific objective is to understand the source of the accelerating expansion of the Universe and discover its very nature that physicists refer to as *dark energy*.

Euclid will then address to the following questions:

- is dark energy merely a cosmological constant, as first discussed by Einstein, or
- is it a new kind of field that evolves dynamically with the expansion of the universe?
- alternatively, is dark energy instead a manifestation of a breakdown of General Relativity and deviations from the law of gravity?
- what are the nature and properties of dark matter?
- what are the initial conditions which seed the formation of cosmic structure?
- what will be the future of the Universe over the next ten billion years?

The imprints of dark energy and gravity will be detected from their signatures on the expansion rate of the Universe and the growth of cosmic structures using gravitational lensing effects on galaxies (Weak Lensing) and the properties of galaxy clustering (Baryonic Acoustic Oscillations and Redshift Space Distortion).