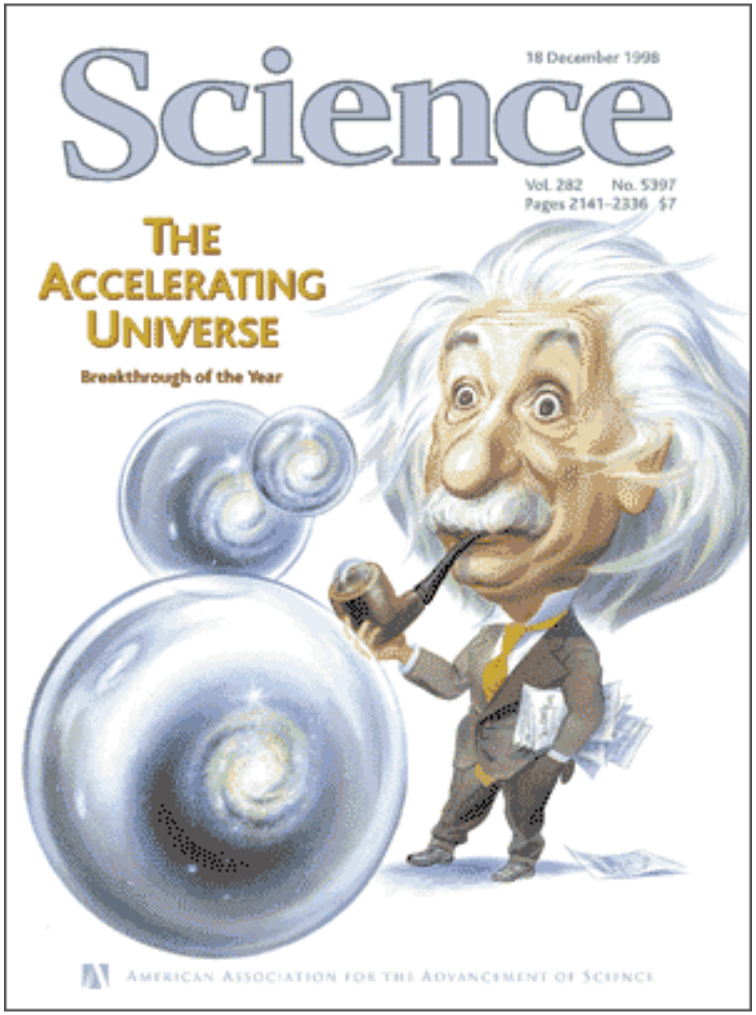
Constraining dark energy with galaxy redshift surveys

A surprise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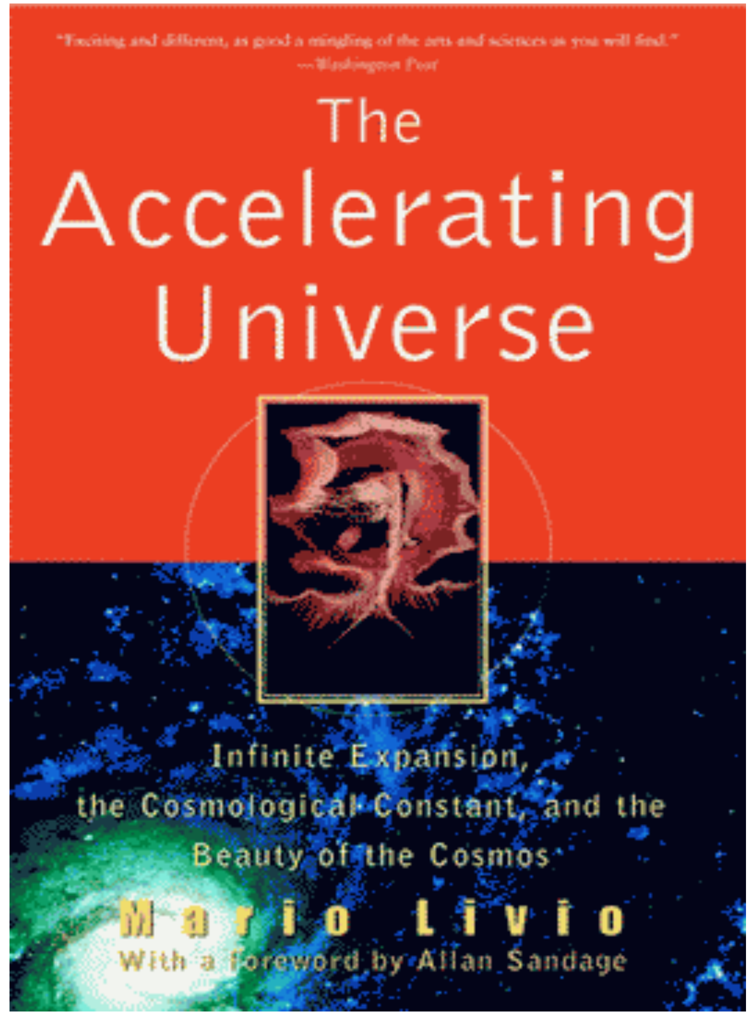
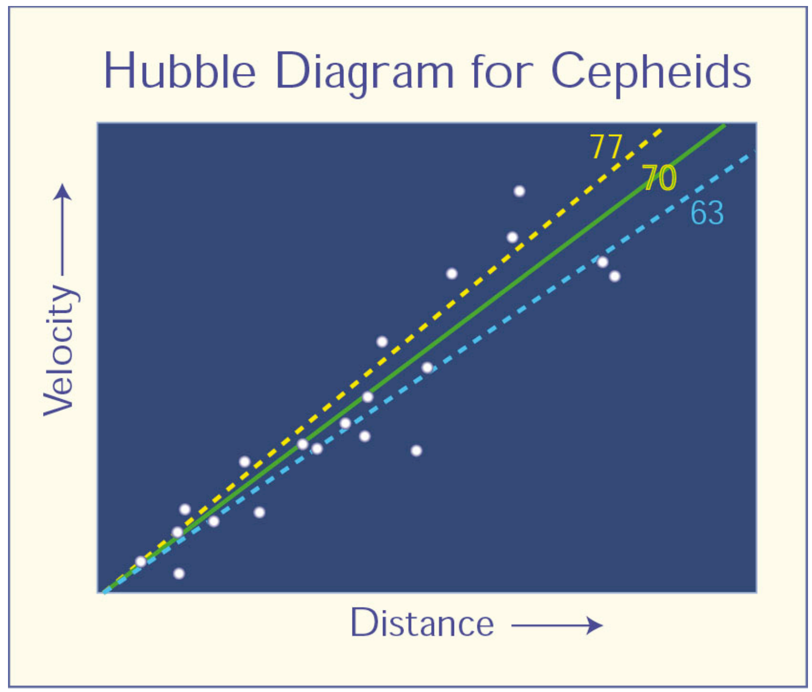
The Accelerating Universe
Breakthrough of the Year
American Association for the Advancement of Science


The Accelerating Universe
Infinite Expansion, the Cosmological Constant, and the Beauty of the Cosmos
Mario Livio
With a foreword by Allan Sandage

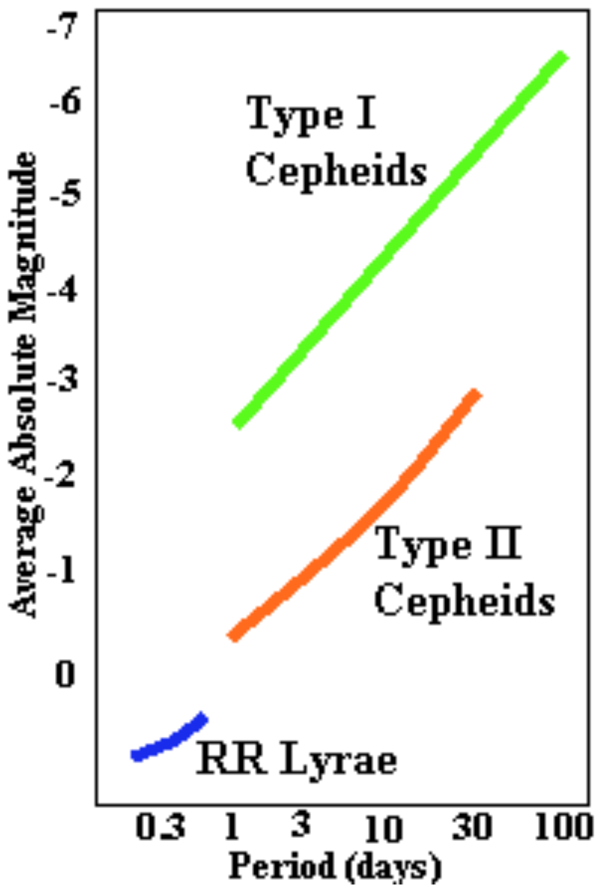
Luminosity distance and standard candles

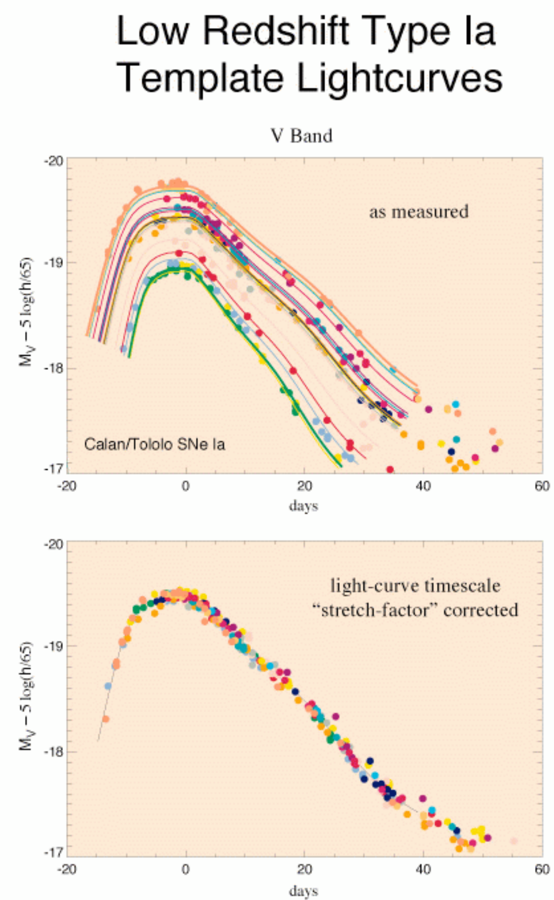
The Hubble diagram

- Taylor expansion of the lumin. distance-redshift relation: $H_0\, d_L/c = z + (1-q_0)z^2/2 + \ldots$
- This is the observational version of the Hubble's law
- It is very difficult to measure distances on cosmological scales
- Need for standard or standardizable candles
- The best we have today are Cepheid stars (PL or PLC relation) and Supernovae Ia (peak brightness - decay time relation)

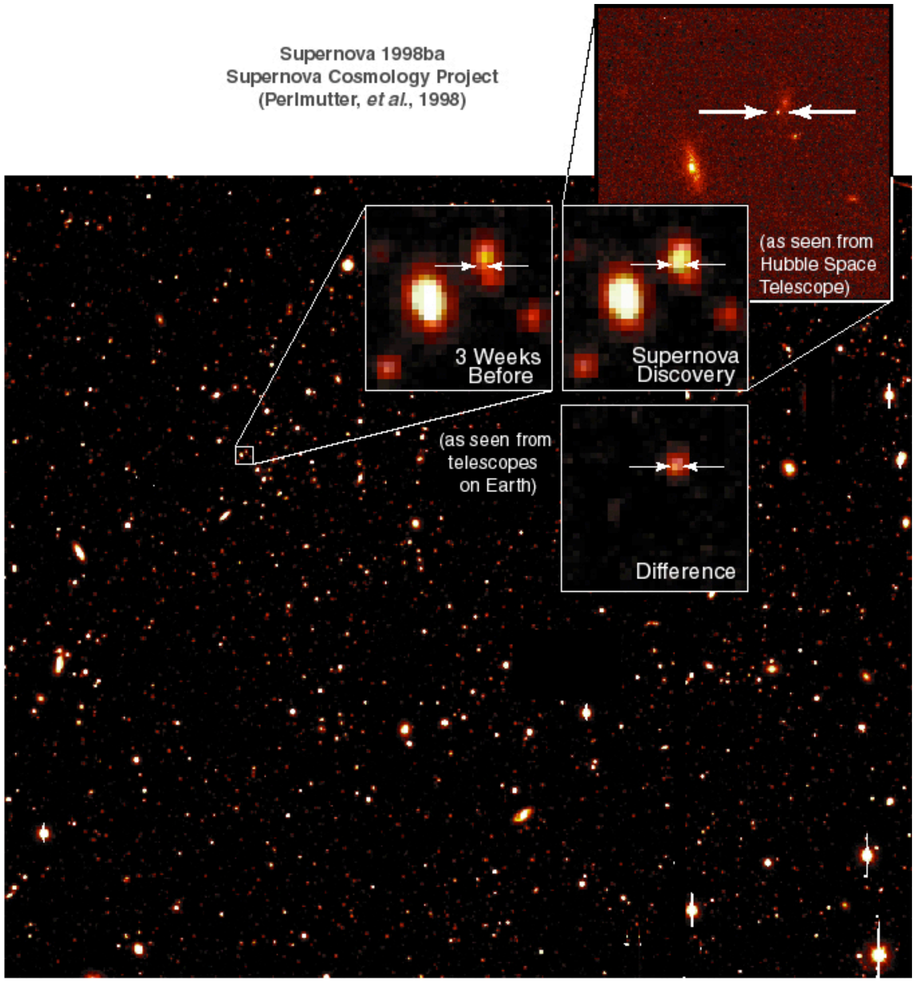


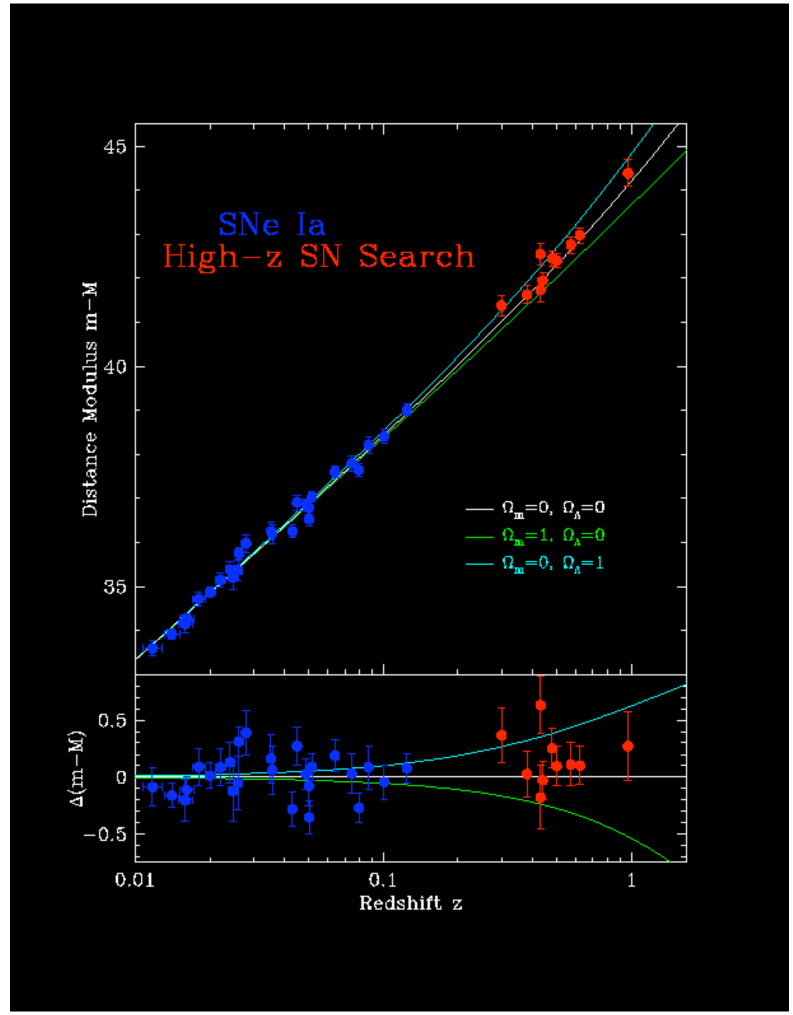
Standardizable candles





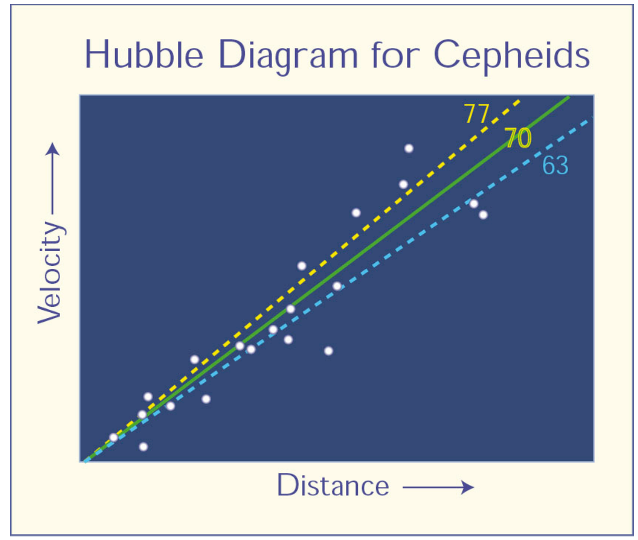
Hubble diagram from SNae Ia

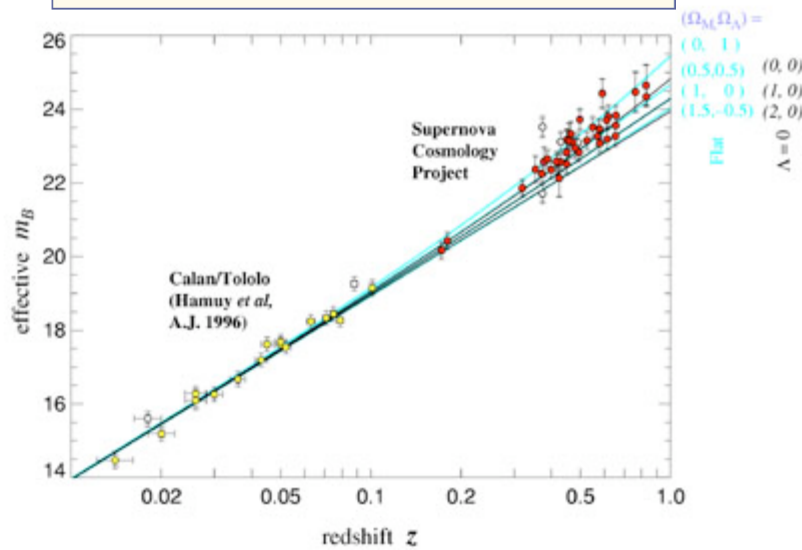




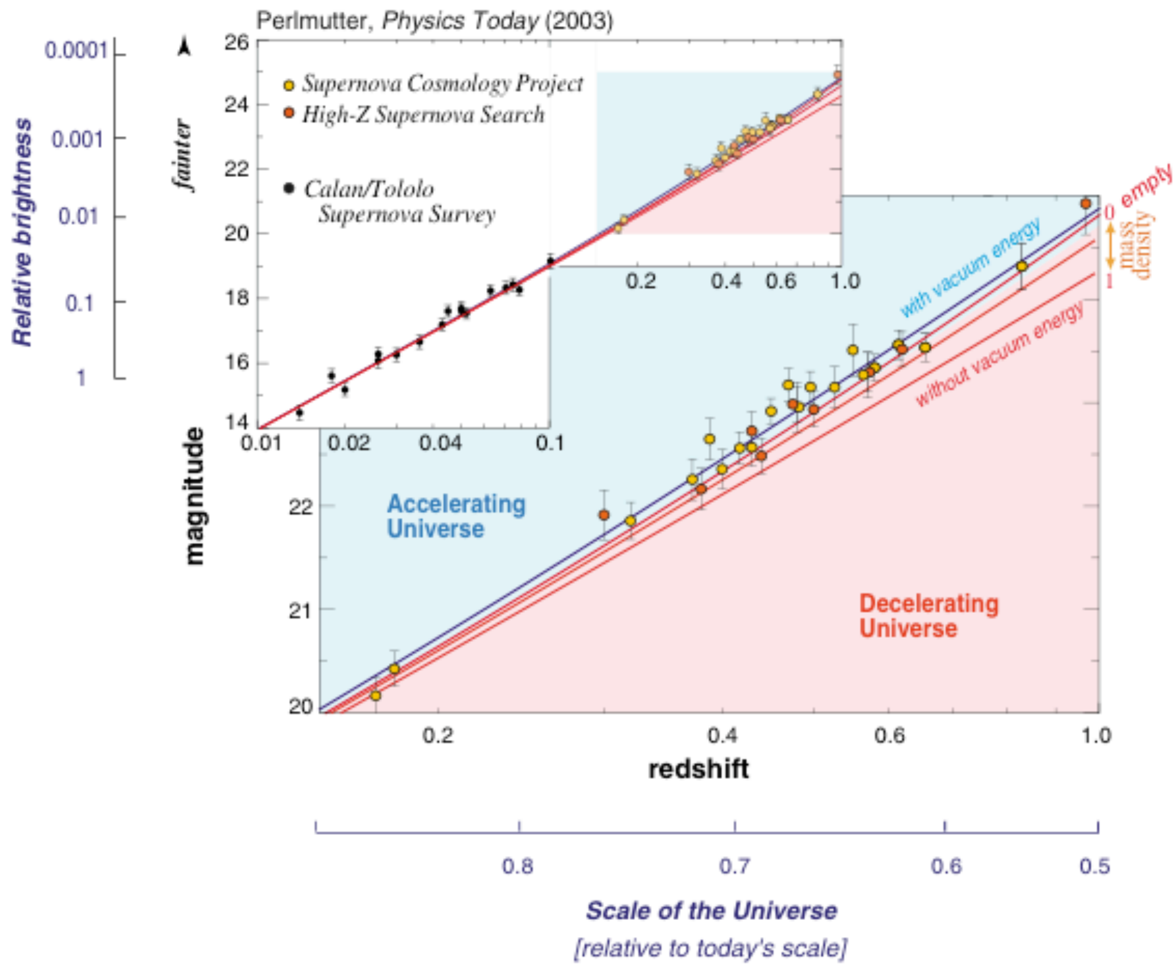
Current estimates

- Improvement: Hipparcos accurate determination of the parallax of local Cepheids
- HST key project (based on Cepheids)
  H_0 = 72 ± 8 km/s/Mpc
  (Freedman et al. 2001)
- Hubble diagram with SNa Ia
  H_0 = 73 ± 7 km/s/Mpc
  (Riess et al. 2005)
- Other estimates from different datasets lie in the same ballpark
- This sets the size and age of the observable universe





Accelerated expansion?

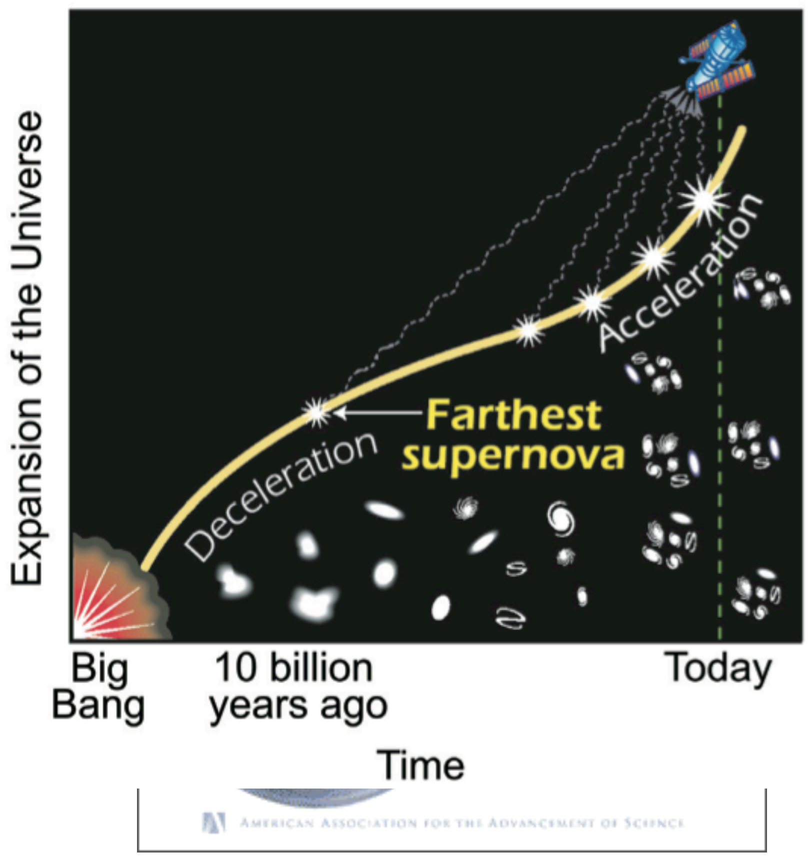


- In 1998, two independent teams found that SNae Ia at z ≈ 0.5 appear about 25% dimmer than they would in a decelerated universe

- 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



- 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 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)

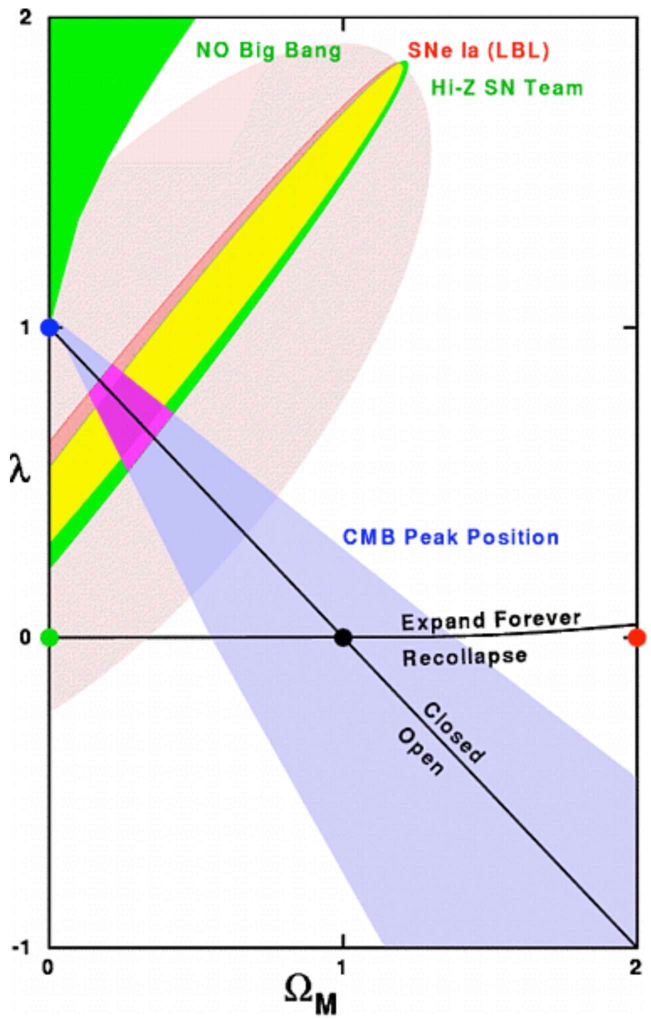
$$T_{ab}^{(\mathrm{vac})} = \frac{\Lambda}{8\pi}g_{ab} \qquad \rho_{\mathrm{vac}} = \frac{\Lambda}{8\pi} \qquad w = \frac{p}{\rho} = -1$$

- Quintessence - An unknown scalar field, ϕ

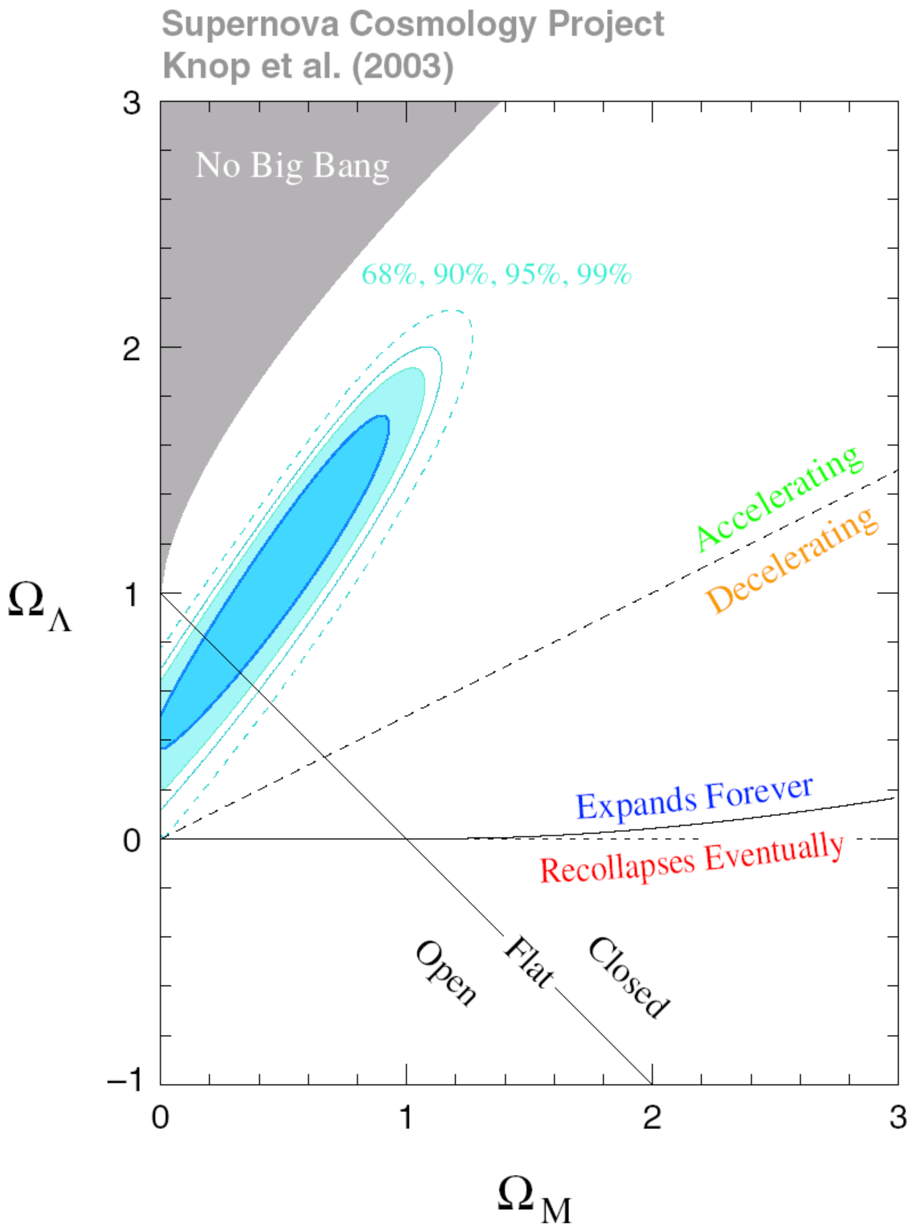
$$w = \frac{\frac{1}{2}\dot{\phi}^2 - V(\phi)}{\frac{1}{2}\dot{\phi}^2 + V(\phi)},$$

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

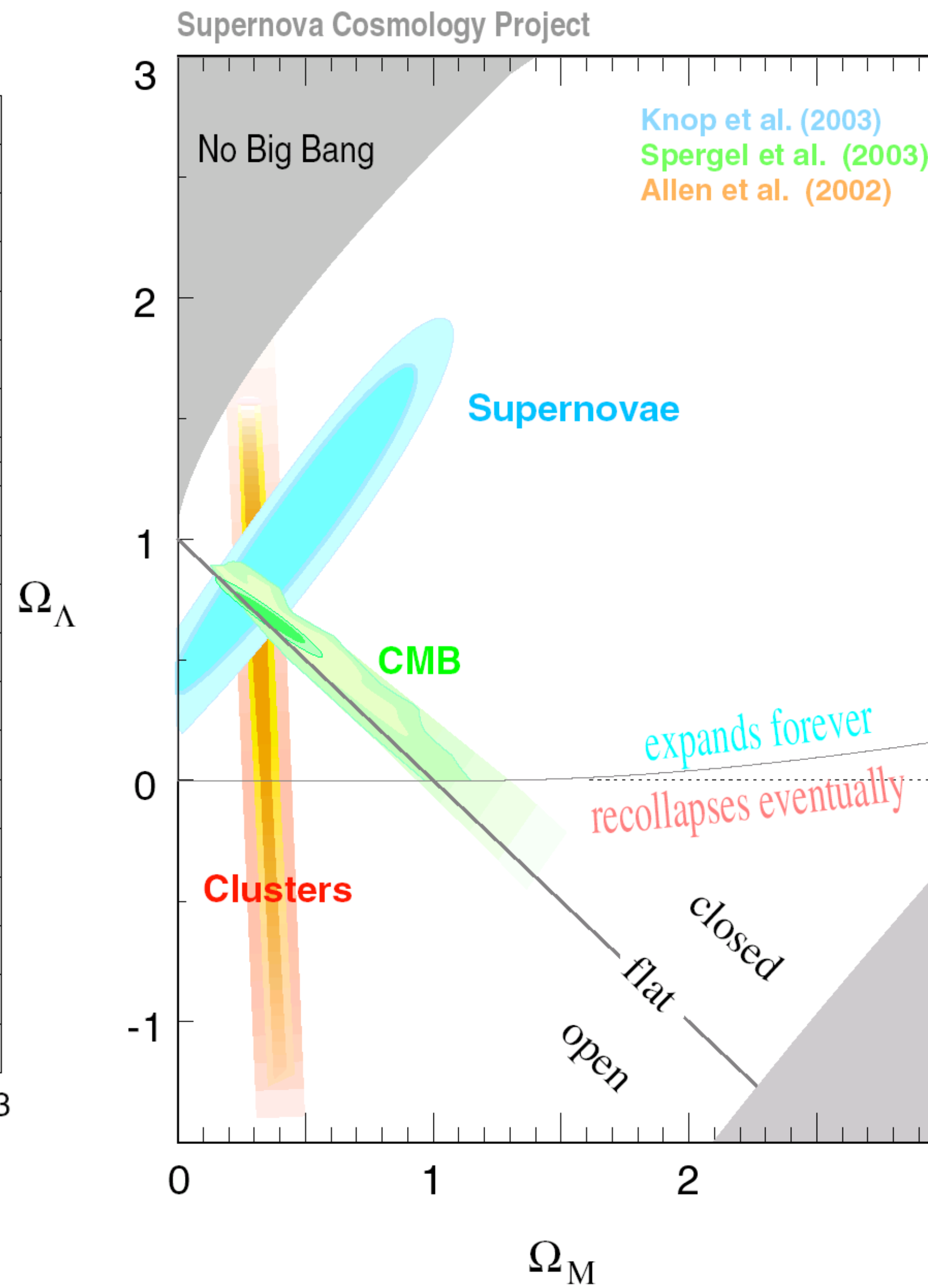
A non-vanishing cosmological constant



- 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



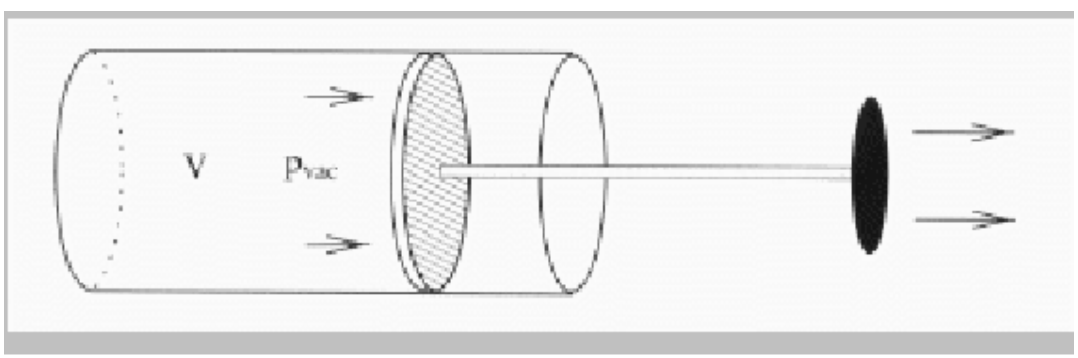
Supernova Cosmology Project
Knop et al. (2003)
No Big Bang
68%, 90%, 95%, 99%
Accelerating
Decelerating
Expands Forever
Recollapses Eventually
Open
Flat
Closed
ΩΛ
ΩM
3
2
1
0
−1
0
1
2
3



Supernova Cosmology Project
No Big Bang
Knop et al. (2003)
Spergel et al. (2003)
Allen et al. (2002)
Supernovae
CMB
Clusters
expands forever
recollapses eventually
closed
flat
open
ΩΛ
ΩM
3
2
1
0
-1
0
1
2
3

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

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

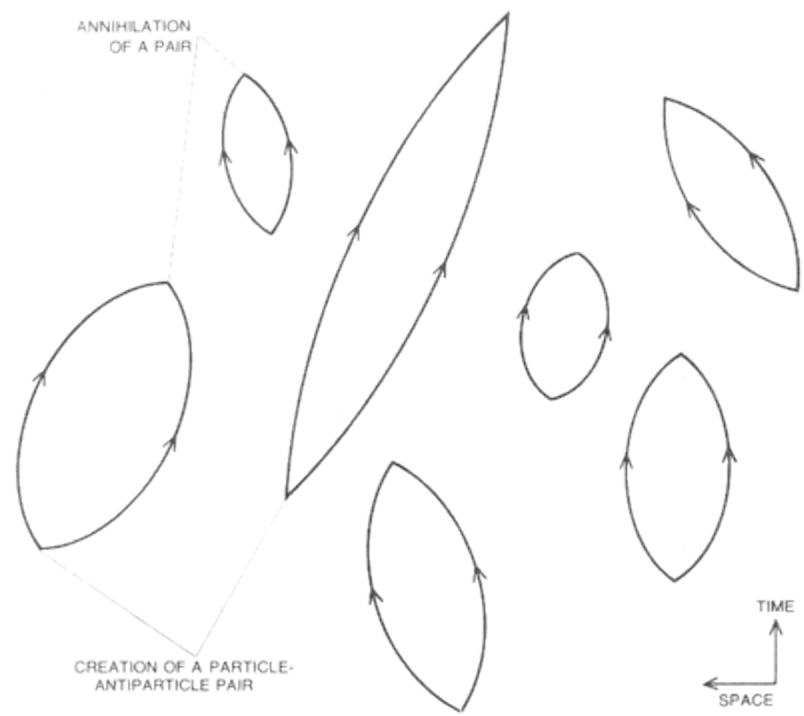
which requires that $P = -\rho c^2$. The tt and xx components are also invariant because $\gamma^2(1 - \beta^2) = 1$.

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



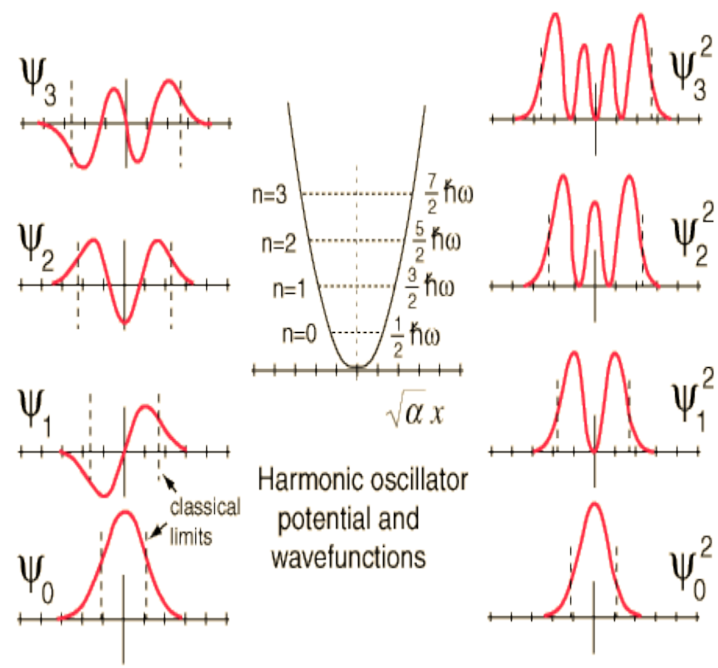
Zero-point energy (Nullpunktsenergie)

- Alternatively, vacuum energy can be seen as the sum of the zero-point energies of the quanta of the fields

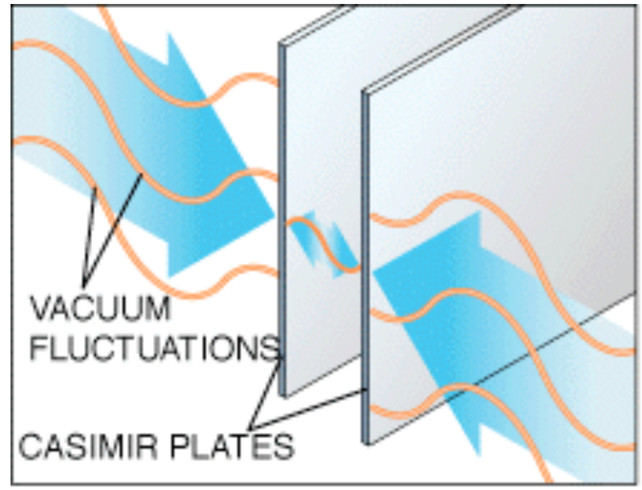
- The minimum energy of an harmonic oscillator is $E_0=h\nu/2$, this is called the zero-point energy

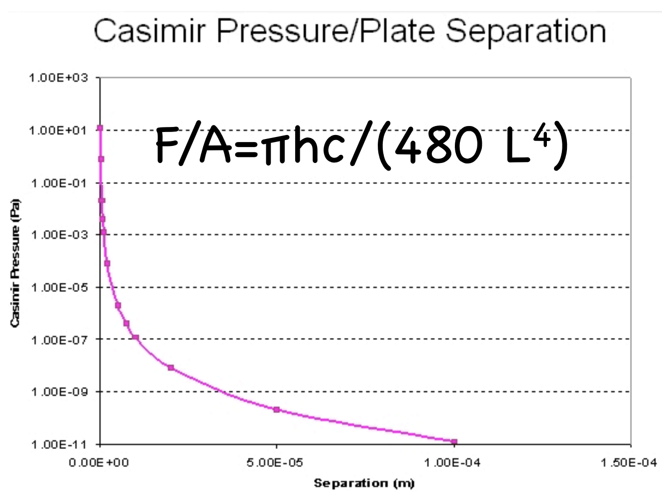
- Quantum field theory can be regarded as a collection of infinitely many harmonic oscillators and therefore QFT predicts a non-zero vacuum energy

- Unfortunately we have no idea how to calculate it in a realistic way



Casimir effect





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

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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 $\alpha \to \infty$ 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 x 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

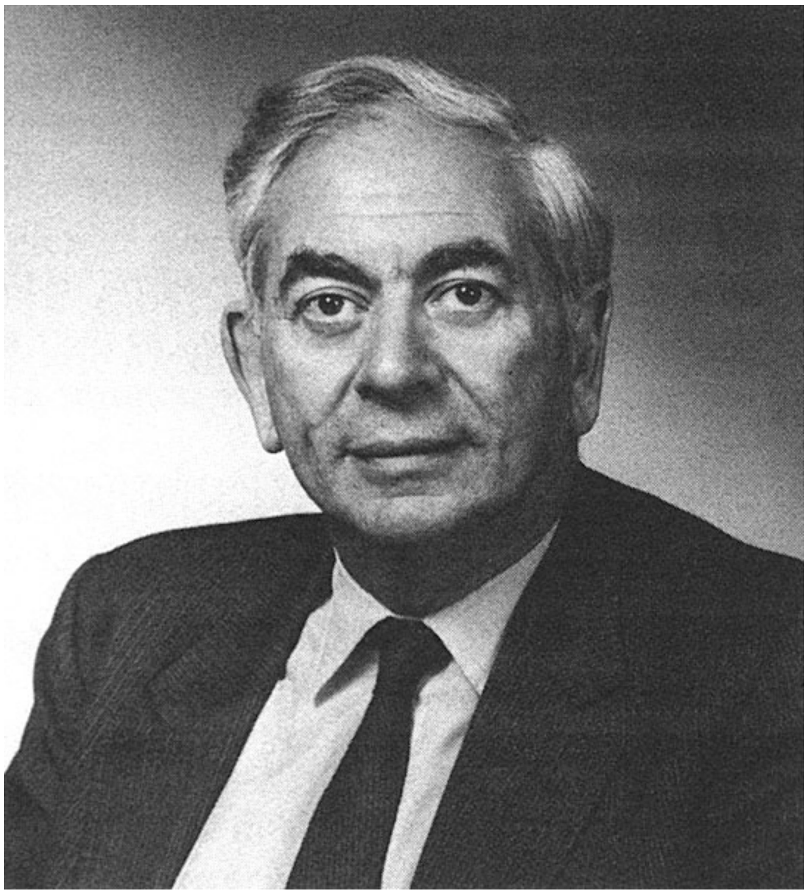
At the heart of the problem

- 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



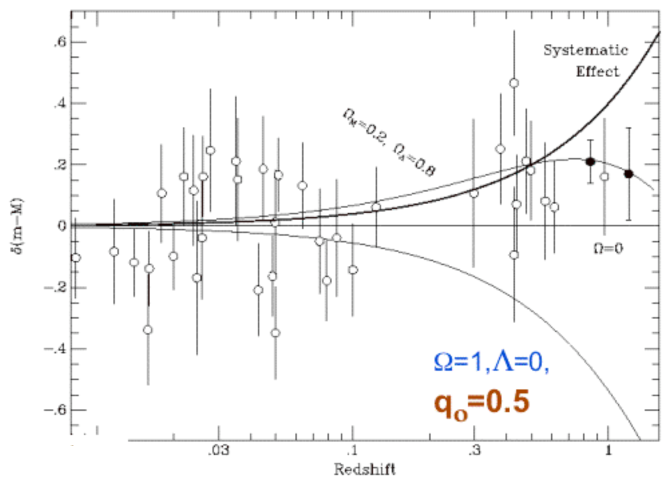
- "Even in its ground state, a quantum system possesses fluctuations and an associated zero-point energy, since otherwise the uncertainty principle would be violated. In particular the vacuum state of a quantum field has these properties. For example, the electric and magnetic fields in the electromagnetic 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 $\approx 10^{-33}$ 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

Searching for a mundane solution

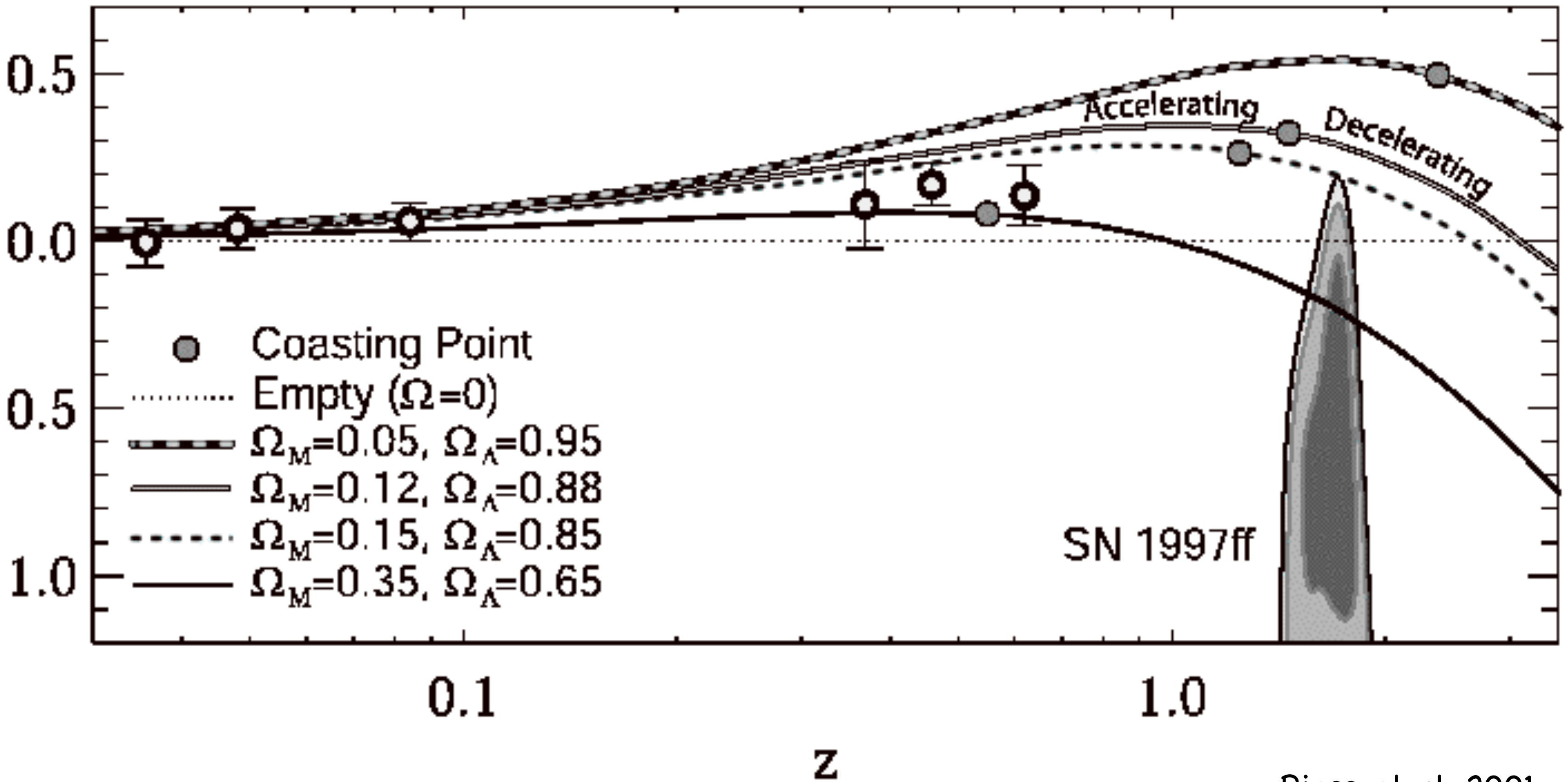


Possible systematic effects that mimic an acceleration:

- Dust (but reddening has not been detected)
- High-z Snae are different from local ones (metallicity effect?)

Remember, however, that there are other independent datasets which point towards the same accelerated solution

Slightly reassuring news: SN 1997ff



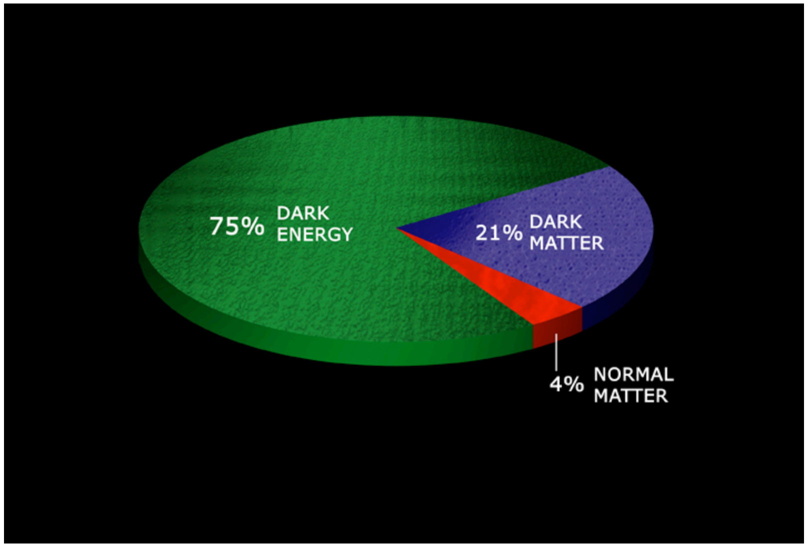
Riess et al. 2001

A census of the Universe

- Stars: $\Omega_* \approx 0.004$
- Gas: $\Omega_{gas} \approx 0.04$
- DM: $\Omega_{DM} \approx 0.25$
- DE: $\Omega_{DE} \approx 0.75$
- CMB: $\Omega_{CMB} \approx 5.0 \times 10^{-5}$
- Neutrinos (if massless): $\Omega_\nu \approx 3.4 \times 10^{-5}$

- We live in a flat (or nearly flat) universe dominated by the contributions of non-relativistic matter and dark energy

What's next?



- We have a concordance model of the Universe supported by many independent observations
- The outcome is shocking: 96% of the energy in the Universe seems to be in unknown forms
- The next step is moving from inventory to understanding (S. Carroll)

Describing dark energy

- Simplest parameterization: w=constant. It fully describes the vacuum case and, together with Ω_Λ Ω_m provides a 3-parameter description of the dark sector. This, however, does not describe scalar fields or modified gravity.

- A number of phenomenological models for w(z) have been explored. The most commonly used is: $w(a)=w_0+w_a(1-a)=w_0+w_a\, z/(1+z)$. There are then 4-param. for the dark sector.

- Another approach is to invert the redshift-distance relation to get w(z):

$$1+w(z)=\frac{1+z}{3}\,\frac{3H_0^2\Omega_M(1+z)^2+2(d^2r/dz^2)/(dr/dz)^3}{H_0^2\Omega_M(1+z)^3-(dr/dz)^{-2}}$$

(truly model independent but noisy derivatives)

Figure of merit

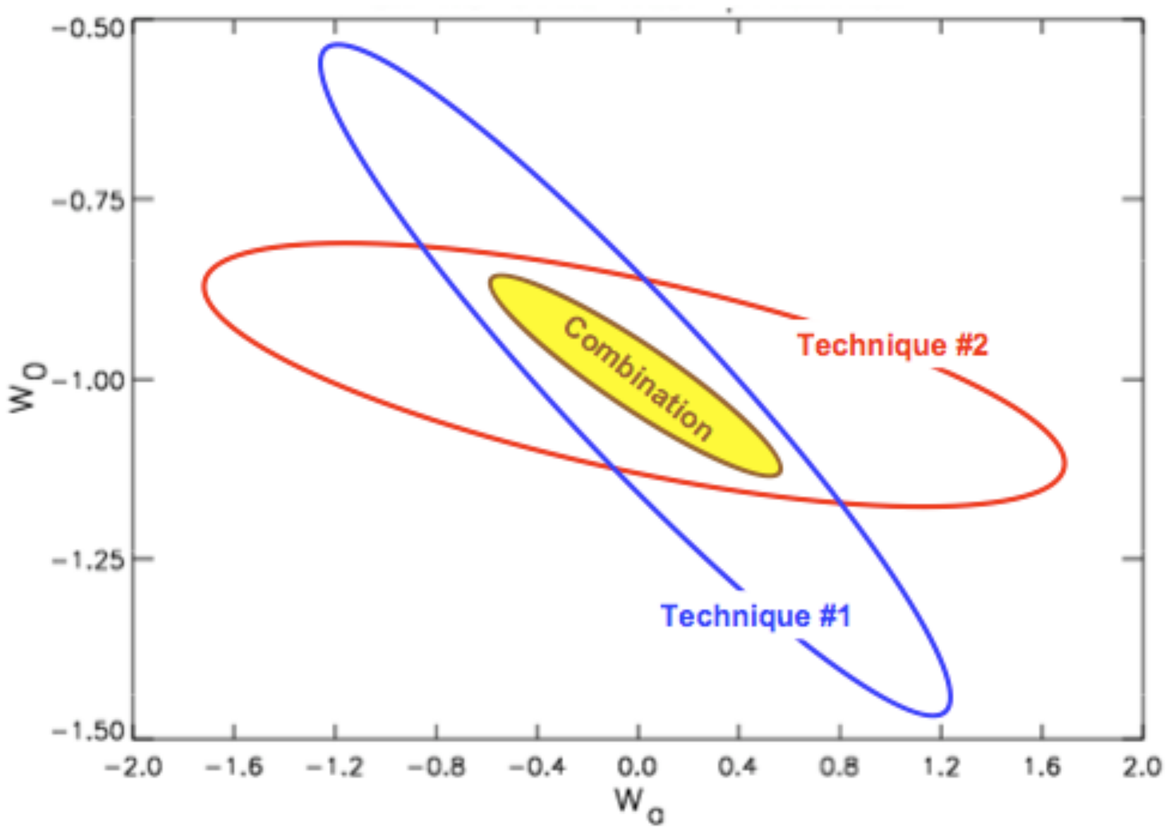


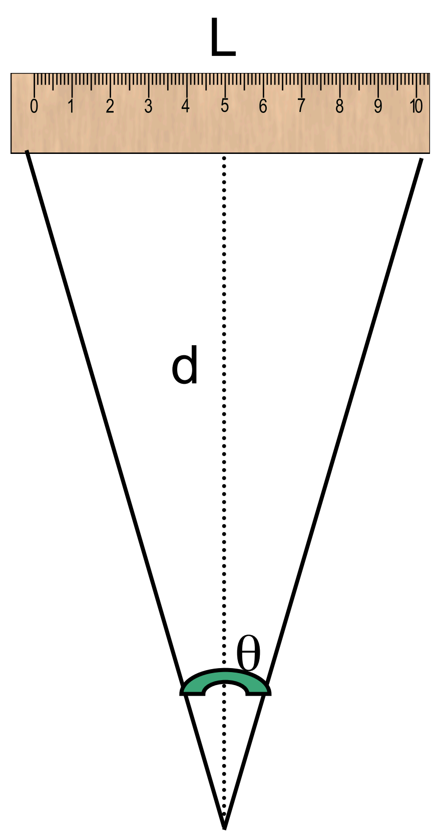
Figure of merit = 1 / (area of the ellipse)

Observational consequences of DE

Dark energy modifies the expansion history of the Universe and thus:

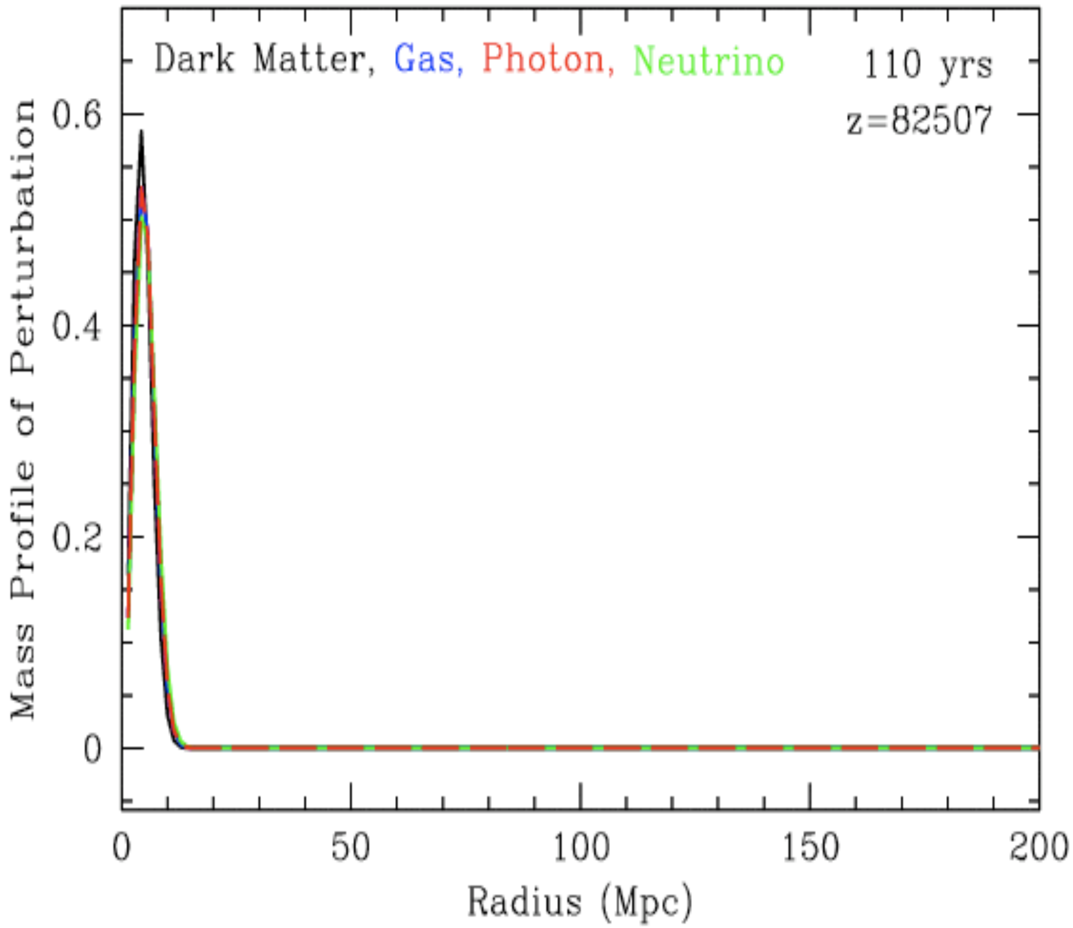
- Changes the evolution of the Hubble parameter
- Modifies the distance-redshift relation
  (to probe it we need standard candles or standard rulers)
  - SN Ia, GRBs (?), acoustic baryonic oscillations
- Alters the growth of density fluctuations
  (to probe it we need to follow the evolution of structure in large volumes) weak lensing, galaxy clusters, int. Sachs-Wolfe
- Consistency of different methods provides a test of GR

The ideal standard ruler

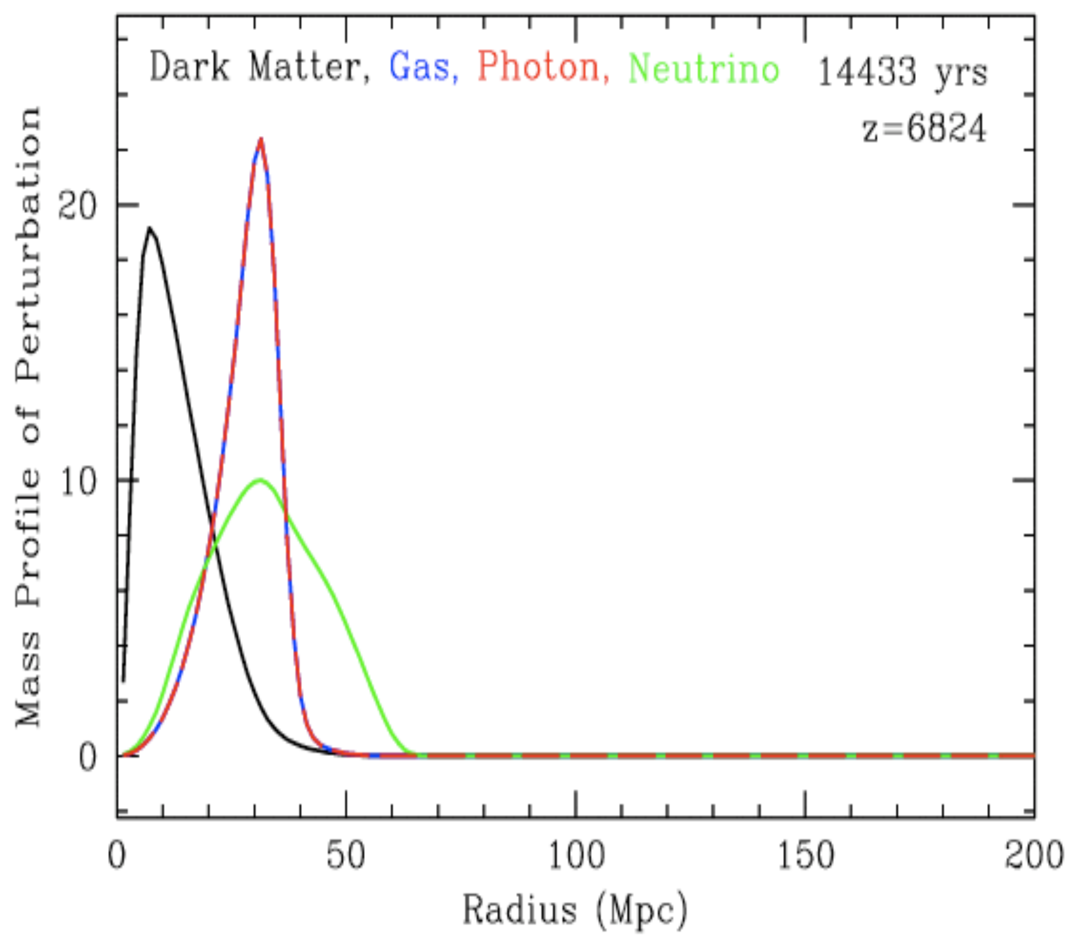


- We need to be able to measure the ruler over much of the volume of the universe
- We need to be able to make ultra-precise measurements of the ruler (1% accuracy to get 5% accuracy in the equation of state for dark energy)
- Answer: baryonic acoustic oscillations

BAOs: a Green function approach



BAOs: a Green function approach



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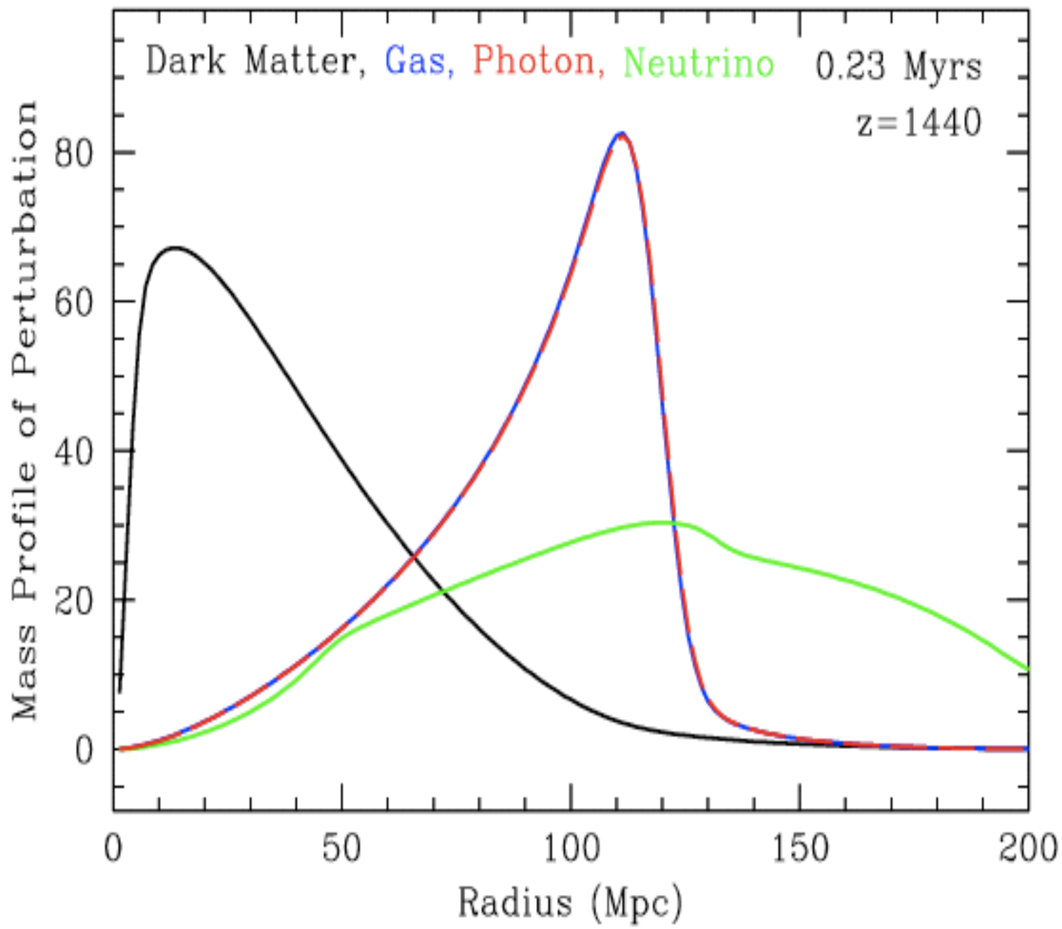

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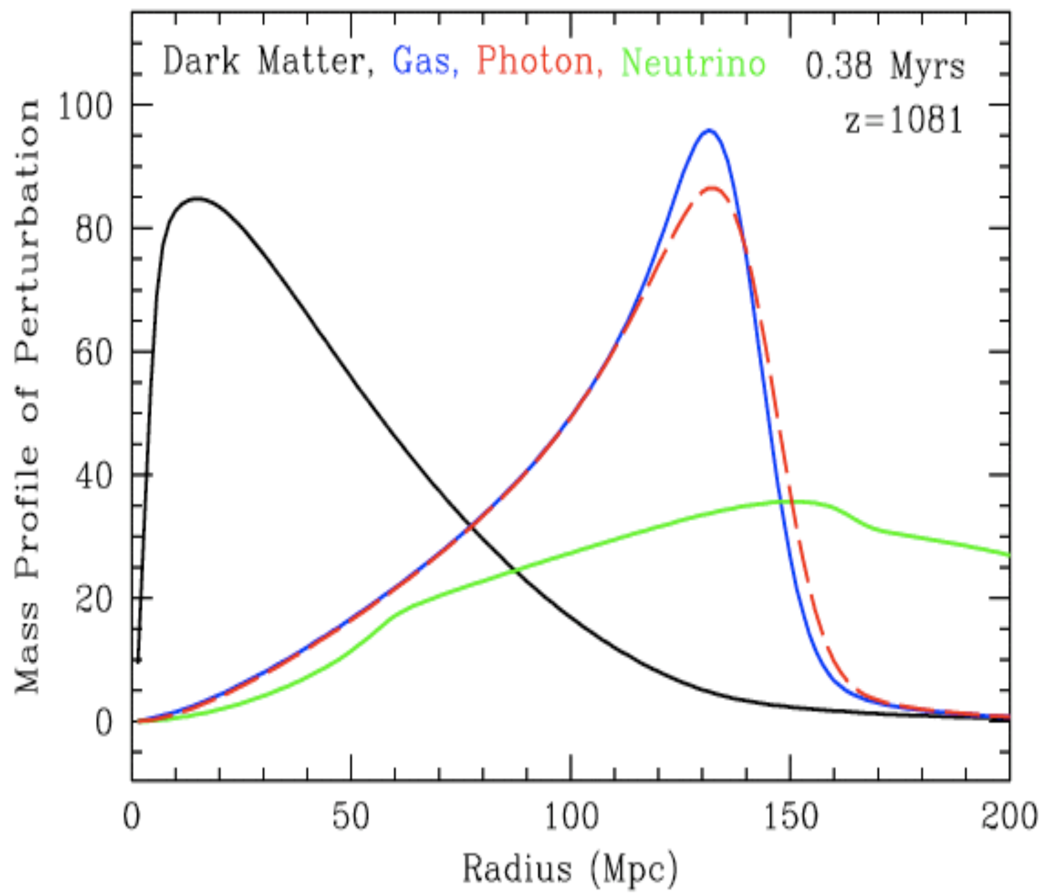
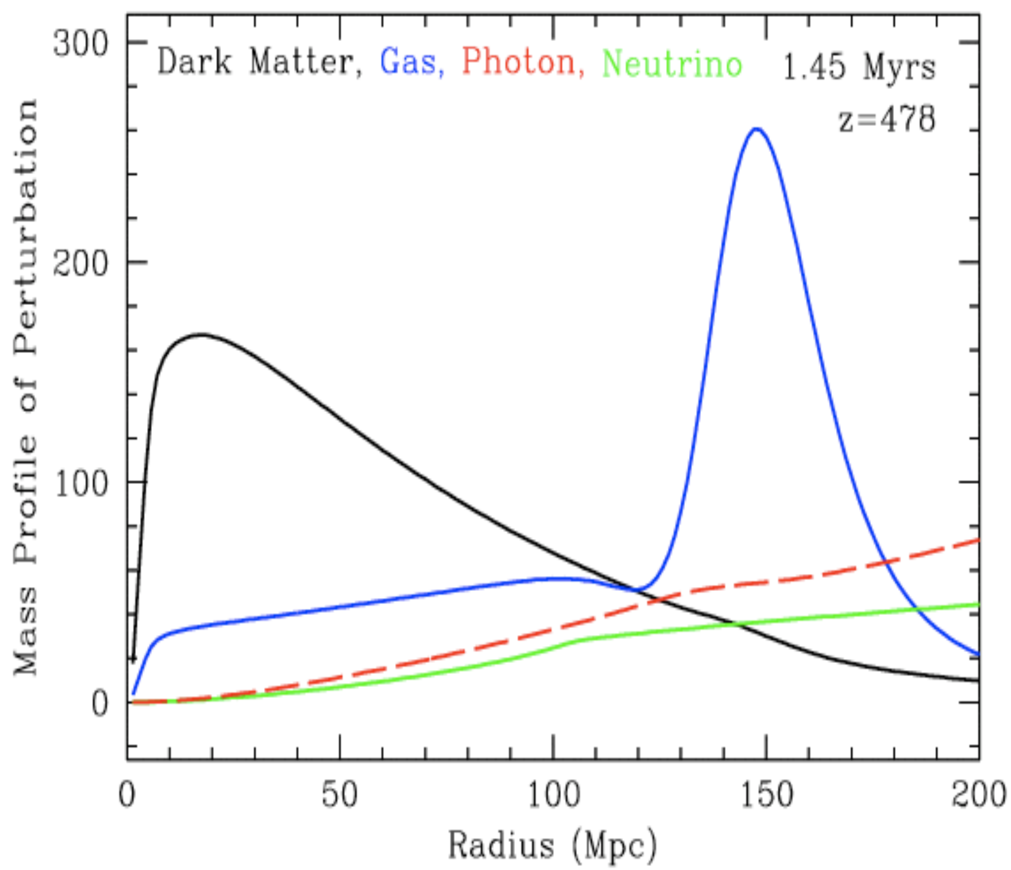


BAOs: a Green function approach



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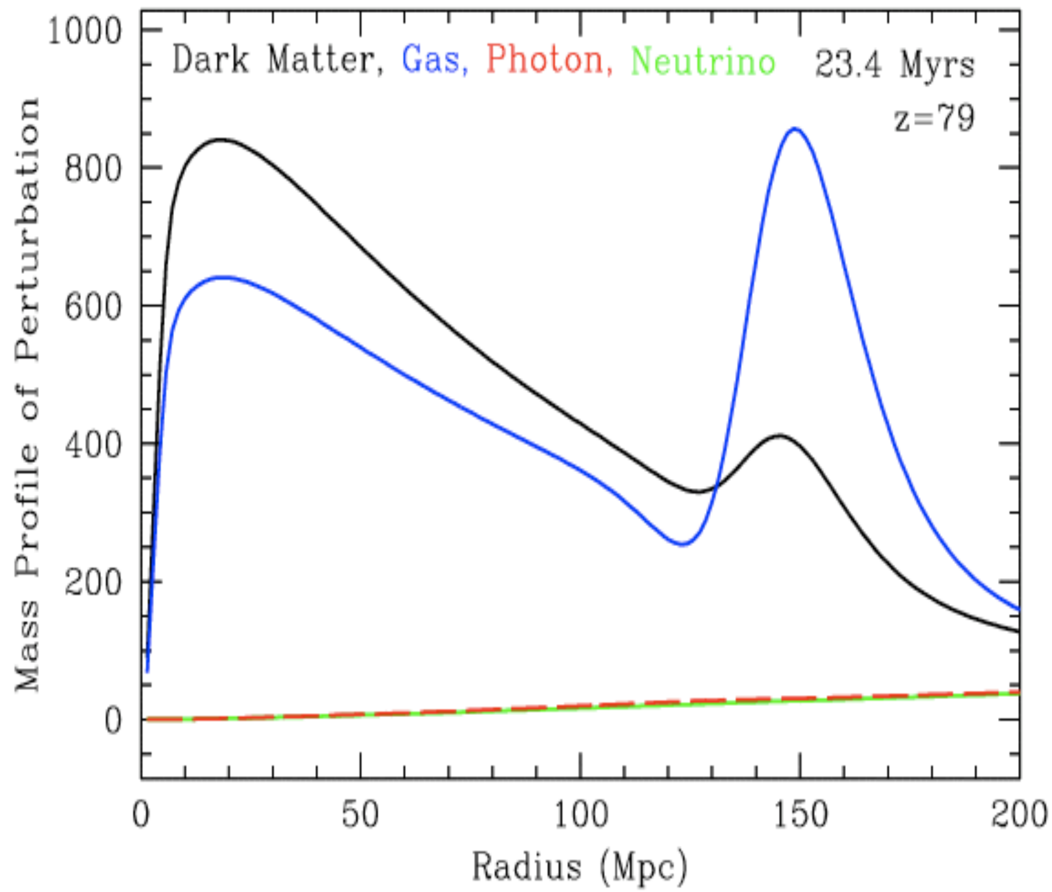

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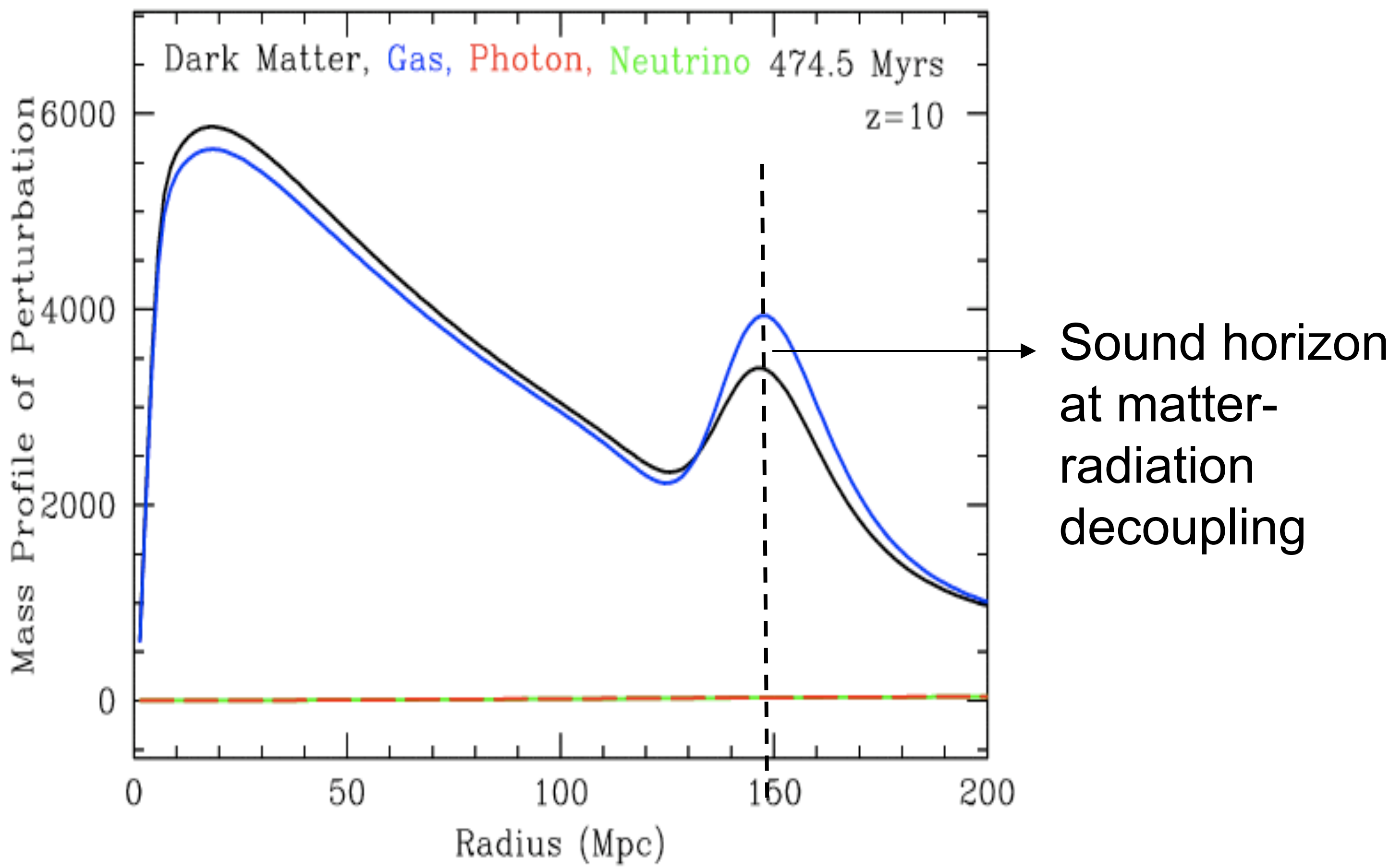
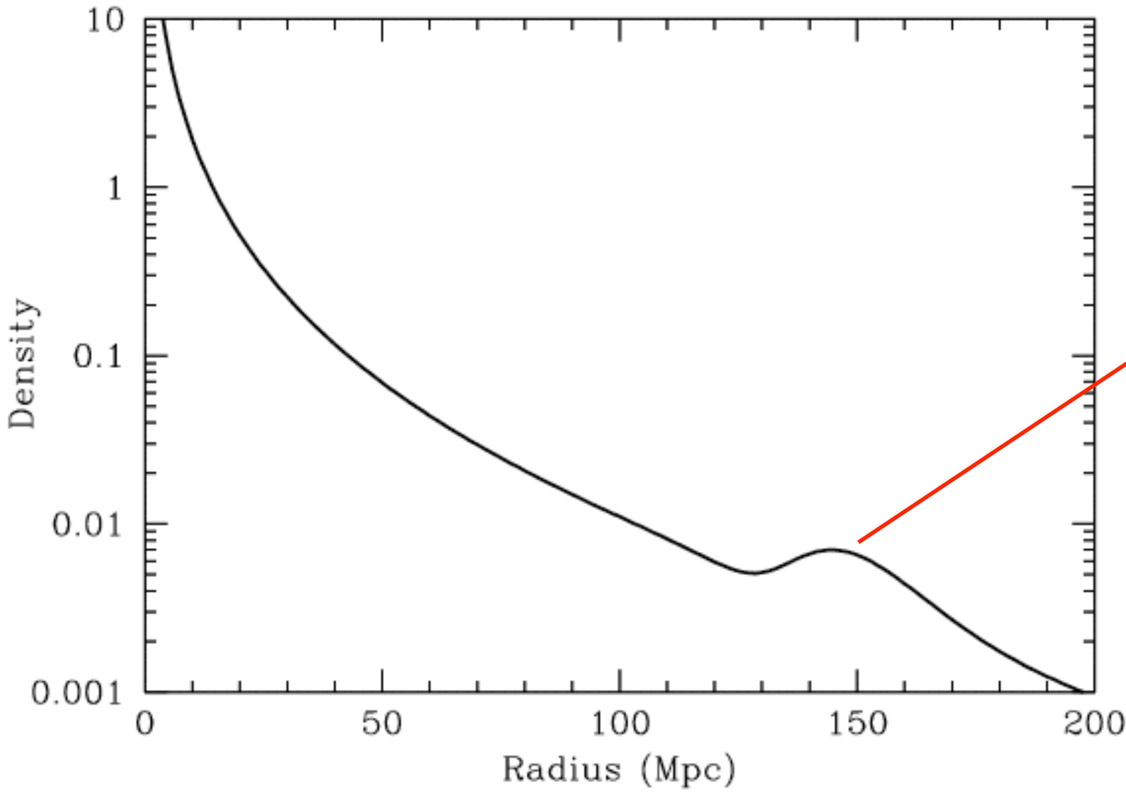


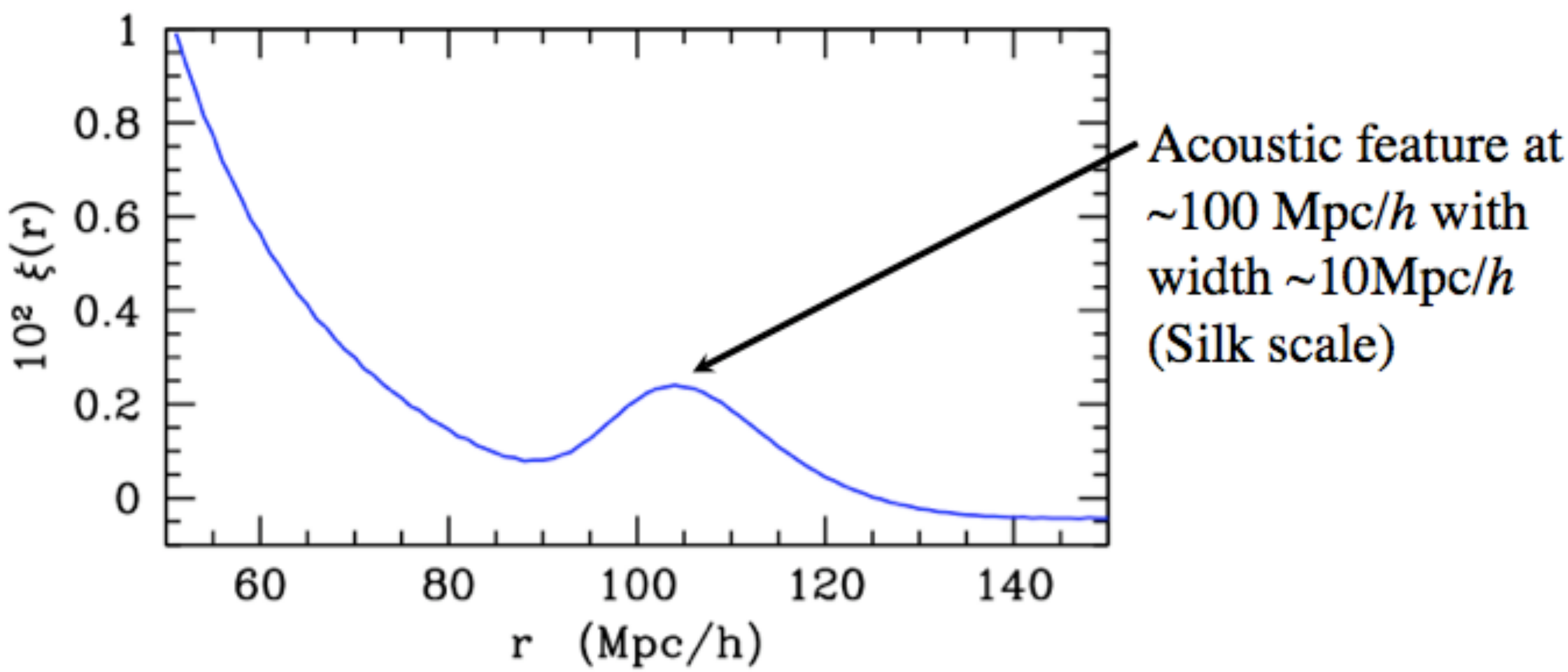
BAOs: the density profile



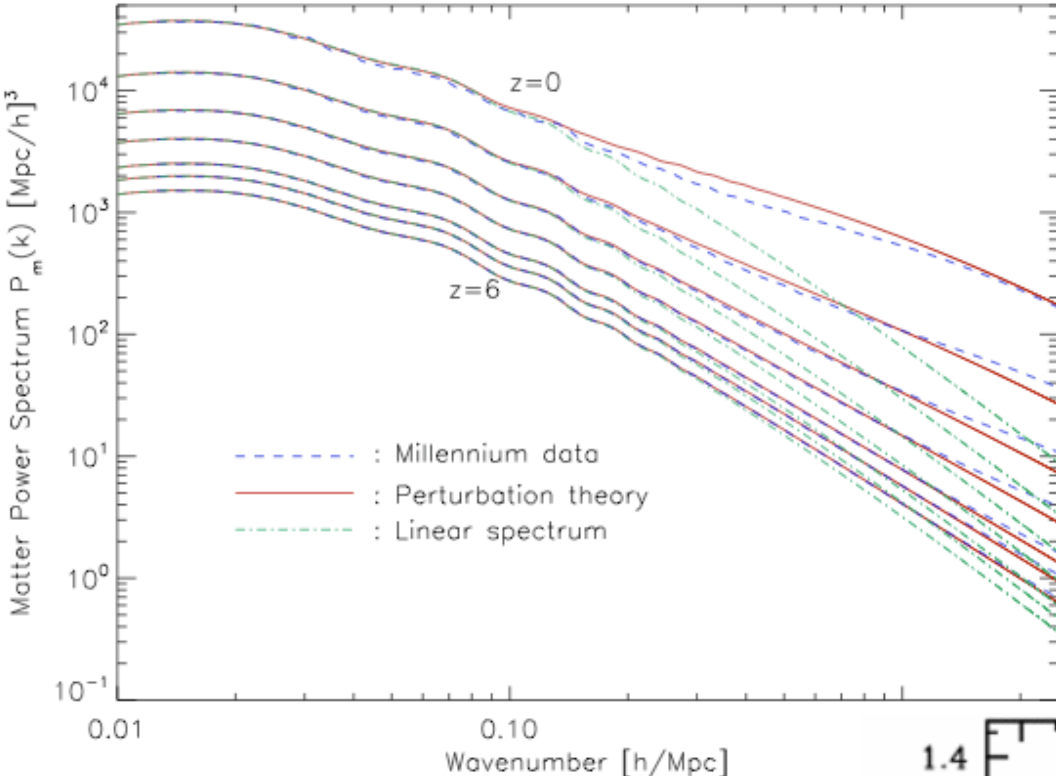
Slight excess at ~ 150 Mpc The exact value depends on cosmology but can be calibrated using CMB anisotropies

BAOs 2-point correlation function

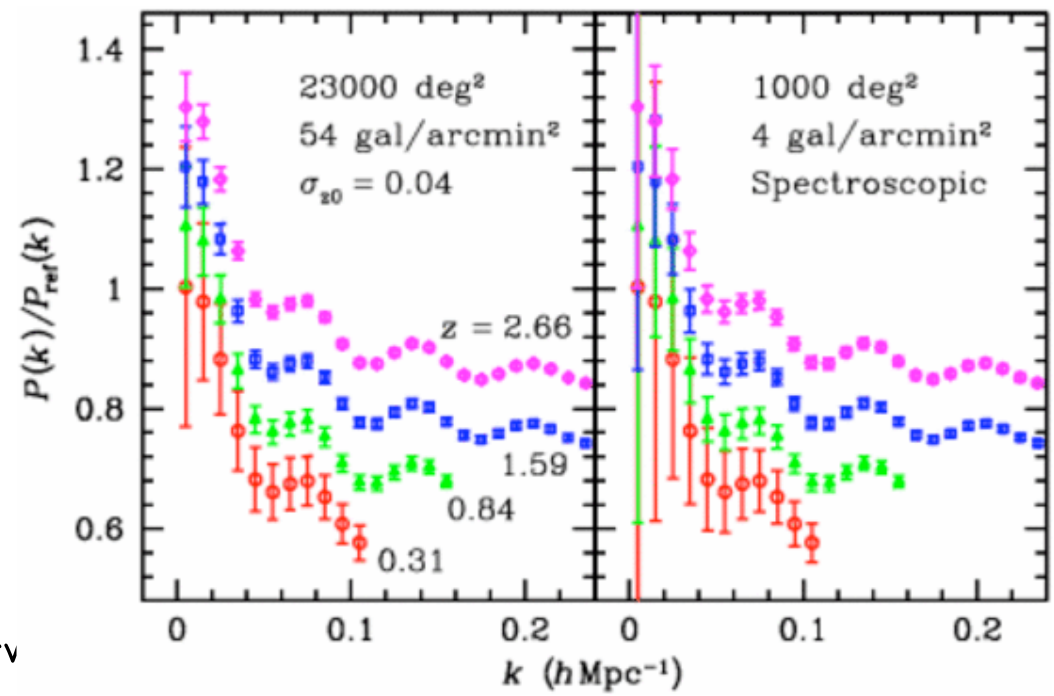
The acoustic bump is frozen into the matter power spectrum and provides a standard ruler with which to measure radial and transverse distances as a function of redshift. Non-linear effects broaden the bump and shift it by ~0.5% (not an issue for first generation experiments but an issue for future ones!)



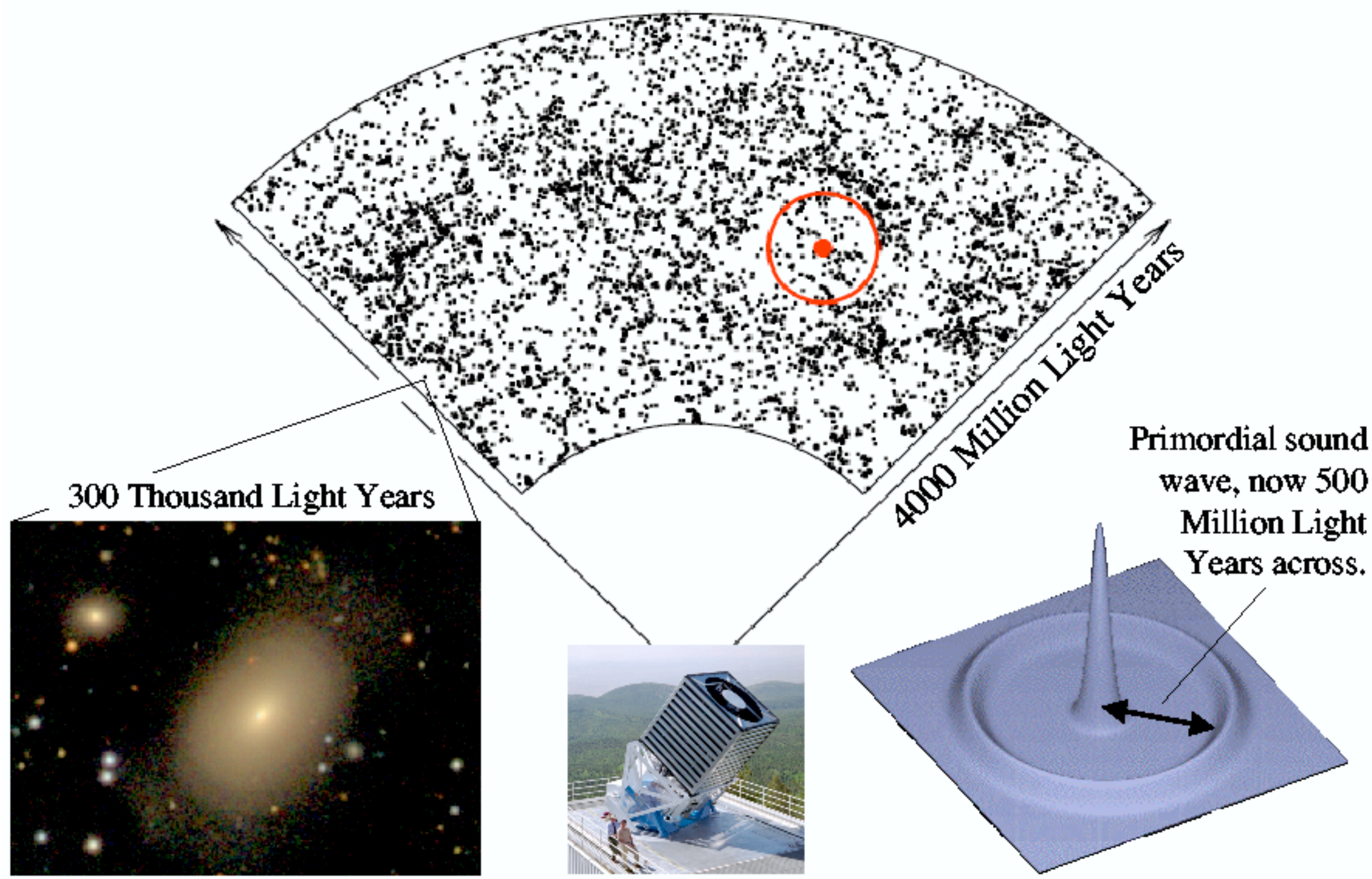
Power spectrum



In Fourier space the signature of primordial acoustic waves manifests itself as a damped (almost) harmonic series of peaks



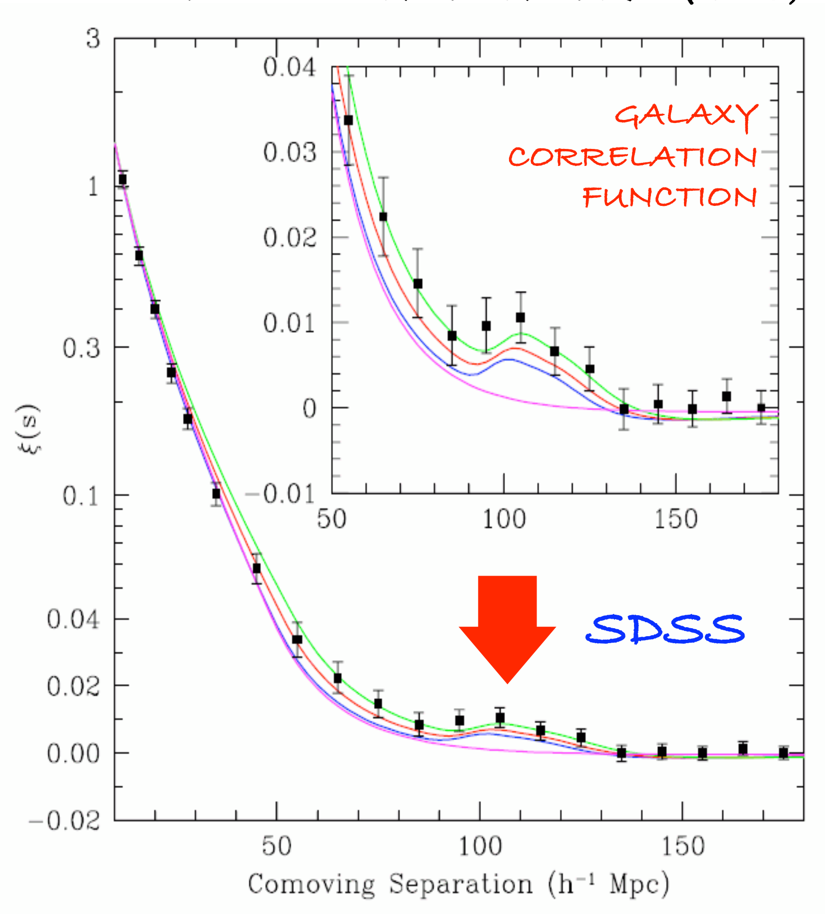
Baryonic oscillations



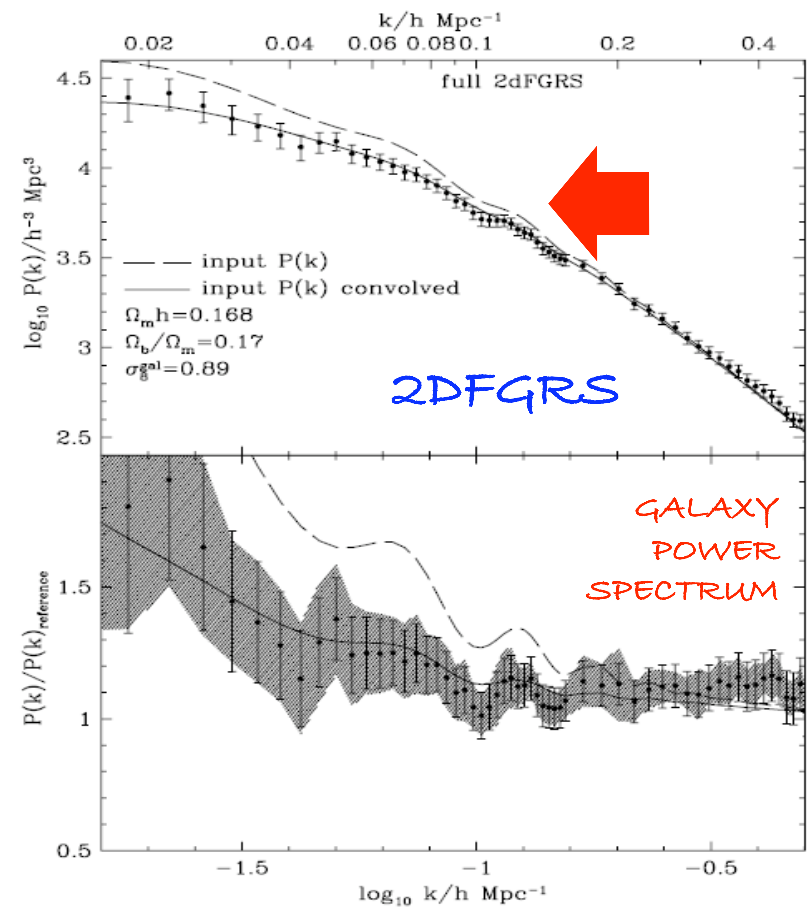
Measuring BAO from LSS

THE BAO IN THE GALAXY DISTRIBUTION AT Z~0 WERE FIRST DETECTED IN THE 2DFGRS AND SDSS GALAXY REDSHIFT SURVEYS...

SDSS: EISENSTEIN ET AL. (2005)

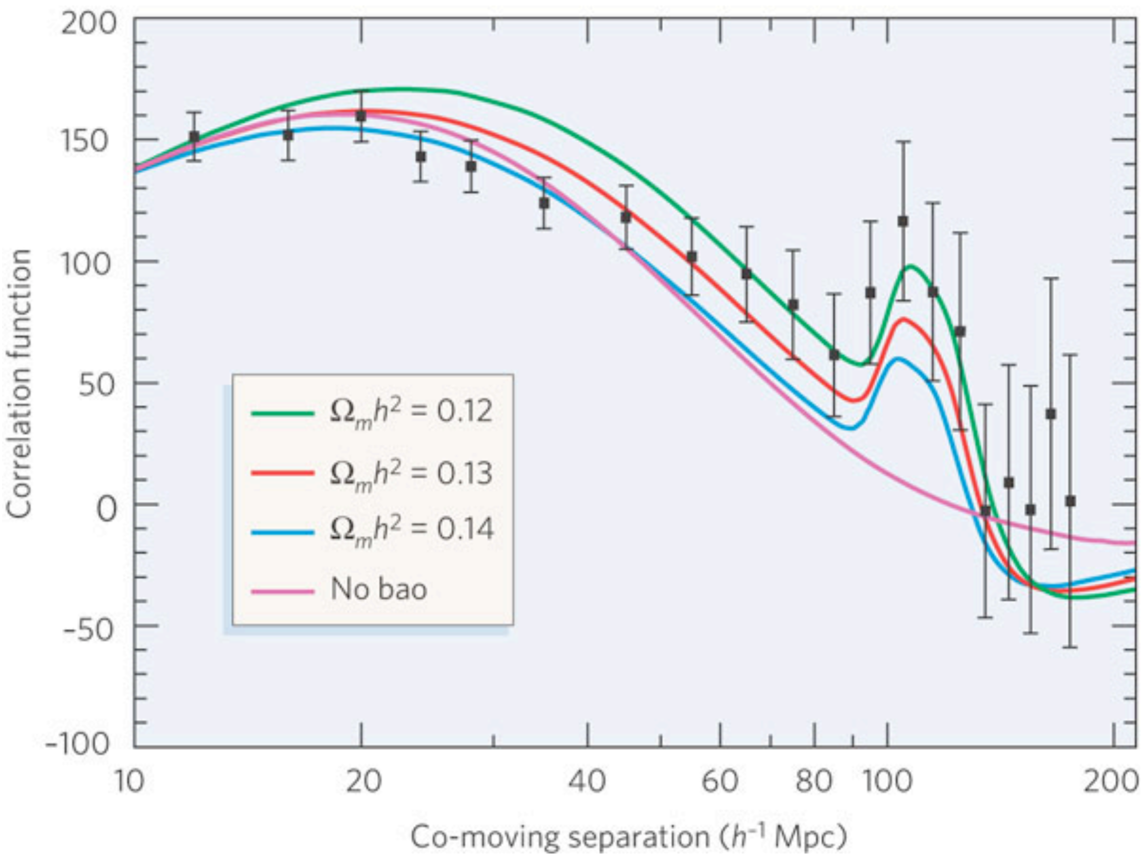


2DFGRS: COLE ET AL. (2005)



The current state of the art

Eisenstein et al. 2005, Cole et al. 2005, Padmanabhan et al 2007



SDSS-LRGs at z=0.35 (luminous red galaxies)

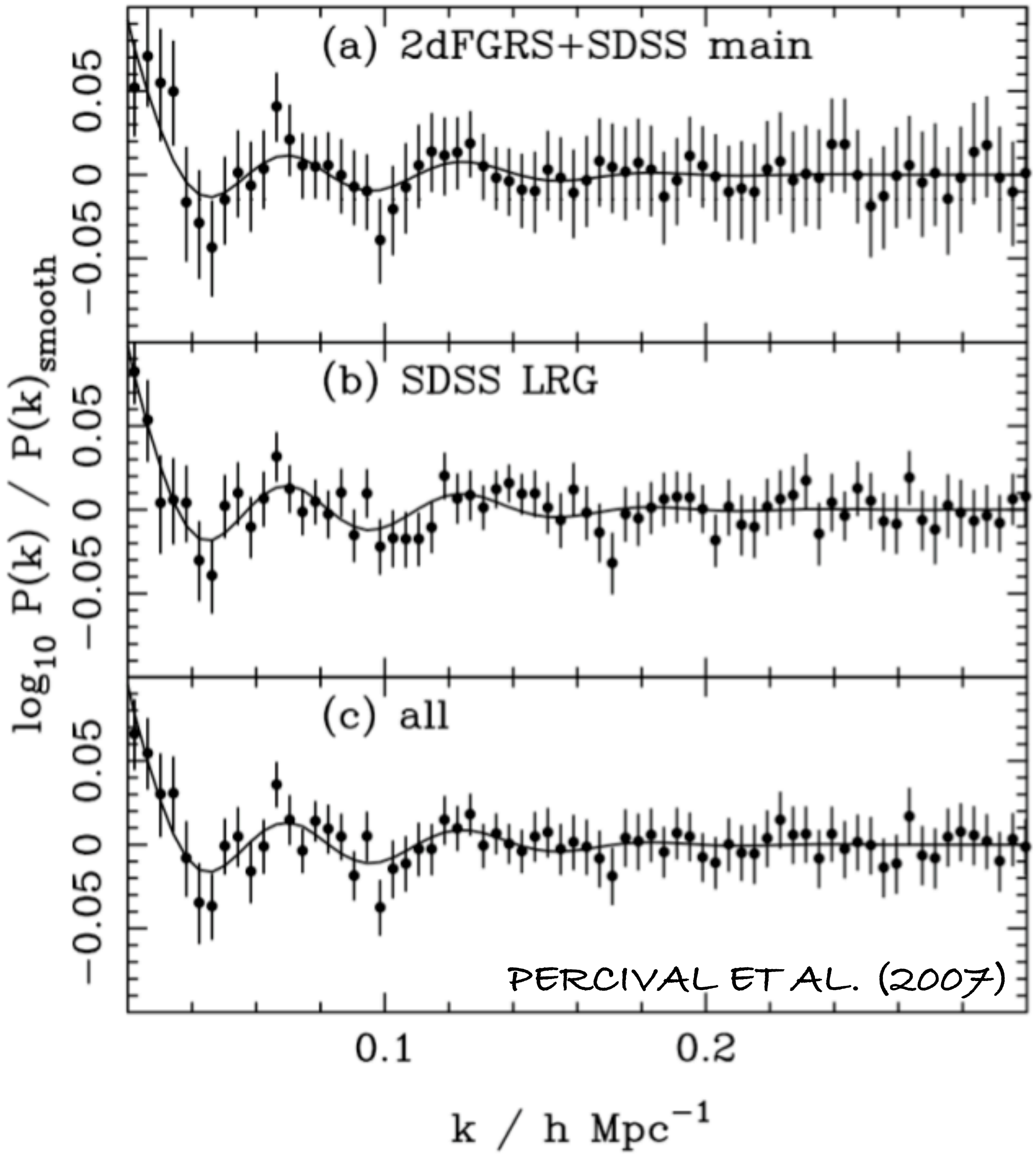
3.4σ detection of BAOs

Ratio of distances to z=0.35 and and to z=1100 determined to 4% accuracy

Absolute distance to z=0.35 determined to 5% accuracy

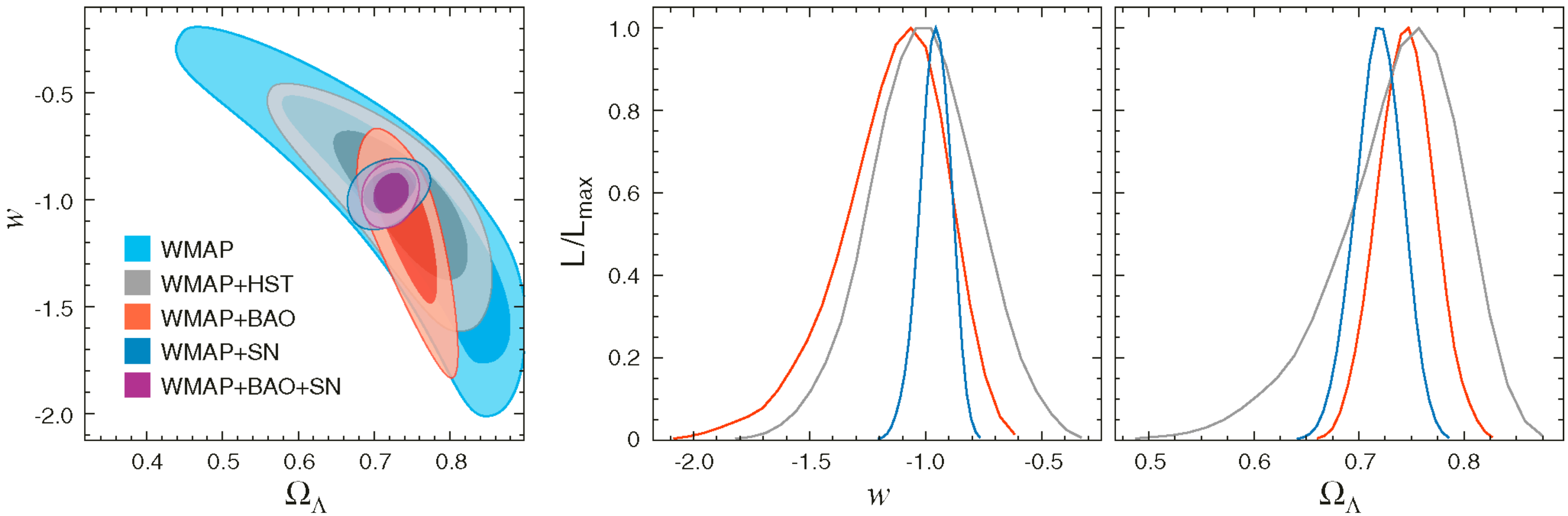
Current state of the art

- BAO detected with 99.74% confidence in combined sample using all of 2dfgrs + sdss Main + SDSS LRGs
- Combined with WMAP this gives Ω_m= 0.256 ± 0.027 (68% CL)



The current state of the art

Bennett 2006



A look into the future

TOP(?) TEN Cosmology surveys

- Cosmic microwave background
  1. planck - ultimate cmb survey, launched on MAY 14 2009!
- Dark energy surveys - spectroscopy (BAO)
  1. wigglez - first z>0.5 BAO survey for evolving w
  2. BOSS - massive BAO dark energy survey at z~0.5
  3. WFMOS - BAO Dark energy surveys at z~1 & z~3
- DARK ENERGY surveys - imaging (BAO/SNE/WL/cl)
  1. DES/pan-STARRS/LSST - OPTICAL imaging; sne/wl/cl/BAO
  2. eROSITA – all sky X-ray clusters; DE via cluster growth
  3. SPT - sZE clusters to z~2; DE via cluster growth
- Formation and assembly of galaxies
  1. GAMA - detailed z~0 LSS, relation of Mass & light
  2. RAVE/APOGEE/HERMES/WFMOS/GAIA - assembly of the milky way and local group galaxies
  3. JWST - assembly of earliest galaxies

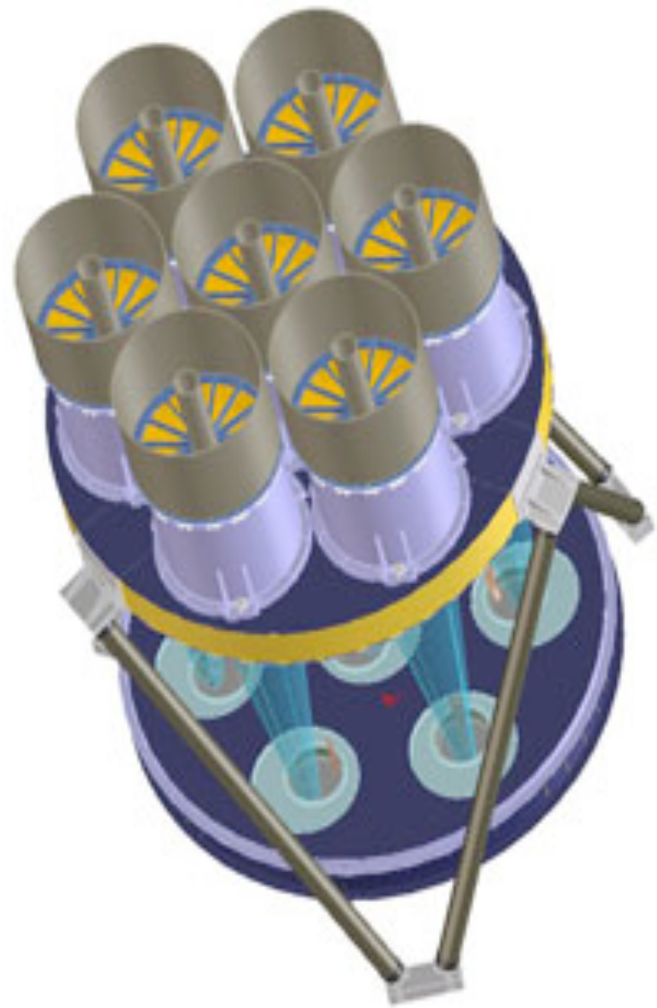
Advantages of BAO surveys

- BAO - absolute standard rod calibrated by CMB
  - linear physics; depends only on Ω_m and Ω_b
  - CMB calibration GIVES absolute scale at z=1100
- in principle get ~1% distances over a wide range of redshifts, so a potent probe of dark energy
  - can measure H(z) radially and D_A(z) tangentially
  - requires large samples: ~10^6 galaxies over ~1 Gpc^3
- Complementary to other dark energy probes
  - measures different cosmological properties
  - different physical basis and systematics
    - non-linear clustering on small scales
    - z-space distortions of the clustering pattern
    - scale-dependent bias of galaxies

eROSITA

extended Roentgen Survey with an Imaging Telescope Array

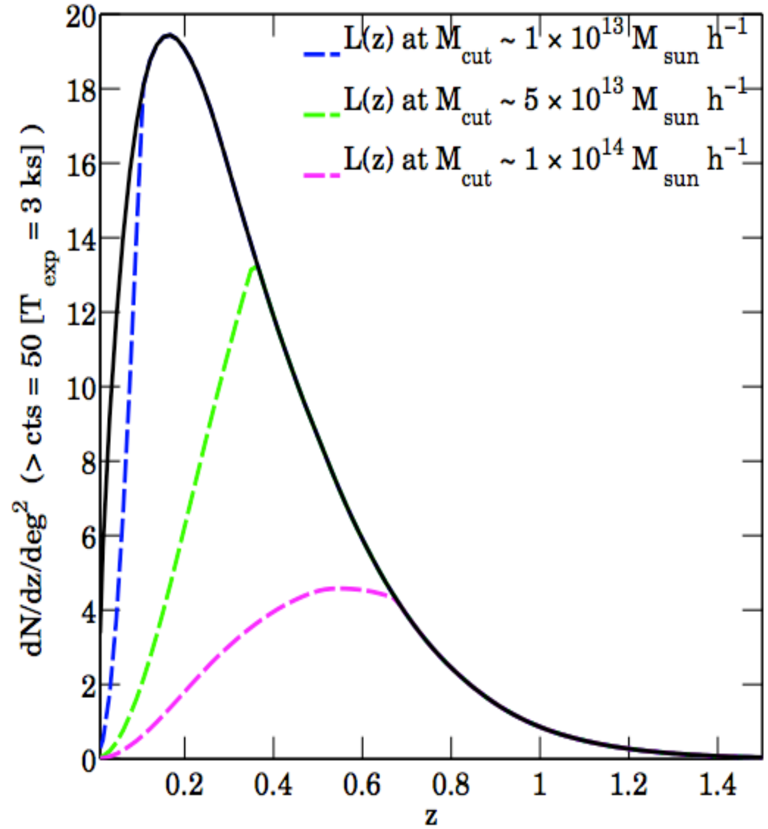
- Primary instrument onboard the Russian Spectrum-Roentgen-Gamma satellite (SRG)
- German-Russian mission. Launched from Baikonur in 2012 (leased by Kazakhstan to Russia)
- L2 orbit
- First all-sky imaging survey in the medium energy X-ray band up to 10 keV with unprecedented spectra and angular resolution
- 7 Wolter-1 mirror modules (containing 54 shells each), special detectors



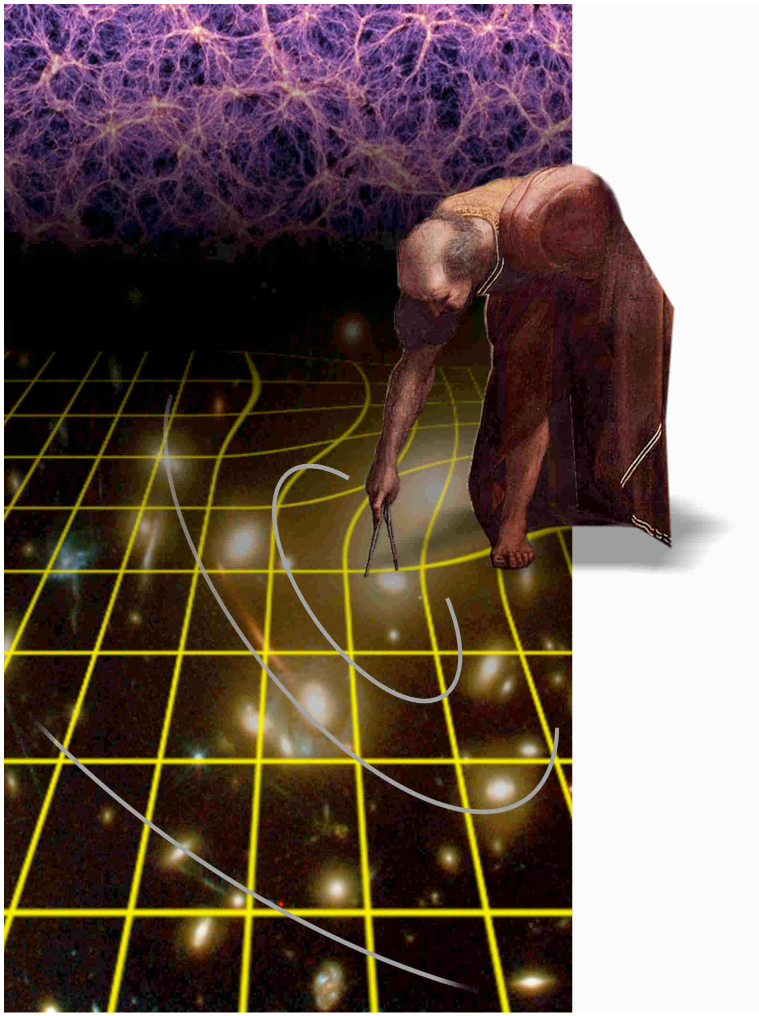
eROSITA science goals

- Detect the hot intergalactic medium of 10^5 galaxy clusters and groups for studies of structure formation and cosmology
- Detect all obscured accreting black holes in nearby galaxies
- Study galactic X-ray sources

Pillepich, CP & Reiprich 2011



The EUCLID mission

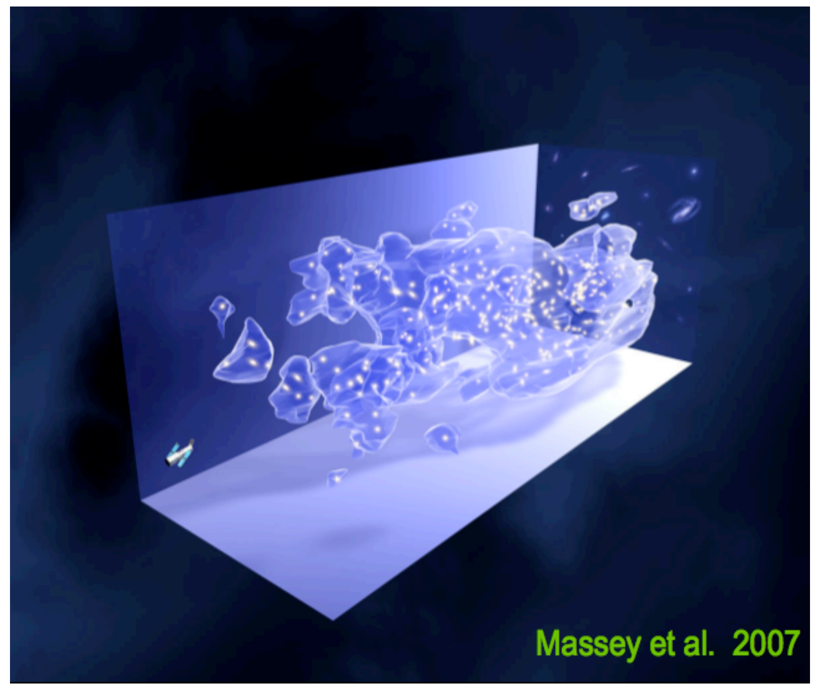


- M-class mission within the Cosmic Vision program of the European Space Agency
- "High-precision survey mission to map the geometry of the dark universe"
- Now in the competitive Definition Phase, launch expected in 2018
- >200 people, 30 Institutions, 7 countries

The EUCLID concept

The EUCLID mission is being optimized for two complementary cosmological probes

- Weak gravitational lensing
- Baryonic acoustic oscillations
- Full extragalactic sky survey with 1.2m telescope at L2
- Additional probes: galaxy clusters, redshift-space distortions, integrated Sachs-Wolfe effect
- Legacy science for a wide range of areas in astronomy



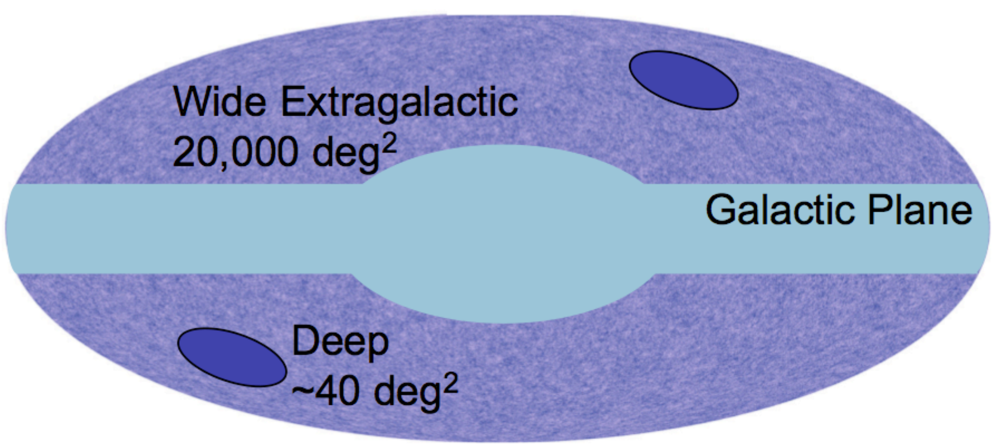
EUCLID imaging surveys

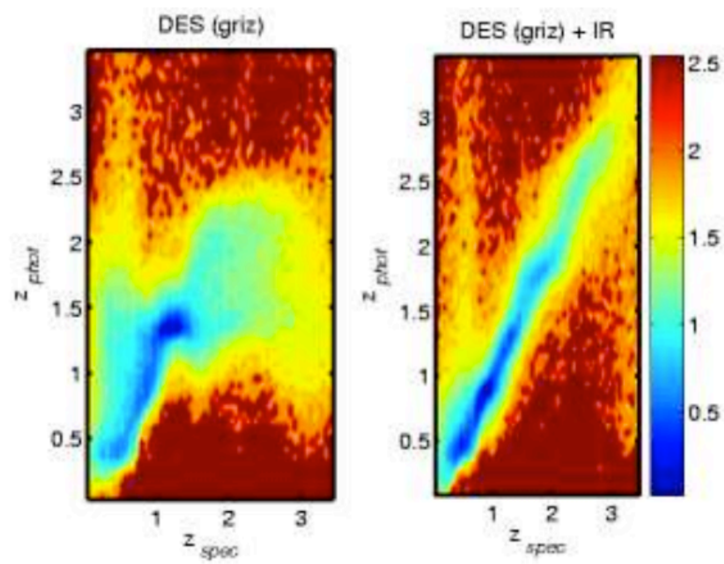
Wide survey (20,000 deg^2)

- Galaxy shape measurements in the visible band to $RIZ_{AB} < 24.5$ (10σ) yielding 30-40 resolved galaxies/arcmin^2 with a median redshift of 0.9
- Near-infrared photometry yielding photometric redshift errors of 0.03-0.05 (1+z) with ground-based complements (DES, PanStarrs)

Deep survey (40 deg^2):

- 2 mag deeper for both visible and NIR data

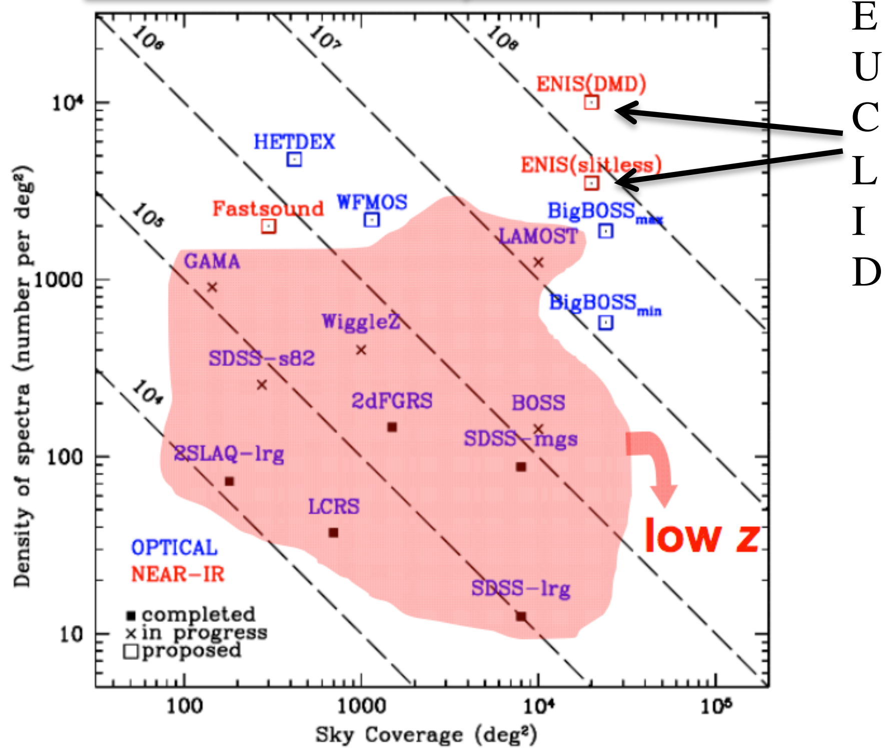




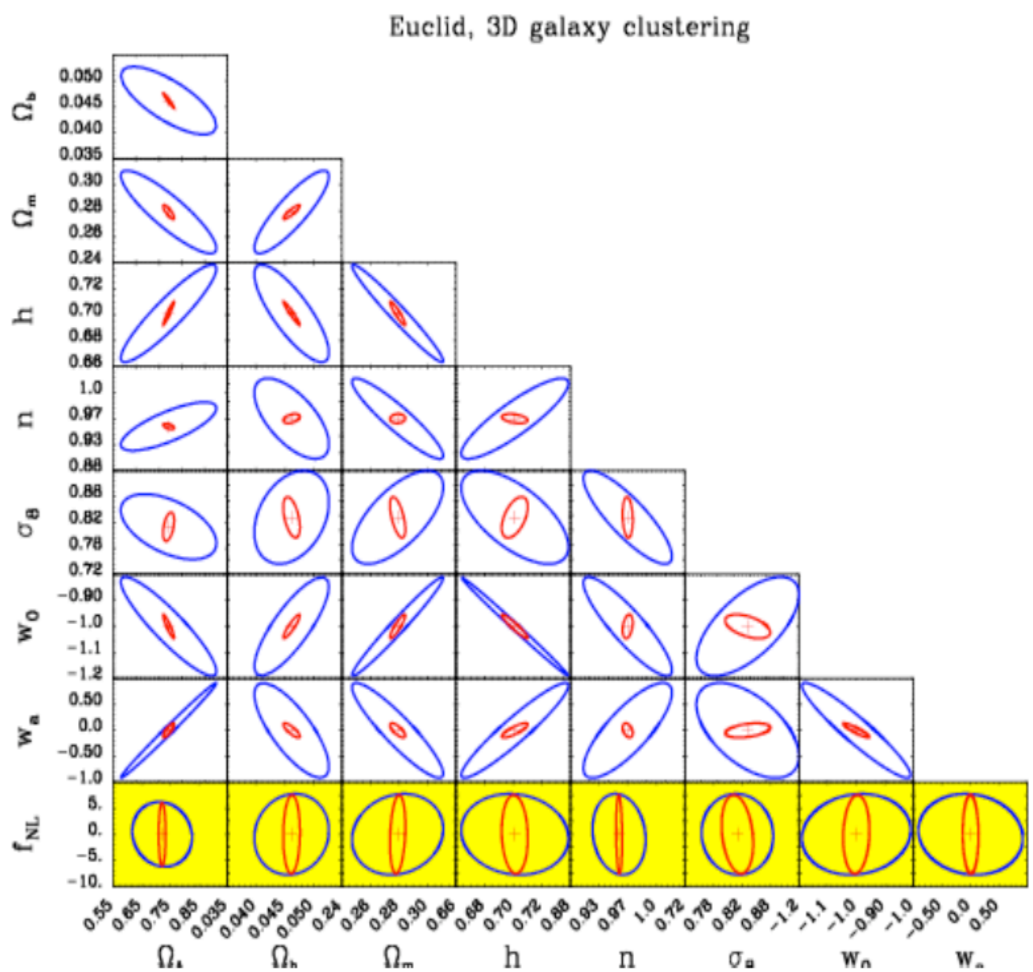
EUCLID spectroscopic survey

- 20,000 deg^2 in 5 yr
- Slitless spectroscopy with spectral resolution R=500 (1-2 μm) in the near infrared
- $F_{H\alpha}$>4x10^{-16} erg s^{-1} cm^{-2} (star-forming galaxies)
- σ_z<0.001(1+z)
- Spectroscopic completeness >0.35 for a total of 70 million galaxy redshifts

Current and future redshift surveys



Impact of EUCLID



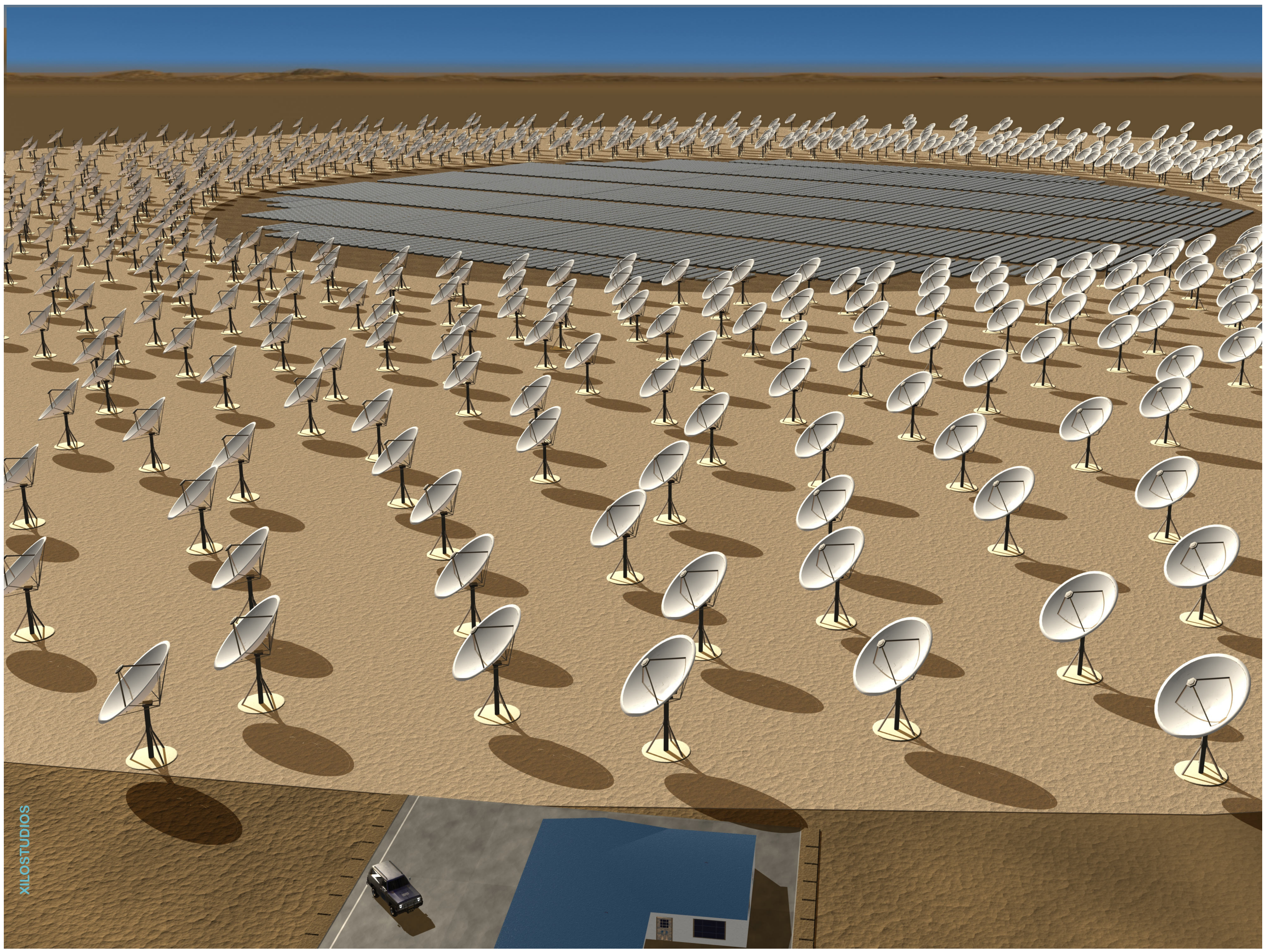
beyond the 10-year horizon

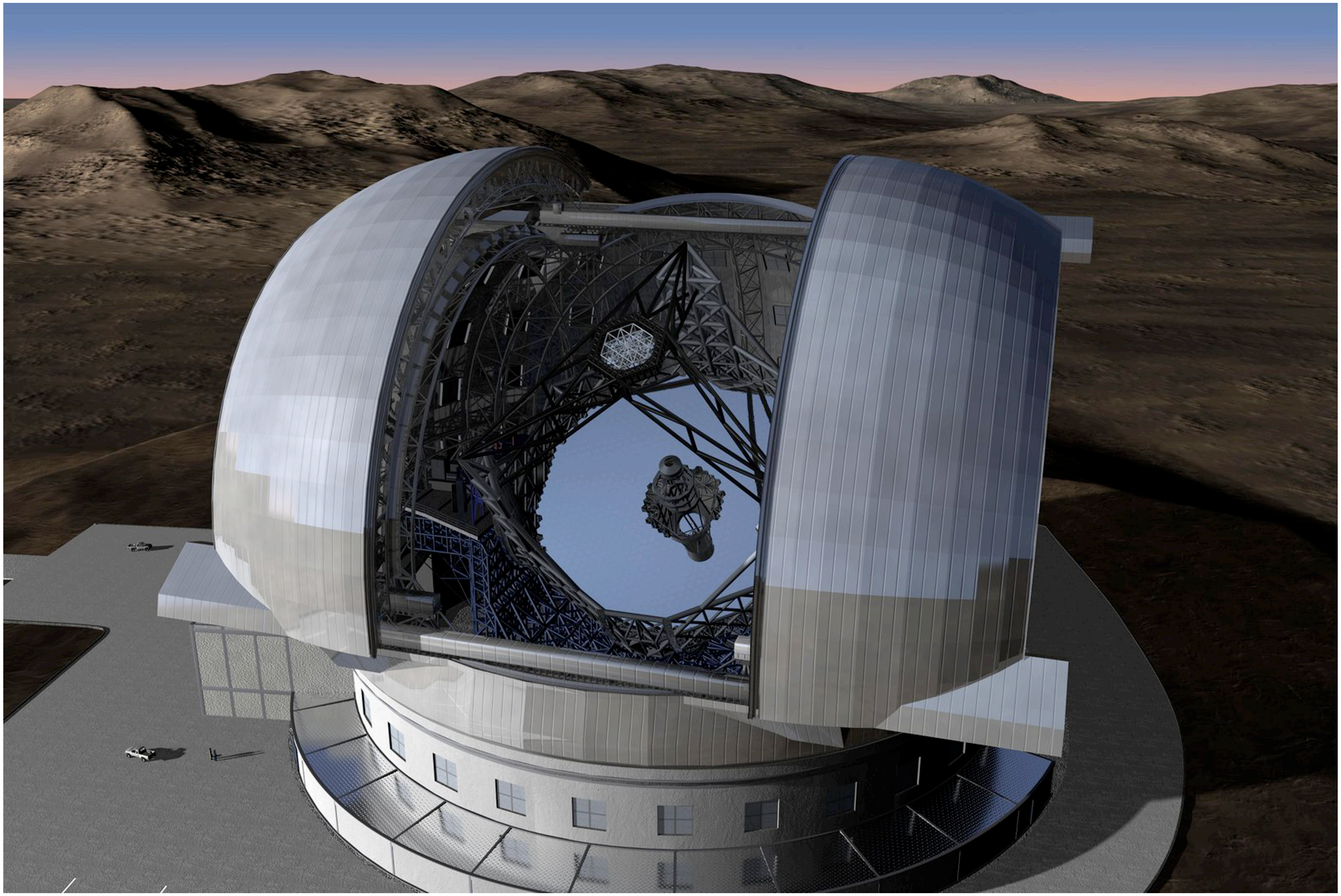
- Some of the BIGGEST advances in capability for cosmology surveys will come on-line just outside the decadal horizon...

- ☐ LSST - ultimate ground-based imaging survey
- ☐ JDEM/EUCLID/??? - ultimate dark energy surveys
- ☐ GMT/TMT/E-ELT - first stars and galaxies
- ☐ ska - HI/AGN/BH throughout the universe

SKA
SQUARE KILOMETRE ARRAY

A million redshifts per year!





E-ELT: 42m, decision to build expected 2010, operational in 2018

Proposed spectroscopic BAO surveys

Project	Redshift	Area (sq. deg.)	n (10^{-4})	FoM
Stage II	-	-	-	53
WiggleZ	0.4-1.0	1,000	3.0	67
HETDEX*	2.0-4.0	350	3.6	70
WFMOS*	0.5-1.3, 2.3-3.3	2,000, 300	5.0	95
BOSS LRG	0.1-0.8	10,000	3.0	86
+QSO	+ 2.0-3.0	+ 8,000		122
LRG+QSO +Stage III		-		331
"Best"	0-2	30,000	10	~600

cf. WMAP6 FoM = 0.13, Planck FoM = 12

Proposed photometric BAO surveys

Project	Redshift	Area (sq. deg.)	n (10^{-4})	FoM
Stage II	-	-	-	53
Pan-STARRS	0-1	20,000	10	76
DES	0-1.4	4,000	10	66
LSST	0-1.4	20,000	10	80
PAU	0-1	10,000	10	94

Conclusions

- A very rich future for cosmological surveys!
- Both imaging & spectroscopy offer powerful routes to the dark energy equation of state
- These surveys also provide valuable data for a wide range of other science - But it is a fine balance of fit-for-purpose & overly-specialised
- Goal: reduce number of Dark energy candidates! tracker quintessence, single exp quintessence, double exp quintessence, axion-photon coupling, holographic dark energy, pseudo-Nambu-Goldstone boson quintessence, cosmic strings, cosmic domain walls, phantom dark energy, Cardassian model, brane cosmology (extra-dimensions), Van Der Waals quintessence, dilaton, generalized Chaplygin gas, quintessential inflation, unified dark matter and dark energy, superhorizon perturbations, ndulant universe, general oscillatory models, Milne-Born-Infeld model, k-essence, chameleon, k-chameleon, f(R) gravity, quiessence, perfect fluid dark energy, adiabatic matter creation, varying G, scalar-tensor gravity, double scalar field, scalar+spinor, quintom model, SO(1,1) scalar field, five-dimensional Ricci flat bouncing cosmology, scaling dark energy, radion, DGP gravity, Gauss-Bonnet gravity, tachyons, power-law expansion, phantom k-essence, vector dark energy, dilatonic ghost condensate dark energy, quintessential Maldacena-Maoz dark energy, superquintessence, vacuum-driven metamorphosis, wet dark fluid...