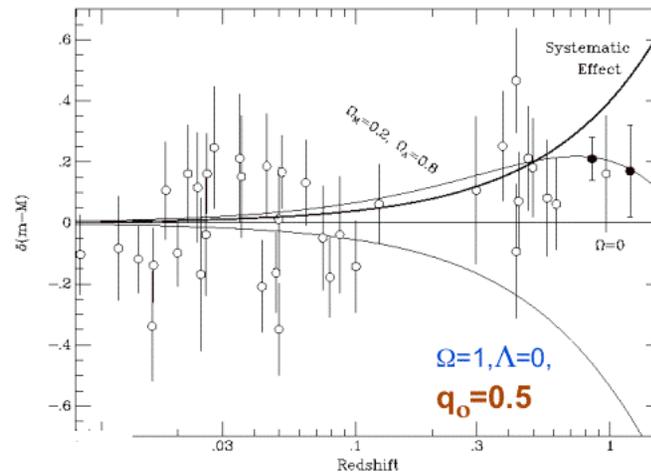


Possible ways out

- 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

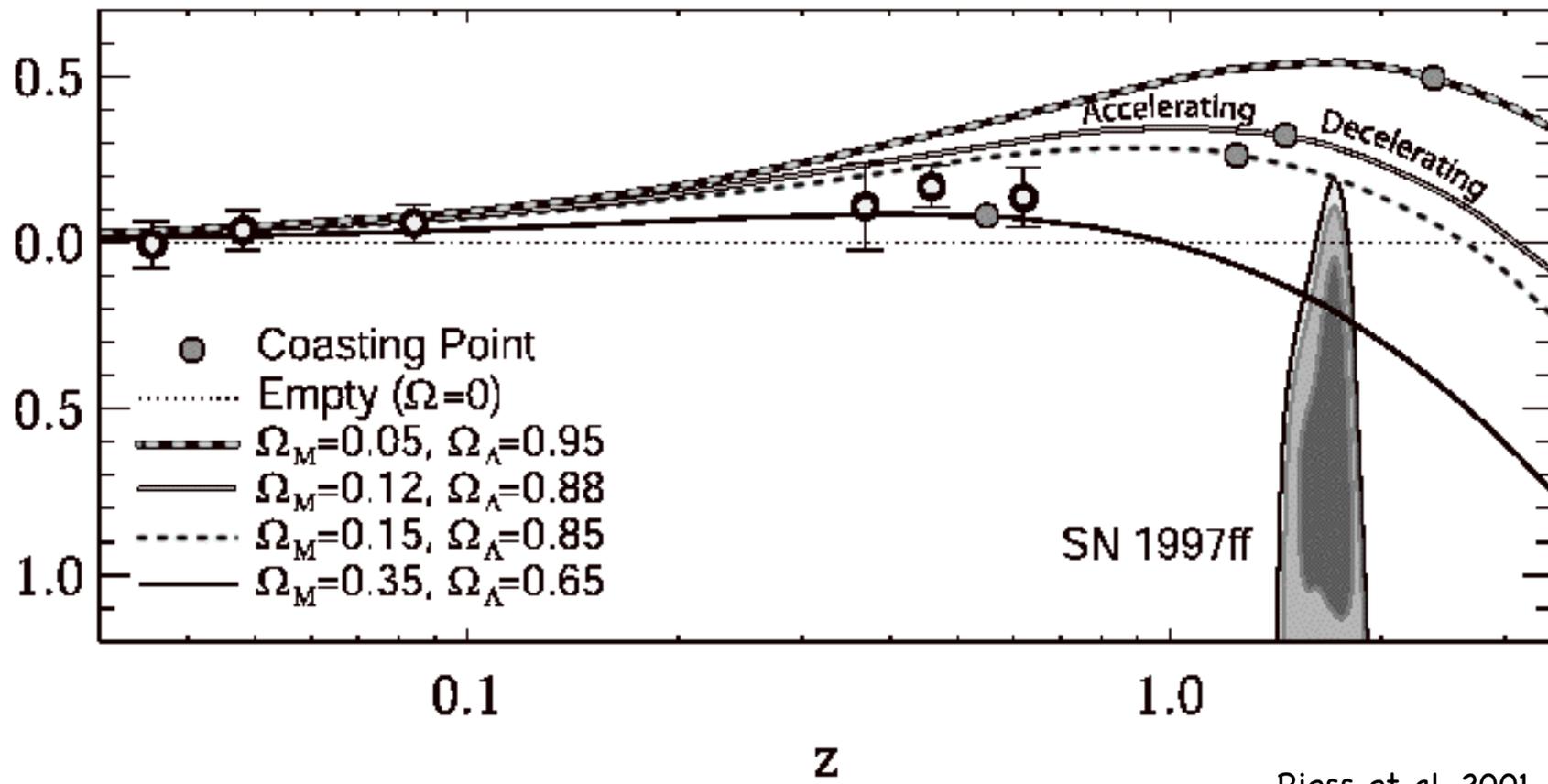


Possible systematic effects that mimic an acceleration:

- 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

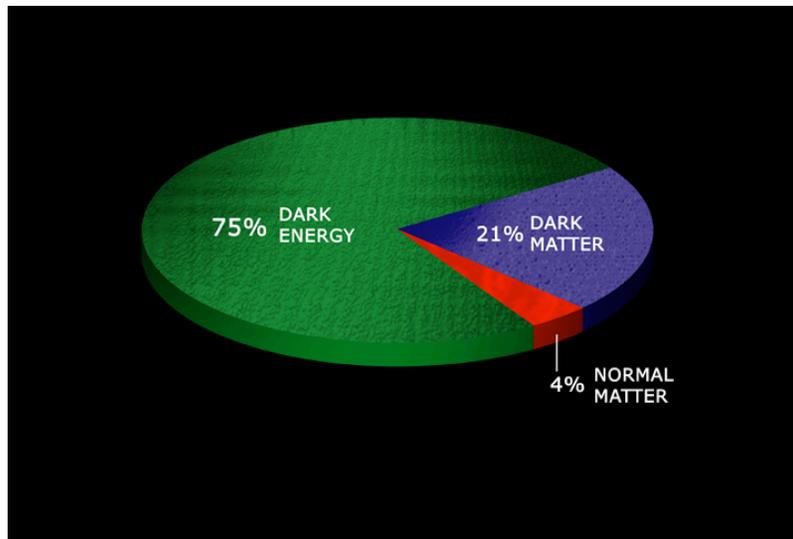
Slightly reassuring news: SN 1997ff



A census of the Universe

- Stars: $\Omega_* \approx 0.004$
- Gas: $\Omega_{\text{gas}} \approx 0.04$
- DM: $\Omega_{\text{DM}} \approx 0.25$
- DE: $\Omega_{\text{DE}} \approx 0.75$
- CMB: $\Omega_{\text{CMB}} \approx 5.0 \times 10^{-5}$
- 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: $w=\text{constant}$. 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 $w(z)$:

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

(truly model independent but noisy derivatives)

Figure of merit

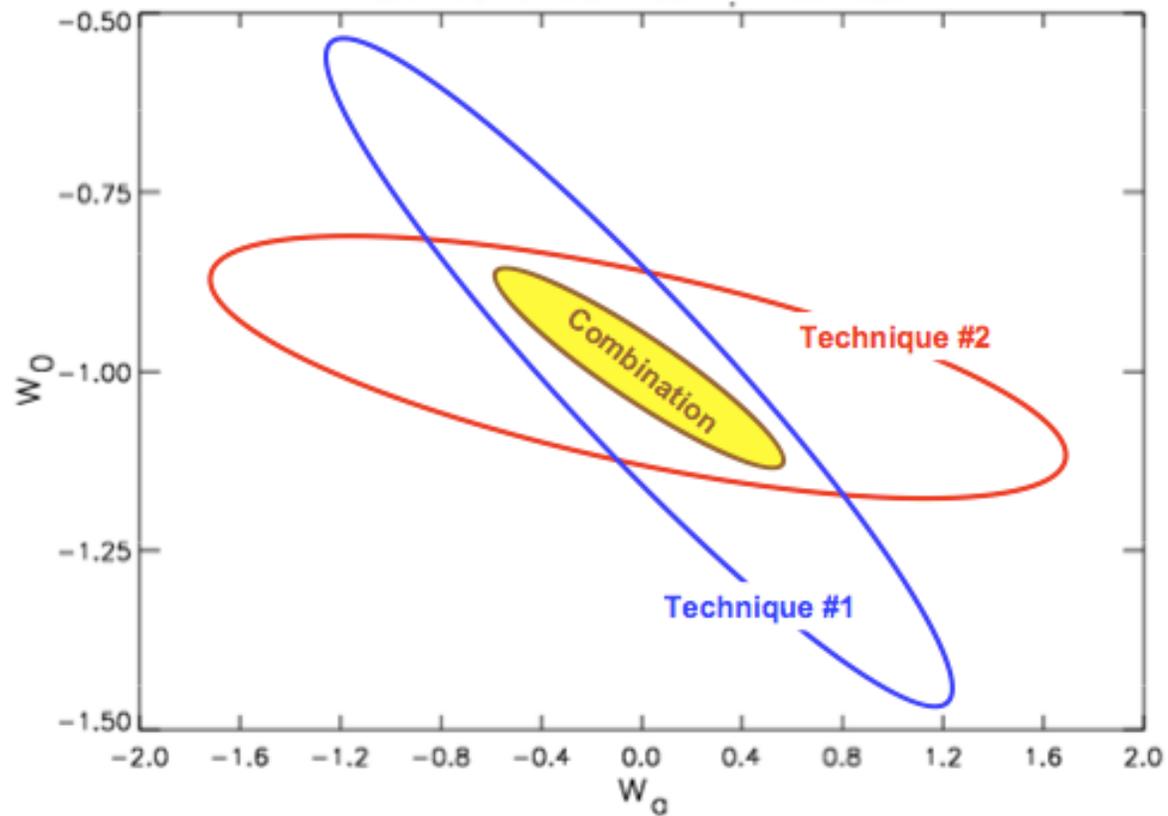
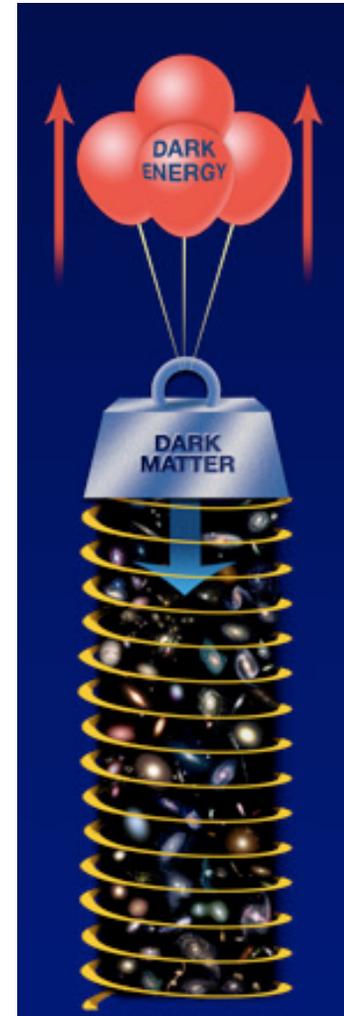


Figure of merit = $1 / (\text{area of the ellipse})$

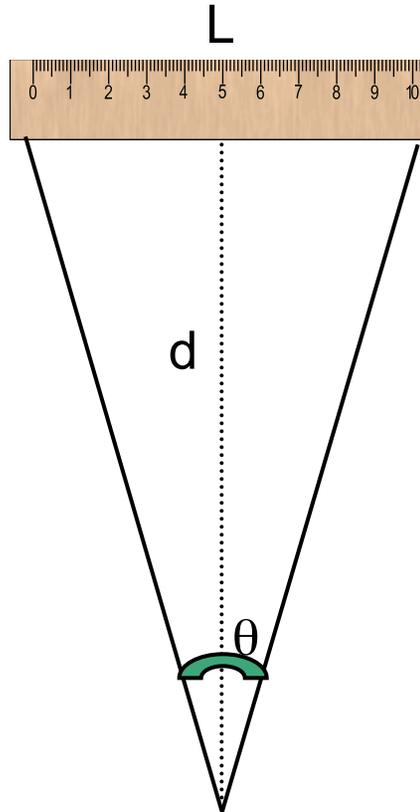
Observational consequences of DE

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**

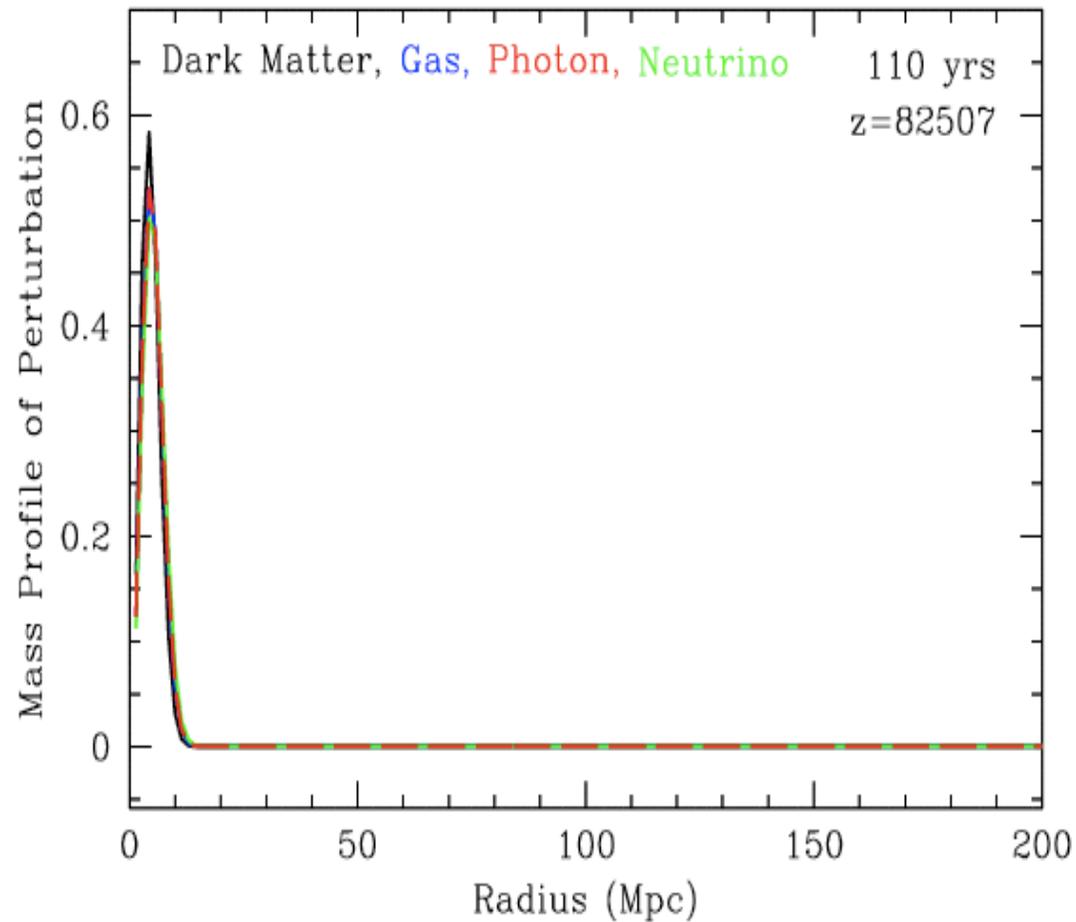


The ideal standard ruler

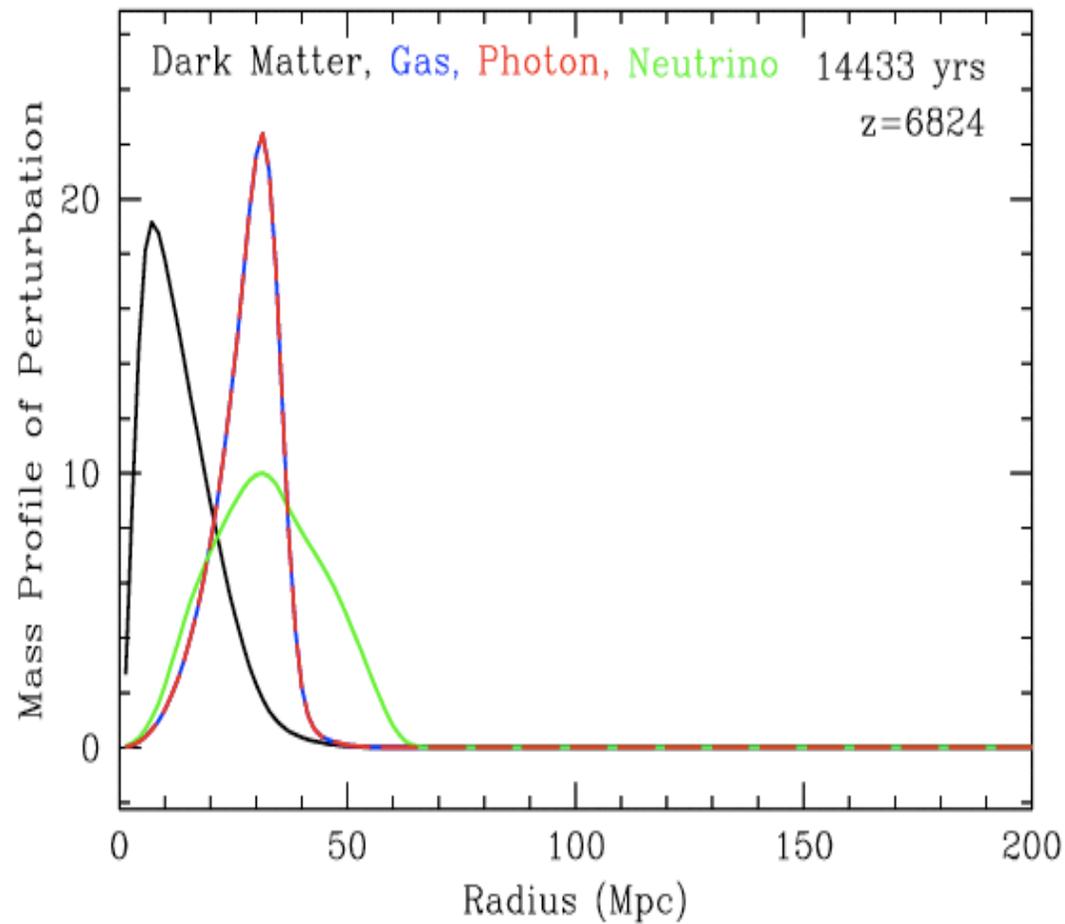


- We need to be able to measure the ruler over much of the volume of the universe
- We need to be able to make ultra-precise measurements of the ruler (1% accuracy to get 5% accuracy in the equation of state for dark energy)
- Answer: **baryonic acoustic oscillations**

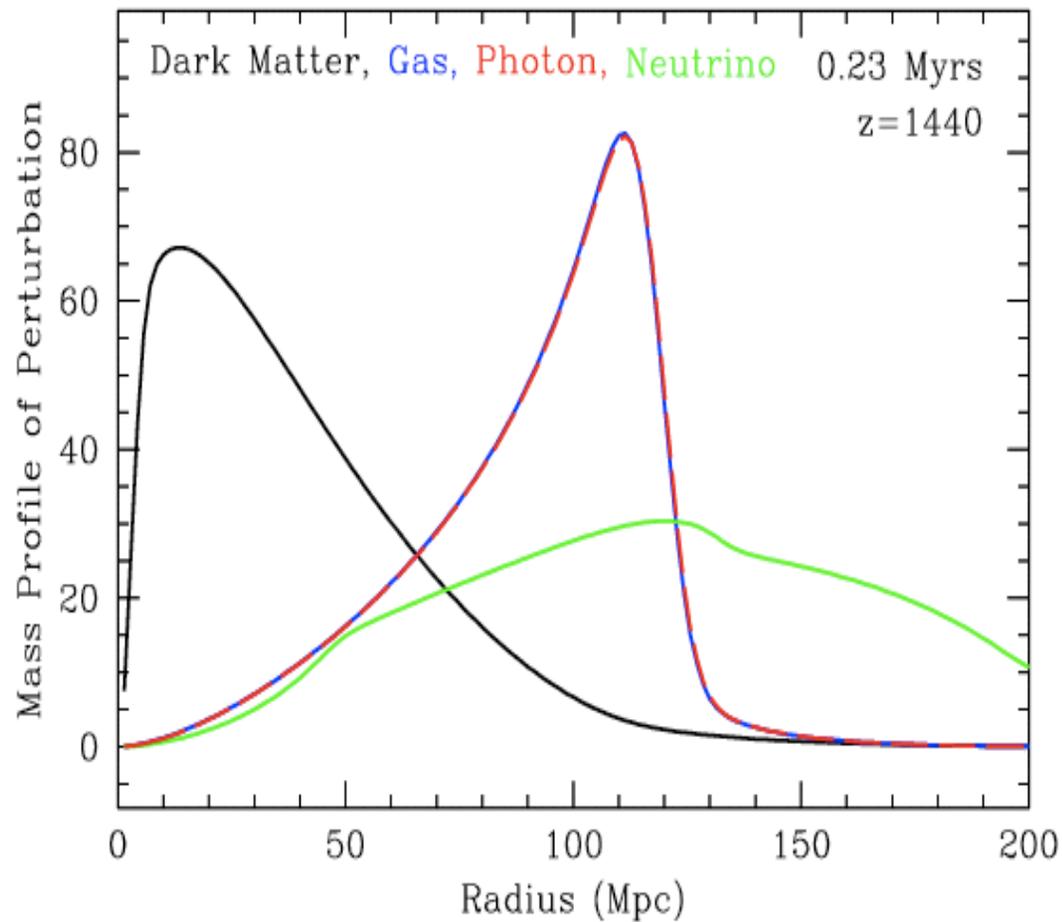
BAOs: a Green function approach



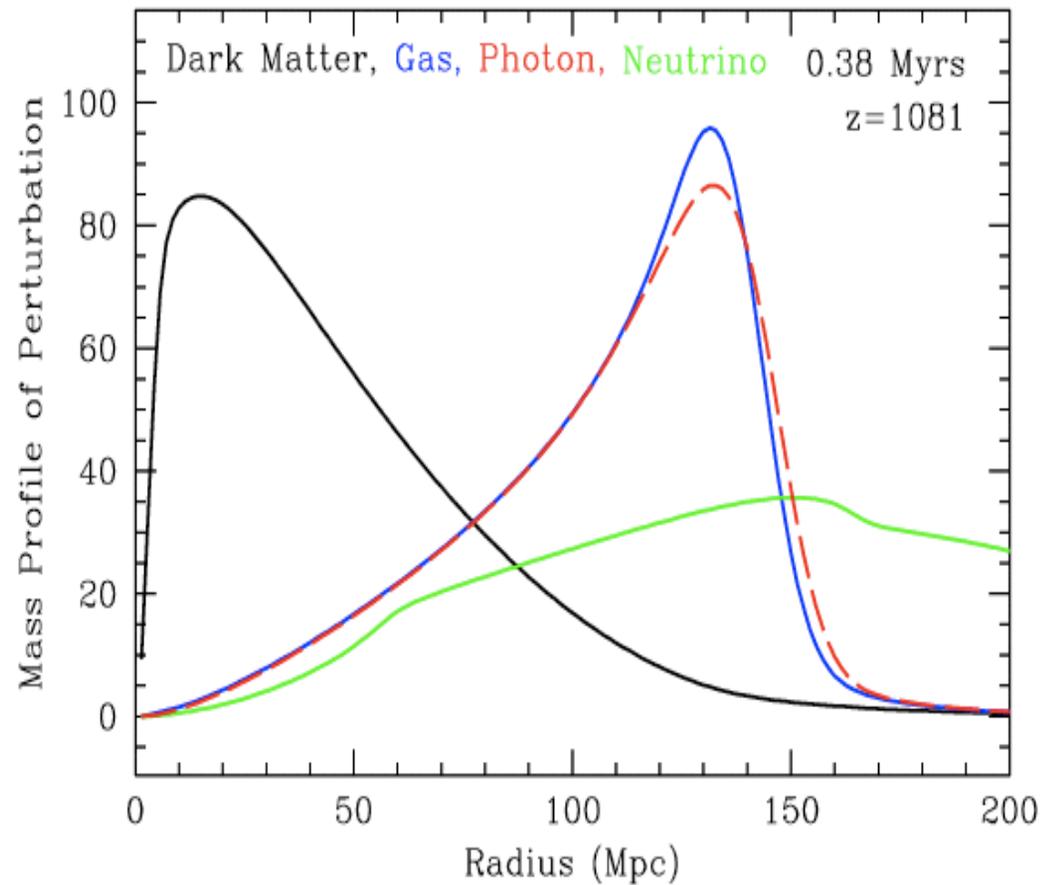
BAOs: a Green function approach



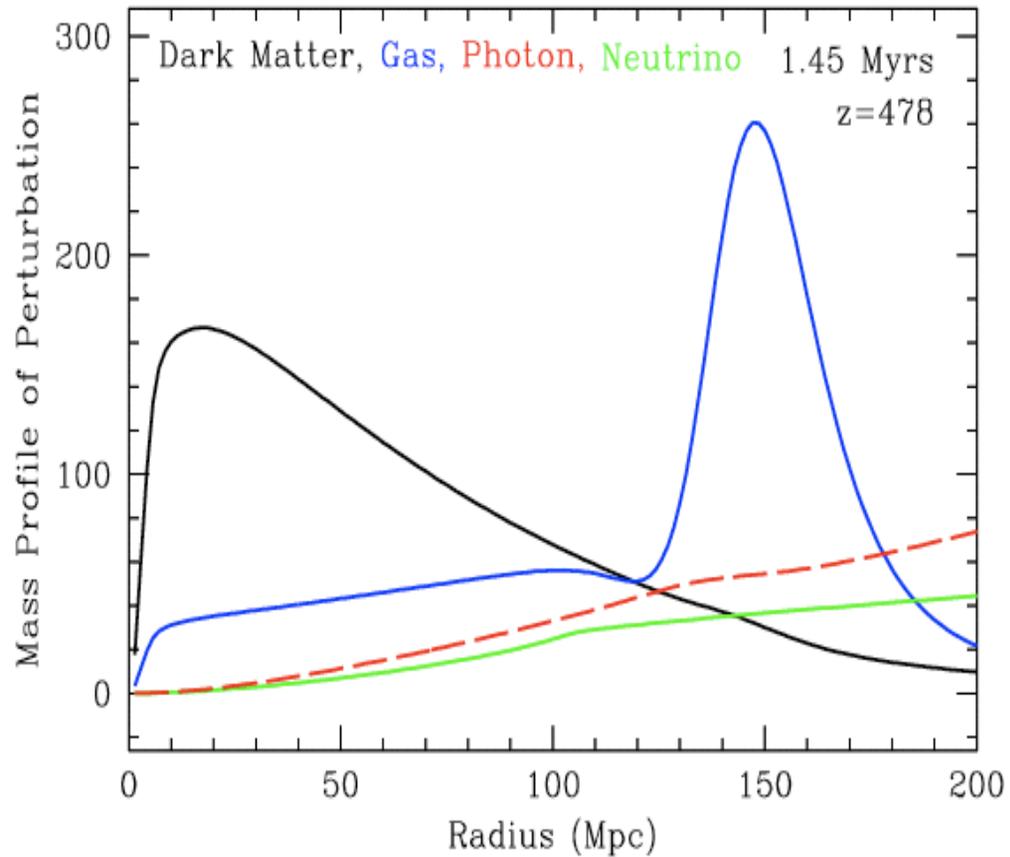
BAOs: a Green function approach



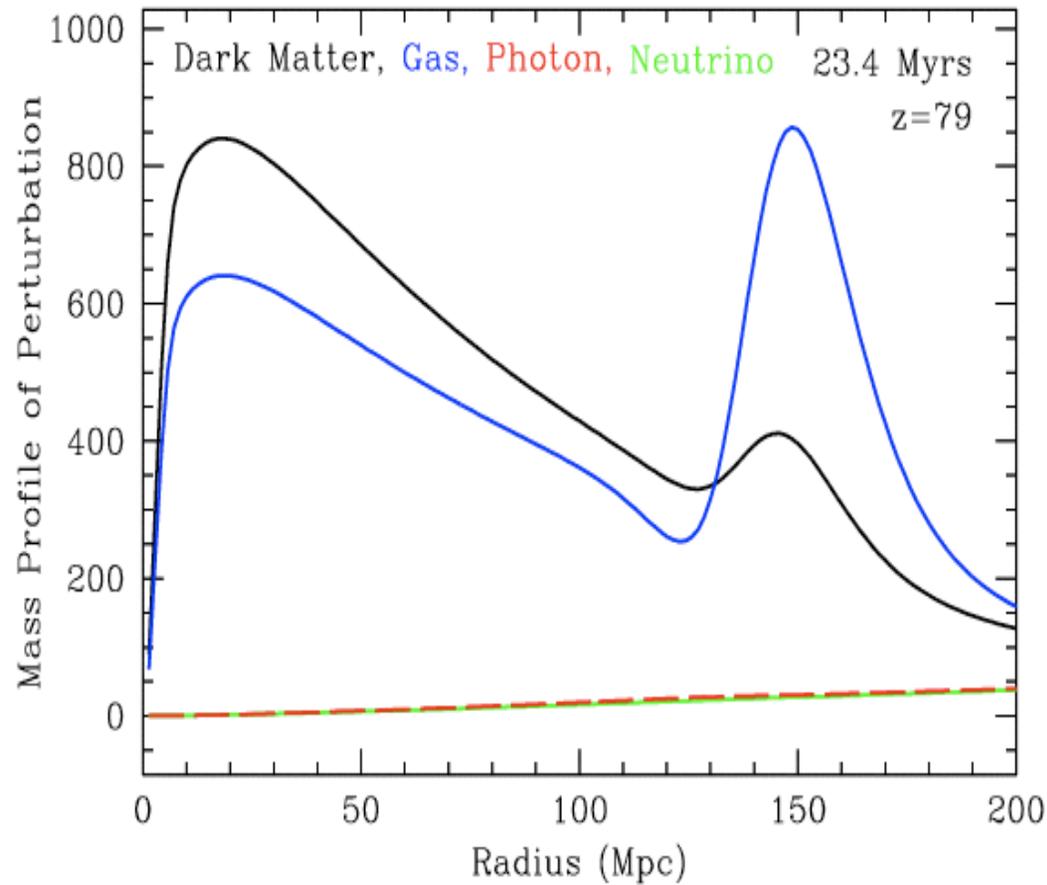
BAOs: a Green function approach



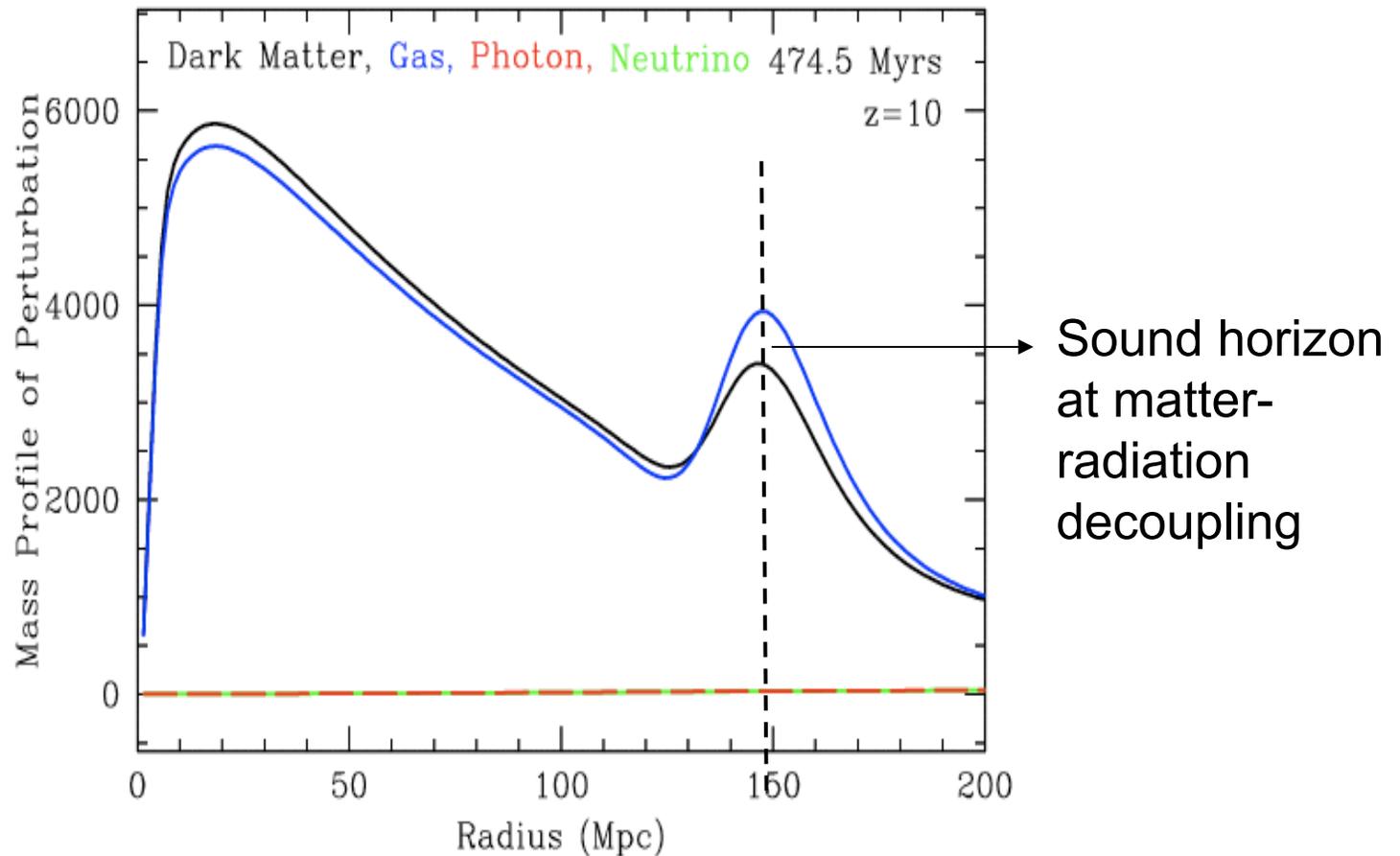
BAOs: a Green function approach



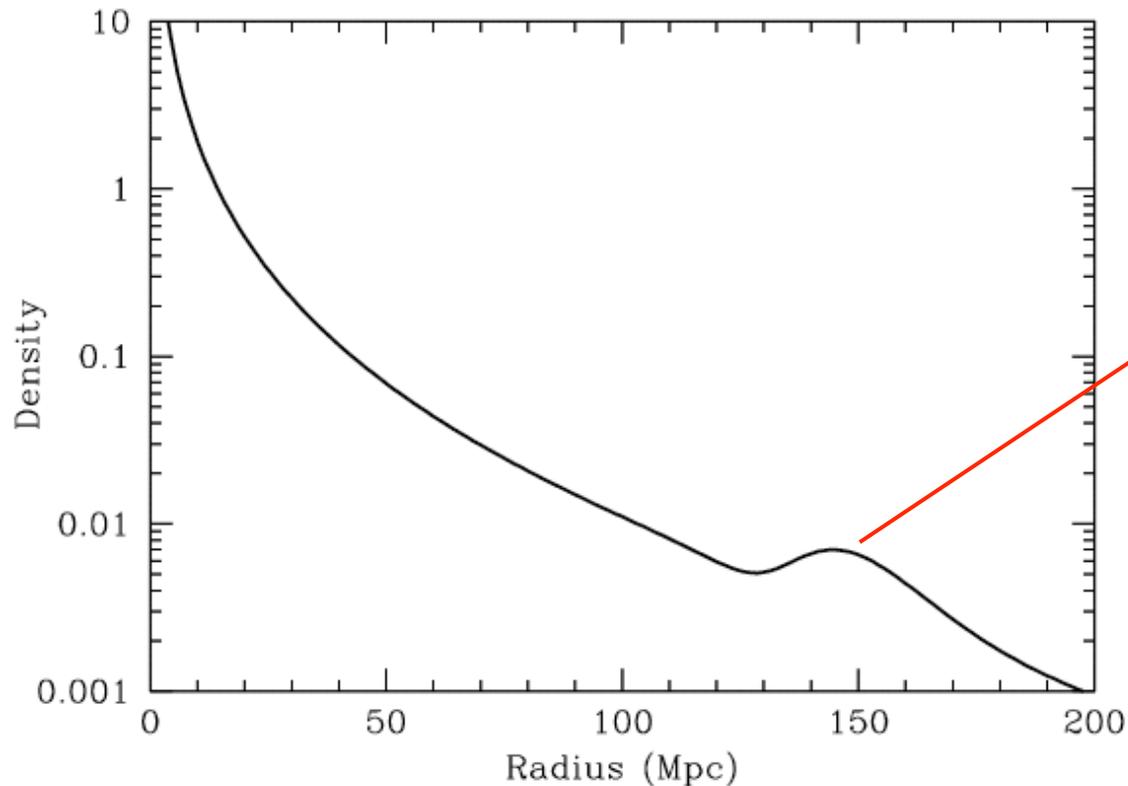
BAOs: a Green function approach



BAOs: a Green function approach



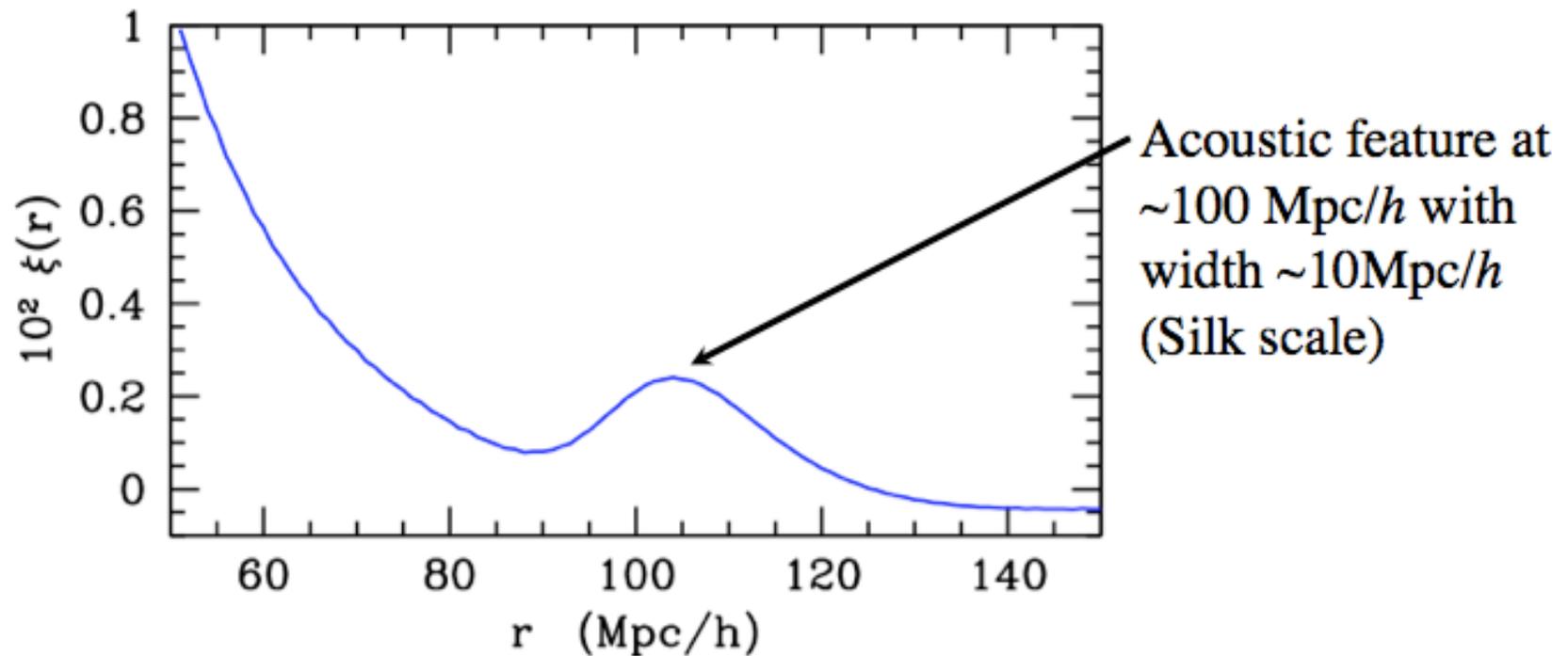
BAOs: the density profile



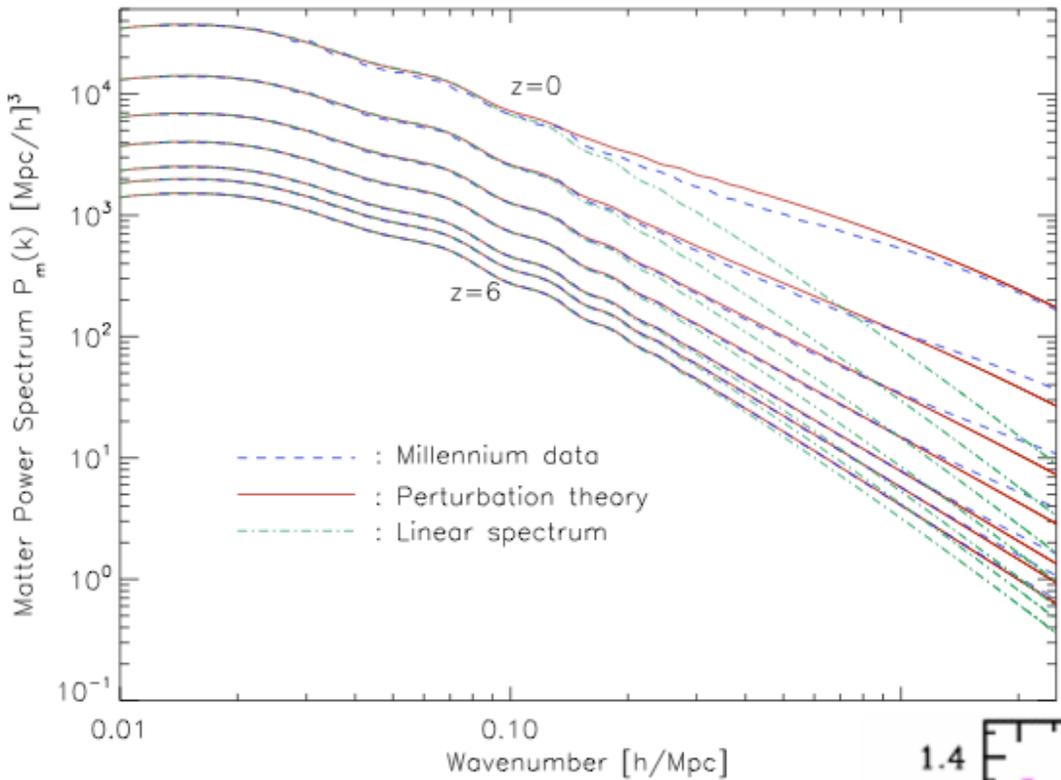
Slight excess
at ~ 150 Mpc
The exact
value
depends on
cosmology but
can be
calibrated
using CMB
anisotropies

BAOs 2-point correlation function

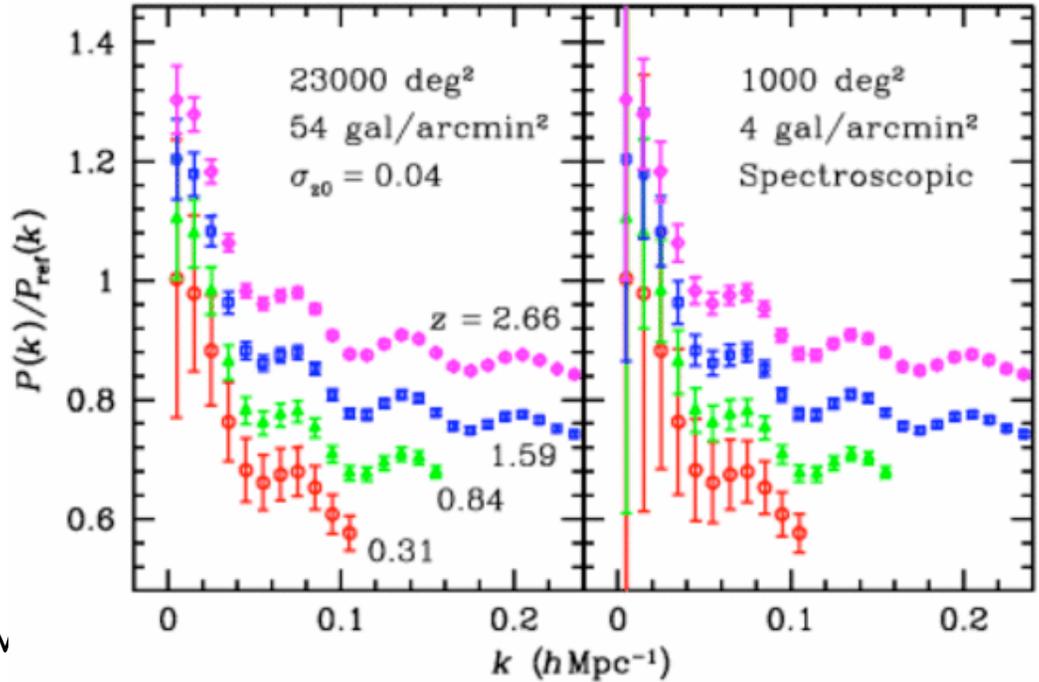
The acoustic bump is frozen into the matter power spectrum and provides a standard ruler with which to measure radial and transverse distances as a function of redshift. Non-linear effects broaden the bump and shift it by $\sim 0.5\%$ (not an issue for first generation experiments but an issue for future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



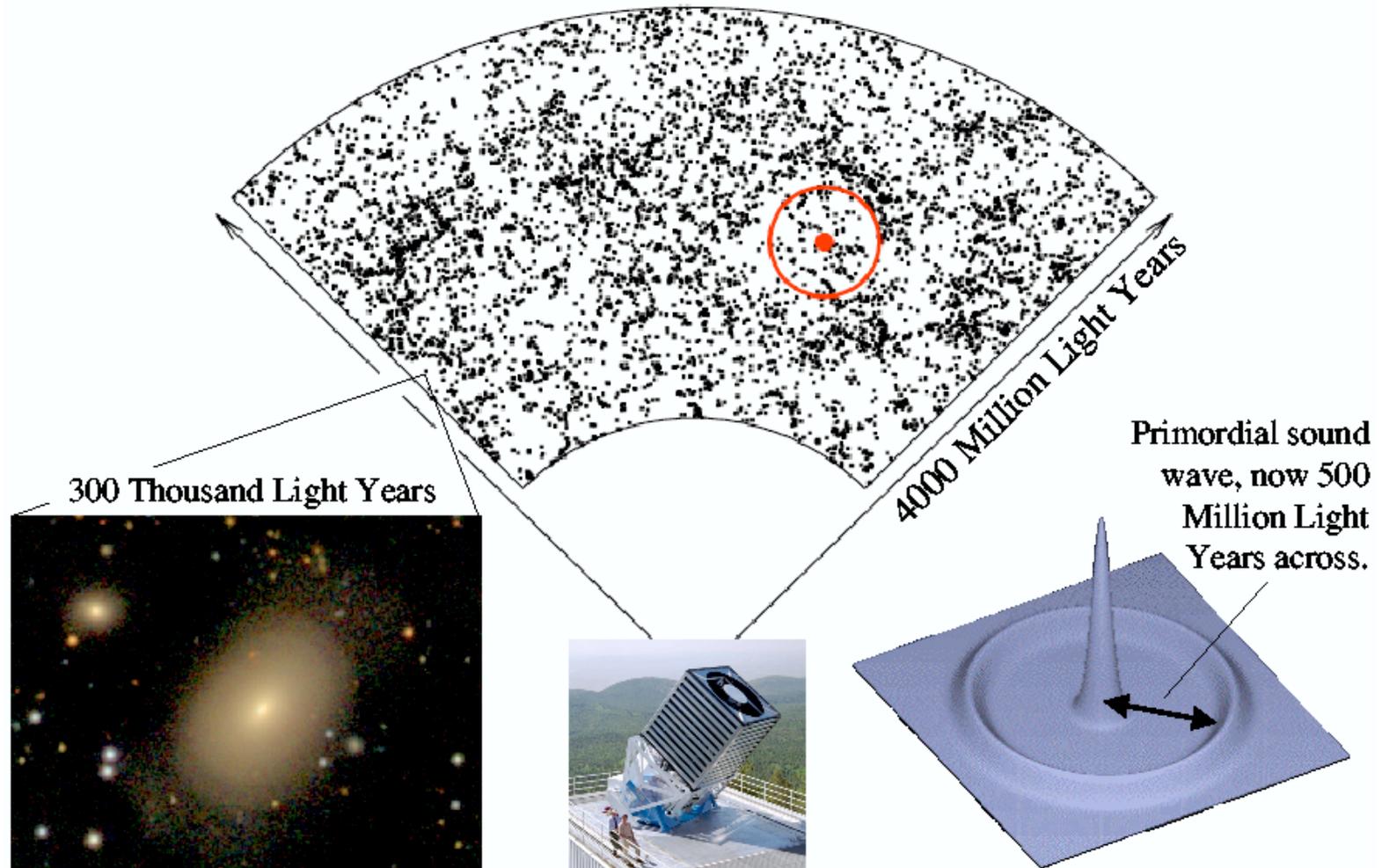
Power spectrum



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

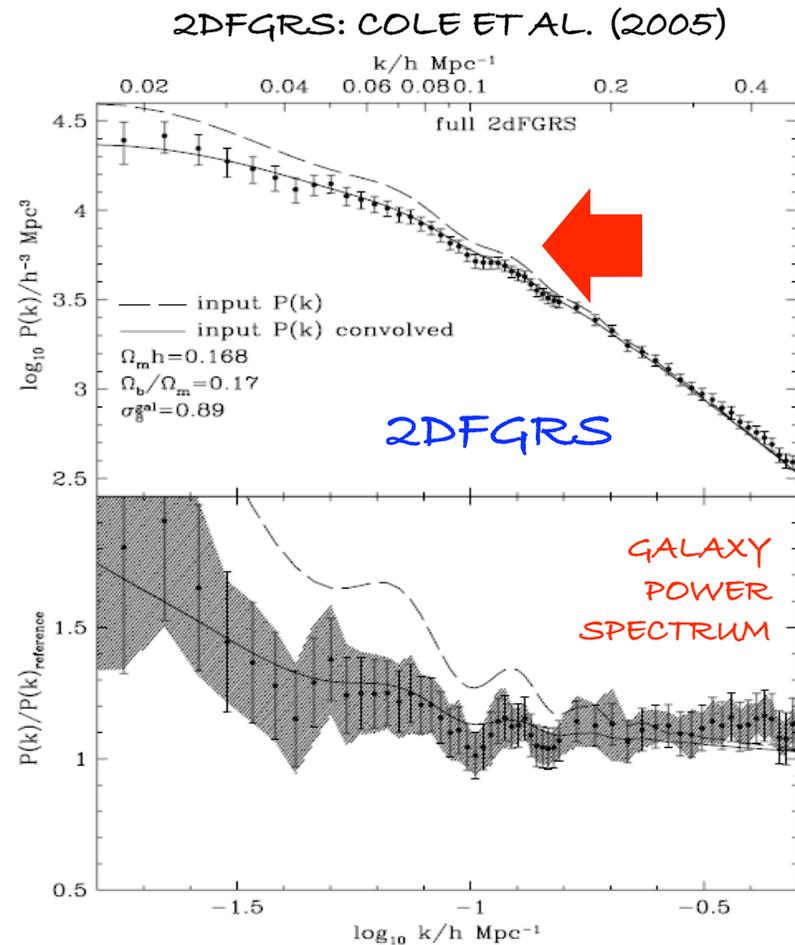
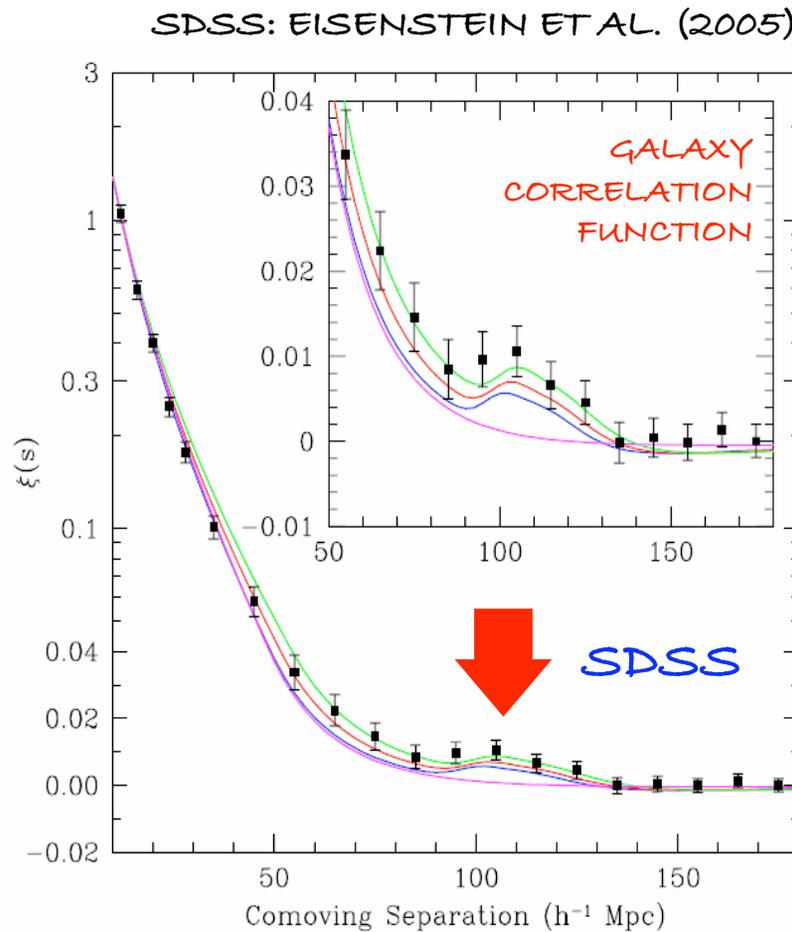


Baryonic oscillations



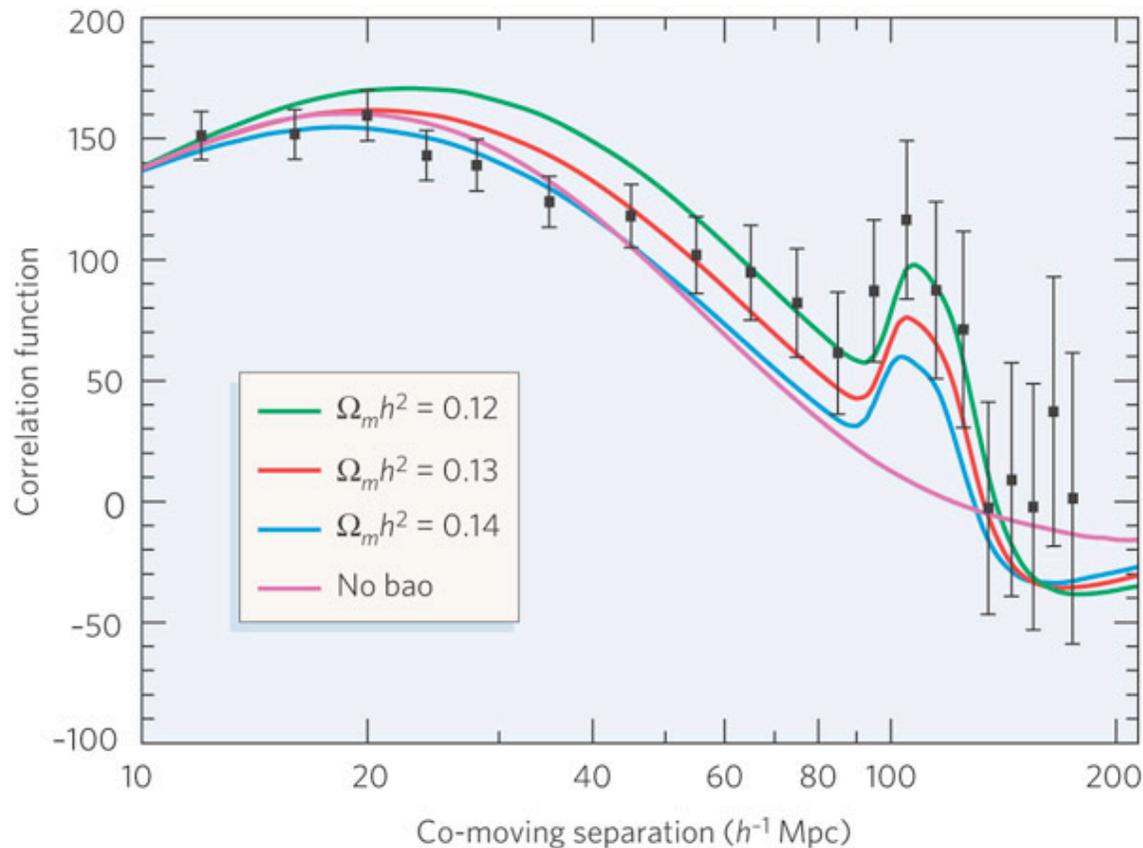
Measuring BAO from LSS

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



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)

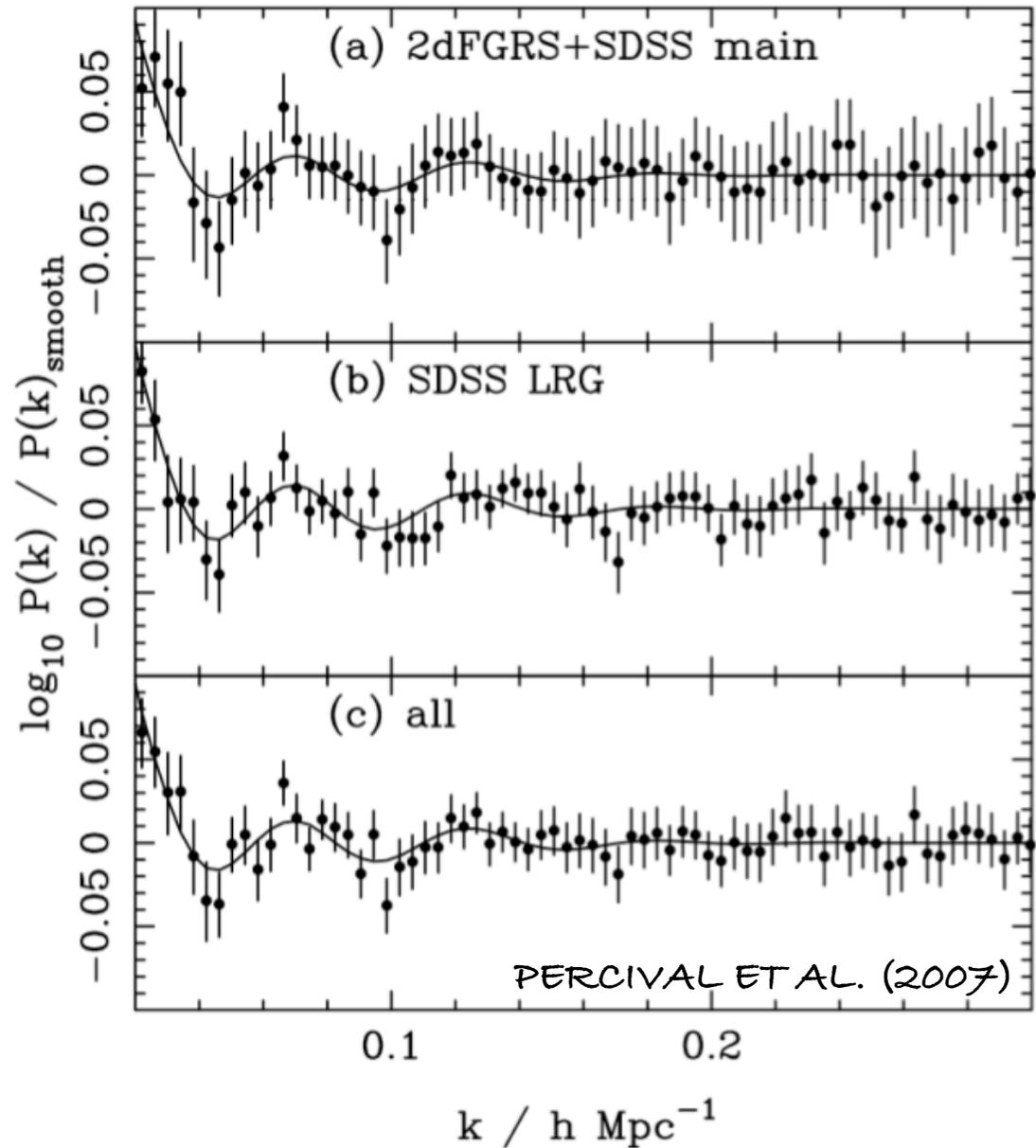
3.4σ detection of BAOs

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

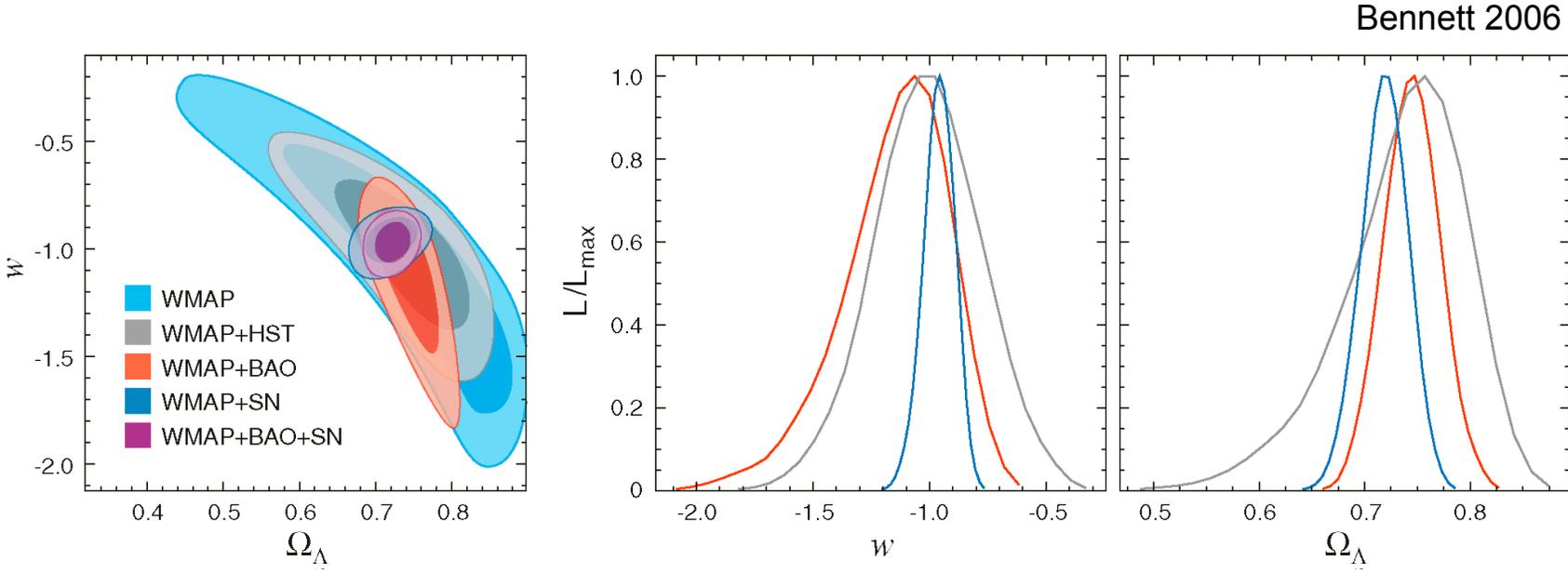
Absolute distance to
 $z=0.35$ determined to
5% accuracy

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 $\Omega_m = 0.256 \pm 0.027$ (68% CL)



The current state of the art



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 $z \sim 0.5$
 3. WFMOS - BAO Dark energy surveys at $z \sim 1$ & $z \sim 3$
- 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 $z \sim 2$; DE via cluster growth
- Formation and assembly of galaxies
 1. GAMA - detailed $z \sim 0$ 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 $\sim 1\%$ 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: $\sim 10^6$ galaxies over $\sim 1 \text{ Gpc}^3$
- 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

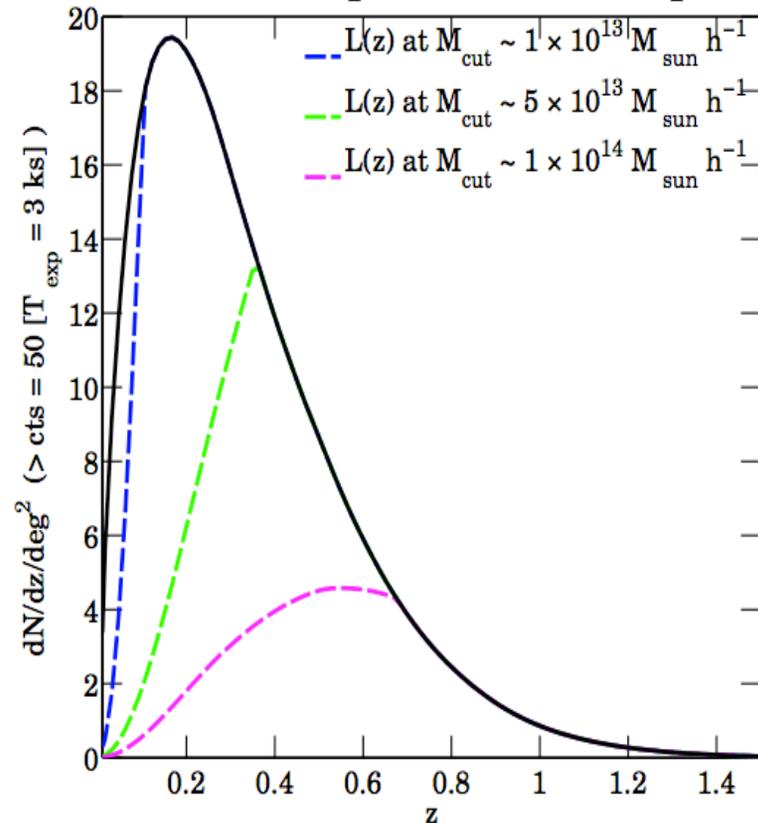
- Primary instrument onboard the Russian Spectrum-Roentgen-Gamma satellite (SRG)
- German-Russian mission. Launched from Baikonur in 2012 (leased by Kazakhstan to Russia)
- L2 orbit
- First all-sky imaging survey in the medium energy X-ray band up to 10 keV with unprecedented spectra and angular resolution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



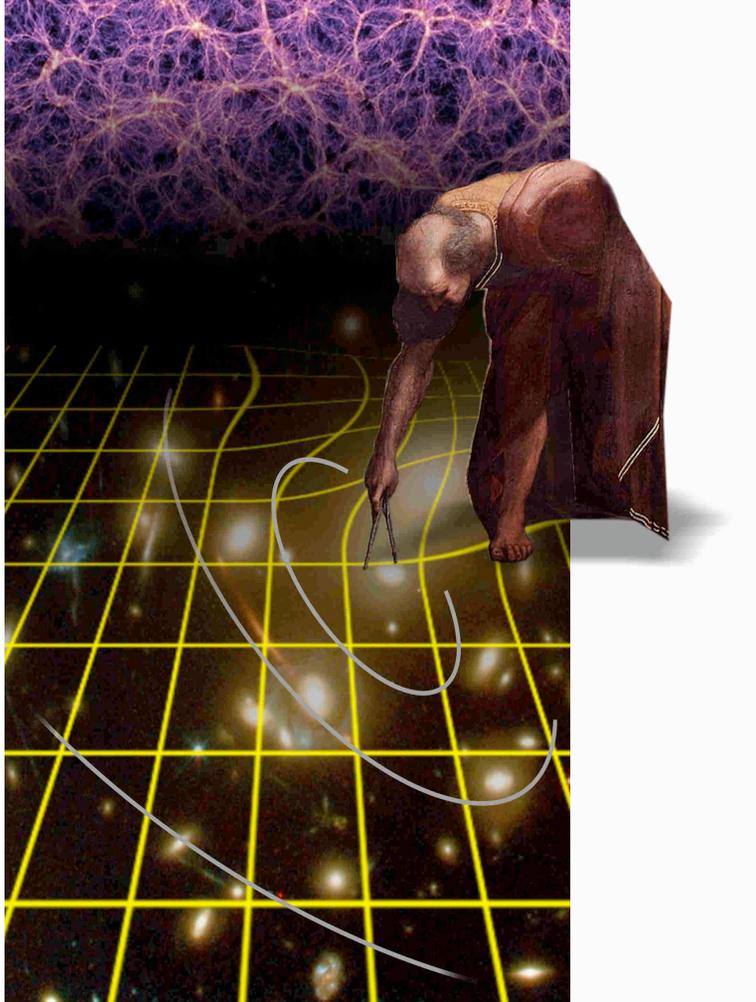
eROSITA science goals

- 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

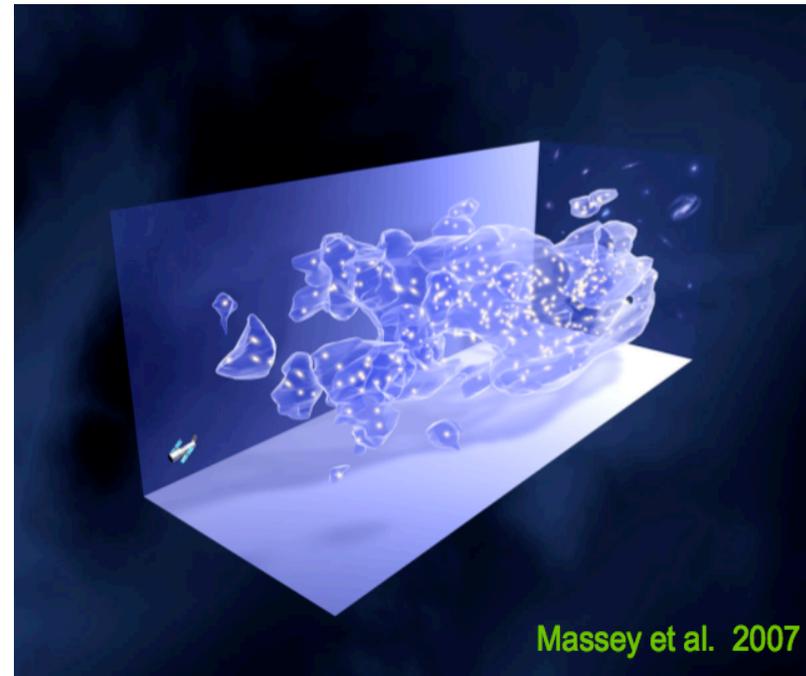


- M-class mission within the Cosmic Vision program of the European Space Agency
- “High-precision survey mission to map the geometry of the dark universe”
- Now in the competitive Definition Phase, launch expected in 2018
- >200 people, 30 Institutions, 7 countries

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



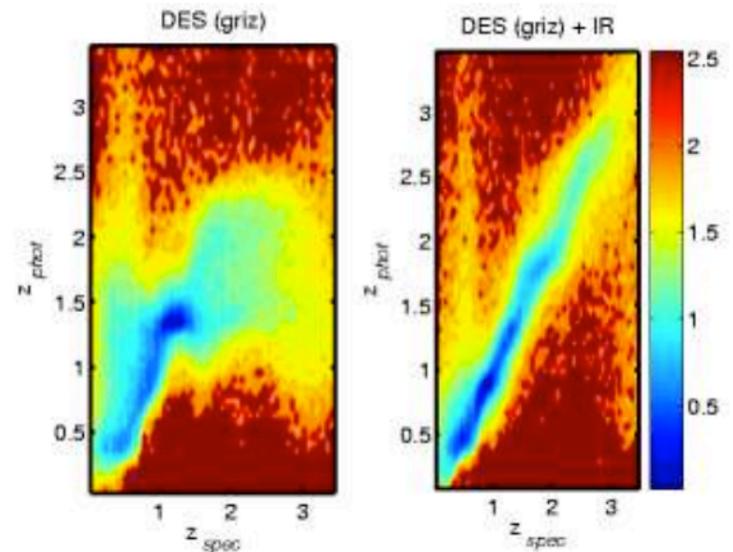
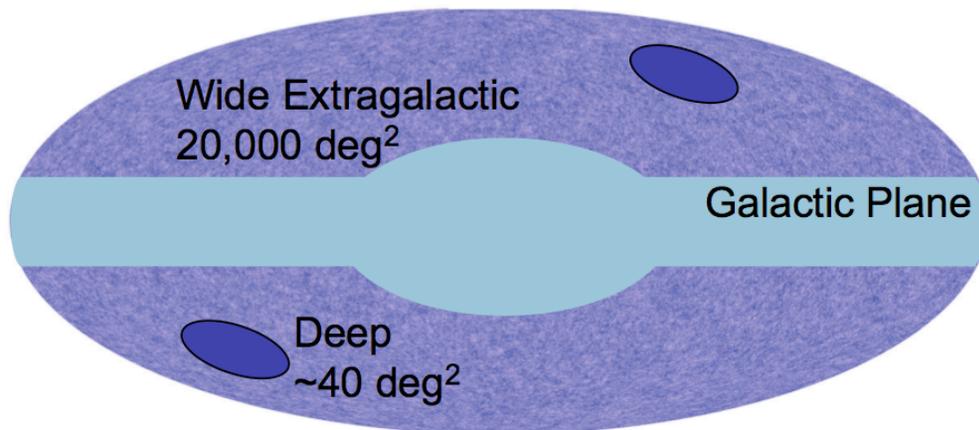
EUCLID imaging surveys

Wide survey (20,000 deg²)

- Galaxy shape measurements in the visible band to $RIZ_{AB} < 24.5$ (10σ) yielding 30-40 resolved galaxies/arcmin² 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)

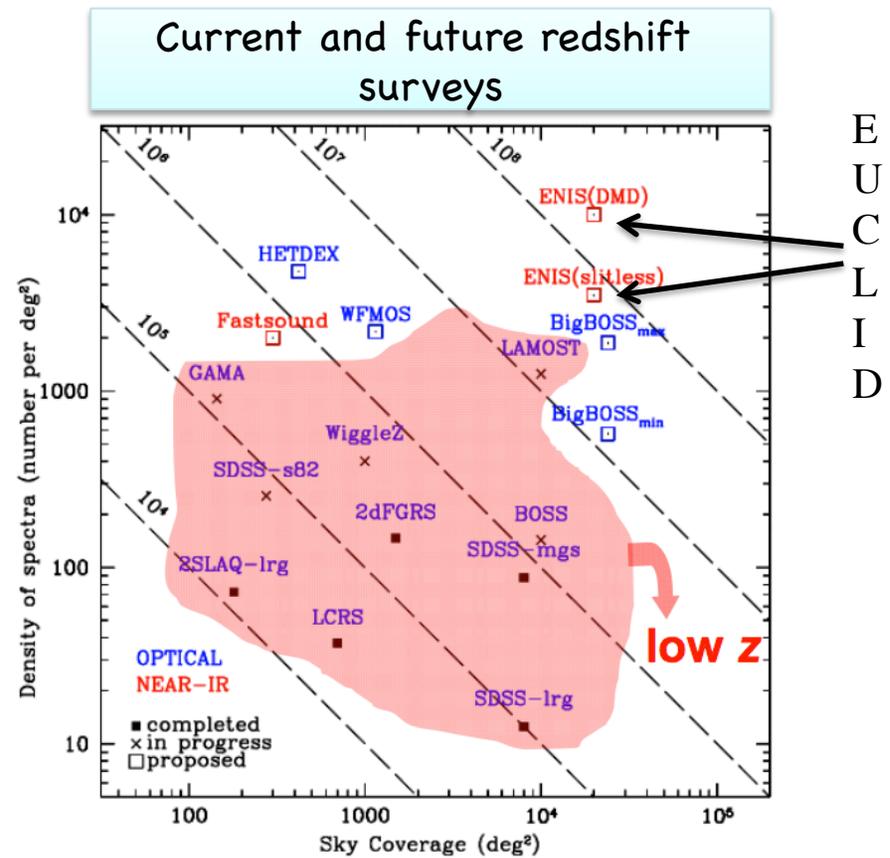
Deep survey (40 deg²):

- 2 mag deeper for both visible and NIR data

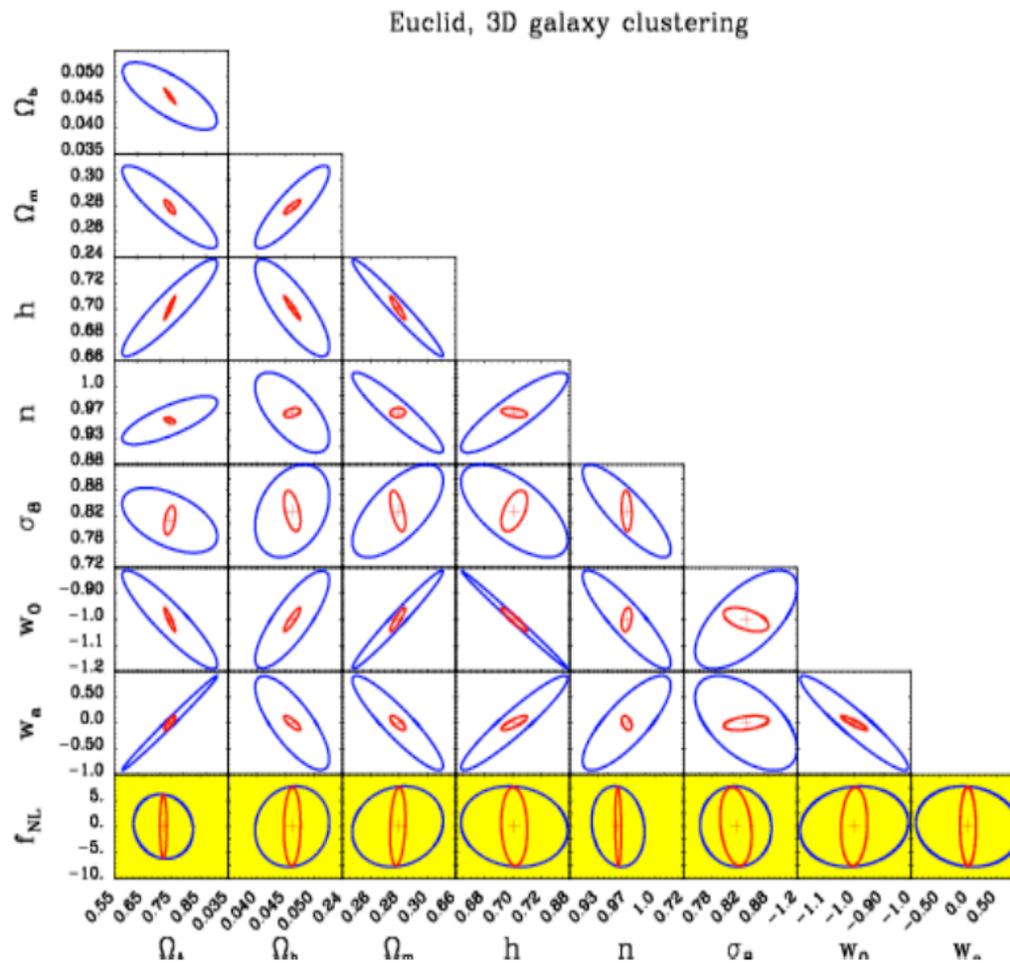


EUCLID spectroscopic survey

- 20,000 deg² in 5 yr
- Slitless spectroscopy with spectral resolution $R=500$ (1-2 μm) in the near infrared
- $F_{\text{H}\alpha} > 4 \times 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2}$ (star-forming galaxies)
- $\sigma_z < 0.001(1+z)$
- Spectroscopic completeness > 0.35 for a total of 70 million galaxy redshifts



Impact of EUCLID



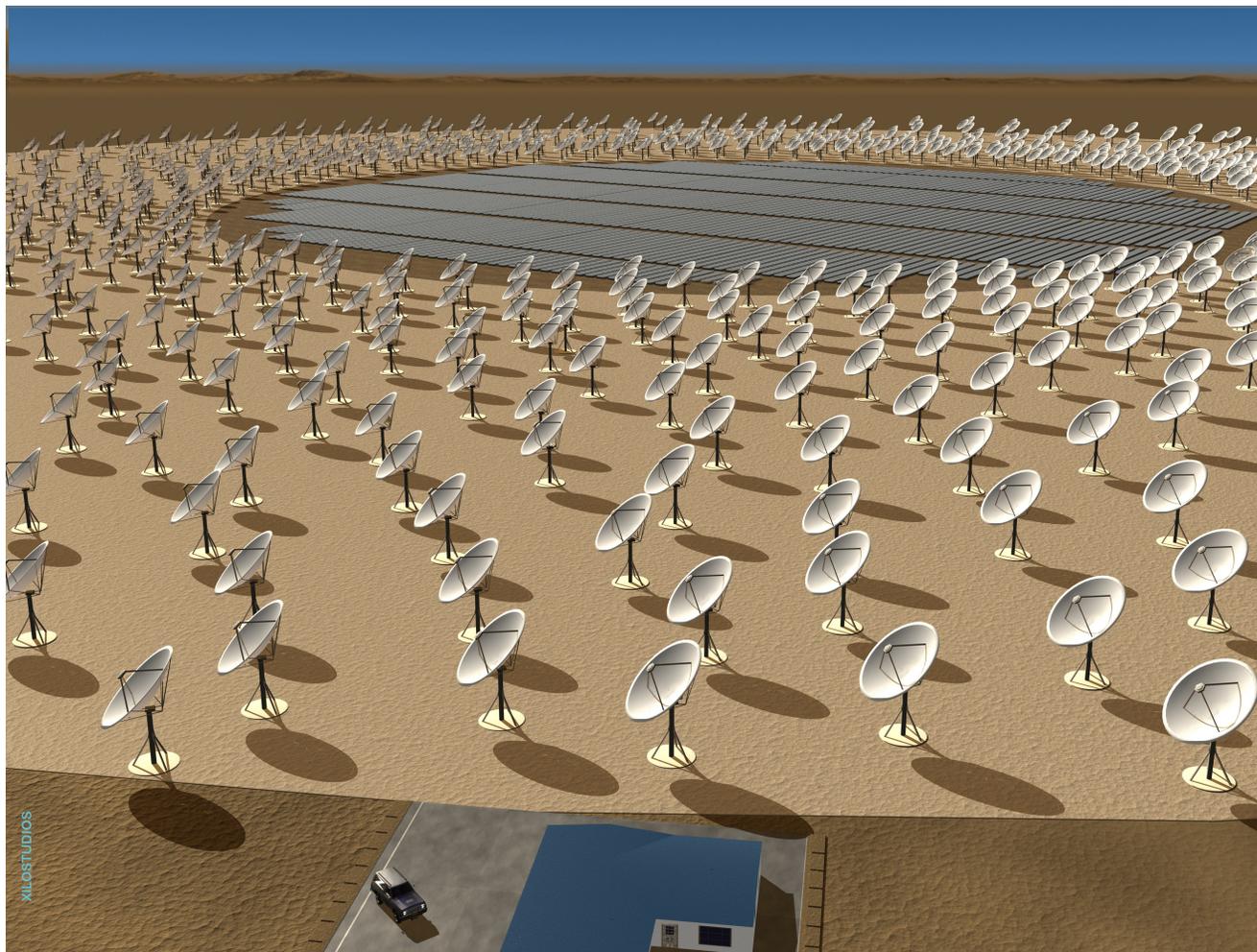
beyond the 10-year horizon

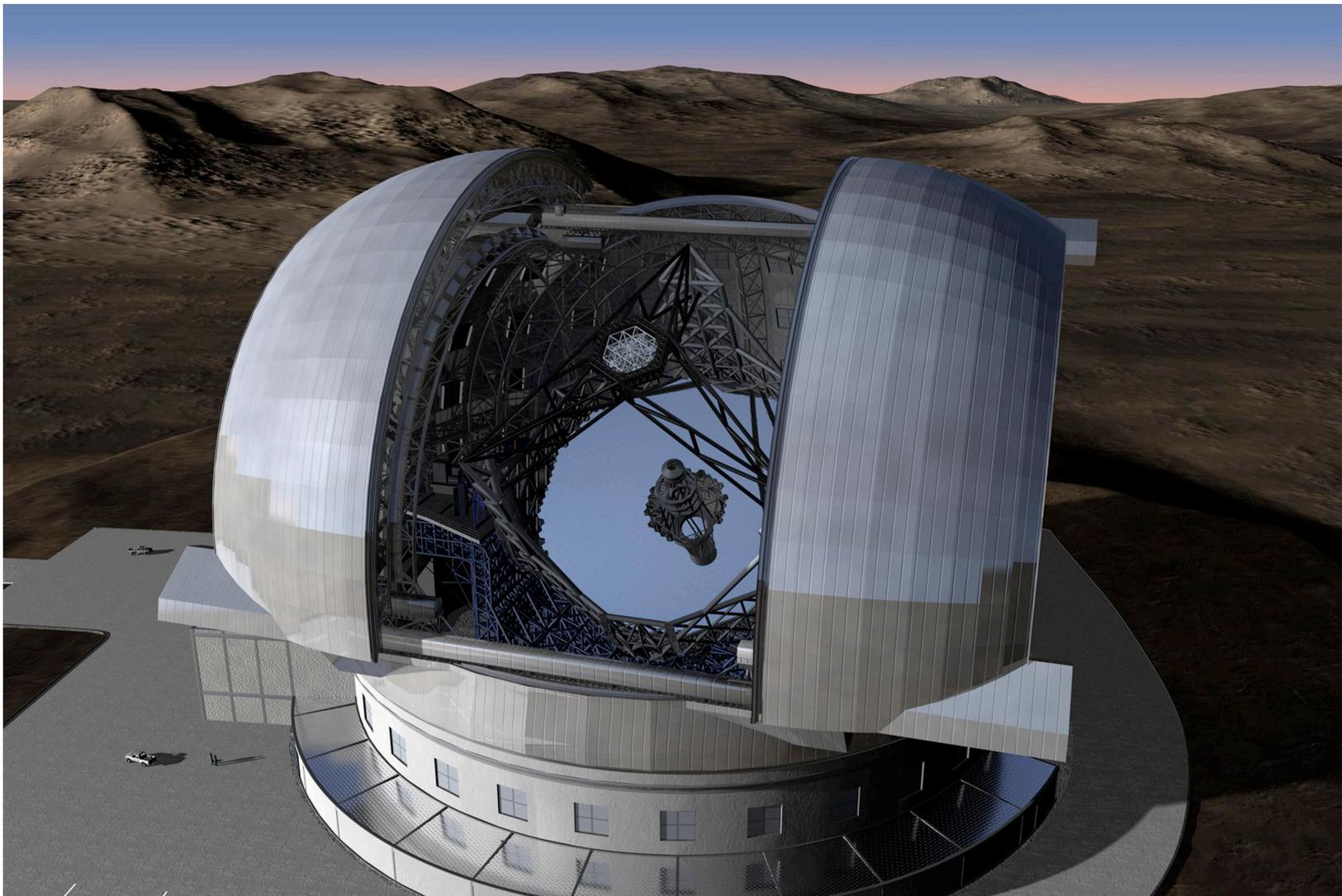
● Some of the BIGGEST advances in capability for cosmology surveys will come on-line just outside the decadal horizon...

- 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



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, inhomogeneous universe, general oscillatory models, Milne-Born-Infeld model, k-essence, chameleon, k-chameleon, $f(R)$ gravity, quiescence, 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...