

Observational Cosmology

Lecture V

C. Porciani

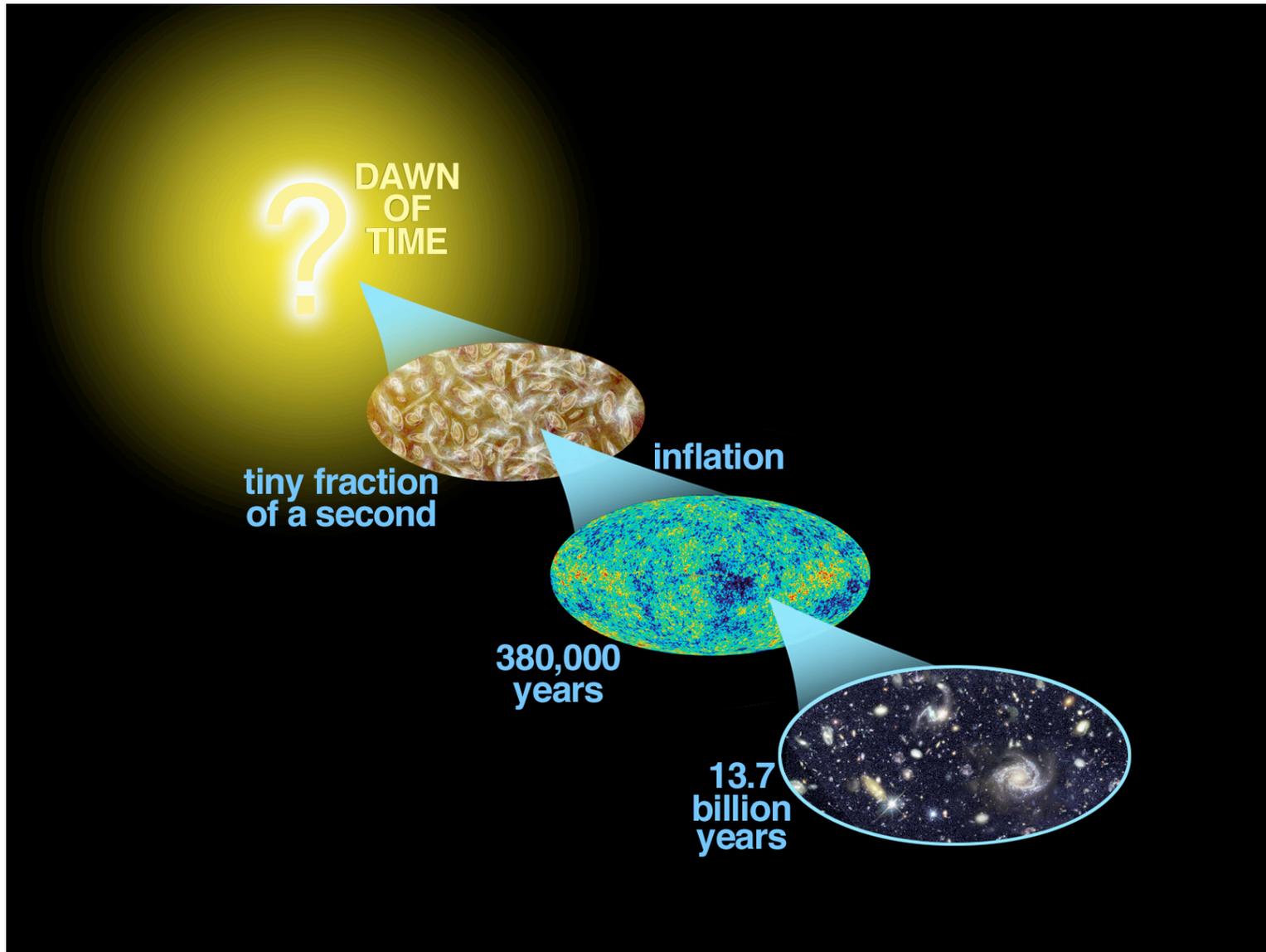
AIfA, Uni-Bonn

Summer Semester 2009

Questions?



Plan of these lectures



What do we mean by “the large-scale structure” of the Universe?

What is a “massive redshift survey”?

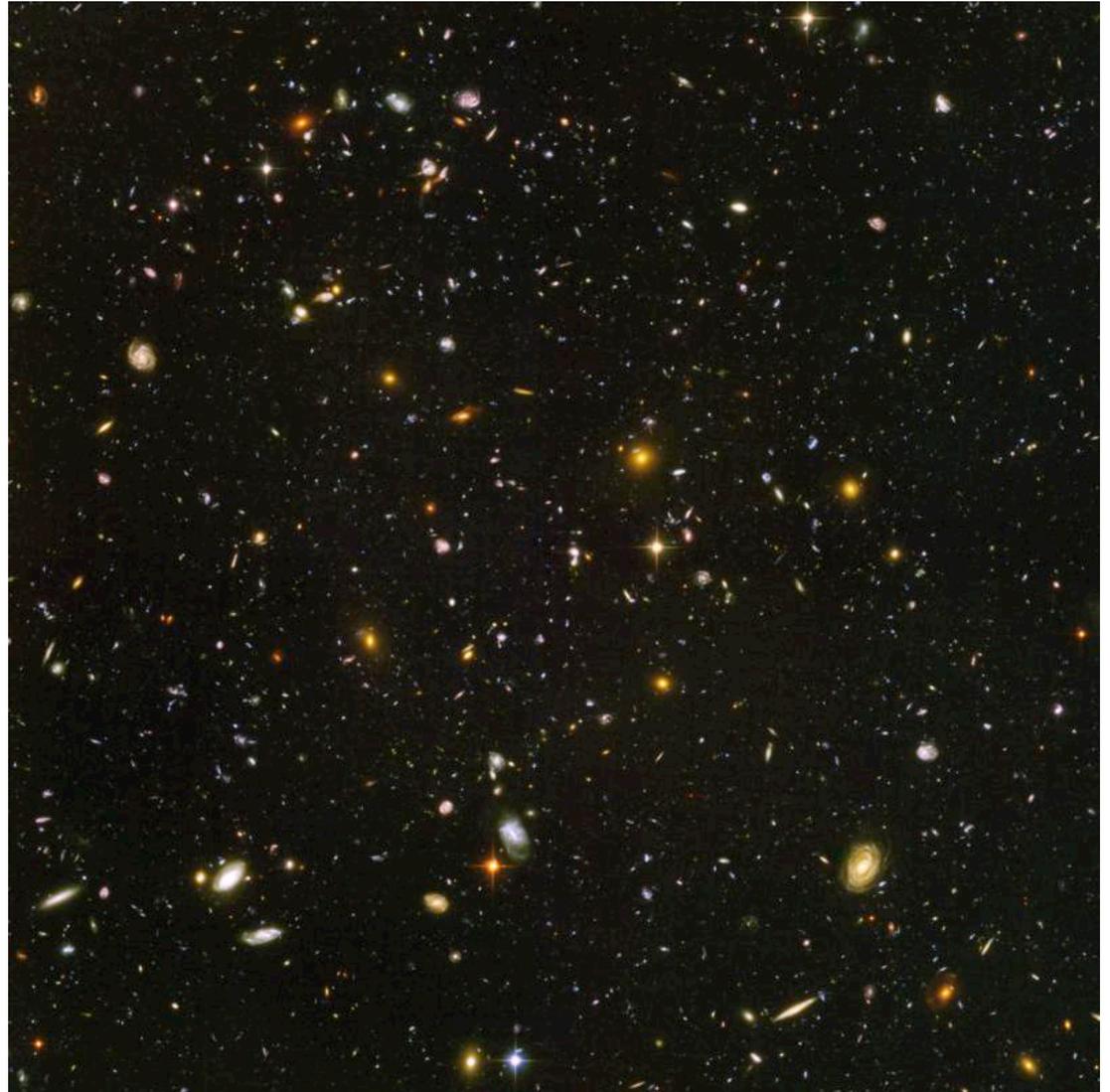
Courtesy of the HUDF team

The deepest image of the universe in the optical waveband

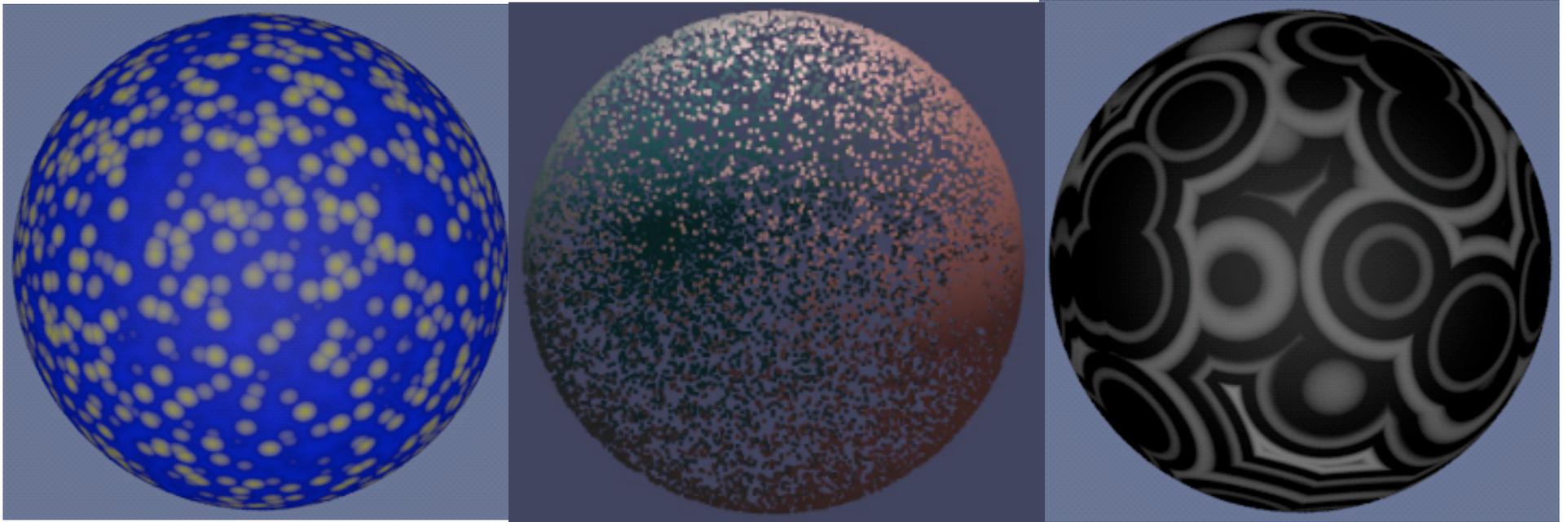
It contains $\sim 10^4$ galaxies in a solid angle corresponding to 1/50 of the Moon

The whole sky corresponds to 12.7 million times more solid angle

Galaxies are the fundamental building blocks of the distribution of luminous matter



How are galaxies distributed on the sky?



The Lick galaxy survey

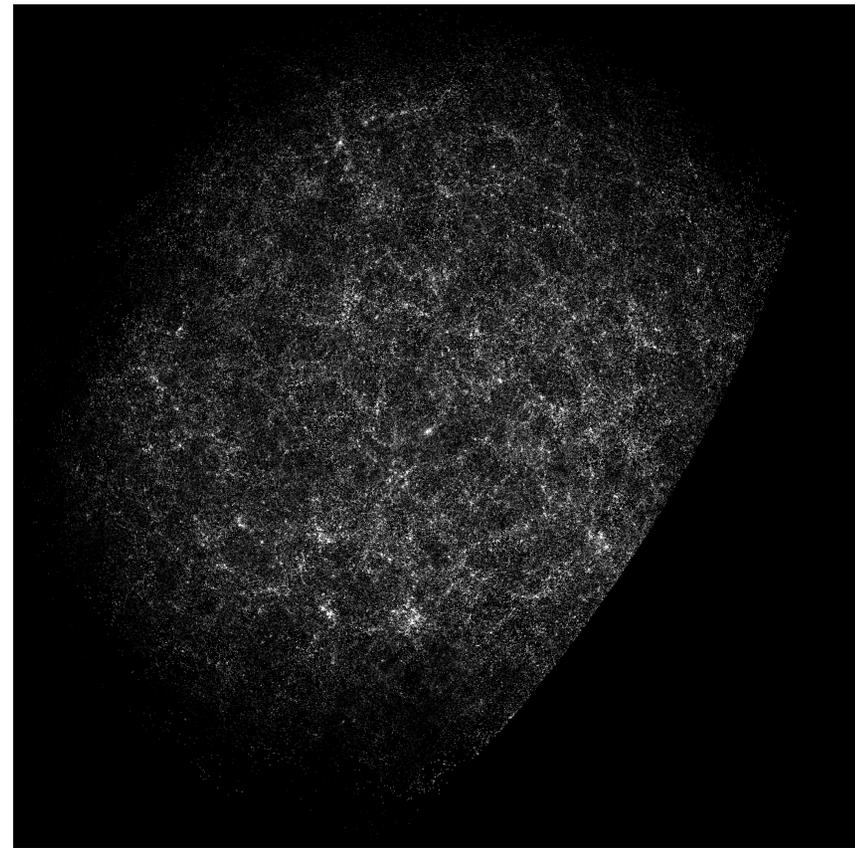
The Lick survey conducted at the Lick observatory in Santa Cruz during the 1950s recorded the position of 10^6 galaxies in 10 years.

It provided the first evidence that **galaxies are not distributed at random on the sky**

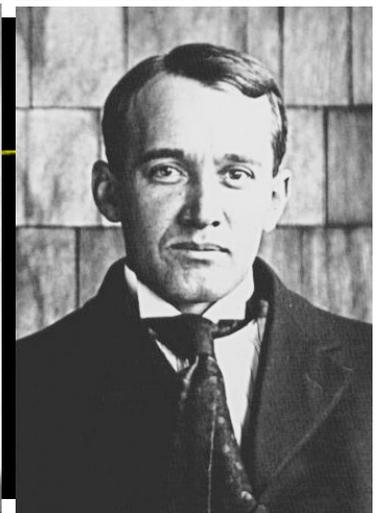
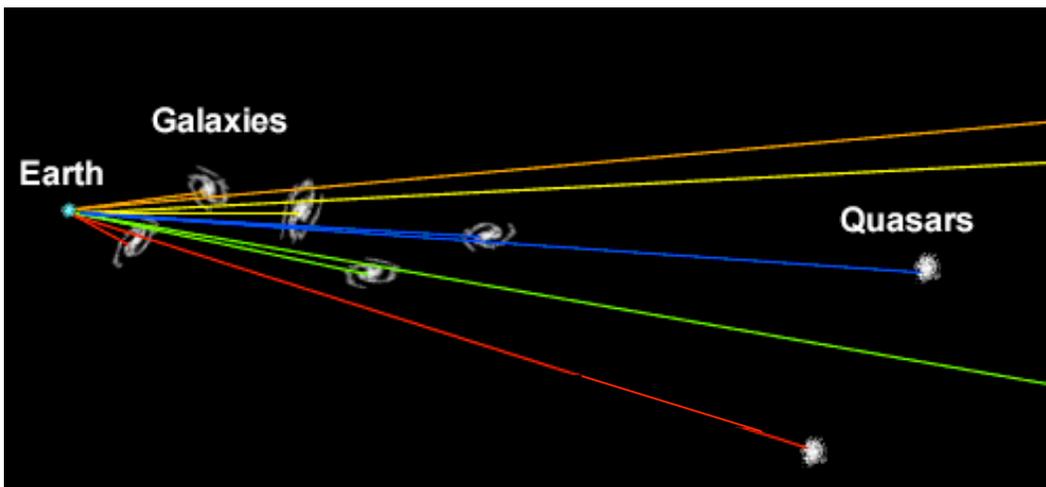
(Totsuji & Kihara 1969, Peebles & Hauser 1974, Groth & Peebles 1977)

Projected filamentary structure is evident but what is the corresponding 3D distribution?

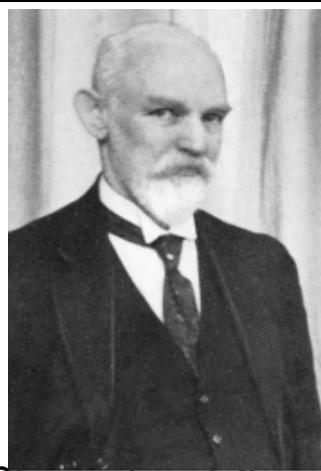
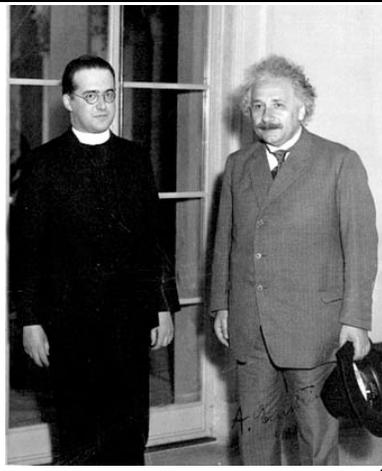
Shane & Wirtanen 1967



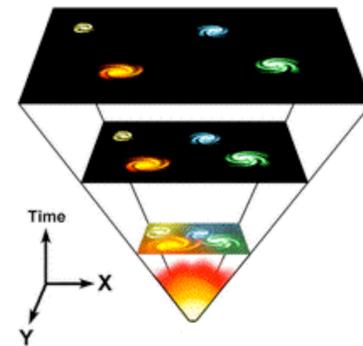
Adding the third dimension



C. Porciani

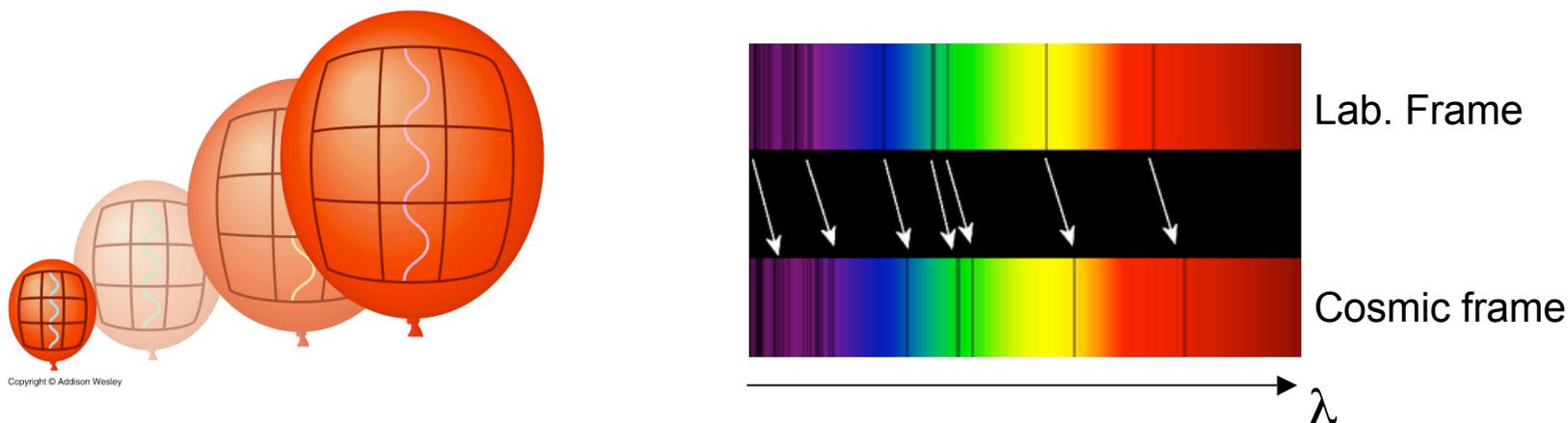


Observational Cosmology



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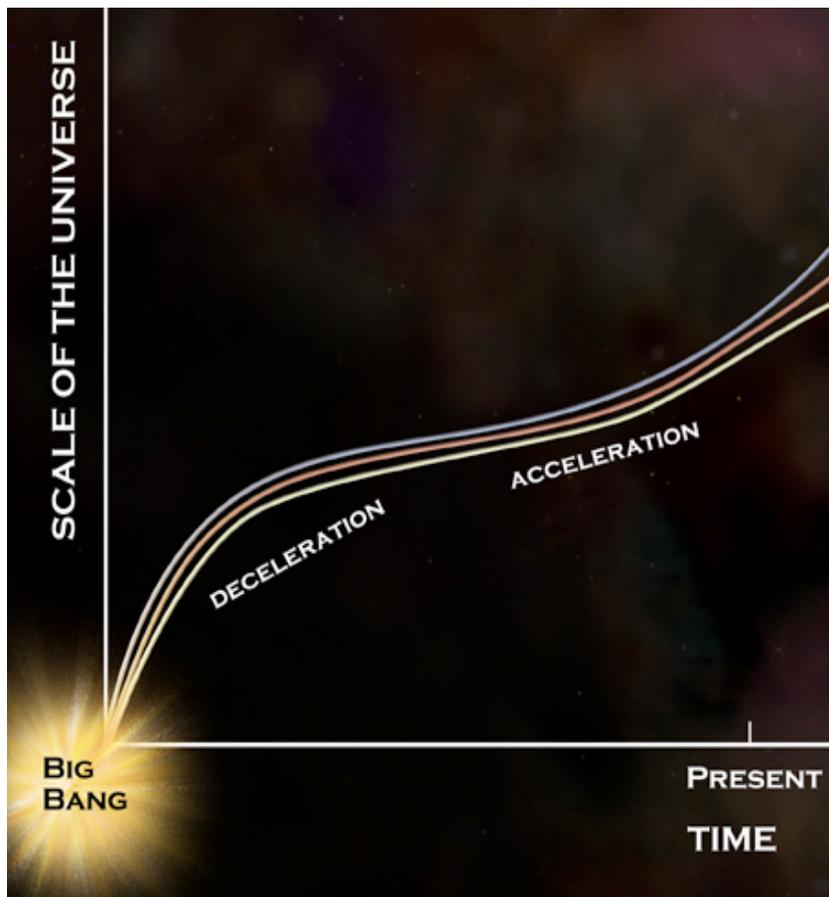
Adding the third dimension



- Cosmological redshift: the wavelength of EM signals is stretched by the cosmic expansion.
- Spectra are shifted in frequency towards the red by a factor $1+z = (\text{present-day size of the universe})/(\text{size at photon emission})=a(t_0)/a(t_{em})$

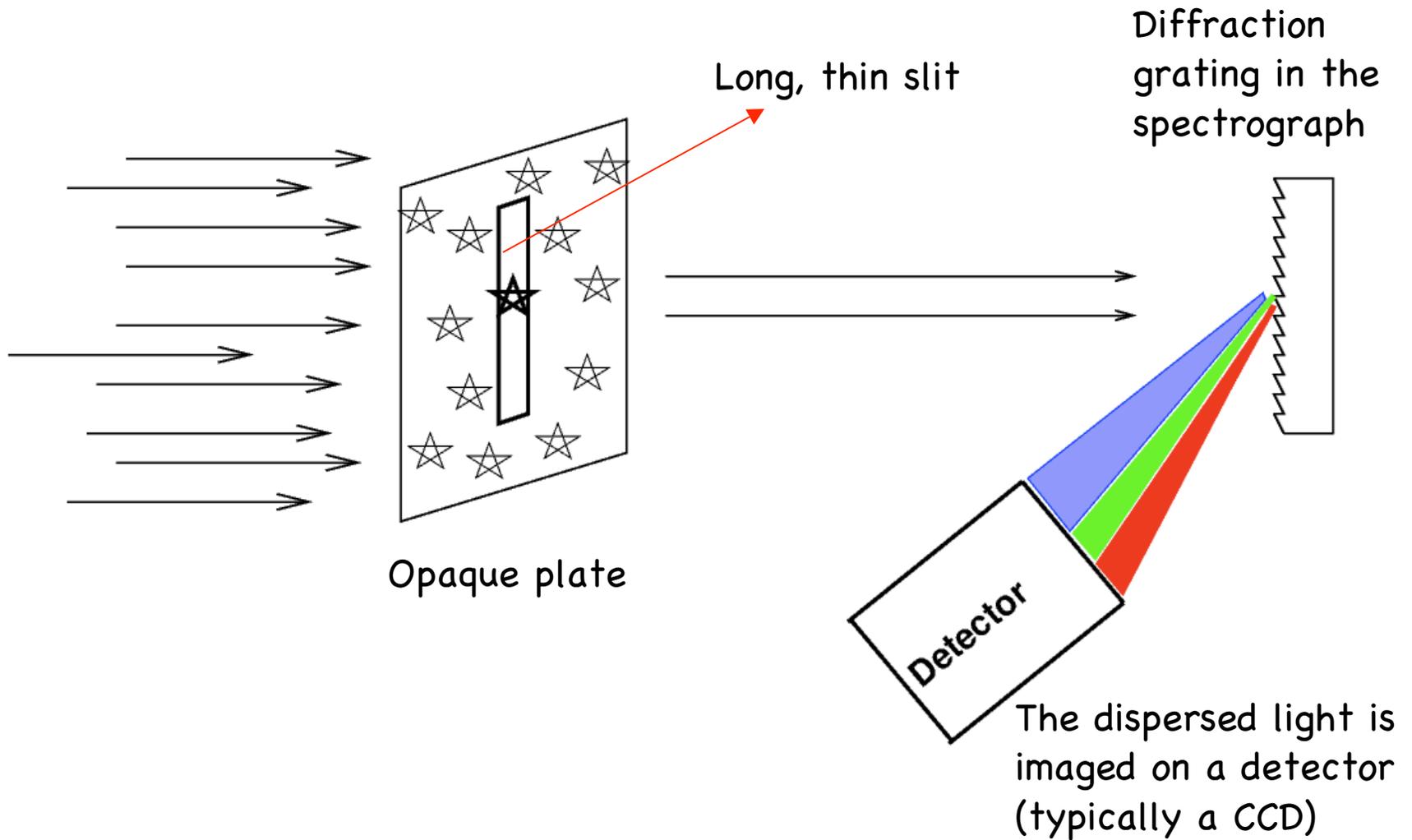
$$1 + z = \lambda_{obs} / \lambda_{em}$$

Adding the third dimension - II

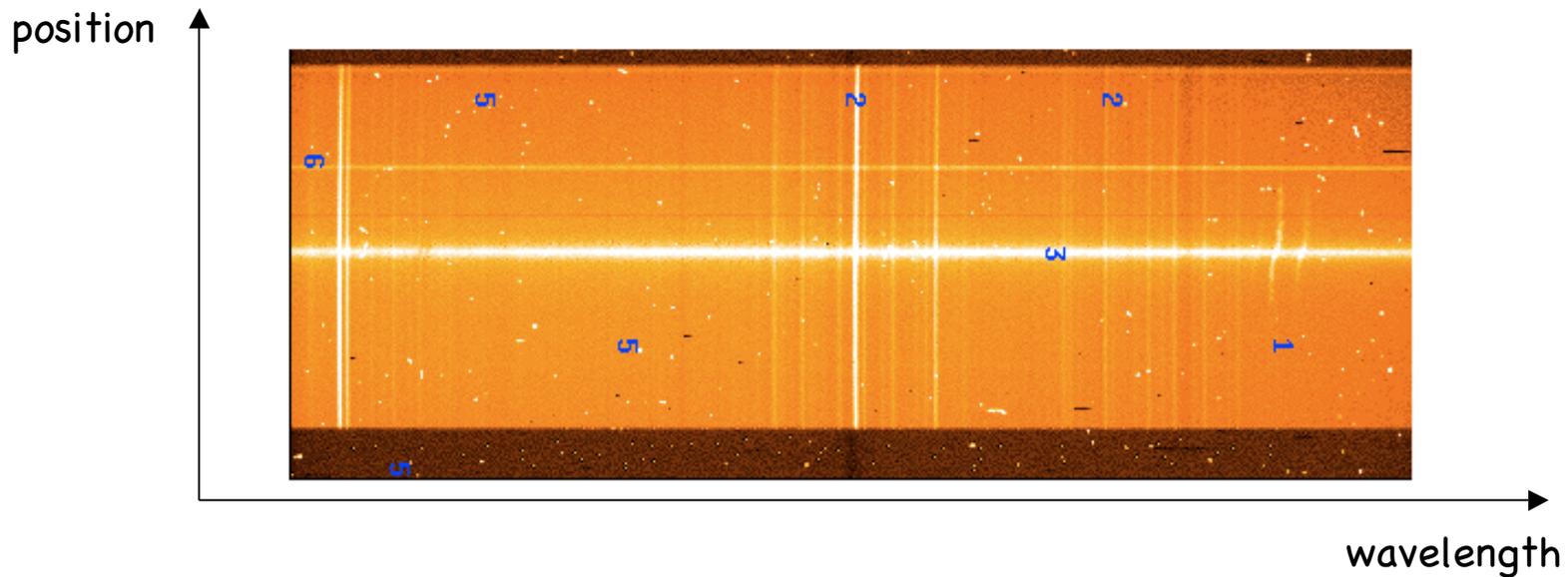


- Knowing the cosmic expansion history, $a(t)$, would allow us to convert the ratio of scale factors into a look-back time:
 $t_{\text{now}} - t_{\text{em}}$
- Then, taking into account that EM signals propagate at constant velocity, c , one could derive the radial distance on our past-light cone corresponding to a given cosmological redshift.
- Measuring redshifts is then necessary to study the galaxy distribution in three dimensions

Slit spectroscopy



A raw galaxy spectrum



- This is the typical output of a spectrograph mounted on a telescope.
- Can you identify the origin of the different features?

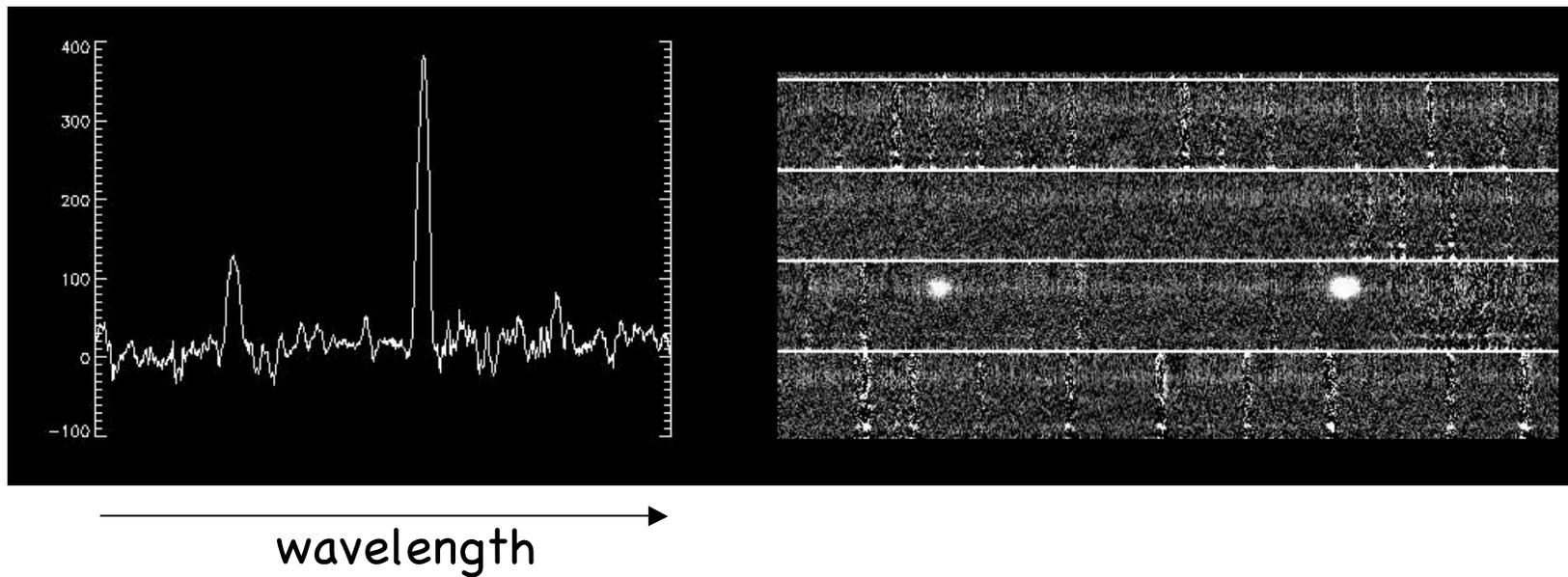
Answer

1. Emission lines from the observed galaxy (note that the galaxy is rotating)
2. Emission lines from the Earth's night sky
3. Continuum from the observed galaxy
5. Cosmic rays
6. Continuum from a nearby star

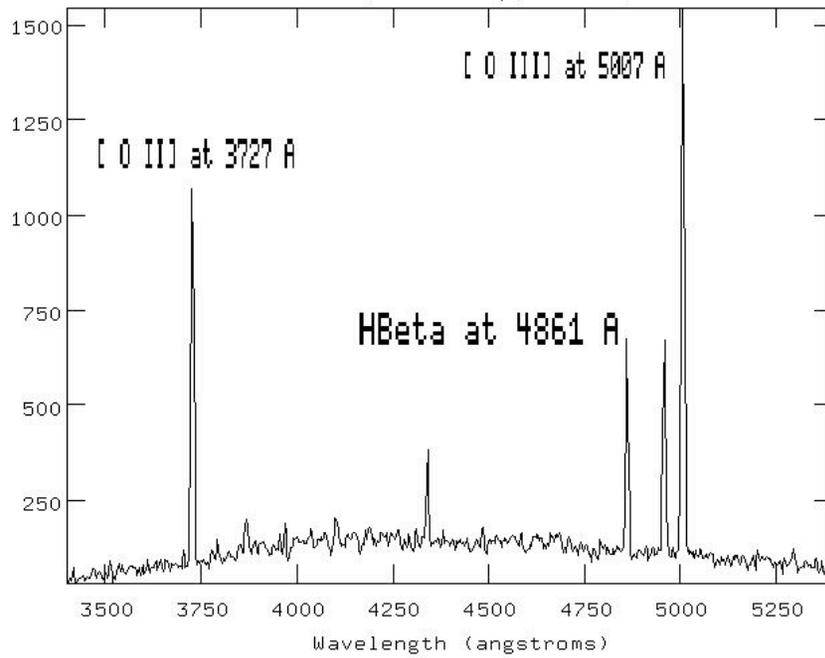
Spectrum of a galaxy with a faint continuum

1D spectrum

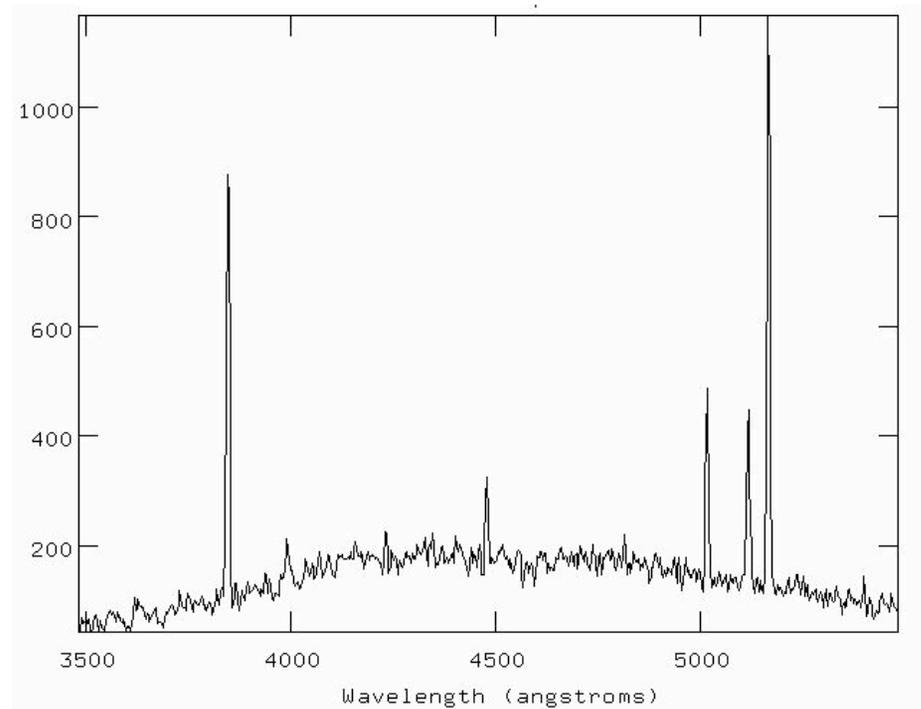
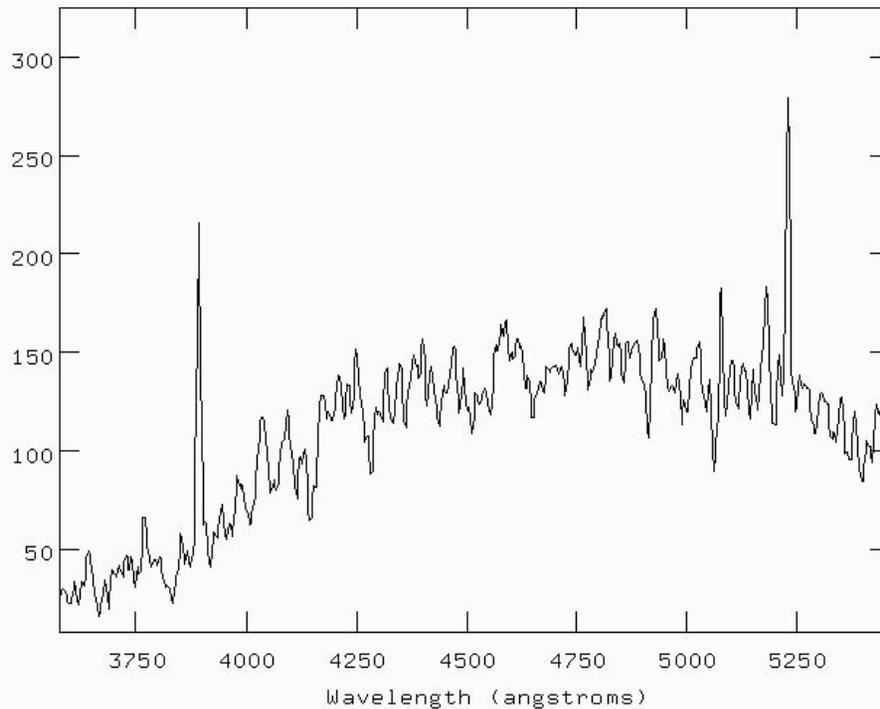
2D spectrum



Measuring galaxy redshifts

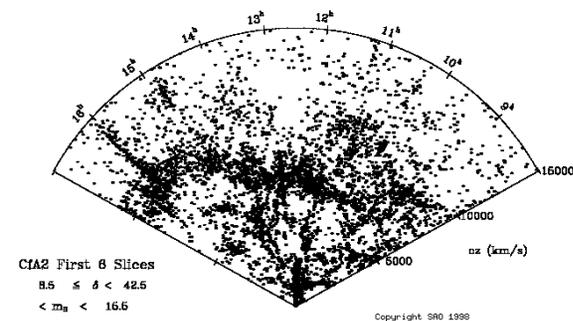
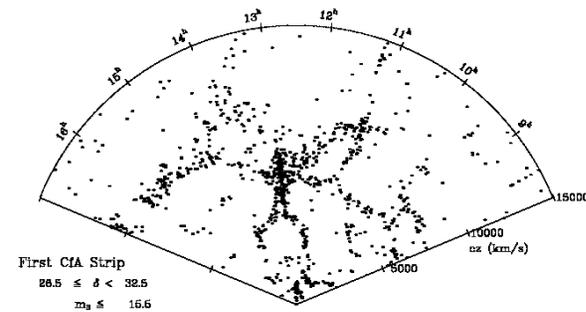


Template spectrum at $z=0$

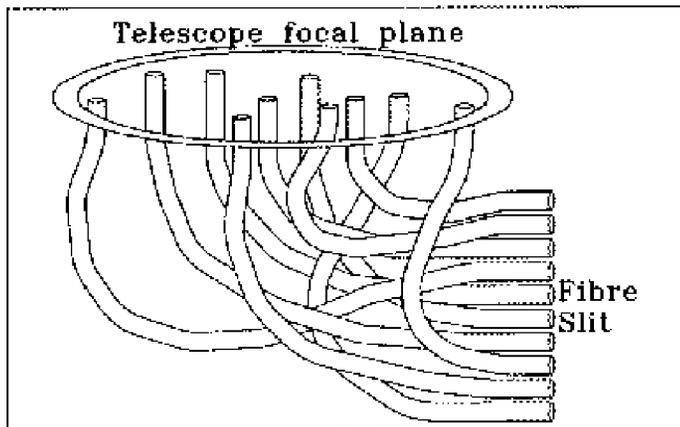


Early redshift surveys: revealing the LSS

- Taking spectra of faint galaxies needs large telescopes and long integration times!
- The first redshift surveys were completed in the 1980s and 1990s (e.g. CfA, IRAS, Las Campanas)
- They measured 10^3 to 10^4 galaxy redshifts. Demonstrated the existence of LSS but not good enough for statistics

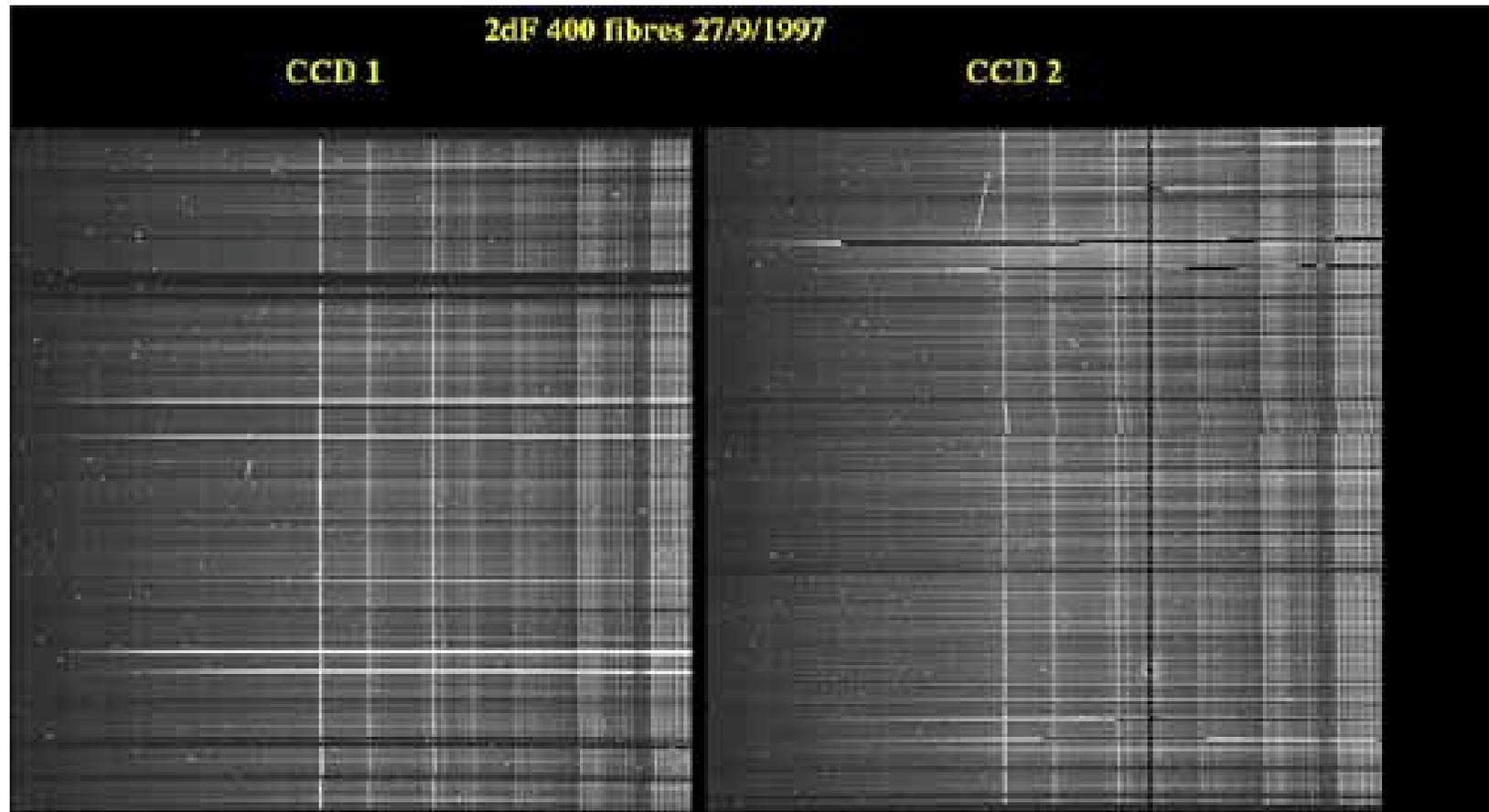


Multi-object spectroscopy



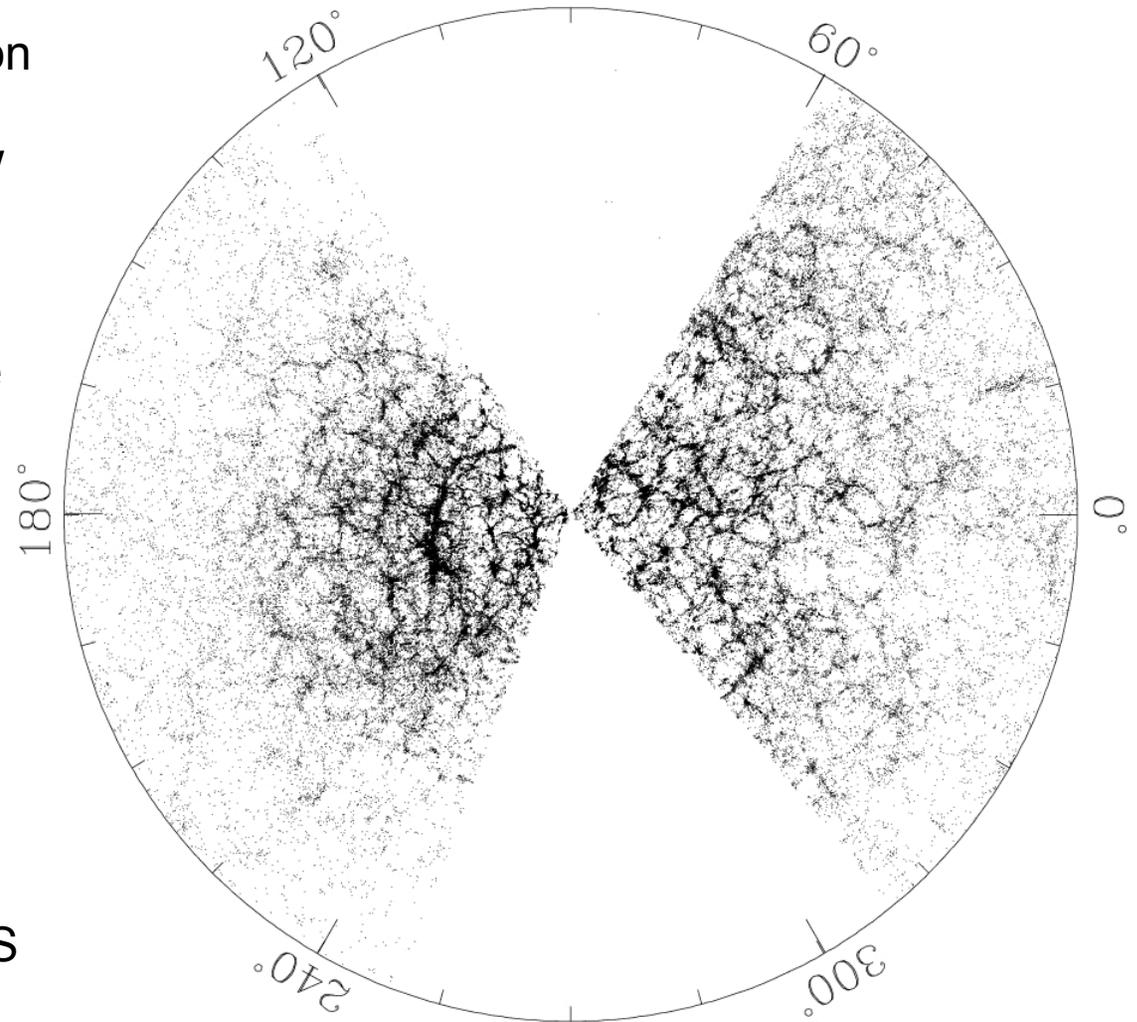
- Single-slit spectroscopy does not make full use of the imaging capability of a telescope: several objects are imaged but only one is used
- Multi-slit and Fibre-fed spectrographs solve this problem.
- In the latter case, a set of optical fibers are positioned in the focal plane of the telescope so that each is illuminated by a target object. The fibers are then connected to a series of position in the spectrograph

Multi-object spectra

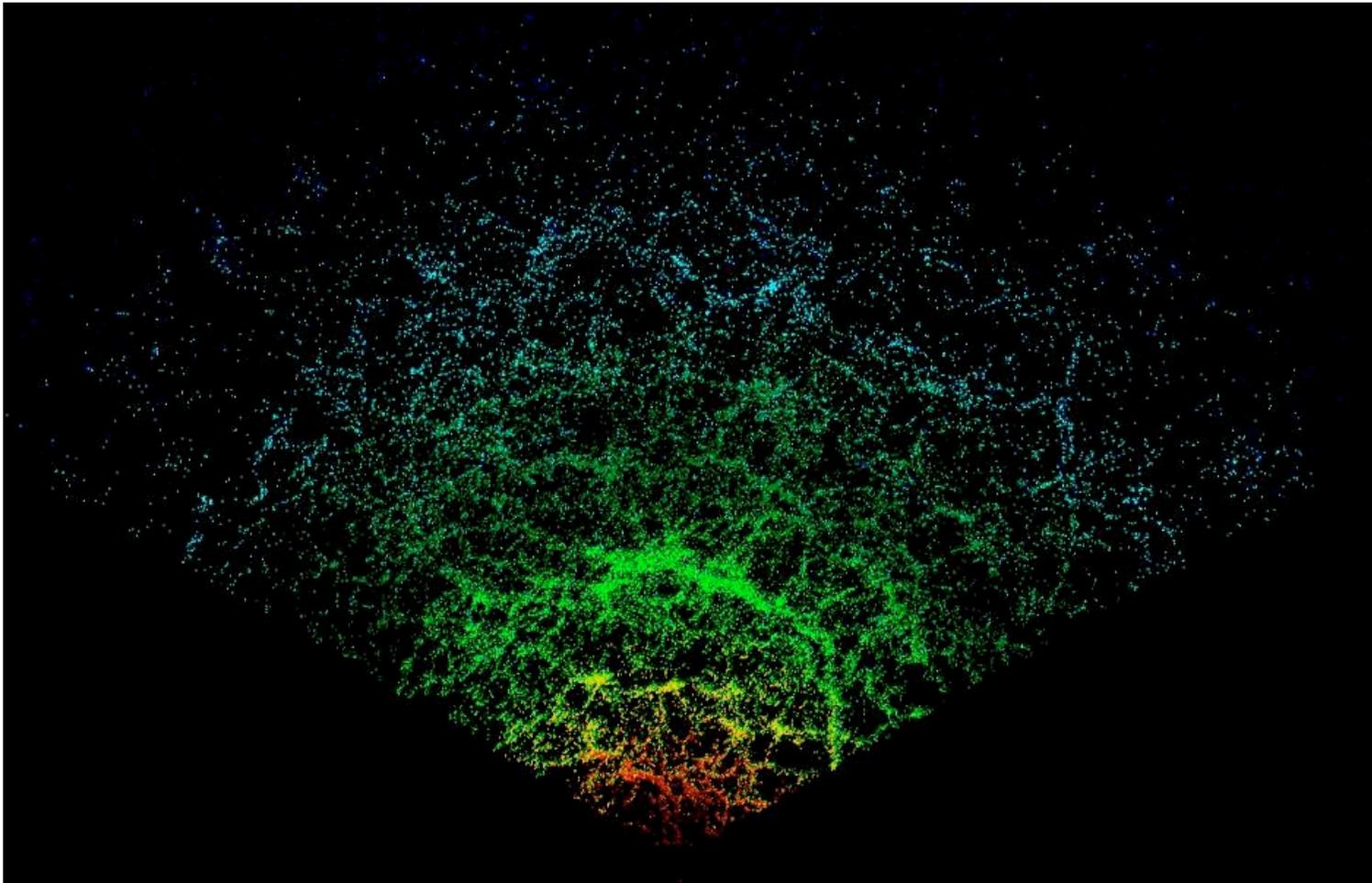


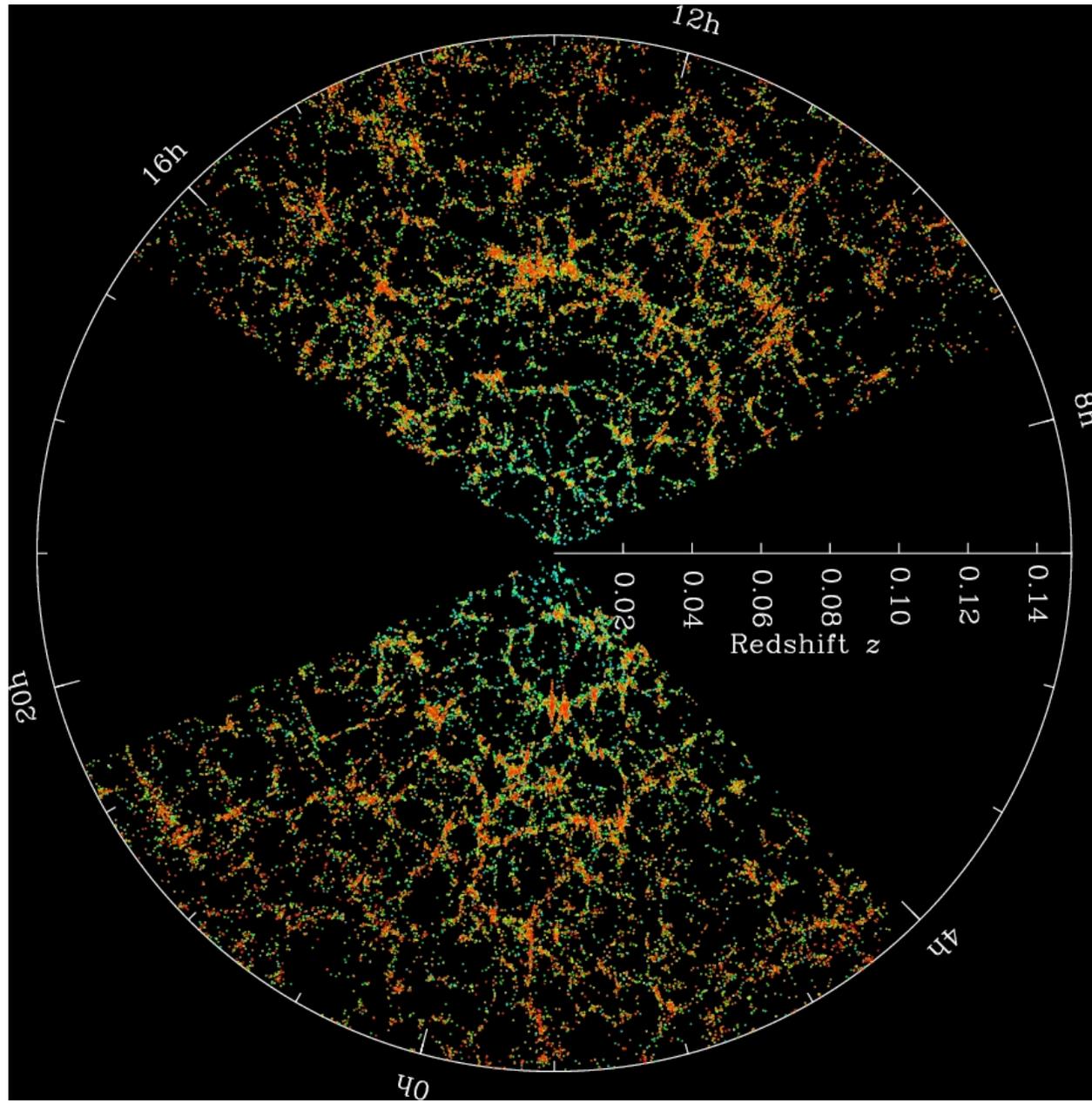
Massive redshift surveys

- Multifibre technology, digitalization and multiobject spectrographs now allow us to measure redshift of millions of galaxies on a time scale of a few years.
- Recently completed or ongoing surveys: (local) 2dF, SDSS, 6dF
(high-z) VVDS, DEEP2, zCOSMOS



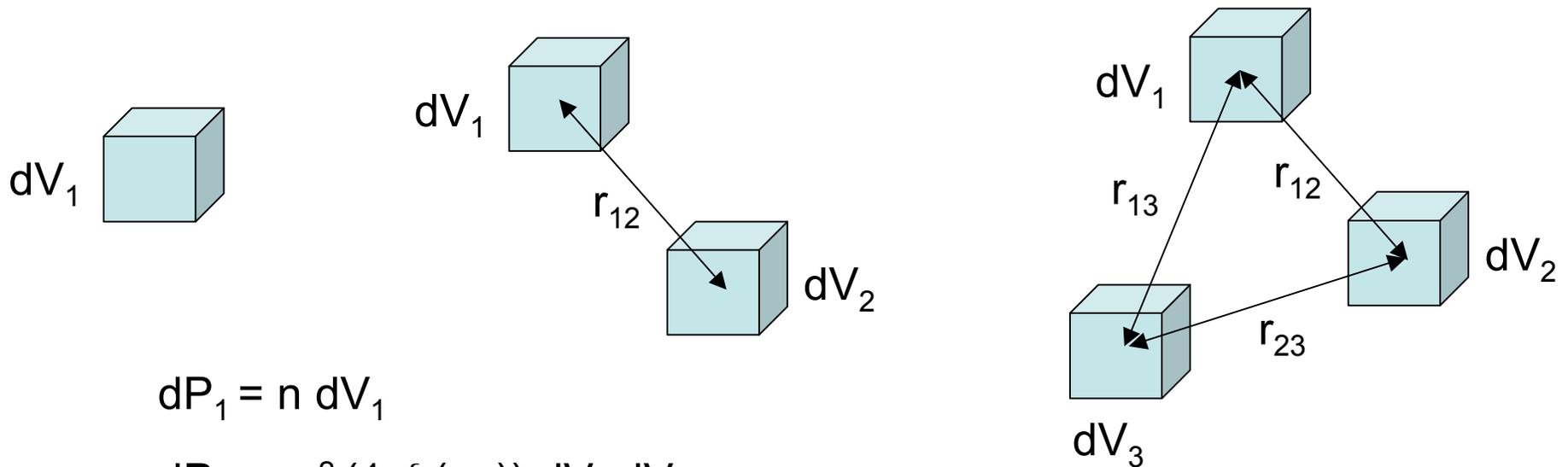
The Sloan Digital Sky Survey





Correlation functions

Consider a stationary point process with mean density n and write the probability of finding N points within N infinitesimal volume elements



$$dP_1 = n dV_1$$

$$dP_{12} = n^2 (1 + \xi(r_{12})) dV_1 dV_2$$

$$dP_{123} = n^3 (1 + \xi(r_{12}) + \xi(r_{13}) + \xi(r_{23}) + \zeta(r_{12}, r_{13}, r_{23})) dV_1 dV_2 dV_3$$

Power spectra

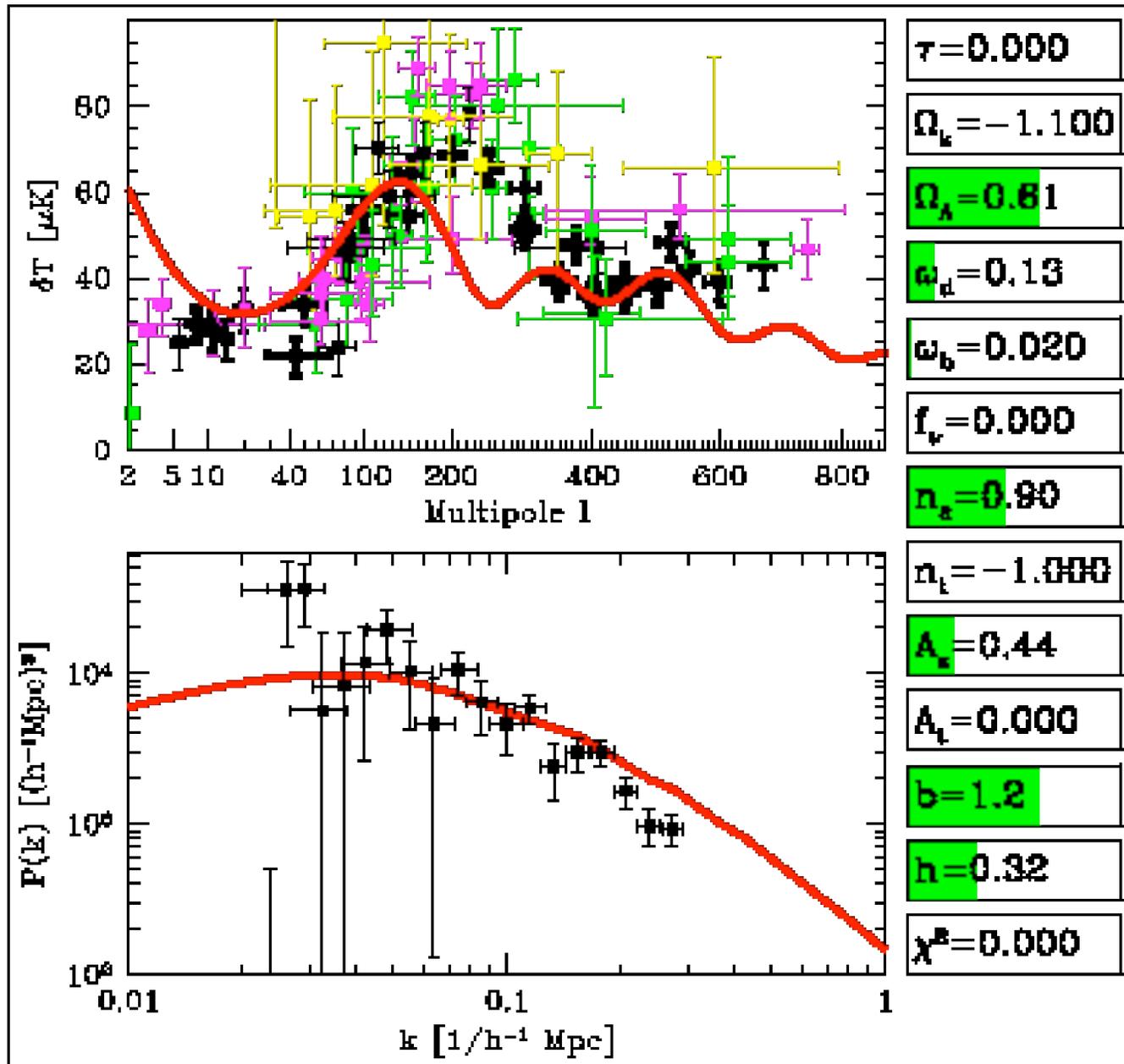
N-spectrum defined via the expectation value of the product of N+1 Fourier transforms of the overdensity field

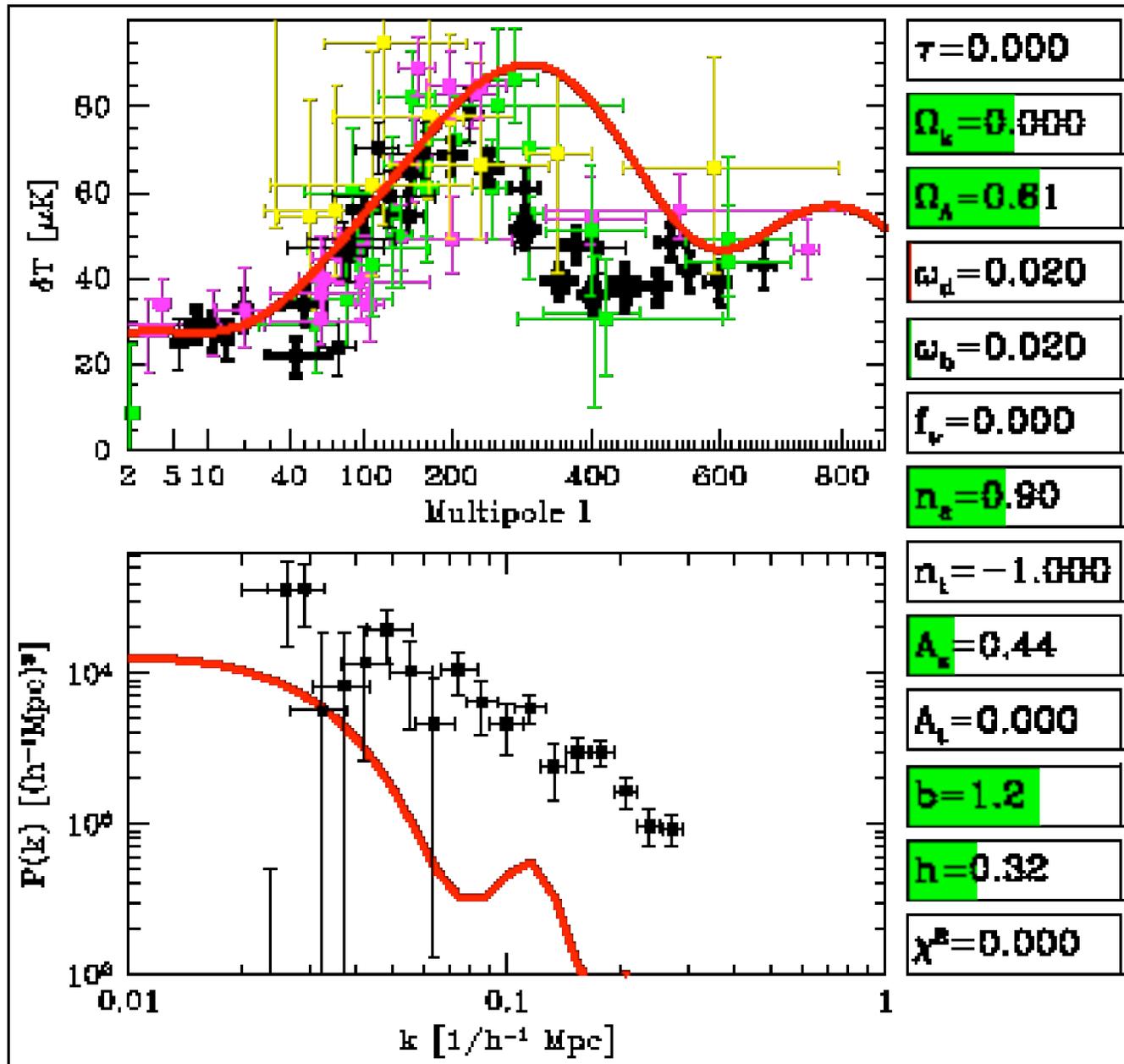
$$\langle \tilde{\delta}(\vec{k}) \tilde{\delta}(\vec{q}) \rangle = (2\pi)^3 P(k) \delta_D(\vec{k} + \vec{q})$$

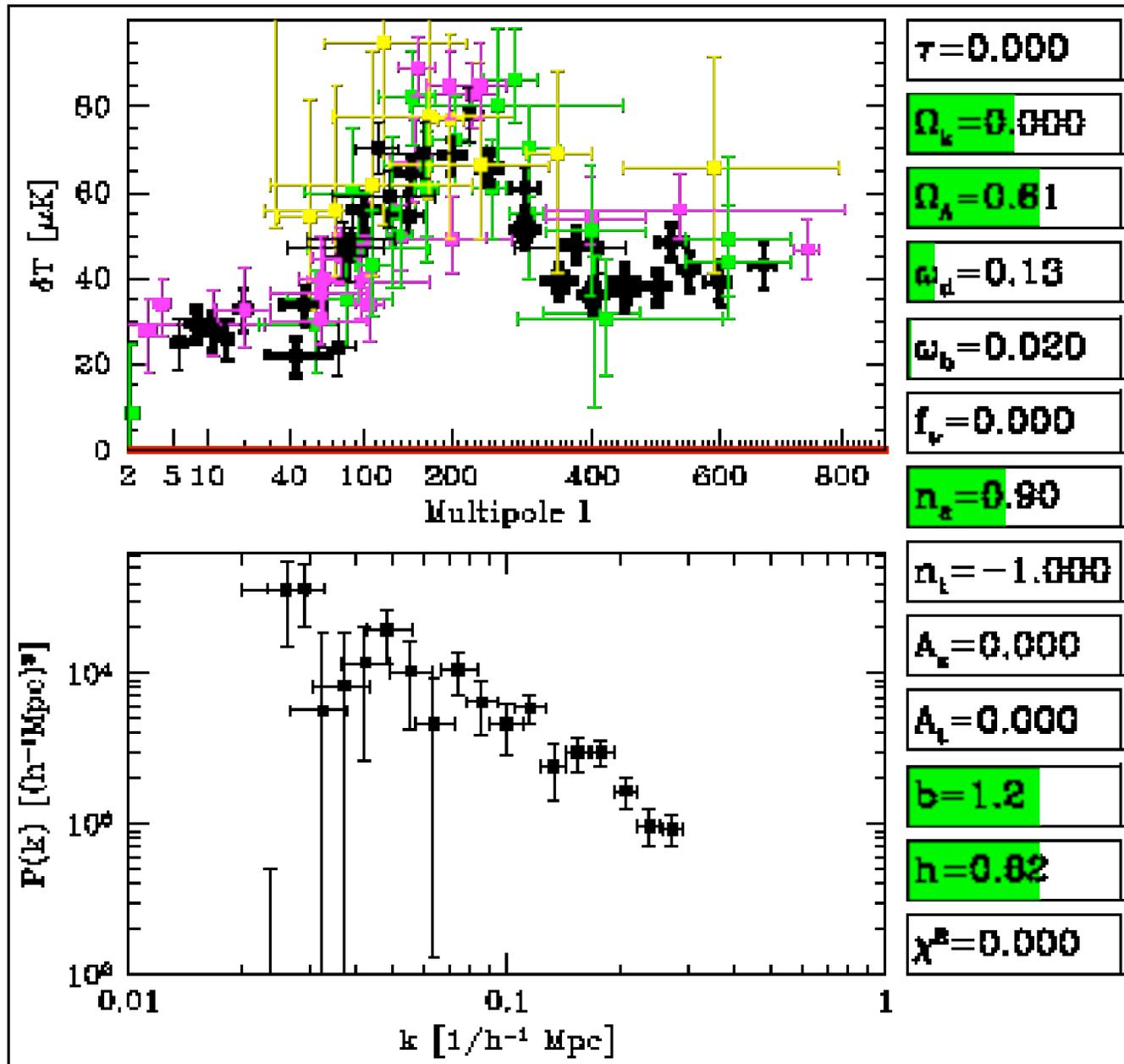
$$\langle \tilde{\delta}(\vec{k}) \tilde{\delta}(\vec{q}) \tilde{\delta}(\vec{p}) \rangle = (2\pi)^3 B(k, q, p) \delta_D(\vec{k} + \vec{q} + \vec{p})$$

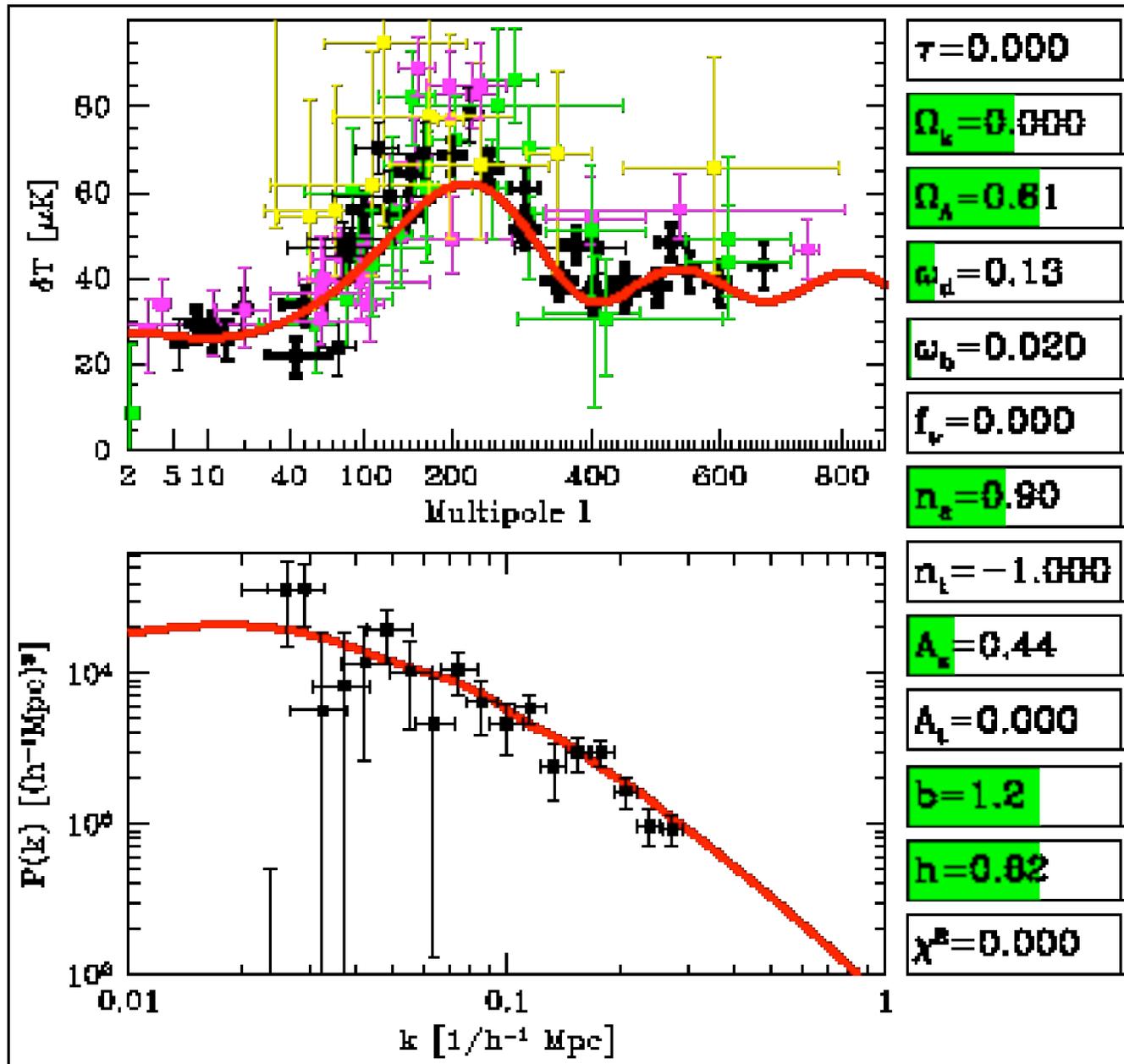
Wiener - Khintchine theorem:

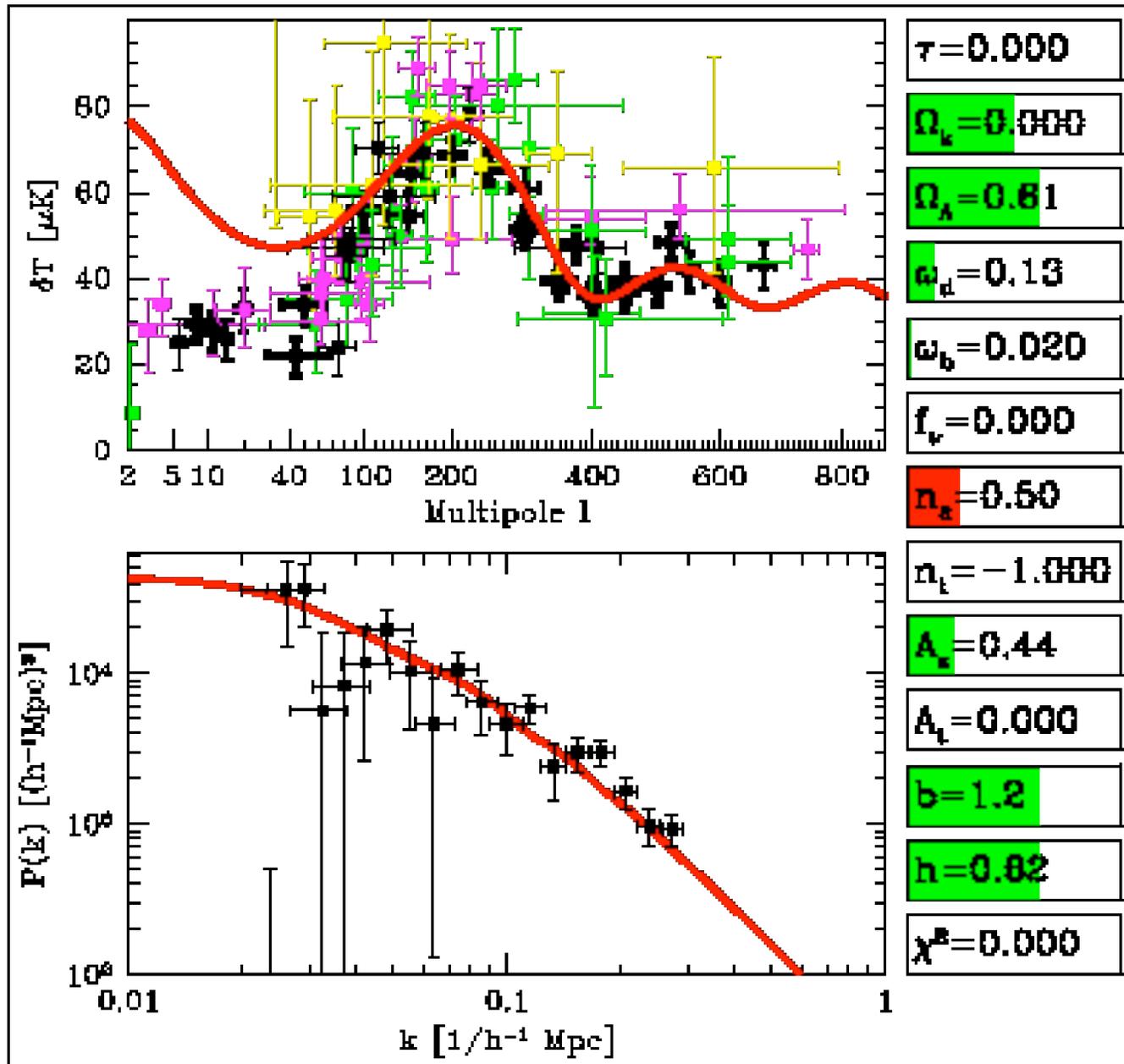
$$\xi(r) = \frac{1}{2\pi^2} \int_0^\infty k^2 P(k) j_0(kr) dk$$



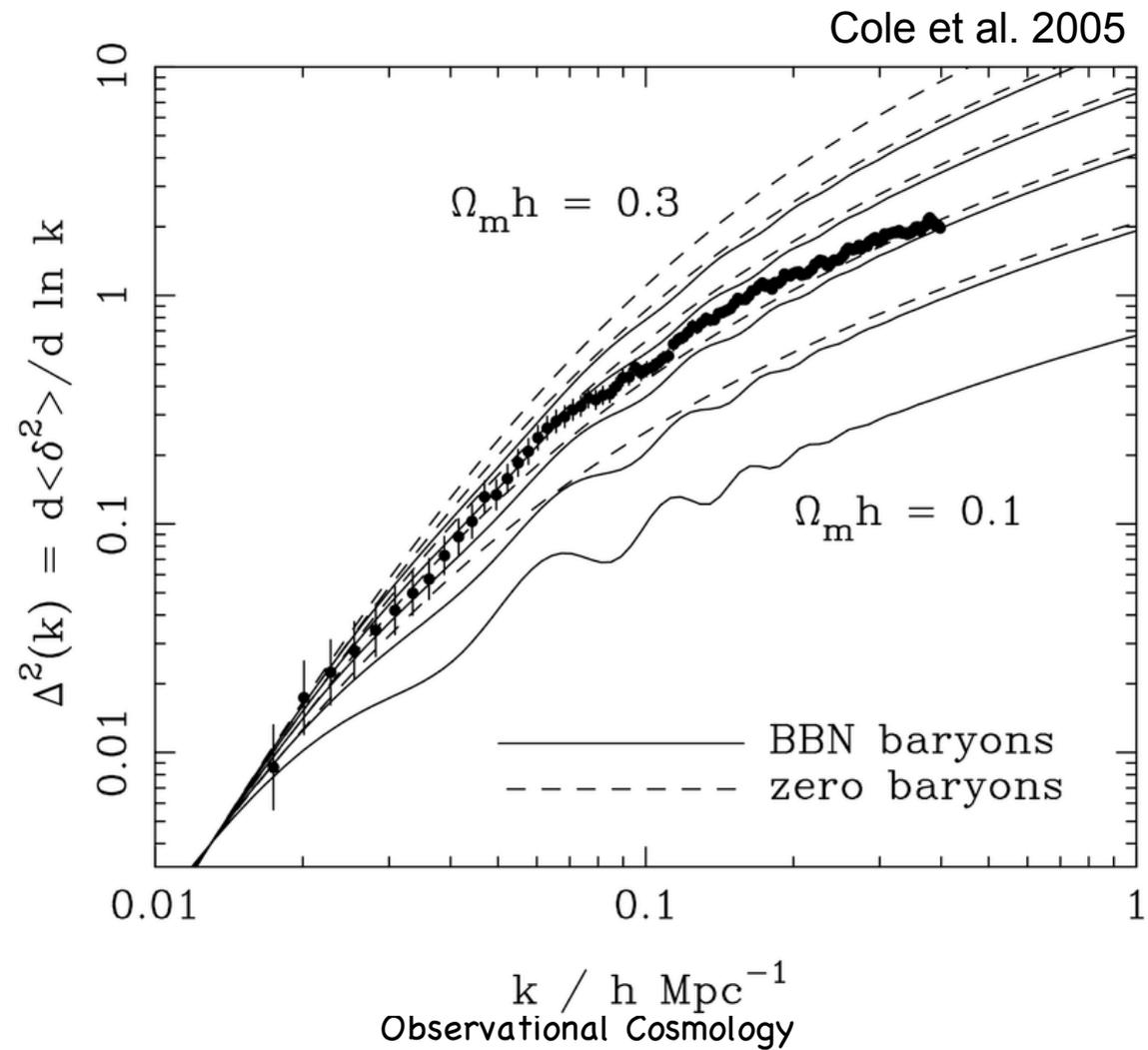








Cosmology from galaxy clustering



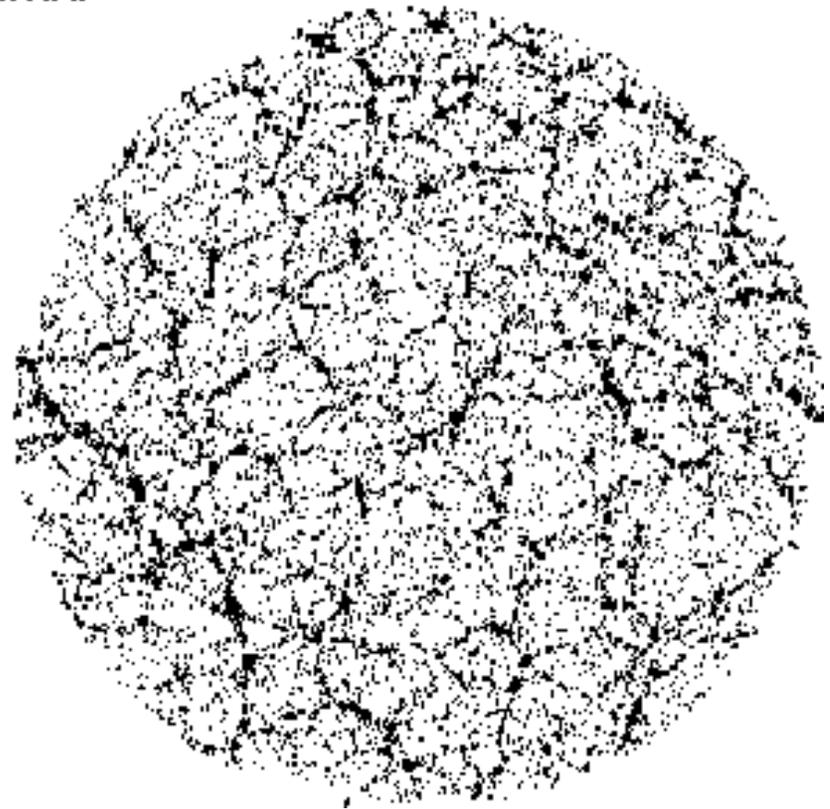
Complications...

I- Redshift-space distortions

Redshift-space distortions

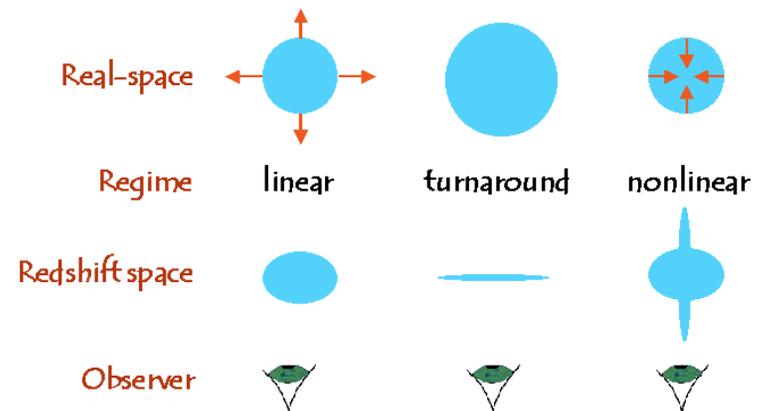
- Density fluctuations generate velocities on top of the global cosmic expansion
- The observed redshift of a galaxy includes a radial Doppler component:
 $1+z_{\text{obs}} = (1+z) (1+v_r/c)$
- Our 3D maps of the universe are “distorted”. The size of the distortions depends on cosmology.

0.00

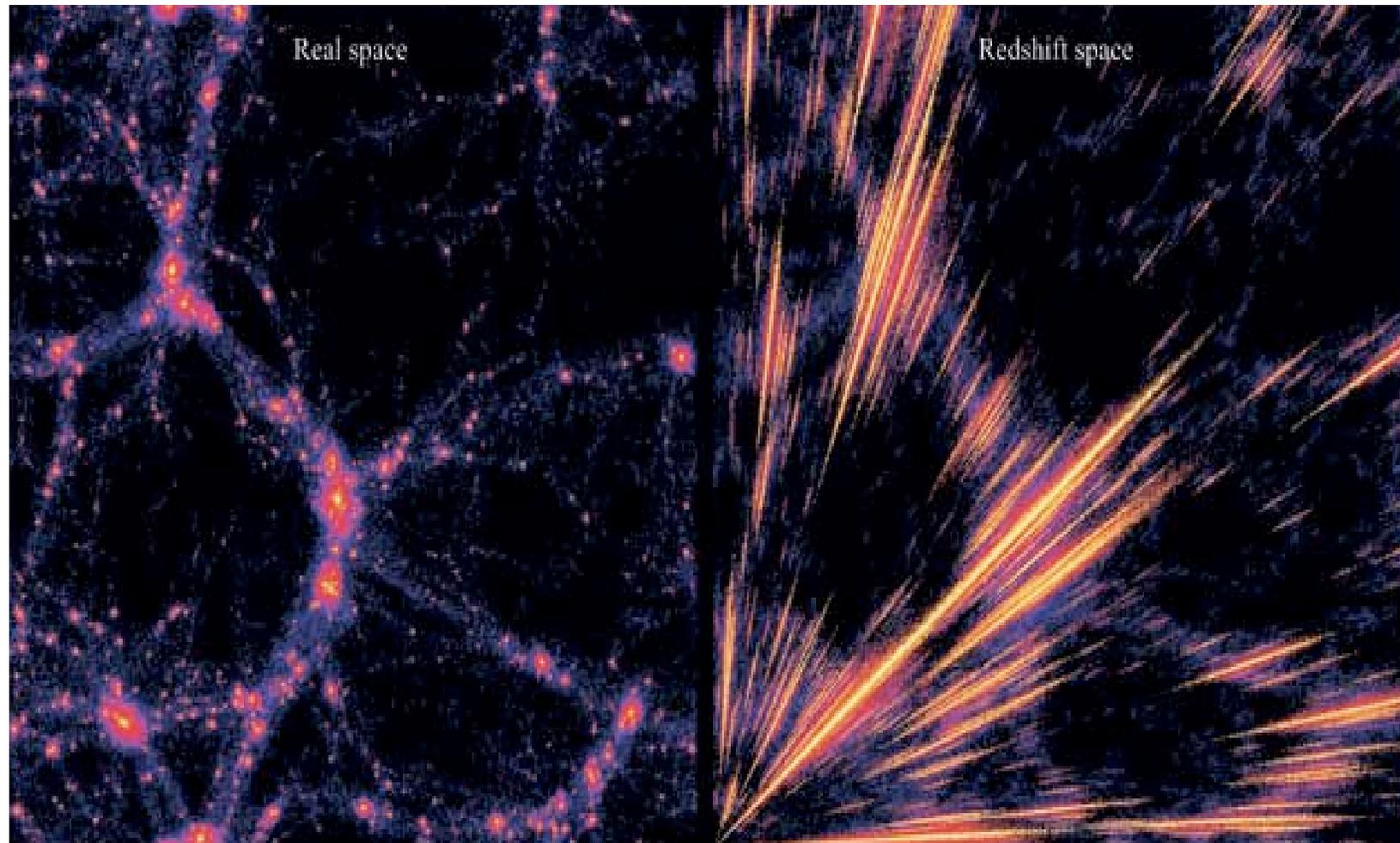


Redshift distortions

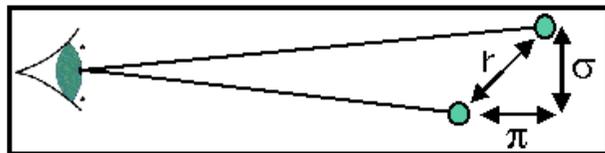
- Fingers of God: Radial stretching pointing towards the observer. They come about because of random velocities in clusters of galaxies
- Large overdensities lead to a coherent infall motion: walls appear denser and thicker, voids bigger and emptier



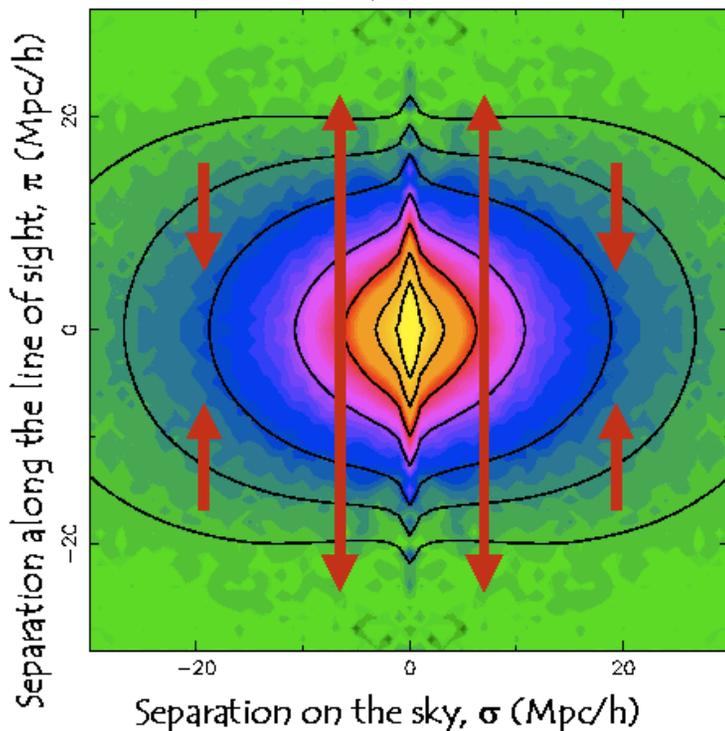
A closer look



Anisotropic correlation function



Hawkins et al. (2002). astro-ph/0212375
2dFGRS: $\beta = 0.47 \pm 0.09$



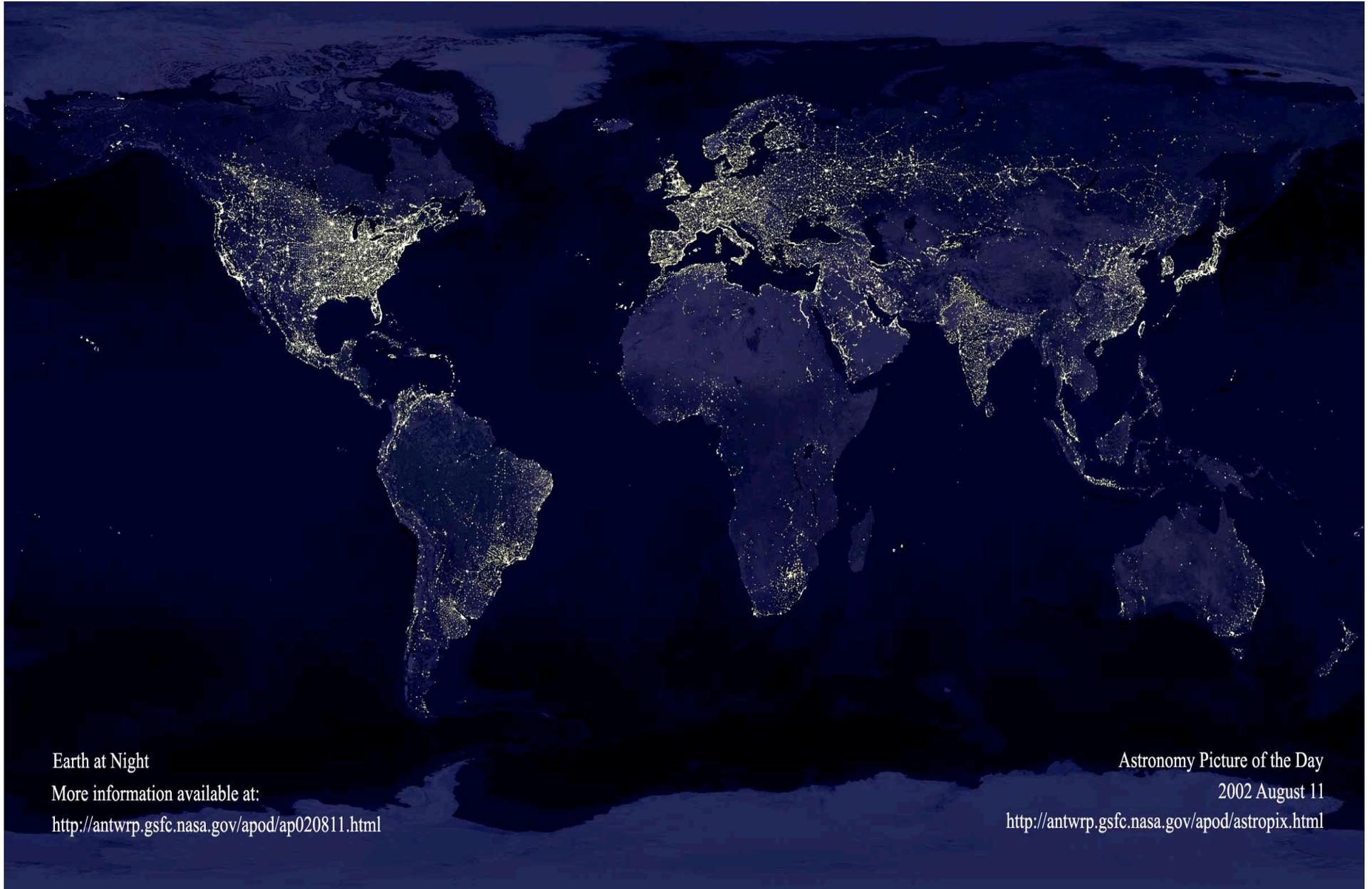
- Redshift distortions generate anisotropies in the 2-point correlation function
- The finger-of-god effect can be used to determine the velocity dispersion (and thus the typical mass) of the galaxy groups
- The squashing effect on large scales can be used to further constrain the cosmological model

Complications...

II- Galaxy biasing (where cosmology meets astrophysics)

Light does not trace mass

- We observe galaxies and use them to map the cosmic web
- Theory, however, predicts the mass distribution
- So far we have a limited understanding of the galaxy formation process (a complicated (g)astrophysical problem)
- It is clear, anyway, that galaxies form in special regions of the density field with different statistical properties



Earth at Night

More information available at:

<http://antwrp.gsfc.nasa.gov/apod/ap020811.html>

Astronomy Picture of the Day

2002 August 11

<http://antwrp.gsfc.nasa.gov/apod/astropix.html>

Different galaxies cluster differently

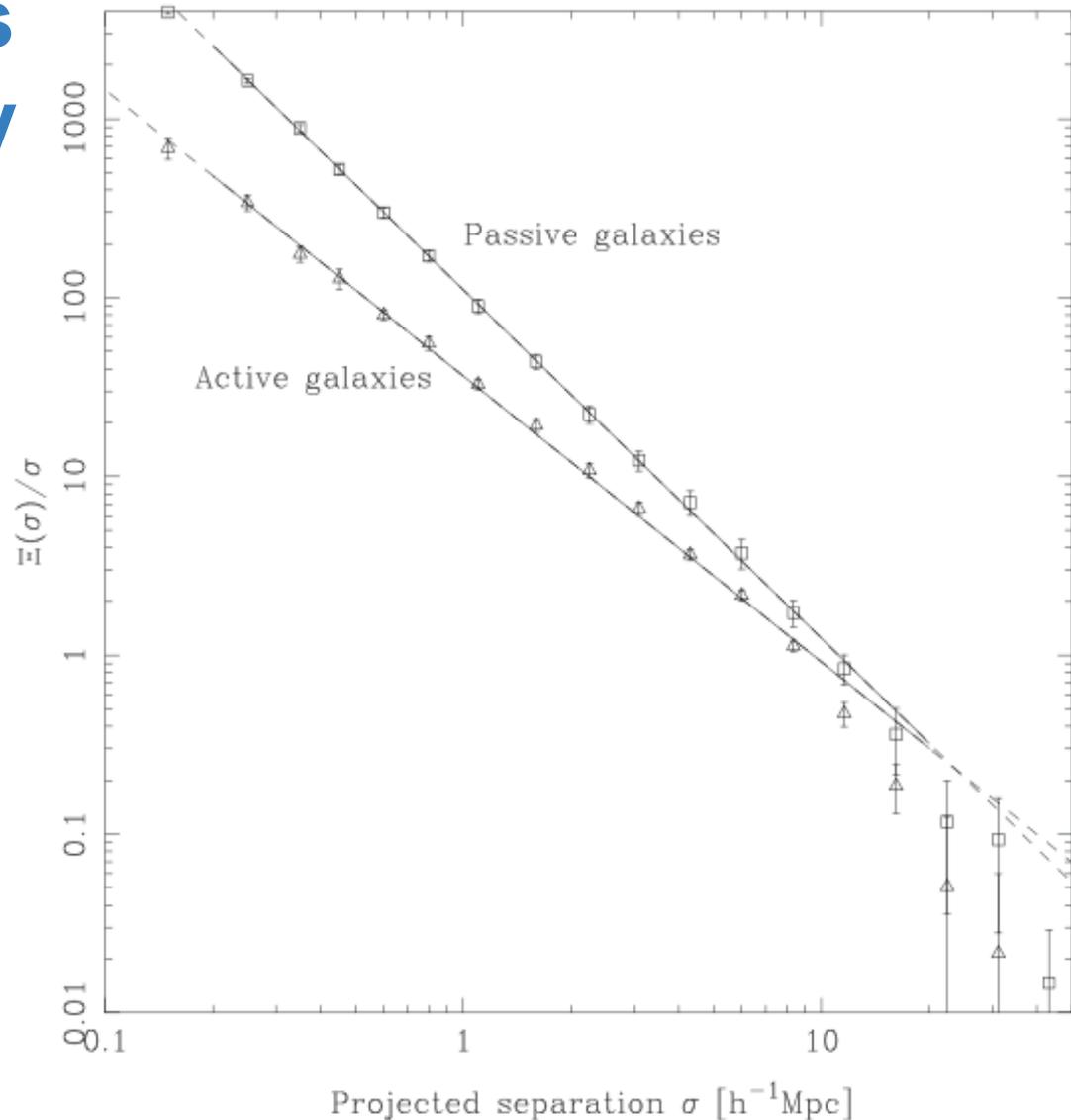
96791 2dF galaxies with redshifts between 0.01 and 0.15

Spectral classification based on principal component analysis

Power-law fit, $\xi(r) = (r_0/r)^\gamma$

Early-type (passively evolving):
 $\gamma = 1.95 \pm 0.03$,
 $r_0 = 6.10 \pm 0.34 \text{ Mpc}/h$

Late-type (star-forming):
 $\gamma = 1.60 \pm 0.04$,
 $r_0 = 3.67 \pm 0.30 \text{ Mpc}/h$

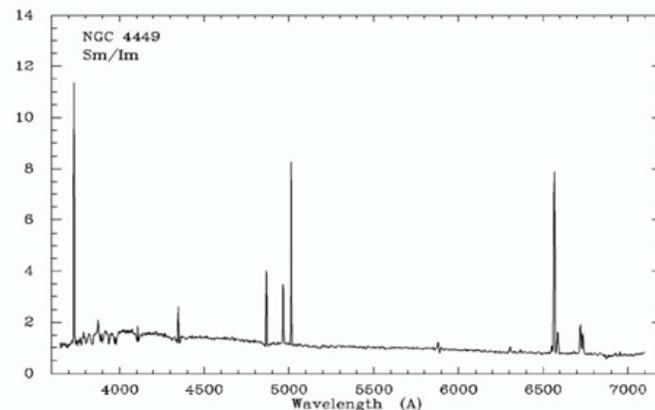
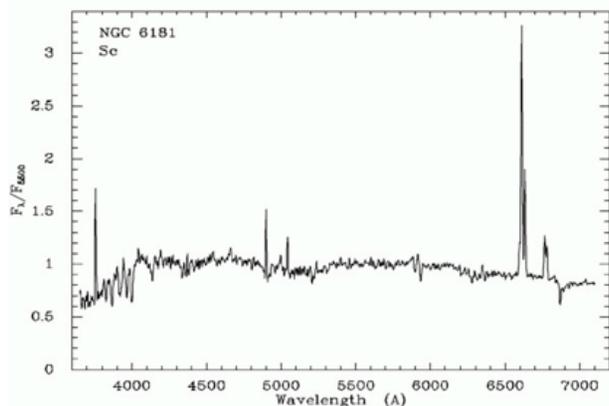
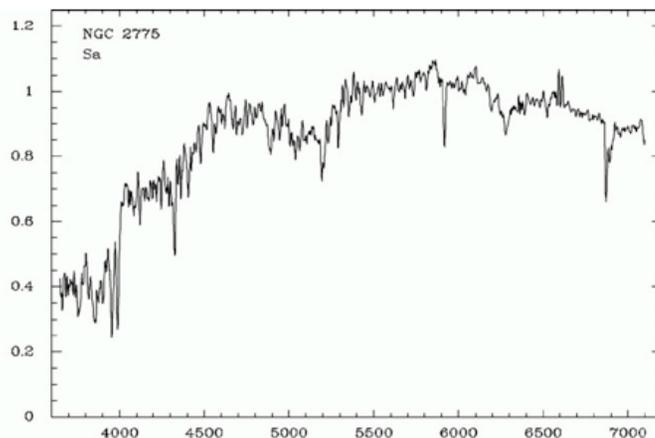
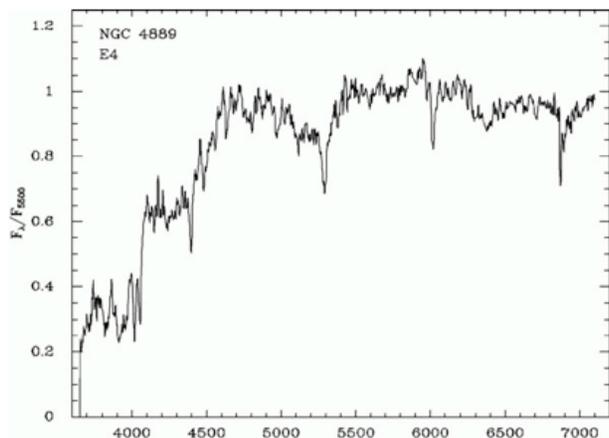


What did we learn?

- On separations larger than a few Mpc, models show that the ratio between the matter power spectrum and the galaxy power spectrum is nearly constant
- This implies that we can use the shape of the galaxy power spectrum to determine the cosmology
- Galaxy clustering gives $\Omega_m h \approx 0.2$, which for an Hubble constant $h=0.7$ gives $\Omega_m \approx 0.25-0.3$
- Combining this with the results of the CMB ($\Omega_{\text{tot}} \approx 1$), it suggests that 75% of the energy in the universe is in an unknown form, the so-called dark energy

Photometric redshifts

Galaxy spectra

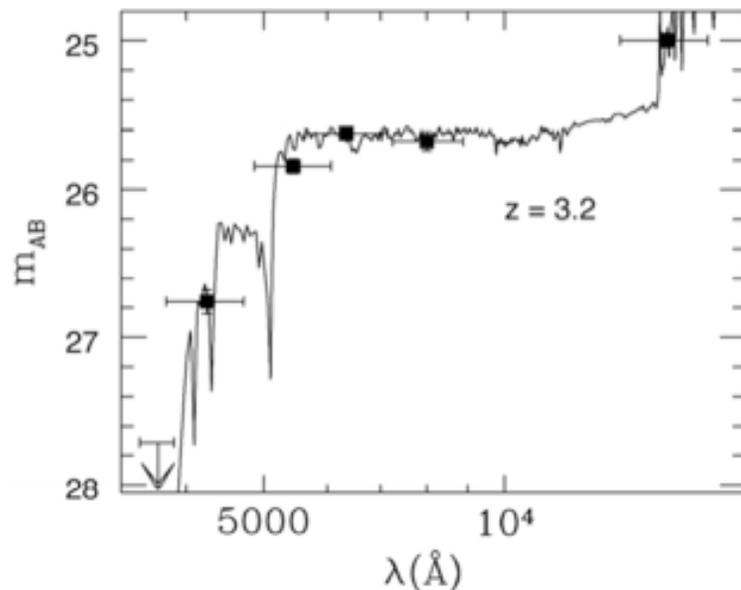


Galaxies show a variety of optical spectra which can be classified based on:

- strength of blue continuum
- composite stellar absorption features
- strength of nebular emission lines

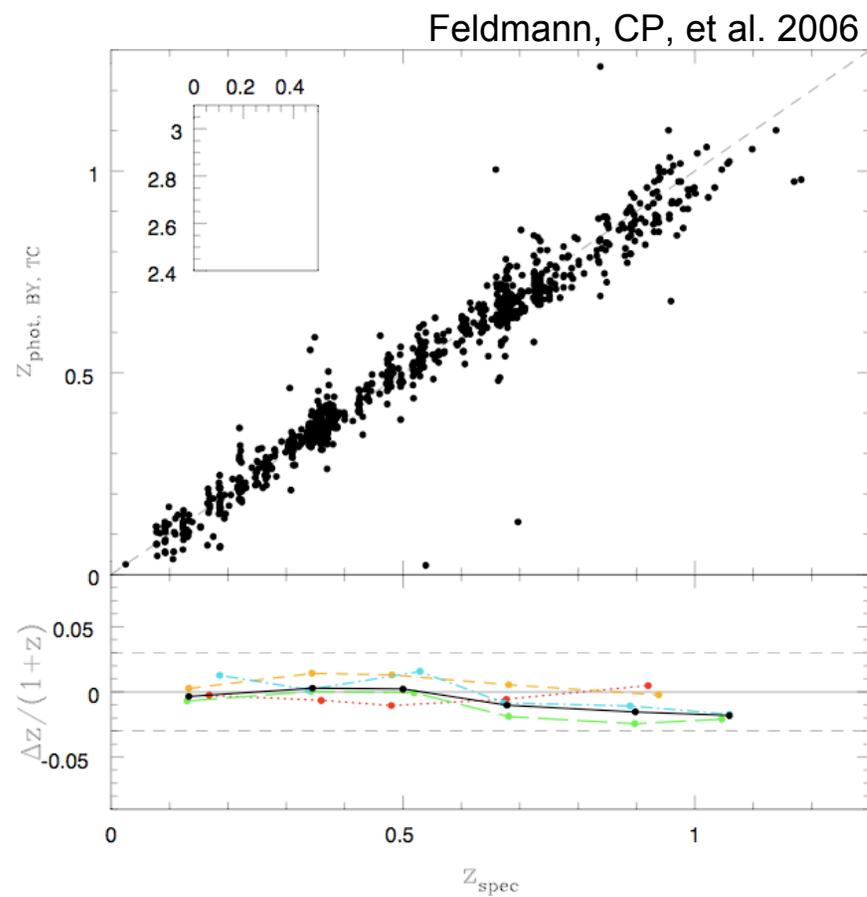
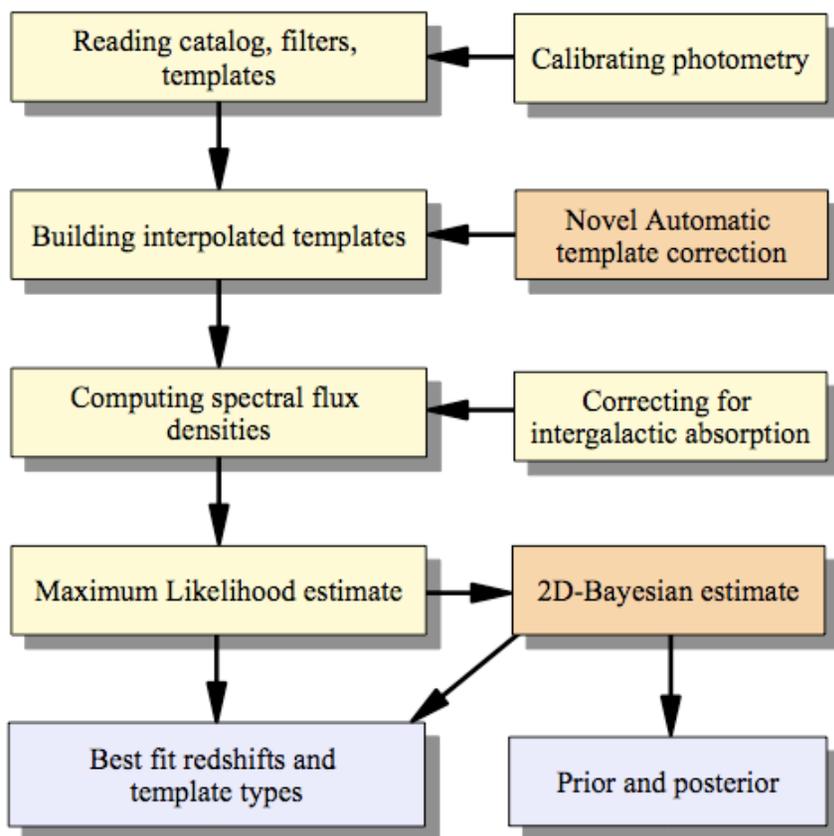
Templates of the different classes can be easily built

Photometric redshifts



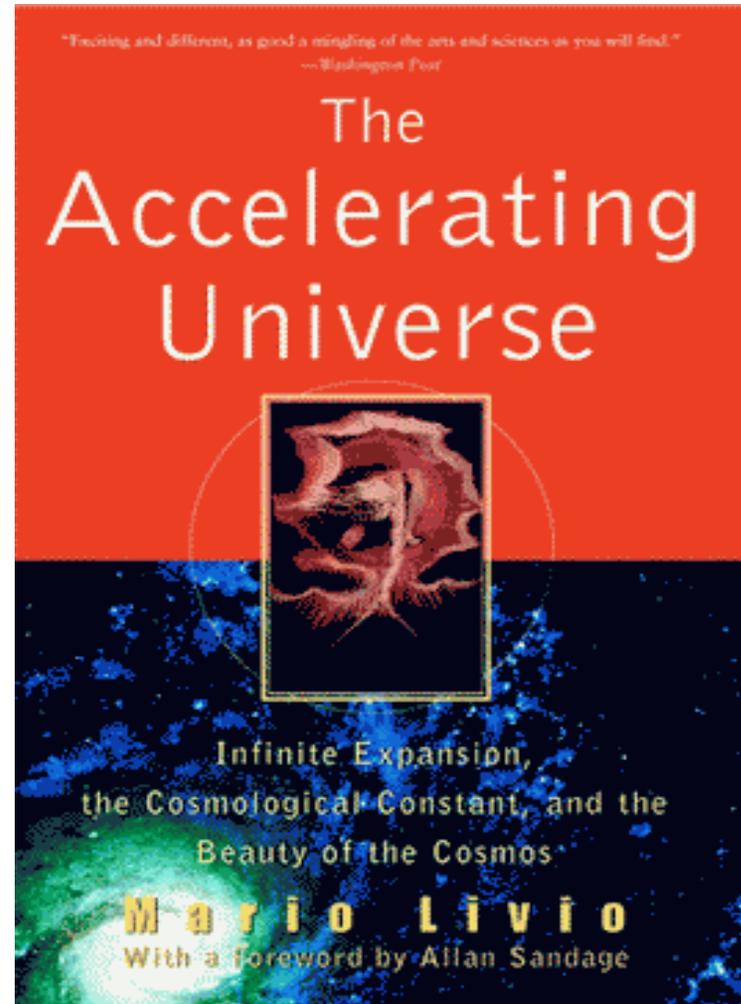
- Cheap estimate (in terms of observational time) of galaxy redshifts using multi-color, broadband photometry instead of spectroscopy
- It simply chooses the best-fitting redshifted spectrum out of a library of templates (either observationally or theoretically motivated)
- Rather than observing narrow spectral features of galaxy spectra (such as emission lines) this technique concentrate on broad features (such as spectral breaks) and the overall shape of a spectrum

Photometric redshifts



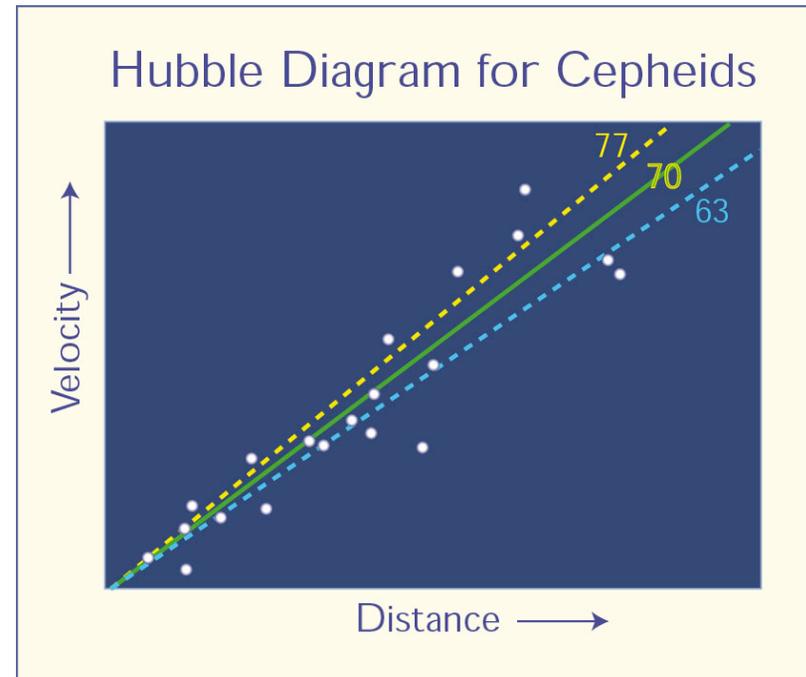
Constraining dark energy with galaxy redshift surveys

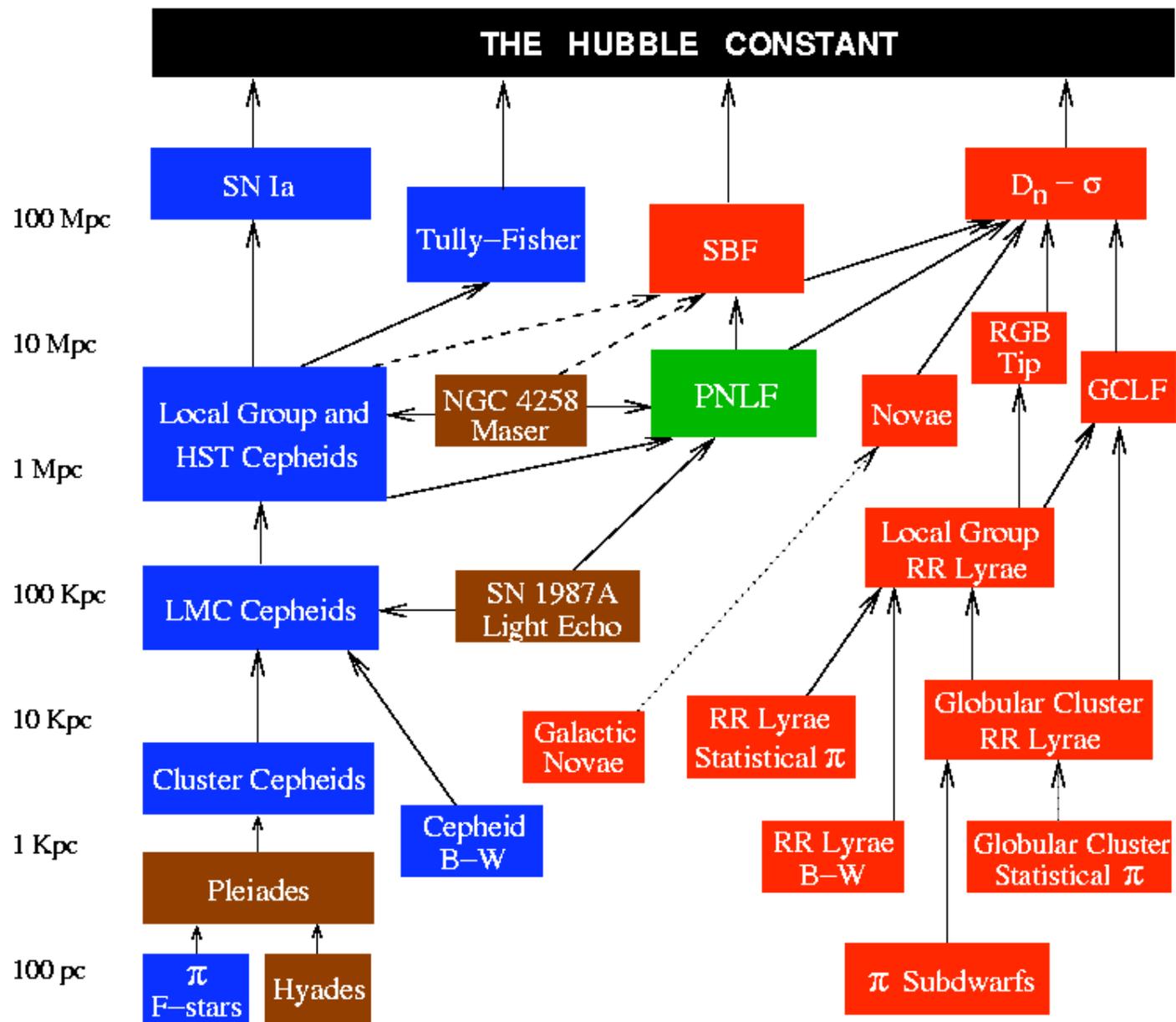
A surprise



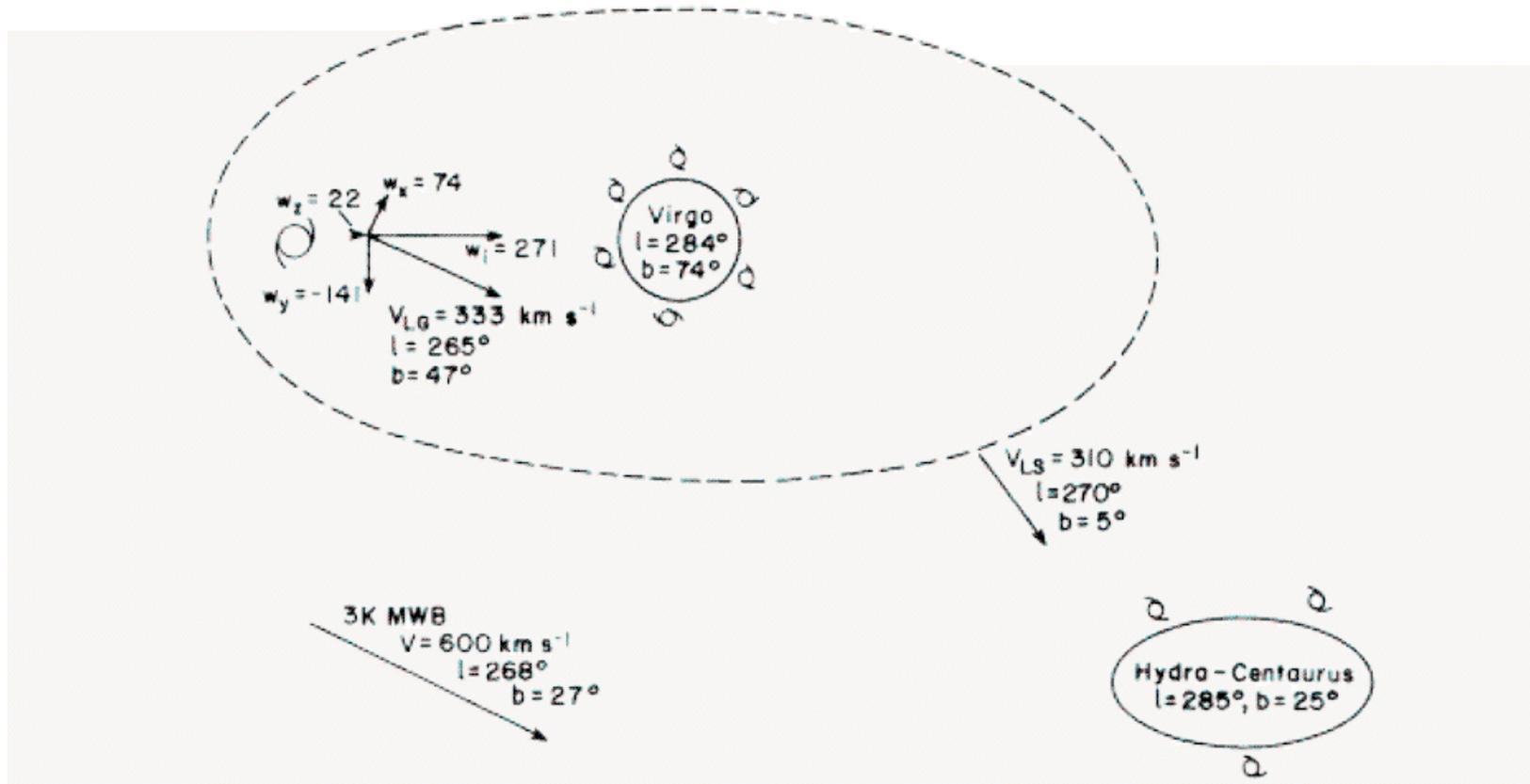
The Hubble diagram

- Taylor expansion of the lumin. distance-redshift relation:
 $H_0 d_L/c = z + (1-q_0)z^2/2 + \dots$
- 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)

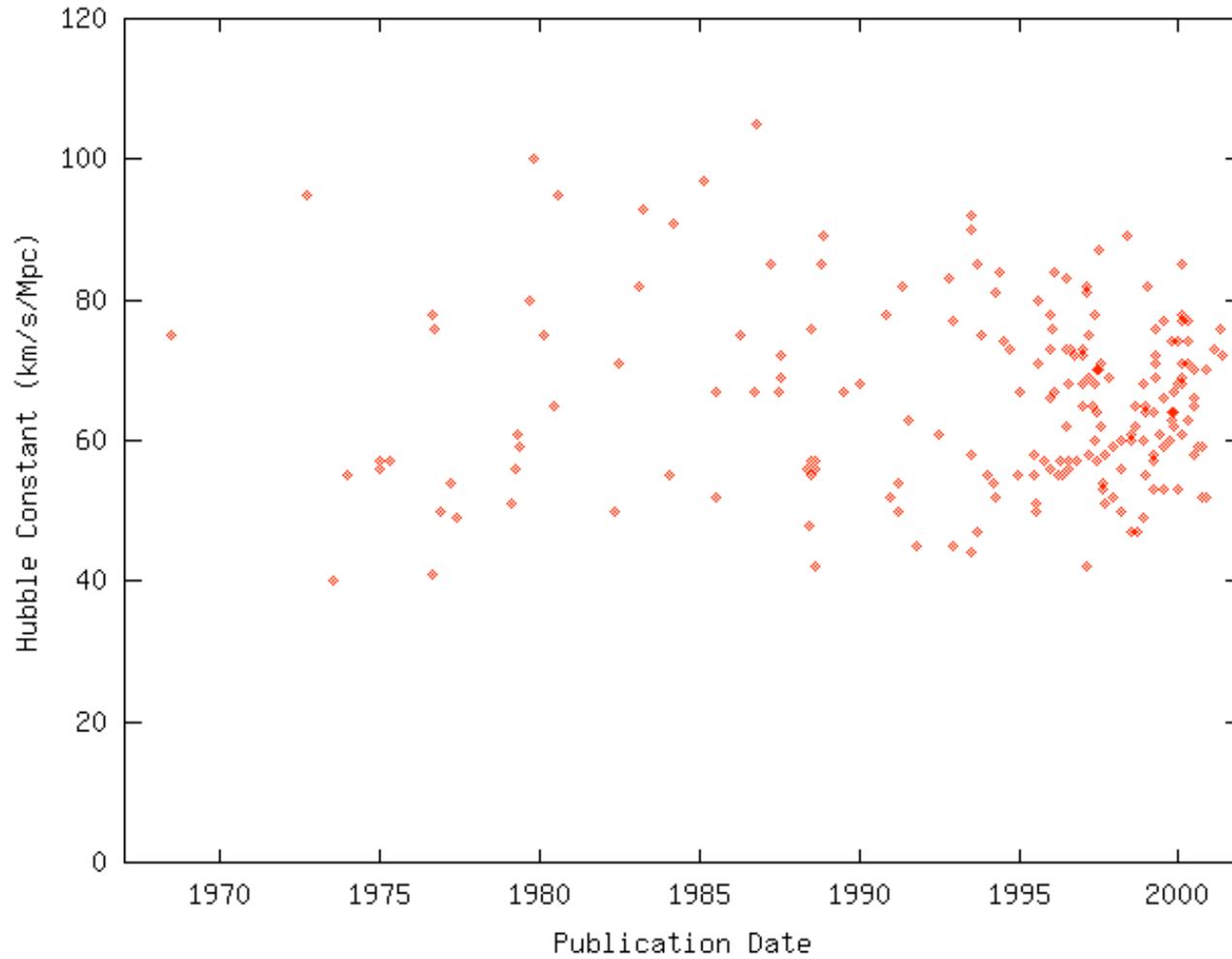




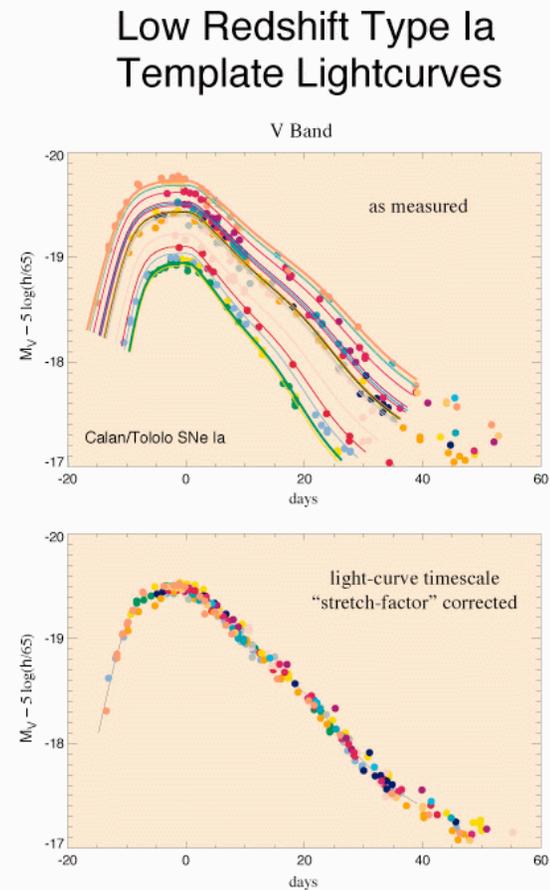
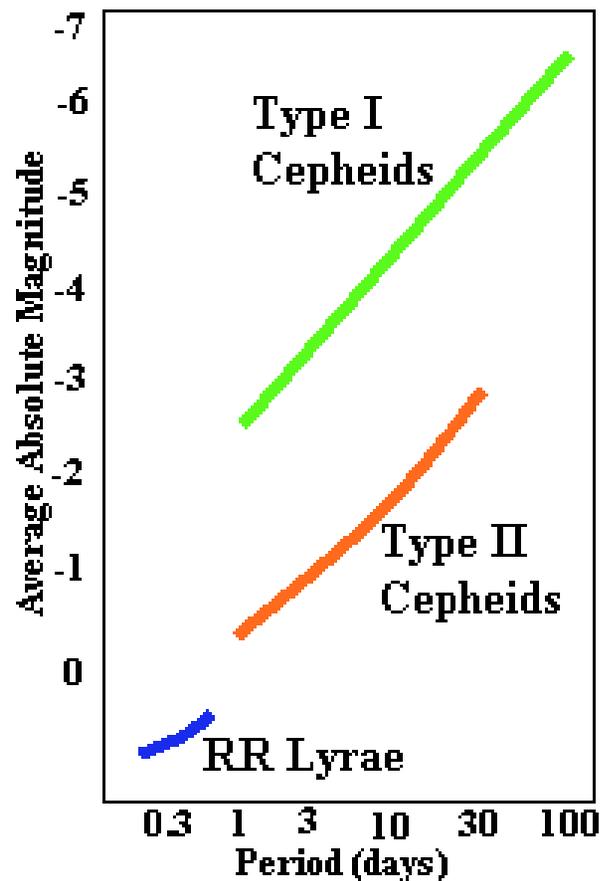
Local flows



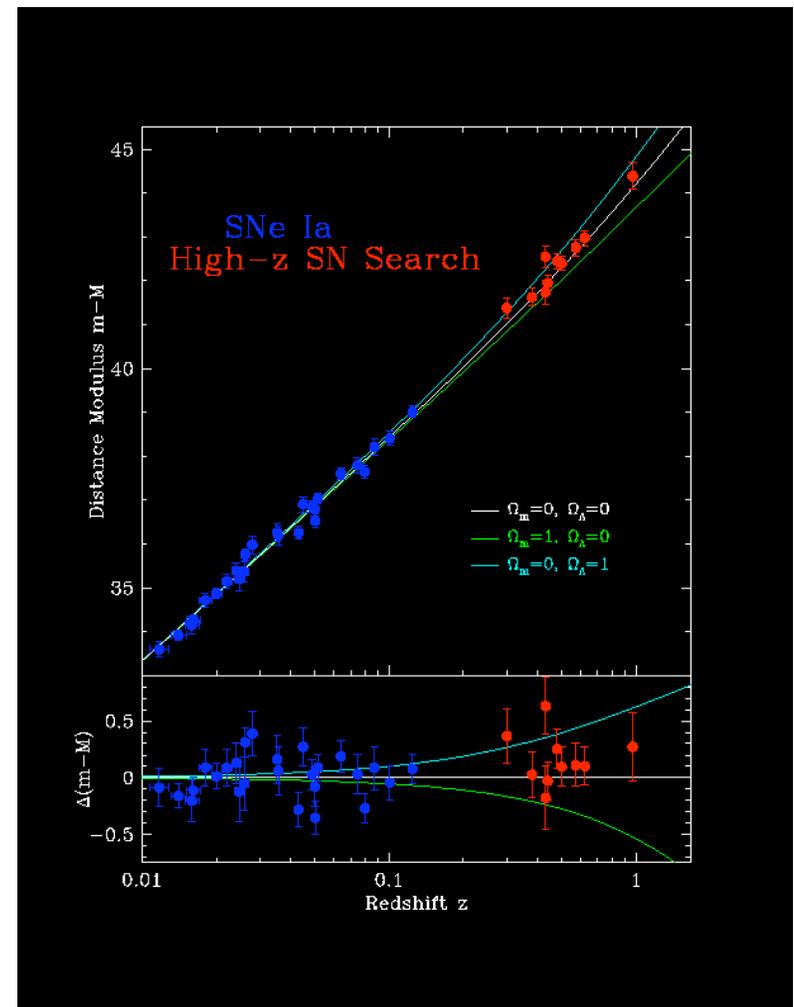
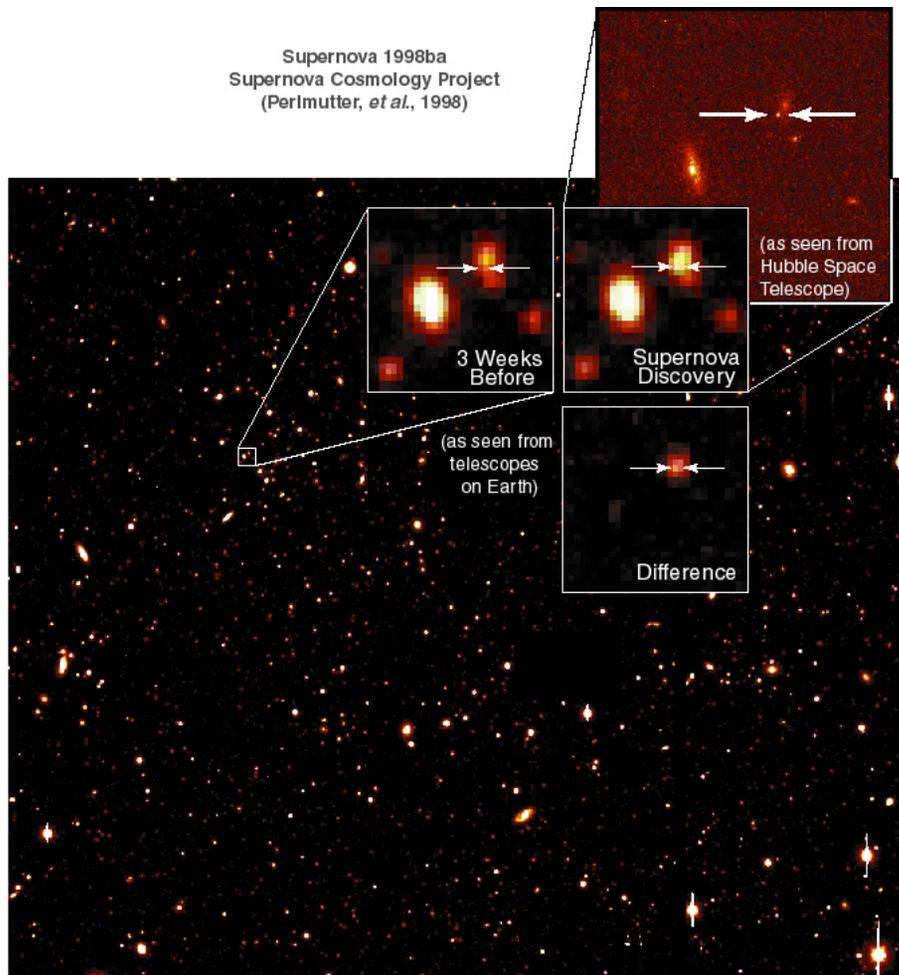
Published values of H_0



Standardizable candles

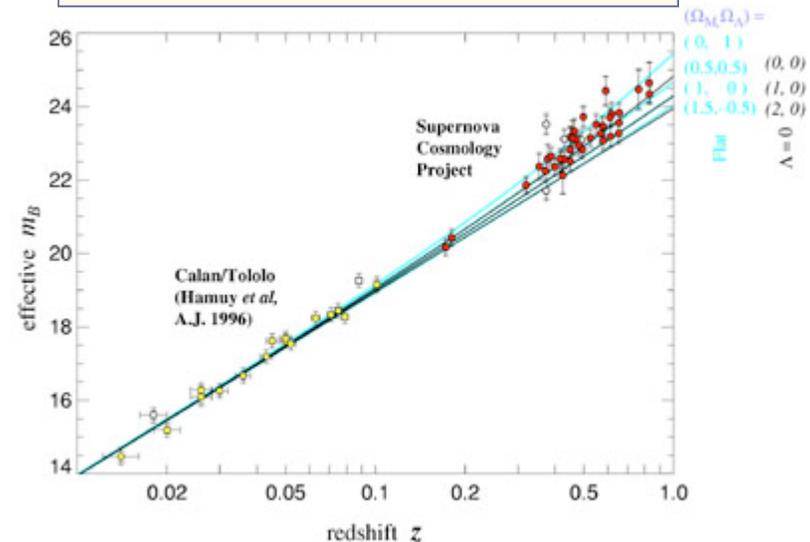
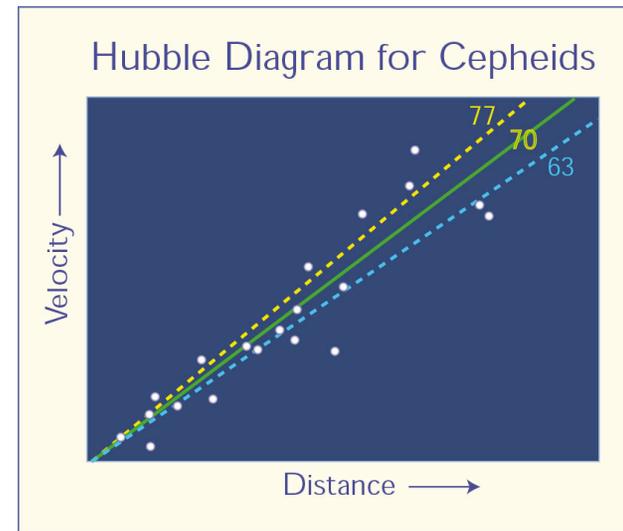


Hubble diagram from SNe Ia

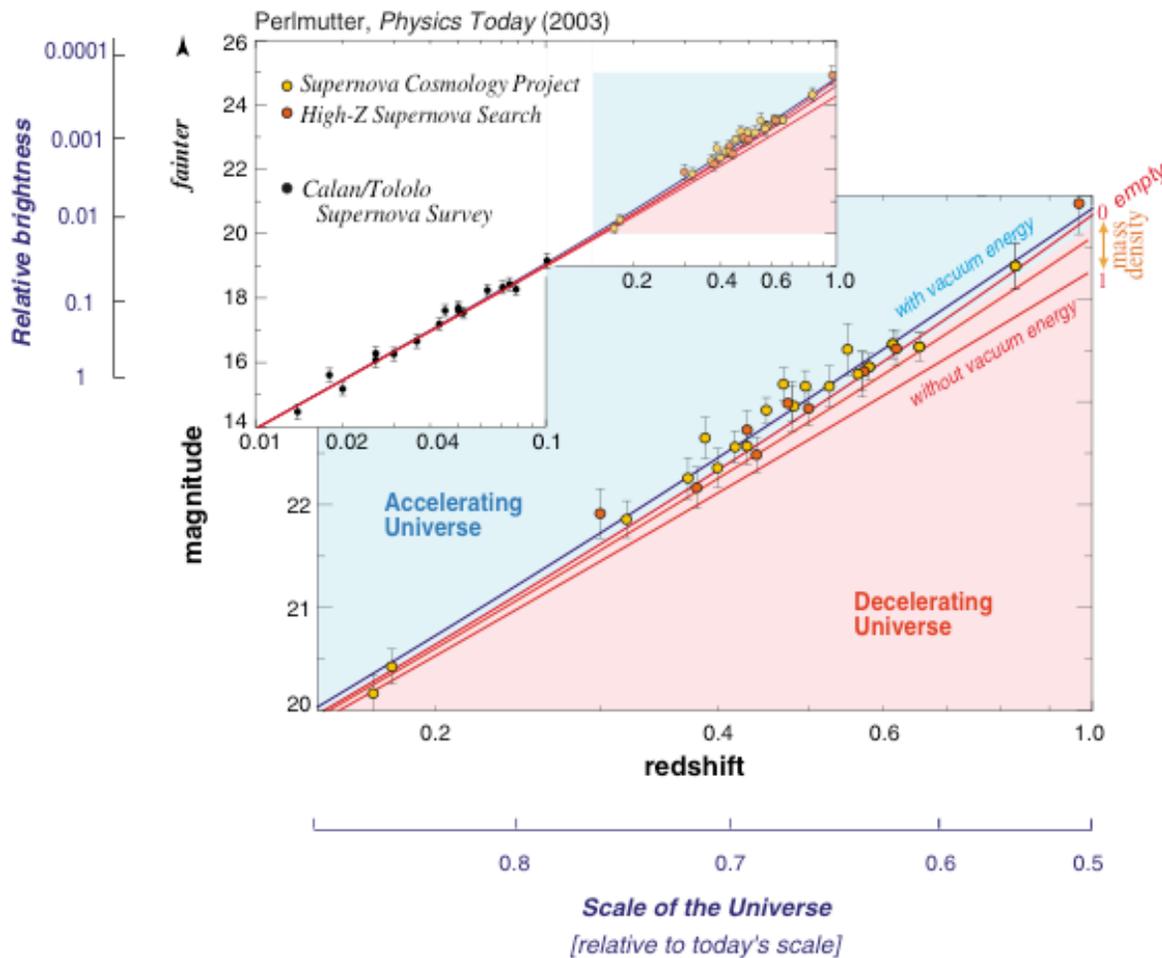


Current estimates

- Improvement: Hipparcos accurate determination of the parallax of local Cepheids
- HST key project (based on Cepheids)
 $H_0 = 72 \pm 8$ km/s/Mpc (Freedman et al. 2001)
- Hubble diagram with SNa Ia
 $H_0 = 73 \pm 7$ 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?

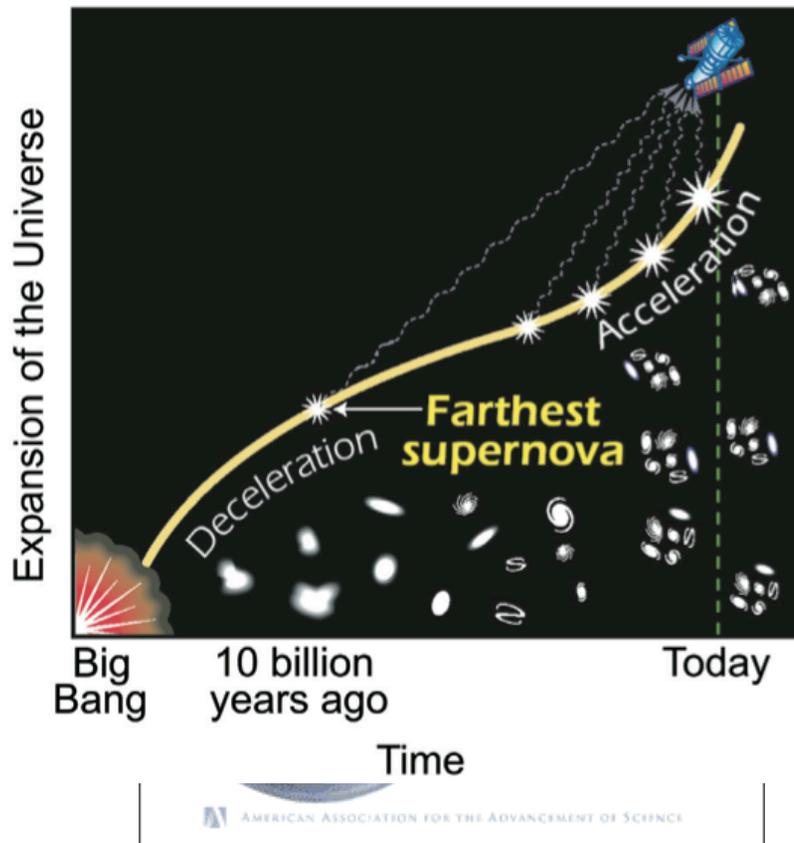


- In 1998, two independent teams found that SNa_e Ia at $z \approx 0.5$ appear about 25% dimmer than they would in a decelerated universe

- 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



- 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)

$$R_{\mu\nu} - \frac{1}{2}R g_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} \qquad \frac{\ddot{a}}{a} = -\frac{4\pi G}{3} \left(\rho + \frac{3p}{c^2} \right) + \frac{\Lambda c^2}{3}$$

- Quantum-vacuum energy (Zel'dovich 1968)

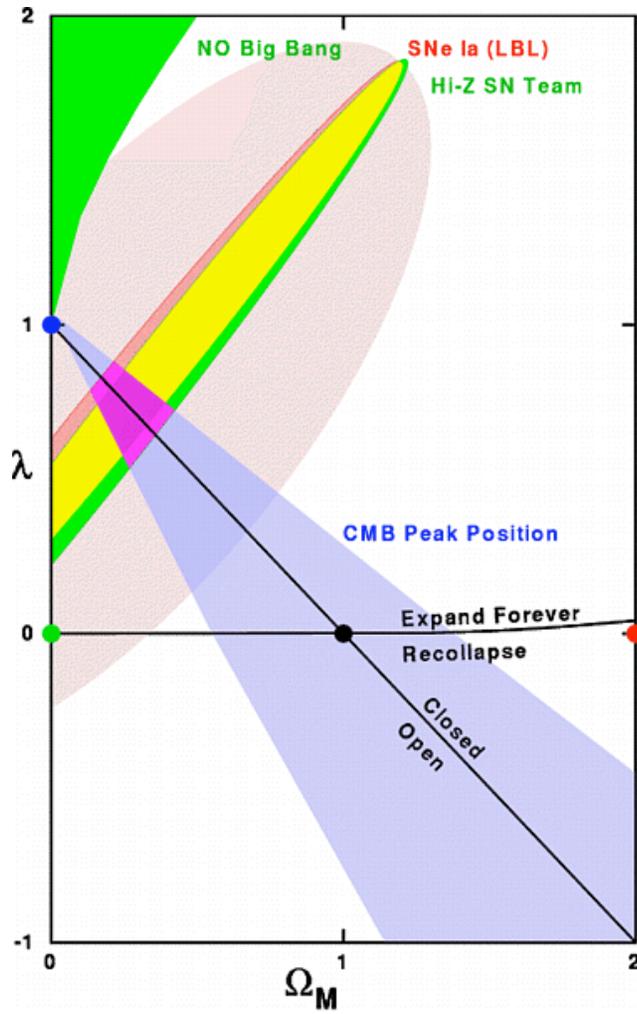
$$T_{ab}^{(\text{vac})} = \frac{\Lambda}{8\pi} g_{ab} \qquad \rho_{\text{vac}} = \frac{\Lambda}{8\pi} \qquad w = \frac{p}{\rho} = -1$$

- Quintessence - An unknown scalar field, ϕ

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

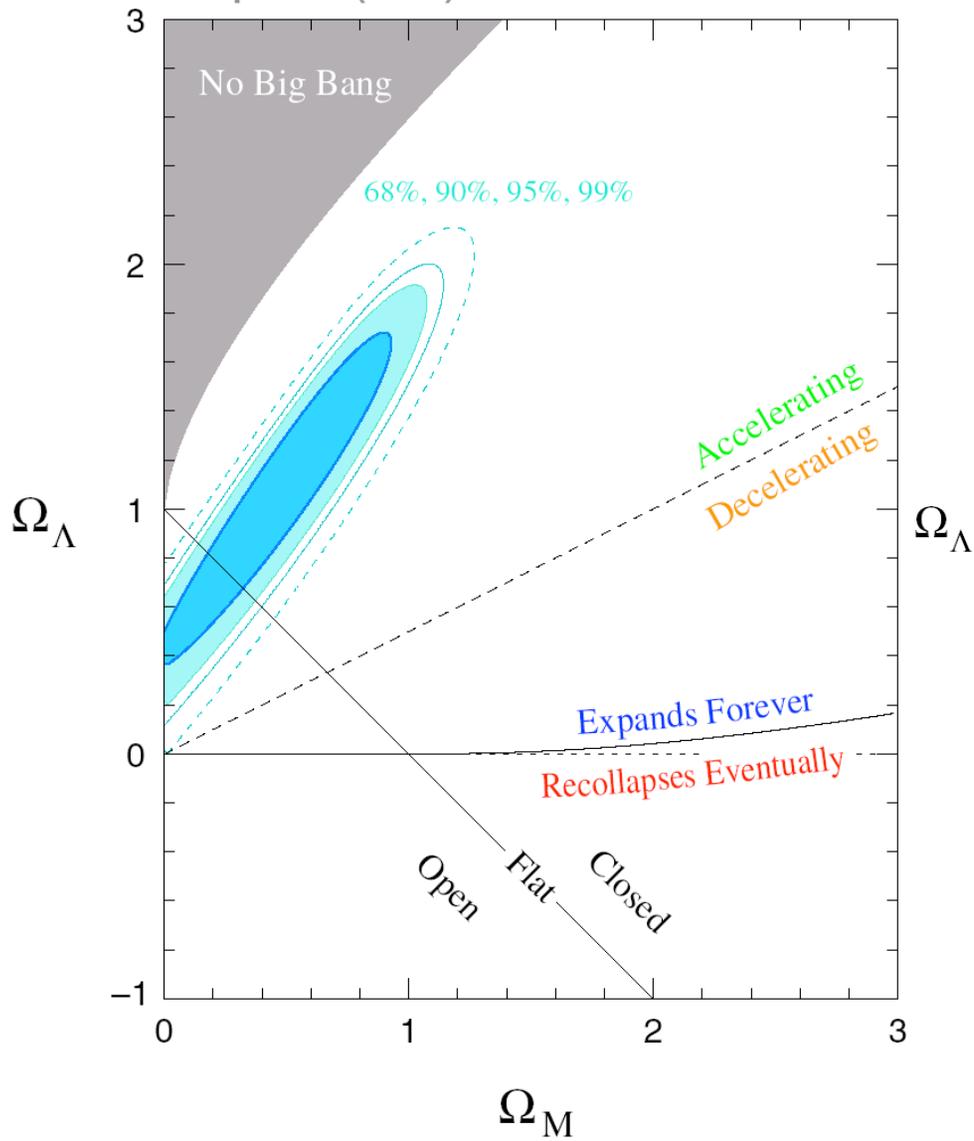
- A sign that Einstein's gravity is wrong on large scales

A non-vanishing cosmological constant

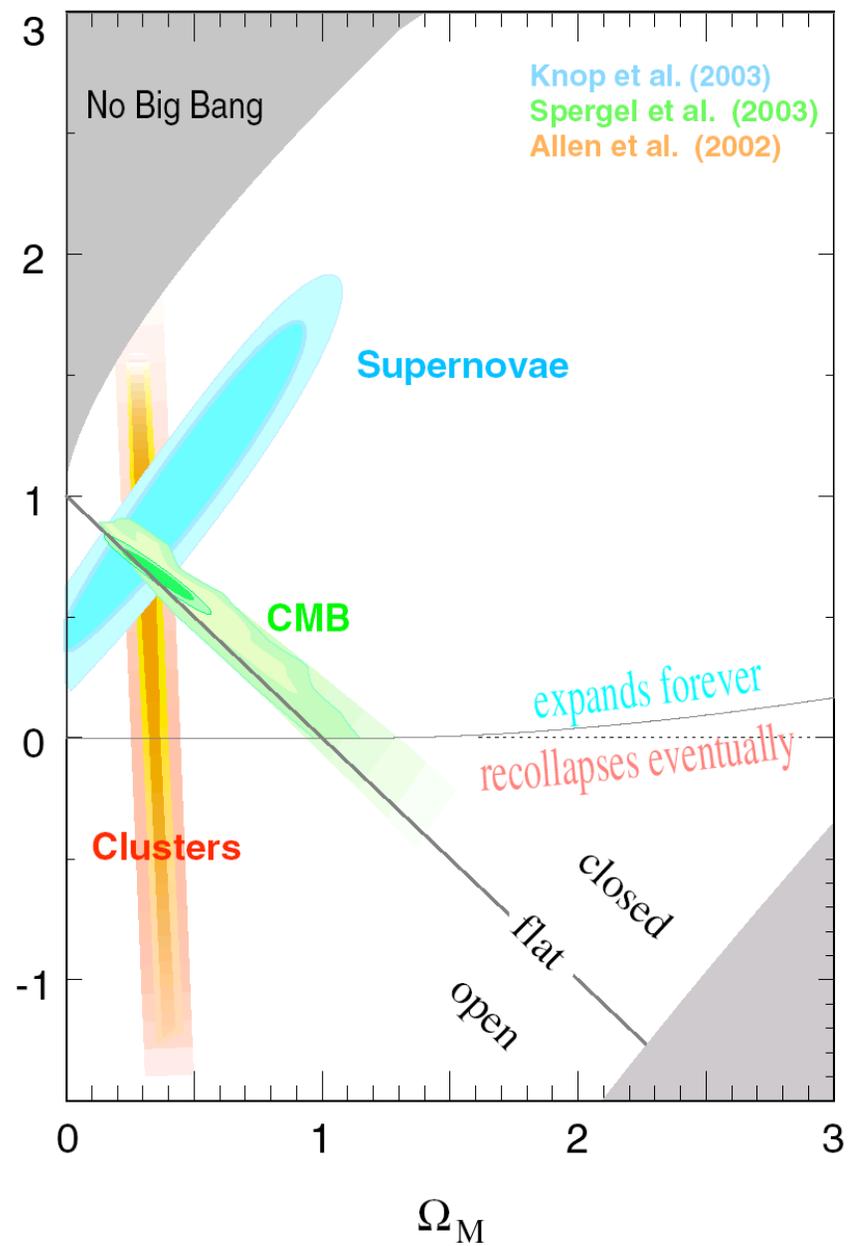


- The simplest explanation of cosmic acceleration is that Einstein's cosmological constant is small but positive
- In this case fitting the SNe Ia Hubble diagram gives $0.8 \Omega_m - 0.6 \Omega_\Lambda \approx -0.2 \pm 0.1$
- As we will see, CMB anisotropies suggest that $\Omega_m + \Omega_\Lambda \approx 1.0$
- 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)

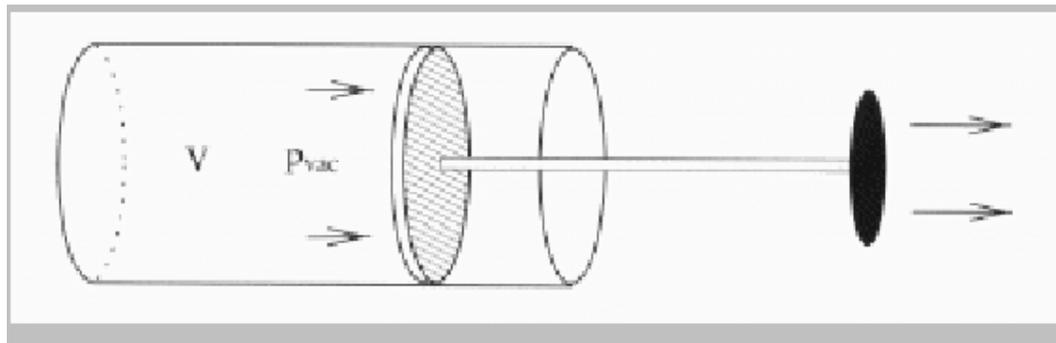


Supernova Cosmology Project



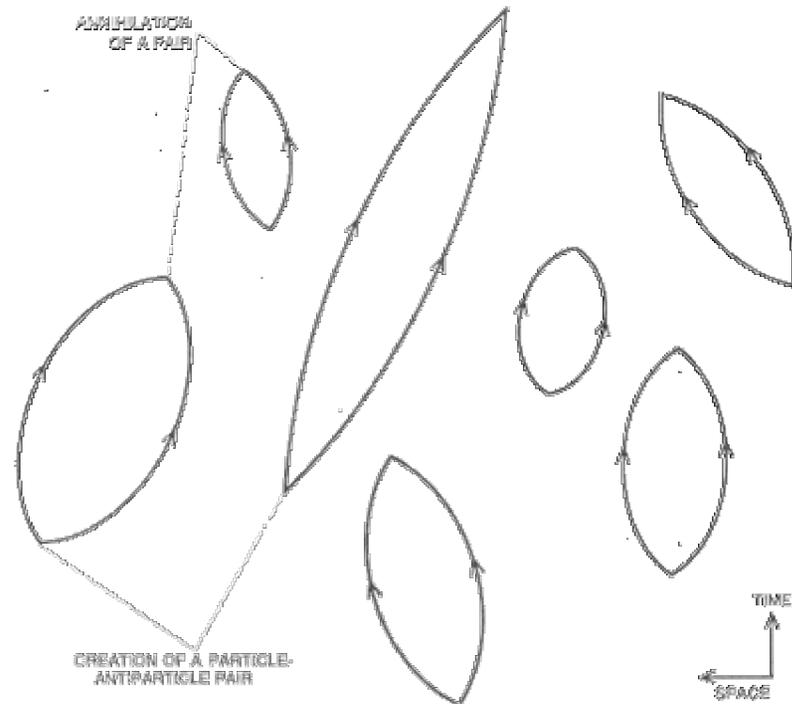
Modern interpretation of Λ

- 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.



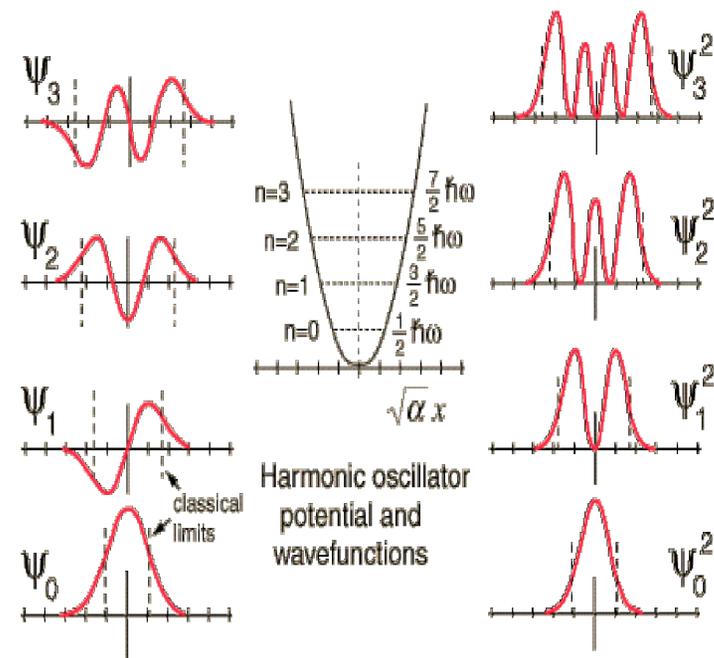
A dynamic vacuum state

- 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 teeming with virtual particles pairs
- Therefore empty space can have an energy density associated to it

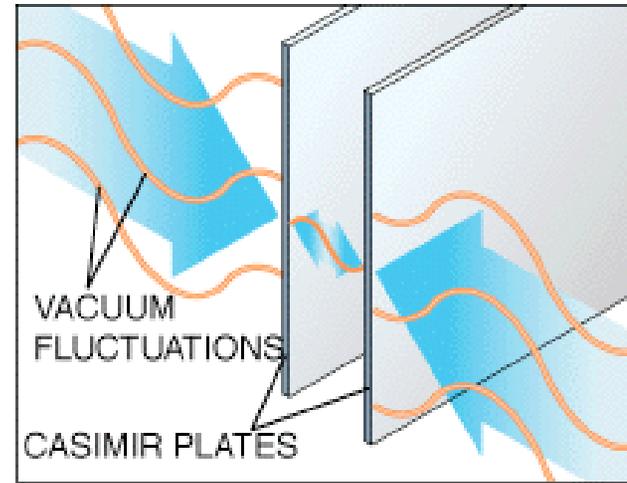


Zero-point energy

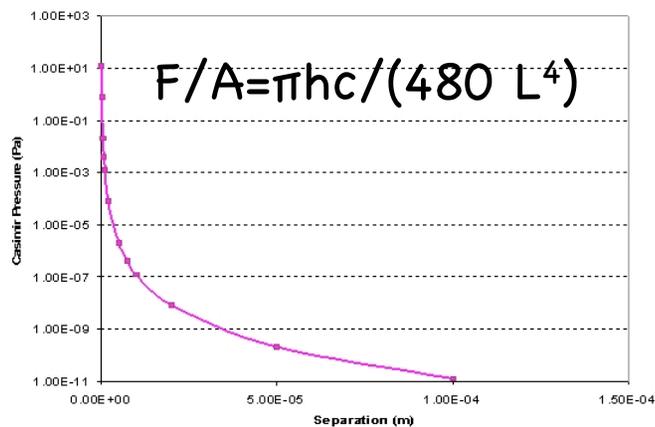
- Alternatively, vacuum energy can be seen as the sum of the zero-point energies of the quanta of the fields
- The minimum energy of an harmonic oscillator is $E_0 = \hbar\nu/2$, this is called the zero-point energy
- Quantum field theory can be regarded as a collection of infinitely many harmonic oscillators 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



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 1997 by Steven Lamoreaux and by many others afterwards.

The vacuum energy problem

- The measured value of Λ implies that the vacuum “mass” density is rather small $\approx 6 \times 10^{-27} \text{ kg m}^{-3}$ (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 $\approx 10^{96} \text{ kg m}^{-3}$
- 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 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

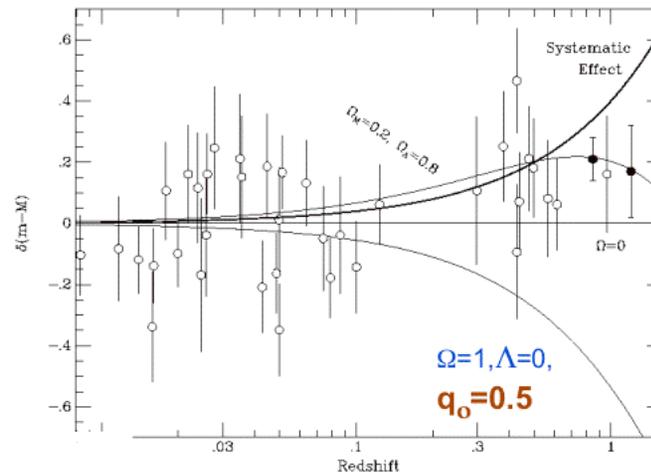


- "Even in its ground state, a quantum system possesses fluctuations and an associated zero-point energy, since otherwise the uncertainty principle would be violated. In particular the vacuum state of a quantum field has these properties. For example, the electric and magnetic fields in the electromagnetic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

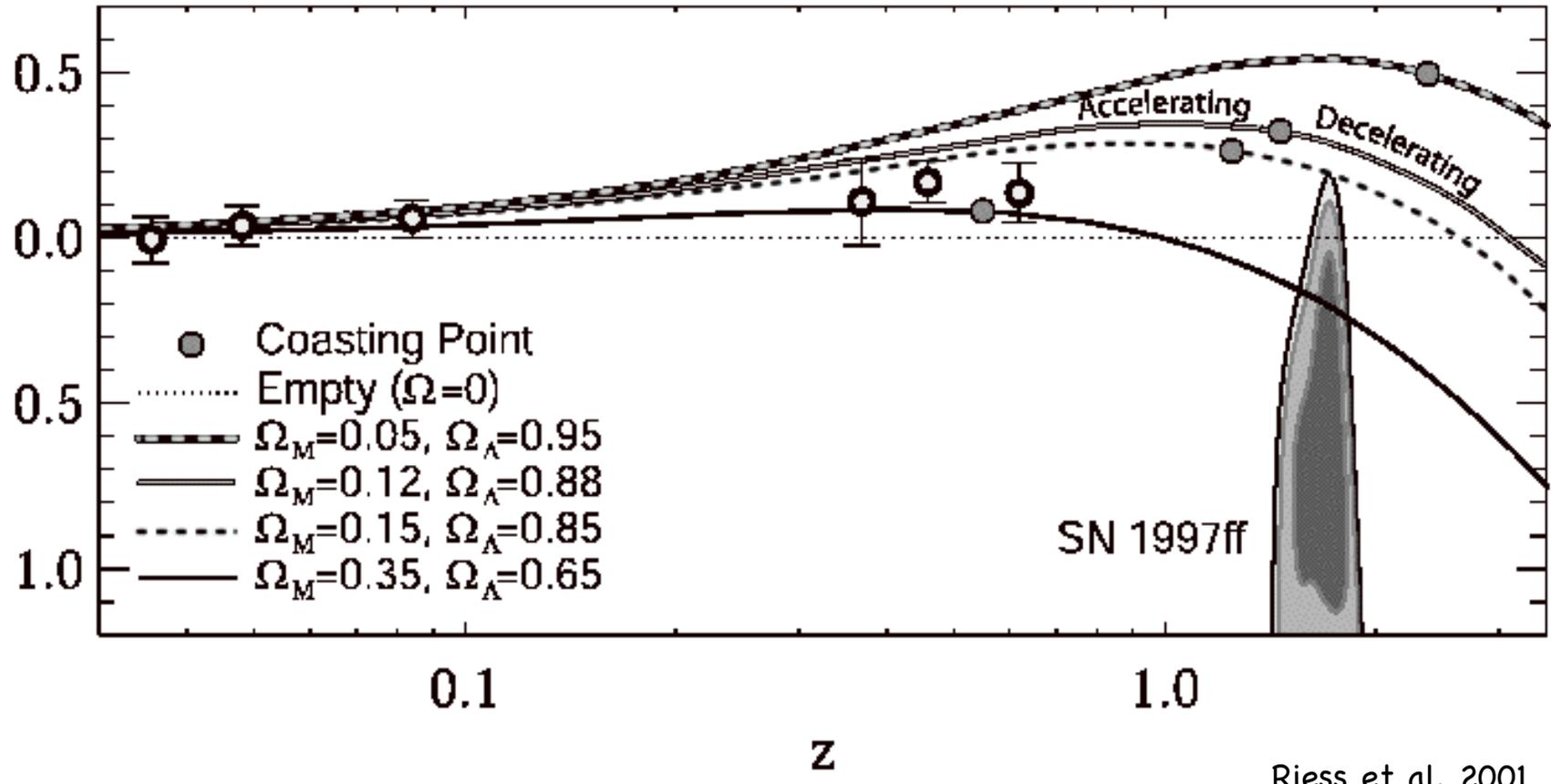


Possible systematic effects that mimic an acceleration:

- 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

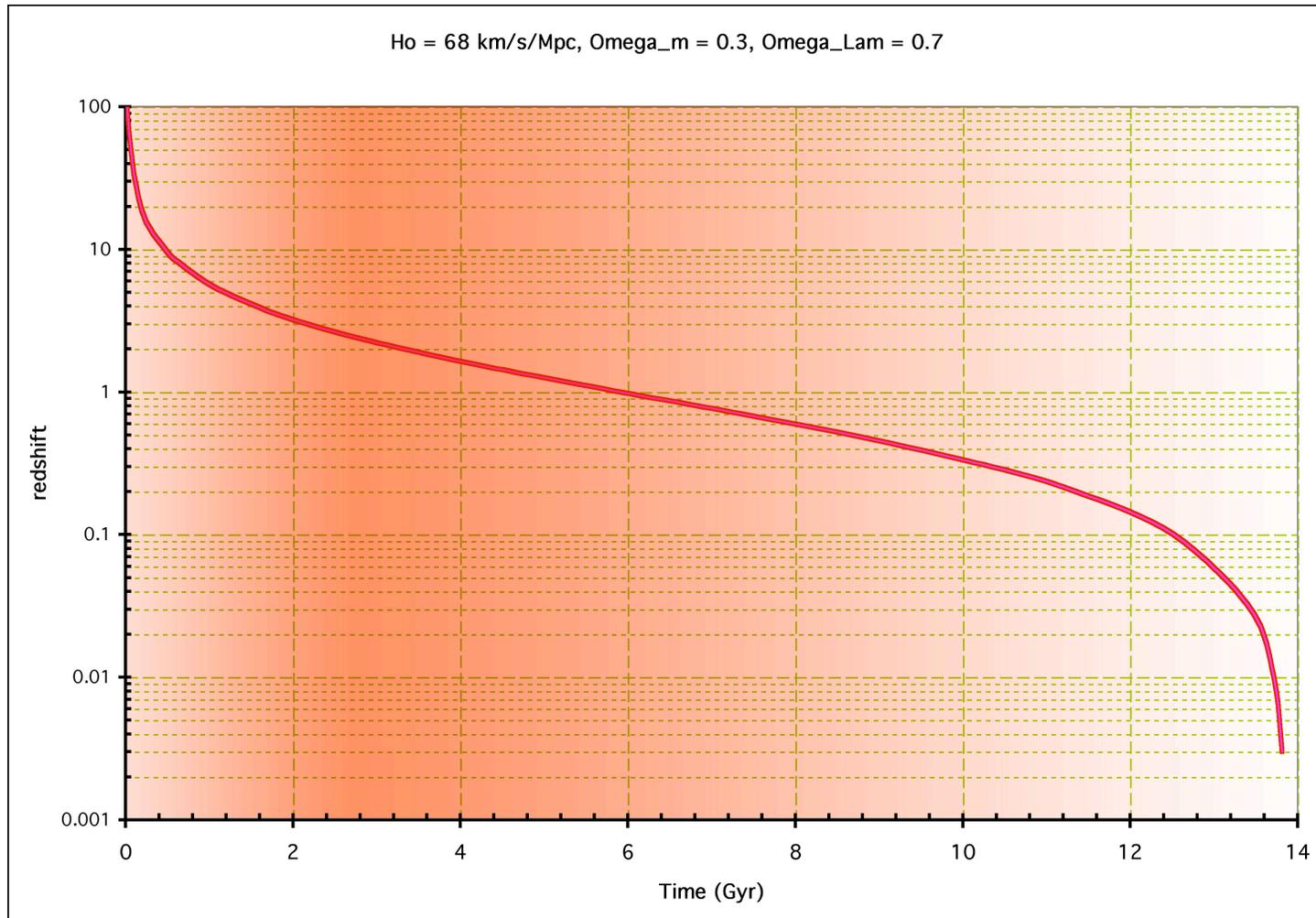
Slightly reassuring news: SN 1997ff



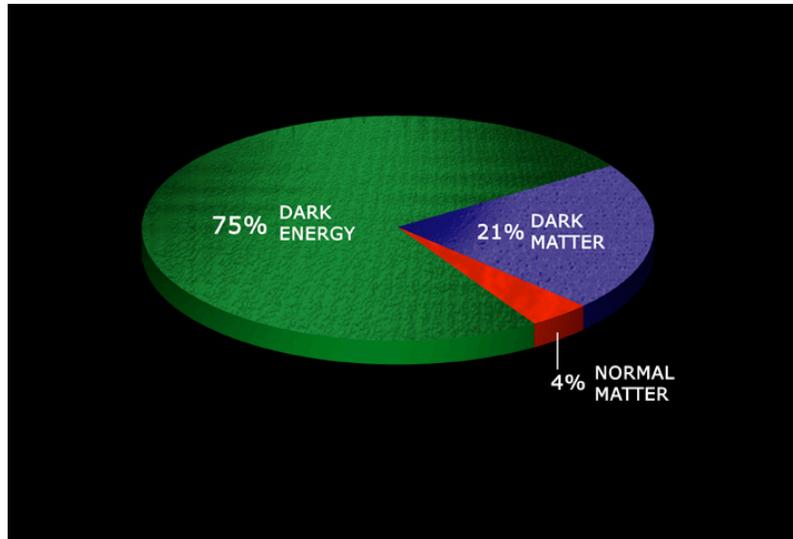
A census of the Universe

- 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

Redshift vs time



What's next?

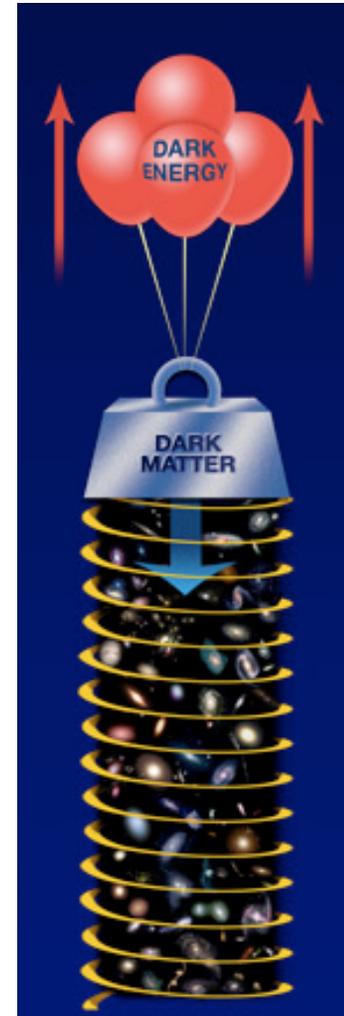


- We have a concordance model of the Universe supported by many independent observations
- The outcome is shocking: 96% of the energy in the Universe seems to be in unknown forms
- The next step is moving from inventory to understanding (S. Carroll)

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**



Data driven phenomenological approach

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

Figure of merit

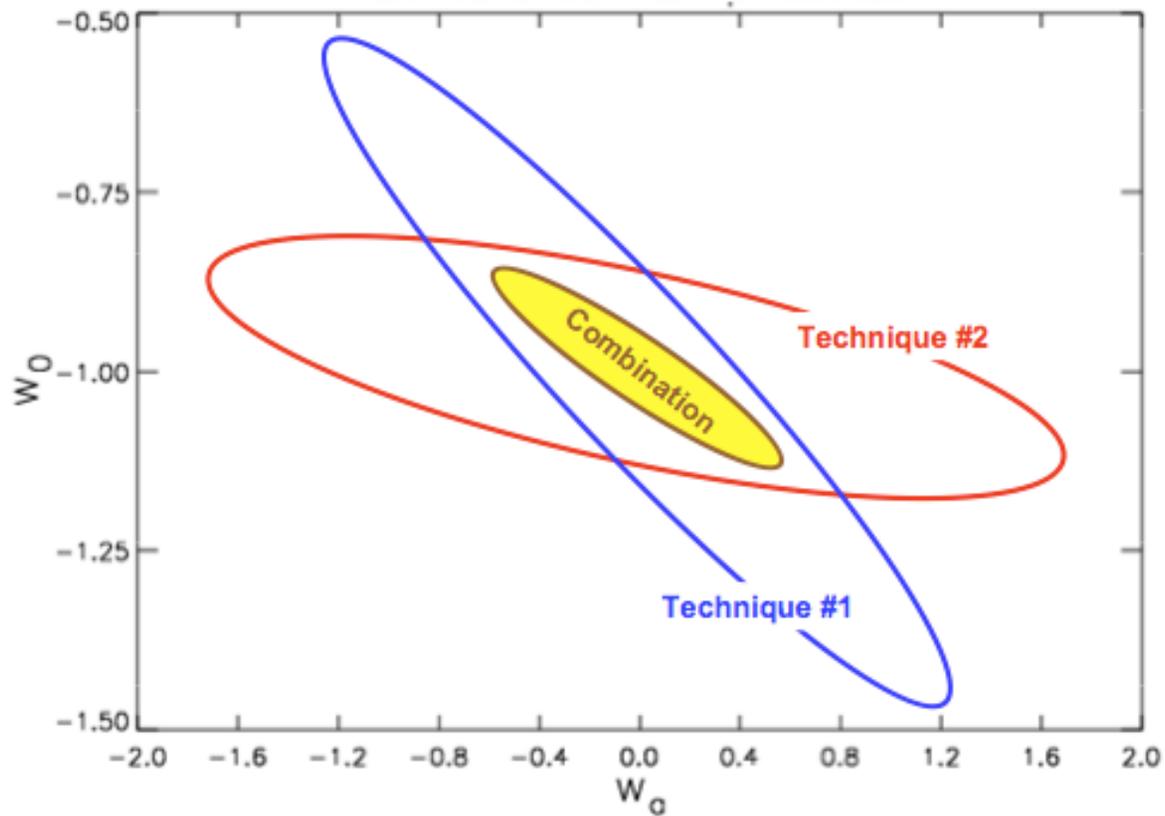
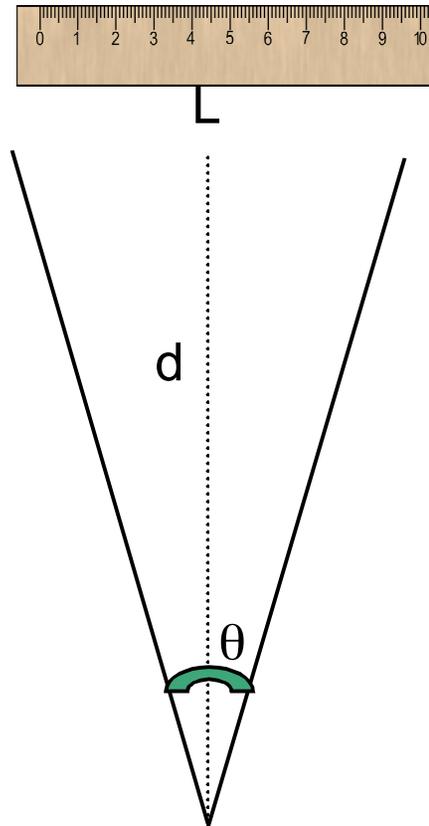


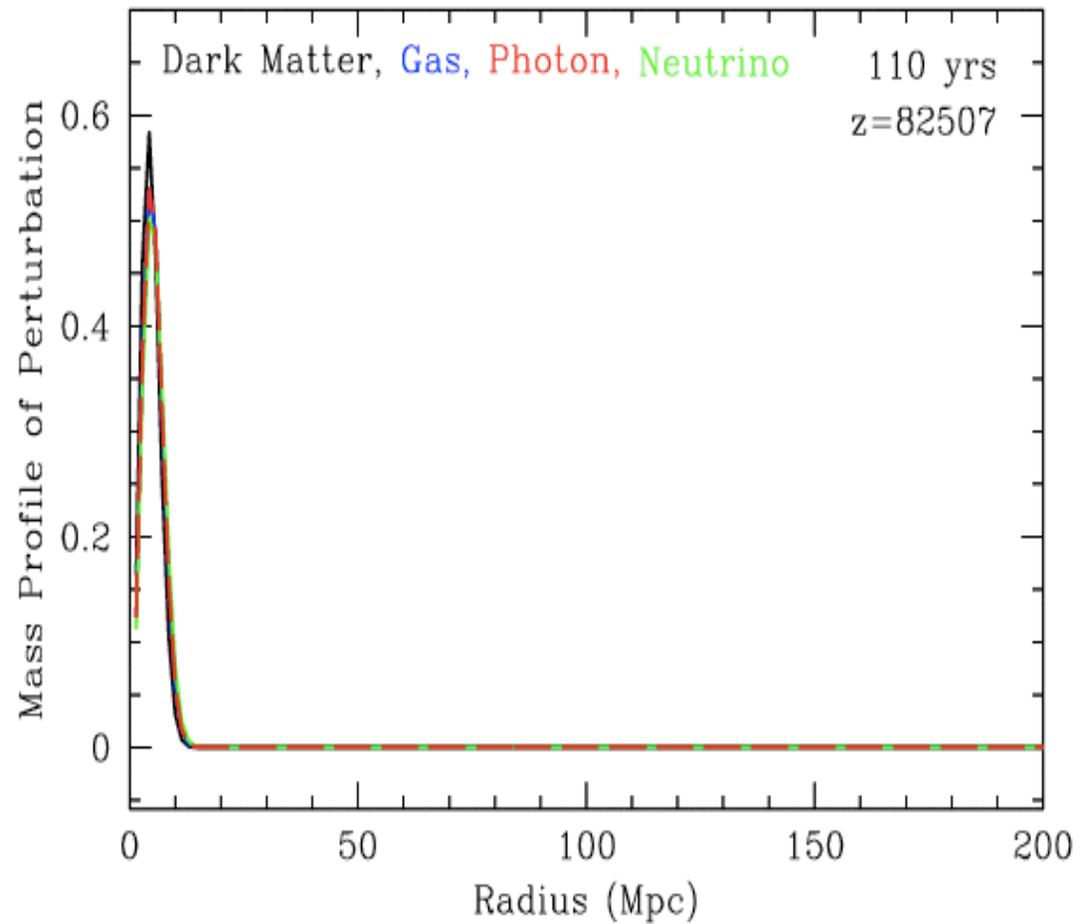
Figure of merit = $1 / (\text{area of the ellipse})$

The ideal standard ruler

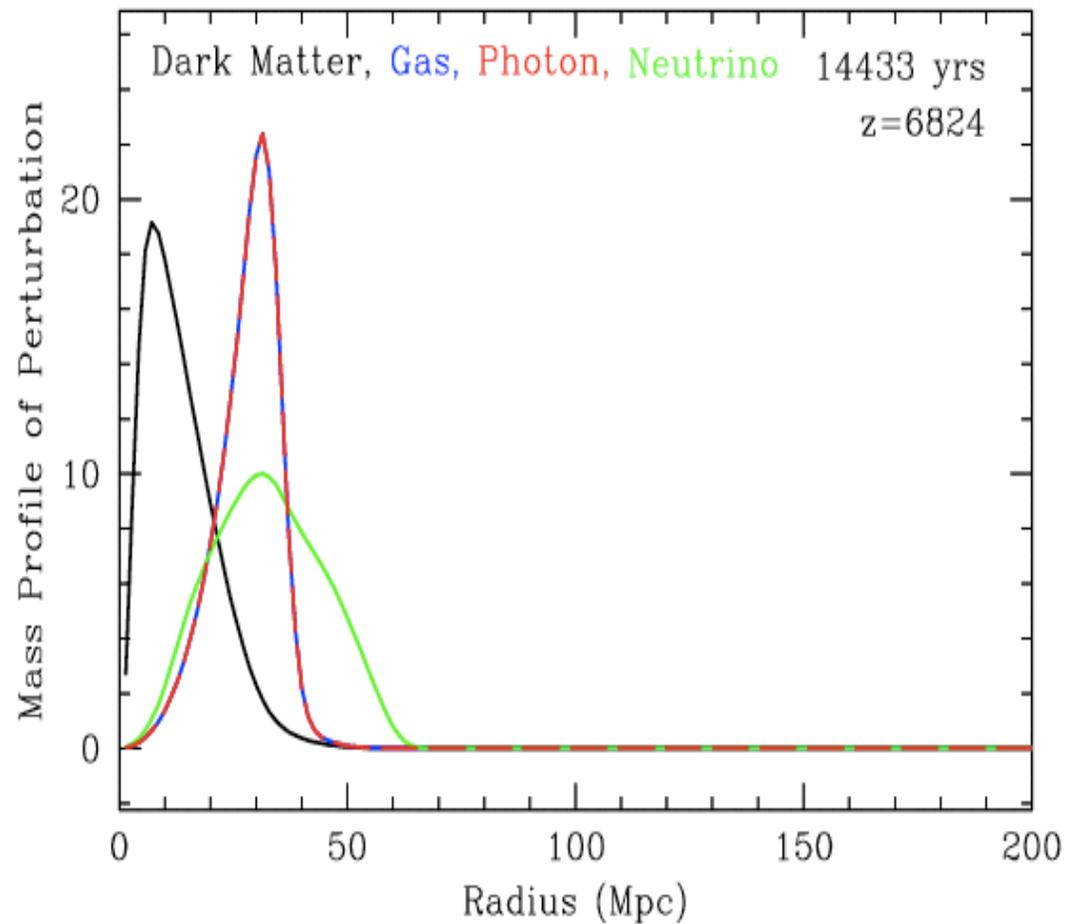


- We need to be able to measure the ruler over much of the volume of the universe
- We need to be able to make ultra-precise measurements of the ruler (1% accuracy to get 5% accuracy in the equation of state for dark energy)
- Answer: **baryonic acoustic oscillations**

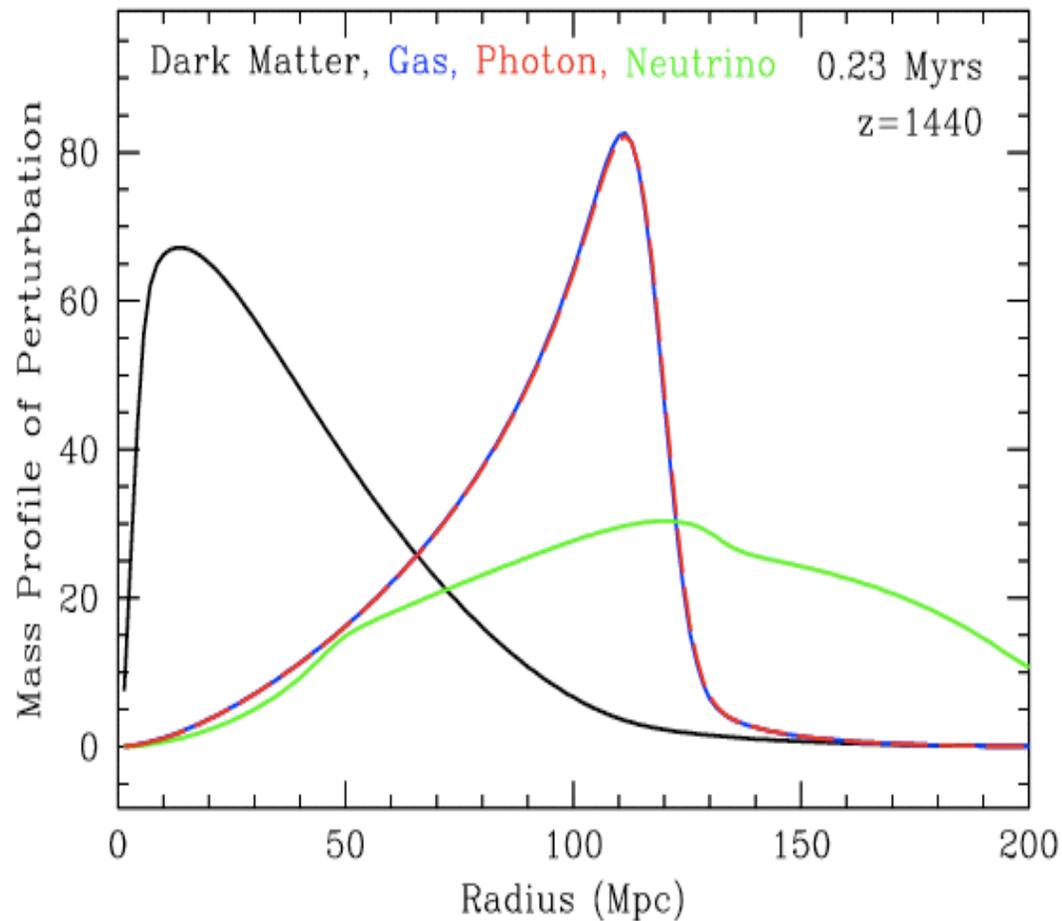
BAOs: a Green function approach



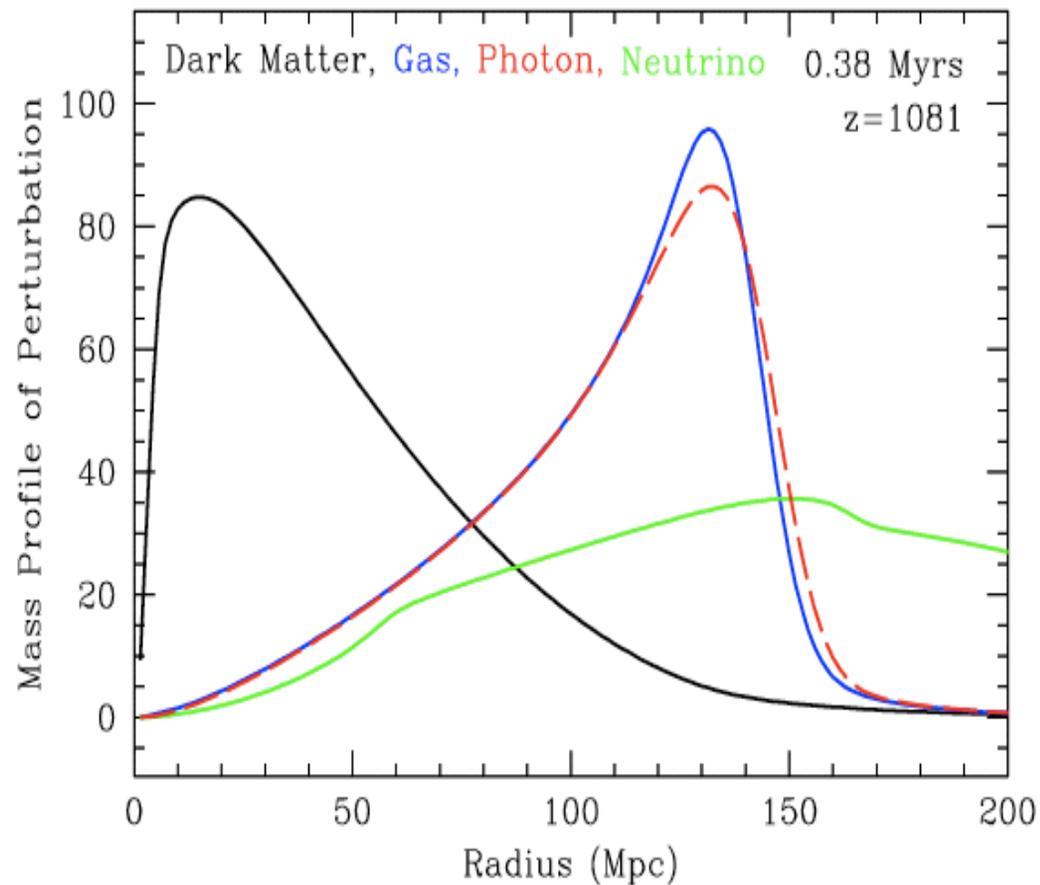
BAOs: a Green function approach



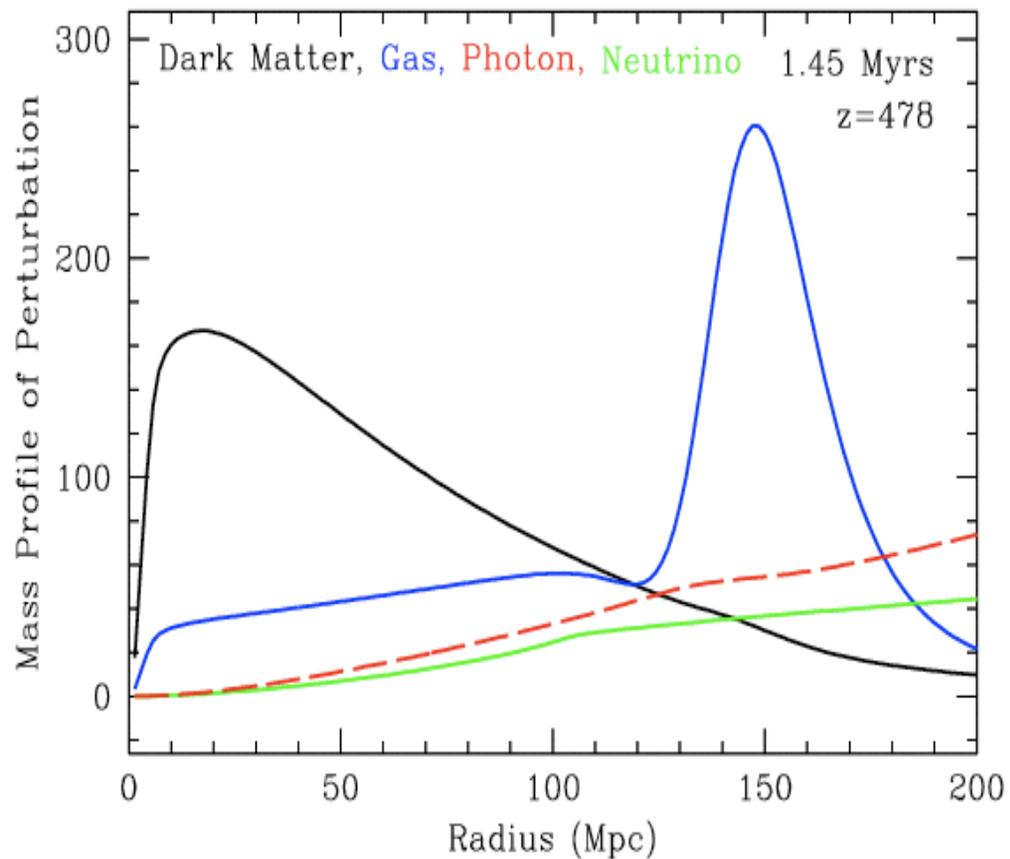
BAOs: a Green function approach



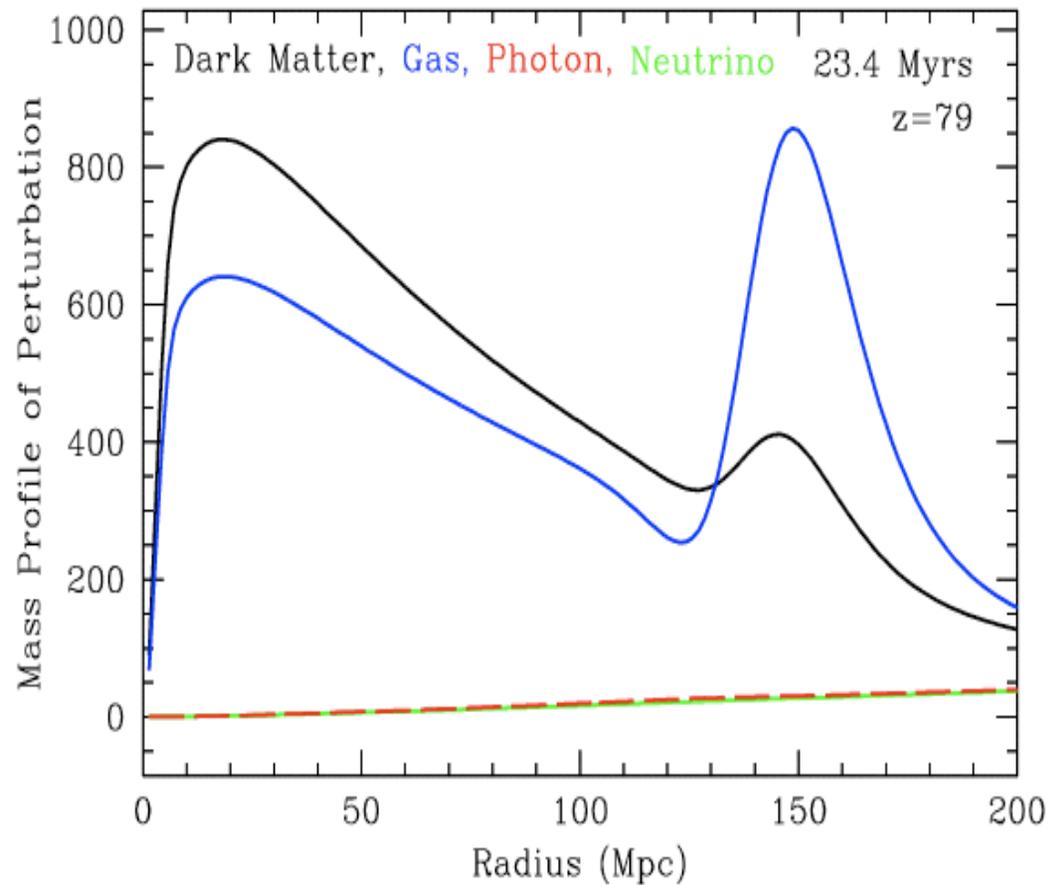
BAOs: a Green function approach



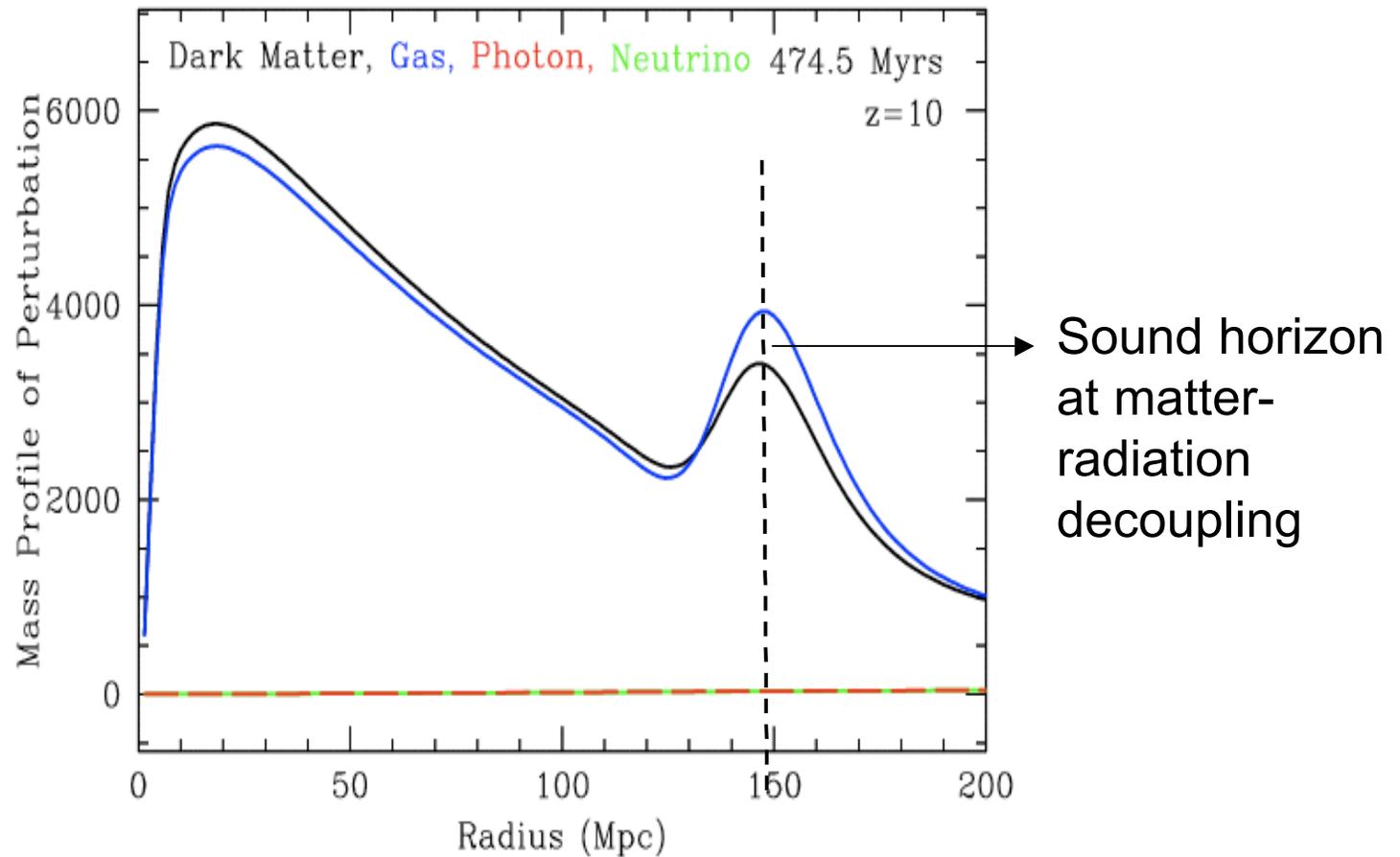
BAOs: a Green function approach



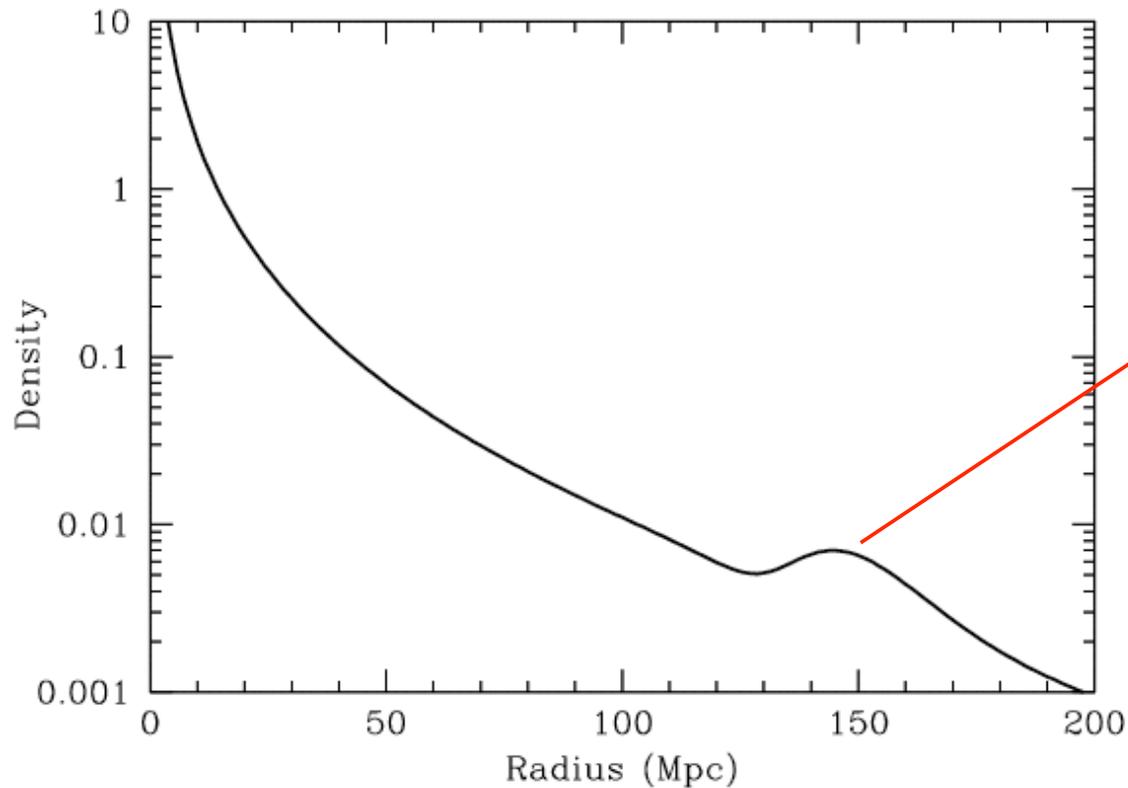
BAOs: a Green function approach



BAOs: a Green function approach

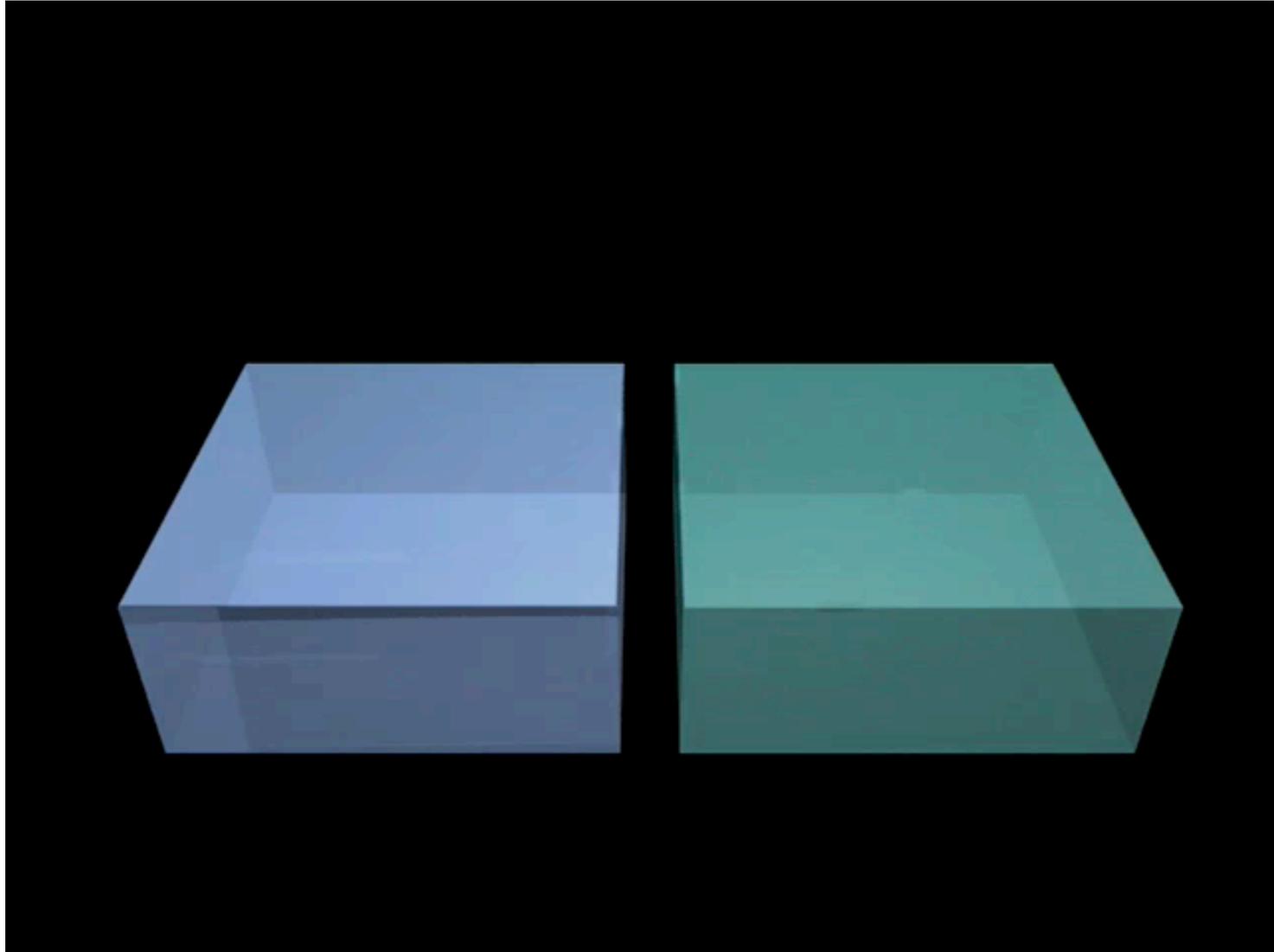


BAOs: the density profile



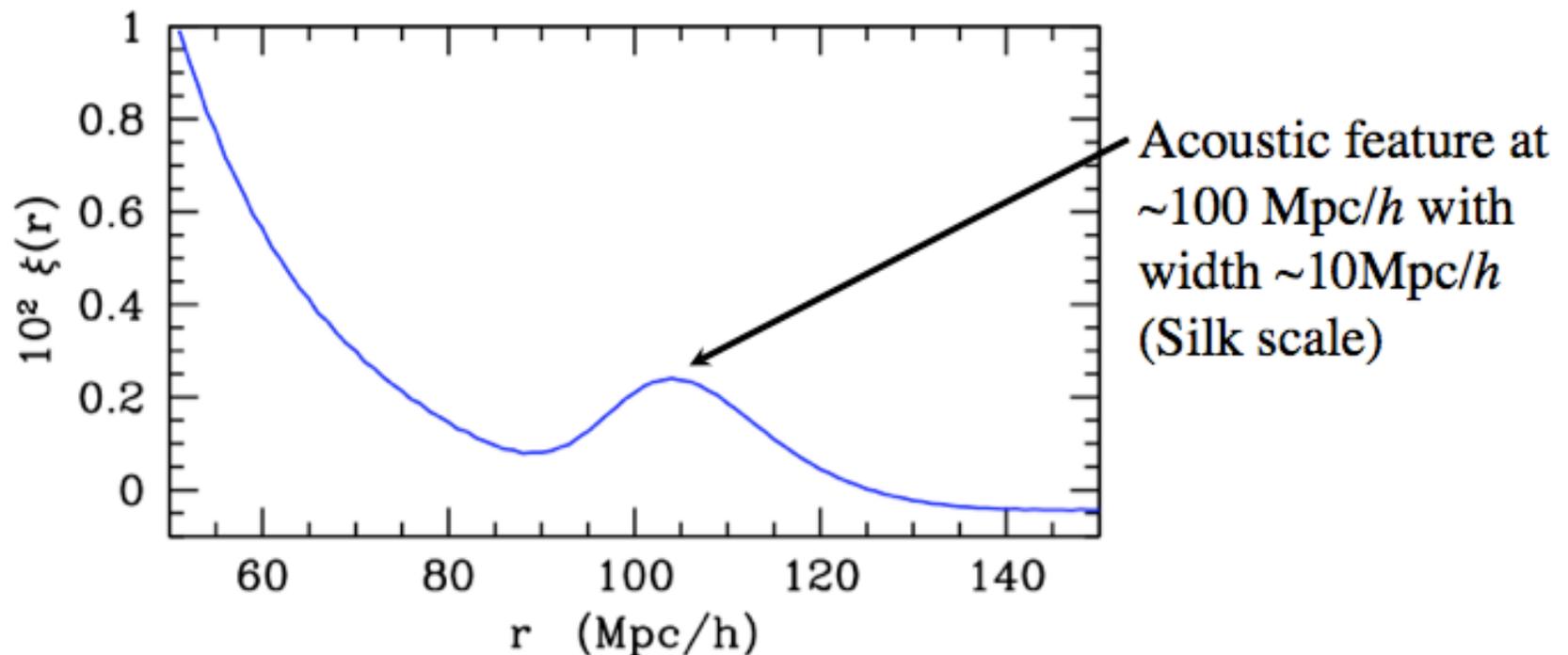
Slight excess
at ~ 150 Mpc
The exact
value
depends on
cosmology
but can be
calibrated
using CMB
anisotropies

CMB fluctuations and sound waves

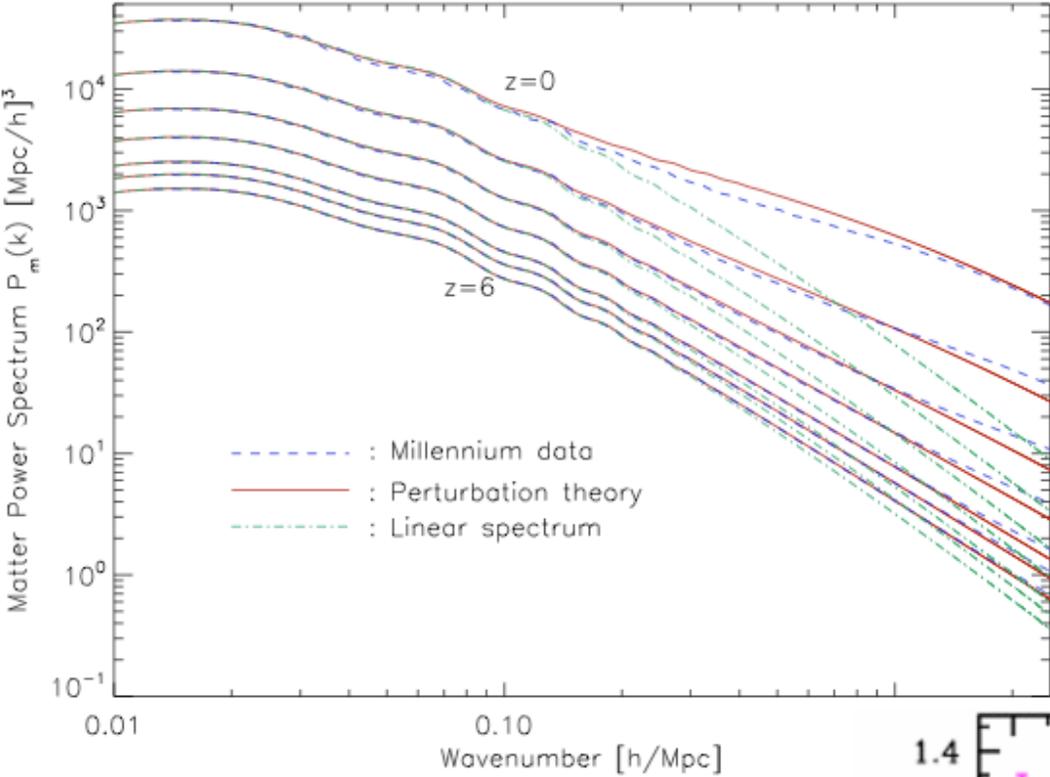


BAOs 2-point correlation function

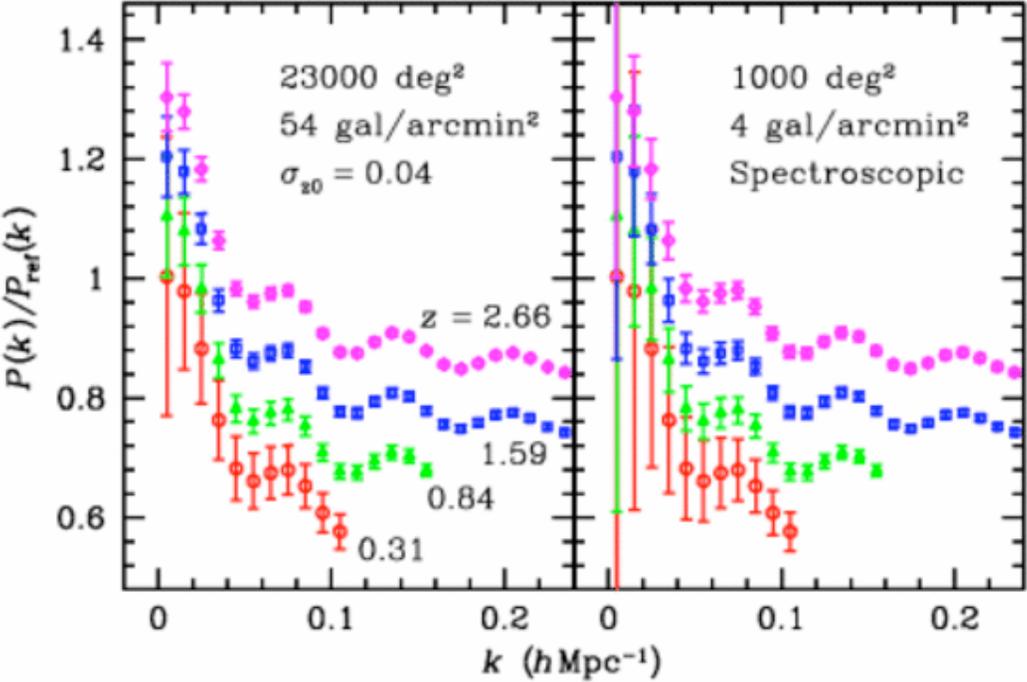
The acoustic bump is frozen into the matter power spectrum and provides a standard ruler with which to measure radial and transverse distances as a function of redshift. Non-linear effects broaden the bump and shift it by $\sim 0.5\%$ (not an issue for first generation experiments but an issue for future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



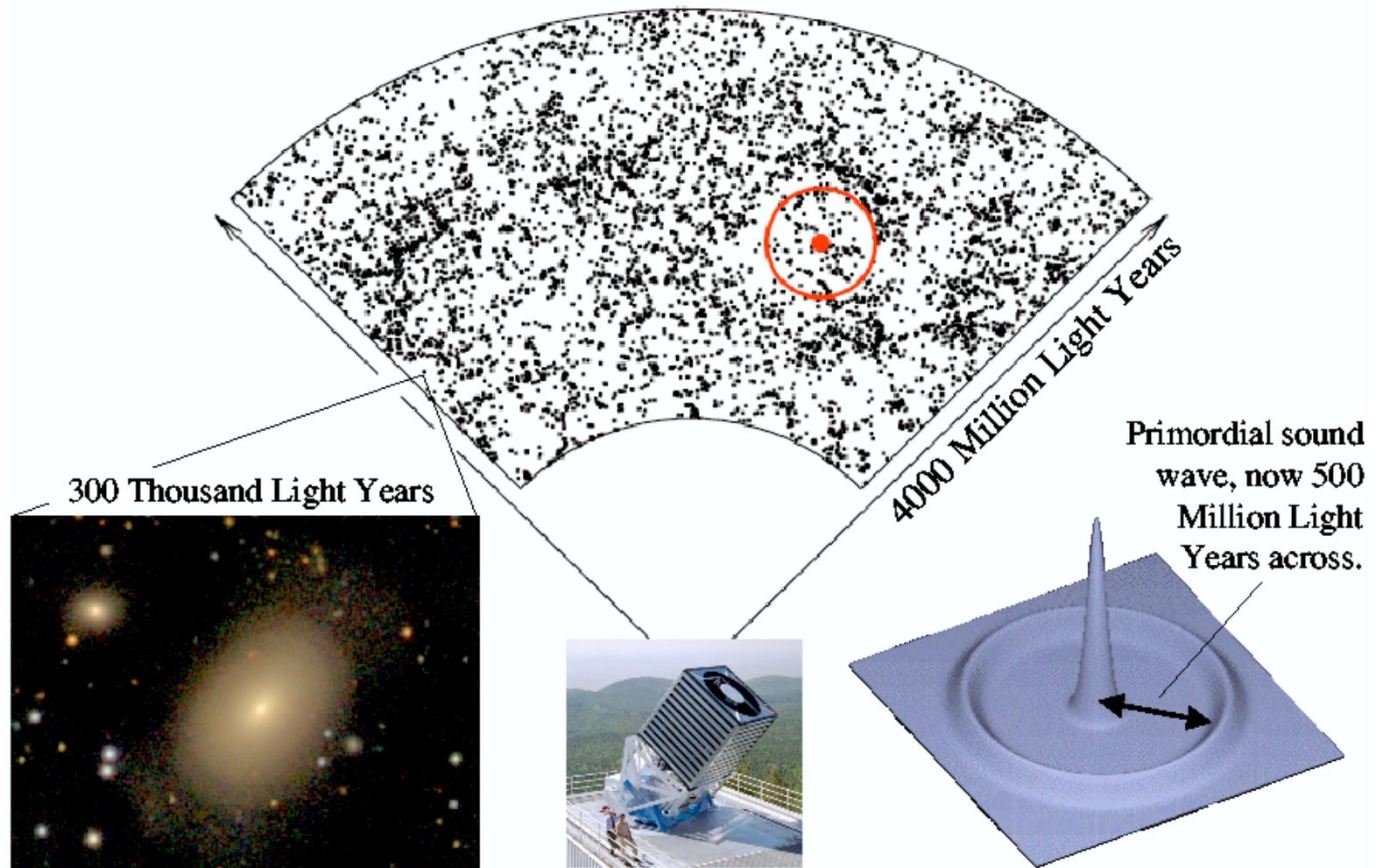
Power spectrum



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



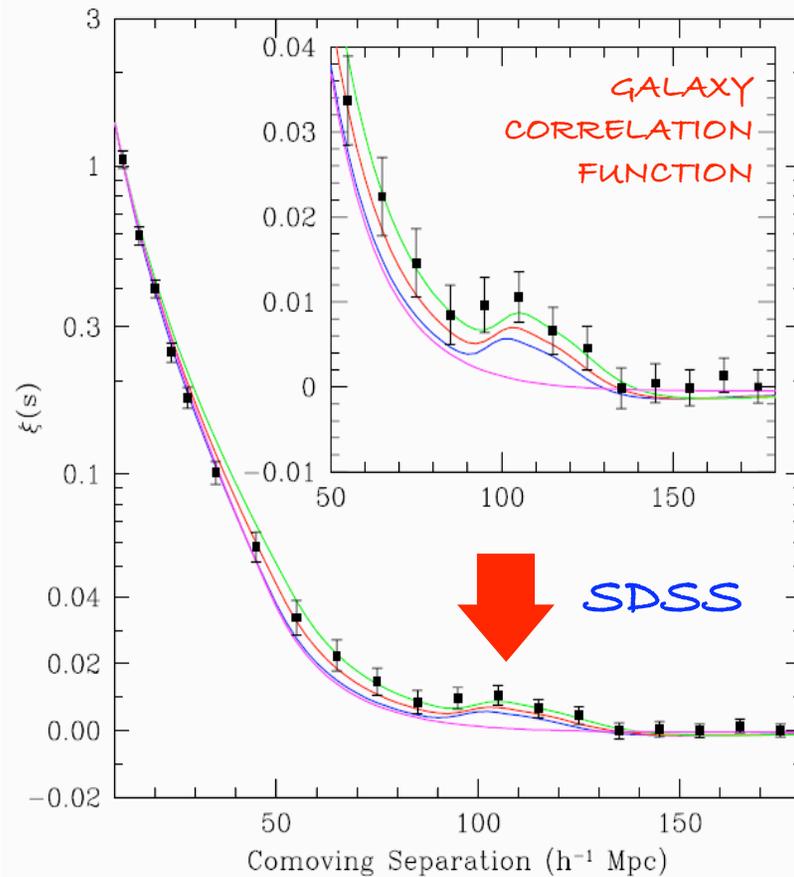
Baryonic oscillations



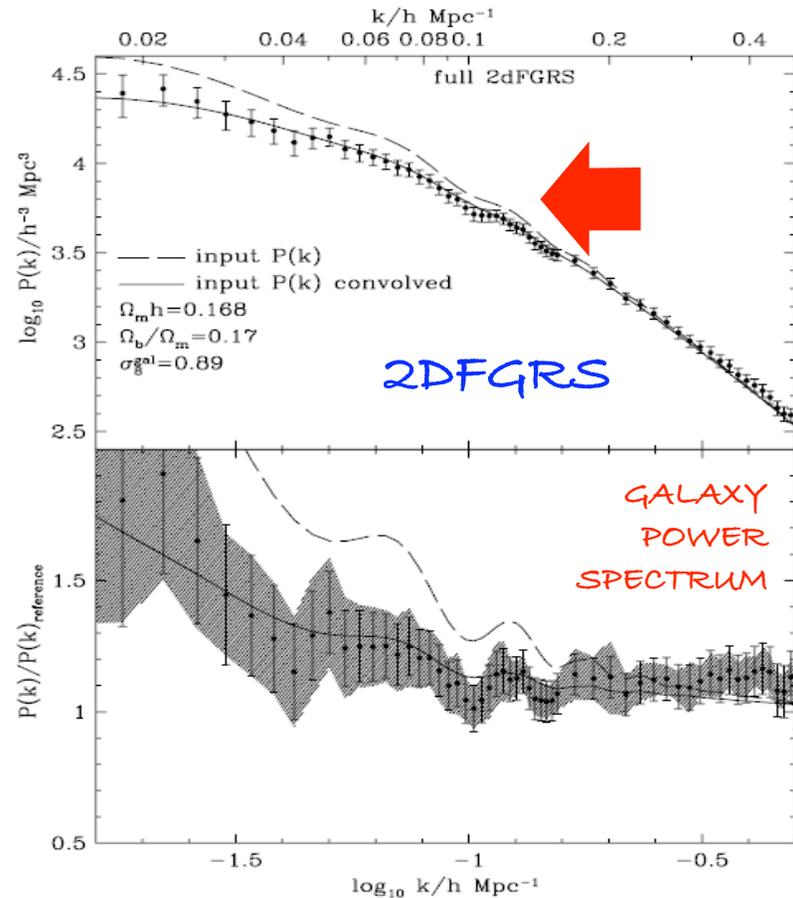
Measuring BAO from LSS

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

SDSS: EISENSTEIN ET AL. (2005)

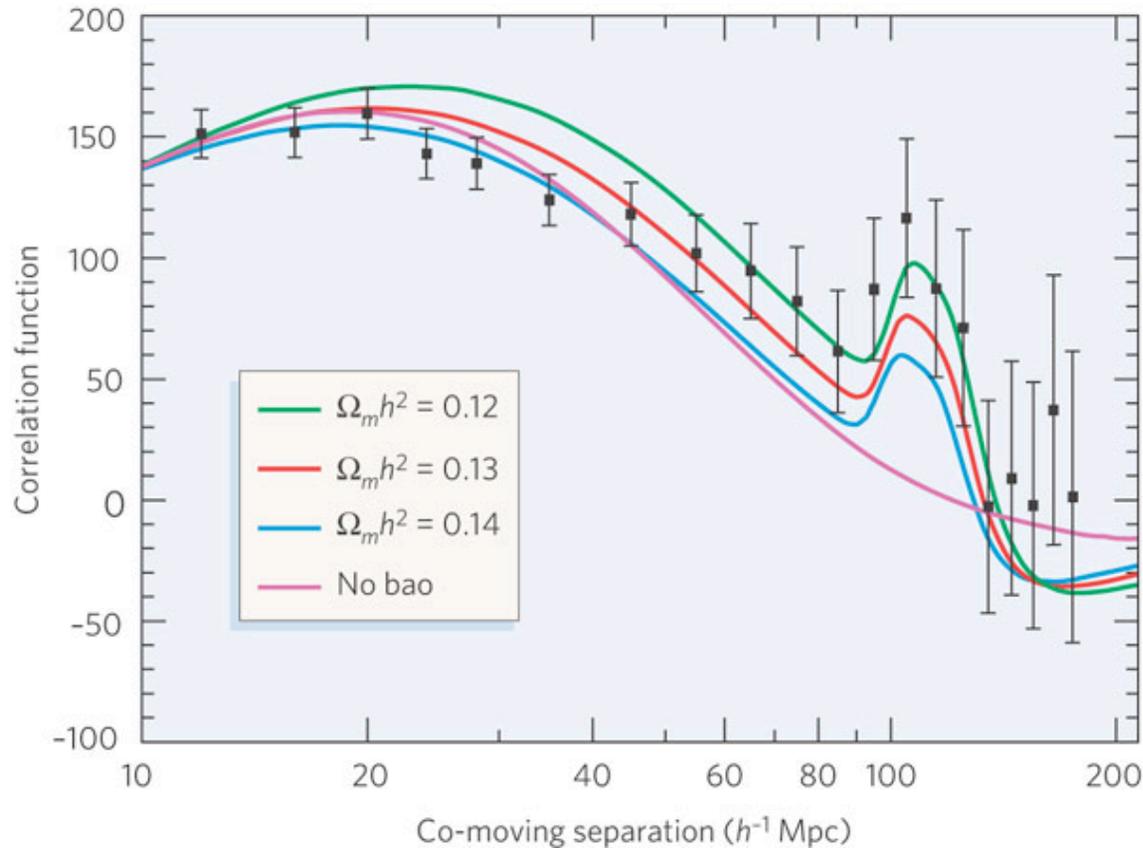


2DFGRS: COLE ET AL. (2005)



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)

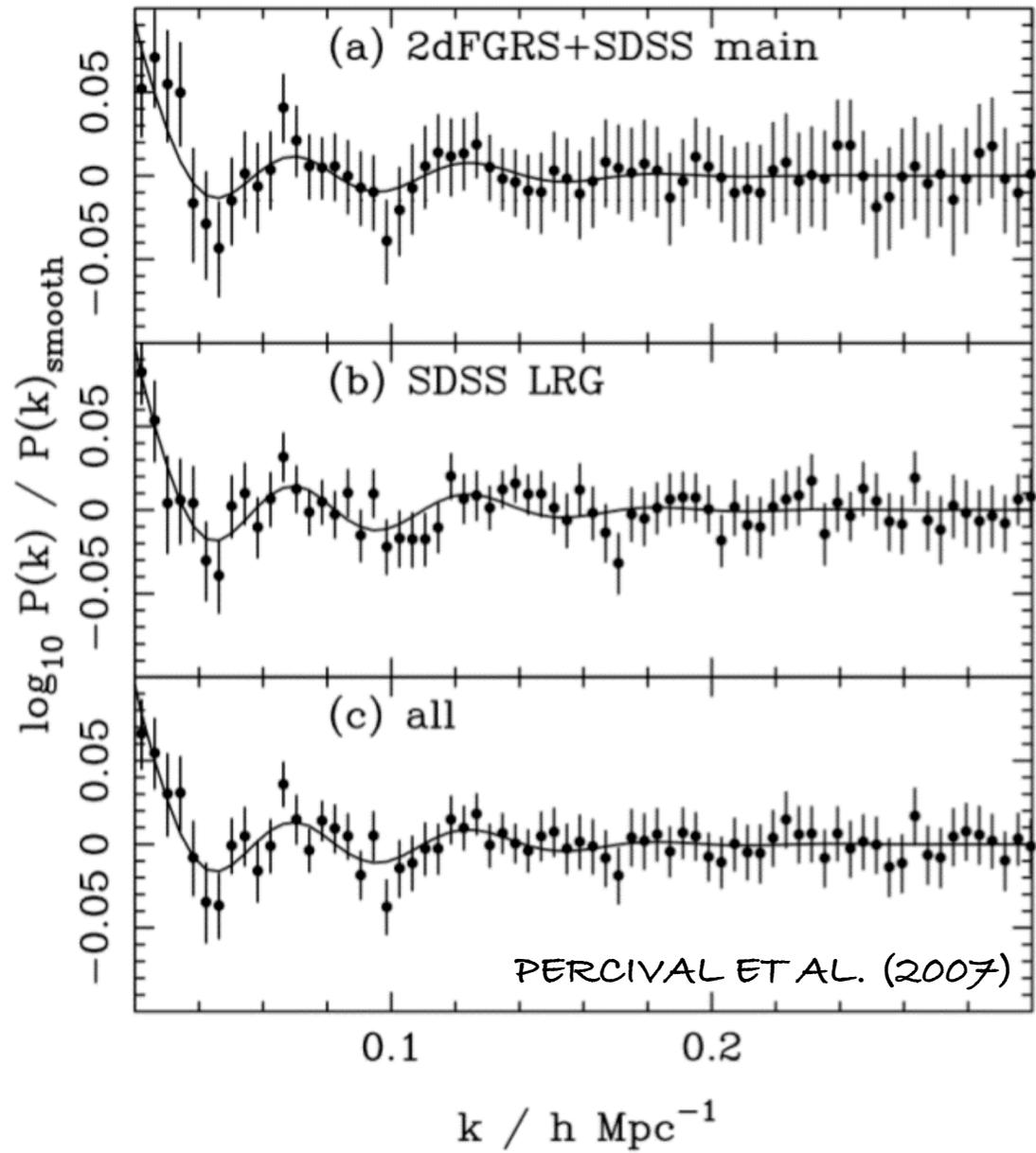
3.4σ detection of BAOs

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

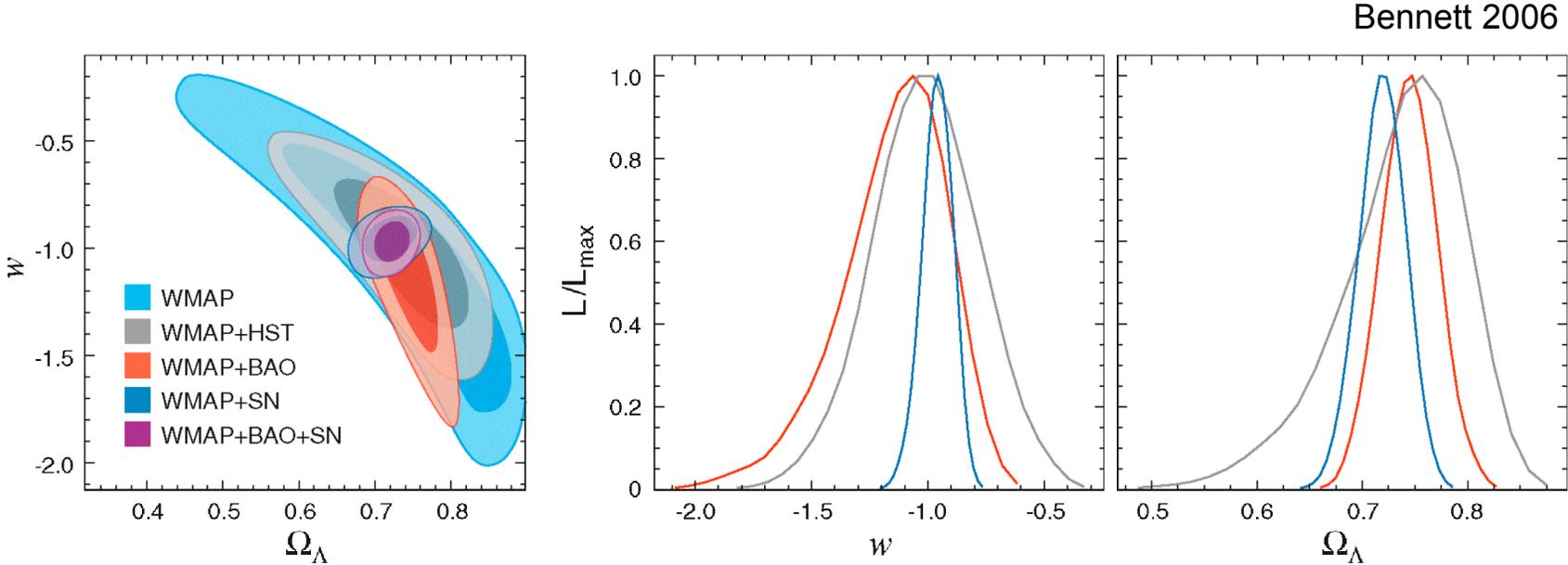
Absolute distance to
 $z=0.35$ determined to
5% accuracy

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



Bennett 2006

A look into the future

TOP(?) TEN Cosmology surveys

- Cosmic microwave background
 1. planck - ultimate cmb survey, launched on MAY 14!
- 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-STARRS1 - OPTICAL imaging; sne/wl/cl/BAO
 2. VISTA - NIR complement to DES/PS1 (SEDS, photo-Z)
 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

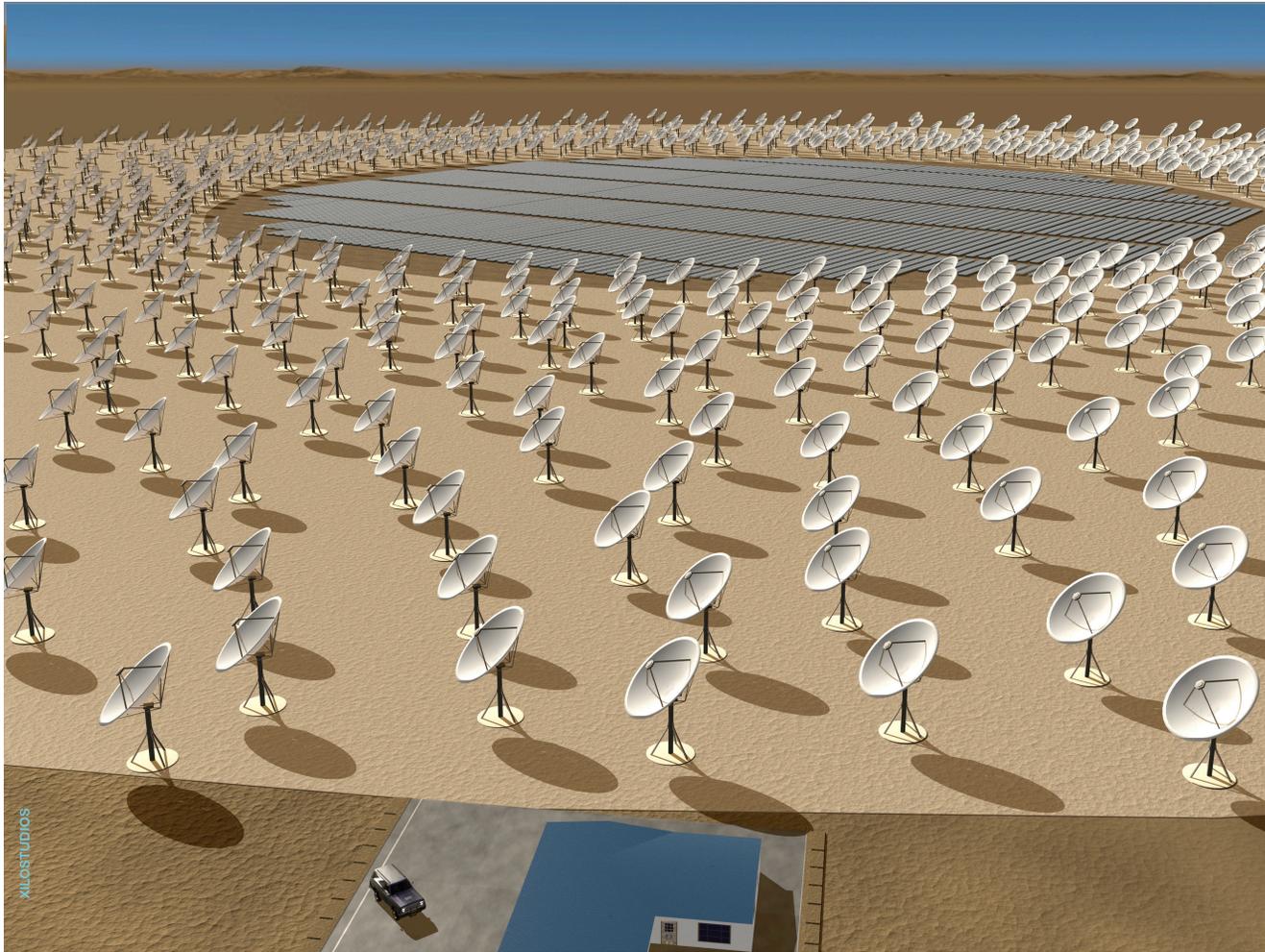
beyond the 10-year horizon

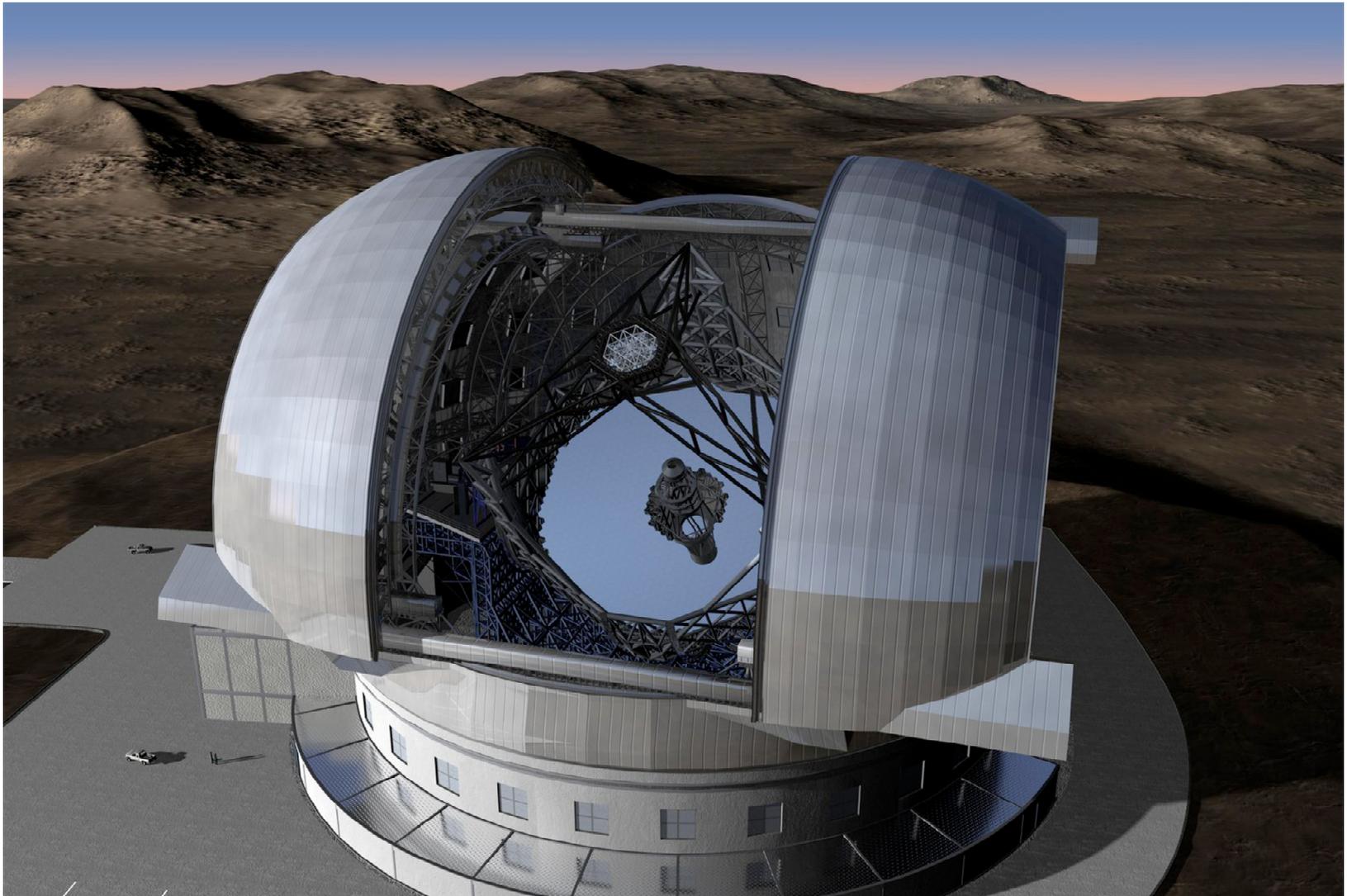
- Some of the BIGGEST advances in capability for cosmology surveys will come on-line just outside the decadal horizon...

- 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

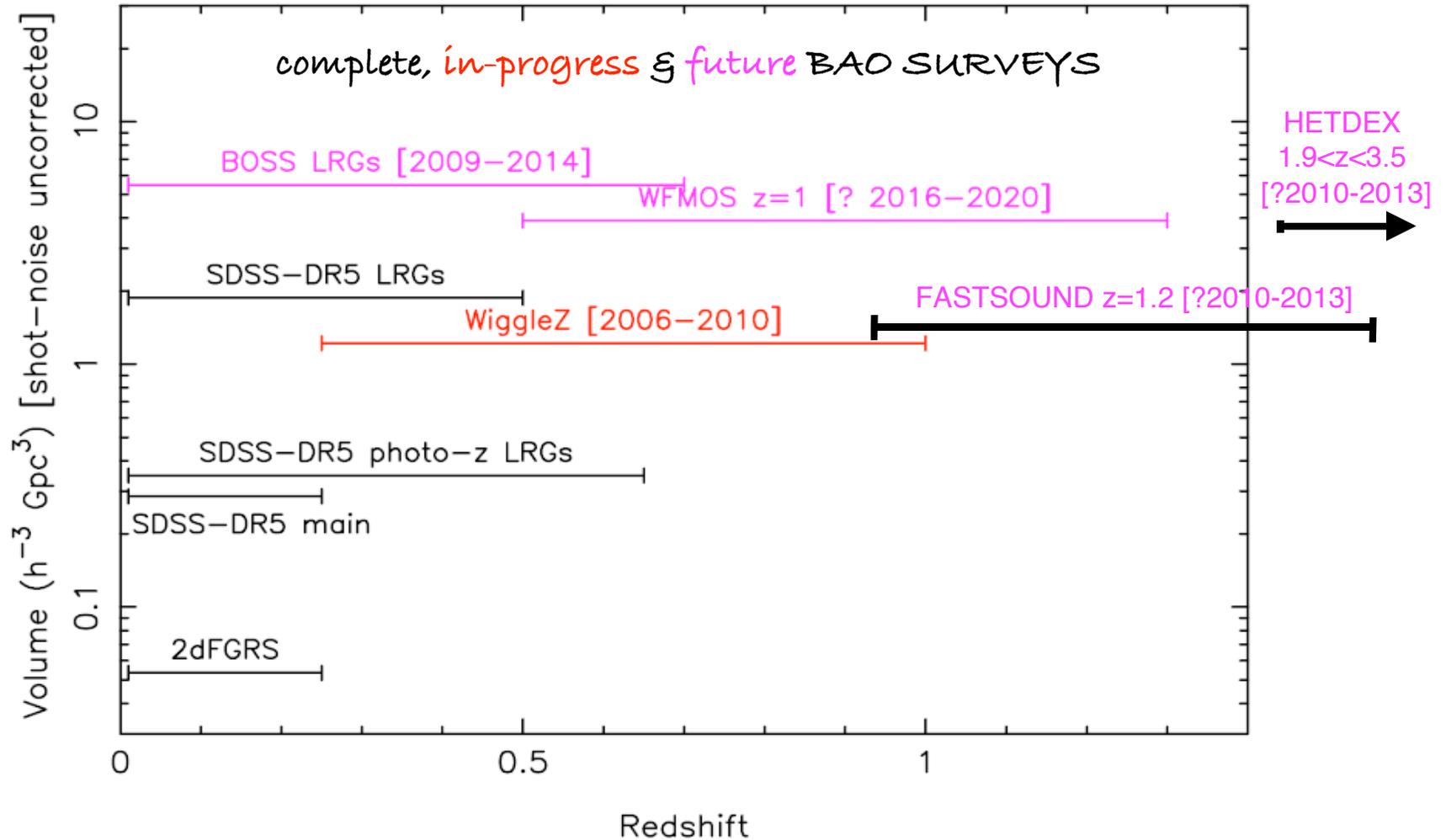
Advantages of BAO surveys

- 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

Survey	Telescope / instrument	$N(Z) / 10^6$	Dates	Status
WiggleZ	AAT/AAΩ	0.2	2007-2010	In progress
FastSound	Subaru/FMOS	0.6	2010-2013	Proposal
BOSS	SDSS	1.5	2009-2013	Starting
HETDEX	HET/VIRUS	1.0	2010-2013	Part funded
LAMOST-DE	LAMOST	t.b.d.	2010-201?	Proposal
WFMOs-DE	Subaru/wfmos	>2	2013-2016	Funding?
JDEM	NASA/JDEM	>100	2012+	Status?
SKA	SKA	>100	2020+	FUTURE

C.

BAO survey comparison



The WiggleZ survey

- Project goals:
 - The first 'high' redshift ($z > 0.5$) BAO survey
 - Survey 240,000 galaxies with median $z \sim 0.6$
 - BAO scale to 2% and test $w_0 = -1$ over $z \sim 0.25 - 1.0$

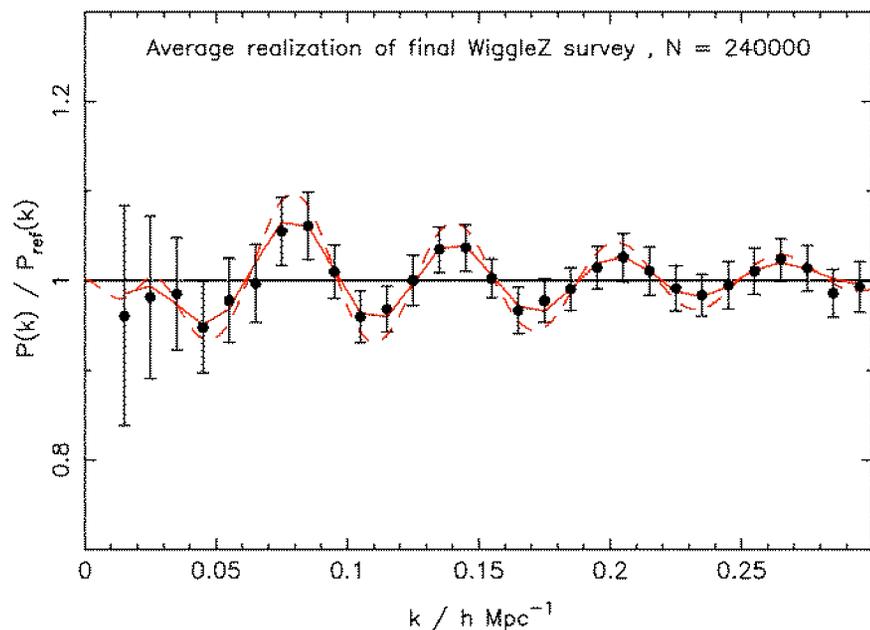
- Survey observations and sample:
 - Star-forming galaxies from GALEX & SDSS/RCS2
 - FUV-NUV-opt colours select 'Lyman-break' galaxies at $z > 0.5$
 - covers $\sim 1000 \text{ deg}^2$ on sky & a volume of $\sim 1 \text{ Gpc}^3$
 - AAOmega gives redshifts to $z \sim 1$ in 1 hour

- Status and results:
 - About two-thirds complete; finish by July 2010
 - Preliminary RESULTS & forecast constraints

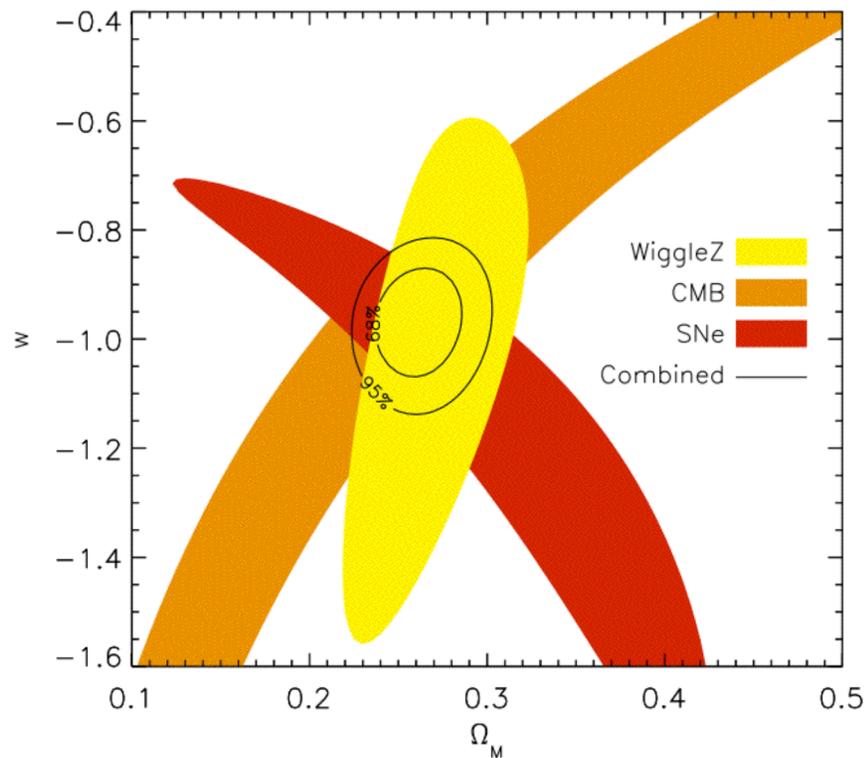
Survey parameter	Survey plan	March 2009	Survey end
Sky coverage	1000 DEG ²	675 DEG ²	1000 DEG ²
Number of nights	220	157	240
Good weather fraction	75%	66%	66%
Number of WiggleZ spectra	340,000	266,000	410,000
NUMBER OF WIGGLEZ GOOD Z'S	240,000	139,000	215,000
WiggleZ z-completeness	70%	70%	70%
Number of AAT pointings	1200	807	1235
Number of GALEX orbits	1250	1142	1250
Duration of survey	AUGUST 2006 – JULY 2010		

wigglez Survey forecasts

- PREDICTED UNCERTAINTIES BASED ON CURRENT RESULTS AND MONTE CARLO SIMULATIONS OF THE EXPECTED FINAL DATASET:
 - $\sim 2.7\%$ IN TANGENTIAL SCALE AND $\sim 4.3\%$ IN RADIAL SCALE
 - $< 2\%$ PRECISION ON MEASUREMENT OF OVERALL BAO SCALE
 - $\sim 5\%$ PRECISION IN 3 REDSHIFT INTERVALS OVER $Z=0.25-1.0$

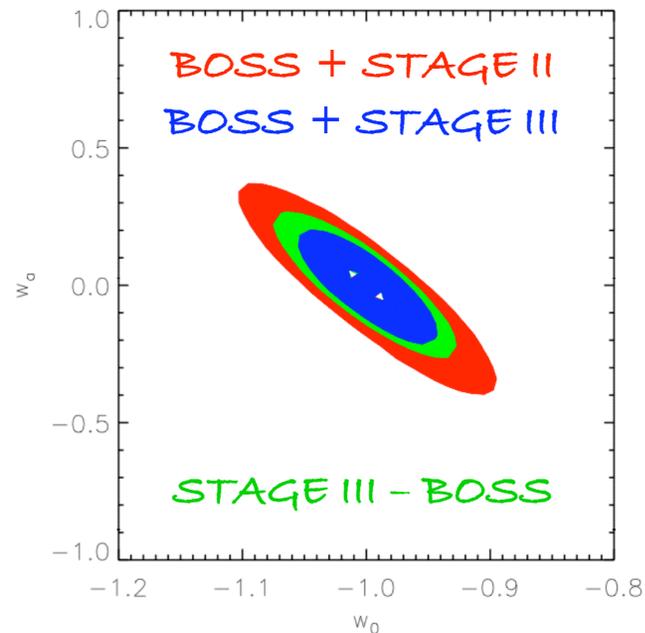
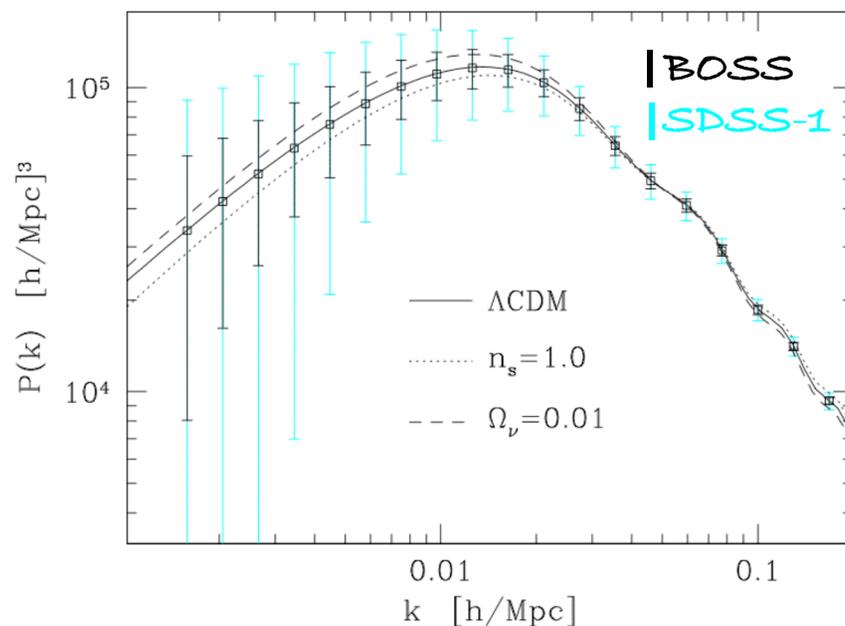


$$\Delta\Omega_m = 0.02, \Delta W_0 = 0.07$$



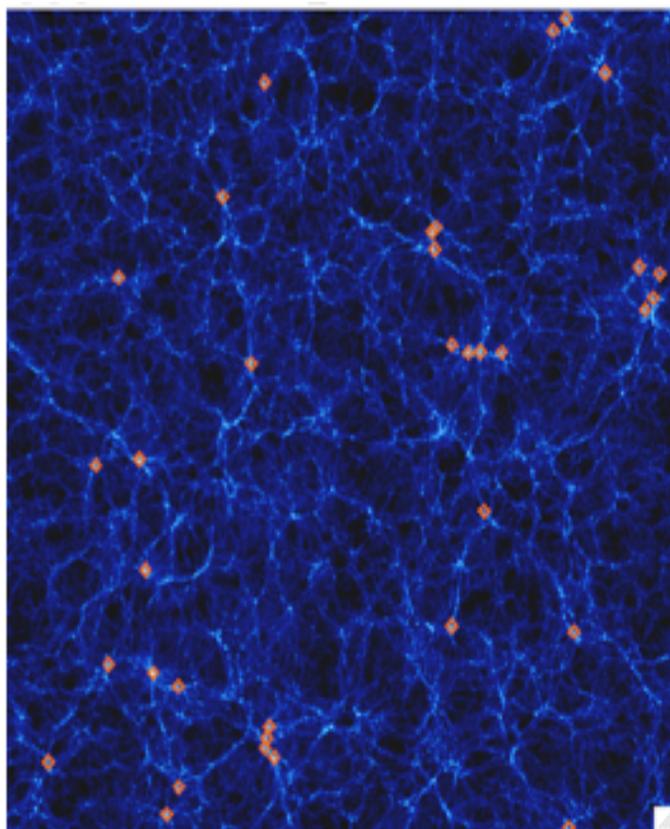
BOSS - SDSS-III BAO survey

- baryon oscillation spectroscopic survey
- Dark time observations fall 2009-spring 2014
- 1000-fibre spectrograph; 360-1000nm at $R \sim 2000$
- 1.5×10^6 Luminous red galaxies: 10^4 deg^2 , $z < 0.7$
- 1.6×10^5 QSOs: Ly-alpha forest spectra, $2.2 < z < 3.0$
- $D_a(z)$ to 1% at $z = 0.3, 0.6$ & 1.5% at $z = 2.5$; $H(z)$ to 2%

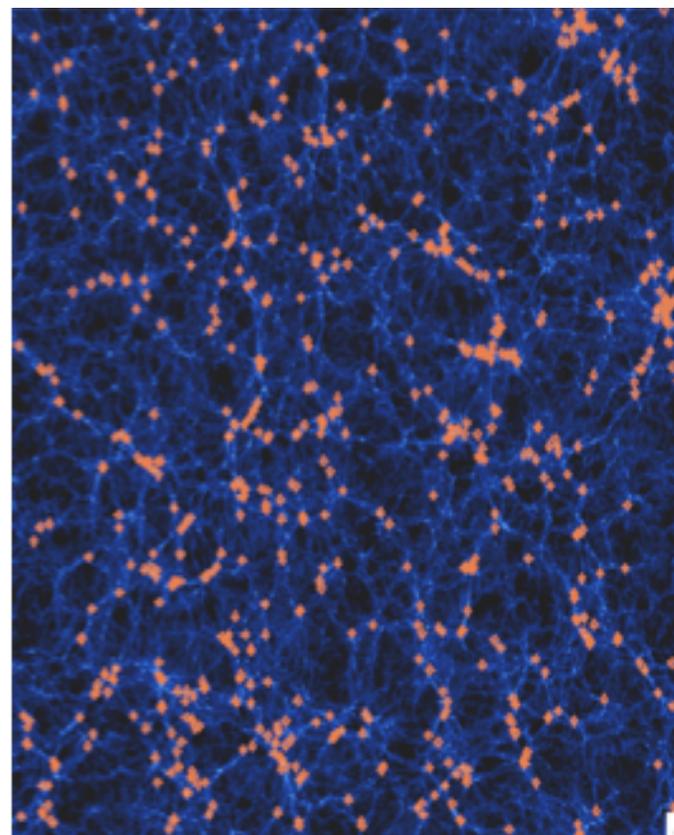


BOSS vs SDSS at $z=0.5$

A slice 500 Mpc/h across and 10 Mpc/h thick



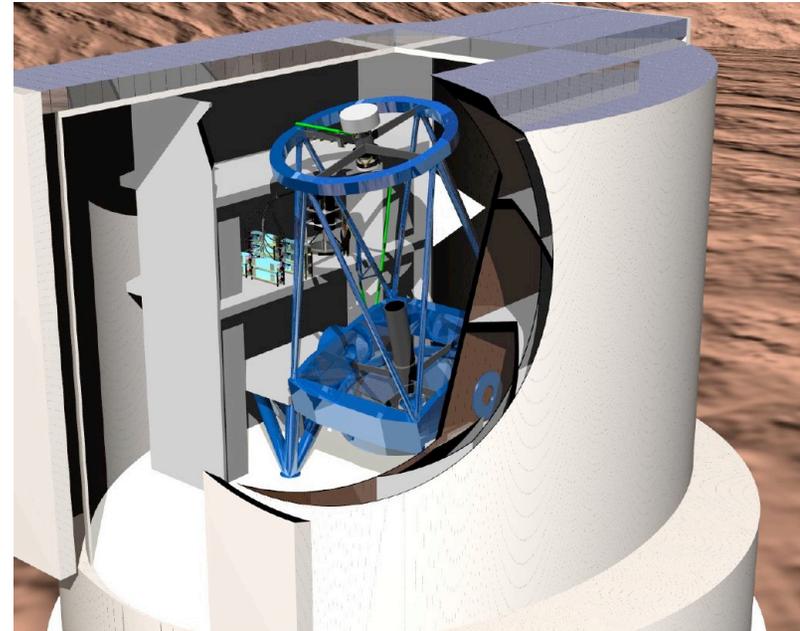
SDSS



BOSS

WFMOS BAO

- WIDE-FIELD MULTI-OBJECT SPECTROGRAPH ON SUBARU
- 4000-FIBRE SPECTROGRAPH;
400-1000NM AT R~2000
- INSTRUMENT TO BE BUILT
(FUNDING? SURVEY IN 2013?)
- STRATEGY DEPENDS ON BOSS/HETDEX HI-Z SUCCESS:
- lo-z only: 8.8×10^6 ELGS OVER 6150 DEG² AT $\langle Z \rangle \sim 1.2$ x
 $D_a(Z)$ TO 0.48%, $H(Z)$ TO 0.75% x
 DETF F.O.M. = 78
- Lo-z+hi-z: 5.8×10^6 ELGS OVER 3450 DEG² AT $\langle Z \rangle \sim 0.4$ x
 $D_a(Z)$ TO 0.75%, $H(Z)$ TO 1.2% x PLUS
 4.5×10^5 ELGS OVER 2700 DEG² AT $\langle Z \rangle \sim 2.5$ x
 $D_a(Z)$ TO 1.1%, $H(Z)$ TO 1.8% x
 COMBINED DETF F.O.M. = 21



Wigglez vs boss vs wfmos

	no curvature			with curvature		
survey	FOM	$\Delta(W_0)$	$\Delta(W_a)$	fom	$\Delta(W_0)$	$\Delta(W_a)$
wigglez	5.5	0.58	1.59	1.1	1.11	4.25
boss (no qso)	36	0.20	0.59	6.6	0.47	1.98
boss (+ qso)	40	0.19	0.53	21	0.21	0.71
wfmos	60	0.13	0.41	21	0.20	0.73
stage III Sne	39	0.21	0.65	3.7	0.46	2.51
combined	99	0.10	0.33	78	0.12	0.38

imaging DARK ENERGY SURVEYS

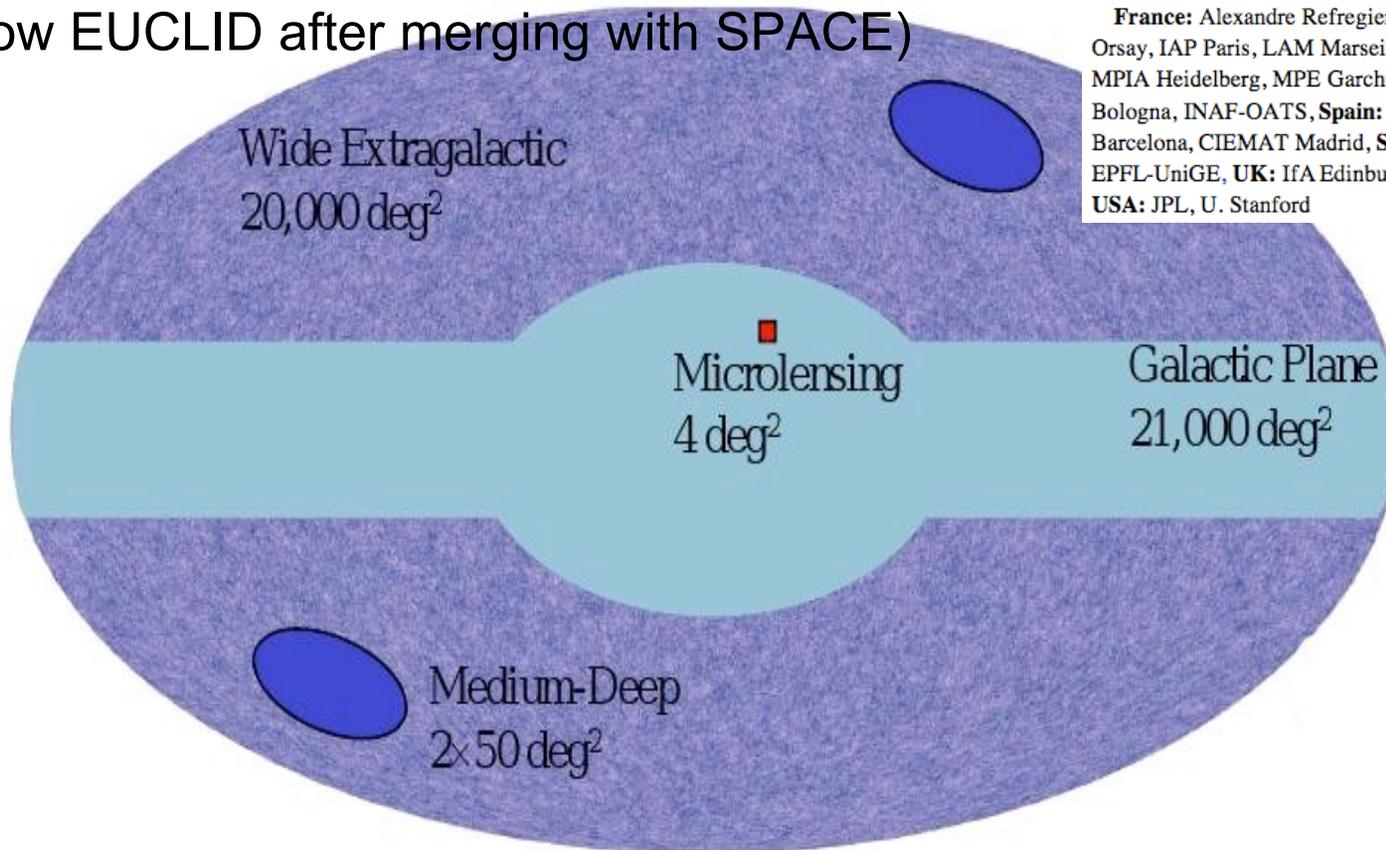
Survey	Depth (mag or redshift)	Area (sq deg)	Imaging Filters/ Spectra Resolution	Schedule
KIDS(+Viking)	$r' < 24.4$	1500	ugri ZYH	2008-2013
DES(+VHS)	$r < 24$	5000	grizYJHK	2011-2016
Pan-STARRS1	$r < 24$	15000	grizY	2008-2012
Pan-STARRS4	$r < 25.6$	30000	grizY	2012-2017
Hyper-Suprime	$r < 25$	2000	BVRiz	2011-2016
Skymapper	$g < 22.9$	15000	Uvgriz	2008-2011
PAU	$i < 23$	8000	50 narrow bands	2010-2015
LSST	$g < 26$	30000	Ugriz	2014-2014
SNAP	$R < 28.3$	4000	9 visible and IR	2015-2021
<i>Euclid- Photometric</i>	<i>(RIZ) < 24.5</i>	<i>20000</i>	<i>(RIZ)+YJH</i>	<i>2017- 2020</i>

- Imaging surveys Are able to utilize multiple methods of measuring the DE equation of state:
 - Weak lensing - A very powerful method, but requires excellent image quality
 - Growth of structure - clusters, ISW Effect
 - Supernovae - requires repeat obsvns to detect
 - BAO - via photo-z's, but ALSo requires spectro-z's

The Dark UNiverse Explorer



(now EUCLID after merging with SPACE)



France: Alexandre Refregier (PI, CEA Saclay), IAS Orsay, IAP Paris, LAM Marseille, **Germany:** U. Bonn. MPA Heidelberg, MPE Garching, **Italy:** INAF-OARM, U. Bologna, INAF-OATS, **Spain:** ICE, Barcelona, IFAE Barcelona, CIEMAT Madrid, **Switzerland:** ETH Zurich, EPFL-UniGE, **UK:** IfA Edinburgh, UCL London, MSSL, **USA:** JPL, U. Stanford

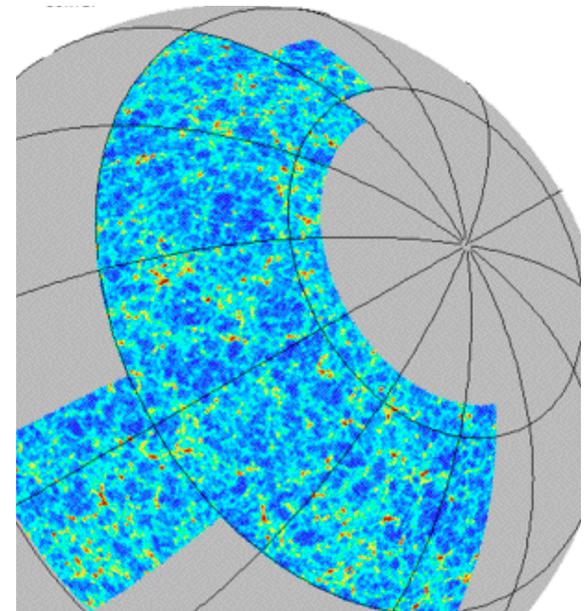
FOM = 400 (1600 combined with Planck)

JDEM US competitors
ADEPT, SNAP-L, Destiny



Dark energy survey

- DES is 5000 deg² survey of sgp to measure dark energy via BAO (photo-z's), weak lensing, SNE, and cluster counts
- Use blanco 4m at ctio with a new 520 megapixel camera at prime focus having a 2.2° field
- plan - construction 2008-2011, then 525 nights 2011-2016
- Survey area overlaps with spt sZE and VISTA VHS surveys
- 12 institutions, >100 people



DARK ENERGY SURVEY

- 5000 deg² in grizy to r=24 PLUS 40 deg² repeated
- 3x10⁸ PHoto-z's in volume of 23(Gpc/h)³ to z=2
(NEED 10⁶ spectro-z's to calibrate)

FOUR PROBES OF DARK ENERGY

□ GALAXY CLUSTERS

- Z'S & MASSES FOR 10⁵ CLUSTERS TO Z>1

- 10⁴ CLUSTERS WILL HAVE SIZE FROM SPT

□ WEAK LENSING

- SHAPES FOR 3X10⁸ GALAXIES

□ BARYON ACOUSTIC OSCILLATIONS

- 3X10⁸ GALAXIES WITH PHOTO-Z'S TO Z>1

□ SUPERNOVAE

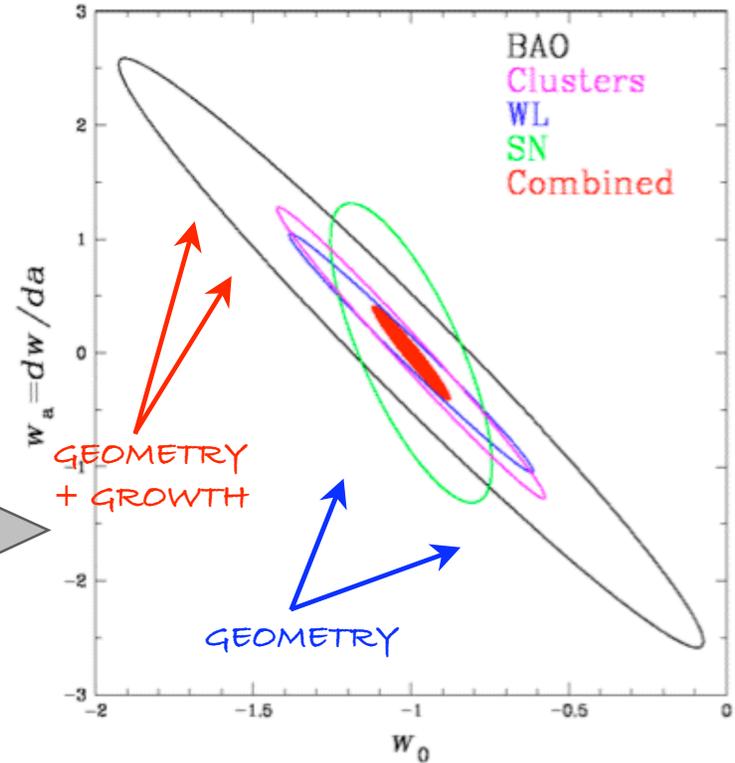
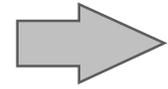
- >9 DEG² SURVEY, ~10³ SN IA TO Z~1

SENSITIVE TO
GROWTH OF
STRUCTURE &
GEOMETRY

SENSITIVE TO
GEOMETRY

DARK ENERGY SURVEY

- MULTIPLE methods give tighter constraints and cross-checks on systematics
- planck CMB prior, curvature and galaxy bias marginalised
- DETF F.o.M. GAIN of a factor of 4.6 relative to stage II



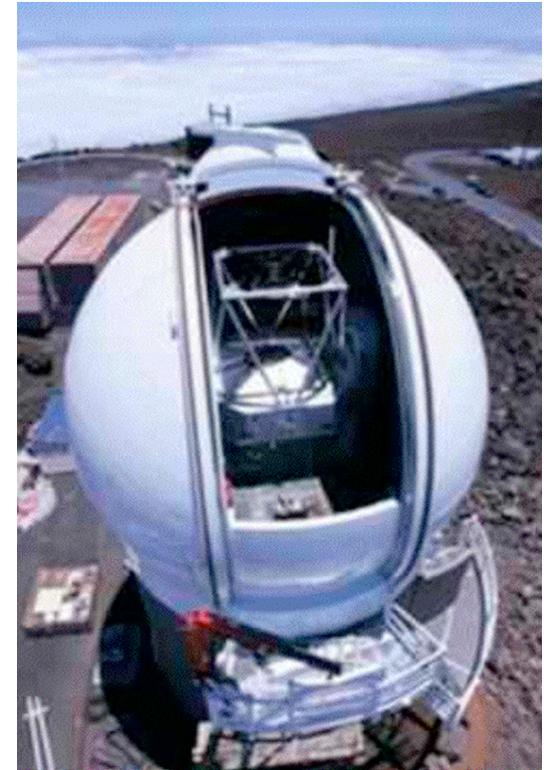
Method	$\sigma(\Omega_{DE})$	$\sigma(w_0)$	$\sigma(w_a)$	z_p	$\sigma(w_p)$	DETF FoM
BAO	0.010	0.097	0.408	0.29	0.034	72.8
Clusters	0.006	0.083	0.287	0.38	0.023	152.4
Weak Lensing	0.007	0.077	0.252	0.40	0.025	155.8
Supernovae	0.008	0.094	0.401	0.29	0.023	107.5
Combined DES	0.004	0.061	0.217	0.37	0.018	263.7
DETF Stage II Combined	0.012	0.112	0.498	0.27	0.035	57.9

Table 1: 68% CL marginalized forecast errorbars for the 4 DES probes on the dark energy density and equation of state parameters, in each case including Planck priors *and* the DETF Stage II constraints. The last column is the DETF FoM; z_p is the pivot redshift. Stage II constraints used here agree with those in the DETF report to better than 10%.



PAN-STARRS1

- 1.8m Telescope with 7 deg² field and 1.4 gigapixel camera
- $R \sim 24$ in 30s, 7000 deg²/night
- all-sky (3 steradians) survey to $R \sim 26$; weak lensing, cluster abundances, Photo-z BAO
- medium/deep-field surveys with multi-epoch repeats for SN IA



PS1 Surveys	Filters	Percent time
3 π Steradian Survey	g, r, i, z, y	56
Calibration Fields	g, r, i, z, y	2
Medium Deep Survey	g, r, i, z, y	25
Solar System "Sweet Spot" Survey	r	5
Stellar Transit Survey - "PanPlanets"	i	4
Microlensing in M31 "Pandromeda" Survey	g, r, i, z, y	2
Principal Investigator Discretionary Time		6

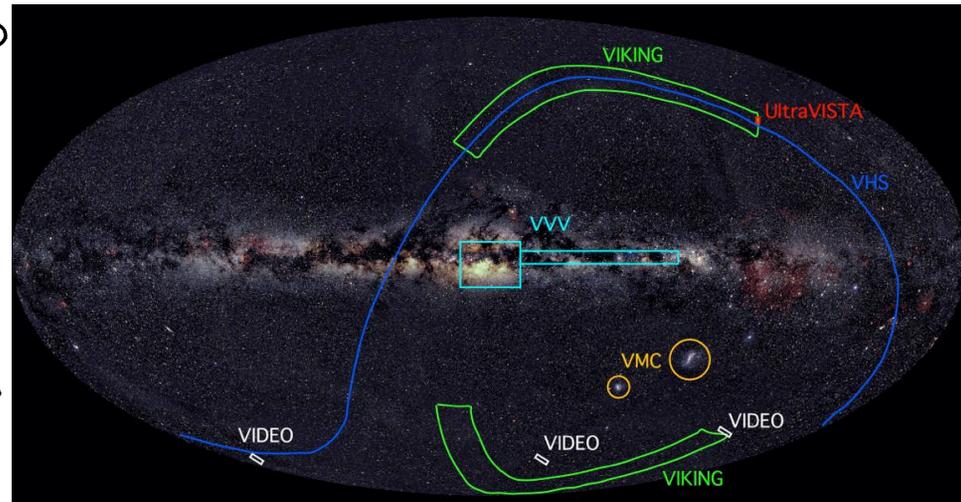


VISTA surveys

- VISTA: 4m wide-field (1.65° FoV) survey telescope at Paranal with near-IR (ZYj k_s), 67 megapixel camera having effective area 0.6 deg^2
- TWO vista public surveys are relevant to DE...

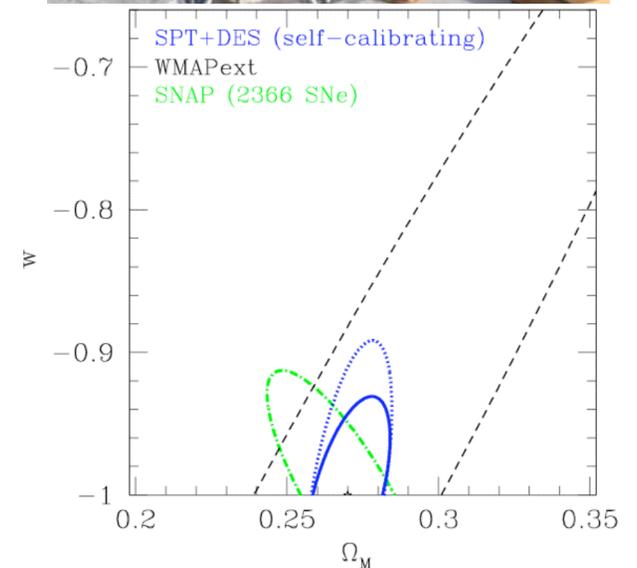
Survey	Area	LIMITING MAGNITUDES (5 $_$)
VHS	20,000	Y=21.2 J=21.2 H=20.6 K_s =20.0
VIKING	1,500	Z=23.1 Y=22.3 J=22.1 H=21.5 K_s =21.2

- VIKING & DES HAVE 5000 DEG^2 OVERLAP; IMPROVES PHOTO-Z'S BY $2\times$ FOR $Z > 1$;
- VHS WILL YIELD DE VIA LATE-TIME INTEGRATED SACHS-WOLFE EFFECT





- SPT is 10m mm/submm telescope at south pole with a 960-element TES bolometer at 95, 159, 225, 270GHz
- survey of 4000 deg² to detect 2×10^4 clusters with Mass $> 2 \times 10^{14} M_{\text{sol}}$ using the Sunyaev-Zel'dovich effect (n.b. SZE is z-independent)
- Dark energy constraints from cluster number density evolⁿ
- with cluster z's can measure w_0 to 5% precision (DES will provide Photo-z's for clusters)
- Systematics are primary issue



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...