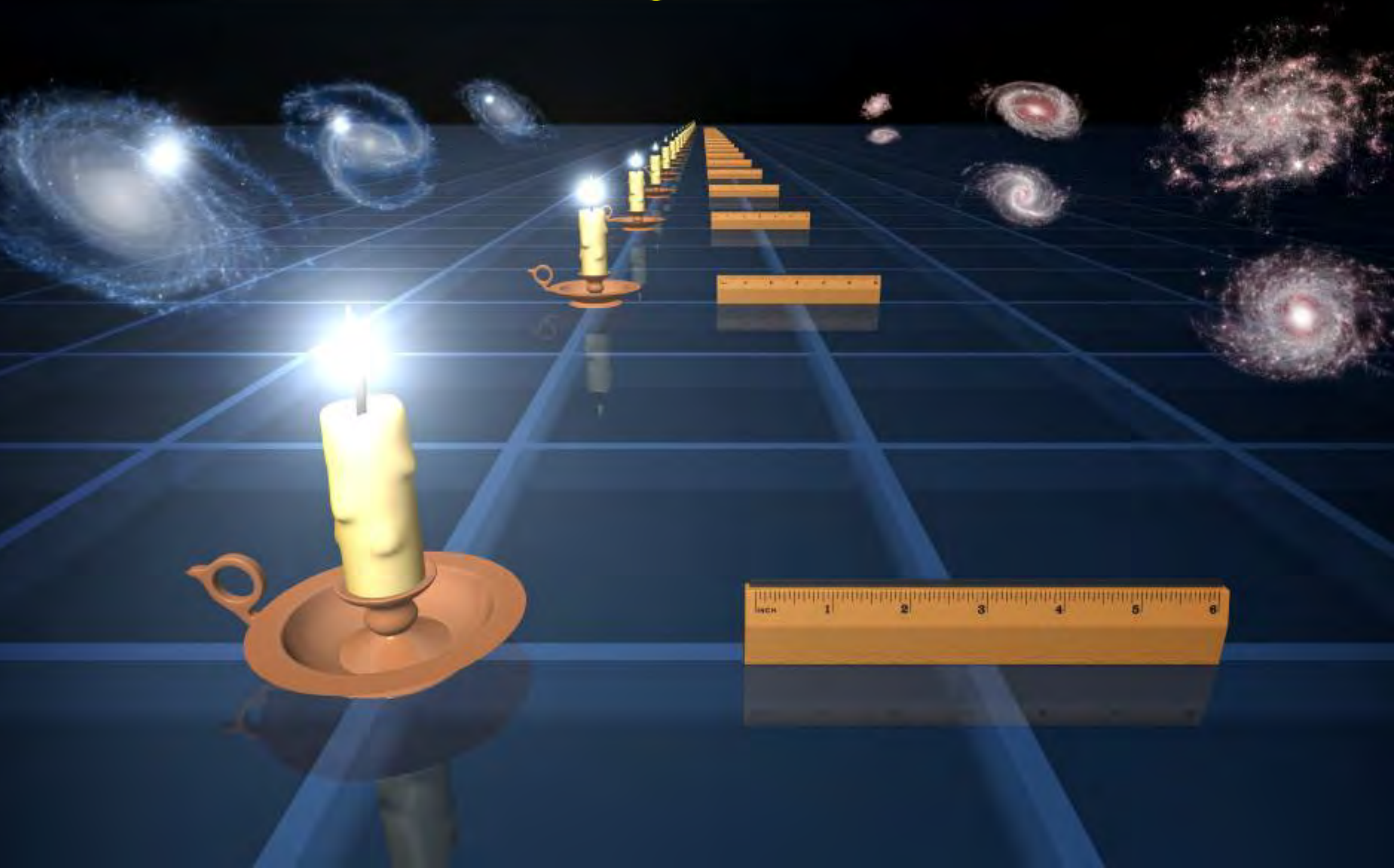
Ay 21

Cosmological Tests



Tests for the Expansion of the Universe

- Tolman surface brightness (SB) test
  - In a stationary, Euclidean universe $SB = const.$
  - In an expanding universe, $SB \sim (1+z)^{-4}$
  - In a “tired light” model, $SB \sim (1+z)^{-1}$
- Time dilation of Supernova light curves
  - Time stretches by a factor of $(1+v/c) = (1+z)$
- The match between the energy density and T^4 for the blackbody and the CMBR
  - For a blackbody, energy density $u \sim T^4$
  - In an expanding universe, for photons, energy density is $u \sim (1+z)^4$, and since $T \sim 1/\lambda \sim (1+z)$, $u \sim T^4$

The Tolman Surface Brightness Test

Surface brightness is flux per unit solid angle: $B = \frac{f}{dw}$

This is the same as the luminosity per unit area, at some distance *D*. In cosmology, $B = \frac{L}{D_L^2}\frac{D_A^2}{dl^2}$

In a stationary, Euclidean case, $D = D_L = D_A$, so the distances cancel, and $SB = const.$ But in an expanding universe, $D_L = D\,(1+z)$, and $D_A = D\,/\,(1+z)$, so:

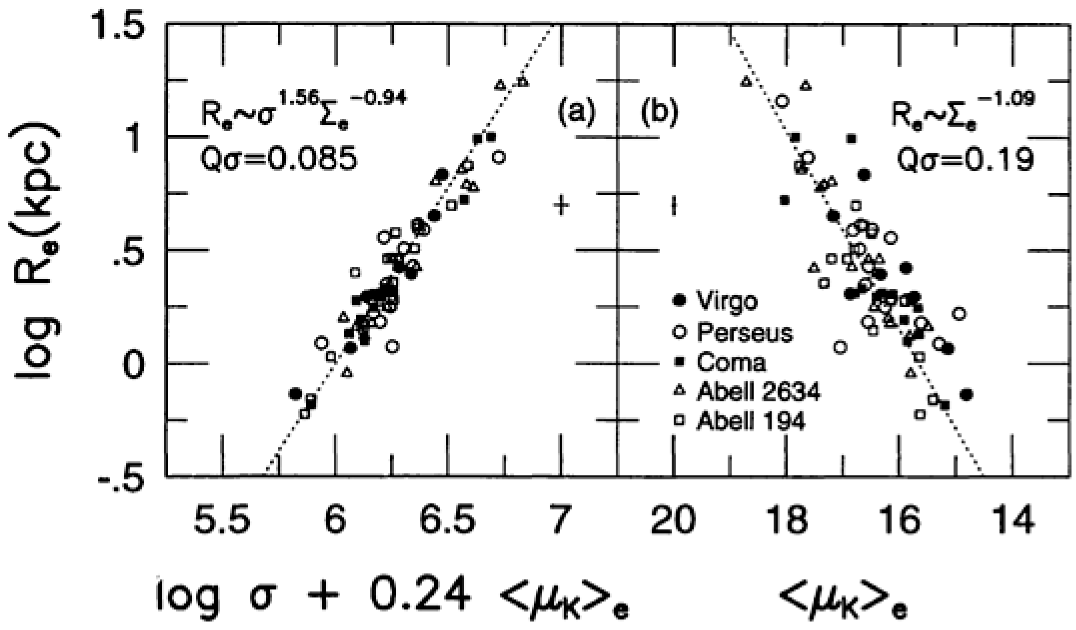
$$B = \frac{L}{dl^2}\frac{D_A^2}{D_L^2} = \frac{L}{dl^2}(1+z)^{-4}$$

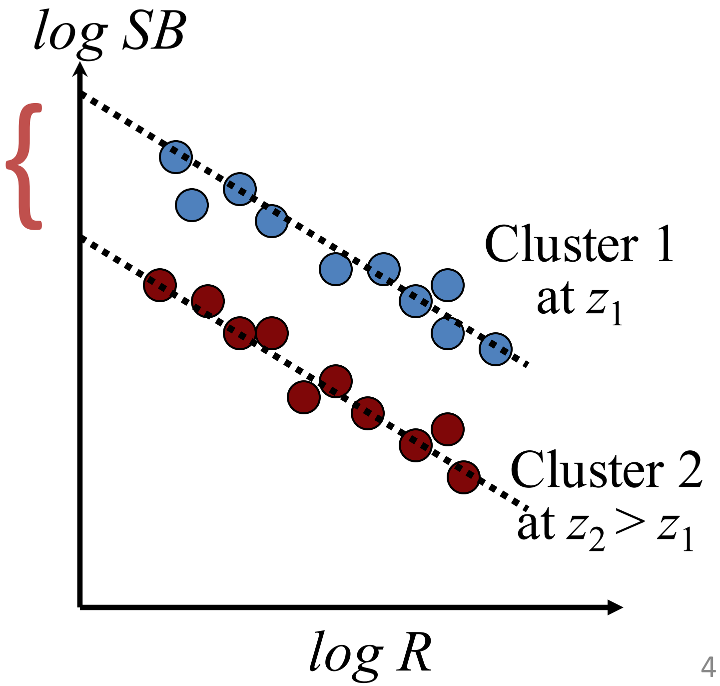
Note that this is independent of cosmology!

Performing the The Tolman Test

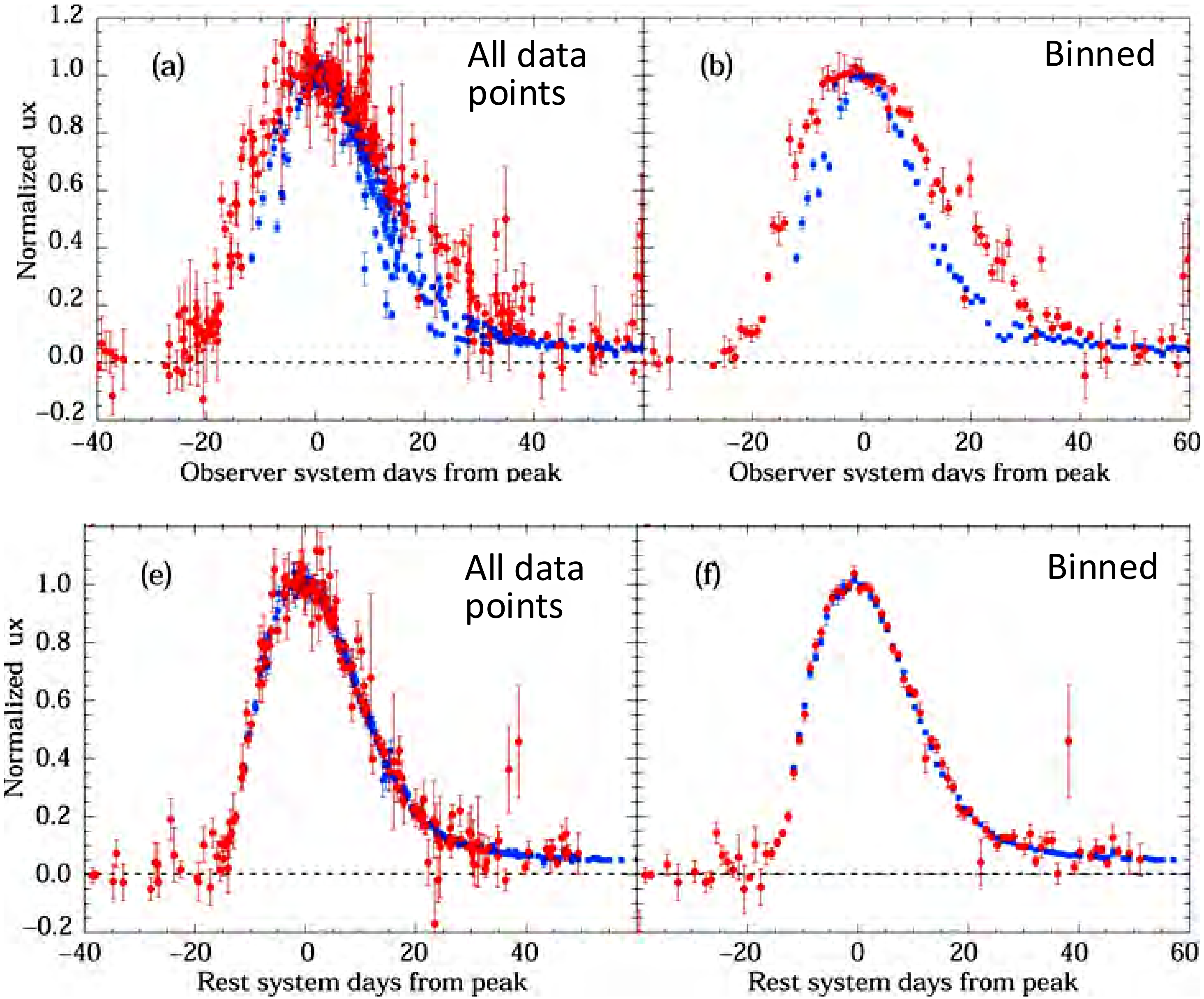
We need a standard (constant) unit of surface brightness = luminosity/area, to observe at a range of redshifts (a “standard fuzz”?)

A good choice is the intercept of surface brightness scaling relations for elliptical galaxies in clusters





Time Dilation of Supernova Lightcurves



Blue dots: a low-z dataset

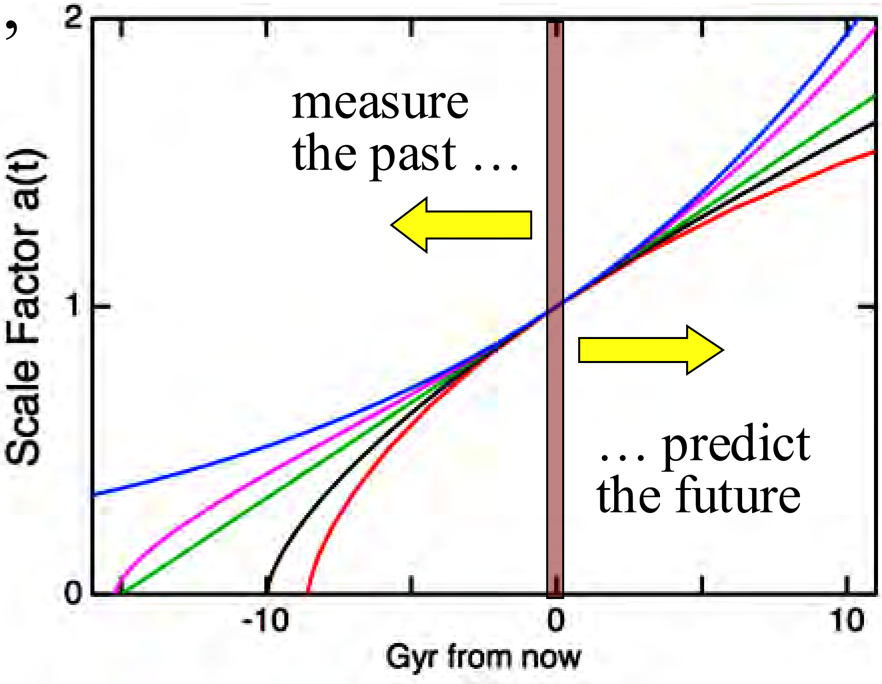
Red dots: a high-z dataset

After applying the proper stretch factor

(Goldhaber et al.)

Cosmological Tests: The Why and How

- The goal is to determine the global geometry and the dynamics of the universe, and its ultimate fate
- The basic method is to somehow map the history of the expansion, and compare it with model predictions
- A model (or a family of models) is assumed, e.g., the Friedmann-Lemaitre models, typically defined by a set of parameters, e.g., H_0, $\Omega_{0,m}$, $\Omega_{0,\Lambda}$, q_0, etc.

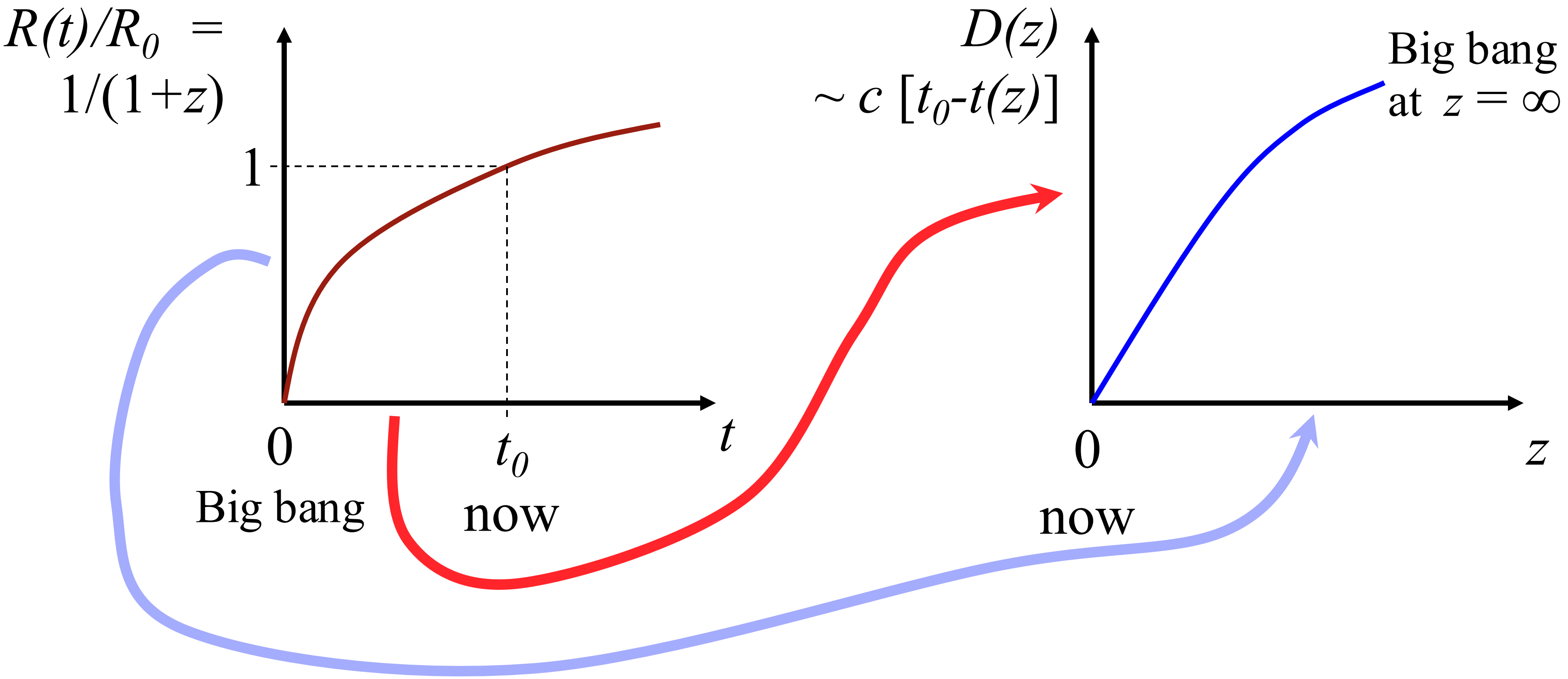


measure the past …

… predict the future

- Model equations are integrated, and compared with the observations

The Basis of Cosmological Tests

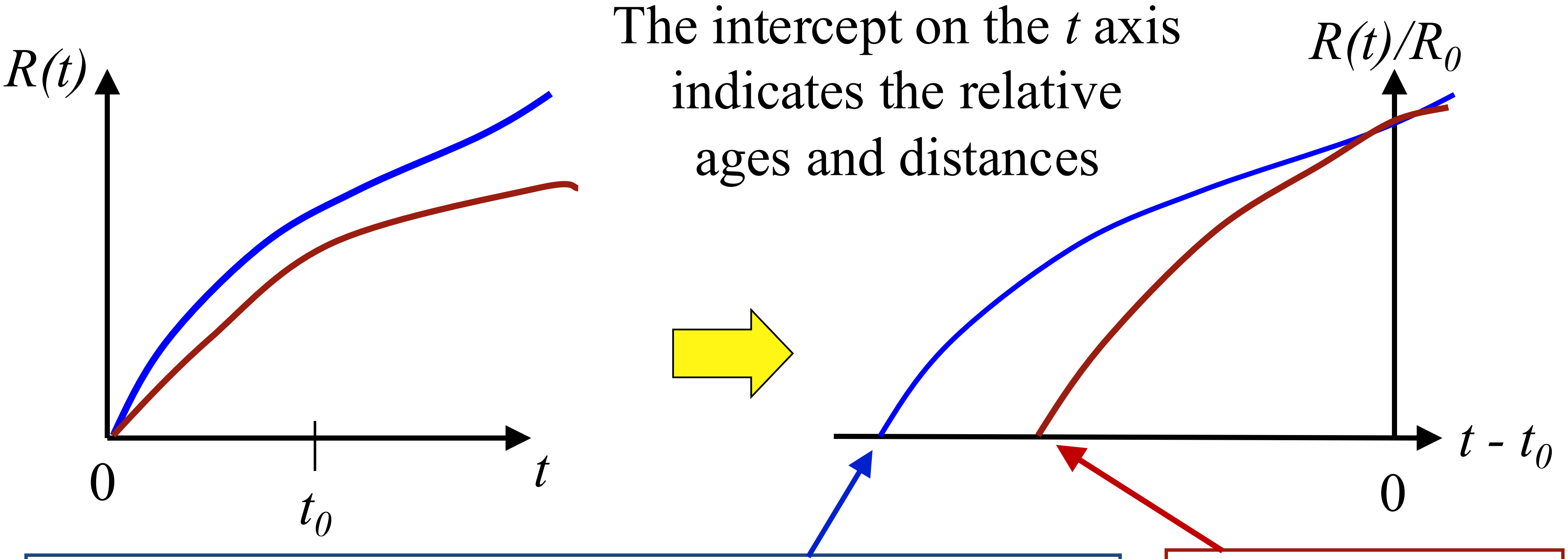


Swap the axes, so that redshift becomes the independent variable, and use distance instead of the lookback time

All cosmological tests essentially consist of comparing some measure of *relative* distance (or look-back time) to redshift. *Absolute* distance scaling is given by the H_0.

Cosmological Tests: Expected Generic Behavior of Various Models

Shift the models to the same expansion rate (H_0) here and now (t_0)



The intercept on the *t* axis indicates the relative ages and distances

Models with a lower density and/or positive Λ expand faster, are thus larger, older today, have more volume and thus higher source counts, at a given *z* sources are further away and thus appear fainter and smaller

Models with a higher density and lower Λ behave exactly the opposite

The Types of Cosmological Tests

- The Hubble diagram: flux (or magnitude) as a proxy for the luminosity distance, vs. redshift - requires “*standard candles*”
- Angular diameter as a proxy for the angular distance, vs. redshift - requires “*standard rulers*”
- Source counts as a function of redshift or flux (or magnitude), probing the evolution of a volume element - requires a population of sources with a constant comoving density - “*standard populations*”
- Indirect tests of age vs. redshift, usually highly model-dependent - “*standard clocks*”
- Local dynamical measurements of the mass density, Ω_{m0}
- If you measure H_0 and t_0 independently, you can constrain a combination of Ω_{m0} and Ω_Λ

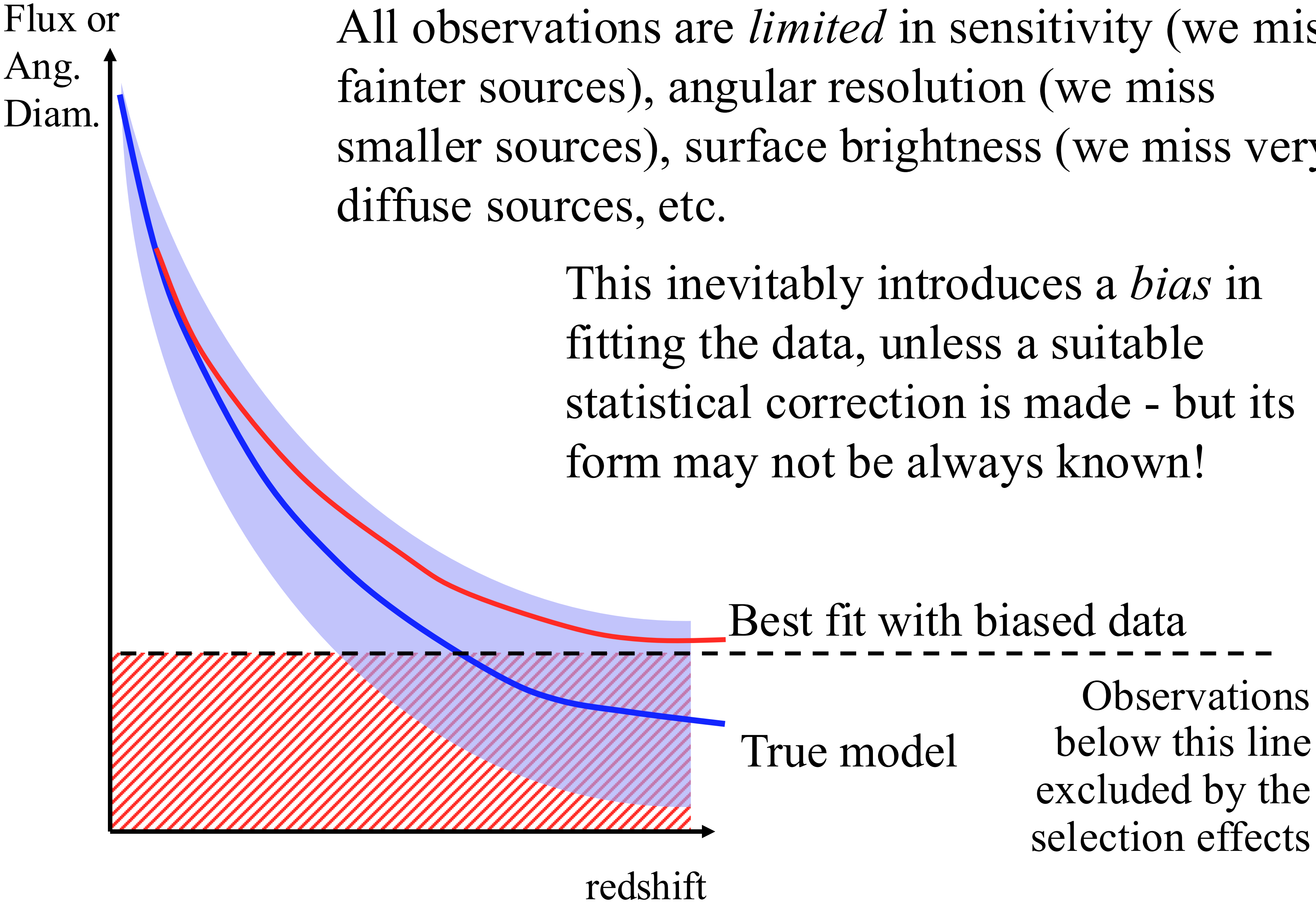
Cosmological Tests: A Brief History

- A program of "classical" cosmological tests (Hubble diagram, angular diameter test, source counts) was initiated by Hubble, and carried out at Palomar and elsewhere by Sandage and others, from 1950s through 1970s
- Galaxies, clusters of galaxies, and radio sources were used as standard candles, rulers, or populations. Unfortunately, all are subject to strong and poorly constrained ***evolutionary effects***, which tend to dominate over the cosmology - this foiled most of the attempted tests, and became obvious by 1980's
- In the late 1990's, Supernova Ia Hubble diagram, and especially measurements of CMBR fluctuations power spectra (essentially an angular diameter test) ***completely redefined the subject***
- The cosmological parameters are now known with a remarkable precision - a few percent; this is the era of "***precision cosmology***"

Selection Effects and Biases

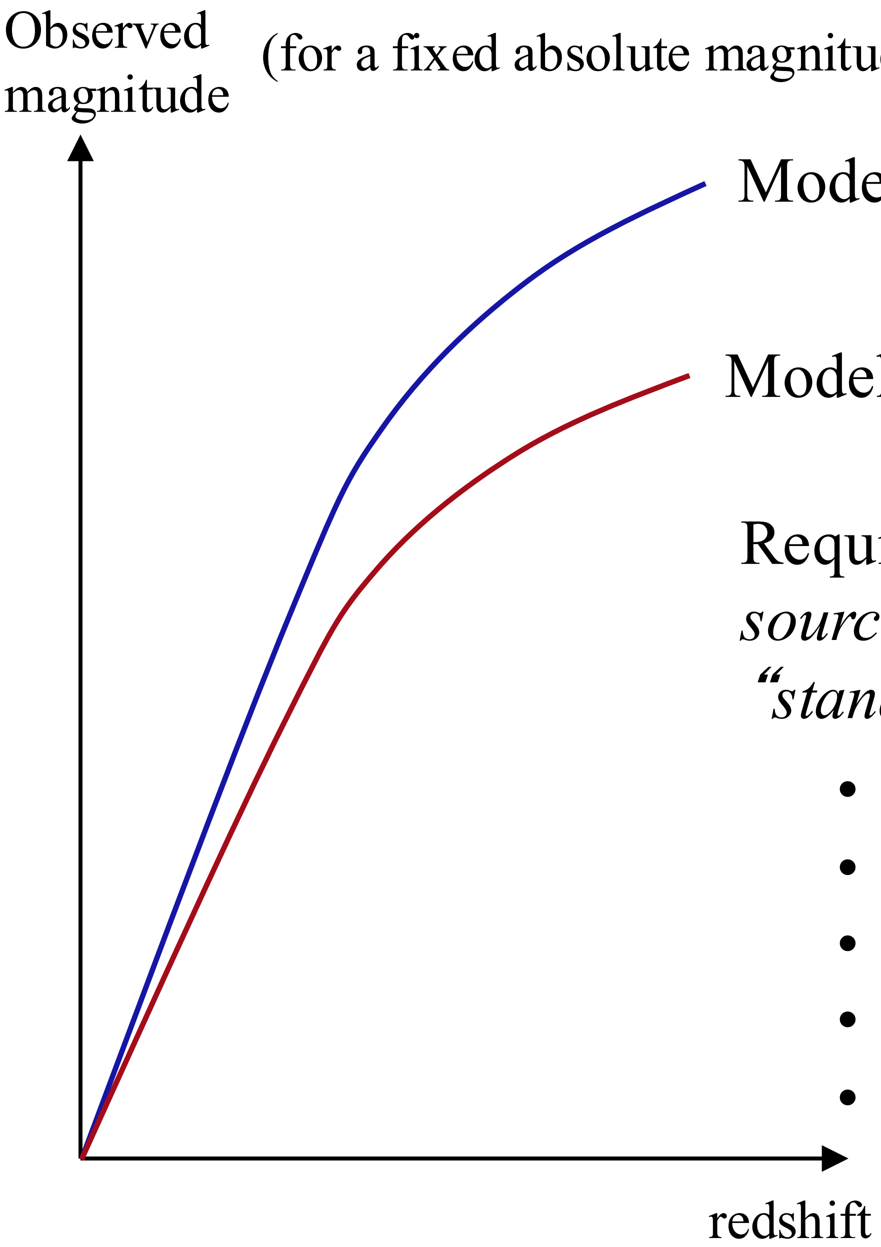
All observations are *limited* in sensitivity (we miss fainter sources), angular resolution (we miss smaller sources), surface brightness (we miss very diffuse sources, etc.

This inevitably introduces a *bias* in fitting the data, unless a suitable statistical correction is made - but its form may not be always known!



The Hubble Diagram

(for a fixed absolute magnitude it indicates the luminosity distance)



Model with a lower density and/or $\Lambda > 0$

Model with a higher density and/or $\Lambda \leq 0$

Requires a population on *non-evolving sources with a fixed luminosity - "standard candles"*. Some candidates:

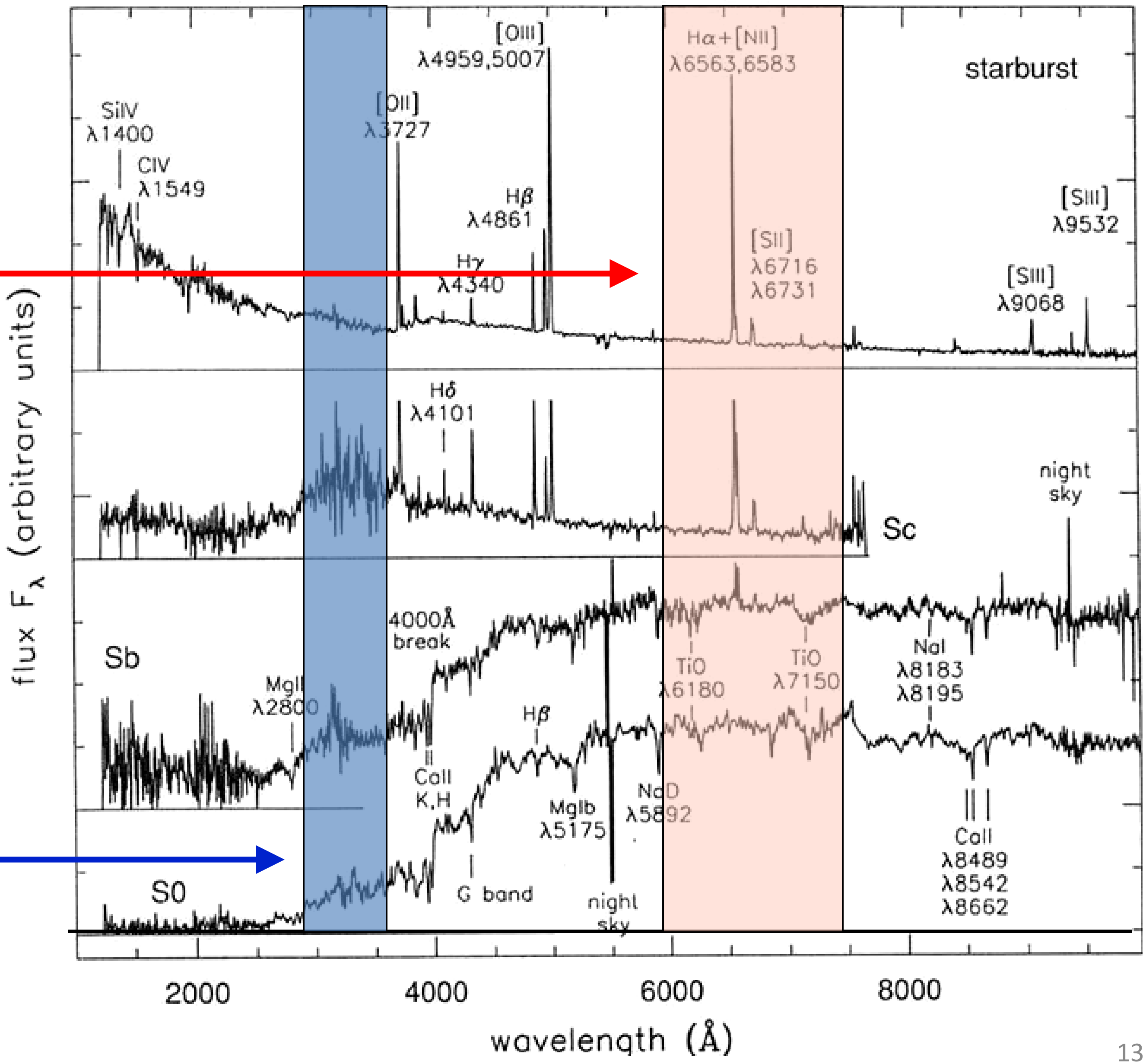
- Brightest cluster ellipticals
- Supernovae of type Ia
- Luminosity functions in clusters
- GRB afterglows ??
- …

The K-Correction

Photometric measurements are always obtained in some bandpass fixed in the *observer's frame*, e.g., the *U,B,V,R…*

But in a *redshifted galaxy*, this bandpass now samples some other (bluer in the galaxy's restframe) region of the spectrum, and it is also (1+*z*) times narrower

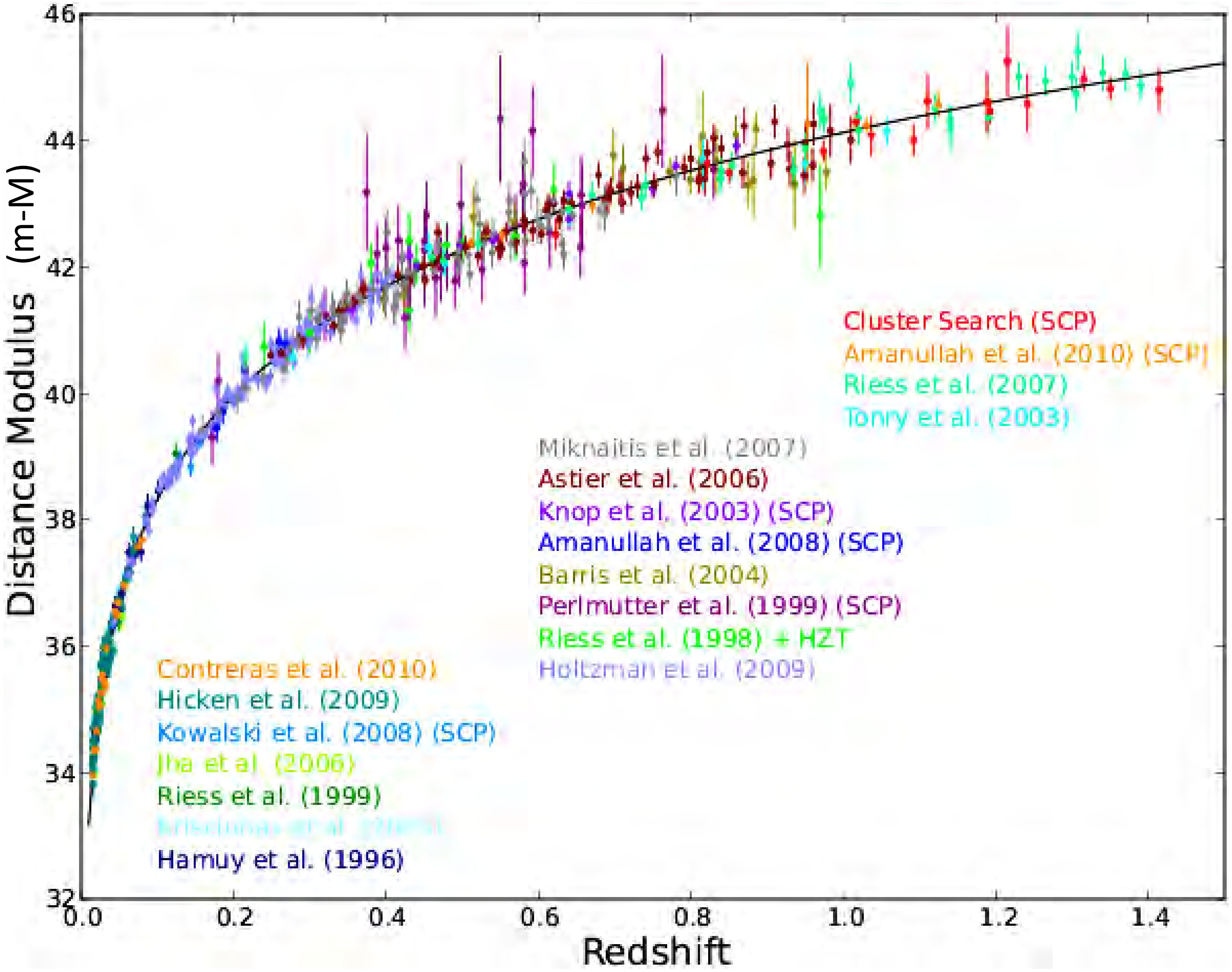
Galaxy spectra of different types



The Supernova Ia Hubble Diagram

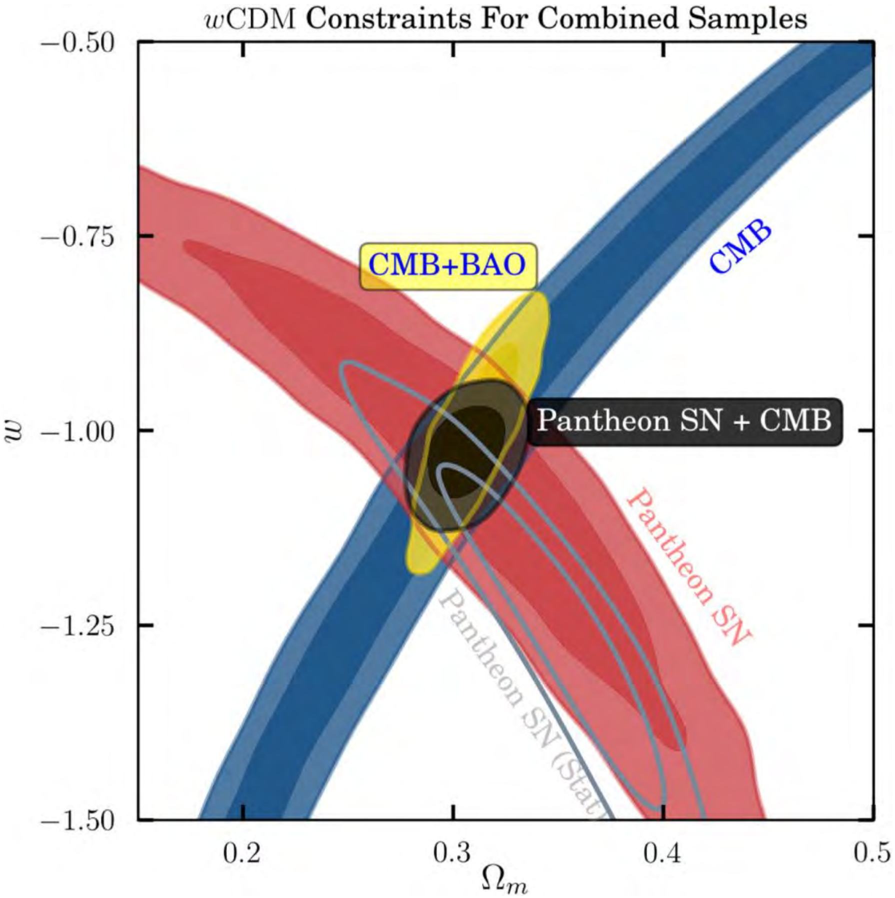
- The field was reborn with the advent of the SN Ia Hubble diagram, following the standardization of their peak brightness using light curve shapes
- There are still some unknowns:
  - Explosions not fully understood; many possible models: Chandrasekhar-mass models, deflagrations vs. detonations
  - Progenitor systems not well known: white dwarfs yes, but double degenerate vs. single degenerate binaries …
- SN Ia are not really standard candles …
  - There are large variations in light curve shapes, colors, spectral evolution, and some clear outliers; possible differences in physical parameters, e.g, Ni mass
- But they ***are*** good distance indicators, after the empirical correction for light curve shapes
- Do they evolve (e.g., due to metallicity)? Maybe a little

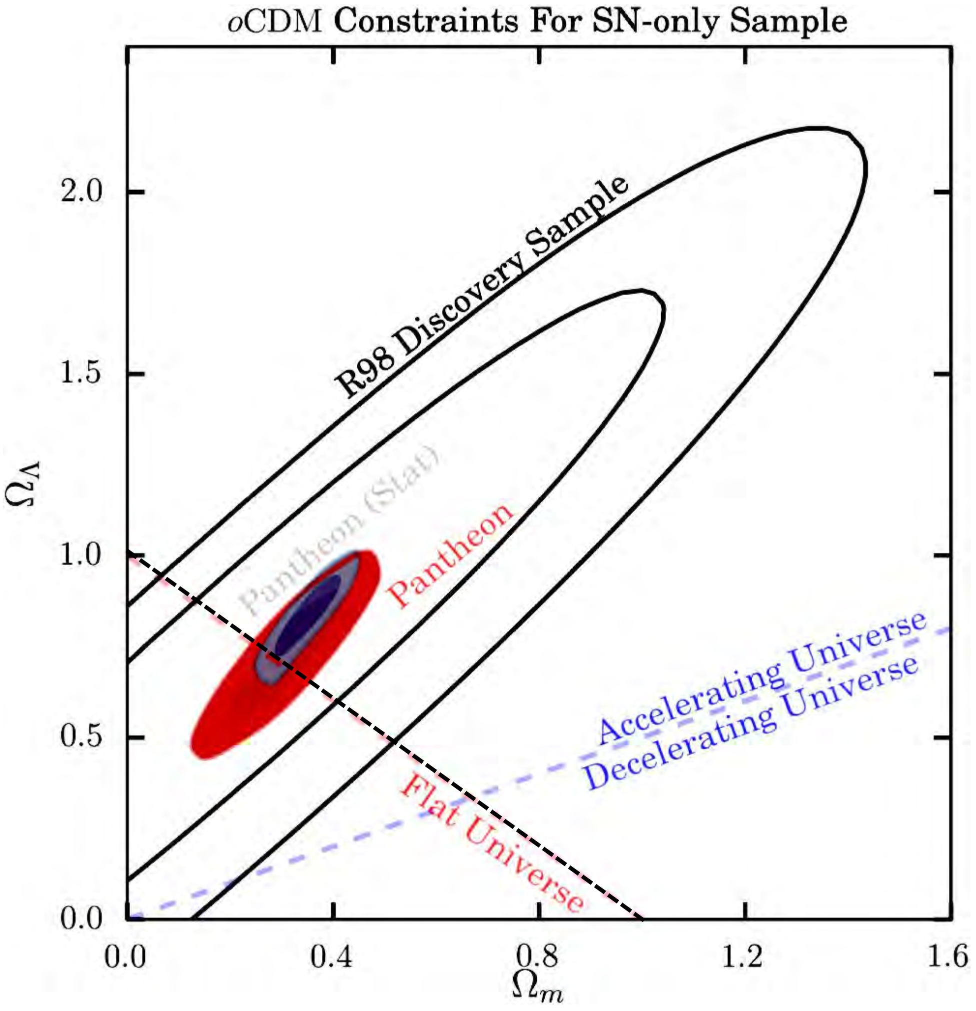
A Modern Version of the SN Hubble Diagram



SN Hubble Diagram Results

Scolnic et al. combined SN sample ("Pantheon")





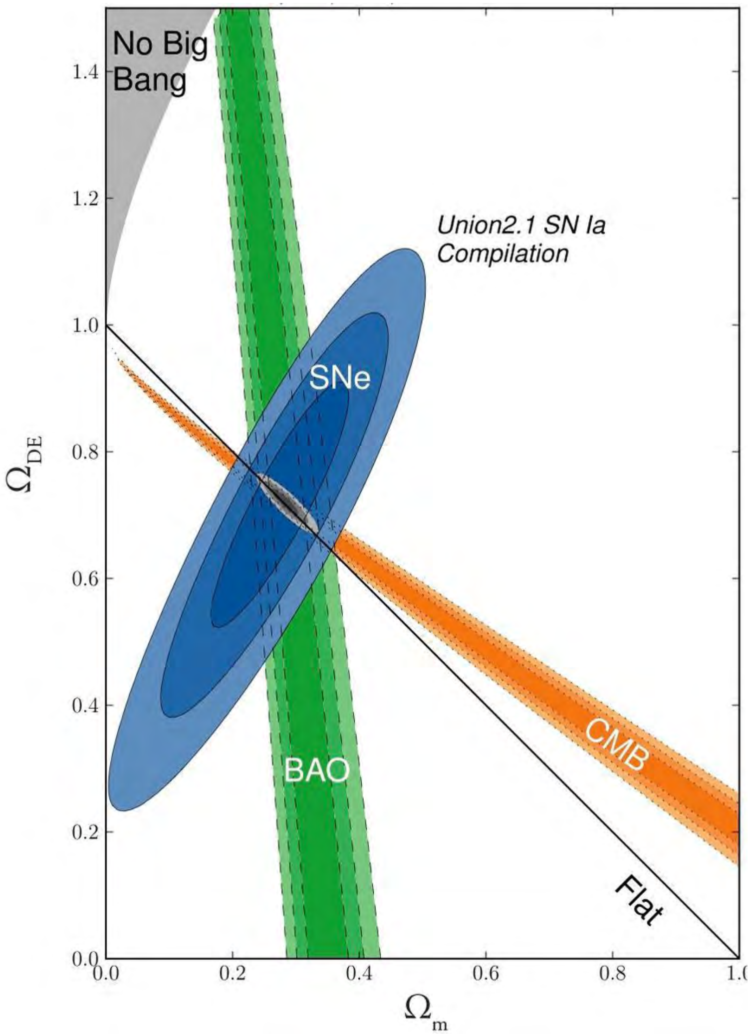
← Constraints on Dark Energy from SN and other data

Why Elongated Error Ellipses?

Because the function that is being fitted (in this case luminosity distance vs. redshift) is a 1-dimensional line in a 2-dimensional parameter space (Ω_m and Ω_Λ), and the two parameters can have similar effects, e.g., positive $\Omega_\Lambda \sim$ lower $\Omega_{m.}$

This is called *parameter degeneracy*.

(This is generally true, not specific to cosmology)

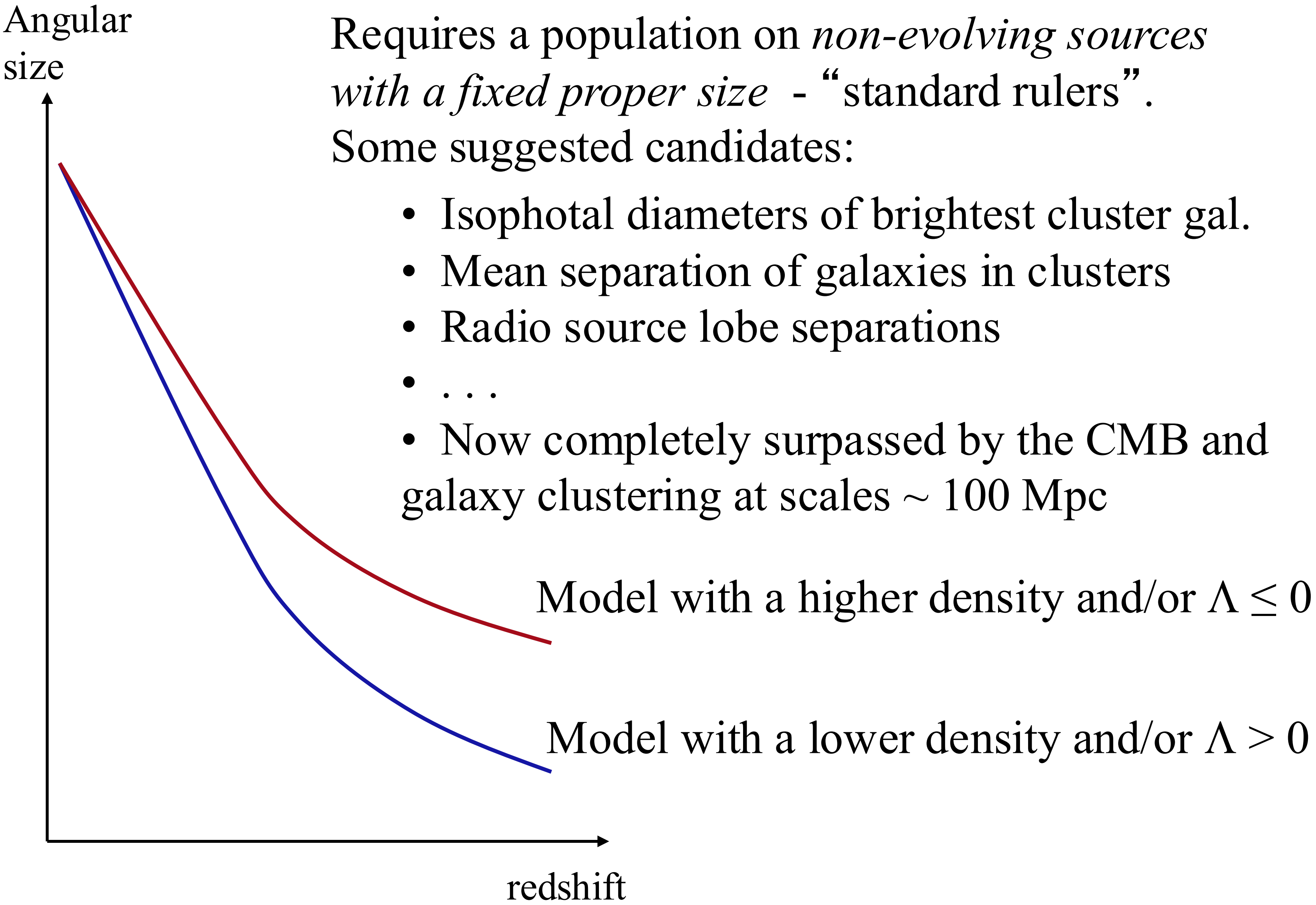


The trick is to find complementary measurements where the error ellipses intersect at an angle. This is the case for the Hubble diagram and the angular diameter test.

The Angular Diameter Test

Requires a population on *non-evolving sources with a fixed proper size* - “standard rulers”. Some suggested candidates:

- Isophotal diameters of brightest cluster gal.
- Mean separation of galaxies in clusters
- Radio source lobe separations
- . . .
- Now completely surpassed by the CMB and galaxy clustering at scales ~ 100 Mpc



The Modern Angular Diameter Test: CMB Fluctuations

- Uses the *size of the particle horizon* at the time of the recombination (the release of the CMB at $z \sim 1100$) as a *standard ruler,* ~ 100 Mpc h^{-1} (comoving)
- This governs the *largest wavelength of the sound waves produced in the universe* then, due to the infall of baryons into the large-scale density fluctuations
- These *sound waves cause small fluctuations in the temperature of the CMB* ($\Delta T/T \sim 10^{-5} - 10^{-6}$) at the appropriate angular scales (~ a degree and less)
- They are measured as the angular power spectra of temperature fluctuations of the CMBR
- This also manifests as an "excess" galaxy clustering at lower redshifts at the same physical scale (baryon acoustic oscillations), giving us the same standard ruler at lower redshifts

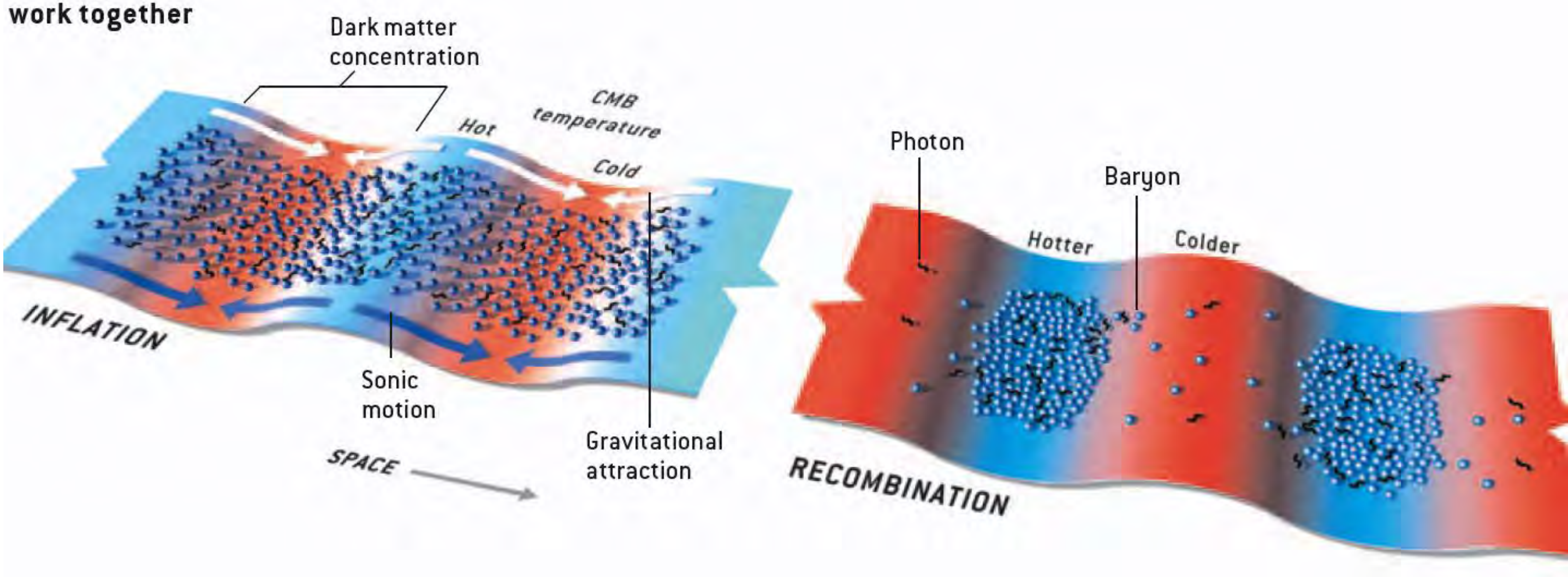
The Cosmic Sound

Large-scale density fluctuations in the early universe attract baryons and photons. Their streaming motion, compression, generate sound waves.

INFLUENCE OF DARK MATTER modulates the acoustic signals in the CMB. After inflation, denser regions of dark matter that have the same scale as the fundamental wave (*represented as troughs in this potential-energy diagram*) pull in baryons and photons by gravitational attraction. (The troughs are shown in red because gravity also reduces the temperature of any escaping photons.) By the time of recombination, about 380,000 years later, gravity and sonic motion have worked together to raise the radiation temperature in the troughs (*blue*) and lower the temperature at the peaks (*red*).

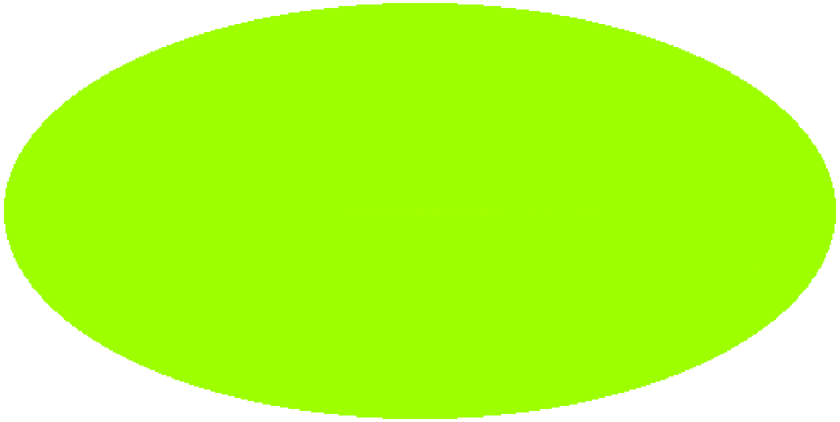
FIRST PEAK

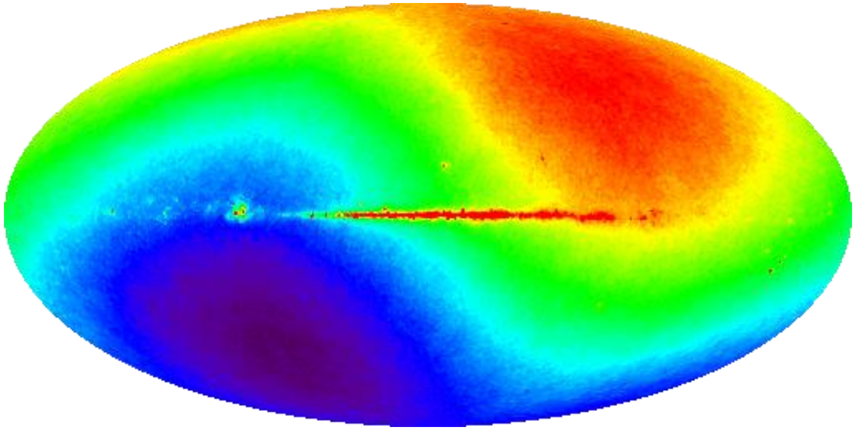
Gravity and sonic motion work together



(from Hu & White 2004)

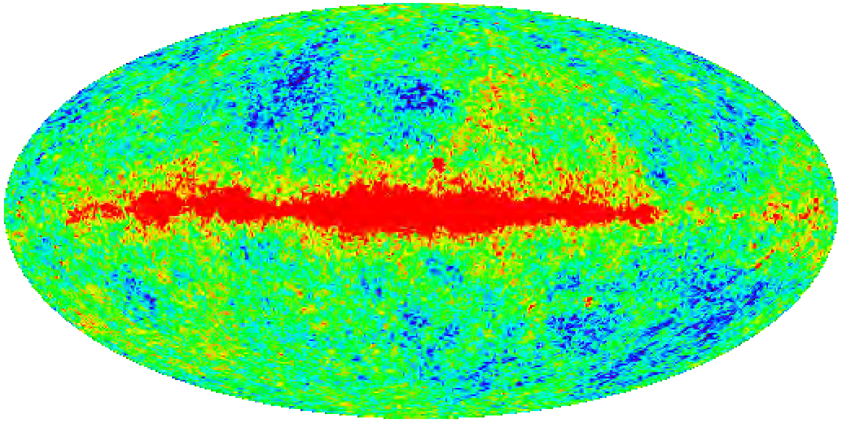
The CMBR sky from WMAP ➡

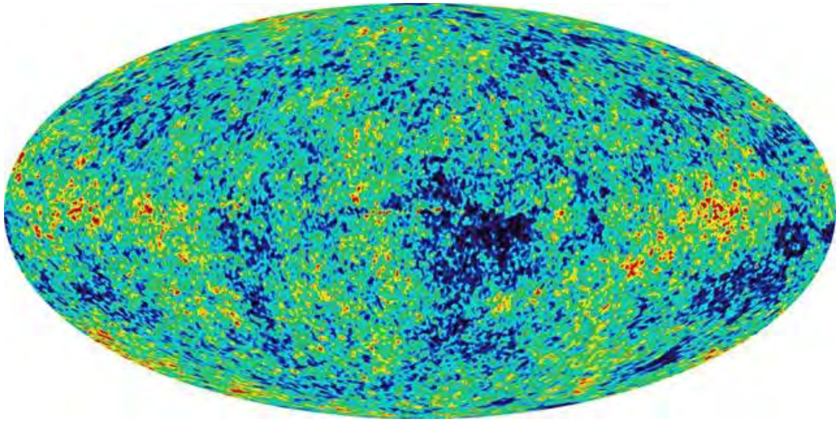




⬅ Enhance the conttrast by 10^3

Remove the dipole and
enhance the contrast to 10^5 ➡

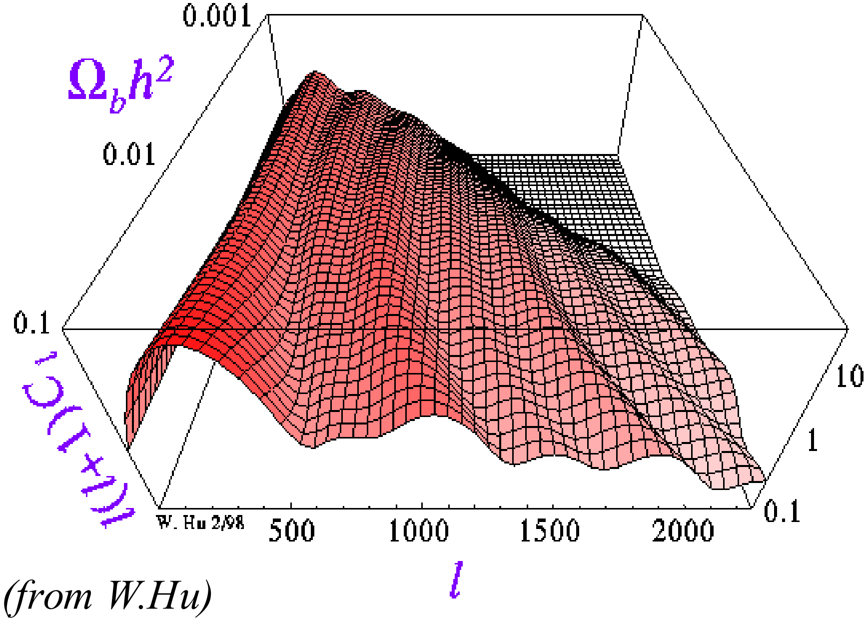




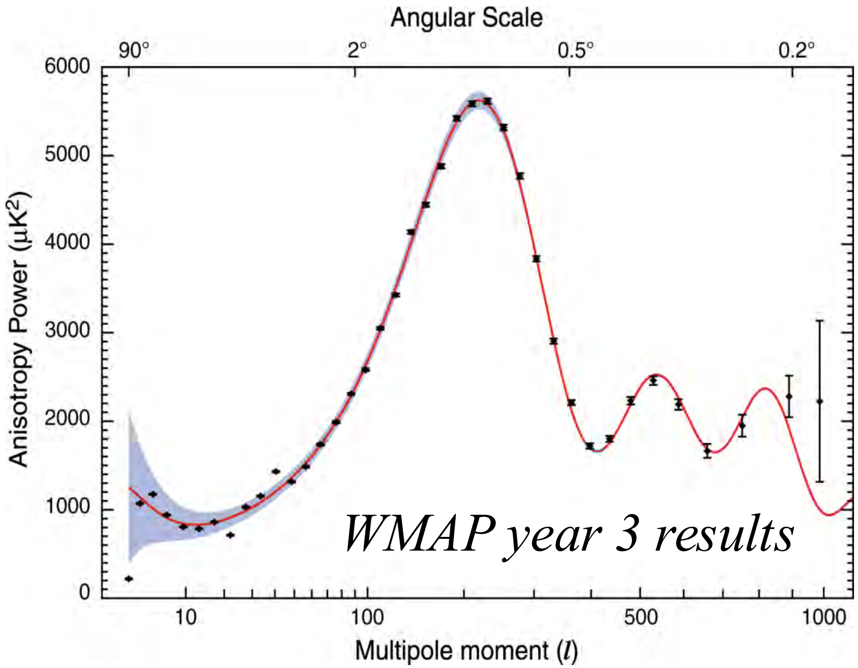
⬅ Remove the Galaxy, the
contrast is 10^6 and see the
primordial density fluctuations

Acoustic Peaks in the CMBR

- The largest wavelength corresponds to the size of the particle horizon at the time, which depends on the cosmological parameters (Ω_m , Ω_Λ , Ω_k)
- Higher overtones (harmonics) incorporate a more complex interplay of baryons, dark matter, and radiation pressure
- The pattern is frozen in the CMB temperature fluctuations at the time of the decoupling



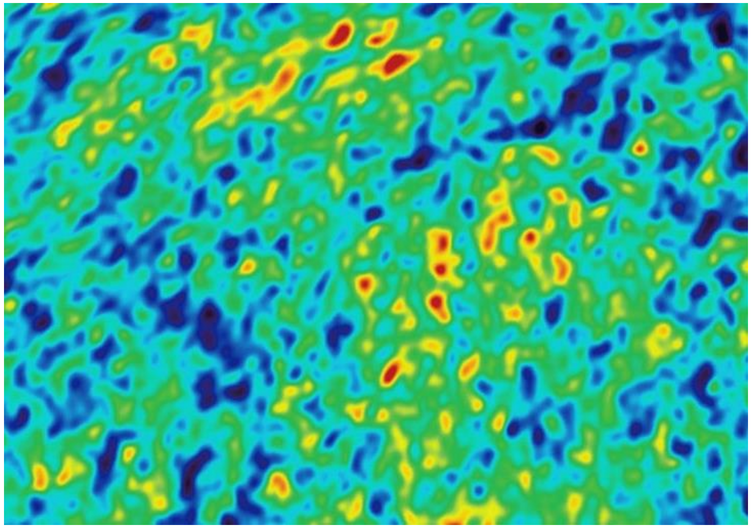
(from W.Hu)

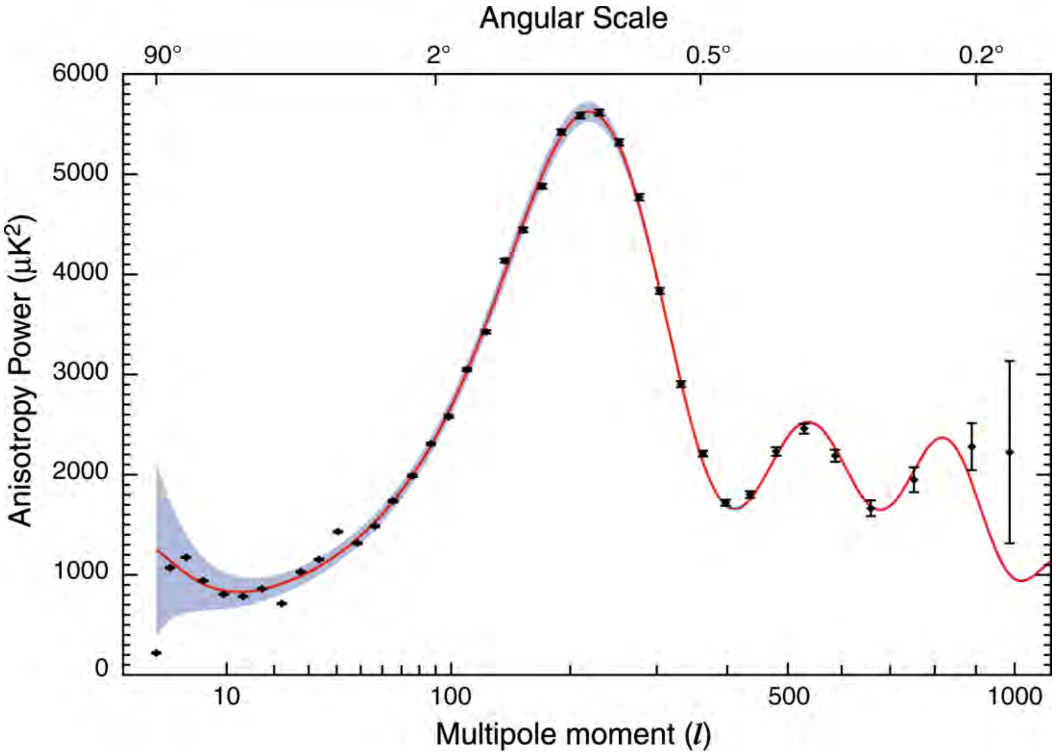


WMAP year 3 results

A Characteristic Fluctuation Scale ~ 1°

Physically this corresponds to the size of the particle horizon at the the time of the decoupling, and thus to the longest sound wavelength which can be present: *The observable size of the whole universe at the time is the "standard ruler"*

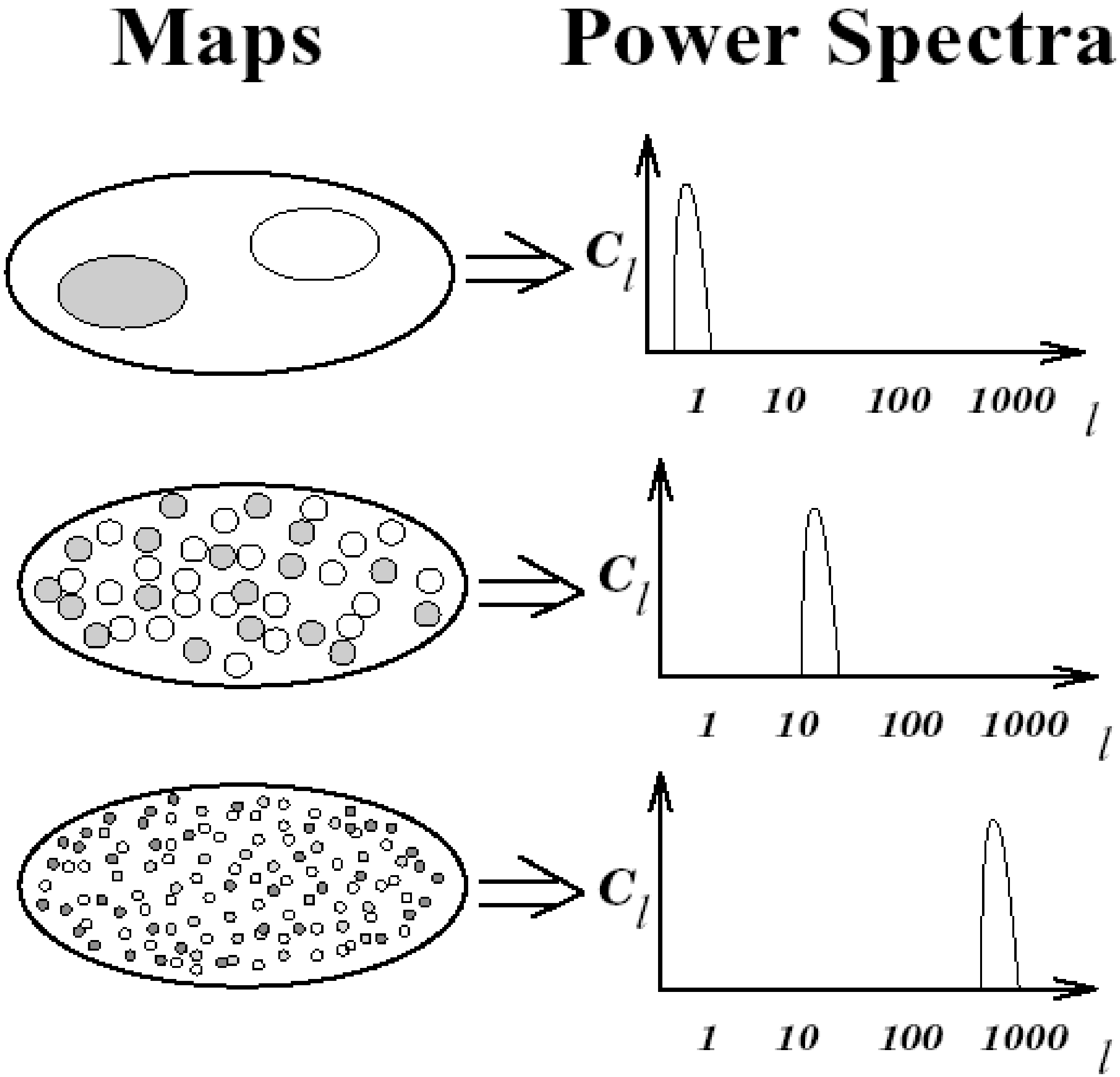




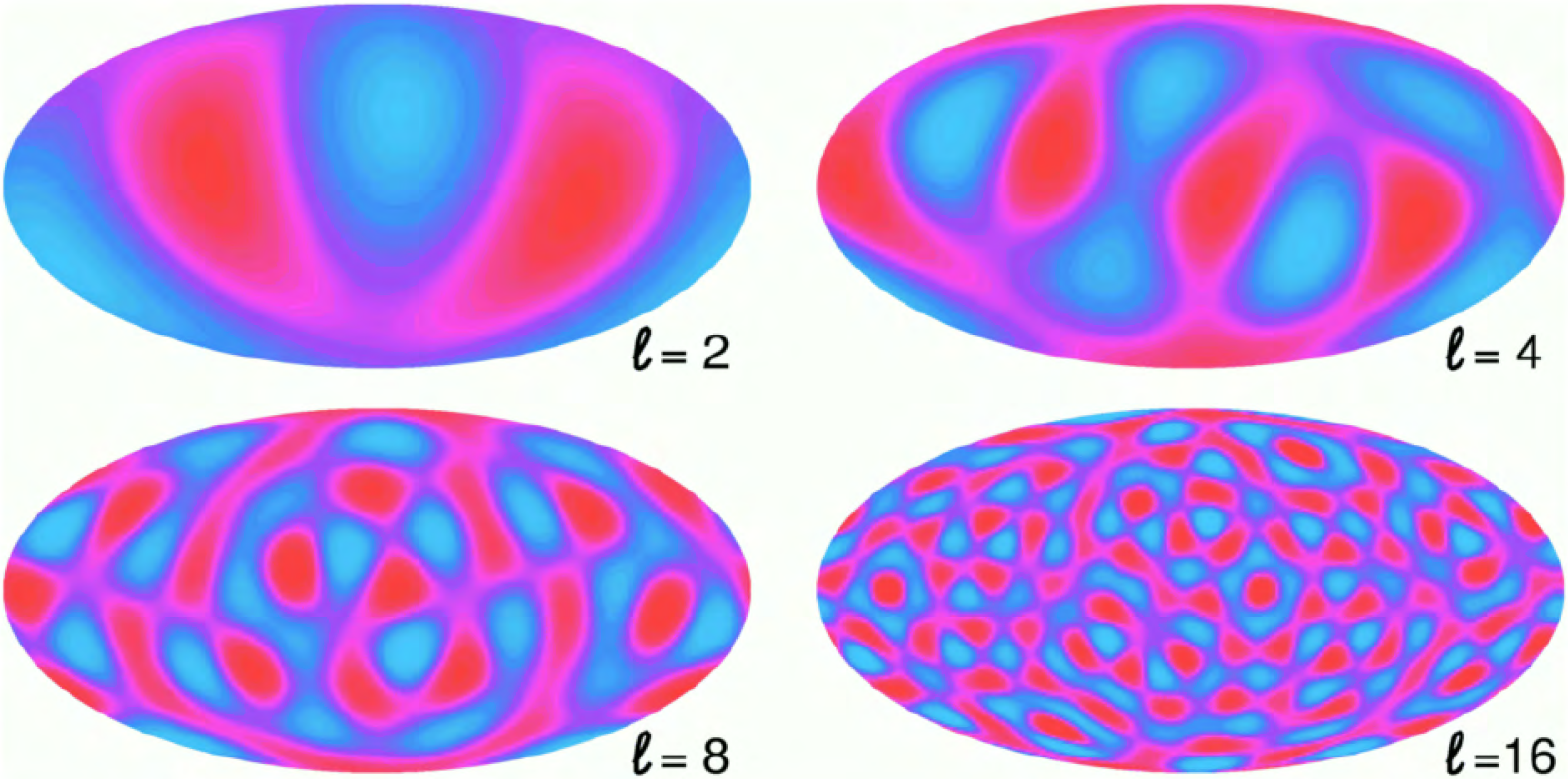
We quantify that through the spherical multipole angular power spectrum (like the Fourier power spectrum, but on a sphere). The positions and the relative amplitudes of the peaks depend on the values of the cosmological parameters

The Angular Power Spectrum

To quantify this, we evaluate the angular (spherical harmonic) power spectra

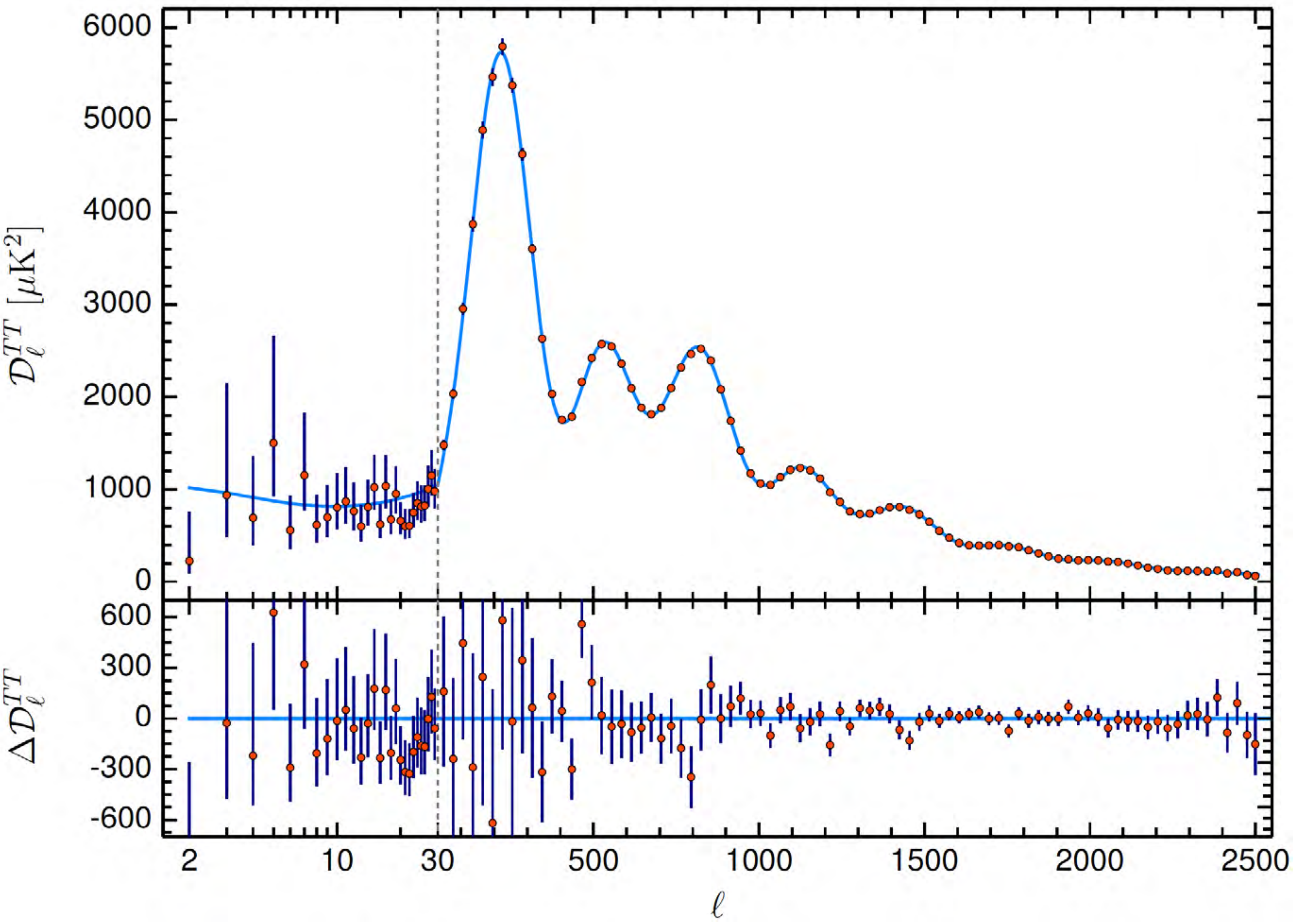


Spherical Harmonic Decomposition



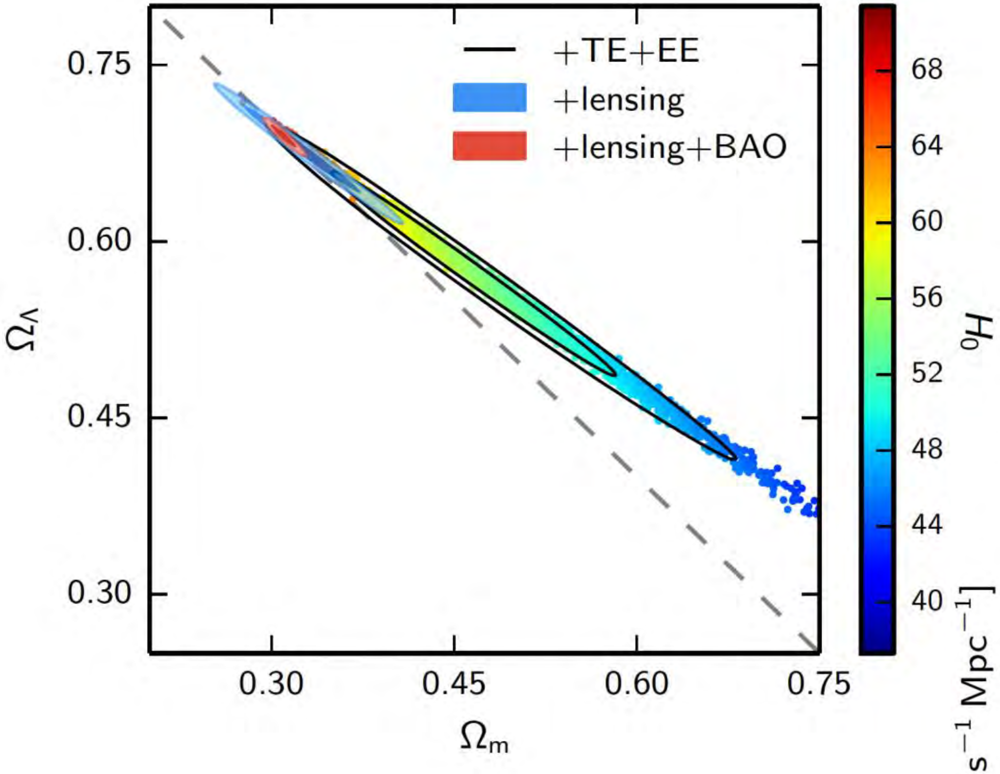
(from N. Wright)

CMB Angular Power Spectrum: *Planck* (2018)

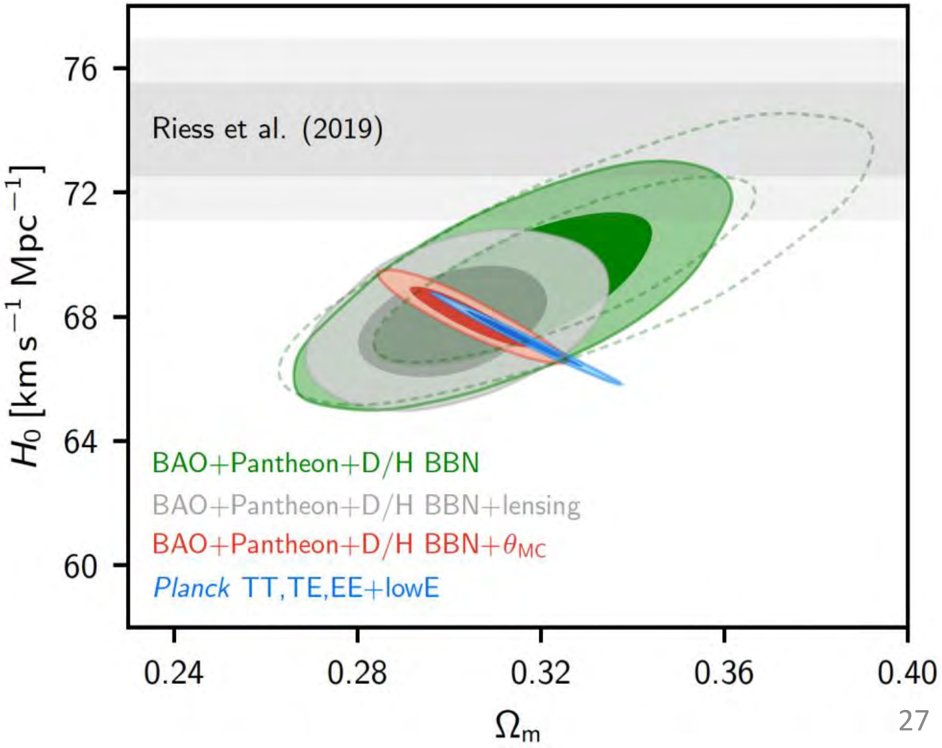


Some *Planck* Results

Matter density, vacuum energy (cosmological constant), and H_0

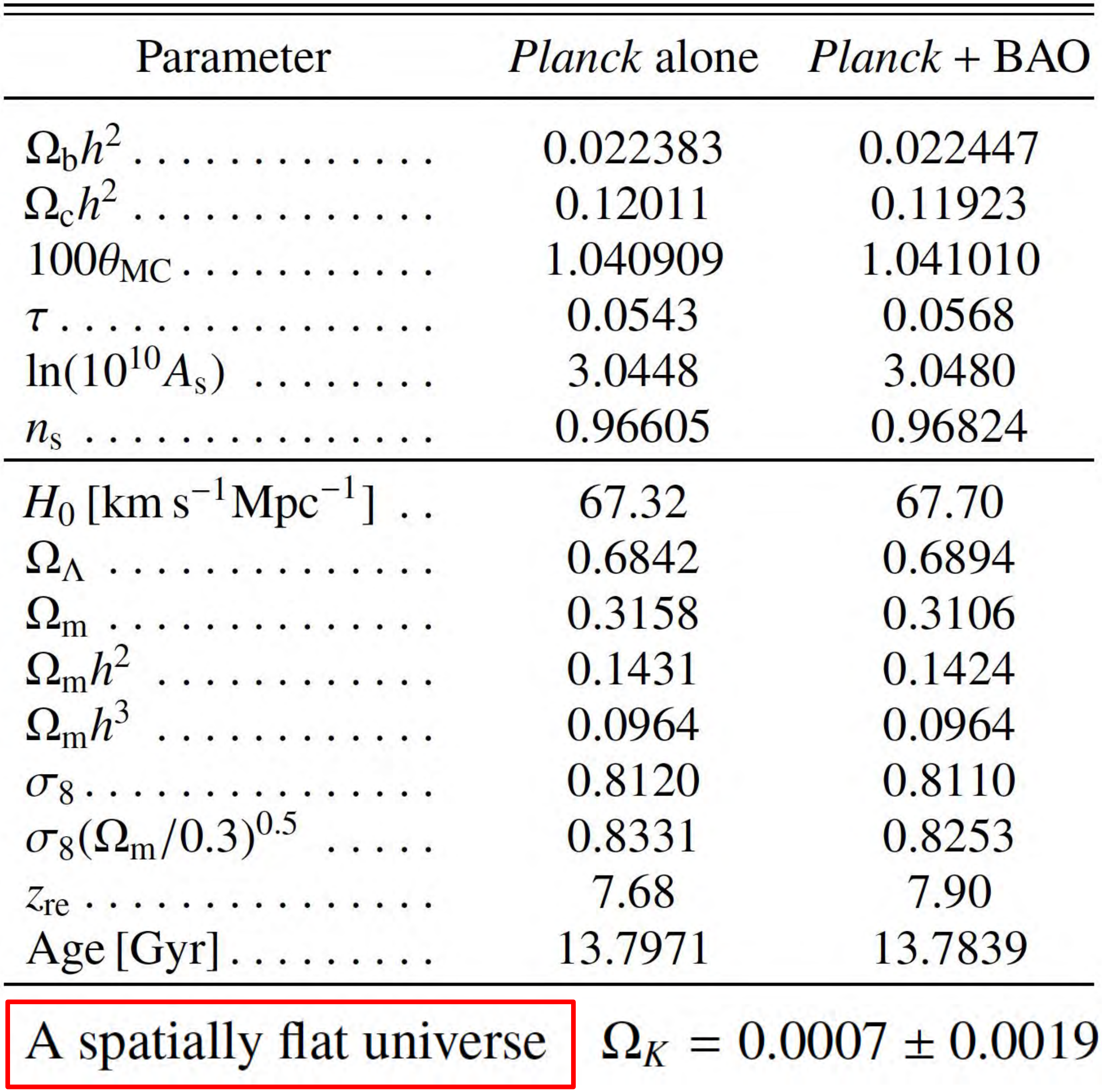


Best fit parameters are correlated, thus the elongated error ellipses



Combining data from *Planck* and other measurements →

Some *Planck* Results



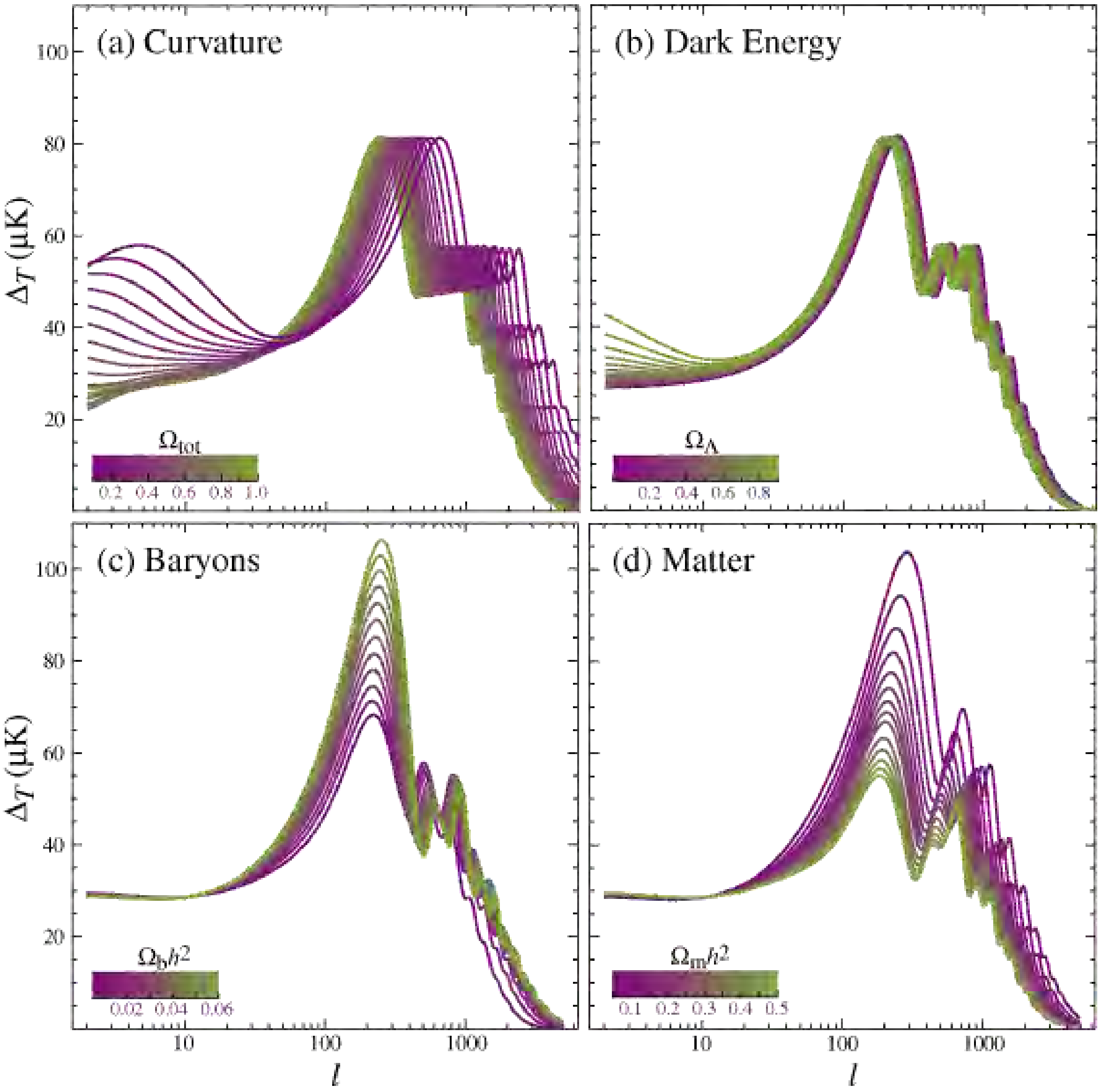
Parameter	*Planck* alone	*Planck* + BAO
$\Omega_b h^2$	0.022383	0.022447
$\Omega_c h^2$	0.12011	0.11923
$100\theta_{MC}$	1.040909	1.041010
τ	0.0543	0.0568
$\ln(10^{10} A_s)$	3.0448	3.0480
n_s	0.96605	0.96824
H_0 [km s^{-1}Mpc^{-1}]	67.32	67.70
Ω_Λ	0.6842	0.6894
Ω_m	0.3158	0.3106
$\Omega_m h^2$	0.1431	0.1424
$\Omega_m h^3$	0.0964	0.0964
σ_8	0.8120	0.8110
$\sigma_8(\Omega_m/0.3)^{0.5}$	0.8331	0.8253
z_{re}	7.68	7.90
Age [Gyr]	13.7971	13.7839

A spatially flat universe $\Omega_K = 0.0007 \pm 0.0019$

Notice the precision!

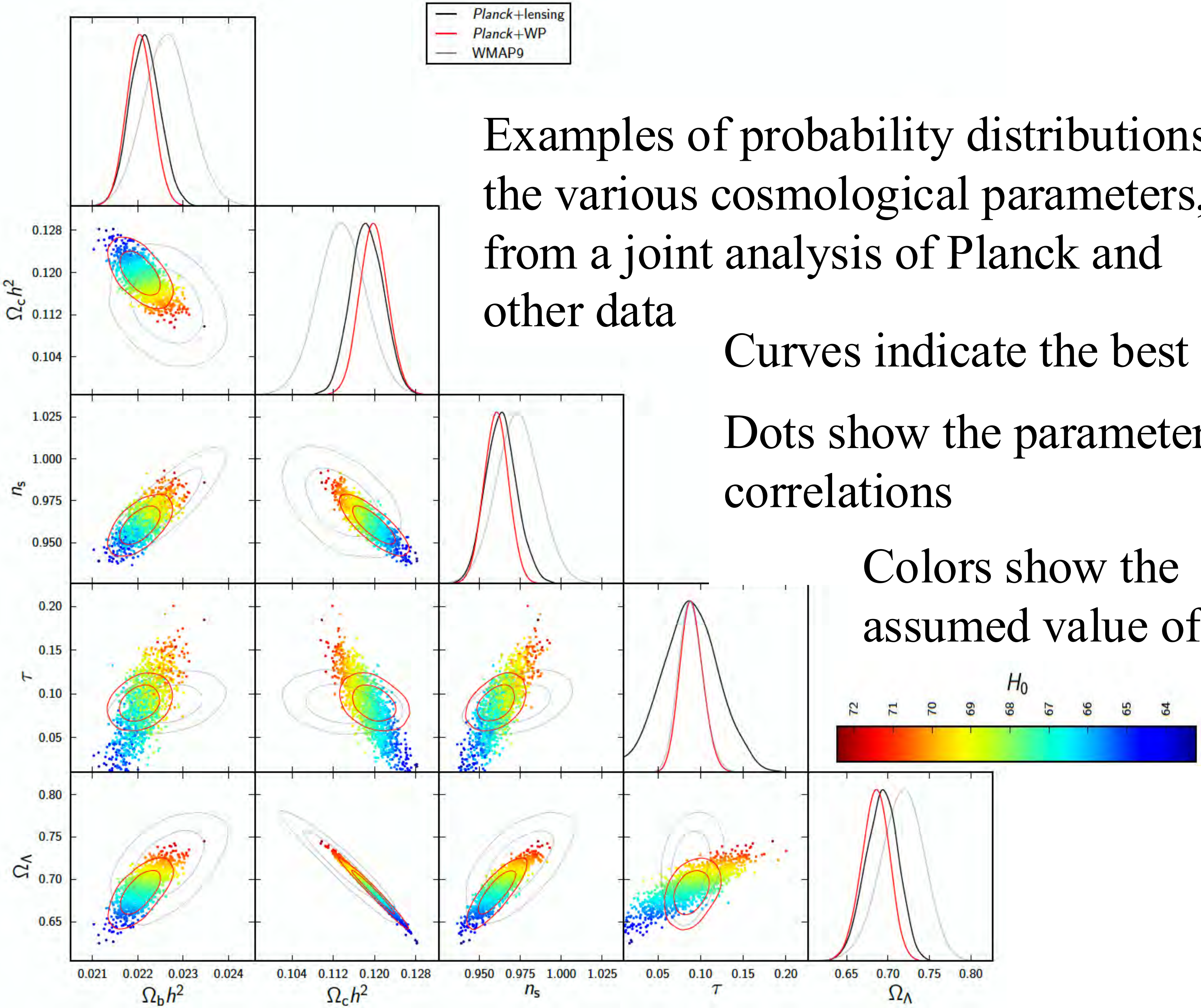
They also measure many other parameters of a cosmological interest

Positions and amplitudes of peaks depend on a variety of cosmological parameters in a complex fashion



Estimating Cosmological Parameters

- Many observables depend on *complicated combinations of individual cosmological parameters*; this is especially true for the analysis of CMB experiments
- Thus, one really gets probability contours or distributions in a multi-dimensional parameter space, which can then be projected on any given parameter axis
- Generally, this entails a very laborious and computationally intensive parameter estimation
- It helps if one can declare some of the parameters to be fixed *a priori*, on the basis of our knowledge or prejudices, e.g., "We'll assume that the univese is flat", or "we'll assume the value of H_0 from the HST Key Project", etc.



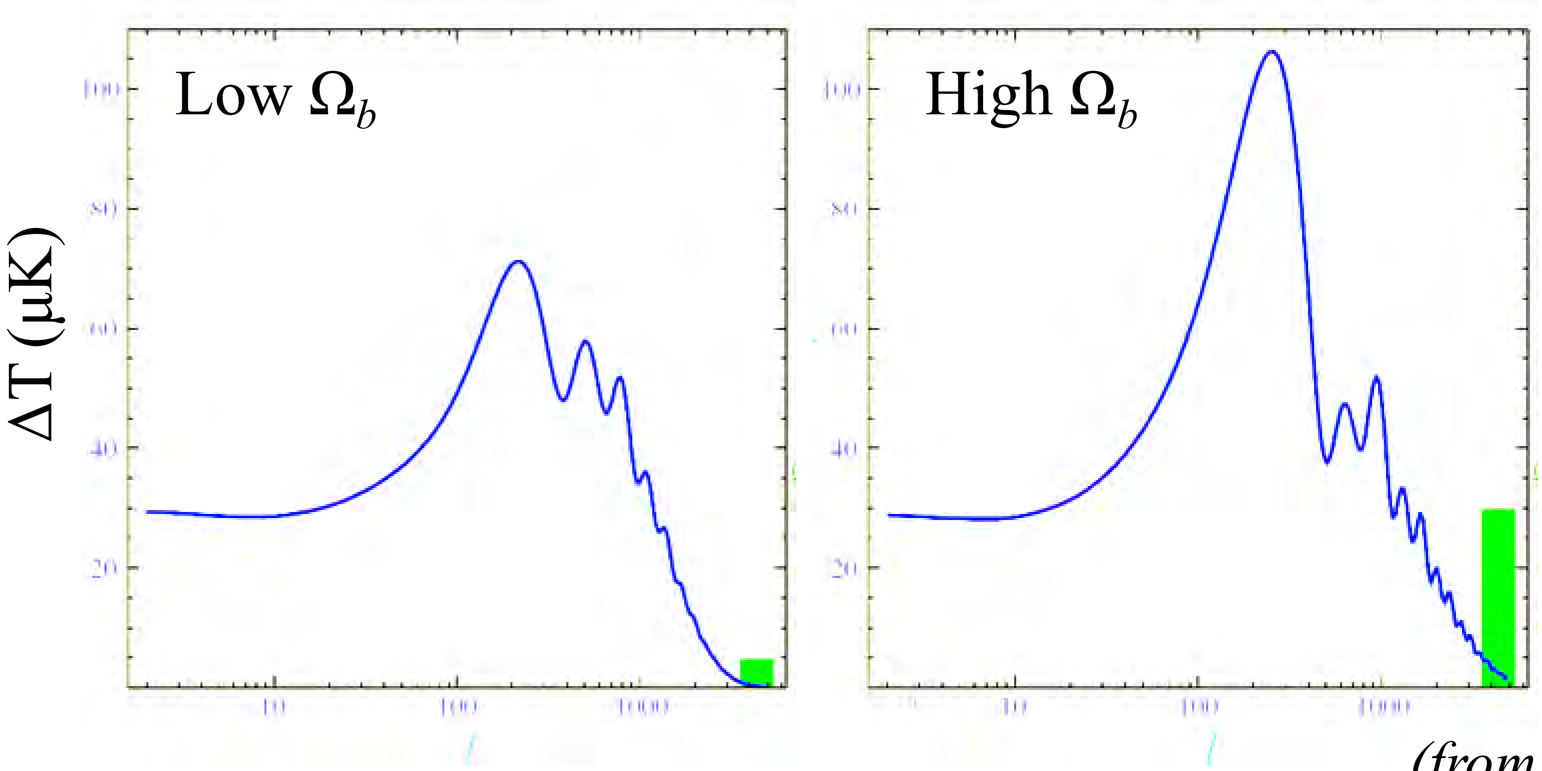
Examples of probability distributions of the various cosmological parameters, from a joint analysis of Planck and other data

Curves indicate the best fits

Dots show the parameter correlations

Colors show the assumed value of H_0

Baryon Content of the Universe



(from W. Hu)

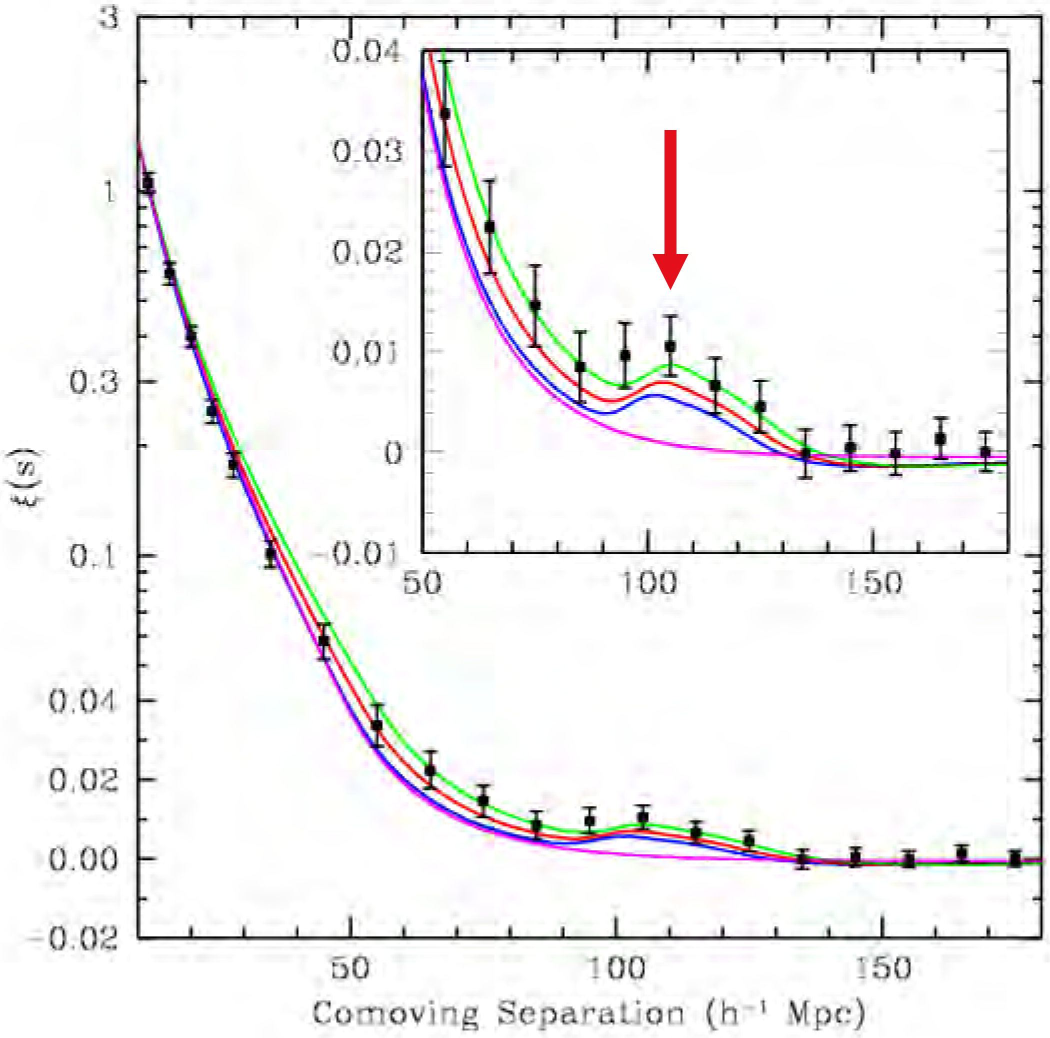
Increasing the fraction of baryons:

- Increases the amplitude of the Doppler peaks
- Changes the *relative* strength of the peaks - odd peaks become stronger relative to the even peaks (compressions/rarefactions)

Planck results: $\Omega_b h^2 = 0.022068 \pm 0.00033$

Baryon Acoustic Oscillations (BAO)

Eisenstein et al. 2005 (using SDSS red galaxies); also seen by the 2dF redshift survey



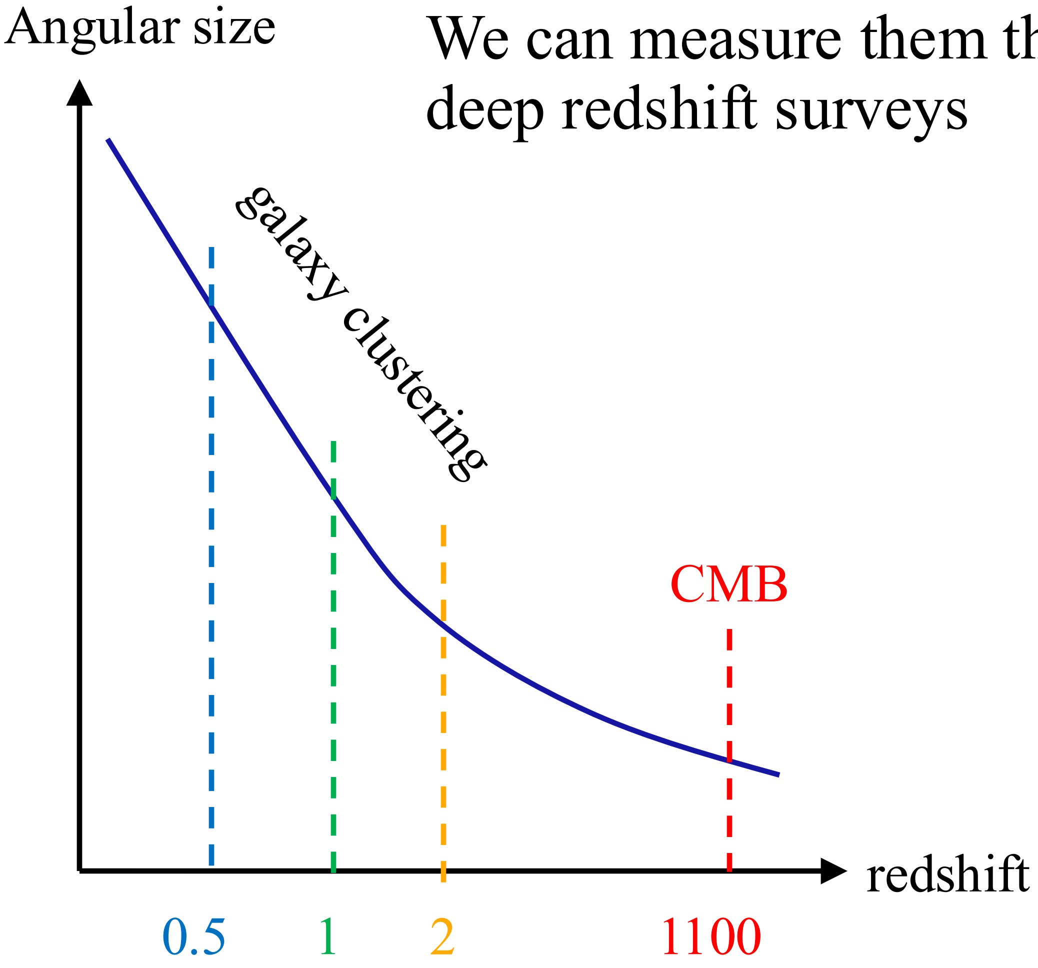
The 1st Doppler peak seen in the CMBR imprints a *preferred scale for clustering of galaxies*.

Detection of this feature in galaxy clustering at $z \sim 0.3$ gives us another instance of a “standard ruler” for an angular diameter test, at redshifts $z < 1100$

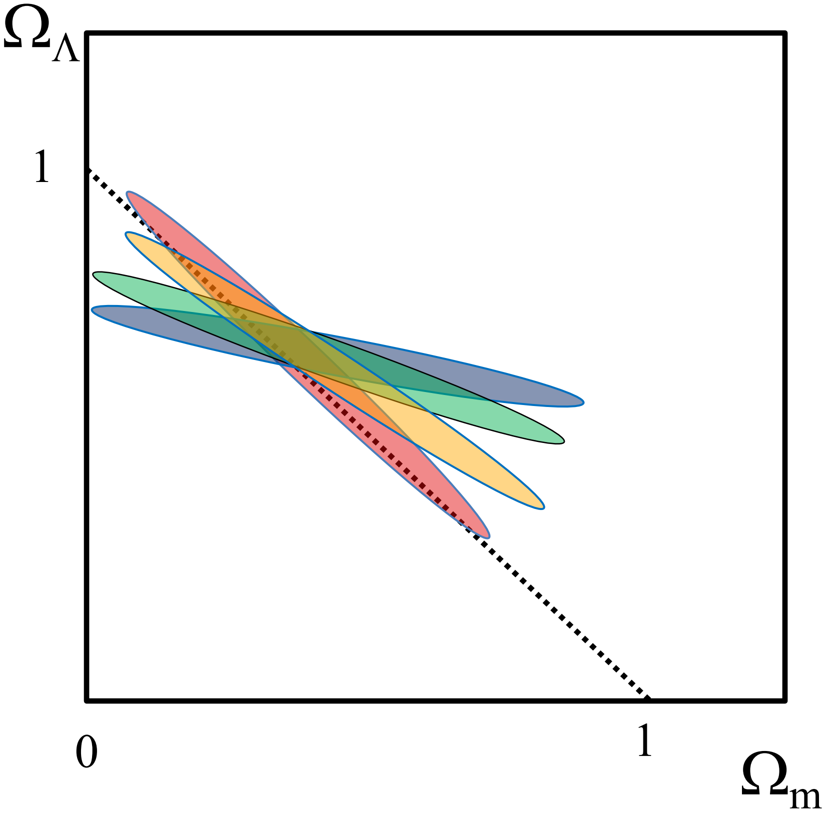
Current and future redshift surveys can do much better

BAO at Different Redshifts

We can measure them through galaxy clustering in deep redshift surveys



Measuring the “standard ruler” at different redshifts



Error ellipses rotate, and together provide a tighter constraint

Some Illustrative *Planck* Results (2013)

Curvature Ω_k and the EOS parameter *w*

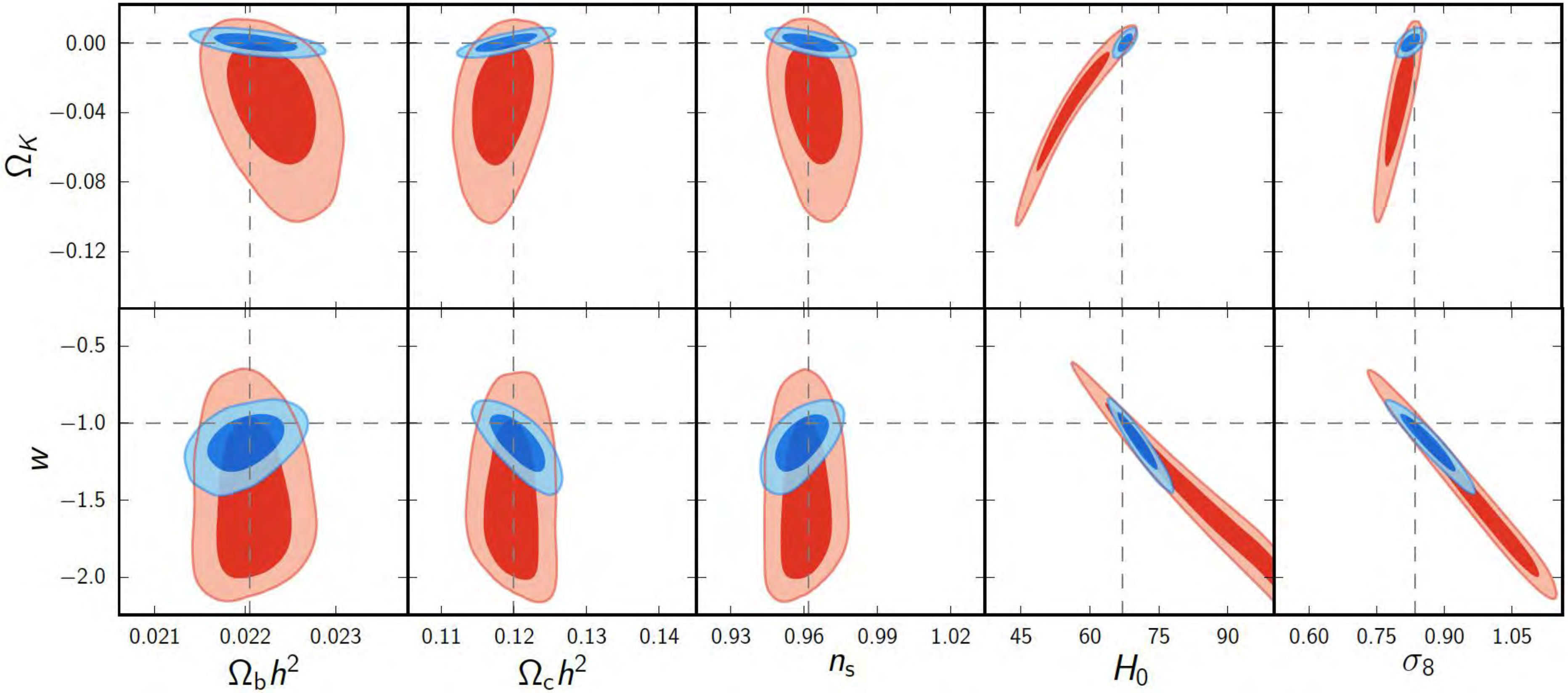
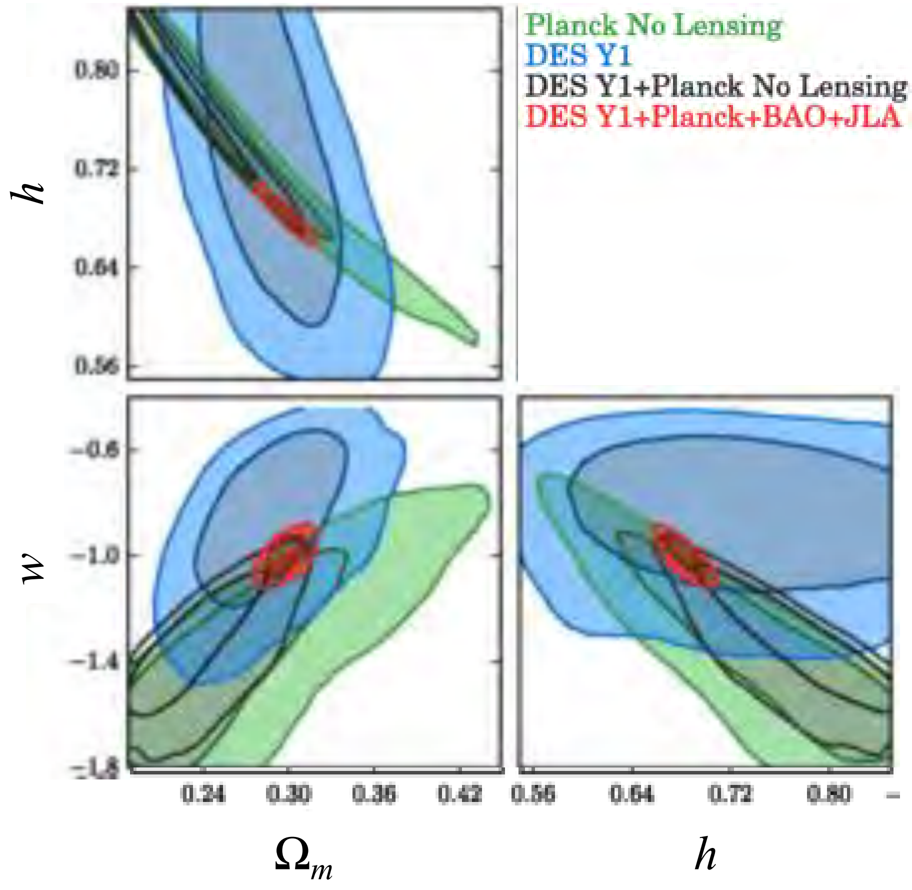
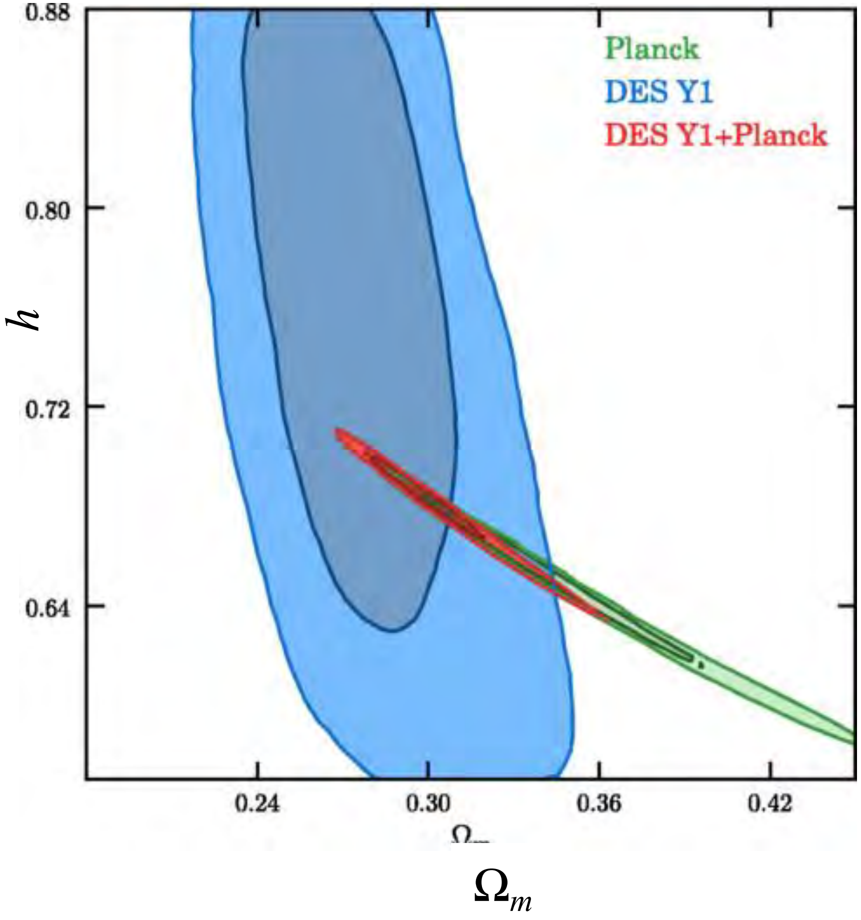


Fig. 21. 68% and 95% confidence regions on one-parameter extensions of the base ΛCDM model for *Planck*+WP (red) and *Planck*+WP+BAO (blue). Horizontal dashed lines correspond to the fixed base model parameter value, and vertical dashed lines show the mean posterior value in the base model for *Planck*+WP.

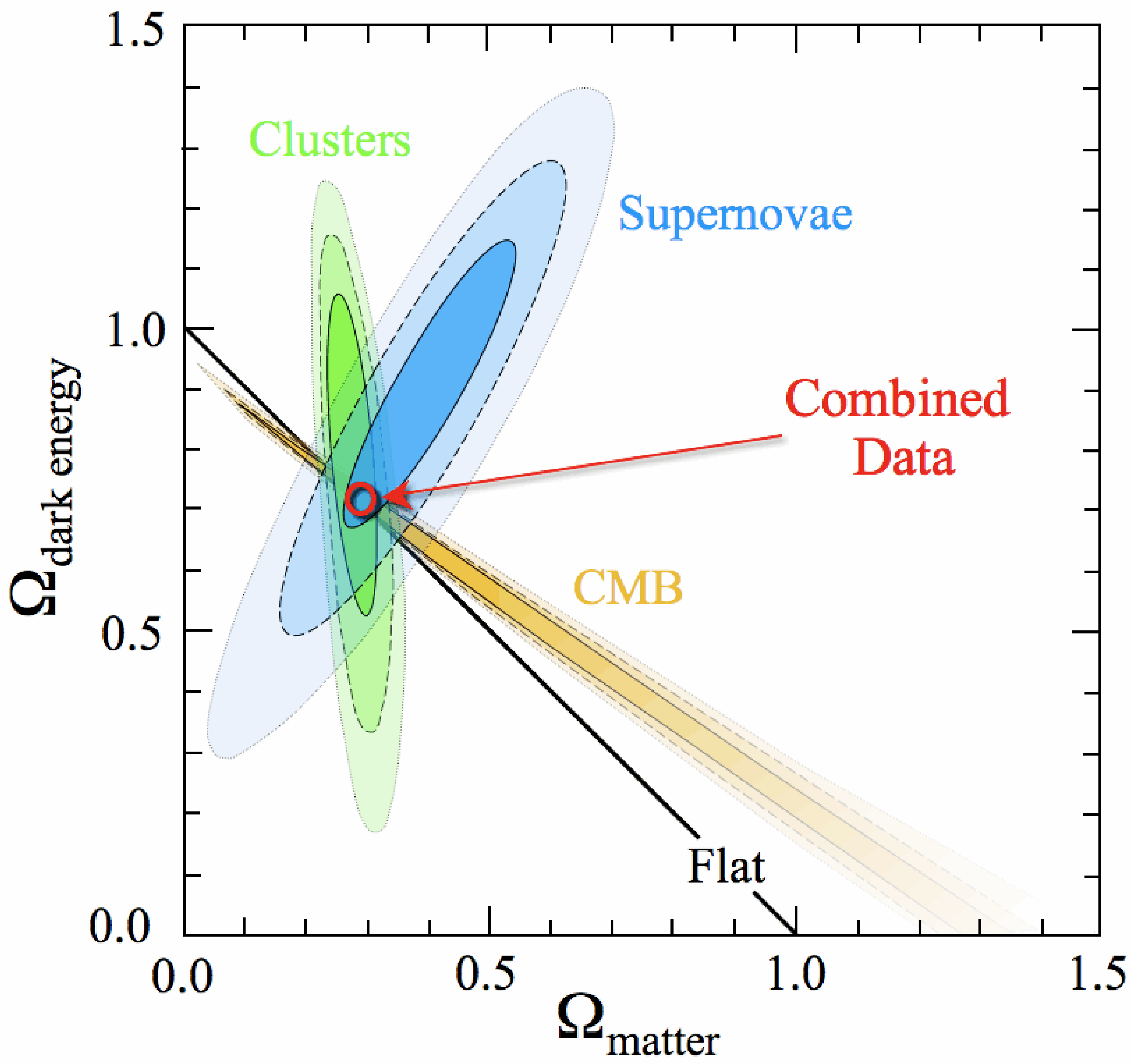
The Dark Energy Survey (DES)

From the evolution of galaxy clustering (BAO) and the weak gravitational lensing





The Cosmic Concordance



Multiple types of *different*, *independent* measurements and different cosmological probes all agree

(Not all are shown here, e.g., local Ω_m measurements, BAO, BBNS, ages of globular clusters, etc.)

The Component Densities

at z ~ 0, in critical density units, assuming *h* ≈ 0.7

Total matter/energy density: $\Omega_{0,tot} \approx 1.00$ From CMB, and consistent with SNe, LSS

Matter density: $\Omega_{0,m} \approx 0.30$ From local dynamics and LSS, and consistent with SNe, CMB

Baryon density: $\Omega_{0,b} \approx 0.05$ From cosmic nucleosynthesis, and independently from CMB

Luminous baryon density: $\Omega_{0,lum} \approx 0.005$ From the census of luminous matter (stars, gas)

Since: $\Omega_{0,tot} > \Omega_{0,m} > \Omega_{0,b} > \Omega_{0,lum}$

There is baryonic dark matter

There is non-baryonic dark matter

There is dark energy

Cosmological Tests Summary

- Tests of the global geometry and dynamics: *correlate redshifts (~ scale factors) with some relative measure of distance (~ look back time)*; could use:
  - "standard candles" (for luminosity distances; e.g., SNe)
  - "standard rulers" (for angular diameter dist's; e.g., CMB fluc's)
  - "standard abundances" (for volume-z test; e.g., rich clusters)
- Get matter density from local dynamics or LSS
- Combine with constraints from the H_0, ages
- There are often parameter couplings and degeneracies, especially with the CMB alone
- Multiple approaches provide cross-checks, break degeneracies
- ***Concordance cosmology*** is now fairly well established (aside from the Hubble constant tension)