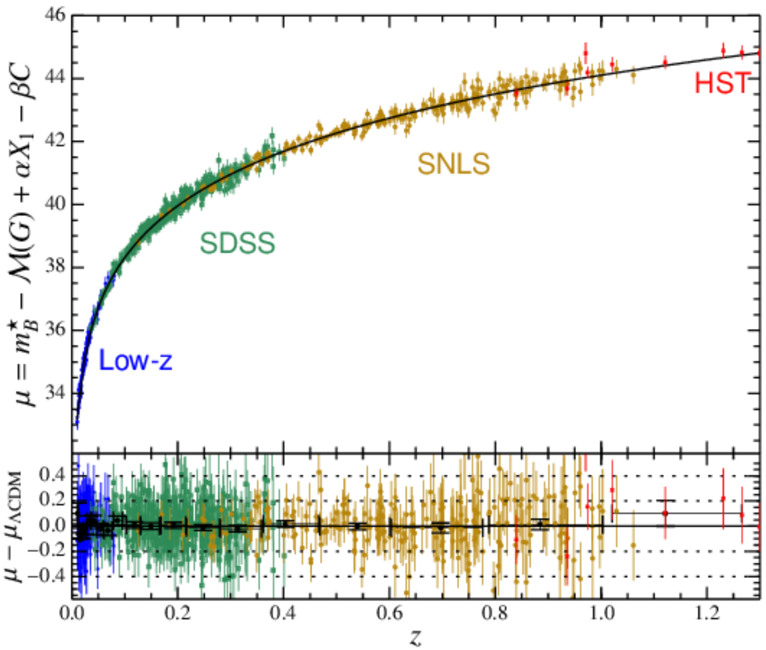
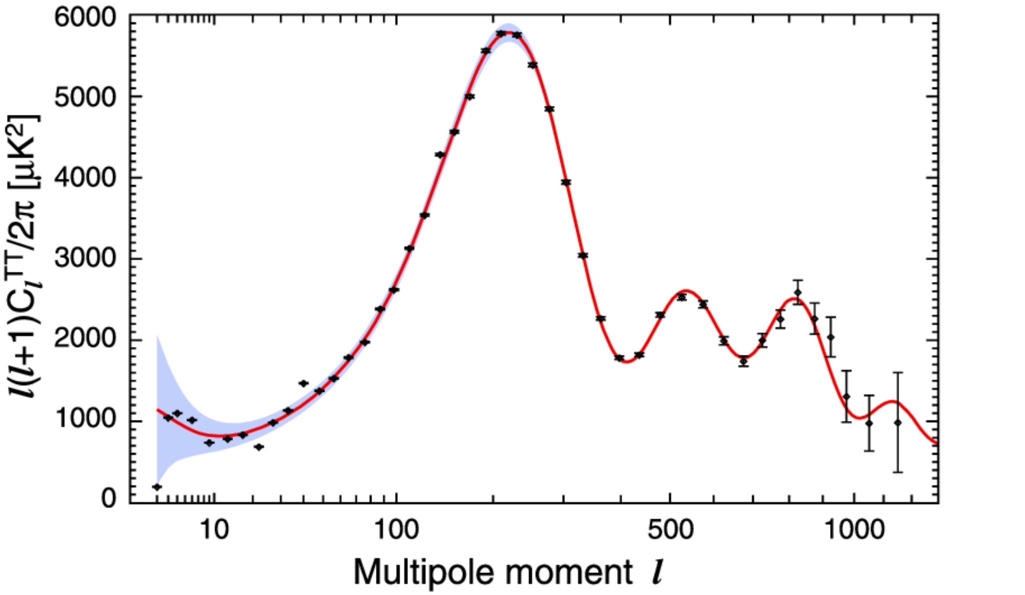
Honours Cosmology Week 6:
Cosmological observations

This week we will describe the different observations that allow us to test the cosmological model and measure its parameters





Cosmological observations

At the end of this week you should be able to …

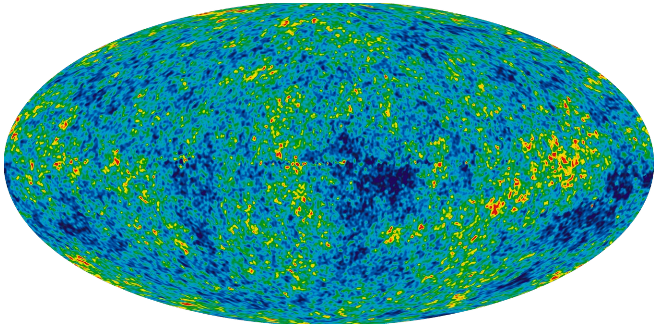
- … describe the use of **standard candles**, including Type Ia supernovae, to map out cosmic distances
- … describe the **acoustic oscillations** in the early Universe that imprint a standard ruler in both the CMB and the galaxy distribution
- … describe how **galaxy redshift surveys** can be used to map out the large-scale structure of the Universe
- … know about the **leading unsolved problems** in cosmological science!

Cosmological observations

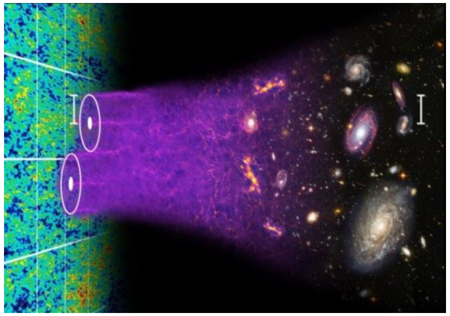
- What are the main types of observations that we use today to *test the cosmological model*?

Supernovae as standard candles

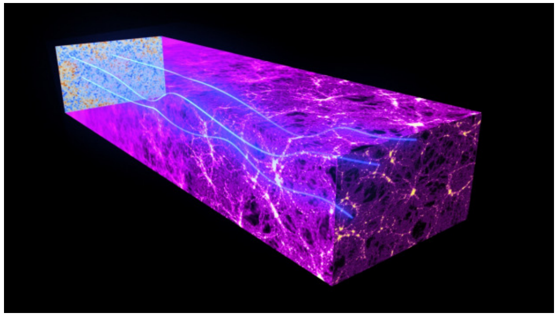
Cosmic Microwave Background



Acoustic oscillations as standard rulers



Gravitational lensing

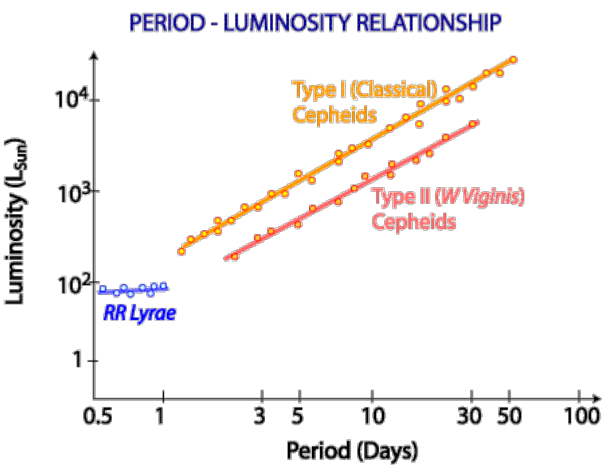


Standard candles

- A *standard candle* is an object of known intrinsic luminosity, whose apparent brightness can be used to measure astronomical distances

Cepheid or RR Lyrae stars

Variable stars with a known period-luminosity relation

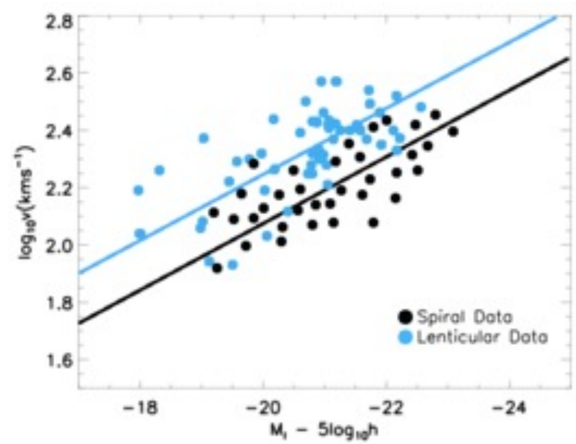


Supernovae

Characteristic explosions at the end of a star's life

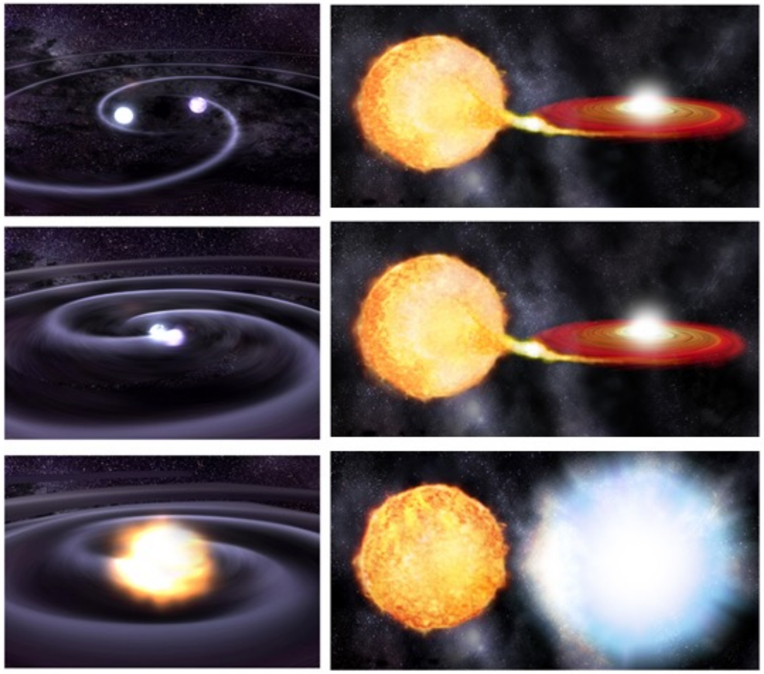
Galaxy correlations

Galaxy luminosity is correlated with rotation speed (Tully-Fisher relation)



Supernovae

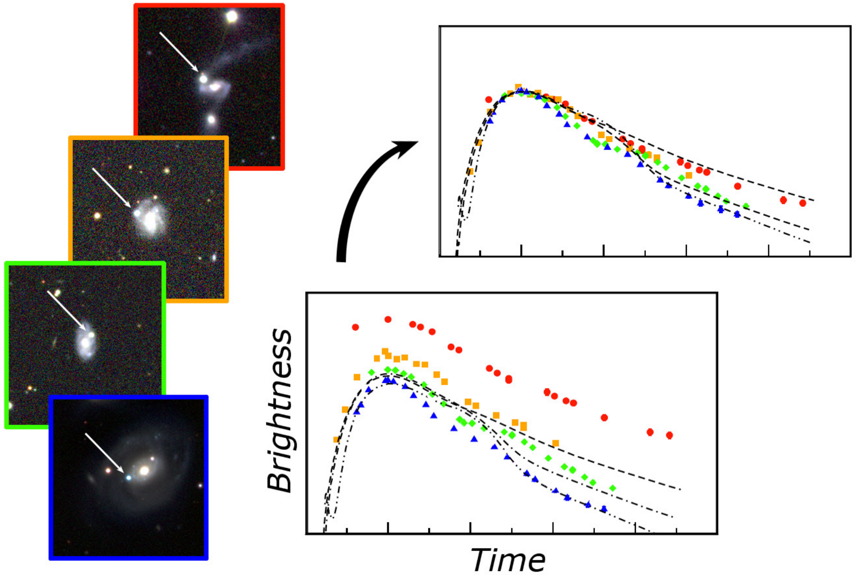
- We’ll focus on the most important type of standard candle in the distant Universe: *Type Ia supernovae*
- These evolve in binary systems where mass is transferred to a white dwarf star, pushing it over the Chandrasekar limit



Supernovae

- Type Ia supernova are *very luminous* ($M_B \sim -19.5$) and hence can be detected in the distant Universe

- They are *standardisable candles*: although each supernova has a different light curve, they may be calibrated to a common peak brightness using the rate of decline (faster → fainter)

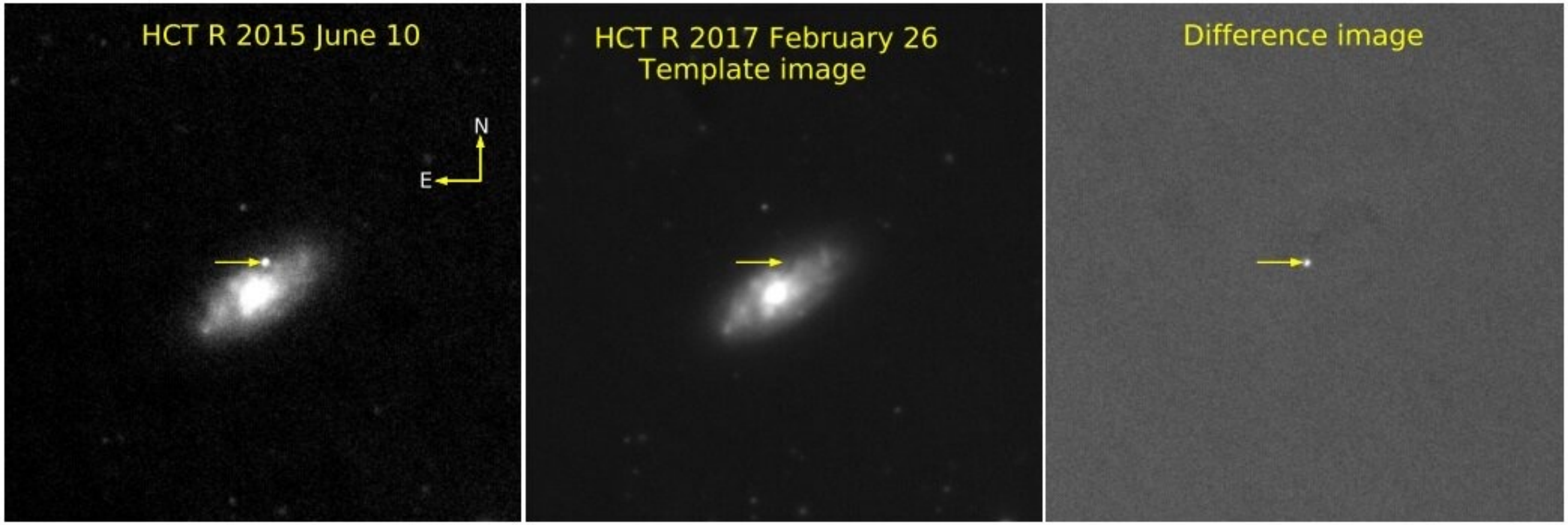


- Other corrections to the peak brightness are also performed, such as for dust extinction and for the type of host galaxy

- After these corrections, the supernovae are standard candles within ~ 0.15 magnitudes

Supernovae

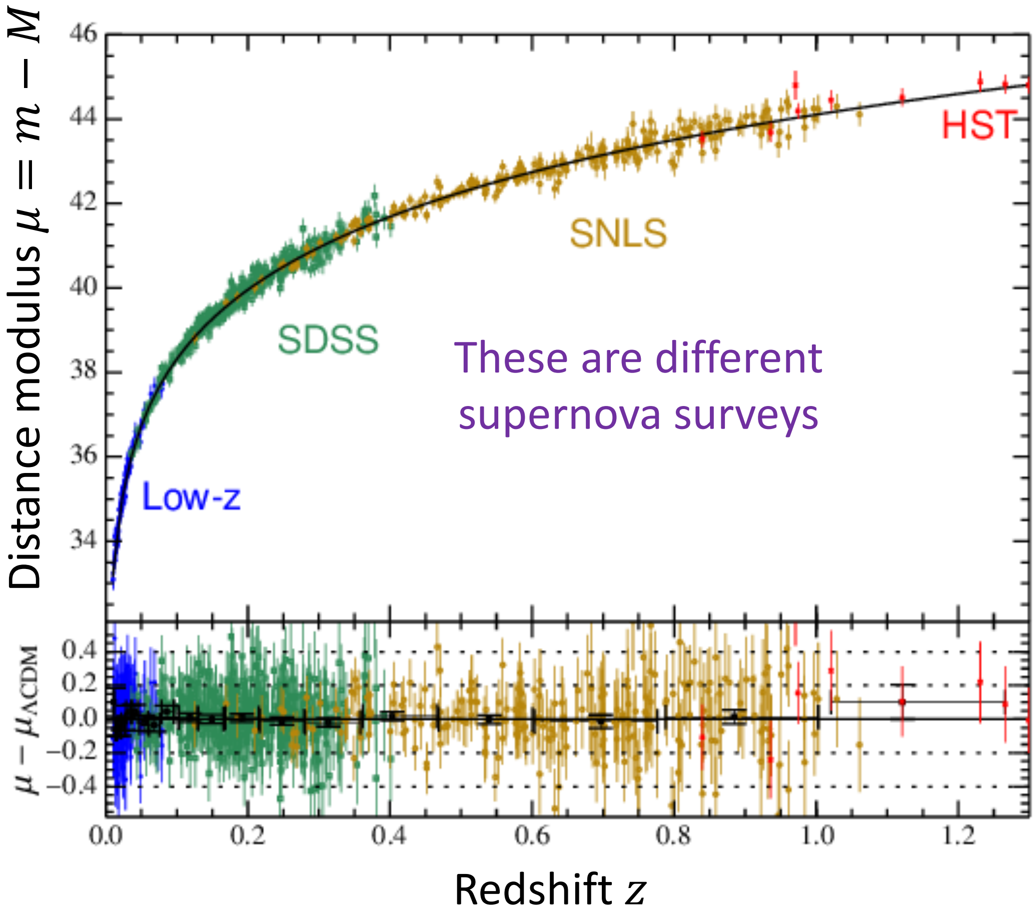
- We can find supernovae in the distant Universe through *difference imaging* in CCD searches



- There are *many modern datasets* such as the Supernova Legacy Survey (SNLS), SDSS supernova survey, HST supernova surveys, Dark Energy Survey, Palomar Transient Factory, Carnegie Supernova Project …

Supernovae

- A plot of the apparent magnitude of Type Ia supernovae against redshift is known as a *supernova Hubble diagram*



The **distance modulus μ** is the difference between apparent and absolute magnitudes

It's related to the luminosity distance by $\mu = 5\log_{10} D_L(\text{Mpc}) - 25$

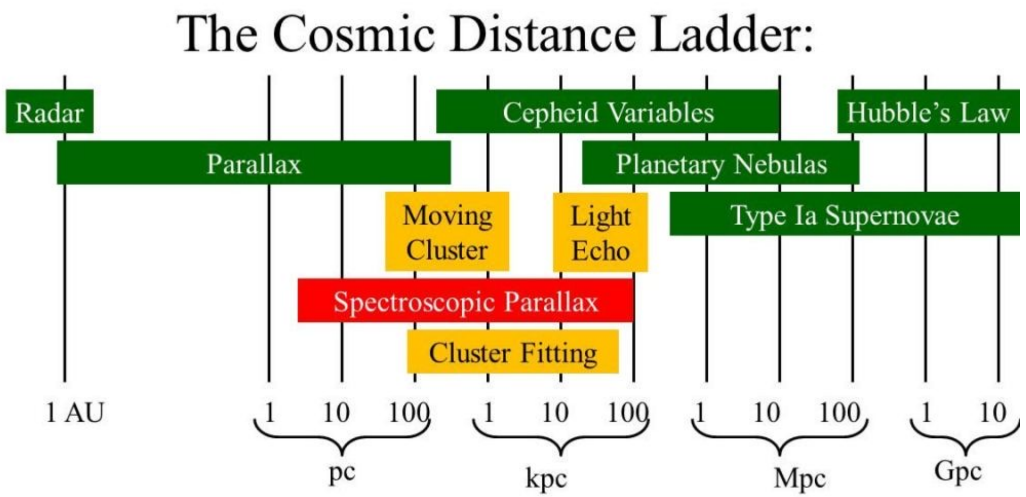
Since the luminosity distance at a given redshift can be predicted using the Friedmann equation, **supernovae can be used to determine cosmological parameters** such as $H_0, \Omega_m, \Omega_\Lambda$

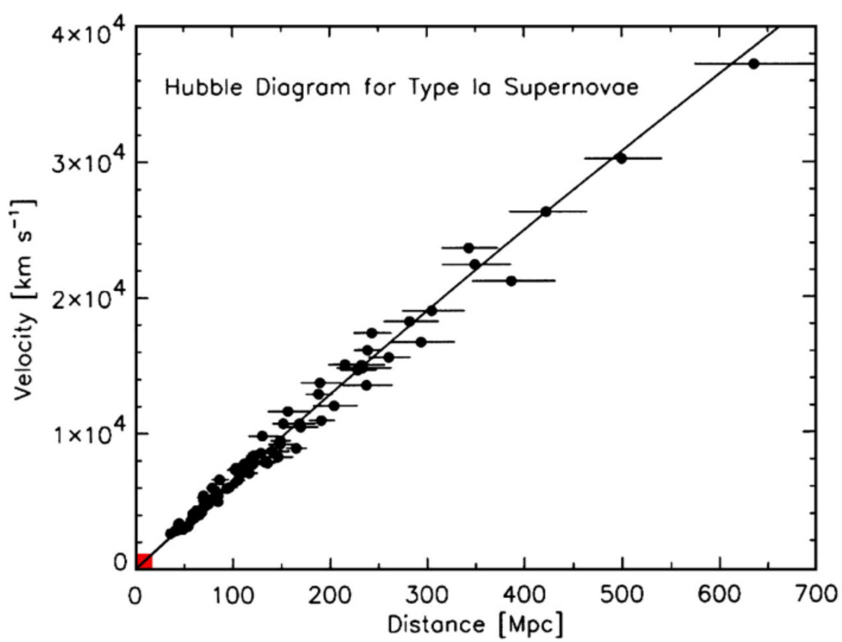
Supernovae

- The supernova luminosity calibration is transferred from nearby to more distant objects using a *cosmic distance ladder*

- Here's an example of a *fit for Hubble's constant* using supernovae

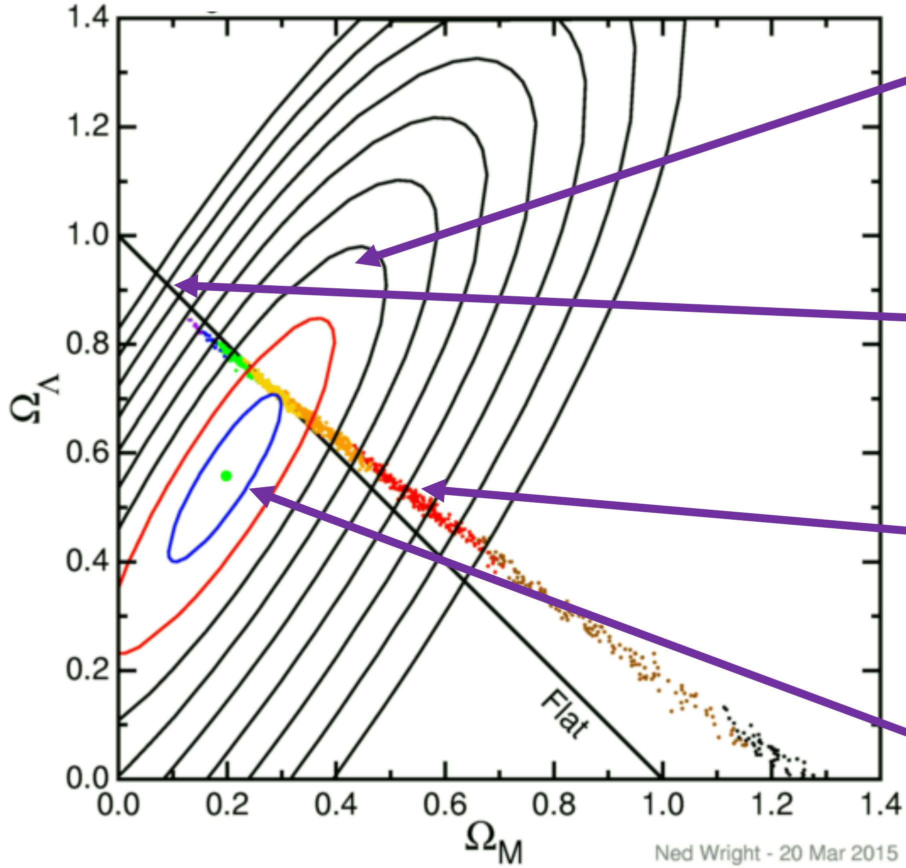
- Recent determinations (see later slide) give $H_0 \approx 74\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$





Supernovae

- Here's an example of a *fit for the density parameters* $(\Omega_m, \Omega_\Lambda)$ using a recent supernovae sample



These contours indicate confidence regions for the $(\Omega_m, \Omega_\Lambda)$ values, where the central regions are 68% and 95%

This line would be consistent with a flat Universe (i.e., $\Omega_m + \Omega_\Lambda = 1 \rightarrow \Omega_K = 0$)

These points are consistent with the Cosmic Microwave Background data

The supernovae clearly favour a ΛCDM universe with $\Omega_m \approx 0.3$, $\Omega_\Lambda \approx 0.7$

Standard rulers

- A *standard ruler* is an object of known intrinsic physical size, whose apparent angular size can be used to measure astronomical distances

Standard ruler distances are based on apparent sizes

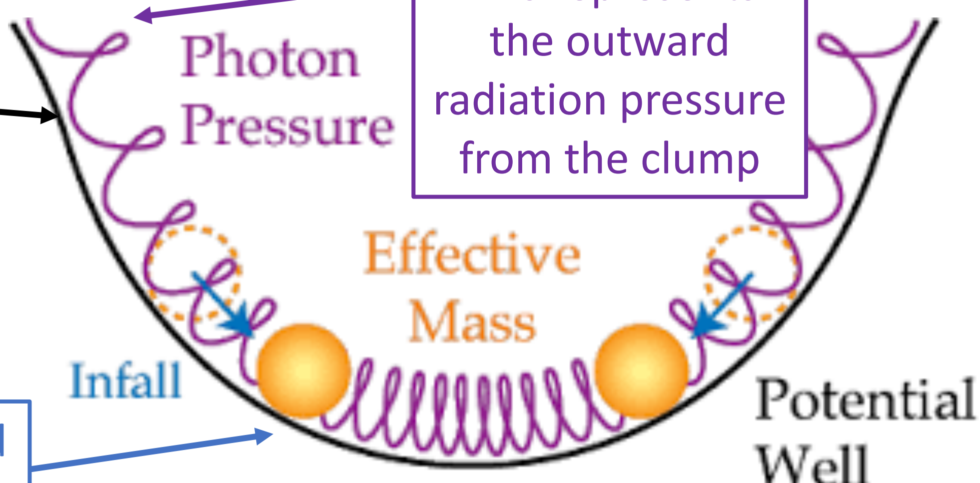
Standard candle distances are based on apparent luminosities

Acoustic oscillations

- The most important cosmic standard ruler is a feature of the early Universe called *acoustic oscillations*
- Acoustic oscillations describe the sound waves that propagate in the plasma prior to the generation of the CMB, owing to the opposing forces of *gravity* and *radiation pressure*

This represents the gravitational potential well of a clump of dark matter

This represents the outward radiation pressure from the clump



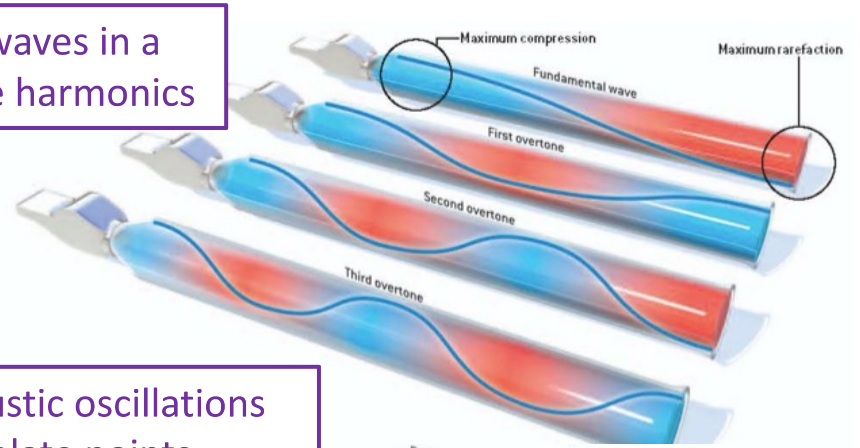
The balance between these inward and outward forces results in an oscillation

This represents inward force due to gravity

Acoustic oscillations

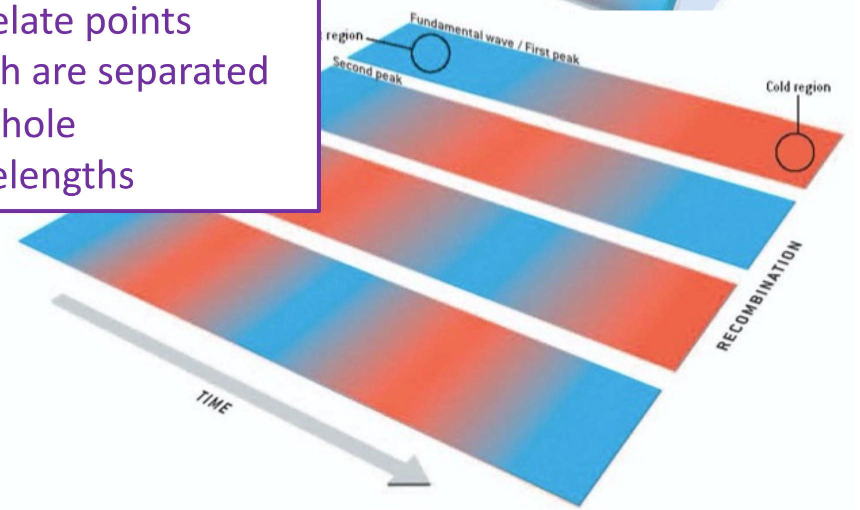
- Acoustic oscillations are a standard ruler because they *travel a fixed distance in the time before recombination* (when the radiation pressure disappears)

Sound waves in a pipe are harmonics



- This distance is called the *sound horizon* r_s (at recombination) and has a comoving length $147\ \mathrm{Mpc}$ (this is calibrated by the CMB)

Acoustic oscillations correlate points which are separated by whole wavelengths

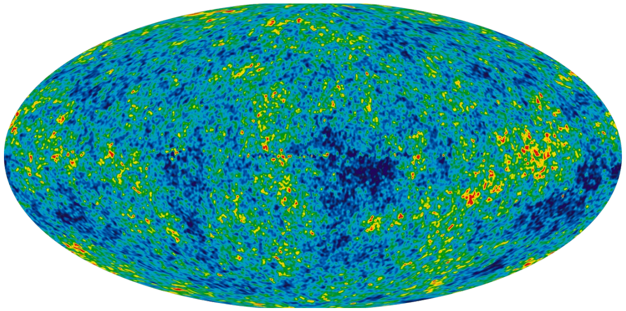


- The sound horizon is imprinted in both the *CMB temperature fluctuations* and the *galaxy distribution*

Angular power spectrum

- We study these effects in the CMB by measuring its *angular power spectrum*

Temperature fluctuations in the CMB

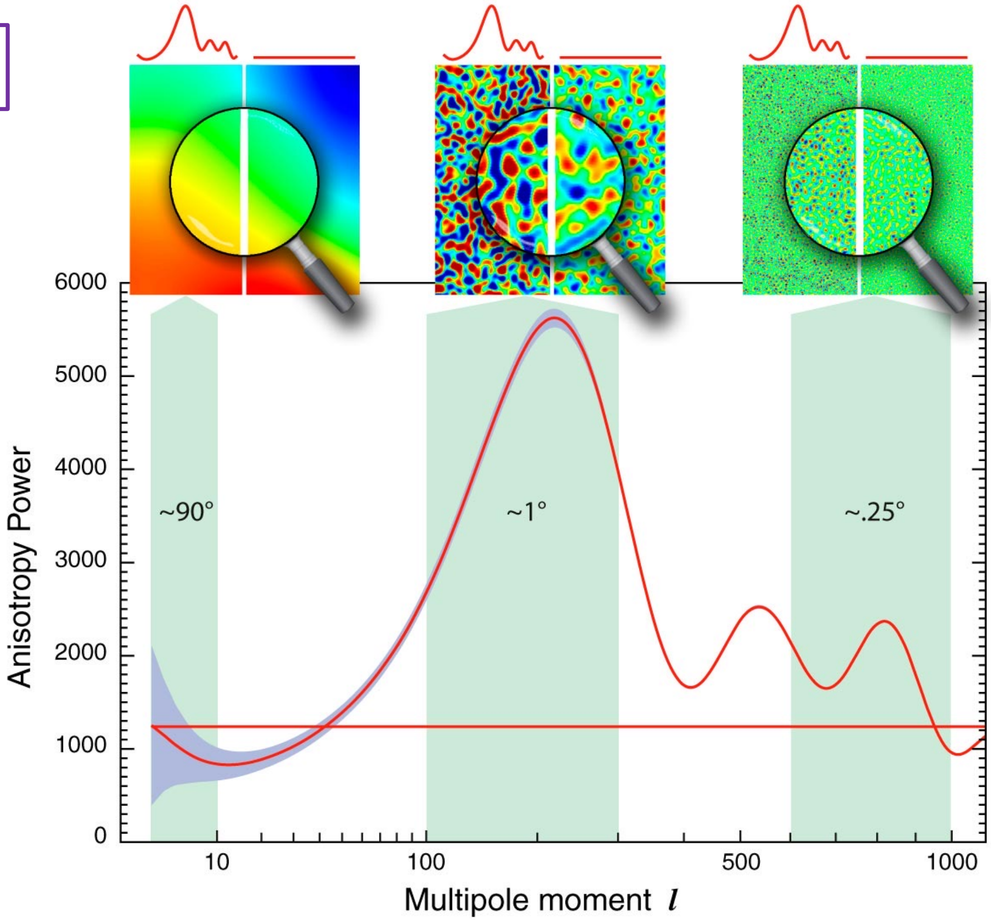


Express this temperature map as spherical harmonic functions

$$T(\theta, \phi) = \sum_{lm} a_{lm} Y_{lm}(\theta, \phi)$$

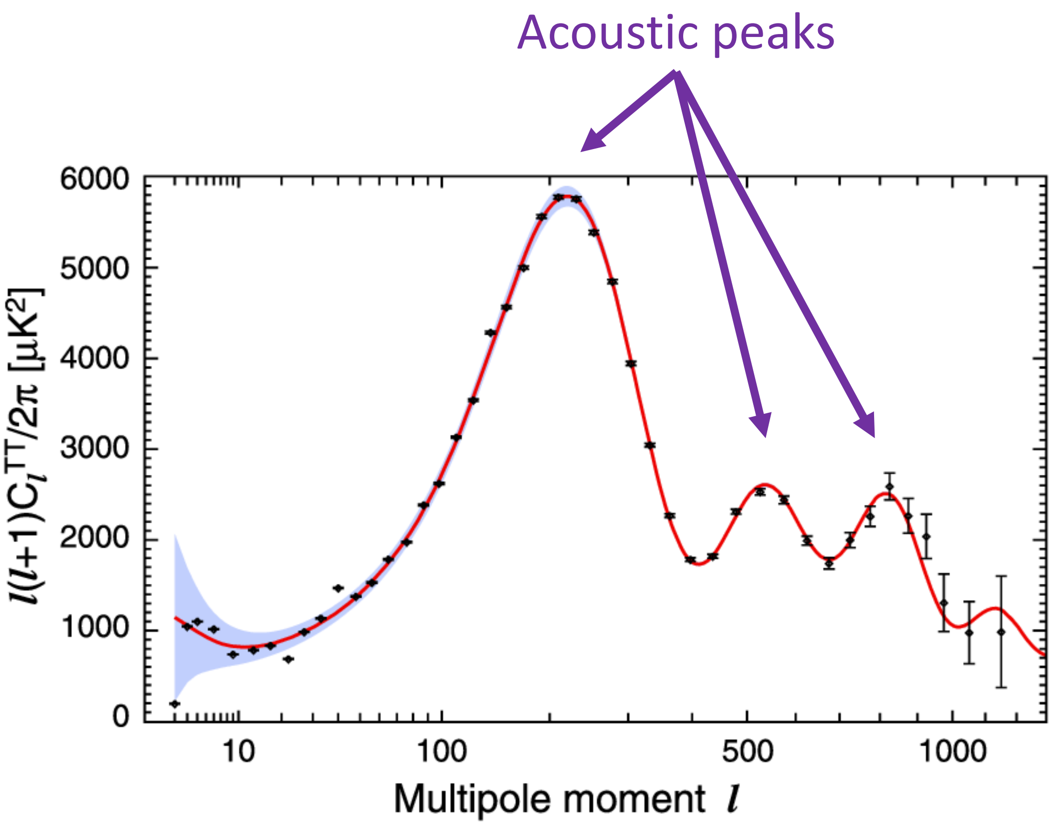
with angular power spectrum

$$C_l = \langle |a_{lm}|^2 \rangle$$



Angular power spectrum

- The peaks in the CMB angular power spectrum are *acoustic oscillations* corresponding to harmonics of the sound horizon



The observed angular separation corresponding to the first harmonic is

$$\theta = \frac{r_s}{r(z = 1100)} \approx 0.9^\circ$$

This corresponds to multipole moment of the angular power

$$l = \frac{180^\circ}{\theta} \approx 200$$

as seen in the data!

Angular power spectrum

- The CMB angular power spectrum may be used to fit the parameters of the *standard ΛCDM cosmological model*:

Describes fluctuation spectrum from inflation

Hubble's constant

Dark energy

Matter density

Baryon density

CDM density

Overall clumpiness

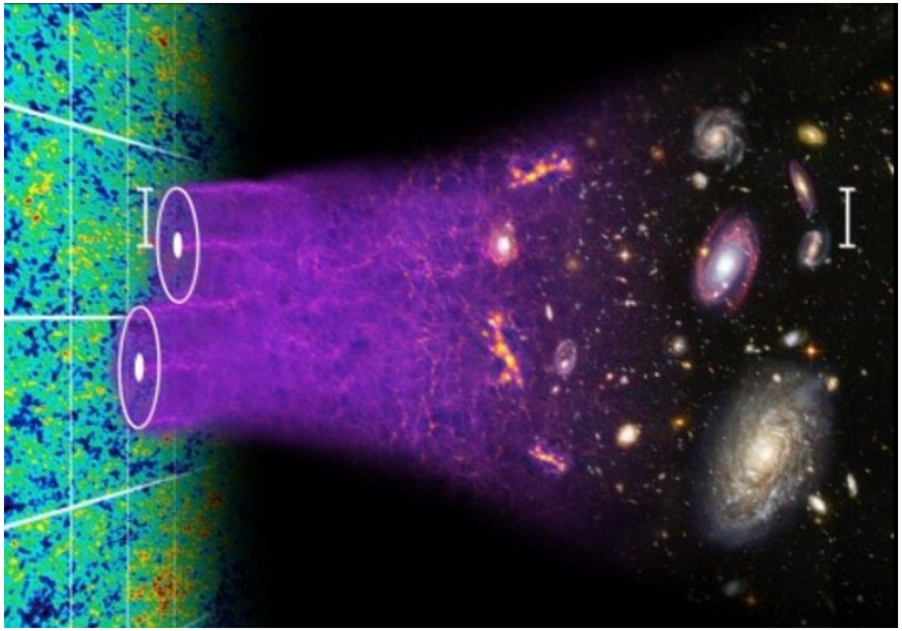
Redshift of reionisation

Parameter	TT+lowP+lensing 68% limits	TT,TE,EE+lowP+lensing+ext 68% limits
n_s	0.9677 ± 0.0060	0.9667 ± 0.0040
H_0	67.81 ± 0.92	67.74 ± 0.46
Ω_Λ	0.692 ± 0.012	0.6911 ± 0.0062
Ω_m	0.308 ± 0.012	0.3089 ± 0.0062
$\Omega_b h^2$	0.02226 ± 0.00023	0.02230 ± 0.00014
$\Omega_c h^2$	0.1186 ± 0.0020	0.1188 ± 0.0010
σ_8	0.8149 ± 0.0093	0.8159 ± 0.0086
z_{re}	$8.8^{+1.7}_{-1.4}$	$8.8^{+1.2}_{-1.1}$
Age/Gyr	13.799 ± 0.038	13.799 ± 0.021

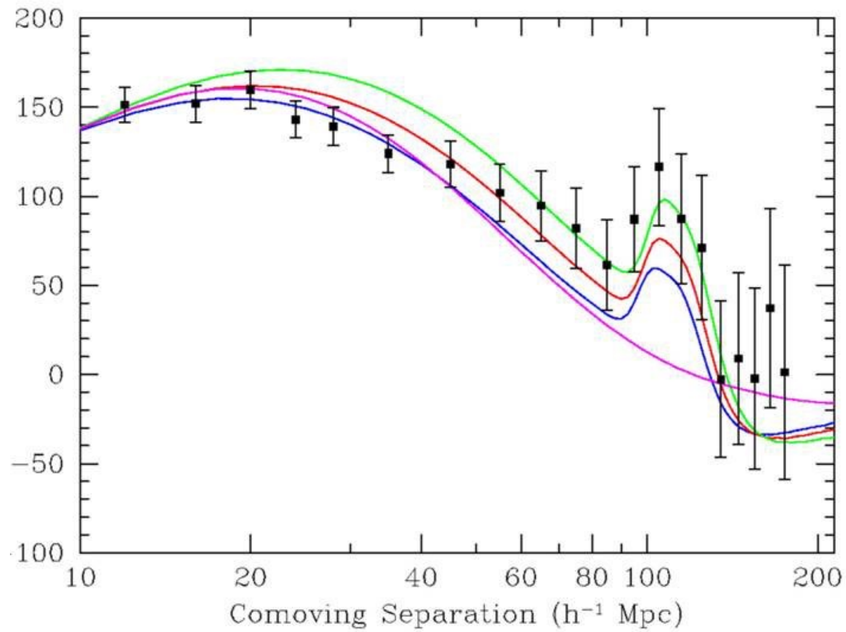
Acoustic oscillations

- Since galaxies form at the sites of CMB fluctuations, the acoustic oscillations are imprinted in the galaxy distribution as a *preferred separation of galaxies*

There is a slight excess of galaxy pairs separated by the sound horizon scale



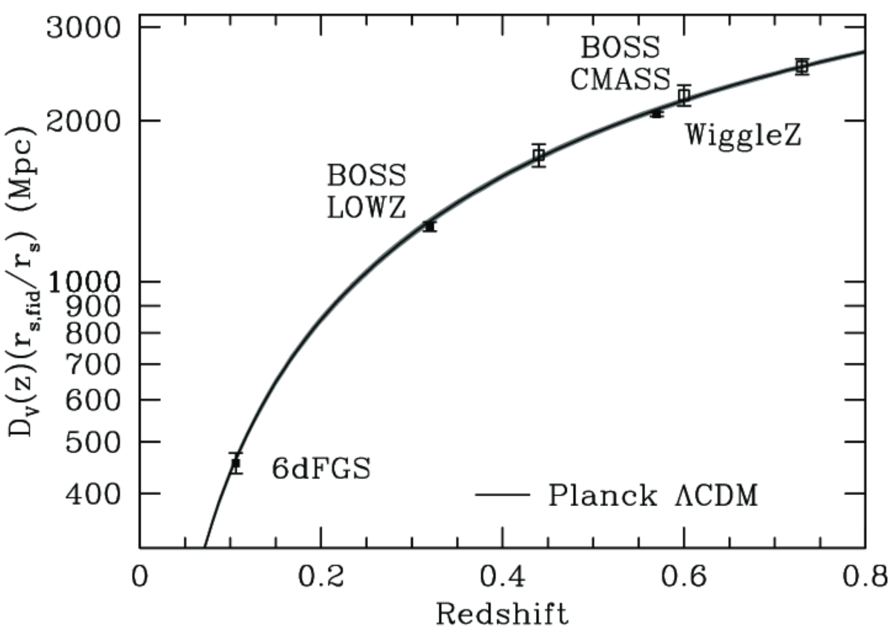
Galaxy correlation function ~ number of pairs with each separation



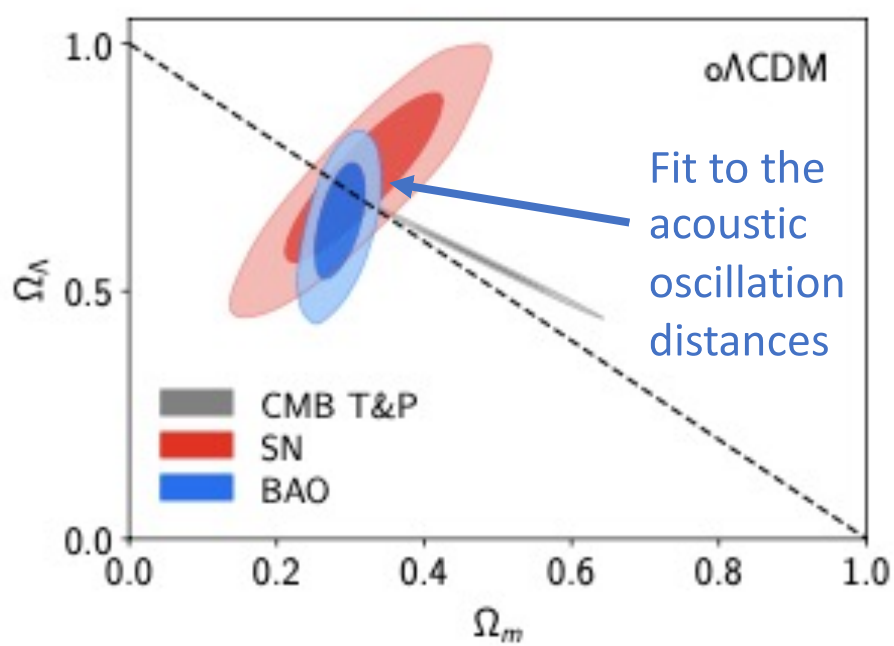
Acoustic oscillations

- If the acoustic peak signature is measured by galaxy surveys at different redshifts, it may be used as a *standard ruler for mapping out distances* and hence *measuring parameters*

Recent distance measurements from galaxy redshift surveys

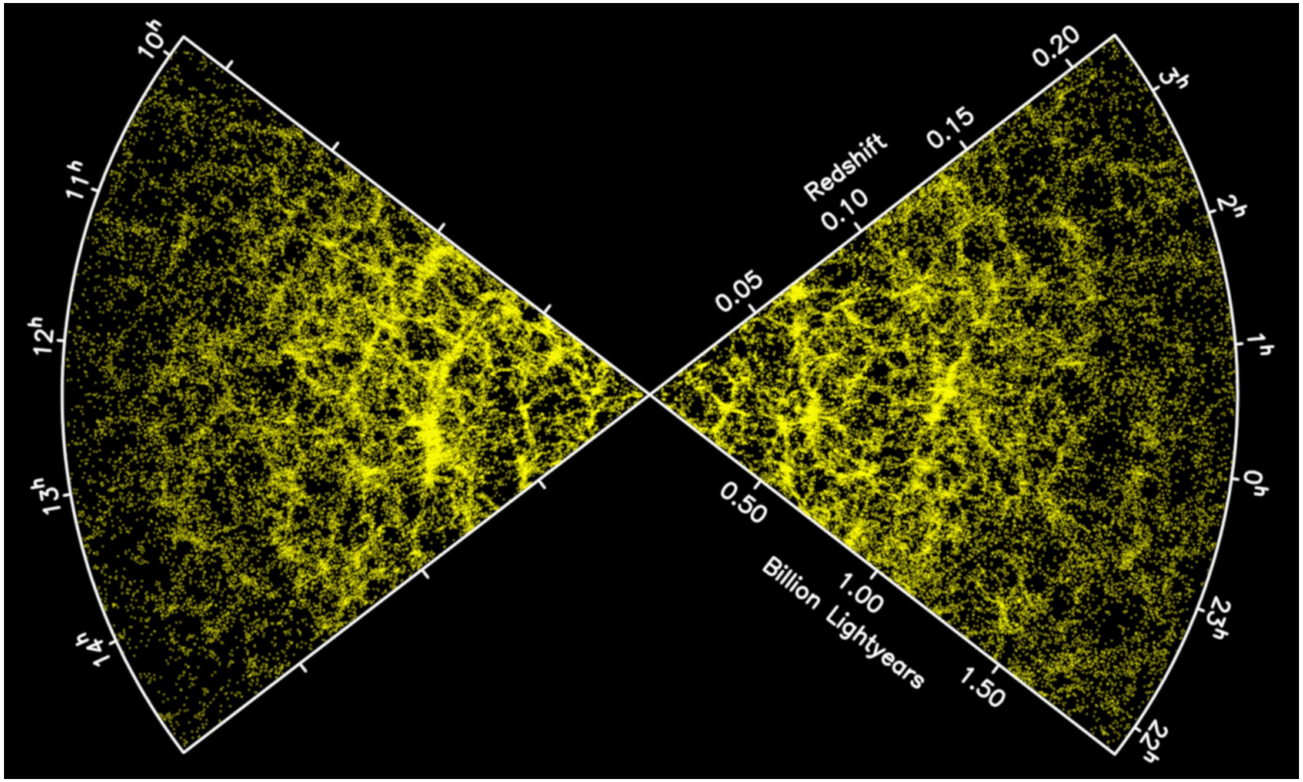


Recent density parameter fit based on the standard ruler



Galaxy redshift surveys

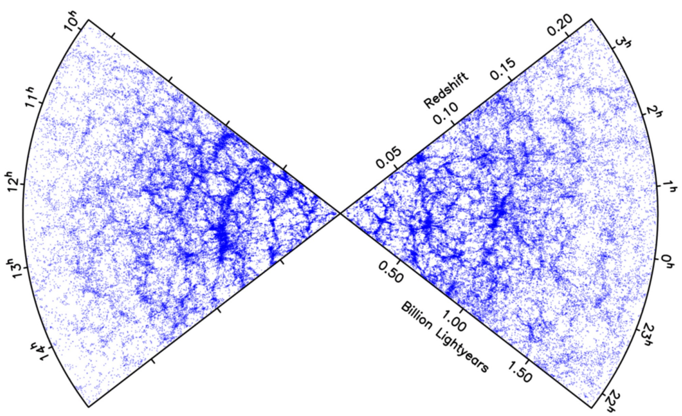
- Galaxy redshift surveys obtain spectra for millions of galaxies and (using a distance-redshift relation) locate their positions in a *3D map of large-scale structure*

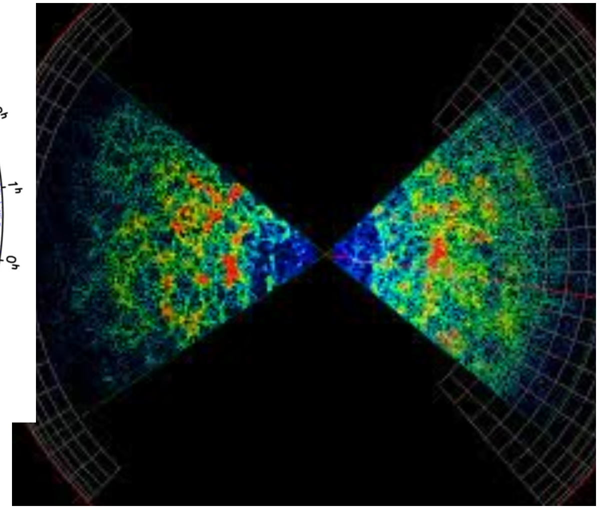


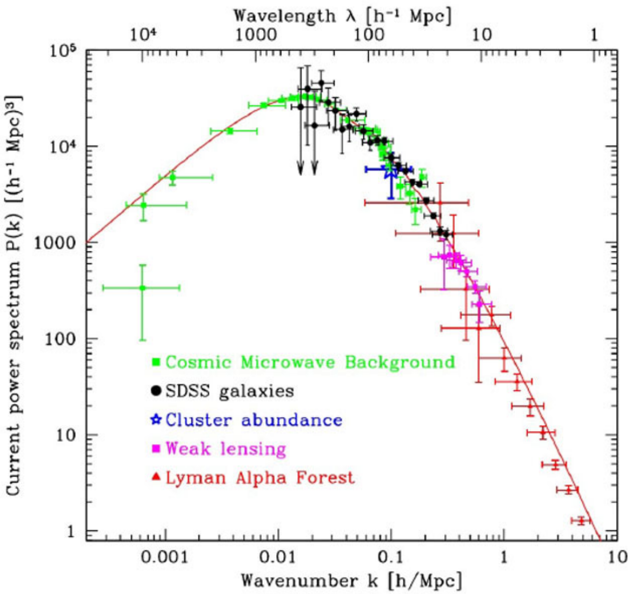
Galaxy clustering

- Similar to the CMB, galaxy redshift surveys can be analysed by a *power spectrum* (this time, in 3D)

Galaxy distribution across the survey (points) → Smoothed into a density field → Converted to a power spectrum







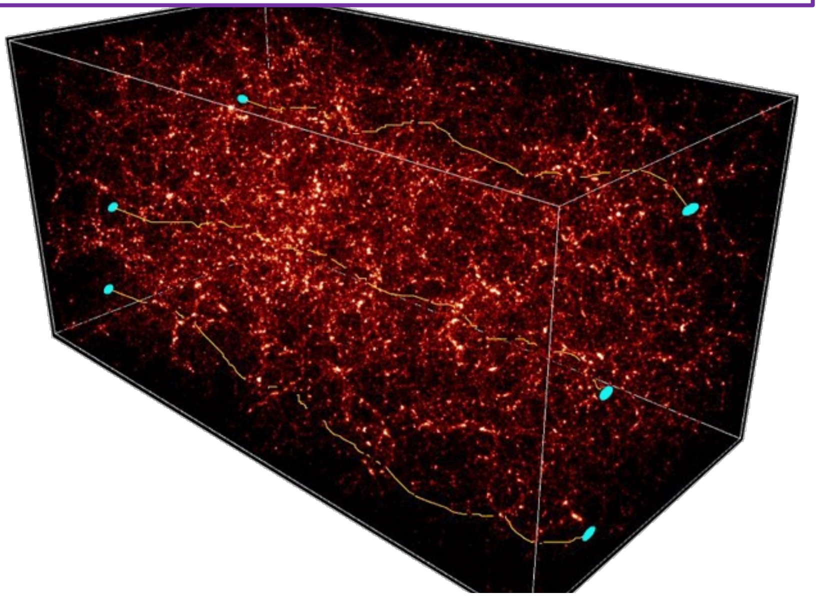
The density field $\delta(x)$ is transformed into a Fourier transform $\tilde{\delta}(k) = \int \delta(x)\, e^{ikx}\, dx$, then a power spectrum $P(k) = \left|\tilde{\delta}(k)\right|^2$

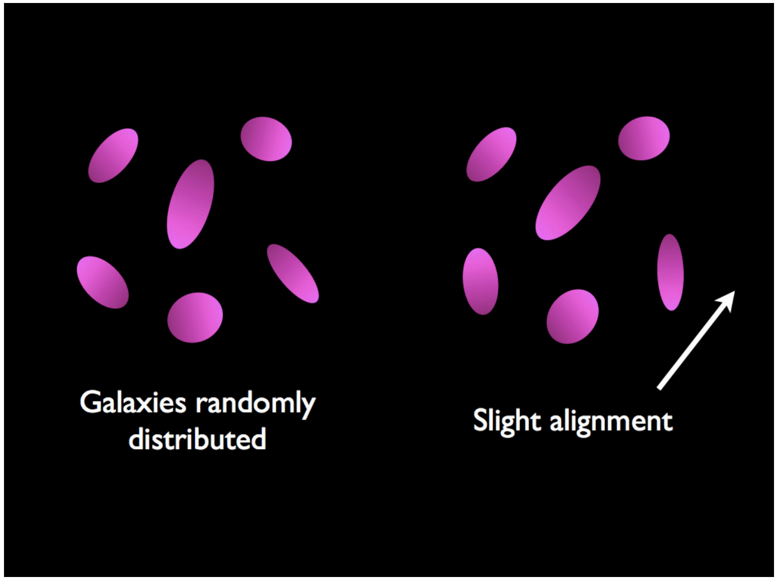
Gravitational lensing

- Another of today's most important cosmological probes is *weak gravitational lensing* or *cosmic shear*

Light rays experience deflections as they travel through the Universe

These deflections cause the shapes of background galaxies to slightly align

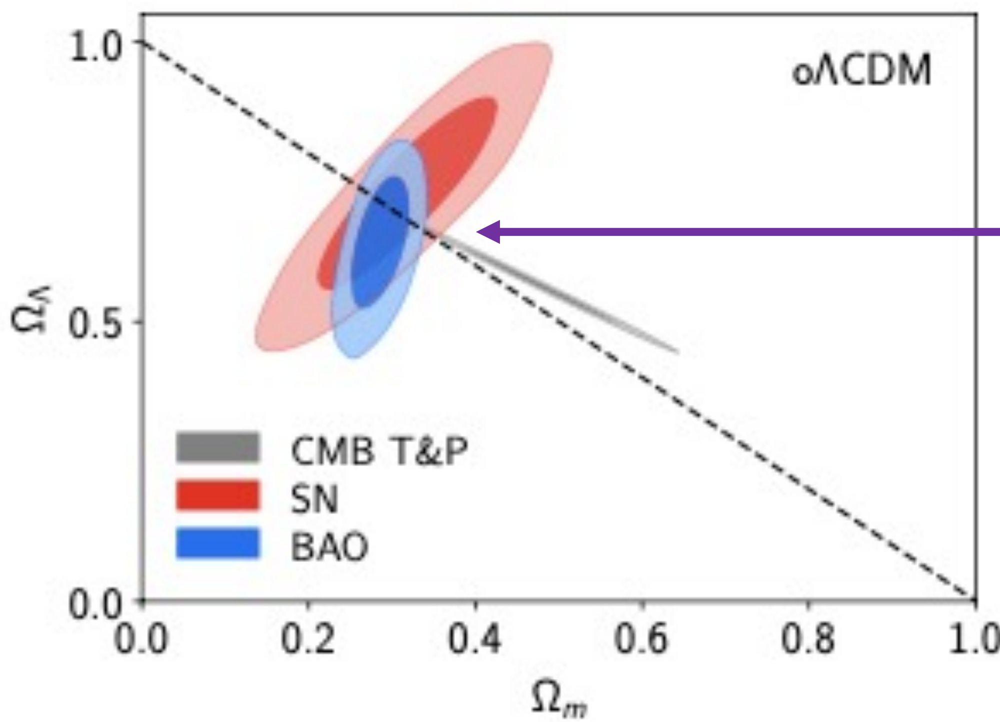




Gravitational lensing can be used to trace the matter power spectrum, distance-redshift relation, growth of structure and gravitational physics

Summing up

- On the one hand – different types of observations generally agree that the *"ΛCDM model" is a good description of the Universe*



Analyses of data from …

- Cosmic Microwave Background Temperature & Polarization (**CMB T&P**)
- Supernovae (**SN**)
- Acoustic Oscillations (**BAO**)

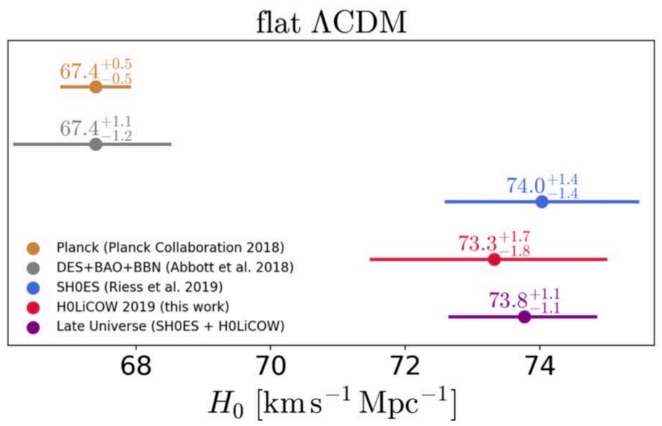
… all intersect in a model with $\Omega_m \approx 0.3, \Omega_\Lambda \approx 0.7$

Summing up

- On the other hand – there are several *significant disagreements regarding the precise details!*

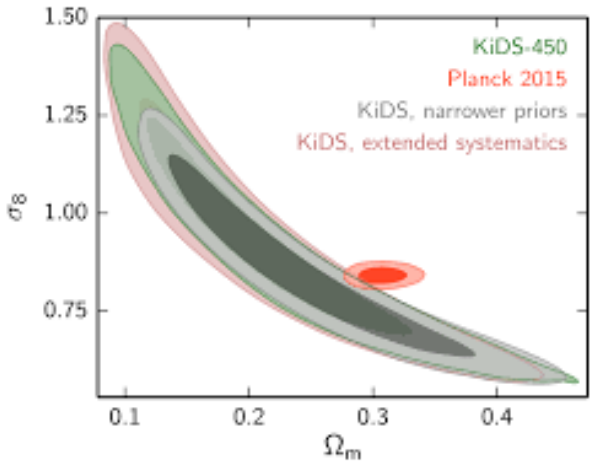
The Hubble tension

Local distance indicators measure a higher Hubble constant ($H_0 \approx 74$) than the value inferred from the CMB ($H_0 \approx 67$) !



The growth tension

Gravitational lensing measures that the Universe is "less clumpy" (lower Ω_m, σ_8) than is inferred from the CMB



Summing up

- Although we've made amazing progress in identifying the cosmological model, there's a lot of work to do!
  - What is the *true nature of dark energy*, and is its equation of state really a constant $w = -1$?
  - What is the *true nature of dark matter*?
  - What *caused inflation* in the early Universe?
  - What is the *true value of Hubble's constant*, and why do measurements from local distance indicators disagree with the value inferred from the CMB?

Key take-aways

- Type Ia supernovae constitute a **standardizable candle** for cosmology that can be used to determine Hubble's constant and the density parameters
- Sound waves propagating in the early Universe imprint **acoustic peak signatures** in both the CMB and the galaxy distribution, which may be used as a standard ruler
- **Galaxy redshift surveys** and **weak gravitational lensing** surveys are important probes of structure in the Universe
- Although the ΛCDM model constitutes a good description of all these datasets, **important discrepancies remain** such as the Hubble tension and growth tension