Cosmological Observations

Cosmological probes

The main steps needed to constrain a cosmological model are:

step 1: construct a **theoretical model**

step 2: **compute a cosmological function** from the theoretical model:
(most of what we have been studying in this course fits in this step)

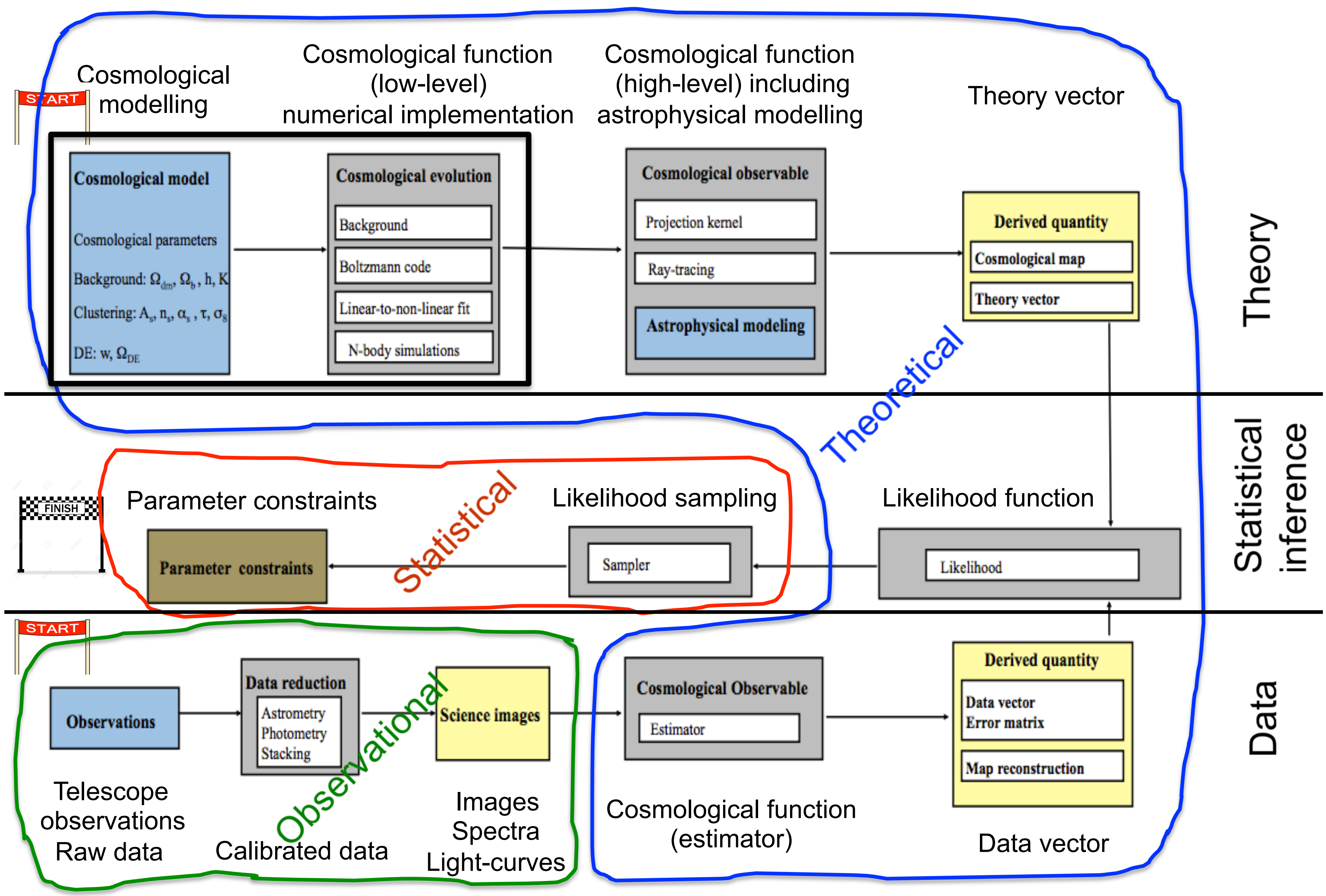
step 3 - **detect a sample** of astrophysical objects and **measure an observable**

step 4 - measure the sample **redshifts**

step 5 - **estimate the cosmological function** from the observations: by defining an estimator, which has S/N and bias properties

step 6 - **estimate the parameter values** by comparing the measured physical property with the one computed with the theoretical model: inference

step 7 - test the validity of the theoretical model by **analysing its goodness-of-fit:**
model evidence



Cosmological modelling
Cosmological function (low-level) numerical implementation
Cosmological function (high-level) including astrophysical modelling
Theory vector
START
Cosmological model
Cosmological parameters
Background: Ω_{dm}, Ω_b, h, K
Clustering: A_s, n_s, α_s, τ, σ_8
DE: w, Ω_{DE}
Cosmological evolution
Background
Boltzmann code
Linear-to-non-linear fit
N-body simulations
Cosmological observable
Projection kernel
Ray-tracing
Astrophysical modeling
Derived quantity
Cosmological map
Theory vector
Theory
Theoretical
FINISH
Parameter constraints
Parameter constraints
Statistical
Likelihood sampling
Sampler
Likelihood function
Likelihood
Statistical inference
START
Observations
Data reduction
Astrometry
Photometry
Stacking
Observational
Science images
Cosmological Observable
Estimator
Derived quantity
Data vector
Error matrix
Map reconstruction
Data
Telescope observations Raw data
Calibrated data
Images Spectra Light-curves
Cosmological function (estimator)
Data vector

The procedure connects theory with observations.

Theoretical side:
We need to consider **cosmological functions** that are model-dependent and that are possible to compute as function of the cosmological parameters (i.e. they carry cosmological information).

Examples**:** **distances**; **volume**; **correlation functions**; **power spectra**

Observational side:
We need to define observables from which the cosmological functions can be measured.

Observing the Universe

Probes of geometry

In the **homogeneous** universe
(populated with ‘test particles’ or ‘tracers’)
possible **observables** are

redshift (of sources in the sky)
(with spectroscopy or with
photometry + SED templates)

angular separation between 2 points in
the sky

flux (from sources)

number counts (of sources)

Probes of structure

In the **inhomogenous** universe
(with a spatial distribution of
large-scale structures)
possible **observables** are

map of CMB temperature

map of CMB polarization

map of galaxy positions

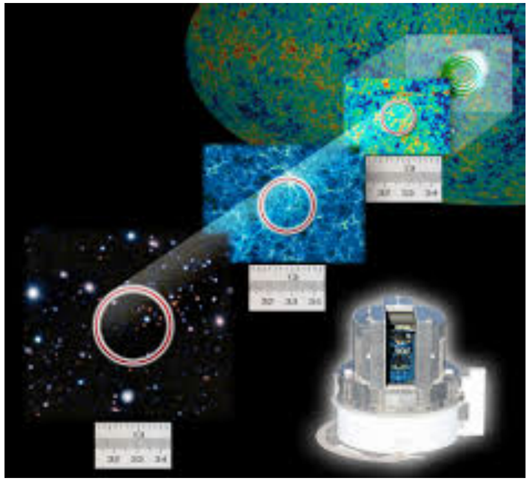
map of galaxy shape distortions

map of galaxy velocities

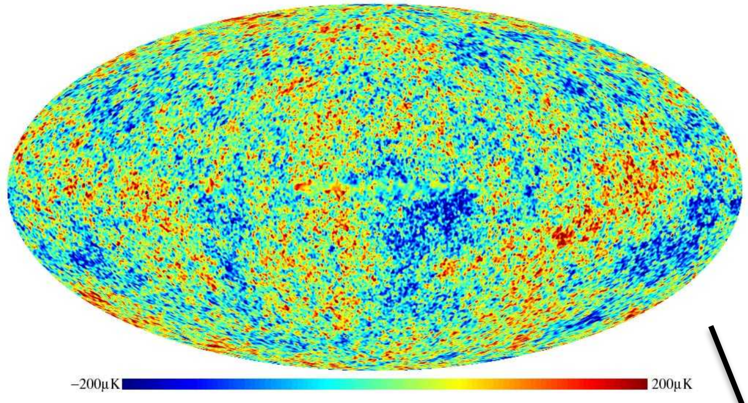
map of HI clouds

Measuring the Universe

Probes of geometry

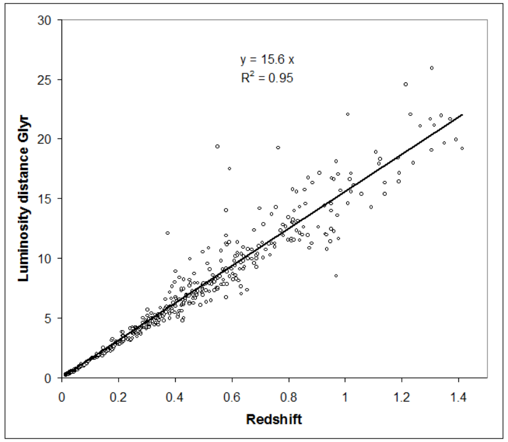


Probes of structure



observables

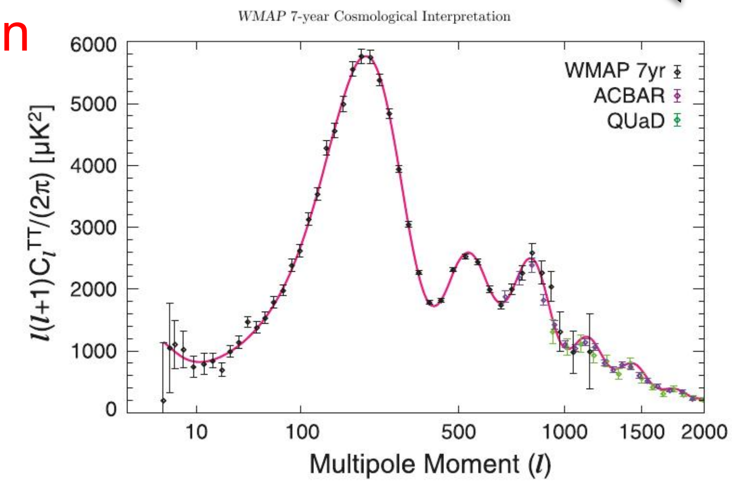
cosmological function



e.g. Distance (z)

Ω_i, w_i, H_0

Ω_i, w_i, H_0,
n_s, σ_8, τ_{re}



e.g. Clustering (r)

Let us now go through the steps:

step 1 - Theoretical model
step 2 - Model predictions

step 3 - **Define a useful sample and observable**

There is a type of sources that is very useful to build observables: sources with a universal feature across their population: known as **standard sources**.

Standard sources are useful in cases where the cosmological function can be measured from a relation between an observable and a (non-cosmological) physical property of the observed sources. In that case, it is useful that the physical property is known in advance in a cosmological model-independent way.
(However, if that is not possible, that property can usually also be estimated from the observations).

They are mainly used with the cosmological probes of geometry (to estimate the parameters of the homogeneous universe)

There are various types of standard sources:

Standard Candles - sources with universal luminosity

An example are the **supernovae** (however they are not exactly standard but can be standardized)

a good observable to use is the **magnitude**:

magnitude (measured) + luminosity (known) → **luminosity distance**

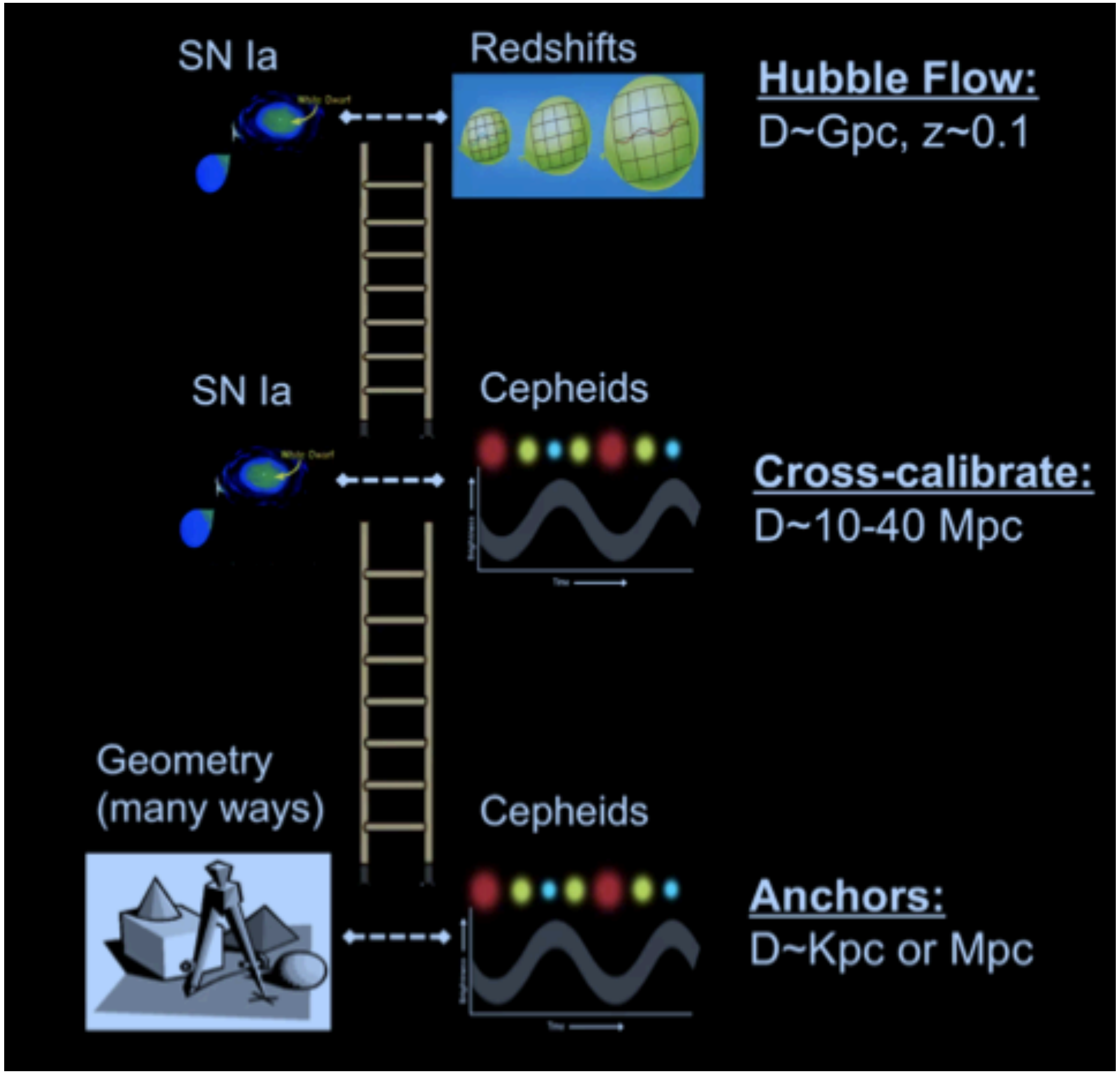
+ z (measured) → **D_L (z; parameters)** from observations

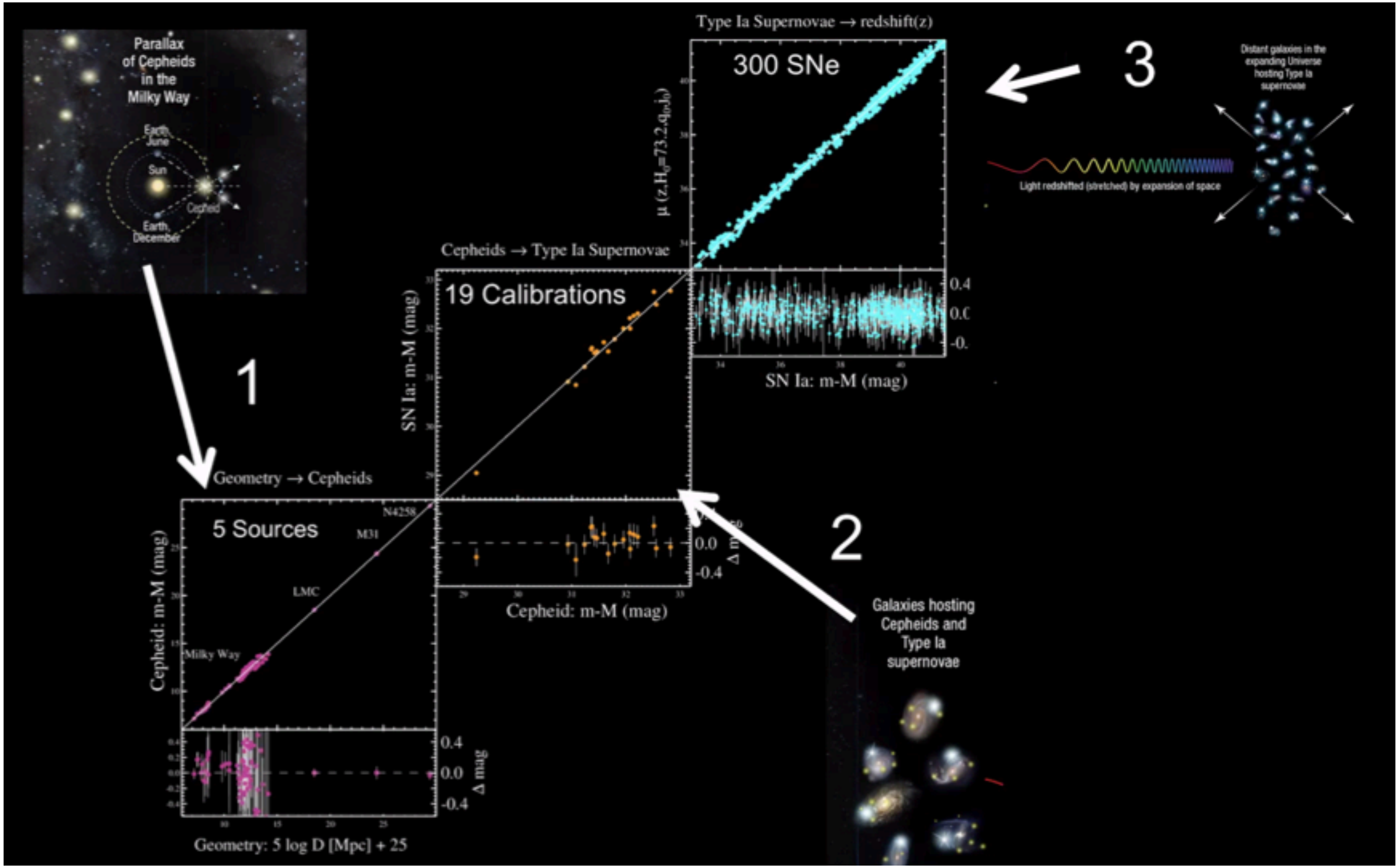
Observationally → magnitude measured from flux

Theoretically → need to obtain the absolute magnitude (the physical property) and to computethe cosmological function

D_L (z; parameters) (it is an integral of H(z) from z = 0 to z_s)

The **standard property** (the SN luminosity) is determined by observing SNe in nearby galaxies with known distances → the method includes a **model-independent calibration** procedure: the **distance ladder.**





Parallax of Cepheids in the Milky Way
Earth, June
Sun
Cepheid
Earth, December
1
Geometry → Cepheids
5 Sources
N4258
M31
LMC
Milky Way
Cepheid: m-M (mag)
Δ mag
Geometry: 5 log D [Mpc] + 25
Cepheids → Type Ia Supernovae
19 Calibrations
SN Ia: m-M (mag)
Cepheid: m-M (mag)
2
Galaxies hosting Cepheids and Type Ia supernovae
Type Ia Supernovae → redshift(z)
300 SNe
SN Ia: m-M (mag)
3
Distant galaxies in the expanding Universe hosting Type Ia supernovae
Light redshifted (stretched) by expansion of space

Another example of standard candles are the **gamma-ray bursts** (GRB)

The amplitude of the peak of the emission was found (empirically) to be strongly correlated with the isotropic intrinsic emission → **this relation may be used to calibrate their luminosities**.

$$\log E_{\mathrm{p,i}}(\mathrm{keV}) = m \log E_{\mathrm{iso}}(10^{52}\mathrm{erg}) + q$$ (Amati relation)

Luminosity + **magnitude** + z → **Distance** (z)

GRB could be used to measure distances to high-redshift (z~8)

Standard Rulers or standard rods - sources with universal size

Example of a standard ruler is the **sound horizon**, such as the **BAO scale** (**baryon acoustic oscillations**) and the **CMB 1st peak**

a good observable to use is the **angular size:**

r_angular (measured) + r_physical (known) → **angular diameter distance**

+ z (measured) → D_A **(z ; parameters)**

Observationally → the angular sizes are measured from the multipole where the peak appears in the power spectrum.

Theoretically → need to compute the physical sizes (are horizons and thus can be computed from H(z)) and the cosmological functions $D_A(z)$

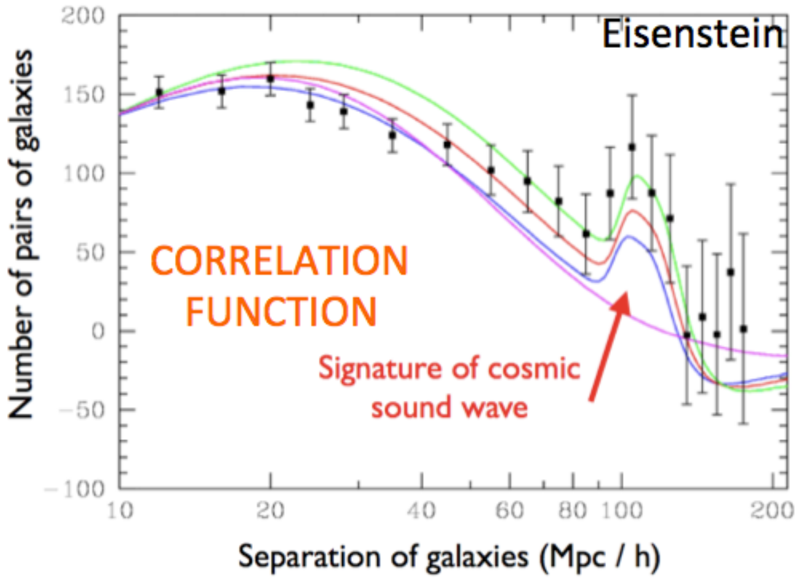
Notice that here the **standard property** (the sound horizon size) is computed in a **cosmological model-dependent** way.

Other (older) examples of standard rulers are the average separation of galaxies in a cluster, or the separation of radio lobes - however, these methods are dominated by the evolution of the sources and not by the cosmological dependence.

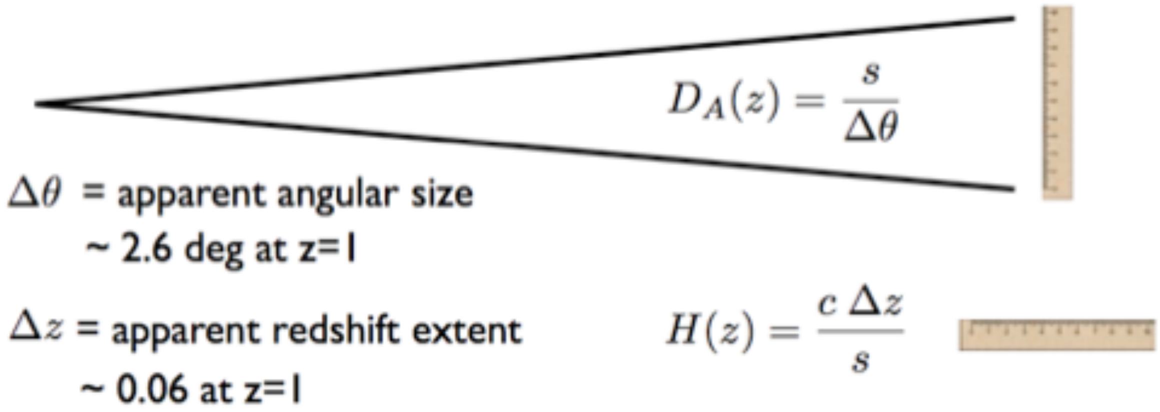
The BAO peak is a standard ruler

(an object for which we know the intrinsic size, so observing its apparent size, gives us the distance)

Using samples of galaxies at different redshifts we can detect the peak at different angular separations and obtain independent data points.
This allows us to get higher-precision results.



Also notice that, because the sound wave propagated isotropically, we can measure the peak at different directions, i.e., we can look for excess correlations in the 3D space around each galaxy → **BAO is a standard ruler in 3D**



if there is a galaxy at z=1.00, there is a high probability of finding another one at z=1.06

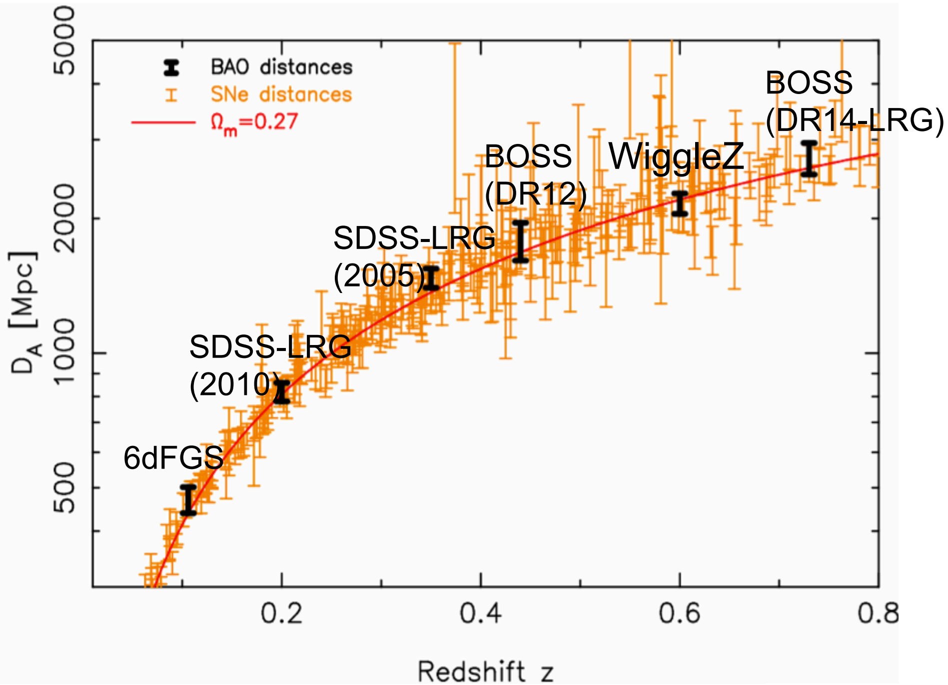
Just like the diameter angular distance is the radial distance that multiplies the angular separation to get the physical size, the physical size can also be obtained by multiplying a redshift separation by a Hubble radius (another “type of triangle”).

A combination of $D_A(z)$ and $H(z)$ defines the radial distance appropriate to multiply a 3D dimensionless separation (combination of angular and redshift separations): this is called the volume distance D_V (with two parts angular and one part radial)

$$D_V(z) = \left[(1+z)^2 D_A(z)^2 \frac{cz}{H(z)} \right]^{1/3}$$

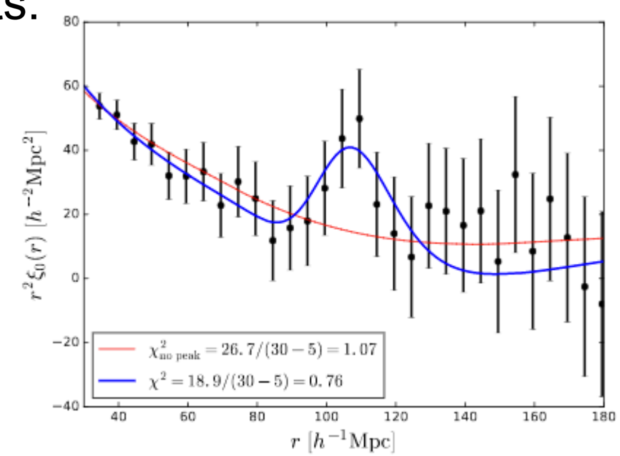
D_V (z, par) * dimensionless separation (measured) = physical size (z, par)

There are much less BAO (angular diameter distance) measurements than SN (luminosity distance) measurements, which is currently the main cosmological probe of the background Universe



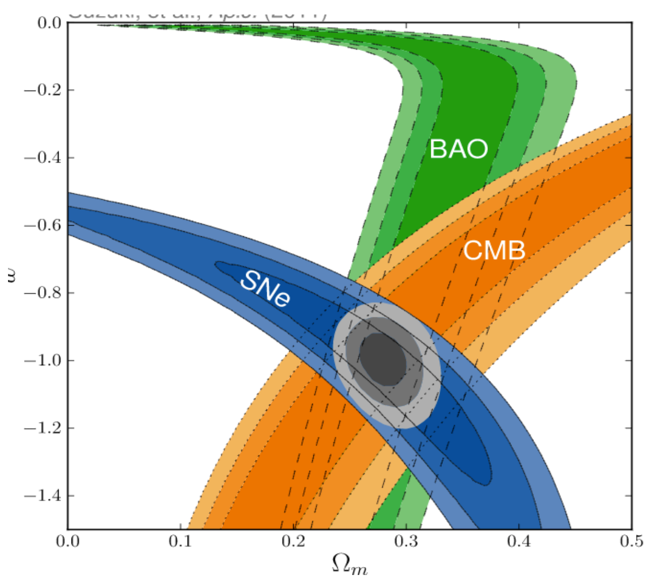
but BAO is a promising method with several strong points:

- BAO error bars are much smaller than for SN, because each data point is obtained from the correlation function measured for order 10^4-10^5 galaxies - higher precision



- BAO and SN are not affected by the same systematics, do not suffer from the same biases → provide independent tests

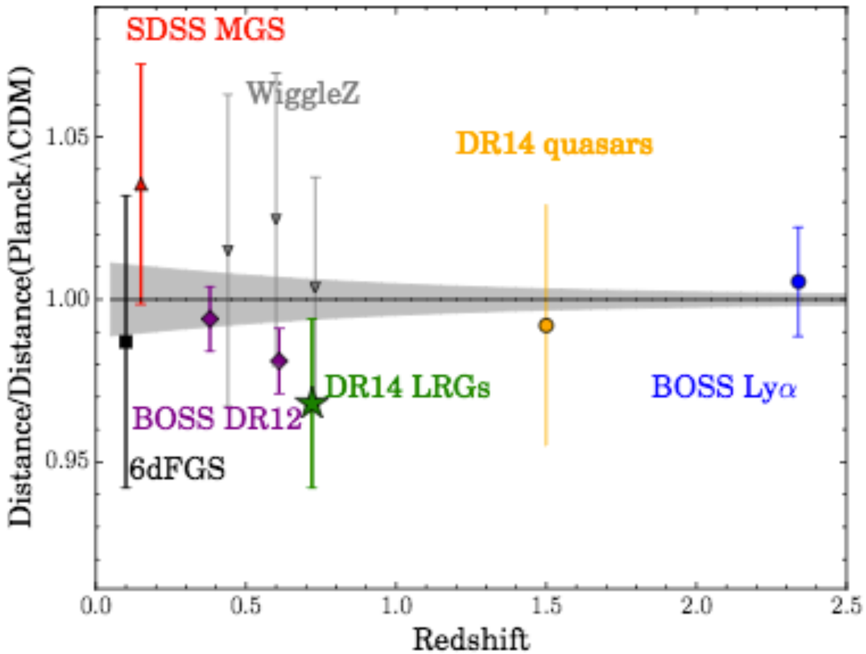
- they probe a different combination of distances → constrain different combinations of the cosmological parameters - complementarity.



- BAO can probe higher redshifts than SN: SN cannot be detected in very distant galaxies, while the matter power spectrum can be measured from a large variety of astrophysical samples:

the BAO peak was already detected at higher-z

i) in the power spectrum of quasars;
ii) in the power spectrum of molecular clouds that are detected because they leave absorption lines in the spectra of background quasars (the Lyman-alpha forest method)



Standard Spheres - sources with universal shape

Standard spheres are large expanding regions that we believe are intrinsically spherical because of isotropy (no prefered directions, so no prefered alignment with our line-of-sight).

Examples are: **Voids,** and Large **absorption regions** in front of quasars (**Lyman-α forest**).

a good observable to use is the **size ratio:**

r_angular $\delta\theta$ (measured) + r_physical transverse (unknown) → distance

r_radial δz (measured) + r_physical longitudinal (unknown) → distance

Take the ratios

$\delta\theta / \delta z$ (measured)

+ z (measured) → **D (z ; parameters) / H (z; parameters)**

Notice that the ratio allows us to cancel-out the dependence on the physical property (the sizes o the regions) and the method gives directly the cosmological function D/H. This ratio method is called the **Alcock-Paczynski test.**

Standard Populations - sources with universal comoving density

a good observable is the **number counts**

N (measured) in a volume (angular extension and z extension)

+ N (known) → physical volume

+ z (measured) → **V (z ; parameters)**

Observationally → N observed in the defined volume.

Theoretically → need to compute the physical volume (can be computed from H(z) and D_A(z)), and know the standard N value

A cluster sample is a standard population

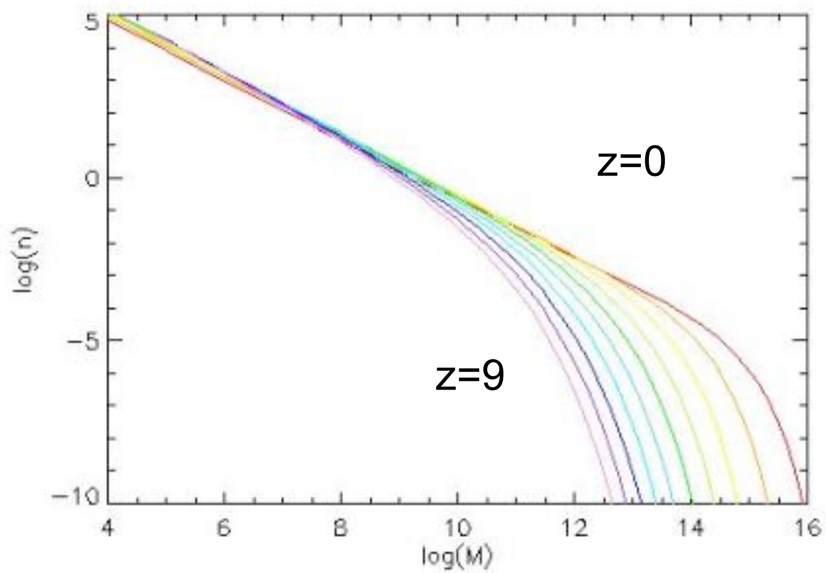
The mass function provides the model-dependent number density of cluster halos → comparing with the observed **cluster abundance** allows us to constrain the cosmological parameters → it is a **cosmological probe** of structure formation.

This probe is mainly sensitive to:

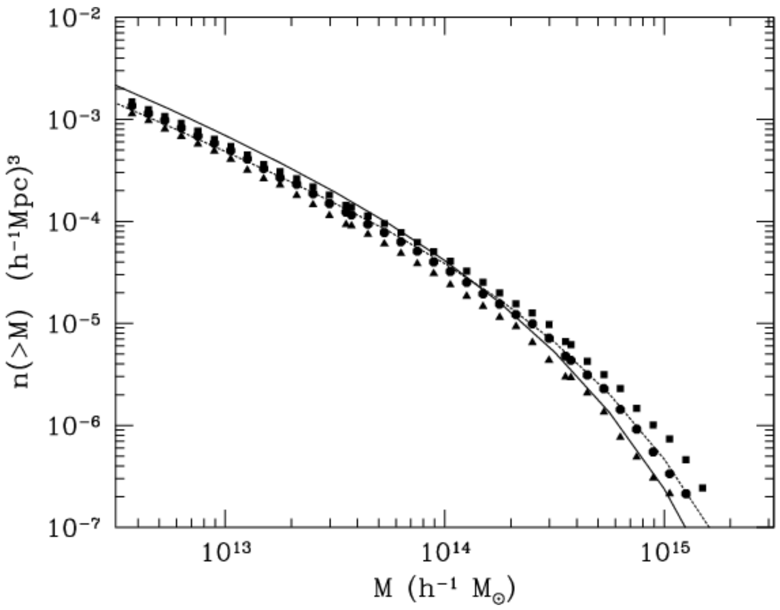
- Ω_m
- linear power spectrum at z=0 → from which we can compute σ for each scale M (or R)
- δ_c (t): $\delta_c = 1.68 / D(t)$ → it increases with z

The general behaviour of the mass function dn(M,z) is to

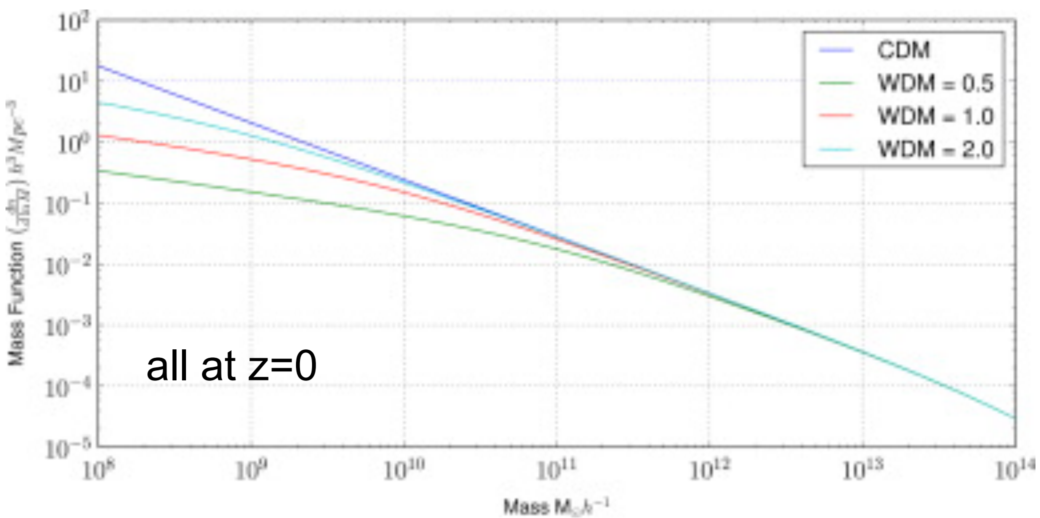
- **decrease with mass** (larger scales have smaller σ, i.e., smaller amplitude of the power spectrum)
- **decrease with redshift** (larger δ_c threshold at higher z, meaning there are less collapsed structures then)



Cluster abundance measurements



allow us to constrain the cosmological model when comparing with the models predictions for the theoretical mass function



Standard Sirens - sources with universal GW frequency and phase

An example is a binary system of coalescing massive black holes **MBHB**
(however they are not standard but may be theoretically modelled → **templates**)

the observable is the **amplitude of the gravitational waves**

Amplitude in the 2 polarizations (measured with 2 detectors)

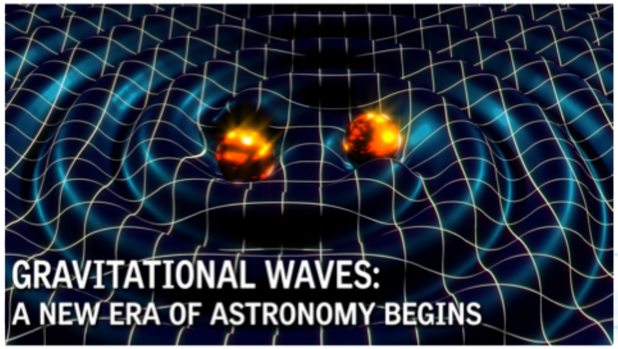
+ frequency and phase (fit from templates)

+ position and orientation (from measurements at different points of the orbit)
→ distance and mass_z

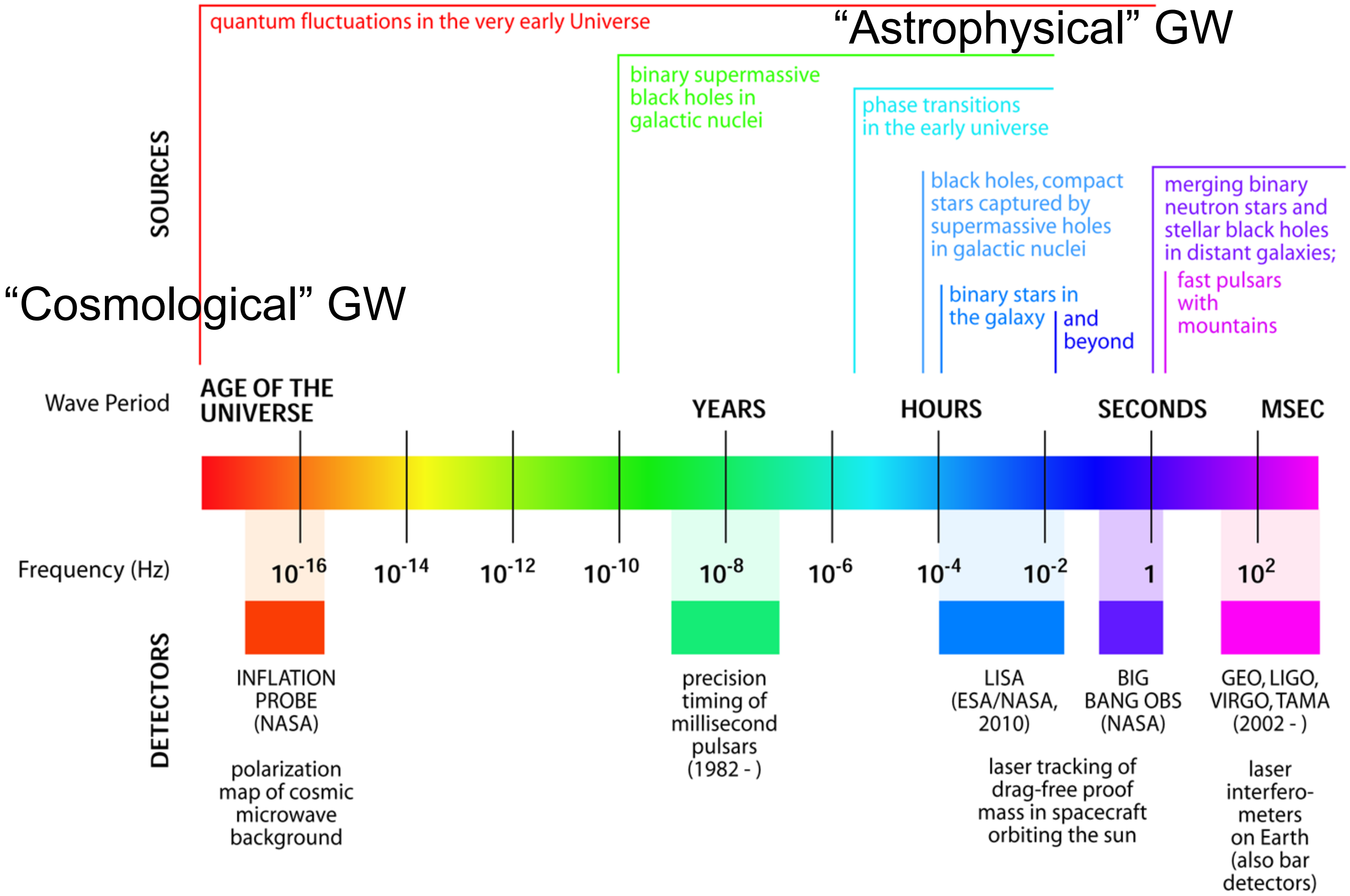
+ z (measured from counterparts) → **D (z ; parameters) and mass**

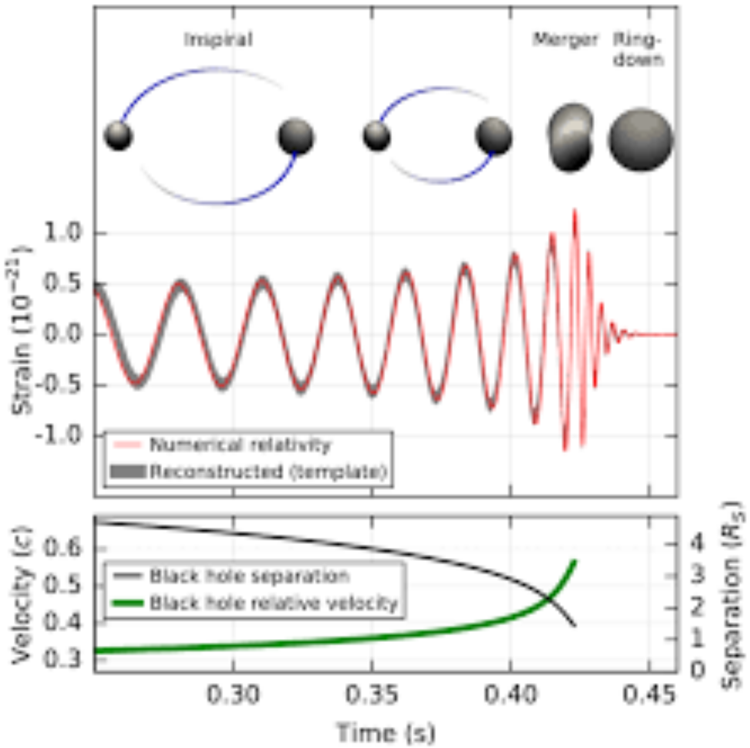
Observationally → wave properties

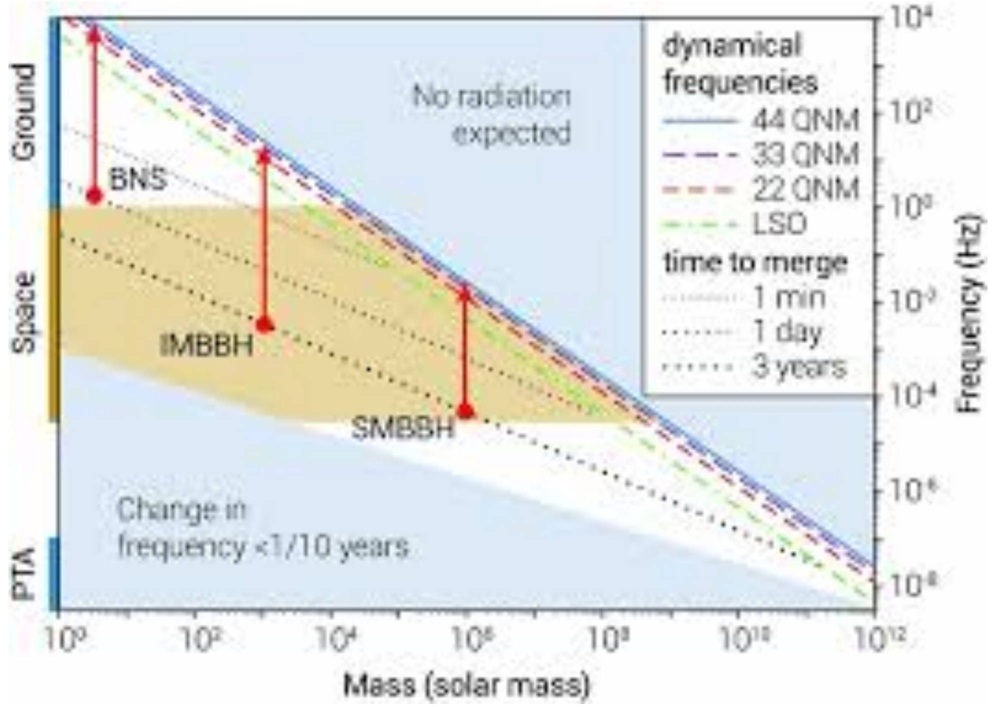
Theoretically → need to compute the wave properties from a cosmological model-independent template, and the cosmological function D(z)

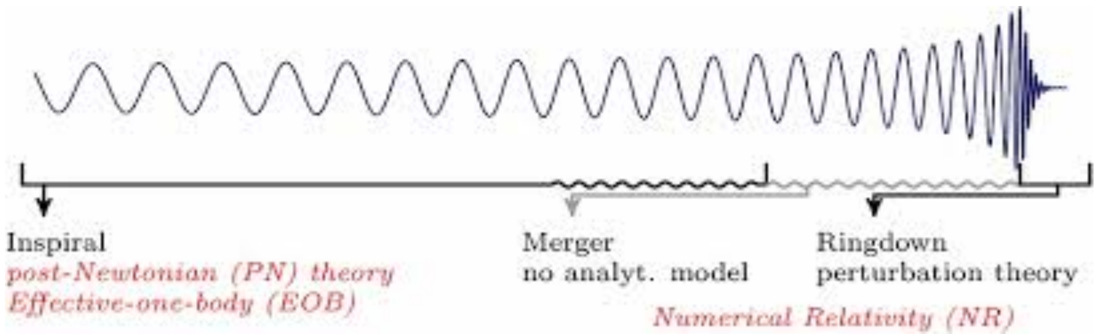


GRAVITATIONAL WAVE SPECTRUM




Inspiral
Merger
Ring-down
Strain (10^{-21})
Numerical relativity
Reconstructed (template)
Velocity (c)
Separation (R_S)
Black hole separation
Black hole relative velocity
Time (s)


Ground
Space
PTA
No radiation expected
BNS
IMBBH
SMBBH
Change in frequency <1/10 years
dynamical frequencies
44 QNM
33 QNM
22 QNM
LSO
time to merge
1 min
1 day
3 years
Mass (solar mass)
Frequency (Hz)


Inspiral
post-Newtonian (PN) theory
Effective-one-body (EOB)
Merger
no analyt. model
Ringdown
perturbation theory
Numerical Relativity (NR)

$$h_+ = \frac{2\mathcal{M}_z^{5/3}[\pi f(t)]^{2/3}}{D_L}\left[1 + (\hat{L}\cdot\hat{n})^2\right]\cos[\Phi(t)] \ ,$$

$$h_\times = \frac{4\mathcal{M}_z^{5/3}[\pi f(t)]^{2/3}(\hat{L}\cdot\hat{n})}{D_L}\sin[\Phi(t)] \ .$$

h - amplitude of the 2 components (strain) - observed and computed from GR (post-Newtonian PN analytical perturbation theory, numerical relativity, weak-field limit cosmological tensor perturbations)

f - frequency

Φ - phase

n - position vector

L - orientation (angular momentum)

Many parameters to fit simultaneously → large degeneracies

position and orientation - in space observations (LISA) get it from measurements from different points of the orbit - many data points during the merging time

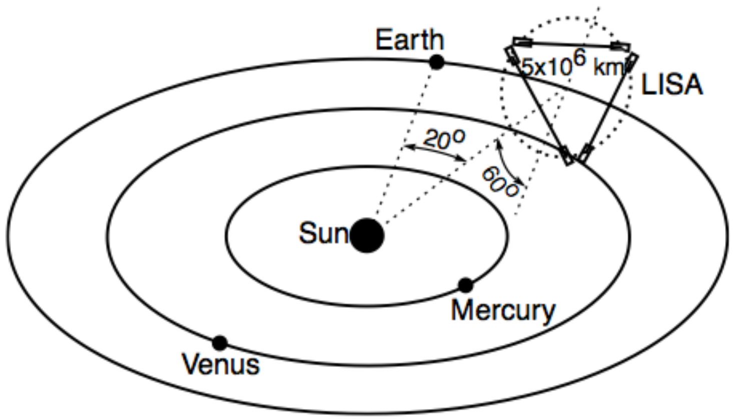
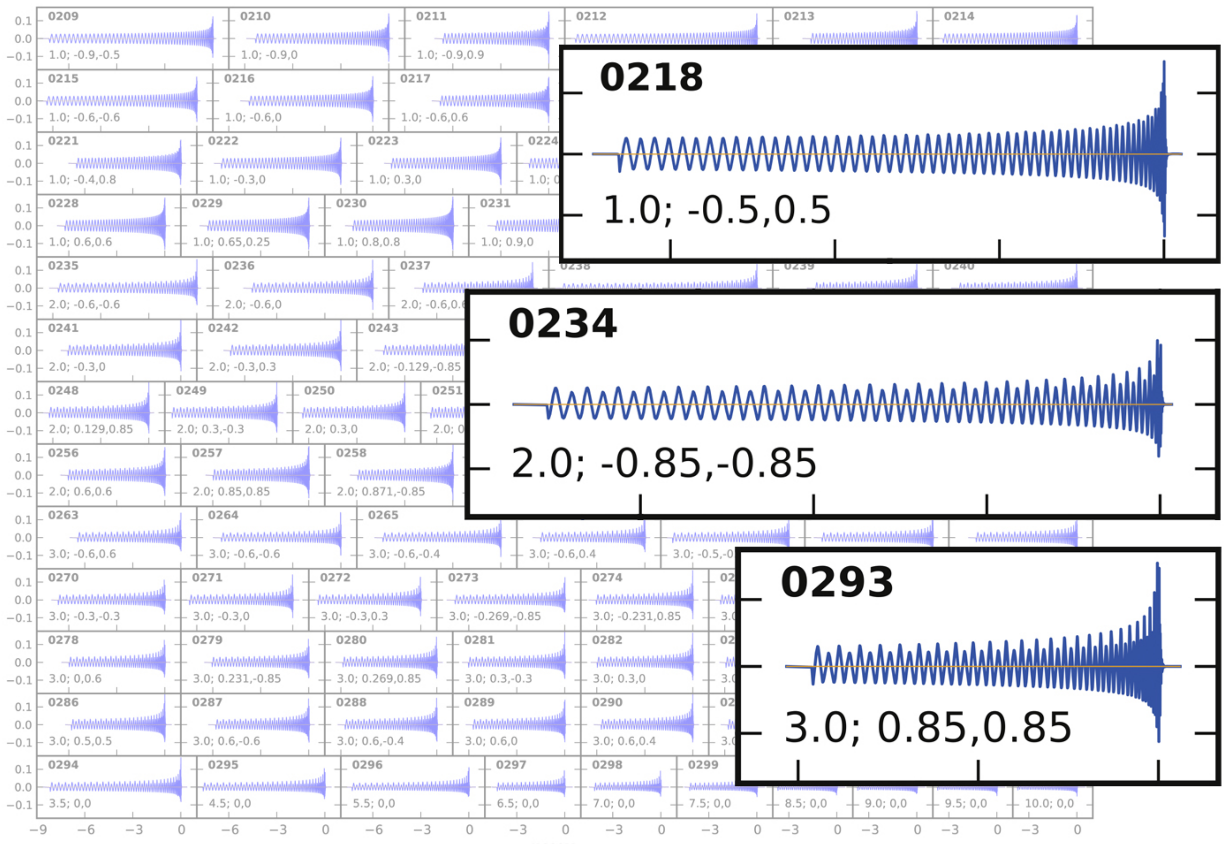


FIG. 1.— Illustration of the *LISA* antenna's orbit. The constellation "rolls" as its centroid orbits the sun, completing one full revolution for each orbit.

other wave properties are not measured directly but can be fitted by using theoretical templates

(spin, masses)



the 2 remaining unknowns are D_L and M_z

M_z, the chirp mass, is the effective mass of the binary (times the cosmological degeneracy 1+z)

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}} \, (1+z)$$

There is a mass/redshift degeneracy because the timescale of the orbital movement depends on redshift.→ a local binary with masses $(1+z)m_1$ and $(1+z)\, m_2$ is indistinguishable from a distant binary at z with masses m_1 and m_2.

This test measures D_L but to get the cosmological information from $D_L(z)$ we still need to measure the redshift → need to find the electromagnetic counterpart.

Need to find the source location with good accuracy and then search there for the optical or radio source → measure z as usual

Naturally, not all cosmological probes need to rely on standard sources.
This is usually the case with the **cosmological probes of structure formation**, where the cosmological functions are not distances, but power spectra.

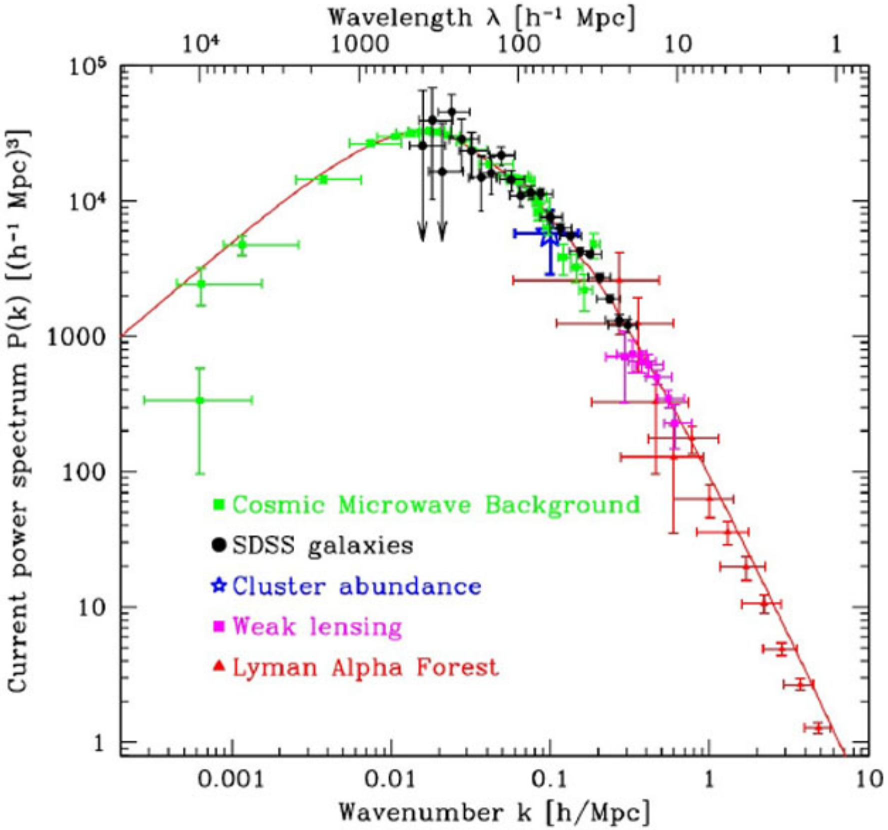
The various probes measure different power spectra, all related with the two fundamental power spectra:

LSS Matter power spectrum → structure in the dark matter density field + effect of baryons (oscillations).
It is a function of redshift.

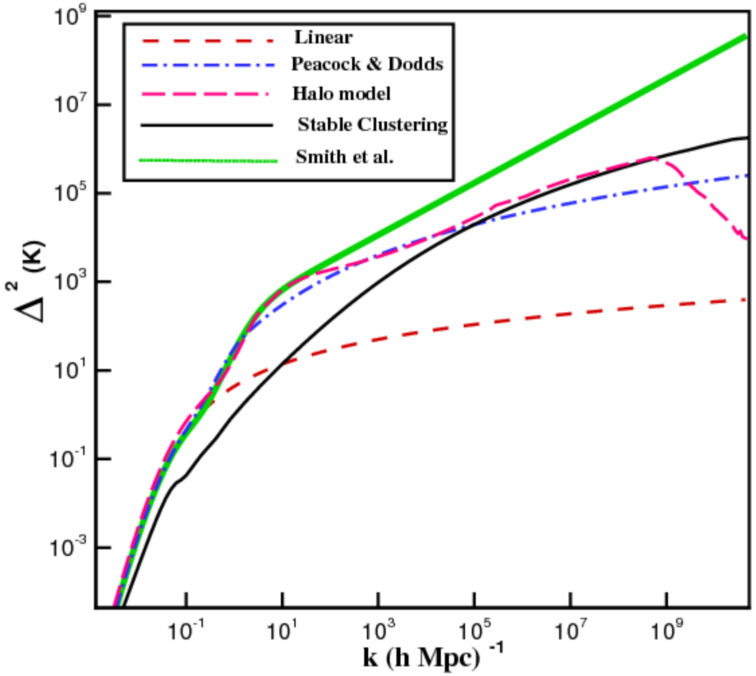
CMB Temperature power spectrum → anisotropy in the cosmological photons temperature field → structure in the radiation/baryon plasma density field.
At a fixed redshift (recombination).

Dark matter power spectrum

P(k)



$\Delta^2(k) \sim k^3\, P(k)$ (dimensionless and also showing non-linear power spectrum)

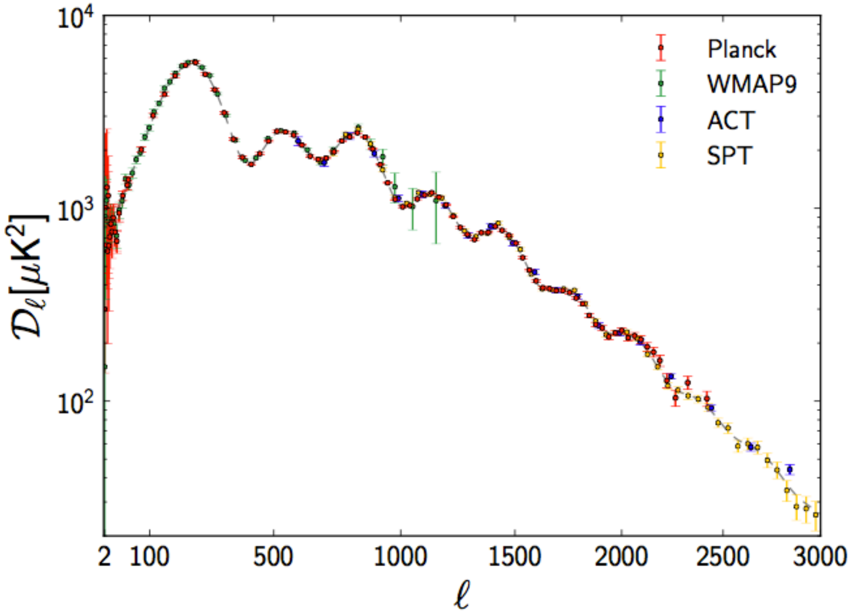


Main feature: large scales grow more than small scales during radiation epoch → change of shape and formation of a peak

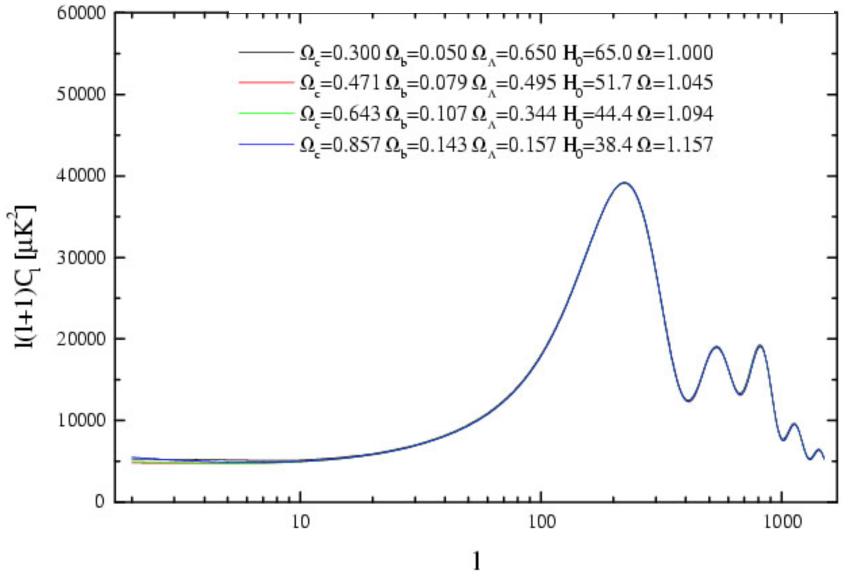
There are many cosmological probes of the matter power spectrum. They use different observables and probe different scales and redshifts.

CMB power spectrum

D(l) = l(l+1) C(l)
(dimensionless and showing a wide range of scales)



D(l) = l(l+1) C(l)
(dimensionless and showing better the larger scales)



Main feature: the baryon/radiation plasma compresses and decompresses → oscillations on scales l > ~200, θ< ~1 deg

There is one cosmological probe of the CMB power spectrum.

These two power spectra that summarize the evolutions of dark matter and baryonic matter perturbations can be **estimated from two fundamental maps in nature:**

map of the spatial distribution of cosmological structures - LSS - (linear and non-linear inhomogeneities in the dark matter density field)

map of the anisotropies of the cosmic background radiation - CMB - (linear inhomogeneities in the plasma density field)

Notice that after decoupling, the baryon inhomogeneities tend to the dark matter ones, and the radiation inhomogeneities tend to zero → ***there are no other independent maps of the density distribution of dark matter, baryonic matter and radiation*** → All maps used in cosmological probes are related to these two.

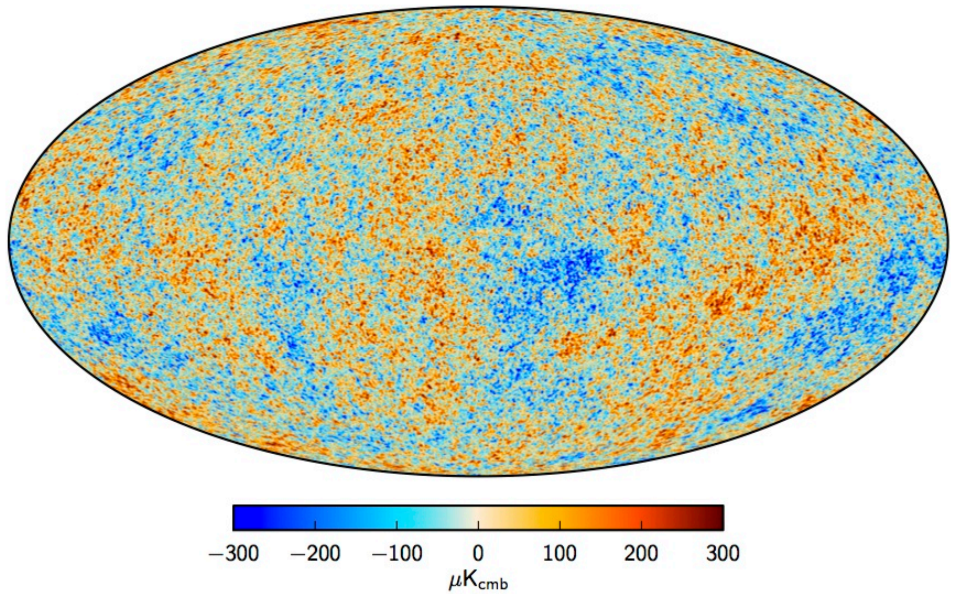
There may be independent maps of other cosmological species (neutrinos, clustering dark energy) - not observed yet.

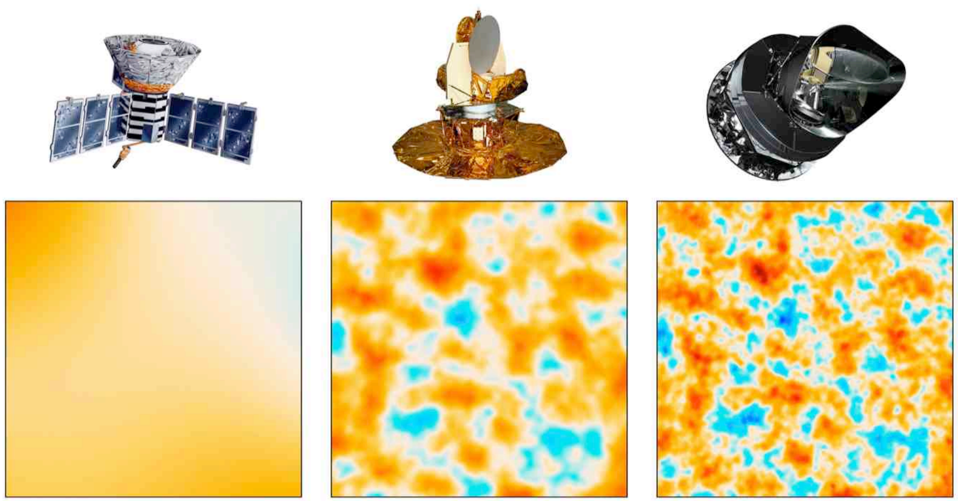
There are various cosmological probes of structure:

Cosmic Microwave Background

Observationally → the **CMB power spectrum** (cosmological function) is estimated from the observed correlation function of the temperature anisotropies δ_T (observable)

Theoretically → need to compute the temperature power spectrum from the plama perturbations





COBE WMAP Planck

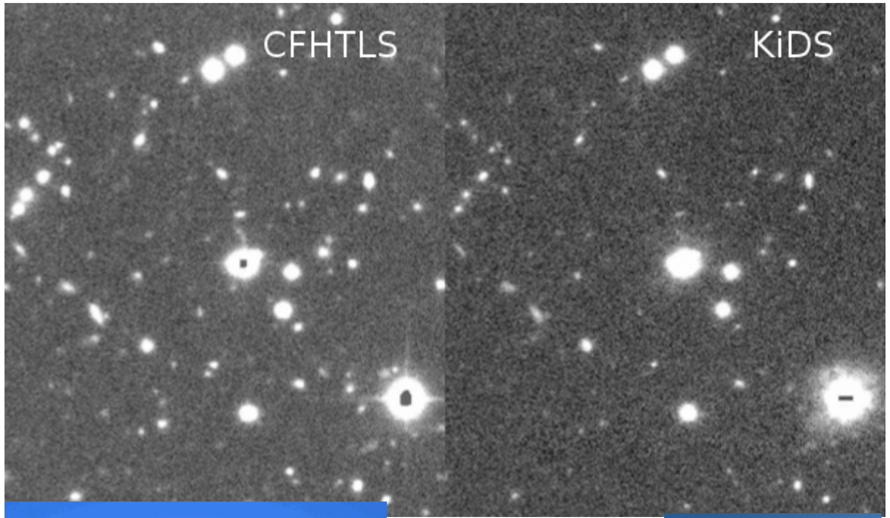
$\delta\_b/r \rightarrow \delta\_T$

The observed δ_T is an unbiased tracer of δ_b/r

Weak Lensing

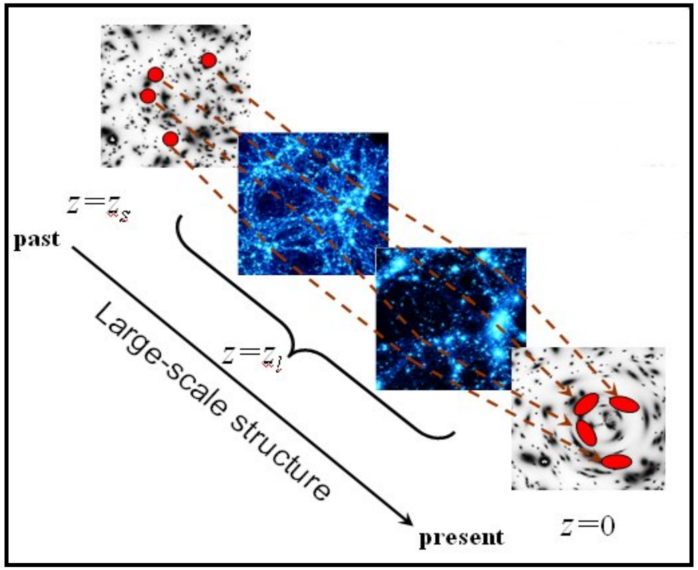
Observationally → the gravitational lensing distortions **shear power spectrum** (measured cosmological function) is estimated from the observed correlation function of galaxies ellipticities (observable)

Theoretically → need to compute the shear power spectrum from the gravitational potential power spectrum that in turn is related with the matter power spectrum



(CFHT)

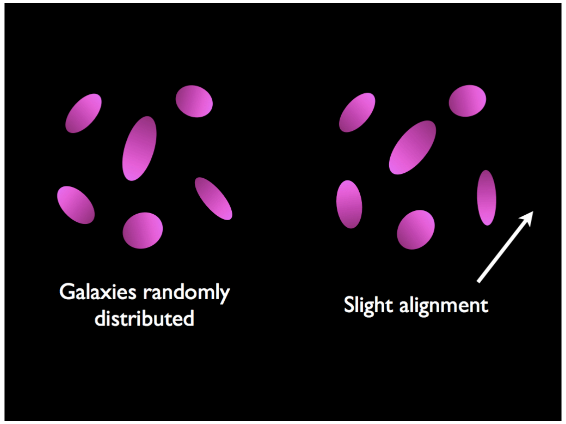
(VST)



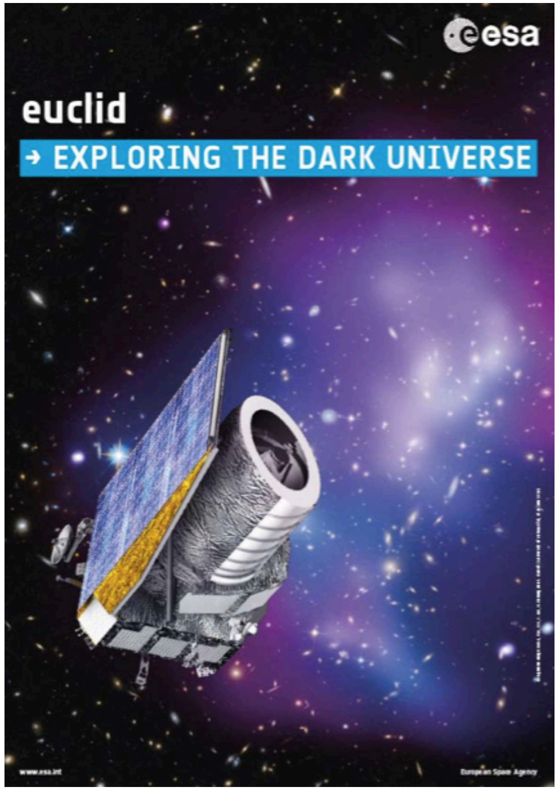
δ_dm → shear γ

It goes from 2D galaxy ellipticities → to 2D correlation function of shear → to 2D correlation function of dark matter

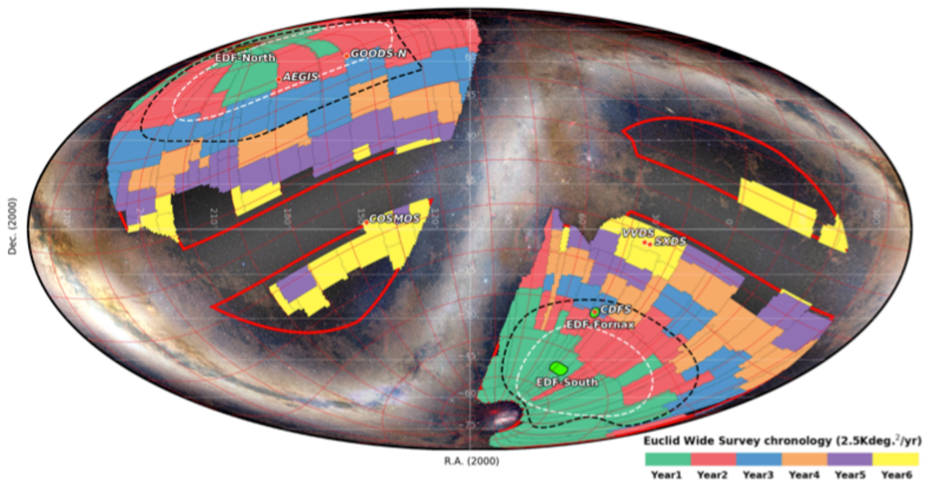
The observed ellipticity correlations are an unbiased measurement of shear correlations if the galaxies are originally randomly oriented.



The observed shear gravitational lensing distortion is an unbiased tracer of δ_dm.



The Euclid mission (ESA) - launch in July 2023 - will bring large-scale structure measurements to the level of precision of Planck CMB measurements

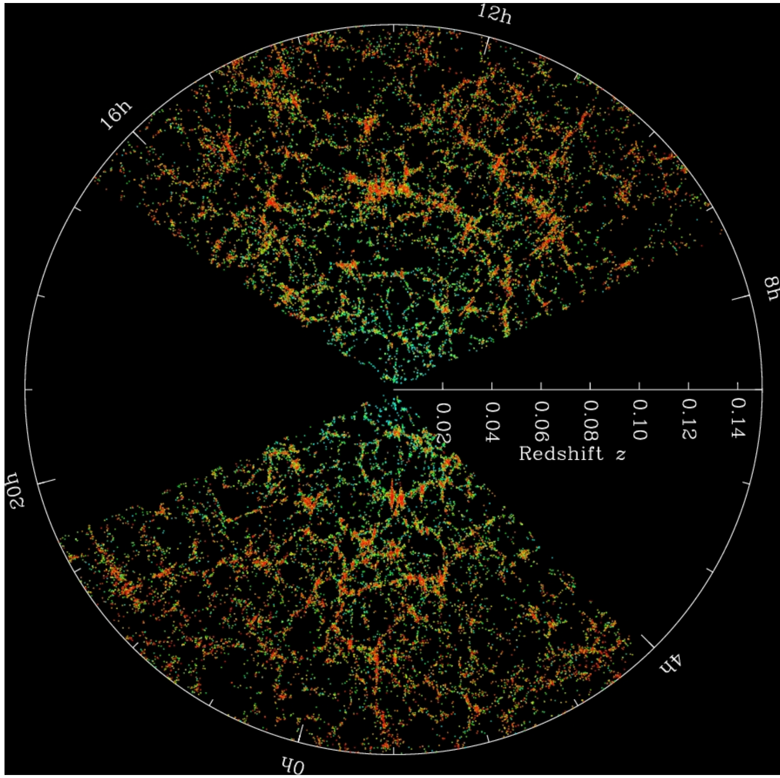


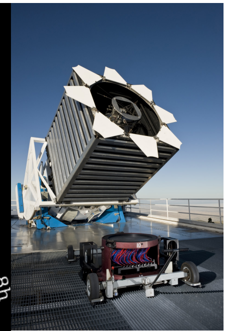
Galaxy Clustering

Observationally →

the **angular correlation function in real space**, the **correlation function in redshift space**, and the **BAO peak** are three cosmological functions measured from the observed spatial distribution of galaxies (observable)

Theoretically → need to compute the matter power spectrum and its BAO peak, and the redshift-space distortions





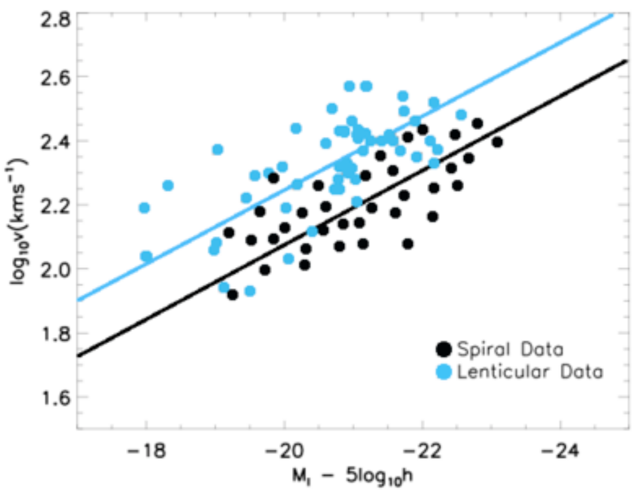
SDSS

$\delta\_dm \rightarrow \delta\_g$

The observed δ_g is a biased tracer of δ_dm,
i.e., light only follows matter in an approximate way.

Peculiar velocity

The **Tully-Fisher relation** is an empirical relation for spiral galaxies between their rotational velocities and luminosity.
(other relations exist for elliptical galaxies)



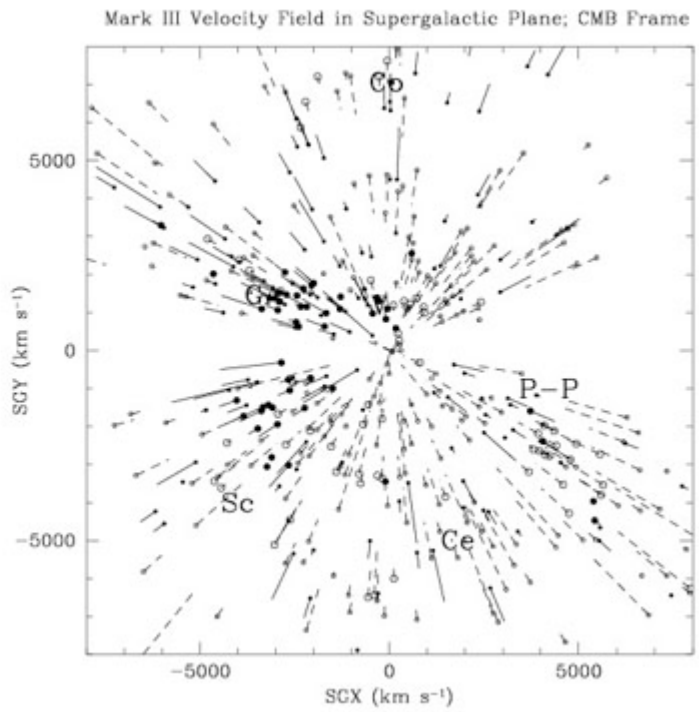
Measuring the rotational velocity → get the luminosity

Measuring the flux → get the distance

Measuring the redshift → get the distance, assuming the galaxy is in the Hubble flow

The two distances are in general different → meaning that the redshift is due to expansion velocity + peculiar velocity

This method allows us to observe a map of peculiar velocities



The **spatial distribution of observed galaxy peculiar velocities** (measured cosmological function) is related with the gravitational potential power spectrum (and the matter power spectrum)

$$
\begin{aligned}
\langle v(\mathbf{r}) v^*(\mathbf{r}) \rangle &= \frac{9H_0^4}{4a^2}\Omega_m^2 \frac{1}{(2\pi)^3} \int_0^{2\pi} \mathrm{d}\phi \int_0^{\pi} \sin\theta \, \mathrm{d}\theta \int_0^{\infty} P_\delta(k) \frac{k^2}{k^2} \, \mathrm{d}k = \\
&= \frac{1}{2\pi^2} \frac{9H_0^4}{4a^2}\Omega_m^2 \int_0^{\infty} P_\delta(k) \, \mathrm{d}k \propto \int_0^{\infty} P_\delta(k) \, \mathrm{d}k \,,
\end{aligned}
$$

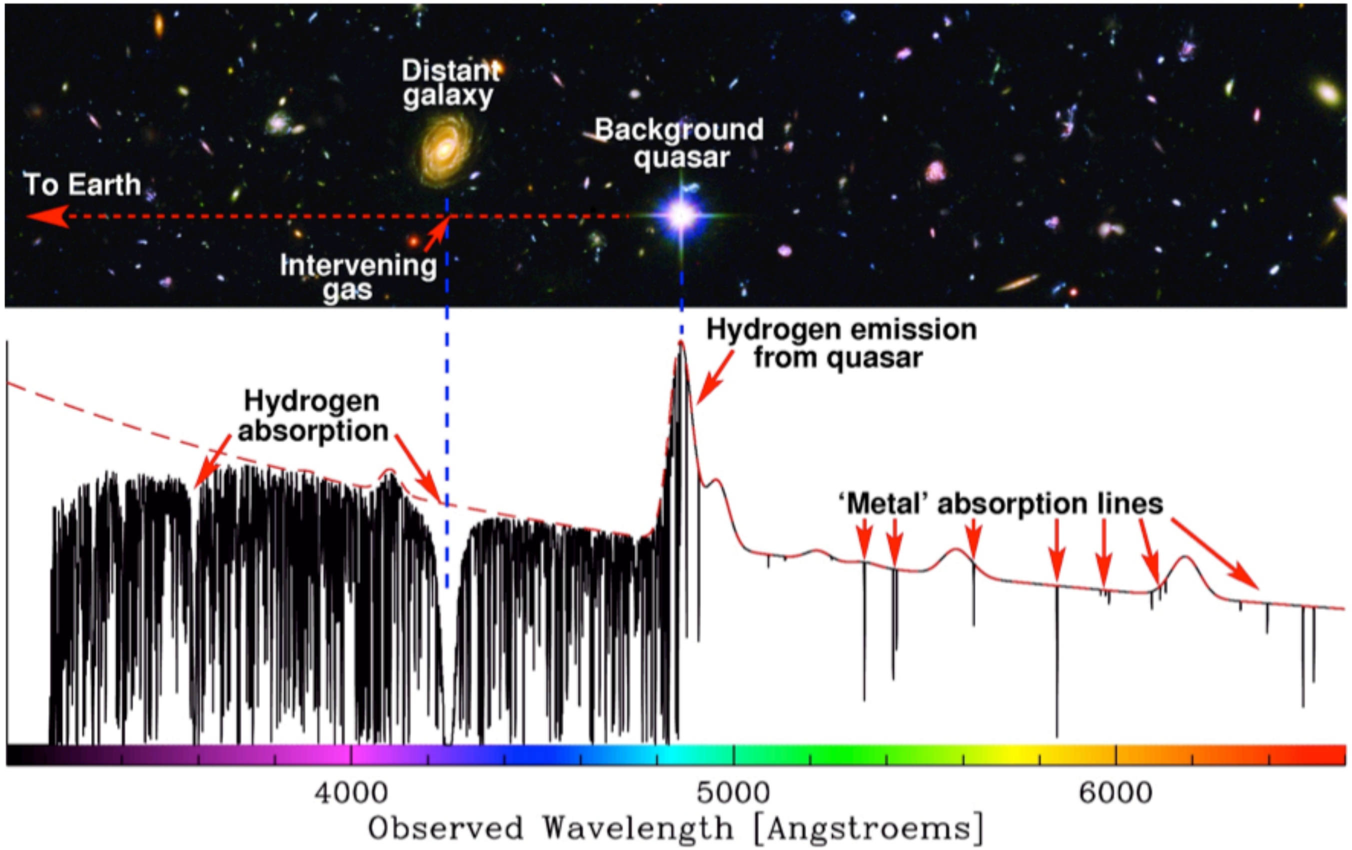
Lyman-alpha forest

observations of **absorption lines in the spectra of quasars** allow us to estimate the **spatial distribution of neutral hydrogen** (measured cosmological function), which relates with the matter power spectrum at high redshift.

Quasars are early galaxies in a time when the universe still has many non-collapsed regions, made of dark matter and neutral hydrogen.

The ionization energy of the neutral hydrogen is 13.6 eV (912 A), the Lyman limit. There is absorption of Ly-alpha (and other Lyman lines emitted by quasars) by the HI clouds (absorbers) → absorption lines in the quasar spectra.

The HI clouds are spread along the line-of-sight at various redshifts → for each redshift the absorption occurs at a different wavelength → ranging from the Ly-alpha rest-frame wavelength 1216 A (due to recent absorption) to the Ly-alpha line observed wavelength 1216 (z+1) (due to immediate absorption) → this process creates a ‘forest’ of Ly-alpha lines.



Quasar at z = 3

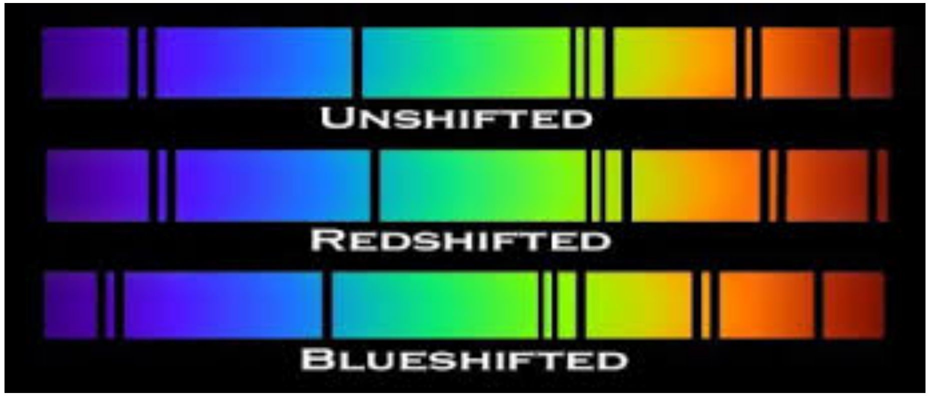
The width of each Lyman-alpha absorption line is an indication of the amount of matter density at the redshift of the cloud.

Observing many quasars (many lines-of-sight) we can map the spatial matter distribution at high-z → this thus is a probe of structure formation.

step 4 - **Measuring the redshift of the sources**

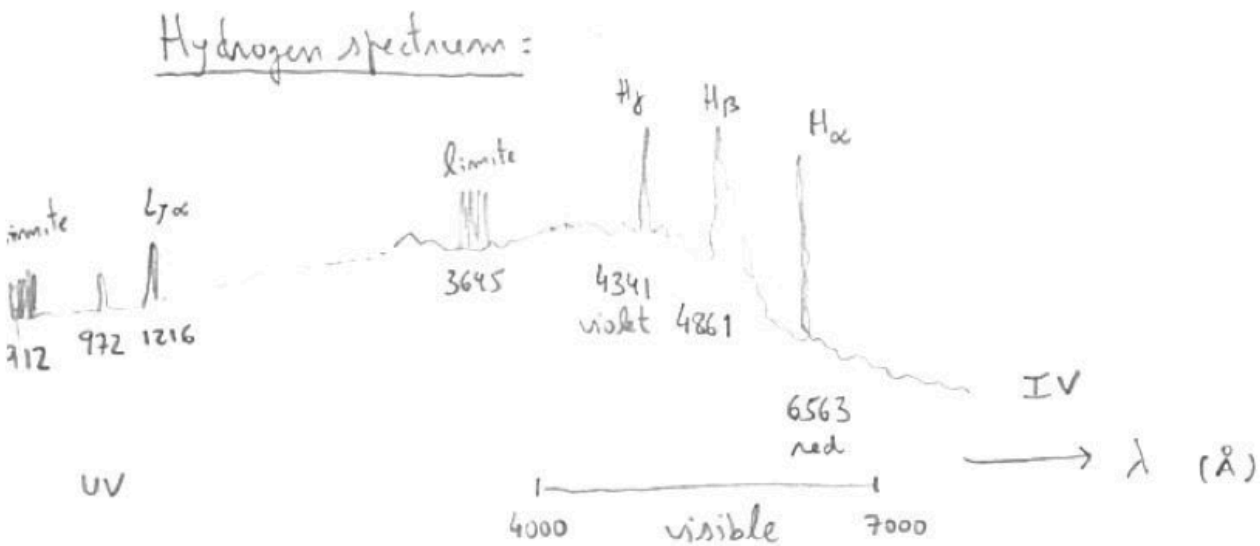
Most cosmological probes require the knowledge of the redshifts of the observed objects, since the cosmological functions are functions of redshift

Spectroscopic redshifts



A galaxy has hydrogen in its interstellar medium (neutral atomic hydrogen HI → 21 cm hyperfine transition; and ionized HII), and in the stars.

Partially ionized hydrogen emits H lines from bound-bound transitions. Fully ionized hydrogen emits a continuum from free-bound transitions, and there is also continuum emission from a combination of blackbody emitters at various temperatures.



For low redshifts z < 1

The most prominent features in the Hydrogen spectra are the Balmer series lines, the transitions to $n=2$

$H_\alpha = n_3 \to n_2$

$H_\beta = n_4 \to n_2$

$H_\delta = n_5 \to n_2$

etc.

$$\lambda_{Balmer} = 3645 \frac{n^2}{n^2-4}$$

$n=3 \Rightarrow \lambda_{H_\alpha} = 6563 \text{Å}$

$n \to \infty \Rightarrow \lambda \to 3645 \text{Å}$ Balmer limit

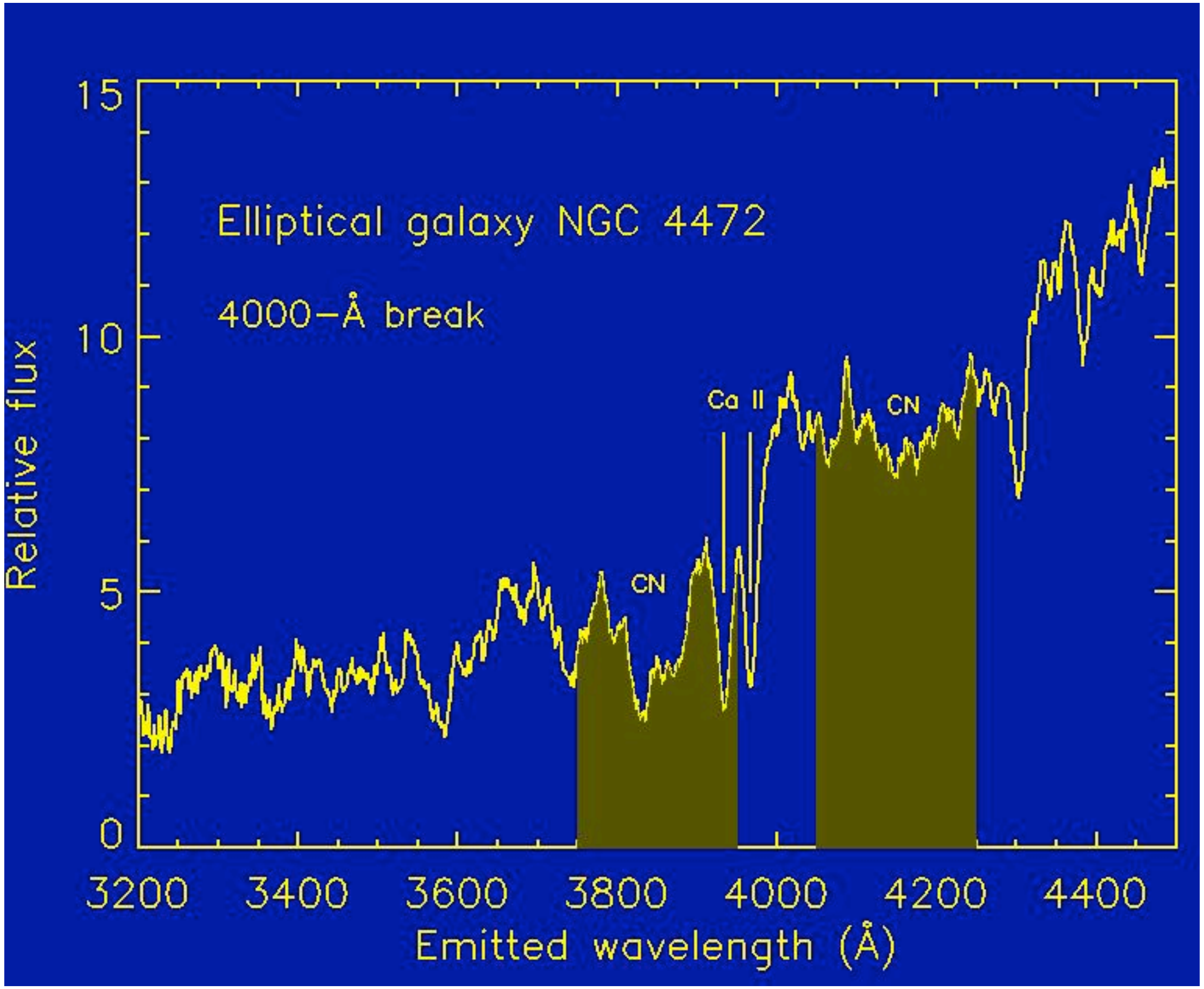
The atmosphere of the stars will absorb some of the emitted photons and its H atoms will become excited (bound-bound transition).

The atmospheres of the stars absorb some of the transitions and produce absorption lines.

The 'metals' in the atmosphere of stars, already ionized by H emission from the stars, may absorb all frequencies larger than a certain threshold (blanket absorption)→ producing a break in the spectrum, the **4000 Angstrom break of the Balmer series**

This is especially visible if there are no young stars (hot blues stars, emission at UV)

The redshift of
a galaxy is measured
identifying emission
and absorption lines,
and also from features
in the continuous
spectrum, such as
the Balmer jump
and the 4000A break



The 4000 Angstrom break measured from the ratio of the fluxes from the two shaded regions, or from the color U-B

For intermediate redshifts 1.3 < z < 2.5 → the **redshift desert**

For objects at $z \gtrsim 1.3$ the break enters in the IR.

It stays in the difficult regions of the NIR from $z = 1.3$ to $z = 2.5$ — the <u>redshift desert</u>

(only observable with space telescopes)

We can compute: $z = \frac{\lambda_0 - \lambda_e}{\lambda_e}$

$\lambda_e = 4000$ Å

$z = 0 \Rightarrow \lambda_0 = 4000$ Å

$z = 1.3 \Rightarrow \lambda_0 = 4000 \cdot 1.3 + 4000 = 9200$ Å $= 0.92\ \mu m$

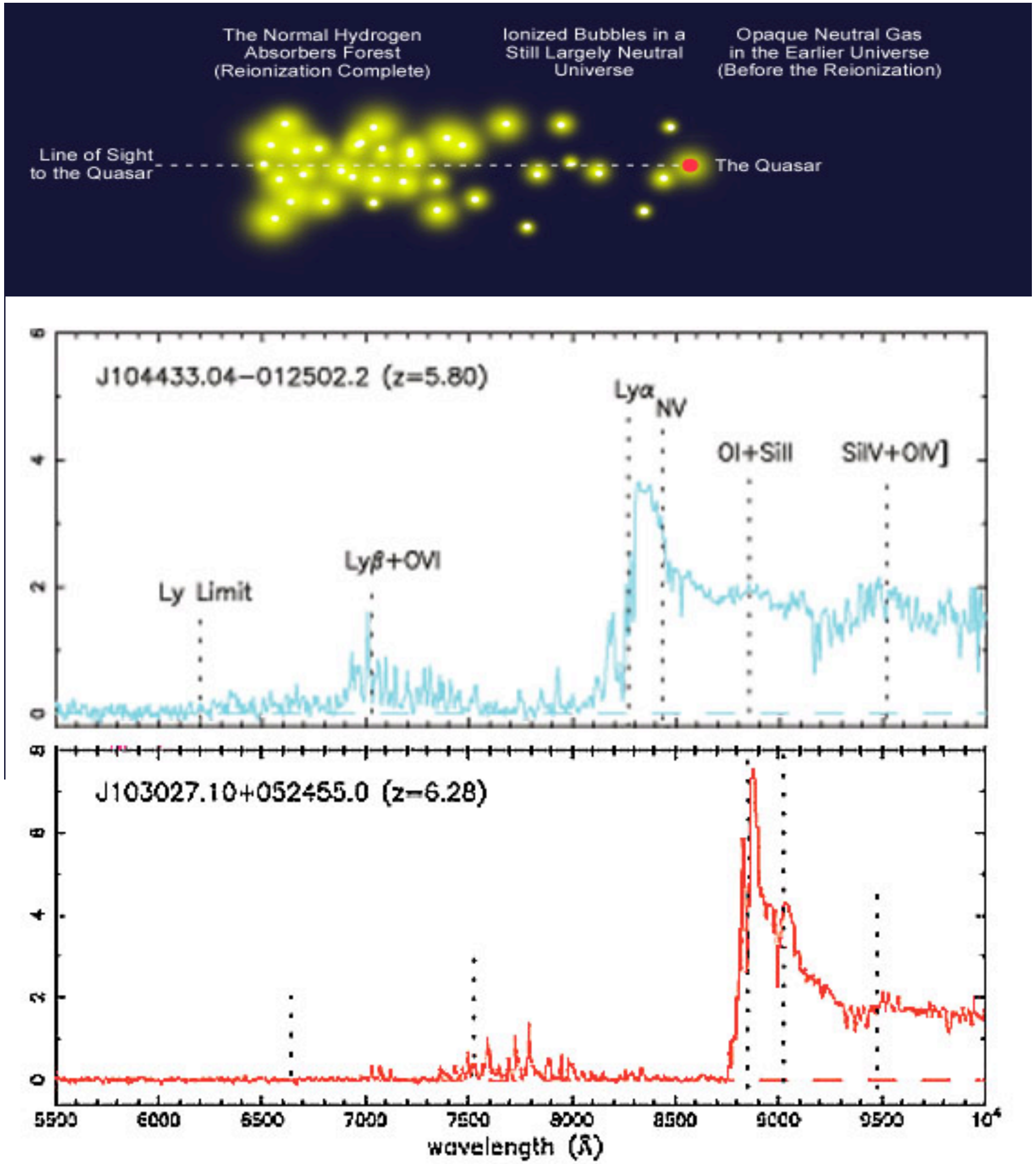
$z = 2.5 \Rightarrow \lambda_0 = 10000 + 4000 = 14000$ Å $= 1.4\ \mu m$

For higher redshifts z > 3 → the **Lyman series** is a better feature (higher energy, H transitions to n=1)

Lyα is visible for example if $\lambda_0 = 6000$ Å $\Rightarrow z = \frac{6000 - 1216}{1216} = 4$

Used for very distant galaxies and quasars.

For higher redshifts z ~ z_reionization → the Gunn-Peterson trough



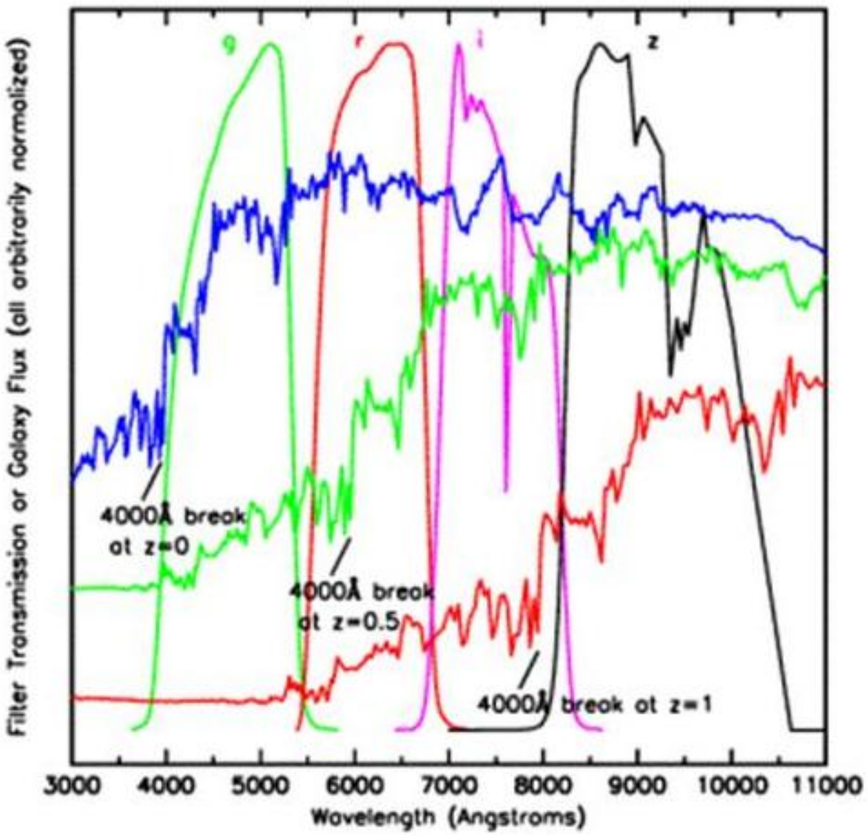
After the CMB release, the photons start to travel freely, **but the Universe is not completely transparent**.

The neutral HI medium is very opaque → all photons with energy corresponding to H n1 transitions (the Lyman series) are completely absorbed by HI clouds.

This does not affect CMB photons but affects photons emitted by the first sources in the Universe → Lyman emission from the few quasars already existing is completely absorbed to the left of Lyα, creating the GP trough (a trench) → a direct detection of the beginning of reionization (and the end of the dark ages).

Photometric redshifts

Photo-z is a more recent technique to measure a redshift without using spectroscopy.



DES - 4 bands and z evolution

The object is observed in several bands.

It is like a low-resolution spectrum.

The observation is then compared with a template:

models for the Spectral Energy Distribution SED, for various types of galaxies at various z, convolved with the filters used.

These mock observations (the templates) are used to fit the observations or as training sets in machine learning procedures → the result is a **Probability Density Function** for the redshift
(and not a single number with an error bar).

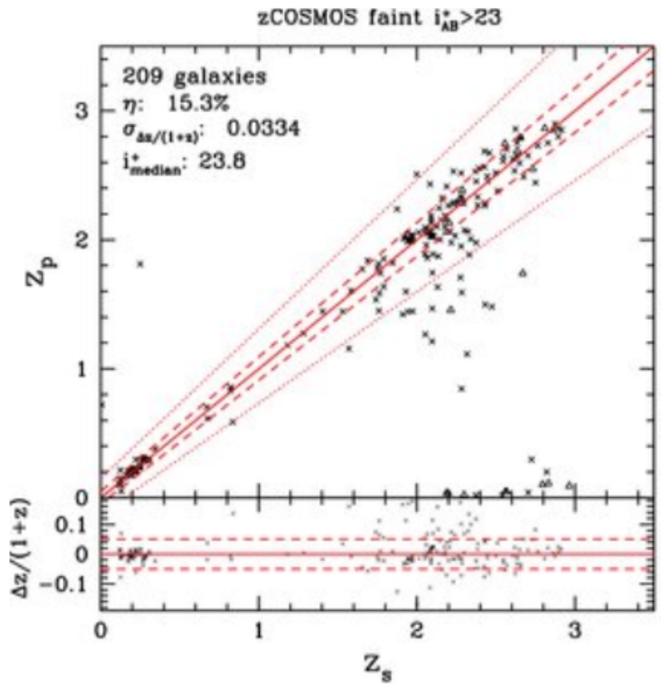
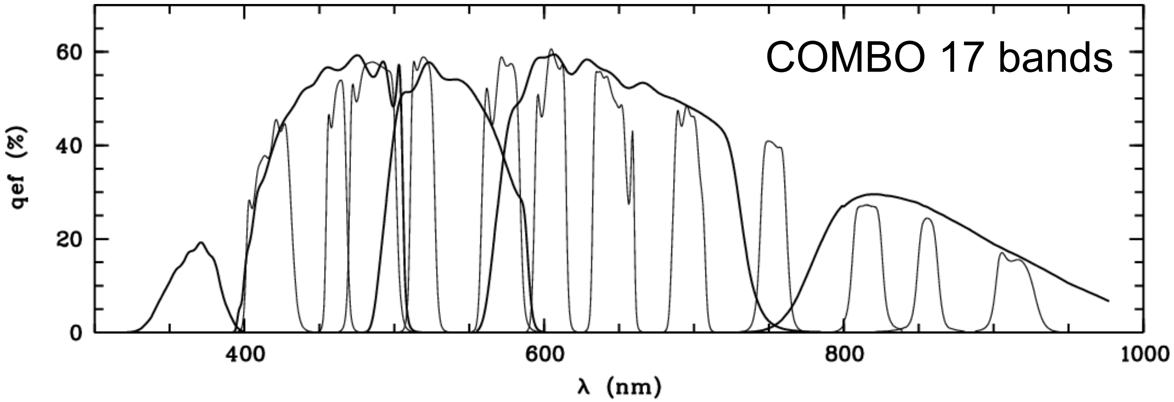


Photo-z have larger uncertainties than Spectro-z,
and need many bands,



but the data are much faster to get: one CCD of the telescope camera contains the light (images) of many galaxies (**many photo-z**). But the amplitude of each wavelength of the spectrum of one galaxy occupies one pixel in the CCD → one exposure of the field-of-view (FoV) only contains **a few spectra** (confusion limit).

Euclid: 1 FoV (0.5 deg^2) will contain ~30 000 images of galaxies but only ~300 spectra.