Origins & Evolution of the Universe

an introduction to cosmology – Fall 2014

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http://www.strw.leidenuniv.nl/~hoekstra/TEACHING/OEU/OEU.html

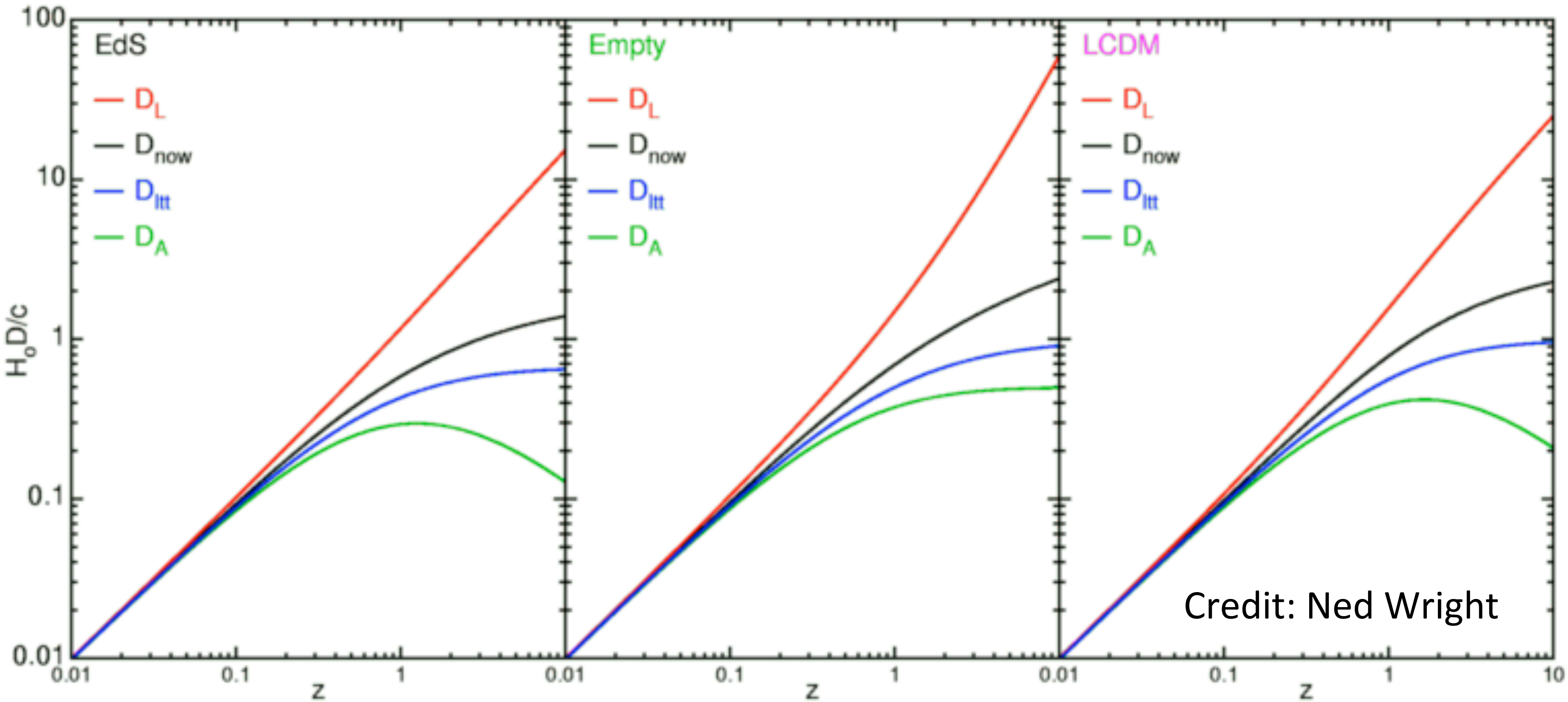
Distance-redshift relation

The relation between distance and redshift depends on cosmology and thus can be used to constrain cosmological parameters.

But we cannot measure proper distance… but we can define other distances in terms of observables.

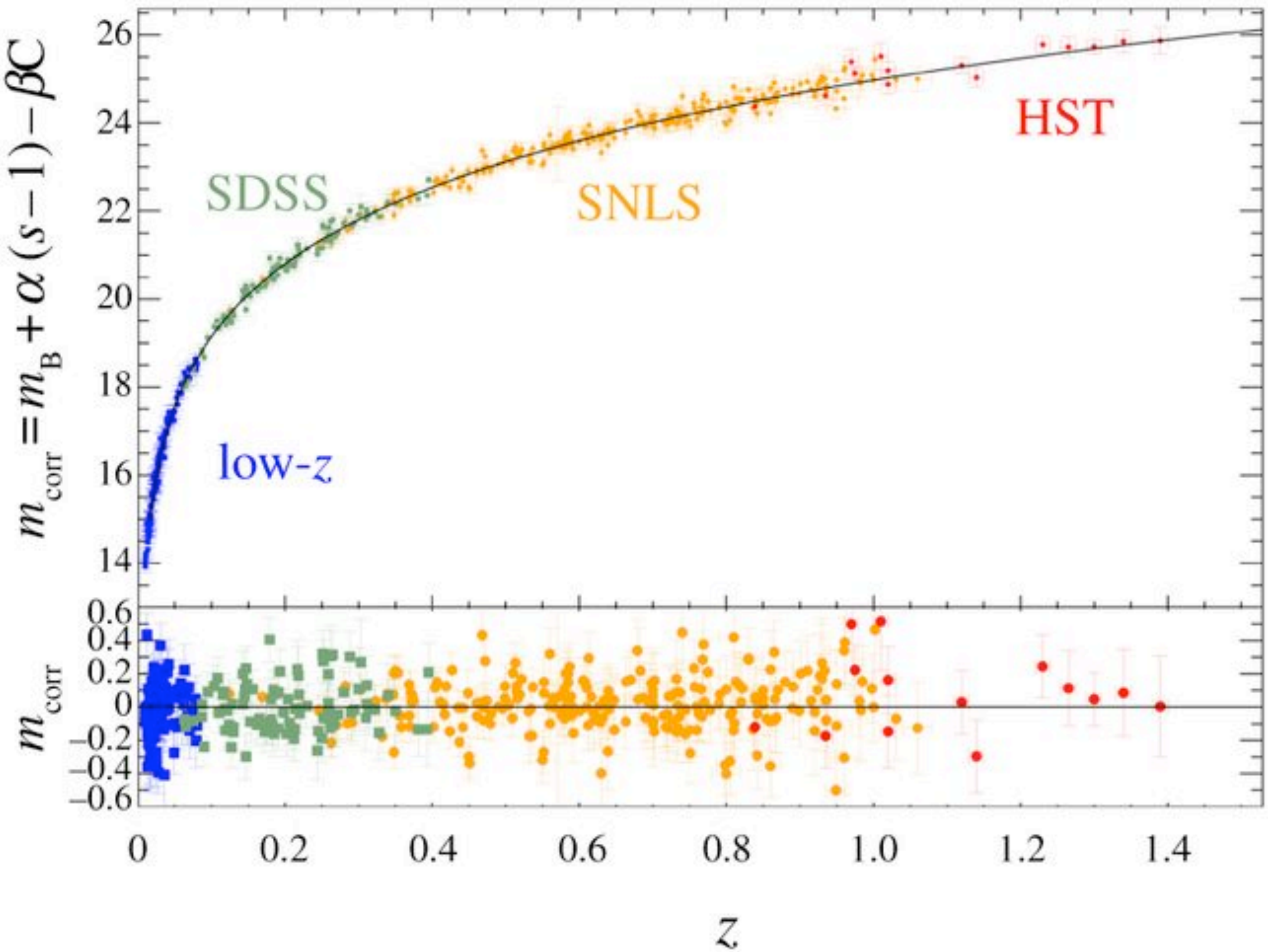
- Luminosity distance
- Angular size distance

Distance-redshift relations…

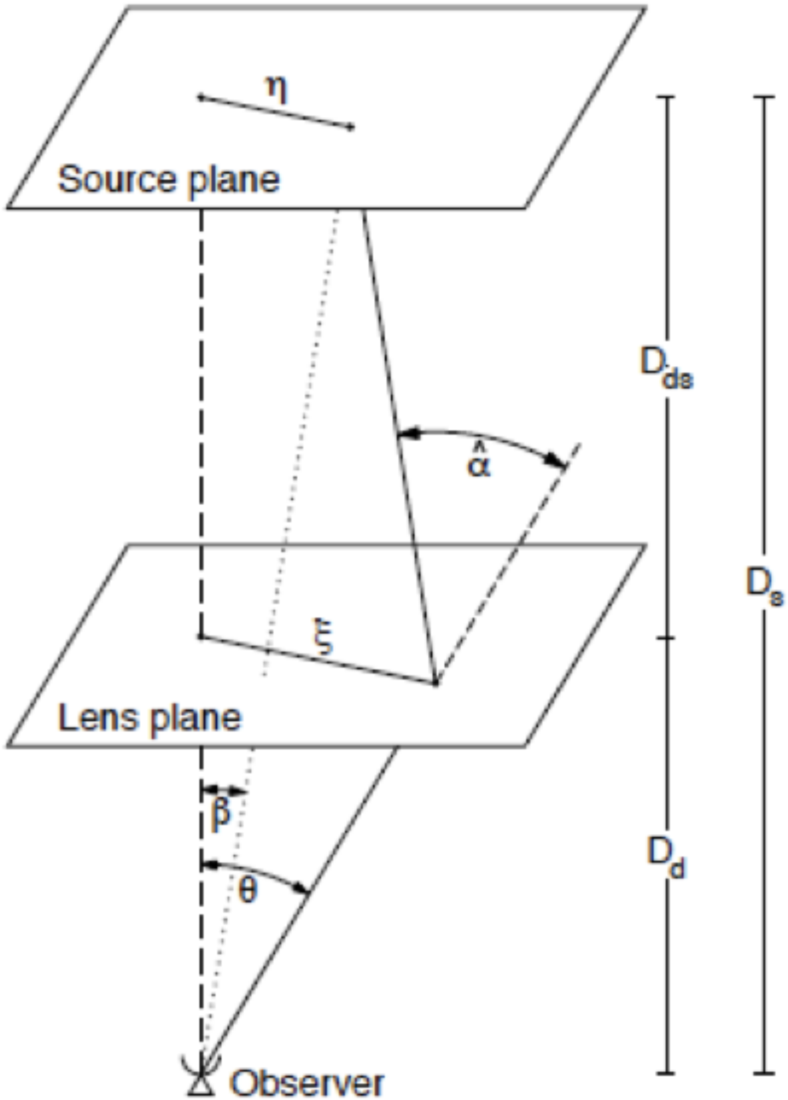


… depend on cosmological parameters!

(a) Distance-redshift relations



Gravitational lensing



angular diameter distances!

$$\boldsymbol{\eta} = \frac{D_\mathrm{s}}{D_\mathrm{d}}\boldsymbol{\xi} - D_\mathrm{ds}\hat{\boldsymbol{\alpha}}(\boldsymbol{\xi})$$

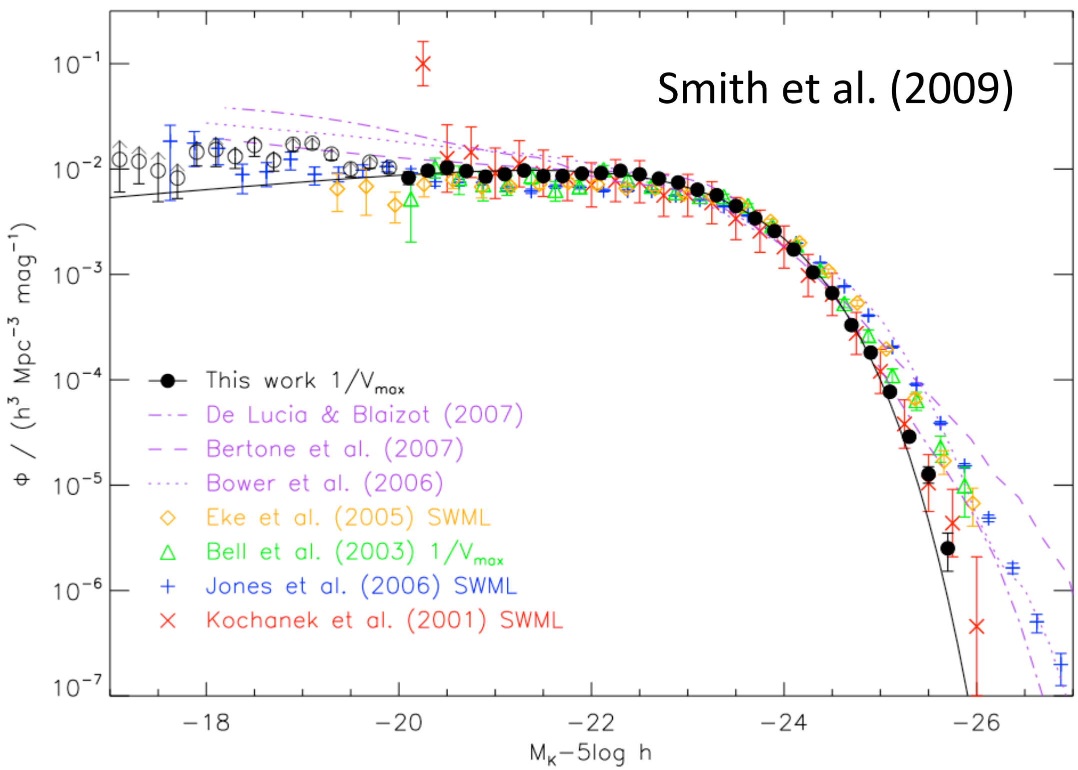
Weighing the Universe

The expansion history and the contents of the Universe are directly related. Rather than attempt measuring distances, one can try to “weigh” the Universe.

Oort’s method: if we measure the luminosity density and can figure out the mean M/L then we can estimate the mean density.

Weighing the Universe

The luminosity density can be determined using the luminosity function from redshift surveys.



Weighing the Universe

The mass-to-light ratio is trickier because we need to account for the dark matter.

Clusters were proposed as representative for the Universe as they are large collapsed objects.

Cluster masses can be determined from galaxy redshifts, X-ray observation or weak lensing studies.

These indicated Ω_m~0.2 (<<1)…

Matter differs

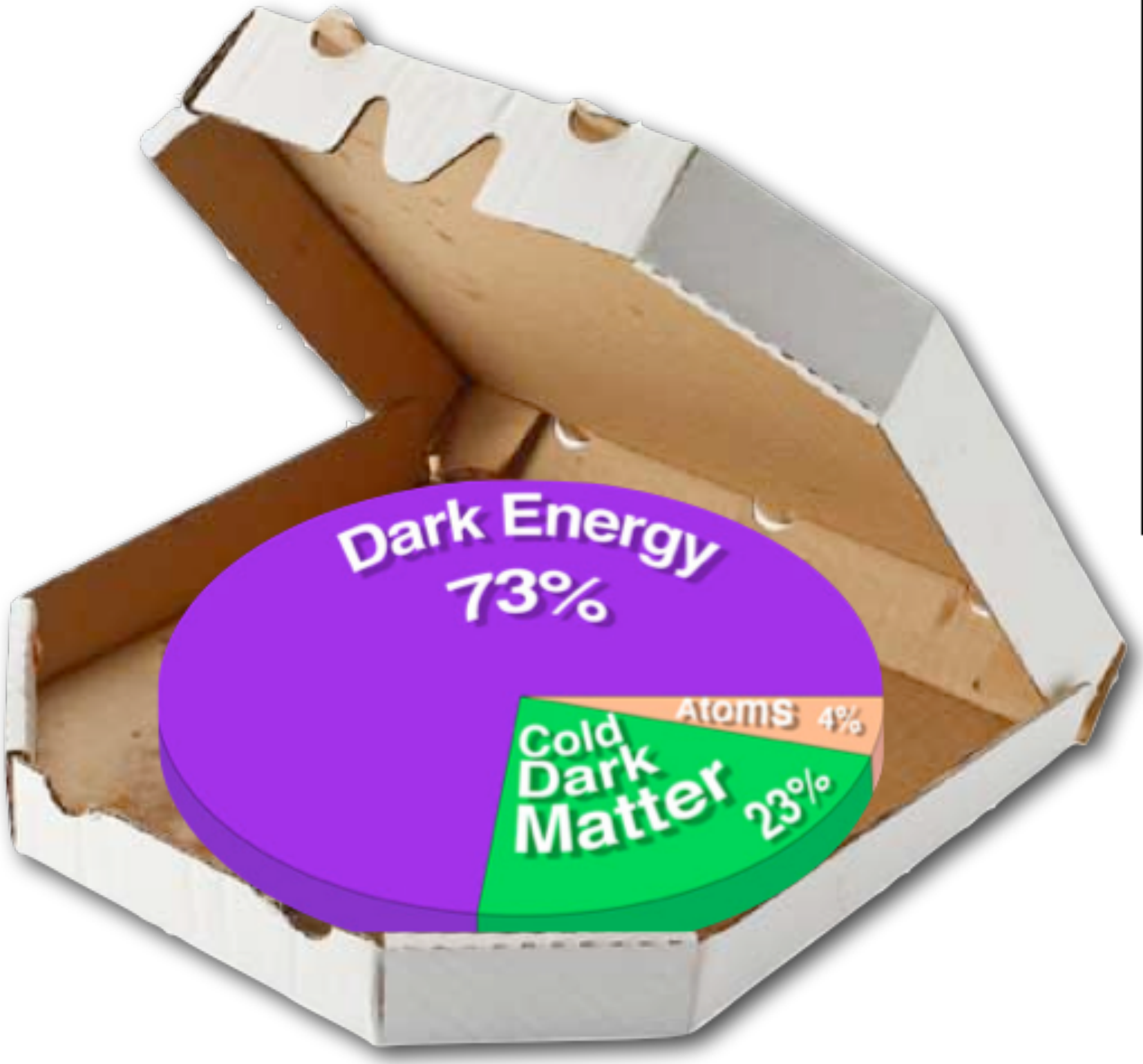
So far we treated all matter the same, because the equation-of-state is the same for baryonic* matter and non-baryonic dark matter. But we will need to make this distinction from now on.

$\Omega_{DM,0} \approx 0.23$ + a little bit from neutrinos

$\Omega_{baryon,0} \approx 0.04$

* baryons are particles made of three quarks

The standard model of cosmology



Ingredients
(per Universe)

DE: 73%
CDM: 23%
H: 3%
He: 1%
neutrinos: 0.3%

Cosmic Microwave Background

Although a range of observational techniques can and have been used to constrain cosmological parameters, most of the progress in the past decades has come from improved measurements of the cosmic microwave background (CMB).

It is time to study this in more detail…

We saw last time that $T_{CMB}=2.72548\pm0.00057$ K, but was this always the case?

Cosmic Microwave Background

There was a time where the Universe was so hot that all the hydrogen was ionized. Photons and plasma were tightly coupled due to frequent interactions.

As the temperature dropped the protons and electrons combined into neutral hydrogen and decoupled from the photons: the Universe became neutral and transparant. This occurred at $z_{rec} \approx 1100$.

This is called *recombination*. Note that the Universe is currently ionized again…

Mix at z_{rec}

We have to distinguish between baryonic matter (= particles made from three quarks) and non-baryonic dark matter.

Why?

$$\rho_{DM}(z_{rec}) = \Omega_{DM,0}\rho_{crit,0}(1+z_{rec})^3 \approx 1.8\times 10^{12}\,\mathrm{MeV/m^3}$$

$$\rho_{b}(z_{rec}) = \Omega_{b,0}\rho_{crit,0}(1+z_{rec})^3 \approx 2.8\times 10^{11}\,\mathrm{MeV/m^3}$$

$$\rho_{\gamma}(z_{rec}) = \Omega_{\gamma,0}\rho_{crit,0}(1+z_{rec})^4 \approx 3.8\times 10^{11}\,\mathrm{MeV/m^3}$$

dark matter : baryons : photons = 6.4 : 1.4 : 1

The hot big bang

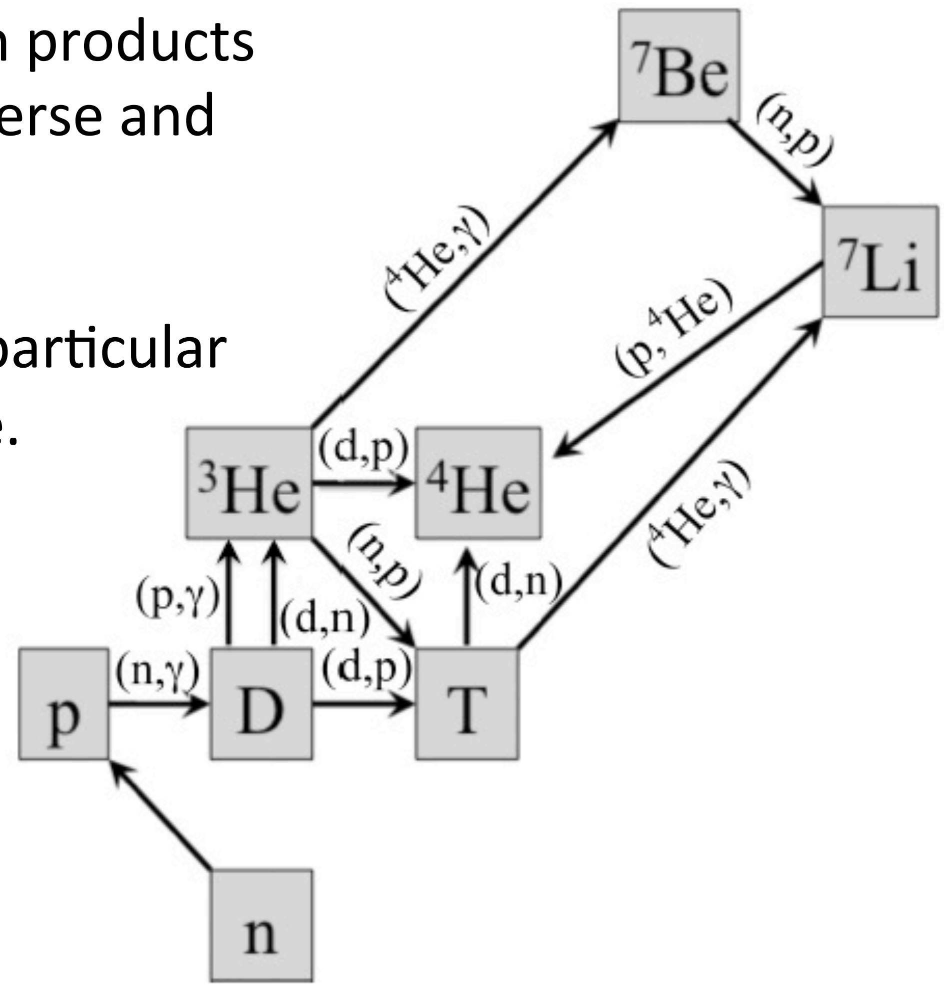
The Universe started in a very hot phase

- It acted as a nuclear reactor (for the first 10-20 minutes)
- elementary particle ‘alfabet soup’ (even earlier)

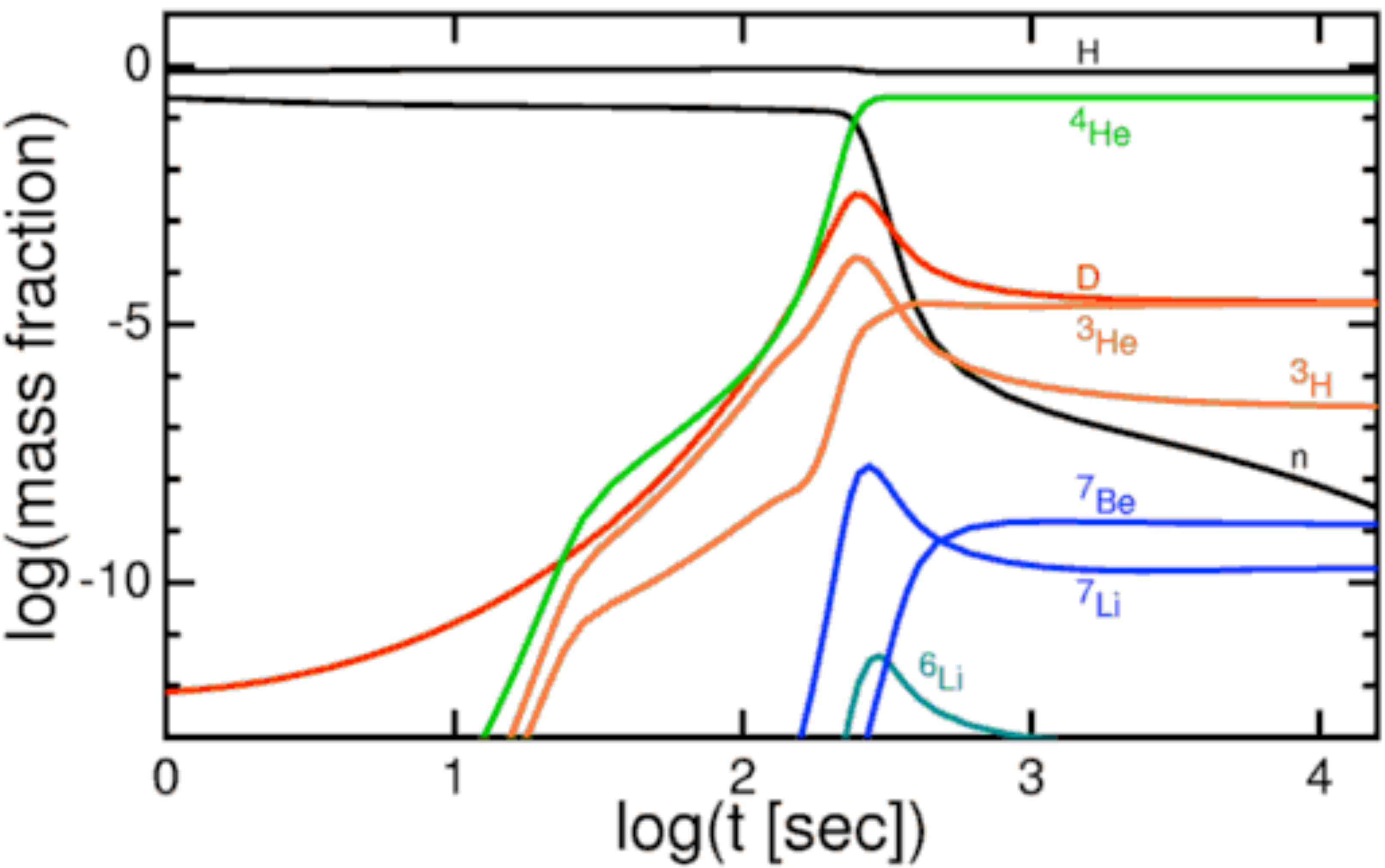
This **Big Bang nucleosynthesis** can give strong constraints on the density of protons in the early universe and be used to test our understanding of high energy particle physics.

Big Bang Nucleosynthesis

We can calculate the reaction products from expanding, cooling universe and compare the results to the composition seen today in atmospheres of old stars: in particular light elements H, D, He, Li, Be.



Big Bang Nucleosynthesis



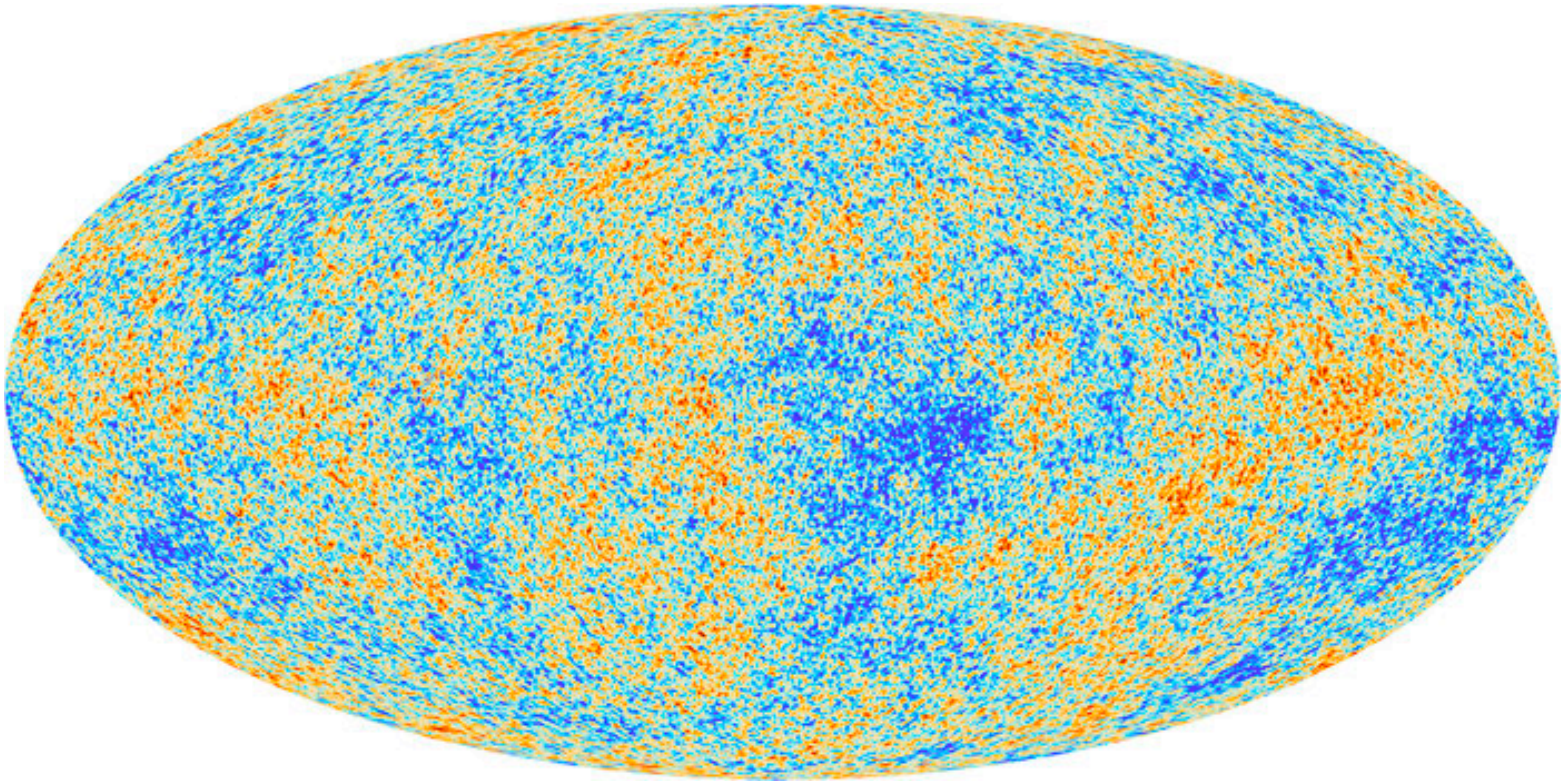
Acoustic oscillations

The early Universe was radiation dominated: matter (both dark and baryonic) cannot collapse efficiently because of all the radiation.

After matter-radiation equality: baryons collapse into dark matter perturbations. Acoustic oscillations start.

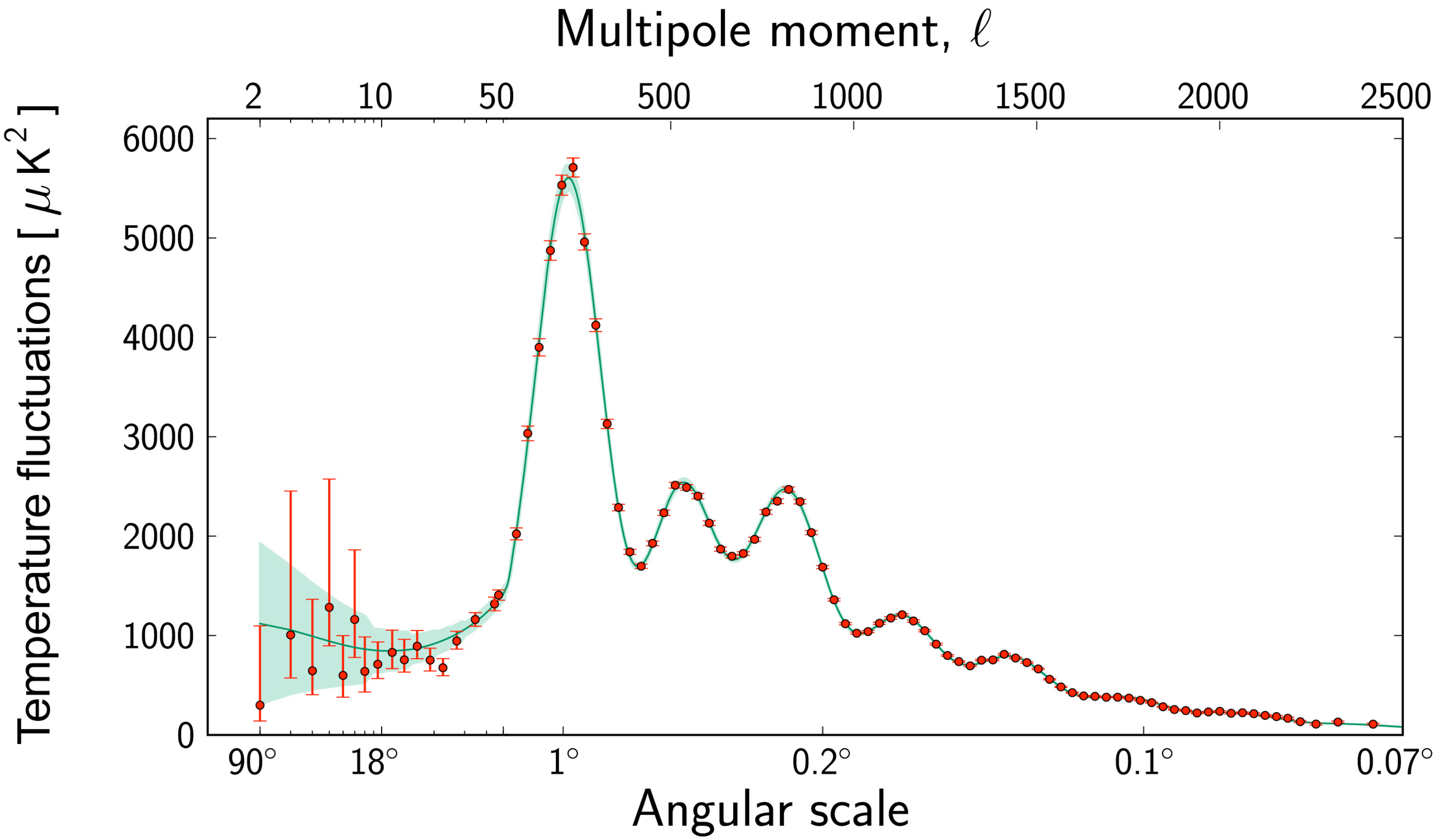
At matter-radiation decoupling: the Universe becomes transparent and oscillations are frozen and the CMB temperature fluctuations reflect the underlying density fluctuations.

The CMB seen by Planck



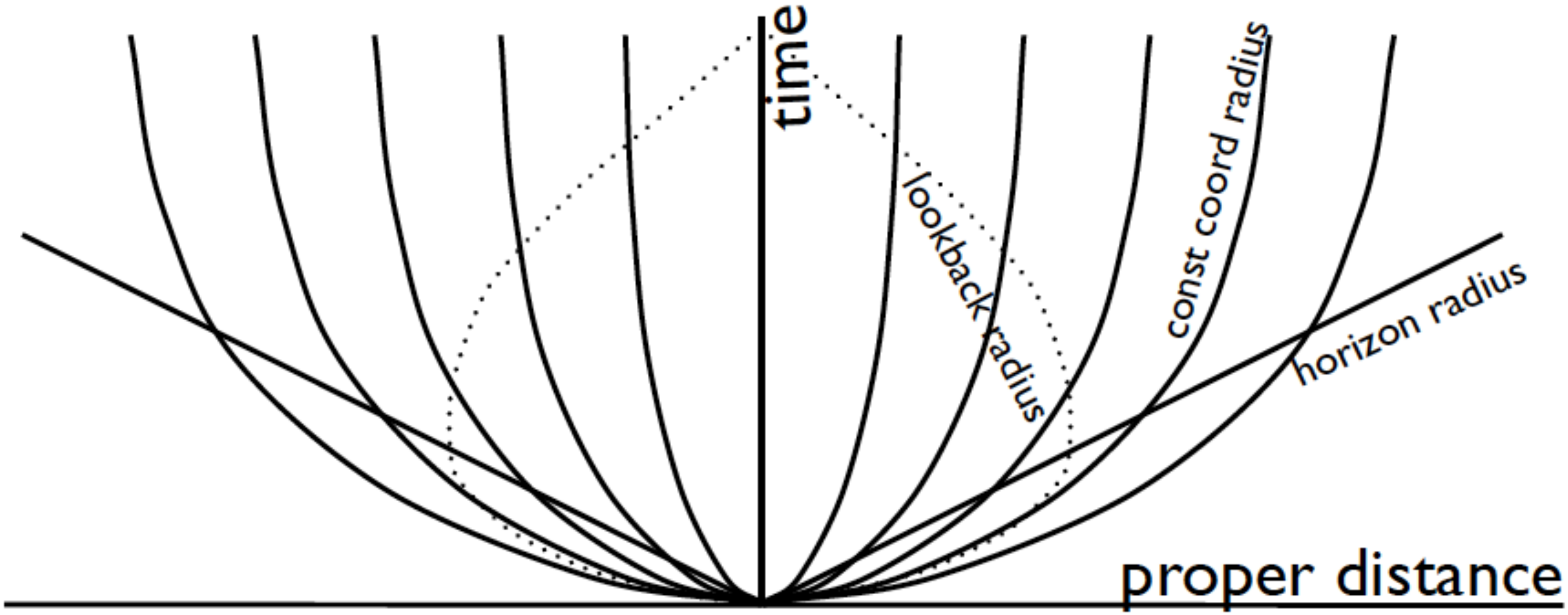
The excellent black body spectrum and the small temperature fluctuations imply that the early Universe was very simple: easy to model?

Statistics of fluctuation



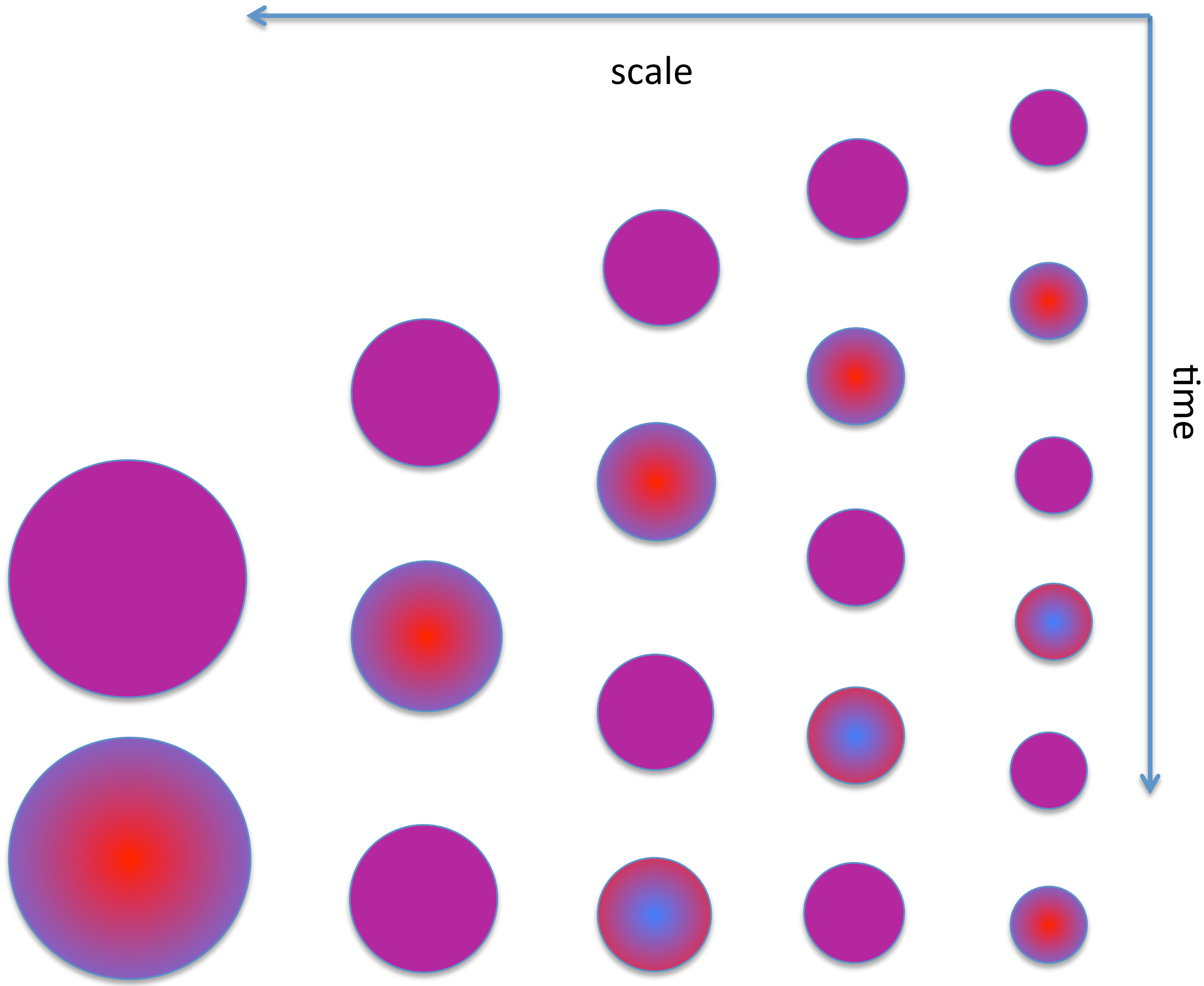
We can indeed predict the power spectrum of fluctuations for a set of initial conditions.

Horizon in flat Ω_m=1 model



Recall that larger structures enter the horizon later.

Acoustic oscillations



Acoustic oscillations

As we will see, recombination occurred at a $z_{rec} \approx 1100$.

The Hubble radius is then $c/H(z_{rec}) \approx 0.2$ Mpc.

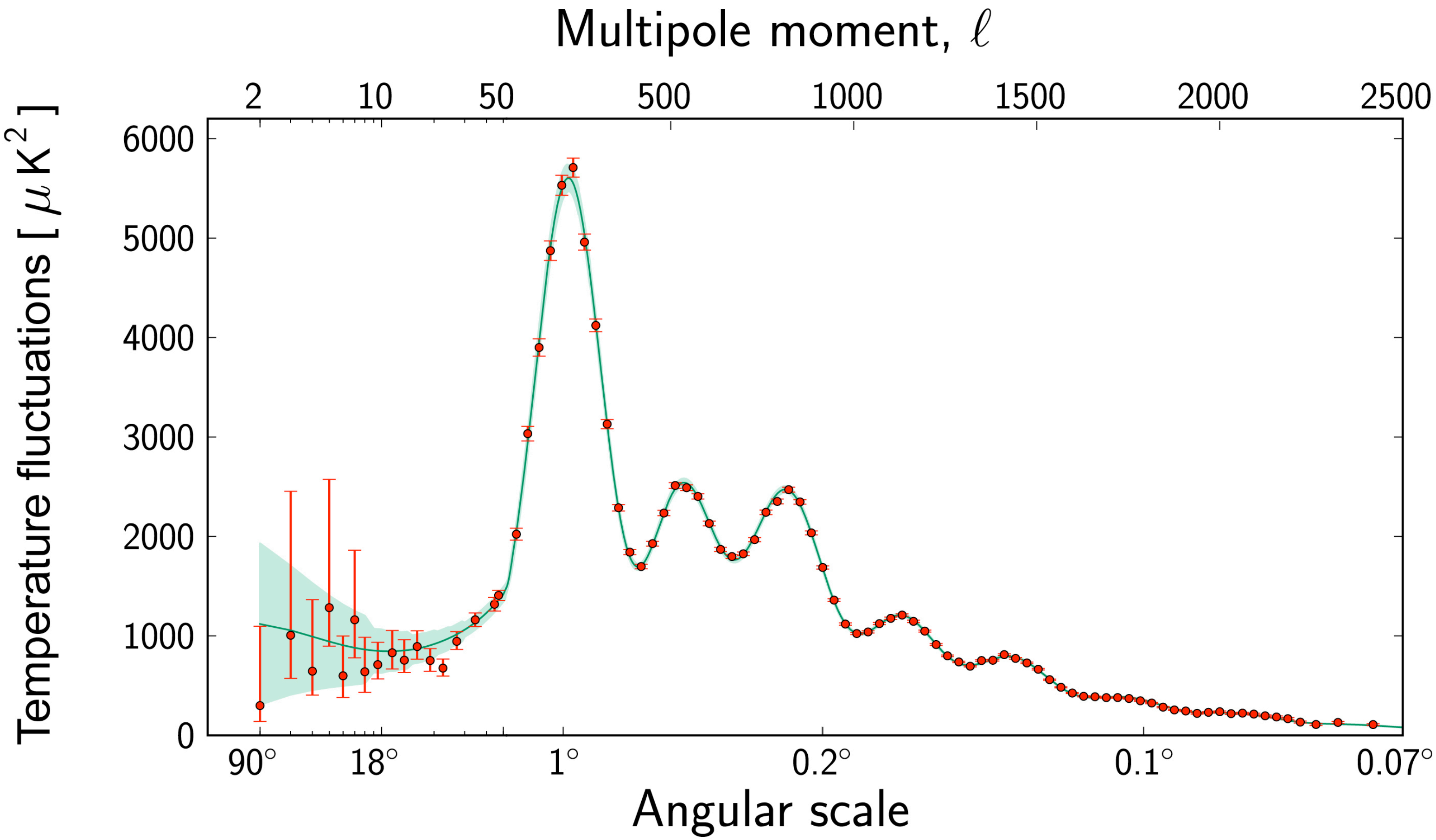
The angular diameter distance is (as $z_{rec} \gg 1$) $\approx \frac{d_{hor}(t_0)}{z_{rec}}$

For *our* Universe the Hubble radius will have an angular size, as seen from Earth, of

$$\theta_H = \frac{c / H(z_{rec})}{d_A} \approx \frac{0.2Mpc}{13Mpc} \approx 1^\circ$$

but for other initial conditions the size will be different!

Statistics of fluctuation



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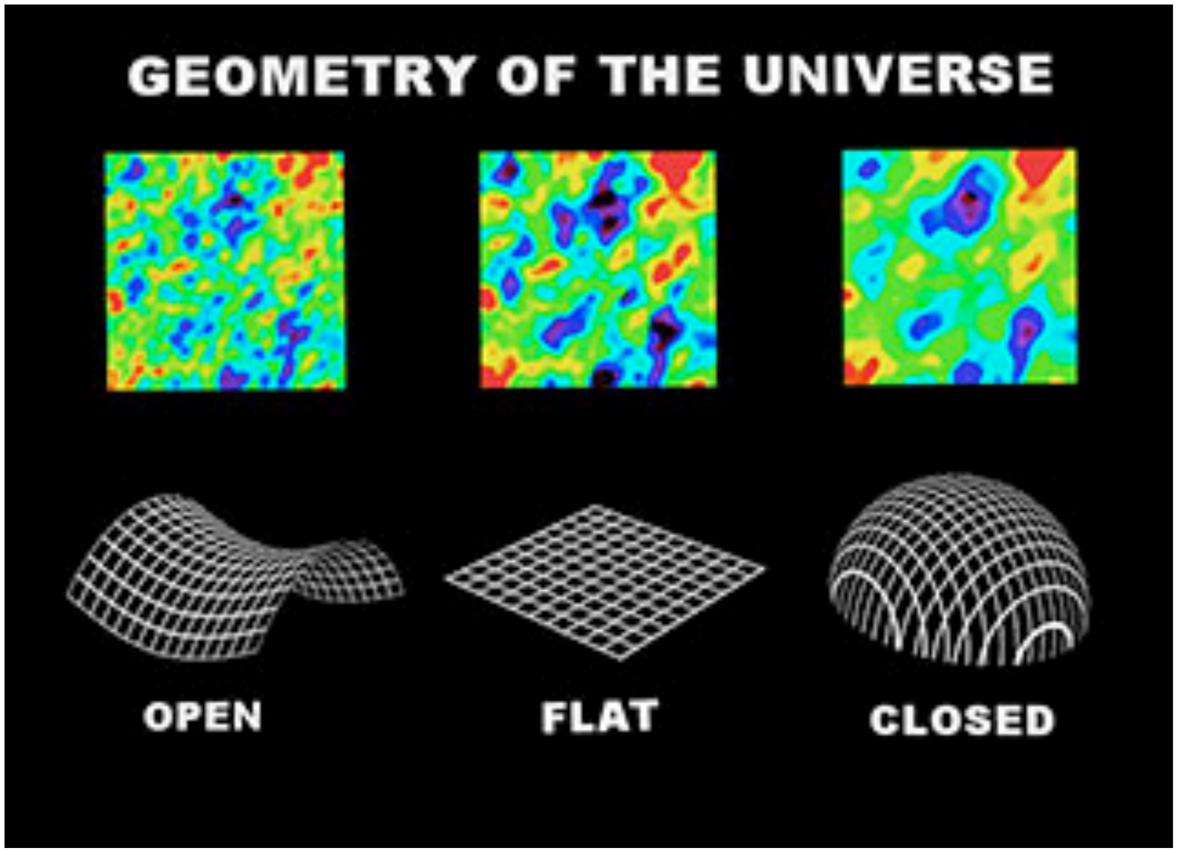
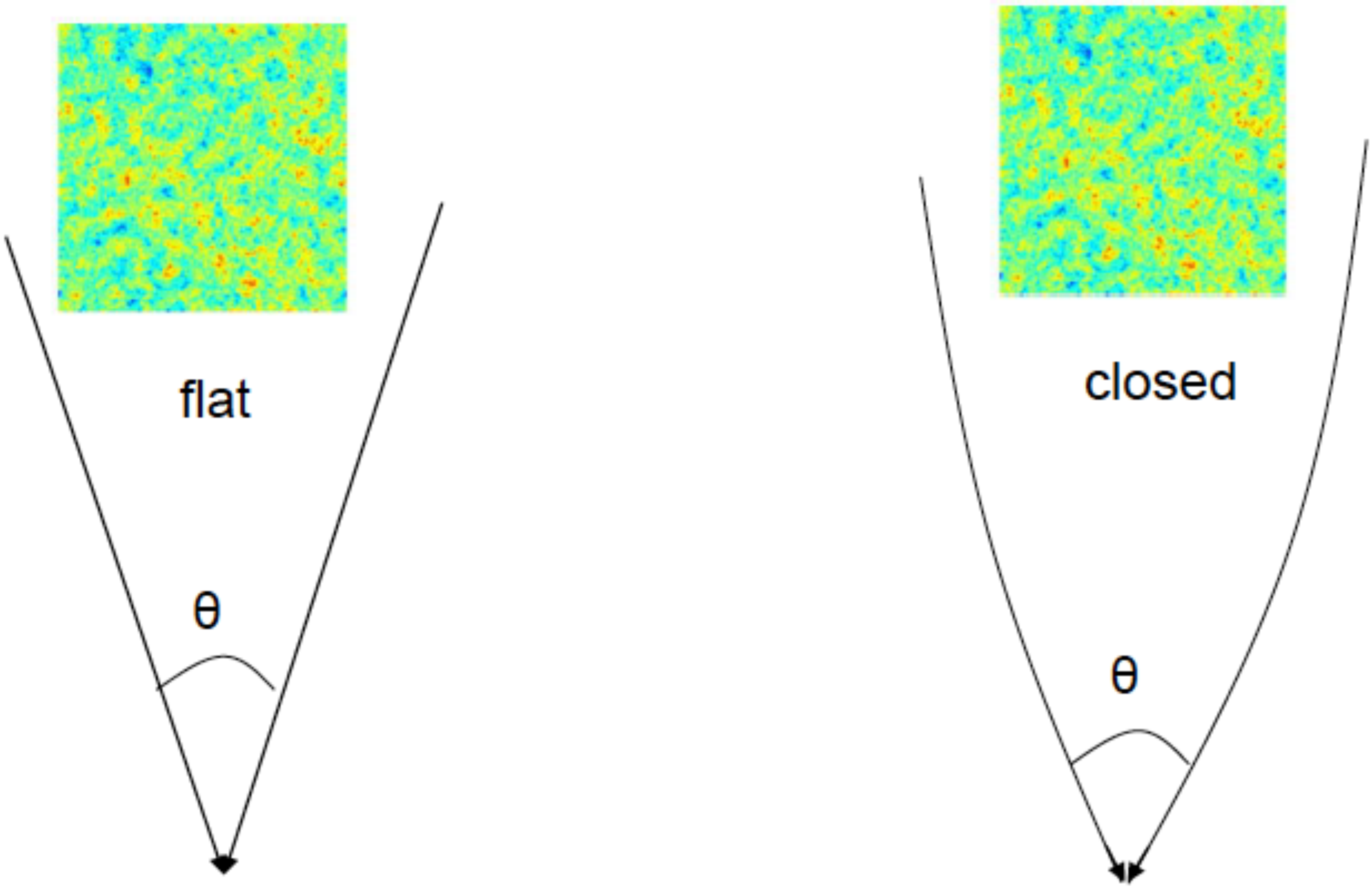
Angular diameter distance

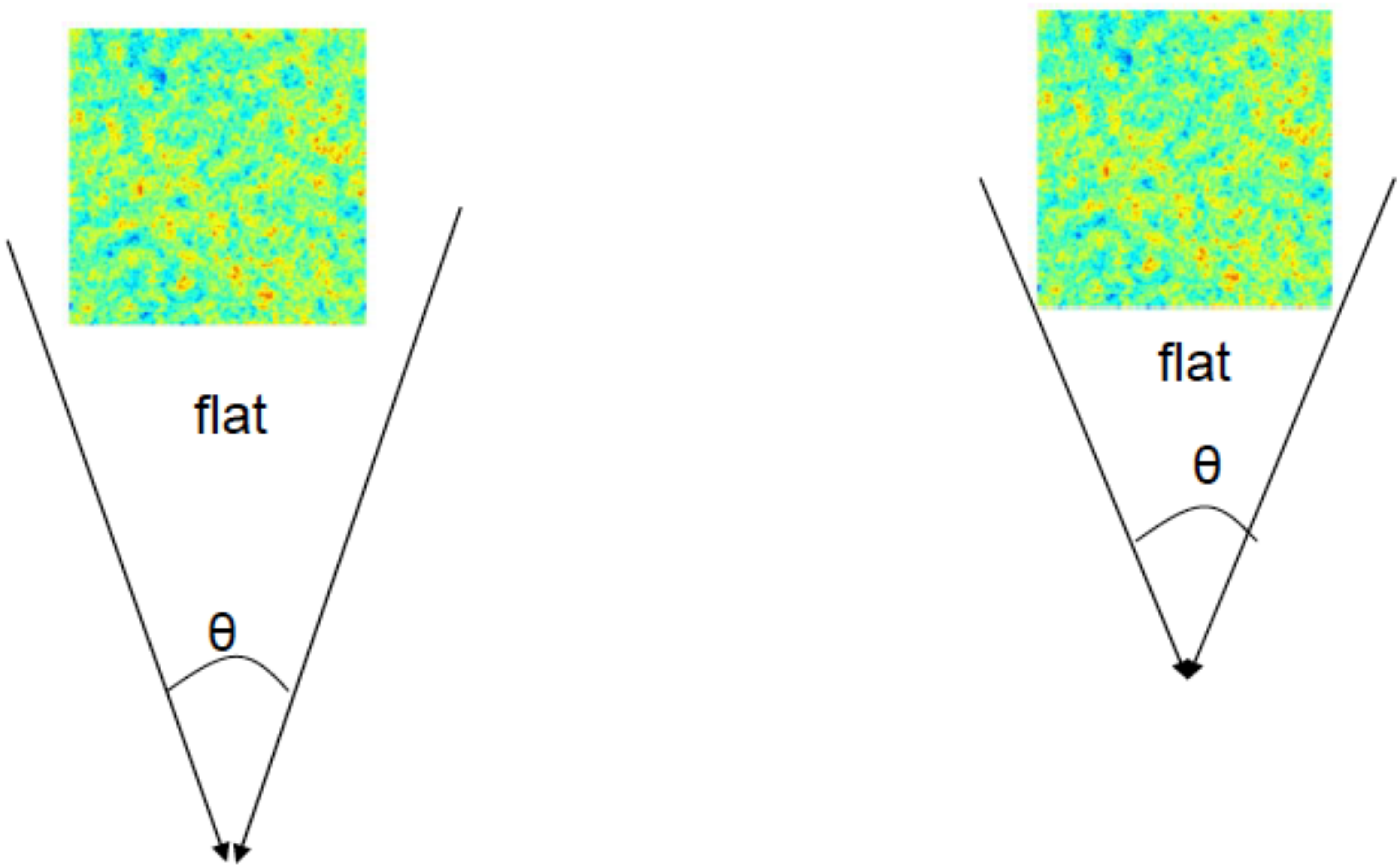


The observed angles depend on geometry *and* the distance to the surface of last scattering.

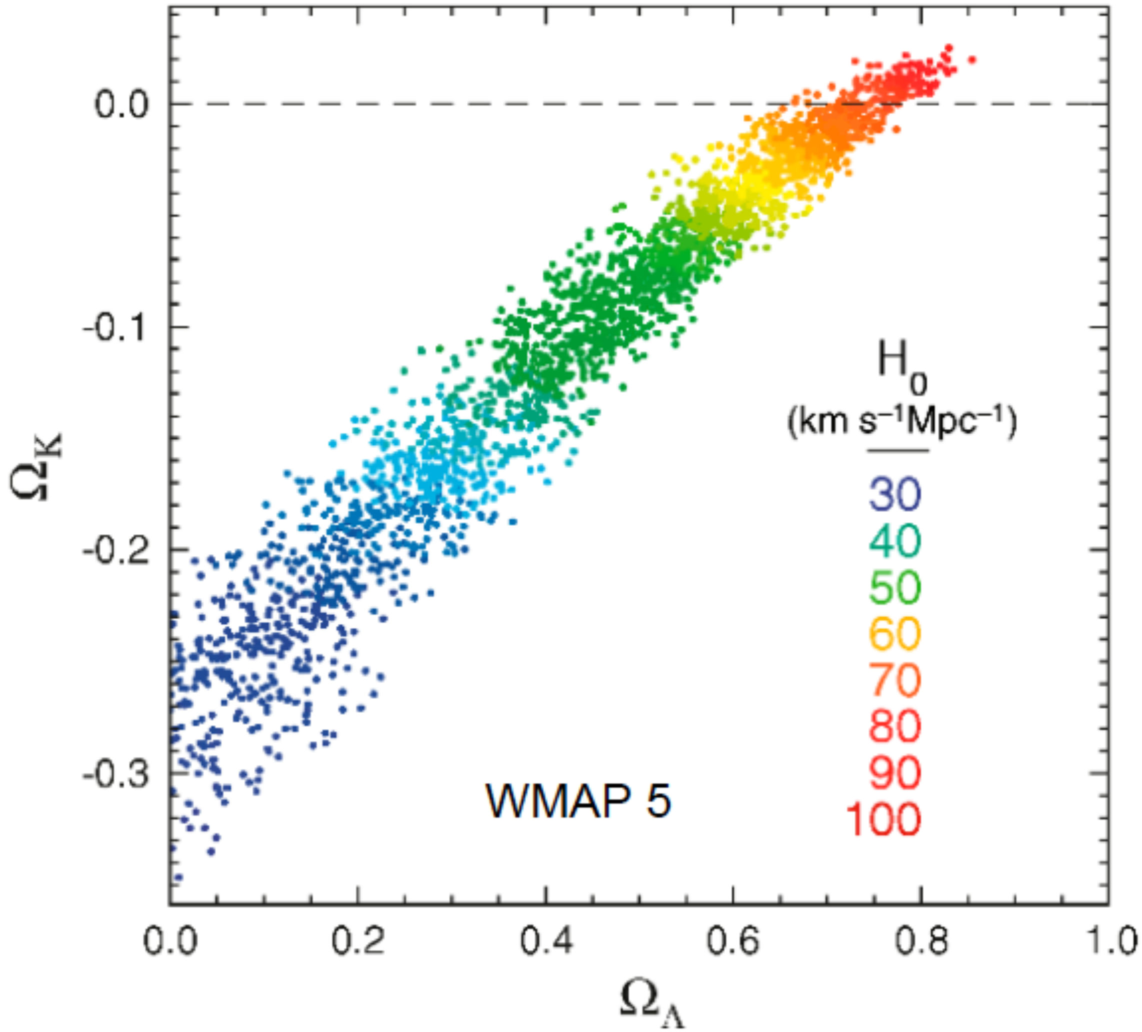
Distance to recombination



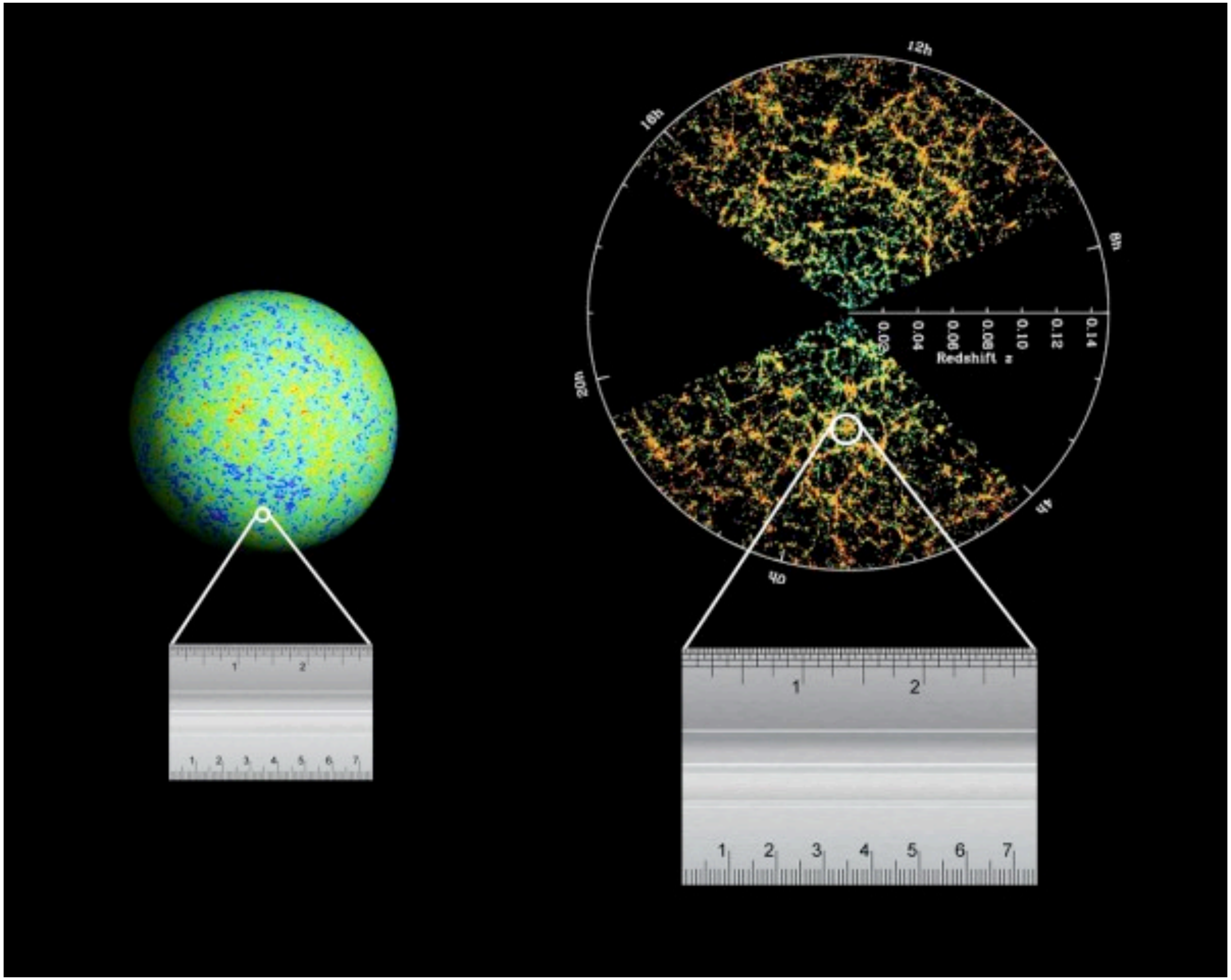
Distance to recombination



Parameter degeneracies



Cosmic ripples in the galaxy distribution



Need to combine probes