Baryon acoustic oscillations

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Saas Fee lectures Engelberg
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Baryons

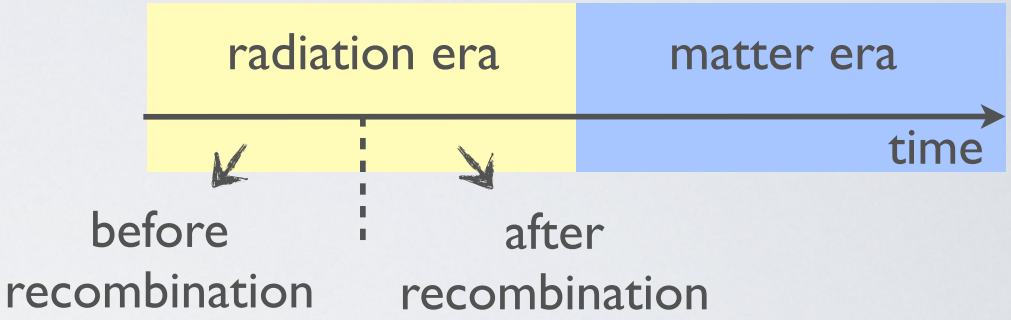
- We have neglected the **baryons**: we suppose that dark matter is the only matter component.
- Link with observation: we assume that the distribution of baryons **follow** that of the dark matter.
- The baryons **do not contribute** to the gravitational potential: they just fall into it.
- **Successful** approach: the baryons constitute only 15 percent of the total matter.
- Missing point: **baryon acoustic oscillations**.

Oscillations

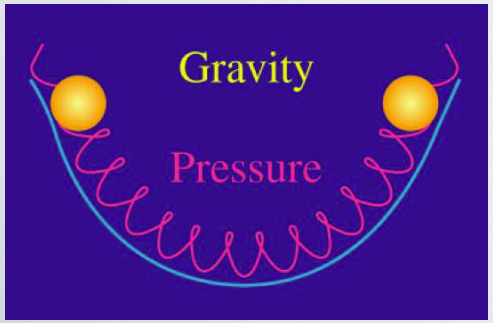
Difference between baryons and dark matter: **interaction** with **photons**.

- Dark matter evolution: two stages

- Baryons evolution: three stages



Before recombination: photons and baryons are tightly **coupled**. They behave as a **single fluid**, governed by two opposite forces.



- gravitational attraction
- radiation pressure

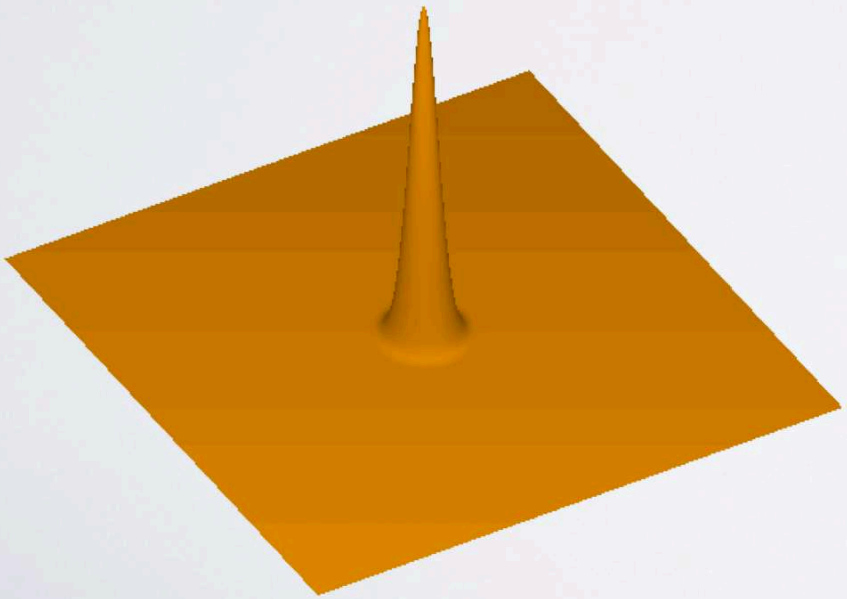
→ send a **sound wave** through the universe

Sound wave

- At **recombination**: electrons and protons combine to form neutral hydrogen. The interaction with the photons stops.
- This process leaves an impact on the matter **power spectrum**.

In real space

Toy model: an over-density at a single point in the universe.



The fluid propagate until recombination:

- the photons escape
- the baryons stay

Shell of **baryons** at distance $150\ \mathrm{Mpc}$

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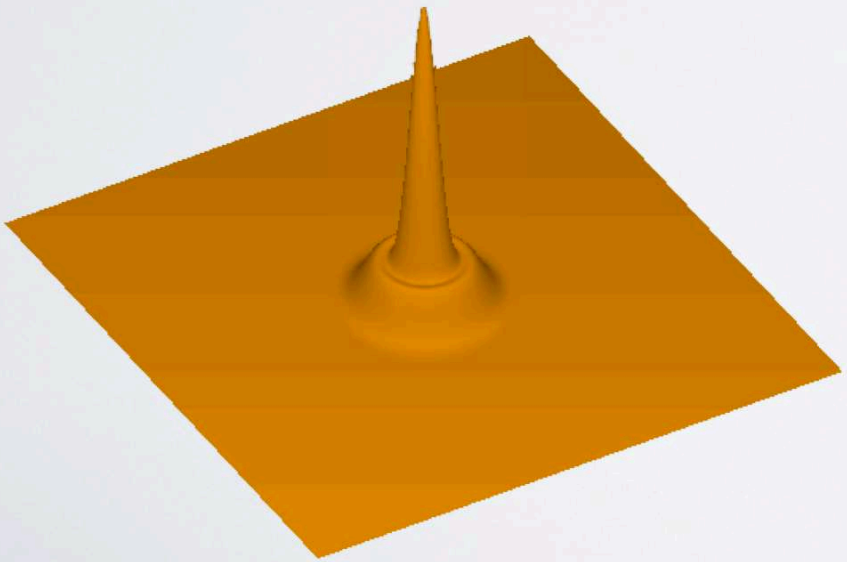

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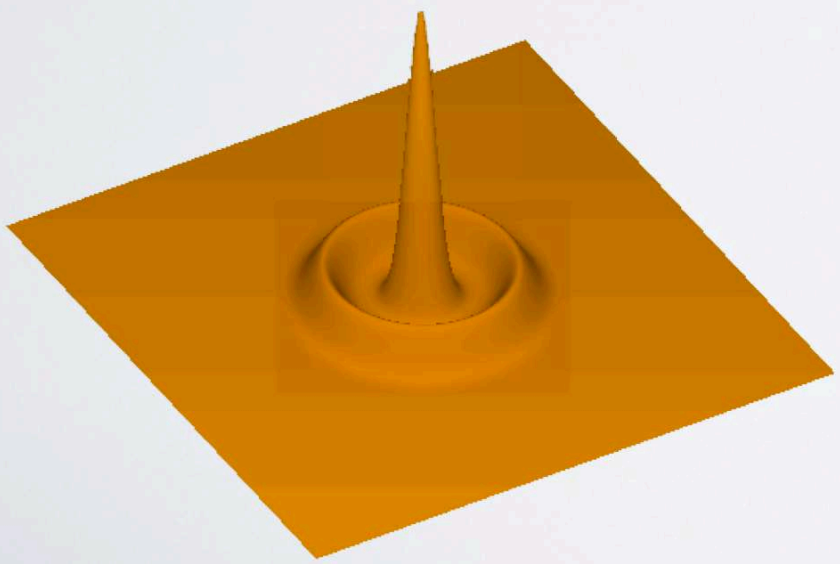

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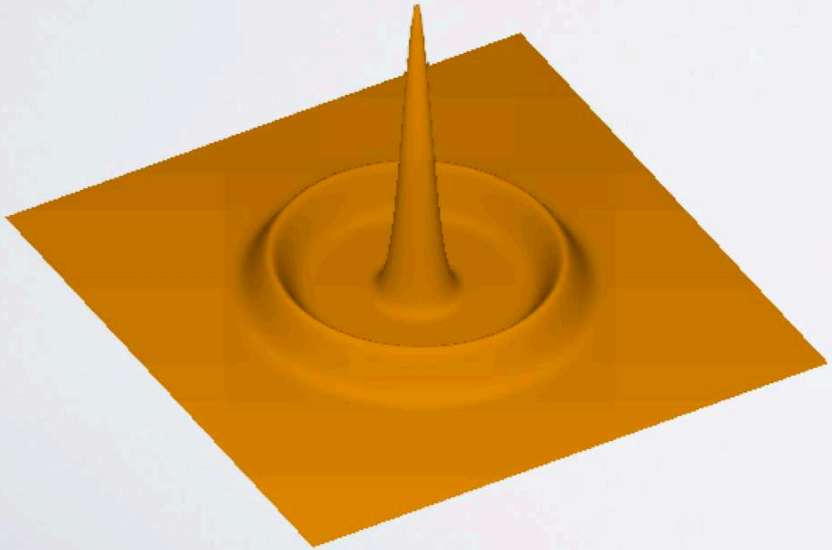

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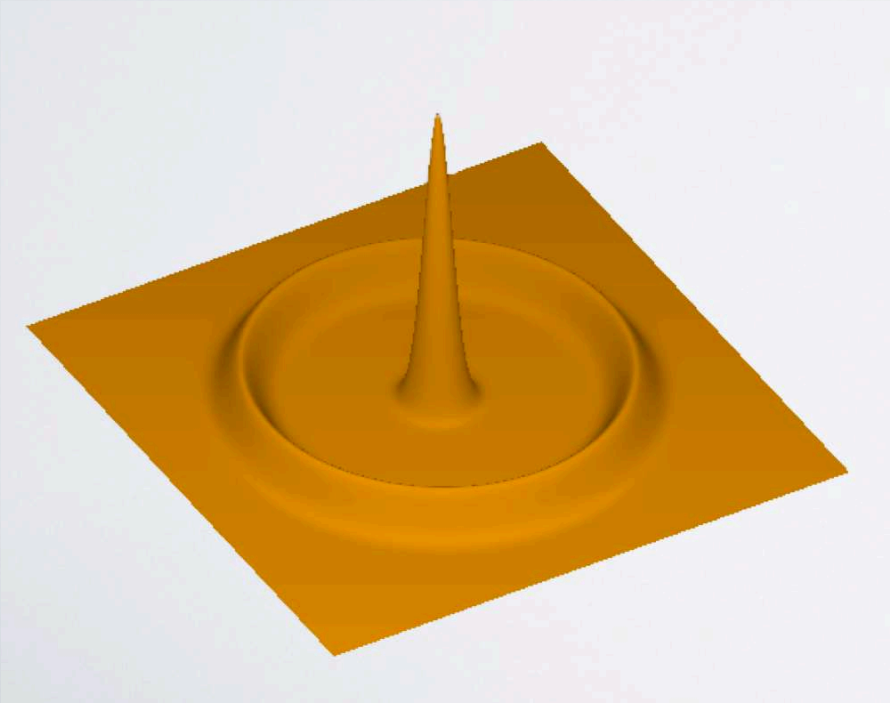

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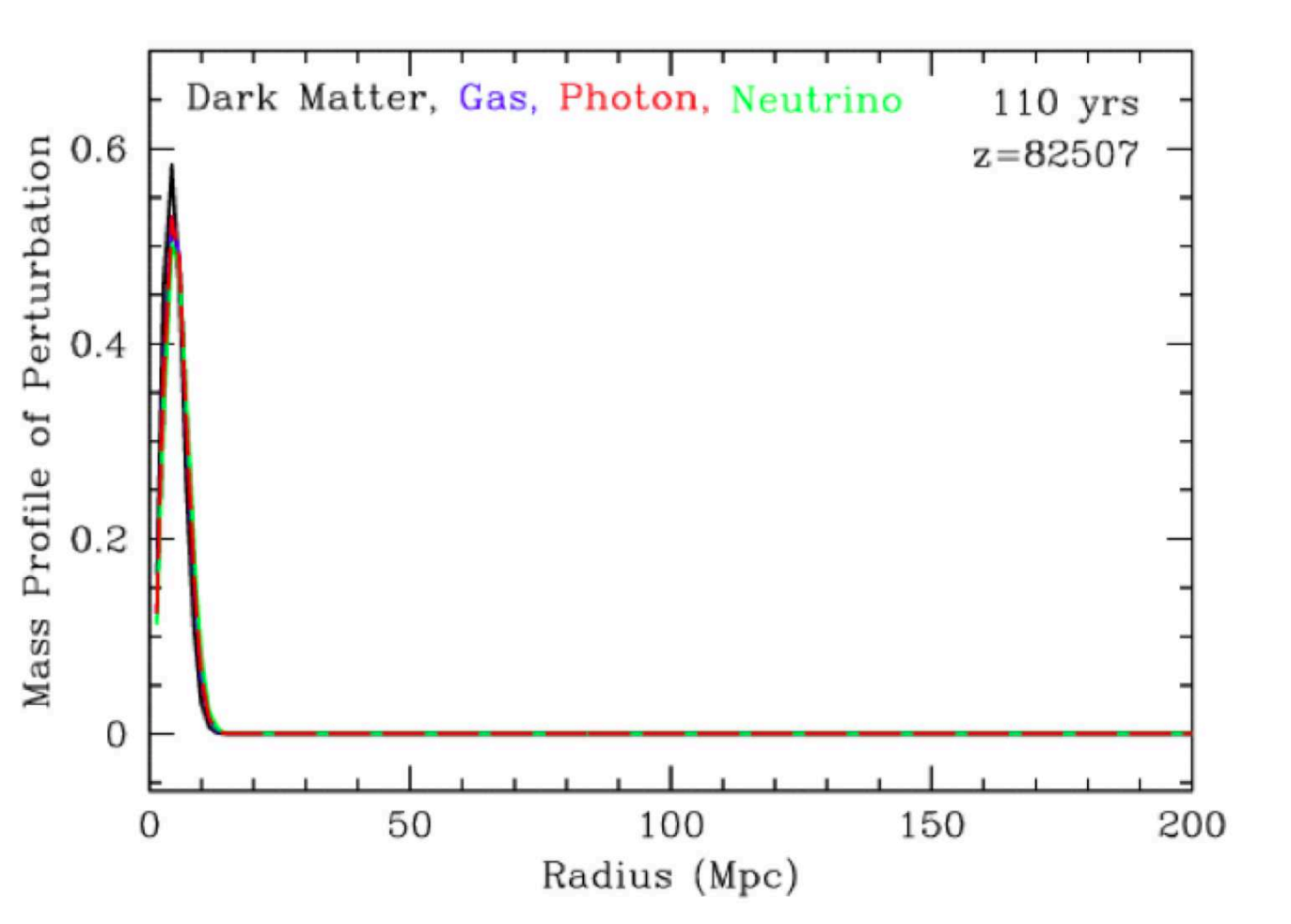
Distribution of fluids



Eisenstein, Seo, and White (2007)

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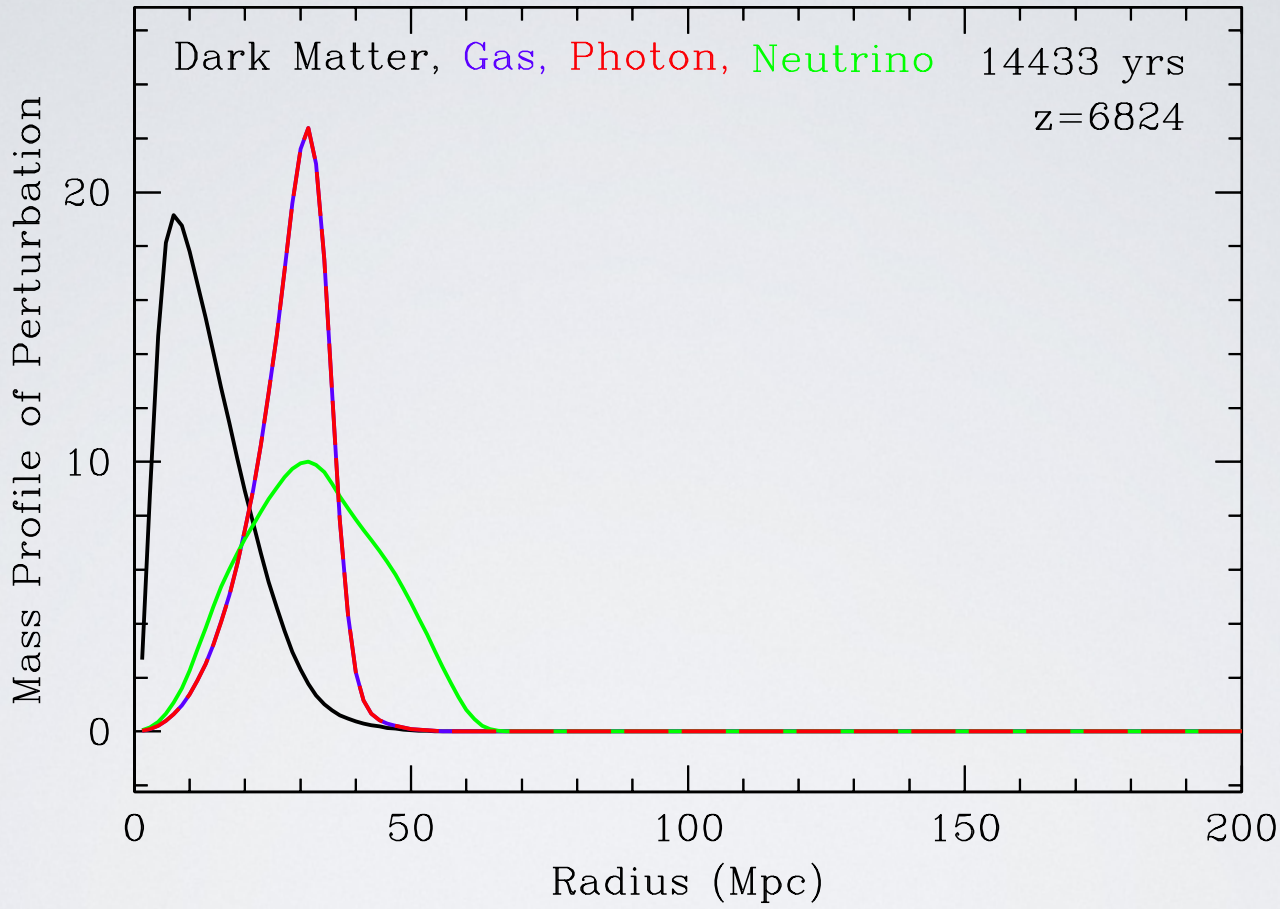

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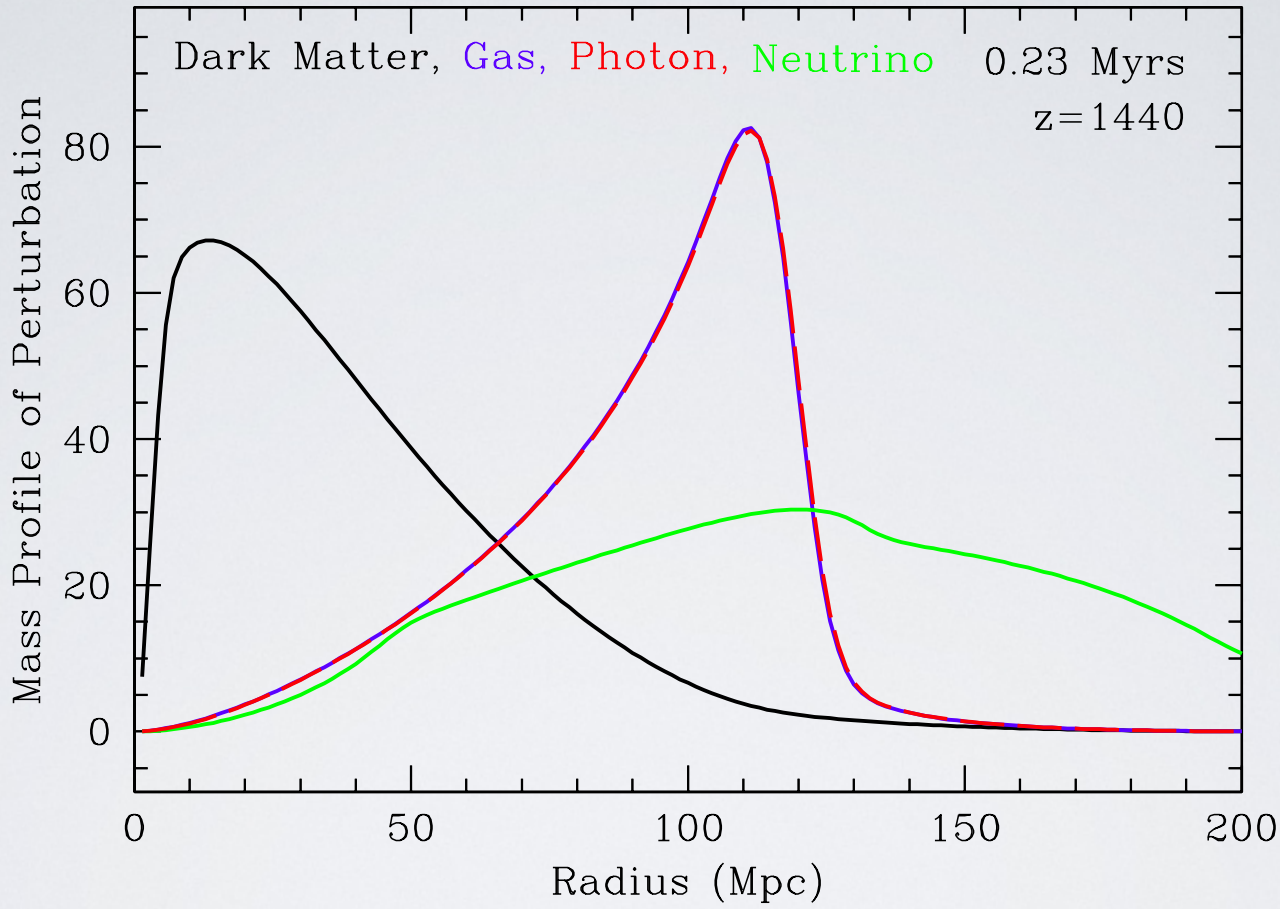

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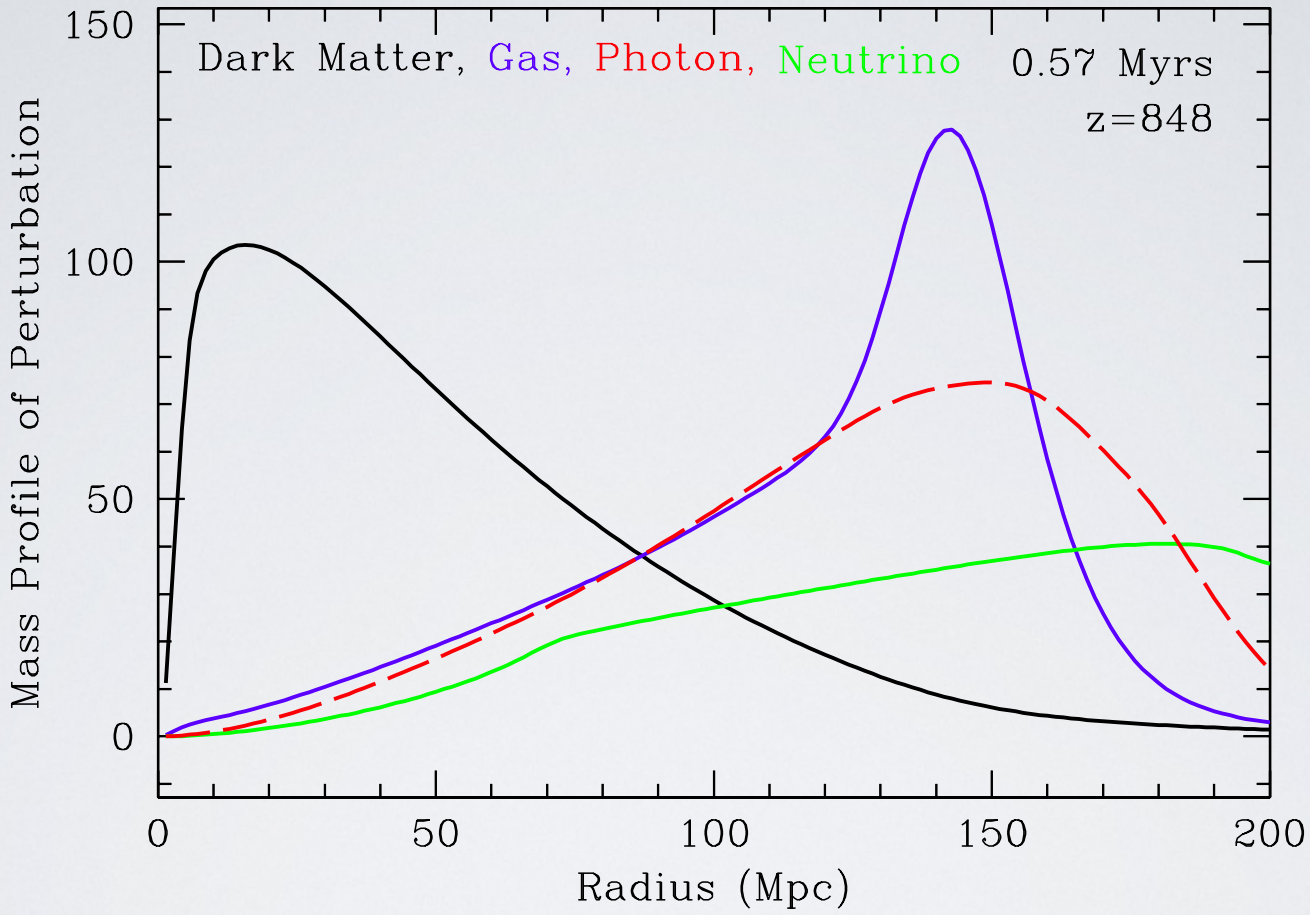

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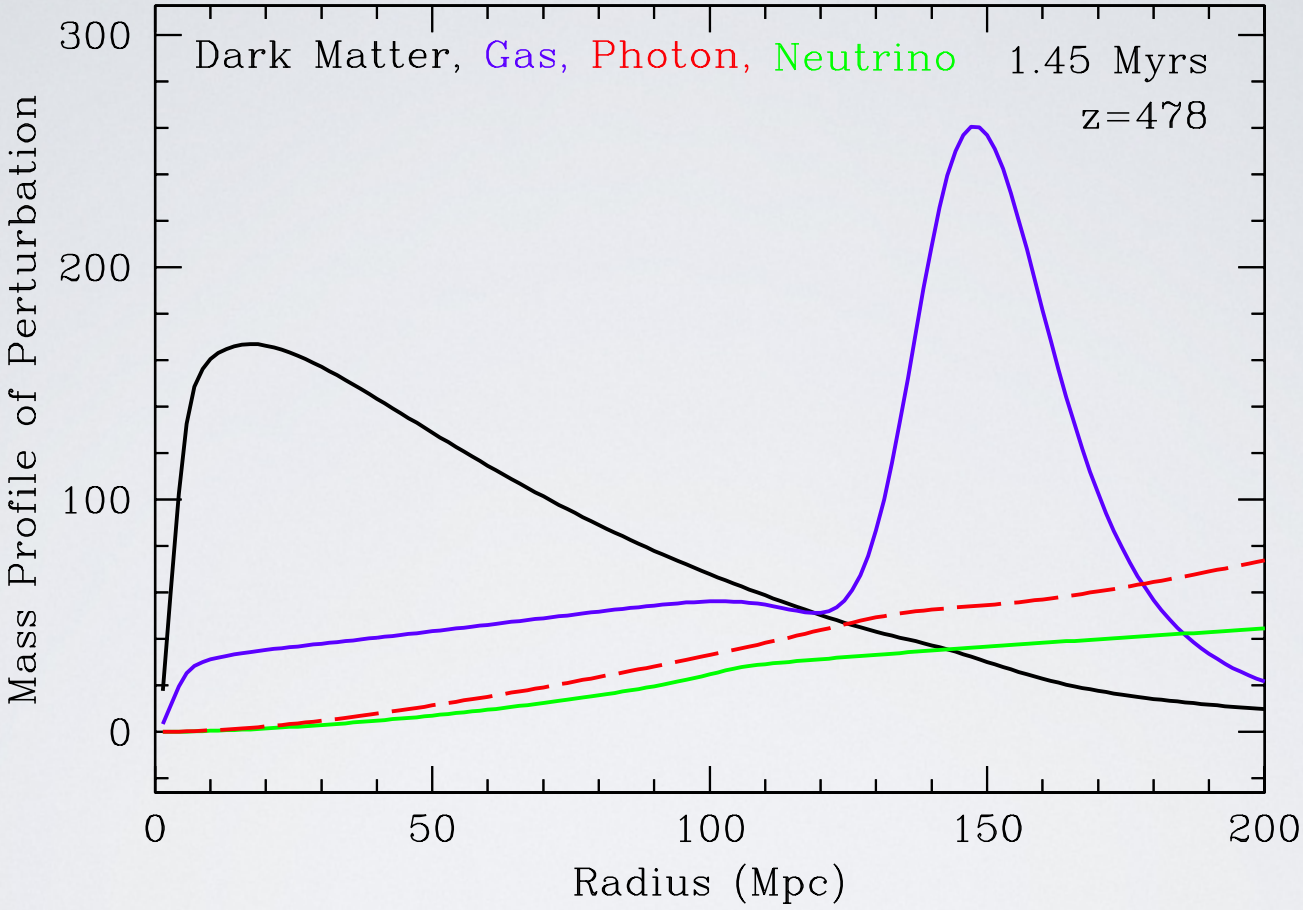

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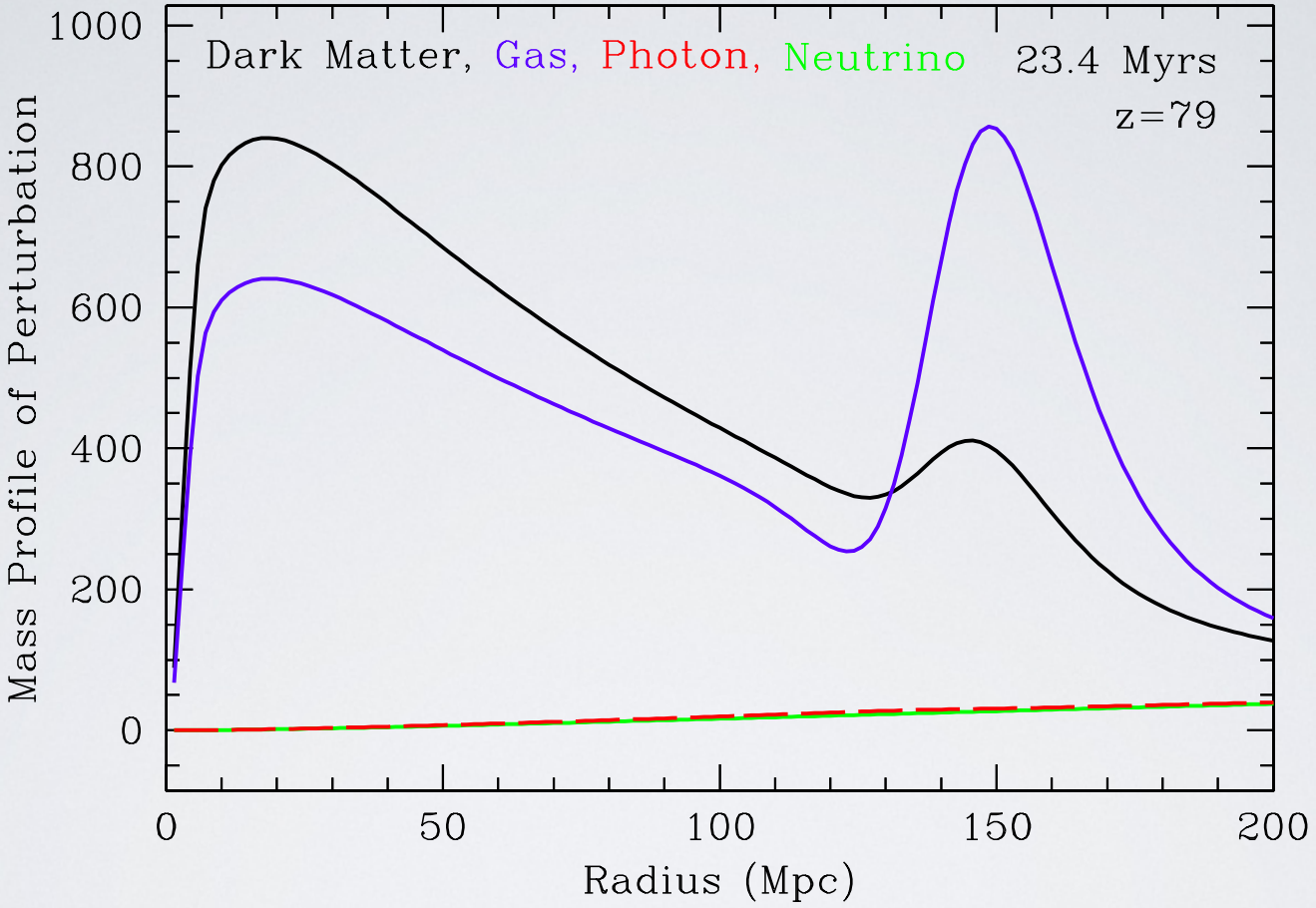

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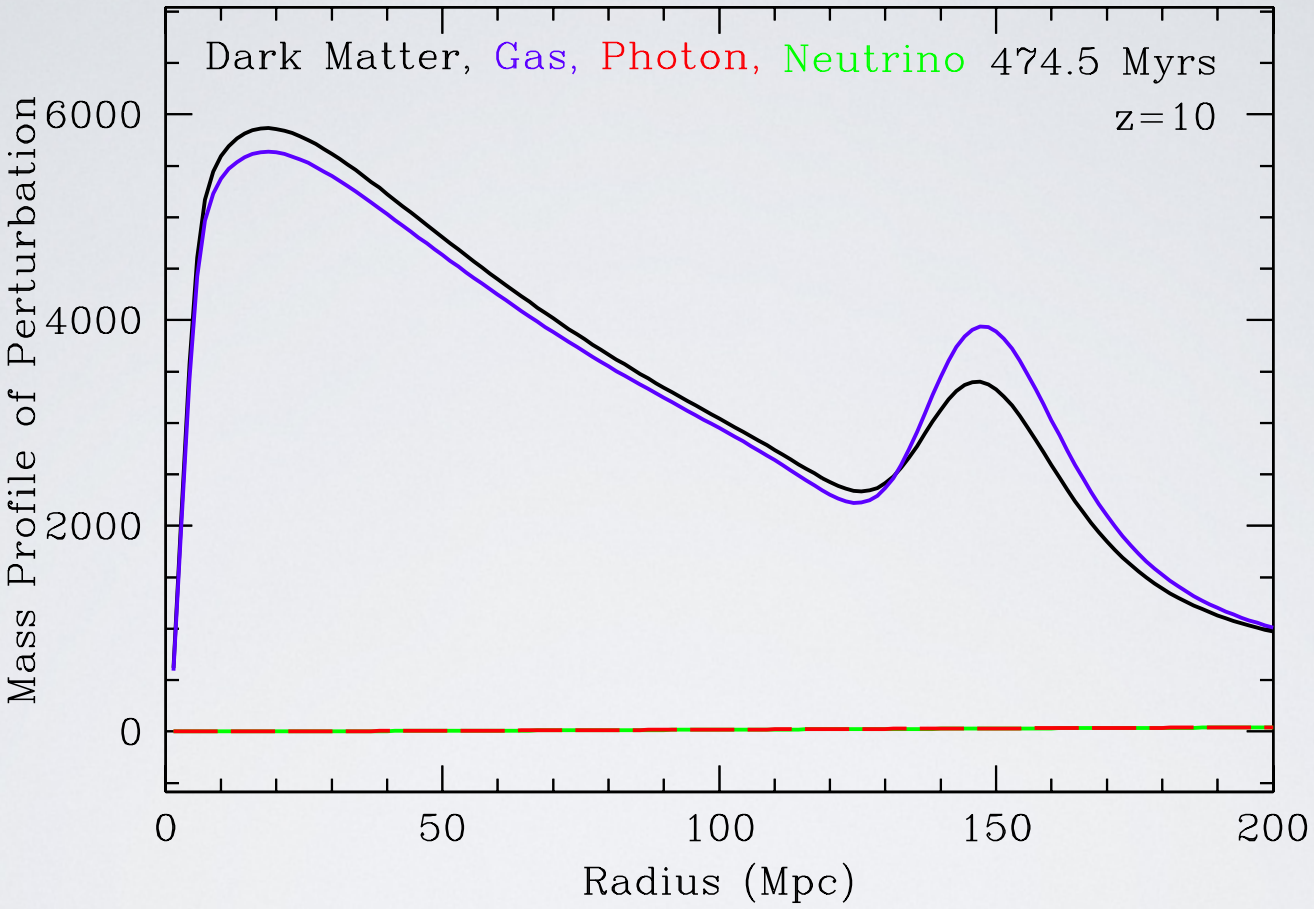
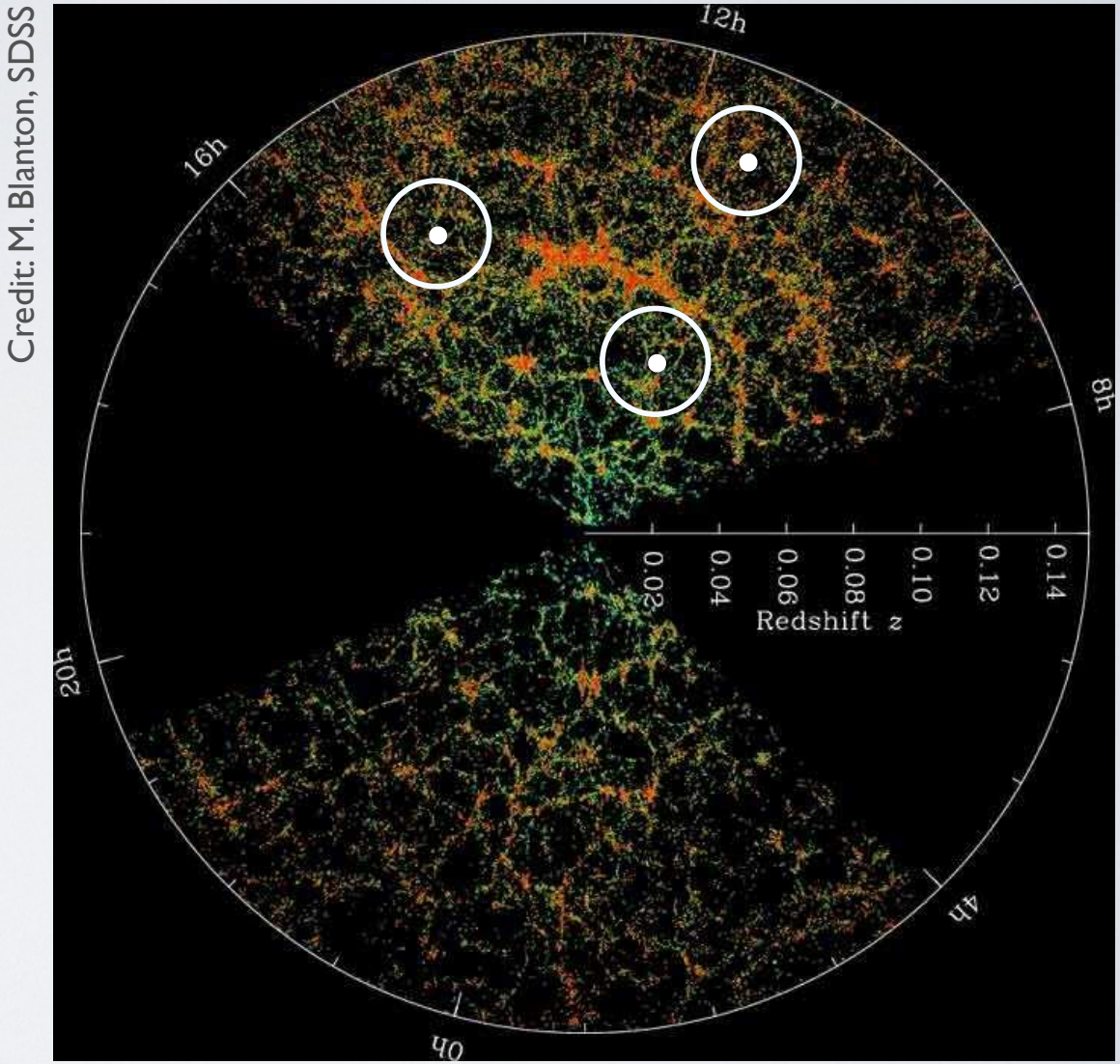


Eisenstein, Seo, and White (2007)

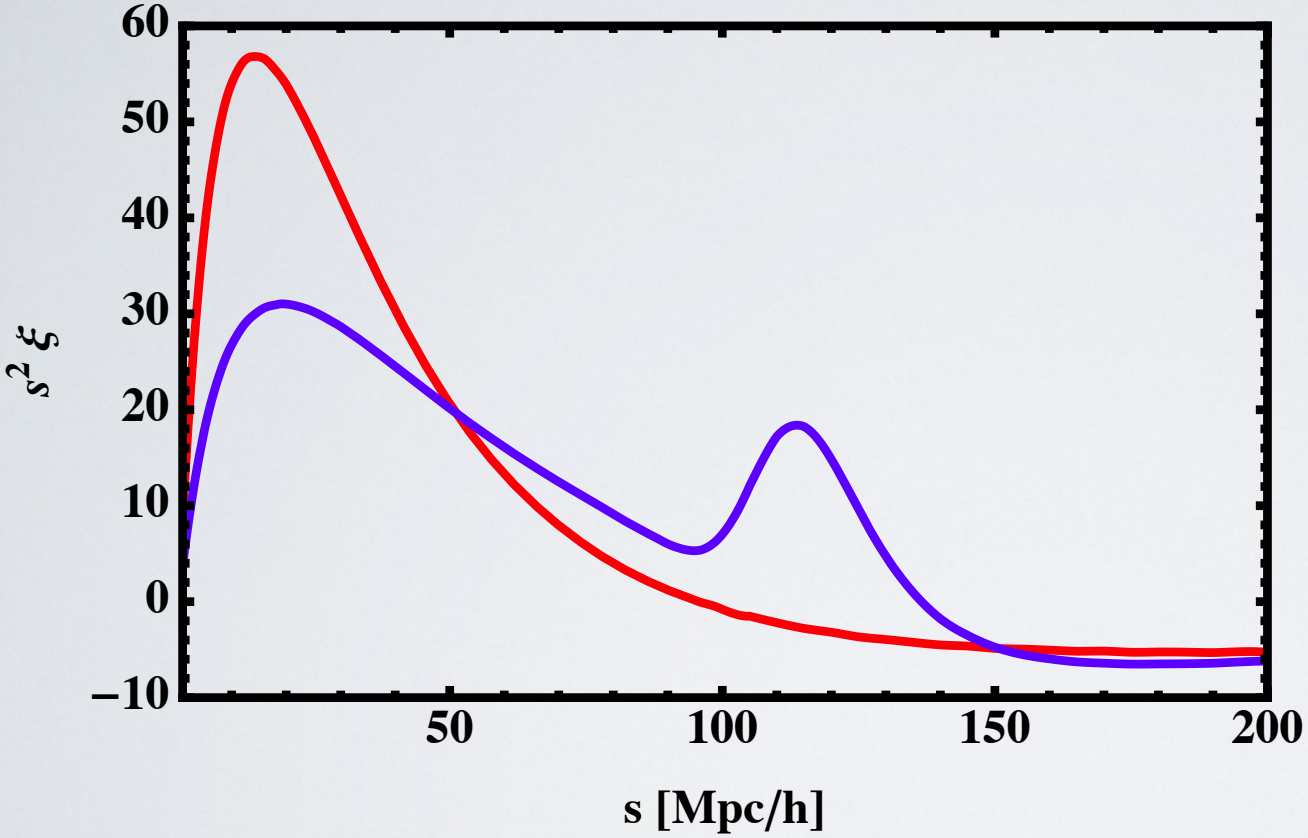
Galaxy survey

Real universe: superposition of over-densities → **statistical signal**.

- There is a larger probability to find galaxies separated by $150\ \mathrm{Mpc}$.
- The two-point correlation function has a **bump** at the sound horizon.



Correlation function



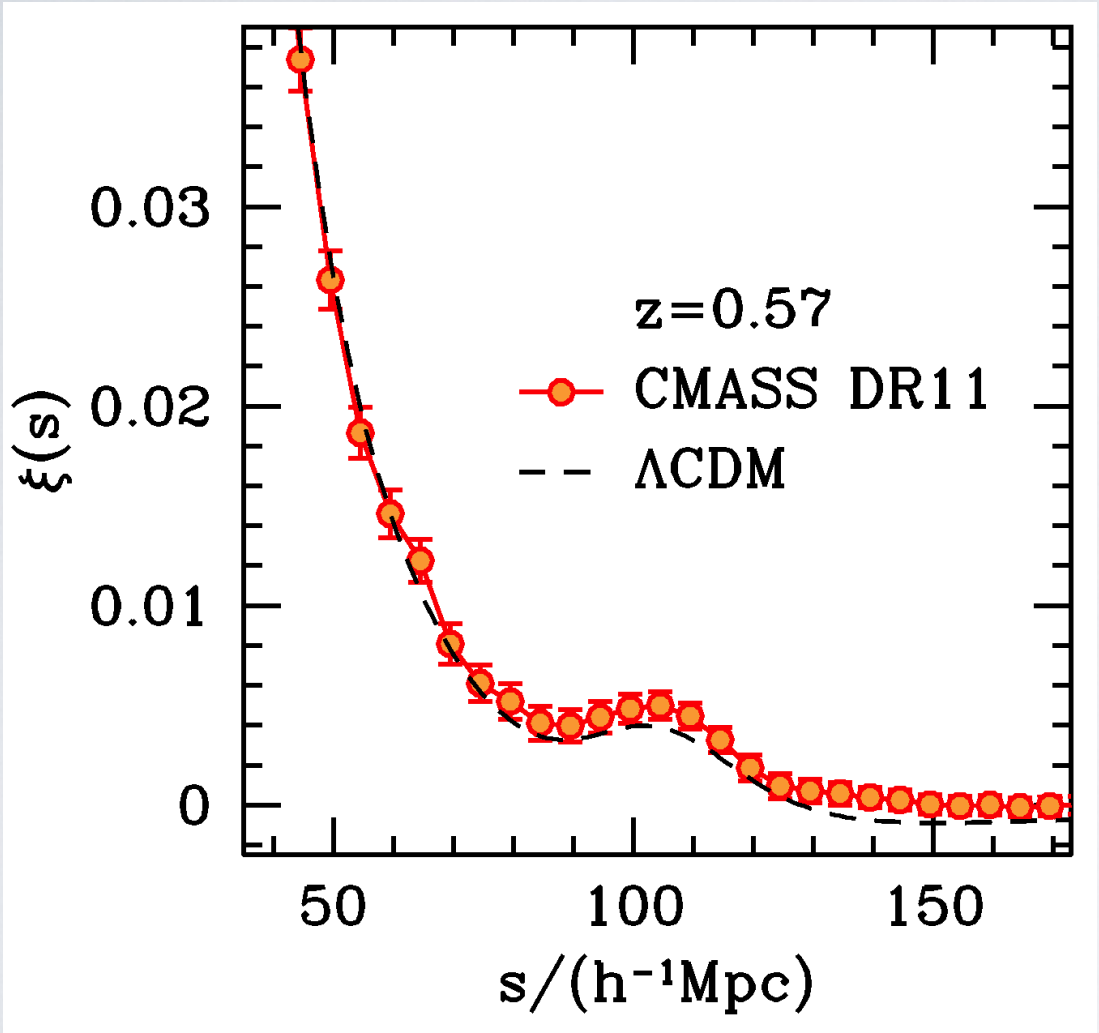
Peak at:

$150\ \mathrm{Mpc} \simeq 110\ \mathrm{Mpc}/h$

Direct signature of baryons: no bump in a dark matter only universe.

Correlation function

SDSS III, arXiv:1312.4854



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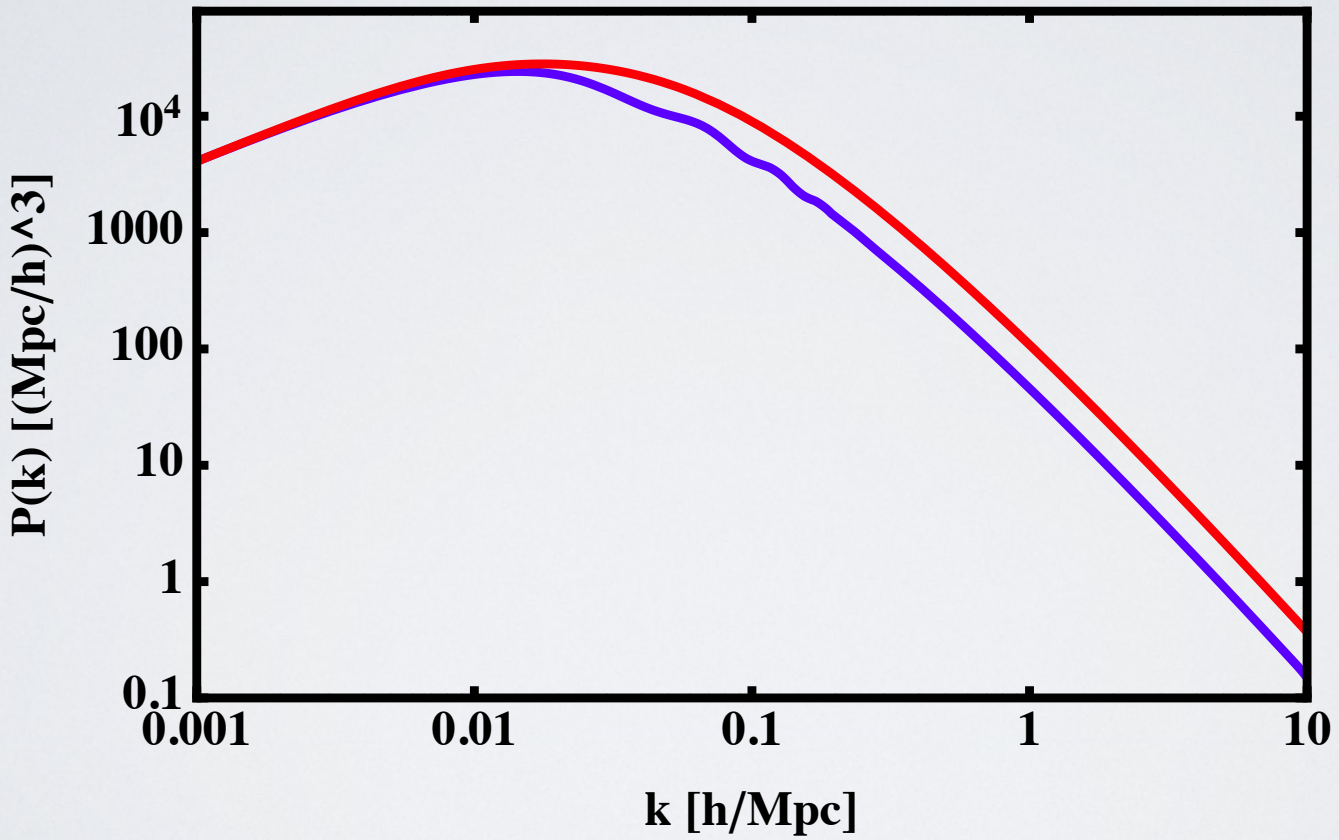
Power spectrum

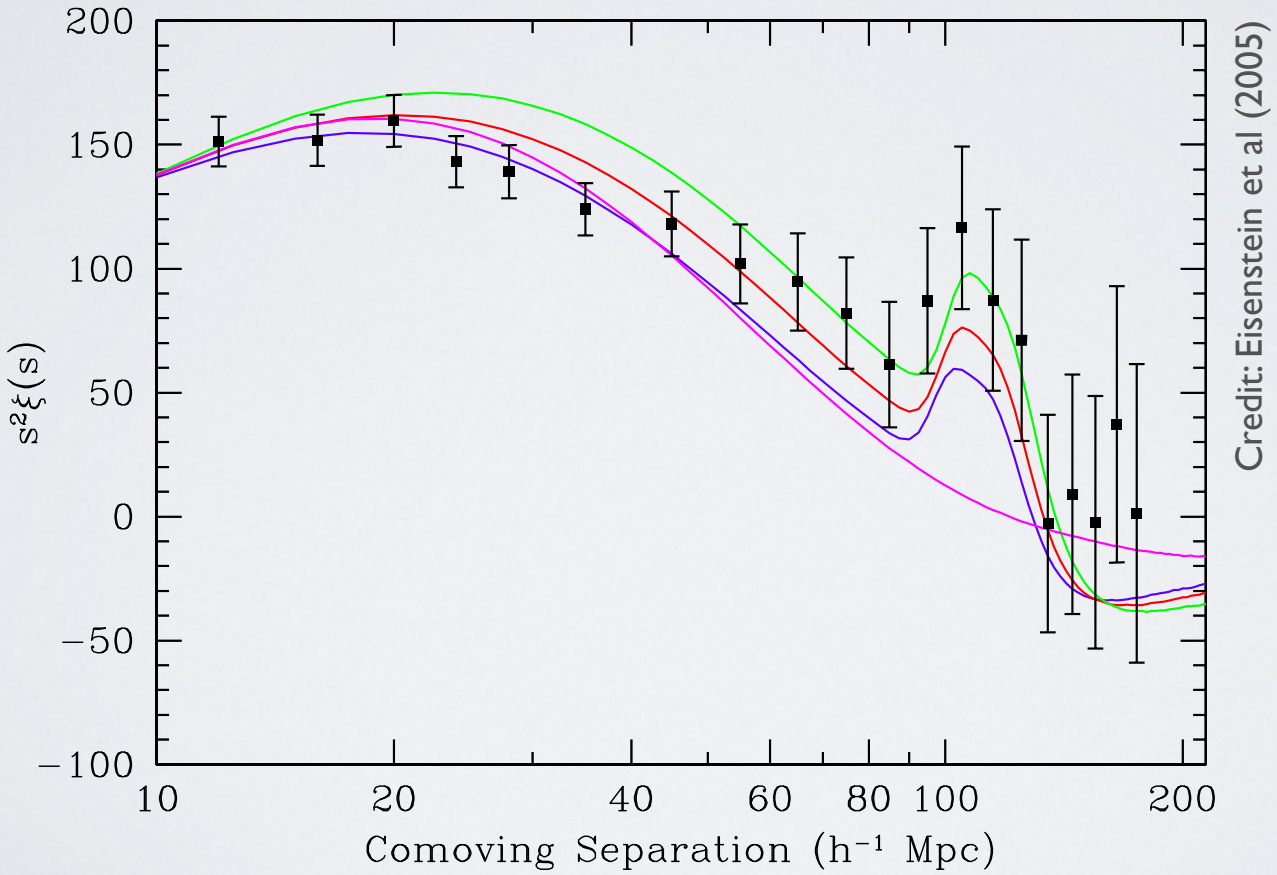
The bump in the correlation function translates into **oscillations** in the power spectrum.



Information

What can we learn from the BAO?

The **amplitude** of the peak depends on the baryons-dark matter ratio



Sound horizon

Position of the peak: distance travelled by the fluid from the big bang until recombination = **sound horizon**.

$$s_h = \int_0^{\eta_{\rm rec}} d\eta \; c_S = \int_{z_{\rm rec}}^{\infty} dz \; \frac{c_S}{H(z)}$$

Sound speed: $$c_S = \frac{1}{3\left(1 + \frac{3\rho_b}{4\rho_\gamma}\right)}$$

The sound horizon depends on:

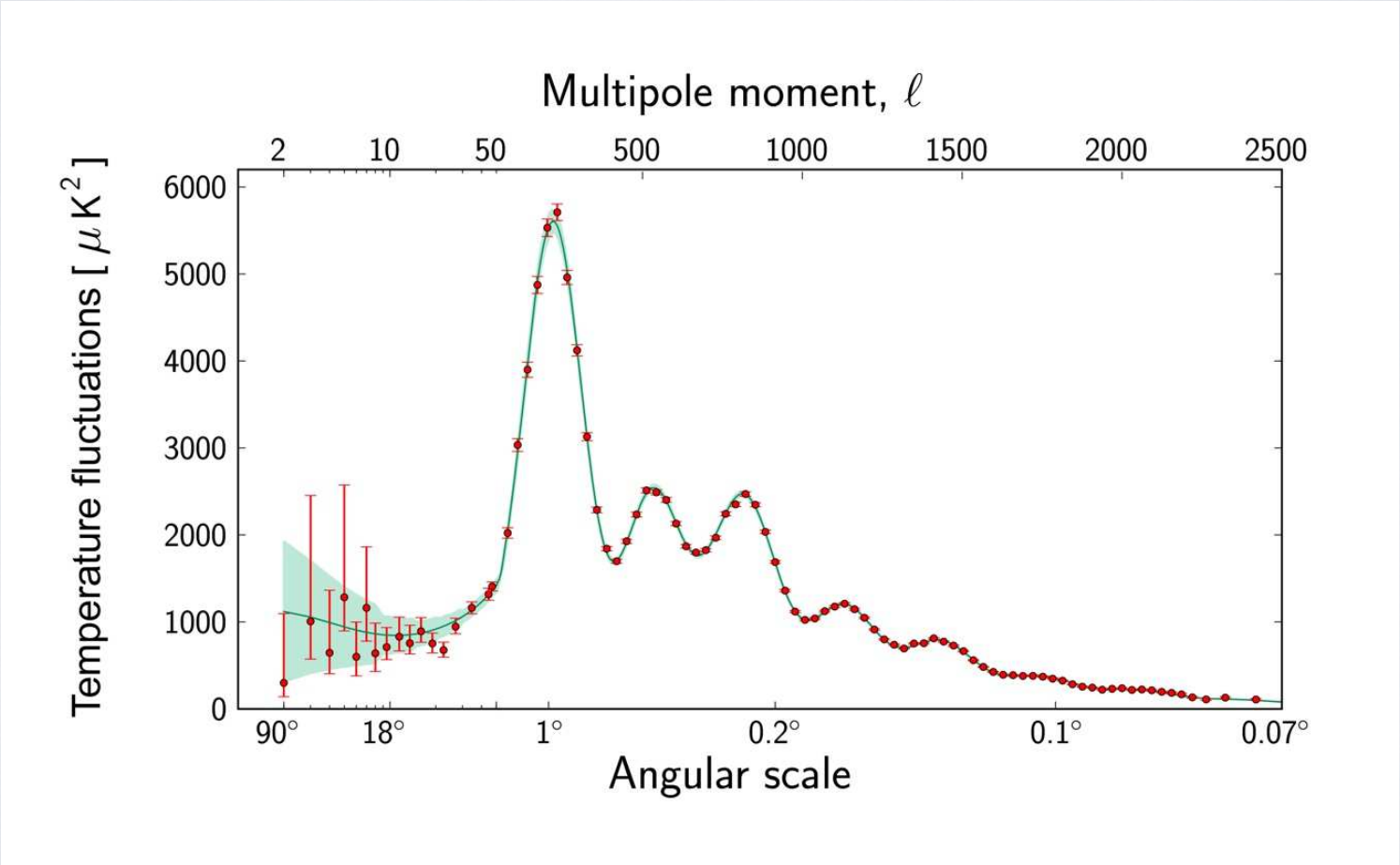
- **Baryon-photon** ratio: more baryon → smaller velocity.
- Time of **decoupling**
- **Expansion** rate from the big bang until recombination.

The position of the bump allows to measure these quantities.

Sound horizon in the CMB

The sound horizon can be measured in the CMB.

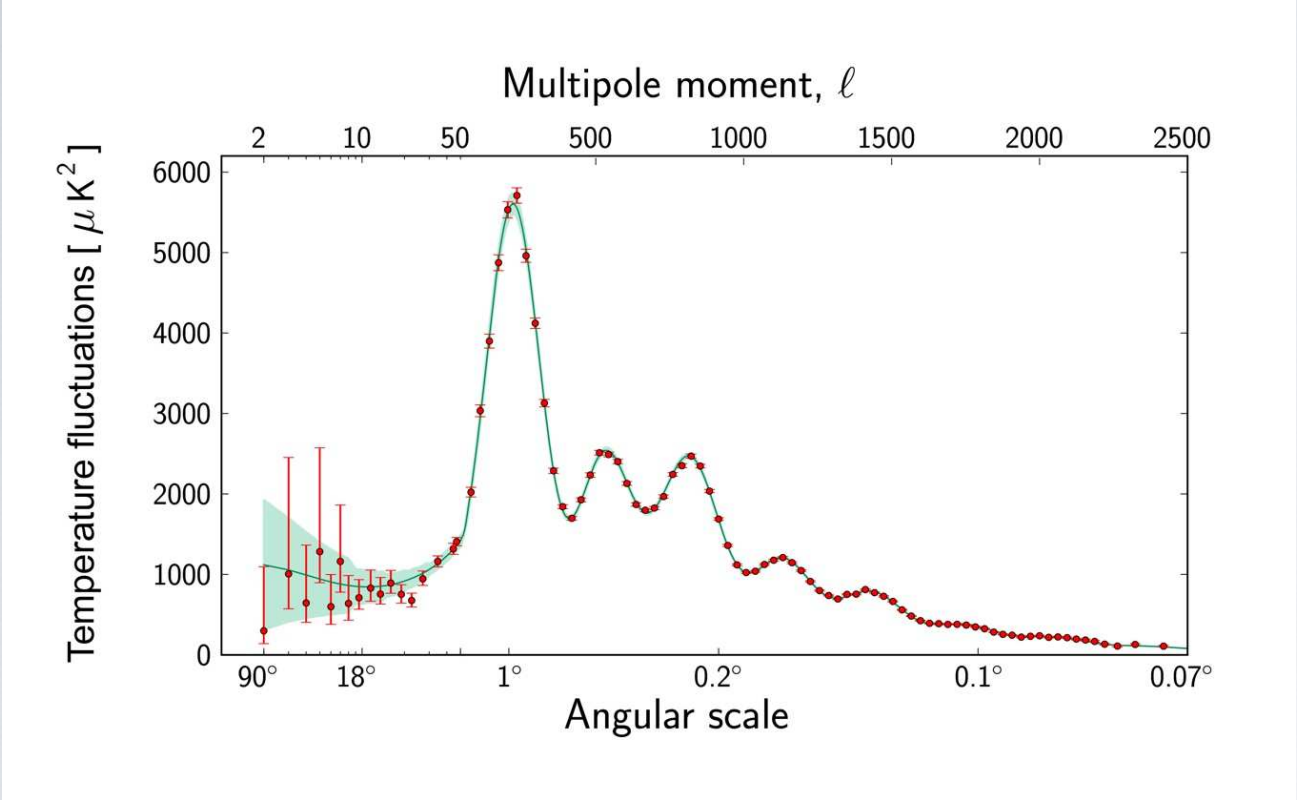
The baryon acoustic **oscillations** are imprinted in the CMB **temperature**.



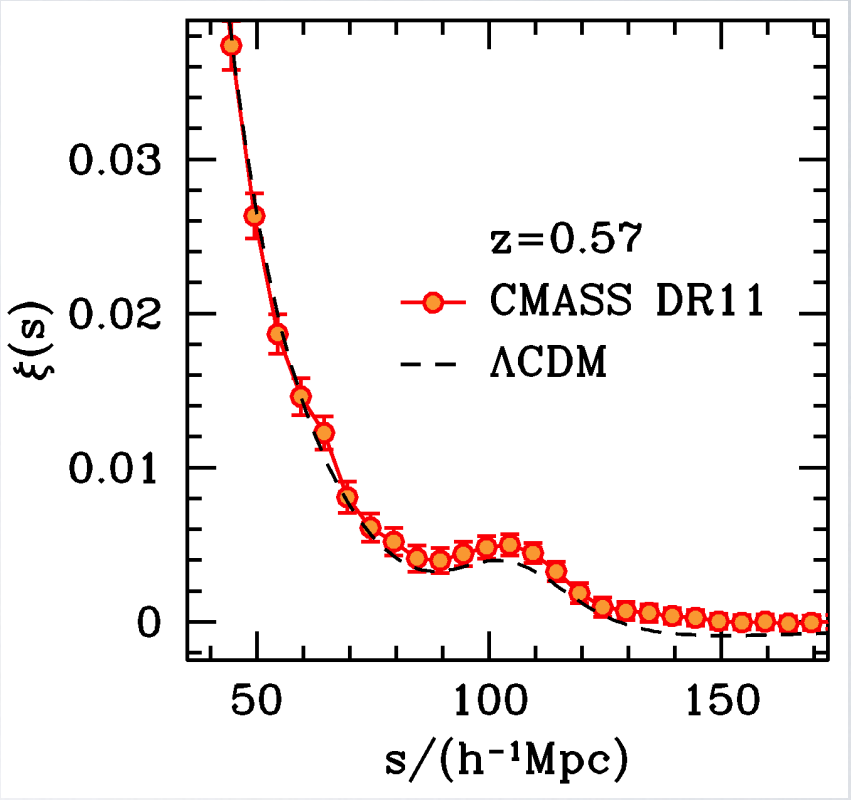
ESA and the Planck Collaboration

Comparison

CMB



Galaxy correlations



Order one effect

One **percent** effect

Why is it interesting to measure the BAO scale?

Standard ruler

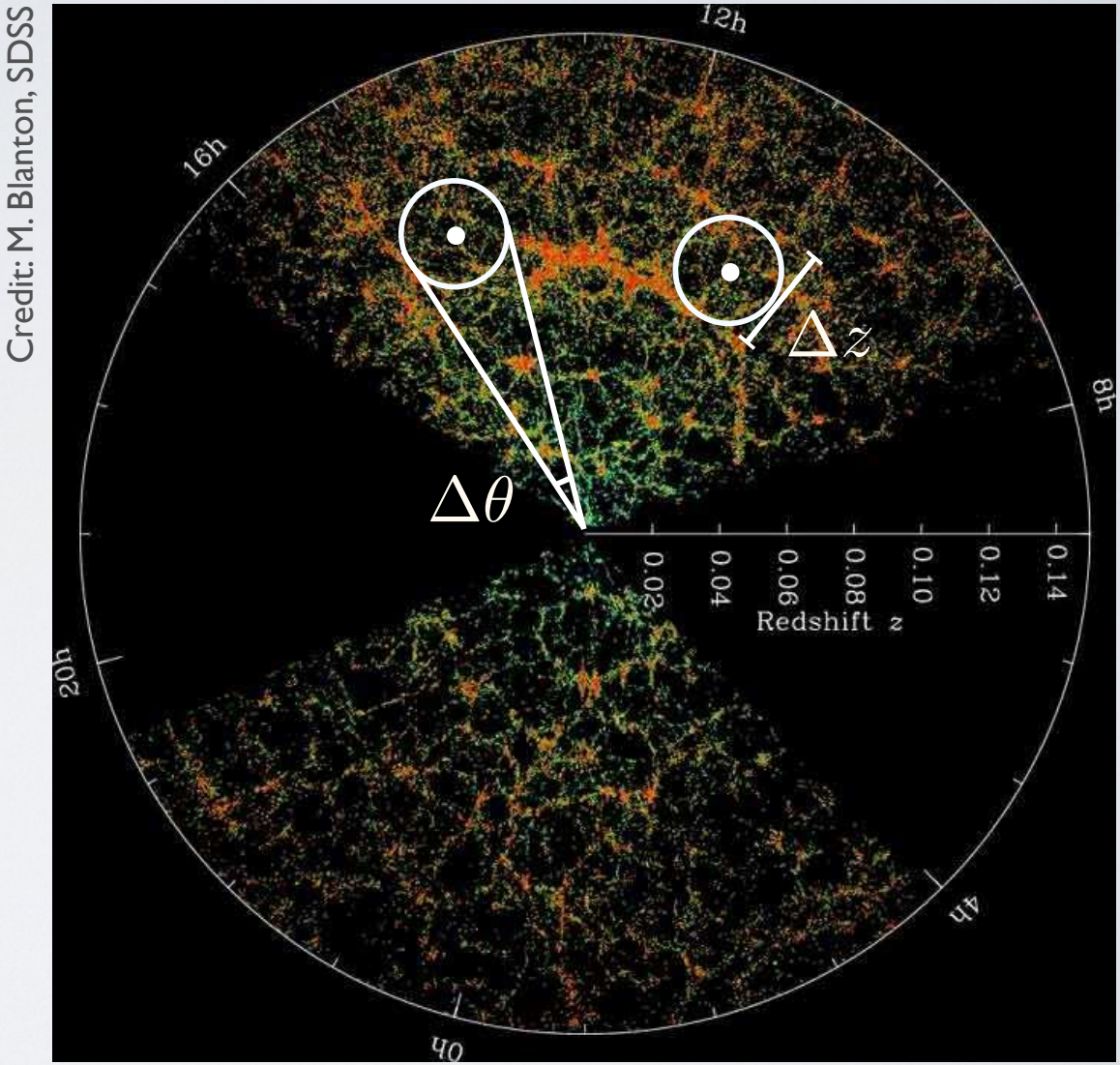
BAO provide a **standard ruler** → measure the **expansion** rate.

The correlation function peaks at a **comoving** distance of 150 Mpc.

We measure:

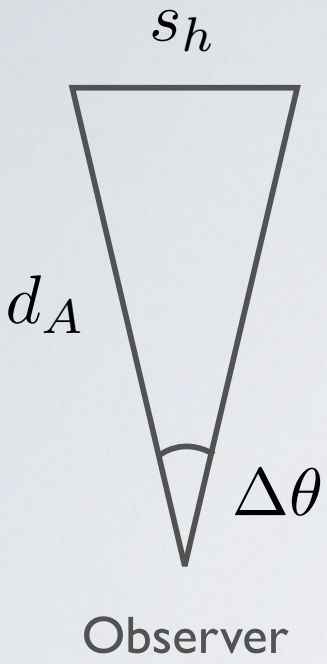
- **angular** separations
- **redshift** separations

Observed bump at:
$\Delta\theta$ and Δz



Transverse BAO

We can relate $\Delta\theta$ and Δz to s_h (known from CMB)



$$s_h = d_A \cdot \Delta\theta$$

known measured

We infer $$d_A(z) = \frac{1}{1+z}\int_0^z dz' \frac{1}{H(z')}$$

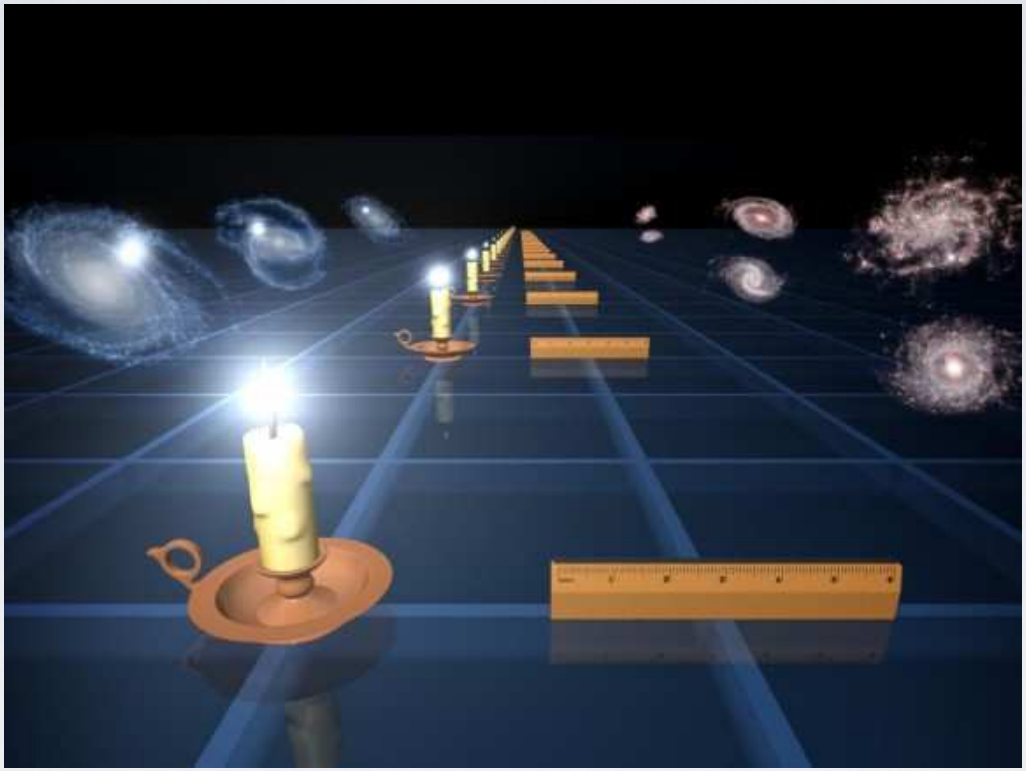
Measuring $\Delta\theta$ provides a measure of the **expansion rate**.

In a flat universe with a cosmological constant:

$$d_A(z) = \frac{1}{1+z}\int_0^z dz' \frac{1}{\sqrt{\Omega_r(1+z')^4 + \Omega_m(1+z)^3 + \Omega_\Lambda}}$$

Luminosity distance

The transverse measurement is very similar to luminosity distance measurements from **supernovae** .

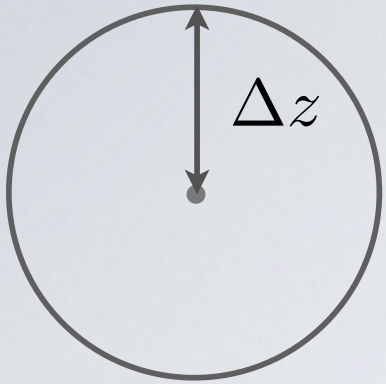


Credit: NASA/JPL-Caltech/R. Hurt (SSC)

We know the intrinsic **luminosity**, measure the **flux** and infer the distance.

We know the intrinsic **size**, measure the **angular size** and infer the distance.

Radial BAO



Relation between Δz and s_h

$$dt = a dr \qquad dt = \frac{dt}{da}\frac{da}{dz} dz$$

$$\frac{1}{\dot{a}} = \frac{a}{H}$$

$$s_h = \frac{1}{H(z)} \Delta z$$

Measure H directly!

Without separation between transverse and radial distance, the BAO peak is measured at the **average distance**

$$D_V(z) = \left[z(1+z)^2 \, d_A^2(z) H^{-1}(z) \right]^{1/3}$$

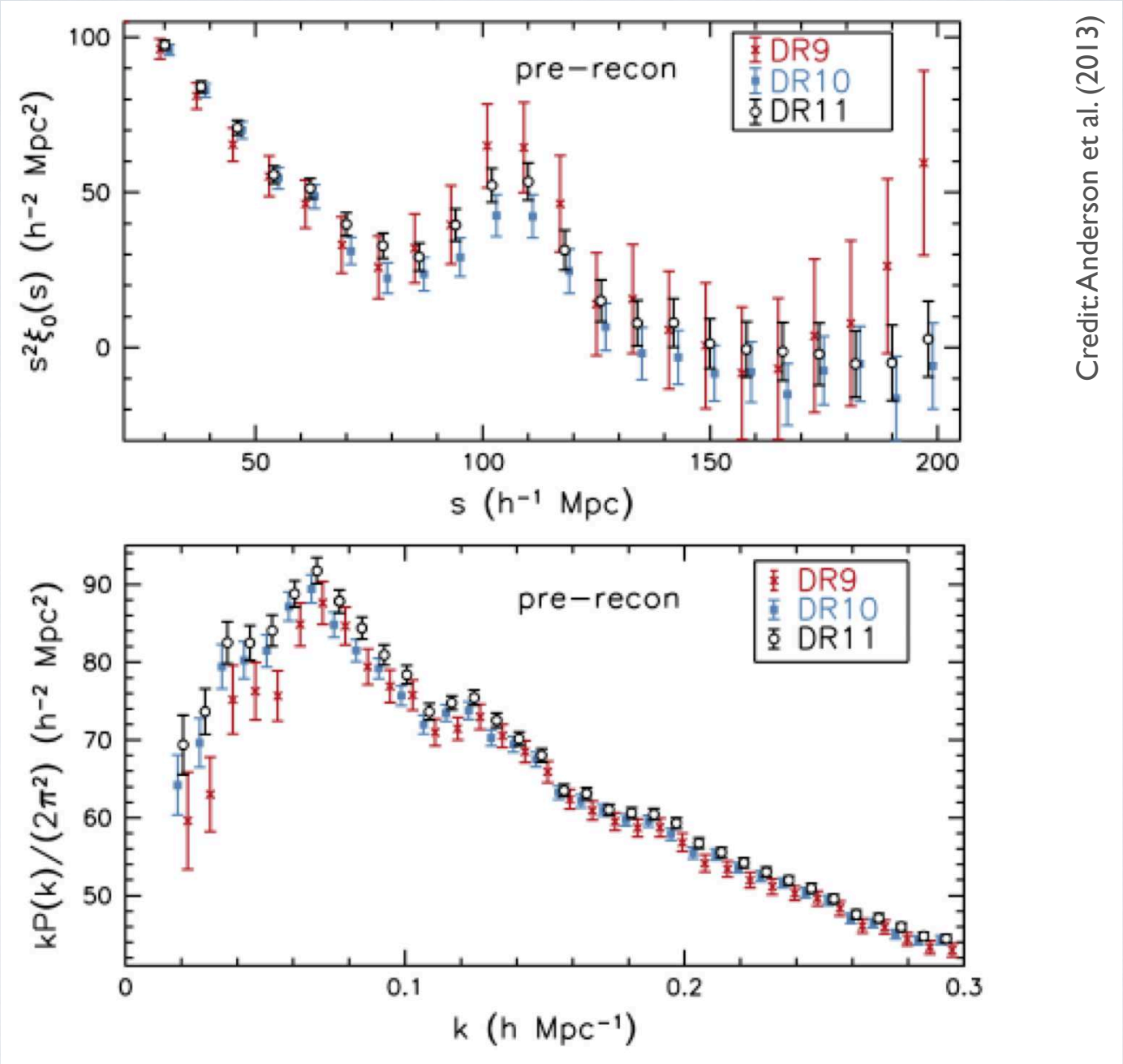
Observations

The second effect of baryons is less noticeable on Figure 7.13 and indeed may never get measured in real life either. [...] It is the traces of these oscillations that are imprinted on the matter transfer function. They are barely (if at all) detectable because baryons are such a small fraction of the total matter. Dodelson: Modern Cosmology p. 209

- What is the **amplitude** of the BAO excess in terms of the **number** of galaxies? **Bassett (2012)**
- Let's pick up one galaxy in the survey and calculate the average **number** of galaxies in a **BAO shell**.
- Typical number density: $n \sim 10^{-4}\ \mathrm{Mpc}^{-3}$
- Volume of shell: $V = 4\pi \cdot 150^2 \cdot 5\ \ \mathrm{Mpc}^3 \sim 10^6\ \ \mathrm{Mpc}^3$
- Random distribution: 100 galaxies in the shell.

BAO excess 1% → **one** extra galaxy!

BOSS results



Credit: Anderson et al. (2013)

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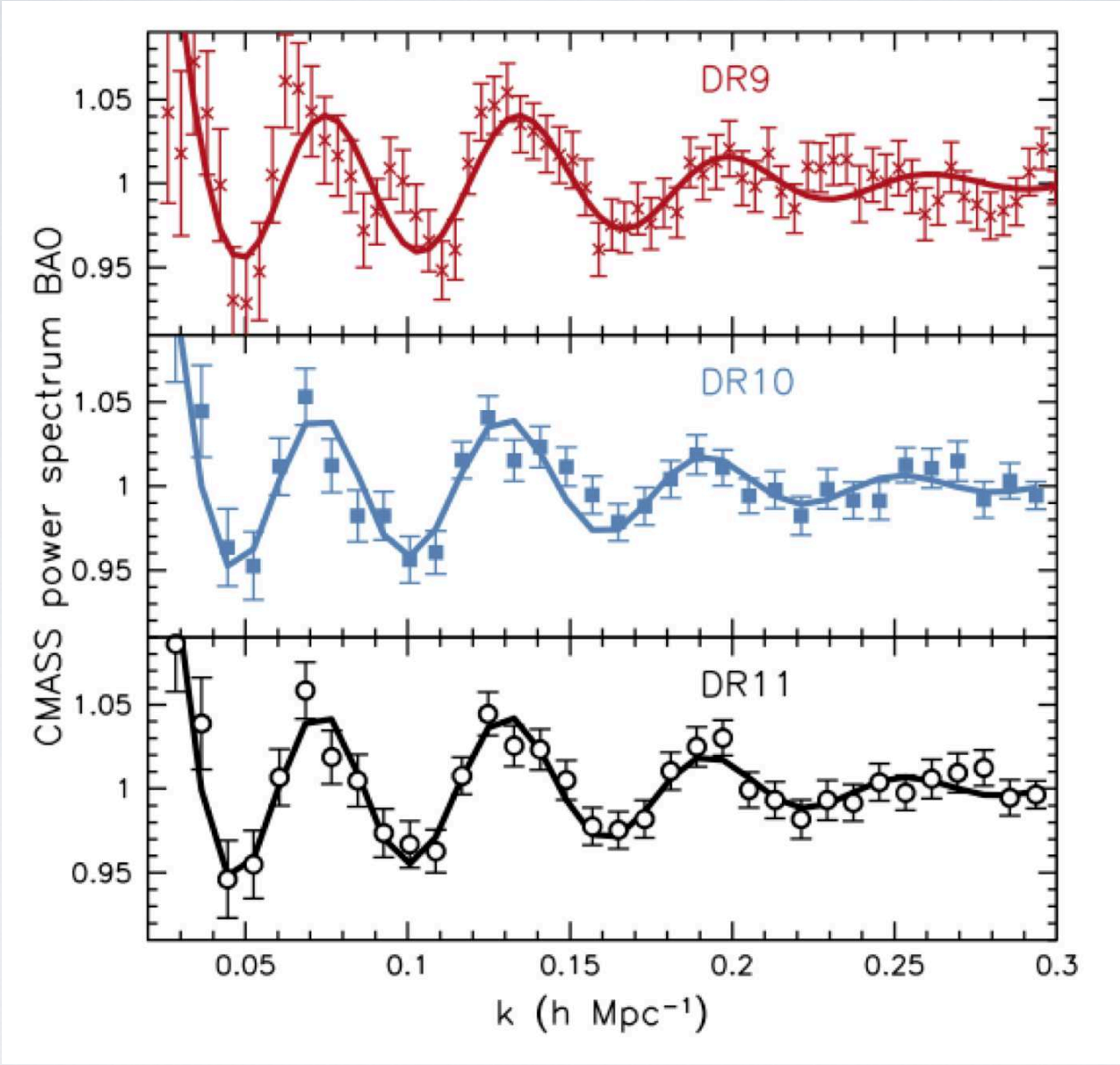
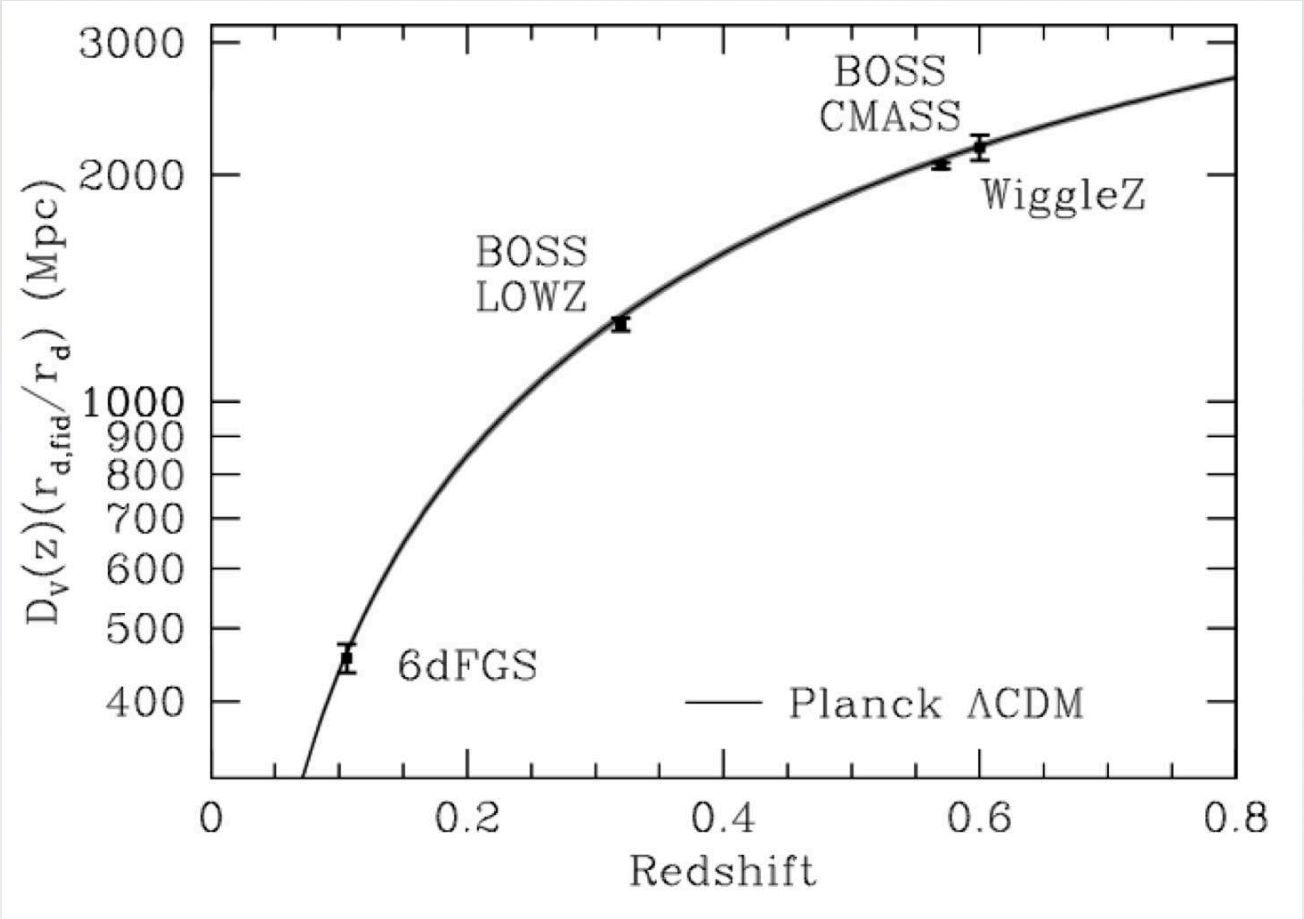


Credit: Anderson et al. (2013)

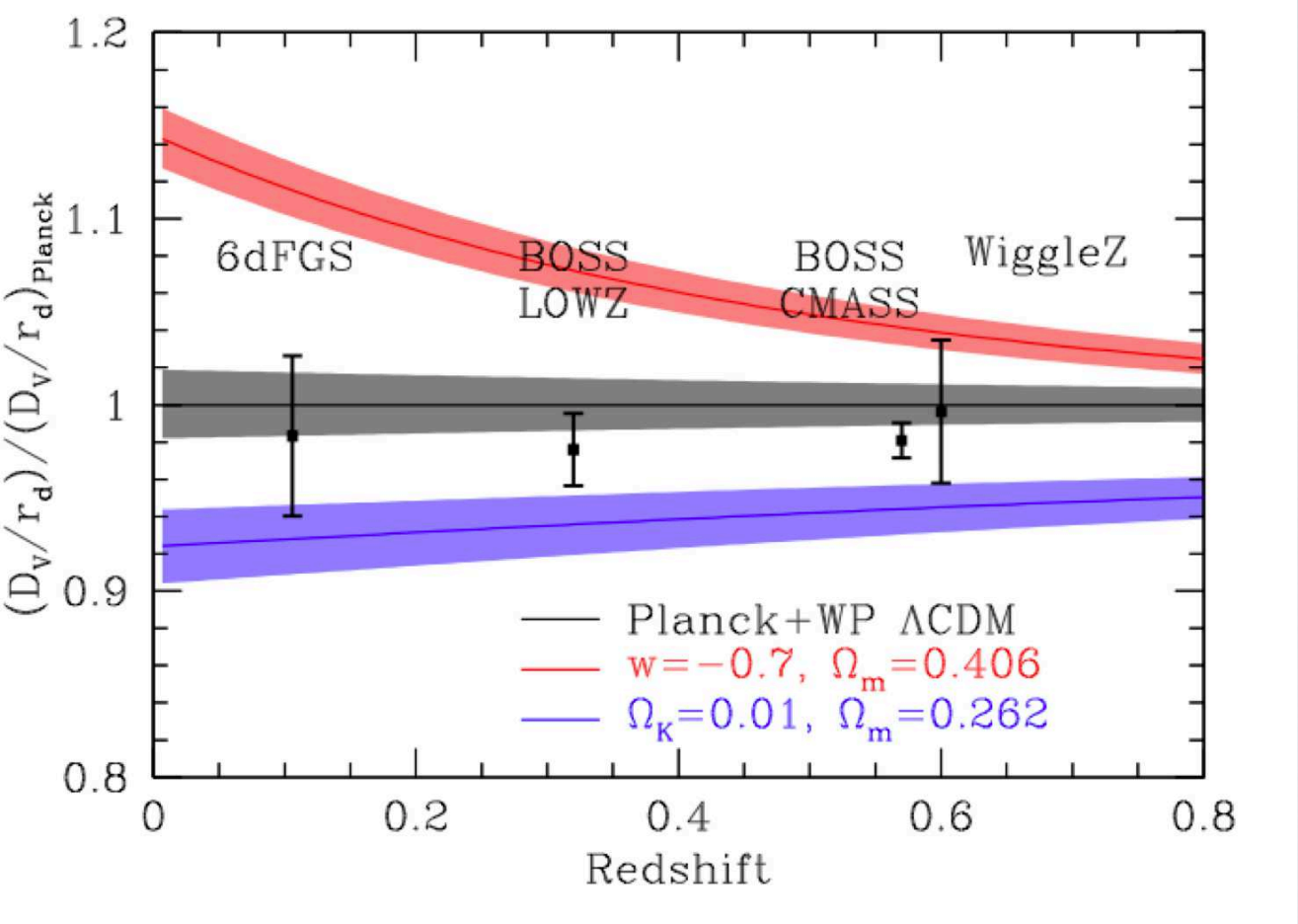
Divided by the smooth spectrum

Distance measurements



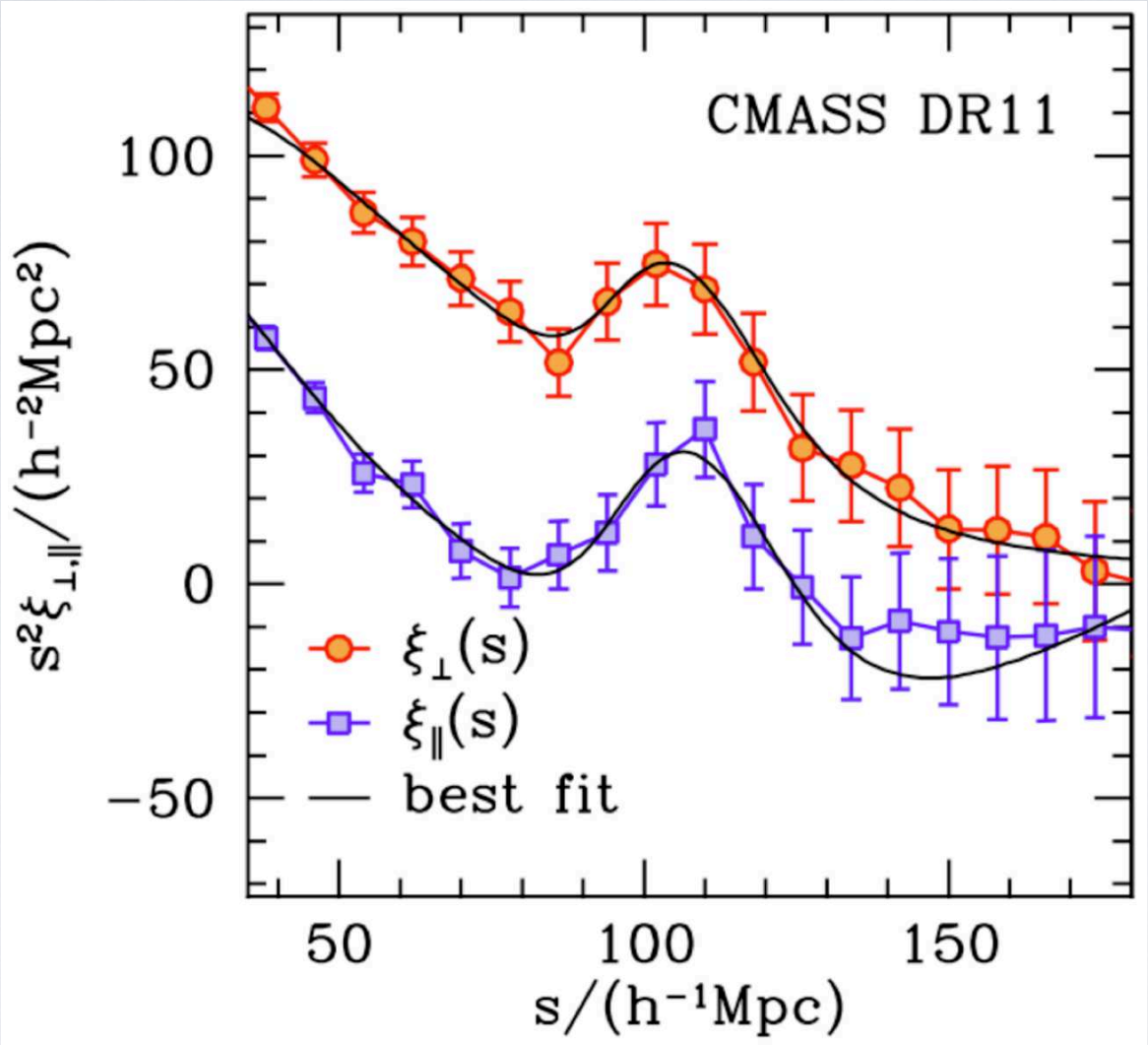
Credit: Anderson et al. (2013)

Accelerating universe



Credit: Anderson et al. (2013)

Separation: radial and transverse



Credit: Anderson et al. (2013)

Direct measurement of d_A and H at $z = 0.57$