Summary

- Calculation of the dark matter power spectrum.

- Evolution of δ_{dm}

$$\delta''_{dm} + \mathcal{H}\delta'_{dm} = -k^2\Phi + 3\mathcal{H}\Phi' + 3\Phi''$$

- Evolution of Φ

$$\Phi'' + 3(1 + c_S^2)\mathcal{H}\Phi' + c_S^2 k^2 \Phi = 0$$

valid for constant $c_S^2 = w$

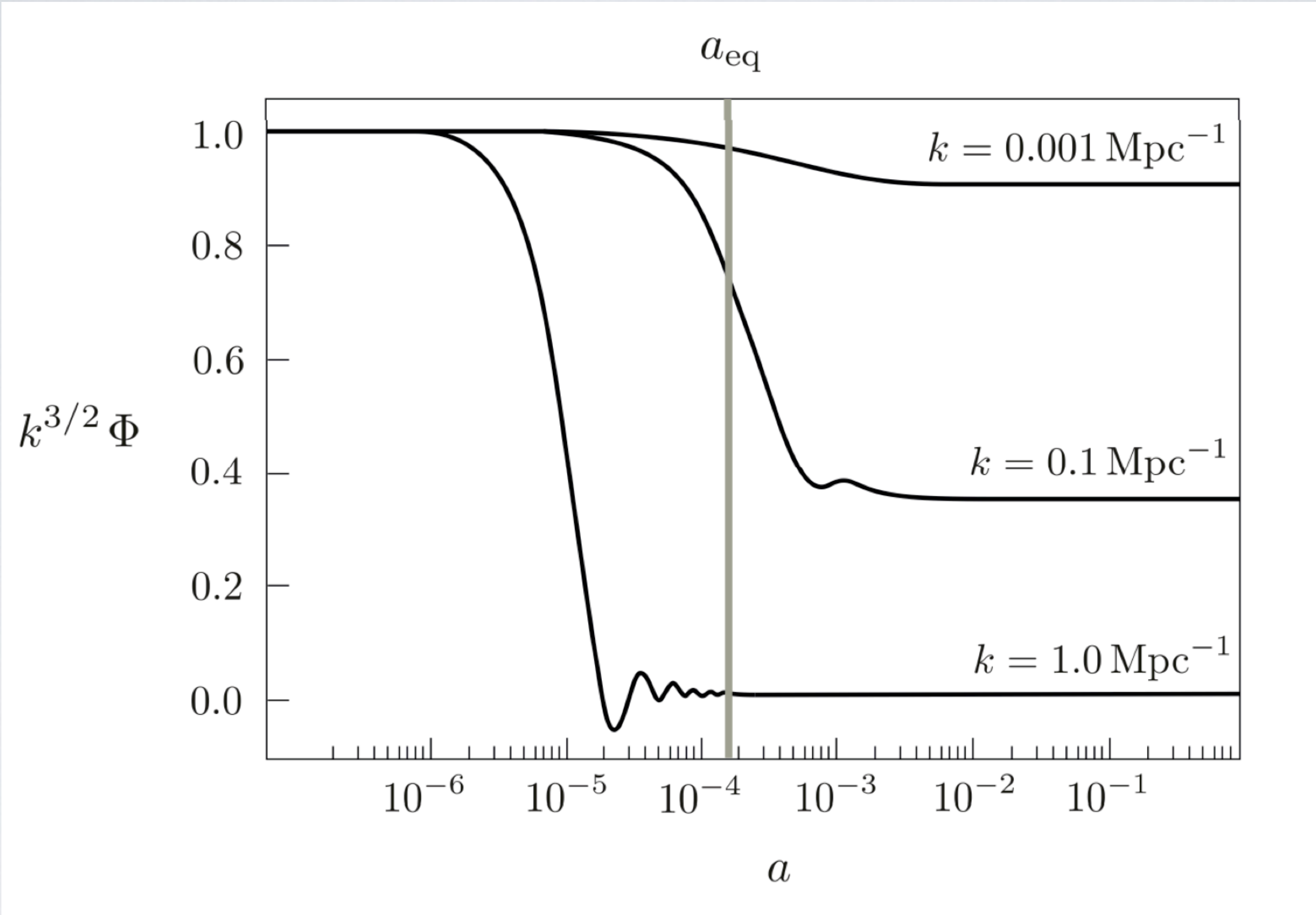
- Solution at three different stages

  modes are outside the horizon

  modes are inside the horizon during radiation domination

  modes are inside the horizon during matter domination

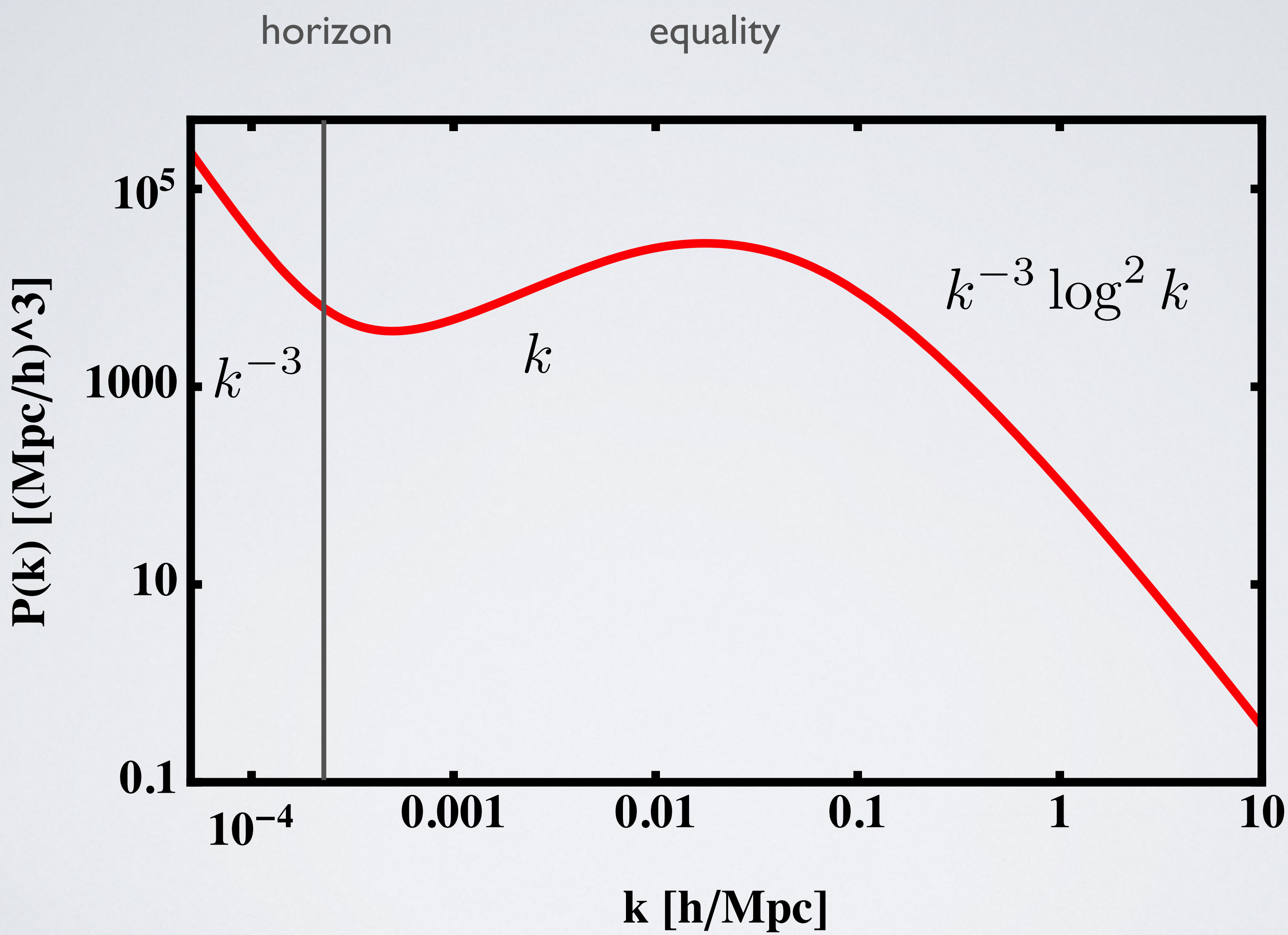
Summary



Credit: D. Baumann, cosmology lecture

Summary

Use the solution to calculate the dark matter perturbations



Summary

- How dark energy modifies the power spectrum.

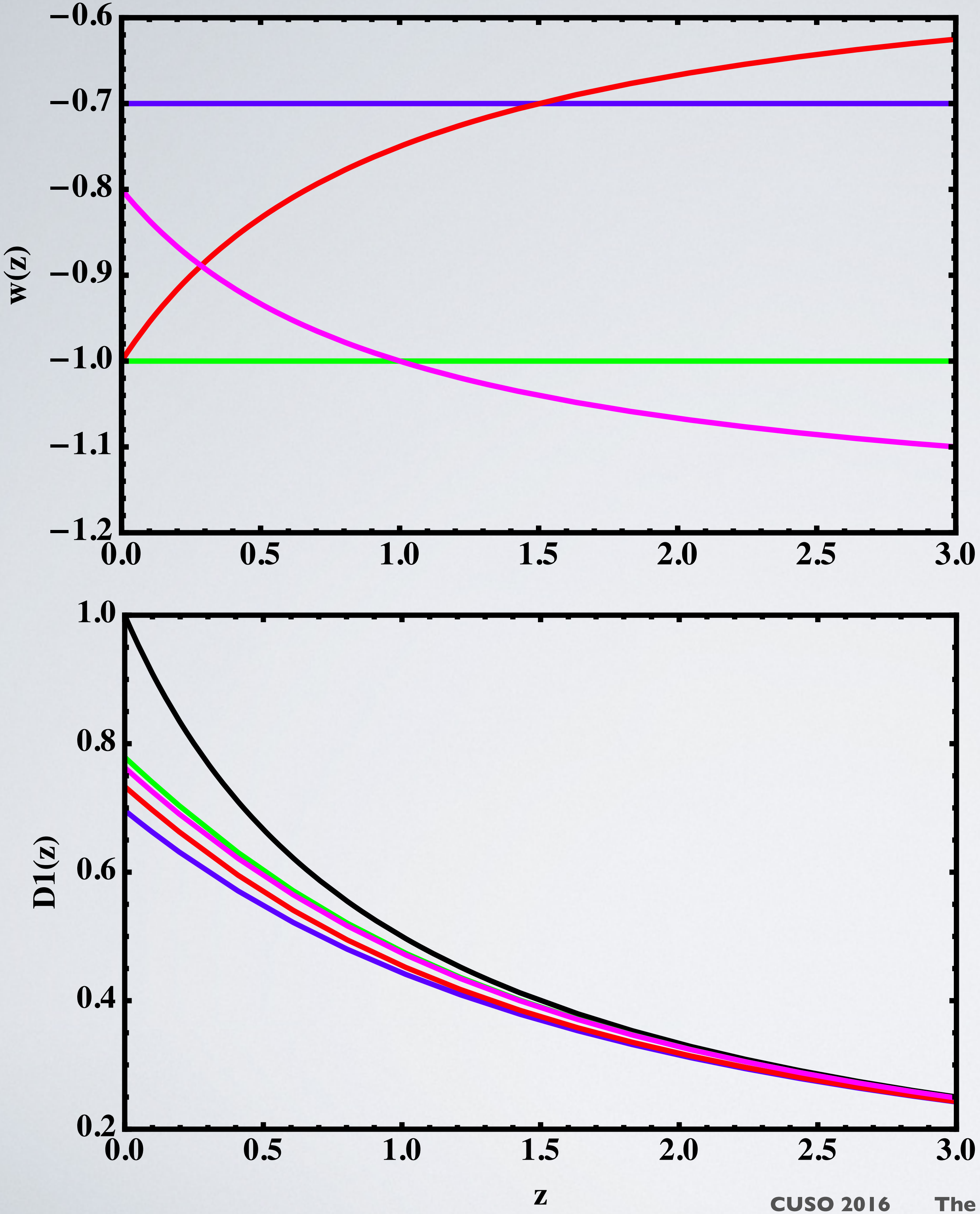
- If dark energy does not cluster, its impact is only through the background.

- Since dark energy started to dominate recently, all the scales are affected in the same way.

$$\delta_{dm}(\mathbf{k},\eta) = D_1(a)T_\delta(k)\Phi_p(\mathbf{k})$$

- Evolution equation for the growth rate.

$$\frac{d^2 D_1}{da^2} + \left(\frac{d\ln H}{da} + \frac{3}{a}\right)\frac{dD_1(a)}{da} - \frac{3}{2}\frac{\Omega_{m0}}{a^5}\left(\frac{H_0}{H}\right)^2 D_1(a) = 0$$



no dark energy

$w = -1$

$w = -0.7$

$w_0 = -1 \quad w_a = 0.5$

$w_0 = -0.8 \quad w_a = -0.4$

$$w = w_0 + w_a \frac{z}{1+z}$$

Summary

Redshift-space distortions

- We observe the redshift and not the distance.

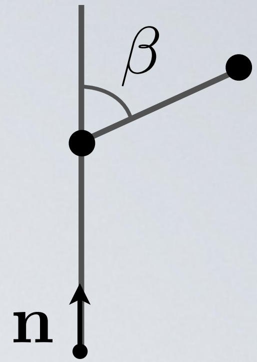
- The redshift is affected by inhomogeneities

$$1+z=\frac{a_O}{a_S}\left[1+(\mathbf{v}_S-\mathbf{v}_O)\cdot\mathbf{n}+\Psi_O-\Psi_S-\int_0^{r_S}dr(\dot\Phi+\dot\Psi)\right]$$

- The observed distance between the observer and the galaxy is modified.

$$\delta_{\rm obs}=\delta-\frac{1}{\mathcal{H}}\partial_r(\mathbf{v}\cdot\mathbf{n})$$ at leading order in $k/\mathcal{H}$

Summary



- Calculation of the correlation function

monopole

quadrupole

$$\xi = D_1^2\left\{\left(b^2+\frac{2bf}{3}+\frac{f^2}{5}\right)\mu_0(s)-\left(\frac{4bf}{3}+\frac{4f^2}{7}\right)\mu_2(s)P_2(\cos\beta)\right.$$
$$\left.+\frac{8f^2}{35}\mu_4(s)P_4(\cos\beta)\right\}$$

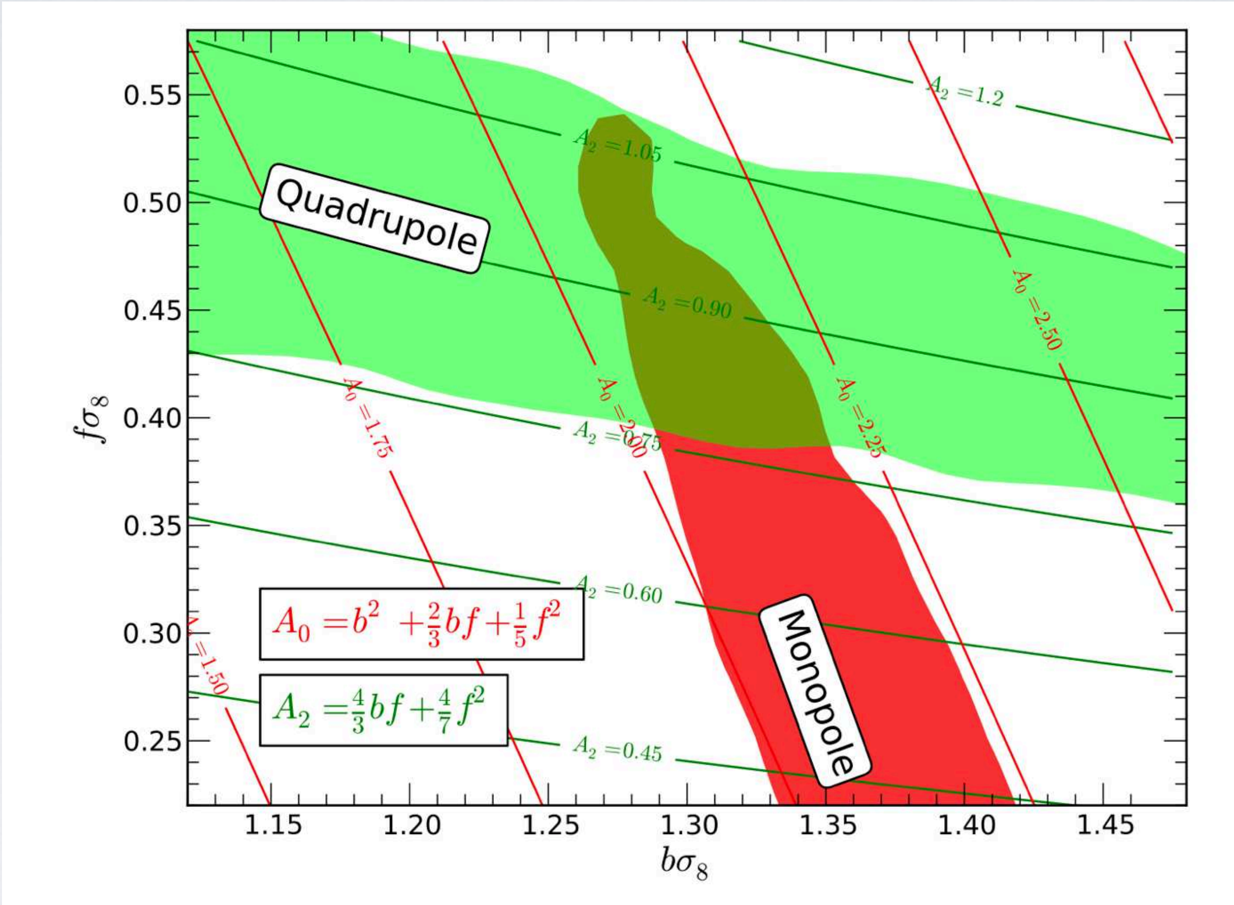
hexadecapole

$$\mu_\ell(s)=\frac{A}{2\pi^2}\int\frac{dk}{k}\left(\frac{k}{H_0}\right)^{n_s-1}T_\delta^2(k)\,j_\ell(k\cdot s) \qquad f=\frac{a}{D_1}\frac{d}{da}D_1$$

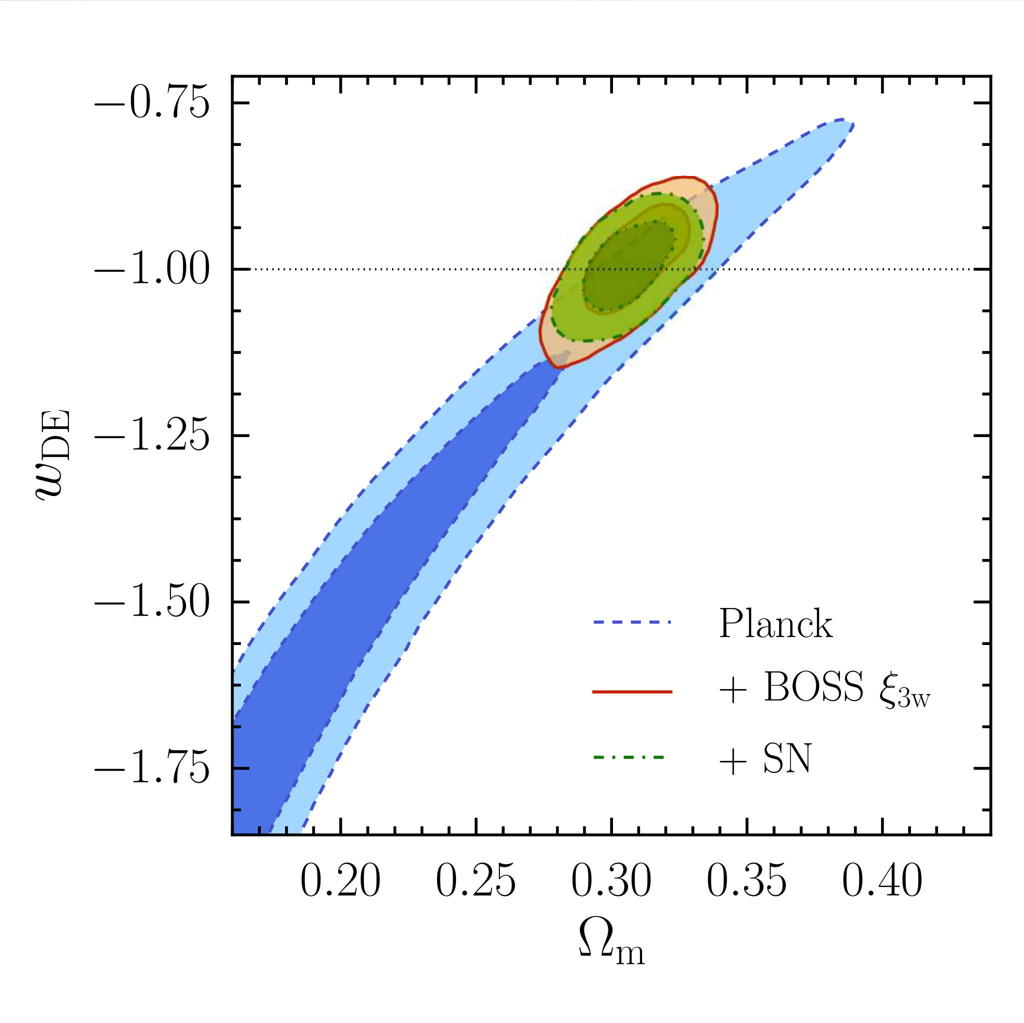
- We use the dependence in the angle to measure separately b and f

Summary

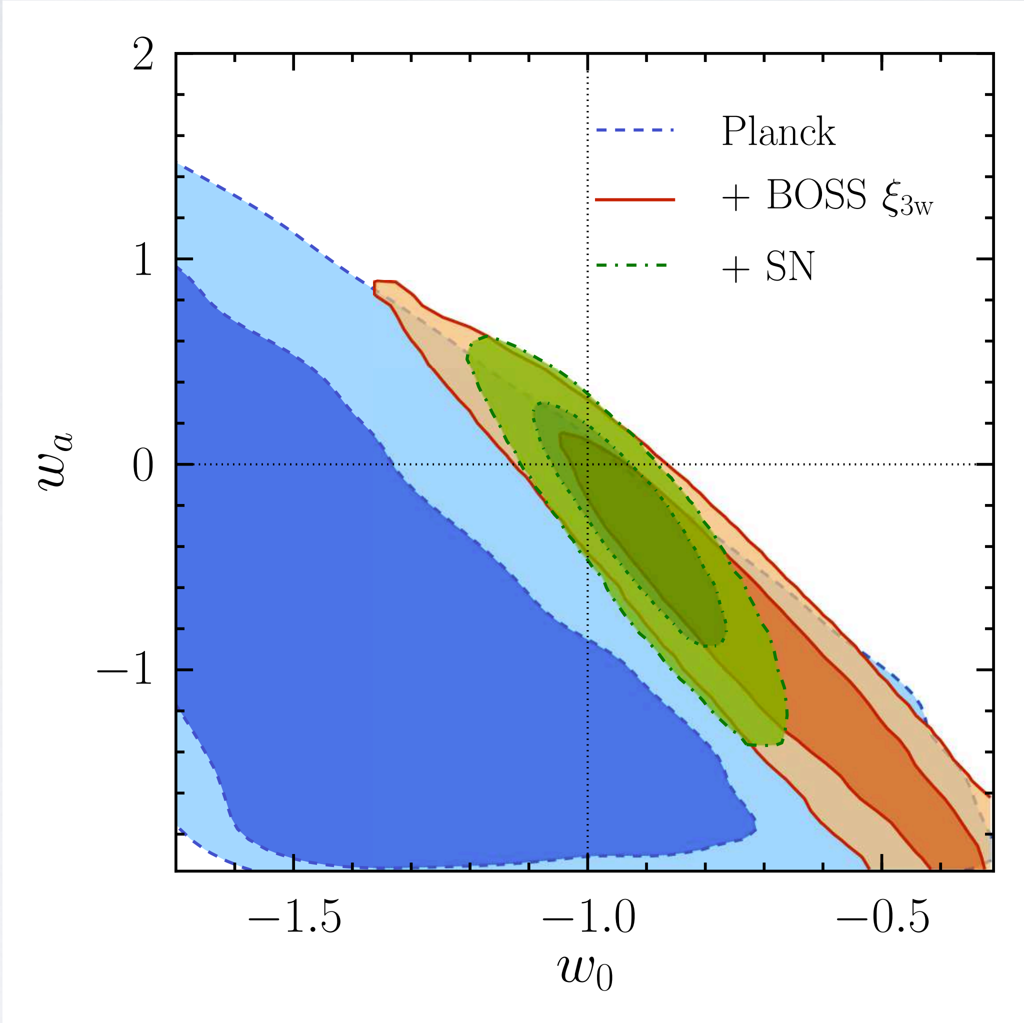
L. Samushia et al, arXiv:1312.4899



Summary



Sanchez et. al., arXiv:1607.03147



$$w = w_0 + w_a \frac{z}{1+z}$$

Outline

♦ Include the impact of baryons: baryon acoustic oscillations.

♦ Go beyond linear calculation: second order perturbation theory and Press Schechter formalim.

♦ Go beyond the sub-horizon calculation and include relativistic effects.

Baryon acoustic oscillations

Baryons

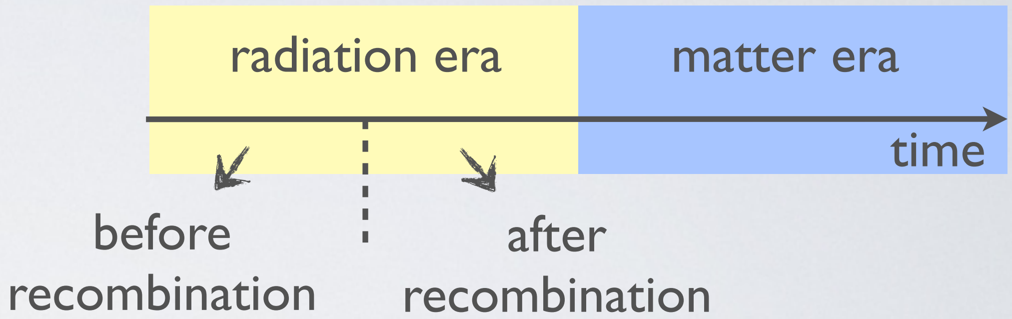
- We have neglected the **baryons**: we suppose that dark matter is the only matter component.
- Link with observation: we assume that the distribution of baryons **follow** that of the dark matter.
- The baryons **do not contribute** to the gravitational potential: they just fall into it.
- **Successful**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

Oscillations

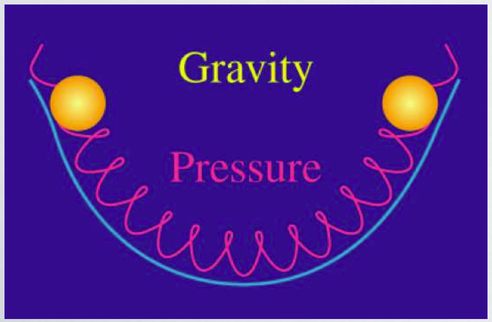
Difference between baryons and dark matter: **interaction** with **photons**.

- 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

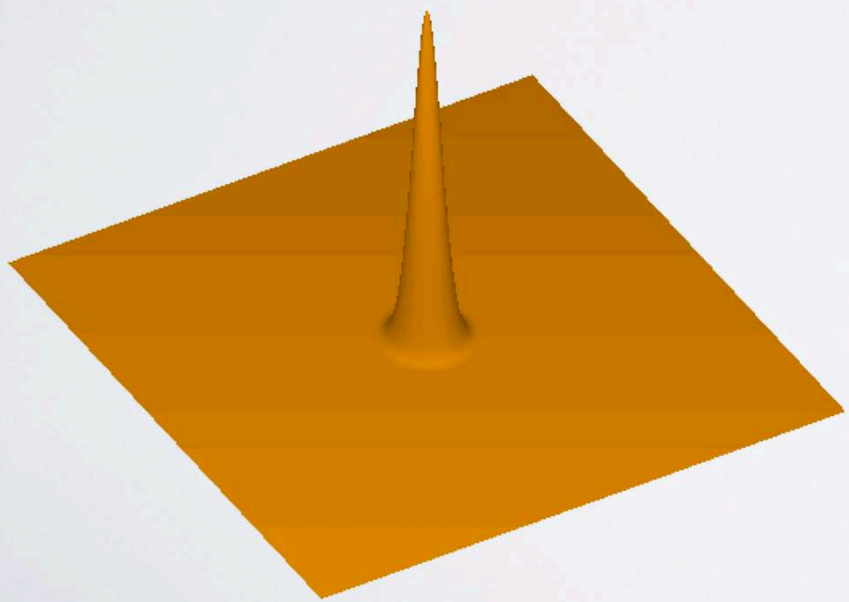
Sound wave

- 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 Mpc

Sound wave

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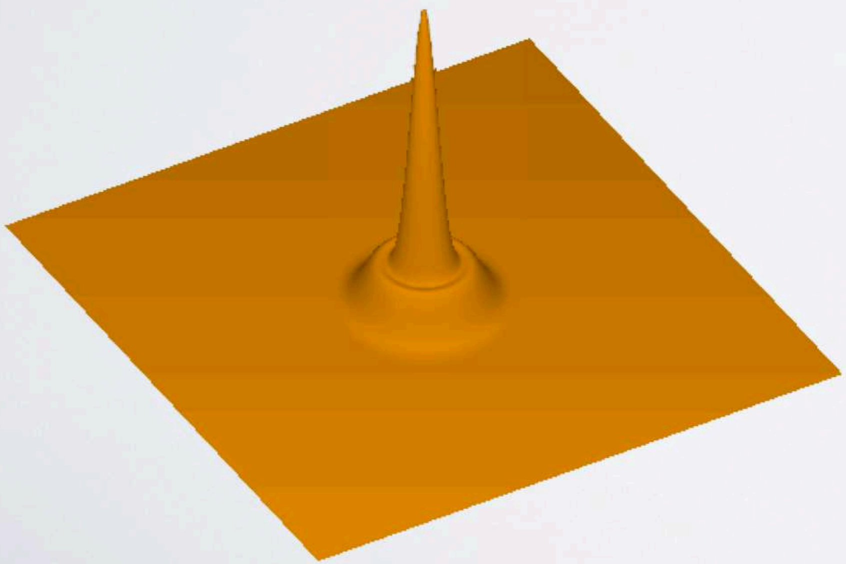

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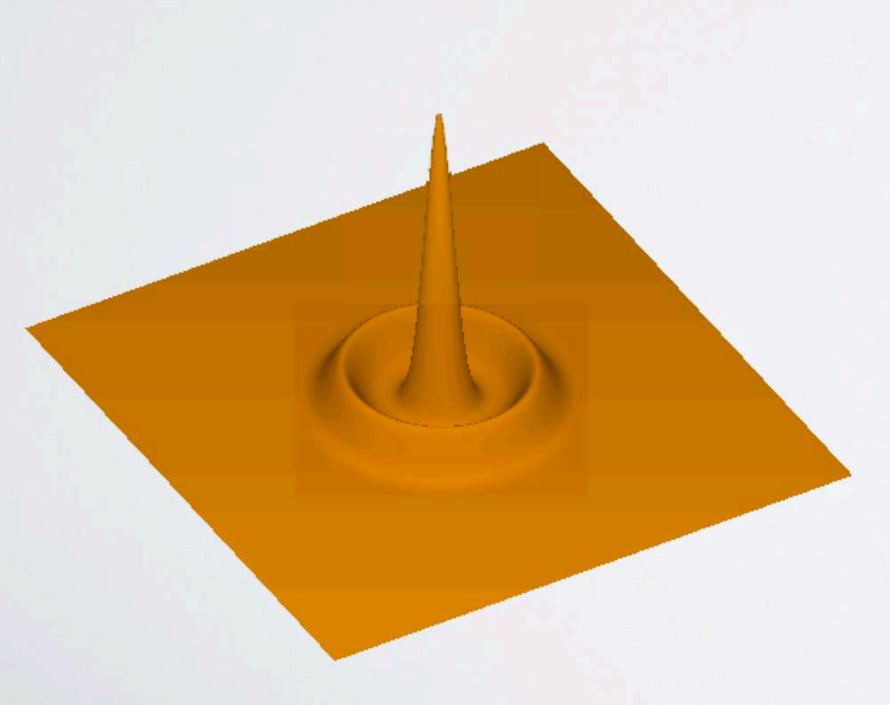

The fluid propagate until recombination:

- the photons escape
- the baryons stay

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

Sound wave

- At **recombination**: electrons and protons combine to form neutral hydrogen. The interaction with the photons stops.
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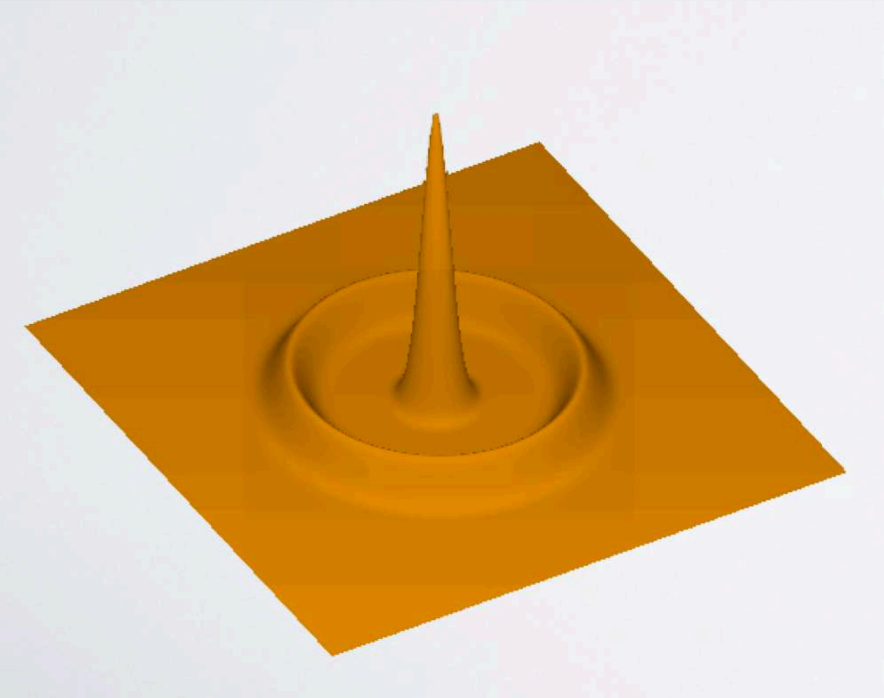
In real space

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



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Shell of **baryons** at distance 150 Mpc

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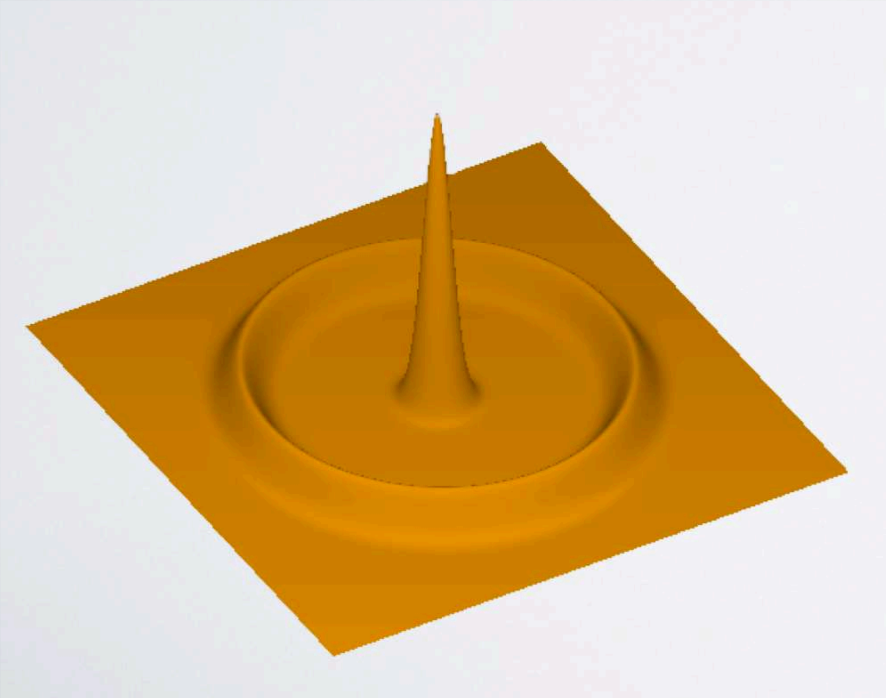
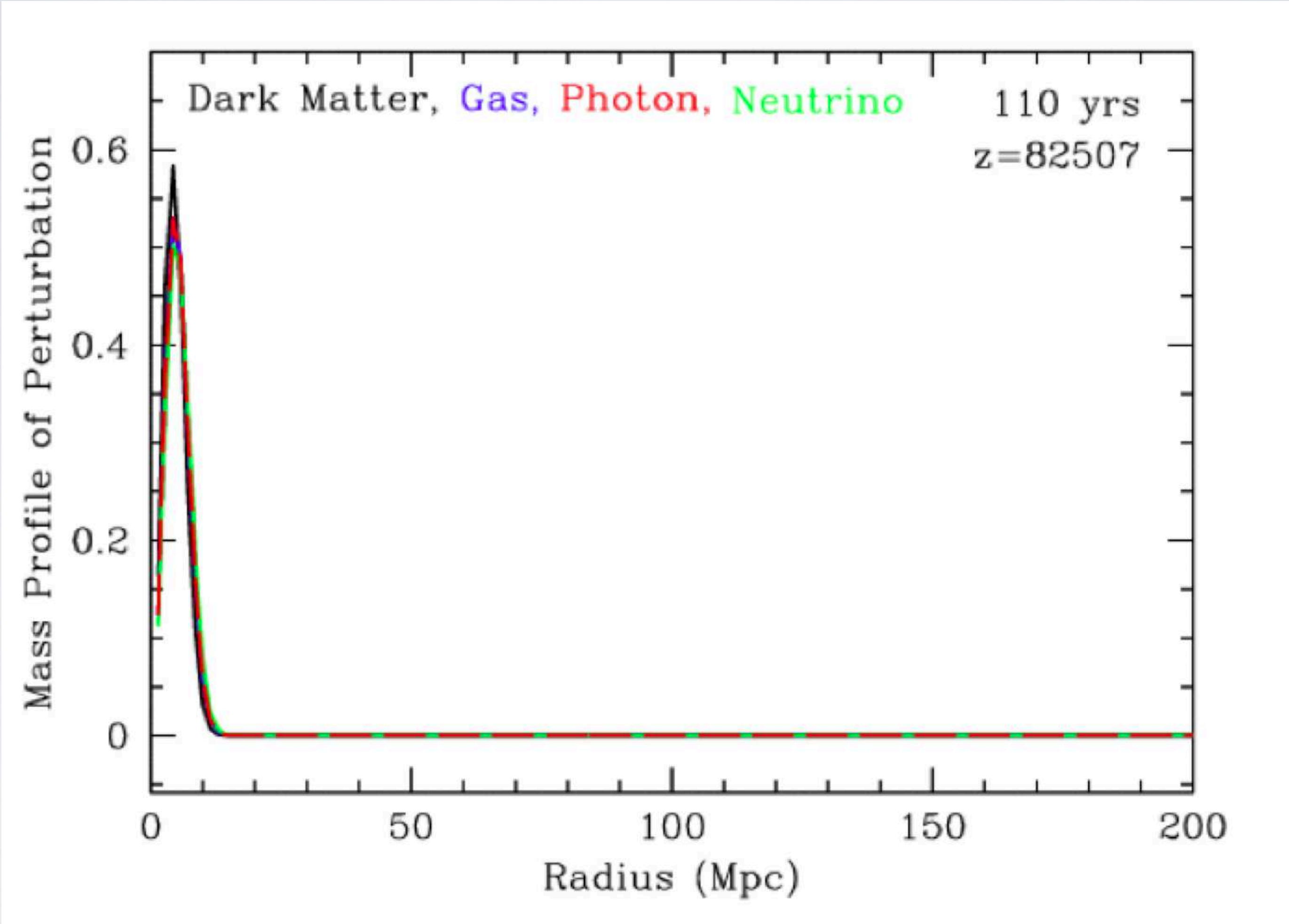


The fluid propagate until recombination:

- the photons escape
- the baryons stay

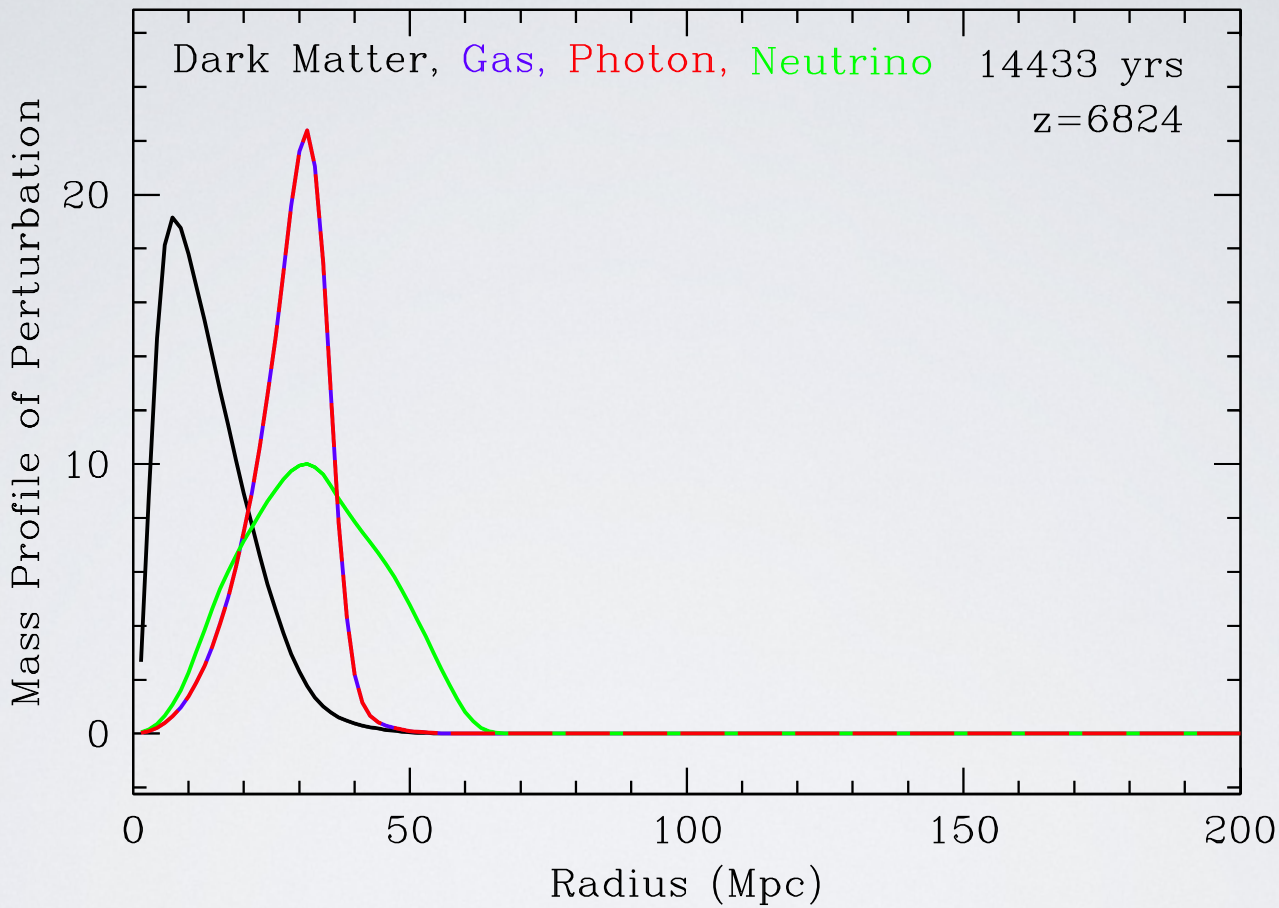
Shell of baryons at distance 150 Mpc

Distribution of fluids



Eisenstein, Seo, and White (2007)

Distribution of fluids



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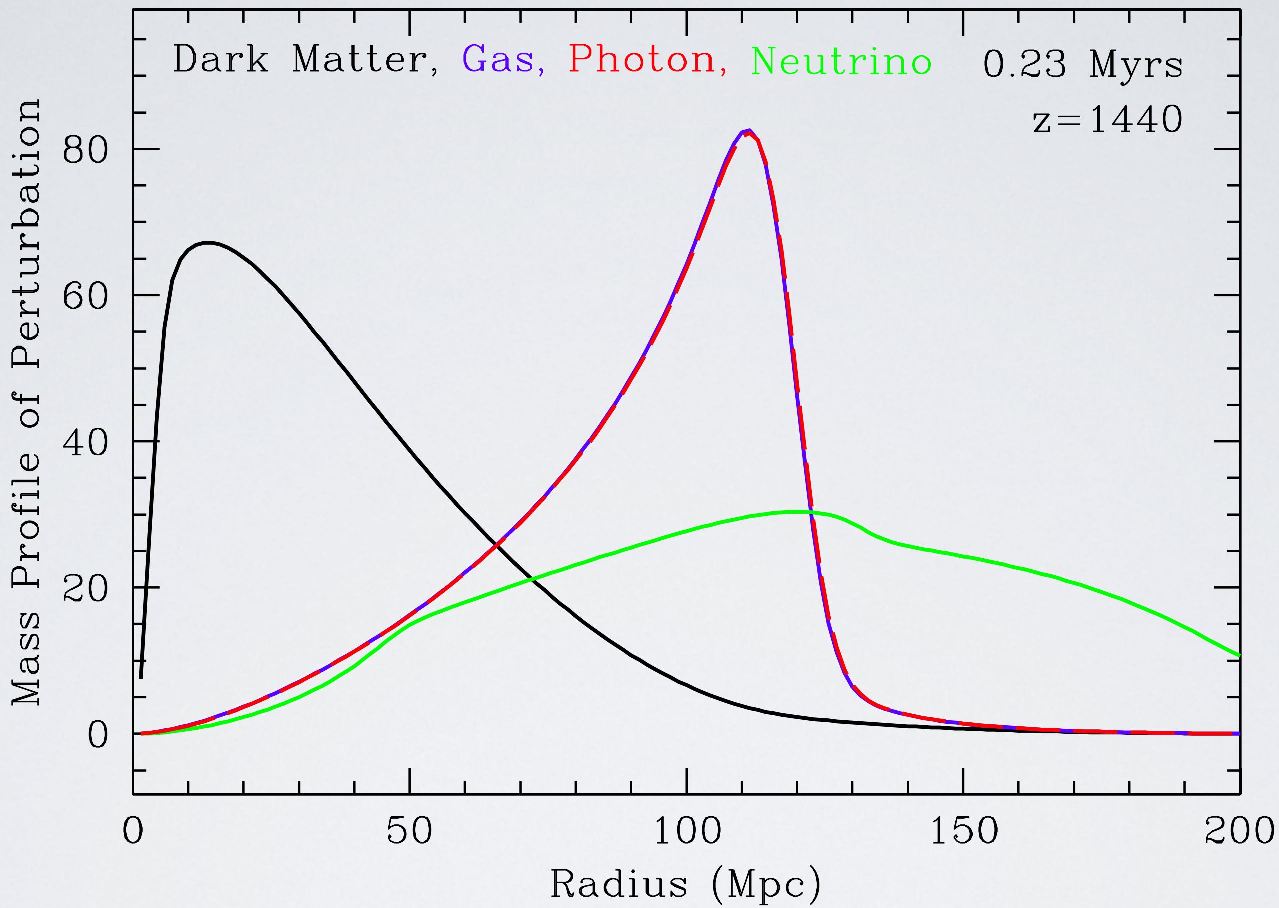
Distribution of fluids



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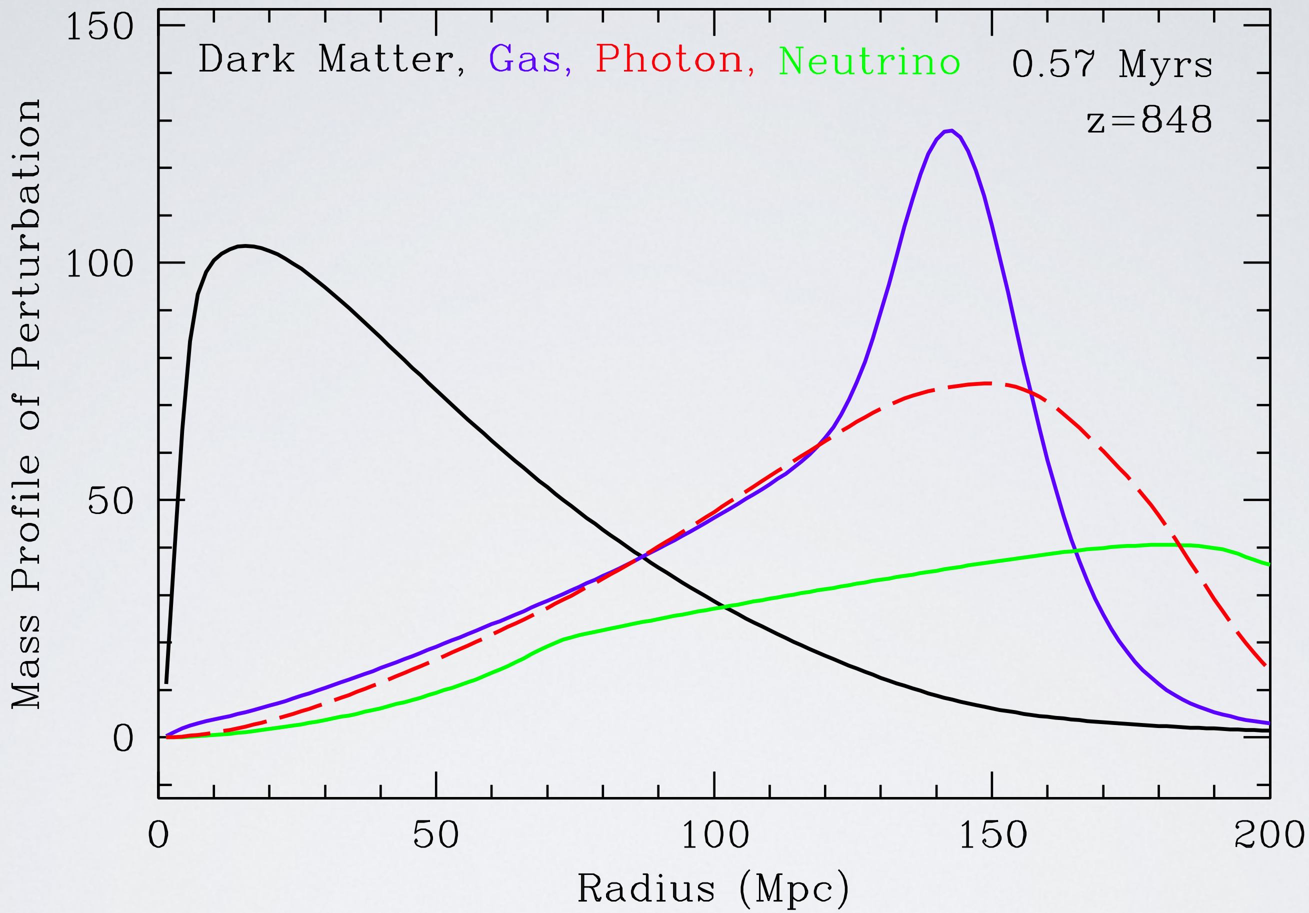
Distribution of fluids



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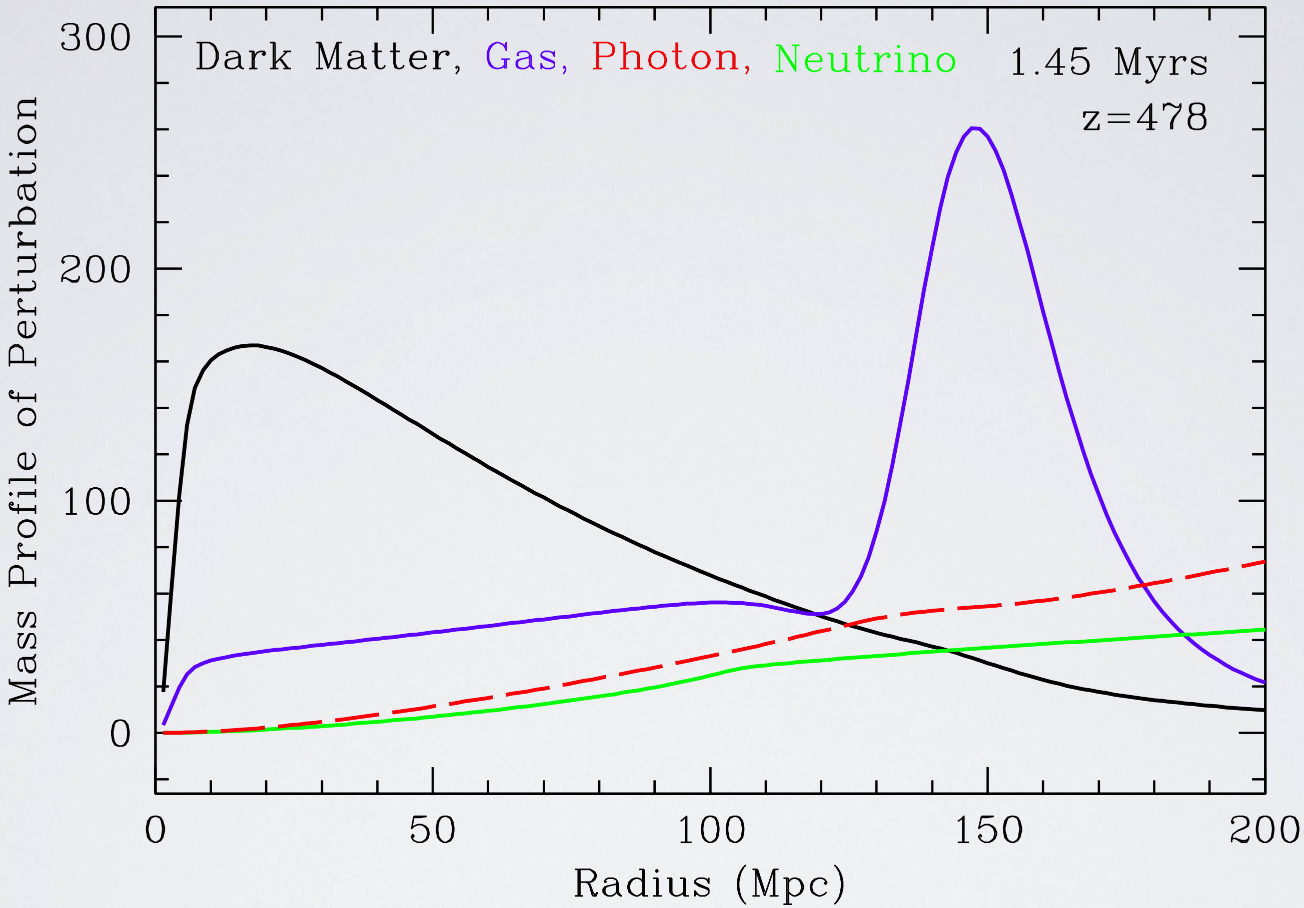

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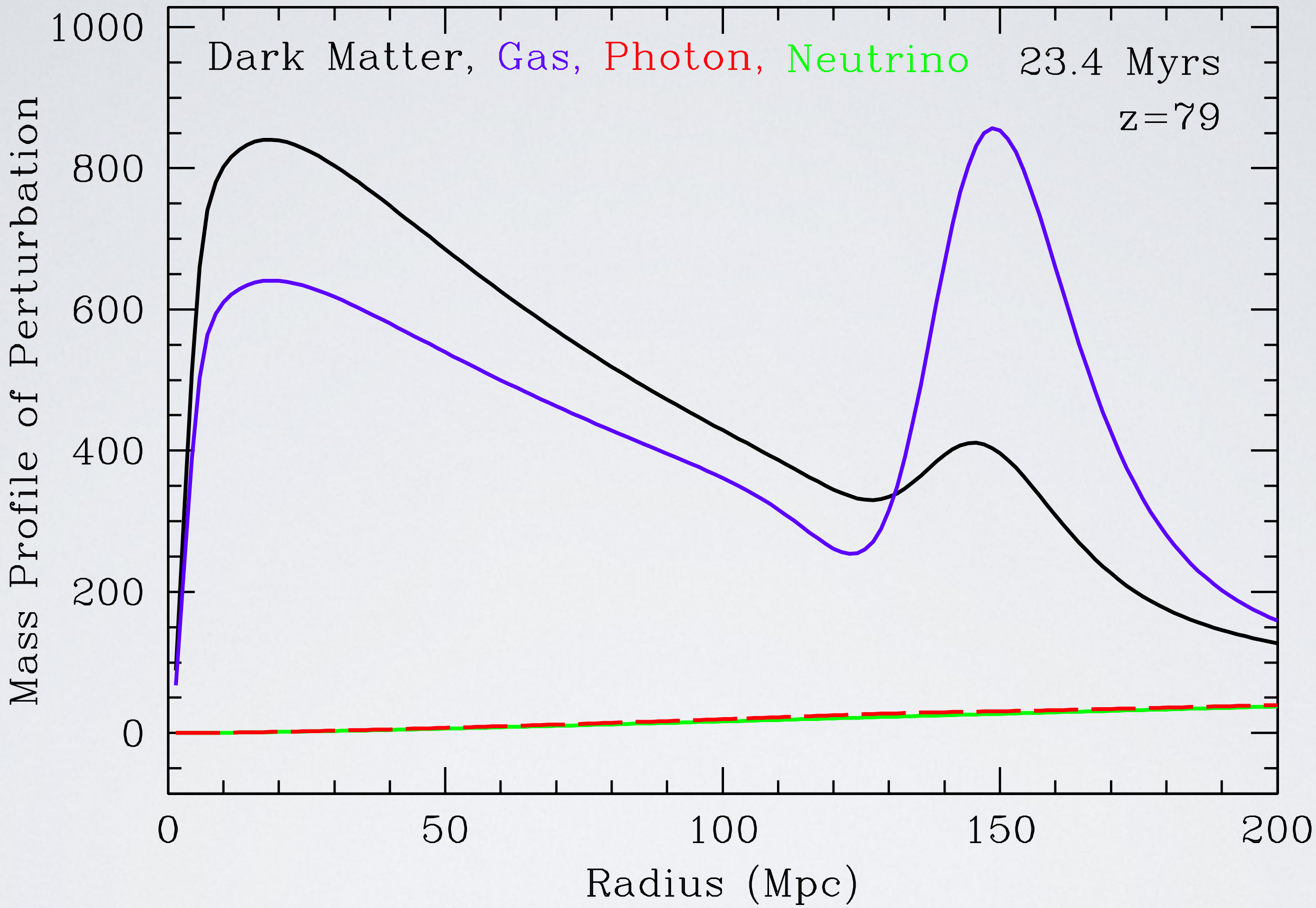
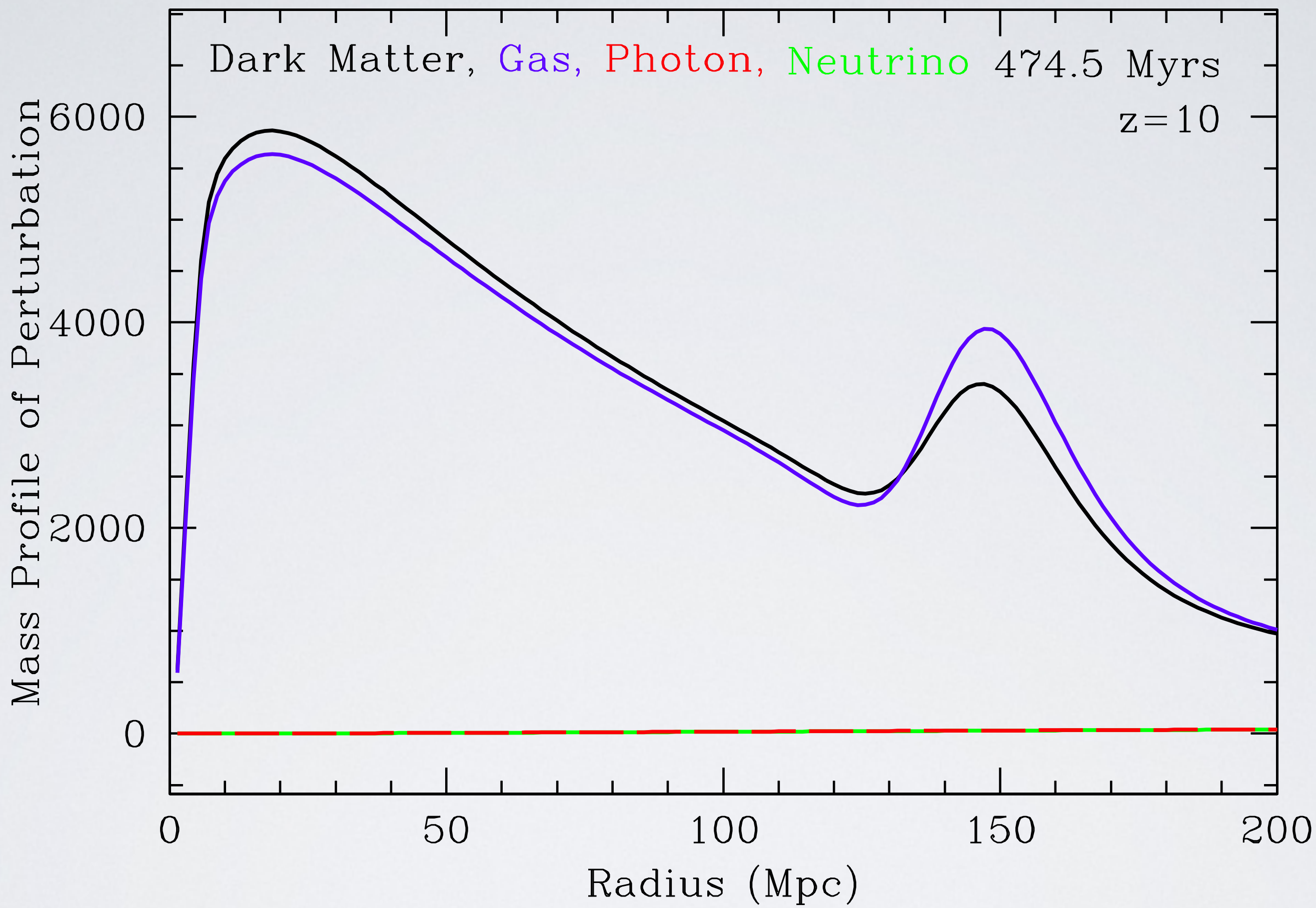
Distribution of fluids



Eisenstein, Seo, and White (2007)

Distribution of fluids



Eisenstein, Seo, and White (2007)

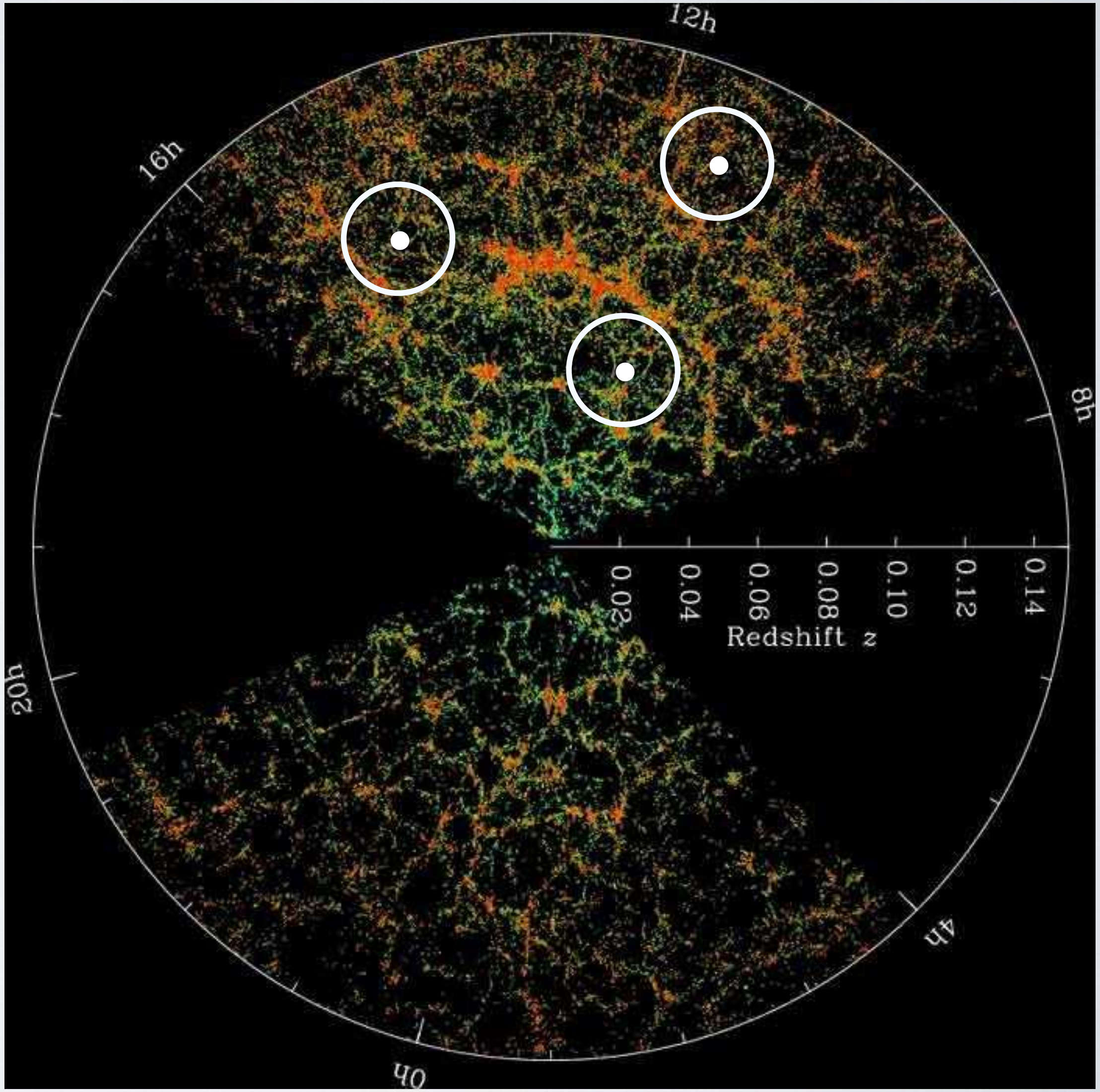
Galaxy survey

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

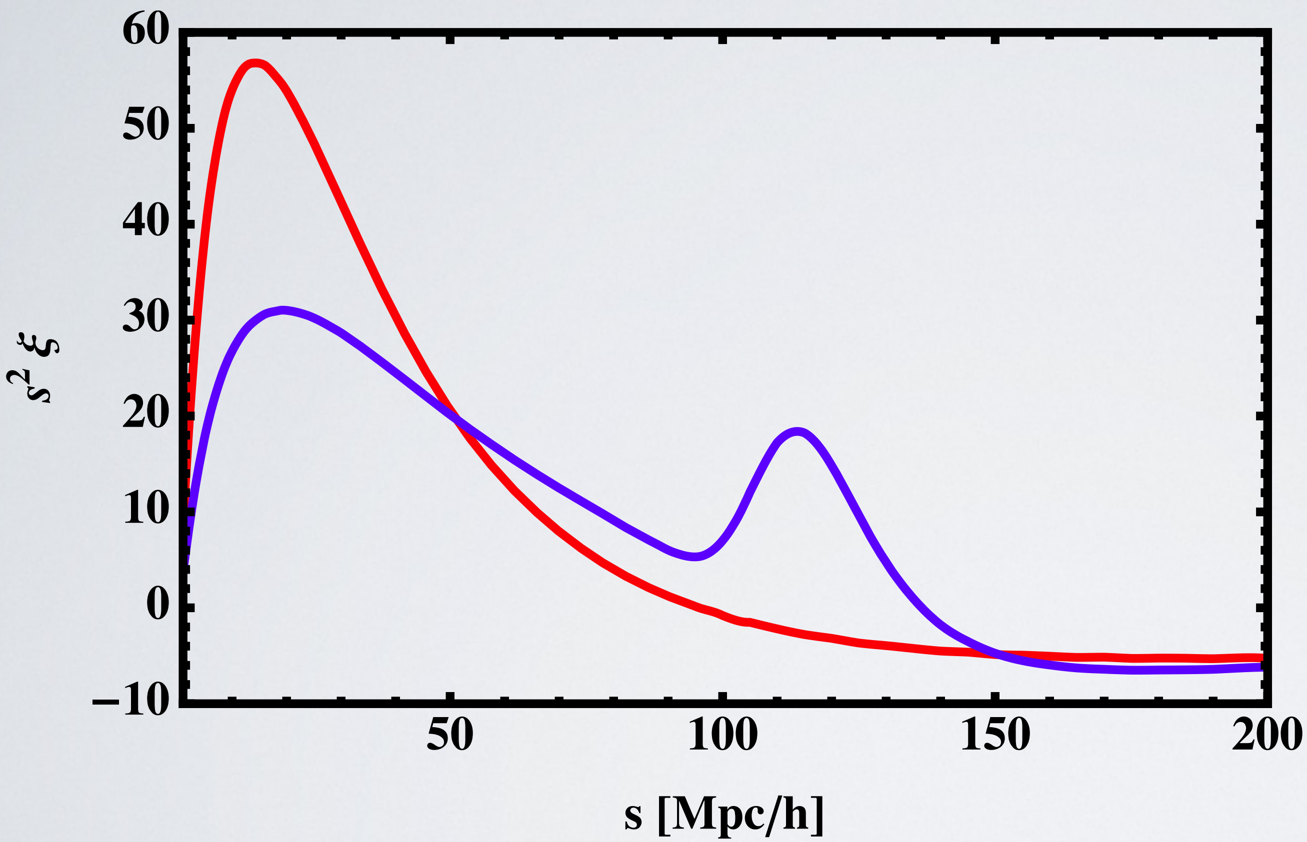
- There is a larger probability to find galaxies separated by $150\ \mathrm{Mpc}$.

- The two-point correlation function has a bump at the sound horizon.

Credit: M. Blanton, SDSS



Correlation function



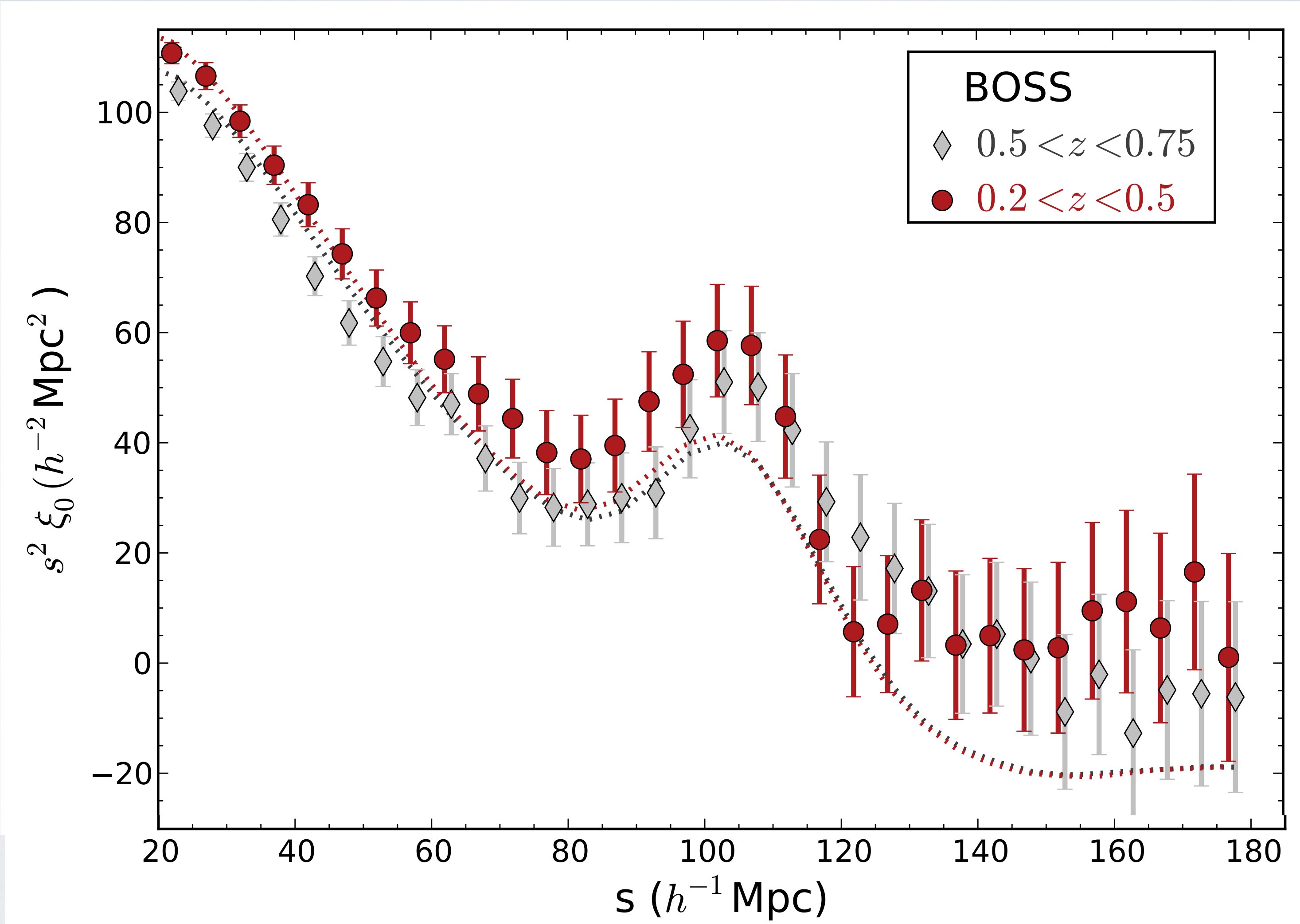
Peak at:

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

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

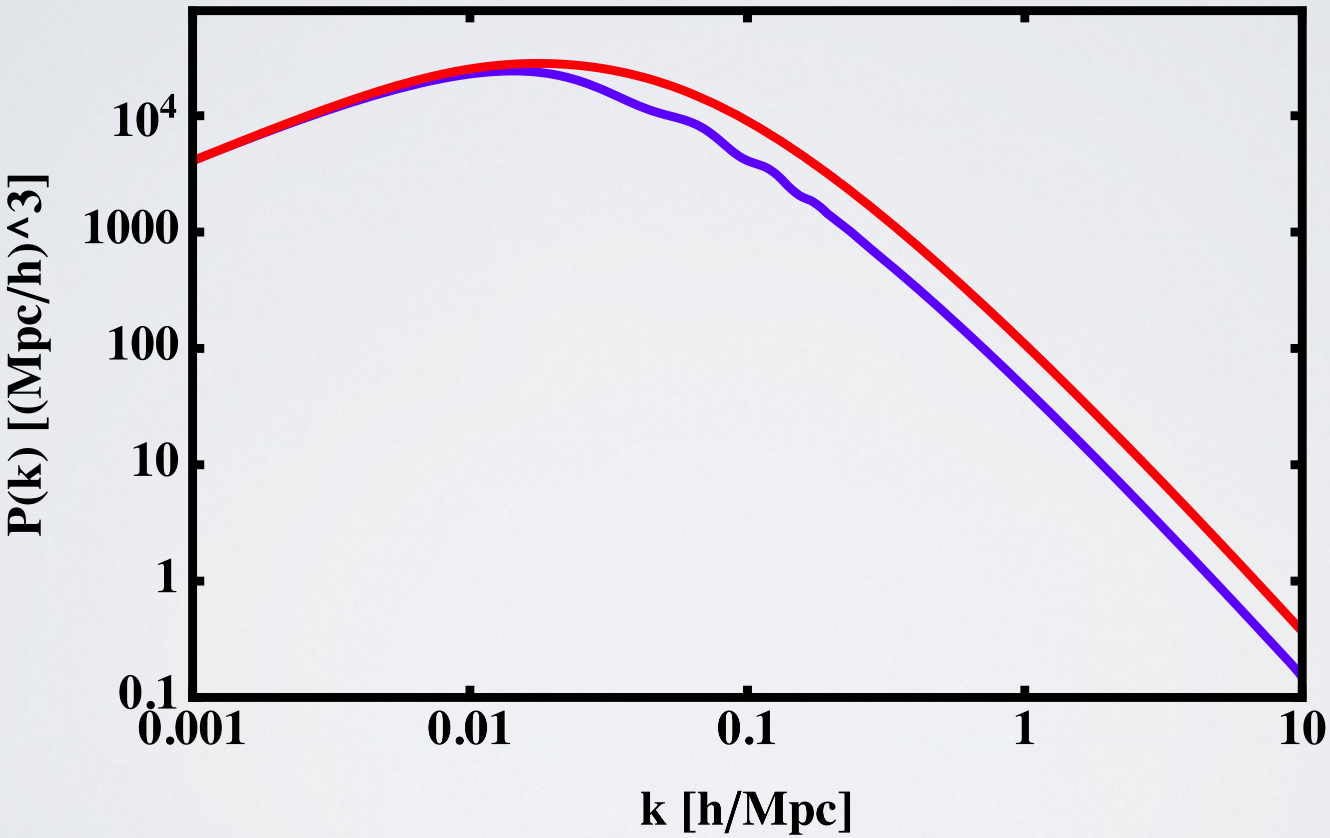
Correlation function

Credit: Ross et al. (2016)



Power spectrum

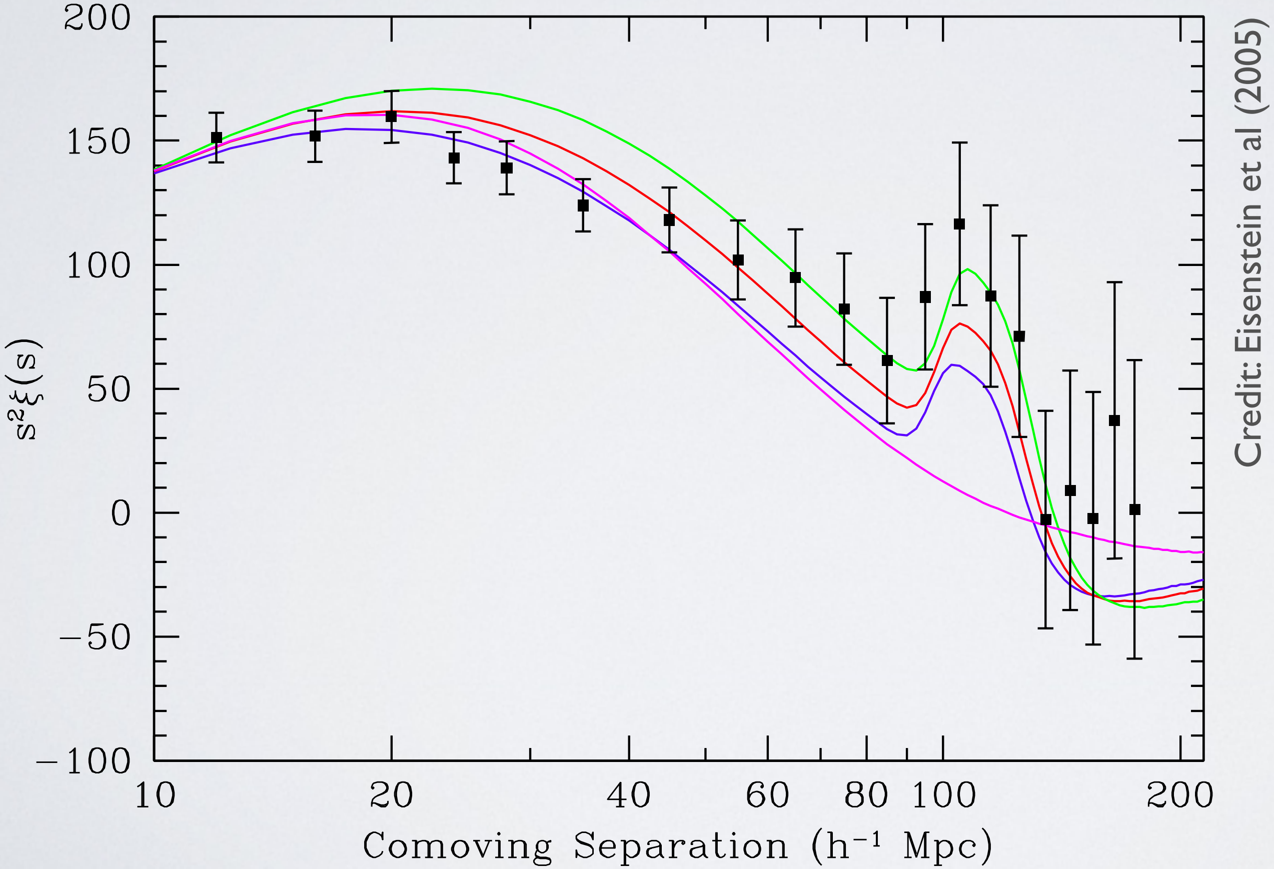
The bump in the correlation function translates into **oscillations** in the power spectrum.



Information

What can we learn from the BAO?

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



$$\Omega_b h^2 = 0.024$$

$$\Omega_m h^2 = 0.12$$

$$\Omega_m h^2 = 0.13$$

$$\Omega_m h^2 = 0.14$$

no baryons

$$\Omega_m h^2 = 0.105$$

Sound horizon

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

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

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

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.

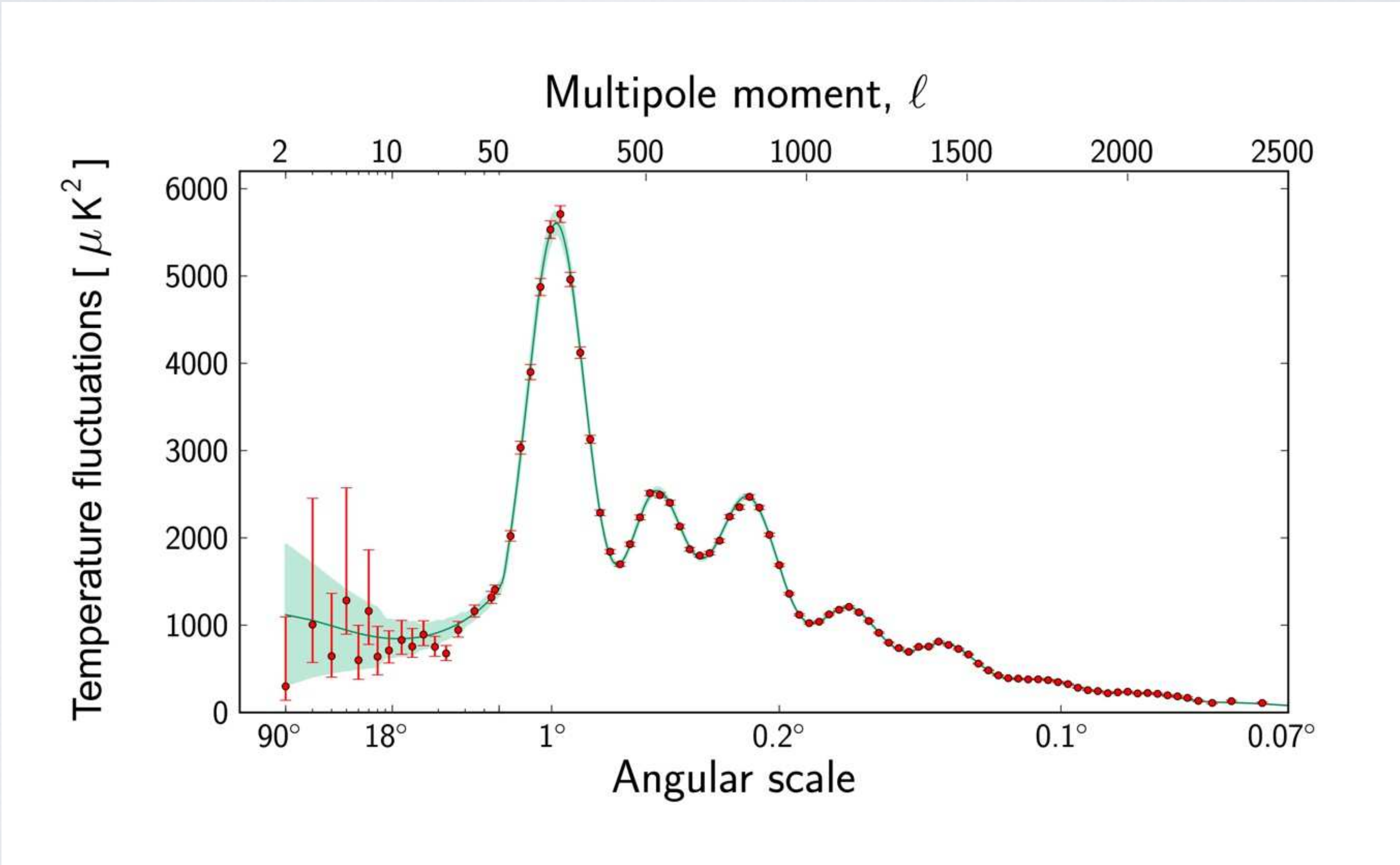
Sound horizon in the CMB

The sound horizon can be measured in the CMB.

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

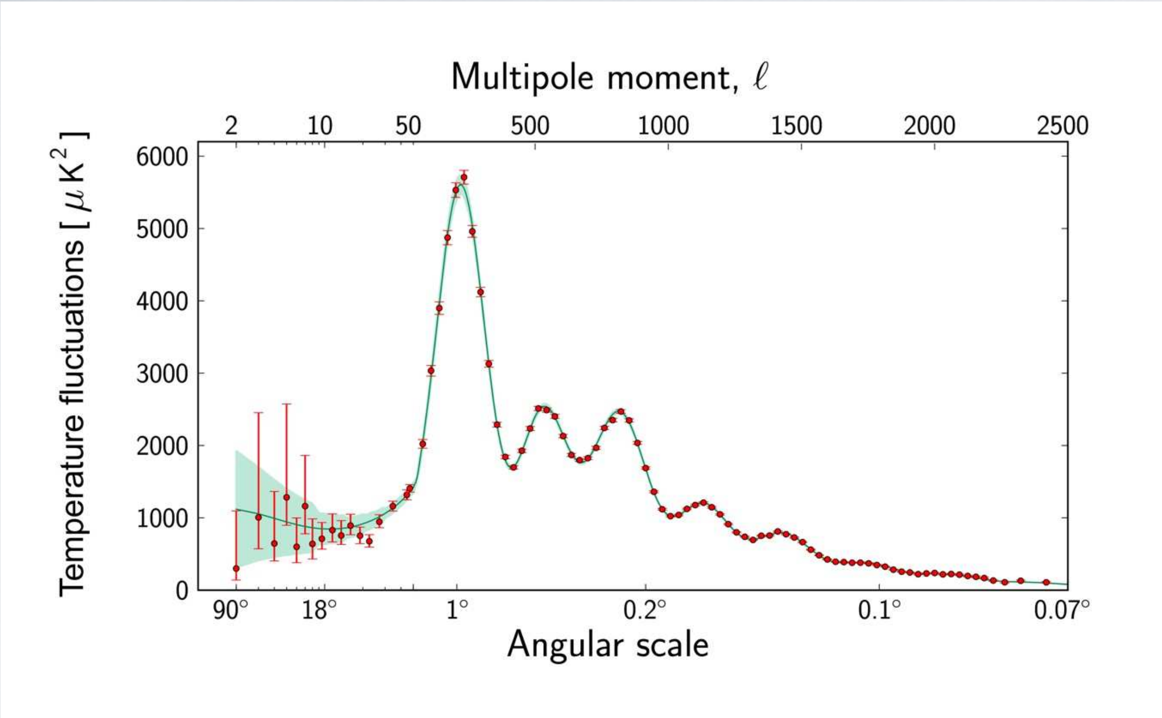
slightly different sound horizon because baryon decoupling differs from photon decoupling

ESA and the Planck Collaboration

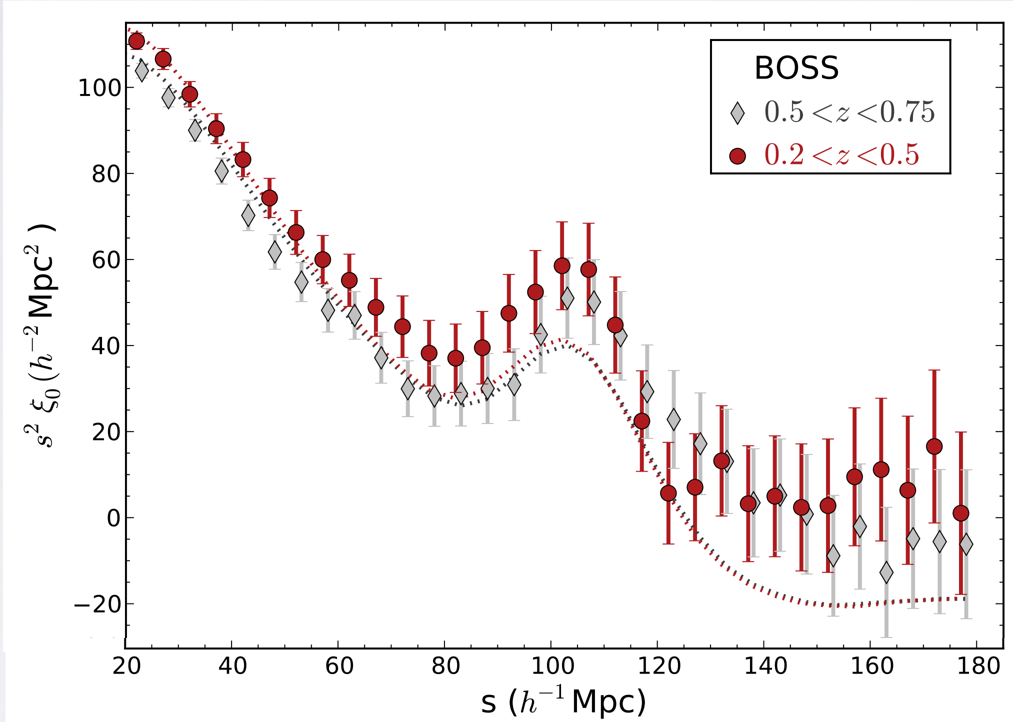


Comparison

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 $150\ \mathrm{Mpc}$.

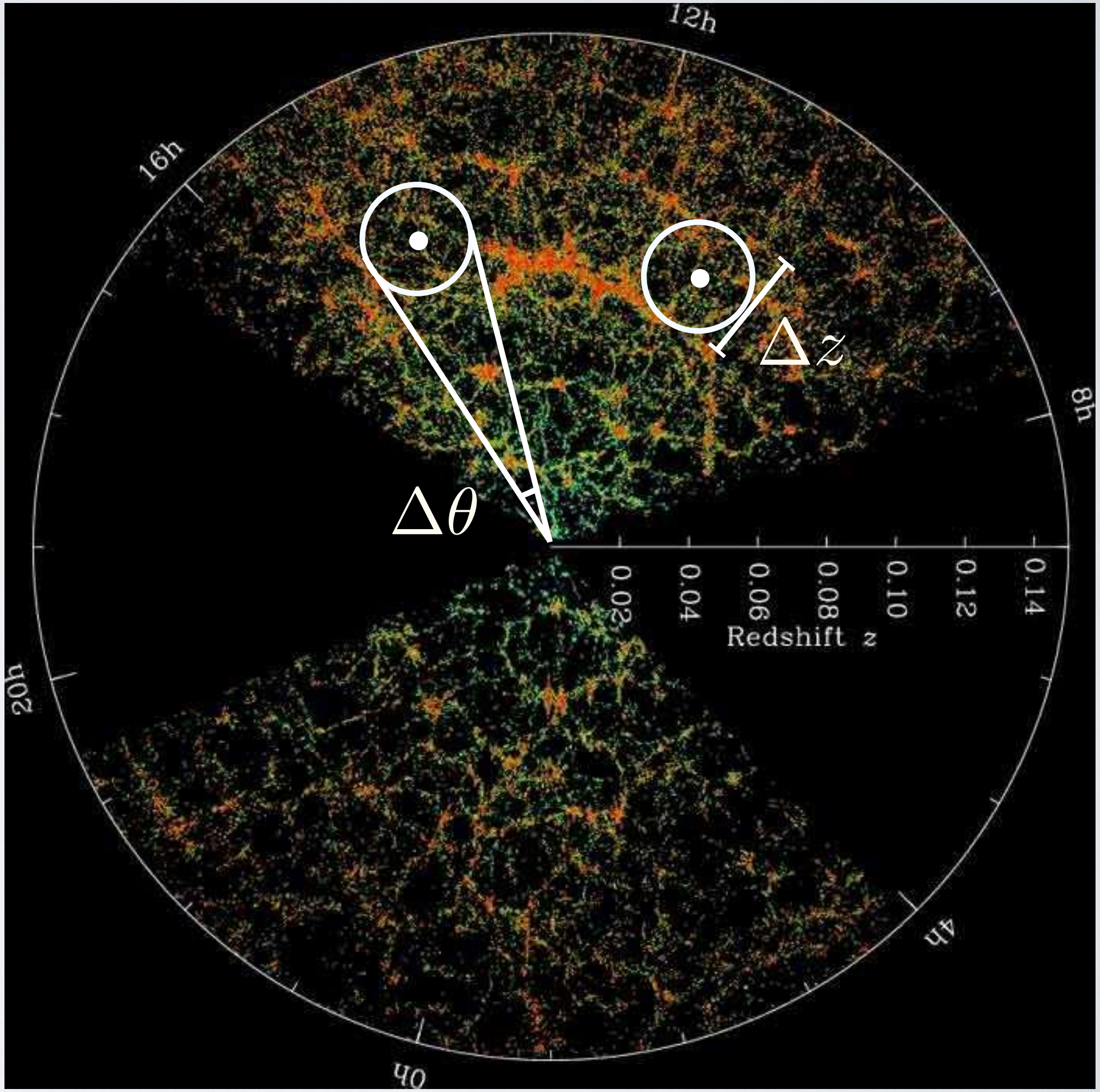
We measure:

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

Observed bump at:

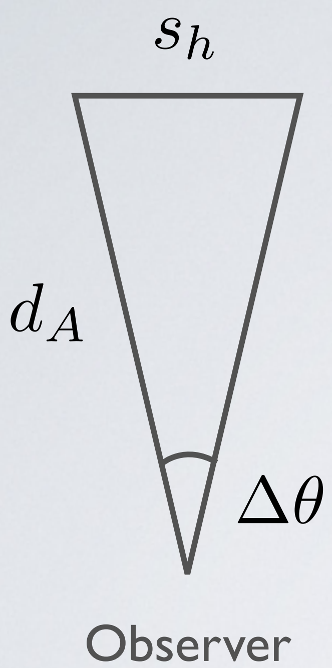
$\Delta\theta$ and Δz

Credit: M. Blanton, SDSS



Transverse BAO

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



$$\underbrace{s_h}_{\text{known}} = d_A \cdot \underbrace{\Delta\theta}_{\text{measured}}$$

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**.

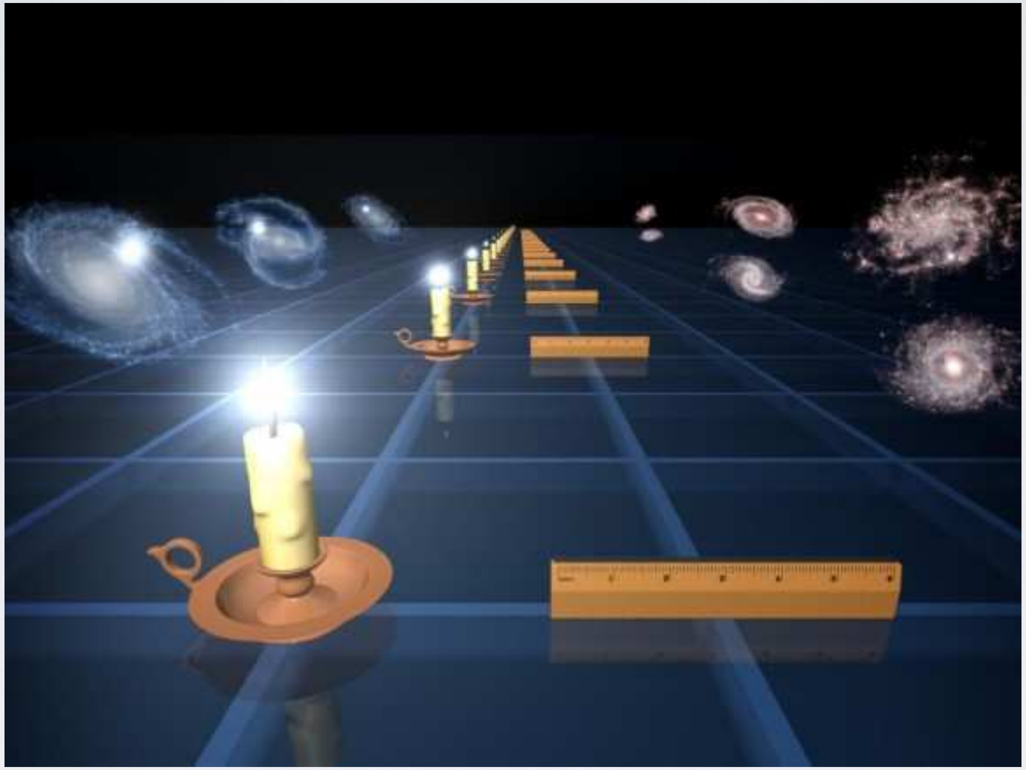
In a flat universe with a cosmological constant:

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

Luminosity distance

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

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

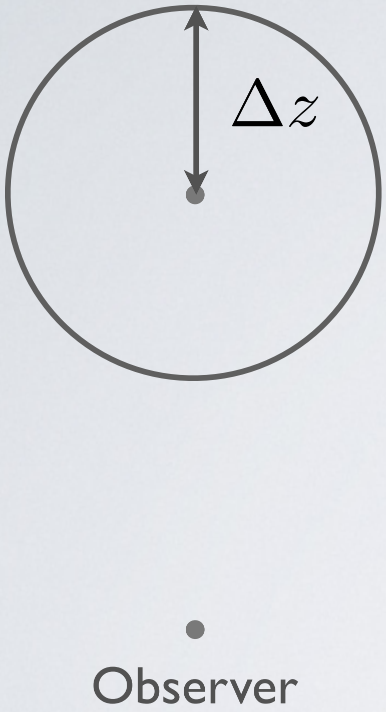


We know the intrinsic **luminosity**, measure the **flux** and infer the distance.

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

Radial BAO

Relation between Δz and s_h



$$s_h = dr = -\frac{dt}{a} = -\frac{1}{a}\frac{dt}{da}\frac{da}{dz}dz$$

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

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

Measure H directly!

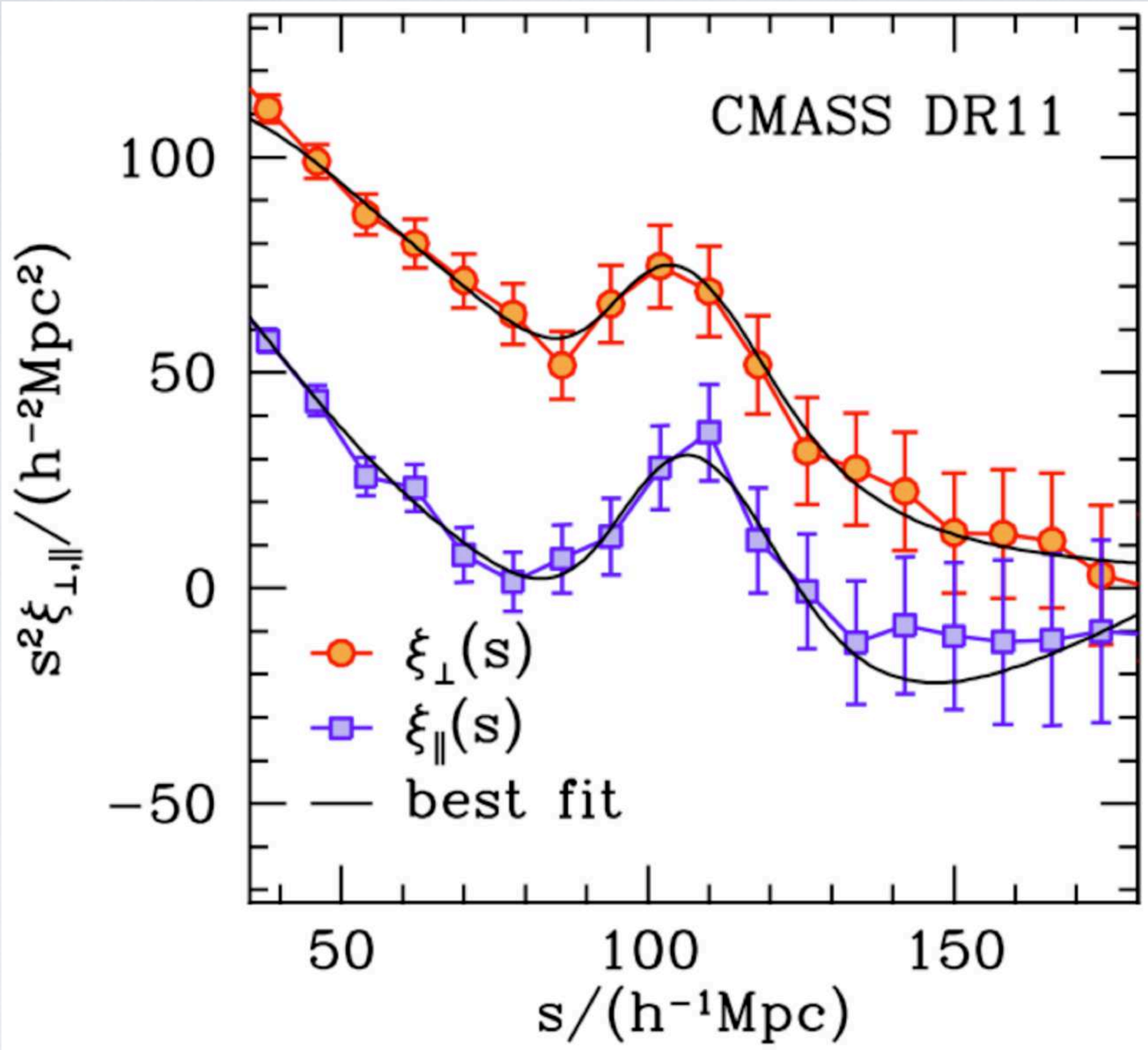
Observations

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% $\rightarrow$ **one** extra galaxy!

Observations



Credit: Anderson et al. (2013)

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

In practice

- Two problems:

  We **loose** a lot of pairs

  We must account for **redshift-space** distortions

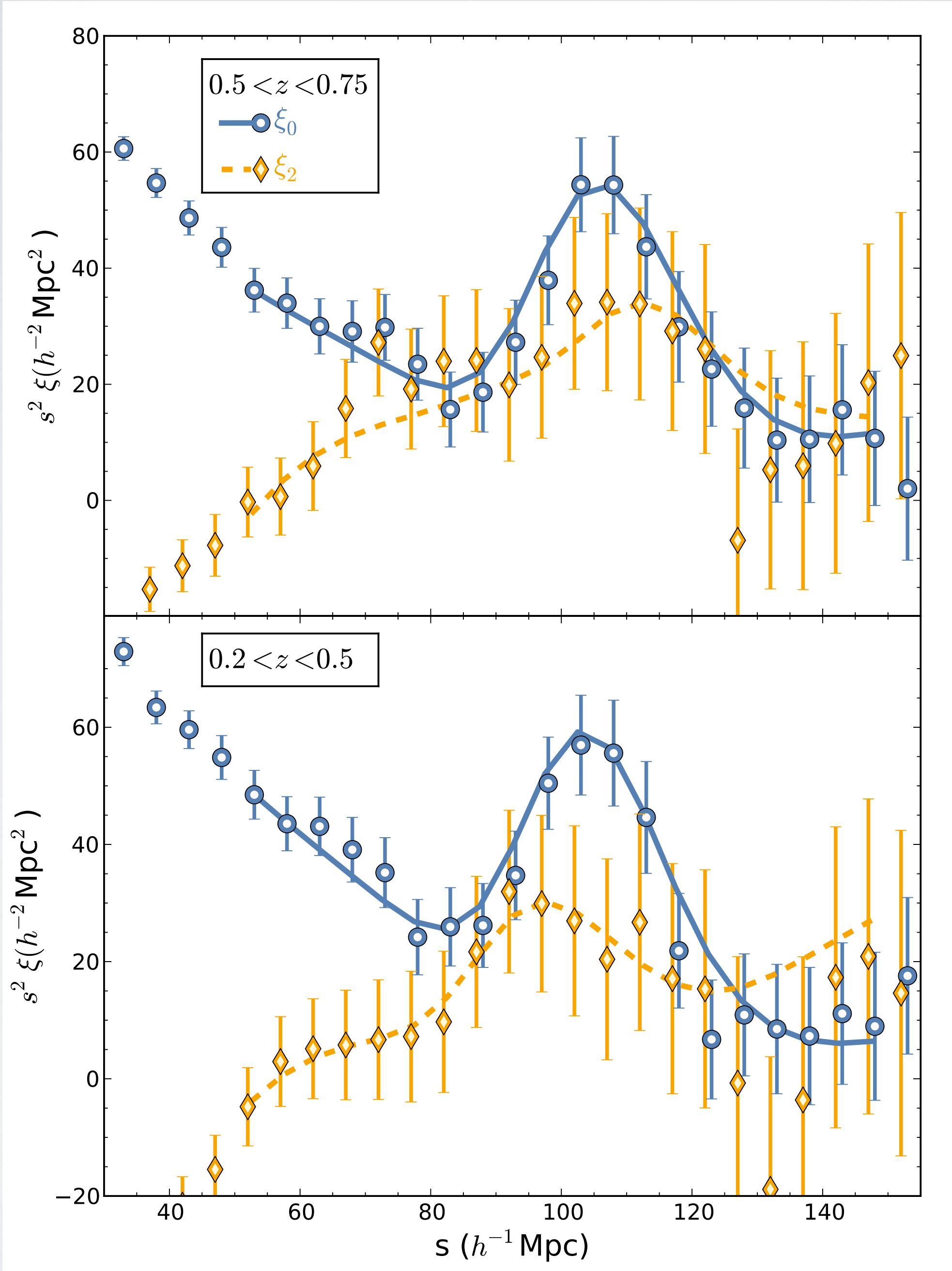
- Solution: look at the position of the peak in the **monopole** and **quadrupole** $\rightarrow$ measure different combinations of distance and Hubble parameter.

- Problem: we need a **cosmology** to infer s and β. How can we then use the position of the peak to constrain cosmology?

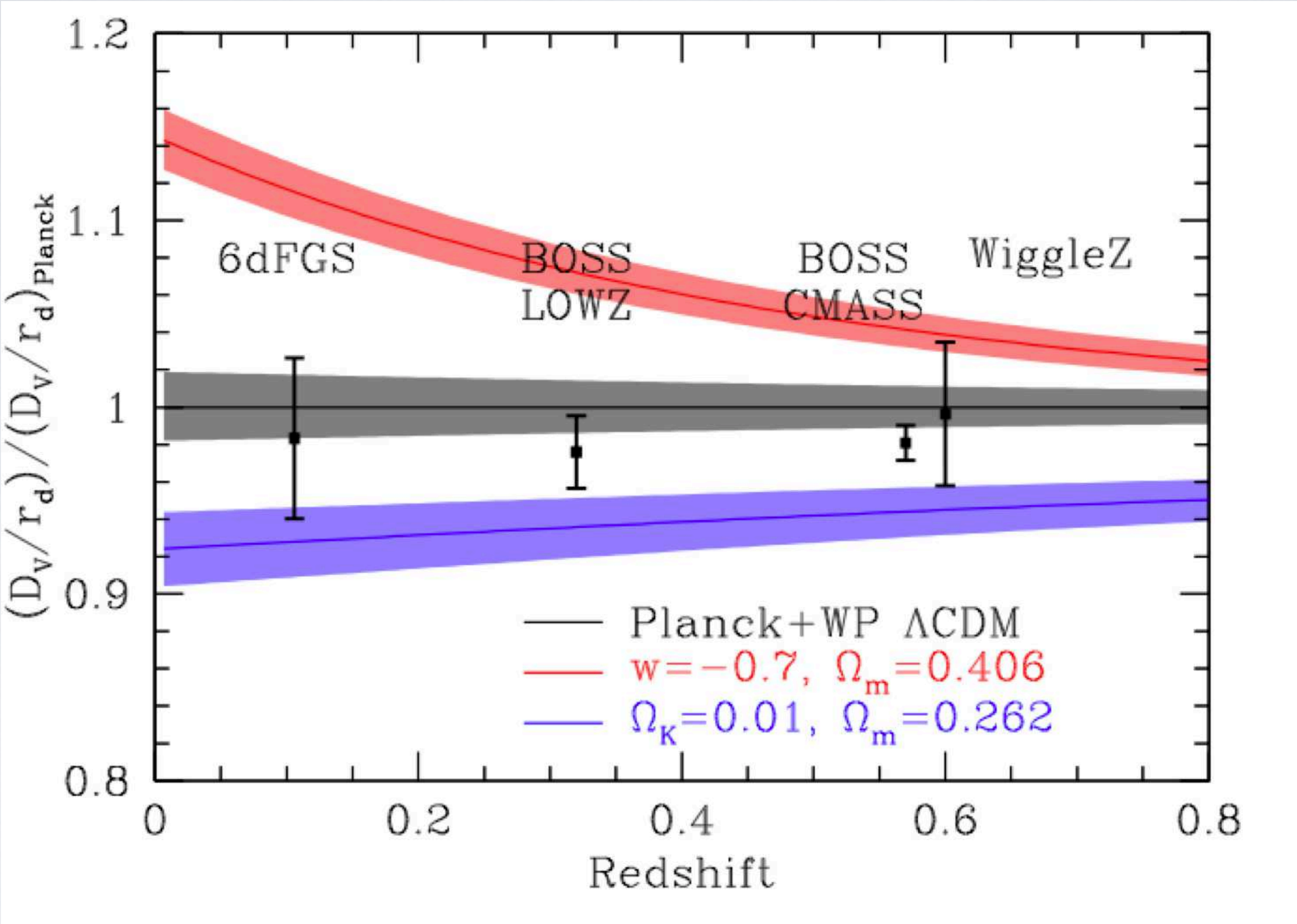
- Way out: look at how a change in cosmology affects the multipoles.

BOSS results

Credit: Ross et al. (2016)



Accelerating universe

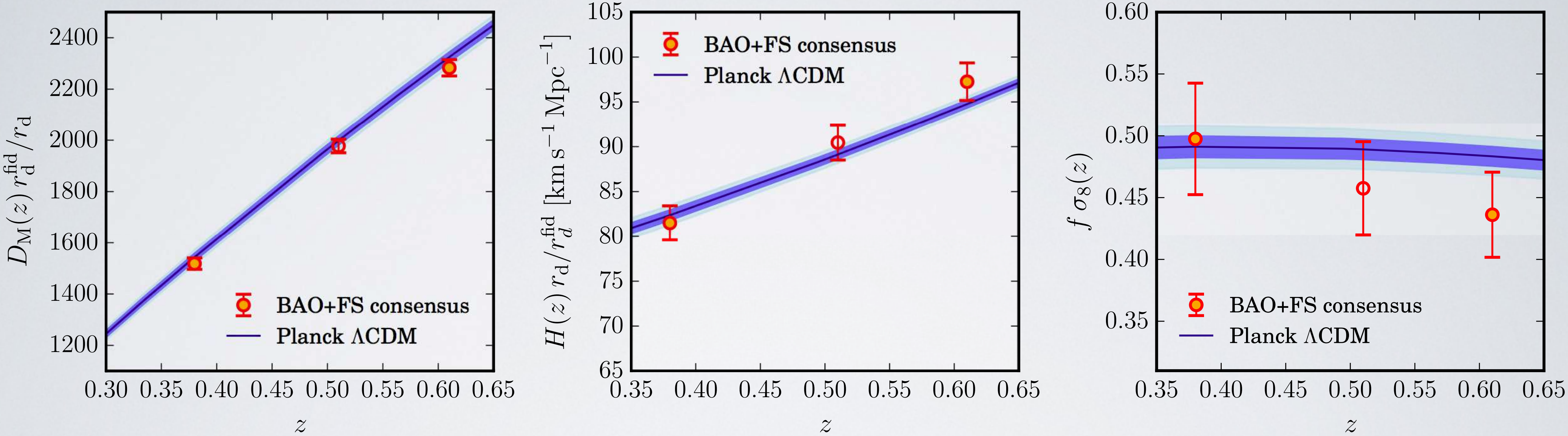


Credit: Anderson et al. (2013)

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

Latest results

Credit: Alam et al. (2016)



Constraints

Alam et al. (2016)