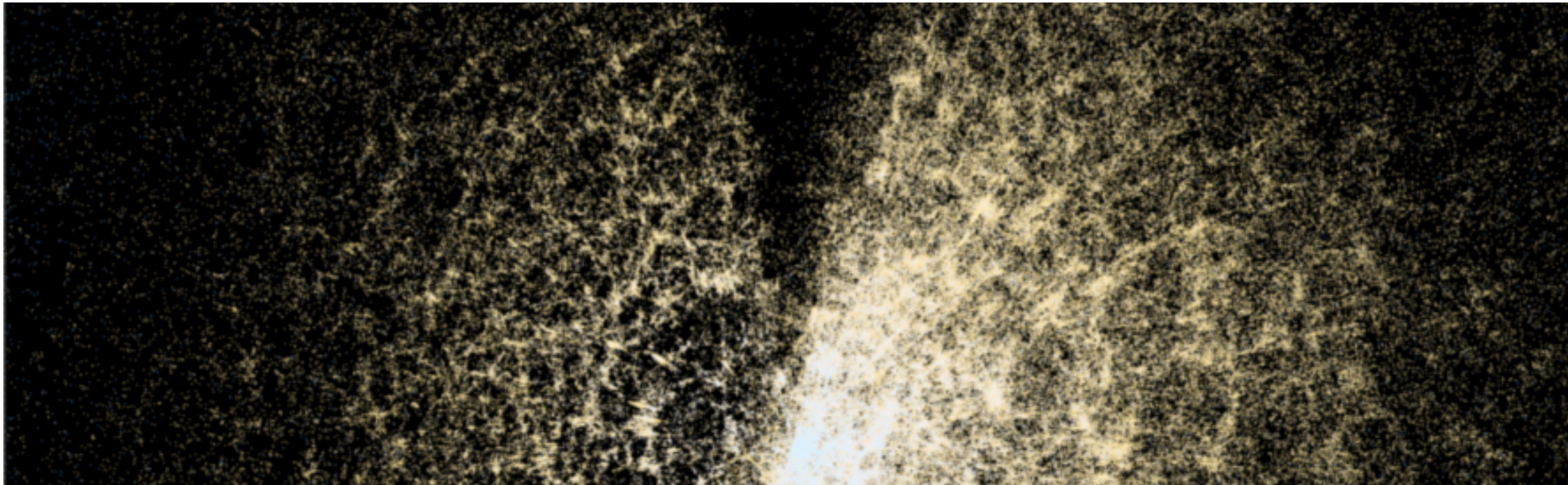


Baryon acoustic oscillations and redshift-space distortions

Ariel G. Sánchez

MAX-PLANCK-GESELLSCHAFT

LAPIS 2018: Cosmology in the era of large surveys - 23.04.2018

Lecture 1: BAO

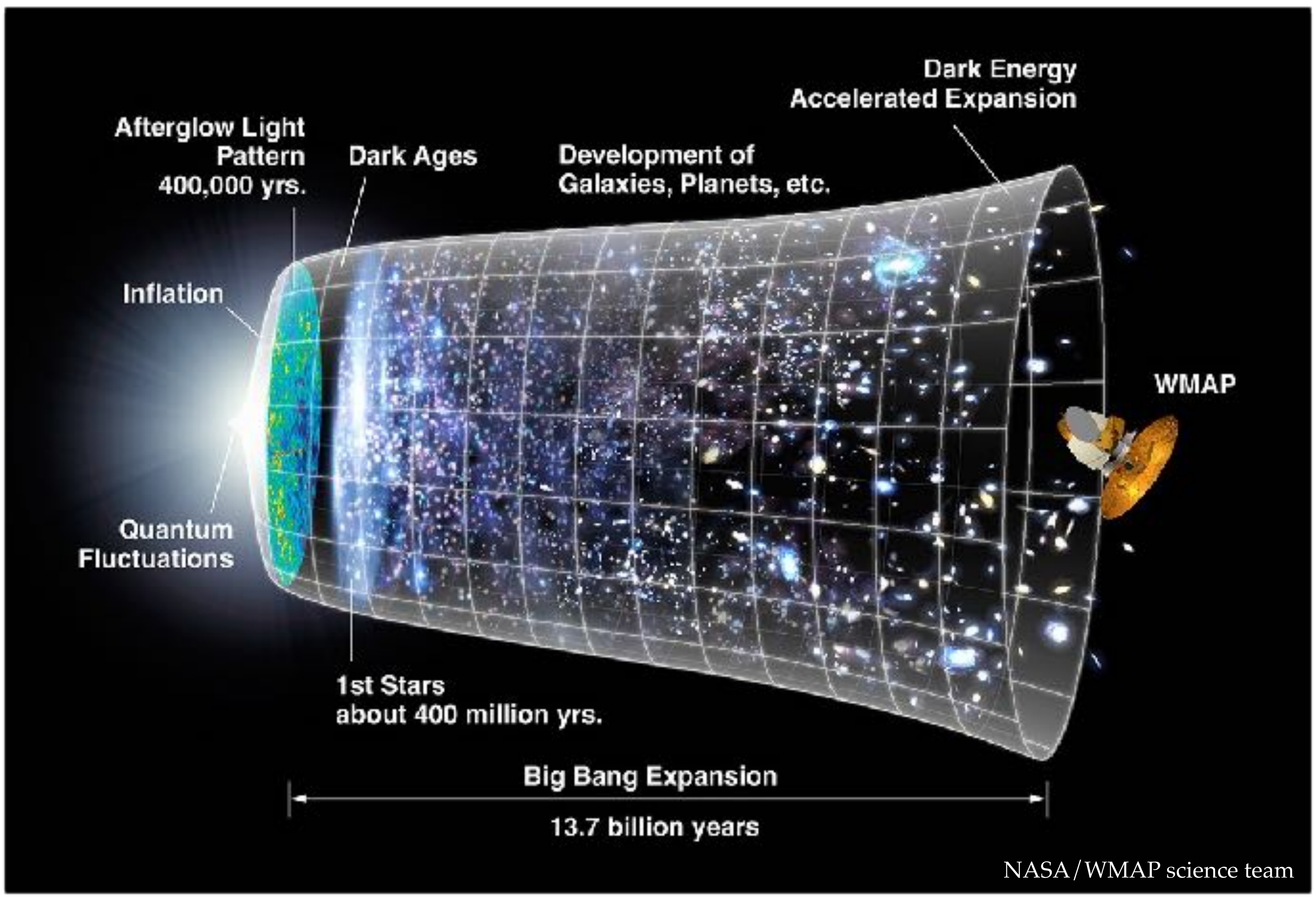
- Introduction: cosmology from LSS observations.
- Baryon acoustic oscillations (BAO).
- Galaxy redshift surveys.
- Potential systematic errors.
- Angle-averaged vs anisotropic measurements.
- Present-day BAO measurements.

Lecture 2: RSD

- Redshift-space distortions (RSD).
- The density - velocity relation.
- Impact of RSD on clustering measurements.
- Modelling of RSD beyond the linear regime.
- Current cosmological constraints from BAO & RSD.
- Forecasts for future surveys.

Observational cosmology

- A wealth of high precision observations have shown us a more complex Universe than previously thought.



Observational cosmology

- The origin of cosmic acceleration is one of the most important open problems in cosmology.

- A mysterious *dark energy* must dominate the energy budget of the Universe.

$$w_{\rm DE} = \frac{p_{\rm DE}}{\rho_{\rm DE}}$$

- The ΛCDM model: vacuum energy, $w_{\rm DE} = -1$.

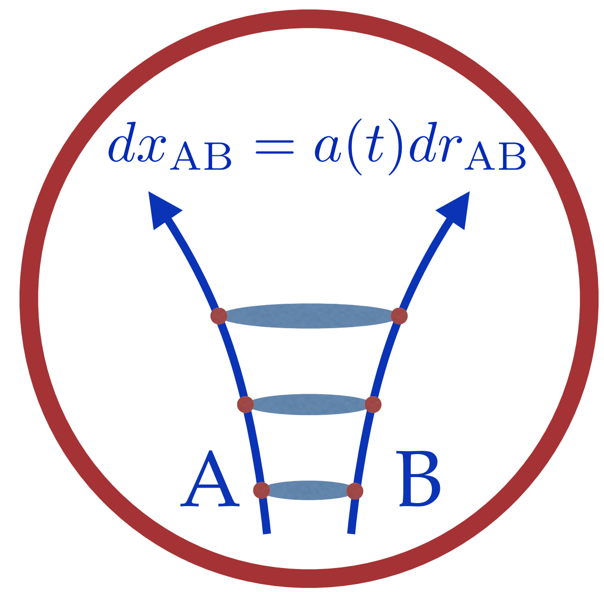
- Alternatively, CA indicates a failure of GR, which needs to be modified.

Cosmology from LSS observations

- Observational effects of cosmic acceleration:

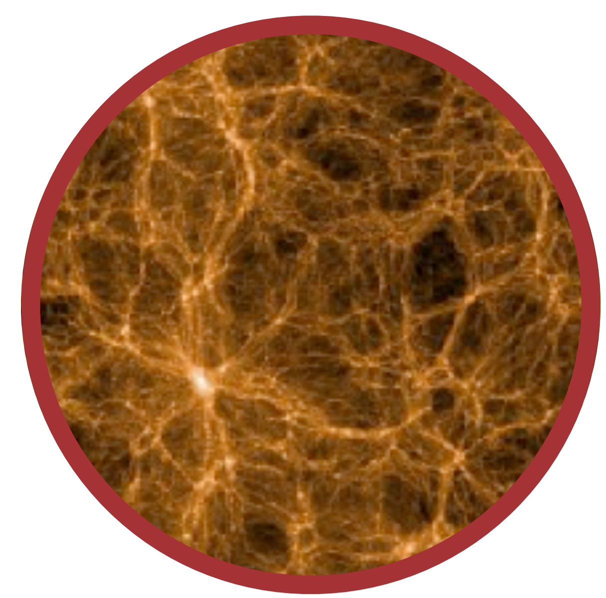
  - Expansion history of the Universe:

$$H(z) = \frac{\dot{a}}{a} \qquad r(z) = \int_0^z \frac{c\,dz'}{H(z')}$$



  - Growth of density fluctuations:

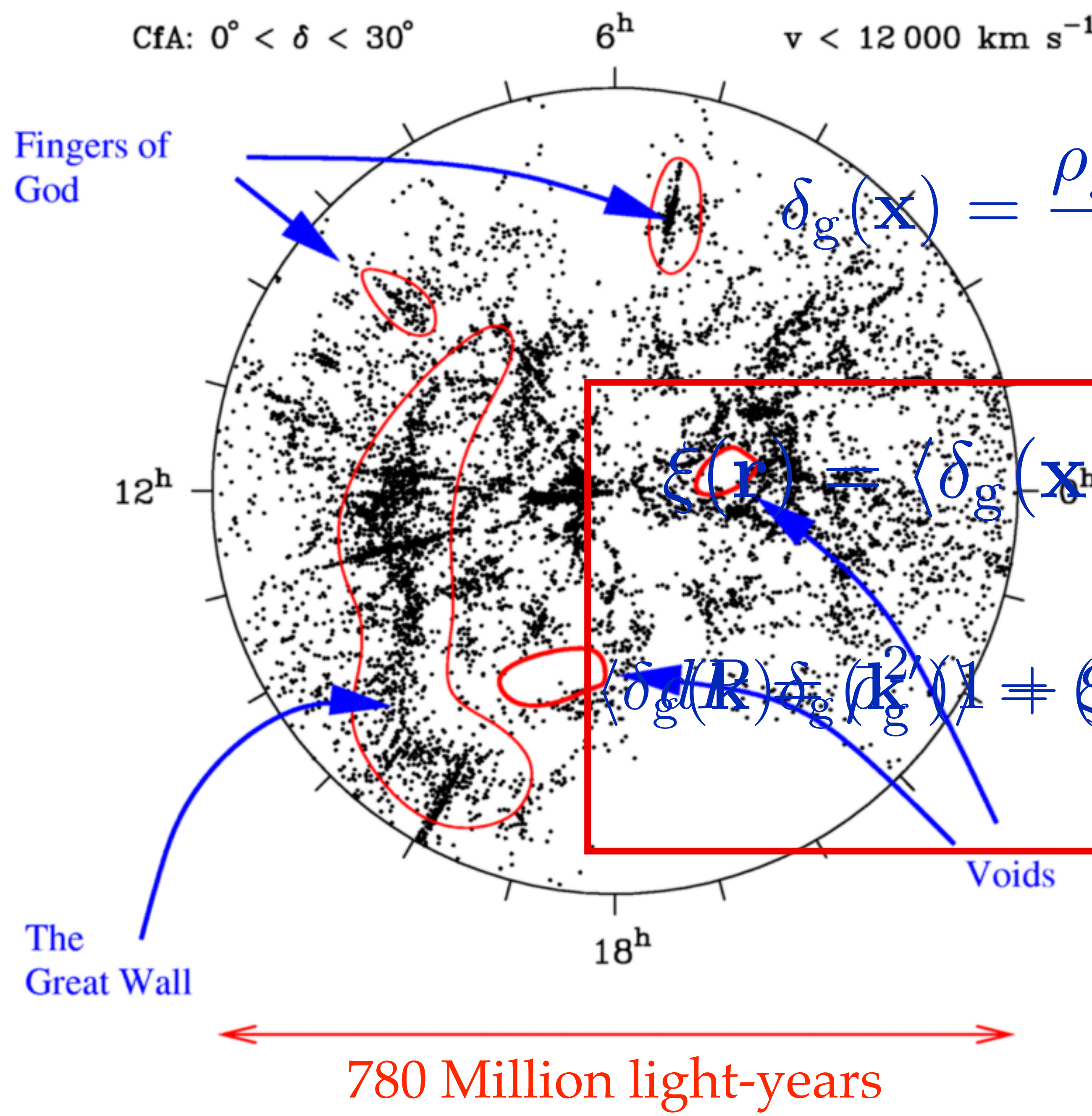
$$\delta = \frac{\rho - \bar{\rho}}{\bar{\rho}}$$



- Both effects can be probed by LSS observations

Cosmology from LSS observations

- Statistical analyses of large-scale structure



$$\delta_{\rm g}(\mathbf{x}) = \frac{\rho_{\rm g}(\mathbf{x}) - \bar{\rho}_{\rm g}}{\bar{\rho}_{\rm g}}$$

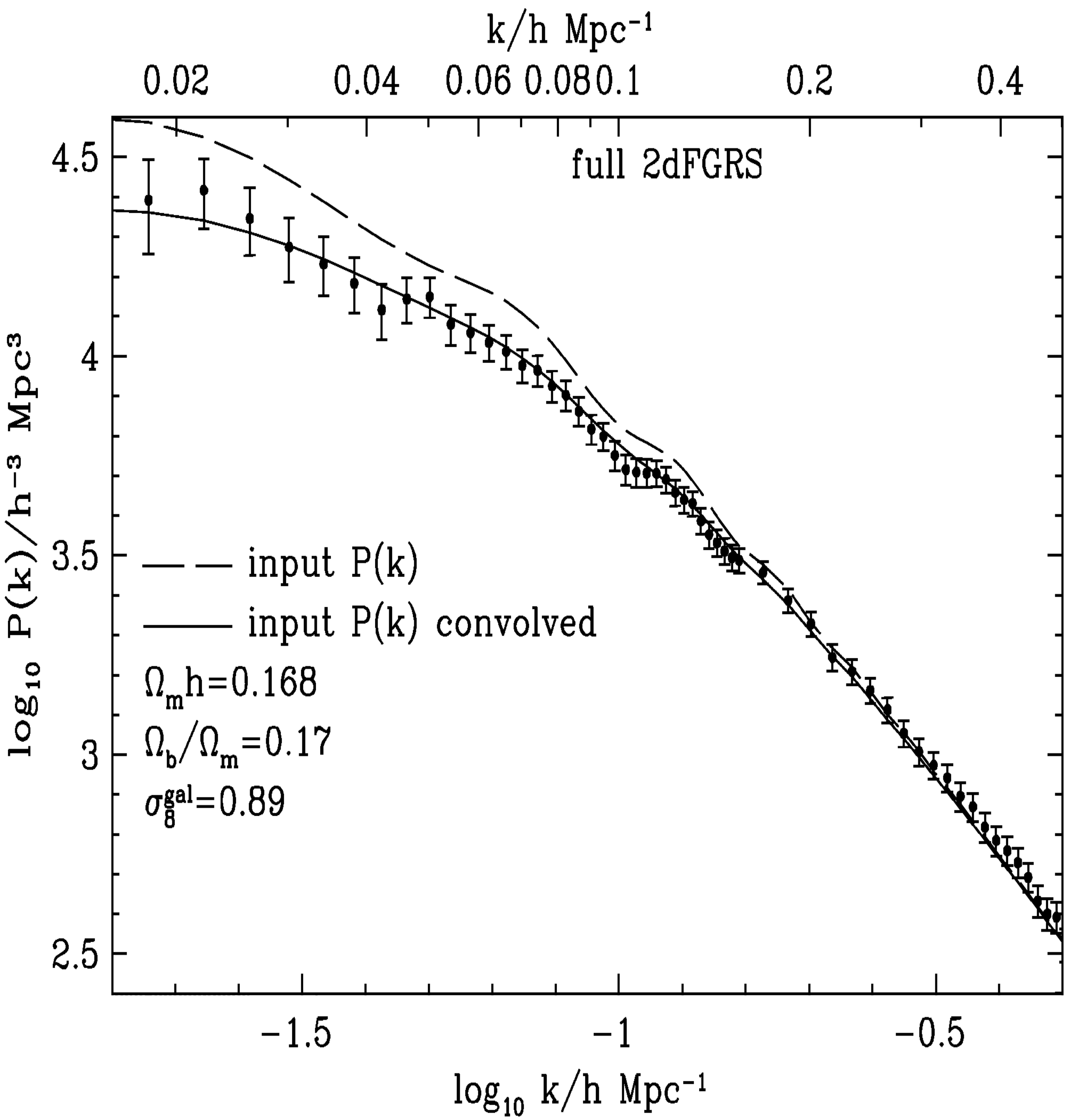
$$\xi(\mathbf{r}) = \langle \delta_{\rm g}(\mathbf{x})\delta_{\rm g}(\mathbf{x}+\mathbf{r})\rangle$$

$$dP = \bar{n}^2(1+\xi(r_{12}))\,dV_1\,dV_2$$

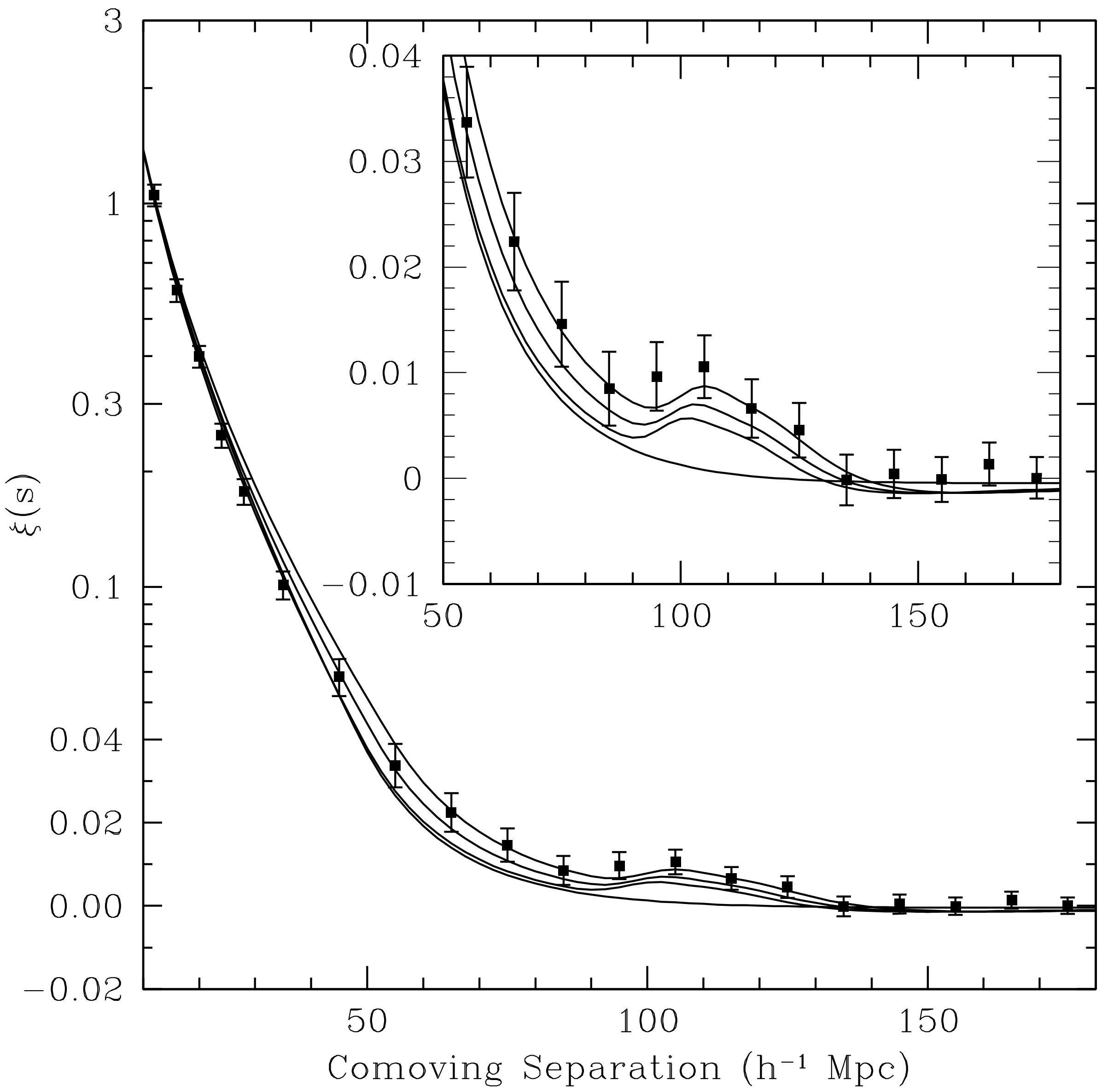
$$\langle \delta_{\rm g}(\mathbf{k})\delta_{\rm g}(\mathbf{k}')\rangle = (2\pi)^3\delta_{\rm D}(\mathbf{k}+\mathbf{k}')P(k)$$

Cosmology from LSS observations

- Statistical analysis of large-scale structure



Cole et al. (2005)



Eisenstein et al. (2005)

Newtonian perturbations

- In static Euclidean space the evolution of a fluid follows the equations

$$\dot{\rho} + \nabla \cdot (\rho \mathbf{v}) = 0, \qquad \text{continuity}$$

$$\dot{\mathbf{v}} + (\mathbf{v} \cdot \nabla)\mathbf{v} = -\frac{\nabla p}{\rho} - \nabla \Phi_{\mathrm{N}} \qquad \text{Euler}$$

$$\nabla^2 \Phi_{\mathrm{N}} = 4\pi G \rho \qquad \text{Poisson}$$

- Decomposing ρ and p into background and perturbations, these equations can be combined into

$$\ddot{\delta\rho} - c_{\mathrm{s}}^2 \nabla^2 \delta\rho = 4\pi G \bar{\rho} \delta\rho \qquad c_{\mathbf{s}}^2 = \frac{\delta p}{\delta \rho}$$

Newtonian perturbations

- Fourier transforming and defining the Jeans length as

$$\lambda_{\rm J} = \frac{2\pi}{k_{\rm J}} \equiv c_{\rm s}\sqrt{\frac{\pi}{G\bar{\rho}}}$$

this equation can be written as

$$\ddot{\delta\rho} + c_{\rm s}^2 k_{\rm J}^2 \left(\frac{k^2}{k_{\rm J}^2} - 1\right)\delta\rho = 0$$

- For modes with wavelengths

$\lambda \gg \lambda_{\rm J} \;\; (k/k_{\rm J} \ll 1) \;\; \rightarrow$ exponential growth

$\lambda \ll \lambda_{\rm J} \; , (k\lambda_{\rm J} \gg 1) \;\; \rightarrow$ waves of constant amplitude

Linear evolution of density fluctuations

- An expanding universe requires a full treatment within GR.
- Working in the long. gauge, focusing on scalar modes…
- Considering only dark matter and radiation…
- The energy cons. equations $\nabla^\mu T_{\nu,\mu} = 0$ can be written as

$$\delta'_{\rm m} - k^2 v_{\rm m} = 3\Phi',$$
$$\frac{3}{4}\delta'_\gamma - k^2 v_\gamma = 3\Phi',$$
$$v'_{\rm m} + \mathcal{H} v_{\rm m} = -\Phi,$$
$$v'_\gamma + \frac{1}{4}\delta_\gamma = -\Phi.$$

Conformal time: $dt = a(\tau)d\tau$

$$\mathcal{H} = \frac{a'}{a}$$

Φ is a GR version of the Newtonian potential

Acoustic oscillations

- Neglecting gravitational effects, we can write

$$\delta_\gamma'' + c_\mathrm{s}^2 k^2 \delta_\gamma = 0 \qquad c_\mathrm{s} = 1/\sqrt{3}$$

- The solution corresponds to acoustic waves

$$\delta_\gamma(\tau) = \delta_\gamma(0) \cos\left(k r_\mathrm{s}(\tau)\right) + \frac{\delta_\gamma'(0)}{k c_\mathrm{s}} \sin\left(k r_\mathrm{s}(\tau)\right)$$

- where the *sound horizon* is given by

$$r_\mathrm{s}(\tau) = \int_0^\tau c_\mathrm{s}\,\mathrm{d}\tau$$

the maximum distance that a wave can travel until time τ

- The initial conditions (all modes are super-horizon) imply

$$\delta_\gamma(0) = -2\Phi_\mathrm{i}, \quad \delta_\gamma'(0) = 0.$$

Impact of baryons

- Prior to recombination, b and γ are tightly coupled due to Thomson scattering -> *photon-baryon fluid*.
- Baryons contribute to the total momentum density

$$(\rho_{\rm b} + p_{\rm b})\,\mathbf{v}_{\rm b} + (\rho_\gamma + p_\gamma)\,\mathbf{v}_\gamma = (1+R)\,(\rho_\gamma + p_\gamma)\,\mathbf{v}_\gamma$$

where

$$R = \frac{\rho_{\rm b} + p_{\rm b}}{\rho_\gamma + p_\gamma} = \frac{3}{4}\frac{\rho_{\rm b}}{\rho_\gamma}$$

ratio of the momenta of baryons and photons

- Including b and Φ, the Euler and continuity eqs. can still be combined as

$$\left[(1+R)\,\delta'_\gamma\right]' + \frac{k^2}{3}\delta_\gamma = -\frac{4k^2}{3}\,(1+R)\,\Phi + 4\left[(1+R)\,\Phi'\right]'$$

Impact of baryons

- Assume a constant gravitational potential Φ.
- Assume that the change in R is slow compared to the frequency of the oscillations

$$\frac{R'}{R} \ll \omega = k c_{\mathrm{s}}$$

- We can then write

$$\left[\delta_\gamma + 4\left(1+R\right)\Phi\right]'' + k^2 c_{\mathrm{s}}^2 \left[\delta_\gamma + 4\left(1+R\right)\Phi\right] = 0$$

- where

$$c_{\mathrm{s}}^2 = \frac{1}{3(1+R)} \quad \rightarrow \quad r_{\mathrm{s}}(\tau) = \int_0^\tau \left[\frac{1}{3(1+R)}\right]^{1/2} \mathrm{d}\tau$$

The cosmic microwave background

- The multiple scatterings quickly thermalise the radiation, leading to a perfect blackbody spectrum.

$$E_\nu \mathrm{d}\nu = \frac{8h}{c^3}\frac{\nu^3 \mathrm{d}\nu}{e^{h\nu/k_\mathrm{B}T} - 1}$$

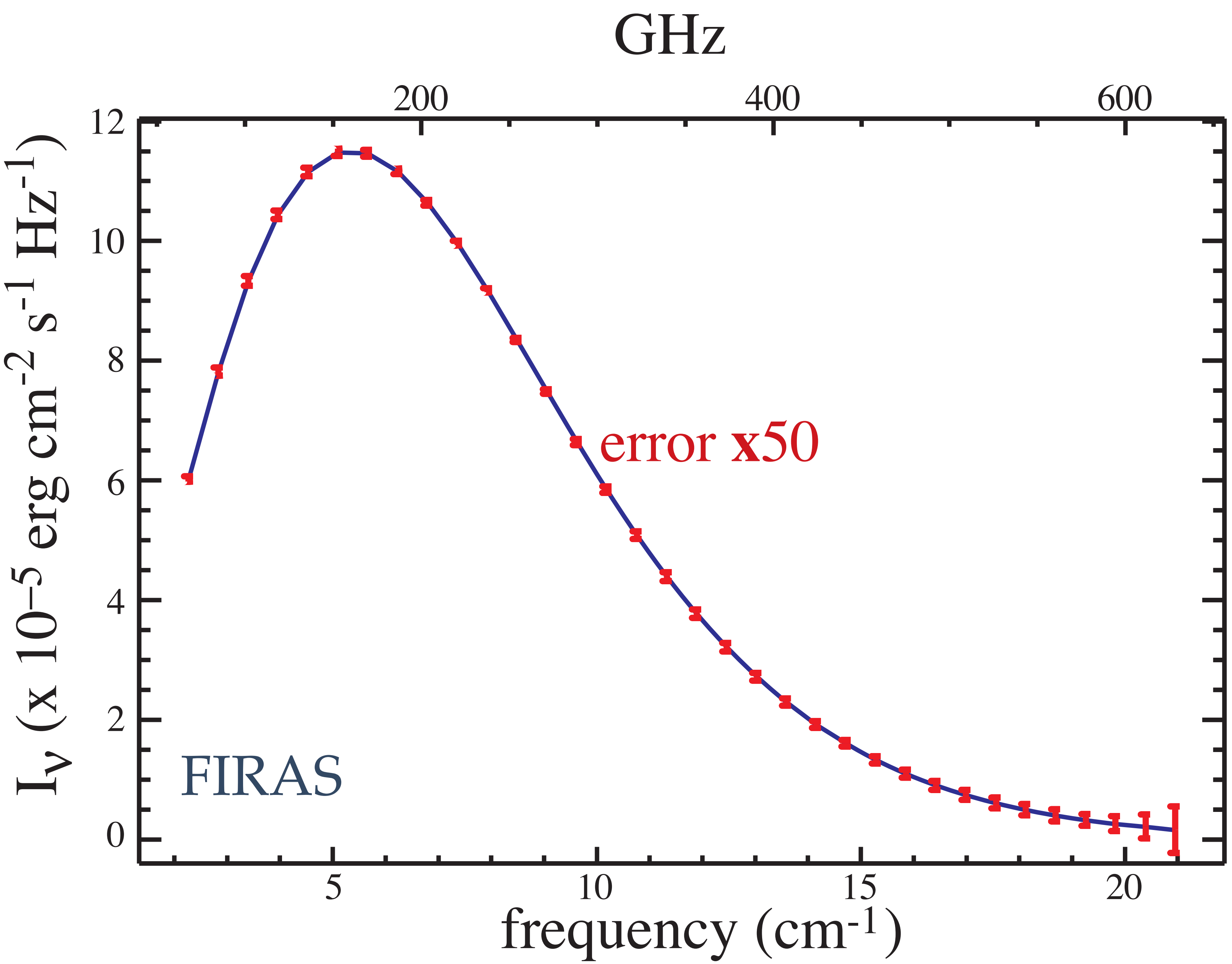
- Cosmic expansion rescales ν as a^{-1}, changing T as

$$T \propto a^{-1}$$

- At *recombination*, the Universe becomes cold enough to form neutral hydrogen.
- Photons decouple from baryons, forming the CMB we observe today.

The cosmic microwave background

- The CMB is the best blackbody spectrum in nature.



The cosmic microwave background

- The signature of BAO is also present in the CMB.

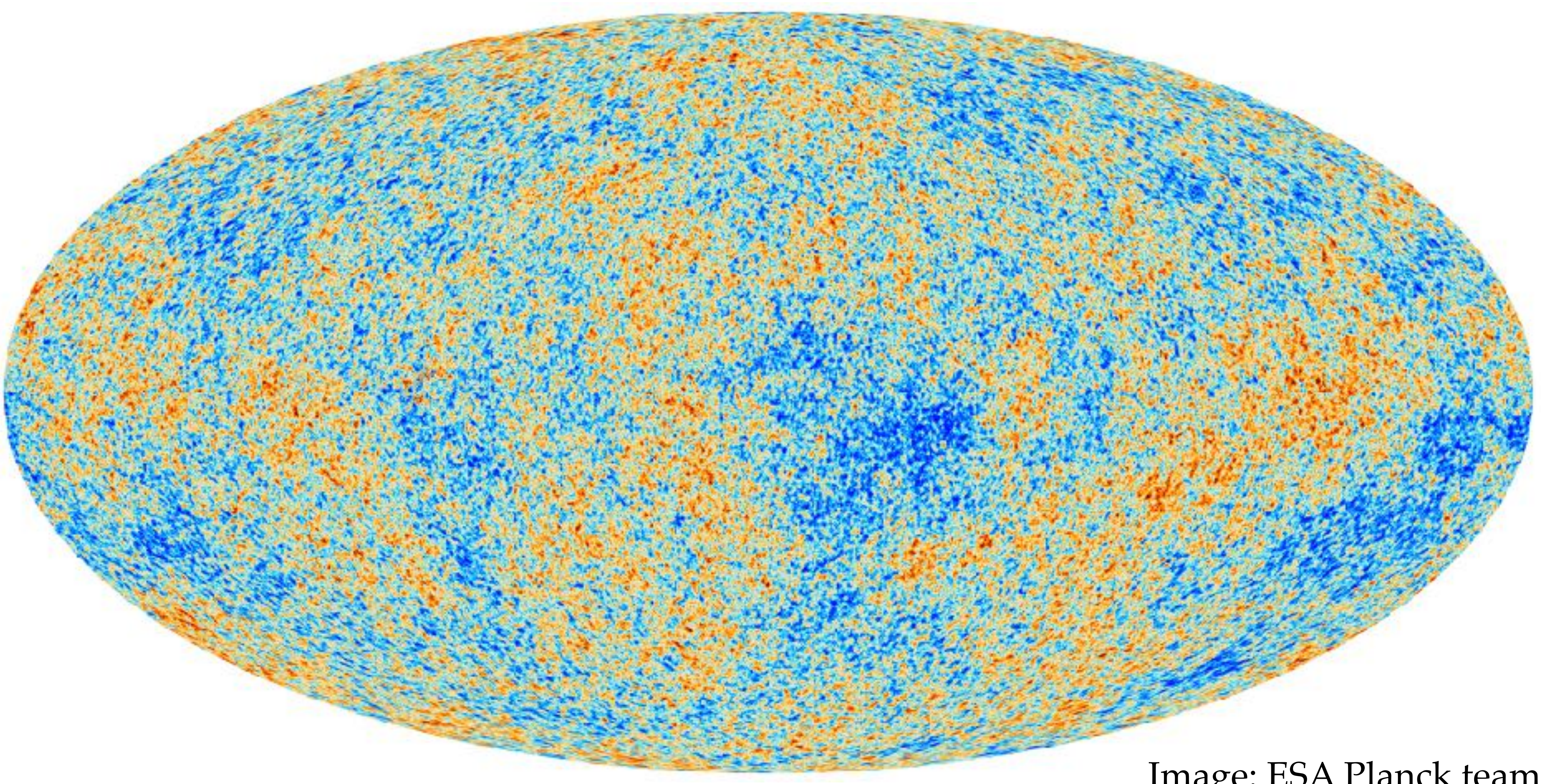


Image: ESA Planck team

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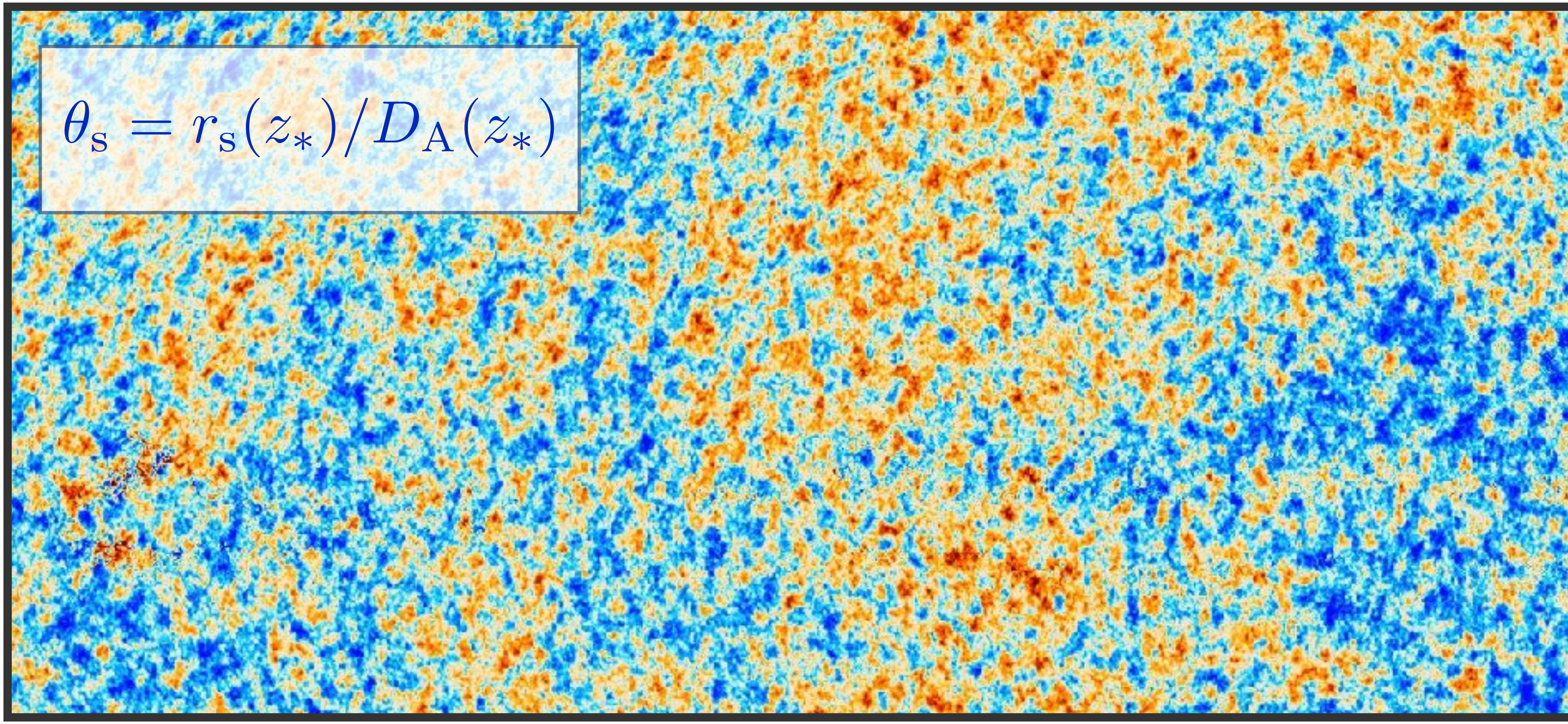

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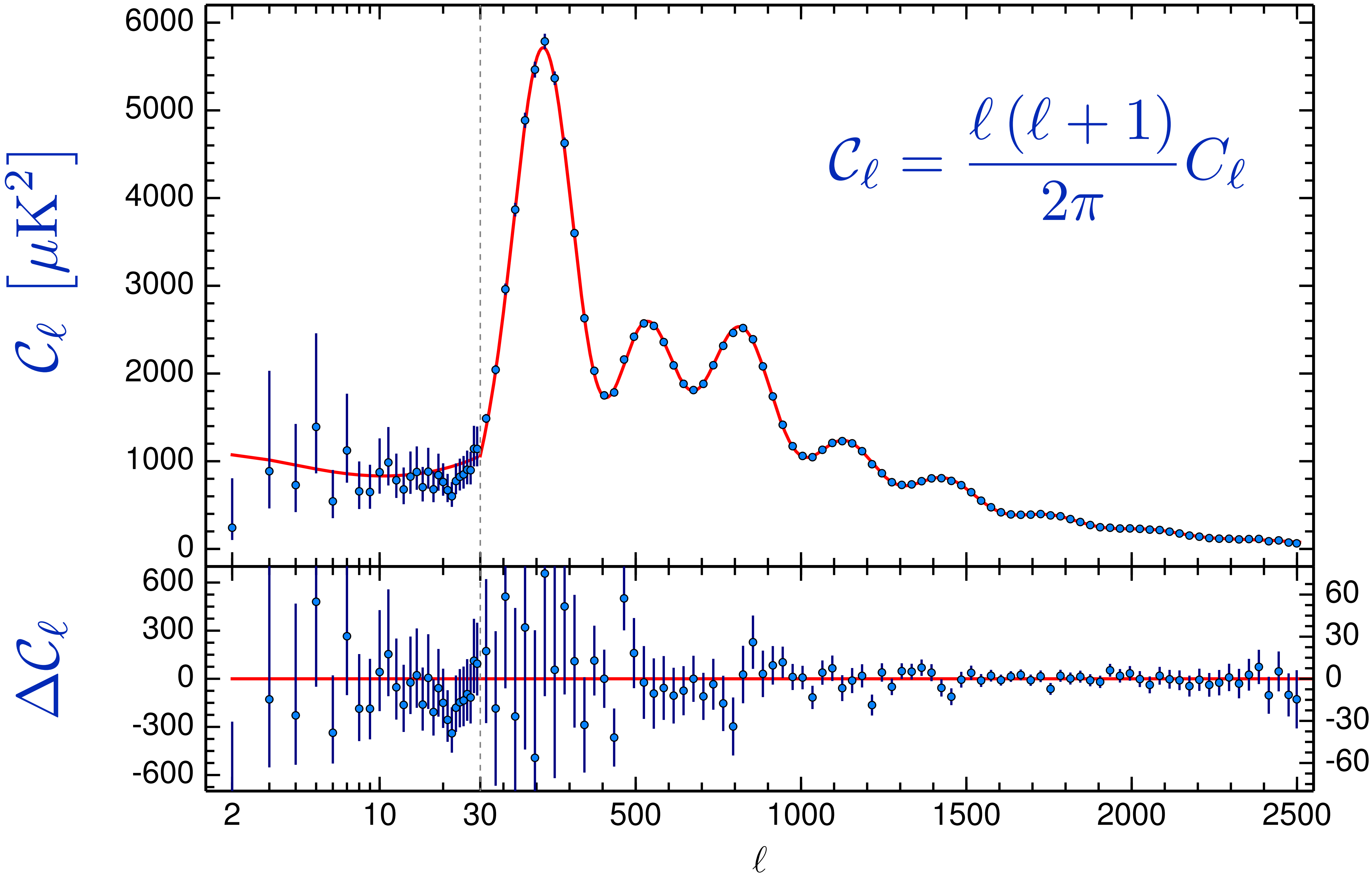

Baryon Acoustic Oscillations

- Consider the behaviour of single density fluctuation.

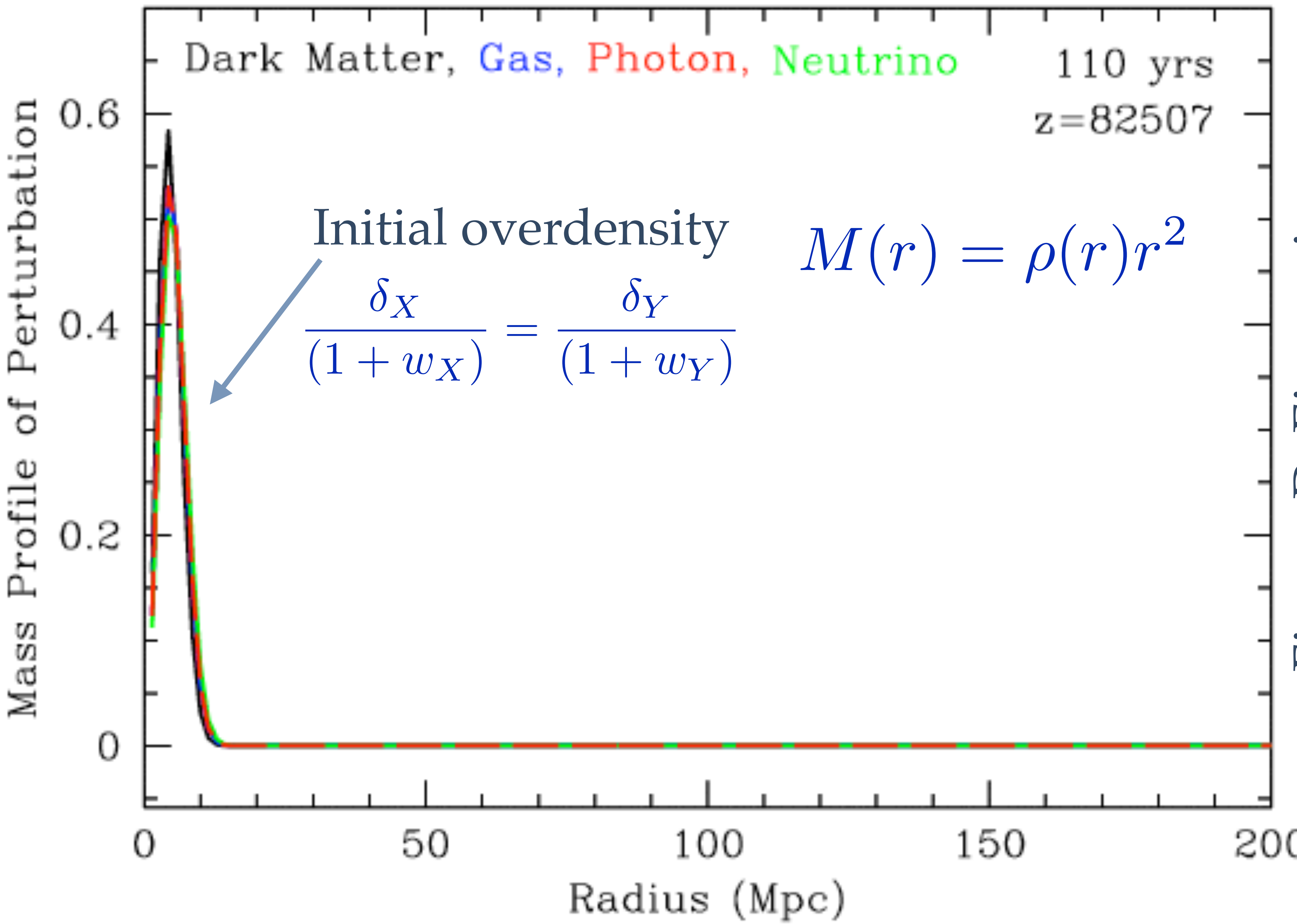

Figure: D. Eisenstein

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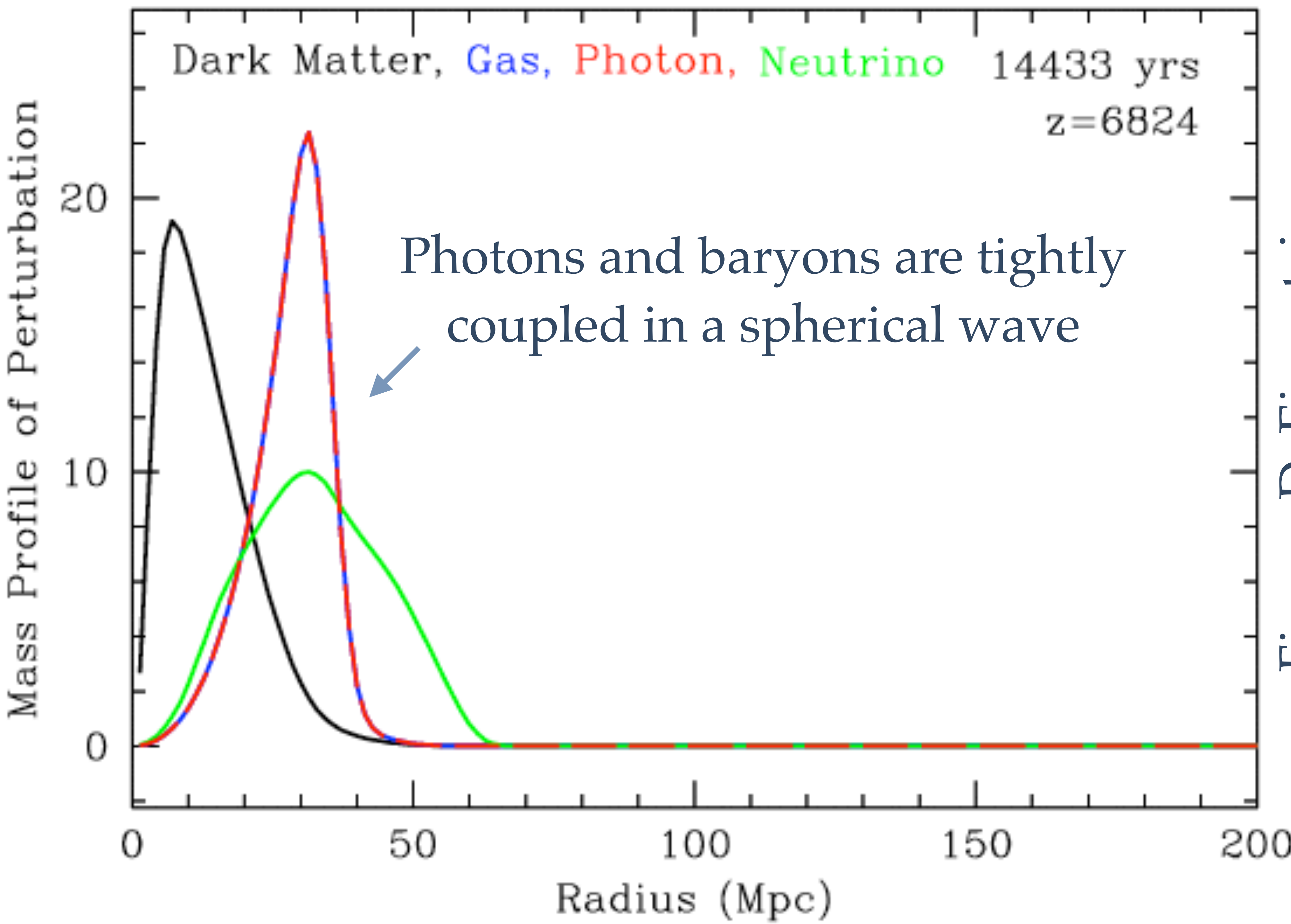

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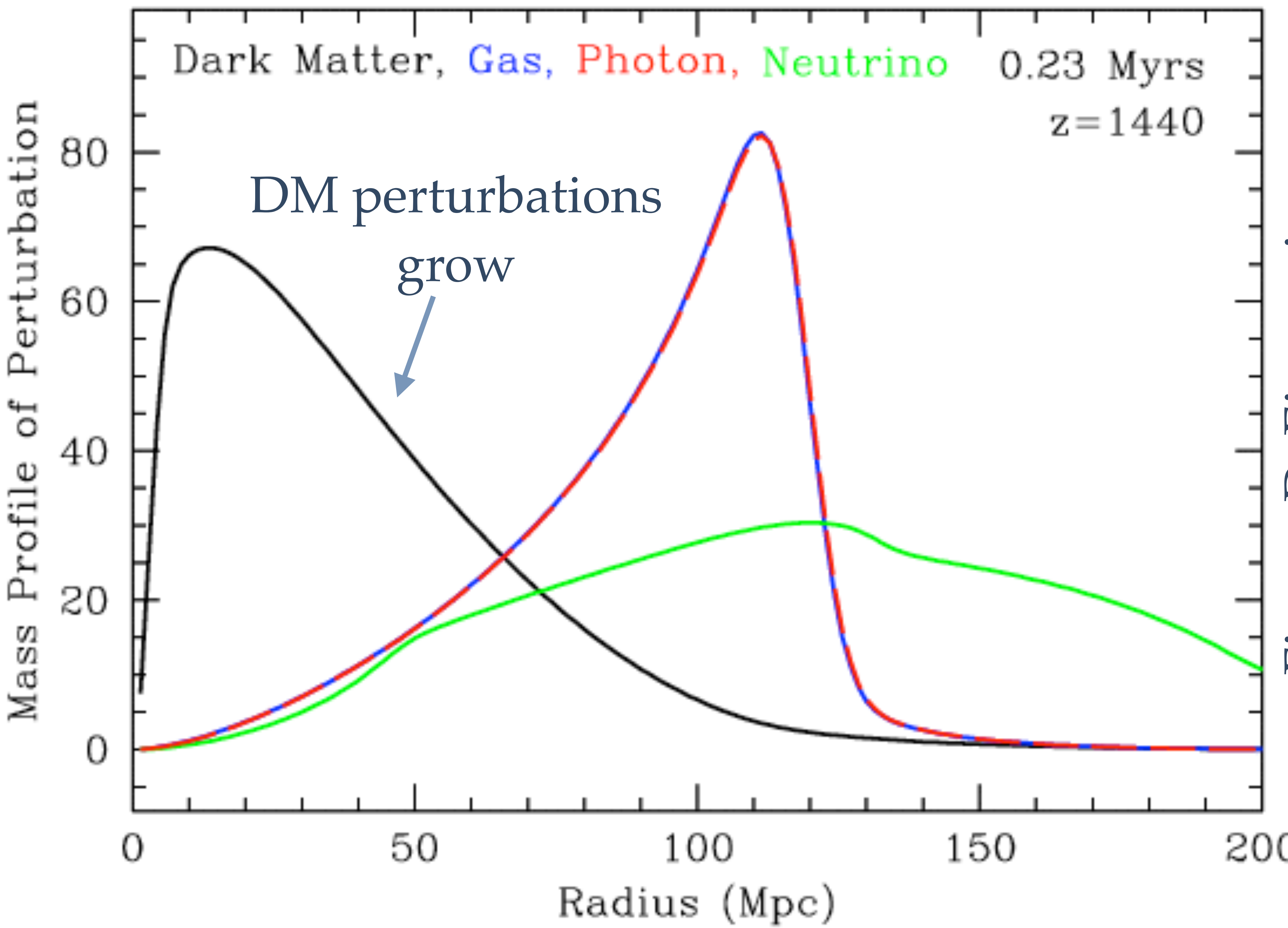

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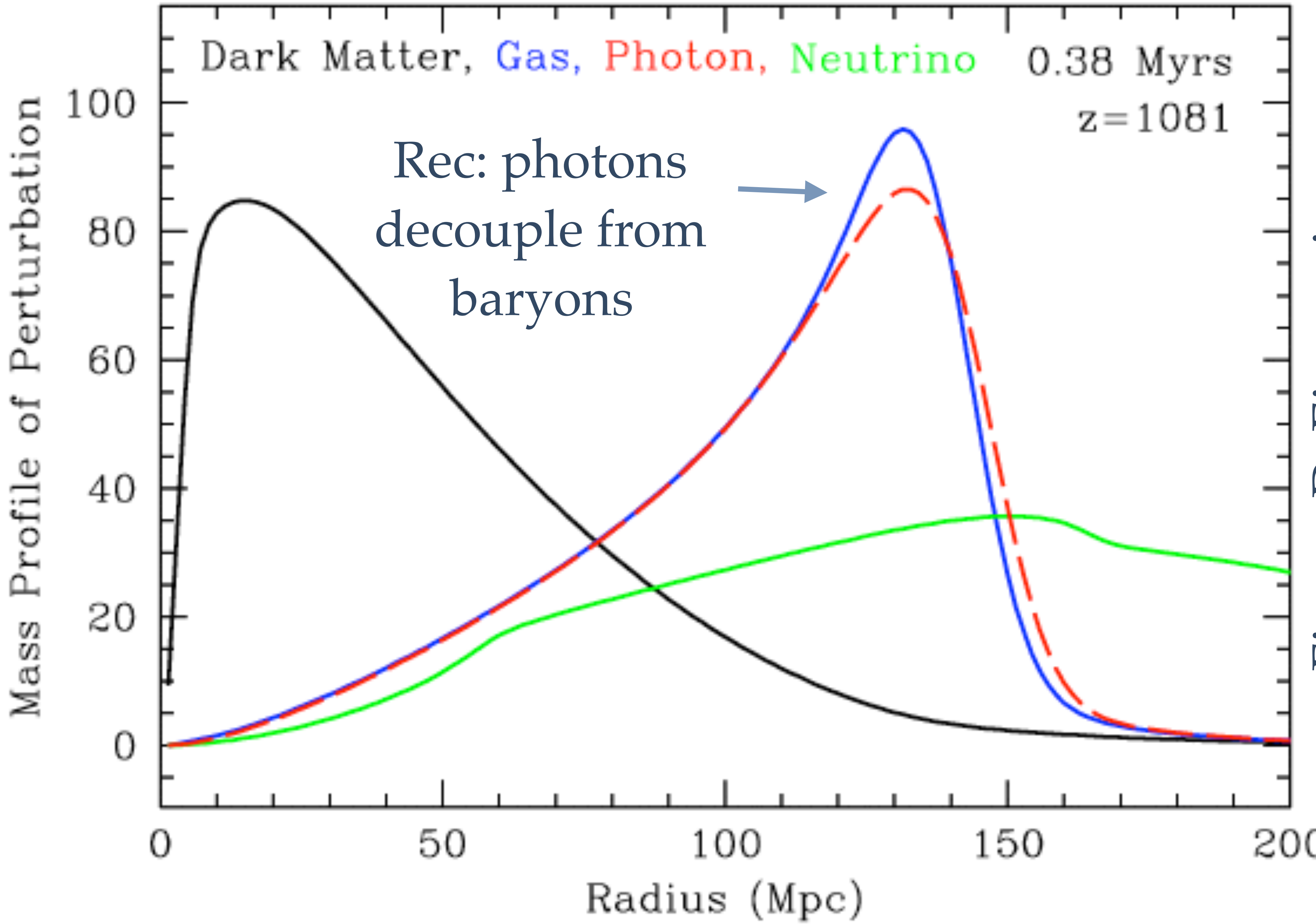

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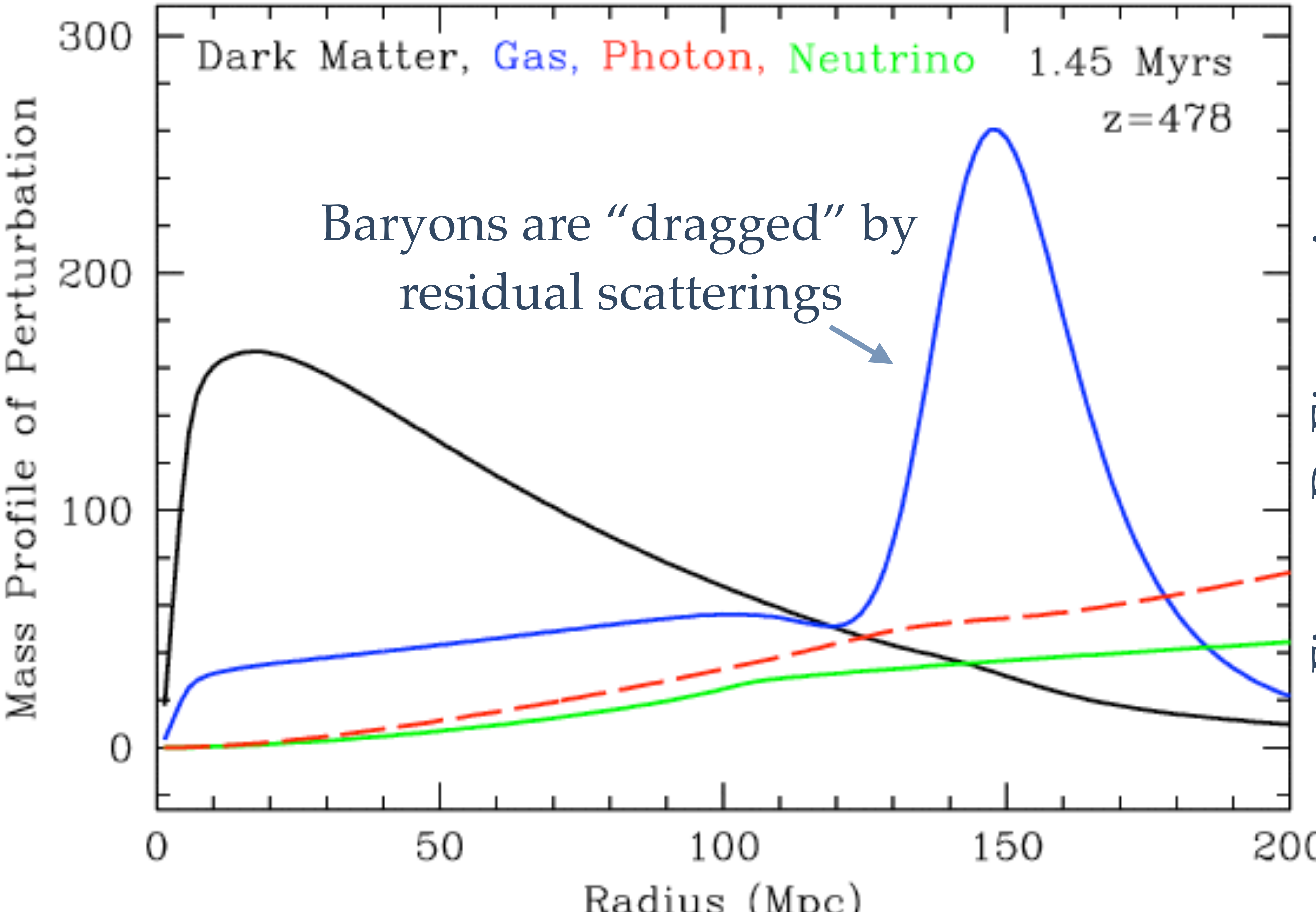

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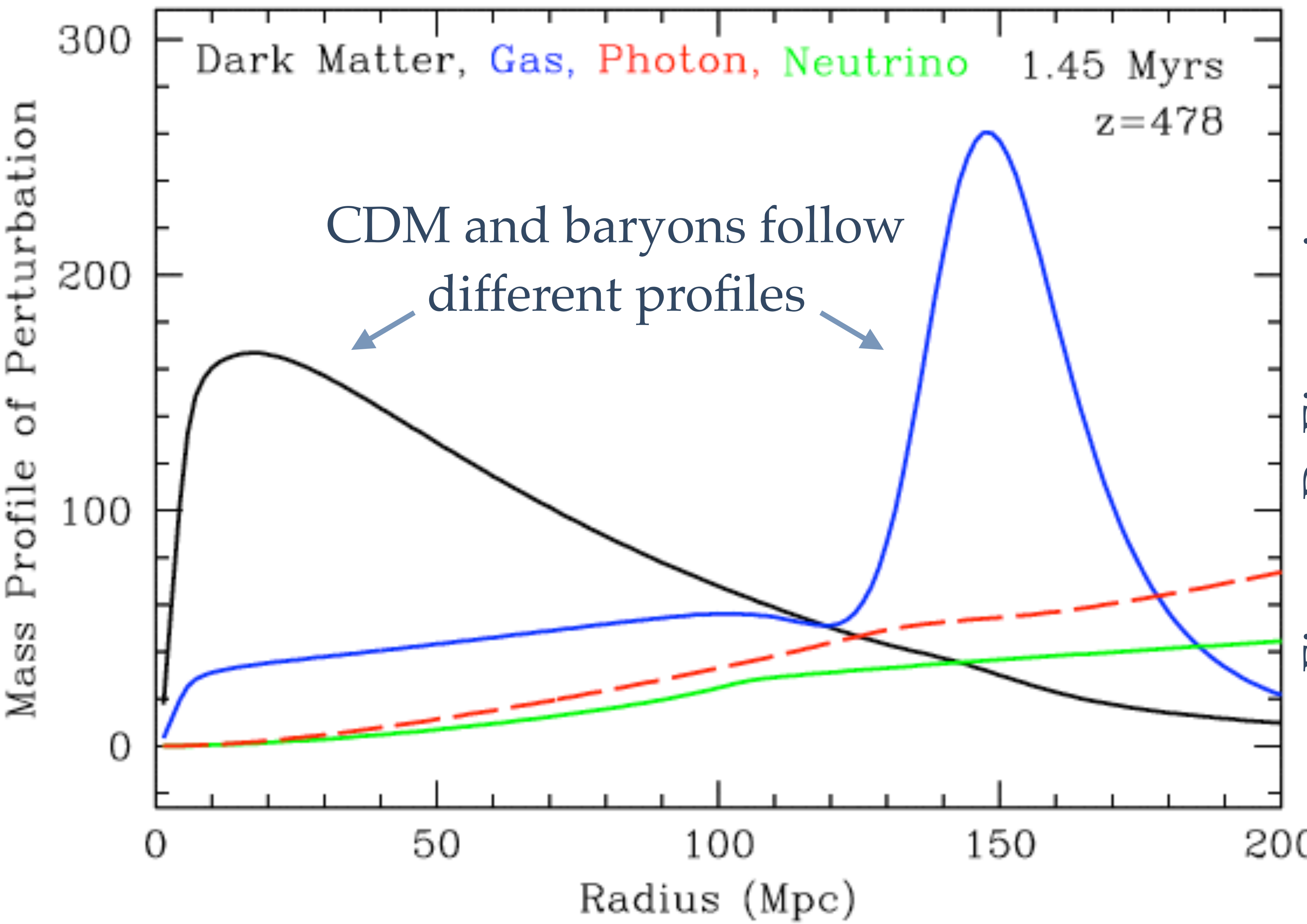

Figure: D. Eisenstein

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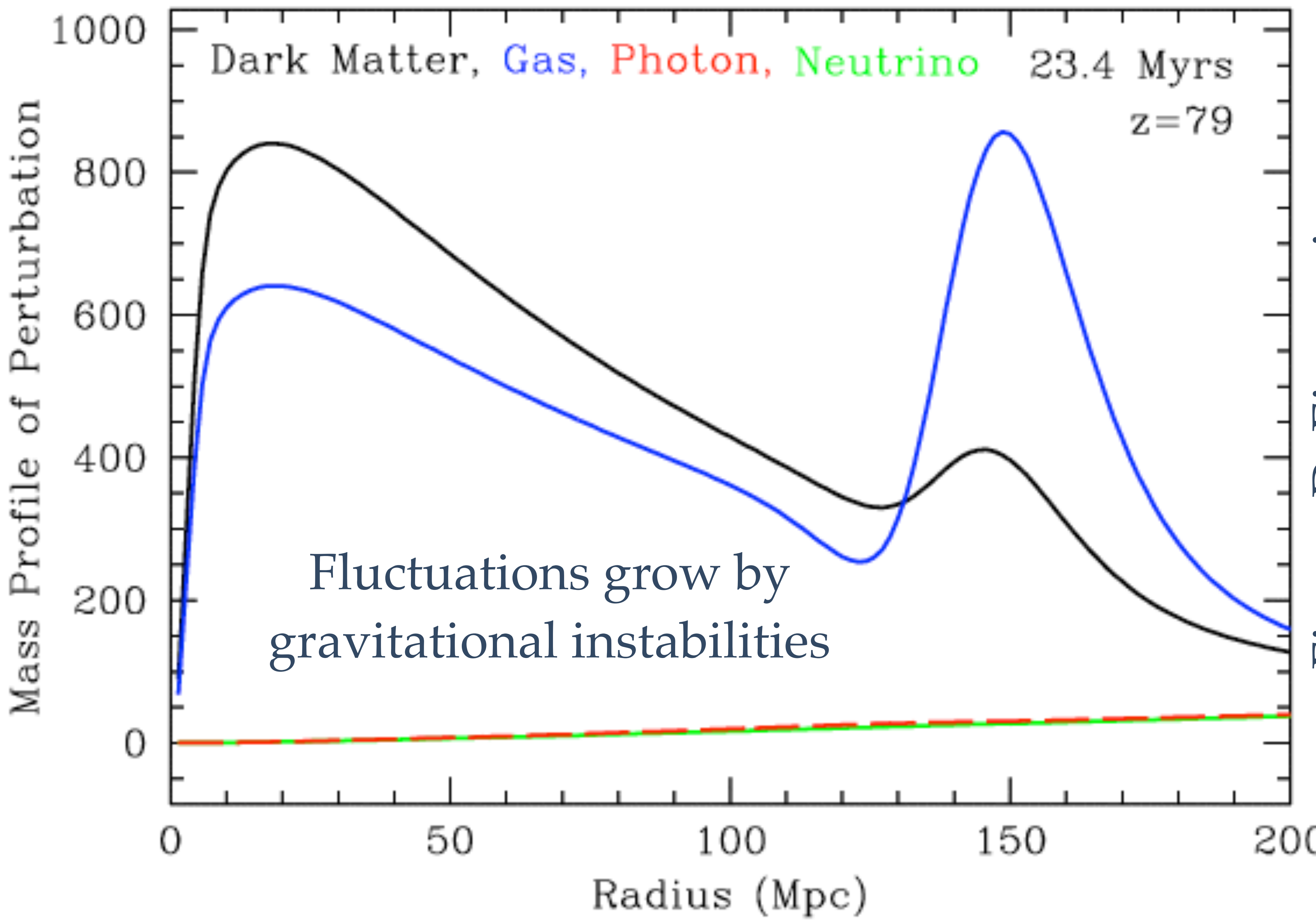

Fluctuations grow by gravitational instabilities

Figure: D. Eisenstein

Baryon Acoustic Oscillations

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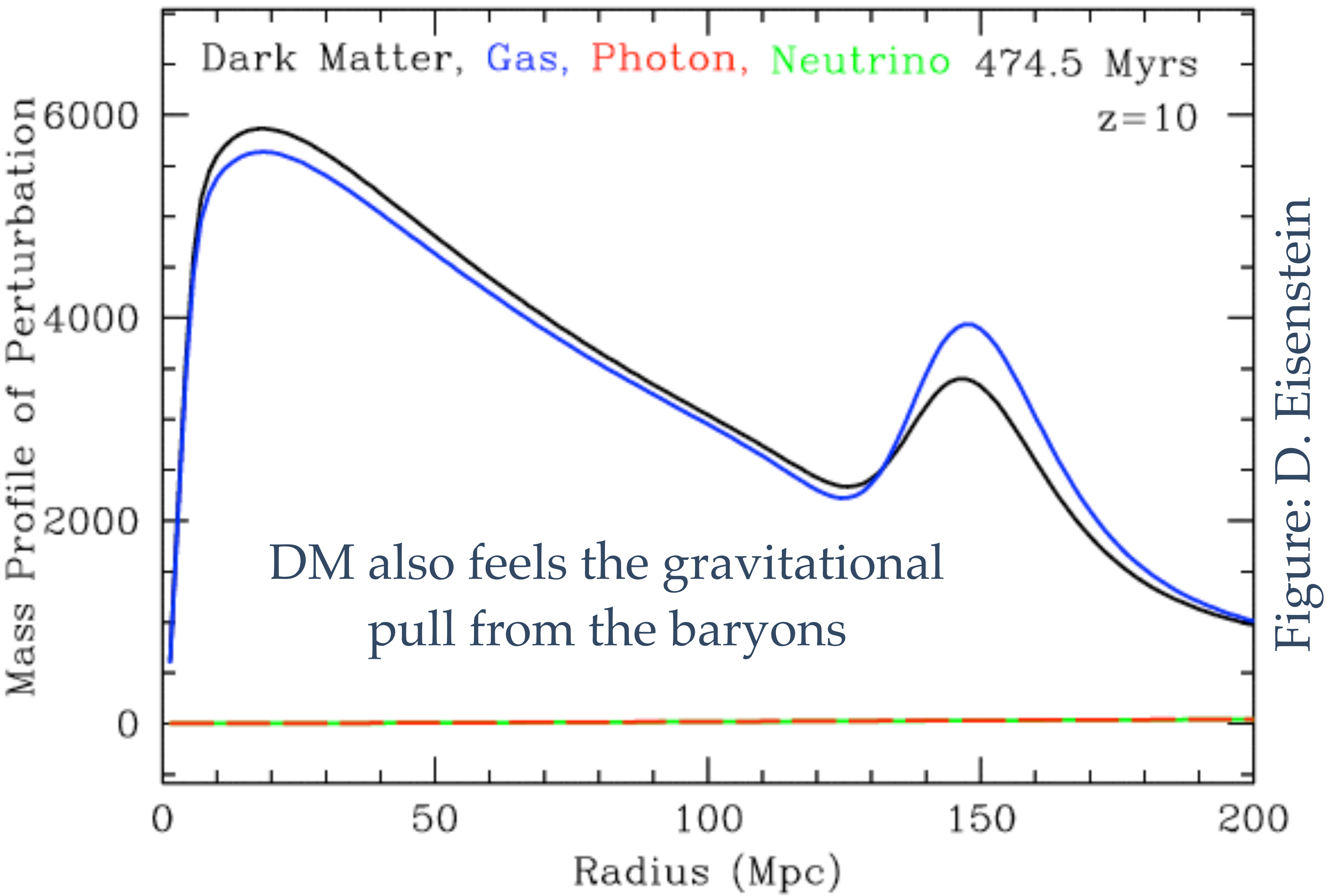

Figure: D. Eisenstein

Baryon Acoustic Oscillations

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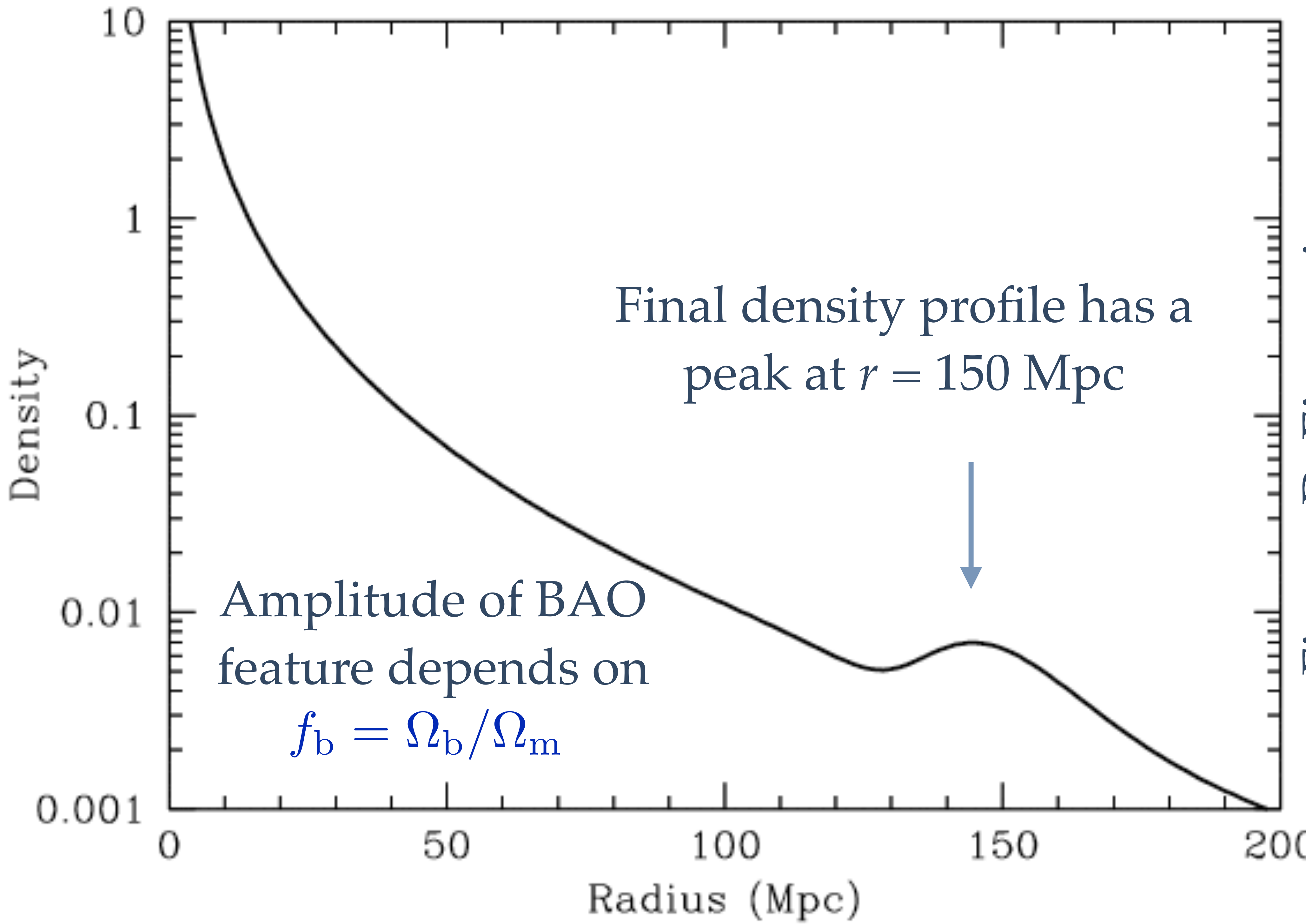

Figure: D. Eisenstein

Baryon Acoustic Oscillations

- Galaxies form in overdense regions.
- Several galaxies will form at the central peak.
- These will be surrounded by a spherical shell of galaxies at

$$r = r_{\mathrm{s}}(z_{\mathrm{d}})$$

- The real universe has multiple density peaks.

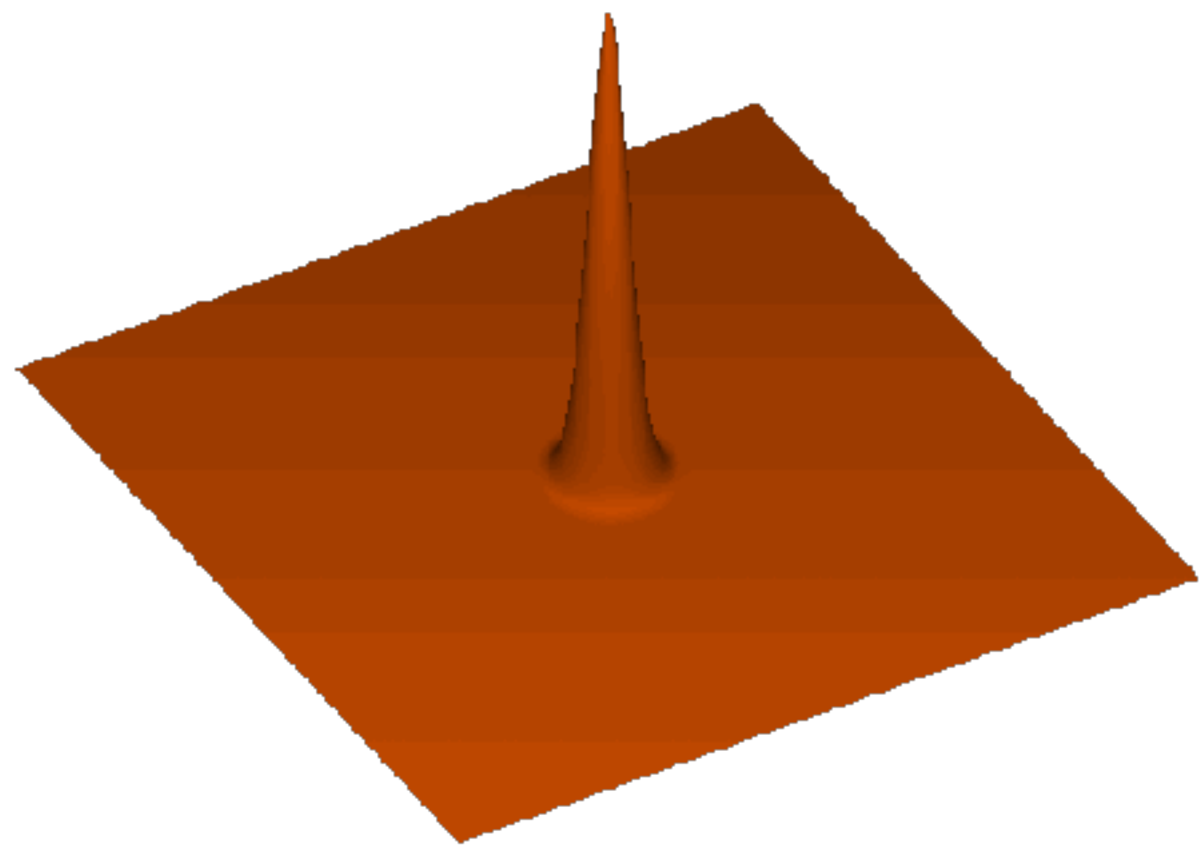

Figure: D. Eisenstein

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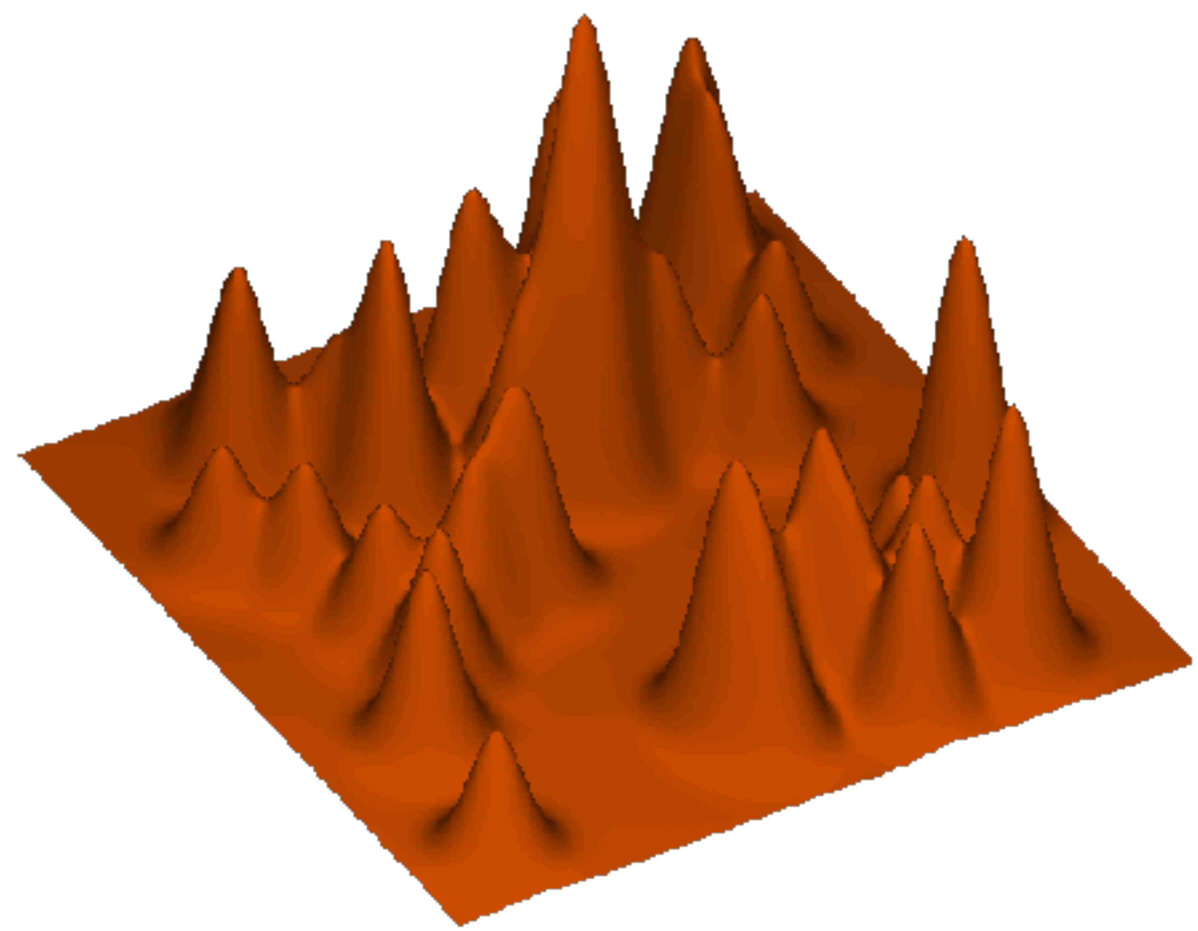
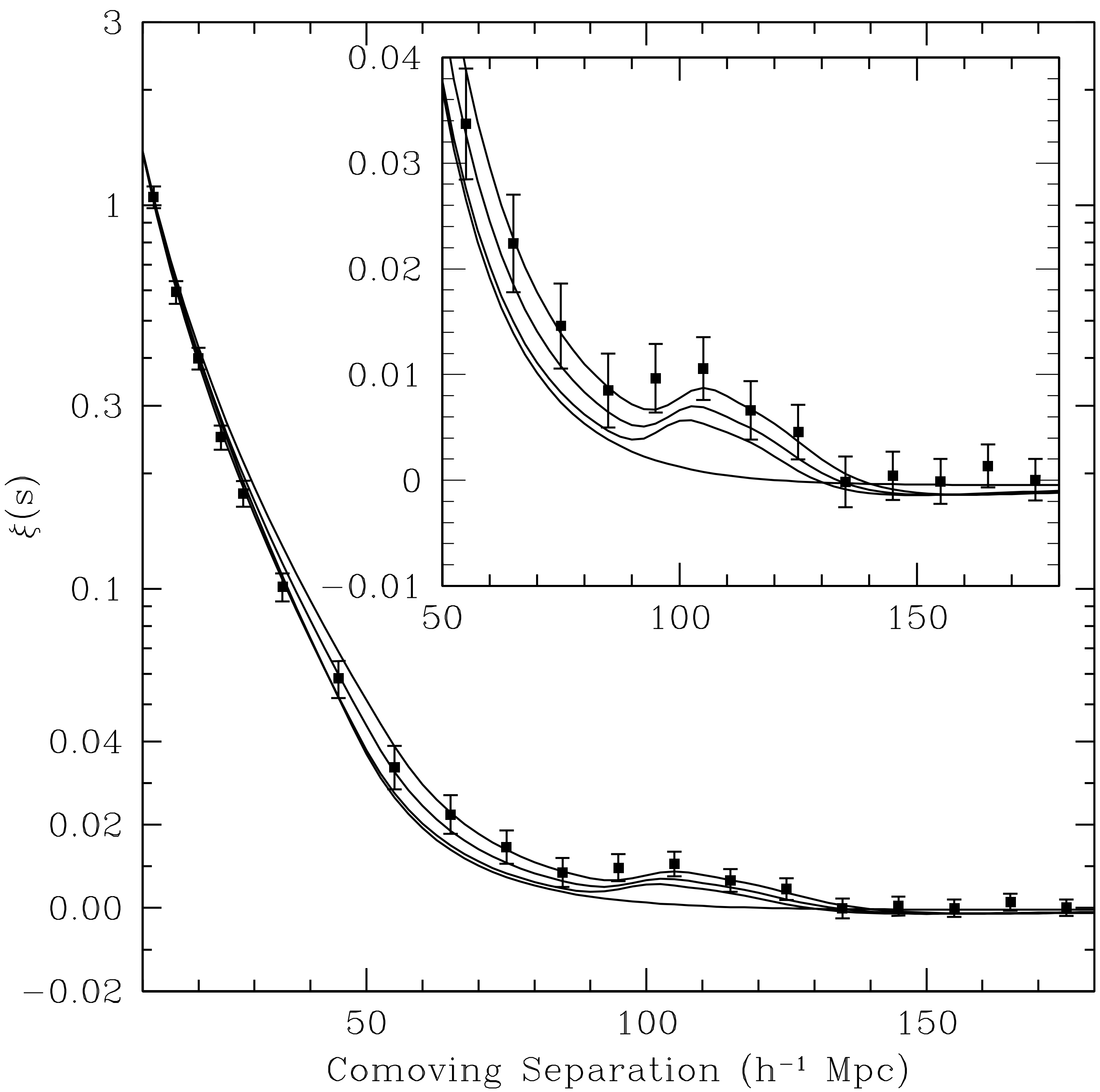


Figure: D. Eisenstein

Baryon Acoustic Oscillations

- First detection of the BAO peak (SDSS-LRG).
- Confirmed by other techniques and samples.
- Confirms a prediction of the standard model.
- BAOs are related to the sound

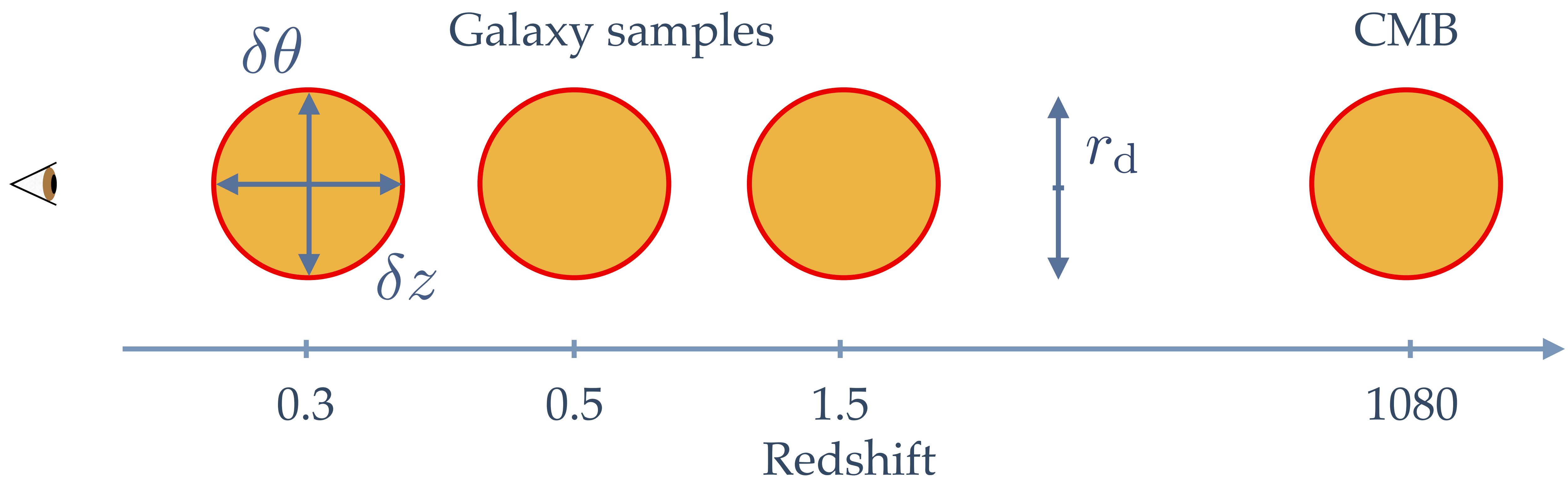
$$r_{\rm d} = r_{\rm s}(z_{\rm drag})$$



Eisenstein et al. (2005)

Baryon Acoustic Oscillations

- BAO can be used as a standard ruler.



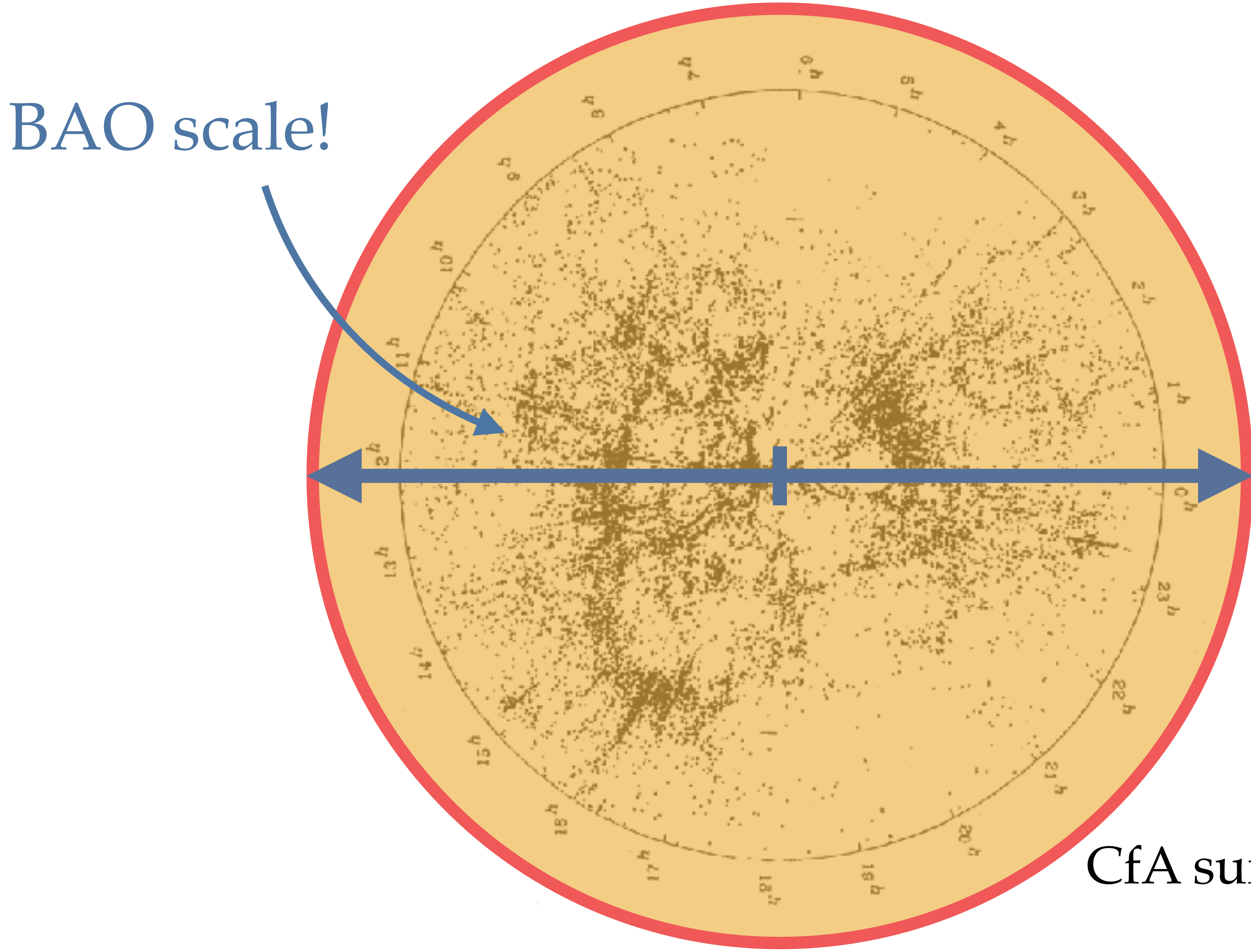
$$D_{\rm M}(z) = r_{\rm d}/\delta\theta \qquad H(z) = c\,\delta z/r_{\rm d}$$

- Angle-averaged measurements can only measure

$$D_{\rm V}(z) = \left(D_{\rm M}(z)^2 cz/H(z)\right)^{\frac{1}{3}}$$

Galaxy redshift surveys

- BAO measurements require large volumes!



CfA survey (1989)

Galaxy redshift surveys

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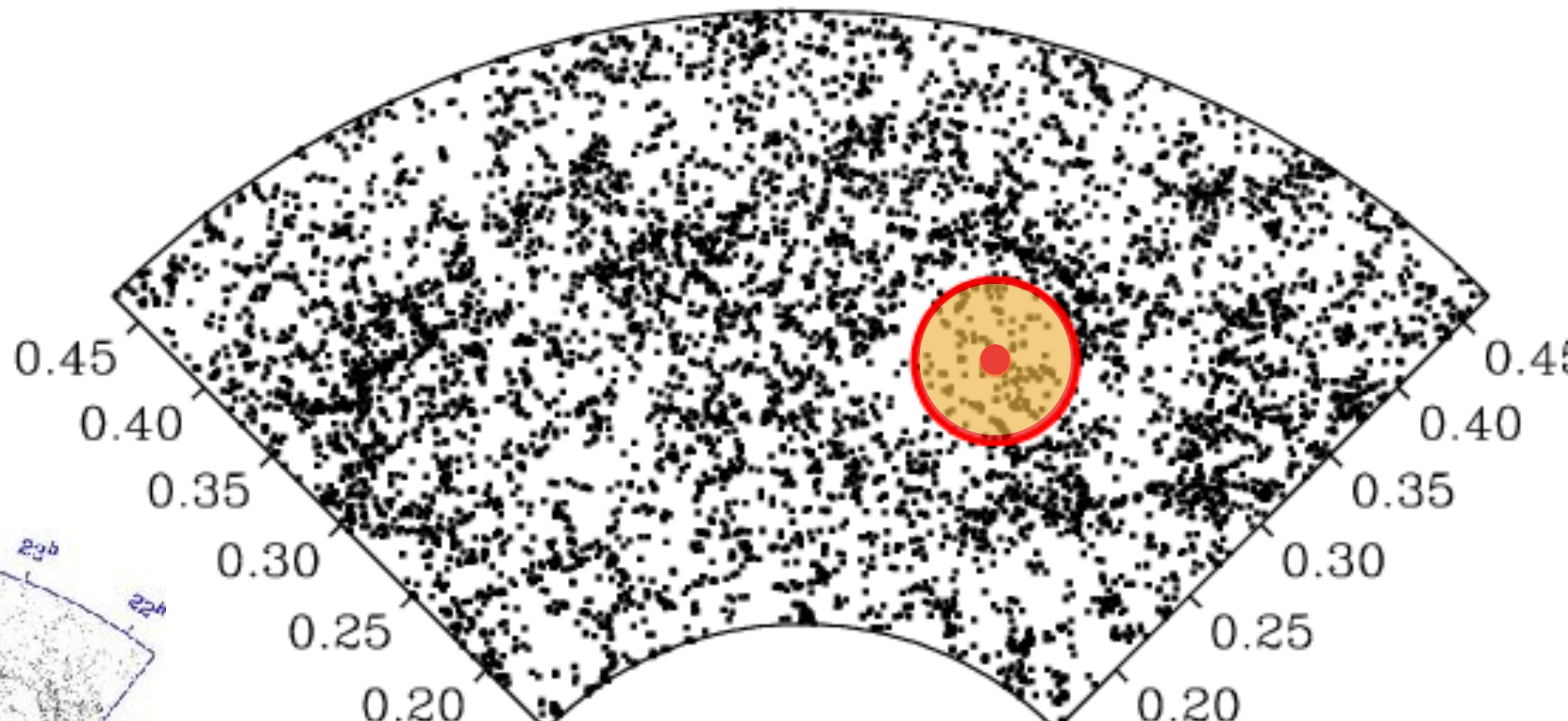
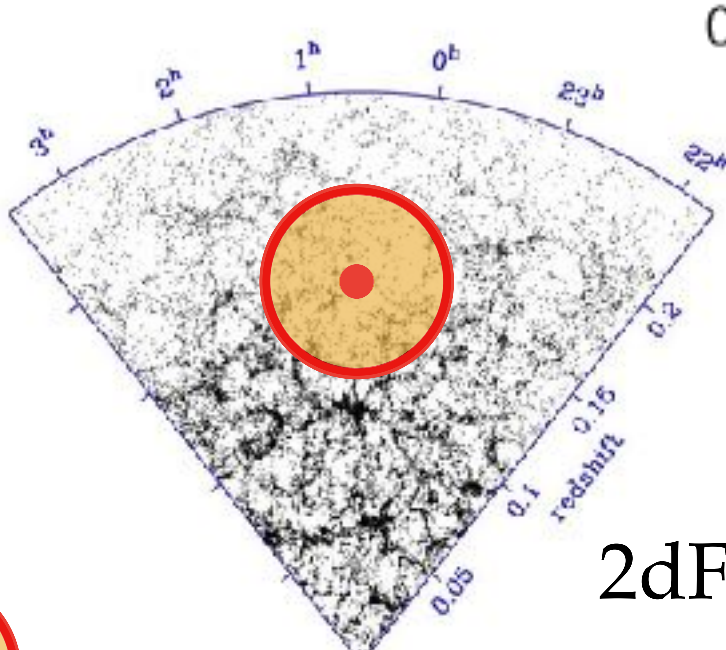
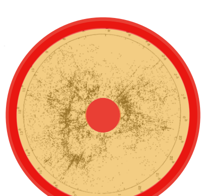


SDSS - LRGs (2009)



2dFGRS (2003)



CfA survey (1989)

BOSS in a nutshell

- Designed to tackle CA through BAO measurements

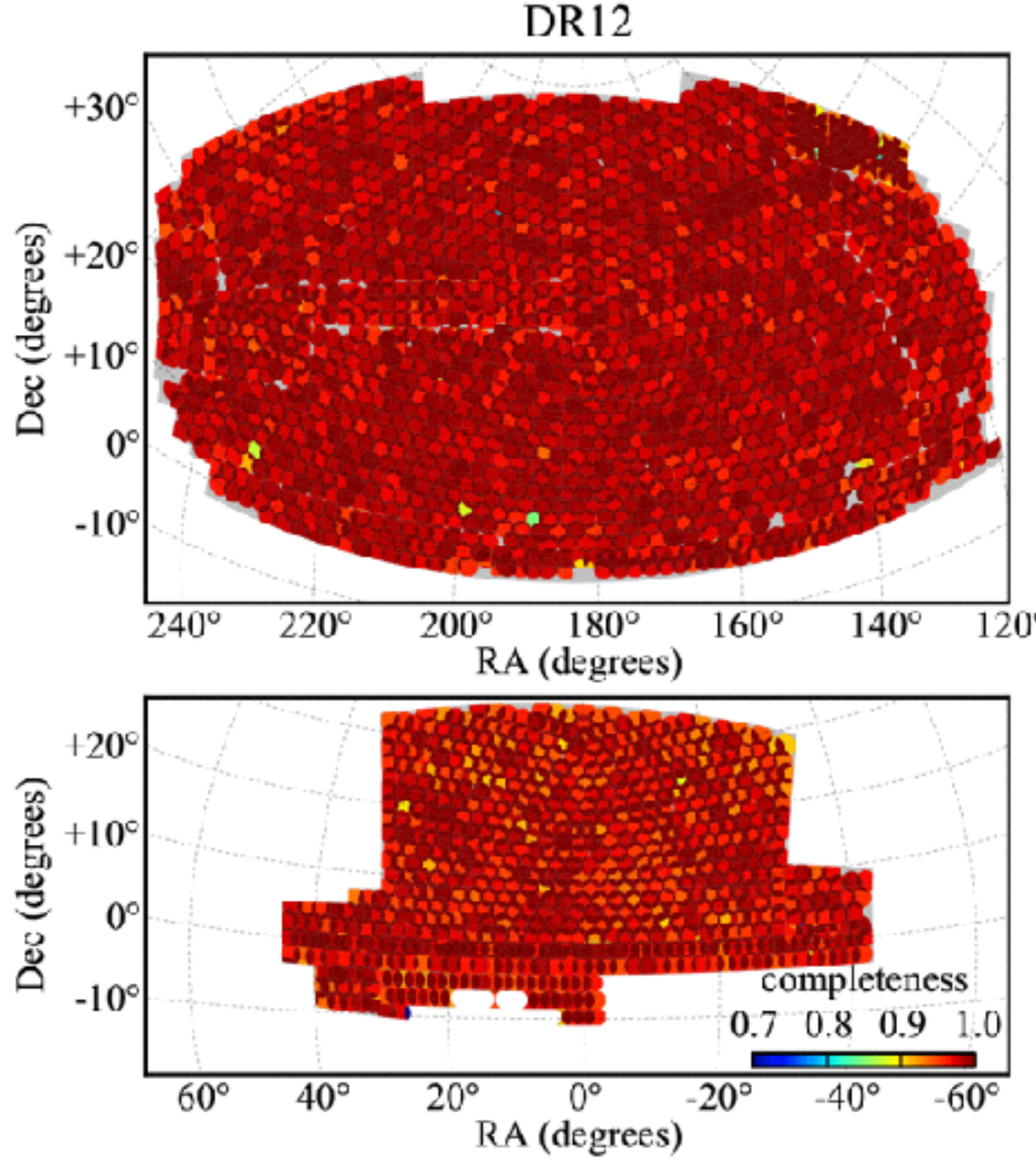
- Total area of 10,200 deg².

- Positions for 1.2×10^6 LGs

  - LOWZ, with $0.1 < z < 0.43$

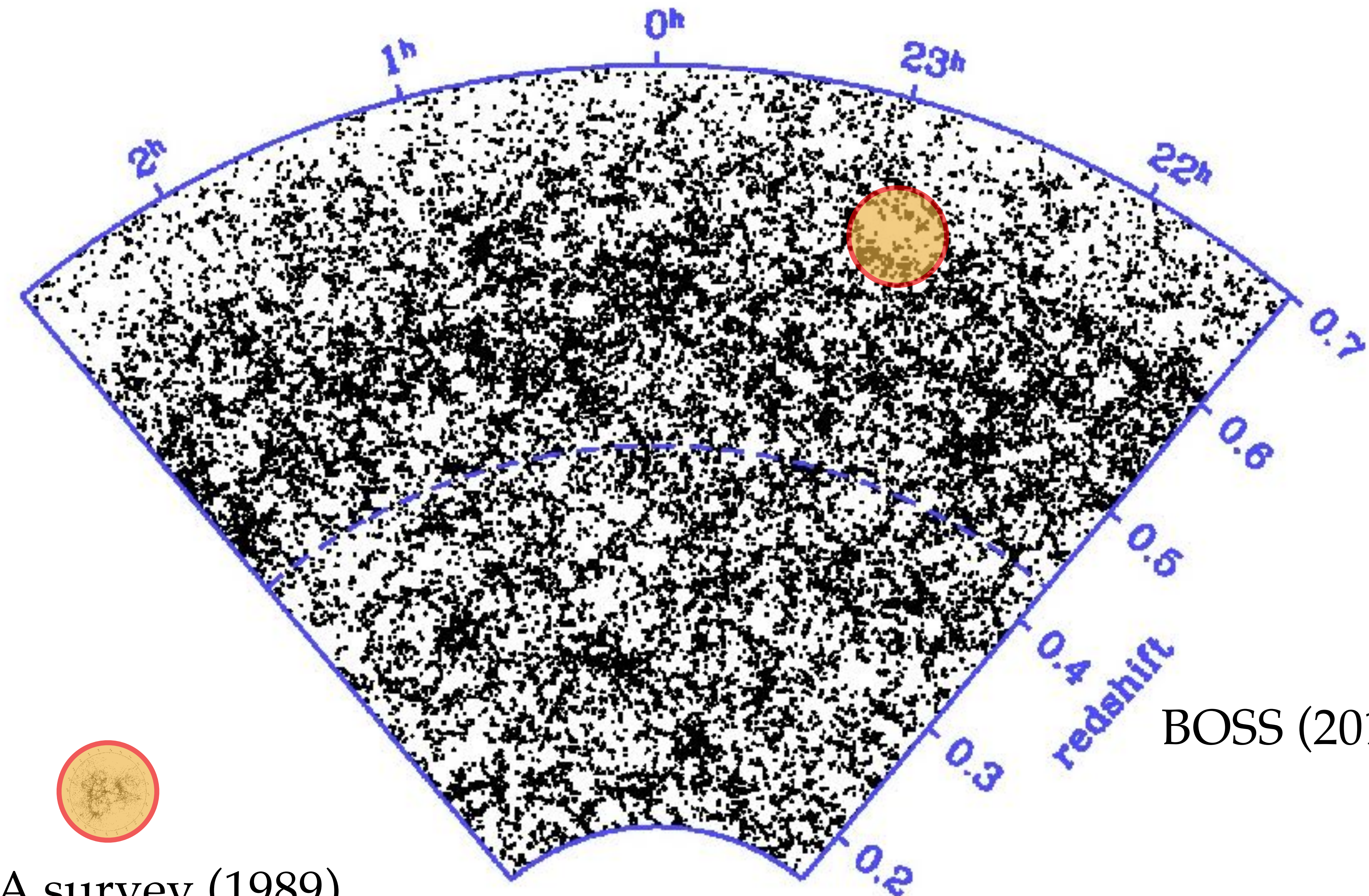
  - CMASS, with $0.43 < z < 0.7$

- A sample of 1.6×10^5 QSO, $2.3 < z < 2.8$



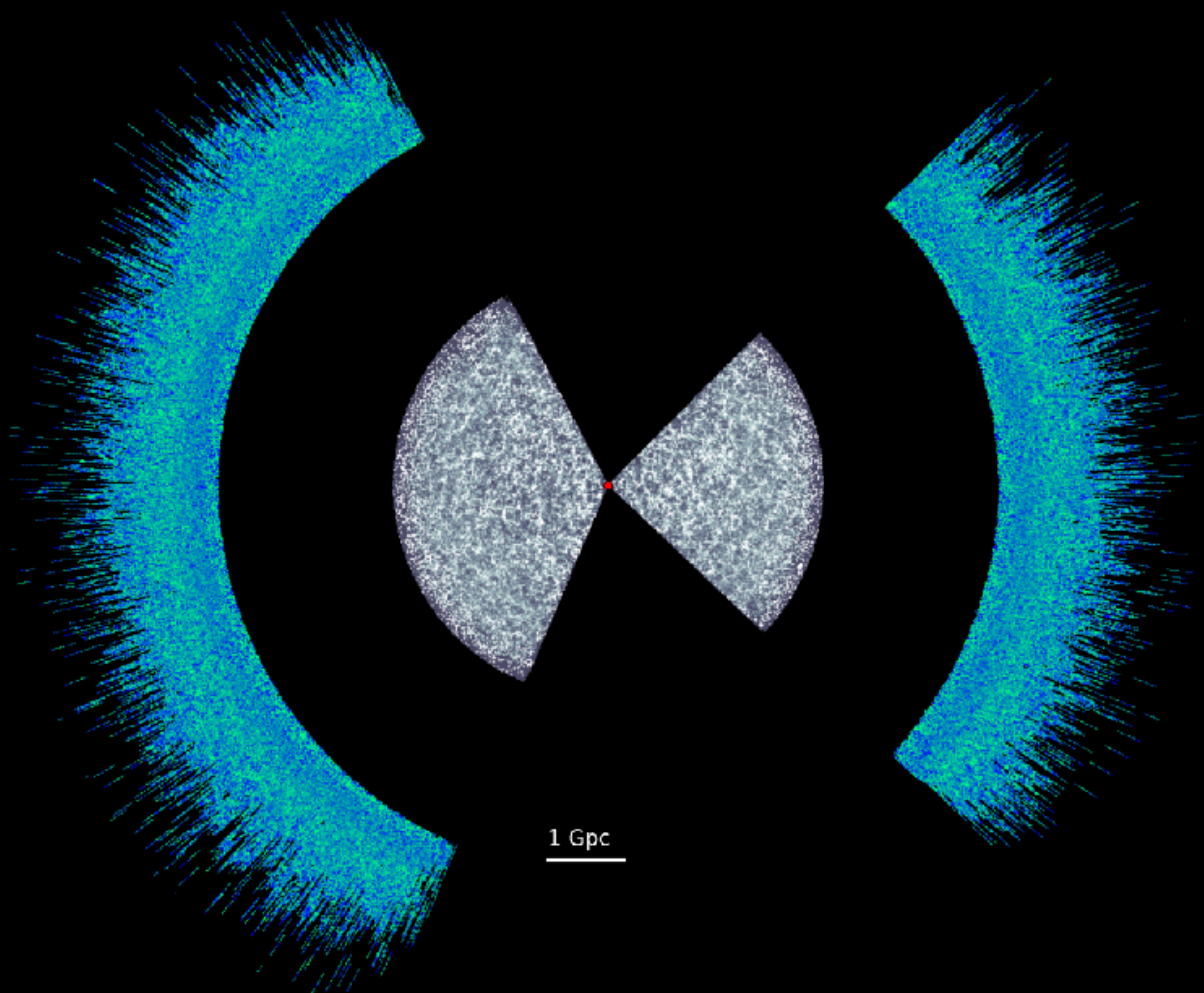
Reid et al. (2015)

BOSS in a nutshell



BOSS (2016)

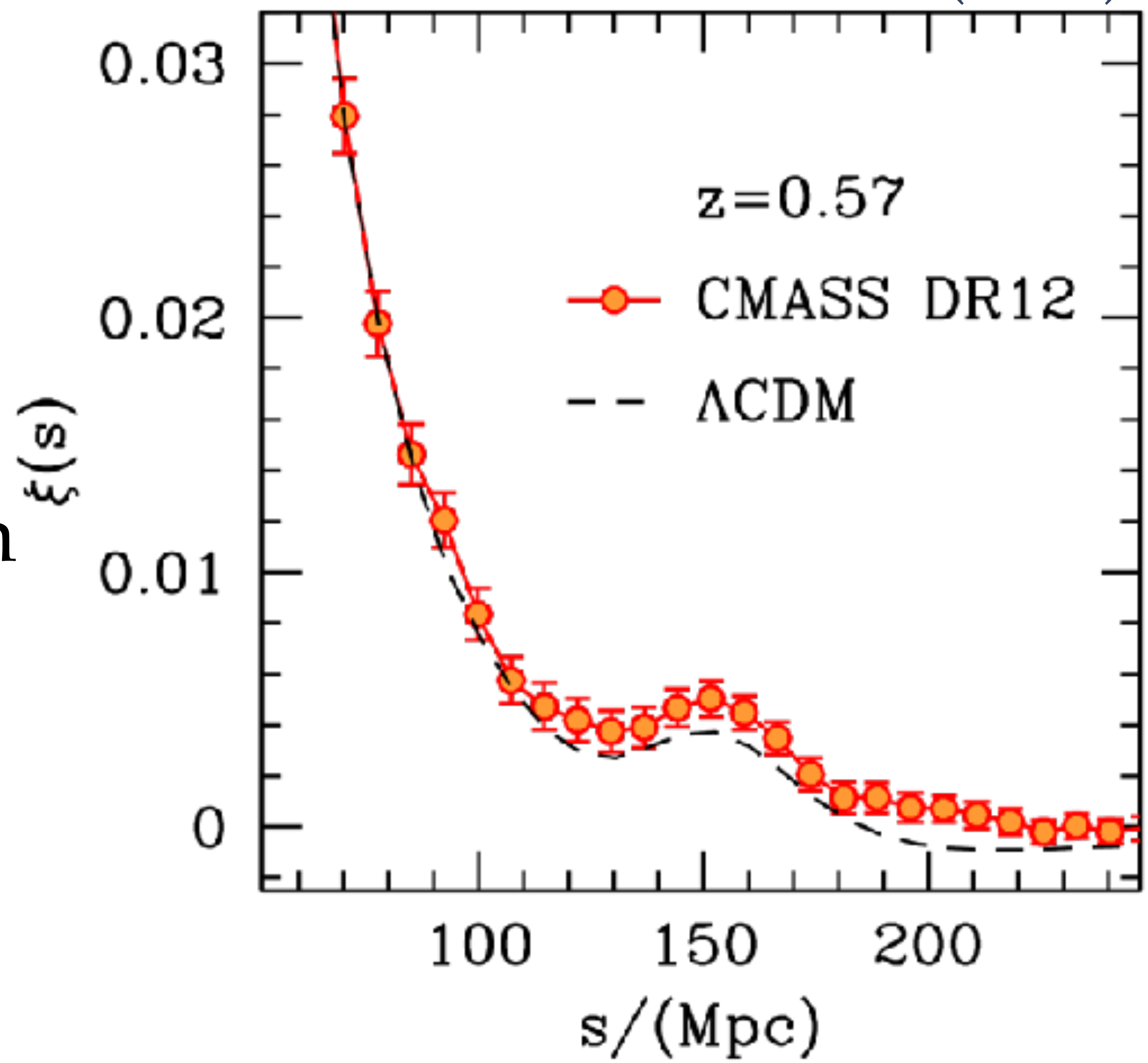
CfA survey (1989)


1 Gpc

BOSS in a nutshell

- CMASS-DR12 monopole correlation function.
- Great improvement in statistical uncertainties.
- High-significance detection of BAO signal.
- Leads to accurate distance measurements.

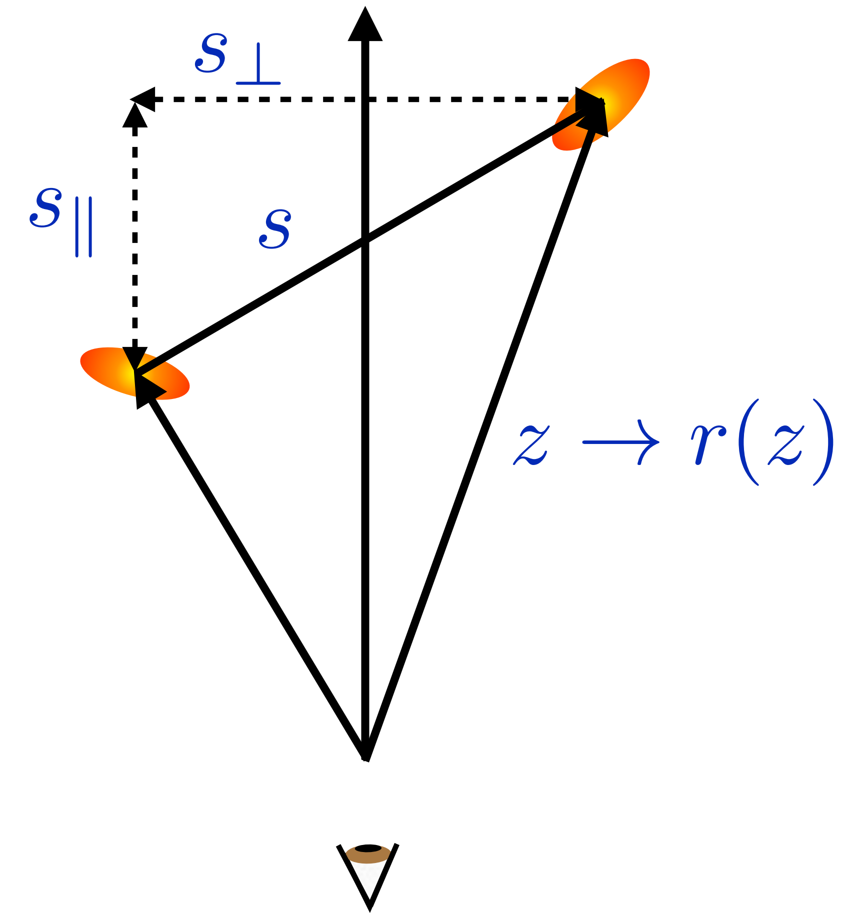
Sánchez et al. (2017)



BAO measurements

- Clustering measurements require a fiducial cosmology.
- Different choices lead to a rescaling

$$s'_\perp = \frac{D'_\mathrm{M}(z_\mathrm{m})}{D_\mathrm{M}(z_\mathrm{m})} s_\perp, \quad s'_\parallel = \frac{H(z_\mathrm{m})}{H'(z_\mathrm{m})} s_\parallel$$



- Angle-averaged measurements are only sensitive to the change in $d^3 s$

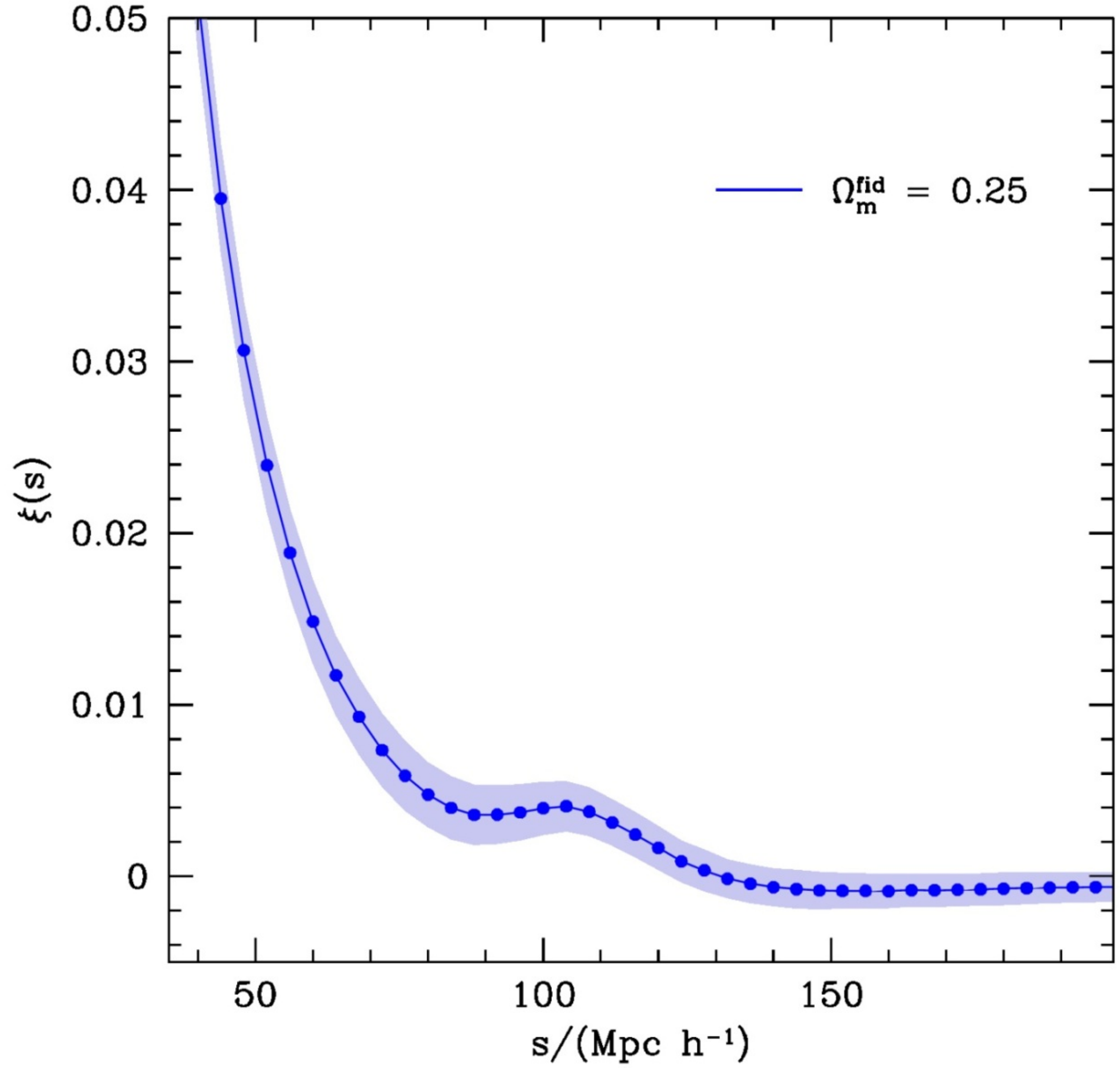
$$d^3 s' = \left(\frac{D'_\mathrm{V}(z_\mathrm{m})}{D_\mathrm{V}(z_\mathrm{m})} \right)^3 d^3 s, \qquad D_\mathrm{V}(z) = \left(D_\mathrm{M}(z)^2 cz / H(z) \right)^{\frac{1}{3}}$$

- Pair separations are then rescaled as

$$s' = \left(D'_\mathrm{V}(z) / D_\mathrm{V}(z) \right) s$$

BAO measurements

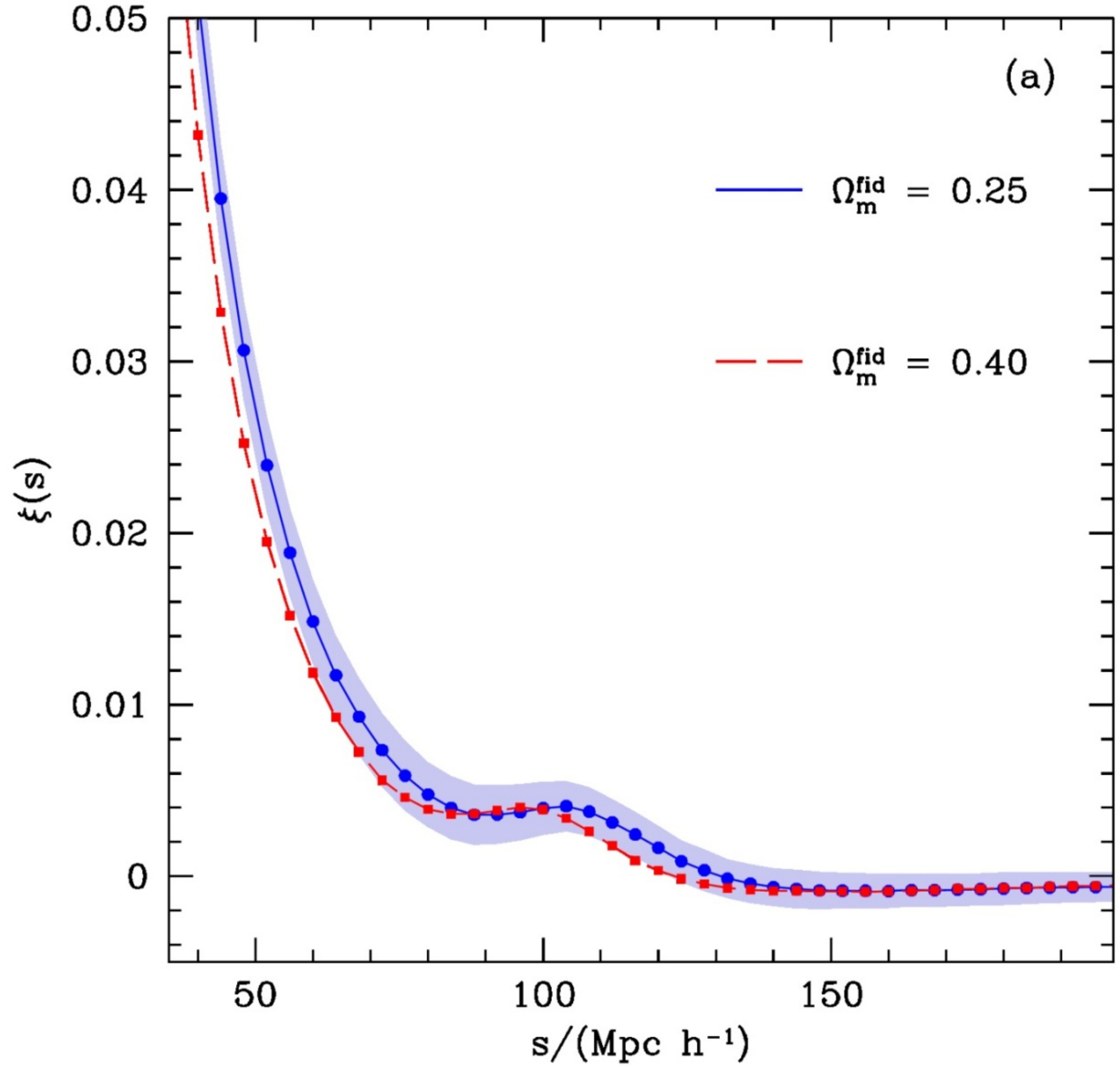
- Results depend on the fiducial cosmology.



Sánchez et al. (2012)

BAO measurements

- Results depend on the fiducial cosmology.

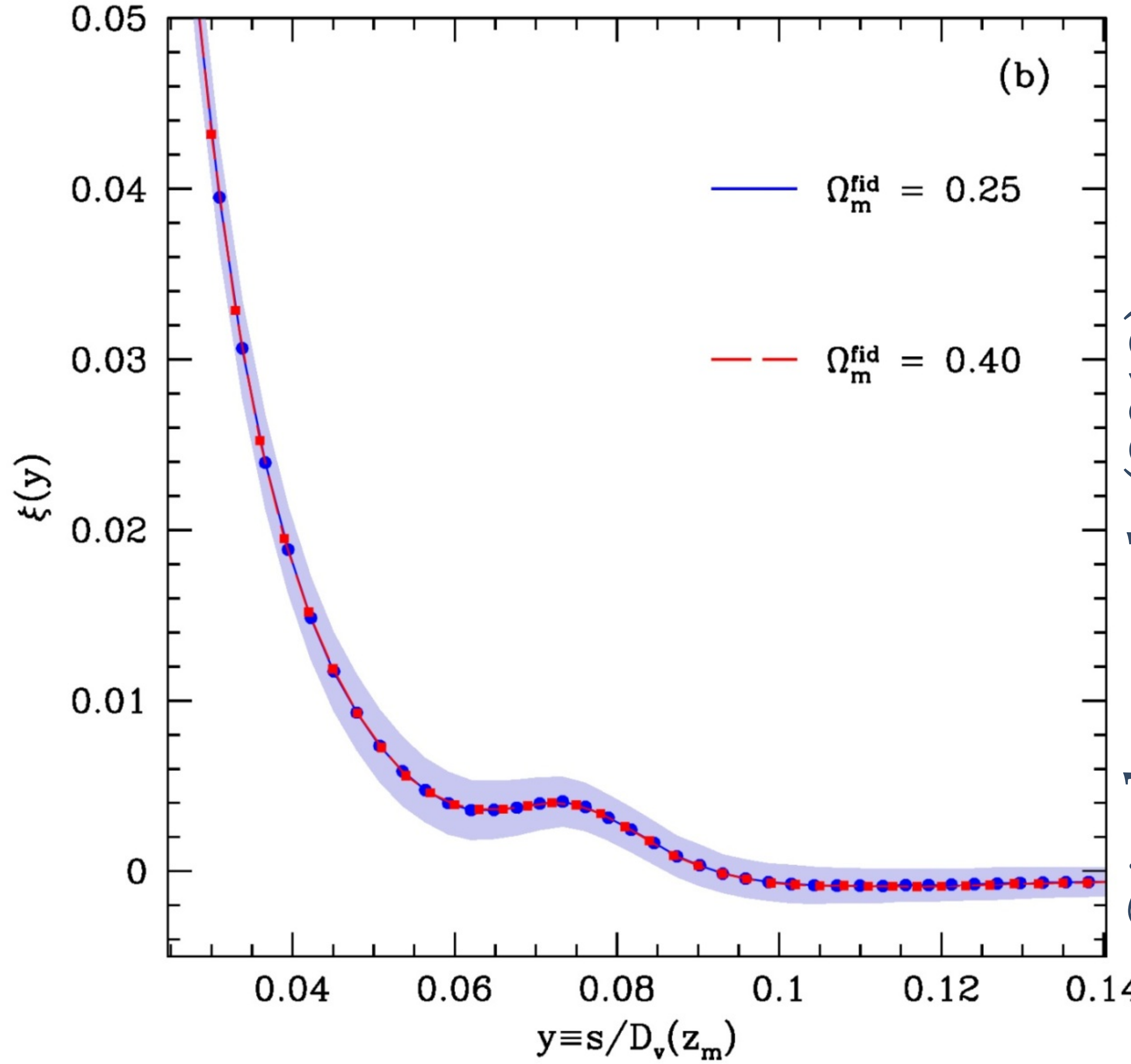


Sánchez et al. (2012)

BAO measurements

- Results depend on the fiducial cosmology.
- This effect can be removed using the variable y:

$$y \equiv r/D_{\mathrm{V}}^{\mathrm{fid}}(z_{\mathrm{m}})$$



Sánchez et al. (2012)

BAO measurements

- Results depend on the fiducial cosmology.

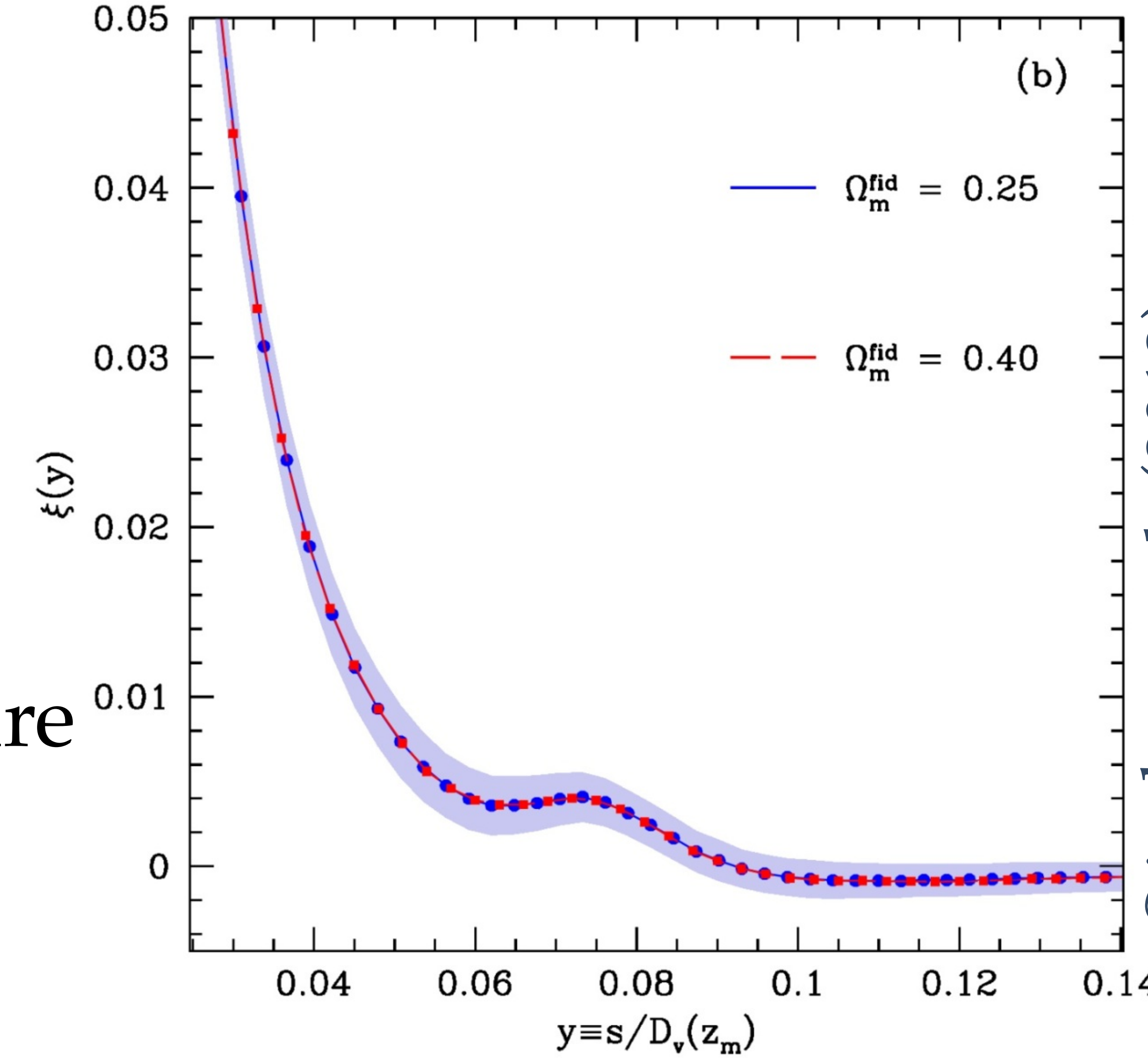
- This effect can be removed using the variable y:

$$y \equiv r/D_{\rm V}^{\rm fid}(z_{\rm m})$$

- Associating the position of the peak with $r_{\rm d}$, we measure

$$y_{\rm d} \equiv r_{\rm d}/D_{\rm V}^{\rm fid}(z_{\rm m})$$

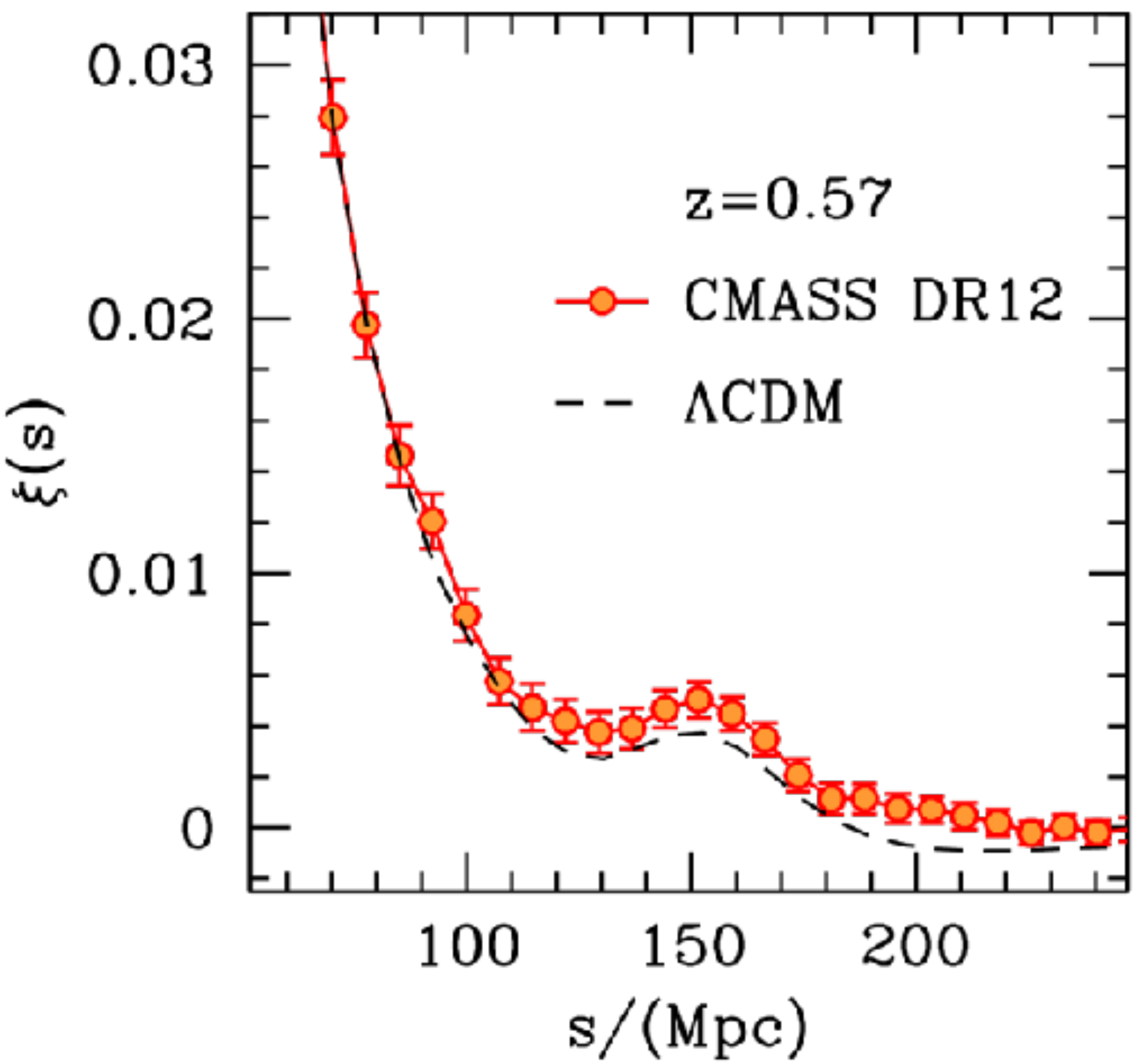
$$\alpha = \frac{D_{\rm V}(z) r_{\rm d}^{\rm fid}}{D_{\rm V}^{\rm fid}(z) r_{\rm d}}$$

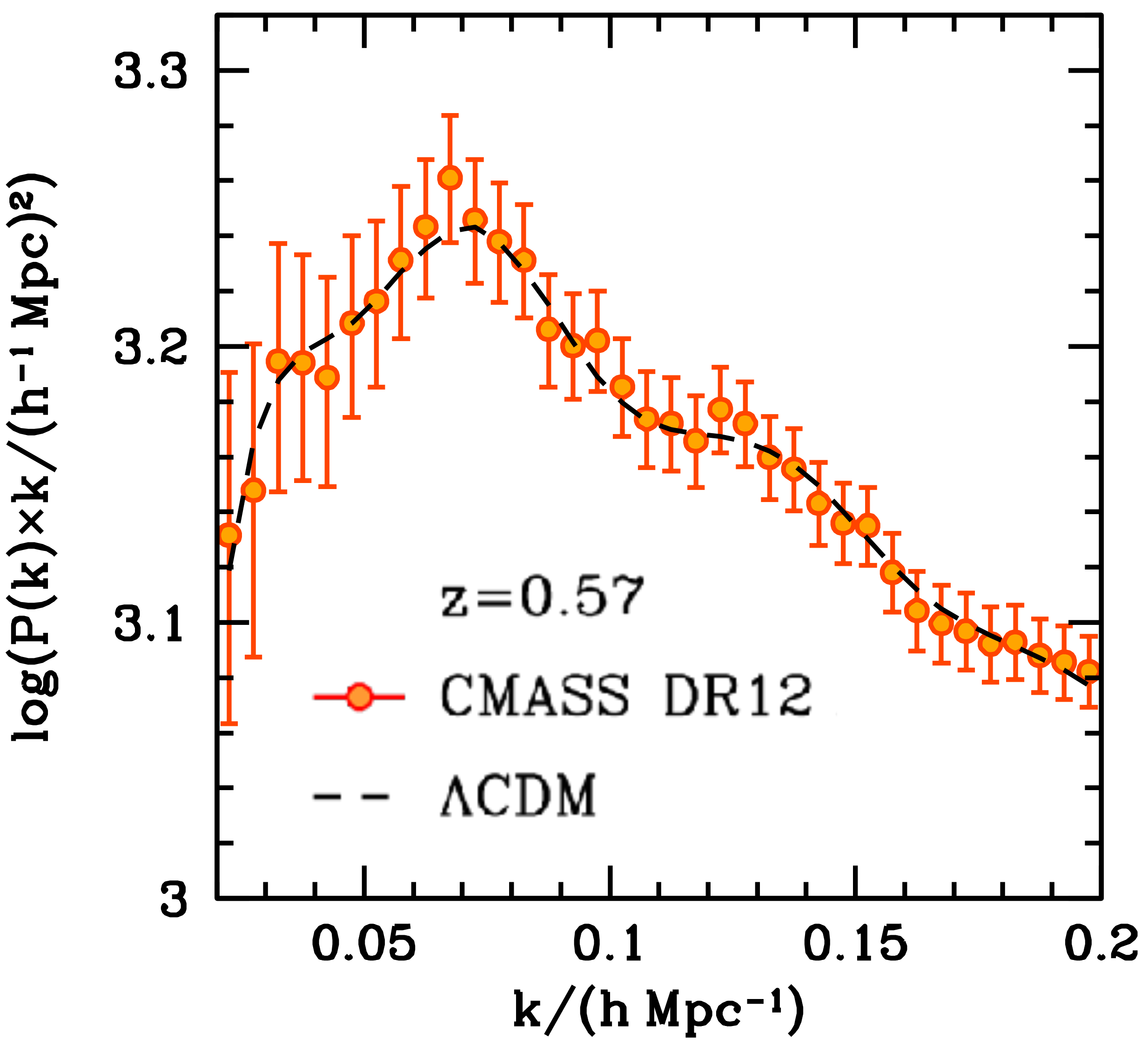


Sánchez et al. (2012)

BAO measurements

- Great opportunity for accurate cosmological constraints.





Potential systematic effects

- Systematic errors can dominate final error budget.
- Key issue: how does the BAO signal evolves with time?
- In practice, BAOs are not precisely a standard ruler (Crocce & Scoccimarro 2008, Sánchez et al. 2008).
- Our models must take into account
  - Non-linear evolution ($\delta \gtrsim 1$)
  - Redshift-space distortions ($z_{\rm obs} = z_{\rm cos} + u_{\|}/c$)
  - Galaxy bias (light ≠ matter, $\delta_{\rm g} = b_1\delta + \frac{b_2}{2}\delta^2 + \dots$)

Potential systematic effects

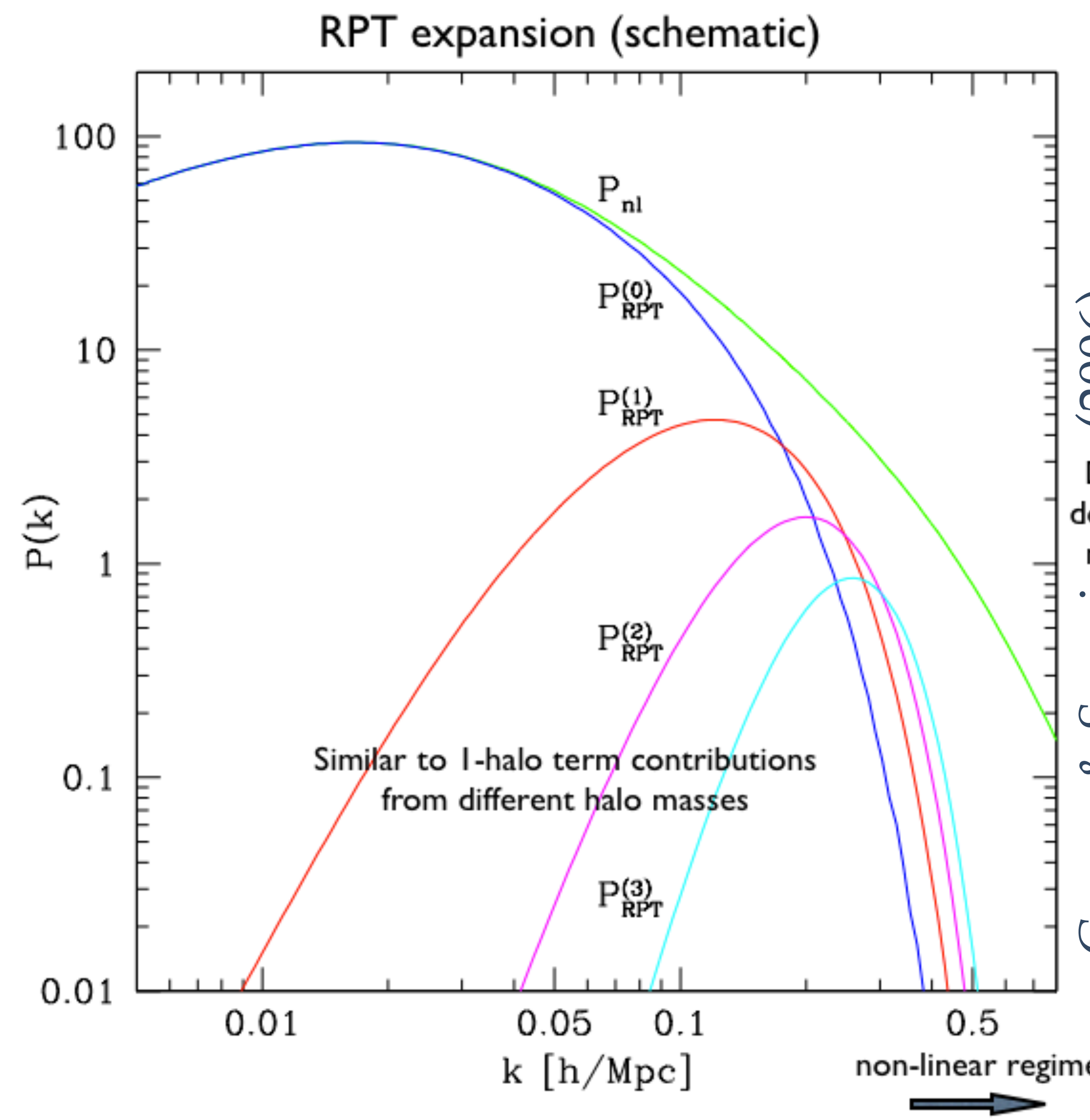
- The non-linear power spectrum can be written as

$$P(k) = P_{\rm L}(k)G(k)^2 + P_{\rm MC}(k)$$

- Mode-coupling terms affect different scales.
- For the correlation function

$$\xi(s) = \xi_{\rm L}(s) \otimes G(s)^2 + \xi_{\rm MC}(s)$$

- NL evolution damps the BAO signal



Crocce & Scoccimarro (2006)

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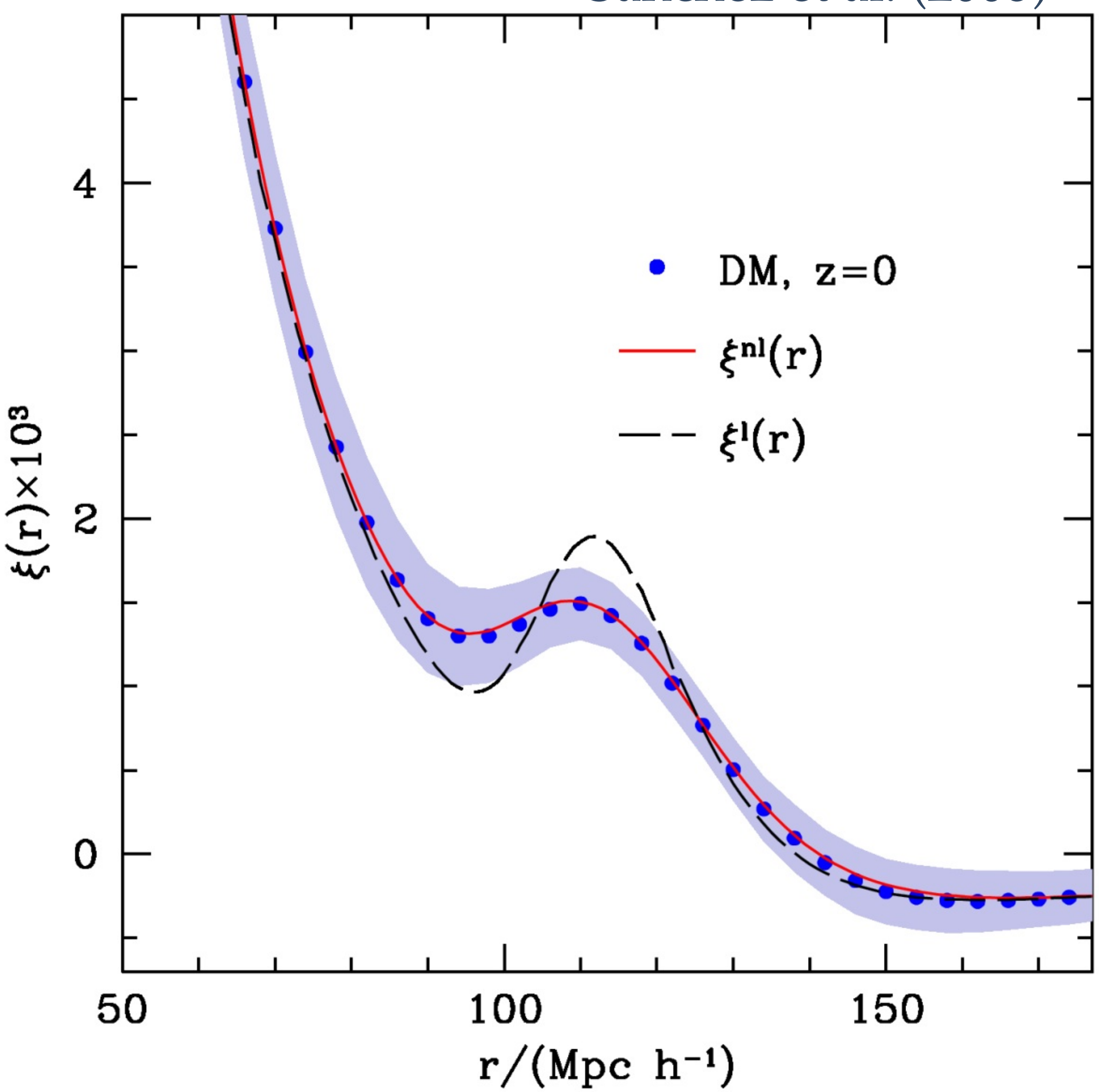
$$\xi(s) = \xi_{\rm L}(s) \otimes G(s)^2 + \xi_{\rm MC}(s)$$

- NL evolution damps the BAO signal

Sánchez et al. (2008)



Potential systematic effects

- RSD's main effect is to boost clustering amplitude.

$$S \equiv \frac{\xi_s(r)}{\xi(r)} = \left(1 + \frac{2}{3}f + \frac{1}{5}f^2\right)$$

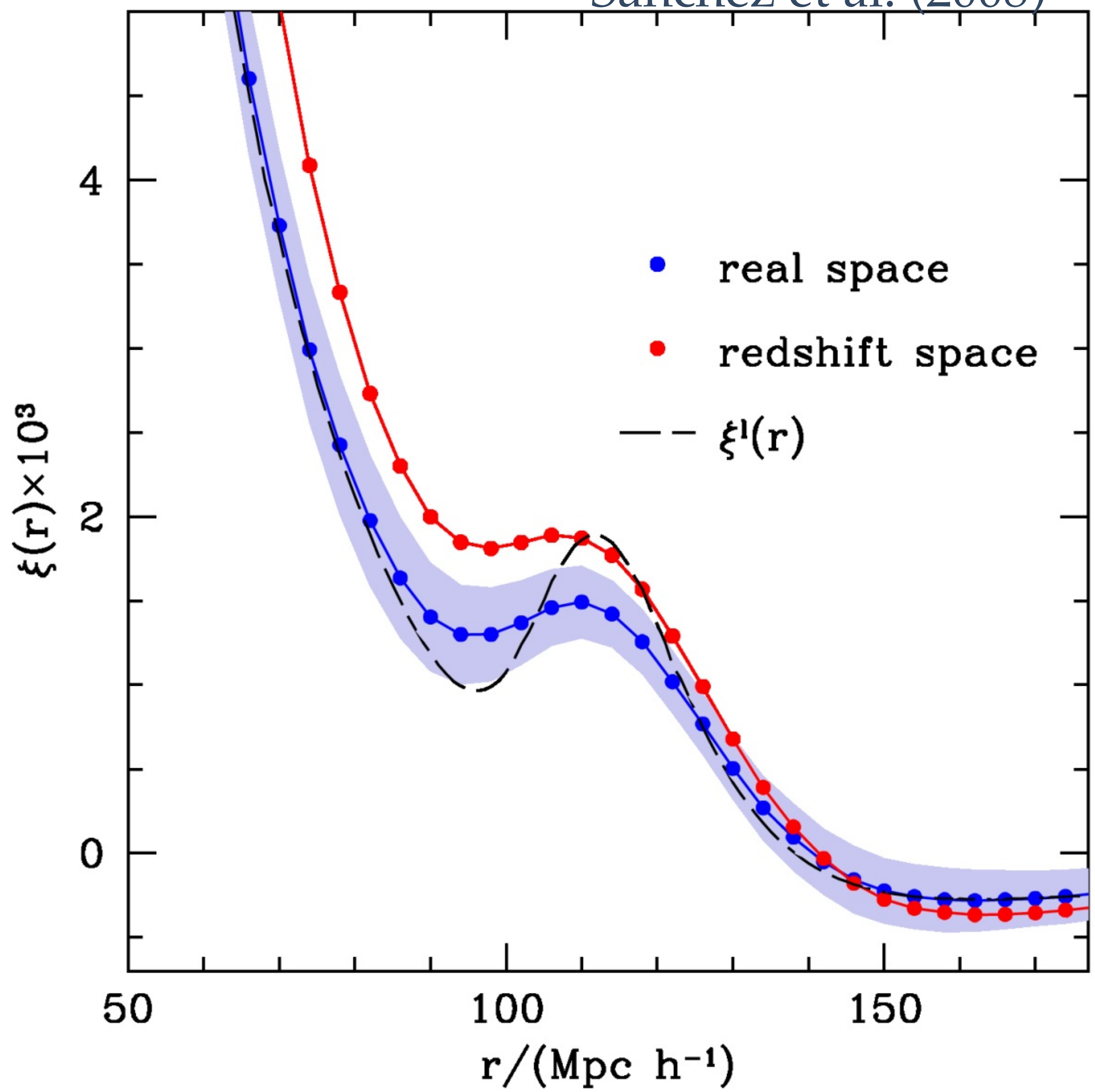
$$f = \mathrm{d}\ln D/\mathrm{d}\ln a$$

- RSD lead to an extra damping of the BAO peak.

- Further degrade the BAO signal.

-

Sánchez et al. (2008)



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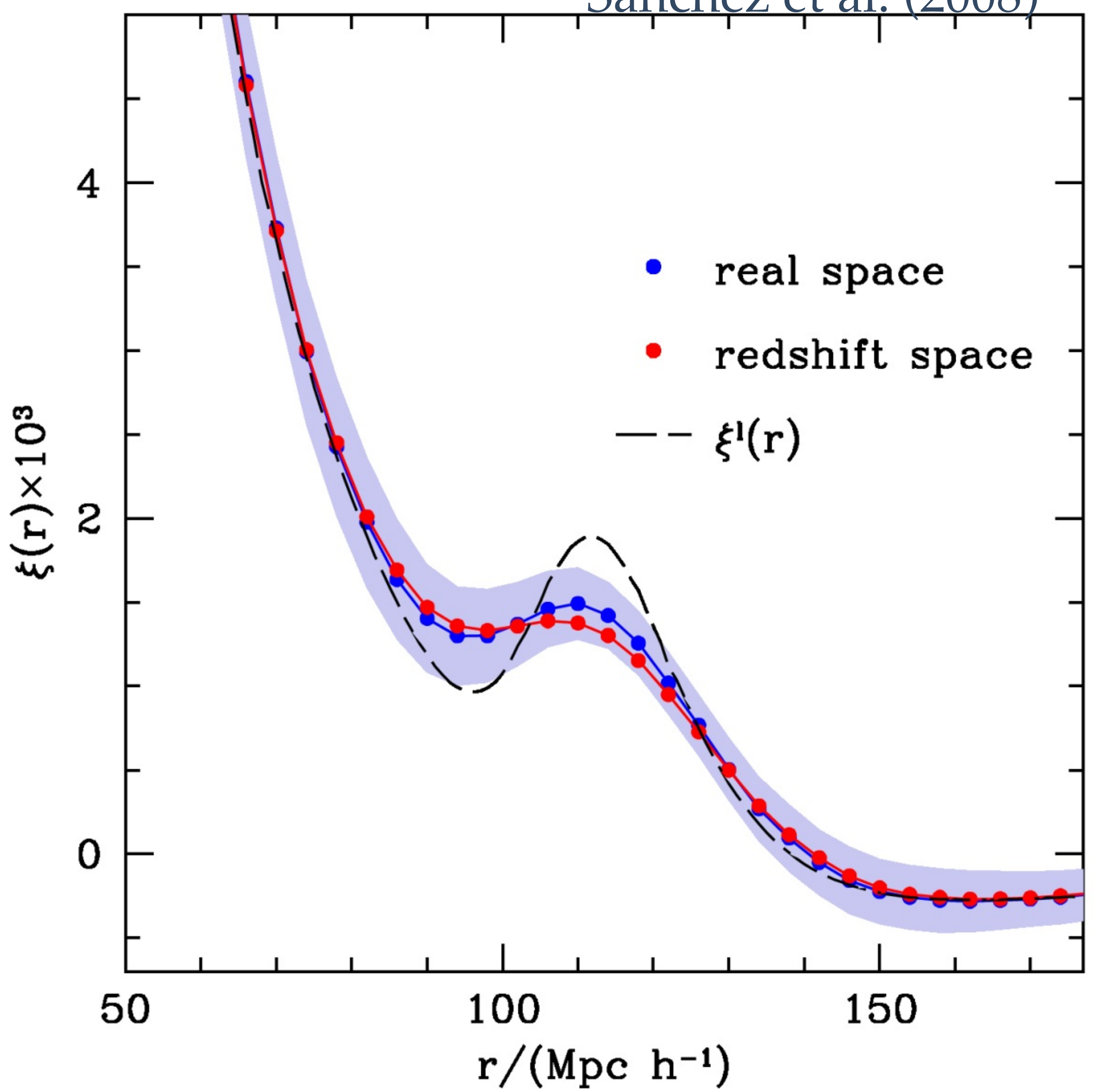


Potential systematic effects

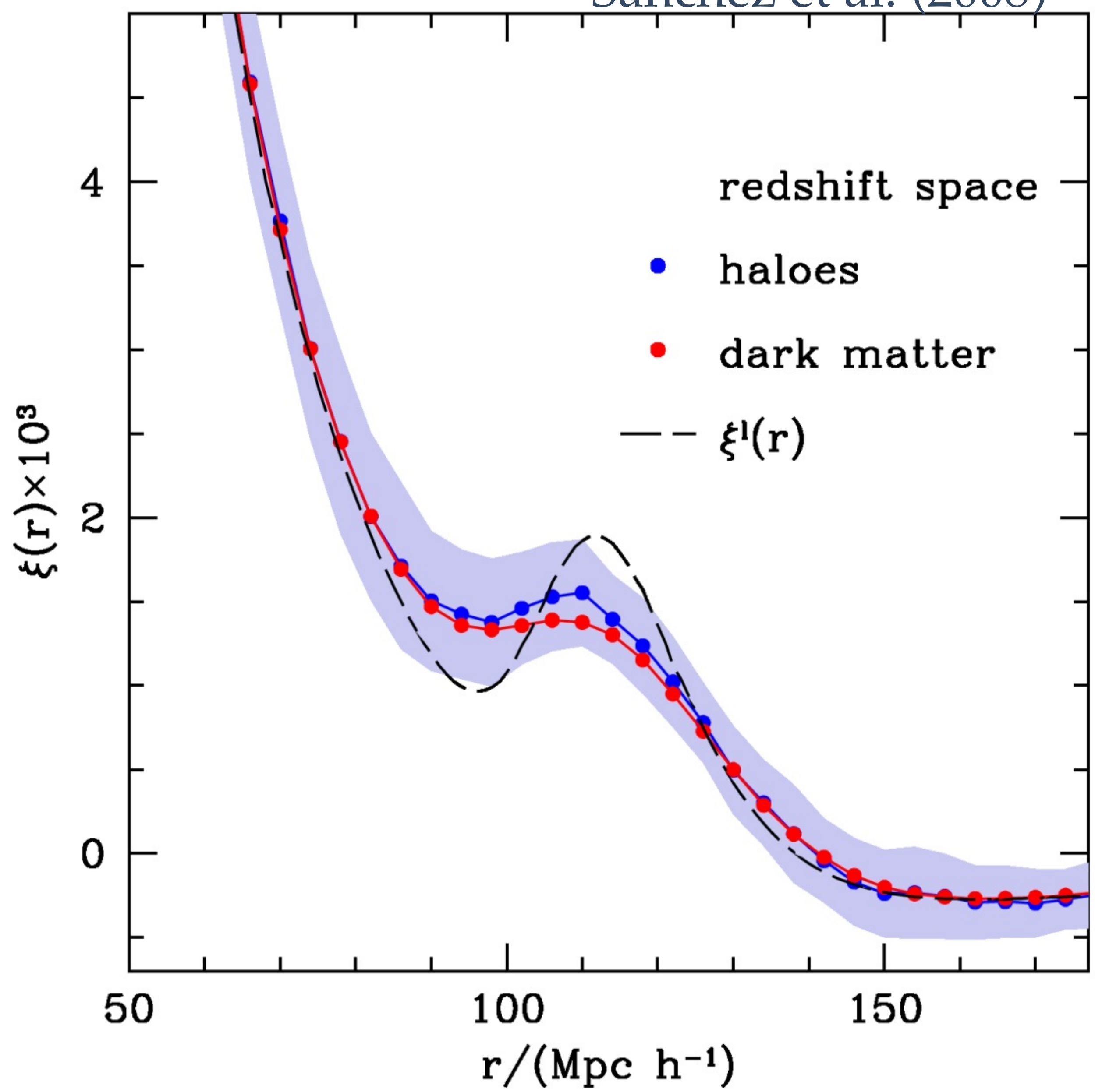
- Our observations probe the galaxy density field.
- On large scales, a linear relation is expected:

$$\delta_{\rm g}(\mathbf{r}) = b\delta(\mathbf{r})$$

$$\xi_{\rm g}(r) = b^2\xi(r)$$

- The effects of NL and RSD depend on the halo sample.

Sánchez et al. (2008)



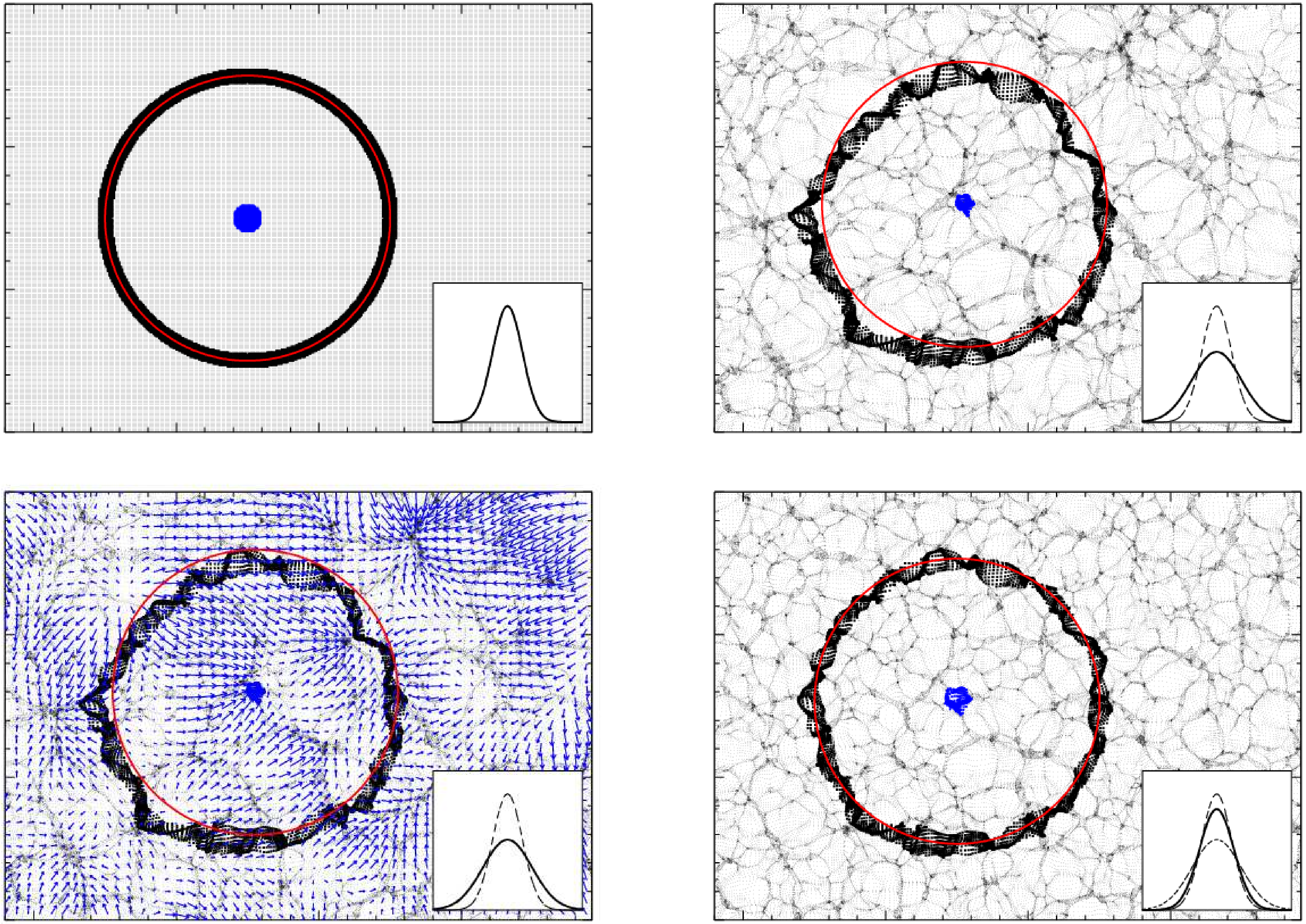
Reconstruction techniques

- The damping of the BAO limits the attainable accuracy.
- Reconstruction attempts to "un-do" these distortions.
- Construct a *displacement field* Ψ as

$$\nabla \cdot \Psi + \frac{f(z)}{b} \nabla \cdot (\Psi_s \, \hat{s}) = -\frac{\delta_{\rm g}}{b}$$

- Significantly improve BAO distance measurements.
- Requires the knowledge of b and $f(z)$.

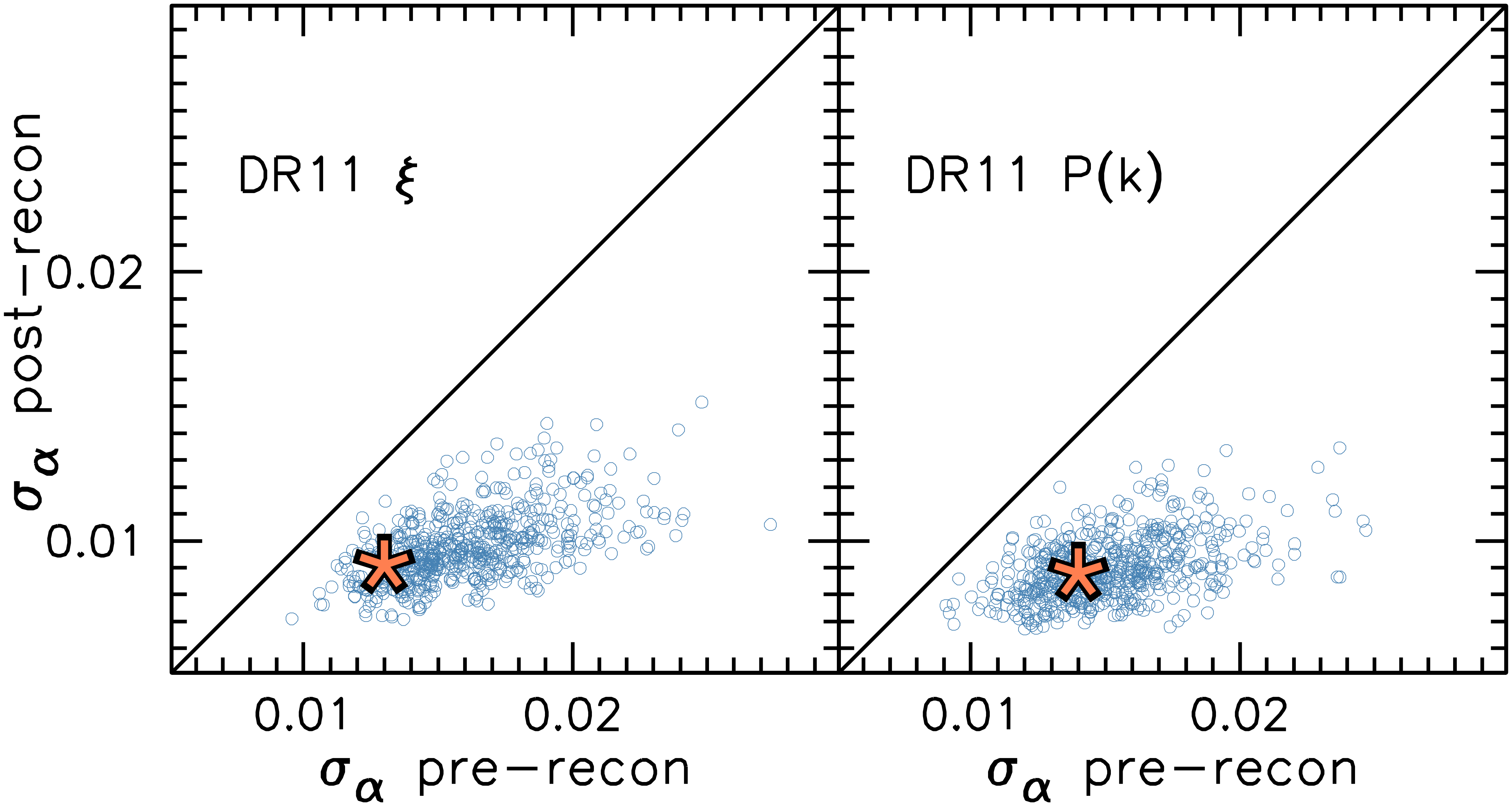
Reconstruction techniques



Padmanabhan et al. (2012)

Reconstruction techniques

- Impact of reconstruction on mock data

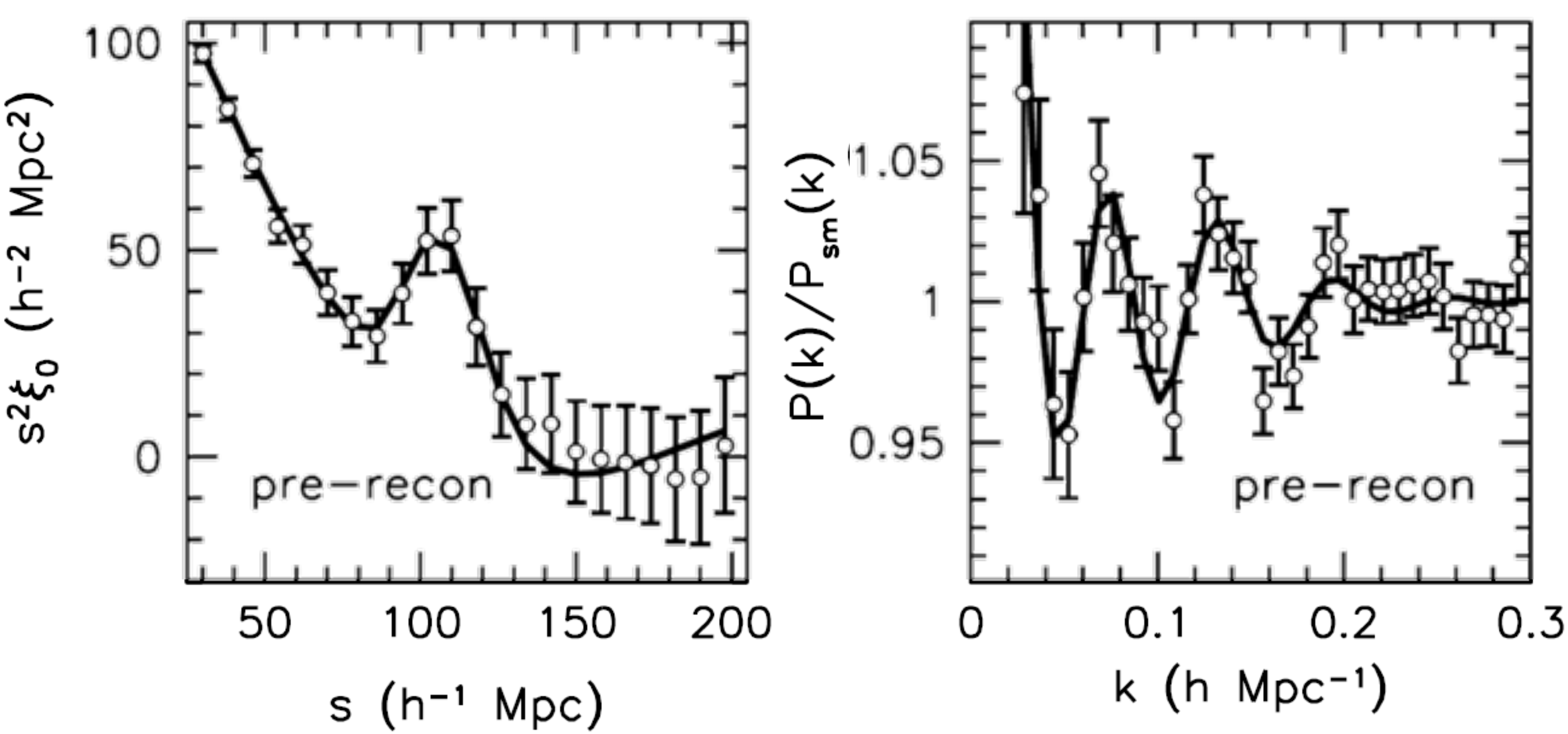


Anderson et al. (2014)

Reconstruction techniques

- CMASS DR11: a 1% distance measurement to $z = 0.57$

$$D_{\rm V}(0.57) = (2056 \pm 20)\left(r_{\rm d}/r_{\rm d}^{\rm fid}\right)\ {\rm Mpc}$$



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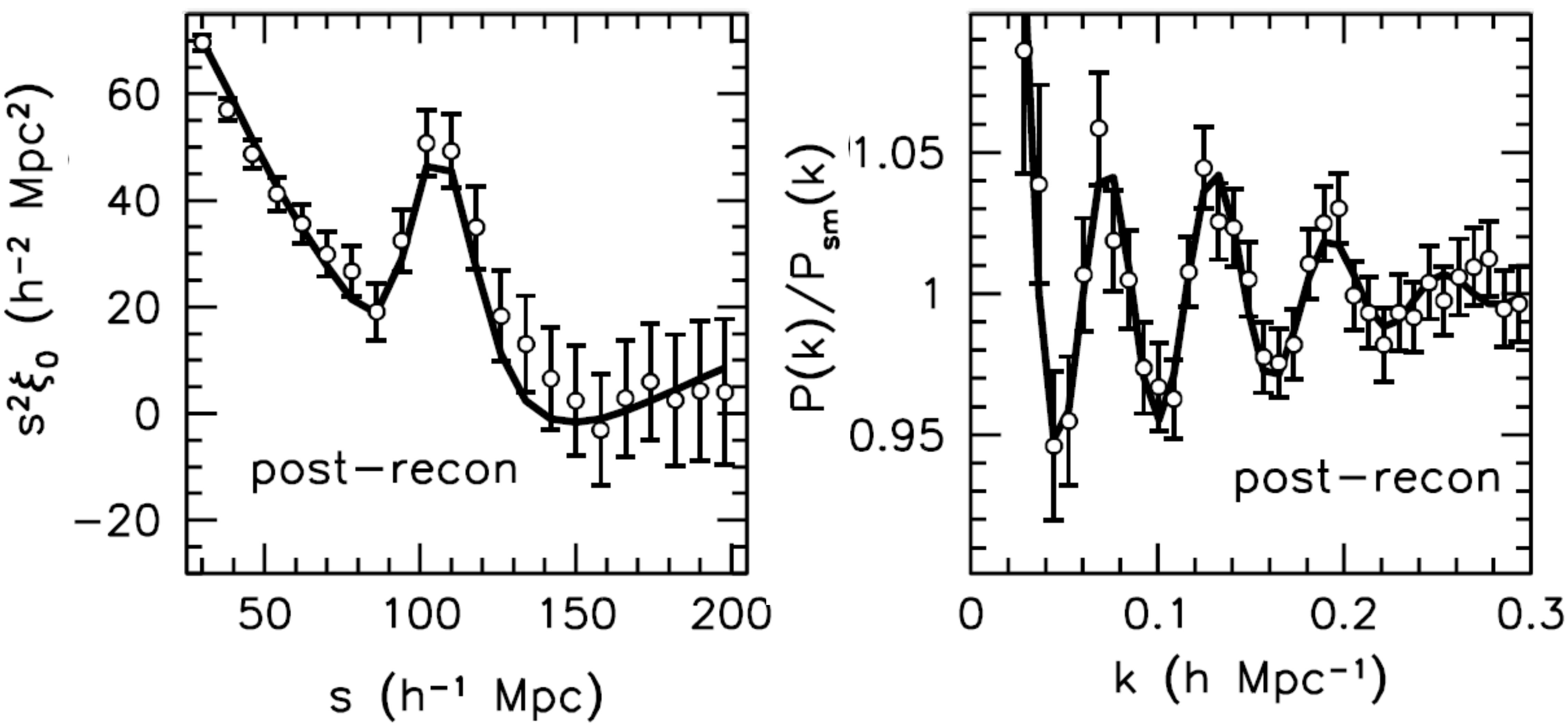
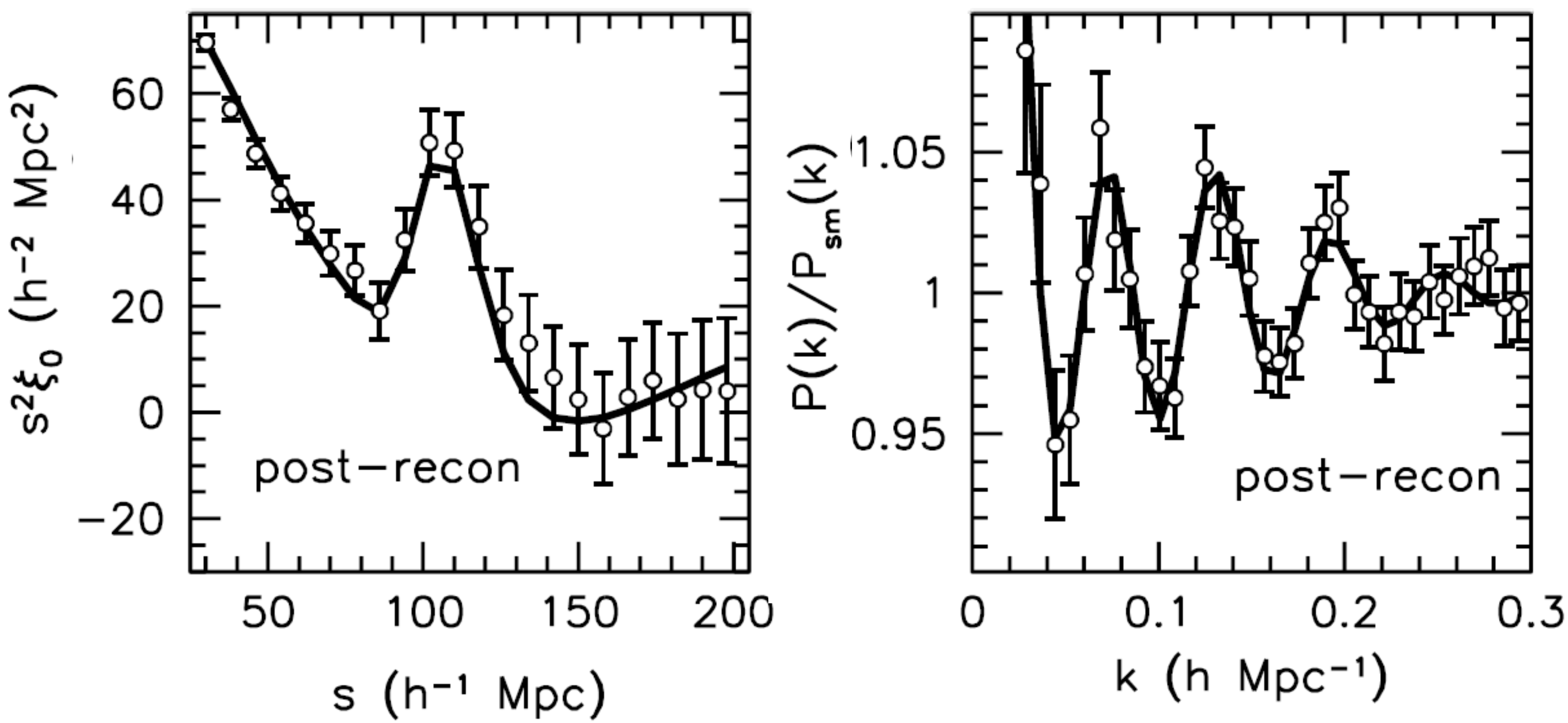


Reconstruction techniques

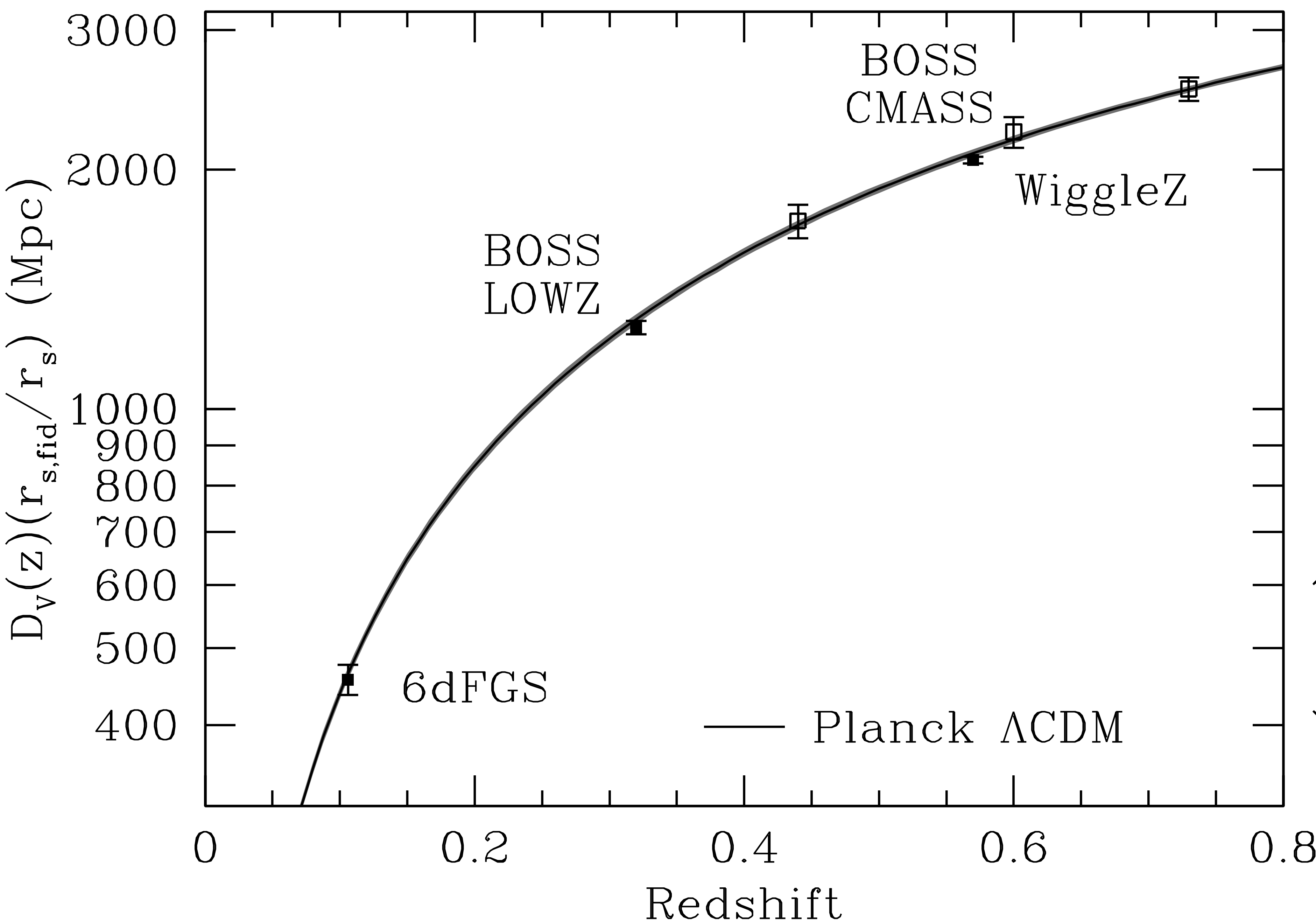
- LOWZ DR11: a 2% distance measurement to $z = 0.32$

$$D_{\mathrm{V}}(0.32) = (1264 \pm 25)\left(\frac{r_{\mathrm{d}}}{r_{\mathrm{d}}^{\mathrm{fid}}}\right)\,\mathrm{Mpc}$$



BAO-only analyses

- Consistent with Planck constraints (assuming ΛCDM).



Anderson et al.(2014)

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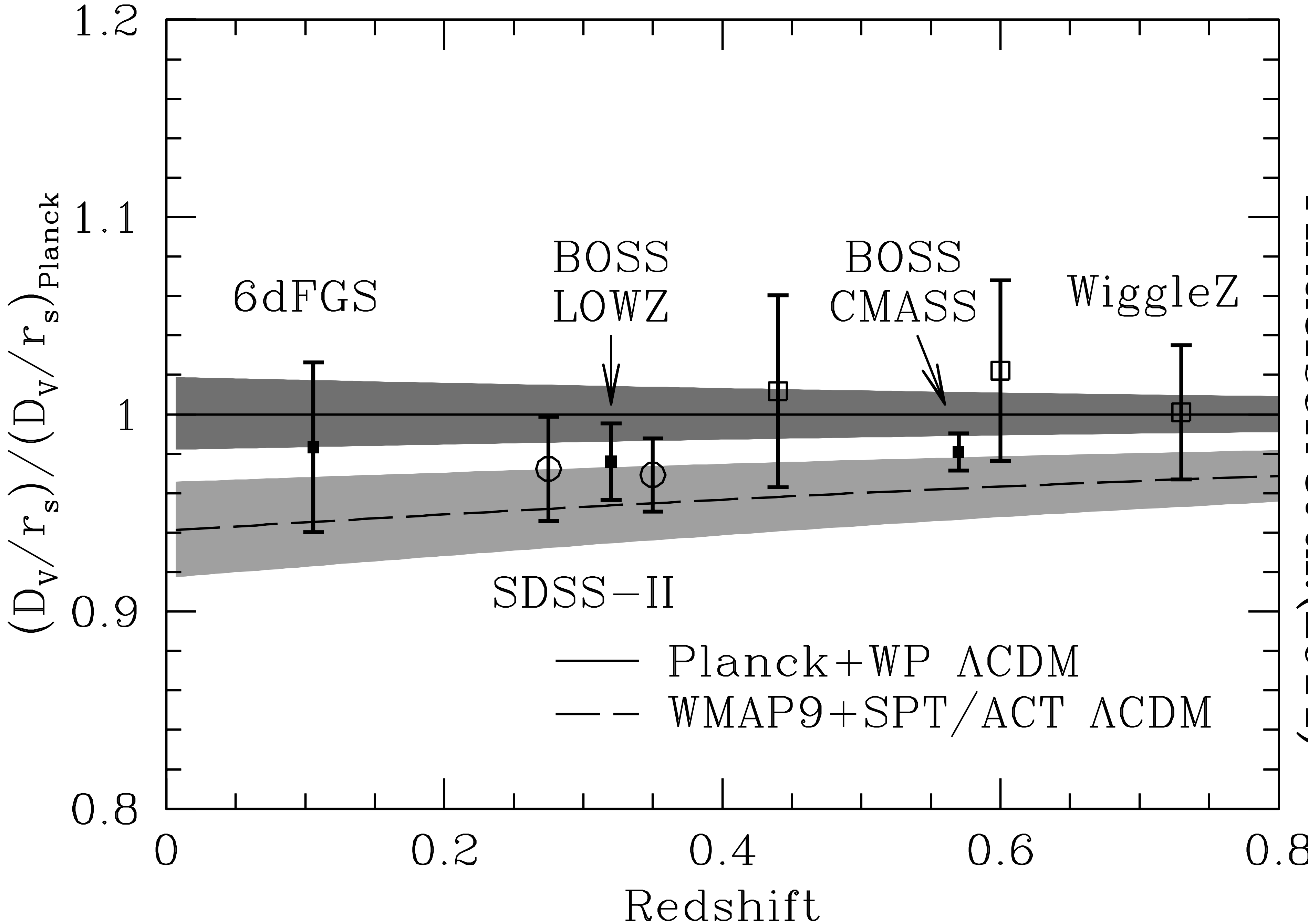
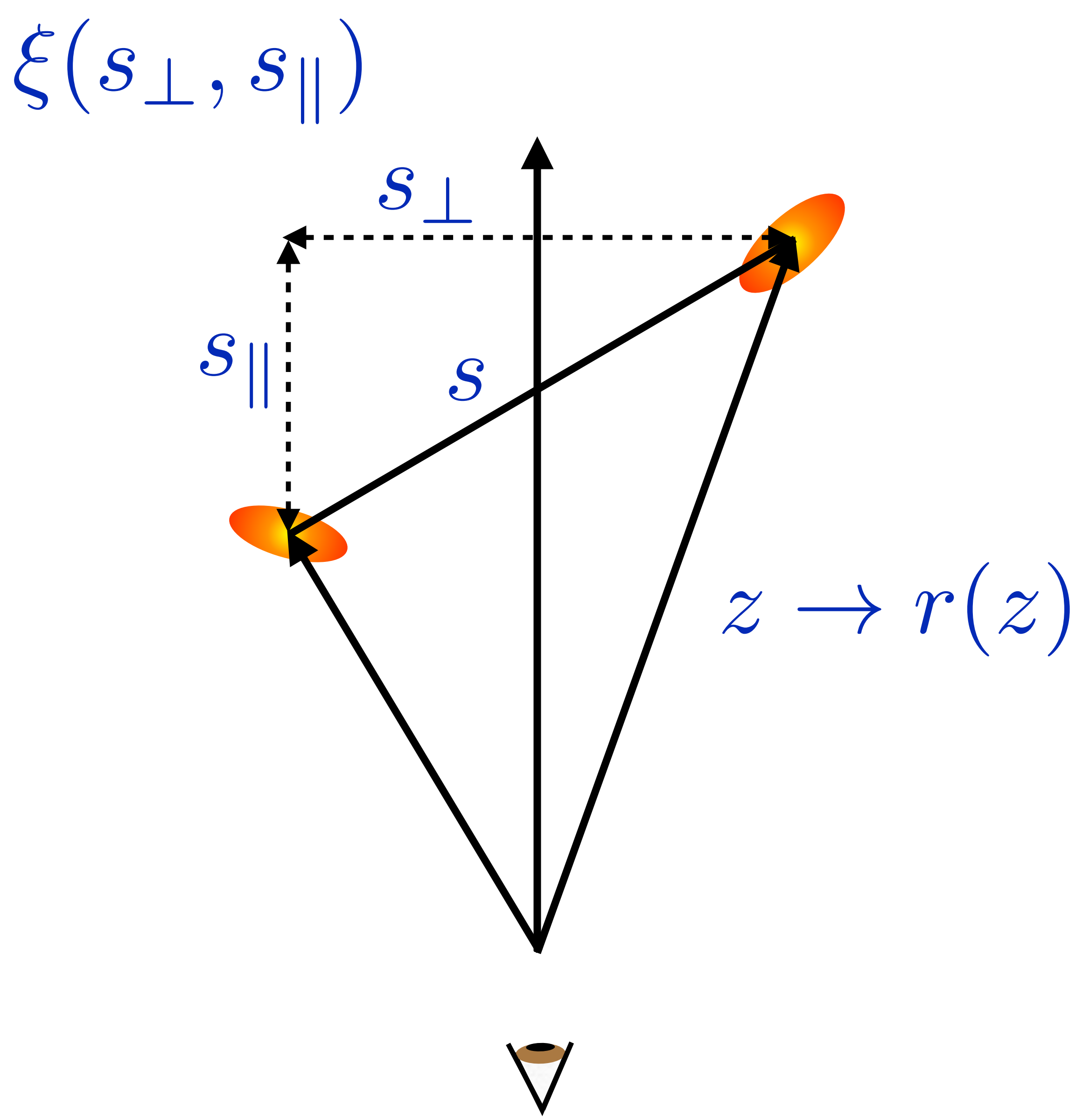
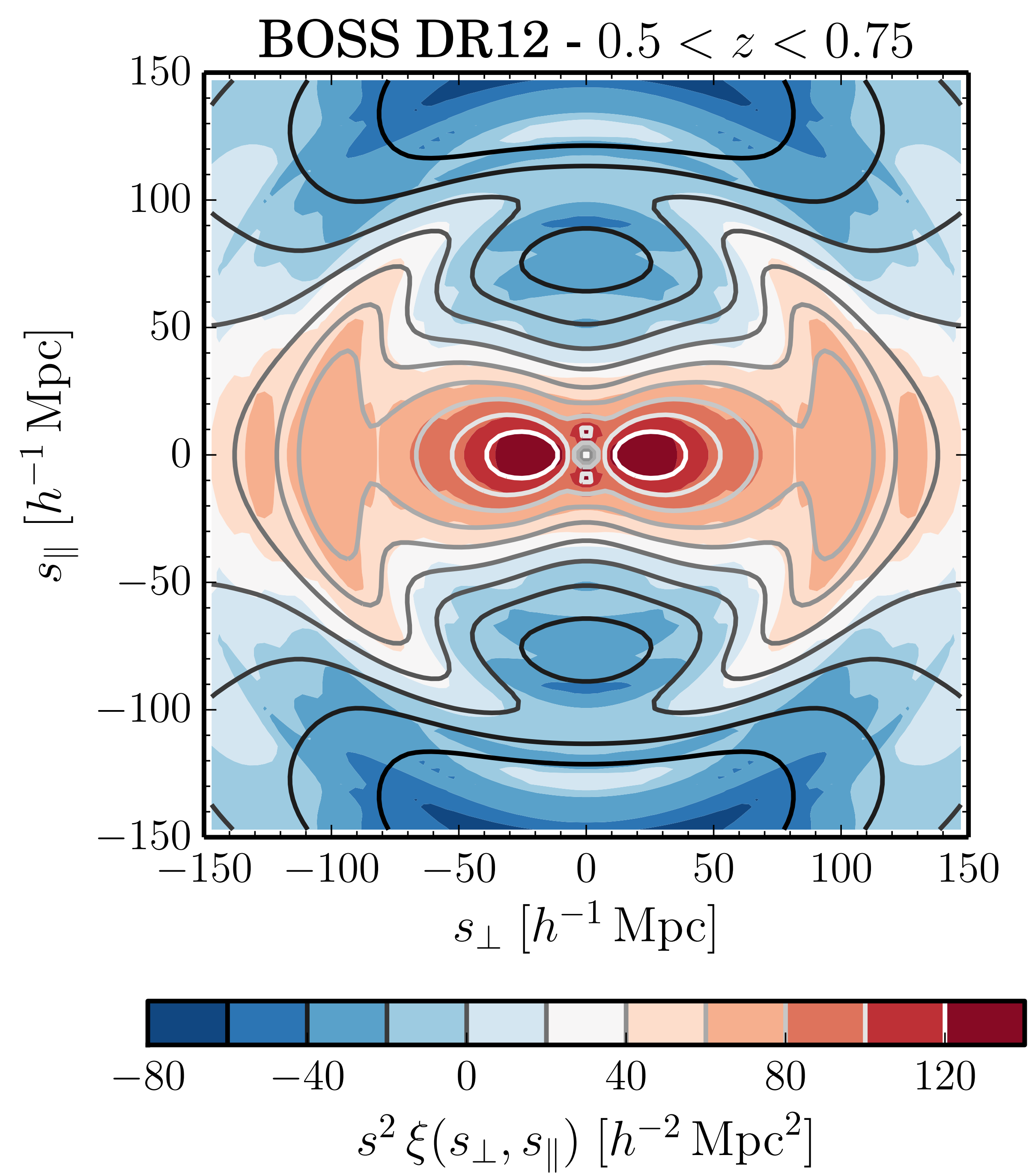


Anderson et al.(2014)

Anisotropic clustering

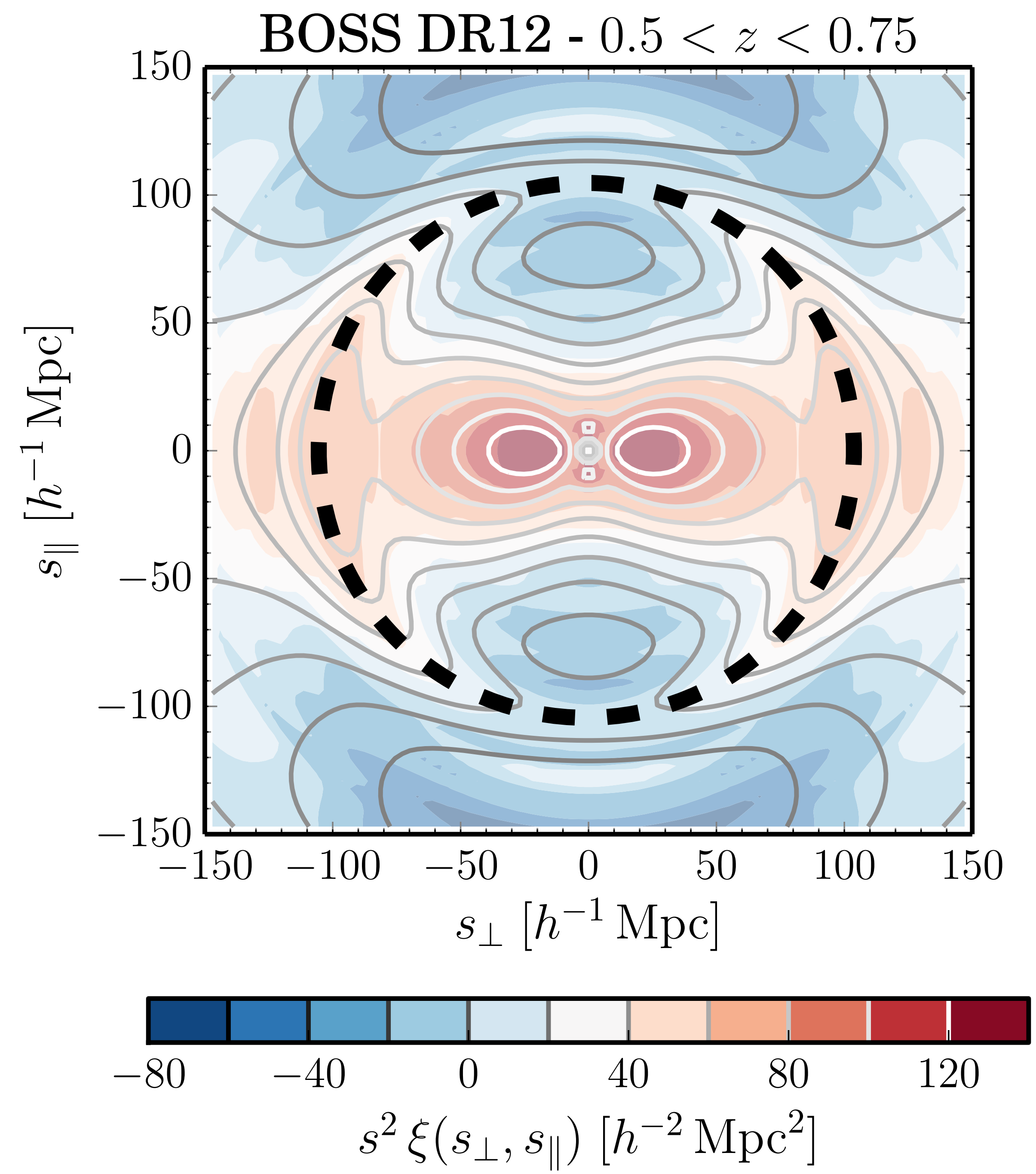
- BOSS-DR12 anisotropic correlation function $\xi(s_\perp, s_\parallel)$





Anisotropic clustering

- BOSS-DR12 anisotropic correlation function $\xi(s_\perp, s_\parallel)$
- BAO signal appears as a ring at $s = 110$ Mpc/h.
- RSD distort the contours, which deviate from perfect circles.
- Using $\xi(s_\perp, s_\parallel)$ is difficult (low S/N, cov. matrix)



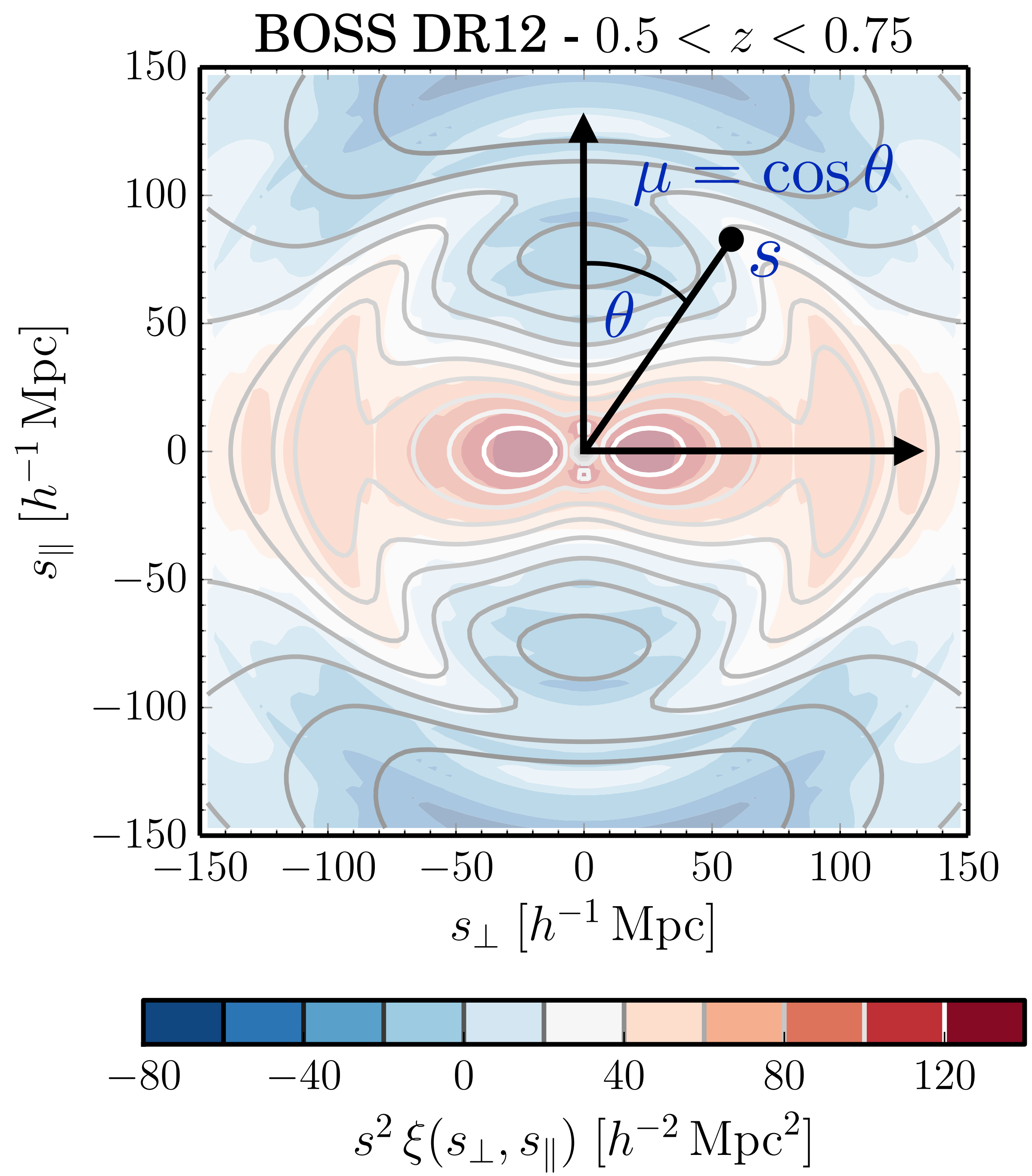
Anisotropic clustering

- Project $\xi(s_\perp, s_\parallel)$ into Legendre multipoles:

$$\xi_\ell(s) = \frac{(2\ell+1)}{2} \int_{-1}^{1} \xi(\mu, s)\, L_\ell(\mu)\, \mathrm{d}\mu$$

- Alternatively, use *clustering wedges* (Kazin, Sánchez & Blanton, 2012)

$$\xi_{\mu_1}^{\mu_2} = \frac{1}{\mu_2 - \mu_1} \int_{\mu_1}^{\mu_2} \xi(\mu, s) \mathrm{d}\mu$$



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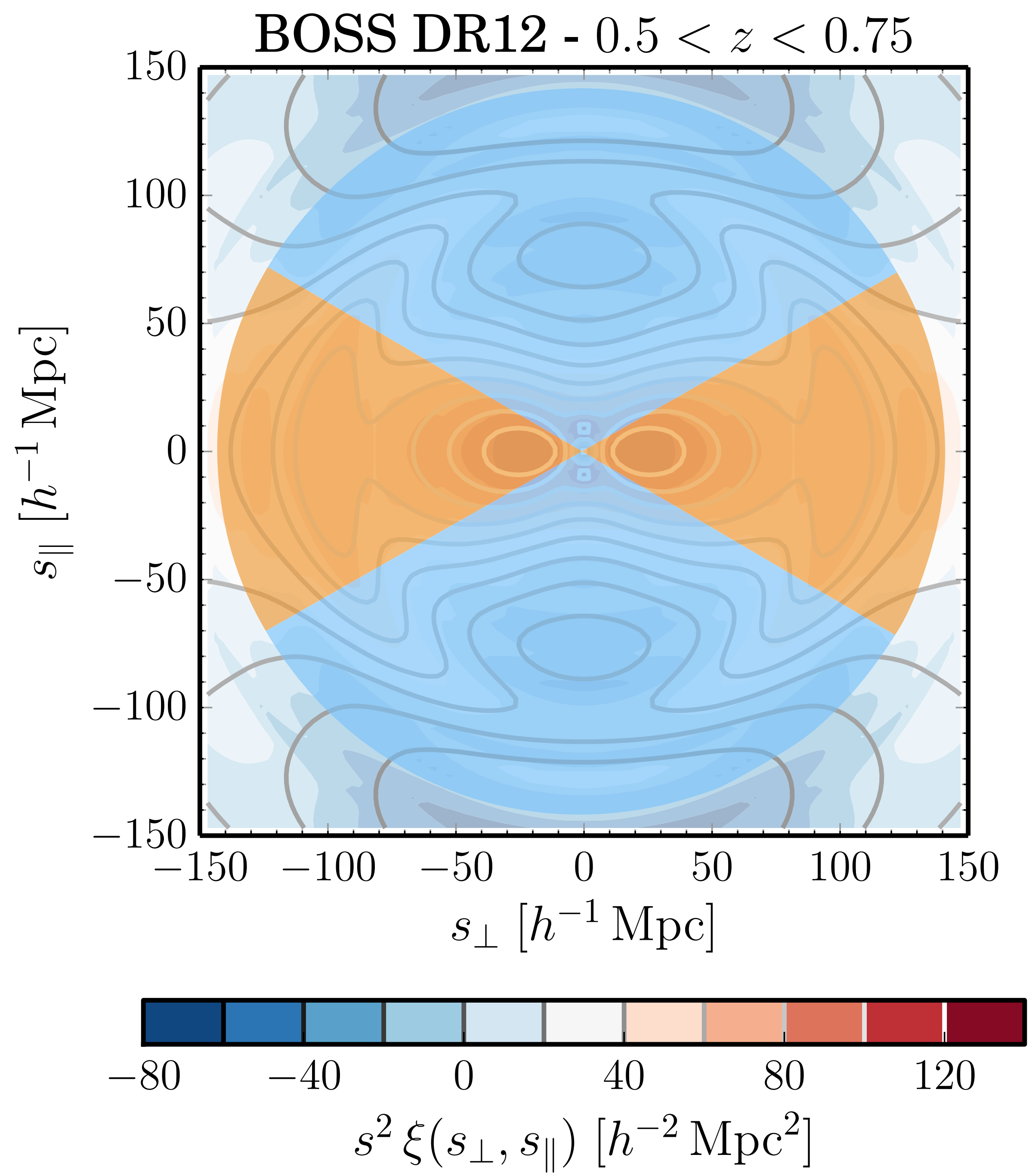
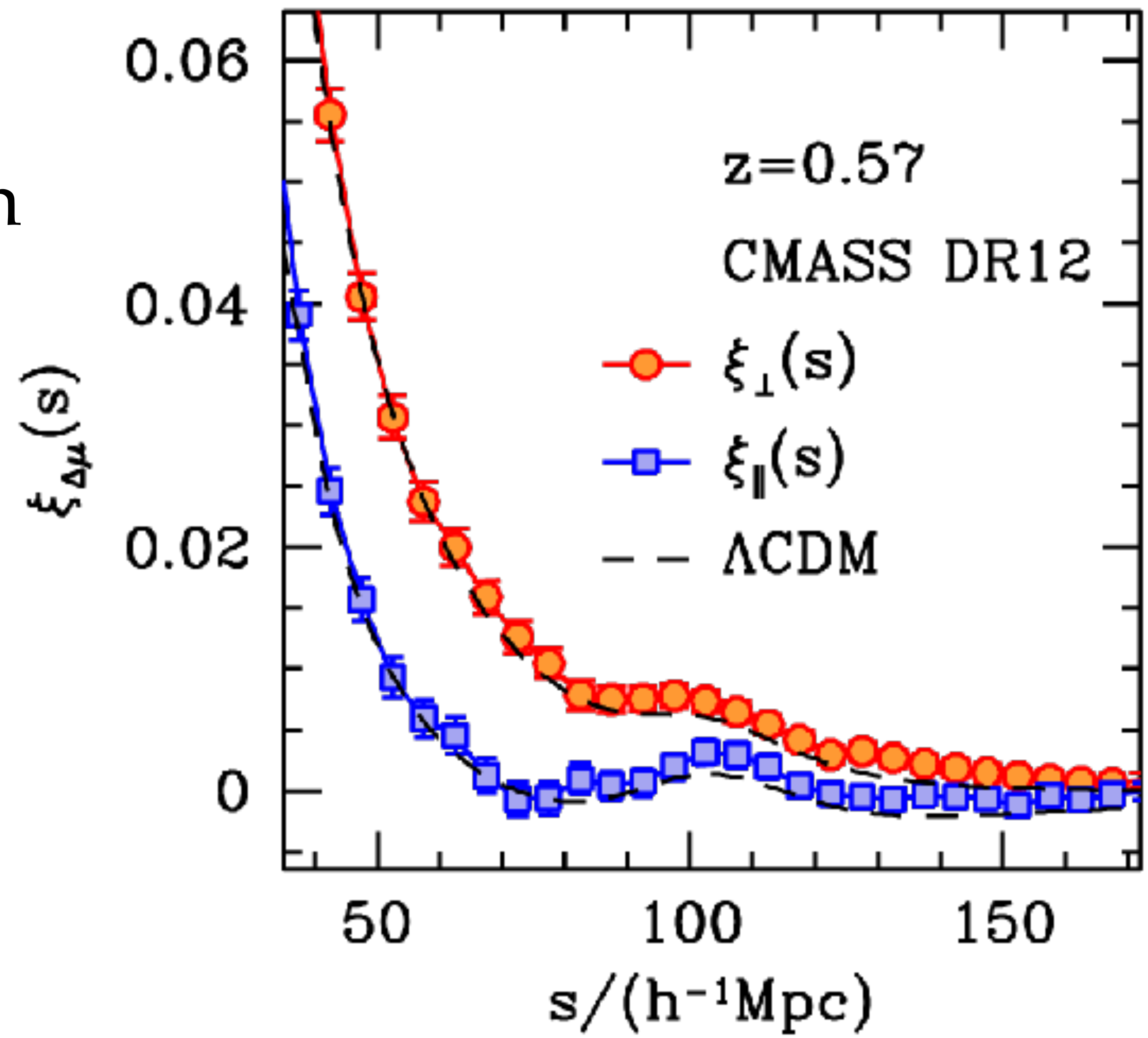


Anisotropic clustering

- CMASS-DR12 clustering wedges $\xi_{\perp,\parallel}(s)$.
- BAO signal can be seen in both wedges.
- Exploit full constraining power of BAO signal.

$$D_{\mathrm{M}}(z)/r_{\mathrm{d}}$$

$$H(z) \times r_{\mathrm{d}}$$



Anisotropic clustering

- Anisotropic BAO measurements constrain

$$y_{\perp} = D_{\mathrm{M}}(z)/r_{\mathrm{d}}$$
$$y_{\parallel} = D_{\mathrm{H}}(z)/r_{\mathrm{d}}$$

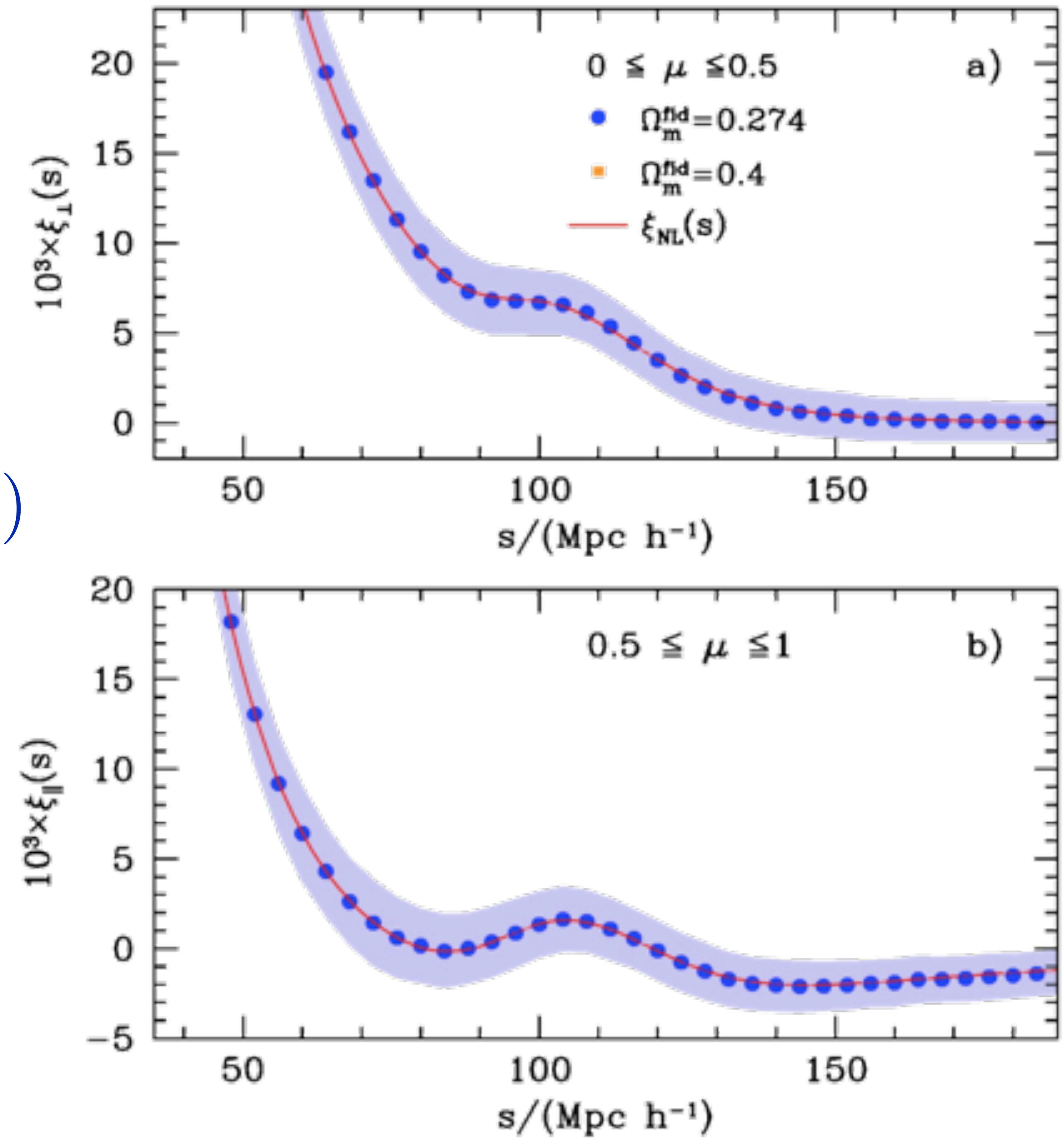
where $D_H(z_{\mathrm{m}}) = c/H(z_{\mathrm{m}})$

- Alternative basis:

$$D_{\mathrm{V}}(z)/r_{\mathrm{d}}$$

$$F_{\mathrm{AP}}(z) = D_{\mathrm{M}}(z)H(z)/c$$

The *Alcock-Paczynski parameter*



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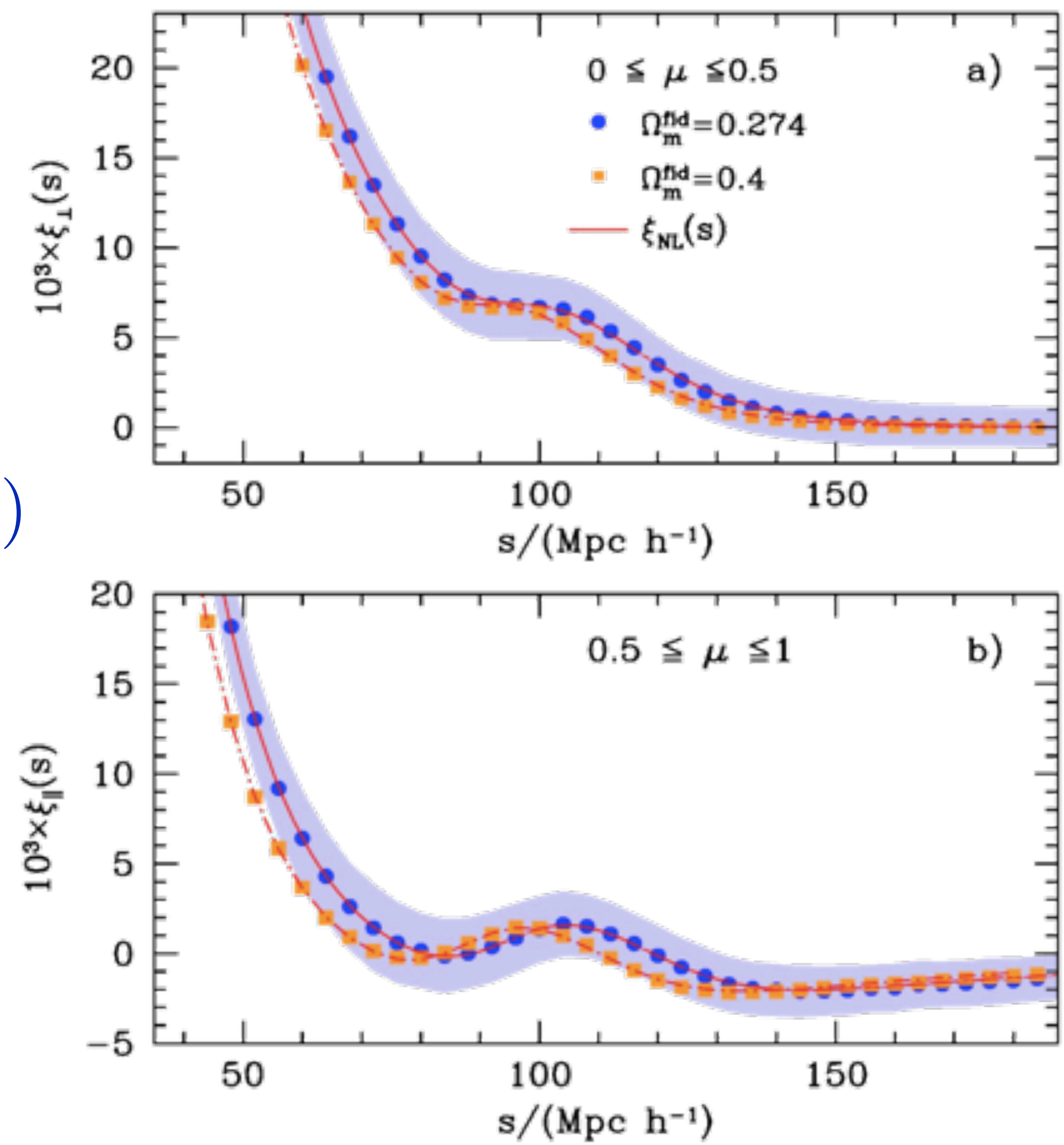

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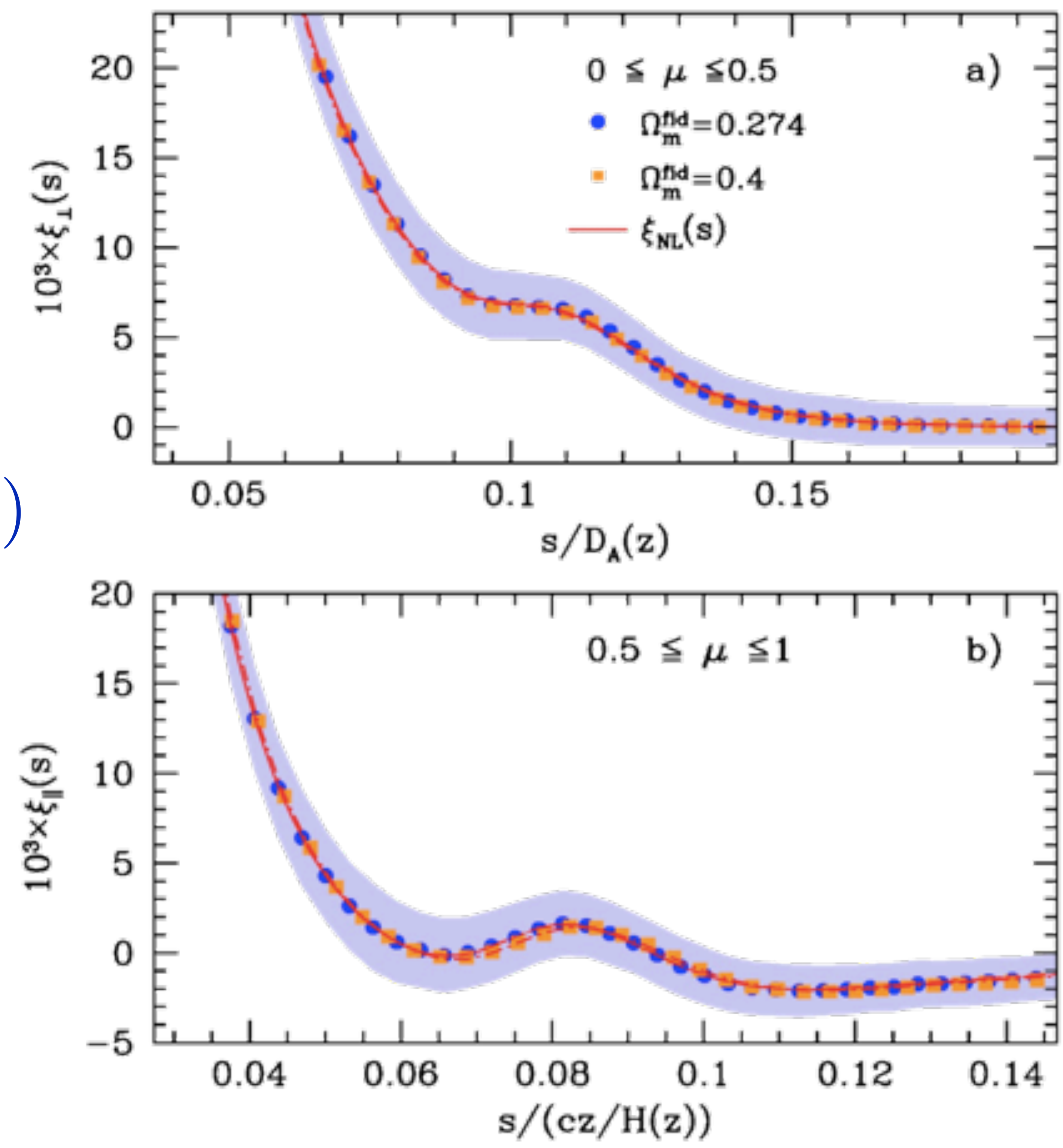
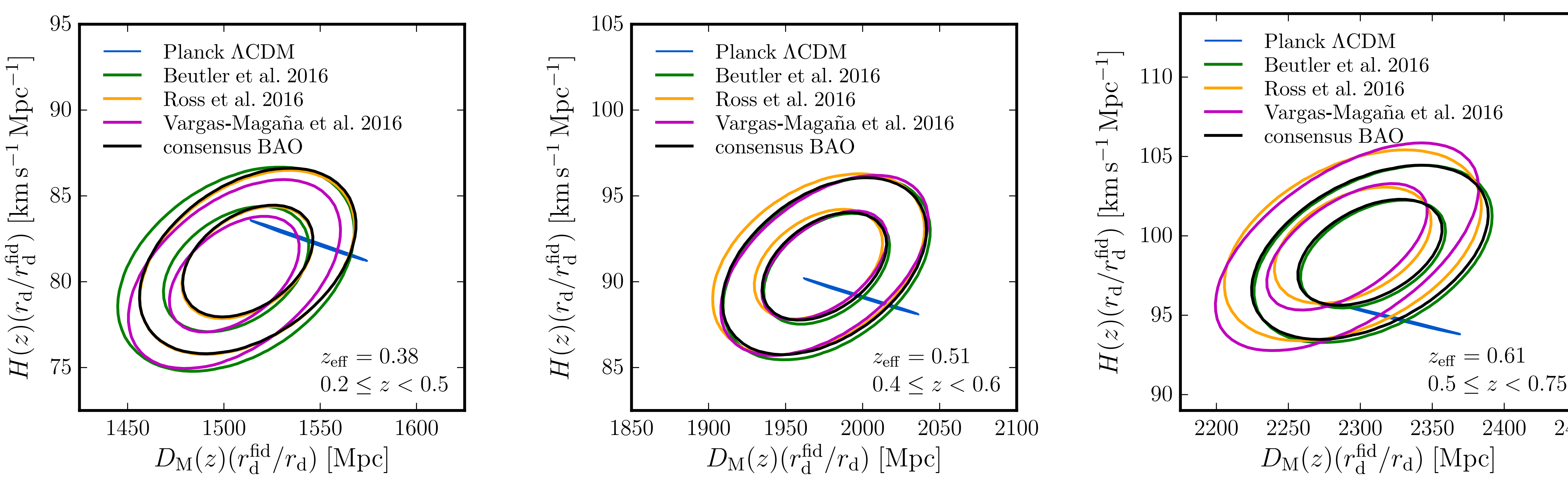


Anisotropic BAO measurements

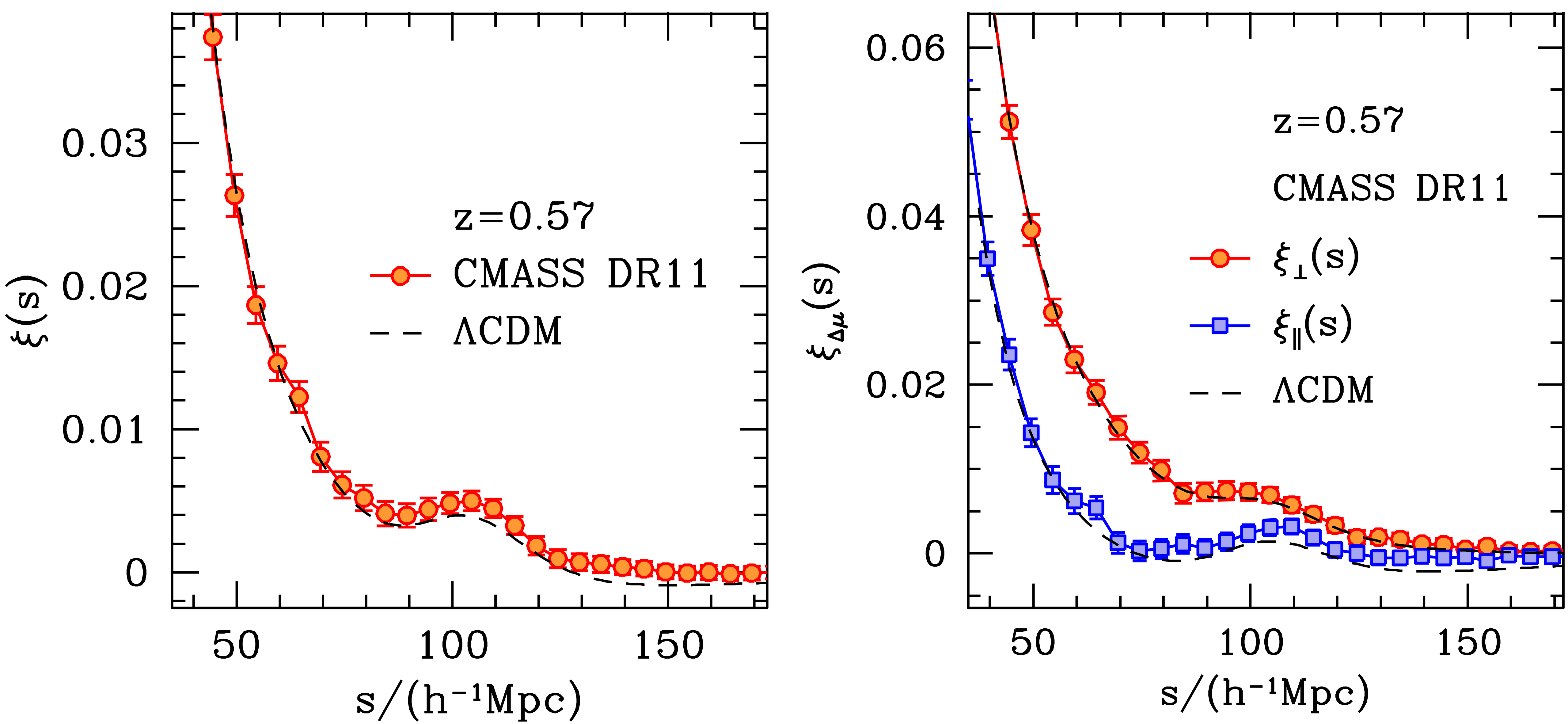
- Final anisotropic BAO measurements from BOSS.
- Post-reconstruction anisotropic analyses.
- Complete agreement with Planck ΛCDM predictions.



Alam et al.(2017)

Full-shape clustering analyses

- Clustering measurements contain additional information beyond BAO.



Sánchez et al.(2014)

Lecture 1: BAO

- Introduction: cosmology from LSS observations.
- Baryon acoustic oscillations (BAO).
- Galaxy redshift surveys.
- Potential systematic errors.
- Angle-averaged vs anisotropic measurements.
- Present-day BAO measurements.