Cosmological analysis of the completed BOSS

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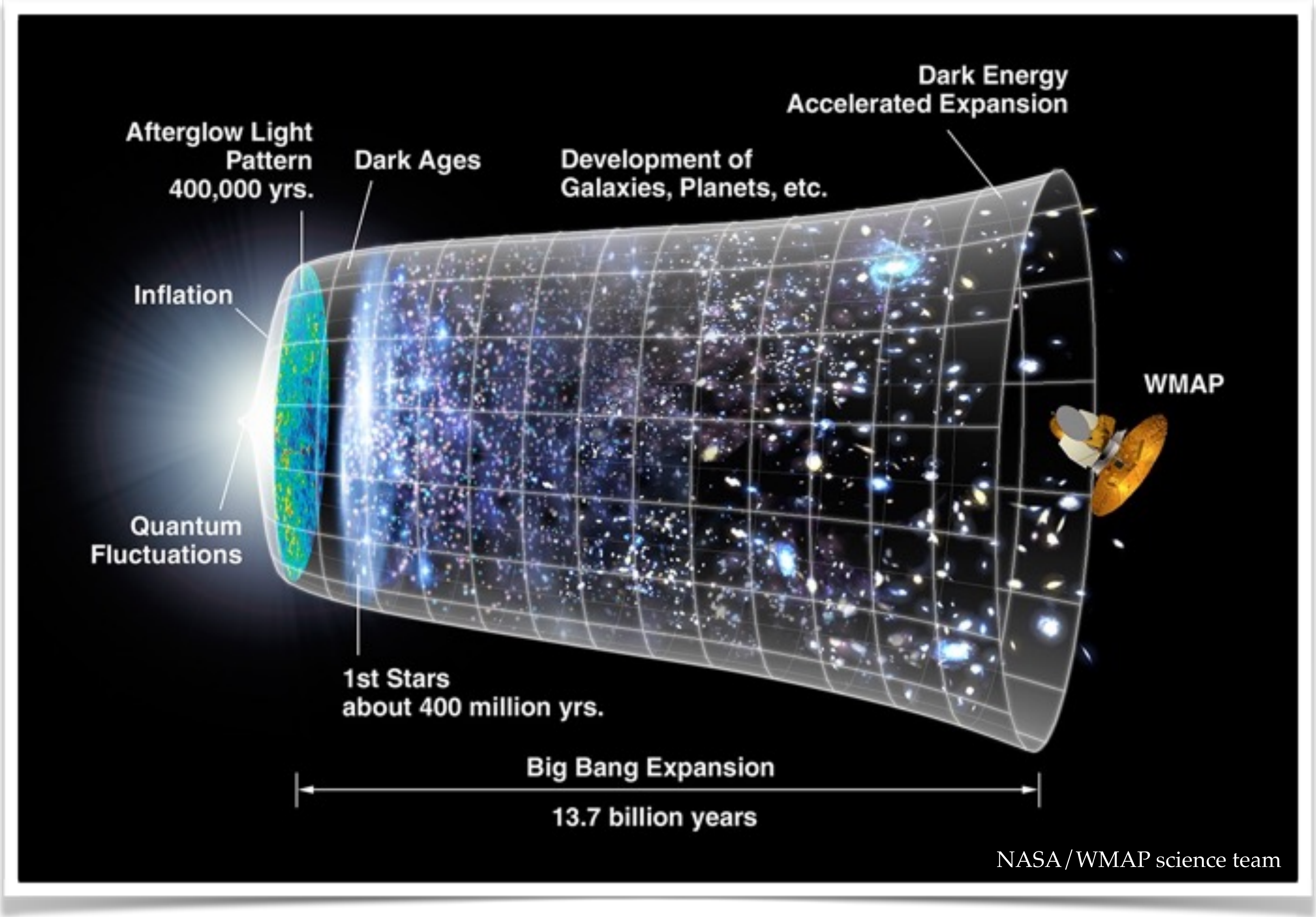
DESY colloquium - Zeuthen - 30.11.2016

Outline

- Cosmology from large-scale structure observations.
- The Baryon Oscillation Spectroscopic Survey (BOSS).
- Anisotropic clustering measurements.
- Cosmological constraints from BOSS-DR12.
- The DR12 BOSS *consensus* cosmological constraints.

Observational cosmology

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



NASA/WMAP science team

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.

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

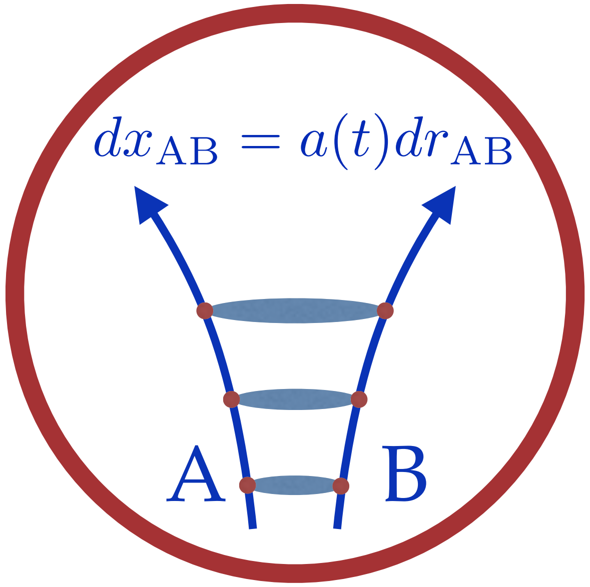
- The ΛCDM model: vacuum energy, $w_{\rm DE} = -1$.

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

Cosmology from LSS observations

- Observational effects of cosmic acceleration:

  - Expansion history of the Universe:



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

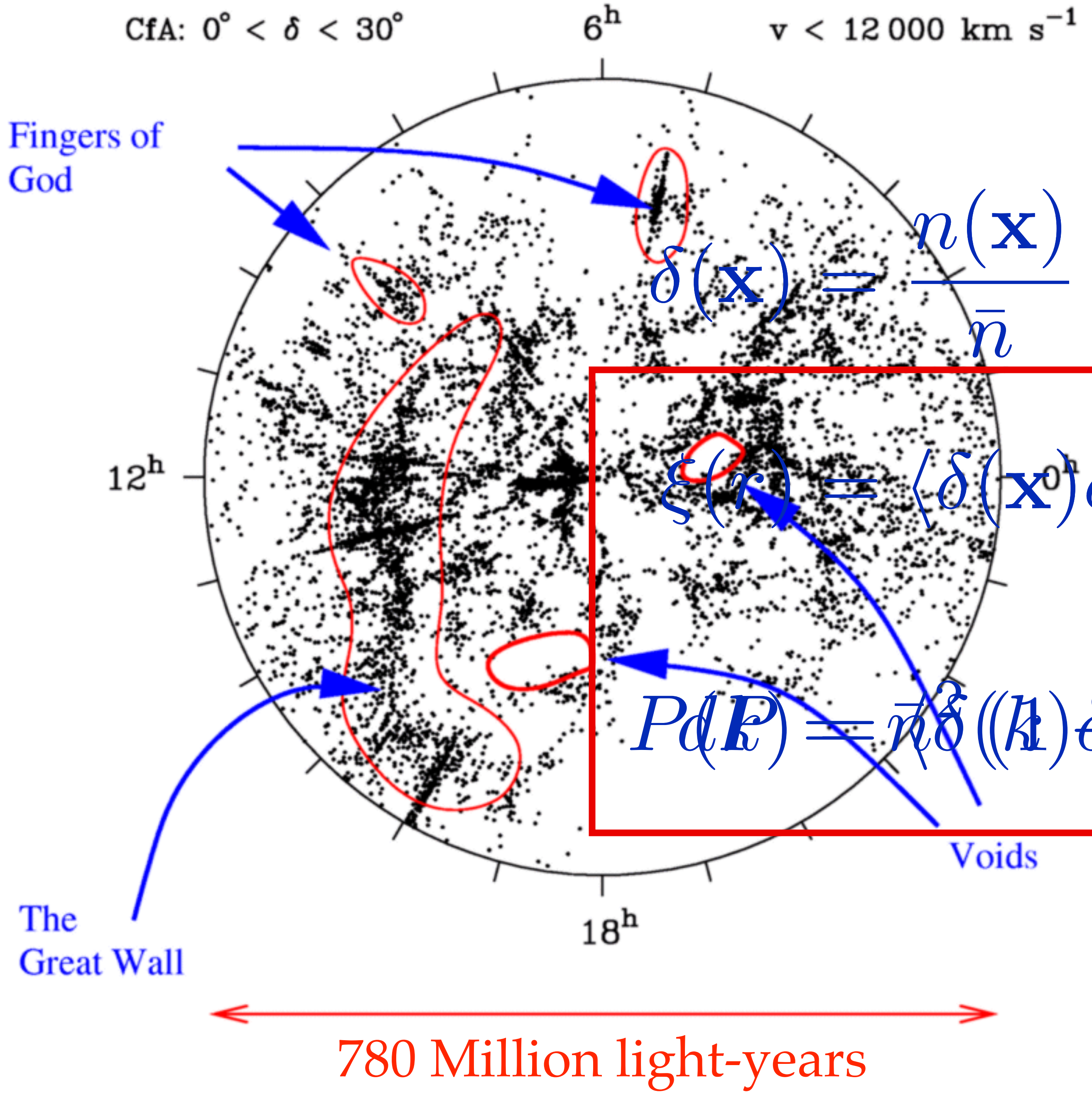
  - Growth of density fluctuations:

$$\delta = \frac{\rho - \bar{\rho}}{\bar{\rho}} \qquad \ddot{\delta} + 2H\dot{\delta} = 4\pi G\bar{\rho}\delta$$

- Both effects can be probed by LSS observations

Cosmology from LSS observations

- Statistical analysis of large-scale structure



$$\delta(\mathbf{x}) = \frac{n(\mathbf{x})}{\bar{n}} - 1$$

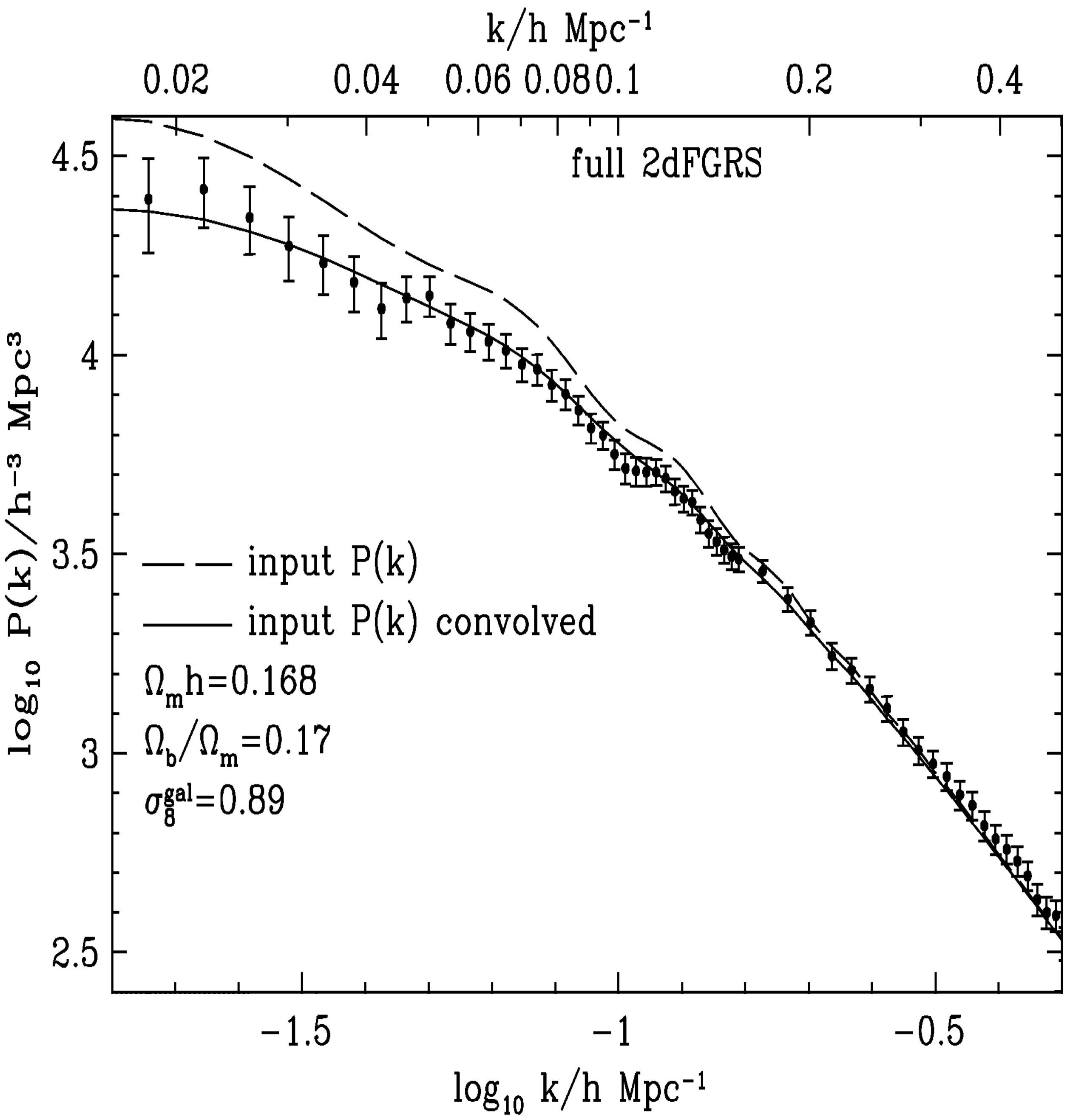
$$\xi(r) = \langle \delta(\mathbf{x})\delta(\mathbf{x}+\mathbf{r}) \rangle$$

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

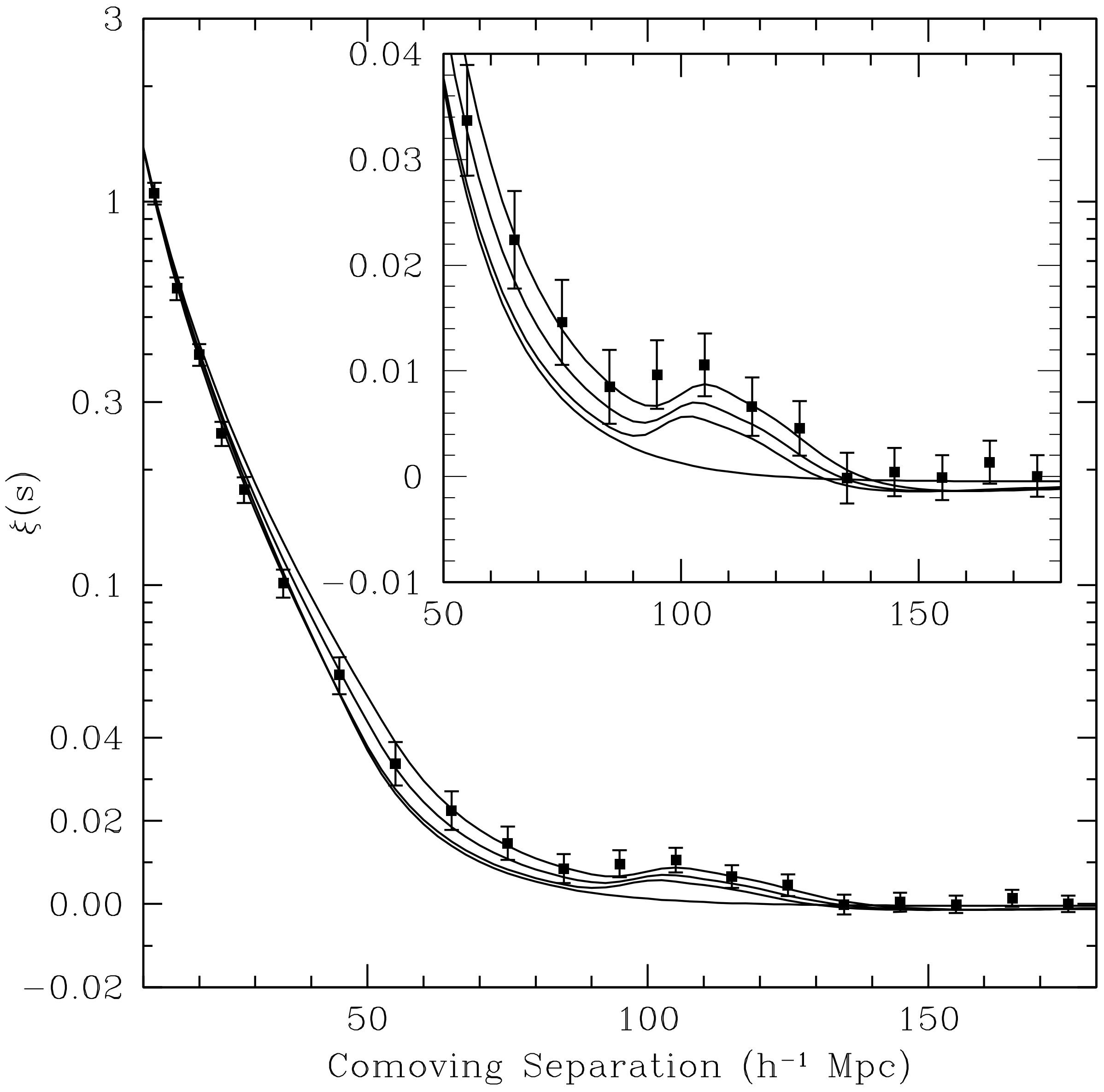
$$P(k) = \langle \delta(k)\delta^*(k) \rangle$$

Cosmology from LSS observations

- Statistical analysis of large-scale structure



Cole et al. (2005)



Eisenstein et al. (2005)

Baryon Acoustic Oscillations

- The BAO signal is also present in the CMB.

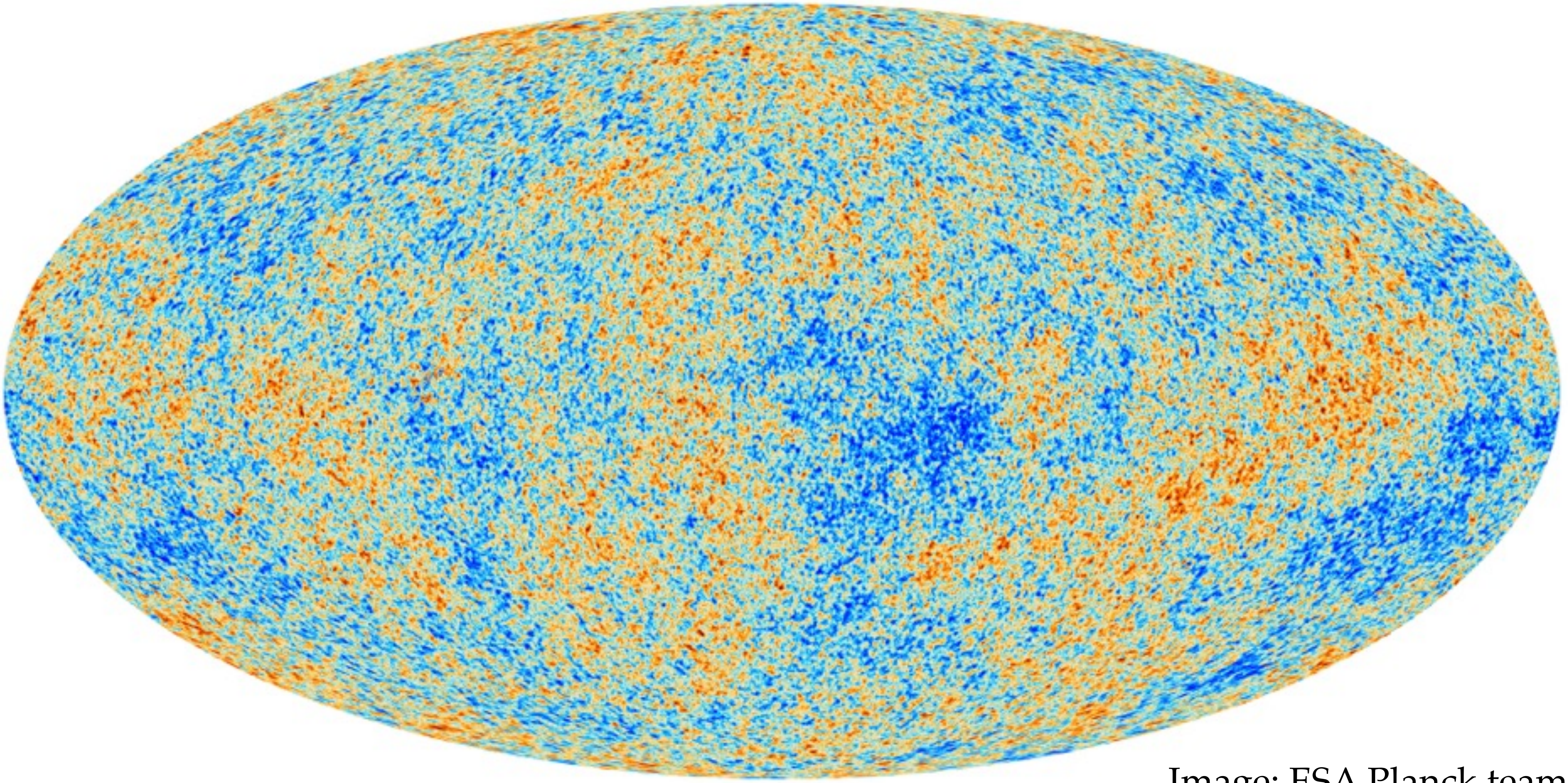


Image: ESA Planck team

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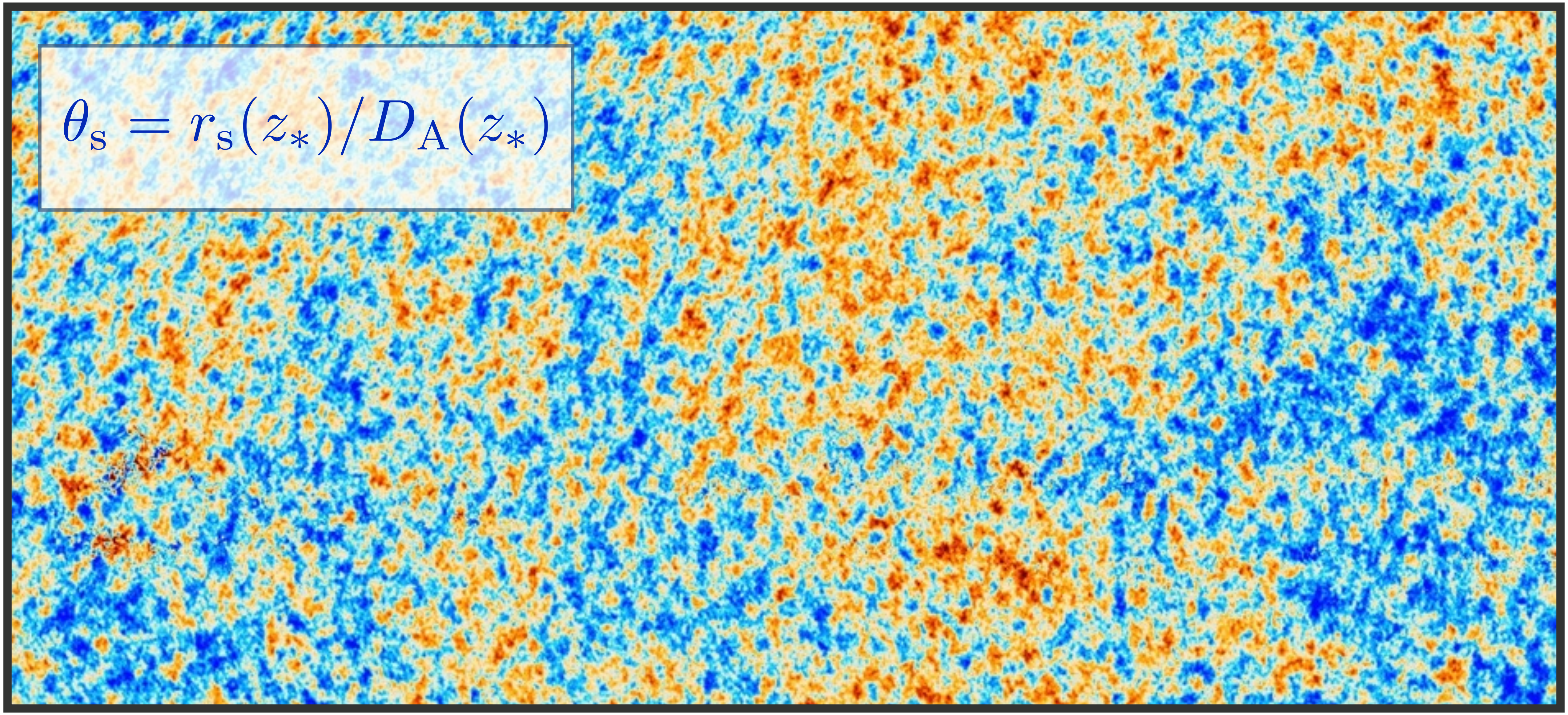
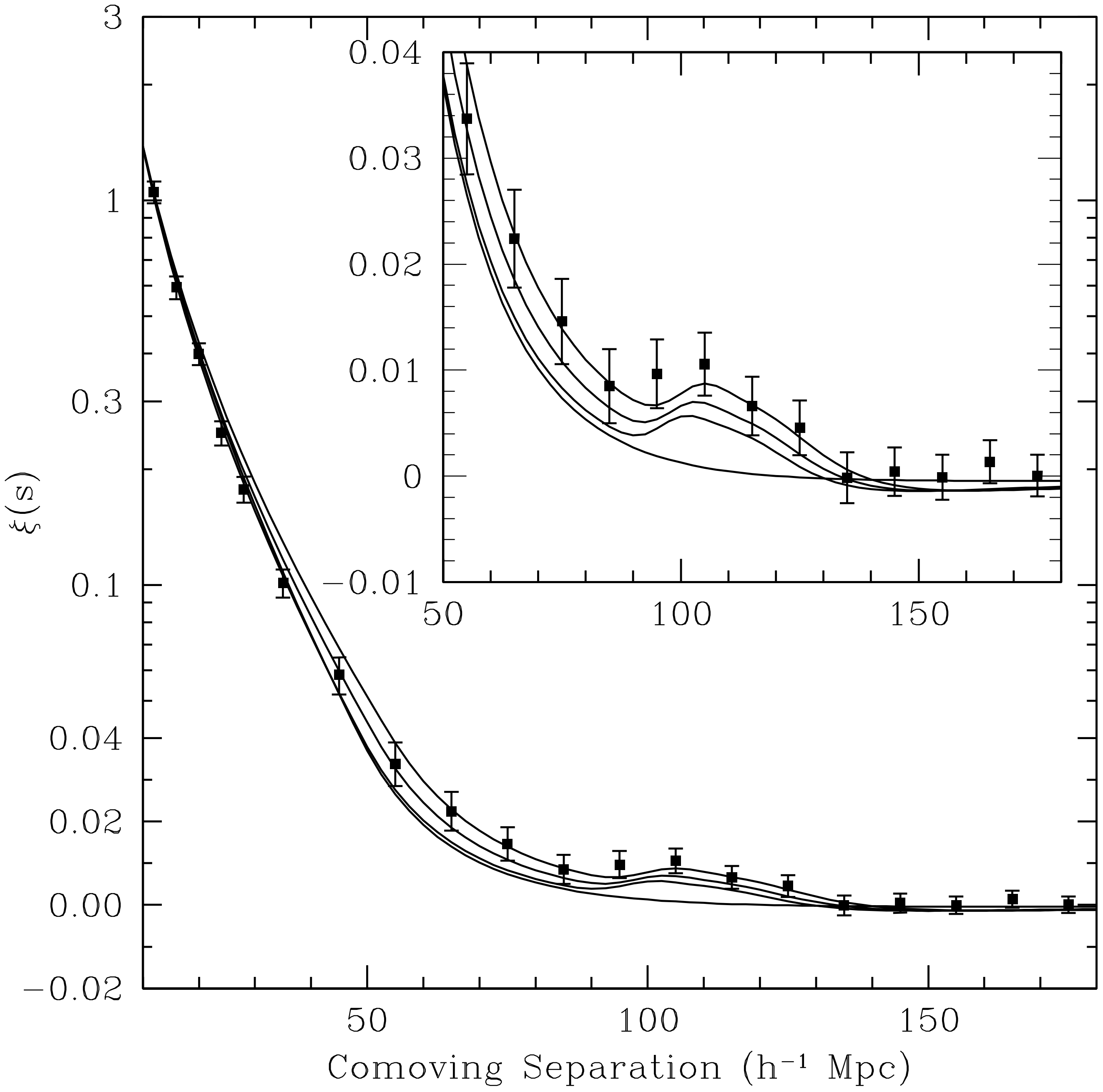


$$\theta_\mathrm{s} = r_\mathrm{s}(z_*)/D_\mathrm{A}(z_*)$$

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

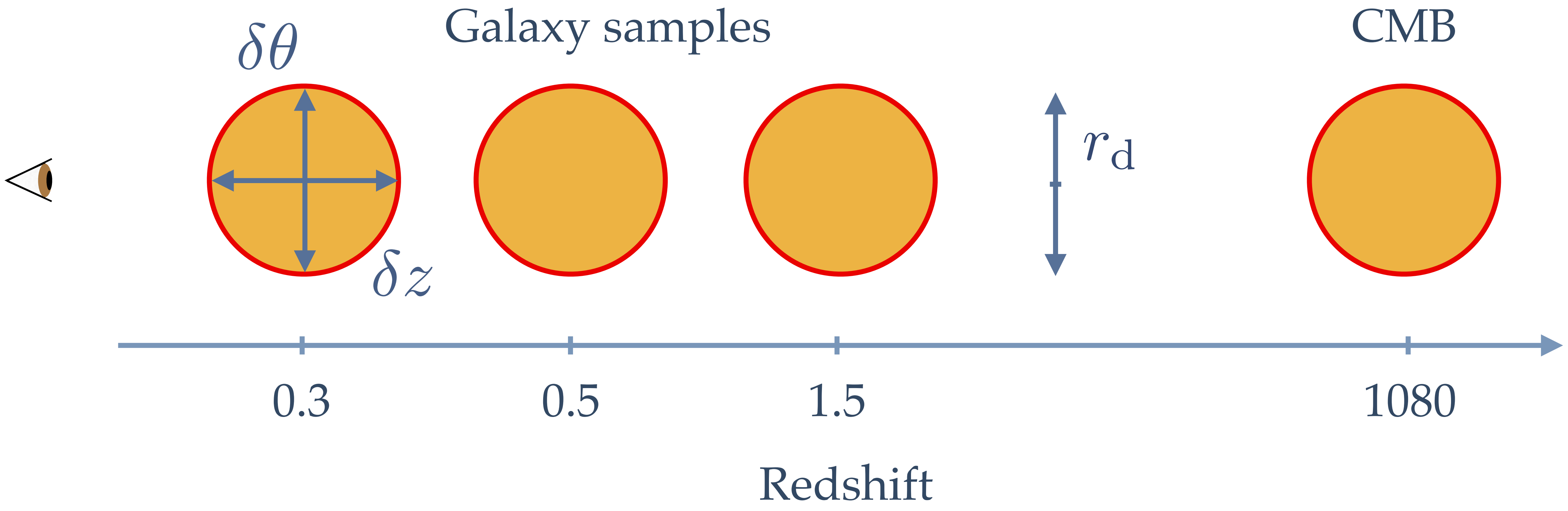
$$r_\mathrm{d} = r_\mathrm{s}(z_\mathrm{drag})$$



Eisenstein et al. (2005)

Baryon Acoustic Oscillations

- BAO can be used as a standard ruler.



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

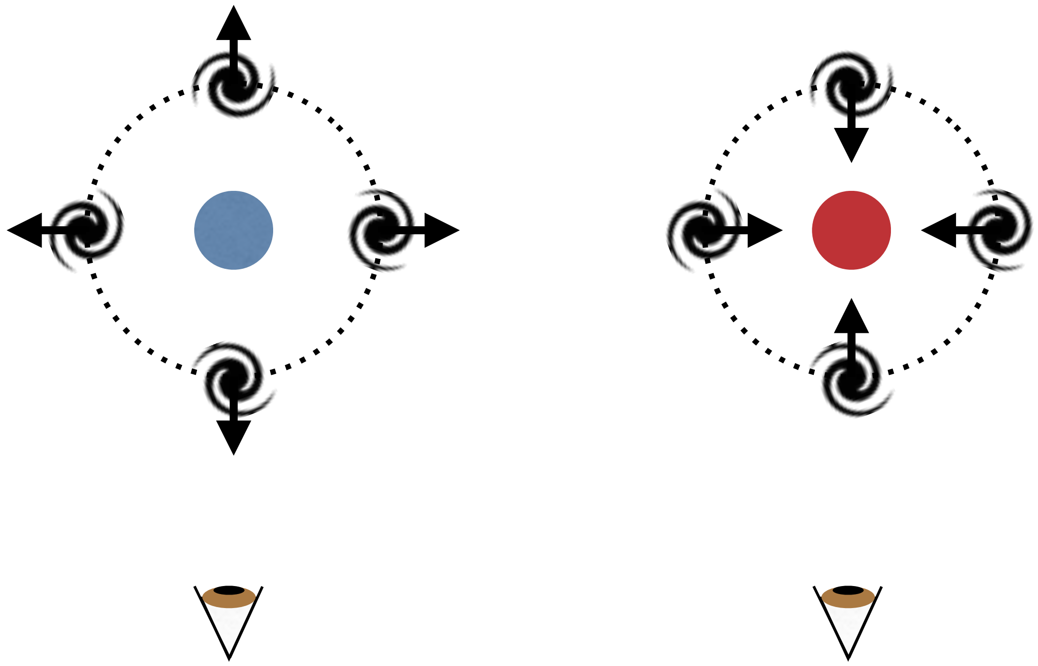
A probe of the expansion history of the Universe.

Redshift-space distortions

- The observed redshifts are affected by peculiar velocities.

$$(1+z_{\mathrm{obs}}) = (1+z_{\mathrm{cos}})(1+v/c)$$

- Velocities depend on the density field itself.



RSD constrain the growth of structure.

$$f(z) = \frac{\mathrm{d}\ln D}{\mathrm{d}\ln a}$$

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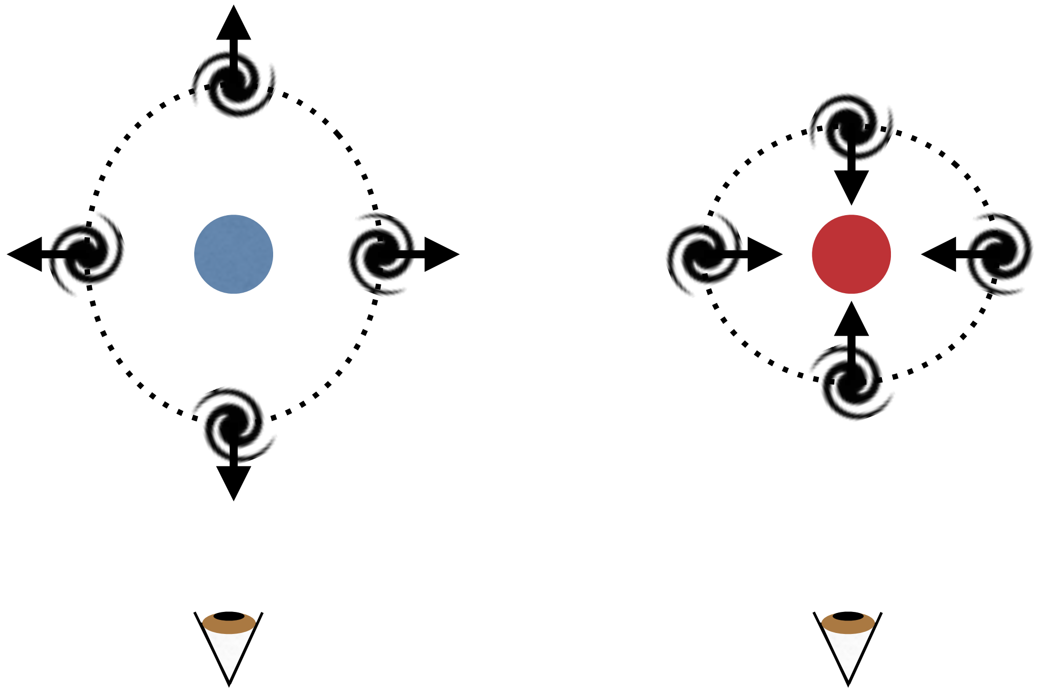

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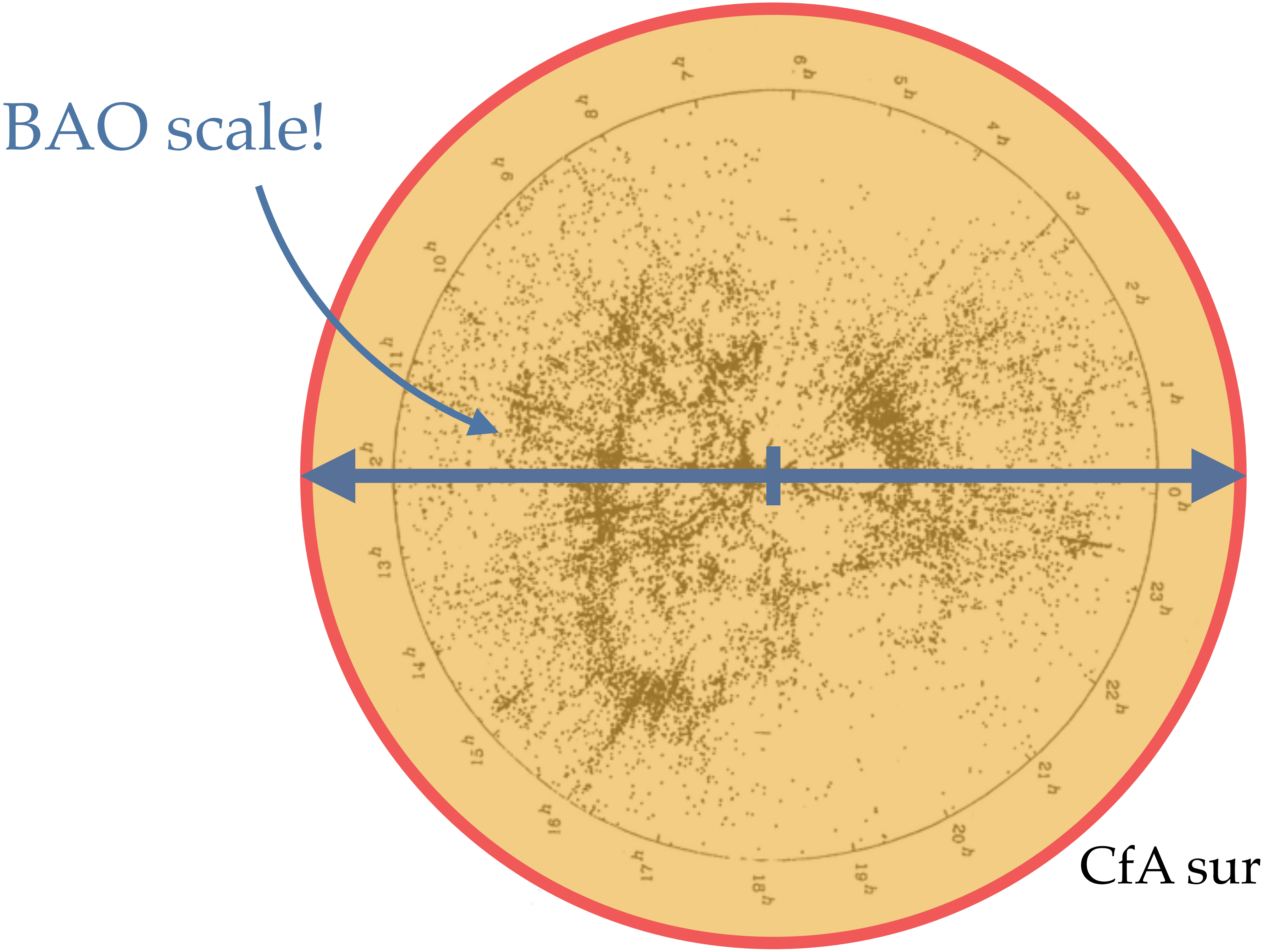
Galaxy redshift surveys

- Galaxy clustering measurements require large volumes!



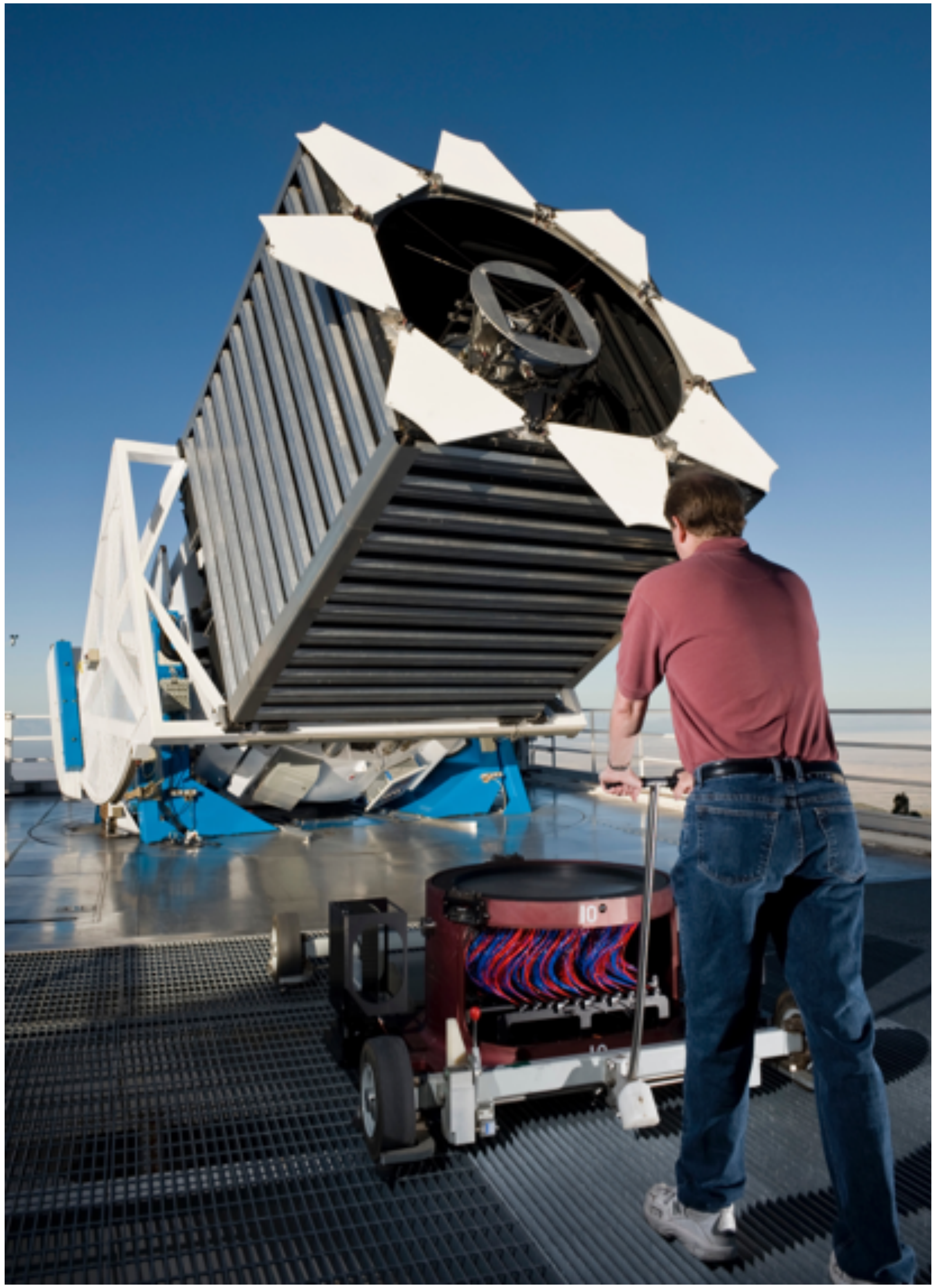
CfA survey (1989)

BOSS in a nutshell

- Designed to tackle CA through BAO measurements
- Final DR in Dec. 2014.
- Total area of 10,200 deg^2.
- 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, $2.3 < z < 2.8$



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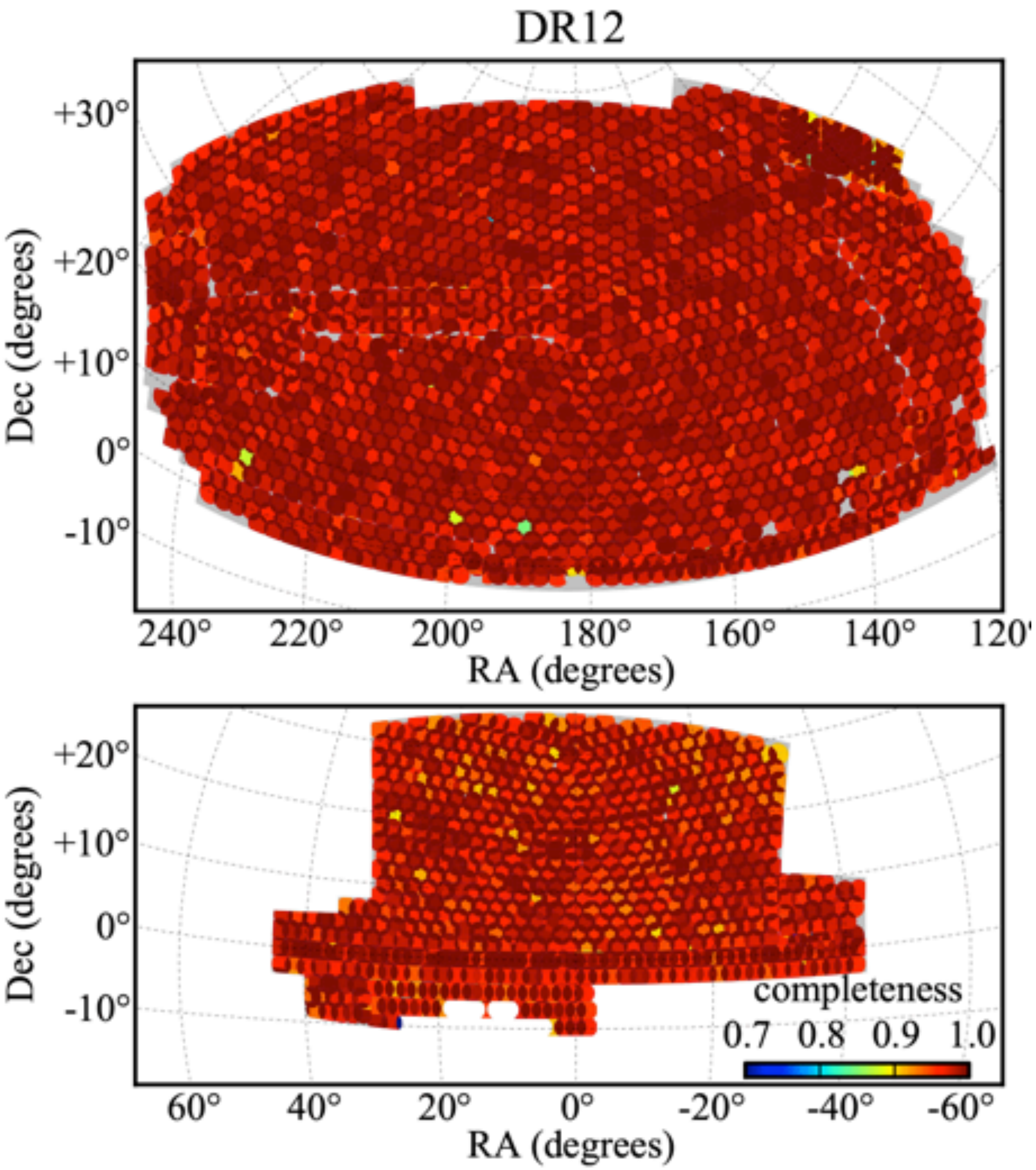
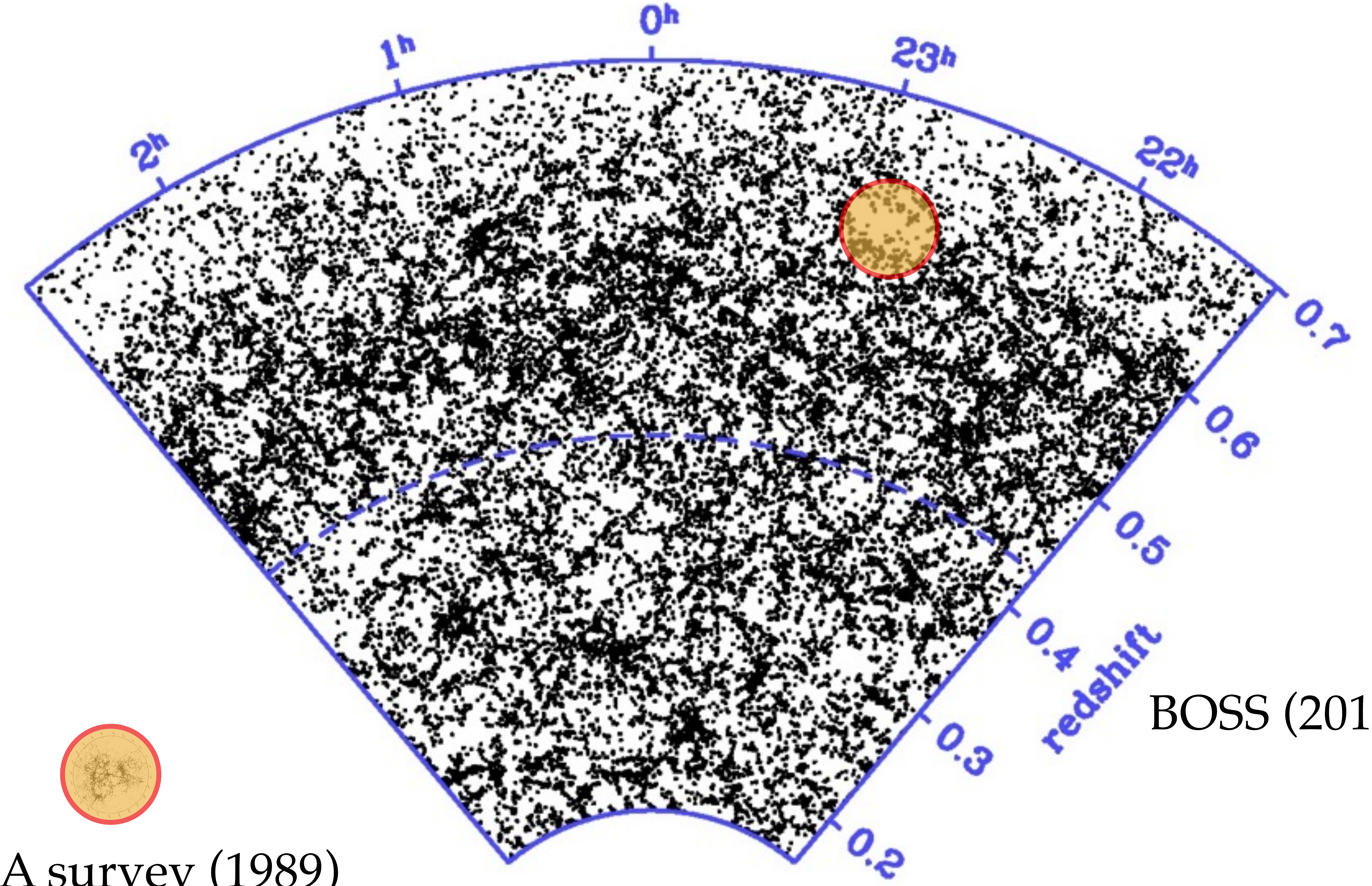


Reid et al. (2015)

BOSS in a nutshell

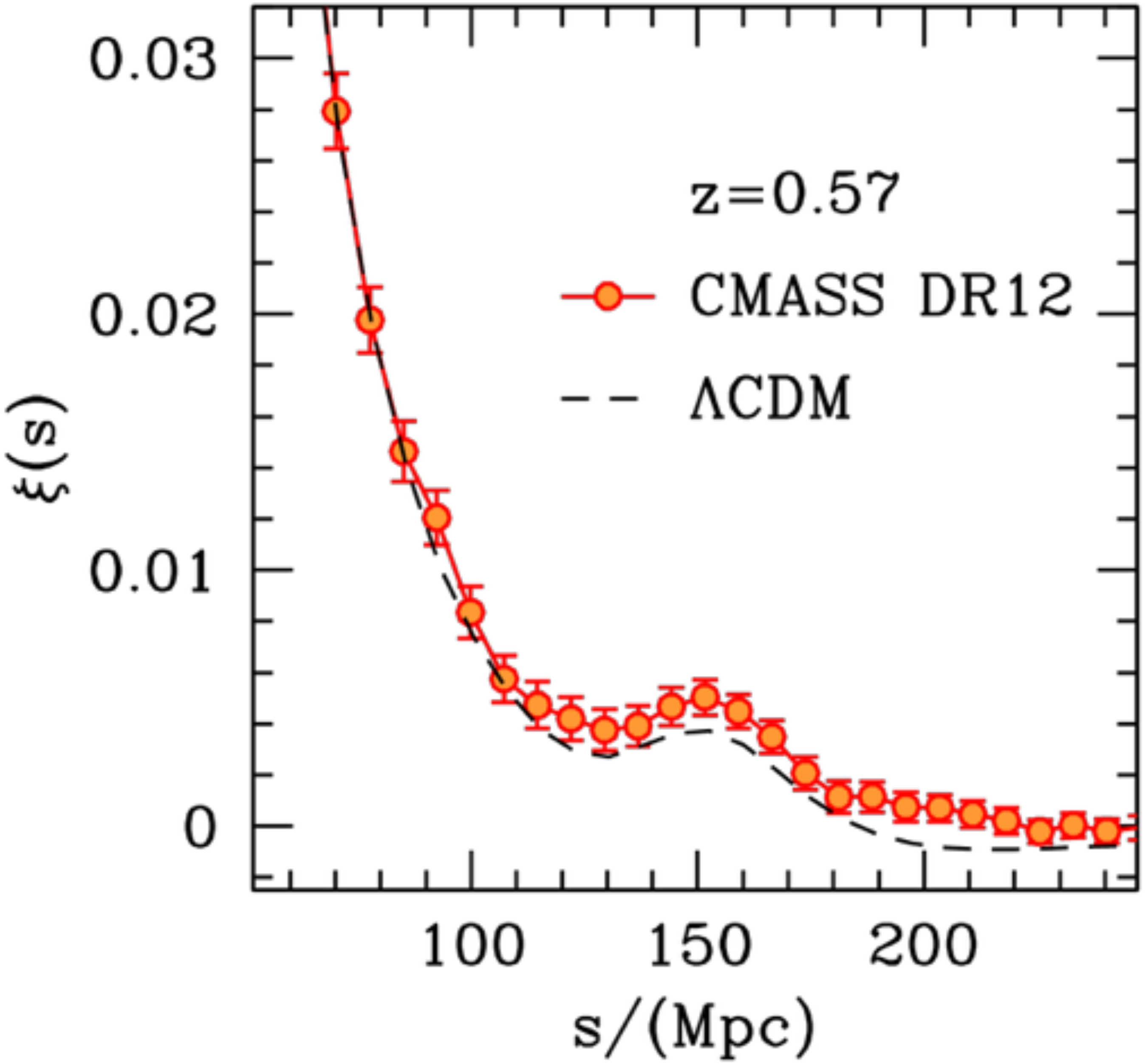


BOSS (2016)

CfA survey (1989)

BOSS in a nutshell

- CMASS-DR12 monopole correlation function.
- Great improvement in statistical uncertainties.
- High-significance detection of BAO signal.
- Excellent opportunity for accurate cosmological constraints.

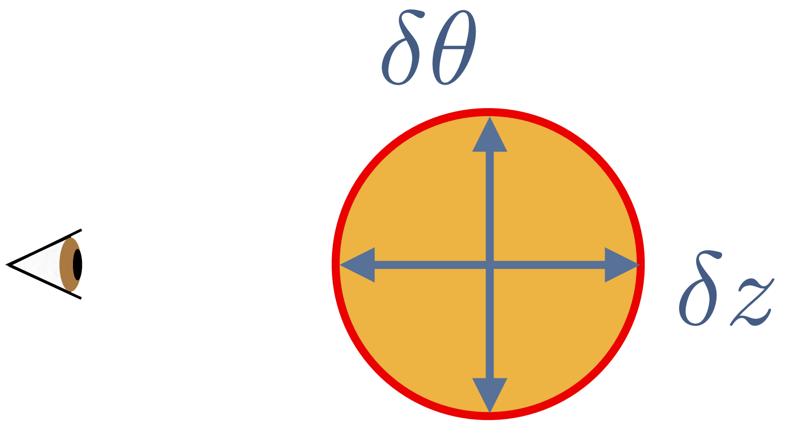


Modelling of LSS observations

- 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, $\delta_{\rm g} = b_1\delta + \frac{b_2}{2}\delta^2 + \ldots$)

Angle-averaged measurements

- Angle-averaged measurements have a limited constraining power.



BAO: only sensitive to a volume-averaged distance.

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

RSD: growth of structure is degenerate with galaxy bias

$$P_0(k) = b^2\left(1 + \frac{2}{3}\frac{f}{b} + \frac{1}{5}\left(\frac{f}{b}\right)^2\right)P(k)$$

Anisotropic clustering

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

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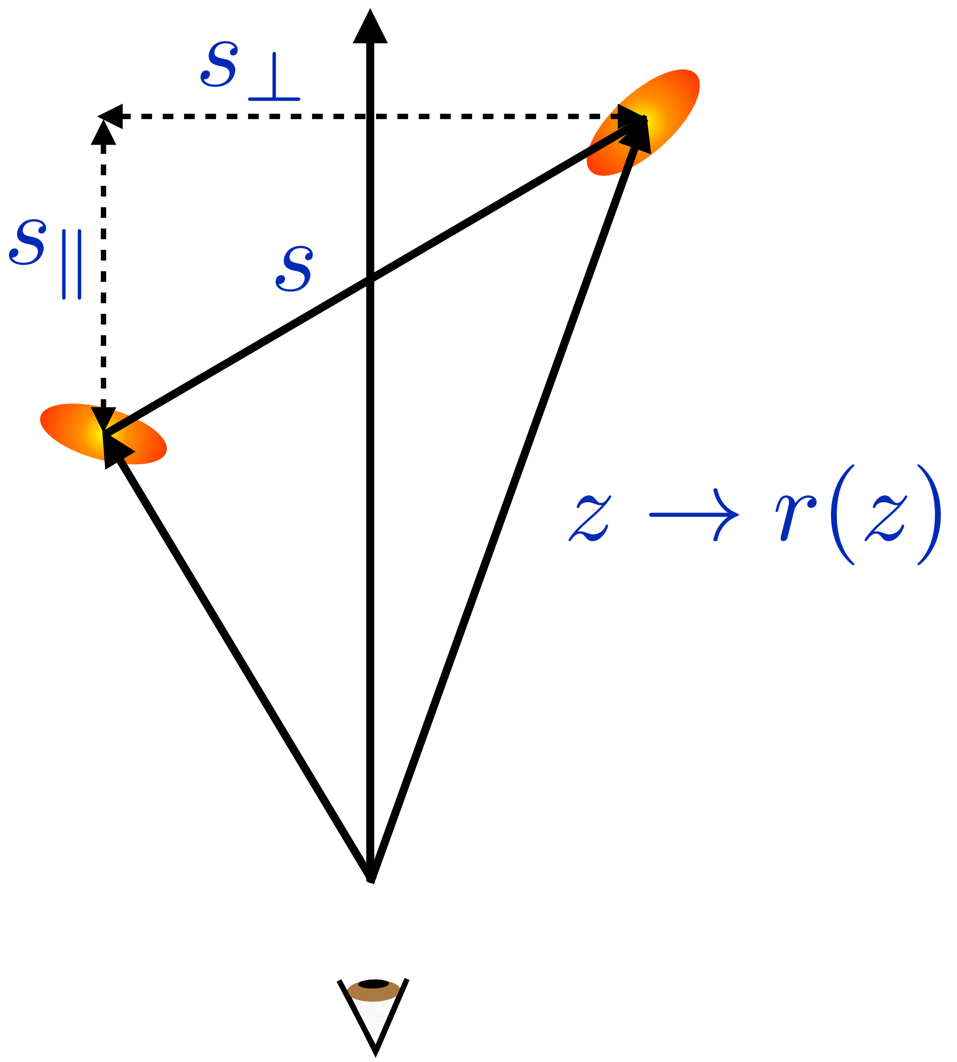
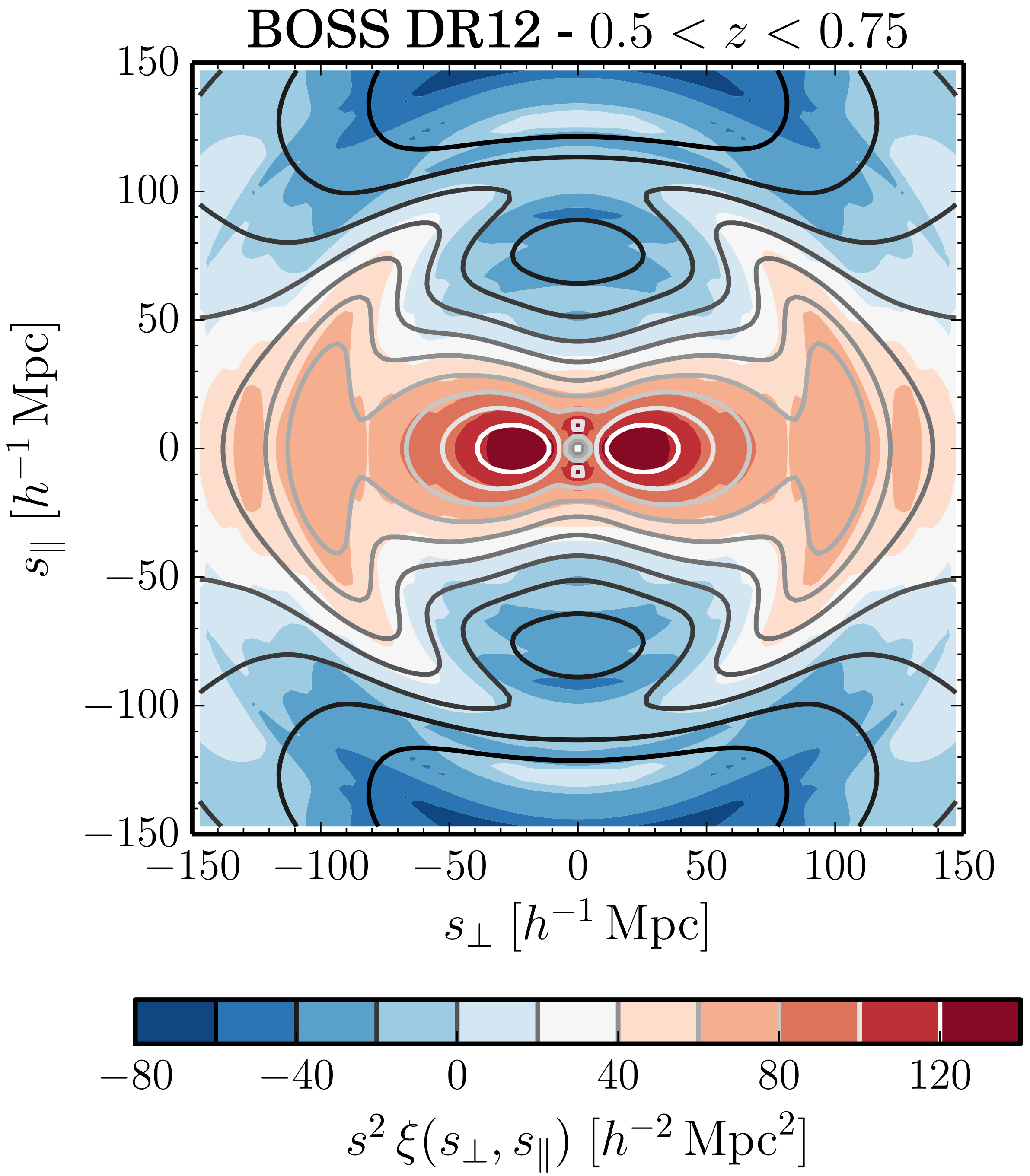
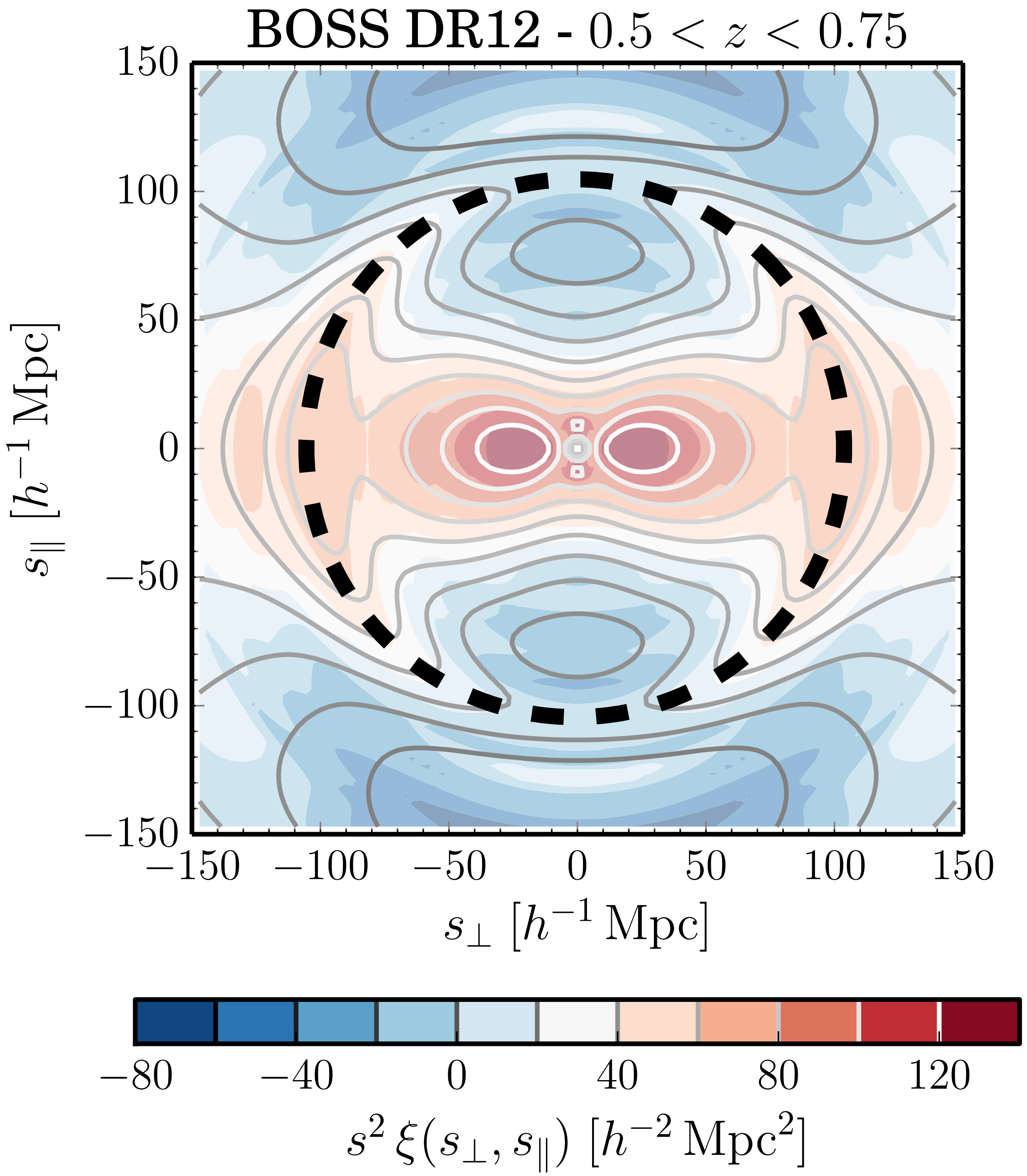




Anisotropic clustering

- 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

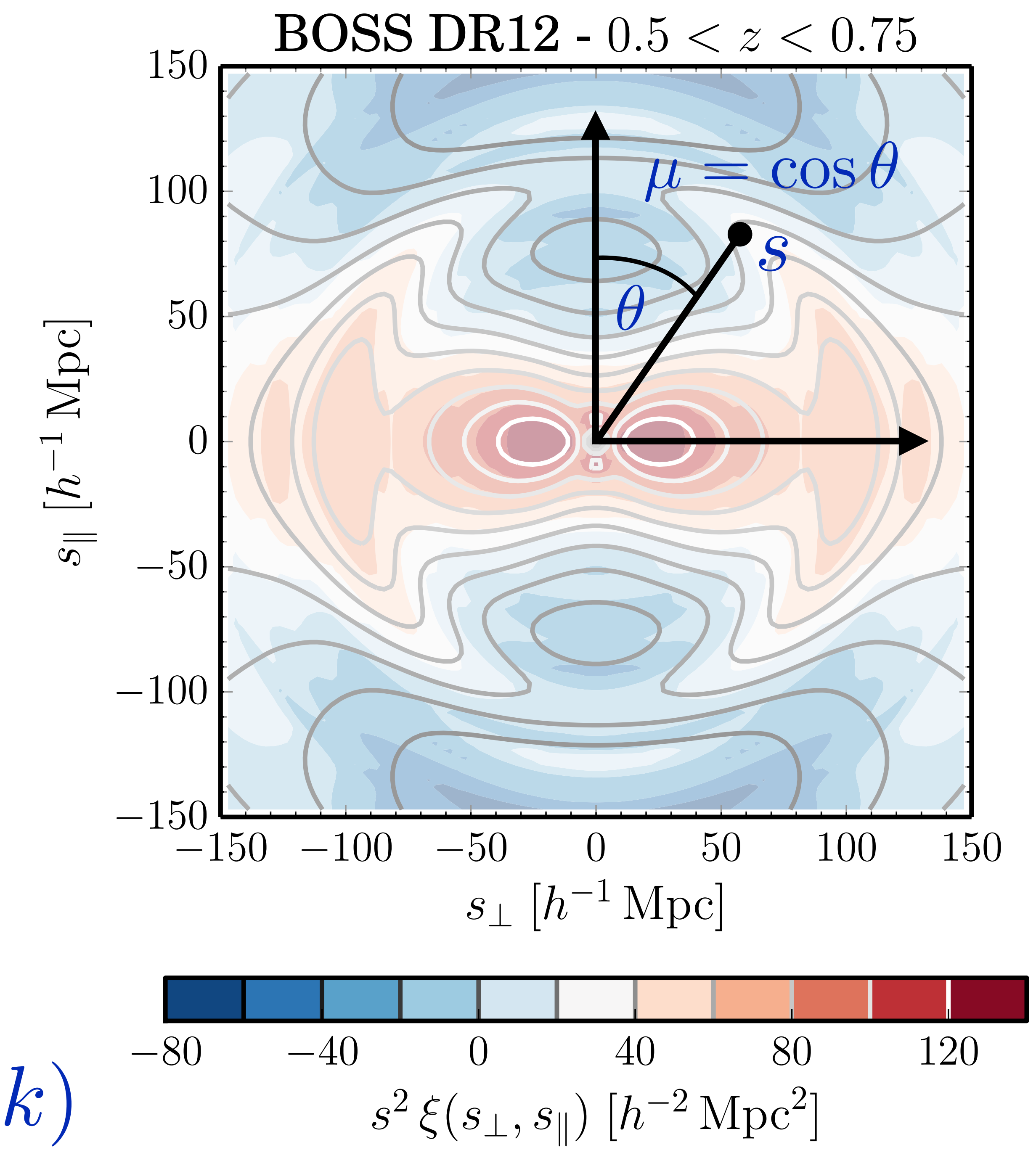
- Project $\xi(s_\perp, s_\parallel)$ into Legendre multipoles:

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

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

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

- In Fourier space: $P_\ell(k)$, $P_{\mu_1}^{\mu_2}(k)$



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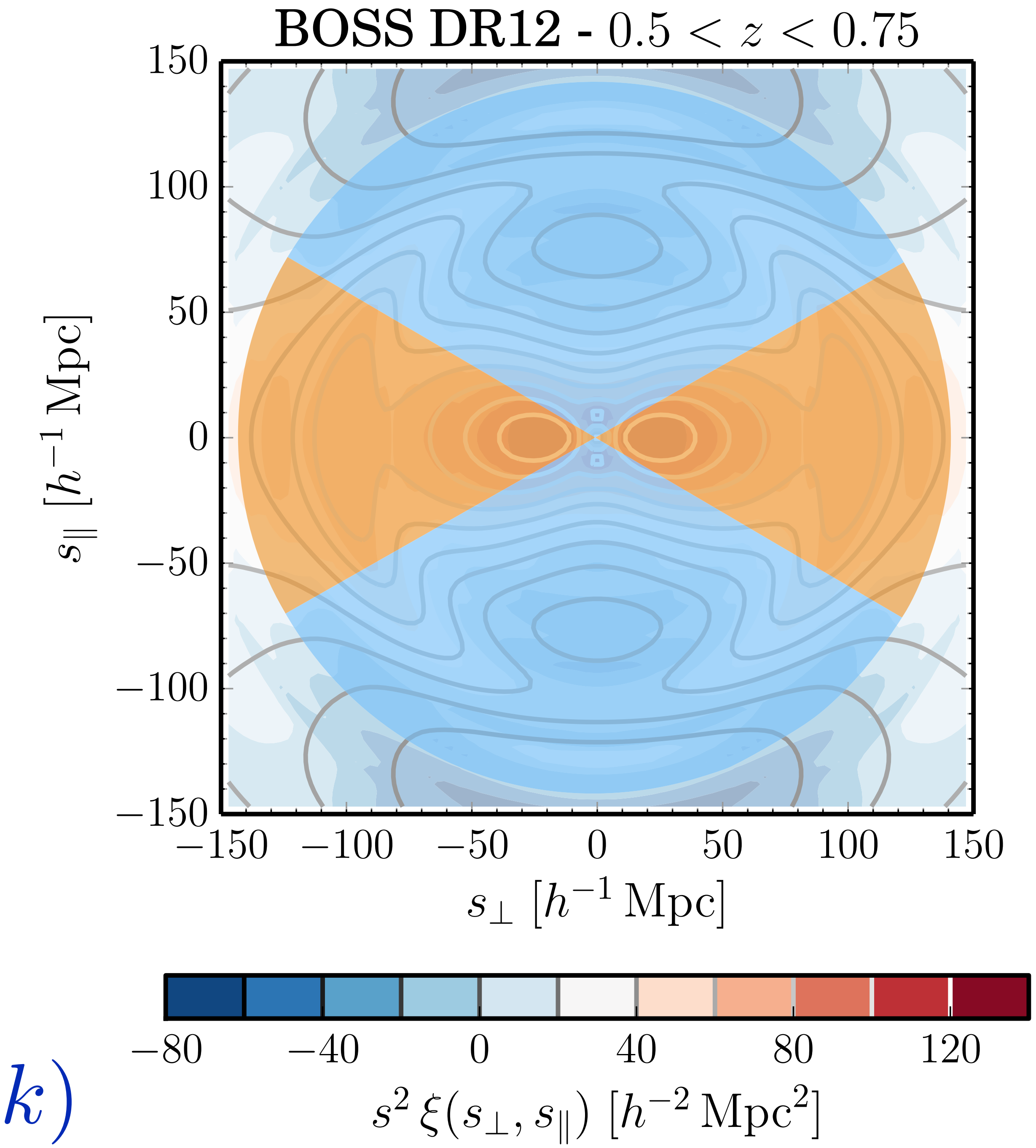


Anisotropic clustering

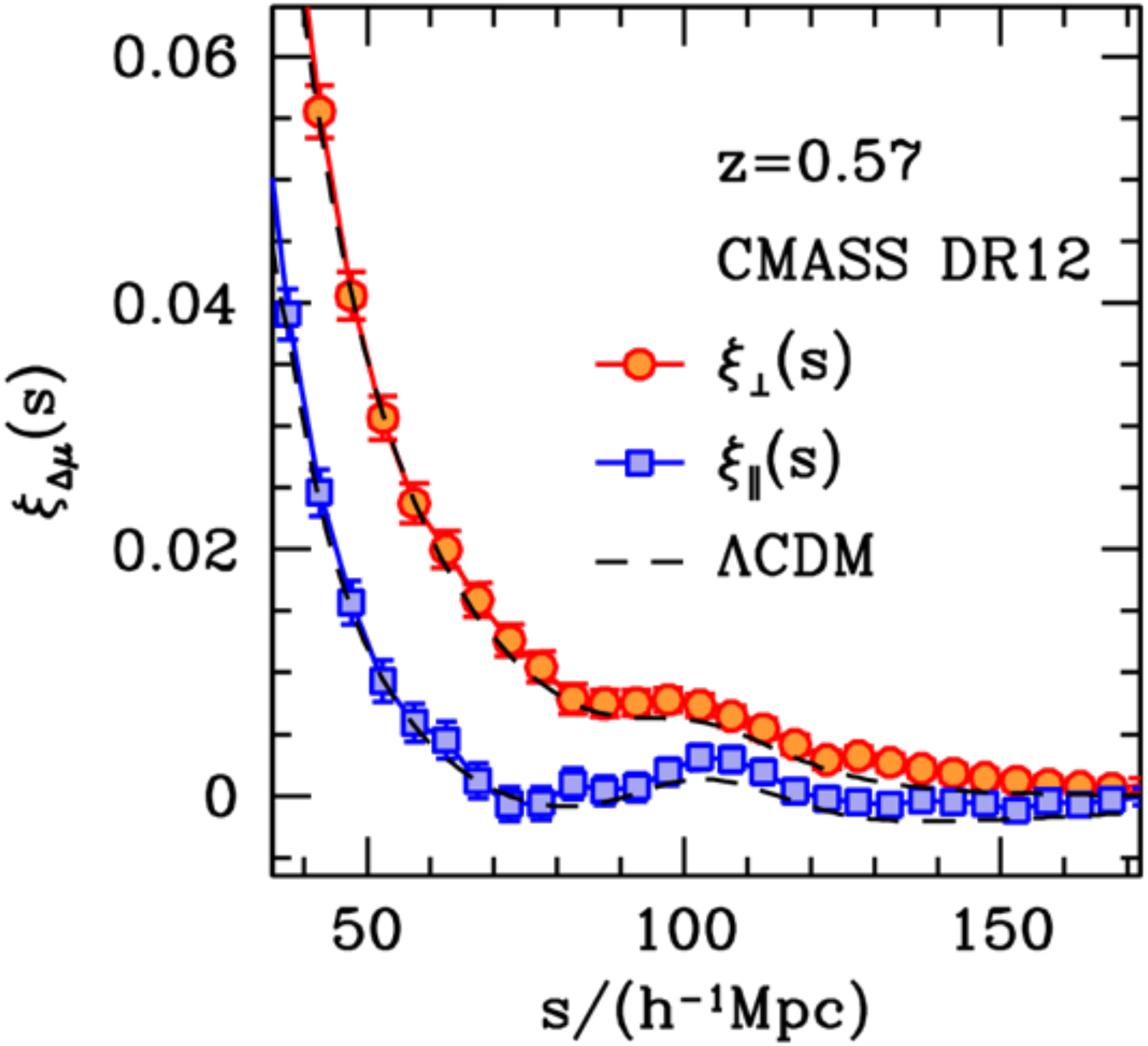
- CMASS-DR12 clustering wedges $\xi_{\perp,\parallel}(s)$.

- BAO signal can be seen in both wedges.

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

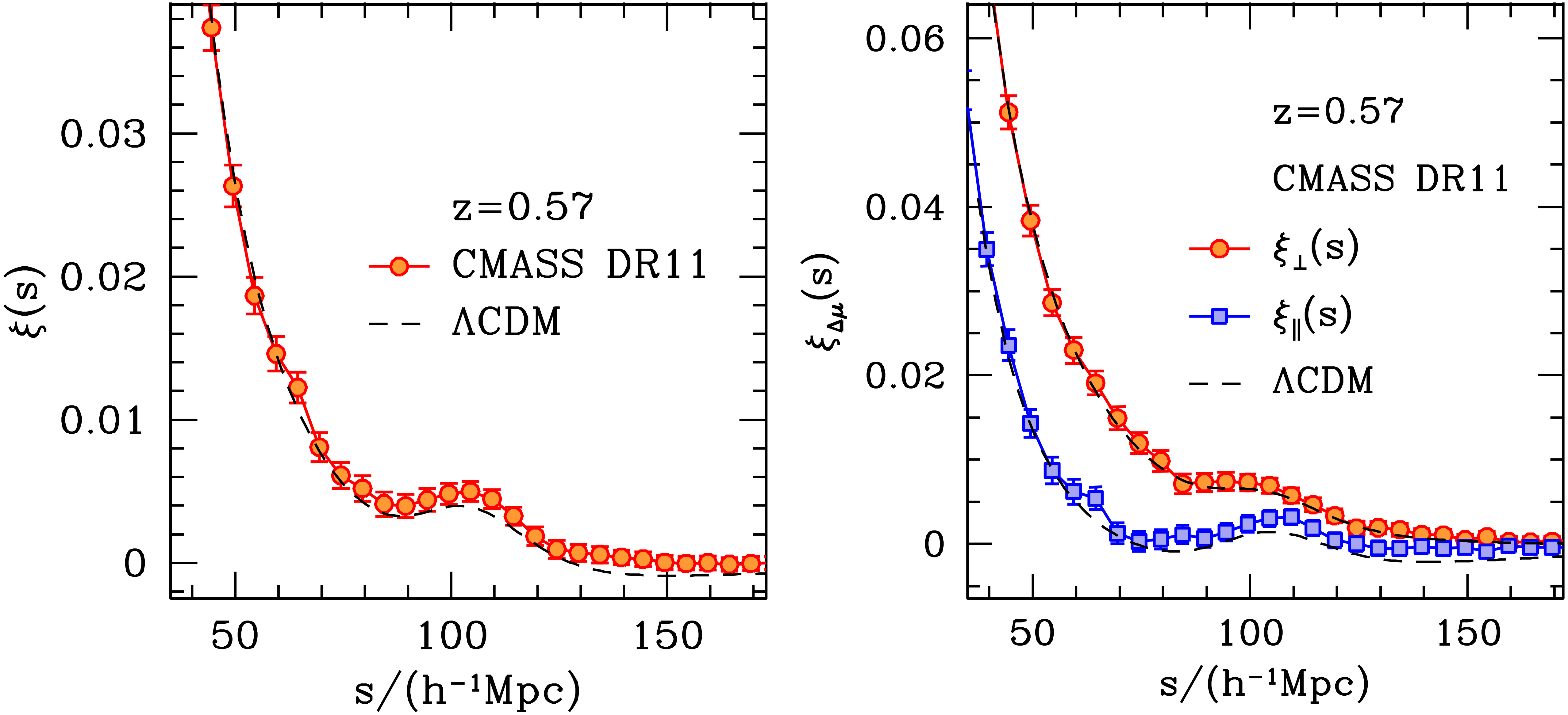
- RSD lead to differences in shape and amplitude.

$$f\sigma_8(z)$$



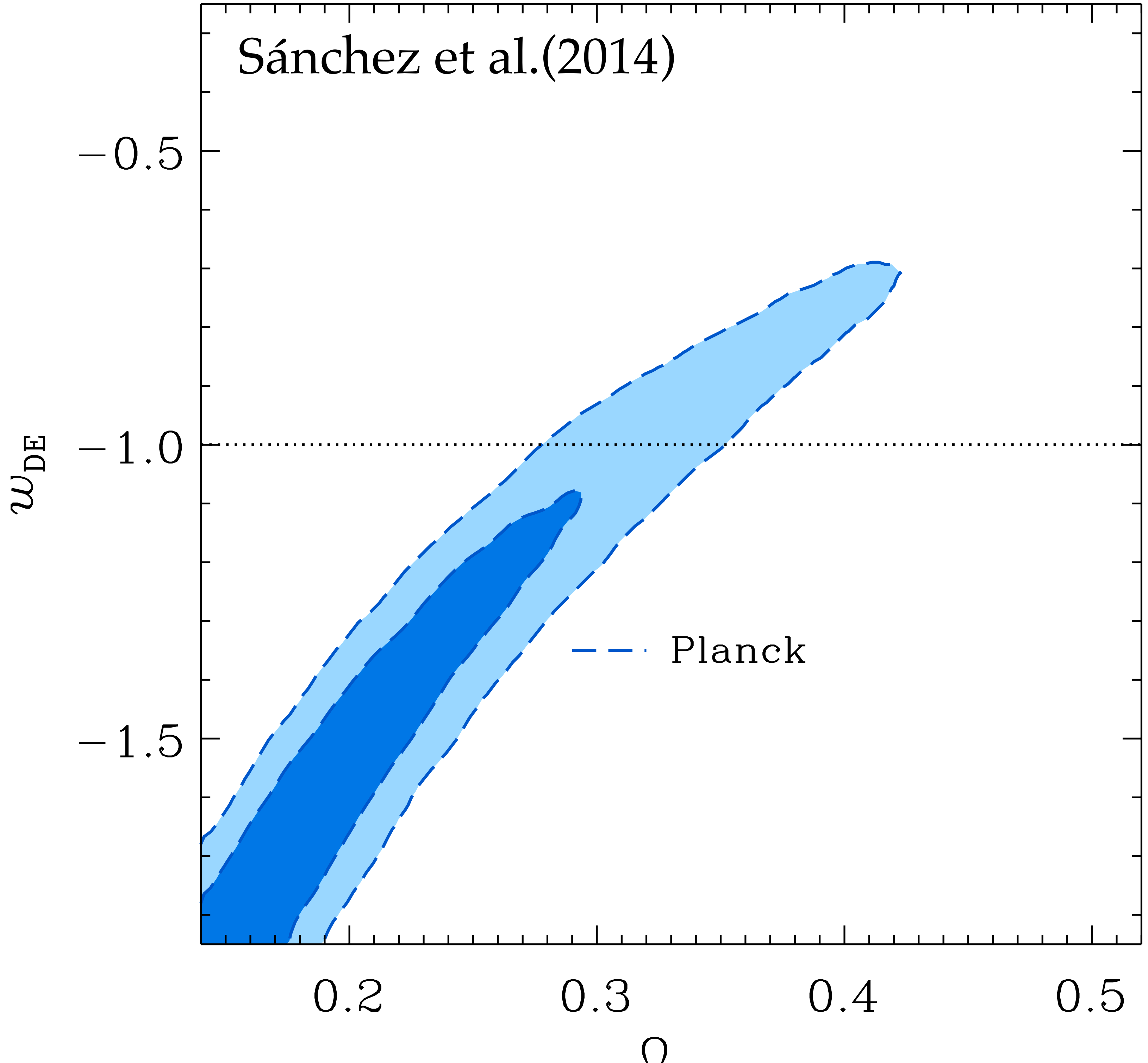
Results from previous data releases

- Constraining power of anis. clustering measurements



Sánchez et al.(2014)

The dark energy equation of state



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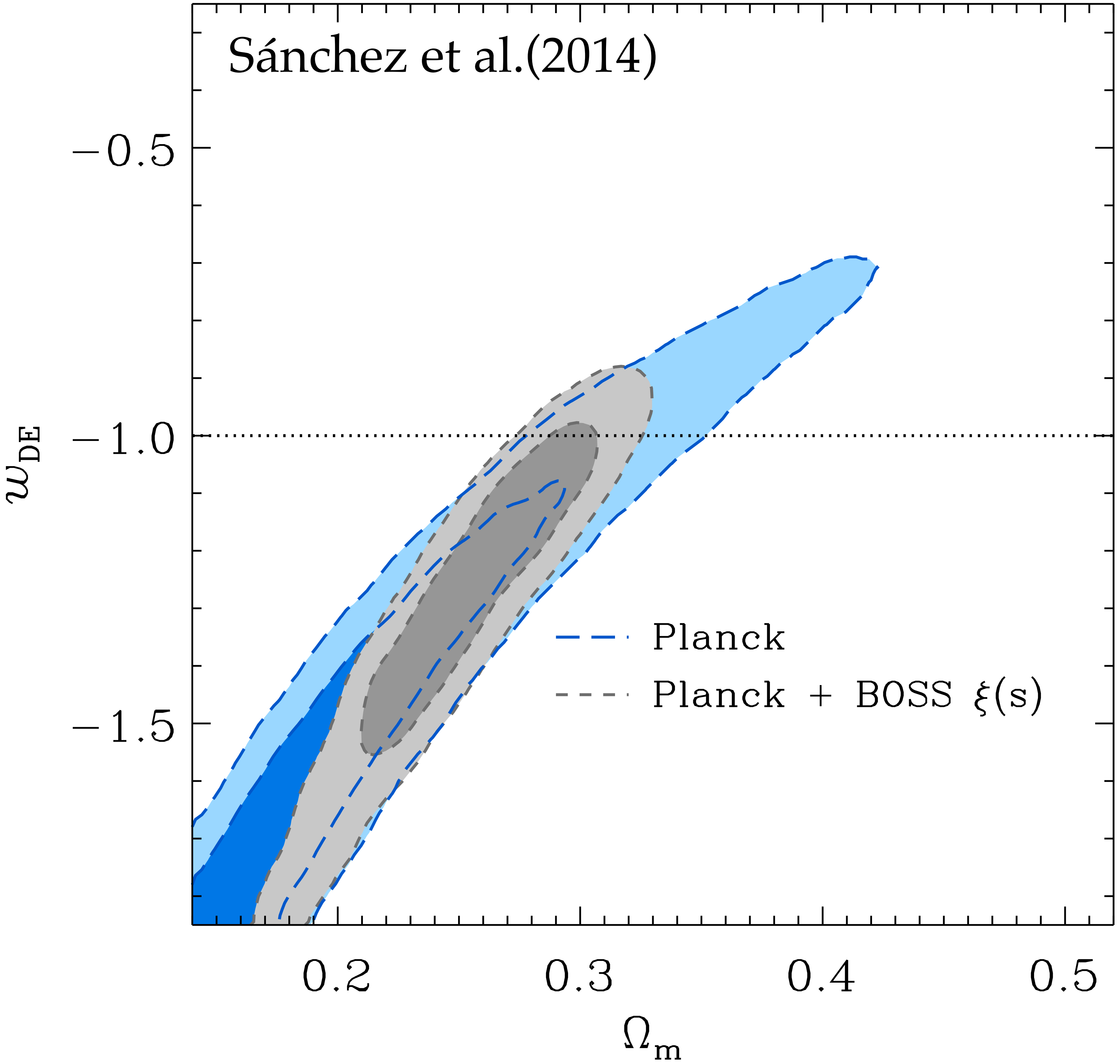
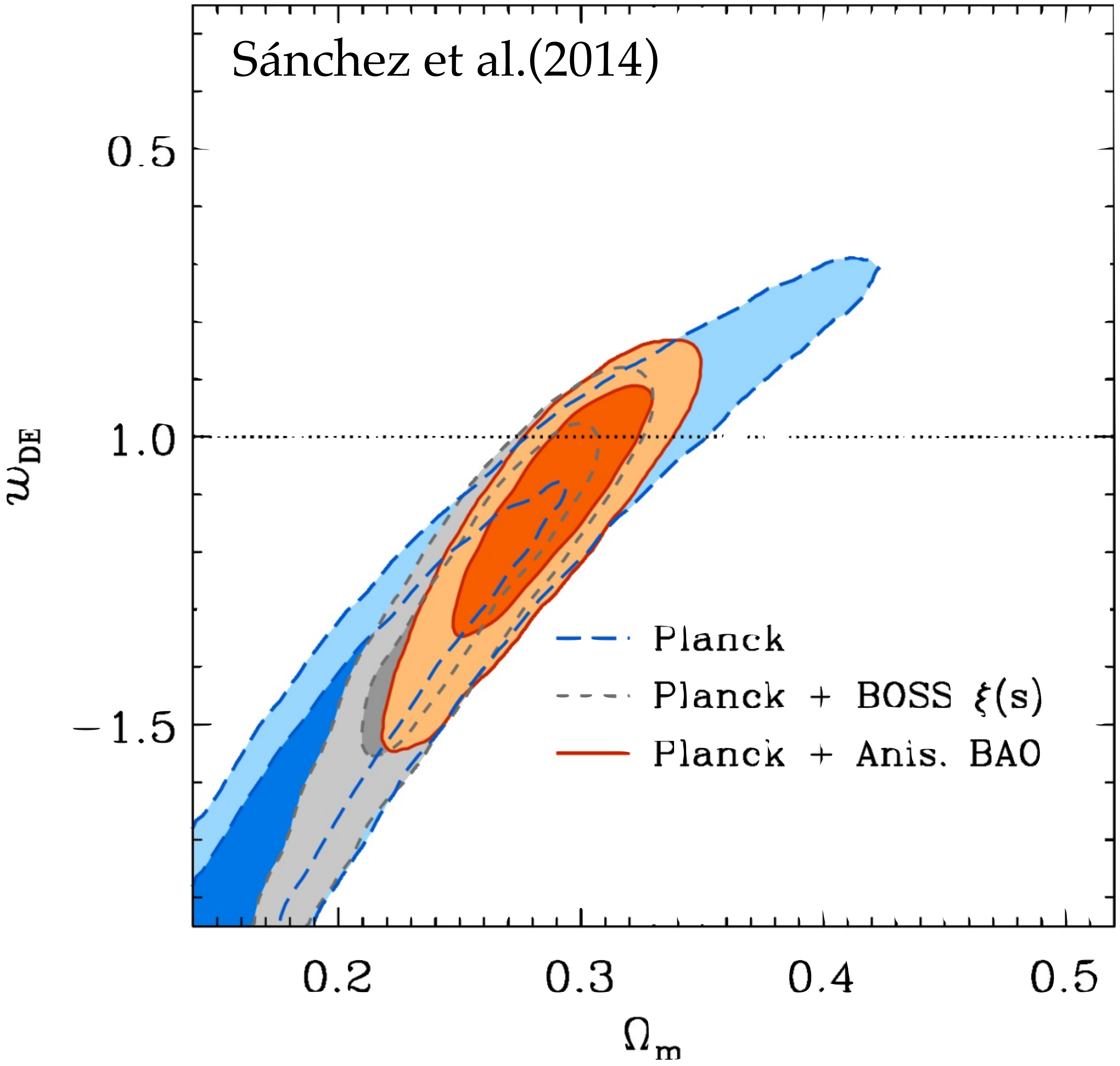


Planck + BOSS $\xi(s)$

$$\Omega_{\mathrm{m}} = 0.249^{+0.034}_{-0.026}$$

$$w_{\mathrm{DE}} = -1.31^{+0.21}_{-0.16}$$

The dark energy equation of state



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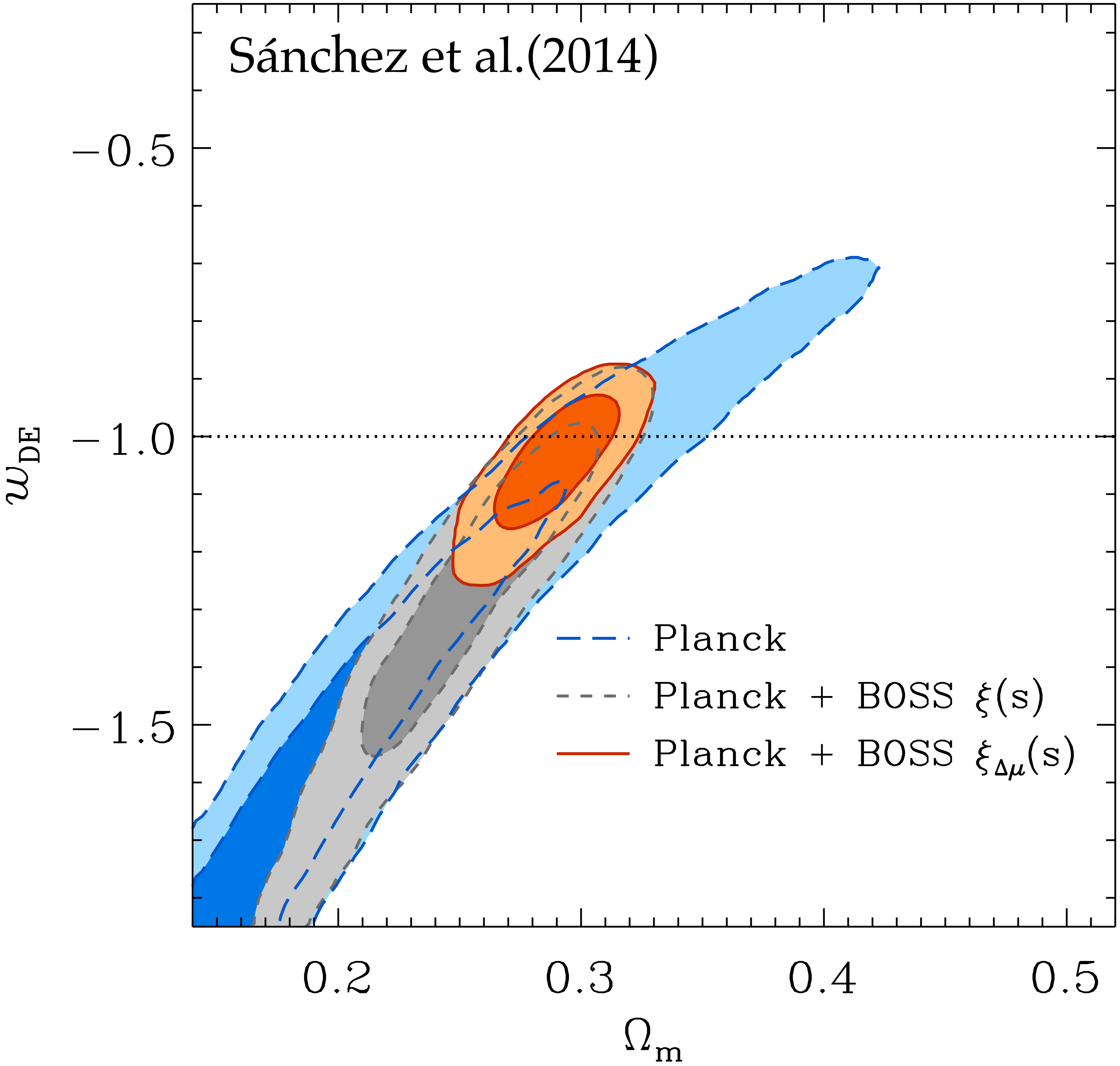

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Planck + BOSS $\xi_{\Delta\mu}(s)$

$$\Omega_{\rm m} = 0.288 \pm 0.016$$

$$w_{\rm DE} = -1.051 \pm 0.076$$

Final BOSS papers

- BAO-only: Beutler et al. (2016a), Ross et al. (2016), Vargas-Magaña et al. (2016)
- Full-shape: Beutler et al. (2016b), Grieb et al. (2016), Sánchez et al. (2016a), Shatpaty et al. (2016)
- Supporting papers: Sánchez et al. (2016), *Tinker et al*. (2016)
- Final alphabetical paper: Alam et al. (2016).
- Tomographic analyses: Salazar-Albornoz et al. (2016), Wang et al. (2016), Zhao et al. (2016).

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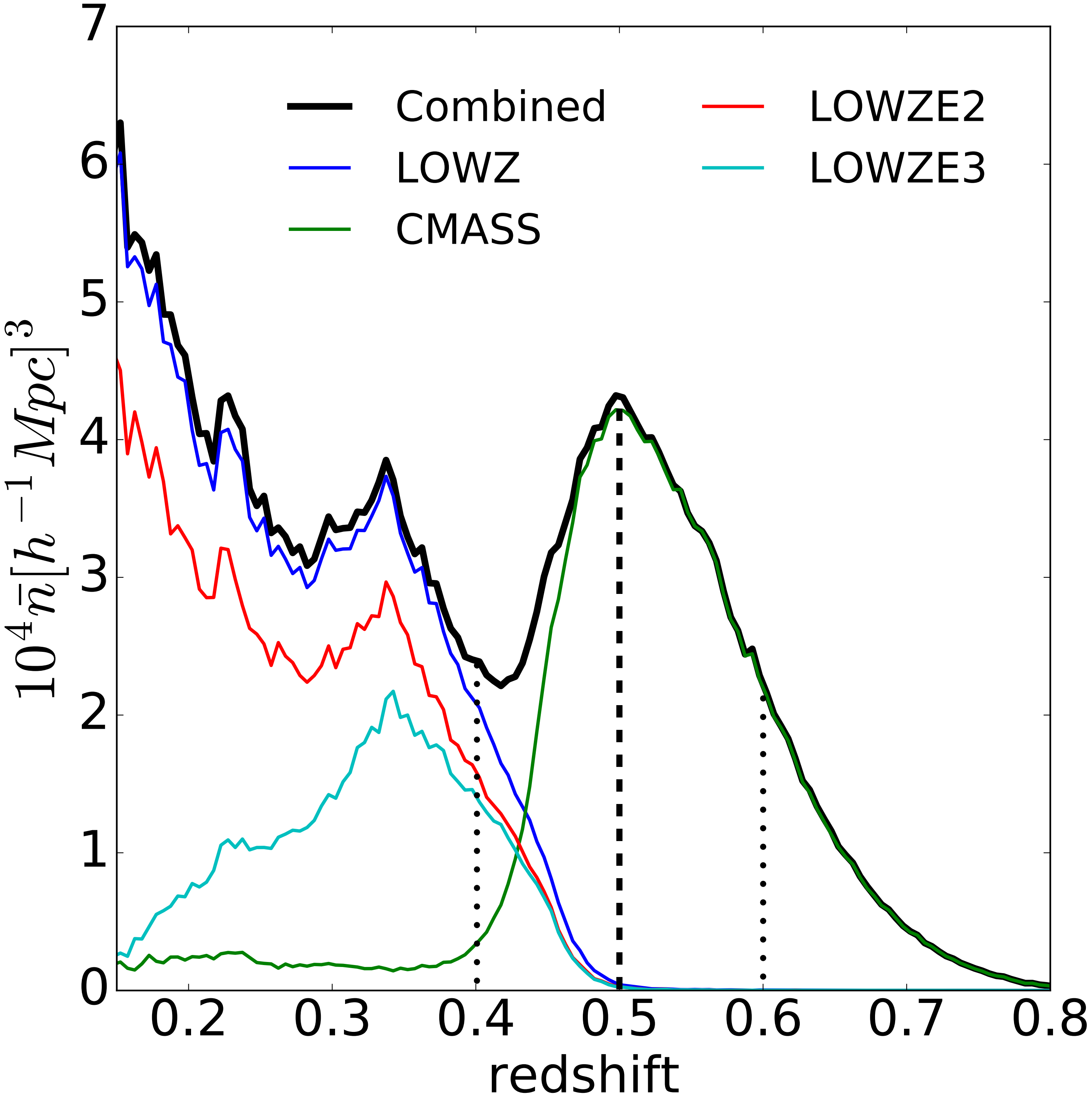
Final BOSS galaxy samples

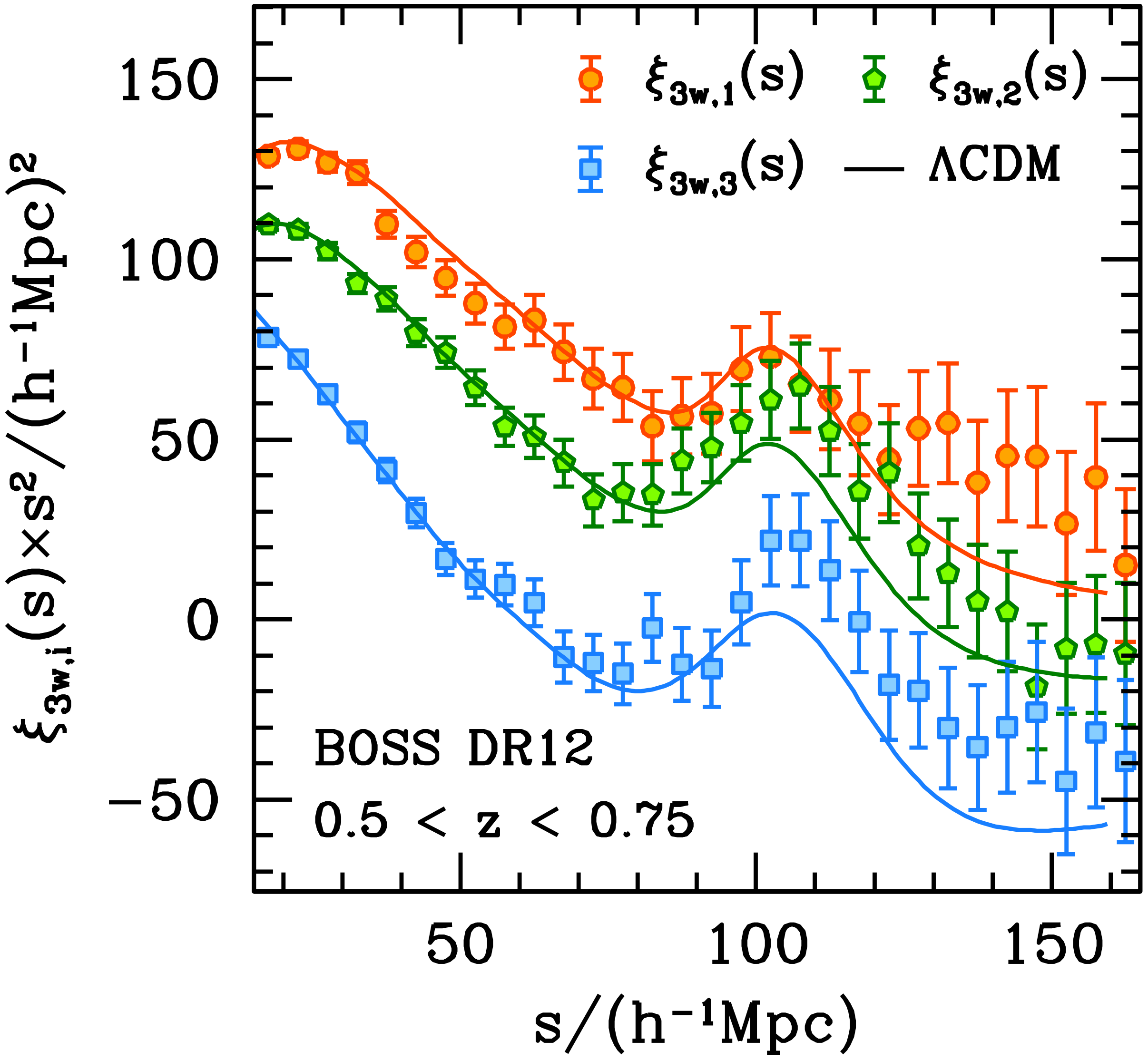
- The *combined sample*: LOWZ, CMASS & *EARLY* regions



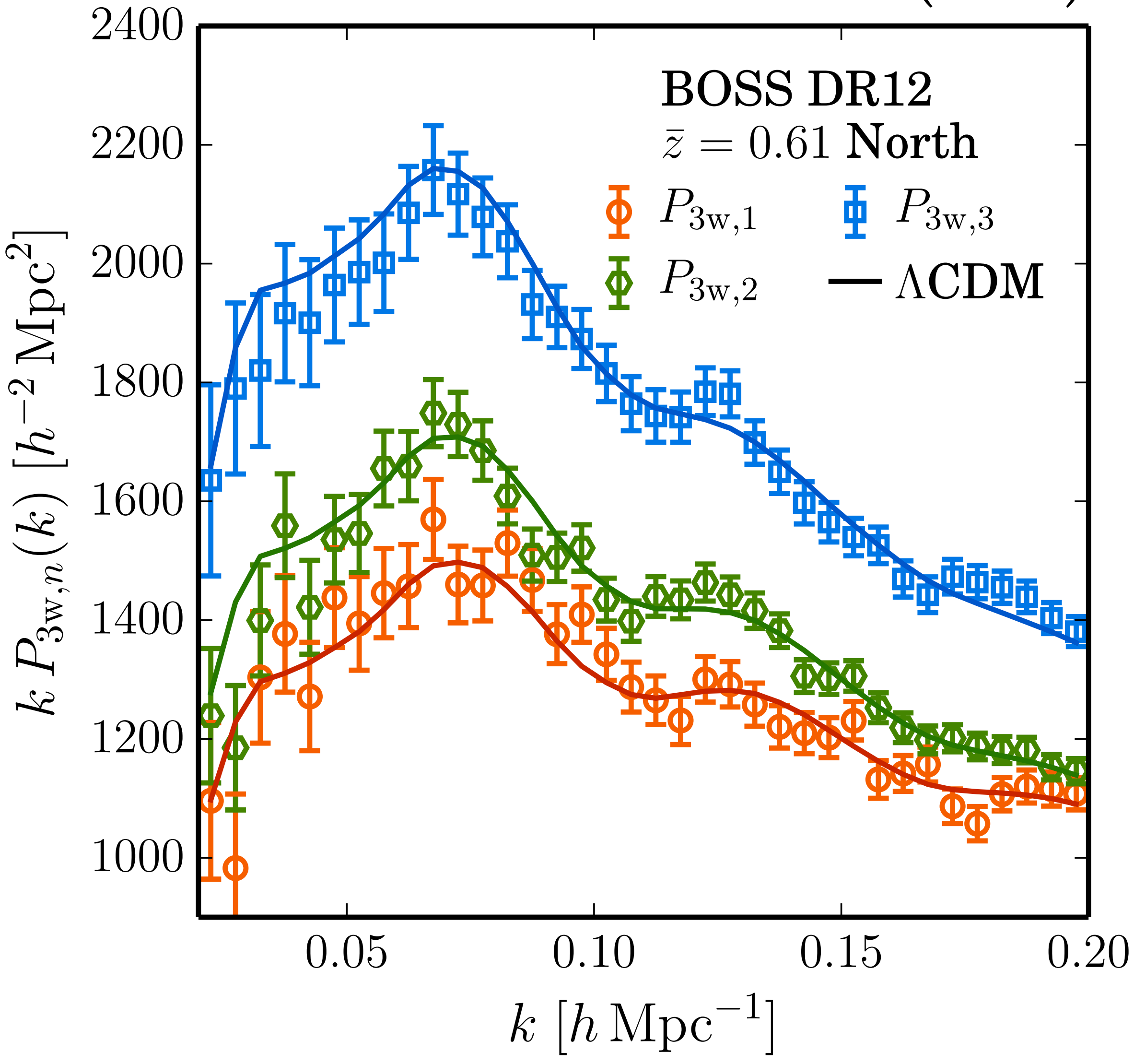
Anisotropic clustering

- BOSS DR12 clustering wedges:

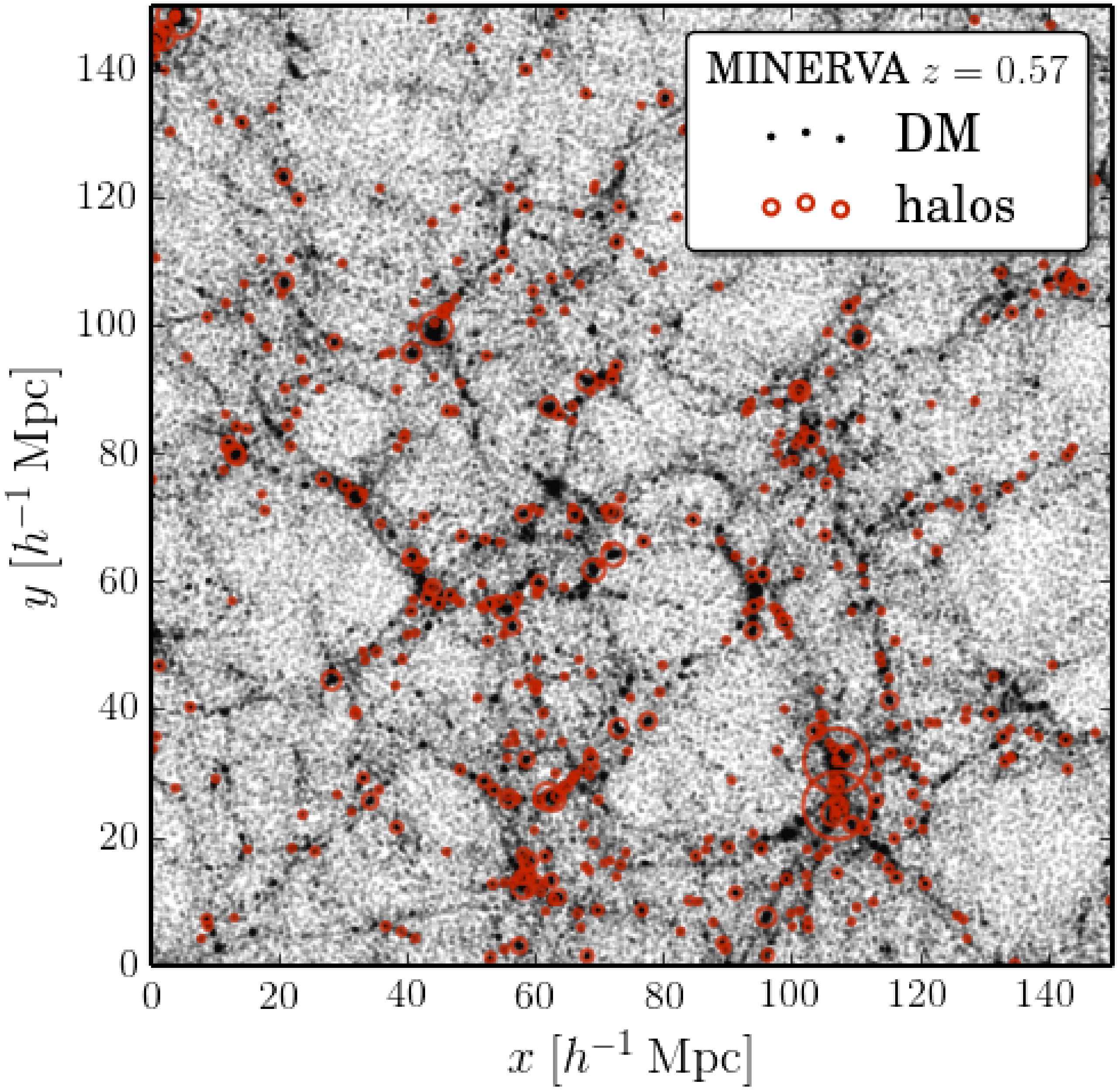
Sánchez et al. (2016a)



Grieb et al. (2016)

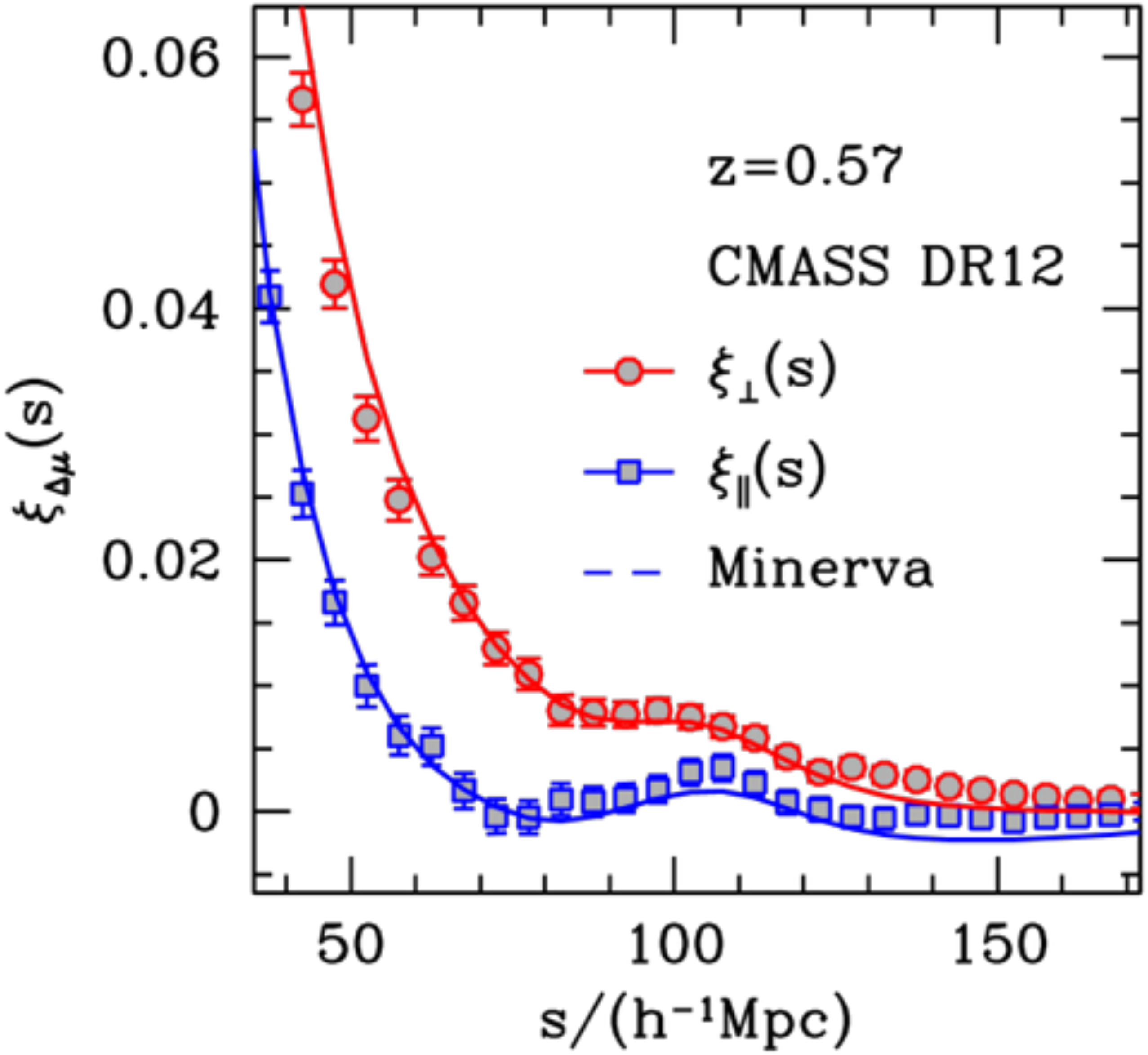


Modelling BAO & RSD



- MINERVA: a set of 100 DM N-body simulations.
- Cosmology from WMAP +BOSS DR9 ($\Omega_{\mathrm{m}} = 0.285$)
- $L_{\mathrm{BOX}} = 1.5$ Gpc/h, $N = 1000^3$
- Snapshots at $z = 0, 0.3, 0.57$, 1 & 2
- Galaxies with HOD matching CMASS $\xi(s)$

Modelling BAO & RSD



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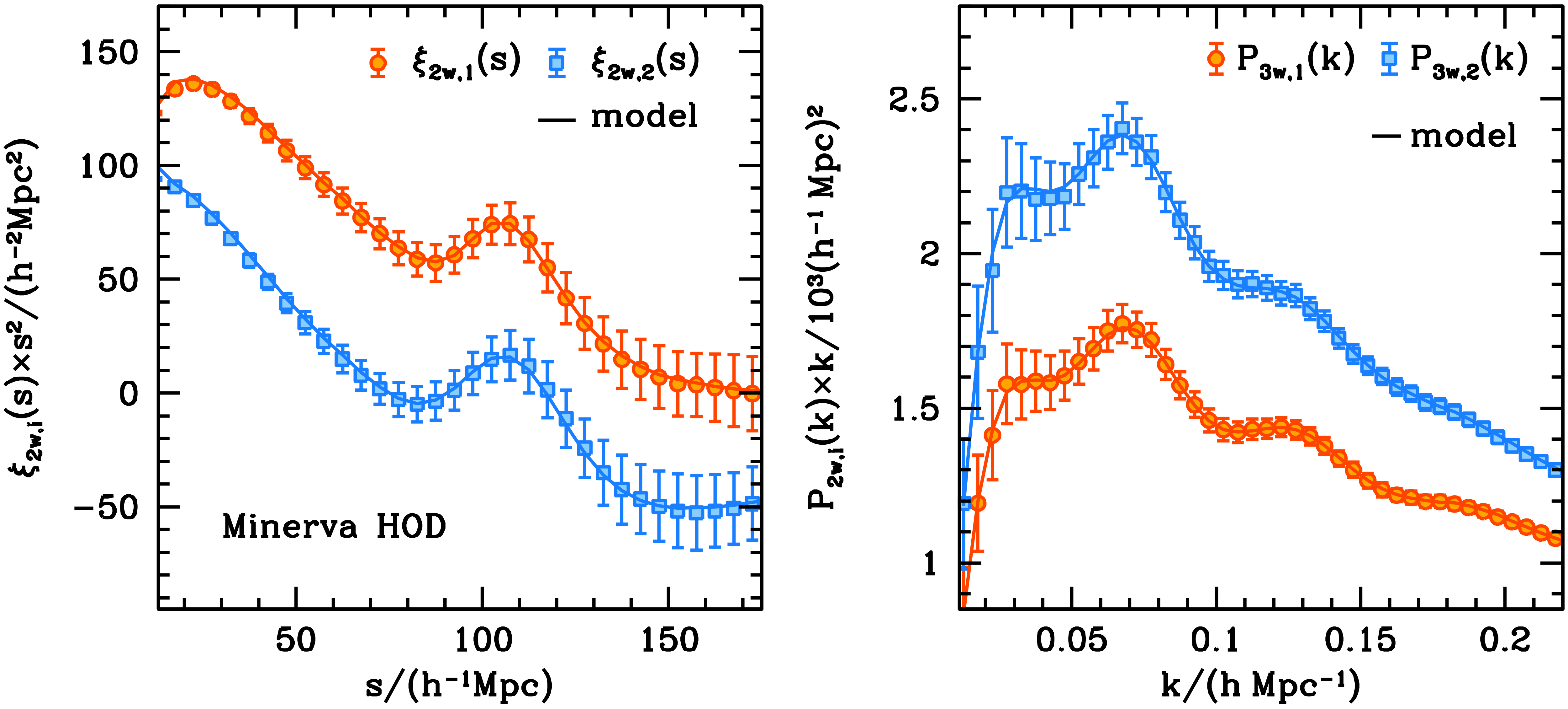
Modelling BAO & RSD

- Excellent agreement with Minerva



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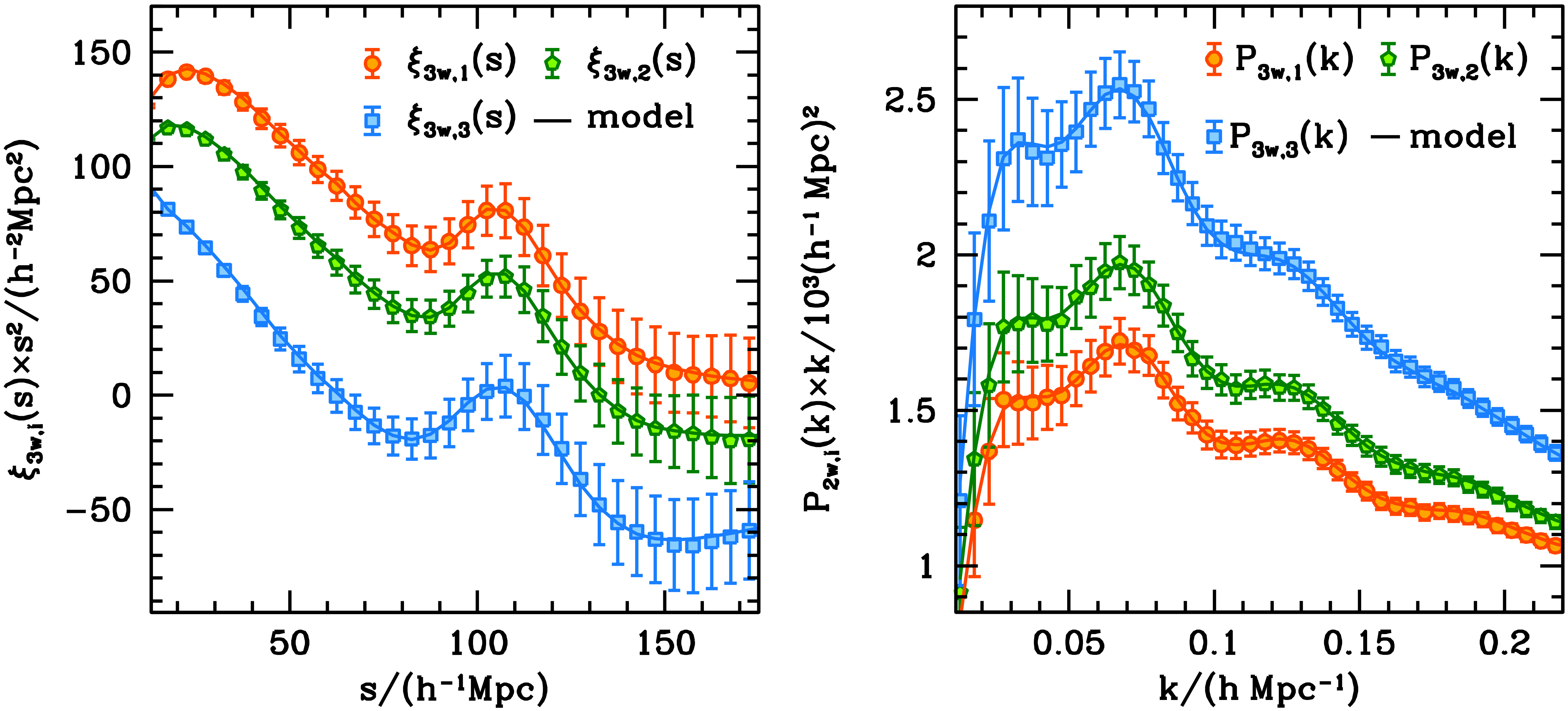
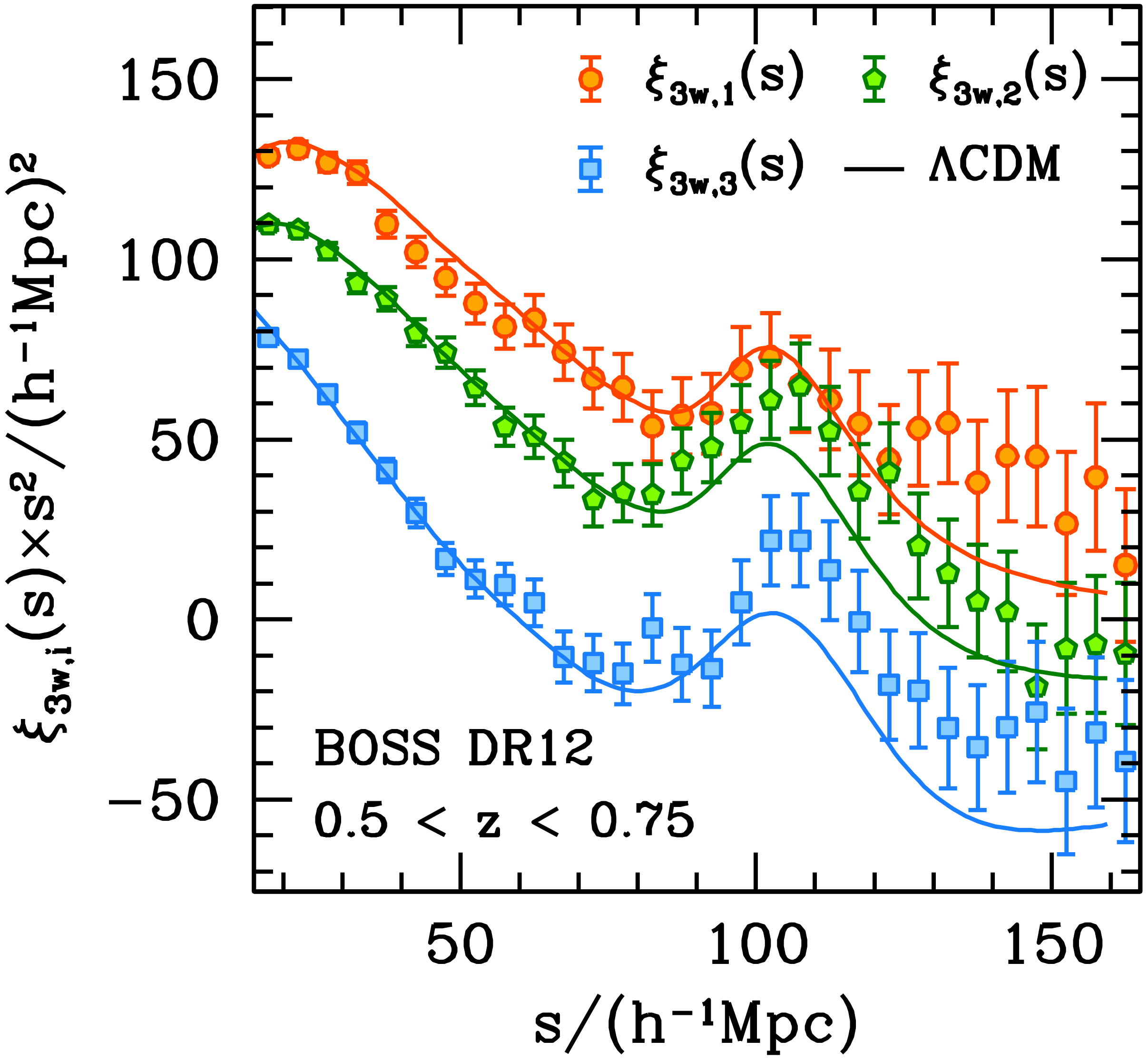


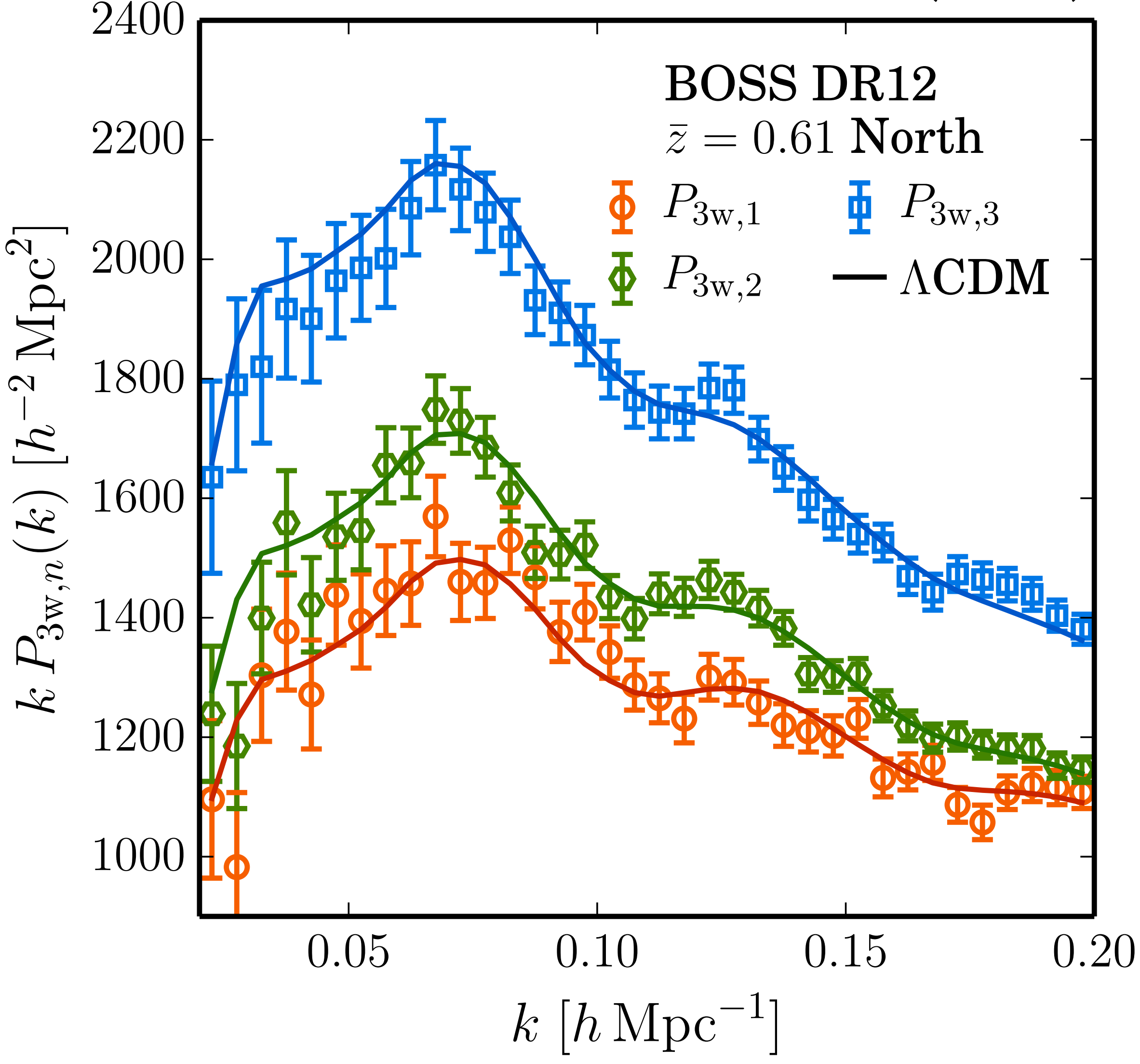
Anisotropic clustering

- BOSS DR12 clustering wedges:

Sánchez et al. (2016a)



Grieb et al. (2016)



Clustering tomography

- Potential problems of 3D clustering measurements:

  - Require a fiducial cosmology to transform z into r.

  - Correspond to the average over a large volume.

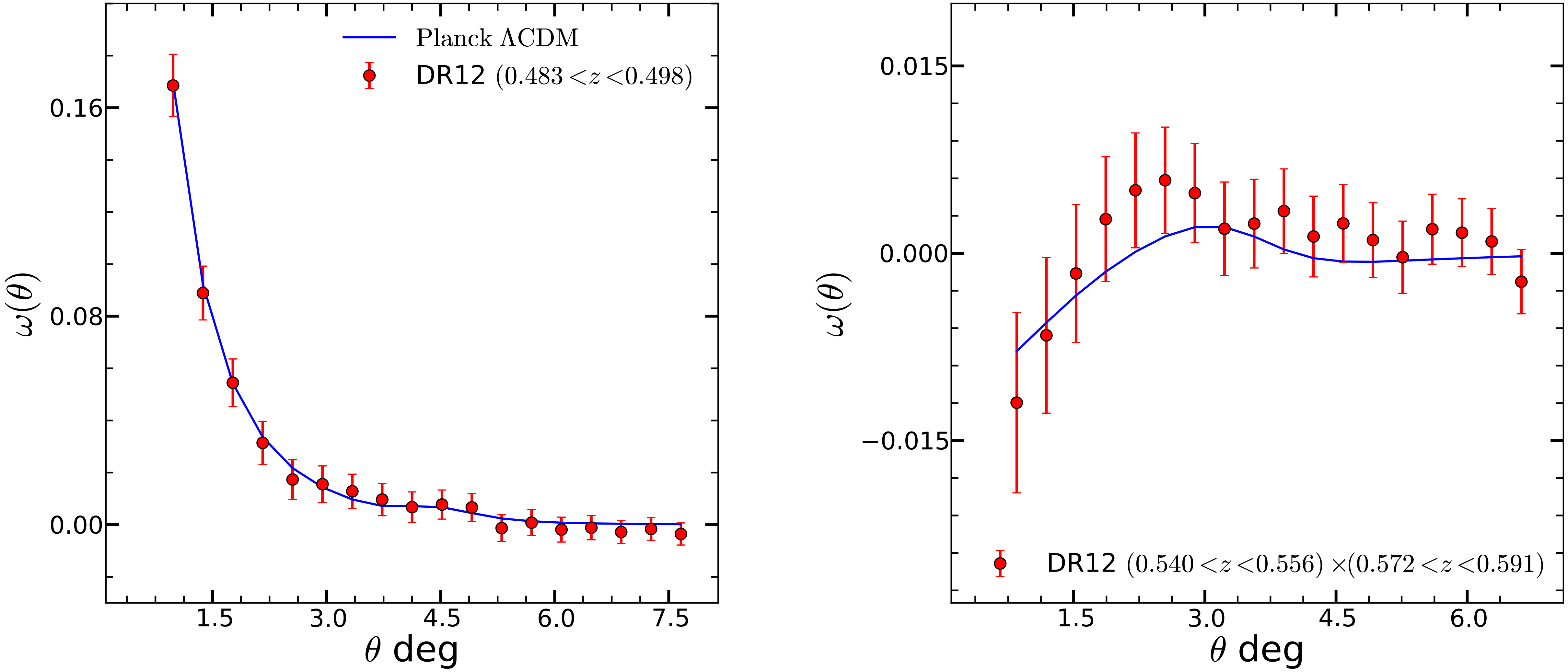
- Alternative: measure $w(\theta)$ in thin redshift shells (Salazar-Albornoz et al. 2014).

  - Relies on observable quantities (no fid. cosmology).

  - Probes the redshift evolution of the galaxy clustering.

Clustering tomography

- Tomographic analysis of BOSS DR12.



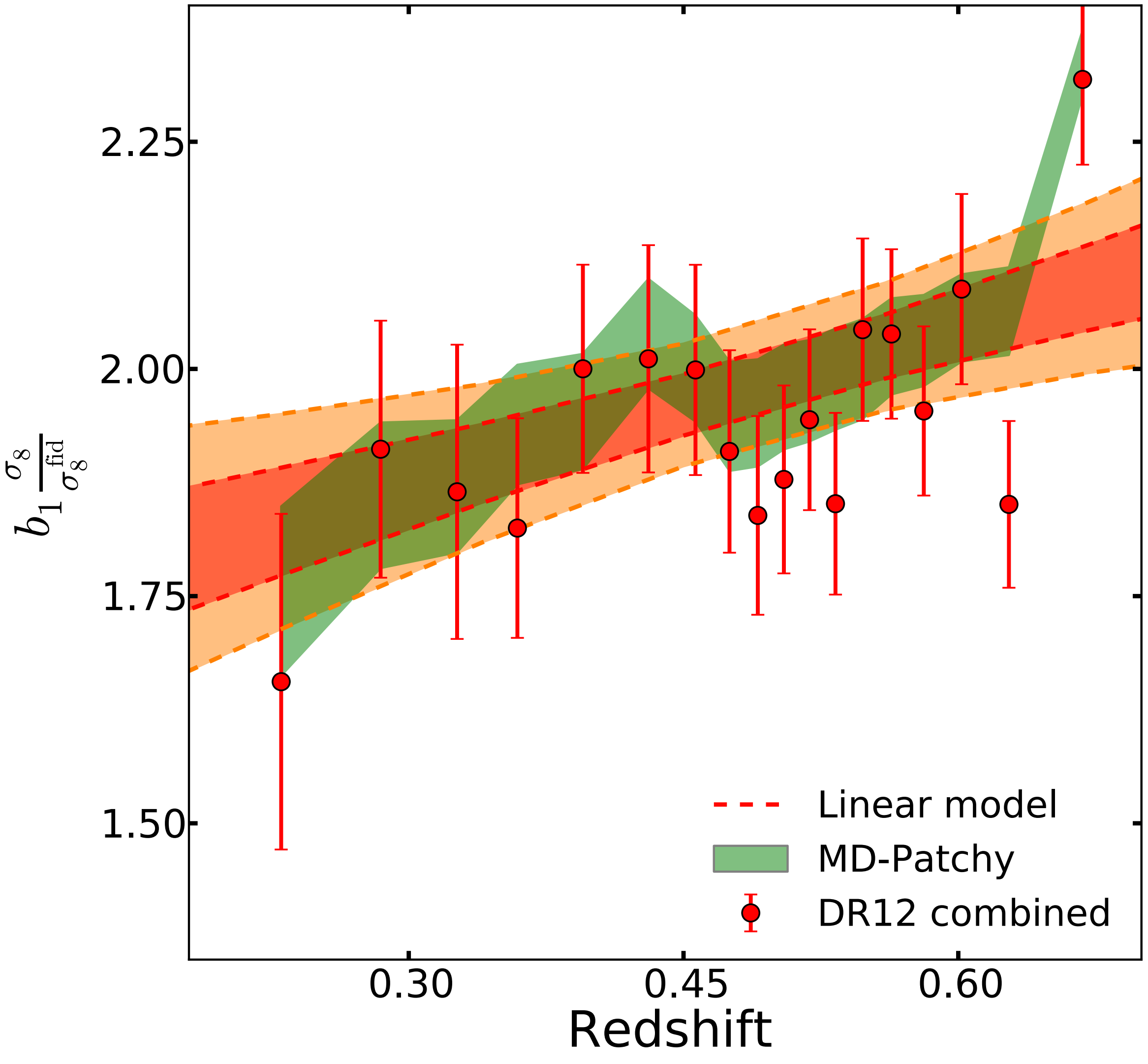
Salazar-Albornoz et al. (2016)

Clustering tomography

- We can explore the redshift evolution of the linear bias.
- Points show individual fits to 18 $w(\theta)$ BOSS measurements.
- The green band shows the result from PATCHY.
- The dashed lines show the constraints on $b(z)$ assuming

$$b(z) = b_1 + b'(z - z_{\mathrm{ref}})$$

Salazar-Albornoz et al. (2016)



The ΛCDM model

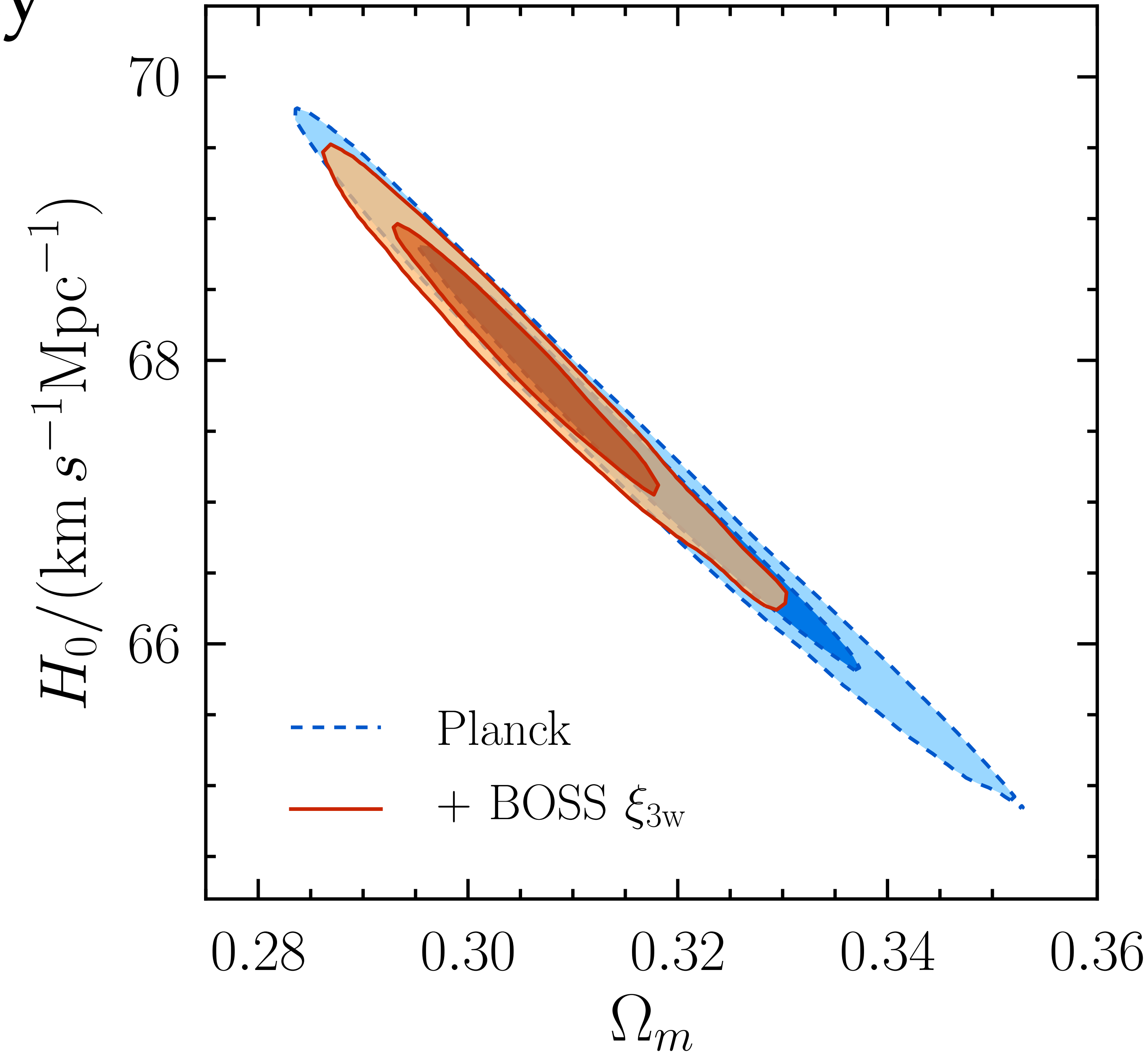
- Basic parameters of ΛCDM measured to high accuracy

$$\Omega_{\rm m} = 0.315 \pm 0.013$$
$$h = 0.6727 \pm 0.0099$$

$$\Omega_{\rm m} = 0.3054 \pm 0.0087$$
$$h = 0.6798 \pm 0.0065$$

- BOSS prefers slightly lower $\Omega_{\rm m}$ than Planck

Sánchez et al. (2016a)



The dark energy equation of state

- Our results are consistent with the ΛCDM model.

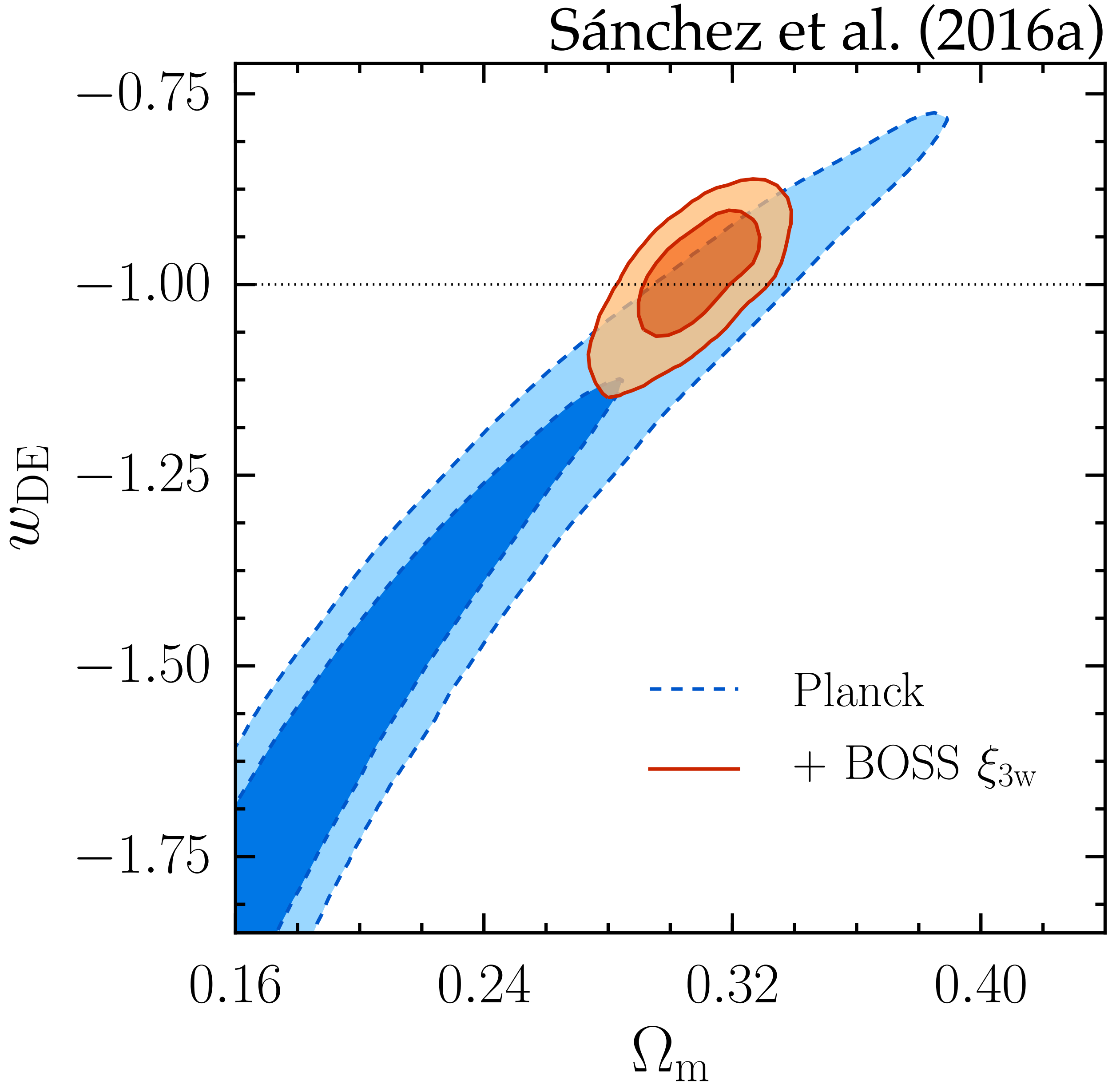
- Assuming a constant $w_{\rm DE}$

$$\boxed{\begin{aligned} w_{\rm DE} &= -0.991 \pm 0.055 \\ \Omega_{\rm m} &= 0.308 \pm 0.013 \end{aligned}}$$

- Our previous analysis

$$\delta w_{\rm DE} = 0.076 \text{ (DR11)}$$

$$\delta w_{\rm DE} = 0.072 \text{ (DR12)}$$



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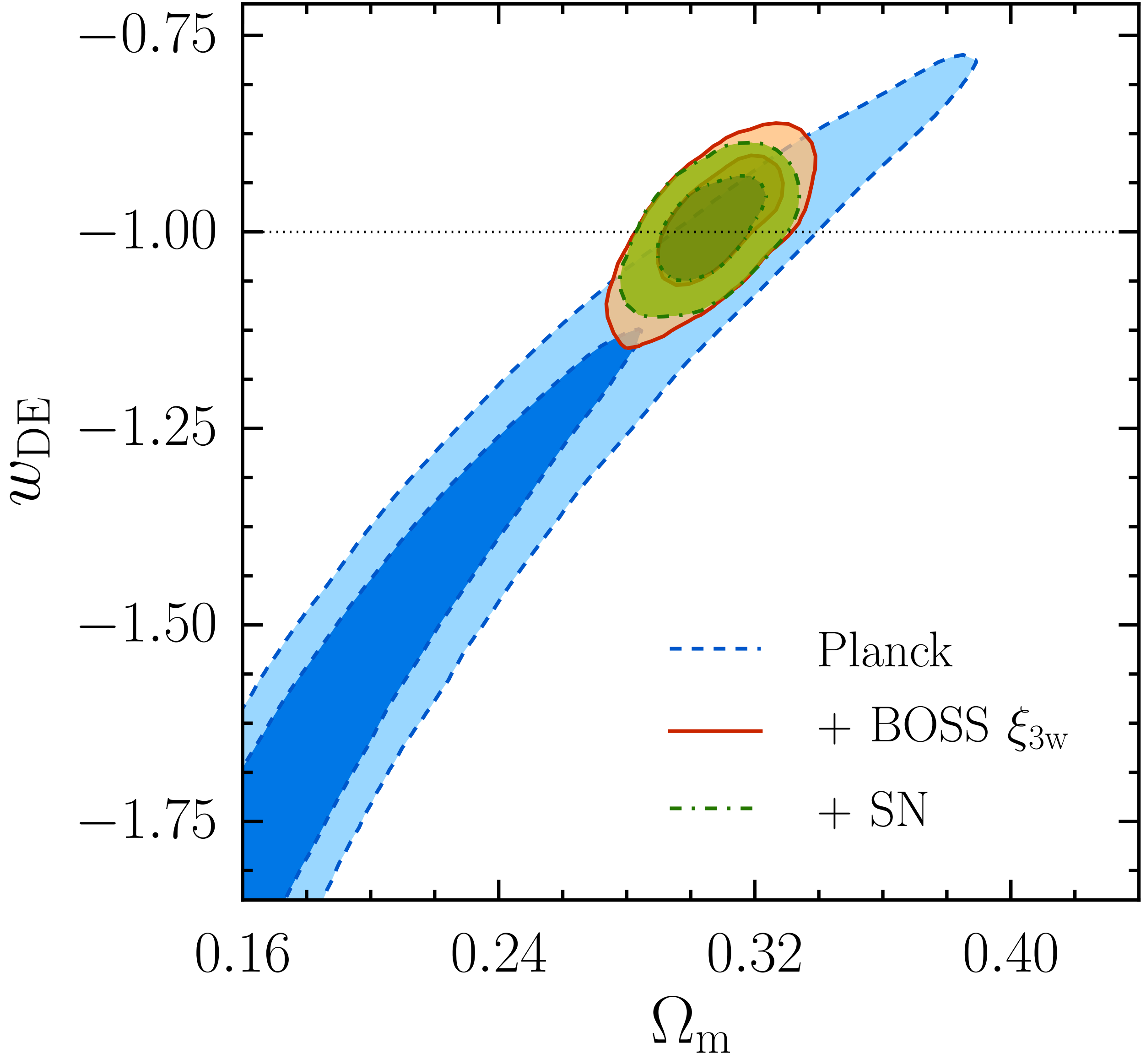
$$\boxed{\begin{aligned} w_{\mathrm{DE}} &= -0.991 \pm 0.055 \\ \Omega_{\mathrm{m}} &= 0.308 \pm 0.013 \end{aligned}}$$

- Adding SN information

$$\boxed{\begin{aligned} w_{\mathrm{DE}} &= -0.996 \pm 0.042 \\ \Omega_{\mathrm{m}} &= 0.306 \pm 0.010 \end{aligned}}$$

Sánchez et al. (2016a)



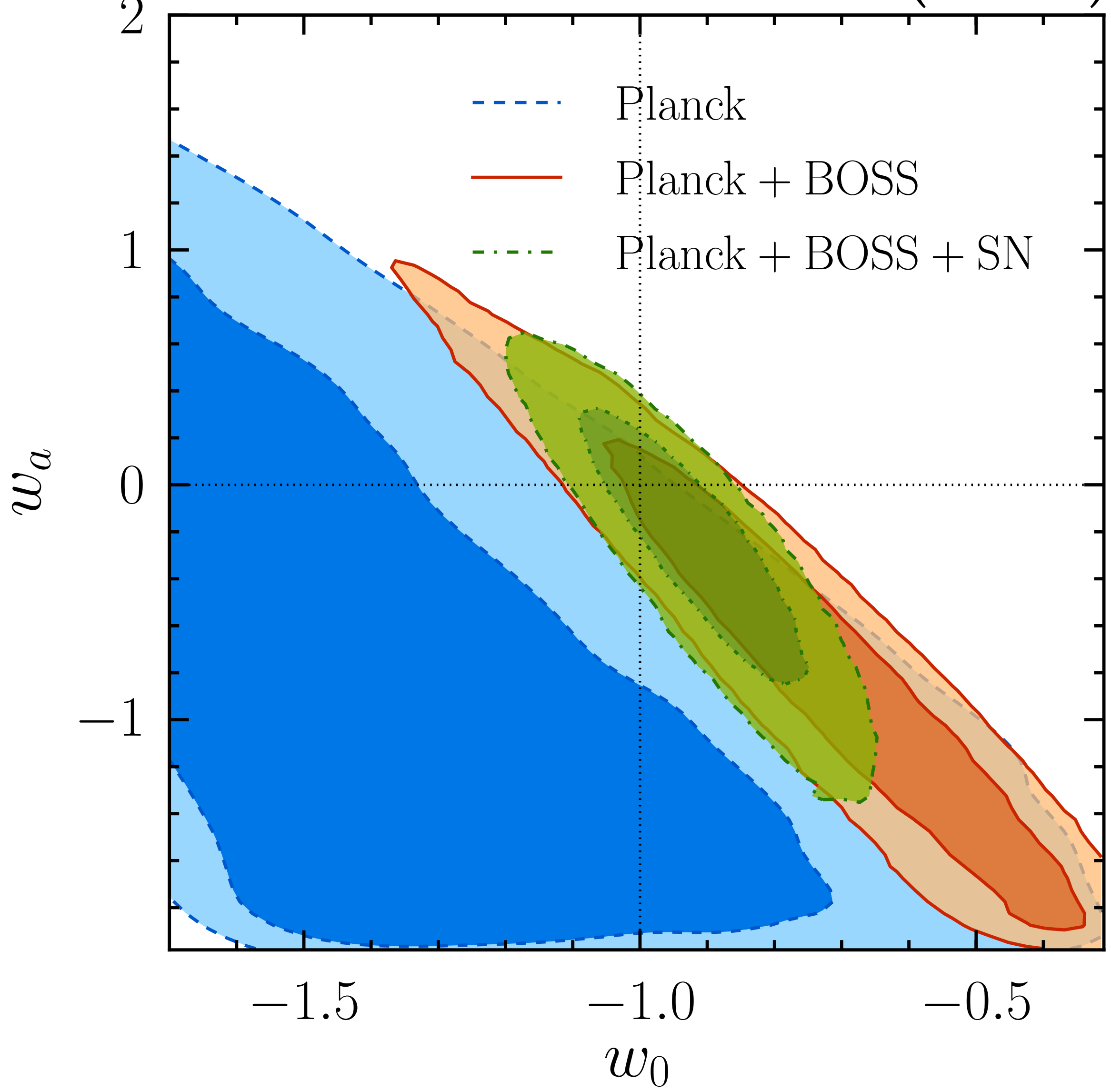
The dark energy equation of state

- Our results are consistent with the ΛCDM model.
- Allowing $w_{\rm DE}$ to evolve as

$$w_{\rm DE}(a) = w_0 + w_a\,(1 - a)$$

$$\boxed{\begin{aligned} w_0 &= -0.92 \pm 0.11 \\ w_a &= -0.32 \pm 0.40 \end{aligned}}$$

Sánchez et al. (2016a)



Testing general relativity

- General relativity predicts

$$f(z) = \Omega_{\mathrm{m}}(z)^{\gamma}$$

with $\gamma \simeq 0.55$

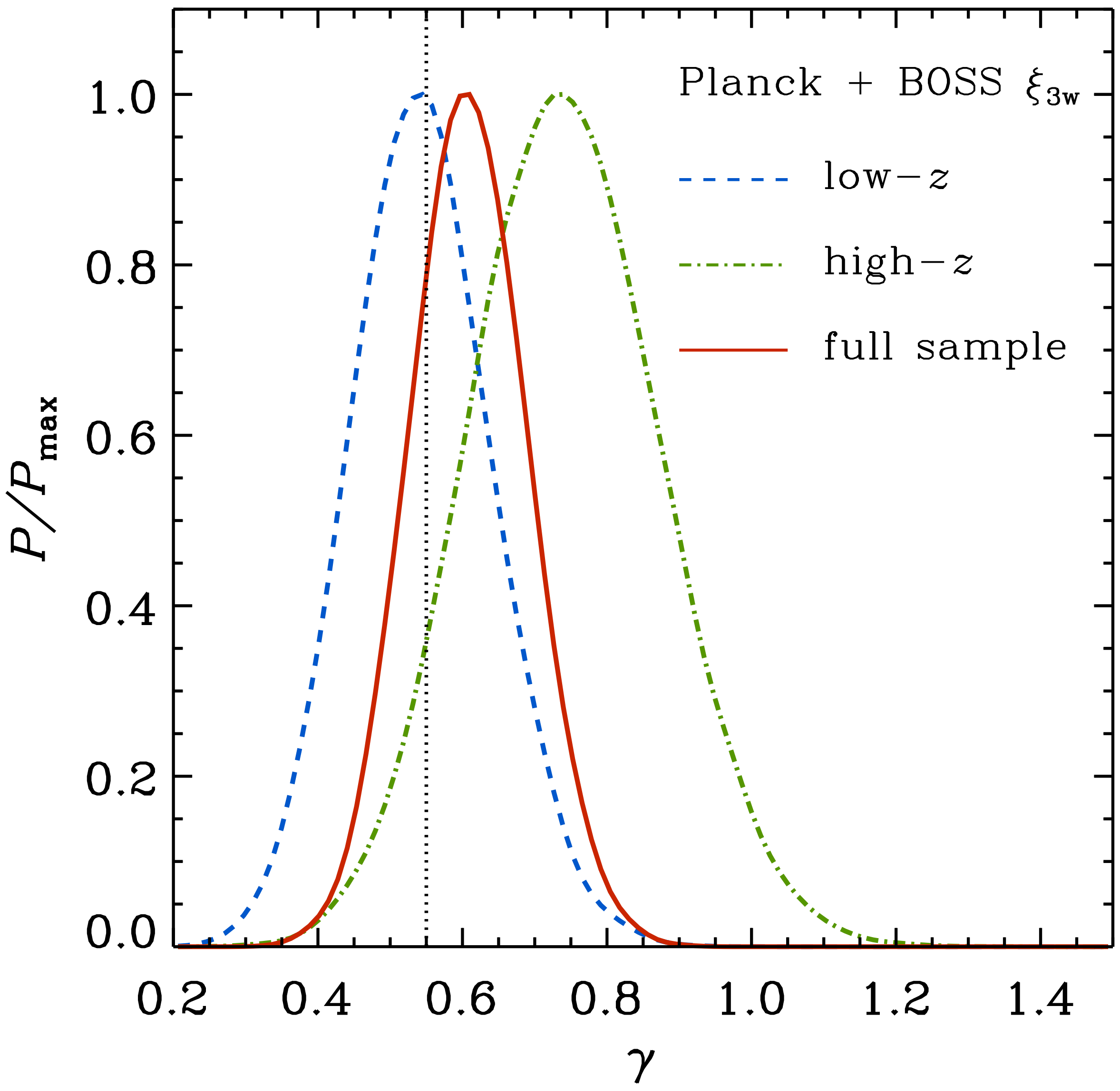
- Deviations from this value could indicate a failure of GR.

- Combining Planck+BOSS

$$\gamma = 0.61 \pm 0.08$$

$$\gamma = 0.69 \pm 0.15 \quad \mathrm{(DR11)}$$

Sánchez et al. (2016a)



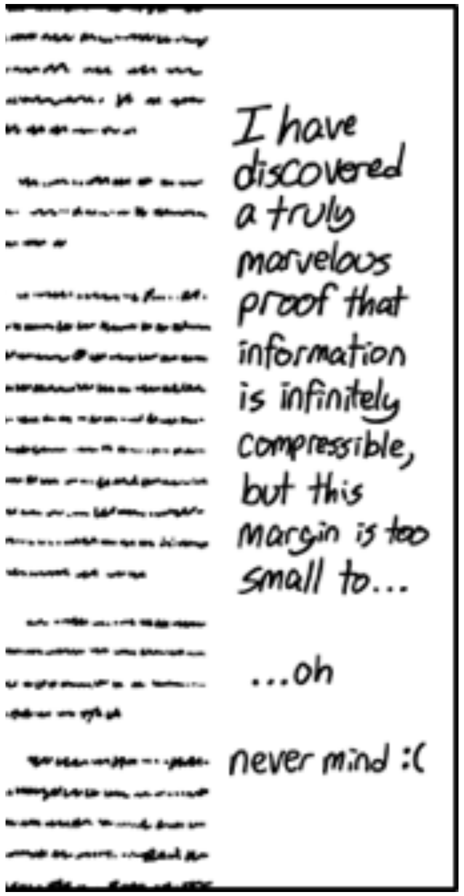
BOSS consensus constraints

- Galaxy surveys require considerable resources from the community.
- Effort to maximise the information extracted from these data sets.
- Question often posed as which statistic or method should be used (e.g. $P(k)$ vs $\xi(s)$).
- Additional information can be obtained from the combination of different results.

BOSS consensus constraints

- Galaxy clustering information can be compressed into a set of parameters $\mathbf{D}$ (e.g. $D_{\rm M}(z)/r_{\rm d}, H(z)r_{\rm d}, f\sigma_8(z)$)
- A set of m measurements $\mathbf{D}_i$, $\mathbf{C}_{ii}$ can be combined into a set of *consensus constraints* $\mathbf{D}_{\rm c}$, $\mathbf{C}_{\rm c}$ (Sánchez et al. 2016b)

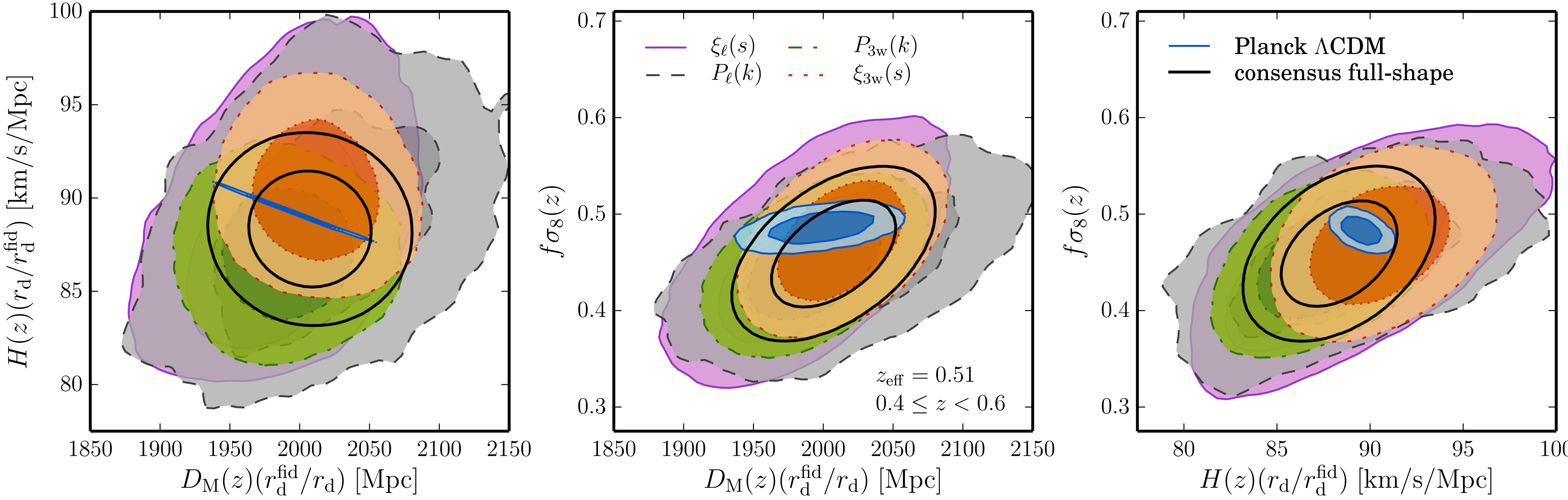
$$\left.\begin{array}{l} \mathbf{D}_{\rm tot} = (\mathbf{D}_1, \cdots, \mathbf{D}_m) \\[2em] \mathbf{C}_{\rm tot} = \begin{pmatrix} \mathbf{C}_{11} & \cdots & \mathbf{C}_{1m} \\ \vdots & \ddots & \vdots \\ \mathbf{C}_{m1} & \cdots & \mathbf{C}_{mm} \end{pmatrix} \end{array}\right\} \mathbf{D}_{\rm c},\ \mathbf{C}_{\rm c}$$



http://xkcd.com/

BOSS consensus constraints

- Application to BOSS DR12 results:



Alam et al. (2016)

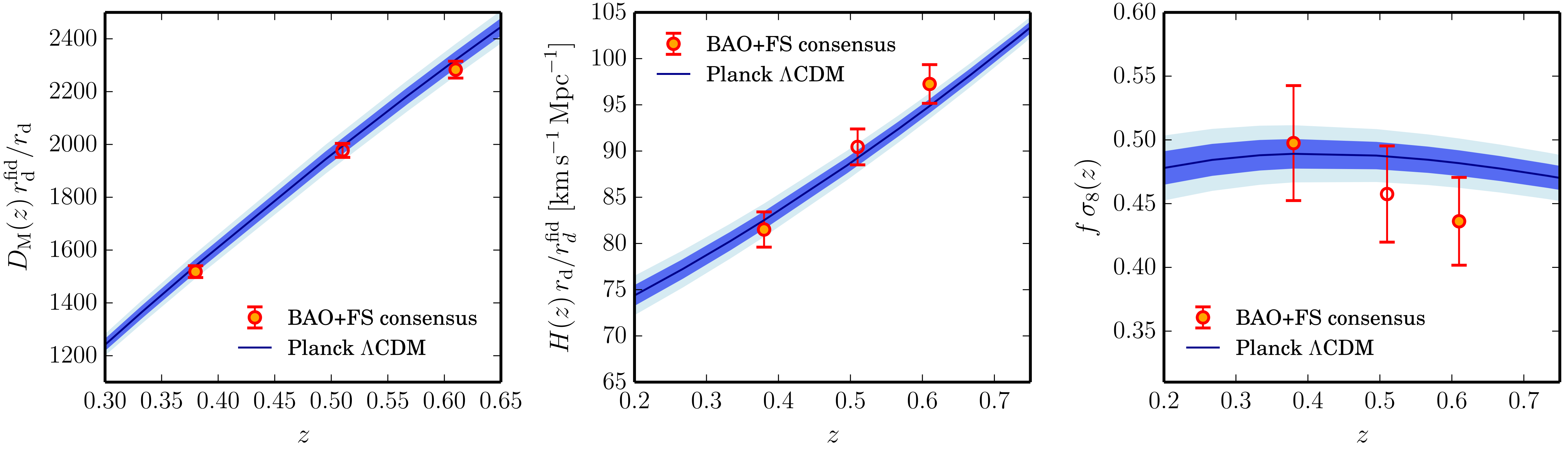
- Consensus constraints are ~10 to 20% tighter than the most accurate measurement from the original set.

- Good agreement with the Planck ΛCDM prediction.

BOSS consensus constraints

- All analyses are combined into our final consensus constraints on $D_{\rm M}(z)$, $H(z)$ and $f\sigma_8(z)$

https://www.sdss3.org/science/boss_publications.php

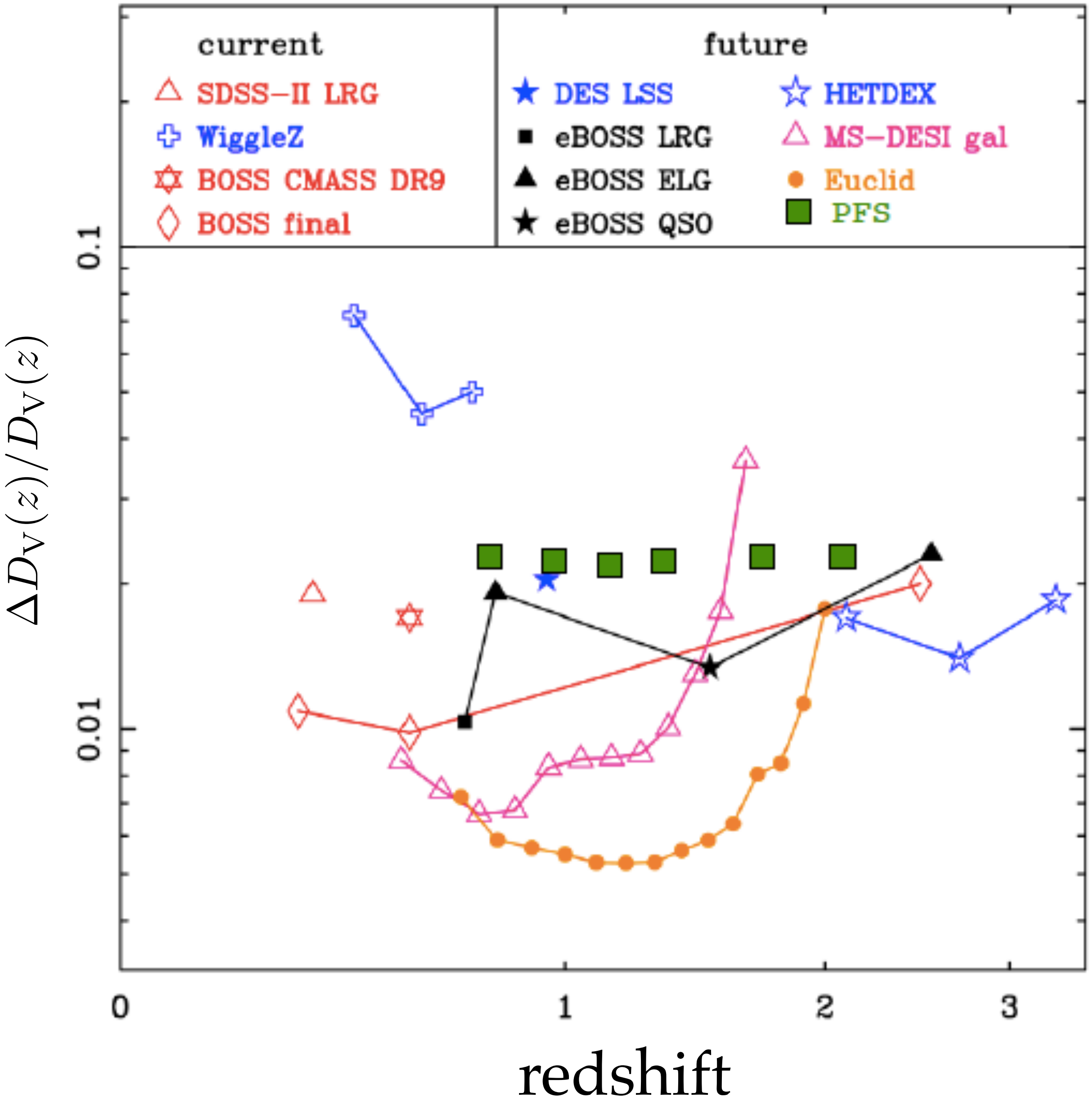


- Cosmological implications explored in Alam et al. (2016)

Future galaxy surveys

- A new generation of large volume galaxy surveys:
  - BOSS: LG at $0.2 < z < 0.7$ & QSO $2.3 < z < 2.8$
  - **eBOSS**: LRGs, ELGs, QSO at $0.7 < z < 2.8$
  - **PFS**: ELGs, $0.6 < z < 2.2$
  - **HETDEX**: Ly-α emitters, $1.9 < z < 3.5$
  - **Euclid:** H-α emitters, $0.6 < z < 2$

Figure: Will Percival



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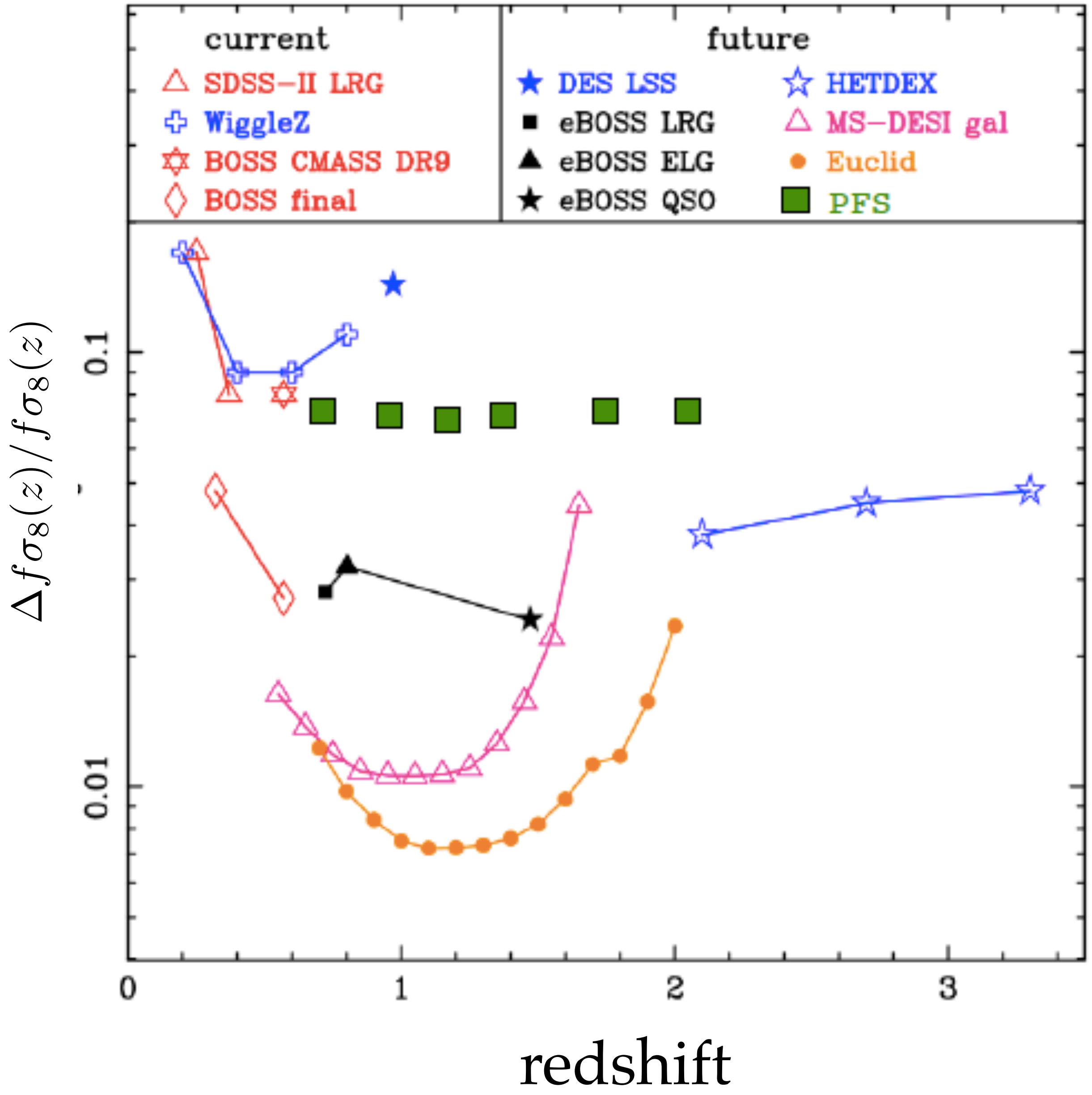

Final remarks

- Analysis of the final BOSS galaxy sample completed.
- Several analysis methods based on the same underlying model.
- Improved methodology leads to an increase in the constraining power of the sample.
- BOSS has shown that BAO & RSD can be used as robust and accurate cosmological probes.
- A quality jump in our use of LSS to constrain deviations from ΛCDM, which will be extended to future surveys.