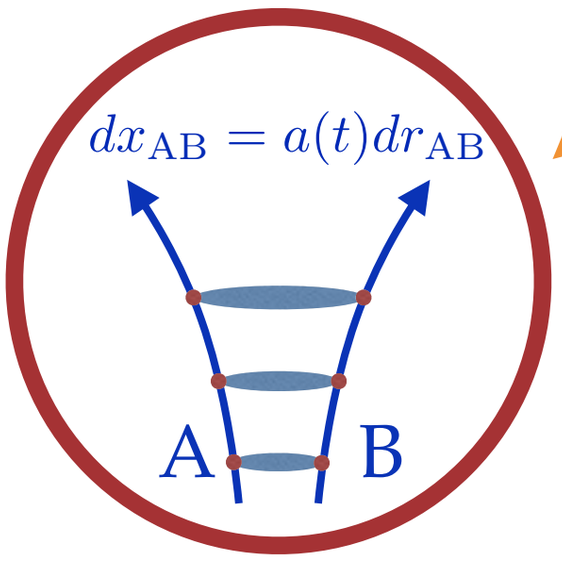
The information content of LSS measurements

Ariel G. Sánchez

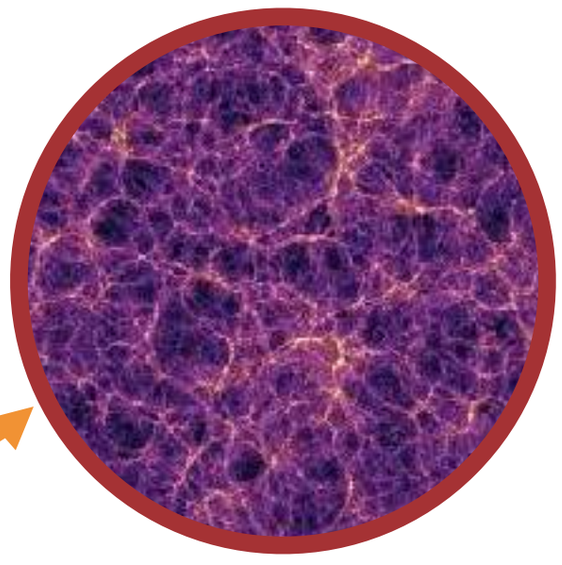
Mock Córdoba, Córdoba, 08.04.2019

Observational cosmology

- Multiple data have cemented a standard model: **ΛCDM**.
- CMB data can accurately constrain its basic parameters.
- **Galaxy clustering**: a powerful route to **stress-test ΛCDM**.
- CMB-based predictions of:



The Universe's
expansion
and
structure growth
histories.



Both can be probed by **galaxy clustering** measurements!

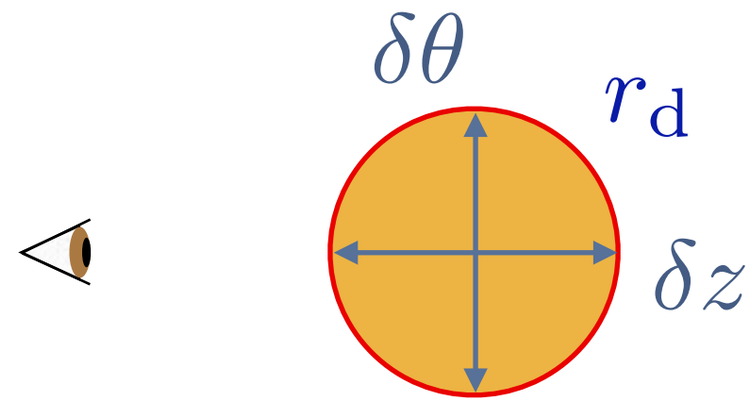
Cosmology from LSS observations

- The combined power of baryon acoustic oscillations (BAO) and redshift-space distortions (RSD)

BAO: A robust standard ruler.

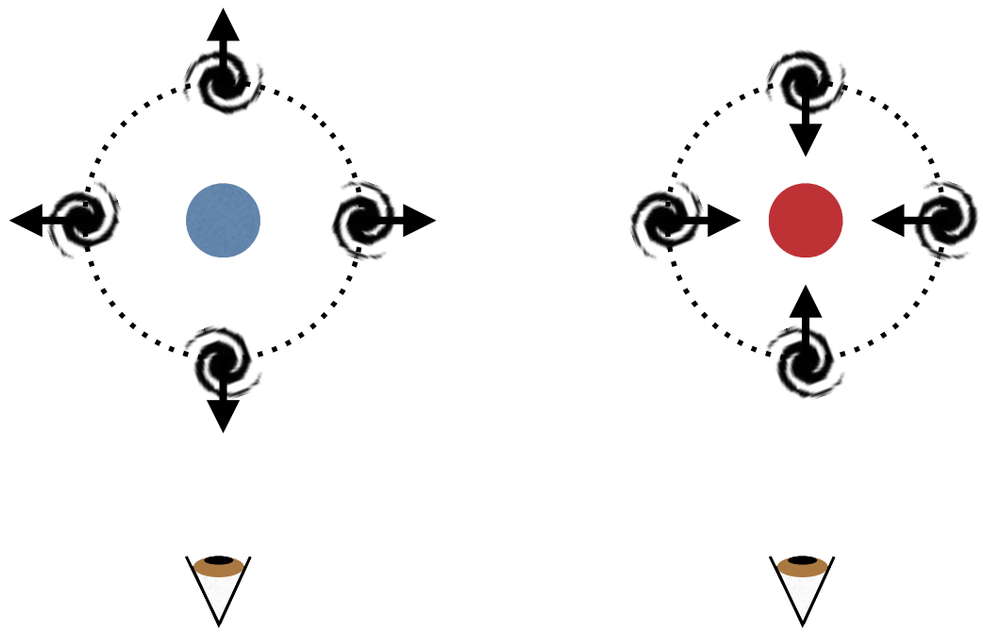
$$D_{\rm M}(z) = r_{\rm d}/\delta\theta$$

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



RSD: measure the growth-rate of cosmic structure.

$$f(z) = \frac{{\rm d}\ln D}{{\rm d}\ln a} \qquad f\sigma_8(z)$$



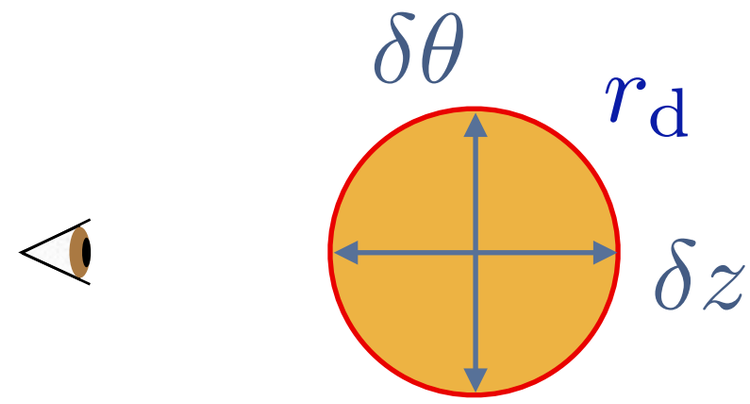
Cosmology from LSS observations

- The combined power of baryon acoustic oscillations (BAO) and redshift-space distortions (RSD)

BAO: A robust standard ruler.

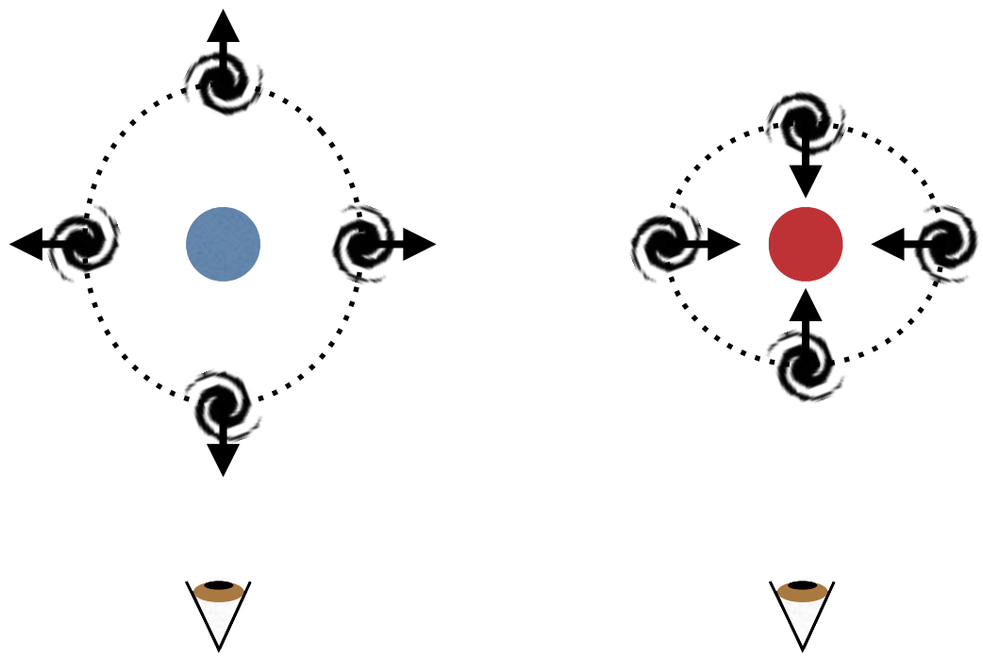
$$D_{\rm M}(z) = r_{\rm d}/\delta\theta$$

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



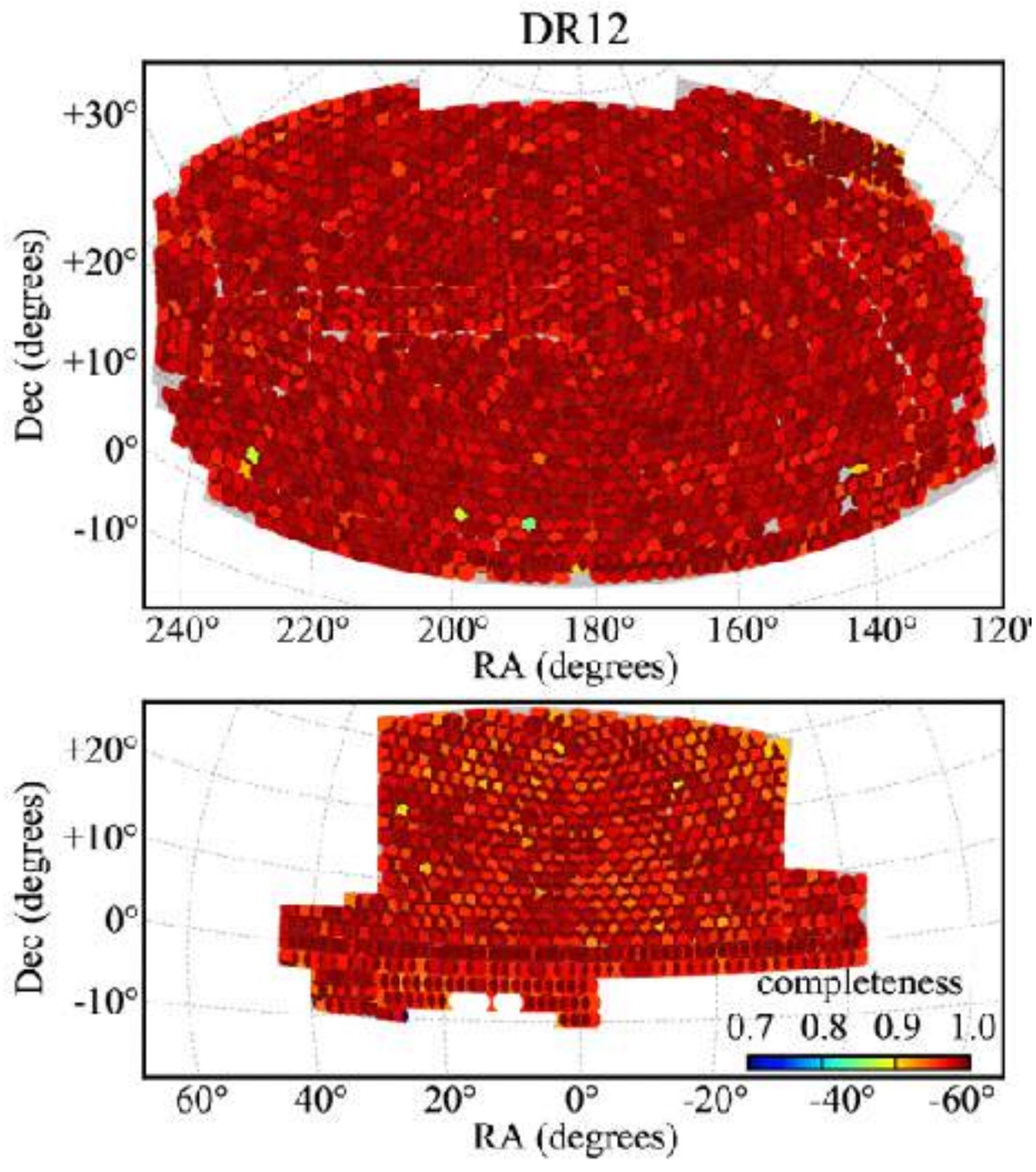
RSD: measure the growth-rate of cosmic structure.

$$f(z) = \frac{{\rm d}\ln D}{{\rm d}\ln a} \qquad f\sigma_8(z)$$



BOSS in a nutshell

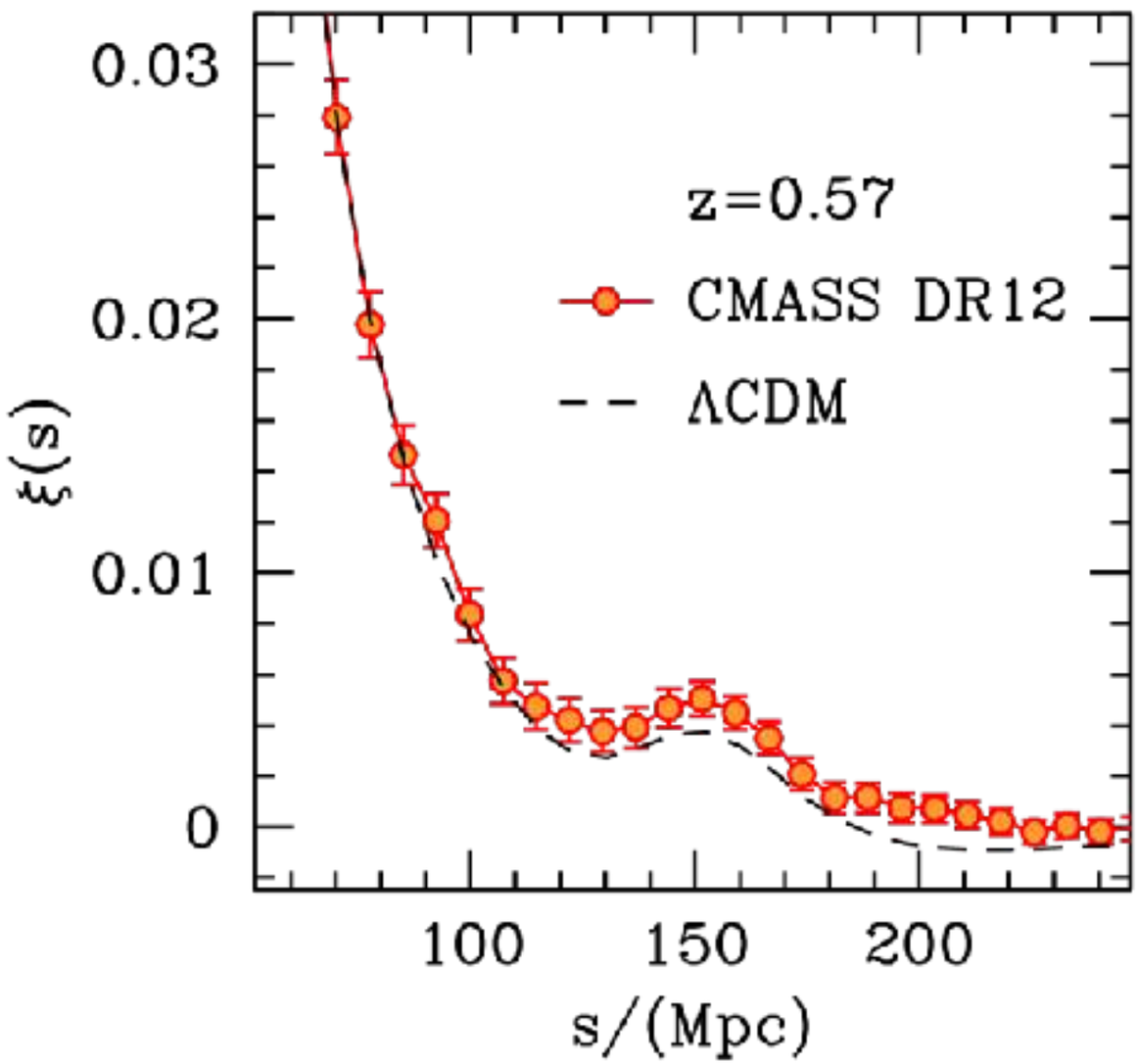
- The largest galaxy catalogue available today.
- Total area of 10,200 deg^2.
- Positions for 1.2×10^6 LGs
  - LOWZ, with $0.1 < z < 0.43$
  - CMASS, with $0.43 < z < 0.7$
- A sample of 1.6×10^5 QSOs, $2.3 < z < 2.8$

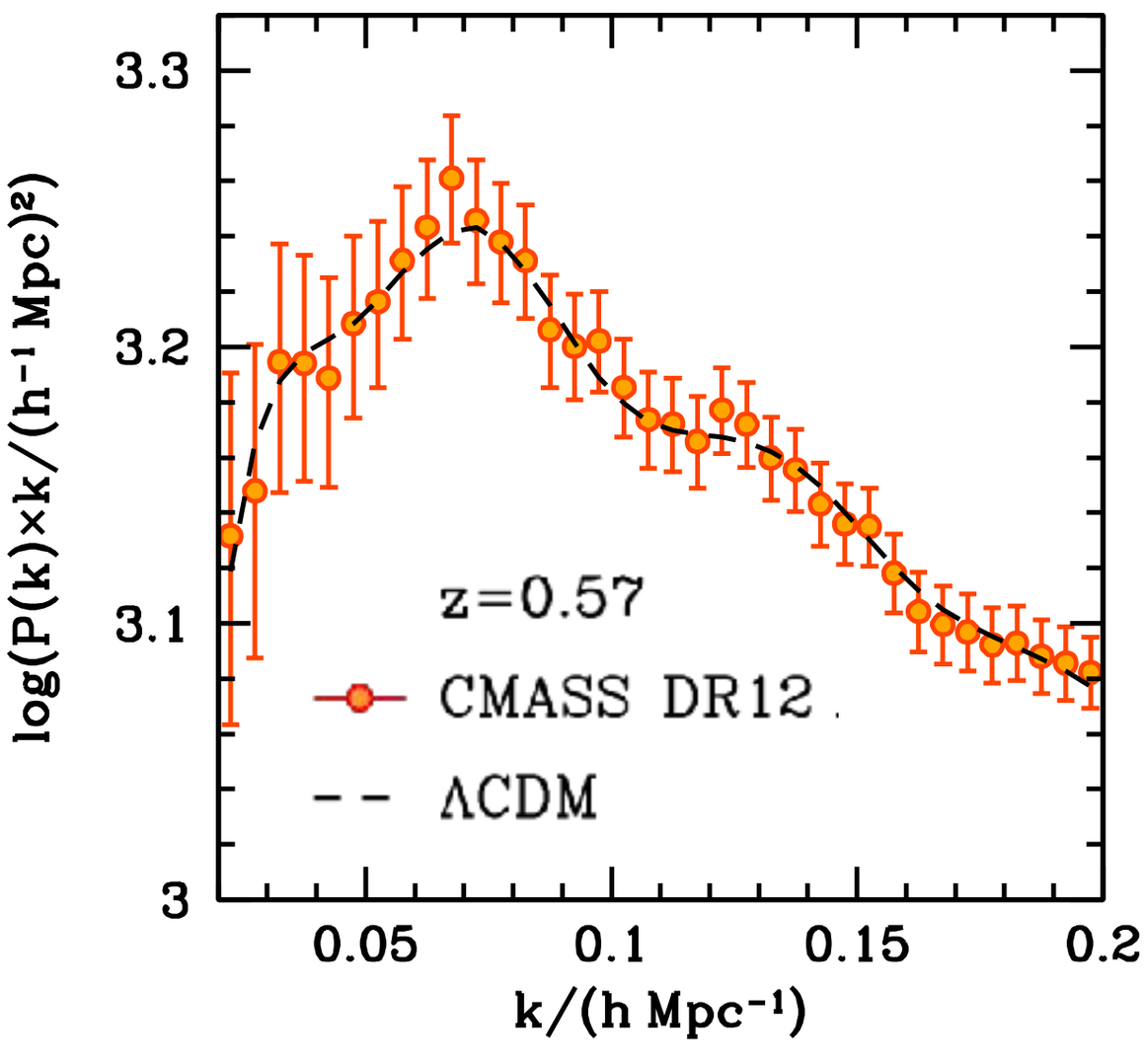


Reid et al. (2016)

Galaxy clustering observables

- BAO signal in the clustering of BOSS galaxies.

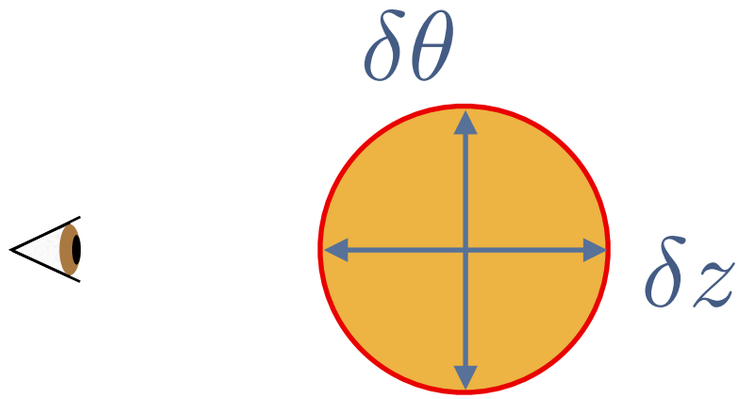




Angle-averaged measurements

- Angle-averaged measurements have a limited constraining power.

BAO: only sensitive to a volume-averaged distance.



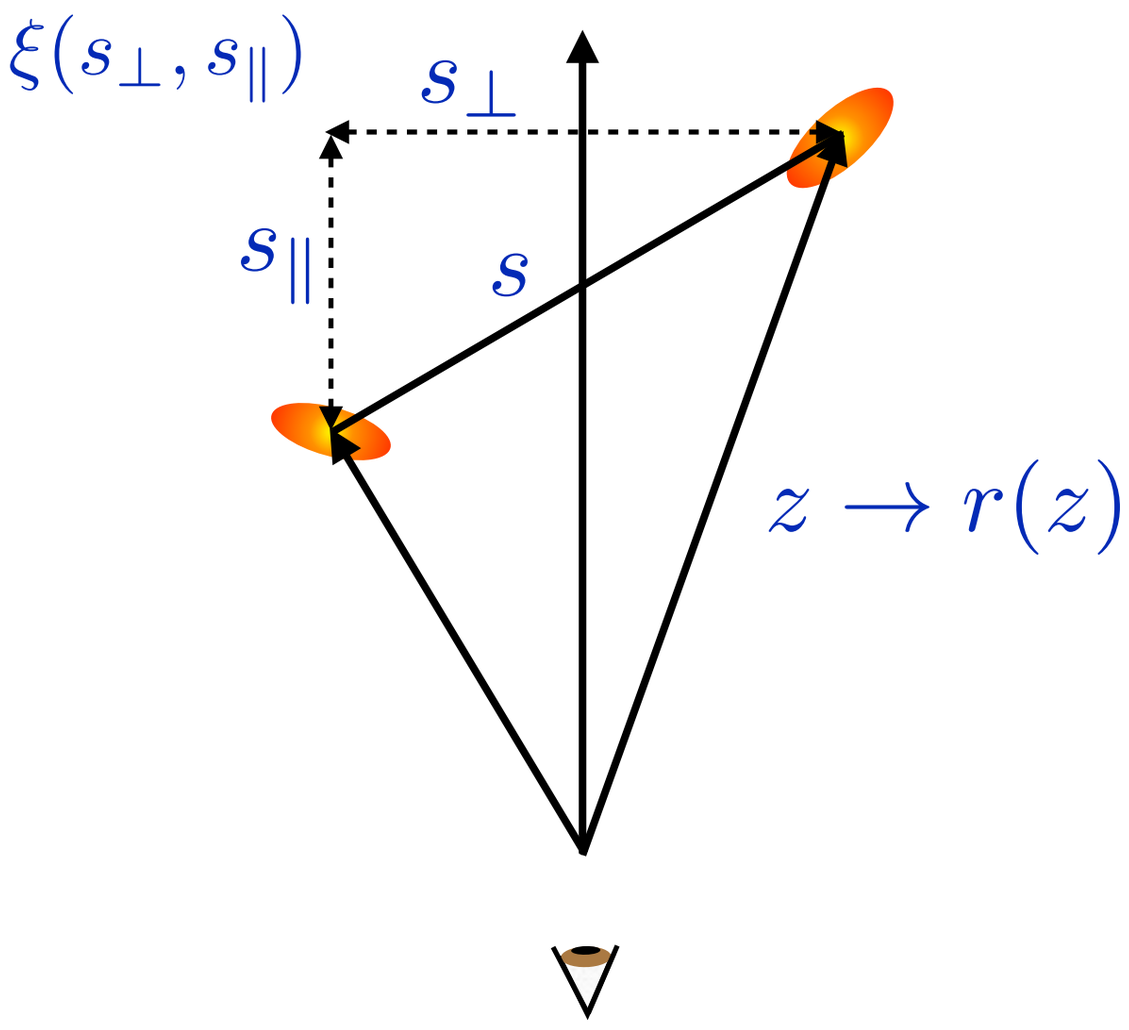
$$D_{\rm V}(z) = \left(D_{\rm M}(z)^2 cz/H(z)\right)^{\frac{1}{3}}$$

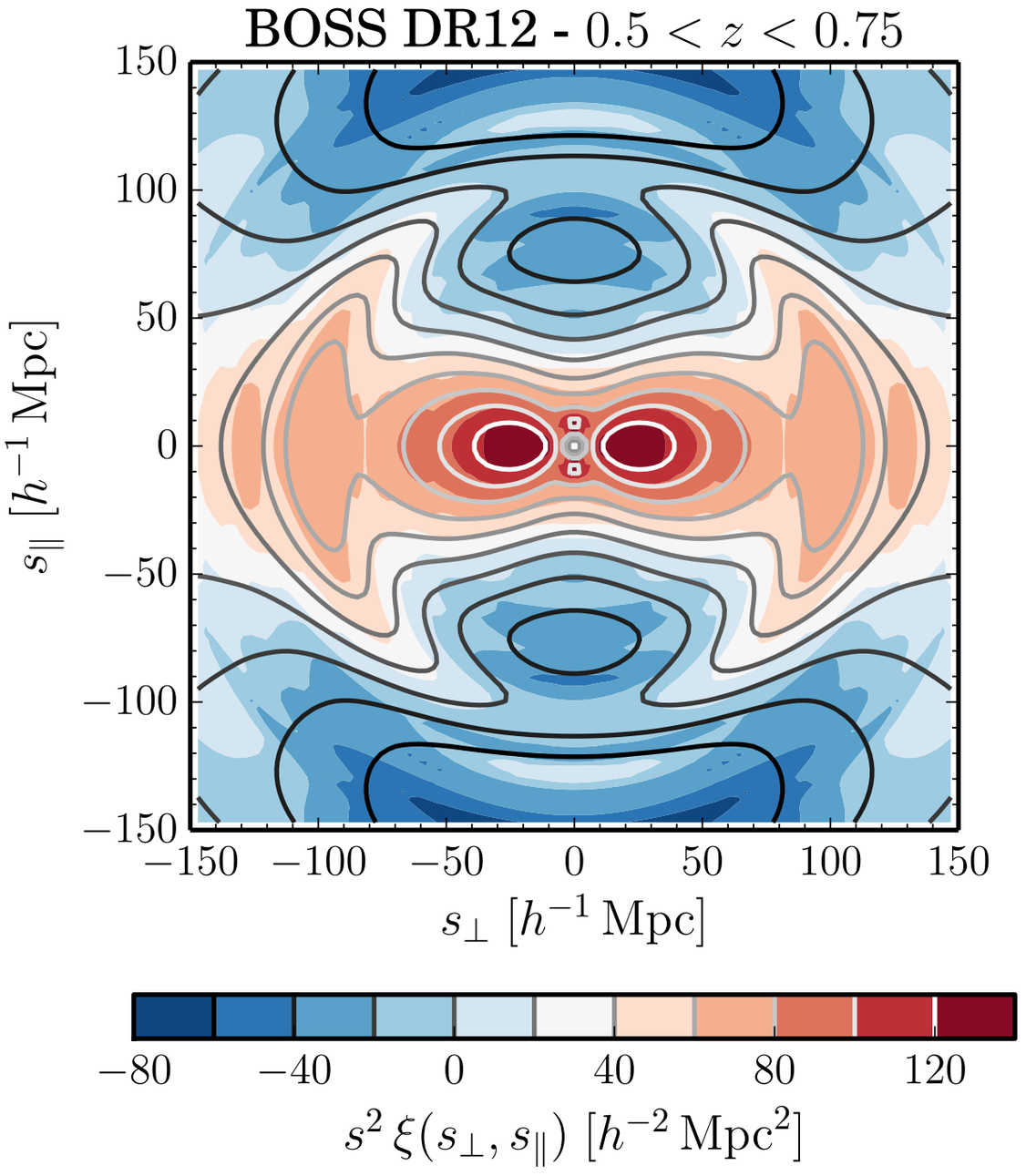
RSD: growth of structure is degenerate with galaxy bias

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

Anisotropic clustering

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





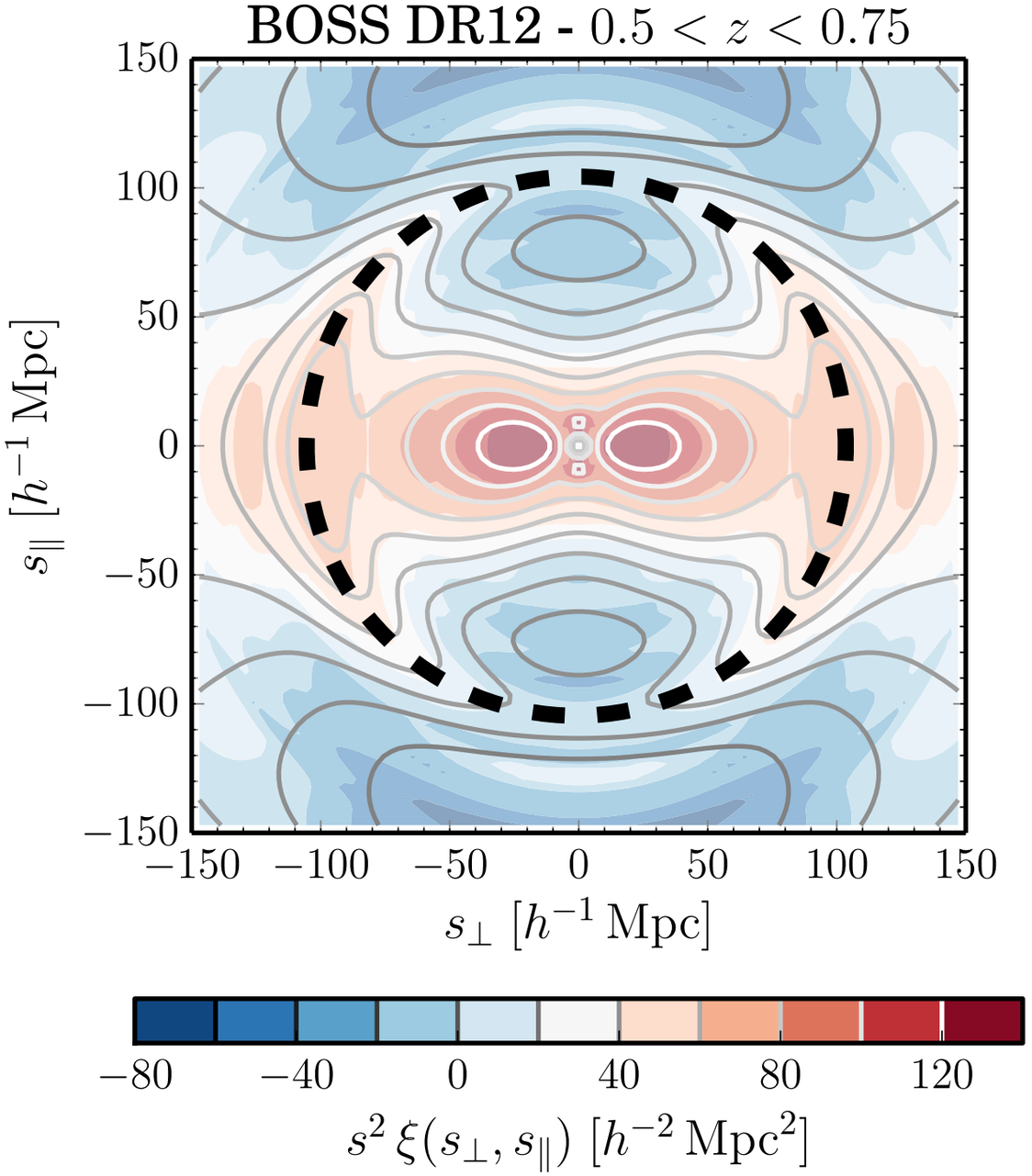
Anisotropic clustering

- 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)



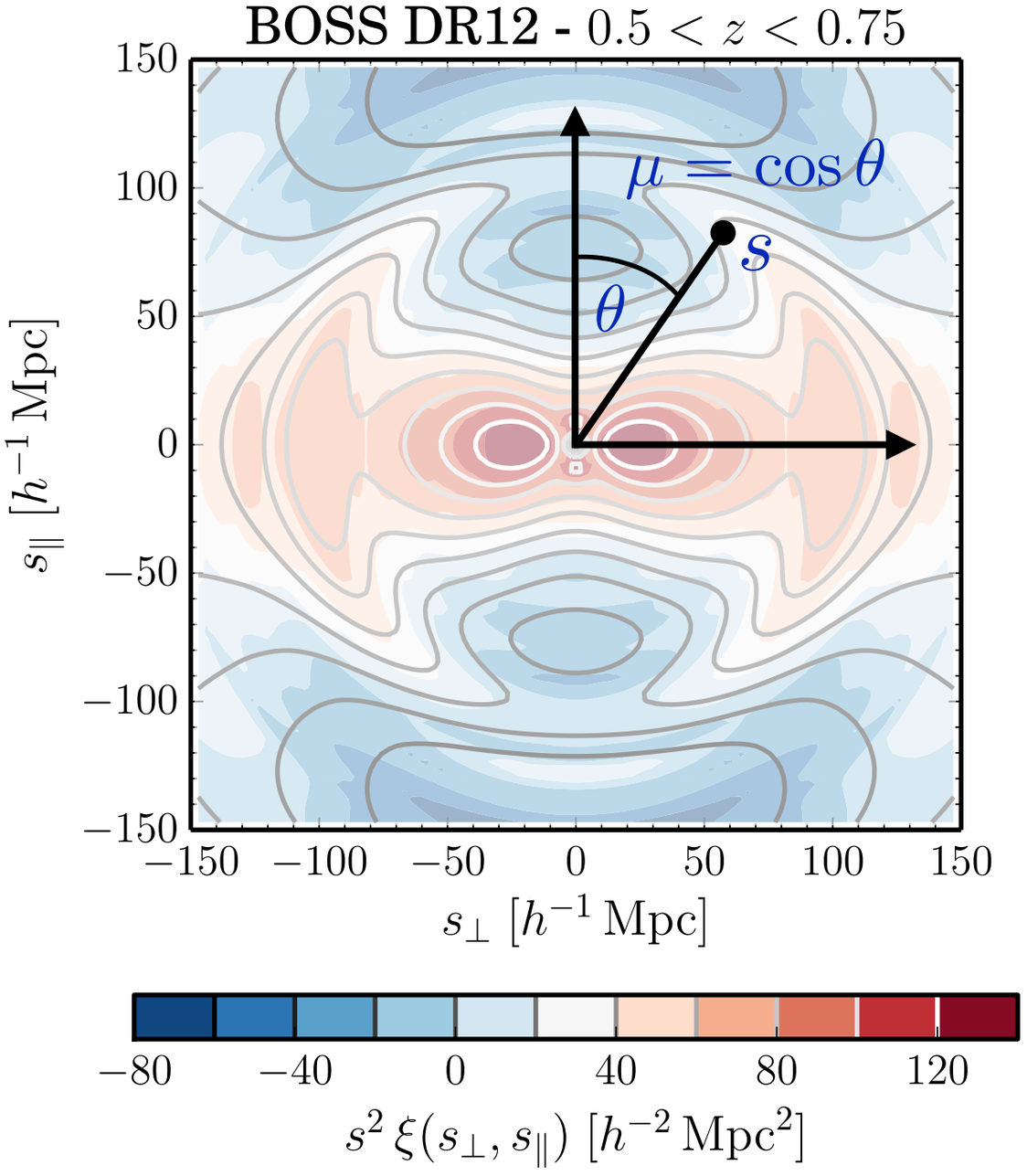
Anisotropic clustering

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

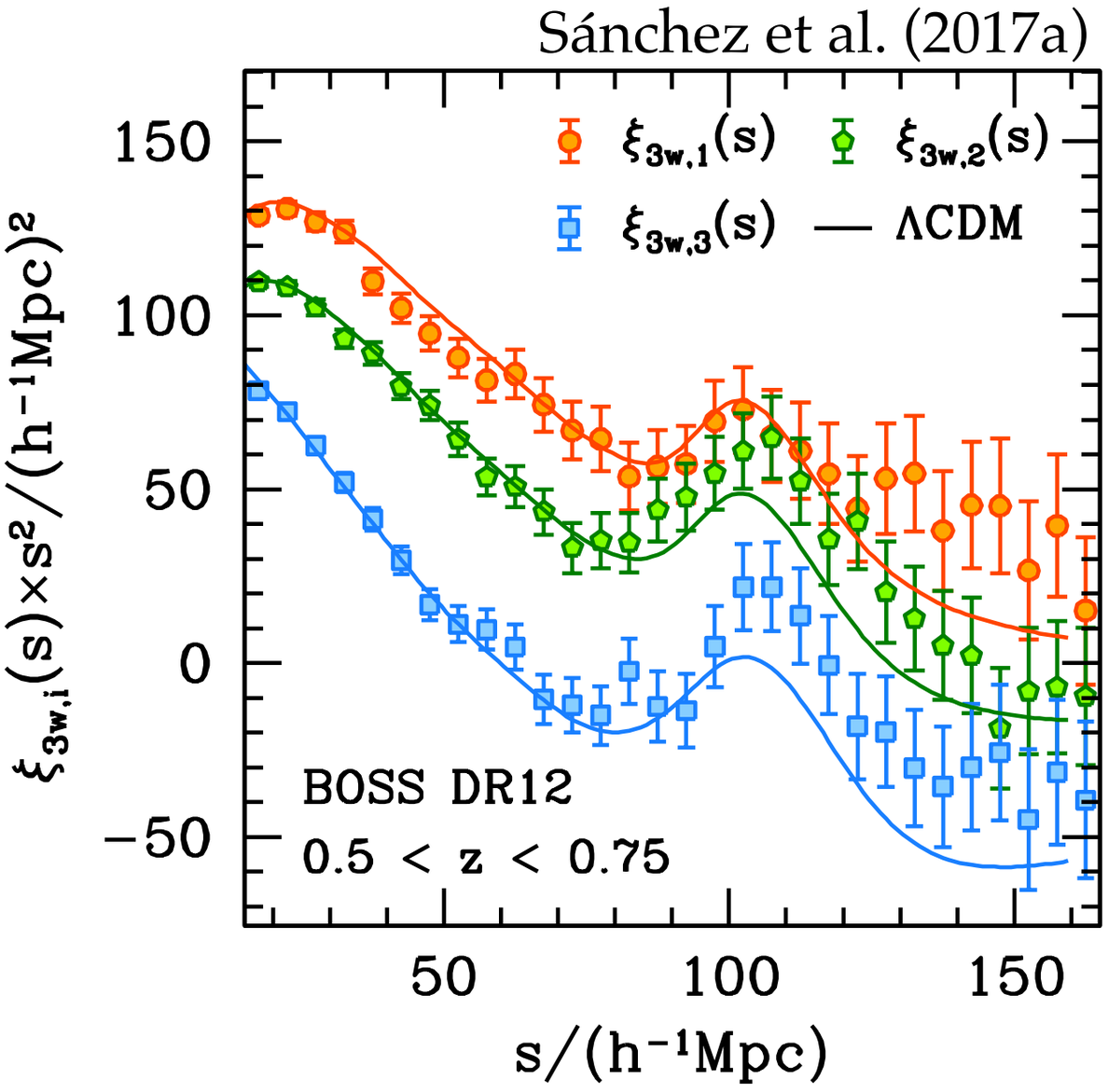
$$\xi_\ell(s) = \frac{(2\ell+1)}{2} \int_{-1}^{1} \xi(\mu, s)\, L_\ell(\mu)\, \mathrm{d}\mu$$

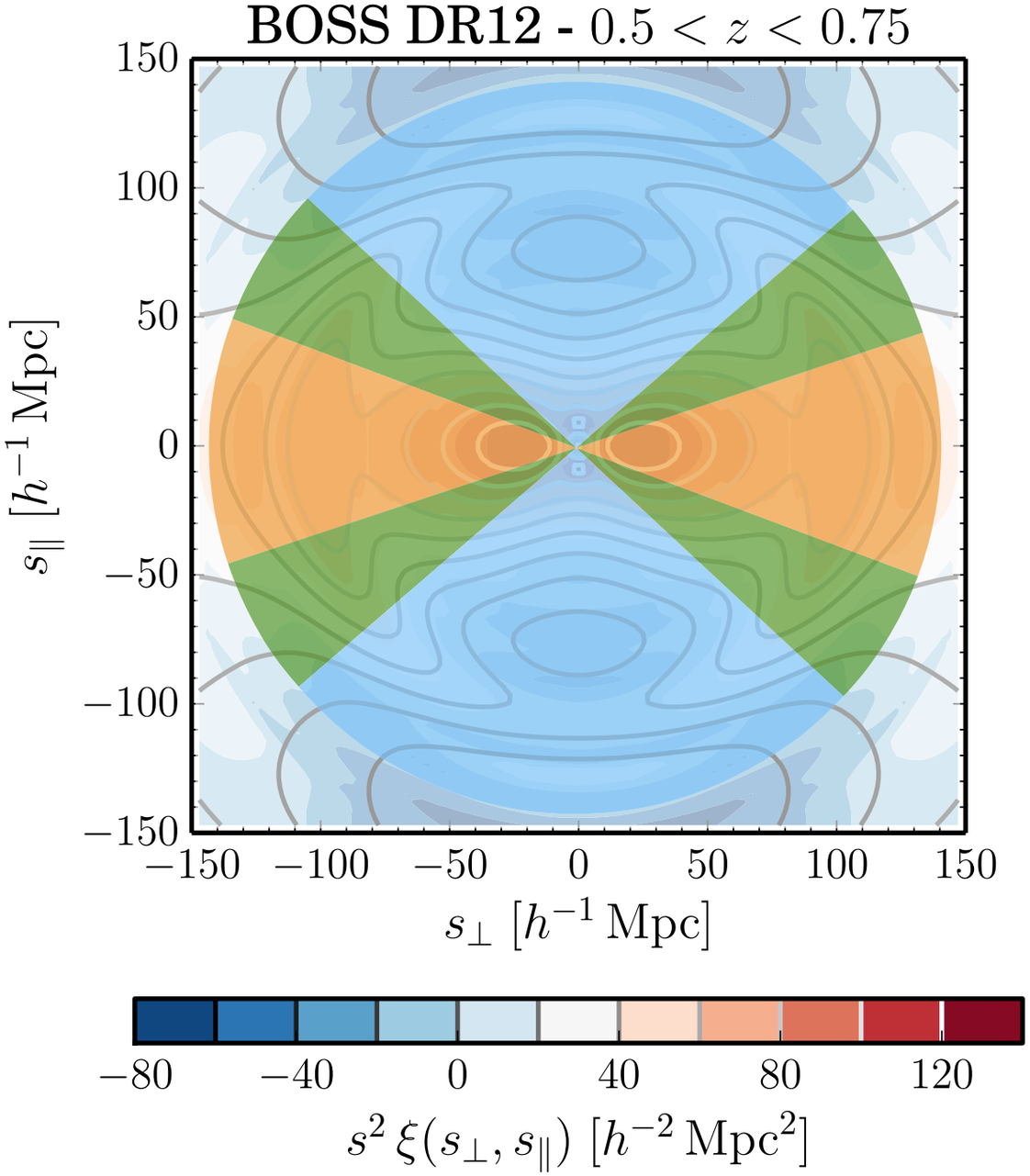
- Alternatively, use *clustering wedges* (Kazin, Sánchez & Blanton, 2012)

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



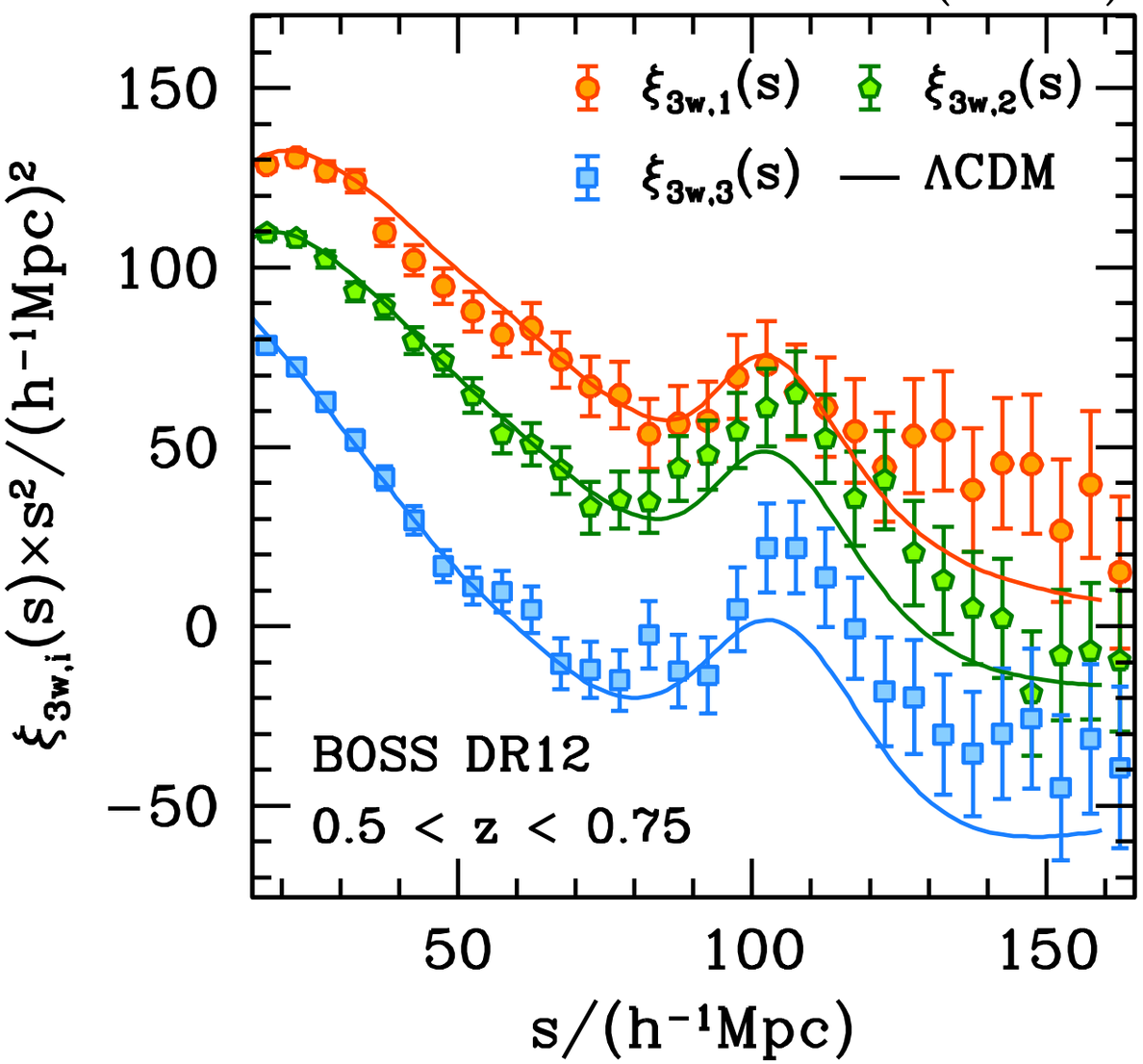
Anisotropic clustering



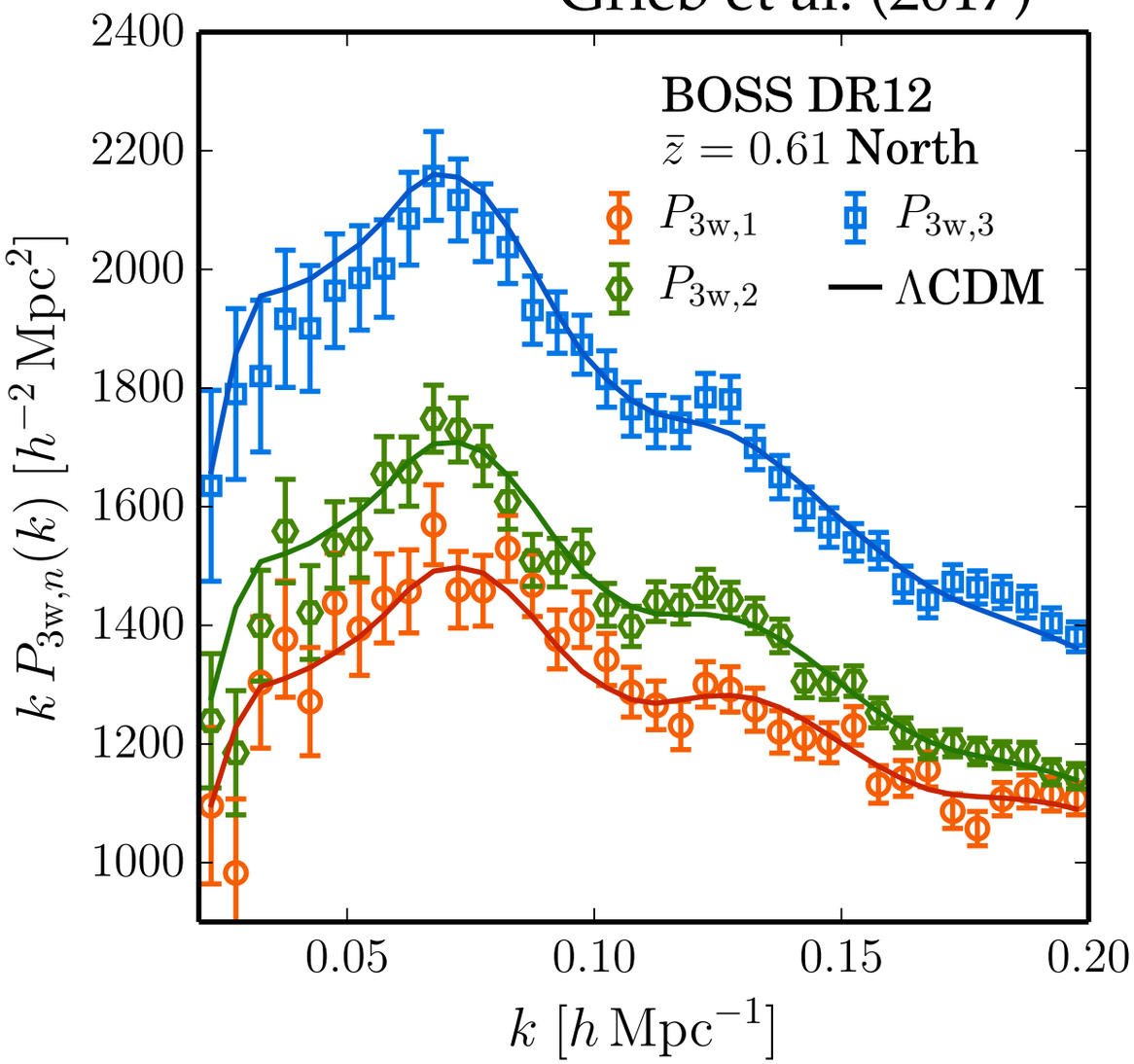


Anisotropic clustering

Sánchez et al. (2017a)



Grieb et al. (2017)



Modelling BAO & RSD

- Our final model can be written as

$$P(k,\mu) = W_\infty(ifk\mu)\, P_{\rm novir}(k,\mu),$$

Corrections associated with virialized regions

Coherent flow towards high-density regions.

- Modelling layers:

  - **Non-linear matter clustering**: gRPT (Crocce, Scoccimarro)

  - **Galaxy bias**: Chan et al. (2012)

$$\delta_{\rm g} = b_1\delta + \frac{b_2}{2}\delta^2 + \gamma_2\,\mathcal{G}_2 + \gamma_3^-\,\Delta_3\mathcal{G} + \ldots$$

  - **RSD:** Scoccimarro (2004), TNS (2010); non-Gaussian $W_\infty(\lambda)$

$$W_\infty(\lambda) = \frac{1}{\sqrt{1-\lambda^2 a_{\rm vir}^2}}\,\exp\left(\frac{\lambda^2\sigma_v^2}{1-\lambda^2 a_{\rm vir}^2}\right),$$

Modelling BAO & RSD

- Our final model can be written as

$$P(k,\mu) = W_\infty(ifk\mu)\, P_{\rm novir}(k,\mu),$$

Corrections associated with virialized regions

Coherent flow towards high-density regions.

- Modelling layers:

  - **Non-linear matter clustering**: gRPT (Crocce, Scoccimarro)

  - **Galaxy bias**: Chan et al. (2012)

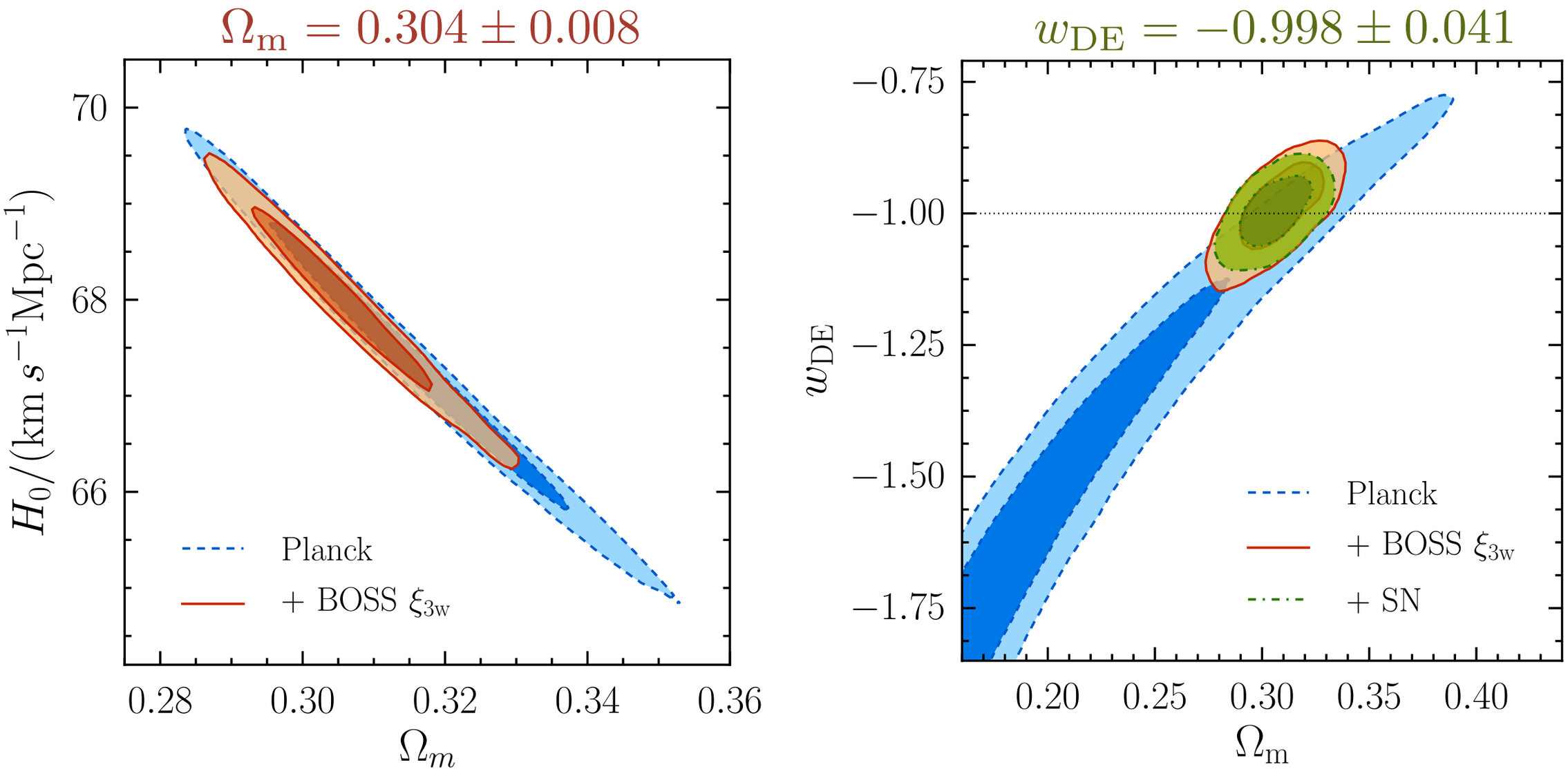
$$\delta_{\rm g} = b_1\delta + \frac{b_2}{2}\delta^2 + \gamma_2\,\mathcal{G}_2 + \gamma_3\,\Delta_3\mathcal{G} + \ldots$$

  - **RSD:** Scoccimarro (2004), TNS (2010); non-Gaussian $W_\infty(\lambda)$

$$W_\infty(\lambda) = \frac{1}{\sqrt{1-\lambda^2 a_{\rm vir}^2}}\,\exp\left(\frac{\lambda^2\sigma_v^2}{1-\lambda^2 a_{\rm vir}^2}\right),$$

Observational cosmology

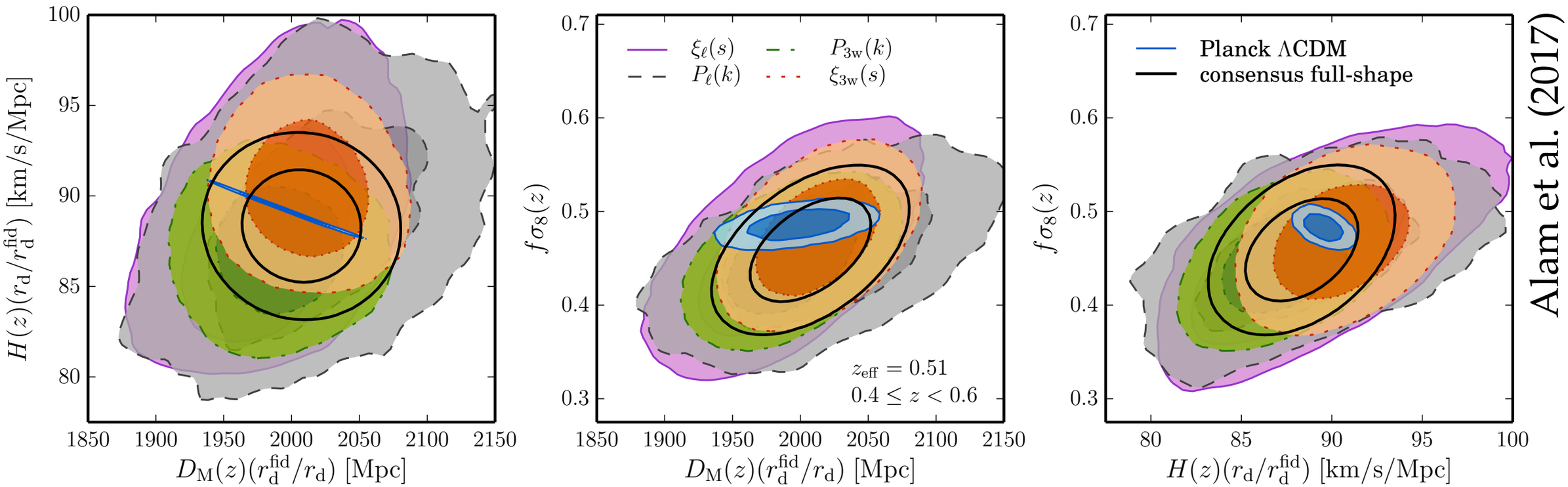
Cosmological constraints in good agreement with ΛCDM



Sánchez et al. (2017a), Grieb et al. (2017), Salazar-Albornoz (2017)

BOSS consensus constraints

- Different analyses can be combined into a set of *consensus constraints* (Sánchez et al. 2017b)



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

- Good agreement with the Planck ΛCDM prediction.

Galaxy redshift surveys

- A new generation of large-volume surveys

eBOSS: LRGs, ELGs, QSO at $0.7 < z < 2.8$

HETDEX: Ly-α emitters, $1.9 < z < 3.5$

PFS: ELGs, $0.6 < z < 2.4$

DESI: LRGs, ELGs, QSO at $0.4 < z < 3.5$

Euclid: H-α emitters, $0.6 < z < 2$

QSO clustering in eBOSS

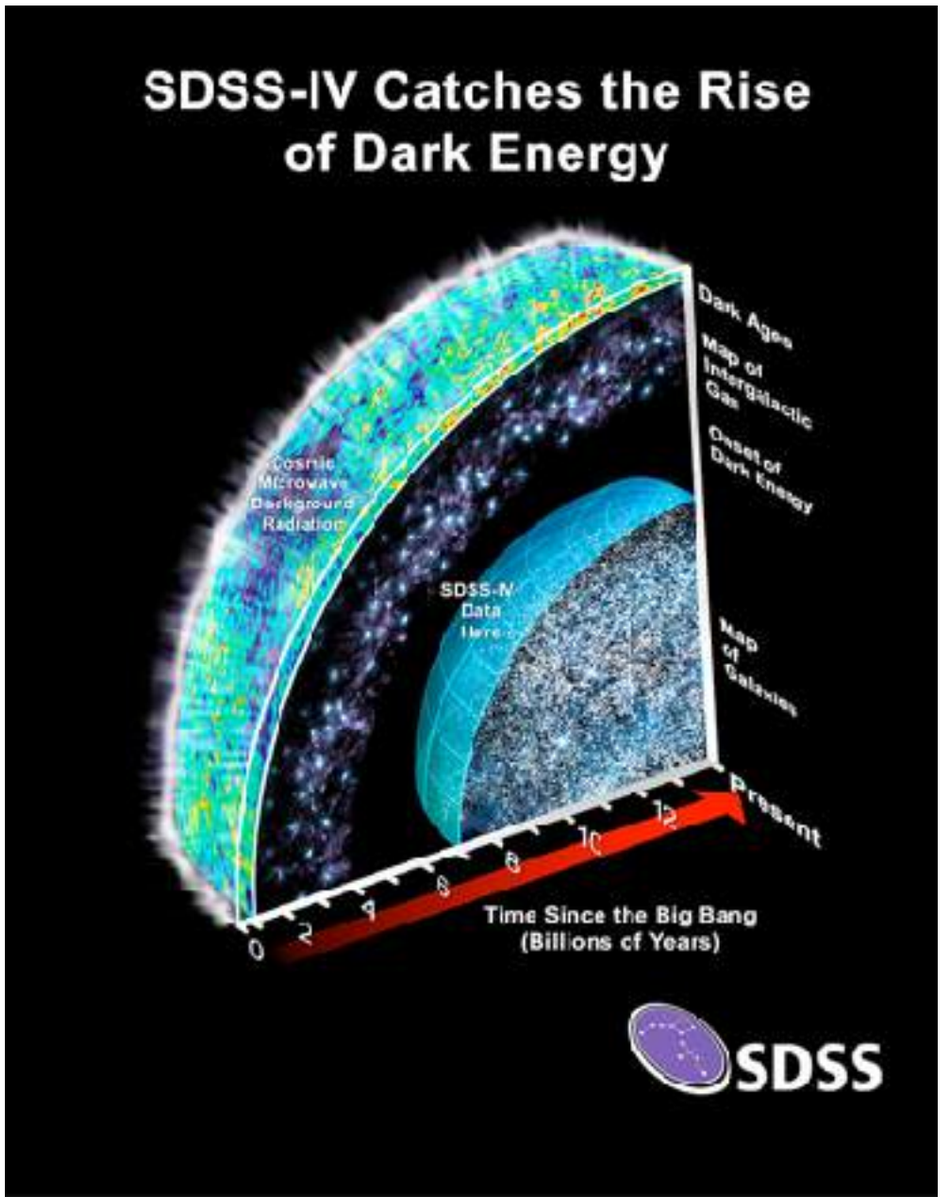
- QSOs open up a new z window for clustering studies.

- Bridge gap between BOSS gal. and Ly-α measurements.

- DR14 sample: ~147,000 QSOs, $0.8 < z < 2.2$.

- BAO distance measurements at $z = 1.52$ (Ata et al. 2018).

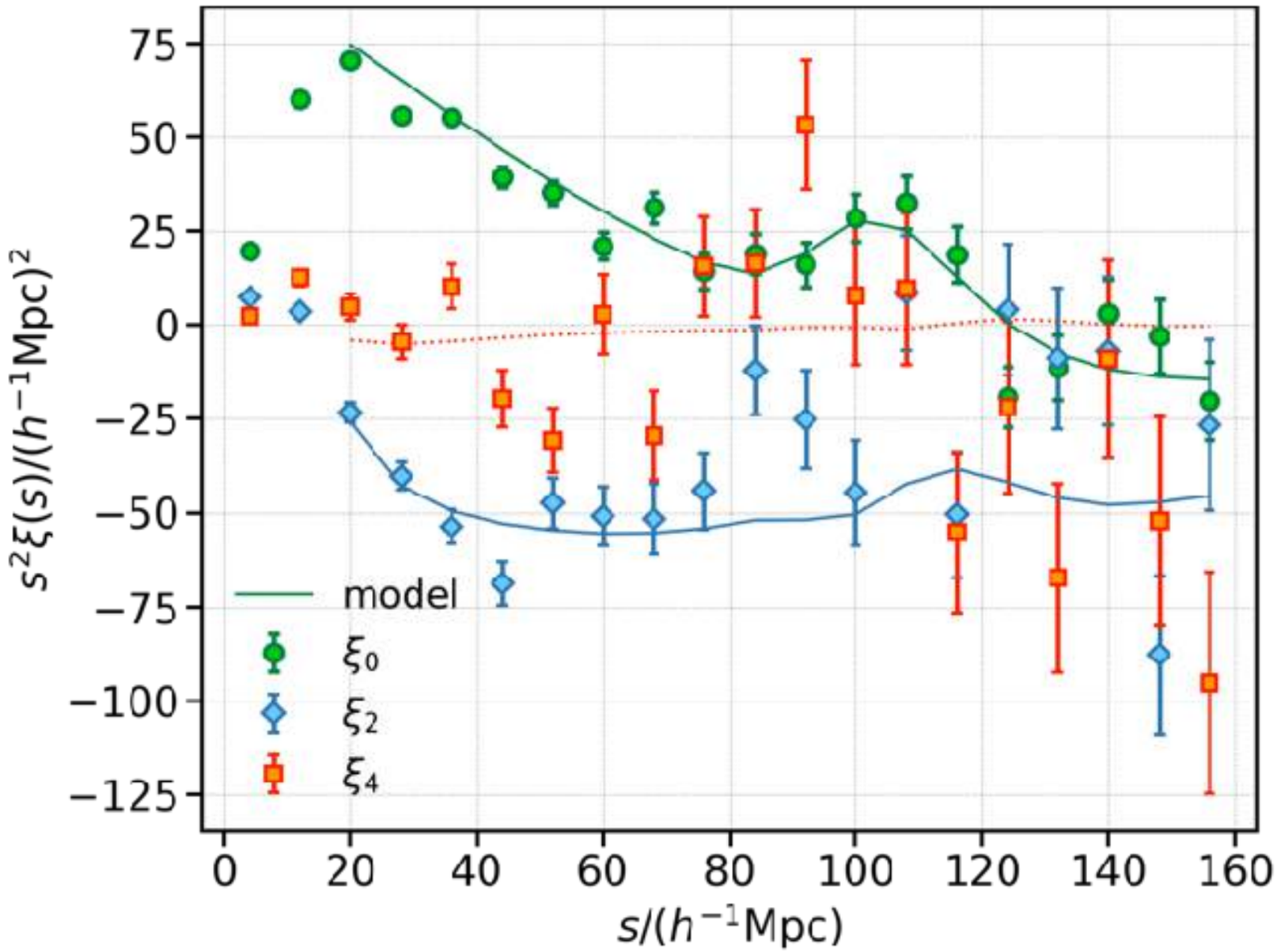
$$D_{\rm V}(z = 1.52) = 3843 \pm 147 \left(\frac{r_{\rm d}}{r_{\rm d}^{\rm fid}}\right) \ {\rm Mpc}$$



QSO clustering in eBOSS

- Anisotropic clustering in the eBOSS DR14 QSO sample.

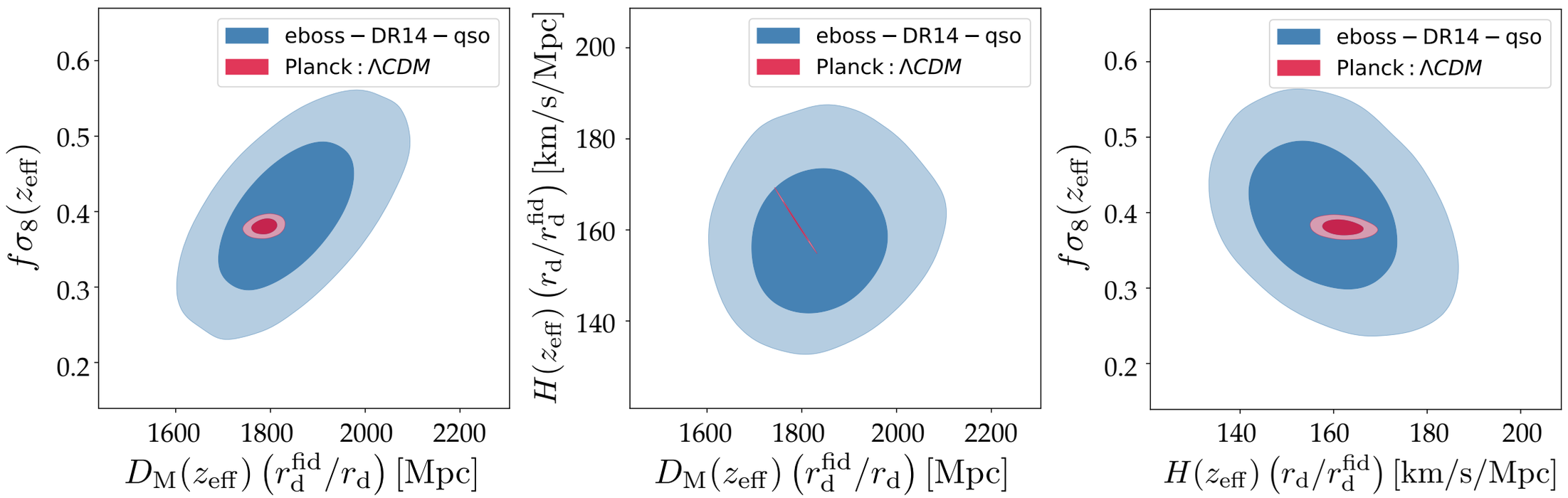
Hou et al. (2018)



QSO clustering in eBOSS

- Anisotropic clustering in the eBOSS DR14 QSO sample.
- Model of final BOSS, extended to account for z errors.

Hou et al. (2018)

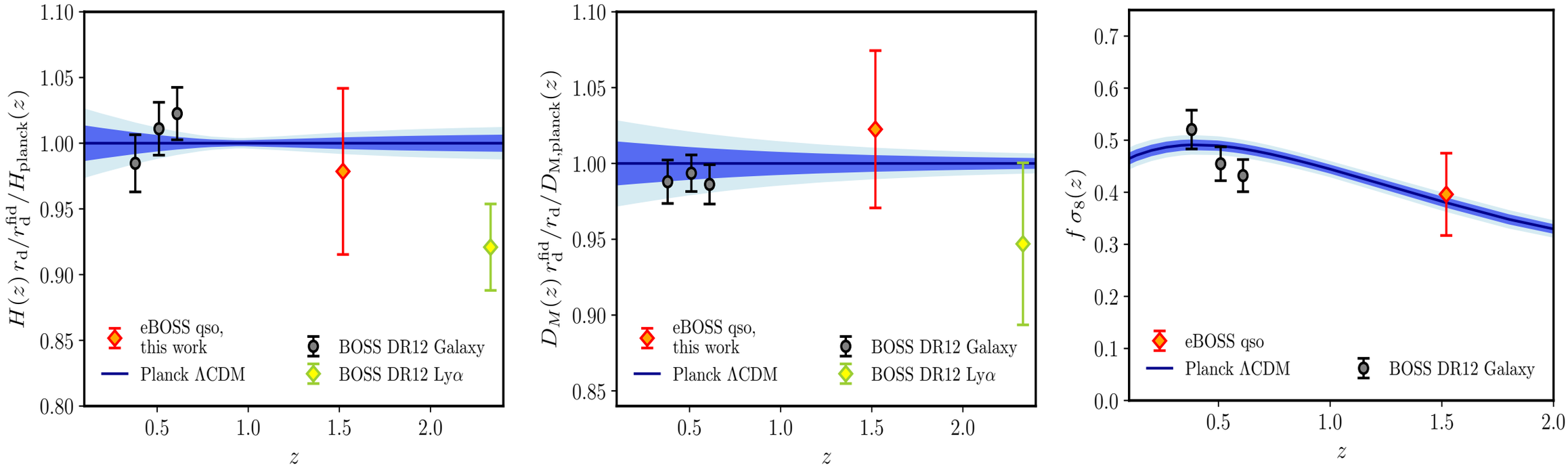


- Final eBOSS QSO sample contains twice as many objects.
- Ongoing cosmological analysis (Hou et al. in prep).

QSO clustering in eBOSS

- Anisotropic clustering in the eBOSS DR14 QSO sample.
- Model of final BOSS, extended to account for z errors.

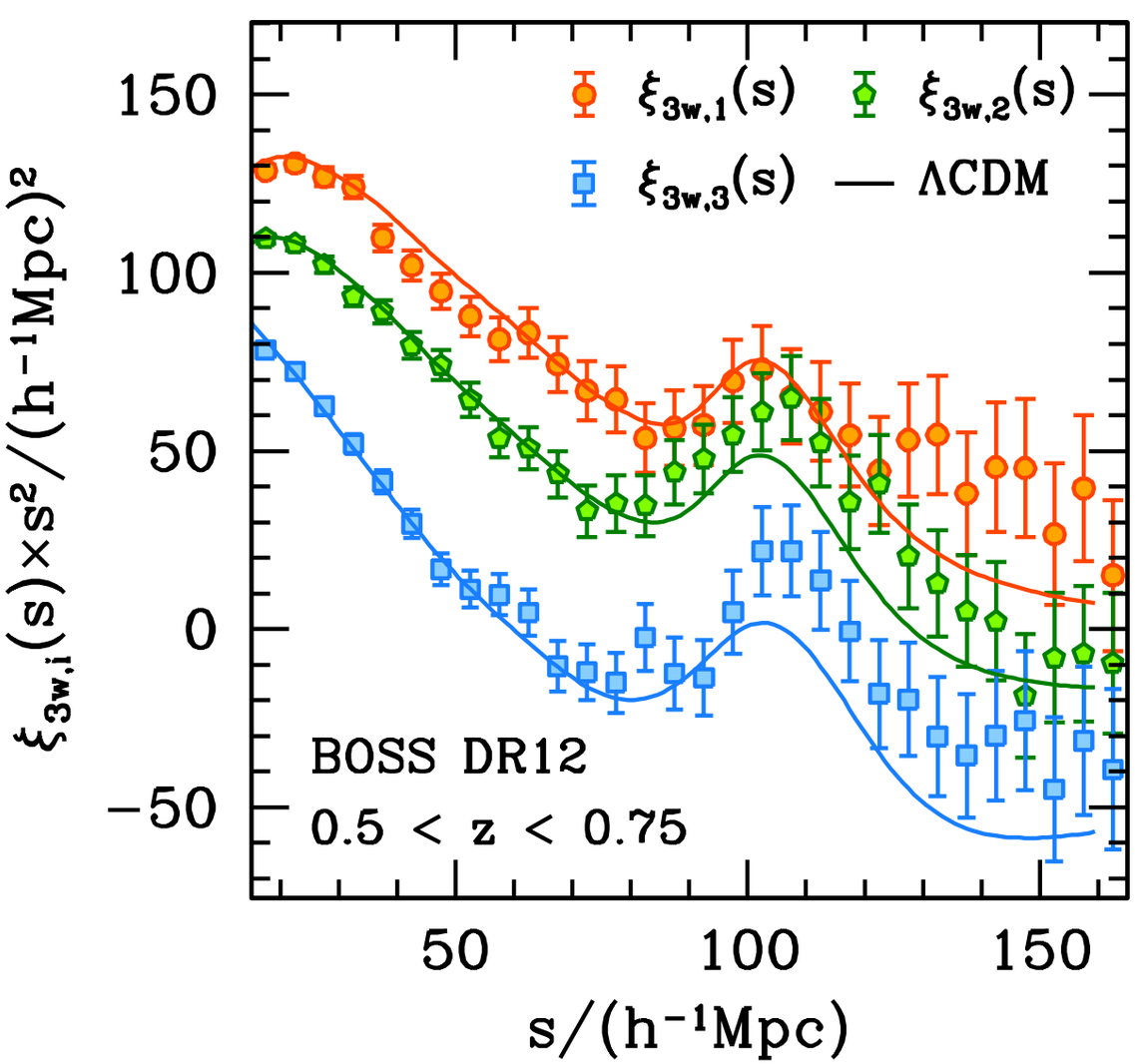
Hou et al. (2018)

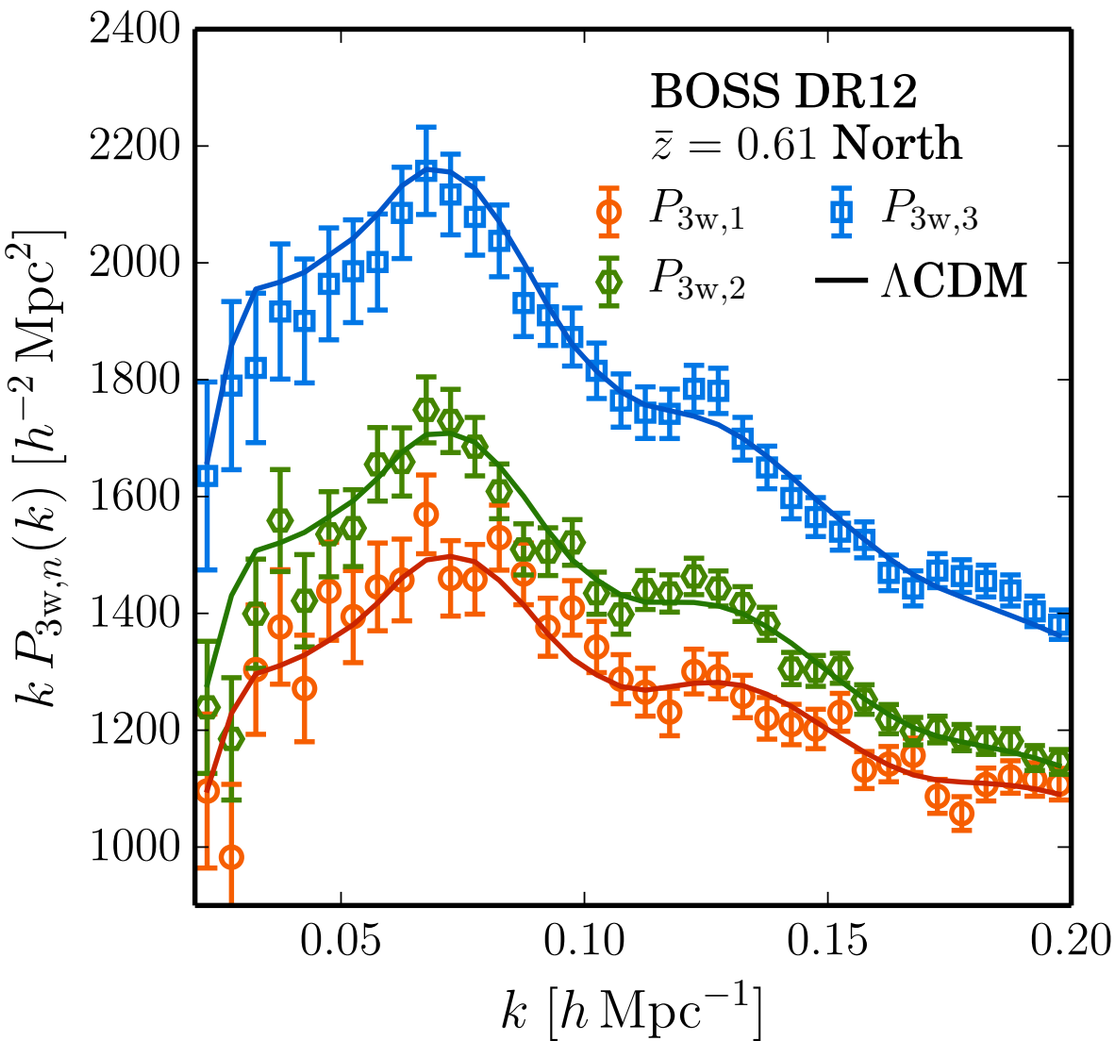


- Final eBOSS QSO sample contains twice as many objects.
- Ongoing cosmological analysis (Hou et al. in prep).

Robust cosmological forecasts

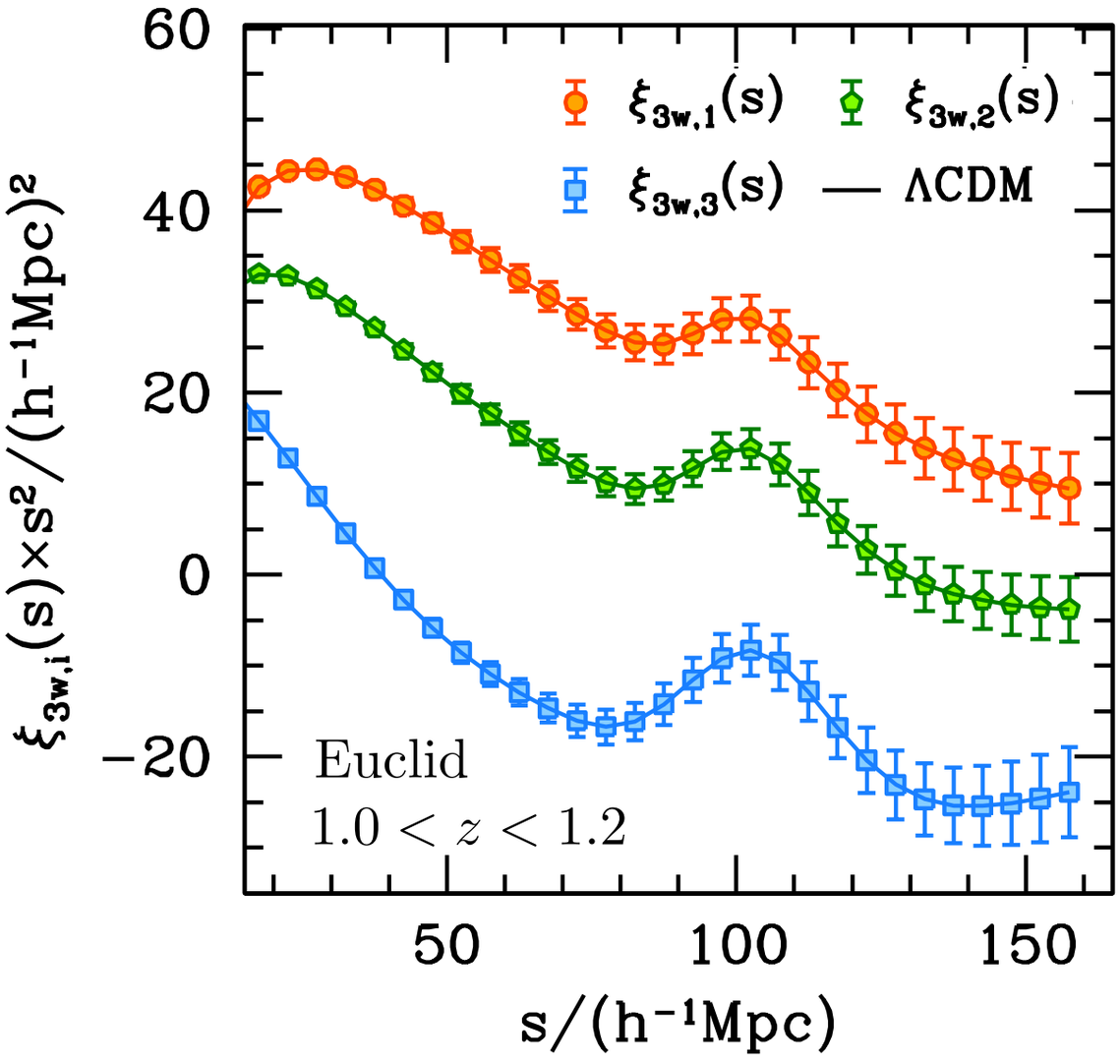
- Use a model to predict $\xi_\ell(s)$, $\xi_{\rm w}(s)$, $P_\ell(k)$, $P_{\rm w}(s)$.
- Gaussian cov. matrices (Grieb et al. 2016).

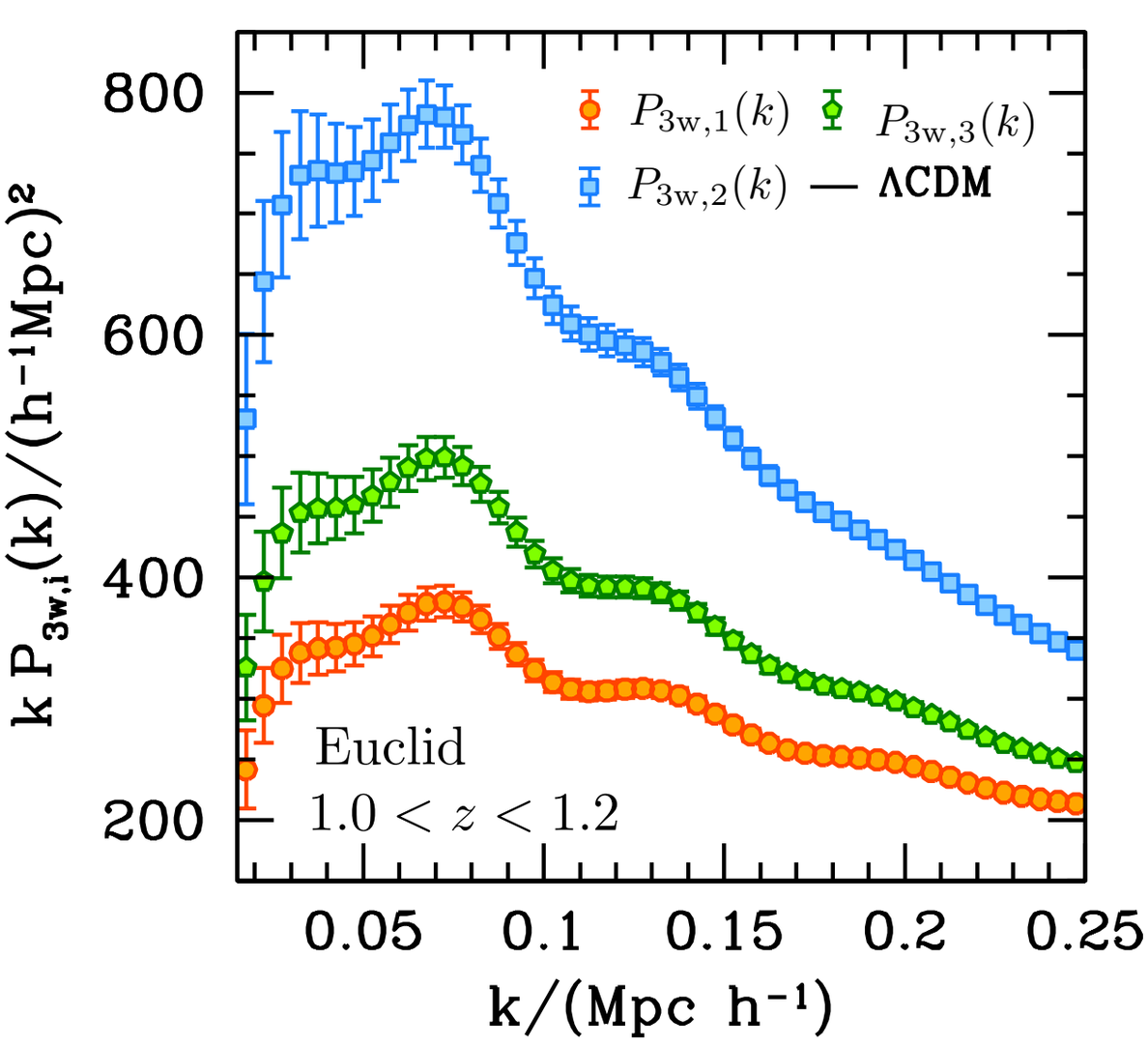




Robust cosmological forecasts

- Use a model to predict $\xi_\ell(s)$, $\xi_{\rm w}(s)$, $P_\ell(k)$, $P_{\rm w}(s)$.
- Gaussian cov. matrices (Grieb et al. 2016).





Robust cosmological forecasts

- Use a model to predict

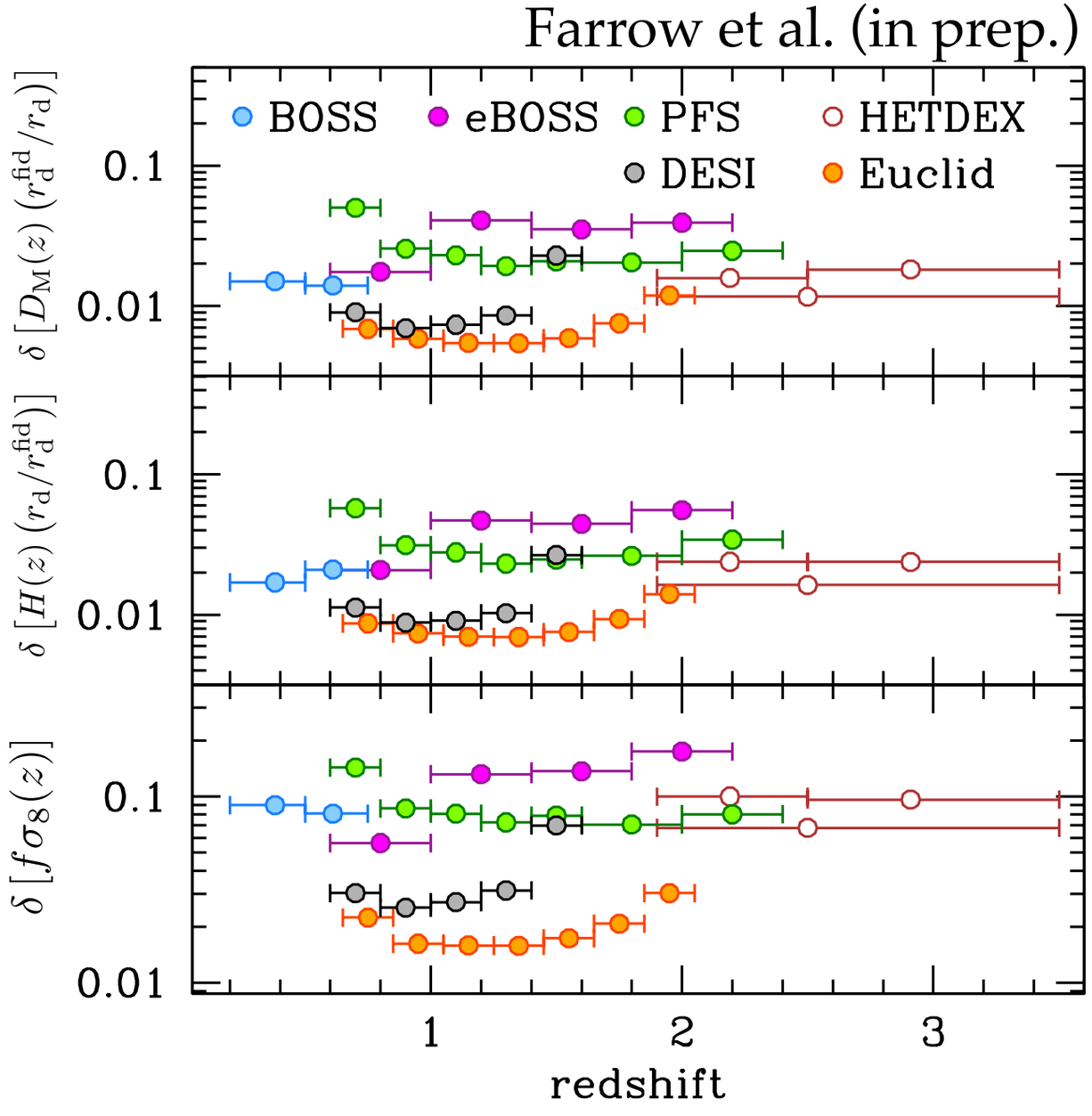
  $\xi_\ell(s),\ \xi_{\rm w}(s), P_\ell(k),\ P_{\rm w}(s)$

- Gaussian cov. matrices (Grieb et al. 2016).

- Construct the likelihood function $\mathcal{L} \propto \mathrm{e}^{-\chi^2/2}$.

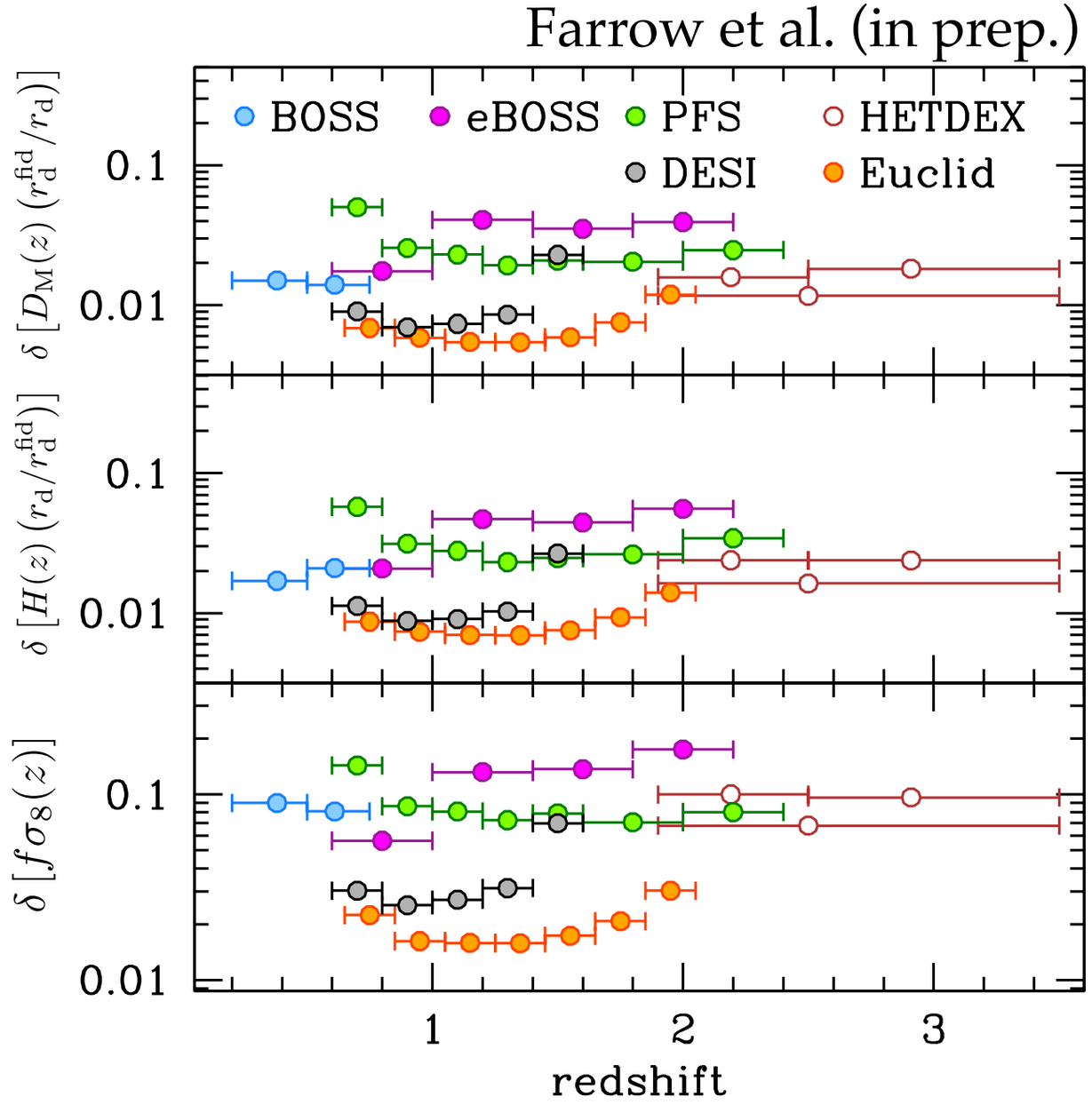
- Can be explored with MCMC or Fisher matrices

$$F_{ij} = -\left\langle \frac{\partial^2 \ln \mathcal{L}}{\partial\theta_i \partial\theta_j} \right\rangle \Bigg|_{\boldsymbol{\theta}_0}$$



Robust cosmological forecasts

- Forecasts based on consistent assumptions.
- Galaxy clustering only (no WL or Ly-alpha).
- New *Euclid* forecasts will be released soon.
- HETDEX covers a unique redshift range.



Final remarks

- GC probes the expansion and growth of structure history of the Universe.

- These measurements can be compared against CMB-based predictions assuming ΛCDM.

- Current data from BOSS and eBOSS in agreement with the standard model.

- New data will shape our understanding of cosmic history.

- Test the ΛCDM paradigm to much higher accuracy.