Cosmological Constraint from the Measurement of
Baryon Acoustic Oscillations & Redshift Space Distortion

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Outline

Physics of BAO & RSD by Leyao Wei

BAO Observation by Anning Gao

BAO Reconstruction by Jiayi Li

Cosmological Constraints from BAO by Jiayi Li

Credit: Daniel Eisenstein

Baryon Acoustic Oscillations

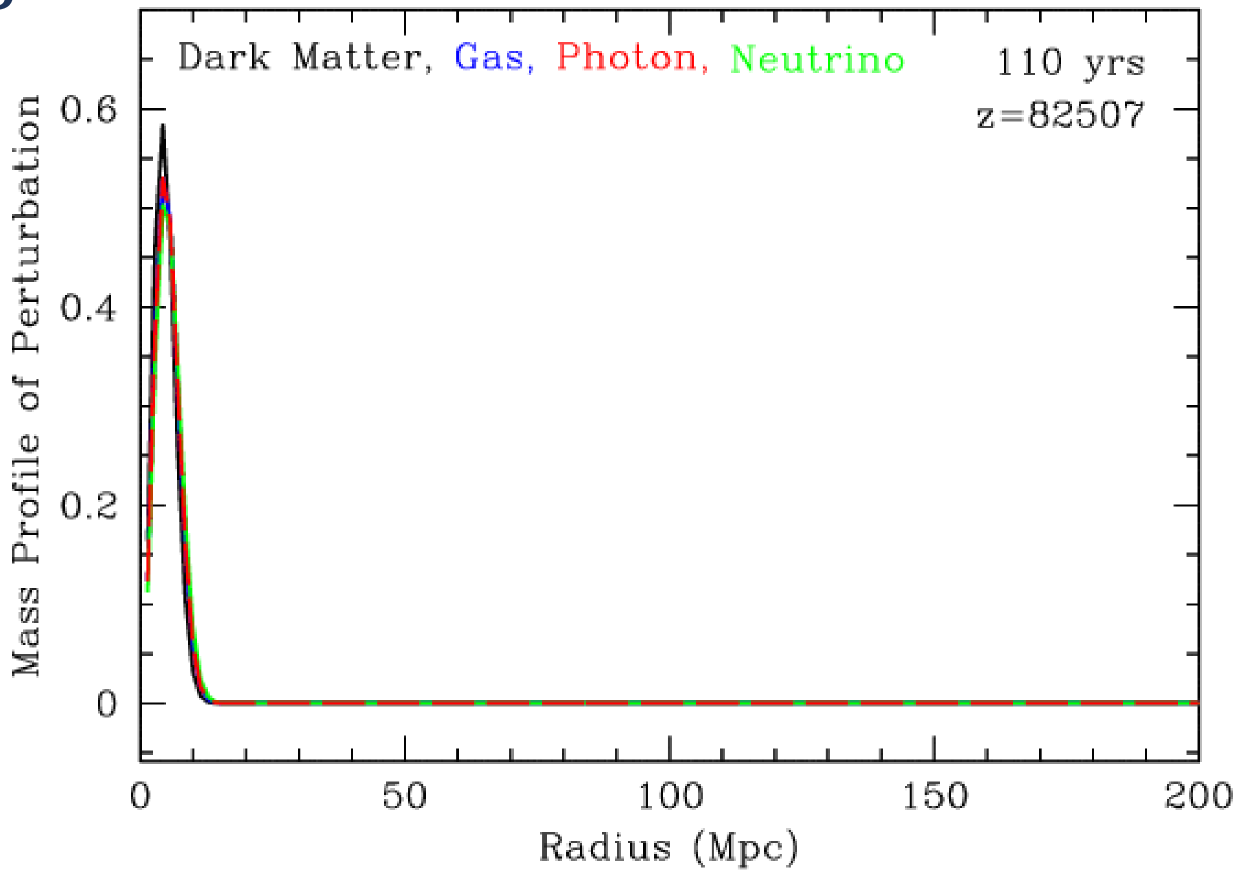
- Before decoupling:

Baryon couples with radiation and oscillates

- After decoupling:

The acoustic wave got frozen and baryon remain as over-density structure

Mass profile for different species



Credit: Daniel Eisenstein

Baryon Acoustic Oscillations

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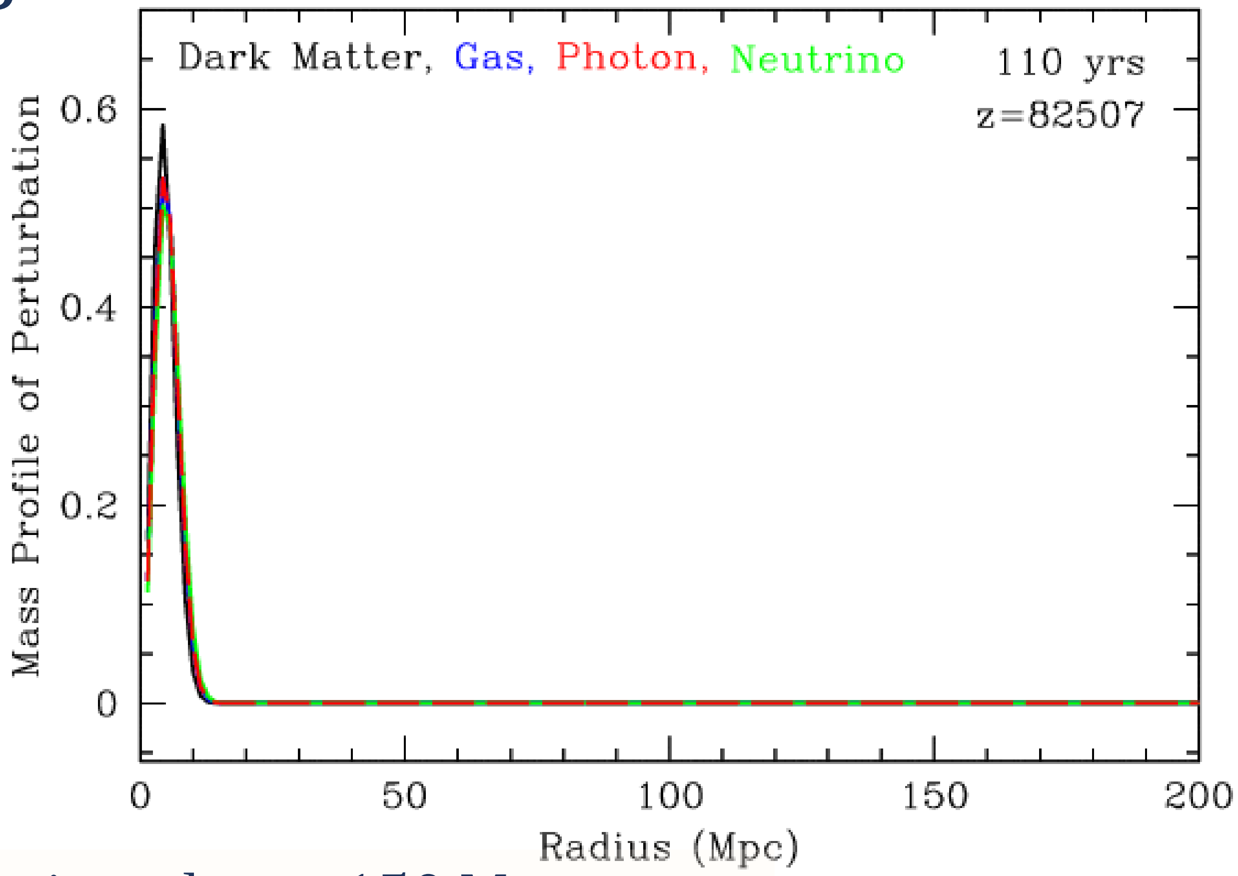

- Before decoupling:

  Baryon couples with radiation and oscillates

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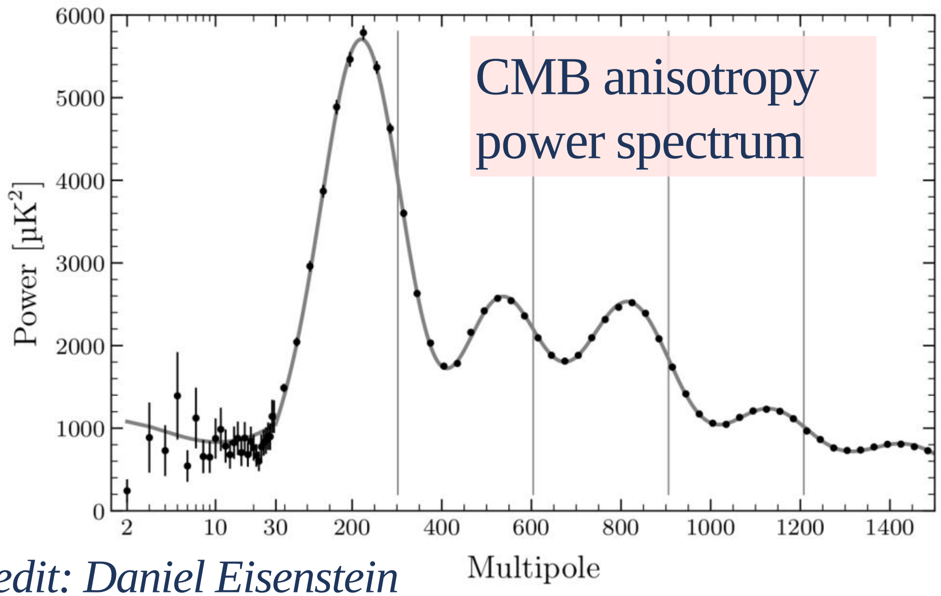
CMB anisotropy power spectrum



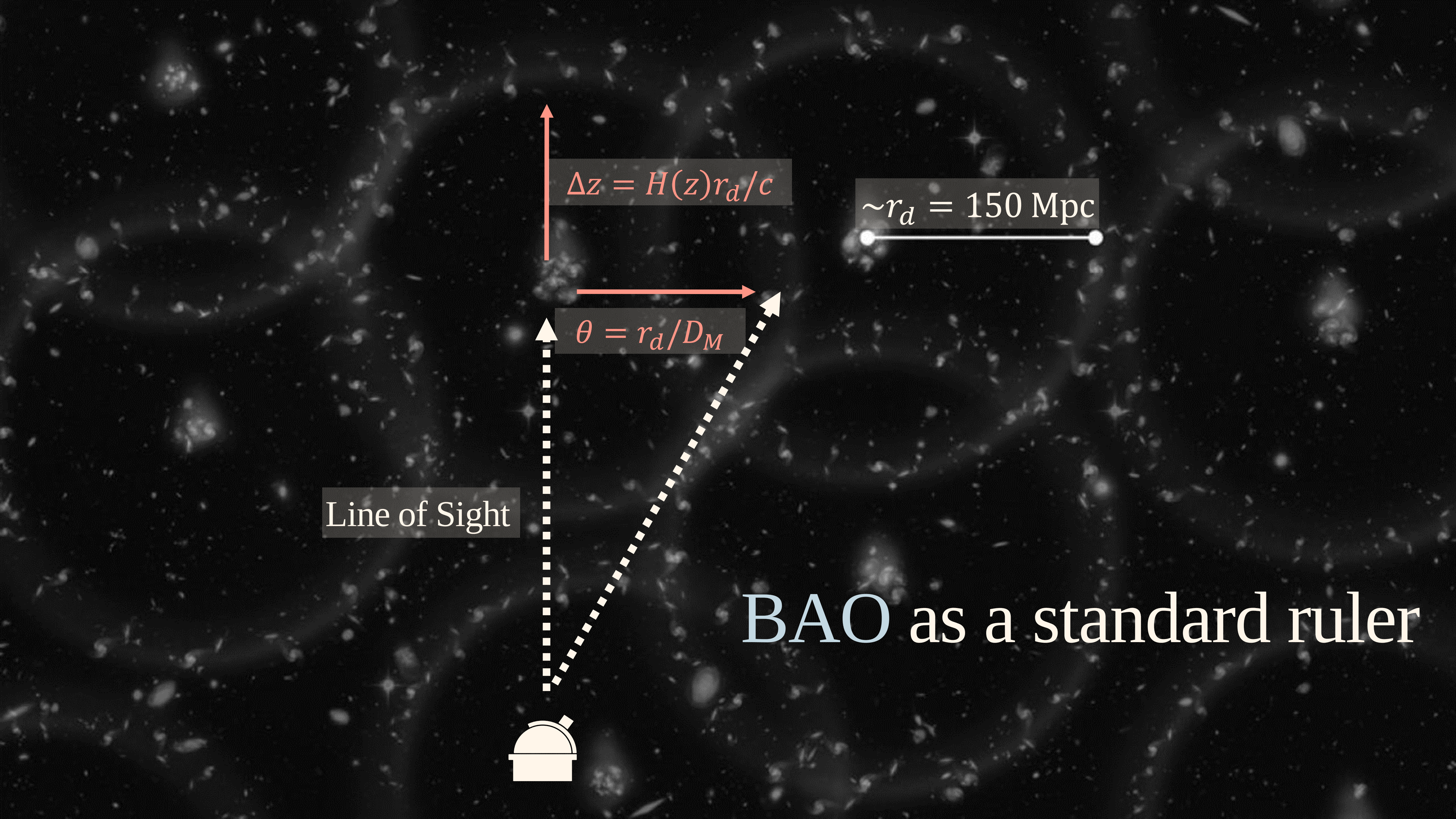
Credit: Daniel Eisenstein

- Acoustic scale $r_d \sim 150$ Mpc

  Can be measured from the CMB anisotropy power spectrum

- Avoid the impact of non-linear structure formation

BAO can be a cosmological standard ruler



$\Delta z = H(z) r_d / c$
$\sim r_d = 150\ \mathrm{Mpc}$
$\theta = r_d / D_M$
Line of Sight
BAO as a standard ruler

BAO for cosmological constraint

- Friedmann equation:

$$\frac{H^2(z)}{H_0^2} = \Omega_m(1+z)^3 + \Omega_r(1+z)^4 + \Omega_k(1+z)^2 + \Omega_\phi \frac{u_\phi(z)}{u_\phi(z=0)}$$

BAO for cosmological constraint

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- Comoving line-of-sight distance & Comoving angular diameter(transverse) distance

$$D_C(z) = \frac{c}{H_0}\int_0^z dz' \frac{H_0}{H(z')}$$

$$D_A(z) \approx D_C\left[1 + \frac{1}{6}\Omega_k\left(\frac{D_C}{c/H_0}\right)^2\right]$$

BAO for cosmological constraint

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$$\frac{H^2(z)}{H_0^2} = \Omega_m(1+z)^3 + \Omega_r(1+z)^4 + \Omega_k(1+z)^2 + \Omega_\phi \frac{u_\phi(z)}{u_\phi(z=0)}$$

- Comoving line-of-sight distance & Comoving angular diameter(transverse) distance

$$D_C(z) = \frac{c}{H_0}\int_0^z dz' \frac{H_0}{H(z')} \qquad D_A(z) \approx D_C\left[1 + \frac{1}{6}\Omega_k\left(\frac{D_C}{c/H_0}\right)^2\right]$$

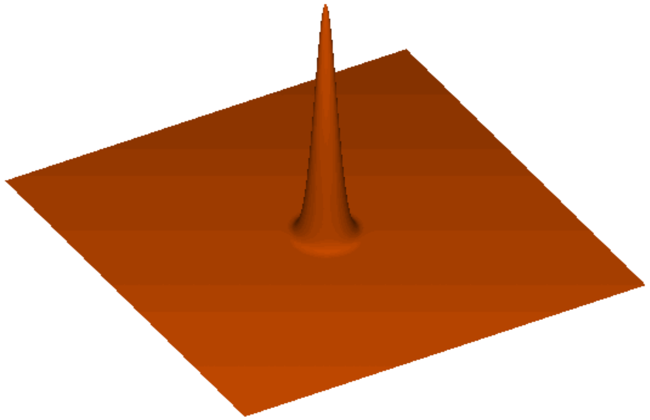
- Dark energy:

$$\Omega_\phi \frac{u_\phi(z)}{u_\phi(z=0)} \qquad w(z) = p_\phi(z)/u_\phi(z) \longrightarrow w(a) = \begin{cases} -1 \\ w \\ w_0 + w_a(1-a). \end{cases}$$

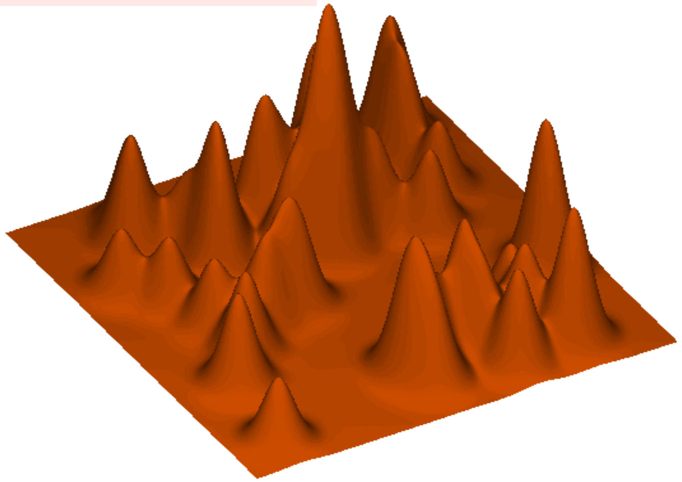
- Measurement: Ω_m, $H_0 r_d$
- Combing Measurement: H_0, neutrino mass, equation of state for dark energy

BAO in the real universe

Single Acoustic Wave

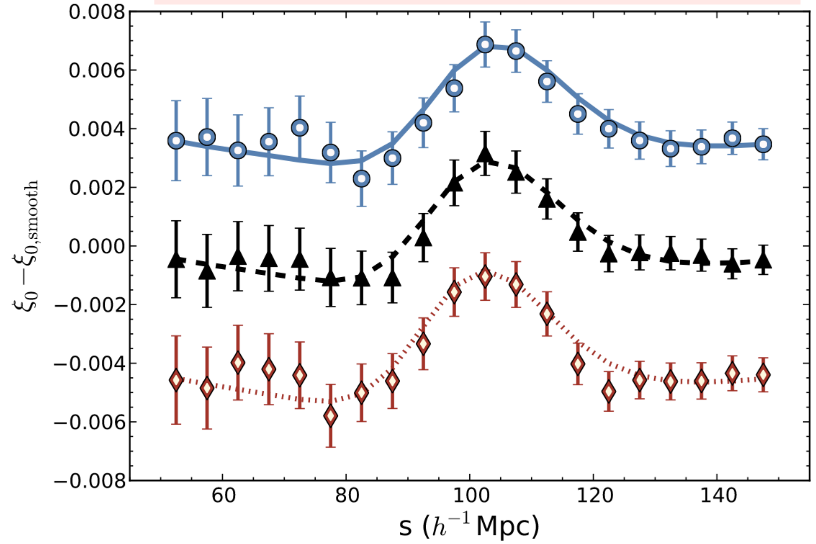


In the Real Universe

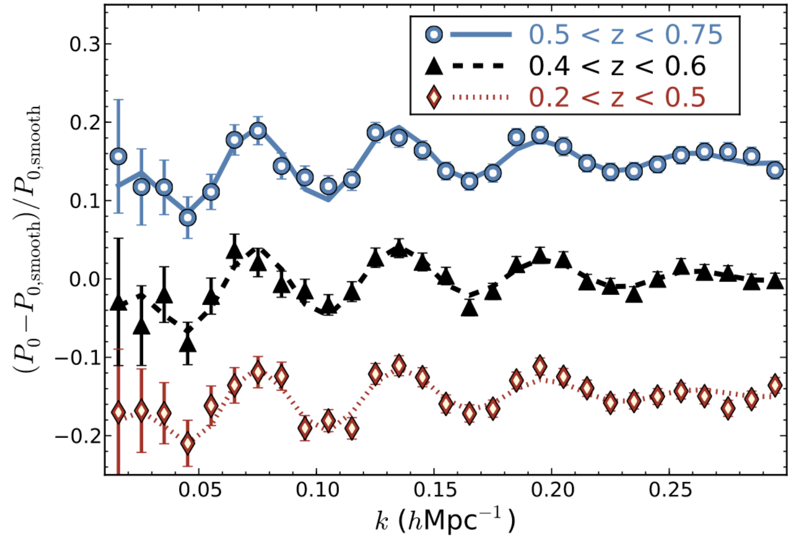


Derive the BAO signal from galaxy clustering

BAO peak in the 2-points correlation function



A series of peaks in the power spectrum

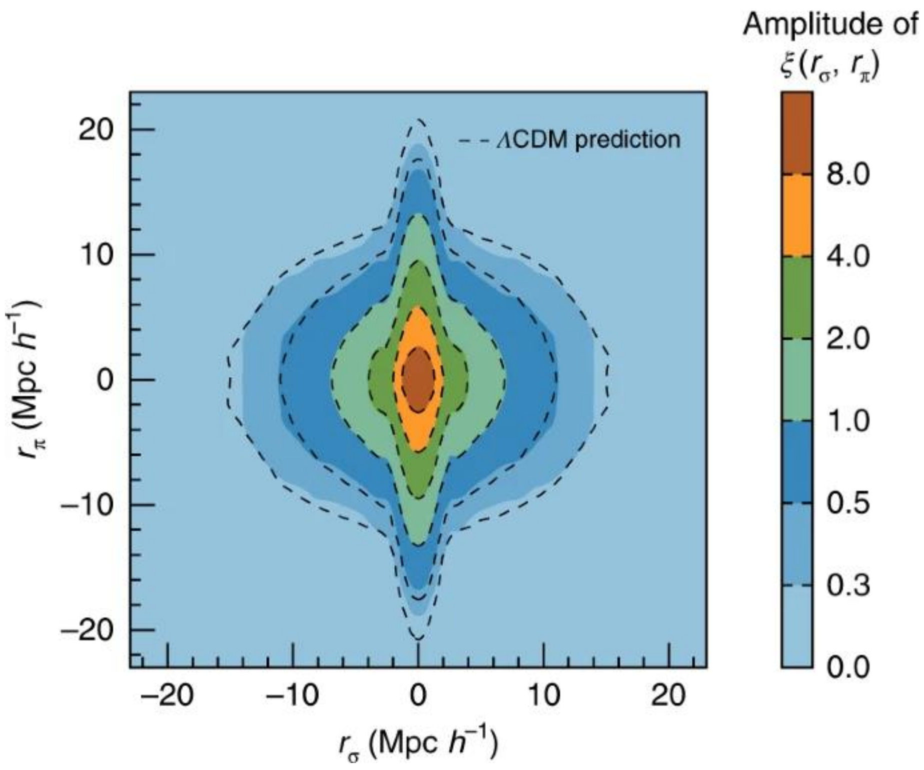


Credit: Daniel Eisenstein

Step into the real universe: Redshift Space Distortion

- Galaxies are not just in the Hubble flow…

Galaxy line of sight velocity = Hubble flow + Peculiar velocity



Redshift-space galaxy power spectrum

Real-space matter power spectrum

$$P_g(k,\mu) = [b_g(z) + \mu^2 f(z)]^2 P(k)$$

$$\beta = f(z)/b_g(z)$$

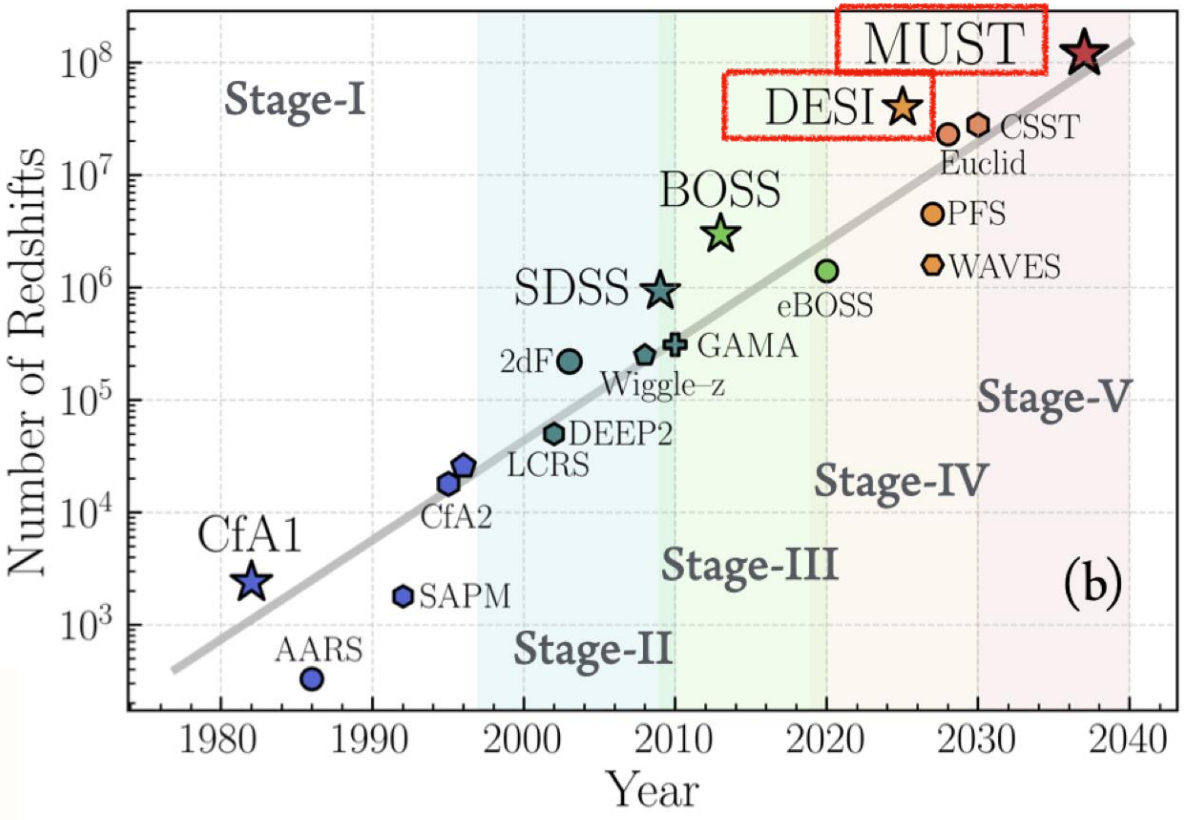
Containing the information for the growth of structure:

$$f(z)\sigma_8(z)$$

Cosmological Spectroscopic Survey

- For BAO & RSD measurement:
  - Require precise distance measurement
  - Require to map enormous volume of the universe

Ongoing Stage-IV survey DESI
& Upcoming Stage-V survey MUST



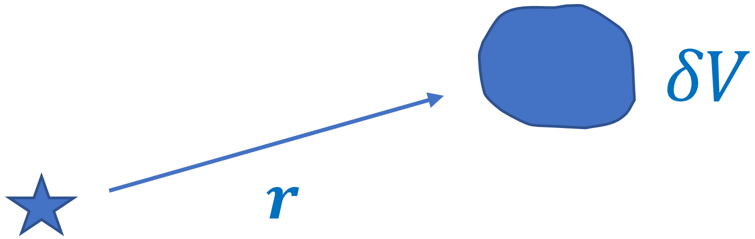
Observation

- How can we estimate the BAO scale? **2-point correlation function**

Theoretically: spatial average of overdensity $\xi(r) = \langle \delta(\boldsymbol{x})\delta(\boldsymbol{x}+\boldsymbol{r}) \rangle$

Observationally: the **excess probability** of finding another tracer

$$\delta P = n[1 + \xi(r)]\delta V$$



Observation

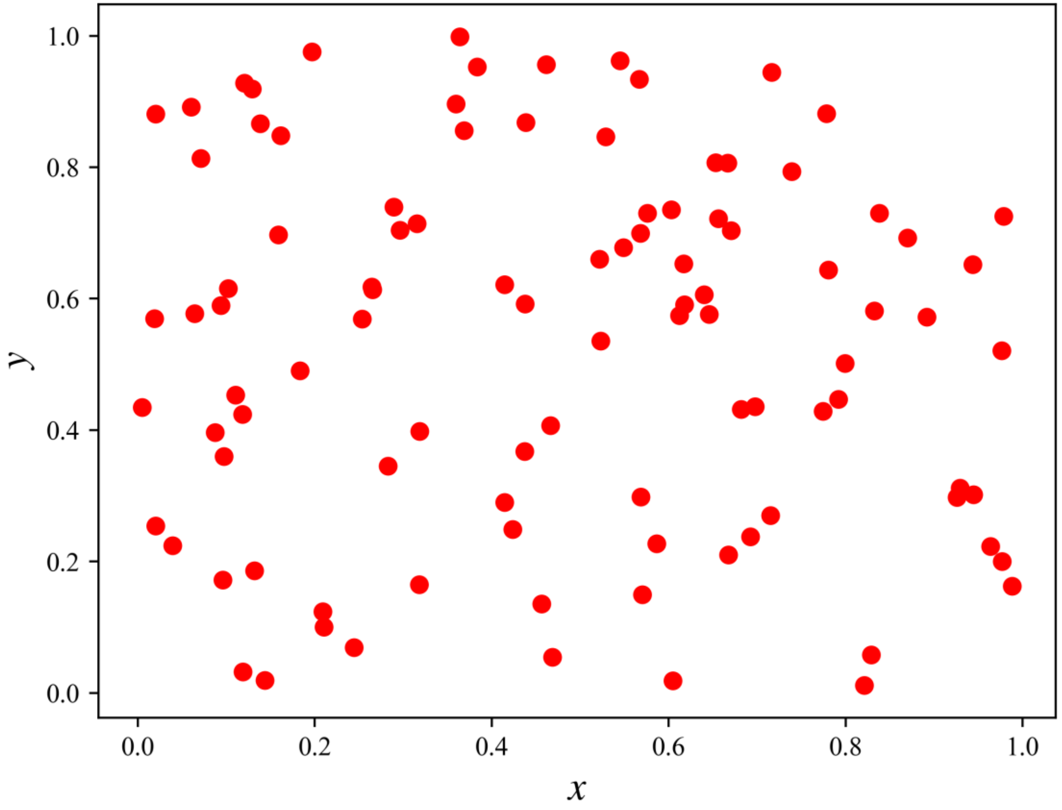
- How to measure the correlation function? **Counting Pairs**

Trivial Estimator:

$$\xi(r) = \frac{DD}{RR} - 1$$

Landy-Szalay Estimator: (1993)

$$\xi(r) = \frac{DD - 2DR + RR}{RR}$$



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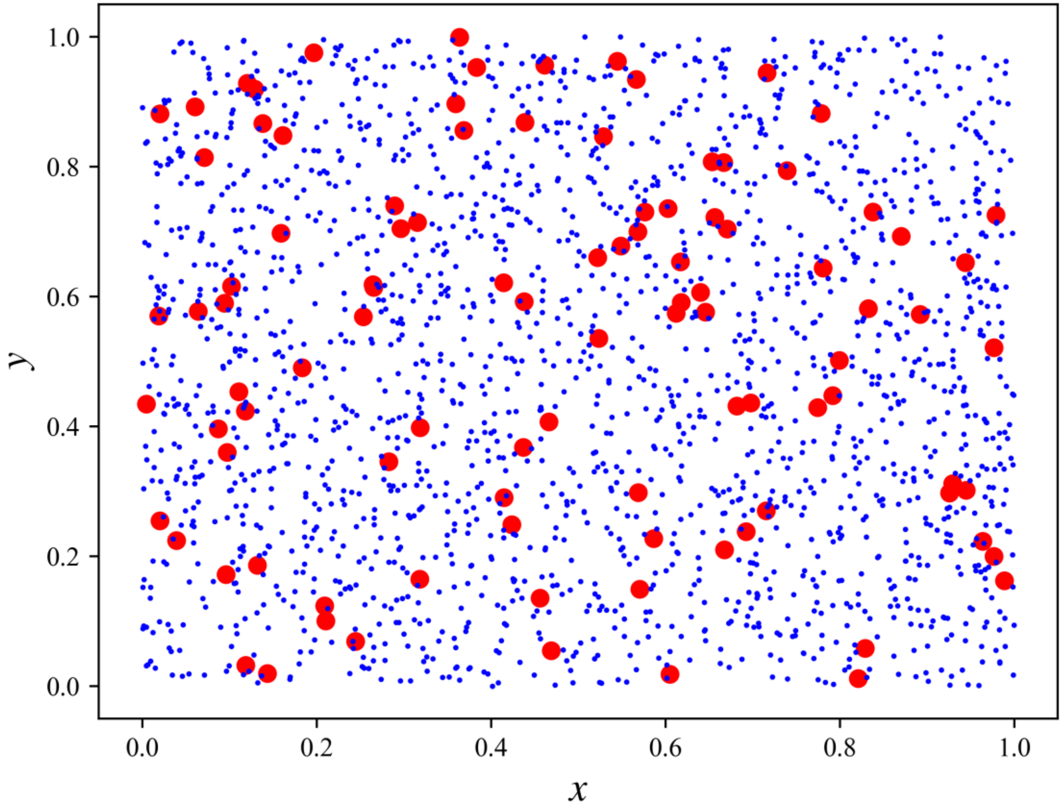


Observation

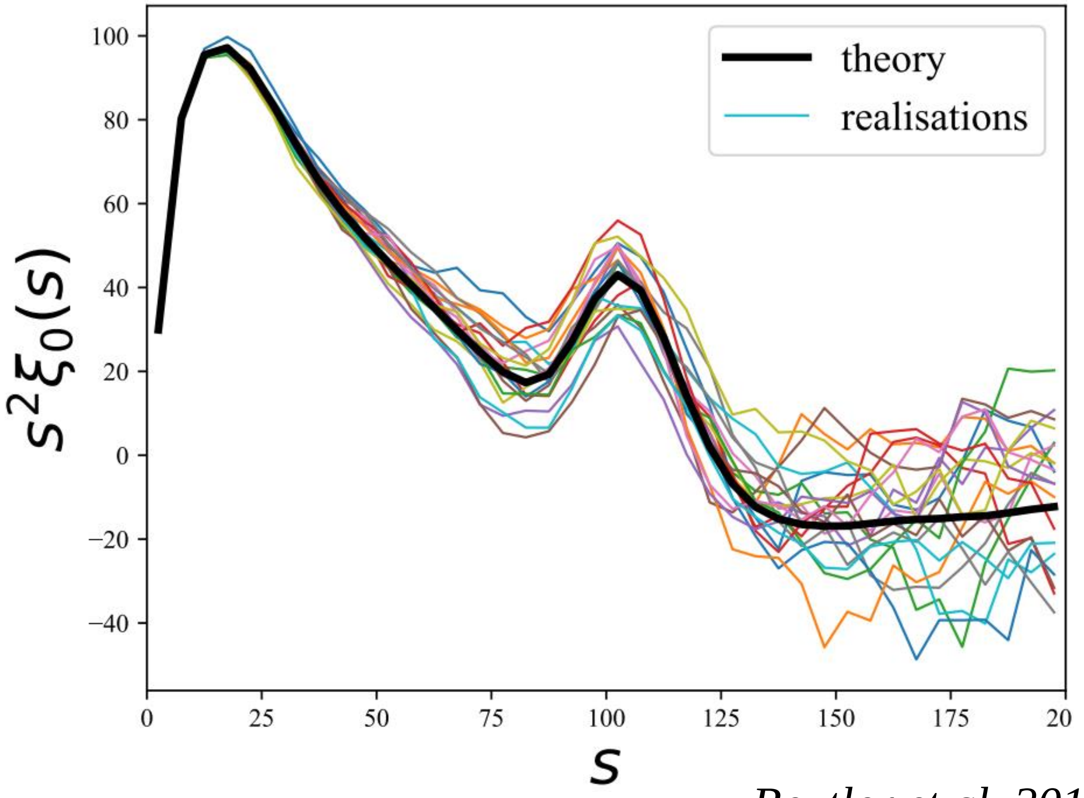
- How to estimate the error bar? **<u>Running simulations</u>**

Sources of statistical uncertainty:

1. Limited survey volume: <u>Cosmic Variance</u>

2. Discrete sampling: <u>Shot Noise</u>

$$Cov = \frac{1}{N-1}\sum_{n=1}^{N}(\xi_i - \bar{\xi})(\xi_i - \bar{\xi})^T$$



Beutler et al. 2011

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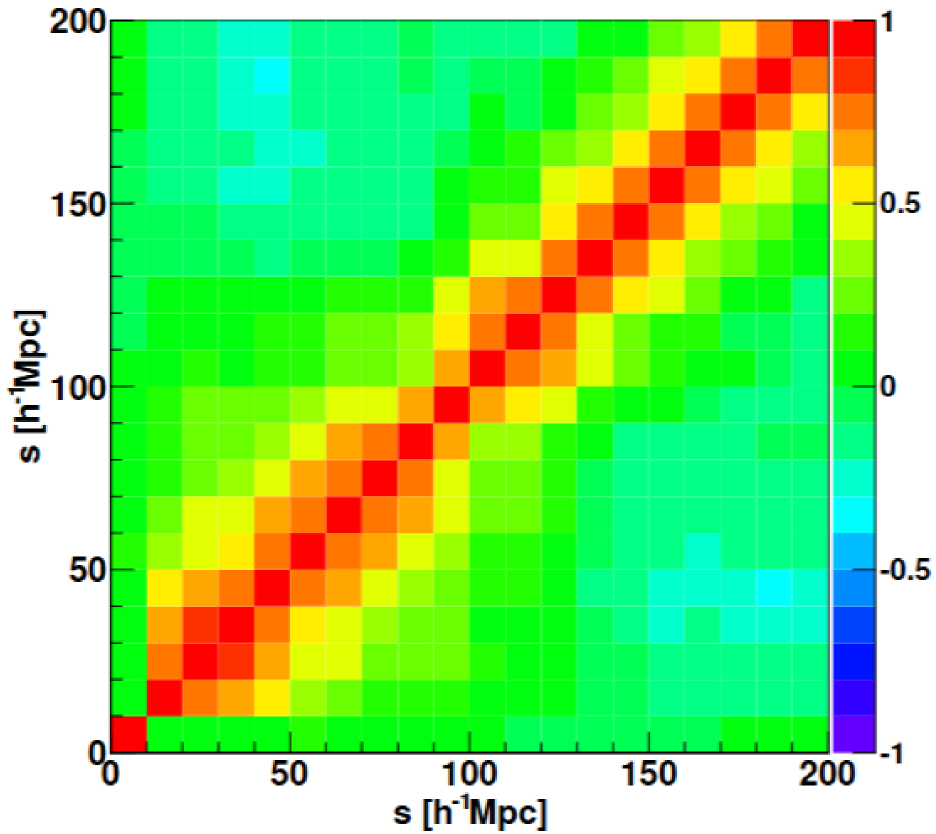


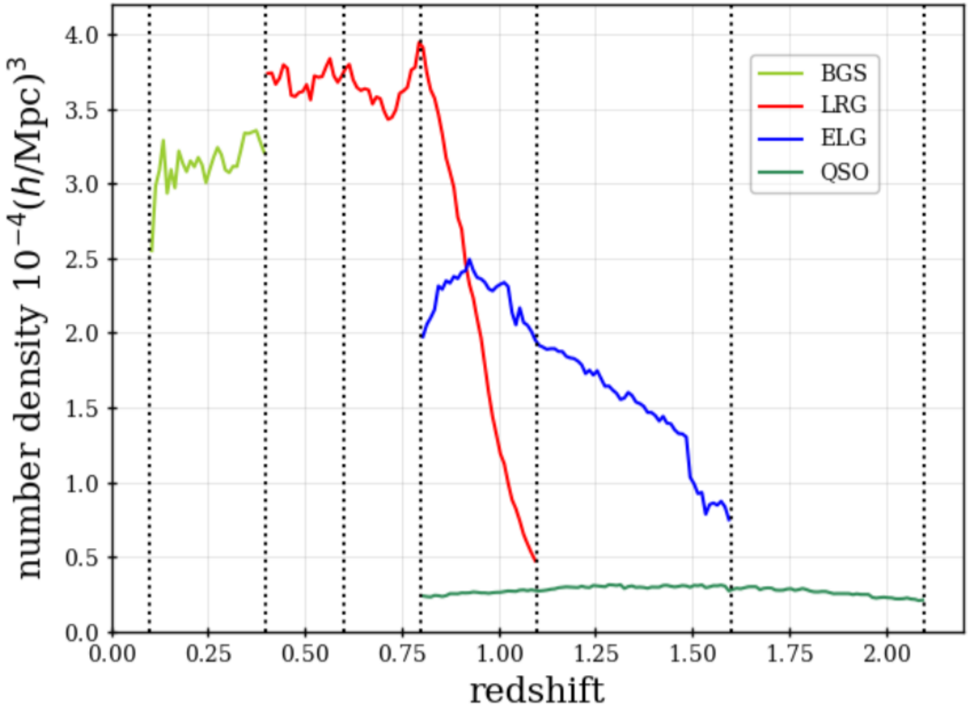
Beutler et al. 2011

Observation

- Which targets do we need to observe?   **<u>Target Selection</u>**

1. High number density
2. Distinguishable features to measure redshift

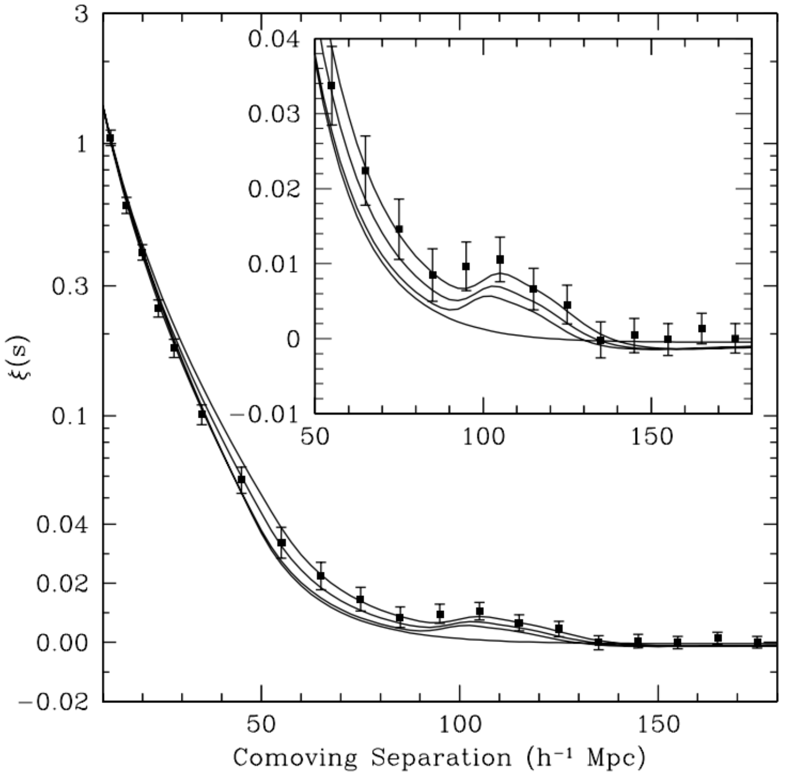
- Luminous Red Galaxies (**LRG**): break at 4000Å
- Emission Line Galaxies (**ELG**): [O II] doublet emission
- Quasi-stellar Objects (**QSO**): Lyα, Mg II, C IV emissions
- Bright Galaxy Sample (**BGS**) (low-z), Lyman-α Forest (high-z), …



DESI 2024 III

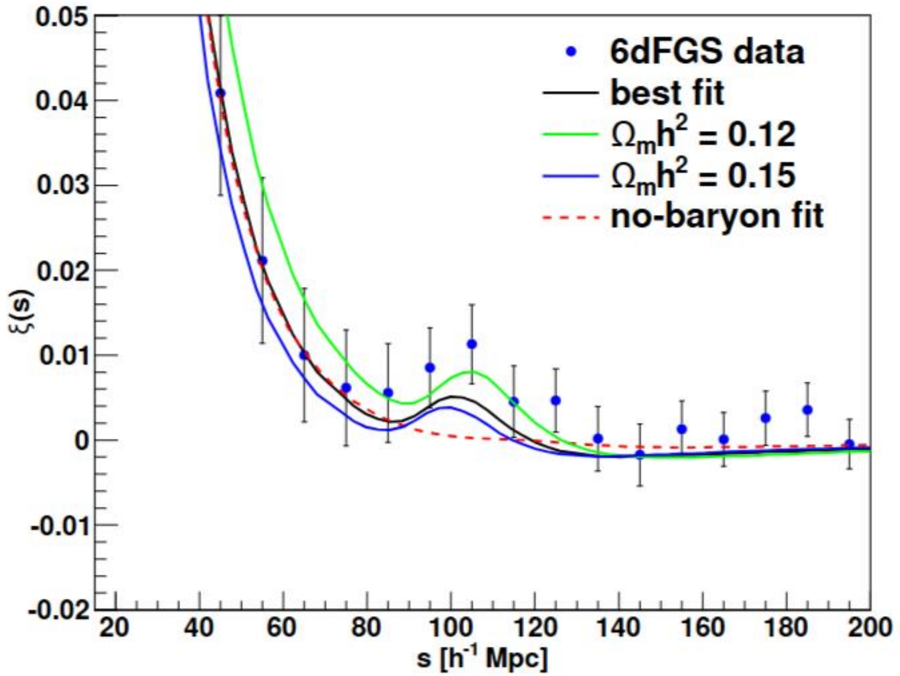
Observation

Eisenstein et al. 2005



SDSS 46,748 LRGs

Beutler et al. 2011



6dFGS 75,117 galaxies

Observation

DESI 2024 III: BAO from Galaxies and Quasars

BGS: 300,017, $z_{\text{eff}} = 0.30$

LRG1: 506,905, $z_{\text{eff}} = 0.51$

LRG3+ELG1: 1,876,164, $z_{\text{eff}} = 0.93$

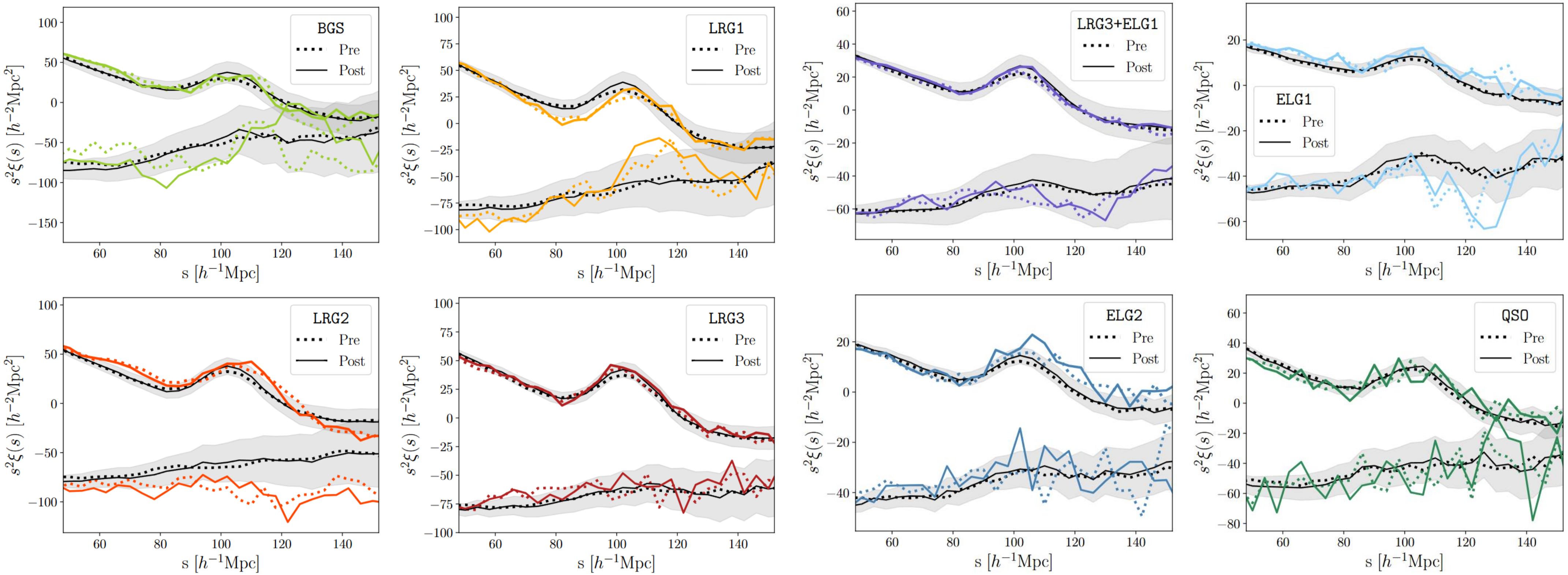
ELG1: 1,016,340, $z_{\text{eff}} = 0.95$

LRG2: 771,875, $z_{\text{eff}} = 0.71$

LRG3: 859,824, $z_{\text{eff}} = 0.92$

ELG2: 1,415,687, $z_{\text{eff}} = 1.32$

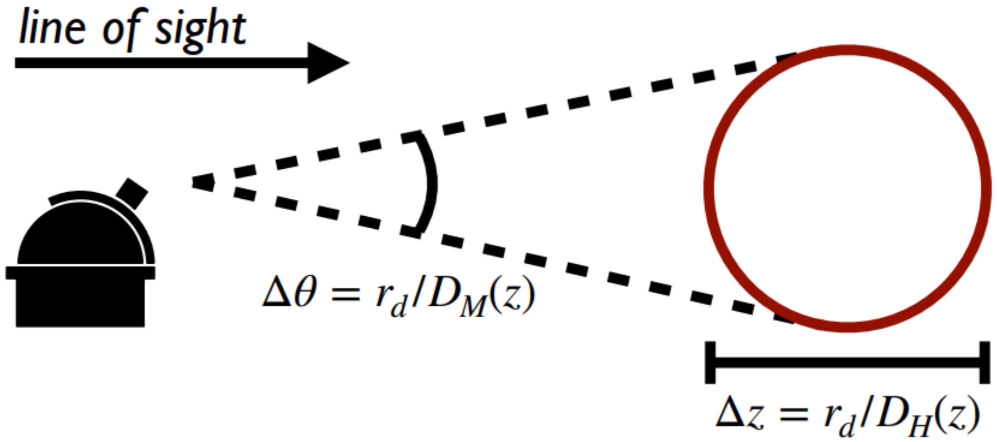
QSO: 1,016,340, $z_{\text{eff}} = 1.49$



Observation

- But where is cosmological parameters?

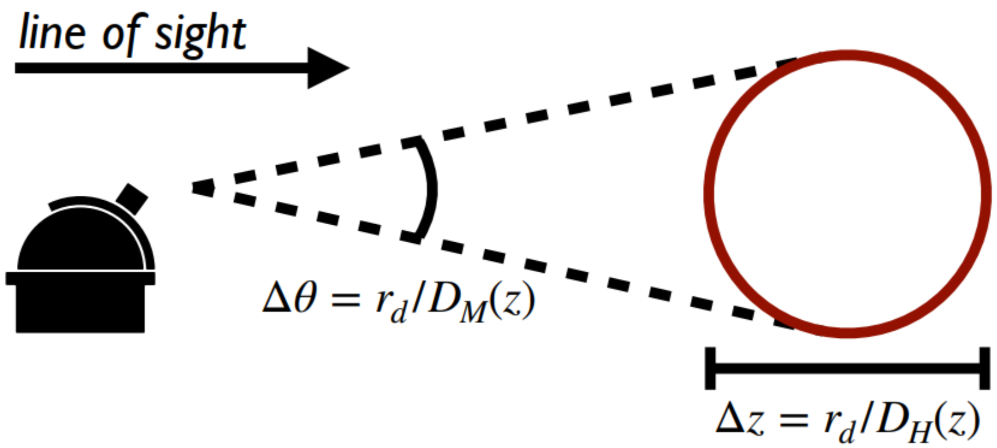
Observation



- But where is <u>cosmological parameters</u>?

We always assume a fiducial cosmology when <u>**calculating distances**</u>!

Observation



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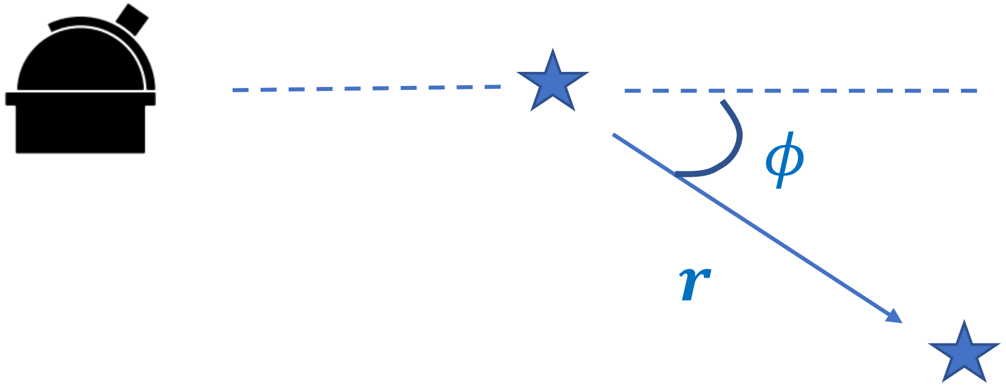
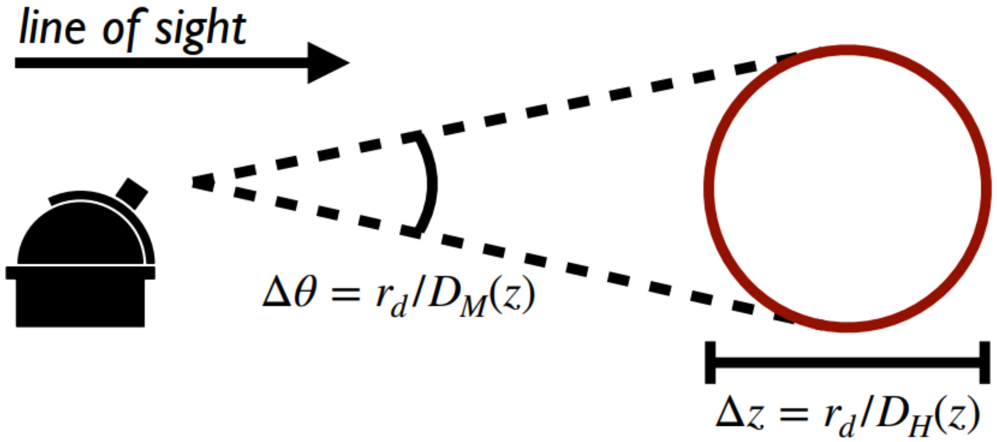
$\xi(r)$? $\xi(r, \cos\phi)$!



Observation



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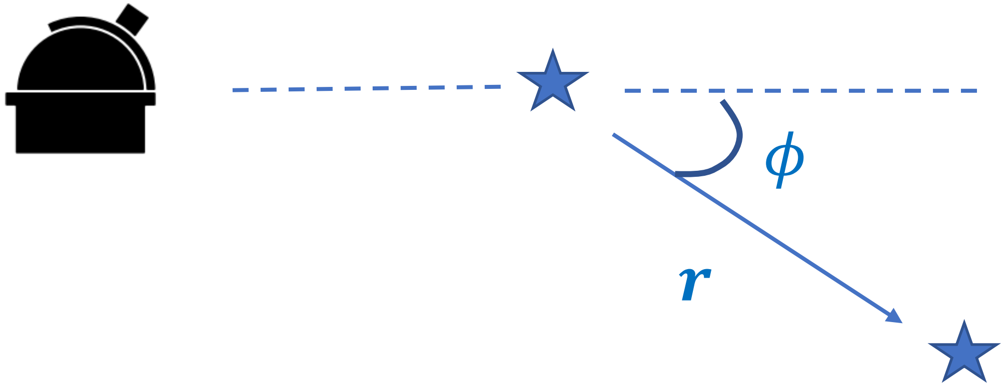
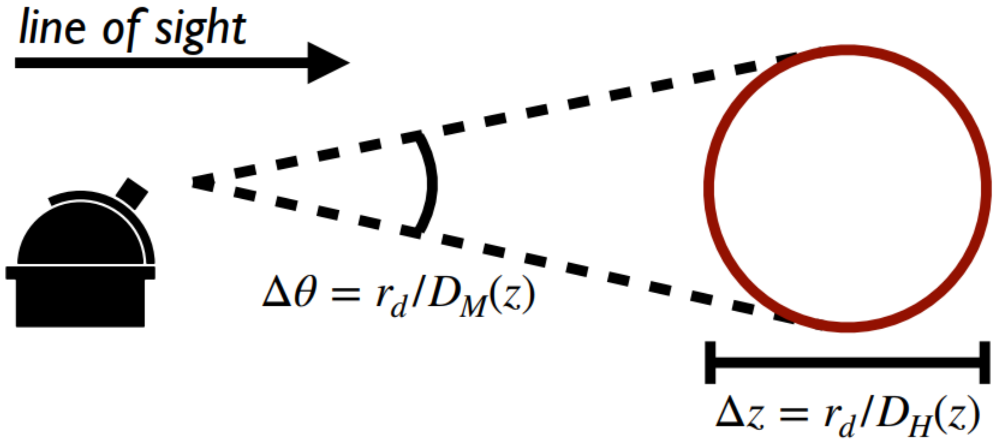


Multipole Expansion:

$$\xi_l(r) = \int_{-1}^{1} L_l(\cos\phi)\,\xi(r,\cos\phi)\ \mathrm{d}\cos\phi$$

$L_l(\cos\phi)$: Legendre polynomials

Observation



$$\alpha_\parallel = \frac{[H(z)r_d]^{\mathrm{fid}}}{H(z)r_d}$$

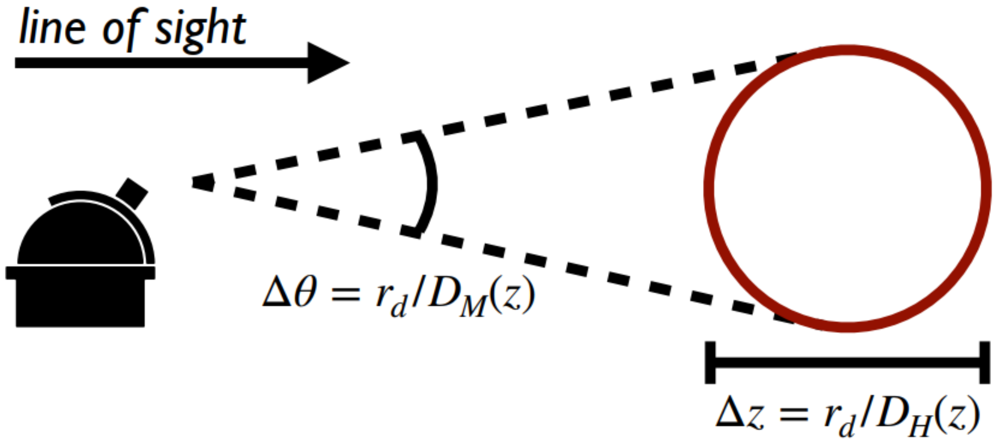
$$\alpha = \alpha_\perp^{2/3}\alpha_\parallel^{1/3} \text{ : Isotropy}$$

$$\alpha_\perp = \frac{D_M(z)/r_d}{[D_M(z)/r_d]^{\mathrm{fid}}}$$

$$1+\epsilon = \left(\frac{\alpha_\parallel}{\alpha_\perp}\right)^{1/3} \text{: Anisotropy}$$

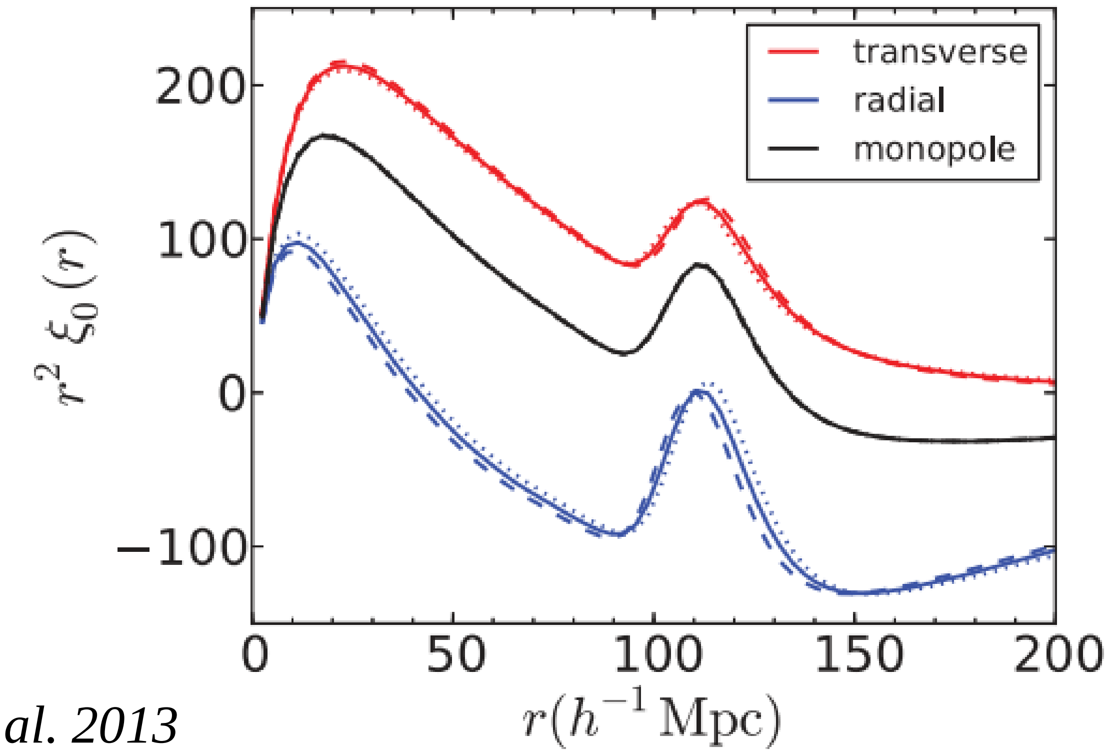
$$\xi_0(r)^{\mathrm{measure}} \approx \xi_0(\alpha r)^{\mathrm{true}} \text{: Isotropic Shift of BAO peak!}$$

Observation

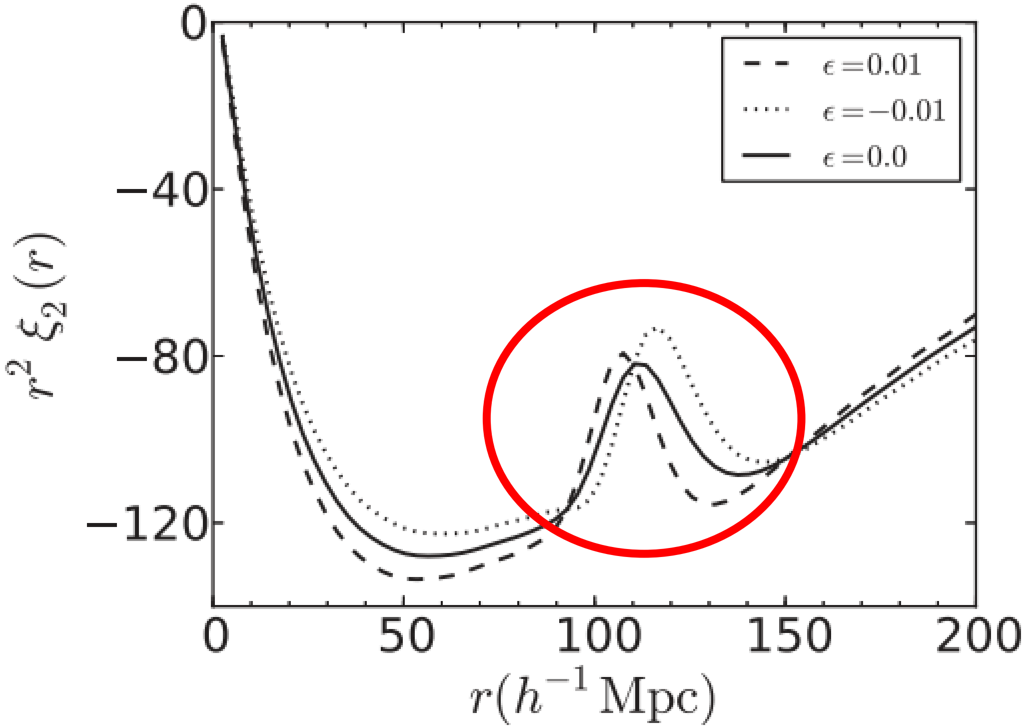


$$1 + \epsilon = (\alpha_{\parallel}/\alpha_{\perp})^{1/3}$$

$l = 0$



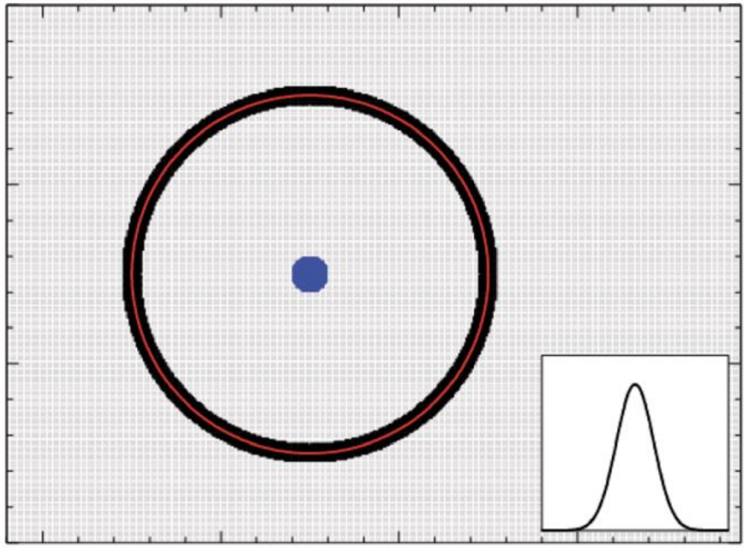
$l = 2$

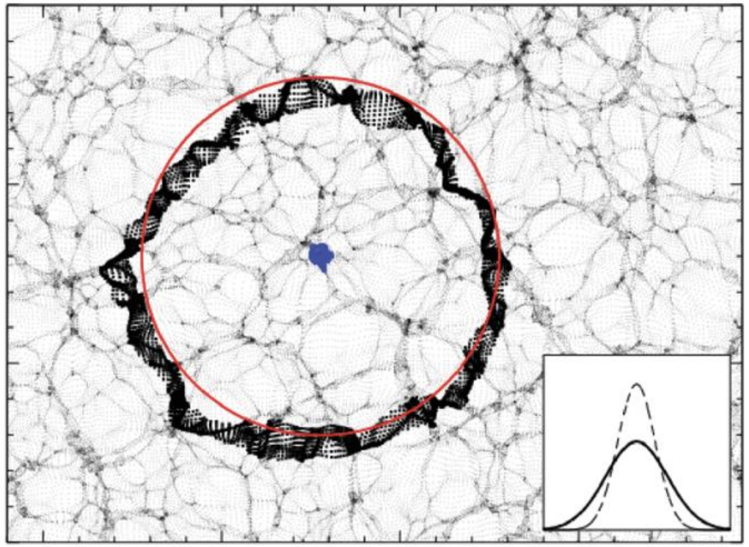


Xu et al. 2013

The distortion of BAO Signal

- **Non-linear gravitational effect:** Influences galaxy position





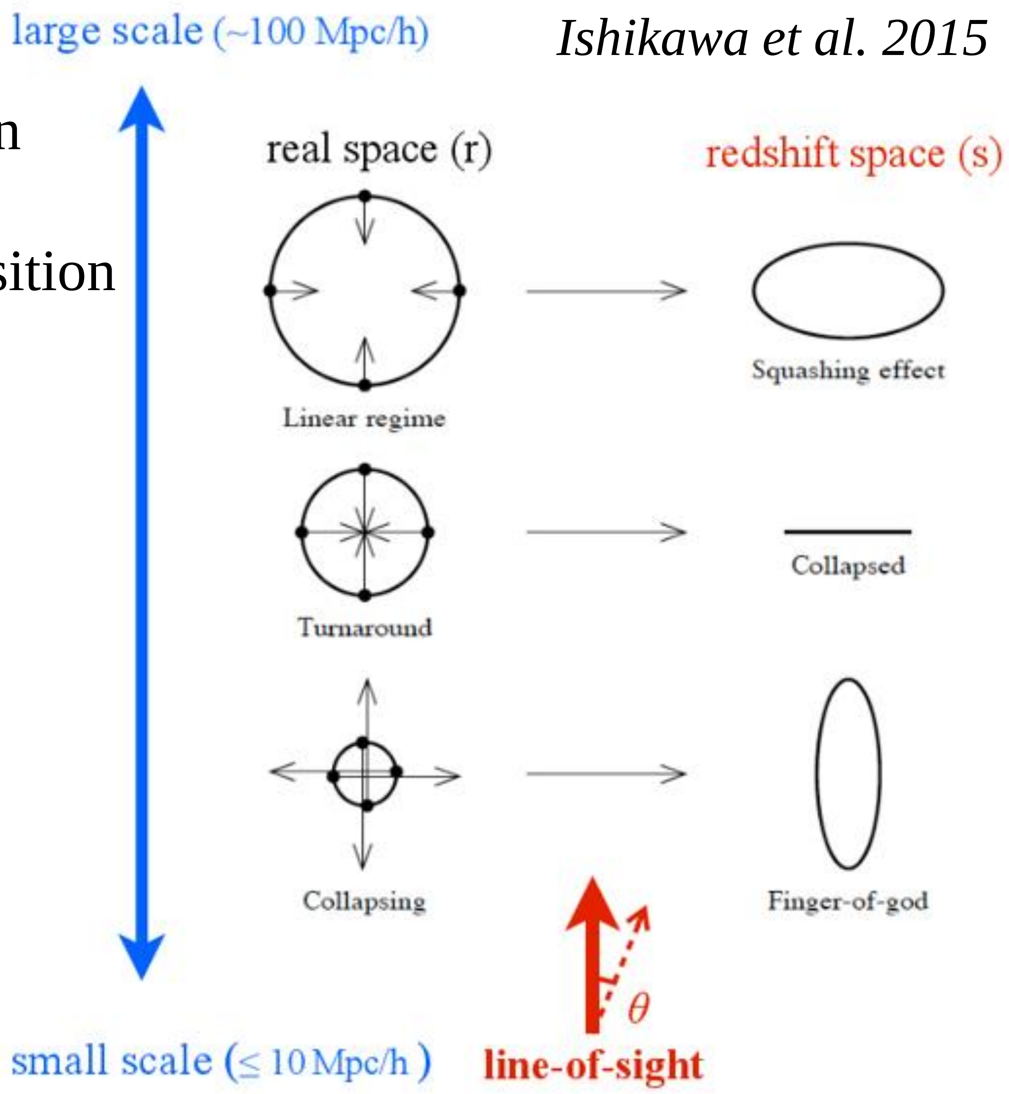
Padmanabhan et al. 2012

The distortion of BAO Signal

- **Non-linear gravitational effect:** Influences galaxy position
- **Redshift-space distortion:** Influences observed galaxy position

$$z = z_{\mathbf{Hubble}} + z_{\mathbf{peculiar}}$$

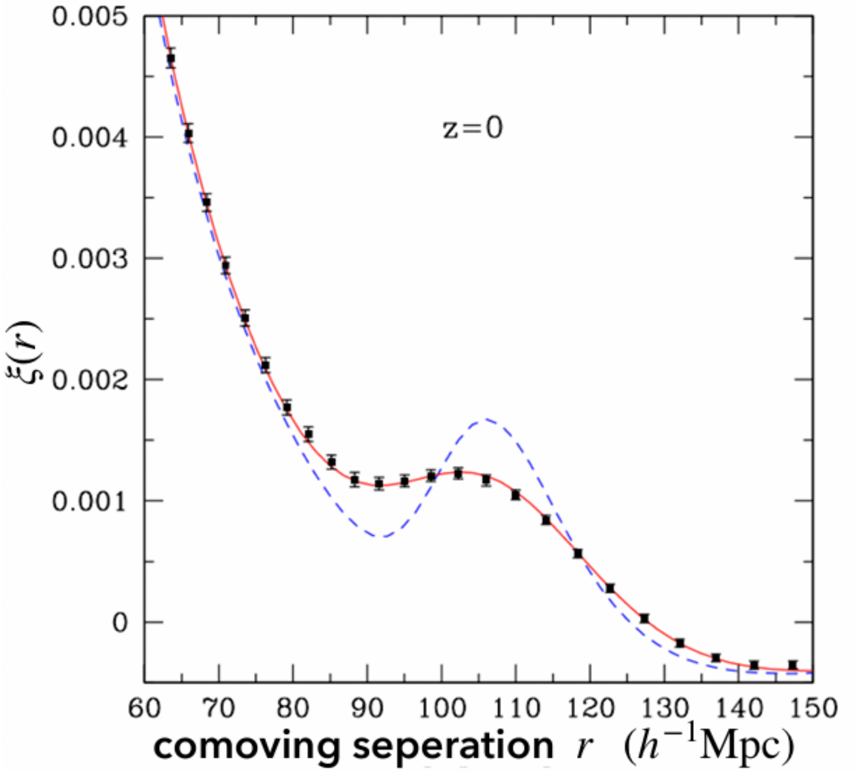
Ishikawa et al. 2015



Why BAO Reconstruction

- **Non-linear gravitational effect:** Influences galaxy position
- **Redshift-space distortion:** Influences observed galaxy position

Broaden and shift BAO peak



Moscardini et al. 2017

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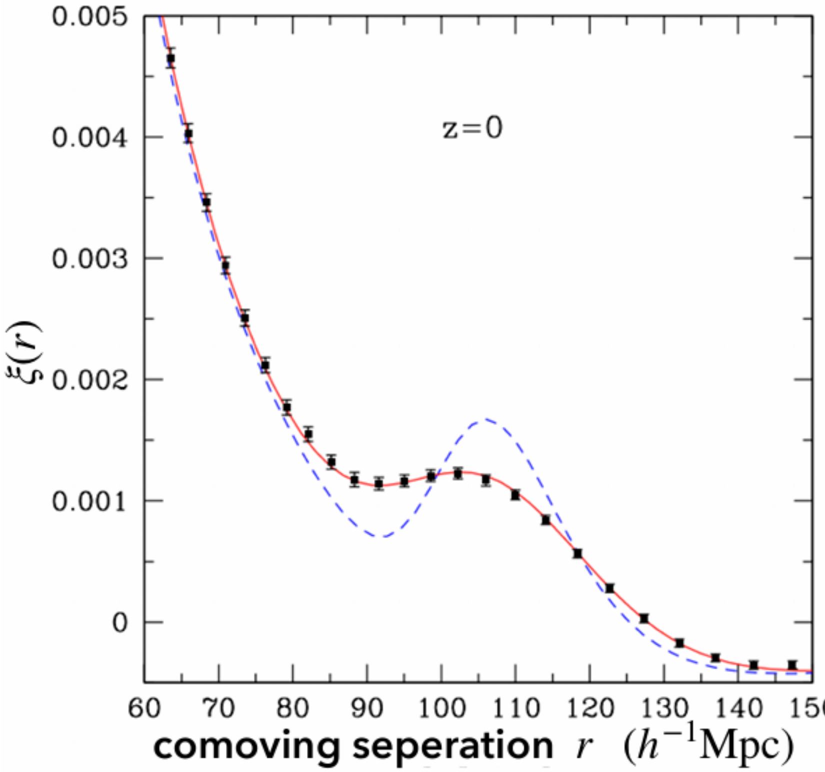
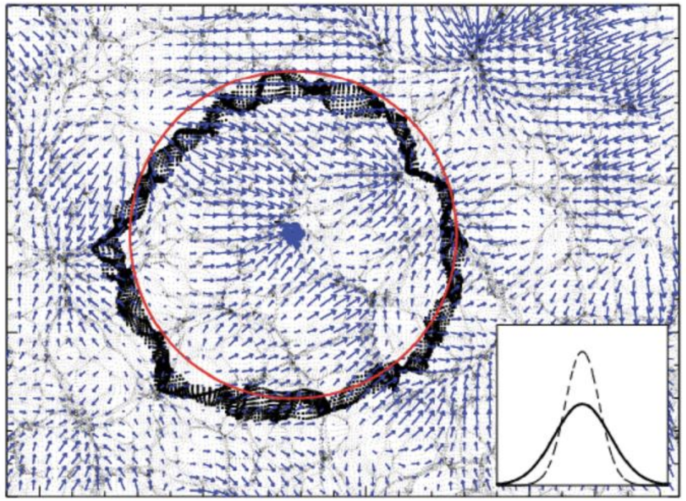


To enhance the S/N of BAO signal

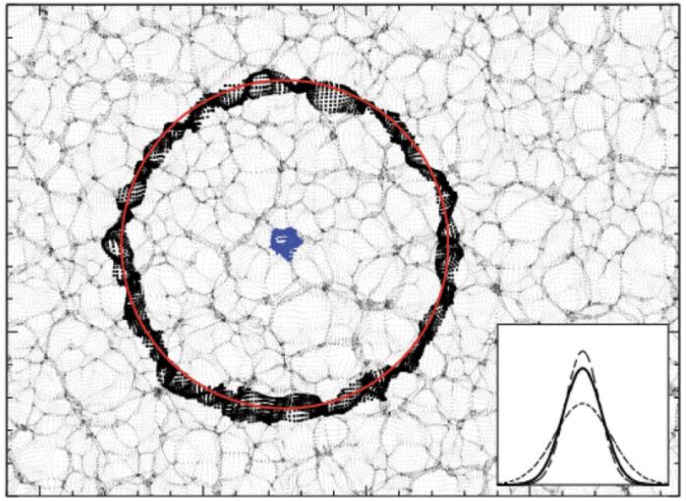
BAO Reconstruction

Moscardini et al. 2017

How to Reconstruct BAO



detected density distribution field

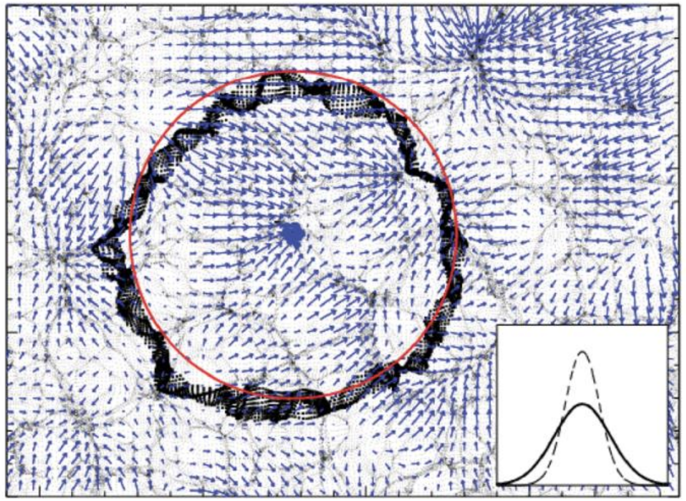


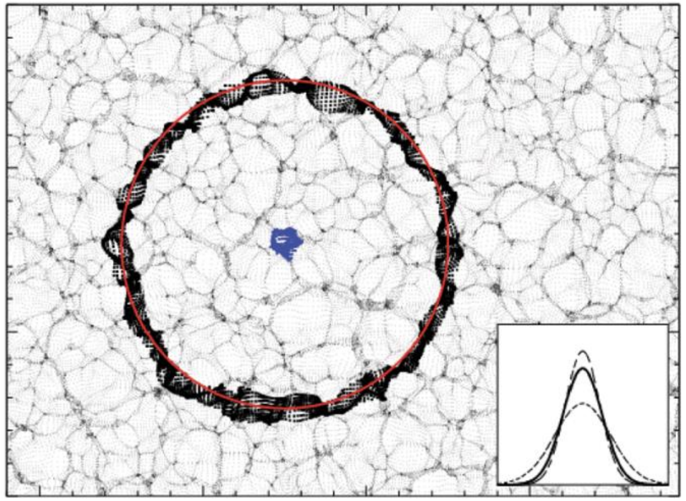
recovered density distribution field

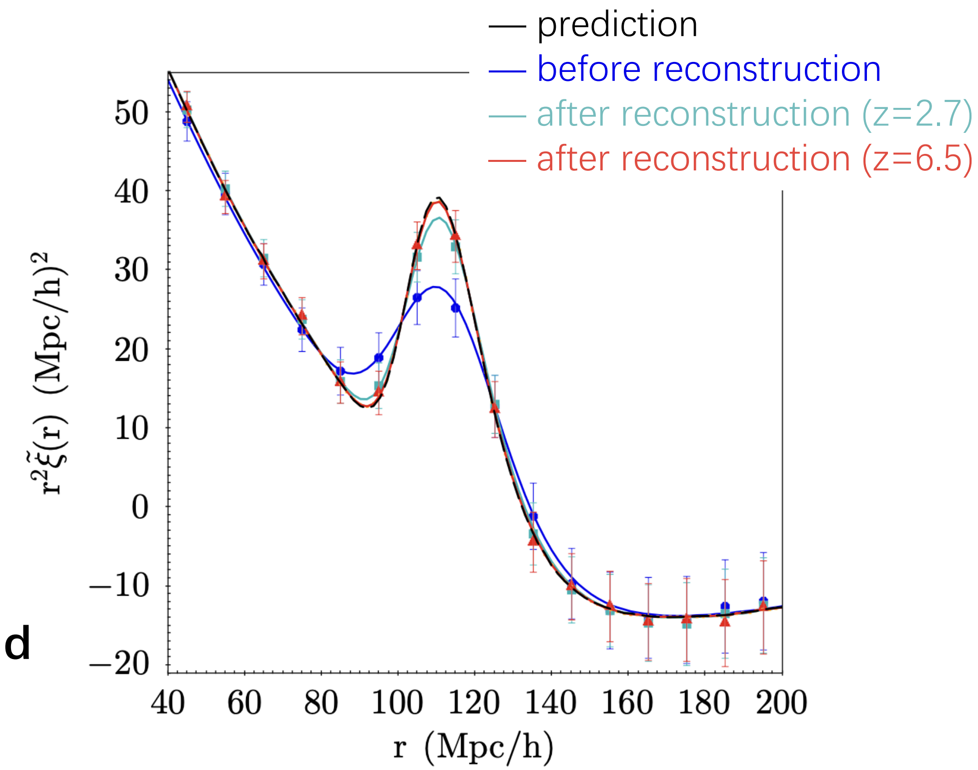
displacement field

Padmanabhan et al. 2012

How to Reconstruct BAO







detected density distribution field **recovered density distribution field**

displacement field

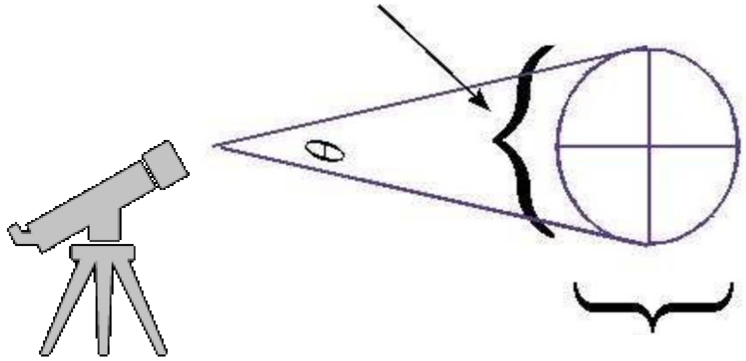
Padmanabhan et al. 2012

E. Sarpa et al, 2018

Cosmological constraints

Observable: $D_A(z)/r_d$, $H(z)r_d$

$$\Delta\theta = r_d/[(1+z)D_A(z)]$$



$$\Delta z = r_d H(z)/c$$

Cosmological constraints

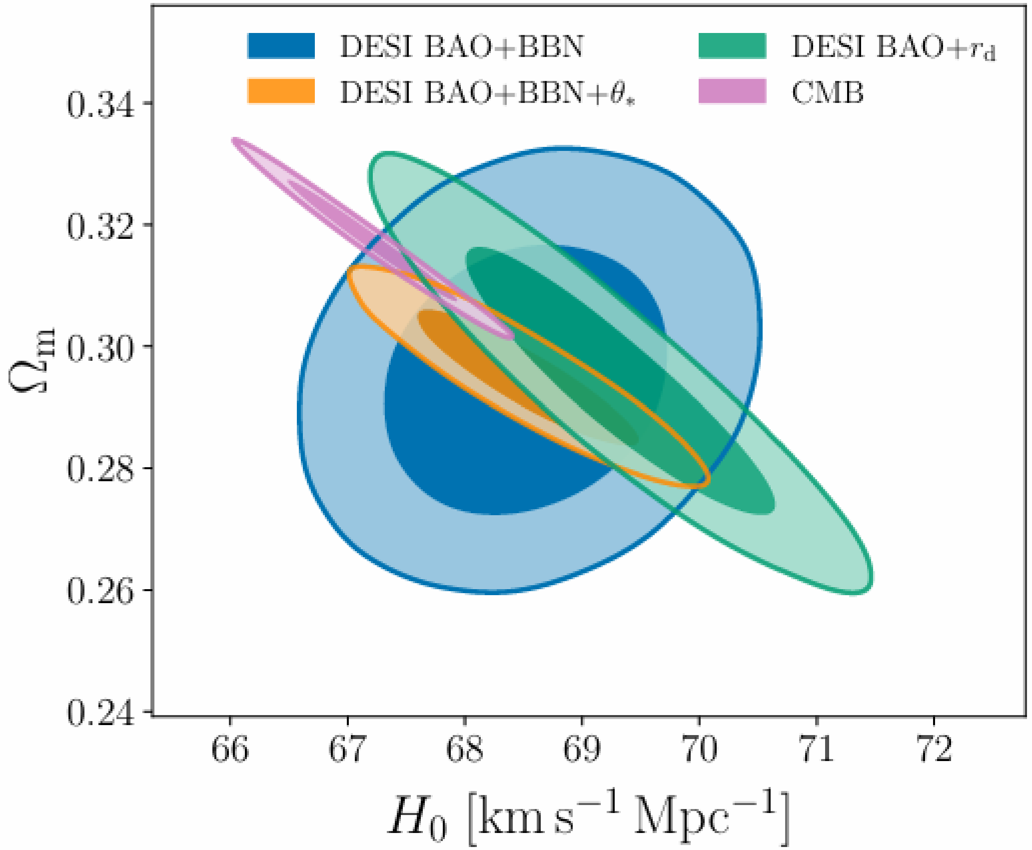
$r_d h$ degeneracy

Combined with BBN, CMB, SN…

Observable: $D_A(z)/r_d$, $H(z)r_d$

FlatΛCDM

$$H(z) = H_0\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}$$



DESI 2024 VI

Cosmological constraints

$r_d h$ degeneracy

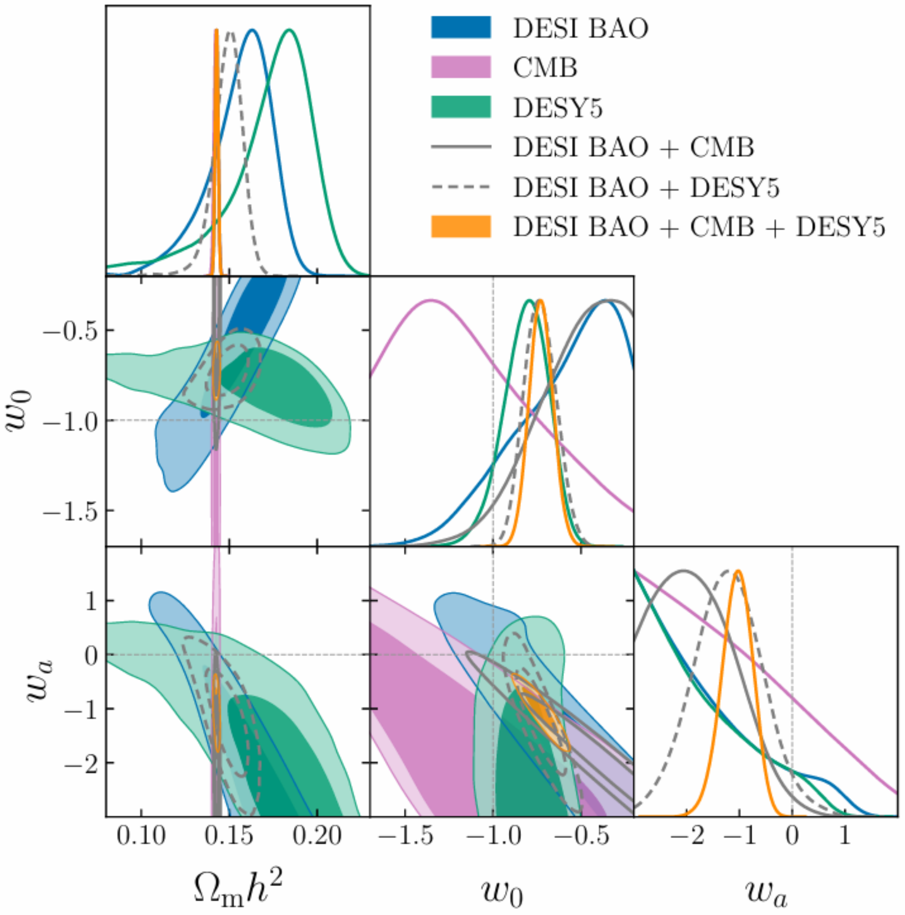
Combined with BBN, CMB, SN…

Observable: $D_A(z)/r_d$, $H(z)r_d$

$$\mathrm{Flat}w_0w_a\mathrm{CDM}$$

$$H(z) = H_0\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda(1+z)^{3(1+w(a))}}$$

$$w(a) = w_0 + w_a(1-a)$$



DESI 2024 VI

Summary

- BAO serves as a **standard ruler** and provides measurements of Ω_m and $H_0 r_d$.
- RSD comes from galaxies' **peculiar velocity** and constrains the structure growth.
- BAO signal can be detected with **correlation functions** and can be strengthened with **BAO reconstruction.**
- Current constraint from DESI 2024 (alone):

$$\Omega_m = 0.295 \pm 0.015,$$
$$r_d h = (101.8 \pm 1.3)\ \text{Mpc}$$