BAO measurement from the eBOSS Quasar clustering at z=1.5

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The clustering of the SDSS-IV extended Baryon Oscillation Spectroscopic Survey DR14 quasar sample: First measurement of Baryon Acoustic Oscillations between redshift 0.8 and 2.2

Metin Ata[1], Falk Baumgarten[1,2], Julian Bautista[3], Florian Beutler[4], Dmitry Bizyaev[5,6], Michael R. Blanton[7], Jonathan A. Blazek[8], Adam S. Bolton[3,9], Jonathan Brinkmann[5], Joel R. Brownstein[3], Etienne Burtin[10], Chia-Hsun Chuang[1], Johan Comparat[11], Kyle S. Dawson[3], Axel de la Macorra[12], Wei Du[13], Hélion du Mas des Bourboux[10], Daniel J. Eisenstein[14], Héctor Gil-Marín⋆[15,16], Katie Grabowski[5], Julien Guy[17], Nick Hand[18], Shirley Ho[19,20,21], Timothy A. Hutchinson[3], Mikhail M. Ivanov[22,23], Francisco-Shu Kitaura[24,25], Jean-Paul Kneib[8,26], Pierre Laurent[10], Jean-Marc Le Goff[10], Joseph E. McEwen[27], Eva-Maria Mueller[4], Adam D. Myers[3], Jeffrey A. Newman[28], Nathalie Palanque-Delabrouille[10], Kaike Pan[5], Isabelle Pâris[26], Marcos Pellejero-Ibanez[24,25], Will J. Percival[4], Patrick Petitjean[29], Francisco Prada[30,31,32], Abhishek Prakash[28], Sergio A. Rodríguez-Torres[30,31,33], Ashley J. Ross†[27,4], Graziano Rossi[34], Rossana Ruggeri[4], Ariel G. Sánchez[11], Siddharth Satpathy[20,35], David J. Schlegel[19], Donald P. Schneider[36,37], Hee-Jong Seo[38], Anže Slosar[39], Alina Streblyanska[24,25], Jeremy L. Tinker[7], Rita Tojeiro[40], Mariana Vargas Magaña[12], M. Vivek[3], Yuting Wang[13,4], Christophe Yèche[10,19], Liang Yu[41], Pauline Zarrouk[10], Cheng Zhao[41], Gong-Bo Zhao‡[13,4], Fangzhou Zhu[42]

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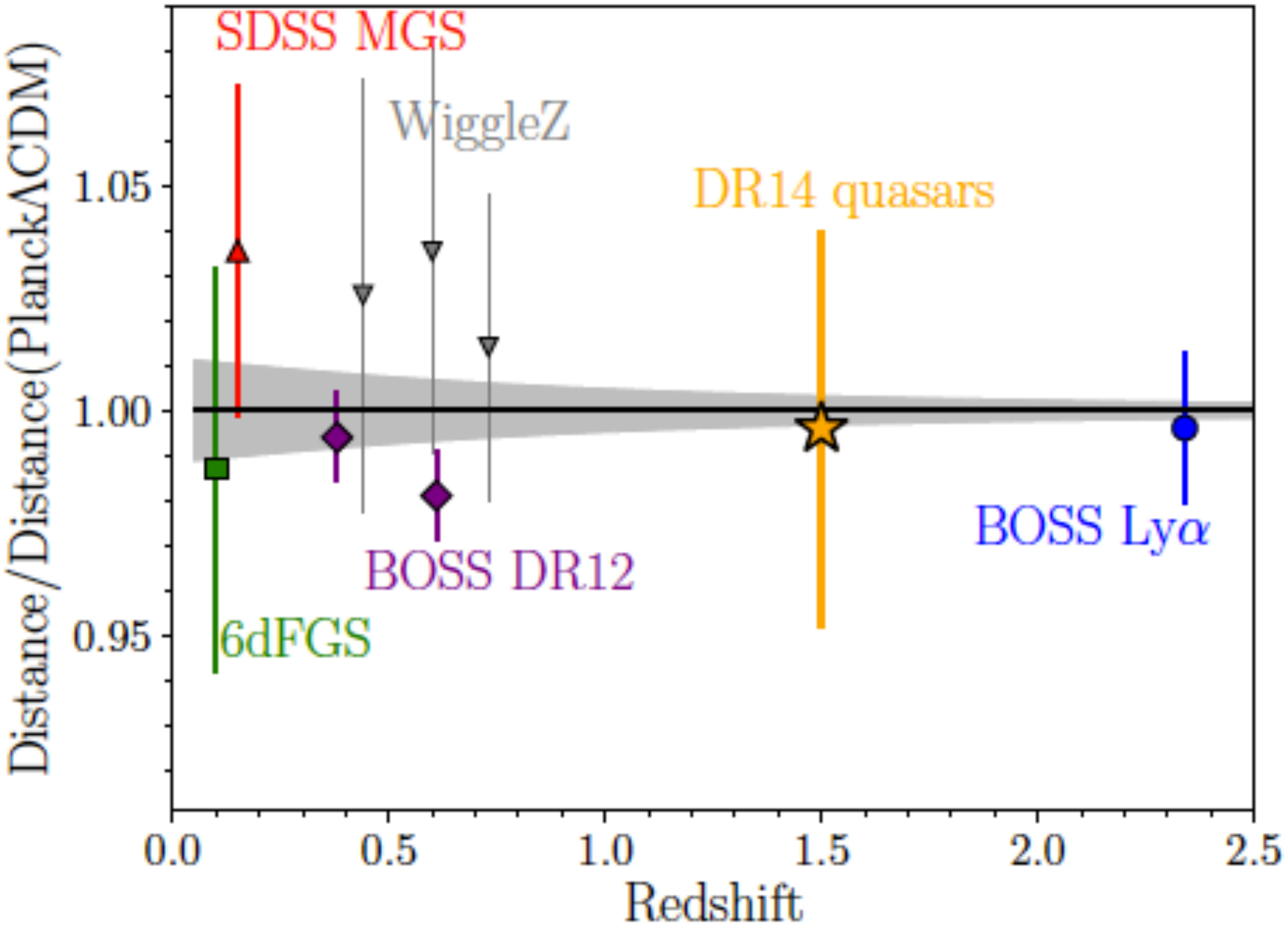
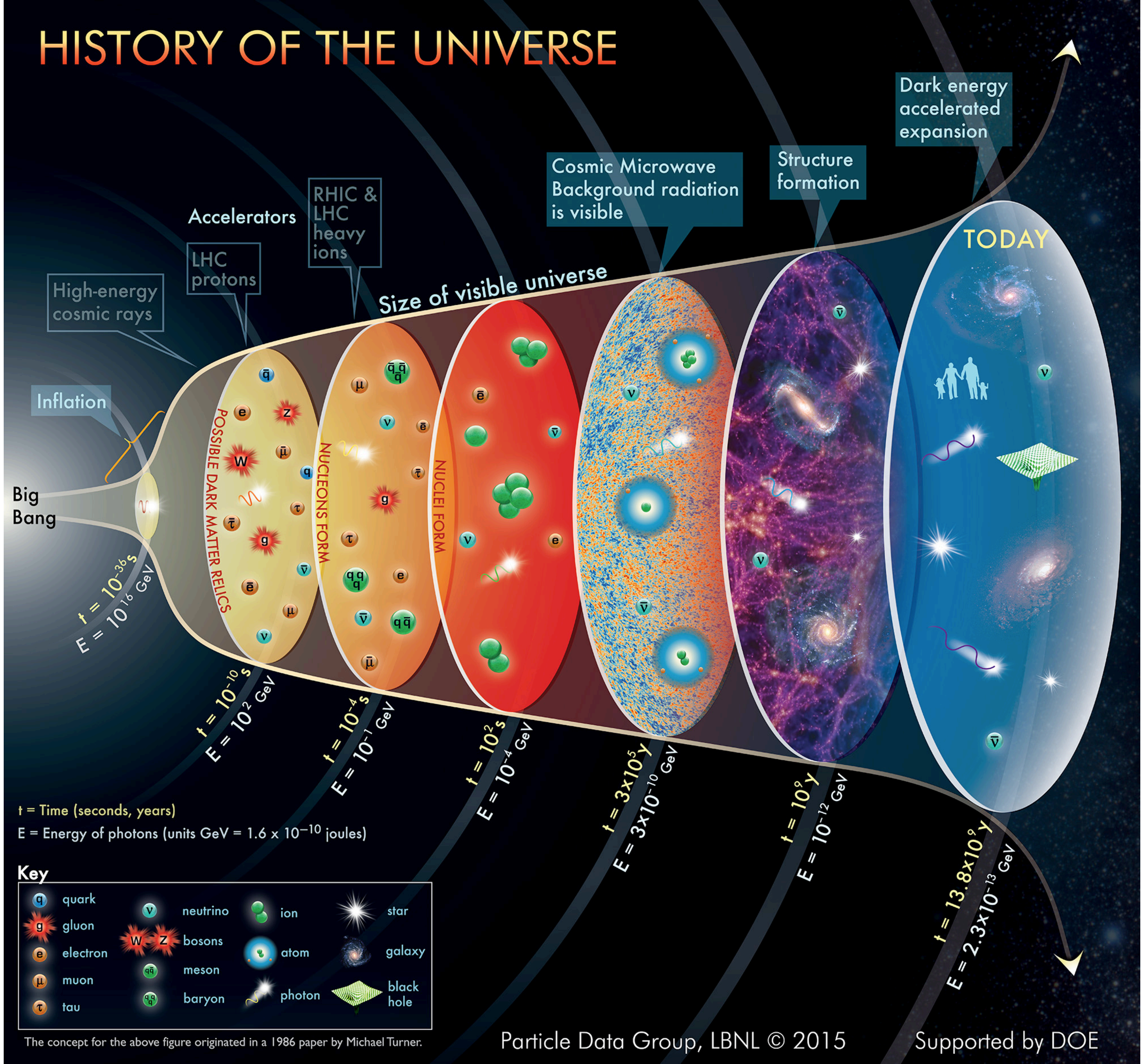


SDSS MGS
WiggleZ
DR14 quasars
BOSS DR12
6dFGS
BOSS Lyα
1.05
1.00
0.95
0.0
0.5
1.0
1.5
2.0
2.5
Redshift
Distance/Distance(PlanckΛCDM)

OUTLINE

- Introduction of Baryon Acoustic Oscillation
- Introduction of the SDSS-IV/eBOSS
- Quasar clustering
- Data analysis
- Results


HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Structure formation
Cosmic Microwave Background radiation is visible
RHIC & LHC heavy ions
Accelerators
LHC protons
High-energy cosmic rays
Size of visible universe
TODAY
Inflation
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
t = 10^{-36} s
E = 10^{16} GeV
t = 10^{-10} s
E = 10^{2} GeV
t = 10^{-4} s
E = 10^{-1} GeV
t = 10^{2} s
E = 10^{-4} GeV
t = 3×10^{5} y
E = 3×10^{-10} GeV
t = 10^{9} y
E = 10^{-12} GeV
t = 13.8×10^{9} y
E = 2.3×10^{-13} GeV
t = Time (seconds, years)
E = Energy of photons (units GeV = 1.6×10^{-10} joules)
Key
quark
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
The concept for the above figure originated in a 1986 paper by Michael Turner.
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Evolution of the scale of our universe

Friedmann Equations:

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{4\pi G\rho}{3} - \mathrm{K}\frac{c^2}{a^2}$$

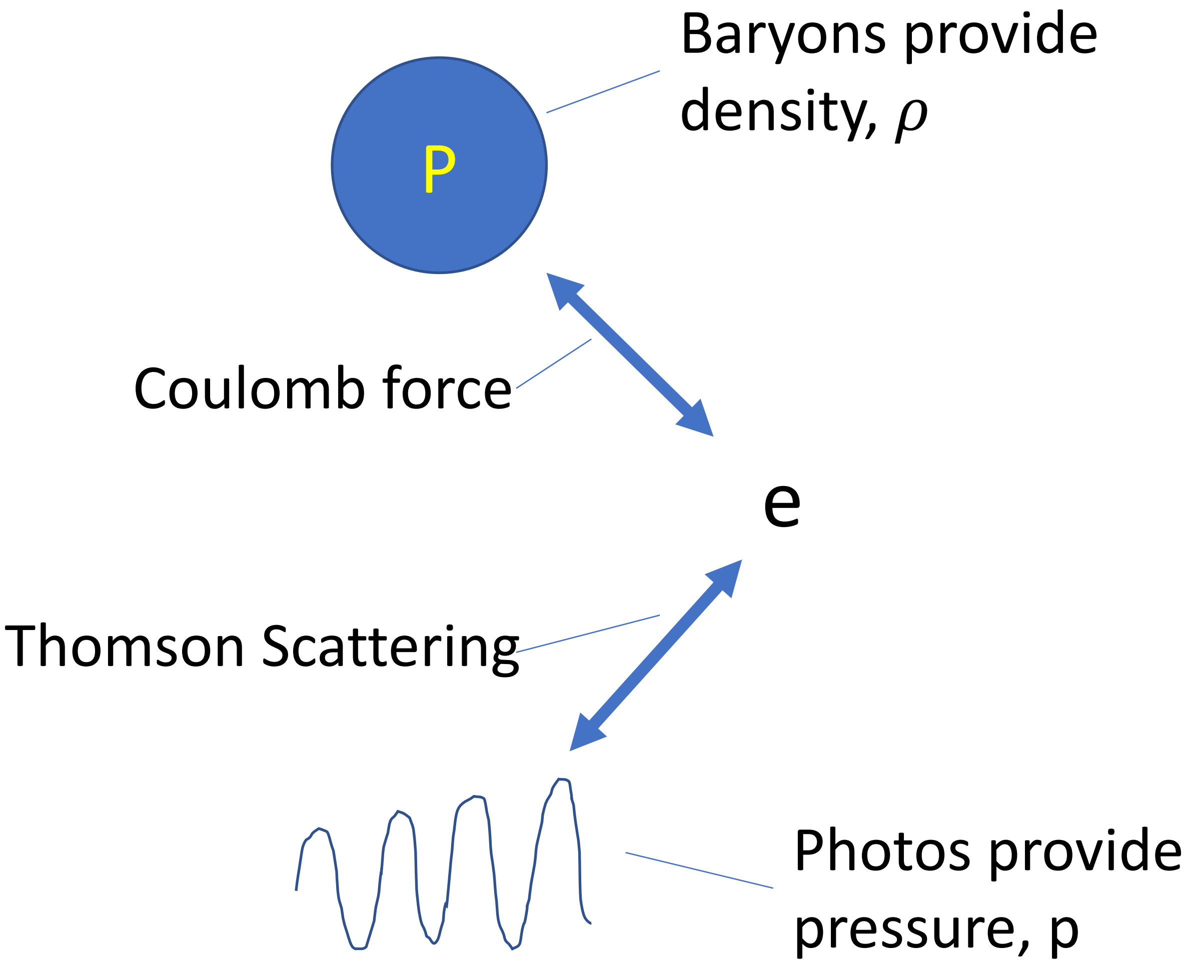
$$\left(\frac{\ddot{a}}{a}\right) = -\frac{4\pi G}{3}\left[\rho + 3P\right]$$

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{4\pi G(\rho_m + \rho_w)}{3} - \mathrm{K}\frac{c^2}{a^2}$$

$$\left(\frac{\ddot{a}}{a}\right) = -\frac{4\pi G}{3}\left[\rho_m + 3w \cdot \rho_w\right]$$

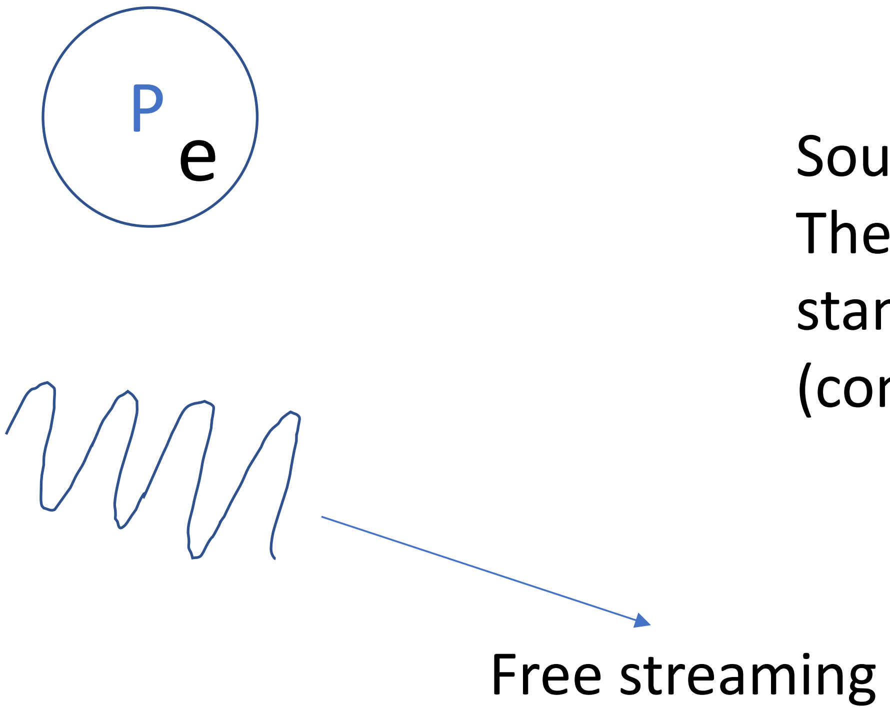
K=0, w=-1 :	LCDM
w=-1:	oLCDM
K=0, w=constant:	wCDM
W=constant:	owCDM

Baryon Acoustic Oscillation



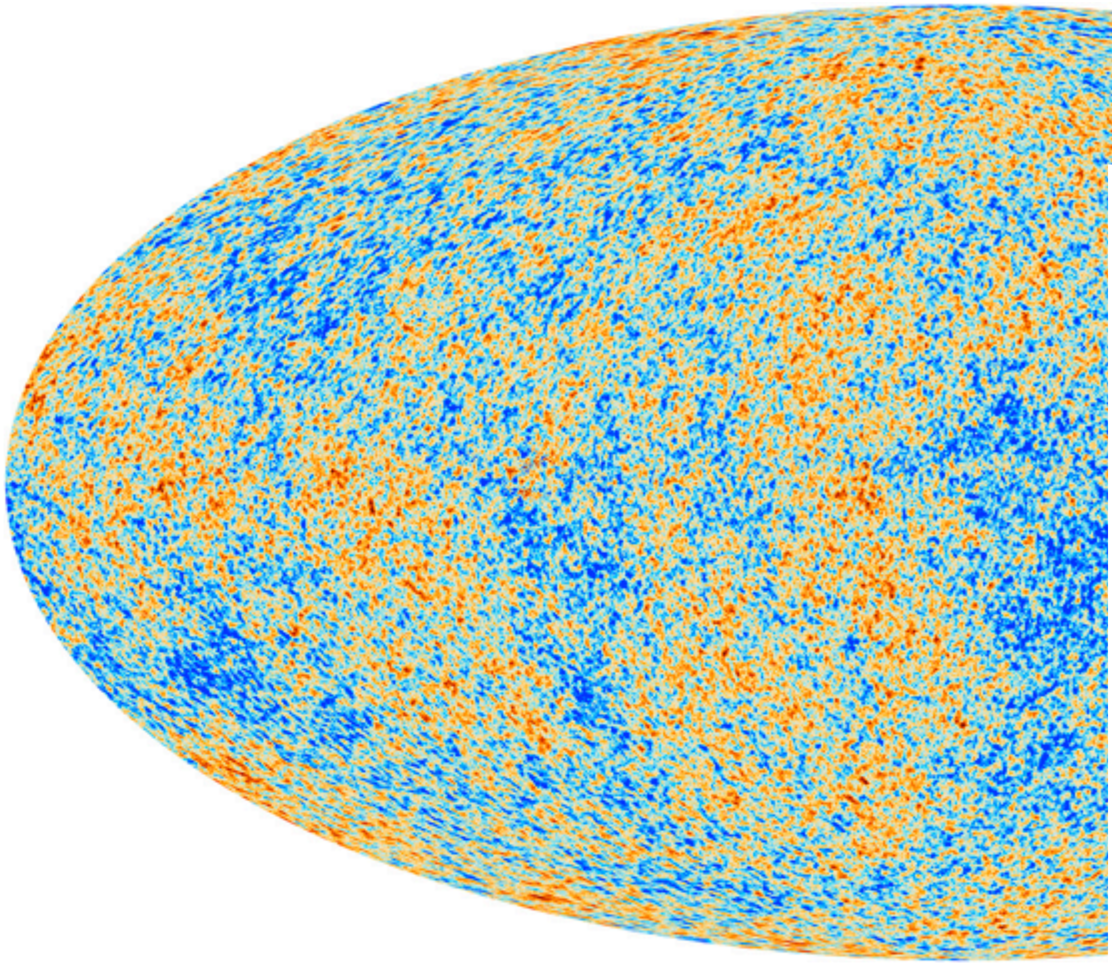
$$\boxed{sound\ speed = \sqrt{\frac{dp}{d\rho}}}$$

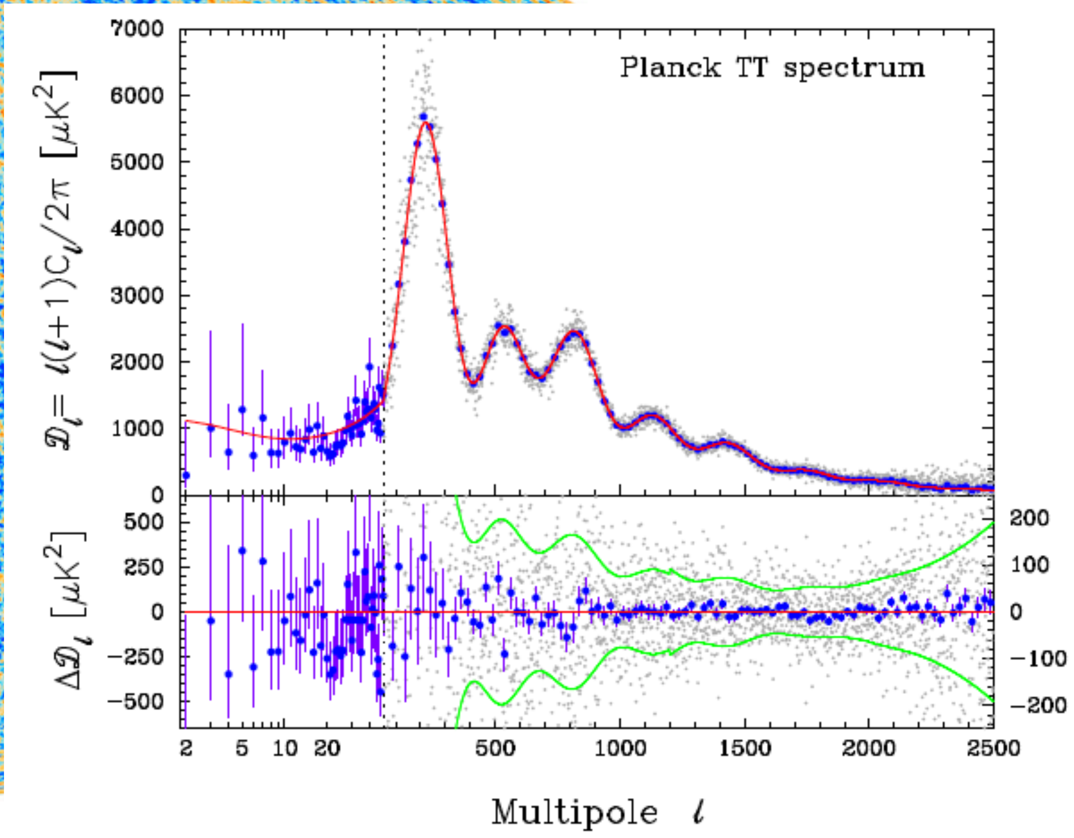
Baryon Acoustic Oscillation



Sound waves froze at the last scattering
The sound horizon can be considered as a standard ruler of ~150 Mpc (comoving space)

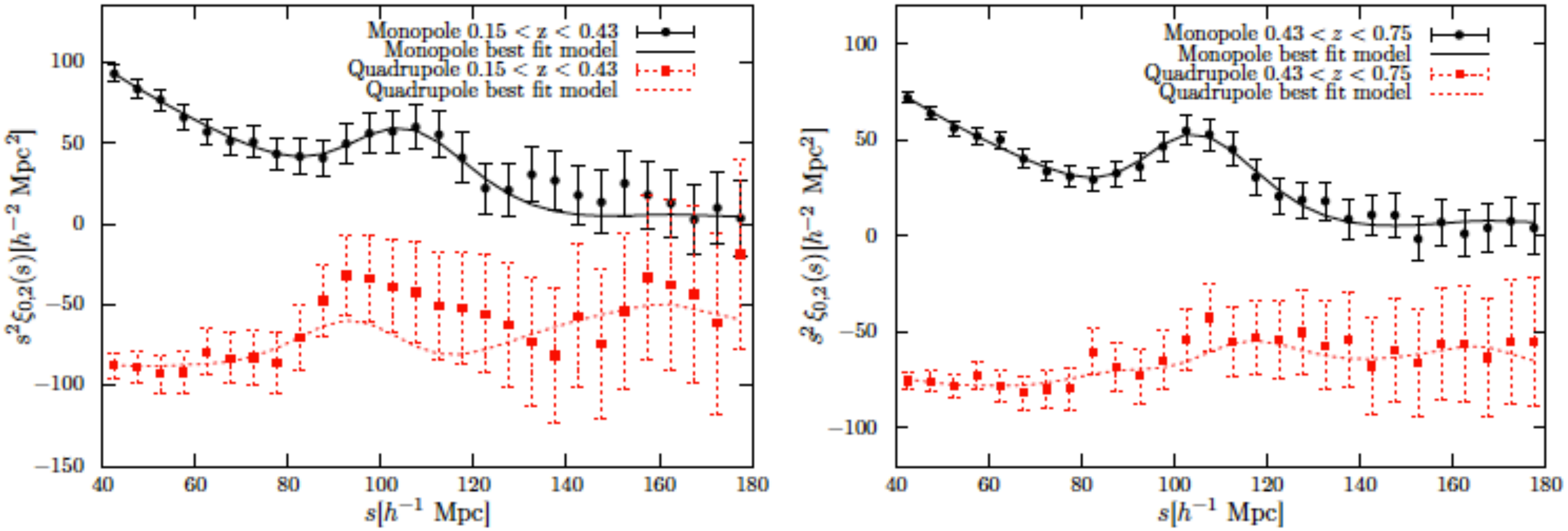
Baryon Acoustic Oscillations in the Density distribution measured from CMB





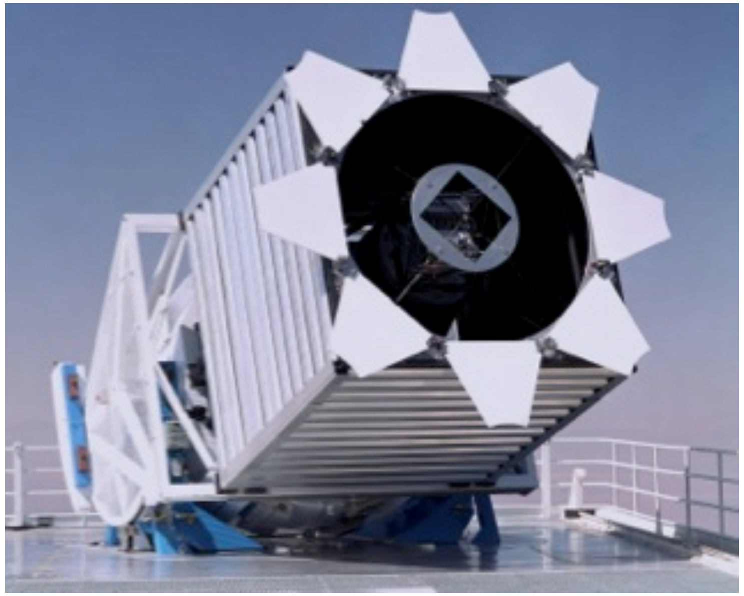
BAO in the Density distribution measured from galaxy sample

Chuang et al. 2016



We can measure the evolution of dark energy by measuring the evolution of the density distribution.

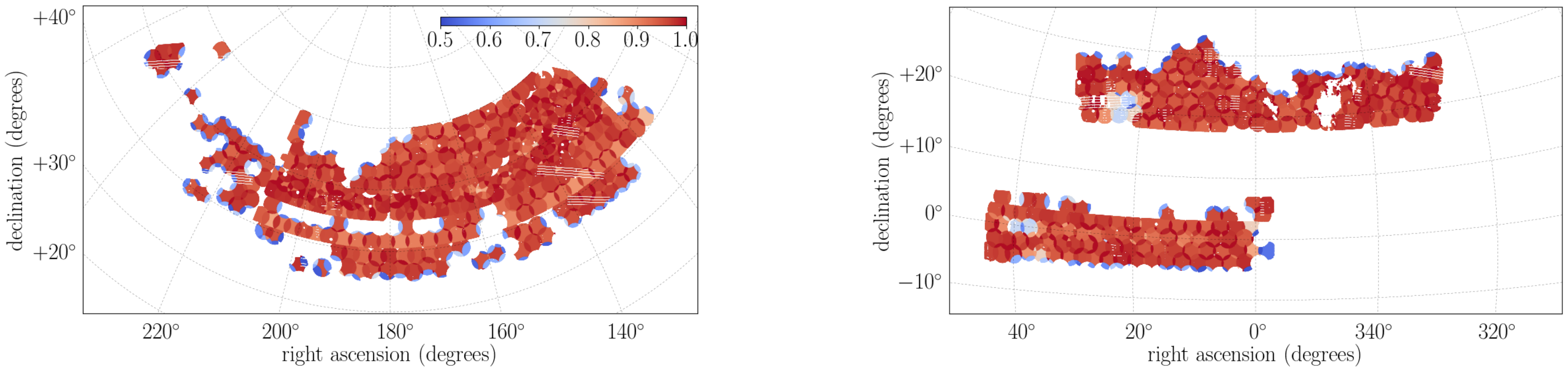
Sloan Digital Sky Survey IV (SDSS-IV)



- 2.5-meter Sloan Telescope at the Apache Point Observatory in New Mexico, USA.
    1. APO Galaxy Evolution Experiment 2 (APOGEE-2)
    2. Mapping Nearby Galaxies at APO (MaNGA)
    3. Time-Domain Spectroscopic Survey (TDSS)
    4. SPectroscopic IDentification of ERosita Sources (SPIDERS)
    5. Extended Baryon Oscillation Spectroscopic Survey (eBOSS)

eBOSS (Survey-IV/extended Baryon Oscillation Spectroscopic Survey)

- Currently operating and collecting luminous red galaxies (LRG, $0.6 < z < 1.0$), emission line galaxies (ELG, $0.7 < z < 1.1$), quasars (QSO, $0.8 < z < 2.2$)



Current footprint for QSO data (north galactic cap on the left)

eBOSS quasar target selection (Myers et al. 2015)

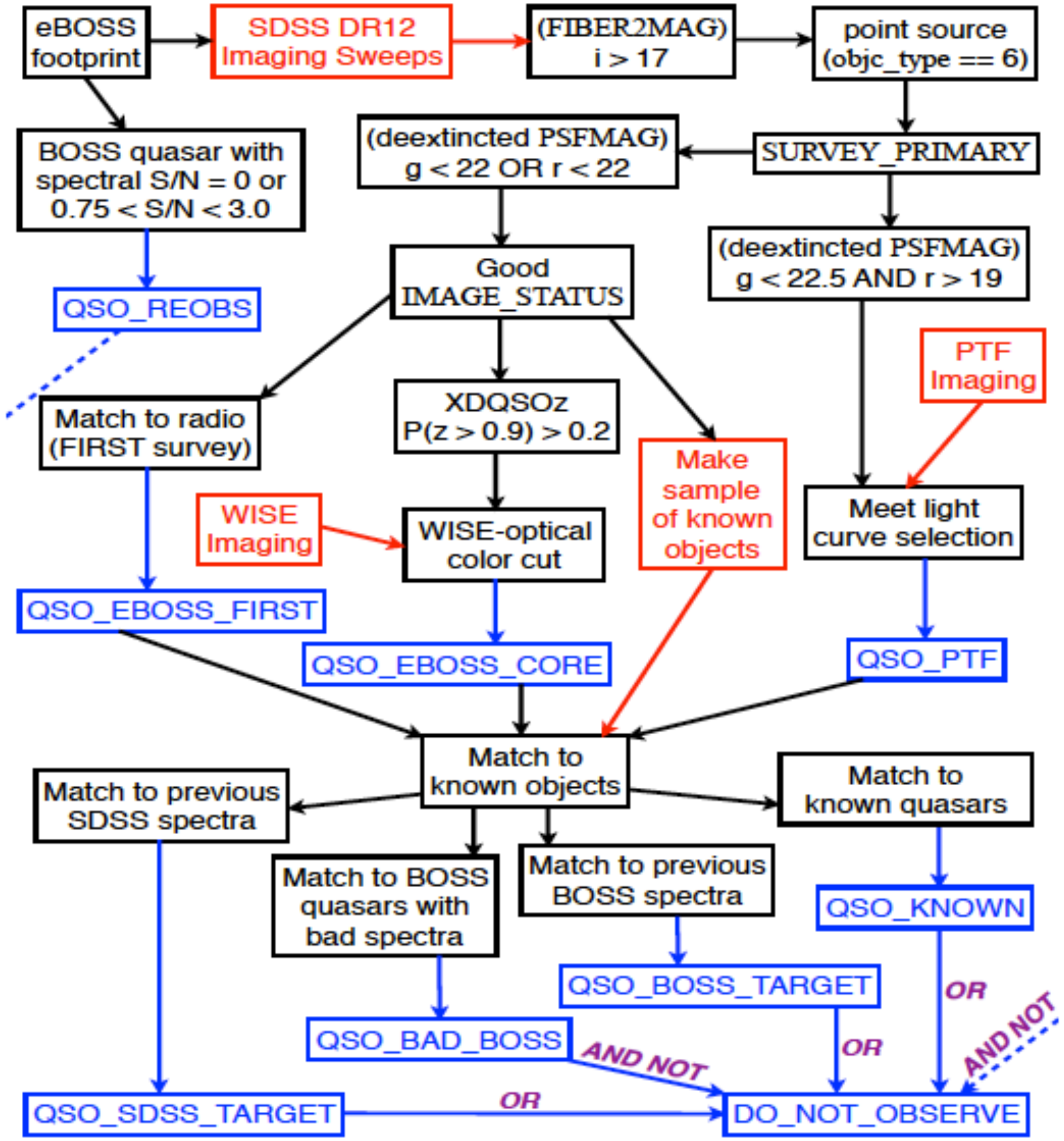
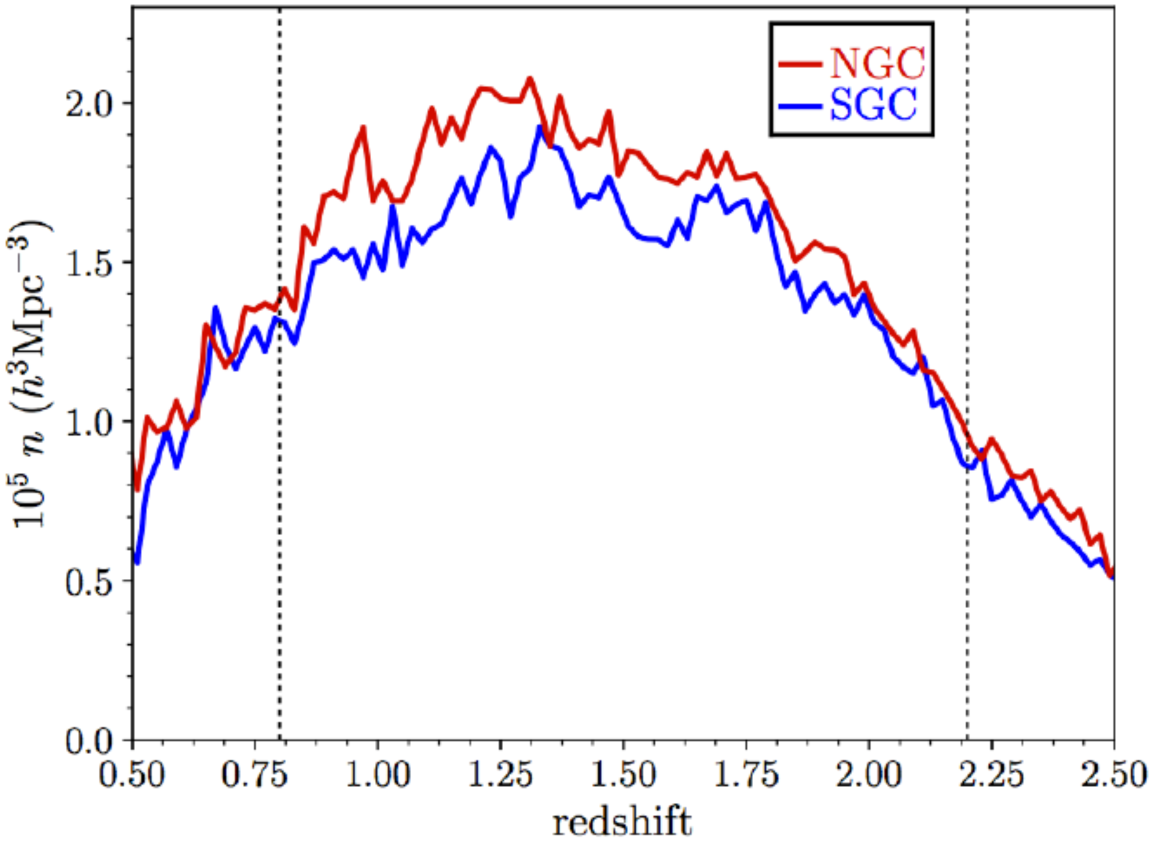


Figure 1. Flowchart depicting *eBOSS* quasar target selection. Red boxes represent sources of input information such as imaging (see §3) or catalogs of known objects. Black boxes depict cuts that are made to the input sources as part of the target selection algorithm (see §4). Blue boxes depict output target selection bits (see §4.4). The Boolean terms in purple describe how the four bits produced by matching to previous spectra are combined to set the `DO_NOT_OBSERVE` bit (see §4.4.10). The dashed blue arrow indicates that `QSO_REOBS` targets are *always* reobserved, regardless of the value of `DO_NOT_OBSERVE`. The sample of known objects undergoes the CORE flag and magnitude cuts rather than the *PTF* magnitude cuts. Consequently, *PTF* selection could re-target previously known objects with bad `IMAGE_STATUS` and/or with $22 < g < 22.5$.

Quasar sample

- This study uses ~200,000 quasars in redshift range 0.8 < z < 2.2



Removing the observational systematics

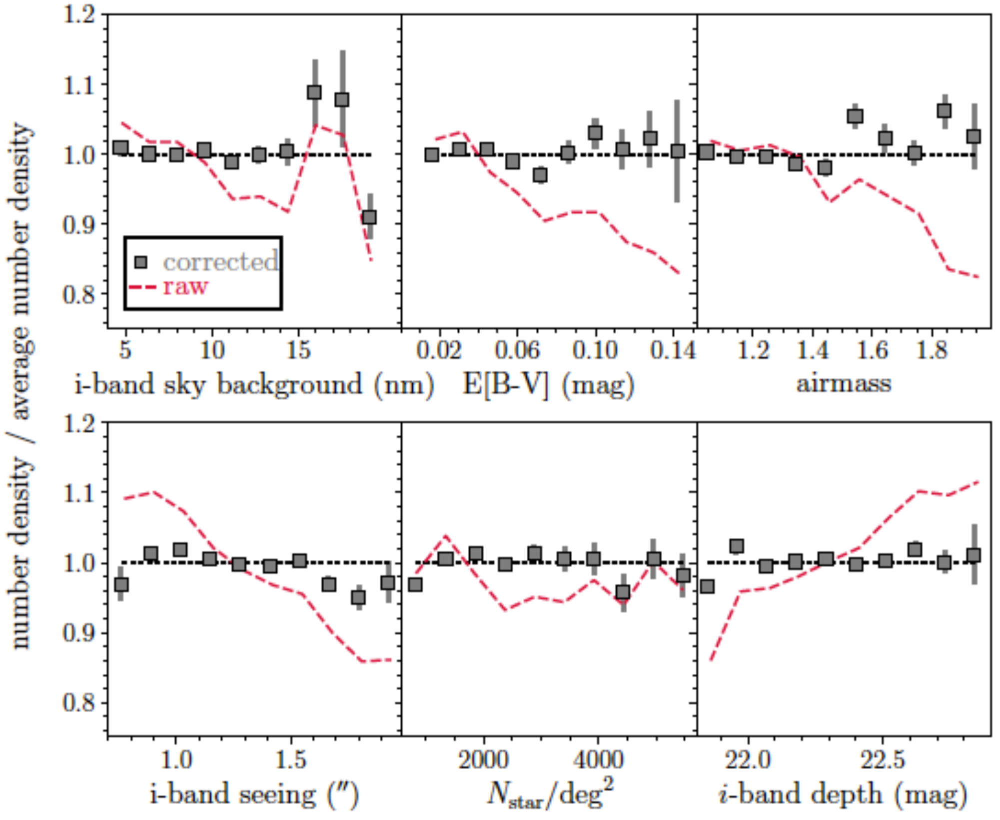
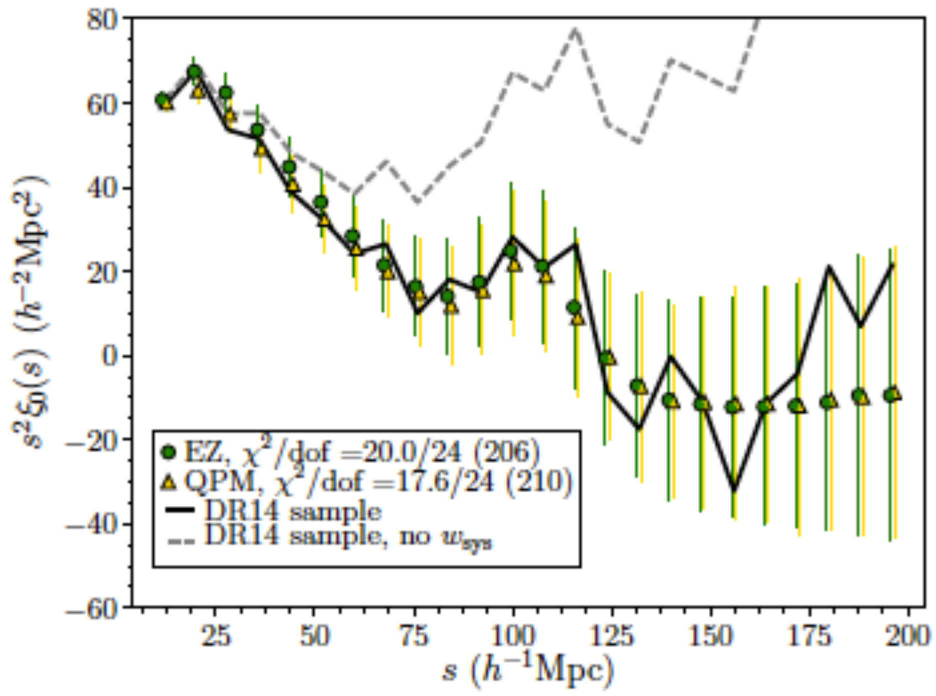


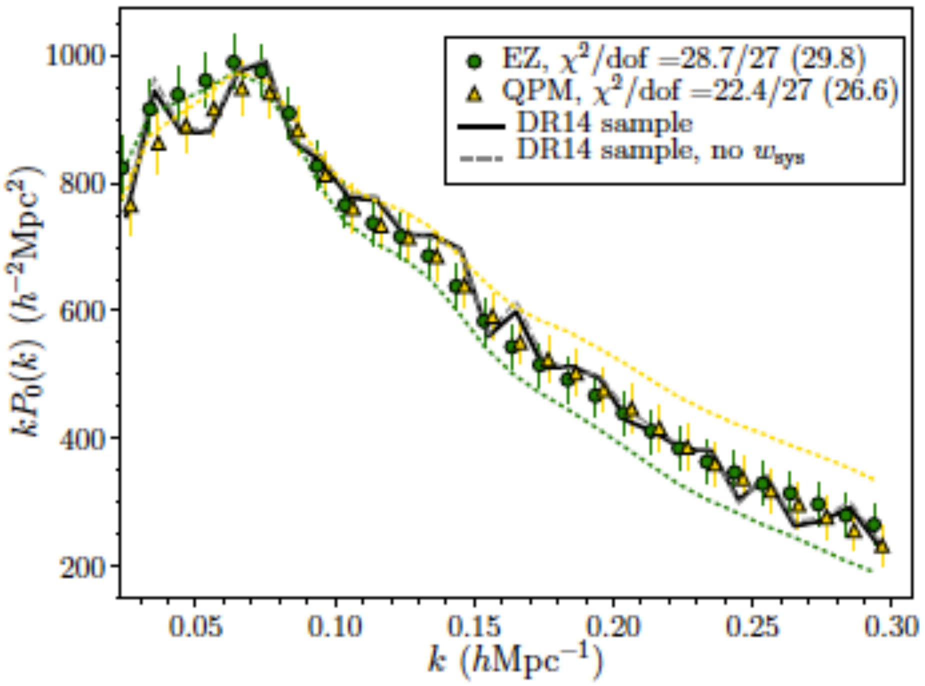
Figure 3. The relationship between the number density of the DR14 quasar sample and various potential systematics before (dashed crimson curves, labeled 'raw') and after (gray squares, labeled 'corrected') weighting for limiting magnitude (depth) and Galactic extinction (E[B-V]). Weighting for limiting magnitude and E[B-V] removes correlations with other potential systematic quantities.

Measure BAO from eBOSS DR14 QSO clustering

Correlation function



Power spectrum



Observed correlation function

1. Convert the redshifts to comoving distances with a fiducial model
2. Minimum variance correlation function estimator(Landy & Szalay 1993):

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

where DD, DR, and RR represent the normalized data-data, data-random, and random-random pair counts respectively in a distance range.

BAO model

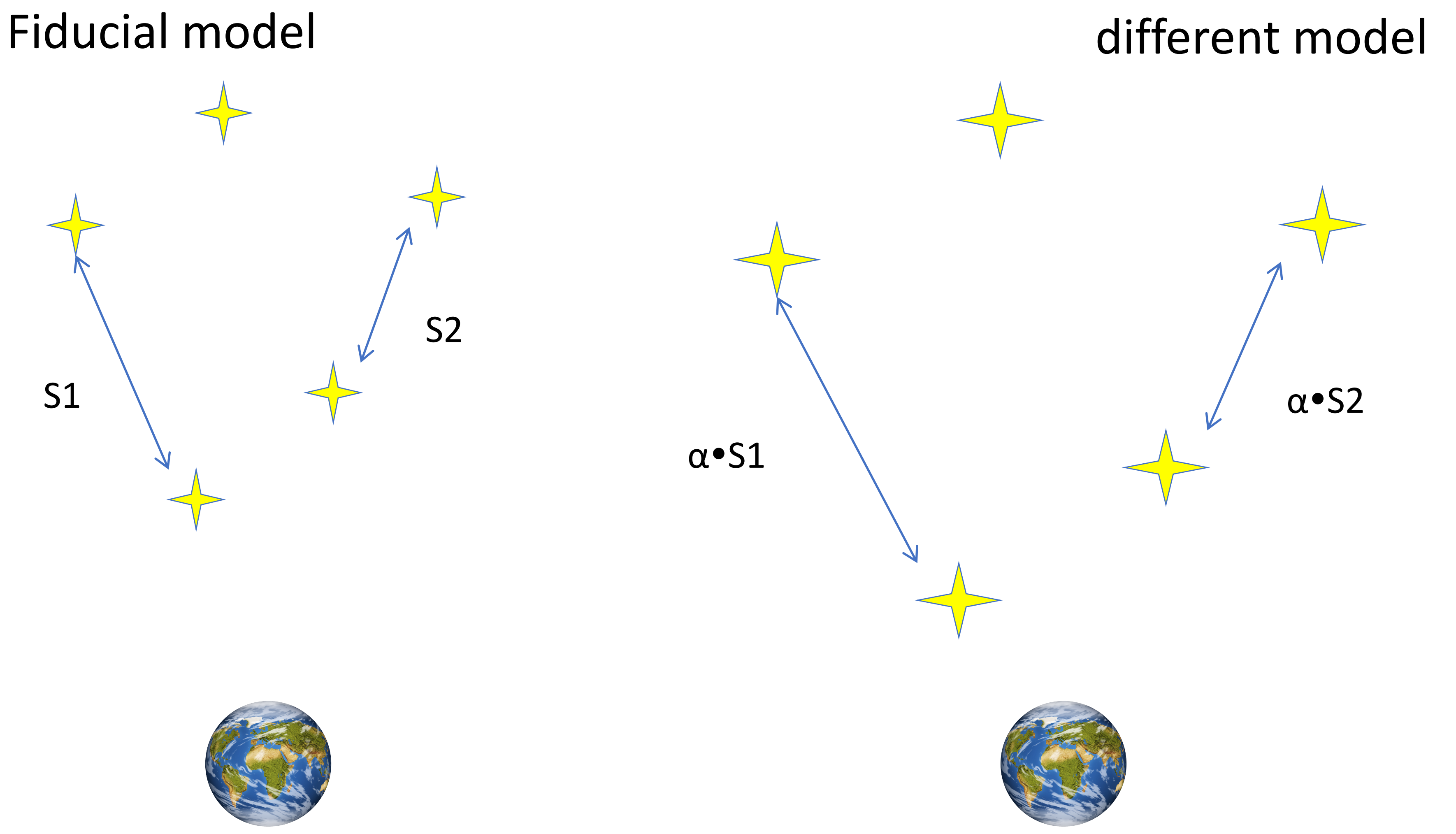
$$P^{\mathrm{mod}}(k) = P^{\mathrm{nw}}(k)\left[1 + \left(\frac{P^{\mathrm{lin}}(k)}{P^{\mathrm{nw}}(k)} - 1\right) e^{-\frac{1}{2}k^2\Sigma_{nl}^2}\right]$$

Compute linear PK (P_{lin}) using CAMB code. No-wiggle PK (P_{nw}) is a smooth function from the formula in Eisenstein and Hu (1998).

$$\xi^{\mathrm{fit}}(s) = B_\xi^2 \xi^{\mathrm{mod}}(\alpha s) + A^\xi(s)$$

$$A^\xi(s) = \frac{a_1}{s^2} + \frac{a_2}{s} + a_3$$

rescaling



Covariance matrix & χ^2

- Use 1000 mock catalogs to estimate the covariance matrix of the given clustering statistics.

$$C_{ij} = \frac{1}{N-1} \sum_{k=1}^{N} (\bar{\xi}_i - \xi_i^k)(\bar{\xi}_j - \xi_j^k),$$

$$\chi^2 \equiv \sum_{i,j=1}^{N_{bins}} \left[\xi_{th}(s_i) - \xi_{obs}(s_i)\right] C_{ij}^{-1} \left[\xi_{th}(s_j) - \xi_{obs}(s_j)\right]$$

Estimate the covariance matrix

- We need thousands of mock catalogues to construct the covariance matrix of the clustering measurements.
- The most reliable mocks are from the realizations of N-body simulations, but…
- It is NOT practical to run thousands of N-body simulations!
- We need an alternative way….

nIFTy workshop in Madrid, 2014

nIFTy workshop: mock catalogues comparison project

Methodology	reference
Log-Normal	Coles & Jones 1991
PTHalos	Manera et al. 2012, 2015
PINOCCHIO (PINpointing Orbit-Crossing Collapsed Hierarchical Objects)	Monaco et al. 2002, 2013
COLA (COmoving Lagrangian Acceleration simulation)	Tassev et al. 2013
PATCHY (PerturbAtion Theory Catalog generator of Halo and galaxY distributions)	Kitaura et al. 2013, 2014
EZmock (Effective Zel'dovich approximation mock catalogue)	Chuang et al. 2015
HALOgen	Avila et al. 2014

Table 1. The methodologies of generating mock halo/galaxy catalogues developed in the last years. The methodologies included in this study are highlighted using bold font.

arXiv:1412.7729v2 [astro-ph.CO] 25 Dec 2014

nIFTy Cosmology: Galaxy/halo mock catalogue comparison project on clustering statistics

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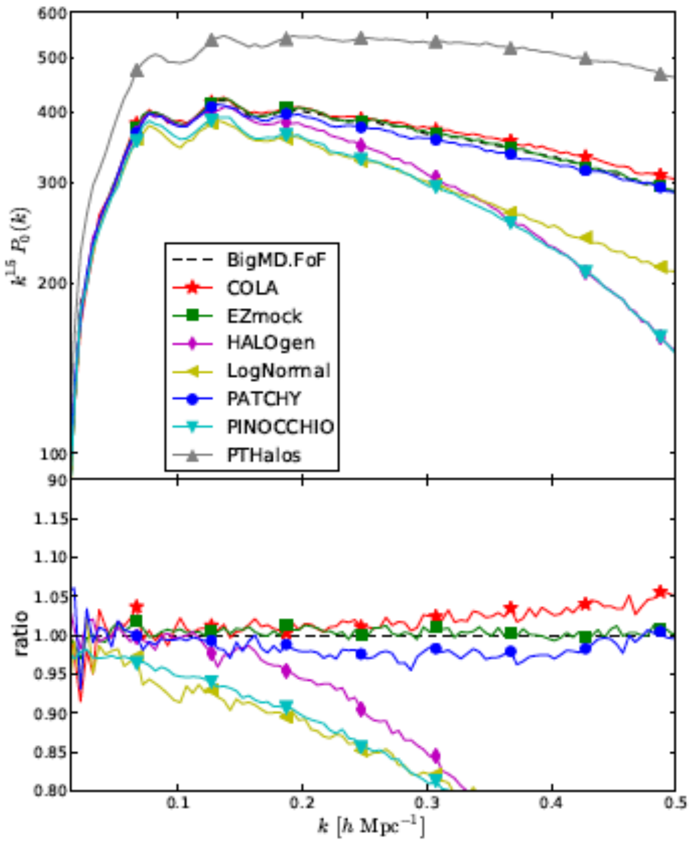
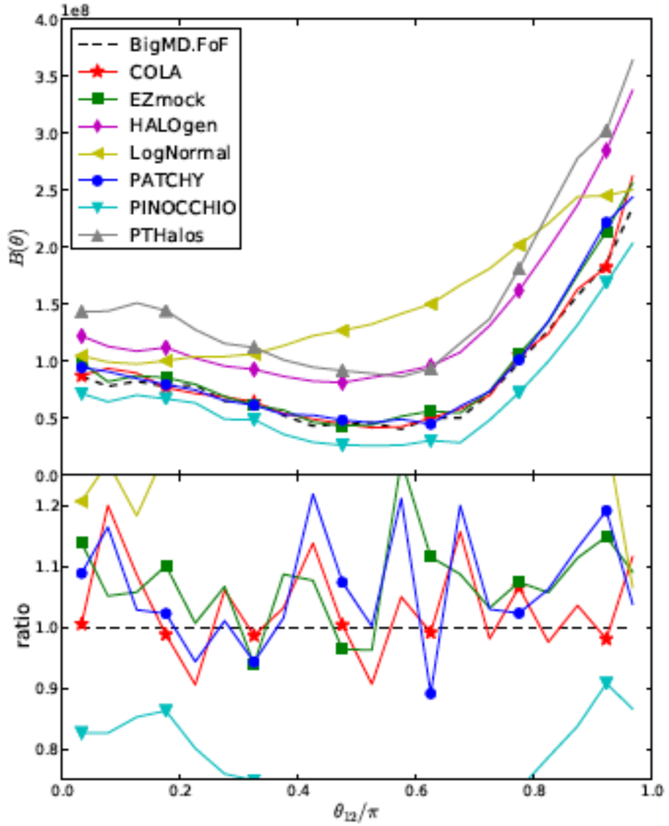
Mock comparison project (nIFTy workshop, Madrid; Chuang et al. 2015, MNRAS, **arXiv:1412.7729**)

P(k)



B(k)



Only COLA, EZmock, and PATCHY reach percentage accuracy at small scales for 2- and 3-point clustering statistics.

Resource requirement

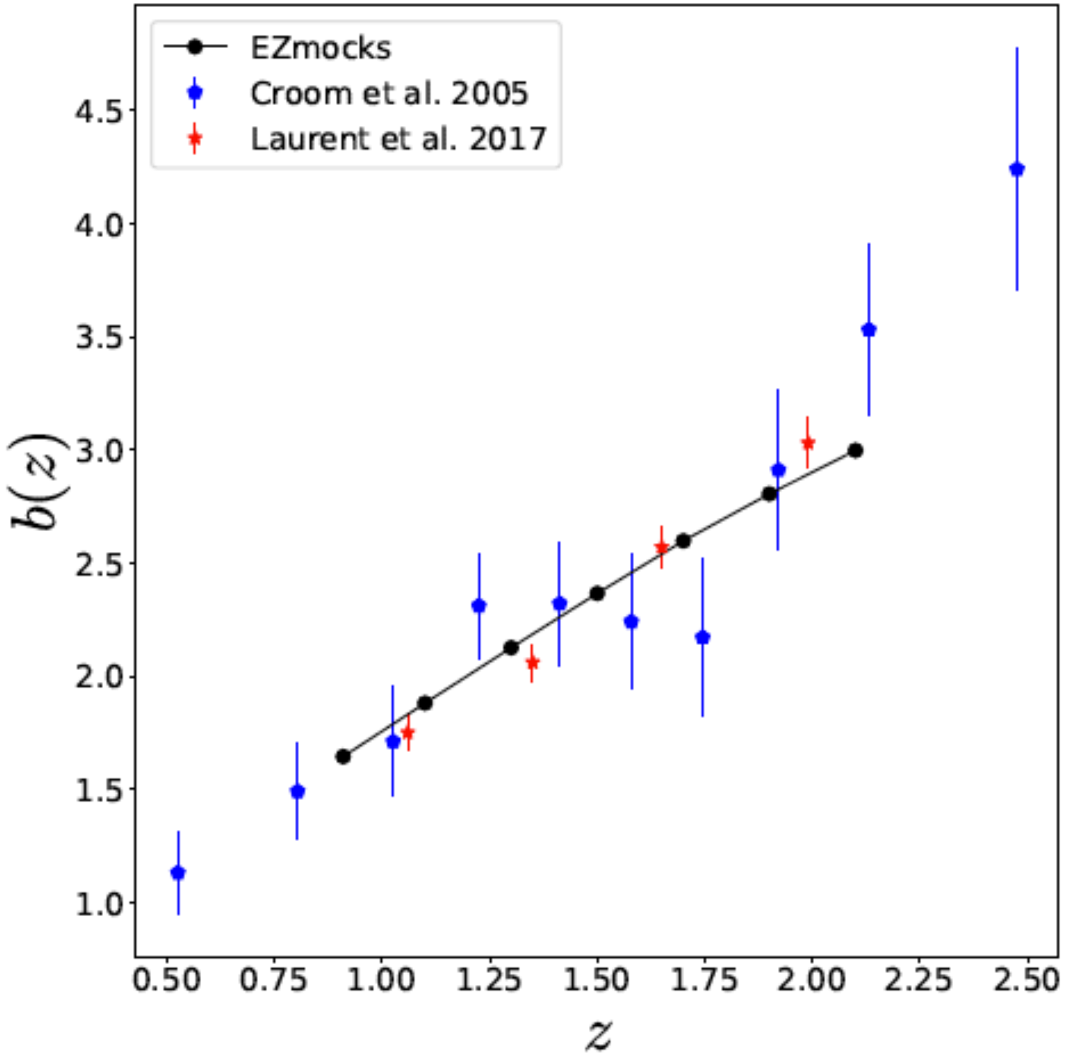
	BigMD	COLA	EZmock	HALOGEN	Log-normal	PATCHY	PINOCCHIO	PTHalos
Particle mesh size	3840^3	1280^3 (3840^3 for force)	960^3	1280^3	1280^3	960^3	1920^3	1280^3
Using white noise	YES	NO	YES	YES	NO	YES	YES	NO
CPU-hour	800,000	130	1.3	6.7	0.5	8	440	45
Memory	8Tb	550Gb	28Gb	260Gb	15Gb	24Gb	890Gb	112Gb

Chuang et al. 2014 (arXiv:1412.7729)

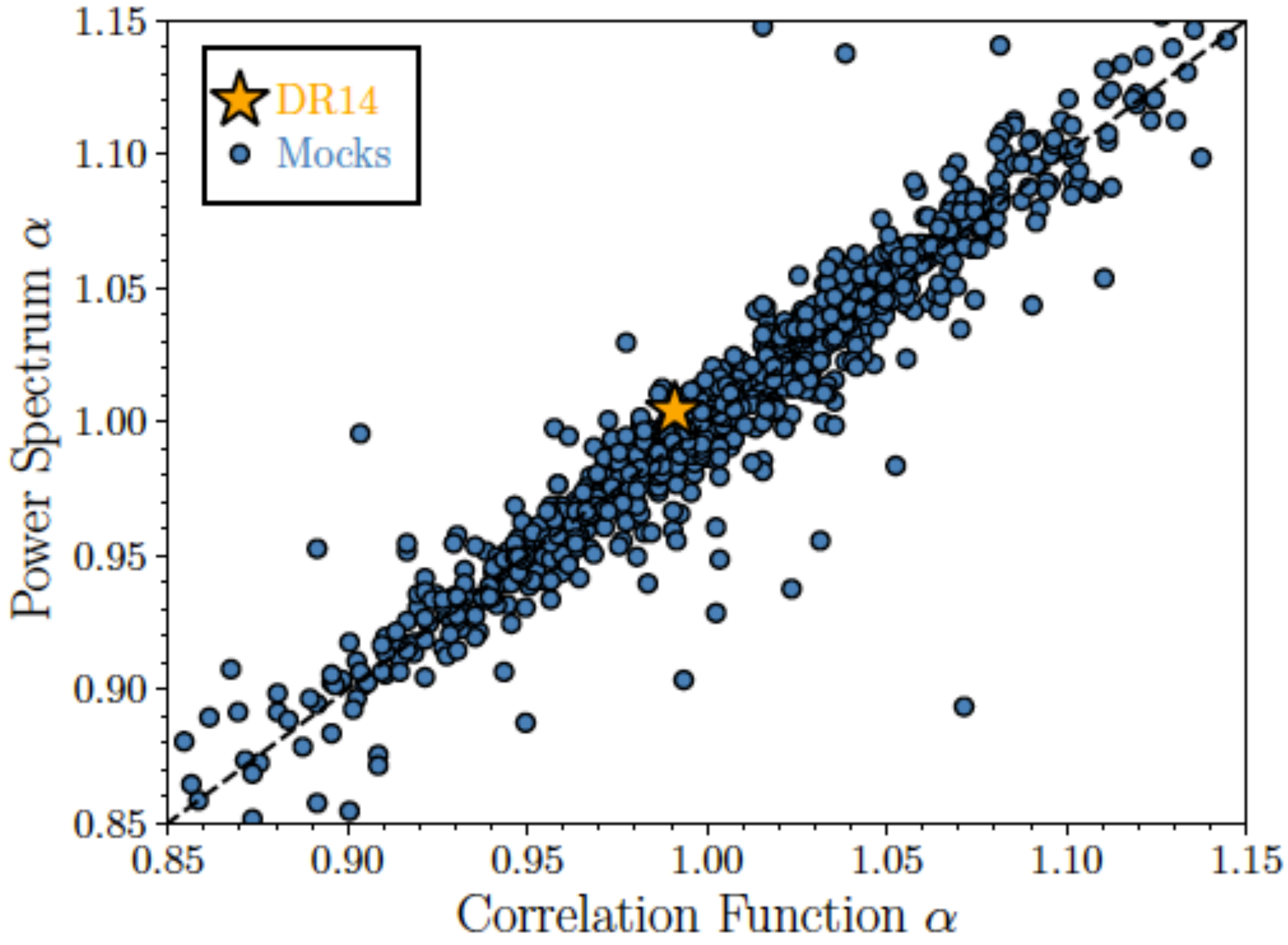
Quasar Mock Catalogues

- Purposes:
  - Constructing covariance matrix
  - Combining the measurements from different methodologies
  - Validating methodologies
- Mocks used in this study:
  - EZmock (Chuang, Kitaura, et al. 2015; Chuang et al. in prep.) – fiducial method for this study (14,000 boxes used)
  - QPM (White et al. 2014) – (100 boxes used)

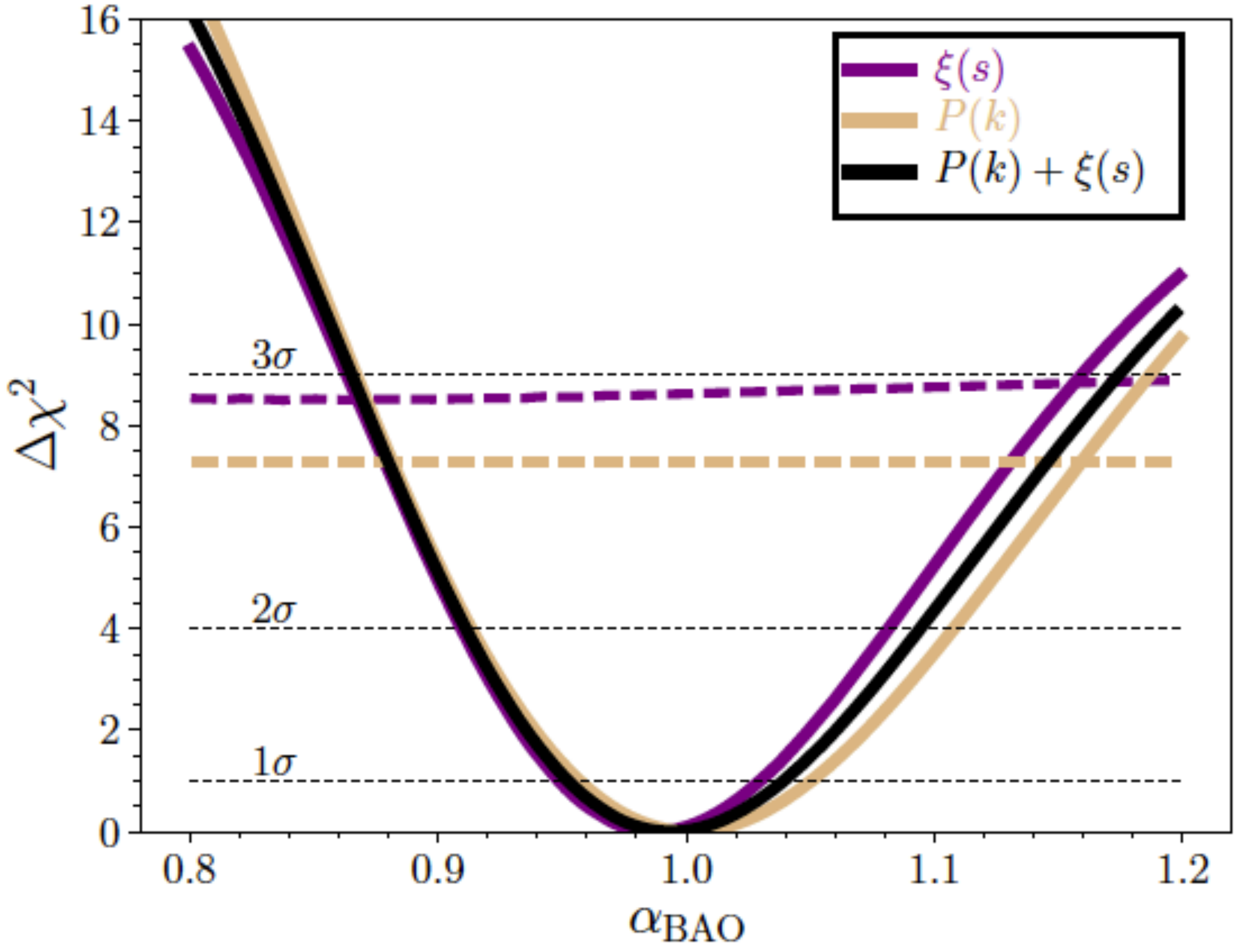
EZmocks reproduce the evolution of QSO bias

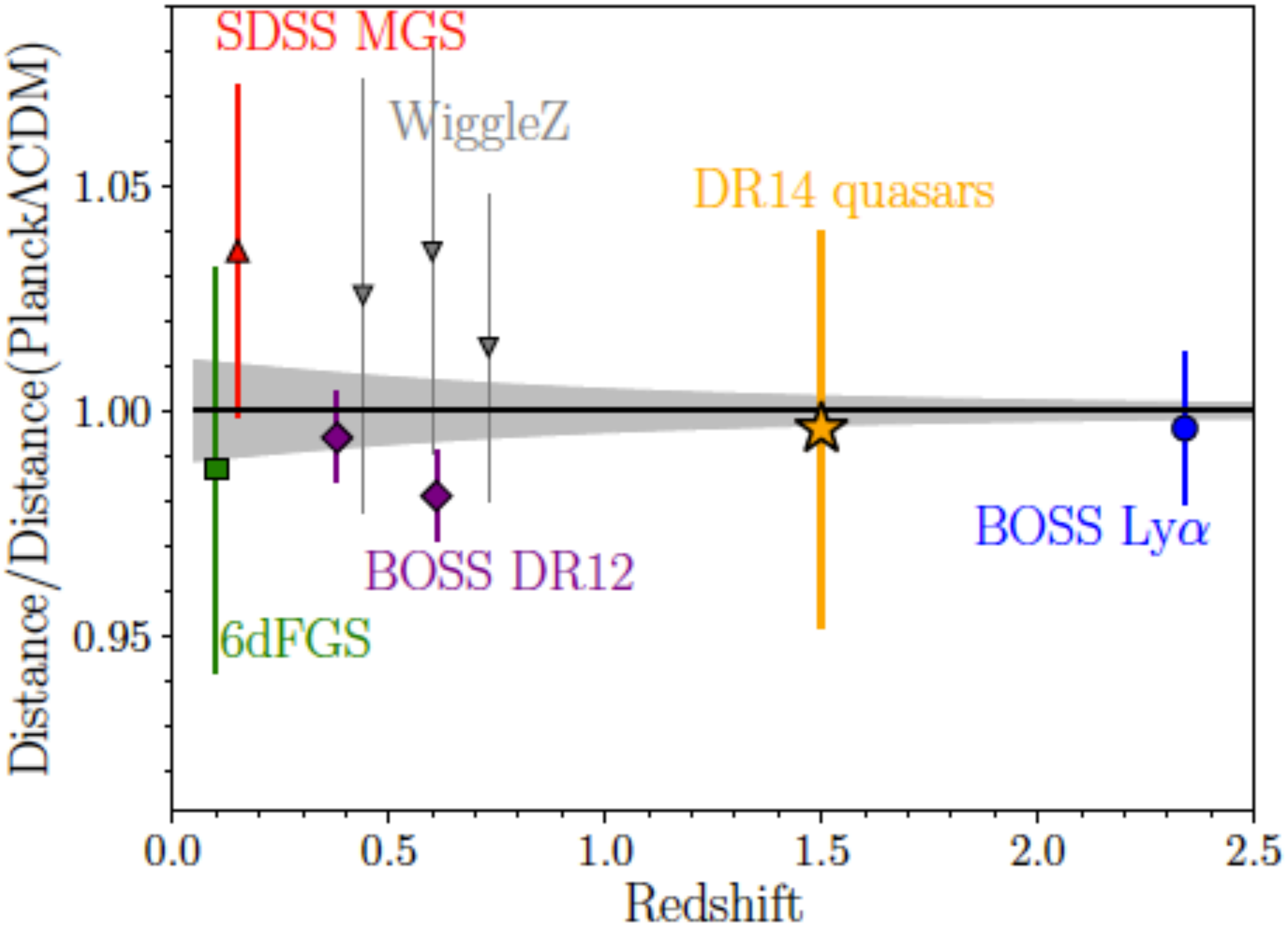


Validating methodologies & combining measurements from different methodologies



case	α	χ^2/dof
DR14 Measurement $P(k) + \xi(s)$	0.996 ± 0.044	–
$\xi(s)$ (combined)	0.991 ± 0.041	9.7/13
$P(k)$ (combined)	1.004 ± 0.047	26.5/33

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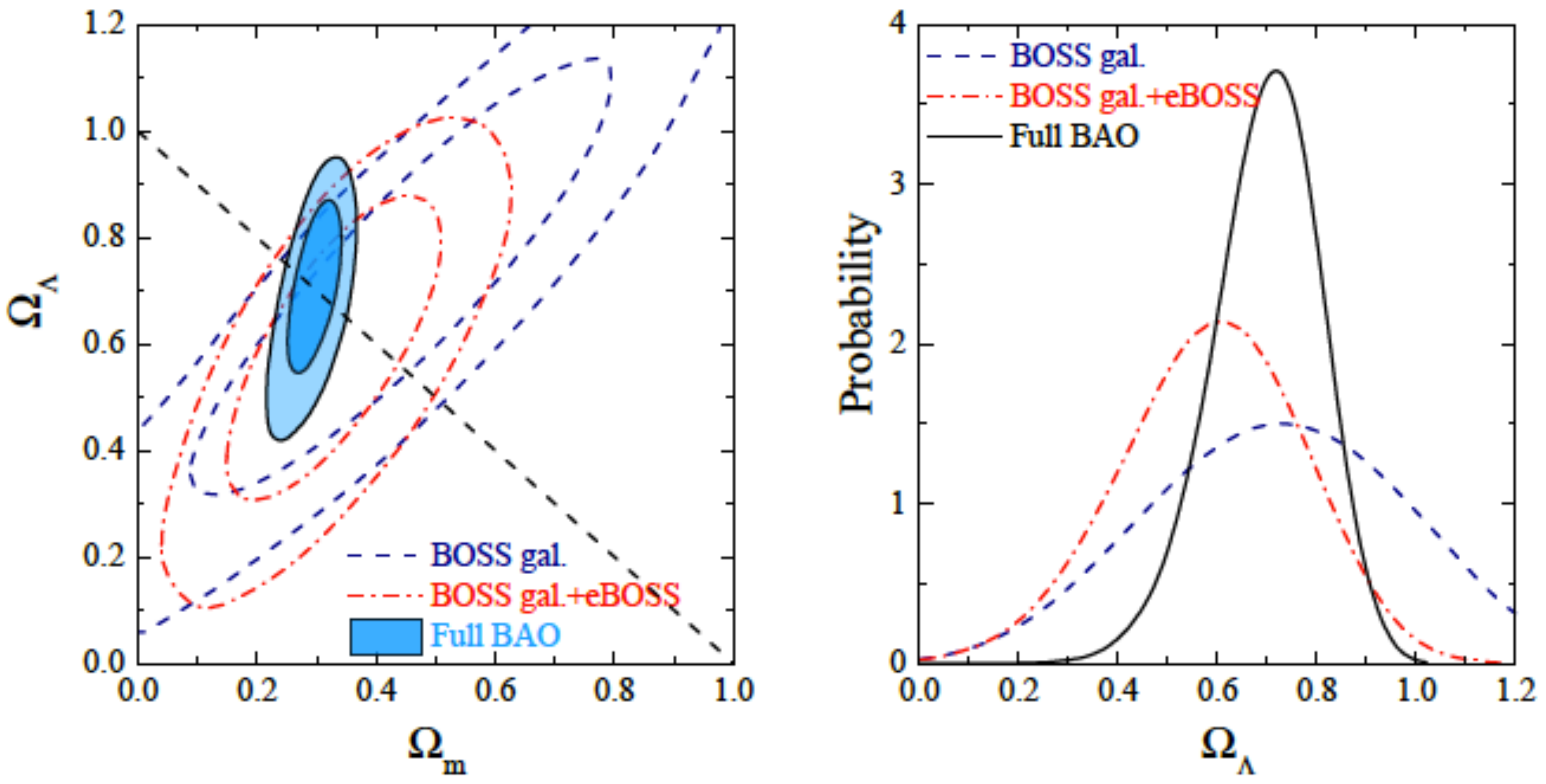
2.0
2.5



BOSS gal.
BOSS gal.+eBOSS
Full BAO
Ω_Λ
Ω_m
0.0
0.2
0.4
0.6
0.8
1.0
1.2
Probability
0
1
2
3
4

Summary

- We provide the first BAO measurement from QSO clustering at z=1.5 (0.8 < z < 2.2).
- We confirm the existence of dark energy with only BAO measurements. The significance of $\Omega_\Lambda > 0$, is raised from 2.9$\boldsymbol{\sigma}$ to 3.3$\boldsymbol{\sigma}$ when adding eBOSS quasar BAO is added to BOSS galaxy BAO measurement.
- This work represents the first cosmological analysis to be done with the eBOSS quasar data. We expect numerous studies to follow, both with this catalog and with future, larger data sets.