

the Extended Baryon Oscillation Spectroscopic Survey

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University of Utah



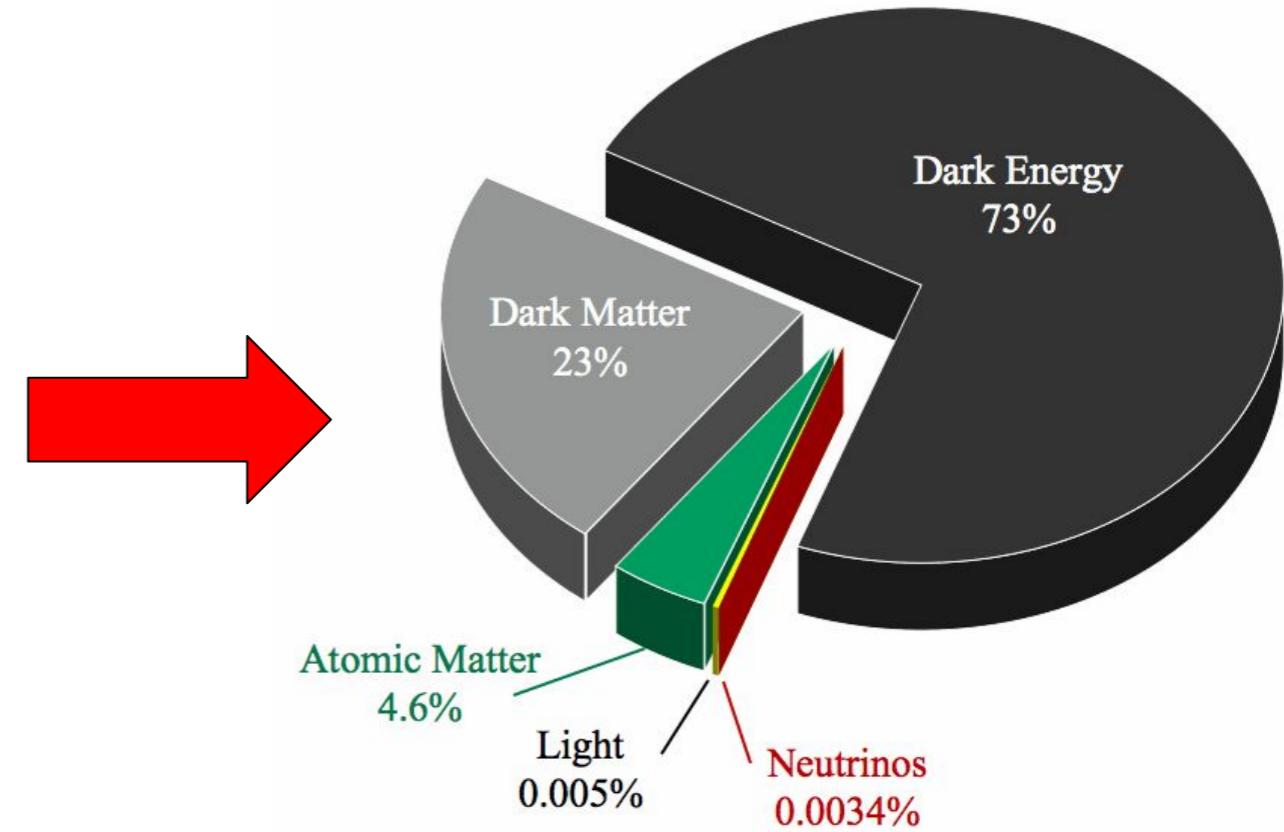
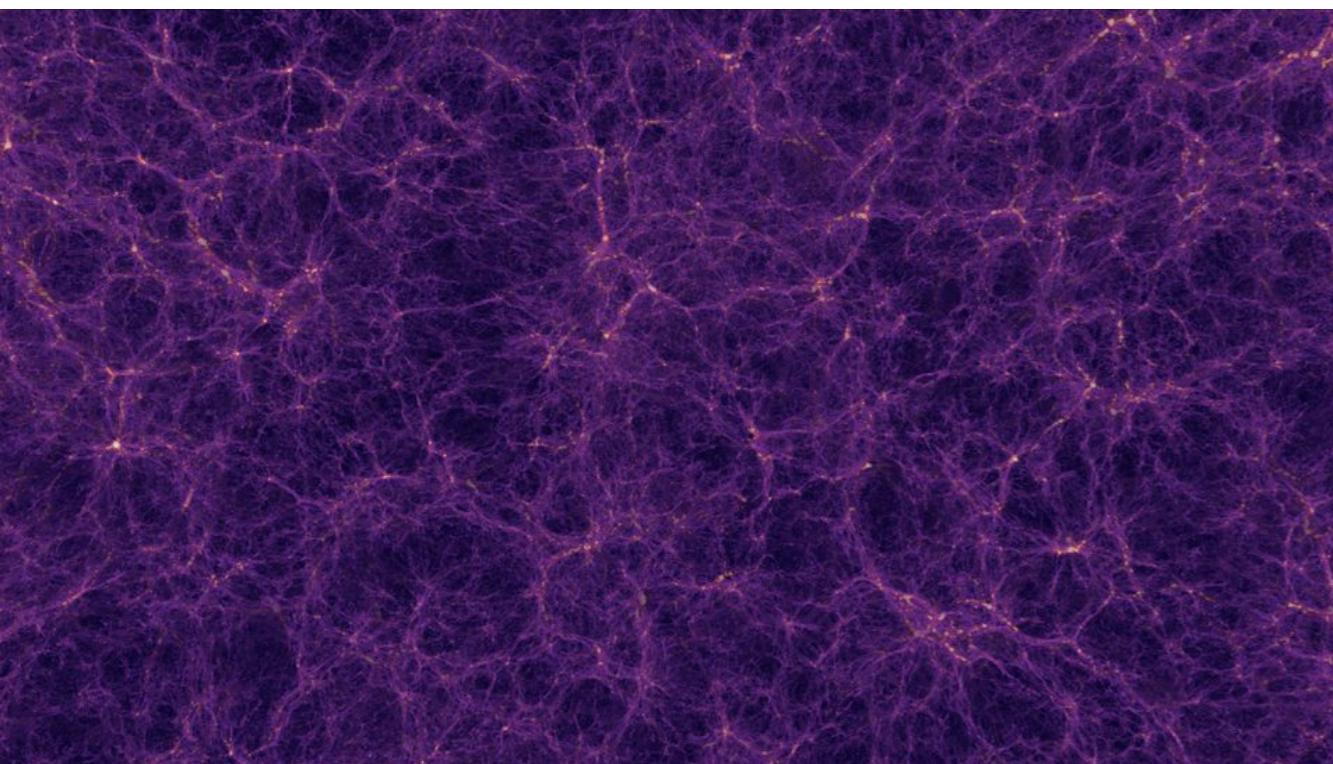
Outline

- Survey and Operations Overview
- Measurements of BAO and RSD
- Cosmology Interpretation

Survey Overview

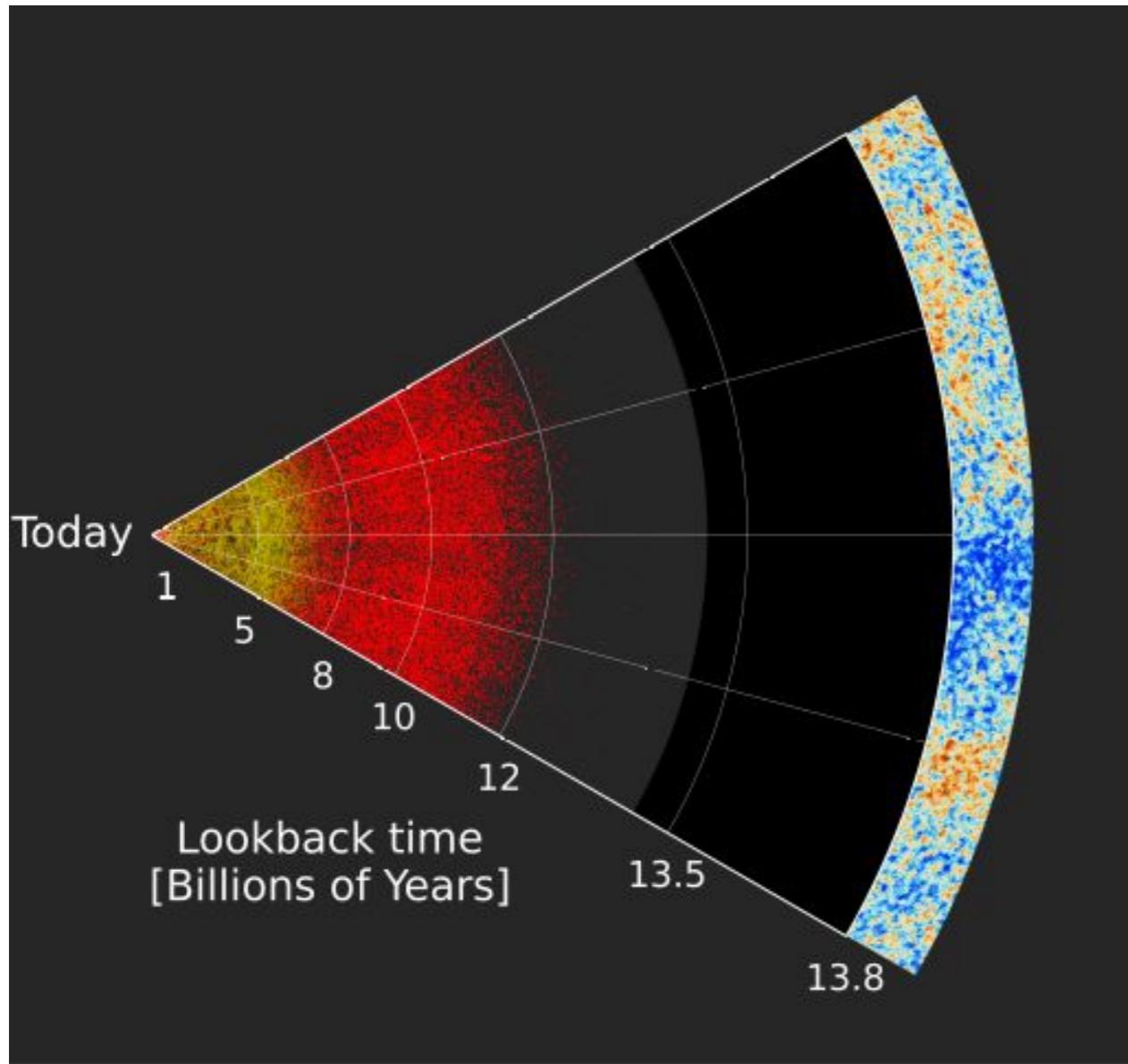
Cosmology with eBOSS

- **Evolving distribution of matter in Universe**
 - Cosmic expansion and growth of structure
- **Derived Measurements:** $H(z)$, $D_M(z)$, $f\sigma_8(z)$
 - Physics of dark energy
 - Composition of the Universe
 - Neutrino mass, Inflation, Laws of gravity

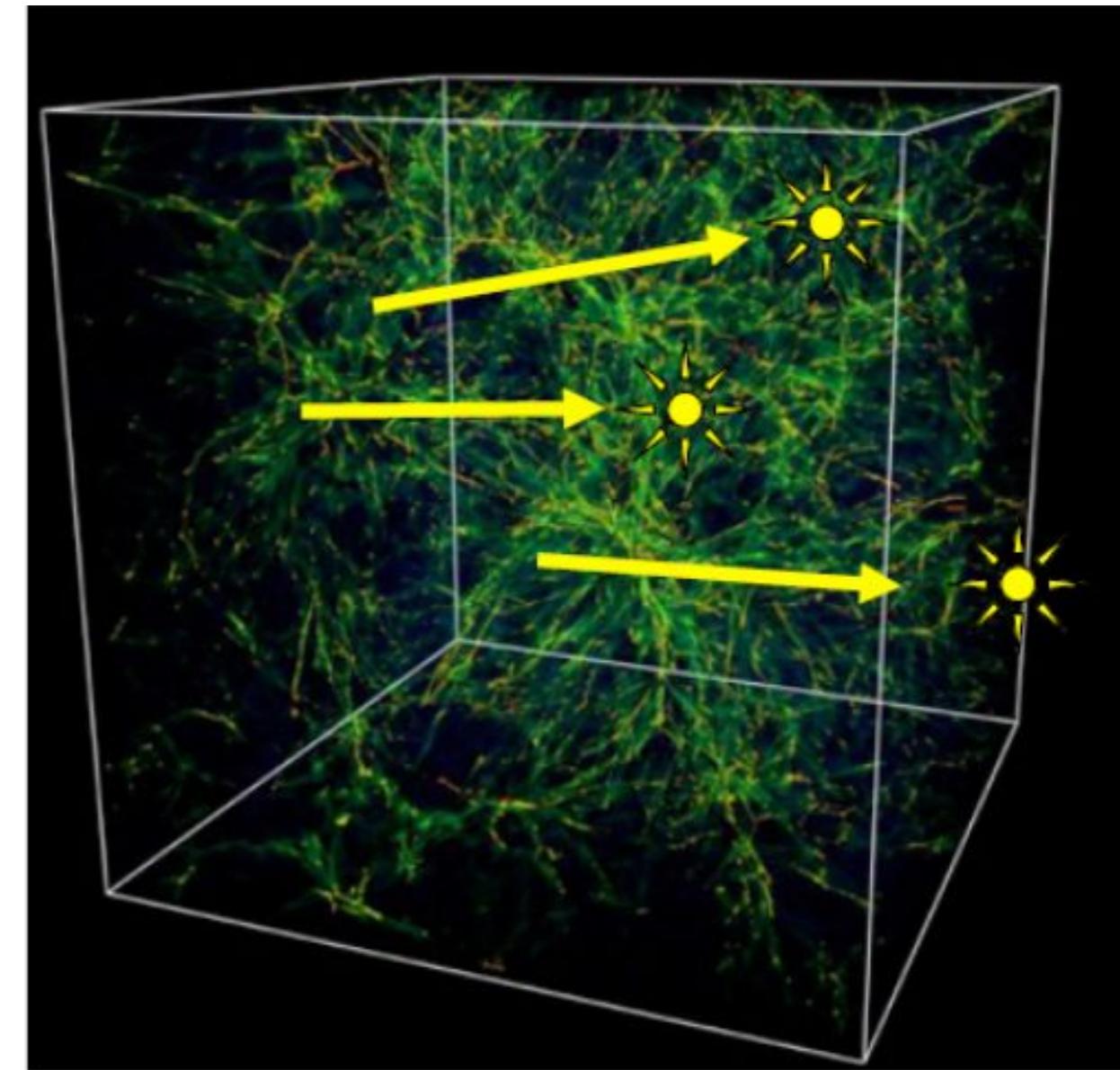


Spectroscopy of the Cosmic Density Field

Direct tracers
Galaxies and quasars ($z < 2.1$)

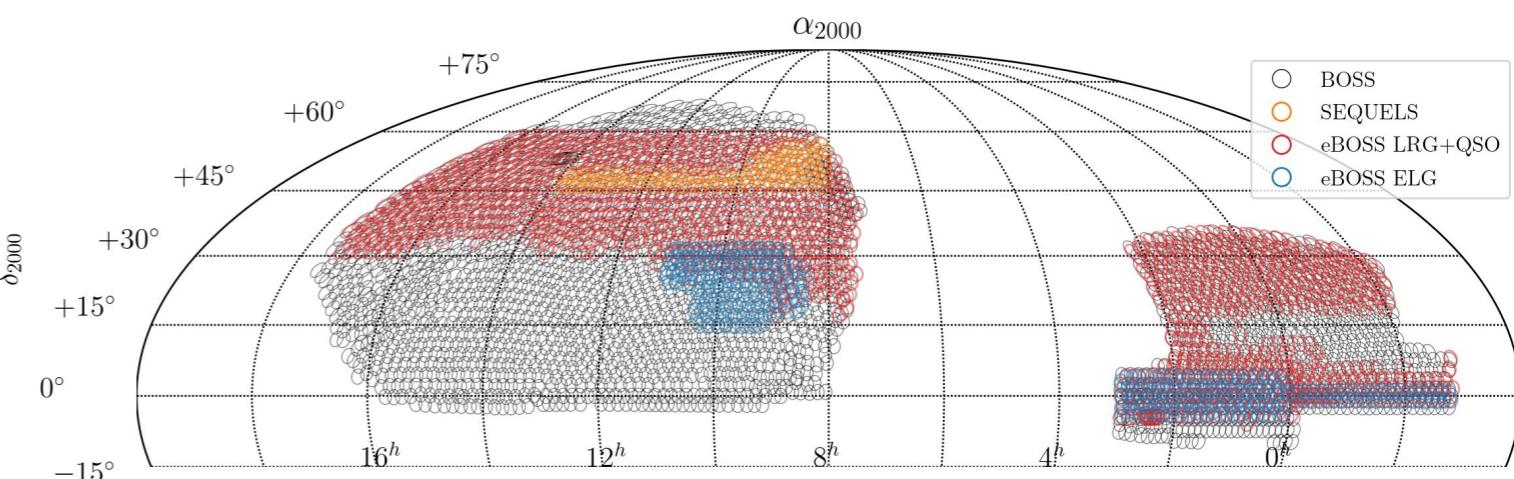
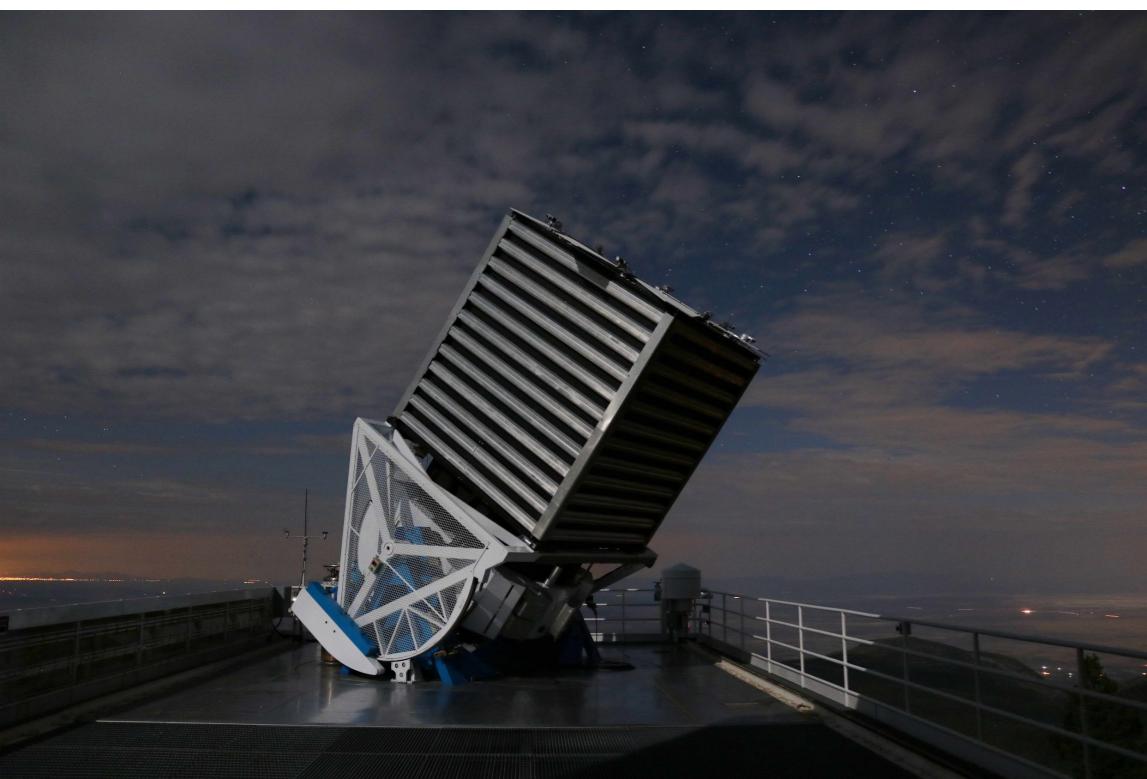


Absorption in quasar spectra by foreground Lyman-alpha forest ($z > 2.1$)

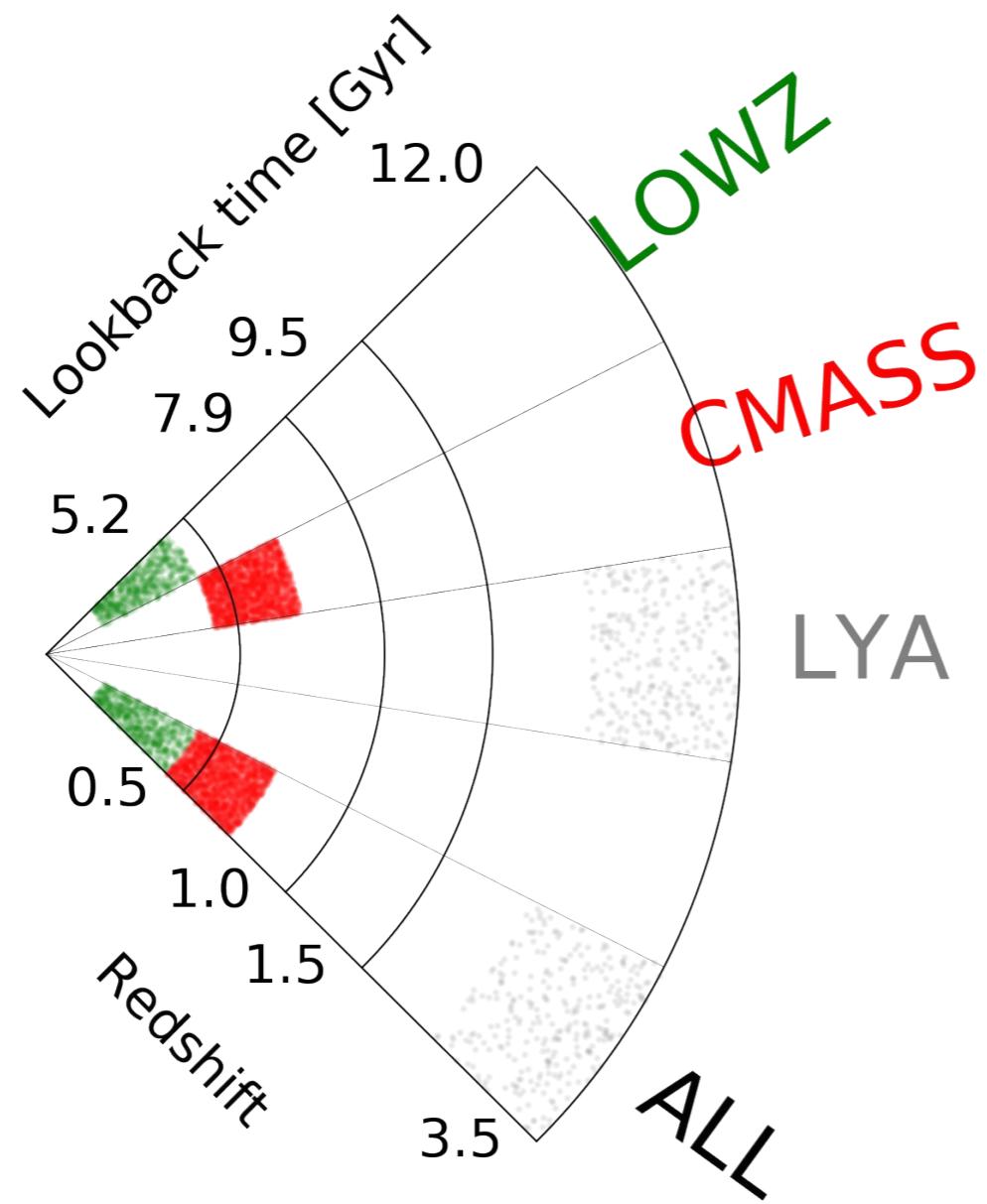
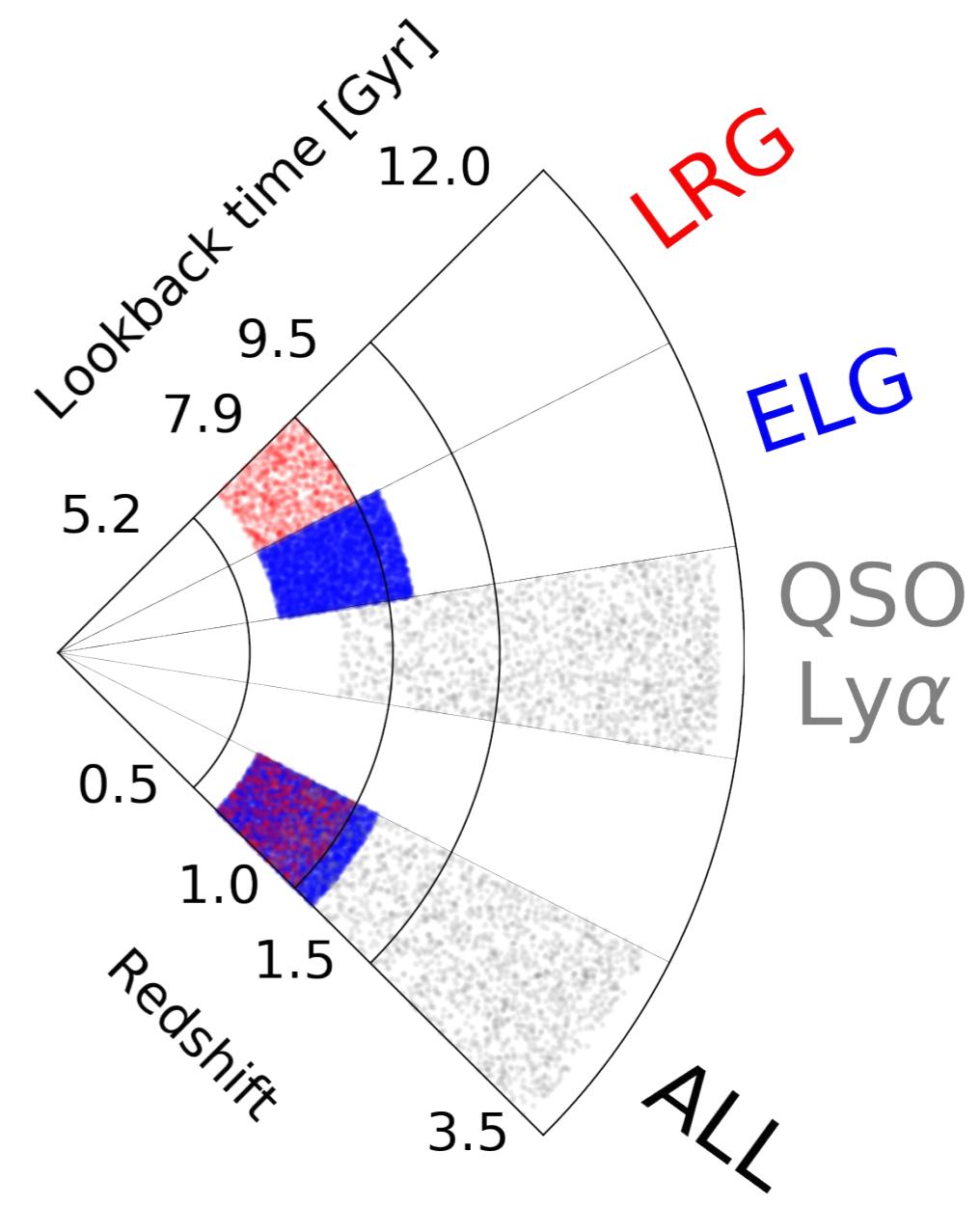


Apache Point Observatory and eBOSS Survey

- eBOSS (2014-2019): Cosmology component within SDSS-IV
 - Luminous Red Galaxies ($0.6 < z < 1.0$; Prakash et al. 2016)
 - Emission Line Galaxies ($0.6 < z < 1.1$; Raichoor et al. 2017)
 - Quasars ($0.8 < z < 2.2$; Myers et al. 2015)
 - Lyman alpha forest ($z > 2.1$)



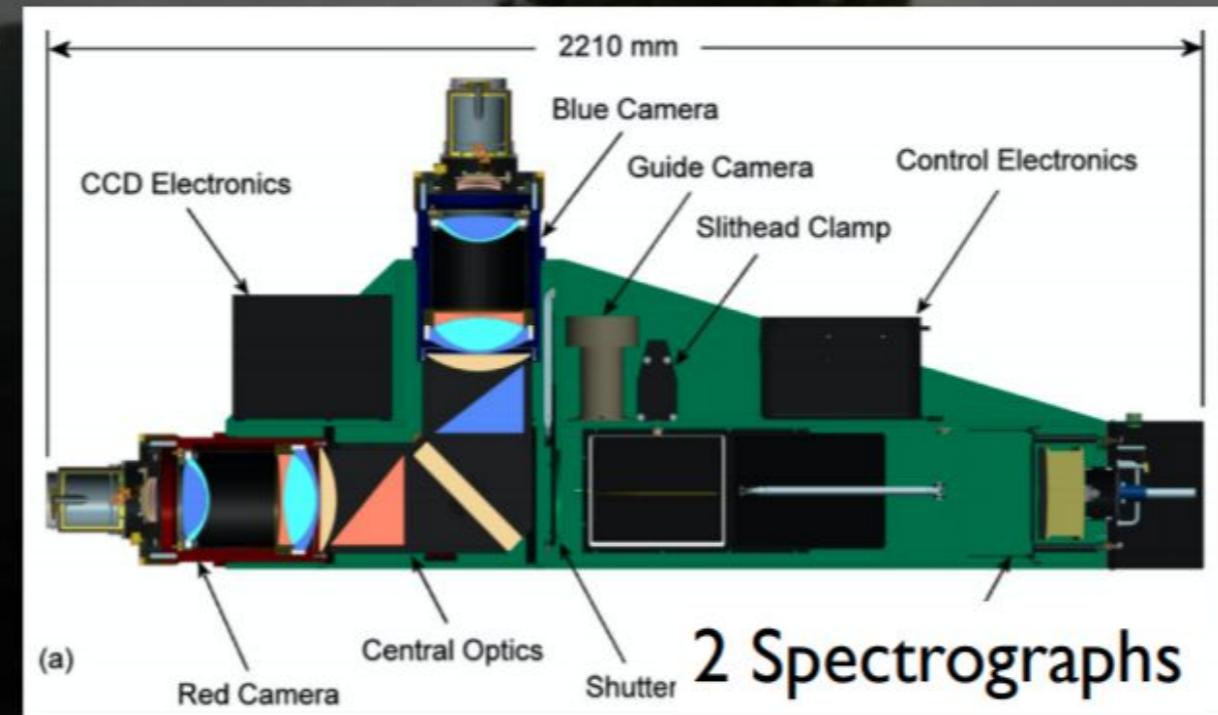
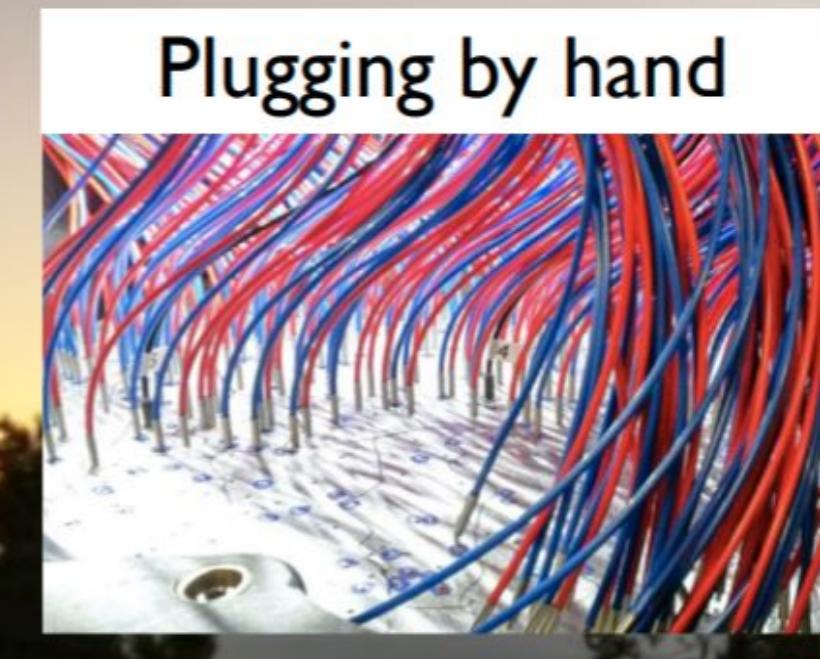
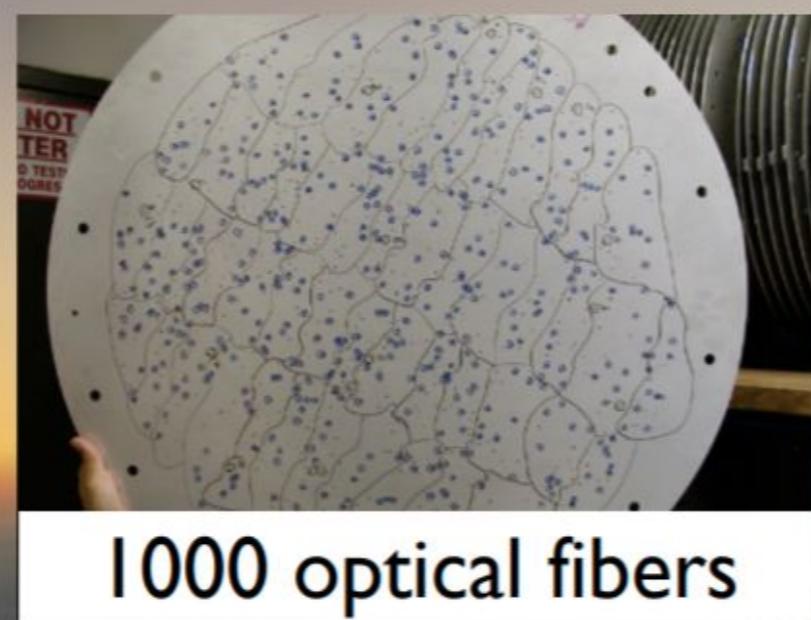
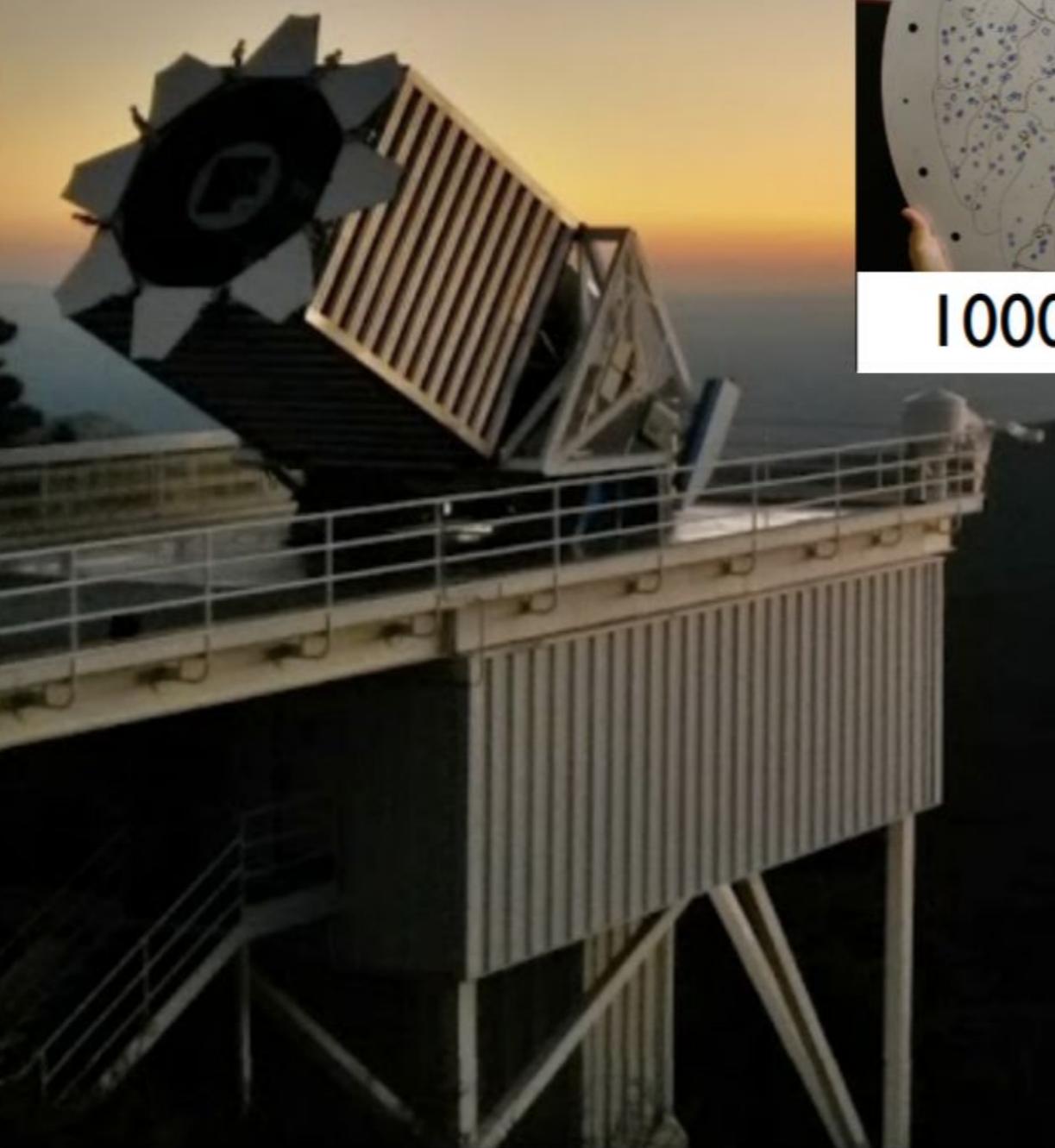
11 Billion Years of Galaxy Clustering

BOSS**eBOSS**



eBOSS Operations

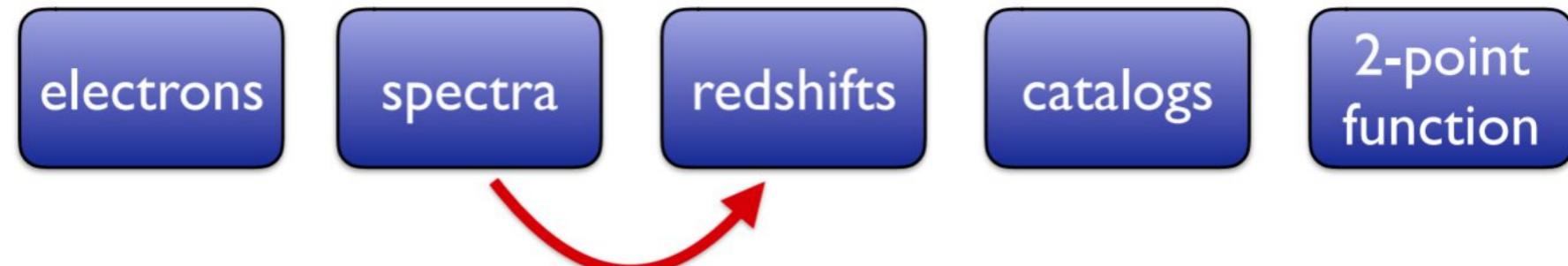
2.5 m telescope
7 deg² field of view



Apache Point Observatory, New Mexico, USA



20 Years of Pipeline Development



| | LRGs | ELGs | QSOs |
|---|--|---------------|---------------|
| Fraction of spectra without reliable redshift | DR12 pipeline: 30% ↓ DR16 pipeline: 4% | 10% | 5% |
| Total number objects with reliable redshifts | 209894 | 223177 | 325226 |
| | + 210005 Lyman-alpha forests | | |

Final Modeling of Data

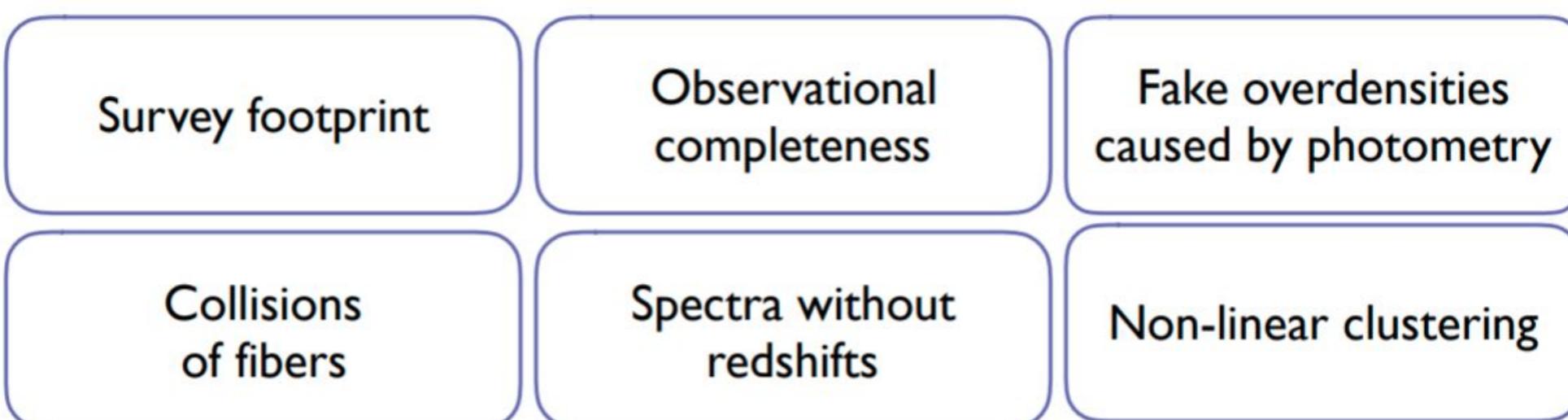


Observable : galaxy overdensity

$$\delta_g(\vec{x}) = \frac{n_g(\vec{x})}{\bar{n}_g} - 1$$

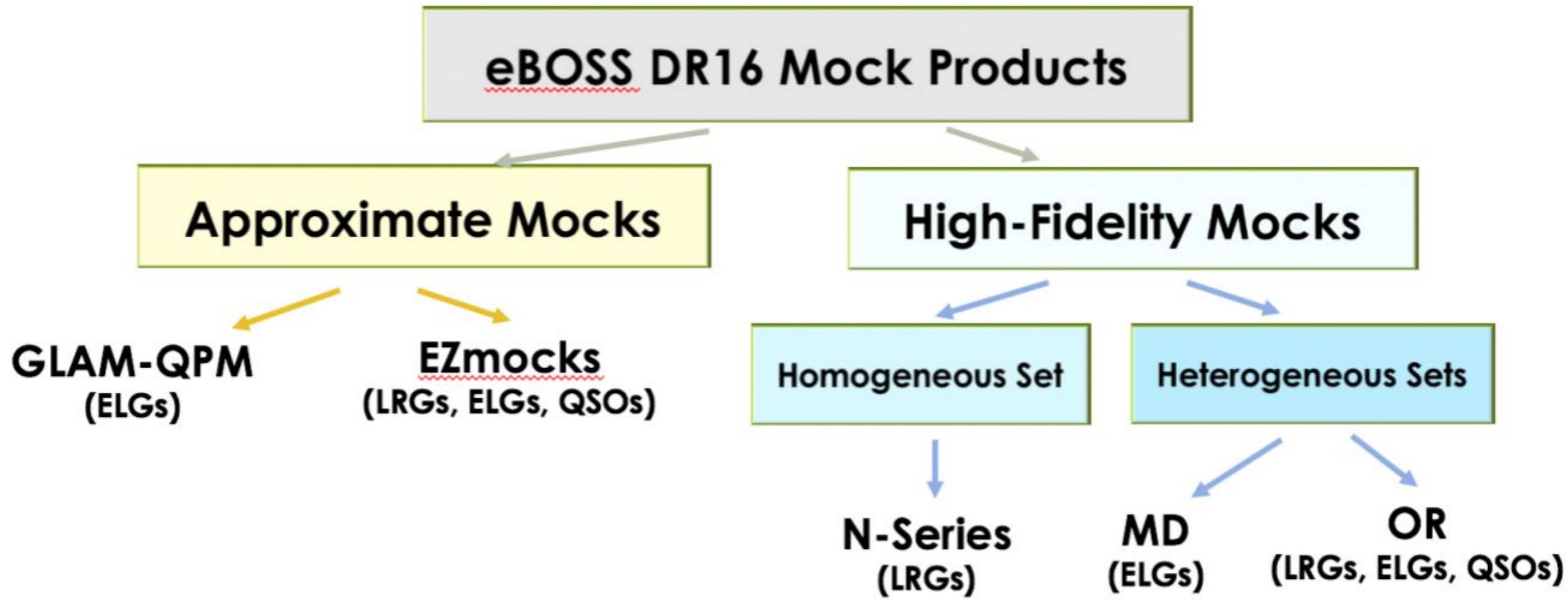
Account and correct for observational systematics:

- BOSS inspired (Reid et al. 2016)
- eBOSS LRGs and QSOs (Ross et al. in prep)
- eBOSS ELGs (Raichoor et al. in prep)



BAO and RSD Measurements

Mock Catalogs

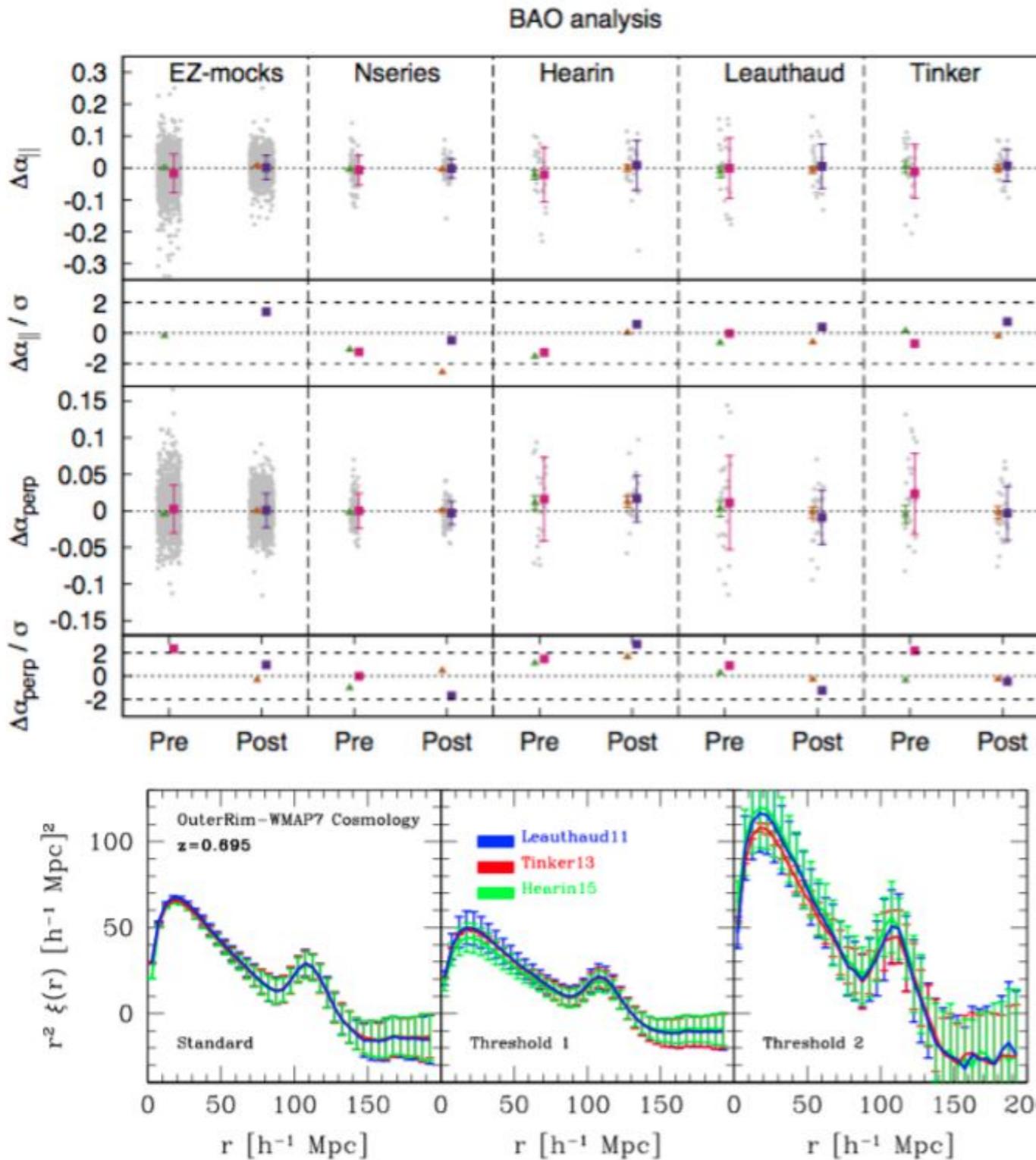


Each synthetic product serves a different science target

Approximate Mocks: covariances, observational systematics

High-Fidelity Mocks: theoretical systematics, analysis pipeline validation, performance & accuracy, analysis biases

Model Testing: LRG Example



UNBLIND SET 1 → HOD VARIATIONS
 UNBLIND SET 2 → REDSHIFT EVOLUTION
 UNBLIND SET 3 → CUSTOMIZATIONS
 UNBLIND SET 4 → HOD VAR. – LARGE BOX

Bautista+ (2020)
 Gil-Marín+ (2020)
 Rossi+ (2020)

BAO Systematics

- (1) Performance of BAO template
- (2) Impact of Reference cosmology
- (3) Effect on Non-Periodicity on BAO
- (4) Impact of HODs on BAO

RSD Systematics

- (1) Optimal Range of scales
- (2) Performance of RSD Modeling
- (3) Impact of Reference cosmology
- (4) Effect on Non-Periodicity on RSD Modeling
- (5) Impact of HODs on RSD Modeling

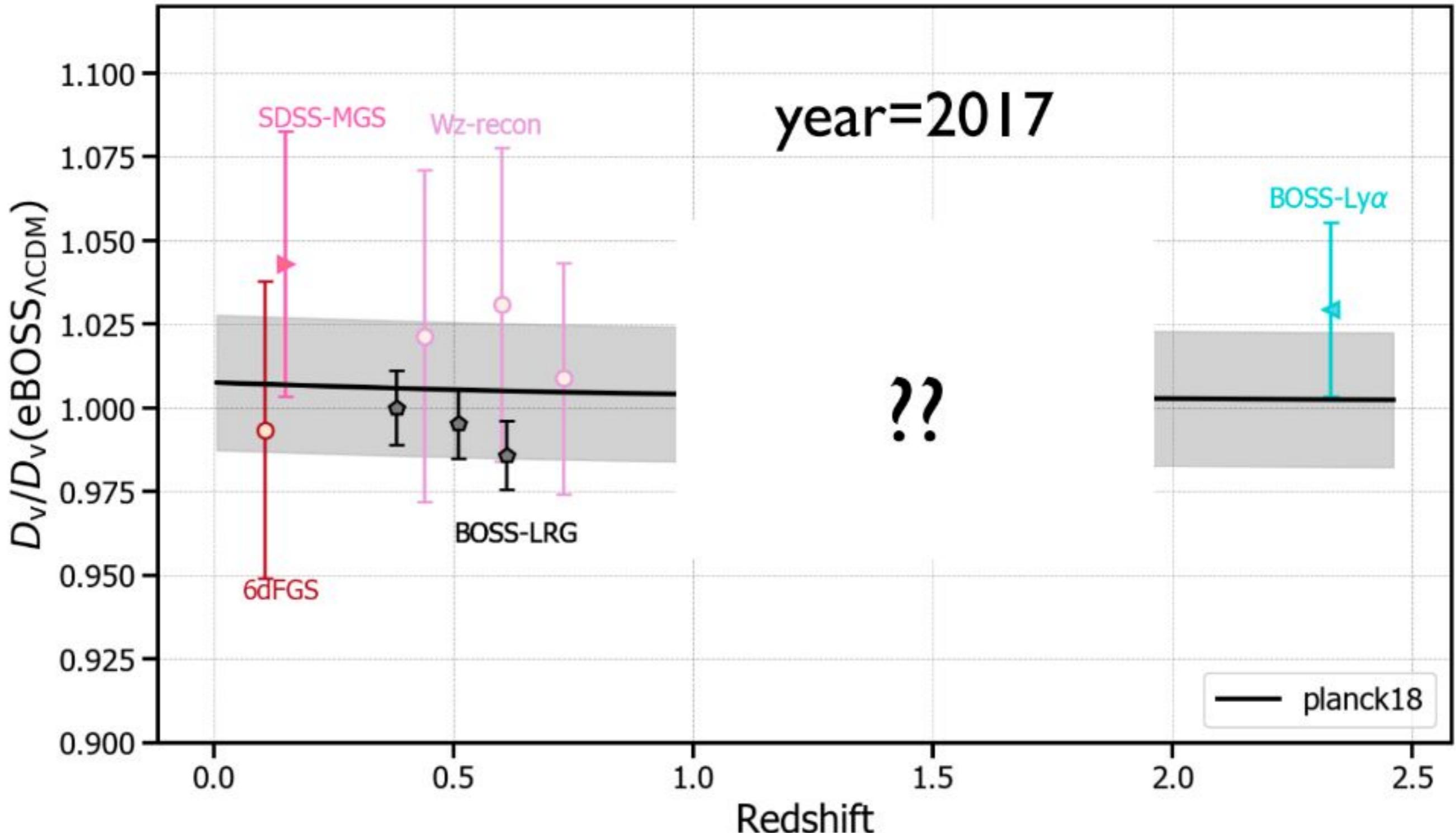
No systematic bias on HOD
~ 0.2σ theoretical systematics ($f\sigma_8$)
Well below statistical uncertainty

Summary of Systematic Errors

- Validation & assessment of systematic aspects related to fitting methods relevant for final consensus results
- Include observational & theoretical systematics + reference cosmology systematics
- **LRG** global systematic budget $\rightarrow 1.5\% [0.2\sigma]$ on $f\sigma_8$
- **ELG** global systematic budget $\rightarrow 4.0\% [0.2\sigma]$ on $f\sigma_8$
- **QSO** global systematic budget $\rightarrow 3.0\% [0.25\sigma]$ on $f\sigma_8$

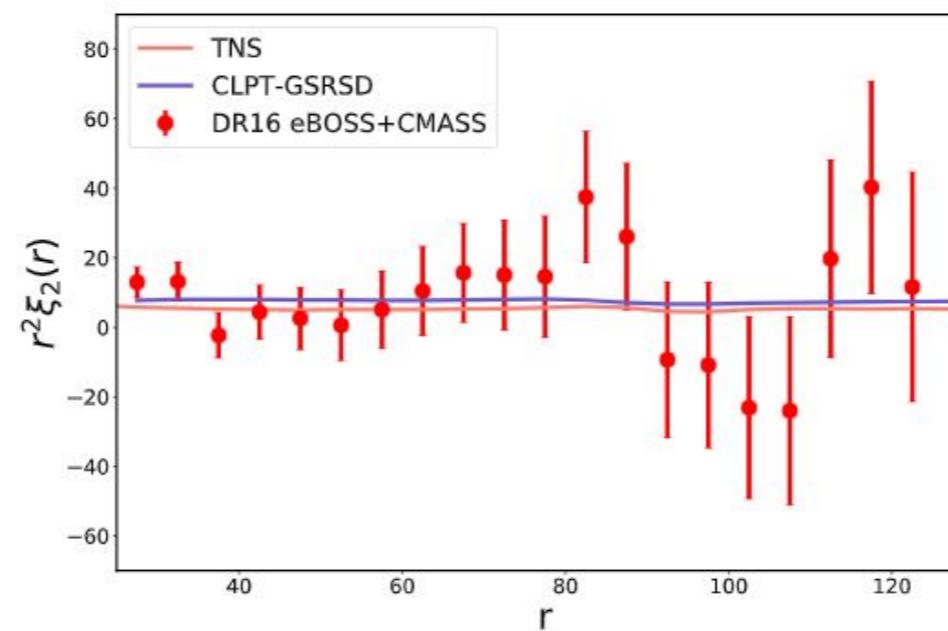
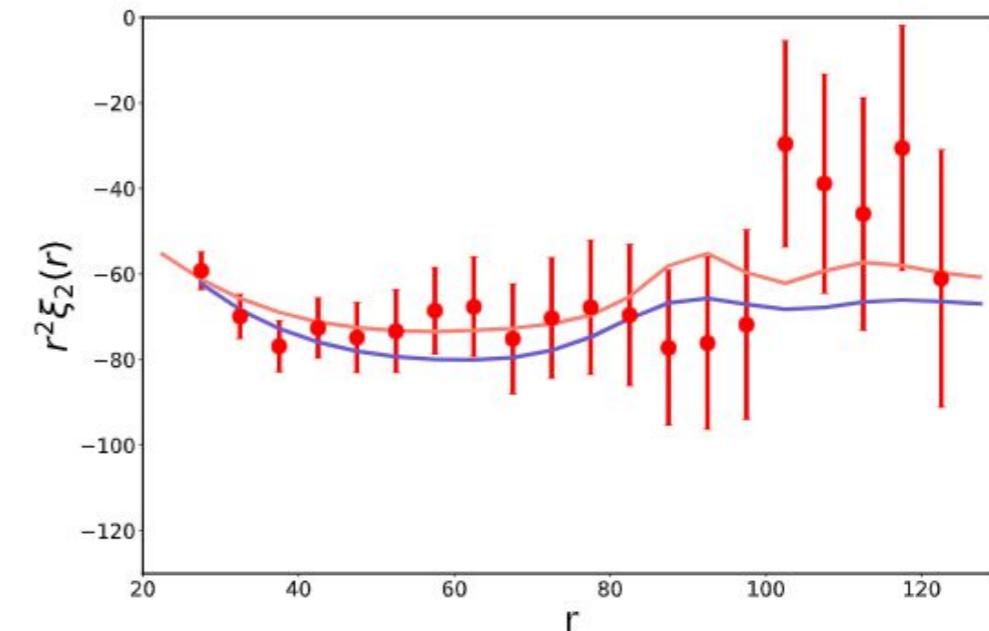
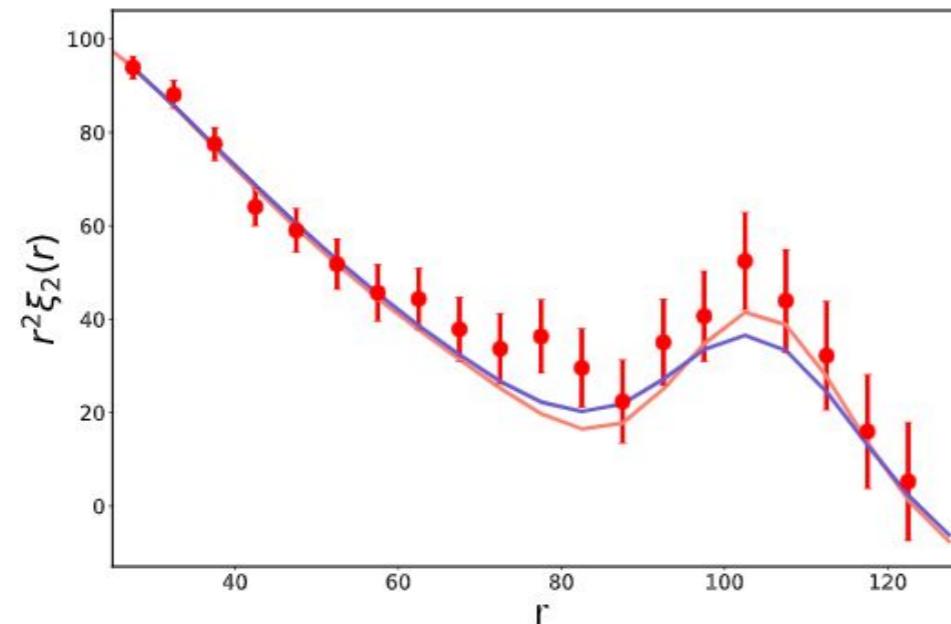
Global systematics well below statistical uncertainties

Pre-eBOSS BAO Hubble Diagram



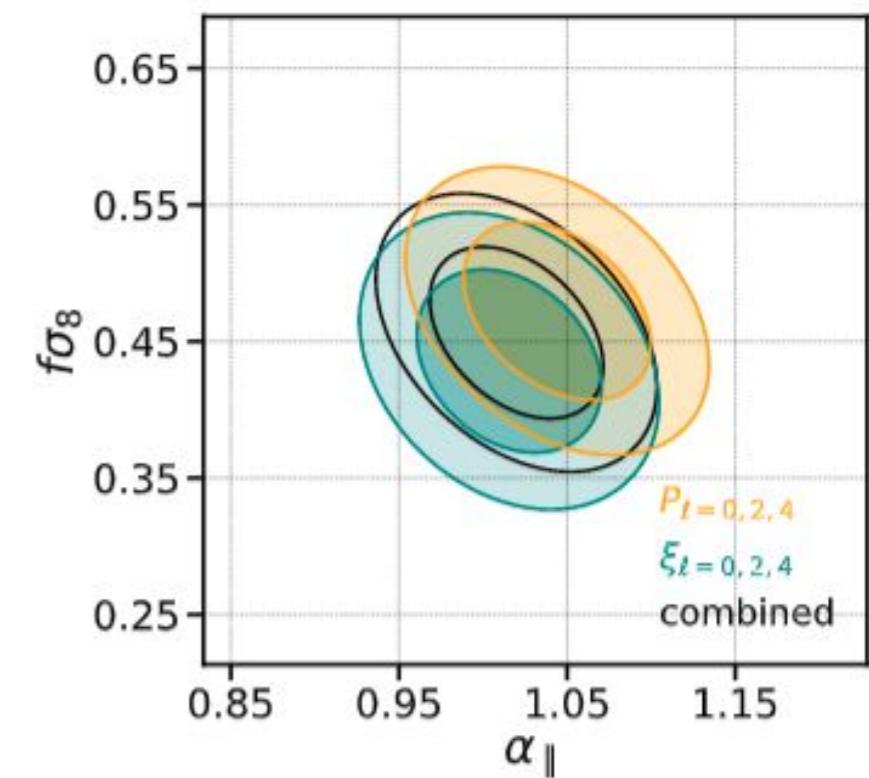
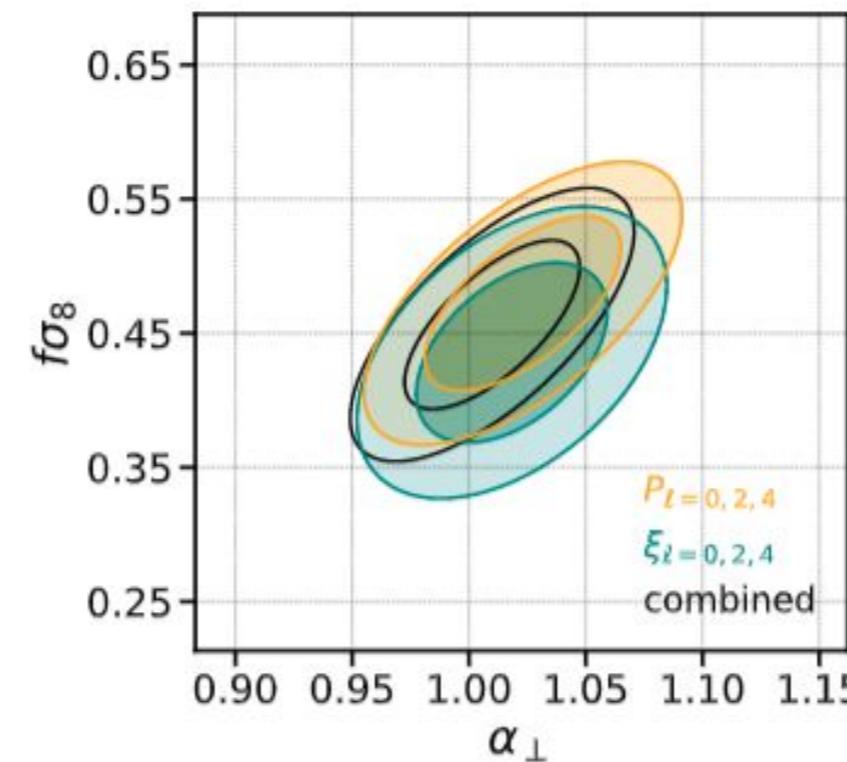
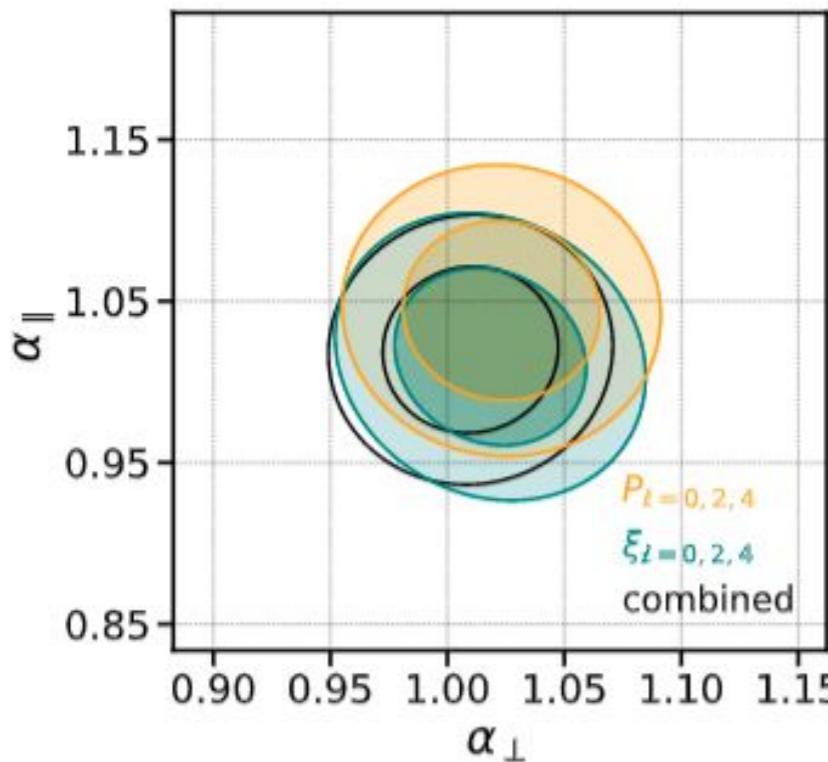
BAO/RSD Measurements

LRG Full Shape Study in Configuration Space

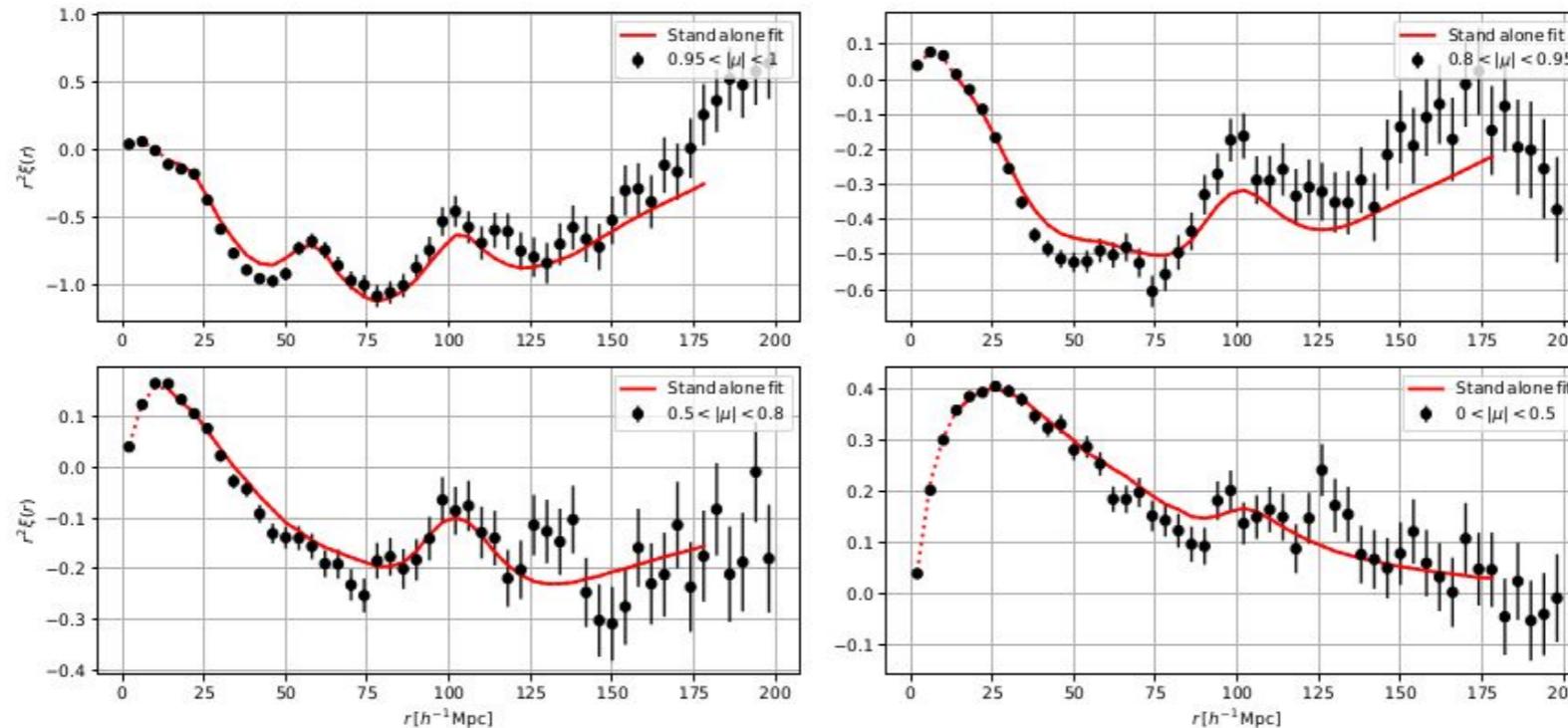


Consensus

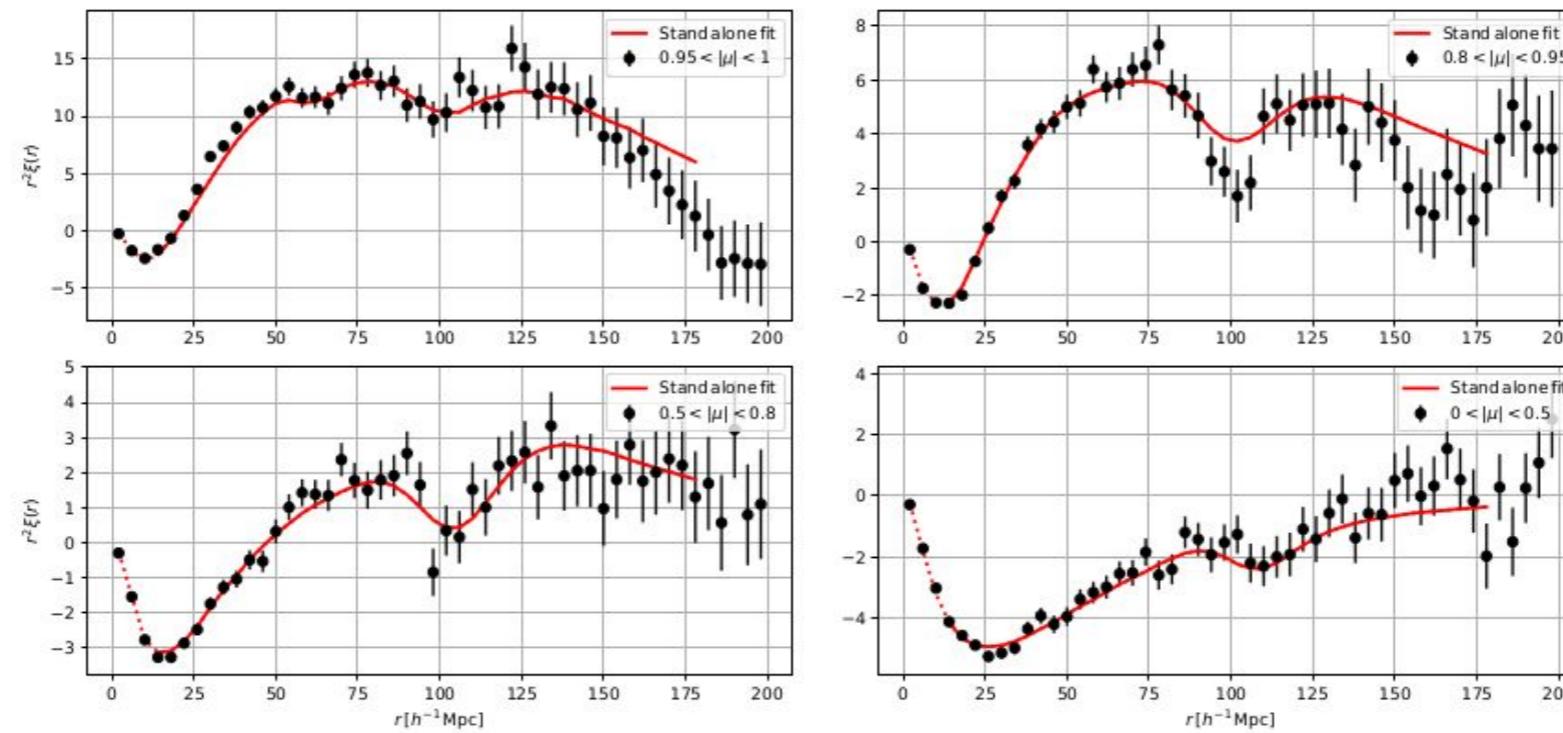
- BAO measured w/reconstruction in LRG and ELG
- BAO/RSD measured in full shape with LRG/ELG/QSO
- Configuration Space and Fourier Space Measurements for each tracer
- Combine BAO/RSD results using mock-calibrated covariance matrices



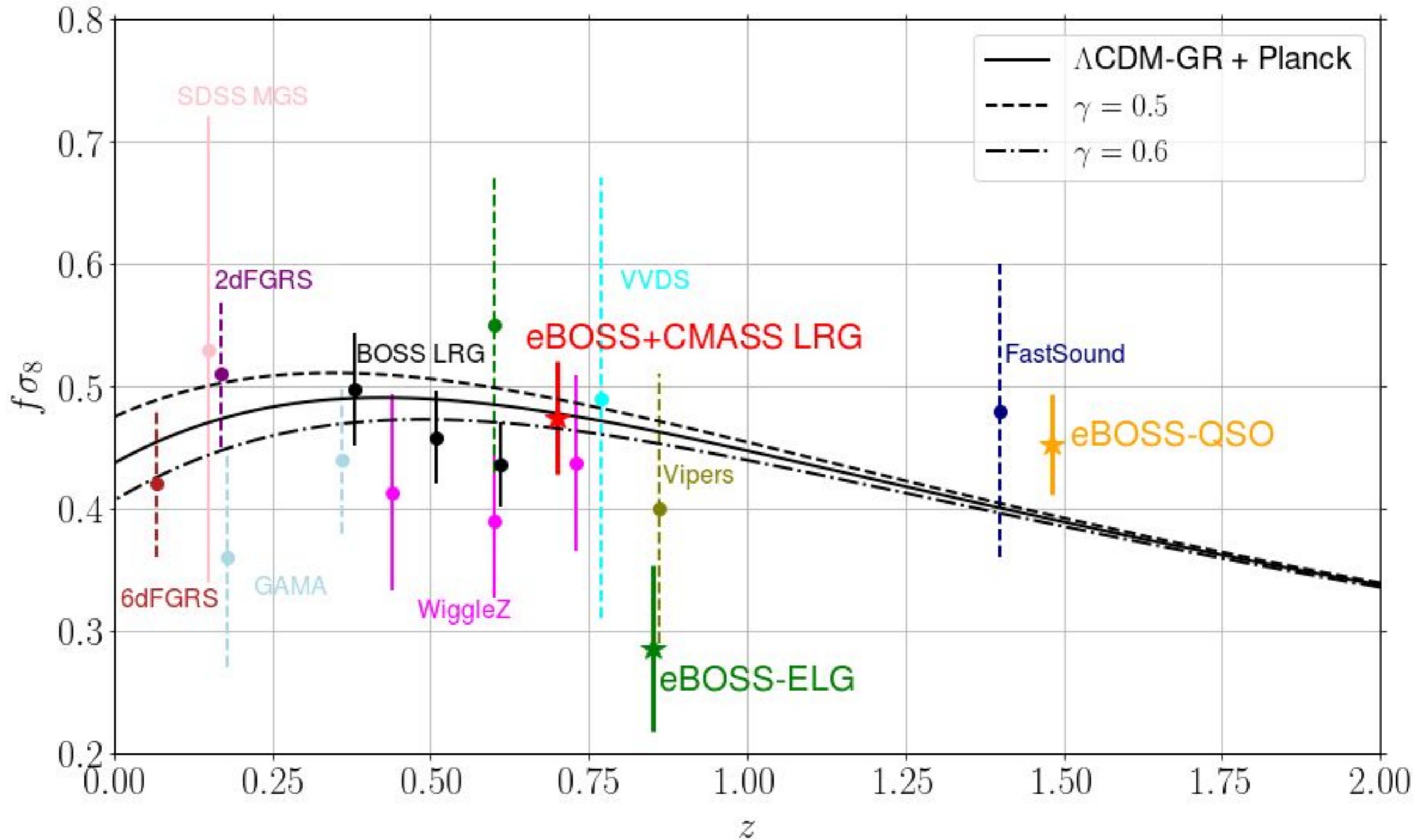
Lyman-Alpha Forest BAO (z=2.33)



$\text{Ly}\alpha(\text{Ly}\alpha)\times\text{QSO}$



Post-eBOSS Growth Measurements

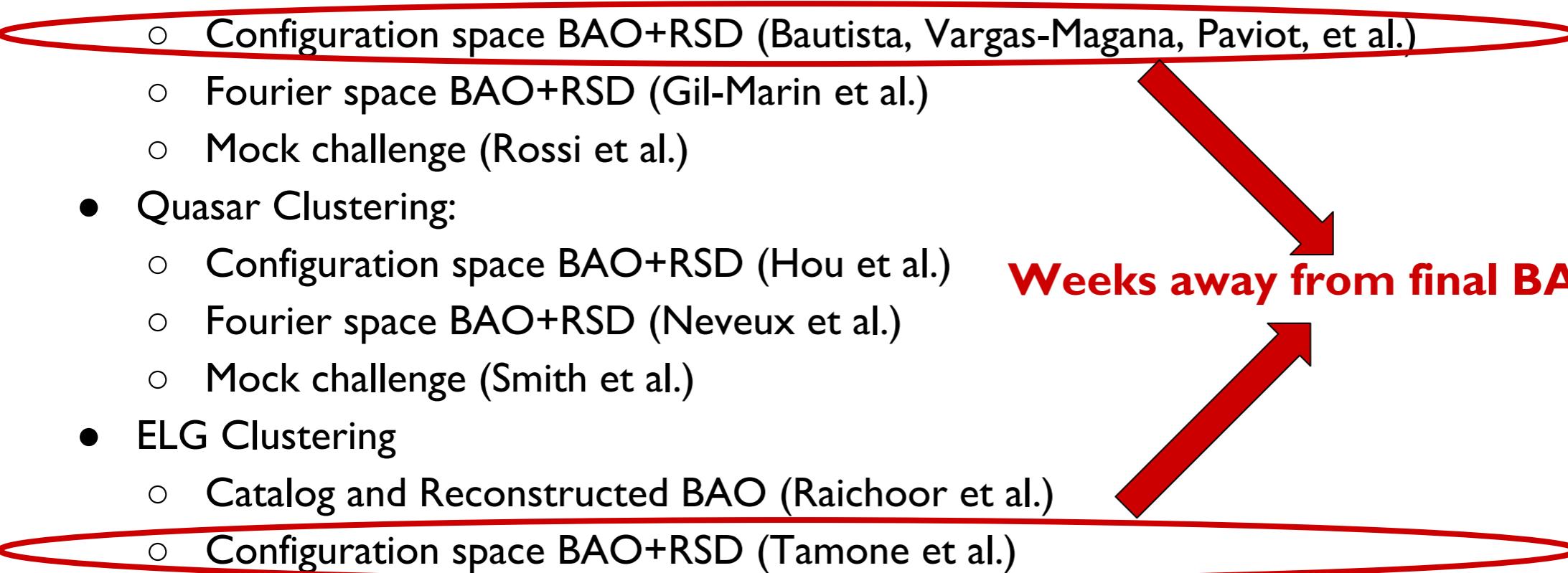


Final Results in Spring 2020

- Clustering Catalogs
 - LRG and QSO Clustering Catalogs (Ross et al.)
 - QSO Catalogs (Lyke et al.)
- LRG Clustering
 - Configuration space BAO+RSD (Bautista, Vargas-Magana, Paviot, et al.)
 - Fourier space BAO+RSD (Gil-Marín et al.)
 - Mock challenge (Rossi et al.)
- Quasar Clustering:
 - Configuration space BAO+RSD (Hou et al.)
 - Fourier space BAO+RSD (Neveux et al.)
 - Mock challenge (Smith et al.)
- ELG Clustering
 - Catalog and Reconstructed BAO (Raichoor et al.)
 - Configuration space BAO+RSD (Tamone et al.)
 - Fourier space BAO+RSD (de Mattia et al.)
 - EZmocks (Zhao et al.)
 - QPM+GLAM mocks (Lin et al.)
- Lyman-alpha Forest Clustering
 - auto and Lyman-alpha-QSO cross correlation BAO (du Mas des Bourboux et al.)

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Weeks away from final BAO/RSD Results

Cosmology Interpretation

Legacy of BOSS/eBOSS

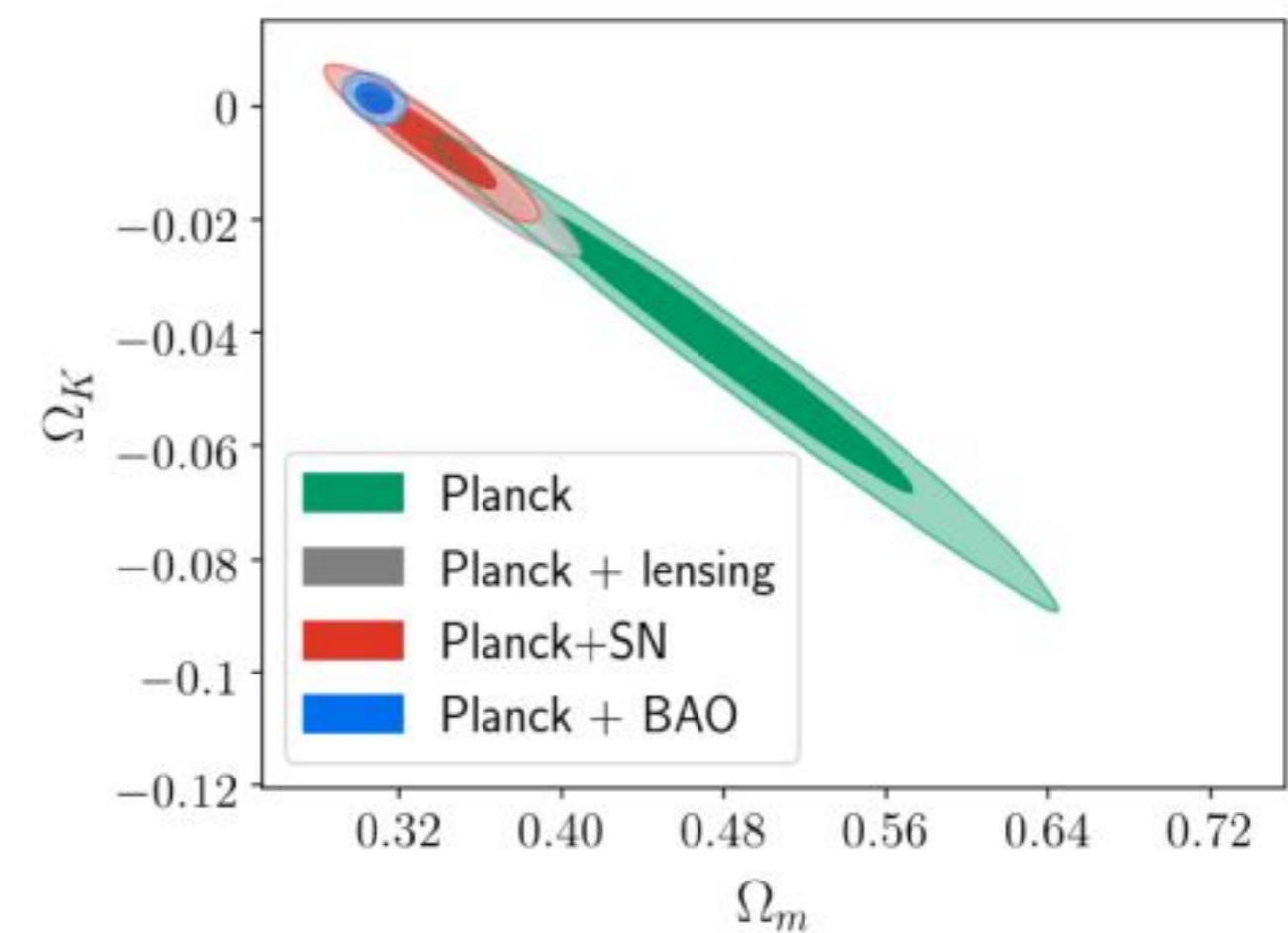
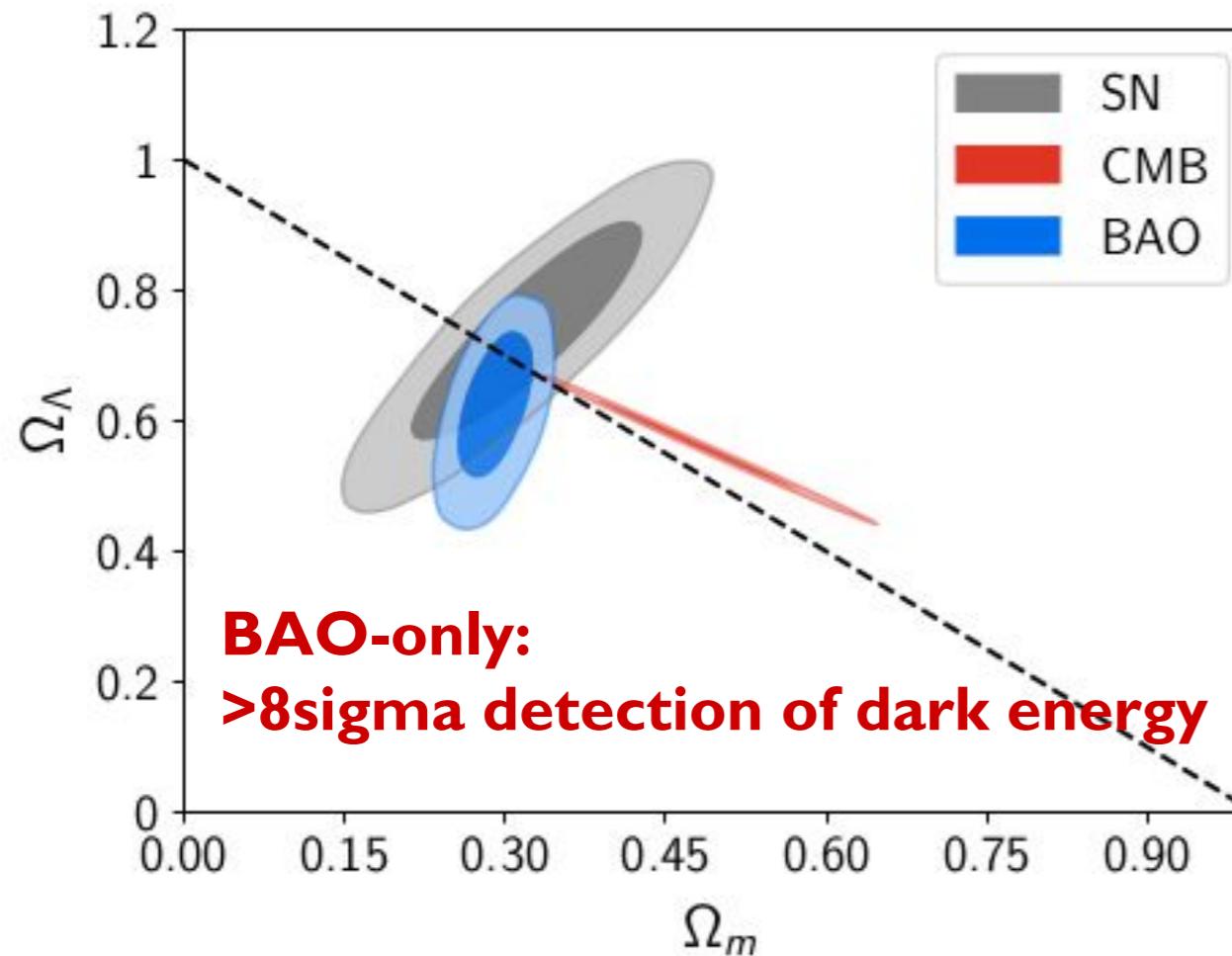
- 2009-2019
 - Conclusion of Stage-III Dark Energy surveys with spectroscopy
 - Over 4M spectra obtained (more spectra than rest of the world combined)
 - Sample larger range of redshift than any other probe
 - Percent-level precision on BAO distance scale at each redshift
 - Growth measurements to $z < 1.5$
- Key Cosmology Questions
 - Dark Energy and curvature: role of BAO relative to SNe and CMB?
 - H₀ tension: robustness of BAO estimates
 - What do we learn from growth?
 - Bounds on the neutrino mass
 - Net advances in cosmology from Stage-III programs

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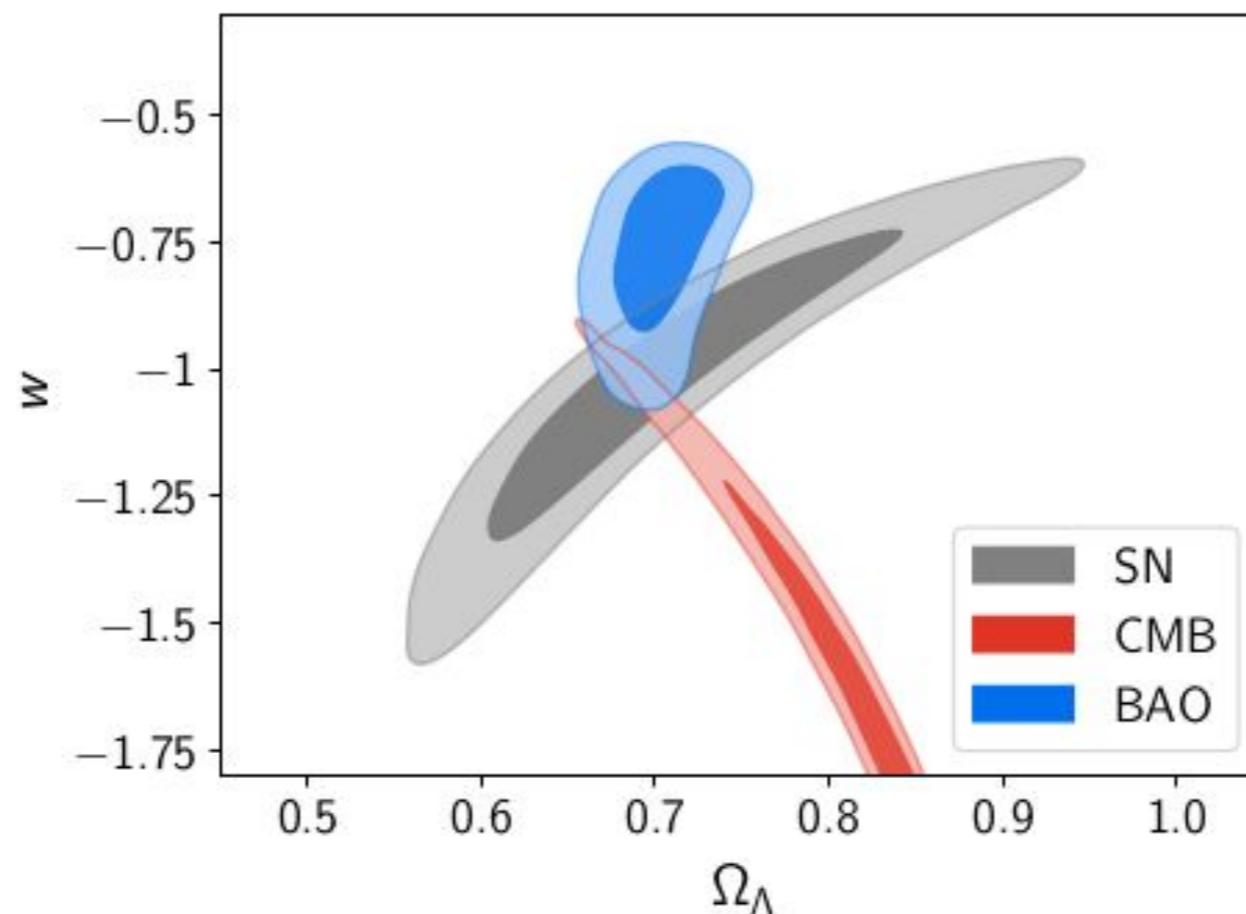
oCDM Cosmology

- BAO-only from SDSS/BOSS/eBOSS
- Pantheon sample of SNe (Scolnic et al, 2018)
- Planck 2018 results (Planck Collaboration, 2018)

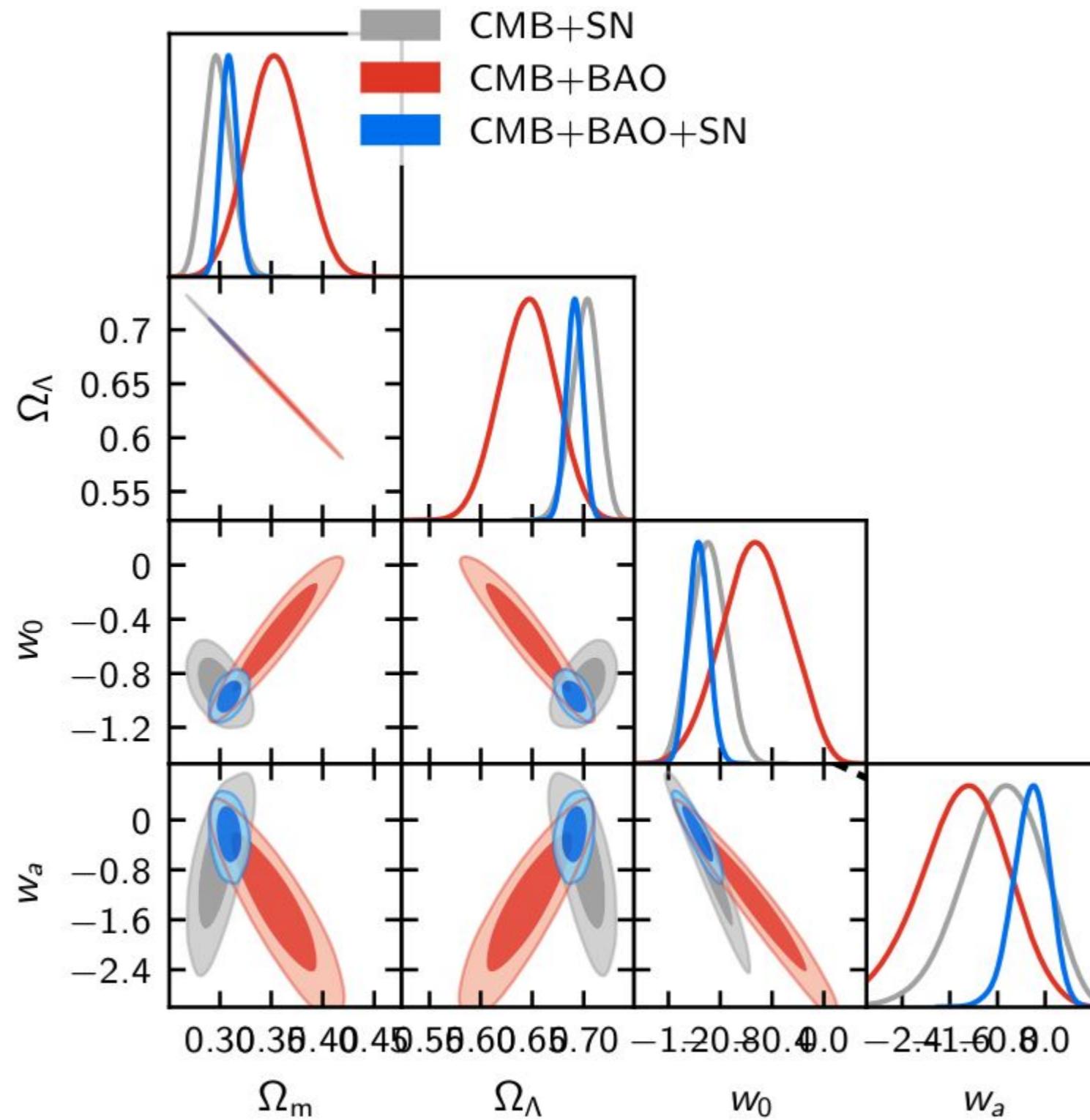


wCDM Cosmology

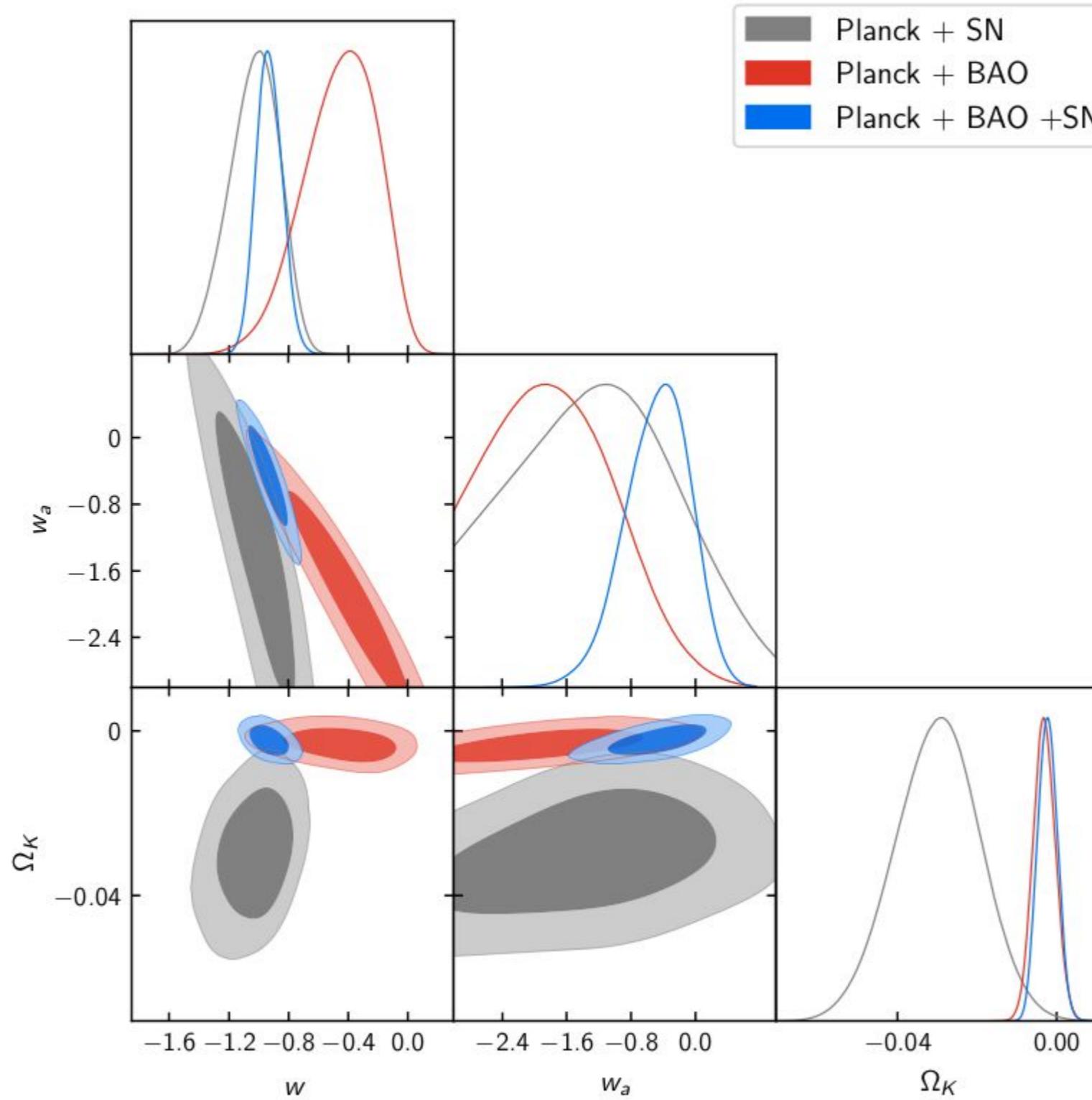
- BAO-only offer tighter constraints than SNe-only
- Degeneracies well-aligned for SNe+CMB
 - SNe+CMB vs BAO+CMB: 1.2X better in Ω_Λ ; 1.5X in w



w0waCDM Cosmology

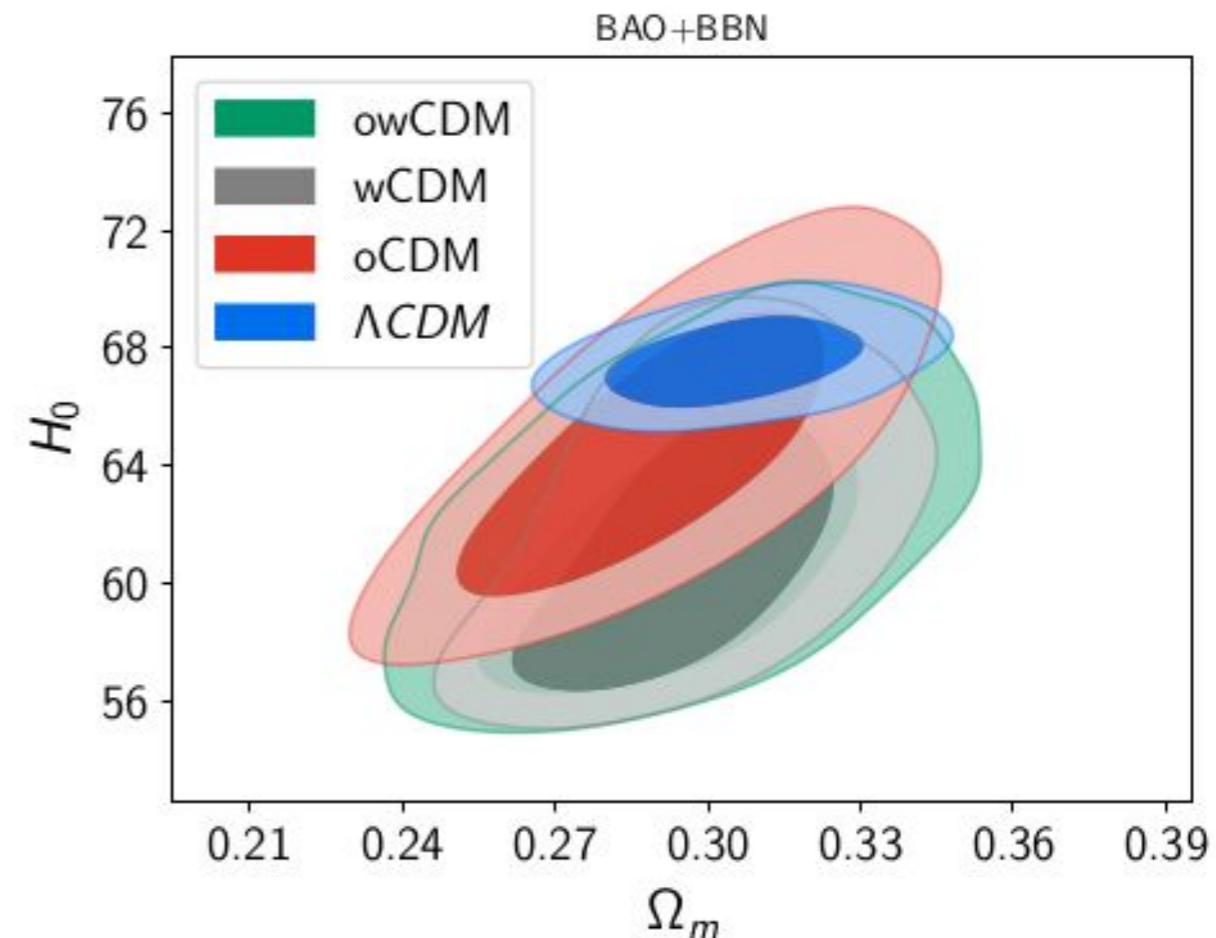


ow0waCDM Cosmology

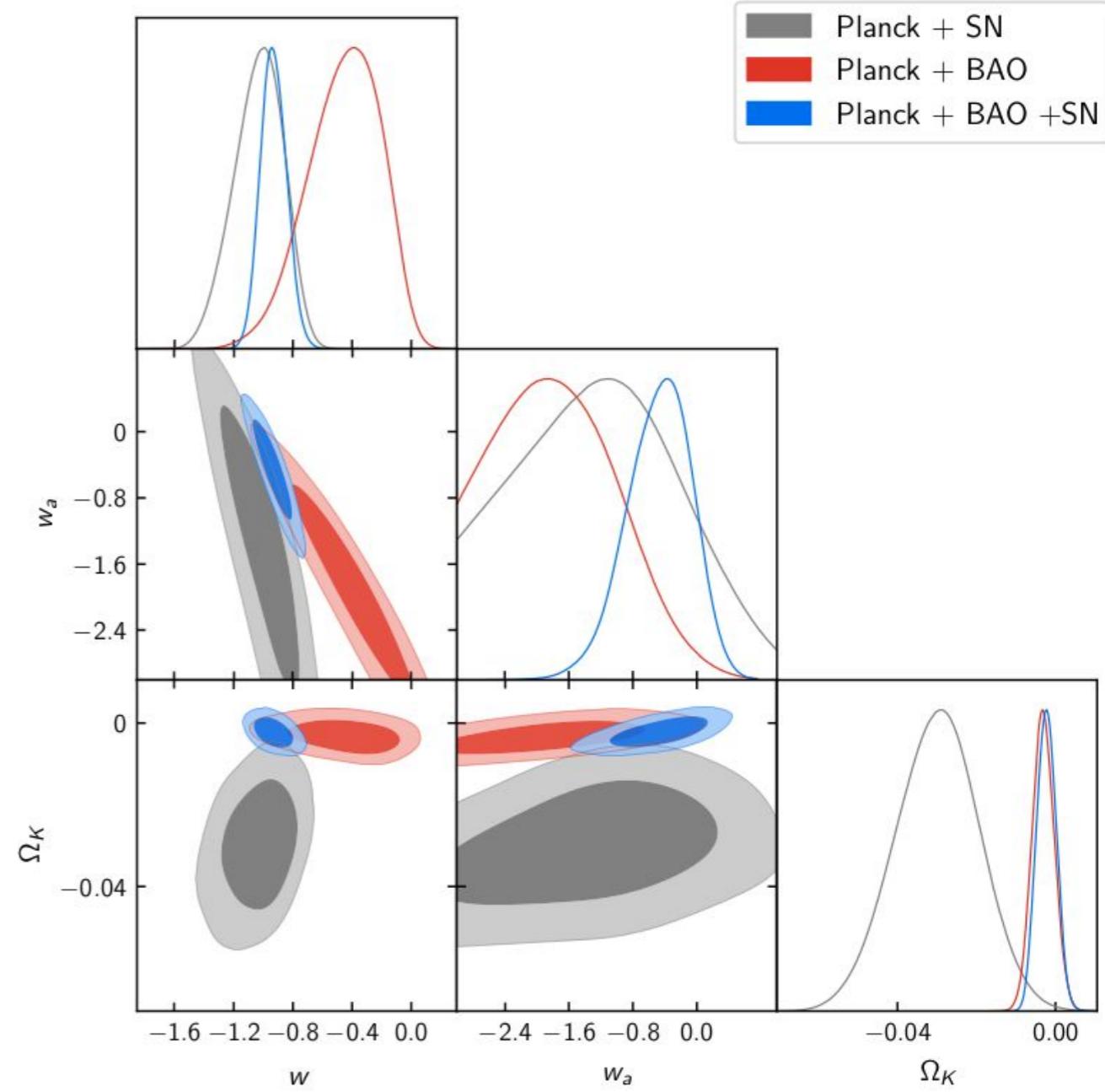
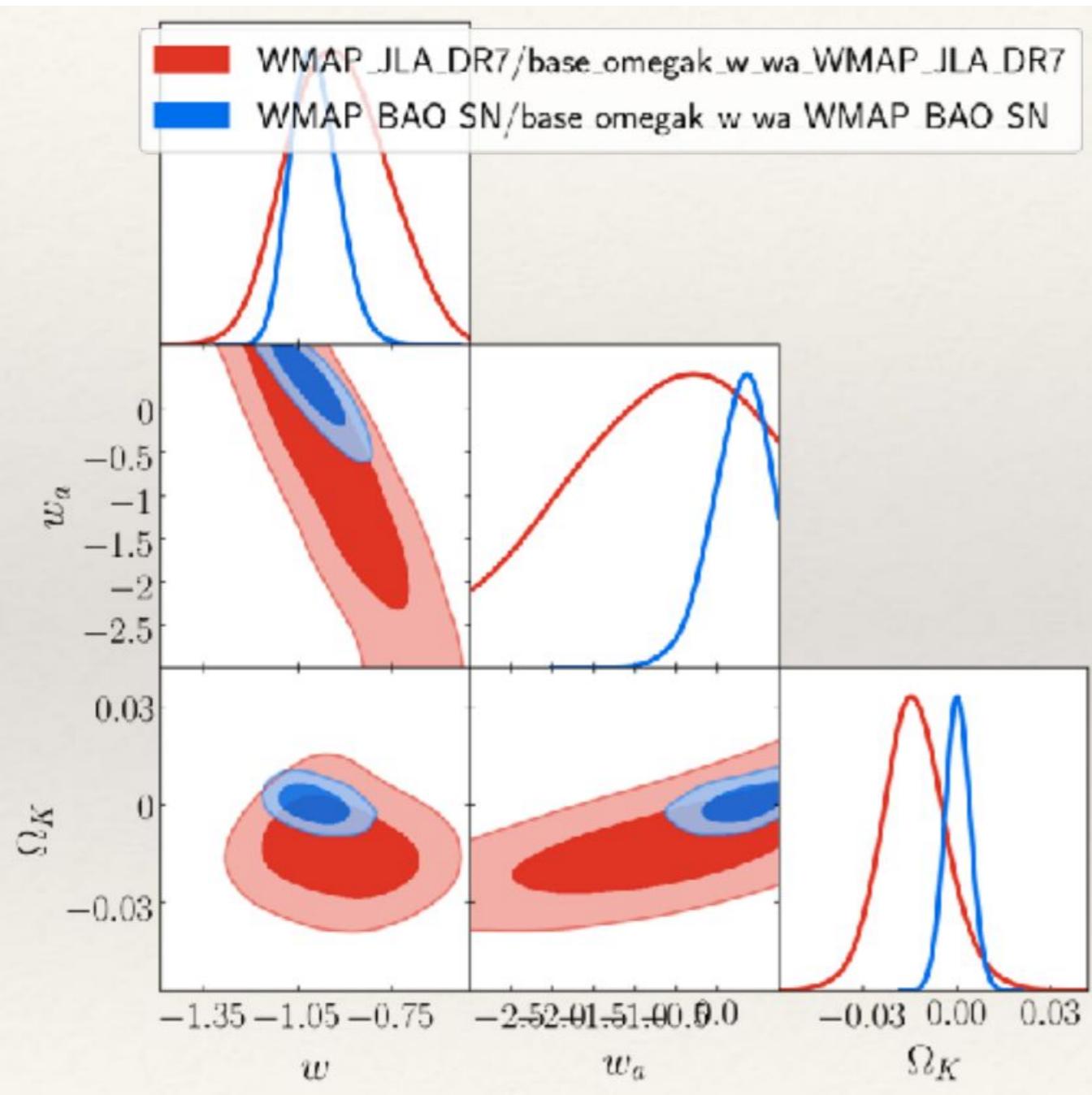


H₀ Tension

| Dataset / Reference | Model | Value in km s ⁻¹ Mpc ⁻¹ |
|--|---------------|---|
| Planck+BAO+SN | Λ CDM | 67.6 ± 0.4 |
| Planck+BAO+SN BAO+SN+CMB- calibrated r_d | ow_0w_a CDM | 67.9 ± 0.9 |
| BAO+SN+CMB- calibrated r_d | Λ CDM | 67.9 ± 0.6 |
| BAO+SN+CMB- calibrated r_d | ow_0wa CDM | 68.0 ± 0.9 |
| BBN+BAO+SN | Λ CDM | 67.6 ± 1.0 |
| BBN+BAO+SN | ow_0wa CDM | 65.8 ± 3.2 |



A Decade of Progress (ow0waCDM)



Summary

- **BOSS/eBOSS:**
 - Conclusion of Stage-III Dark Energy surveys with spectroscopy
 - BAO measurements over 11 Gyr
 - RSD measurements to $z < 1.5$
 - Measurements nearly final
- **Cosmology**
 - BAO offer unique constraints on curvature
 - Complement CMB+SNe, but higher precision in isolation
 - Allow robust estimates of H_0
 - Significant improvements from 2010-2020 surveys
 - Keep an eye out for growth and neutrino interpretation
- **DESI:** Stage-IV experiment commissioning now!