the Extended Baryon Oscillation Spectroscopic Survey

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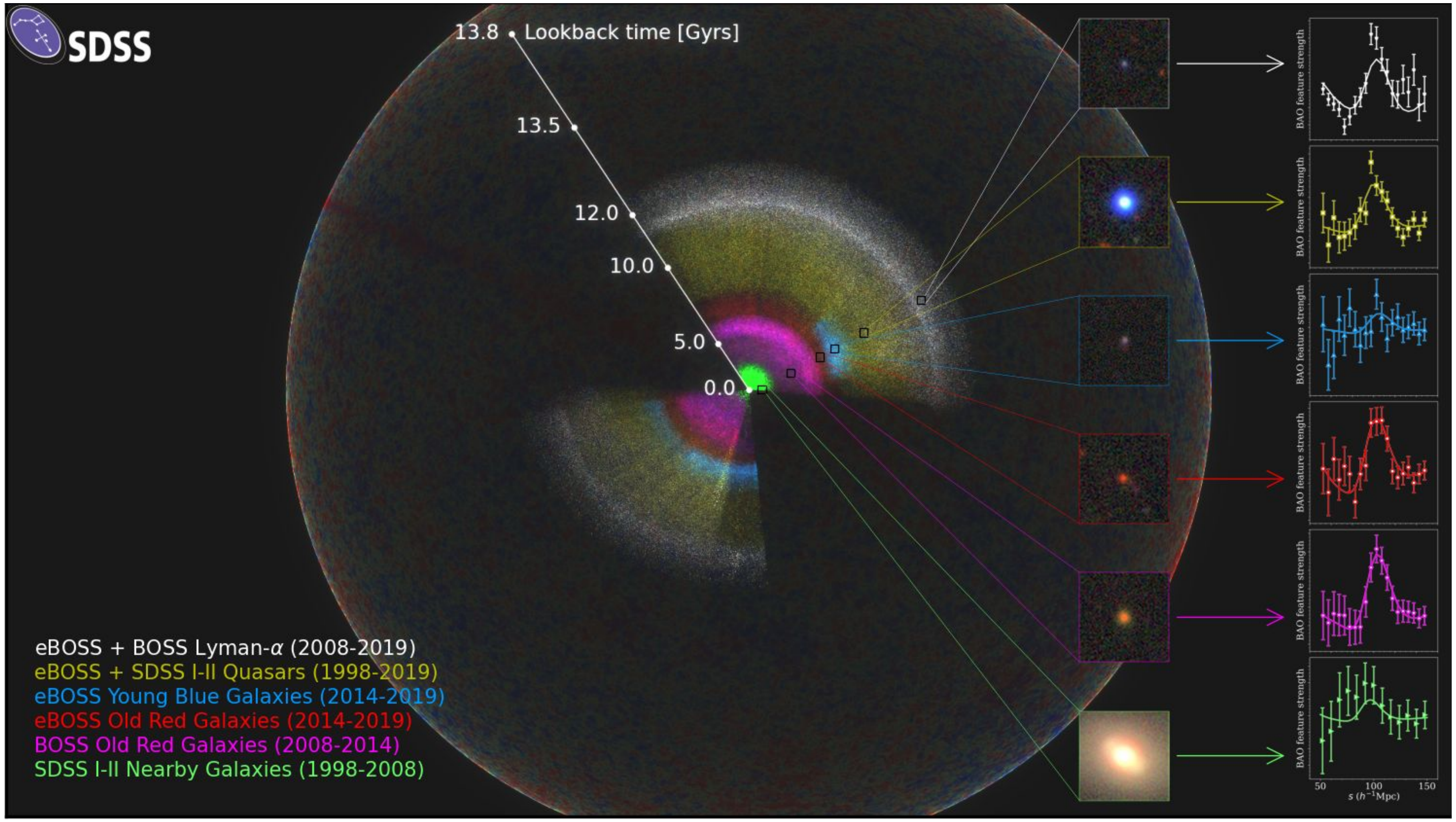
on Behalf of the eBOSS Collaboration

Outline

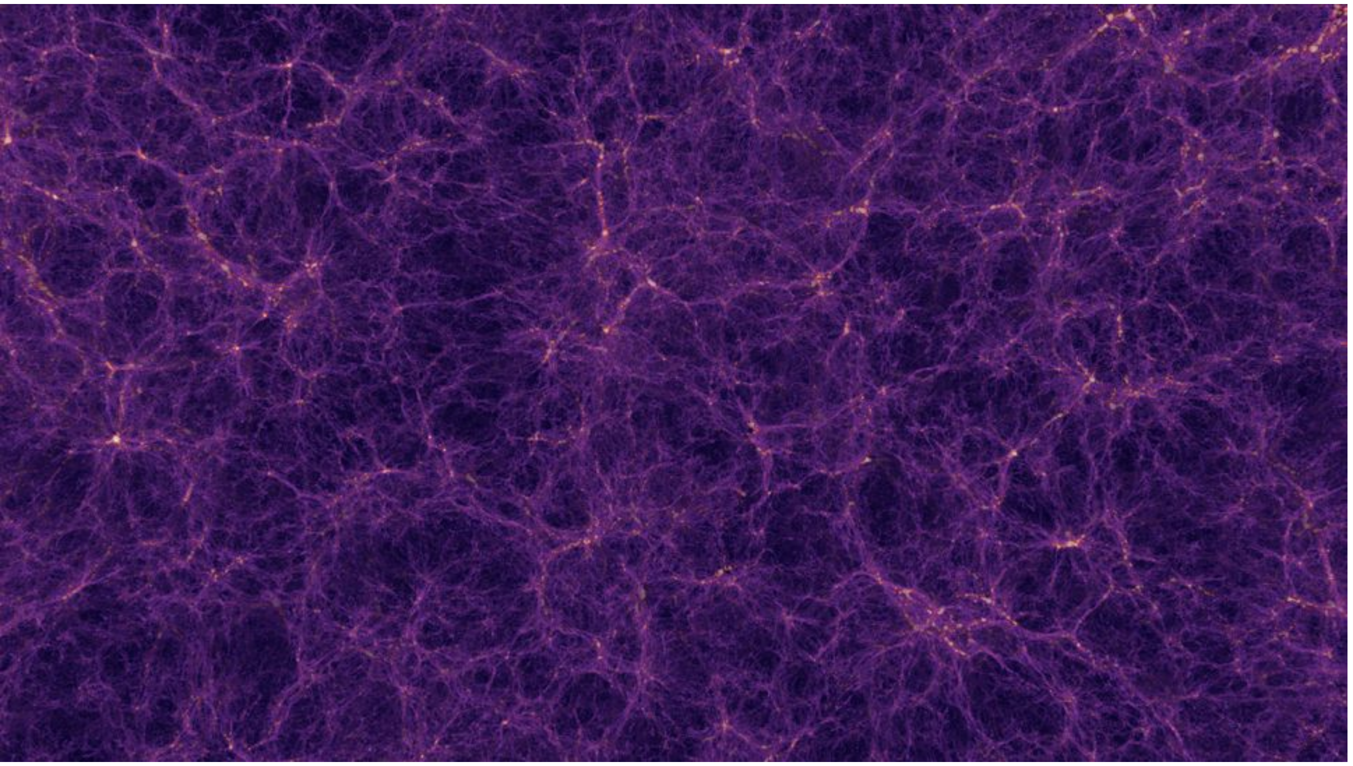
- Background and Survey Overview (completed March 1, 2019!)
- Measurements of BAO and RSD
- Cosmology Interpretation

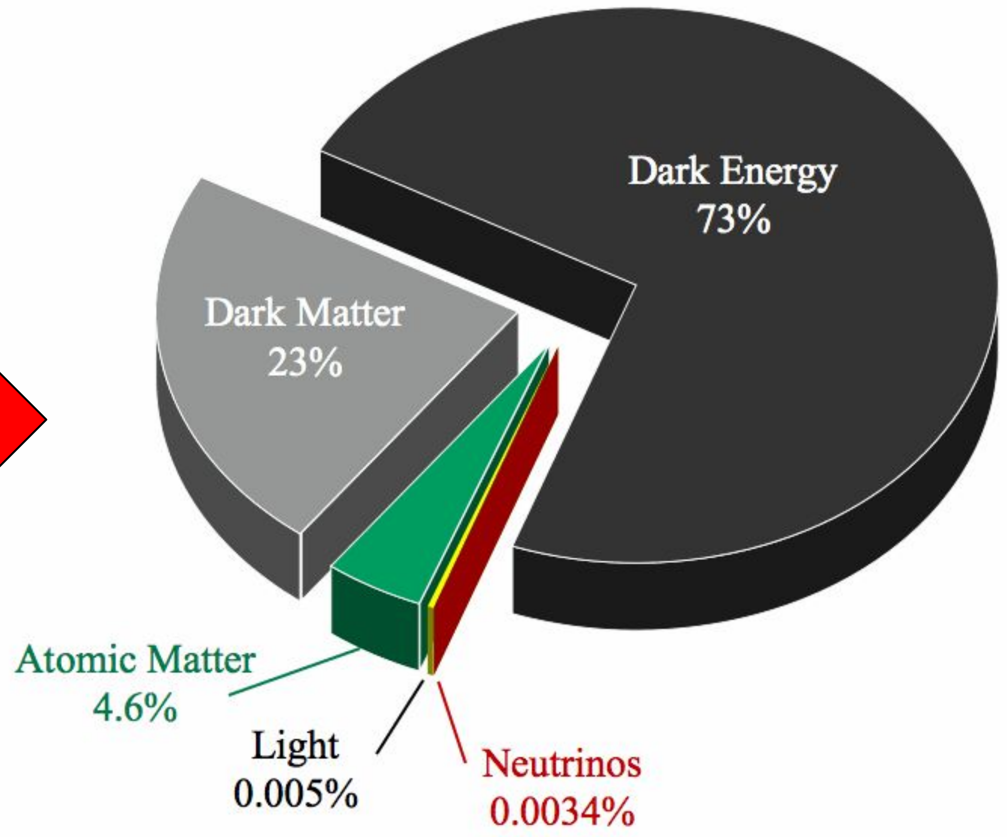


Cosmological Background

Cosmology with Spectroscopic Surveys

- **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





Cosmological Model (Expansion History)

- Friedmann Equation: $$H^2(a) = \frac{8\pi G}{3}\rho(a) - \frac{kc^2}{a^2}$$

- Energy Components: dark (dm), baryonic (b), and total matter (m), neutrinos, photons, dark energy, and curvature

$$\Omega_x = \frac{\rho_x}{\rho_{\rm crit}} = \frac{8\pi G}{3H^2}\rho_x \quad \Omega_k(a) = -\frac{kc^2}{a^2\ H^2(a)}$$

- Dark Energy equation of state

$$w(a) = \begin{cases} -1 \\ w \\ w_0 + w_a(1-a) \end{cases}$$

$$\frac{\rho_{\rm DE}(a)}{\rho_{\rm DE,0}} = \begin{cases} 1 \\ a^{-3(1+w)} \\ a^{-3(1+w_0+w_a)}\exp[-3w_a(1-a)] \end{cases}$$

Cosmological Model (Expansion History)

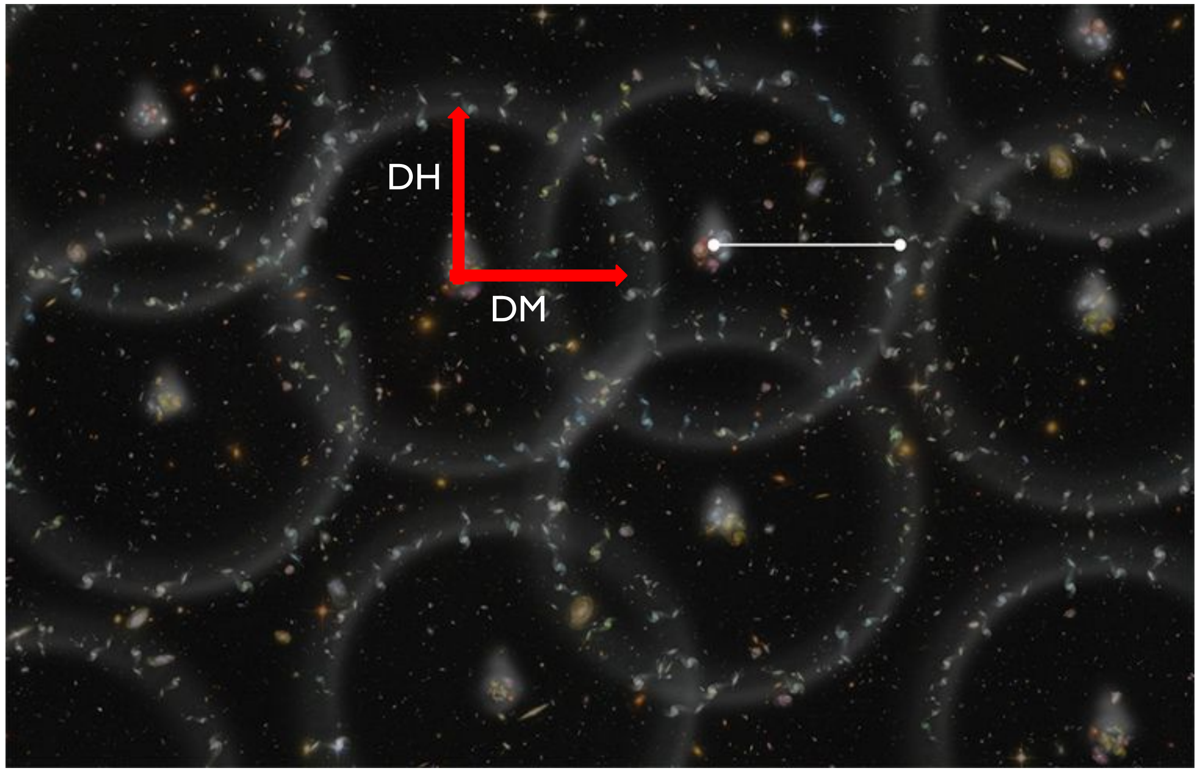
- BAO measure angular diameter distance and H(z)

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

$$D_H(z) = \frac{c}{H(z)}$$

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

$$D_M(z) = \frac{c}{H_0} S_k \left(\frac{D_C(z)}{c/H_0} \right)$$



Cosmological Model (Growth History)

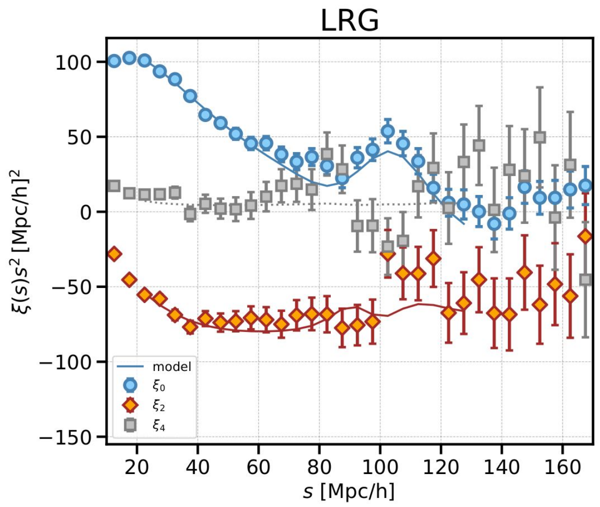
- Scale-independent growth factor: $\delta(\mathbf{x}, t) \;=\; D(t)\delta(\mathbf{x}, t_0)$

- Linear growth equation:

$$\ddot{D} + 2H(z)\dot{D} - \frac{3}{2}\Omega_m H_0^2 (1+z)^3 D = 0$$

- Linear Growth Rate: $f(z) \equiv \dfrac{d\ln D}{d\ln a}$ → $f = \dfrac{\partial \ln \sigma_8}{\partial \ln a}$

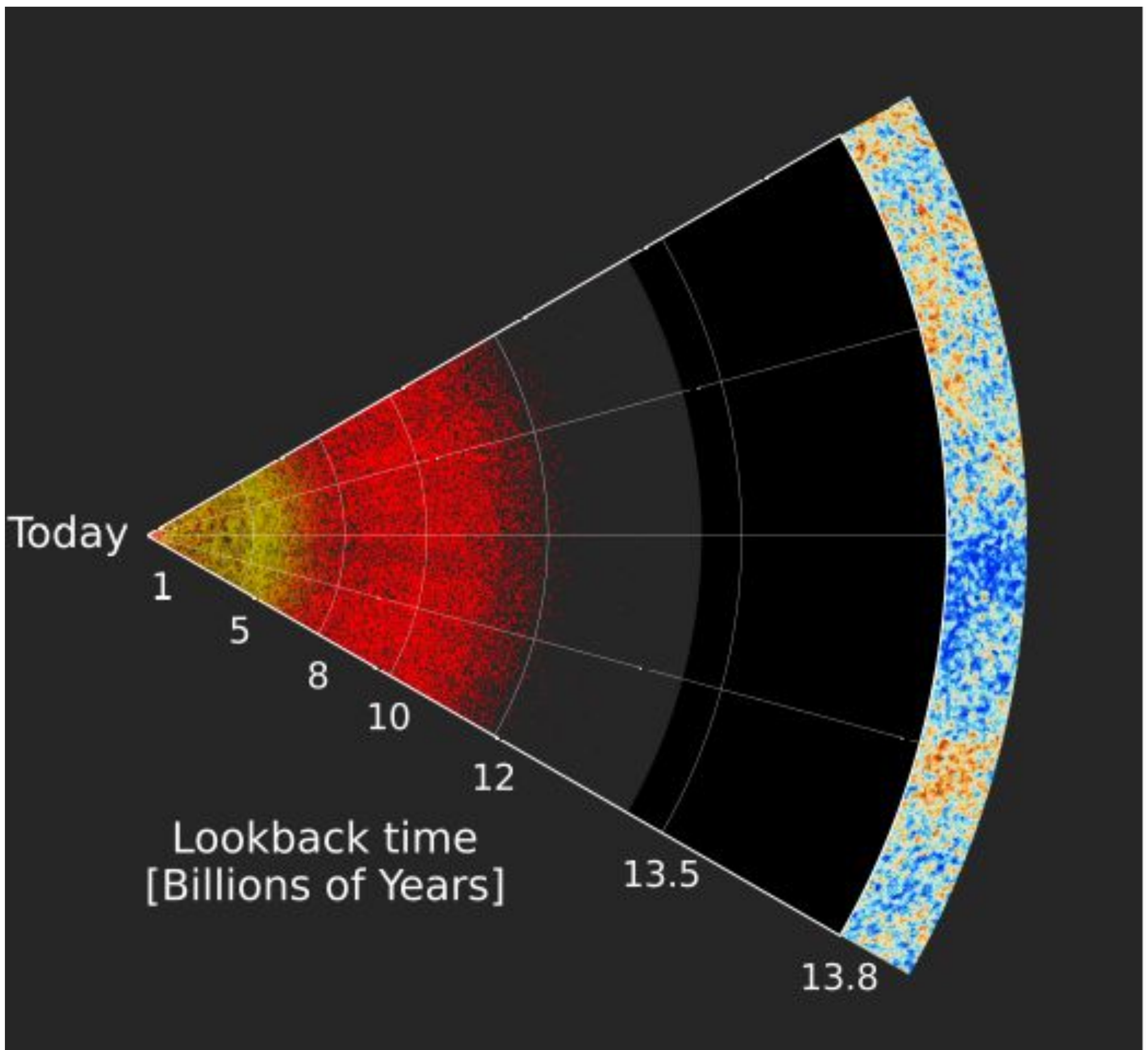
- RSD measure f sigma8

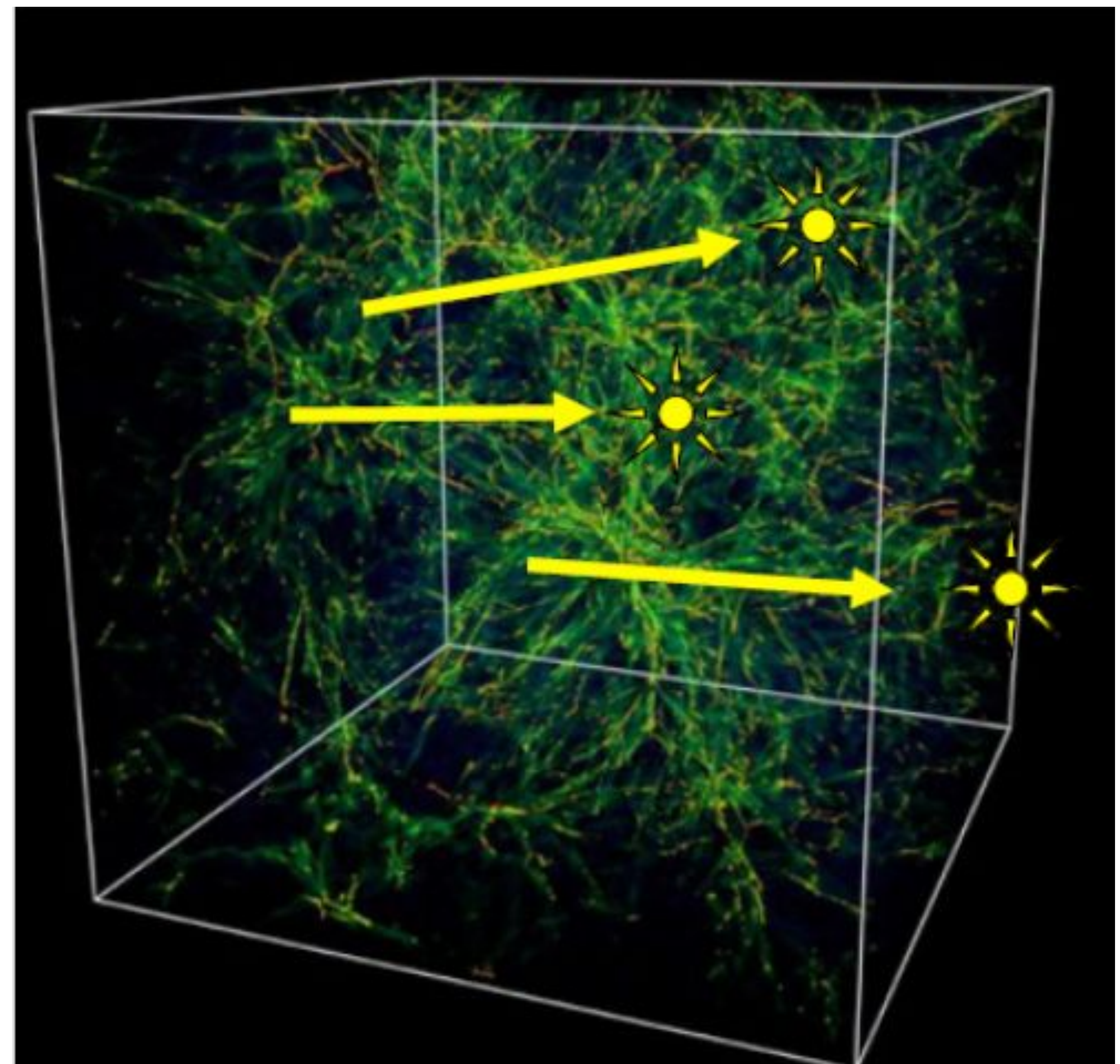


Spectroscopy of the Cosmic Density Field

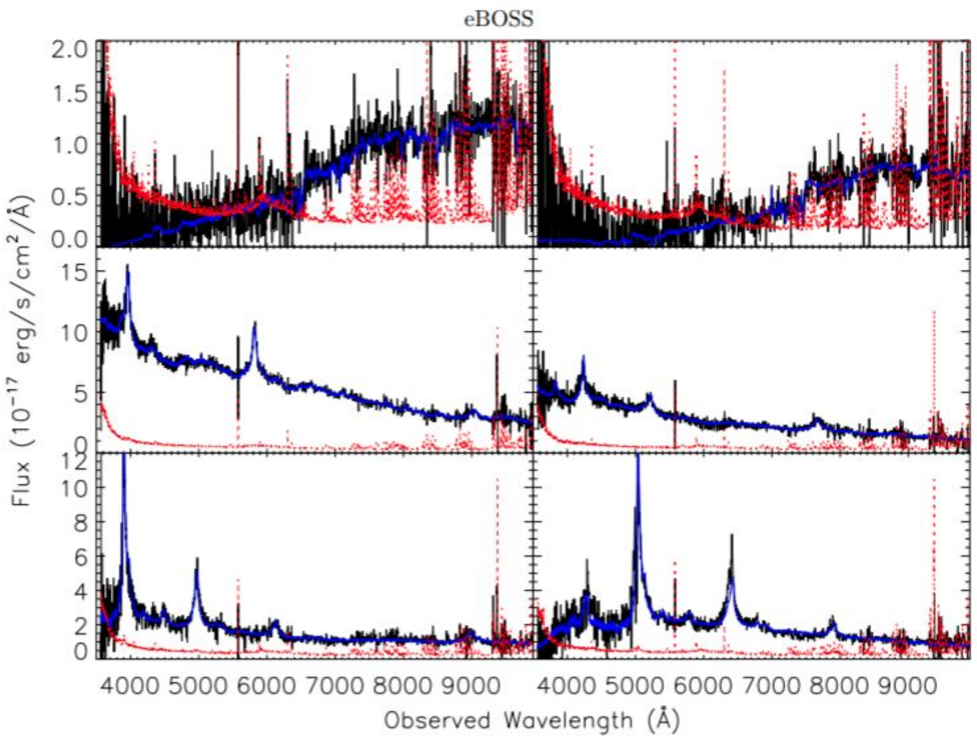
Direct tracers
Galaxies and quasars (z<2.1)

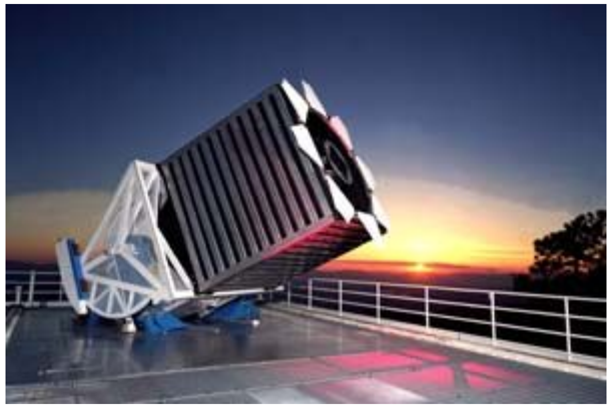
Absorption in quasar spectra by foreground Lyman-alpha forest (z>2.1)

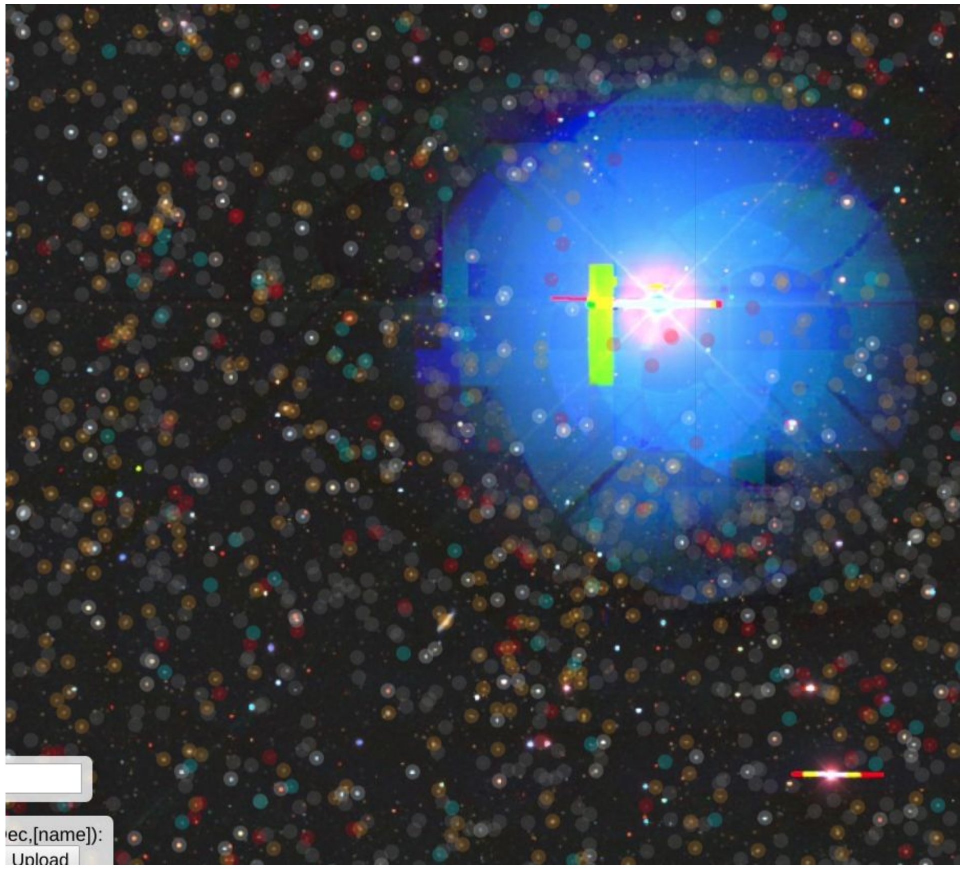


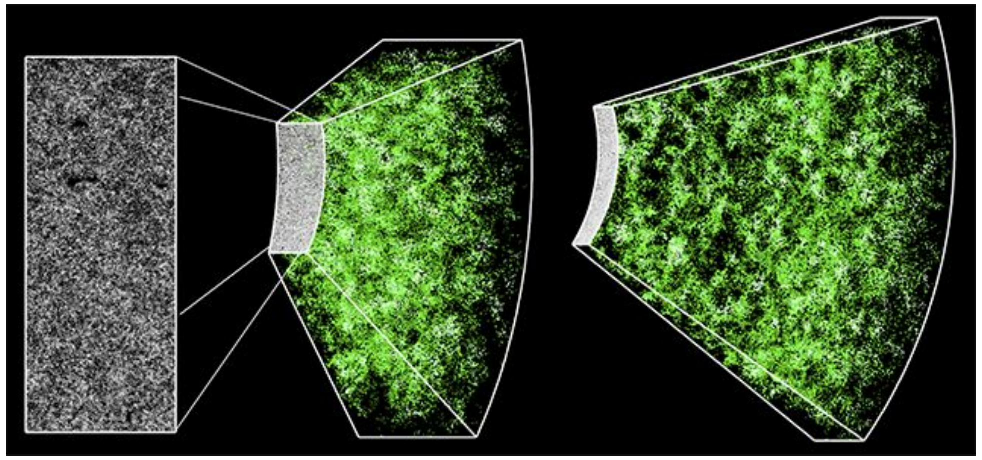


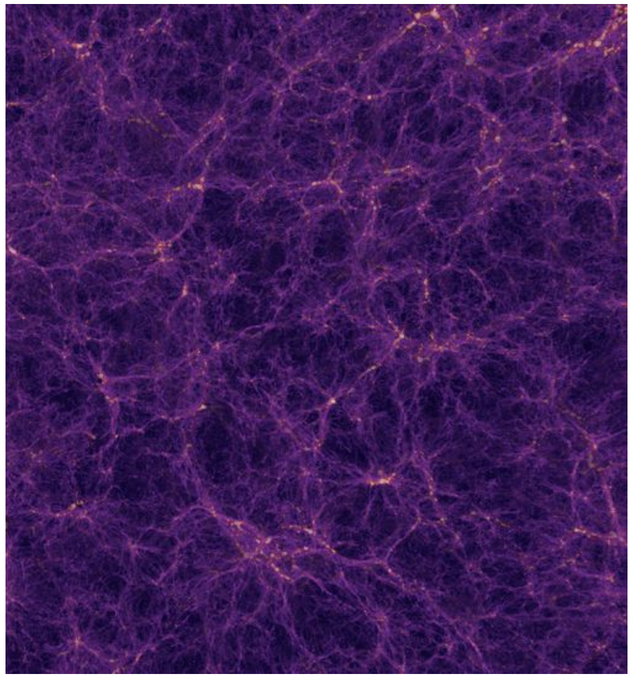
Cosmology with Spectroscopy

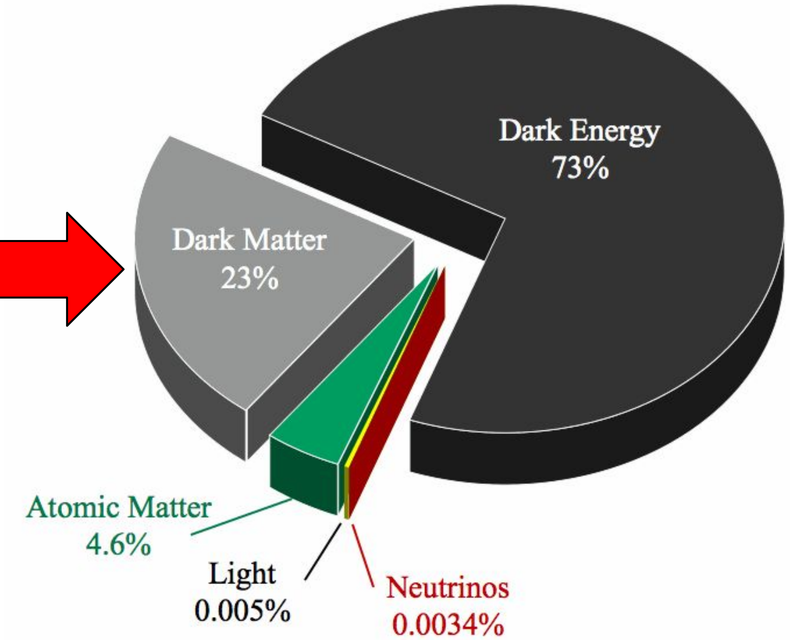












Survey Overview

BOSS: Dawson, Schlegel, et al., 2013, "The Baryon Oscillation Spectroscopic Survey of SDSS-III"

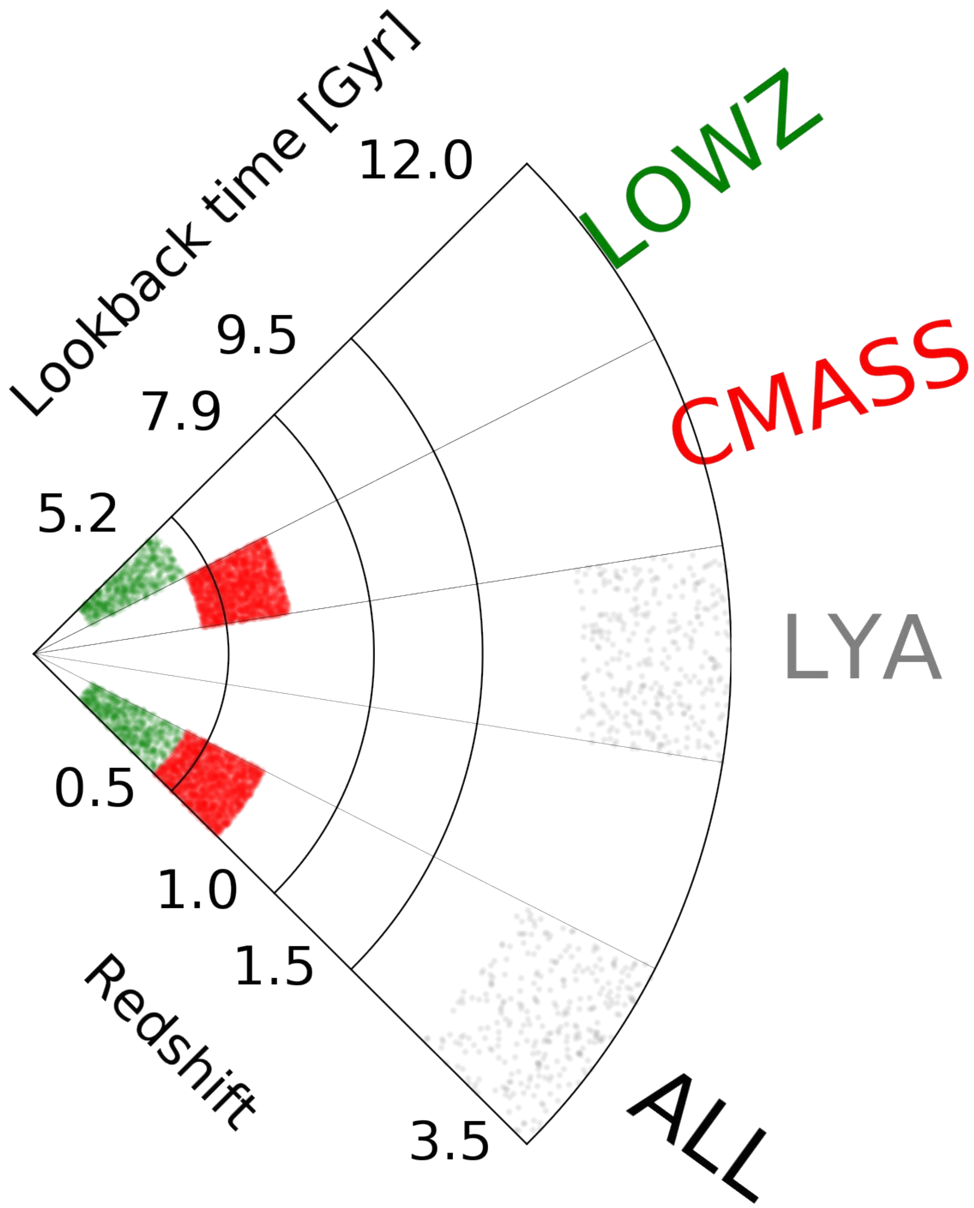
eBOSS: Dawson, Kneib, Percival, et al., 2016, "The SDSS-IV Extended Baryon Oscillation Spectroscopic Survey: Overview and Early Data"

20 Years of Optimization

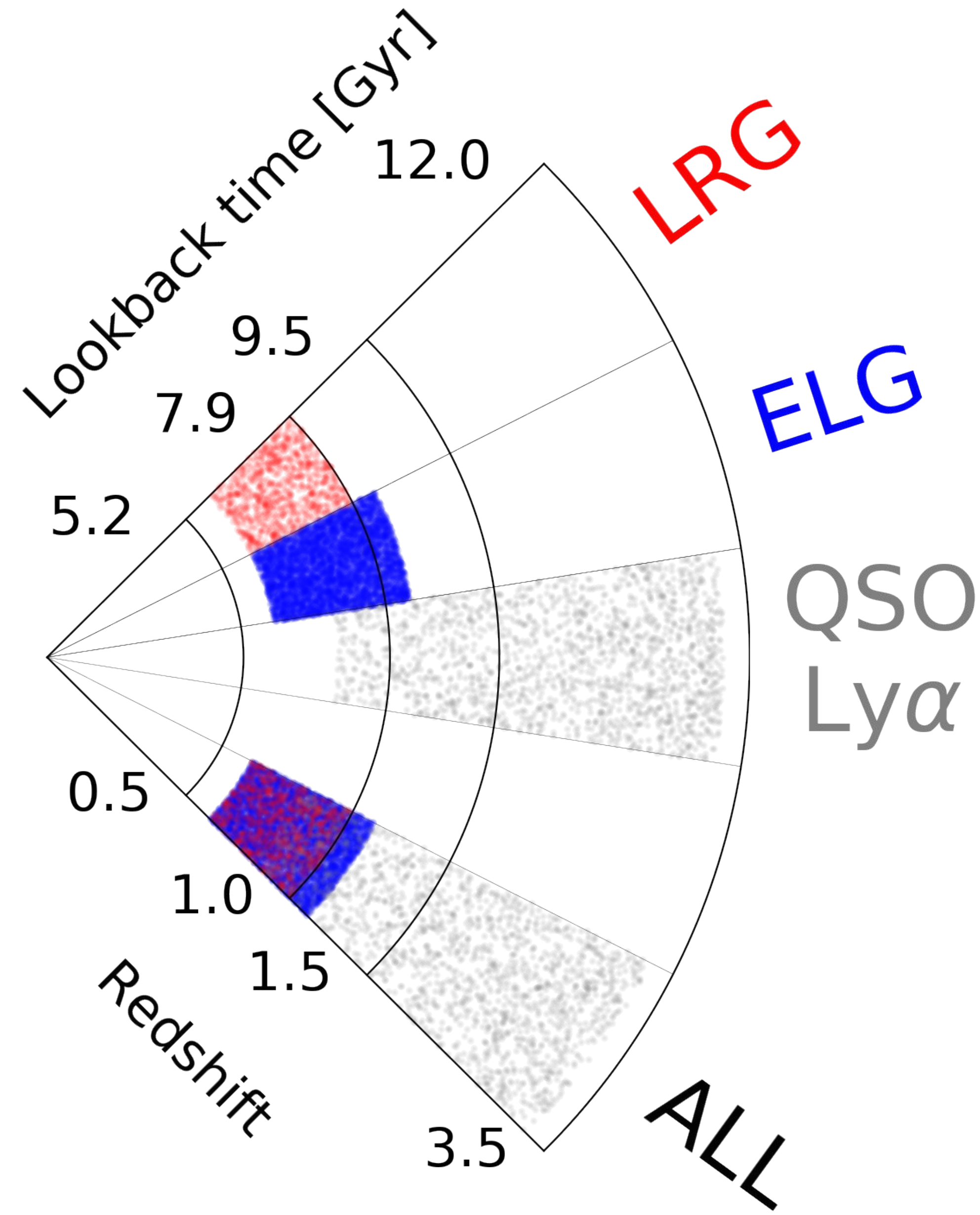
- **Target selection:** well-understood selection functions near imaging limits
- **Mountain Operations:** <1% downtime, near-optimal efficiency
- **Uniformity:** tuned spectroscopic exposure times to real-time data quality
- **Data reduction:** extractions of spectra to S/N<1 with negligible spurious signal
- **Redshift classification:** >90% efficiency, even for faintest targets
- **Catalog creation:** imaging/spectroscopic systematics sub-dominant

11 Billion Years of Galaxy Clustering

BOSS (2009-2014)



eBOSS (2014-2019)

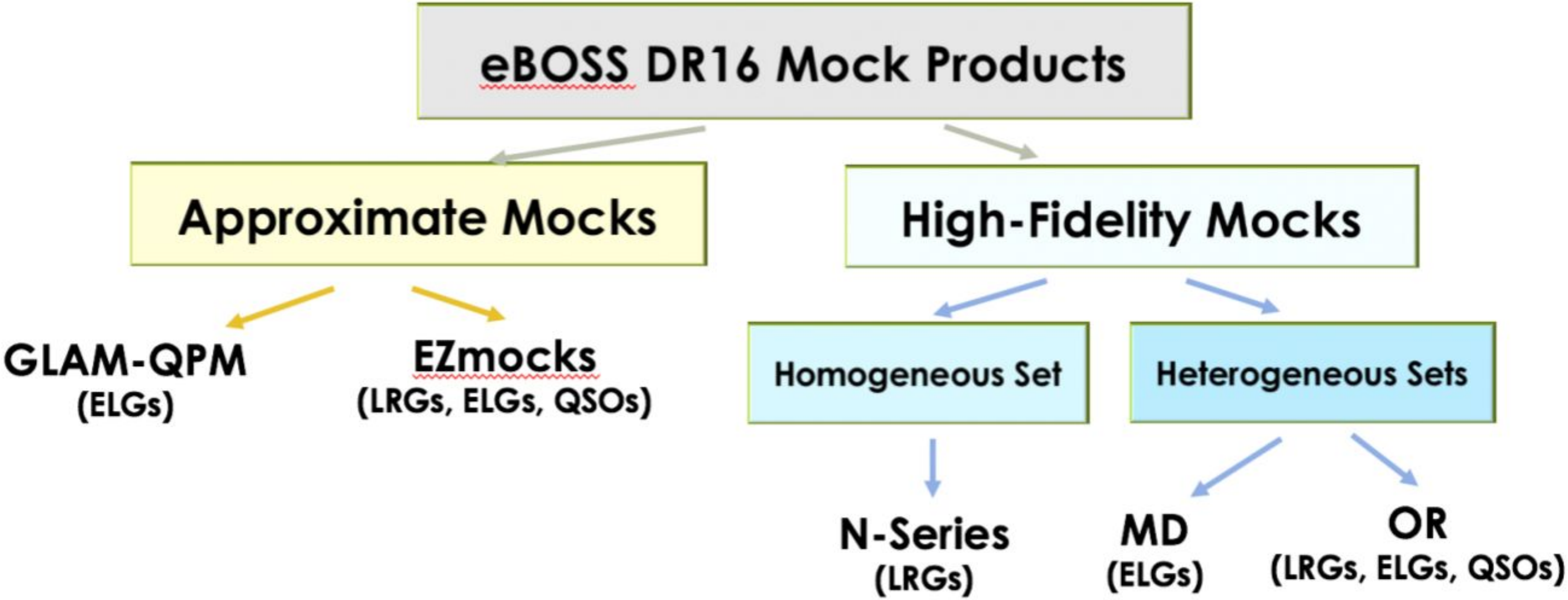


11 Billion Years of Galaxy Clustering

Local MP4

BAO and RSD Measurements

Mock Catalogs



Each synthetic product serves a different science target

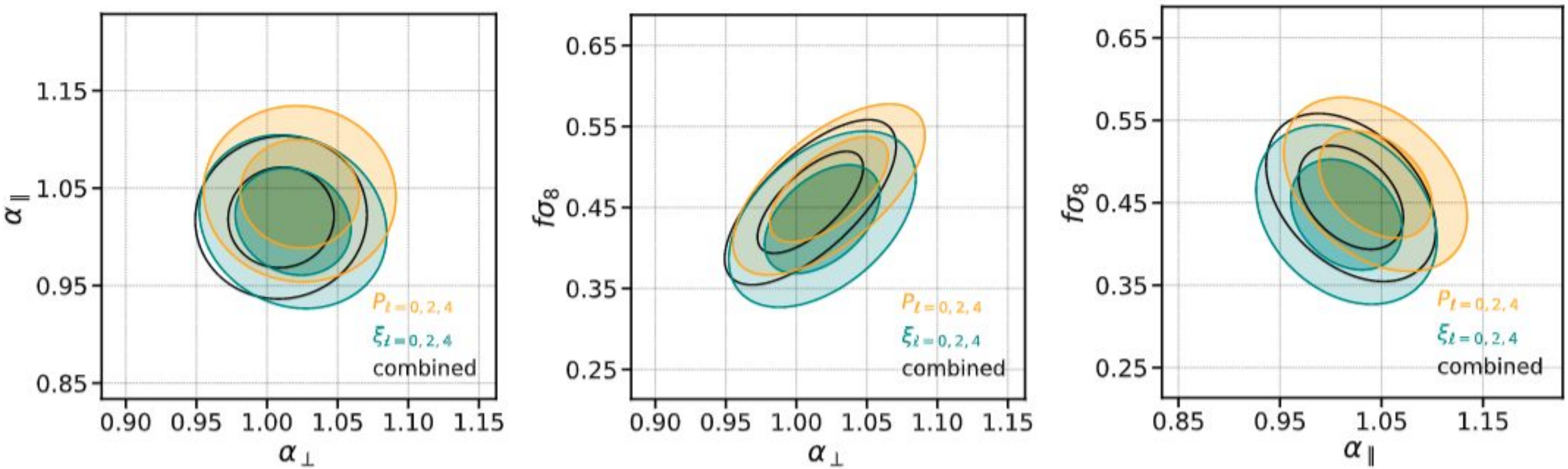
Approximate Mocks: covariances, observational systematics
High-Fidelity Mocks: theoretical systematics, analysis pipeline validation, performance & accuracy, analysis biases

Summary of Systematic Errors

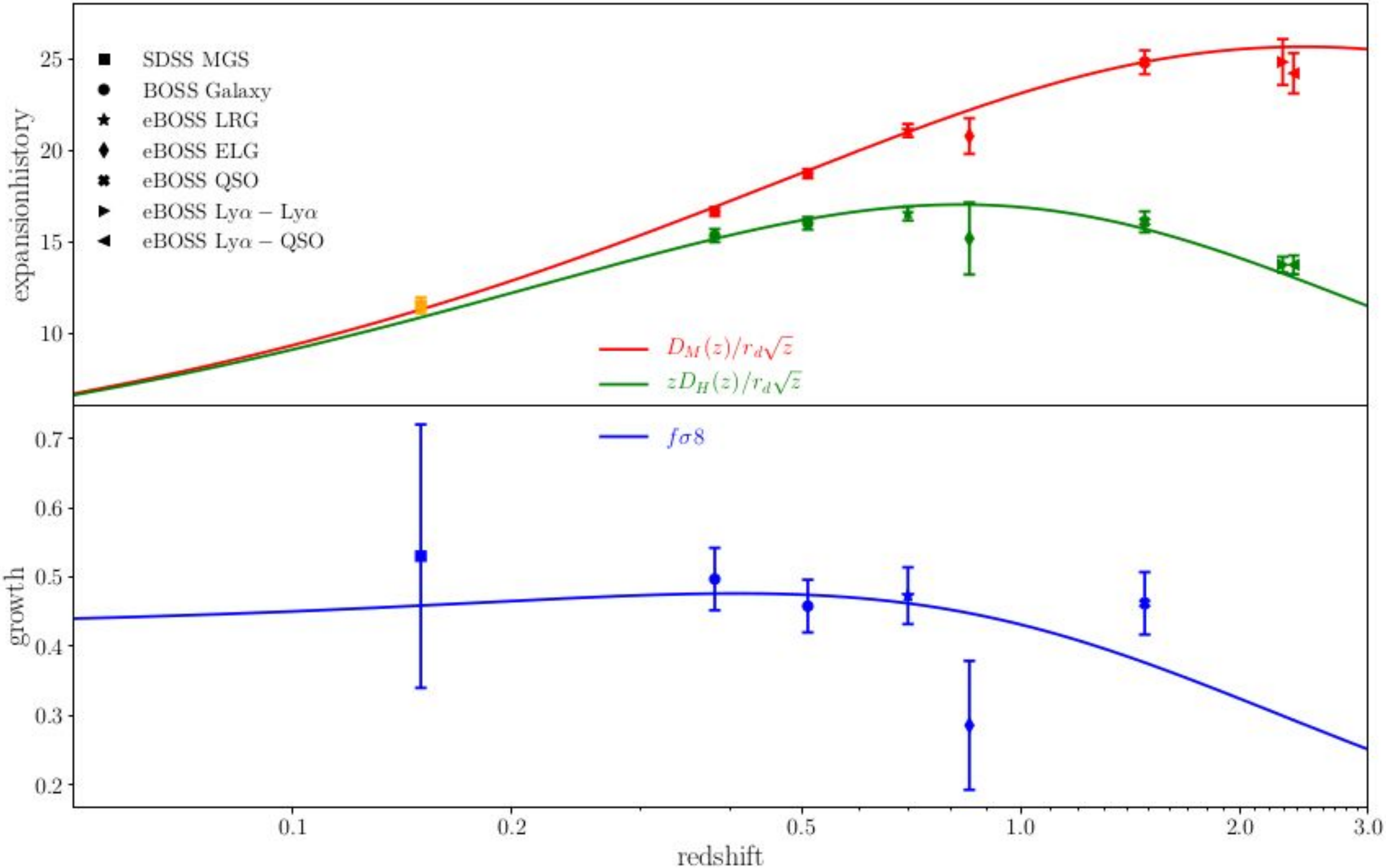
- Modeling, observational artifacts, and fiducial cosmology
- Larger affect on fsigma8 estimates than on BAO estimates
  - ~0.5 sigma on LRG and ELG measurements
  - ~0.3 sigma on quasar measurements
  - Added in quadrature to statistical errors
- No additional increase in Lyman-alpha BAO studies: systematics determined to be sub-dominant

Consensus

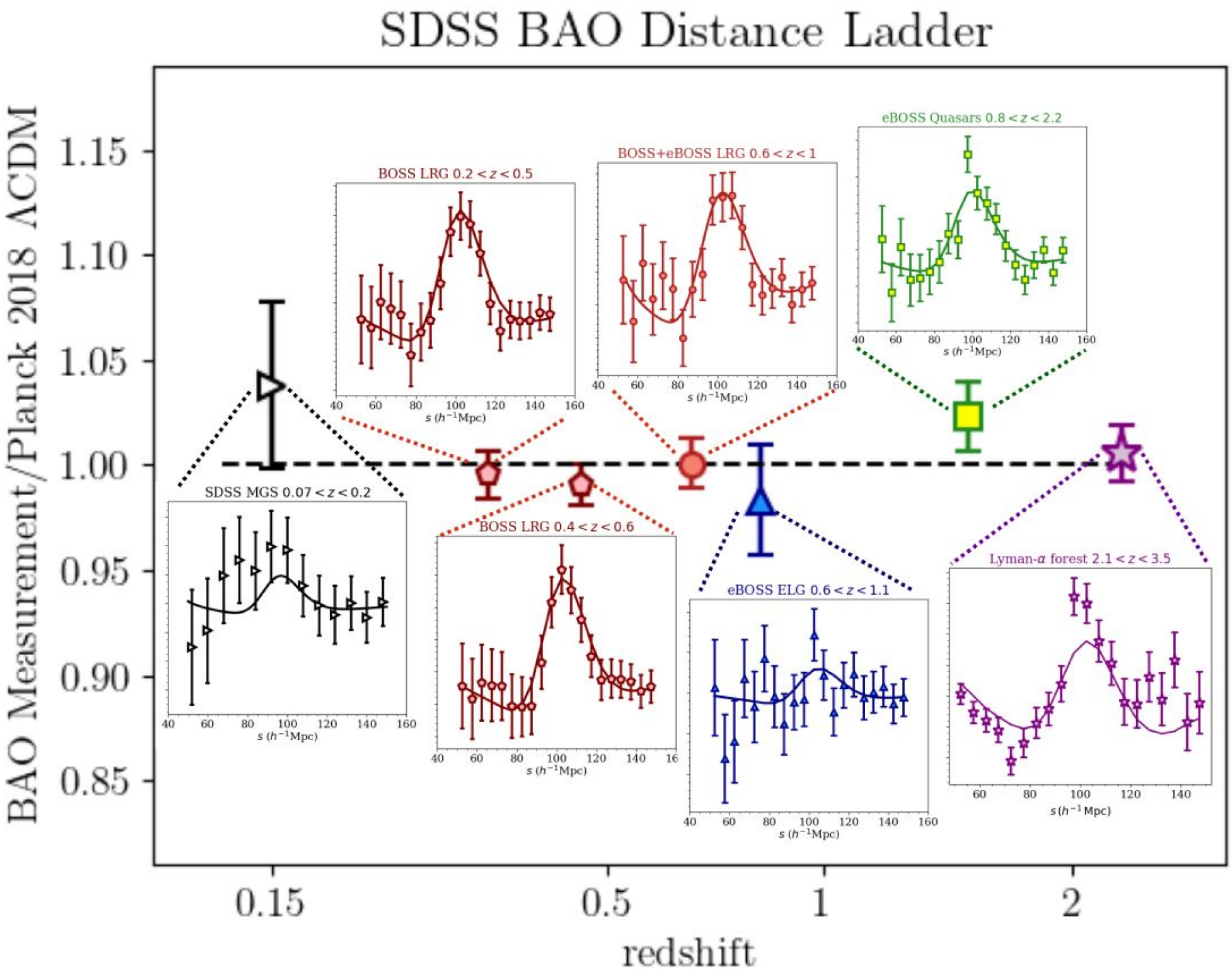
- BAO measured w/reconstruction in LRG and ELG
- BAO/RSD measured in full shape with LRG/ELG/QSO
- Configuration Space and Fourier Space Measurements for each tracer
- Combine BAO/RSD results using mock-calibrated covariance matrices



All BAO and RSD Measurements



Final Results (Primary Science Drivers)



Broadcasting this Effort

- Aggregate precision of the expansion history measurements is 0.70% at redshifts $z < 1$
- Aggregate precision of the expansion history measurements is 1.19% at redshifts $z > 1$
- Aggregate precision of the growth measurements (fsigma8) is 4.78% over the redshift interval $0 < z < 1.5$.

https://test.sdss.org/final-bao-and-rsd-measurements/

Cosmology Interpretation

eBOSS Collaboration, "The Completed SDSS-IV extended Baryon Oscillation Spectroscopic Survey: Cosmological Implications from two Decades of Spectroscopic Surveys at the Apache Point observatory", to appear on arXiv July 20, 2020

Special thanks to Eva-Maria Mueller, Andreu Font-Ribera, Anze Slosar, and Zheng Zheng




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?
  - H0 tension: robustness of BAO estimates
  - What do we learn from growth?
  - Bounds on the neutrino mass
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Parameterizing the Cosmological Model

Extensions to LCDM

	Parameter	Definition
	Ω_m	density parameter of matter
	Ω_c	density parameter of cold dark matter
	Ω_b	density parameter of baryons
	Ω_Λ	density parameter of cosmological constant
	Ω_{DE}	density parameter of dark energy
o	Ω_k	curvature parameter
	$\omega_c = \Omega_c h^2$	physical density parameter of cold dark matter
	$\omega_b = \Omega_b h^2$	physical density parameter of baryons
	H_0	current expansion rate (Hubble constant)
	h	$H_0/100 \mathrm{km\,s^{-1}Mpc^{-1}}$
	θ_{MC}	approximate angular scale of sound horizon (CosmoMC)
	A_s	power of the primordial curvature perturbations at $k = 0.05\mathrm{Mpc}^{-1}$
	σ_8	amplitude of matter fluctuation on $8h^{-1}$Mpc comoving scale
	n_s	power-law index of the scalar spectrum
	τ	Thomson scattering optical depth due to reionization
	N_{eff}	effective number of neutrino-like relativistic degrees of freedom
w	w (w_0)	dark energy equation of state, $w = p_{DE}/\rho_{DE}$ ($c = 1$ units)
w_a	w_a	time derivative of dark energy equation of state parameter (eq.6)
nu	$\sum m_\nu$	sum of neutrino masses

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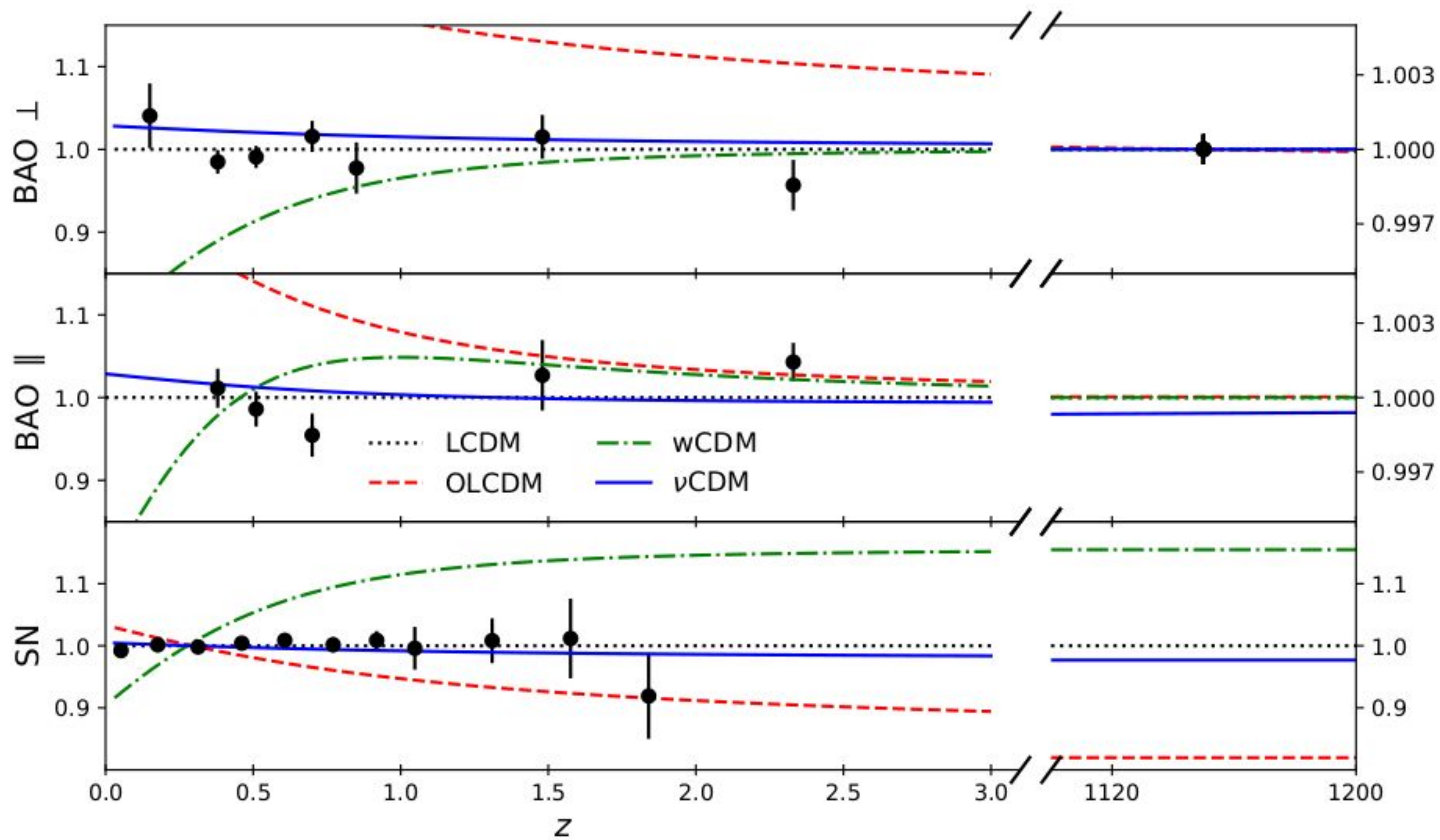
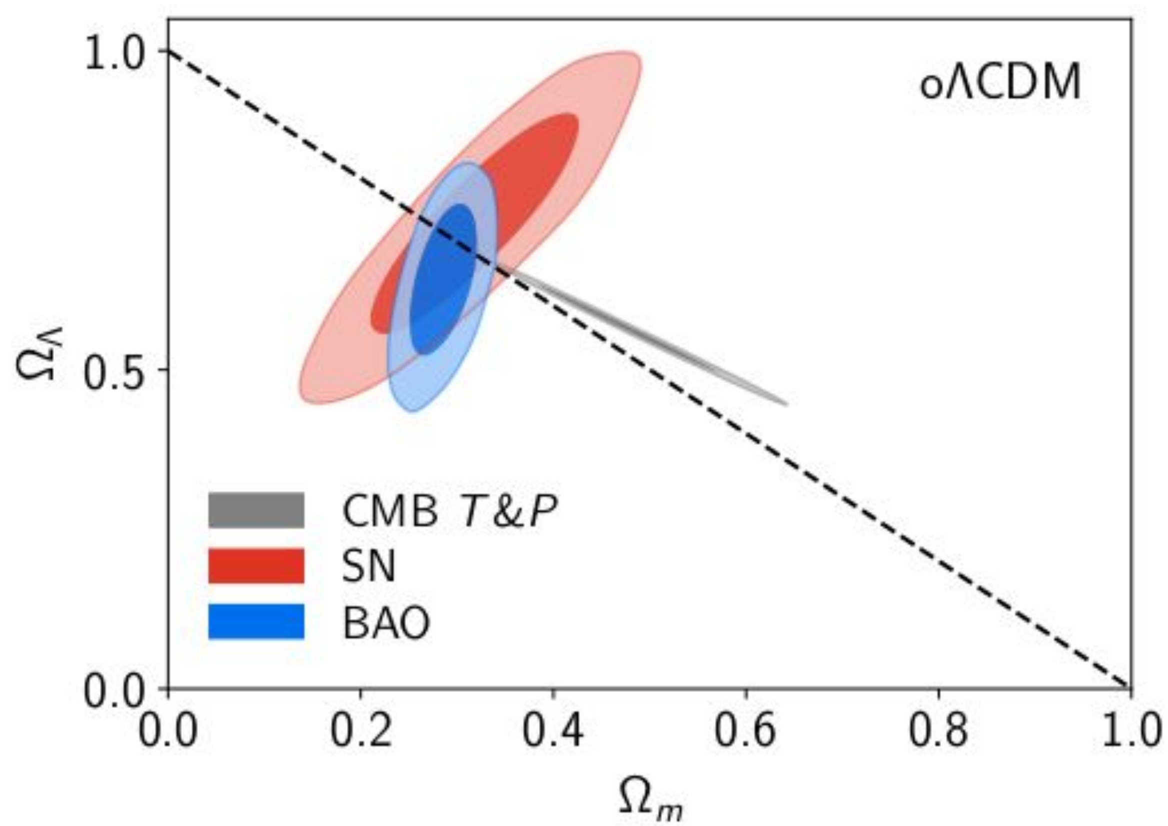
BAO, SNe, and CMB

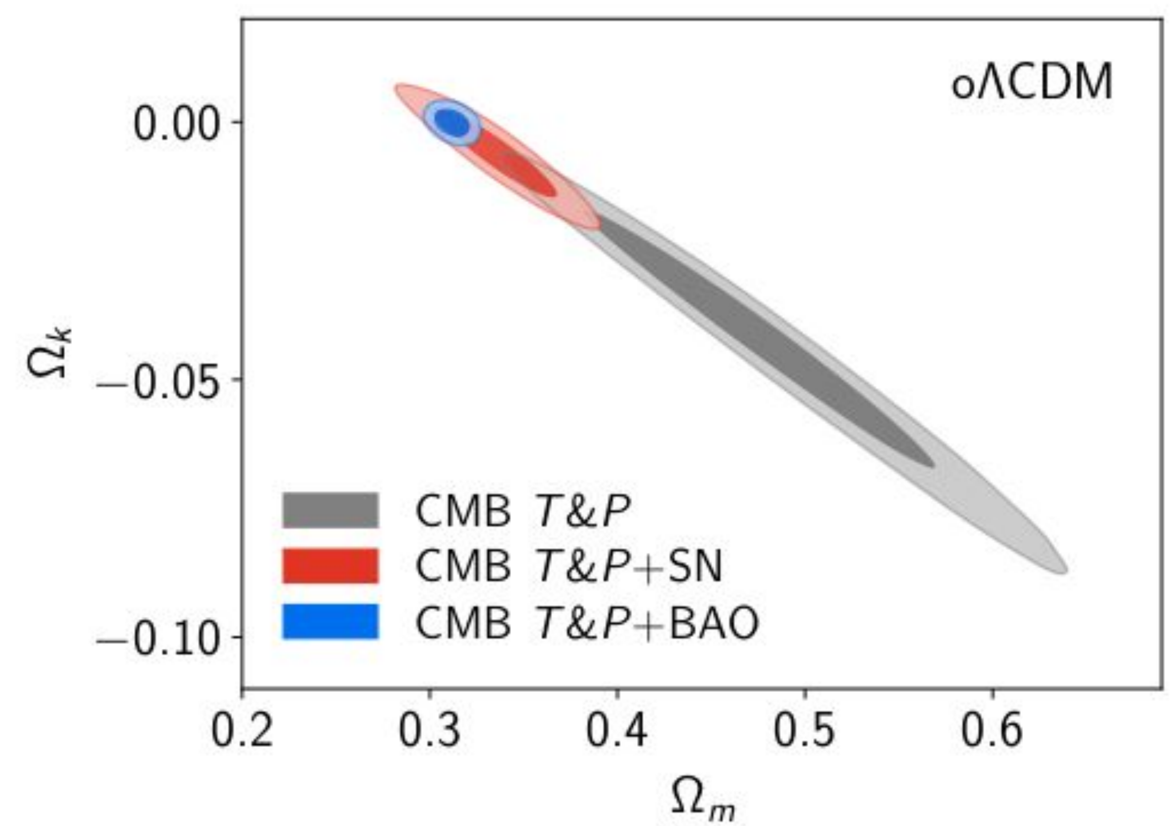
- BAO-only from SDSS/BOSS/eBOSS
- Pantheon sample of SNe (Scolnic et al, 2018)
- Planck 2018 results (Planck Collaboration, 2018)



oLCDM Cosmology

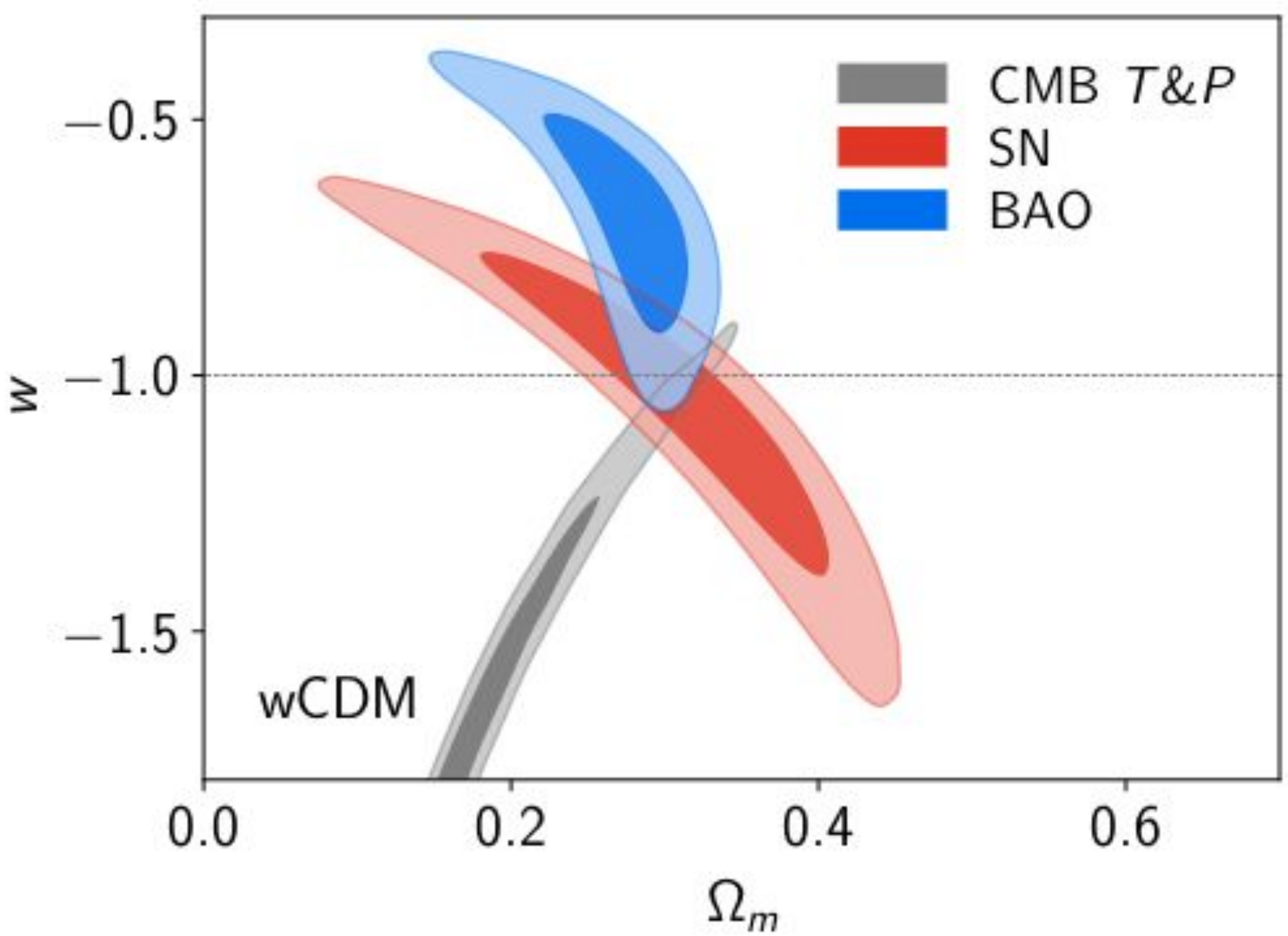
- BAO measurements alone → constraint on the dark energy density with a ~8 sigma confidence detection.
- Combined with Planck temperature and polarization data → order of magnitude improvement on curvature constraints
- Strong evidence for a nearly flat geometry → roughly one order of magnitude within the fundamental limit set by cosmic variance.





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



One Parameter Extensions

		$\Omega_{\rm DE}$	H_0[km/s/Mpc]	Ω_k	w	Σm_ν [eV]
ΛCDM	CMB T&P	0.6836 ± 0.0084	67.29 ± 0.61	–	–	–
	CMB T&P + BAO	0.6881 ± 0.0059	67.61 ± 0.44	–	–	–
	CMB T&P + SN	0.6856 ± 0.0078	67.43 ± 0.57	–	–	–
	CMB T&P + BAO + SN	0.6891 ± 0.0057	67.68 ± 0.42	–	–	–
oΛCDM	CMB T&P	$0.561^{+0.050}_{-0.041}$	$54.5^{+3.3}_{-3.9}$	$-0.044^{+0.019}_{-0.014}$	–	–
	CMB T&P + BAO	0.6882 ± 0.0060	67.59 ± 0.61	-0.0001 ± 0.0018	–	–
	CMB T&P + SN	0.670 ± 0.017	65.2 ± 2.2	$-0.0061^{+0.0062}_{-0.0054}$	–	–
	CMB T&P + BAO + SN	0.6891 ± 0.0057	67.67 ± 0.60	-0.0001 ± 0.0018	–	–
wCDM	CMB T&P	$0.801^{+0.057}_{-0.022}$	> 82.3	–	$-1.58^{+0.16}_{-0.35}$	–
	CMB T&P + BAO	0.694 ± 0.012	$68.4^{+1.4}_{-1.5}$	–	$-1.034^{+0.061}_{-0.053}$	–
	CMB T&P + SN	0.692 ± 0.010	68.3 ± 1.1	–	-1.035 ± 0.037	–
	CMB T&P + BAO + SN	0.6929 ± 0.0075	68.21 ± 0.82	–	-1.026 ± 0.033	–
$\nu\Lambda$CDM	CMB T&P	$0.680^{+0.016}_{-0.0087}$	$67.0^{+1.2}_{-0.67}$	–	–	< 0.268
	CMB T&P + BAO	$0.6890^{+0.0069}_{-0.0061}$	$67.70^{+0.53}_{-0.48}$	–	–	< 0.134
	CMB T&P + SN	$0.686^{+0.011}_{-0.0083}$	$67.47^{+0.83}_{-0.65}$	–	–	< 0.174
	CMB T&P + BAO + SN	0.6898 ± 0.0061	67.76 ± 0.47	–	–	< 0.125

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BAO and the Hubble Constant

- BAO in isolation → relative measures of expansion history
- BAO in combination with early Universe physics → calibrated ruler
- Calibrated ruler → absolute expansion rates, including current expansion rate, H_0
  - Standard physics (e.g. 3 neutrino species) → baryon density, matter density, and CMB temperature offer calibration of standard ruler
  - CMB or Big Bang Nucleosynthesis can offer baryon density
  - Matter density from CMB or distance probes

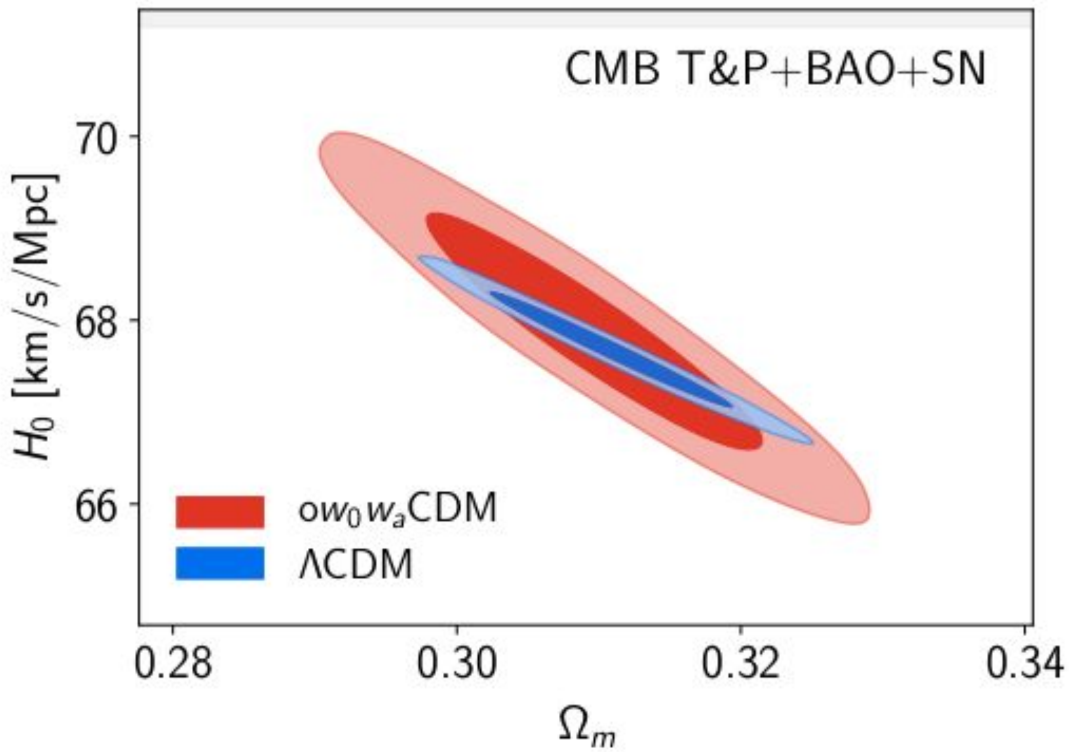
$$H(z) = c\Delta z / r_d$$

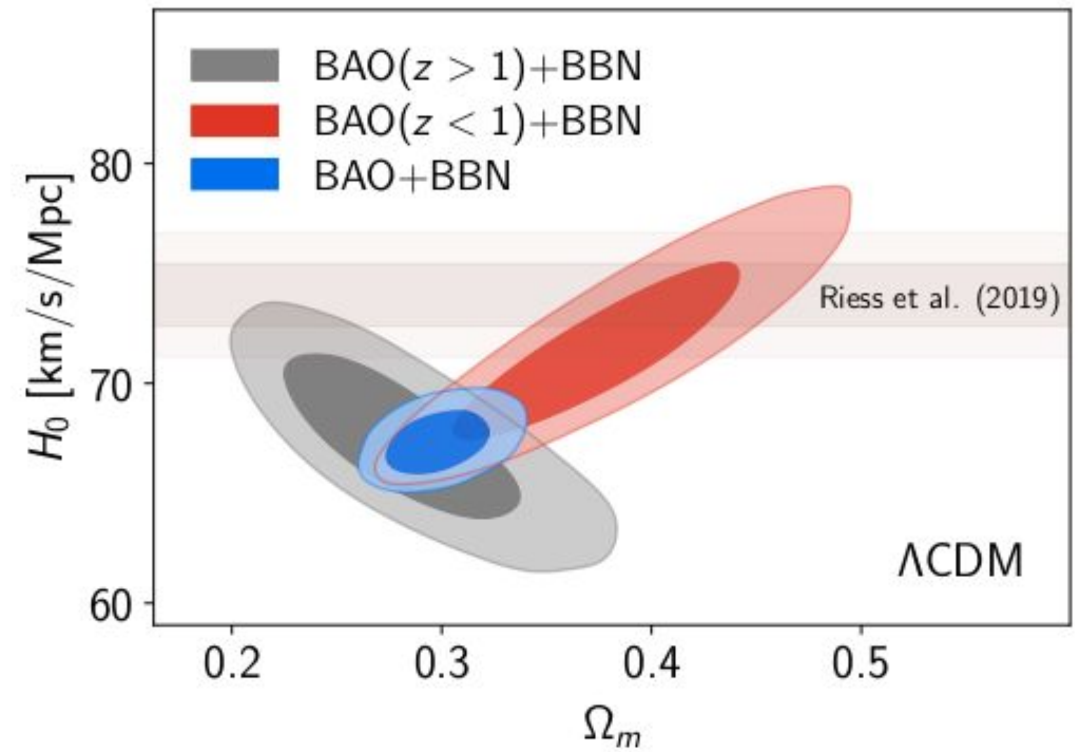
$$r_d = \int_{z_d}^{\infty} \frac{c_s(z)}{H(z)} dz$$

$$D_H(z) = \frac{c}{H(z)}$$

New Physics in Expansion History?

- BAO → insensitive to the strict cosmological priors in CMB-only estimates.
- BAO → insensitive to CMB anisotropies if using LCDM and BBN

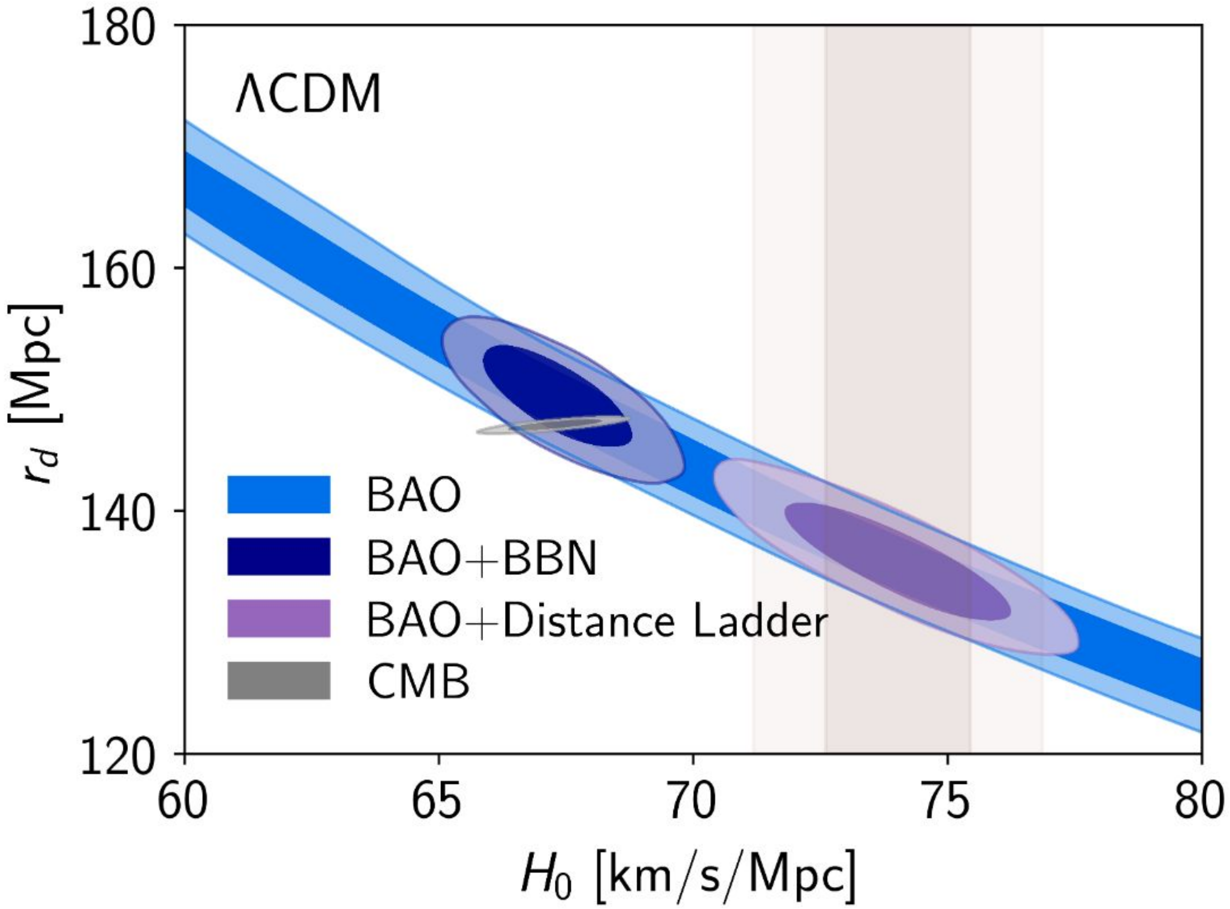




Dataset	Cosmological model	H_0 in km s^{-1}Mpc^{-1}	Comments
CMB T&P+BAO+SN	ow_0w_aCDM	67.87 ± 0.86	Inverse distance ladder
BBN+BAO	ΛCDM	67.27 ± 0.97	No CMB anisotropies
CMB T&P	ΛCDM	67.36 ± 0.54	*Planck* 2018 (a)
CMB T&P	oΛCDM	63.6 ± 2.2	*Planck* 2018 (a)
Lensing time delays	ΛCDM	73.3 ± 1.8	H0LiCOW (b)
Distance ladder	-	74.0 ± 1.4	SH0ES (c)
GW sirens	-	70 ± 10	LIGO (d)
TRGB	-	69.6 ± 1.9	LMC anchor (e)
TFR	-	76.2 ± 4.3	Cosmicflows (f)

H0 Tension

- H0 from BAO → ~10% smaller than those from the Cepheid distance ladder and strong-lensing time delays.
- `H0 tension' can not be restricted to systematic errors in Planck or to the strict assumptions of the LCDM model → new physics?



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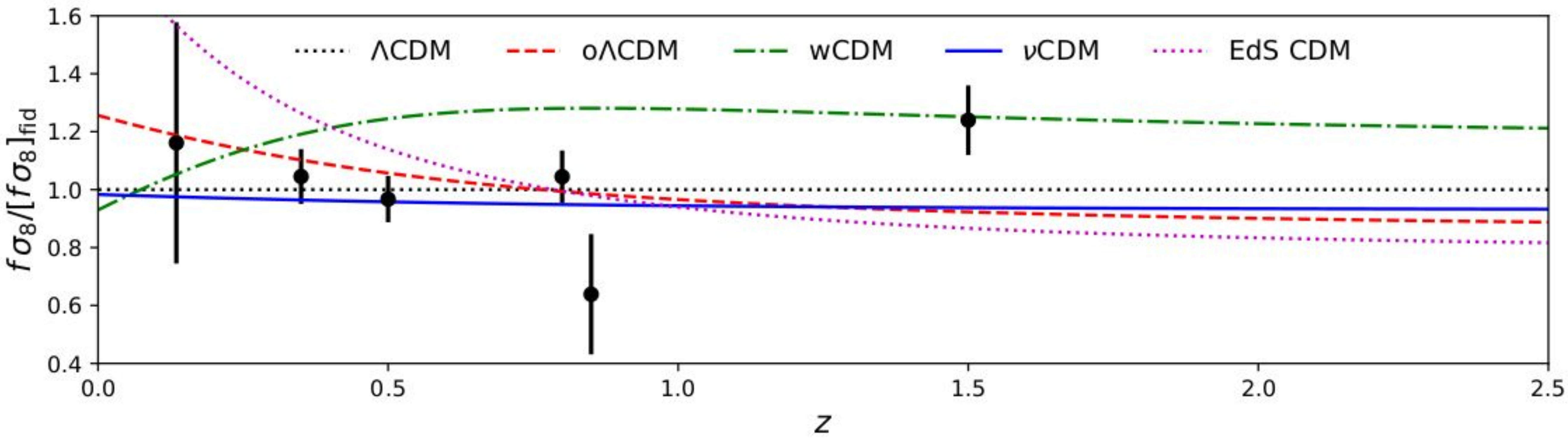
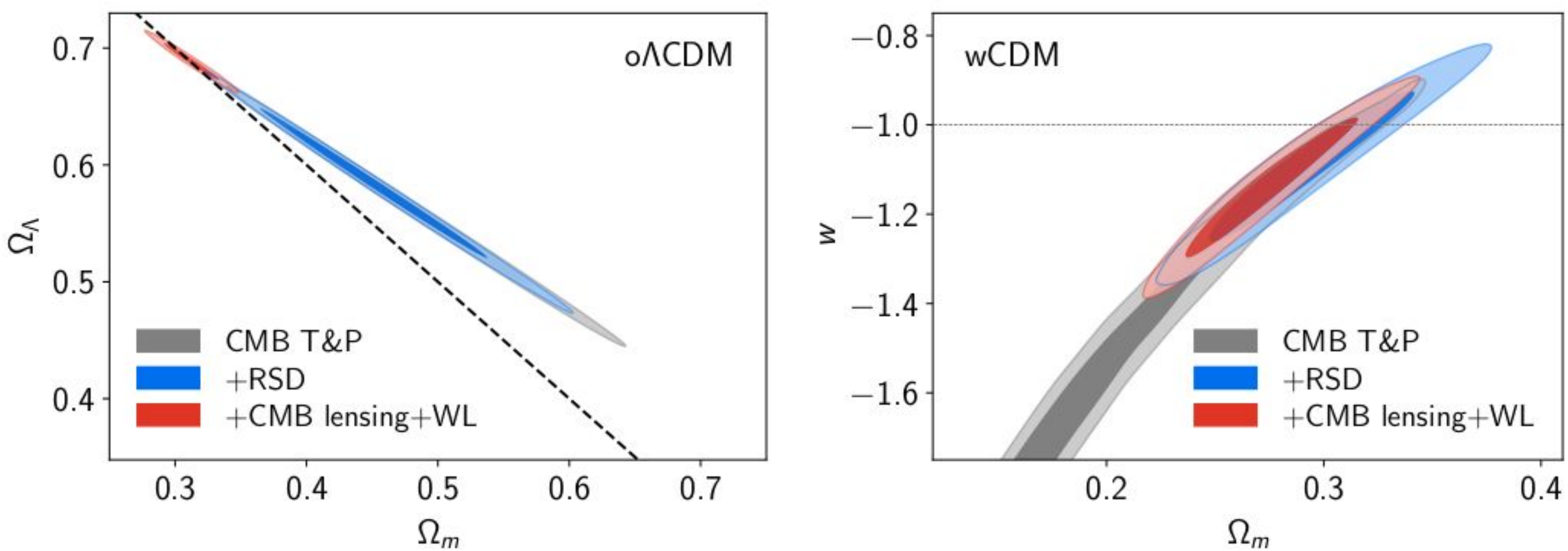
RSD, Lensing, and CMB

- RSD-only from SDSS/BOSS/eBOSS
- Weak Lensing (WL) from DES (Troxel et al, 2018) and Planck
- Planck temperature and polarization (Planck Collaboration, 2018)



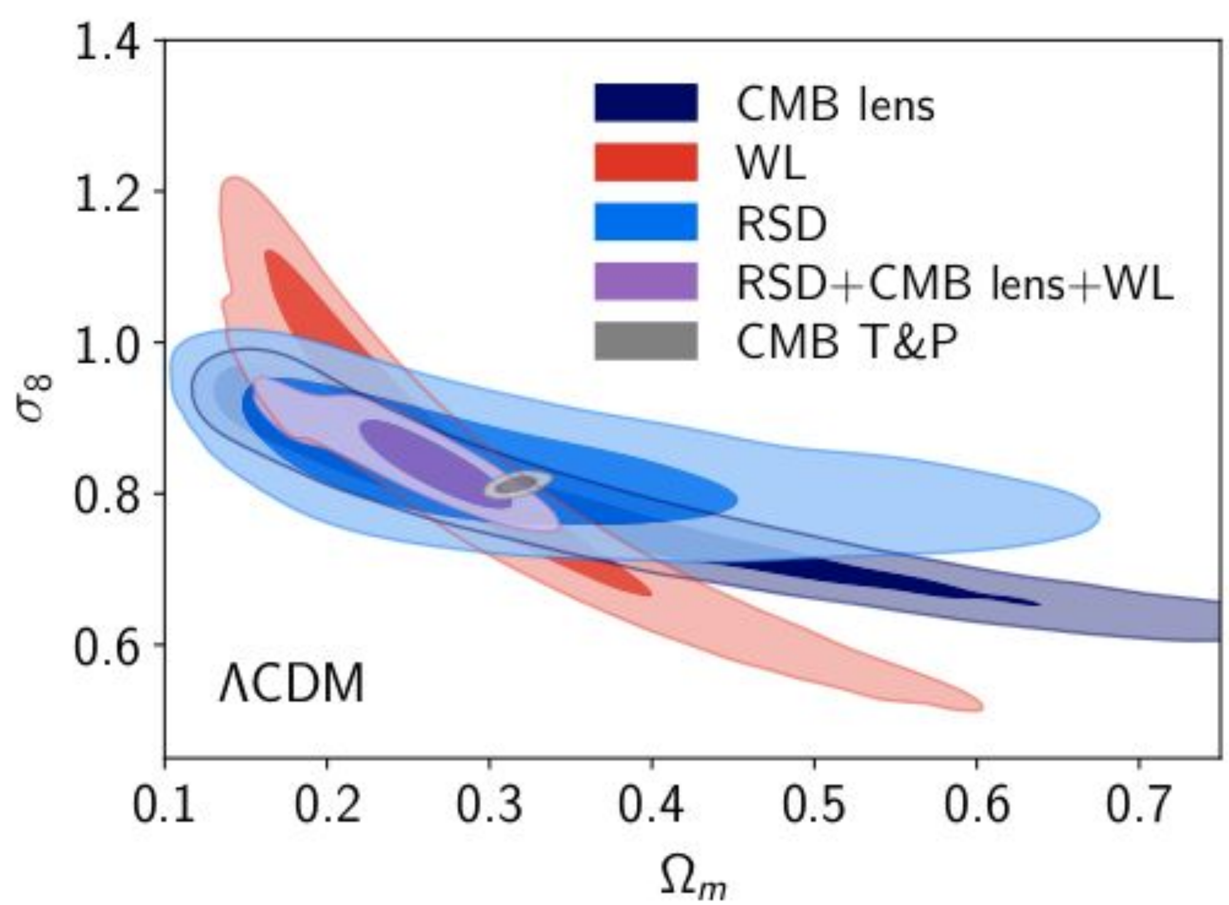
Constraining Dark Energy with Growth

- Growth measurements → factor two to three improvements in precision compared to CMB temperature and polarization data alone.
- Weak lensing data instill a preference for a flat geometry
- RSD instill a preference for a cosmological constant.



New Physics in Structure Growth?

- Analogy to H0 test: local fluctuation amplitude vs CMB fluctuation amplitude
- RSD + WL → current amplitude of matter fluctuations.
- LCDM predictions and GR → consistent picture of structure growth

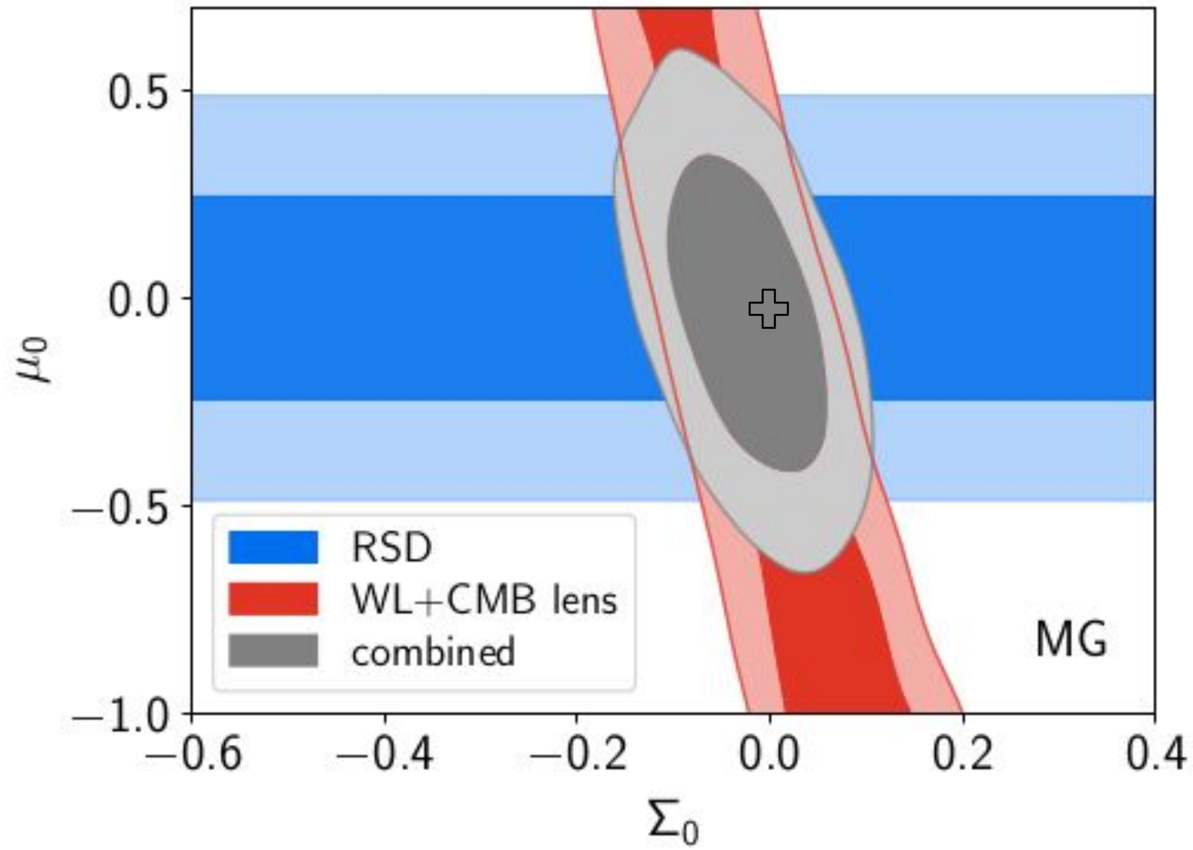


Testing GR

- Differential measurements of growth to test modified gravity
- Allow linear perturbations to Poisson equation
  - RSD measurements probe the gravitational response of matter
  - WL measurements probe that of photons

$$k^2\Psi = -4\pi G a^2(1+\mu(a))\rho\delta$$
$$k^2(\Psi+\Phi) = -8\pi G a^2(1+\Sigma(a))\rho\delta$$

$$\mu(z) = \mu_0 \frac{\Omega_\Lambda(z)}{\Omega_\Lambda}, \quad \Sigma(z) = \Sigma_0 \frac{\Omega_\Lambda(z)}{\Omega_\Lambda}$$



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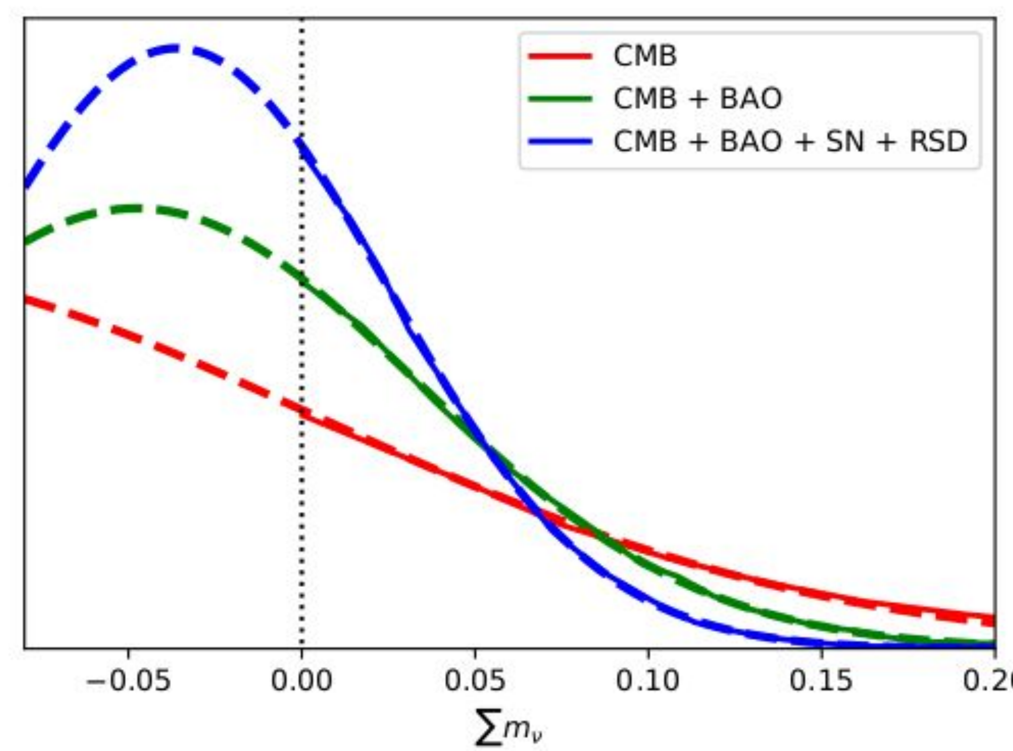
Full Suite of Stage-III Probes

- BAO + RSD from SDSS/BOSS/eBOSS
- Pantheon sample of SNe (Scolnic et al, 2018)
- Weak Lensing (WL), galaxy-galaxy lensing, clustering from DES (Abbott et al, 2018)
- Planck temperature, polarization, and lensing (Planck Collaboration, 2018)

Neutrino Mass

- Planck + Pantheon SNe Ia + DES + BAO + RSD data → tightest constraints to date
  - Uncertainty → ~lower bound of 60 meV allowed by neutrino oscillations
  - Relative to Planck-only → the largest improvement in precision comes from the addition of the SDSS BAO measurements
  - RSD improve the precision by another 30%.

$$\sum m_\nu > 0.0588\,\mathrm{eV} \qquad \text{normal hierarchy,}$$
$$\sum m_\nu > 0.0995\,\mathrm{eV} \qquad \text{inverted hierarchy.}$$



Neutrino Mass

Constraints on neutrino masses and relative probabilities of neutrino models.

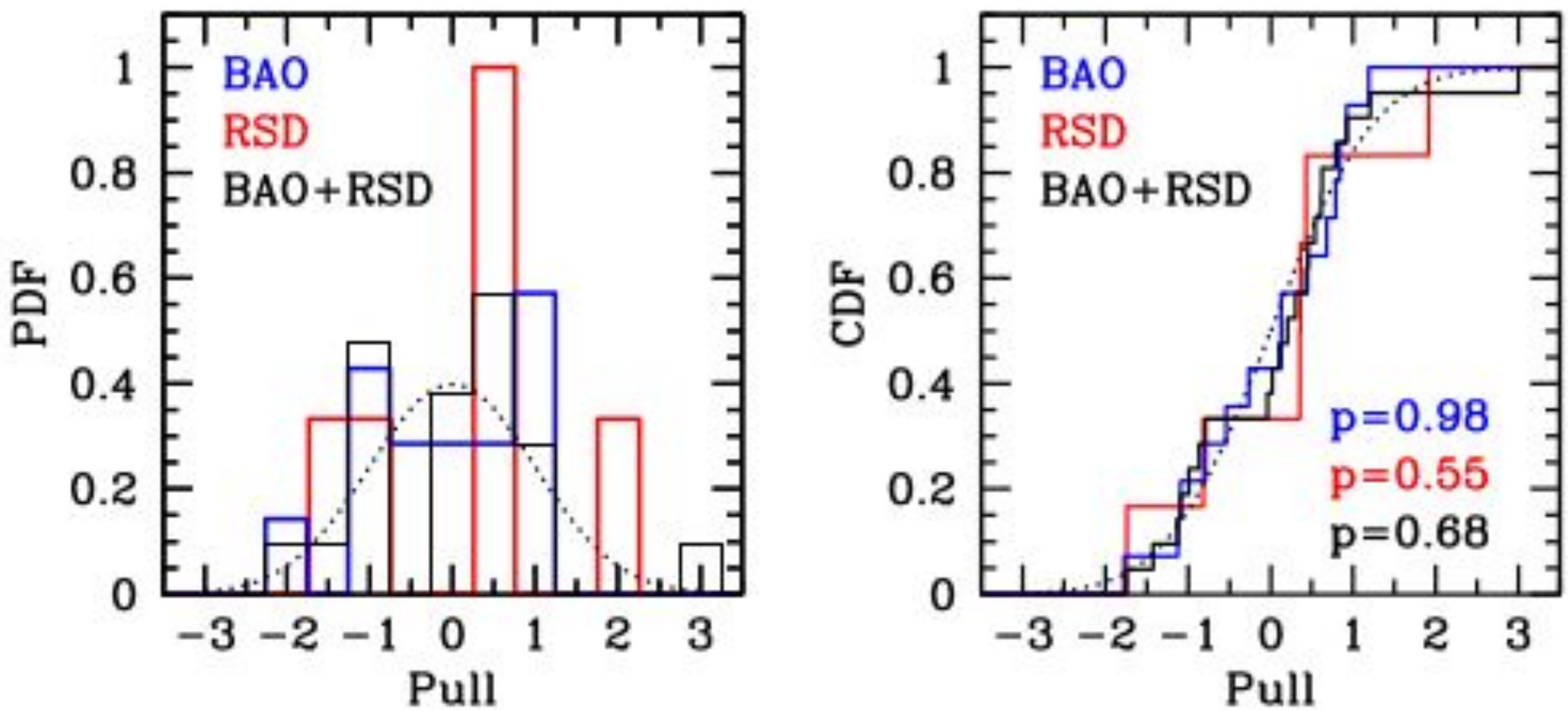
Model	95% upper limit [eV]	$P_{\rm inv}/P_{\rm norm}$	$P_{\rm unphy}$	RMS of Gaussian fit [eV]
Planck	0.264	0.64	0.45	-0.144 ± 0.148
Planck + BAO	0.131	0.37	0.65	-0.048 ± 0.081
Planck + BAO + RSD	0.100	0.22	0.77	-0.037 ± 0.062
Planck + BAO + RSD (wΛCDM)	0.127	0.36	0.70	-0.150 ± 0.104
Planck + SN	0.175	0.50	0.57	-0.110 ± 0.114
Planck + BAO + SN	0.126	0.34	0.67	-0.041 ± 0.076
Planck + BAO + RSD + SN	0.099	0.22	0.78	-0.036 ± 0.060
Planck + BAO + RSD + SN (wΛCDM)	0.120	0.32	0.71	-0.084 ± 0.083
Planck + BAO + RSD + DES	0.132	0.37	0.64	-0.039 ± 0.079
Planck + BAO + RSD + DES (wΛCDM)	0.172	0.50	0.58	-0.181 ± 0.134
Planck + BAO + RSD + SN + DES	0.114	0.29	0.72	-0.036 ± 0.068
Planck + BAO + RSD + SN + DES (wΛCDM)	0.140	0.40	0.66	-0.100 ± 0.096

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?
  - 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

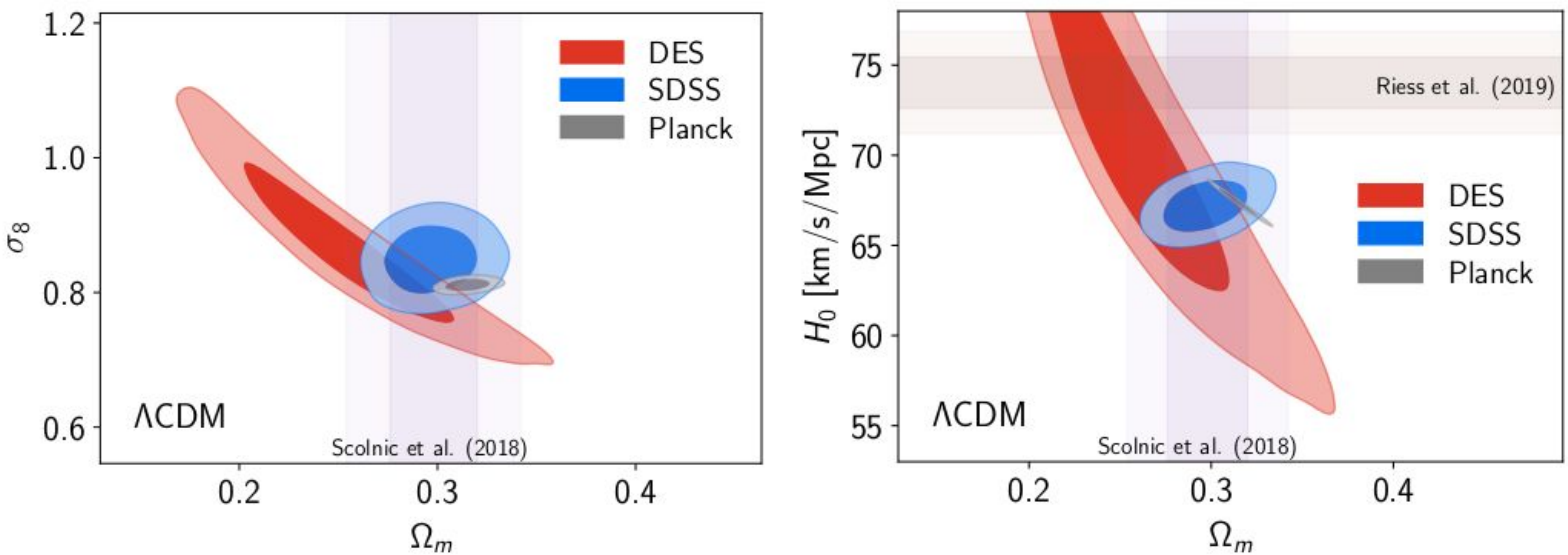
Robustness of SDSS BAO + RSD

- Pull statistics → the full suite of BAO+RSD measurements are fully consistent with the preferred LCDM model



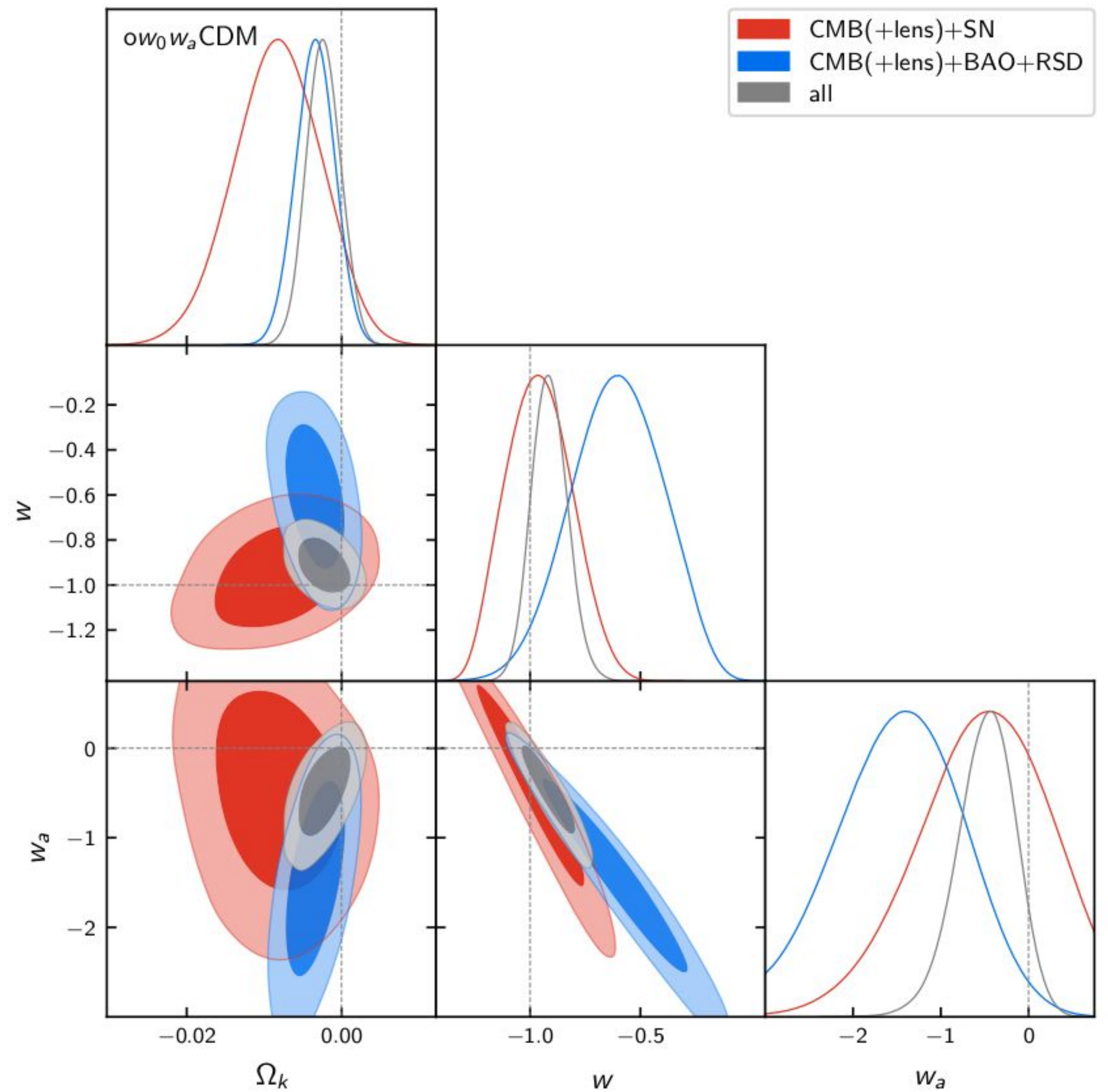
Experimental Consistency

- BAO+RSD consistent with Planck and DES under LCDM
  - CMB and DES: sigma8 tension, Omega_m tension, or no tension?



Constraints from ow0waCDM

- Complementarity of BAO and SNe Ia → tight constraints of curvature and the dark energy equation of state
- Dark Energy Task Force Figure of Merit of 103
- FoM=150 predicted by DETF at conclusion of Stage-III



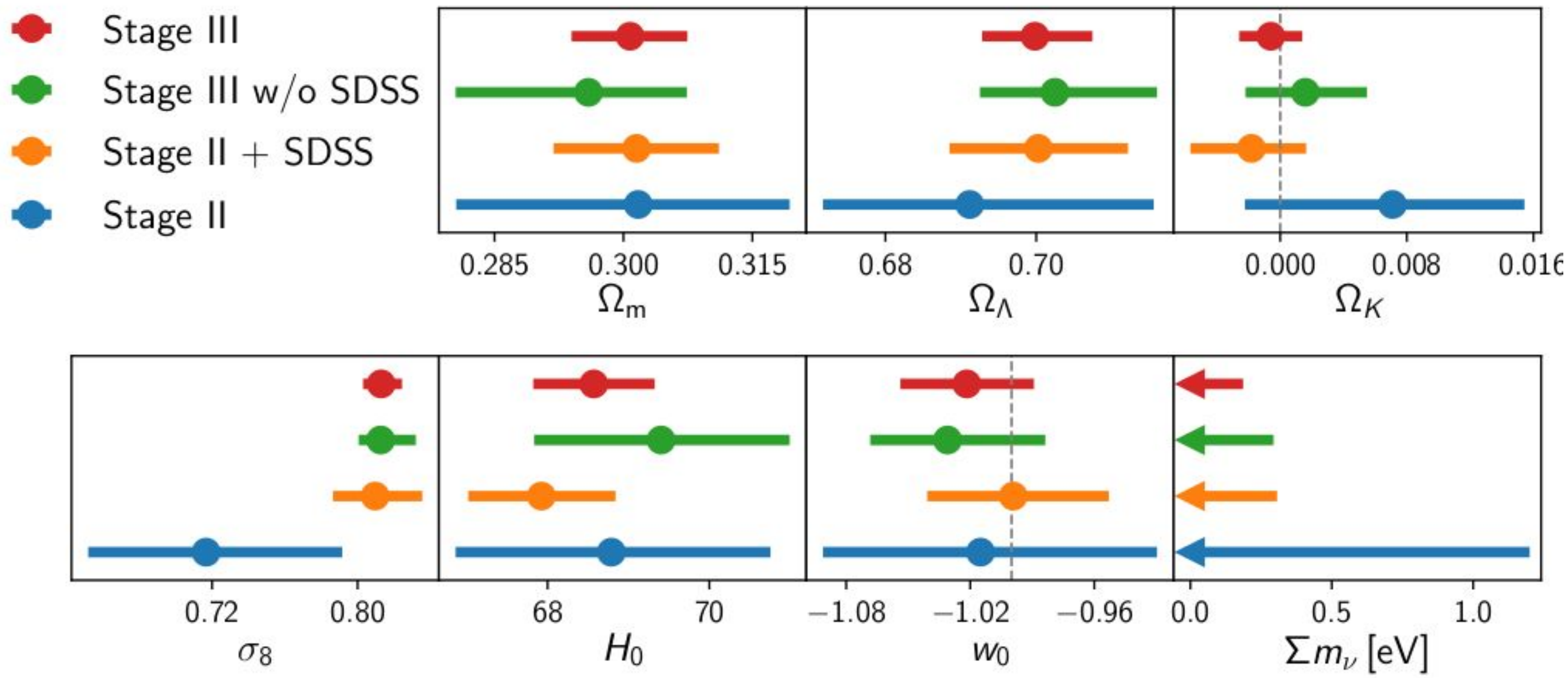
Global Preferred Model

- ~1% precision estimates on the dark energy density, H0, and amplitude of matter fluctuation regardless of cosmological model
- Little degradation in curvature precision with increasing parameters
- Little degradation in neutrino mass with increasing parameters
- w_p(z=0.36) = -1.013 +/- 0.029 in w0waCDM, little degradation with w_a

	Ω_Λ	H_0	σ_8	Ω_K	w_0	w_a	Σm_ν [eV]
ΛCDM	0.6959 ± 0.0047	68.19 ± 0.36	0.8073 ± 0.0056	–	–	–	–
oΛCDM	0.6958 ± 0.0048	68.21 ± 0.55	0.8076 ± 0.0065	0.0001 ± 0.0017	–	–	–
wCDM	0.6992 ± 0.0066	68.64 ± 0.73	0.8128 ± 0.0092	–	-1.020 ± 0.027	–	–
owCDM	0.6997 ± 0.0069	68.59 ± 0.73	0.8127 ± 0.0091	-0.0004 ± 0.0019	-1.023 ± 0.030	–	–
$w_0 w_a$CDM	0.6971 ± 0.0069	68.47 ± 0.74	0.8139 ± 0.0093	–	-0.939 ± 0.073	$-0.31^{+0.28}_{-0.24}$	–
o$w_0 w_a$CDM	0.6988 ± 0.0072	68.20 ± 0.81	0.8140 ± 0.0093	-0.0023 ± 0.0022	-0.912 ± 0.081	$-0.48^{+0.36}_{-0.30}$	–
$m_\nu\Lambda$CDM	0.6975 ± 0.0053	68.34 ± 0.43	$0.8115^{+0.0092}_{-0.0068}$	–	–	–	$< 0.111(95\%)$
m_νwCDM	0.6993 ± 0.0067	68.65 ± 0.73	$0.813^{+0.011}_{-0.0098}$	–	$-1.019^{+0.034}_{-0.029}$	–	$< 0.161(95\%)$

A Decade of Progress (nuow0CDM)

- Stage-II (2010): WMAP + JLA SNe + SDSS/2dFGRS BAO
- SDSS: 50X decrease in curvature/H0/sigma8/w0/neutrino mass posterior volume relative to Stage-II
  - largest improvements in curvature, H0, and neutrino mass precision
  - Stage-II + SDSS: H0 = 67.60 +/- 0.92 km/s/Mpc
- Planck+Pantheon+DES: additional 20X improvent → average 4X per parameter



Summary

- **BOSS/eBOSS**
  - Conclusion of Stage-III Dark Energy surveys with spectroscopy
  - BAO measurements over 11 Gyr & RSD measurements to z<1.5
- **Cosmology**
  - BAO complement SNe, but higher precision in isolation
  - BAO allow robust estimates of H0 not possible otherwise
  - RSD complement WL → favor LCDM model with Planck and support General Relativity
  - SDSS largest role in advancing neutrino mass constraints: 1-sigma uncertainty now comparable to minimum allowed mass
  - LCDM model is preferred by all data: SDSS leads the way in improving precision of late-time cosmological model since 2010

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