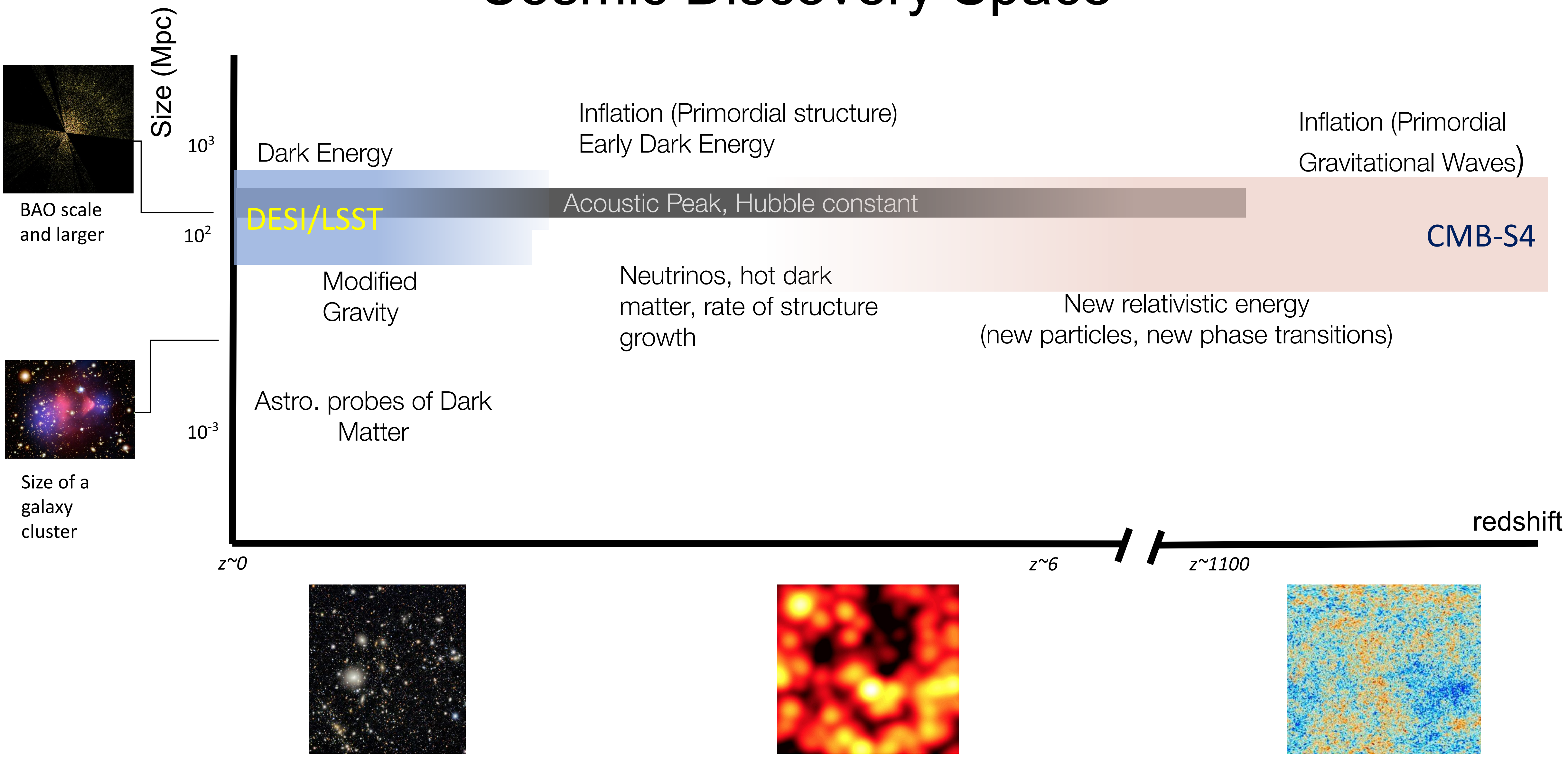
Large-Scale Structure with the Dark Energy Spectroscopic Instrument (DESI)

Kyle Dawson, University of Utah
On behalf of the DESI Collaboration

14th Conference on the Intersections of Particle and Nuclear Physics

Cosmic Discovery Space



Galaxies emitting in optical wavelengths and spatially resolved.

Galaxies and gas emission at redder wavelengths and spatially dense.

Hot dense state. Detectable relics include CMB, gravitational waves and neutrinos.

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Cosmology with Surveys: A Staged Approach

	Imaging	Spectroscopy	Cosmic Microwave Background
Stage-III	**Dark Energy Survey (2013-2019)**	**BOSS/eBOSS (2009-2019)**	**SPT/BICEP/Simons (~2017 –)**
Stage-IV	**Rubin/LSST (~2024 –)**	**DESI (2021 –)**	**CMB-S4 (~2030 –)**

Cosmology with Spectroscopic Surveys

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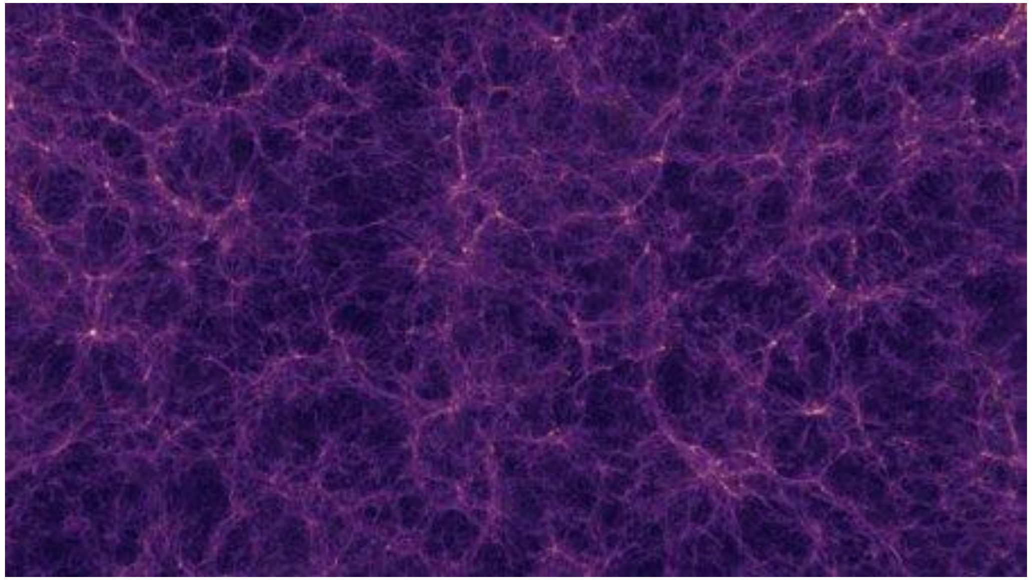
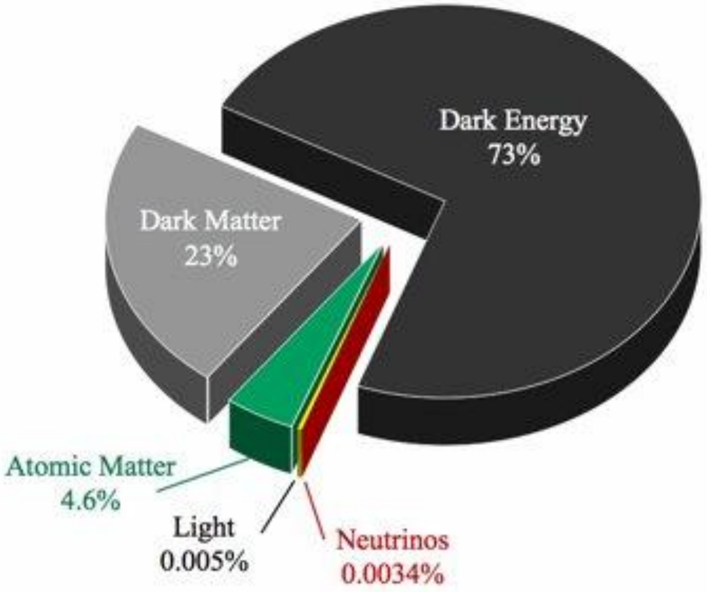
- **Evolving distribution of matter in Universe**
  - Cosmic expansion and growth of structure
- **Derived Measurements: $H(z)$, $D_M(z)$, $f\sigma_8(z)$**
  - Physics of dark energy
  - Composition of the Universe
  - Neutrino mass, Inflation, Laws of gravity

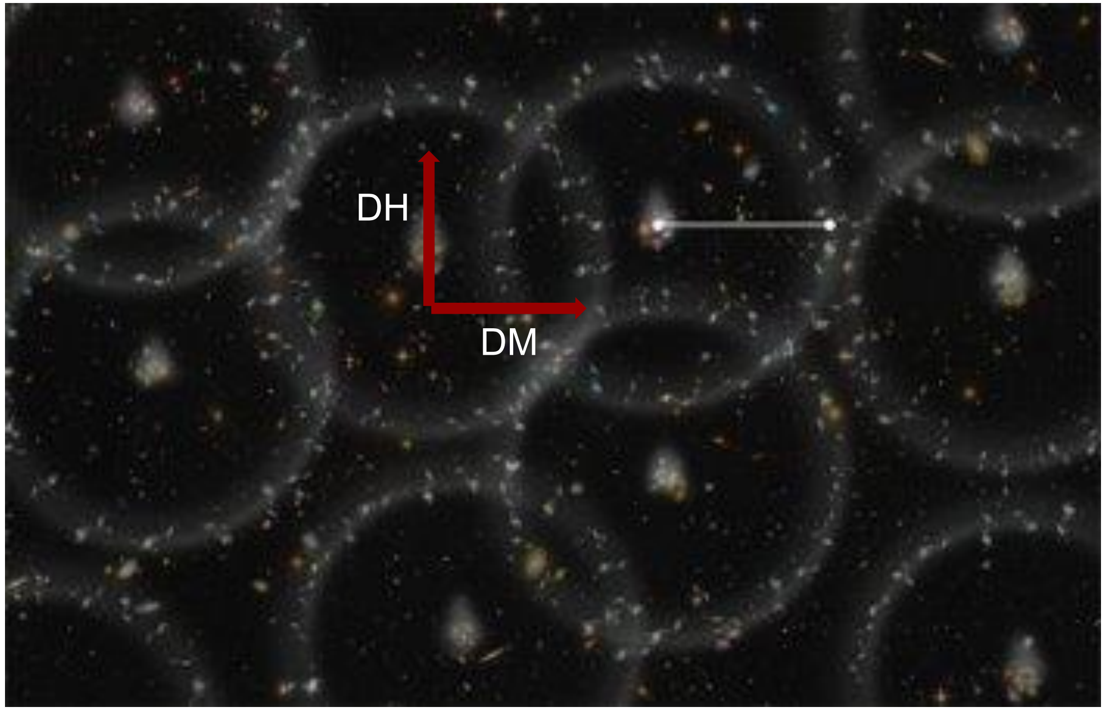




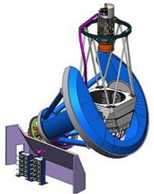
Expansion with Baryon Acoustic Oscillations

- **Friedmann Equation (includes all energy components):**

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



- **Baryon Acoustic Oscillations (BAO)**
  - Measure angular diameter distance and *H(z)*
  - Provide relative distance estimates at many redshifts
  - Constrain energy density as function of redshift



Growth History with Redshift Space Distortions

- **Linear growth equation:**

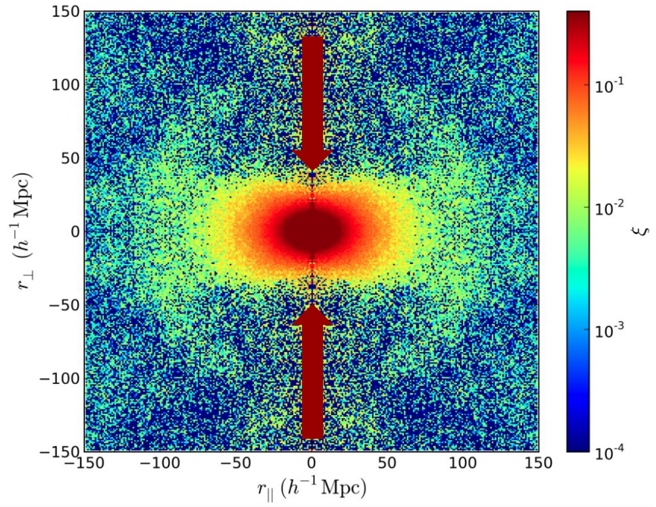
$$\delta(\mathbf{x}, t) \;=\; D(t)\delta(\mathbf{x}, t_0)$$

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

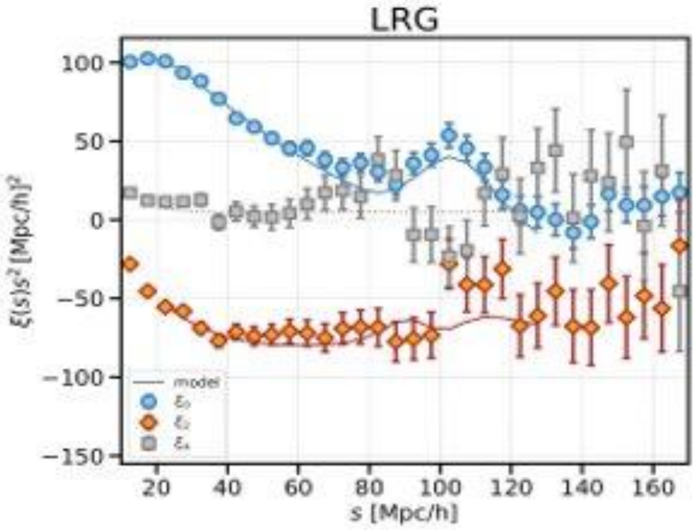
- **Linear Growth Rate:**

$$f(z) \equiv \frac{d\ln D}{d\ln a} \longrightarrow f = \frac{\partial \ln \sigma_8}{\partial \ln a}$$

- **Redshift Space Distortions (RSD) measure f sigma8**



Samushia et al. 2013



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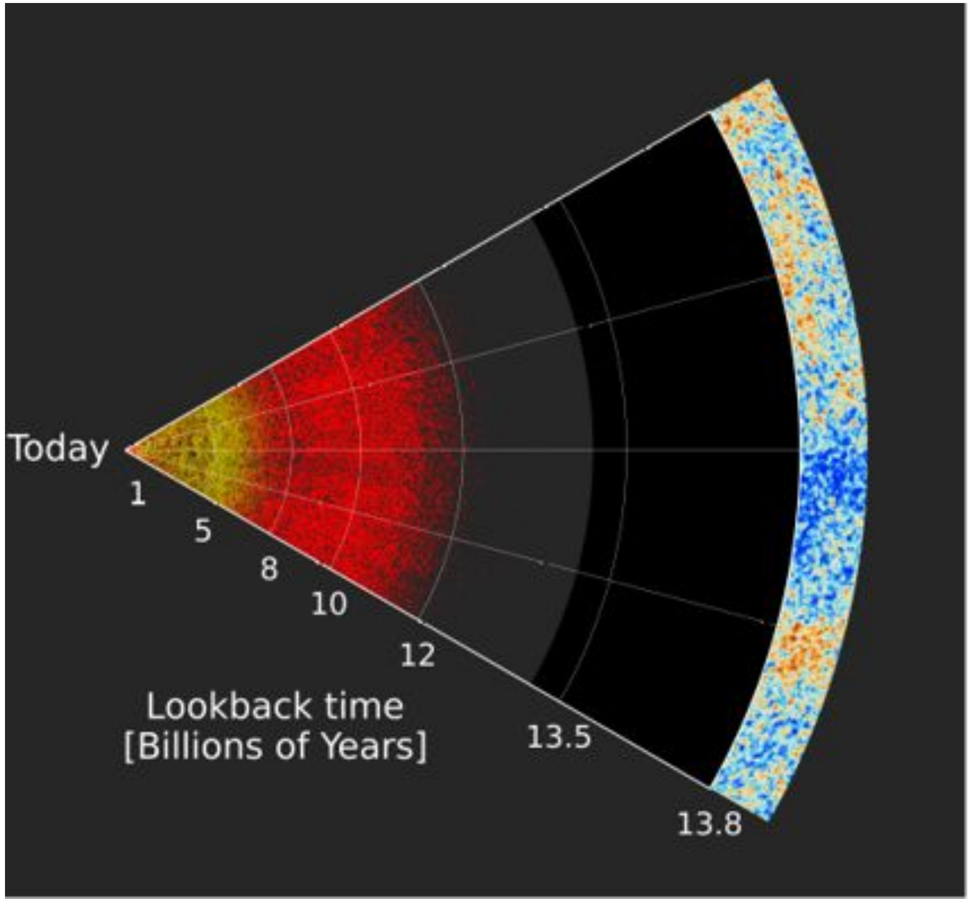
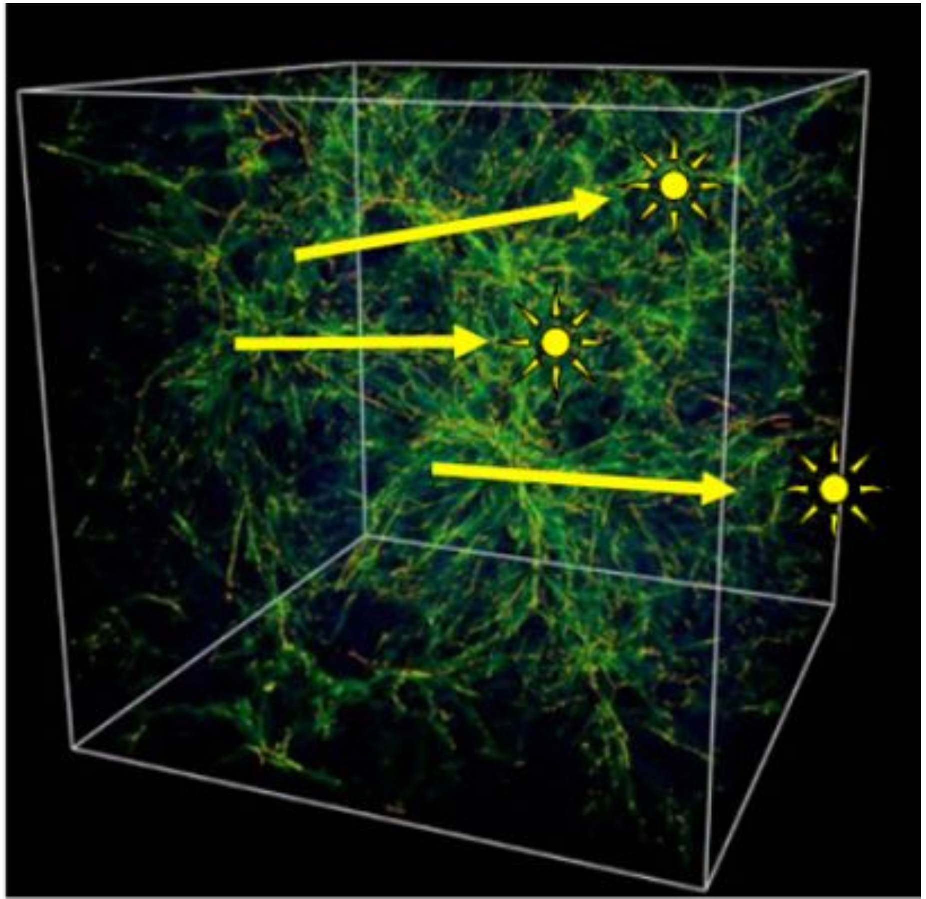
Spectroscopy of the Cosmic Density Field

Direct tracers

Galaxies and quasars (z<2.1)

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





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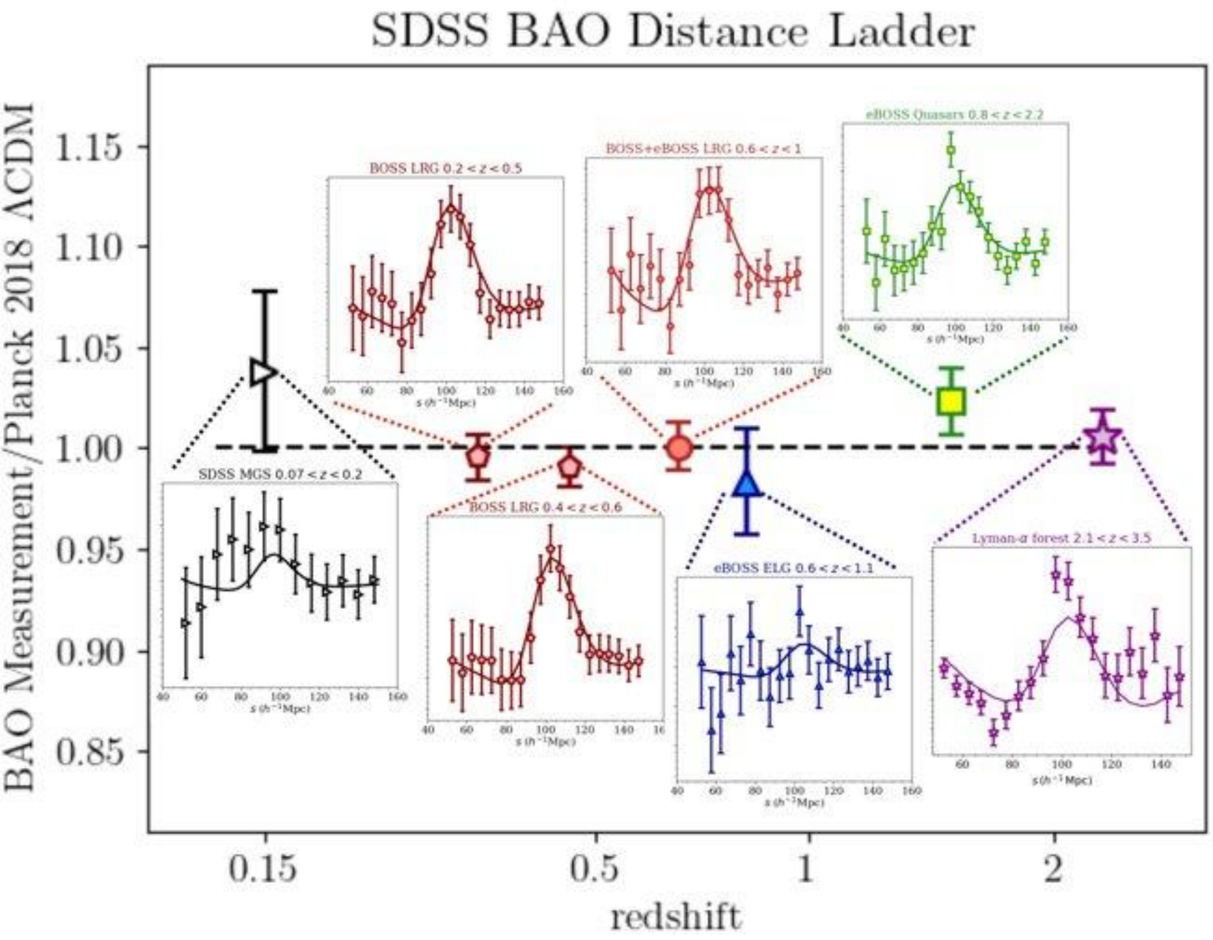
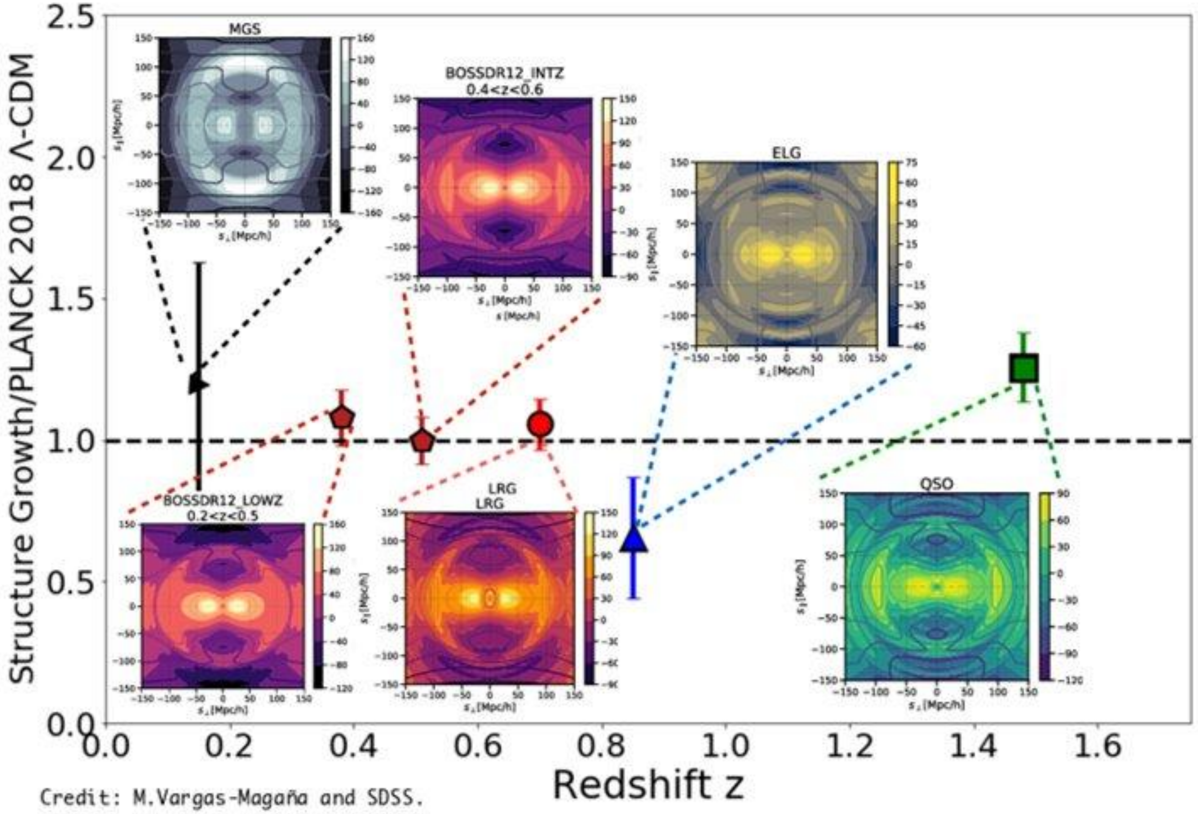
Stage-III Dark Energy Surveys: BAO + RSD





Credit: M.Vargas-Magaña and SDSS.

Stage-III Cosmological Model (eBOSS et al. 2021)

- ~1% precision estimates on the dark energy density, H_0, and amplitude of matter fluctuation regardless of cosmological model
- $w_p(z=0.36) = -1.013$ +/- 0.029 in w0waCDM, little degradation with w_a
- 40X decrease in curvature/H0/sigma8/w0/neutrino mass posterior volume relative to Stage-II
- Planck+Pantheon+DES: additional 25X improvement → average 4X per parameter

	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	$0.813^{+0.011}_{-0.0098}$	–	$-1.019^{+0.034}_{-0.029}$	–	$< 0.161 (95\%)$

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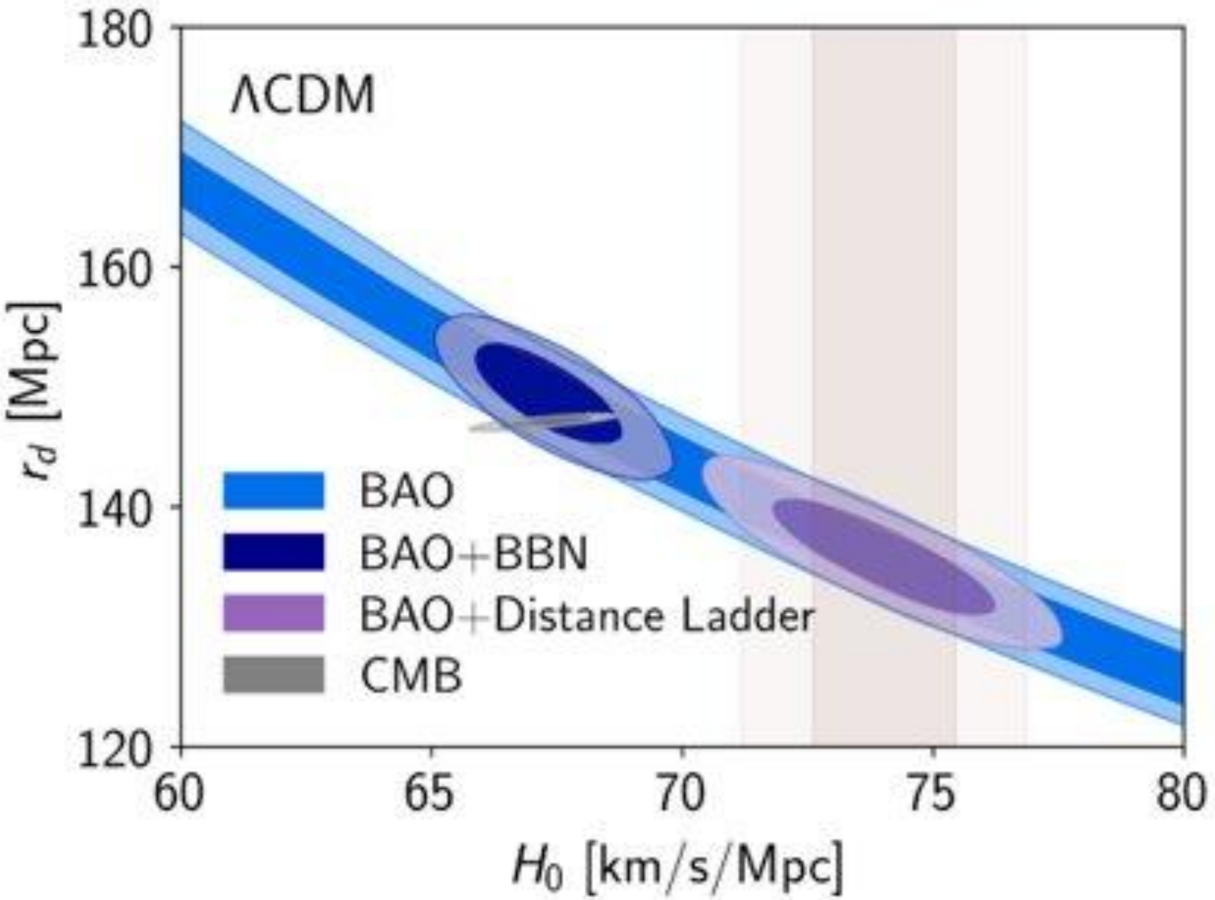
New Physics in Expansion History?

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



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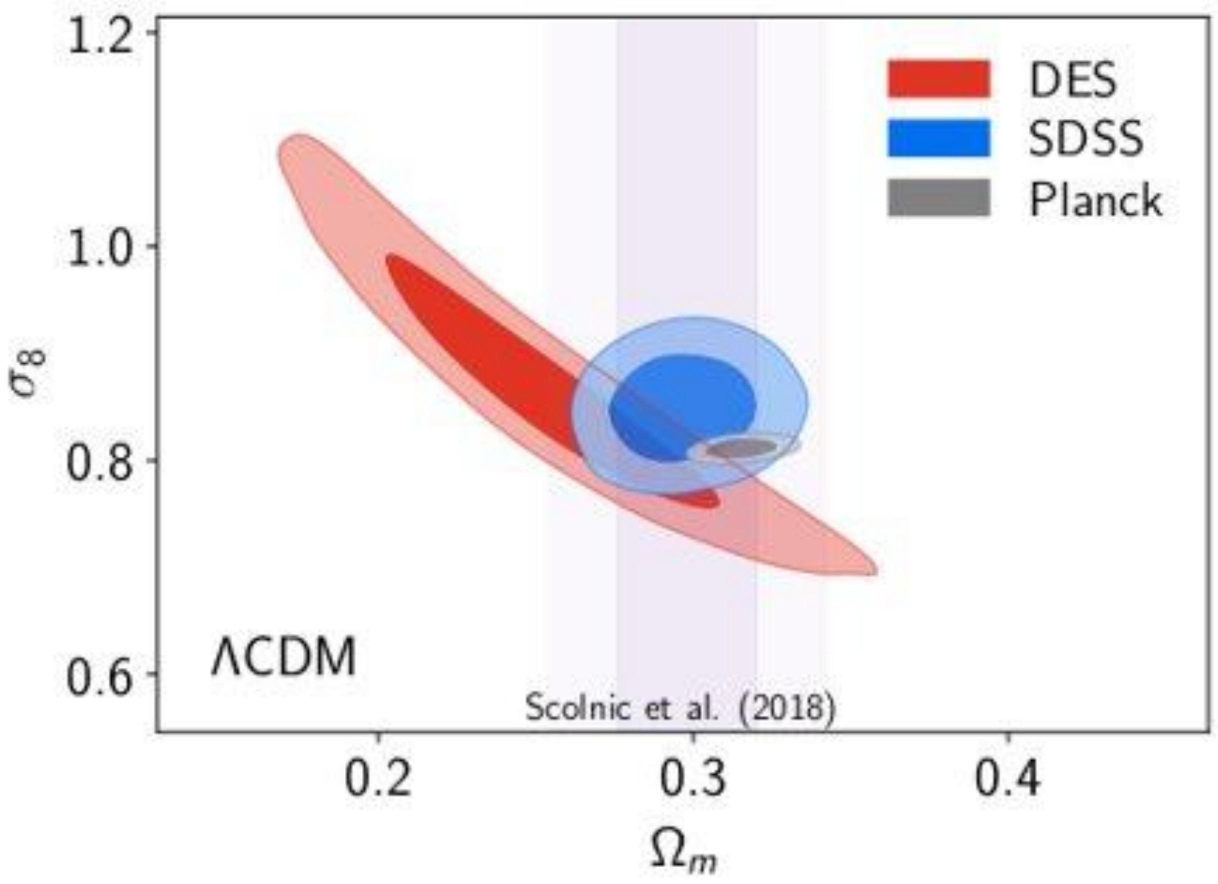
Tension in Growth of Structure?

- **BAO + RSD → 3.5% precision on growth of structure**
- **CMB and DES: sigma8 tension, Omega_m tension, or no tension?**



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Dark Energy Spectroscopic Instrument

- **Located at 4-meter Mayall Telescope in Arizona**
  - Upgraded telescope for wide field spectroscopy
  - Now dedicated to multi-object spectroscopy
- **First Stage-IV Dark Energy Experiment**
  - Optimized for BAO measurements
  - 10X improvement to w0wa posterior area compared to Stage-II Type Ia supernovae measurements
- **Comprehensive cosmology program**
  - Redshift Space Distortions
  - Cross-correlations with other surveys
  - More cosmology, galaxy evolution, and astrophysics

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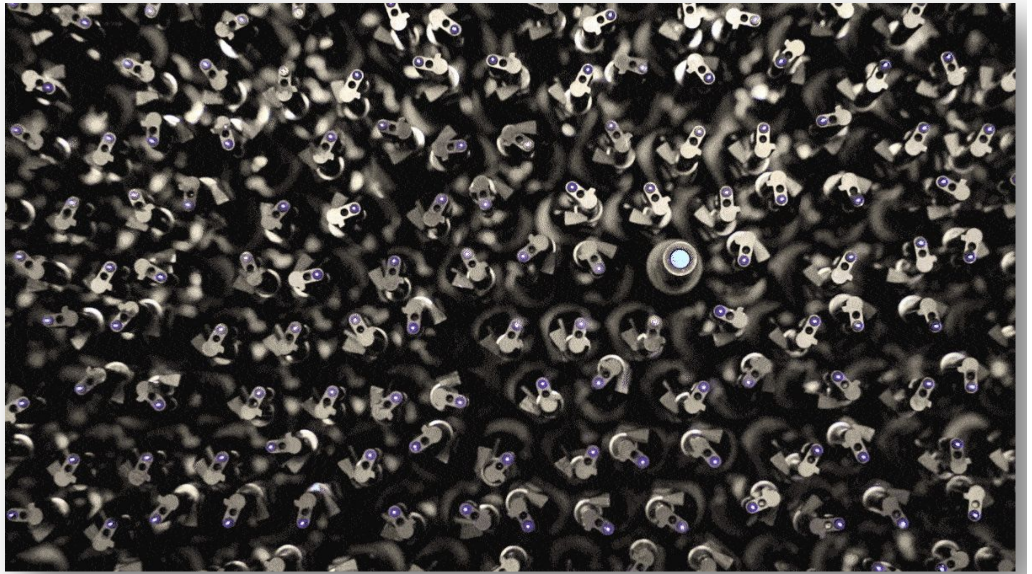
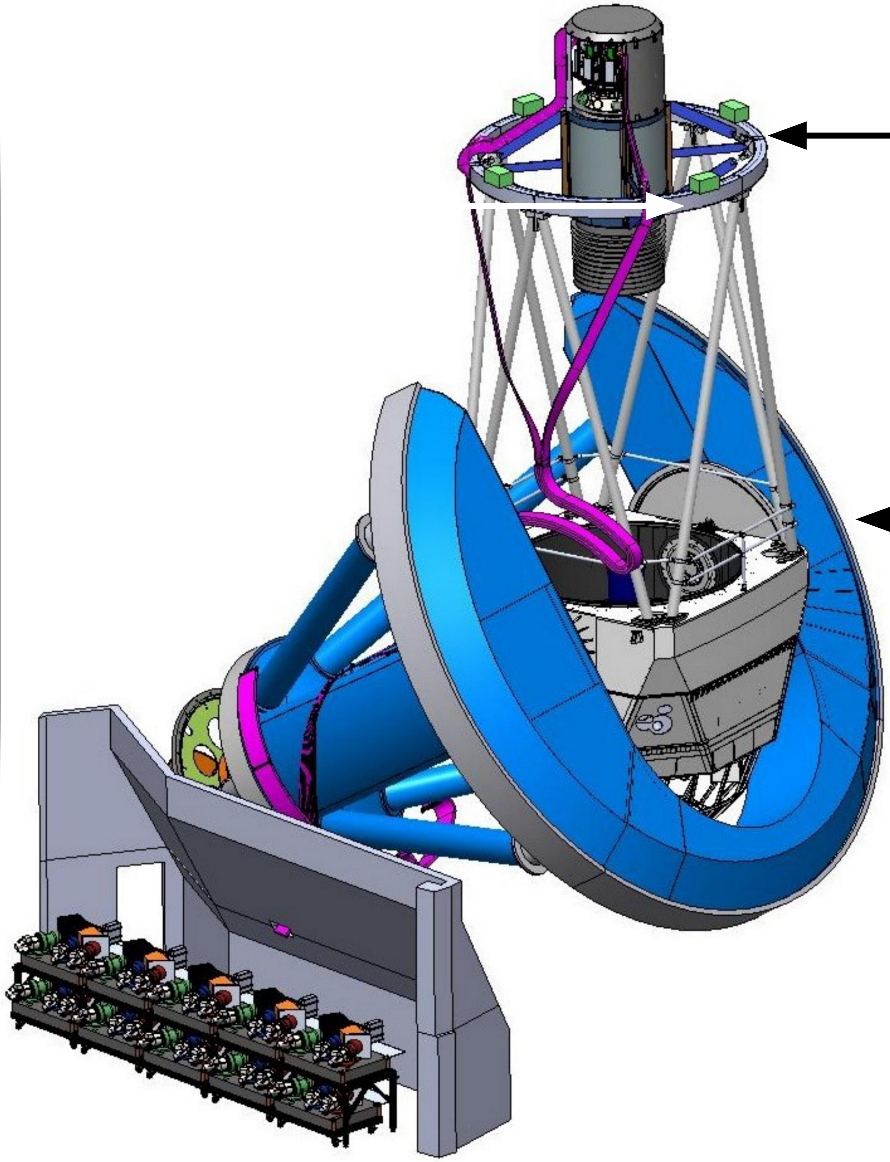
DESI: Massively-multiplexed Spectroscopy



~1 minute to position fibers!



Focal plane assembly with 5000 fiber positioners

Mayall 4m telescope

10 spectrographs (360-980nm)

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Uninterrupted Galaxy and Quasars from 0<z<3.5

3 million quasars + Ly-α forest (1 < z < 3.5)

16 million Emission Line Galaxies

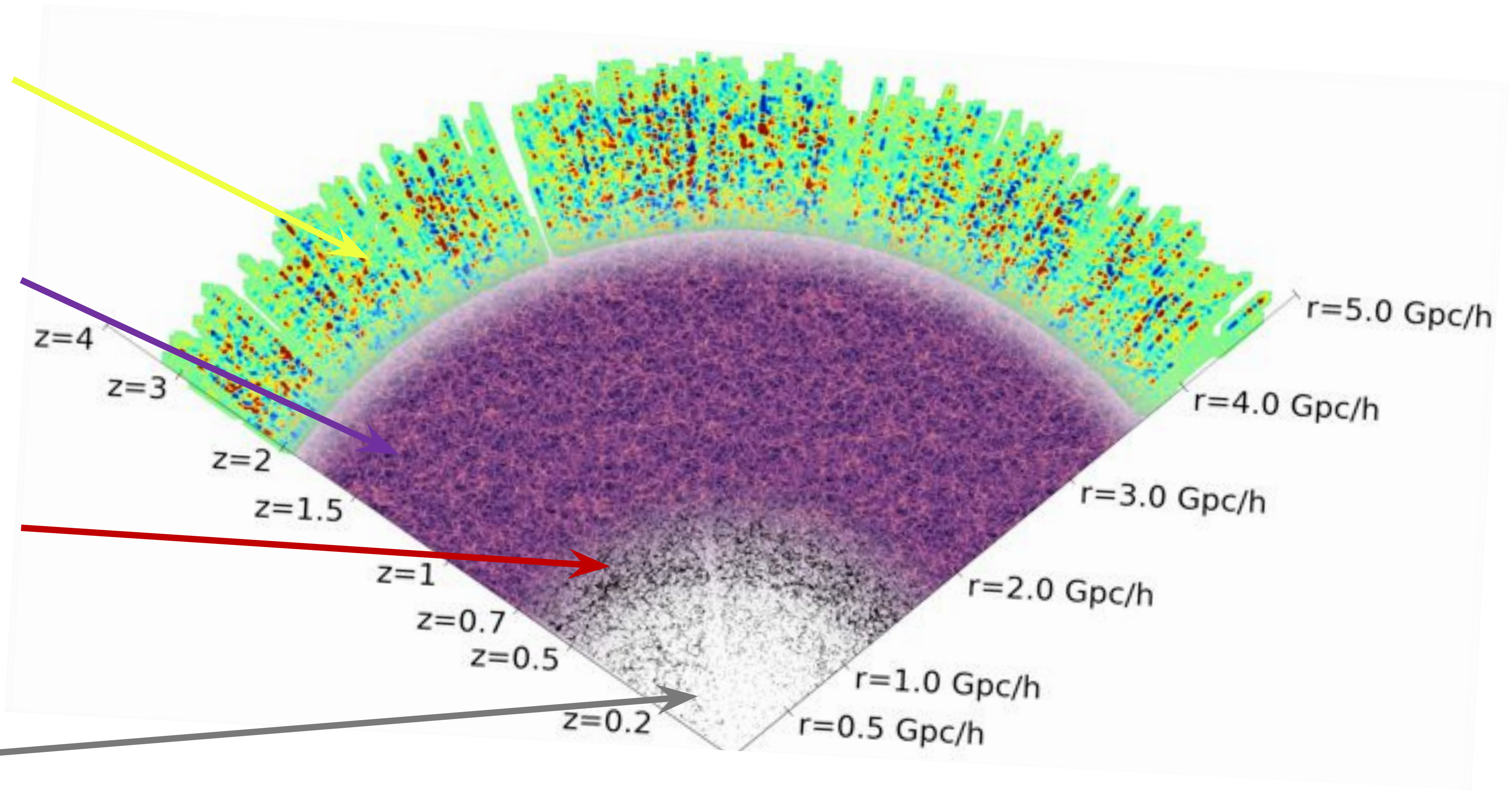
(0.6 < z < 1.6)

8 million Luminous Red Galaxies

(0.4 < z < 1.1)

13 million Bright Galaxies

(0.0 < z < 0.4)



Plus 10 million Milky Way stars

First Year Sample

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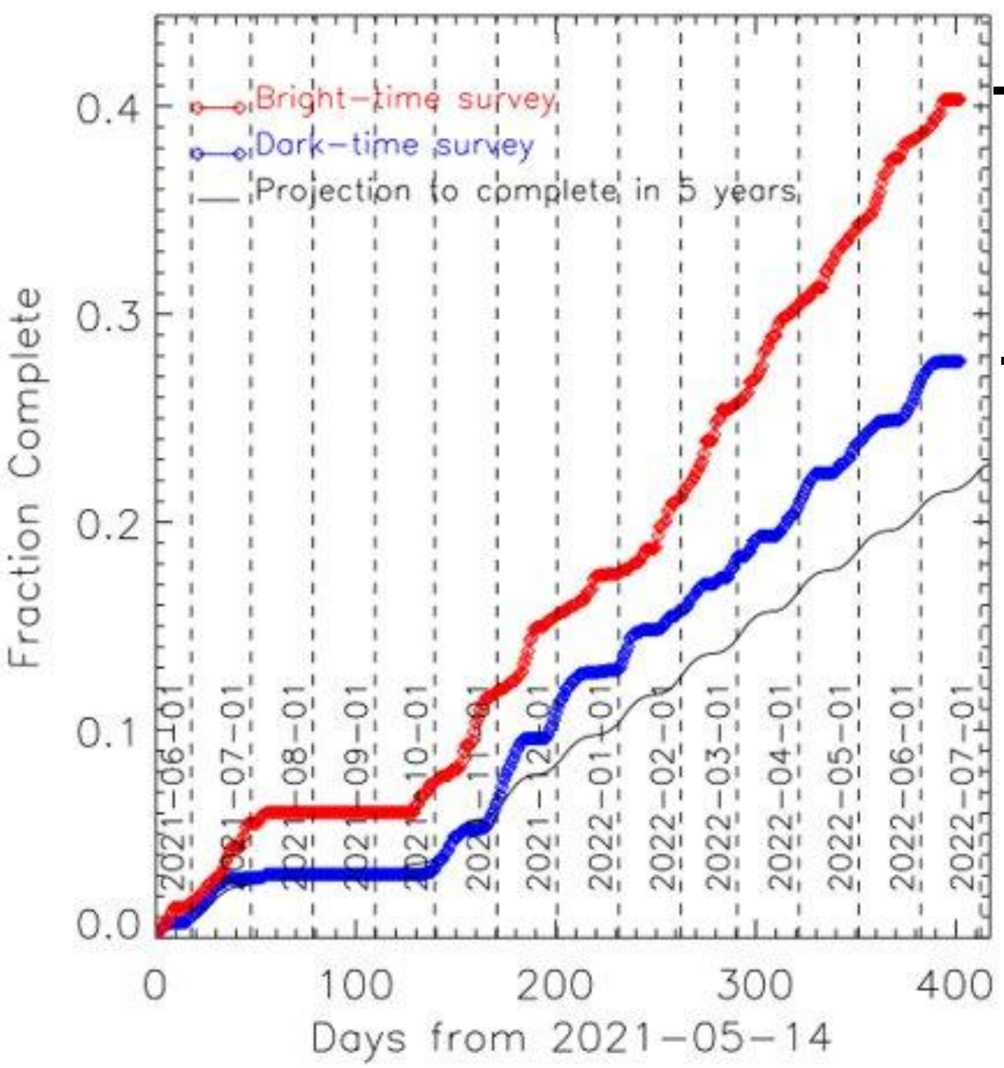

- 6.3M Bright Galaxies ($z<0.5$)
- 2.6M stars

- 2.7M LRGs ($0.4<z<1.1$)
- 4.1M Emission line galaxies ($0.6<z<1.6$)
- 1.7M QSOs ($0.9<z<2.1$ tracers & $z>2.1$ with Lyα forest)

First results on arxiv (8 papers): Validation of Spectroscopic Samples

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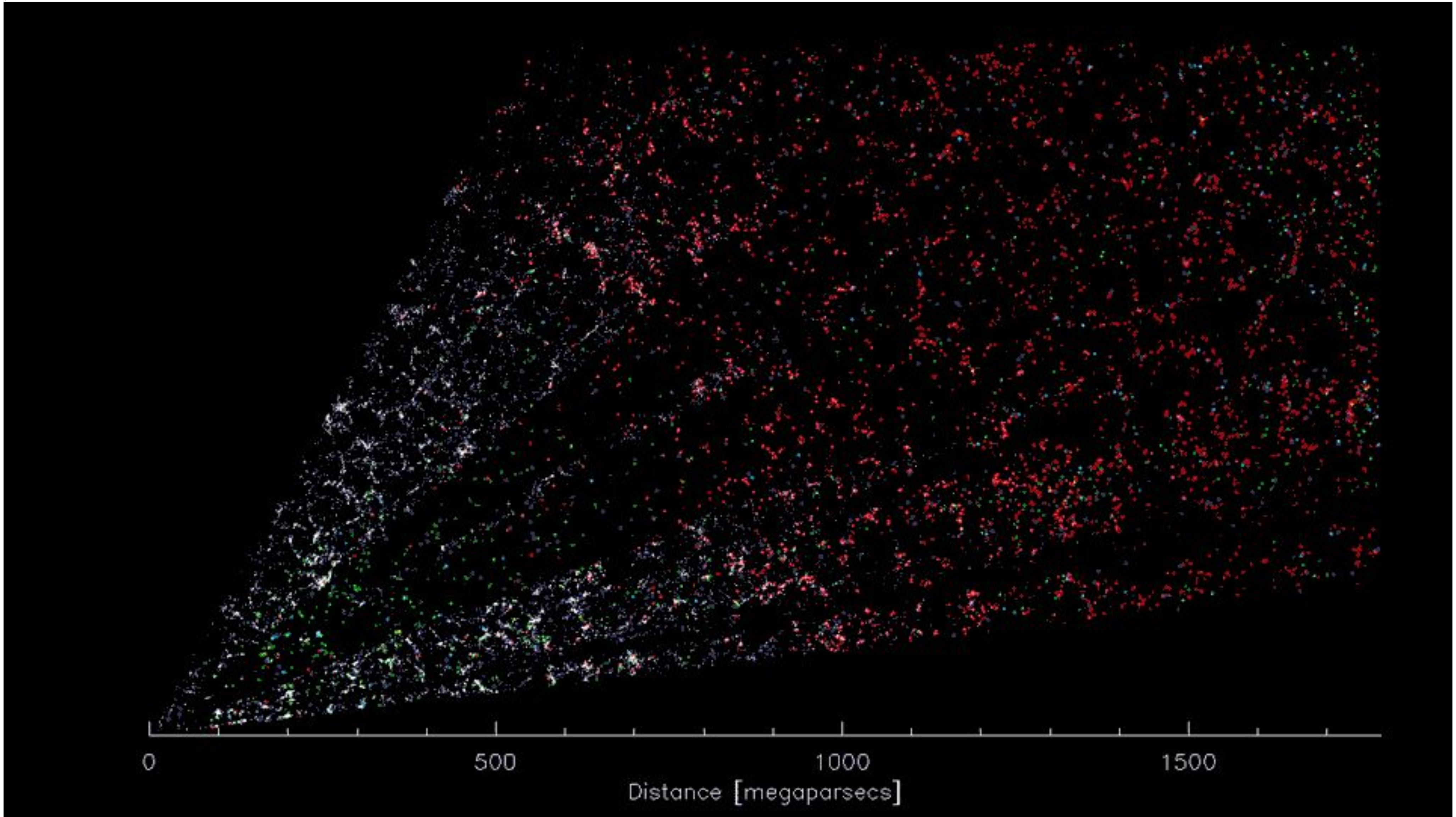
First Year Map



Primary Science Driver: Dark Energy with BAO

- **Stage-III BAO distance measurements:**
  - 0.70% precision at z < 1
  - 1.19% precision at z > 1
- **DESI BAO distance science requirement:**
  - 0.28% precision at z<1.1
  - 0.39% precision at 1.1<z<1.9
  - <1% precision at z>1.9
- **Expect to exceed requirements by ~1.4X in final measurements**

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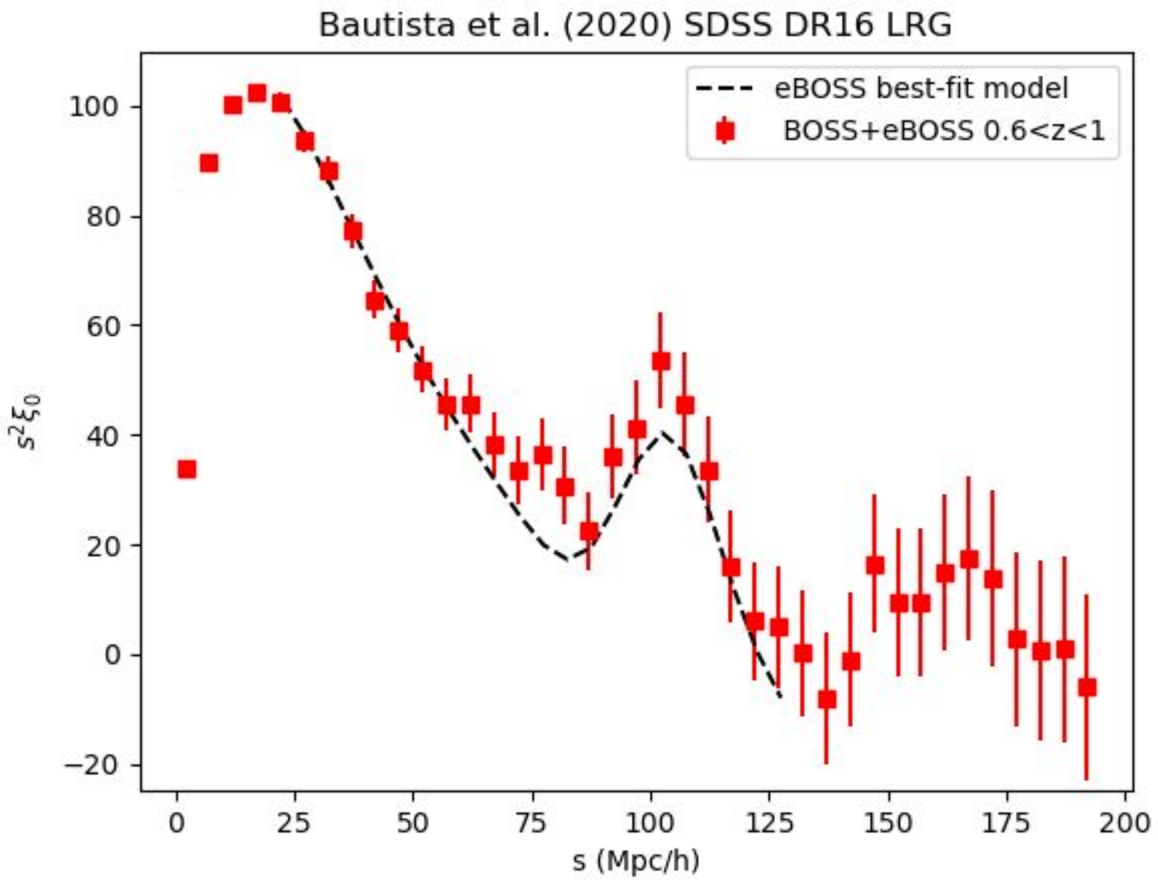
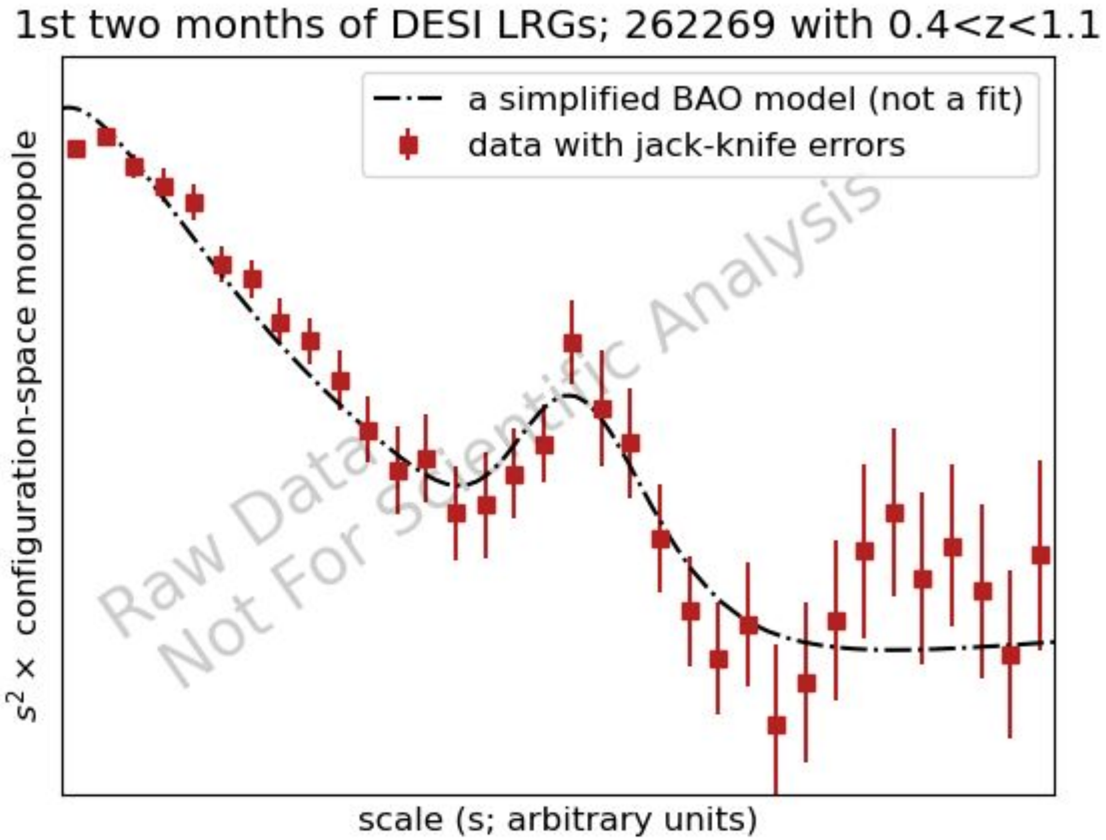
Early BAO results: Correlation function monopole

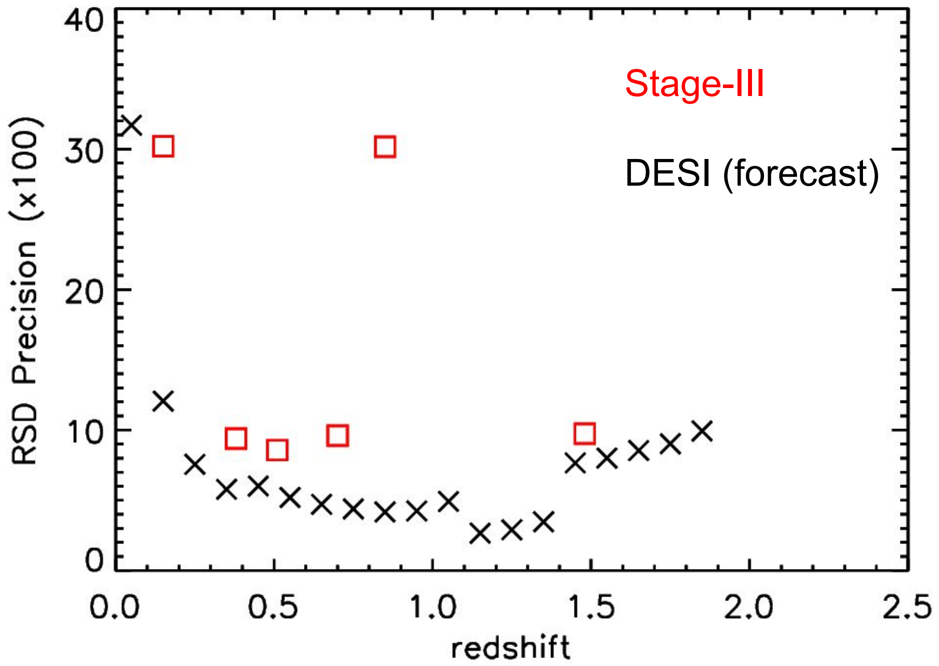
BOSS+eBOSS vs. 2 months of DESI





Beyond BAO: Redshift Space Distortions

- **Stage-III Spectroscopy**
  - 4.78% precision over the redshift interval 0 < z < 1.5
  - 3.5% precision on sigma8, no tension with Planck
- **DESI: 21 independent measurements to z<2.1 with median 5.2% precision**



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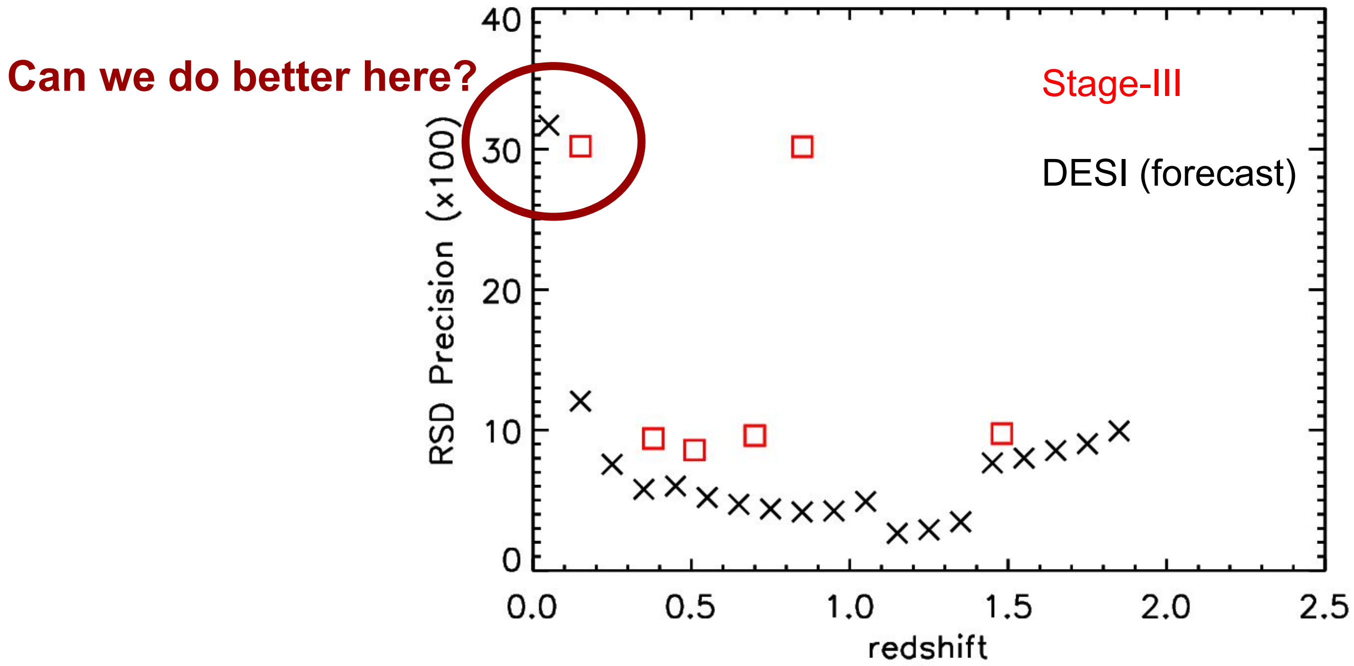

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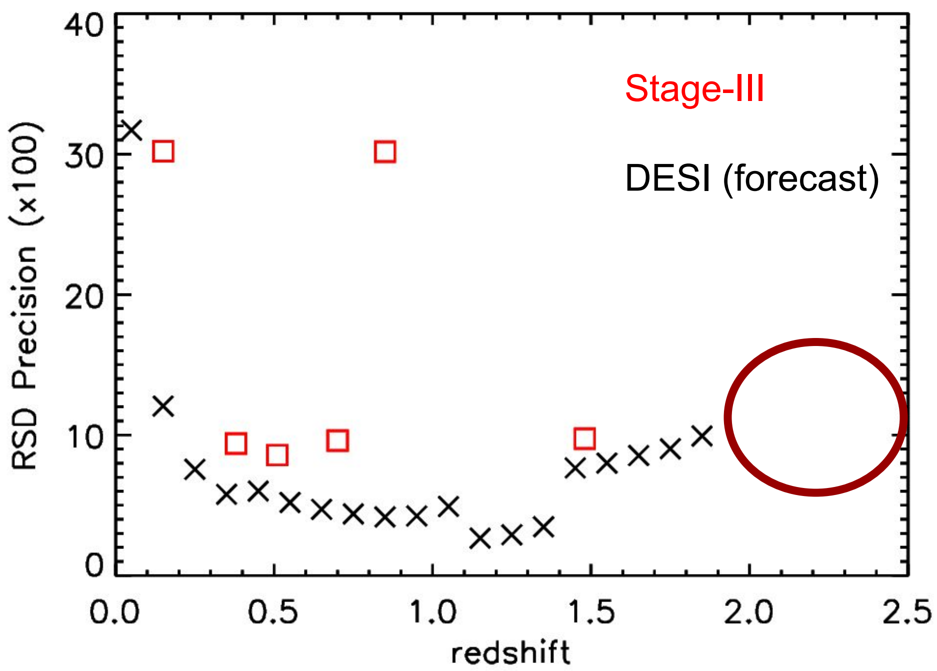

What about this redshift range?

Beyond RSD: Growth of Structure

- **Year 1 strategy**
  - Collaboration-wide demonstration of primary BAO+RSD measurements
  - Measurements of primordial non-Gaussianity in power spectrum
- **Year 3 strategy (in discussion now)**
  - Collaboration-wide effort to enhance growth measurements over all redshifts (explore growth of structure tension)
  - Introduce higher order statistics into cosmology results

Beyond RSD: Growth of Structure

- **Potential Year 3 Key Projects**
  - $z<0.1$ peculiar velocities with Tully Fisher + Fundamental plane + SNe Ia
  - $0.1<z<1.6$ bispectrum (fnl and ~30% improvement on RSD)
  - galaxy-galaxy lensing to constrain RSD nuisance terms
  - CMB-DESI cross-correlations to directly measure sigma8(z)
  - 1D power spectrum in Lyman-alpha forest for sigma8($z>2$)

- **Expect sub-percent precision on sigma8 with final RSD analysis**

- **What improvement on sigma8 is possible relative to RSD only?**

Beyond DESI: High Density Galaxy Clustering

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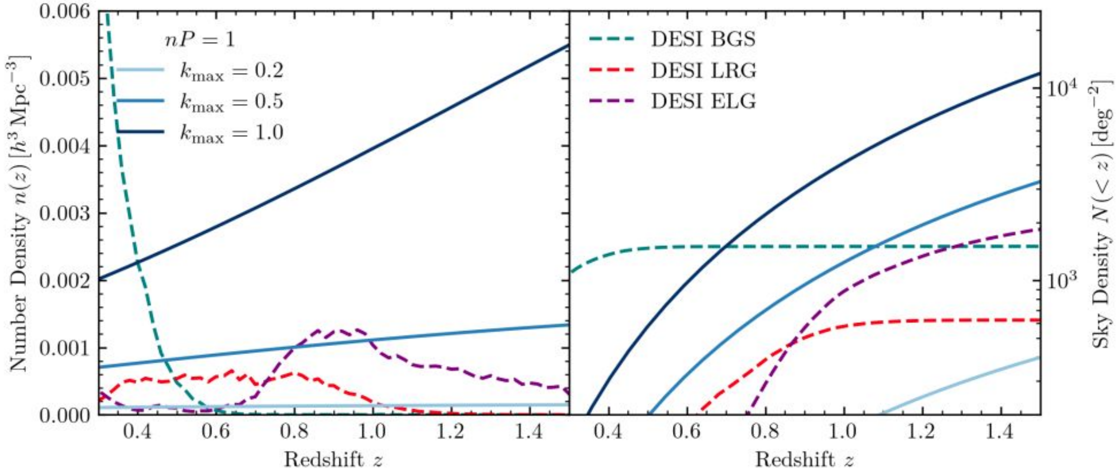
- **0<z<1.5: covers matter-dominated to dark energy dominated regimes**
  - Redshift range where most Dark Energy models are best explored
  - Limited by theory and computing
- **nP=1 approximates optimal balance of number density at a fixed scale**
  - 10,000 galaxies/sqdeg → kmax=1 h/Mpc for z<1.5
- **180M galaxies over Rubin footprint “saturates” cosmological information**



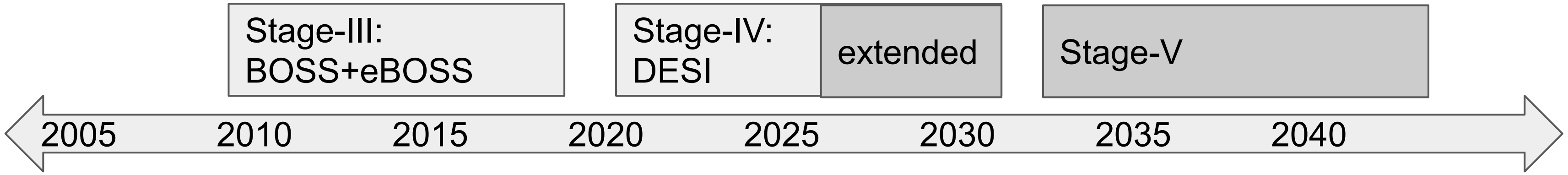
Dawson et al. 2022
Courtesy: Johannes Lange
(Snowmass)

Beyond DESI: High Redshift Galaxy Clustering

- **z>2: matter-dominated regime with massive volume**
  - Experimentally limited with current facilities
  - Spectroscopy of 10's of millions of galaxies over the Rubin footprint would provide high precision **BAO, RSD, neutrino mass, and inflationary constraints**
- **Targets for spectroscopy**
  - Plentiful (**and faint**) Lyman-break and Lyman-alpha emission galaxies
  - Spectroscopy challenging

Beyond DESI: Stage-V Roadmap

- **DESI will remain premier spectroscopic facility in late 2020's**
  - z<1 galaxies easily measured to zfib<21.6
  - z>2 Lyman Break galaxies: ~300/sqdeg
  - z>2 Lyman-alpha emission galaxies: >1000/sqdeg w/new imaging
- **>20M new galaxies overlapping a 10,000 sqdeg Rubin footprint**
- **Sub-percent BAO precision, percent level RSD precision possible at z>2**
- **Immediate tests of concordance cosmology**
- **Pilot new programs during Stage-V construction**



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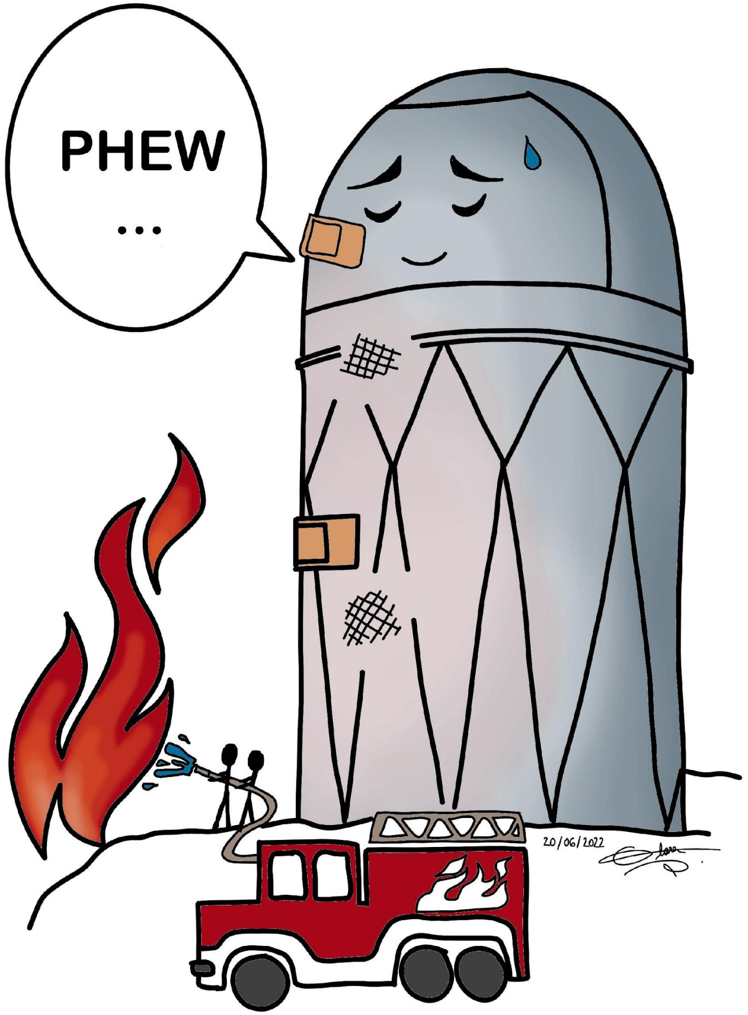
Summary

- **Check arxiv for first major release (1pt statistics)**
- **DESI likely to exceed BAO science requirement**
- **Demonstrate RSD precision in ~1.5yrs**
- **Explore sigma8 improvements with 3yr sample**
- **Snowmass: motivate massive Stage-V expansion over all redshifts**



Credit: Clara Delabrouille

Most important: **Thank you to the firefighters and the NOIRLab staff**

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