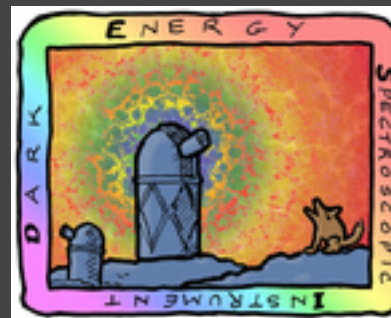


(How CCAPP Produces) Cosmological Results from DESI



THE OHIO STATE UNIVERSITY

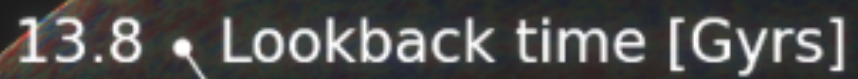
Ashley J. Ross
June 11th 2026



Before DESI (results)



Before DESI (2020):
~3 million redshifts
Collected over ~20
years



13.5 ●

12.0

10.0

5.0

0.0

0.5

redshift

2

Lyman-alpha quasar

Quasar (QSO)

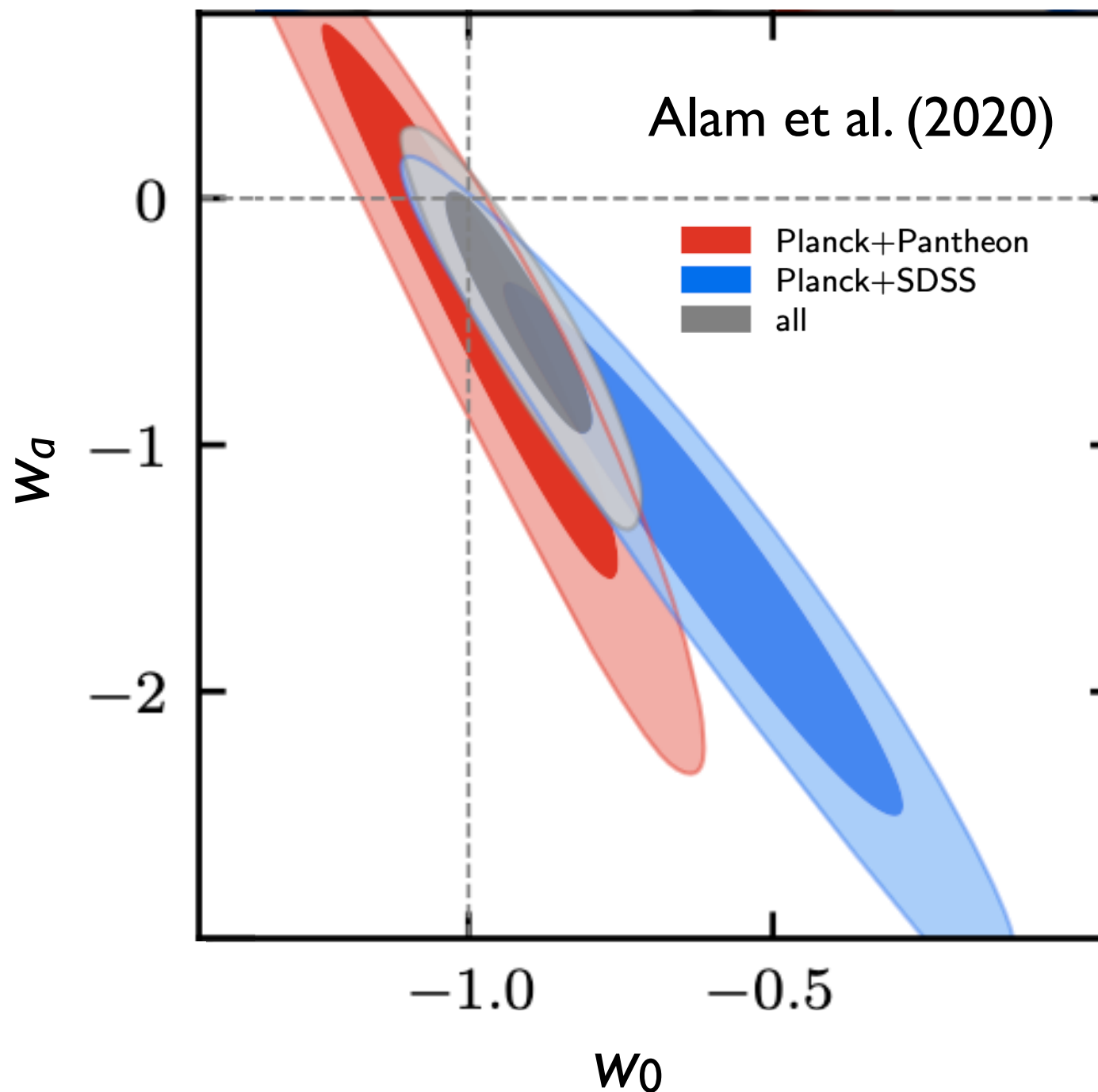
A composite image of a galaxy, likely a spiral galaxy, with a blue text overlay that reads "Emission Line Galaxy (ELG)". The galaxy is shown in a dark, grainy image, with a bright, yellowish-white central region and a blue, diffuse outer region. The text is in a bold, blue, sans-serif font, positioned in the upper right quadrant of the image. The background of the slide is a dark, textured surface with a grid of light blue lines.

Emission Line Galaxy (ELG)

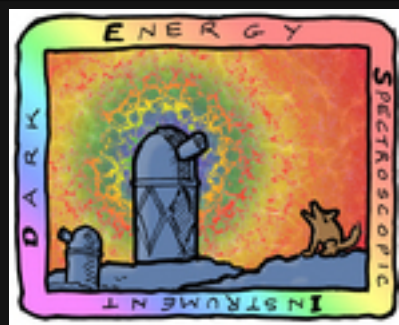
Flux limited (BGS)

Dark Energy Constraints: Pre-DESI

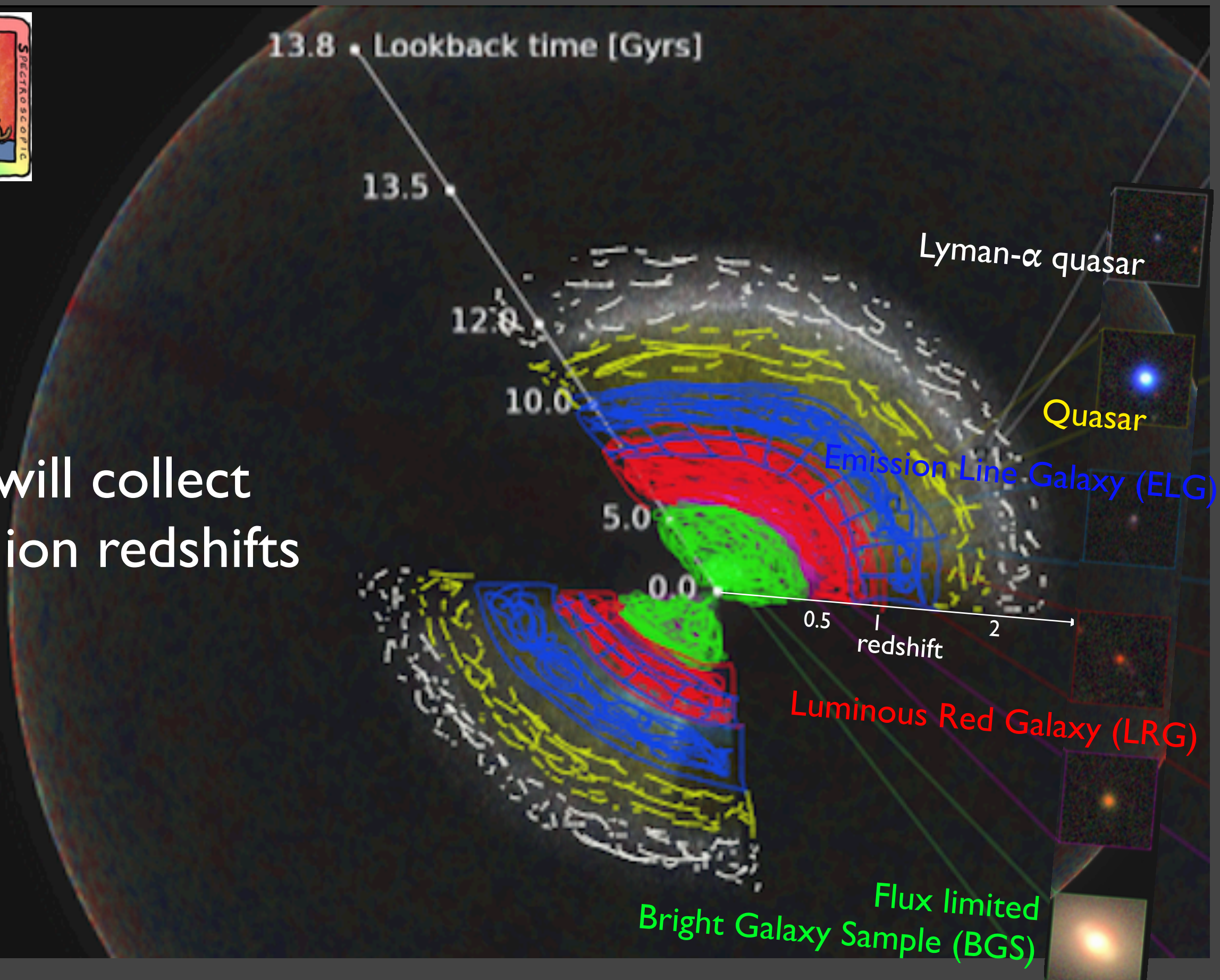
$$w(a) = w_0 + w_a(1 - a)$$



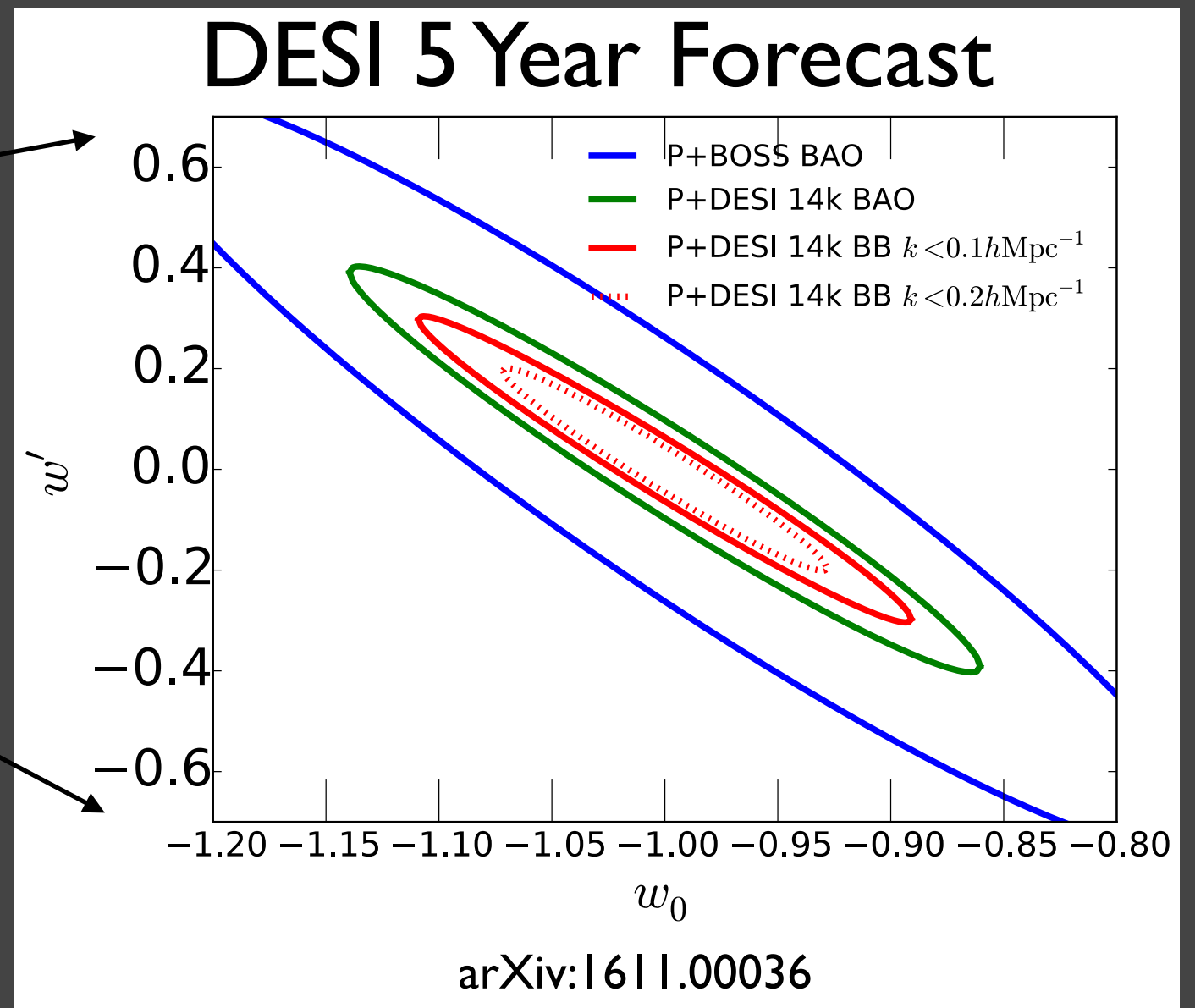
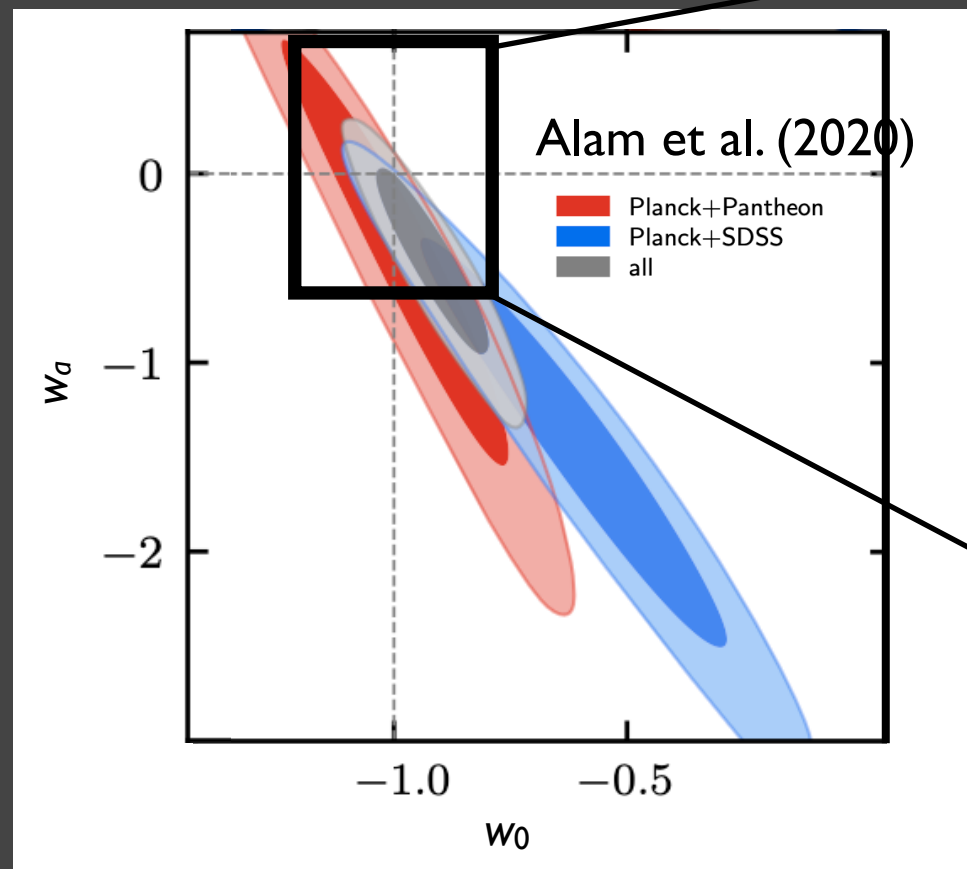
DESI Plan



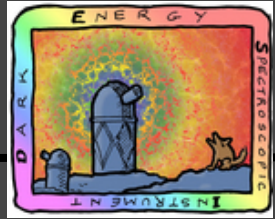
DESI will collect
~35 million redshifts



DESI: Dark Energy Forecast



DESI Achievement



DESI has collected
>47 million redshifts!

Look back time 12 Gyrs

Lyman- α quasar

Quasar

ELG

LRG

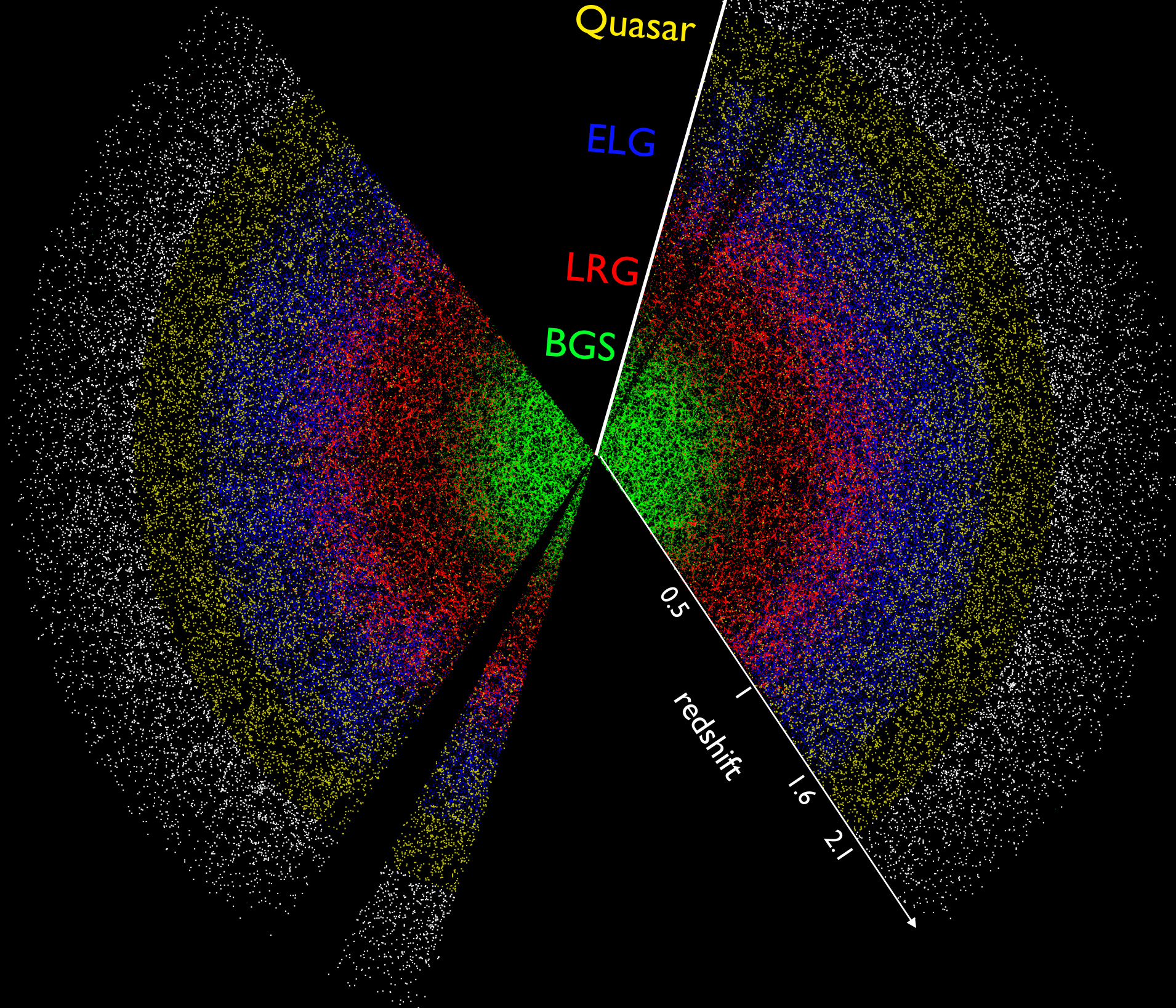
BGS

0.5

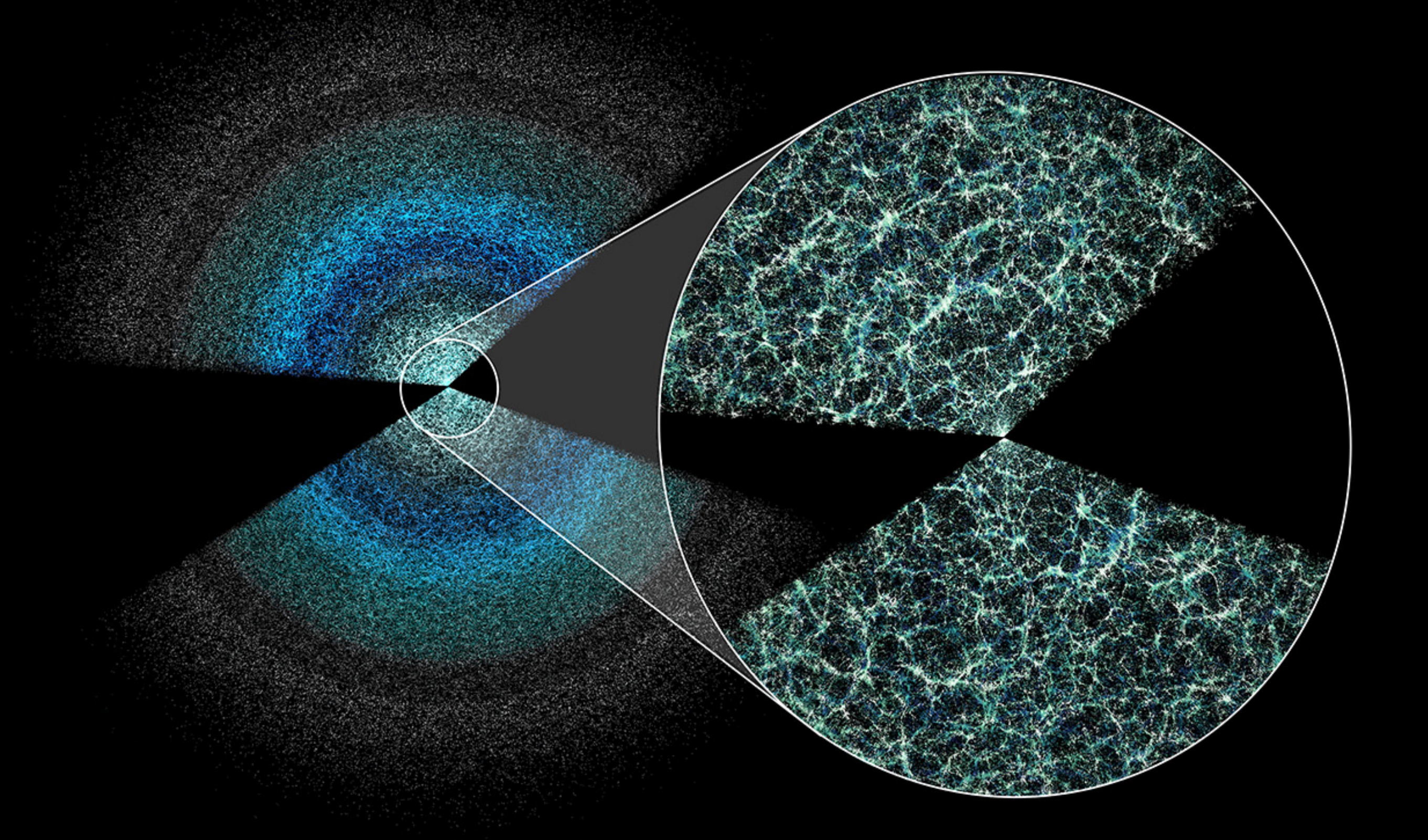
1
redshift

1.6

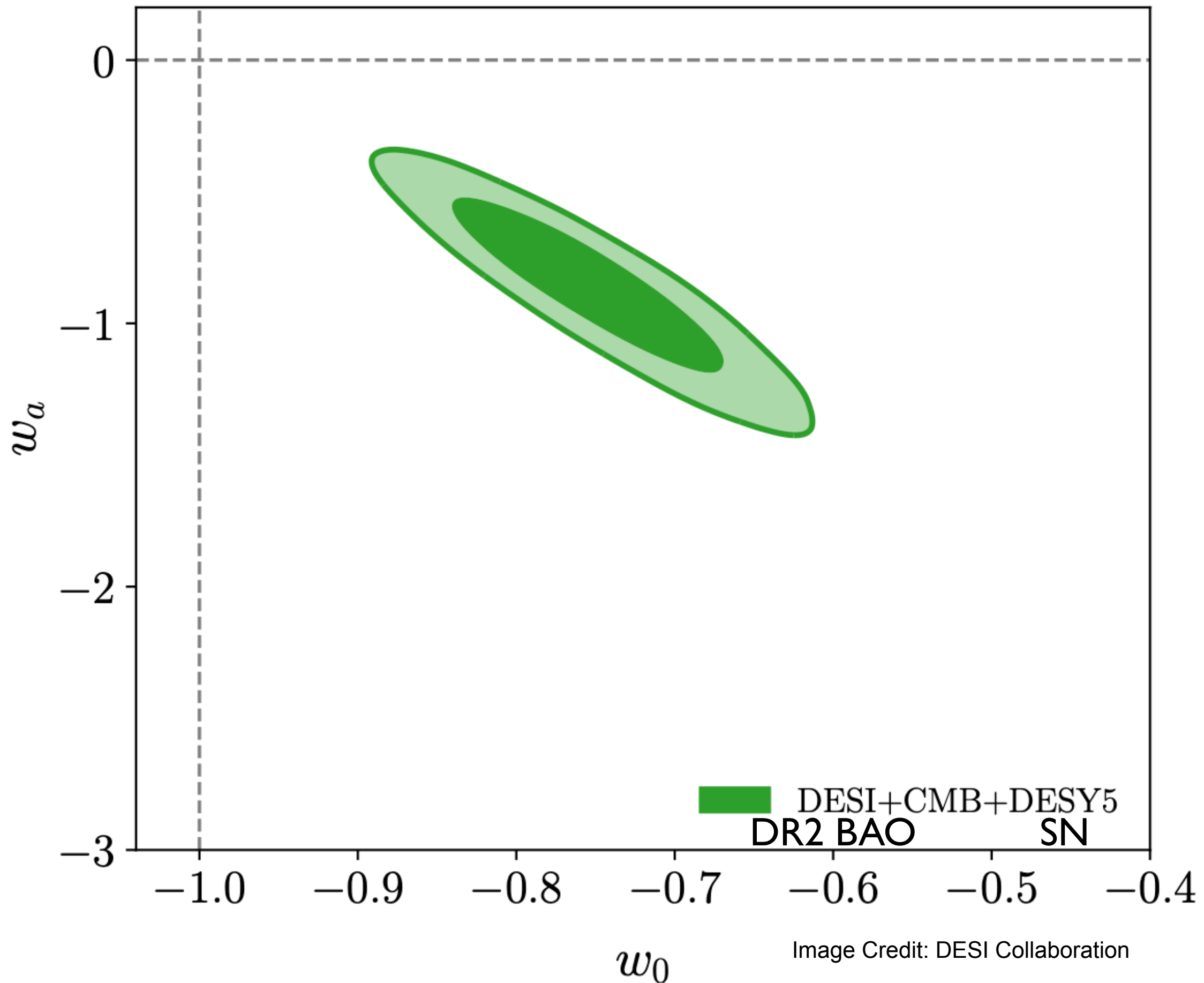
2.1



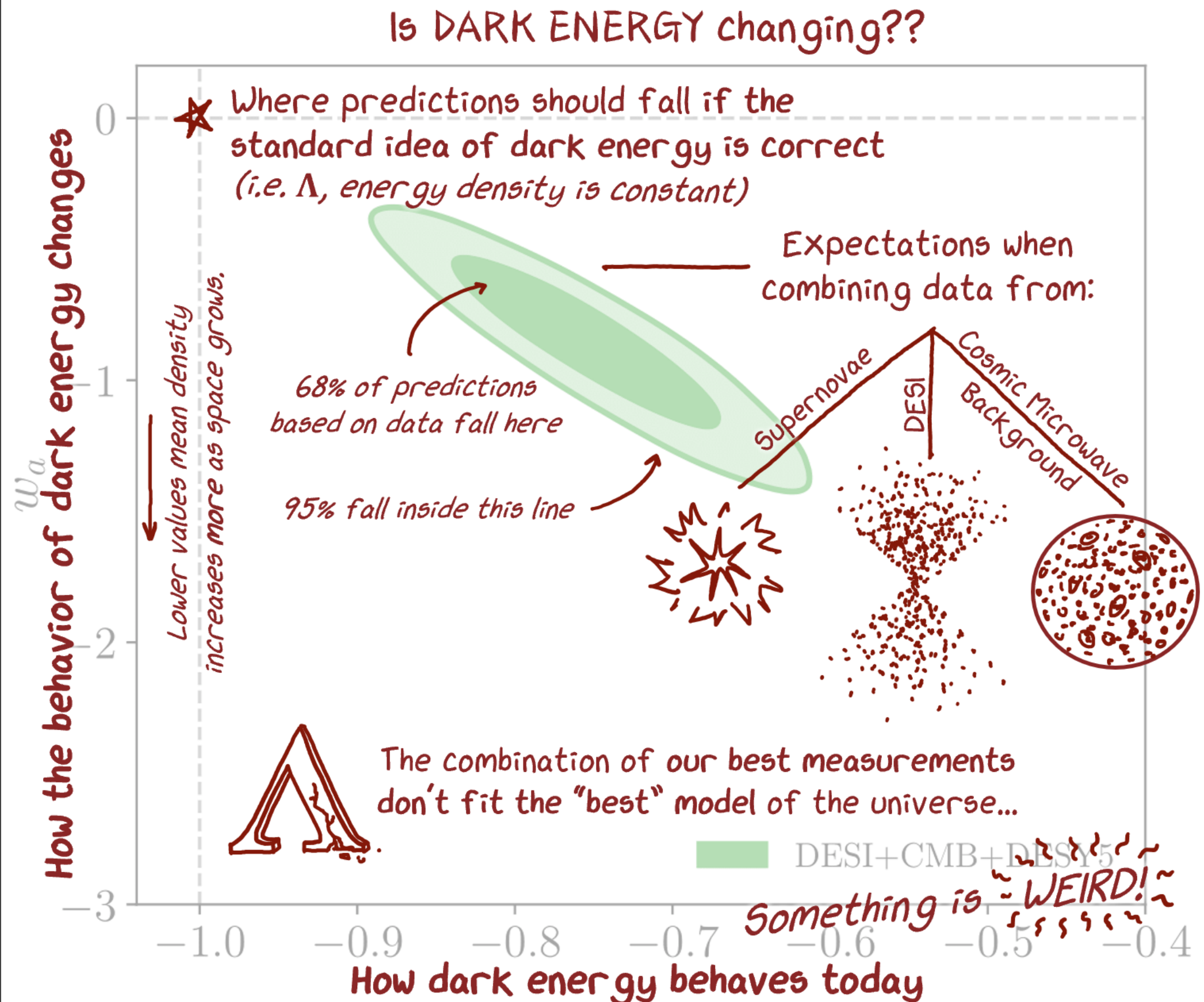
Visualization of DESI structure by Claire Lamman



DESI: DR2 Dark Energy Results

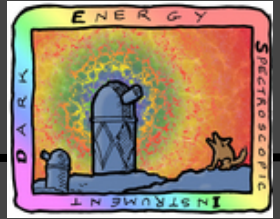


DESI: Dark Energy Results





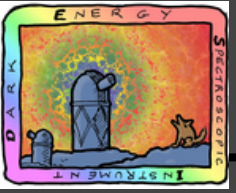
DESI at Ohio State



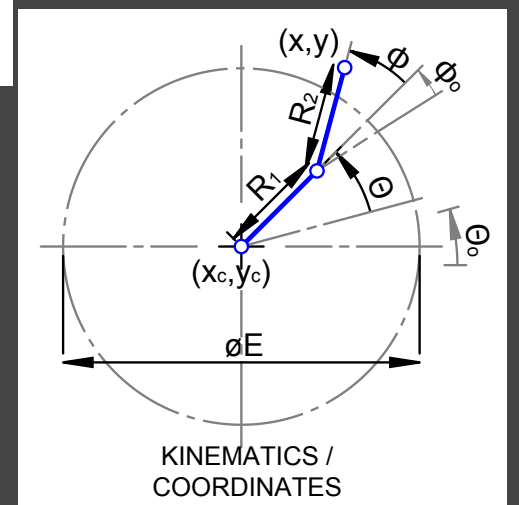
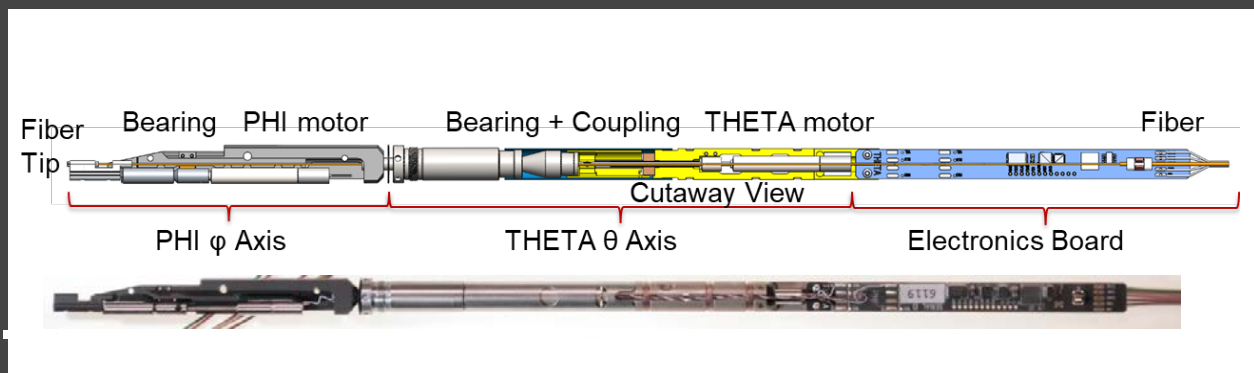
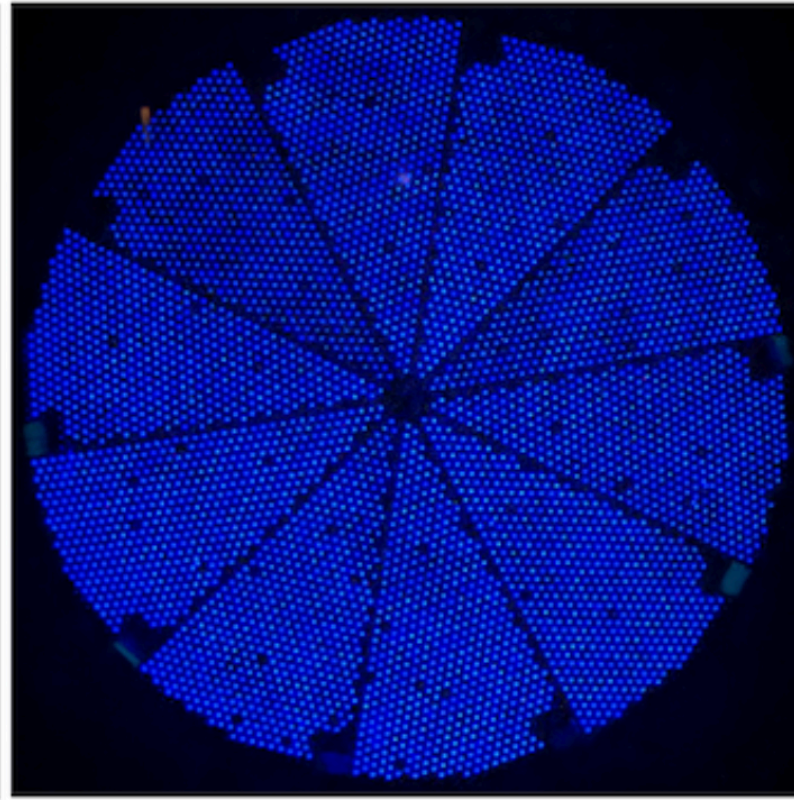
- Brandon Abrego, Matthew Berno, Mikel Charles, Carl Coker, Rebecca Coles, Andrei Cuceu*, Xinyi Chen, Mark Derwent*, Ann Elliott*, Jack Elvin-Poole, Lauren Ennesser, Kevin Fanning*, Simon Filbert, Anning Gao, Nicole Gountanis, Meagan Herbold, Klaus Honscheid*, Jennifer Johnson, Naim Karaçayli, Hui Kong, Claire Lamman*, Camila Martinez, Paul Martini*, Thomas O'Brien, Daniel Pappalardo*, Richard Pogge, Anna Porredon, Mehdi Rezaie*, Ashley Ross*, Charuhas Shiveshwarkar, Jon Shover, Peter Taylor, Suk Sien Tie*, Wyne Turner, David Weinberg, Molly Wolfson, Erik Zaborowski
- Huge effort to get DESI built and operating led by Paul Martini and Klaus Honscheid (former and current Instrument Scientists)



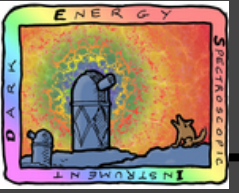
How?: 5000 Spectra at once



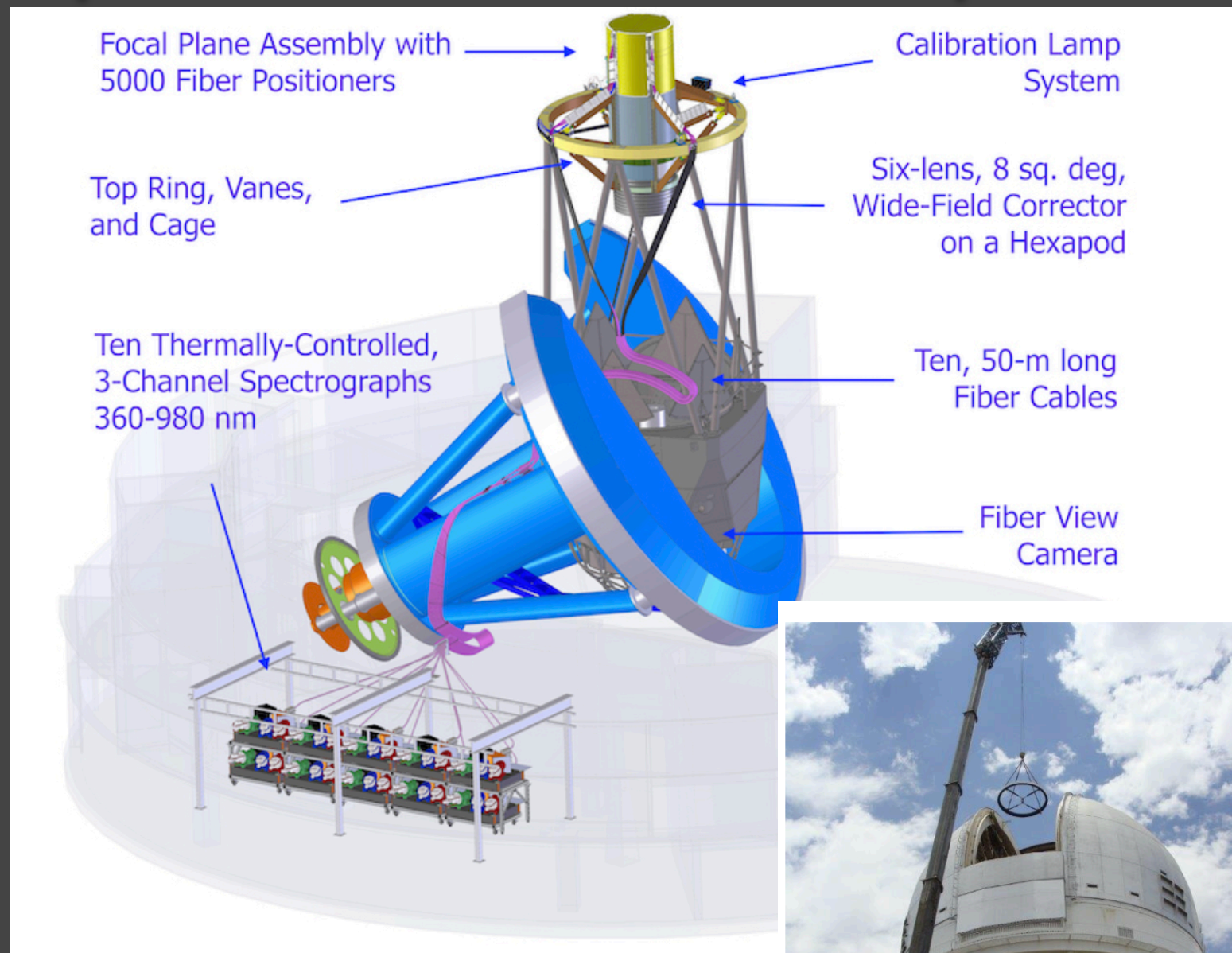
- Robotic positioners move fibers to few micron accuracy so it aligns with targets' sky position (thanks K. Fanning!)
- 10 “petals” each with corresponding spectrograph



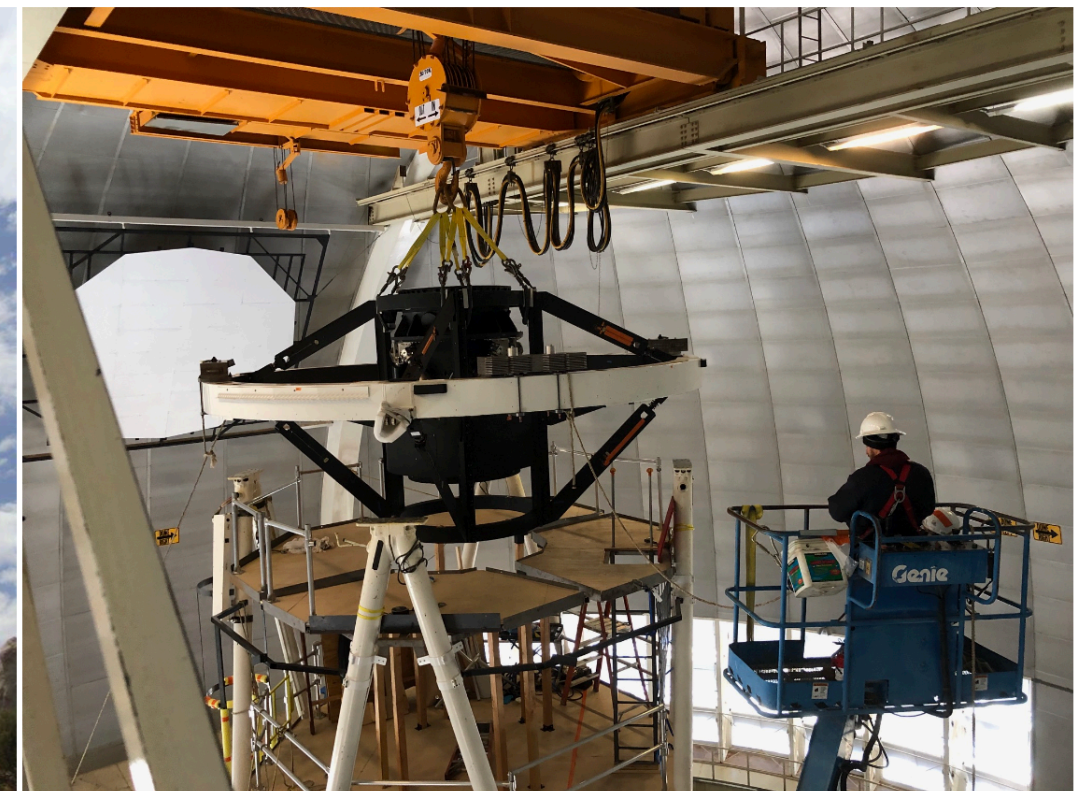
How?: 5000 Spectra at once



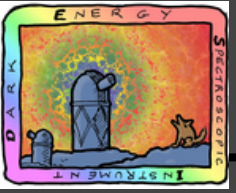
- Entire 4-meter Mayall Telescope at Kitt Peak AZ optimized for best DESI performance



Because of design and care, performance matches that of 10 m Keck (per spectrum!)

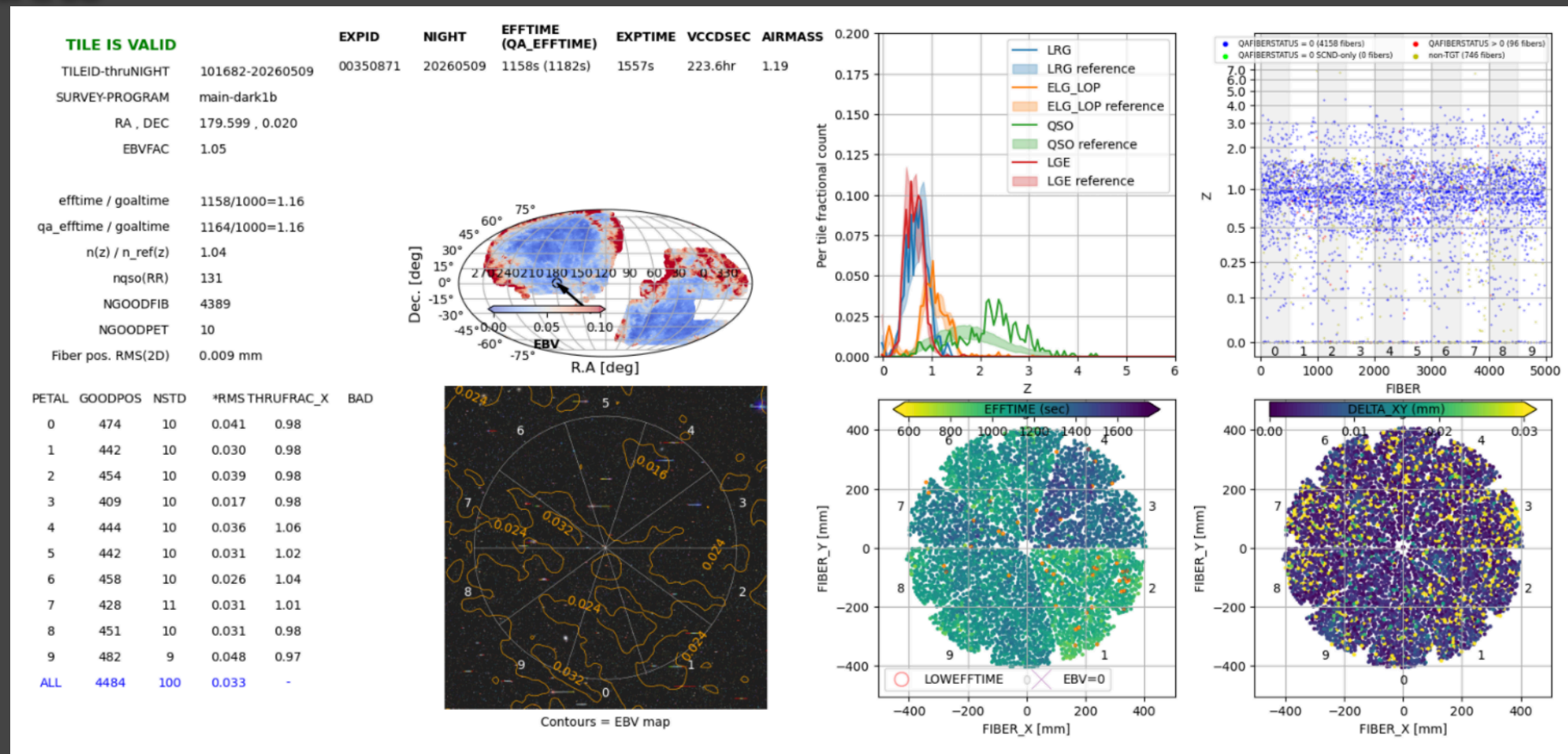


How?: Efficient Operations

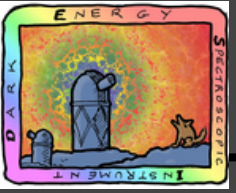


- DESI Operations includes:
 - Instrument (A. Elliott, K. Honscheid, P. Martini)
 - Survey (X. Chen, A. Ross)
 - Data Management
 - Analysis Infrastructure (LSS catalogs + sims; H. Kong, M. Rezaie, X. Chen, A. Ross; link to the Key Projects)
- Tight link between these four quickly provides high-confidence science-ready data products

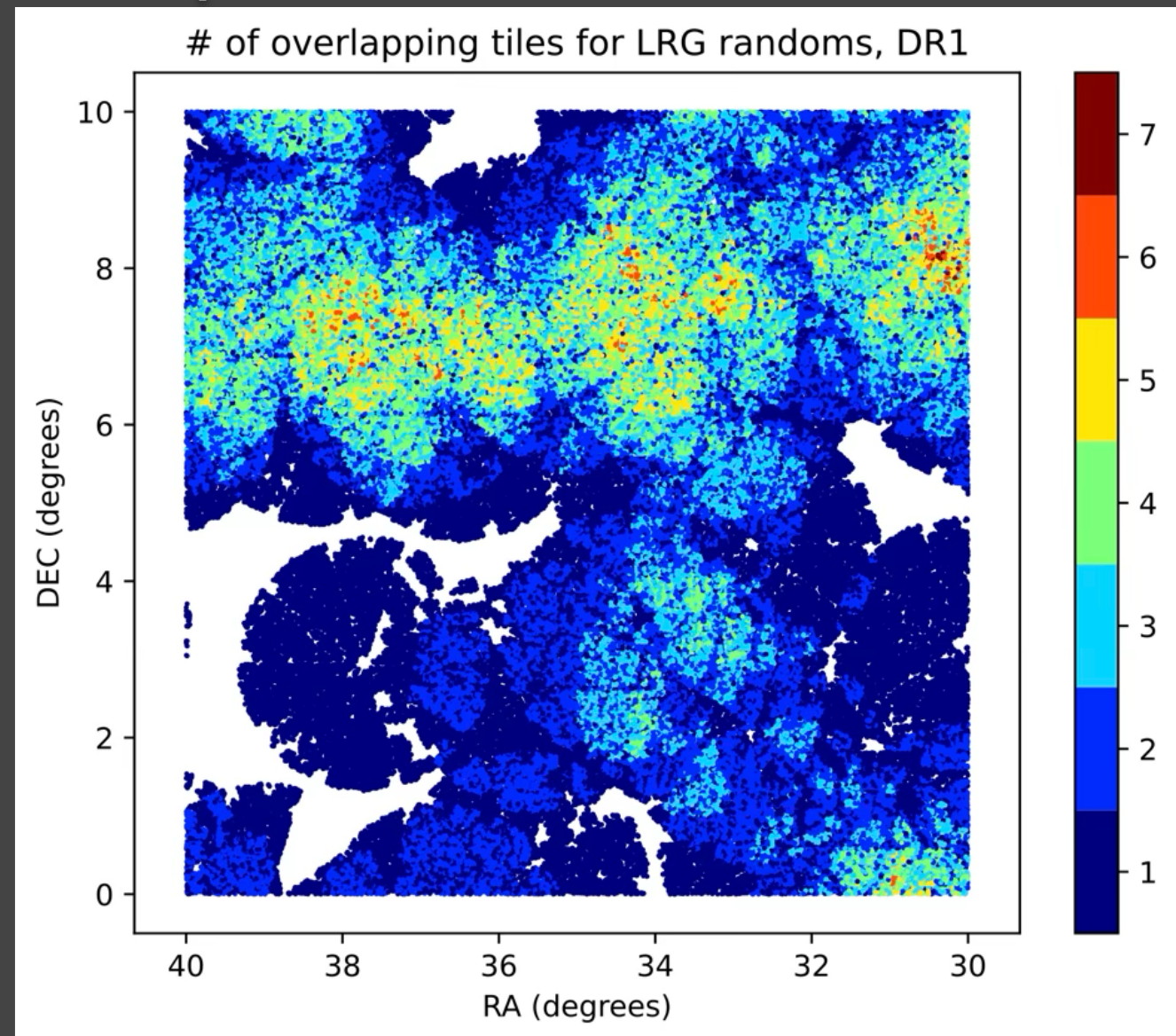
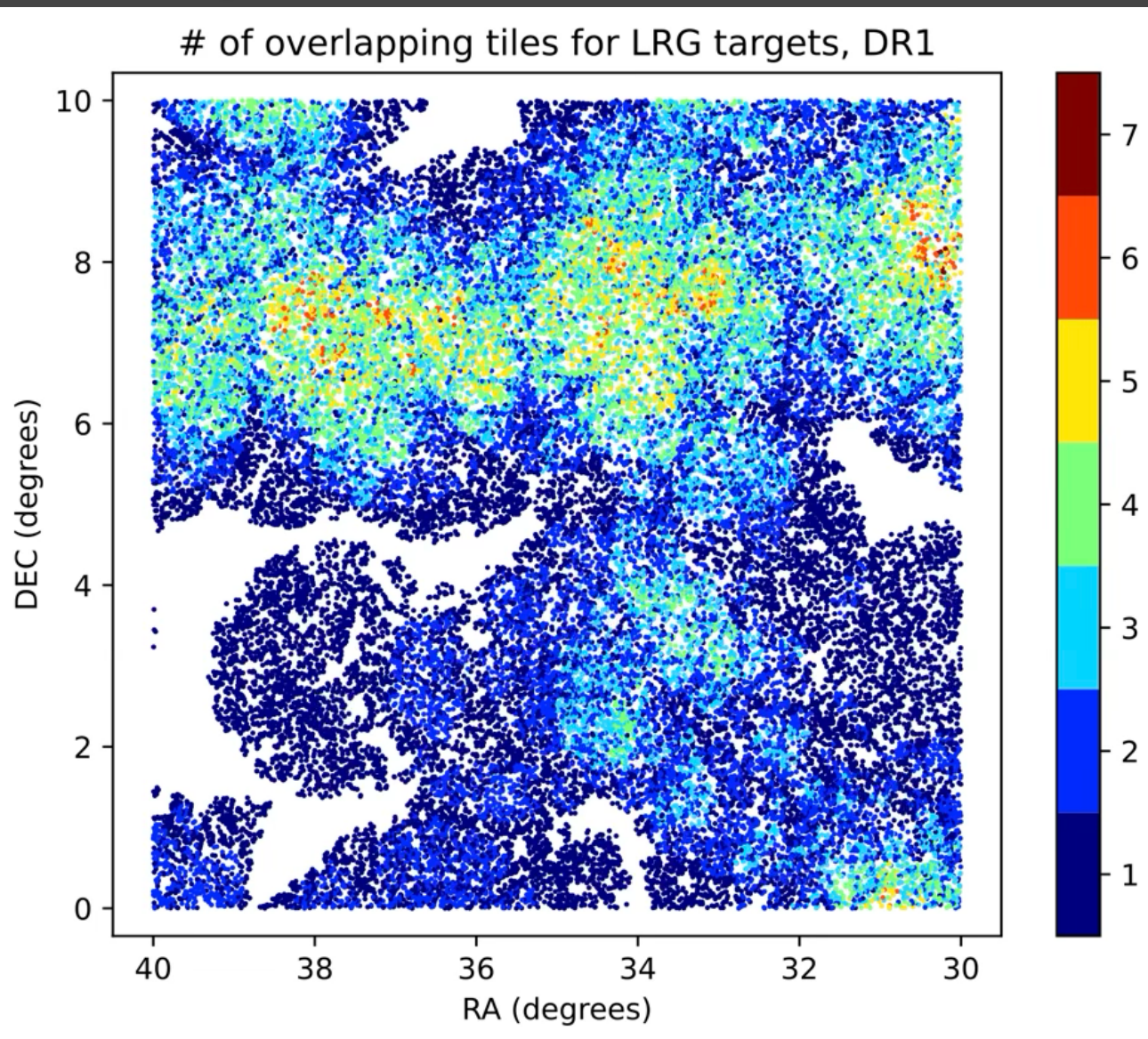
Members of
survey ops team
take weekly
shifts to perform
daily QA



LSS catalogs



- Nutshell: Predict the number density of galaxies as a function of 3D position (e.g., via unclustered “randoms”)
- Provides a reference to measure clustering
- Needs to account for variations in input targets (i.e., “imaging systematics”), instrument performance, survey completeness, etc.
- And, we need to be able to simulate the process



How?: Robust Analysis Pipeline

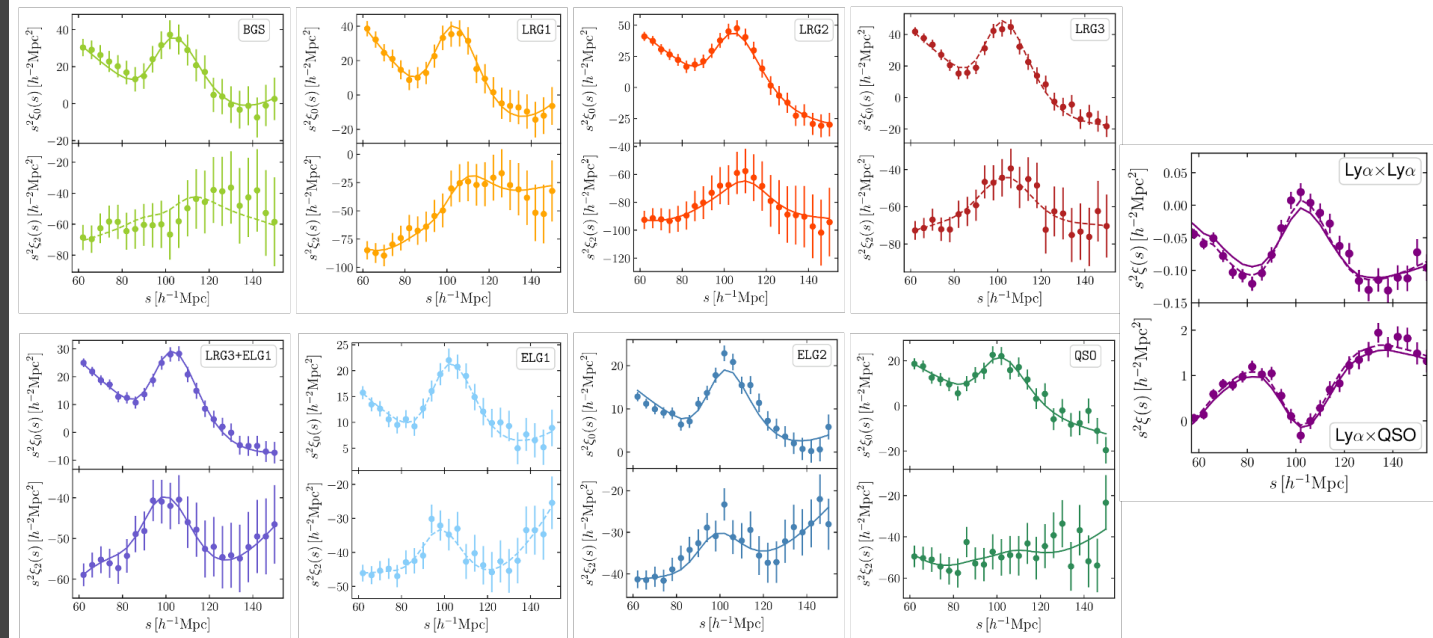
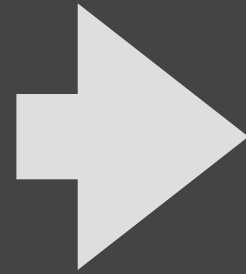
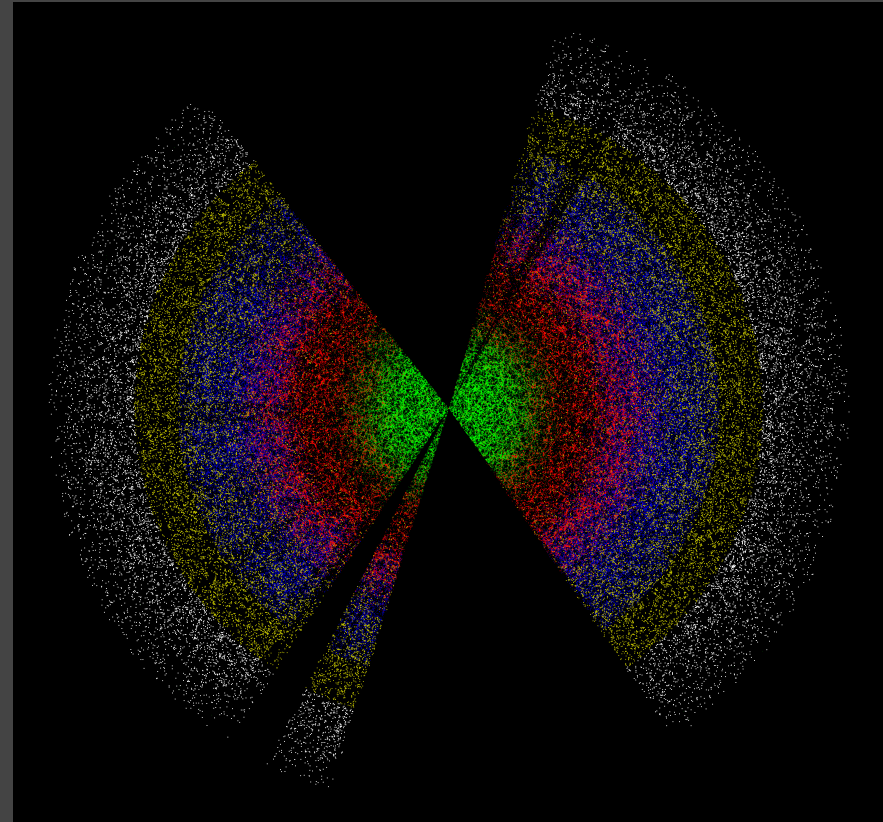
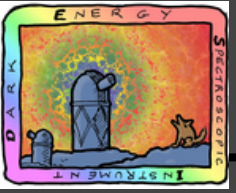
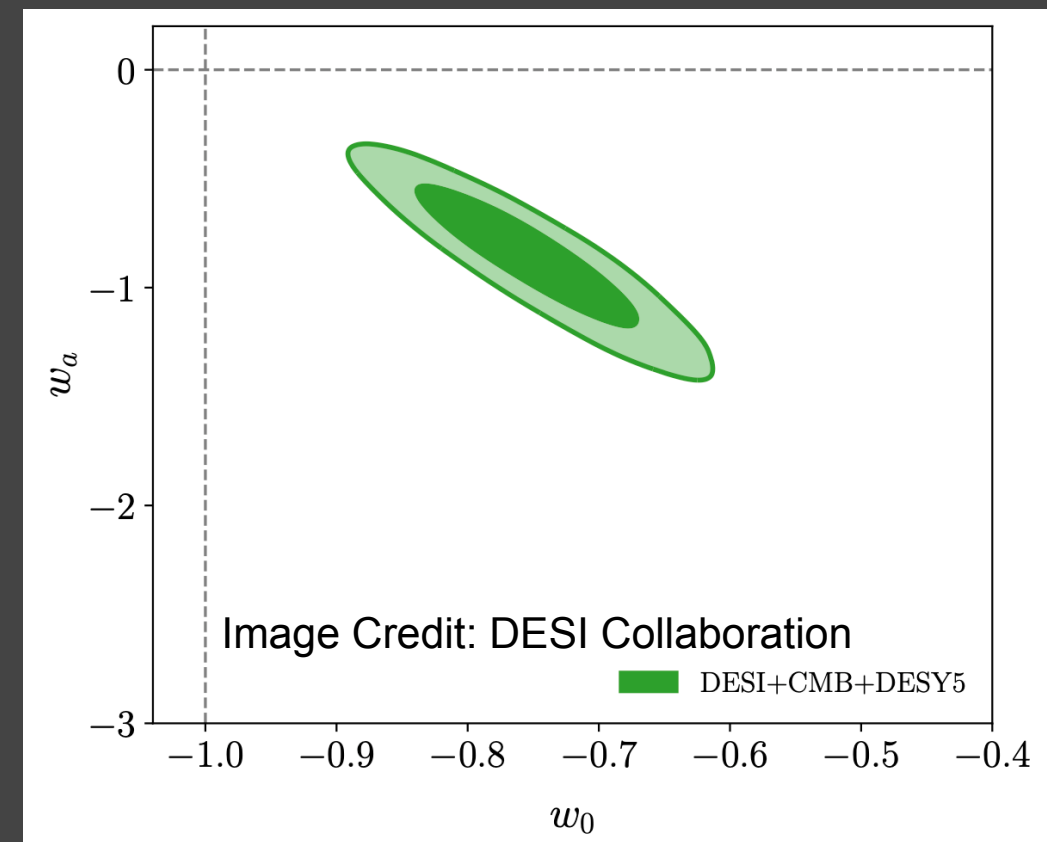
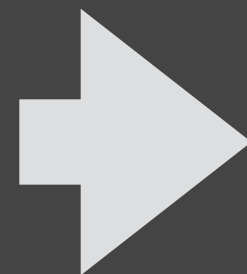
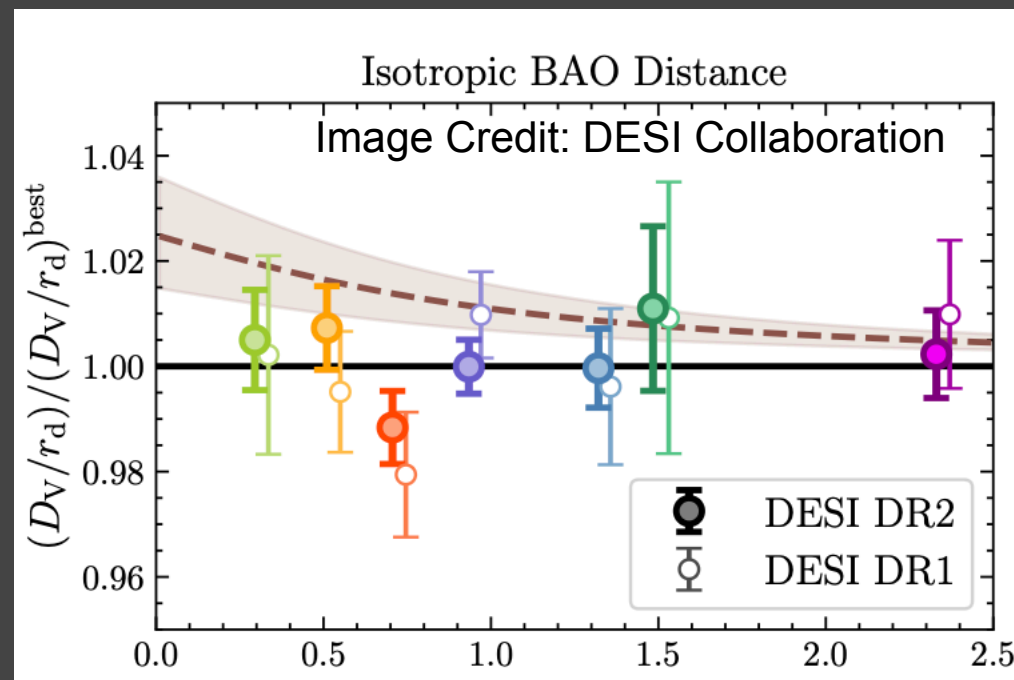
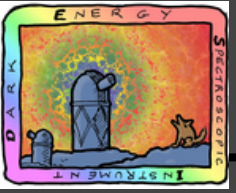


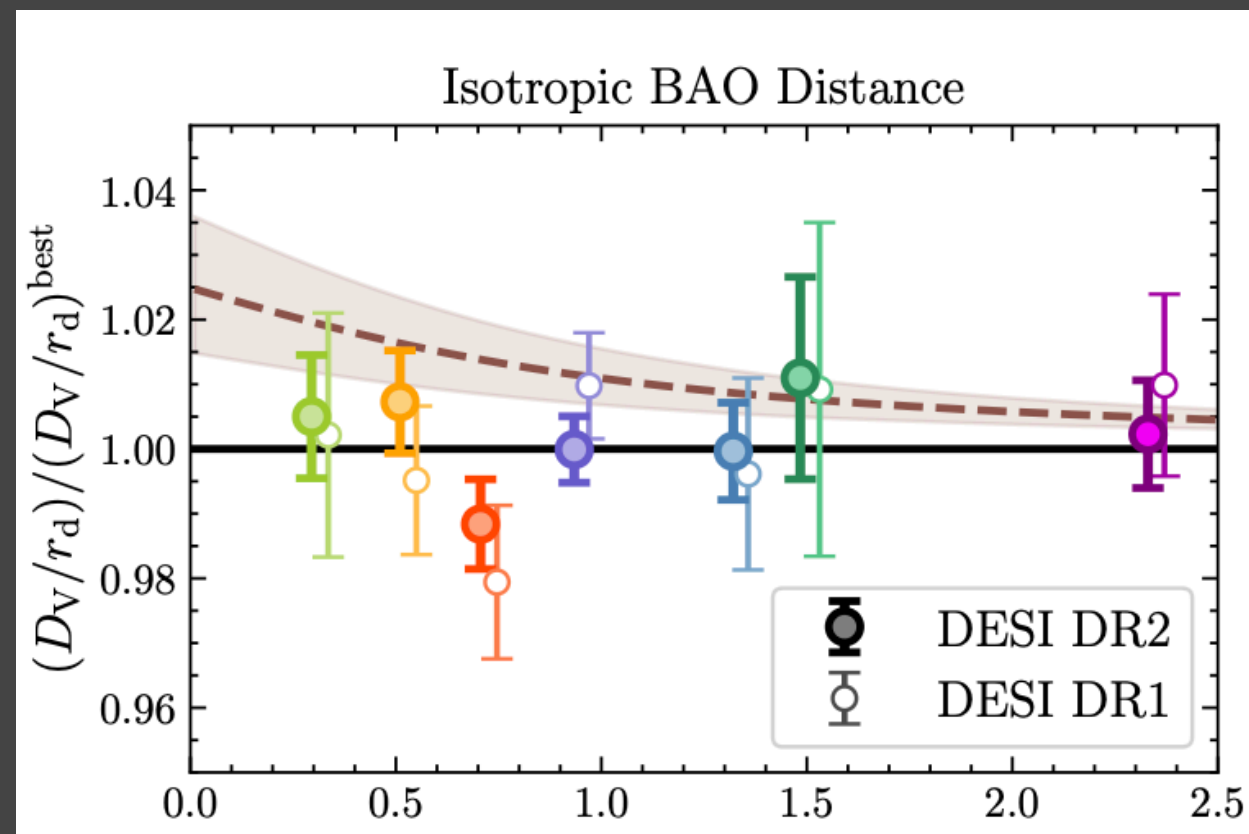
Image Credit: DESI Collaboration



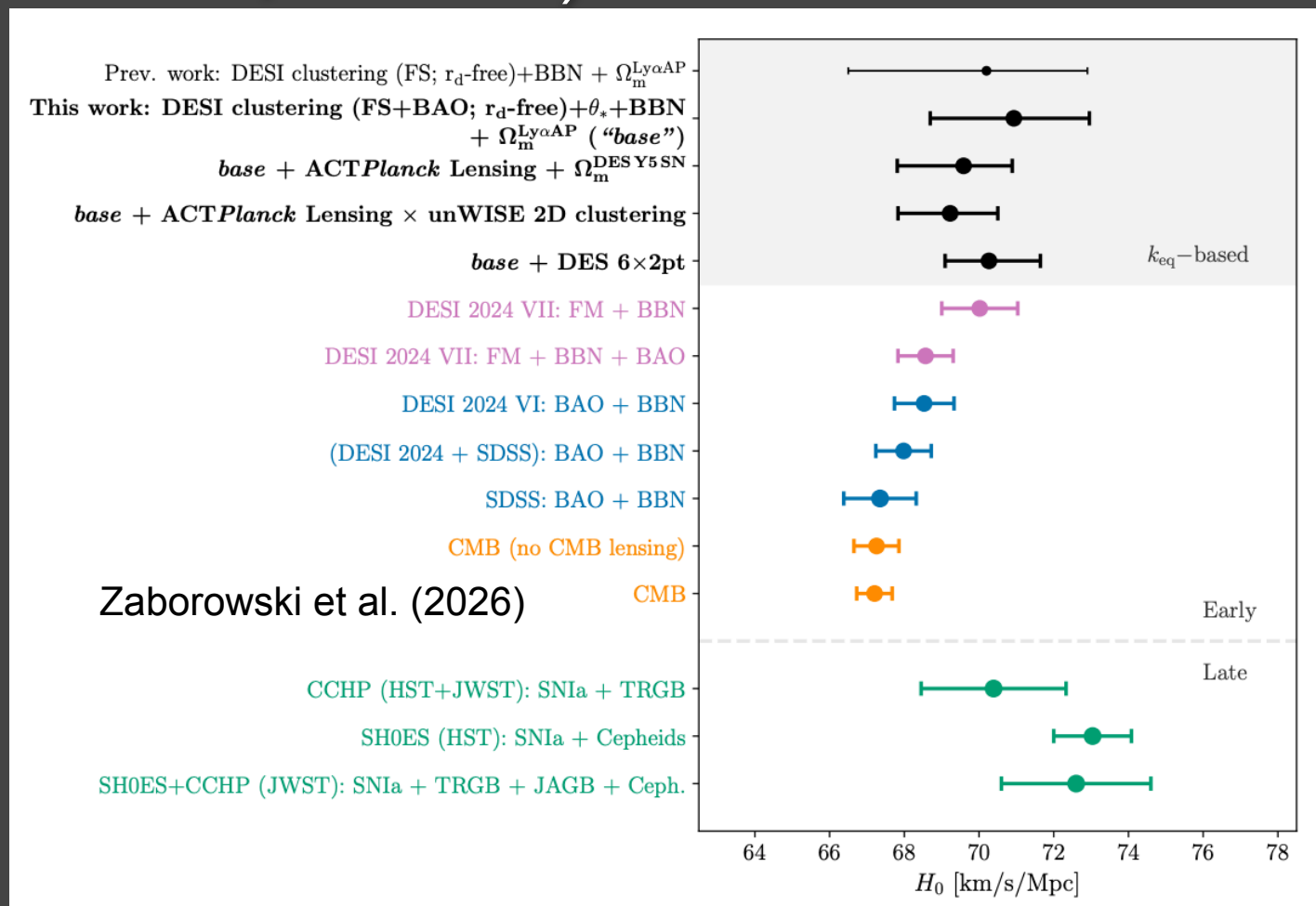
How?: Robust Analysis Pipeline



- 1 year from DR1 to DR2 Dark Energy results
- Required a validated process set by DR1 (led by H. Seo)
- Including:
 - Extensive checks on BAO reconstruction methods (X. Chen)
 - Production and thorough validation of semi-analytical covariance matrices (M. Rashkovetskyi)
 - An excellent Lyman- α group (see Andrei's talk)
- +Great work on the interpretation from D. Weinberg (+thanks for BGS!)



- H_0 measurements led by E. Zaborowski and P. Taylor
- Intrinsic alignment measurements/impact from C. Lamman
- Using more of the BGS sample info (C. Martinez, M. Rashkovetskyi)
- $\text{Ly}\alpha$ - QSO cross correlation using LSS (B. Abrego, N. Karaçaylı)
- DR2 “full-shape” (+CMB lensing, +WL A. Porredon) coming soon
- DR2 primordial non-Gaussianity analysis uncertainty will be ~ 6 on local f_{NL} (CMB is ~ 5 ; X. Chen)



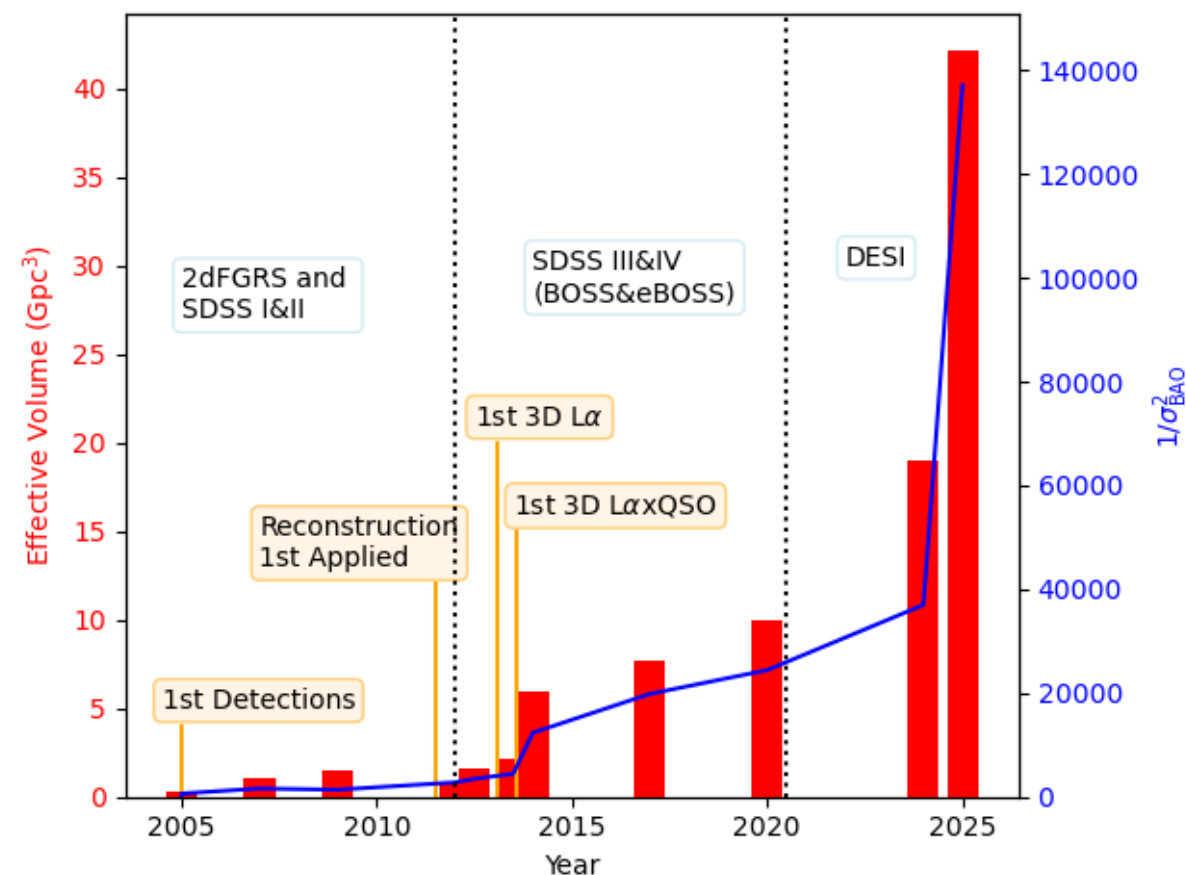
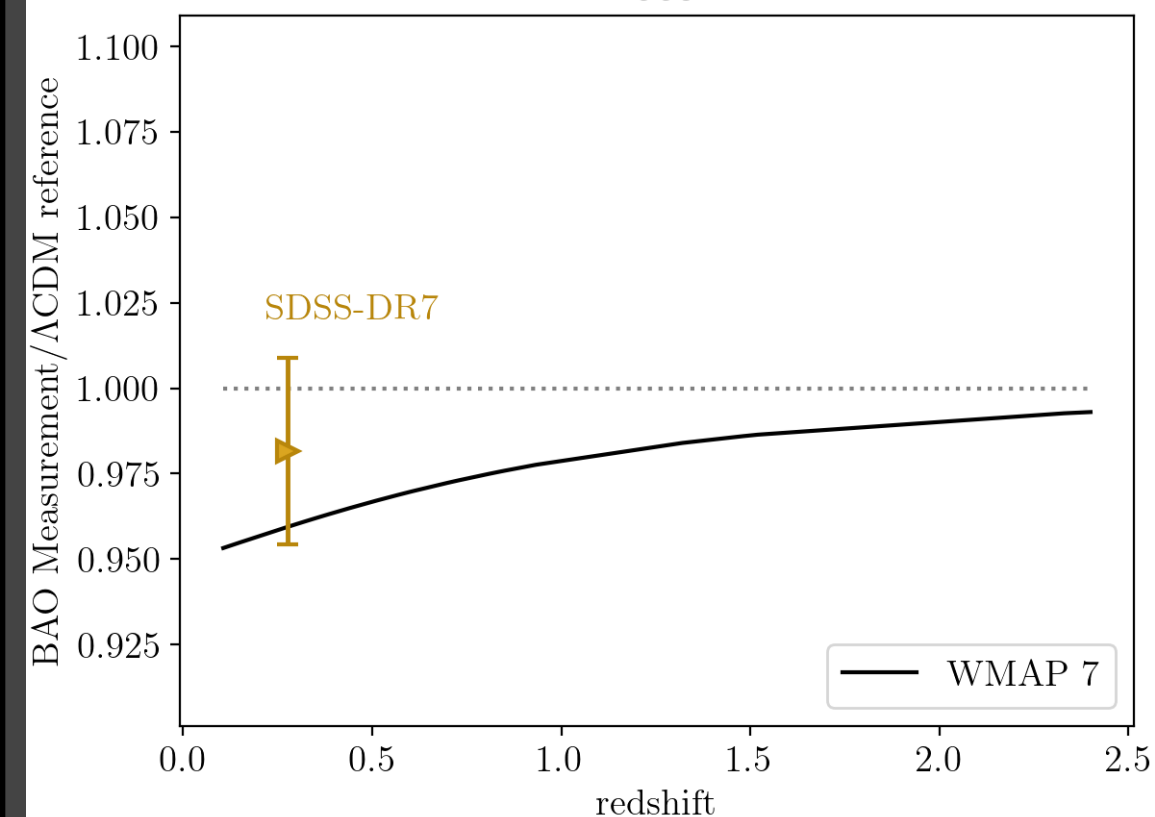
- H_0 measurements led by E. Zaborowski and P. Taylor
- IA measurements from multiplets from C. Lamman
- Using all of the BGS sample info (C. Martinez, M. Rashkovetskyi)
- $\text{Ly}\alpha$ - QSO cross correlation using LSS (B. Abrego, N. Karaçayli)
- DR2 “full-shape” (+CMB lensing, + WL A. Porredon) coming soon
- DR2 primordial non-Gaussianity analysis uncertainty will be ~ 6 on local f_{NL} (CMB is ~ 5 ; X. Chen)
- *Expect DR3 BAO Dark Energy constraints in summer 2027*

- CCAPP support (all manners) has been vital to my continued work on DESI
- Postdoc (2014) → Research Scientist (2018) → Research Faculty (2024)
- (Sorry no pictures, you probably got enough already)

Thank you!!!



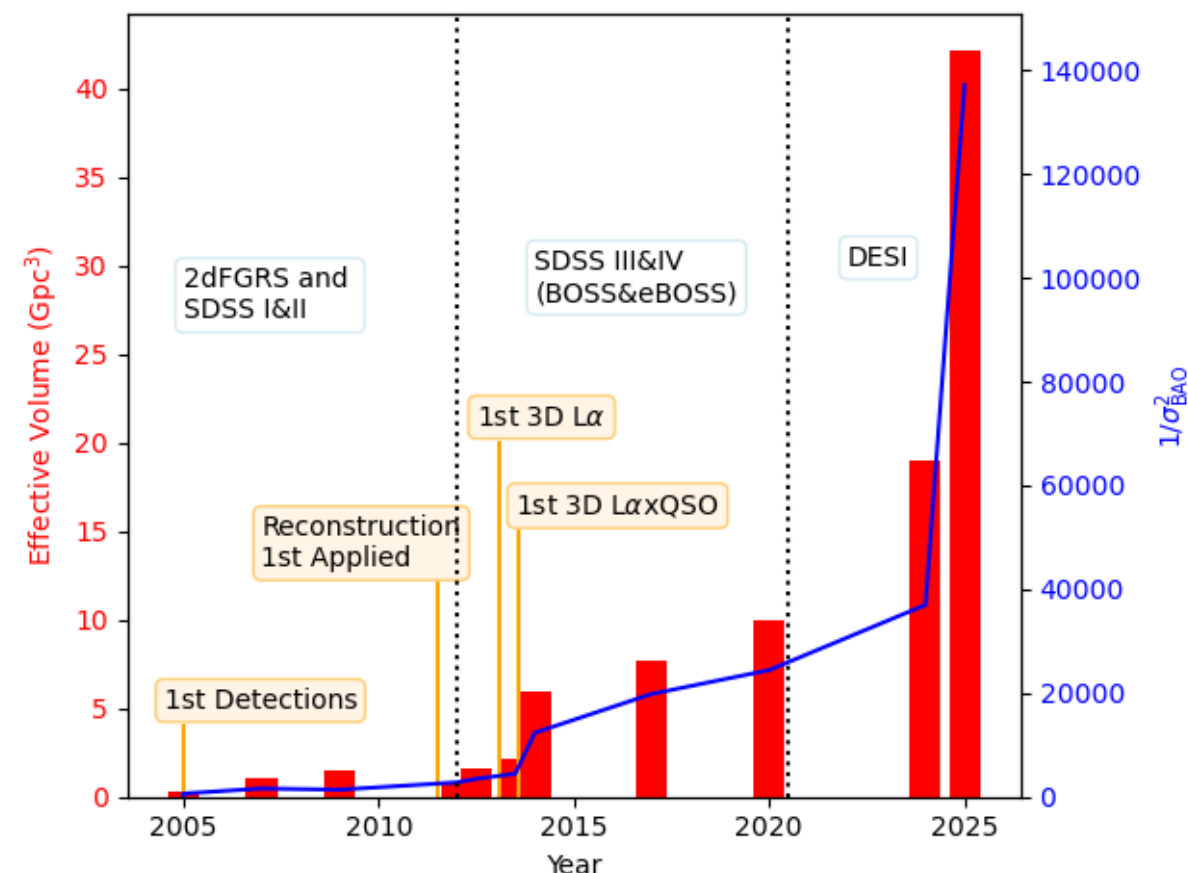
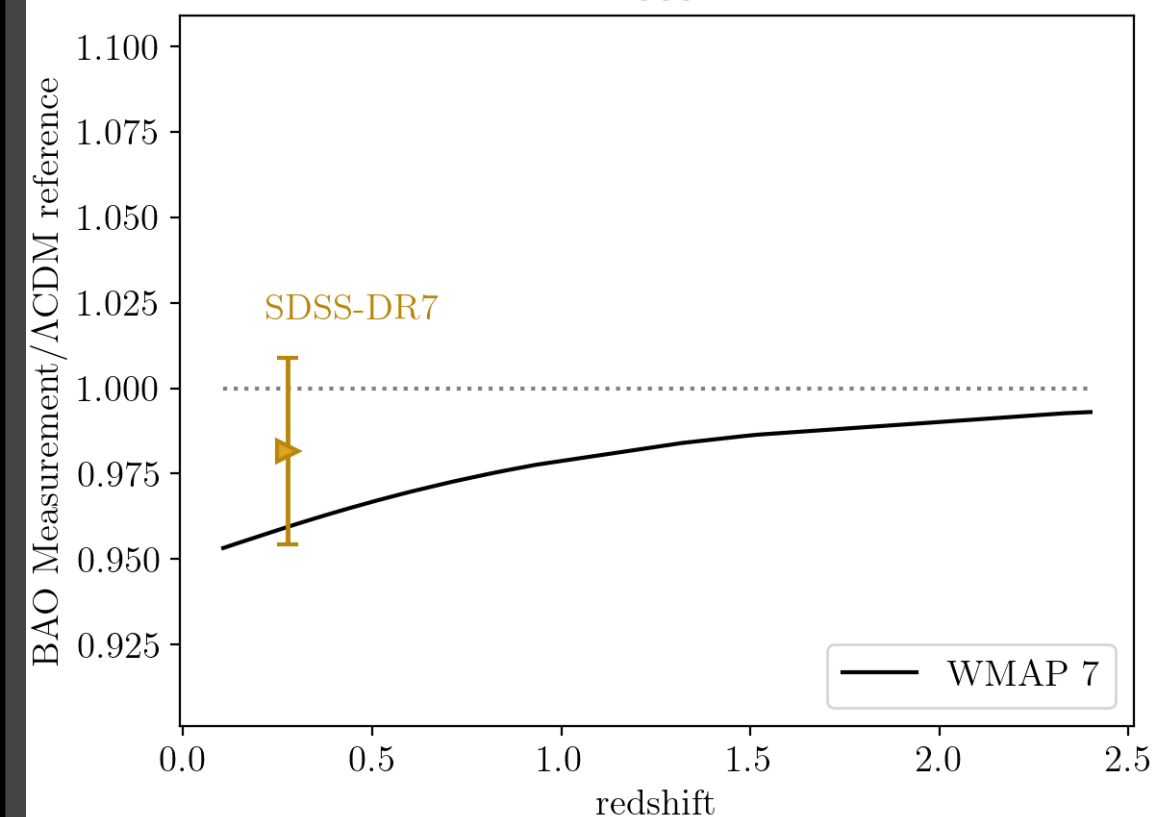
2009



Thank you!!!



2009



Thank you!!!



Cosmological Paradigm

- Cosmological principle:
 - On large-scales Universe is statistically isotropic and homogeneous
- General Relativity: space expands
 - “scale factor” a : 1 today; ~ 0 at $t=0$ (“big bang”); photons are redshifted by $z = 1/a - 1$
 - $H = \frac{\dot{a}}{a}$; $\Omega_x = \frac{\rho_x}{\rho_{\text{crit}}}$
- Friedmann equation for expansion:
$$\left(\frac{H}{H_0}\right)^2 = \underbrace{\Omega_{0,R}a^{-4}}_{\text{radiation}} + \underbrace{\Omega_{0,M}a^{-3}}_{\text{matter}} + \underbrace{\Omega_{0,k}a^{-2}}_{\text{curvature}} + \underbrace{\Omega_{0,\Lambda}}_{\text{cosmological constant}}$$
- Put everything together $d_{\text{comoving}}(z) = \int_0^z \frac{cdz'}{H(z')}$

Outline

- What? (10x larger 3D maps of the structure of the Universe)
- Why? (Dark Energy++)
- How? (5000 robots on a 4-meter telescope)
- When? (Now!)
- Where? (Kitt Peak AZ, here at Ohio State)
- What next? (Fill the remaining volume, > 10x to go)

Why?

- The statistics that characterize the maps we observe are predictable with basic physics
 - Initial conditions (inflation?) + components (matter, energy, radiation) + geometry + model for gravity
 - Early (1977-1990s): LSS maps showed dark matter must be cold in order to form observed structure (ruled out neutrinos)
 - Later (SDSS up to 2020): LSS maps confirmed need for Dark Energy and formed a pillar of “concordance” cosmological constant + cold dark matter (LCDM) cosmology
 - Now (DESI): Is Dark Energy consistent with cosmological constant? What are the statistics of initial conditions? Do structure growth measurements agree with concordance model?
- Each galaxy we measure the position for acts like a “test particle” in the large-scale matter field and its evolution

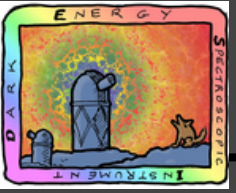
Dark Energy

- What drives the accelerated expansion of the Universe accounting for $\sim 70\%$ of its matter/energy density?

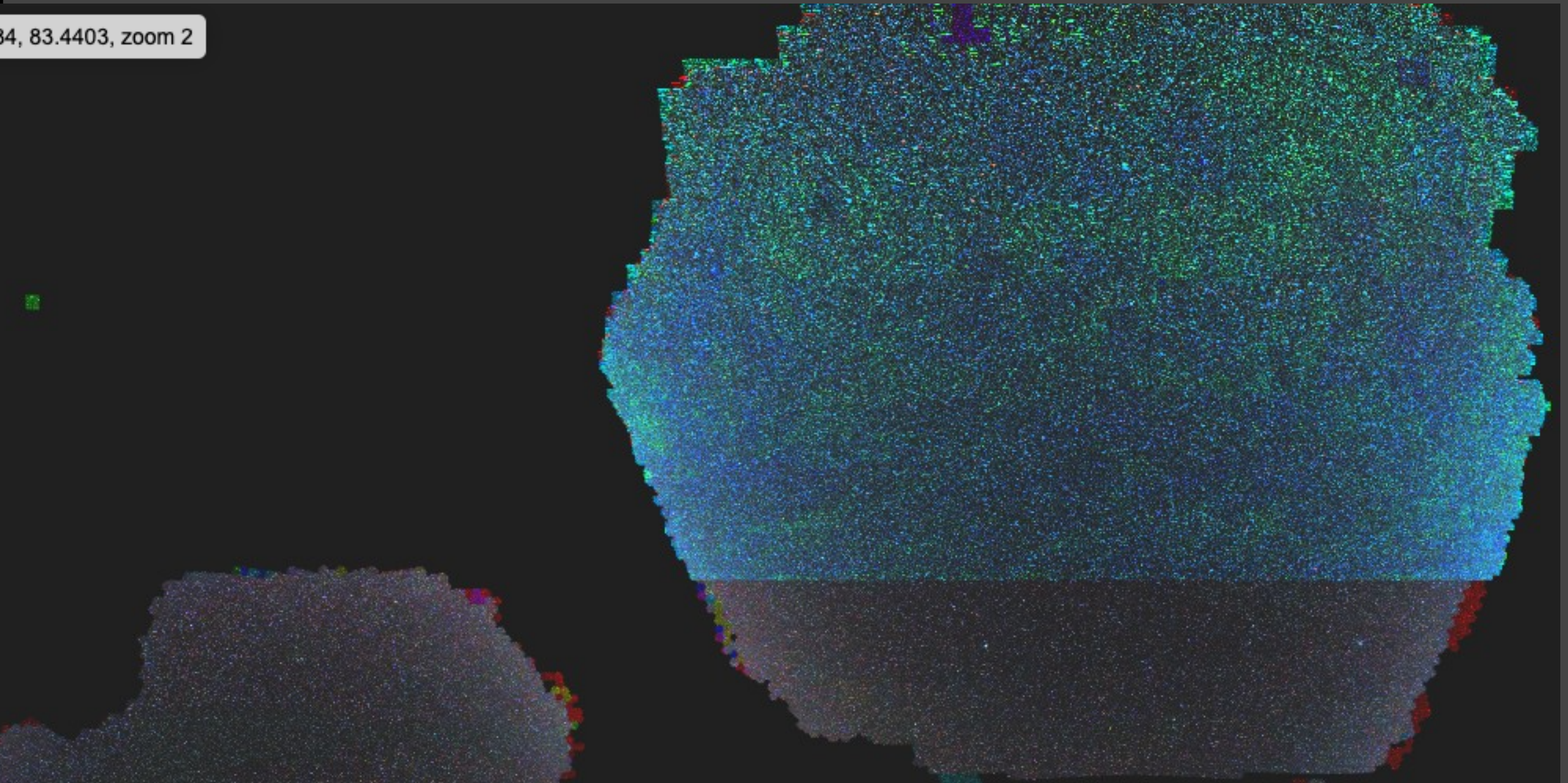
Or, put differently

- Do Einstein's GR equations really include a “cosmological constant”?
 - (Ask Chris Hirata to explain disturbing consequences)
- Typically test by measuring DE equation of state ($P/\rho = -1$ for cosmological constant) and its time evolution

How?: Building the Map

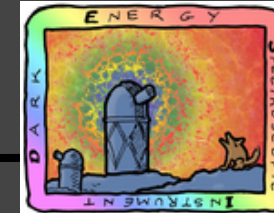


- “Targets” are selected via their flux and color in imaging data from the DESI Legacy Imaging Surveys

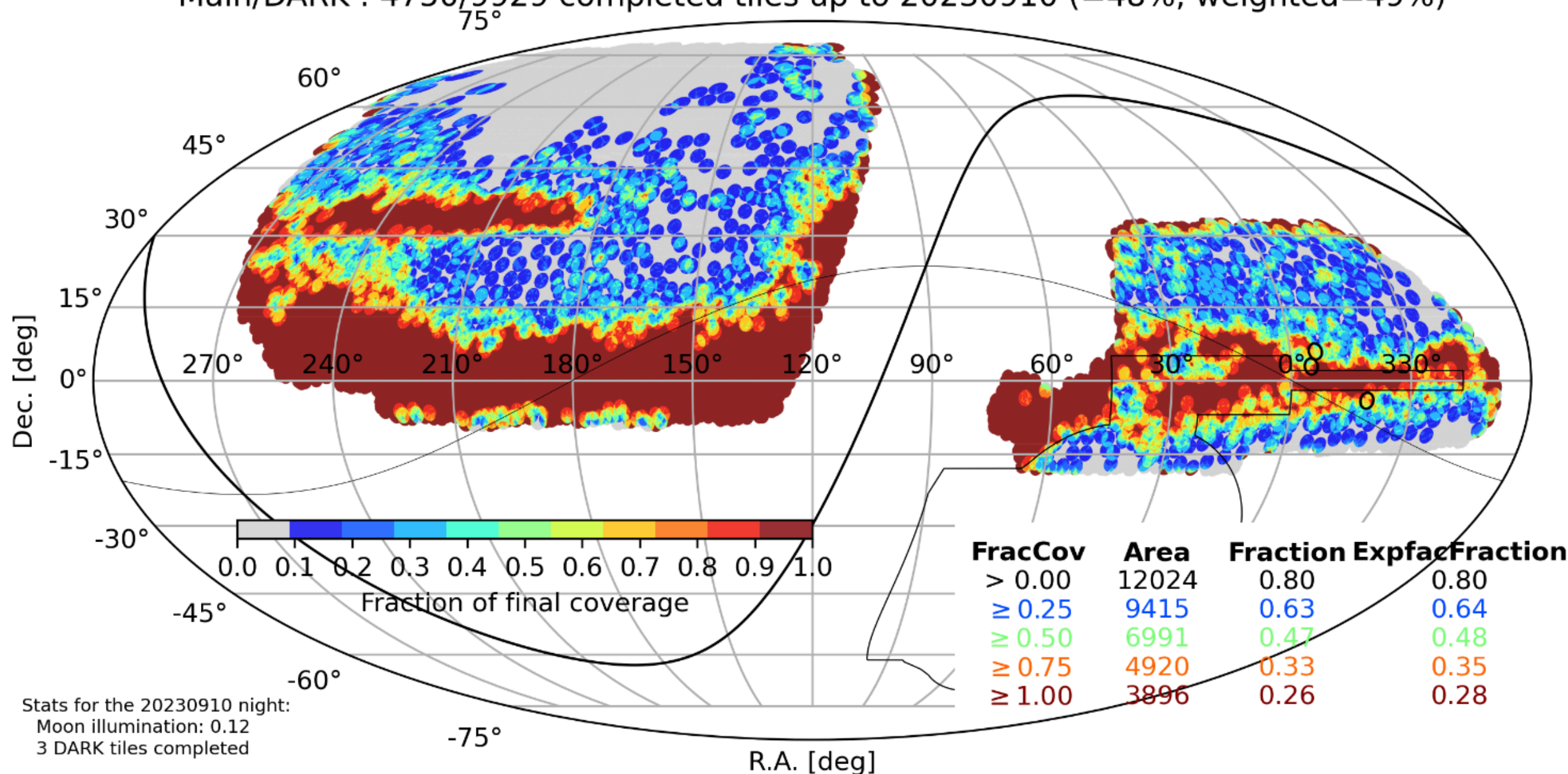


<https://www.legacysurvey.org/viewer>

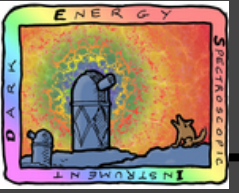
DESI Sky Coverage



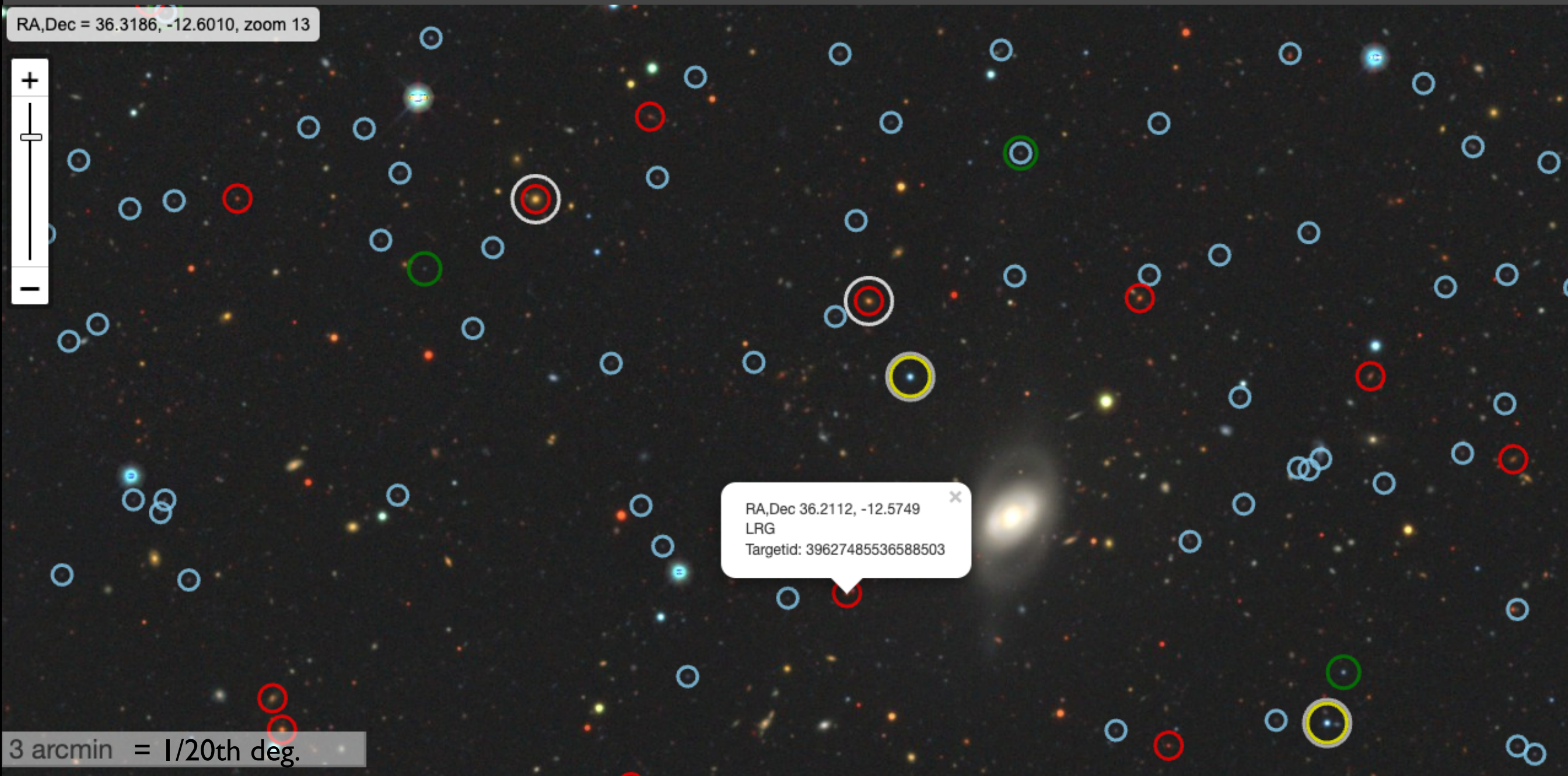
Main/DARK : 4750/9929 completed tiles up to 20230910 (=48%, weighted=49%)



How?: Building the Map

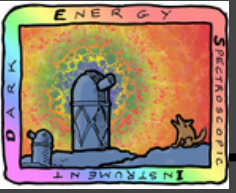


- “Targets” are selected via their flux and color in imaging data from the DESI Legacy Imaging Surveys



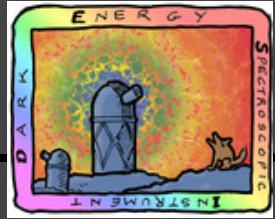
<https://www.legacysurvey.org/viewer>

How?: Building the Map

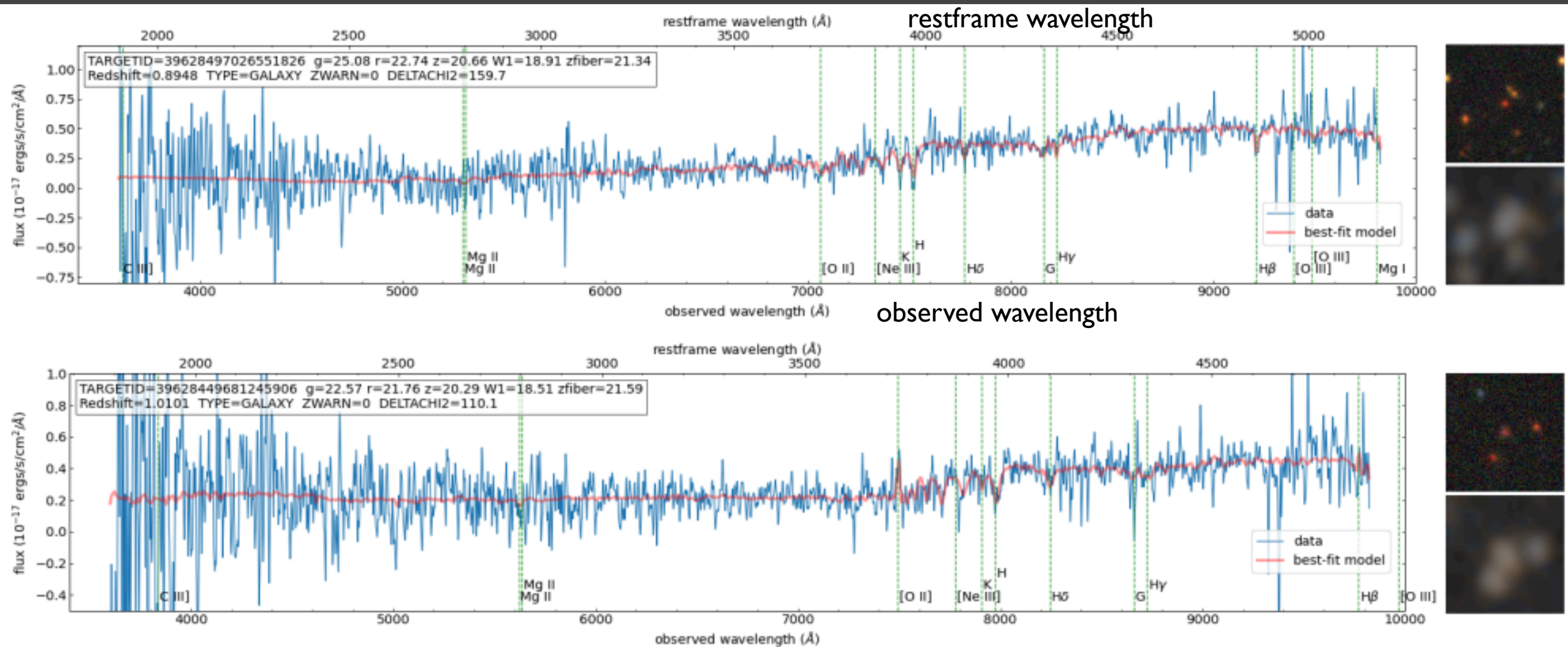


- “Targets” are selected via their flux and color in imaging data from the DESI Legacy Imaging Surveys
- For each target we measure a spectrum and from that a redshift
- Redshift interpreted as cosmological - due to the expansion of space between location and Earth - and converted to co-moving distance
 - +Sky position gives 3D spherical coordinates θ, ϕ, r

DESI LRG

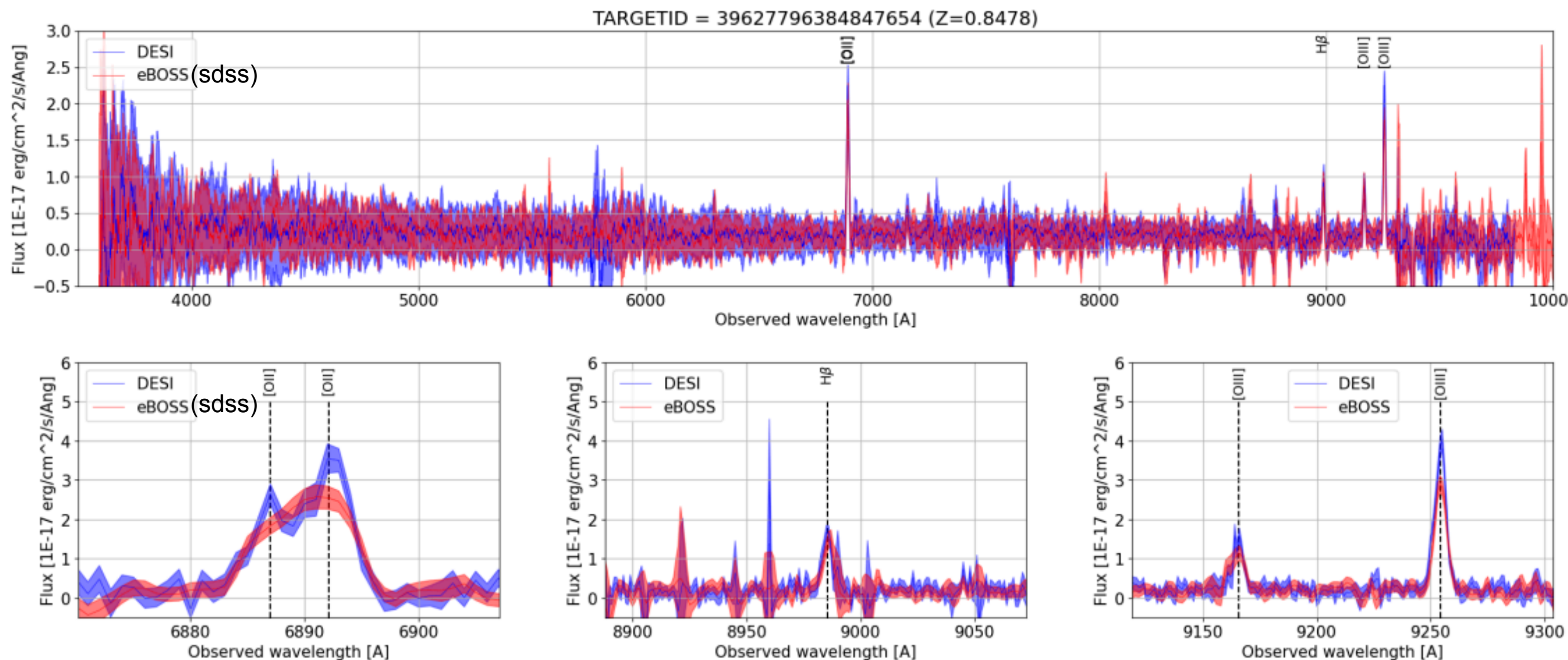


- Luminous red galaxies; large galaxies without recent star formation



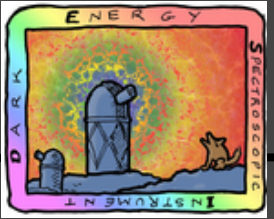
R. Zhou et al. (2022)

-

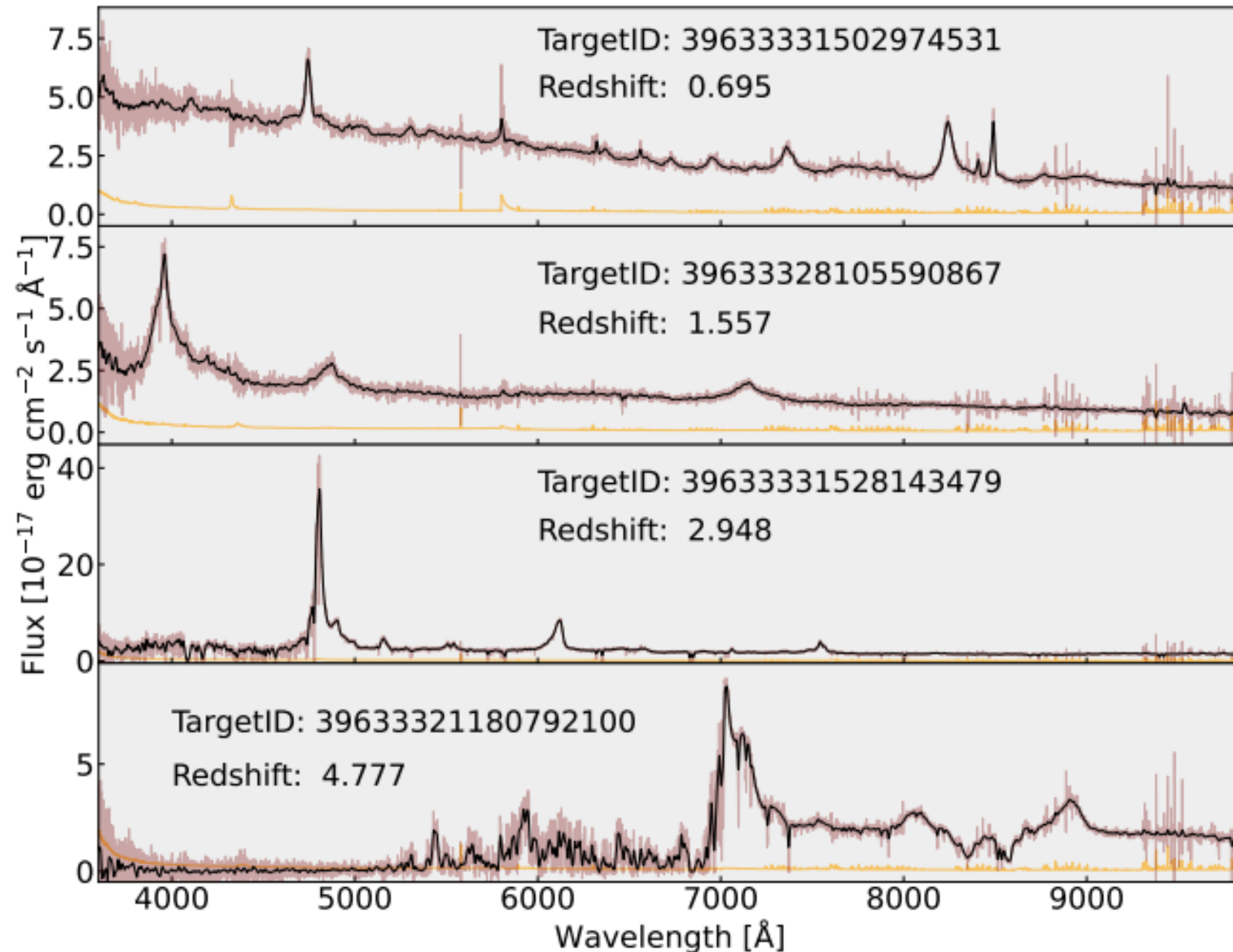


A. Raichoor et al. (2022)

DESI QSO



- Quasars; light emitted from activity around central super-massive black hole overwhelms rest of galaxy

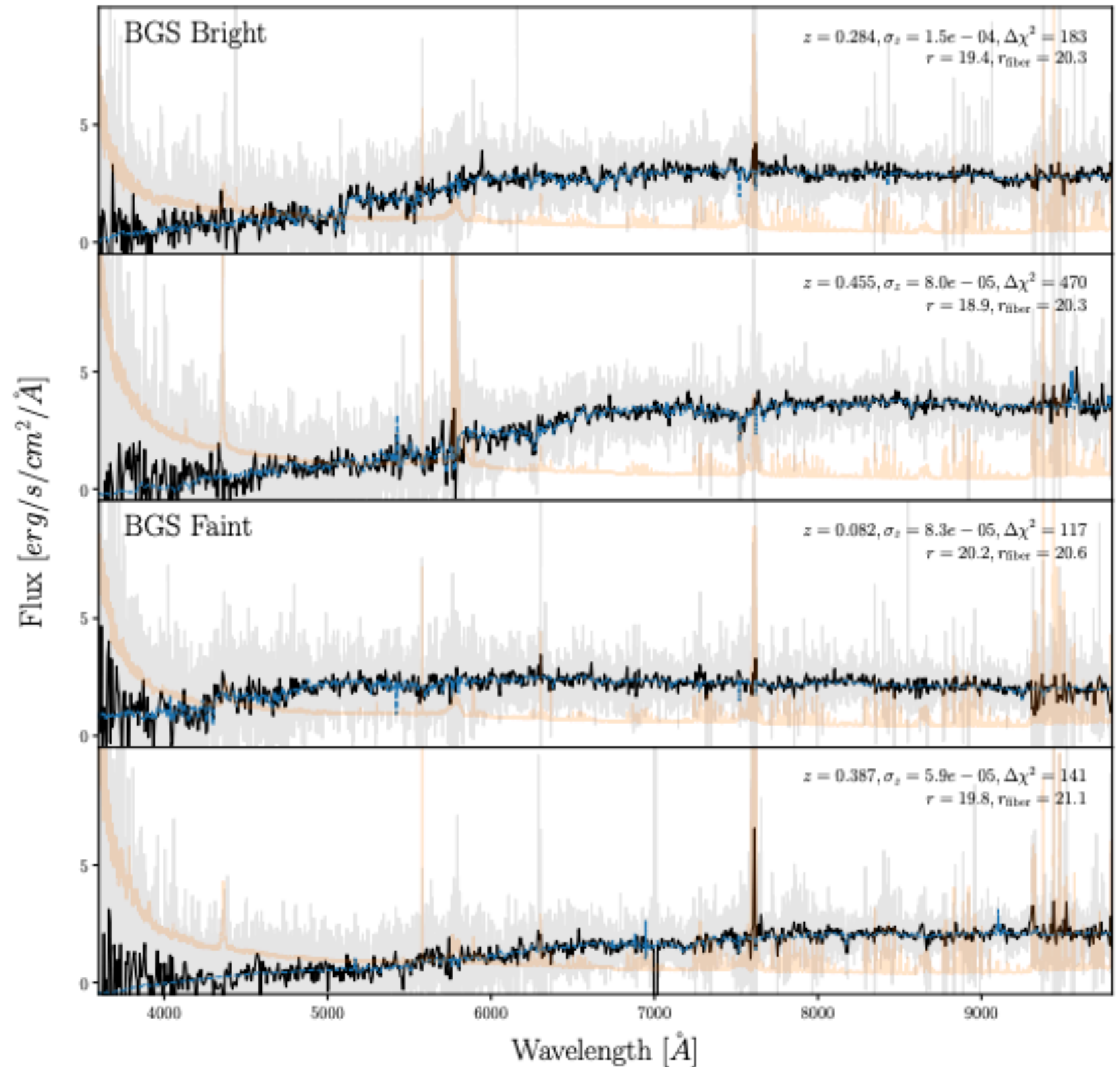


E. Chaussidon et al. (2022)

DESI BGS

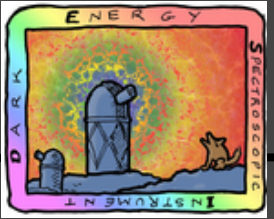


- Bright galaxy sample: Target everything up to some apparent flux limit



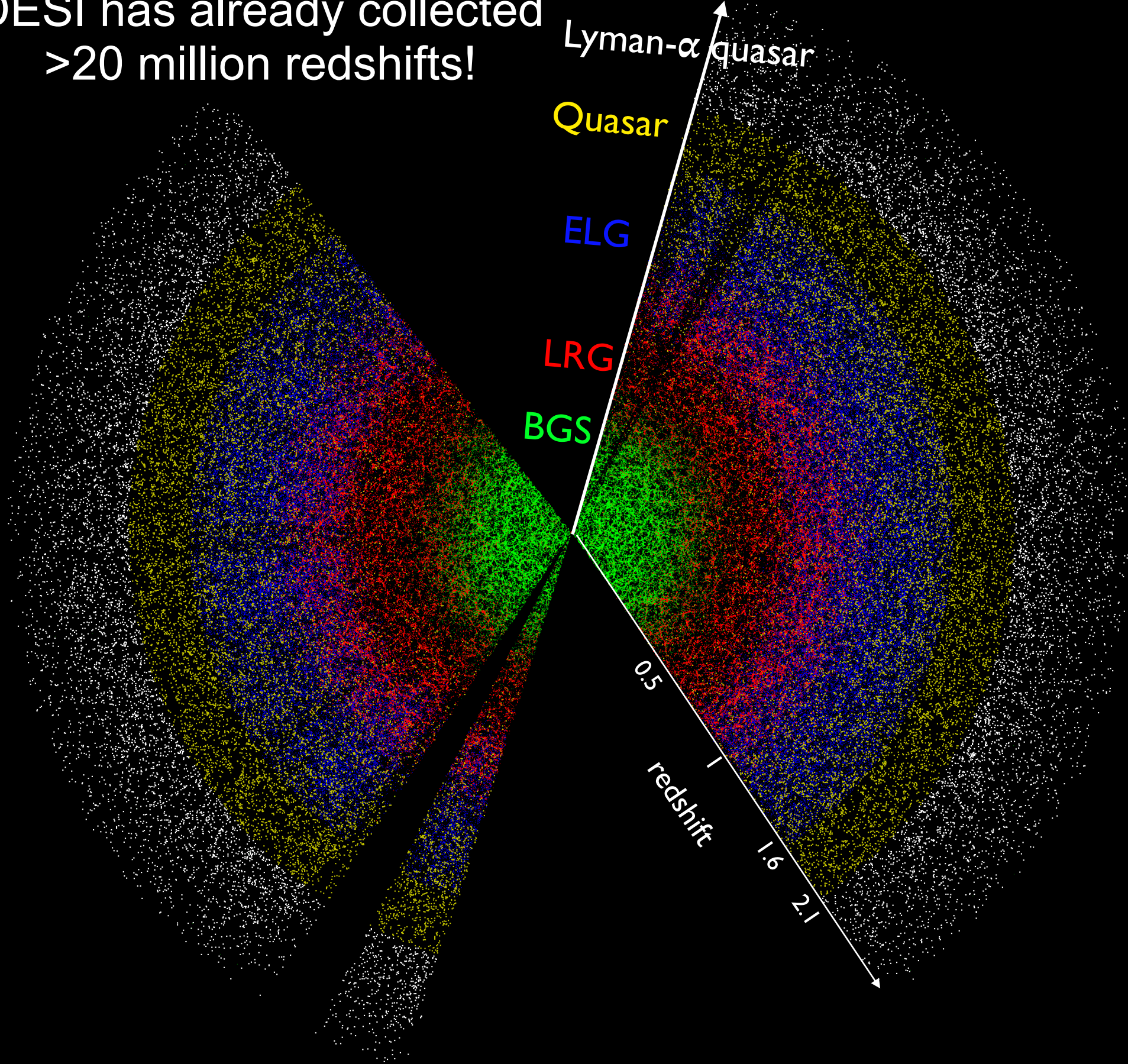
C. Hahn, M. Wilson et al. (2022)

DESI Galaxies

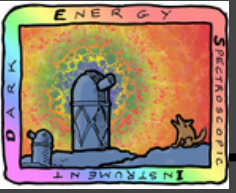


DESI has already collected
>20 million redshifts!

Look back time 12 Gyrs



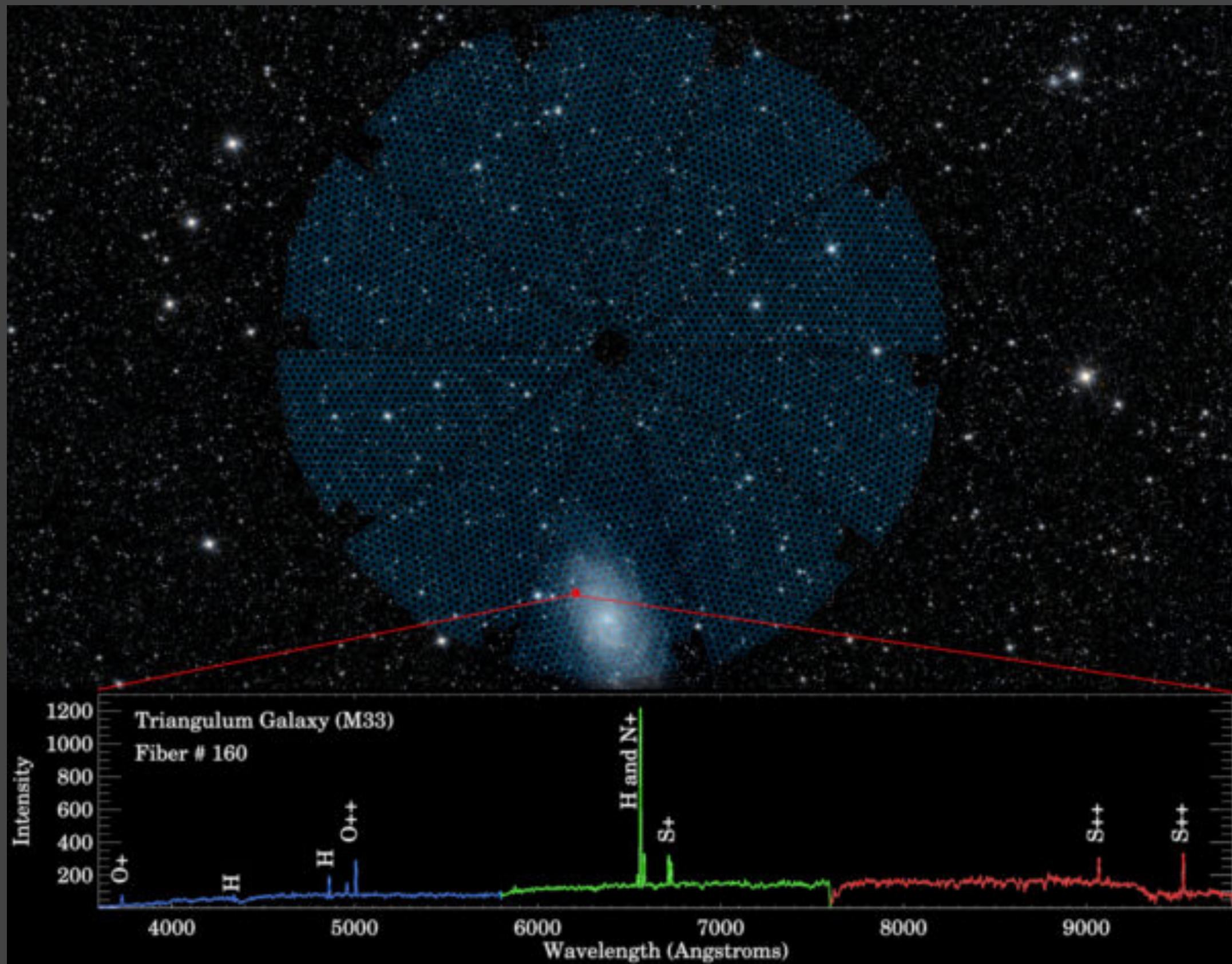
How?: Building the Map



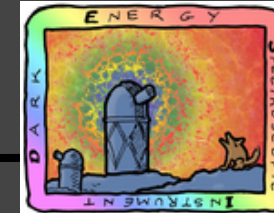
- “Targets” are selected via their flux and color in imaging data from the DESI Legacy Imaging Surveys
- For target we measure a spectrum and from that a redshift
- We measure 5000 spectra at once

DESI: Field of view

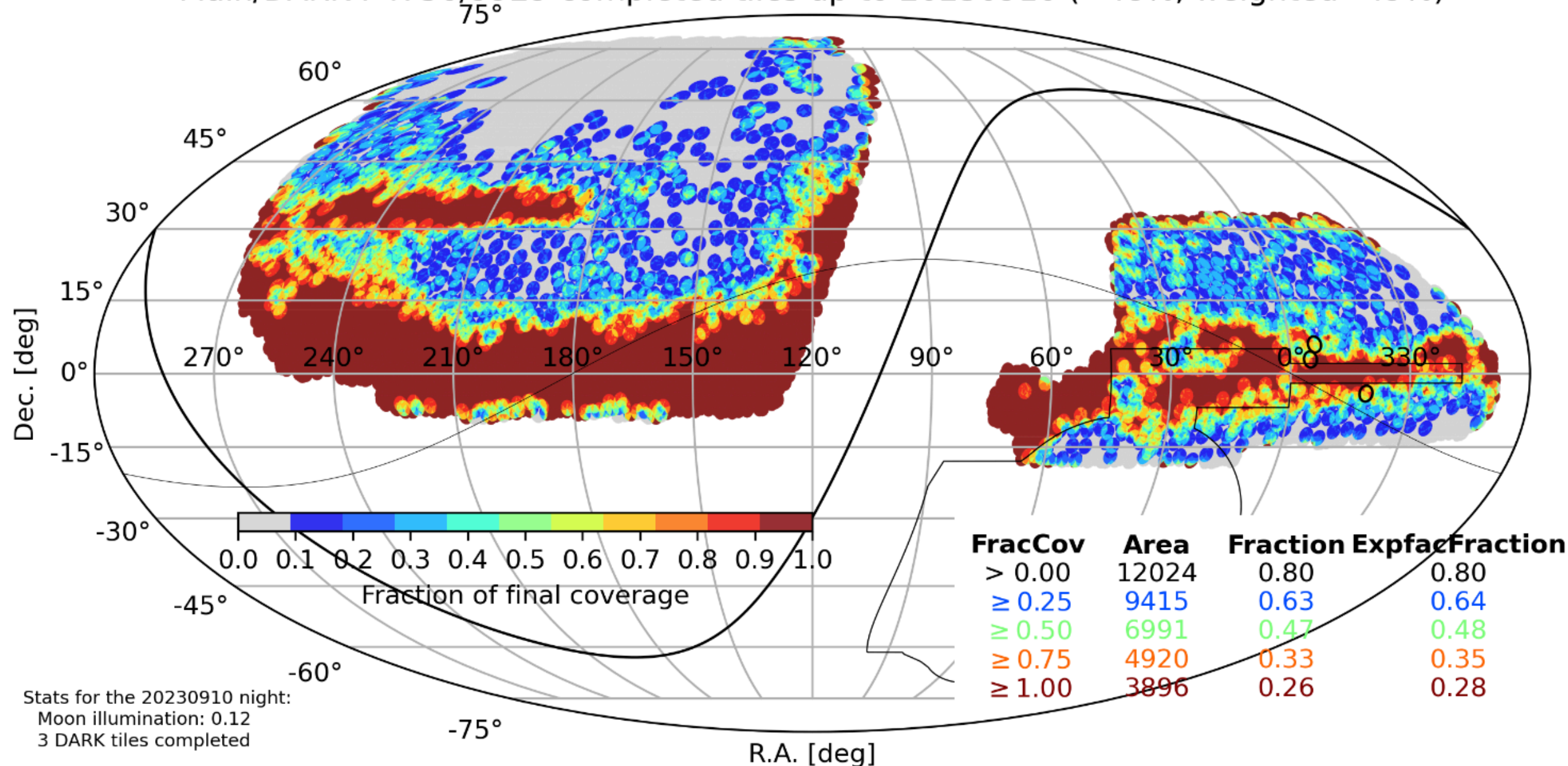
First light press image



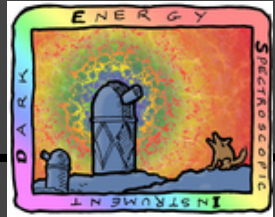
DESI Sky Coverage



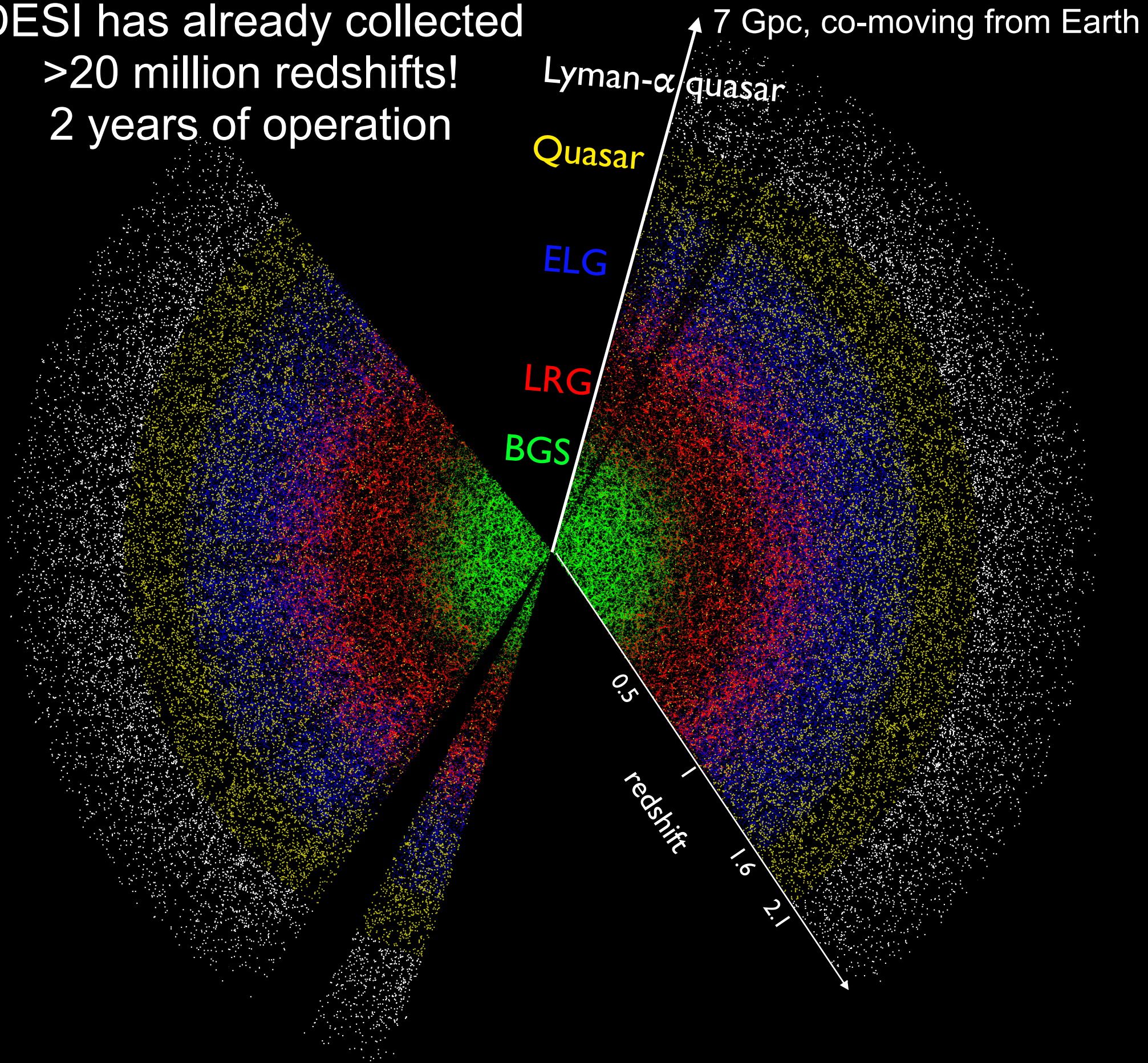
Main/DARK : 4750/9929 completed tiles up to 20230910 (=48%, weighted=49%)



DESI Galaxies



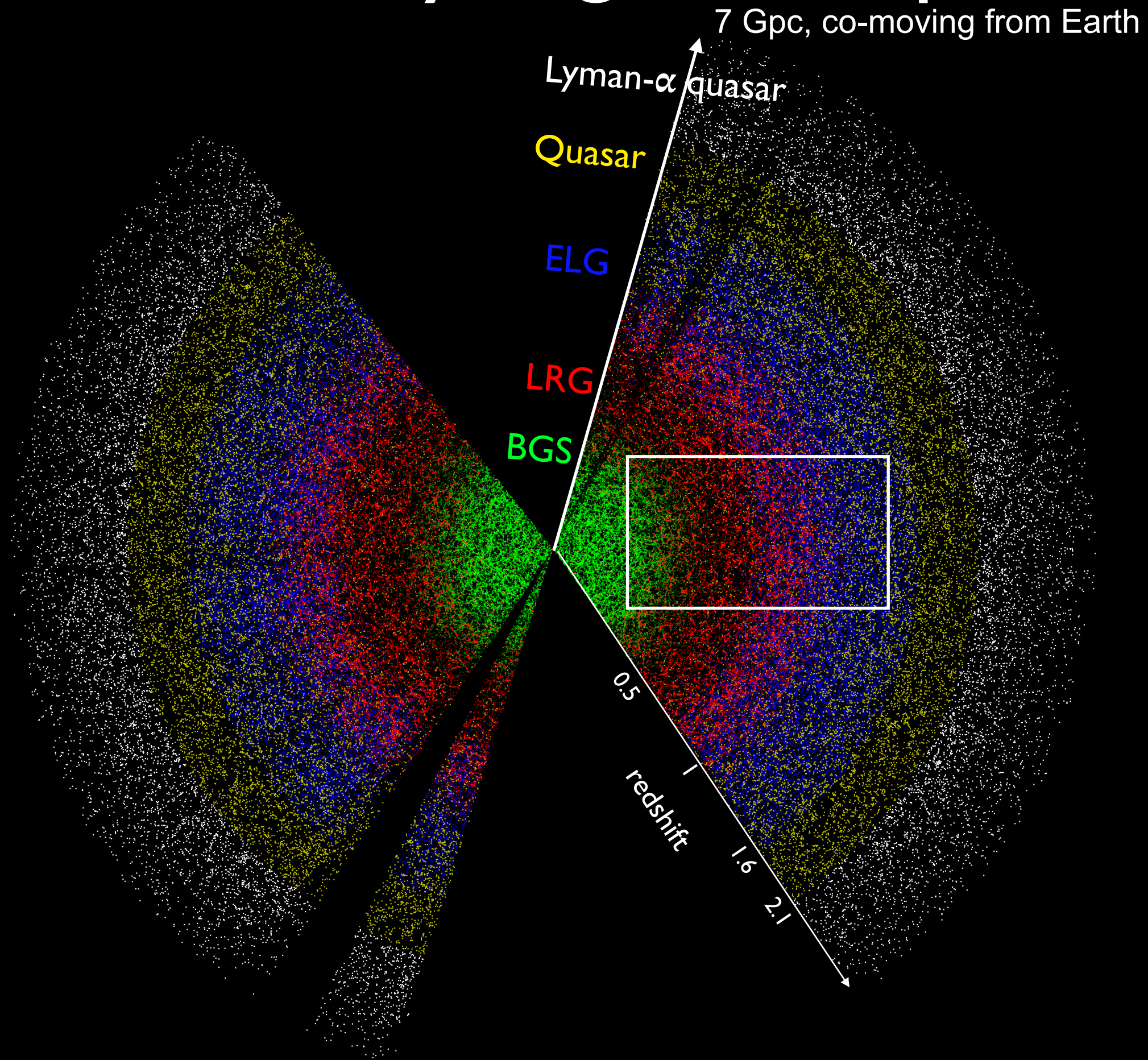
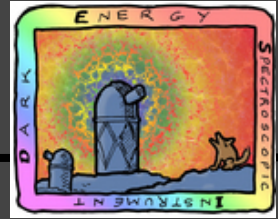
DESI has already collected
>20 million redshifts!
2 years of operation



How?: Analyzing the Map

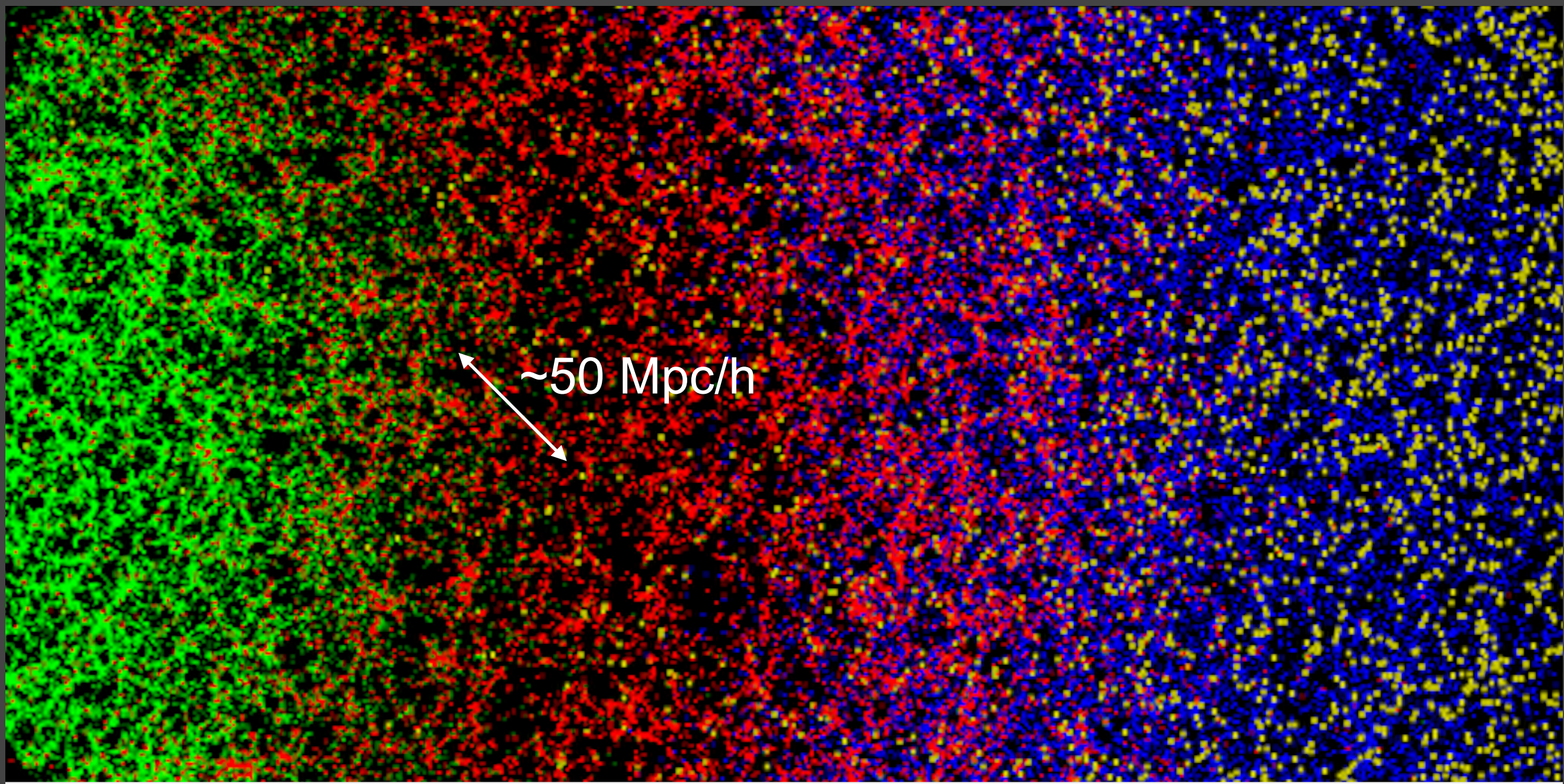
- Millions of galaxies but just one Universe
 - Need statistical characterization of structure in map
- We measure the “clustering” of our maps
 - Essentially, the variance as of function separation
 - “2-point” function; literally count pairs as function of separation and compare to random distribution

Analyzing the map



Analyzing the Map

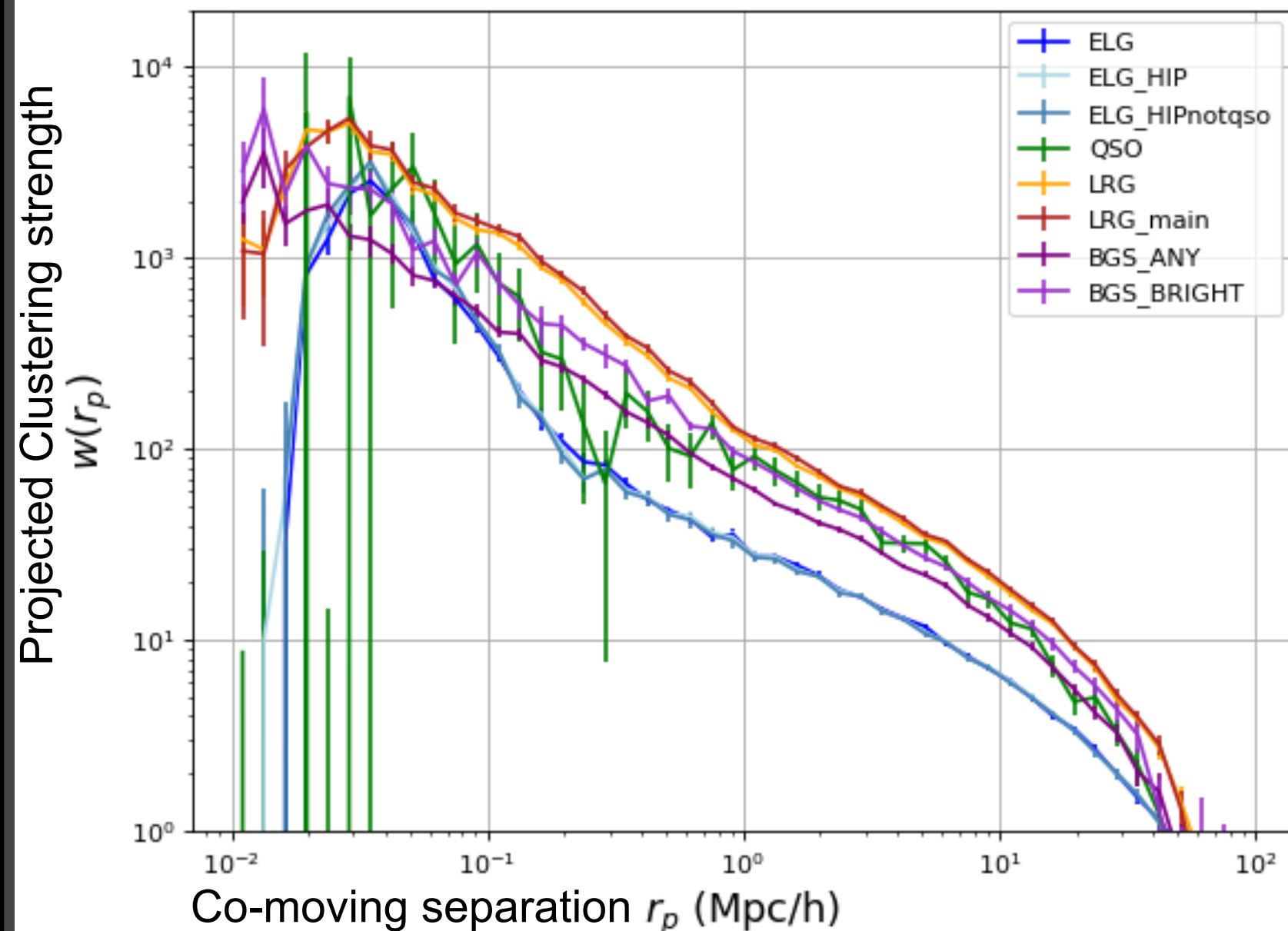
- We measure the “2-point” function
- Literally count pairs as function of separation and compare to random distribution



DESI Clustering

- We measure the “clustering” of our maps
 - Essentially, the variance as of function of co-moving separation

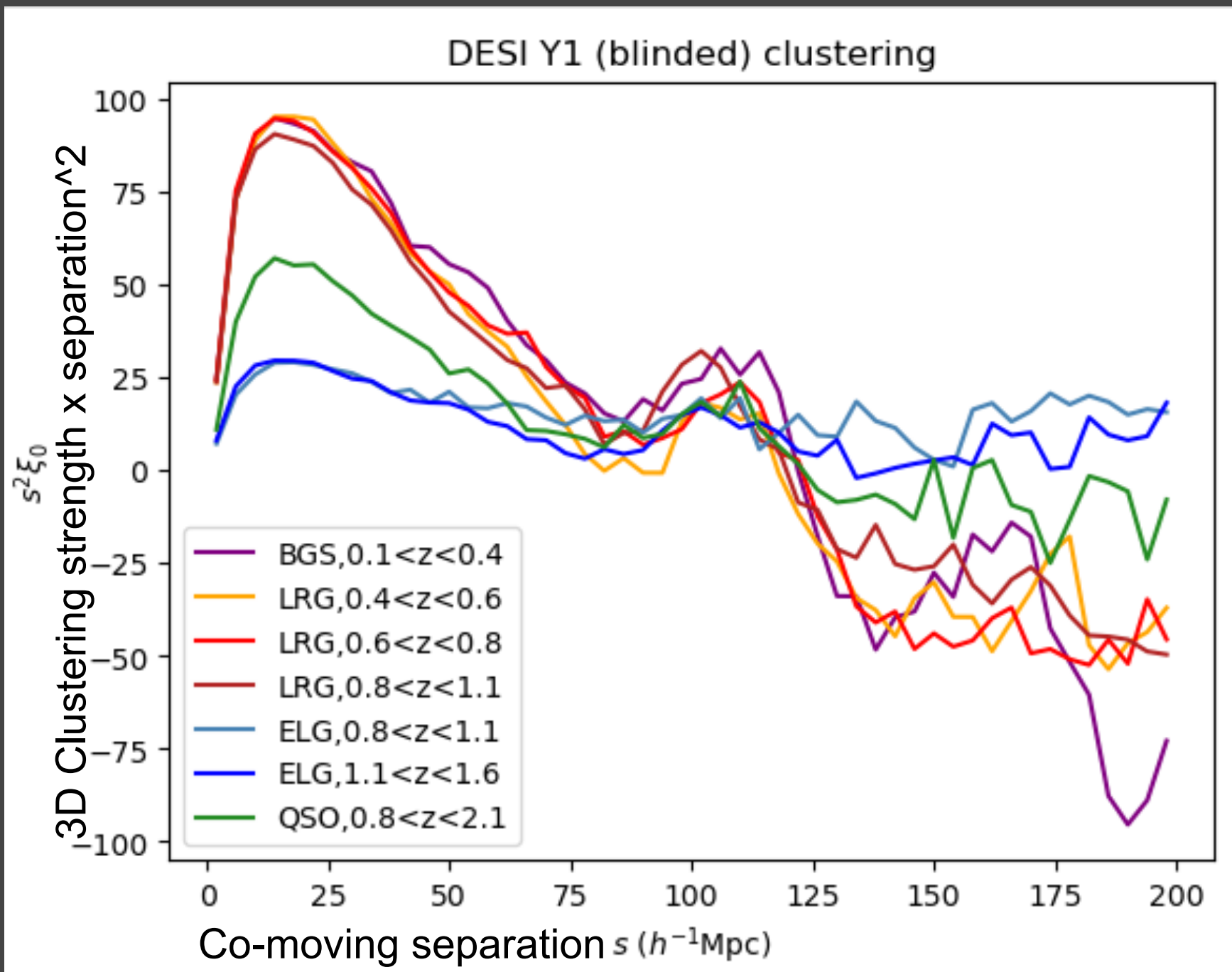
Clustering in Early DESI Data Release ($\sim 10^6$ redshifts)



- Difference in clustering amplitudes is “galaxy bias”
- Cannot directly use clustering amplitude for precision cosmology

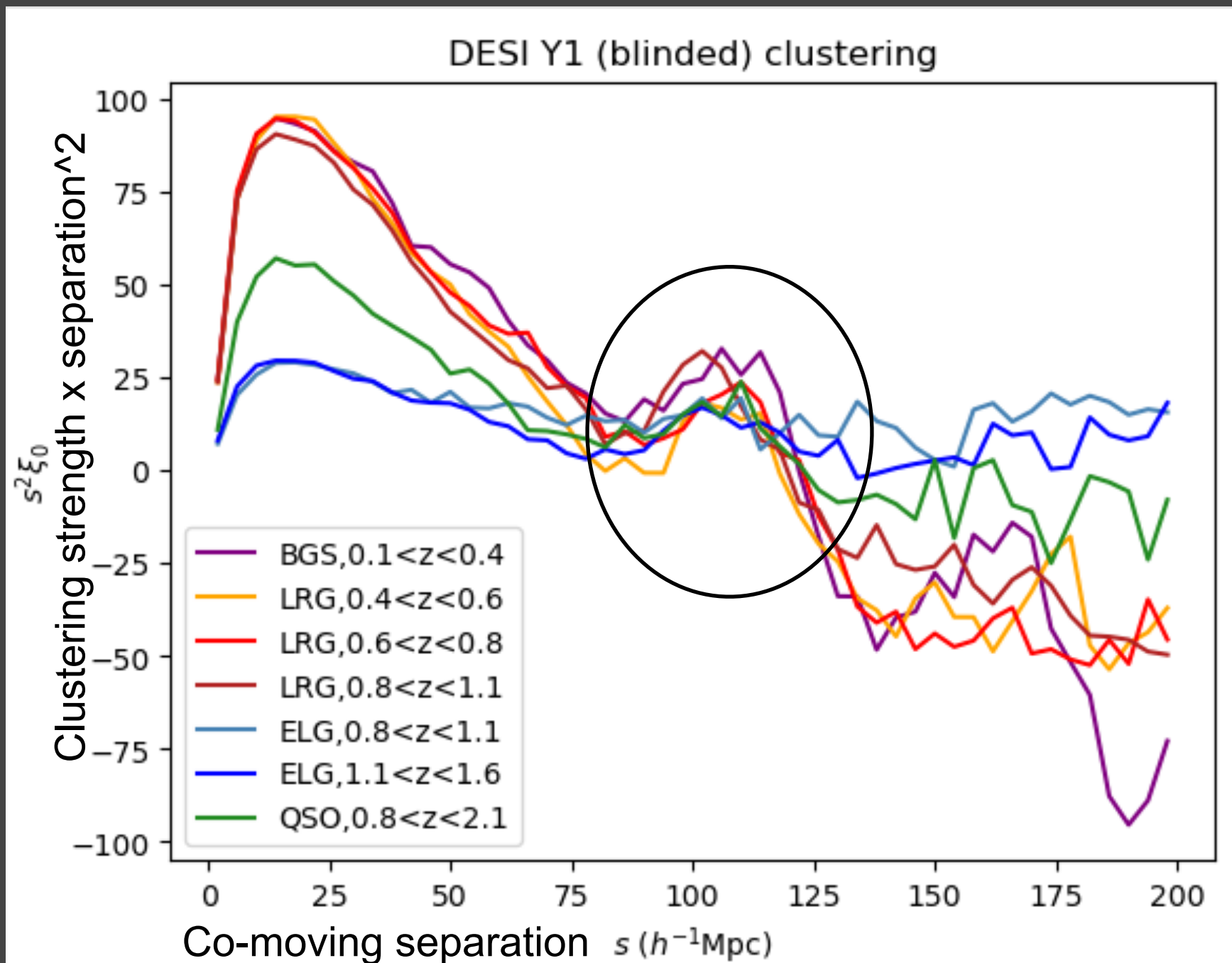
DESI Clustering

- Year 1 sample has 10^7 redshifts



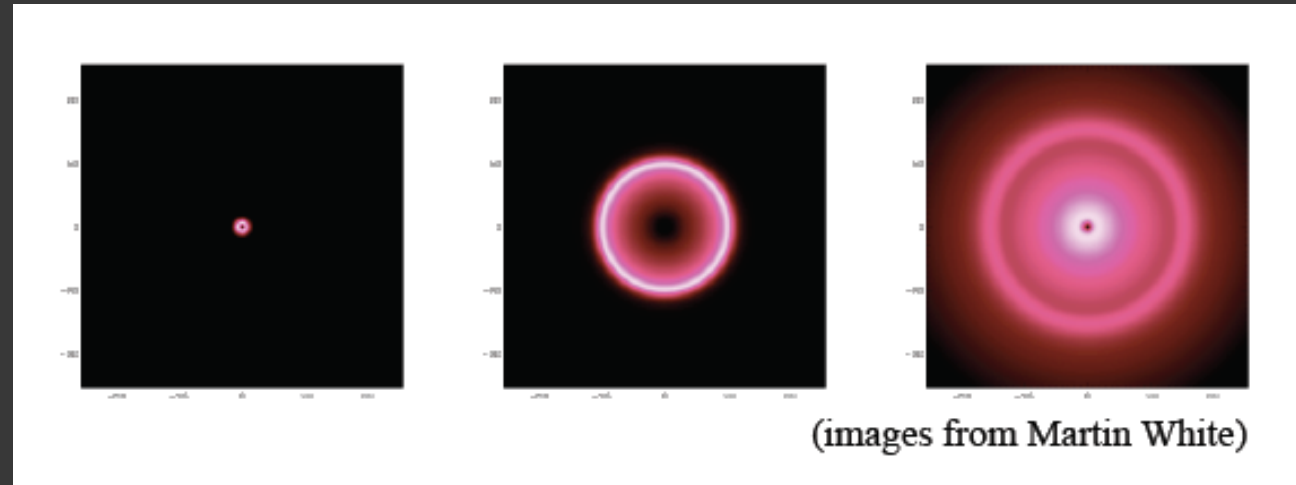
DESI Clustering

- We measure the “clustering” of our maps
 - Essentially, the variance as of function of co-moving separation

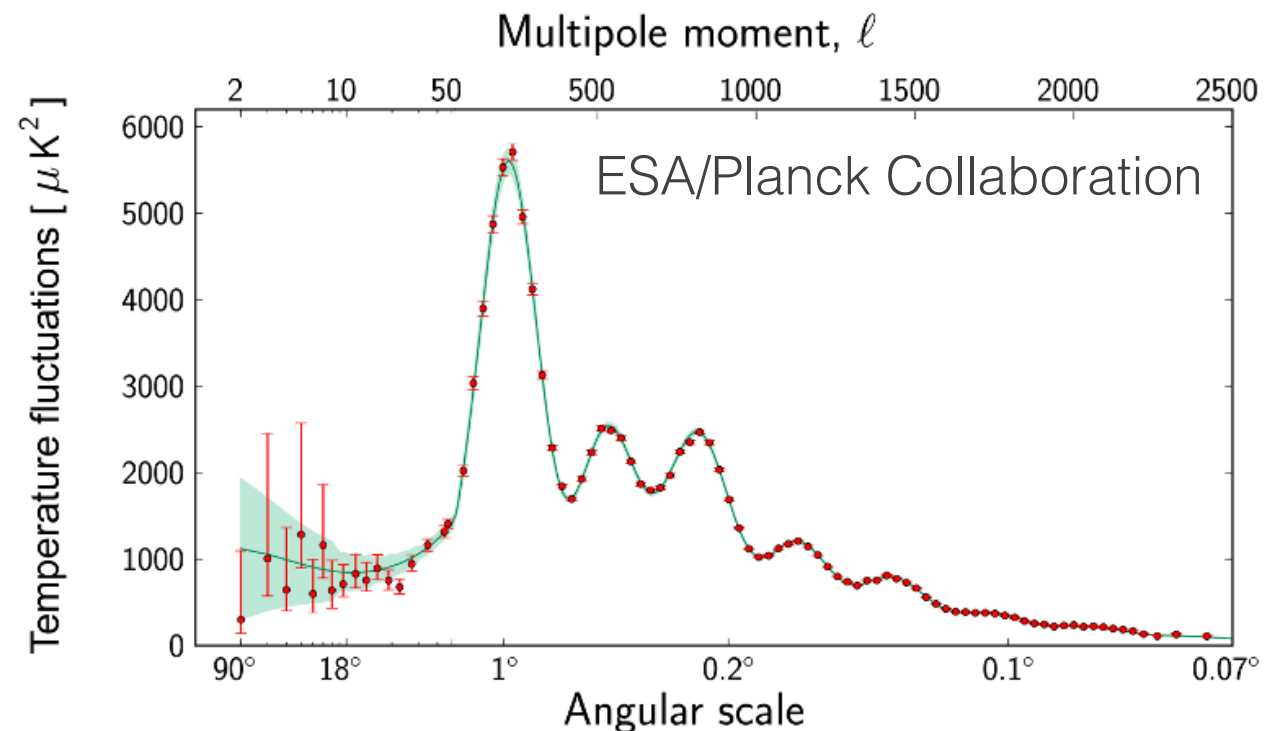
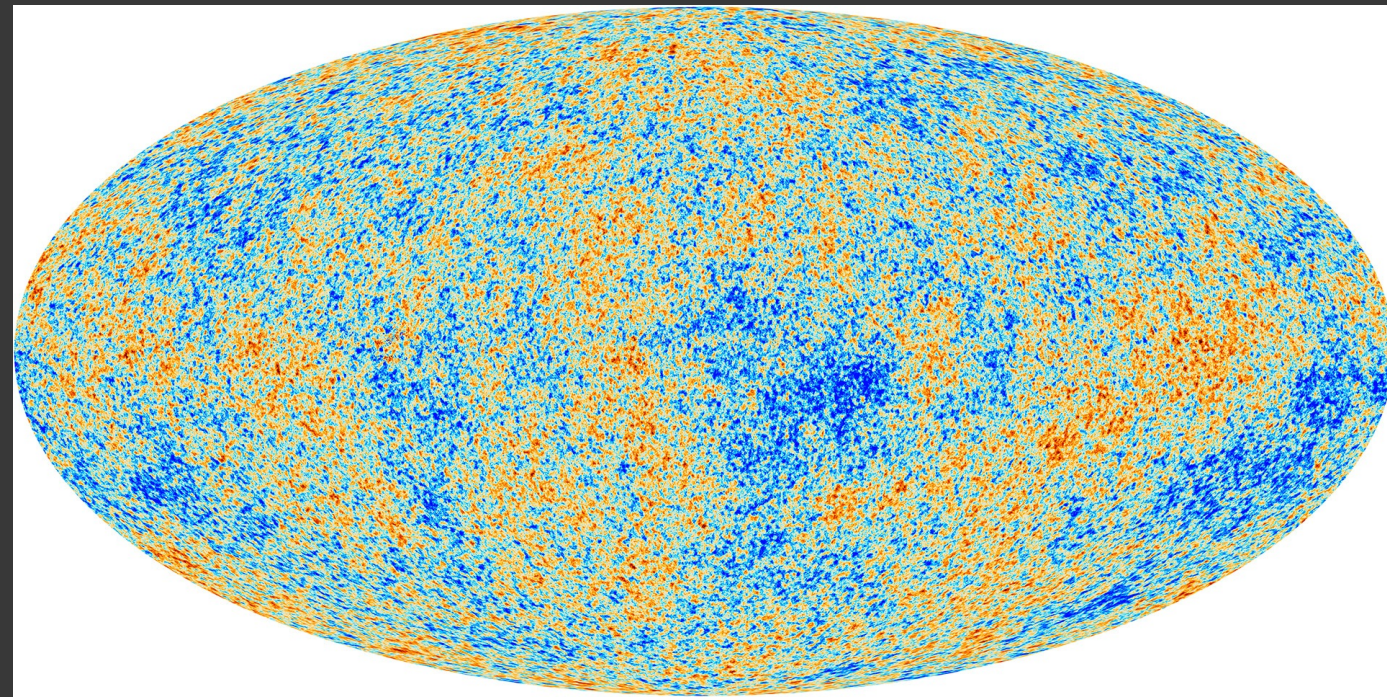


Baryon Acoustic Oscillations

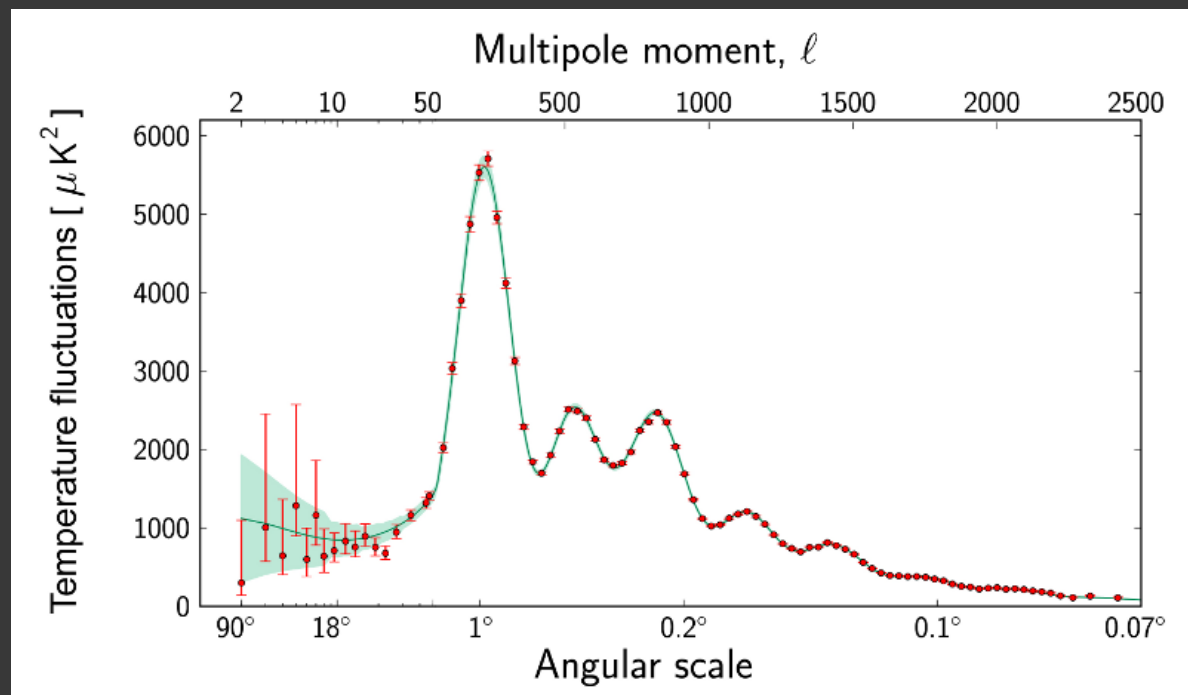
- Early Universe radiation pressure/ matter density $\rightarrow$ standing wave in baryon density



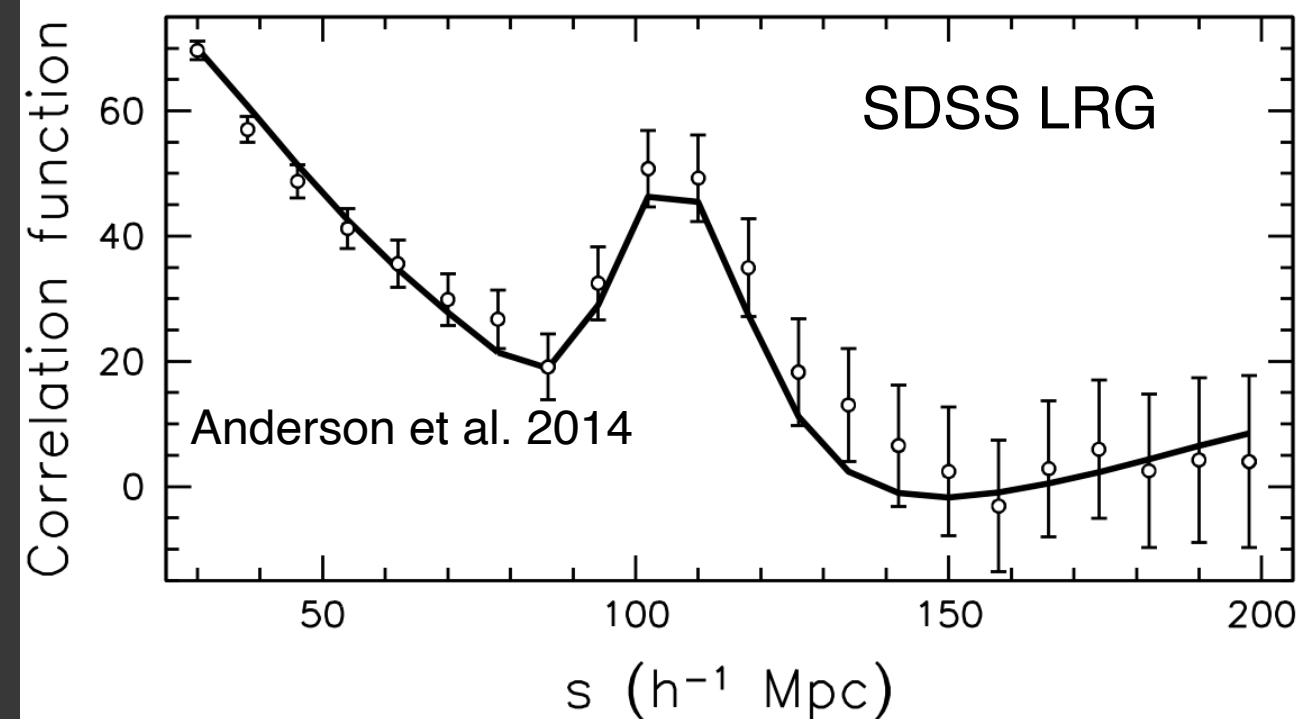
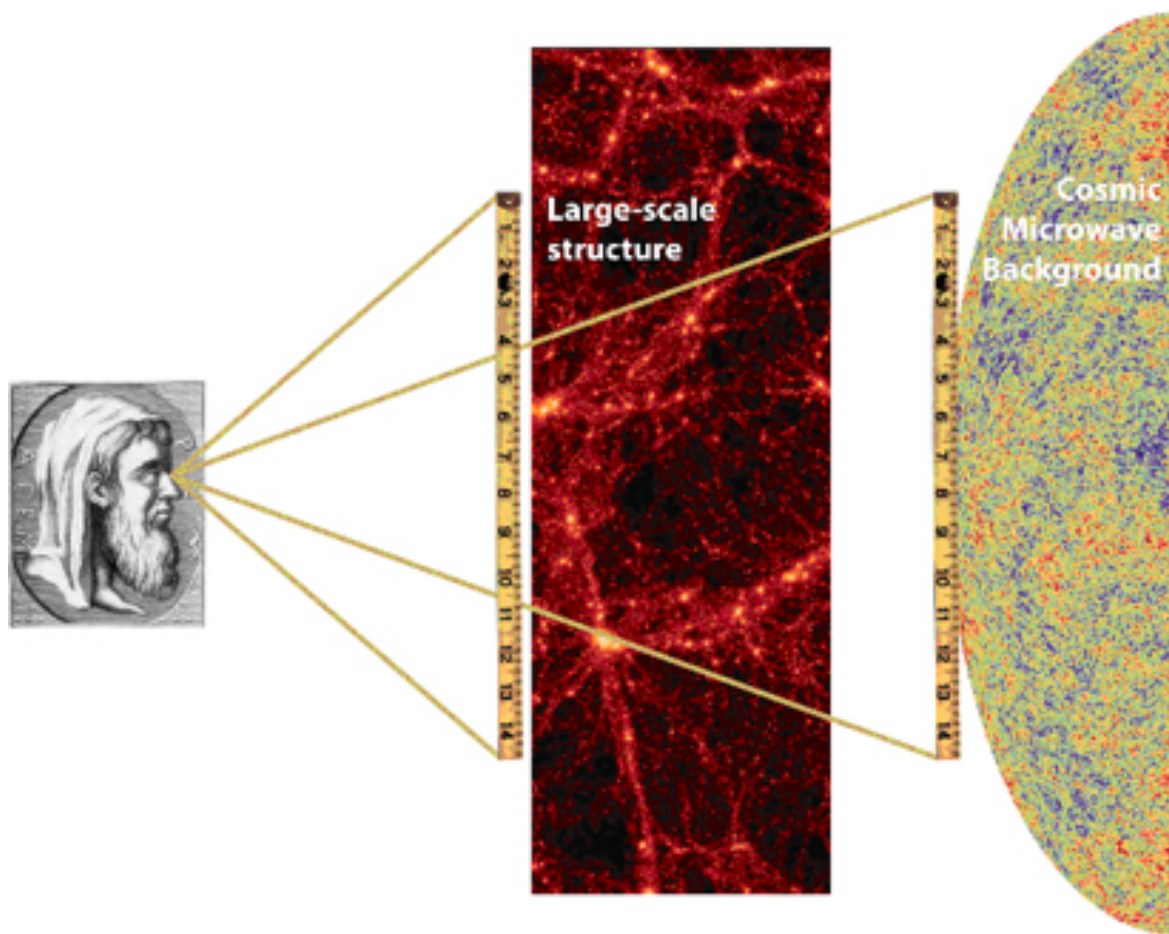
CMB Temperature



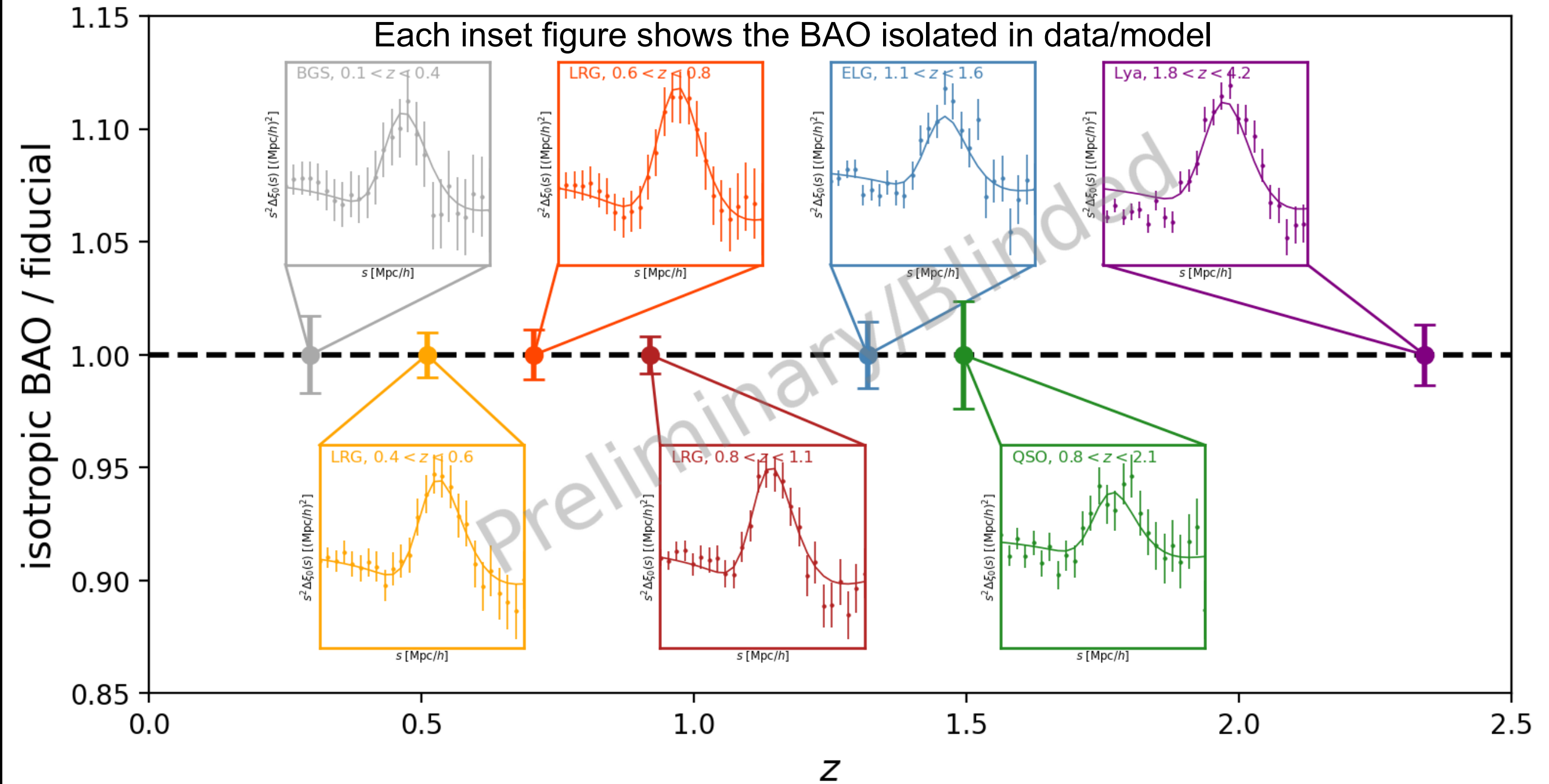
Baryon Acoustic Oscillations



- Preferred co-moving scale frozen into matter distribution
- CMB measurement gives calibrated “standard ruler”

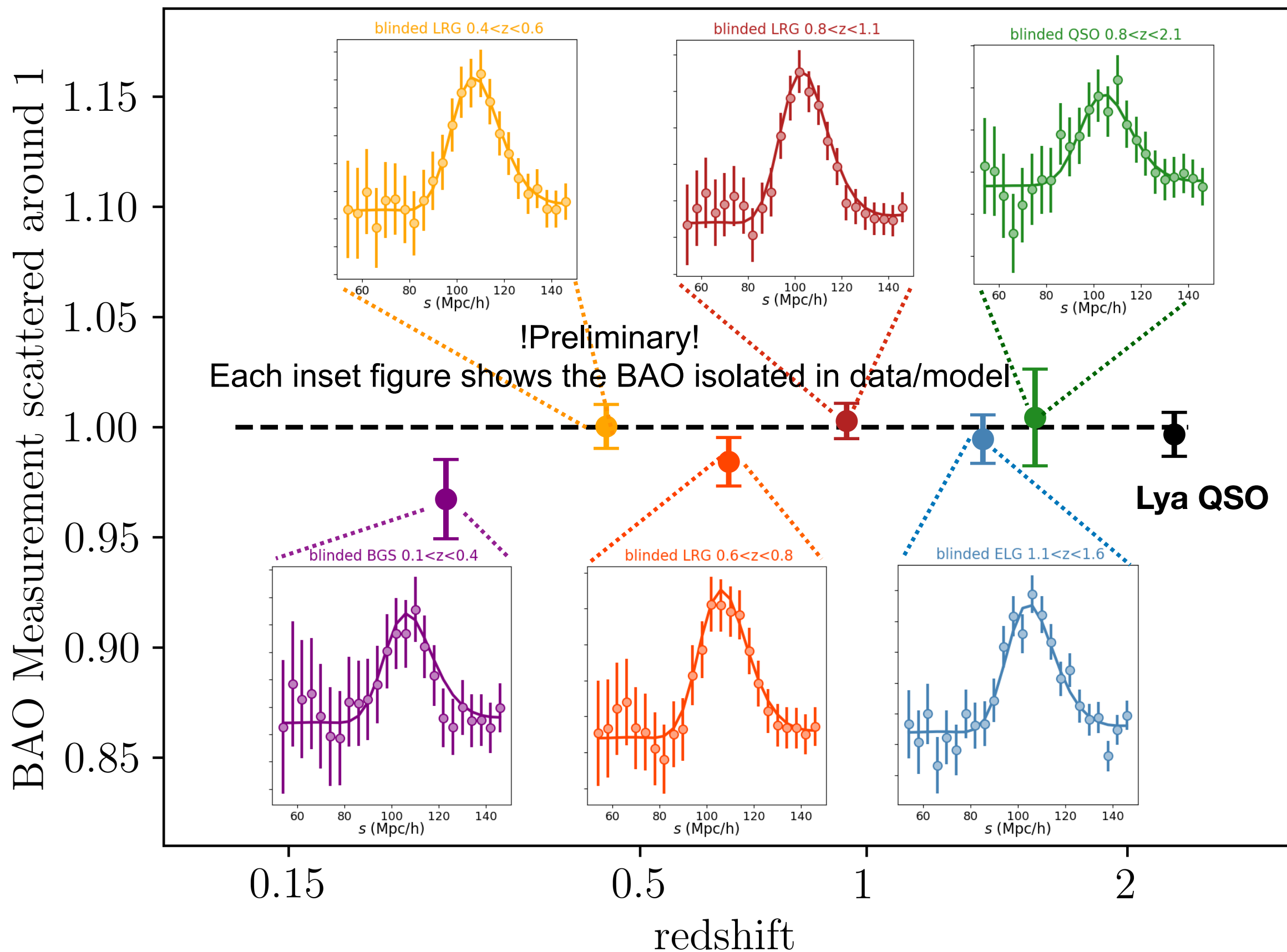


DESI Y1 BAO



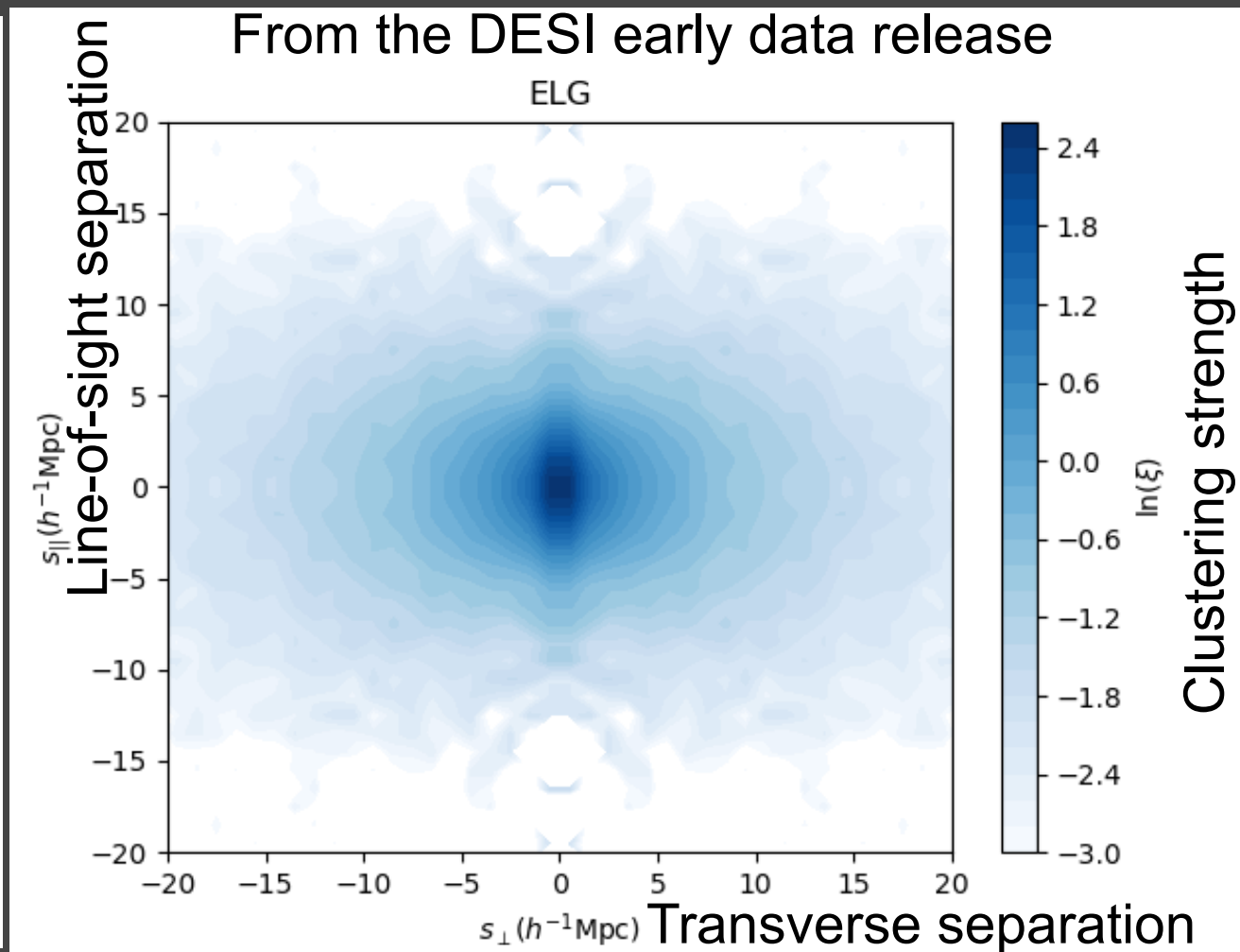
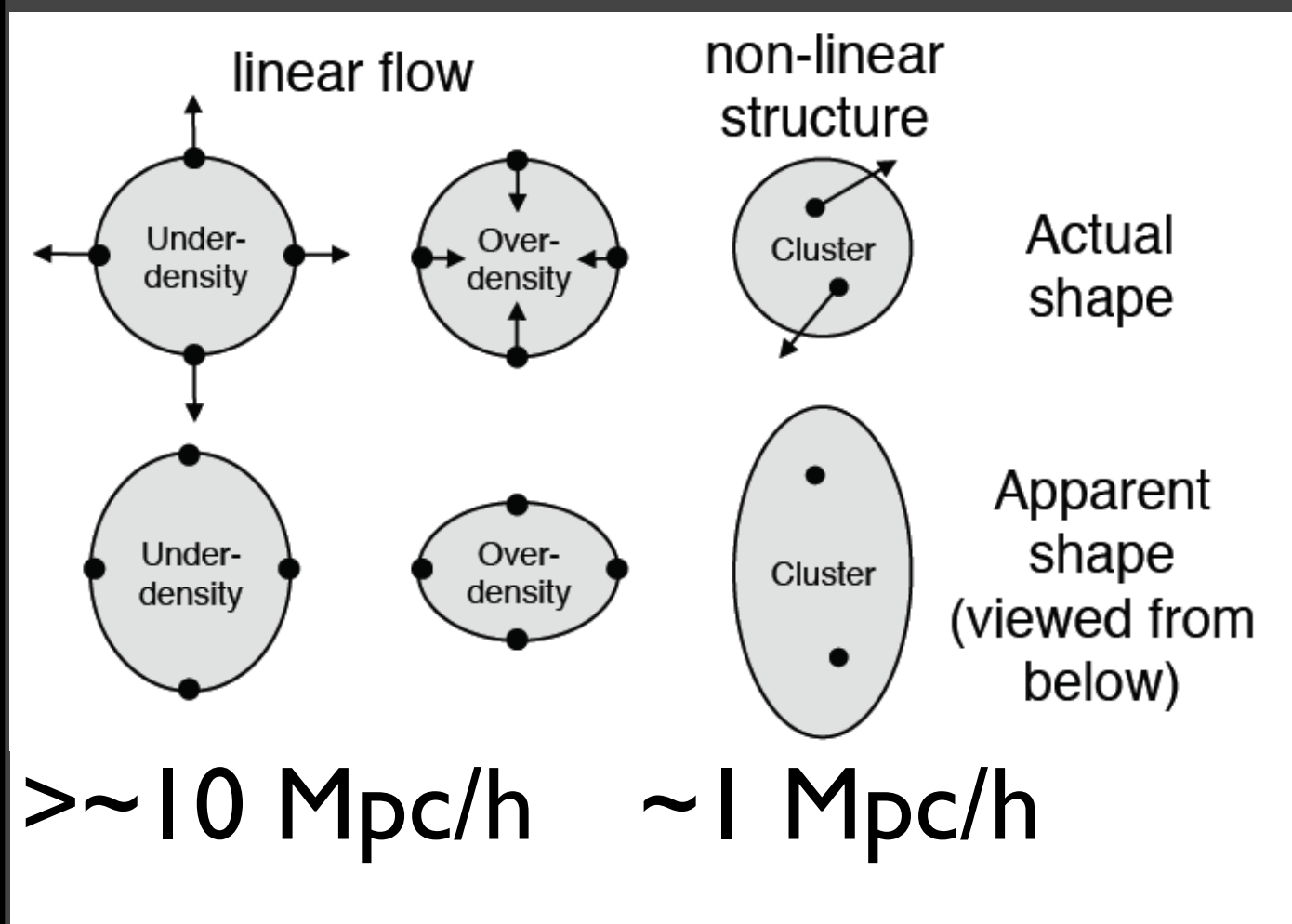
DESI Y1 BAO

DESI Y1 blinded BAO Distance Ladder



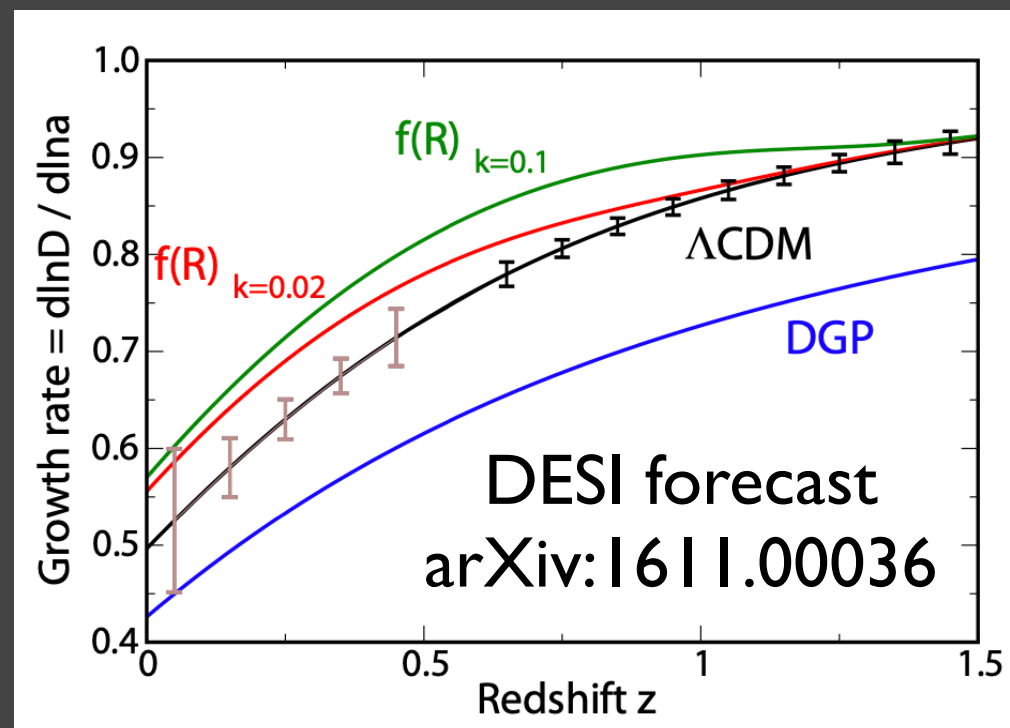
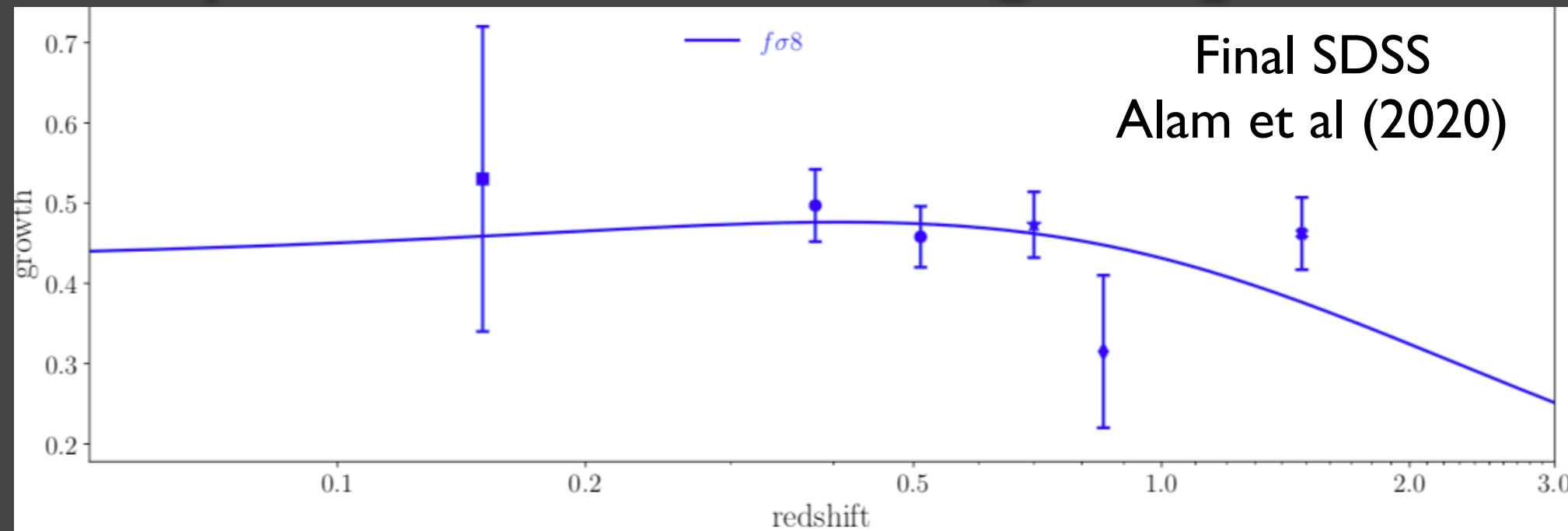
DESI Clustering: Structure Growth

- Galaxies have their own “peculiar” velocities which cause “redshift-space distortions” (RSD) in our maps
 - Different clustering for transverse compared to line-of-sight
 - Amplitude gives rate of structure growth

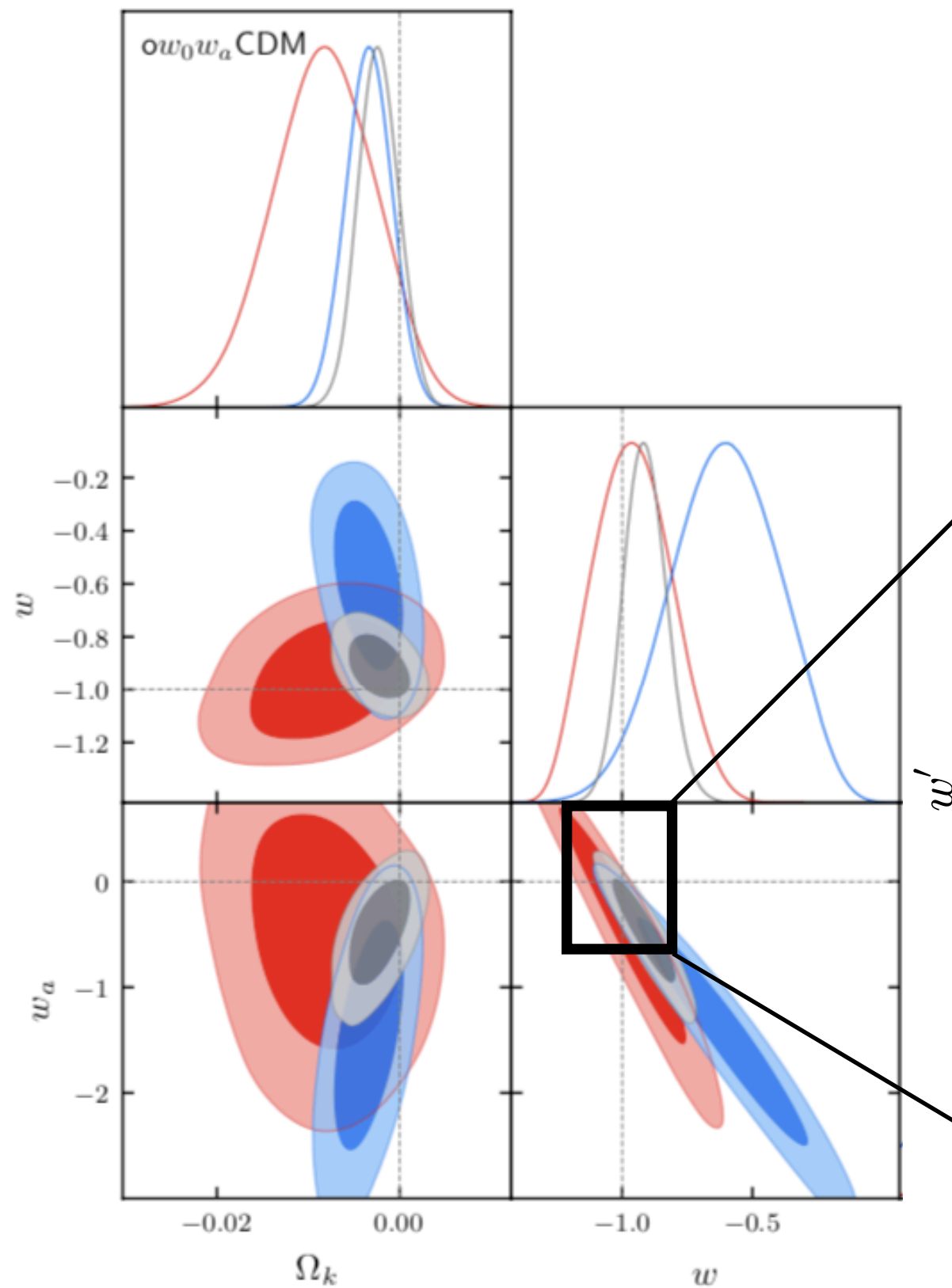


Structure Growth

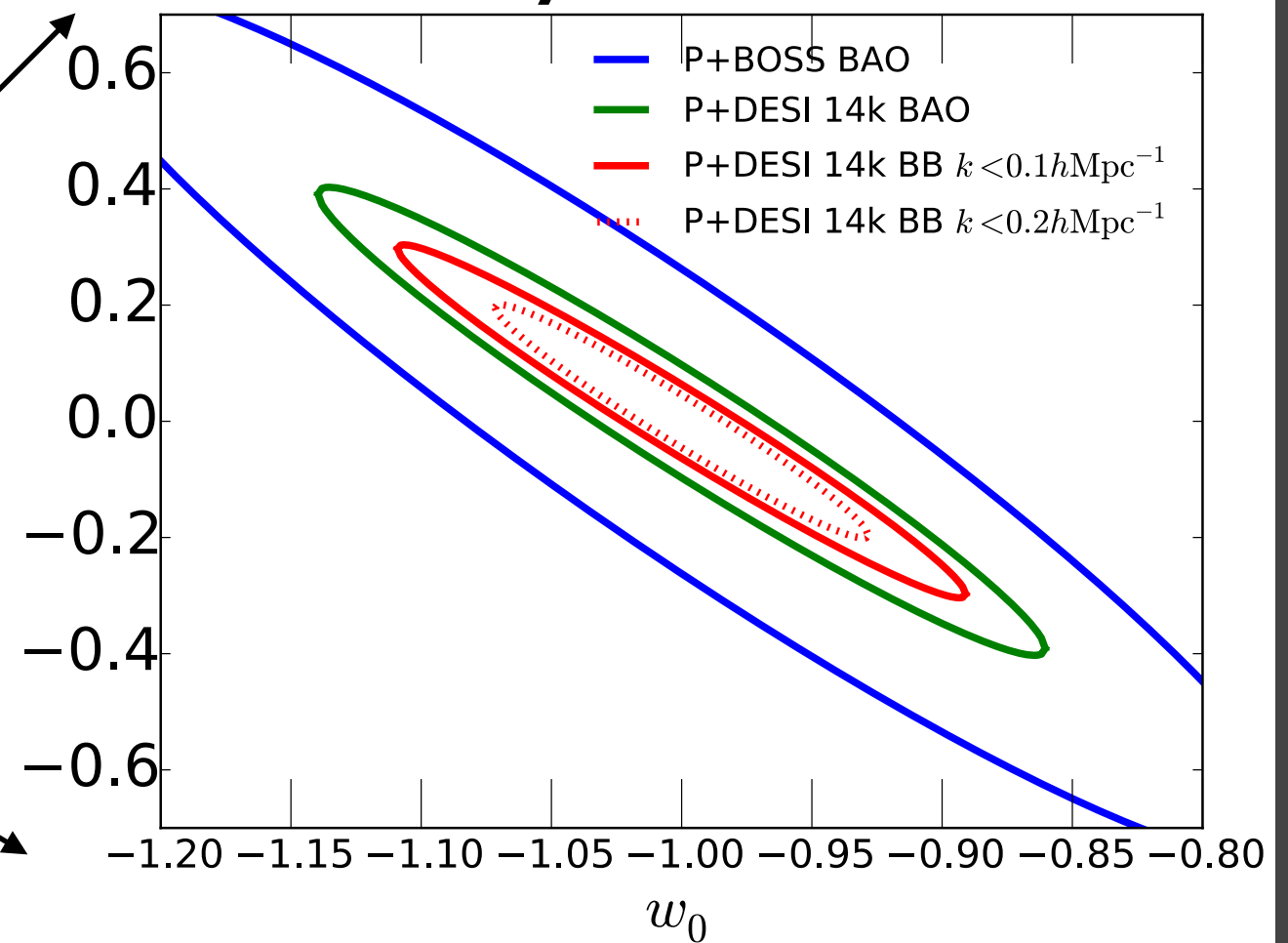
- Structure growth rate depends on matter density, assuming GR
- Conversely, is a test of GR assuming background model



DESI: Dark Energy Forecast



DESI 5 year Forecast



arXiv:1611.00036

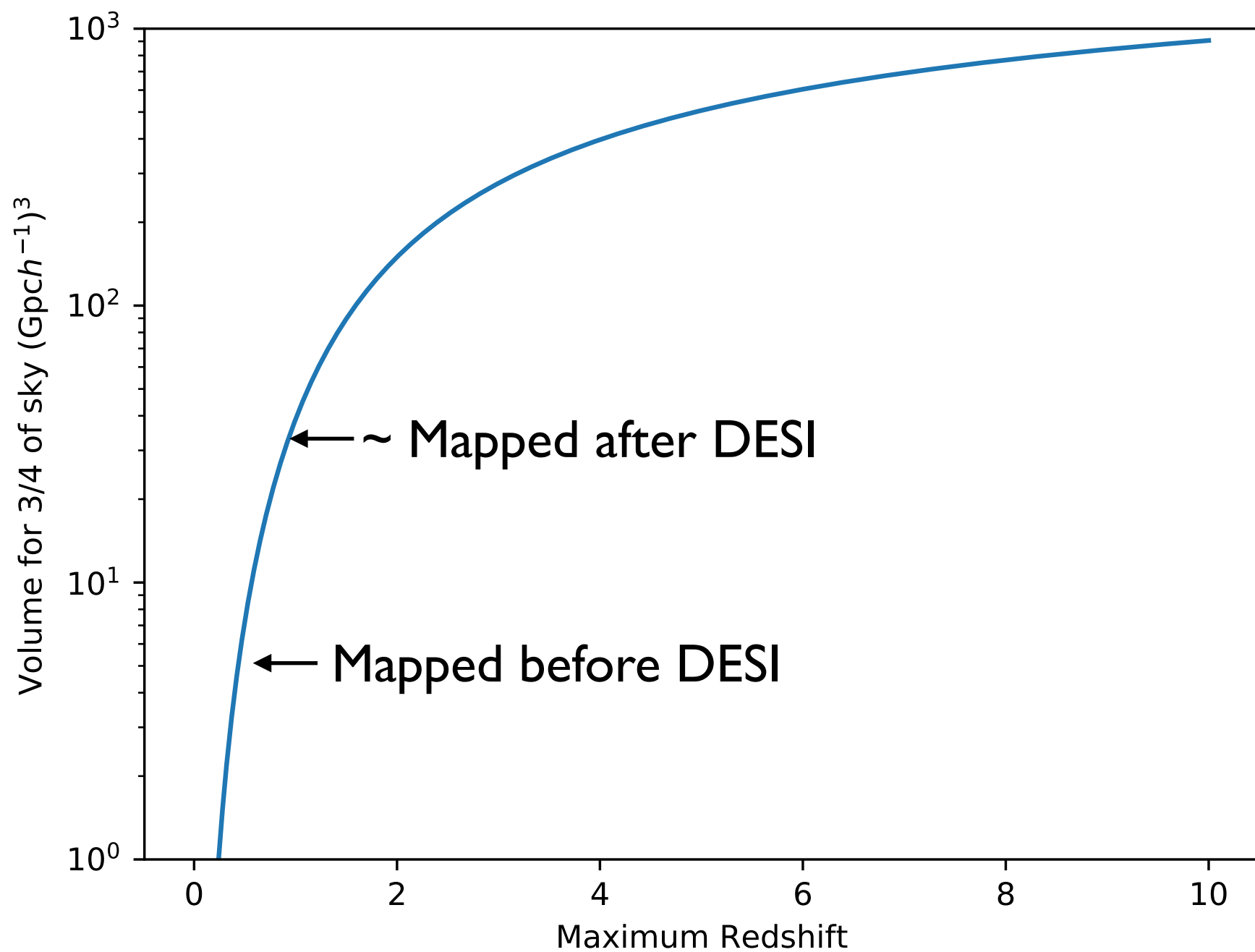
DESI Dark Energy Constraints

- Stay tuned for DESI Y1 results in spring of 2024!

DESI: More than Dark Energy

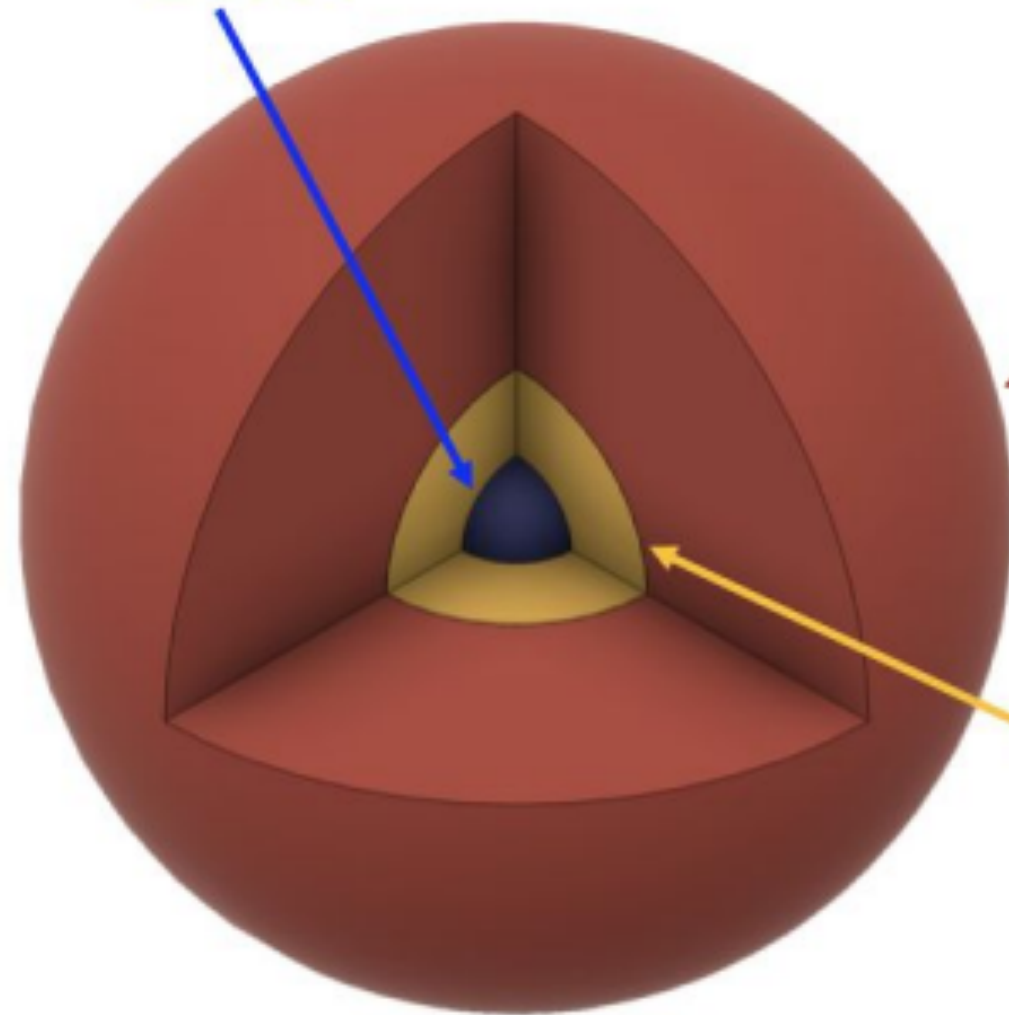
- RSD measurements will help evaluate mild tensions ($\sim 3\sigma$) between CMB + geometry and (some) low redshift structure growth probes
- DESI will provide best to date LSS results on primordial potential
- Galaxy/quasar bias measurements probe galaxy evolution, links between star formation/structure growth/central black hole growth
- DESI is also mapping the Milky Way, getting radial positions of 7 millions stars!

What Next?



Increasing Volume

SDSS

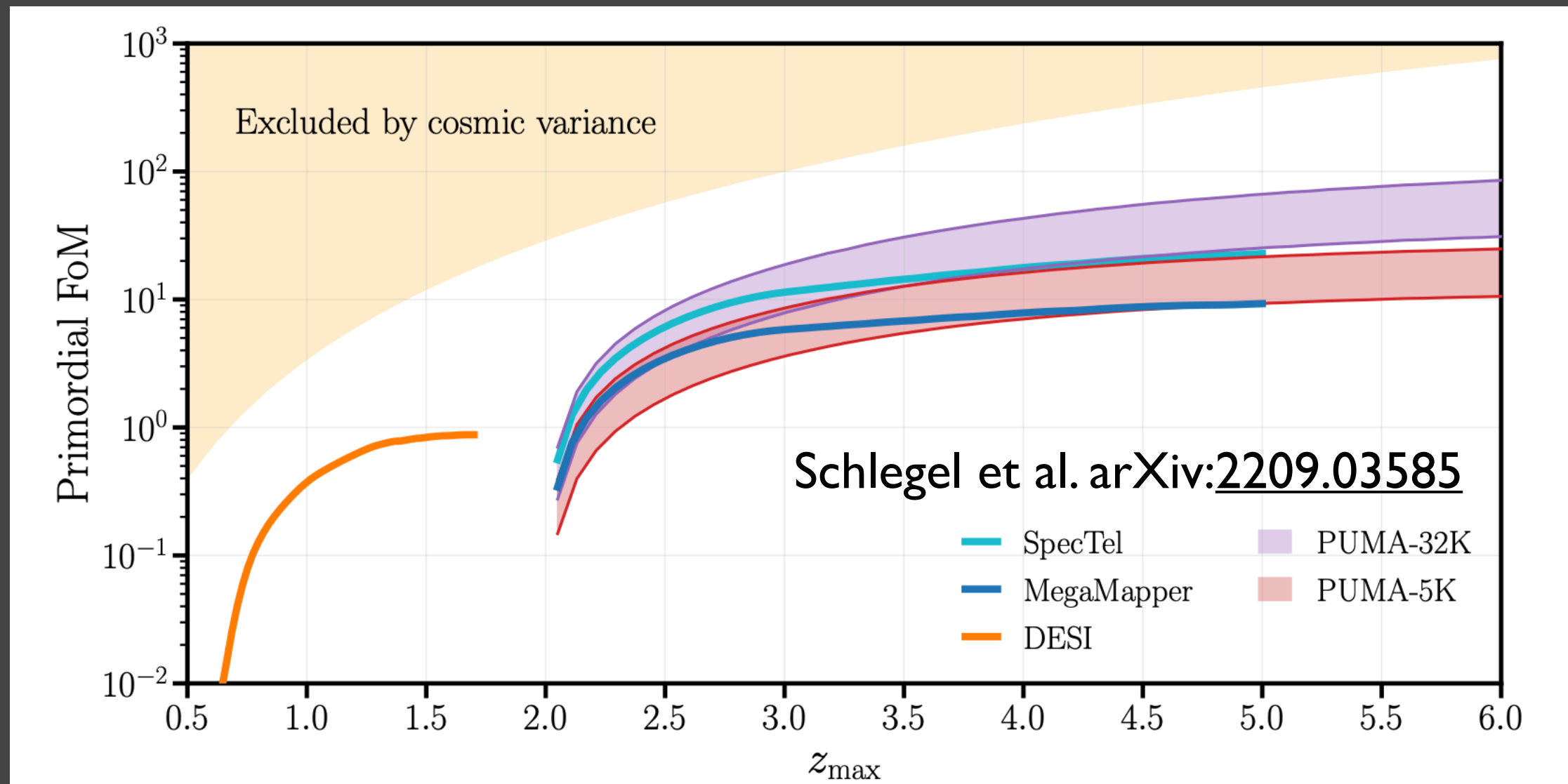


DESI-II/
Stage-5

DESI
Euclid

Credit: D. Kirkby

Available Volume (more sophisticated)



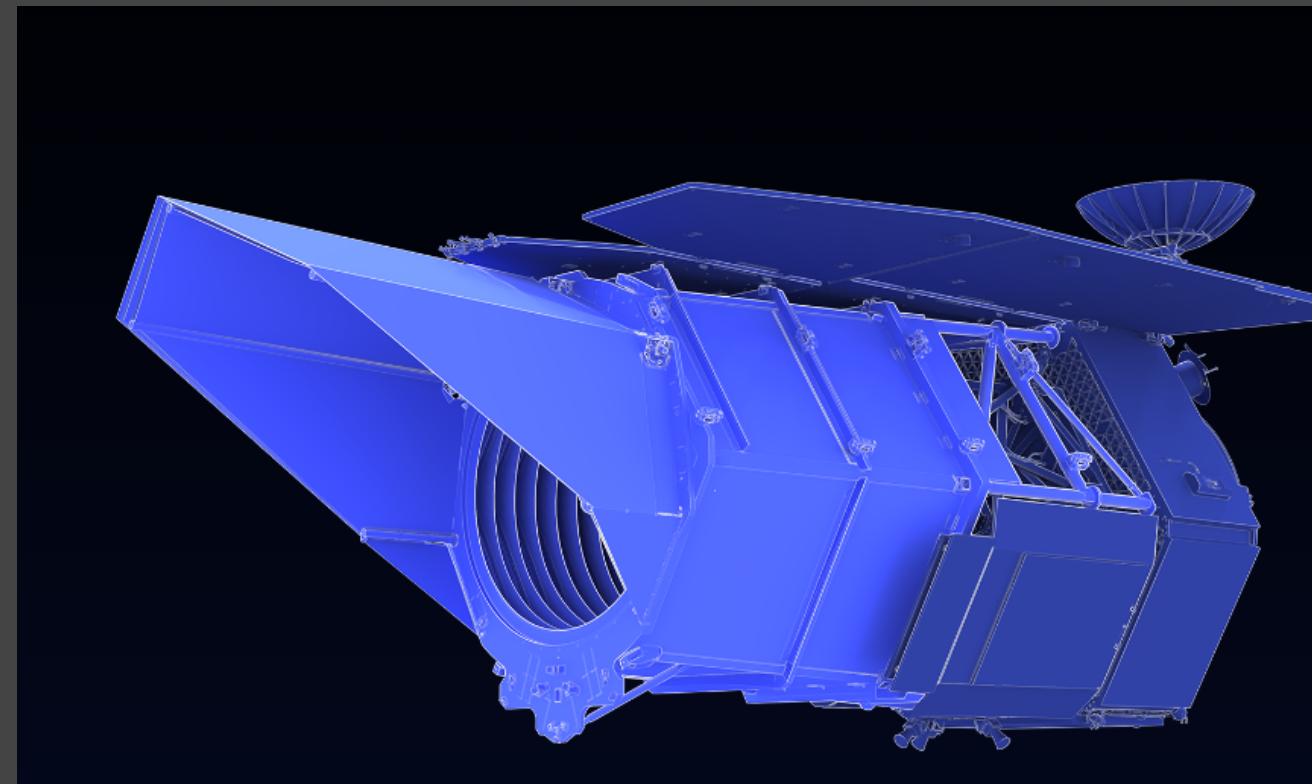
- “Primordial FoM” meant to estimate information available for constraining primordial potential
- i.e., to answer “Why is there any structure in the Universe”

DESI-II

- ~same instrument, five years
 - Pathfinder for high- z surveys to (hopefully) succeed DESI
 - BGS to higher redshift
 - Synergies with LSST
- DESI instrument will continue to be the premier way to gather large numbers of redshifts

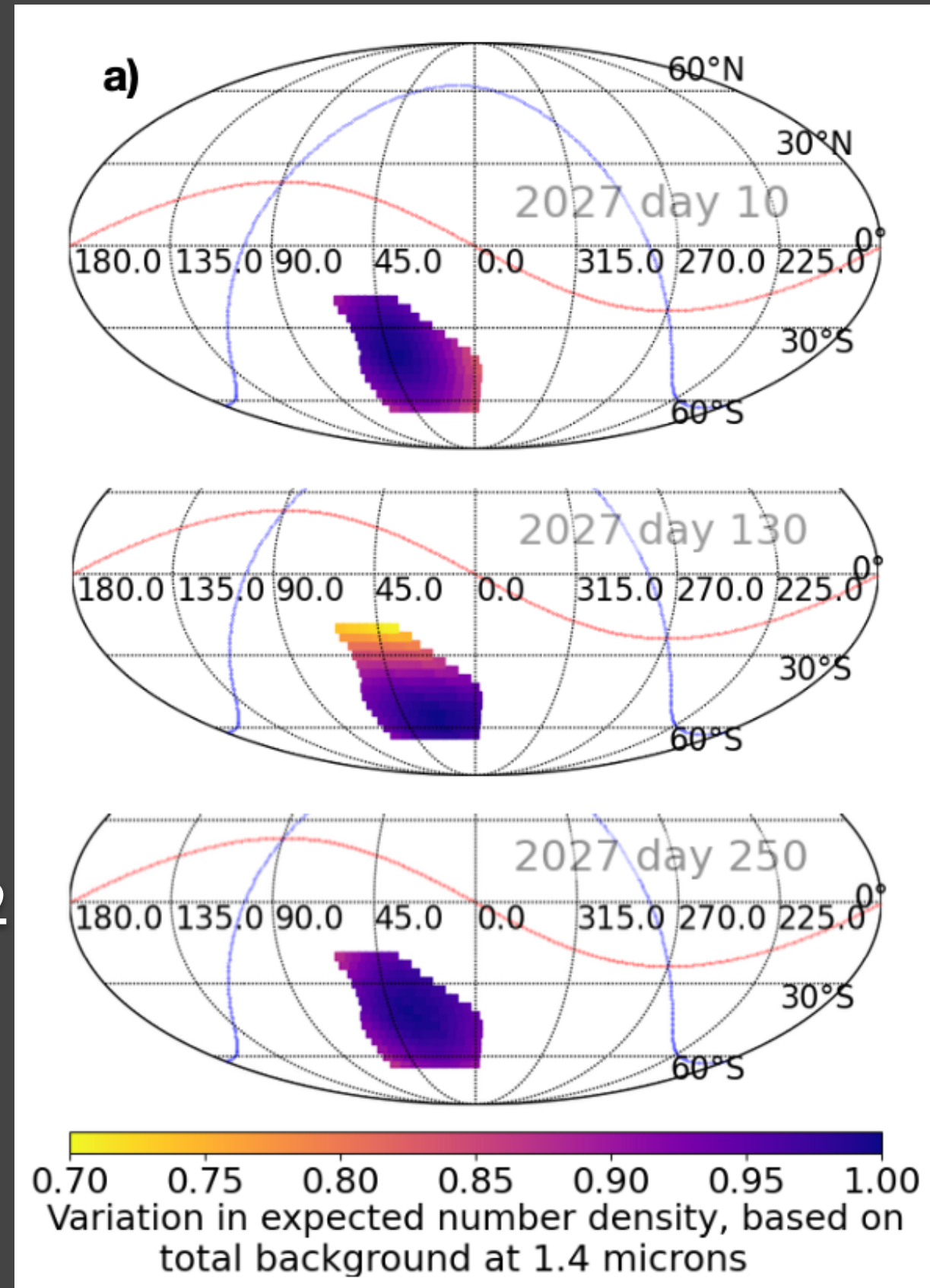
Roman Space Telescope

- Space telescope; size of Hubble with 100x field of view
- 2027 launch date
- Ohio State involved in “Project Infrastructure Teams” for imaging, planet finding, and spectroscopic surveys



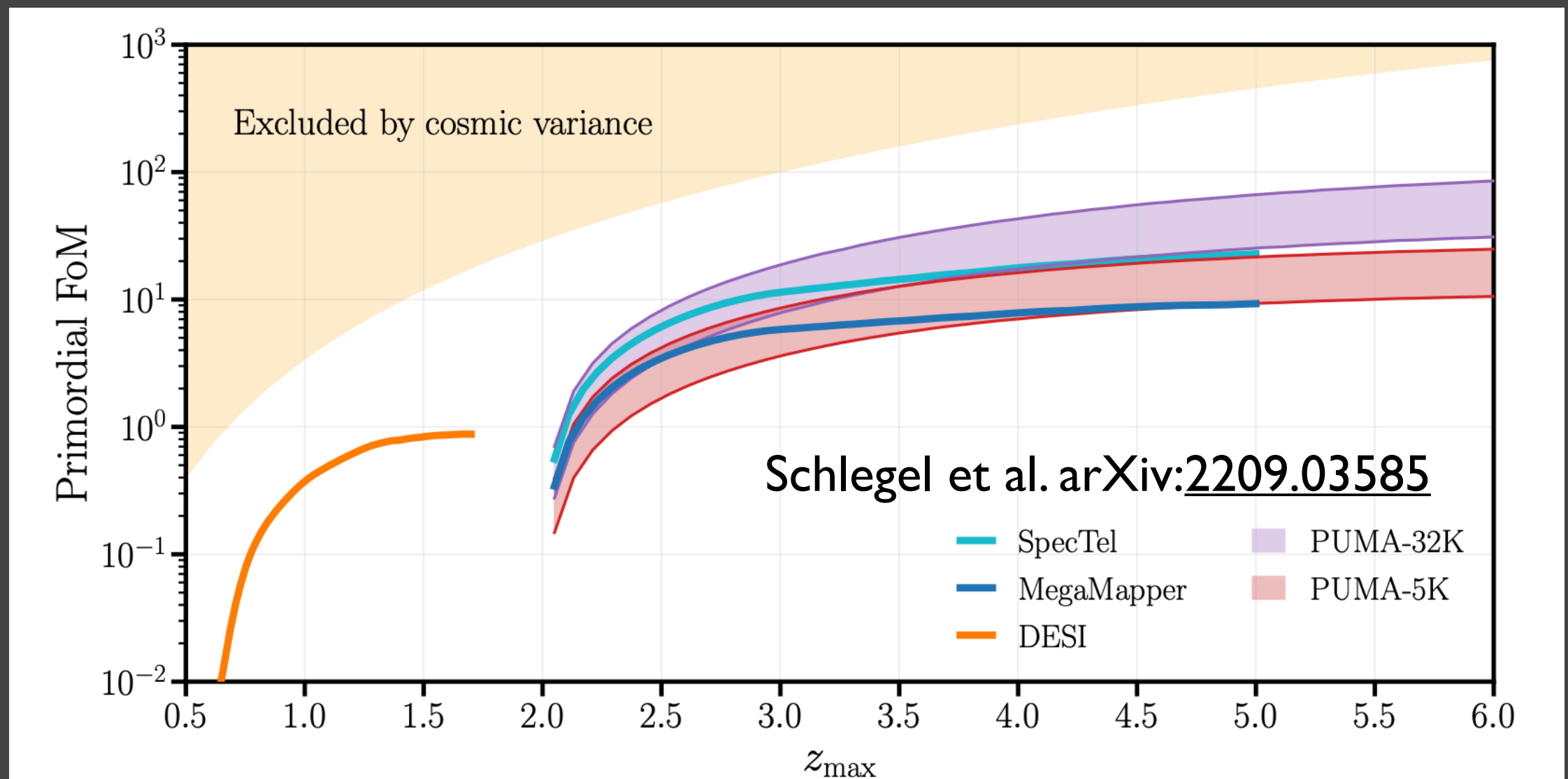
Roman Space Telescope

- Spectra via Grism
 - All light entering telescope is dispersed on same CCDs used for imaging survey
 - (No targets)
- Baseline survey: 0.6 yrs (within 5yr); 10^7 $1 < z < 2$ galaxy redshifts; 2000 deg²
- Dense sampling that fills $1.3 < z < 2$ gap



Spec S5

- New instrument to gather $\sim 20,000$ spectra at a time
- Project start in 2027, survey start in early 2030s



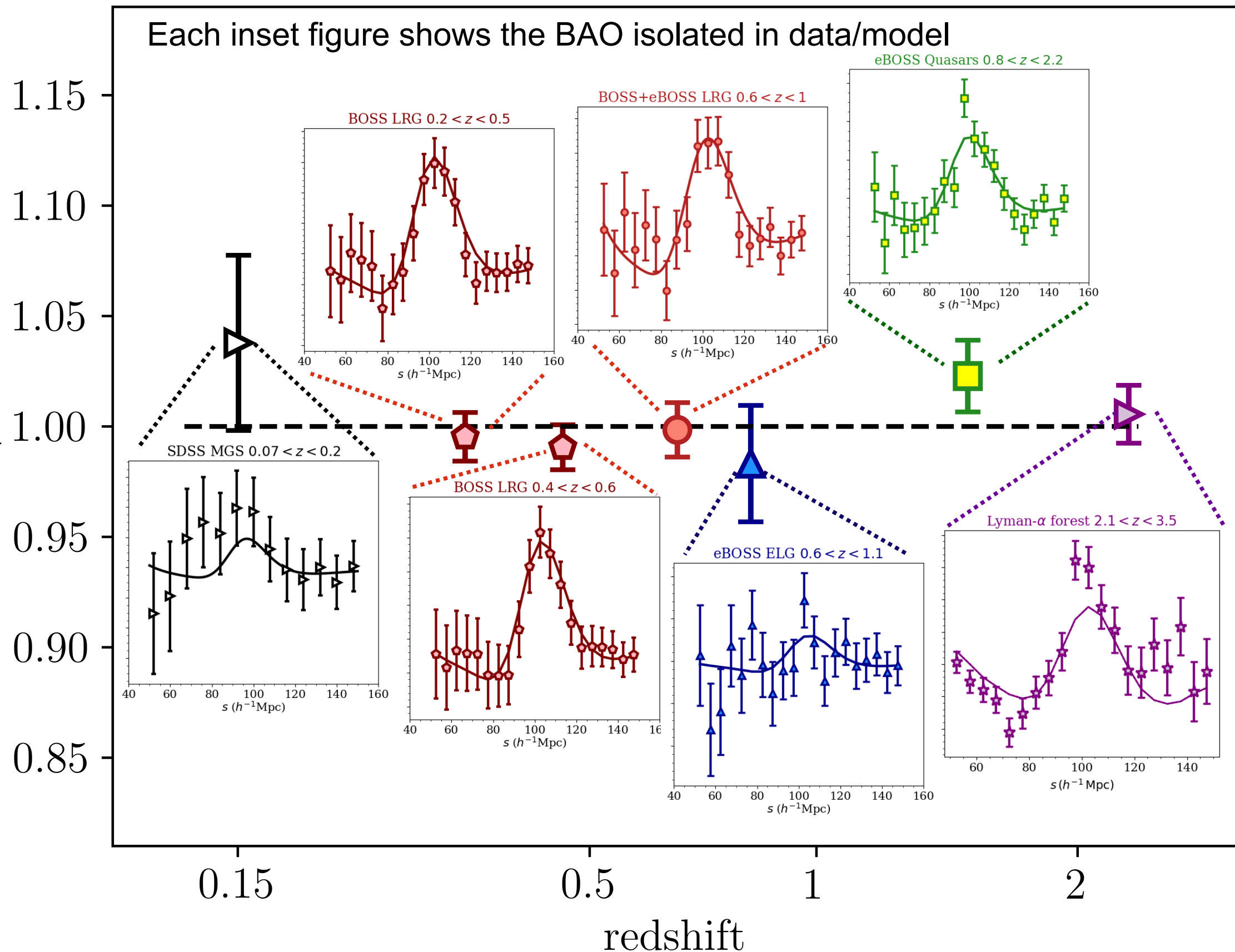
Conclusion

- DESI has produced the largest ever 3D map of cosmic structure
 - Will provide exciting new constraints on cosmology's biggest questions
 - 1st cosmology results spring 2024!
- After DESI, still at least 10x more volume to map
 - Circa 2040, we should have better knowledge of the physics that produced initial structure!

BAO from SDSS

SDSS BAO Distance Ladder

BAO Measurement/Planck 2018 Λ CDM



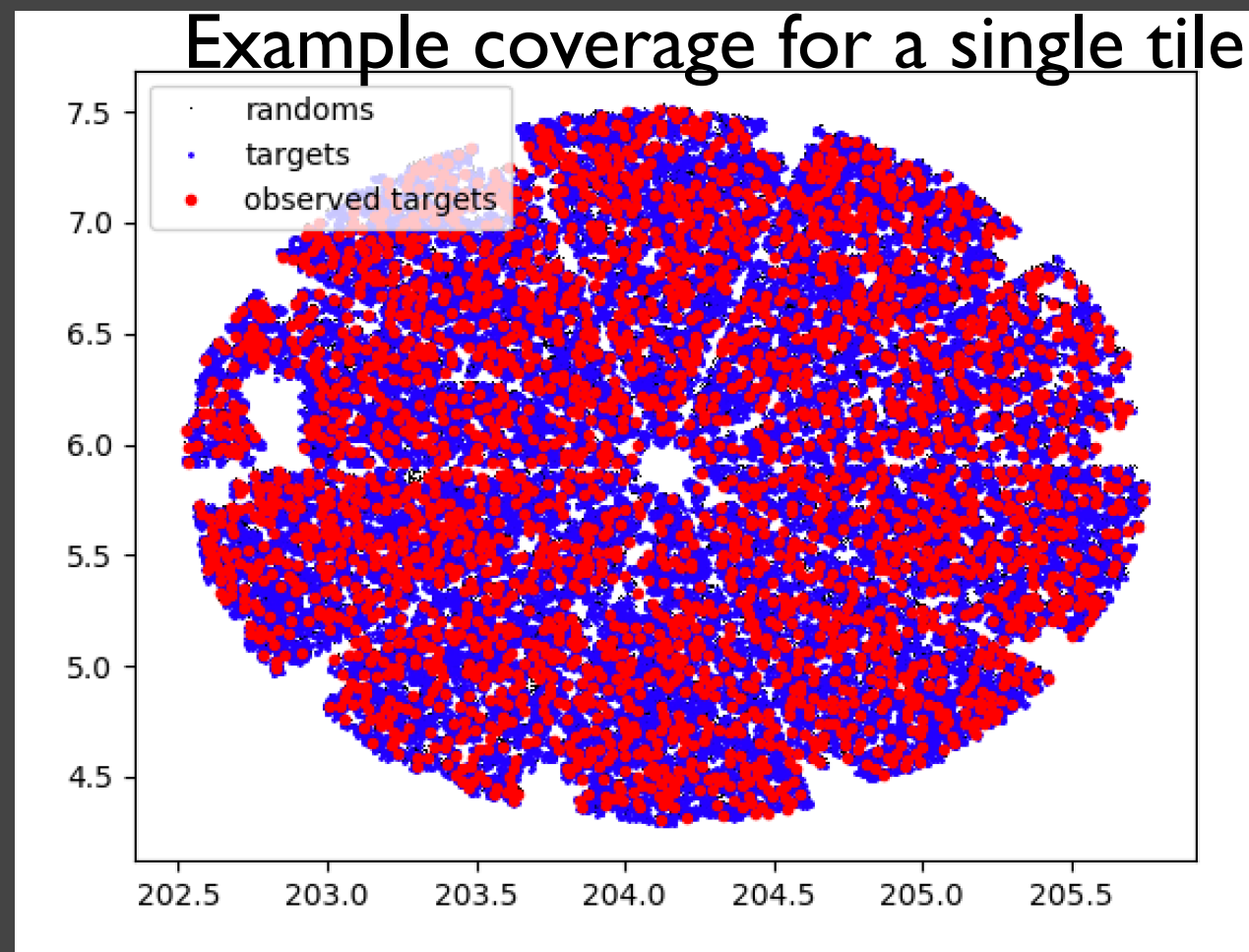
Inflation

- Crazy: Universe expands by factor $> 10^{26}$ when Universe is 10^{-36} seconds old
 - Solve flatness and horizon problems
- (Some debate remains)
- Seeds all structure formation
 - *Any model (inflation or otherwise) needs to predict any statistics we measure for primordial density field

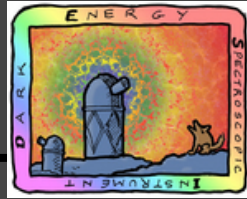
DESI: Observations



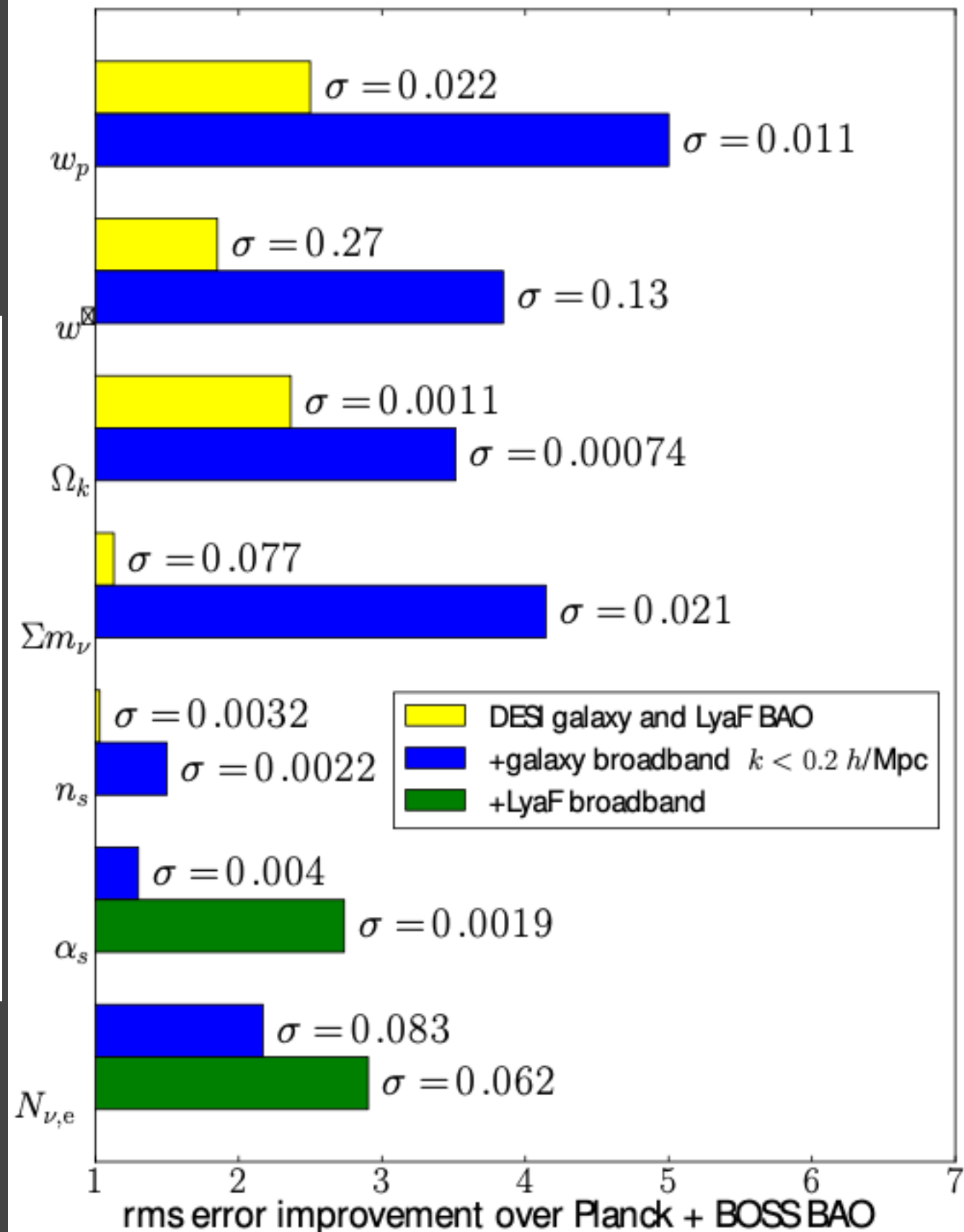
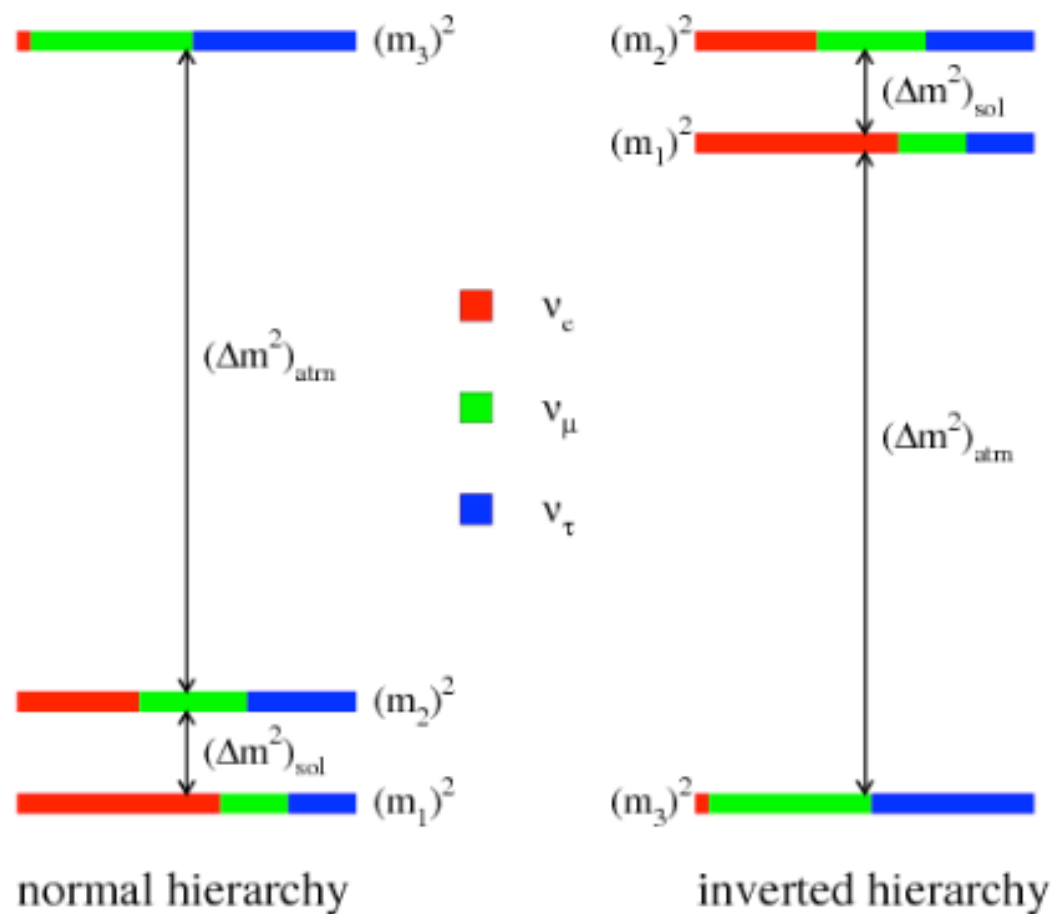
- “tile” by tile, no overlaps until tile validated based on results of spectroscopic pipeline
 - Tile pattern dithered 7 times for dark time and 4 for bright
 - Daily QA of automated pipeline results allows fast buildup in overlapping coverage



Neutrino Mass



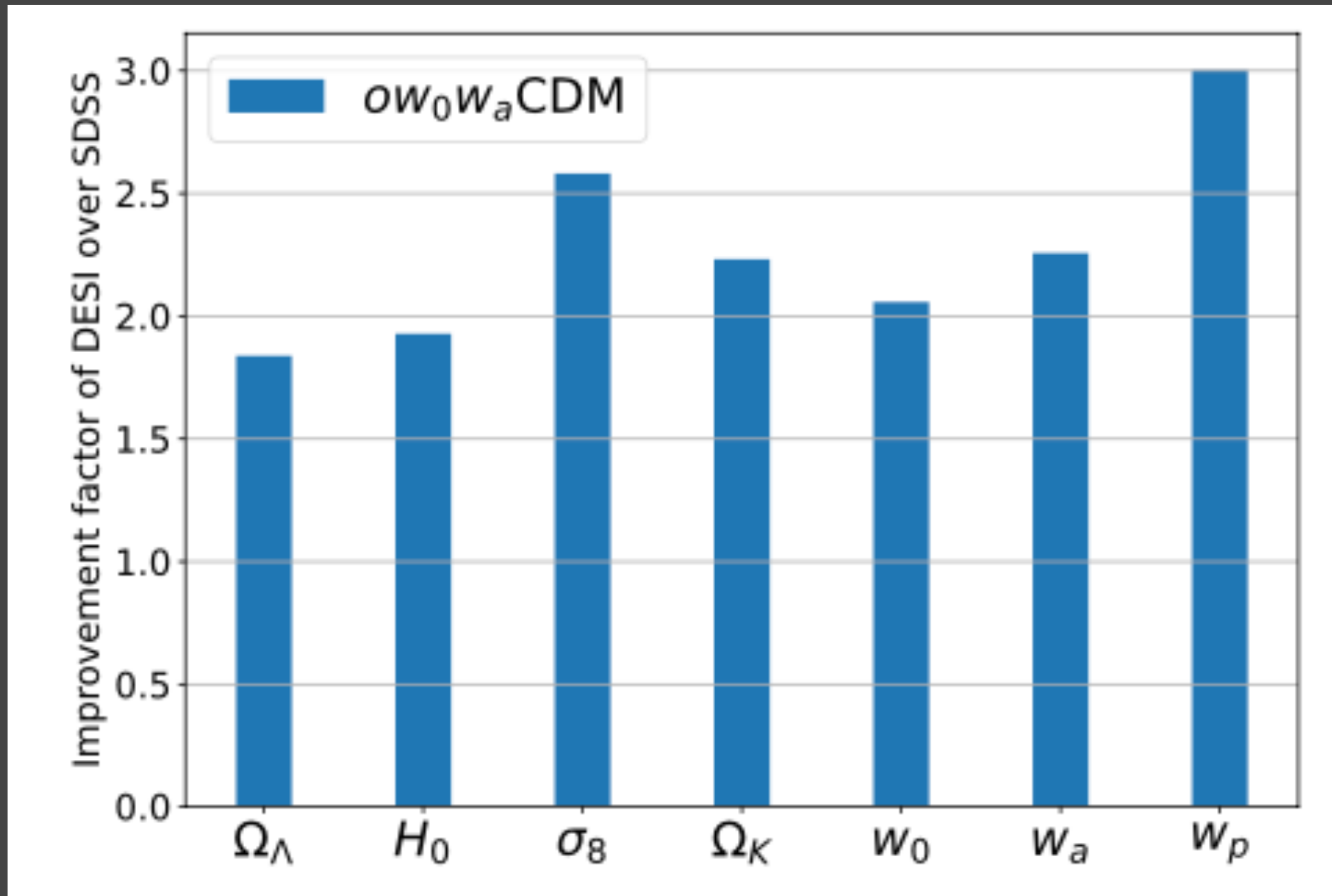
- Forecasts from arXiv:1611.00036



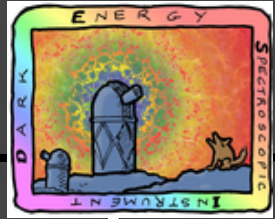
Updated forecast



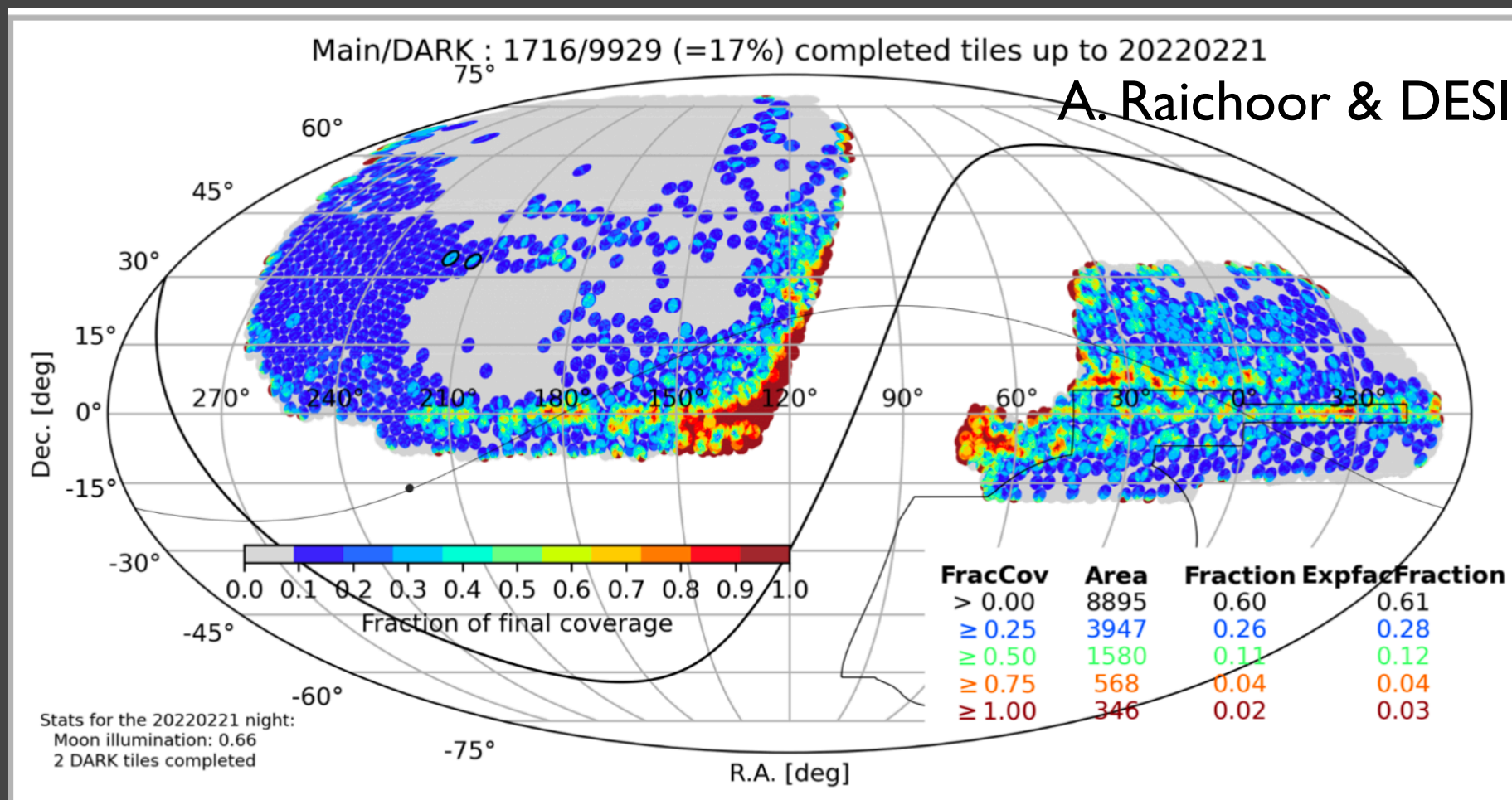
- Forecasts from
arXiv:2306.06307



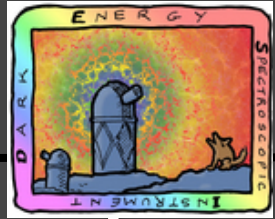
DESI: Observations



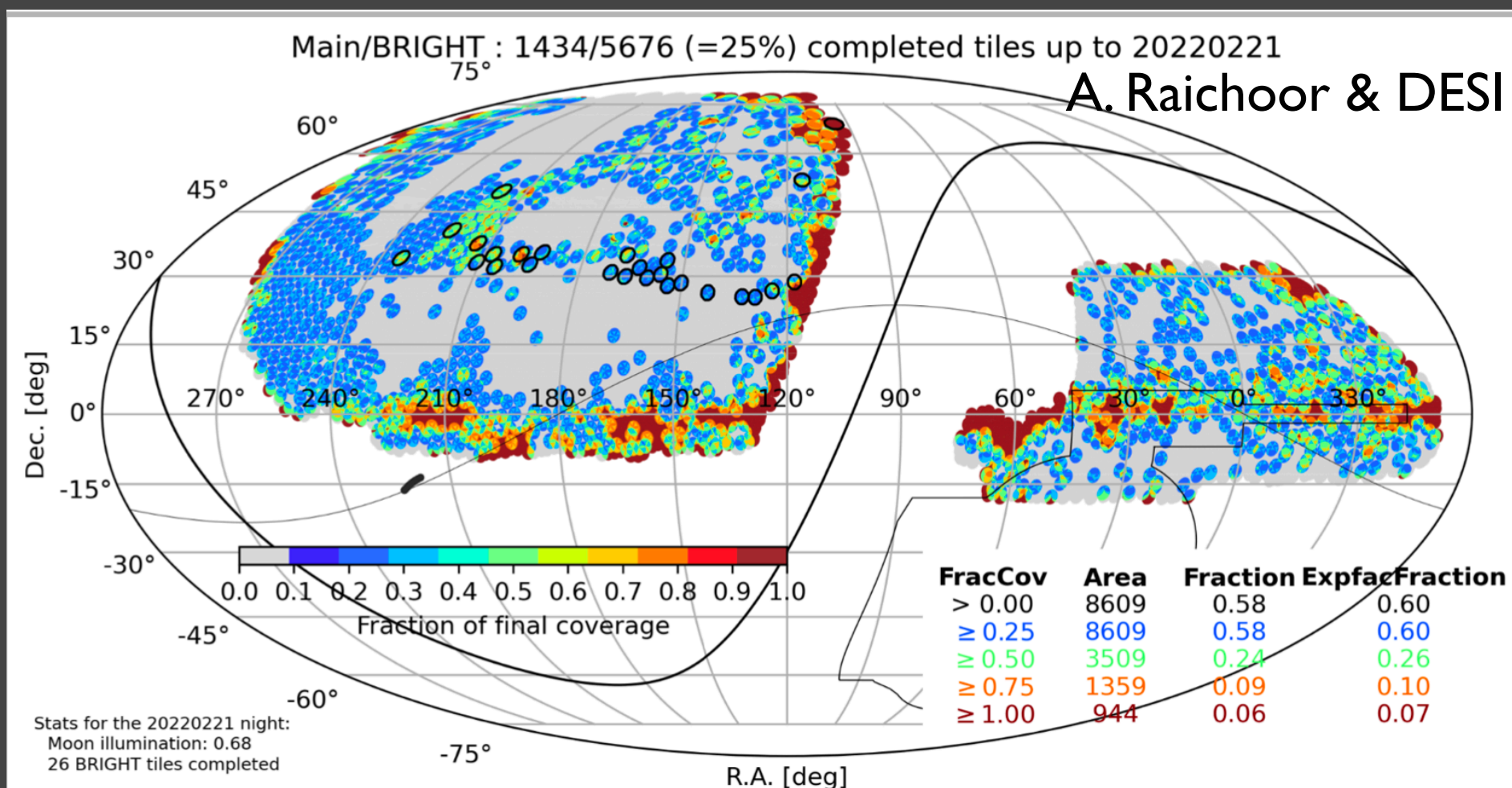
- “tile” by tile, no overlaps until tile validated based on results of spectroscopic pipeline
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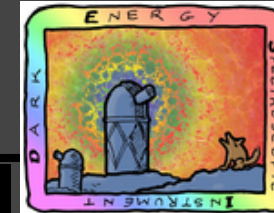
DESI: Observations



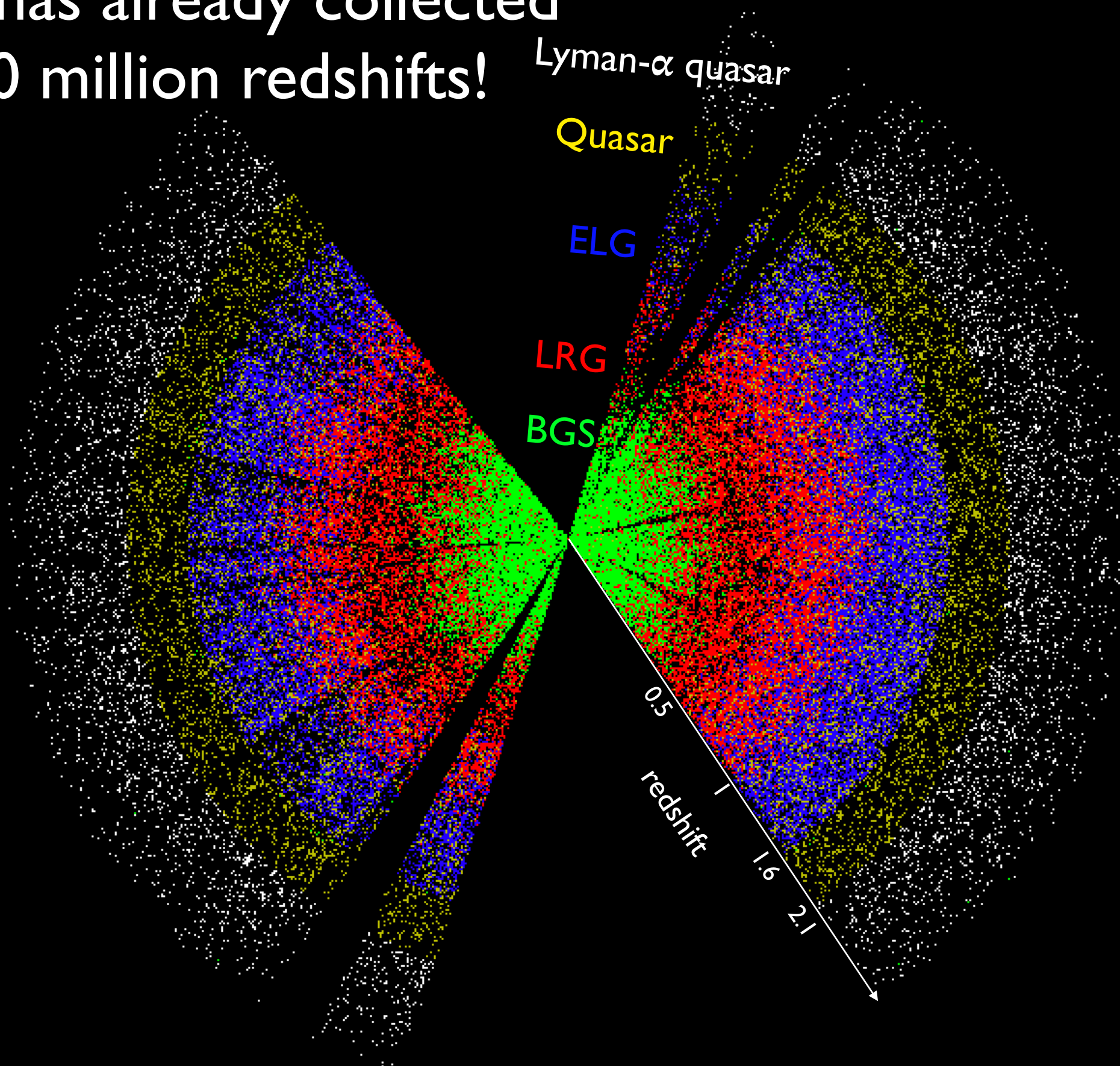
- “tile” by tile, no overlaps until tile validated based on results of spectroscopic pipeline
- Tile pattern dithered 7 times for dark time and 4 for bright
- Daily QA of automated pipeline results allows fast buildup in overlapping coverage



DESI



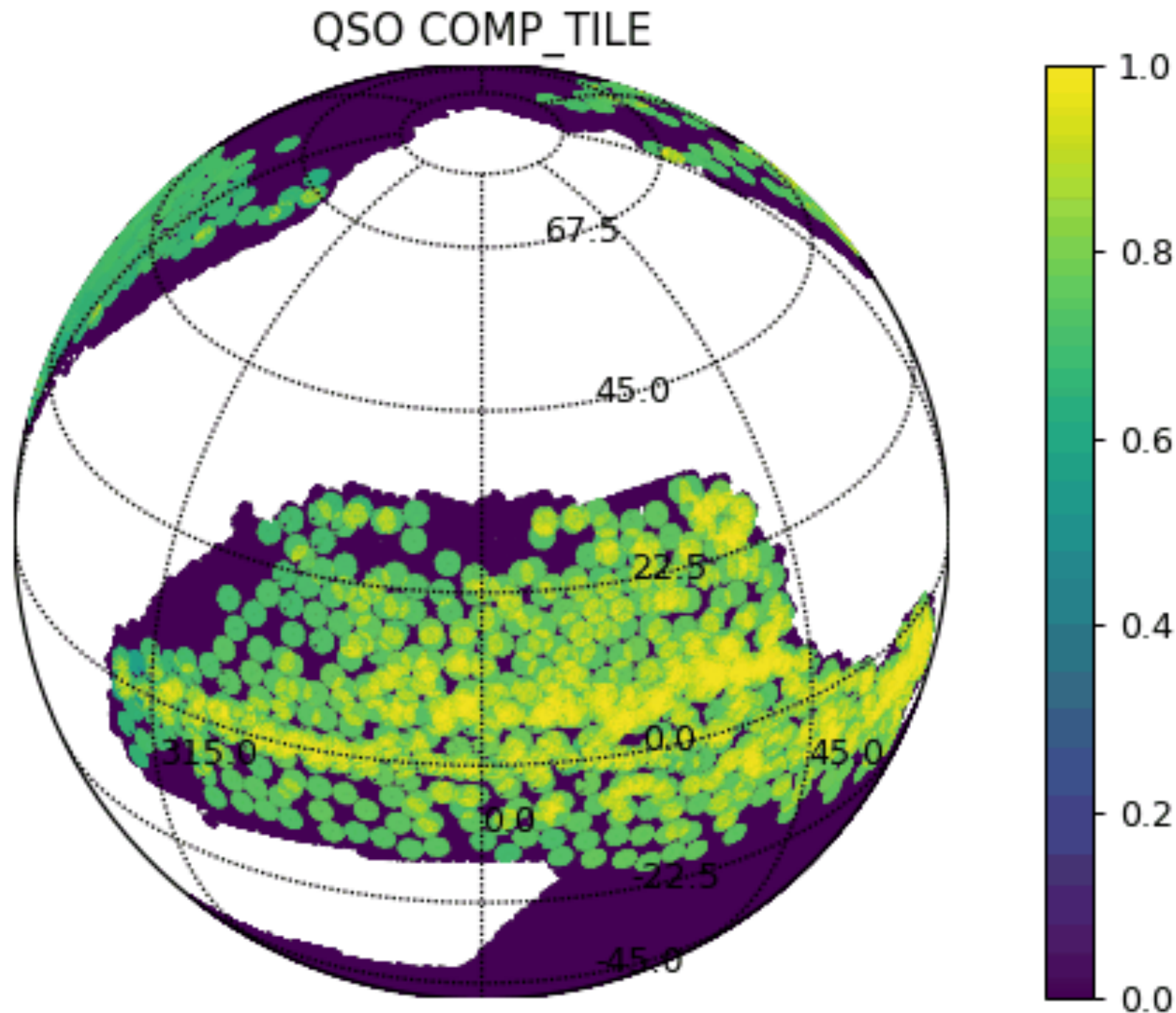
DESI has already collected
>10 million redshifts!



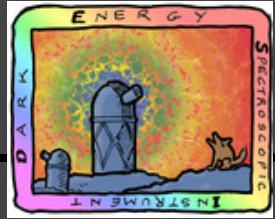
DESI: ~current QSO status



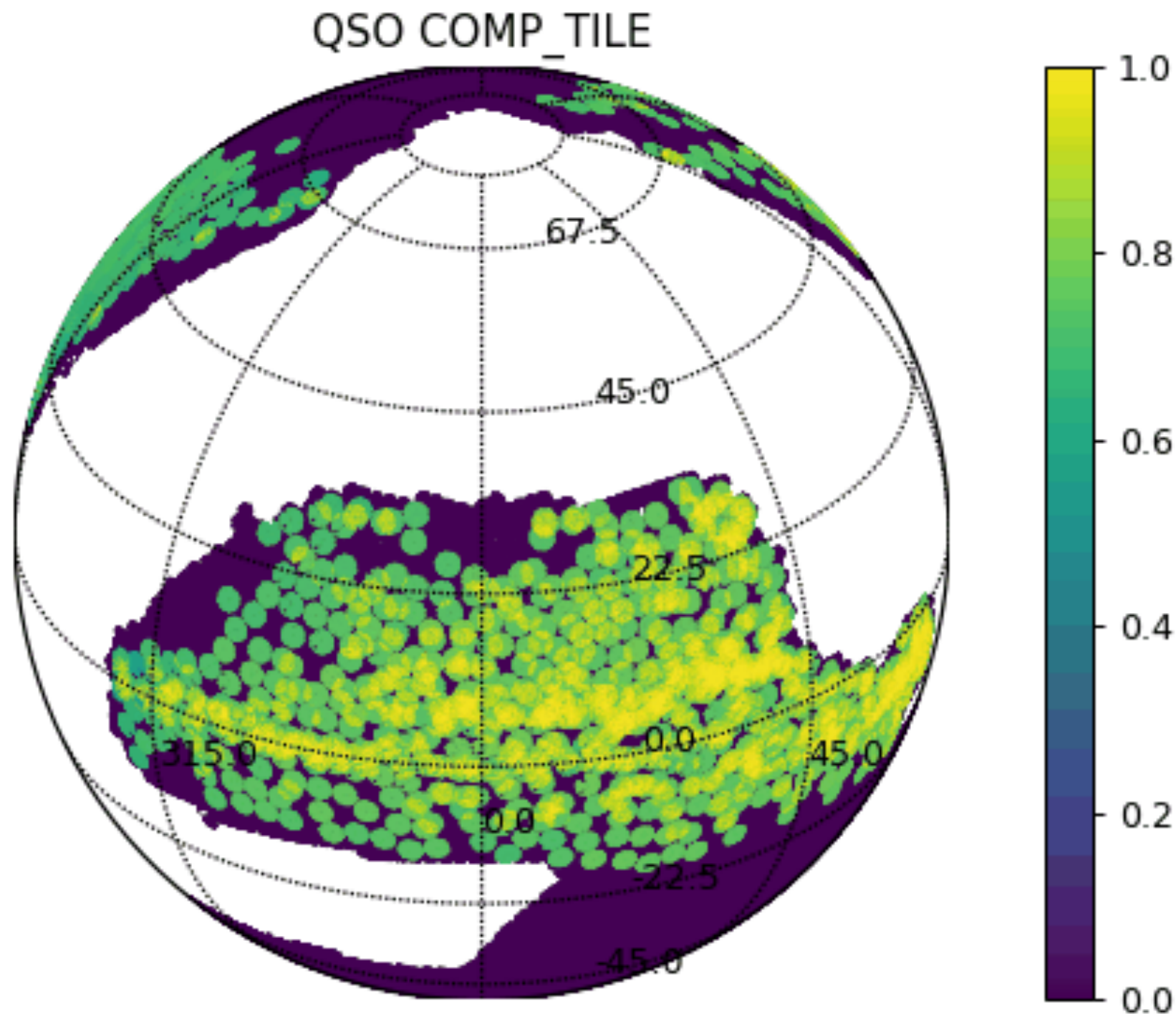
- 1,113,138 good redshifts



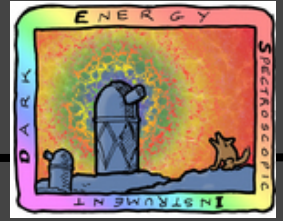
DESI: ~current QSO status



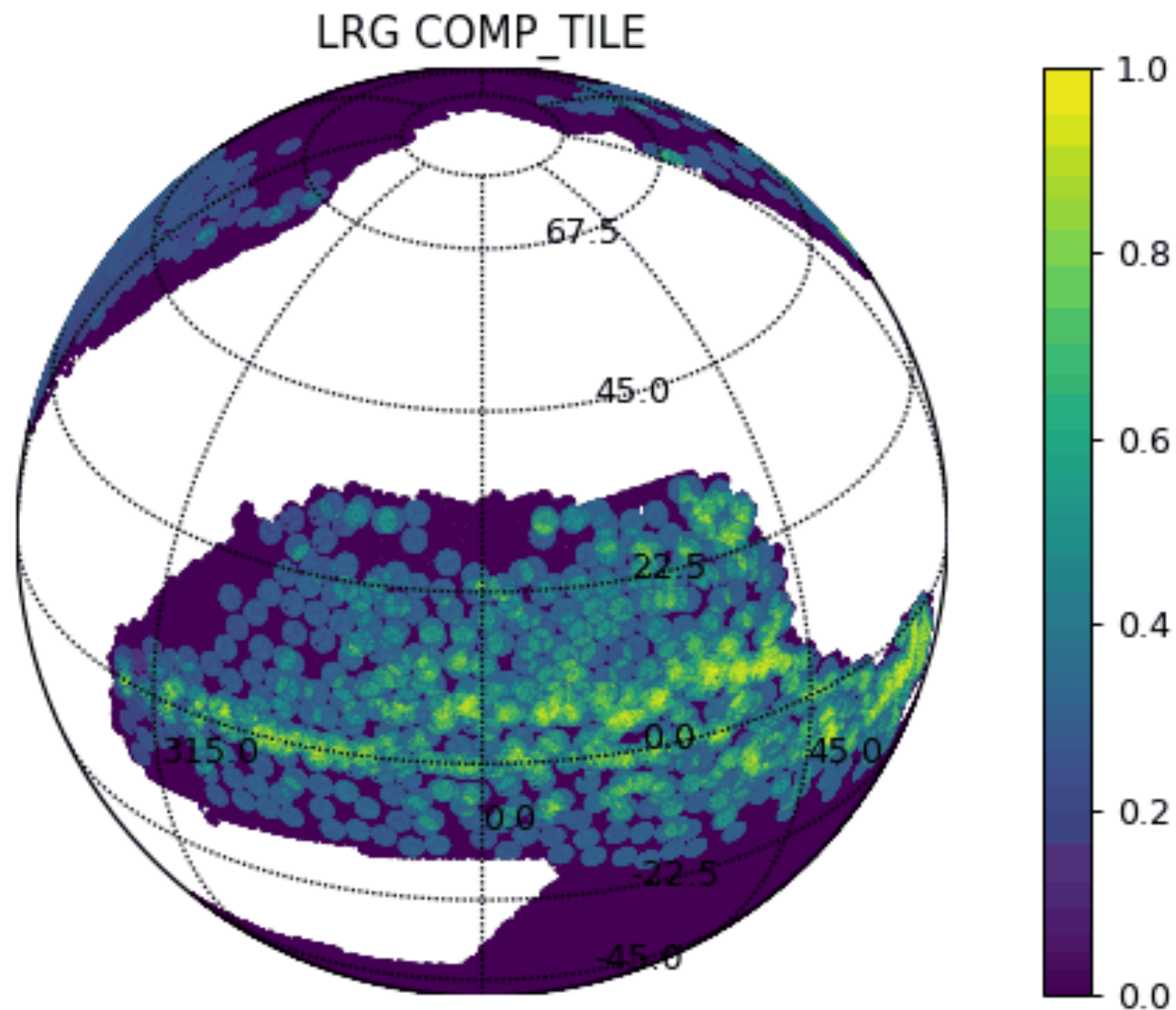
- 1,113,138 good redshifts



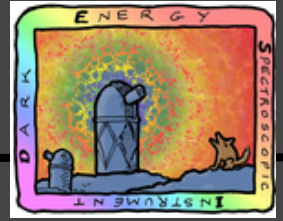
DESI: ~current LRG status



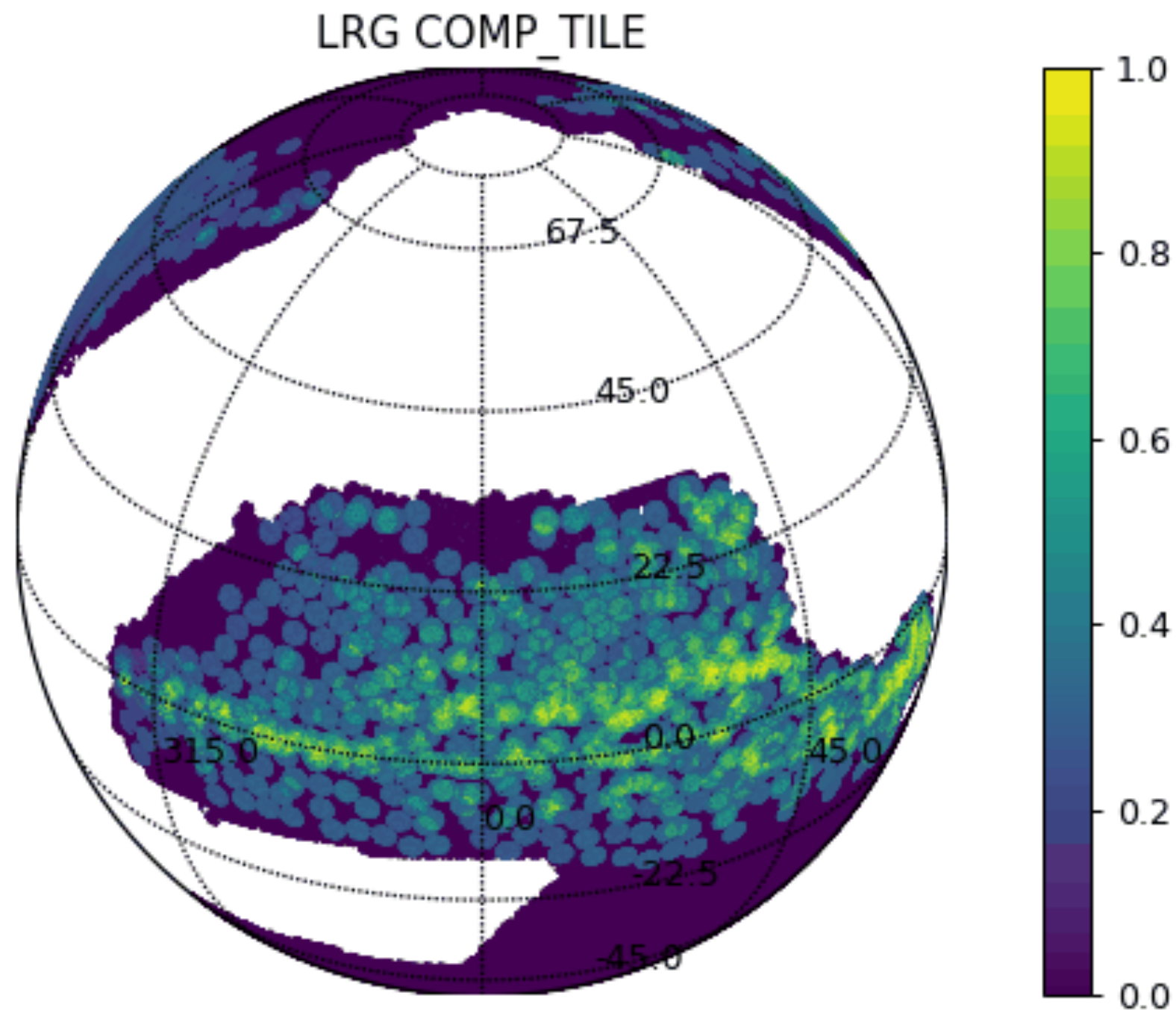
- 1,636,395 good redshifts



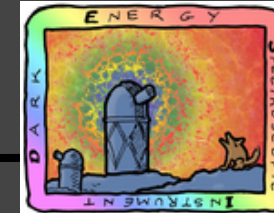
DESI: ~current LRG status



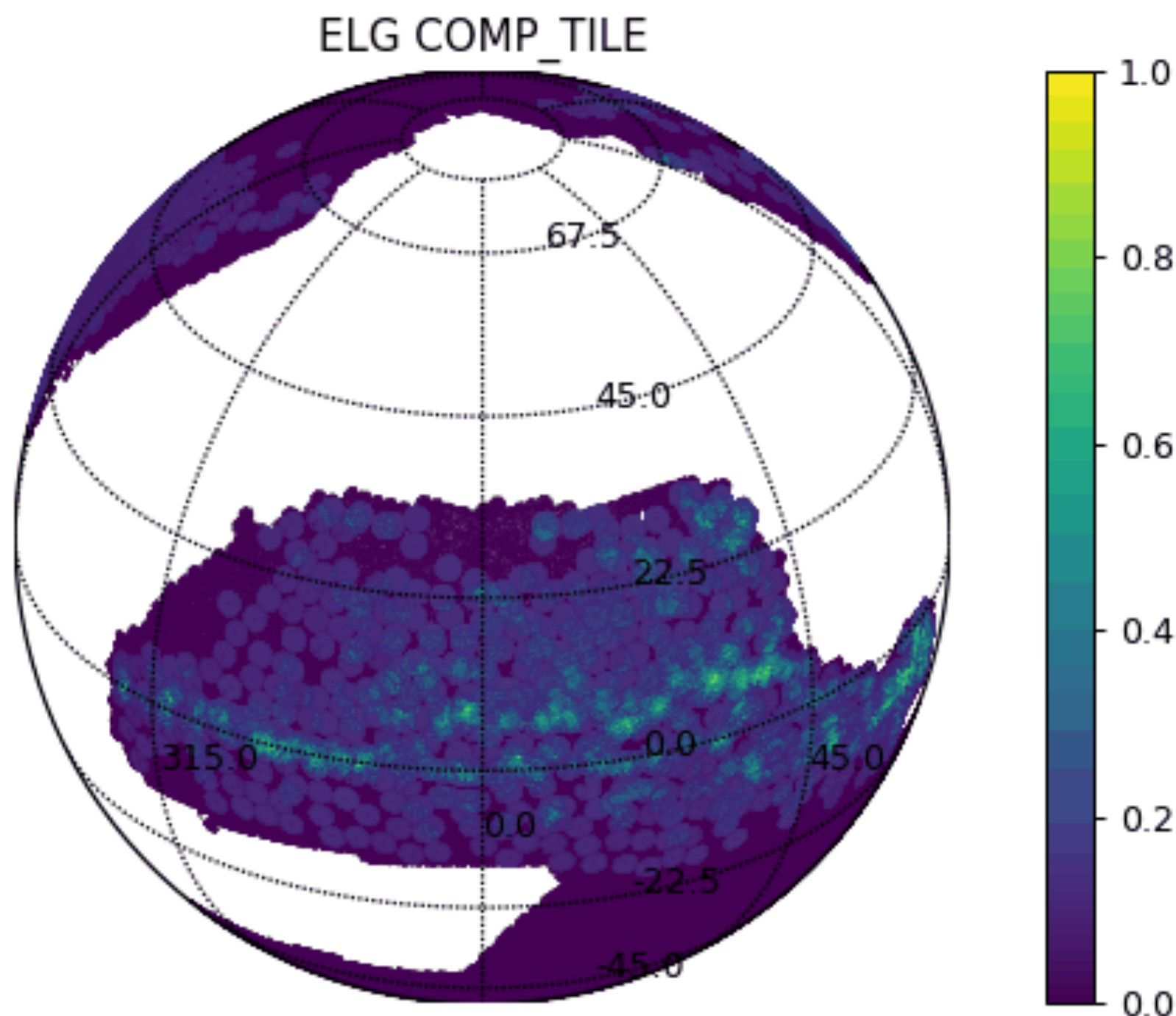
- 1,636,395 good redshifts



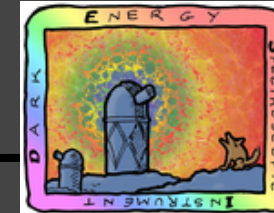
DESI: ~current ELG status



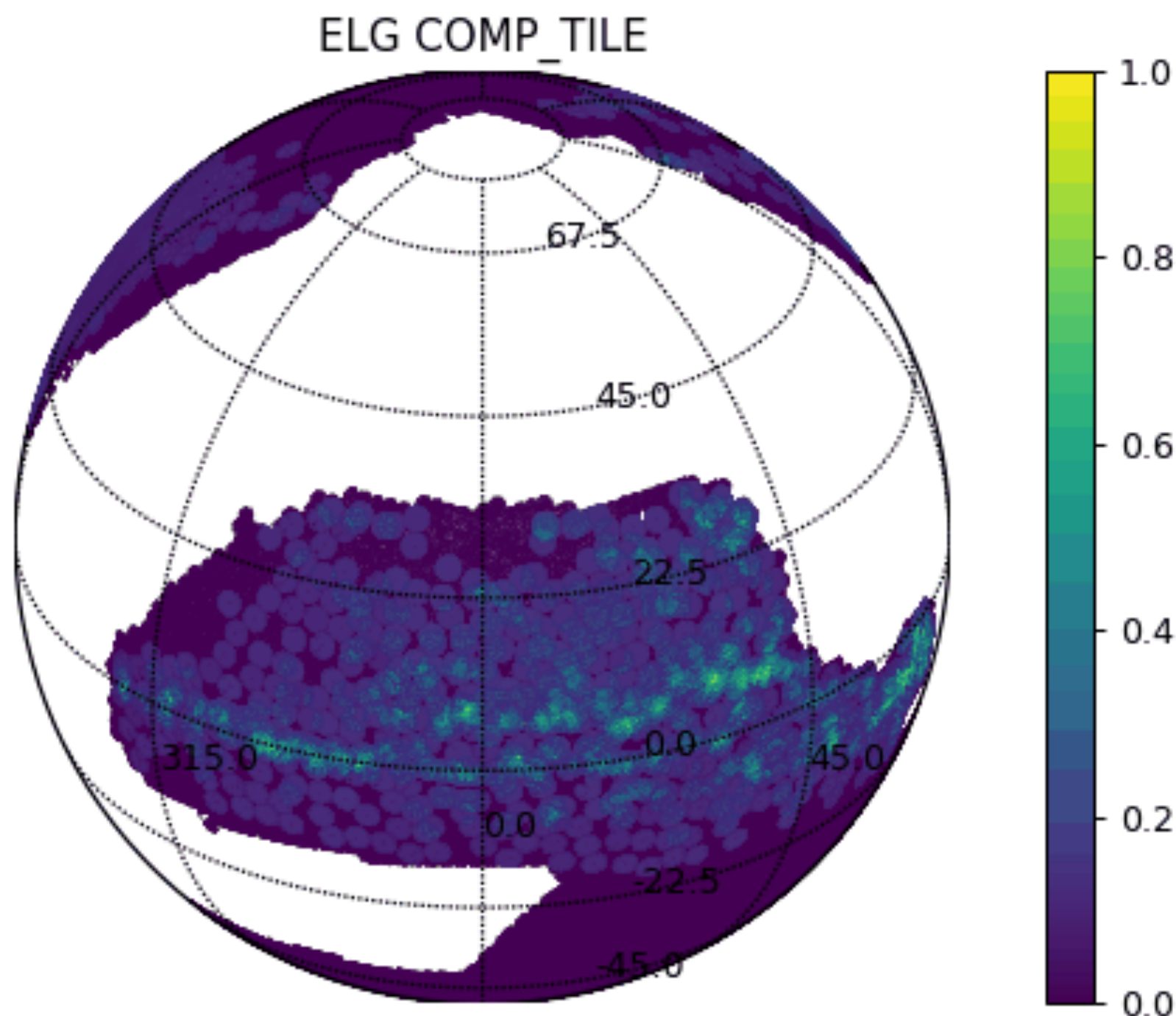
- 2,343,111 good redshifts



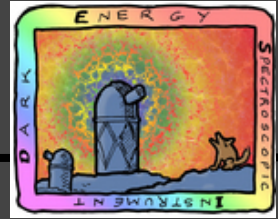
DESI: ~current ELG status



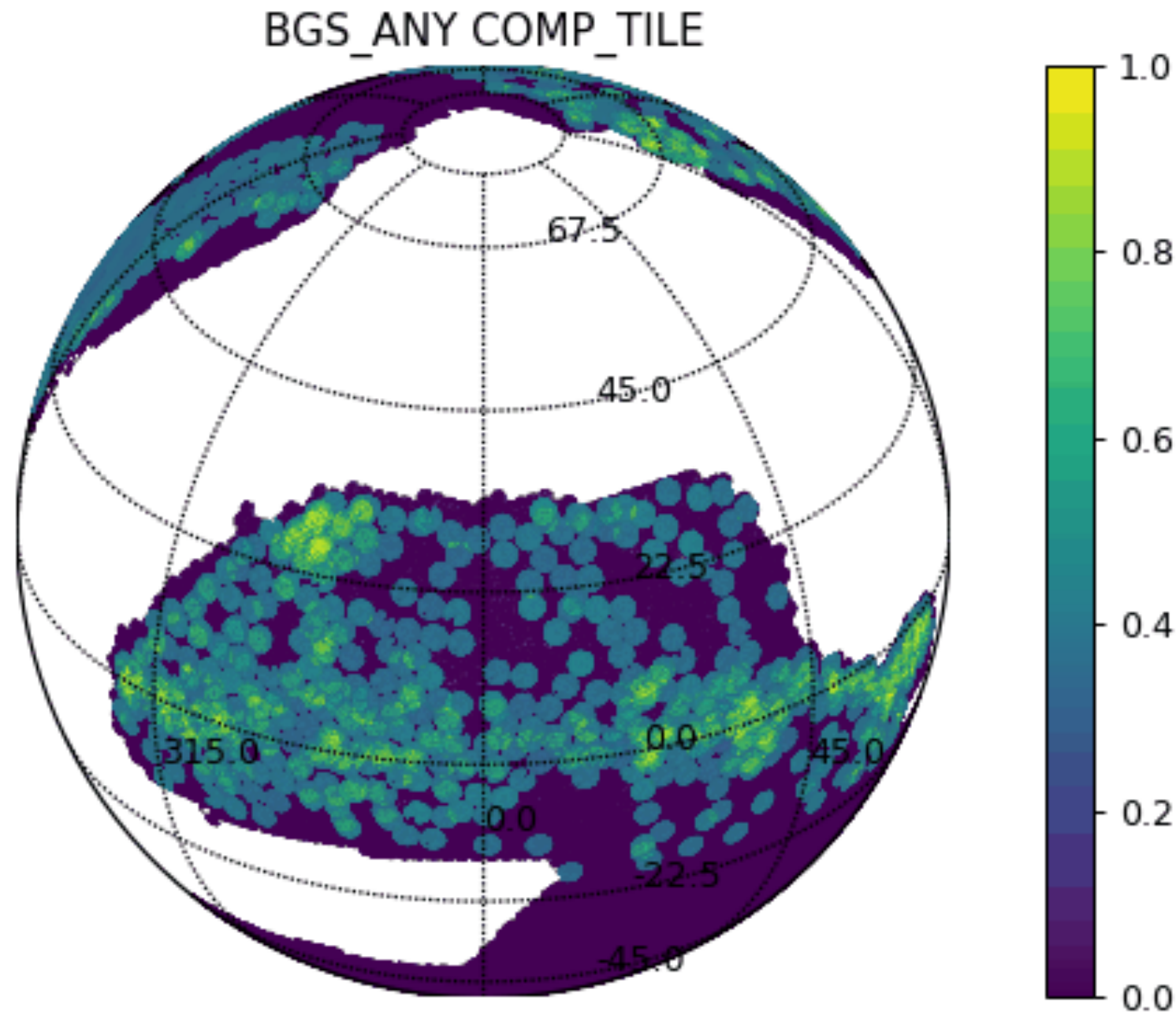
- 2,343,111 good redshifts



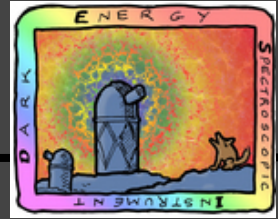
DESI: ~current BGS status



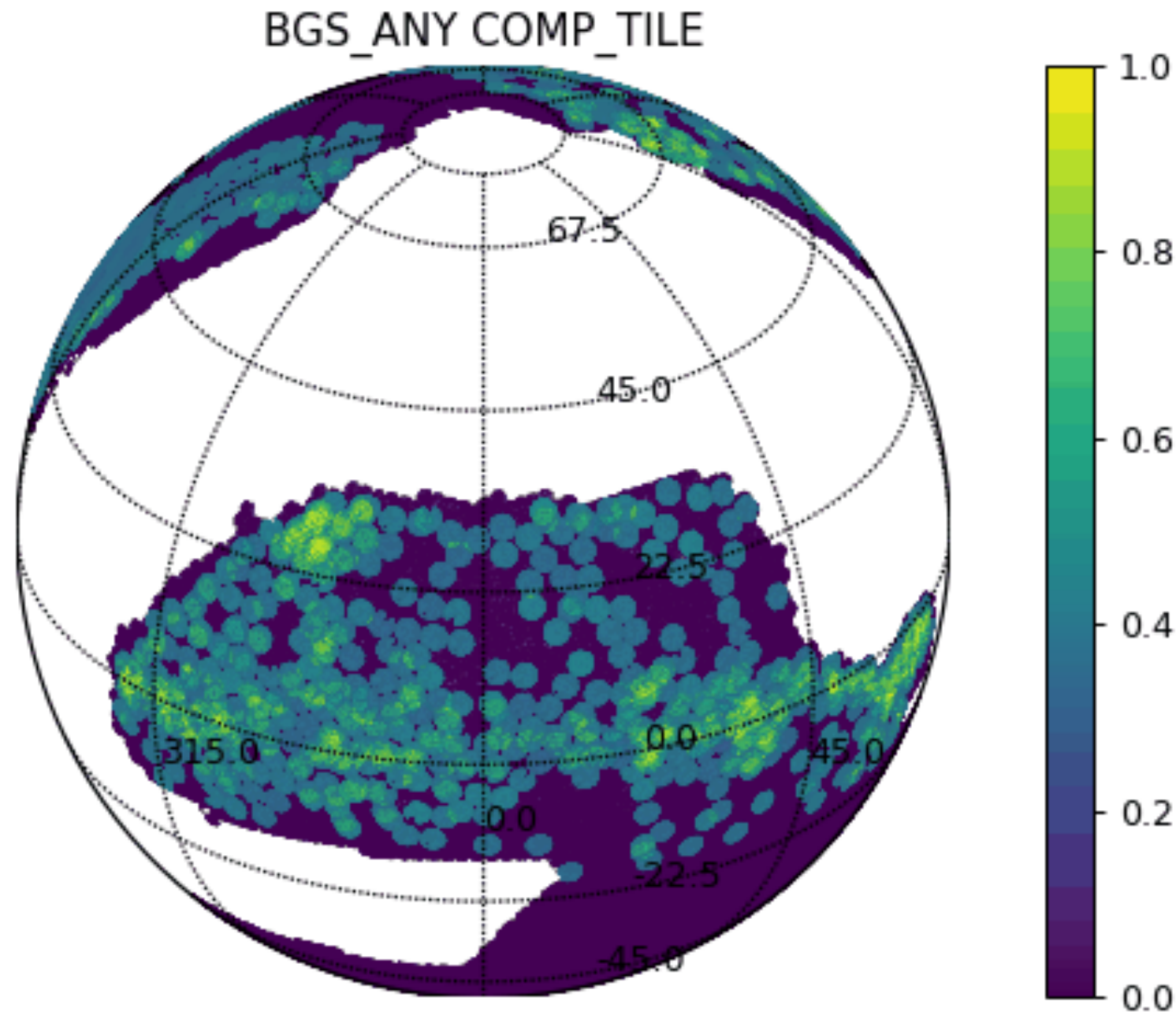
- 4,140,227 good redshifts



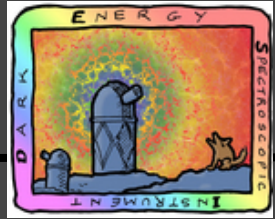
DESI: ~current BGS status



- 4,140,227 good redshifts

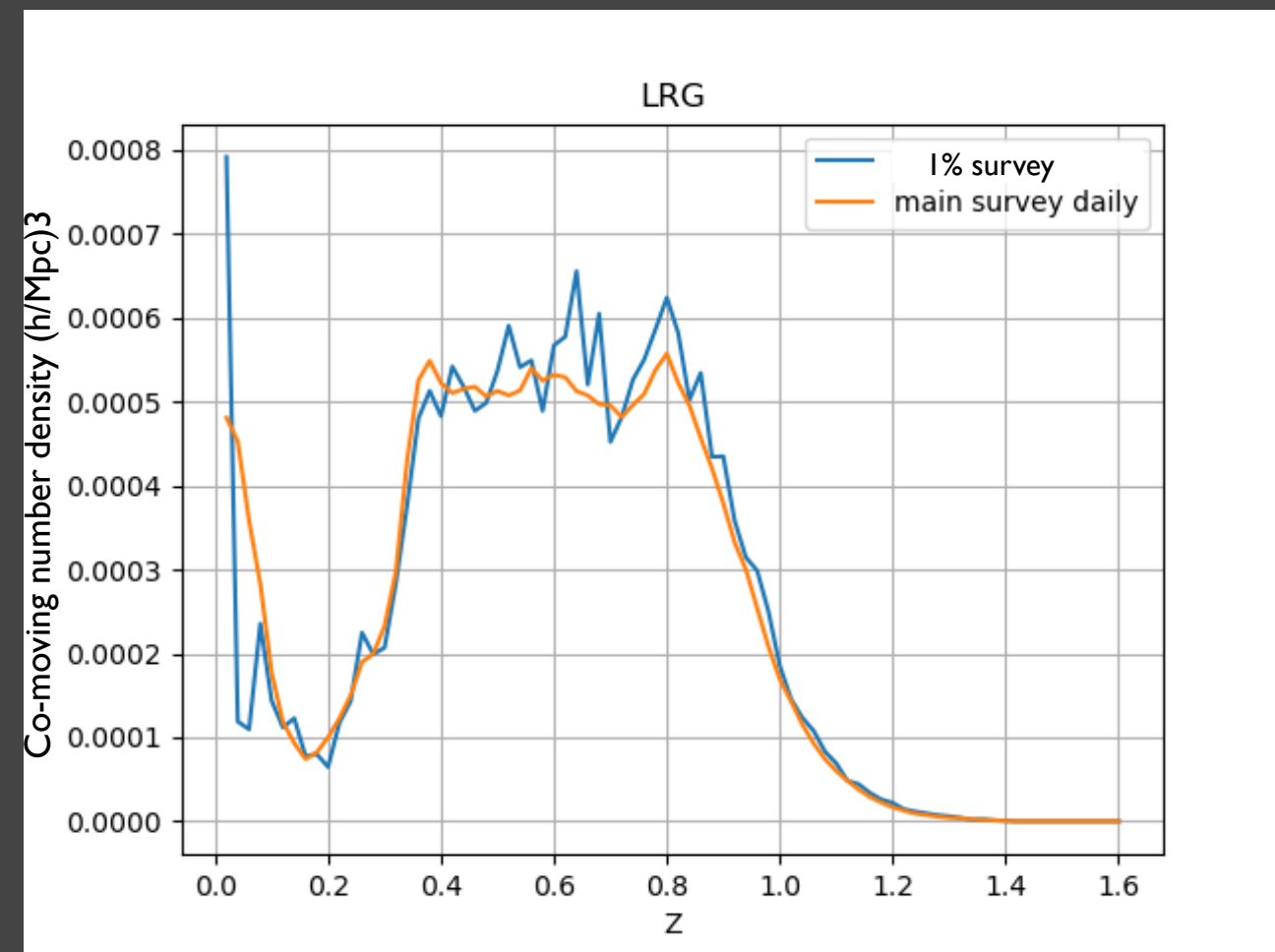
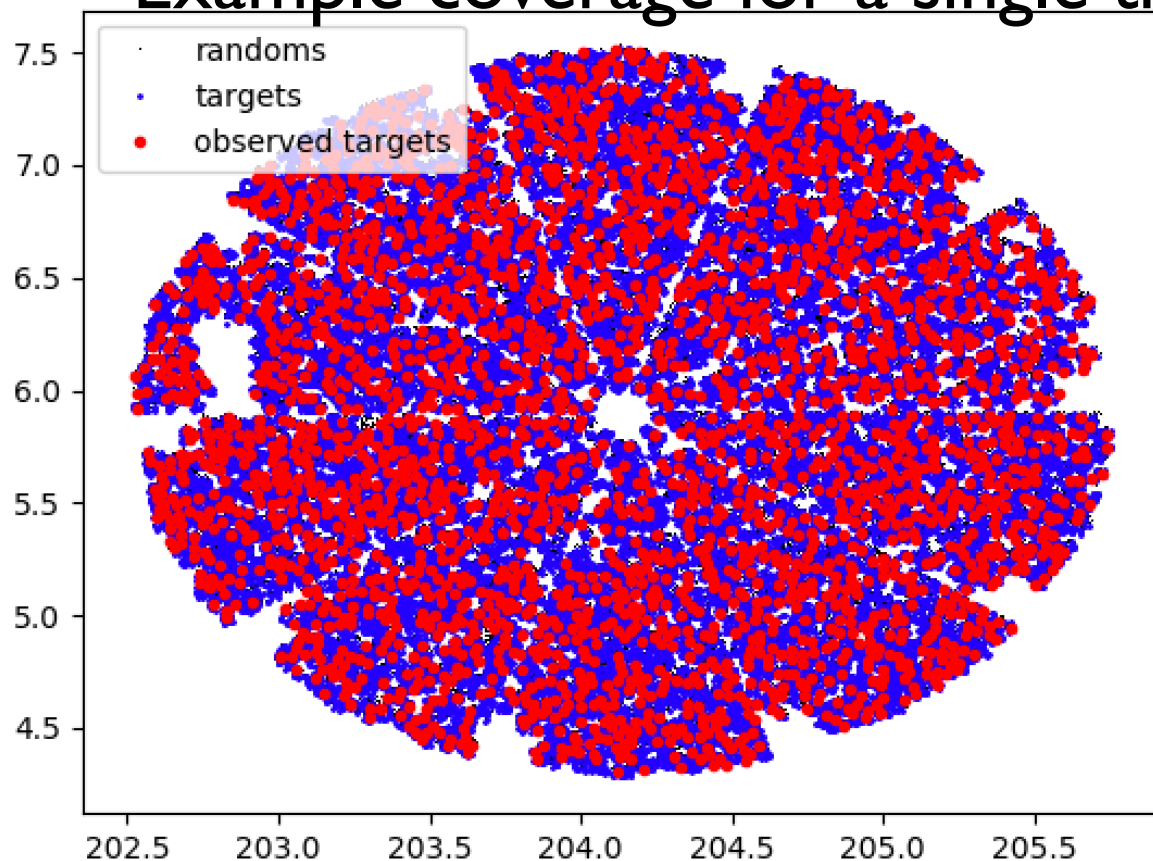


DESI: LSS catalogs

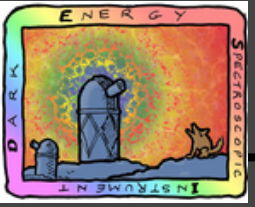


- Clustering statistics are calculated comparing distribution of data to a random sample
 - e.g., the (normalized) number of data pairs compared to random pairs at a given separation
- Randoms are uniform within the “selection function” of the data

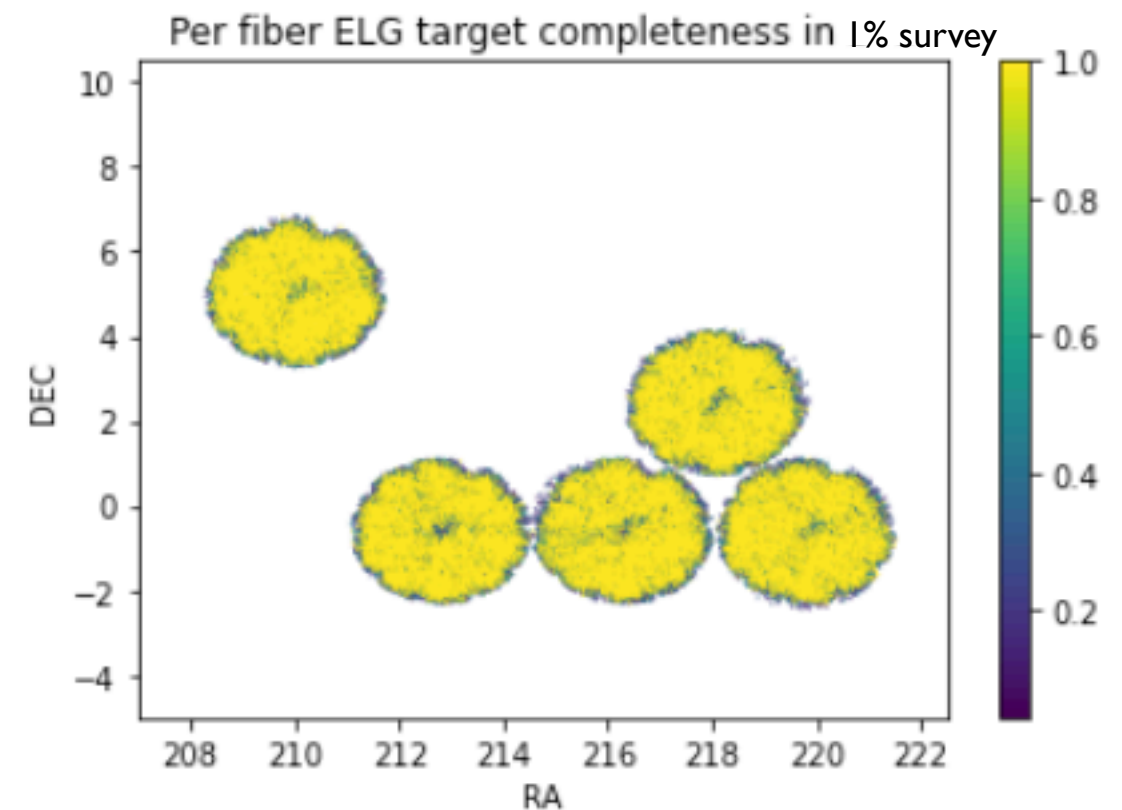
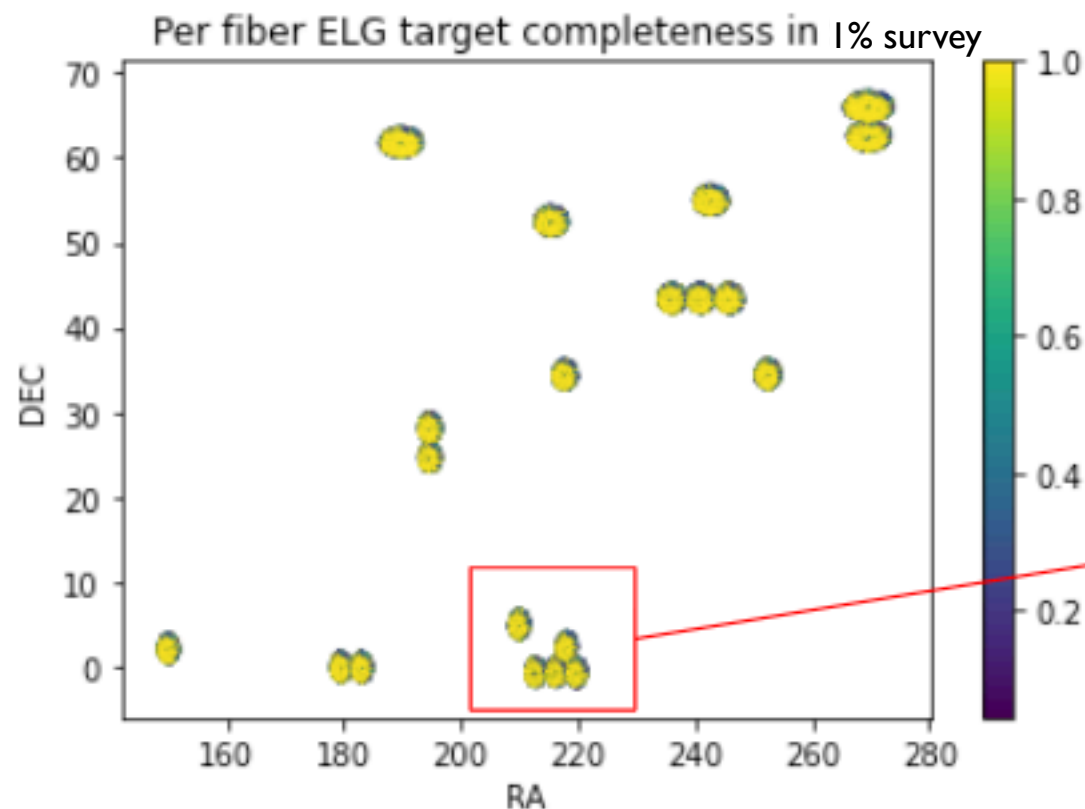
Example coverage for a single tile



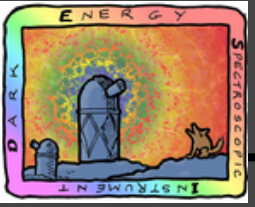
DESI LSS catalogs



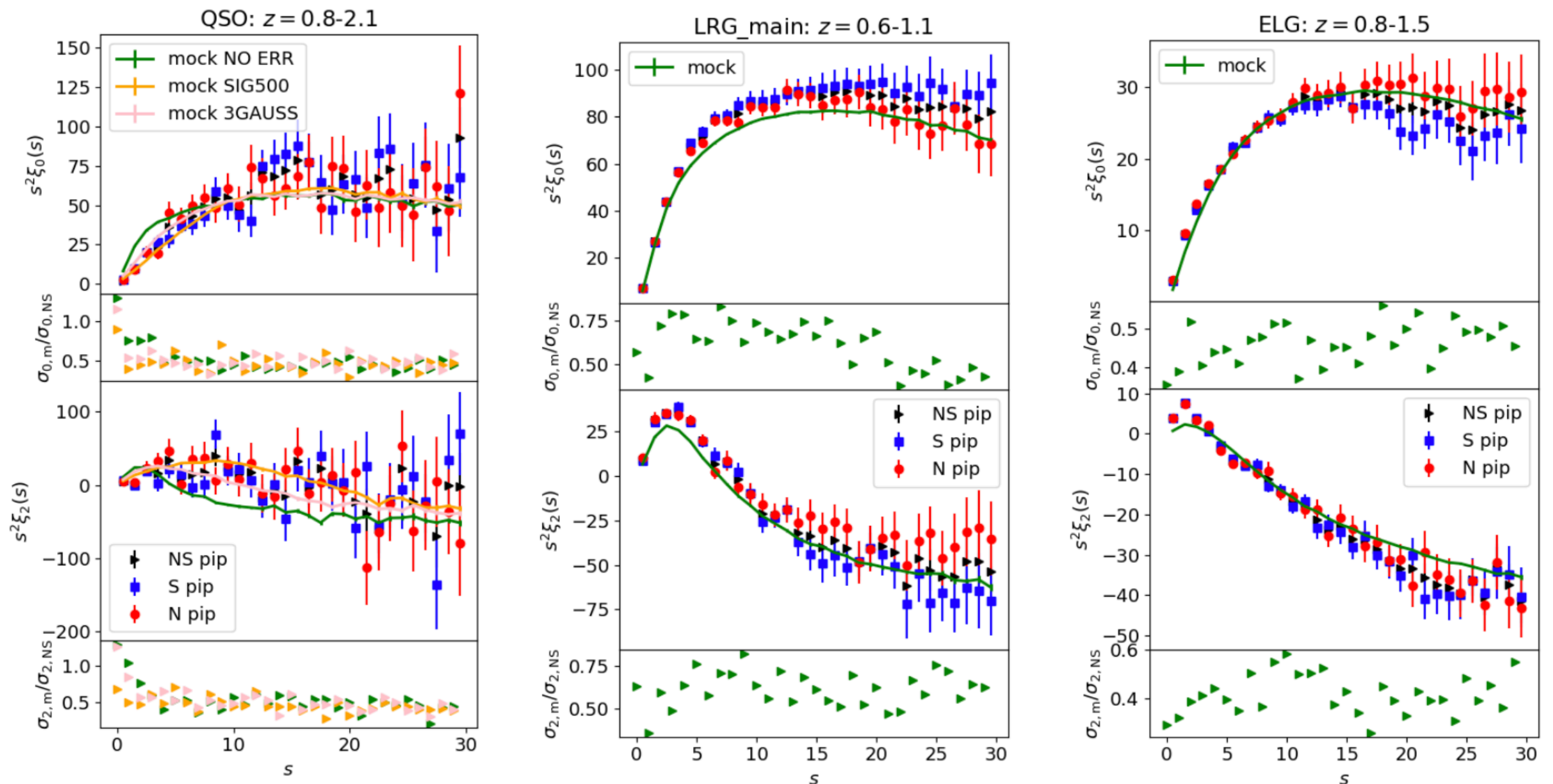
- Most of data taken is currently kept blind from clustering analysis
- Two sets of data allowed to be analyzed:
- “1% Survey”
- High completeness allows confident measure of small-scale clustering and informs mock creation
- 278,978 ELGs, 128,683 LRGs, 36,111 QSOs, 245,566 BGS



DESI 1% survey clustering

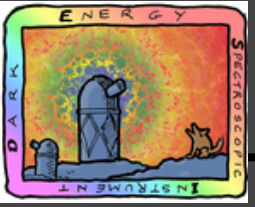


- High completeness allows confident measure of small-scale clustering and informs mock creation
- 278,978 ELGs, 128,683 LRGs, 36,111 QSOs, 245,566 BGS

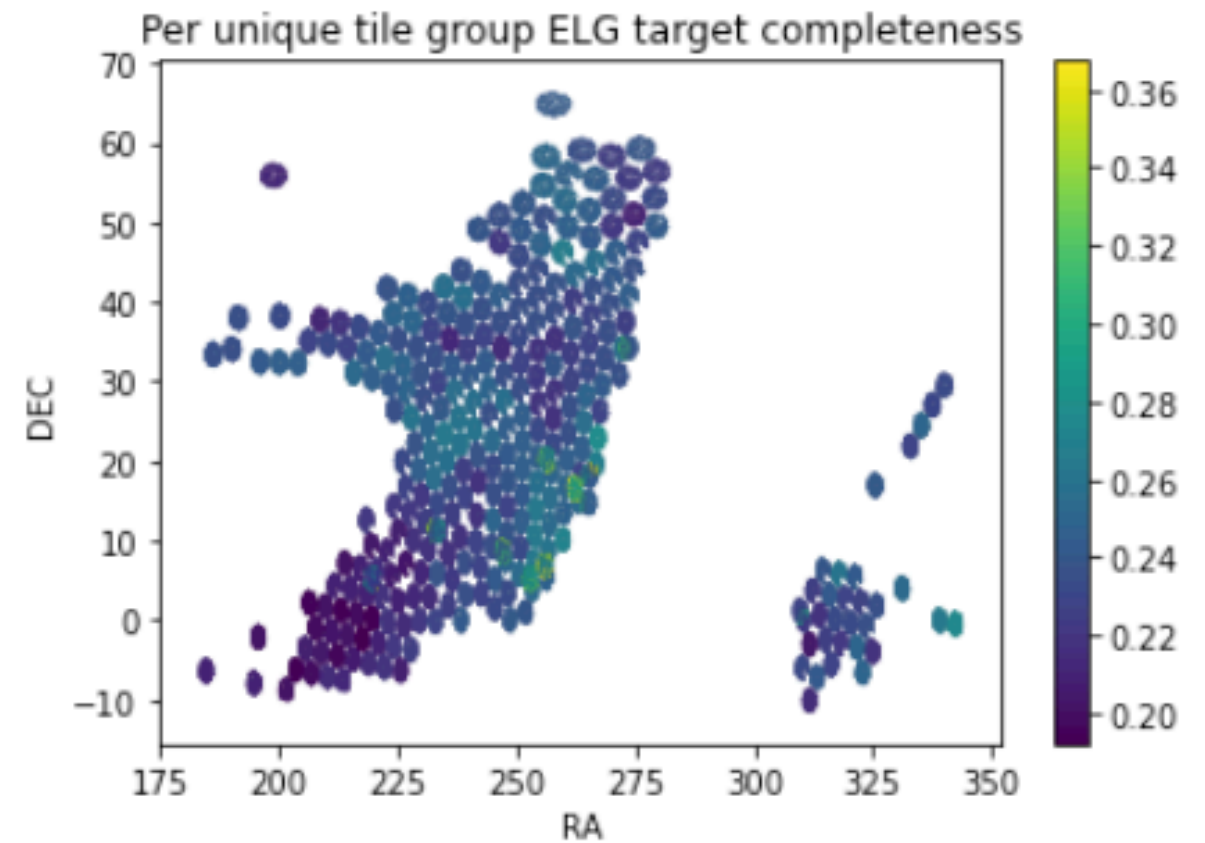
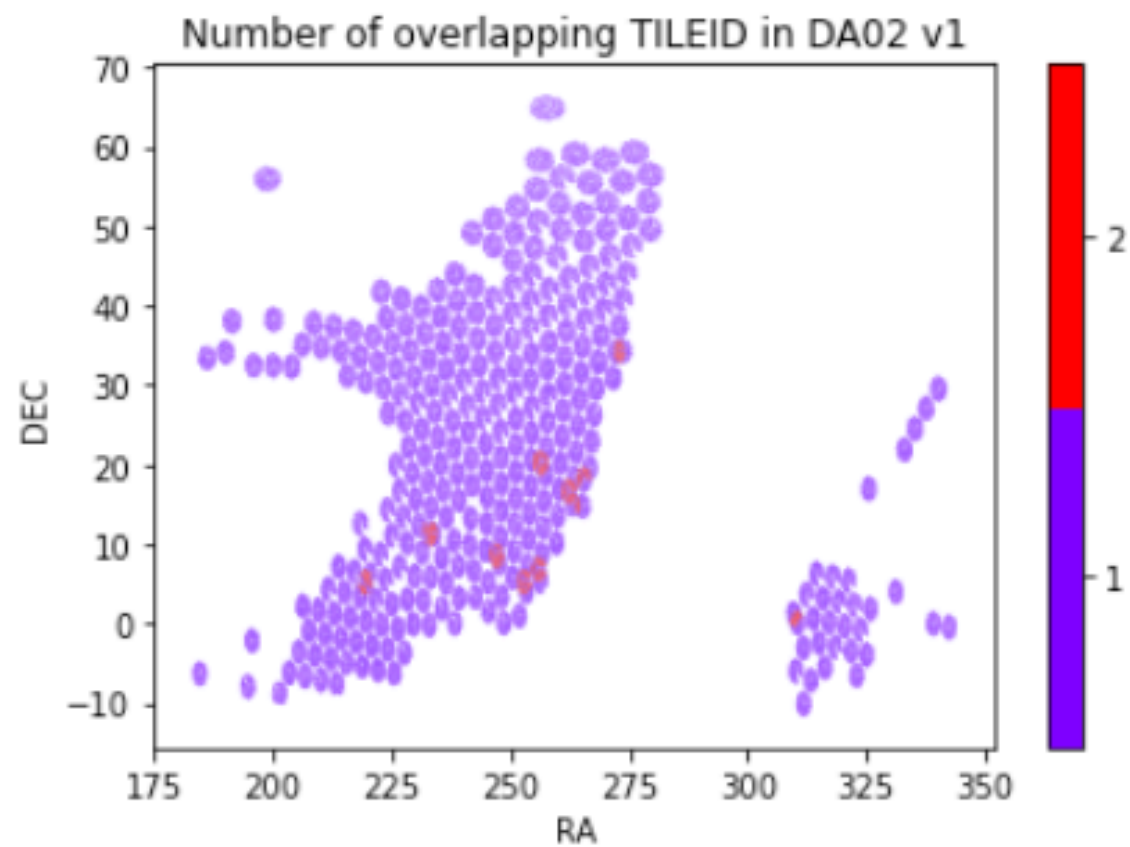


Plots from Andrei Variu

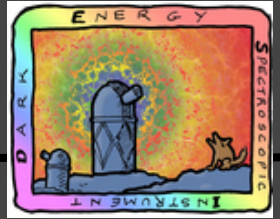
DESI LSS catalogs



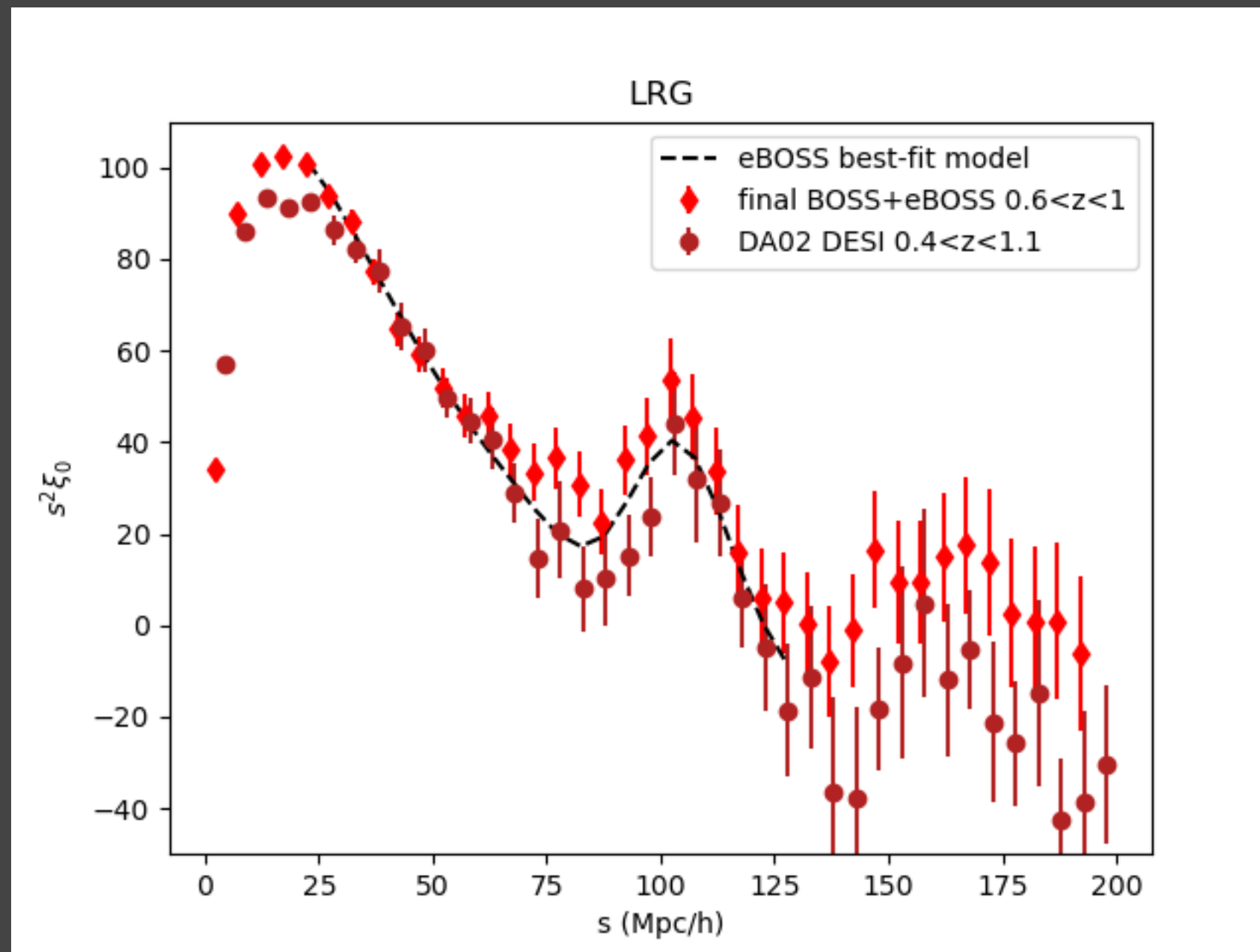
- Most of data taken is currently kept blind from clustering analysis
- Two sets of data allowed to be analyzed:
- 1st ~two months of data “DA02”
- Almost all single pass, so low completeness
- 284,789 ELGs, 302,640 LRGs, 246,987 QSOs, 1,015,218 BGS



DESI DA02 clustering



- 1st ~two months of data “DA02”
- Almost all single pass, so low completeness
- Sample size allowed for analysis comparable to final SDSS sample



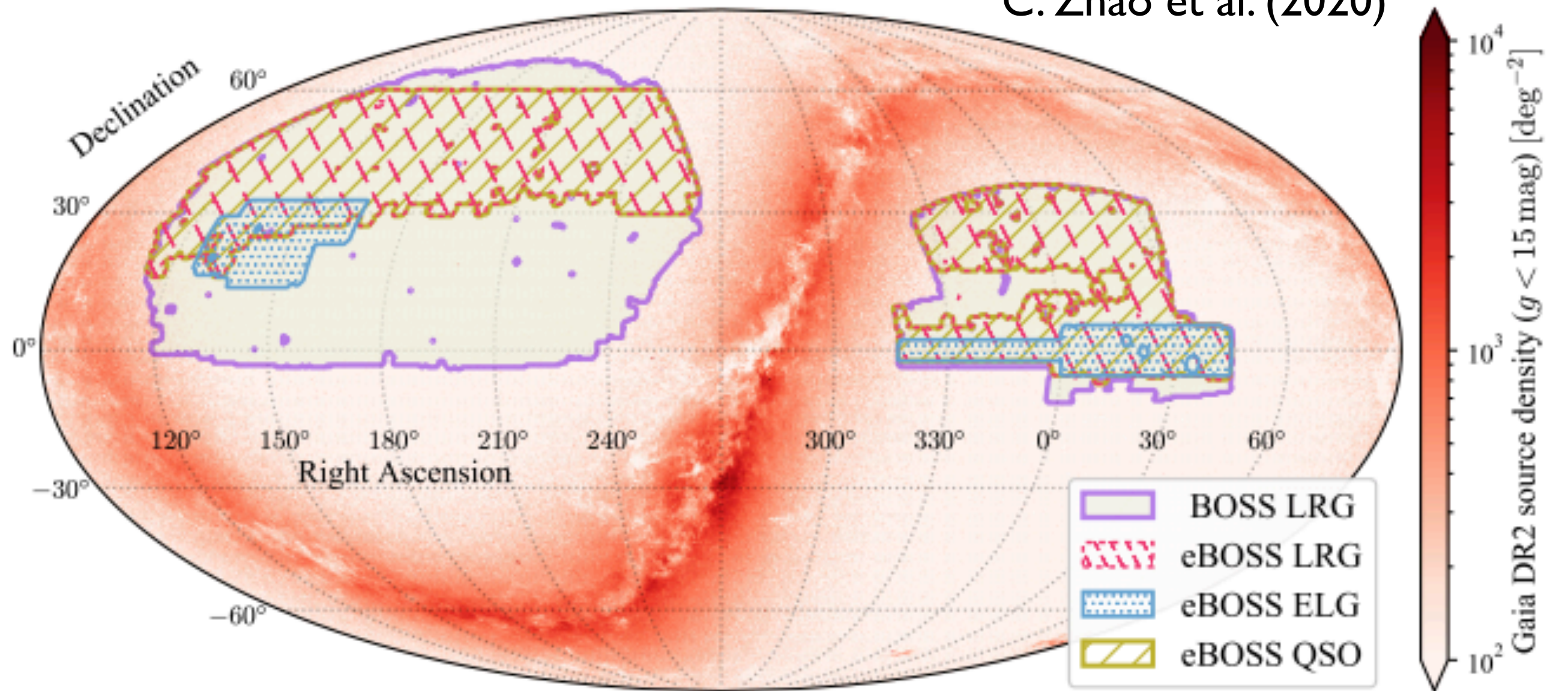
The Sloan Digital Sky Survey I-IV : Two Decades of Galaxy Redshift Surveys

- Uses Sloan telescope at Apache Point NM
- SDSS camera obtained *ugriz* imaging for 3.6×10^8 sources
- SDSS (I/II) and BOSS (III/IV) spectrographs used to obtain > 2.5 million redshifts
- BOSS, 1000 spectra at a time, plugged by hand ->



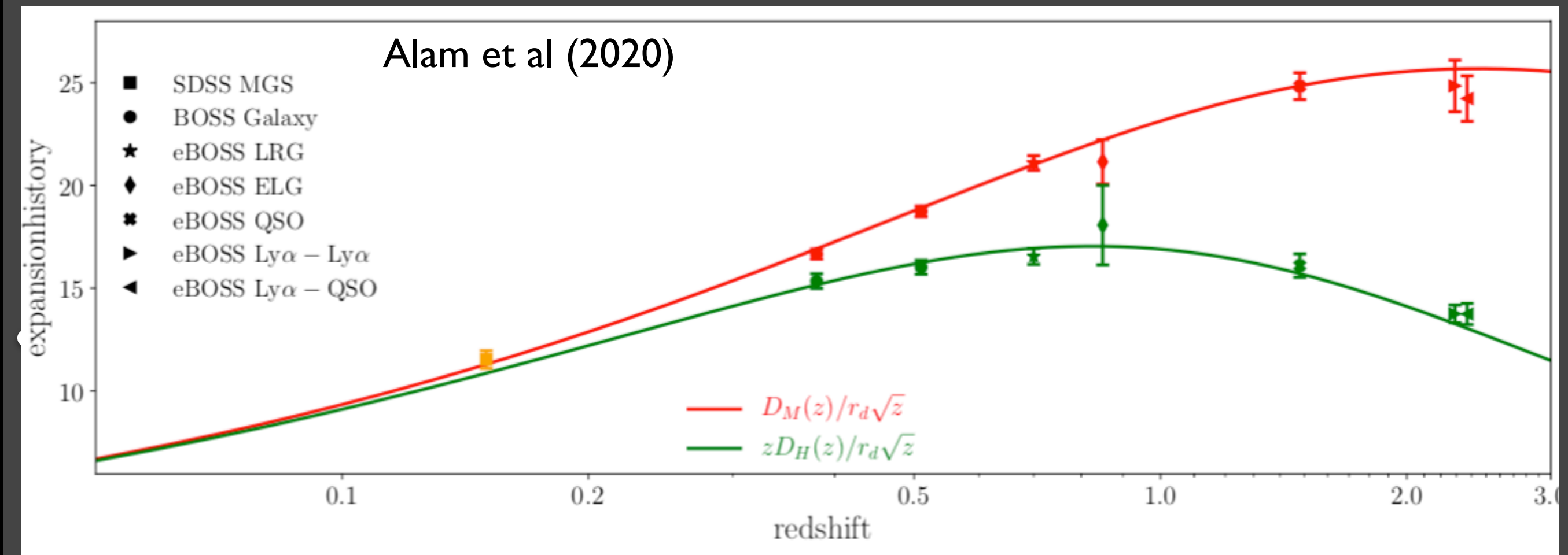
SDSS Maps

C. Zhao et al. (2020)



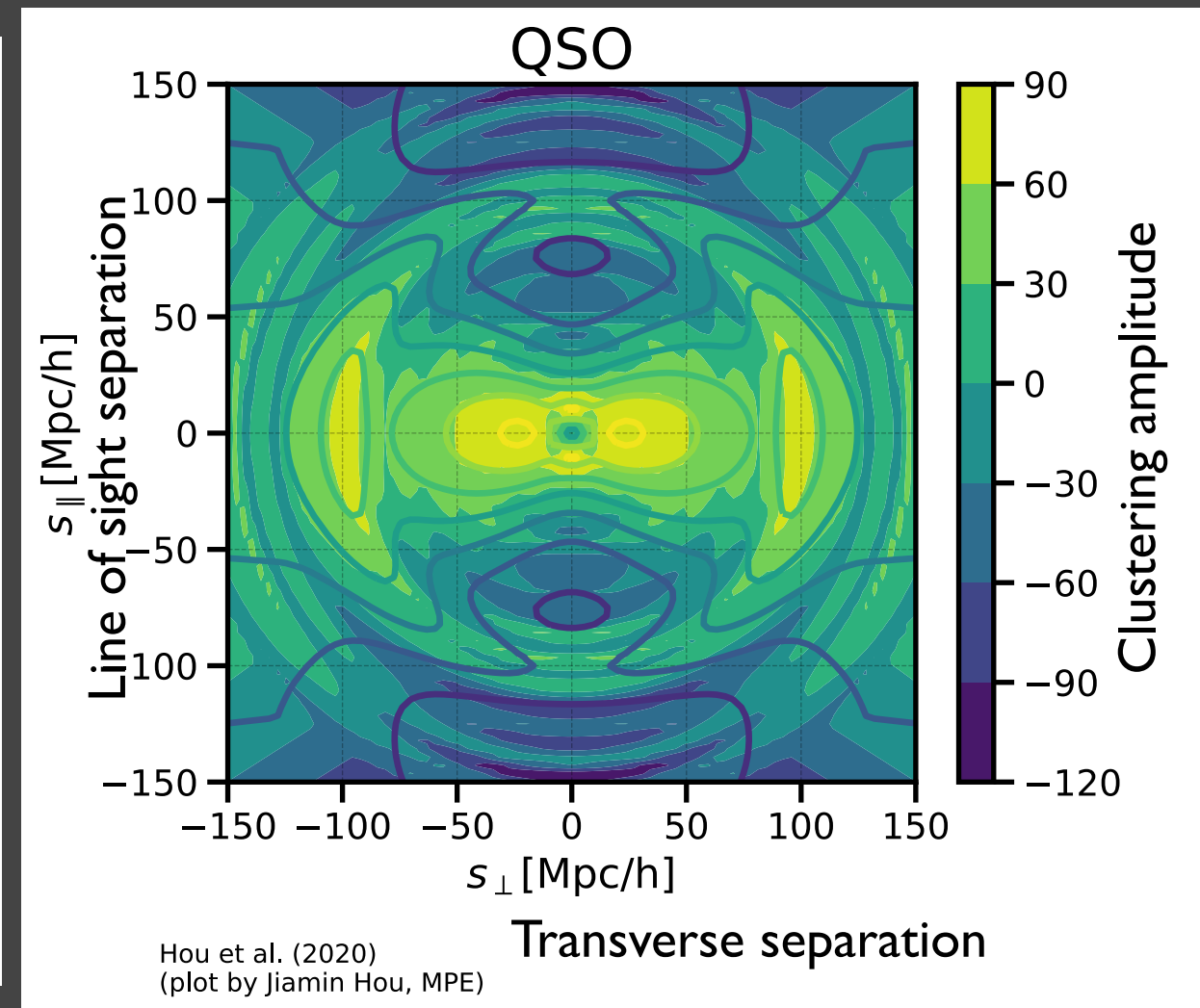
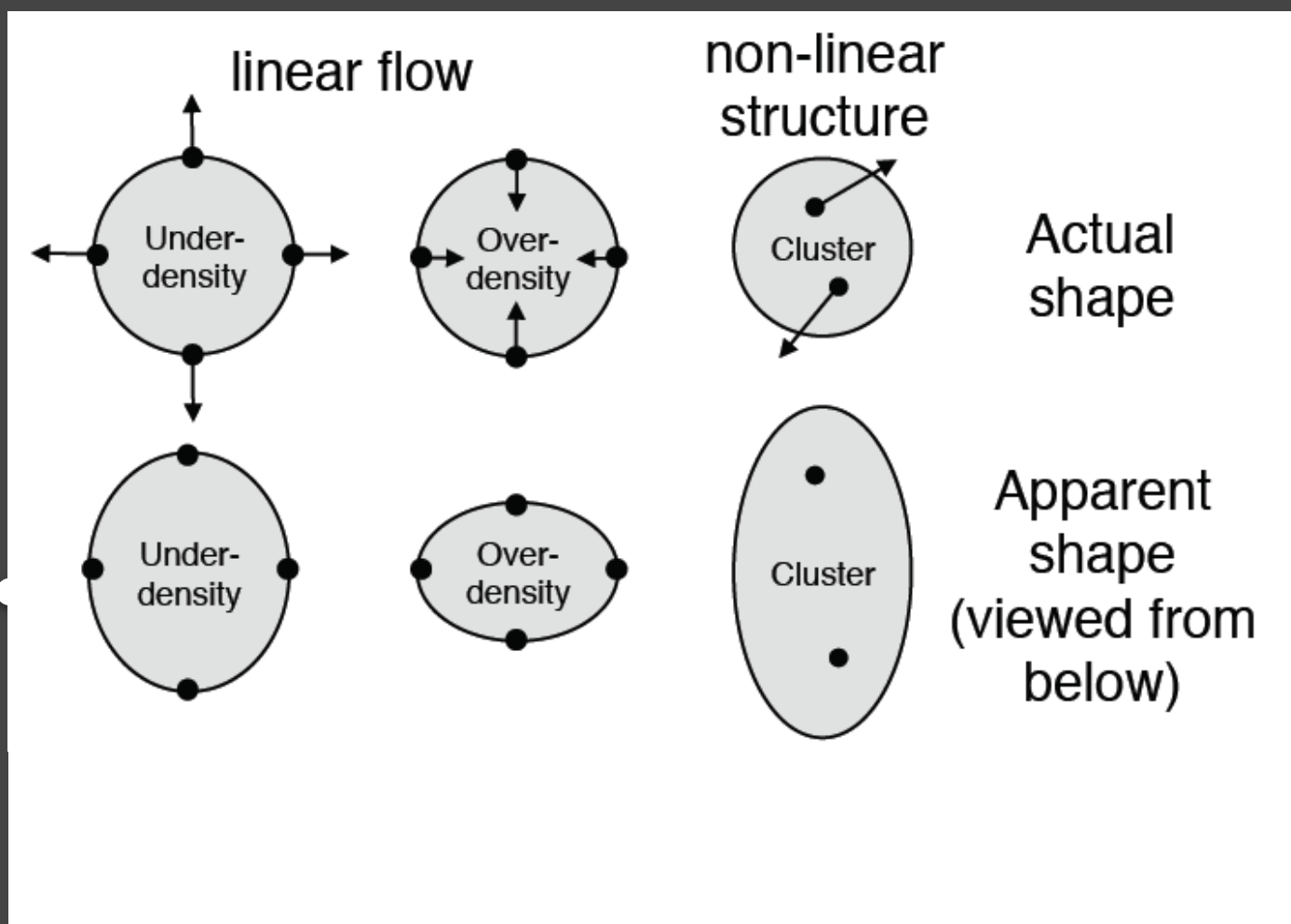
Cosmological Information

- We measure the signature to two distinct physical phenomena
 - I) Position of BAO feature is used as a “standard ruler” to obtain distance(redshift)
 - With enough signal to noise, measurement is broken into transverse and line-of-sight components



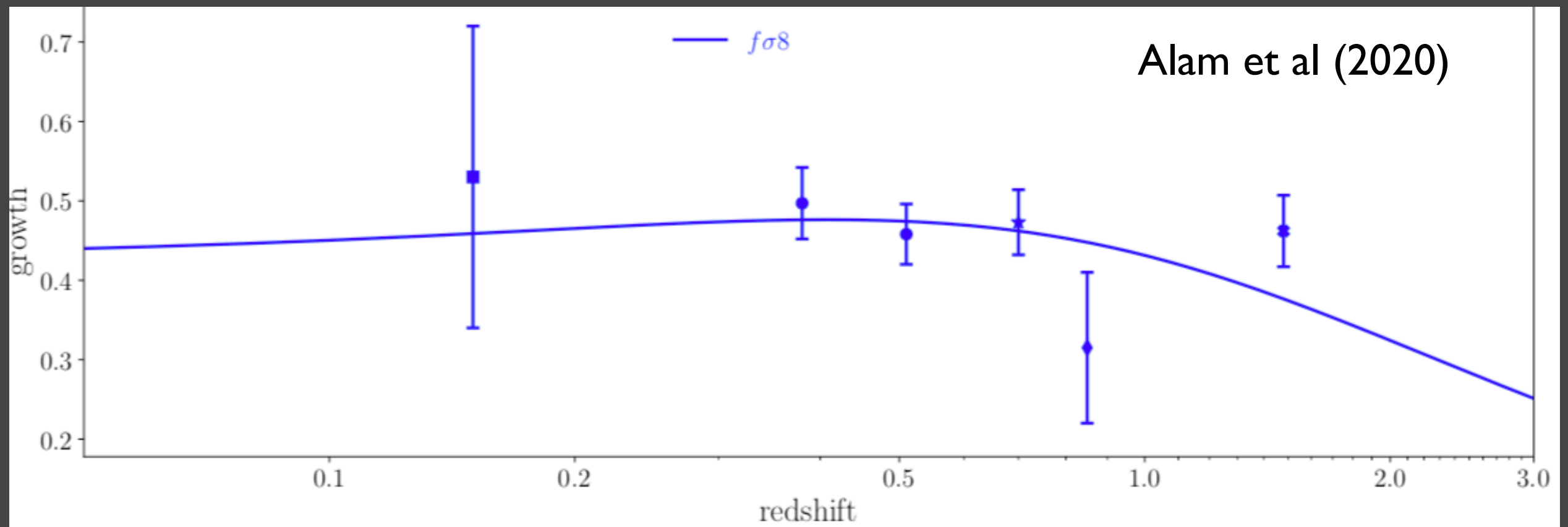
Cosmological Information

- We measure the signature to two distinct physical phenomena
 - 2) RSD: Structure growth gives galaxies peculiar velocities and produces “redshift-space distortions” (RSD) in the 3D maps



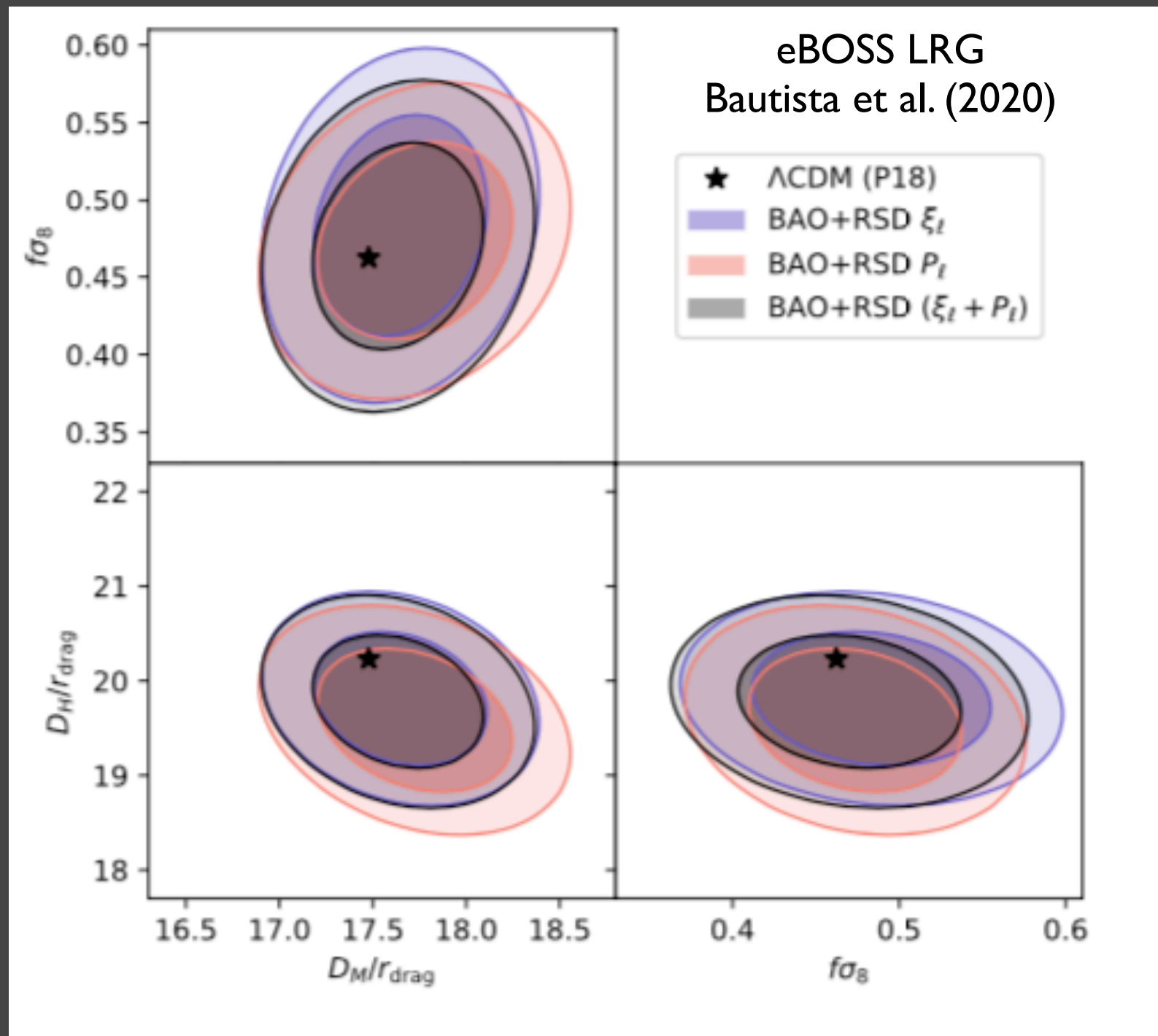
Cosmological Information

- We measure the signature to two distinct physical phenomena
 - 2) Structure growth gives galaxies peculiar velocities and produces “redshift-space distortions” (RSD) in the 3D maps
 - We measure the amplitude and thus the structure growth rate



Cosmological Information

- We measure the signature to two distinct physical phenomena
 - Yields 3x3 likelihood at each* redshift, weakly correlated with background cosmology



Cosmological Results

Alam et al. (2020)

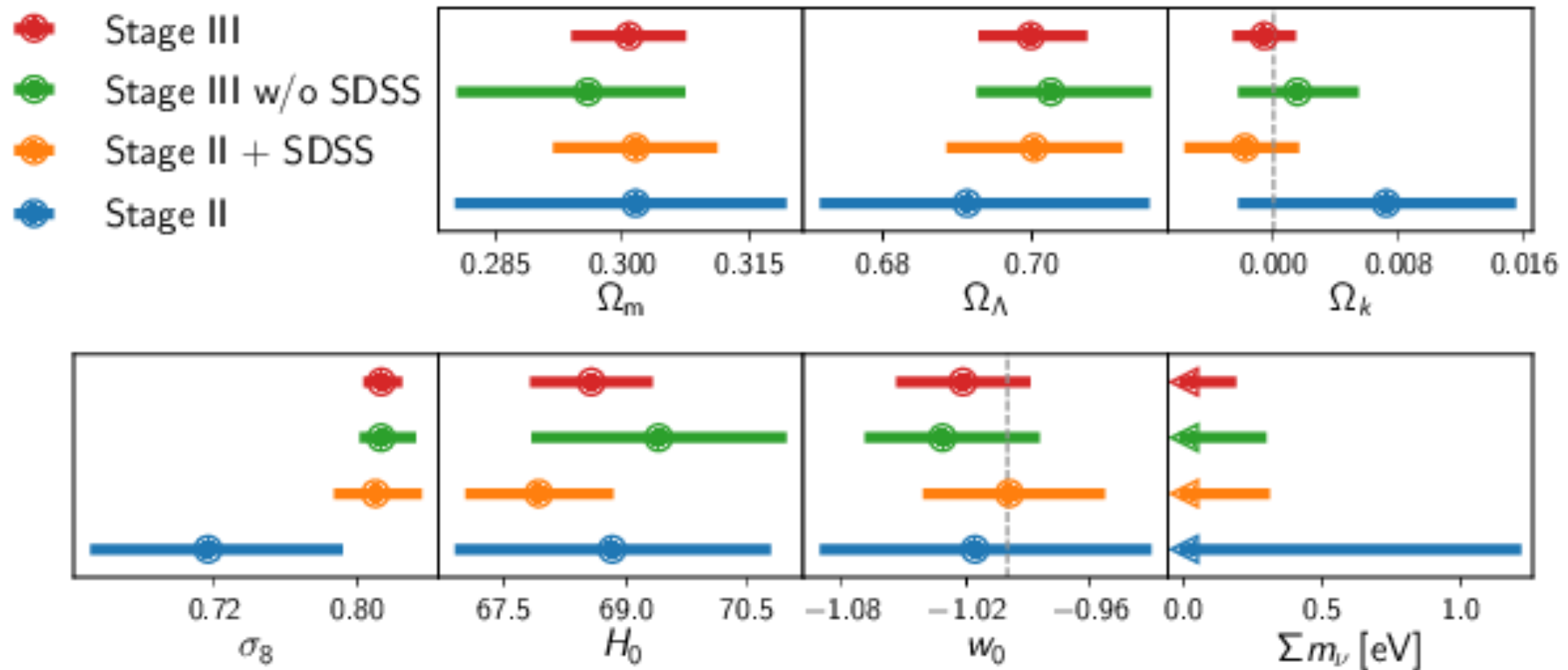


FIG. 14.— Central values and 68% contours for each of the parameters describing expansion history and growth of structure in a ν_{ow} CDM model. Results are shown for each data set combination presented in the text, where Stage-II corresponds to a combination of the WMAP, JLA, and SDSS DR7 data and Stage-III corresponds to a combination of the SDSS BAO+RSD, *Planck*, Pantheon SN Ia, and DES 3×2pt data.

H0

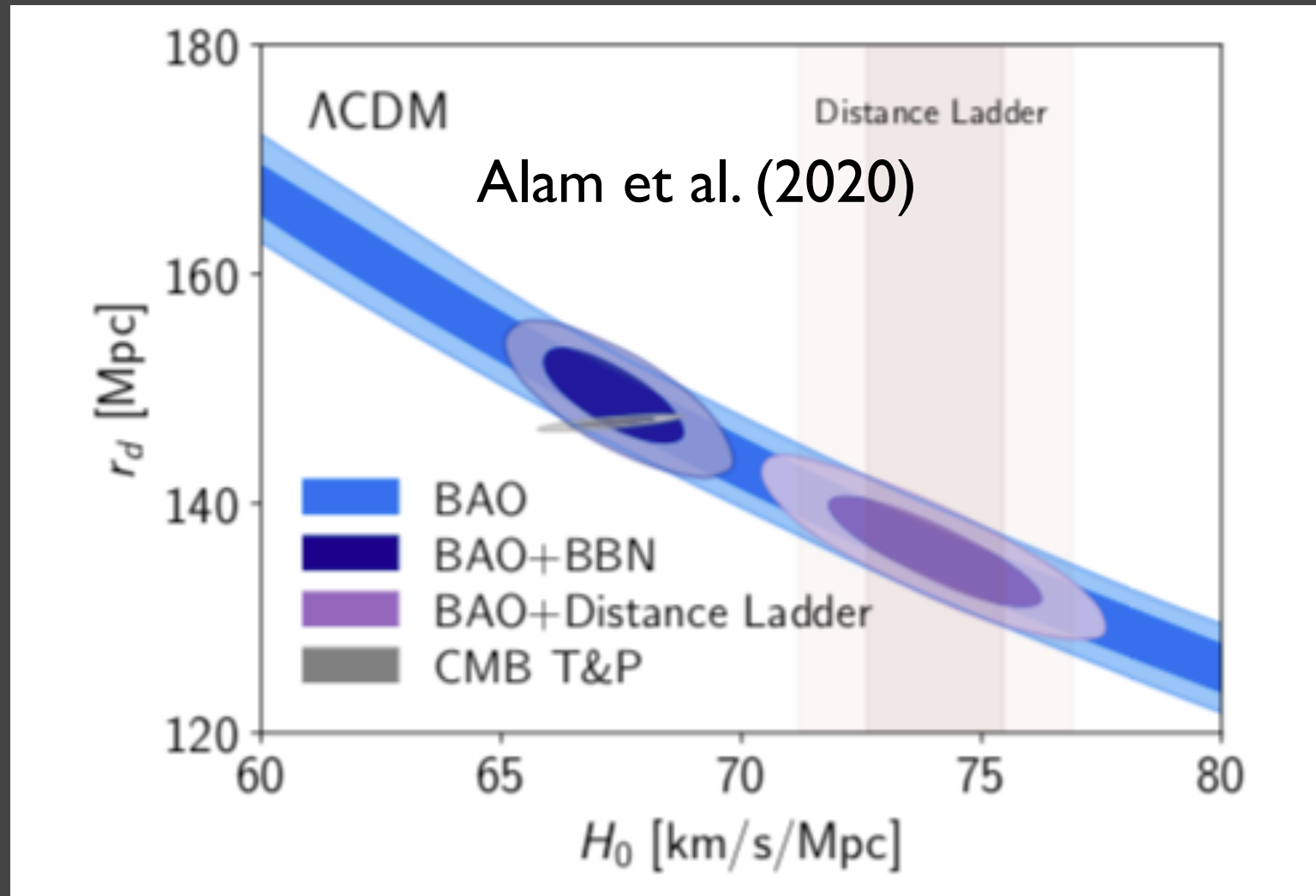
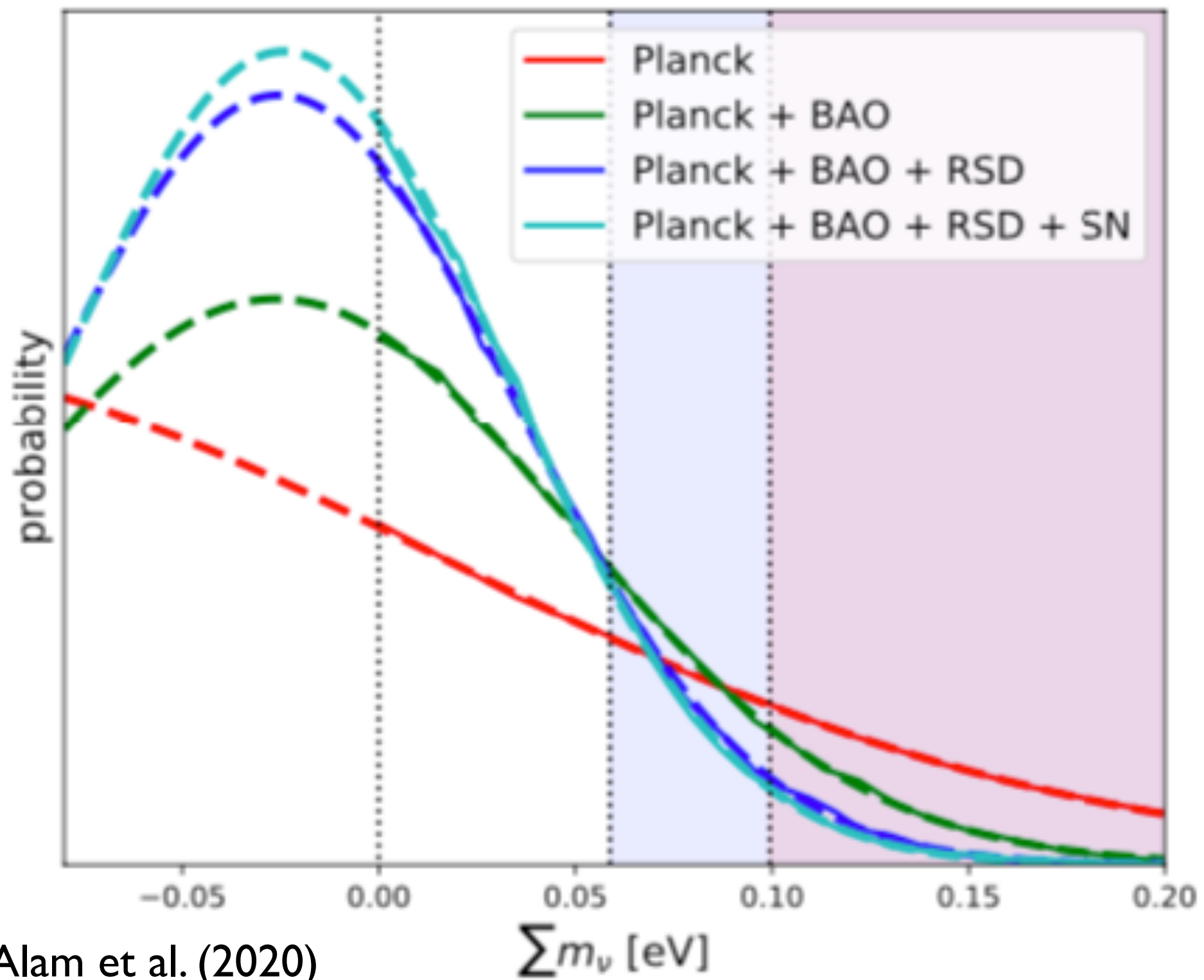


TABLE 5
Hubble parameter constraints.

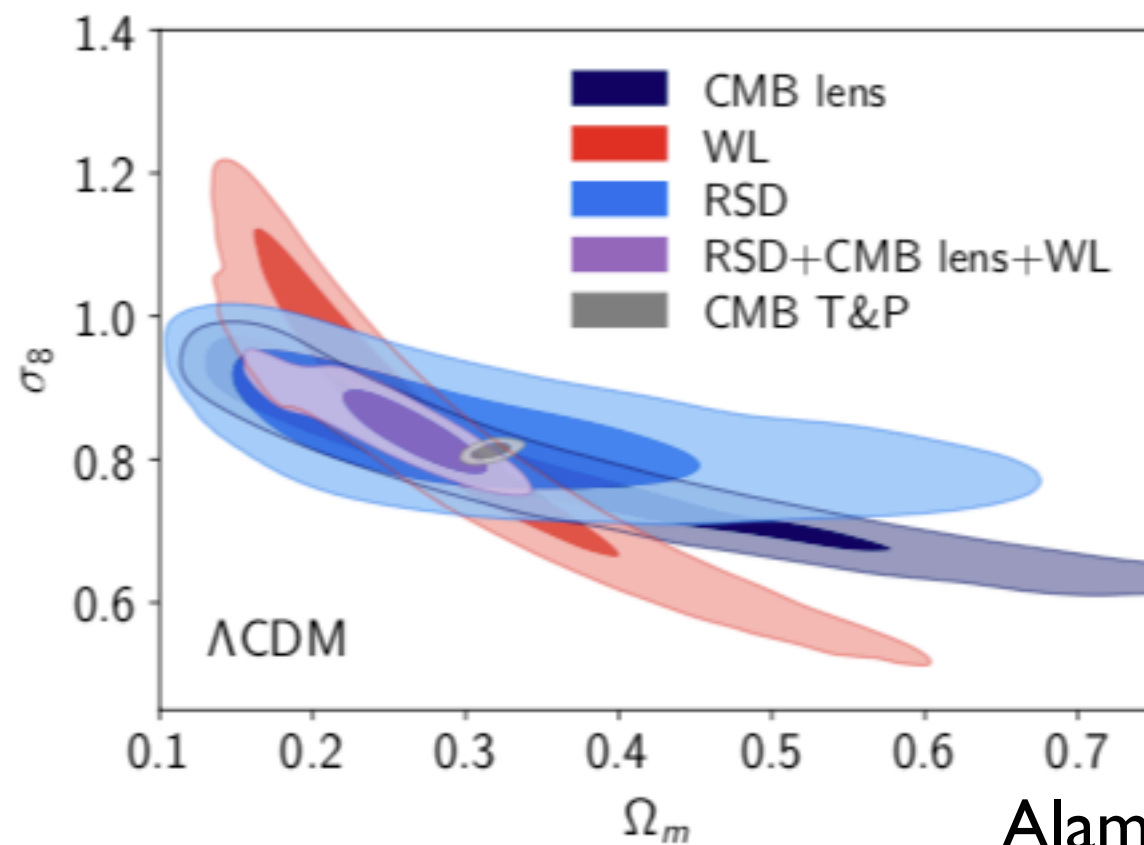
Dataset	Cosmological model	H_0 (km s ⁻¹ Mpc ⁻¹)	Comments
CMB T&P+BAO+SN	ow_0w_a CDM	67.87 ± 0.86	Inverse distance ladder
BBN+BAO	Λ CDM	67.35 ± 0.97	No CMB anisotropies
CMB T&P	Λ CDM	67.28 ± 0.61	<i>Planck</i> 2018 (a)
CMB T&P	$o\Lambda$ CDM	$54.5^{+3.3}_{-3.9}$	<i>Planck</i> 2018 (a)
Lensing time delays	Λ CDM	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)

Neutrino Mass

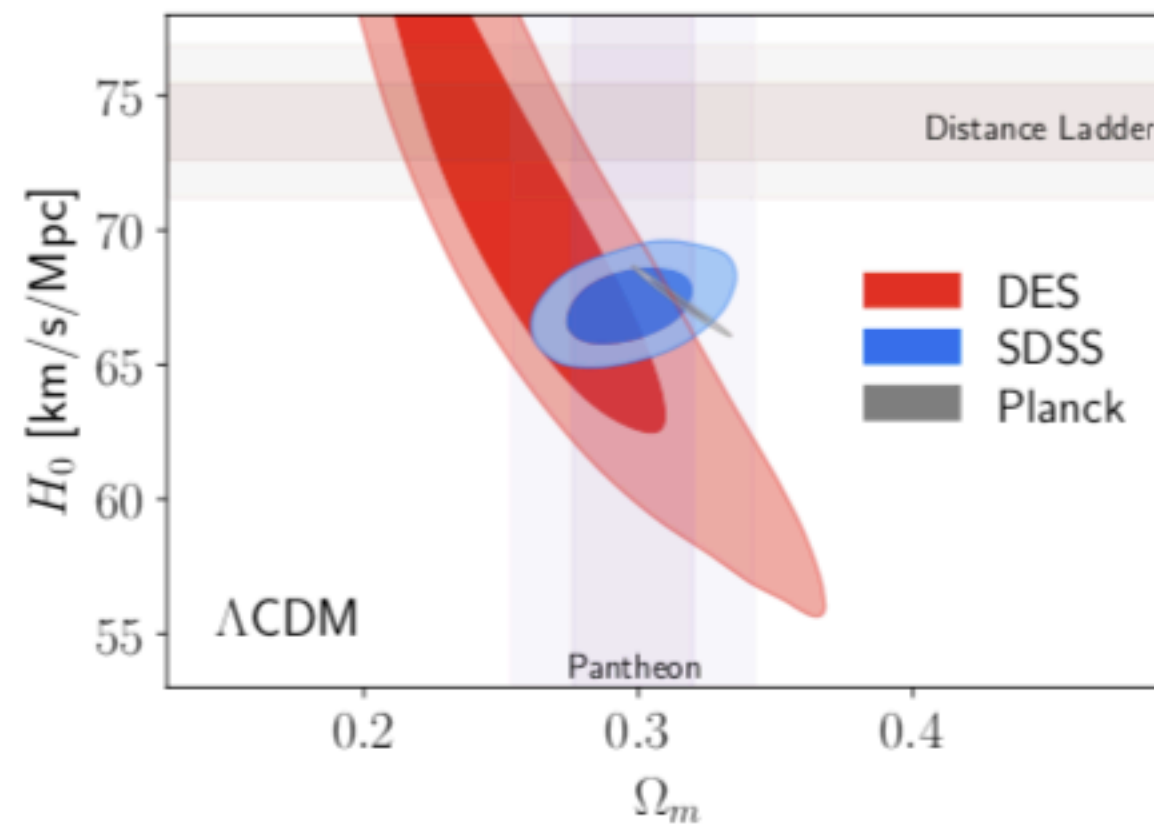
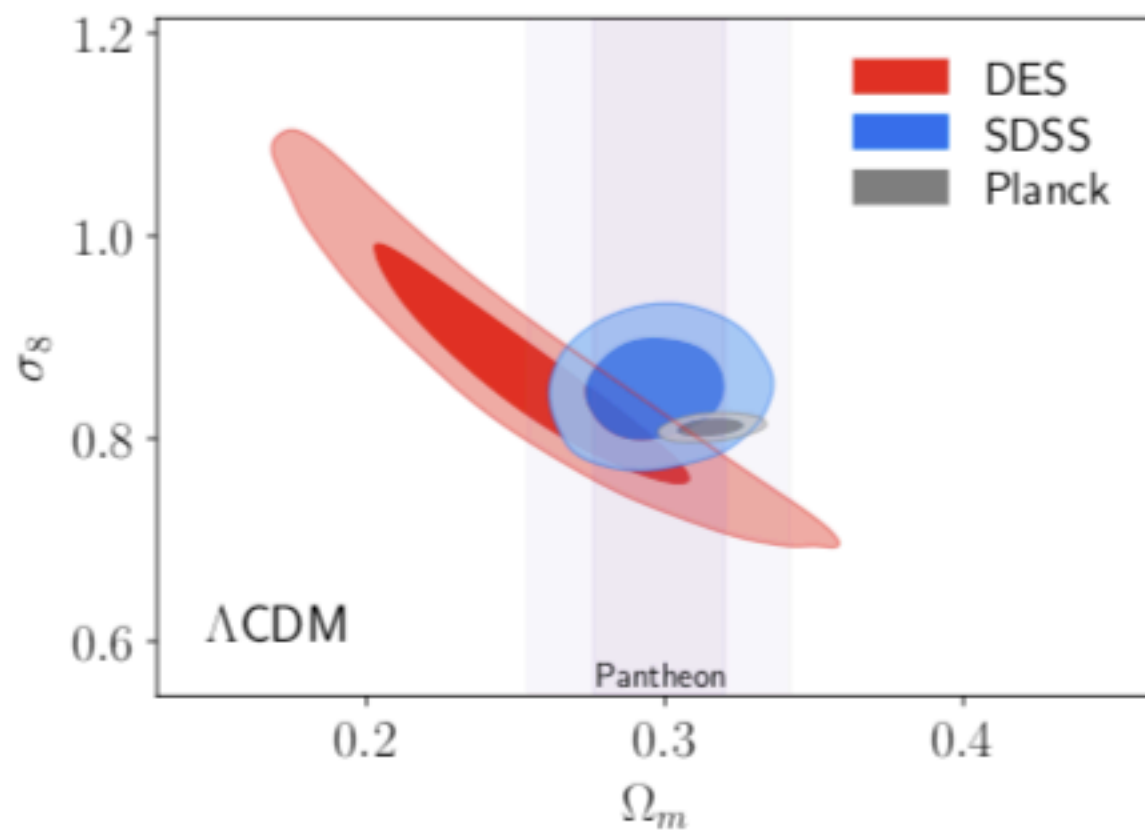
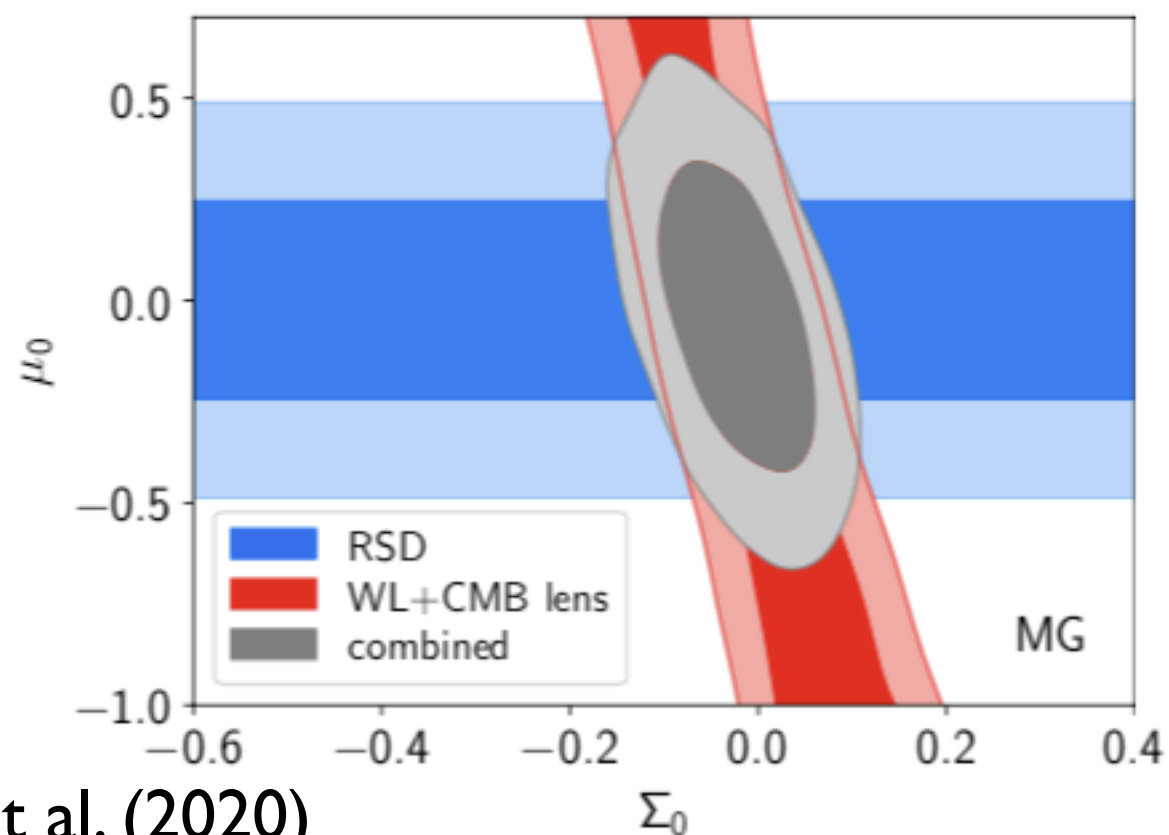


Alam et al. (2020)

Structure Growth



Alam et al. (2020)



Structure Growth

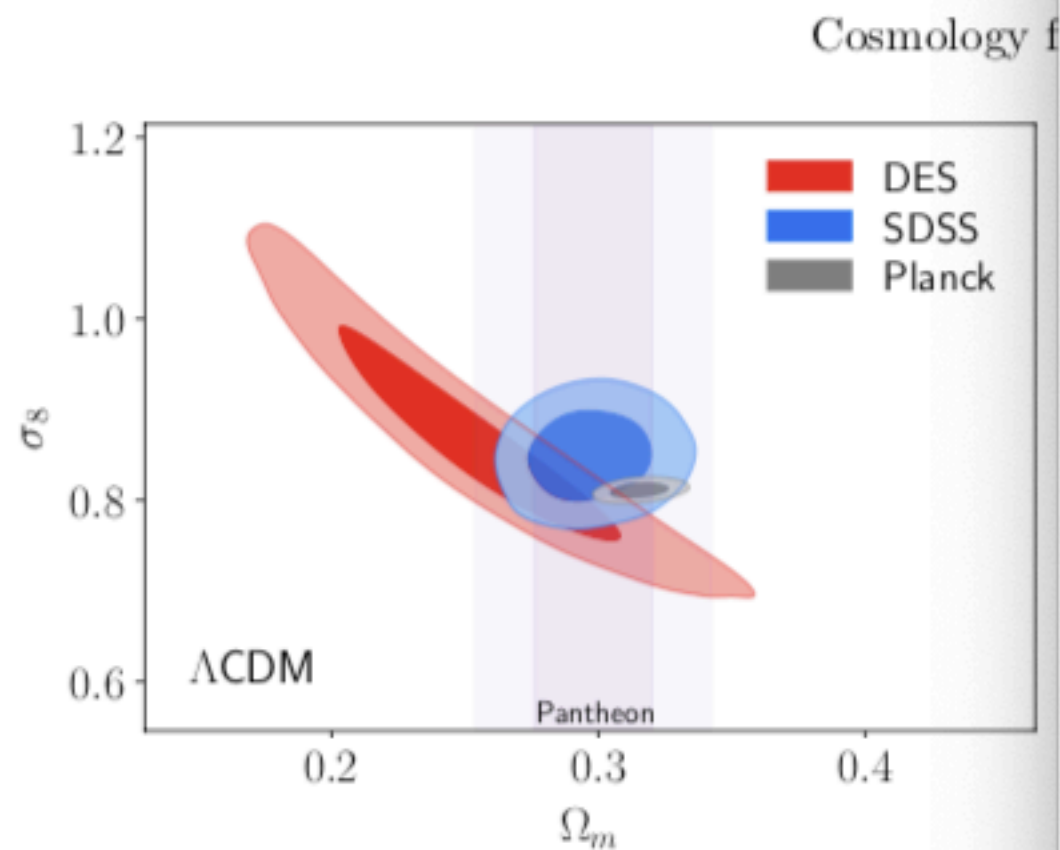
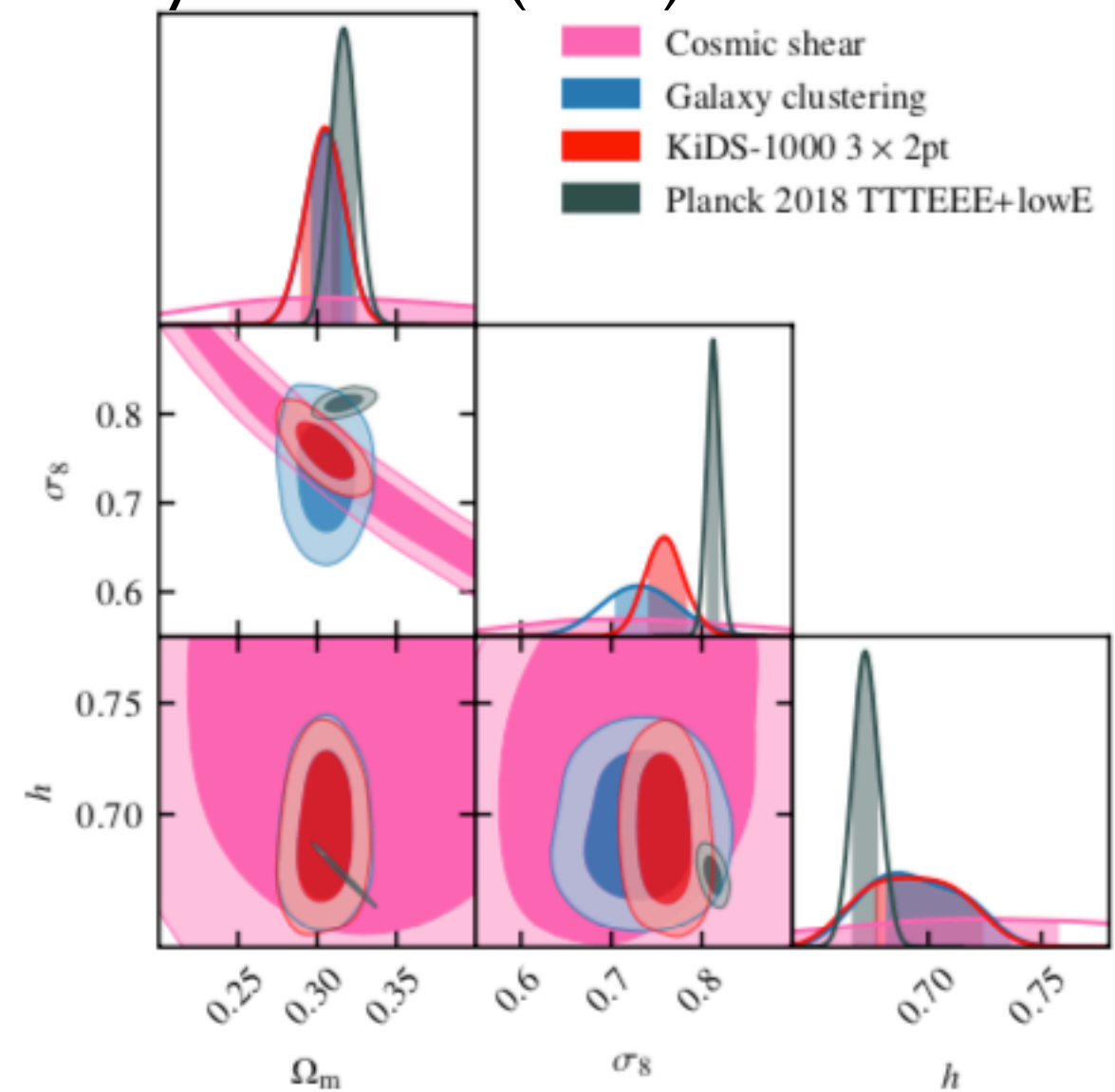


FIG. 11.— **Left:** The Ω_m – σ_8 constraints for a Λ CDM model. A E for the SDSS and DES contours. **Right:** H_0 versus Ω_m under a Λ C the BAO+RSD data are shown in blue, the DES 3×2pt data in red purple bands represent the Pantheon constraints of $\Omega_m = 0.298 \pm 0.0$ bands represent the Cepheid/SNe Ia measurements from [Riess et al.](#)

Heymans et al. (2020)

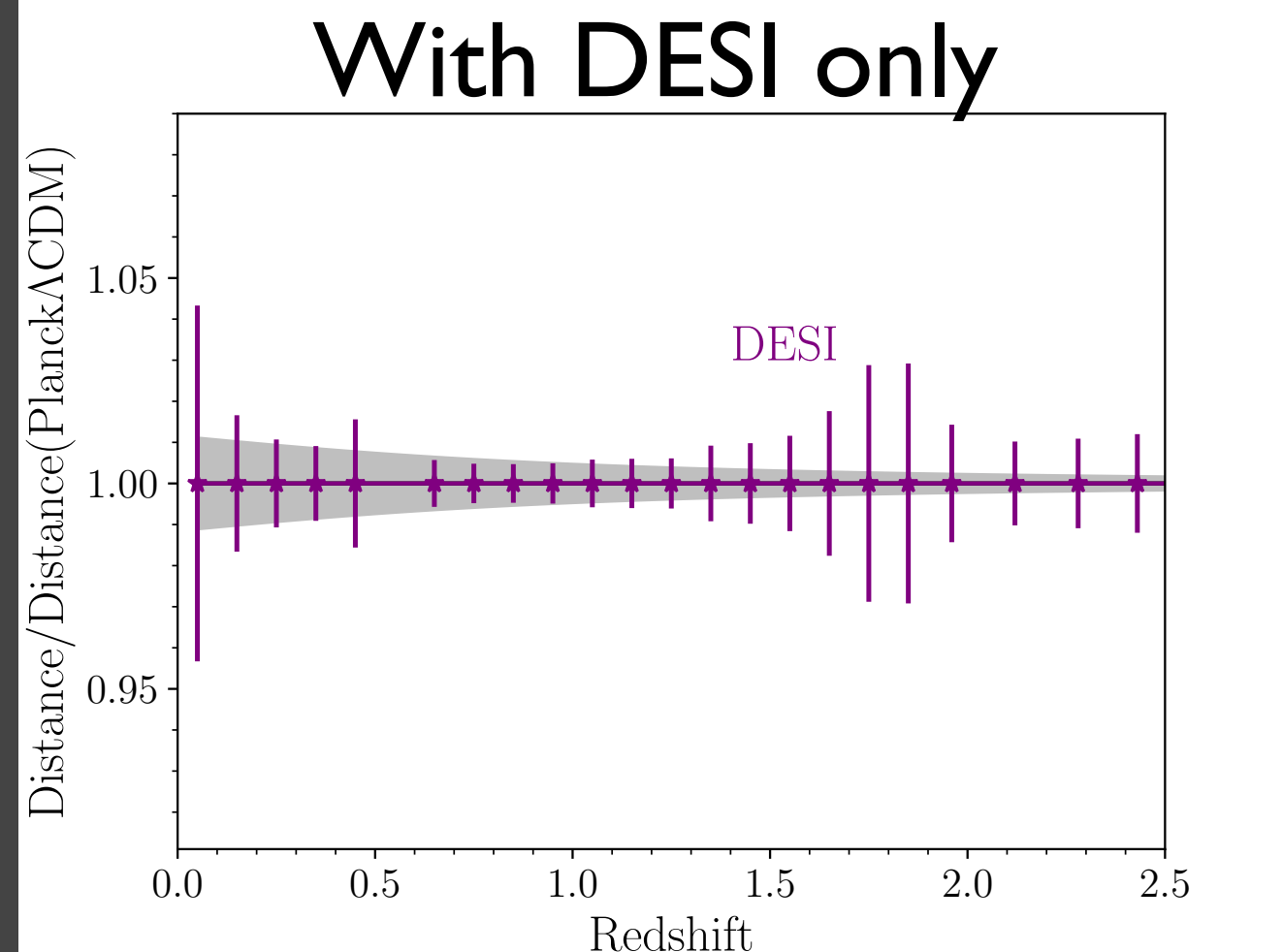
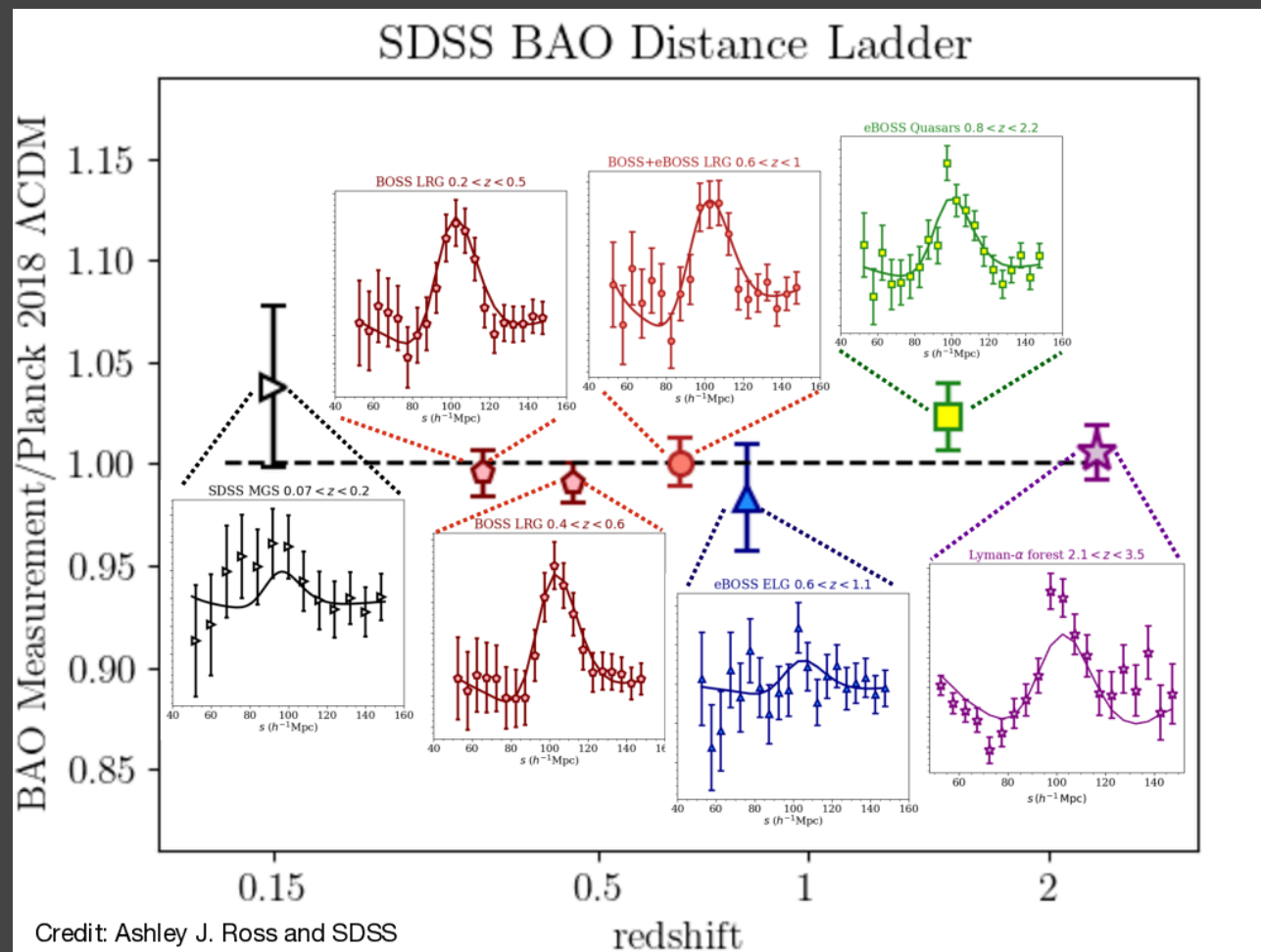


eBOSS Cosmology Results

- Product is culmination of 20 years of work
- H_0 tension between any early Universe calibration of sound horizon and local measurements is strong
- We observe no tension with structure growth
- Need better data to detect neutrino mass (but not *much* better!)
- Λ CDM remains viable

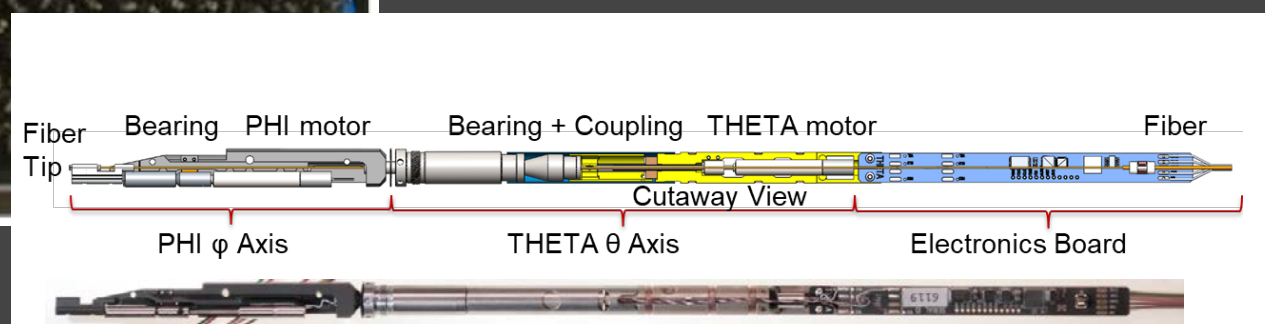
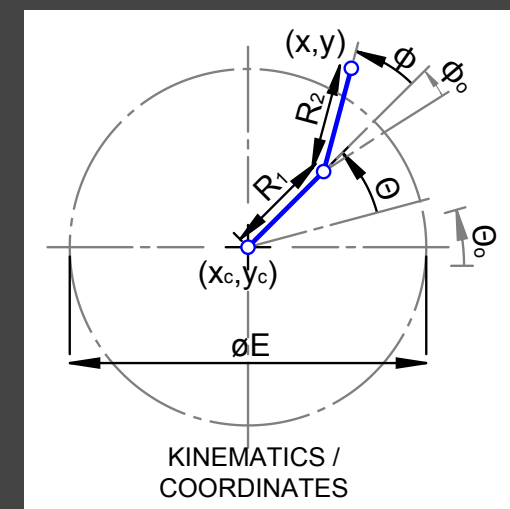
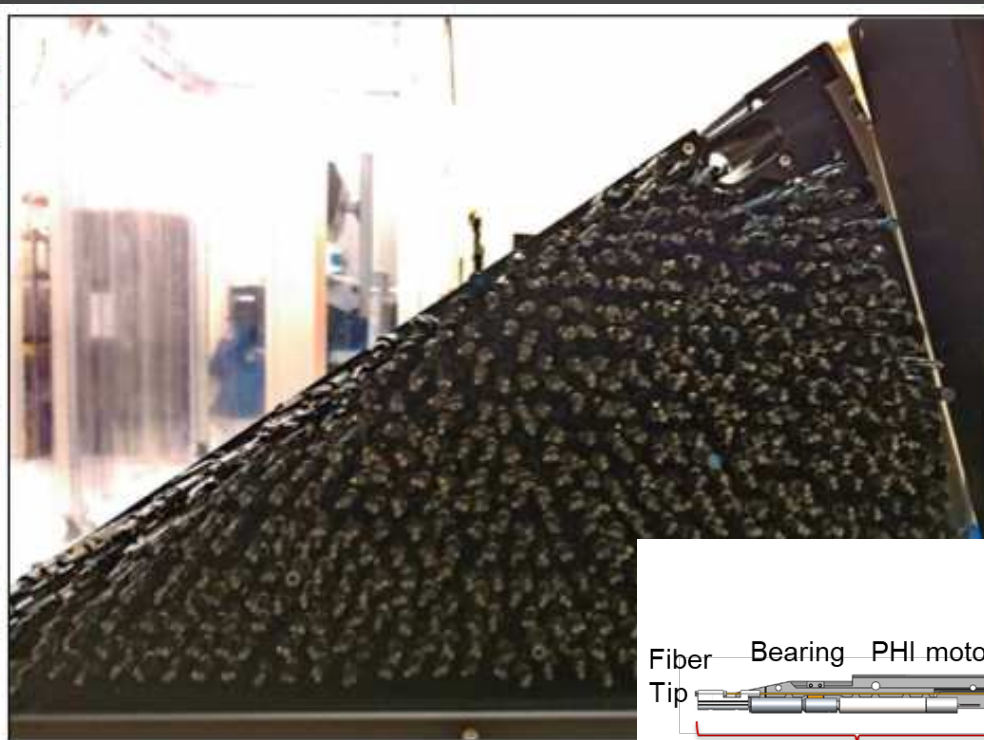
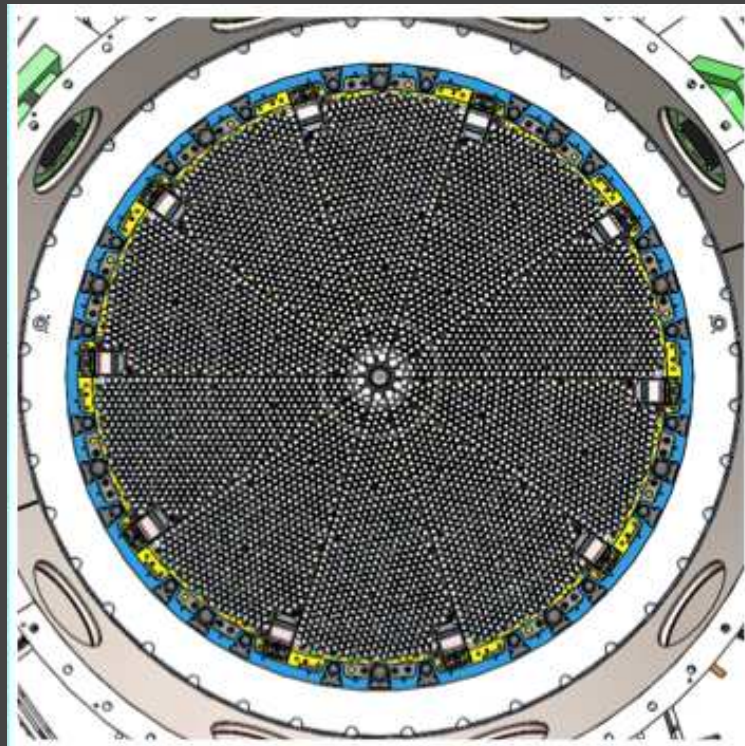
DESI: What is next

- Dark Energy Spectroscopic Instrument
- Collects 5,000 spectra per pointing on 4m Mayall telescope at Kitt Peak
- 5 year survey will collect > 30 million redshifts



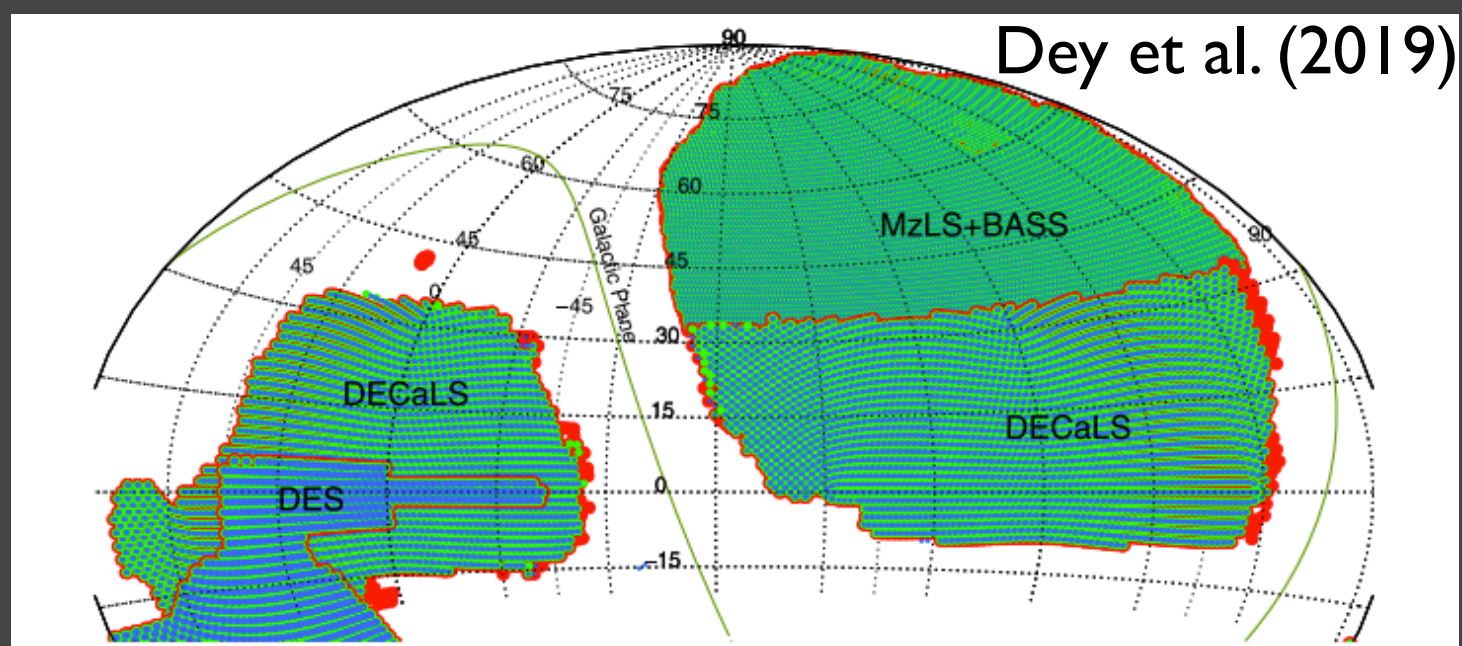
DESI: How?

- Use Mayall 4-m telescope with new optical corrector for 3 deg. field of view
- Populate focal plane with 5000 robotic positioners to collect light down fibers
- 10 groups of 500 fibers (petals) send light to 10 spectrographs



DESI: How?

- Use $> 14,000 \text{ deg}^2$ of DESI Legacy Survey g,r,z + WISE IR imaging to find targets
- Same kinds of tracers as SDSS

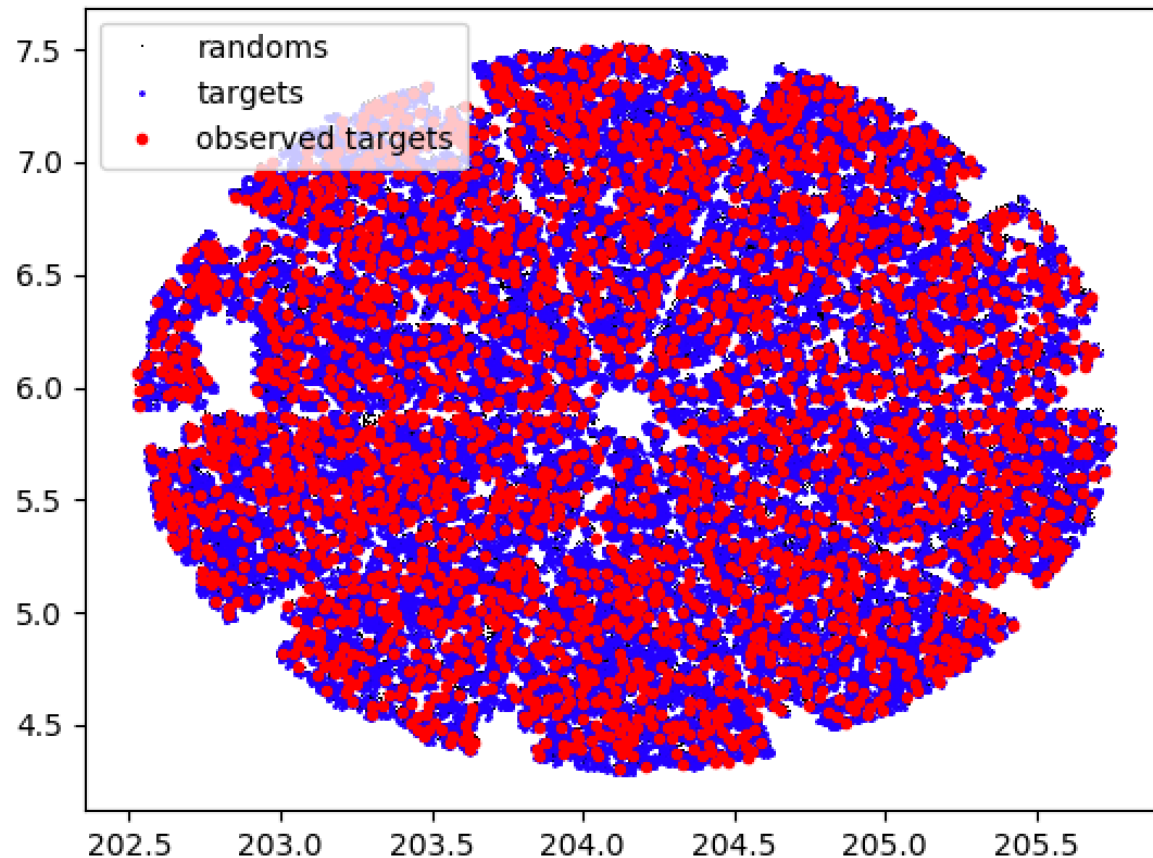


Galaxy type	Redshift range	Bands used	Targets per deg^2	Exposures per deg^2	Good z 's per deg^2	Baseline sample
LRG	0.4–1.0	$r, z, W1$	350	580	285	4.0 M
ELG	0.6–1.6	g, r, z	2400	1870	1220	17.1 M
QSO (tracers)	< 2.1	$g, r, z, W1, W2$	170	170	120	1.7 M
QSO ($\text{Ly-}\alpha$)	> 2.1	$g, r, z, W1, W2$	90	250	50	0.7 M
Total in dark time			3010	2870	1675	23.6 M
BGS	0.05–0.4	r	700	700	700	9.8 M
Total in bright time			700	700	700	9.8 M

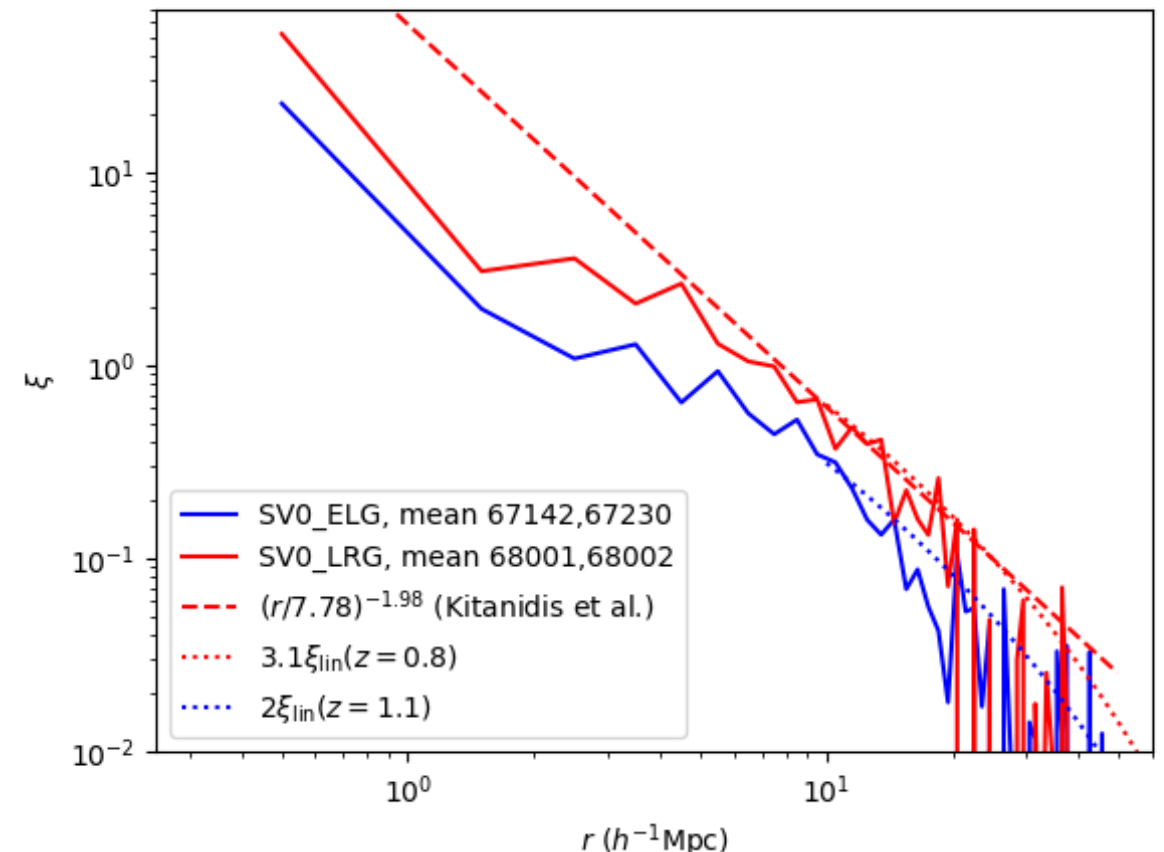
DESI: Status

- Had just finished commissioning when everything was shutdown
- We were observing science targets across full focal plane

Observed distribution of ELGs for one pointing:



Clustering measured for a few Pointings ($< 0.1\%$ of final data):



DESI: Cosmology Outlook

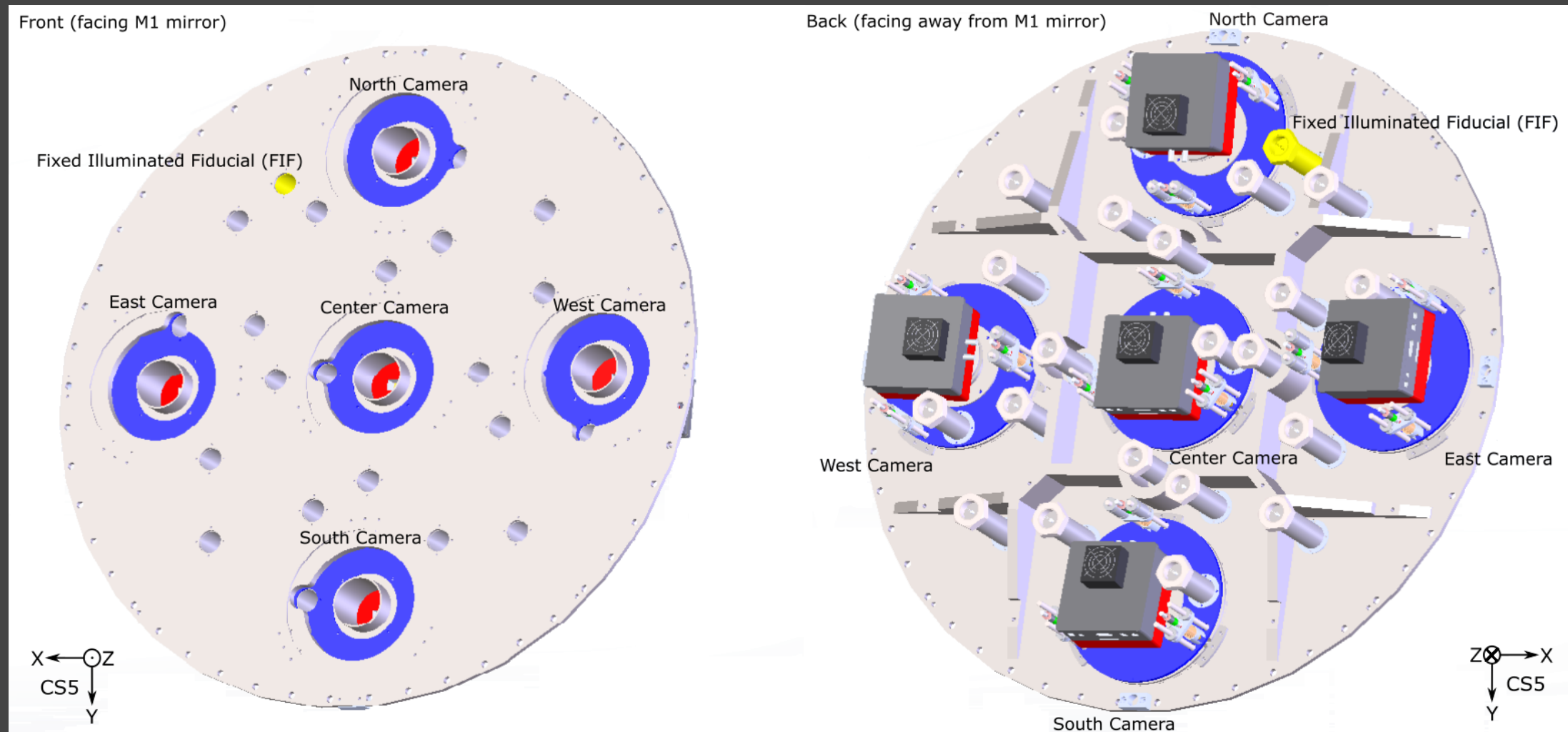
- Great increase in constraints on DE equation of state and its evolution
- Should start seeing effect of massive neutrinos
- Shape of $P(k)$ should rival Planck CMB in ability to constrain primordial $P(k)$
- Many synergies to be exploited with overlapping surveys (e.g., LSST or final DES data with DESI bright galaxy survey as foreground lenses)

Other completed redshift surveys

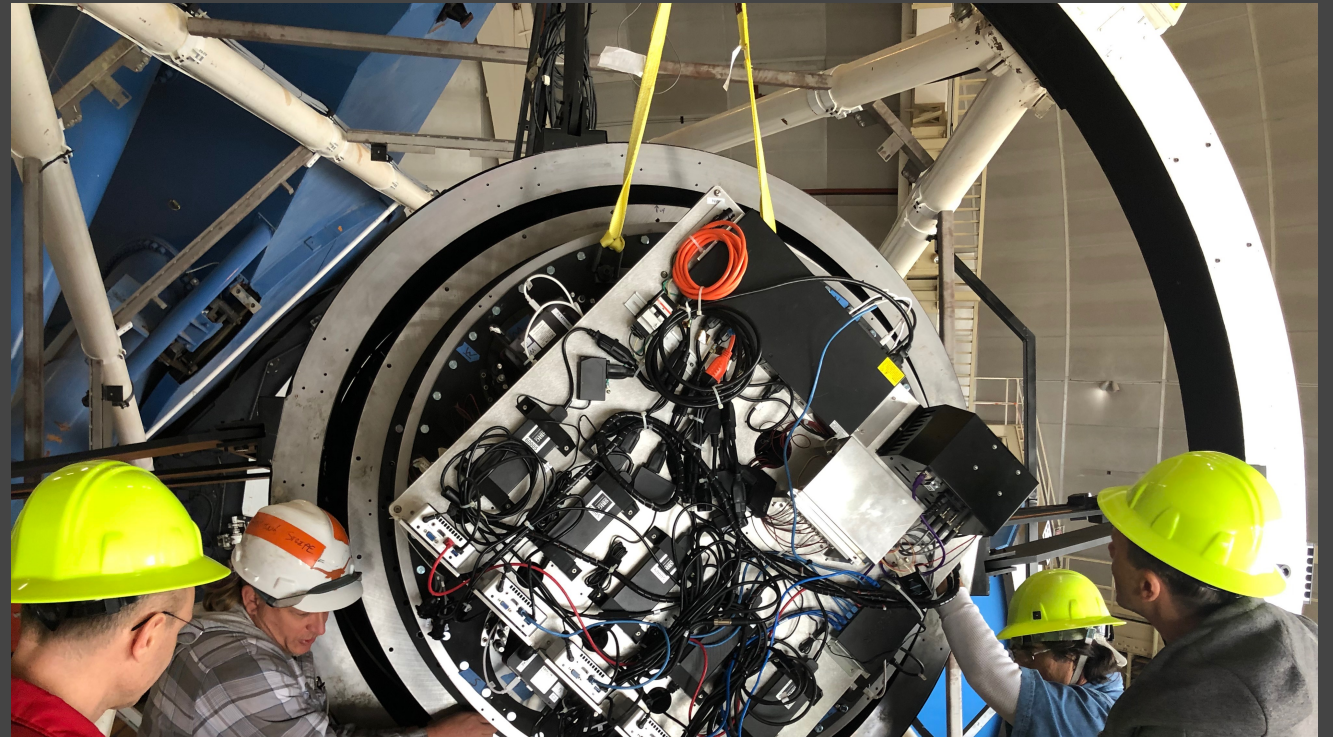
- VIPERS: 90,000 redshifts flux limited $i < 22.5$, $0.5 < z < 1.2$
- GAMA: 300,000 redshifts, flux limited $r < 19.8$, $z < \sim 0.4$
- WiggleZ: 240,000 redshifts, $0.2 < z < 1.0$
- 6dF: 110,000 redshifts, $z \sim 0.1$
- ...
- SDSS I-IV: > 2.5 million redshifts

DESI Commissioning Instrument

- Characterize new optical corrector while focal plane system is being built
- Give more time for DESI to measure galaxy redshifts
- Observing campaign happened April-May



DESI Commissioning Instrument



DESI Commissioning Instrument

- Already learning loads about focusing/optimizing image quality, guiding, tracking/pointing, reason for aperture mask on mirror installed in 1970s

April 4th



April 12th

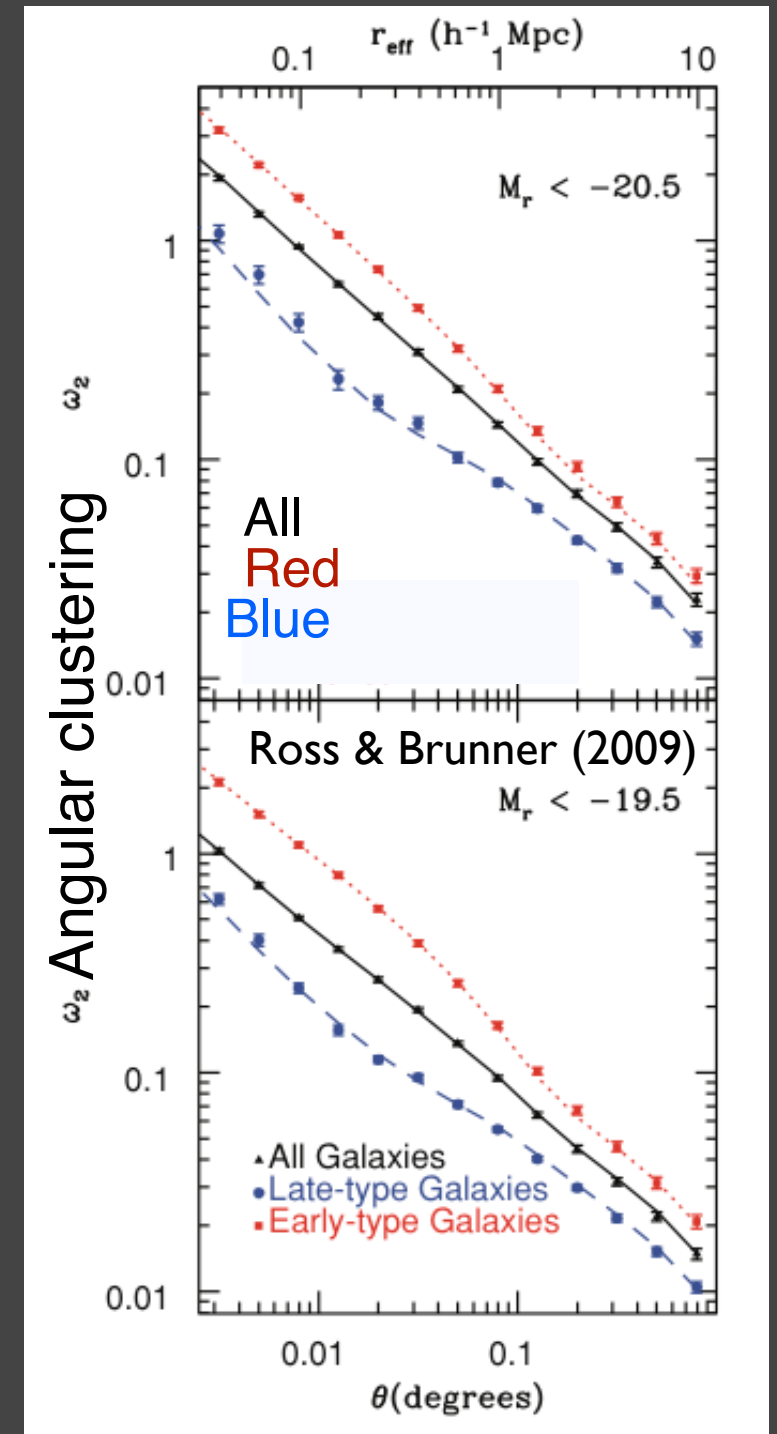


Other future surveys

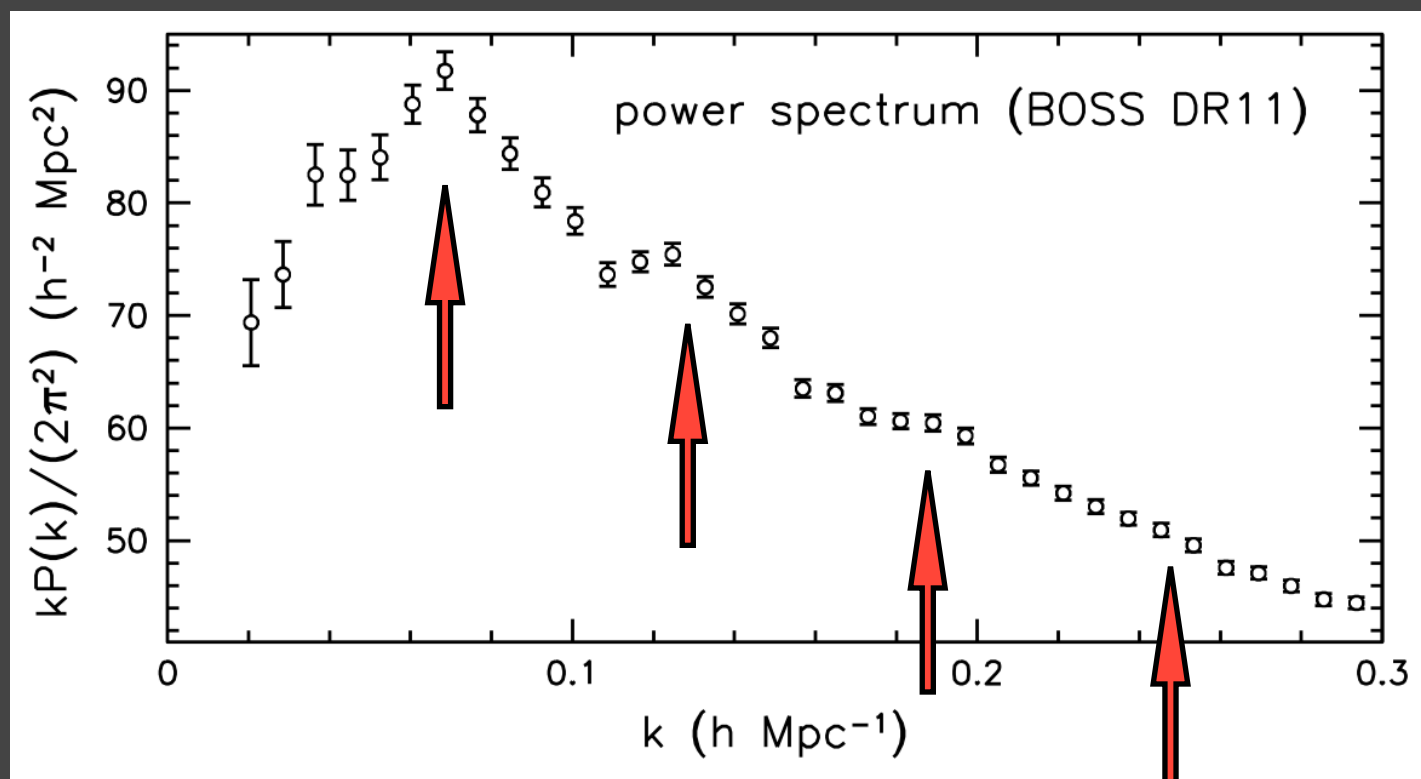
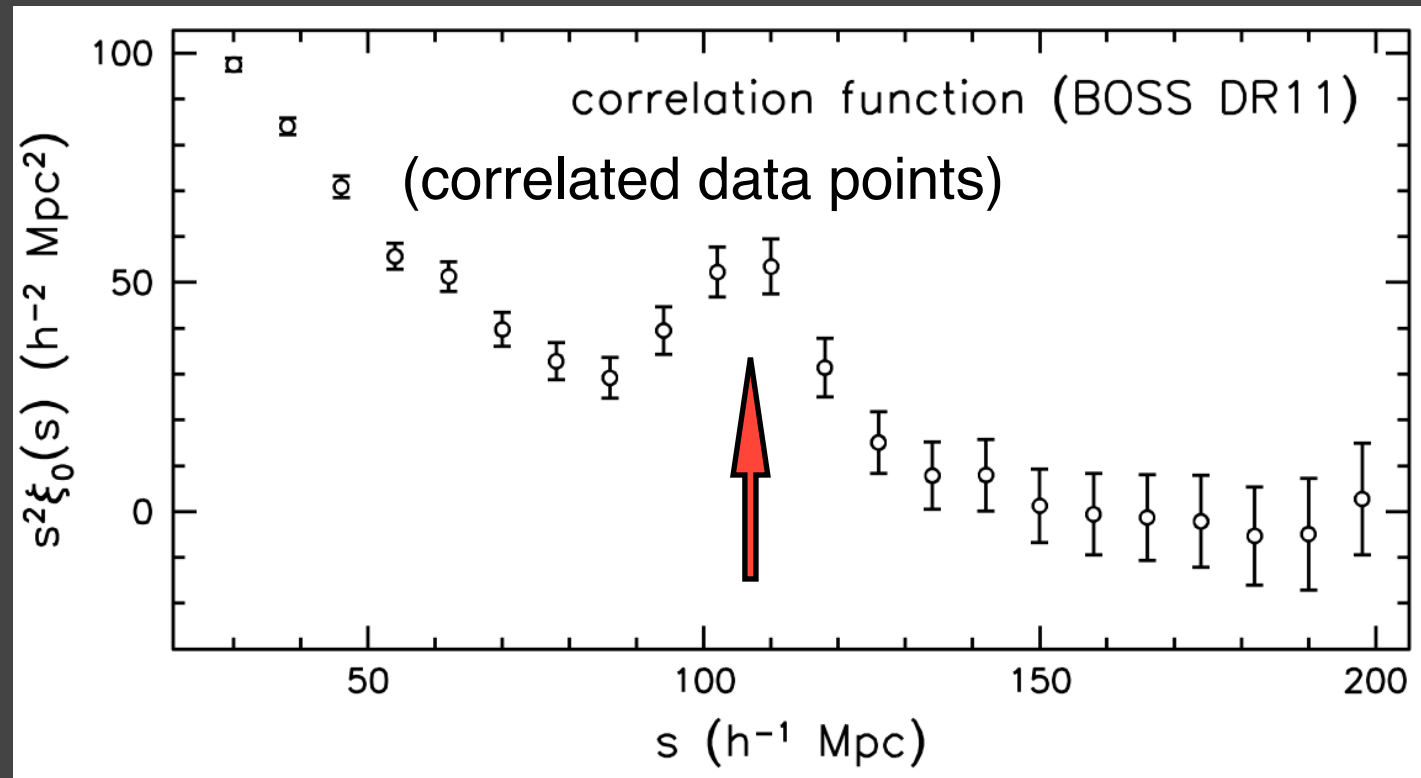
- Euclid: launch ~2022, 35 million galaxy redshifts, slightly higher redshifts than DESI
- 4MOST: 2400 spectra at a time on 4m ESO VISTA telescope; operation starts 2022 (not trying to compete on cosmology)
- WEAVE: 1000 spectra at a time on 4.2m William Herschel Telescope; operation starts soon, cosmology focus on quasars
- WFIRST: mid 2020s launch date, 20 million more redshifts
- Maunakea Spectroscopic Explorer: 4000 fibers on new 11.25m, survey details being defined

Galaxy bias

- Galaxies are biased tracers of matter field
- Some basic theory of galaxy formation/evolution required
- Generally, focus on large (linear) scales



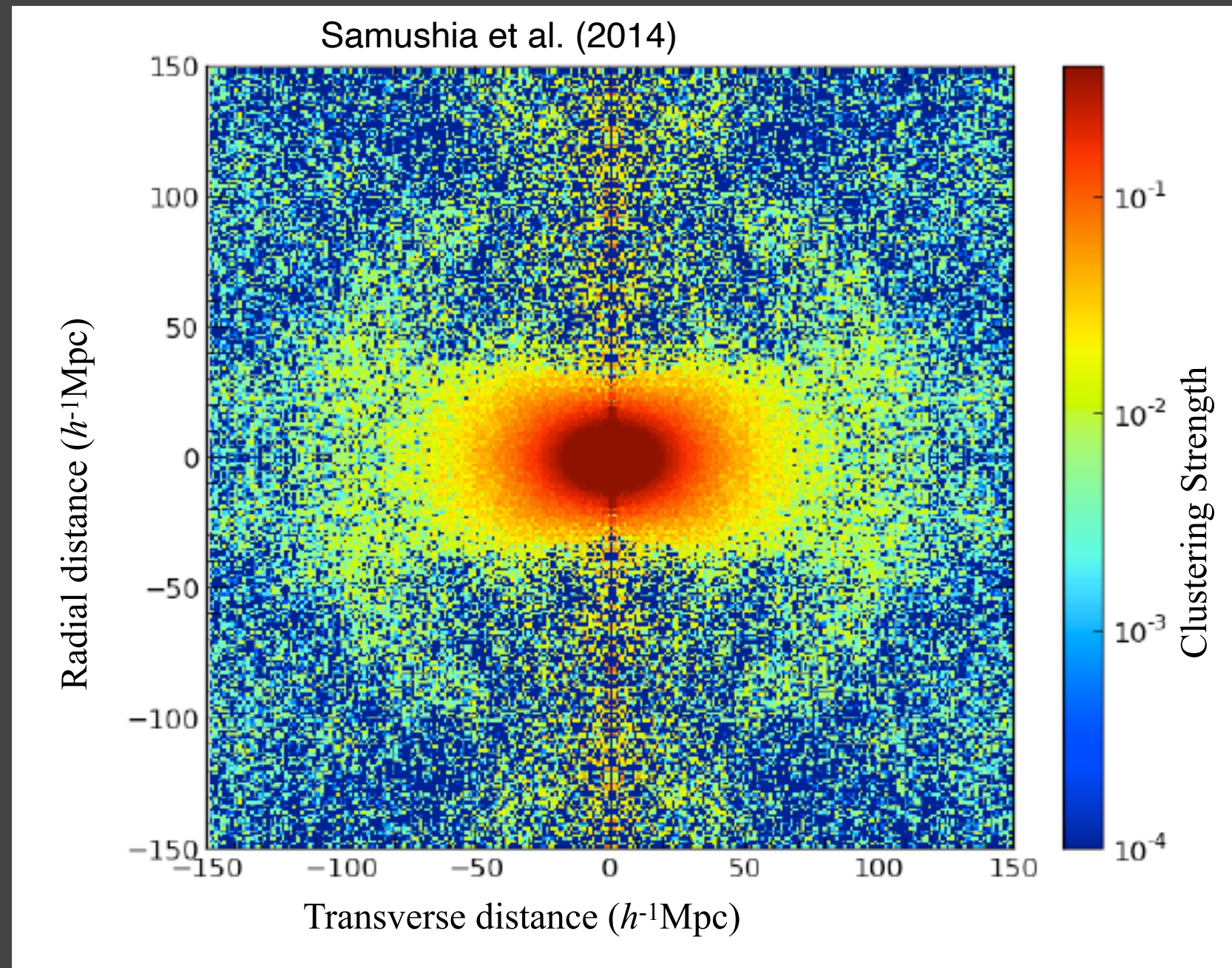
2-point Clustering



- Power spectrum
 $P(k) = \langle \delta_k(k)^2 \rangle$
- Correlation function
 $\xi(r) = \langle \delta(x)\delta(x+r) \rangle$
- $k \sim 2\pi/r$
- r and s interchangeable

Anisotropic Clustering

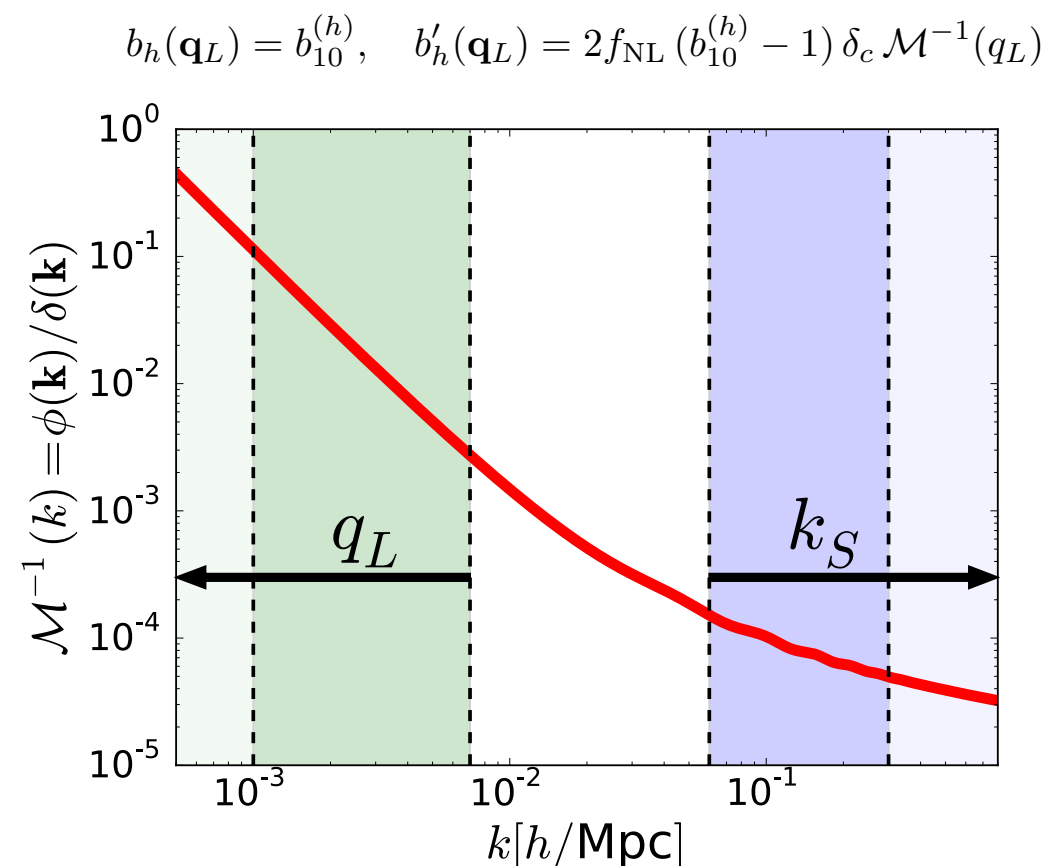
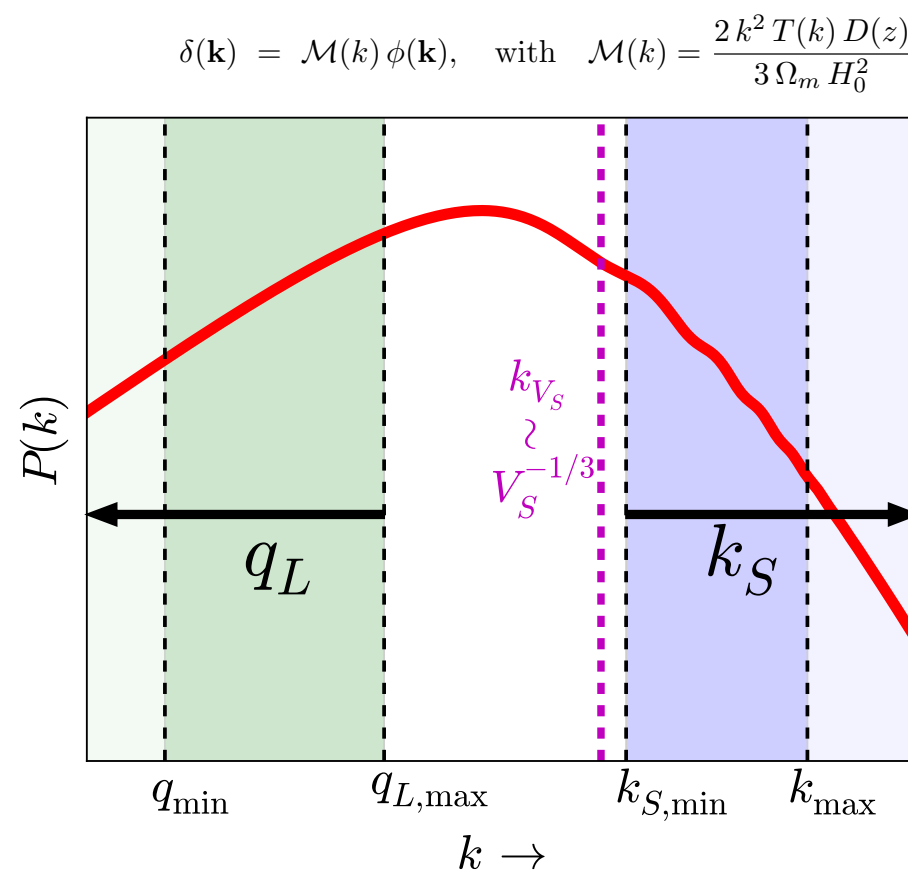
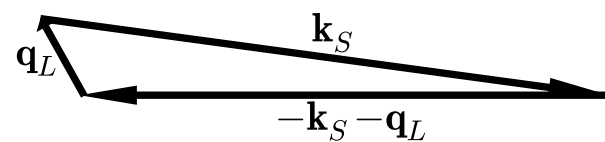
- Degree of anisotropy depends on rate of structure growth, f
 - $f(a) \equiv d\ln(D)/d\ln(a)$; ($a = 1/[1+z]$); f is determined given GR, $\Omega_m(z)$
 - can measure amplitude of velocity field $f\sigma_8$
- Recent work concentrates on measuring combination of $f\sigma_8$ and BAO distances



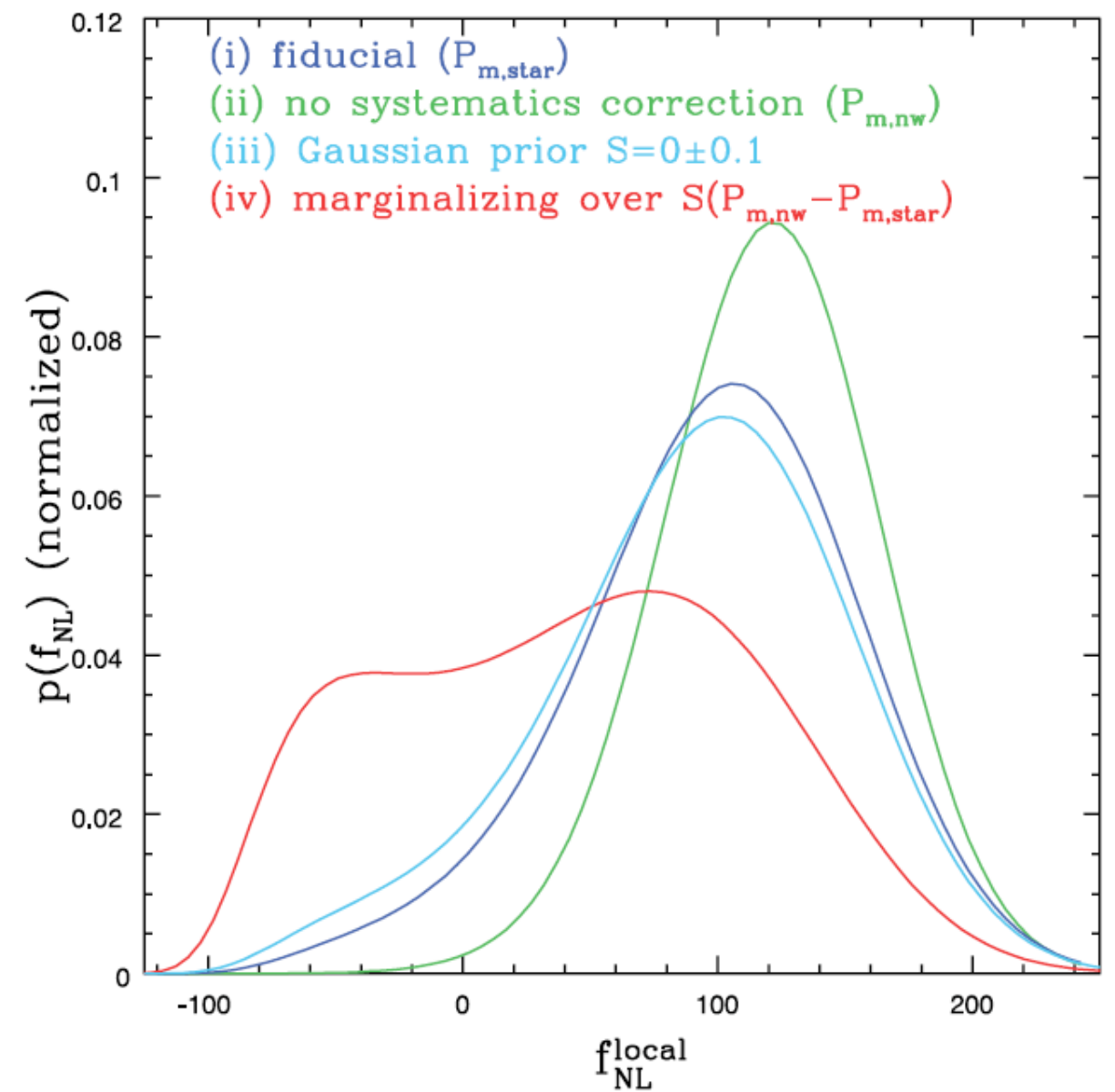
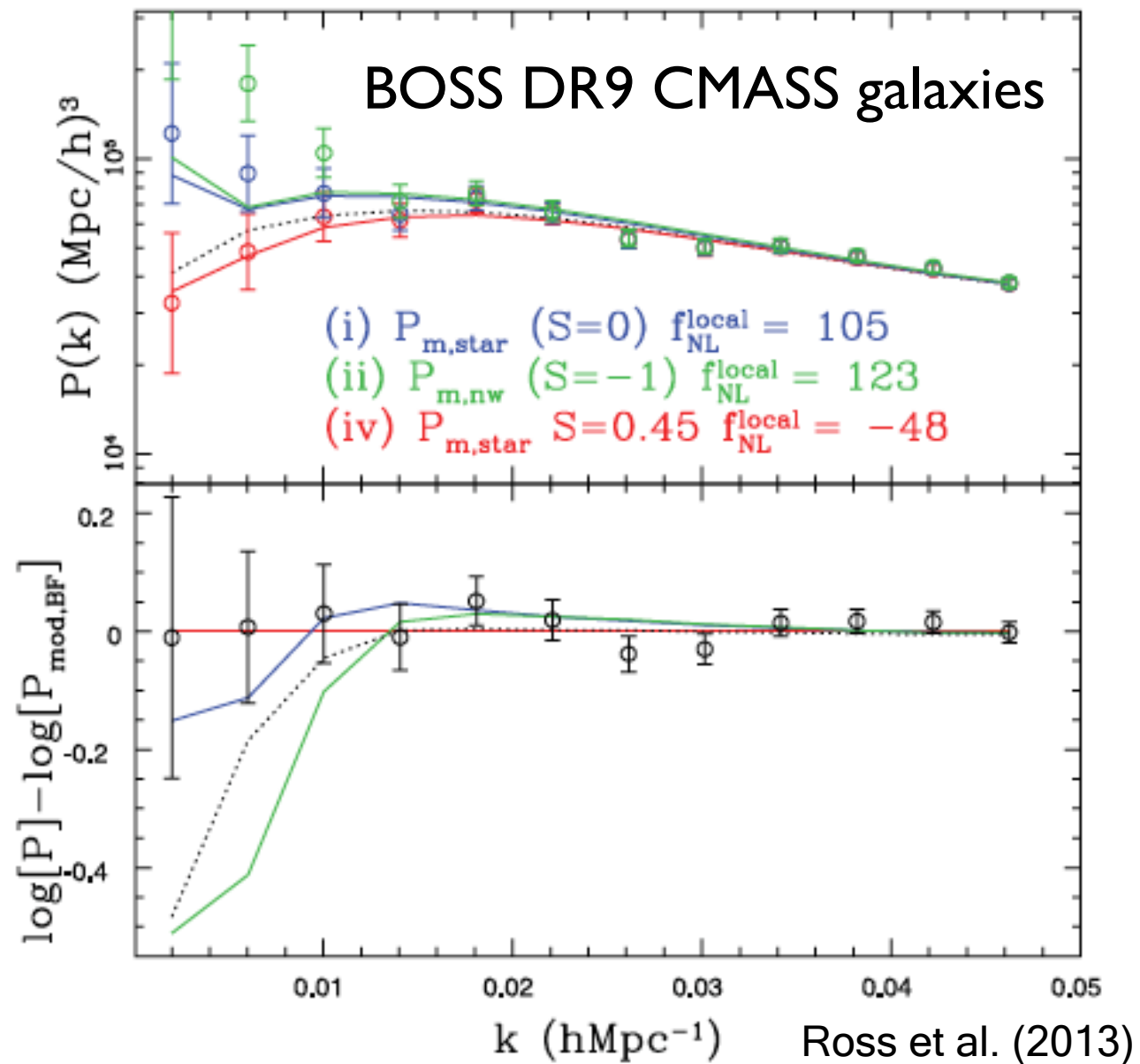
Primordial non-Gaussianity: local f_{NL}

- Amount of non-Gaussianity in primordial field in squeezed k -space triangle configurations
- Introduces coupling between short and long wavelength modes
- And thus scale dependent bias for biased tracers with k^{-2} dependence

de Putter (2018)



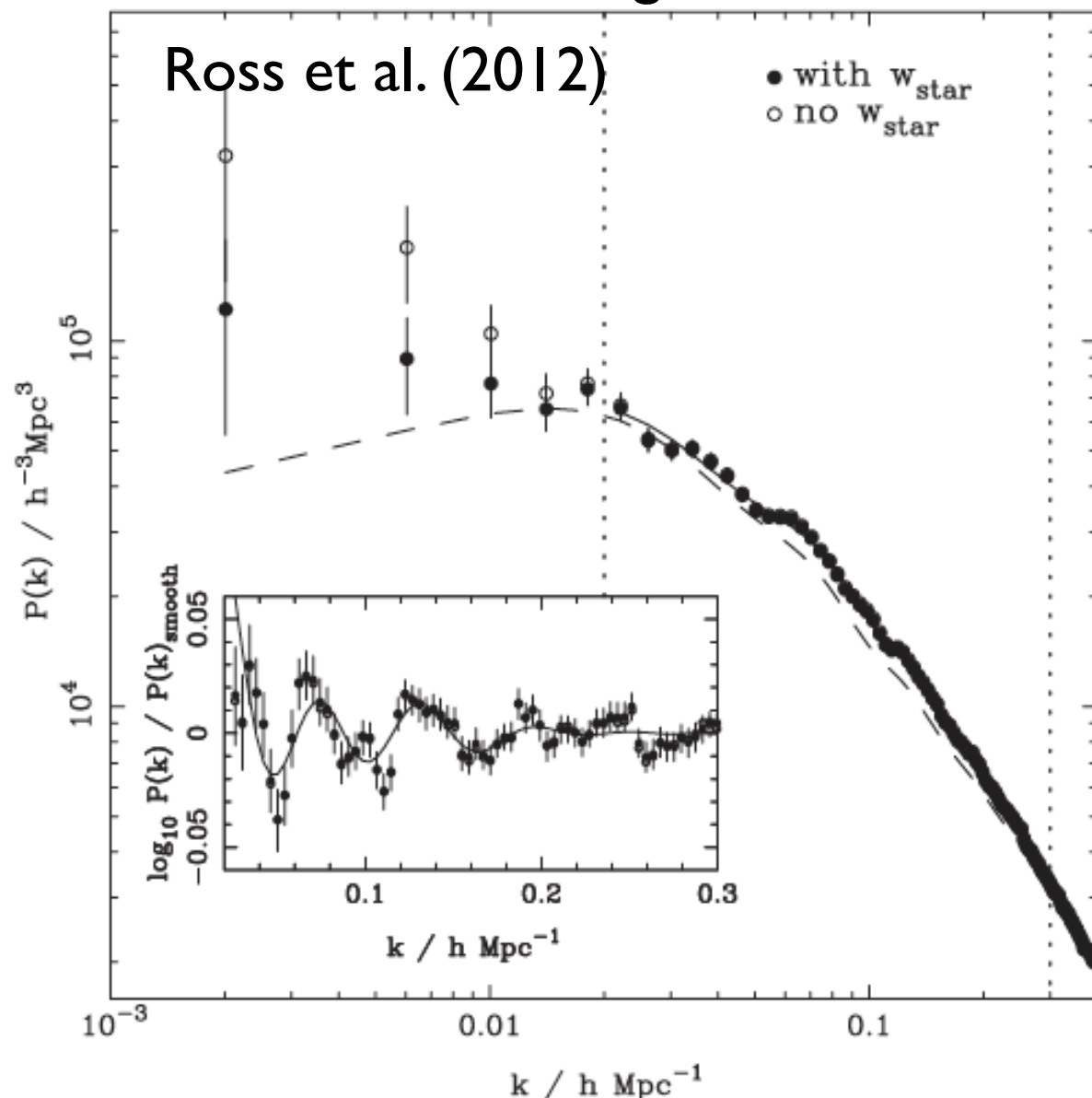
Observational Systematics: f_{NL}



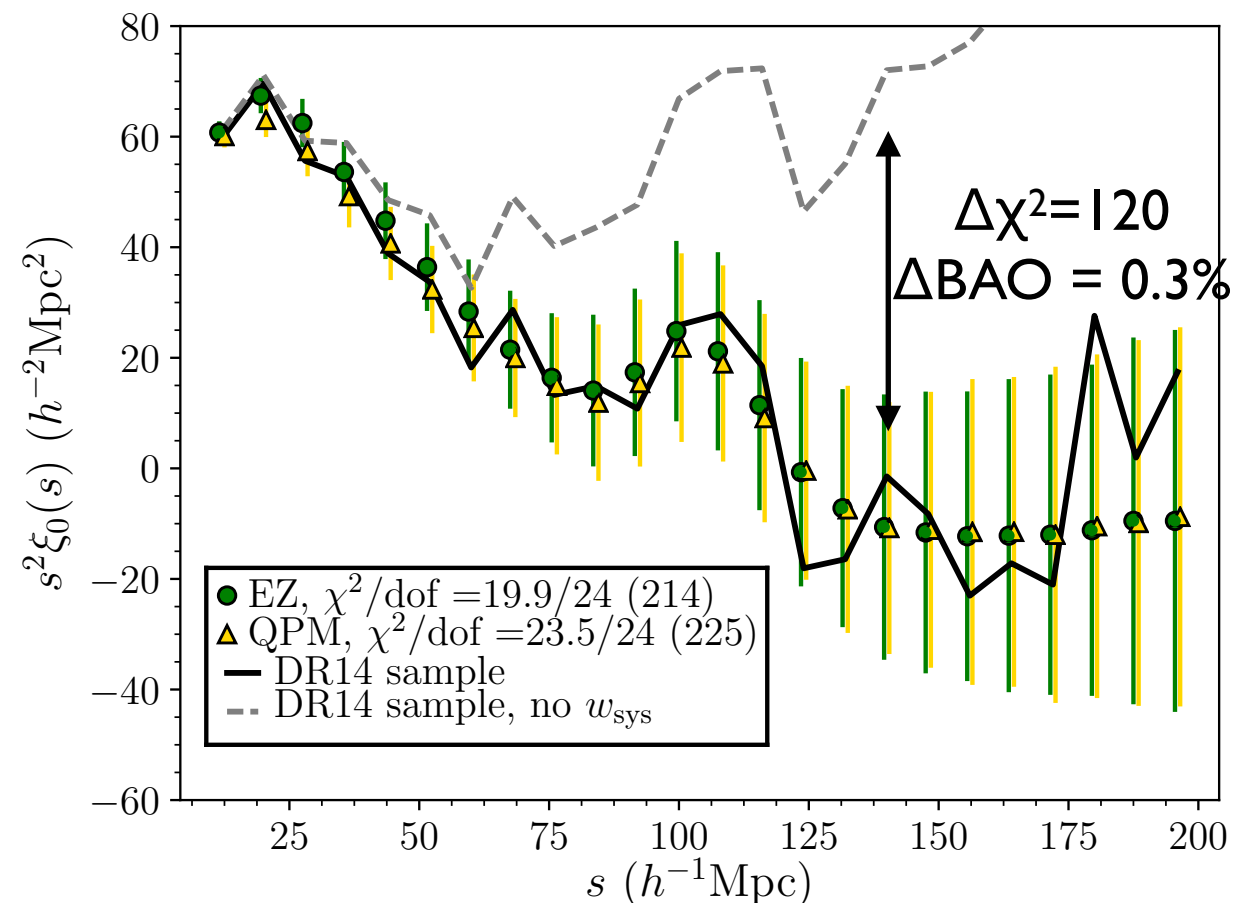
BAO Don't Budge

- BOSS galaxies (Ross et al. 2017), Ly- α forest (Bautista et al. 2017), quasars, DES photozs...

BOSS DR9 CMASS galaxies



eBOSS DR14 quasars
Ata et al. (2017)



BAO

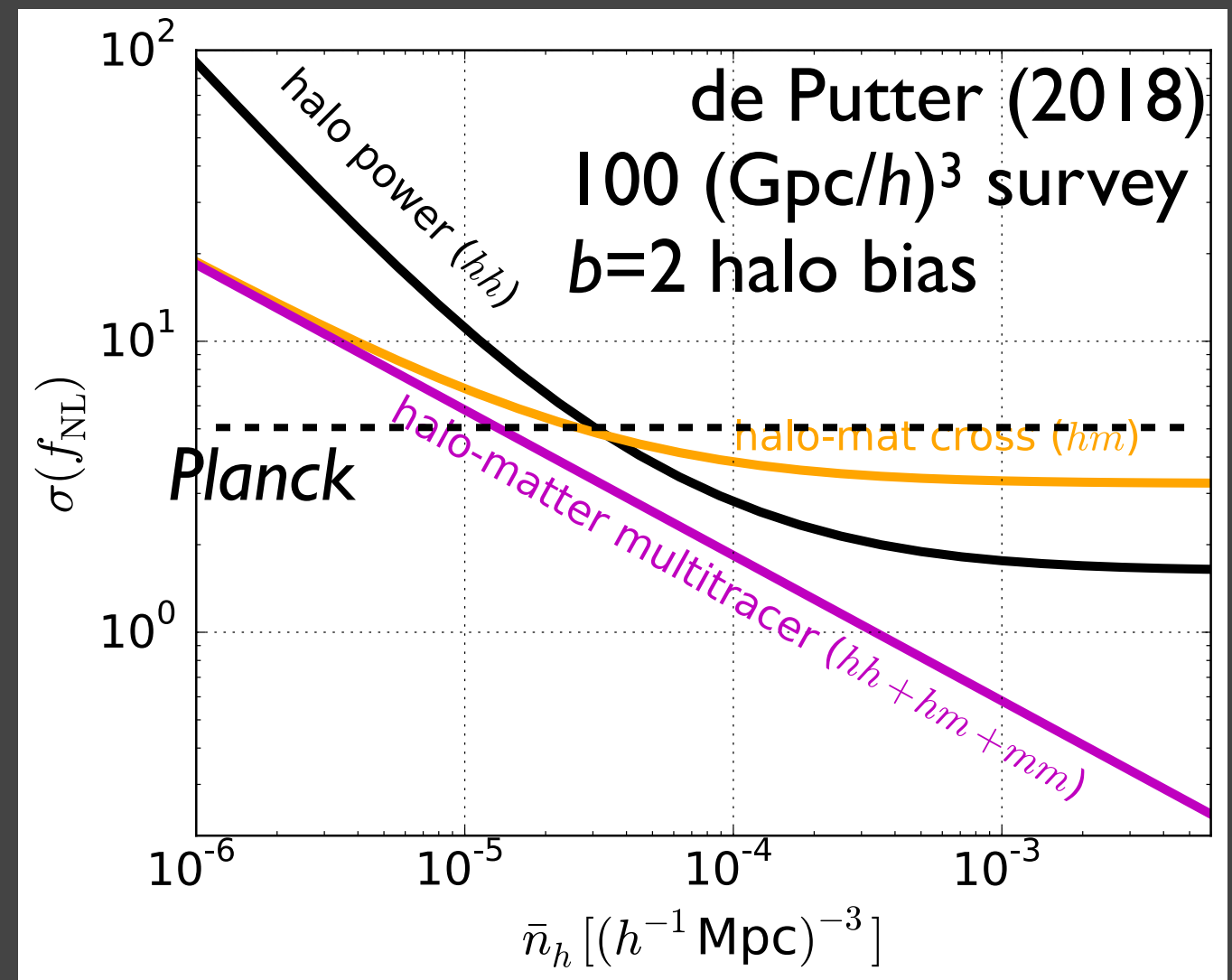
- No significant systematic concerns or technical challenges in obtaining measurements
- More galaxies, more volume: Better Dark Energy constraints

Primordial Potential

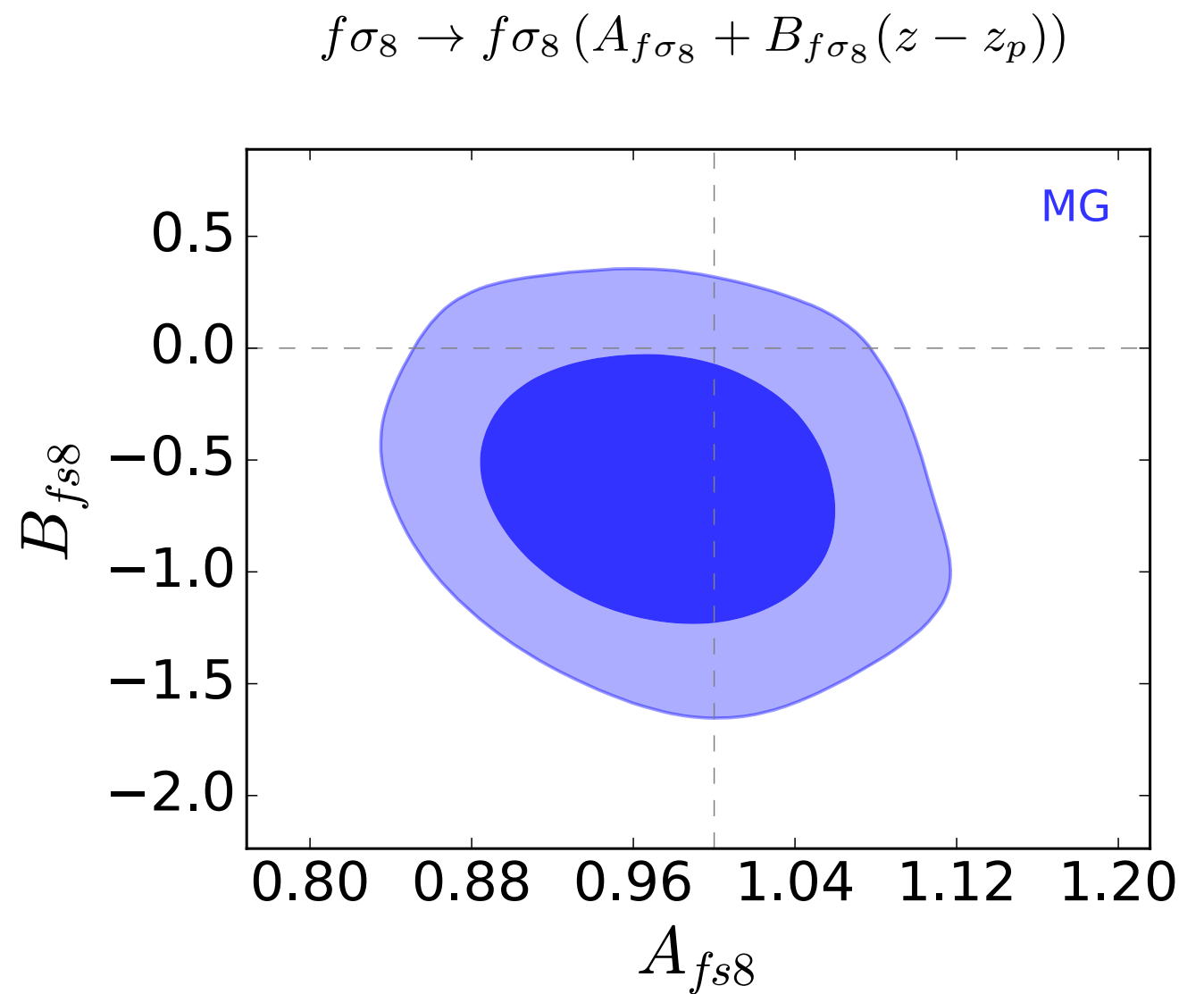
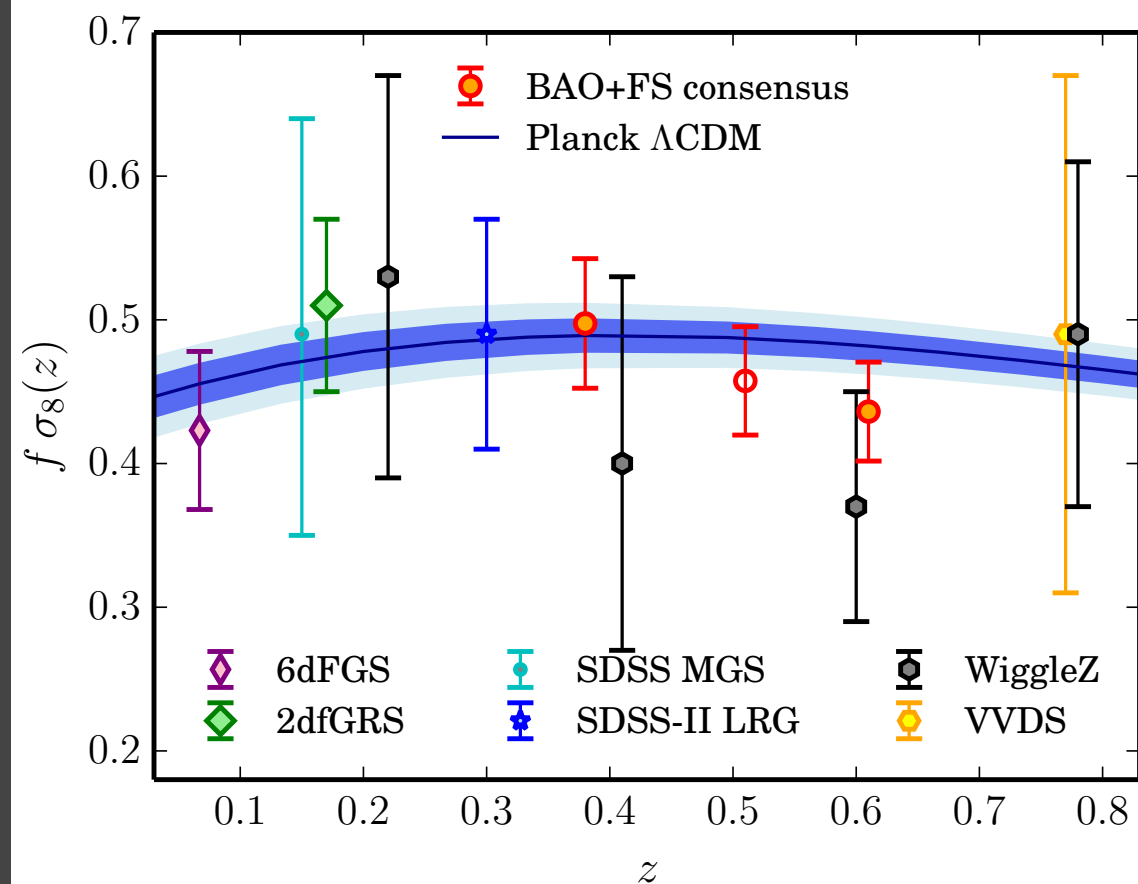
DESI forecasts

Data	σ_{n_s}	σ_{α_s}
Gal ($k_{\max} = 0.1h \text{ Mpc}^{-1}$)	0.0025 (1.3)	0.005 (1)
Gal ($k_{\max} = 0.2h \text{ Mpc}^{-1}$)	0.0022 (1.5)	0.004 (1.3)
Ly- α forest	0.0029 (1.1)	0.0027 (1.9)
Ly- α forest + Gal ($k_{\max} = 0.2$)	0.0019 (1.7)	0.0019 (2.7)

() denotes gain over Planck

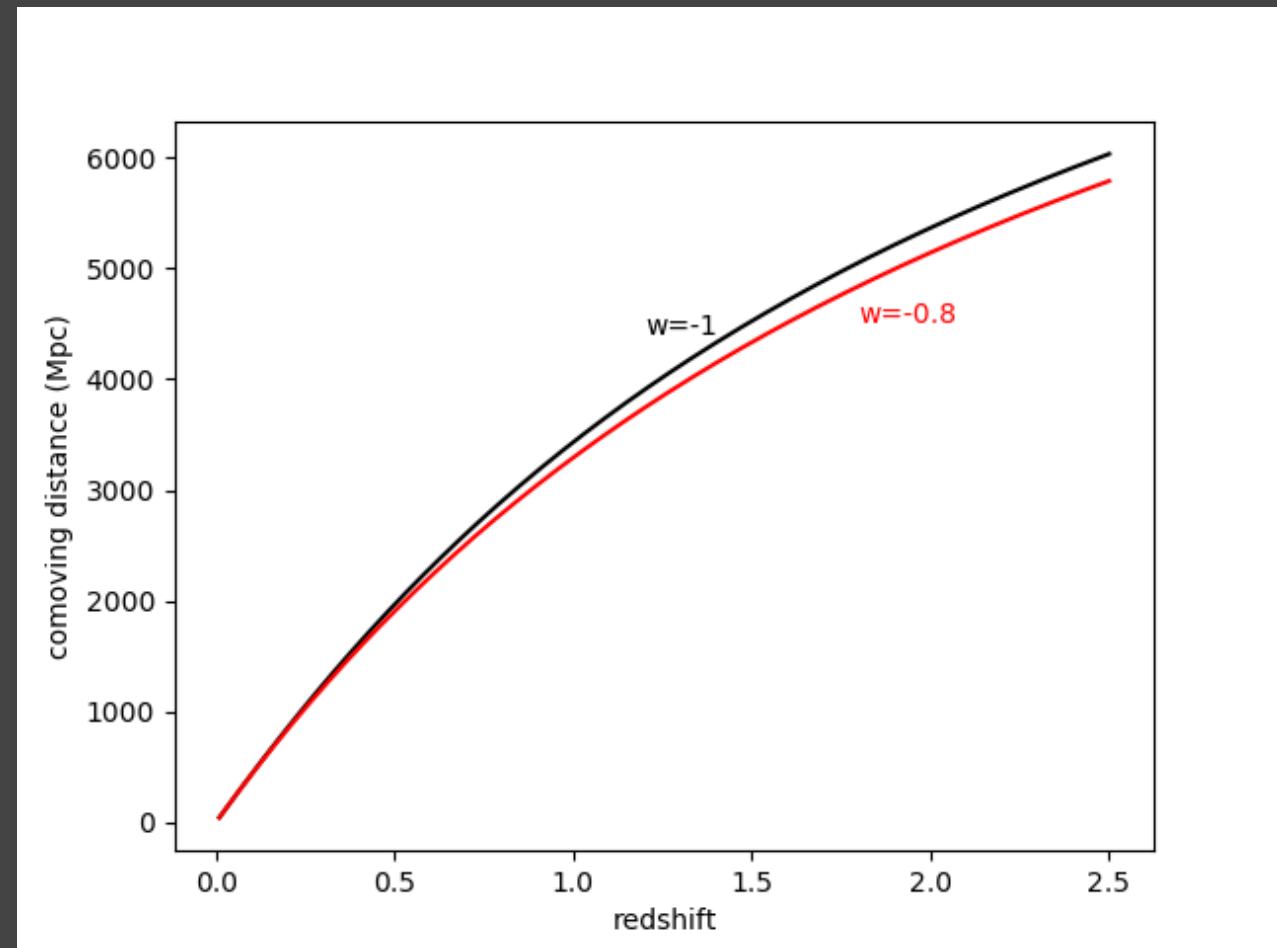


Testing General Relativity



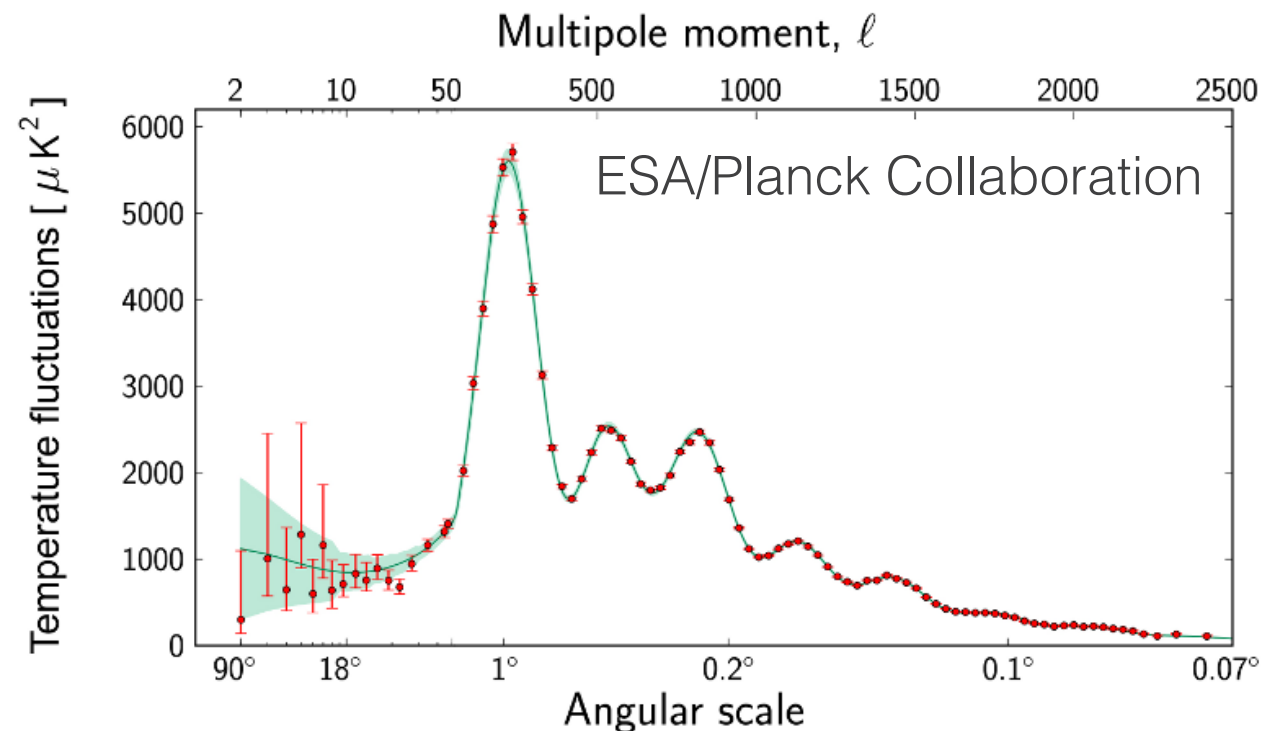
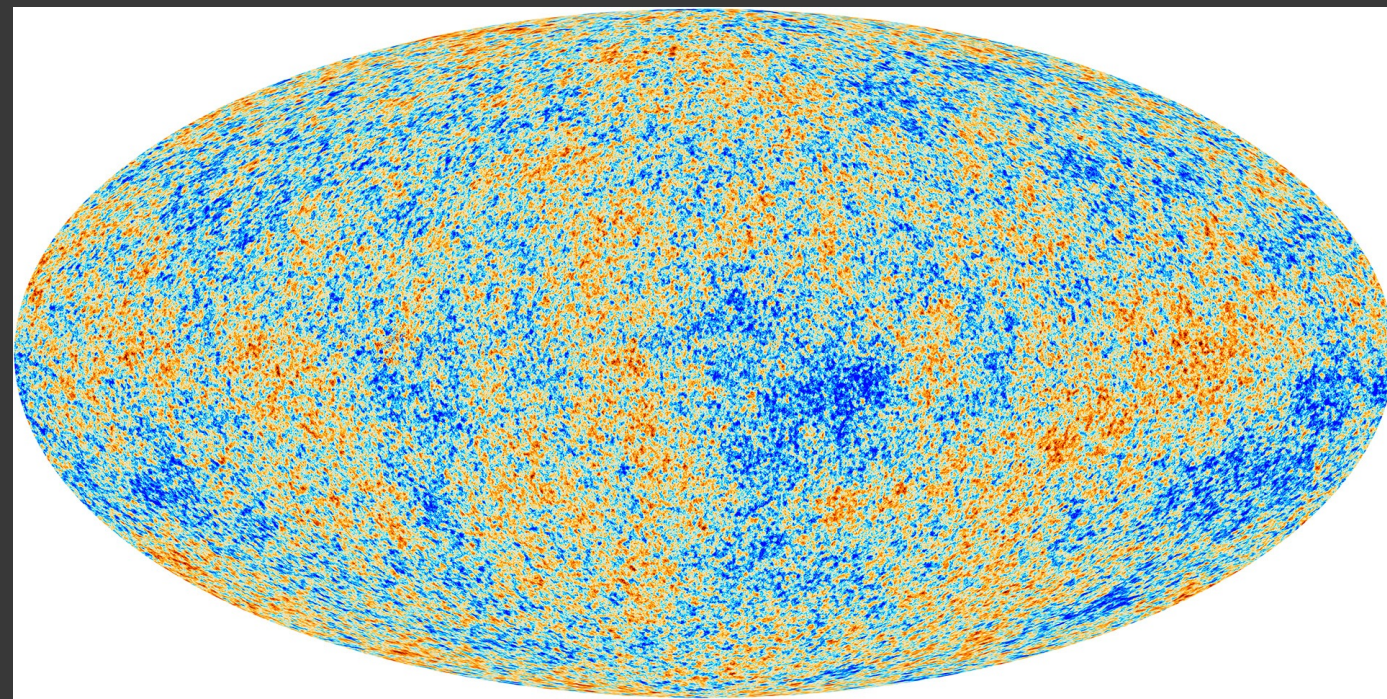
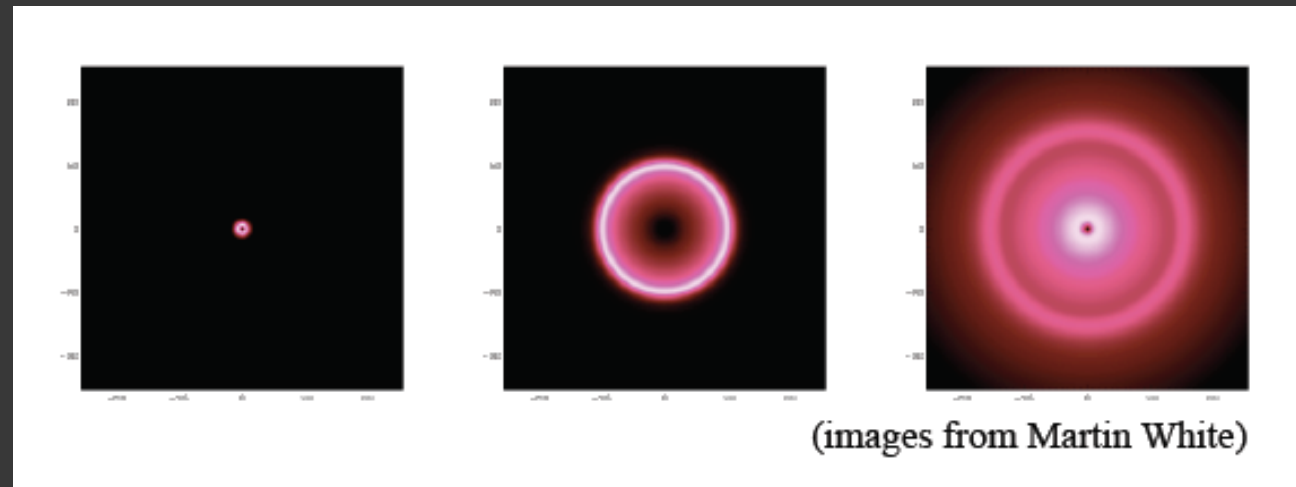
Measuring Dark Energy

- Equation of state $w = p/\rho$
- Cosmological constant, $w=-1$
- common parameterization is $w(a) = w_0 + (1-a)w_a$
- scale factor, $a = 1/(1+z)$



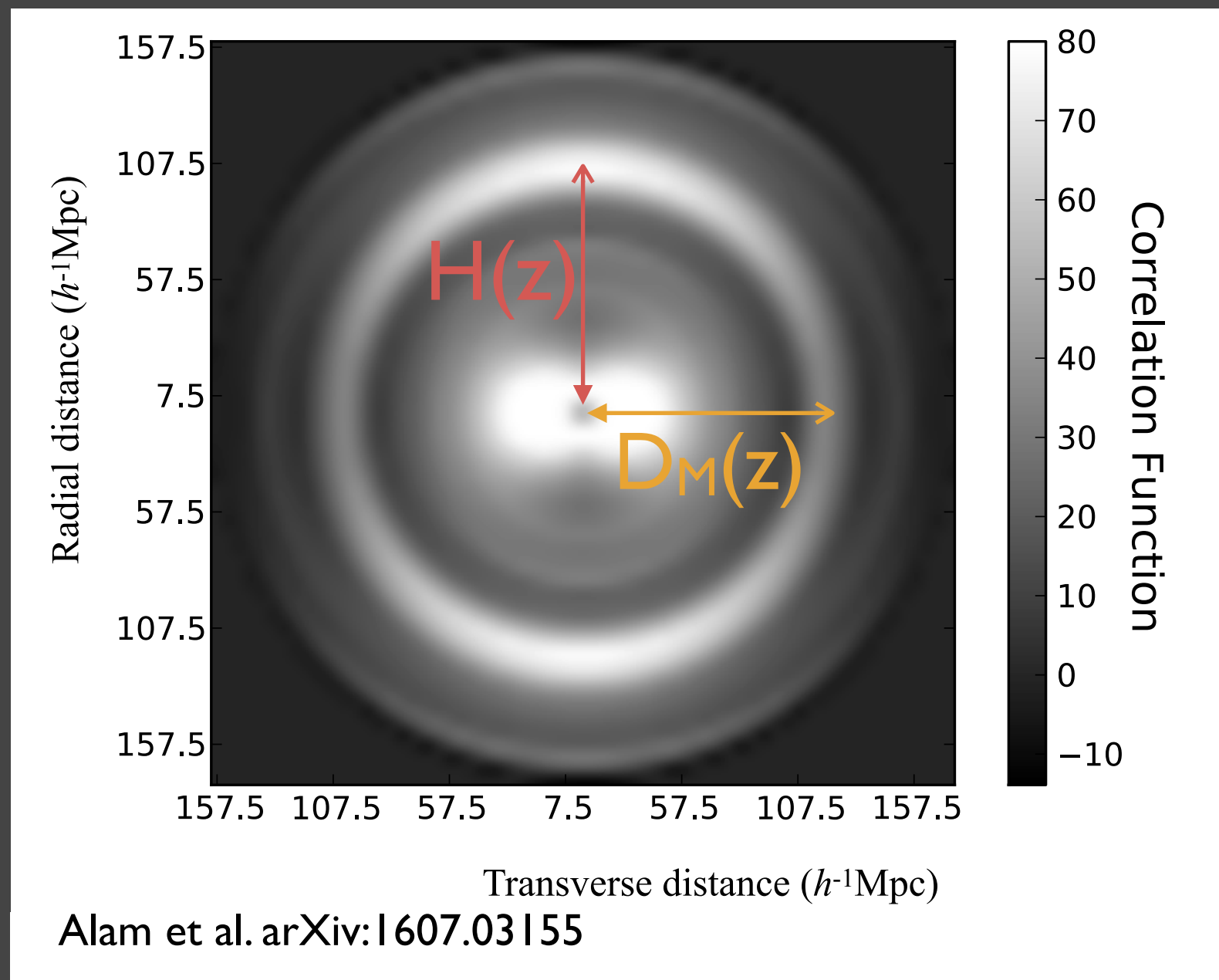
Baryon Acoustic Oscillations

- early Universe radiation pressure/ matter density $\rightarrow$ standing wave in baryon density



What BAO measures

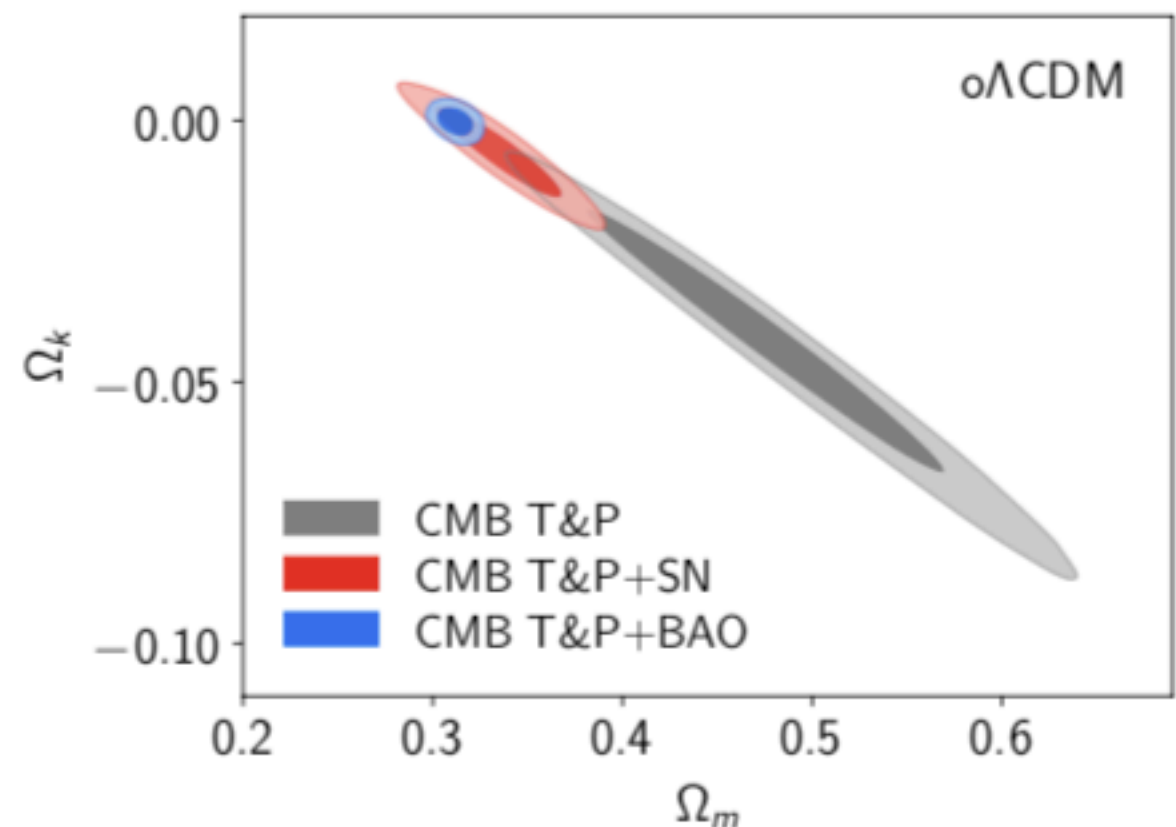
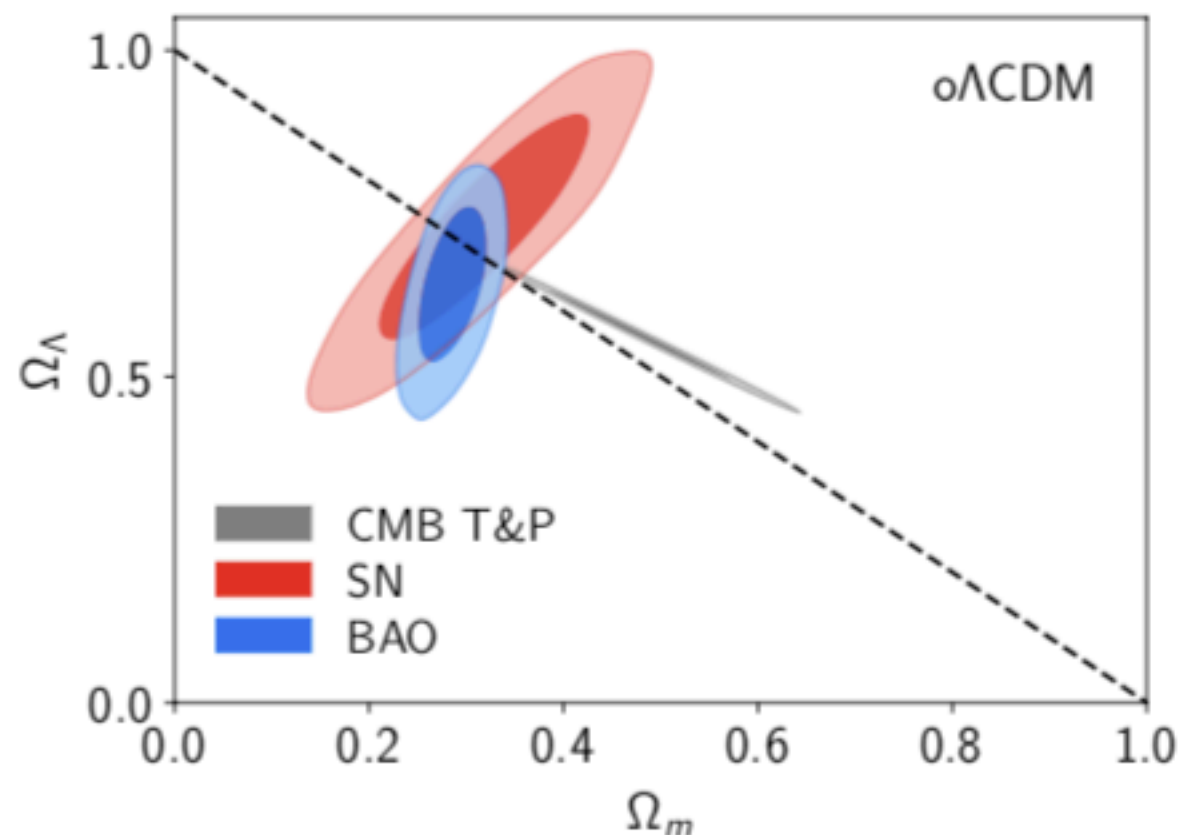
- Radial clustering measures $H(z)$
- Transverse clustering measures $D_M(z) = (1+z)D_A(z)$
- $D_V(z) \equiv [czH^{-1}(z)D_M^2(z)]^{1/3}$; (spherical average)



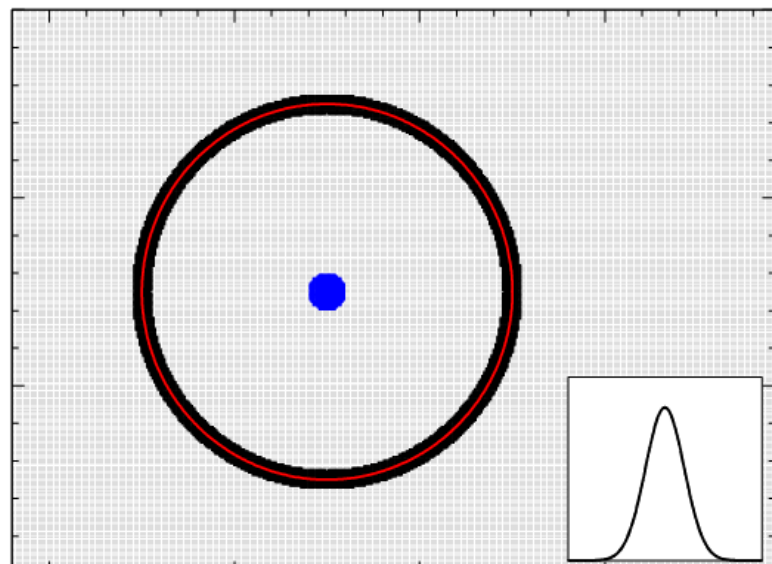
Testing Dark Energy with only BAO

- Treat BAO as *uncalibrated* standard ruler
- BOSS galaxies + eBOSS quasars $> 3\sigma$ detection of DE
- All BAO, 8σ detection!

Alam et al. (2020.)

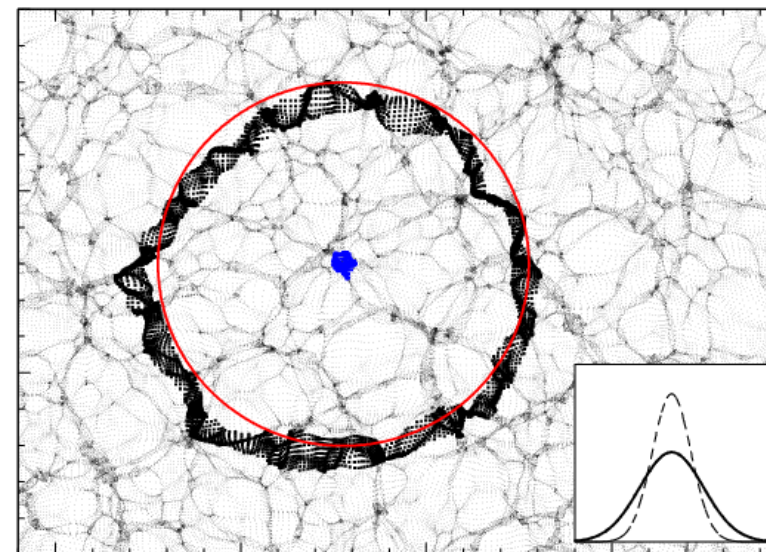


Reconstruction



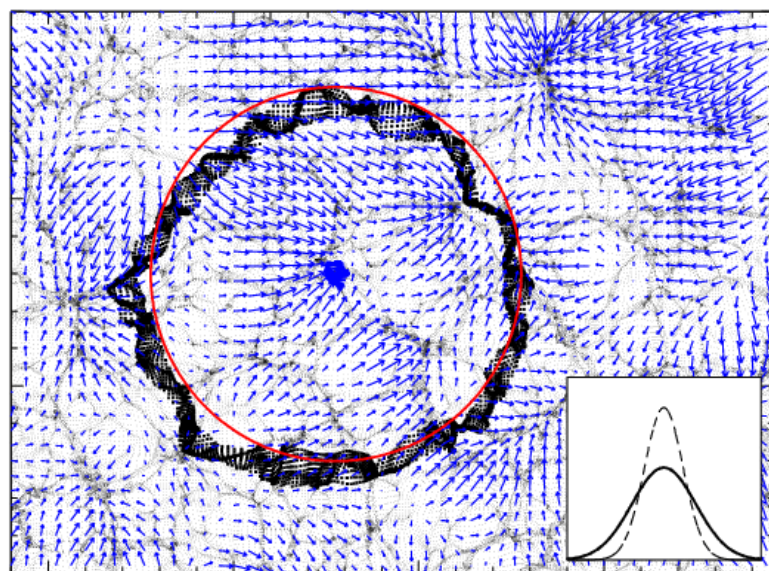
1.

- High z
- Uniform
- Sharp Gaussian



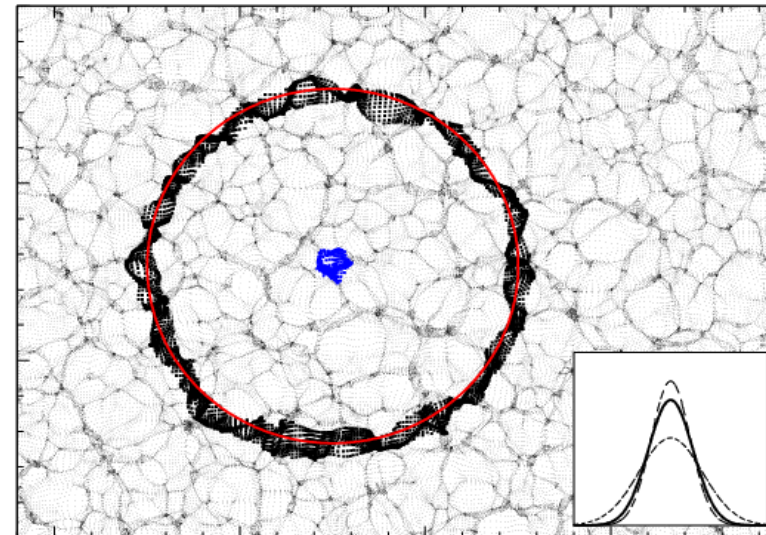
2.

- Evolved to $z=0$
- Ring distorted
- Gaussian wider



3.

- Lagrangian displacements



4.

- Particles moved back.
- Gaussian peak sharper

Figures from Padmanabhan et al. 2012

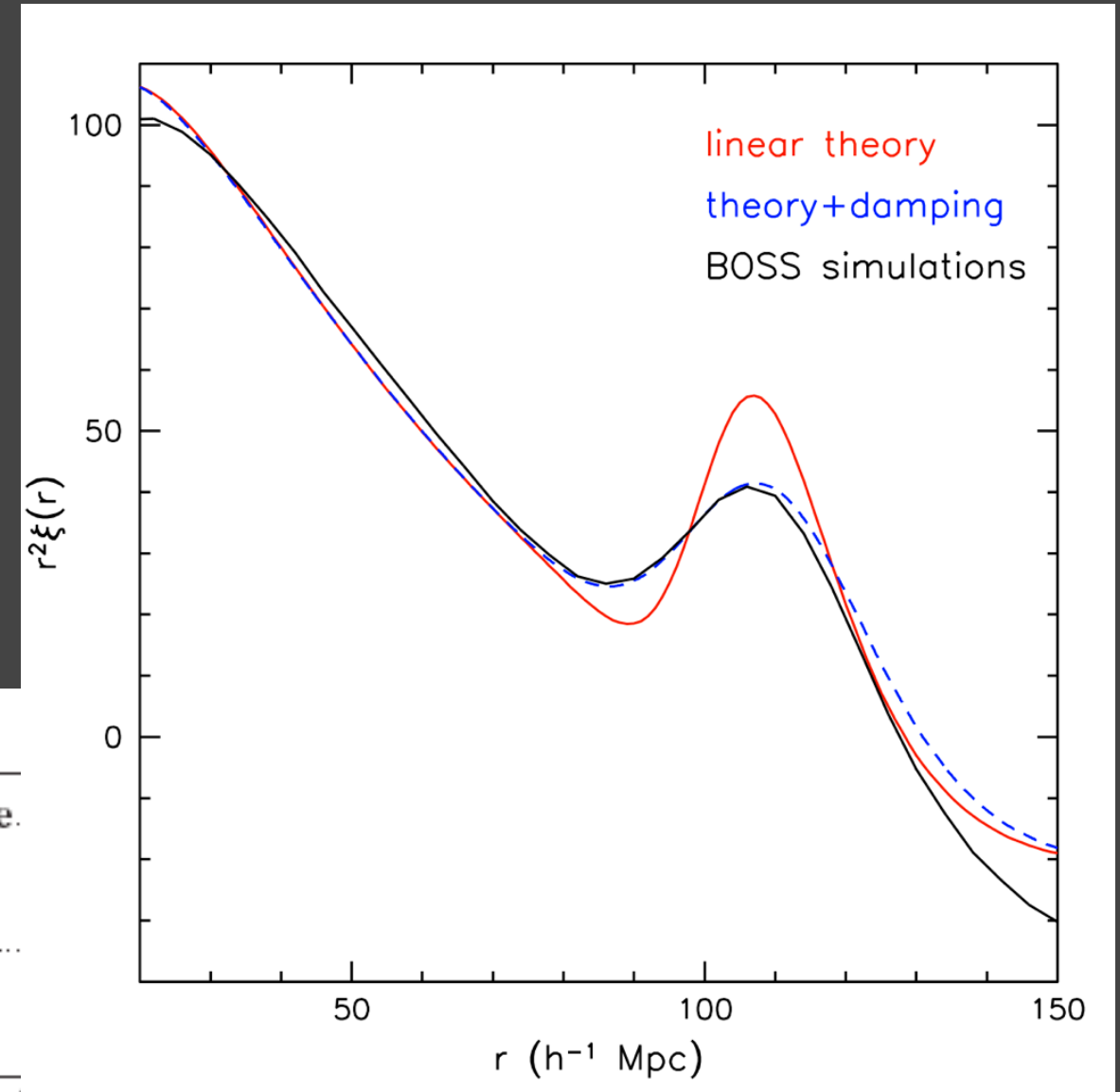
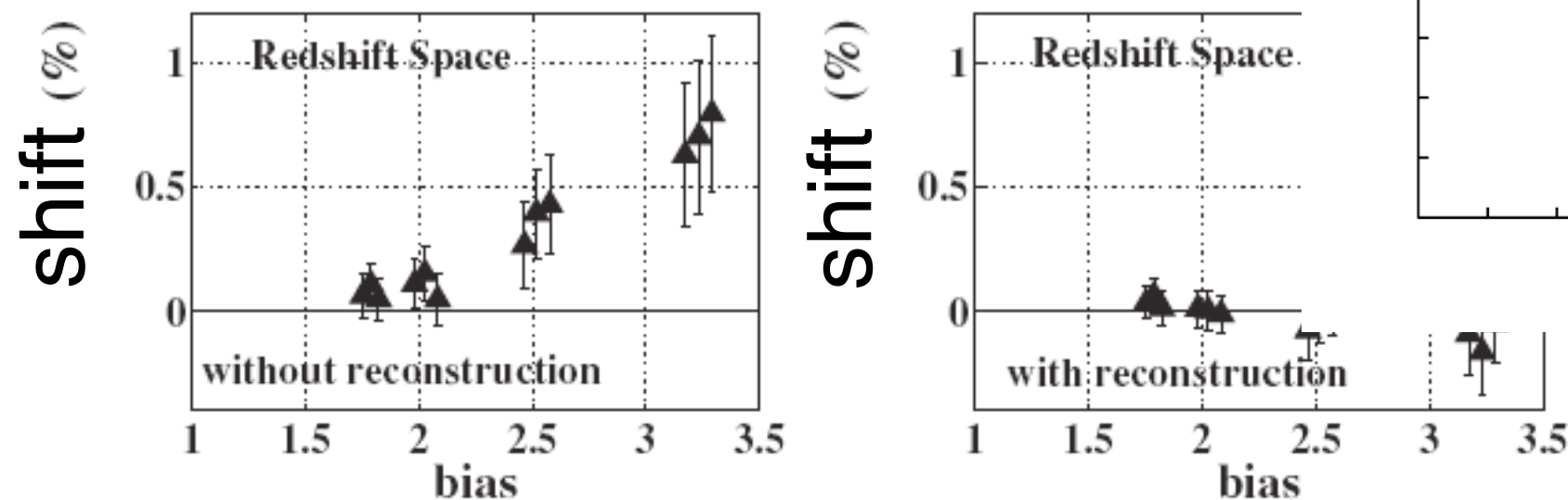
Removes RSD effects

Impact on BAO

Theoretical results + simulations show:

- non-linearities smear BAO scale
- (small) bias (halo mass) dependent shift

Mehta et al. (2011)



Impact on BAO

Theoretical results + simulations show:

- non-linearities smear BAO scale
- (small) bias (halo mass) dependent shift

Mehta et al. (2011)

