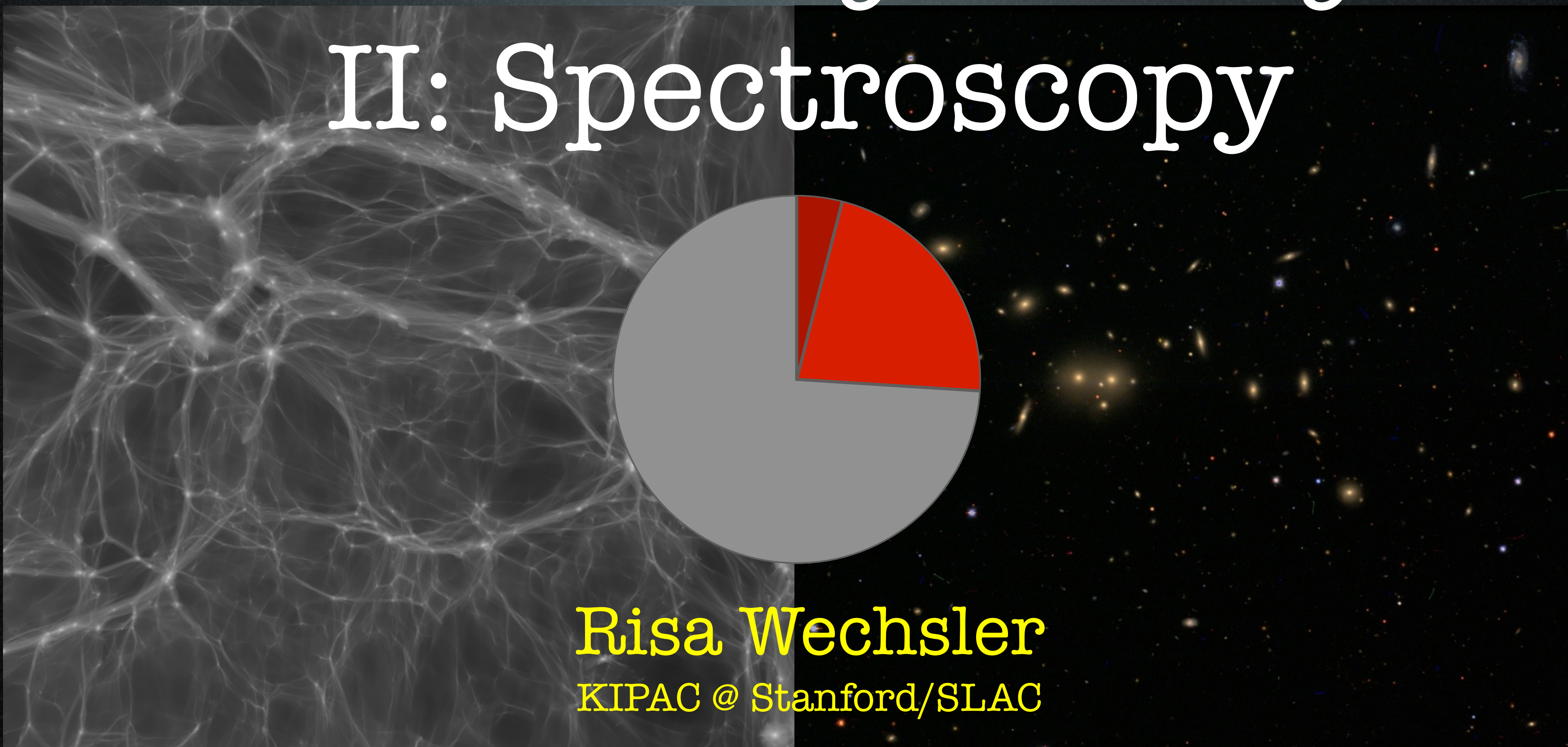
Large-Scale Structure from Galaxy Surveys II: Spectroscopy



Risa Wechsler
KIPAC @ Stanford/SLAC

SLAC SSI August 18, 2017

Mapping the Universe

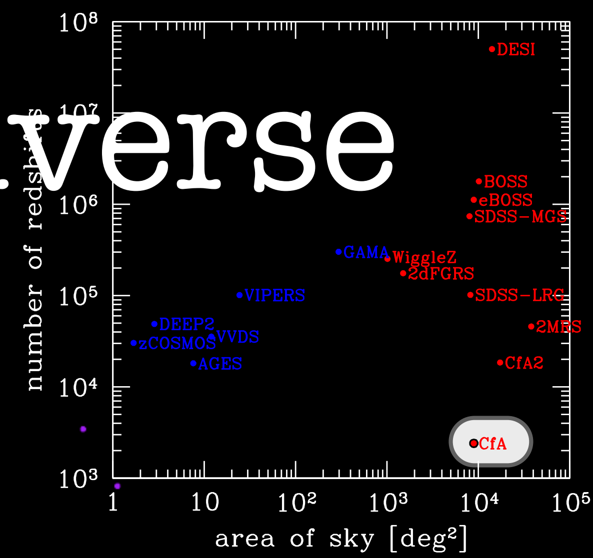
- Last time:
  - 2+D maps of the Universe with imaging surveys
- Today:
  - 3D maps of the Universe with spectroscopic surveys

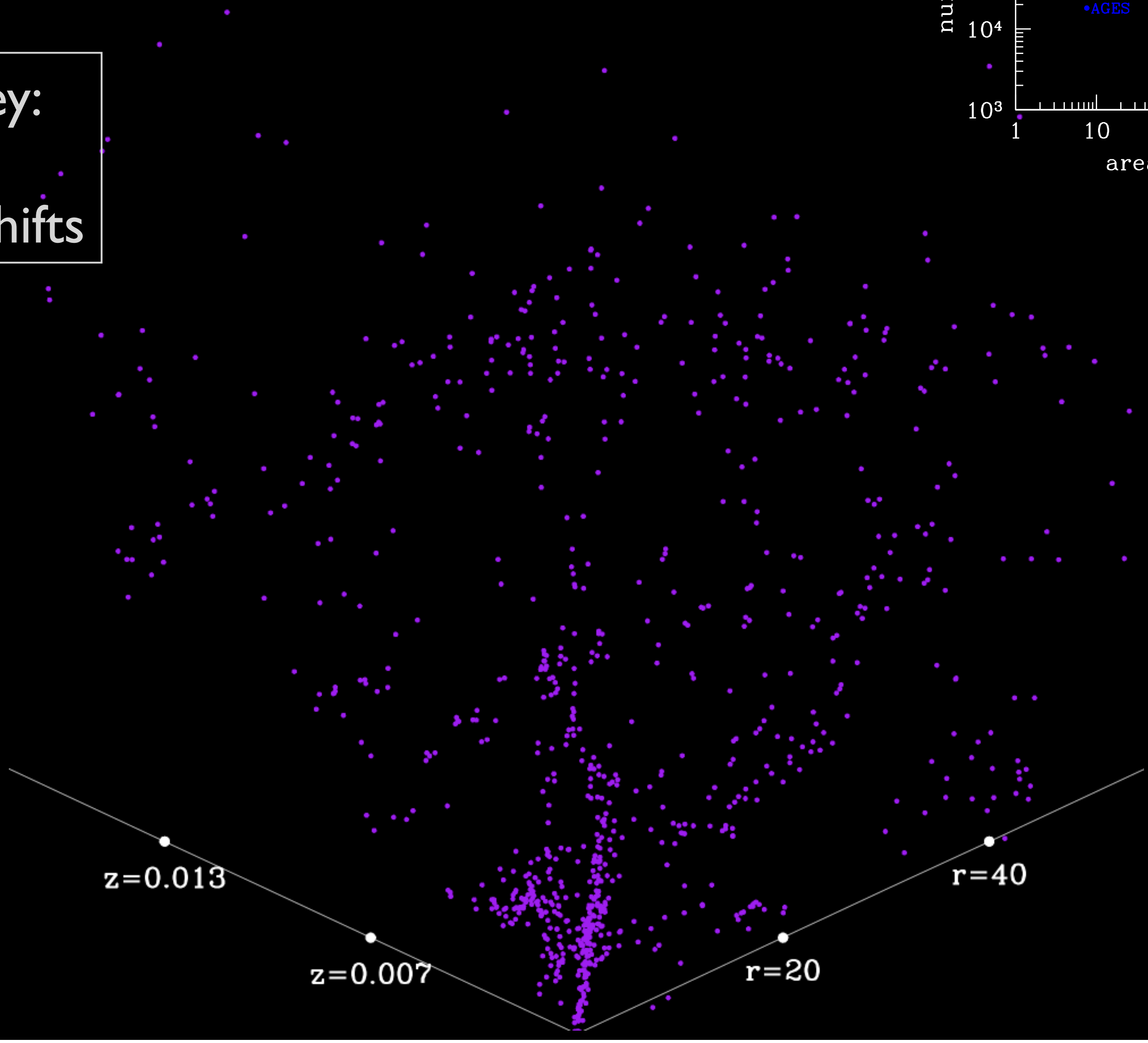
Imaging and Spectroscopic surveys

- 2+D mapping with imaging surveys (SDSS, DES, HSC, Euclid, LSST, WFIRST):
  - weak lensing (geometry+growth)
  - cluster abundance and clustering (mostly growth, some geometry)
  - galaxy clustering, including BAO (geometry+growth)
  - supernovae, strong lensing time delays (geometry)
- 3D mapping with redshift surveys (SDSS, BOSS, DESI, Euclid):
  - Baryon Acoustic Oscillations (BAO) (geometry)
  - Redshift-space distortions (RSD) (growth)
  - Significant additional information for dark energy, inflation, neutrinos from full galaxy power spectrum to small scales, if modeling can keep up with the data

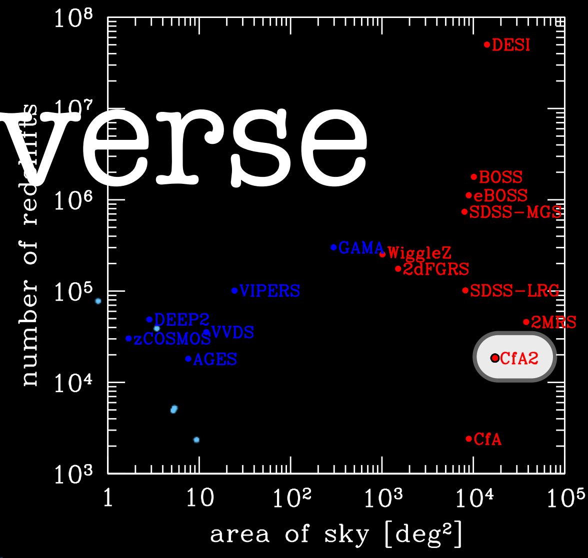
Mapping the Universe

CfA survey:
1983
~2000 redshifts

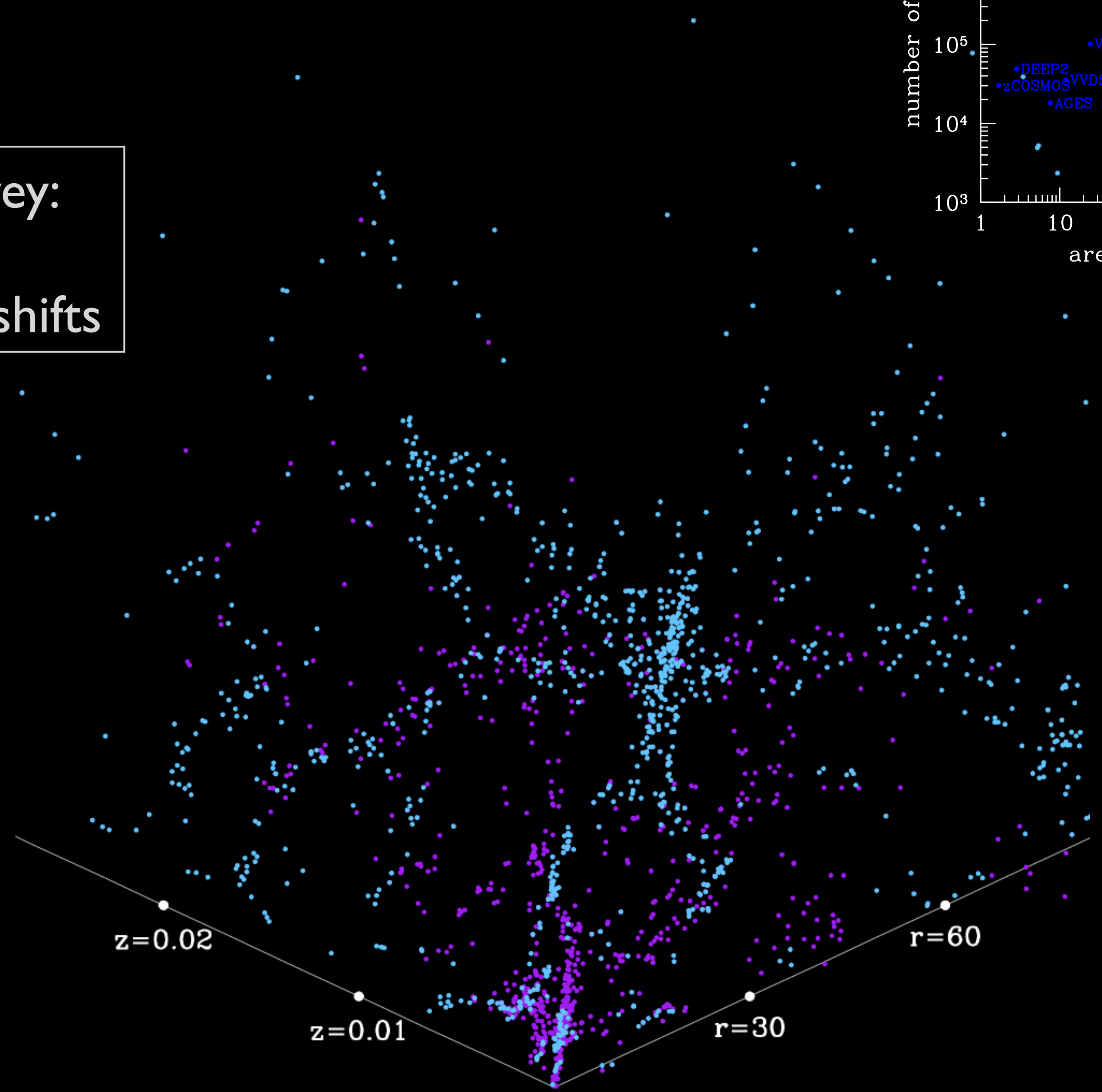




Mapping the Universe

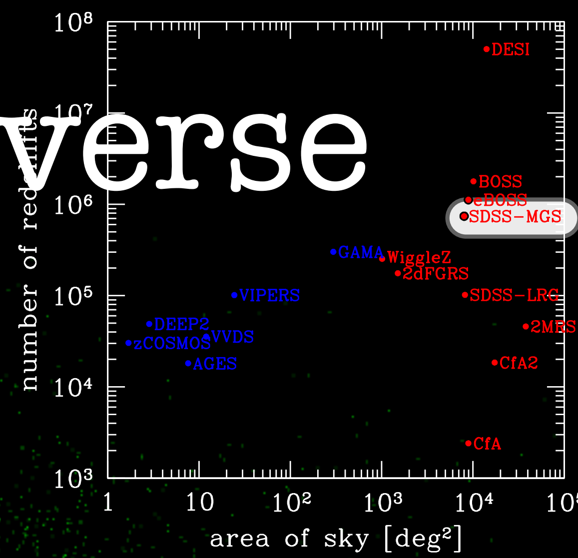


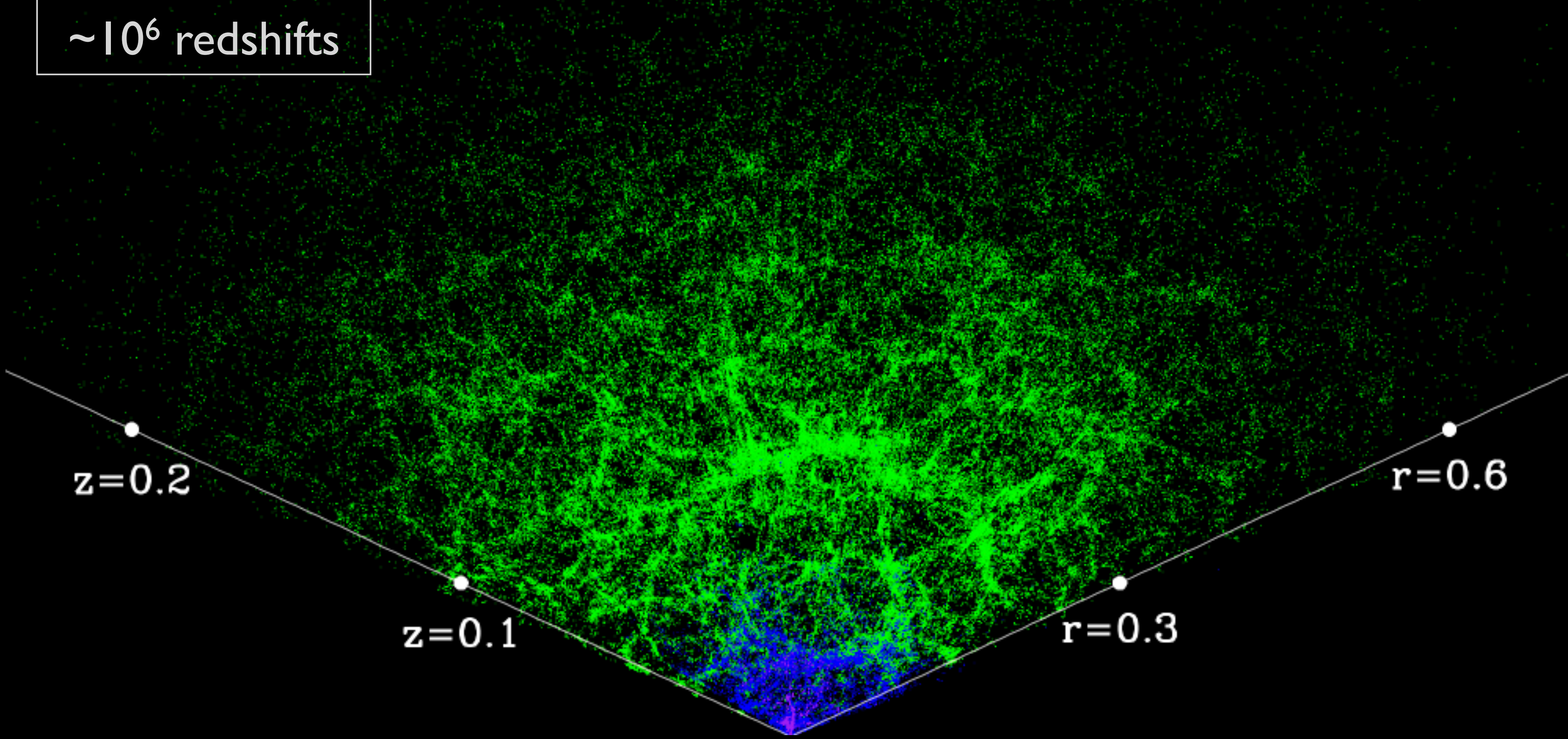
CfA2 survey:
1995
~20000 redshifts



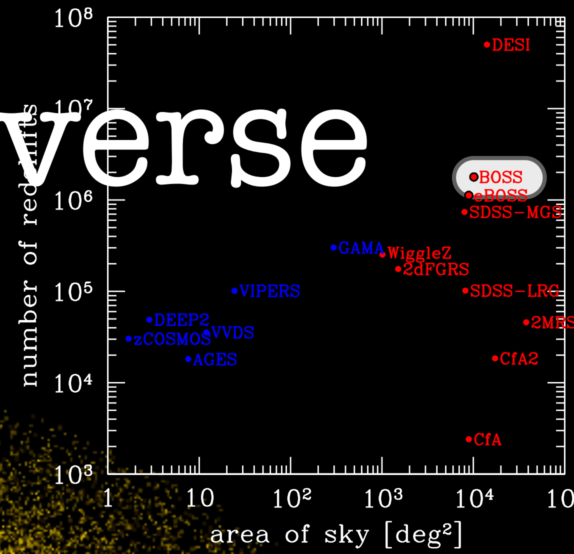
Mapping the Universe

SDSS (MGS)
DR7: 2009
~10^6 redshifts

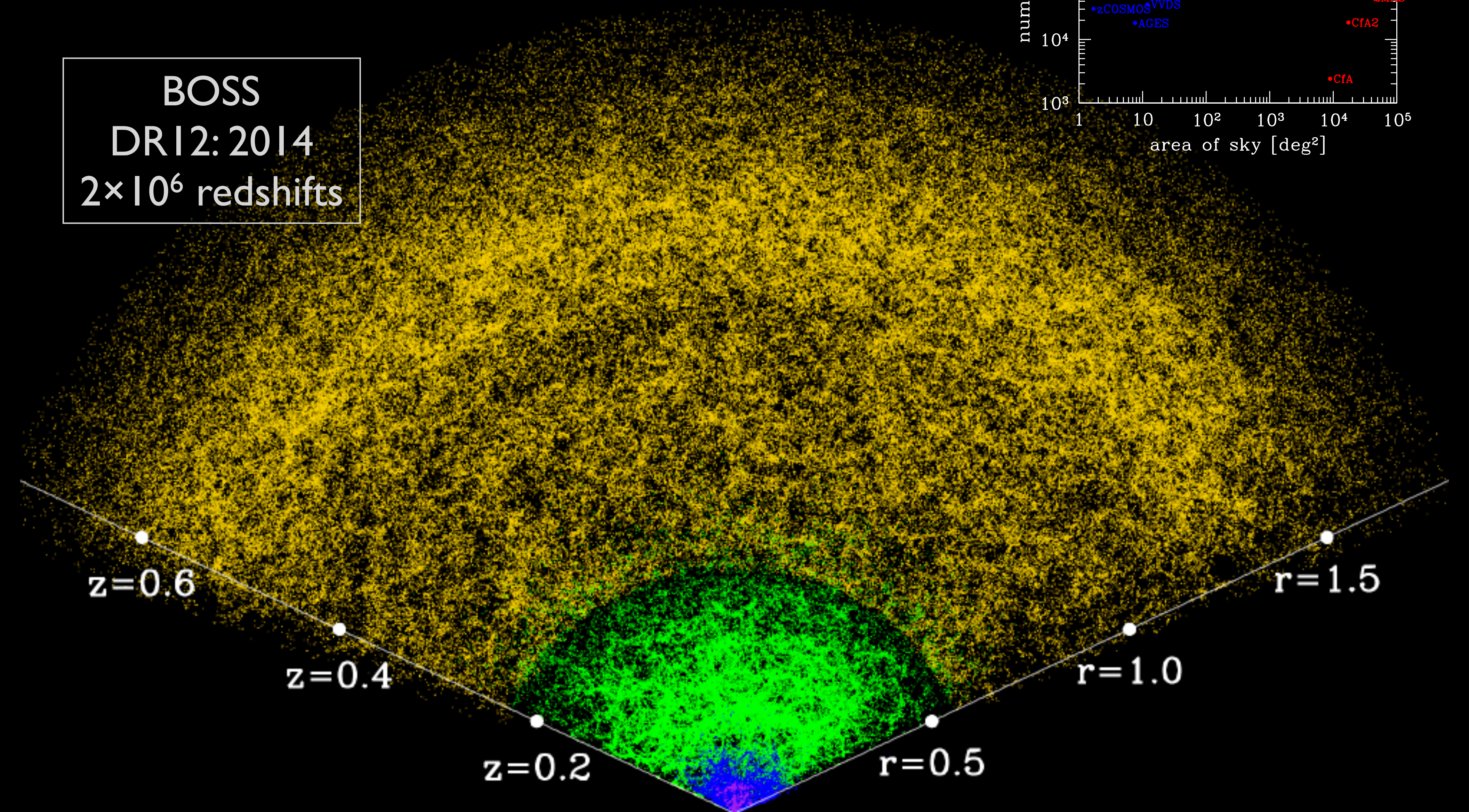




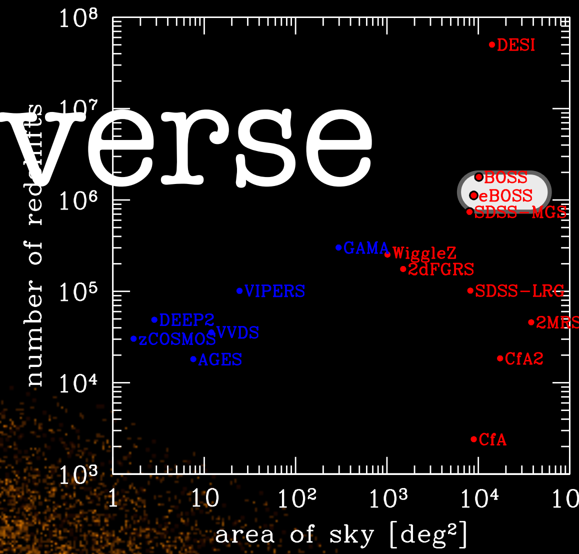
Mapping the Universe



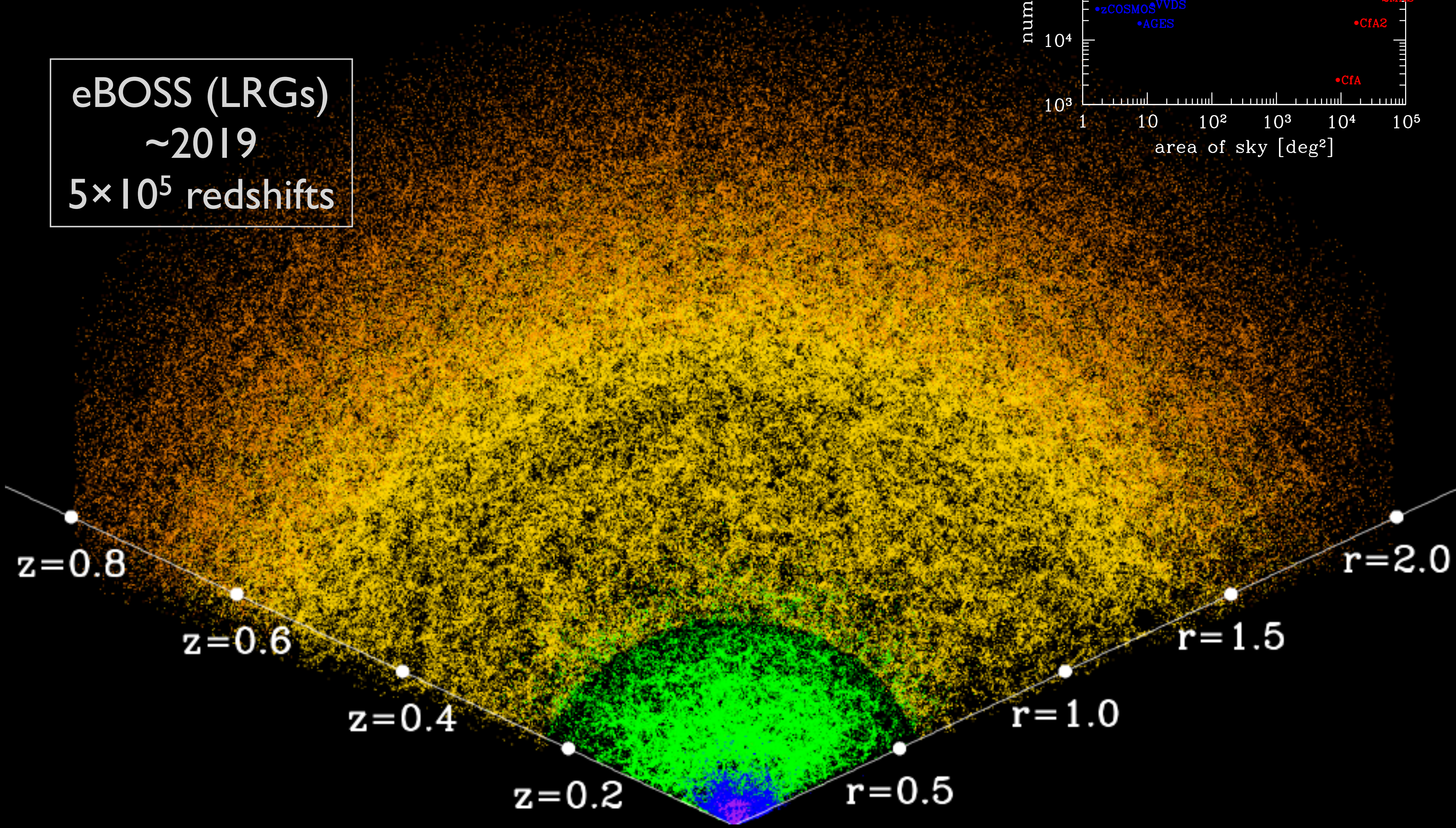
BOSS
DR12: 2014
2×10^6 redshifts



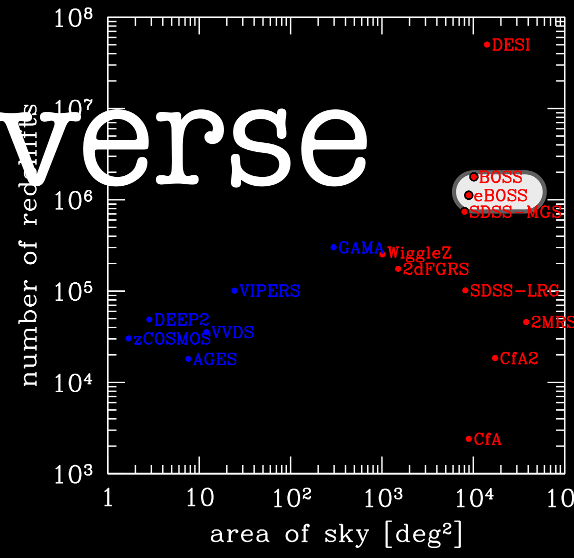
Mapping the Universe



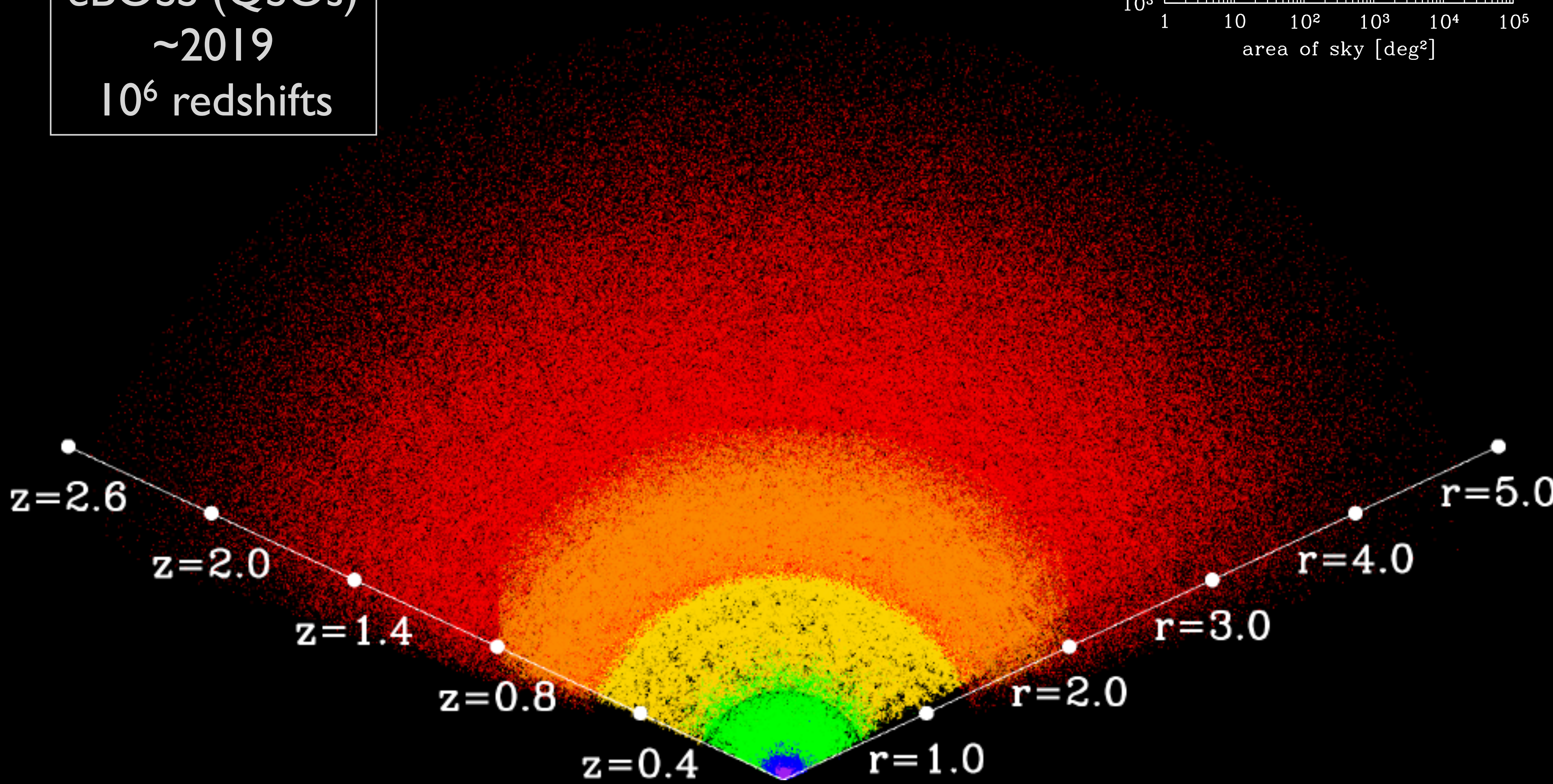
eBOSS (LRGs)
~2019
5×10^5 redshifts



Mapping the Universe



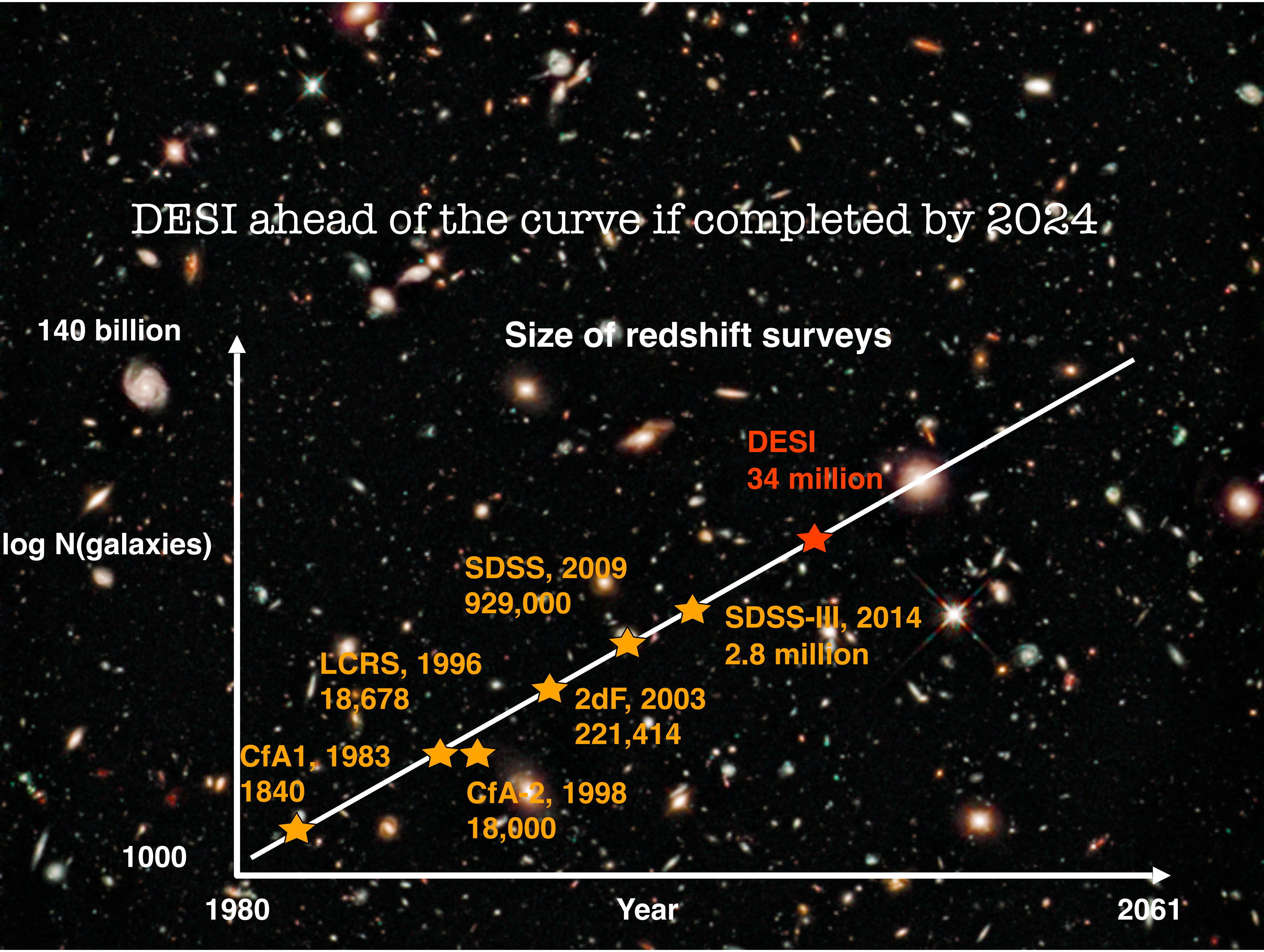
eBOSS (QSOs)
~2019
10^6 redshifts



DESI:

The Dark Energy Spectroscopic Instrument

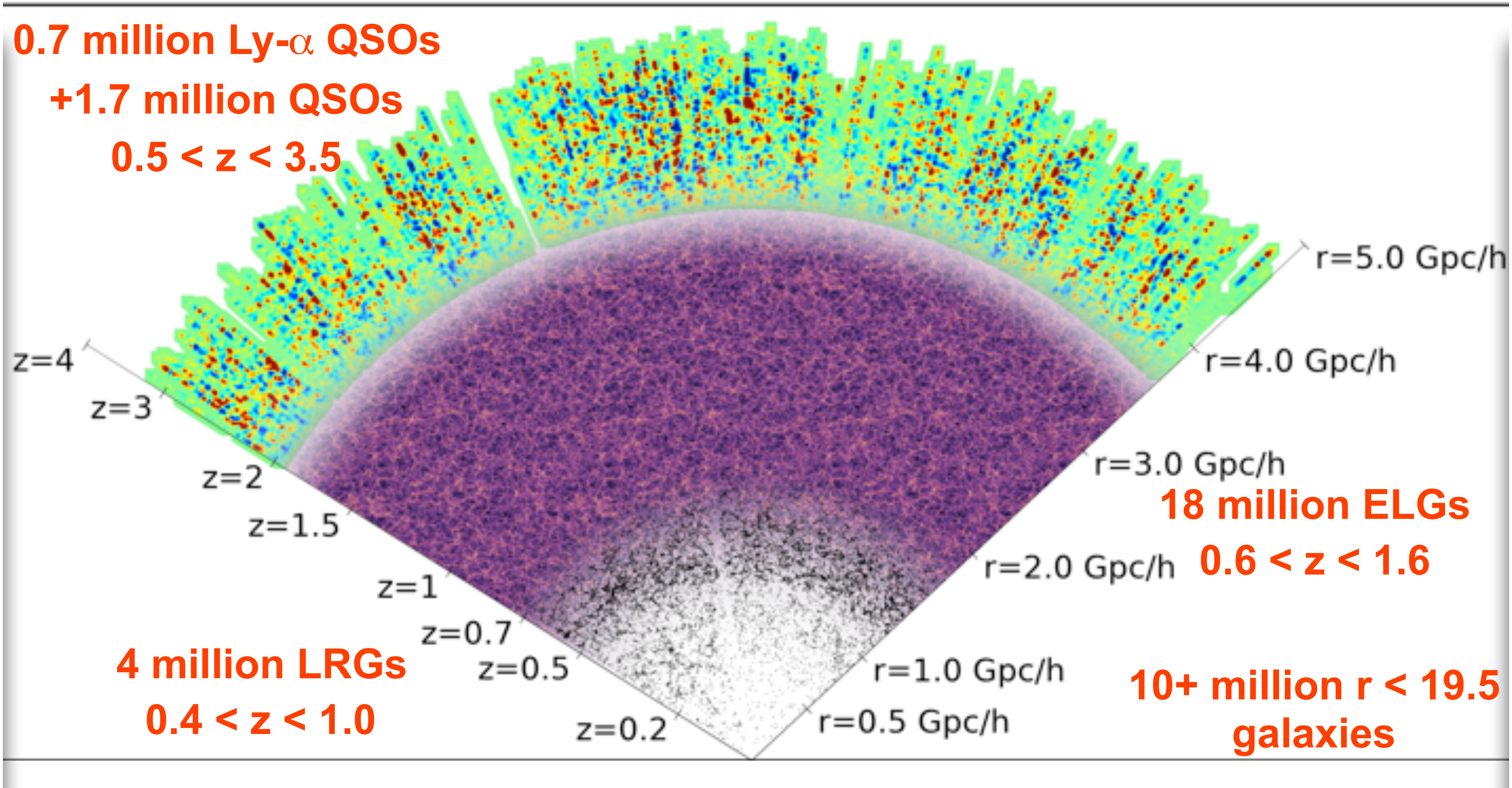
- new instrument: 5000 fibers, 8 deg^2 FOV, 10 3-arm spectrographs with R=2000-5500, 350-980nm
- 14000 sq. degree spectroscopic survey, 2019+5 years
- 35 million galaxy & quasar spectra— more than an order of magnitude increase in # of spectra and volume probed compared to current state-of-the-art



DESI ahead of the curve if completed by 2024
Size of redshift surveys
140 billion
log N(galaxies)
1000
1980
Year
2061
DESI
34 million
SDSS, 2009
929,000
SDSS-III, 2014
2.8 million
LCRS, 1996
18,678
2dF, 2003
221,414
CfA1, 1983
1840
CfA-2, 1998
18,000

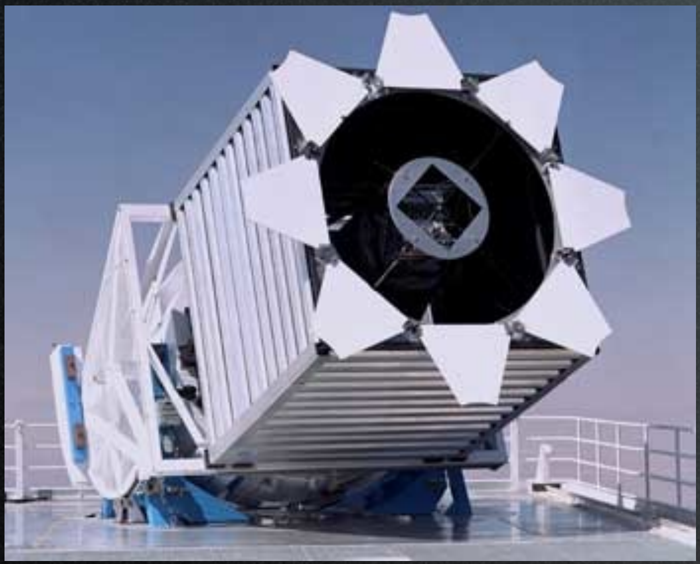
Overview of the DESI Survey

- Probing as much volume as possible, with the "easiest" redshifts
- Four target classes in dark time spanning redshifts z=0.4 ➔ 3.5 (LRGs, ELGs, QSOs)
- Additional Bright Galaxy Survey will target all 10+ M galaxies with r < 19.5 (z=0-0.4)
  - roughly 20 times the volume of SDSS for 0.1L* galaxies



BOSS to DESI

- DESI will be a large step forward: 30M spectra over 50 $(\mathrm{Gpc}/h)^3$ volume.



3X aperture
5X fibers
1.1X field-of-view
~2X resolution (red)

→ 2 million BOSS-quality spectra possible in one lunation!

Dark Energy and Beyond

- Geometry: Measure the expansion rate of the Universe
  - Standard Candle: Supernovae (the distance-redshift relation)
  - Standard Ruler: Baryon Acoustic Oscillations (BAO)
    - The distance-redshift relation $D_A(z)$
    - Directly measure the expansion rate $H(z)$
- Dynamics: Measure the rate at which structures grow in the Universe. Growth rate depends on the matter density --> dark energy density.
  - weak lensing
  - galaxy clusters
  - galaxy clustering including redshift space distortions (RSD)

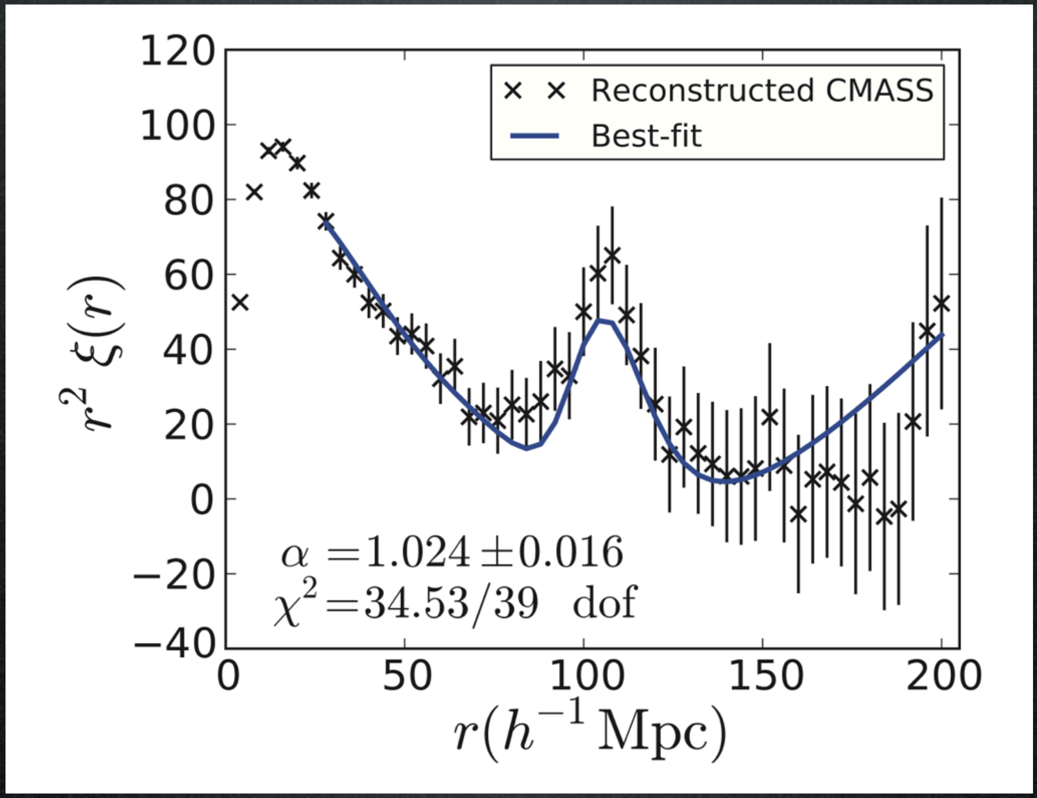
★ GR makes a specific prediction for the relation between the expansion rate and the growth of structure; measuring both allows a test of GR.

★ Can combine measurements of power spectrum from surveys with CMB; measure sum of neutrino masses + inflation parameters, including tilt and running of power spectrum

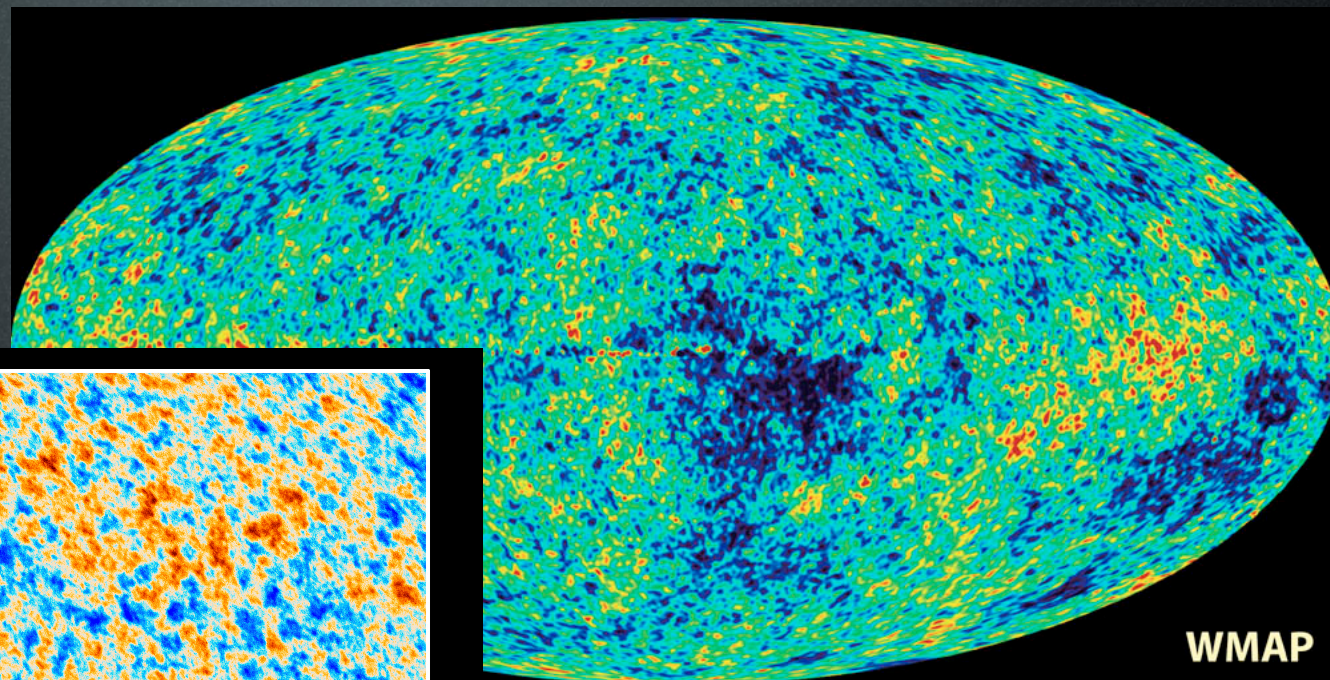
DESI's primary method is Baryon Acoustic Oscillations

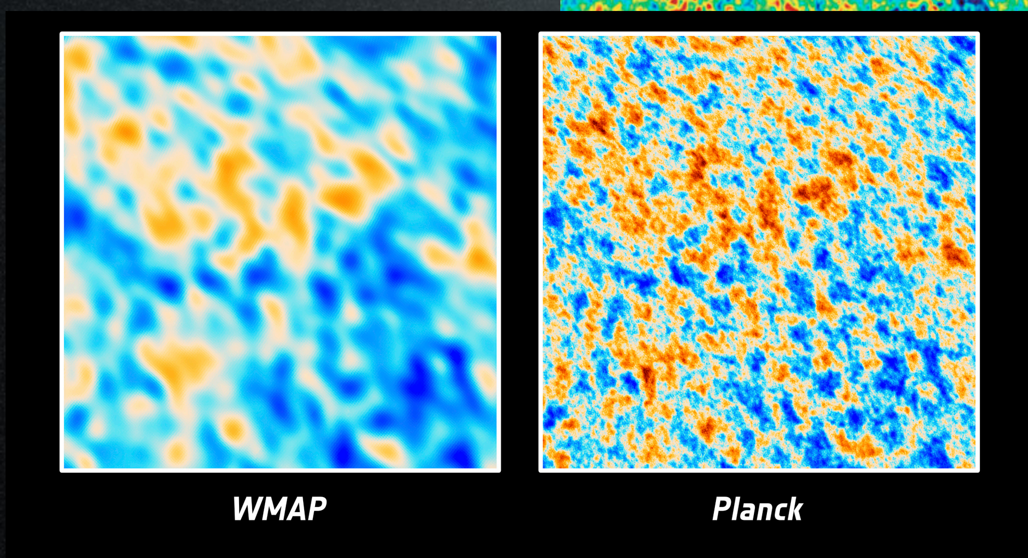
specifically, measurement of a particular physical scale in galaxy clustering that provides a standard ruler.

more generally, precise measures of galaxy & quasar clustering (evolution of matter power spectrum)



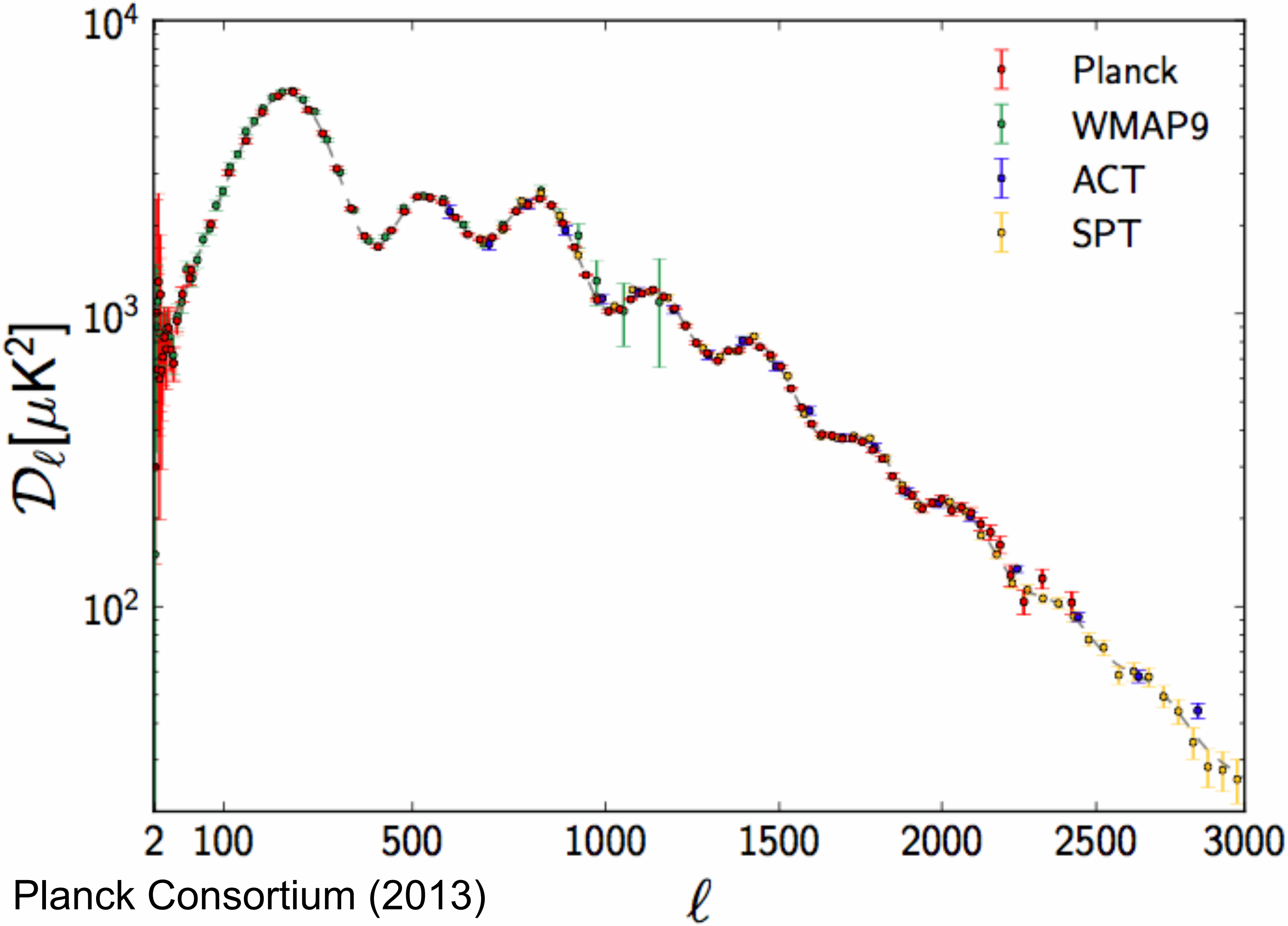
Acoustic Oscillations in the CMB





- Although there are fluctuations on all scales, there is a characteristic angular scale.

Acoustic Oscillations in the CMB



Planck Consortium (2013)

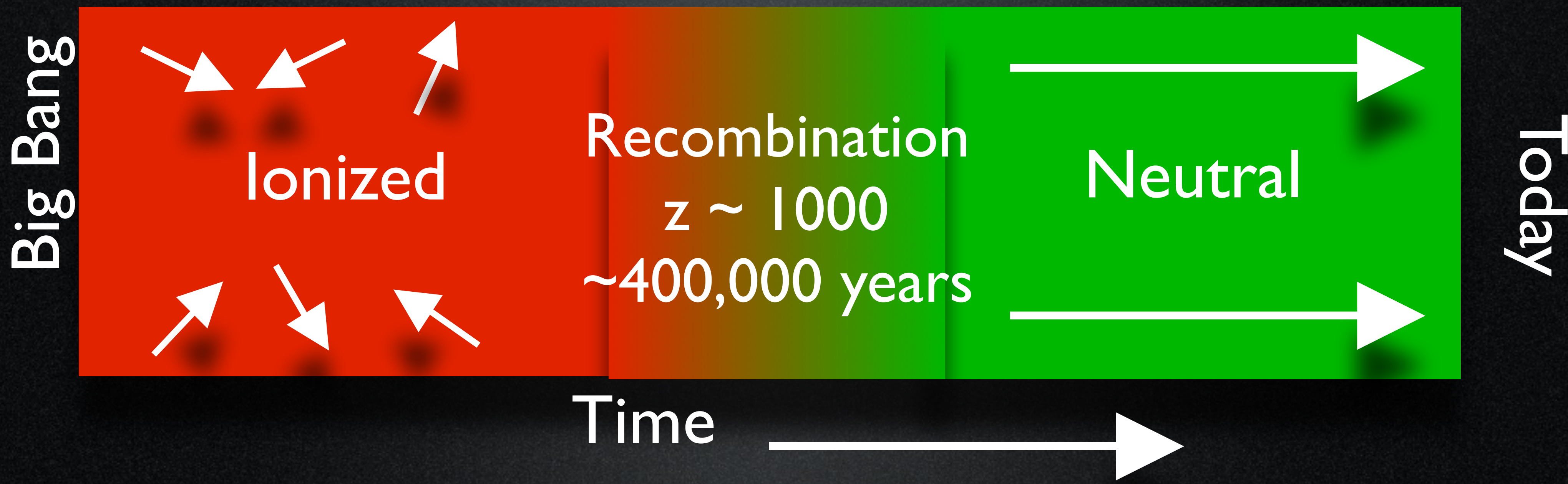
Sound Waves in the Early Universe

Before recombination:

- Universe is ionized.
- Photons provide enormous pressure and restoring force.
- Perturbations oscillate as acoustic waves.

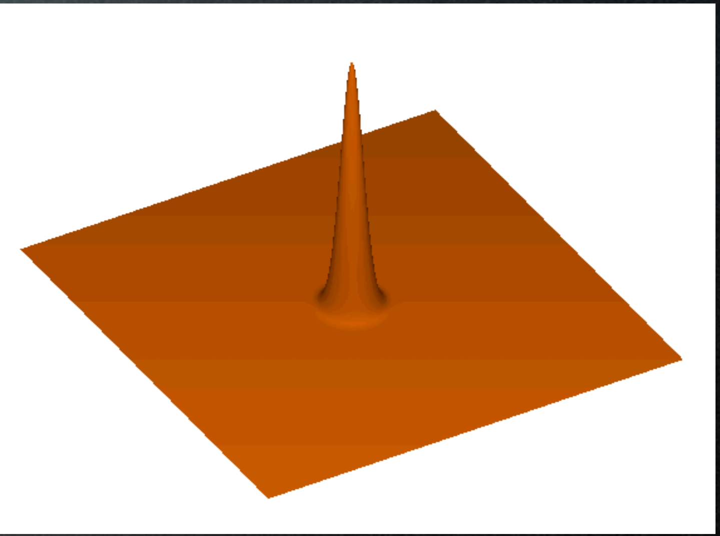
After recombination:

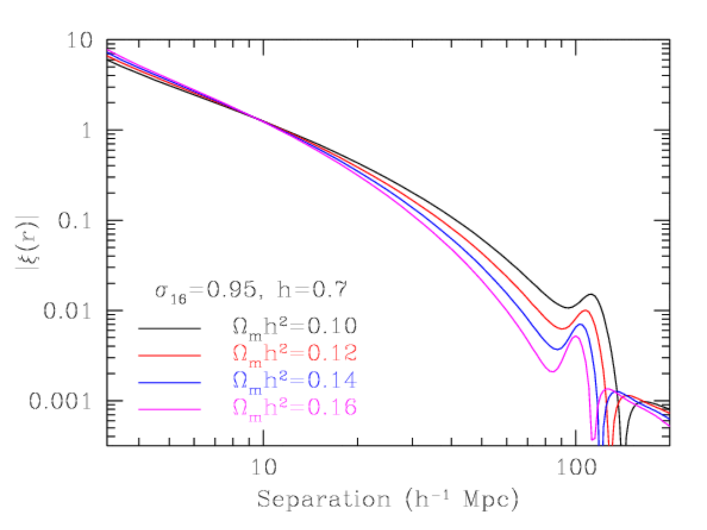
- Universe is neutral.
- Photons can travel freely past the baryons.
- Perturbations grow by gravitational instability.



Sound Waves

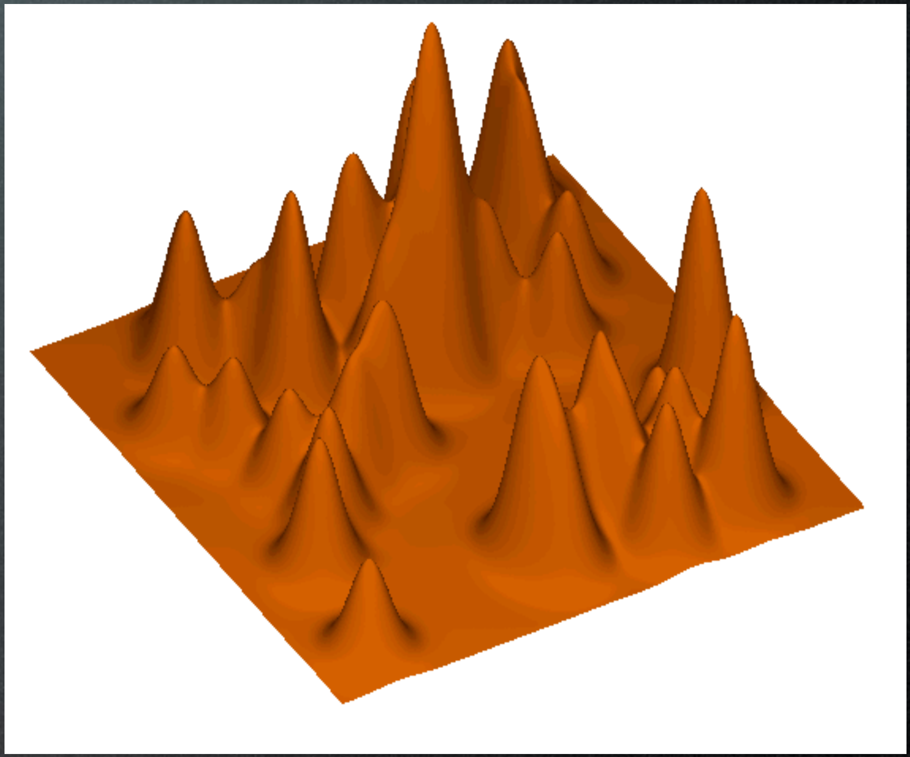
- Each initial overdensity (in DM & gas) is an overpressure that launches a spherical sound wave.
- This wave travels outwards at 57% of the speed of light.
- Pressure-providing photons decouple at recombination. CMB travels to us from these spheres.
- Sound speed plummets. Wave stalls at a radius of 150 Mpc.
- Overdensity in shell (gas) and in the original center (DM) both seed the formation of galaxies.





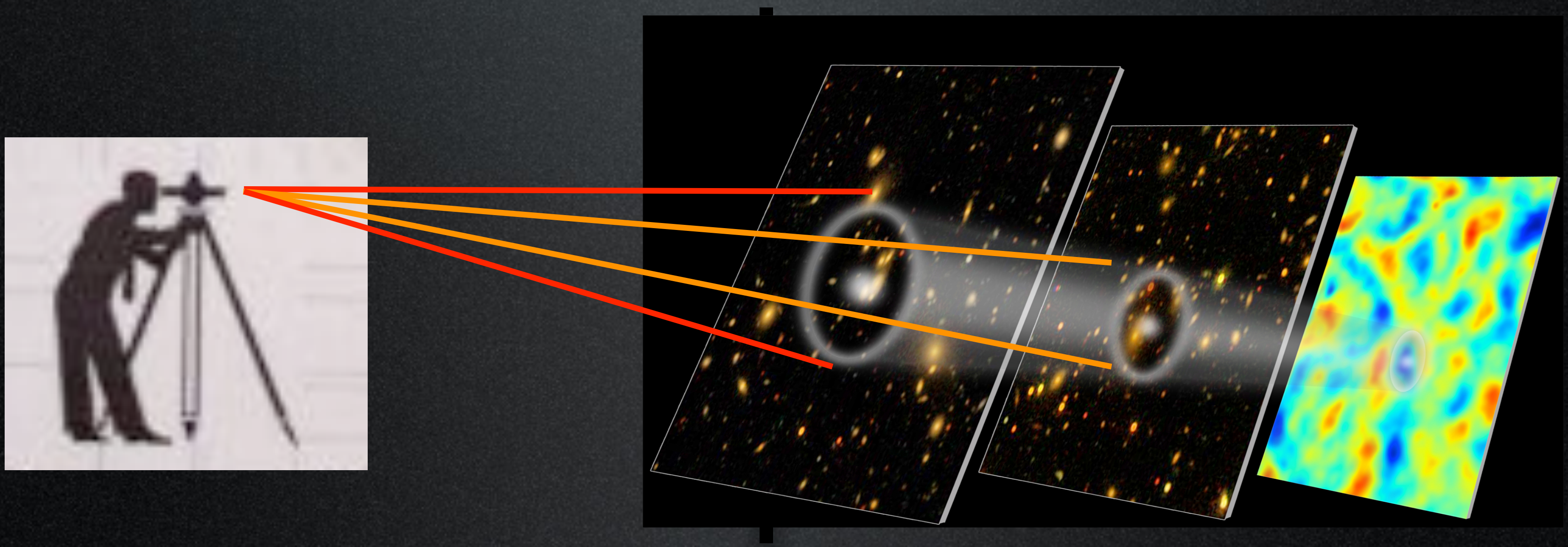
A Statistical Signal

- The Universe is a super-position of these shells.
- The shell is weaker than displayed.
- Hence, you do not expect to see bullseyes in the galaxy distribution.
- Instead, we get a 1% bump in the correlation function.



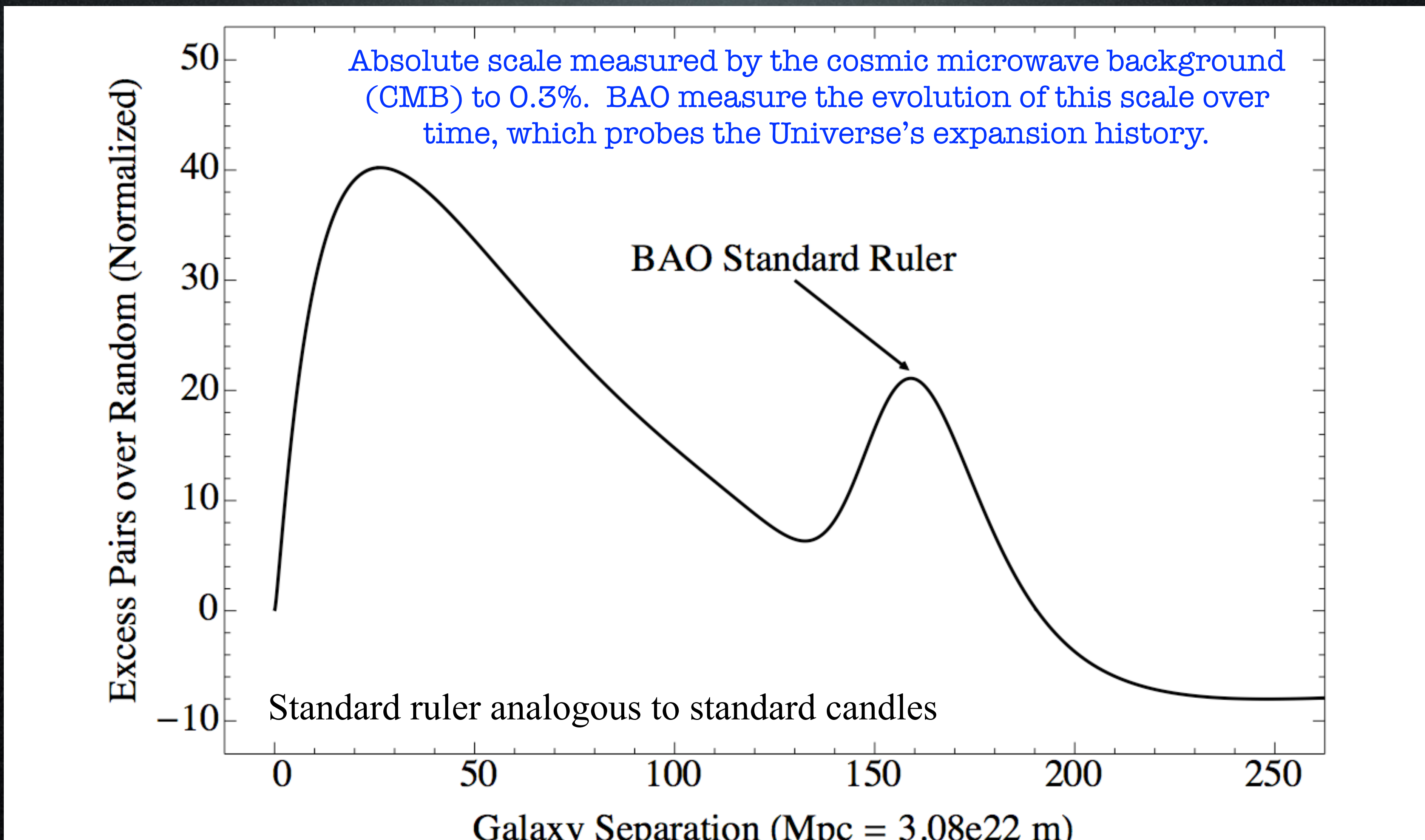
A Standard Ruler

- The acoustic oscillation scale depends on the sound speed and the propagation time.
  - These depend on the matter-to-radiation ratio ($\Omega_m h^2$) and the baryon-to-photon ratio ($\Omega_b h^2$).
- The CMB anisotropies measure these and fix the oscillation scale. Known to 0.3% from Planck data.
- When we see this pattern in the clustering data as an angular scale, we can infer the distance to the galaxies.



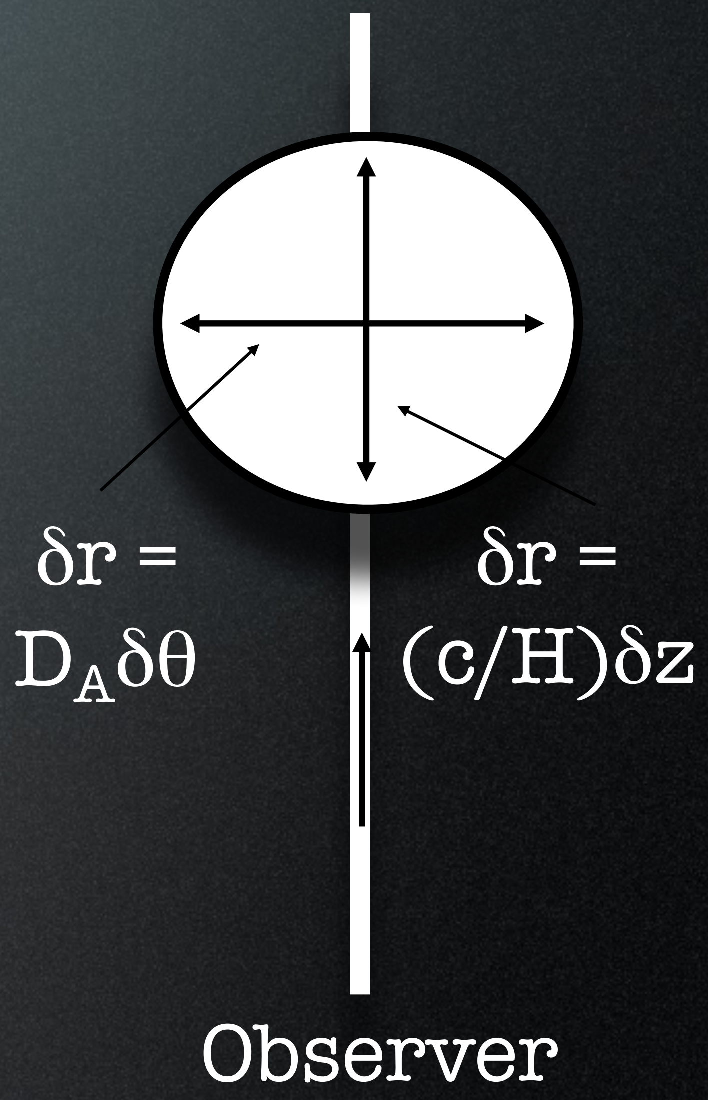
Baryon Acoustic Oscillations

Sound waves in the early Universe imprint correlations in the distribution of galaxies at a fixed physical scale (related to sound speed at recombination).



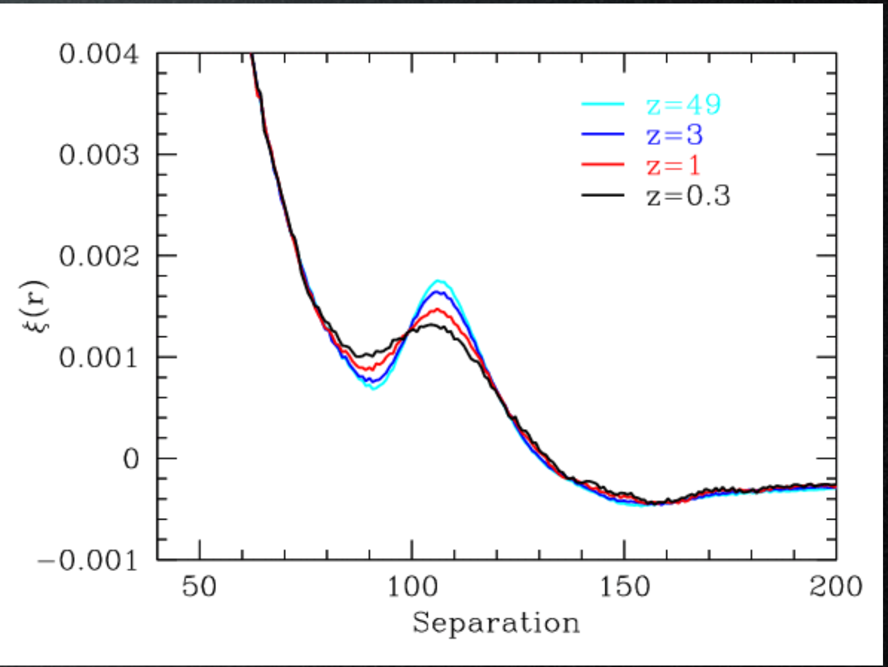
A Standard Ruler

- In cosmology, we actually measure distances along and across the line of sight differently.
- In a redshift survey, we can measure the clustering in both directions.
- Yields $H(z)$ and $D_A(z)$ separately!



Non-linear Structure Formation

- The acoustic signature is carried by pairs of galaxies separated by 150 Mpc.
- Nonlinearities push galaxies around by 3-10 Mpc. Broadens peak, making it hard to measure the scale.
  - Non-linearities are increasingly negligible at z>1. Linear theory peak width dominates.
- Moving the scale requires net infall on 150 Mpc scales.
  - This depends on the over-density inside the sphere, which is about 1%.
  - Over- and underdensities cancel, so mean shift is <0.5%.
  - Simulations confirm that the shift is <0.5%*



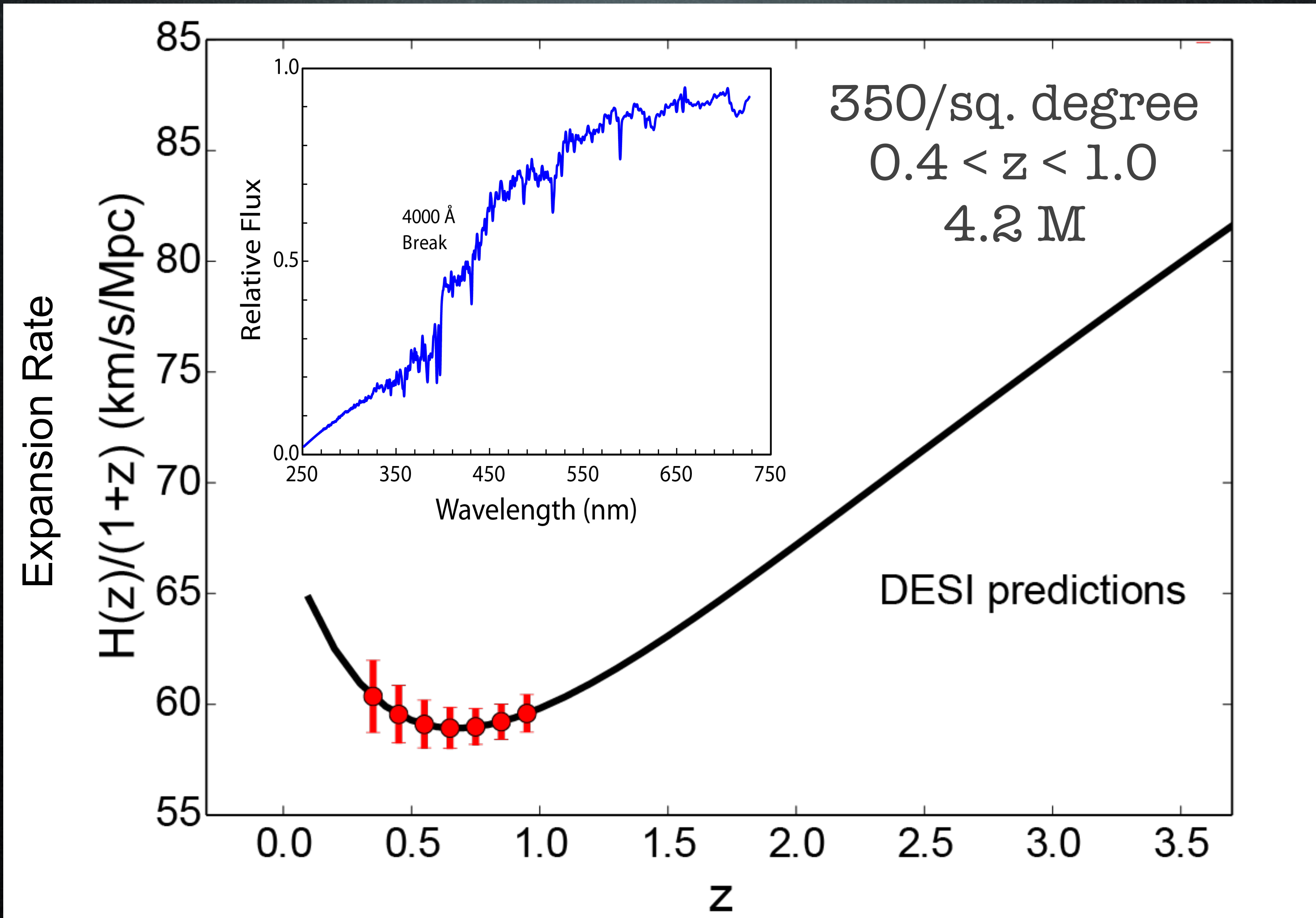
Seo & Eisenstein (2005);
Eisenstein, Seo, & White (2007)

*though still some disagreement about this in the literature.

Virtues of the Acoustic Peaks

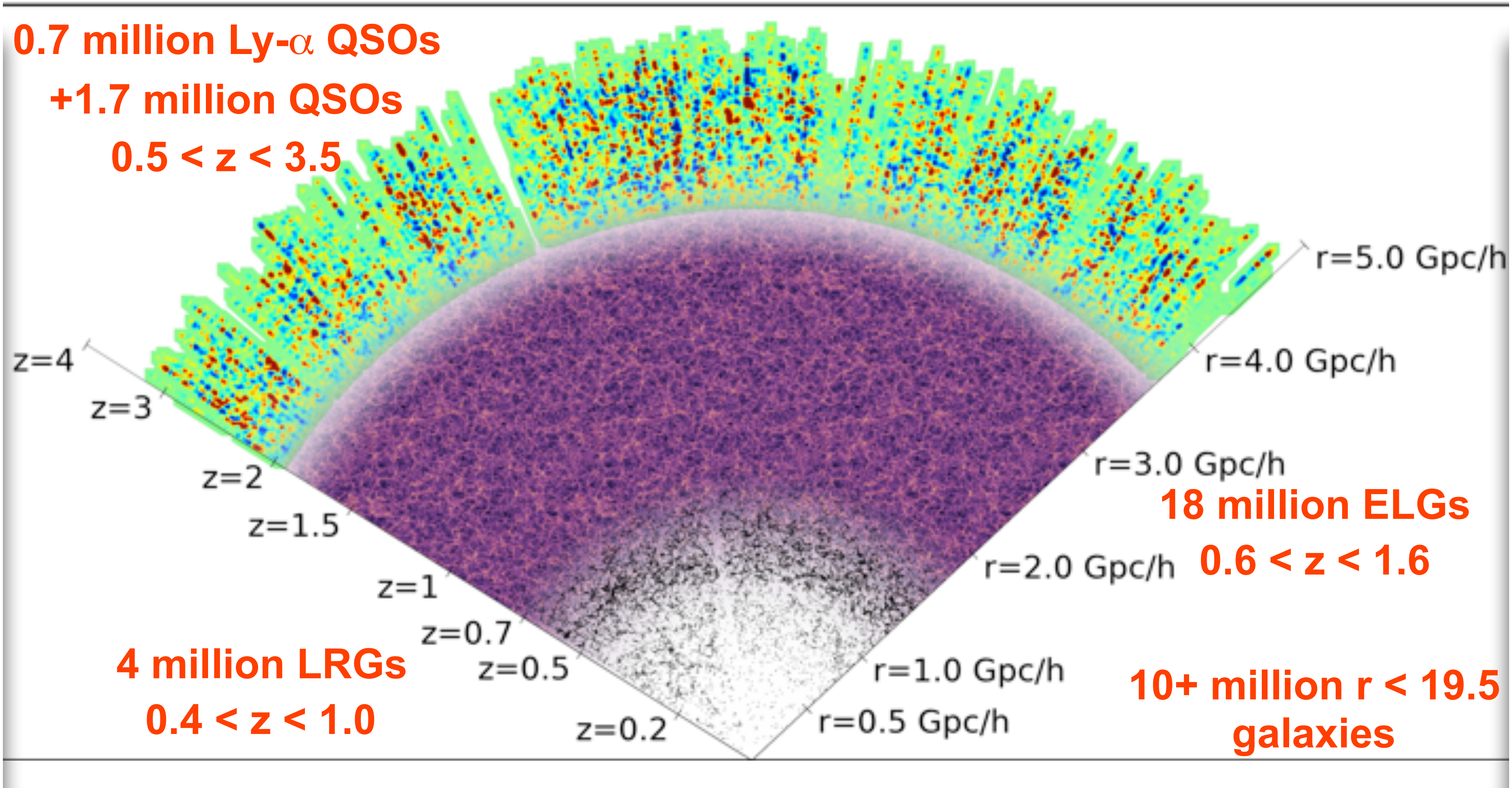
- The acoustic signature is created by physics at z=1000 when the perturbations are 1 in 10^4. Linear perturbation theory works extremely well!
- Measuring the acoustic peaks across redshift gives a geometrical measurement of cosmological distance.
- The acoustic peaks are a manifestation of a preferred scale. Still a very large scale today, so non-linear effects are mild and dominated by gravitational flows that we can simulate accurately.
  - No known way to create a sharp scale at 150 Mpc with low-redshift astrophysics.
- Measures absolute distance, including that to z=1000.
- Method has intrinsic cross-check between H(z) & $D_A(z)$, since D_A is an integral of H.

Luminous Red Galaxies

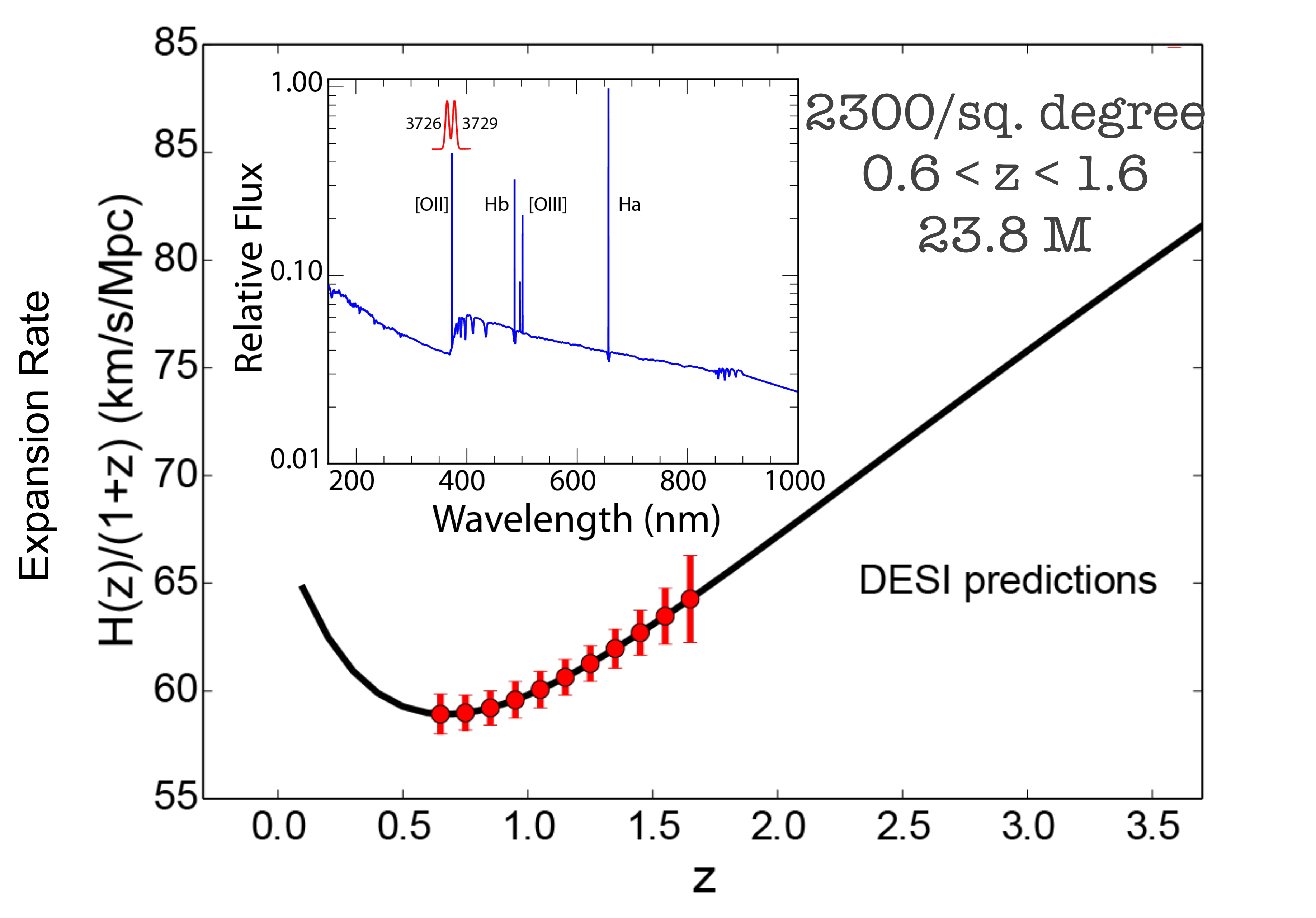


Overview of the DESI Survey

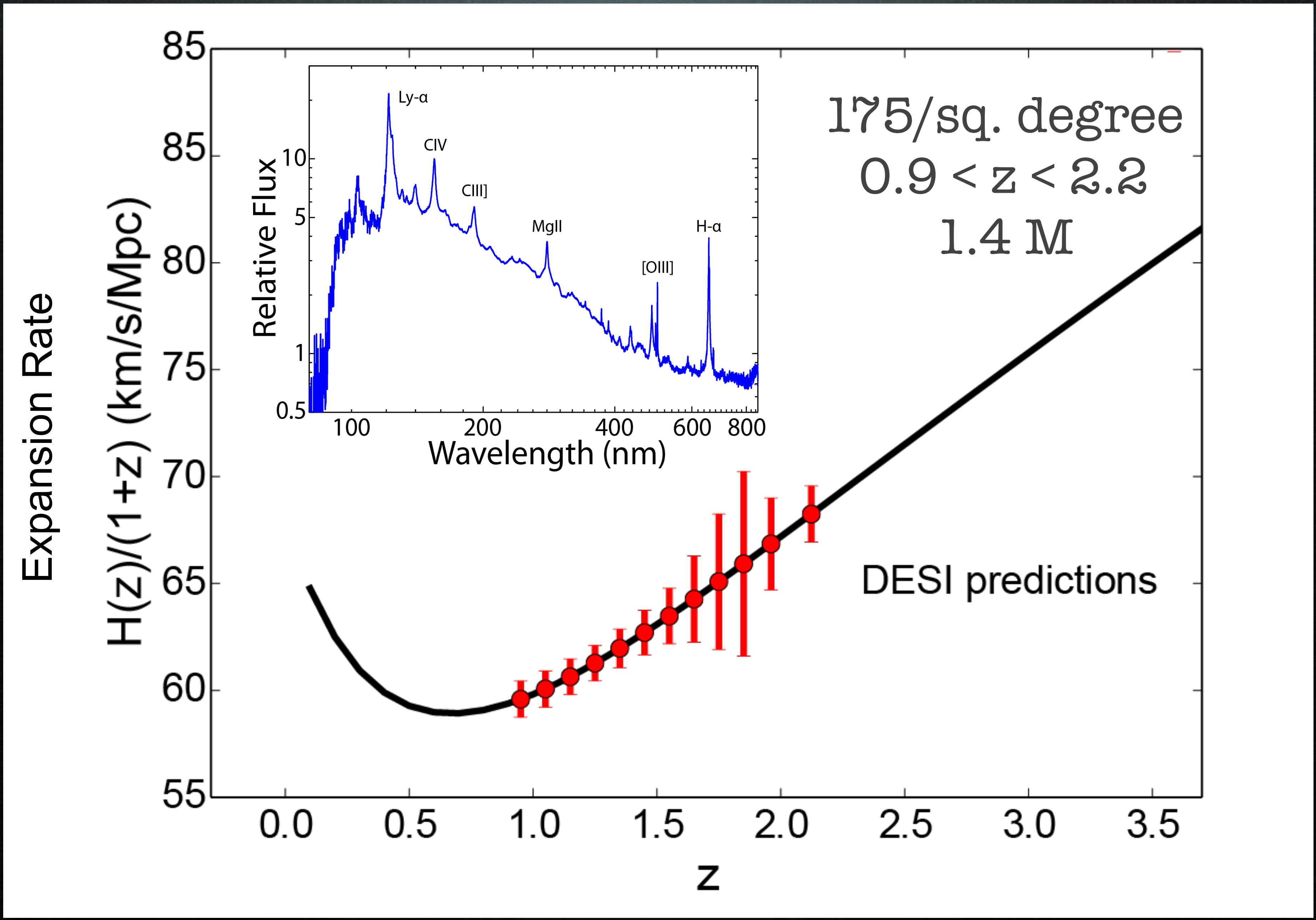
- Probing as much volume as possible, with the "easiest" redshifts
- Four target classes in dark time spanning redshifts z=0.4 ➔ 3.5 (LRGs, ELGs, QSOs)
- Additional Bright Galaxy Survey will target all 10+ M galaxies with r < 19.5 (z=0-0.4)
  - roughly 20 times the volume of SDSS for 0.1L* galaxies



Emission-line Galaxies

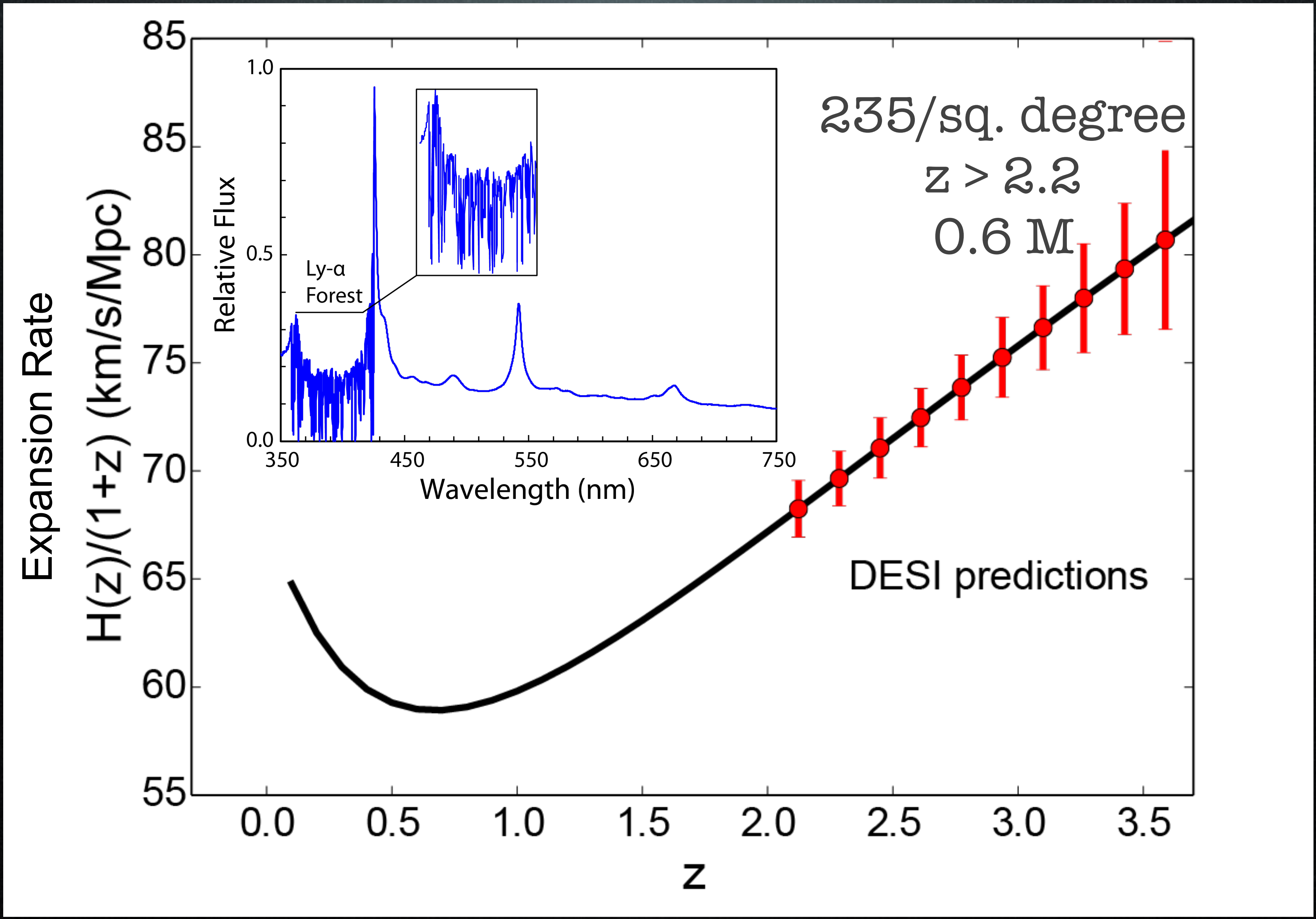


Quasars

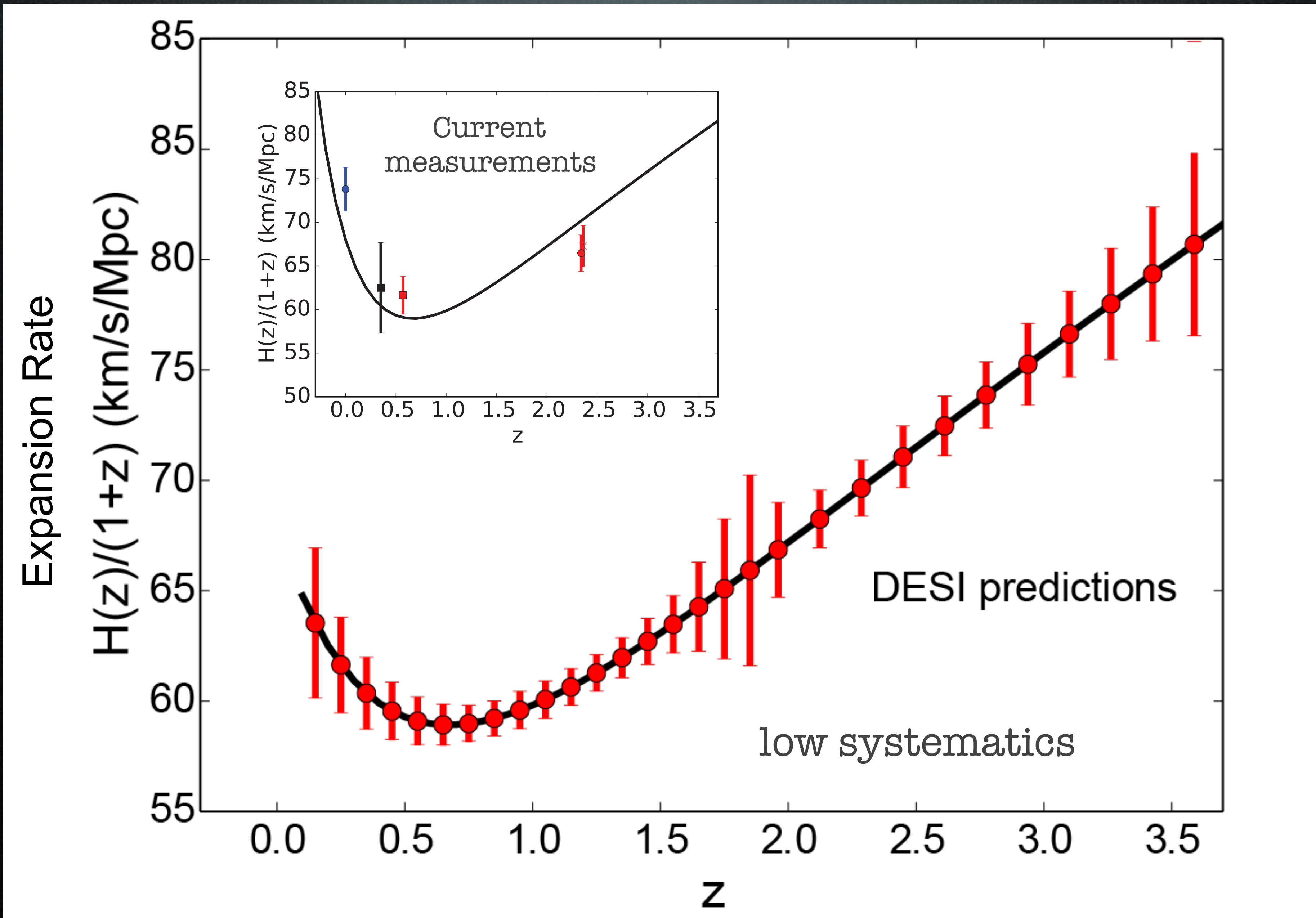


175/sq. degree
0.9 < z < 2.2
1.4 M
DESI predictions
Expansion Rate
H(z)/(1+z) (km/s/Mpc)
z
Relative Flux
Wavelength (nm)
Ly-α
CIV
CIII]
MgII
[OIII]
H-α

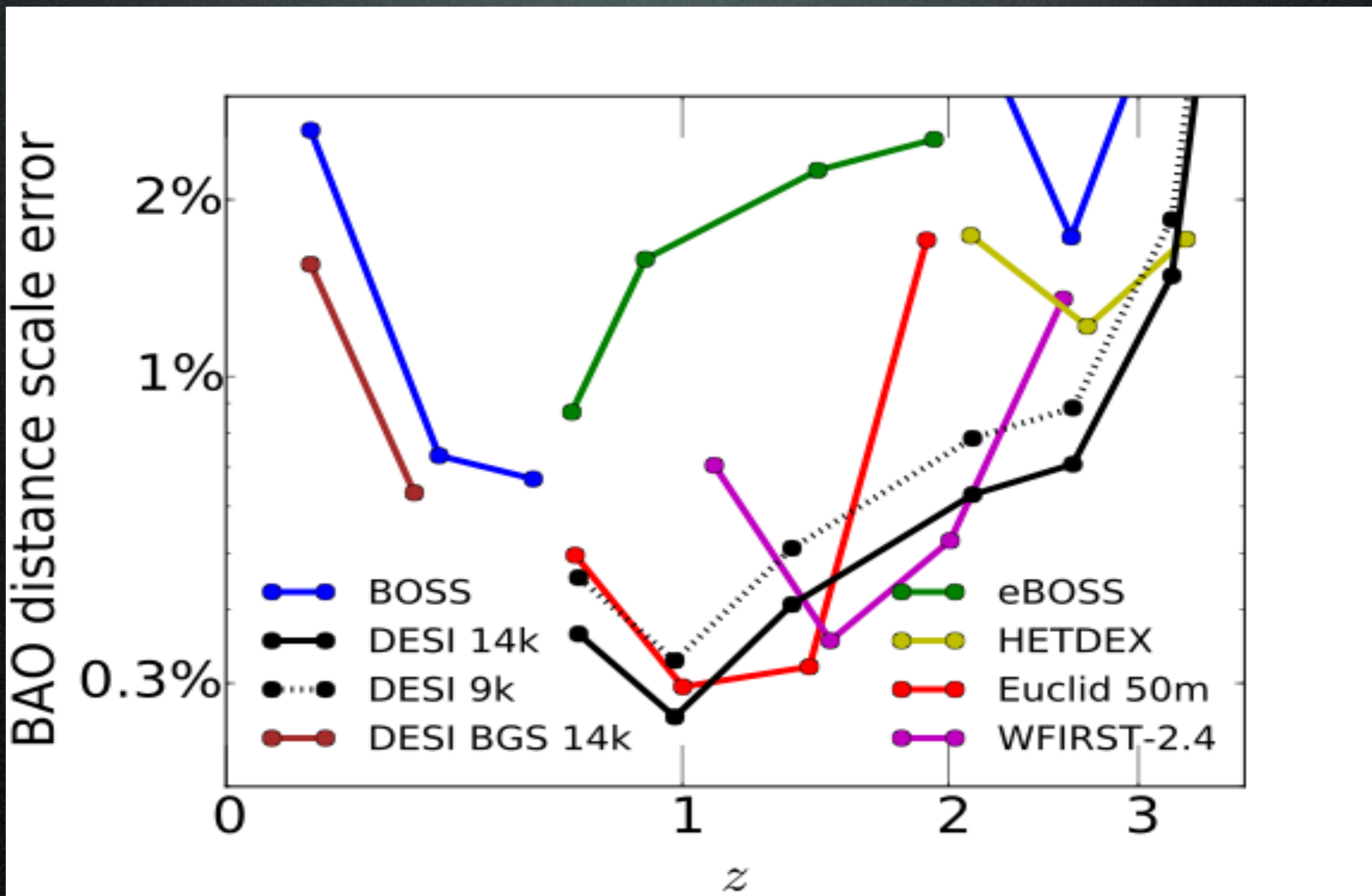
Lyα Forest


235/sq. degree
z > 2.2
0.6 M
DESI predictions
Expansion Rate
H(z)/(1+z) (km/s/Mpc)
z
85
85
80
75
70
65
60
55
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
Relative Flux
Wavelength (nm)
Ly-α
Forest
1.0
0.5
0.0
350
450
550
650
750

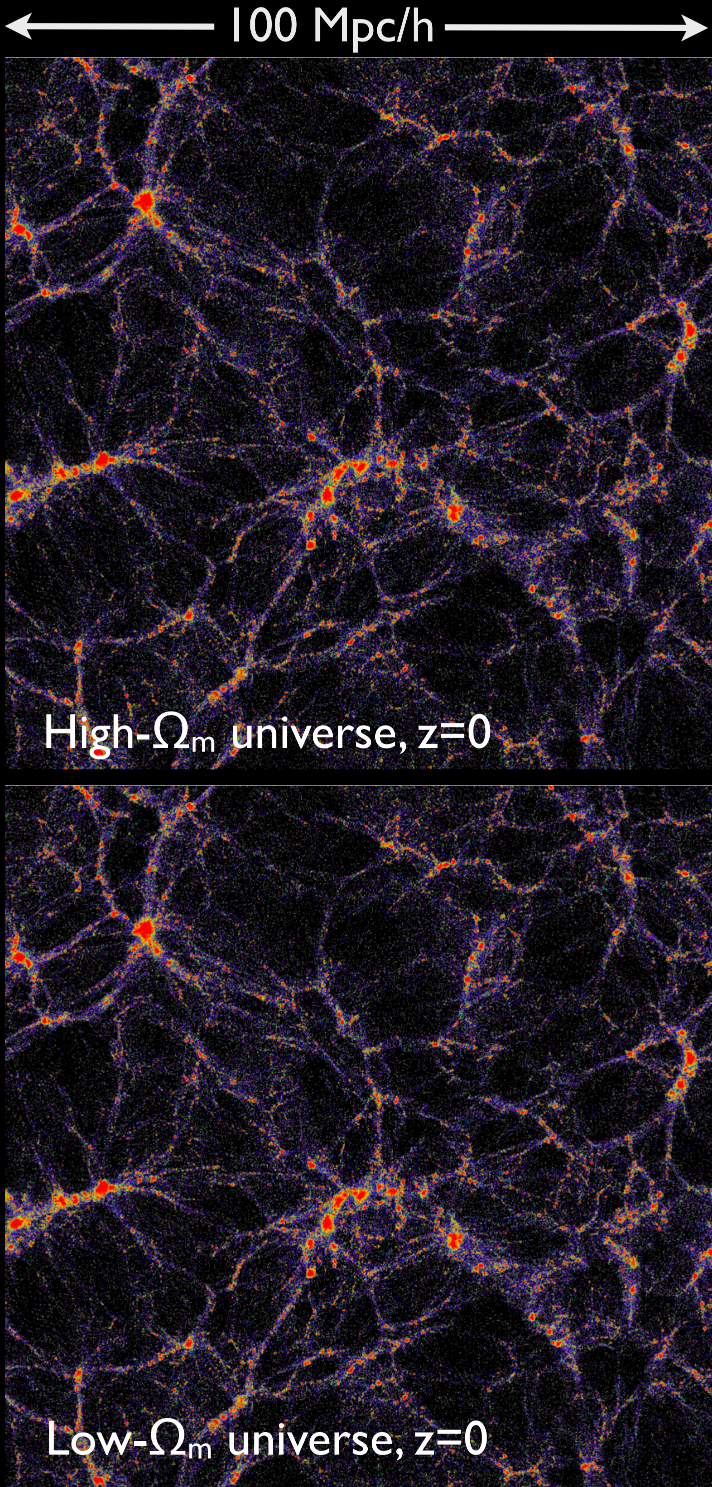
DESI is designed for BAO: accurate measurements of the H(z) and D(z)

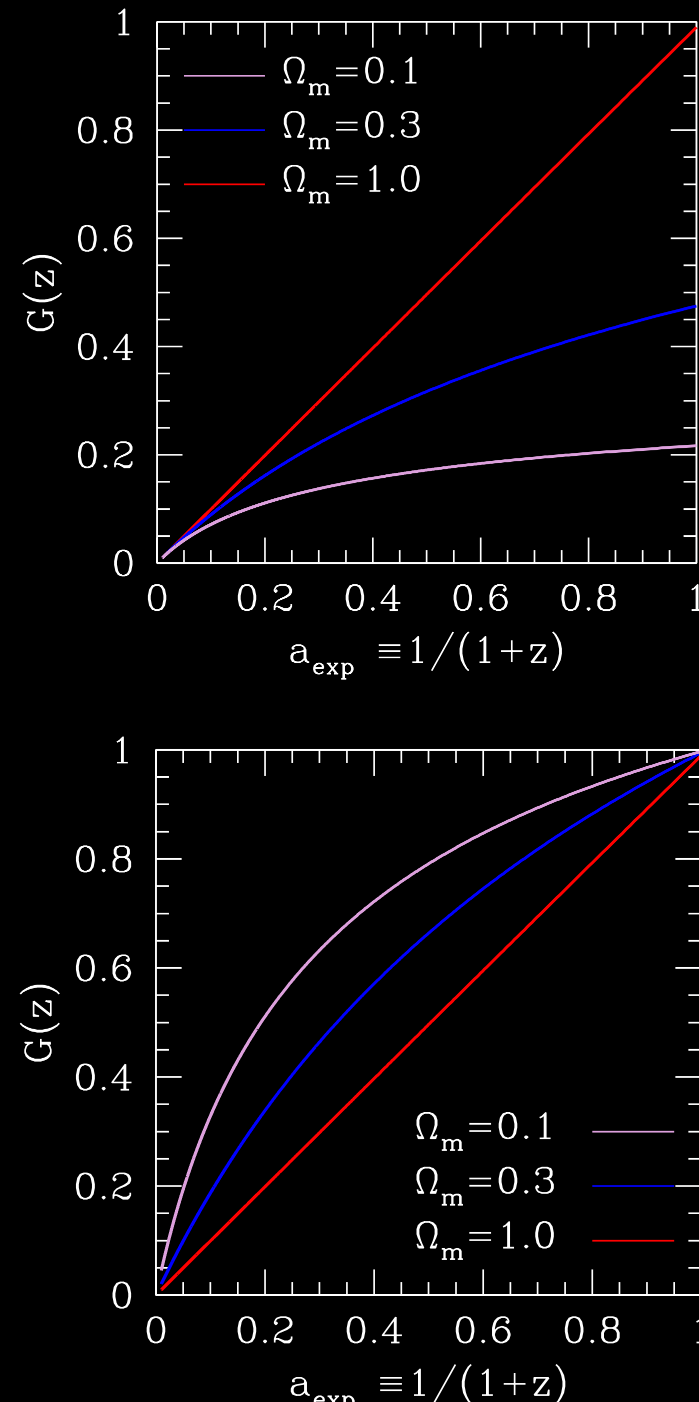


The landscape of planned BAO experiments



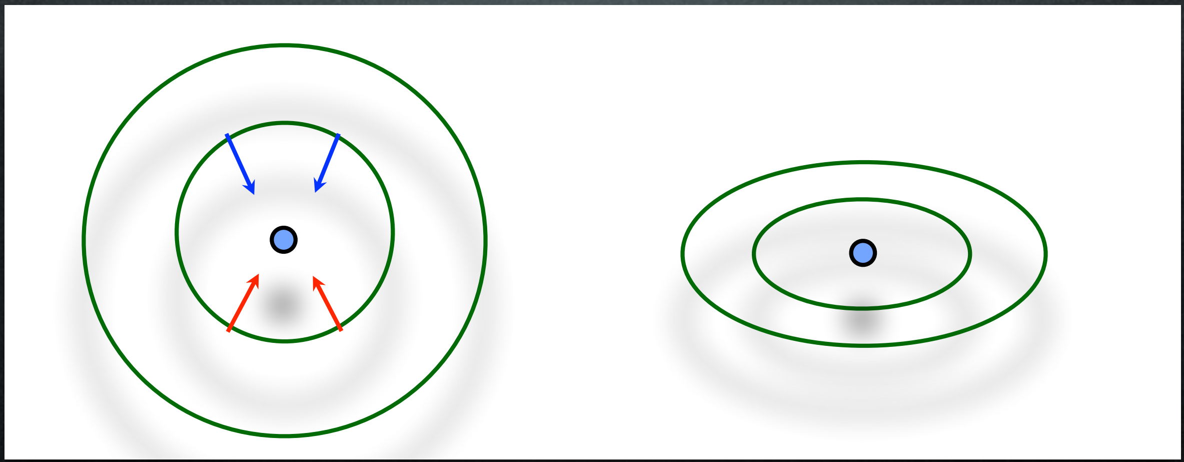
G(z) = growth of structure





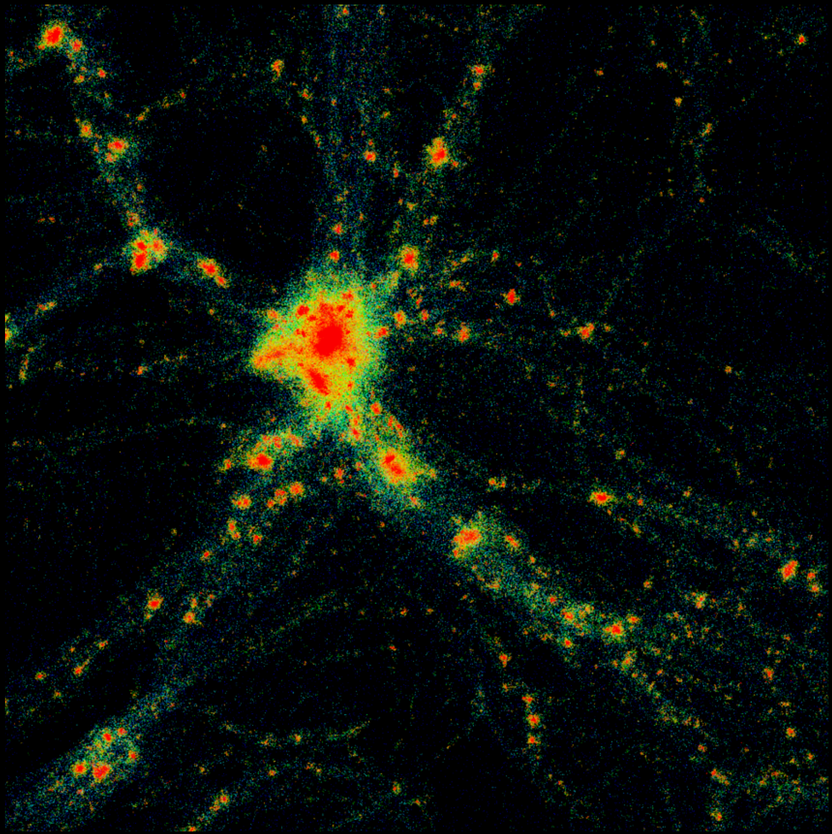
Redshift Space Distortions

- The same galaxy power spectrum that measures the distance scale with BAO can measure the growth rate with redshift space distortions

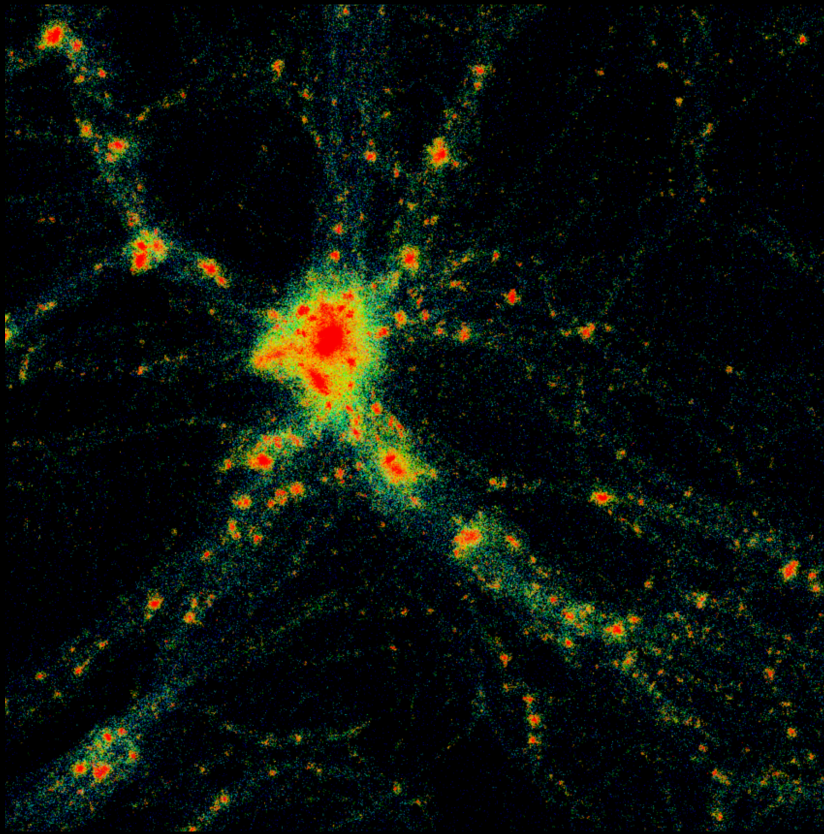


“real” space “redshift” space

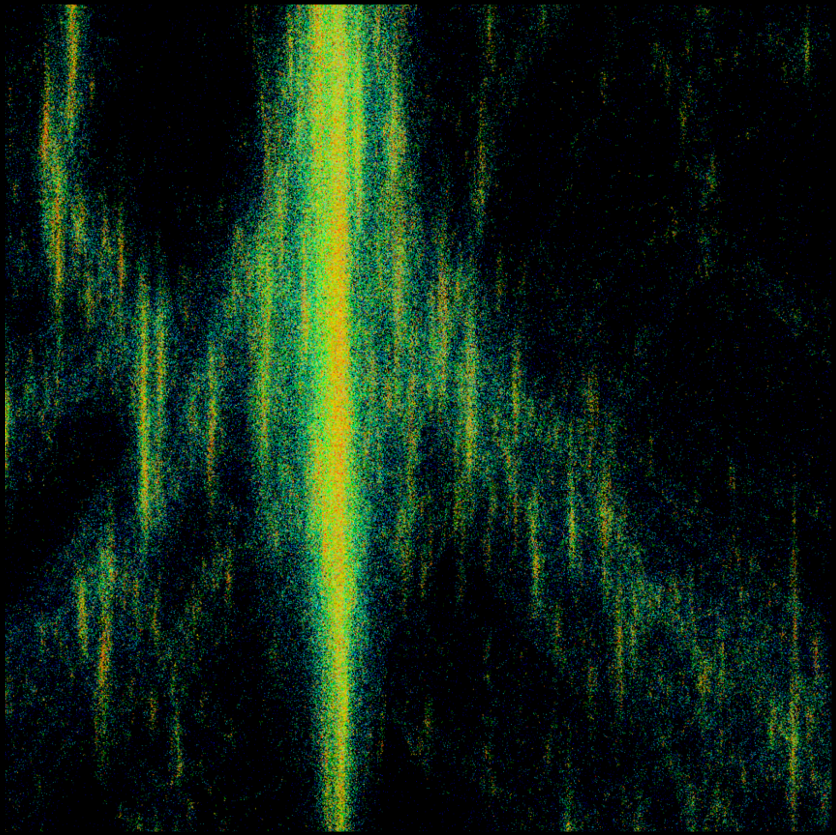
- Coherent infall due to galaxy motions in overdensities v_obs = Hr + v_pec
- Constrains $f\sigma_8$, where f is the growth rate, produces a test of GR



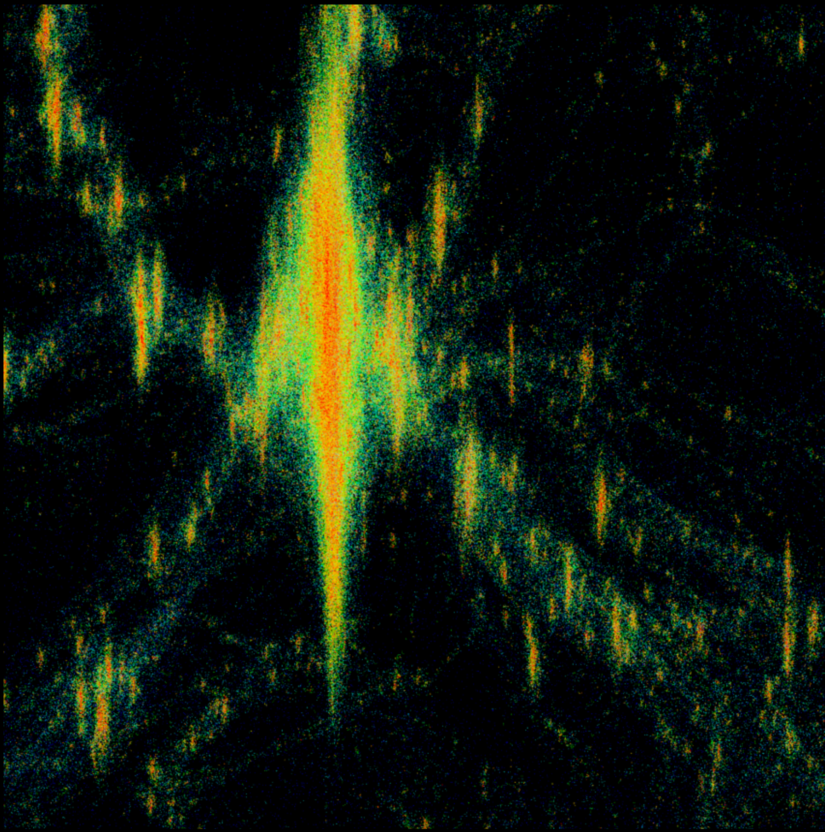
High-Ω_m universe, z=0



Low-Ω_m universe, z=0



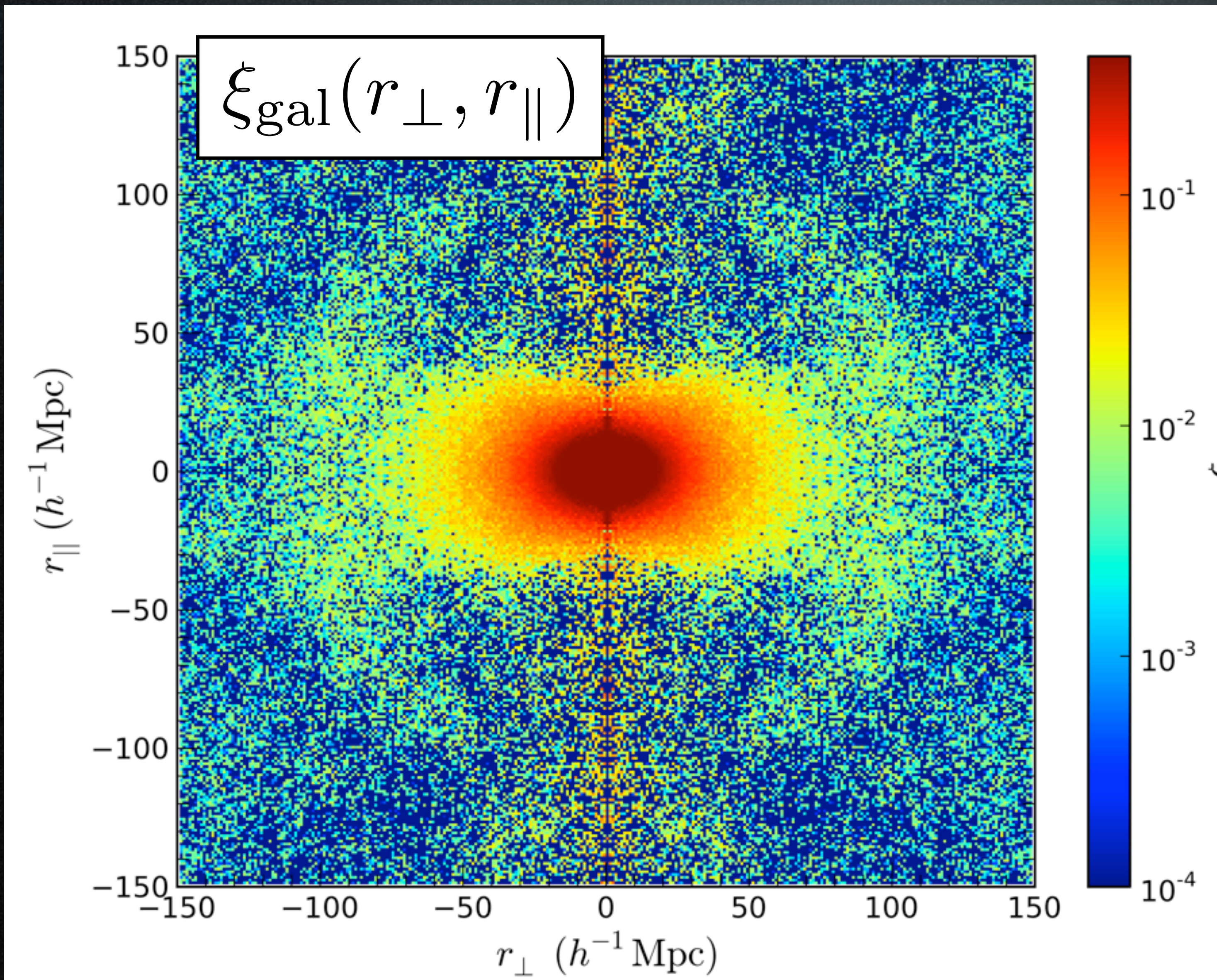
High-Ω_m redshift-space



Low-Ω_m redshift-space

Redshift Space Distortions:

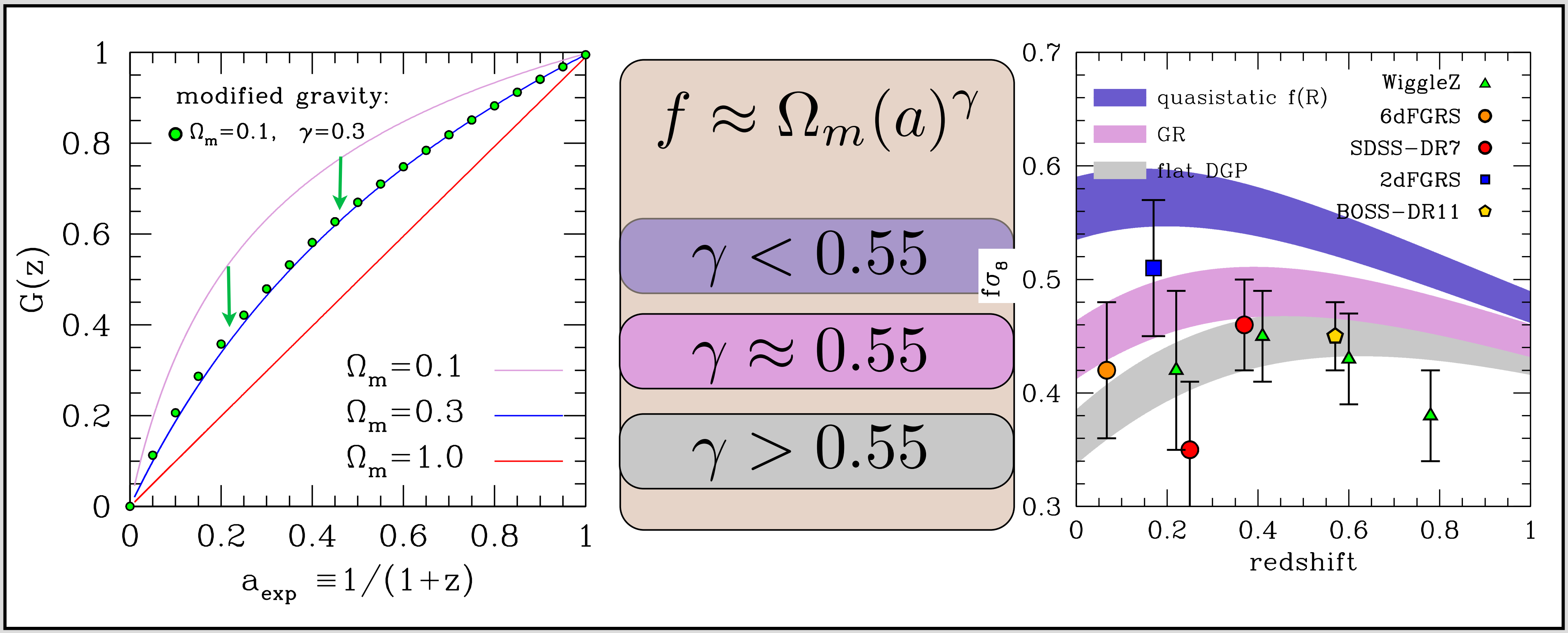
Results from BOSS



DR11 Results
z~0.57

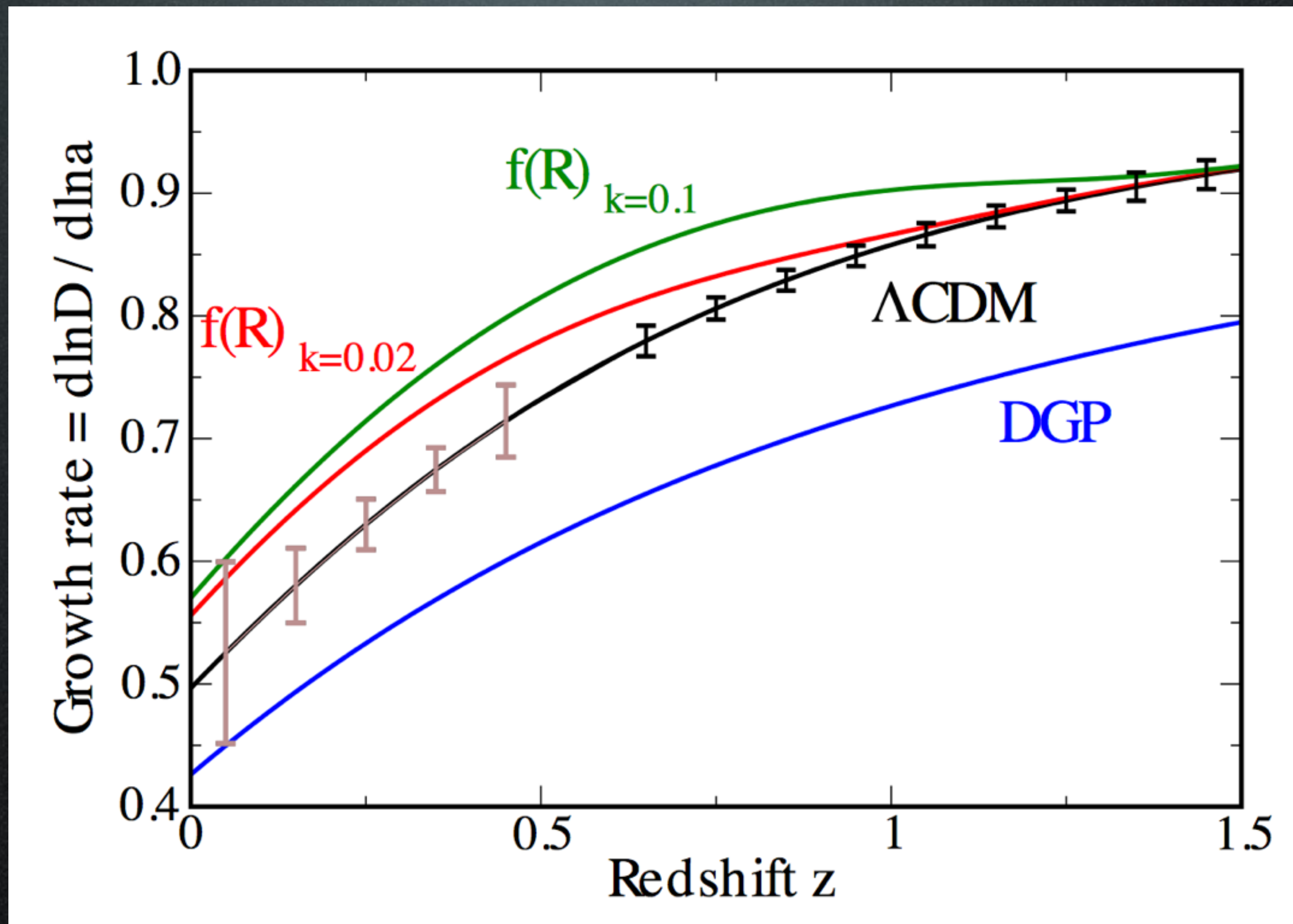
Color scale: amplitude of the correlation function. (Think density on a given scale).

Redshift Space Distortions:
Testing the nature of gravity



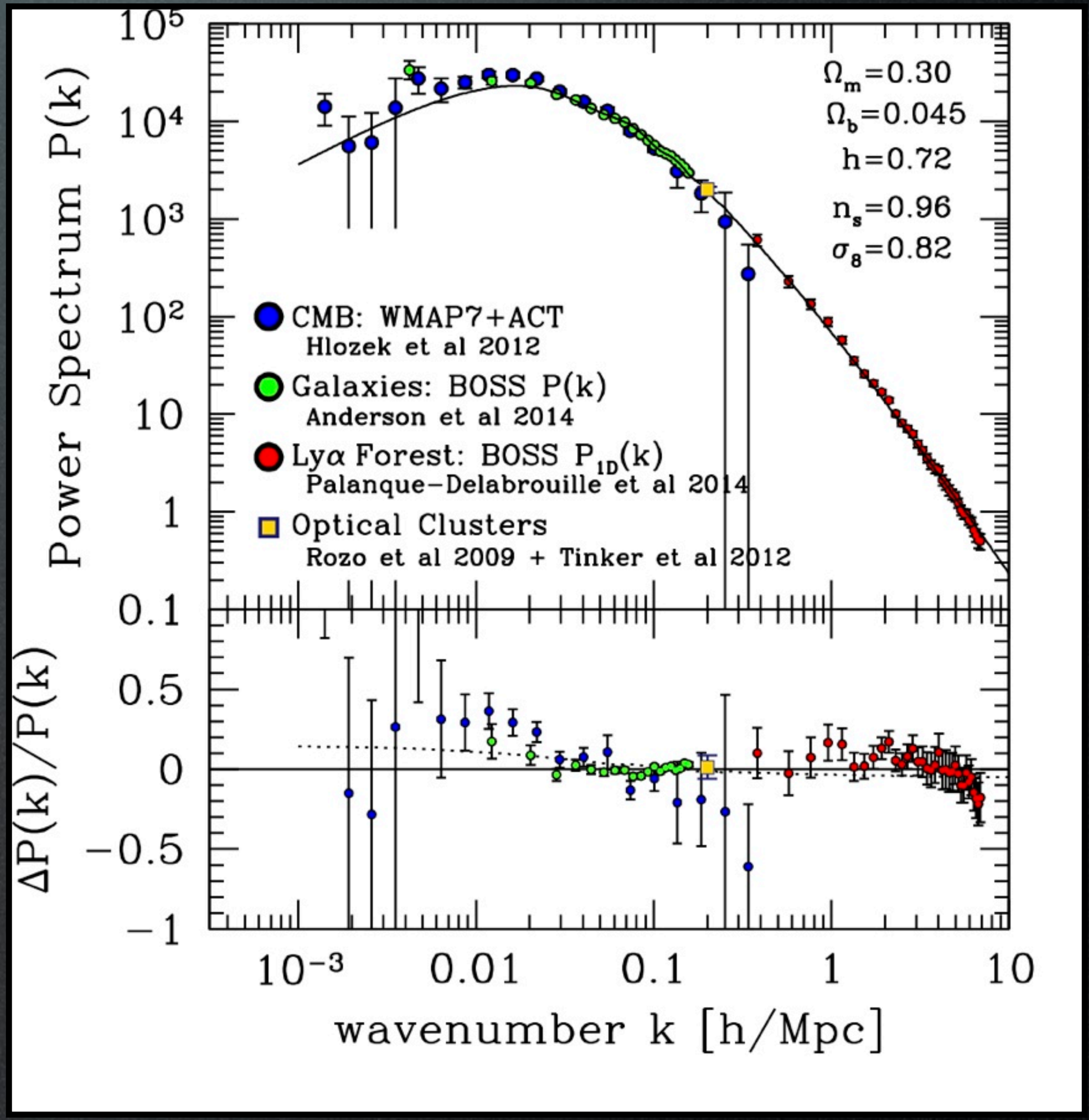
Slide from Jeremy Tinker

Distinguishing Modified Gravity from GR

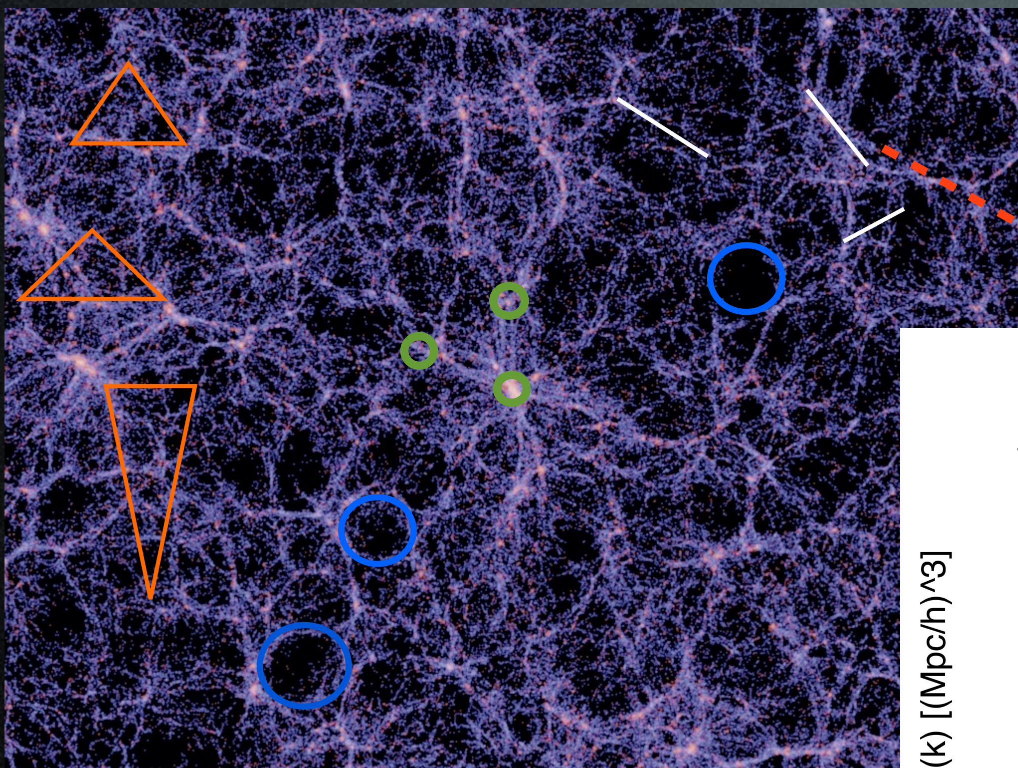


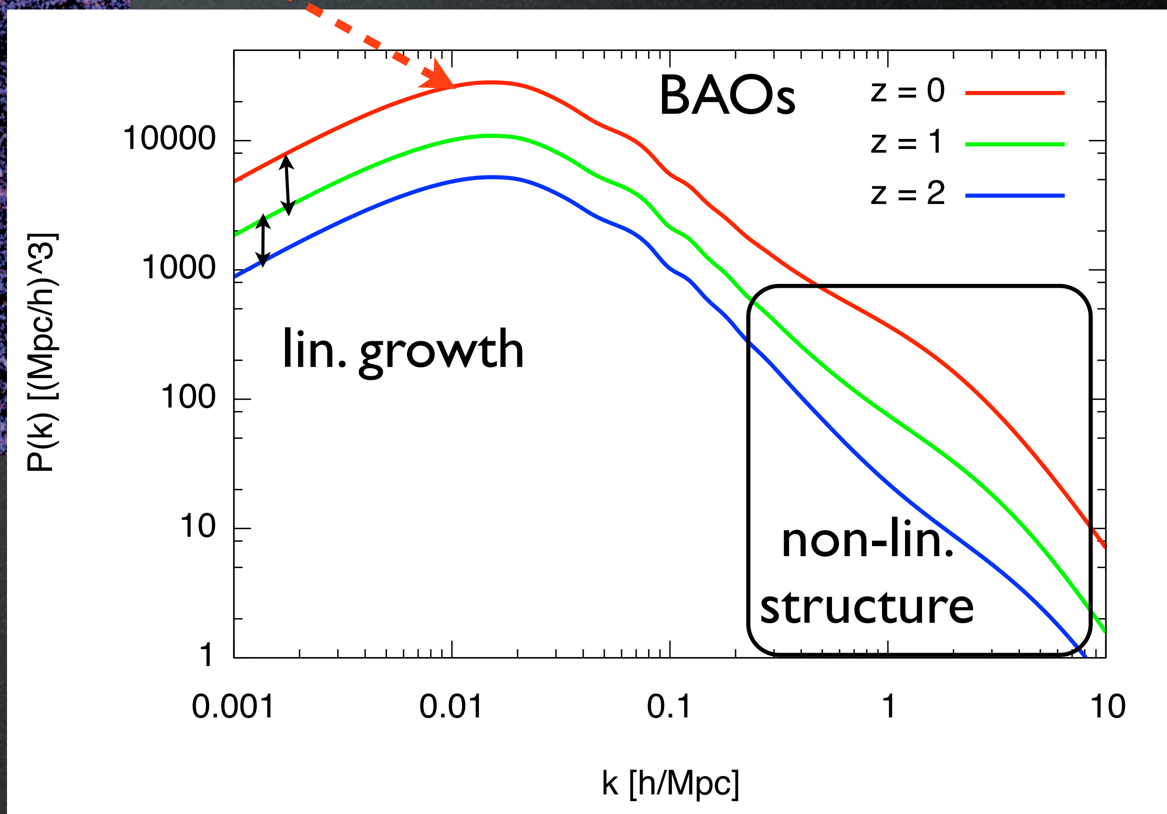
- GR model with a constrained distance-redshift relation makes very specific prediction for the growth rate as a function of redshift. measuring this separately allows you to directly test gravity models.
- DESI will measure the growth rate <1% over $0.5 < z < 1.4$

Spectroscopic surveys also measure the galaxy power spectrum...



More accurate map from a spectroscopic survey





clusters (overdensities)

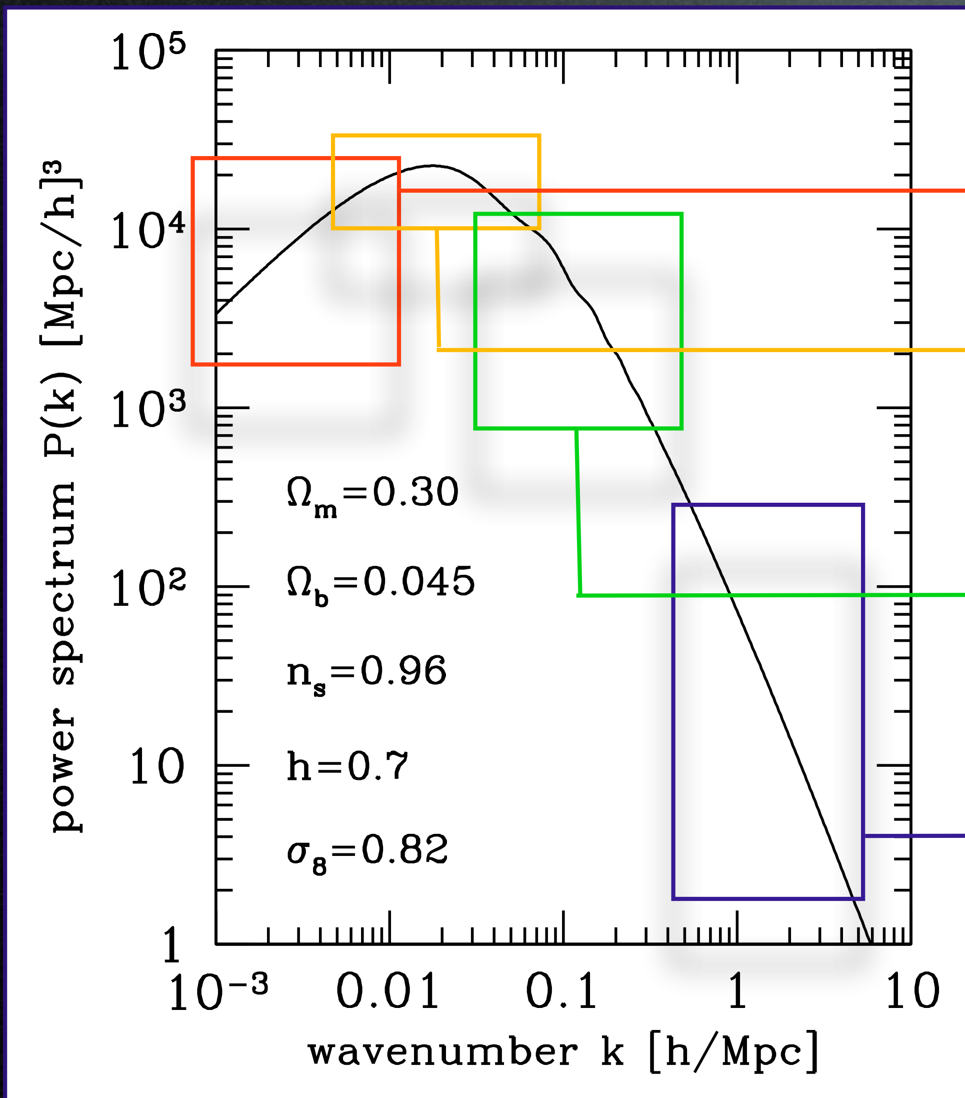
voids (underdensities)

two-point correlations

three-point correlations,...

slide modified from E. Krause

What information does the power spectrum hold?

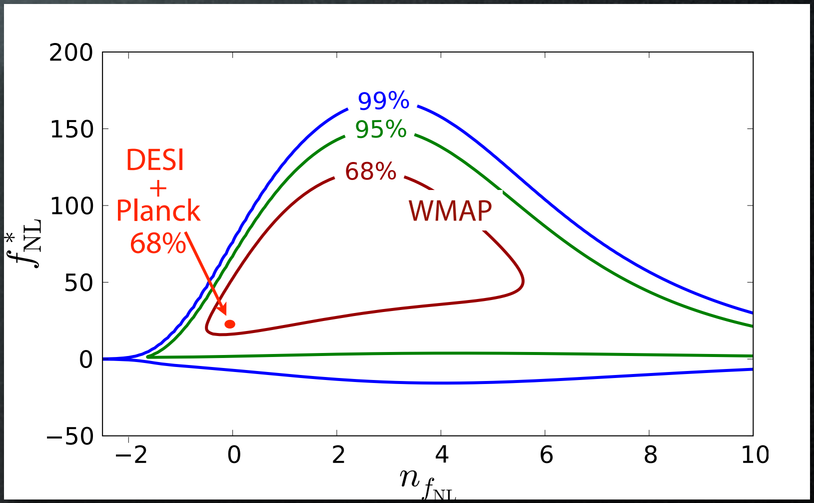


- primordial fluctuations from inflation.
- total matter density: when can fluctuations grow?
- baryon oscillations: our standard ruler.
- the temperature of dark matter (or relativistic particles).

slide from J. Tinker

Measuring the Inflationary Spectral Index

- Inflation models make specific predictions for tilt and running of the spectral index; non-Gaussianity
- CMB constraints on non-Gaussiantiy are now cosmic variance limited
- The galaxy power spectrum can probe these primordial perturbations from inflation using the small-scale power spectrum



(relative improvement over Planck alone)

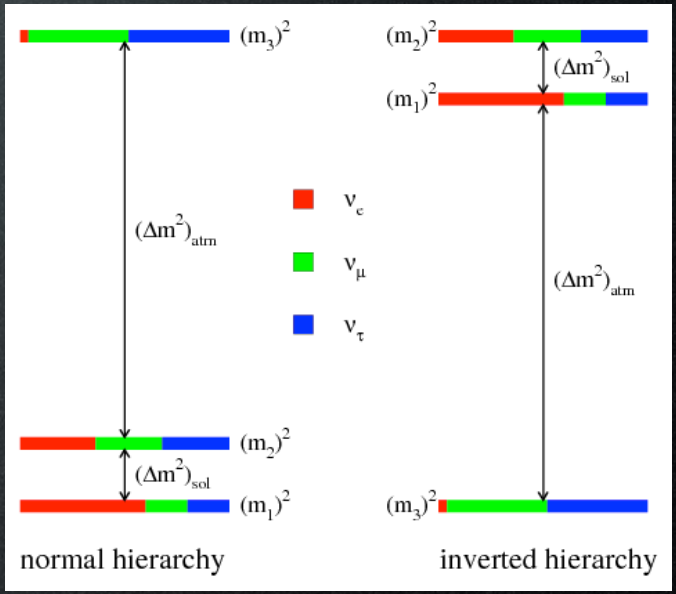
DESI constraints

Data	σ_{n_s}	σ_{α_s}
Gal ($k_{\rm max} = 0.1$ h^{-1}Mpc)	0.0024 (1.6)	0.0051 (1.1)
Gal ($k_{\rm max} = 0.2$ h^{-1}Mpc)	0.0022 (1.7)	0.0040 (1.3)
Ly-α forest	0.0029 (1.3)	0.0027 (2.0)
Ly-α forest + Gal ($k_{\rm max} = 0.2$)	0.0019 (2.0)	0.0020 (2.7)

Measuring Σm_ν

➢ … and possibly the neutrino hierarchy.

- The shape of the power spectrum encodes information about neutrino masses. Massive neutrinos suppress cosmic structure growth.
- DESI + CMB can measure an error of 0.017 eV in the sum of the masses if we can use the power spectrum to k = 0.2, enough to distinguish the normal and inverted hierarchy of mass states.
- Extra relativistic species (e.g. sterile neutrinos) can also be measured by LSS+CMB



Data	$\sigma_{\Sigma m_\nu}$ [eV]
Planck	0.350
Planck+DESI BAO	0.090
Gal ($k_{\max} = 0.1$)	0.024
Gal ($k_{\max} = 0.2$)	0.017

conservative

optimistic

The power of the small-scale power spectrum

- example from DESI -- small scale power significantly improves constraints on
  - dark energy
    - including P(k) with k_{max} = 0.2 improves stated FOM by ~ x5
  - inflation
    - including P(k) with k_{max} = 0.2 gets DESI constraints on running of the PS to be factor of ~3 better than Planck alone
  - neutrinos
    - conservative vs. optimistic projections (how small can trust measurements of the galaxy power spectrum) sets whether or not we can distinguish between normal and inverted hierarchy

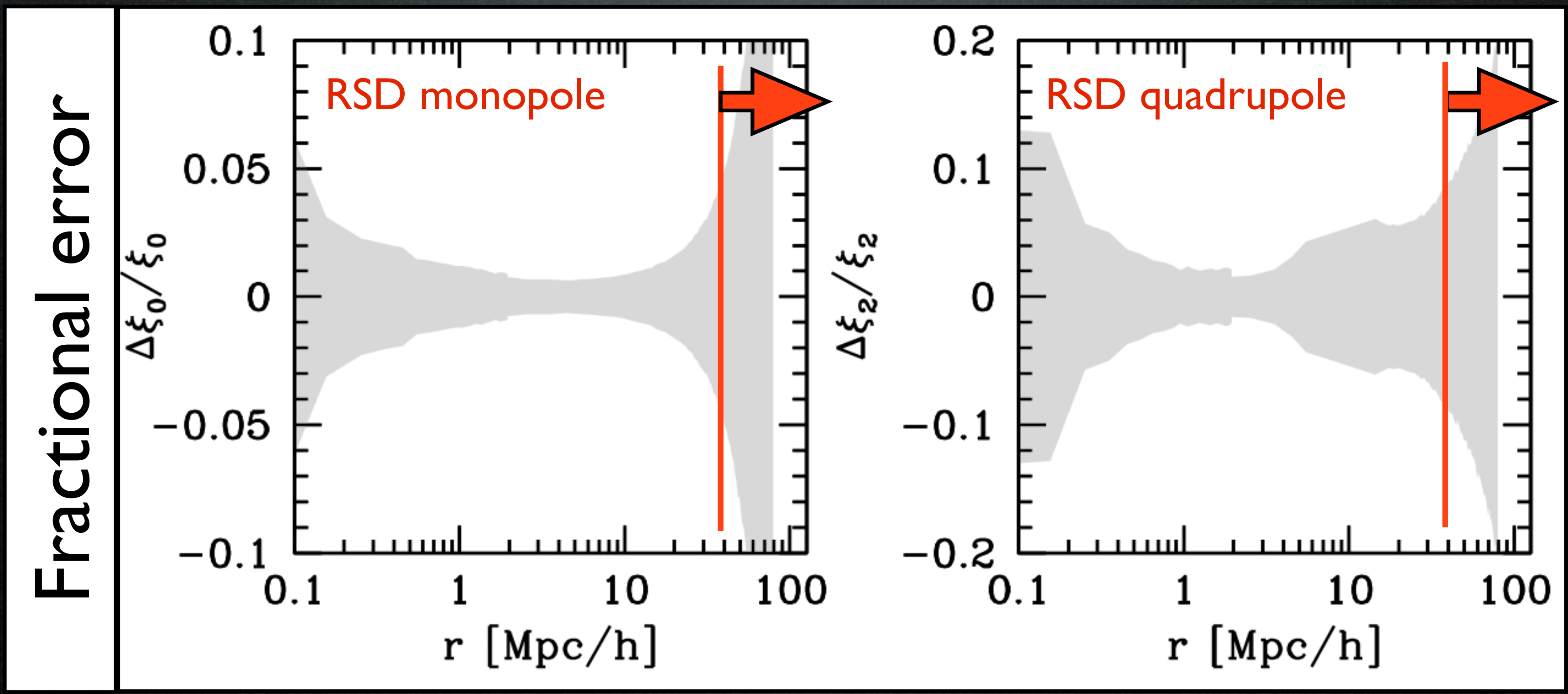
Data	$\sigma_{\Sigma m_\nu}$ [eV]
Planck	0.350
Planck+DESI BAO	0.090
Gal ($k_{\rm max} = 0.1$)	0.024
Gal ($k_{\rm max} = 0.2$)	0.017

conservative

optimistic

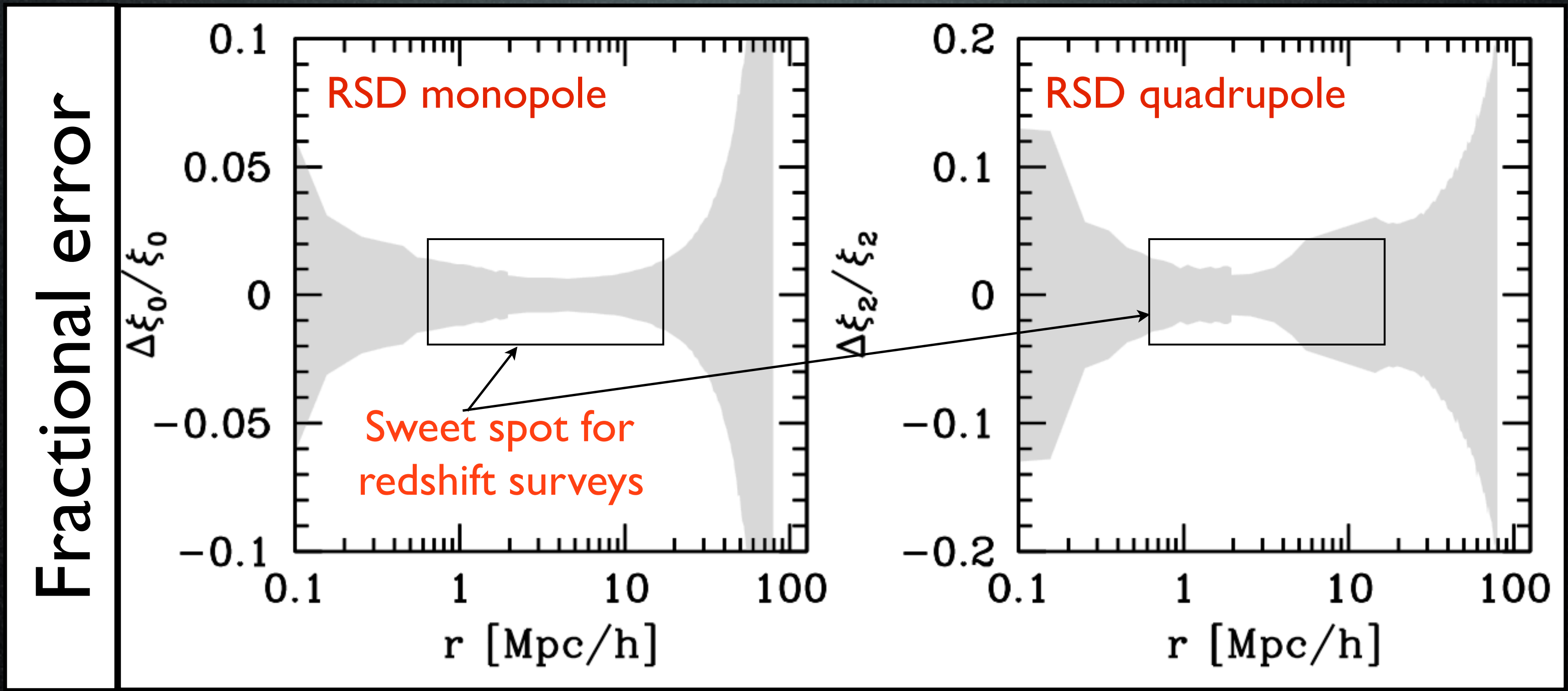
How to beat sample variance

- Probe more volume
- Go to smaller scales!



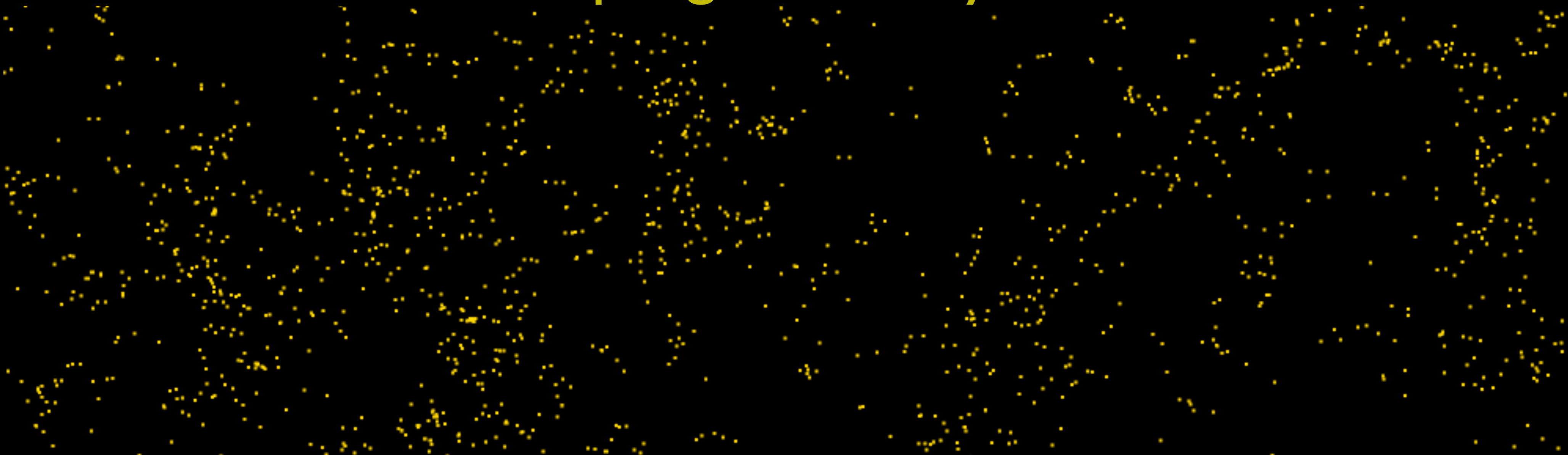
Slide from Jeremy Tinker based on BOSS DR12 errors from QPM mocks: White, Tinker, & McBride 2014

Pushing RSD to smaller scales

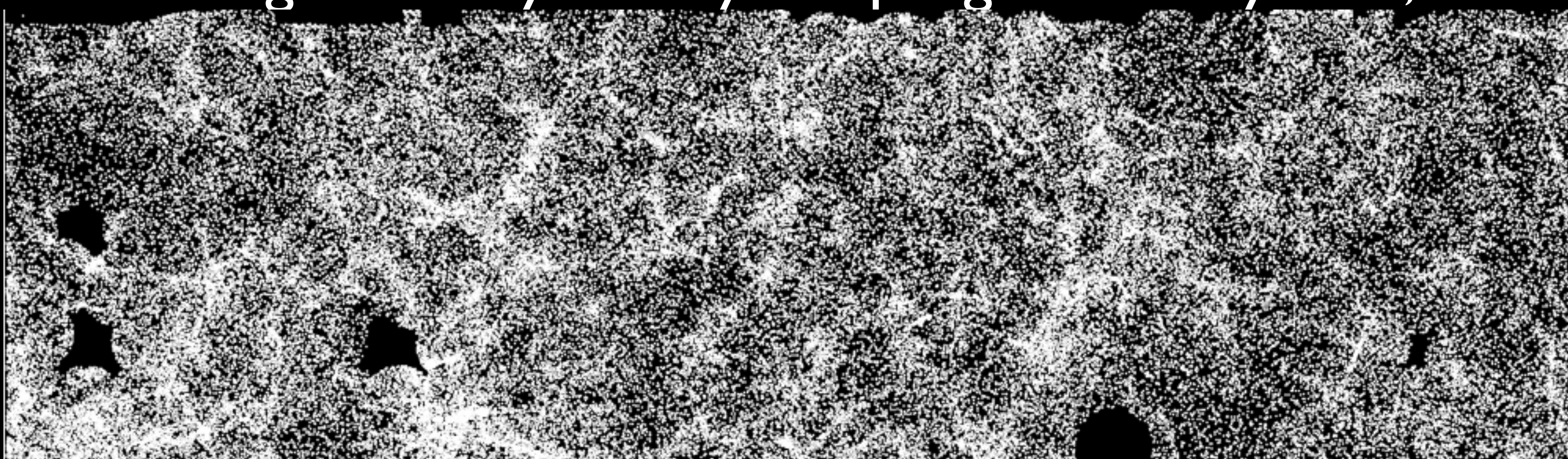


- Requires a bias model for non-linear scales.
- Need to adapt to the type of galaxies modeled.
- Need to quantify the systematic uncertainty.
- Need to achieve sub-% accuracy to meet statistical precision.

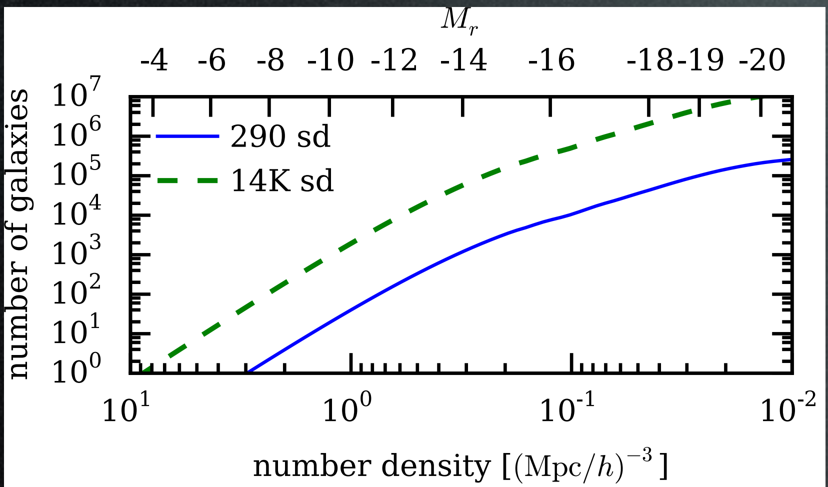
BOSS's sampling of density field, z~0.3



DESI Bright Galaxy Survey sampling of density field, z~0.3



DESI BGS gives a great sample of dwarf galaxies



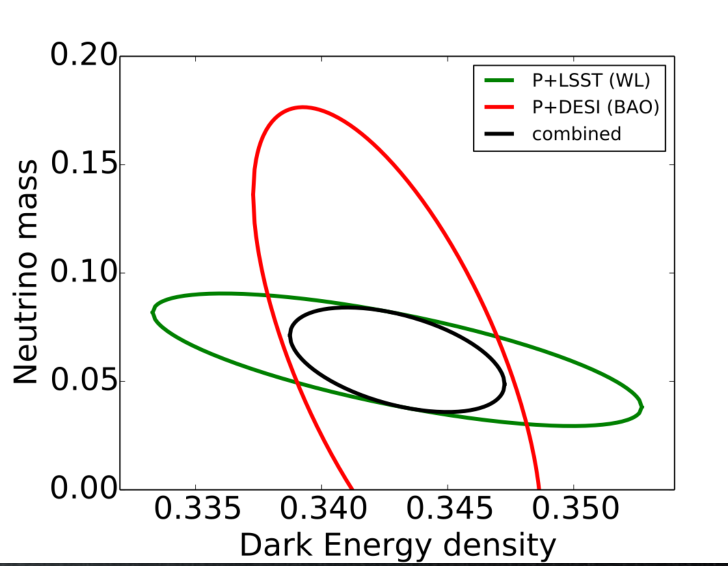
(Mao et al 2015)

- ~50x dwarf galaxy population
    - testing assembly bias in low mass regime [see Mao et al 2015]
    - testing dark matter velocity function
    - properties of dwarf galaxies

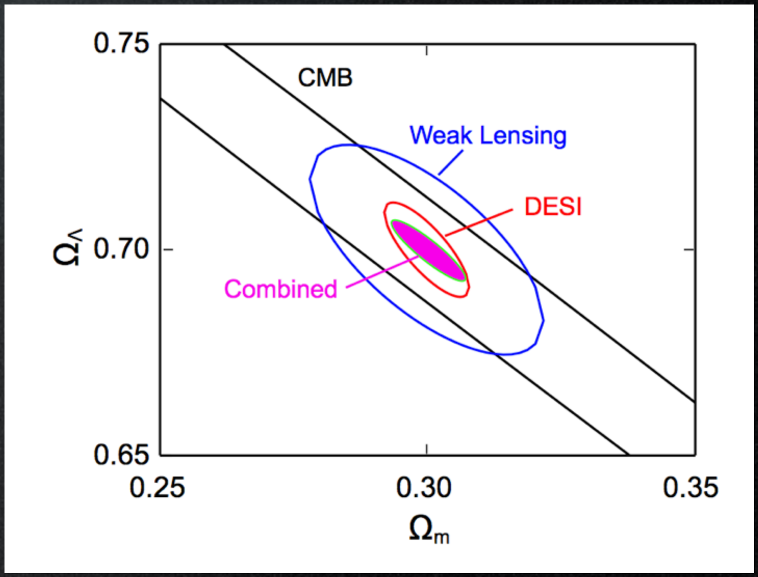
Maximizing the power of future spectroscopic surveys

- How small can we go? If we can model small-scales and the connection between galaxies and their dark matter halos accurately —
  - Significant additional power in redshift space distortions
  - Significant additional power in combined probes, e.g. galaxy-galaxy clustering + galaxy-galaxy lensing+ galaxy-cluster cross-correlations
  - in both cases, data can also be used to constrain the models: a huge opportunity for joint constraints that give both accurate astrophysics and correct cosmology.
- Need to think hard about many unknowns. e.g. velocity bias, assembly bias, impact of feedback on satellite stripping, how to accurately model galaxy-halo connection

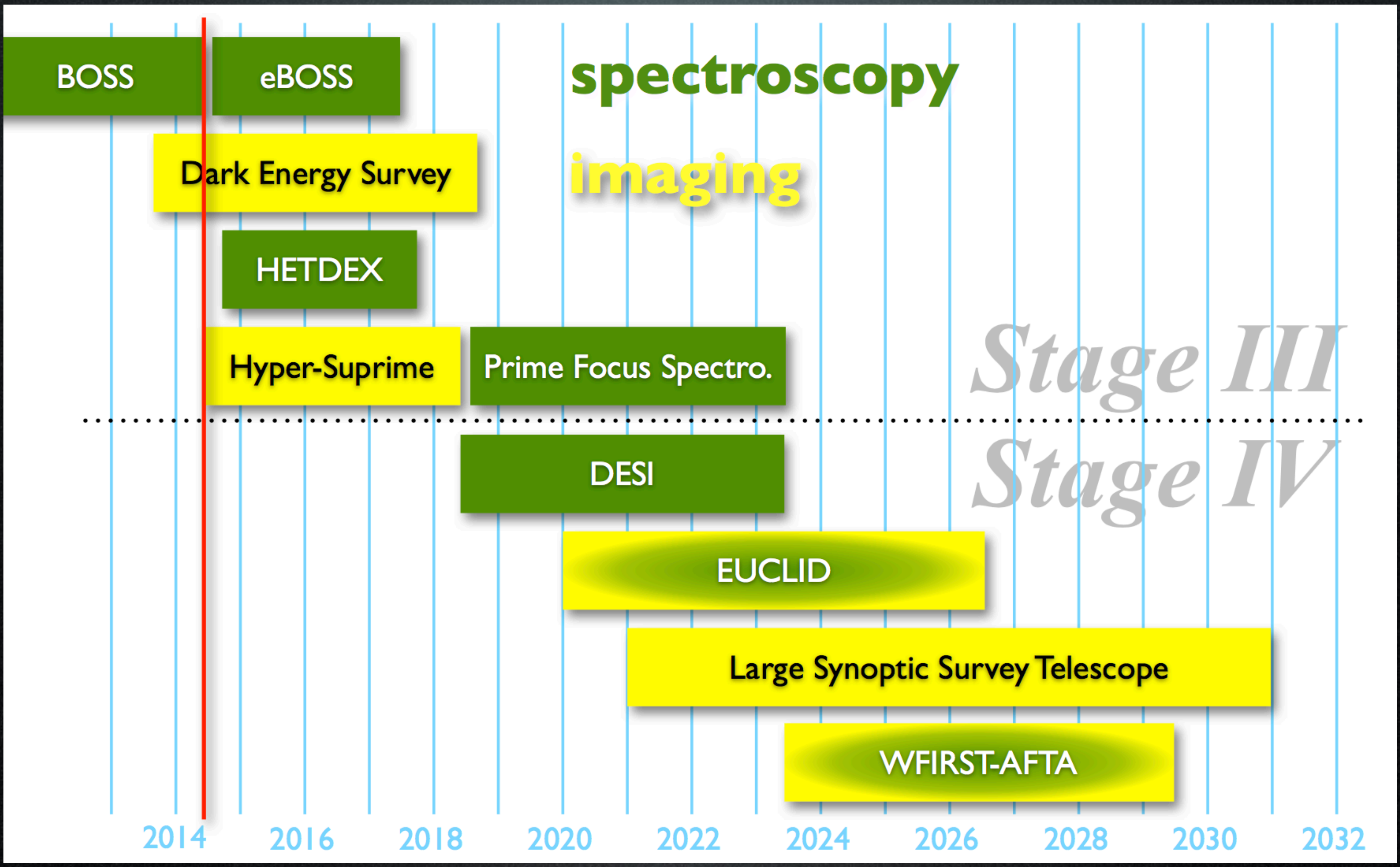
Complementarity between Imaging & Spectroscopy



- Overlap with WL surveys
  - — Further tests of gravity : do mass and light respond the same way?
  - — Systematics
  - — Photo-z calibrations
- Complementarity with SN surveys
  - — Absolute calibration of SN to the CMB distance scale



Dark energy roadmap



Summary

- New spectroscopic surveys will increase #spectra & volume probed x10
  - Baryon Acoustic Oscillations measure the expansion rate
  - Redshift space distortions measure the growth of structure
  - Together they provide precise tests of GR on cosmological scales
- Expected constraints by mid 2020's:
  - Measure distance scale by <0.4% out to z=2
  - Measure Hubble parameter to 1% out to z=4
  - Constrain growth factor to few% out to z=1.5
  - Measure neutrino masses to < 0.02eV
  - Measure ns and dlogn/dlogk < 0.4%
- Largest opportunity in pushing these data further is going to smaller scales — requires accurate modeling in the moderately / highly non-linear regime.
- Also: Dark matter constraints from spectroscopy in the Milky Way halo & streams — possibly probing down to $M \sim 10^5$ substructures