Cosmology: Addressing the Big Questions with Big Spectroscopic Surveys

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Multi-object spectroscopy
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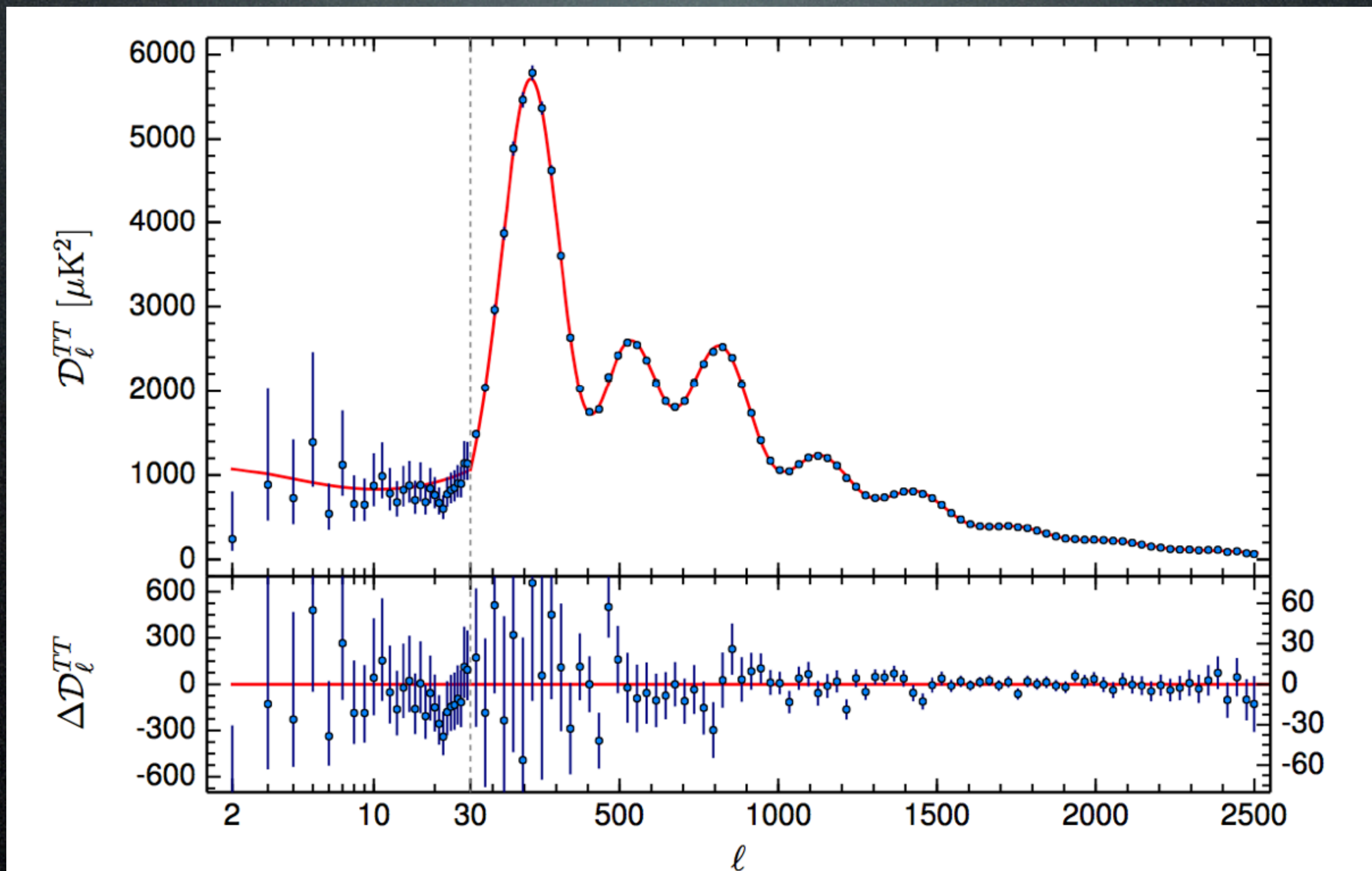
Big questions

- What is accelerating the Universe?
  - is it a new energy component?
    - if so, is it a cosmological constant?
  - is it a modification of gravity?
- How did the Universe begin?
  - can we directly probe the physics of inflation?
- What is the Universe made of?
  - what is the dark matter?
    - is structure formation on all scales consistent with CDM?
  - what are the masses of the neutrinos?
    - can we measure the sum of the neutrino masses from cosmological structure?

The Cosmological Model Post-Planck



The Cosmological Model Post-Planck

baryon density	$\Omega_b h^2$	0.02222 +/- 0.00023
dark matter density	Ω_m	0.308 +/- 0.12
Hubble parameter	H_0	67.8 +/- 0.9 km/s/Mpc
normalization of the power spectrum	σ_8	0.83 +/- 0.015
tilt of the power spectrum	n_s	0.968 +/- 0.006
optical depth	τ	0.066 +/- 0.016
tensor-to-scala		< 0.11
dark energy eq.		06 +/- 0.045
sum of neutrino		< 0.23 eV
spatial curva	Ω_k	< 0.005

best measured parameter (scale of the first peak) is measured to 0.03% (!)

all current data consistent with flat LCDM

are we done yet?

- getting there, but we still don't know the answers to the big questions!
- What is accelerating the Universe?
  - is it a new energy component?
    - if so, is it a cosmological constant?
  - is it a modification of gravity?
- How did the Universe begin?
  - can we probe the physics of inflation?
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next generation spectroscopic surveys will play a major role in answering these questions!

How can we do better?

- Significant additional information in large-scale structure
- Can measure the expansion rate of the Universe with baryon acoustic oscillations (BAO)
  - The distance-redshift relation $D_A(z)$
  - Directly measure H(z)
- Can measure the rate at which structures grow in the Universe (clustering including redshift space distortions (RSD), weak lensing, clusters)
  - Growth function and its derivatives
- This allows us to directly test the relationship between the expansion history and the growth of structure predicted by GR
- Can test gravity on smaller scales using dynamical tracers combined with non-dynamical mass estimates
- Combine power spectrum with large spec surveys with CMB, measure sum of neutrino masses
- Combine power spectrum with large spec surveys with CMB, measure inflation parameters, including tilt and running of power spectrum

Impact of large spectroscopic surveys

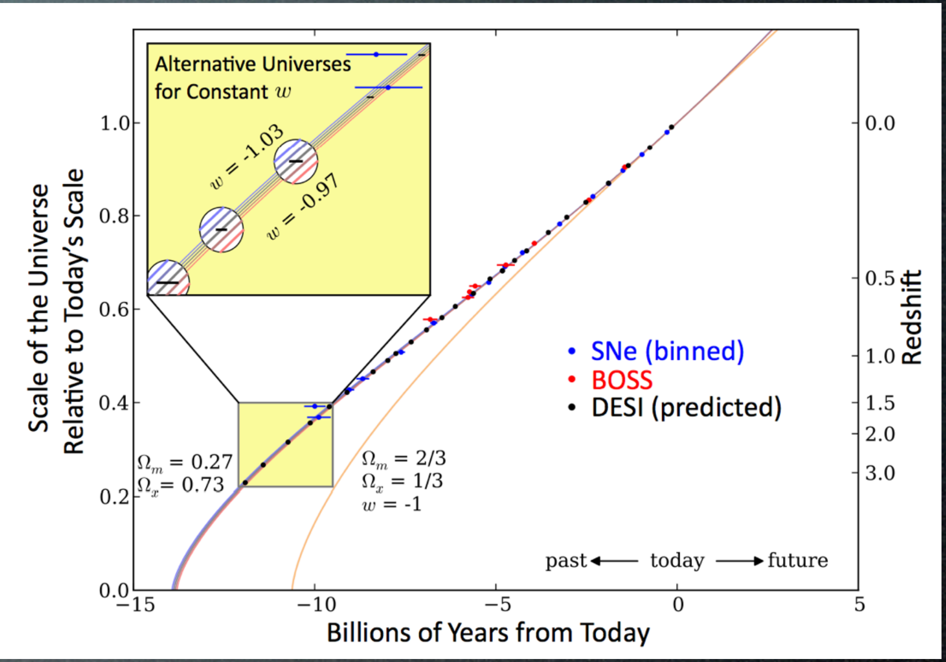
- Redshift surveys:
  - Baryon Acoustic Oscillations
  - Redshift-space distortions
  - Significant additional information from full galaxy power spectrum to small scales, if modeling can keep up with the data
- Imaging surveys + spectroscopy:
  - weak lensing: lens properties + p(z) for background galaxies, combining lensing + clustering
  - cluster redshifts and dynamics
  - cross-correlation with imaging surveys
  - impact of spectroscopy on large numbers of SN to be identified in imaging surveys (e.g. DES, LSST)

this talk

(my biased view)

- going to focus on the potential of DESI, on its own and in synergy with imaging and CMB
- will highlight how this ties into the big questions
- many of the measurements I will discuss are also accessible with other surveys and instruments (WEAVE, Euclid, WFIRST, 4MOST, PFS, HETDEX)
- complementary talk by Bob Nichol, including synergy with SN and imaging surveys.
- will mostly ignore details of the DESI instrument, which will be covered by Brenna Flaugher

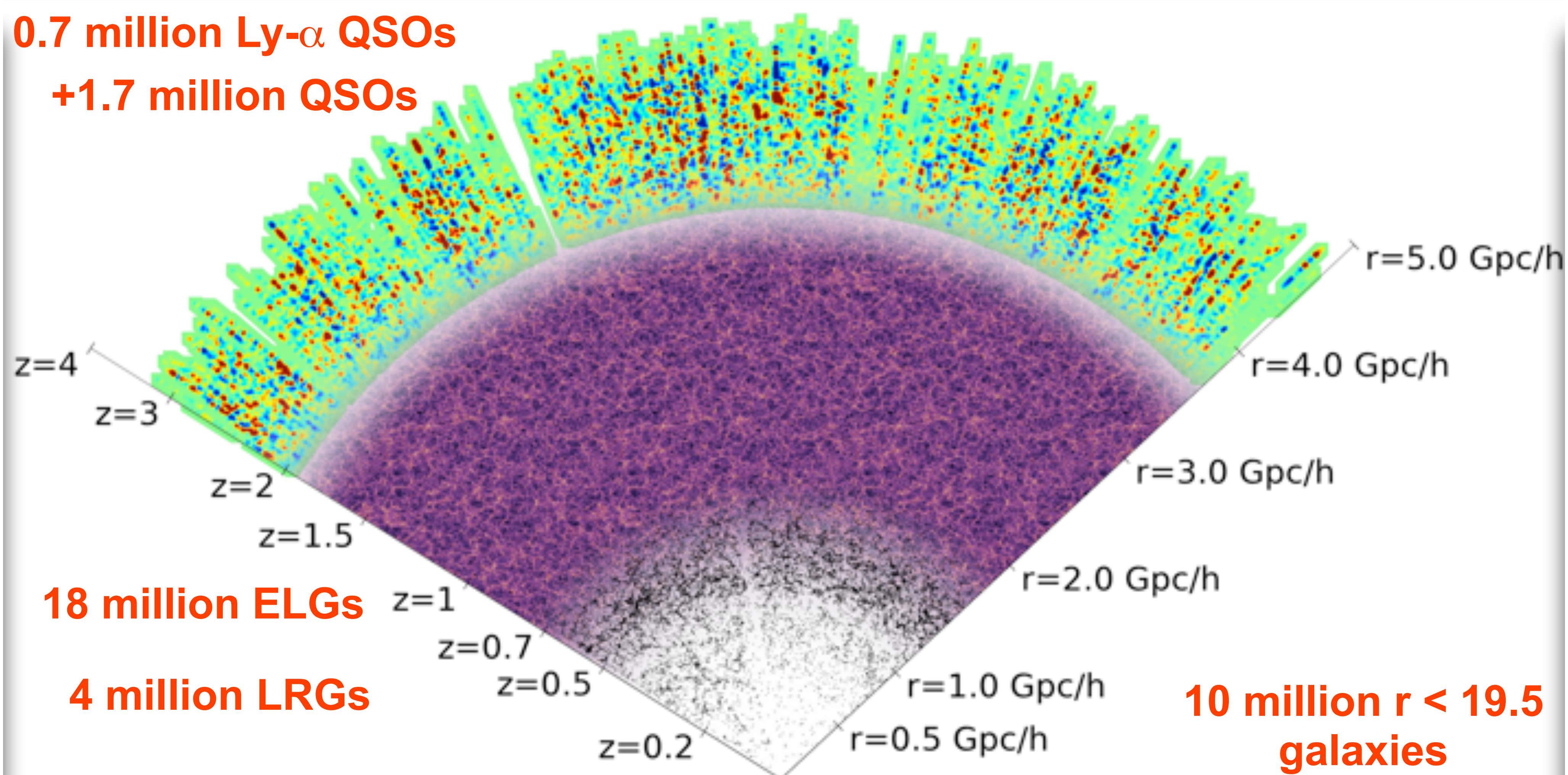
DESI Science Goals



- Distance-redshift relation
  - Measure distance scale to <0.3% between 0.0 < z < 1.1
  - Measure distance scale to <0.4% between 1.1 < z < 1.9
  - Measure H(z) to ~1% in the bin 1.9 < z < 3.7
- Gravitational growth
  - Measure the growth factor to ~ 1% to z=1.5 using RSD
- Beyond Dark Energy
  - Constrain spectral index of primordial perturbations and its running to <0.4%
  - Measure the neutrino masses to <0.017 eV.

Overview of the DESI Survey

- Four target classes in dark time spanning redshifts z=0.4 → 3.5
  - these are roughly the easiest 25 million spectra to measure.
  - includes nearly all the massive black holes in the Universe (LRGs + QSOs)
- Additional Bright Galaxy Survey will target all galaxies with r < 19.5 (z=0.-0.4)



The DESI Surveys

Object Class	Number of Spectra	Redshift Range
bright galaxies, $r < 19.5$	~10 million	$0 < z < 0.4$
luminous red galaxies (LRGs)	4.2 million	$0.4 < z < 1.0$
emission line galaxies (ELGs)	18 million	$0.6 < z < 1.6$
quasars (QSOs)	2.4 million	$0.5 < z < 3.5$
Milky Way stars	> 10 million	---

Bright Galaxy Survey

- DESI Dark Time Survey (LRGs, ELGs, QSOs) will use nearly all of the dark time but this leaves significant time available for bright objects when the moon is too bright or other observing conditions too poor

- Survey of 10M bright ($r<19.5$) galaxies over at least 14k square degrees (possibly up to 20K sq. degrees)

- Very complementary to dark time survey:

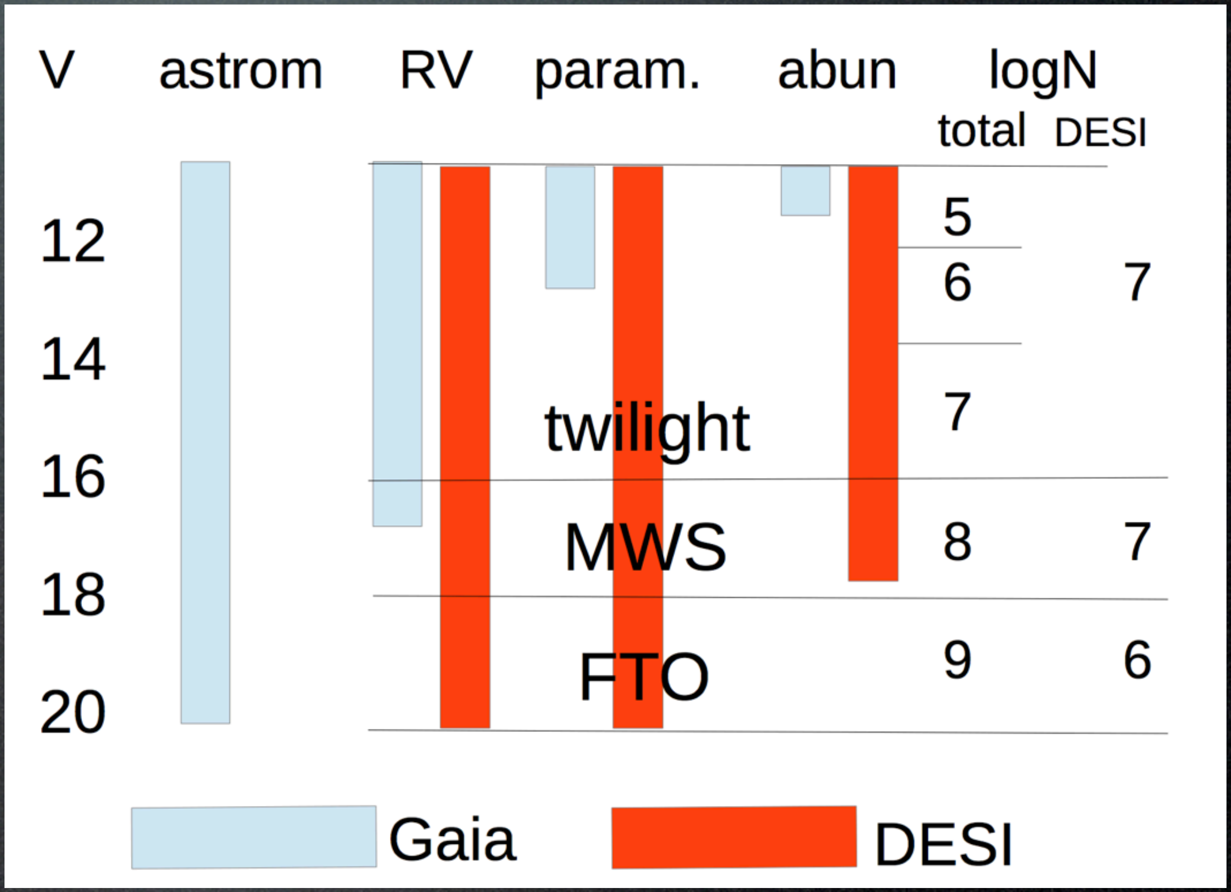
  – Extends measurements of distance scale and growth of structure at low redshift, where dark energy dominates
  – Significant synergies with imaging surveys (DES, LSST, others) e.g.
    – redshift calibration
    – many 10 K's SN host galaxy redshifts for SN
    – combined constraints using spectra and lensing
  – Rich non-cosmology science: galaxy formation, including galaxy environments, groups, dwarf galaxies, etc.

- Plan to interleave this survey with a Milky Way Survey of ~ 10 M stars down to ~ V=18

Milky Way Survey

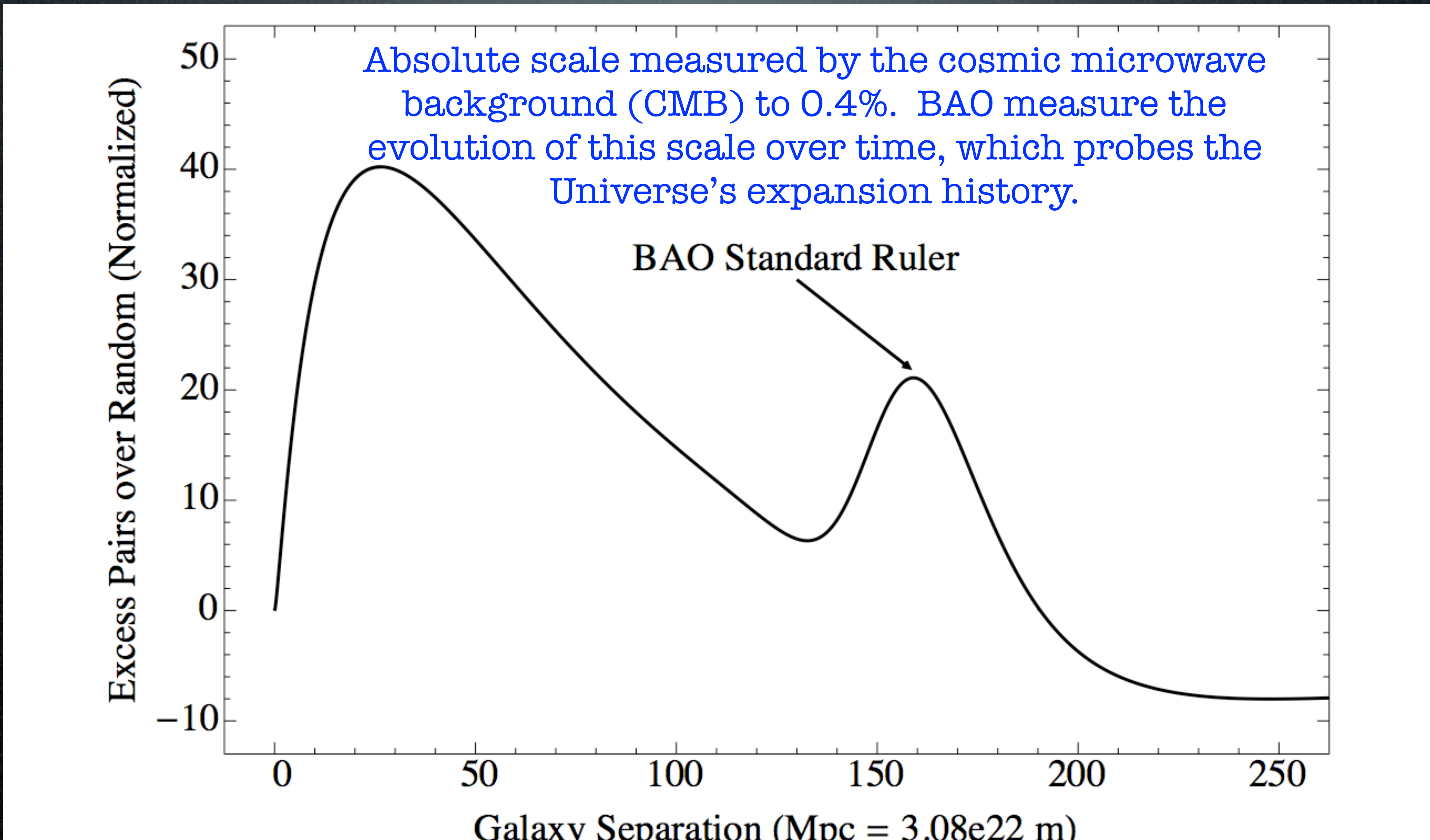
- at least 10 M stars down to ~ V=18
  - very complementary to GAIA
  - S/N = 20 spectra, can do radial velocities and metallicities down to the GAIA limit
  - well beyond Solar neighborhood, probe inner halo and thick disk

- DESI has very fast fiber reconfiguration -- can likely target 10s of millions of bright stars in twilight



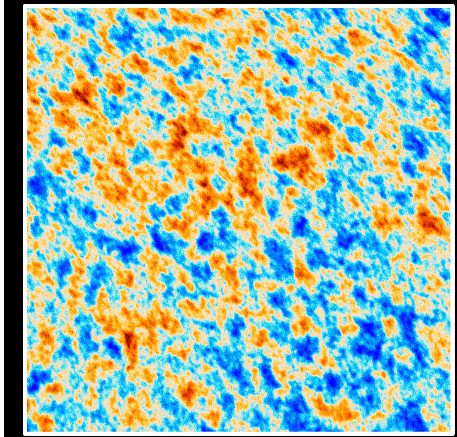
Baryon Acoustic Oscillations

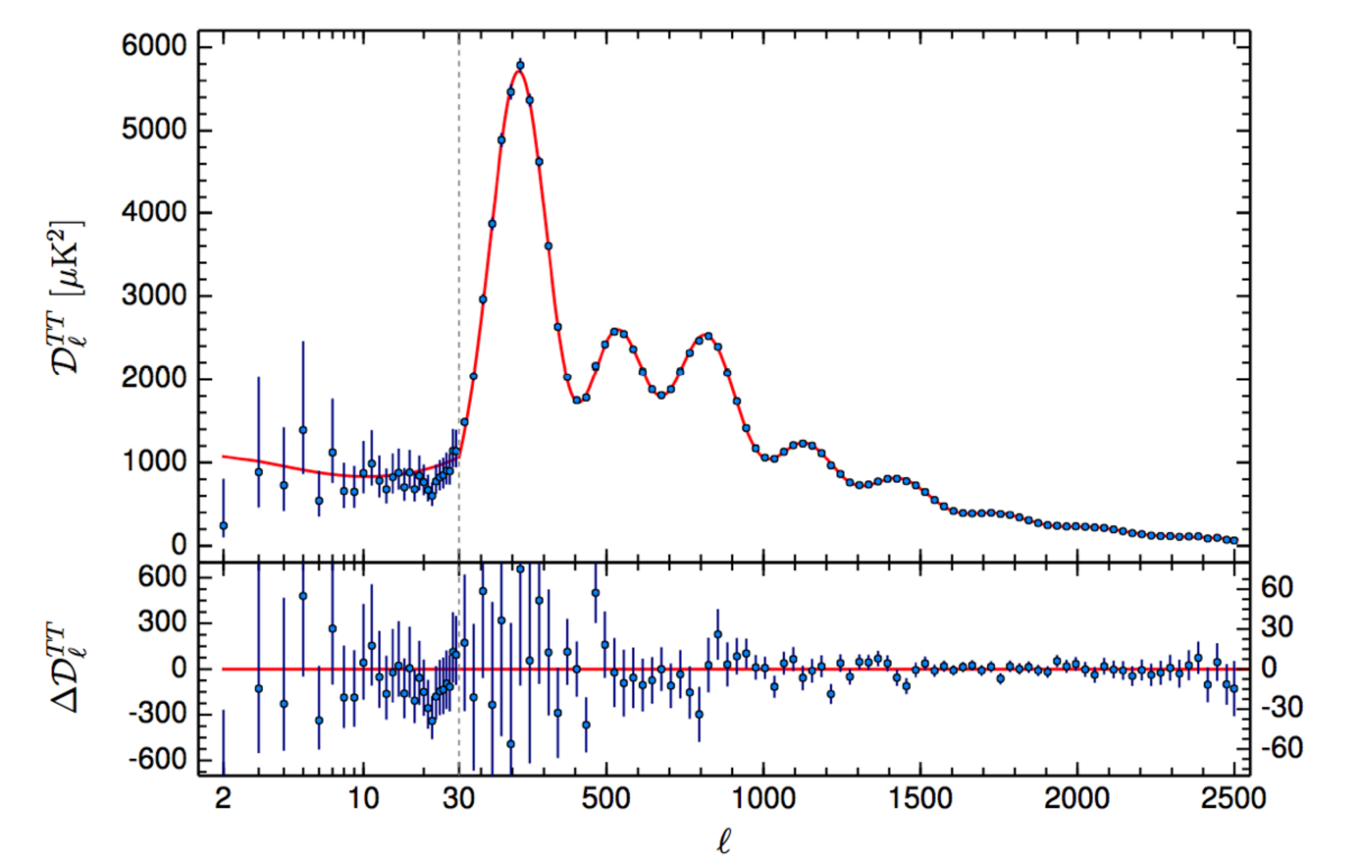
Sound waves in the early Universe imprint correlations in the distribution of galaxies at a fixed physical scale (related to sound speed at recombination).



Standard ruler analogous to standard candles

Acoustic Oscillations in the CMB


Planck



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

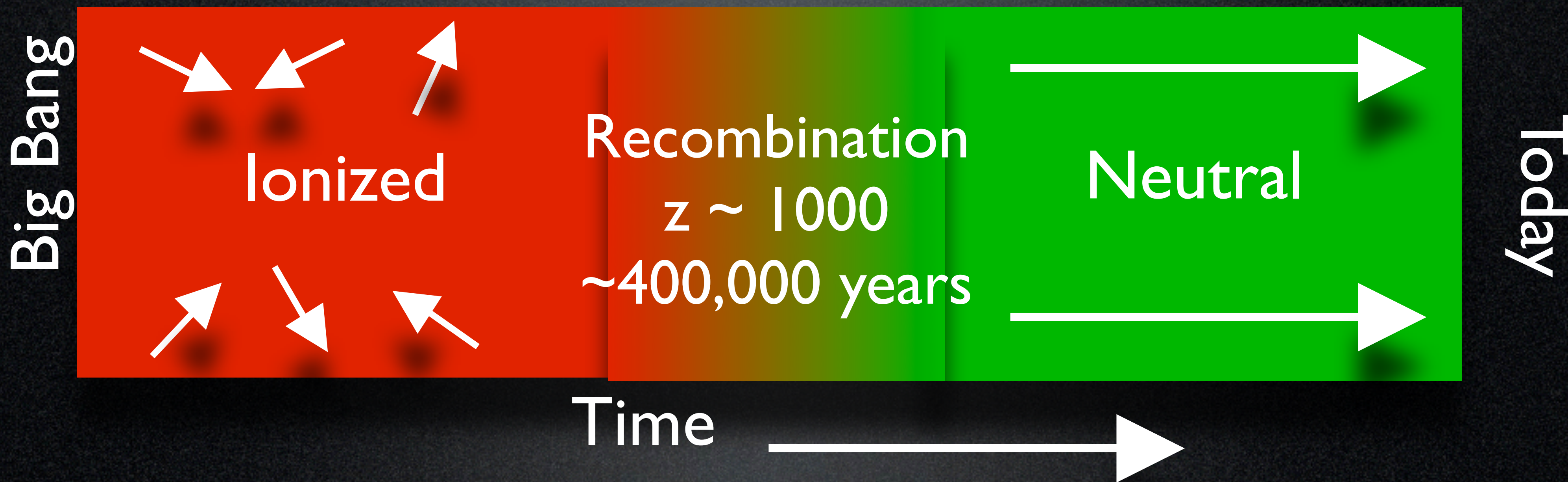
Sound Waves in the Early Universe

Before recombination:

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

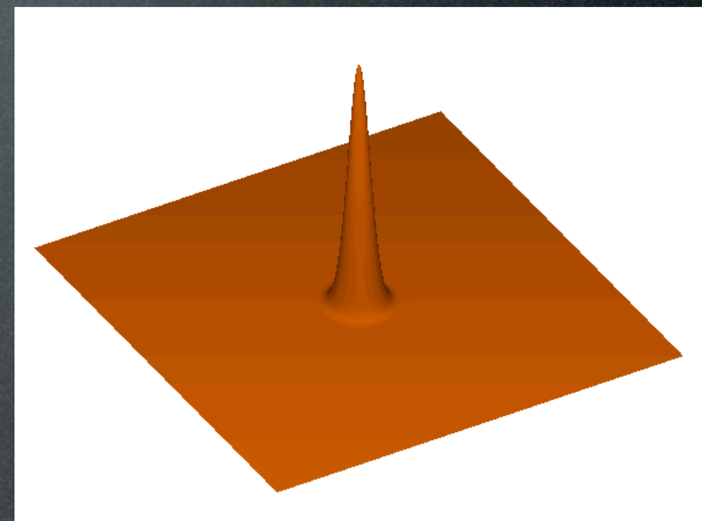
After recombination:

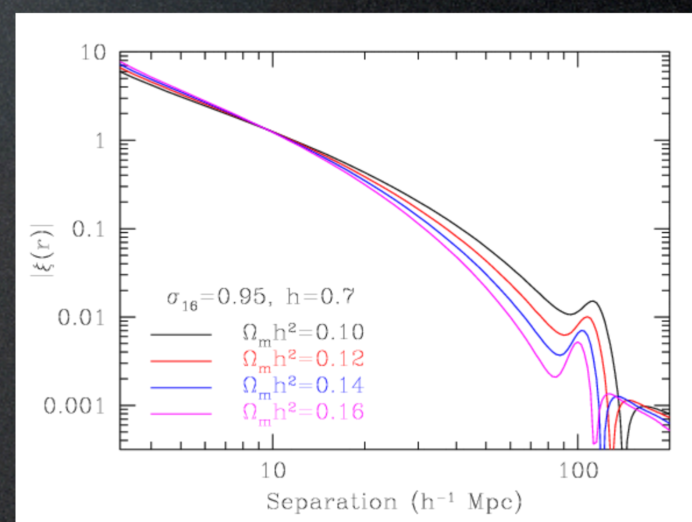
- Universe is neutral.
- Photons can travel freely past the baryons.
- Perturbations grow by gravitational instability.



Sound Waves

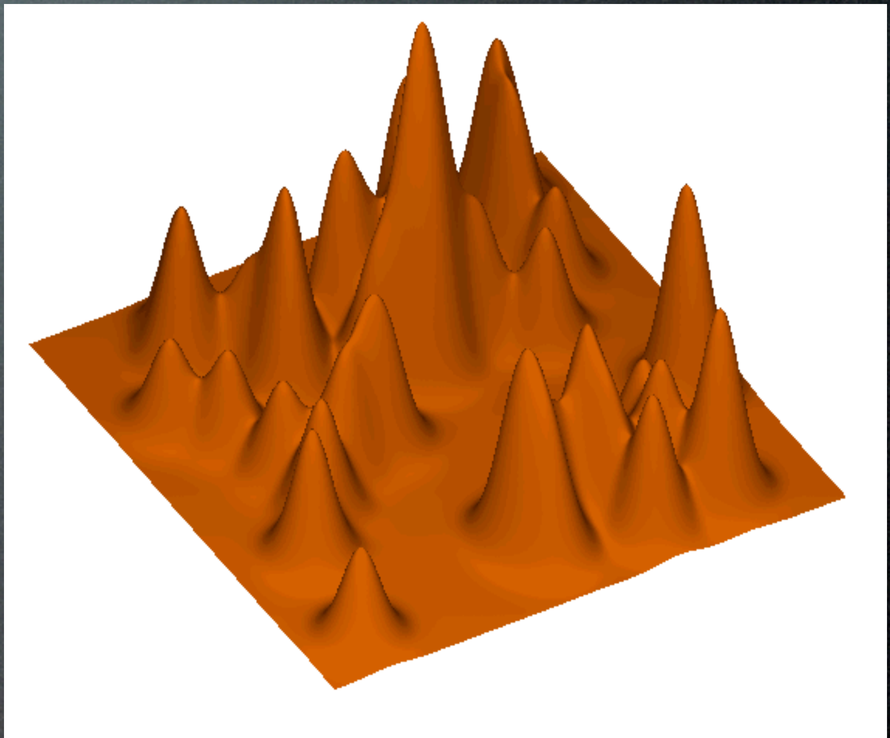
- Each initial overdensity (in DM & gas) is an overpressure that launches a spherical sound wave.
- This wave travels outwards at 57% of the speed of light.
- Pressure-providing photons decouple at recombination. CMB travels to us from these spheres.
- Sound speed plummets. Wave stalls at a radius of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





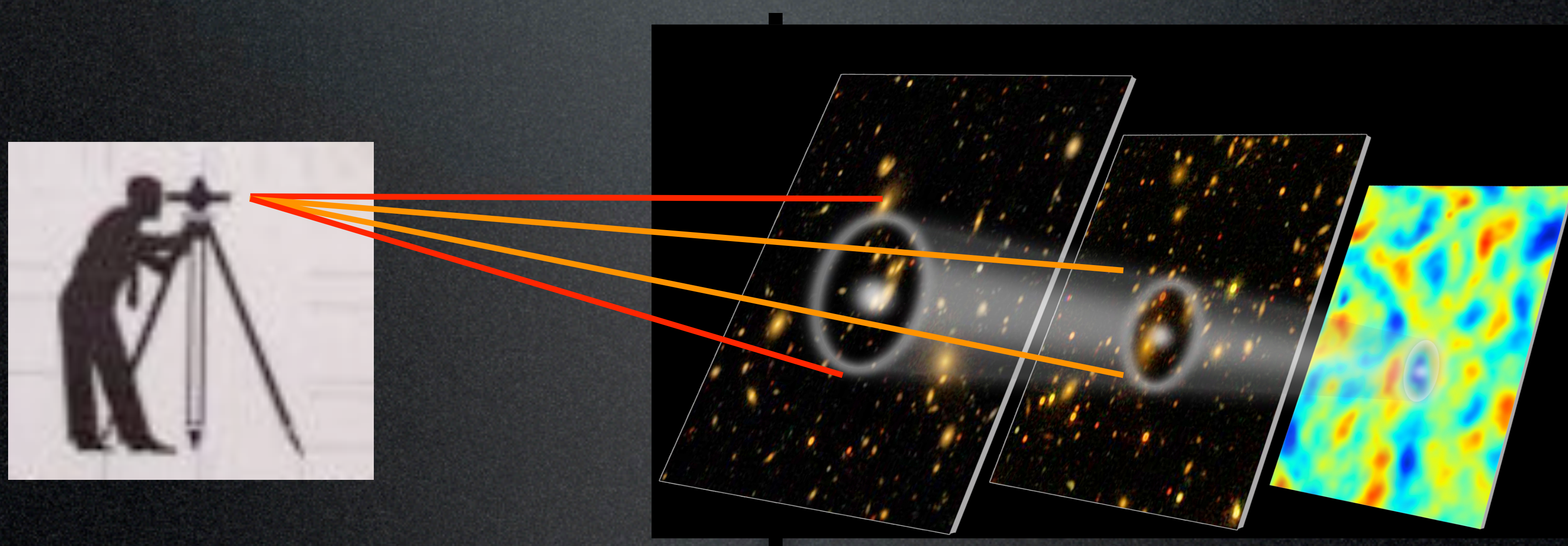
A Statistical Signal

- The Universe is a superposition 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.



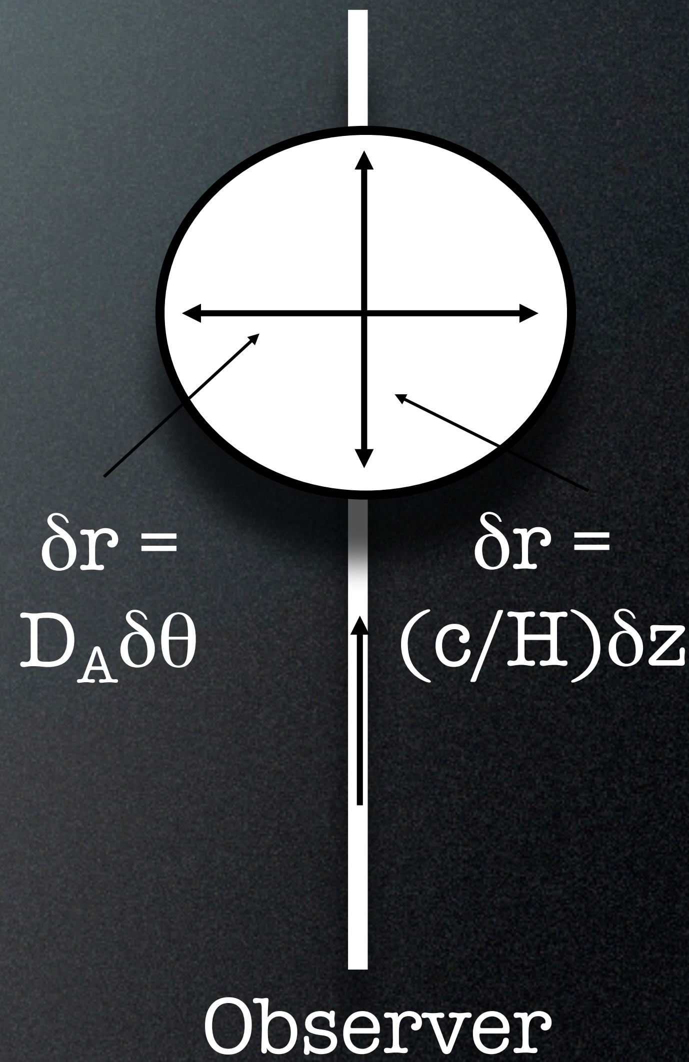
A Standard Ruler

- 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 0.4% from Planck data.
- When we see this pattern in the clustering data as an angular scale, we can infer the distance to the galaxies.



A Standard Ruler

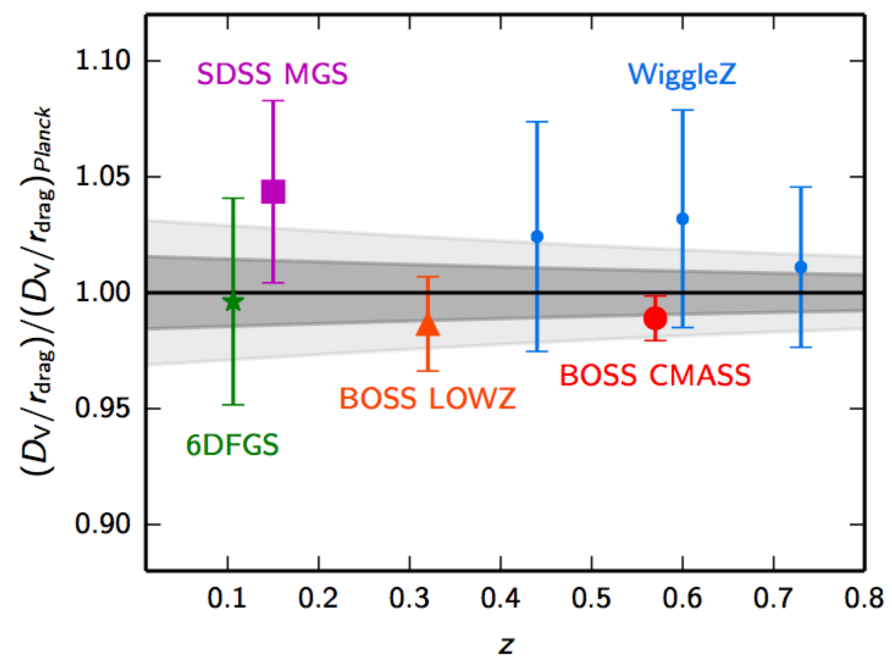
- We measure distances along and across the line of sight differently.
- In a redshift survey, we can measure the clustering in both directions.
- Yields $H(z)$ and $D_A(z)$ separately!

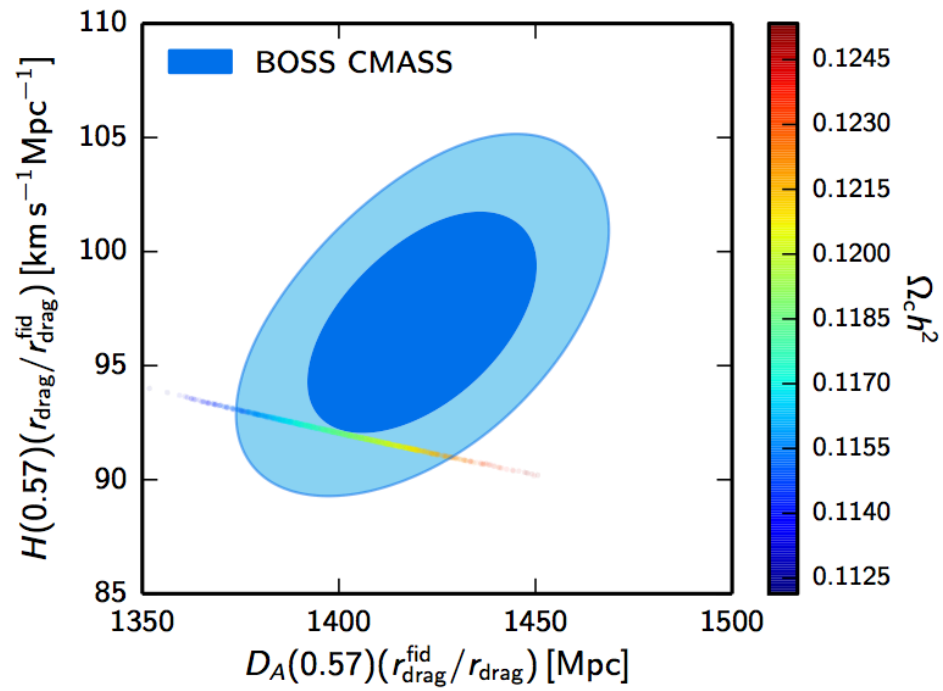


Virtues of the Acoustic Peaks

- 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.
- Method has intrinsic cross-check between H(z) & $D_A(z)$, since D_A is an integral of H.

The Cosmological Model Post-Planck

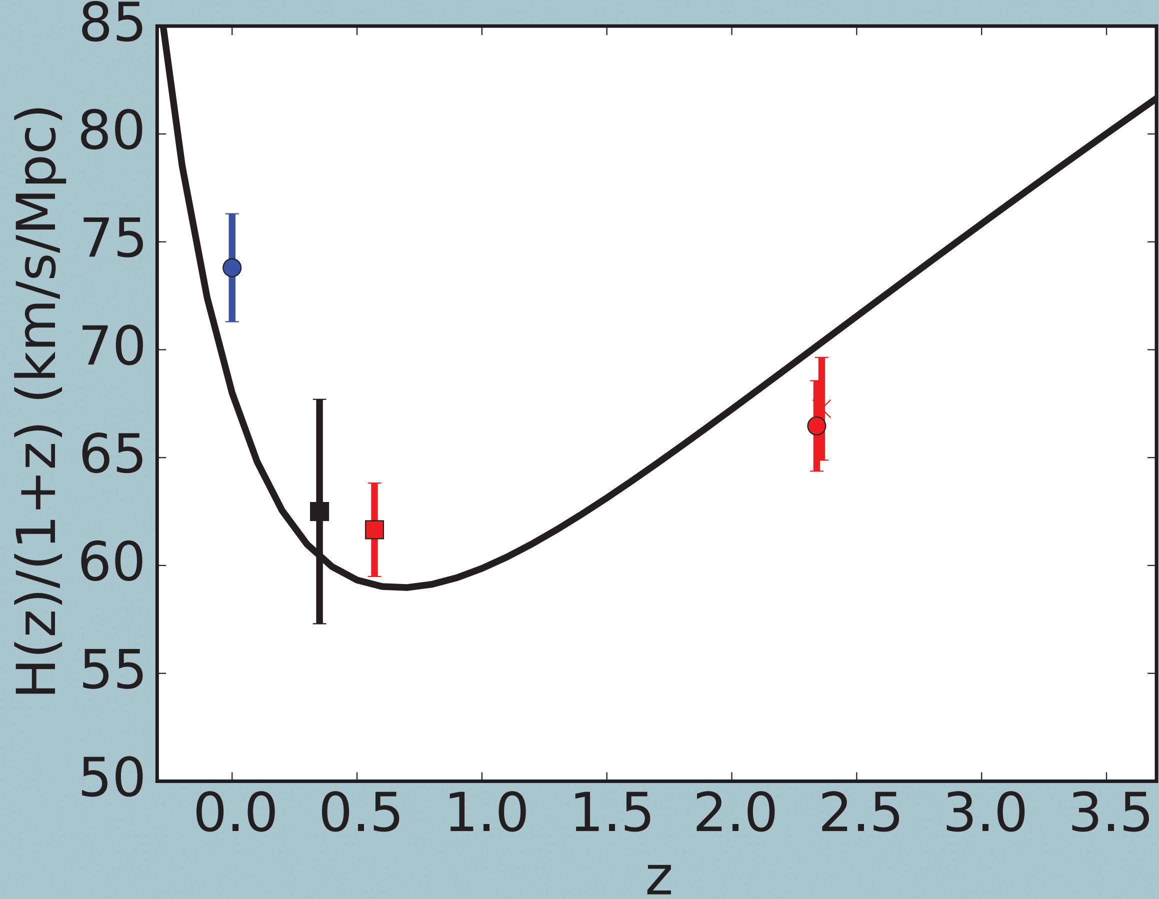




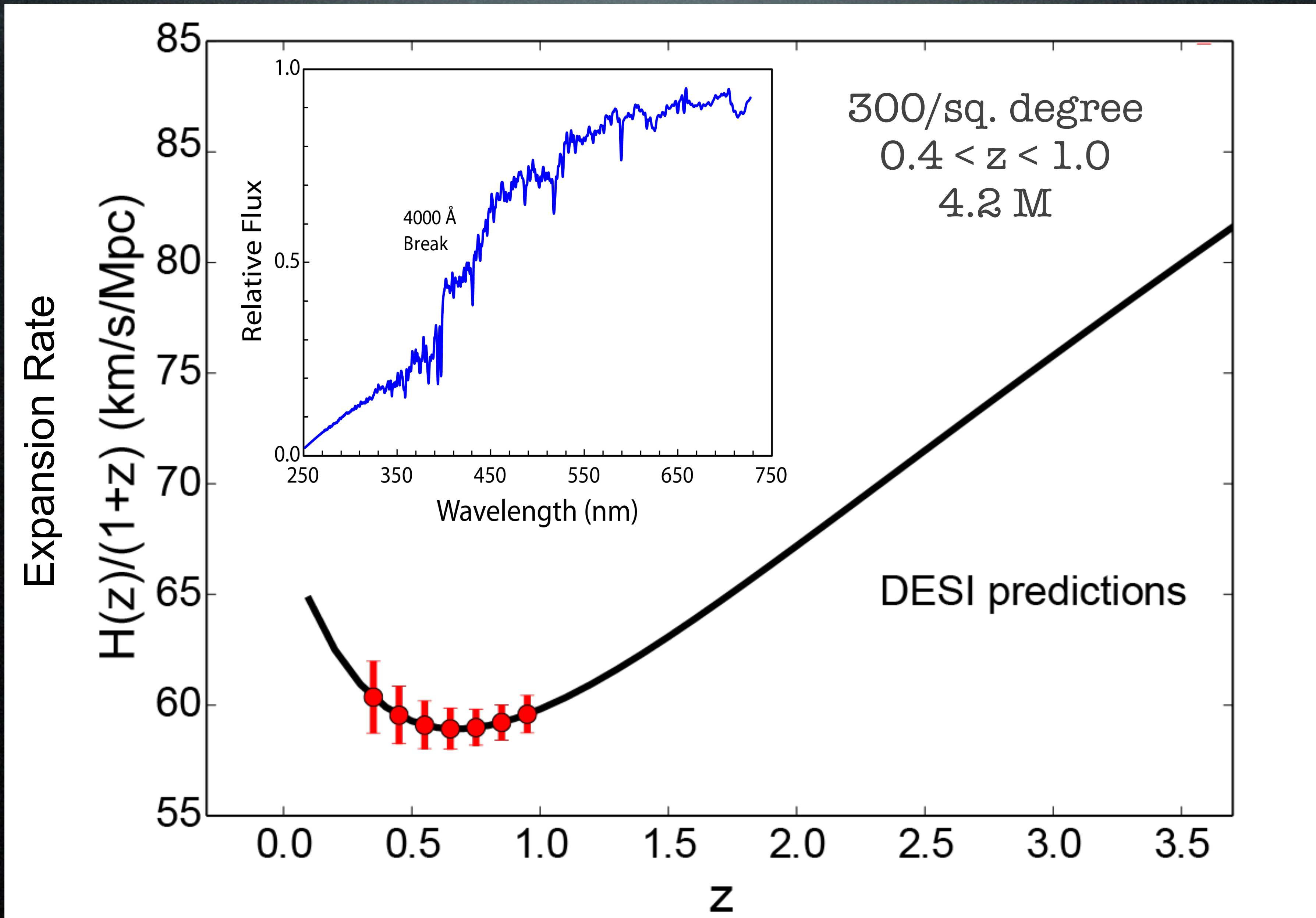
current D(z) measurements from BAO are consistent with Planck predictions for low z

BAO and CMB provide complementary (currently consistent) constraints on rel'n between H(z), D_A(z), Ω_m

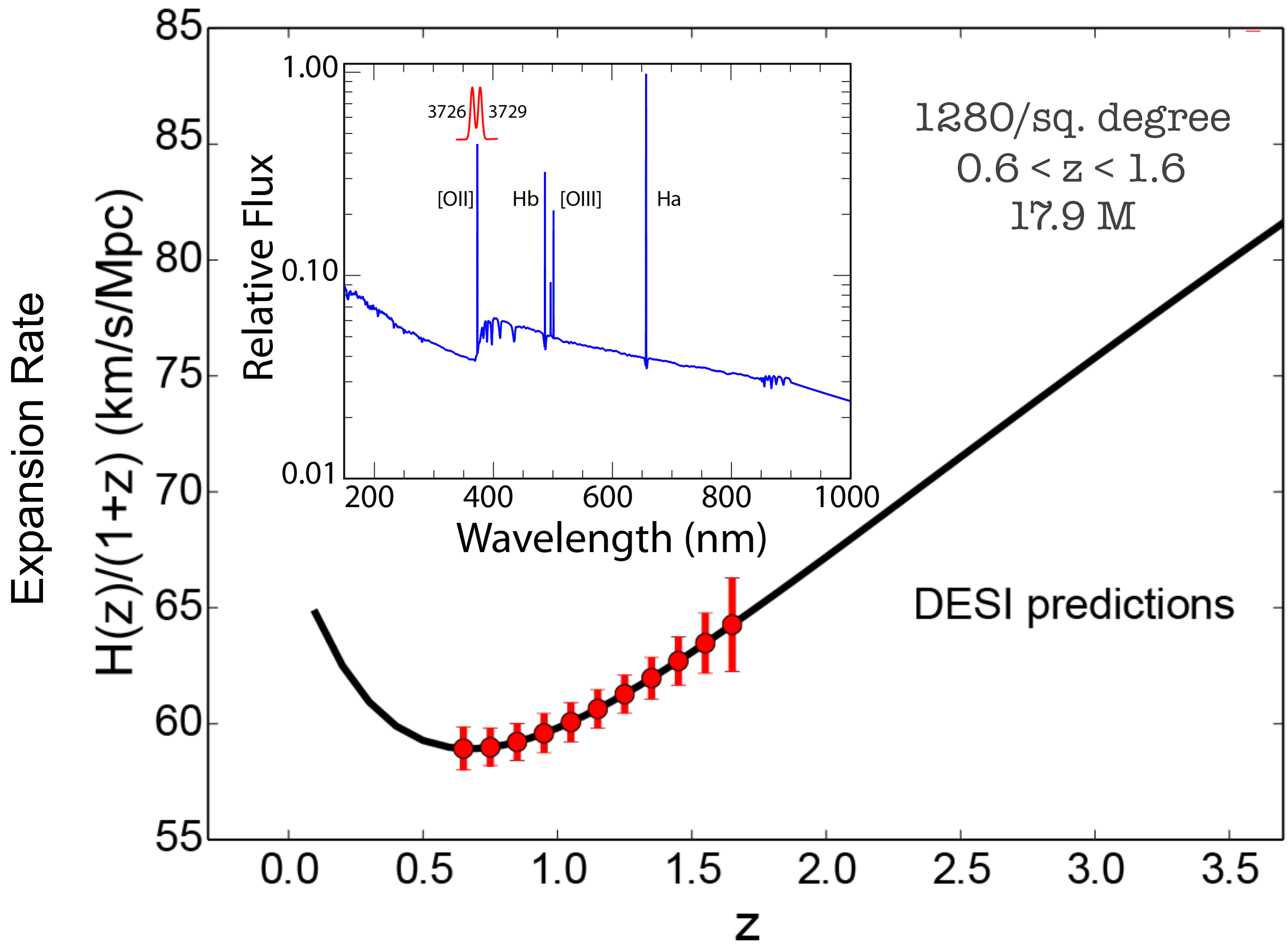
Current constraints on the Hubble parameter



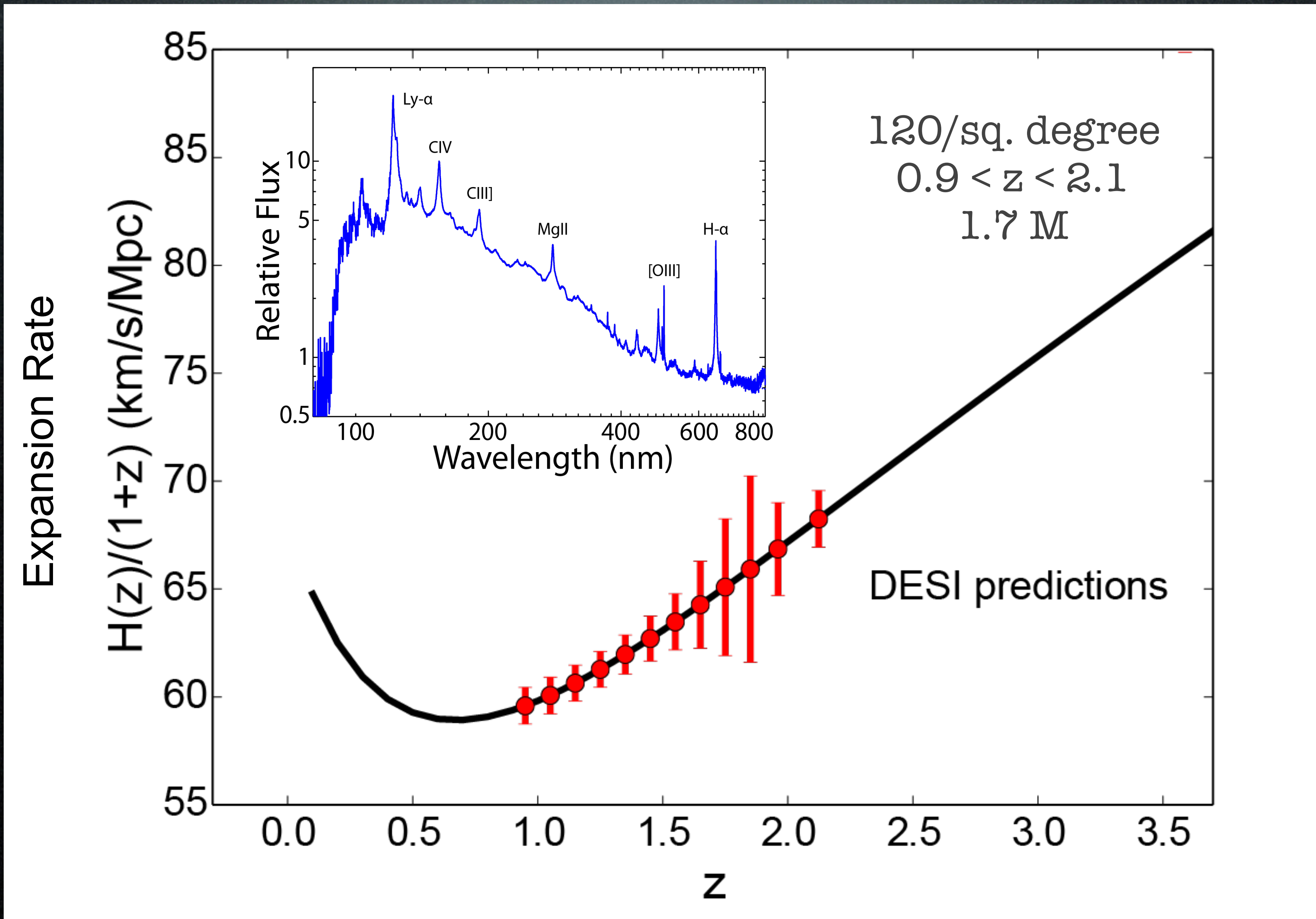
Luminous Red Galaxies



Emission-line Galaxies



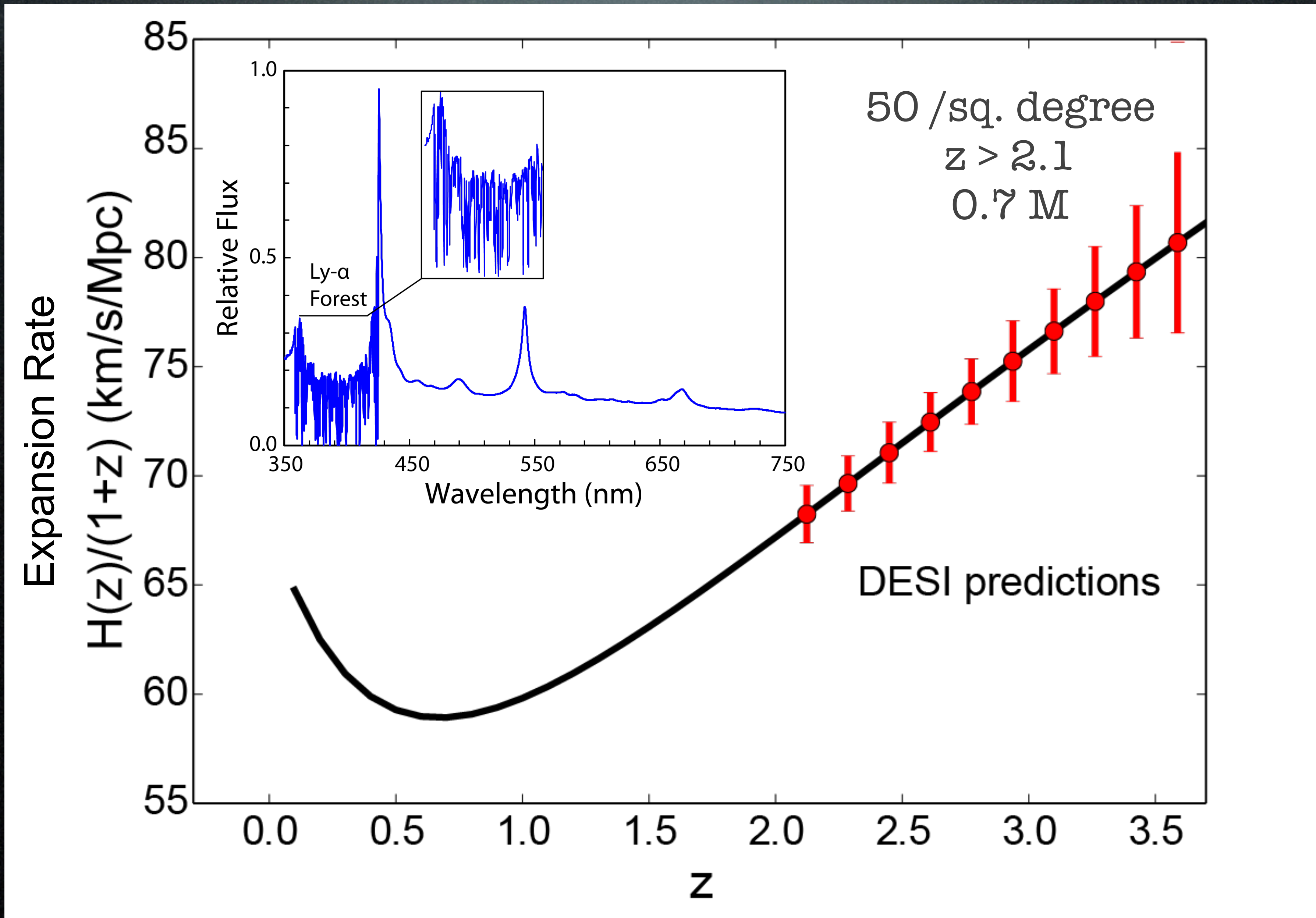
Quasars



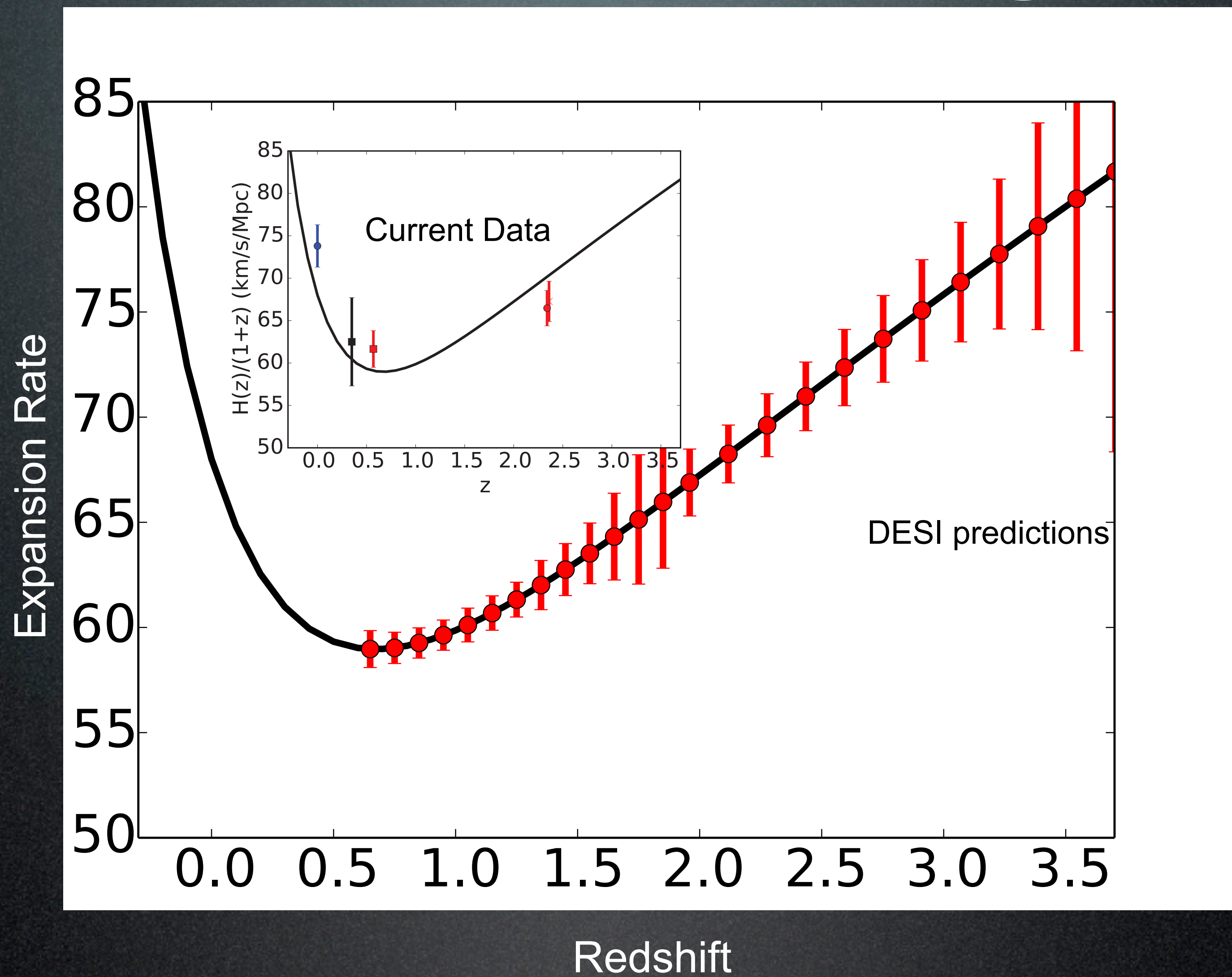
Expansion Rate
H(z)/(1+z) (km/s/Mpc)
85
85
80
75
70
65
60
55
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
z
120/sq. degree
0.9 < z < 2.1
1.7 M
DESI predictions
Relative Flux
Wavelength (nm)
Ly-α
CIV
CIII]
MgII
[OIII]
H-α
10
5
1
0.5
100
200
400
600
800

Lyα Forest

see also
Mat Pieri talk



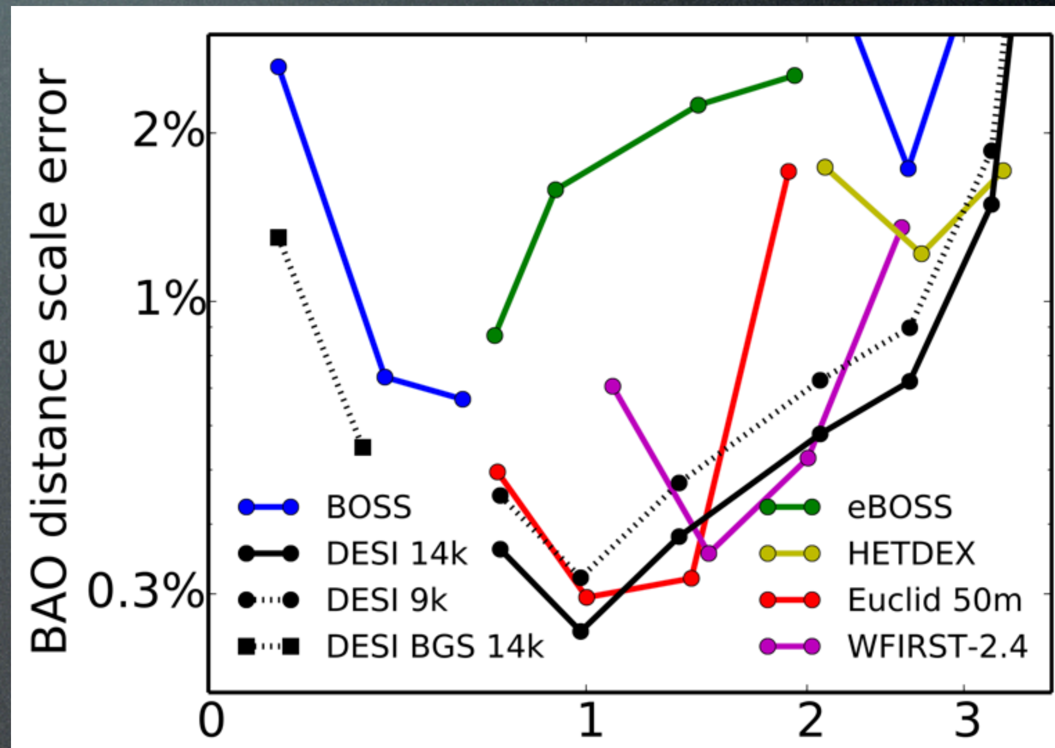
DESI Hubble Diagram



Target type	z range	Target density deg^{-2}	Good z density deg^{-2}	$\Delta z/(1+z)$ precision	$\Delta z/(1+z)$ systematic	Bad z assignment	Complete -ness
LRG	0.4–1.0	350	300	0.0005	0.0002	< 5%	> 95%
ELG	0.6–1.6	2400	1280	0.0005	0.0002	< 5%	> 90%
QSO	< 2.1	170	120	0.0025	0.0004	< 5%	> 90%
Ly-α	> 2.1	90	50	0.0025	-	< 2%	> 72%

Distance scale measurements from BAO in various surveys

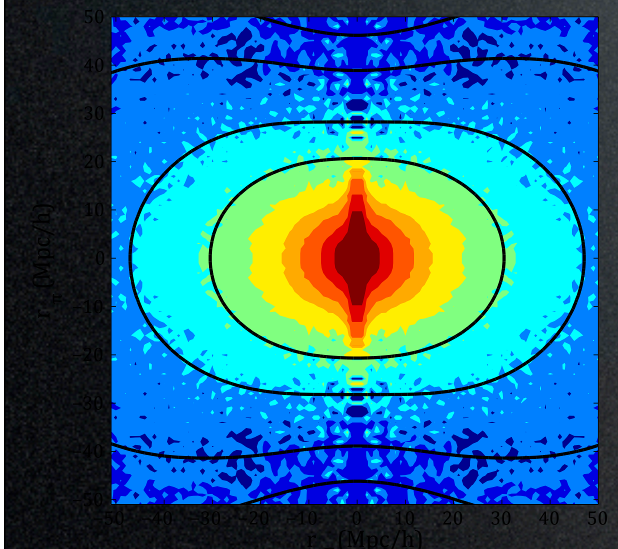
- DESI will have 10-fold more inverse variance on total BOSS distance scale.
- Close to the optimal ground-based optical BAO experiment
  - target all of the available non-dusty sky
  - target the easiest galaxies to get redshifts for
- Complementary with Euclid and WFIRST (less constraining at z=1-2, using different tracers), extend to higher z using quasars.



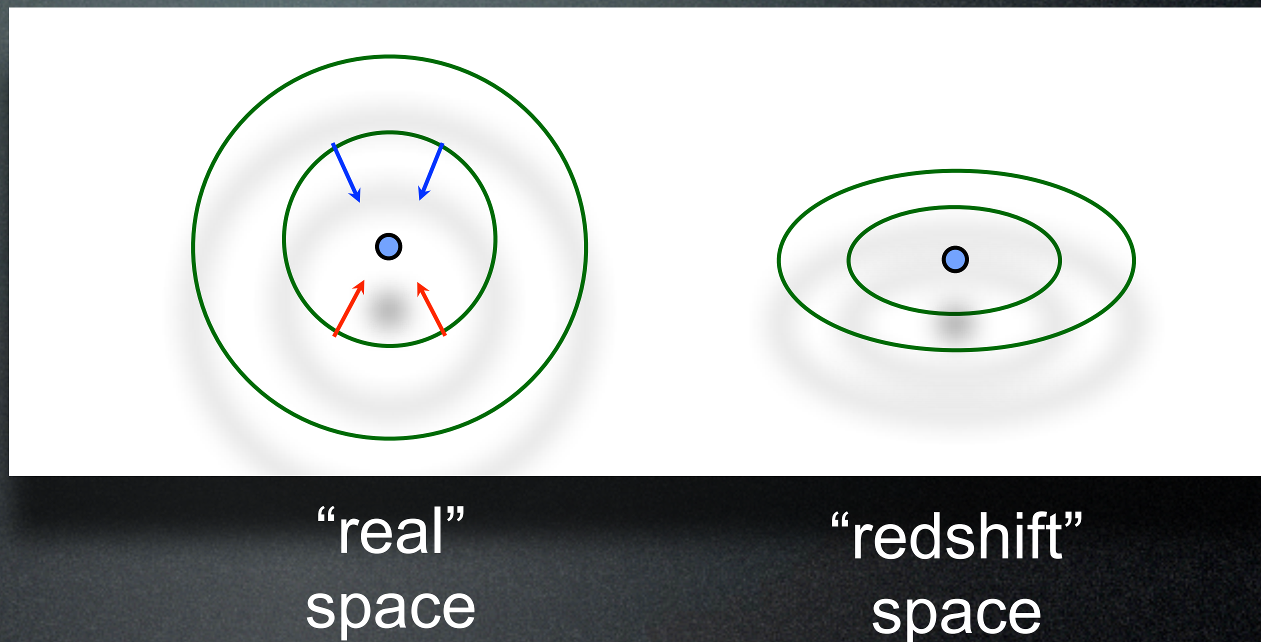
redshift

Beyond BAO

- There is significantly more information in the galaxy power spectrum than just the information from BAO
  - Growth rate
  - Neutrinos
  - Inflation

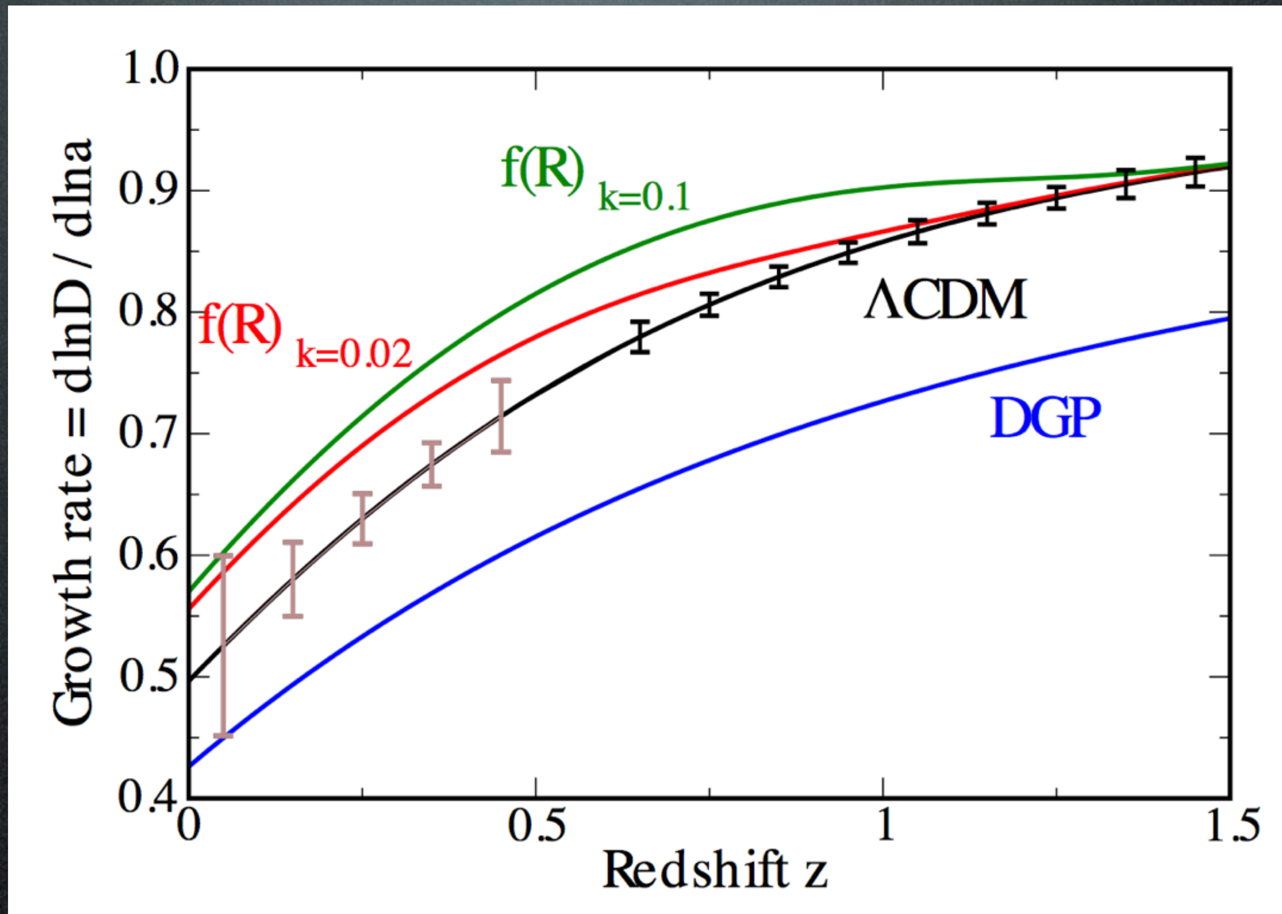


observed redshift space distortions from BOSS



- Anisotropy in the correlation function constrains $f\sigma_8$, where f is the growth rate
- Produces a test of GR
- DESI will measure the growth rate <1% over $0.5 < z < 1.4$

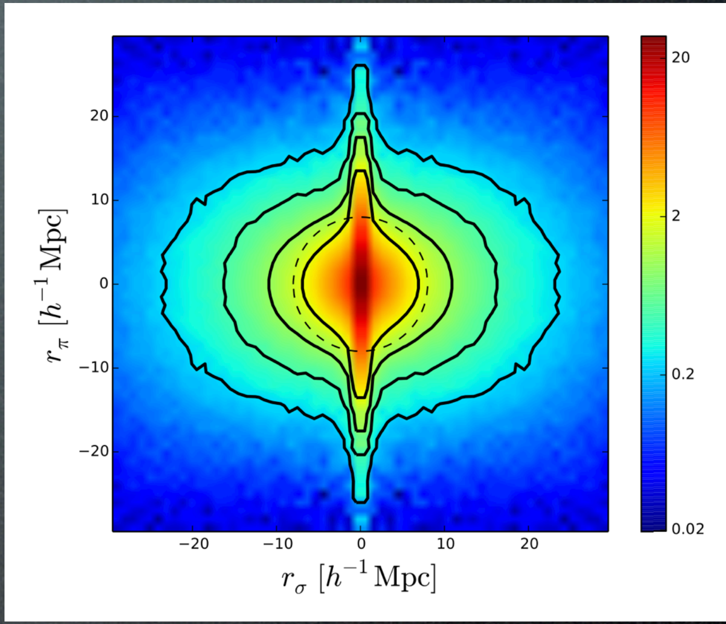
Distinguishing Modified Gravity from GR



a 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.

small-scale clustering

Reid et al 2014

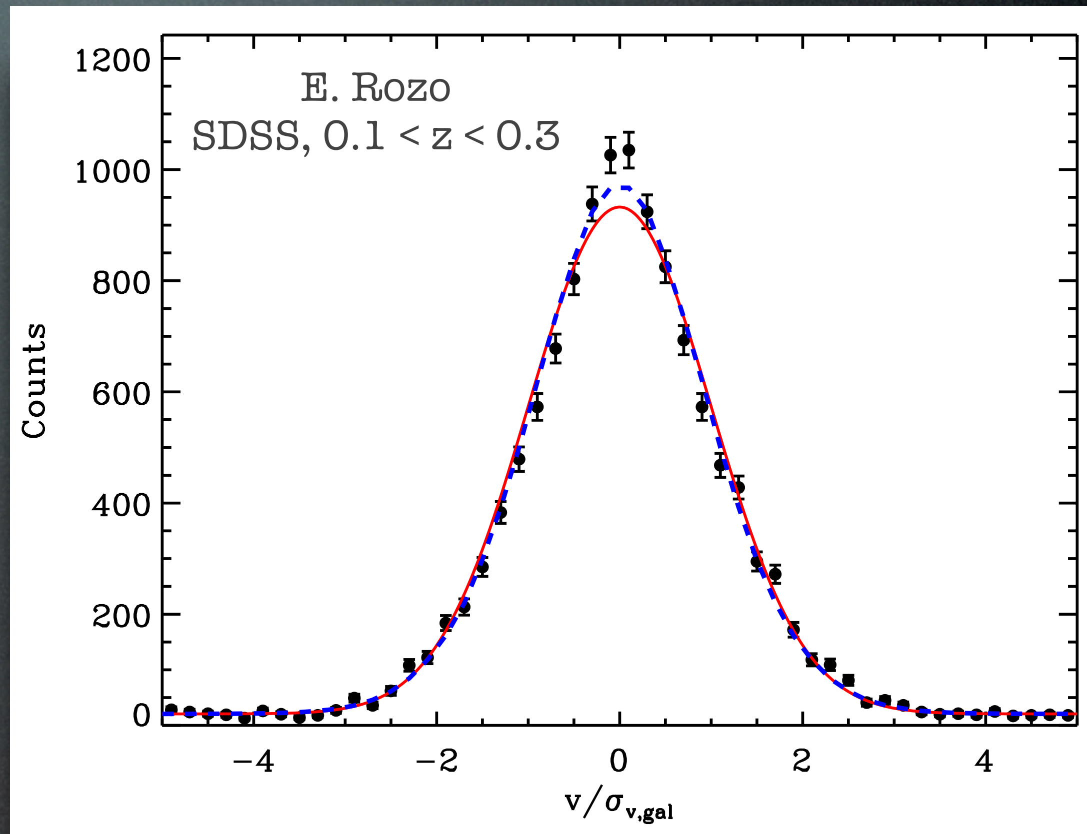


- significant information available in the data on small-scale clustering
  - small-scale redshift space distortions
  - combining galaxy-galaxy clustering with galaxy-galaxy-galaxy lensing
  - testing gravity by comparing dynamical cluster mass estimates with lensing mass estimates
- already becoming theory limited!
- how well can we predict / model
  - galaxy and matter clustering in the 1-halo and transition regime, including impact of baryons?
  - small-scale redshift space distortions?
  - velocity distributions within clusters?

huge potential if the theory accuracy can be improved -- will take massive simulation effort plus better constraints on galaxy formation

Mass calibration of clusters

- stacked central-satellite pairs for redmapper clusters in SDSS
- fit velocity dispersion as a function of richness, stack v/σ_v (predicted dispersion for every pair)
- red curve: gaussian of zero mean and unit variance. blue curve: including some systematics
- statistical precision: 1% in velocity dispersion, 3% in mass -- better than weak lensing!
- systematics TBD!

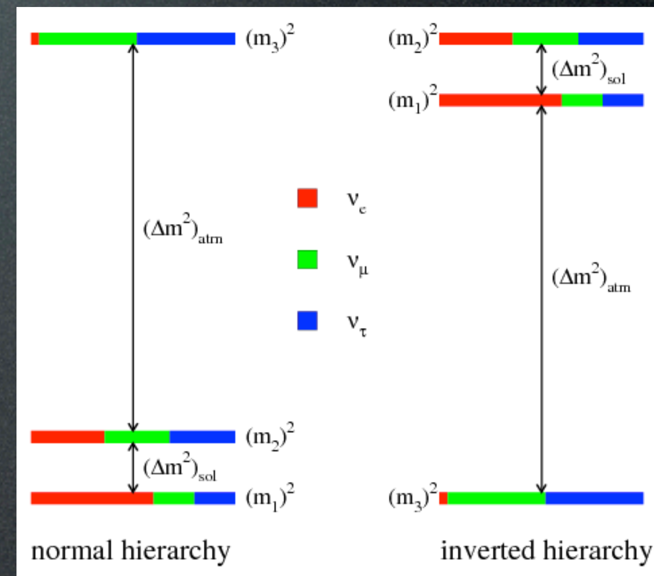


DESI can do this experiment out to z=1 provides test of gravity in overlap regime with WL

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 be measured by LSS+CMB



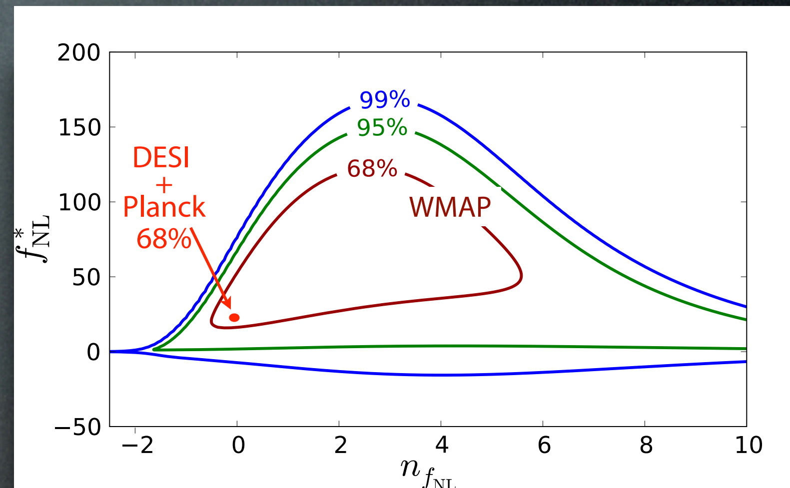
Data	$\sigma_{\Sigma m_\nu}$ [eV]
Planck	0.350
Planck+DESI BAO	0.090
Gal ($k_{max} = 0.1$)	0.024
Gal ($k_{max} = 0.2$)	0.017

conservative

optimistic

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



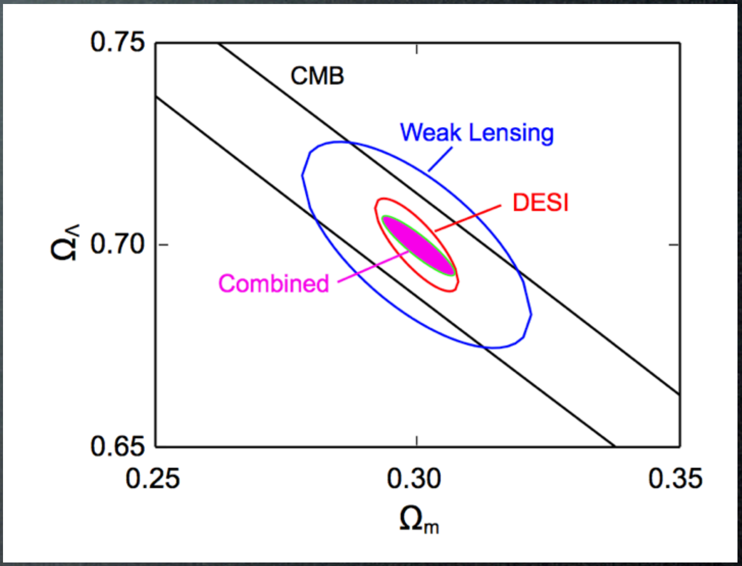
(relative improvement over Planck alone)

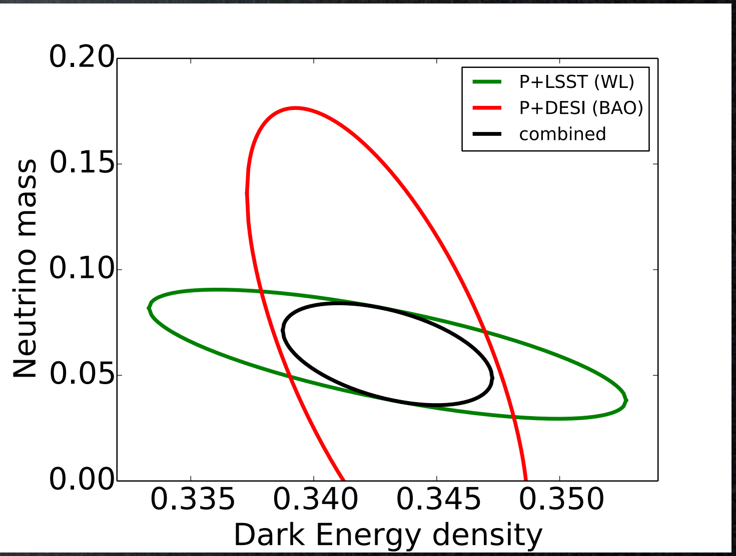
DESI constraints

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)

Complementarity with other surveys

- Complementarity with Weak Lensing surveys (e.g. DESI + DES, HSC, LSST)
  - Tests of gravity: do light and mass respond in the same way?
  - Photo-z calibrations, source of largest sys. error
  - Improved bias modeling, additional galaxy formation science
- Complementarity with SN surveys
  - Wide redshift coverage of BAO overlaps range with best SN errors
  - essentially non-overlapping systematics in distance scale
- Complementarity with CMB surveys
  - Redshift surveys and CMB measure same large-scale structure theory, but in different ways. Combine to produce much stronger constraints on DE, inflation and neutrino masses.





Answering the Big Questions in Cosmology with Big Spectroscopic Surveys

- next generation of spectroscopic surveys will:
  - measure the distance scale to significantly better than 1% over most of the range from z=0-3.5 using BAO, a method with simple physics
  - directly test to better than 1% whether the growth of structure is consistent with the expansion history using redshift space distortions and combinations of clustering and lensing, to distinguish dark energy from modified gravity
  - directly probe the physics of inflation through shape of power spectrum
  - measure or constrain the neutrino mass to < 0.02 eV
- these cosmologically-motivated surveys will also contain 10s of millions of galaxy spectra that are interesting for galaxy formation and AGN physics!

things to keep in mind

- we are moving from a statistics-limited regime to a systematics-limited regime.
- need accuracy, not just precision! lots of hard work to get there.
- cross-checks between various cosmological probes are completely essential.
- our constraints are only as good as our theoretical predictions -- HUGE need for accurate simulations that model realistic galaxy populations as well as survey details
- significantly more information in the data than is being used -- LOTS of room for additional constraining power if we can push theoretical predictions to small scales -- fundamental limit will be our understanding of galaxy formation