DESI: The Dark Energy Spectroscopic Instrument

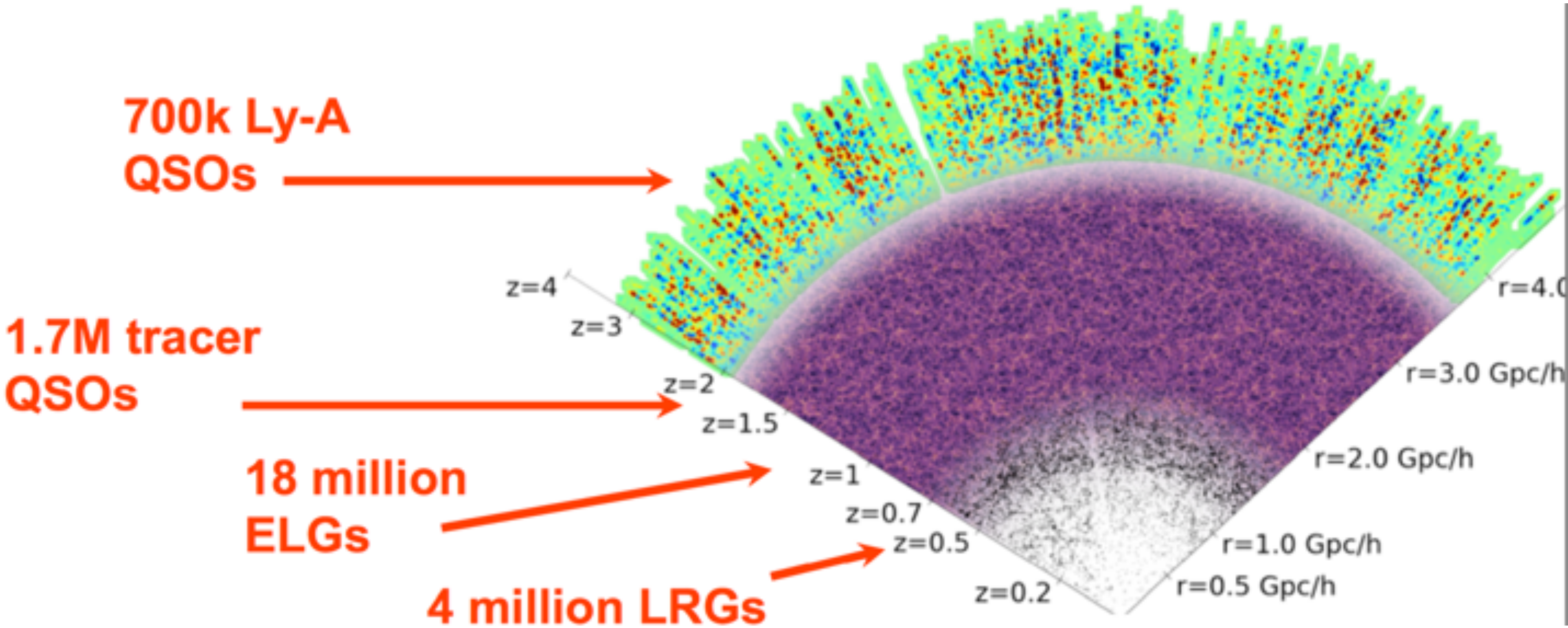
Pat McDonald (LBL)

The Big Goals

- **Answer the ancient questions: How did the Universe begin? What is it made of? What physical laws does it follow?**
- **Learn about the basic contents of the Universe and physical laws by studying the background evolution of the Universe and growth of structure (e.g., dark energy, modified gravity, neutrino masses, dark radiation, certain dark matter properties).**
- **Learn about the early Universe (i.e., inflation) by determining the statistics of the initial perturbations (and maybe curvature).**

DESI Redshift Survey

Four target classes spanning redshifts z=0.4 → 3.5.
~24.5 million redshifts over 14,000 sq. degrees (baseline survey).



DESI Instrument/Collaboration

DESI Timeline

- 2009 BigBOSS proposed
- 2011 DESpec proposal for spectroscopic survey (Fermilab); BigBOSS DOE R&D review
- 2012 DOE issues Mission Need Statement (CD-0) for MS-DESI, DOE Assignment to LBNL as lead lab for MS-DESI, charged to combine the BigBOSS and DESpec collaborations
- 2014 P5 recommends DESI in all but most austere budget scenario
- Just completed successful CD-1 review.

Dark Energy Spectroscopic Instrument

The DESI project will build:

- A 5000 fiber spectrograph
- A corrector to expand field of view to 8 deg^2

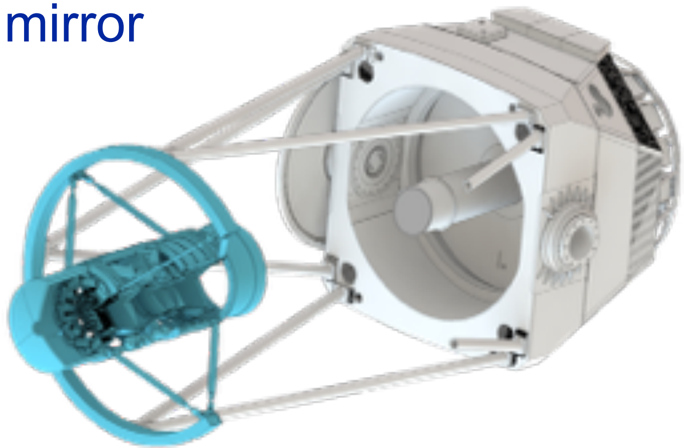
4-m Mayall Telescope on Kitt Peak, AZ

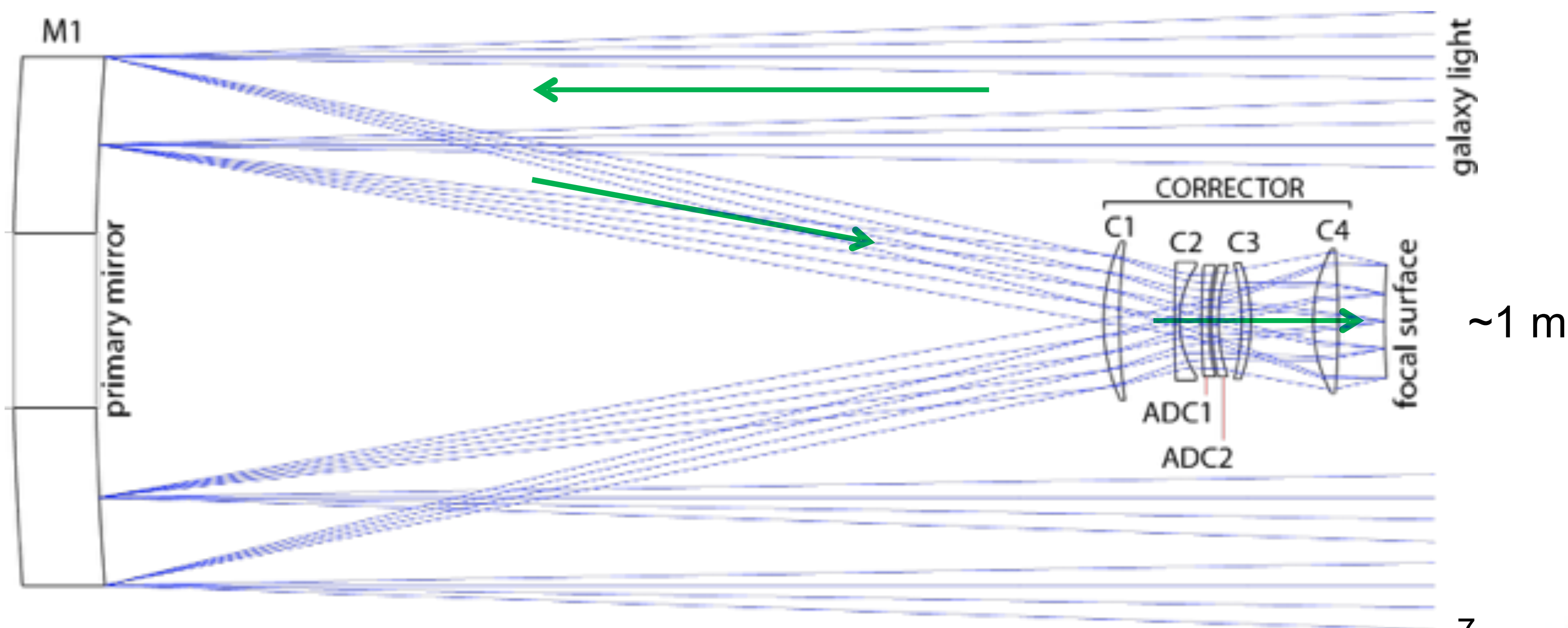
Existing corrector has 0.5 deg.^{2} FoV

(DESI instrument slides drawn from Levi & Bebek CD-1 talks)

Prime Focus Corrector

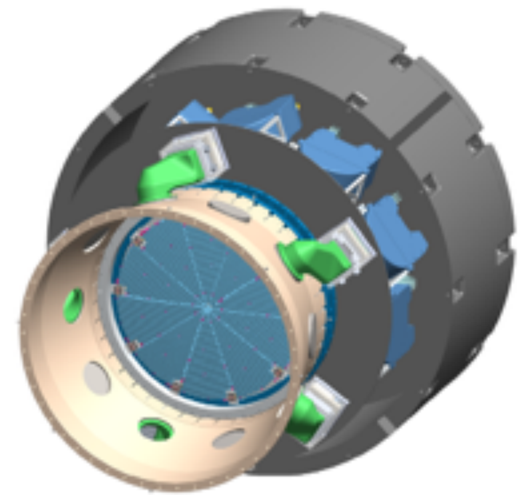
- Collect light from Mayall 4m primary mirror
- Focus on fiber optic tips





Focal Plane System

- Focal plane system
  - Attaches to the back of the corrector barrel
  - Carries the focal plane and support systems
- Petals
  - 10 standalone wedge systems



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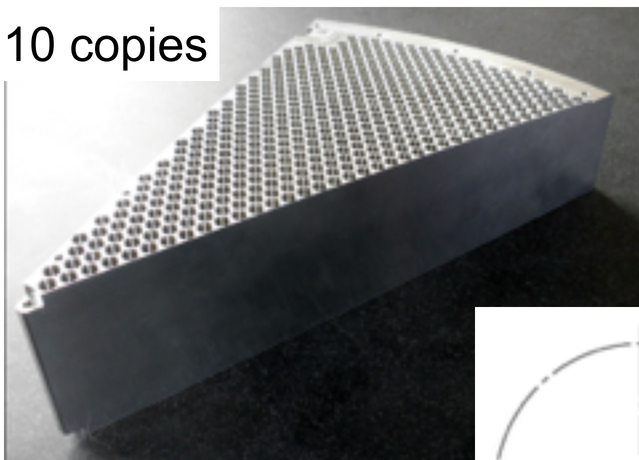
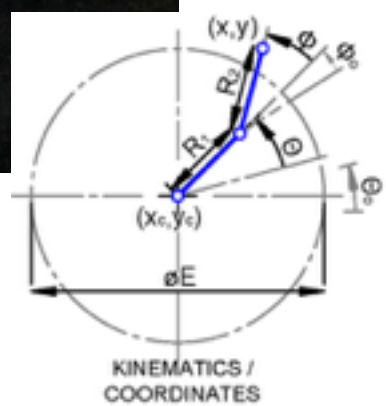
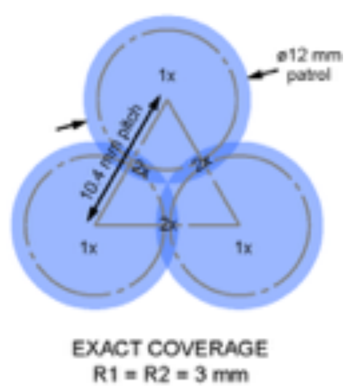


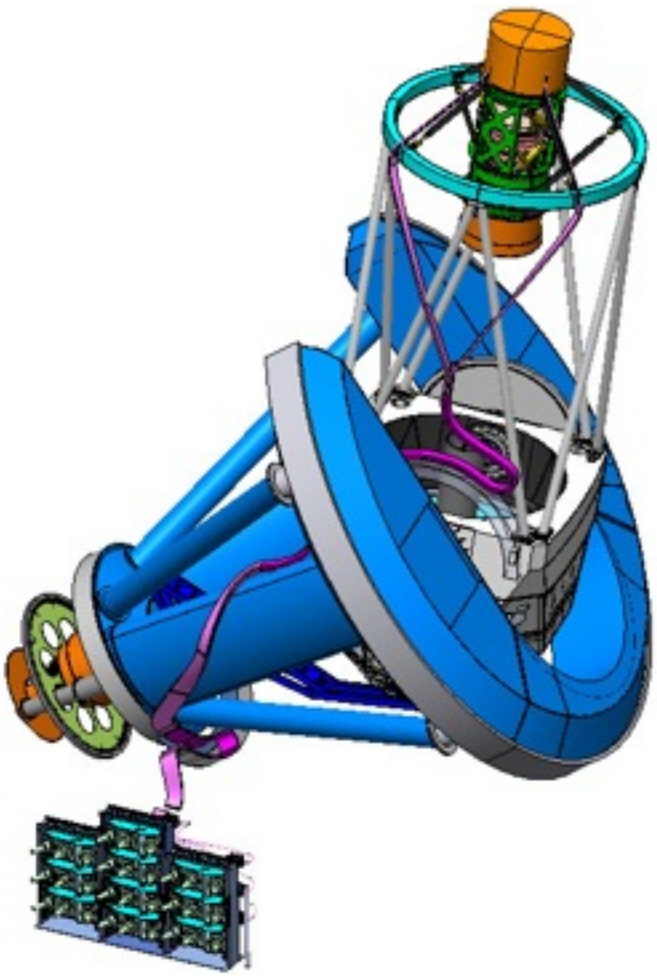
~0.4 m radius



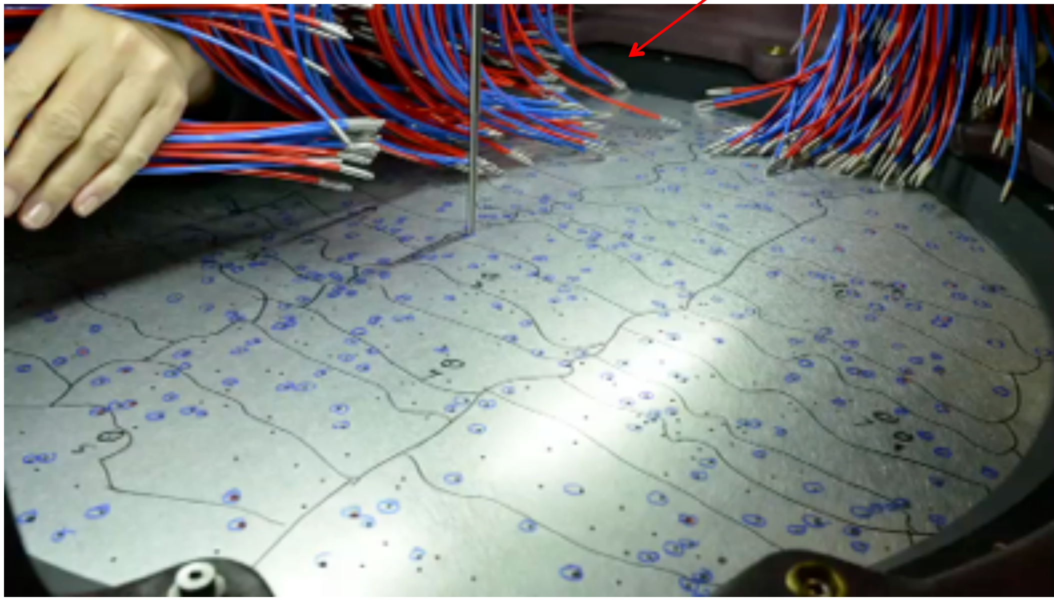


Spectroscopic

The fiber optic system transports the light to
ten 3-arm spectrographs based upon the BOSS design (360-980 nm)

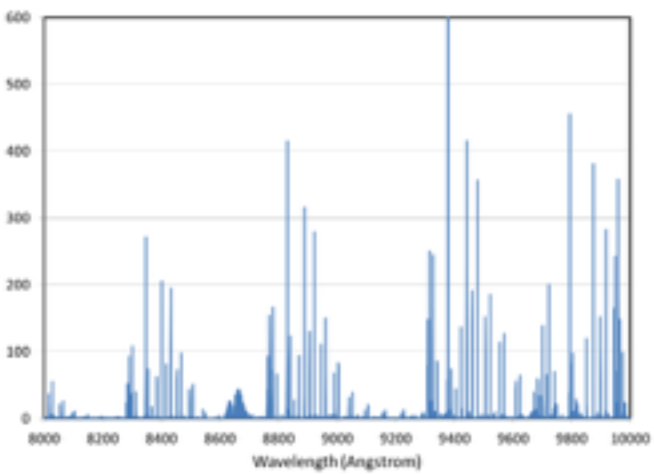


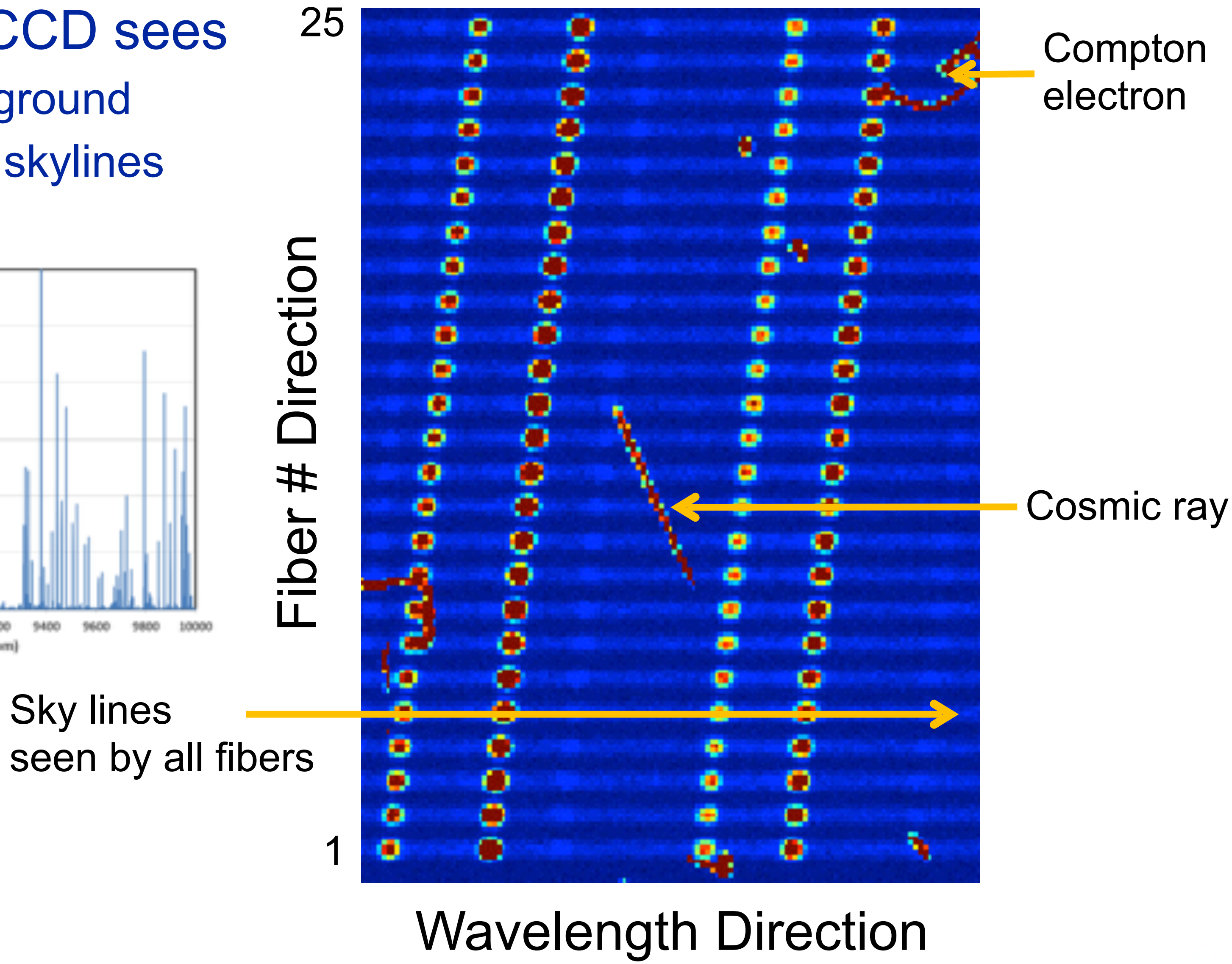
BOSS Experiment
1000 fibers, measured
2M redshifts



Spectra at the CCD

- What the CCD sees
  - Real background
  - Simulated skylines





U.S. Institutions

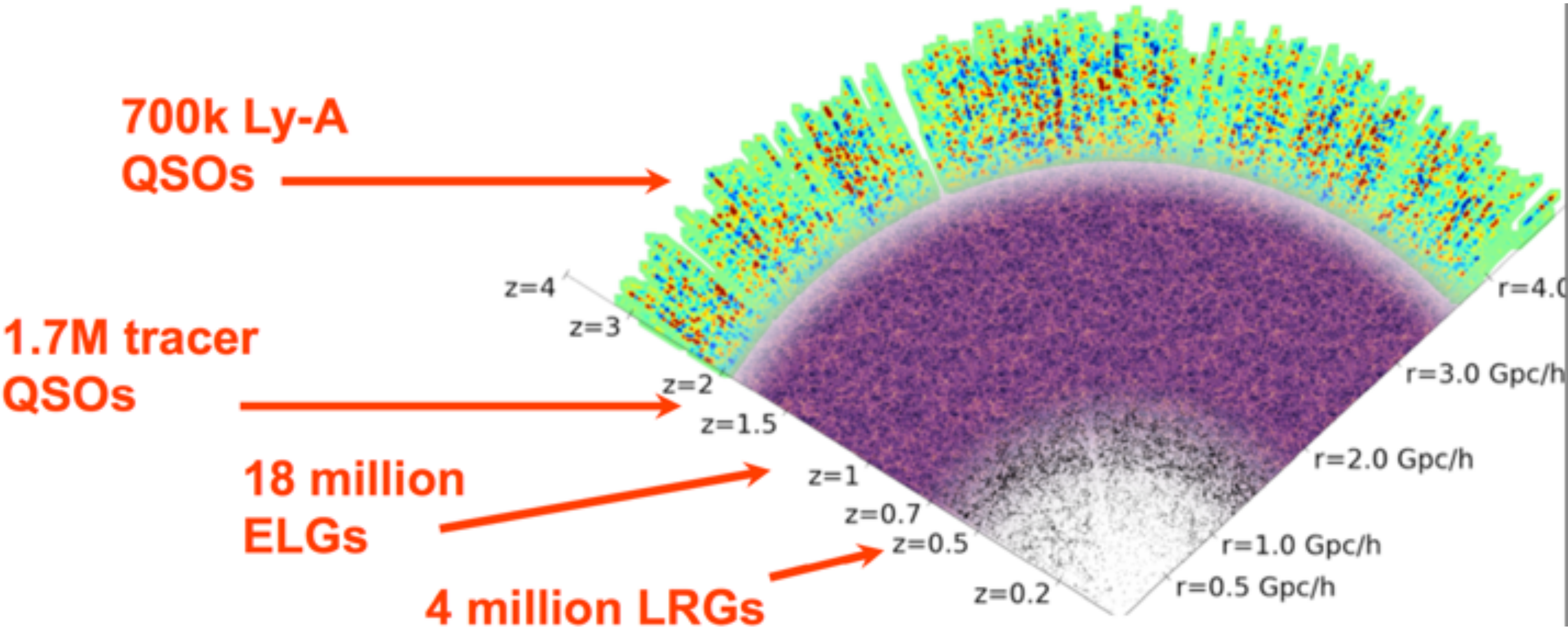
- Argonne National Laboratory
- University of Arizona
- Brookhaven National Laboratory
- University of Calif, Berkeley
- University of Calif, Irvine
- University of Calif, Santa Cruz
- Carnegie Mellon University
- Cornell University
- Fermi National Accelerator Lab
- Harvard University
- University of Kansas
- Kansas State University
- Lawrence Berkeley National Lab
- University of Michigan
- Michigan State University
- National Optical Astronomy Obs.
- New York University
- The Ohio State University
- University of Pittsburgh
- Siena College
- Southern Methodist University
- SLAC National Accelerator Lab
- Texas A&M University
- University of Utah
- Washington University at St. Louis
- University of Wyoming
- Yale University

… 22 US Universities
… 5 DOE Laboratories
… plus 19 foreign institutions
200 collaborators

DESI Survey/Targets

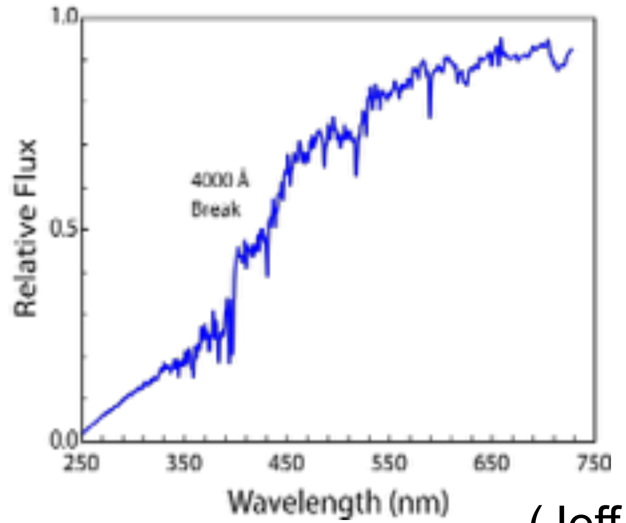
DESI LSS Survey

Four target classes spanning redshifts z=0.4 → 3.5.
~24.5 million redshifts over 14,000 sq. degrees in 5 years (2019-2024)
(~1/3 of sky - largest feasible footprint is 15,300 deg^2)

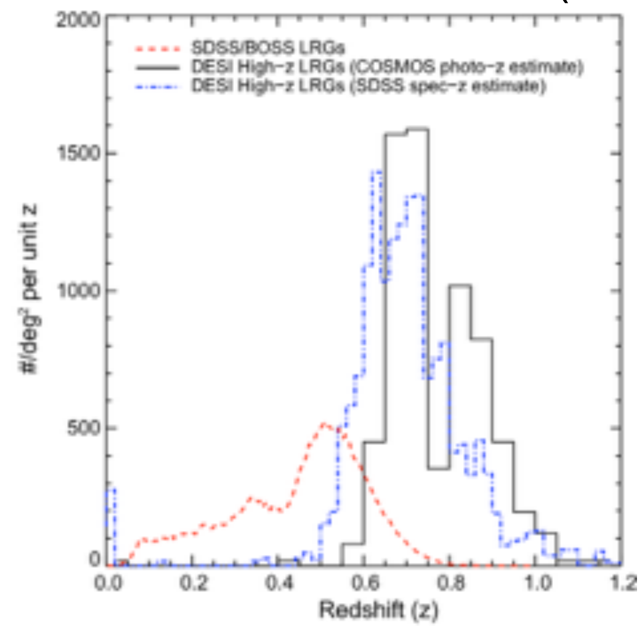


Luminous Red Galaxies

- **LRGs = Luminous Red Galaxies: massive, passively-evolving, high-bias early-type galaxies**
- **4000Å break helps select low-z LRGs and provides redshifts**
- **Workhorses of SDSS/ BOSS**
- **4 million in DESI**

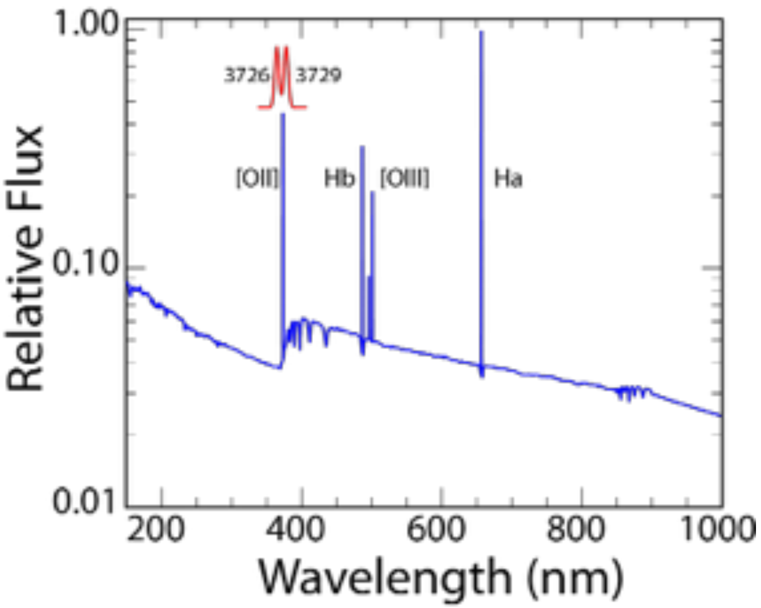


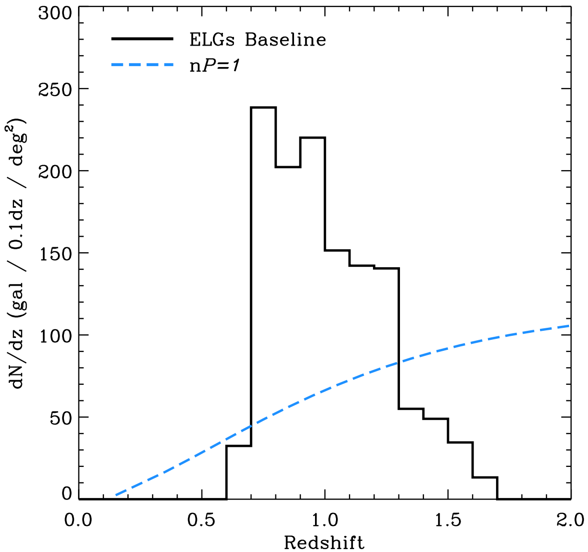
(Jeff Newman)



Emission-line Galaxies (ELGs)

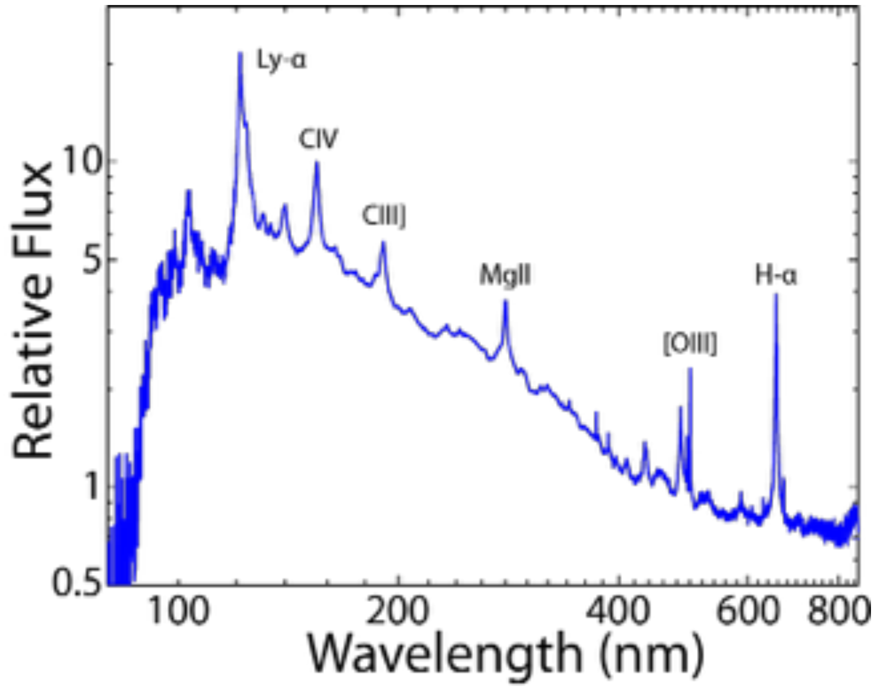
- At high redshifts, quiescent galaxies are rare - Universe's SFR ~10x higher at z=1: drives strong emission lines
- DESI will resolve the [OII] 3727 Å doublet at 0.1<z<1.6: provides a secure redshift from a single feature
- 18 million in DESI
- lower bias than LRGs

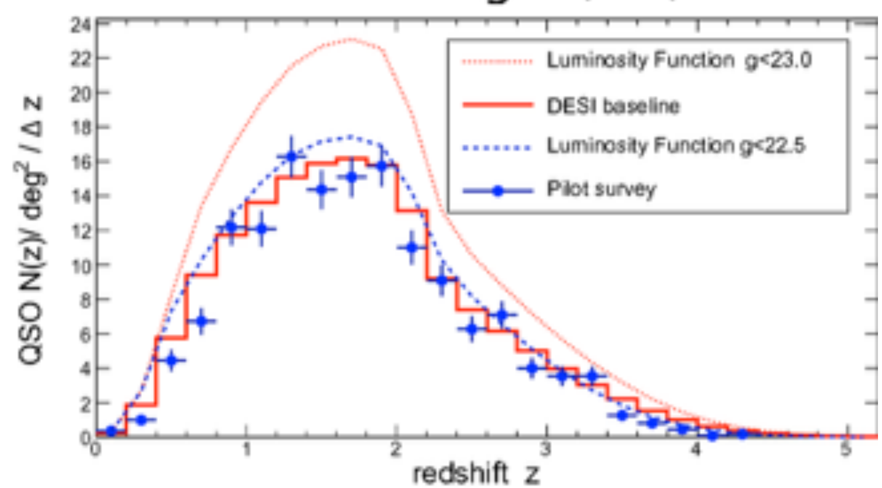




2 QSO Samples: tracers (direct BAO) and Ly-α

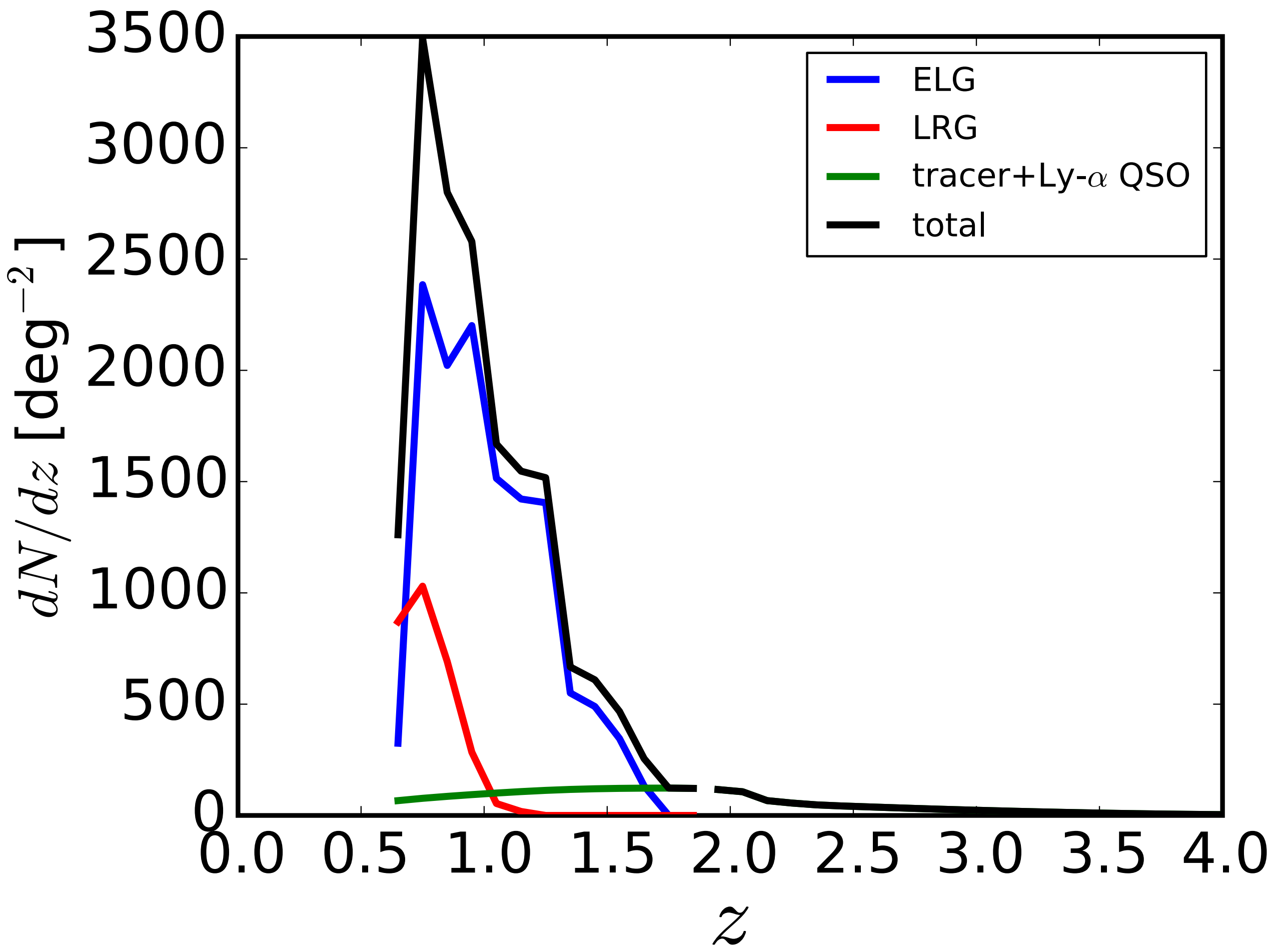
- **QSOs exhibit many emission lines, can obtain secure redshifts even at *z*>1.6**
- **1.7/0.7 million**
- **For *z* > 2.1, can detect Ly-α; cosmological constraints will improve with S/N**
  - **Observe confirmed high-z QSOs up to 4 times**





DESI number densities

- **Number density sets the noise level in an LSS measurement**



LSS Theory

Basics of LSS

- **Density fluctuations of all kinds are described as fluctuations around the field's mean:** $\delta(\mathbf{x}) = \frac{\rho(\mathbf{x}) - \bar{\rho}}{\bar{\rho}}$
- **Fourier transform to obtain the power spectrum quantifying field correlations:** $P(\mathbf{k}) \propto \left\langle \left|\delta_{\mathbf{k}}\right|^2 \right\rangle \qquad k = \frac{2\pi}{\lambda}$
- **On large scales, everything (galaxies, quasars, gas, etc.) traces the mass density power spectrum. The fluctuations are small on very large scales, so the relation between a tracer and mass can be described by a Taylor series, generally called the linear bias model** $\delta_{gi} = b_i \ \delta_m + \epsilon_i + \ldots$
- **(see McDonald & Roy 2009 for a relatively rigorous derivation - this assumes Gaussian initial fluctuations and scale-independent linear growth (e.g., GR+CDM))**

Power spectrum elements

- **The initial spectrum from inflation is close to a power law**

$$P_{\text{inflation}}(k) = A \left(\frac{k}{k_\star}\right)^{n_s + \frac{1}{2}\alpha_s \ln\left(\frac{k}{k_\star}\right) + \ldots}$$

- **This is modified by linear evolution once the modes enter the horizon. The transfer function contains information about dark energy, the matter/radiation ratio, neutrinos, etc.** $P_{\text{mass}}(k,z) = T^2(k,z)P_{\text{inflation}}(k)$
- **At late times, for cold dark matter and GR, the linear growth is scale independent so we often write**

$$P_{\text{mass}}(k,z) = D^2(z)P_{\text{mass}}(k)$$

- **In the linear regime, the power spectrum of a pair of tracers is now (dropping redshift dependence)**

$$P_{ij}(k,\mu) = (b_i + f\mu^2)(b_j + f\mu^2)P_m(k) + \delta^K_{ij}\bar{n}_i^{-1} \qquad \mu = \frac{k_\parallel}{k}$$

- **where** $f(z) = \frac{d\ln D}{d\ln a} \simeq \Omega_m^{0.556}(z)$ **and the noise power is set by the mean number density of the galaxies, i.e.,** $N_i \simeq \bar{n}_i^{-1}$

Observable (linear) power

- **The redshift-space distortions come about, along with geometric distortions, because we can only measure angles and redshifts, not comoving distances, i.e.,**

$$\frac{c\,\Delta\lambda}{\lambda} \simeq \frac{H(z)}{1+z}\Delta x_{\parallel} + \Delta v_{\parallel} \longleftarrow \text{peculiar velocity}$$

observed redshift — radial comoving separation

- **and**

angular separation $\rightarrow \Delta\theta = \dfrac{\Delta x_{\perp}}{(1+z)D_A(z)}$ $\longleftarrow$ transverse comoving separation

- **The Hubble parameter H(z) and angular diameter distance D_A(z) are sensitive to cosmological parameters, e.g., dark energy, as is the linear perturbation growth factor D(z).**

Baryon Acoustic Oscillations

- **Sound waves in the early Universe produce a peak in the clustering of matter at late times. This peak serves as a standard ruler.**
- **Sound speed before decoupling**

$$c_s^2(a) = \frac{\partial p}{\partial \rho} = \frac{c^2}{3}\left(1 + \frac{3\rho_b}{4\rho_\gamma}\right)^{-1}$$

- **Comoving sound horizon**

$$s(a) = \int_0^t \frac{c_s(t')}{a(t')} dt' = \int_0^a \frac{c_s(a')}{a'^2 H(a')} da'$$

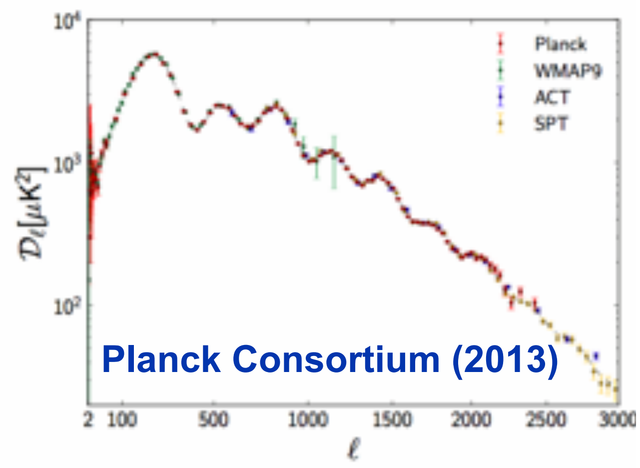
- **matter density from CMB**

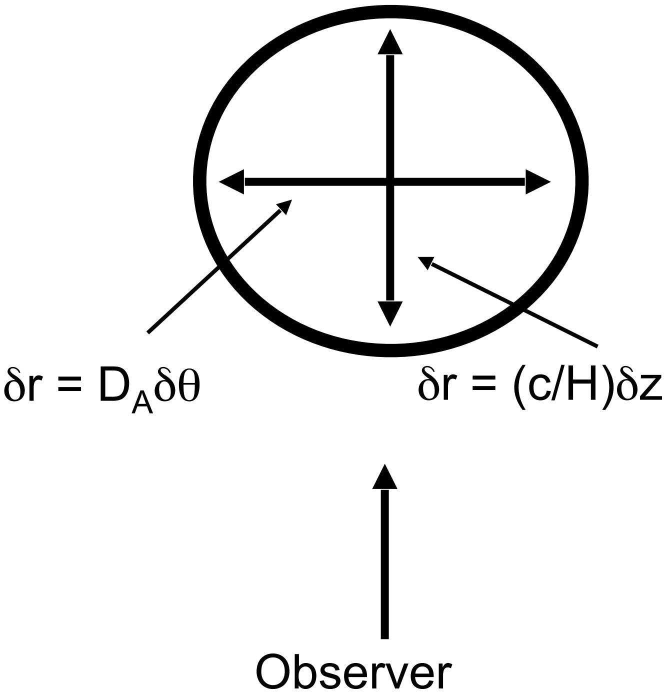
$$H(a) = (H_0/h)[\Omega_m h^2 (1+z)^3 + \Omega_r h^2 (1+z)^4]^{1/2}$$

(movie by Daniel Eisenstein using CMBFast from Seljak & Zaldarriaga)

Using the Standard Ruler

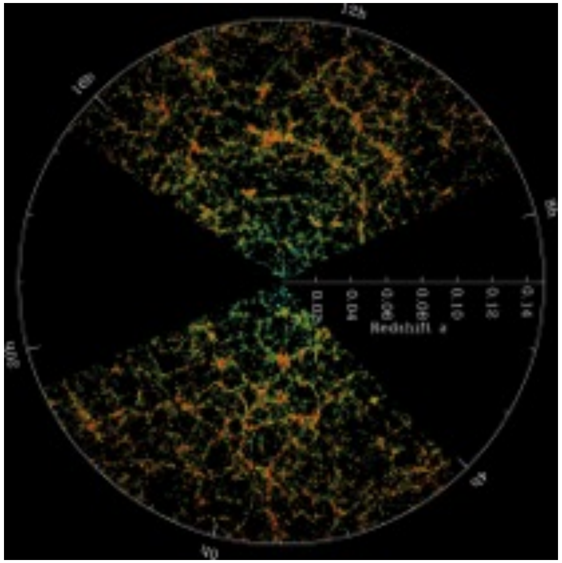
- **The acoustic oscillation scale depends on the sound speed and the propagation time.**
  - **These depend on the matter-to-radiation ratio ($\Omega_m h^2$) and the baryon-to-photon ratio ($\Omega_b h^2$).**
- **The CMB anisotropies measure these and fix the oscillation scale to <0.4%.**
- **In a redshift survey, we can measure this along and across the line of sight.**
- **Yields $H(z)$ and $D_A(z)$!**





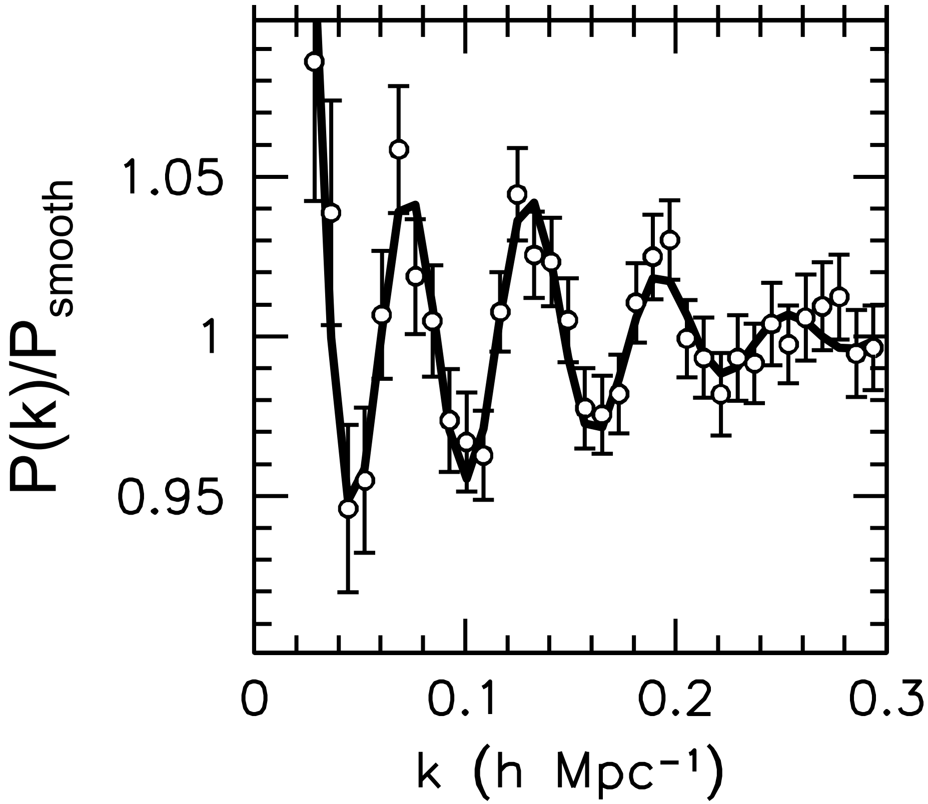
Observing the BAO

- **Study of observational systematic errors in the clustering analysis of galaxy surveys is an old topic.**
  - **Extensive work over the last several decades, with many methods for diagnosing, removing, and avoiding systematic effects.**
- **The BAO application is much easier than general P(k) because the BAO signature is oscillatory and hence strongly differential in scale.**
  - **Observational effects are nearly always broadband, and we simply marginalize against general broadband terms.**
- **Length scale is tied directly to measurement of angles and redshifts, which are much better than 10^{-3}.**



BOSS BAO

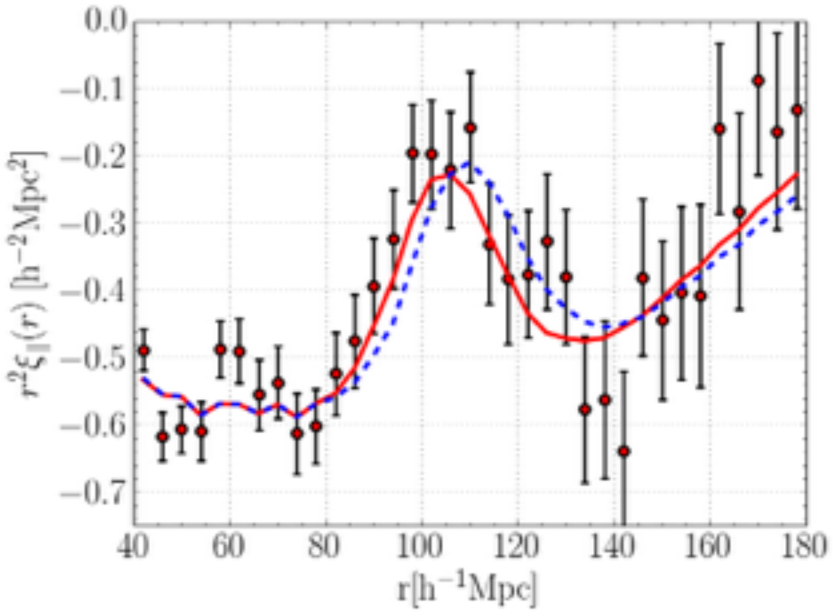
BOSS DR11
CMASS galaxies
z=0.57



Anderson et al. (2014)

BOSS DR11
LyaF, z=2.34

~Radial correlation

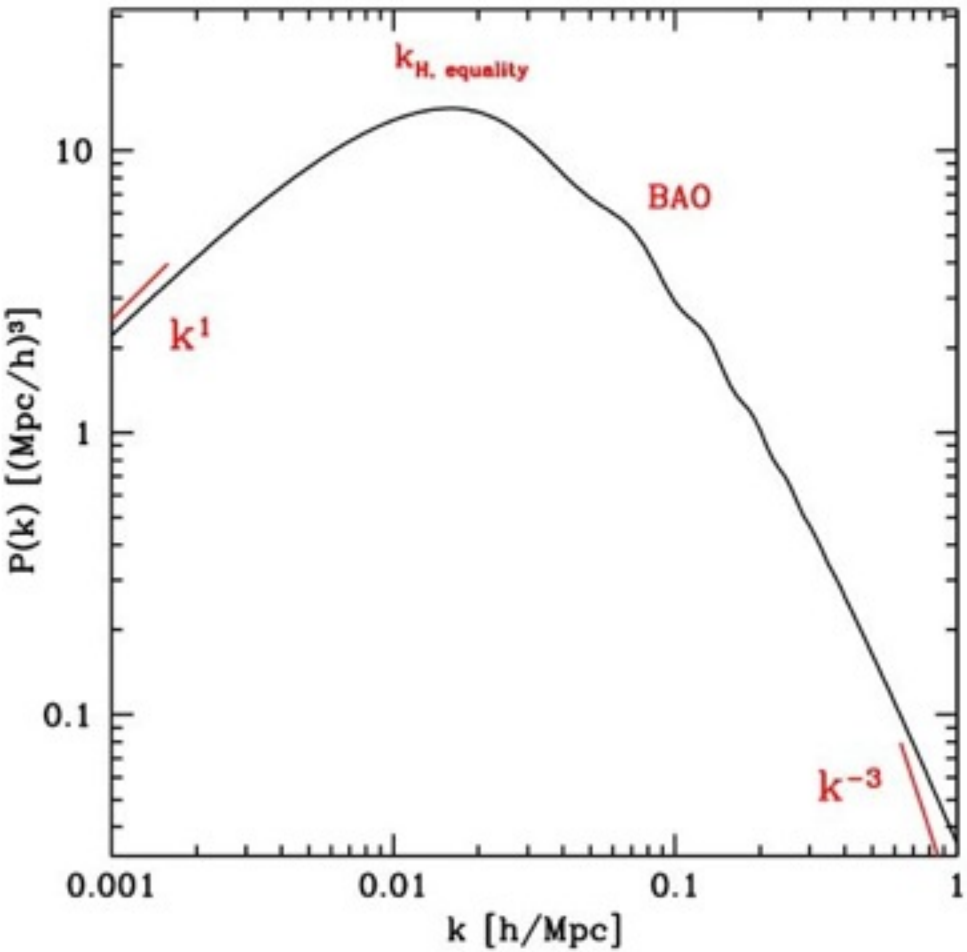


Delubac et al. (2014)

Beyond BAO: Precision RSD/Broadband

- Neutrino mass and inflation constraints are dominated by RSD/broadband, not just BAO (and Dark Energy constraints can be dramatically improved).
- The BAO scale happens to be similar to the non-linear scale, so a survey optimized for BAO will be more or less optimized for RSD or anything else where the information is dominated by the smallest scales you can model.
- DESI will definitely make RSD/broadband measurements, but there is some uncertainty about how well we will be able to model the perturbatively non-linear regime, which we estimate by quoting results for k_max = 0.1 or 0.2 h/Mpc.

Linear theory mass power spectrum



Basic ways to use LSS to study physics:

- Reconstruct the initial conditions that led to observed structure.
- Use features in the structure as rulers to measure the geometry of the Universe.
- Measure the dynamics of the growth of structure, i.e., the rate of growth of density and velocity perturbations.

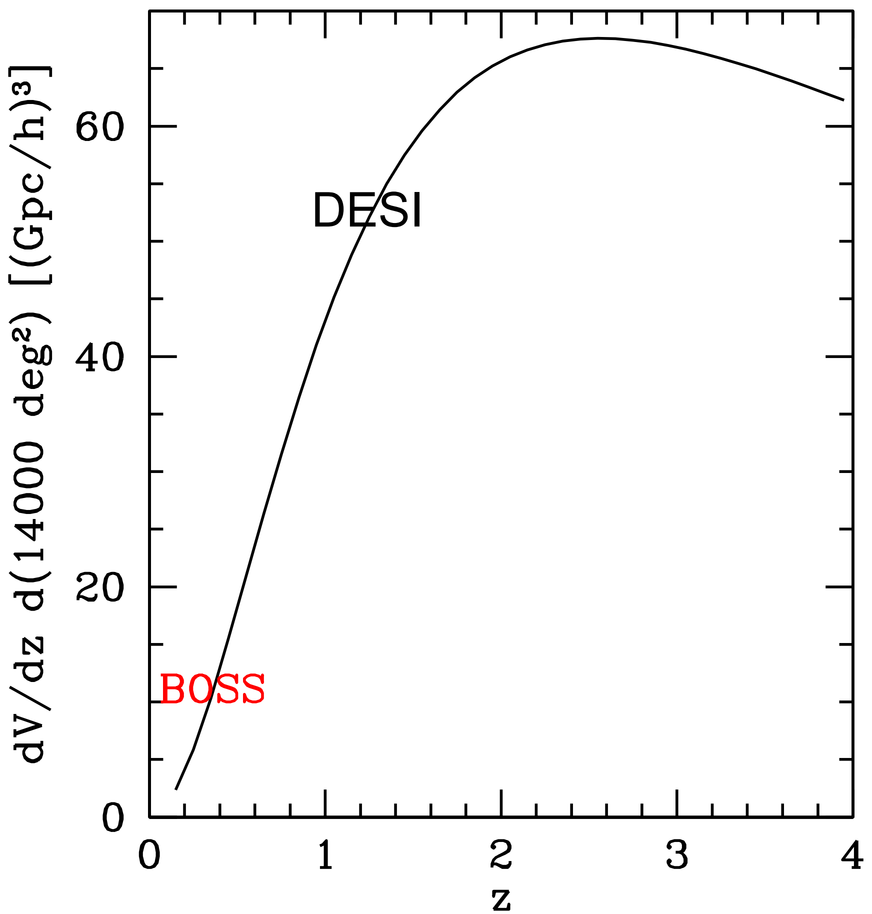
DESI Projections

Forecasts and FoM

- Forecasts involve computing the expected power spectrum errors as a function of redshift and wavevector, based on the volume and densities in the survey, then use Fisher matrices to map the errors on the power spectra to constraints on cosmological parameters.
- We produce forecasts for the BAO distance scale and propagate these to cosmological parameters, or go directly to cosmological parameters for broadband constraints.
- Dark Energy parameter constraints allow us to compute the DETF Figure of Merit.

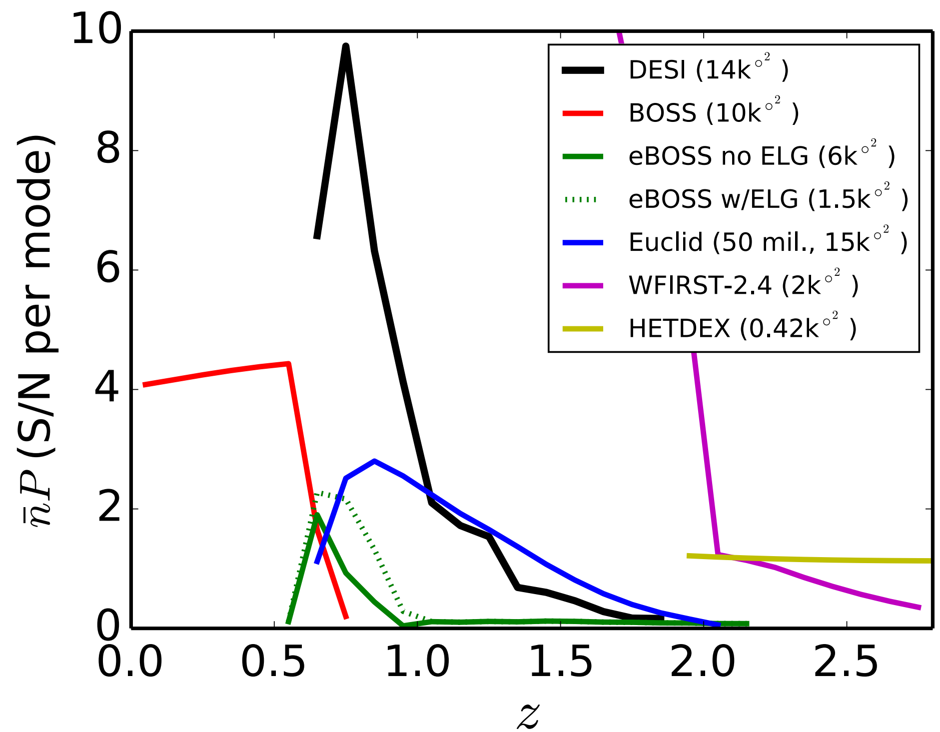
LSS all about mapping volume

$$\left(\frac{\sigma_{P_S}}{P_S}\right)^2 \simeq \frac{4\pi^2}{Vk^2\Delta k\Delta\mu}\left[1+\frac{1}{\bar{n}P_S\left(k,\mu\right)}\right]^2$$



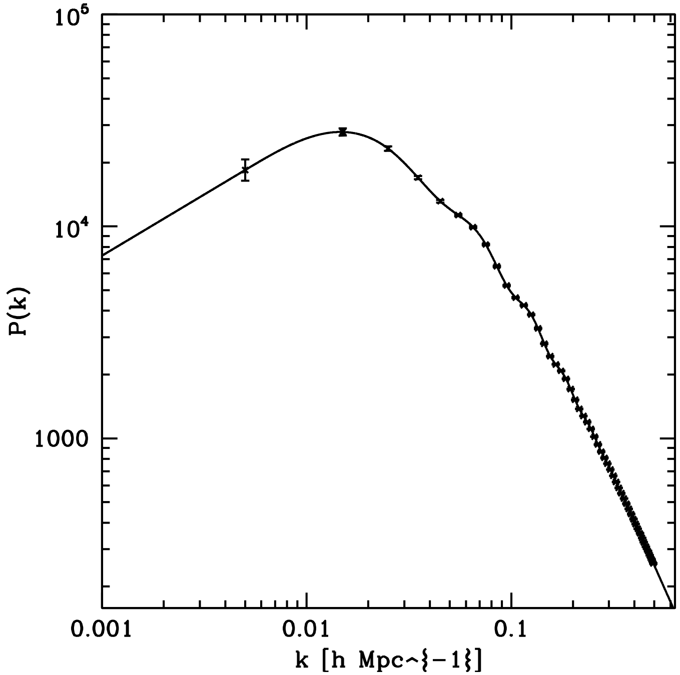
Shot Noise and Sample Variance

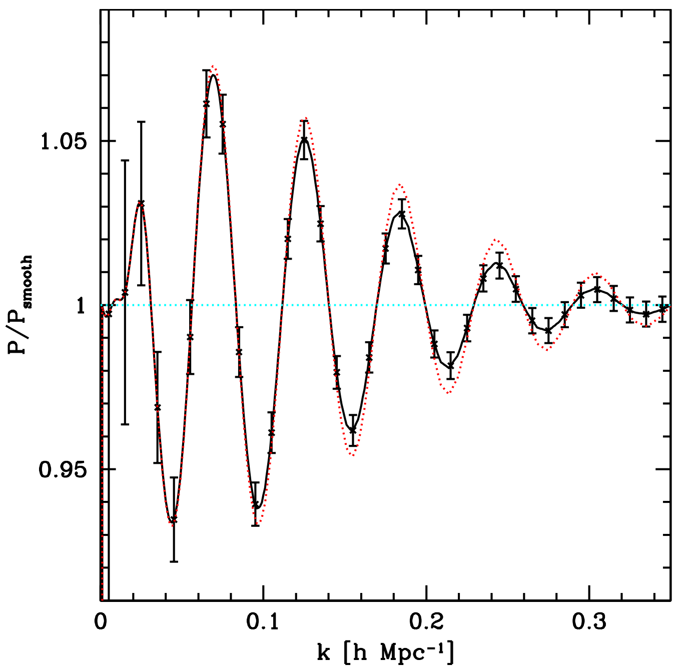
- The ability to measure the power at a given wavevector of the density field is limited by shot noise and sample variance.
- Balance of these is encoded by the product *nP*(k,μ).
  - — We choose *k*=0.14 Mpc/*h*, μ=0.6 as a proxy for BAO performance.
- DESI has *nP*>1 out to *z*~1.3, which means that it is making a map with S/N>1 per mode.
- Large volume at *z*>1.3 still provides good BAO measurements, but not approaching the cosmic variance limit.



$$\left(\frac{\sigma_{P_S}}{P_S}\right)^2 \simeq \frac{4\pi^2}{Vk^2\Delta k\Delta\mu}\left[1+\frac{1}{\bar{n}P_S\left(k,\mu\right)}\right]^2$$

Very precise power measurement



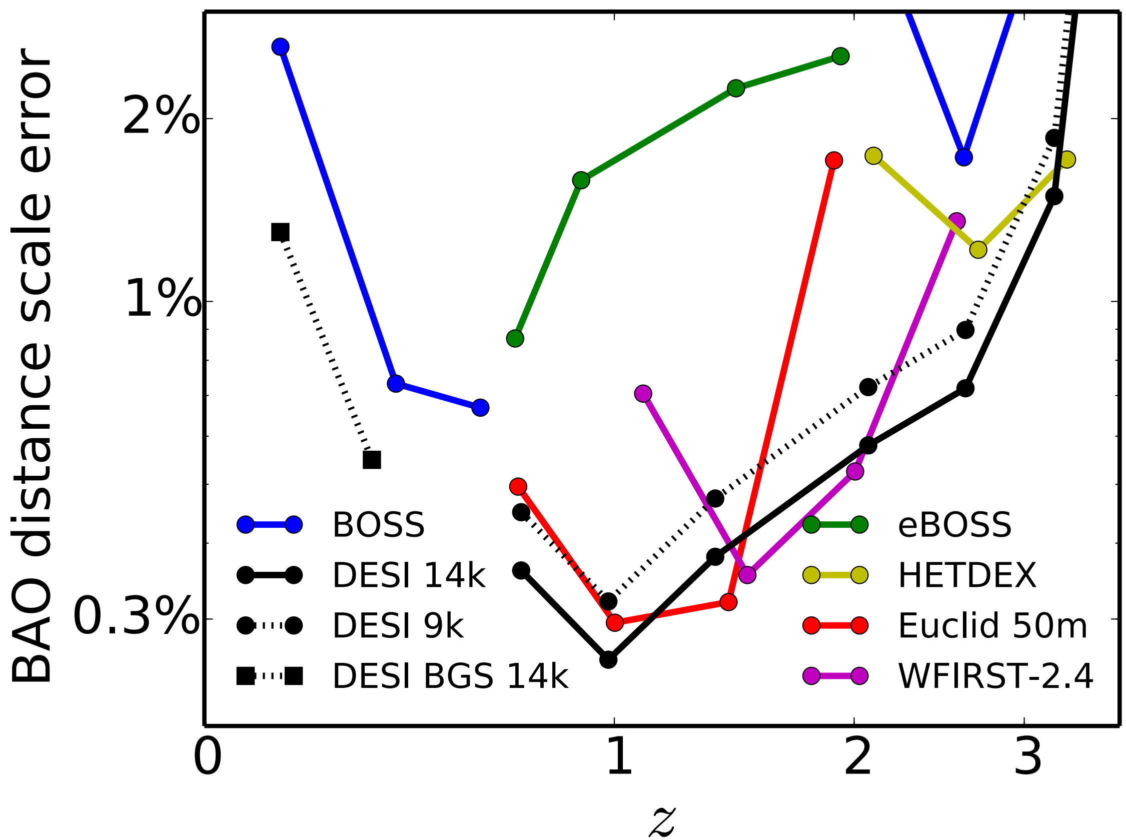


- **Example z=0.5-0.9 measurement.**
- **The position of the BAO wiggles is the standard ruler we use to measure distance scale**
- **"Broadband" refers to using the full, angle-dependent power spectrum**

$$P(k) \propto \left\langle |\delta_{\mathbf{k}}|^2 \right\rangle \propto \mathrm{FT}\left[\langle \delta(\mathbf{x})\delta(\mathbf{x}+\mathbf{r})\rangle\right]$$

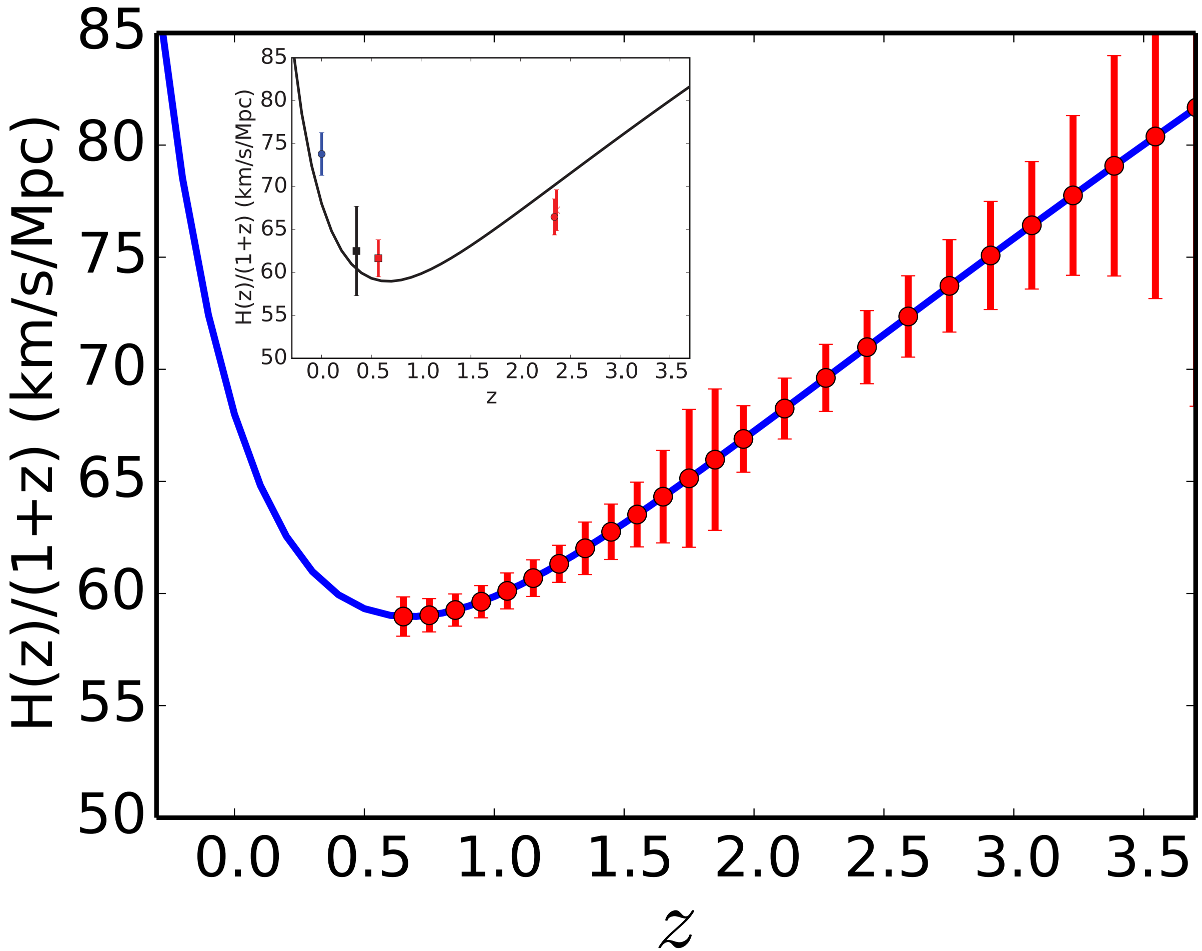
BAO distance errors

- **DESI produces BAO distance errors that are sharply better than Stage III experiments.**
- **Highly competitive with Euclid and covering a wider redshift range because of the Lyα forest.**



Hubble Parameter

- Enormous improvement on the ability to measure H(z).
- At high redshift, H(z) is more direct route to dark energy.

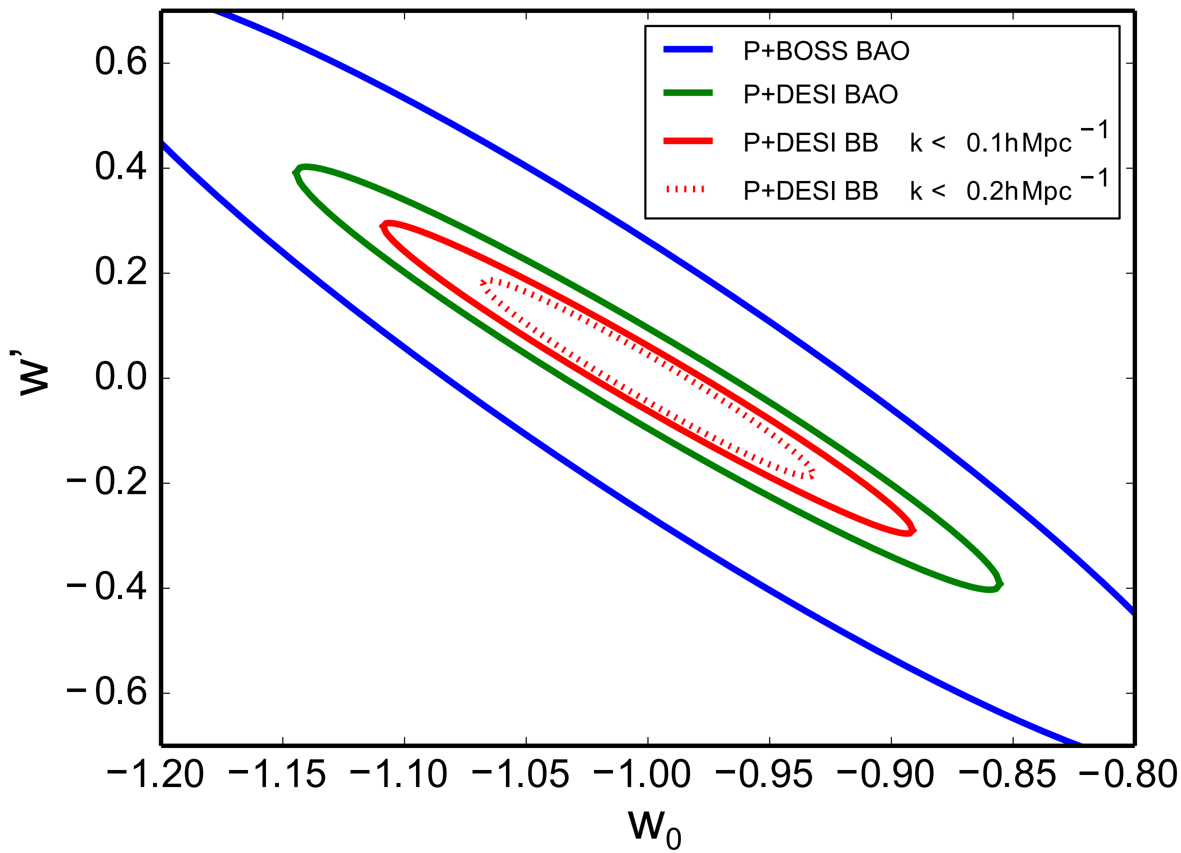


Measuring Dark Energy Properties

$$\frac{\ddot{a}}{a} = \frac{\Lambda}{3} - \frac{4\pi G_N}{3}(\rho + 3p)\,, \qquad w = p/\rho$$

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

- **DETF Figure of Merit (FoM) is defined to be the inverse area of these contours (marginalized over other parameters including curvature)**



Figures of Merit

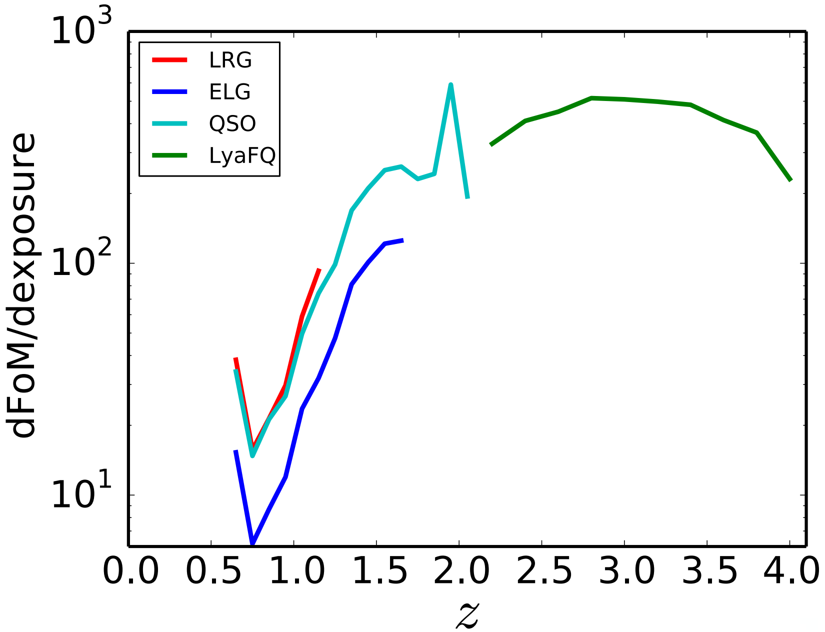
- **We then compute DETF Figures of Merit for various cases.**
  - **Planck + DESI BAO (with and without Lya Forest, 14k)**
  - **Then add broadband galaxy clustering information, which further constrains the distance scale from the Alcock-Paczynski effect. This makes a substantial difference, but is more model dependent.**
- **No information from SNe or WL/Cluster experiments!**

Surveys	FoM	a_p	σ_{w_p}	σ_{Ω_k}
BOSS BAO	37	0.65	0.055	0.0026
DESI 14k galaxy BAO	112	0.72	0.025	0.0013
DESI 14k galaxy and Ly-α forest BAO	$\boxed{143}$	0.74	0.024	0.0011
DESI 14k BAO + gal. broadband to $k < 0.1\ h\ Mpc^{-1}$	303	0.75	0.016	0.0009
DESI 14k BAO + gal. broadband to $k < 0.2\ h\ Mpc^{-1}$	$\boxed{687}$	0.74	0.011	0.0007

(P+LSST Lensing ~221)

Survey Design Trades

- We have considered a range of survey designs.
- The FoM can give some weighting of statistical errors.
  - — Beware that it gives no weight to redundancy of maps, even though that is a valuable systematic test, nor does it include other mitigations of systematics.
  - — Nor any value to non-BAO science, although the large-scale RSD relies on similar wavenumbers to BAO work and hence would scale similarly.
- Basic lessons:
  - — Wider survey area is better.
  - — Better to trade low-redshift targets (*nP*>1) for high-redshift targets (*nP*<1).
  - — LyaF fibers are the most important (per fiber!); low-redshift ELG fibers are the least important.



Optimization & Robustness

- **FoM optimization drove short+long wavelength throughput**
  - **Throughput in the far blue + red more valuable in FoM, i.e. grating choices should optimize near 450 and 900 nm**

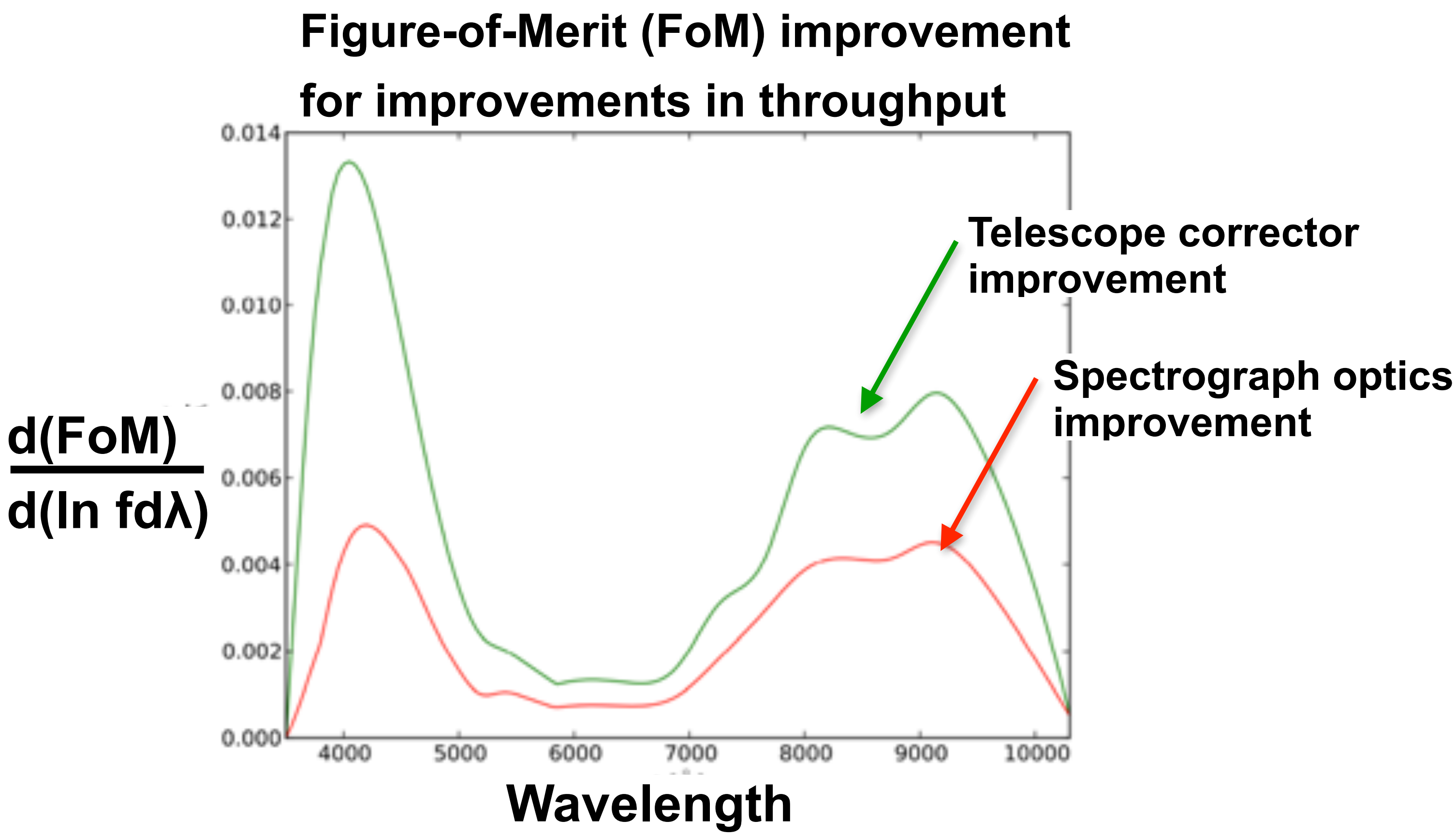
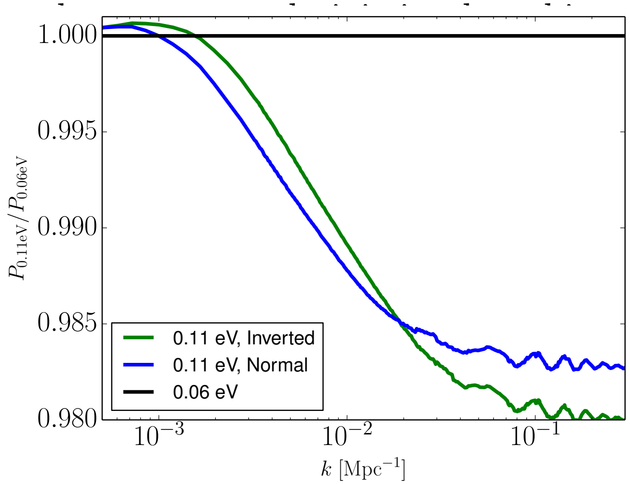
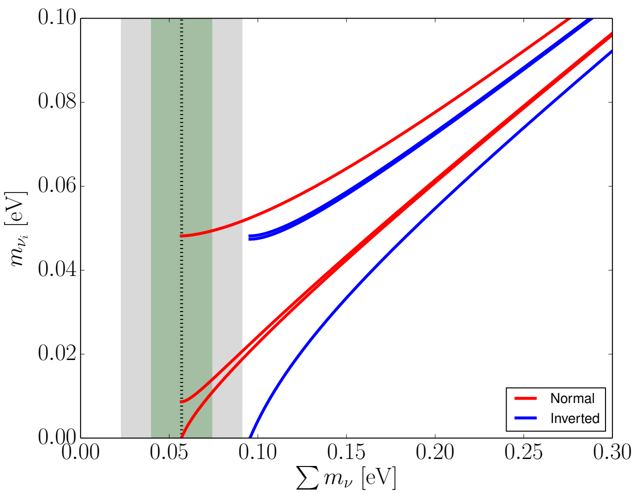


FIG. 2. $\frac{dFoM}{d\ln f d\lambda}$ where $d\lambda$ here is intended to mean that you could integrate it over λ. This is using

Neutrino mass

$$v_{\rm rms} \simeq 3173\,(1+z)\,(0.057\,{\rm eV}/m_\nu)\ {\rm km\ s^{-1}}$$





Experiments (+Planck)	$\sigma_{\Sigma m_\nu}$
DESI BAO	0.09 eV
DESI broadband $k \lesssim 0.1\ h{\rm Mpc}^{-1}$	0.024 eV
LSST	0.020 eV
DESI broadband $k \lesssim 0.2$	0.017 eV
BOSS+Euclid broadband $k \lesssim 0.2$	0.015 eV
BOSS+WFIRST broadband $k \lesssim 0.2$	0.021 eV
LSST+DESI broadband $k \lesssim 0.2$	0.014 eV

- Terrestrial experiments measure differences of mass squared, not overall sum, but set minimum at 0.06 eV for normal hierarchy or 0.1 for inverted.

$$\Delta m^2_{21} = 7.50 \pm 0.20 \times 10^{-5}\ {\rm eV}^2 \qquad \Delta m^2_{32} = 2.32^{+0.12}_{-0.08} \times 10^{-3}\ {\rm eV}^2$$

Beyond Dark Energy: Inflation

- **DESI can probe the primordial perturbations from inflation.**
- **Strong constraints on tilt and running of the spectral index of the primordial spectrum and on non-Gaussianity.**
- **These applications do require more systematic control of the clustering pattern: modeling on small-scales, observational systematics on the very largest scales.**
- **DESI will provide a 3-d view of the density perturbations to complement our view from the CMB.**

Data	σ_{n_s}	σ_{α_s}
Gal ($k_{max} = 0.1$ h^{-1}Mpc)	0.0024 (1.6)	0.0051 (1.1)
Gal ($k_{max} = 0.2$ 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 ($k_{max} = 0.2$)	0.0019 (2.0)	0.0020 (2.7)

Improvement over Planck

Inflationary non-Gaussianity

- Local model

$$\Phi = \phi + f_{\rm NL}\left(\phi^2 - \langle\phi^2\rangle\right) + ...$$

- Planck ~+-5
- Power spectrum only.
- Can do a factor ~2 better with bispectrum? (Sefusatti et al. 2009)

Survey	$\sigma_{f_{\rm NL}}$
BOSS	23
BOSS+eBOSS	11
DESI	3.8
BOSS+Euclid	6.7

Constraining Dark Radiation

- **Constraints on extra relativistic energy density (conventionally measured in units of effective massless neutrino species) can be improved significantly over Planck with either optimistic galaxy modeling or LyaF broadband.**

Scenario	σ_{N_ν}
Planck	0.18
P+ broadband galaxies $k_{\rm max,eff} = 0.1\ h{\rm Mpc}^{-1}$	0.13
+ broadband/1D Lyα forest	~ 0.070
P+ broadband galaxies $k_{\rm max,eff} = 0.2\ h{\rm Mpc}^{-1}$	0.084
+ broadband/1D Lyα forest	~ 0.063

Modified Gravity

$$f(z) = \frac{d\ln D}{d\ln a} \simeq \Omega_m^\gamma(z)$$

- GR $\gamma = 0.556$
- Require perturbations by definition - no BAO only.
- Lensing good for G_9, redshift-space distortions (RSD) for gamma.
- RSD and lensing very complementary.

multiplicative offset G_9 relative to the GR-predicted amplitude at $z = 9$

Experiments (+Planck)	$\sigma_{\Delta\gamma}$	σ_{G_9}
DESI broadband $k \lesssim 0.1\ h\mathrm{Mpc}^{-1}$	0.039	0.033
LSST	0.056	0.017
DESI broadband $k \lesssim 0.2$	0.025	0.030
BOSS+Euclid broadband $k \lesssim 0.2$	0.037	0.028
BOSS+WFIRST broadband $k \lesssim 0.2$	0.050	0.042
LSST+DESI broadband $k \lesssim 0.2$	0.018	0.011

Beyond power spectrum statistics

- In all of these calculations, both for galaxies and LyaF, we have used power spectrum information only. Generally, we can use additional statistics, e.g., the bispectrum, to add constraining power and consistency checks. Basically, the more statistics we can measure, the less degenerate interesting cosmological parameters and systematics/nuisance parameters will become. In the era of very high precision measurements, I think that measuring a rich set of statistics to compare to theory will be critical to the reliability of results.

Summary

- The DESI redshift survey will be ~10 times larger than BOSS, making a continuous map out to z~3.5.
- DESI will improve the Dark Energy Task Force FoM by a factor of 3-4 over Stage III BAO (BOSS) using the BAO distance scale alone, and a factor ~10 using broadband information.
- The effect of neutrino masses will be detected, with the sum constrained to ~0.02 eV using galaxy broadband measurements.
- The inflationary parameters n_s and alpha_s will each be constrained to ~0.002 led by galaxy and LyaF broadband measurements, respectively, and curvature to ~0.001.
- Many other constraints, e.g., on non-Gaussianity, modified gravity, dark radiation, etc. will be obtained.

Bright Galaxy Survey

- DESI Science Consortium is designing a survey of bright galaxies to pursue when moon or other observing conditions are too poor to conduct Key Project observations.
- A survey of 10M bright ($r<19.5$) galaxies over 14k-20k square degrees would have considerable cosmological reach, complementing the Key Project.
  - Improve $z<0.4$ BAO to better than 1%. FoM increases from 143 to 176-194 (depending on BGS area). 23-36% gain!
  - Measure the amplitude/growth of structure at low redshift, where dark energy dominates.
    - Multi-tracer RSD, Cluster/group counts, WL cross-correlations.
  - Many 10k of host galaxy redshifts of SN Ia over the next decade.
  - High sampling density for detailed environment studies and smaller scale modified gravity tests.

Super-DESI