



The Dark Energy Spectroscopic Instrument (DESI) and Survey

Brenna Flaugher

Fermilab

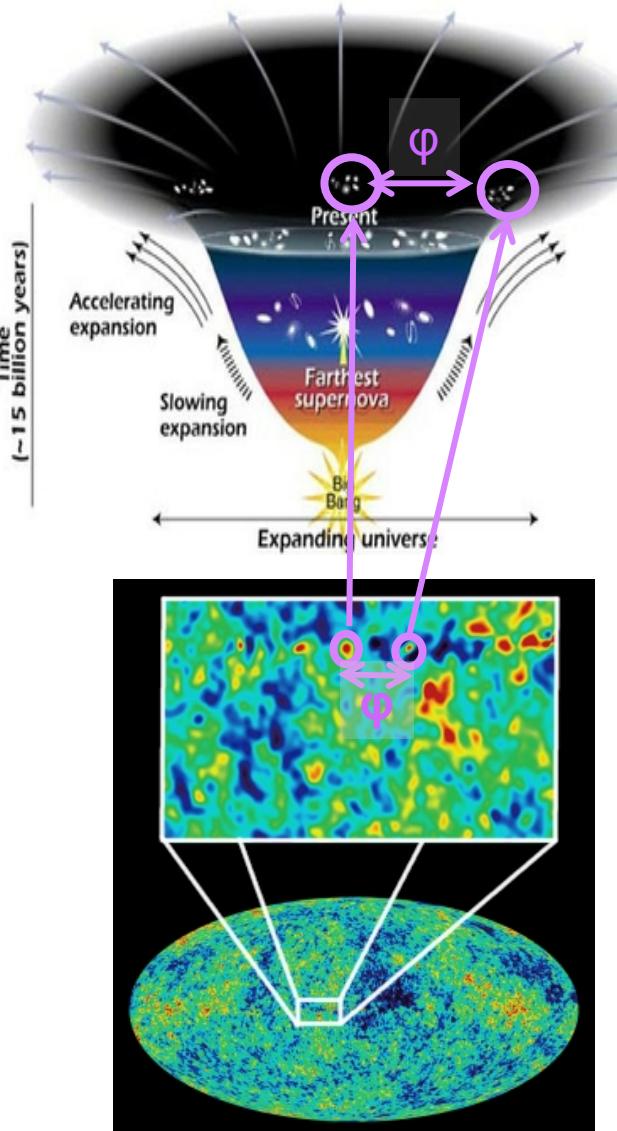
ICHEP Aug. 2016 Chicago



Mystery of Dark Energy



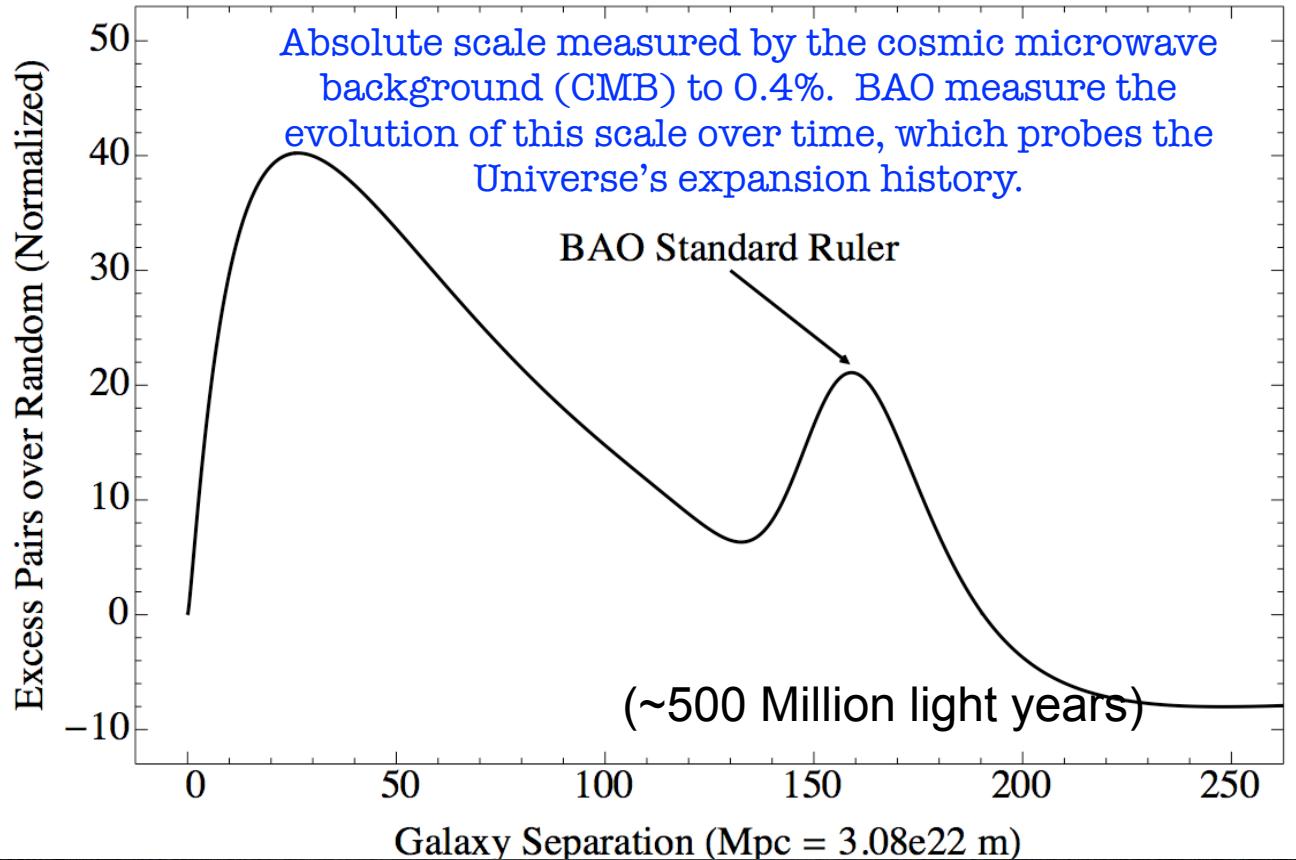
- What is the source of the accelerated expansion of the universe
 - Cosmological constant ($w = -1$)?
 - New long-range repulsive force?
 - Modification of gravity?
 - Other ideas?
- Experimentally we study two major aspects of our universe
 - The expansion history of the universe
 - The growth of structures (such as galaxies and galaxy clusters)
- DESI focuses primarily on measuring the expansion history using a standard ruler: Baryon Acoustic Oscillations (BAO)



Baryon Acoustic Oscillations



Sound waves in the early Universe (~ 400,000 yrs after the big bang) produce a peak in the clustering of matter that shows up in the distribution of galaxies we see today ~ 13 billion years later. Standard Ruler!



BAO is fundamentally a measurement of the separations between galaxies, not the properties of the galaxies themselves:
low systematic uncertainties

Clustering of galaxies tells us about gravity and the neutrino mass

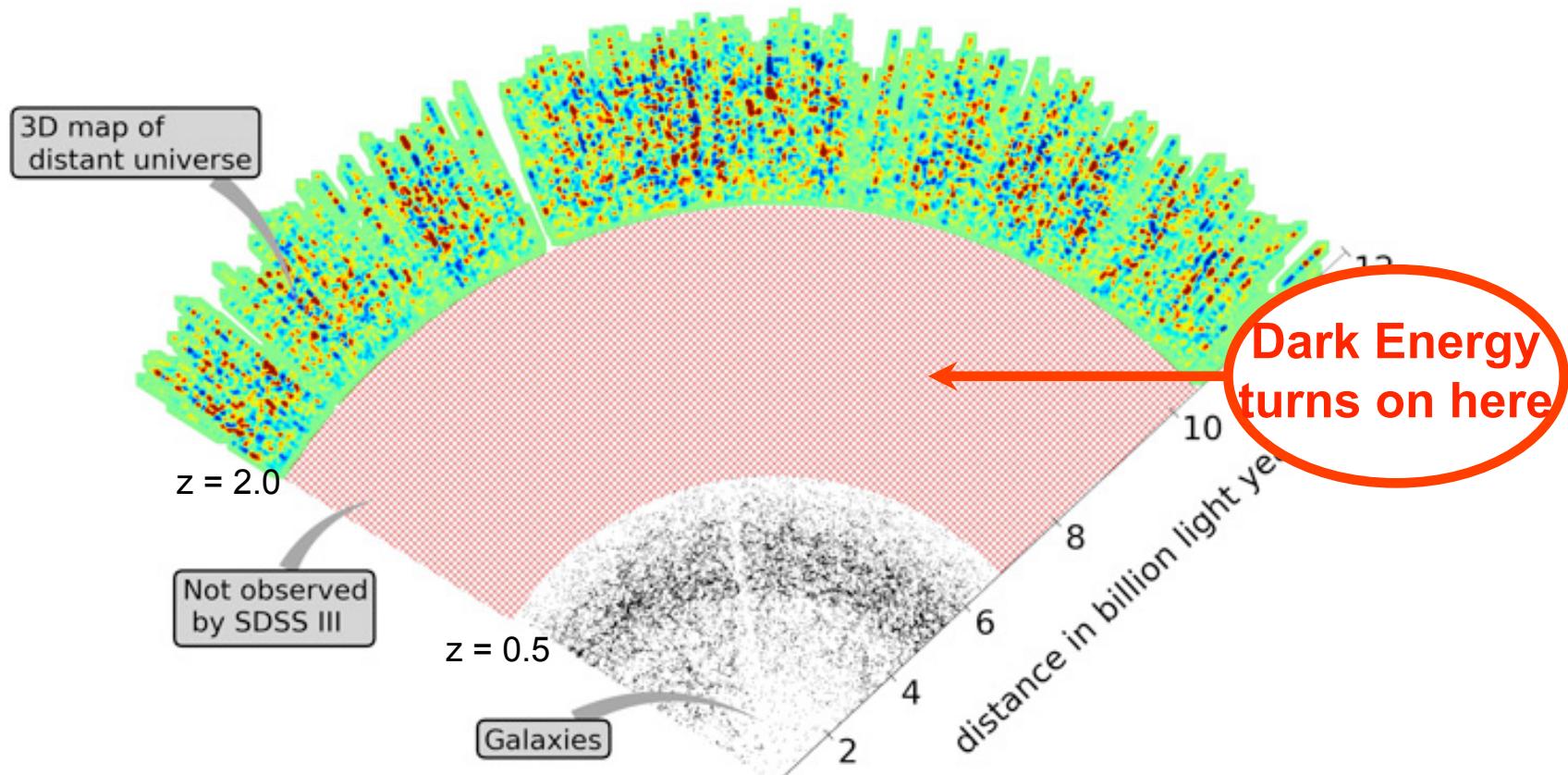


Spectroscopic Surveys before DESI



SDSS, SDSS II and SDSS III (BOSS) have shown the power of spectroscopic surveys but had limited redshift range (<0.7 , >2)

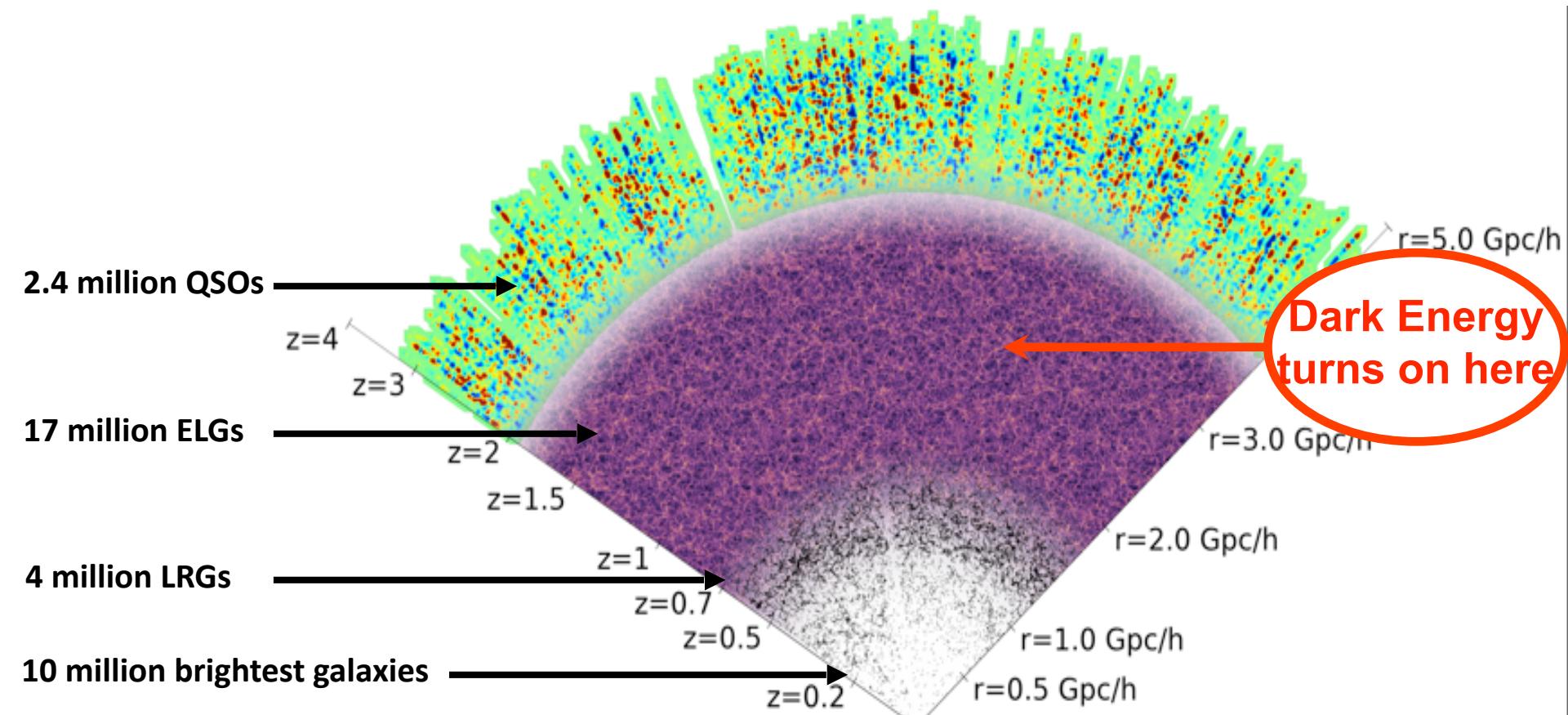
SDSS $\sim 2 h^{-3} \text{Gpc}^3$ \rightarrow BOSS $\sim 6 h^{-3} \text{Gpc}^3$ \rightarrow DESI $\sim 50 h^{-3} \text{Gpc}^3$



DESI Survey: ~ 34M Galaxies, 14K deg²



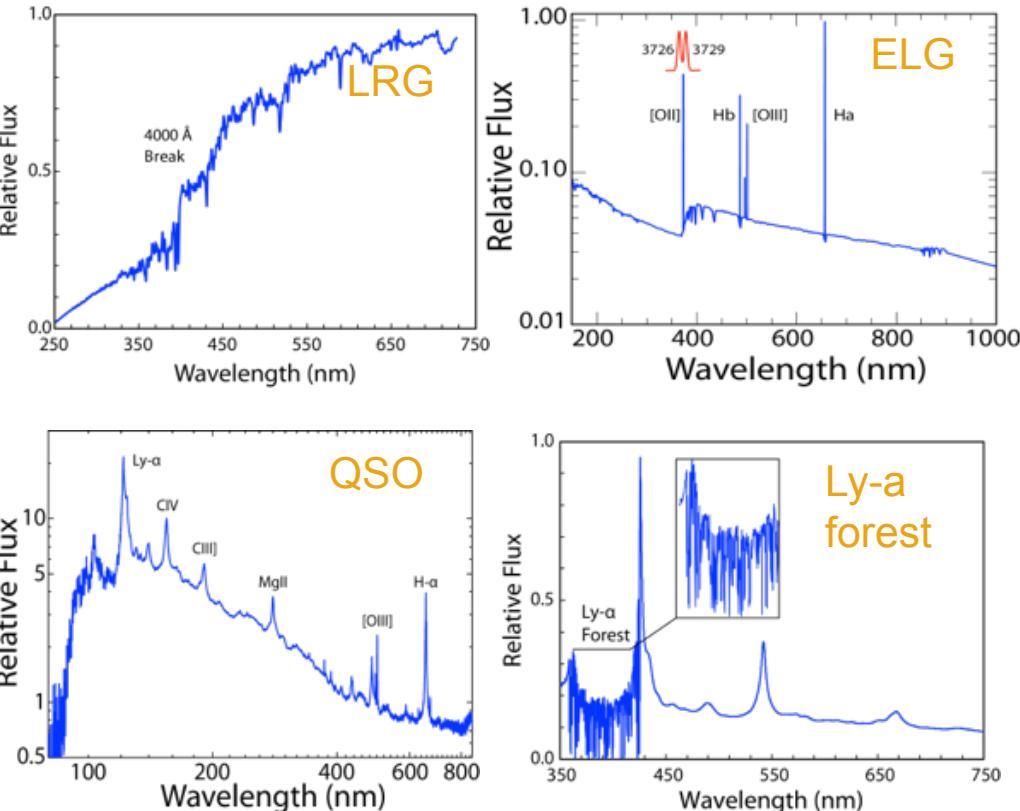
- 10 million Bright Galaxies $0.0 < z < 0.4$
- 4 million Luminous Red Galaxies (LRGs) $0.4 < z < 1$
- 17.1 million Emission Line Galaxies (ELGs) $0.6 < z < 1.6$
- 1.7 million Tracer Quasars (QSOs) $1 < z < 2.1$
- 0.7 million High redshift Quasars probe IGM (Lyman-alpha forest) ($z > 2.1$)



DESI Science Requirements



- Identify spectral features for each type of target
 - Bandpass from 360 – 980 nm, $\Delta z/(1+z) \sim 0.0005$, $\lambda/\Delta\lambda$ resolution $\sim 2000-4000$
 - 3 arm spectrographs to cover full range
- 5 year survey ($\sim 100\%$ of the time)
- 14000 deg² survey size
- 5000 spectra per exposure
- 34 Million targets
- ~ 20 min exposure times.
- $\sim 10,000$ total number of exposures
- **Goal:** $<0.3\%$ uncertainty in the distance scale at $z \sim 1$ and $<1\%$ for $z < \sim 3$



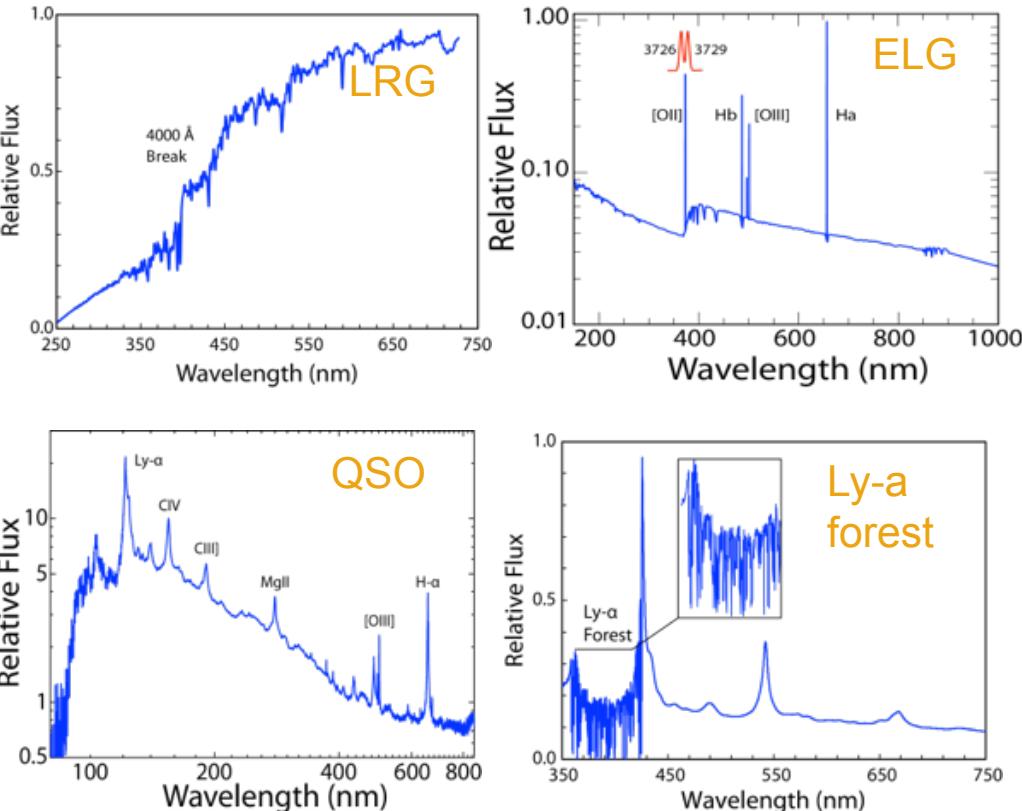
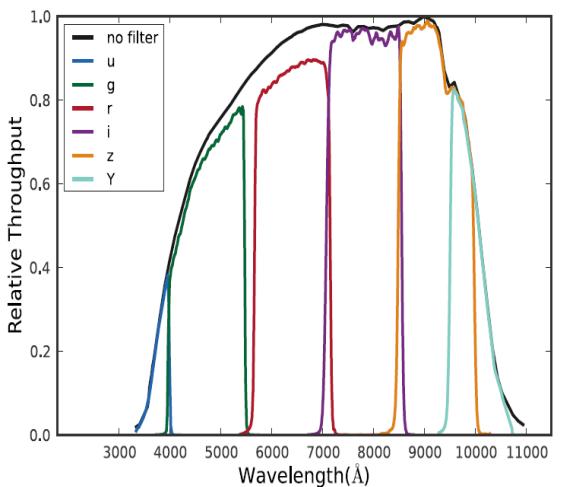
DESI Science requirements



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For comparison: DES measures “photometric” redshifts using 5 filters

$\Delta z \sim 0.01-0.02$ for clusters,
0.1 individual galaxies



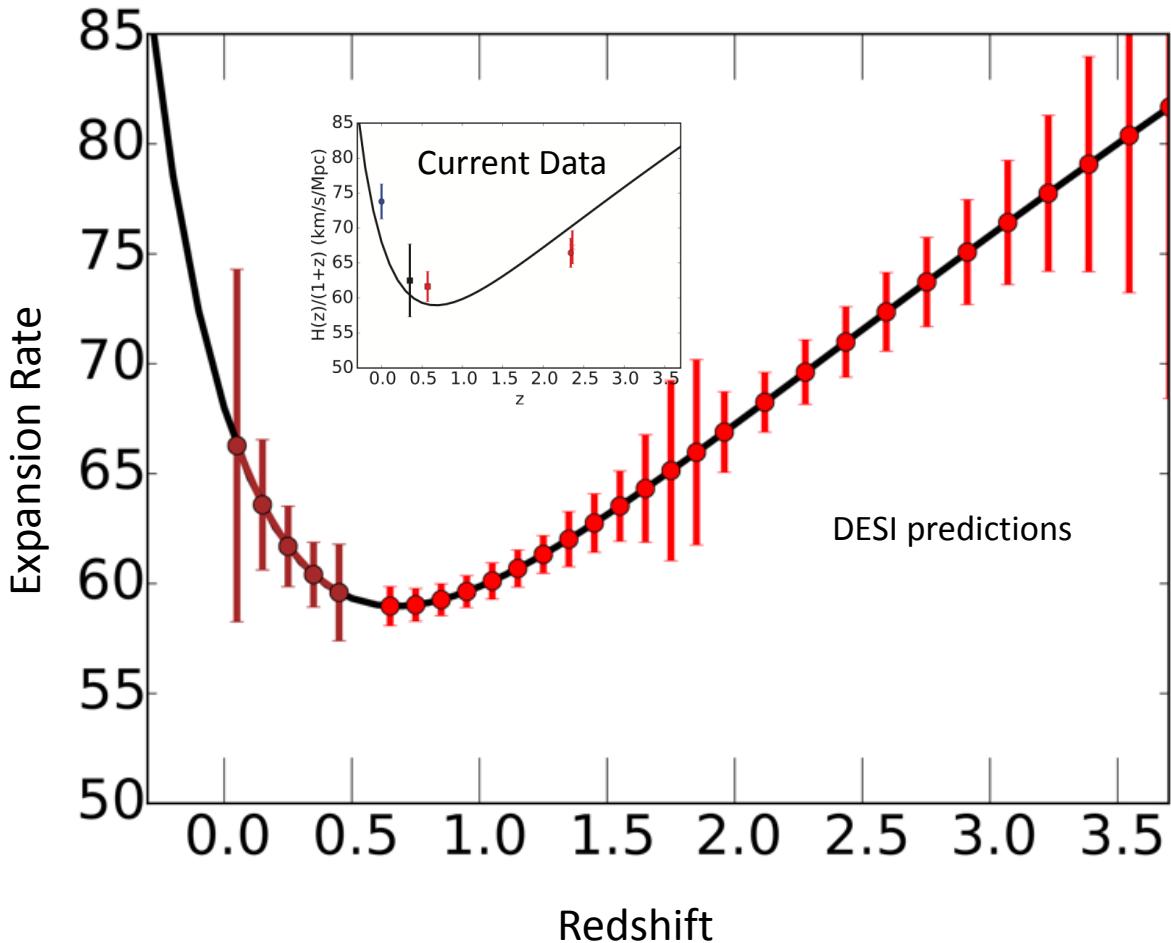
DES is a ~ 2.5 D Survey

DESI is a 3D Survey

DESI Hubble Diagram:



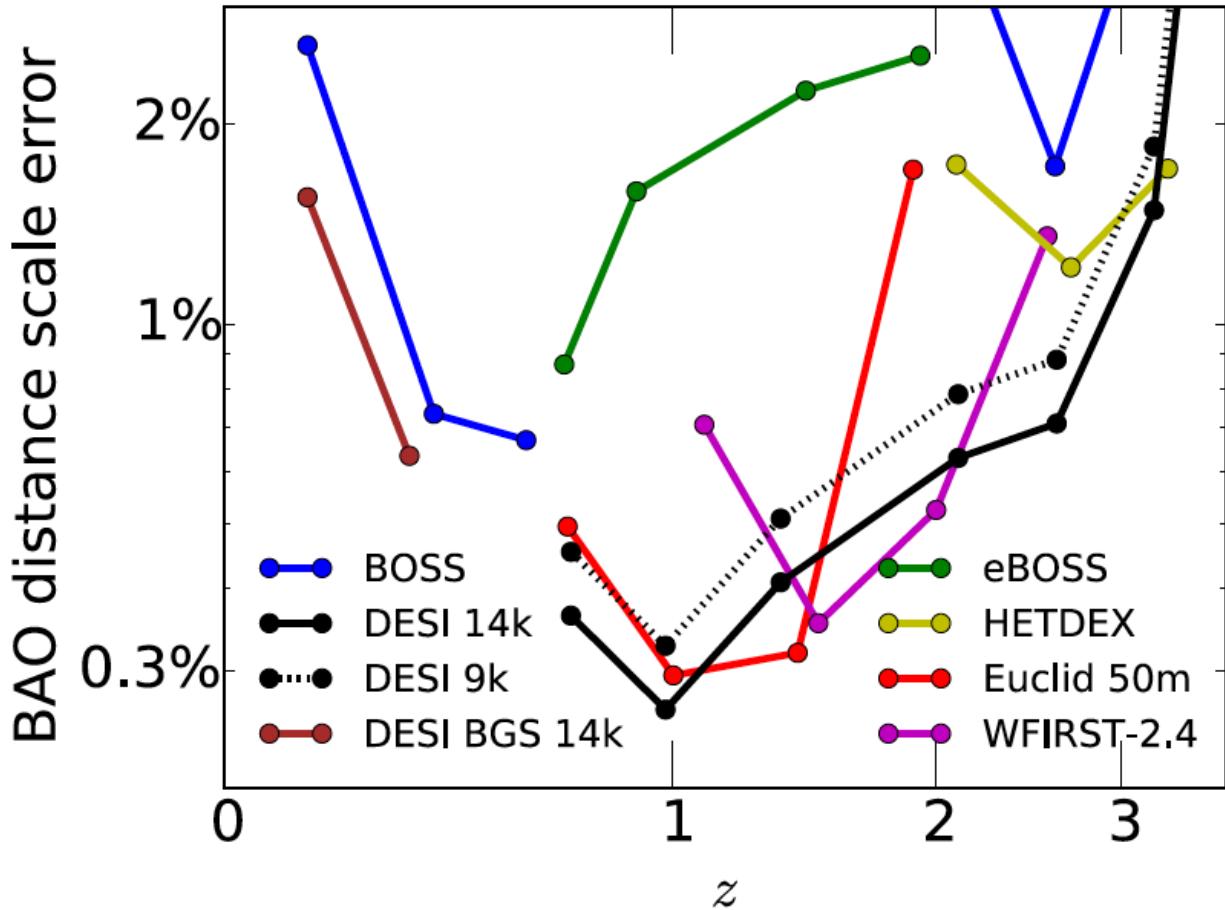
- Estimated Errors after 5 year survey



DESI BAO uncertainties in Context



- Estimated Errors after 5 year survey (2020-2025)

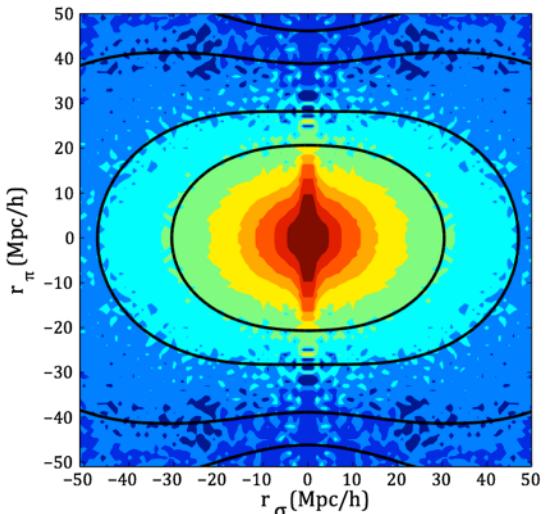


Beyond BAO

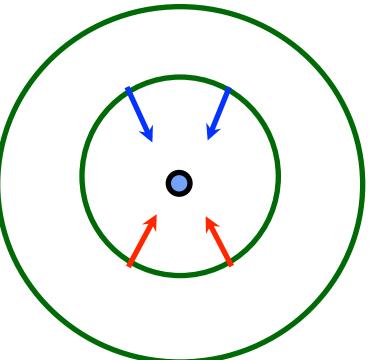


- There is significantly more information in the galaxy power spectrum than just the information from BAO

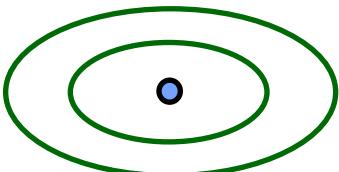
- Growth rate
- Neutrinos
- Inflation



observed redshift space
distortions from BOSS



“real”
space

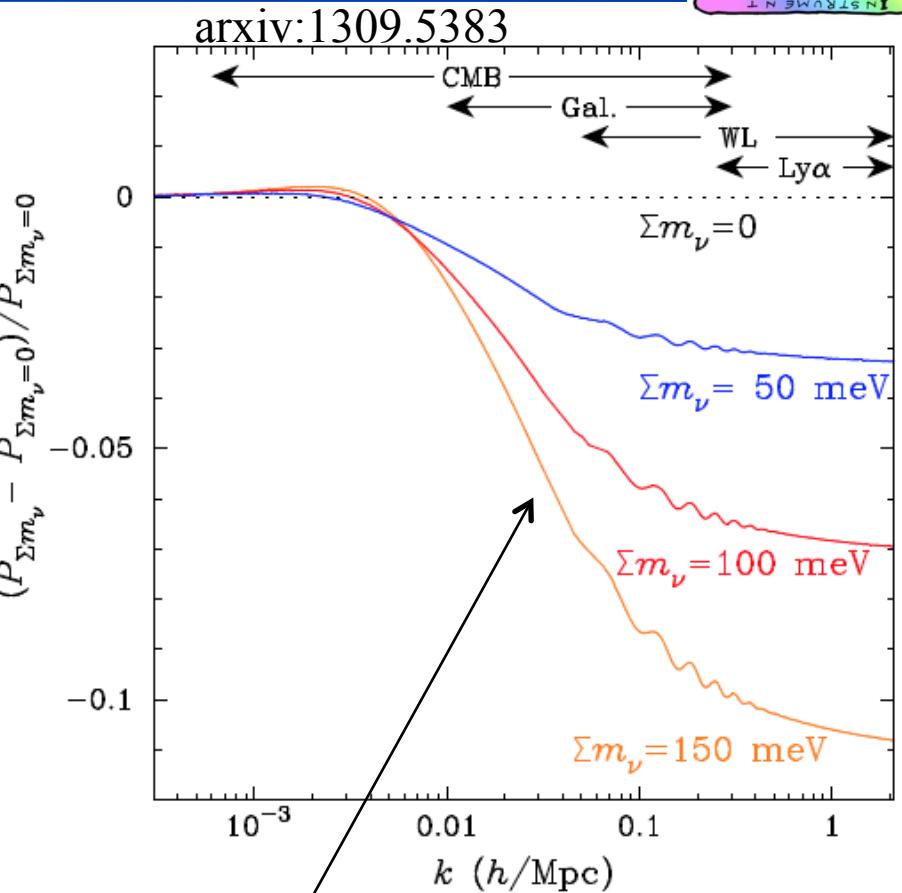
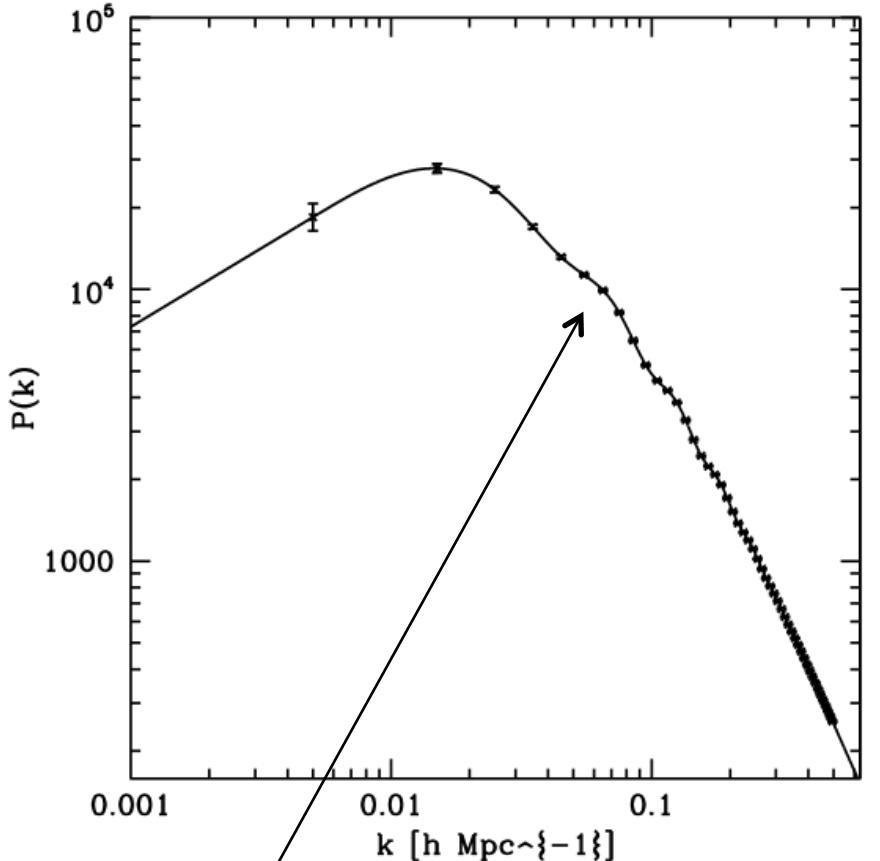


“redshift”
space

- 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 $0.5 < z < 1.4$



Very precise power measurement



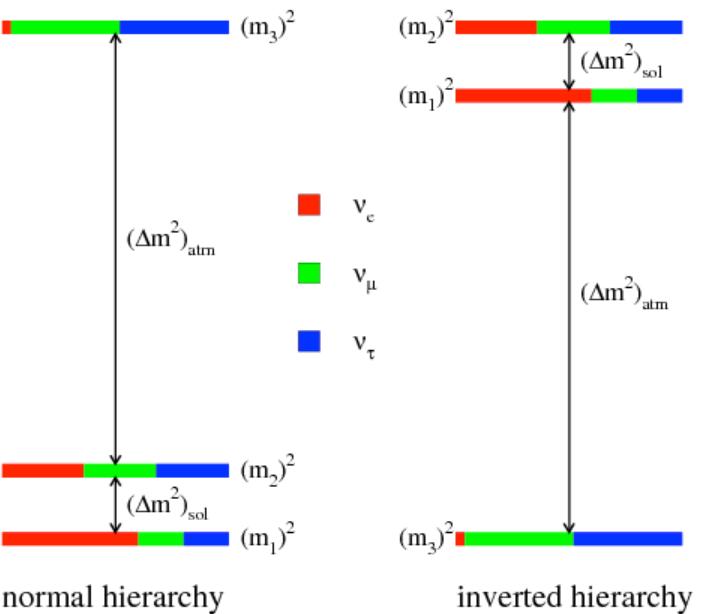
- The position of the BAO wiggles is the standard ruler we use to measure distance scale
- Using the full power spectrum we can extract additional information (eg. neutrino mass)

DESI measures the total neutrino mass



- Large-scale structure (LSS) is sensitive to neutrino properties
- Massive neutrinos decrease small-scale power at low redshift
 - DESI can measure the sum of masses
 - Extra relativistic species (such as sterile neutrinos) can also be measured with LSS and CMB

Data	$\sigma_{\Sigma m_\nu}$ [eV]	$\sigma_{N_{\nu, \text{eff}}}$
Planck	0.350	0.18
Planck+DESI BAO	0.090	0.18
Gal ($k_{\text{max}} = 0.1$)	0.024	0.13
Gal ($k_{\text{max}} = 0.2$)	0.017	0.084
Ly- α forest	0.039	0.11
Ly- α forest + Gal ($k_{\text{max}} = 0.2$)	0.017	0.063



4-meter Telescopes: Ideal for DE



- Twin telescopes run by NOAO built in the 1970s
- Built to hold heavy equipment at Prime focus
- Wide field of view for prime focus instruments > 3 deg.
- DECam in Chile installed in 2012 will operate for ~ 10 years (DES uses 30% of the time for 5 yrs)
- DESI at Kitt Peak (Tucson): Installation begins in 2018, commissioning in 2019, will use ~ 100% of the time for 5 years

Mayall Telescope, Kitt Peak, Tucson, AZ



Blanco Telescope, CTIO, La Serena, Chile



DESI Targets depend on both 4-m



- DESI needs images of all of the available Northern sky to $\sim 5\times$ fainter than SDSS
- DESI collaboration has organized a series of imaging surveys to collect the targets
- Conducted as “public” surveys with immediate public access to the data
- Although DECam is in the south, it can see the southern part of the DESI area

240 nights at Bok 2.3-meter

240 nights at Kitt Peak 4-meter

Mayall Telescope, Kitt Peak, Tucson, AZ



66+ nights at Cerro Tololo 4-meter

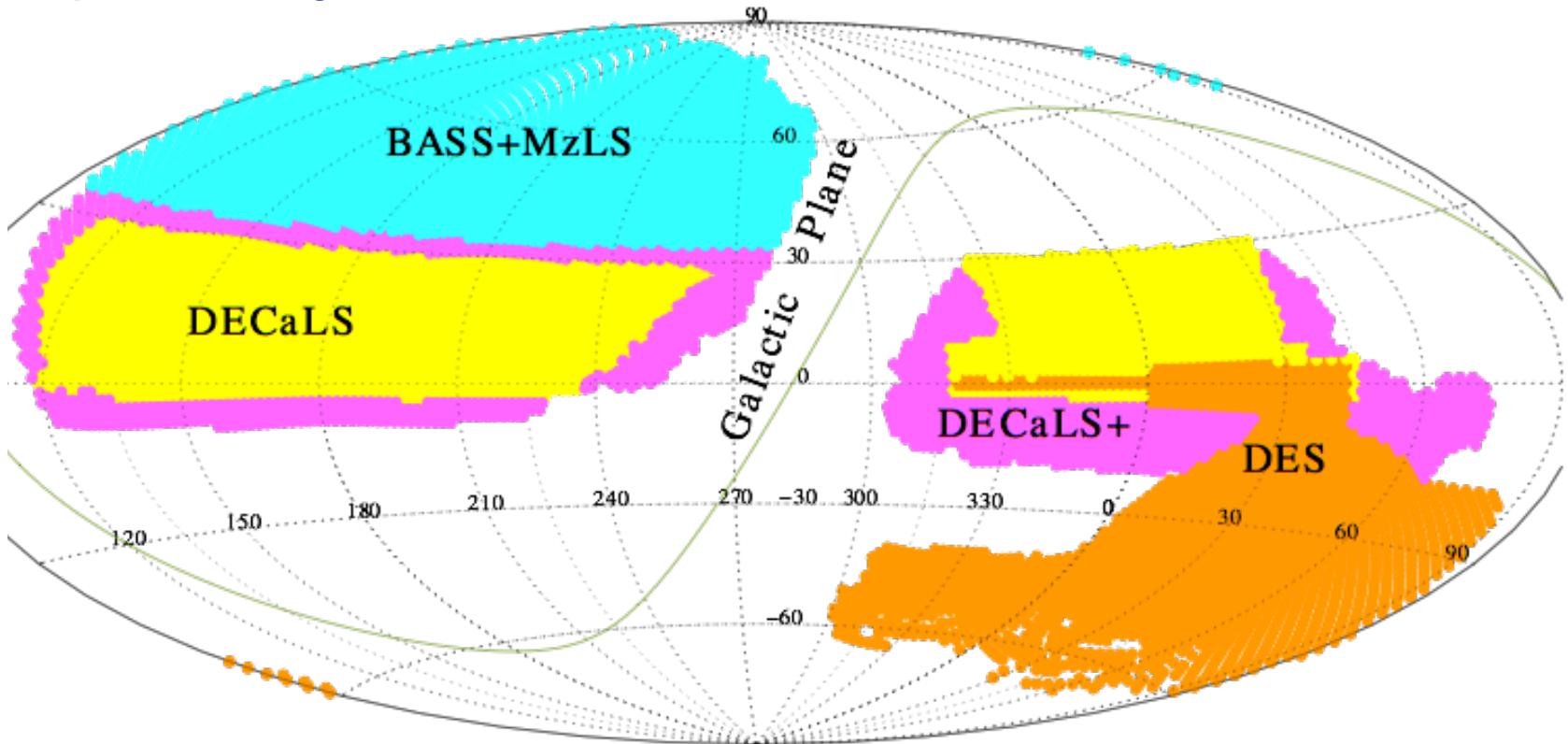
Blanco Telescope, CTIO, La Serena, Chile



DESI Survey: Targets



- DESI collaboration Imaging surveys (BASS, MzLS and DECaLs) will provide targets for DESI



DECaLS uses DECam to survey the southern 9000 deg^2 of the DESI area
Northern area is being covered by a Mayall z and BASS
Regular public data releases





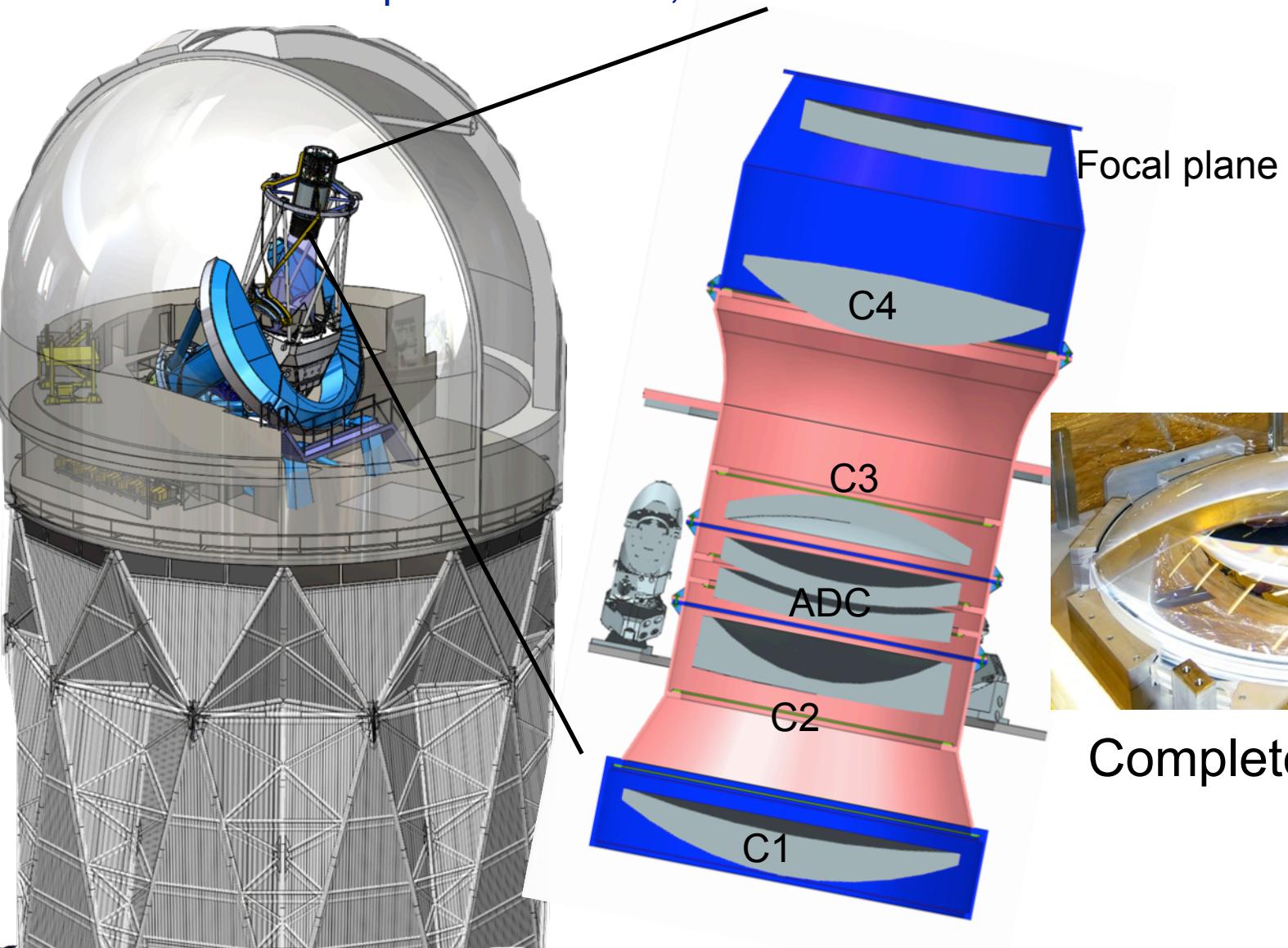
DESI Instrumentation



DESI Instrumentation: Optics



- 6-lenses in optical corrector, ~1-m diameter



Completed C4 Lens

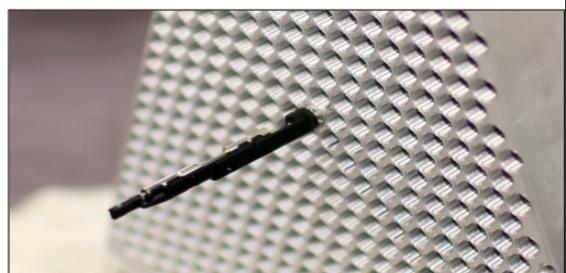
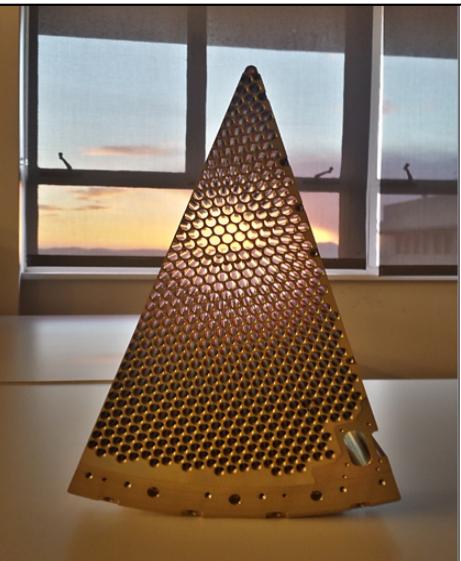
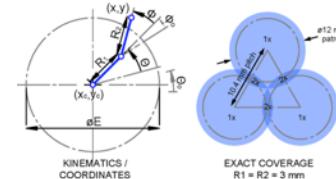
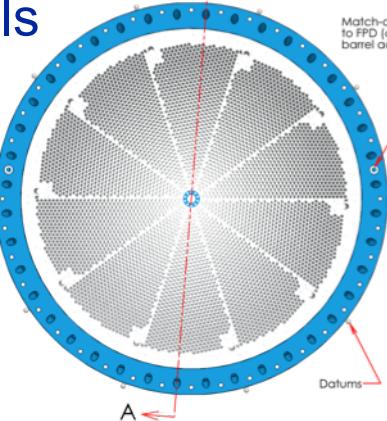
DESI Instrumentation: Focal Plane



Focal Plane 5000 Fiber robots in 10 petals



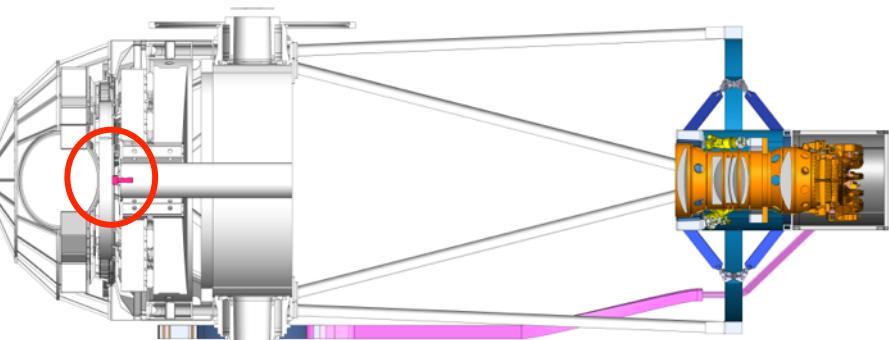
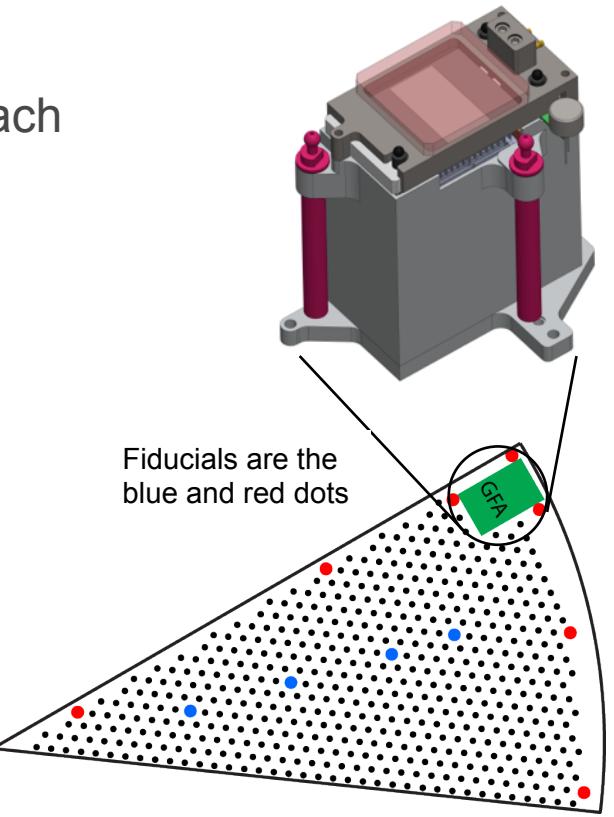
5000
Fibers



DESI Instrumentation: Focal Plane



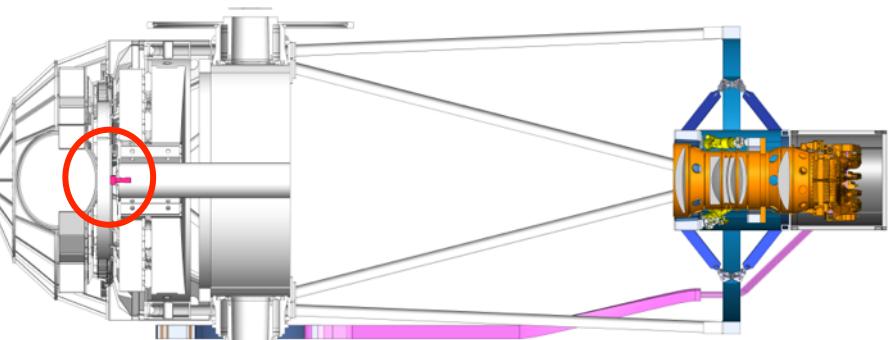
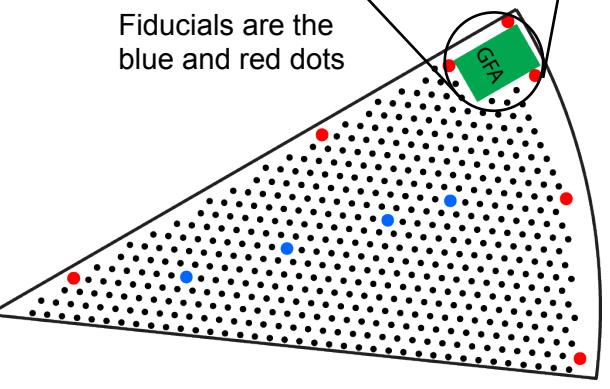
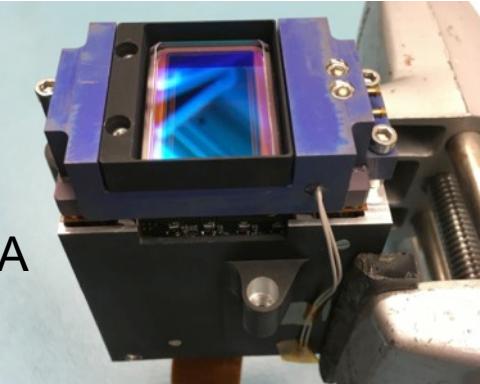
- Guide / Focus / Alignment sensors – 1 per petal
 - Guide star tracking feedback to telescope – 6 units, each ~30 sq. arcmin², > 10 total guide stars
 - Focus and alignment data for hexapod – 4 units
 - Run at ambient temp.
- Illuminated Fiducials – 11 per petal
 - Precisely surveyed to GFA sensors
 - When viewed from the primary mirror through the corrector, provides measure of optical distortion and mechanical deformations
- Fiber view camera (FVC)
 - Observes illuminated fiducials ...
 - ... and backlit fiber positioners
 - Provides feedback for precise alignment of fiber positioners



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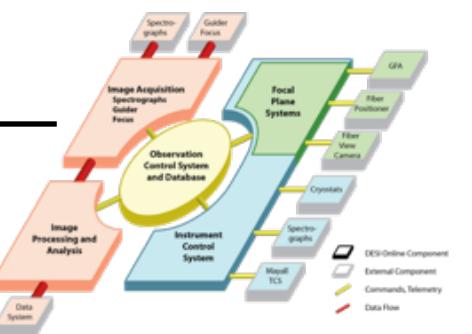
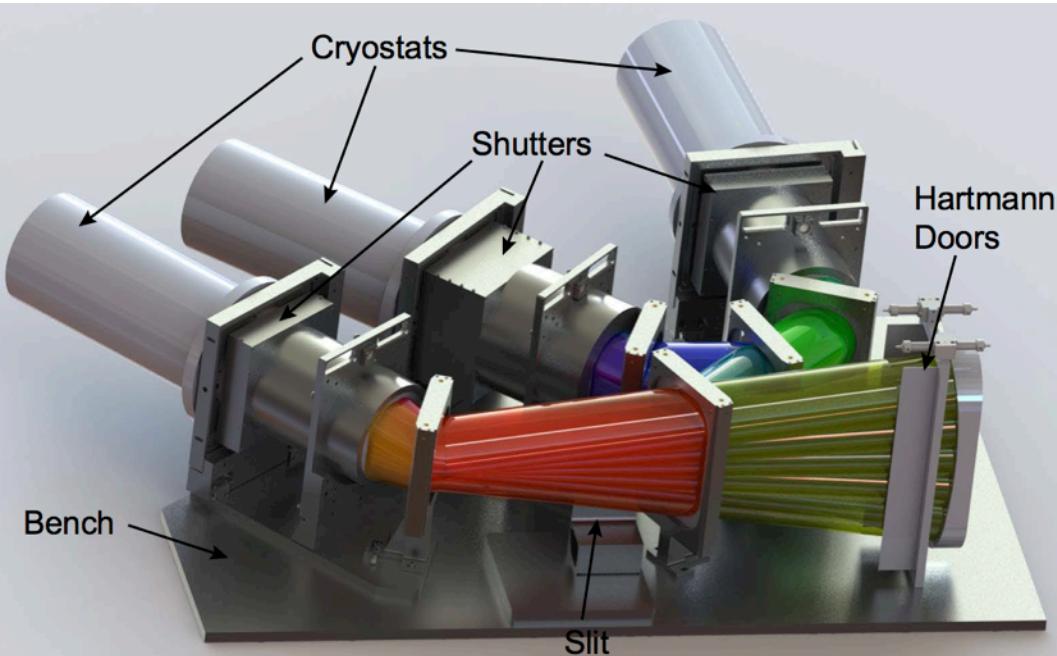
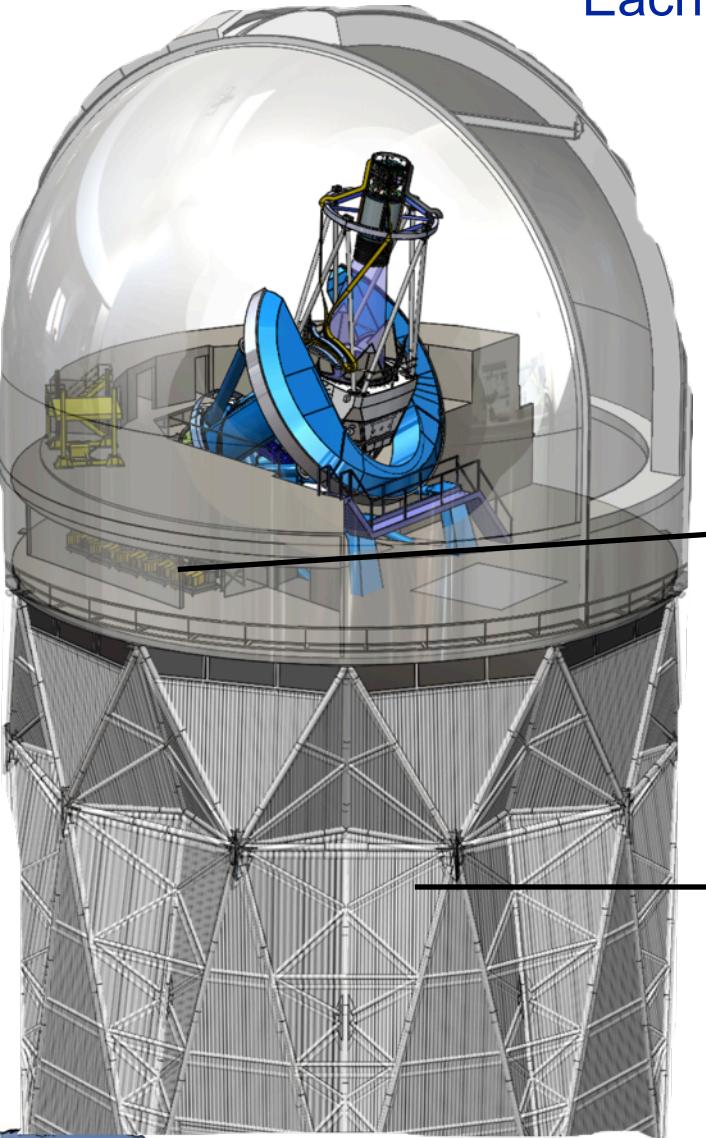


DESI Instrumentation: Spectrographs



10 spectrographs, 5000 simultaneous spectra

Each spectrograph: 500 fibers, 3 arms, 4kx4k CCDs

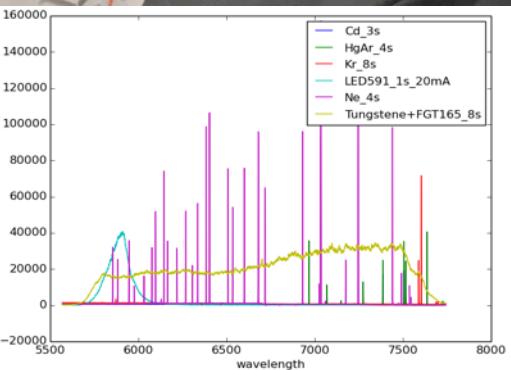
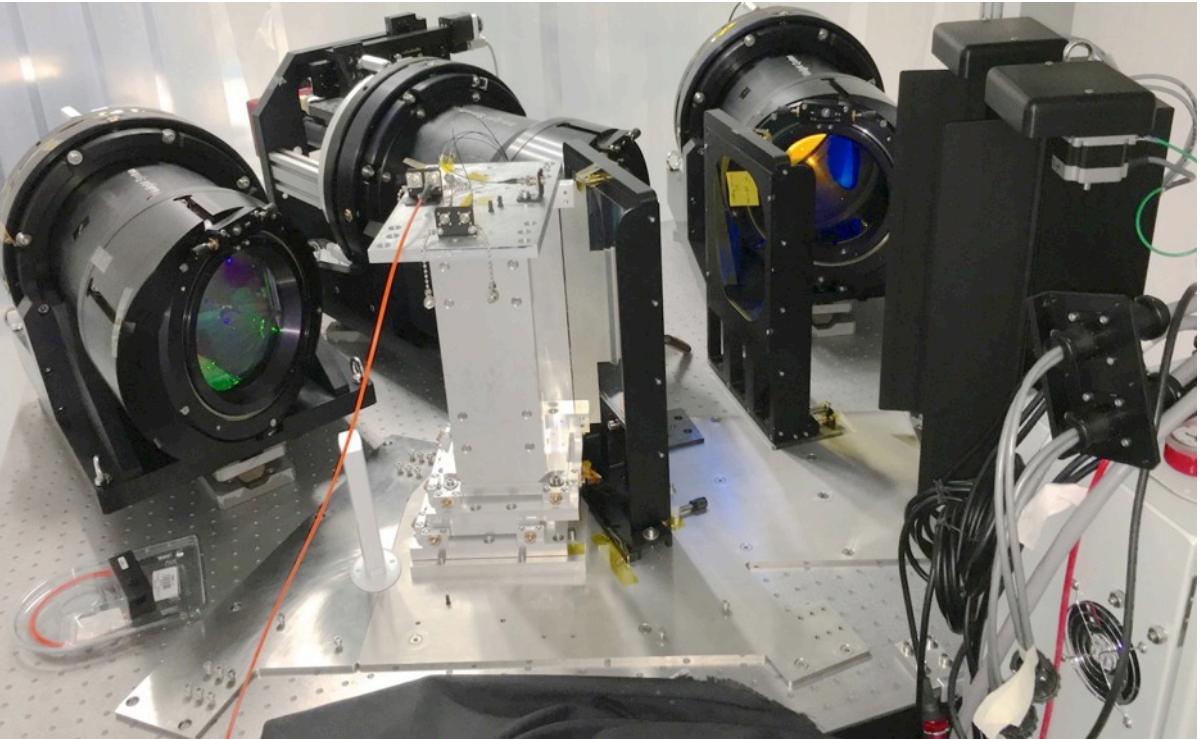
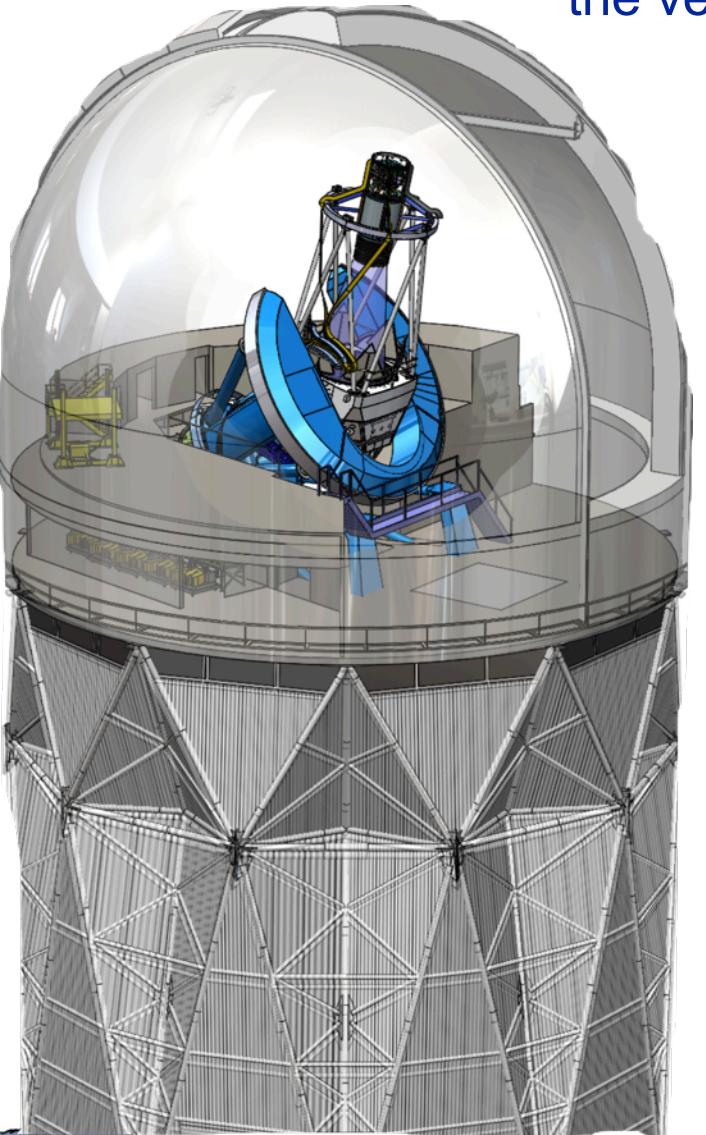


Readout
& Control

DESI Instrumentation: Spectrographs



1st spectrograph is complete and producing data at the vendor!



Red channel data using DESI pipeline, arclamp, continuum, and LED illumination

ProtoDESI: Aug.-Sept. 2016

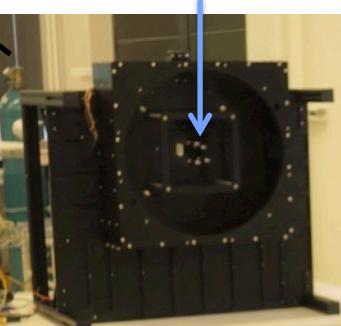


4 fiber positioners plus guide and focus chip
on existing prime focus optical corrector

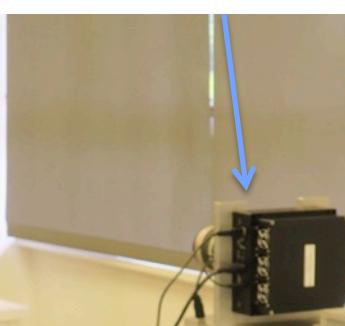
Test ability to put a fiber positioner on a target
and keep it there

Will be installed Aug. 15! Run to end of Sept.

**Positioners
& Fiducials**



**Fiber View
Camera**



**Parker Fagrelius
(GSRA, leads
ProtoDESI)**



Image of Fiducials



Summary



- DESI will make the most precise measurement of the distance scale in both statistical precision and redshift coverage
 - Will essentially complete BAO measurements in the northern sky out to redshift of 1.5.
 - Will measure the distance scale out to redshift of 3.5 using galaxies, quasars and the Lyman alpha forest
 - Will also provide additional cosmological constraints on the neutrino mass and growth of structure
 - Imaging surveys are making good progress collecting targets for the DESI survey
 - DESI received CD-3 approval in June 2016 and is expected to have first light (commissioning) in 2019.



DESI Collaboration



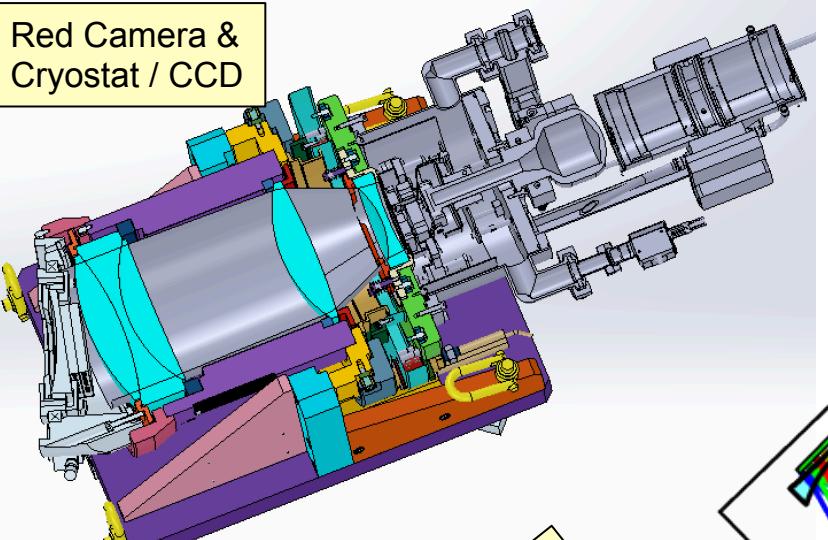
- ~ 200 participants, >50 institutions



Spectrograph (1 of 10)



Red Camera &
Cryostat / CCD



Unit #1 currently complete;
evaluation in progress

CCDs:
4096 x 4096,
15 μm pixels,
500 spectra

~140 mm

