DESI – A Powerful New Instrument for Cosmology

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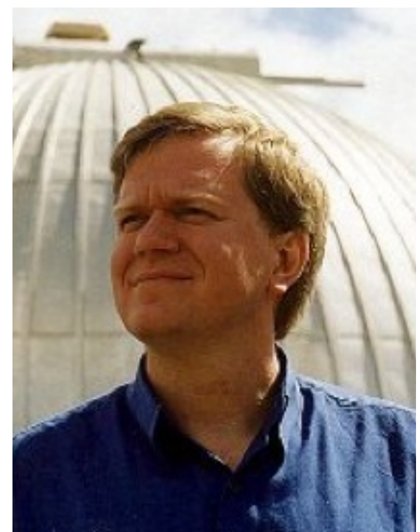
Virtual Astroparticle Colloquium
Gran Sasso Science Institute
L'Aquila, Italy
January 27, 2021

A Revolution in Cosmology!

- In 1998 the Supernova Cosmology Project and the High-z Supernova team used Type Ia supernovae as "standard candles" to construct a Hubble diagram out to z = 1. Contrary to expectations, both found that the expansion of the universe is accelerating!

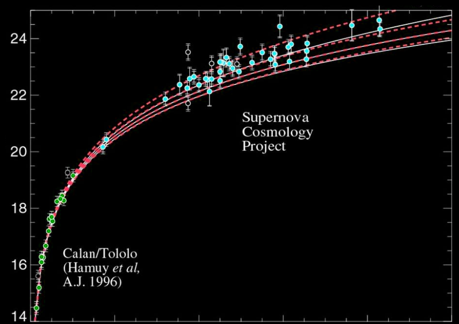
- The "stuff" responsible for this acceleration was given the name "Dark Energy."

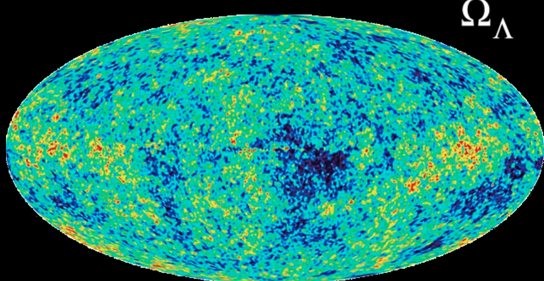
In 2011 Saul Perlmutter, Brian Schmidt and Adam Reiss were awarded the Nobel Prize in Physics for discovering the accelerating universe

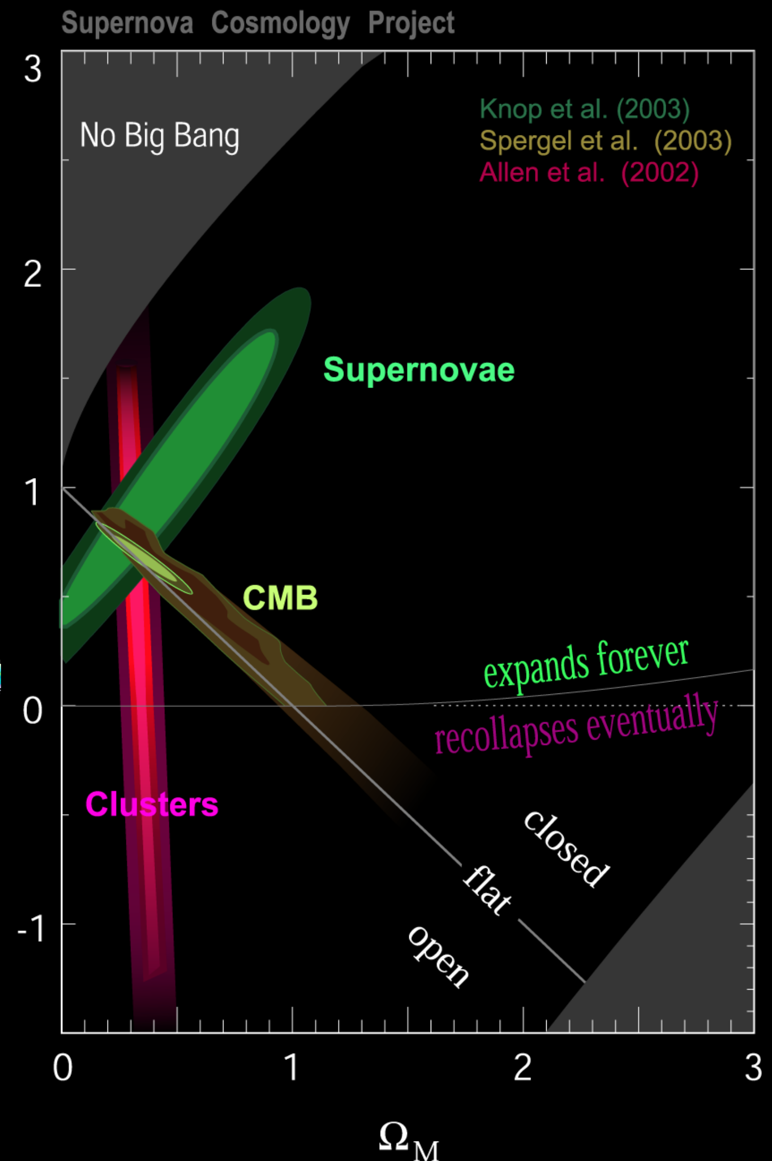


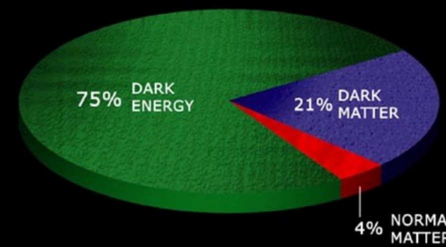
Standard Model for Cosmology

Confirmed by LSS and CMBR fluctuations









75 ± 2% Dark Energy

25 ± 3% Matter

0.5% Bright Stars

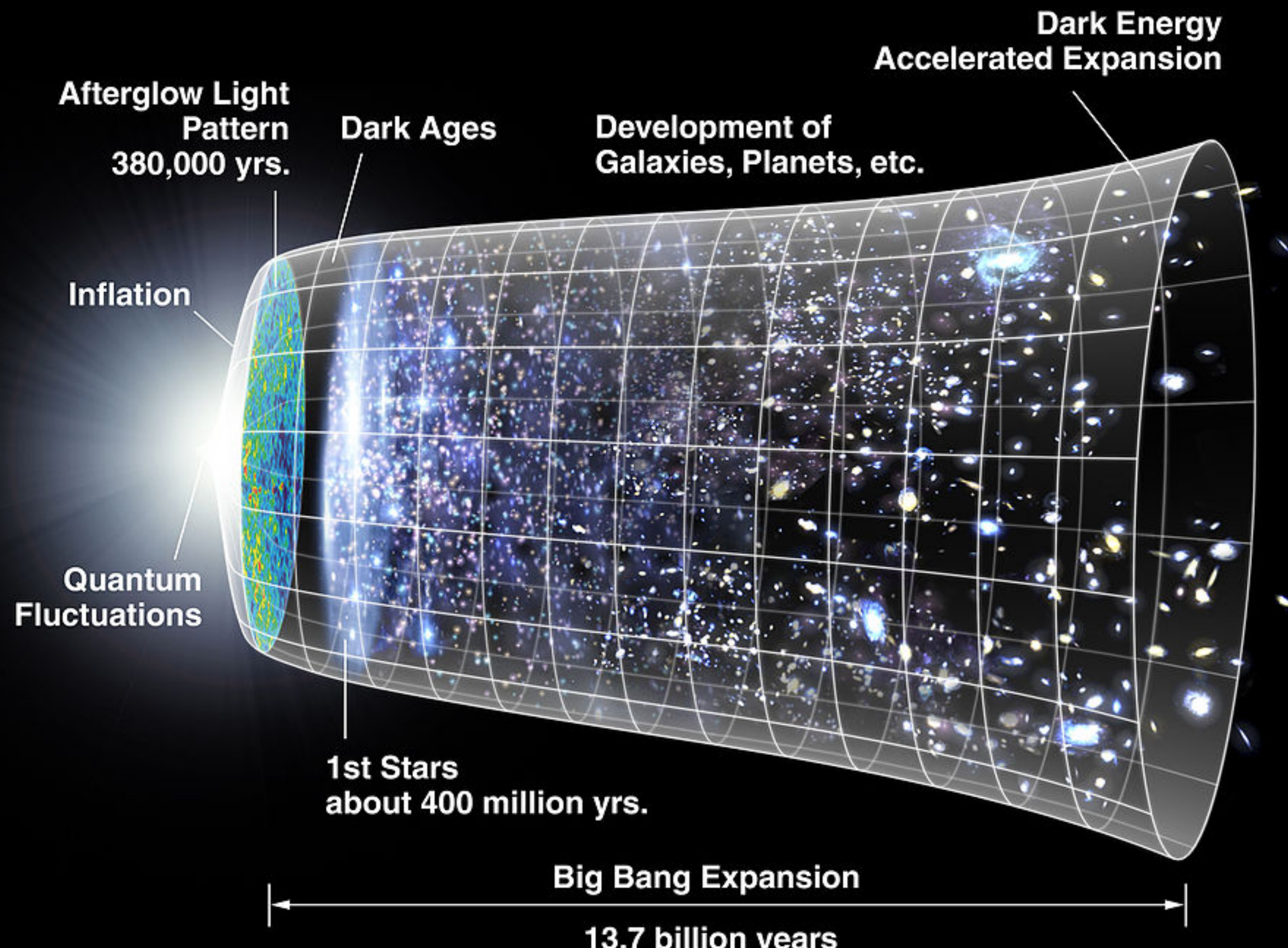
Matter (25%):

20% Dark Matter

4.4% Baryons

0.3% νs

We do not understand 96% of the universe!



Graphic: WMAP

What could cause the expansion of the universe to accelerate?

- Friedmann equation + fluid equation ⇒ acceleration equation.
- **Negative Pressure!** If P < 0 and large, ρ + 3P can be negative ⇒ accelerating universe.
- What could be providing such a negative pressure?
  - Cosmological constant with equation of state w = P/ρ = -1
  - Dynamical field with time varying w?
  - Modified gravity?

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{c^2}\rho \equiv H^2$$

$$+$$

$$\dot{\rho} + 3\frac{\dot{a}}{a}\left(\rho + 3P\right) = 0$$

$$\Downarrow$$

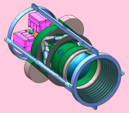
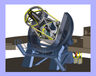
$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3c^2}\left(\rho + 3P\right)$$

Negative Pressure?

- With an ordinary gas of particles, as you increase the volume of a box, the particles dilute.
- Because of the **positive** pressure, the gas does **positive** PdV work **expanding** the box and the energy content of the gas **decreases**.
- A refrigerator!
  $P > 0$, $\rho > 0$, $w = P/\rho > 0$

- With vacuum energy the energy content of a box **increases** with increasing volume.
- The vacuum energy pressure must be **negative** so that **negative** PdV work is done expanding the box and the total vacuum energy in the box increases.
- A "space" heater!
  $P < 0$, $\rho > 0$, $w = P/\rho < 0$

Understanding Dark Energy

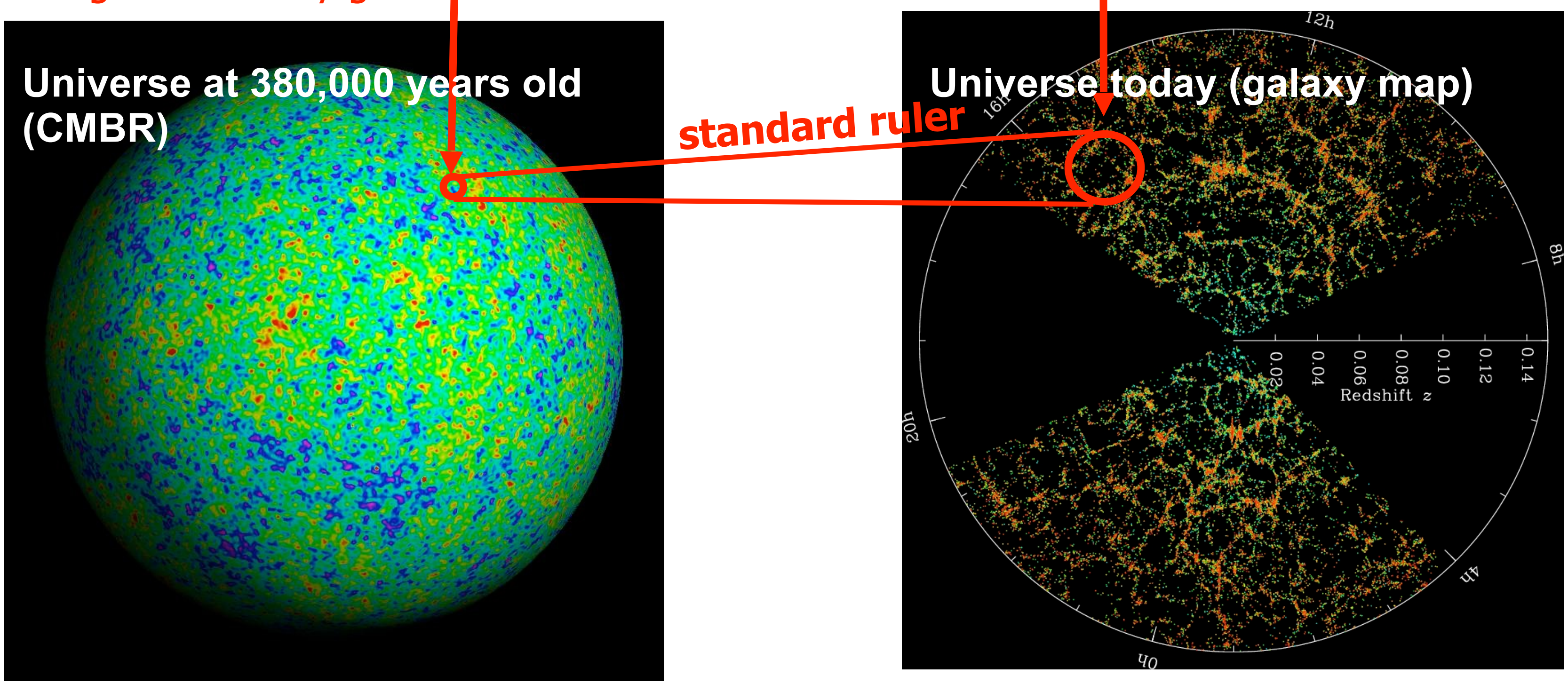
- > Twenty years and still no clue as to the nature of dark energy.
- Understanding Dark Energy is really about understanding the very "fabric" of space-time.
- Strategy: Measure $w(z) = P/\rho$, growth of scale a(z) vs. structure(z).
- Dark Energy Task Force (May, 2006) identified four Observational techniques: Galaxy Clusters (GC), Supernova (SN), Weak Lensing (WL), Baryon Acoustic Oscillations (BAO).
  - DETF figure of merit (FoM) - reciprocal of the area enclosing the 95% confidence limit in the w_0-w_a plane. $w(z)=w_0 + w_a(1-a)$
- Four Stage program recommended
  - Stage I What was already known ✓
  - Stage II Anticipated with ongoing projects at the time ✓
  - Stage III Near term, medium cost existing proposals
    FOM increase > 3 over stage II
    DES  ✓
    5.5 y survey complete, Y1 published, Y3 publications in progress, Y6 by 2022
  - Stage IV Long Term Missions.
    FOM increase > 10 over Stage II
    DESI 

Baryon Acoustic Oscillations (BAO) Standard Ruler at 147 Mpc

- Sound waves propagate at ~$c/\sqrt{3}$ in the plasma of the early universe to the sound horizon (recombination) at 380,000 yr ($z = 1092$).
- Origin of 1° angular scale acoustic peak in Cosmic Microwave Background Radiation ripples.

These fluctuations of 1 part in 10^5 gravitationally grow into...

...these ~unity fluctuations today



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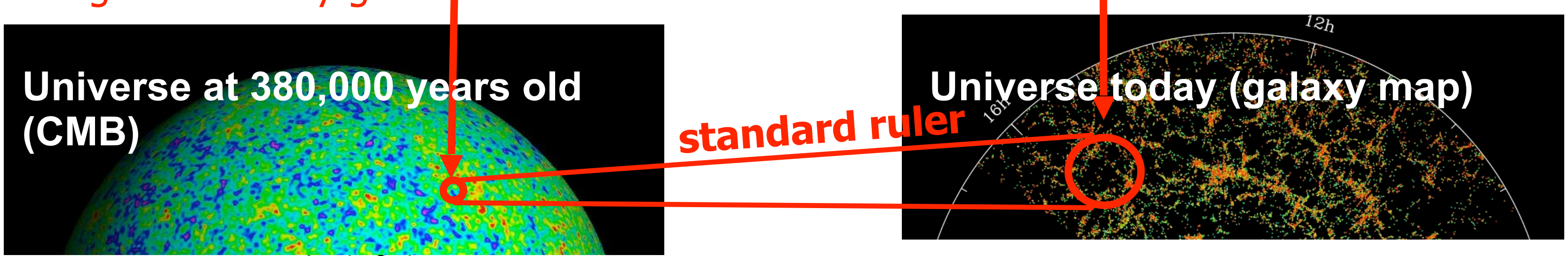
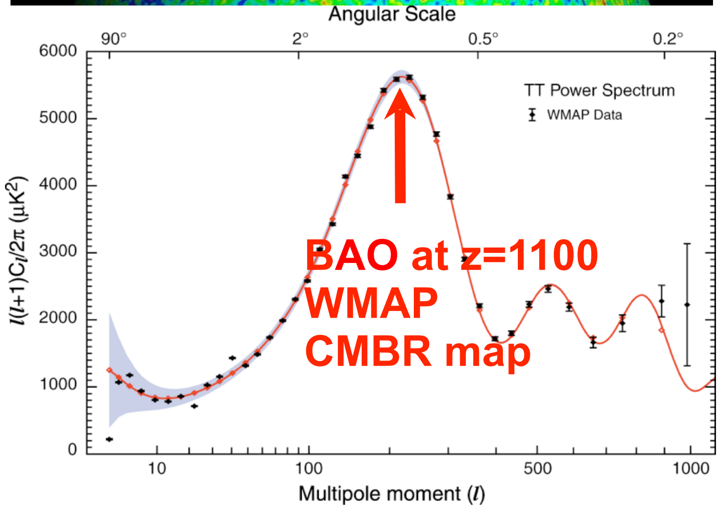
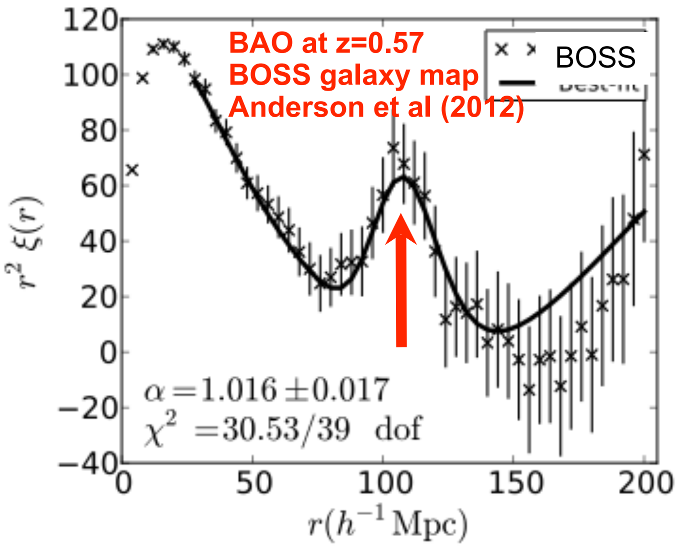
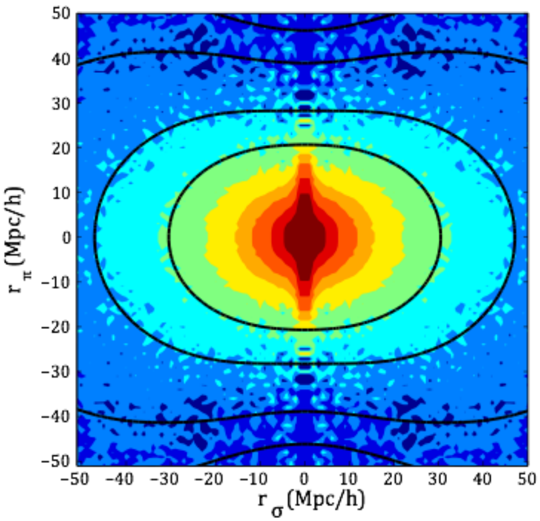




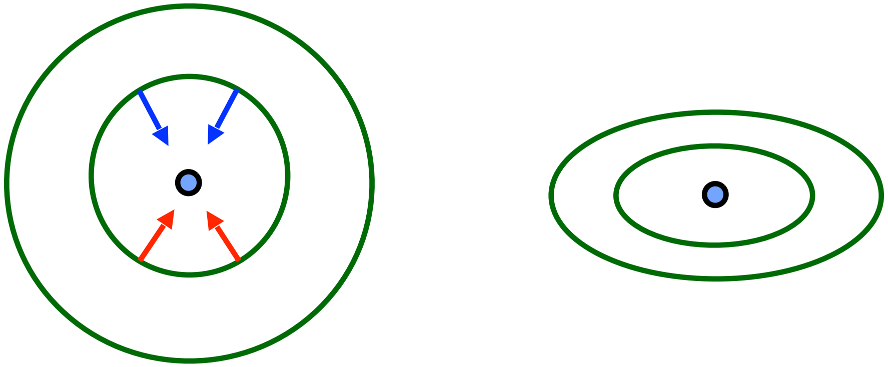


Redshift Space Distortions

- The galaxy power spectrum contains more information than just that 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.
- Differential redshift within galaxy clusters reveals growth of DM halos. More sensitive to w(z) than galaxies alone.
- Produces a test of General Relativity.

The Dark Energy Spectroscopic Instrument (DESI)

- DESI will create the most detailed 3D map of the universe to date
- DESI was installed on the Mayall 4-m Telescope at the Kitt Peak National Observatory in Arizona on Aug 1, 2019. First light Oct. 22, 2019.
- Commissioning successfully completed March 15, 2020. (Now at CD-4)
- ~6 mo. Survey Validation followed by 5 yr targeted spectroscopic survey (Delayed until Dec. 2020 due to COVID-19 pandemic).

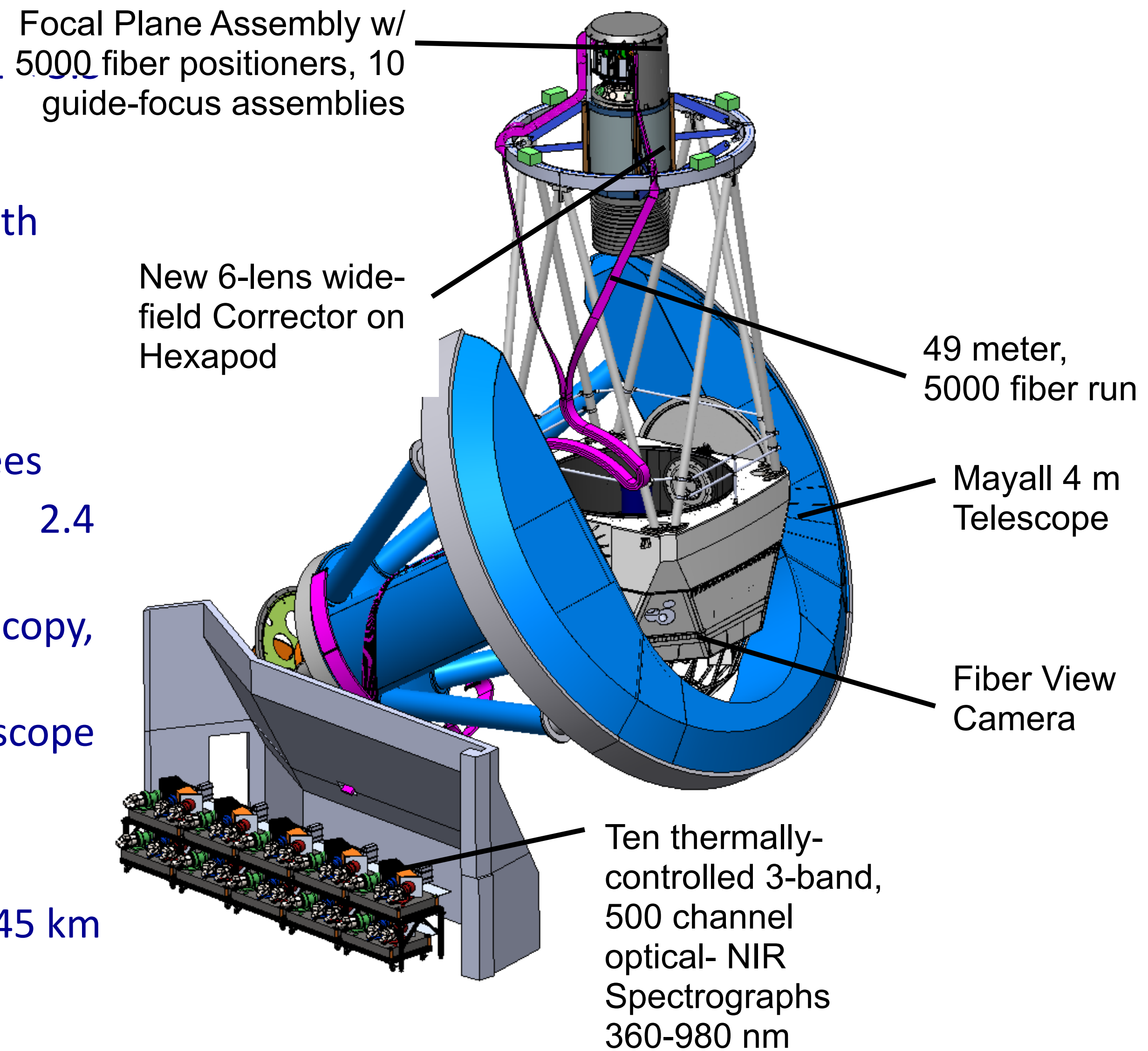
DESI – The 1st Stage IV Experiment On-Sky

- Stage-IV BAO over a broad redshift range: 0.5 < 1.6 LRGs and ELGs 2.2 < Ly-α.
- DESI high-z RSD - < 1% level measure of gravitational growth index γ.

$$f(z) = \Omega_m(z)^\gamma$$

growth rate of structure   matter density

- Sky area: 14,000 square degrees
- 34 million galaxy redshifts 2.4 million quasar Ly-a forests
- > Medium resolution spectroscopy, R up to ~ 5500
- DESI is the most complex telescope instrument ever fielded with 500,000 parts, 5000 fiber positioners, ten 3-band 500-channel spectrographs, and 245 km of fiber optic cables.



The DESI Collaboration

~500 Collaborators, 69 Institutions

Americas:

- Argonne National Lab
- Boston University
- Laboratório Interinstitucional de e-Astronomia, Brazil
- Universidade Estadual Campasino
- Brookhaven National Laboratory
- Carnegie Mellon University
- Cornell University
- Fermi National Accelerator Lab
- Harvard University
- Kansas State University
- Lawrence Berkeley National Lab
- Centro de Investigación y de Estudios Avanzados del Instituto Politécnico Nacional
- Instituto Nacional de Ivestigaciones Nucleares
- Universidad Nacional Autónoma de México
- Universidad de Guanajuato
- NSF's Optical-Infrared Astronomical Research Lab
- New York University
- The Ohio State University
- Ohio University
- Siena University
- Southern Methodist University
- SLAC National Accelerator Lab
- Universidad de los Andes
- University of Arizona
- University of California, Berkeley
- University of California, Irvine
- University of California, Santa Cruz - Lick Observatory
- University of Florida
- University of Kansas
- University of Michigan
- University of Pennsylvania
- University of Pittsburgh
- University of Rochester
- University of Toronto, Canada
- University of Utah
- University of Waterloo
- University of Wyoming
- Yale University

Europe:

- Institut National de Physique Nucléaire et de Physique des Particules
- L'Observatoire Astronomique Marseille-Provence
- Laboratoire d'Astrophysique de Marseille
- Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas
- Institut de Ciències de L'Espai - IEEC/CSIC
- Institut de Física d'Altes Energies, Universitat Autònoma de Barcelona
- Universidad Autónoma de Madrid
- Durham University, UK
- École Polytechnique Fédérale de Lausanne, Switzerland
- Eidgenössische Technische Hochschule Zürich, Switzerland
- Campus de Excelencia Internacional CIE/UAM + CSIC, Universidad Autónoma de Madri
- Instituto de Astrofísica de Andalucía
- Instituto de Astrofísica de Canarias
- Laboratoire de Physique Nucléaire et de Hautes EnergiesLPNHE
- Université Pierre et Marie Curie
- Max Planck Institut
- Saclay - Commissariat à l'énergie atomique et aux énergies alternatives, France
- The Royal Observatory, Edinburgh
- University of Cambridge
- University of Saint Andrews
- University of Warwick
- Universitat de Barcelona
- University College London
- University of Portsmouth, UK
- University of Zurich

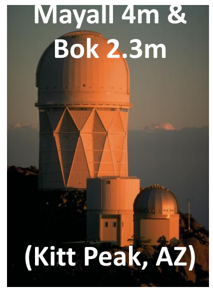
Asia/Pacific:

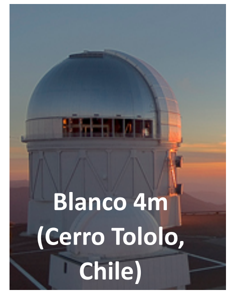
- Beijing Astronomical Observatory
- Large Sky Area Multi-Object Fiber Spectroscopic Telescope
- National Astronomical Observatories, Chinese Academy of Sciences
- Peking University
- KASI, Korea Astronomy and Space Science Institute
- KIAS, Korea Institute for Advanced Study
- Shanghai Jiao Tong University
- Swinburne University of Technology, Australia
- University of Queensland

DESI Legacy Imaging Survey Completed All Public
See http://legacysurvey.org

Three optical surveys completed

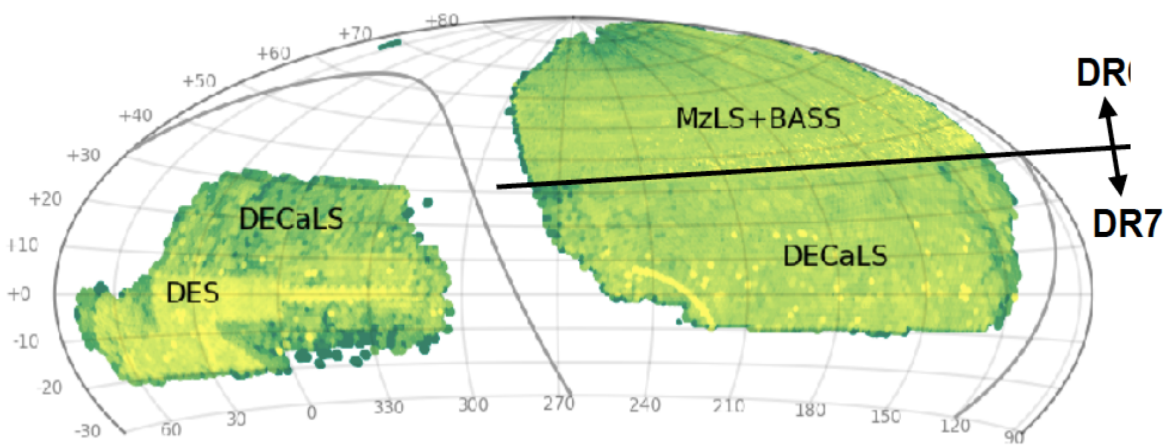
- **North** (*5k deg²*) **BASS** gr-bands, **MzLS** z-band
- **South** (*9k deg²*) **DECaLS** grz bands



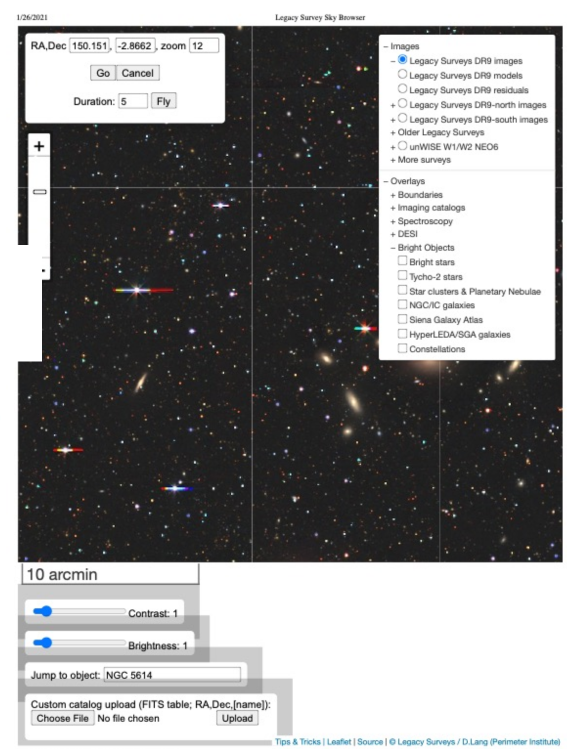


One infrared survey completed

- **All Sky WISE** (NASA satellite)
  W_1 W_2 bands

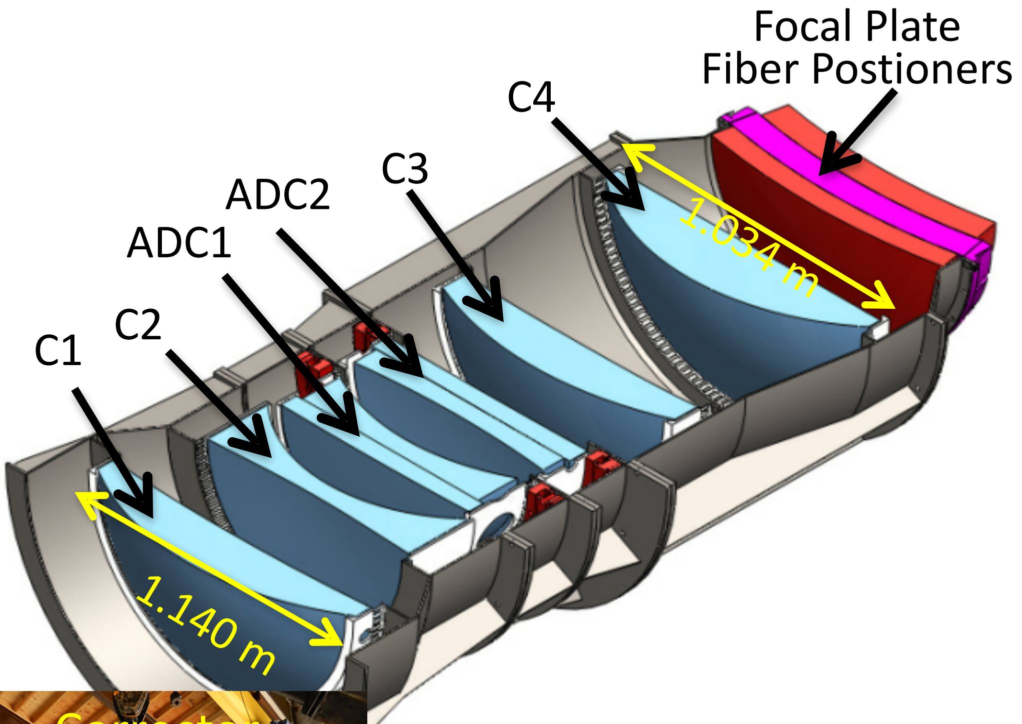


- Images combined using Tractor code
- DR9 published January 2021
- 20,000 sq. deg.
- Depths (AB mag): g < 24.7, r < 23.9, z < 23.0, From WISE W1 < 20.72, W2 < 19.97
- > 2.0 billion unique sources
- Viewer and other tools available
- Tractor Catalogs (photometry + profile/shape), Image Viewer, Image cutouts)

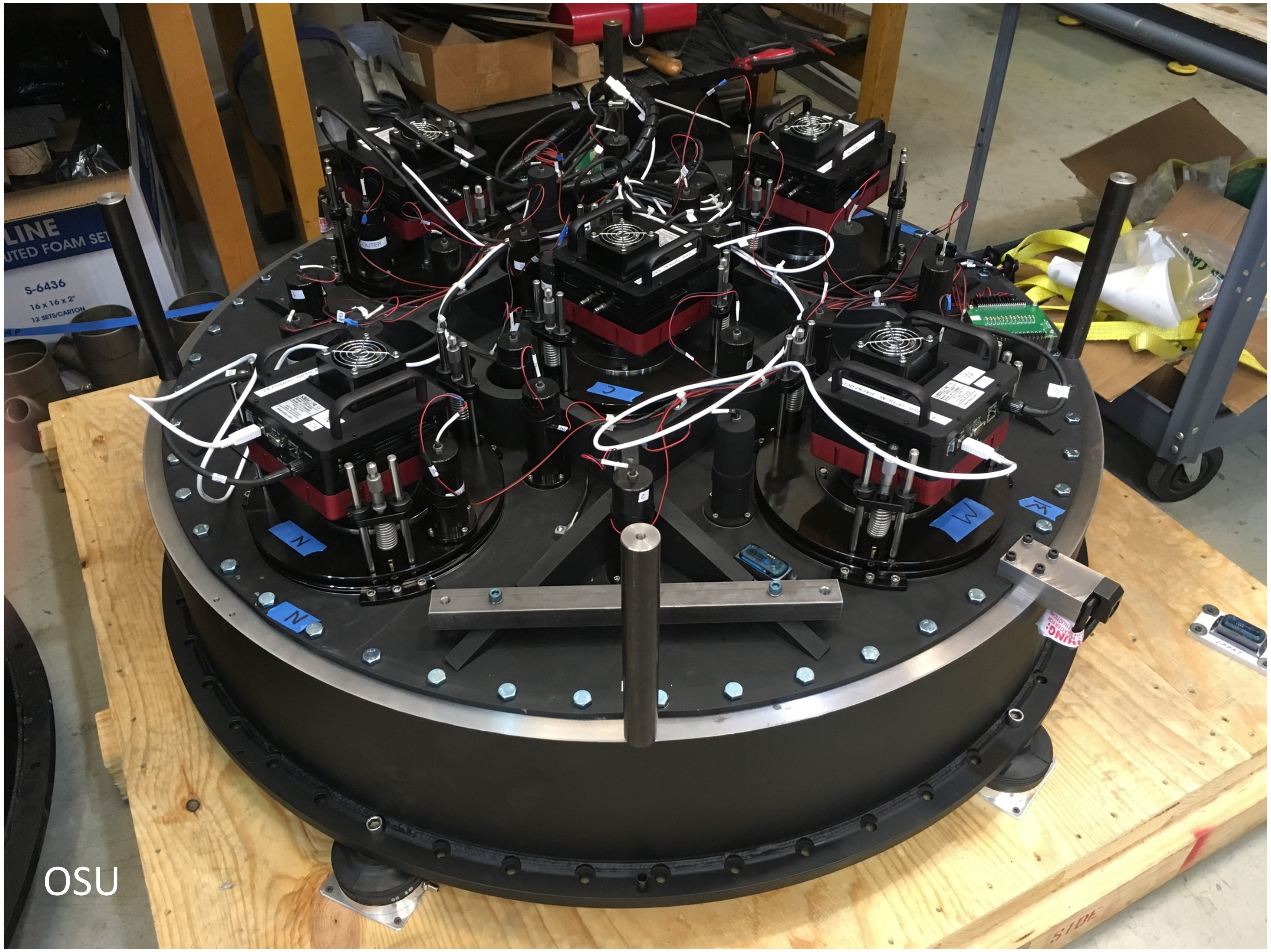


The DESI Optical Corrector

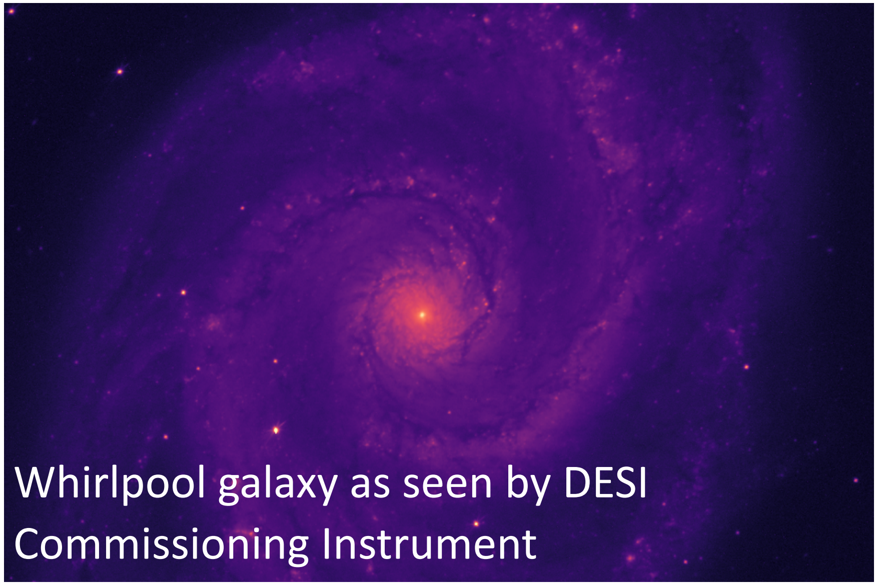
- Magnifies f/2.1 Mayall prime focus to f/4.5 (17.1m EFL)
- 8 sq. deg., 3.2° D FoV new 6-lens corrector
- Two prism based broadband atmospheric dispersion compensators (up to 60° from zenith)
- Geometric blur < 0.4 arcsec FWHM places < 70 μm FWHM spot onto 110 μm fiber over entire 1m focal plane.



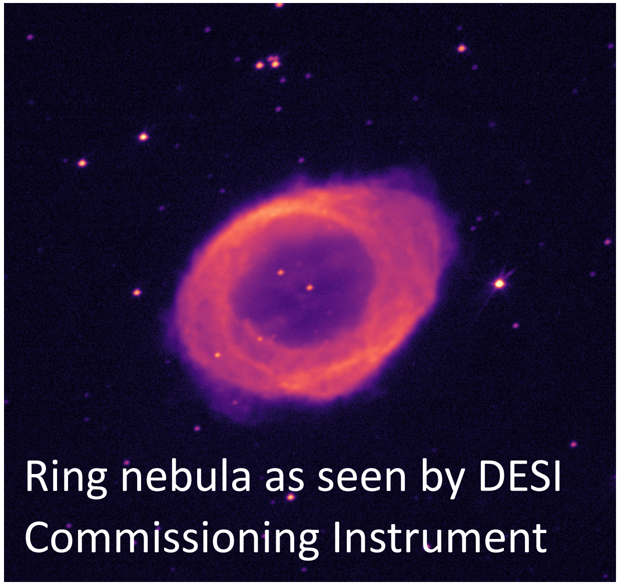
Commissioning Instrument with Commercial Cameras



Corrector Optics On-sky Performance



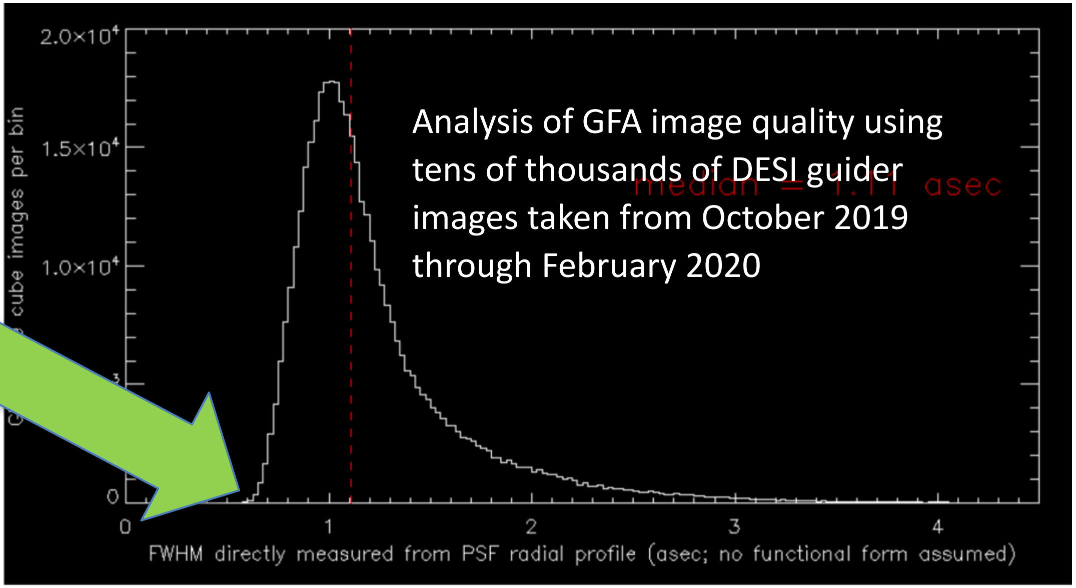
Whirlpool galaxy as seen by DESI Commissioning Instrument



Ring nebula as seen by DESI Commissioning Instrument

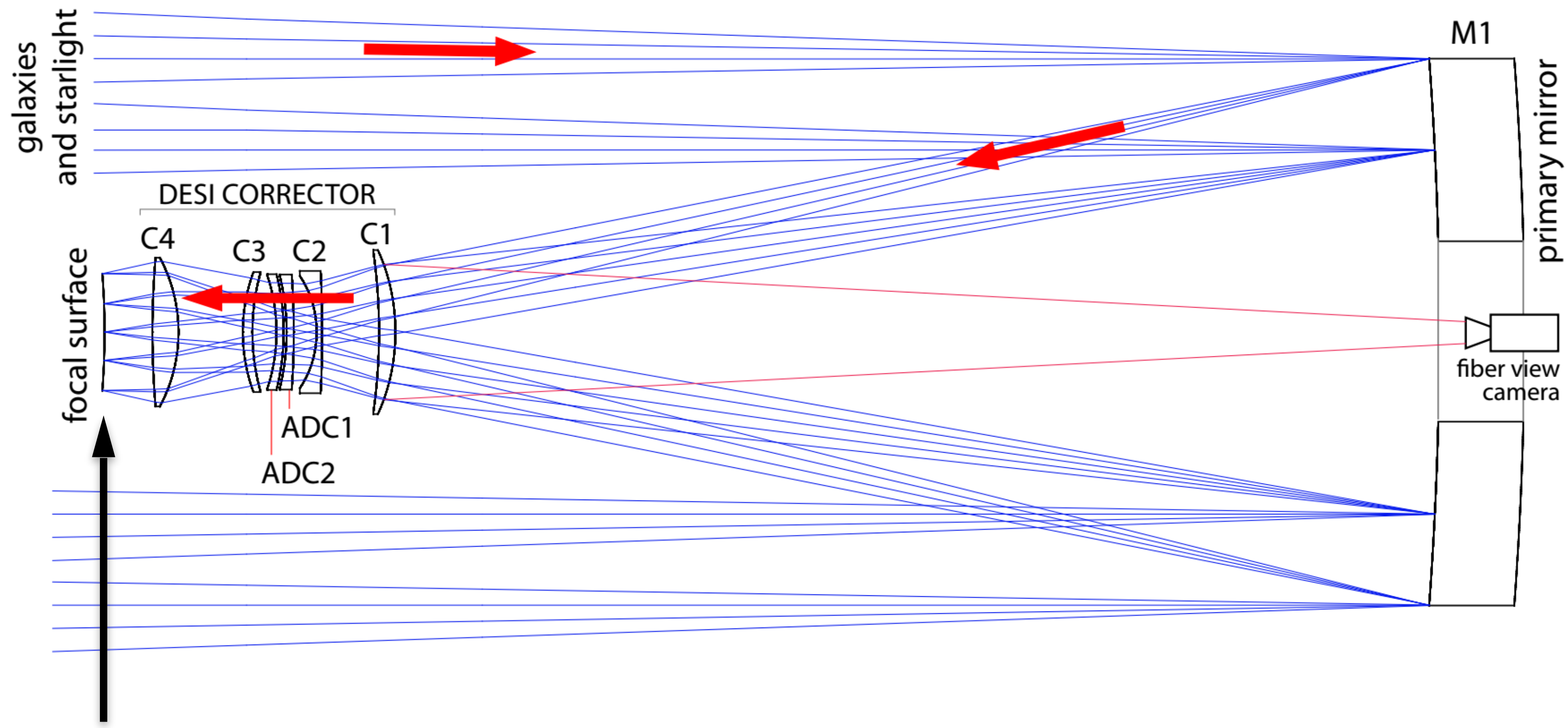
On-sky FWHM values as low as 0.6” confirmed by visual inspection.

Appears to be seeing limited!



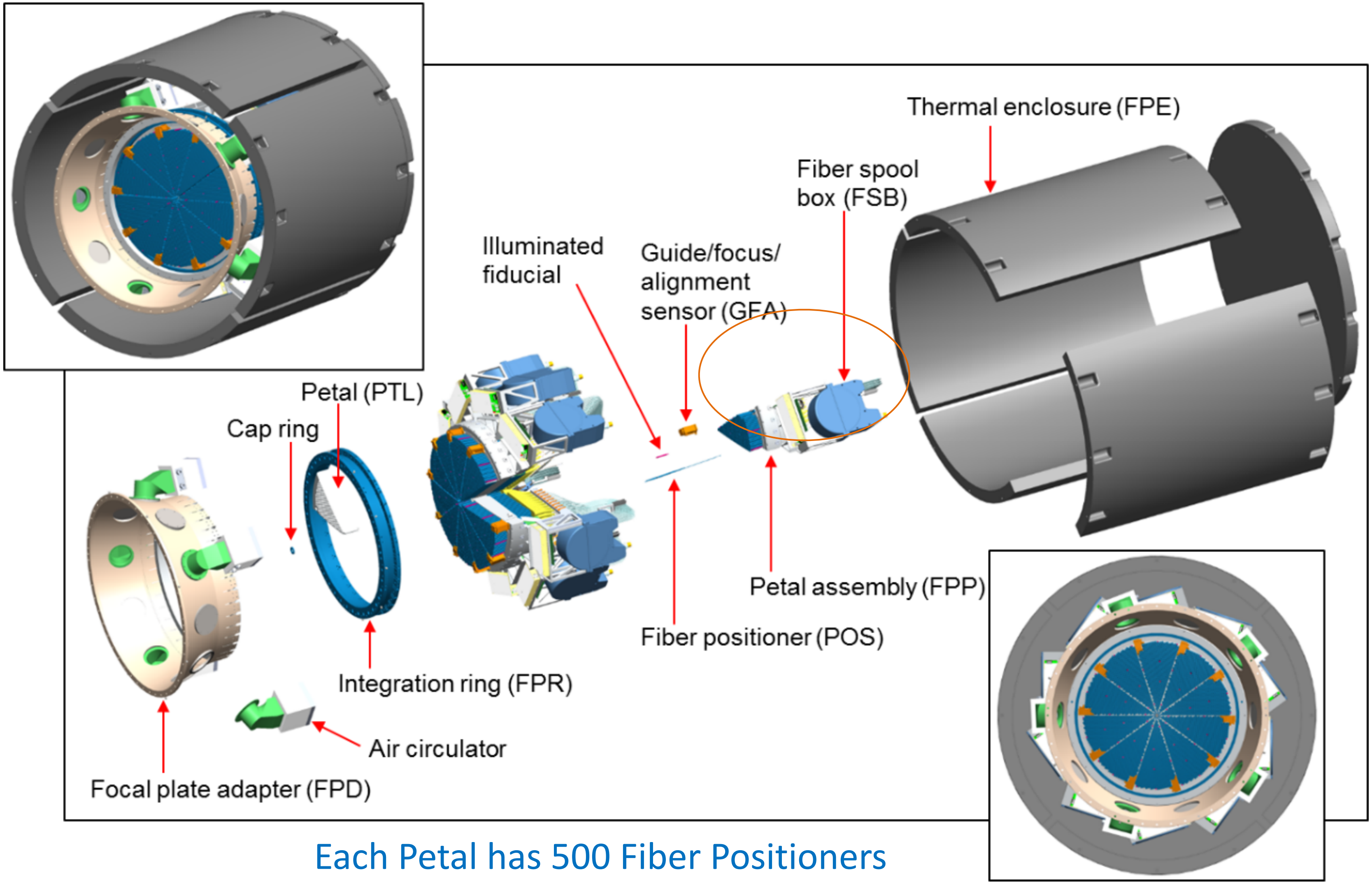
Analysis of GFA image quality using tens of thousands of DESI guider images taken from October 2019 through February 2020

Path of Light from Galaxies to the DESI Fiber Positioners



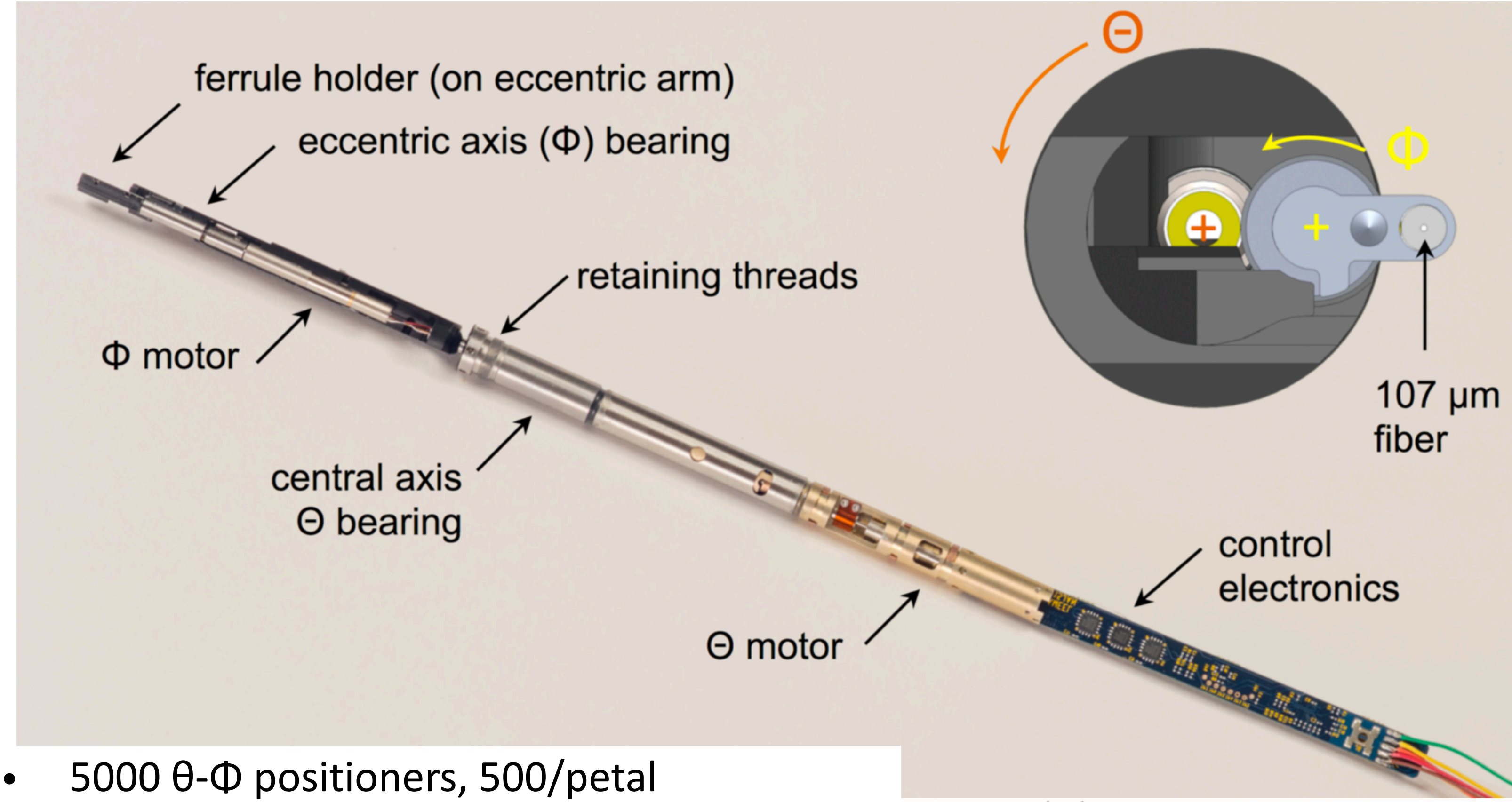
5000 Fiber Positioner Robots go here

Focal Plate Assembly: 10 Petals → 10 Fiber Optic Cables → 10 Spectrographs

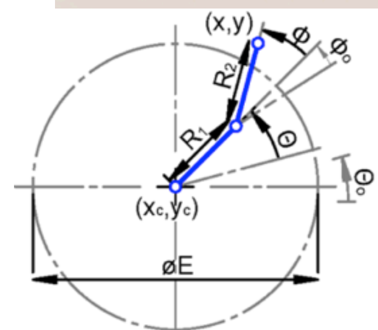


Each Petal has 500 Fiber Positioners

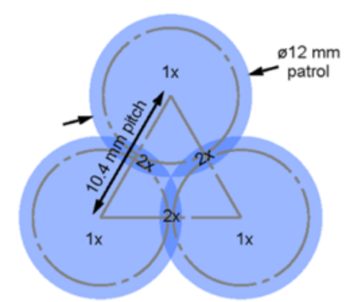
DESI Fiber Positioners



- 5000 θ-Φ positioners, 500/petal
- Simple open-loop PWM design based on miniature (4mm) gear motors.
- 10.4 mm pitch, 12 mm patrol disk
- Fiber-view camera feedback
- < 2 µm rms accuracy w/correction move
- Collision avoidance software

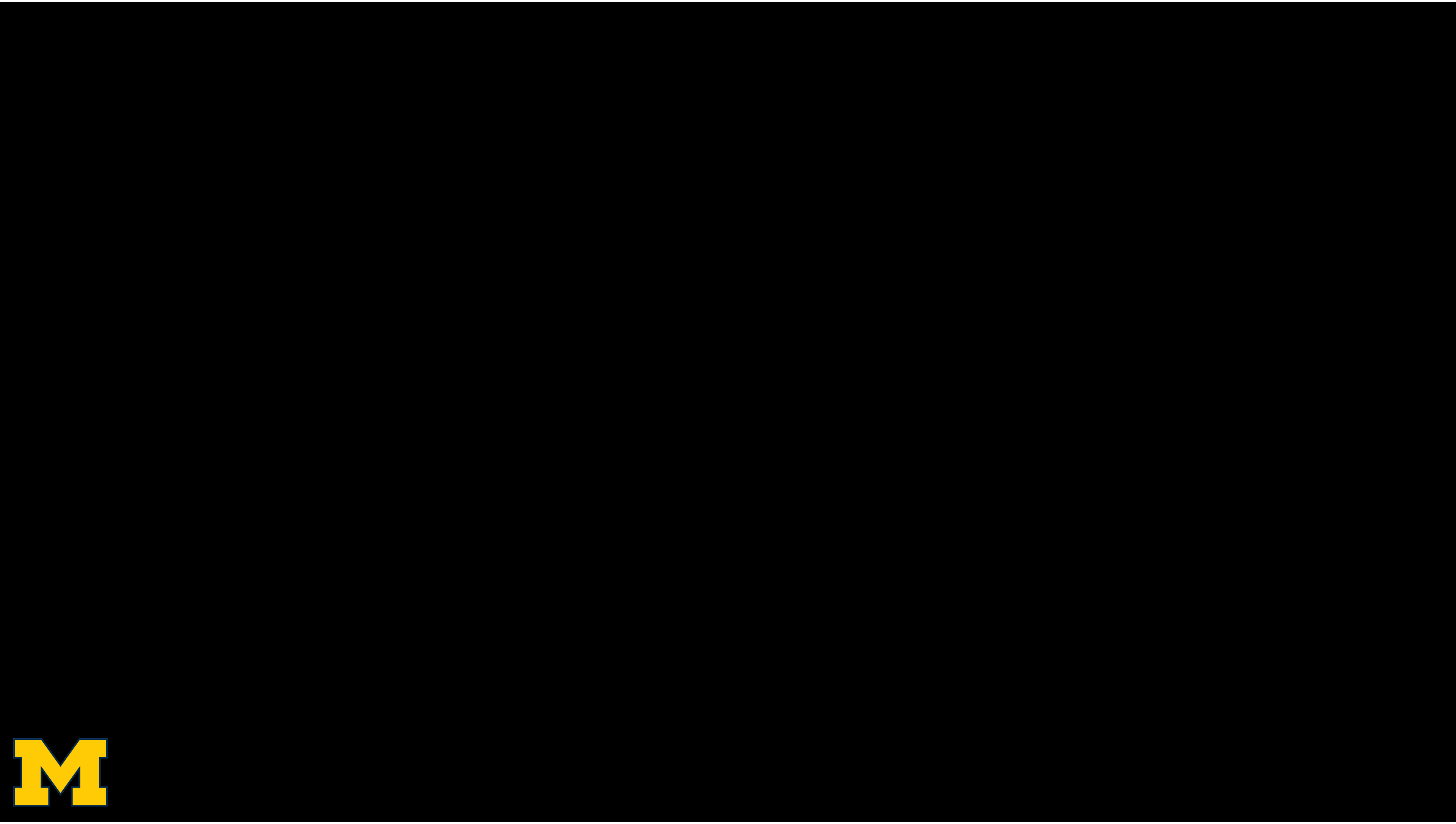


KINEMATICS / COORDINATES

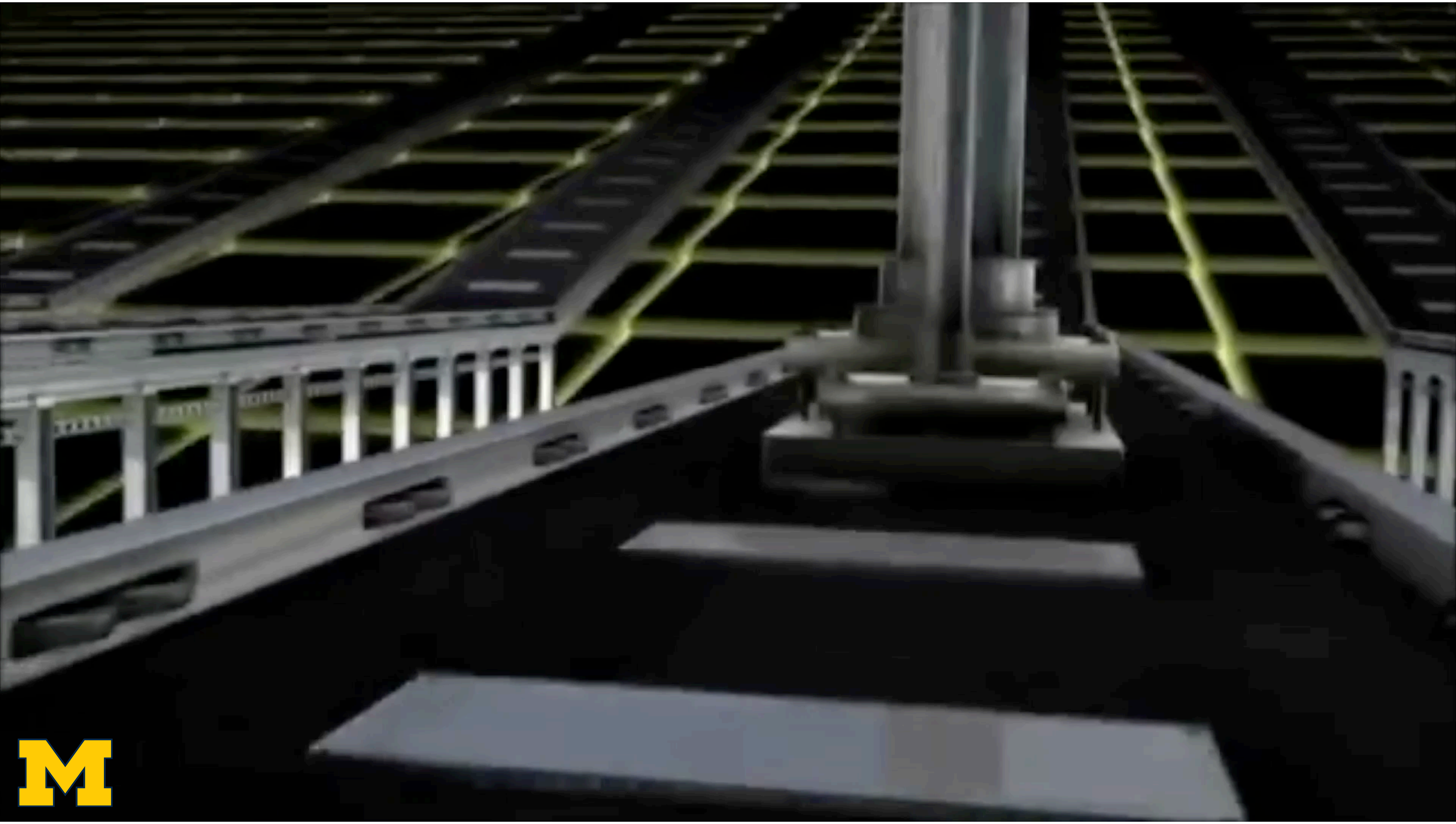


EXACT COVERAGE
R1 = R2 = 3 mm

Fiber Positioner Assembly: Critical Assembly

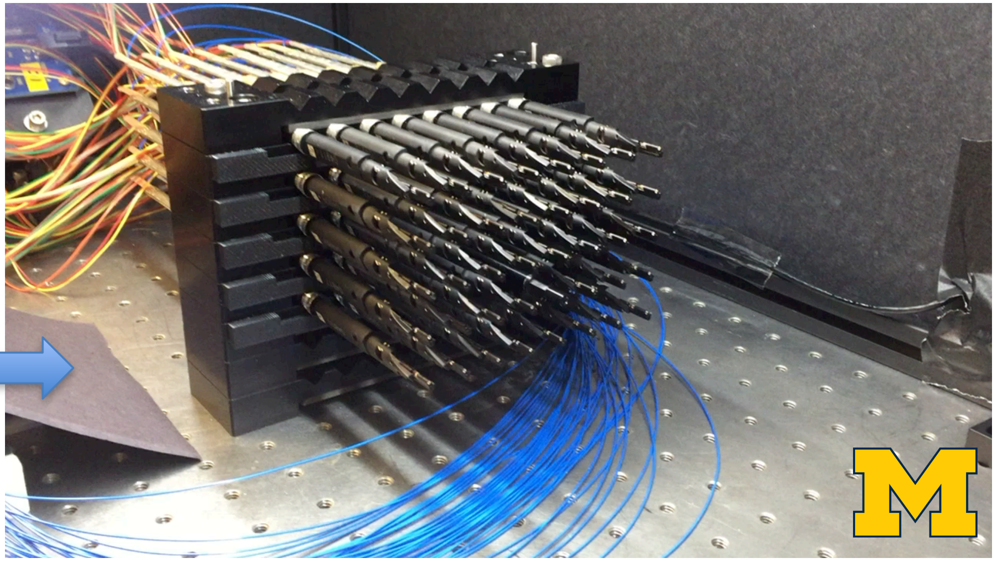


Fiber Positioners: Final Assembly

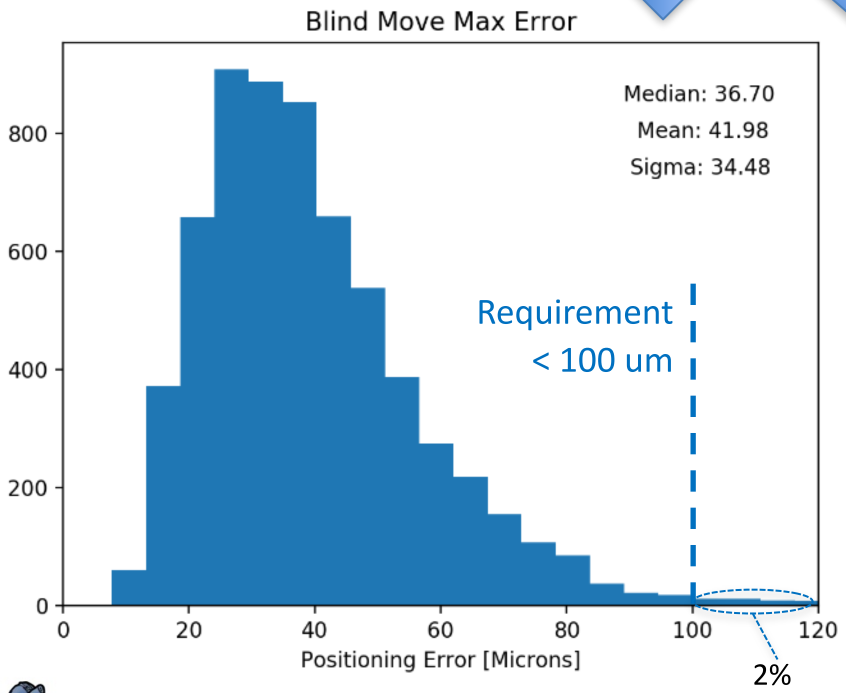


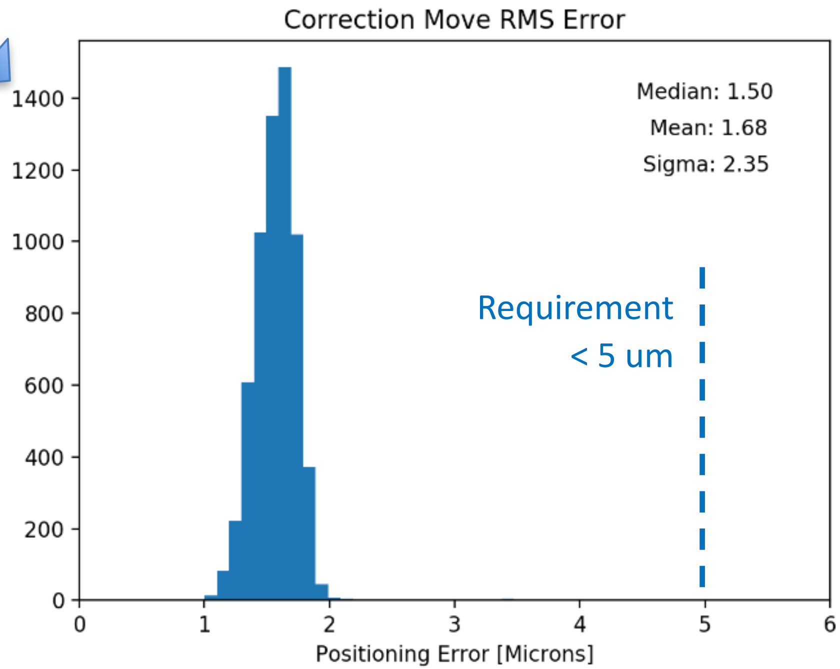
QA/QC Testing

Each Positioner is rigorously tested for x-y accuracy (196 points over patrol disk) and repeatability.



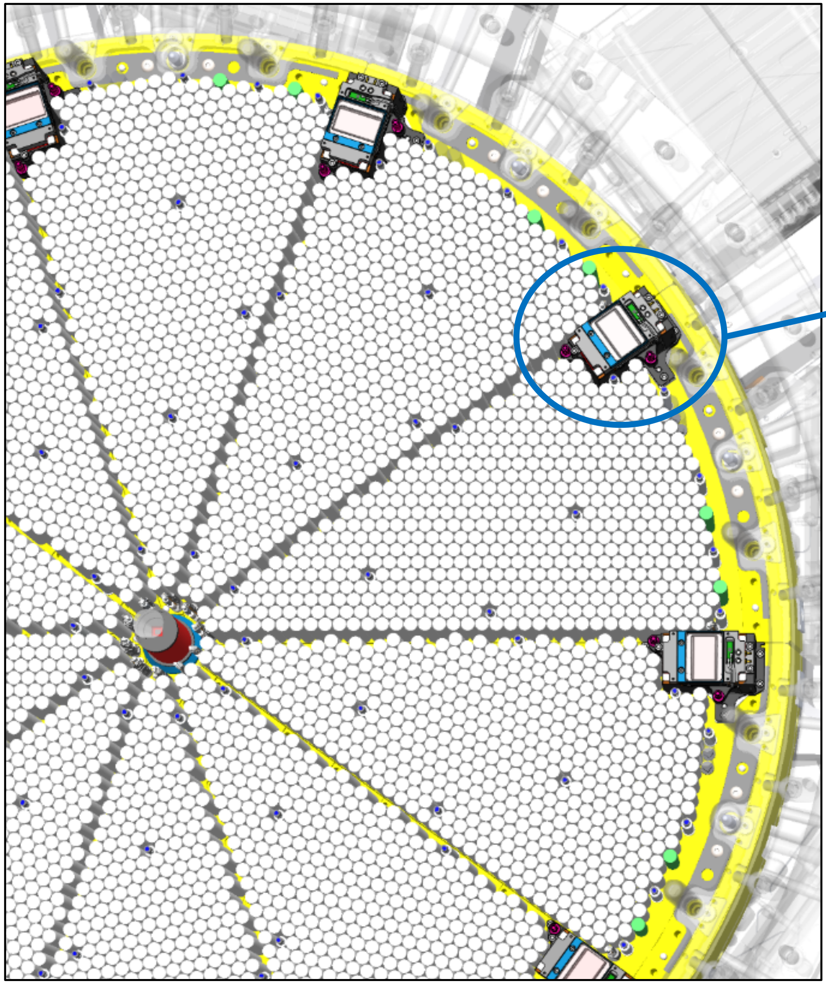
Performance of first 6404 DESI positioners built and tested at the University of Michigan

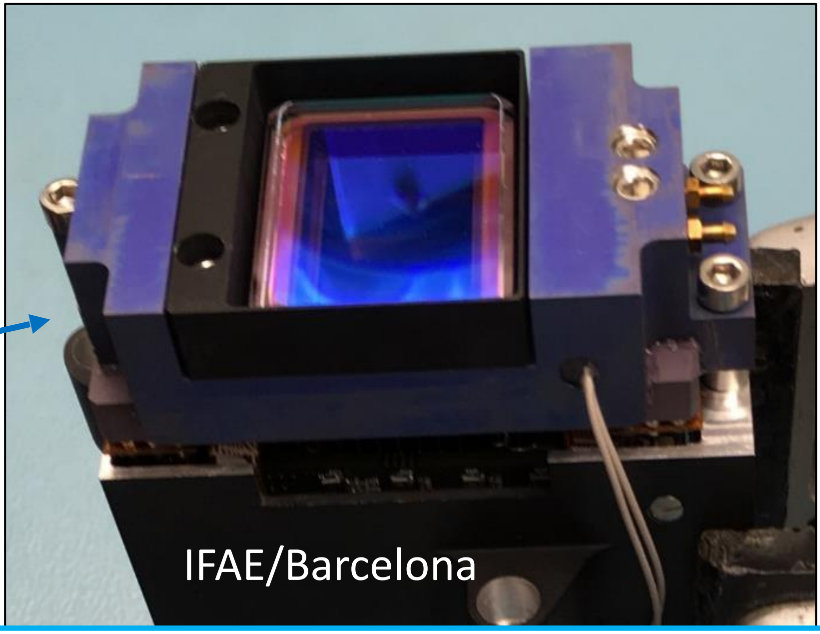




Guide/Focus Assemblies (GFAs)

10 Custom CCD cameras (one per petal) **guide** telescope and **focus/align** the corrector + focal plane on the 6 DOF hexapod





GFA cameras

two types - identical except for optical filter:

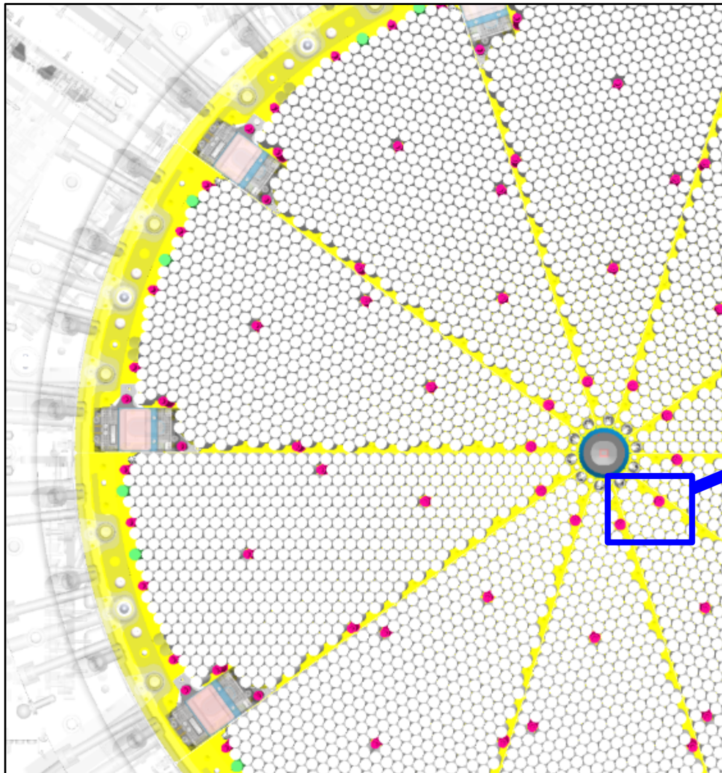
6 x guide star tracking

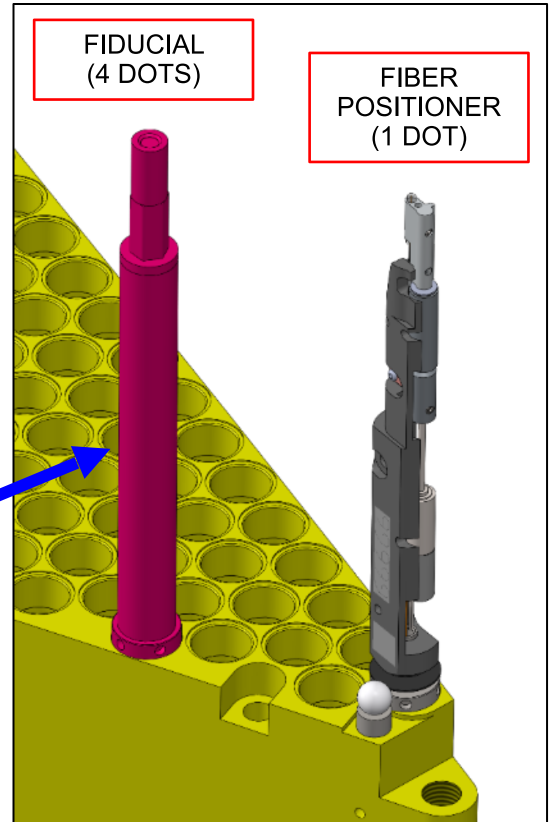
- feedback to telescope

4 x focus and alignment

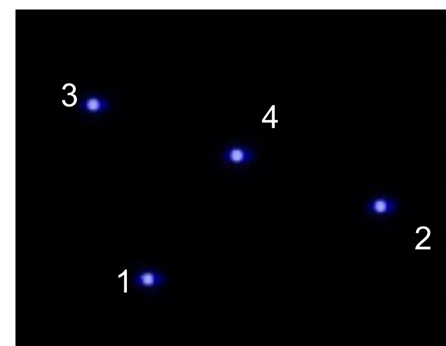
- data for hexapods

Fiducial point sources, embedded throughout the array constrain optical plate scale and distortion polynomials





120 total fiducials
x 4 dots each



- Precisely surveyed to GFA sensors
- When viewed by FVC from near primary mirror through the corrector, provides optical distortion and mechanical deformations data

Fiber View Camera

- Observes illuminated fiducials ... *and* backlit fiber positioners
- Provides feedback to positioners to align fibers to guide stars

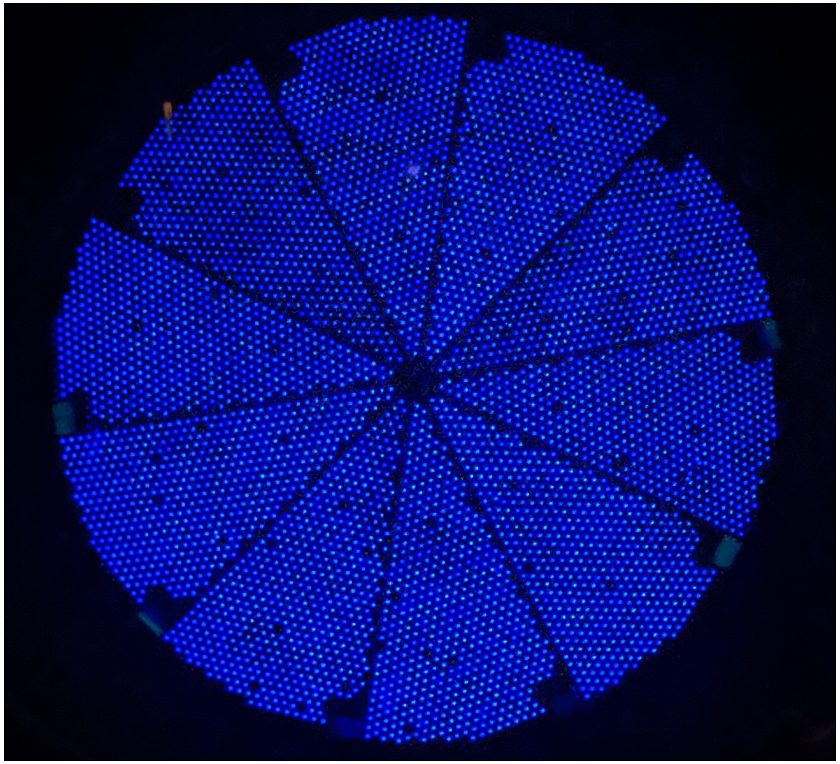
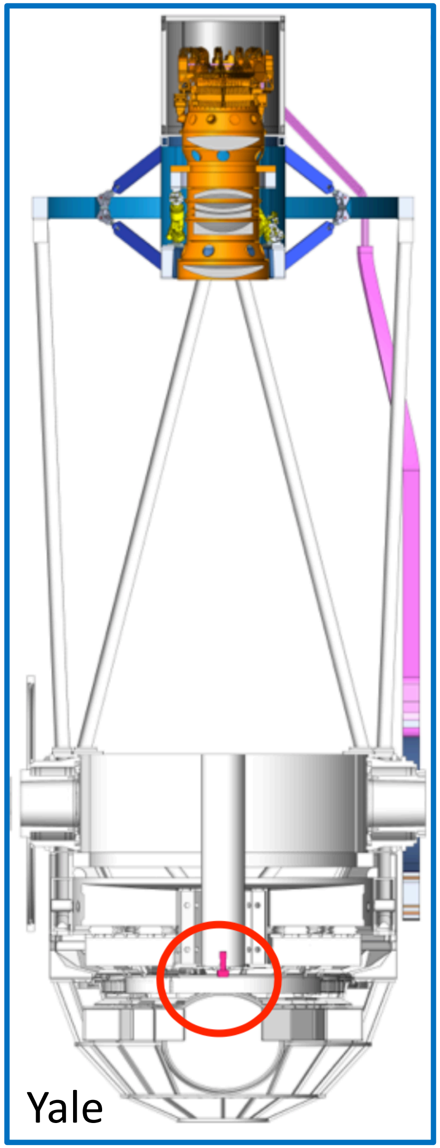
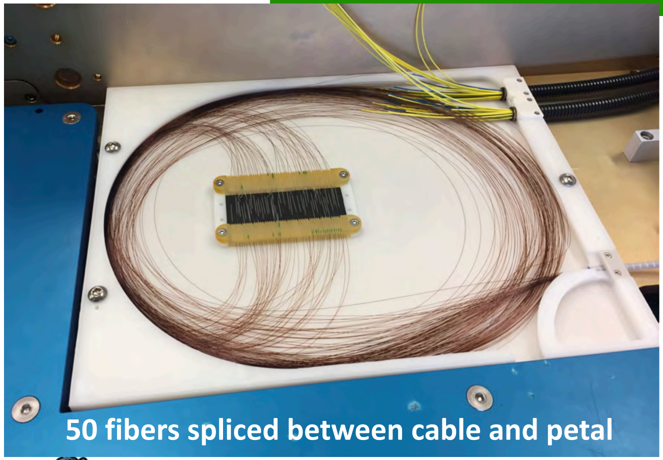
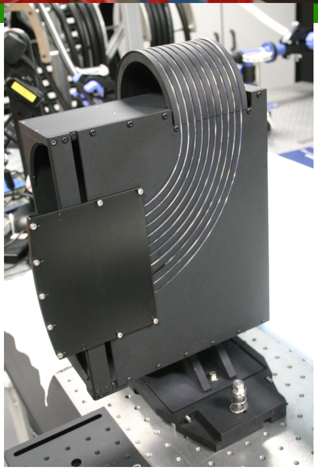


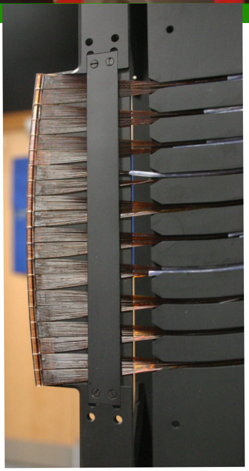
Image of back-illuminated fiber tips of the 10 installed petals, taken through the DESI corrector. Blank spots are GFAs (at petal corners) and fiducial locations.

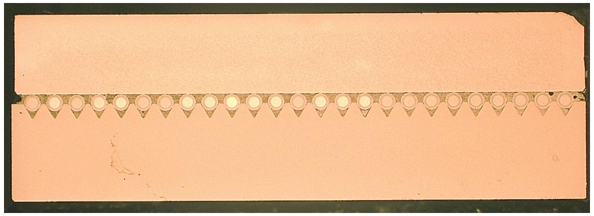


250 km of Fiber Optic Cable



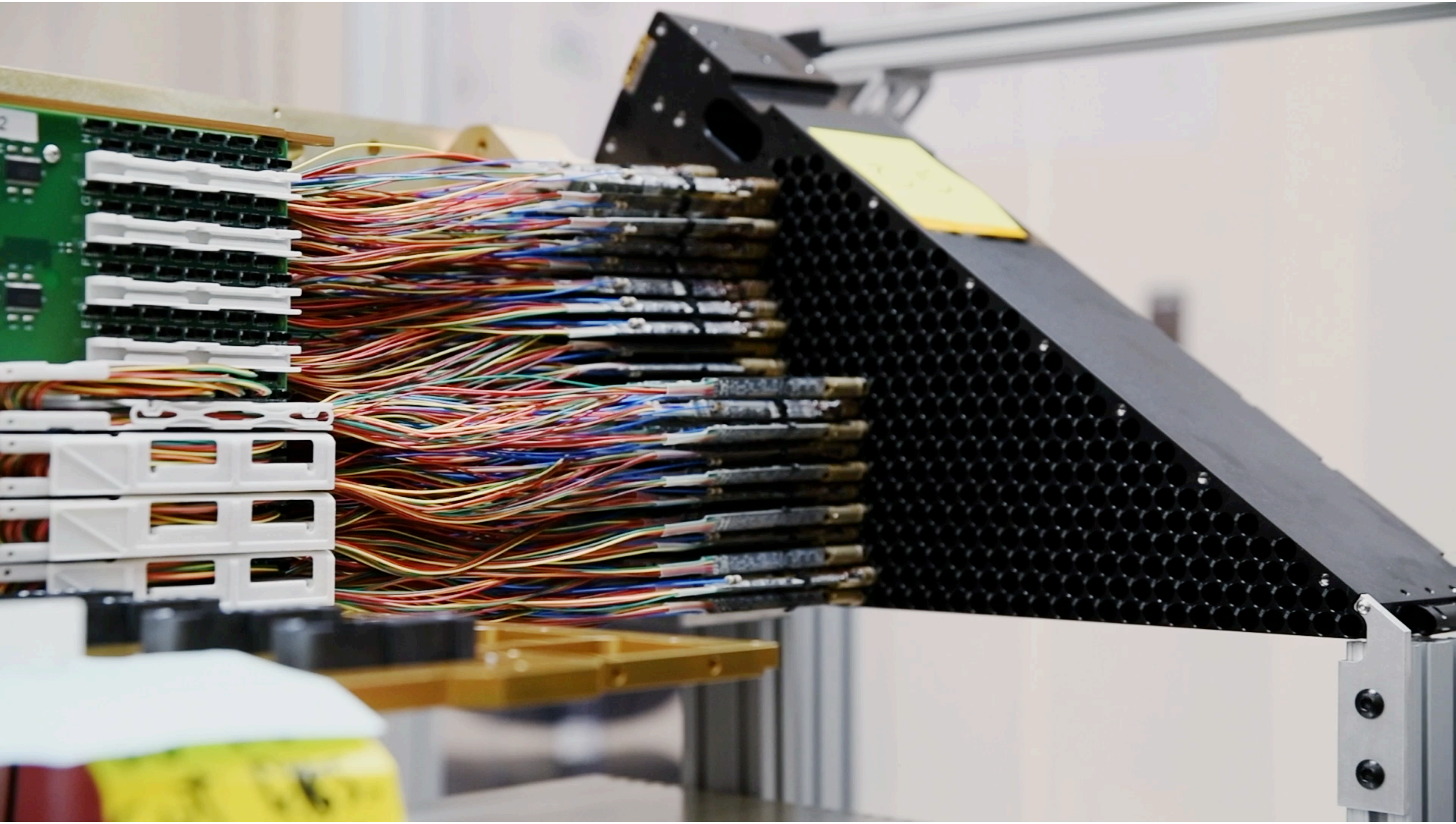




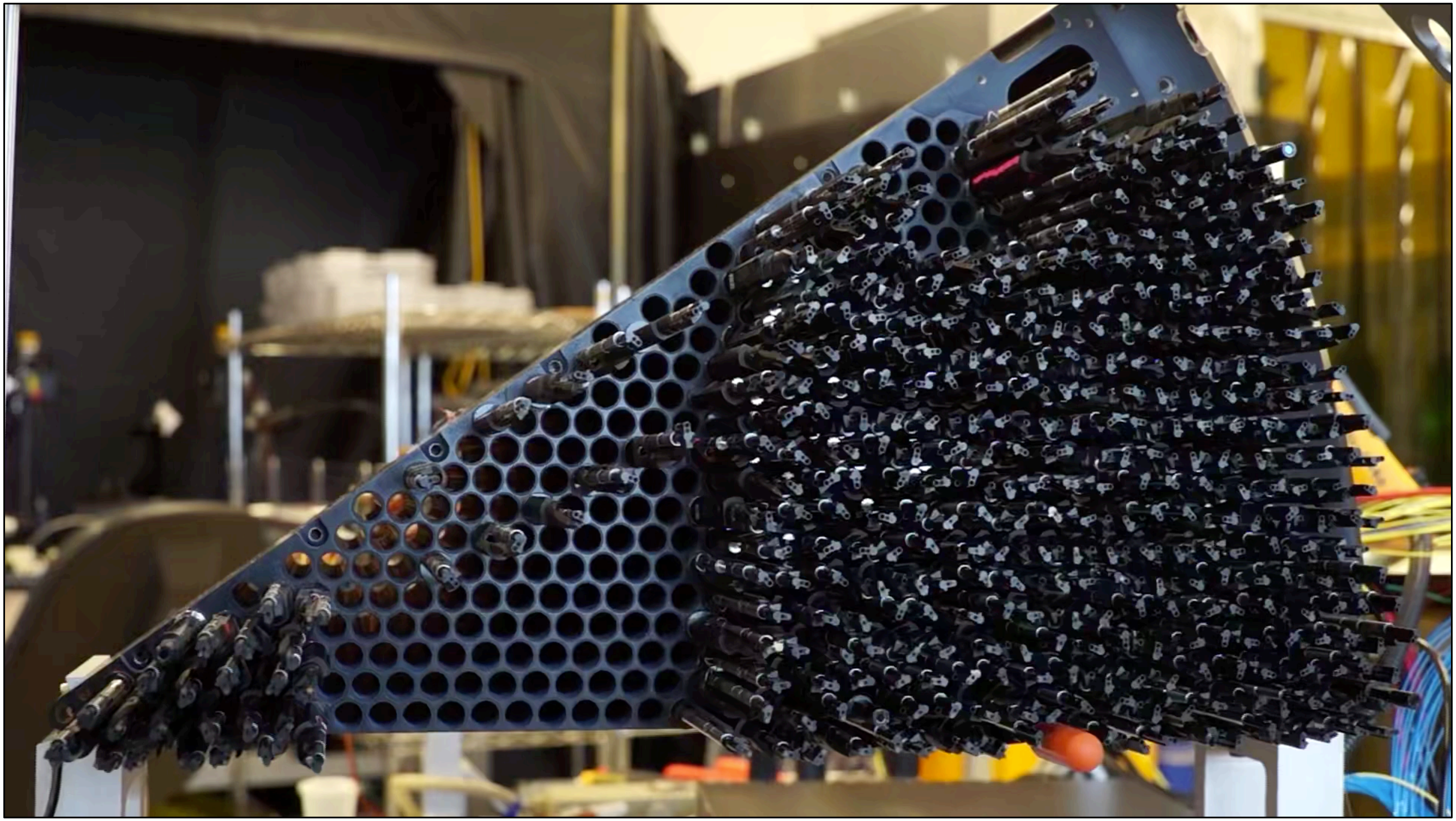


Fiber slit assembly

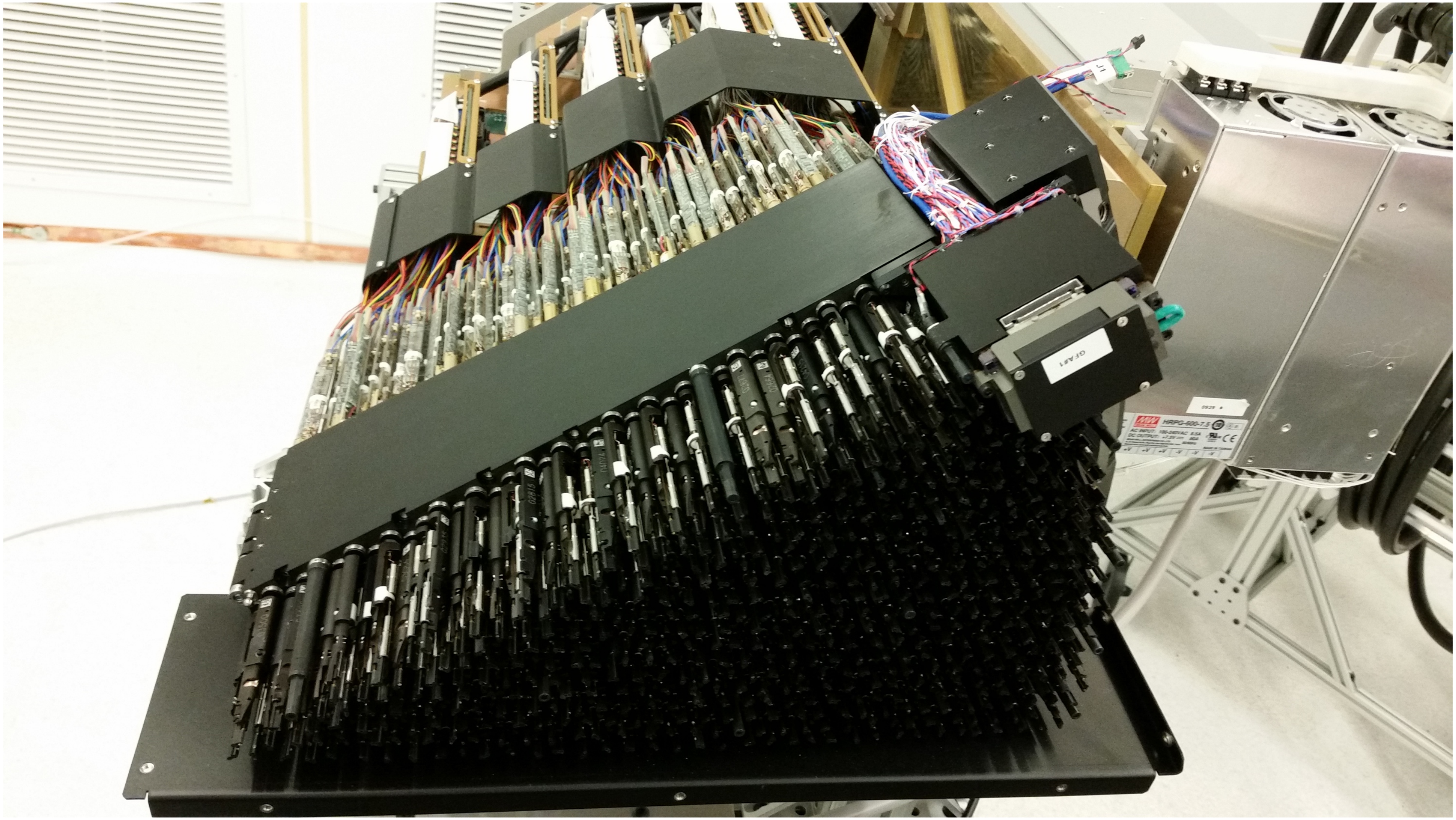
Putting the Focal Plane Together at LBNL

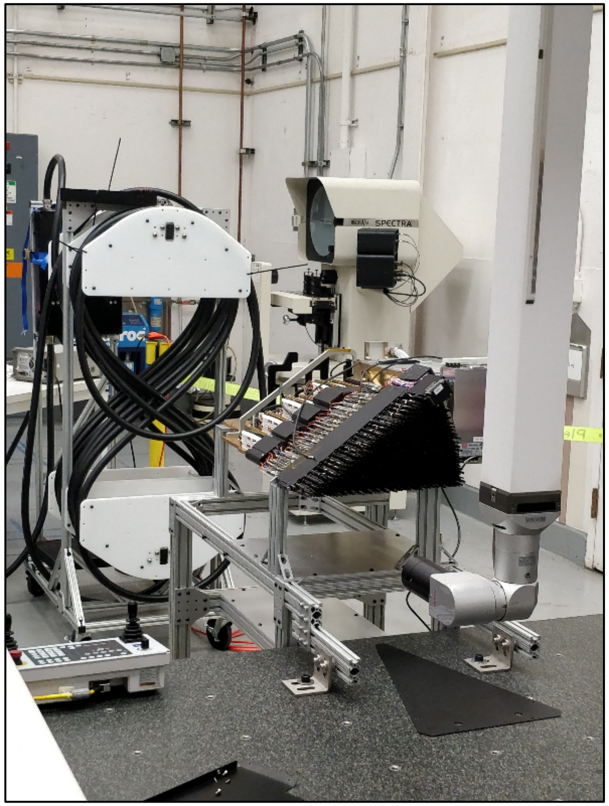


R&D petal with ~ 300 positioners



Completed Petal With 500 Positioners, Fiducials, GFA, Petal Control Computer, Power Supplies…





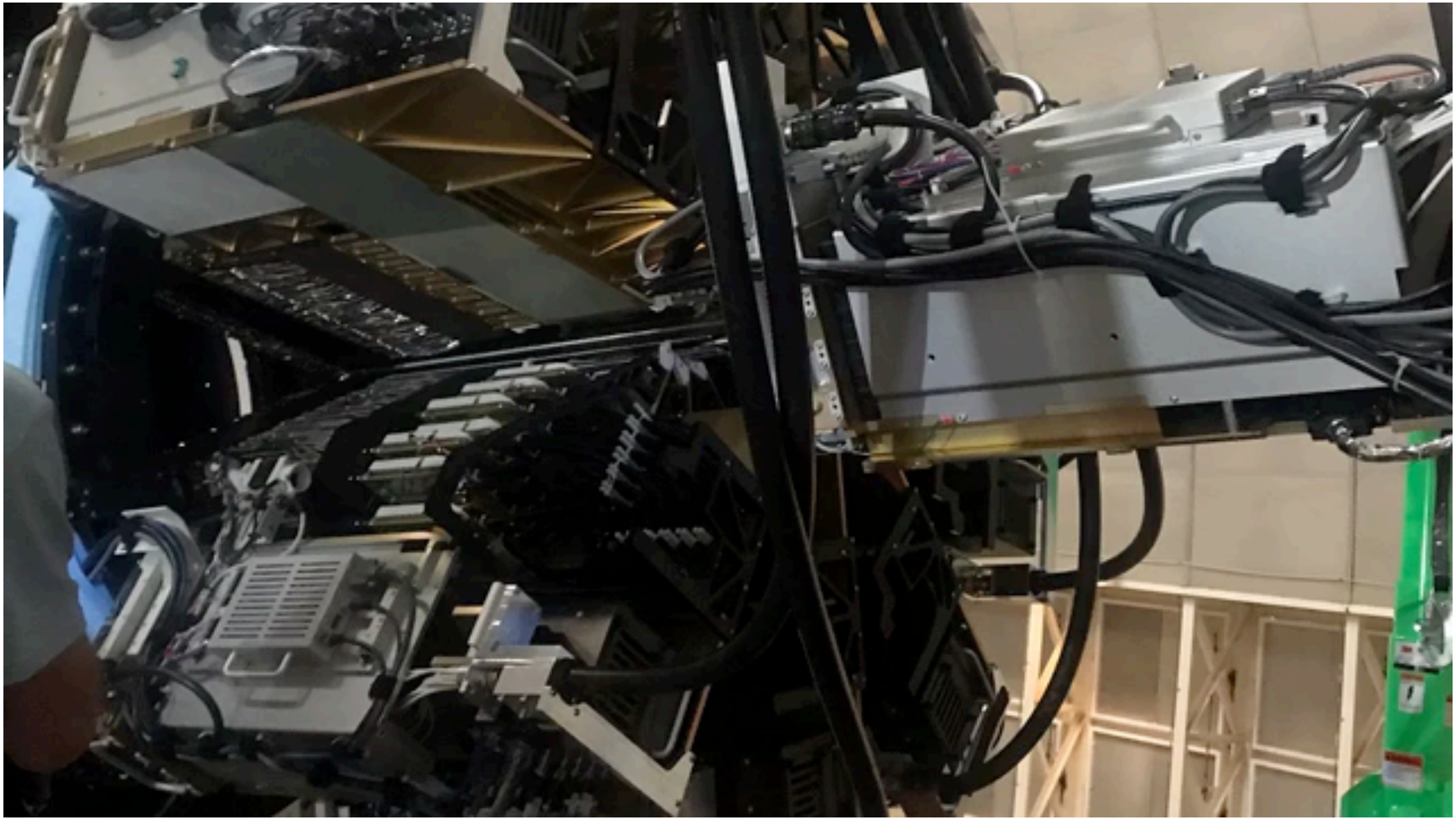
Petal with fiber bundle in metrology

Finished Petals and Fiber Cables Awaiting Shipment to Kitt Peak.

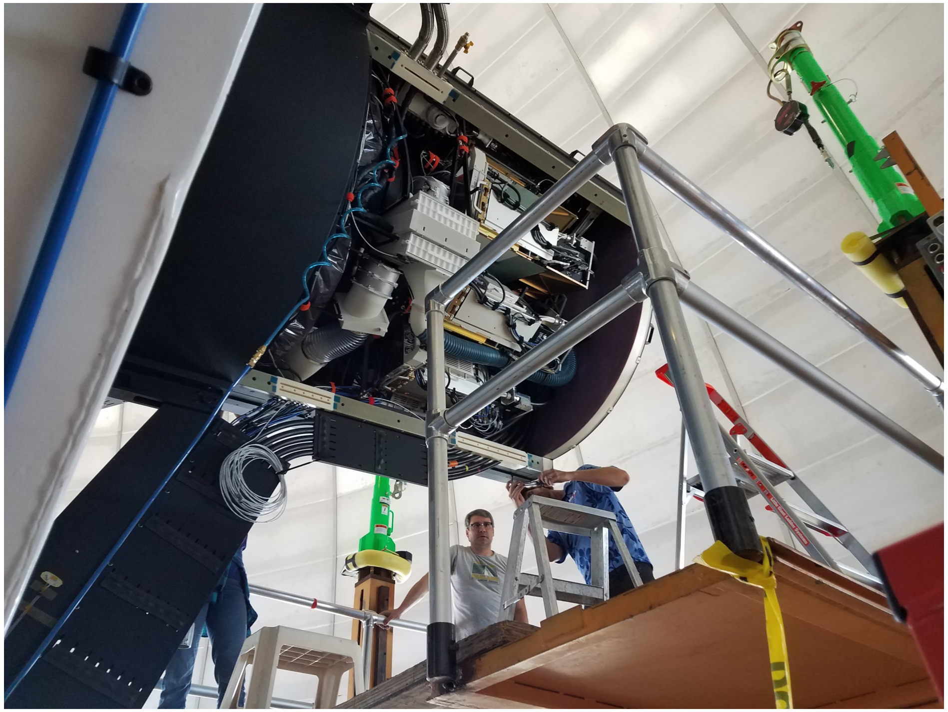
Installing Petals into FP at Kitt Peak

Petal is mounted to installation sled arm and slowly cranked into place

Last Petal Installation



Wrapping Up the Focal Plane

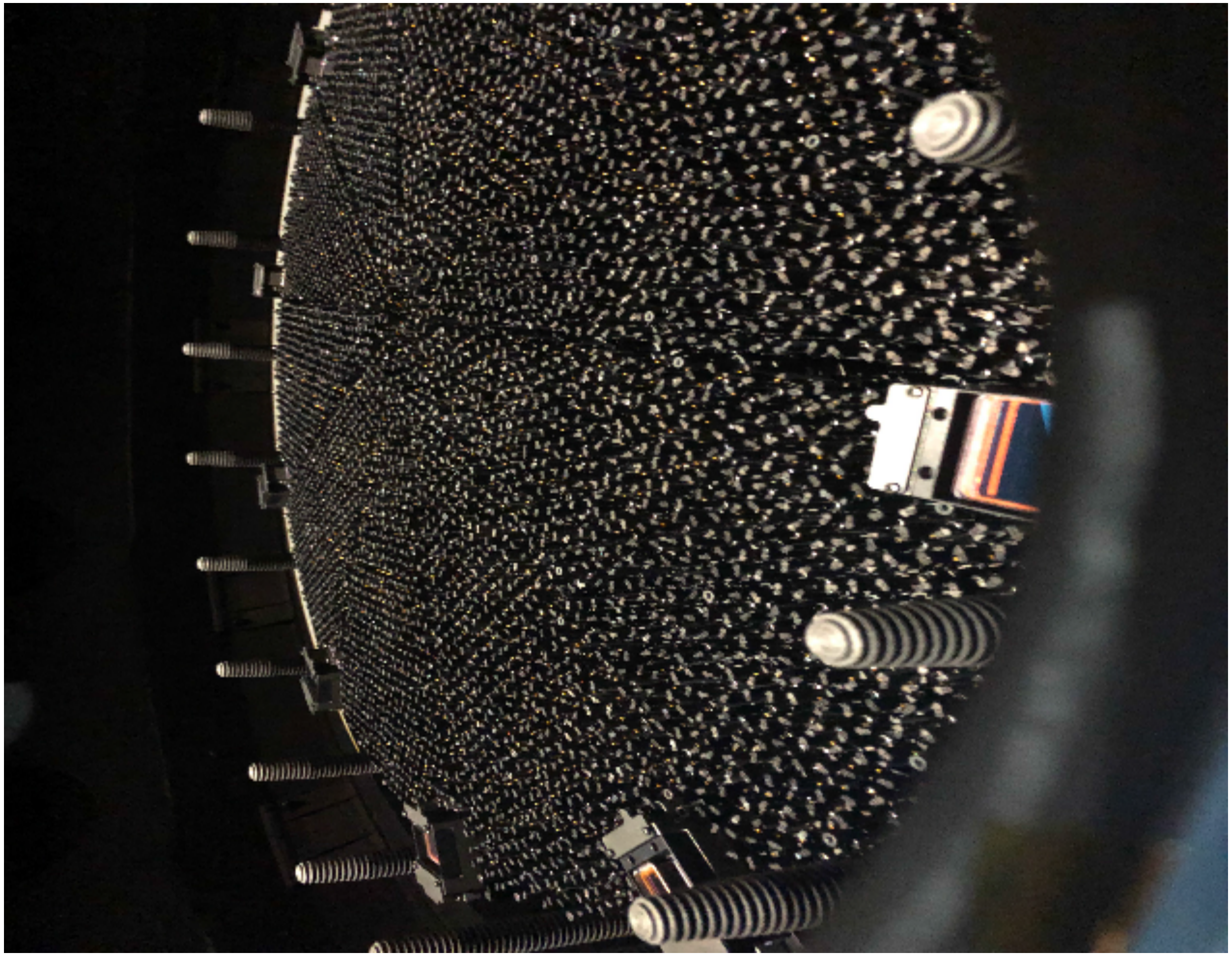


All ten petals installed & electrically verified

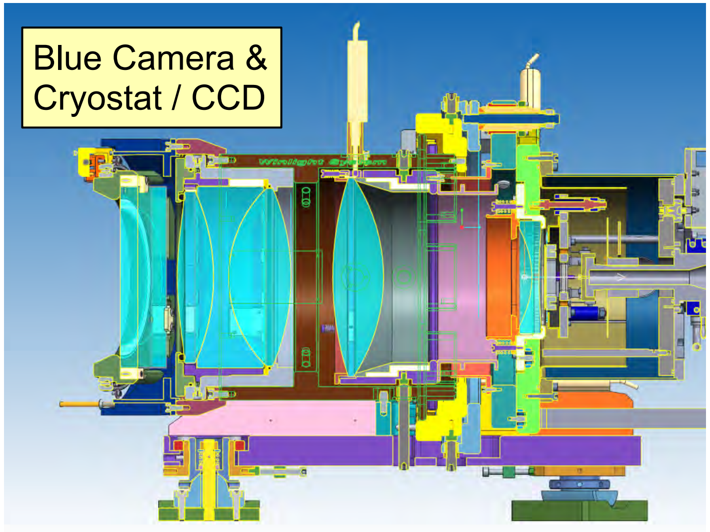
Focal plane inside its environmental enclosure

View of 5000 fiber tips

Telescope side of focal plane viewed through a porthole in the focal plane adapter, showing fiber ends of positioners, and GFAs.

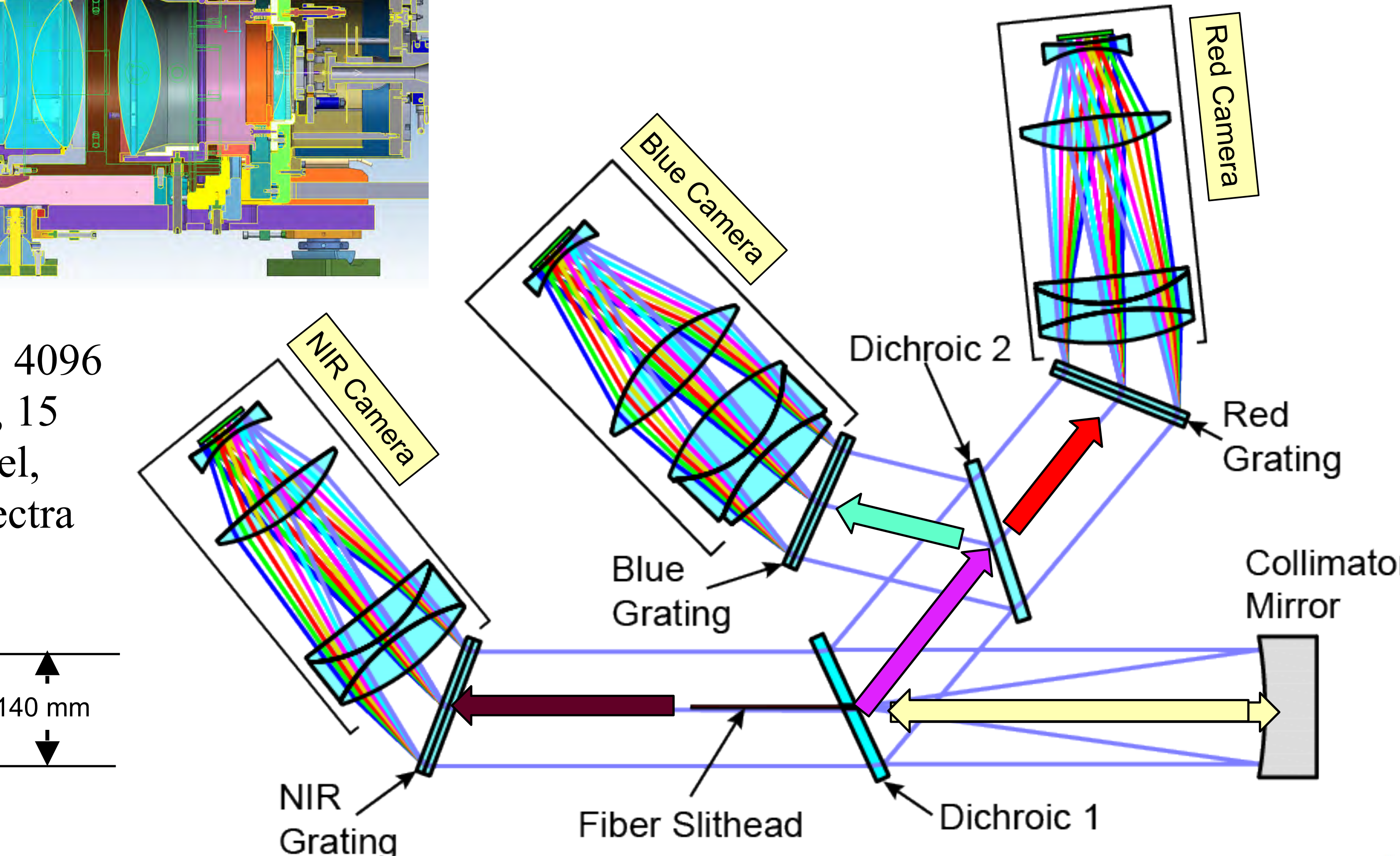


Spectrographs



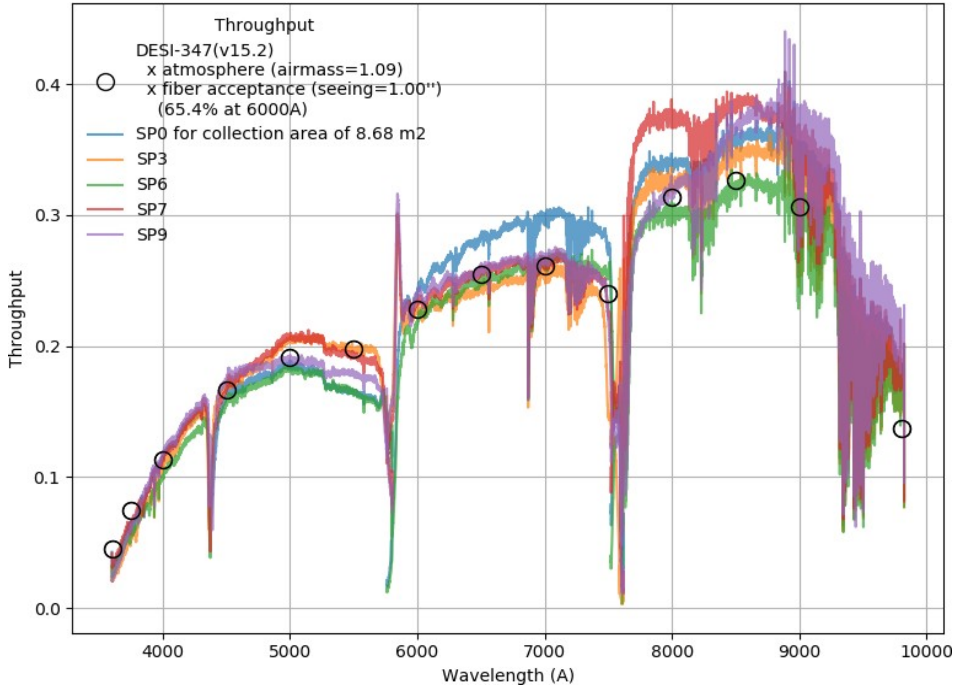
10 fiber fed spectrographs on Mayall floor each w/ 500 channels, three bands (NIR, Red, Blue)

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



Ten Spectrographs Installed in Coudé Room

On-sky end-to-end throughput (lines) vs predictions (circles)



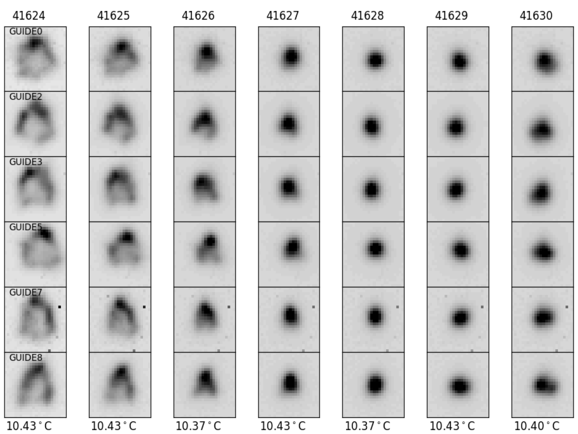
System throughput measured on-sky, real data from standard stars. Exceeds performance specifications at all wavelengths.

10 DESI Spectrographs
30 cryostats, 300 CCDs
500 million pixels!
Spectroscopic pipeline is working well.
Sky background subtraction is working at statistical limit.

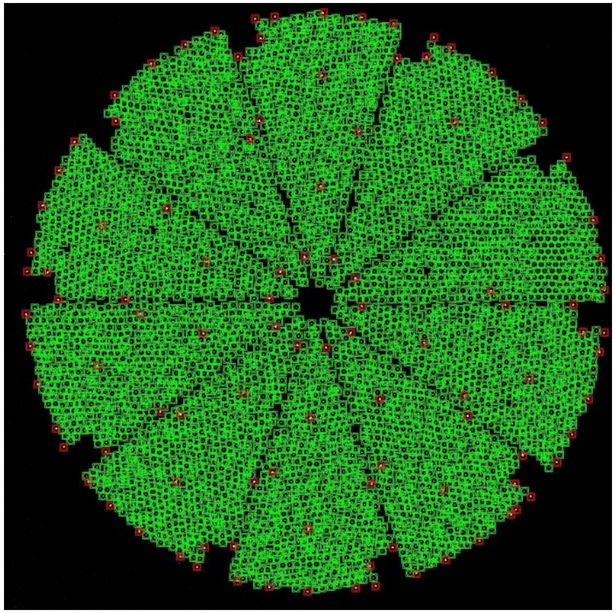
Installation, Commissioning Complete. Survey Validation Underway

- Mayall shut down February 2018 for DESI installation
- DESI elements all installed as of Dec 2019
- Commissioning from October 22, 2019 to March 16, 2020
- Kitt Peak closed down due to COVID-19 pandemic March 22, 2020
- Kitt Peak re-opens with restrictions, re-commissioning November, December, 2020
- Start of Survey Validation, December 14, 2020 and is continuing.

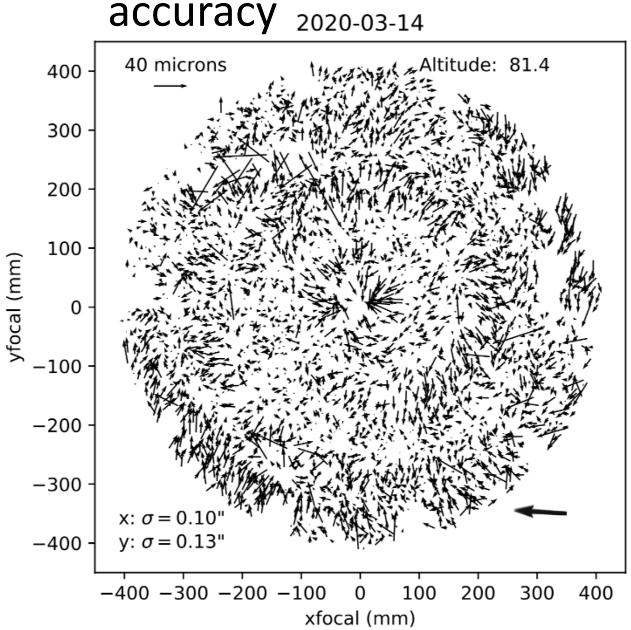
Testing Auto-Focus



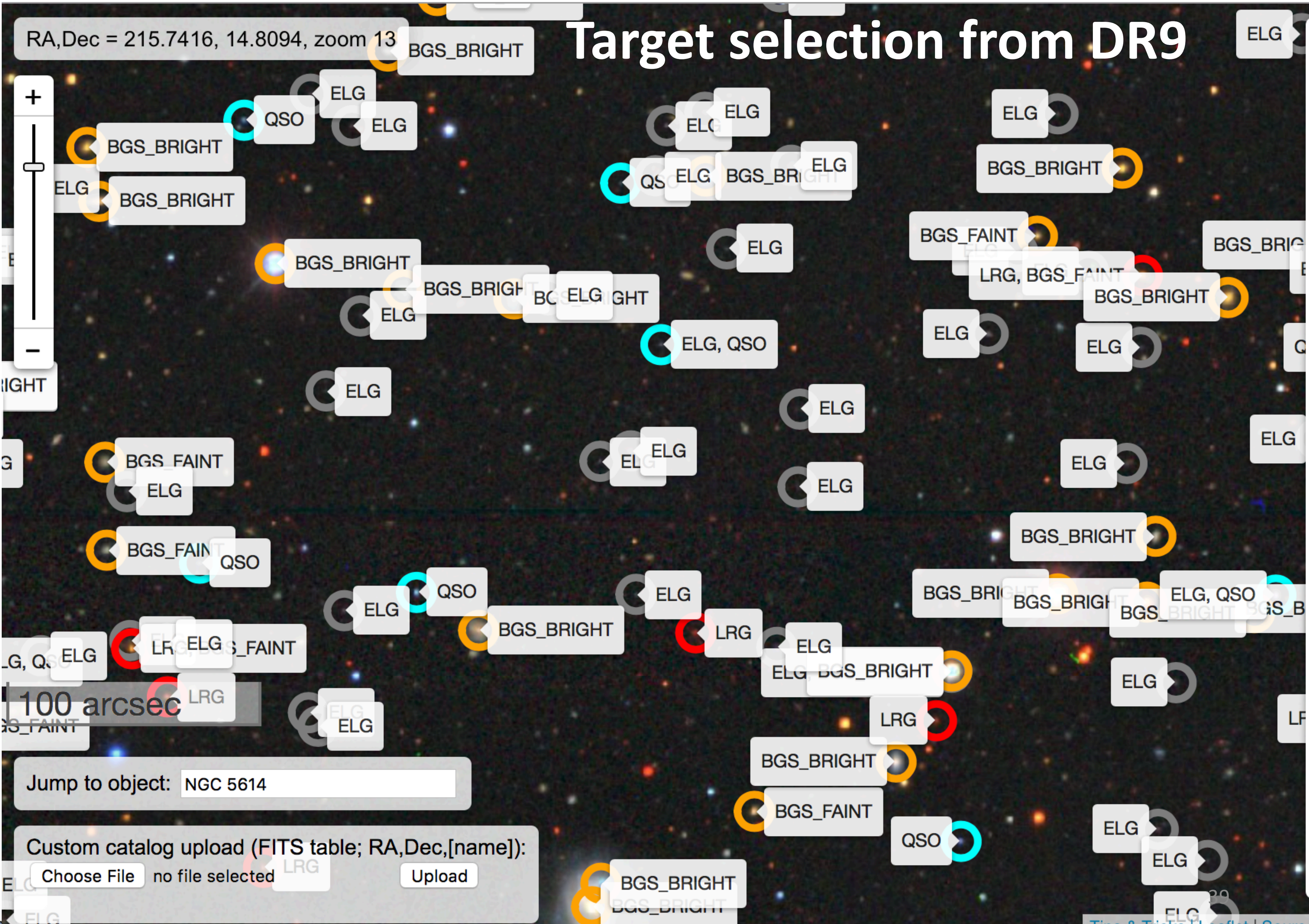
FVC identifying fibers/fiducials



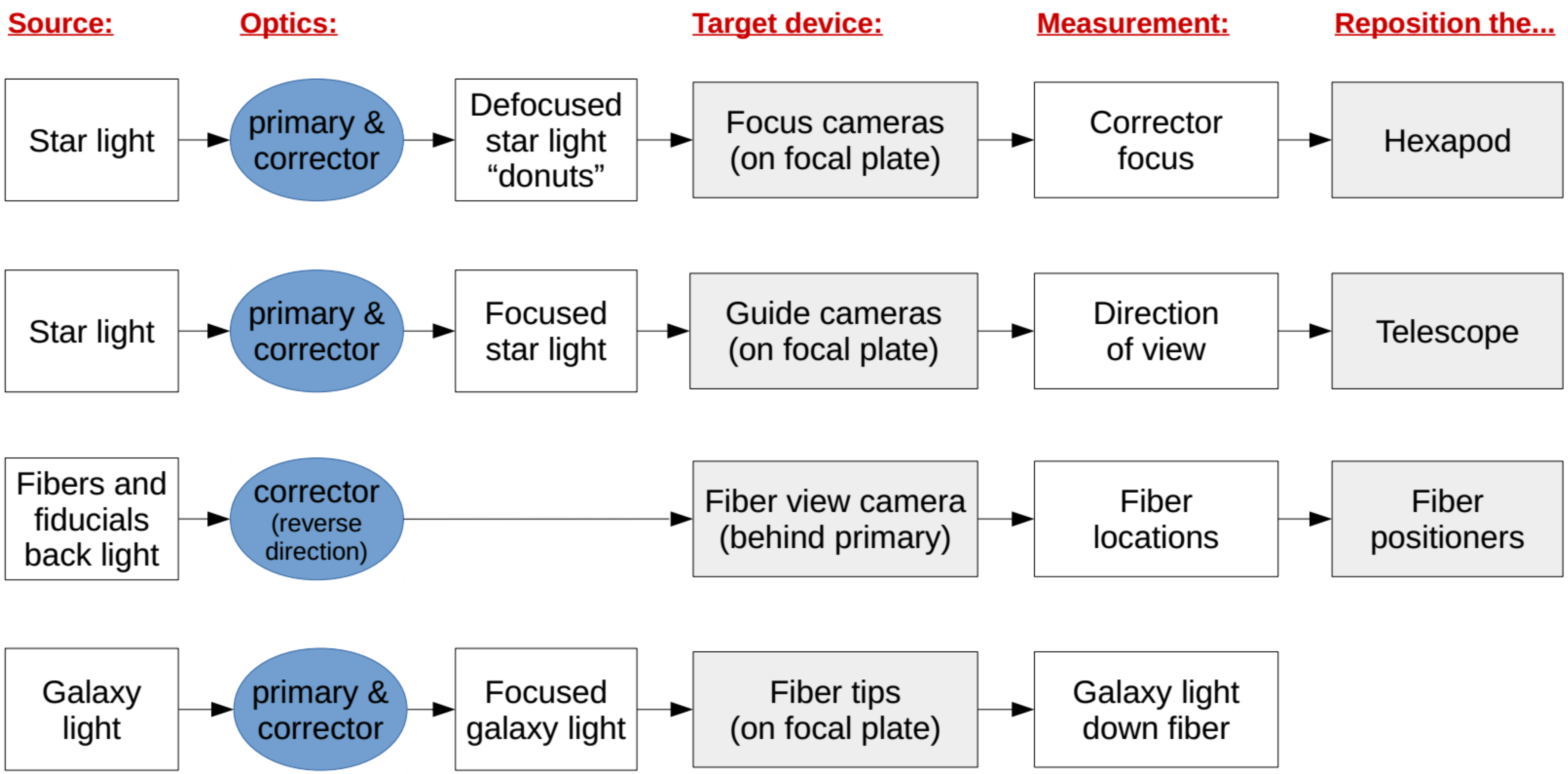
On-sky dithers determine mapping/positioning accuracy



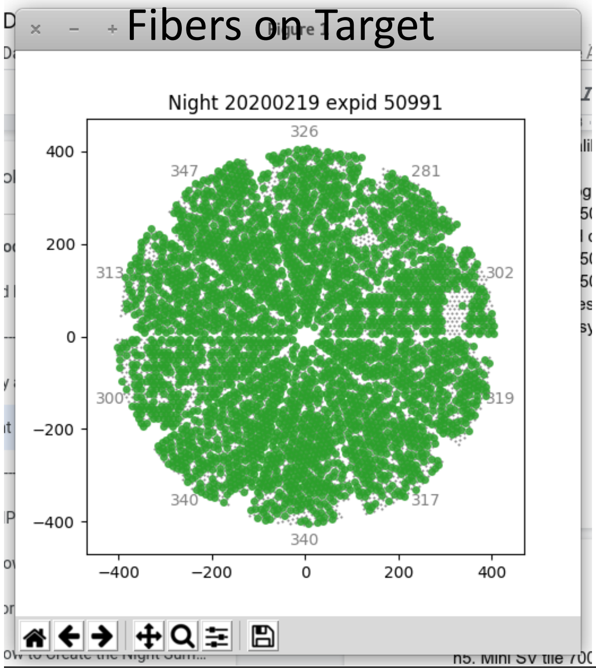
Target selection from DR9

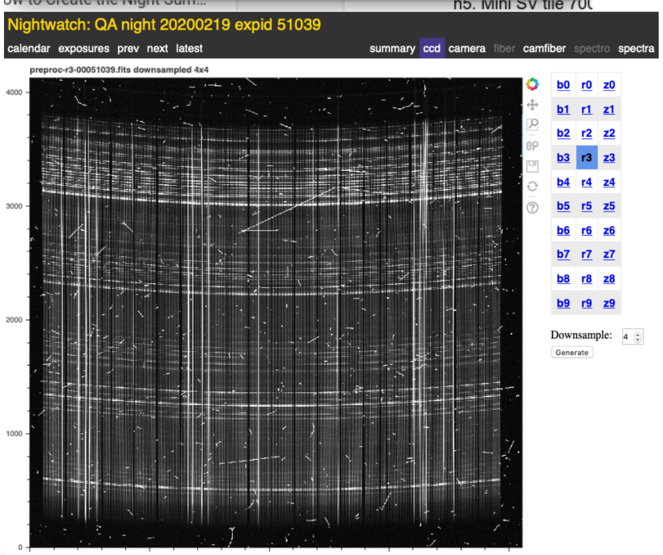


Positioning the Fibers on Galaxy Targets



Active, on-site monitoring

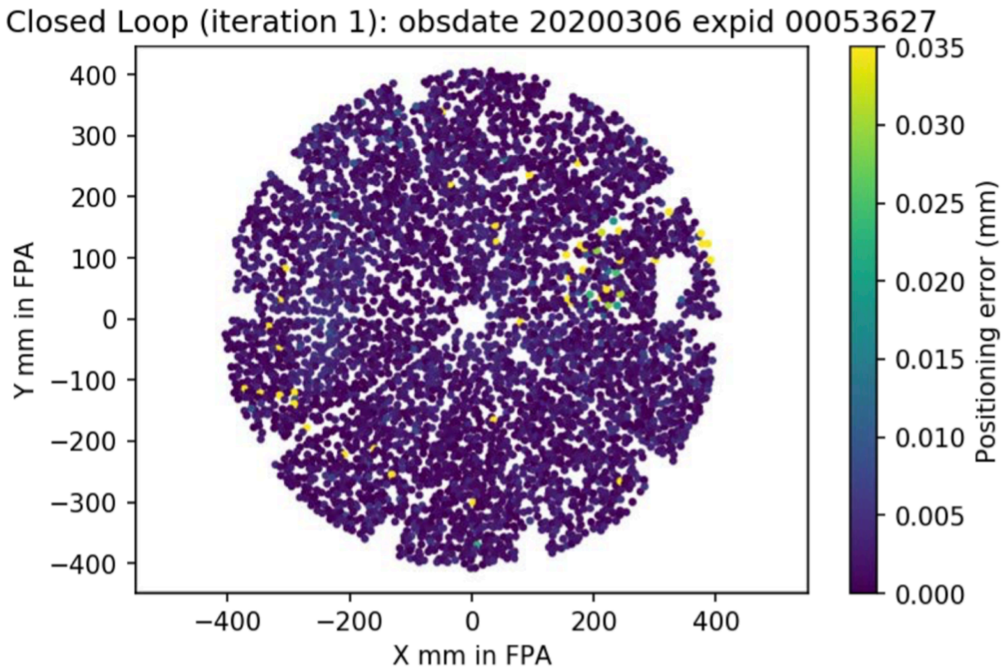


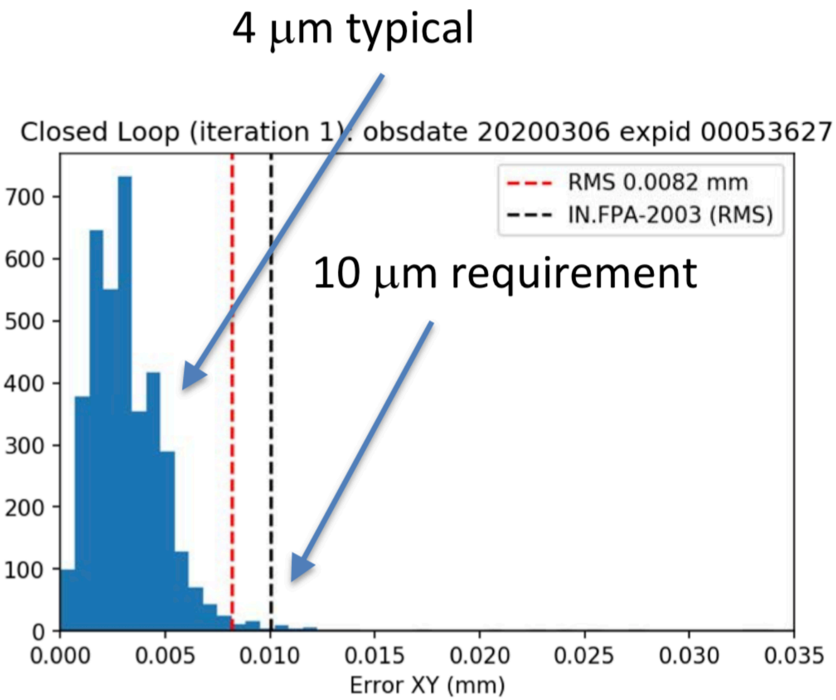


Nightwatch Summary Page

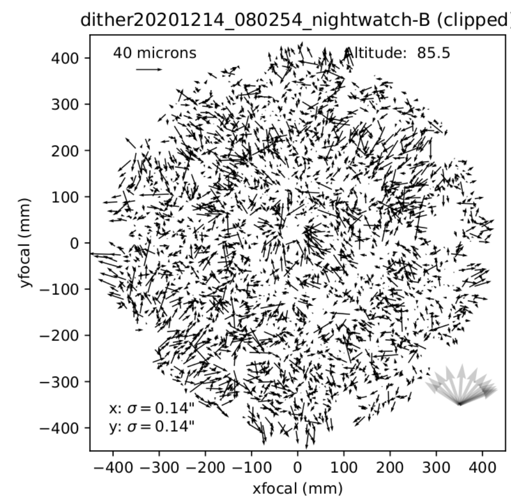
- Spectroscopic pipeline demonstrated on-sky for many millions of targets.
- Galaxy identification, redshift determination, and processing speed exceed survey needs.
- Nightwatch gives observers near-real-time monitoring of data quality.
- DESI has achieved the objective of obtaining simultaneous spectra of **thousands** of galaxies.

Example Exposure: Closed Loop 1 iteration

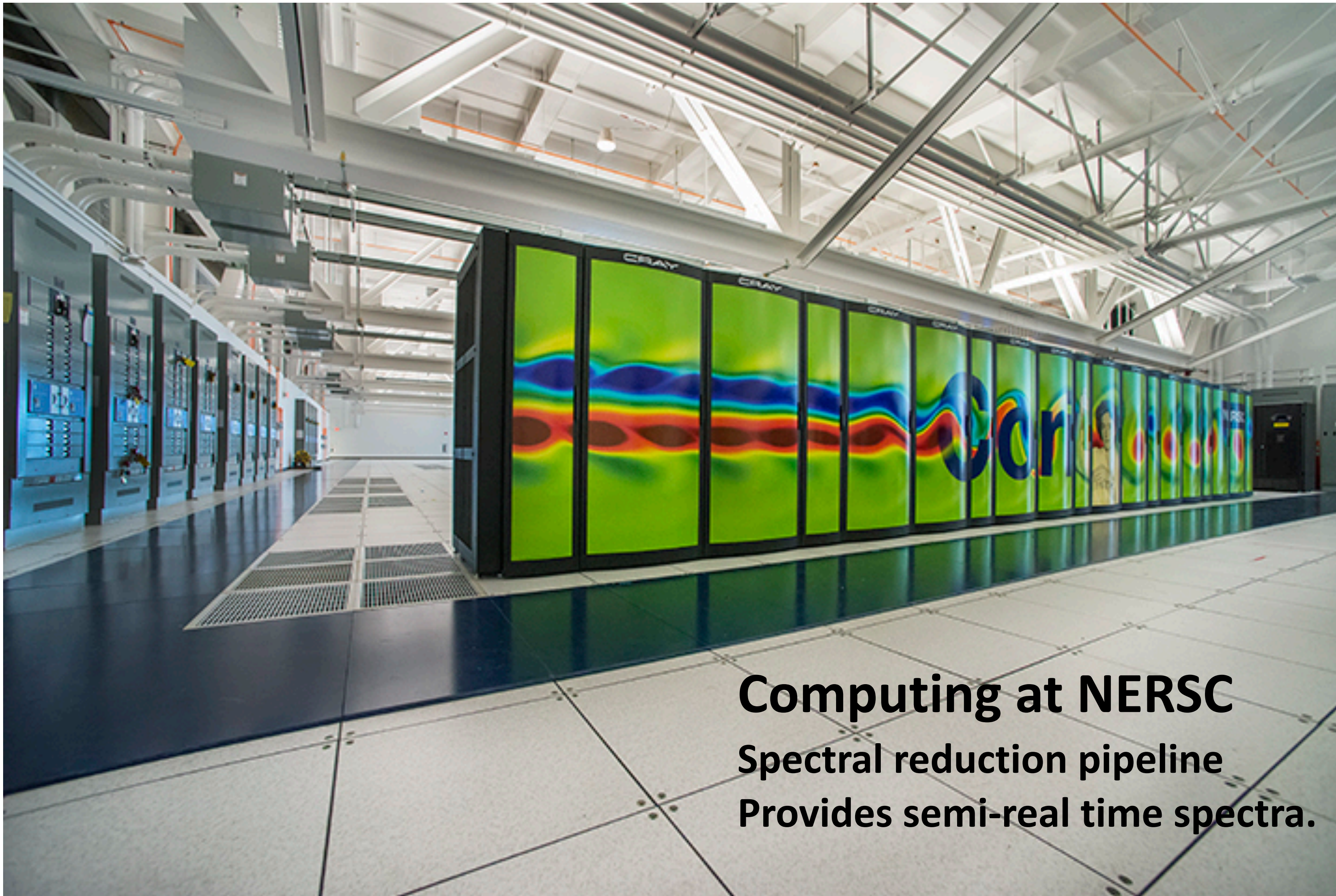




- Left (above) shows errors as distributed on focal plane.
- Right (above)shows histogram of errors.
- Closed loop move with feedback from Fiber View Camera. Positioners have no encoders.
- Dithering of positioners determines pointing accuracy (right below). 0.14" alignment of focal plane coordinate system to sky.



Data Management: Reduced Spectra/ redshifts by breakfast

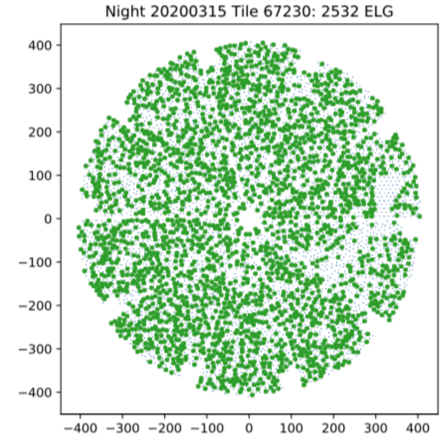


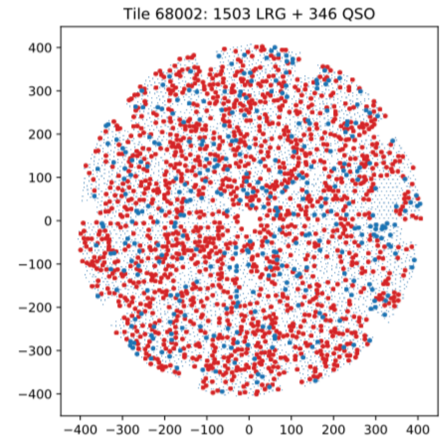
Computing at NERSC

Spectral reduction pipeline
Provides semi-real time spectra.

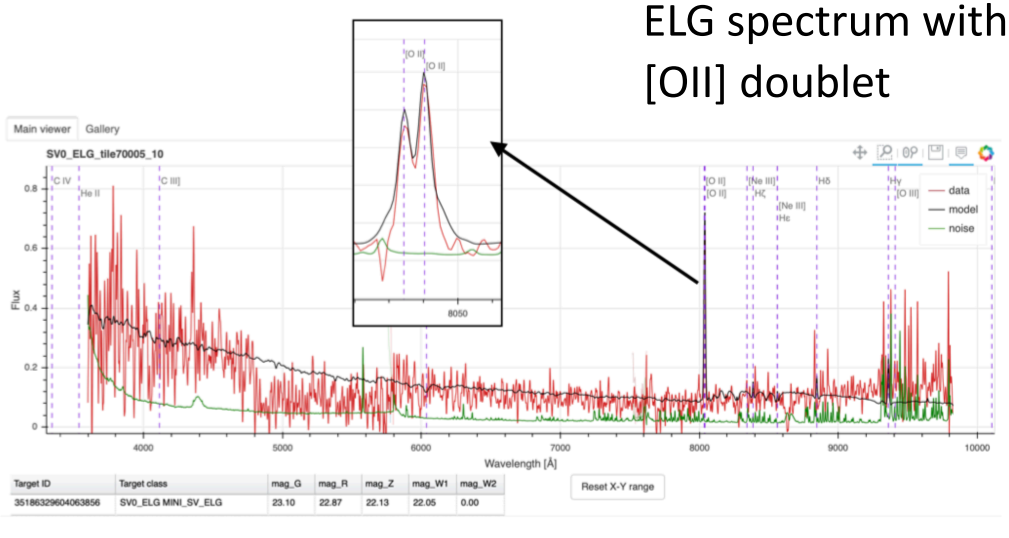
Data Management

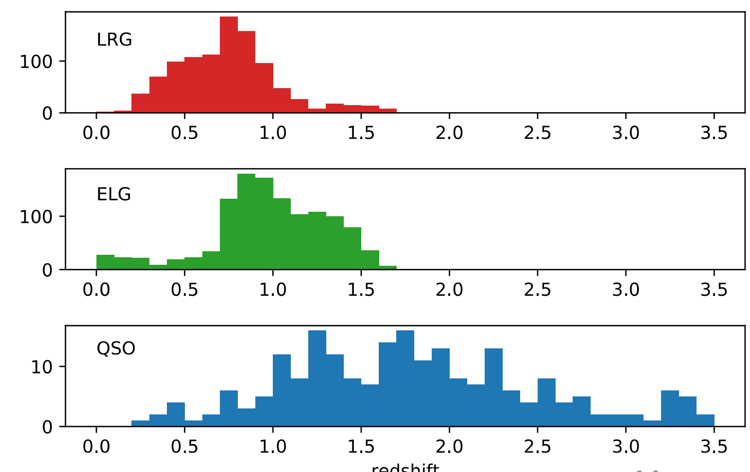
- Data Transfer to NERSC works reliably, fast.
- Spectro pipeline processes data in semi-realtime as they arrive at NERSC. Spectro pipeline keeps up with incoming data
- All target classes observed in SV
- Redshift distribution matches target selection design n(z)
- Collaboration is fully engaged (e.g. visual inspection team)





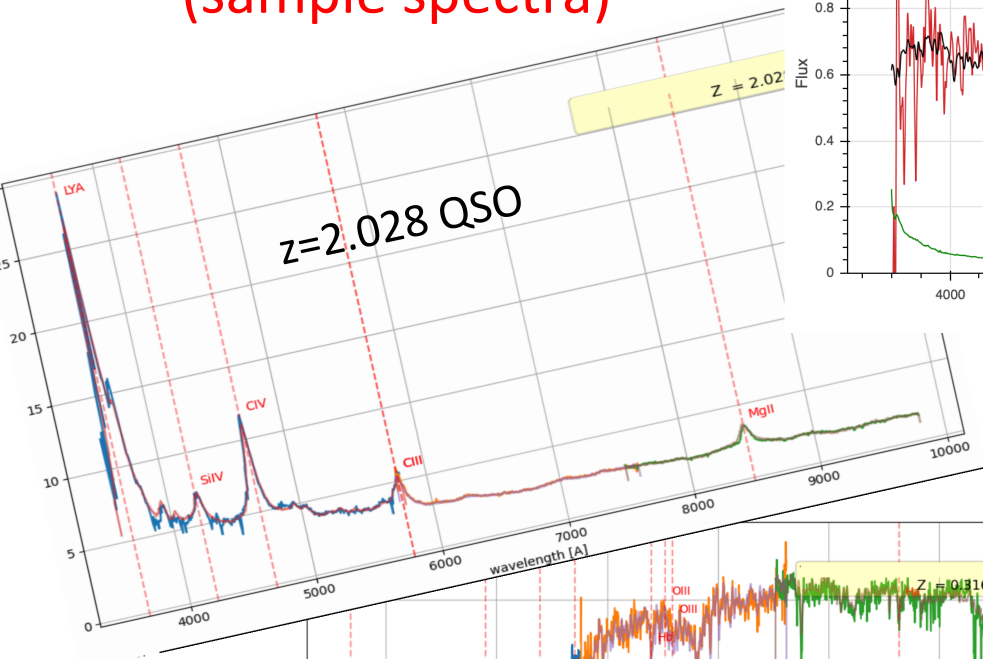
ELG spectrum with [OII] doublet

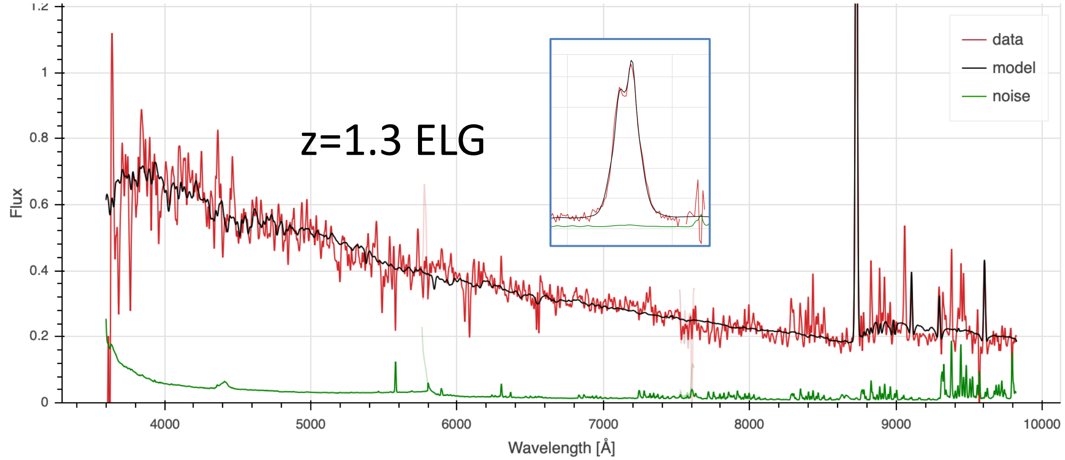


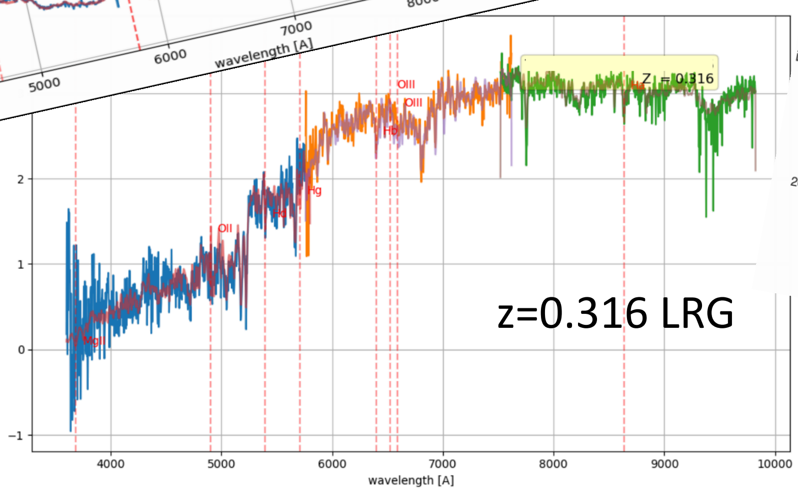


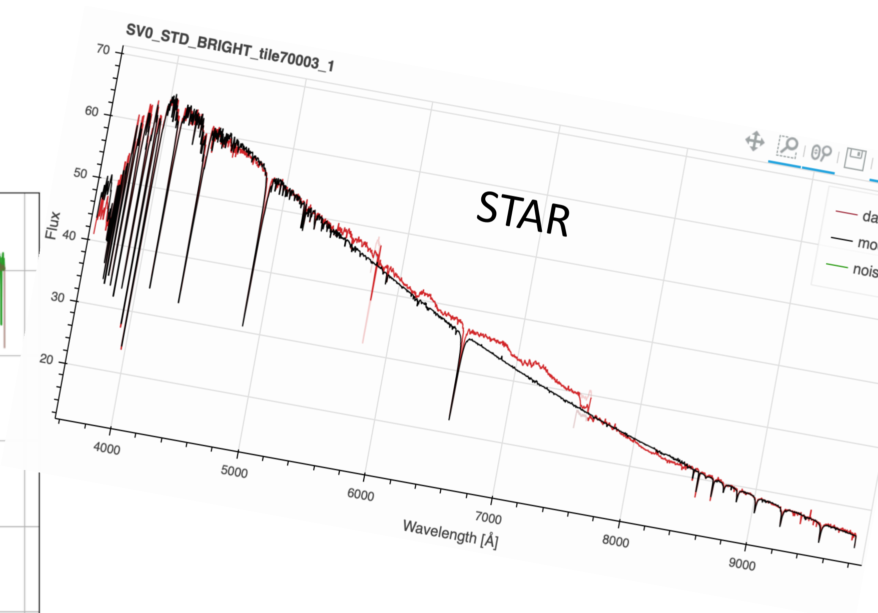
DESI is collecting > 100,000 spectra/night!

Survey Validation
(sample spectra)

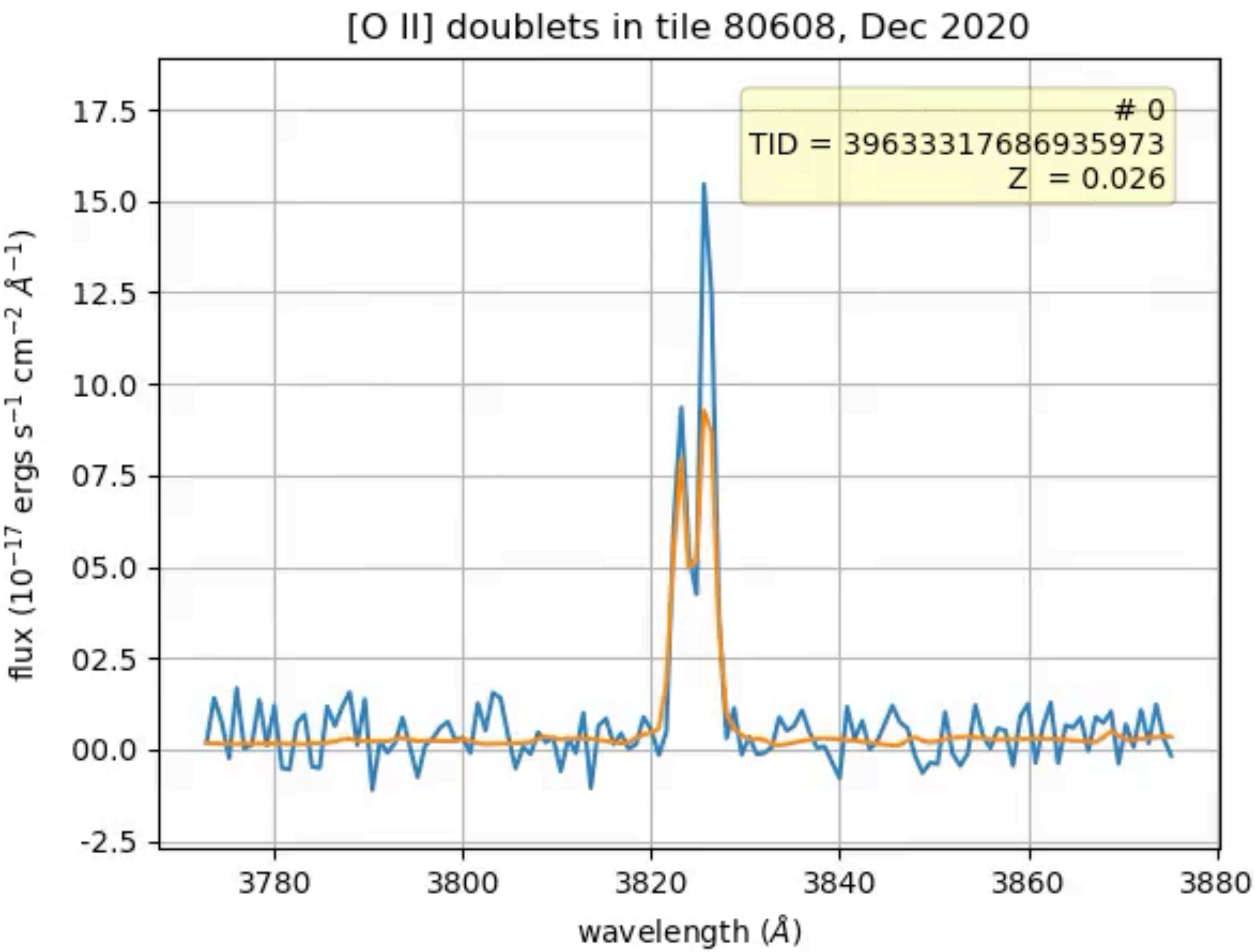








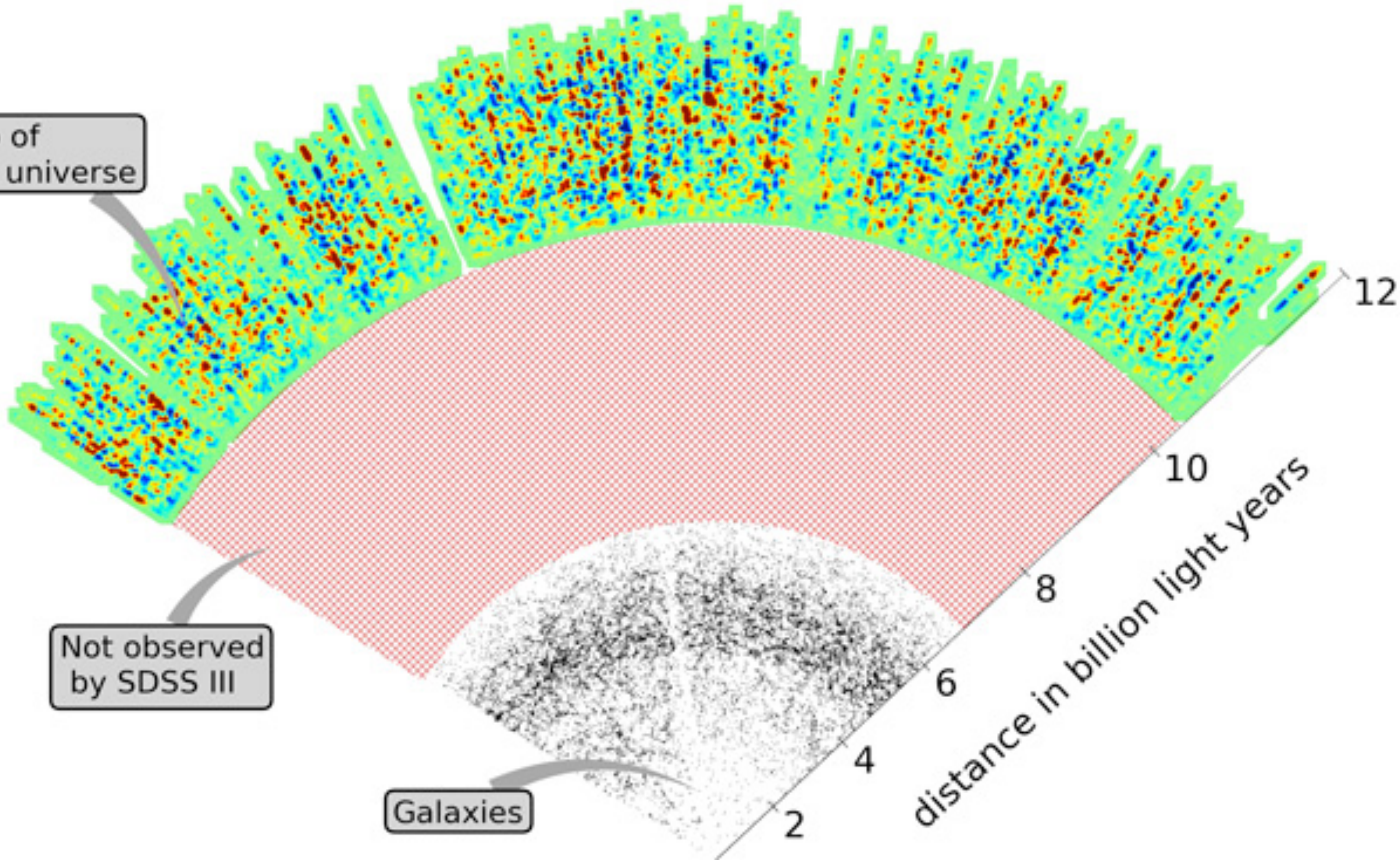
ELG Movie (1 Tile)



The (Hopefully) Near Future

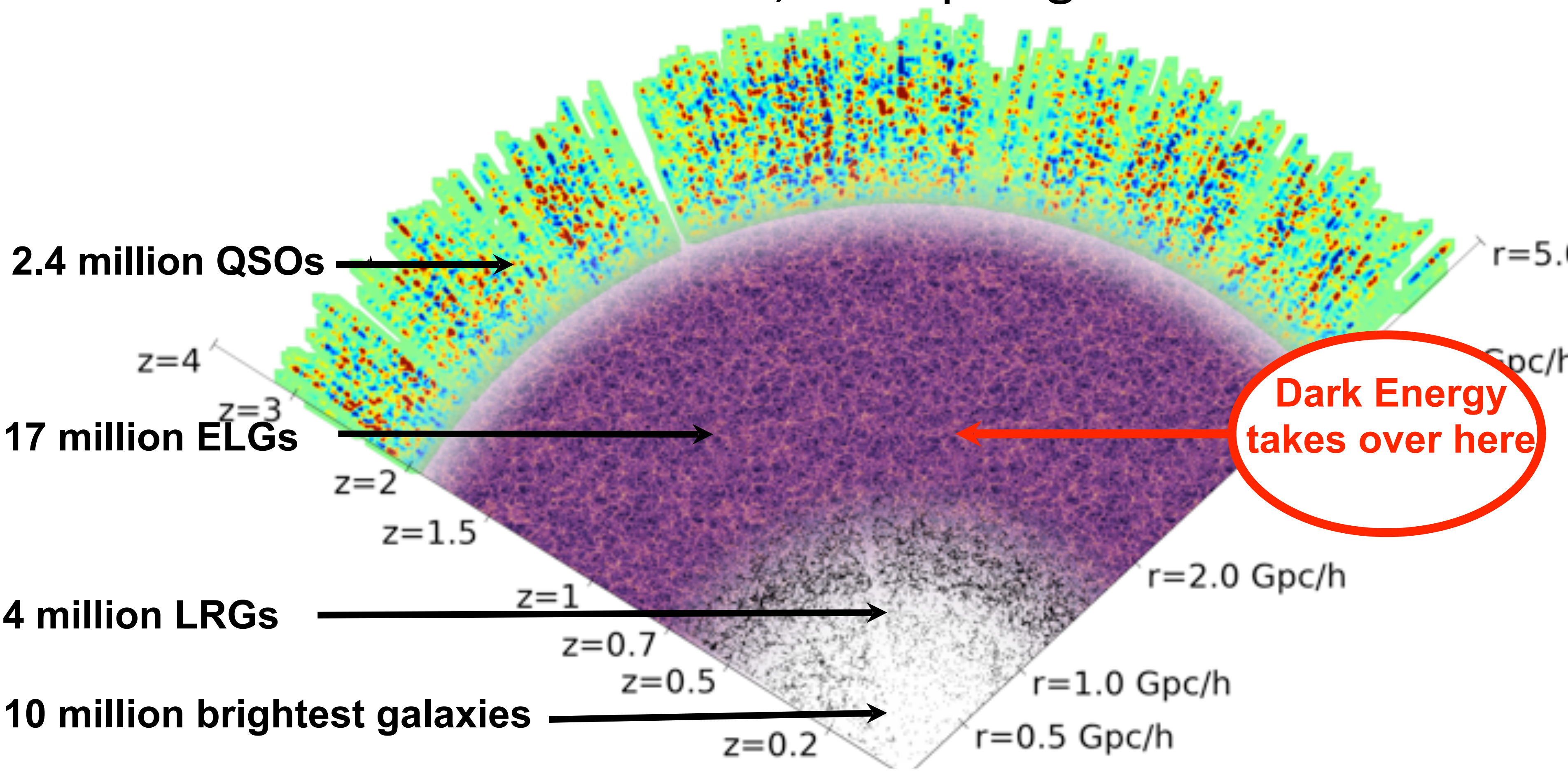
- DESI is working as expected meeting all key performance specifications.
- Survey Validation (6 mo.) has begun Dec. 2020
- 5 y Survey Operations to begin by May. 2021
- What can we expect?

BOSS Sampled a Volume of 6 h^{-3}Gpc^3



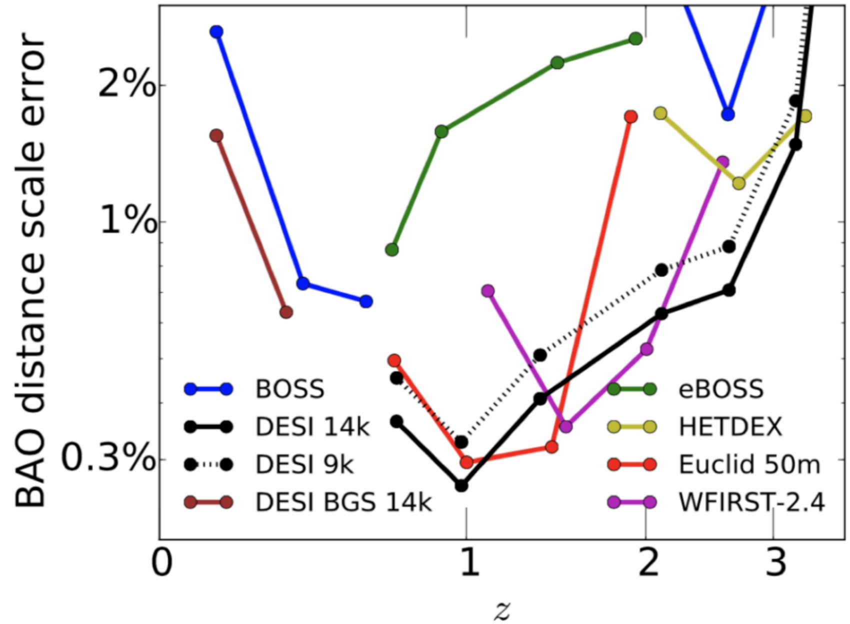
DESI Will Sample a Volume > 50 h^{-3}Gpc^3

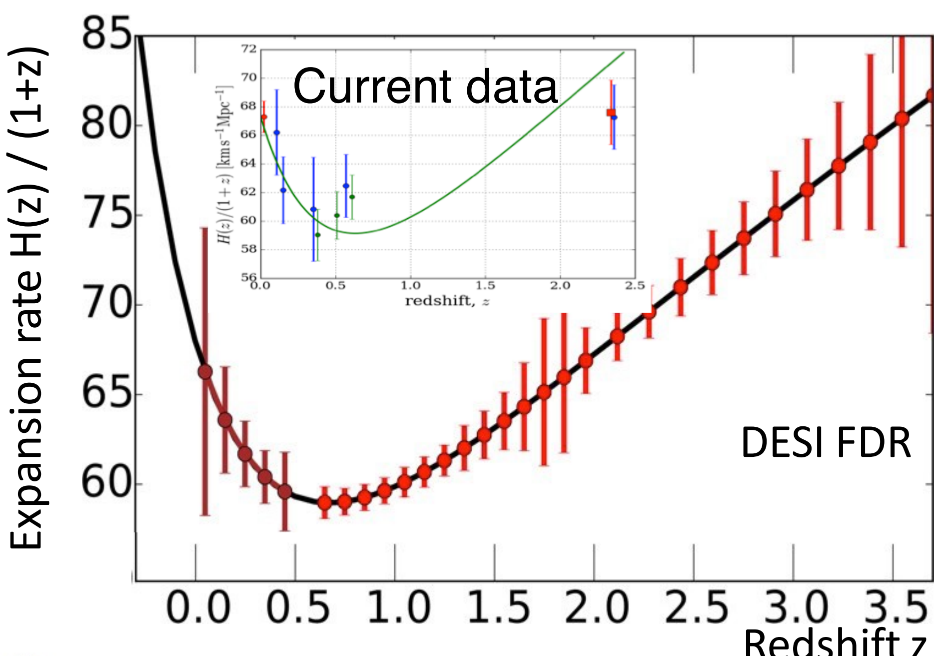
Five target classes spanning redshifts z=0 ➔ 3.5.
~34 million redshifts over 14,000 sq. degrees.

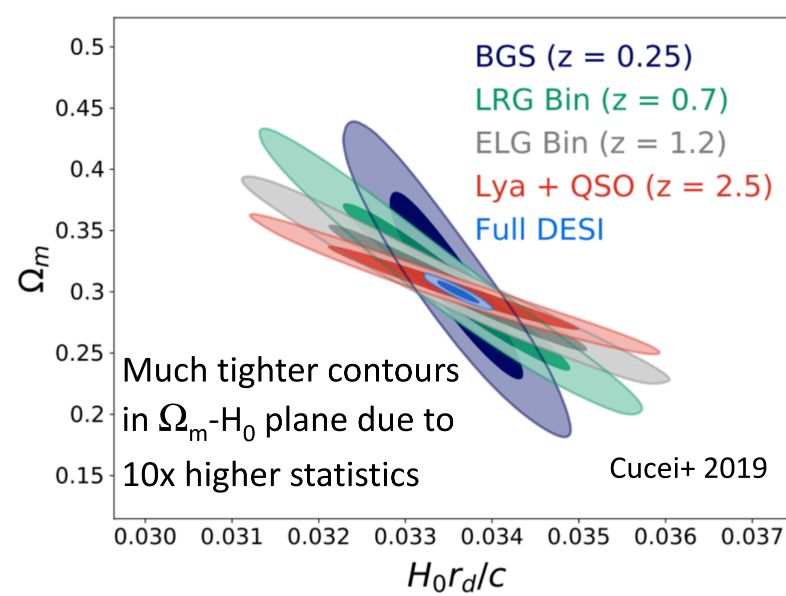


DESI Science Reach

- Measure distance scale from BAO
  - 0.28% precision for 0 < z < 1.1
  - 0.39% precision for 1.1 < z < 1.9
- Measure the Hubble Parameter to 1.05% for 1.9 < z < 3.7 from BAO
- Gravitational growth factor
  - < 1% for 0.5 < z < 1.4 using RSD
- Inflation
  - Constrain the spectral index of primordial perturbations and its running to < 0.4%







In Conclusion

- Dark Energy represents 75% of the universe and yet we have essentially no understanding of its nature. Theorists are stumped.
- Experiments must break the log jam. Study w(z).
- The Dark Energy Survey (DES) is complete. Photometric, Combined techniques. Stage III performance. Y3 papers released within a few months
- DESI has completed Commissioning and Survey Validation is underway. 5y Operations period before summer 2021.
- DESI will extend two techniques (BAO and RSD) to stage IV with a massive spectroscopic survey.
- These experiments and others to follow will allow us to precisely observe the evolution of dark energy over cosmic time and explore the very "fabric" of space-time .

DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

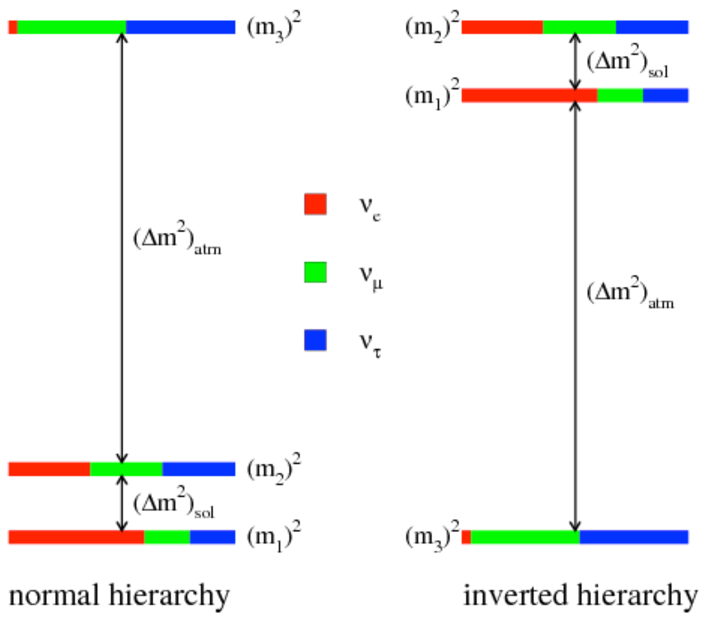
Thanks to our sponsors and 69 Participating Institutions!


Grazie!

DESI Measures Total Neutrino Mass

- Large-scale structure (LSS) is sensitive to neutrino properties
- Massive neutrinos decrease small-scale power at low redshift
  - DESI can measure an error of 0.02 eV in the sum of masses, enough to start to distinguish the normal and inverted hierarchy of mass states
- Extra relativistic species (such as sterile neutrinos) can also be measured with LSS and CMB

Data	$\sigma_{\Sigma m_\nu}$ [eV]	$\sigma_{N_{\nu,\mathrm{eff}}}$
Planck	0.56	0.19
Planck + BAO	0.087	0.18
Gal ($k_{\mathrm{max}} = 0.1h\,\mathrm{Mpc}^{-1}$)	0.030	0.13
Gal ($k_{\mathrm{max}} = 0.2h\,\mathrm{Mpc}^{-1}$)	0.021	0.083
Ly-α forest	0.041	0.11
Ly-α forest + Gal ($k_{\mathrm{max}} = 0.2$)	0.020	0.062



DESI TDR Table 2.11, Figure 2.14