The Dark Energy Spectroscopic Instrument and Beyond

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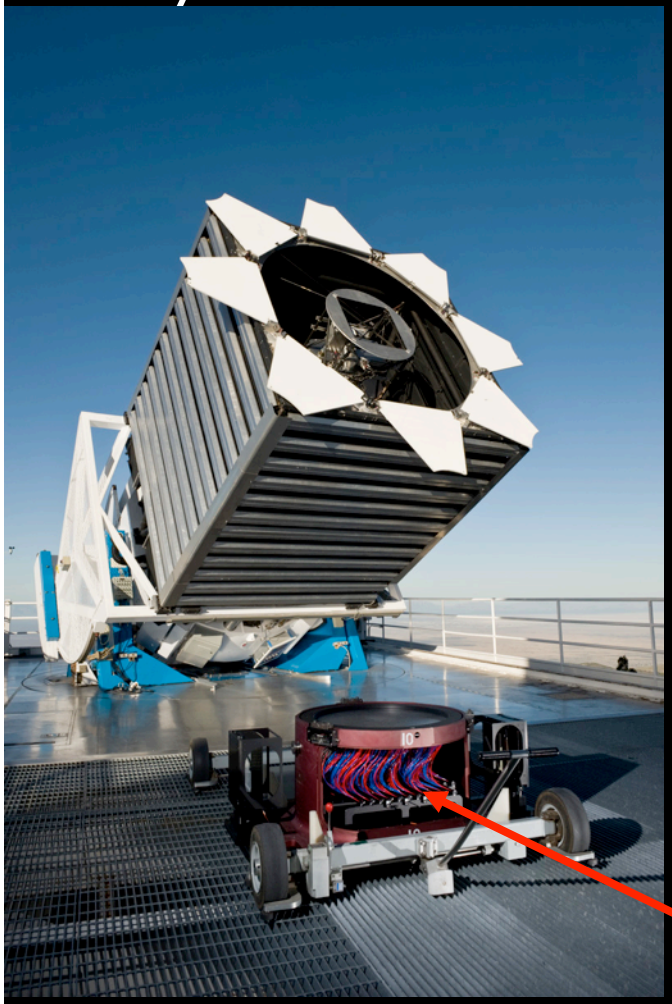
CosKASI Conference, April 2017

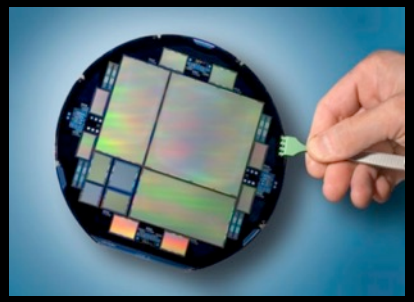
Outline

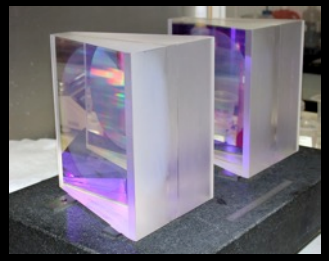
- Introduction: from BOSS to DESI
- DESI Science Goals
- Current status of DESI
- Beyond DESI
- Conclusions

DESI Heritage: BOSS experiment at SDSS
Proposed in 2005
Spectrograph Upgrade 2007 – 2009
Survey 2009 - 2014

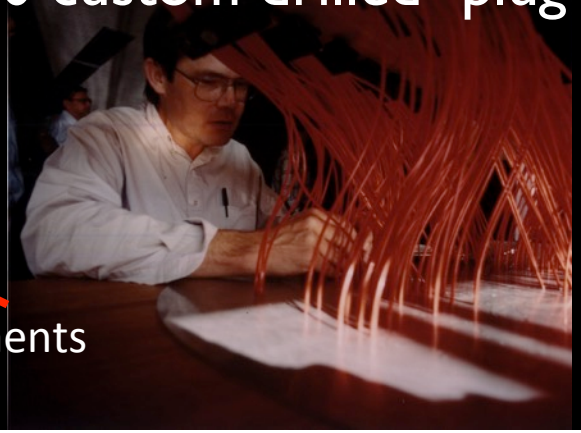
2 two-arm Spectrographs with new VPH gratings and new LBNL CCDs

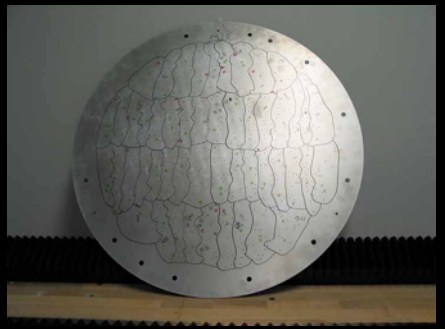






1000 small-core fibers in each of 8 cartridges
+ 2000 custom drilled "plug plates"



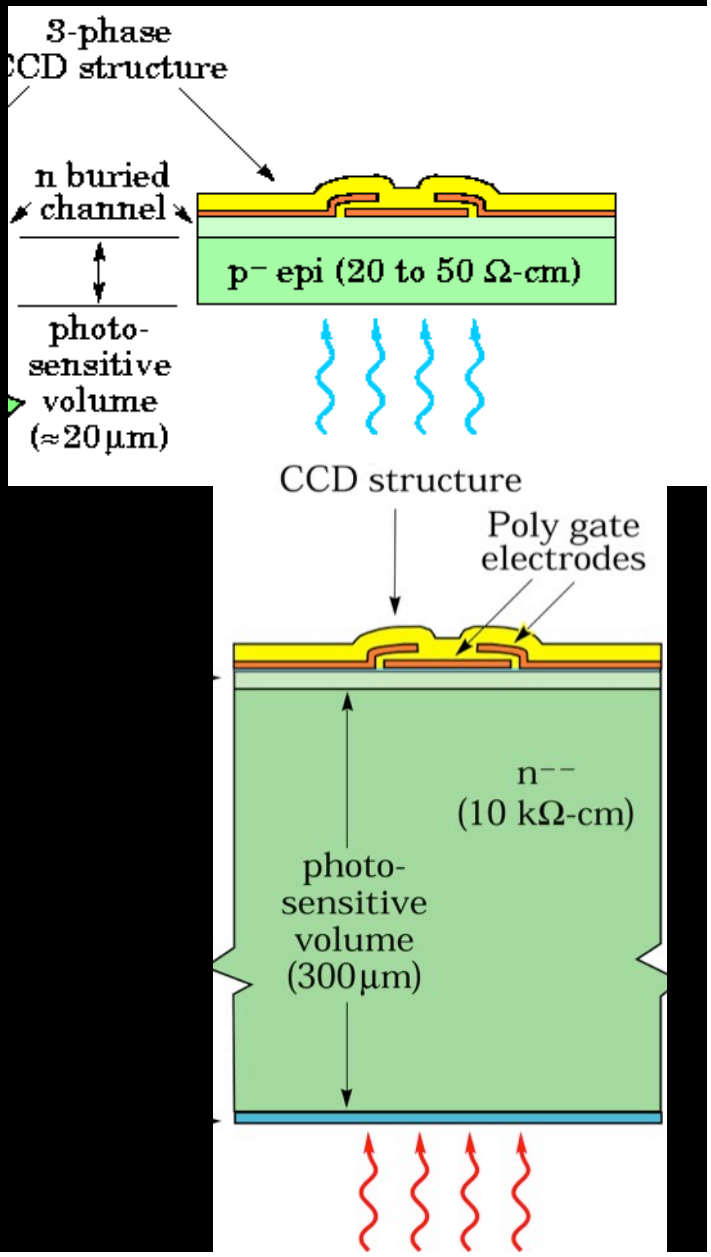


Upgraded spectrographs met all requirements (Smee et al 2012).

Fully Depleted CCDs for Cosmology

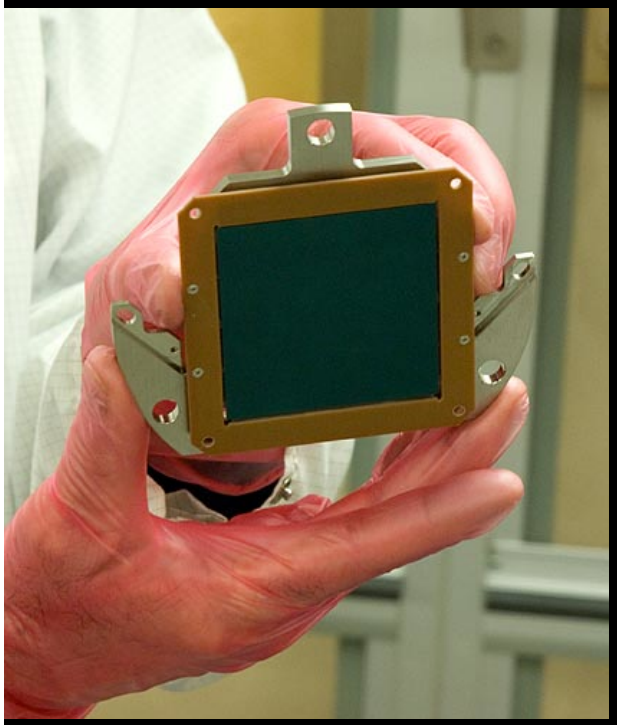
- Most CCDs used in astronomy are thin, ~10 – 20 μm epitaxial depletion
- LBNL CCDs are thick fully depleted p-channel devices (200 – 500 um)
  - — Higher QE over broader wavelength range
  - — Reduced "fringing" at long wavelengths
  - — But more sensitive to cosmic rays
  - — Used in BOSS, Dark Energy Survey, DESI, Hyper SuprimeCam (Hamamatsu),LSST (e2V, ITL)

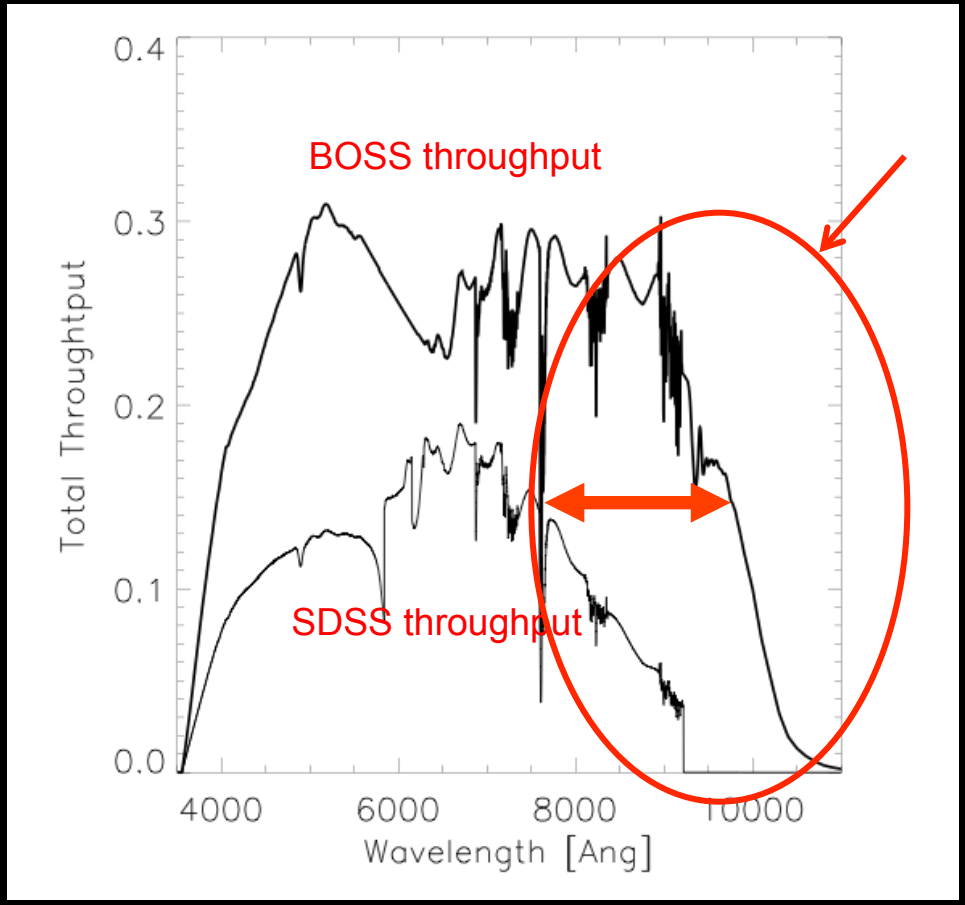
- Patents Issued (Steve Holland)
  - — U.S. Patent 6,259,085 "Fully Depleted Back Illuminated CCD", Jul. 10, 2001.
  - — U.S. Patent 6,025,585 "Low-resistivity photon-transparent window attached to photosensitive silicon detector", Feb. 15, 2000.
  - – U.S. Patent 7,271,468 "High-voltage compatible, fully-depleted CCD", Sept 28, 2007



LBNL 4k x 4k CCDs for BOSS

- Enhanced quantum efficiency essential for BAO up to z~0.7
- LBNL provided 2 fully depleted 4k x 4k CCDs (+ spares) for BOSS





Fully depleted NIR-sensitive LBNL CCD: improved throughput above 800 nm

BOSS Scientific Goals

- 1.5M spectra over 10,000 sq deg with upgraded spectrographs
  - 1000 fibers, higher throughput, extended wavelength coverage
- 1% galaxy BAO distance measurements at z~0.3, 0.6
  - Using reconstruction to remove nonlinear effects- a new, unproven method when BOSS was proposed
- ~1.5% distance measurement at z>2 using Lyman-α forest technique
  - New, unproven technique when BOSS was proposed
- Study growth of structure using redshift-space distortions
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  - Can be used to constrain new theories of gravity as well as the effects of neutrino mass

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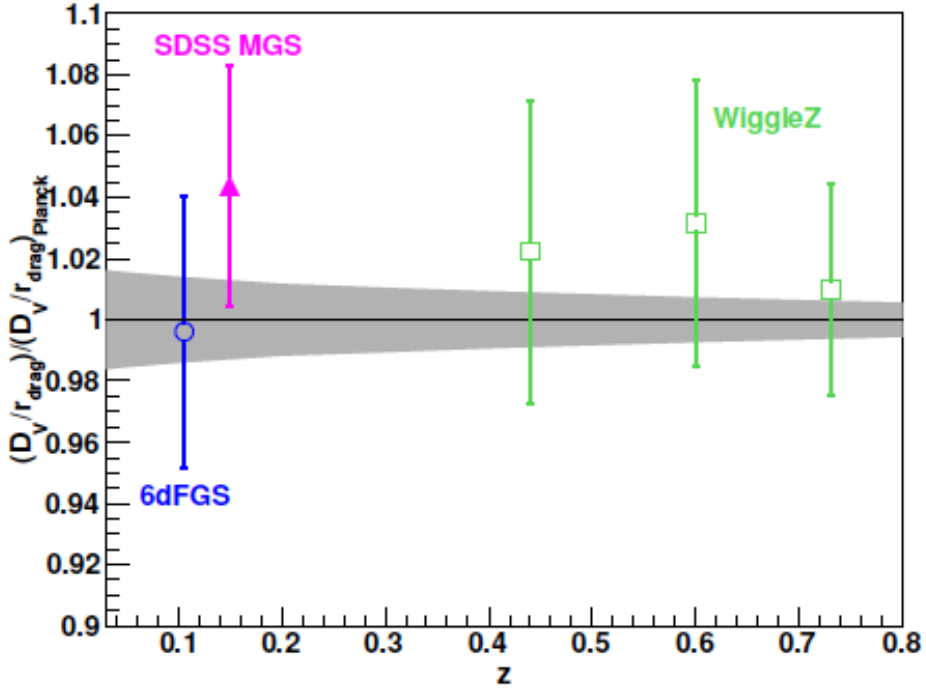
BAO Constraints Before BOSS

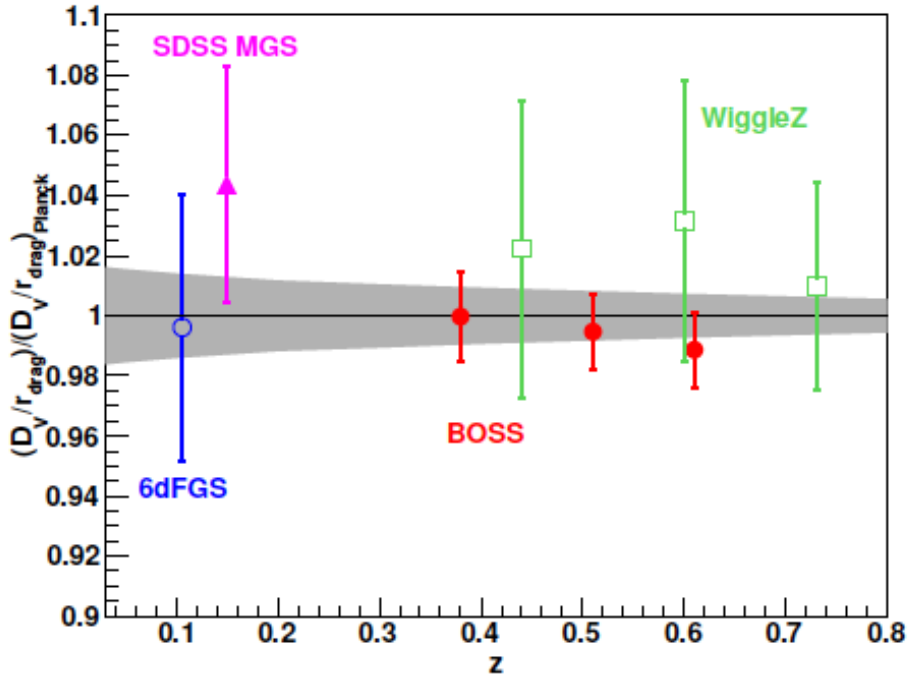
Distance v Redshift compared to Planck fiducial model



$$D_V(z) = \left[(1+z)^2 D_A^2(z) \frac{cz}{H(z)}\right]^{1/3}$$

BAO Constraints After BOSS

Distance v Redshift compared to Planck fiducial model



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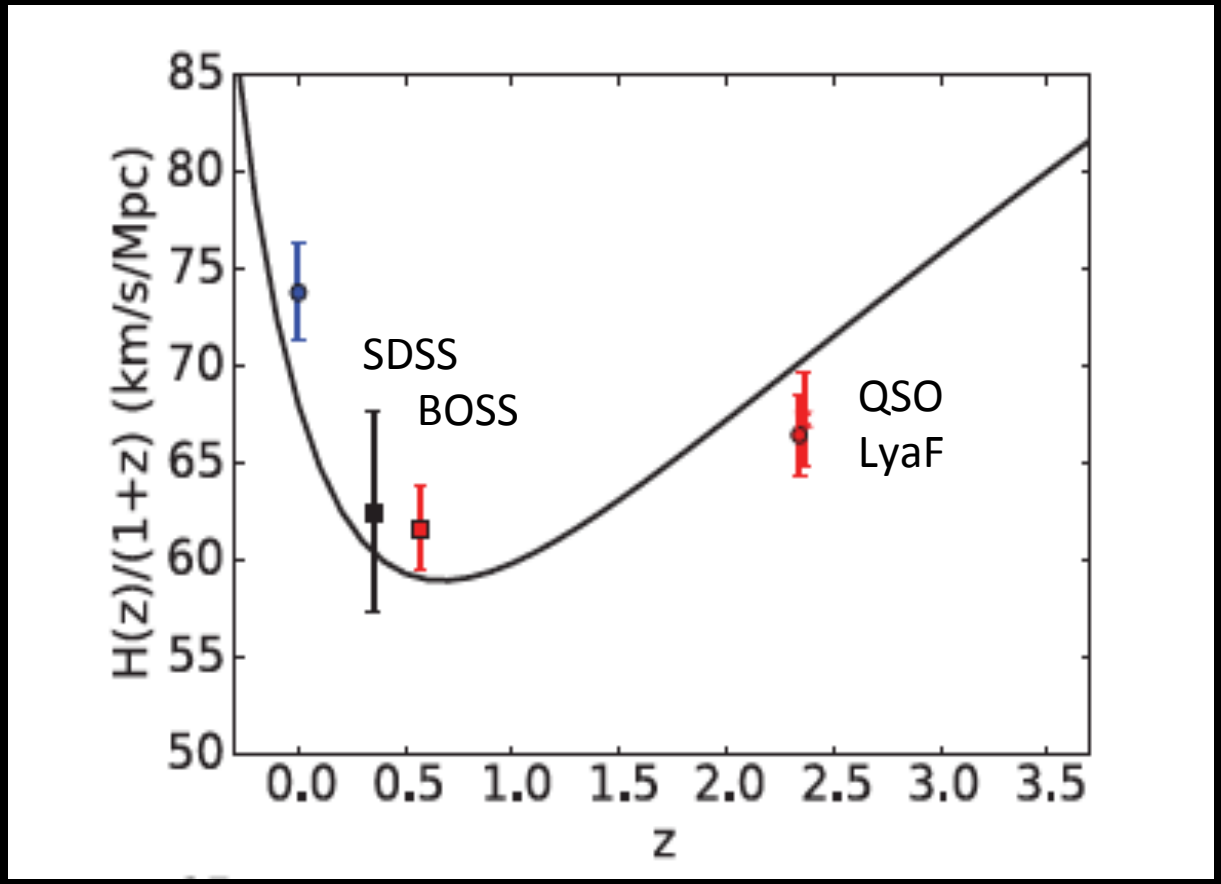
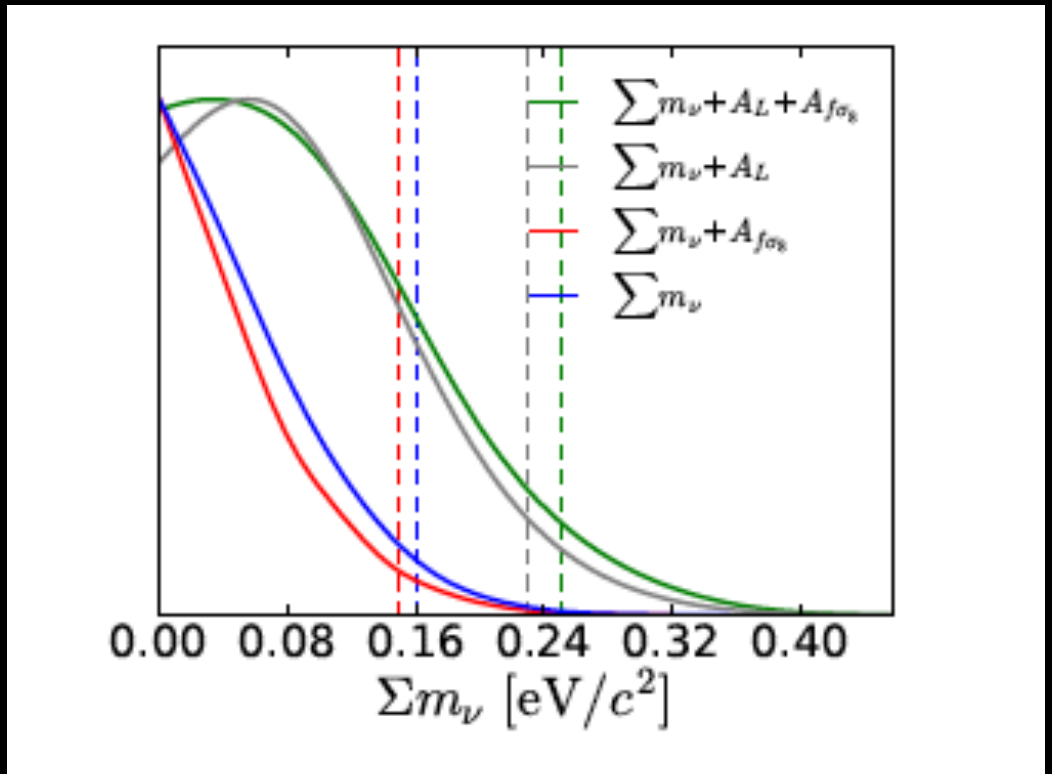
Epoch of Deceleration



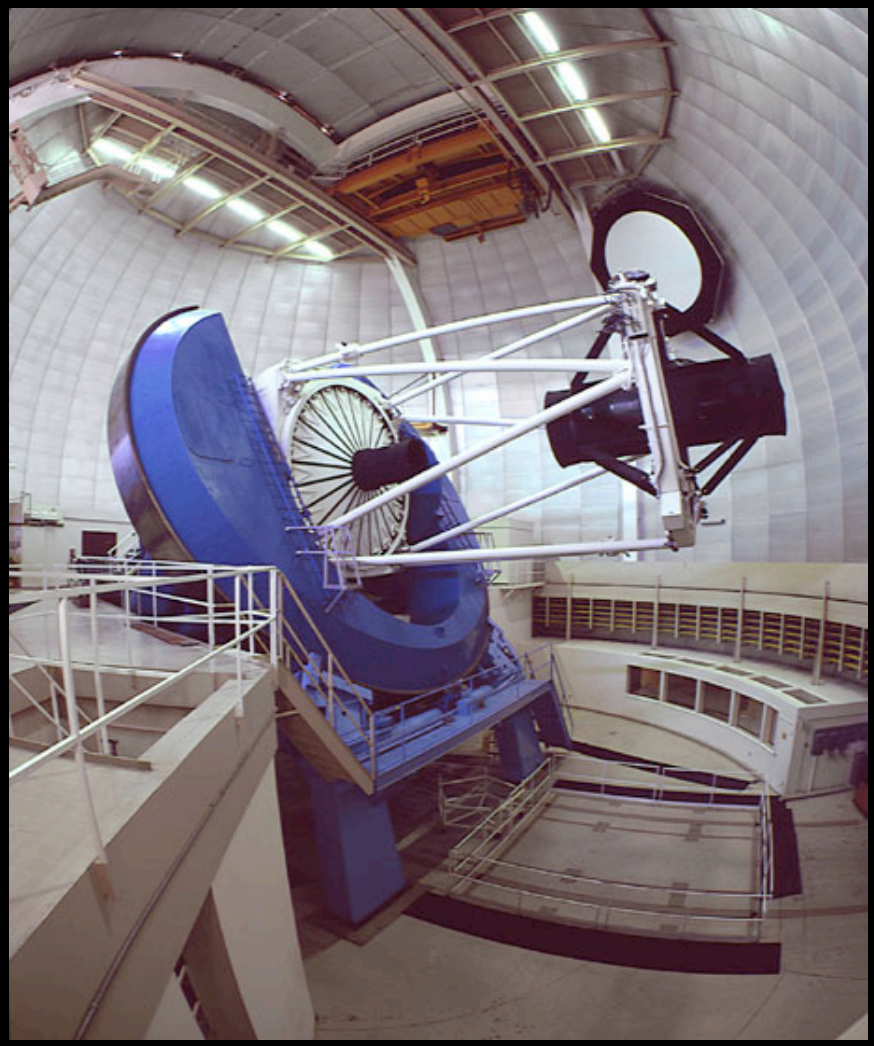
BOSS is also Sensitive to Neutrino Mass

- BOSS measurement of expansion history provides a constraint on neutrino mass $\Sigma m < 0.24$ eV (95% CL)
- This improves to $\Sigma m < 0.16$ eV in combination with the BOSS redshift space distortions and the CMB lensing from Planck
- Compare to minimum value $\Sigma m = 0.06$ eV in the SM



From BOSS to DESI

Kitt Peak, AZ

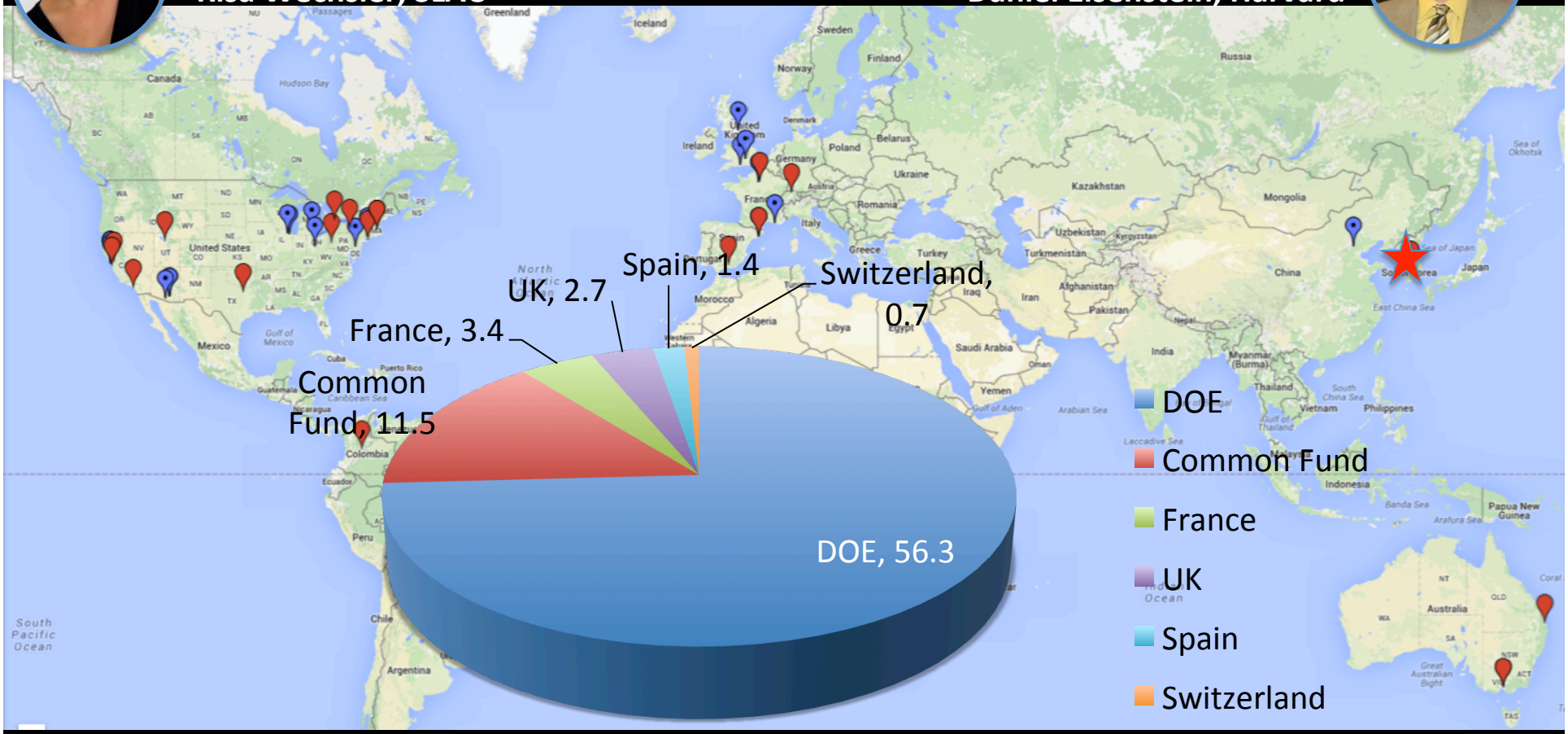


4m Mayall Telescope and
Corrector Inside the Dome

DESI is a collaboration of 470 scientists from an international community of 76 institutions

Spokesperson
Risa Wechsler, SLAC

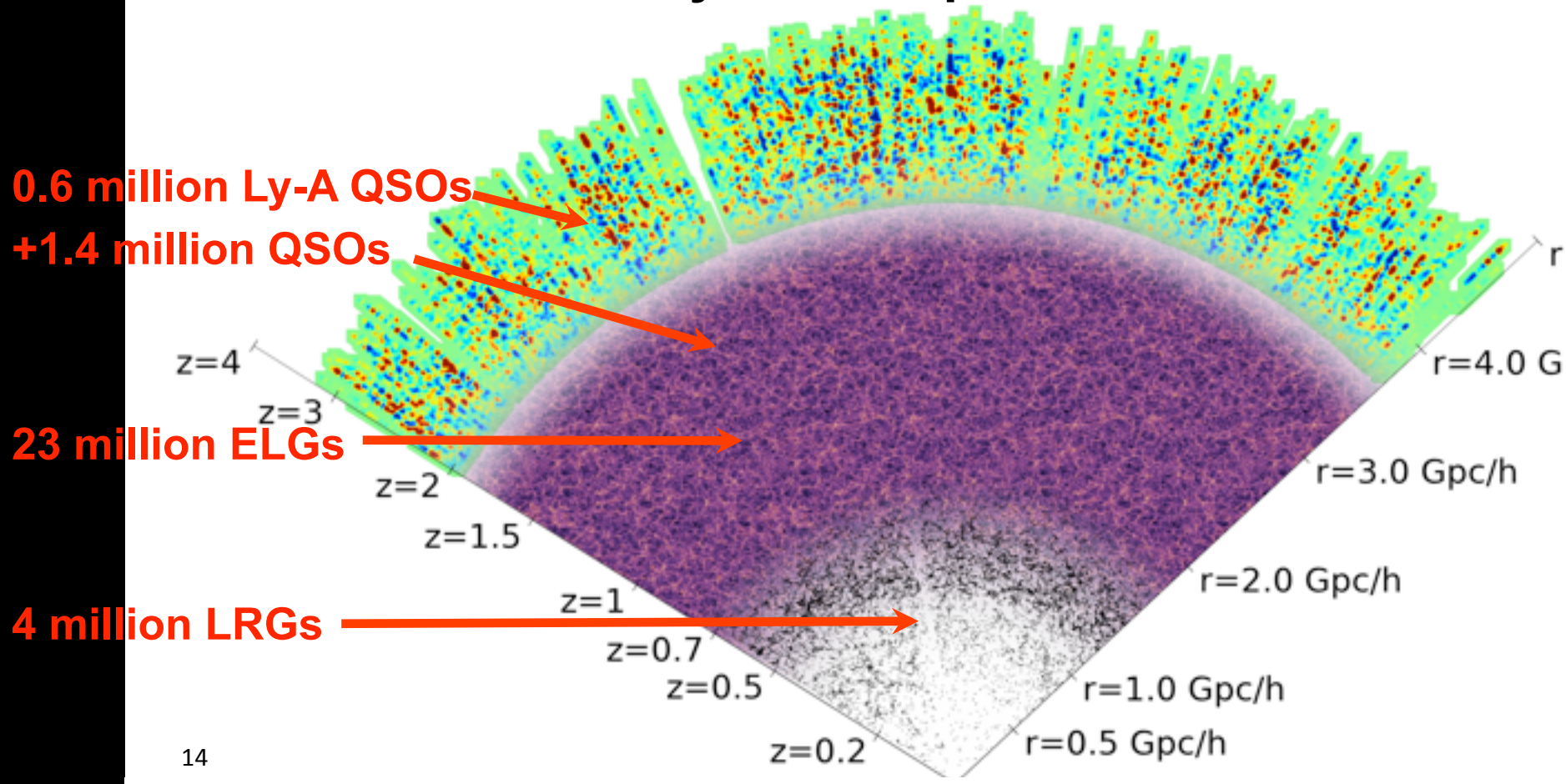
Spokesperson
Daniel Eisenstein, Harvard



Common fund includes $3.4M Foundation funding (Moore, Heising-Simons)

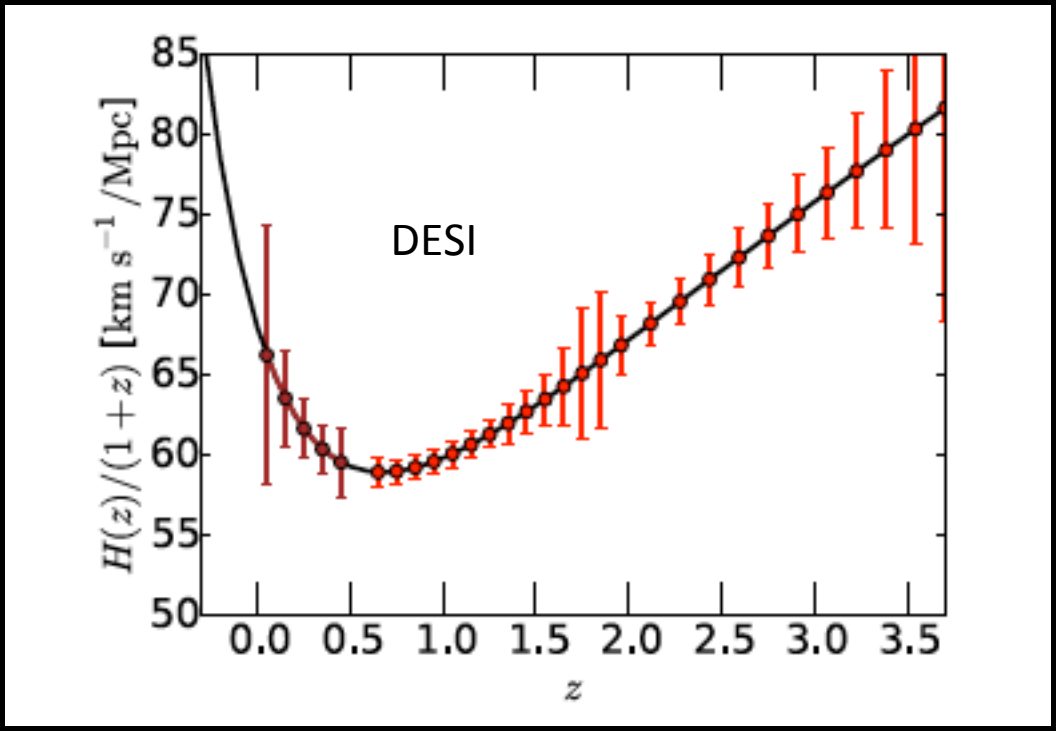
30M DESI Targets

Four target classes spanning redshifts z=0 ➔ 3.5
Selected from imaging data in g, r, z + WISE satellite
Total volume surveyed ~50 Gpc^3/h^3

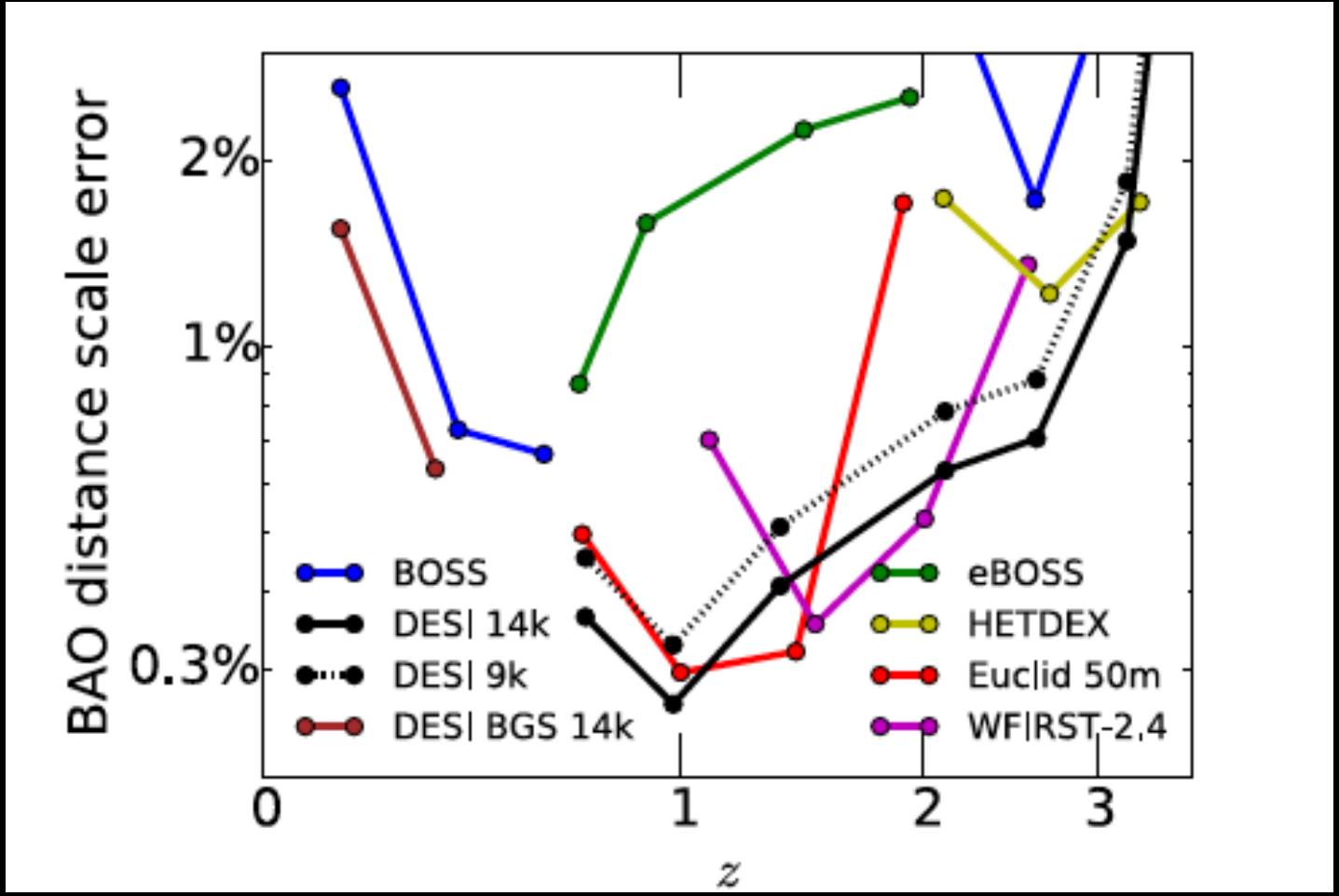


BAO-measured Hubble parameter vs redshift

DESI will provide a unique history of the expansion of the Universe to unprecedented accuracy

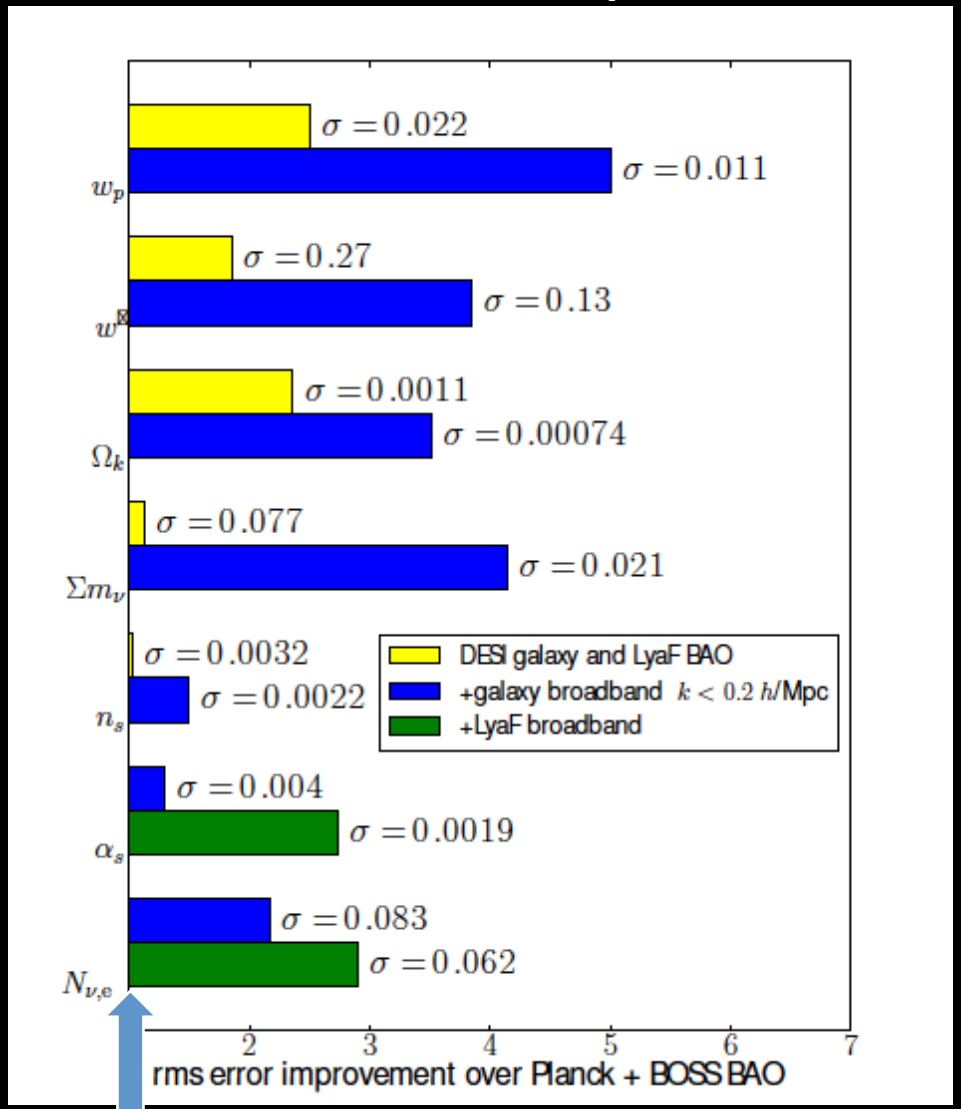


DESI Achieves Distance Precision Comparable to Space Experiments



DESI has Broad Scientific Goals

Improvement over Planck + BOSS (normalized to 1.0):

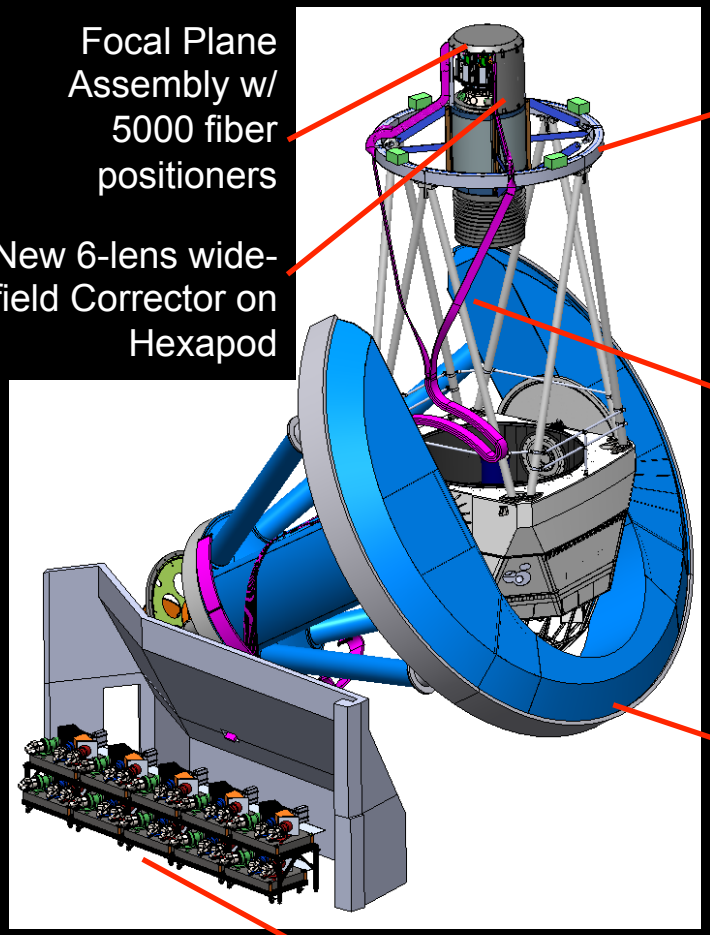


NOW

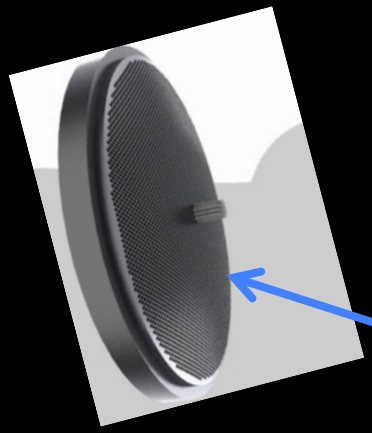
Ref: P. McDonald (LBNL)

From BOSS to DESI

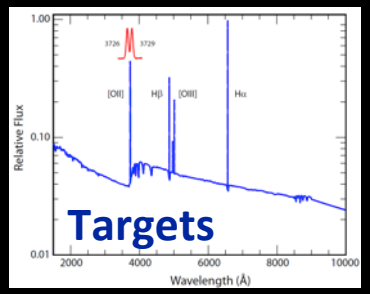
- 2.5 m => 4 m telescope (Mayall, Kitt Peak AZ)
- Automated robotic fiber system, 1000 => 5000 fibers
- Two => ten spectrographs, based on BOSS heritage
- Broader range of target classes: LRG's, ELG's, QSO's
- Sky area: 10,000 => 14,000 square degrees
- Number of redshifts: 1.5 million => 30 million

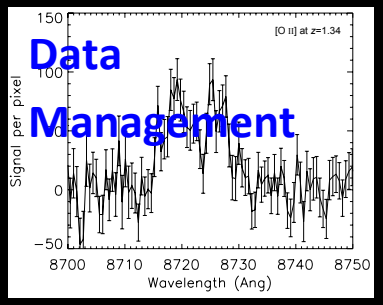


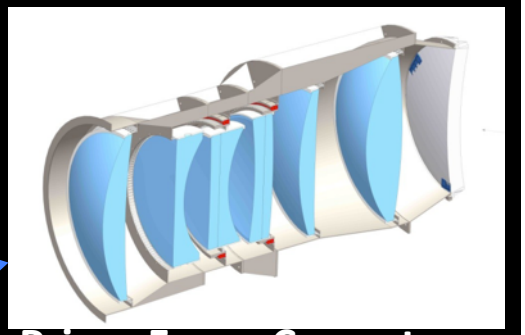
DESI Hardware & Software Elements



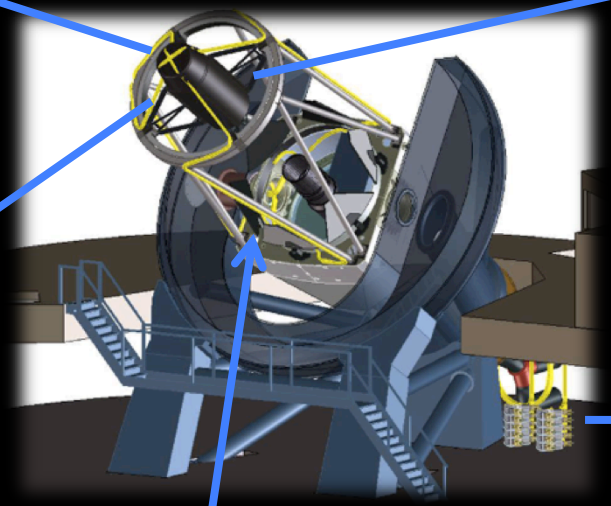
Focal Plate

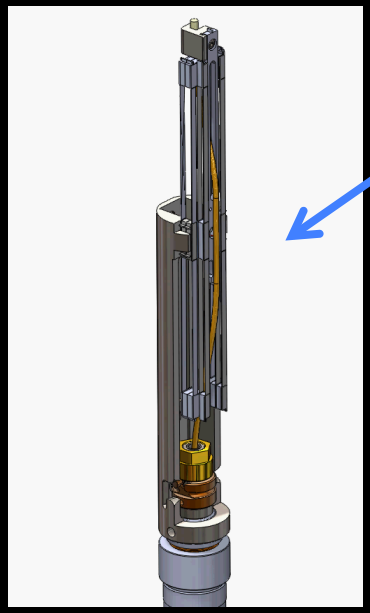




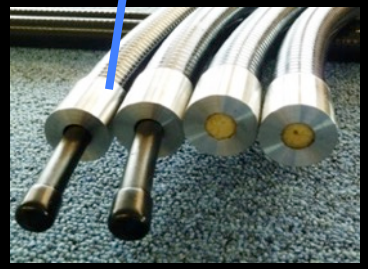


Prime Focus Corrector

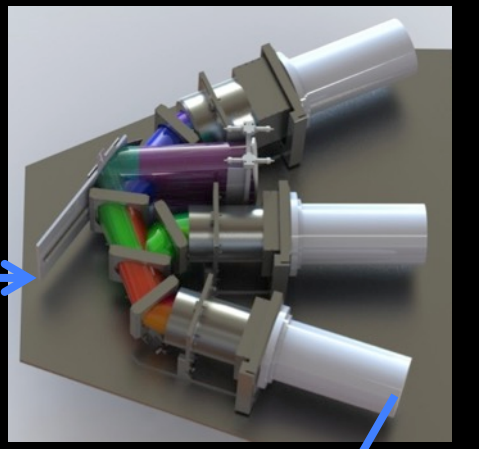




Fiber Positioner



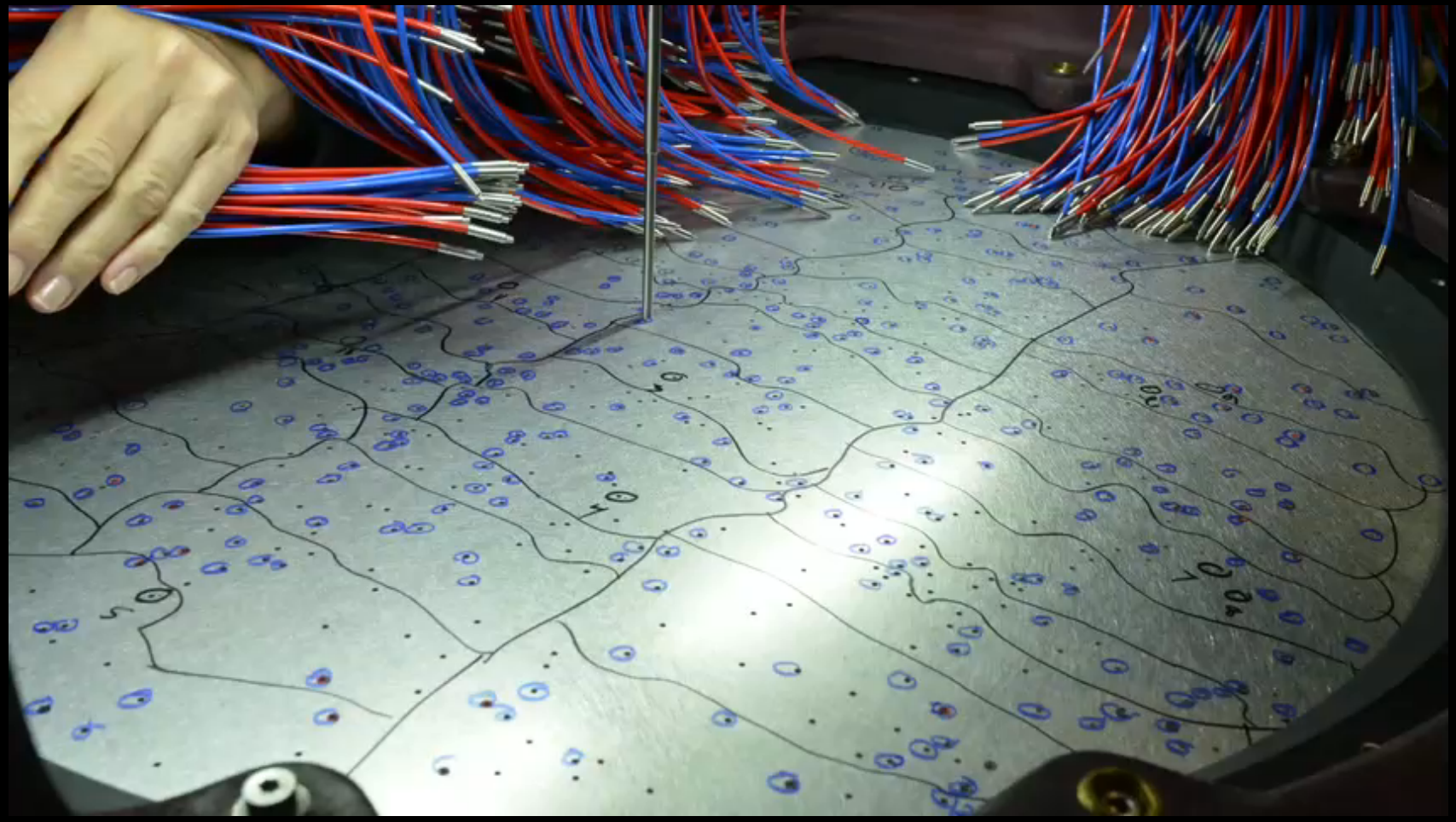
Fiber System



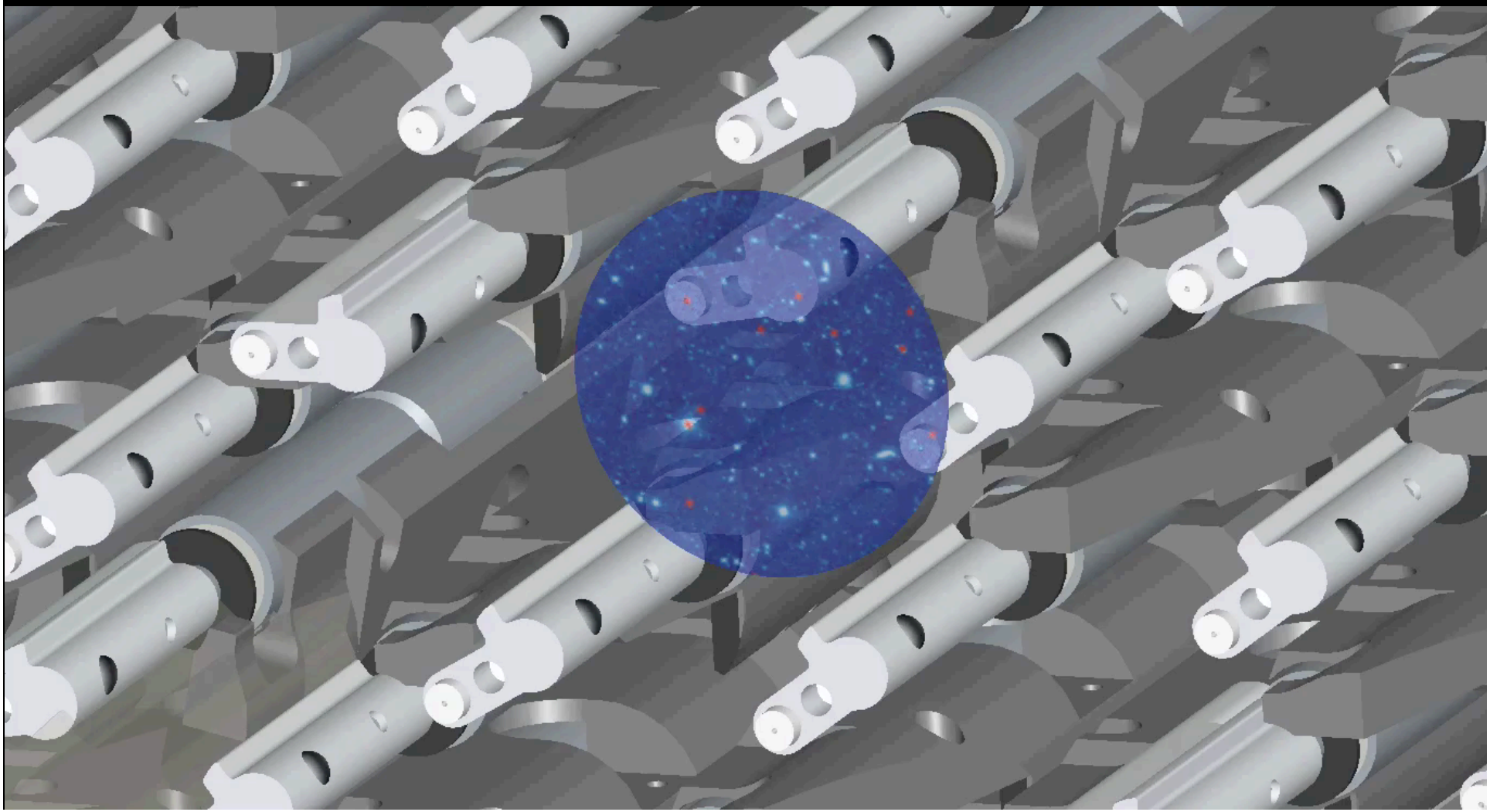
Spectrometer

LBNL CCD's

Plate Plugging for BOSS

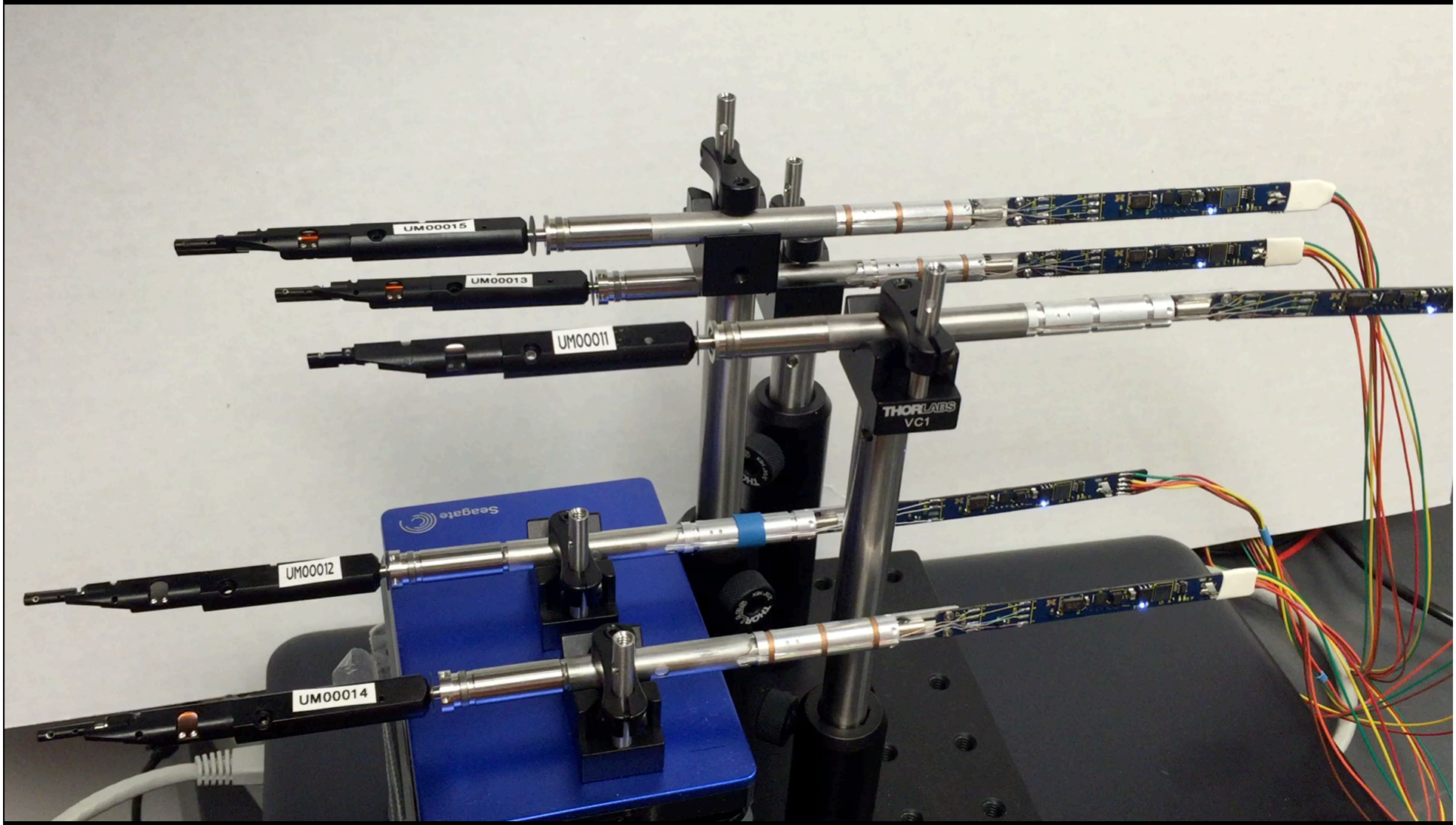


The robot army of DESI replaces hand-plugging of fibers

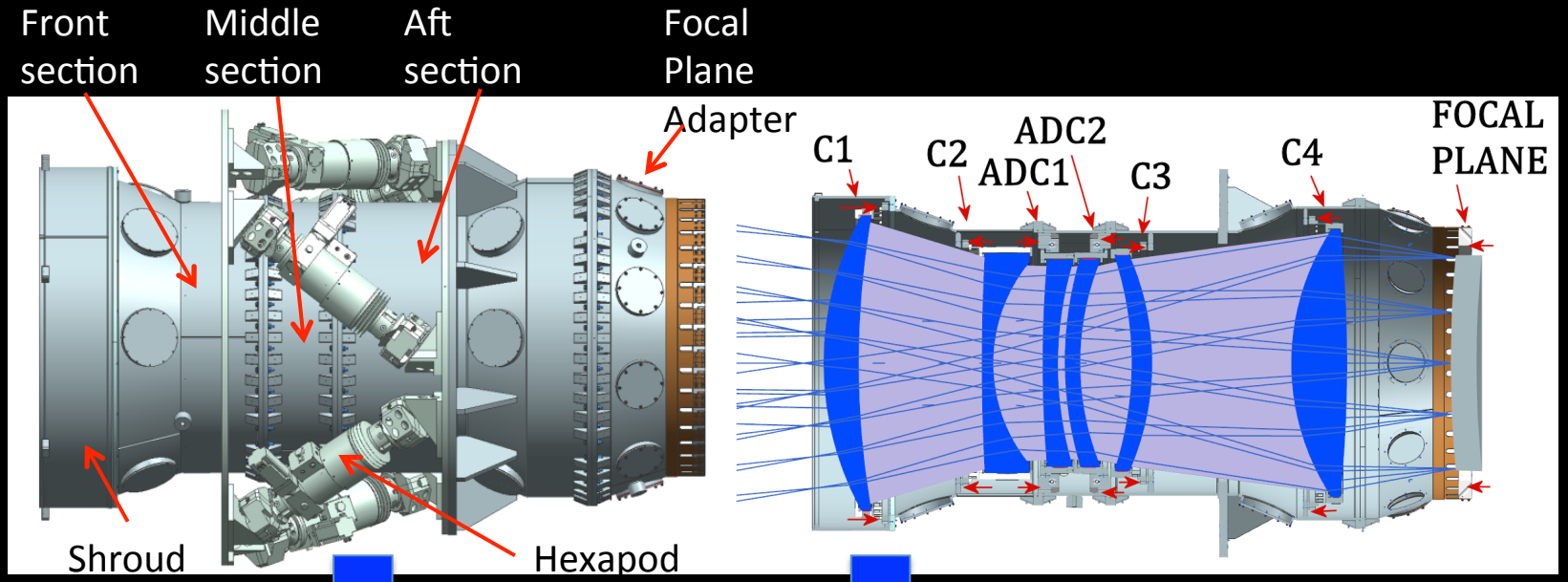


The robot army of DESI replaces hand-plugging of fibers

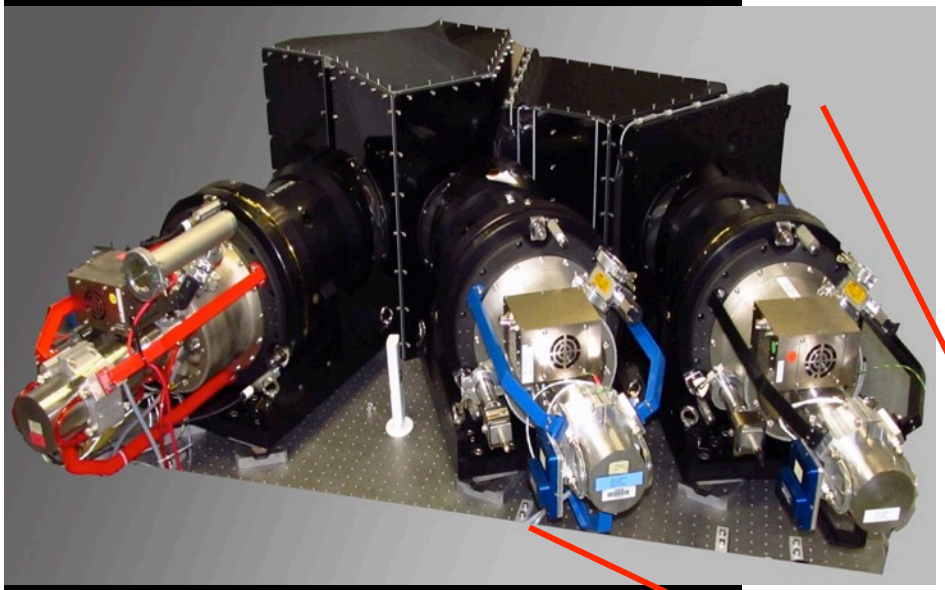
5 of the 5000 robots…

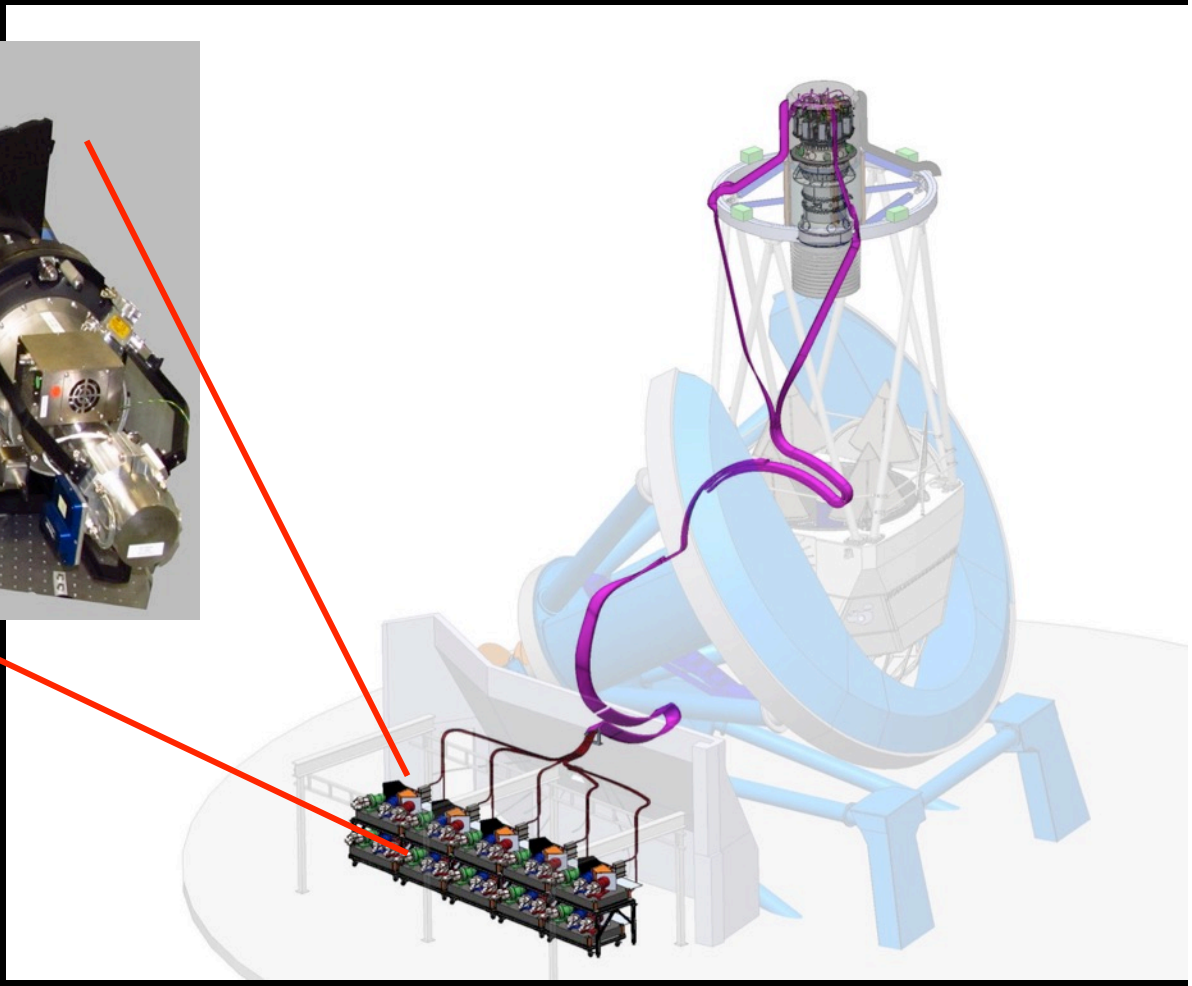


Wide field corrector focuses 8.0 sq-deg FOV on aspheric focal surface.
5 of 6 lenses have completed polishing, 1 has completed AR coating.
Barrel & Cage– FNAL, Optics – Industry, Integrated at Univ College London.



DESI spectrographs: First Demonstrate unit is built and verified; meets all requirements

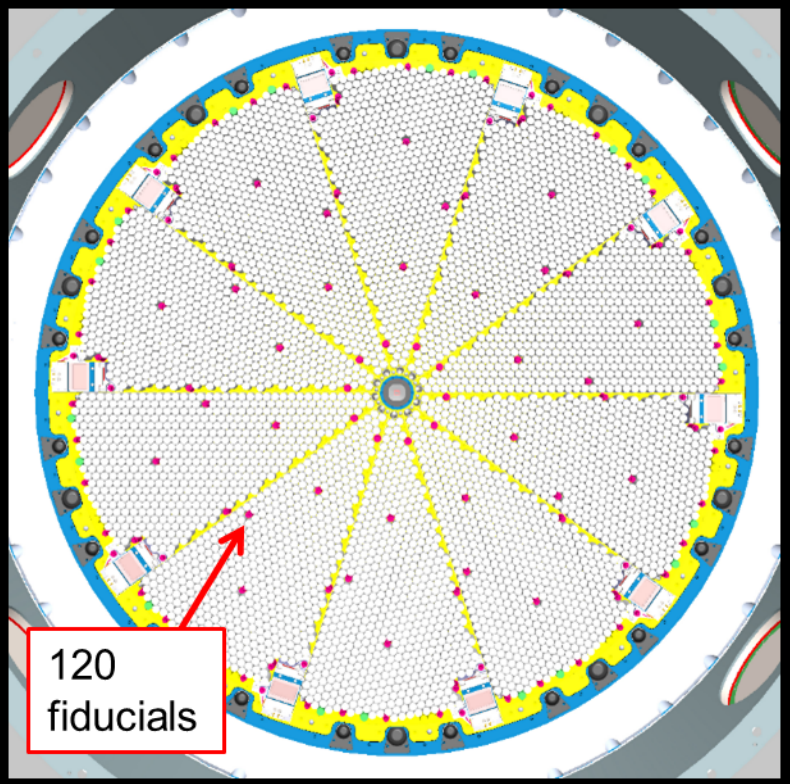


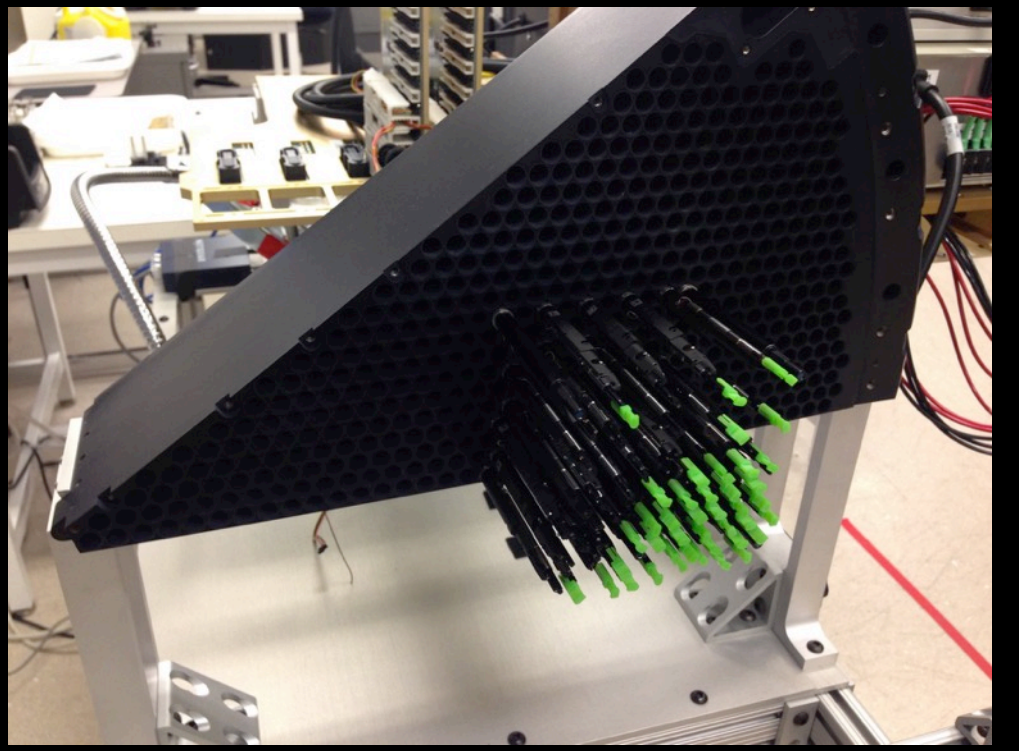


Optics Vendor: Winlight, Pertuis France
Sensors: LBNL/MSL, Univ Arizona
Electronics: LBNL
Gratings: Kaiser Optical
Dichroics: Materion
Cryocoolers: Thales
Testing: Univ. Marseille

Focal plane is comprised of ten petals, each with 500 fibers

First (Engineering Model) petal is assembled and populated



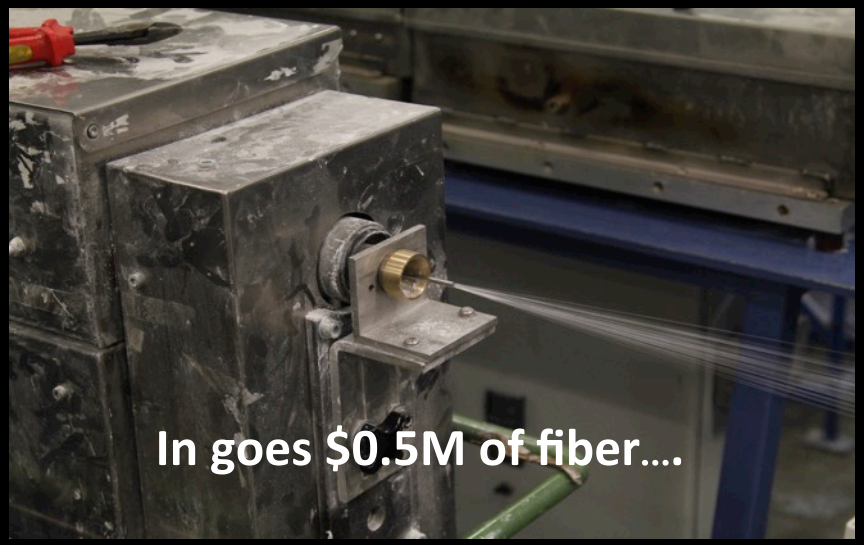


Petal Integration ring is machine at DIAL

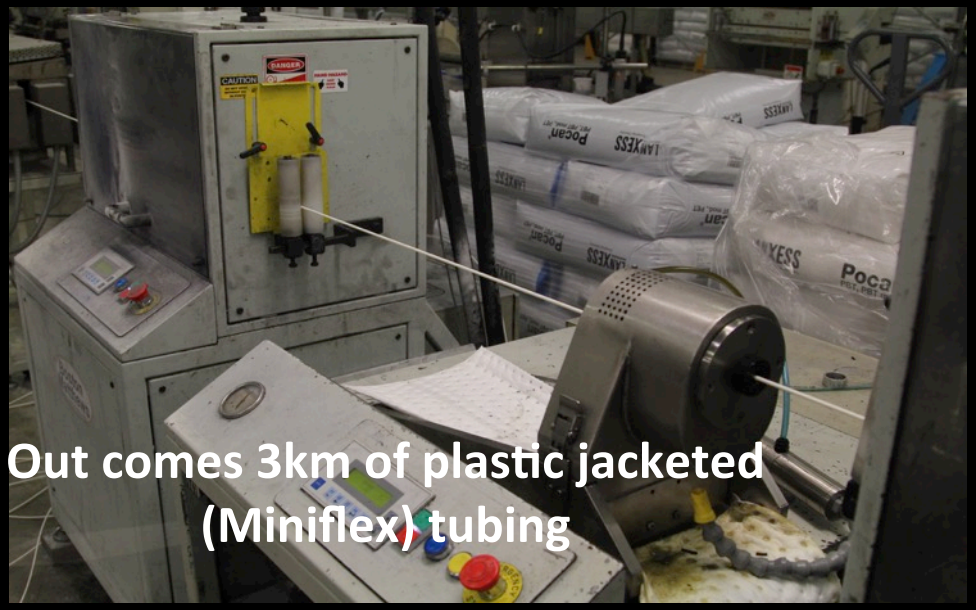
Boston Univ activity

Fiber Bundle Fabrication

Loading 53 science fiber spools….



In goes $0.5M of fiber….



Out comes 3km of plastic jacketed (Miniflex) tubing

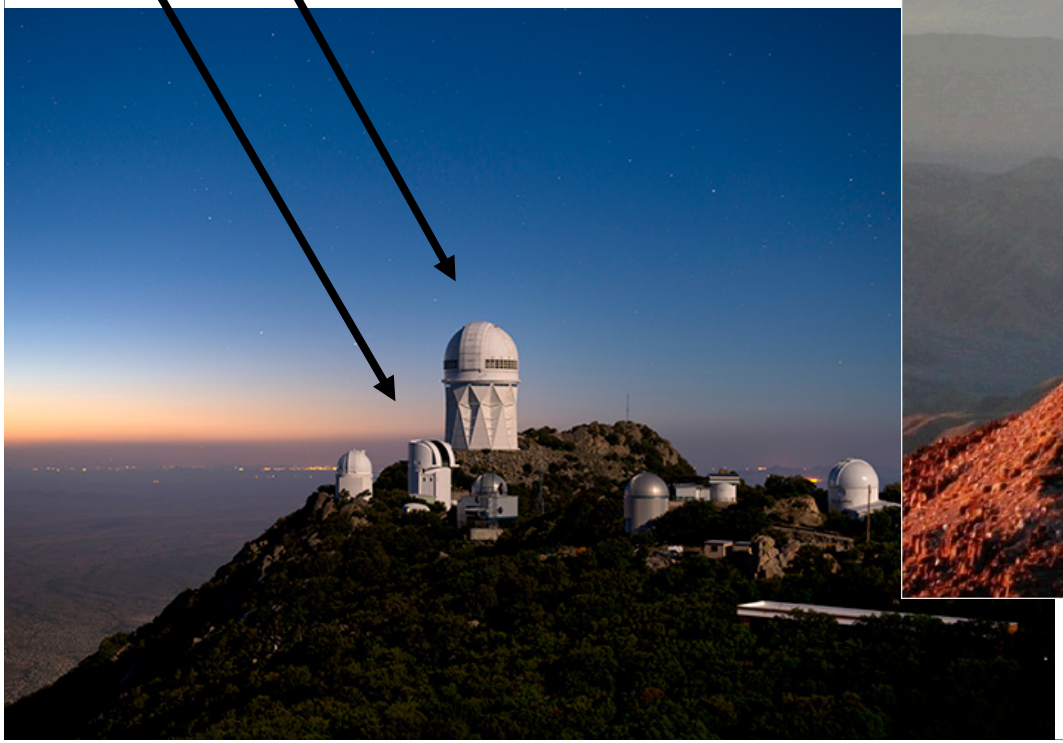
DESI collaboration undertaking major pre-imaging program 2014-2018

Imaging all of the available Northern sky to ~5X fainter than Sloan
Conducted as "public" surveys w/ immediate public access

240 nights at Bok 2.3-meter

400 nights at Kitt Peak 4-meter

150 nights at Cerro Tololo 4-m using DECam

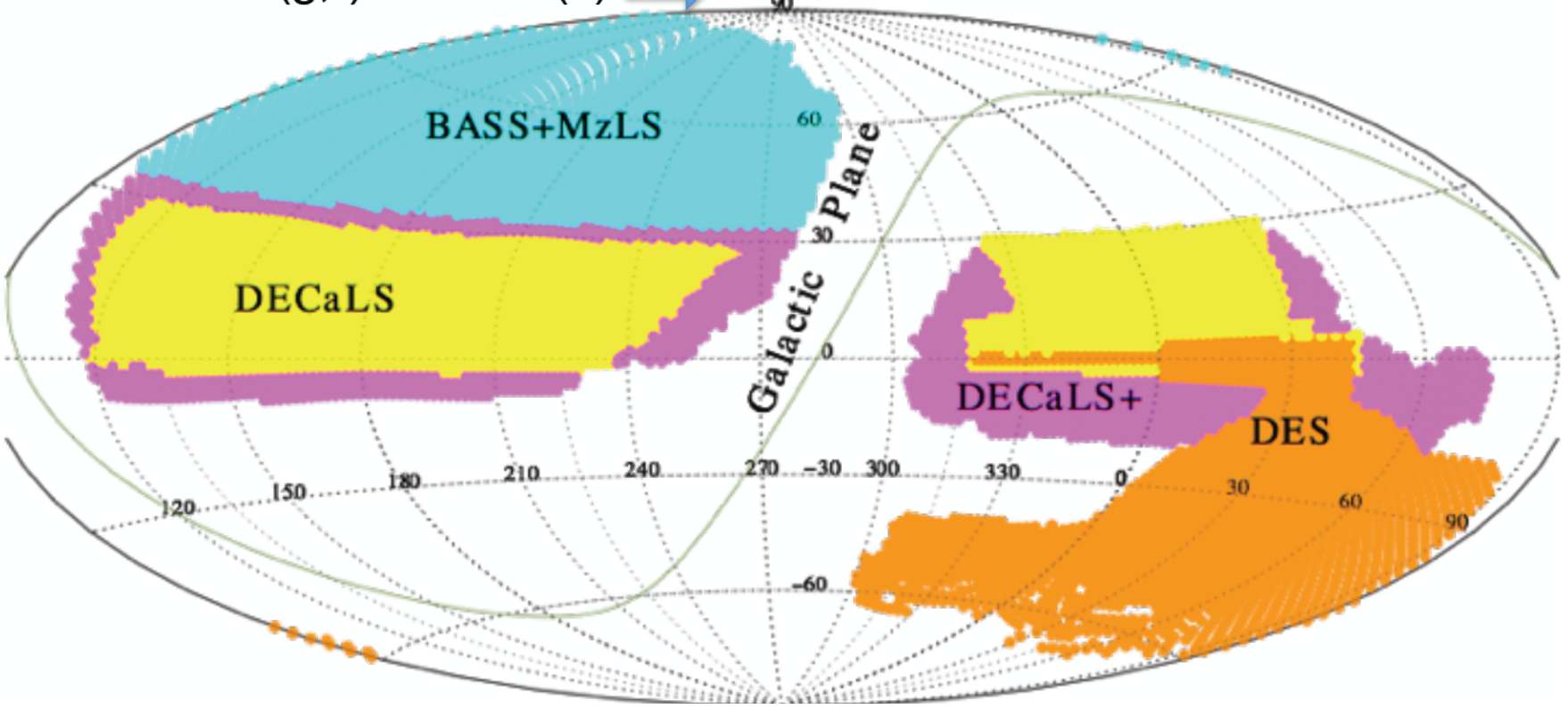


DESI Target Imaging Survey

Three new optical surveys covering 14,000 deg^2 DESI footprint

- DECaLS (g,r,z)
- BASS (g,r) + MzLS (z)

MOSAIC camera on Mayall +
LBNL 500 um thick CCDs



**~800 scheduled nights on Bok, Mayall MOSAIC, Blanco DECam;
on track for completion by November 2018 (MzLS in Nov. 2017)**

High-level DESI Schedule

Milestones	Date
CD-0 Approval (mission need)	September 2012
CD-1 Approval (DESI selected)	March 2015
CD-2 Approval (baseline)	September 2015
CD-3 Approval (construction)	June 2016
Start of Installation	November 2017
Start of Commissioning	February 2019
End of Commissioning (ends project)	July 2019
Survey Validation Survey Begins	July 2019
Science Survey Begins	November 2019
Science Survey End	November 2024

Beyond DESI

- DESI's planned 5-year spectroscopic survey on the Mayall telescope will end in late 2024
  - LSST 10-year imaging survey begins in late 2022
  - Two years of overlap, 2023-24 (~4000 - 8000 sq deg)
- DESI instrument is likely to continue to be a world-leading MOS instrument well beyond 2024
- Is there a scientific case for continued operation of DESI in the LSST era?
  - Focus here is on DESI-2 scientific case
  - Could also play a role in spectroscopic followup, photo-z training and calibration for LSST

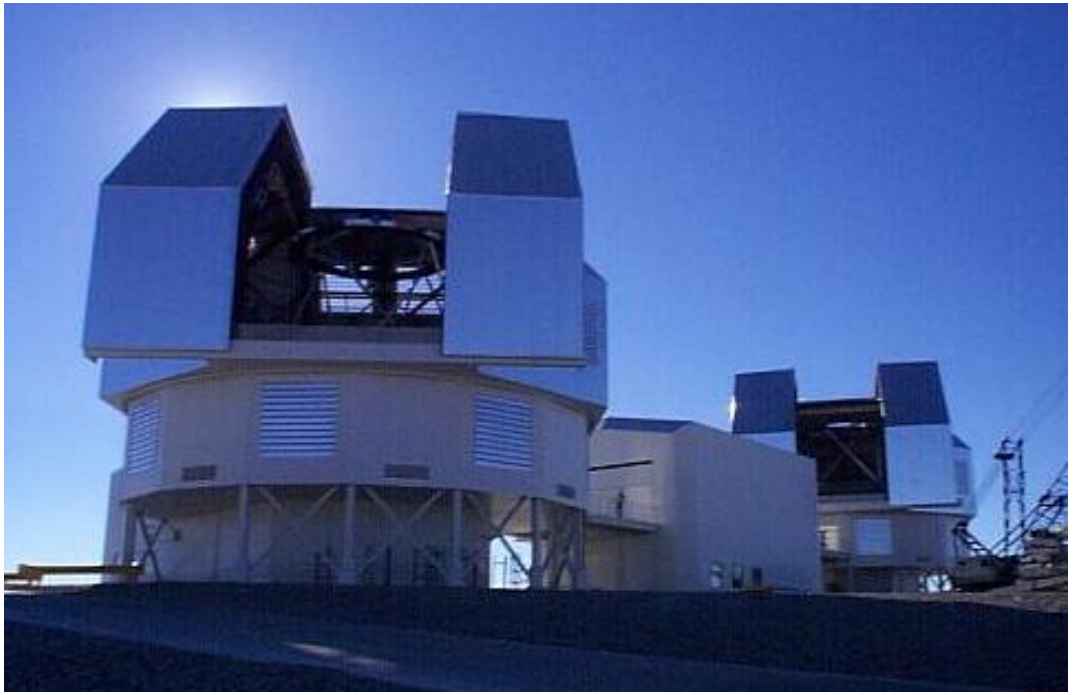
Options for DESI-2

- Several possible scenarios
  - Continue operations on the Mayall with existing DESI instrument; new targets in overlap region with LSST
  - Upgrade DESI instrument and continue on Mayall
  - Move DESI to south (Blanco or larger telescope)
  - Upgrade DESI and move to south
- Informal working group at LBNL is starting to look at the scientific motivations
  - Greg Aldering , Shirley Ho, Alex Kim, Khee-Gan (K.G.) Lee, Patrick McDonald, Aaron Meisner, Peter Nugent, David Schlegel (co-chair), Uros Seljak (co-chair), Zachary Slepian, Martin White

Beyond DESI platforms

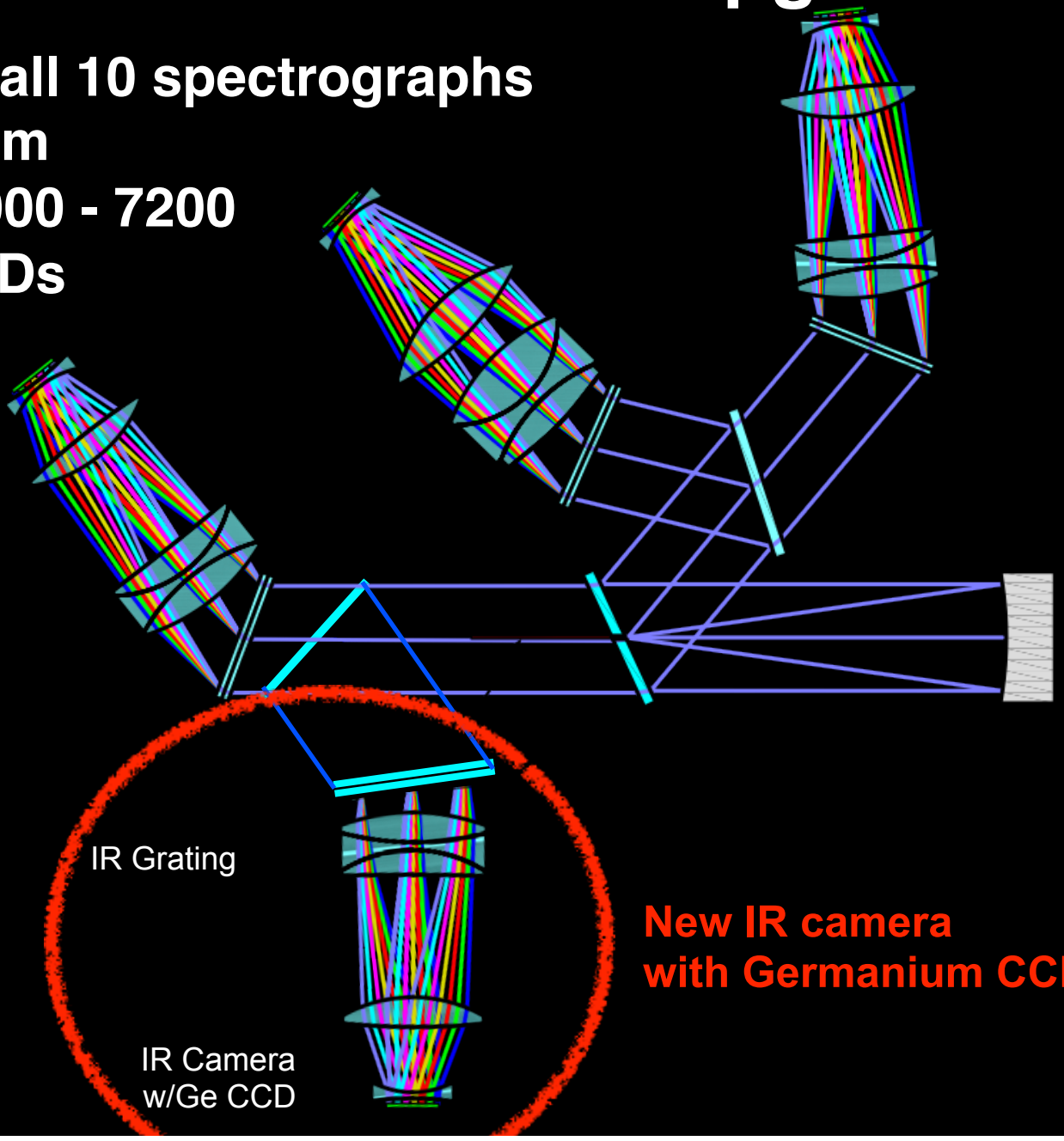
The DESI instrument, an upgrade, or a re-build could technically be carried out on several platforms:

- **Mayall 4-m at Kitt Peak (DESI platform)**
- **Blanco 4-m at Cerro Tololo (DECam platform)**
- **Magellan 6.5-m with existing f/5 corrector *(limited to 2000 fibers)***
- **Magellan 6.5-m with f/3 corrector and larger FOV**
- **MMT 6.5-m or SPMT 6.5-m (twins of Magellan)**



Beyond DESI: instrument upgrade

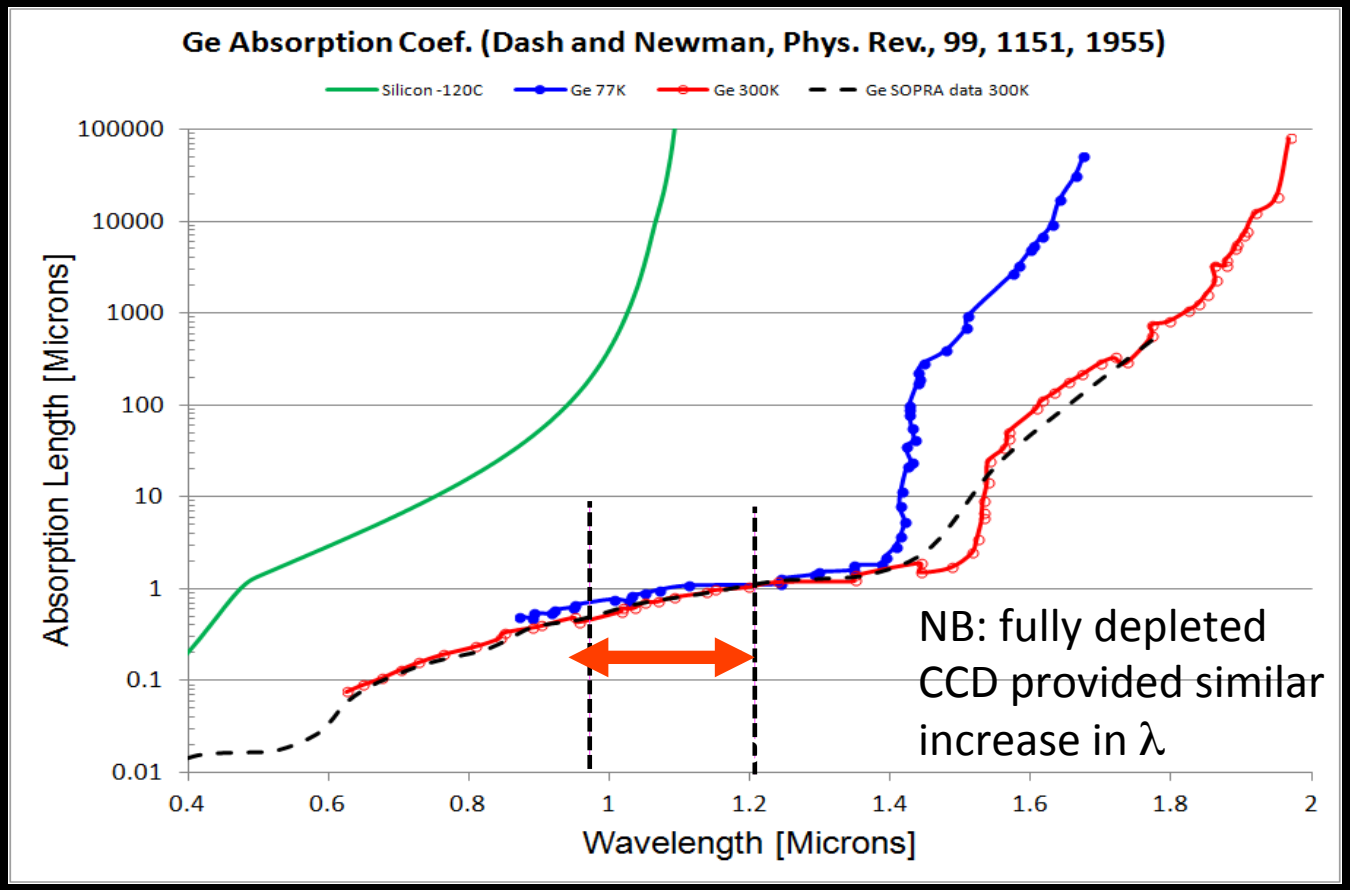
Add 4th arm to all 10 spectrographs
λ = 980 - 1200 nm
Resolution = 6000 - 7200
Germanium CCDs



New IR camera with Germanium CCD

Beyond DESI: instrument upgrade

λ = 980 - 1200 nm is well-matched to Ge CCD detectors



Ge CCDs have potential to perform better than HgCdTe NIR detectors at lower cost; however GeO2 is challenging to work with (water soluble, lower melting point)

Developing Process flow for Ge CCDs (LDRD support)

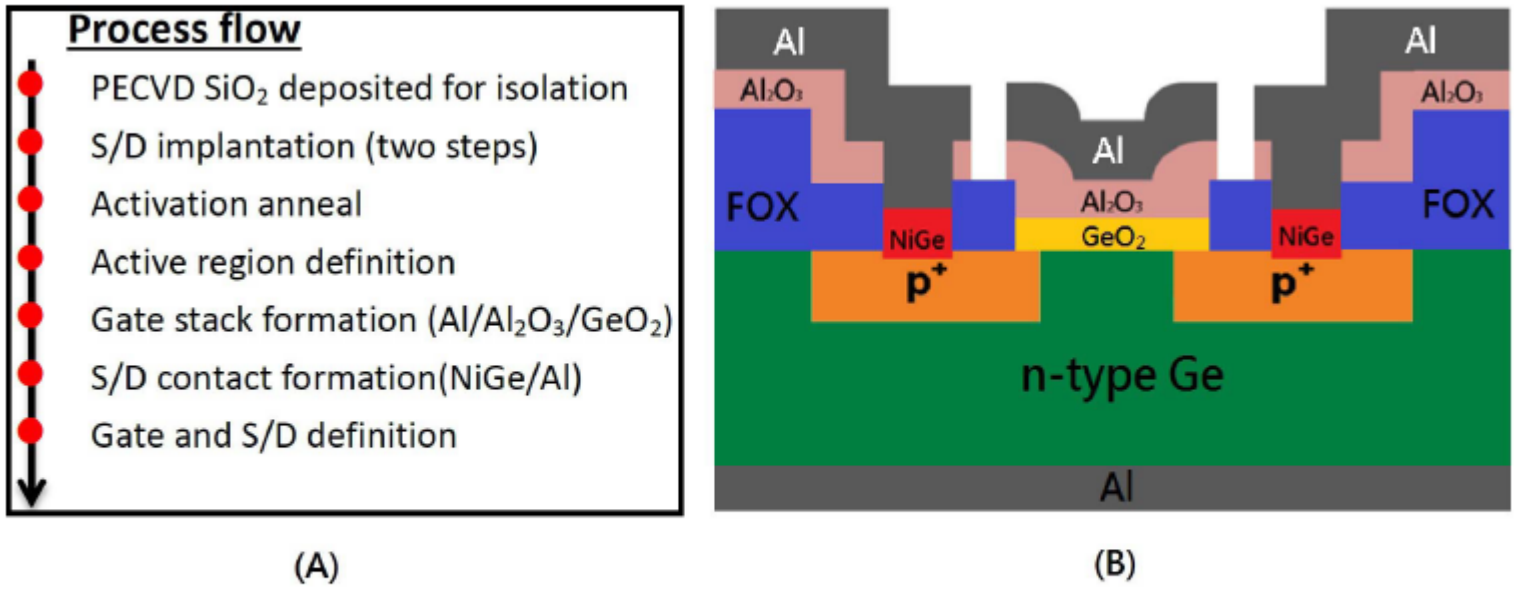
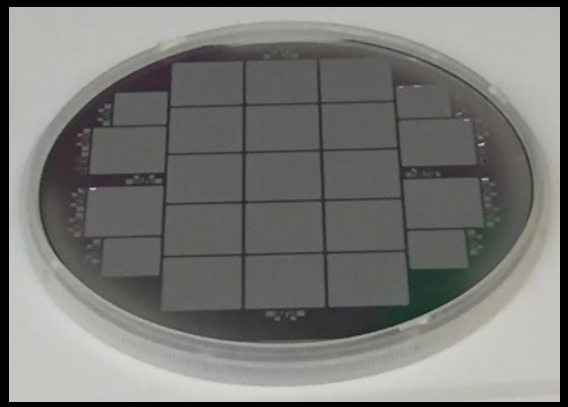


Fig. 1. (a) Gate-last process flow and (b) cross-sectional view of the Ge p-MOSFETs with $Al/Al_2O_3/GeO_2$ gate-stack and NiGe S/D contact.

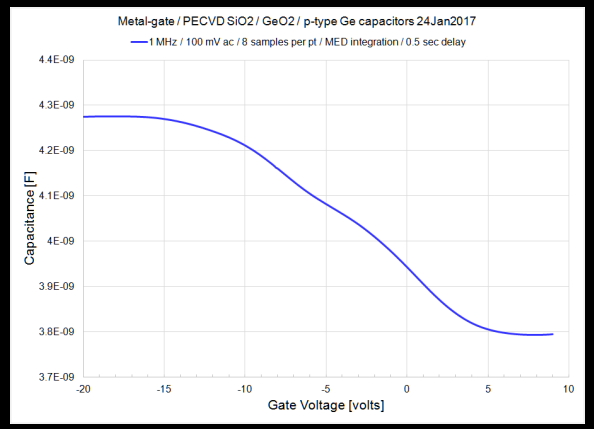
Progress on Ge processing steps at LBNL MicroSystemsLab (Laboratory Directed R&D (LDRD) funding)

- Furnace tube repurposed from silicon oxidation at ~ 950°C to Ge oxidation at ~ 550°C
  - GeO_2 grown in the MSL on photovoltaic-quality Ge with 1.0% uniformity across a 150 mm wafer

550C oxidation to produce GeO_2



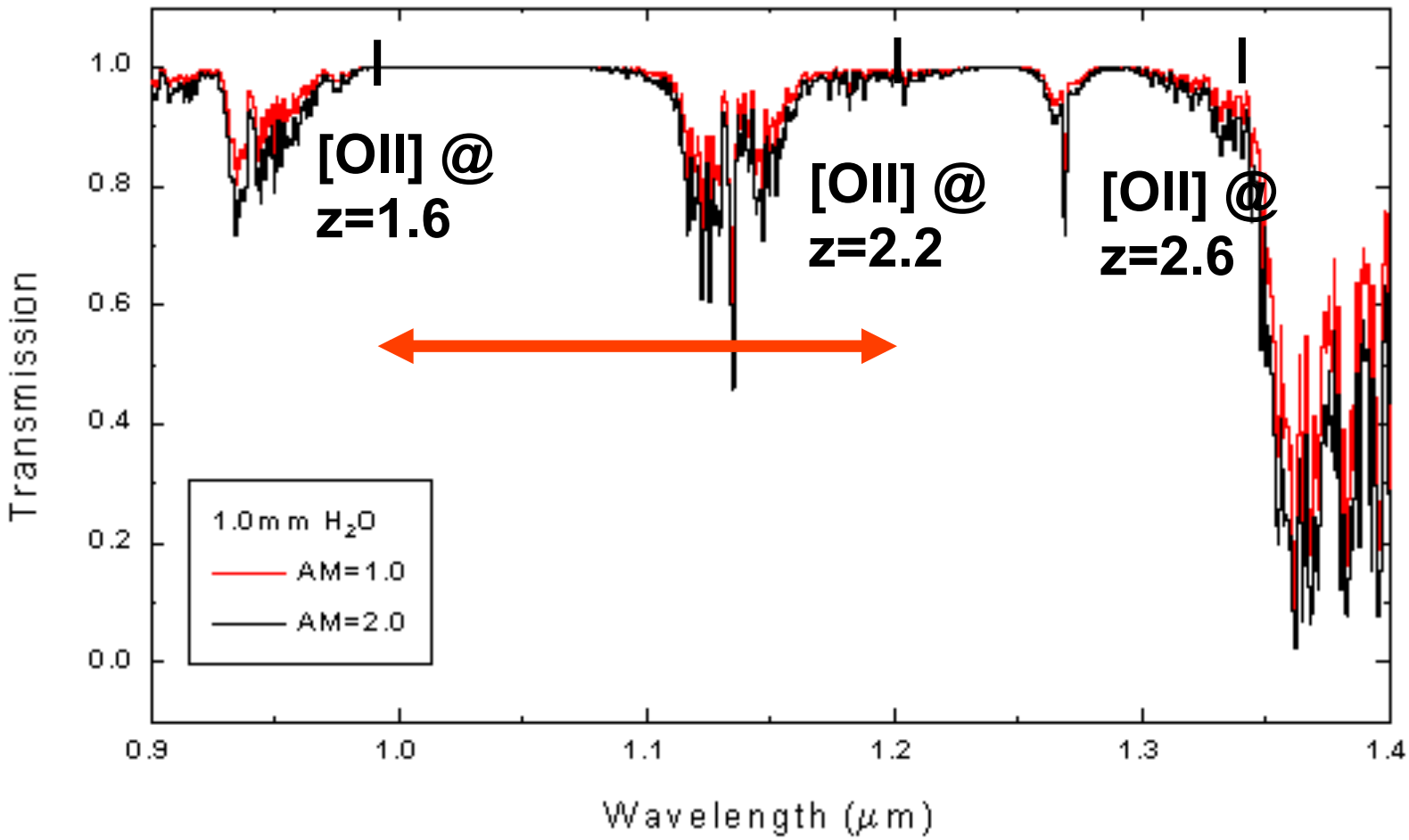
Wafer photograph



Capacitance-voltage plot

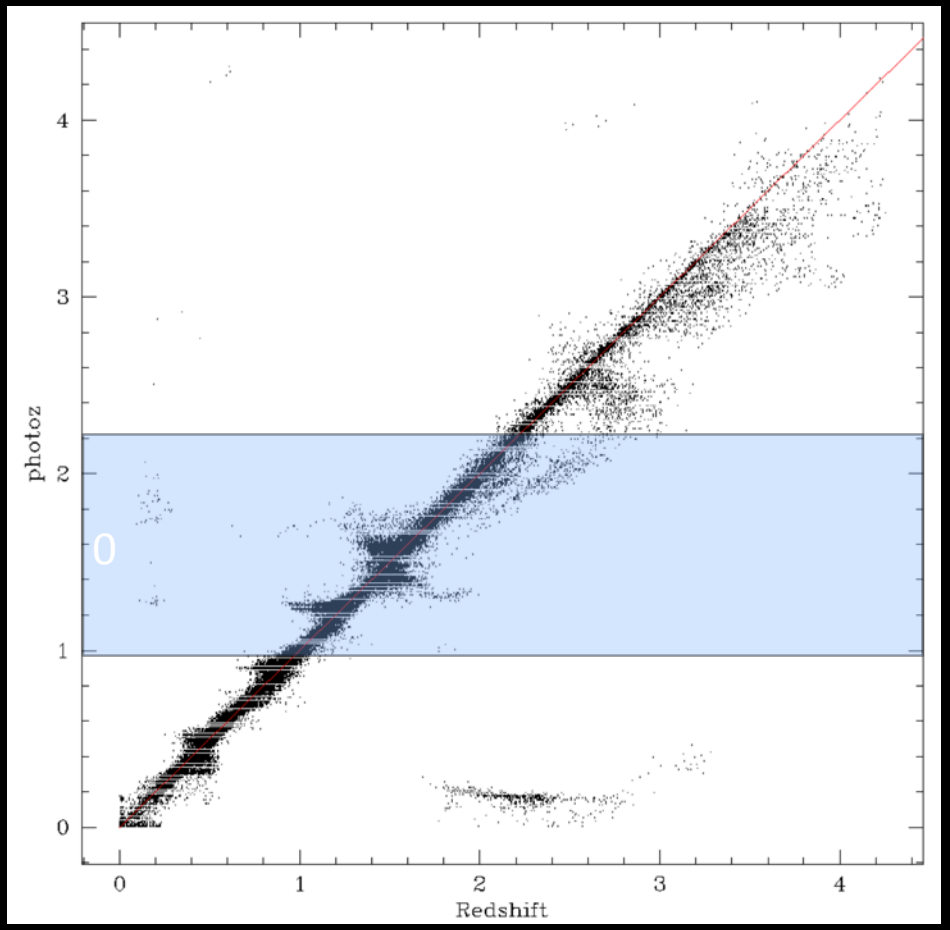
Beyond DESI: instrument upgrade

λ = 980 - 1200 nm is a good atmospheric window from the ground



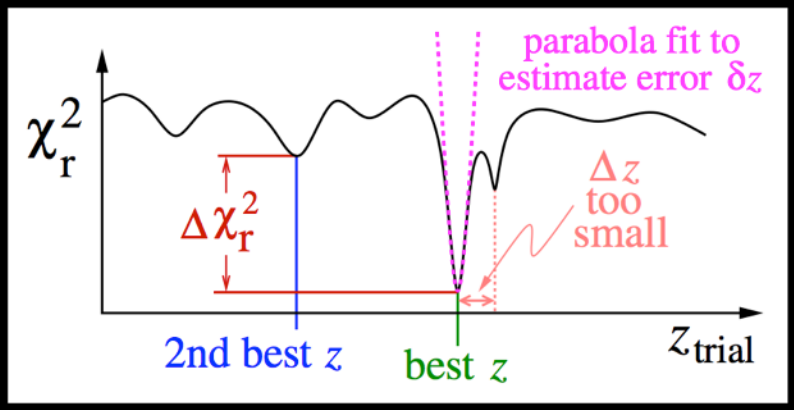
Conceptual design for DESI-Upgrade survey

Select 100M galaxies from LSST with 1 < photo-z < 2.2
+ additional quasars + LBGs at z > 2.2



Redshift

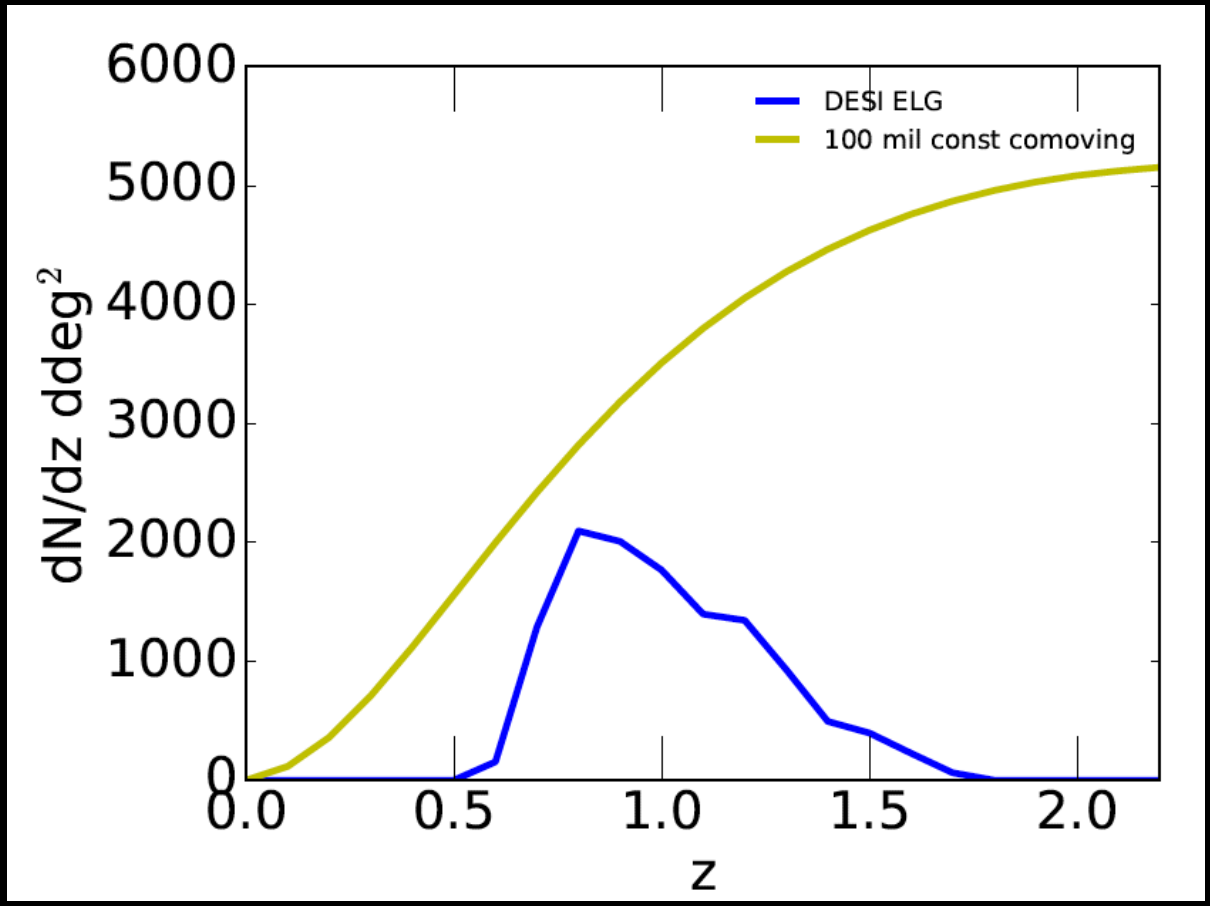
Follow-up spectroscopy with sufficient S/N for converting
Δz = 0.03 → Δz = 0.001



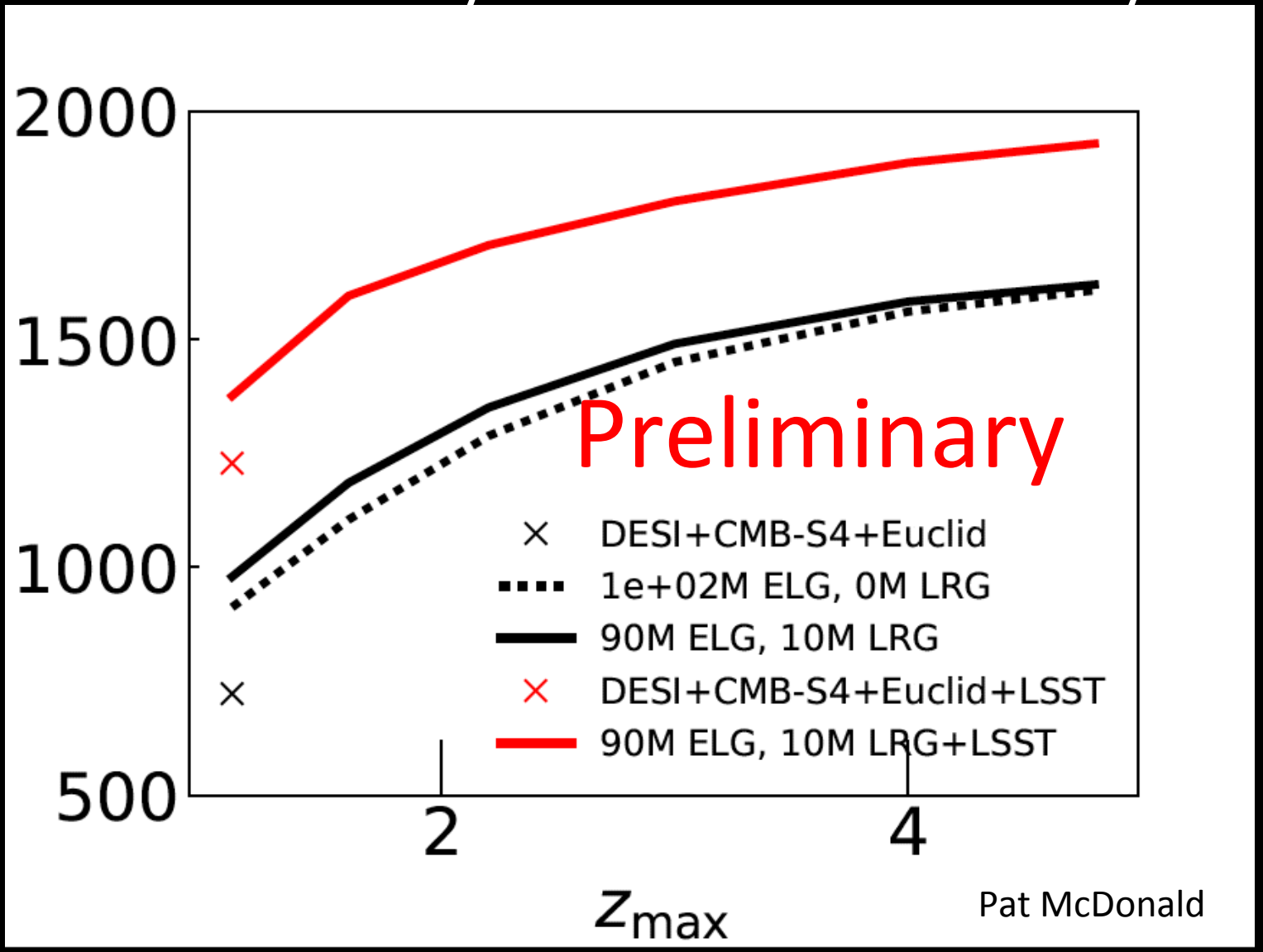
The trick:
DESI operates at S/N > 7
DESI-II at S/N > 3
Bolton, Schlegel et al. 2012

David Schlegel

DN/dz for 100M galaxies with constant co-moving density to z=2.2



Dark Energy Figure of Merit vs Redshift For 100M Galaxy DESI-2 Redshift Survey



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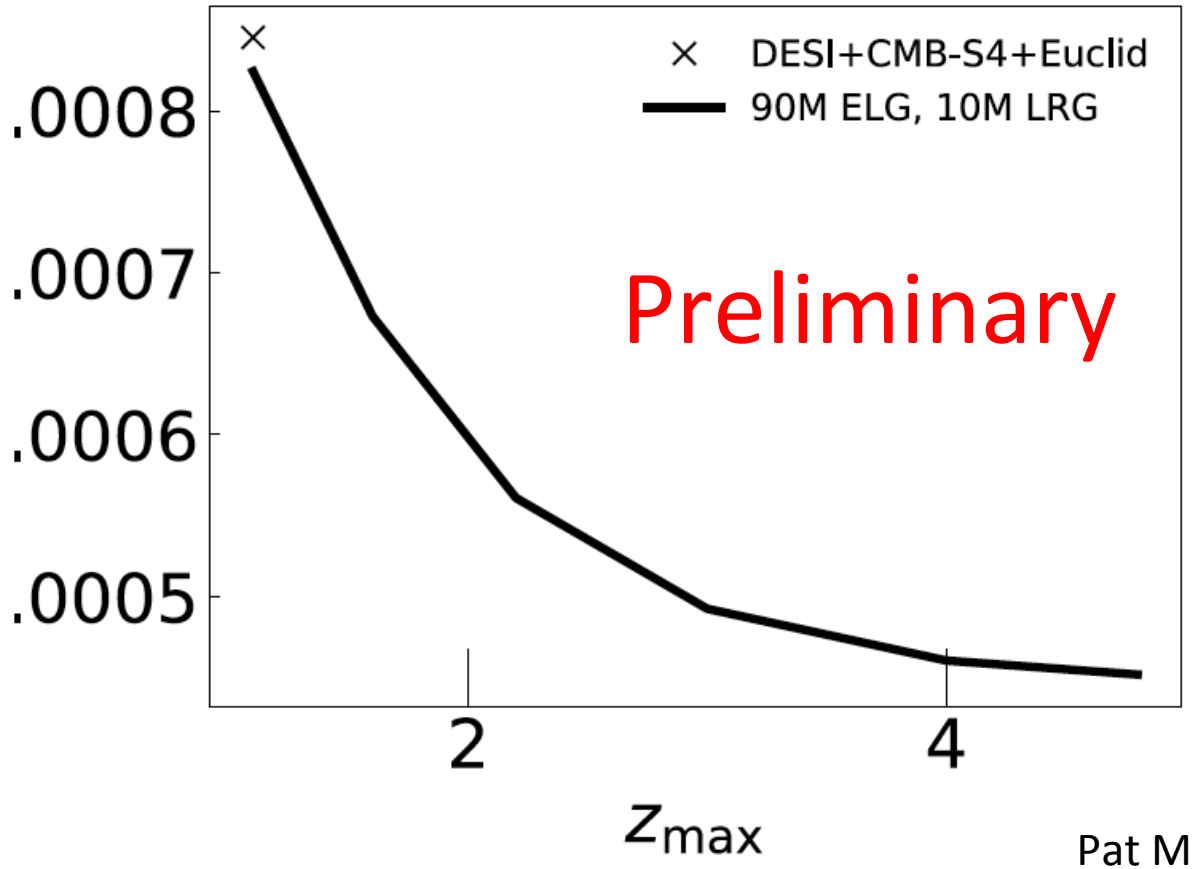
Ω_k constraint for 100M uniformly distributed galaxies up to Zmax



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What Science are we excited about?

Science Case	Larger scale , Higher Redshift?	smaller scale, Lower redshift?
Dark Matter	Lyman alpha forest	substructure, streams, local universe constraints (velocities)
Testing Gravity	Large scale structure constraints	Environment dependent constraints (voids, filaments), Local Universe Constraints (velocities)
Initial conditions	P(K)	high density sample
Dark Energy	Baryon acoustic oscillations, Redshift space distortions	high density sample for RSD
Neutrino Properties	P(k), Lyman alpha forest	P(k) at small scale
Gravity WAVE		HIGH DENSITY SAMPLE
Astrophysics for Galaxies, Clusters	Bias as a function of redshift	Bias, kinectic Sunyaev Zeldovich, velocity

Shirley Ho

Hypothetical Timeline

- **DESI [Nov. 2019- Nov. 2024]**
- **DESI-2 : [Start 2025]**
  - 20 M galaxies /year (3/5 years), 4-10k overlap w/LSST
  - Magnitude limited survey
- **DESI-upgrade : [2026-9]**
  - 20M galaxies/year high-z
  - n(z) ~constant / comoving volume to z=2.2
  - 3X improvement FOM 5 years
- **BOA instrument [203X]**
  - ~ 1 billion objects
  - -> comoving to z=3.2

Summary

- BOSS has greatly increased precision in cosmology with BAO and RSD
  - First 1% galaxy BAO distance measurements
  - First distance measurement at z>2 using Lyman-α forest BAO
  - Redshift space distortion measurement of growth of structure
  - Strong constraints on dark energy, H_0, neutrino masses…
- DESI will be the first Stage IV Dark Energy Experiment
  - Based on successful BOSS experiment
  - In construction, first light in 2018, survey will start in 2019
  - Five year survey will measure 30M redshifts
  - Not just dark energy, but GR, inflation, neutrinos
- The scientific case for DESI-2 is under development
  - Considering several options: site, upgrades, scientific focus
  - Complementarity with LSST/Euclid/WFIRST/CMB-S4
  - Future is promising