3-D cosmic maps from DESI and future redshift surveys

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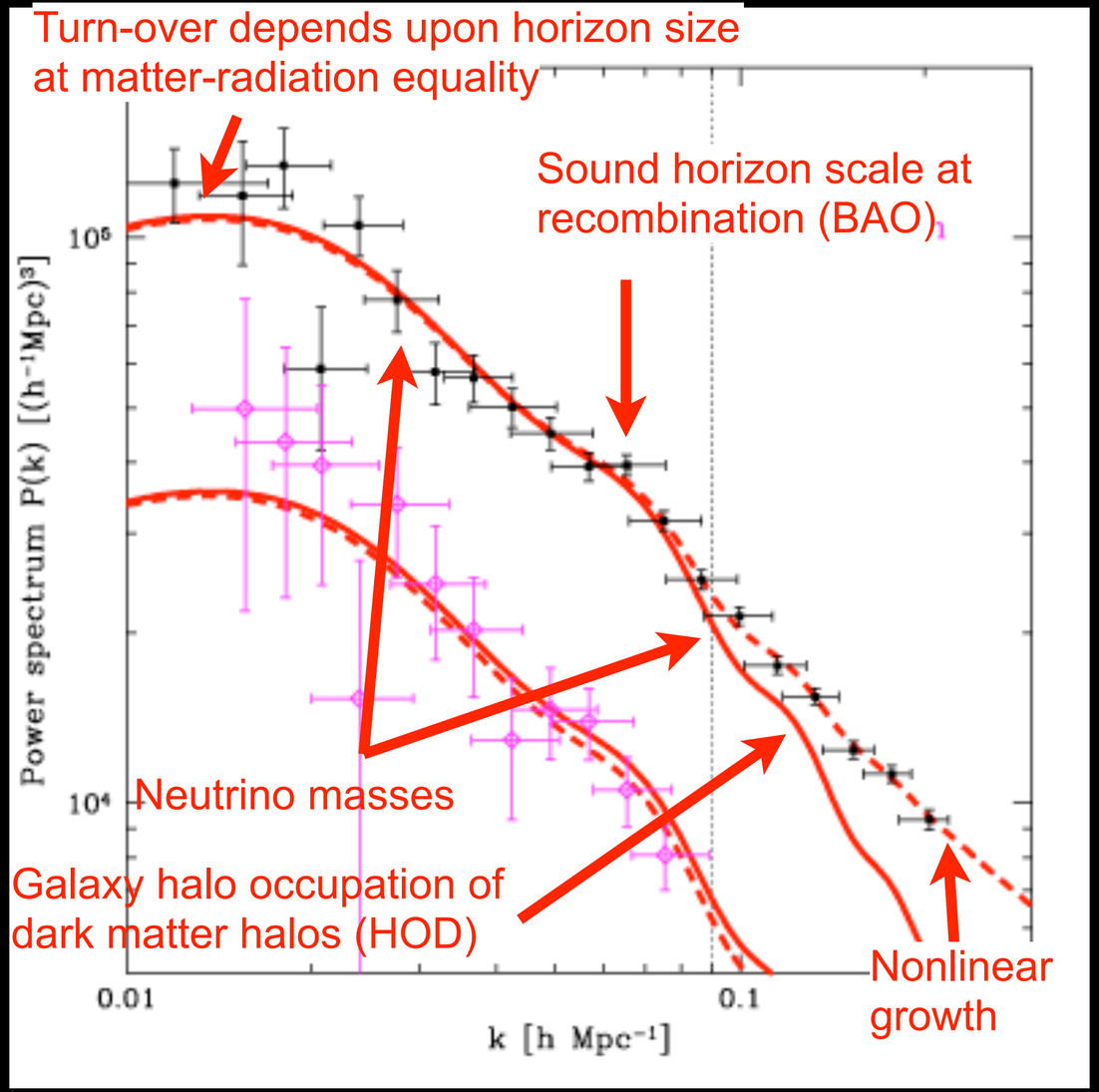
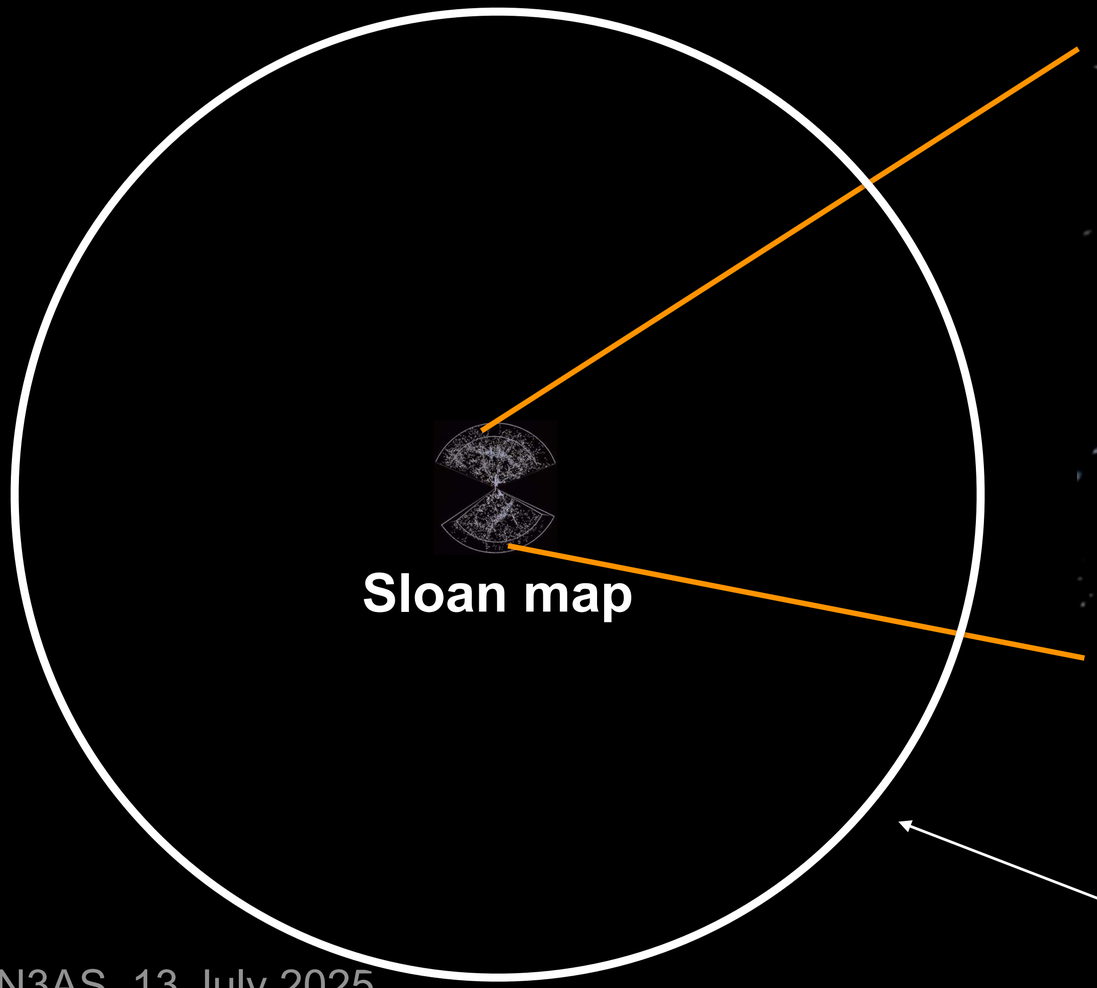
Thanks to the U.S. Department of Energy,
Heising-Simons Foundation, Moore Foundation,
72 participating institutions,
DESI project & science teams

Redshift surveys (3D galaxy maps) have a long, successful history turning the statistics of galaxy clustering —> cosmology



Bigger maps mean better measurements

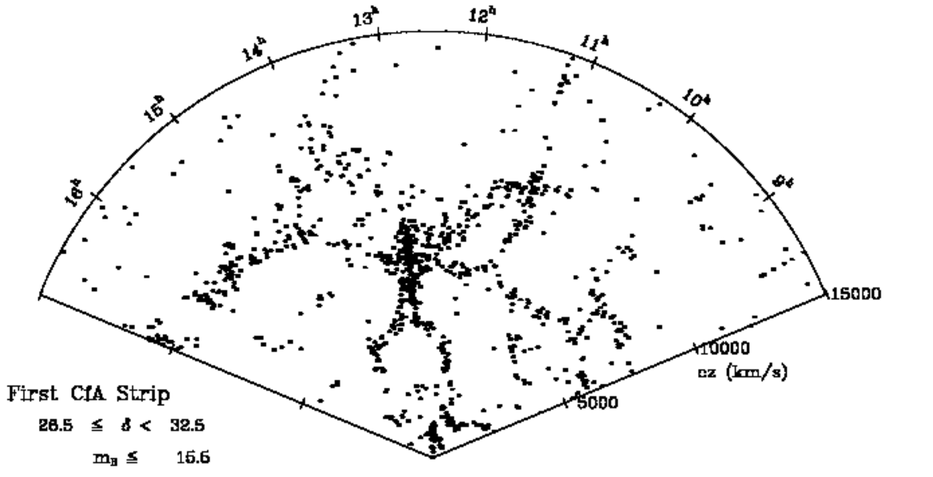
SDSS: 2.5 million galaxies + QSOs (1999 - 2019)
DESI: 40 million galaxies + QSOs (start May 2021)

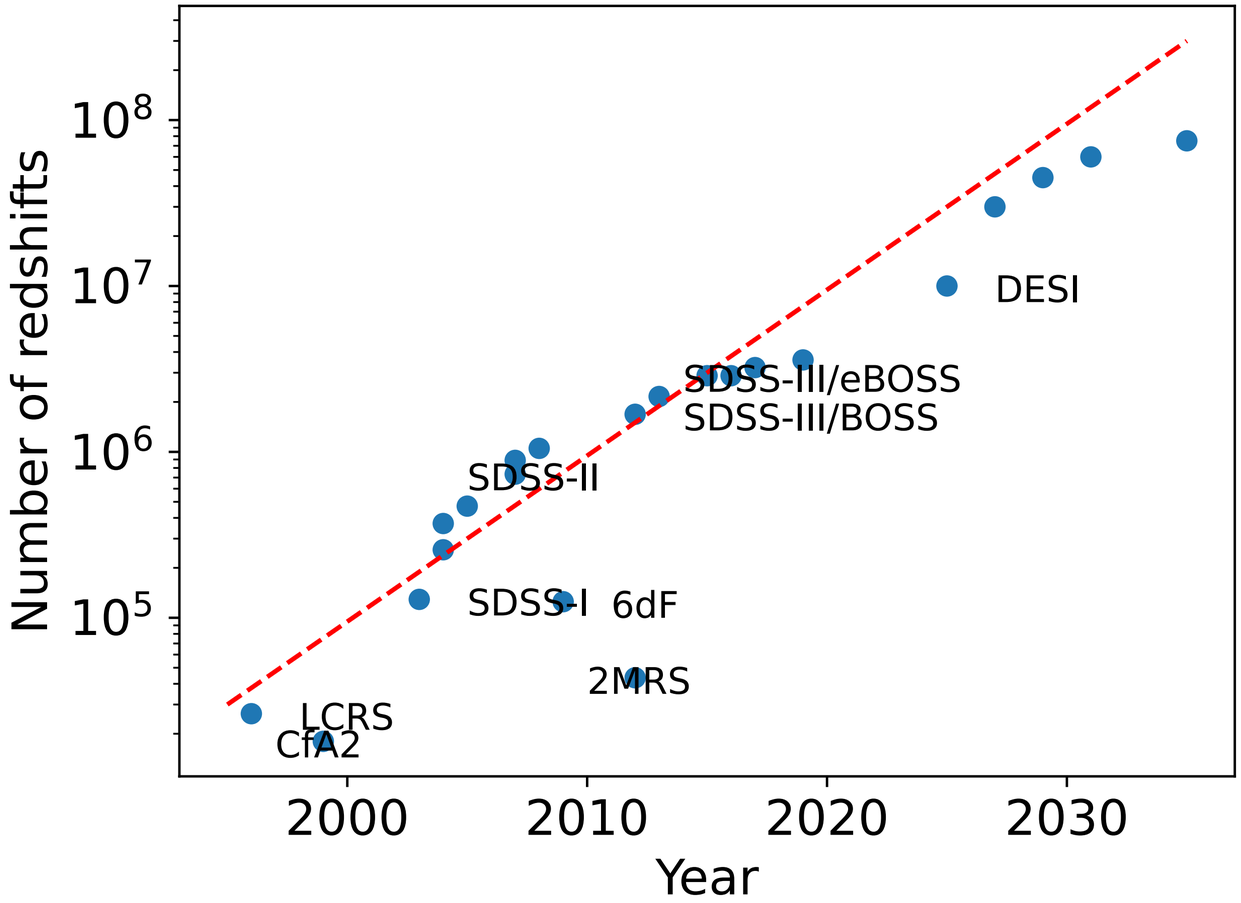


limit of visible Universe

Redshift surveys have rapidly progressed — 10X larger every 10 years + extending to higher redshift

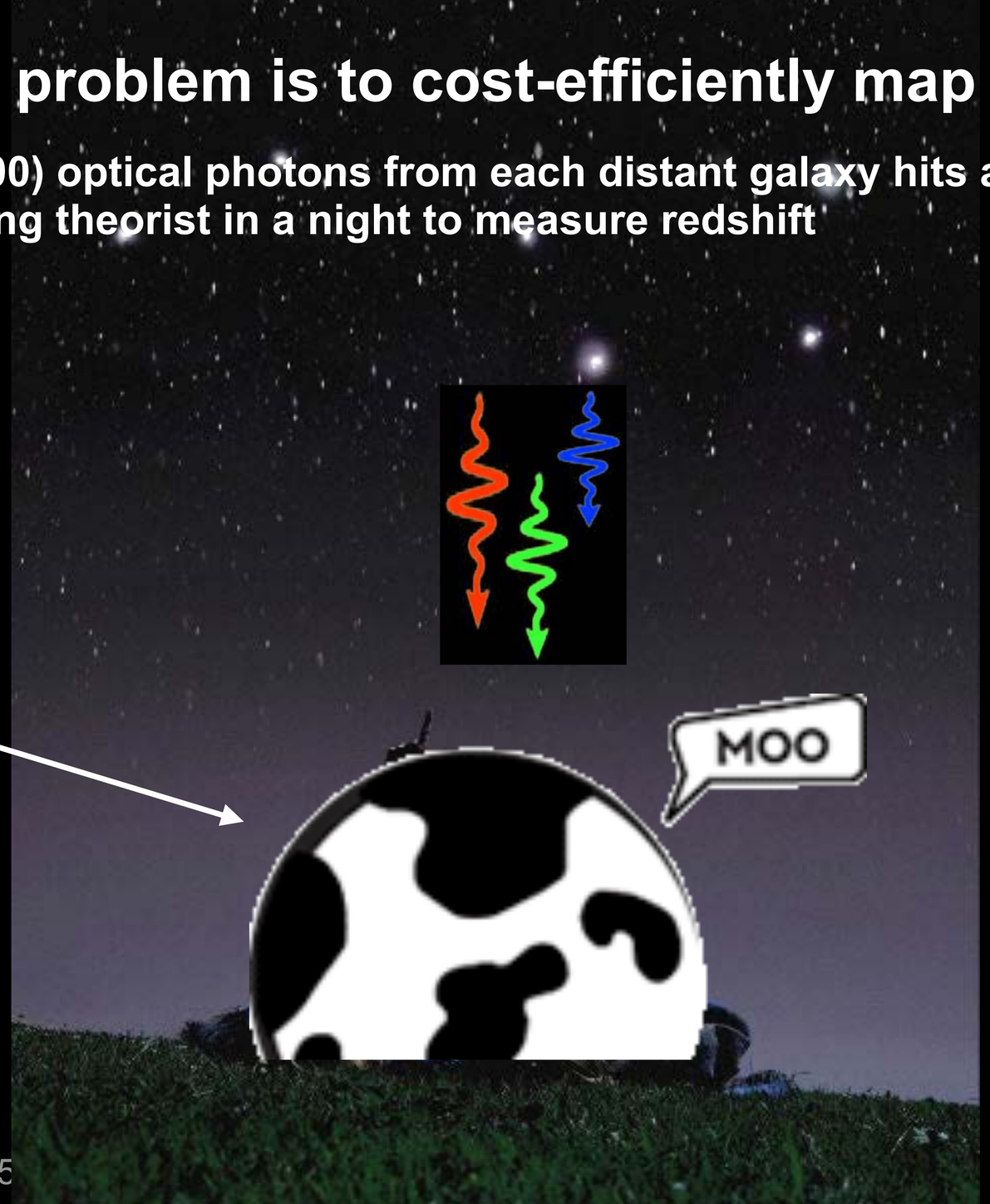
Enables exploring new physics + known physics at better precision





Technical problem is to cost-efficiently map the sky

Enough (~1000) optical photons from each distant galaxy hits a spherical string theorist in a night to measure redshift



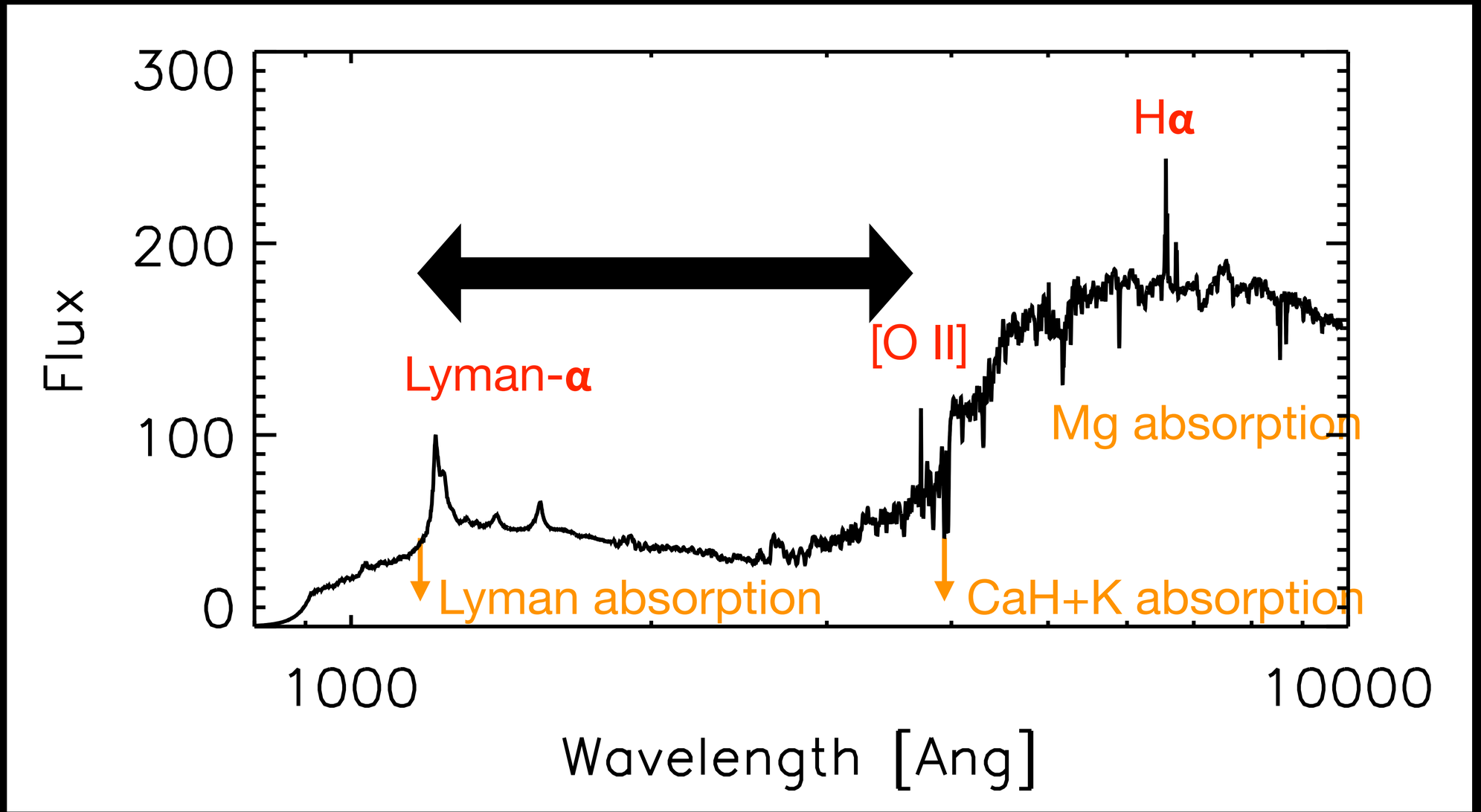
spherical string theorist

Technically possible to measure redshifts for all galaxies in optical/near-IR

—> Require large wavelength range in spectrographs

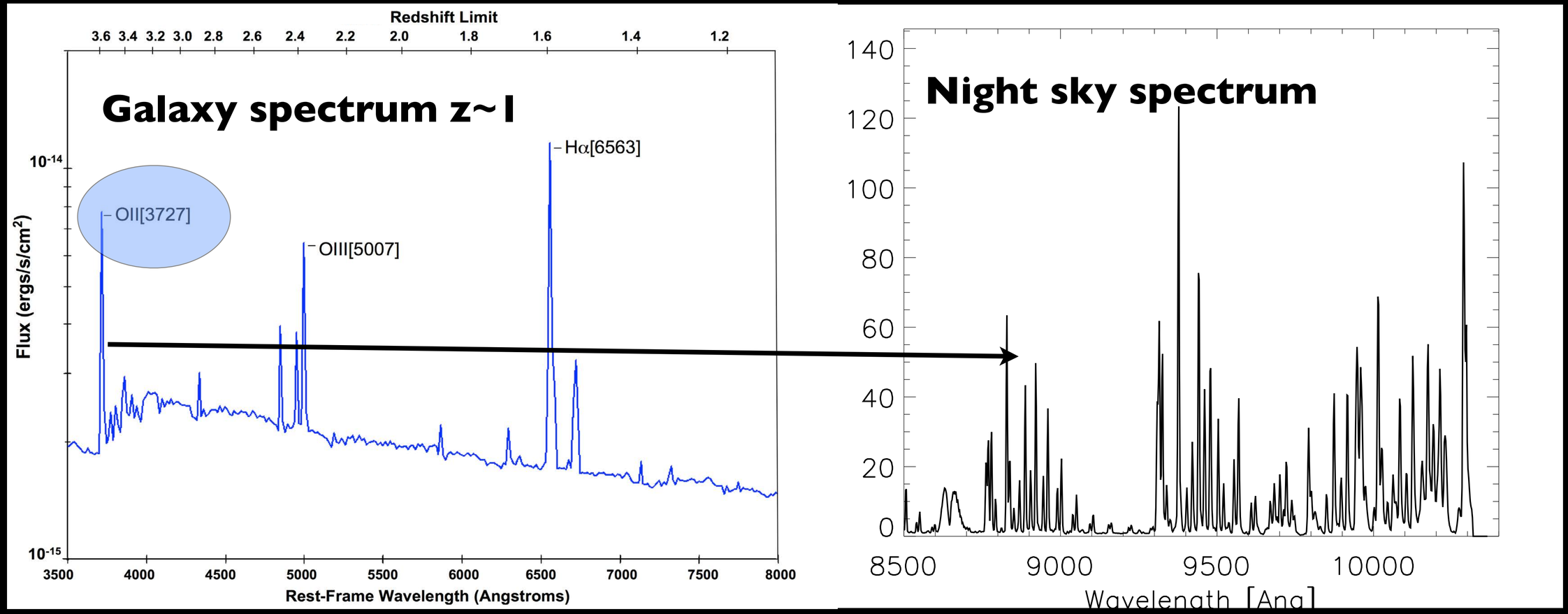
λ_{max} / λ_{min} > 3727/1216 to have bright emission lines at any redshift

> 3840/1216 to have absorption features at any redshift



Technically possible to measure redshifts for all galaxies in optical/near-IR
—> Require spectrograph resolution = $\lambda/\Delta\lambda$

Resolution > 300, or losing cosmological modes
Resolution > 2000, or lose signal/noise on spectral features
Resolution > 5000, or not resolving between sky lines (at λ > 5500 Ang)



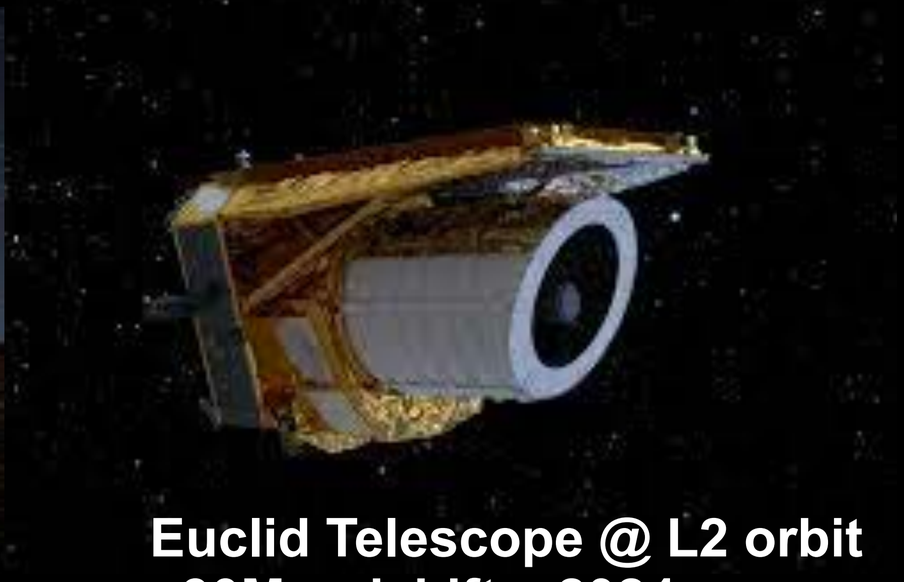
Technical problem is to cost-efficiently map the sky

Most telescopes see only a small patch of sky … and only a few galaxies

200,000 years to survey sky with the Hubble Space Telescope
(we're not doing this)

Stage 4 redshift surveys in the 2020s

DESI @ Mayall, Arizona
40M redshifts, 2021—

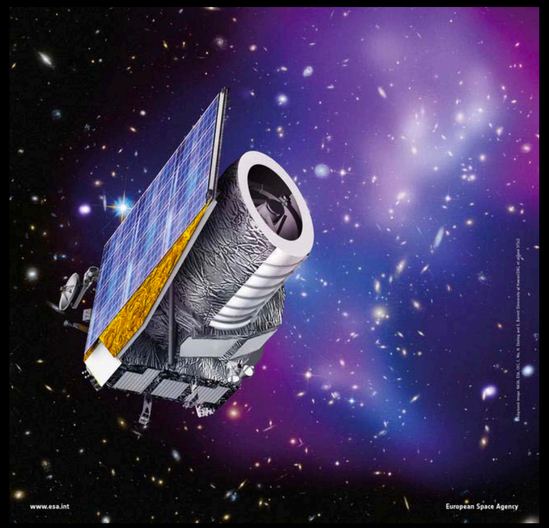


Euclid Telescope @ L2 orbit
~30M redshifts, 2024—

4MOST @ VISTA, Chile
8M redshifts, 2025—

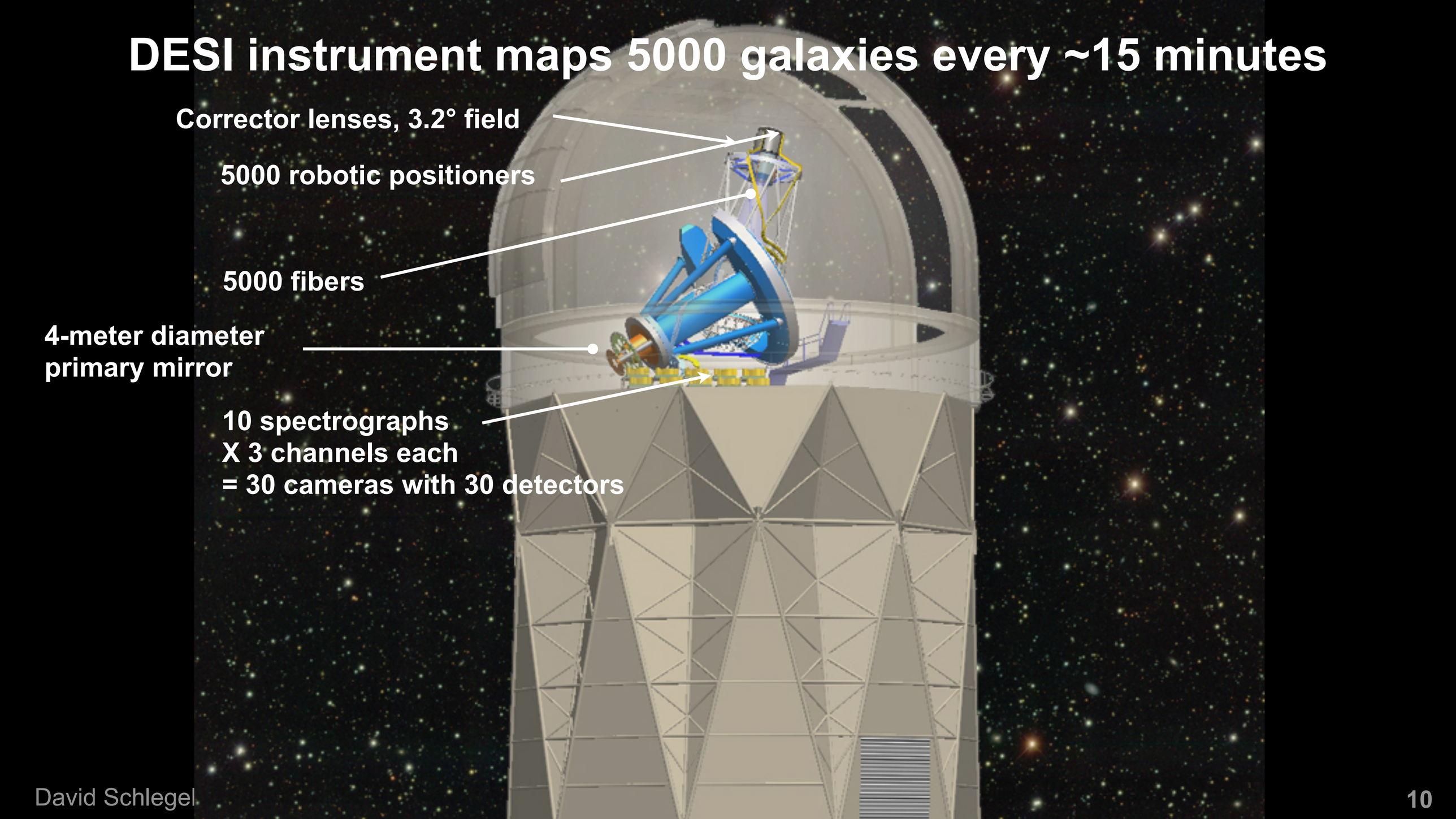
PFS @ Subaru, Hawaii
~4M redshifts, 2025—

WEAVE @ WHT, Spain
~1.2M redshifts, 2025—

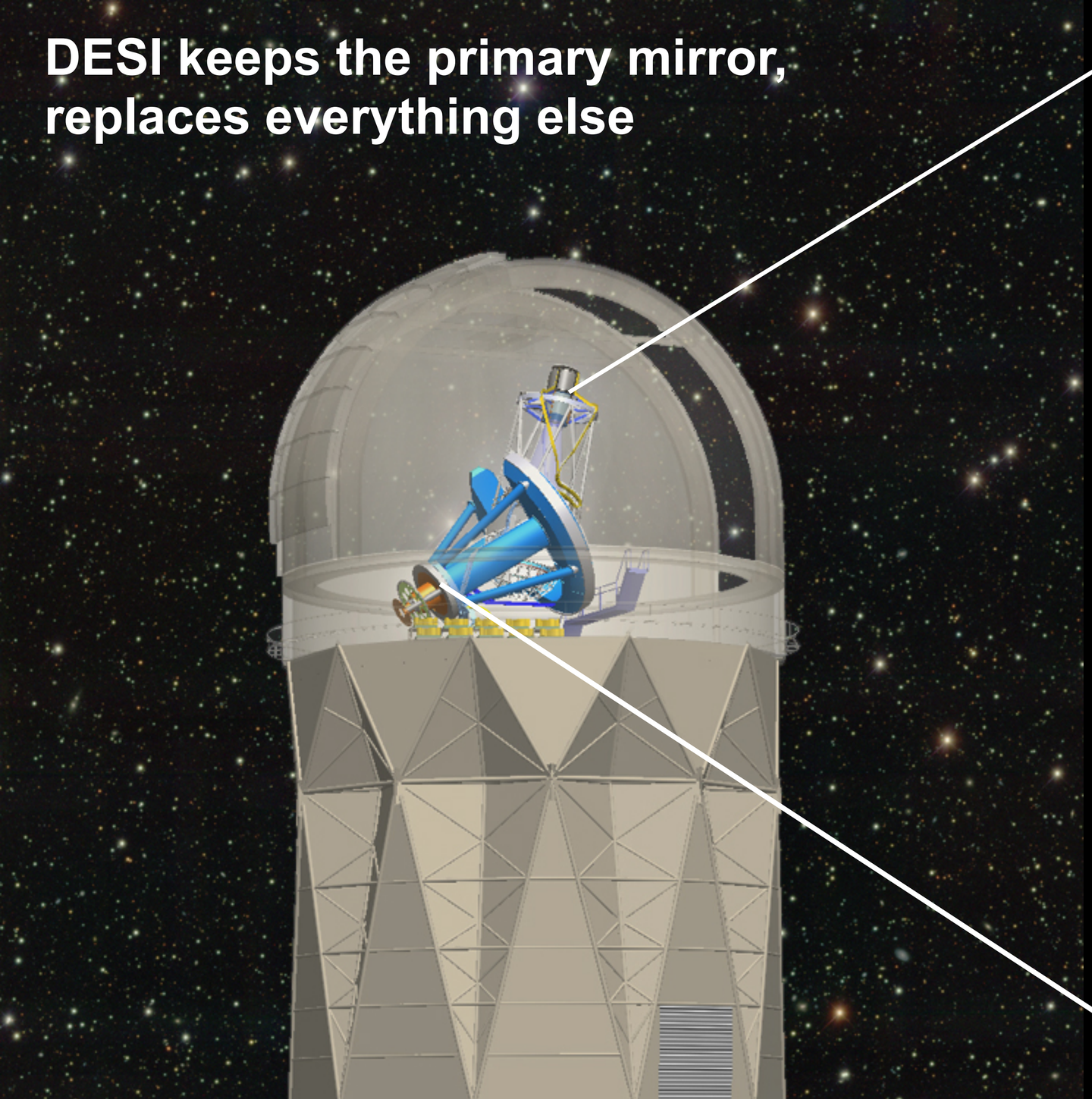


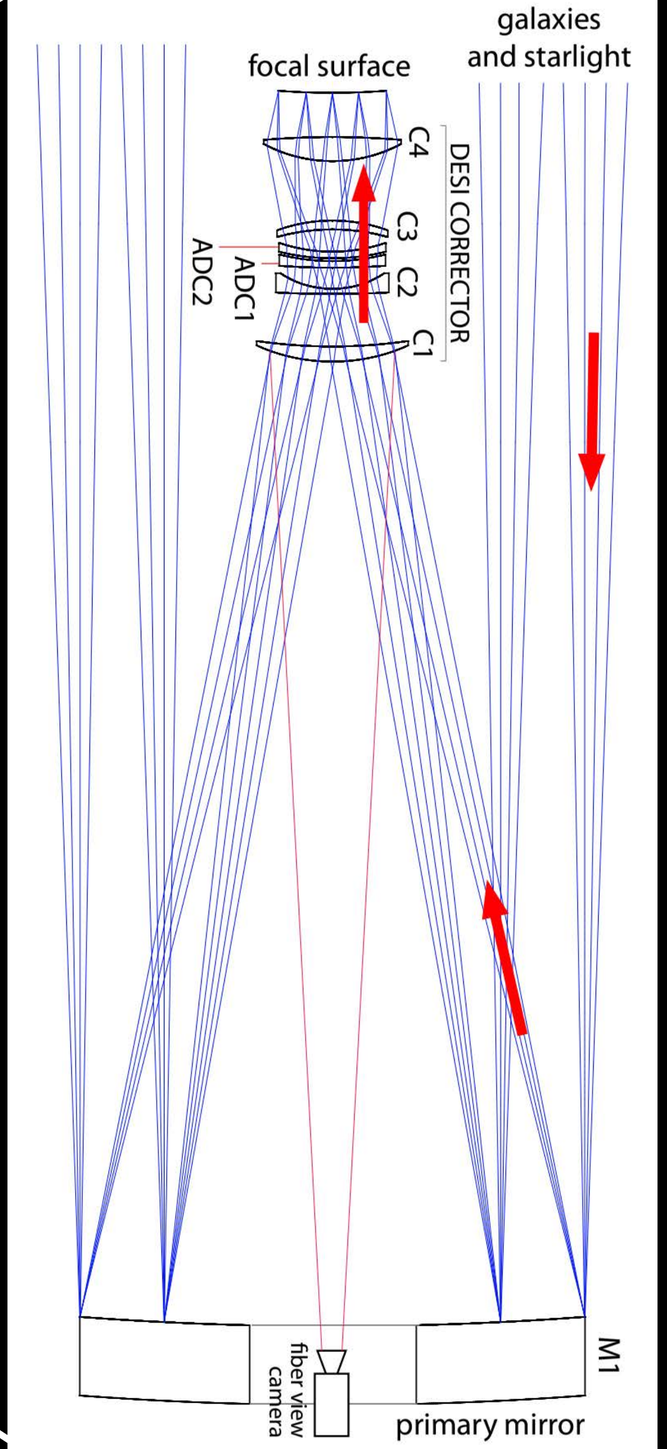
Roman Telescope @ L2 orbit
~30M redshifts, 2027—

DESI instrument maps 5000 galaxies every ~15 minutes



DESI keeps the primary mirror, replaces everything else





“Some assembly required”

August 2017: Existing Mayall dome calibration screen being removed for replacement with larger screen for DESI field of view

DESI installation started 2017… completed 2019

Cage and Ring being delivered to the Mayall telescope building, April 2018

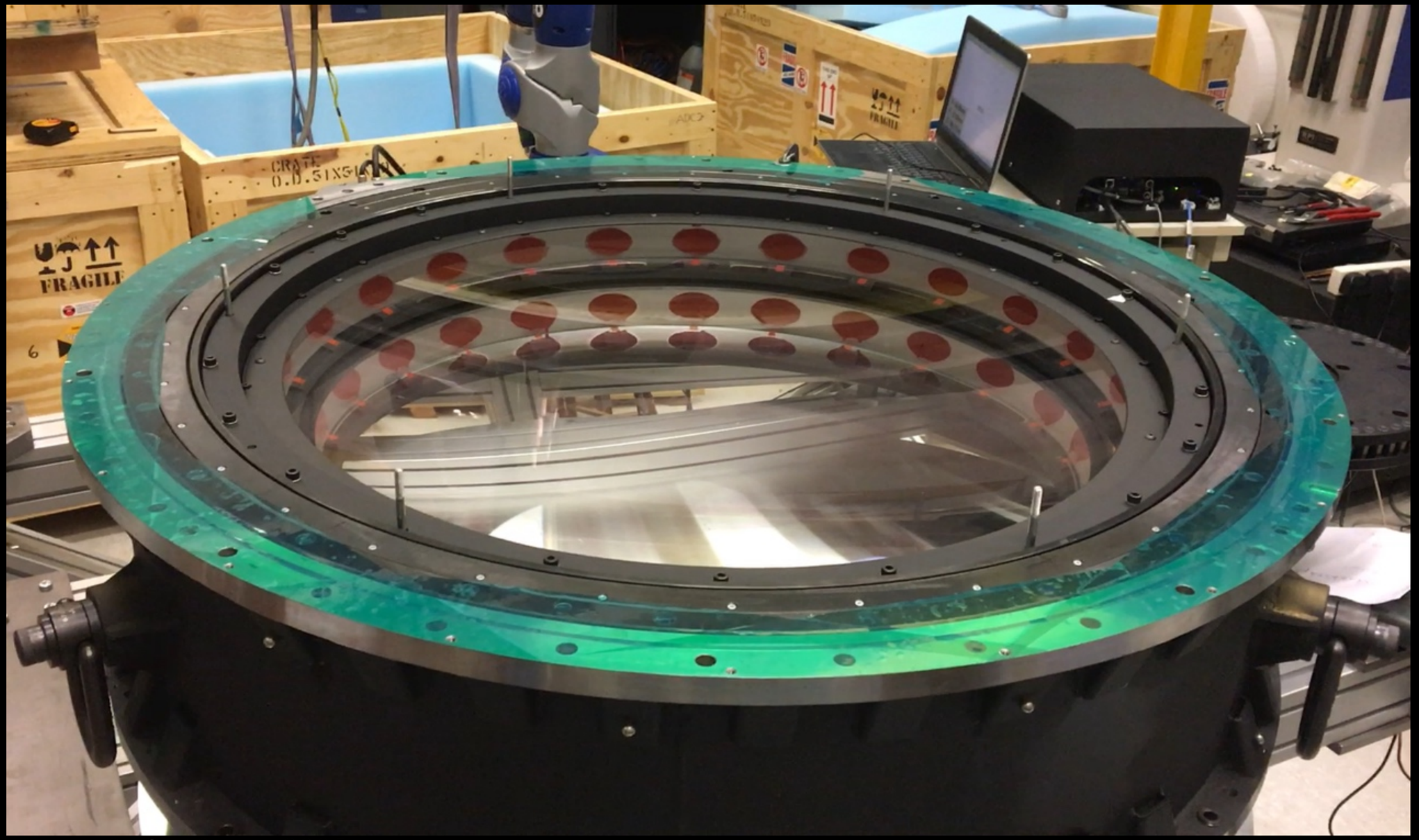
4 years 4 months to polish all six lenses for the DESI corrector

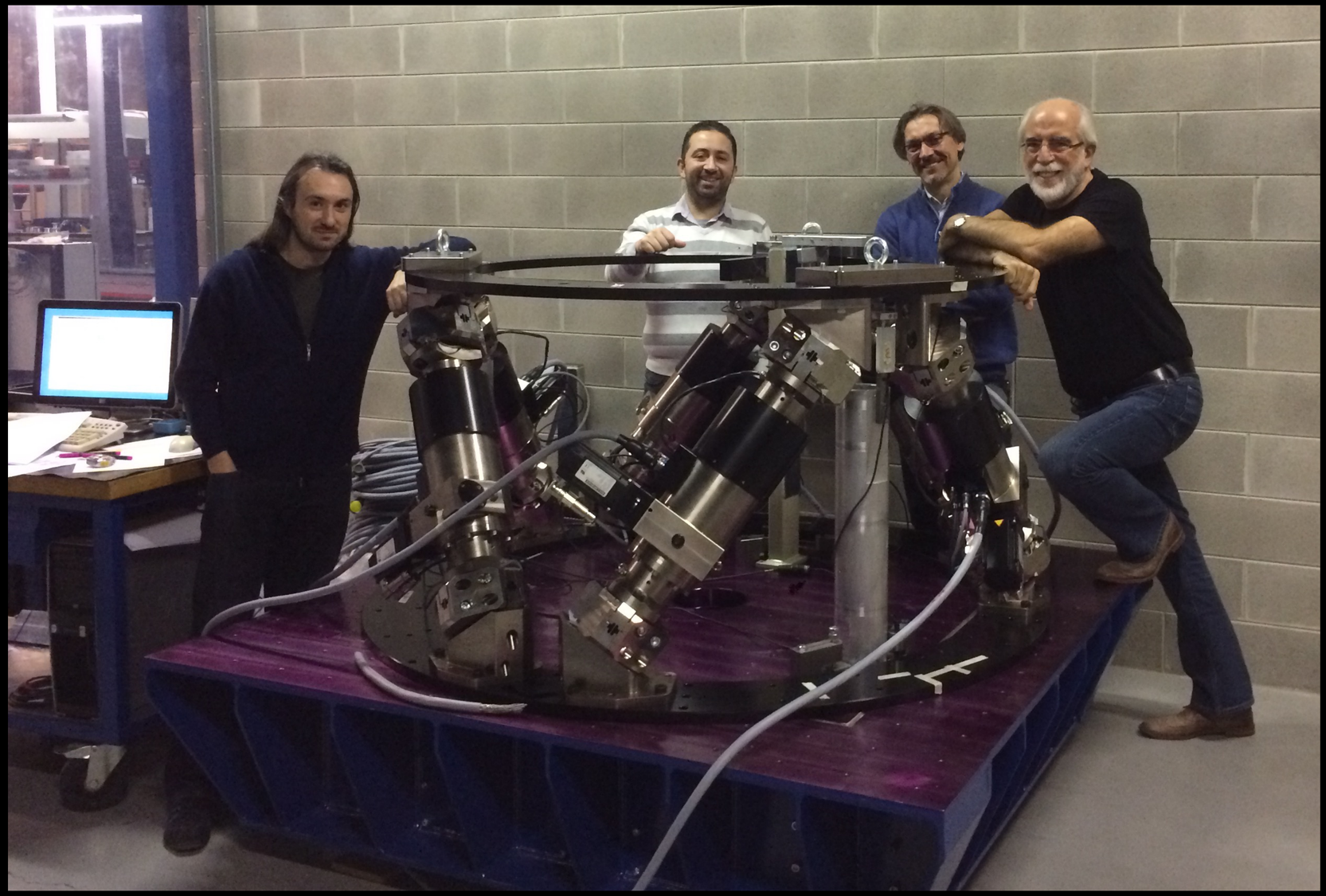
June 2017: Stain on side B of ADC2 is seen with a bright halogen light

This 1.15-meter diameter lens was the largest on any telescope (until last month)

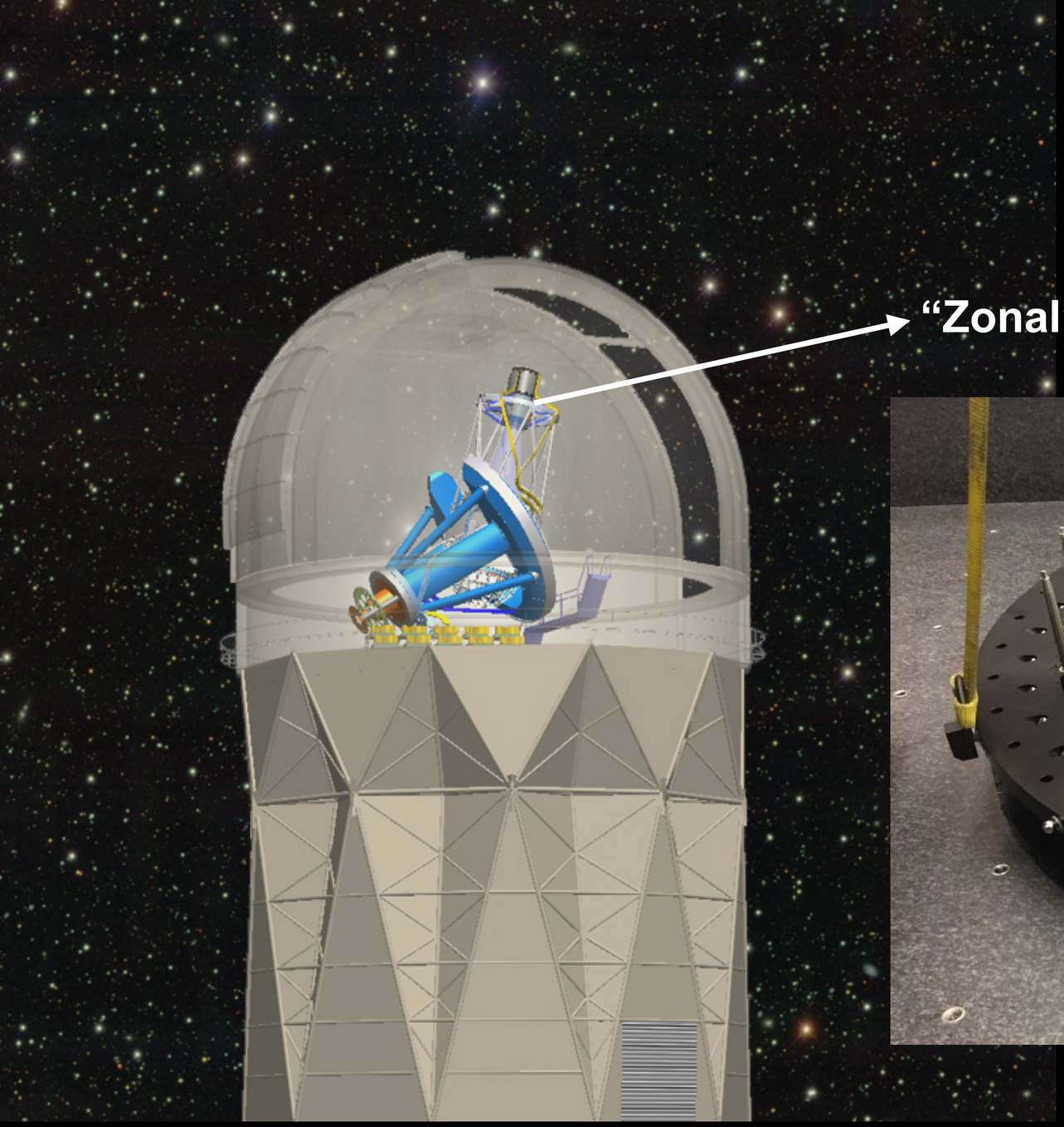
Nov 2016: Fully assembled corrector barrel at Fermilab aligns lenses to ~10 microns

Lenses include an atmospheric dispersion corrector of counter-rotating prisms

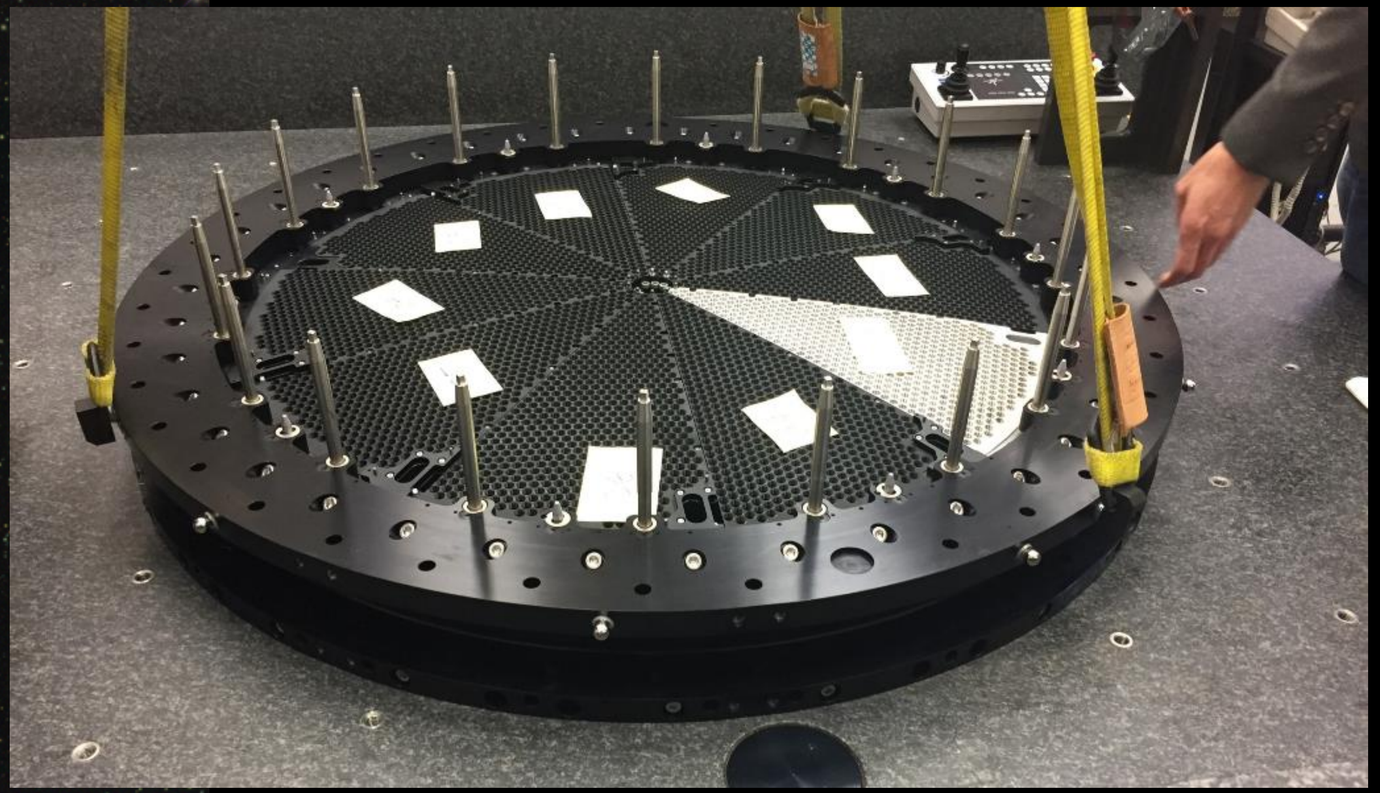


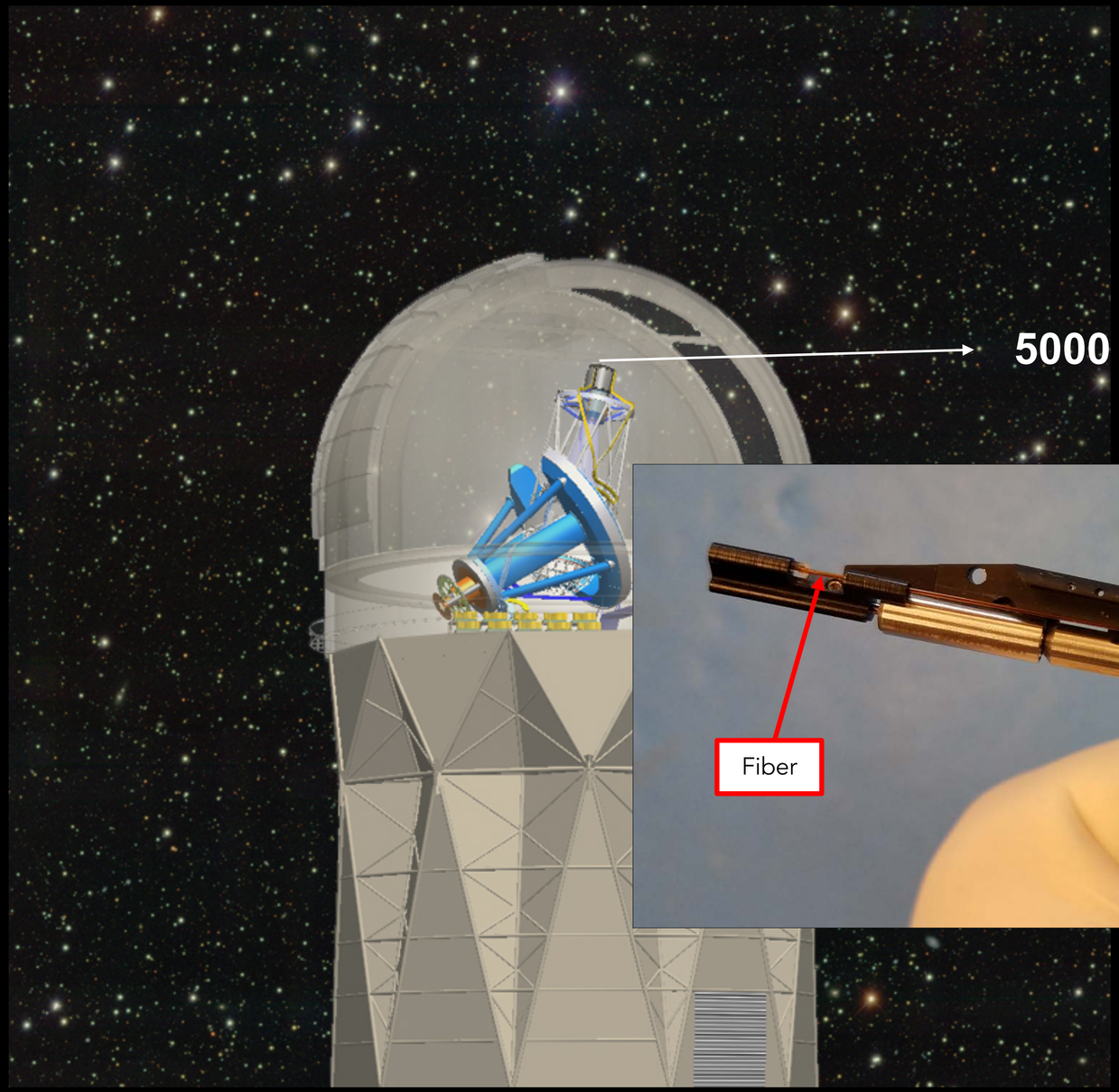


… and a hexapod to actively compensate positioning in 6 dimensions (x, y, z, roll, yaw, pitch) to < 1 micron accuracy

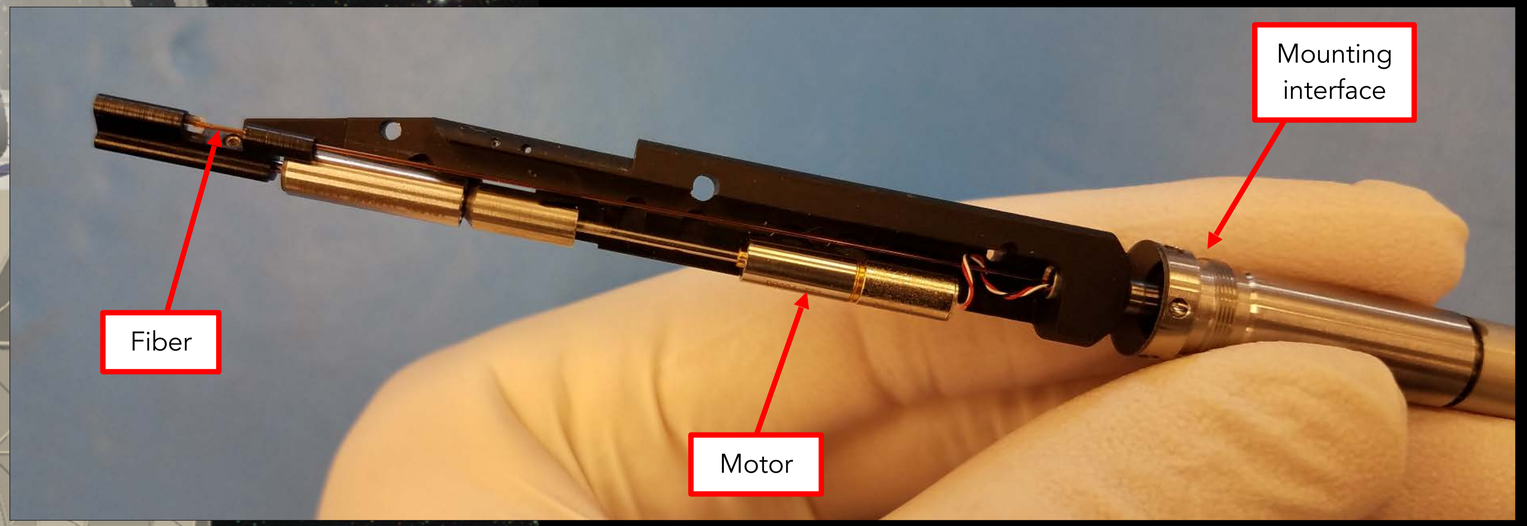


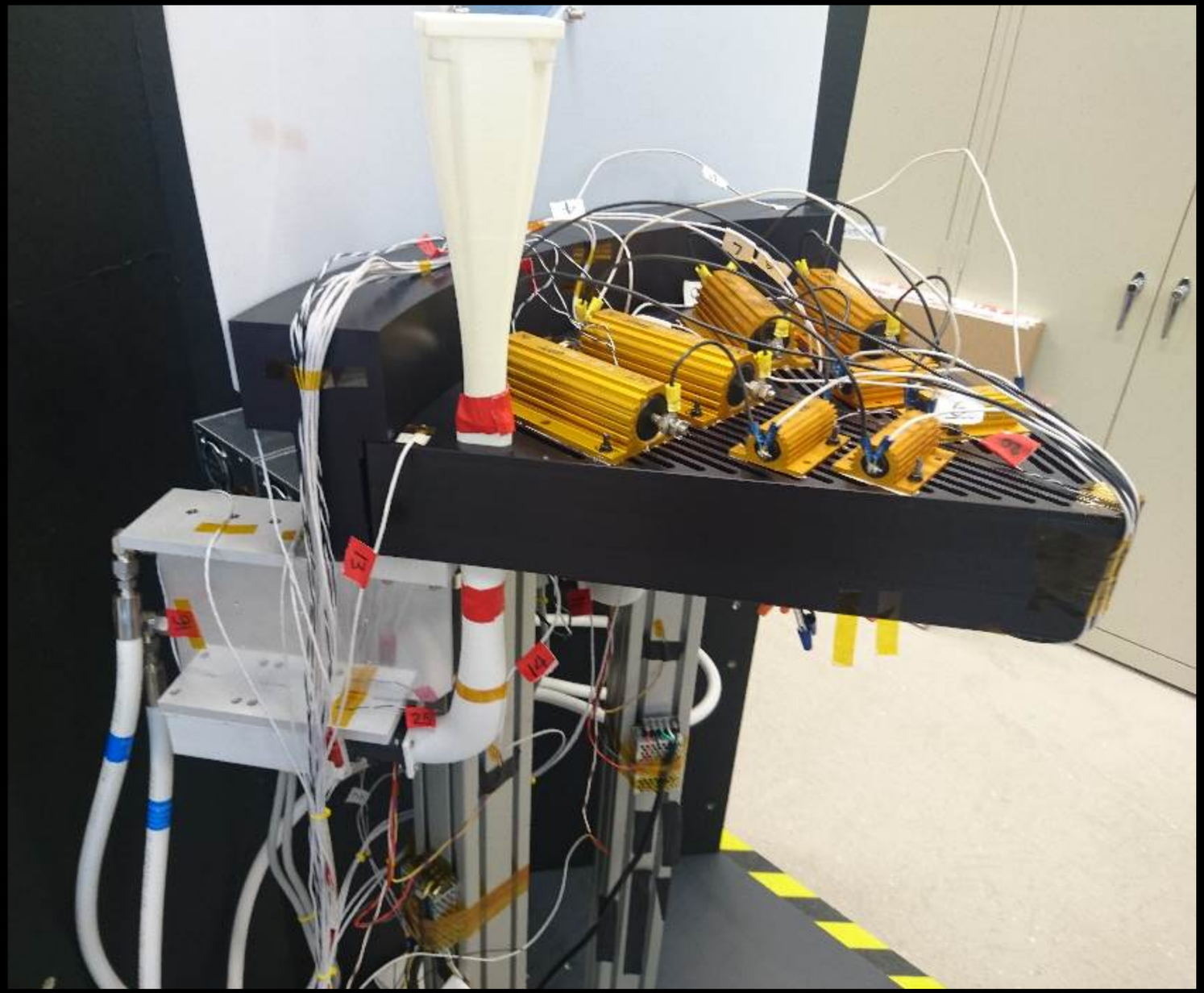
“Zonal” focal plane with 10 wedges





5000 robotic positioners in assembly

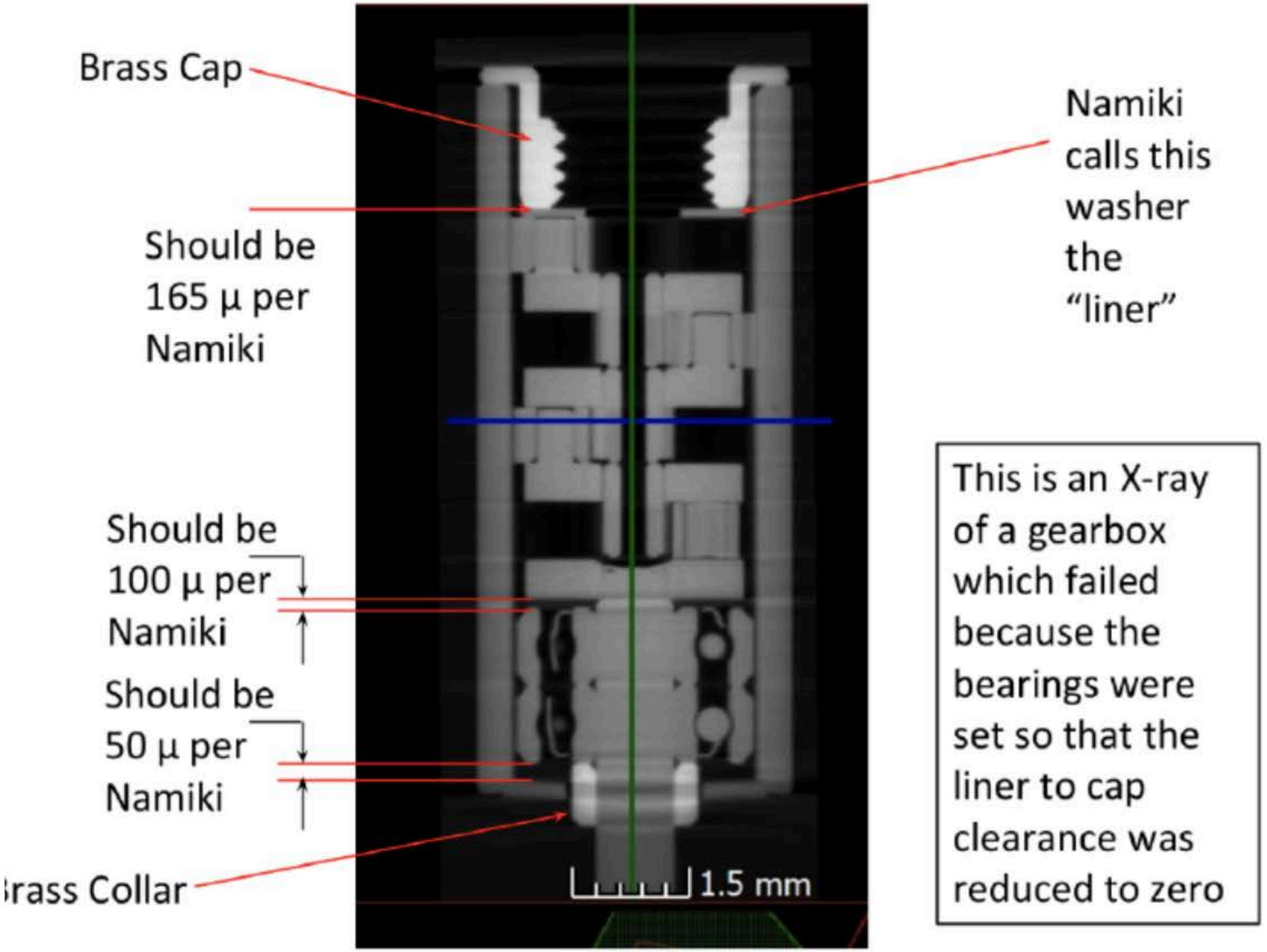




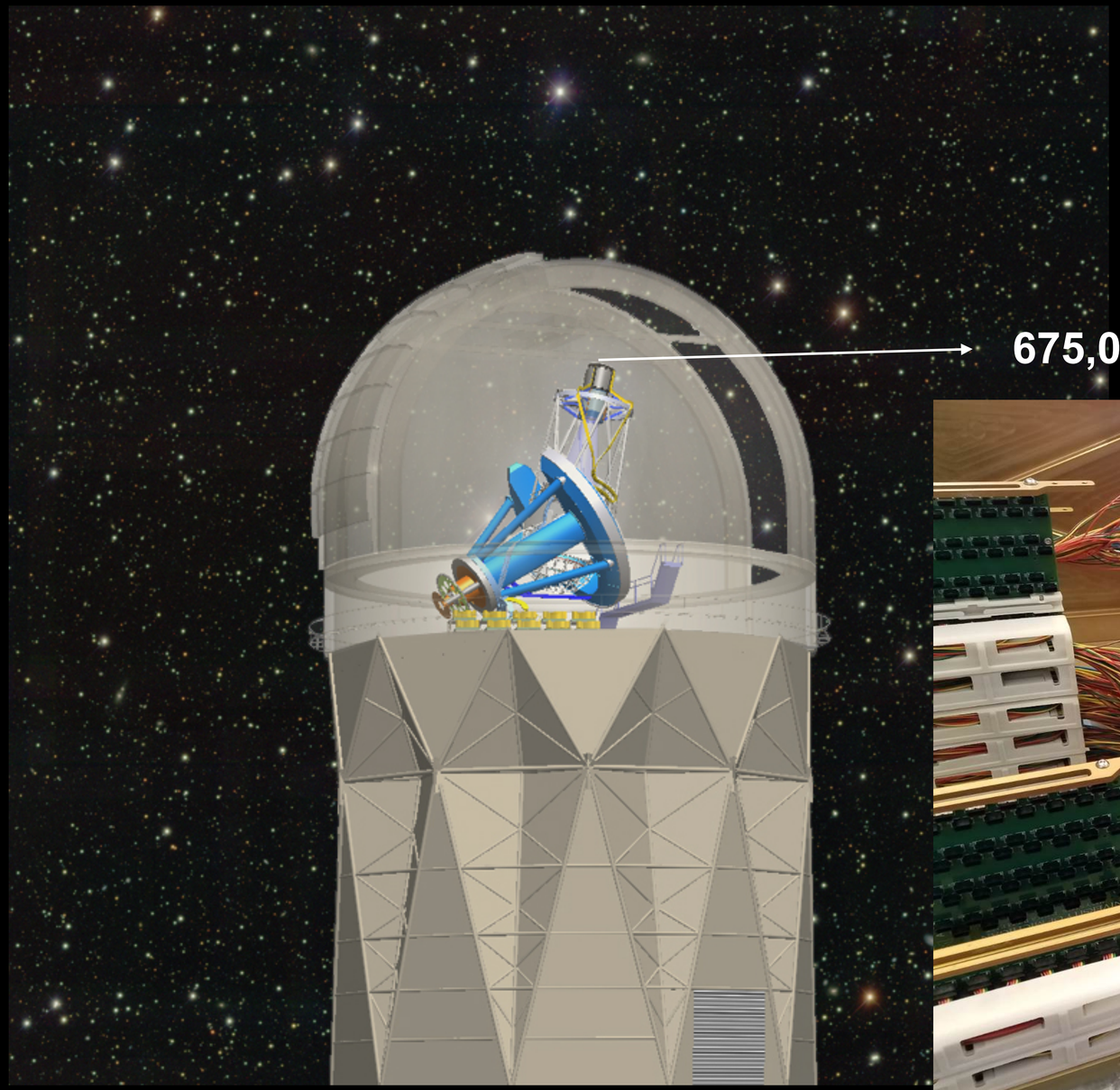
May 2017: Thermal tests, simulating injection of heat from moving 5000 positioners every 15 min

Fiber positioner production halted several times due to problems in parts production, assembly tolerances, and operations

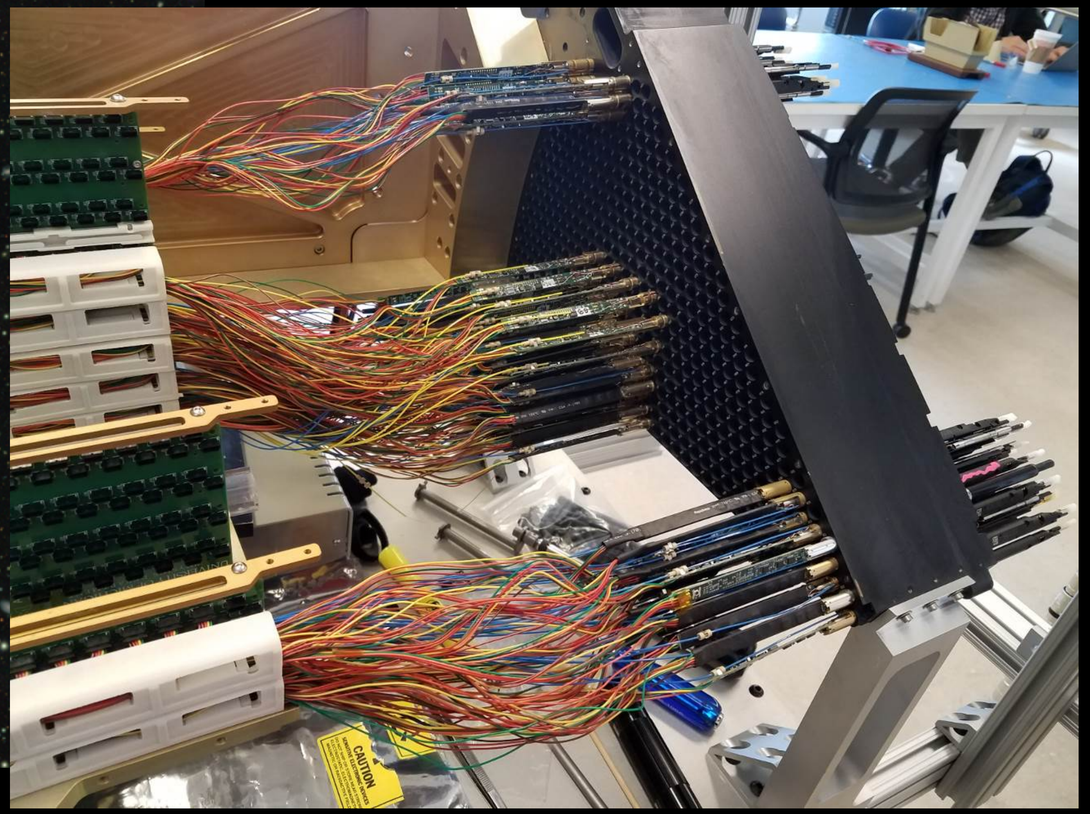
March 2017: Positioner undergoing x-ray analysis to confirm a weld failure in the motor shaft



This is an X-ray of a gearbox which failed because the bearings were set so that the liner to cap clearance was reduced to zero

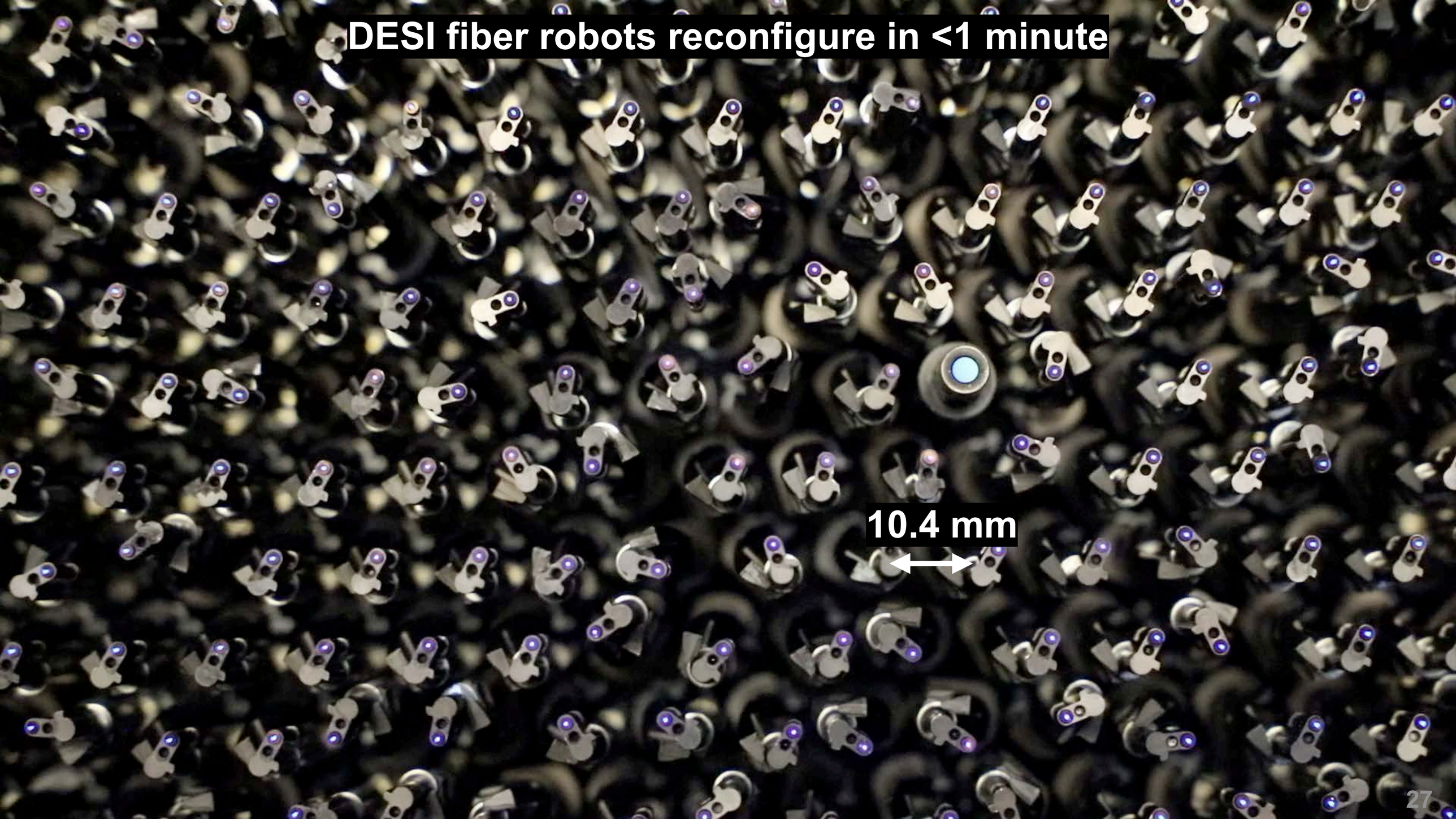


675,000 total parts on this focal plane



Mission accomplished!

The University of Michigan Positioner Team in commemorative T-shirts celebrating production of enough positioners to populate the complete 10-petal DESI focal plane


DESI fiber robots reconfigure in <1 minute
10.4 mm

DESI fibers are plasma-spliced, not “connectorized” to avoid any losses in throughput

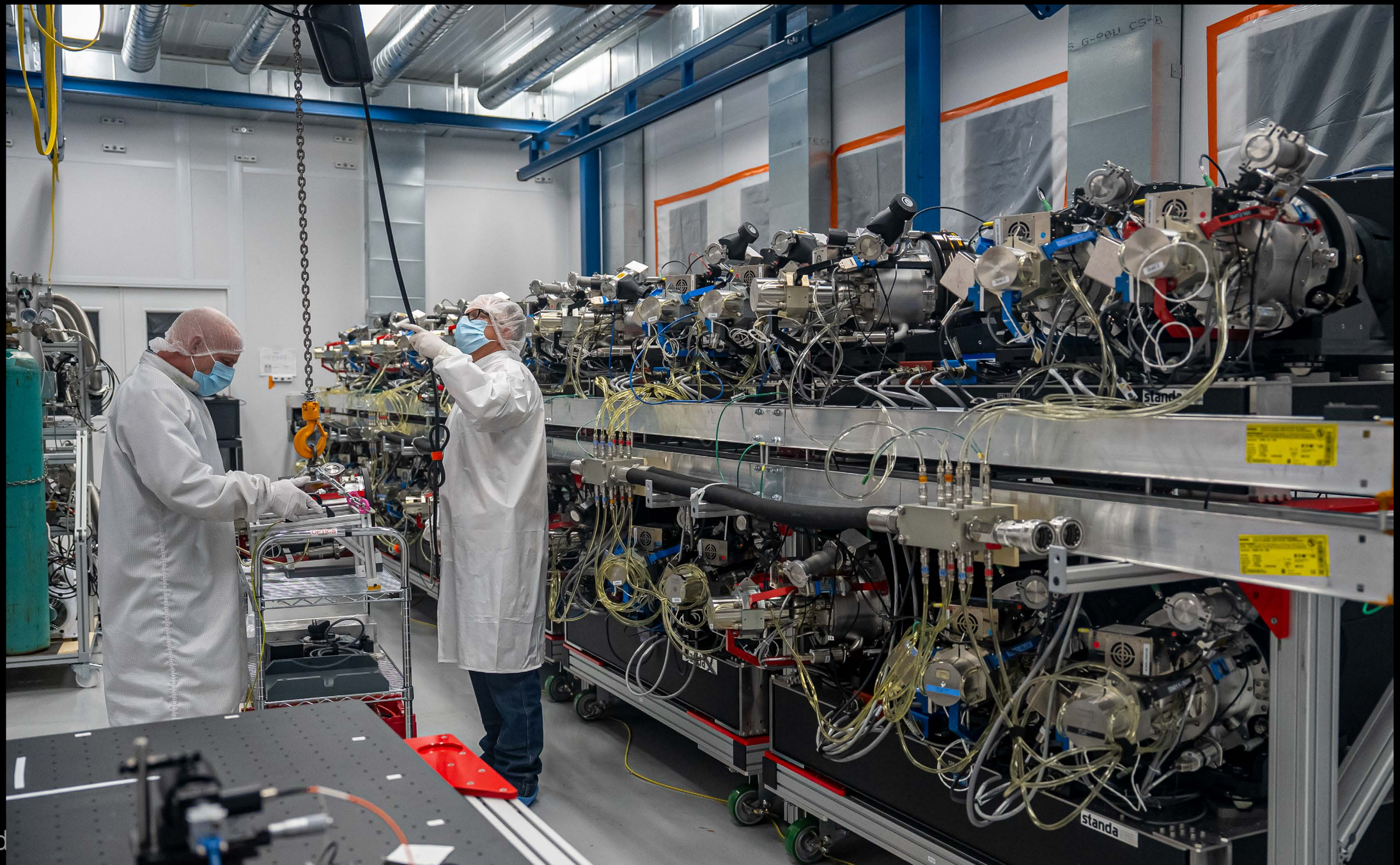
250 km of optical fiber wound in steel-core cables

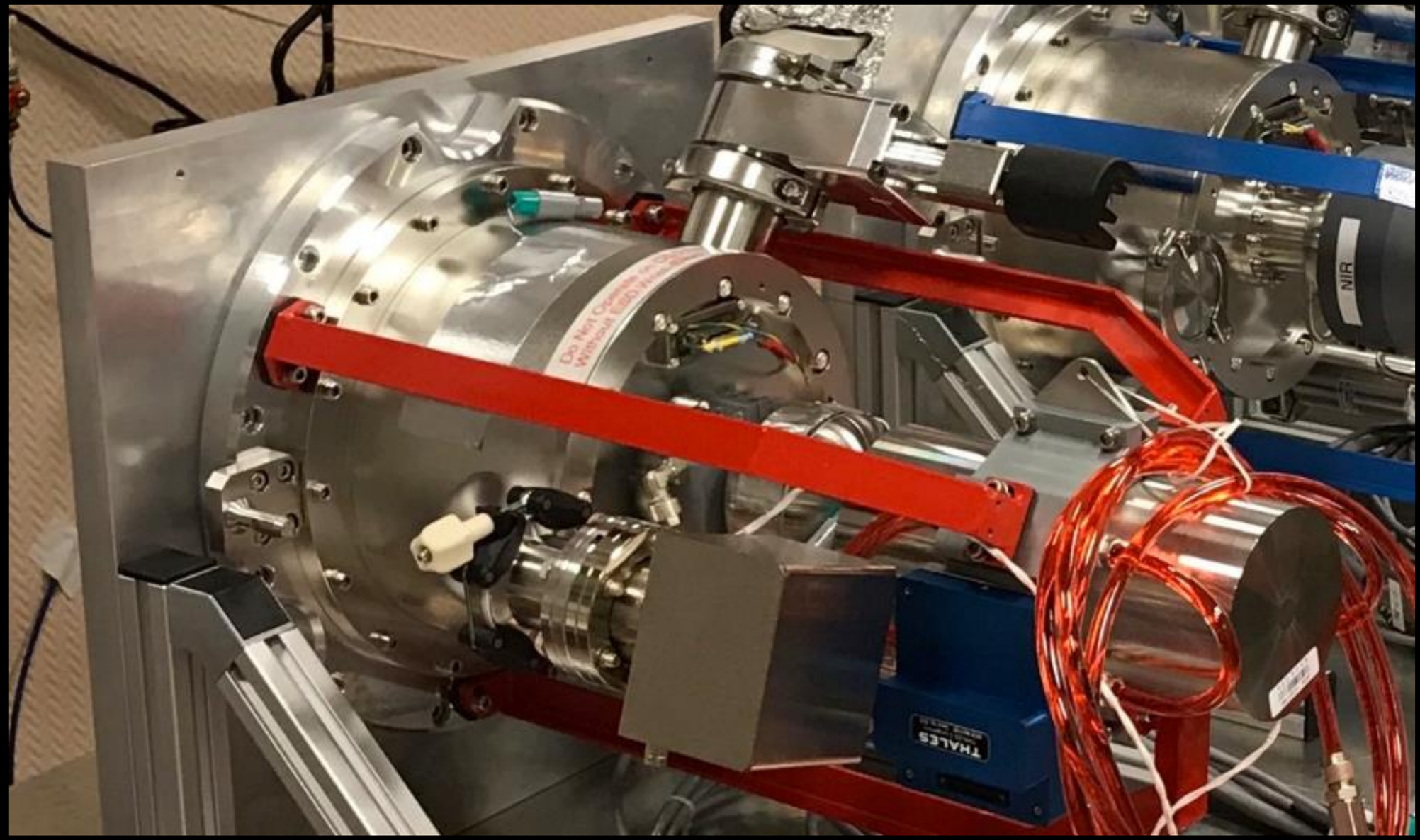
April 2018: Crated Spectrograph and Cryostats with the Winlight Project Manager, Eric Tournayre, prior to shipment from Pertuis France to Kitt Peak

Un-crating the 1st spectrograph at Kitt Peak

… the thing still works.

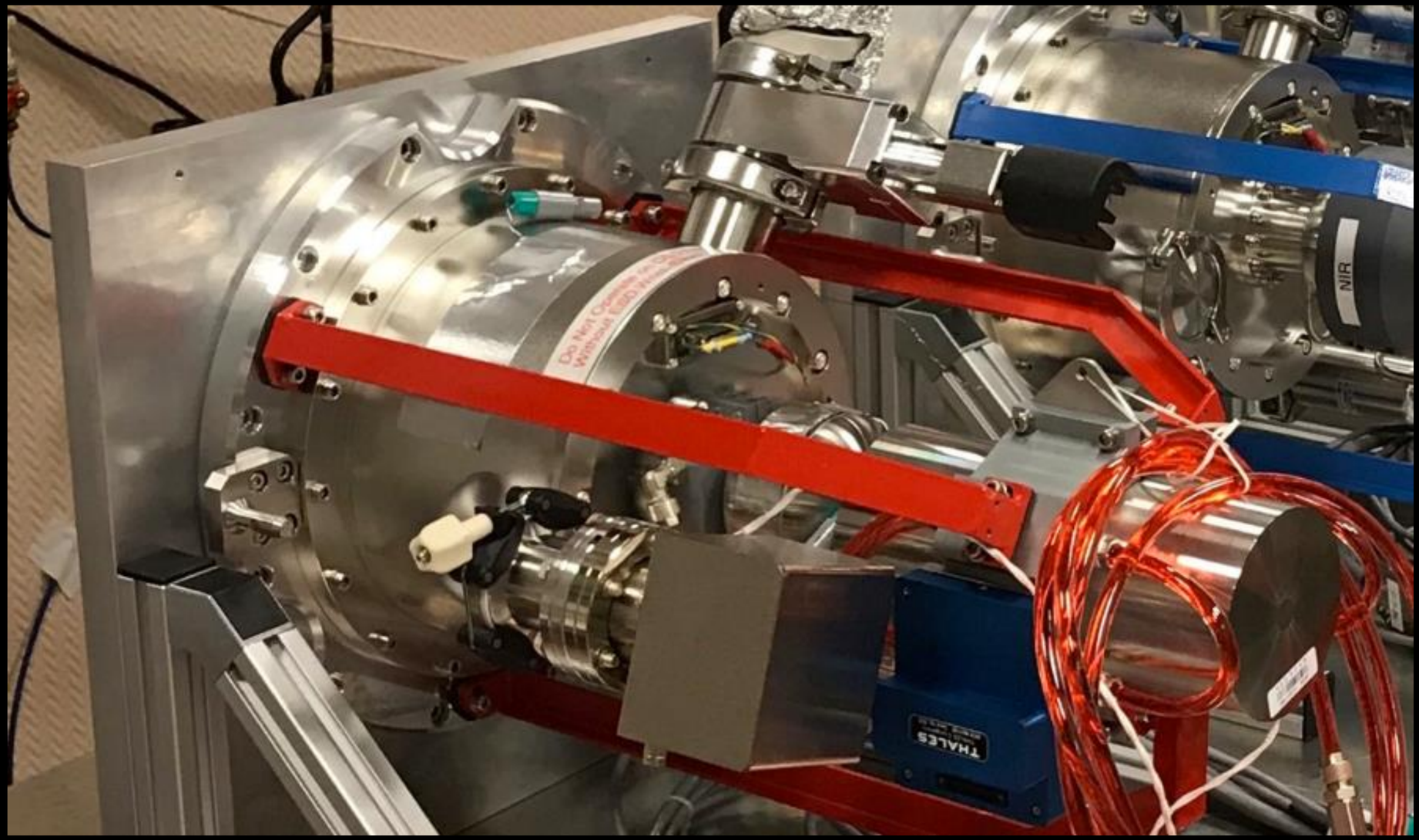
10 DESI spectrographs measure the light in 12000 channels from 0.36-0.98 μm



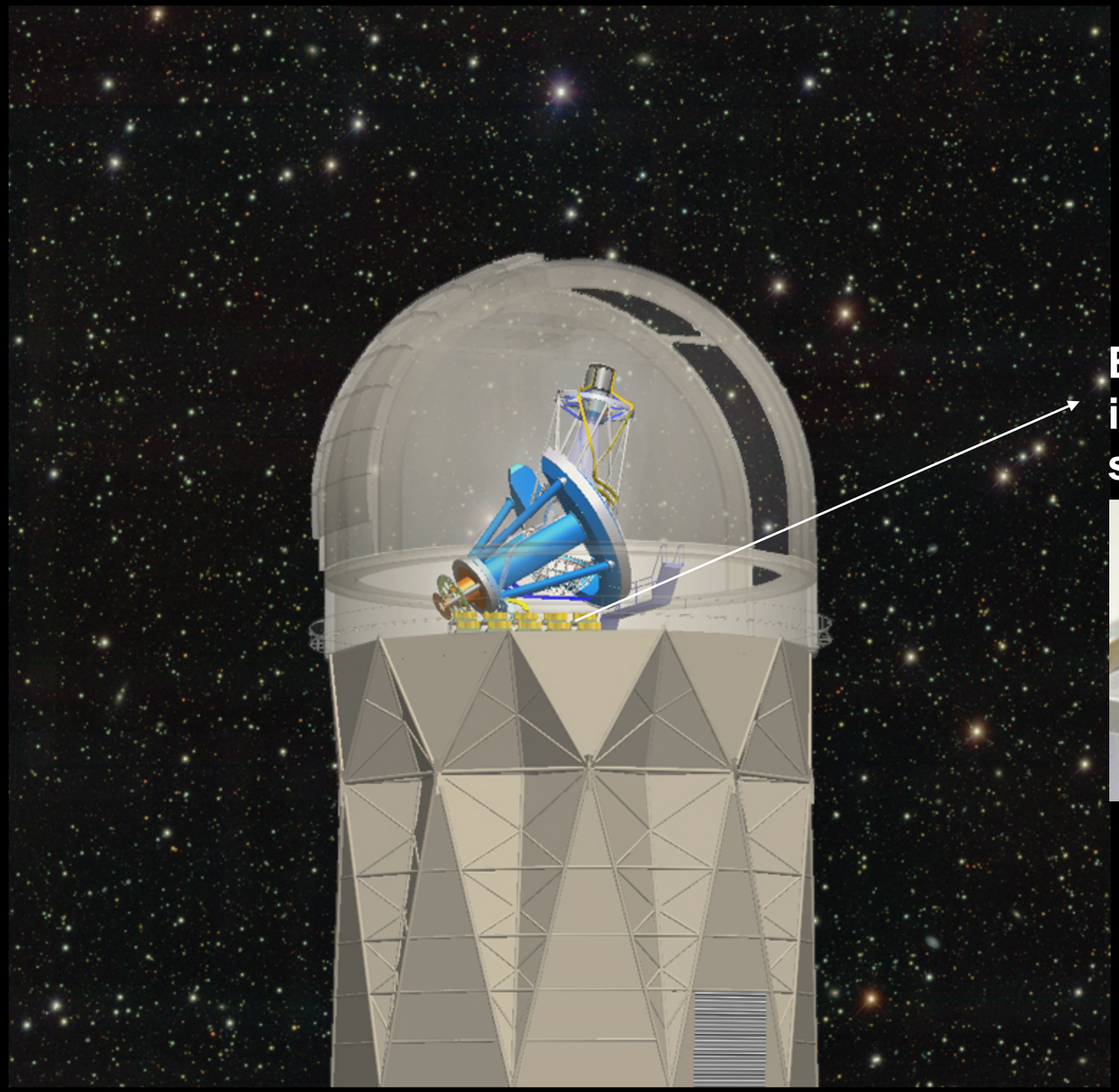


Detector cryostats cooled with linear pulse tubes

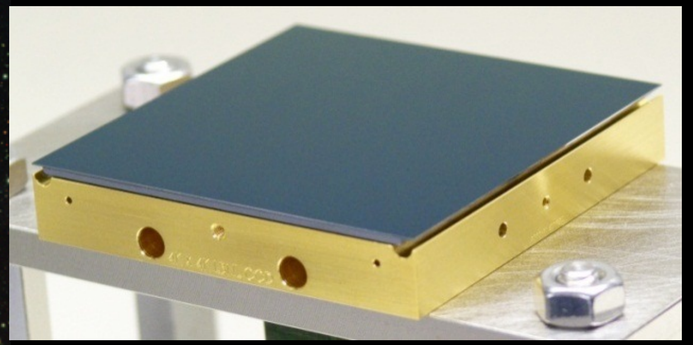
Spectrograph problems: Vibrations from pulse tube coolers were acceptable, until several were running at the same frequency



May 2017: Accelerometer on Spectrograph during vibration testing at Winlight.



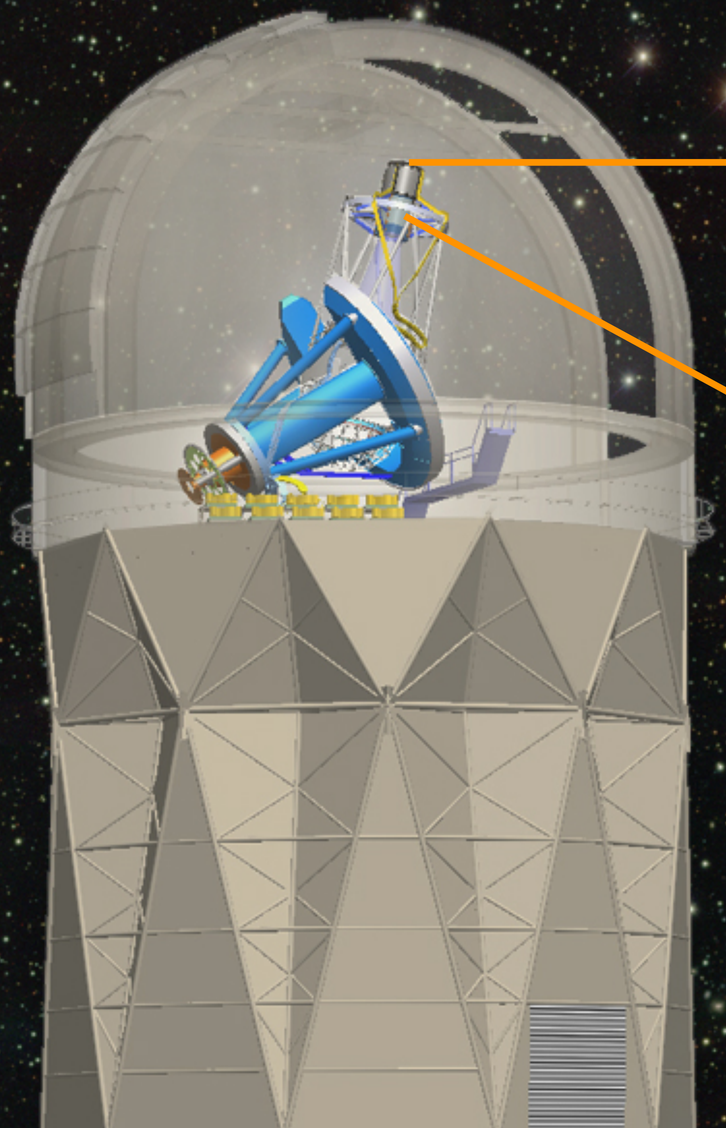
Berkeley Lab “fully-depleted” CCDs, improved in response, noise, cosmetics since DECam



DESI is an international collaboration with components built in the US, United Kingdom, France, Spain, Switzerland

July 12, 2018: Chartered Ukranian An-12 plane to deliver 10 tons of corrector + tooling from the London -> Arizona

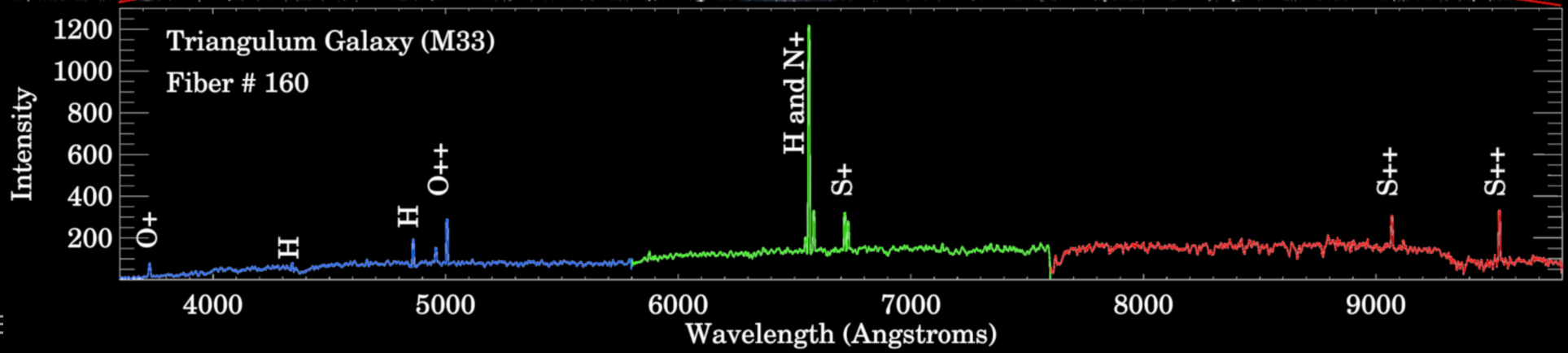
Aug 2018: Corrector re-aligned before installation



DESI “First Light” on Oct 22, 2019
500 fibers on Triangulum Galaxy (M33)

Moon

3.2 degrees

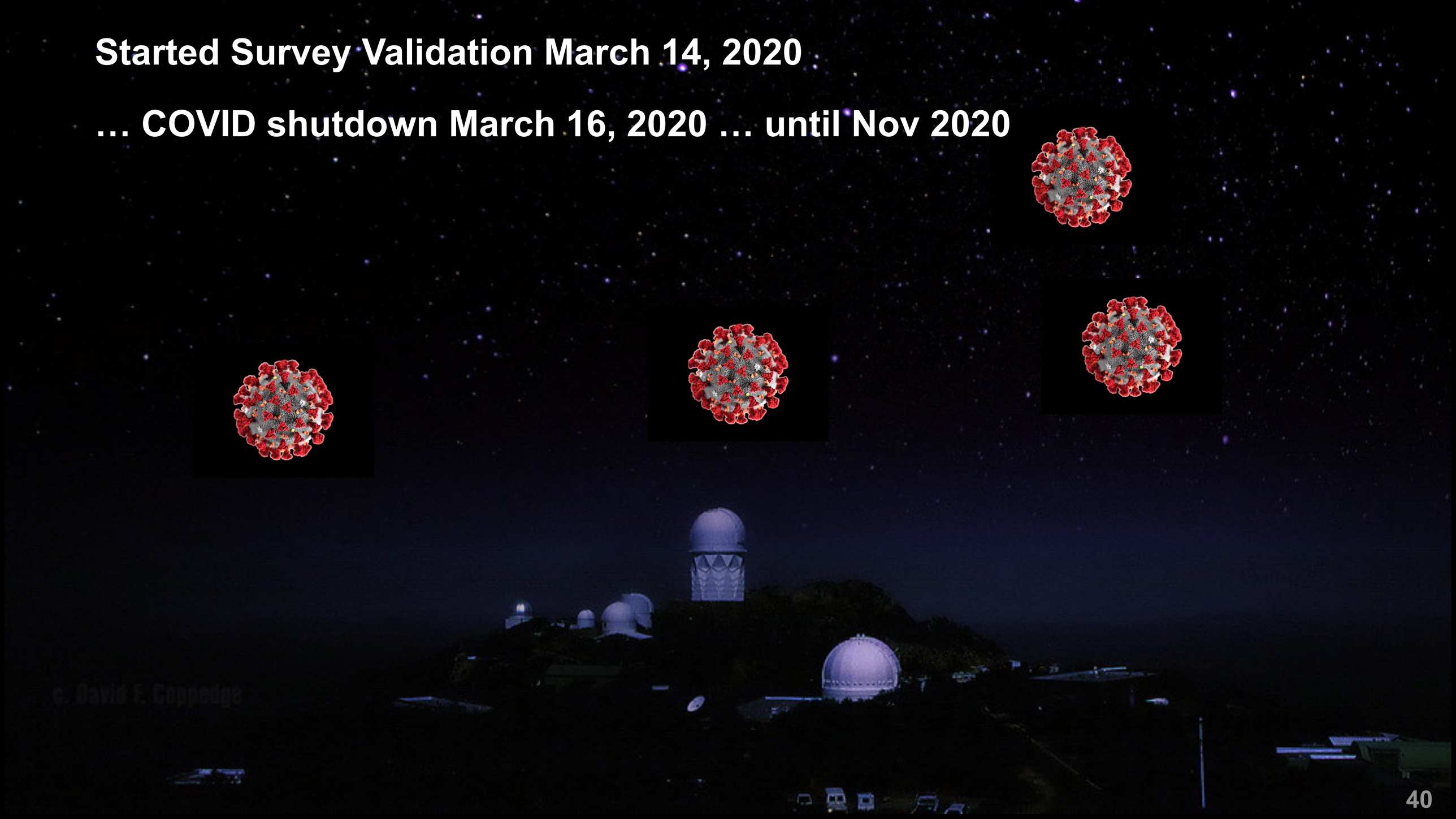


Why the Triangulum Galaxy?

Enterprise-D will visit there in 2364 during warp field tests

Started Survey Validation March 14, 2020

… COVID shutdown March 16, 2020 … until Nov 2020

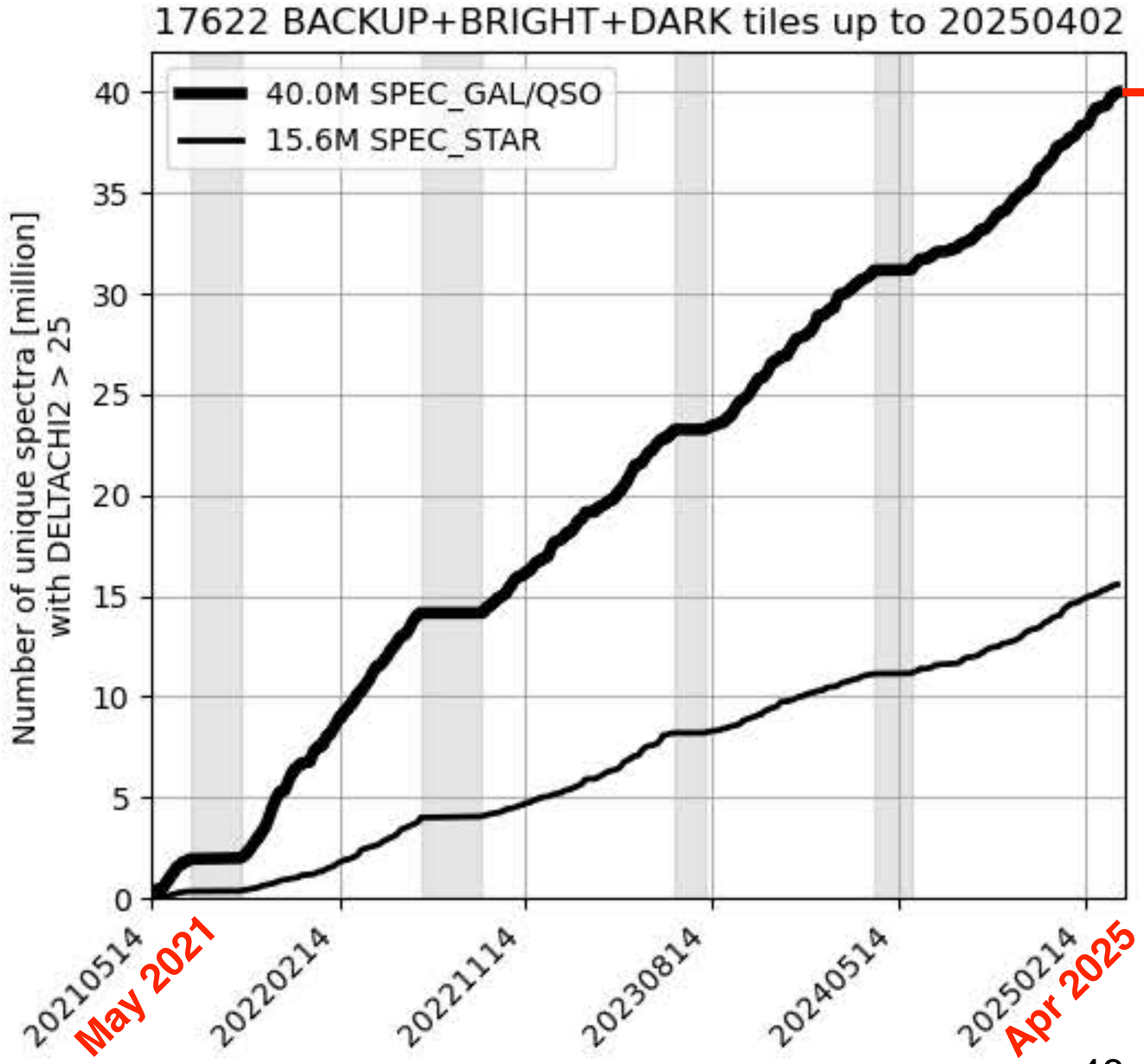


Survey start May 14, 2021

… Contreras Fire shutdown June 14, 2022 … until Sep 10, 2022

Pirates shut down computer access to the observatory Aug 9, 2023
… operated for several months with limited connection

DESI survey ahead of schedule … despite plagues + fires + pirates



40.0 million galaxies+quasars, far more than all previous projects combined

Year	#Galaxies	Survey
1983	2401	CfA Center for Astrophysics Redshift Survey (CfA) http://adsabs.harva
1988	2028	SSRS http://adsabs.harvard.edu/cgi-bin/bib_query?1988ApJ...327..54
1996	26418	LCRS Las Campanas Redshift Survey (LCRS) http://adsabs.harvard.
1999	18000	CfA2 http://adsabs.harvard.edu/abs/1999PASP..111..438F
2000	15411	IRAS PSCz https://arxiv.org/abs/astro-ph/0001117
2003	221414	2dF 2dFGRS Final Data Release https://arxiv.org/abs/astro-ph/03065
2004	23338	2dF QSO https://arxiv.org/abs/astro-ph/0403040
2006	13800	2dF 2SLAQ Luminous Red Galaxy Survey https://arxiv.org/abs/astro-
2009	125000	6dF Galaxy Survey (6dFGS) http://adsabs.harvard.edu/abs/2009MN
2013	35016	VVDS VIMOS VLT https://arxiv.org/abs/1307.0545
2012	43500	2MRS 2MASS Redshift Survey (2MRS) http://adsabs.harvard.edu/abs
2012	38000	DEEP2 Data Release 4 https://arxiv.org/abs/1203.3192
2013	130000	PRIMUS https://arxiv.org/abs/1303.2672
2015	238000	GAMA Data Release 2 https://arxiv.org/abs/1506.08222
2016	86775	VIMOS VIPERS PDR-2 https://arxiv.org/abs/1611.07048
2019	225415	WiggleZ Final Data Release https://arxiv.org/abs/1910.08284
2020	3824313	SDSS Data Release 16 galaxy+QSO samples https://arxiv.org/abs/1

5.0 million redshifts

Image sky

↓

Select targets

↓

Configure fibers

↓

Observe!

↓

Spectra + redshifts

↓

Make 3-D maps

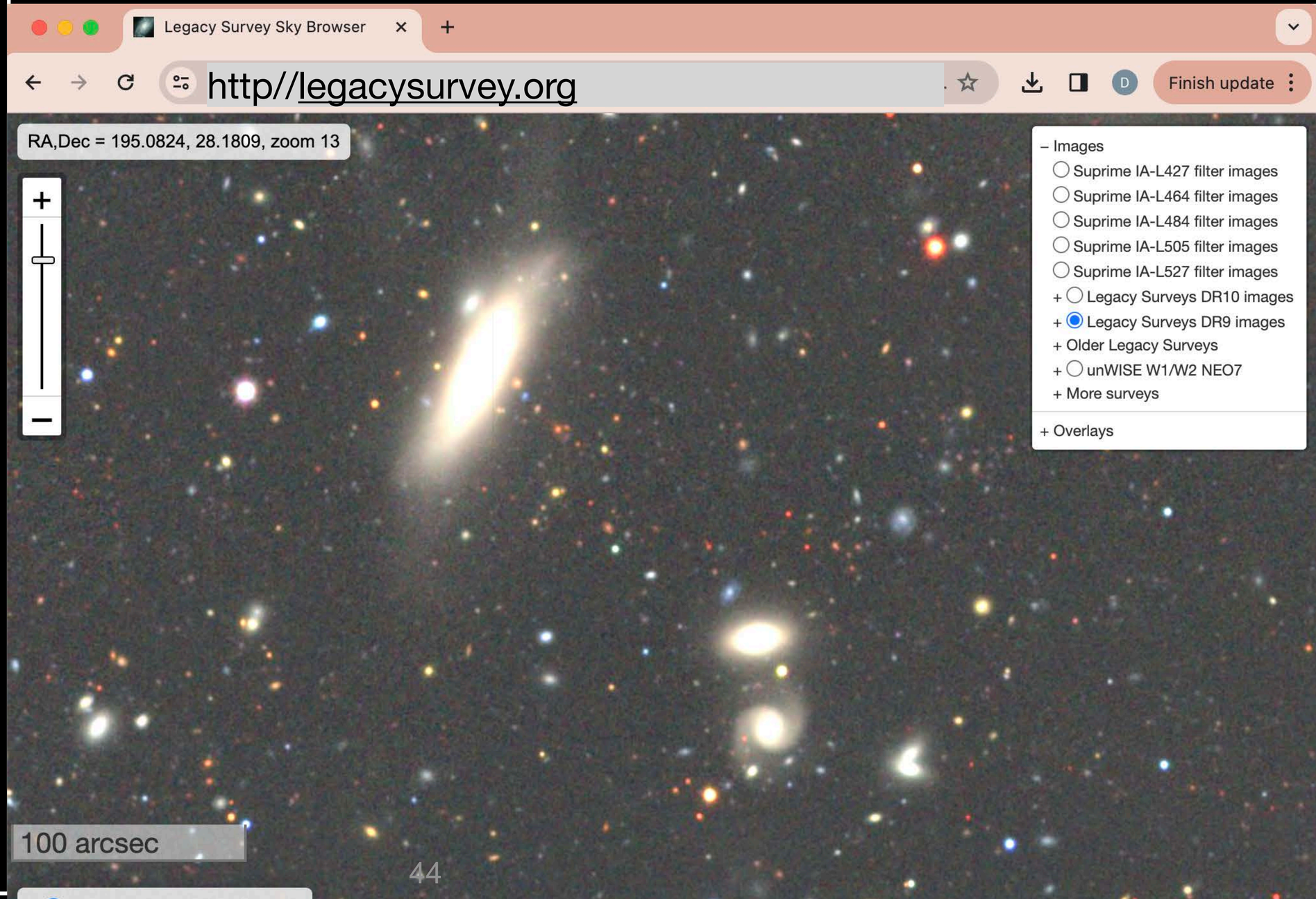
↓

Measure BAO features

↓

Cosmology

Legacy Imaging http://legacysurvey.org
using 1400 nights on 3 telescopes from 2013-2019 to map 40% of the sky



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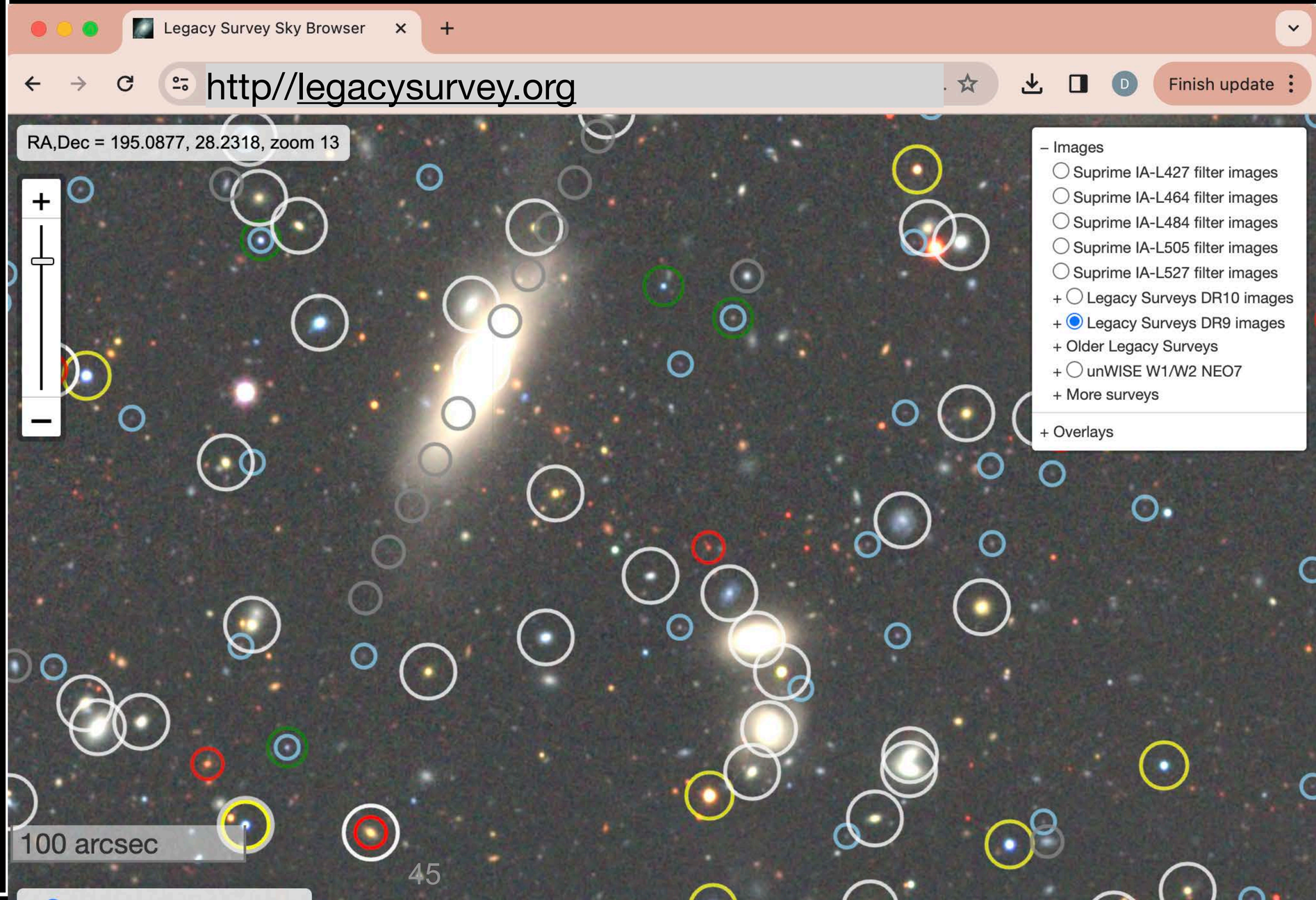

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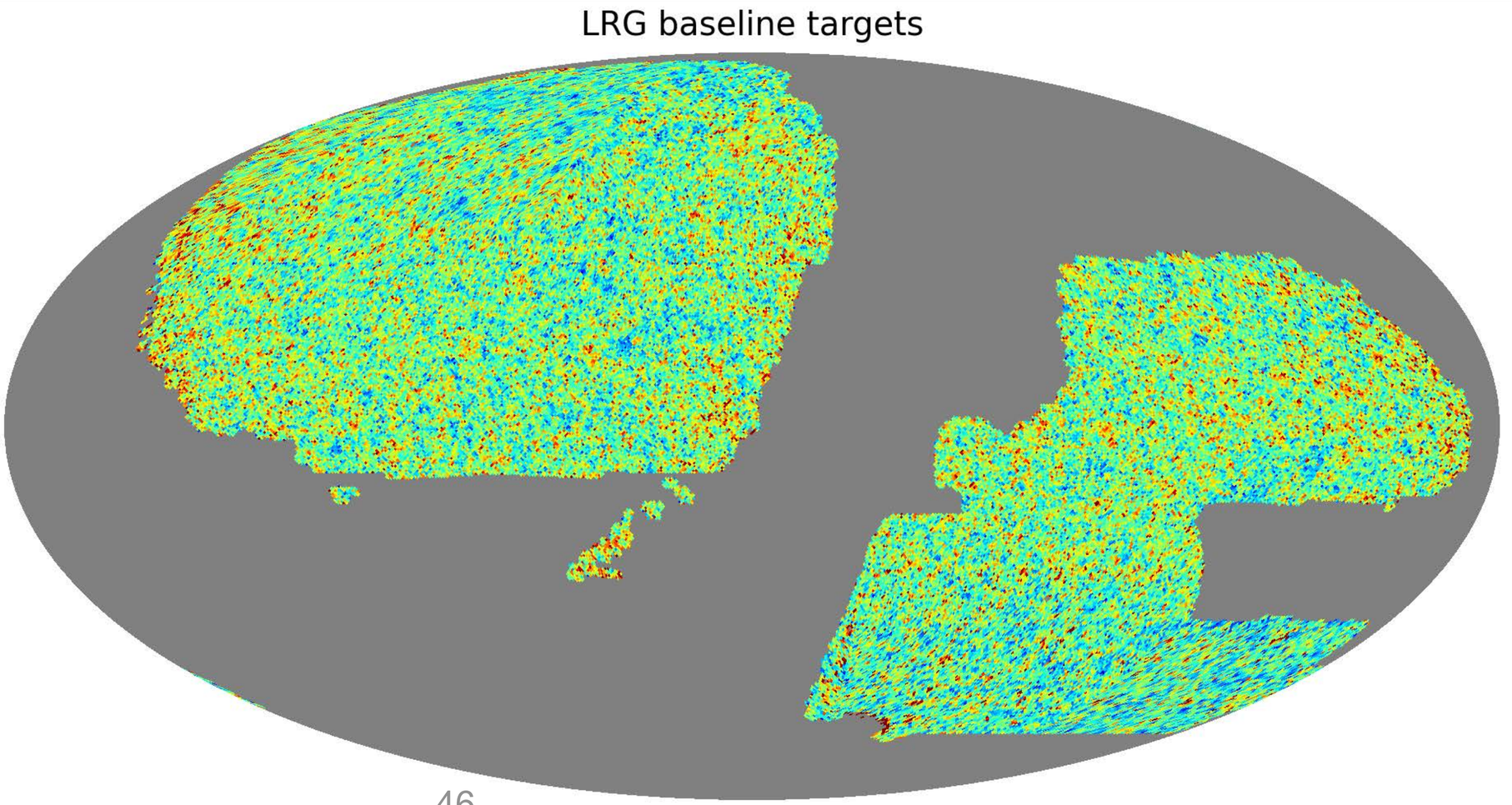
Cosmology

DESI targets cover 14,000 square degrees:

- **13.7 million Bright Galaxy Sample (BGS)**
- **7.5 million Luminous Red Galaxies (LRG**
- **15.7 million Emission Line Galaxies (ELGs)**
- **2.9 million QSOs**



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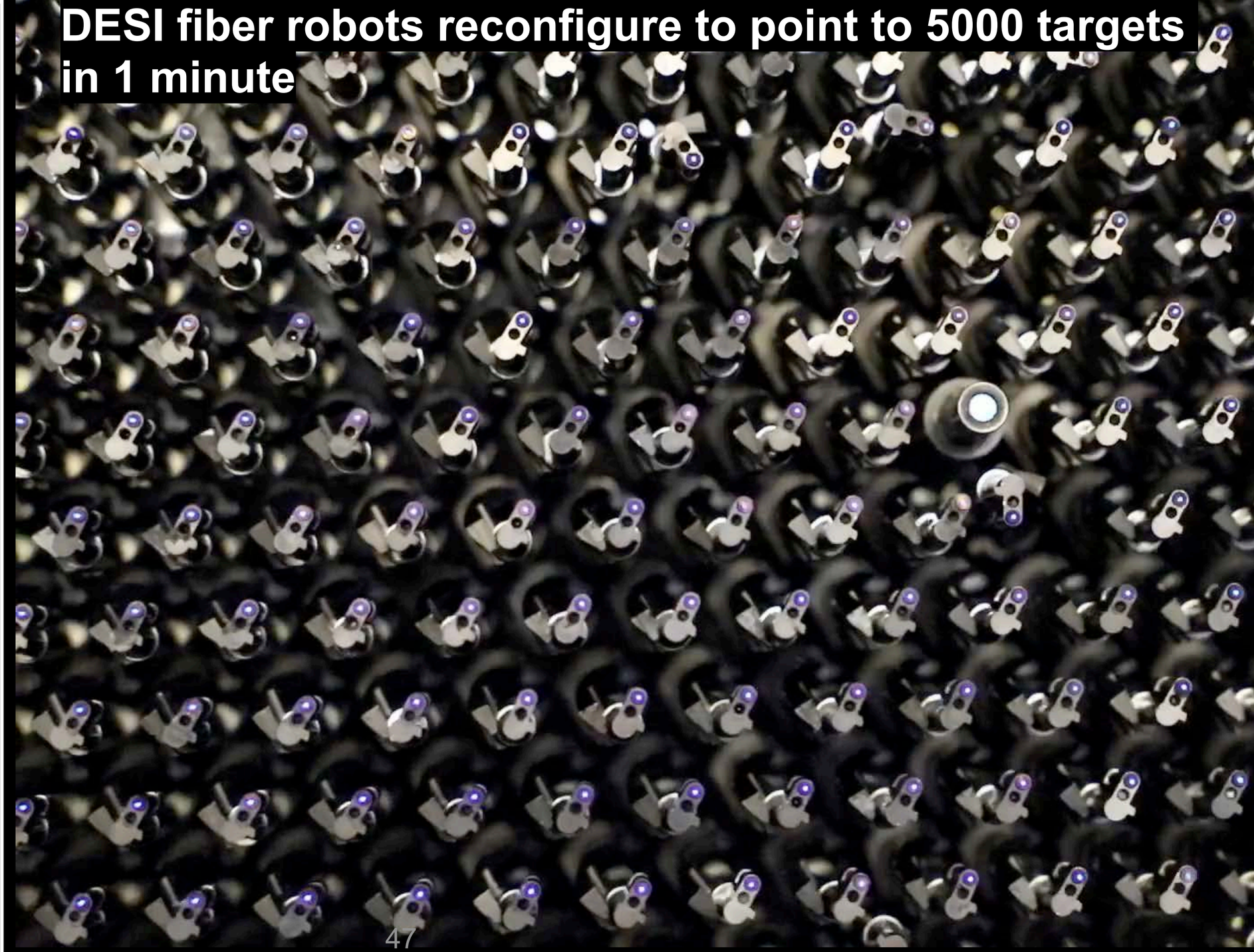

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Cosmology

DESI control room (pre-COVID)

(now we operate with 2 people on-site + collaborators remotely)

Image sky

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Cosmology

Mayall Telescope is dedicated to DESI observing 365 nights/year

Image sky

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Cosmology

DESI spectroscopy is highly uniform

Don't observe to a constant **sky brightness**, observe to a **constant S/N**

- sampling sky, seeing, transparency stopping when $(S/N)^2$ reached

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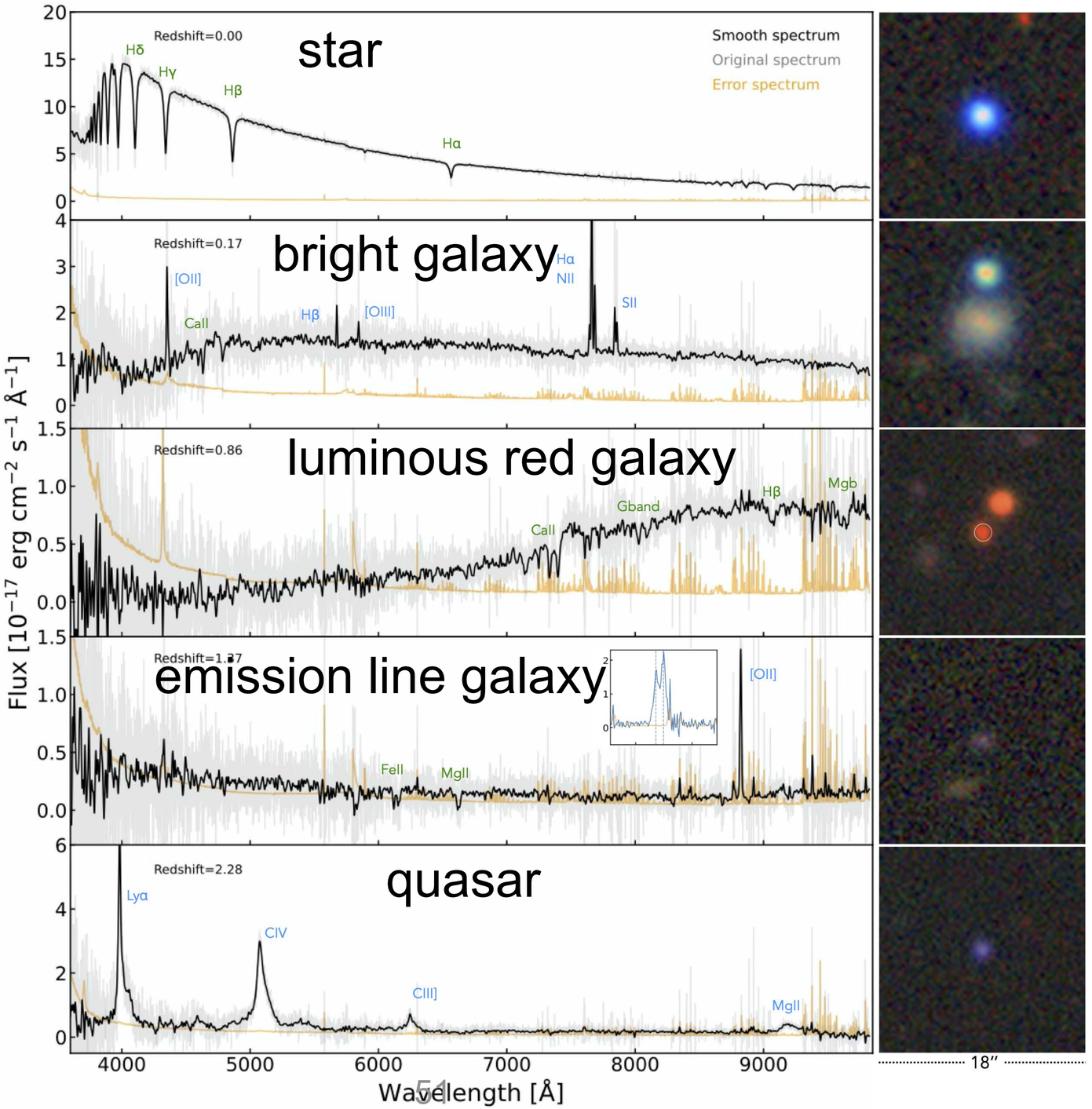

Most DESI galaxies are faint emission line galaxies (ELGs)

Image sky

↓

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Spectra + redshifts

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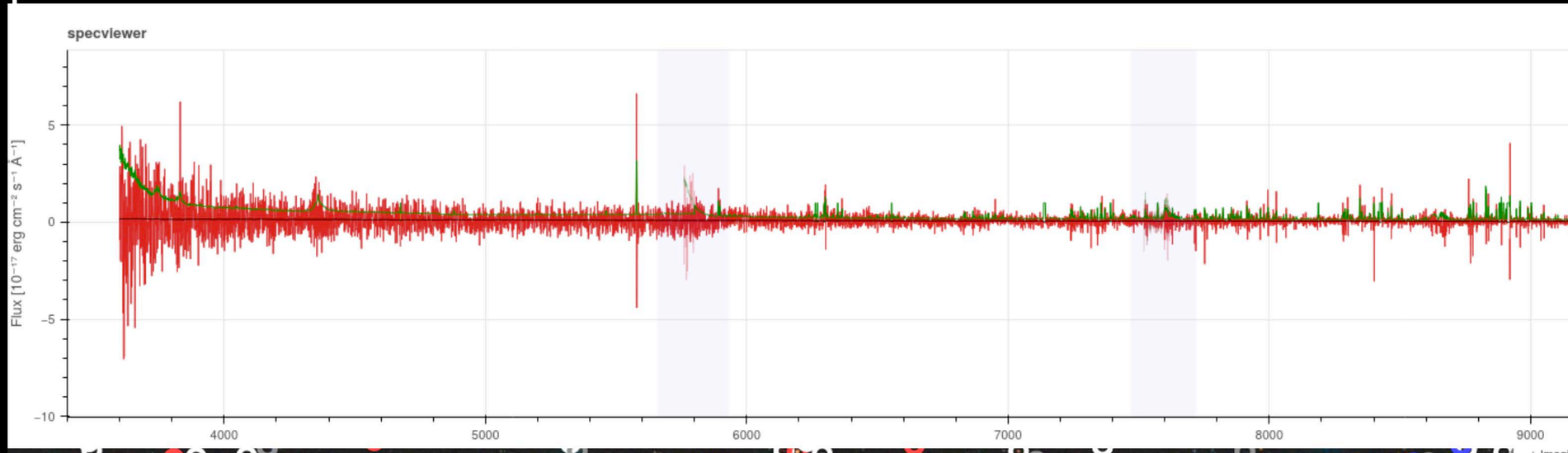

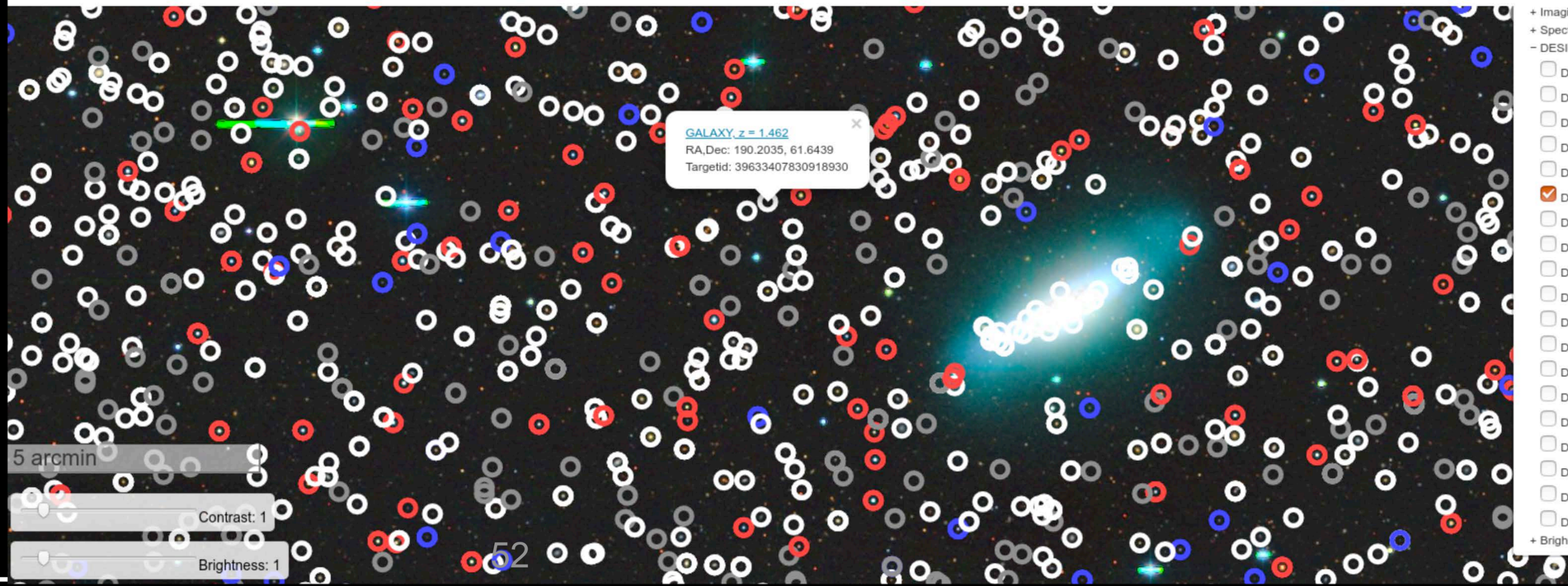

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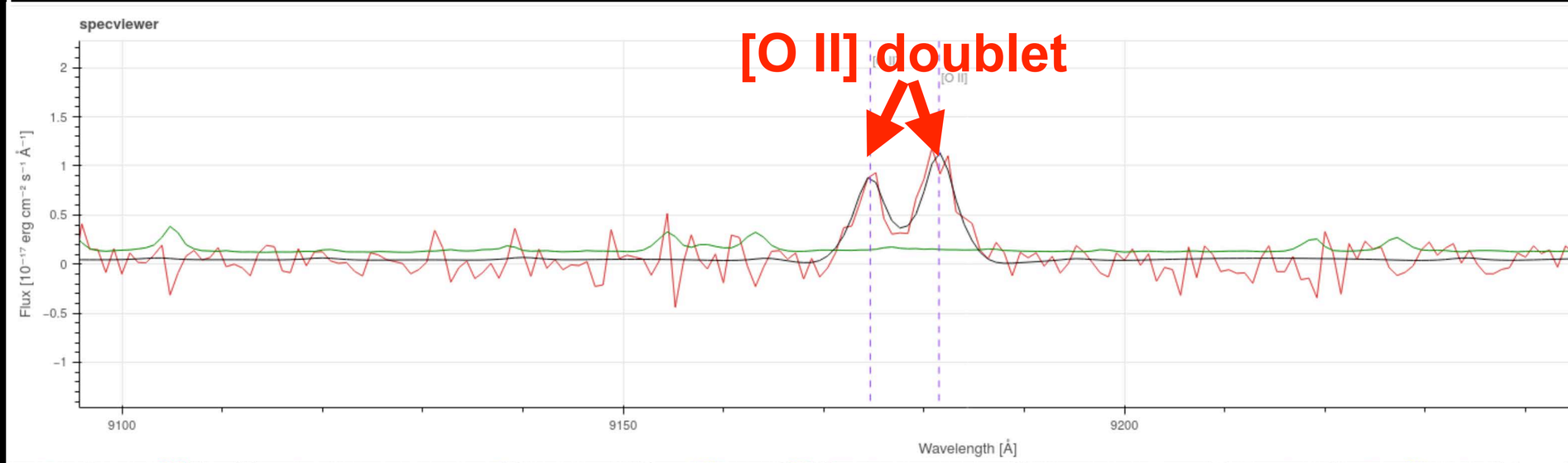

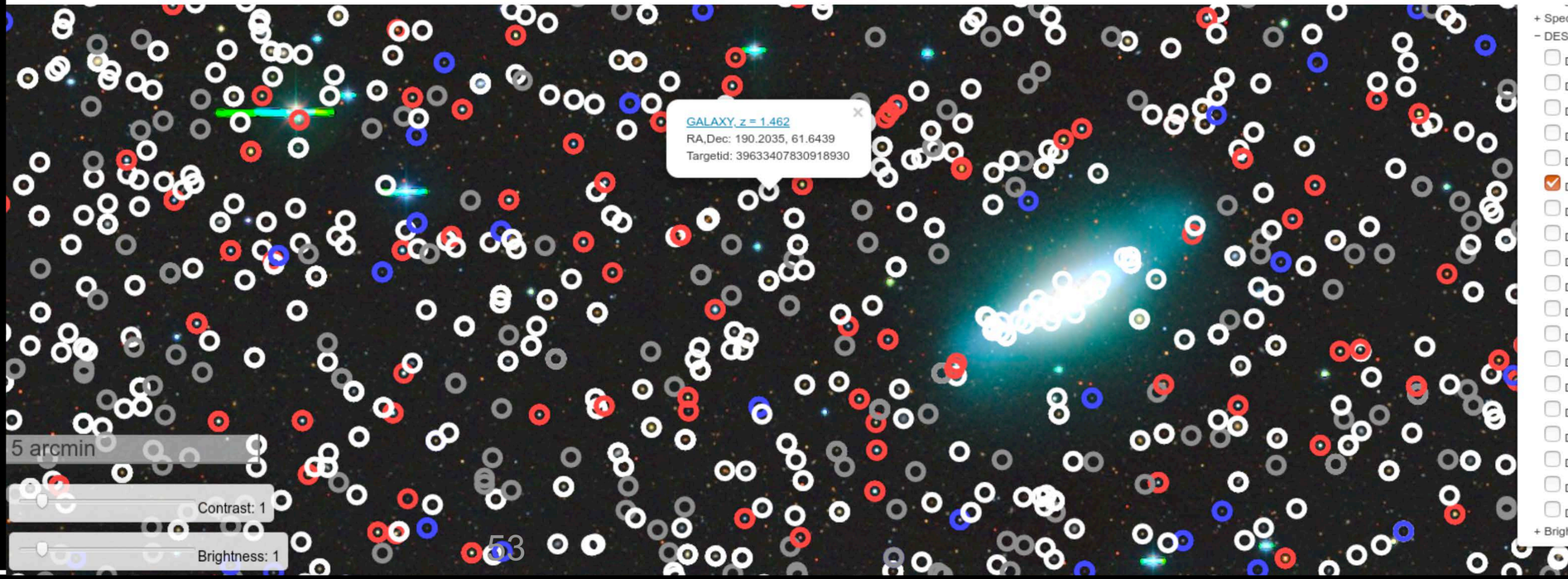

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Measure BAO features

↓

Cosmology

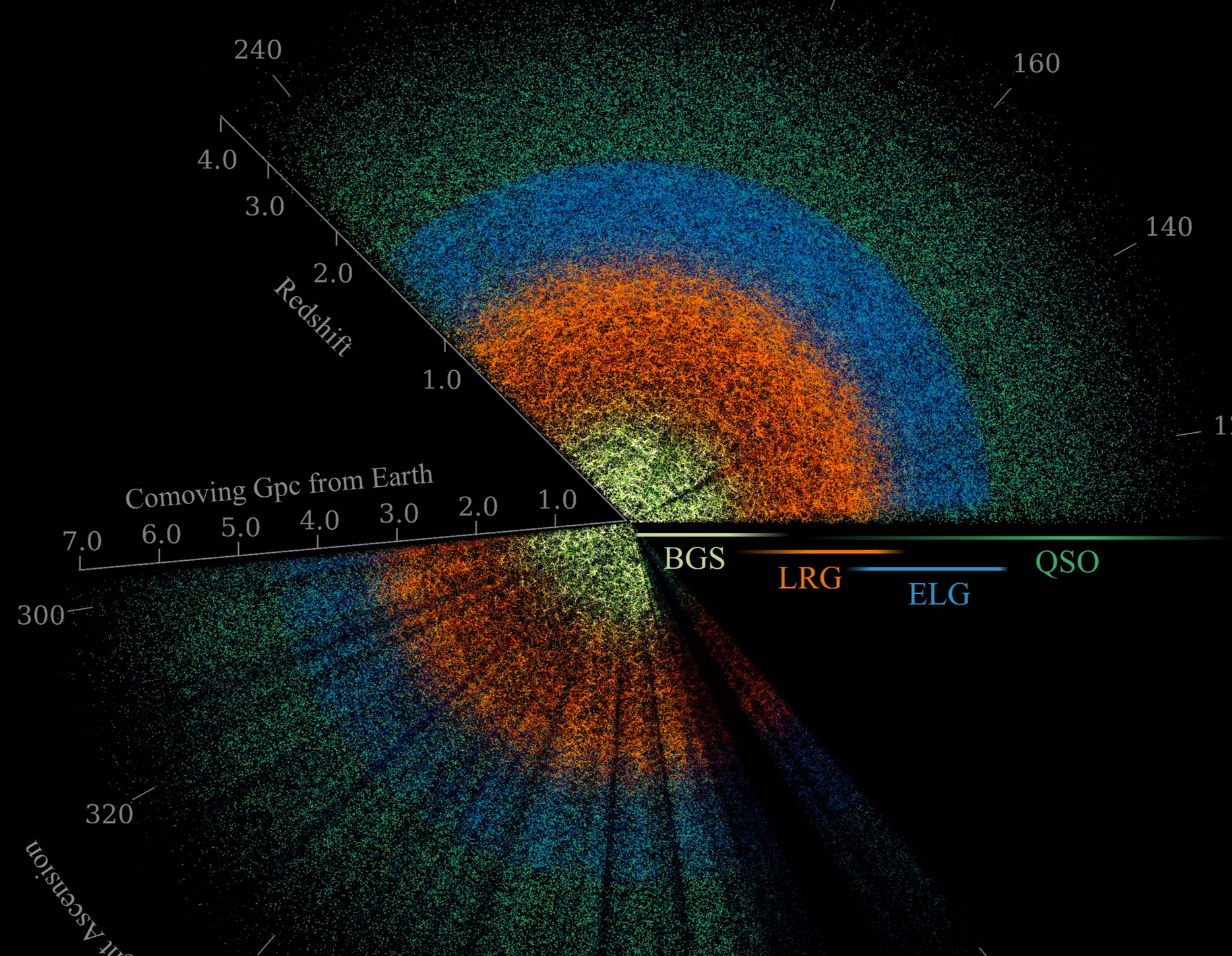

Image sky

↓

Select targets

↓

Configure fibers

↓

Observe!

↓

Spectra + redshifts

↓

Make 3-D maps

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Measure BAO features

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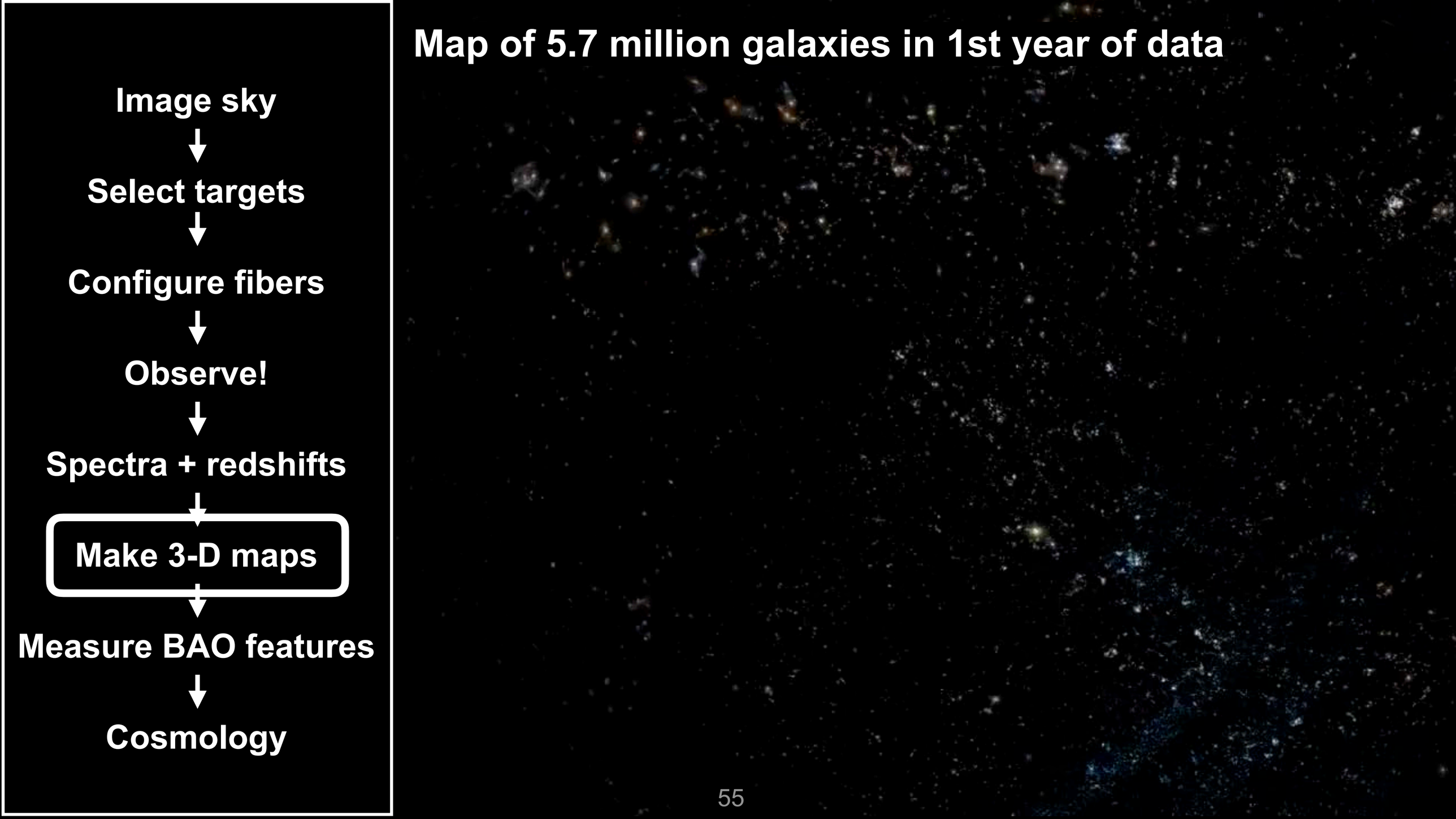
Cosmology



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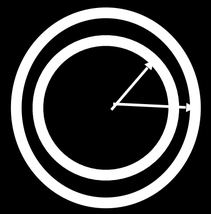
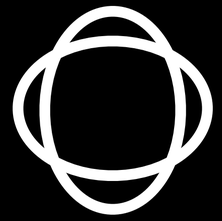
Cosmology

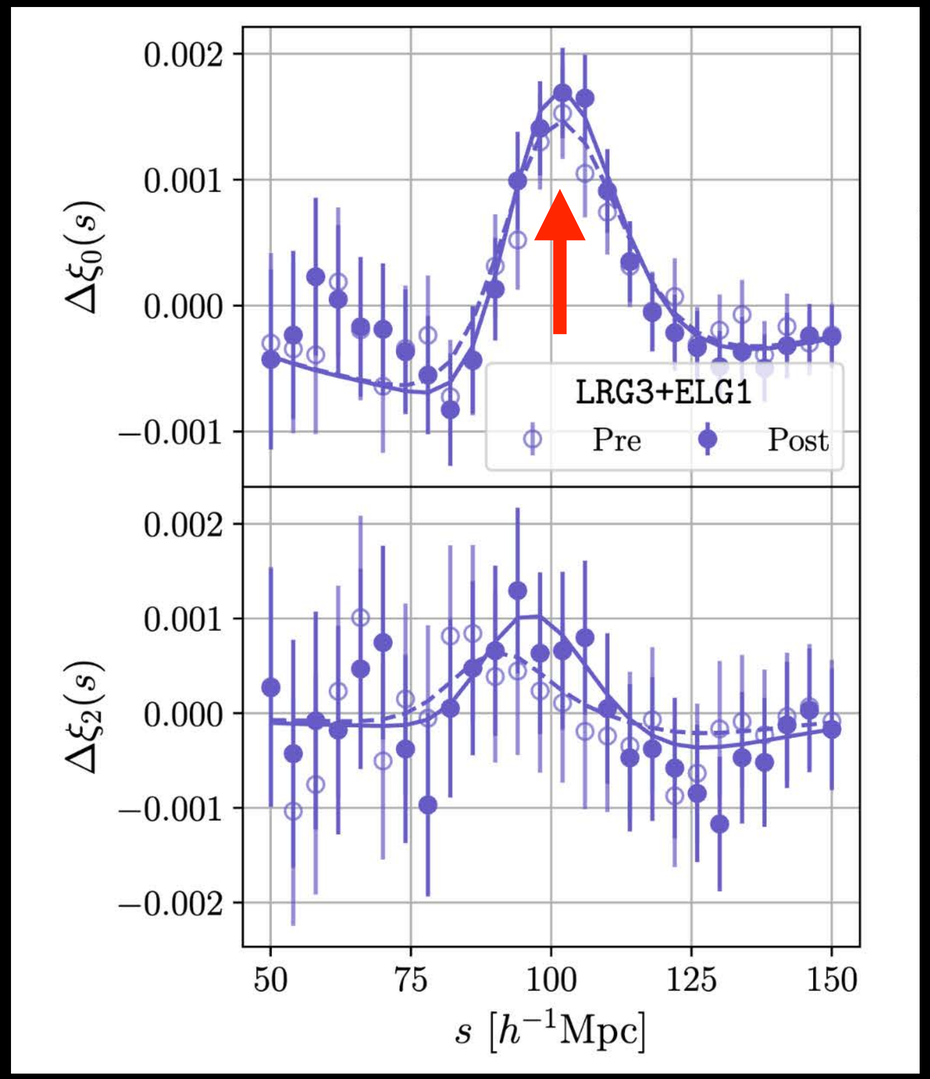
BAO distance scale measured in configuration space

Overall BAO size



BAO anisotropy





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Spectra + redshifts

↓

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Measure BAO features

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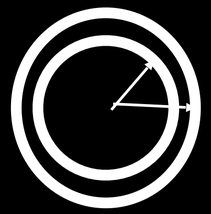
Cosmology

BAO distance scale measured in Fourier space

Overall BAO size



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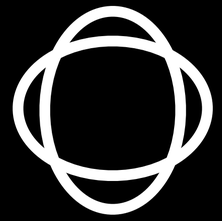
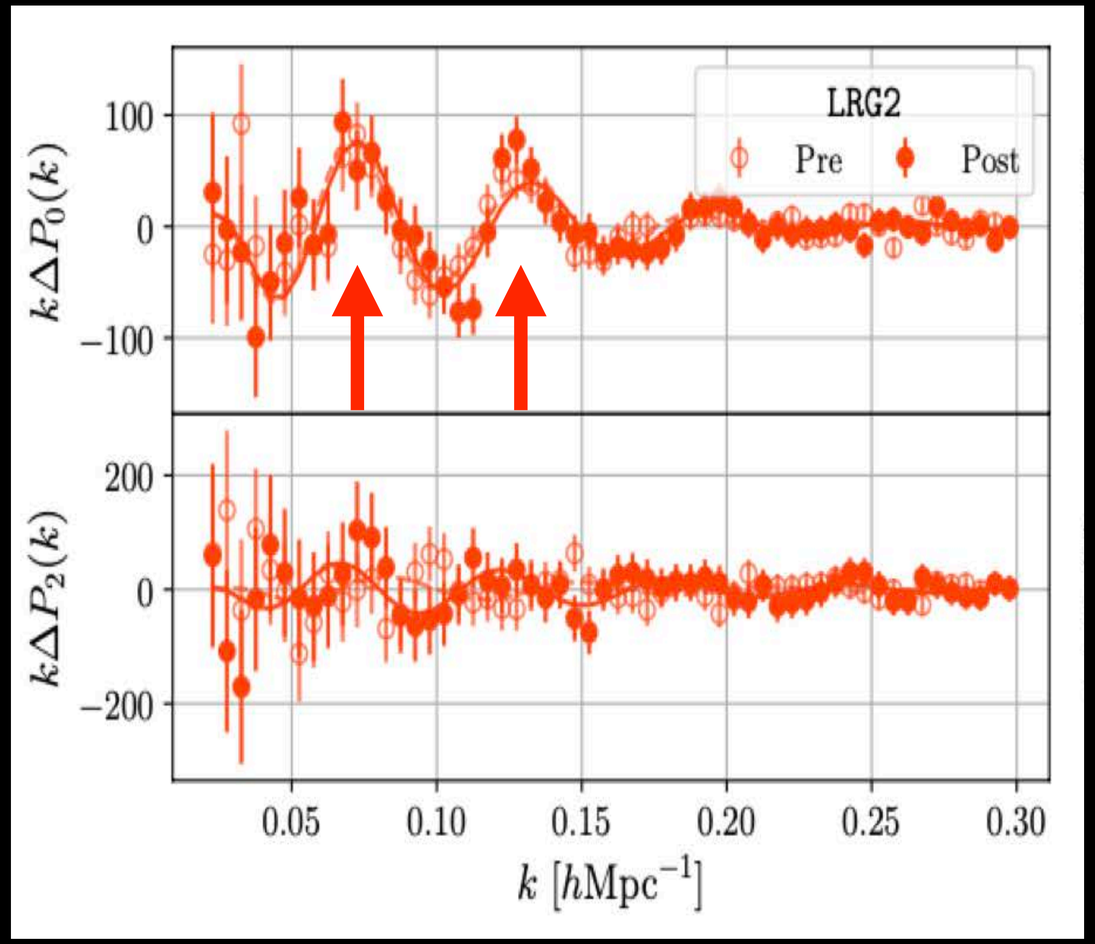
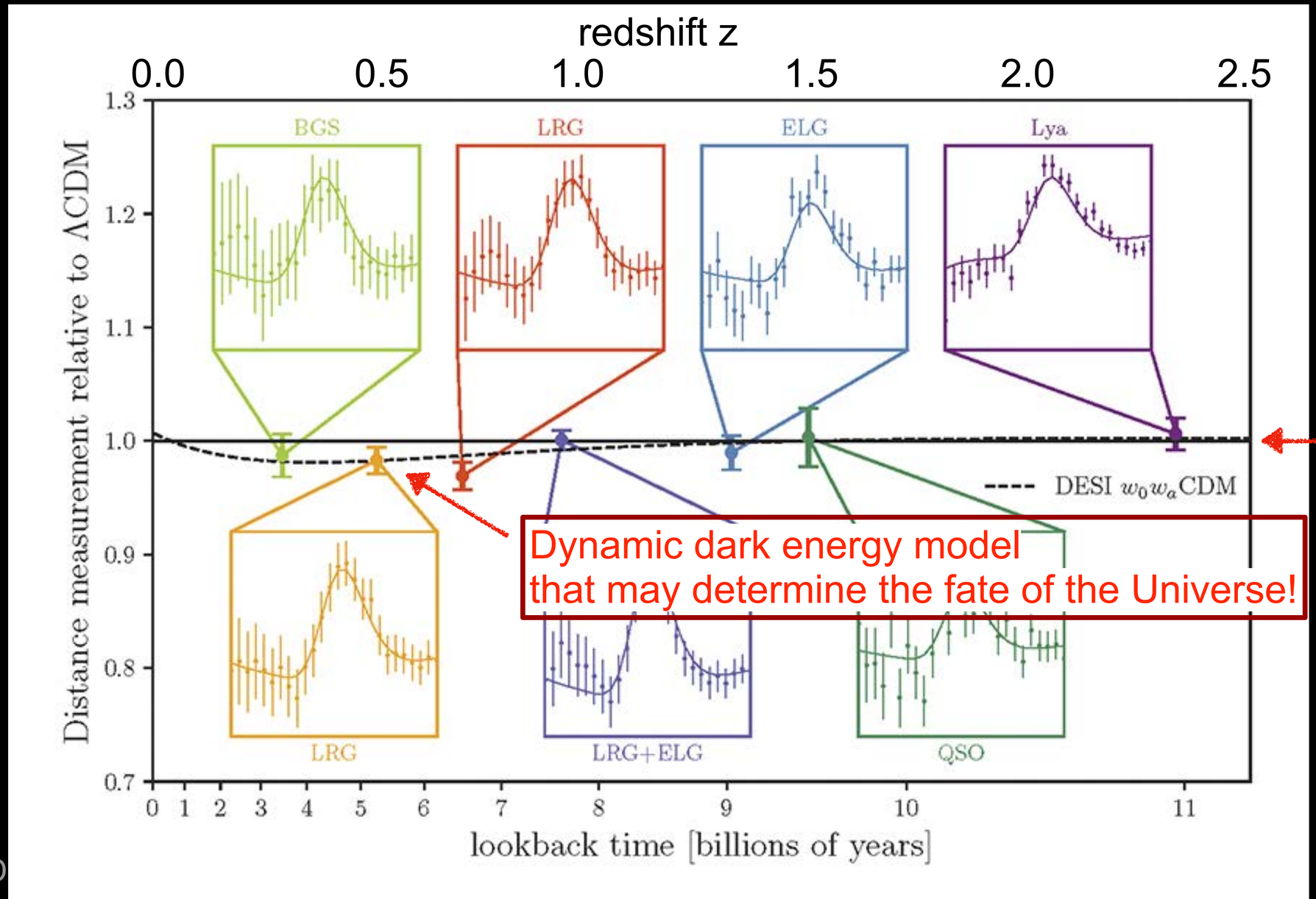




DESI analyses were all conducted blinded

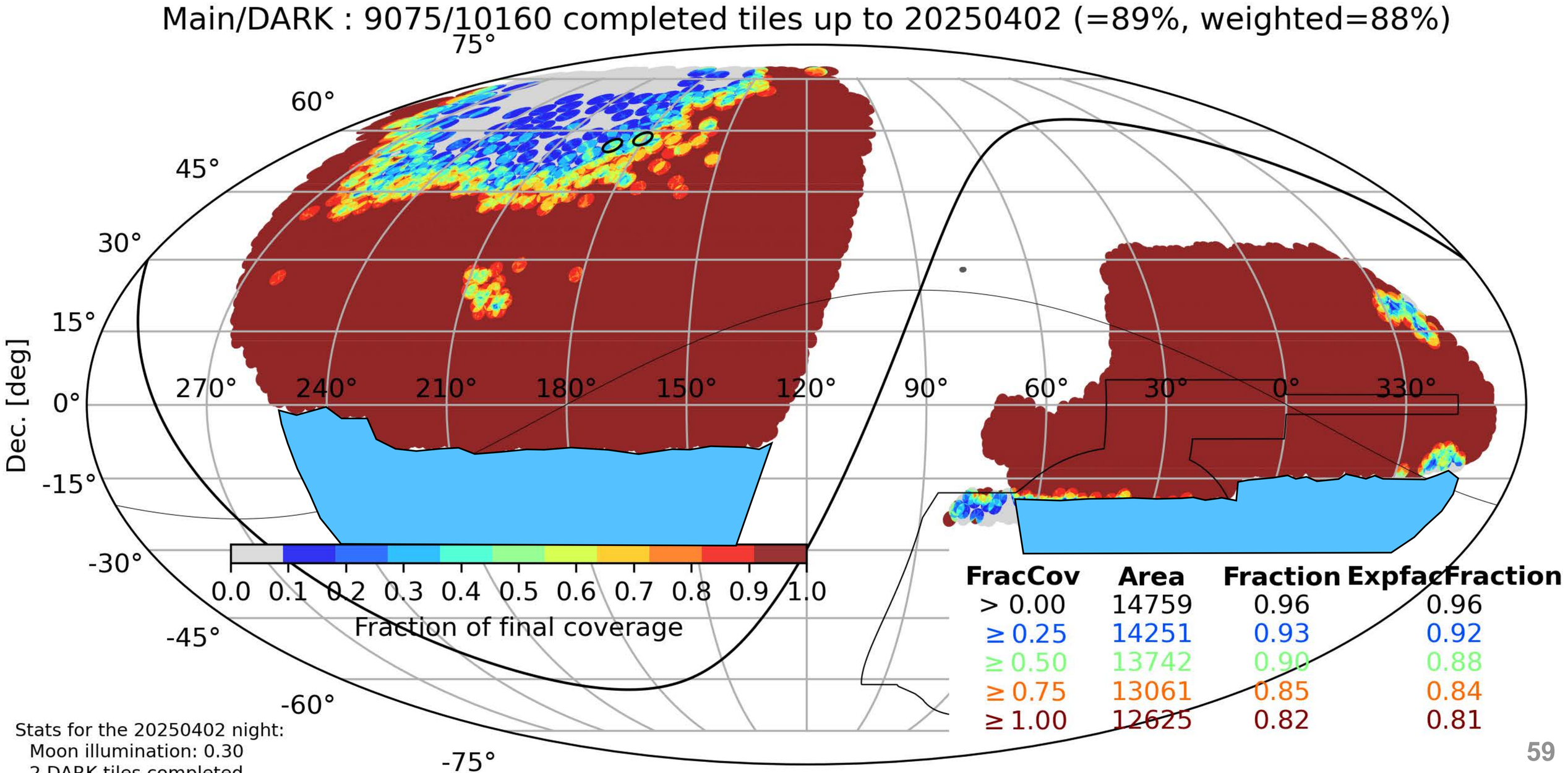
BAO feature well-measured in 7 samples



Best-fit cosmology prior to DESI

Dynamic dark energy model that may determine the fate of the Universe!

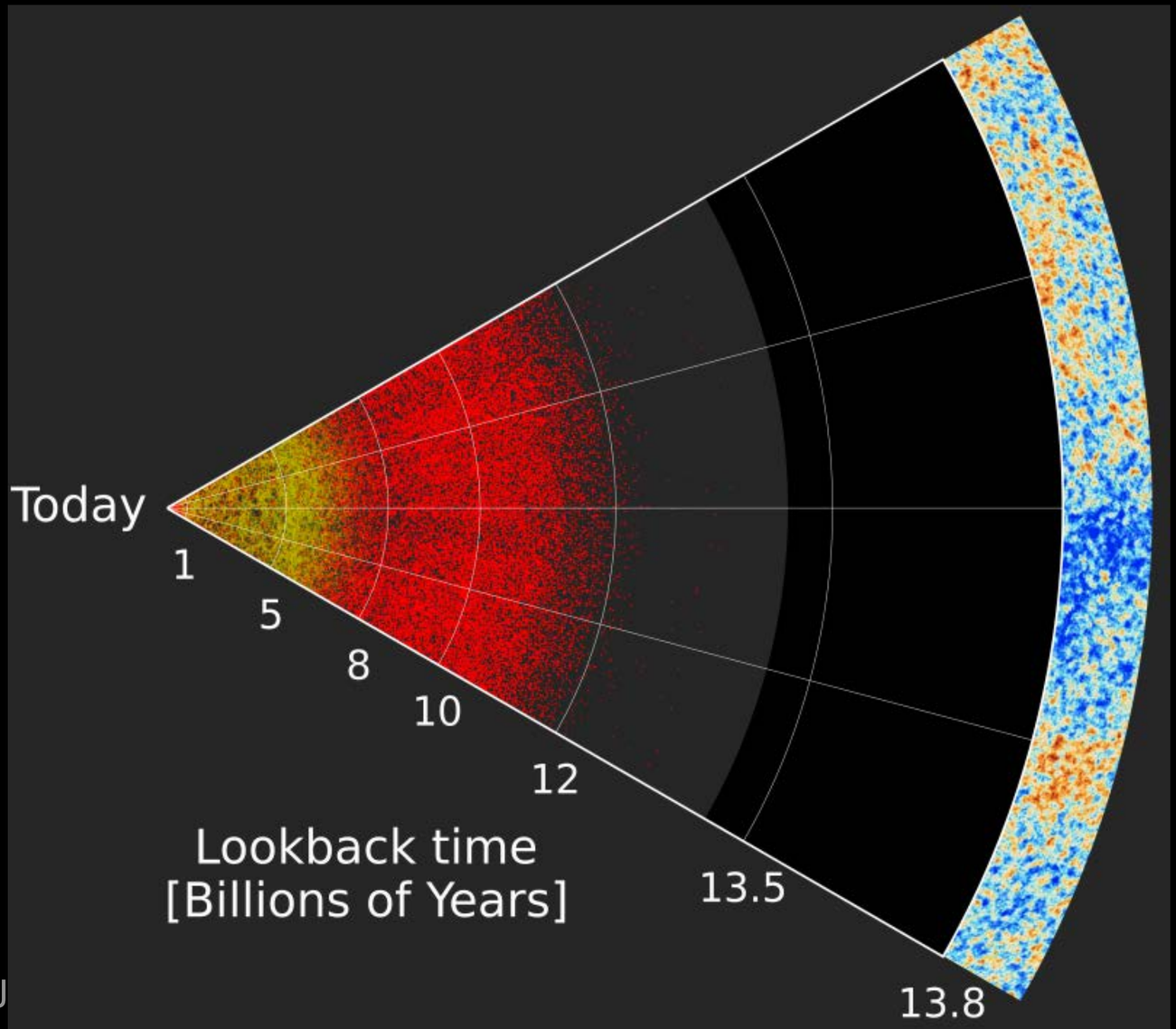
DESI is expanding its footprint to ~ 20,000 deg^2 to confirm dynamic Dark Energy independent of supernova data



What’s next?

DESI + Euclid + PFS + 4MOST will only map a fraction of linear modes

- 75% of modes at z<0.4, 10% at z<1.5, 0.1% at z<4
- Approx. 2 billion linear modes at 0 < z < 4



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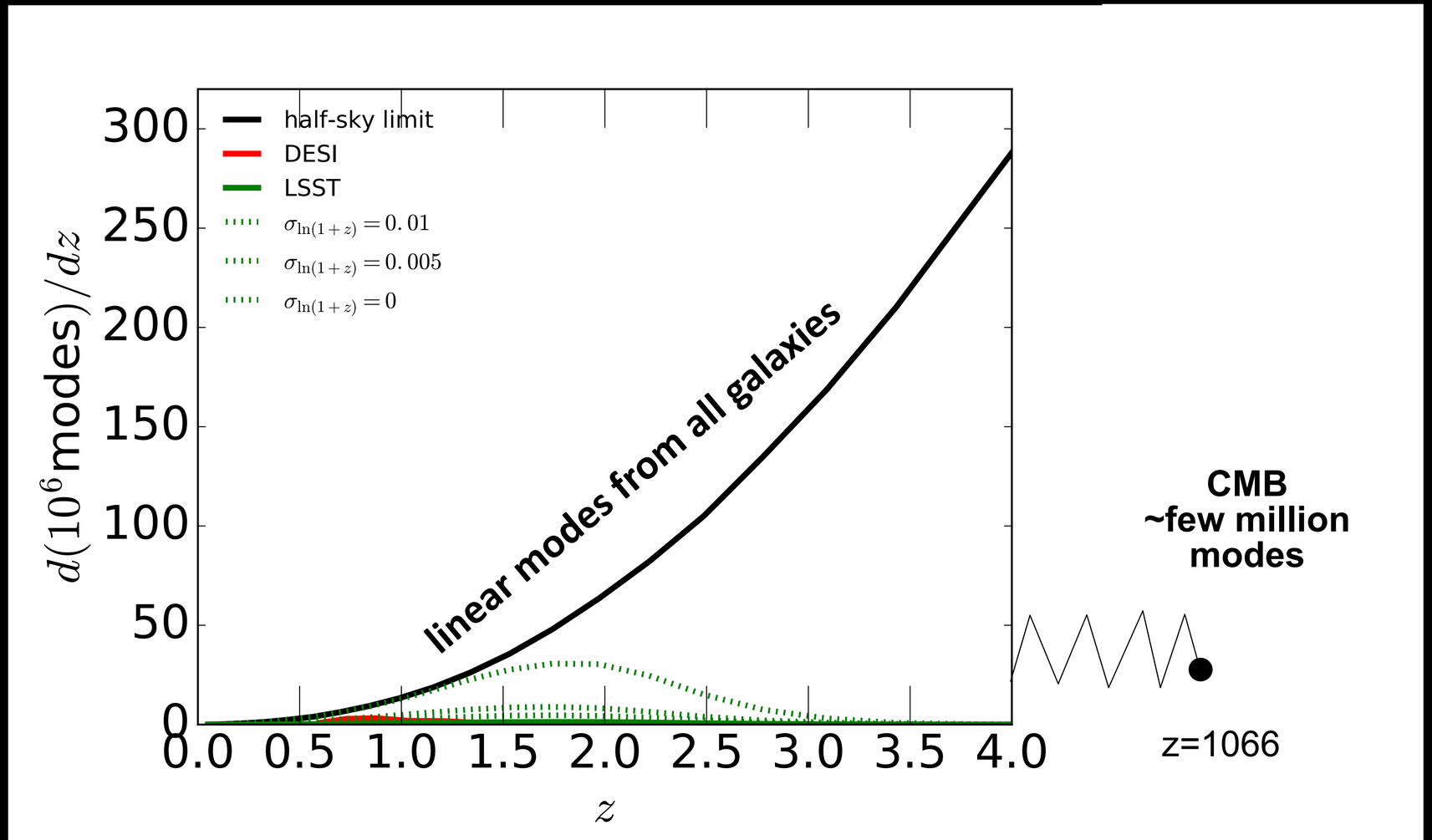
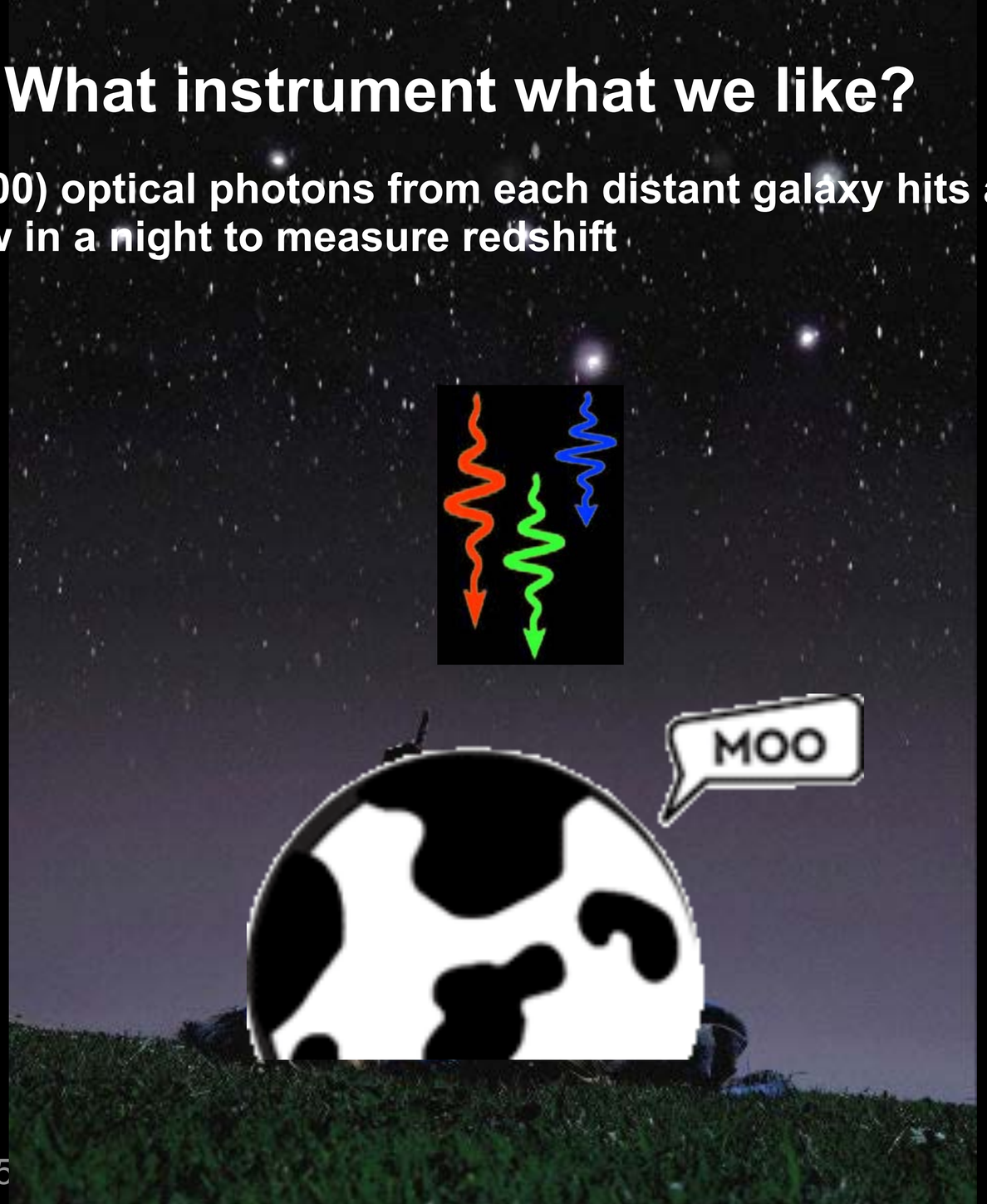


What instrument what we like?

Enough (~1000) optical photons from each distant galaxy hits a spherical cow in a night to measure redshift



What instrument what we like?

The “perfect instrument” on Rubin Observatory

Time-tag, energy-tag every photon with energy resolution of ~5000 over 9.6 deg^2 focal plane, 100 % quantum efficiency

6.9 x 10^{16} photons/night -> 550 PB/night

Would map all linear modes at z < 5 in several years

… if we could build it

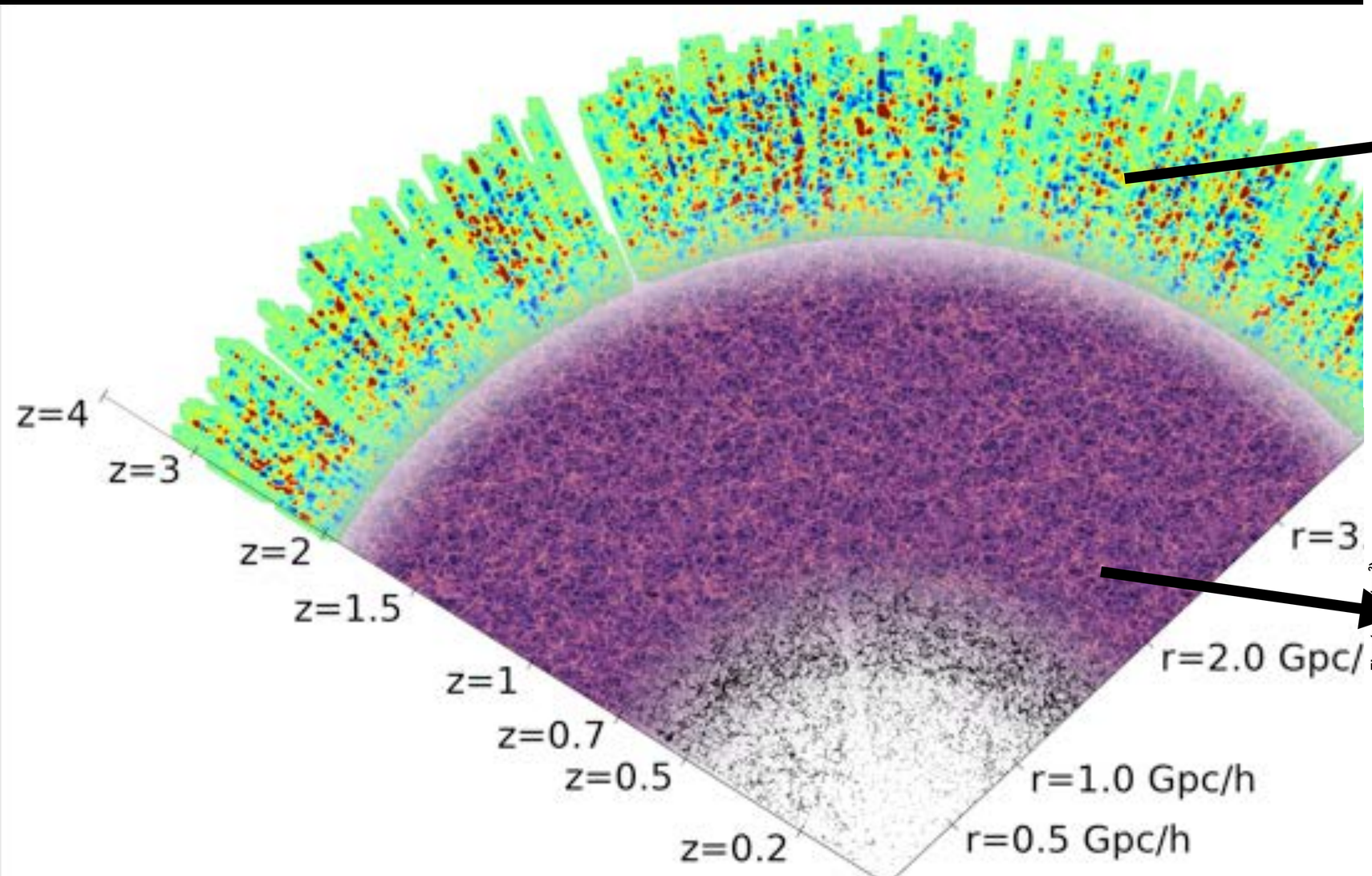
What instrument is realistically next?

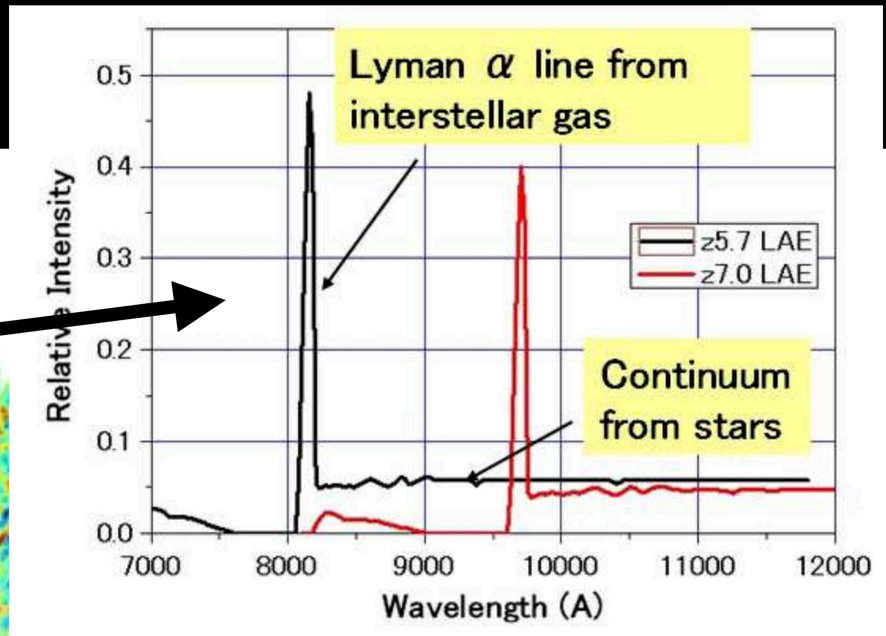
Stage 5 Spectroscopic Survey (Spec-S5) with 15X the mapping speed of DESI

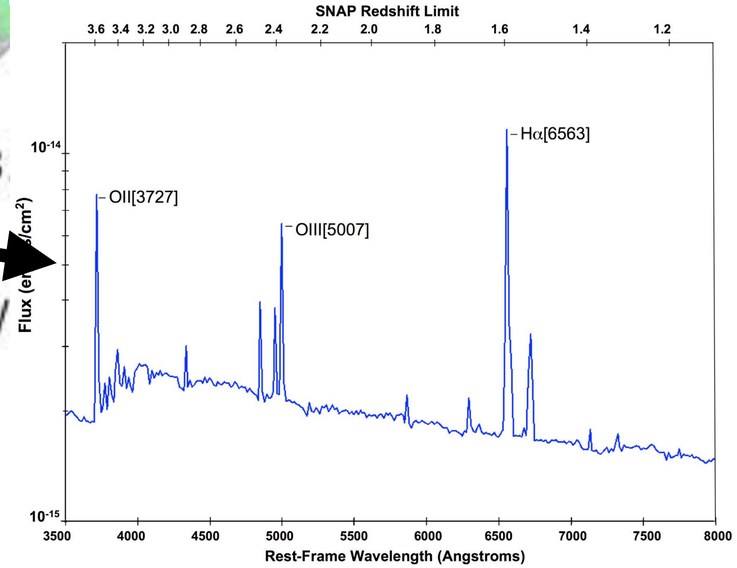
Mayall Telescope (Arizona)

Blanco Telescope (Chile)

The Universe has been kind providing compact galaxies to z=5 and beyond



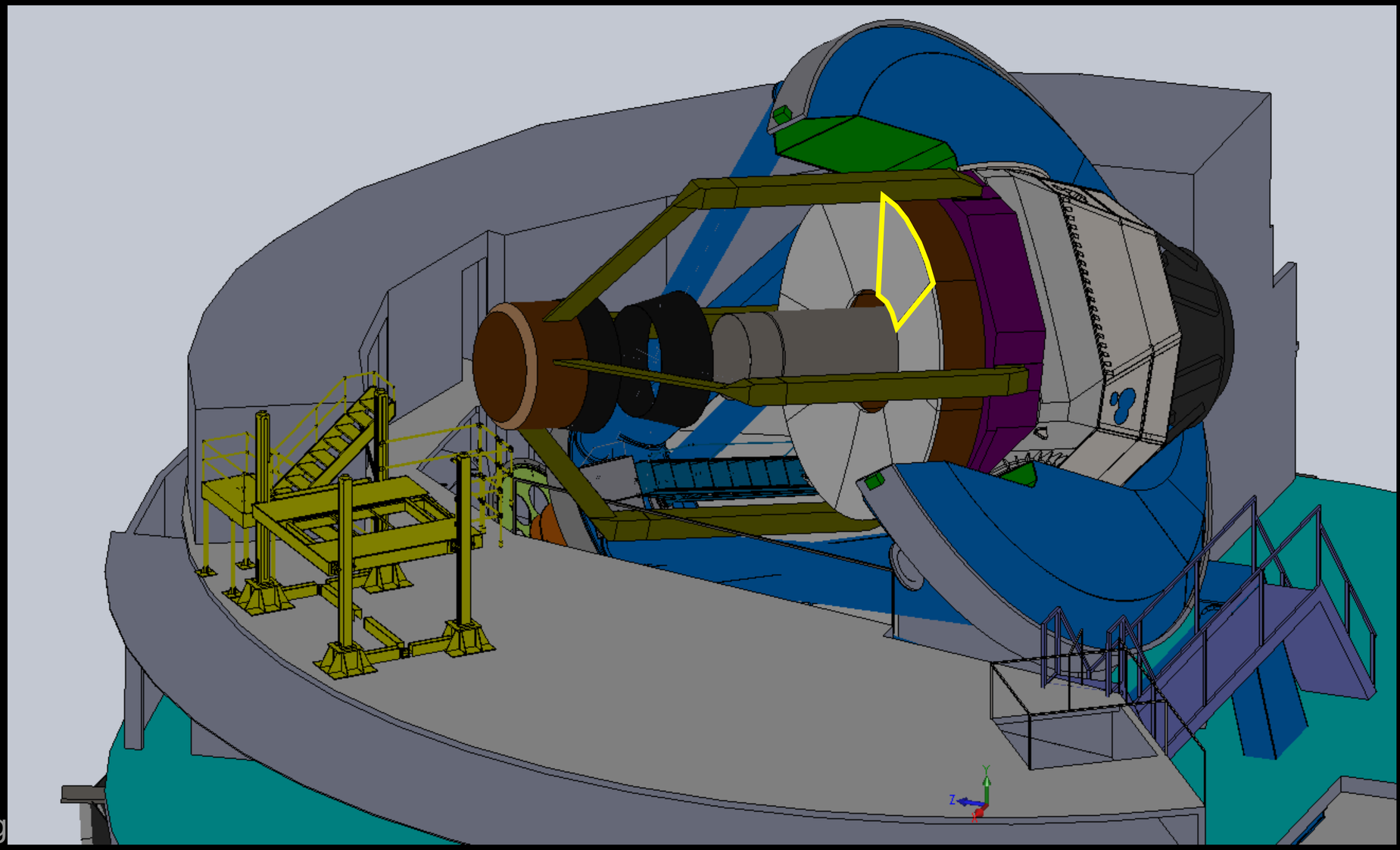




Spec-S5 will have >15X the mapping speed of DESI:
Upgrade **2 existing telescopes**: Mayall (KItt Peak), Blanco (Chile)
to each have **6-meter** collecting mirror, **26,000 fiber robots** (total), **46 spectrographs** (total)

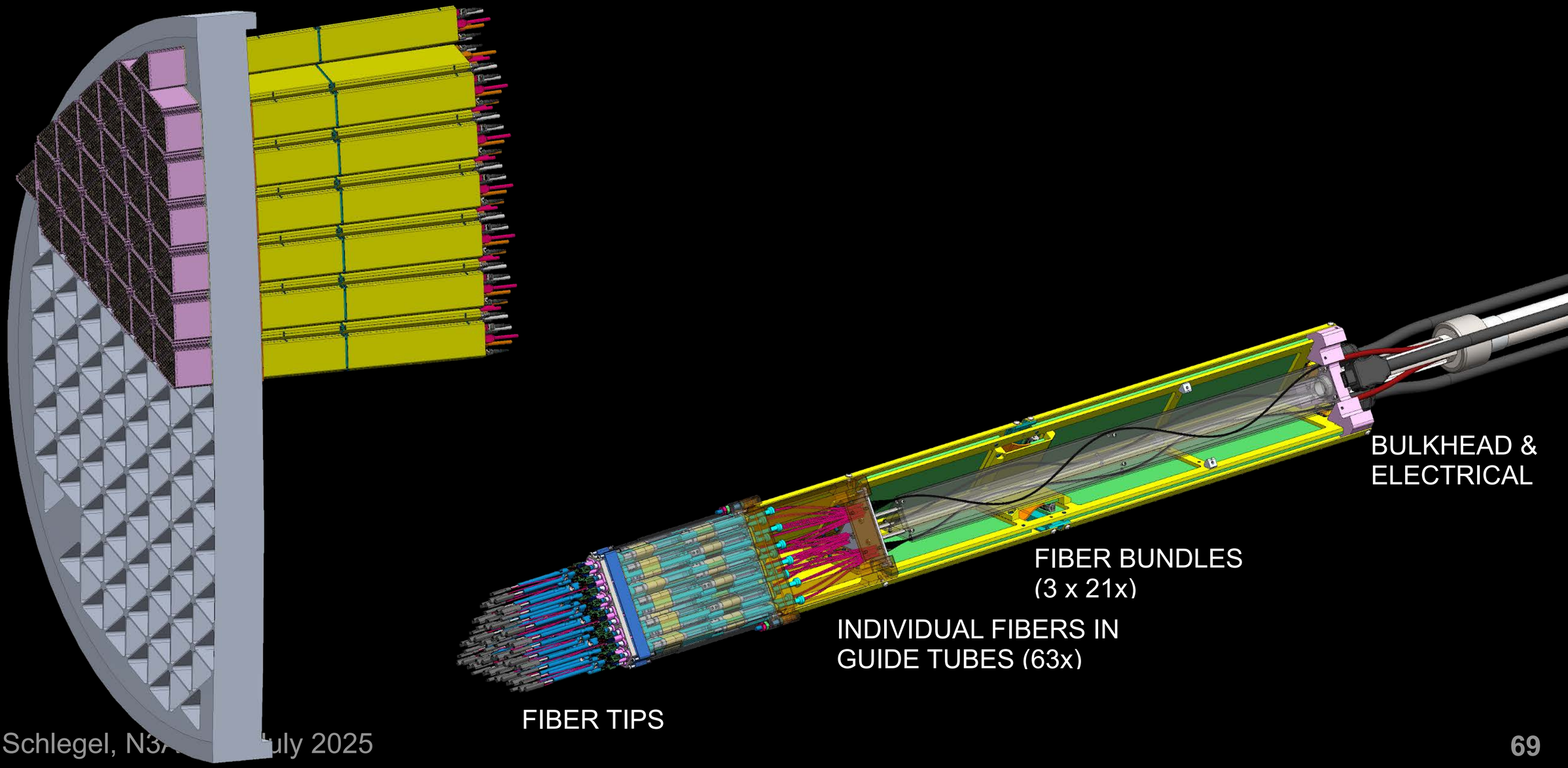
Spec-S5 technology development: Segmented primary mirror

Segmented 6-meter primary mirror, annular shaped, equatorial mount gravity loads
Allows re-use of existing telescopes that can support these massive instruments



Spec-S5 technology development: Miniaturized fiber robots

Robots further miniaturized to 6-mm center-to-center to fit 13,000 robots on a focal plane
63-robot “rafts” commercially manufactured for cost-effectiveness



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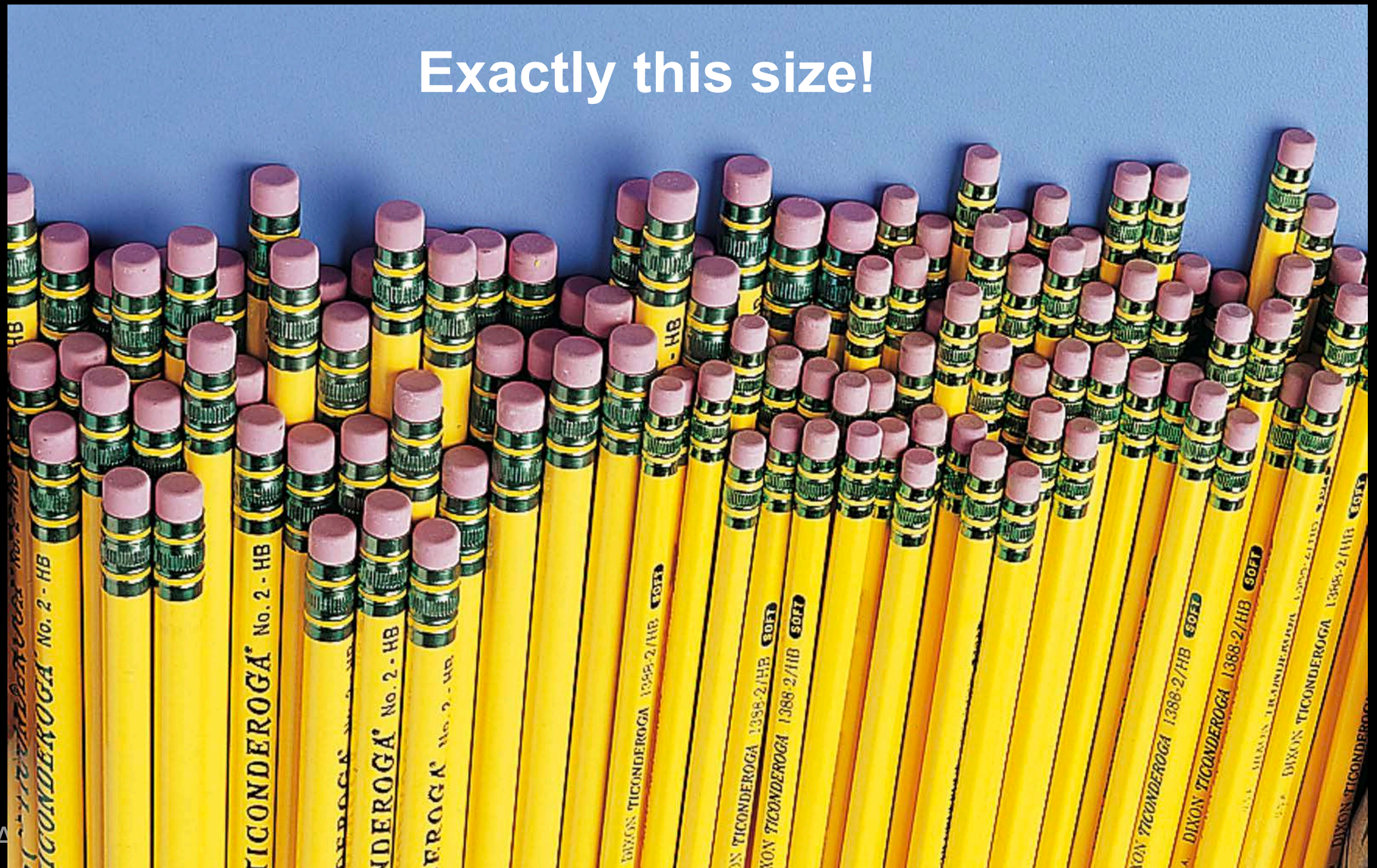
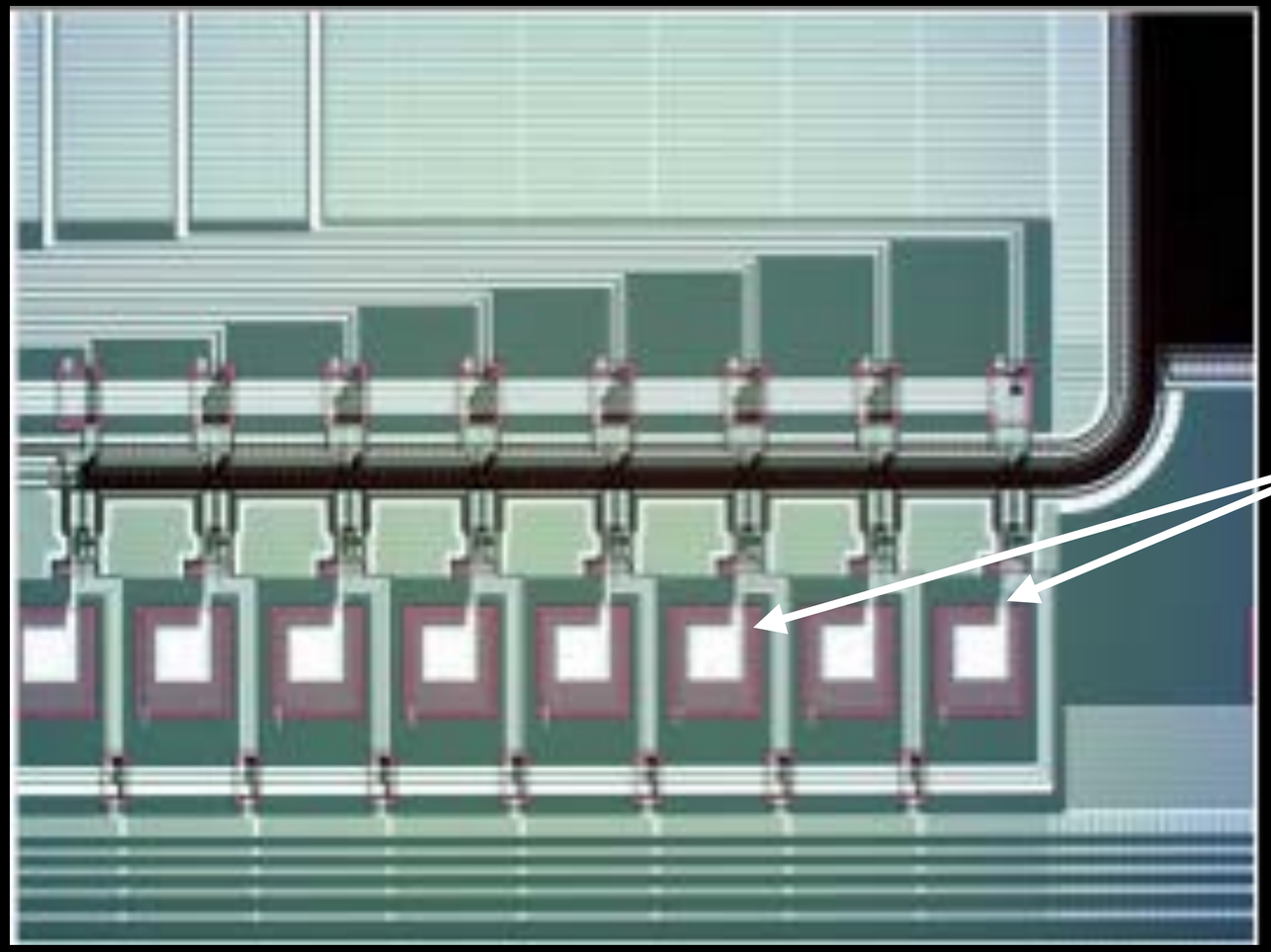


Spec-S5 technology development: MAS CCD detectors

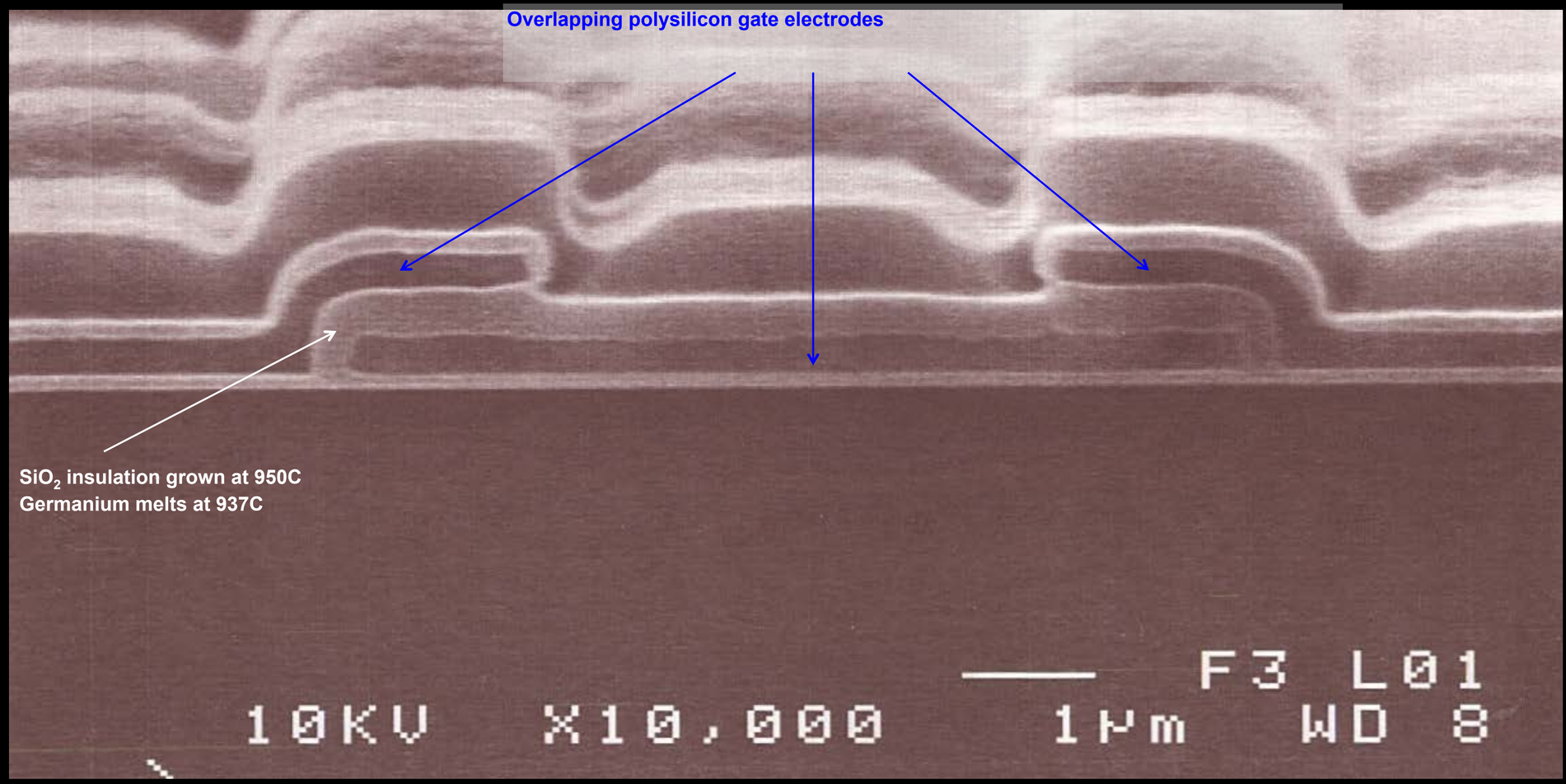
Multi-amplifier sensing CCDs with essentially no read noise —> photon counting
Planned to be deployed on DESI before 2030



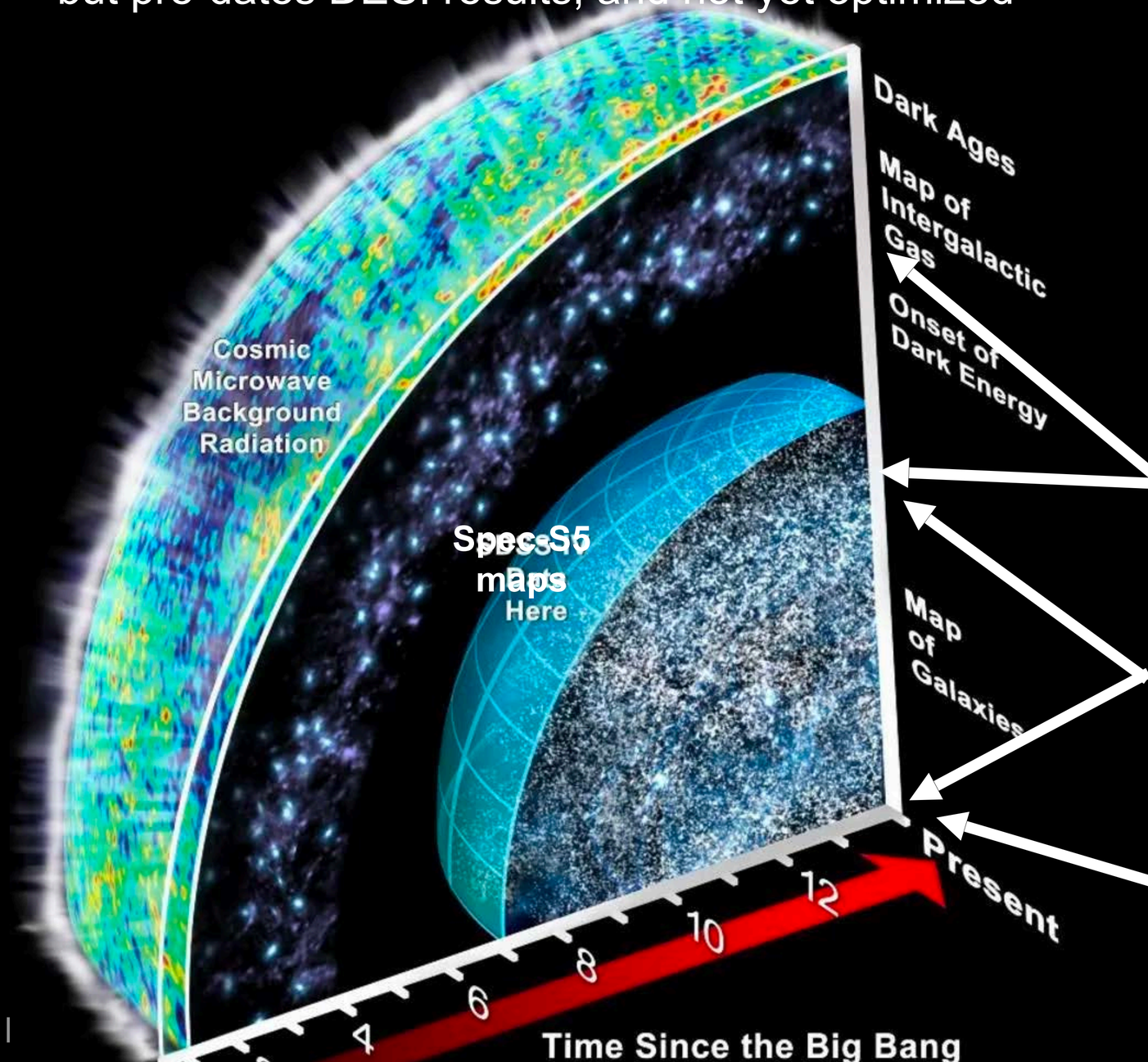
32 Skipper amplifiers
(on one corner of the CCD)

Spec-S5 technology development: Germanium CCD detectors

Extend the wavelength range of spectrographs from 1.0 —> 1.4 micron
(silicon bandgap —> germanium bandgap)



Spec-S5 Reference Mission to address three science cases,
but pre-dates DESI results, and not yet optimized

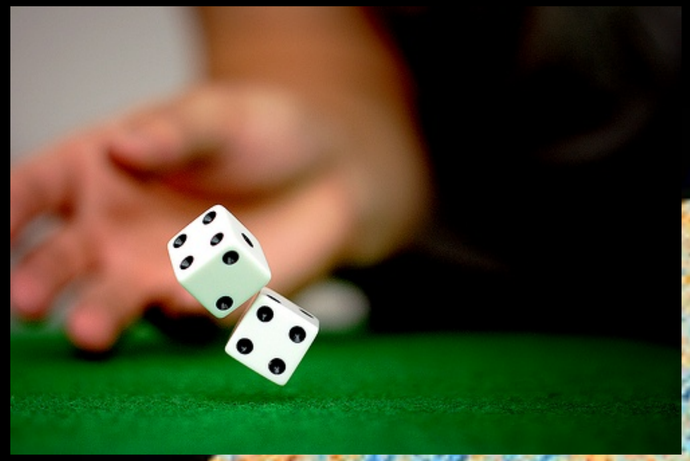


Spec-S5 will map **62 million galaxies**
at z>2 for use in inflation + dark energy

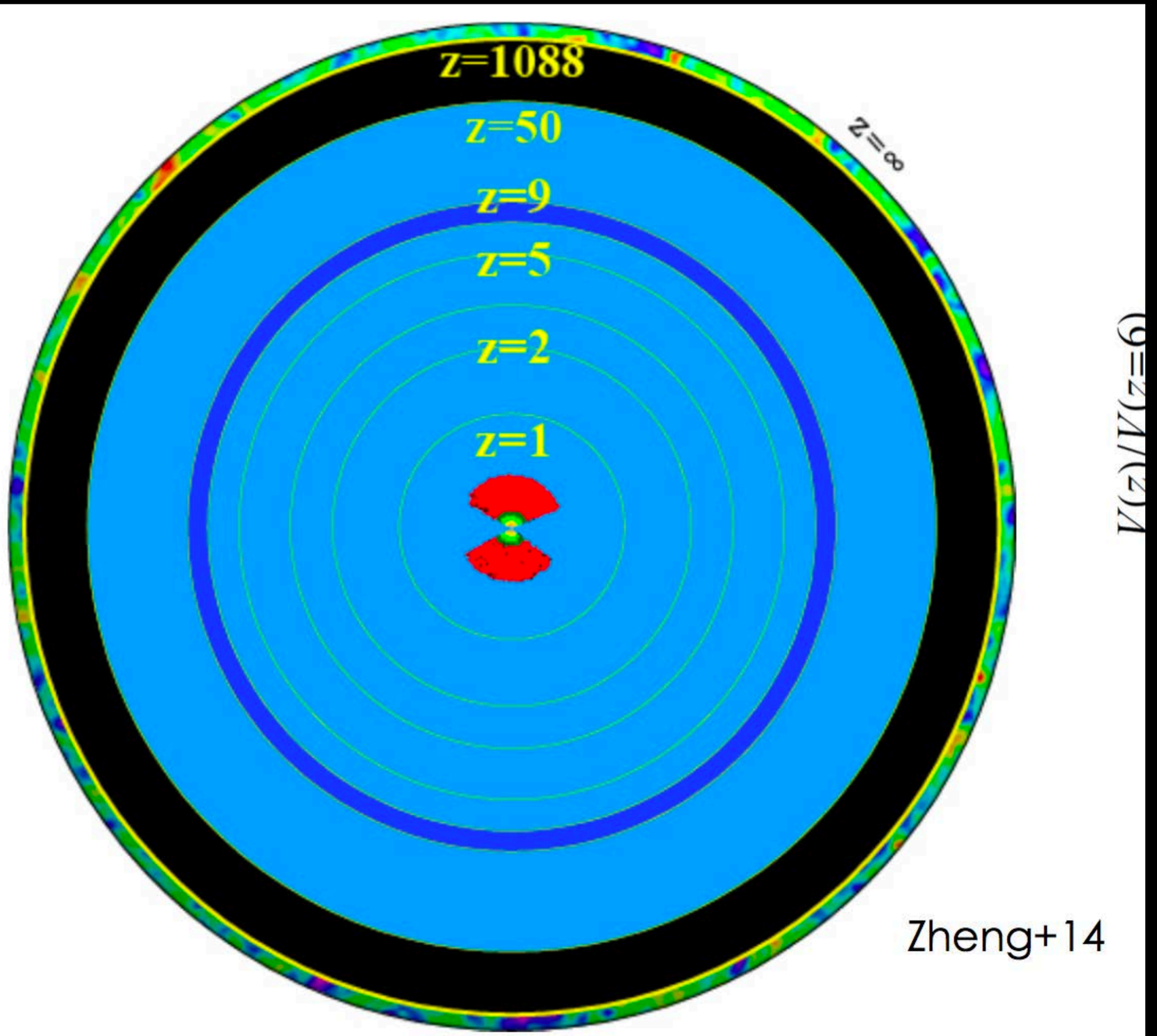
Spec-S5 will map **130 million galaxies**
at z<2 for use in late-time dark energy

Spec-S5 will map **200 million stars**
for dark matter physics (+ dust maps!)

We’ve rolled the dice on the CMB…

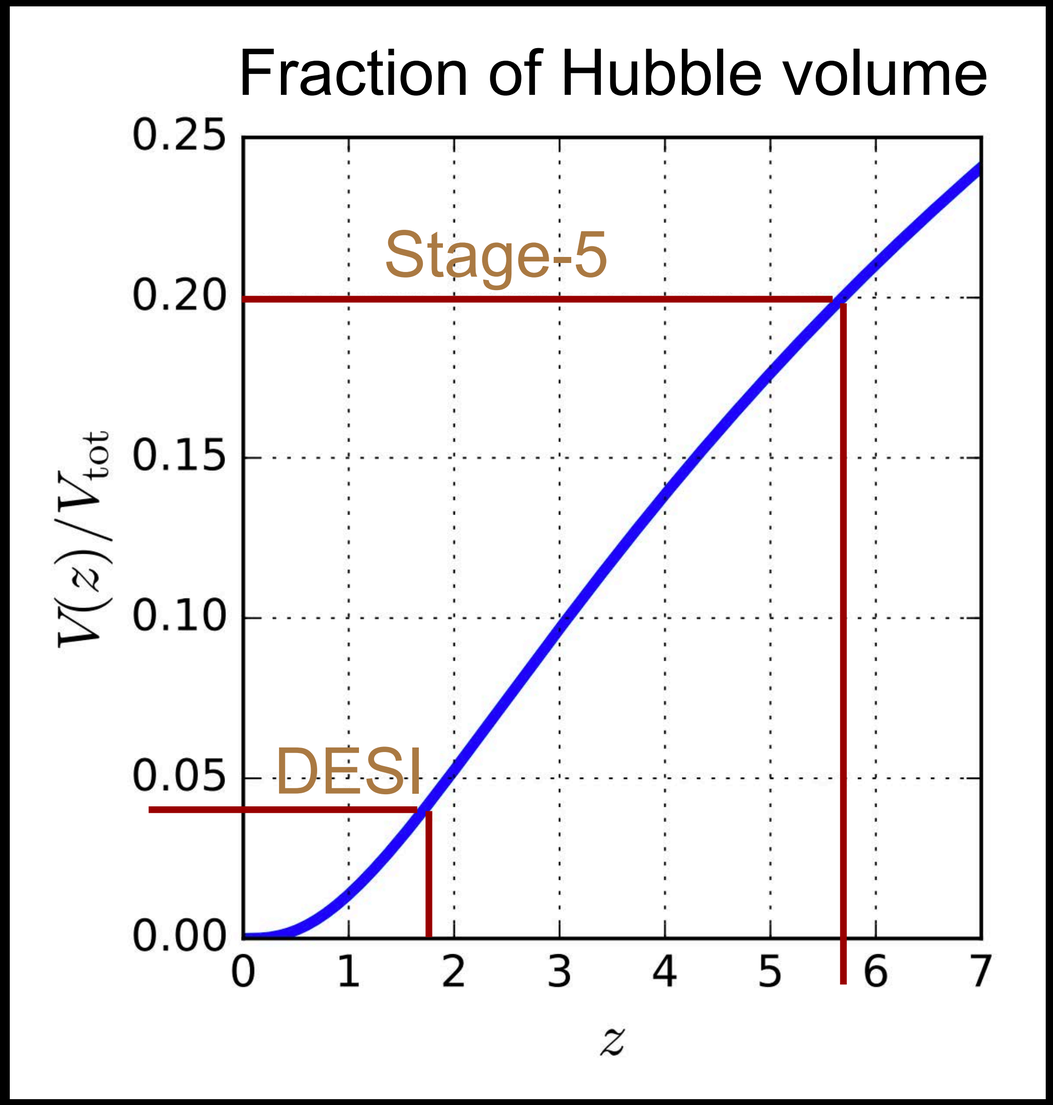


We still have many dice to roll for galaxy maps…



Map more galaxies -> more linear modes -> “primordial figure-of-merit”

- 2 < z < 5 enormous volume only accessible with spectroscopy (Stage 5)
- 5 < z < 20 comparable volume from future radio surveys (Stage 6)



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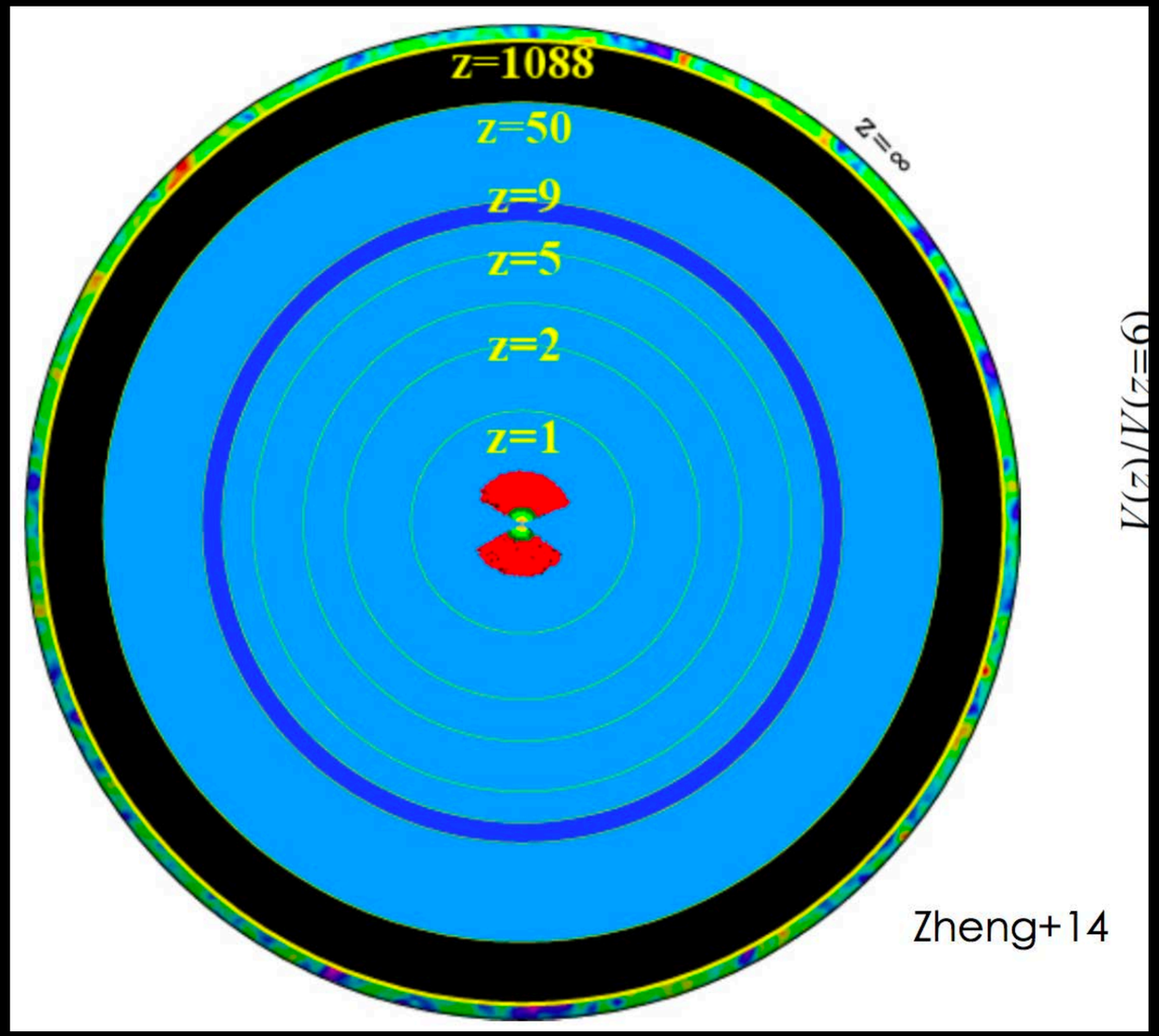
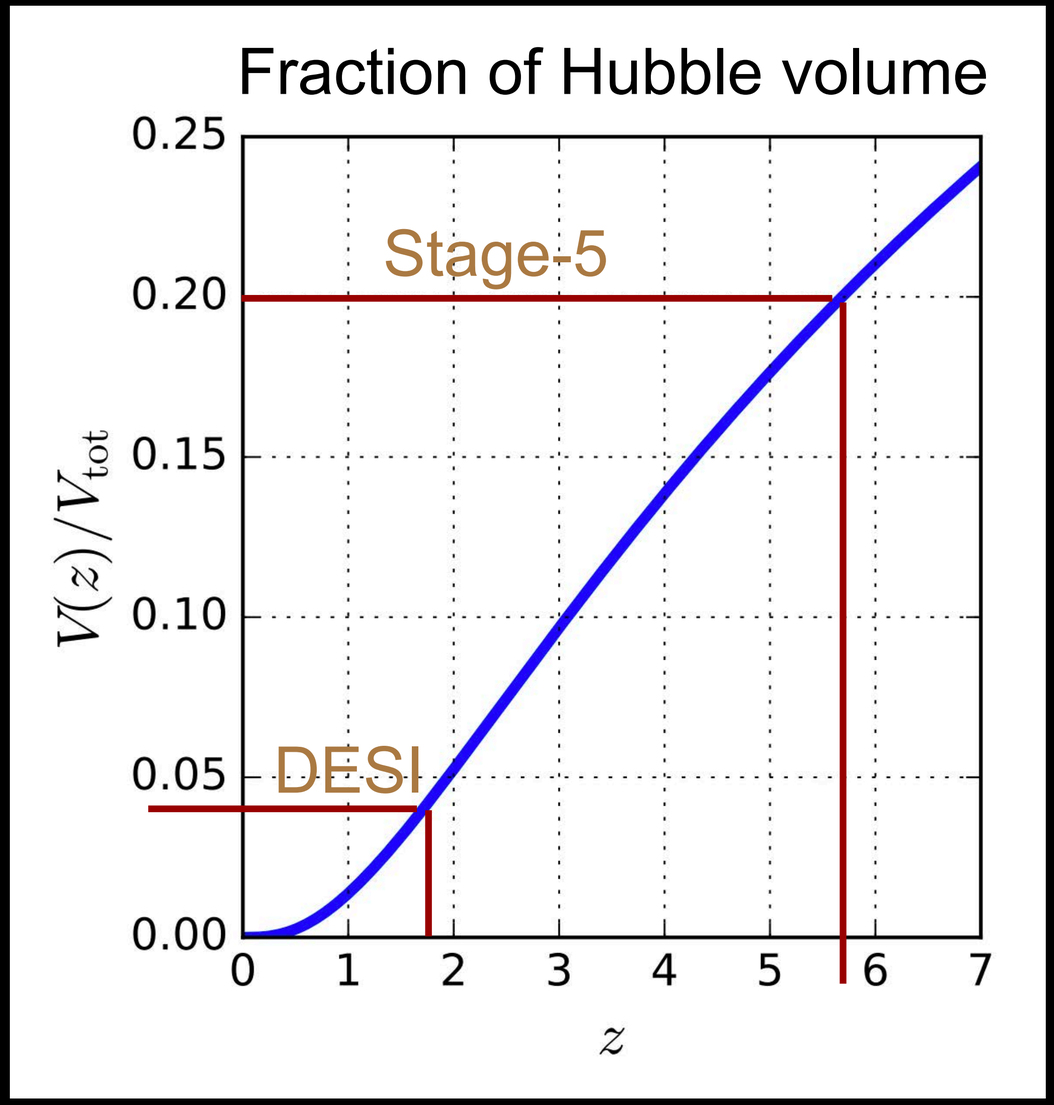
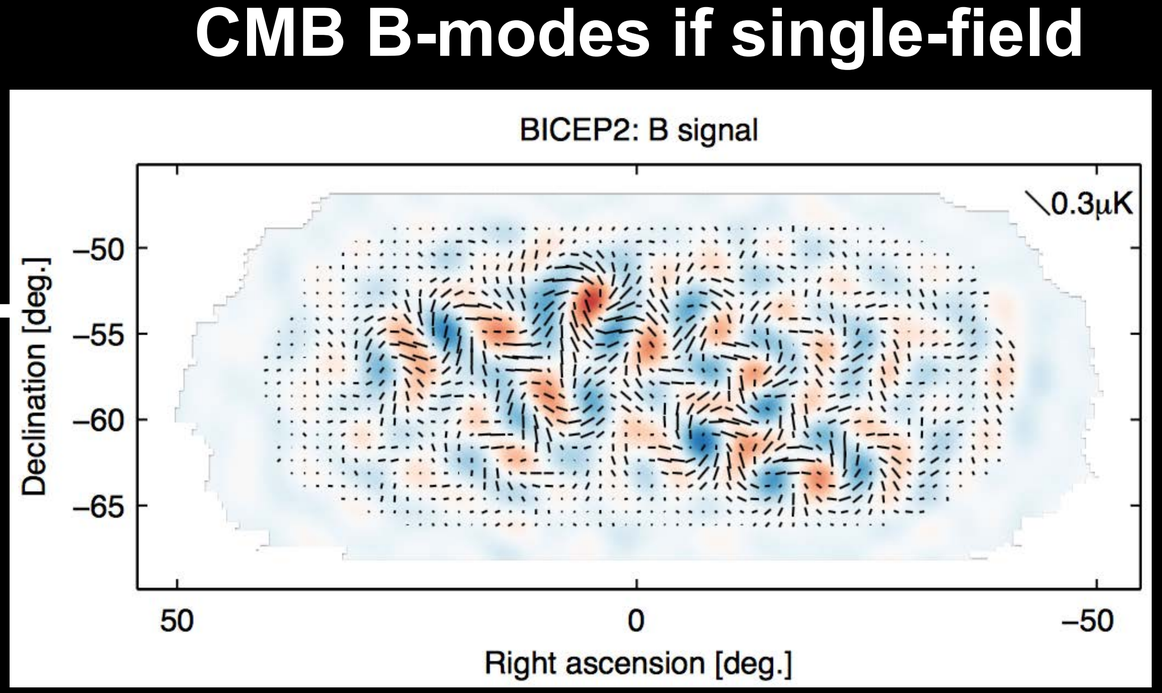


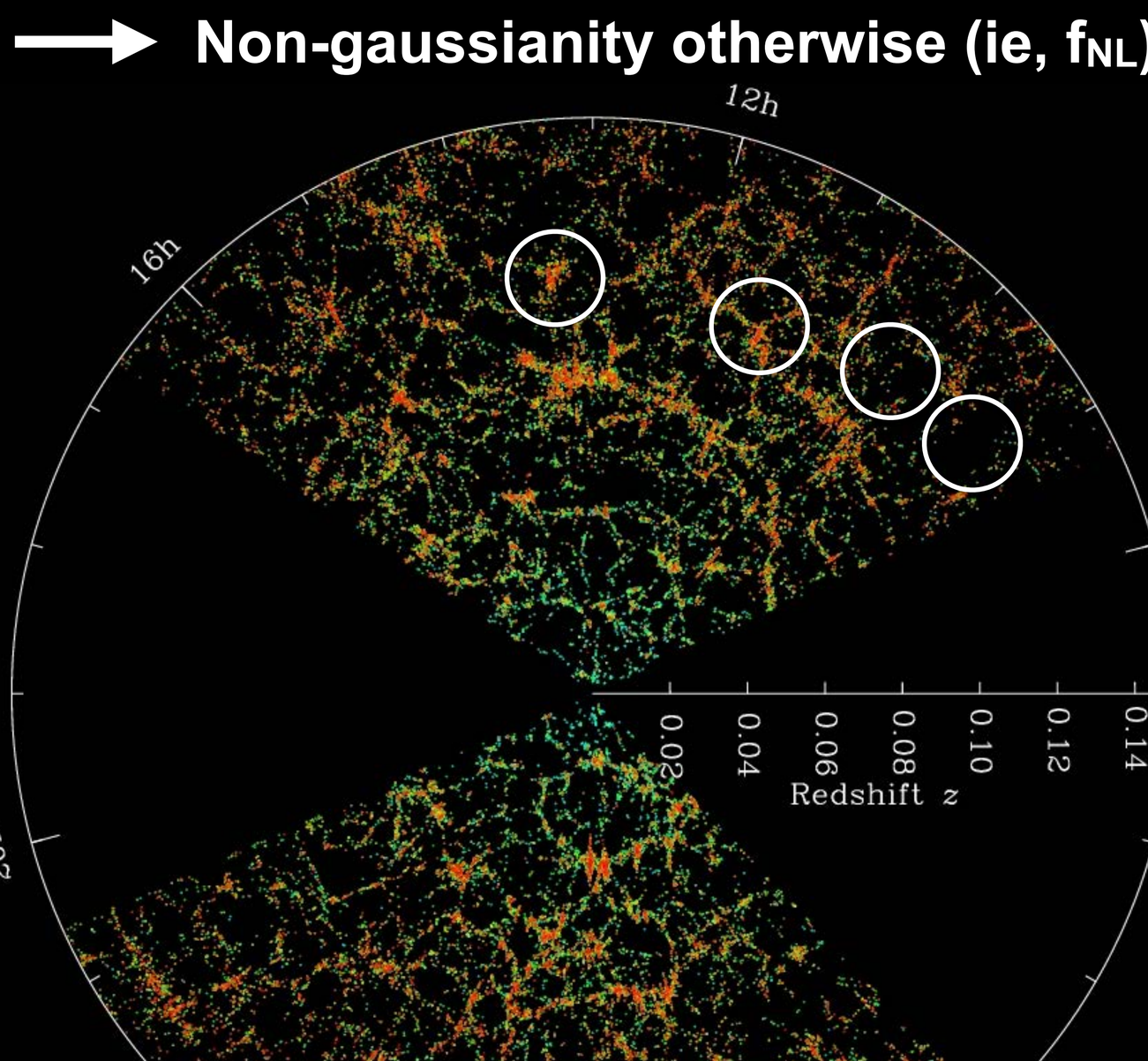


Probing the inflation epoch requires mapping more universe

CMB B-modes if single-field → Non-gaussianity otherwise (ie, f_{NL})

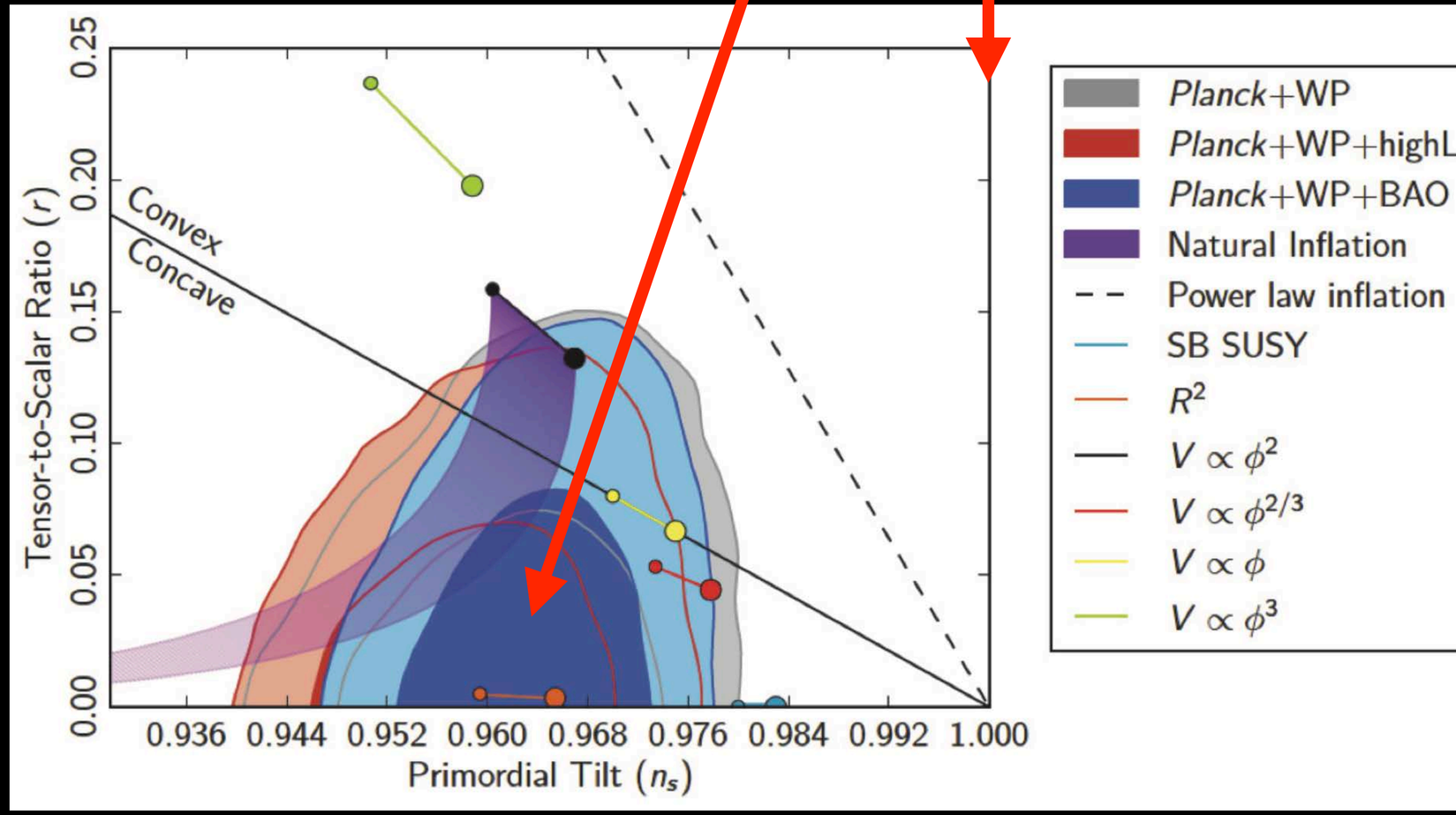


BICEP 2014 (incorrectly-interpreted Milky Way dust)



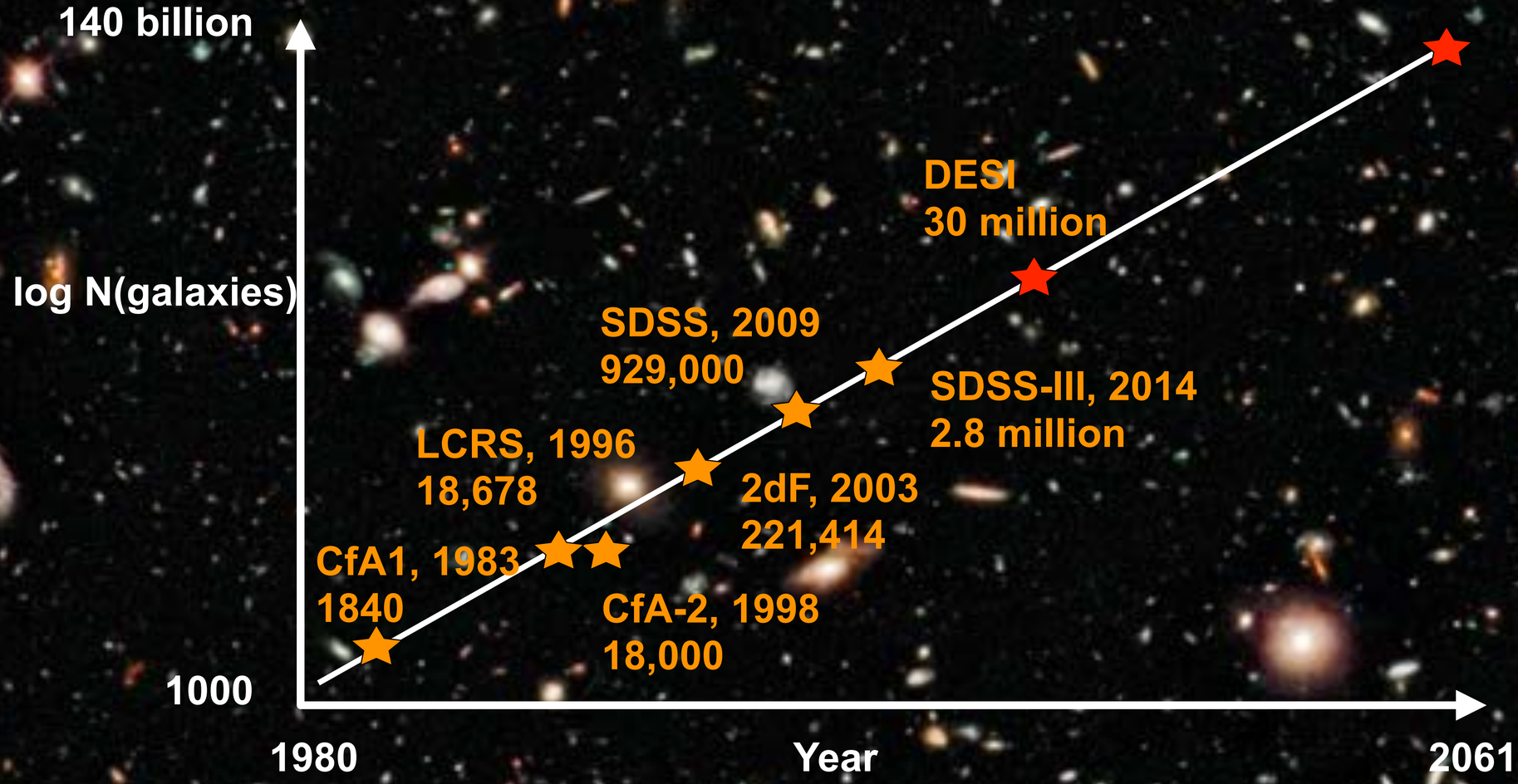
Probing the inflation epoch requires mapping more universe

Galaxy maps + CMB have already measured the primordial fluctuations (and they're not scale-free)



Redshift surveys increasing 10X every 10 years

All linear modes mapped by 2043 — 2 billion galaxies
All detectable galaxies mapped by 2061 — 140 billion galaxies



HST Ultra-Deep Field
10,000 galaxies / (11 arcmin^2)