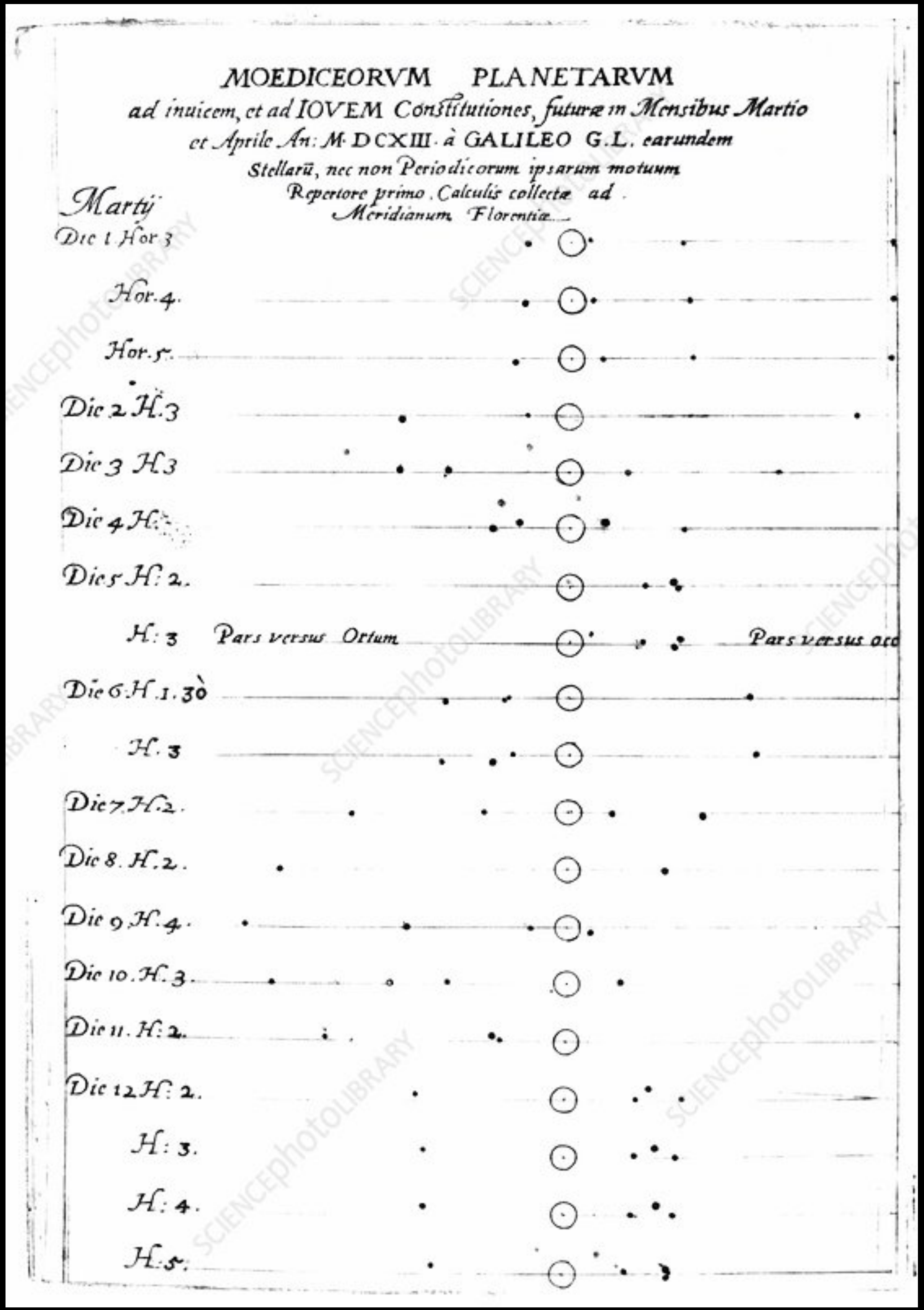
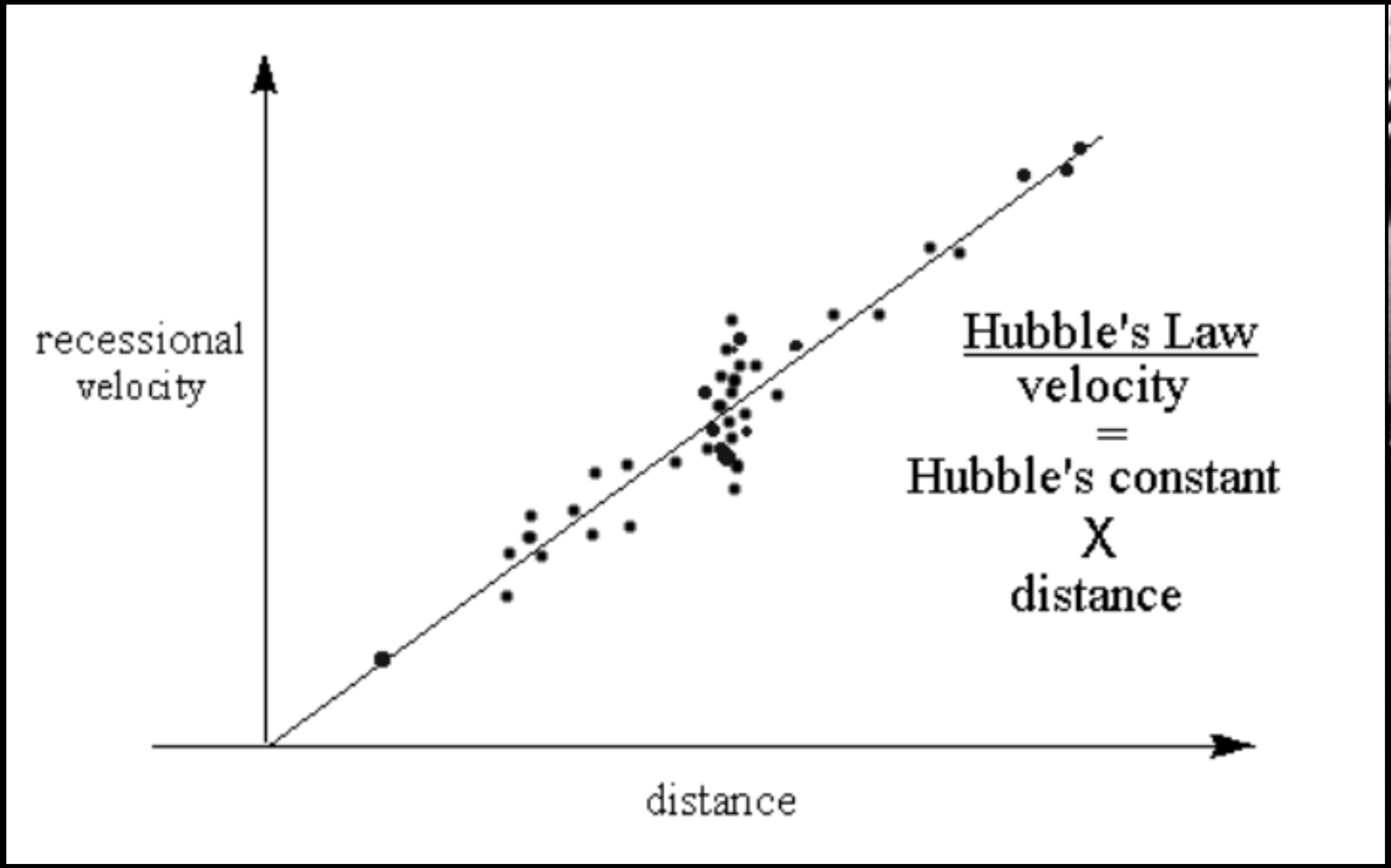
More Than a Pretty Picture: Seeing the Universe Through 5000 Eyes

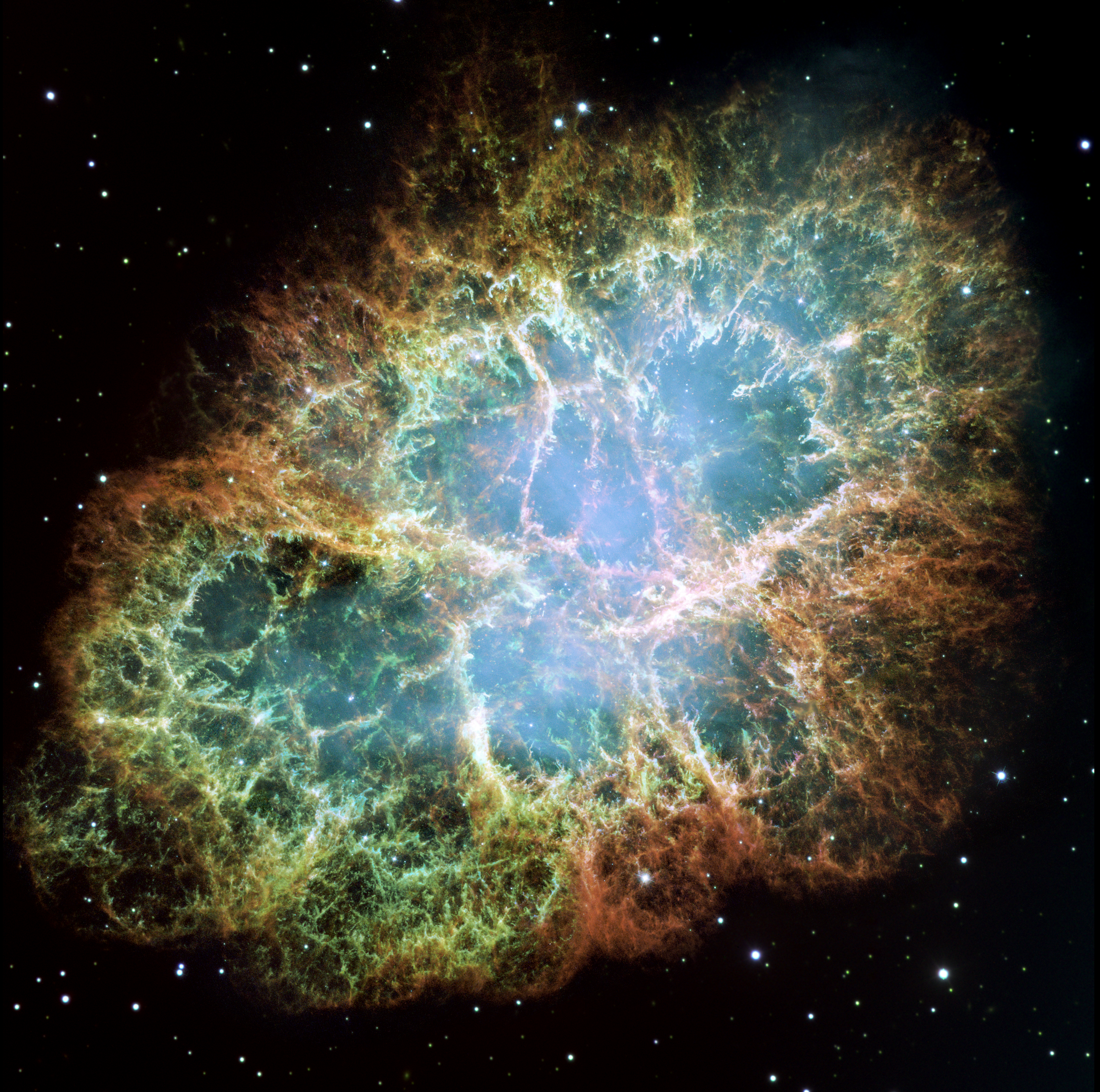
Claire Poppett, UC Berkeley Space Sciences Laboratory
June 2025

Behind every great discovery is a great instrument



No Proof Without Photons: Why Data Rules the Cosmos



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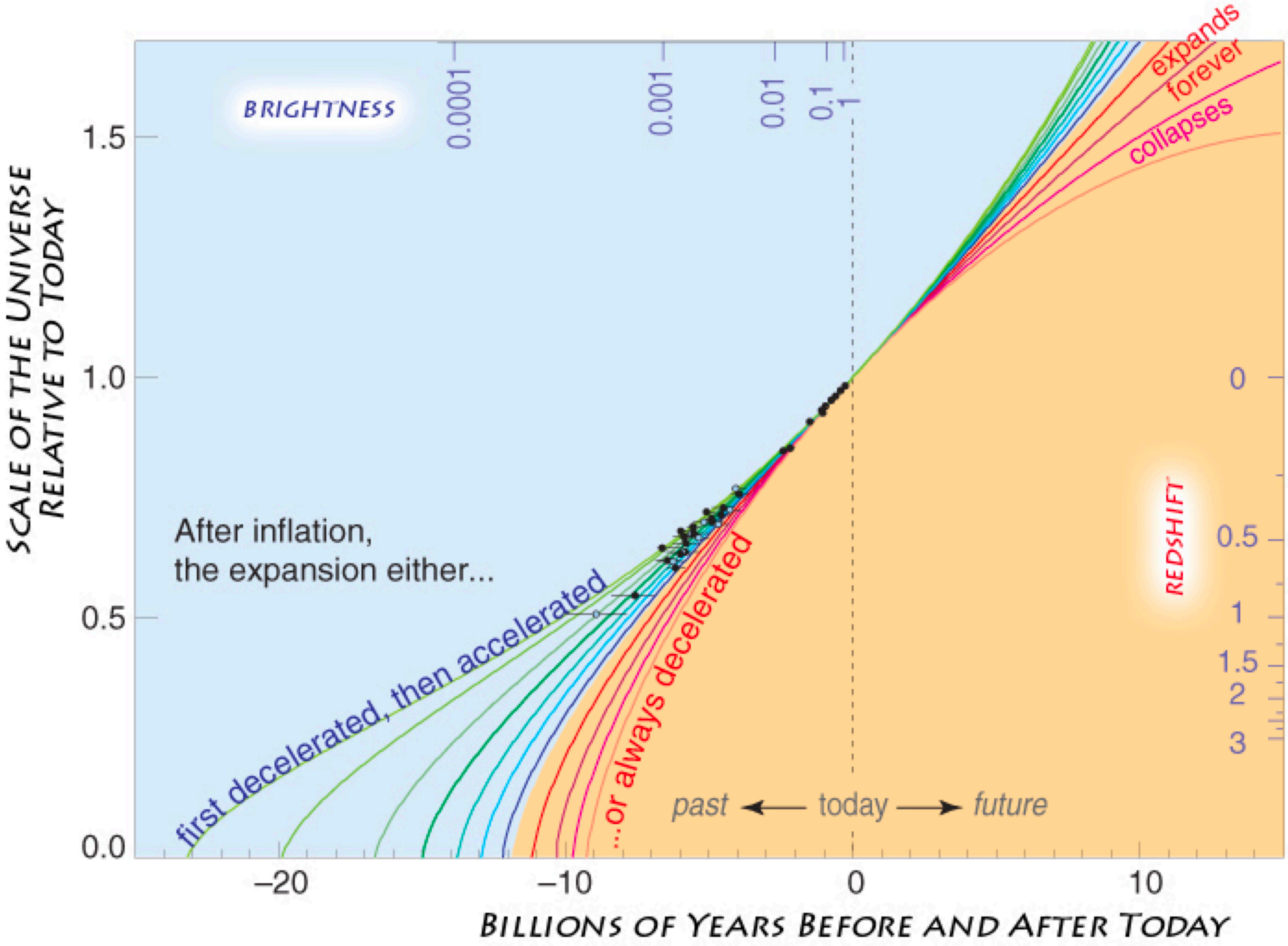
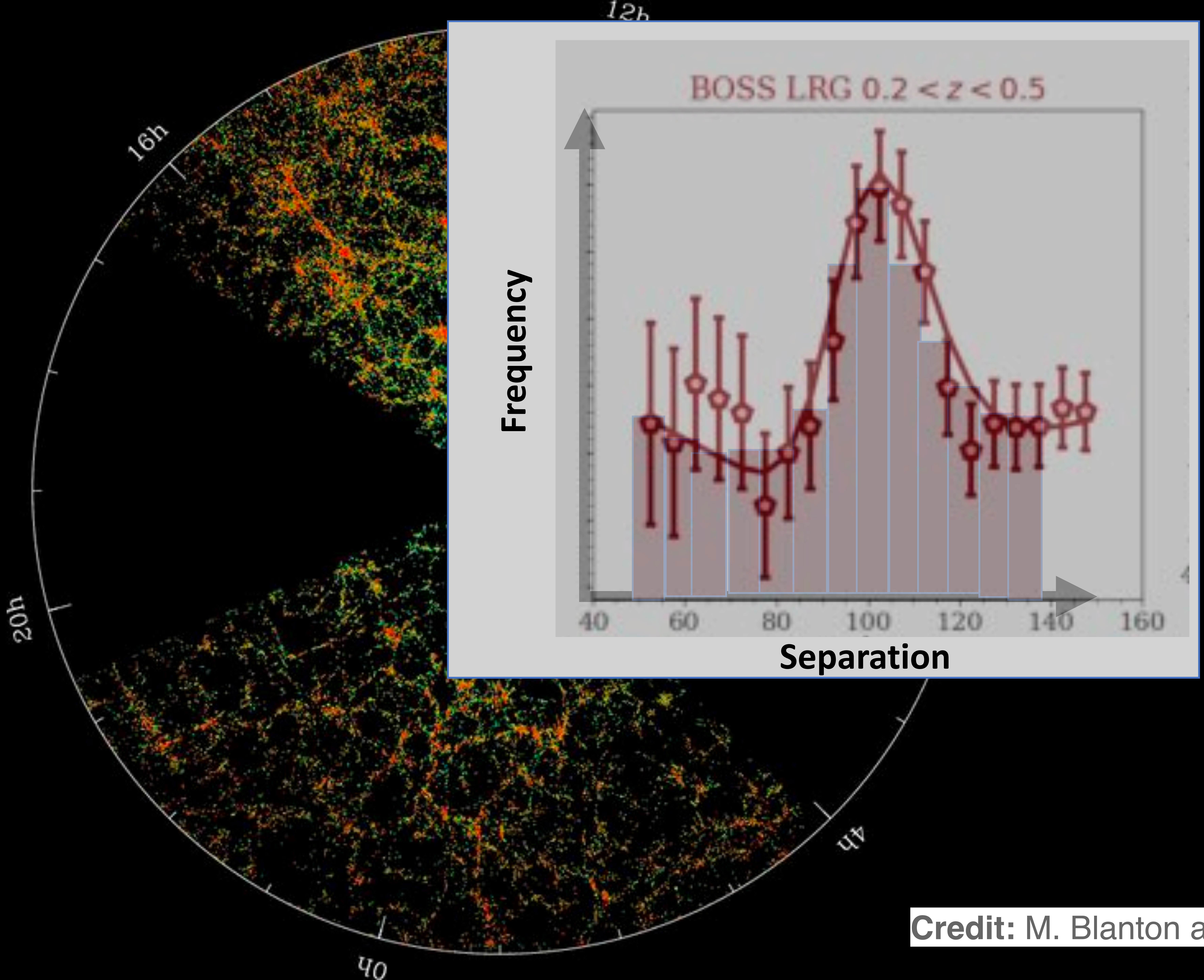
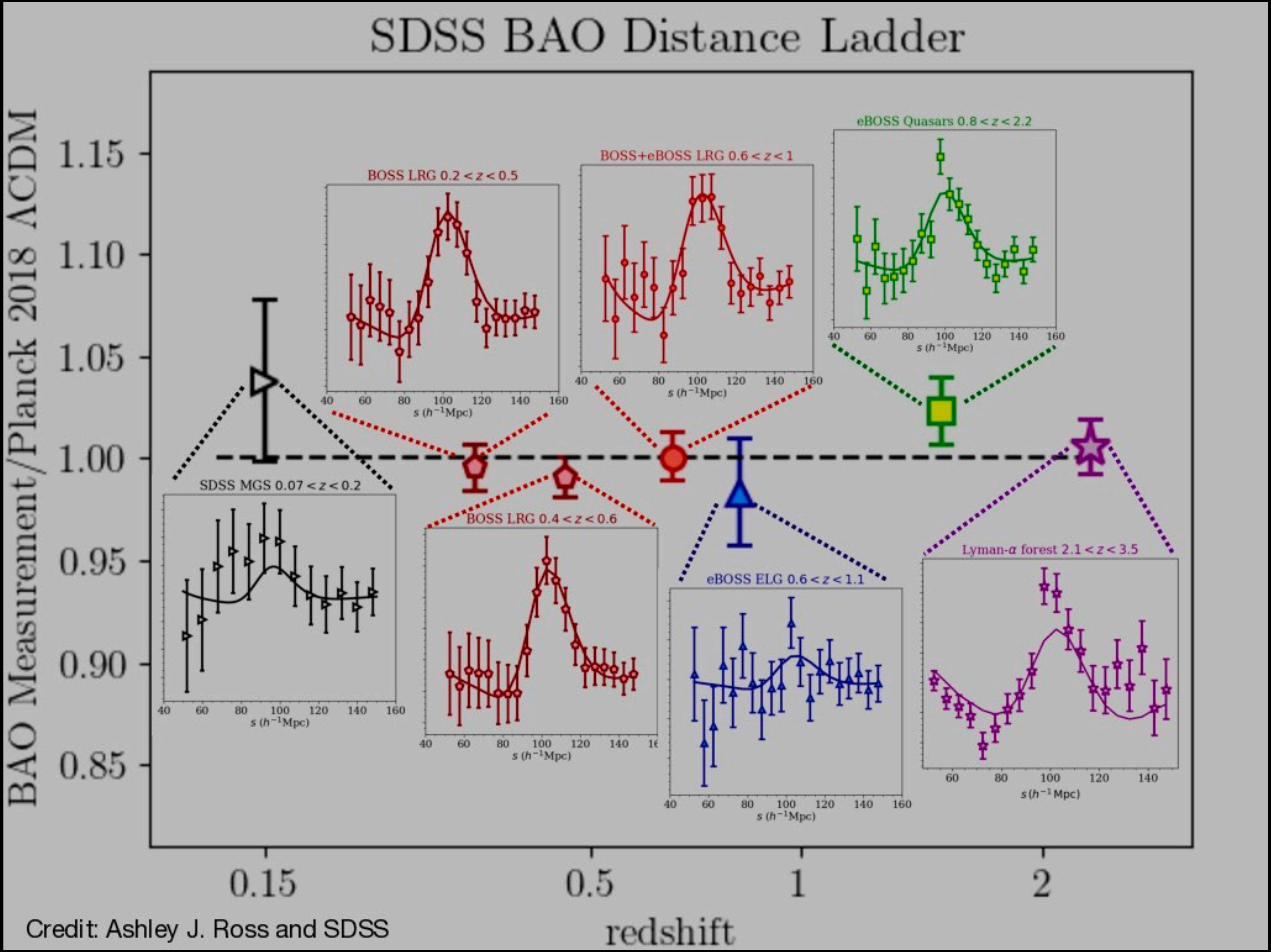


BRIGHTNESS
0.0001
0.001
0.01
0.1
1
expands
forever
collapses
After inflation,
the expansion either...
first decelerated, then accelerated
...or always decelerated
past
today
future
REDSHIFT
0
0.5
1
1.5
2
3
1.5
1.0
0.5
0.0
–20
–10
0
10
SCALE OF THE UNIVERSE RELATIVE TO TODAY
BILLIONS OF YEARS BEFORE AND AFTER TODAY

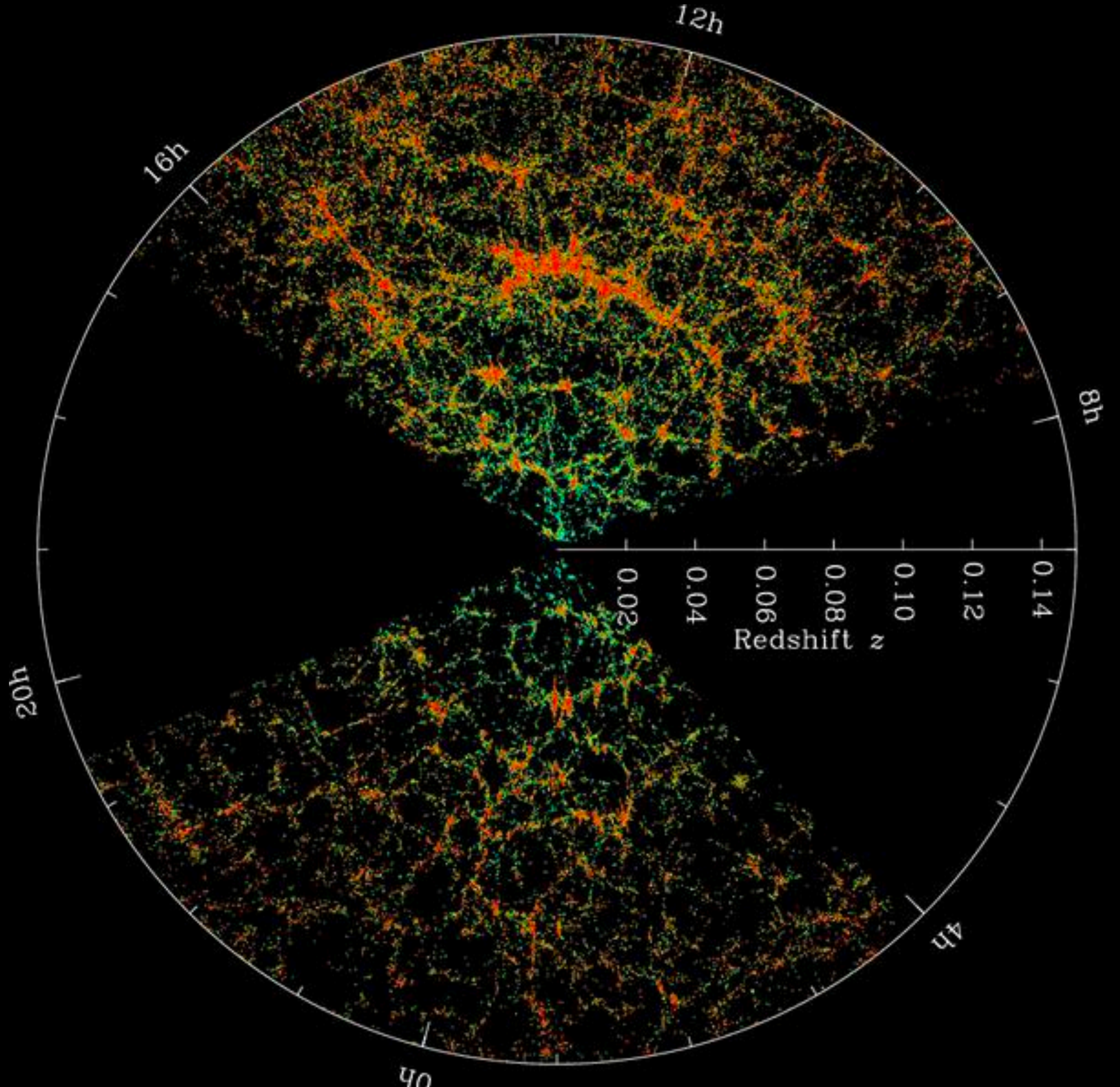
ALFR. NOBEL



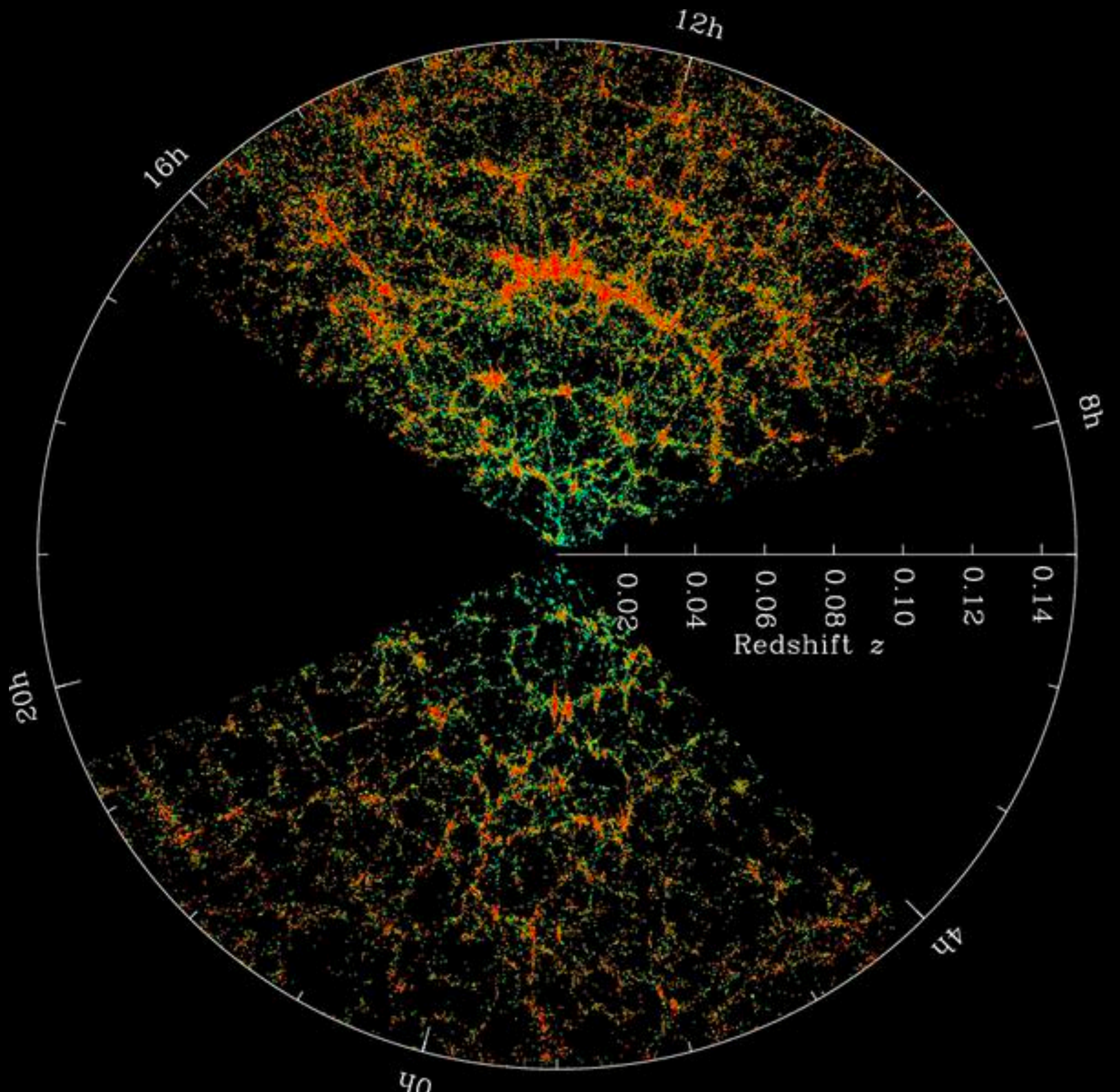
Credit: M. Blanton and SDSS


SDSS BAO Distance Ladder
BAO Measurement/Planck 2018 ΛCDM
1.15
1.10
1.05
1.00
0.95
0.90
0.85
0.15
0.5
1
2
redshift
SDSS MGS 0.07 < z < 0.2
BOSS LRG 0.2 < z < 0.5
BOSS LRG 0.4 < z < 0.6
BOSS+eBOSS LRG 0.6 < z < 1
eBOSS ELG 0.6 < z < 1.1
eBOSS Quasars 0.8 < z < 2.2
Lyman-α forest 2.1 < z < 3.5
s (h⁻¹Mpc)
Credit: Ashley J. Ross and SDSS

How will we measure ~40 million galaxies?

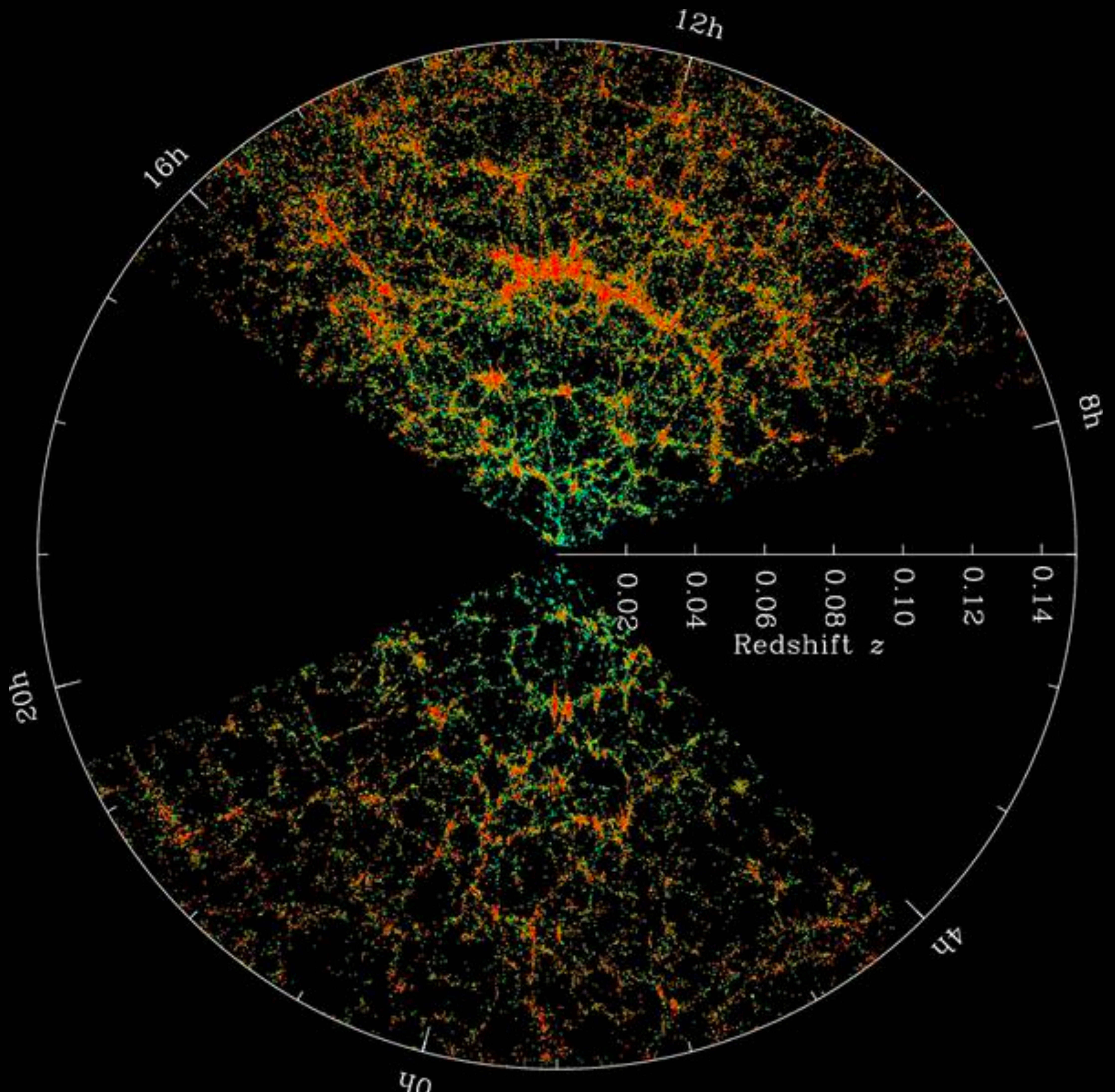


How will we measure ~40 million galaxies?



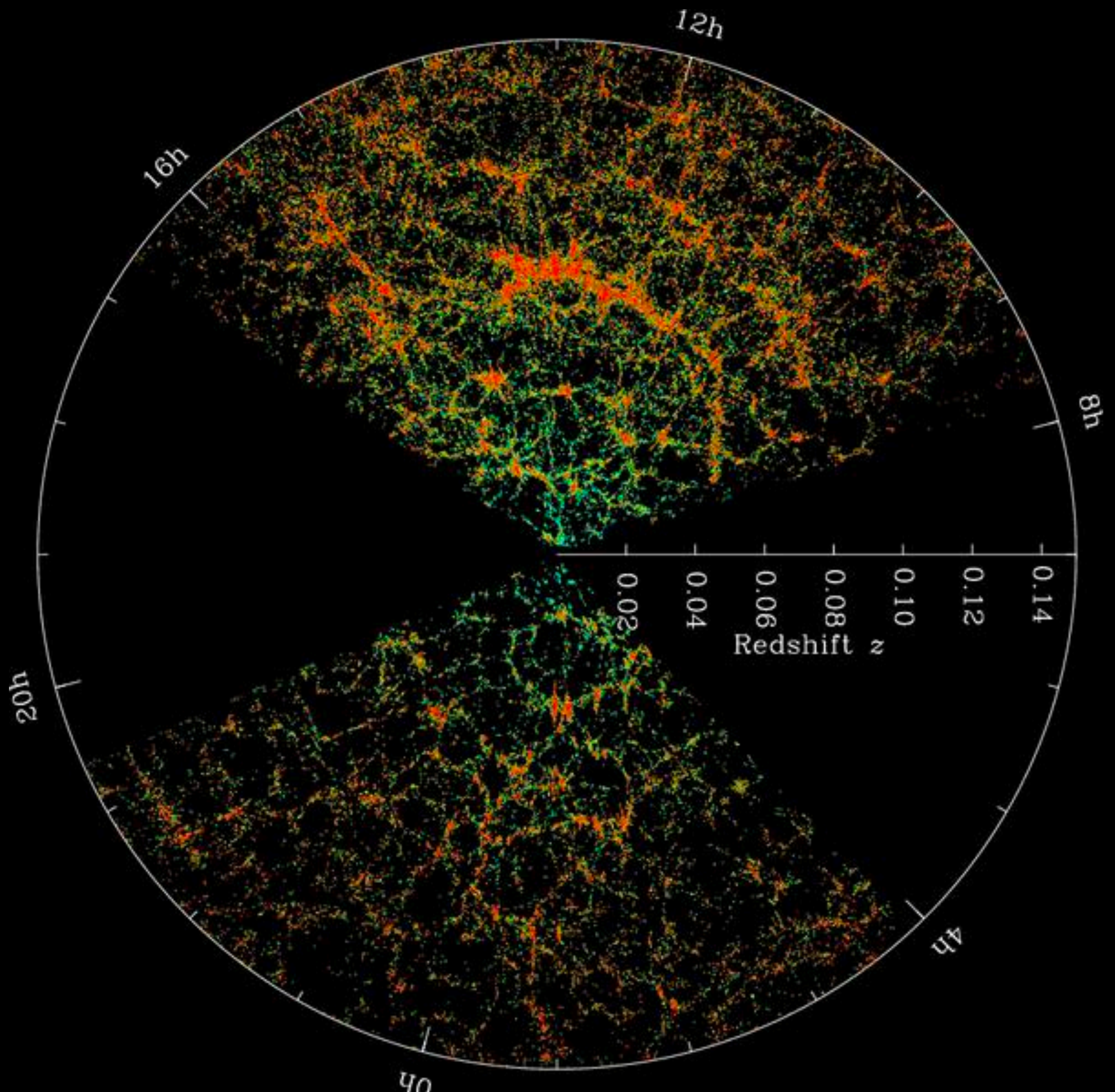
1. **Larger telescopes**
   - **More light, fainter objects**

How will we measure ~40 million galaxies?



1. Larger telescopes
   - More light, fainter objects
2. More multi-plexing
   - More objects in a single observation

How will we measure ~40 million galaxies?



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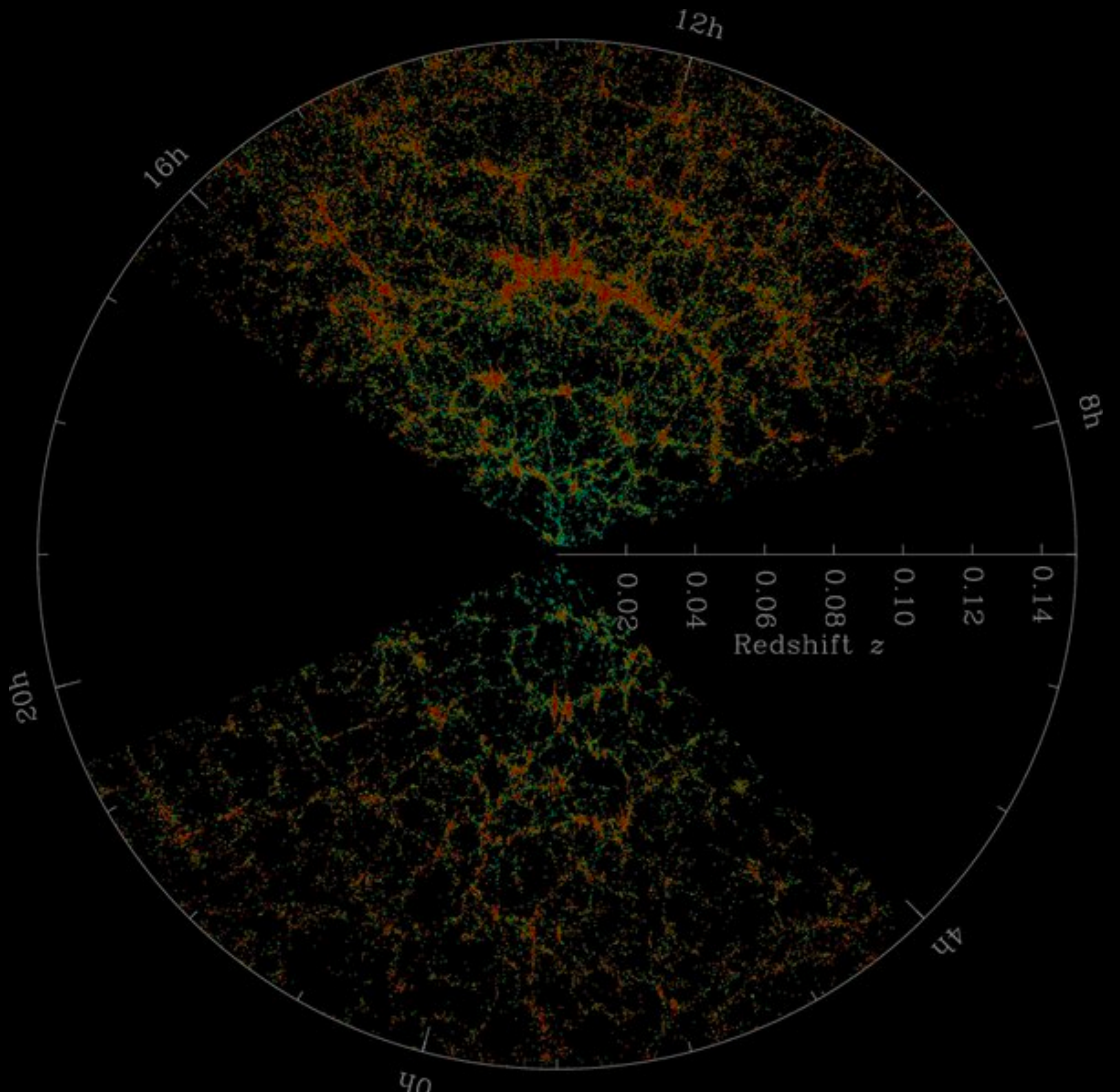
   - More objects in a single observation
3. Better detectors + lower S/N data
   - Better efficiency, fainter objects

How will we measure ~40 million galaxies?



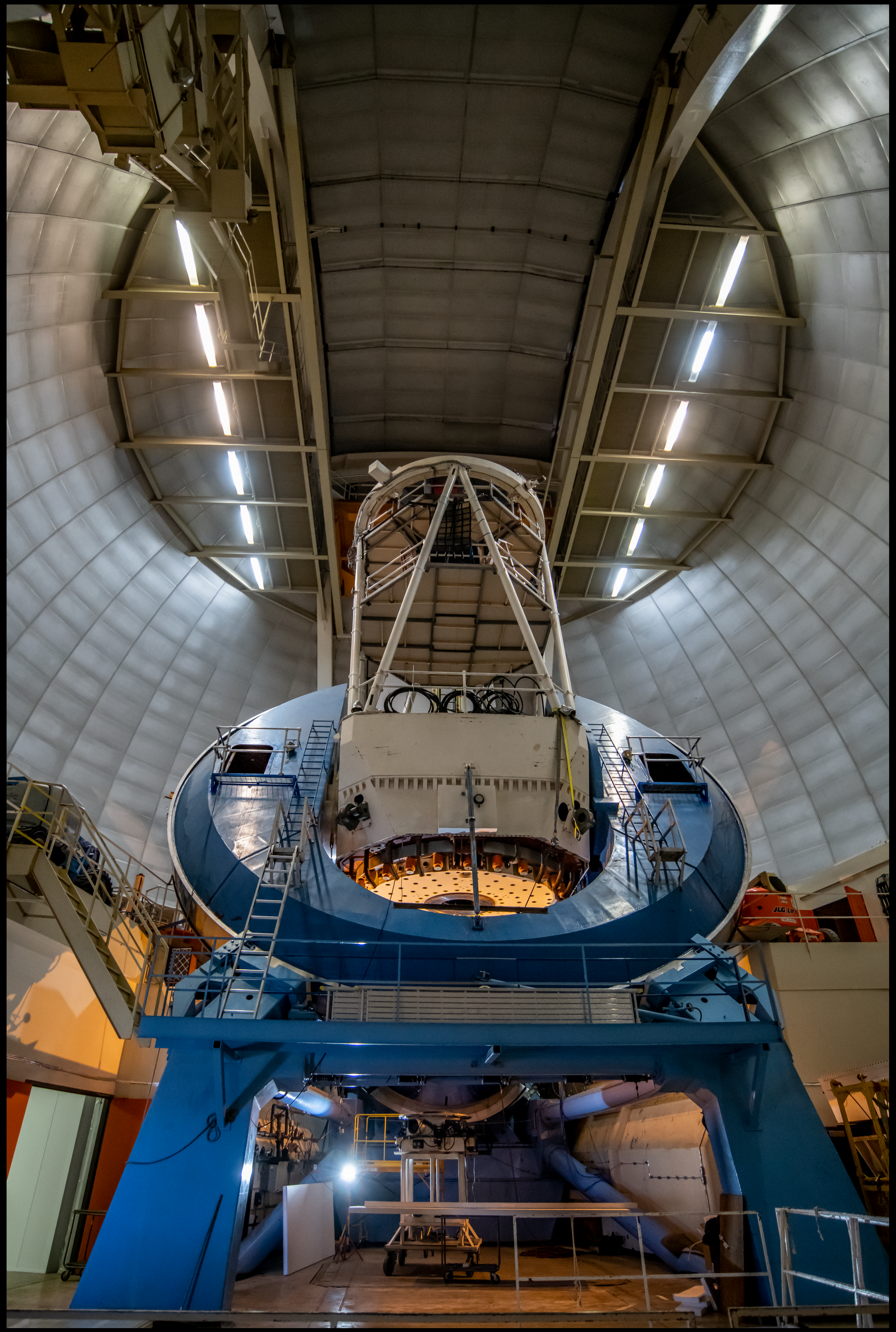
1. Larger telescopes
    - More light, fainter objects
2. More multi-plexing
    - More objects in a single observation
3. Better detectors + lower S/N data
    - Better efficiency, fainter objects

1. Find your own telescope

Mayall Telescope Dome

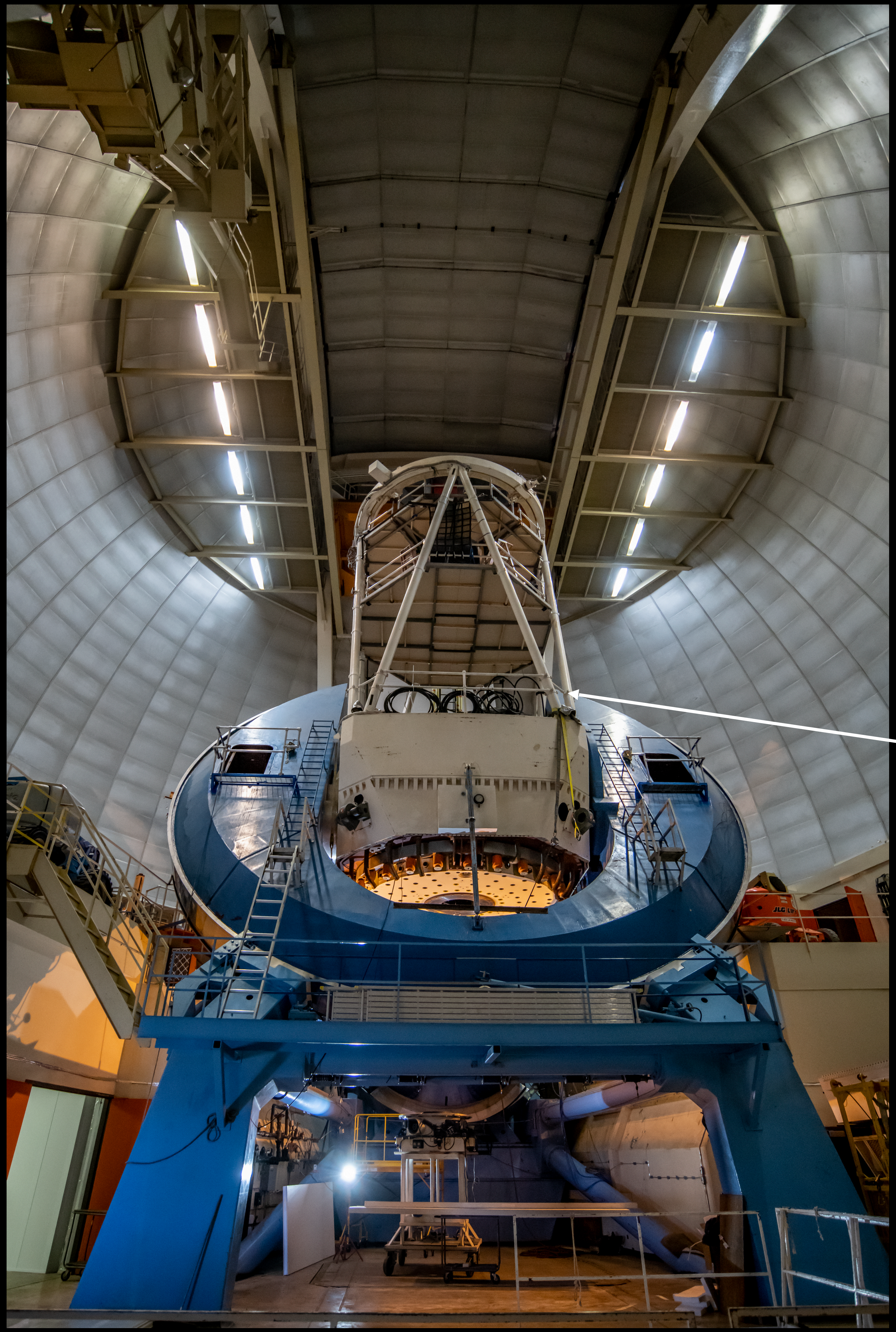
~50 miles south west of Tuscon, Arizona

1. Find your own telescope



- First light in 1973
- Second-largest telescope in the world at that time

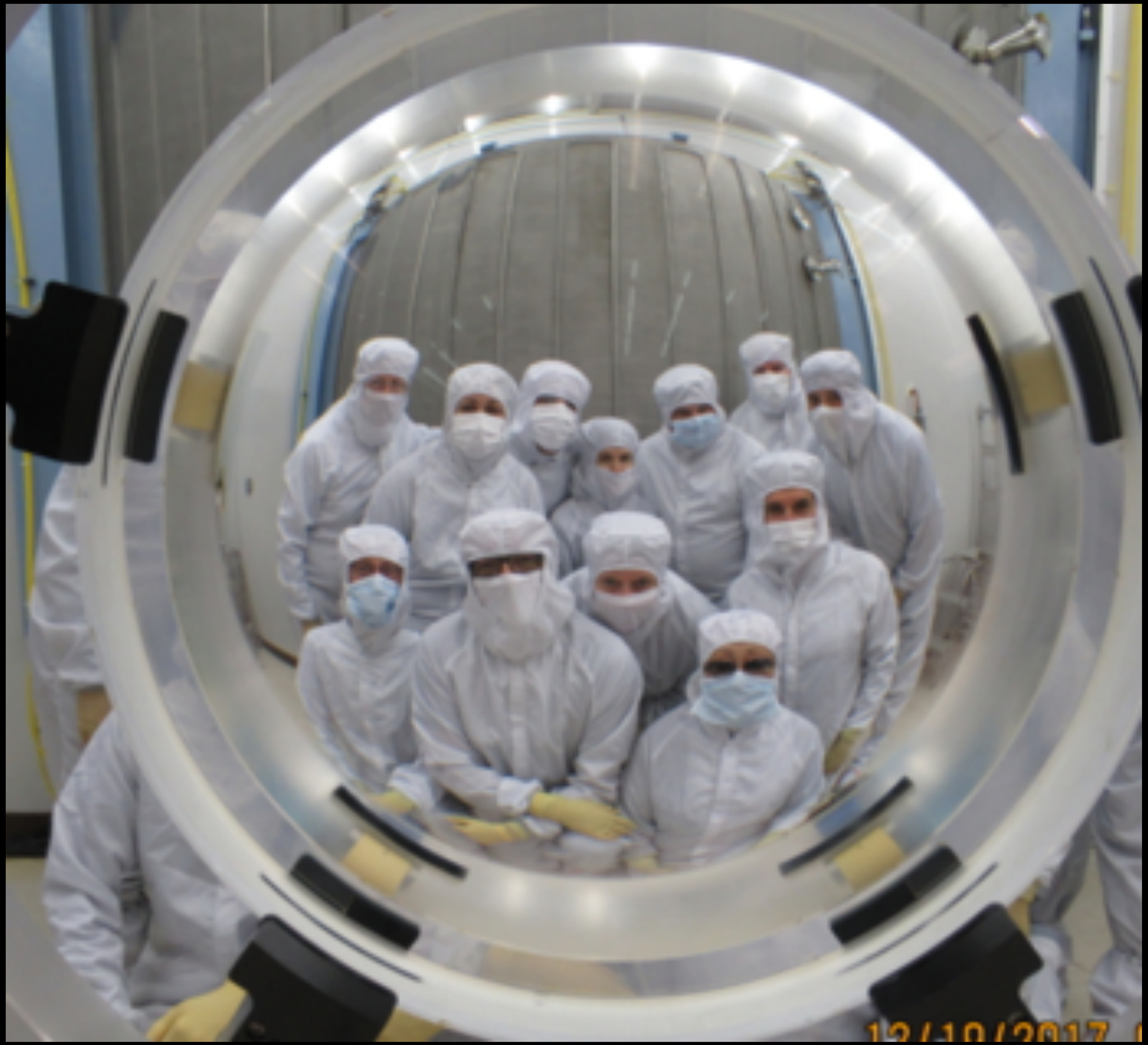
1. Find your own telescope

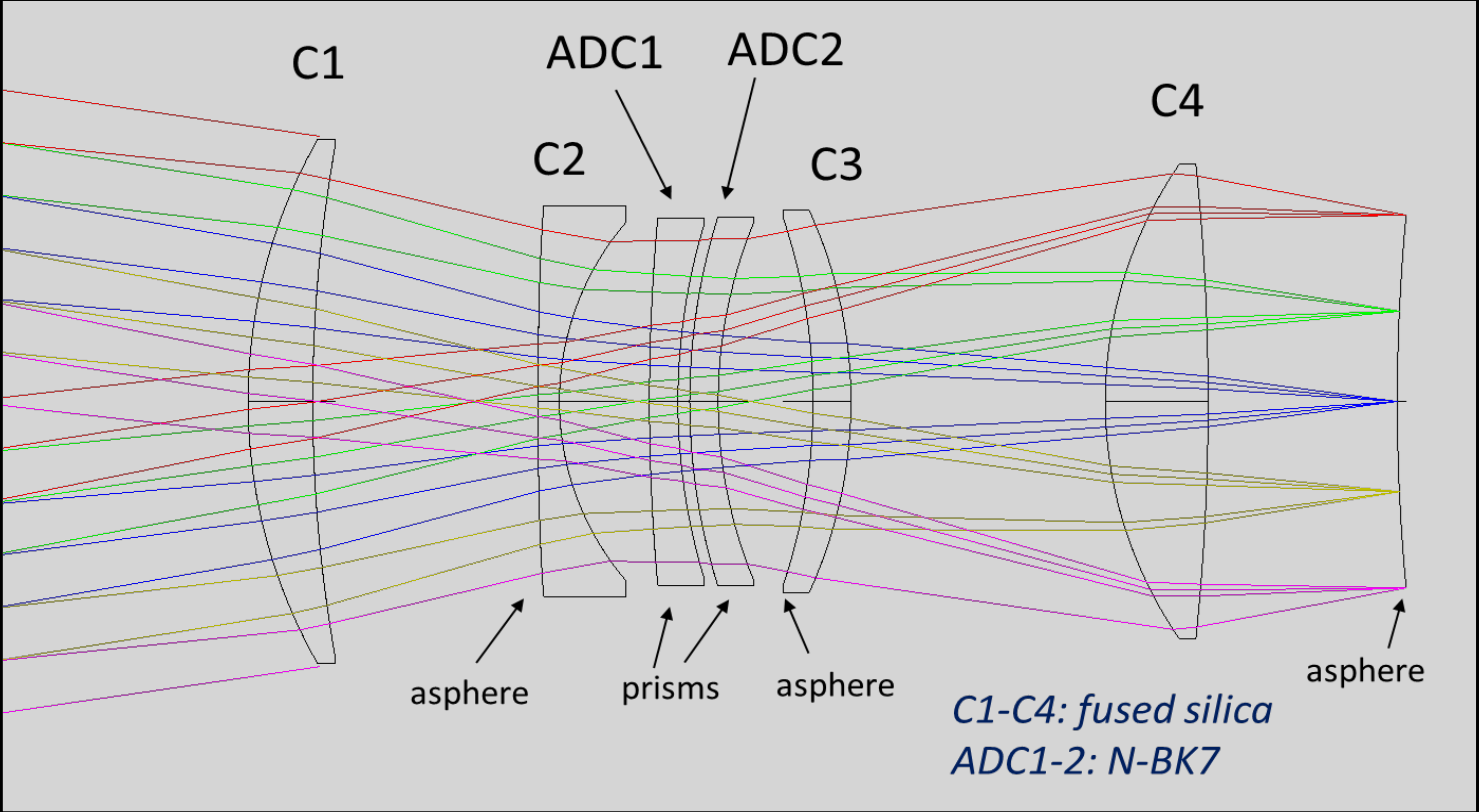


- First light in 1973
- Second-largest telescope in the world at that time

(4meter mirror is here)

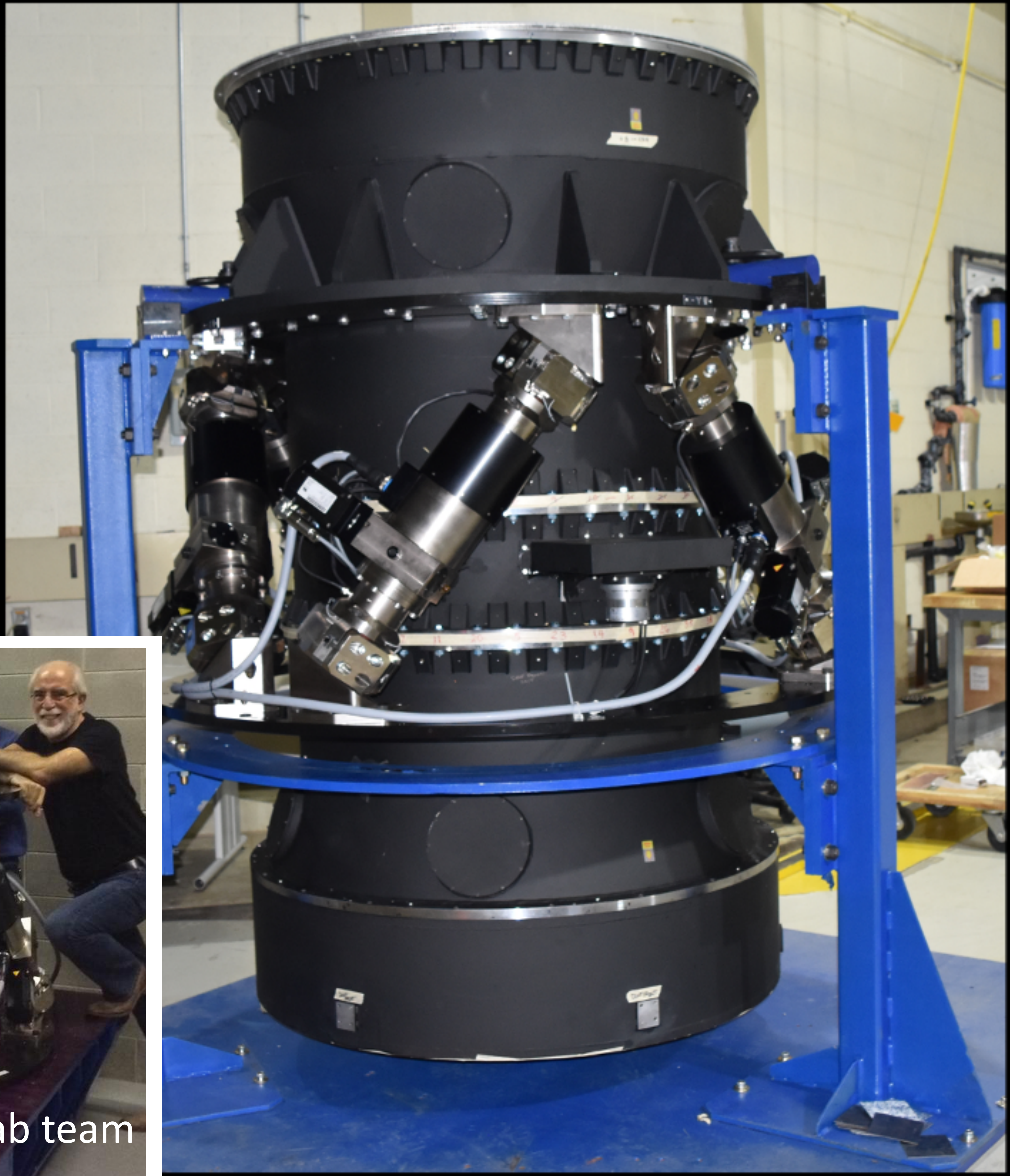
2. Give it a big field of view



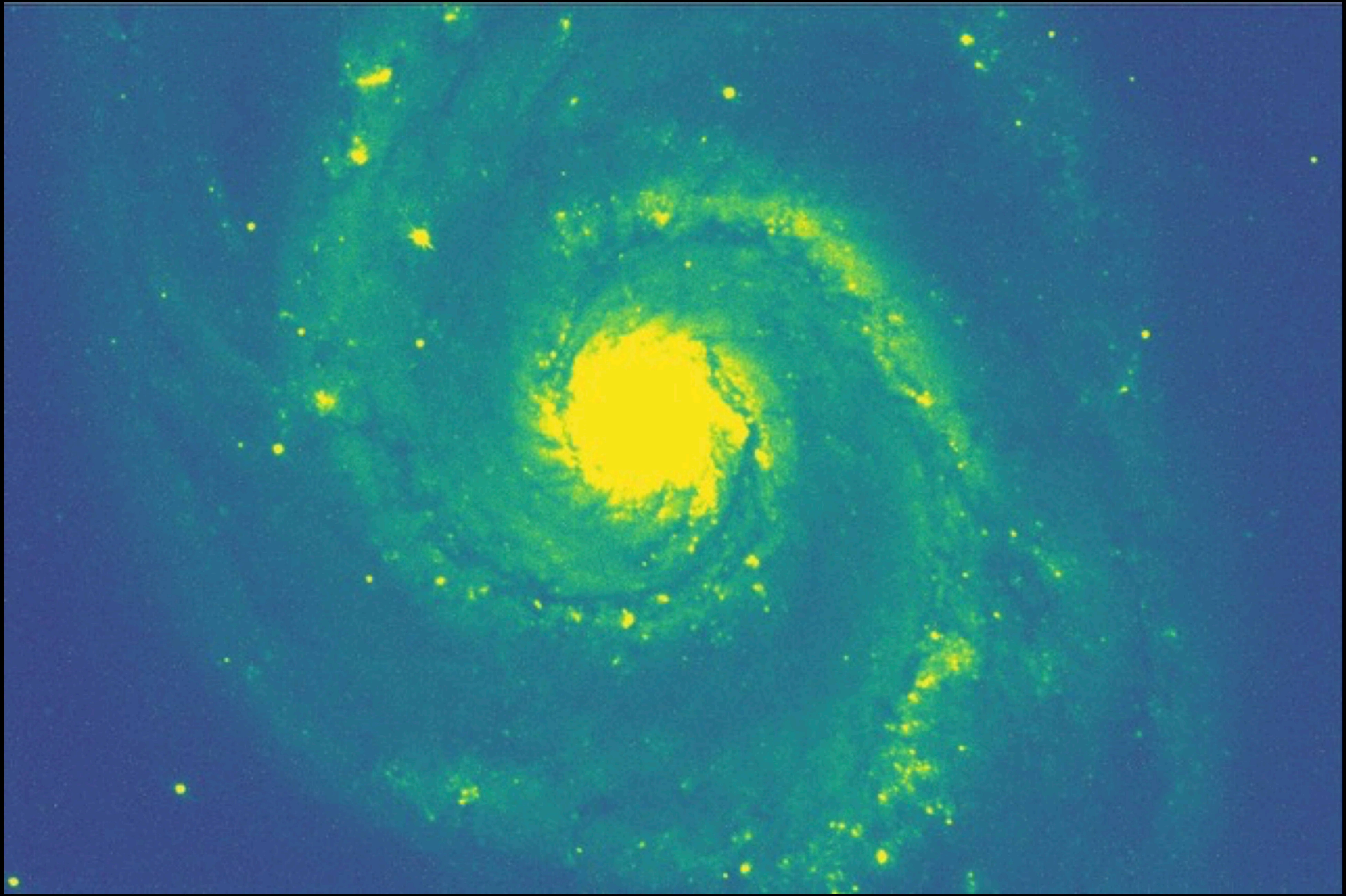

C1
ADC1
ADC2
C2
C3
C4
asphere
prisms
asphere
asphere
C1-C4: fused silica
ADC1-2: N-BK7


David Brooks UCL


Gaston Guitterez and Fermilab team

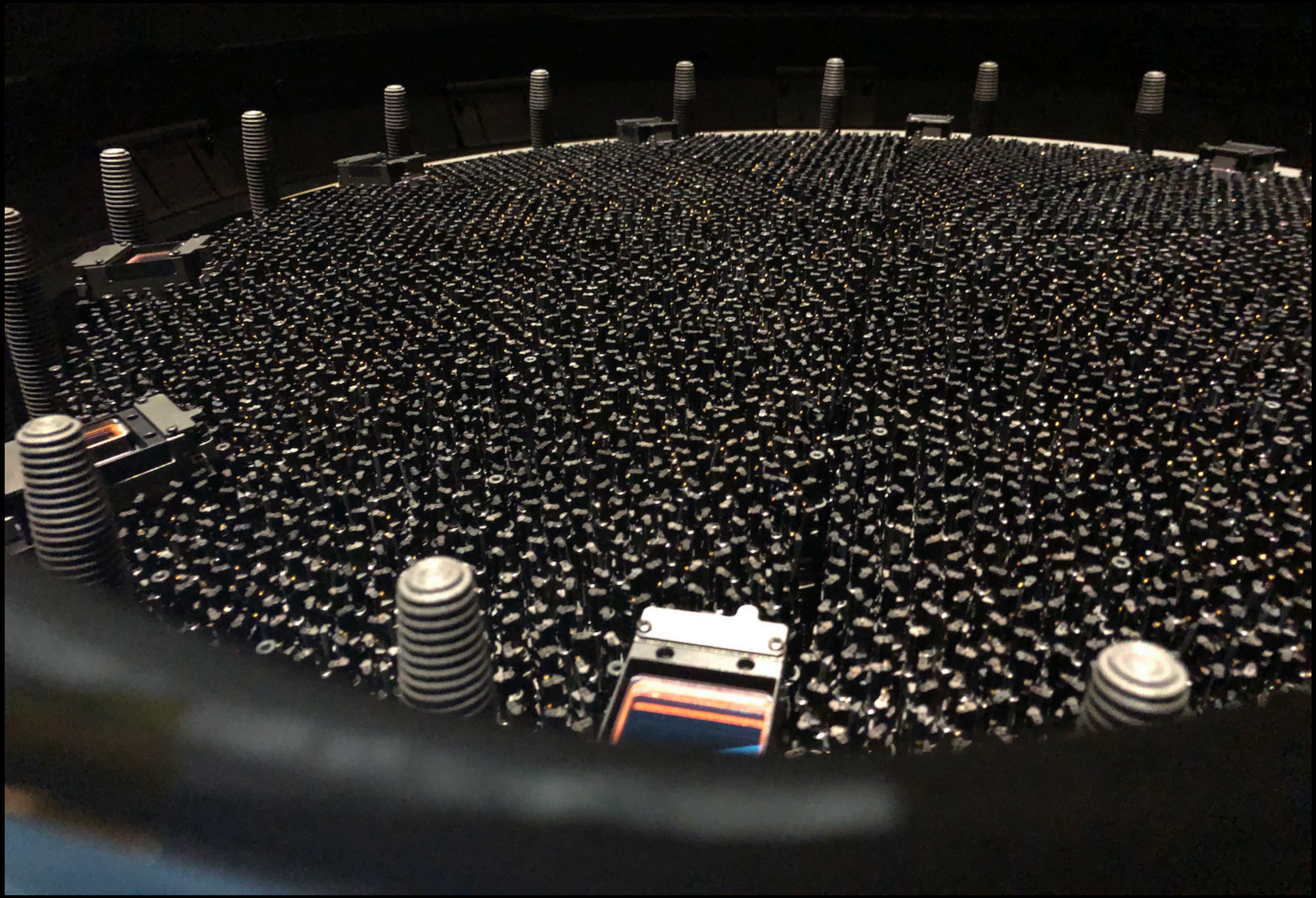



KAPWING



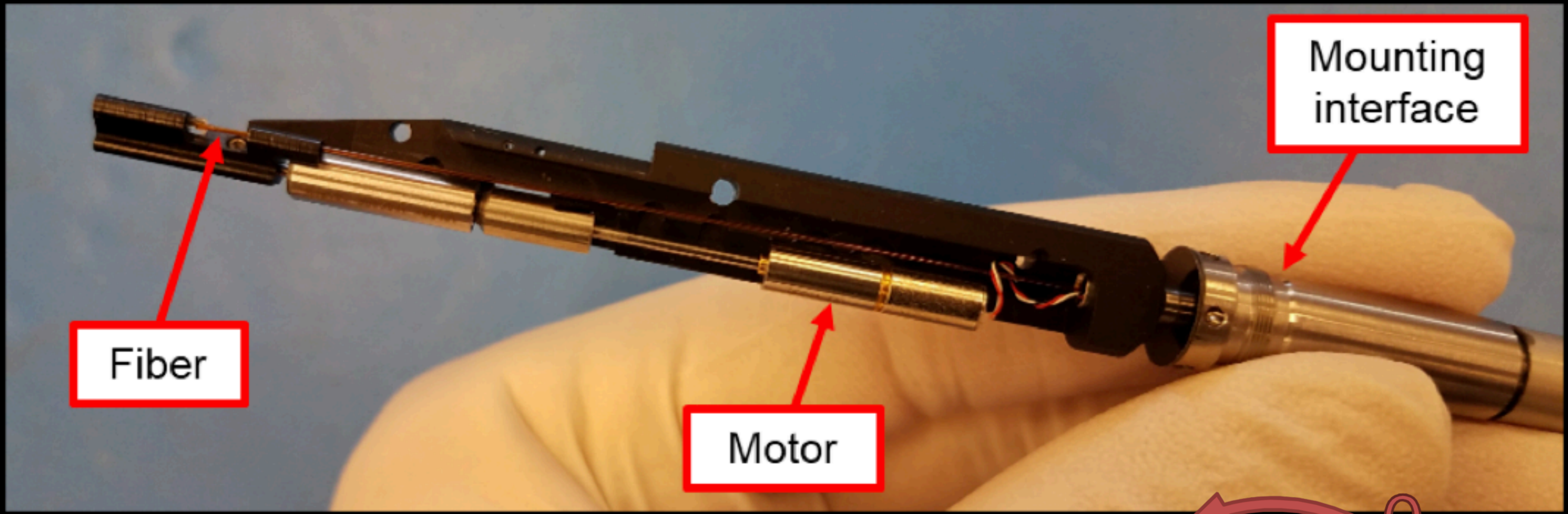
Credit: DESI commissioning instrument

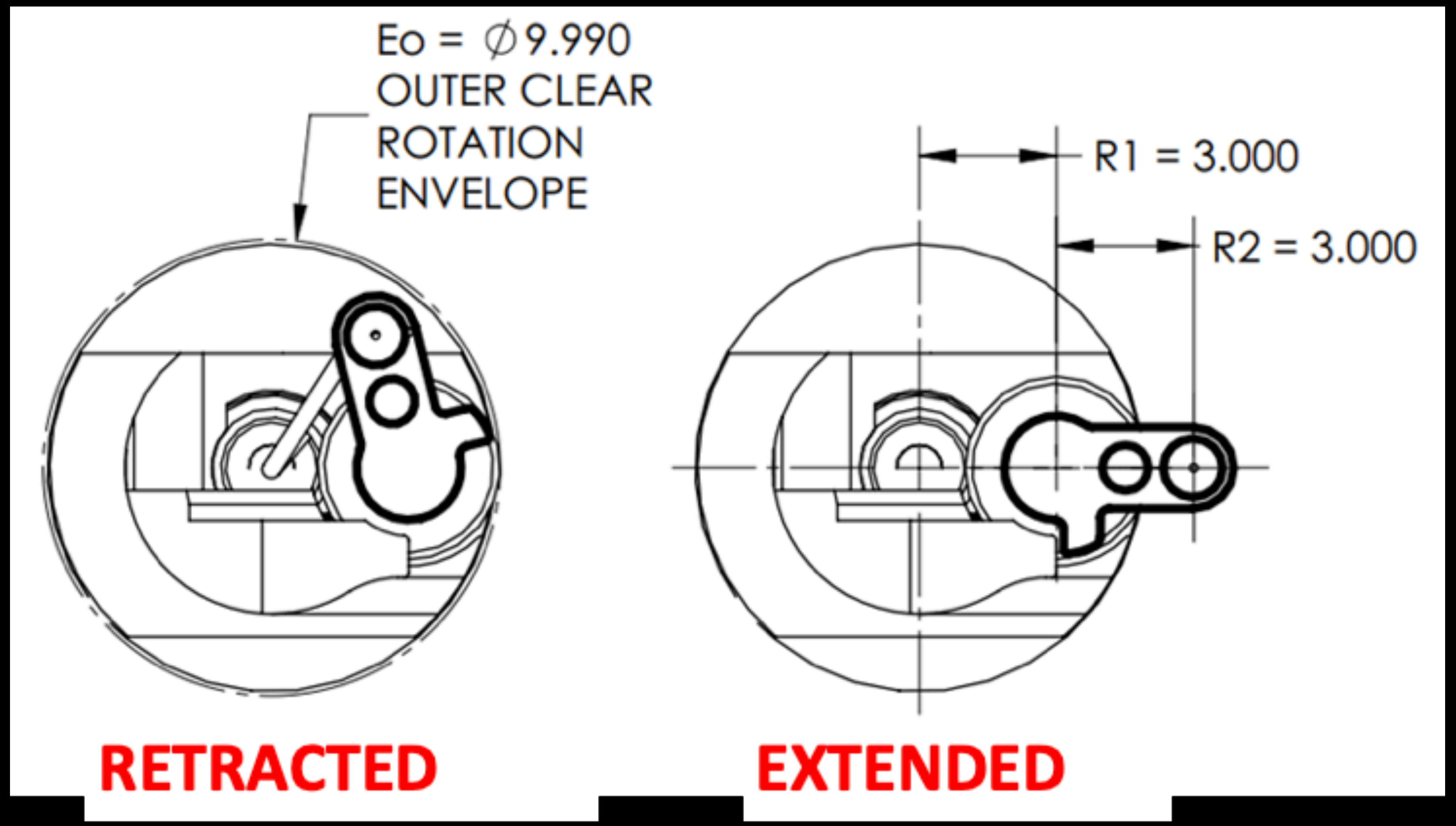
3. Capture as many objects as possible

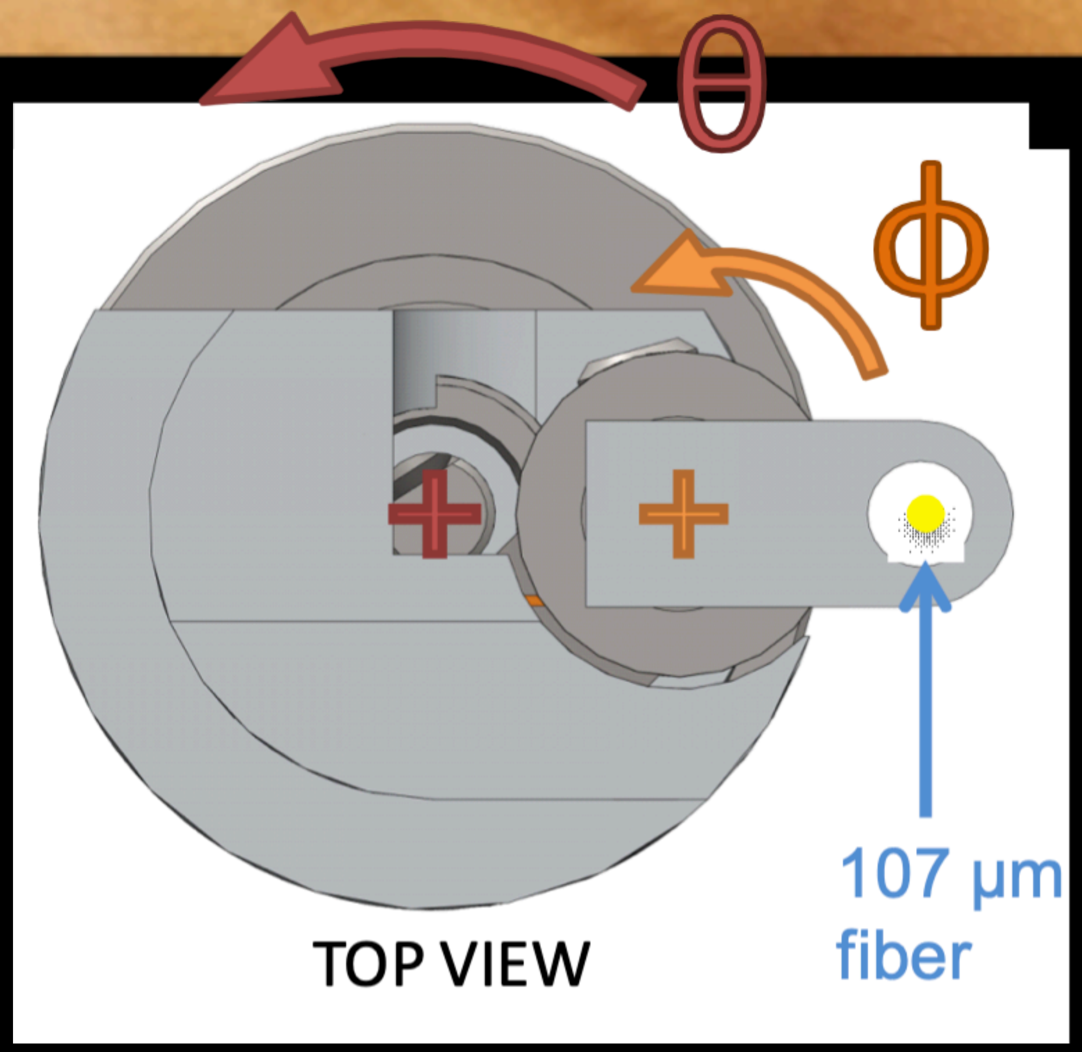


5000 optical fibers positioned to high accuracy with robotic fiber positioners

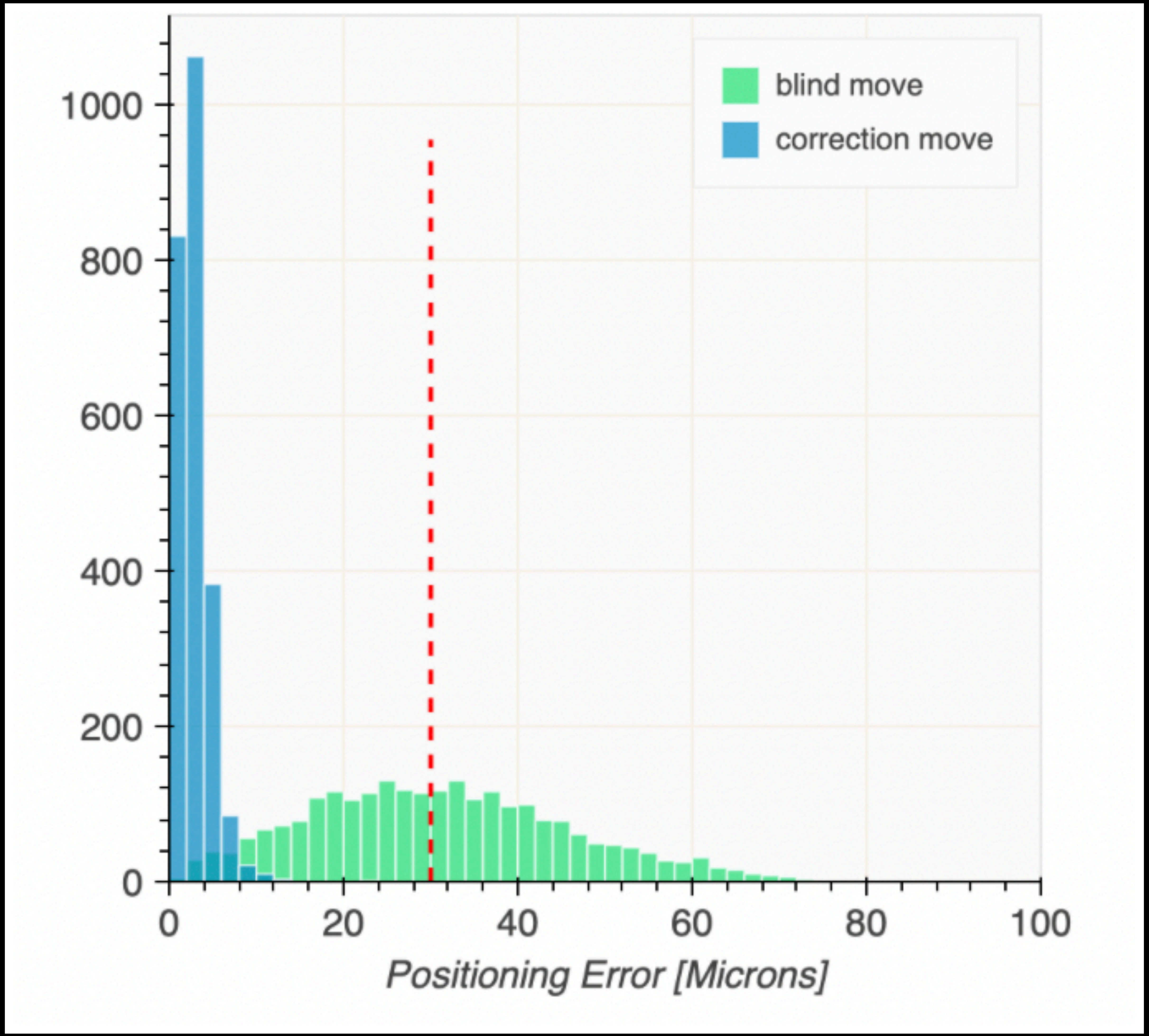
The DESI fiber positioners

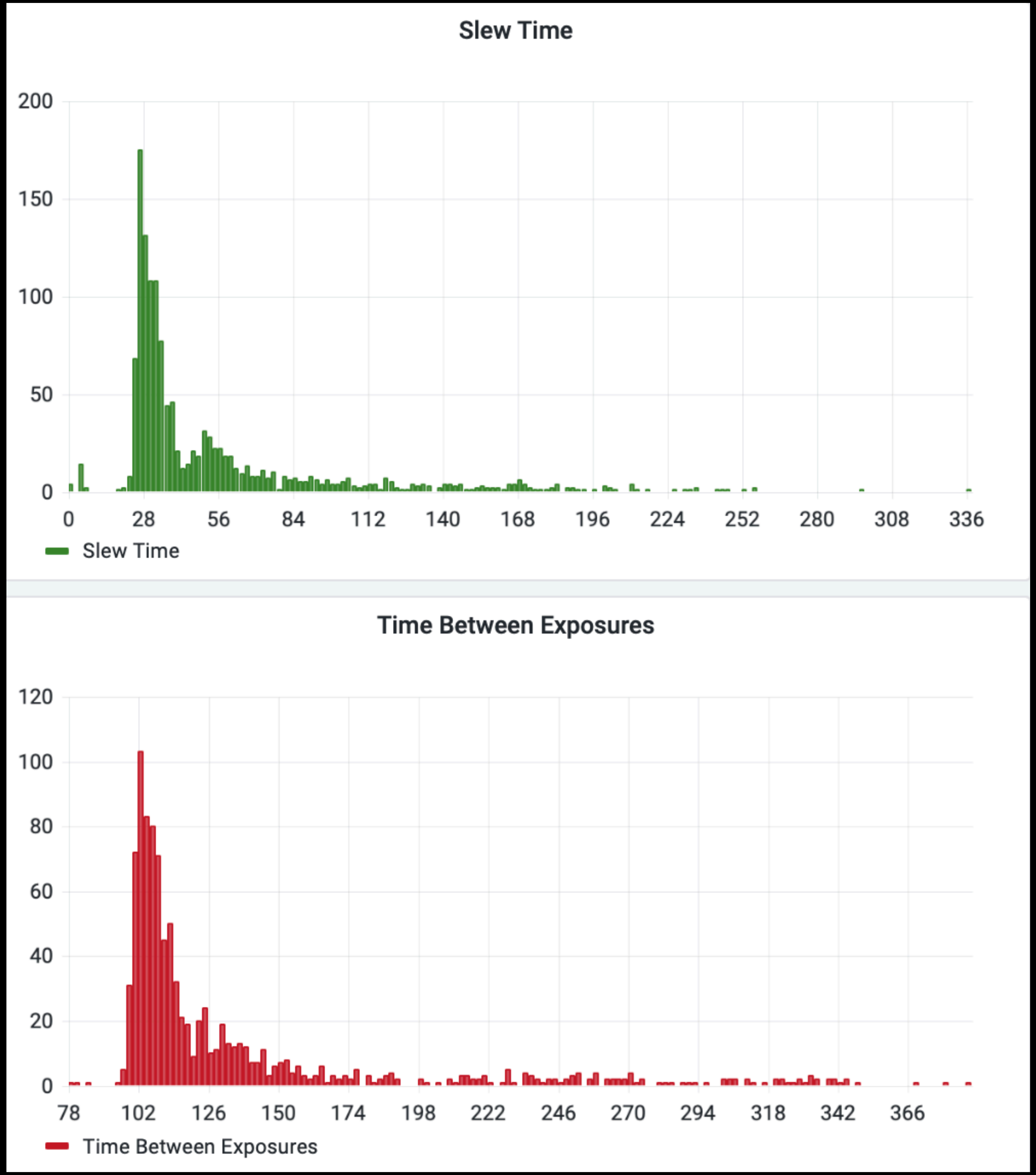




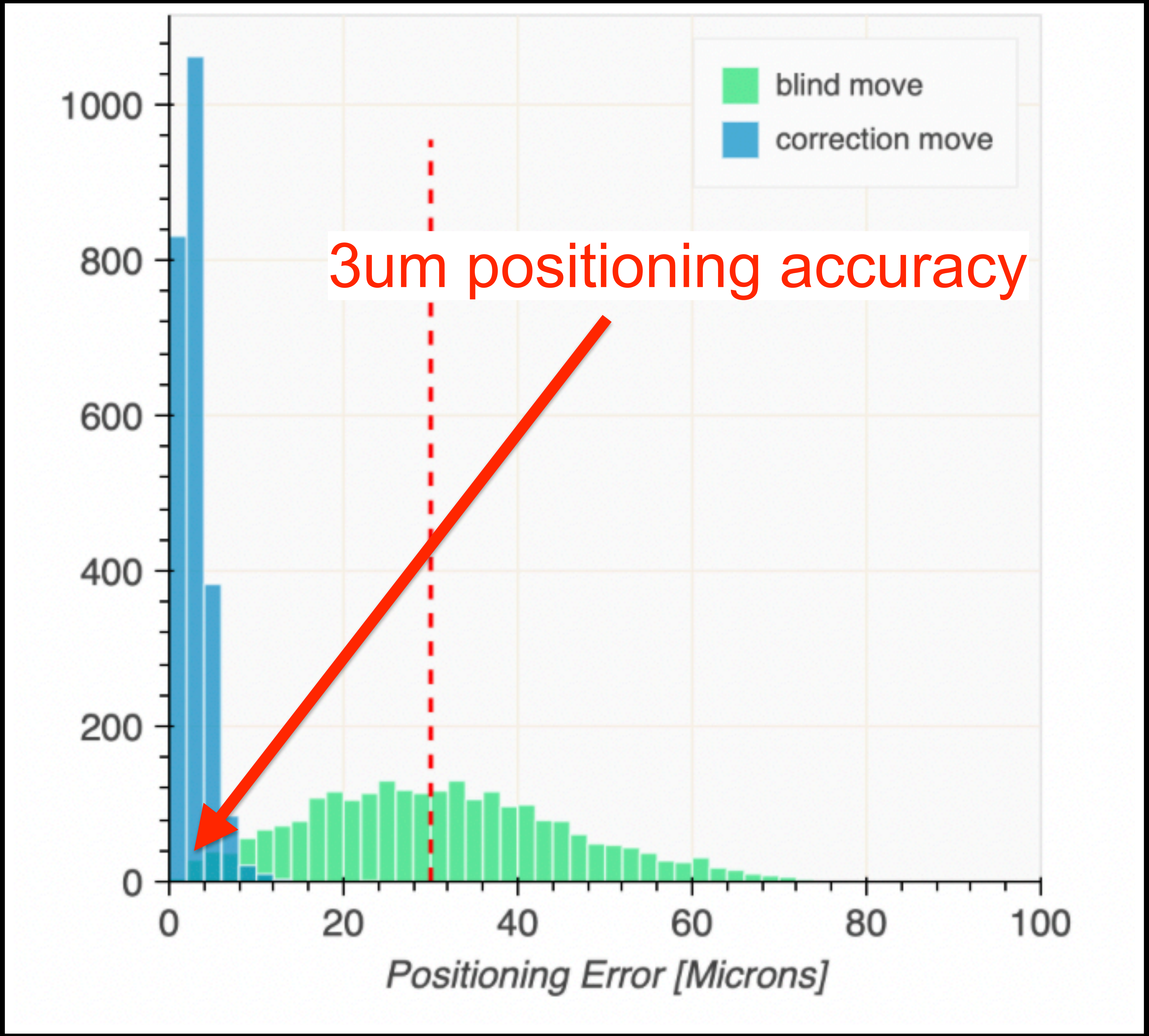


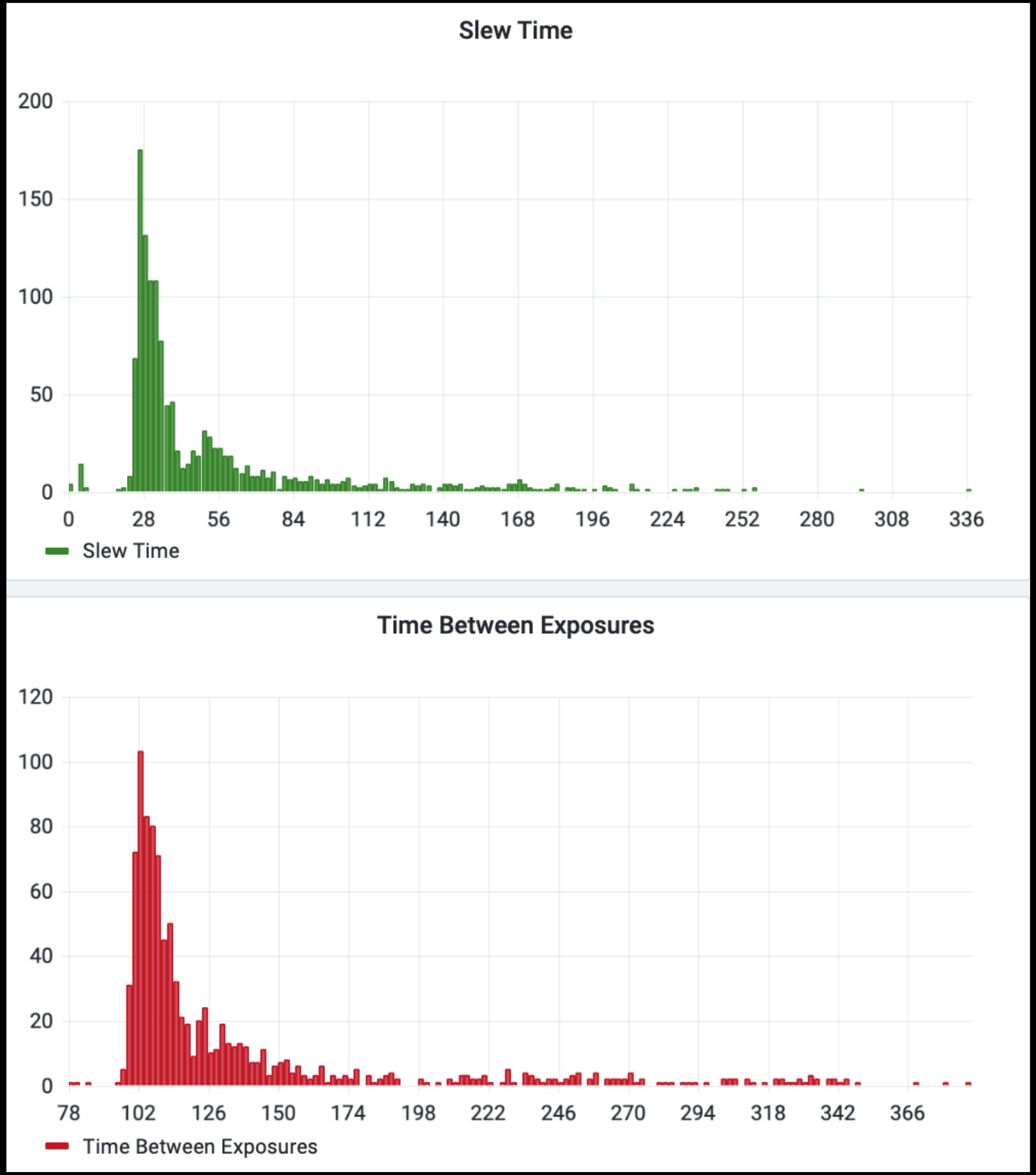
DESI focal plane is efficient and accurate





DESI focal plane is efficient and accurate





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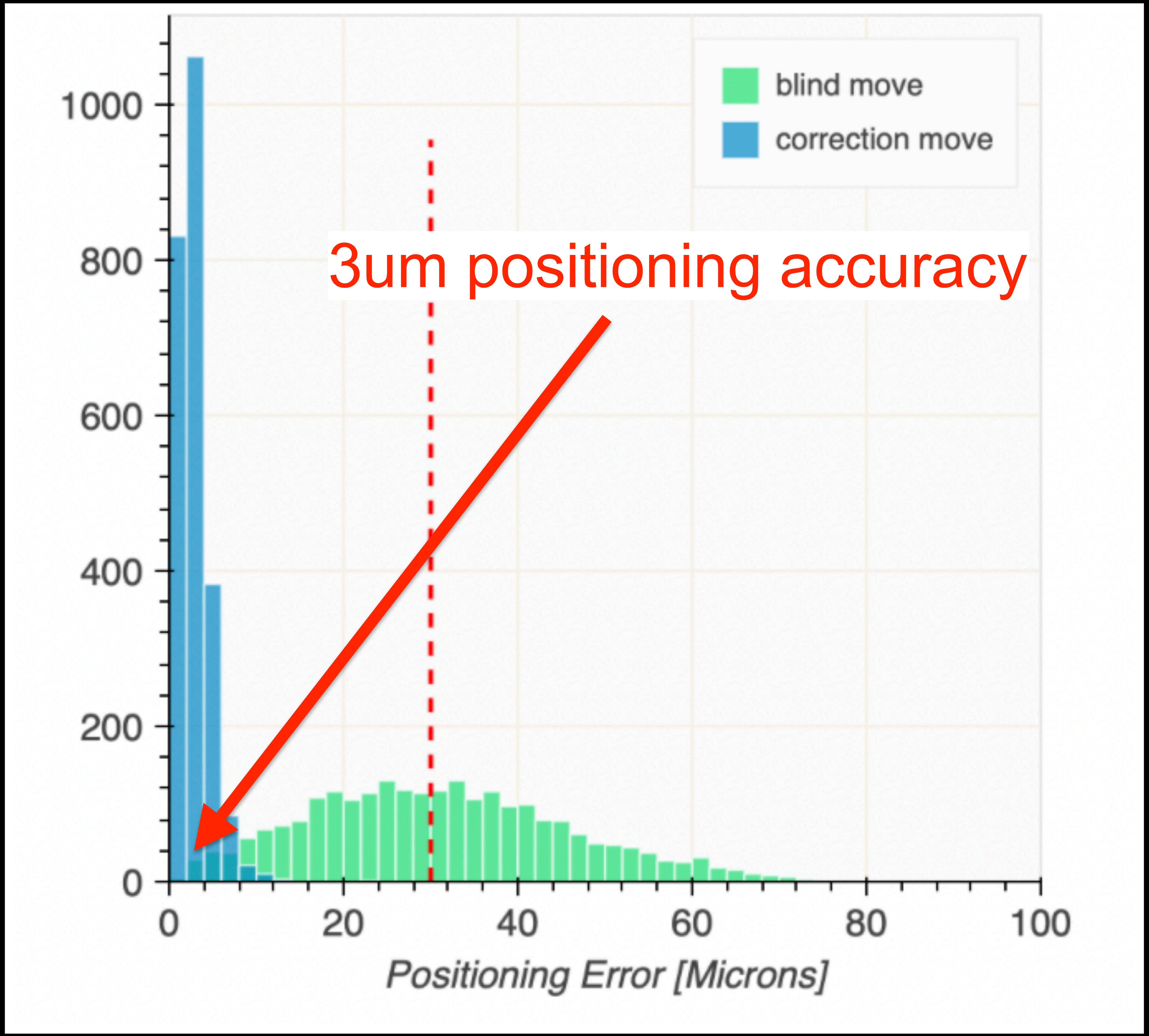
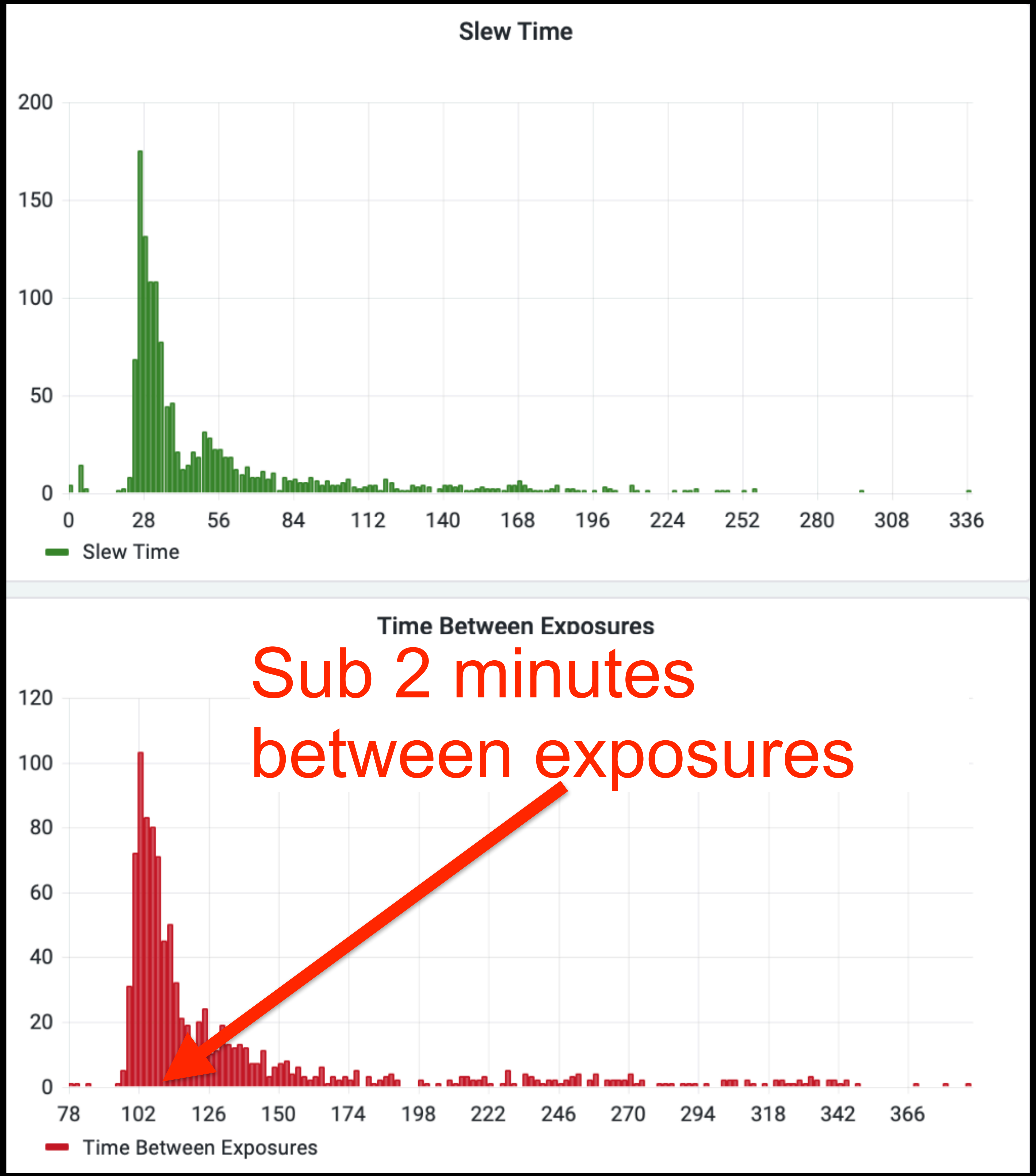
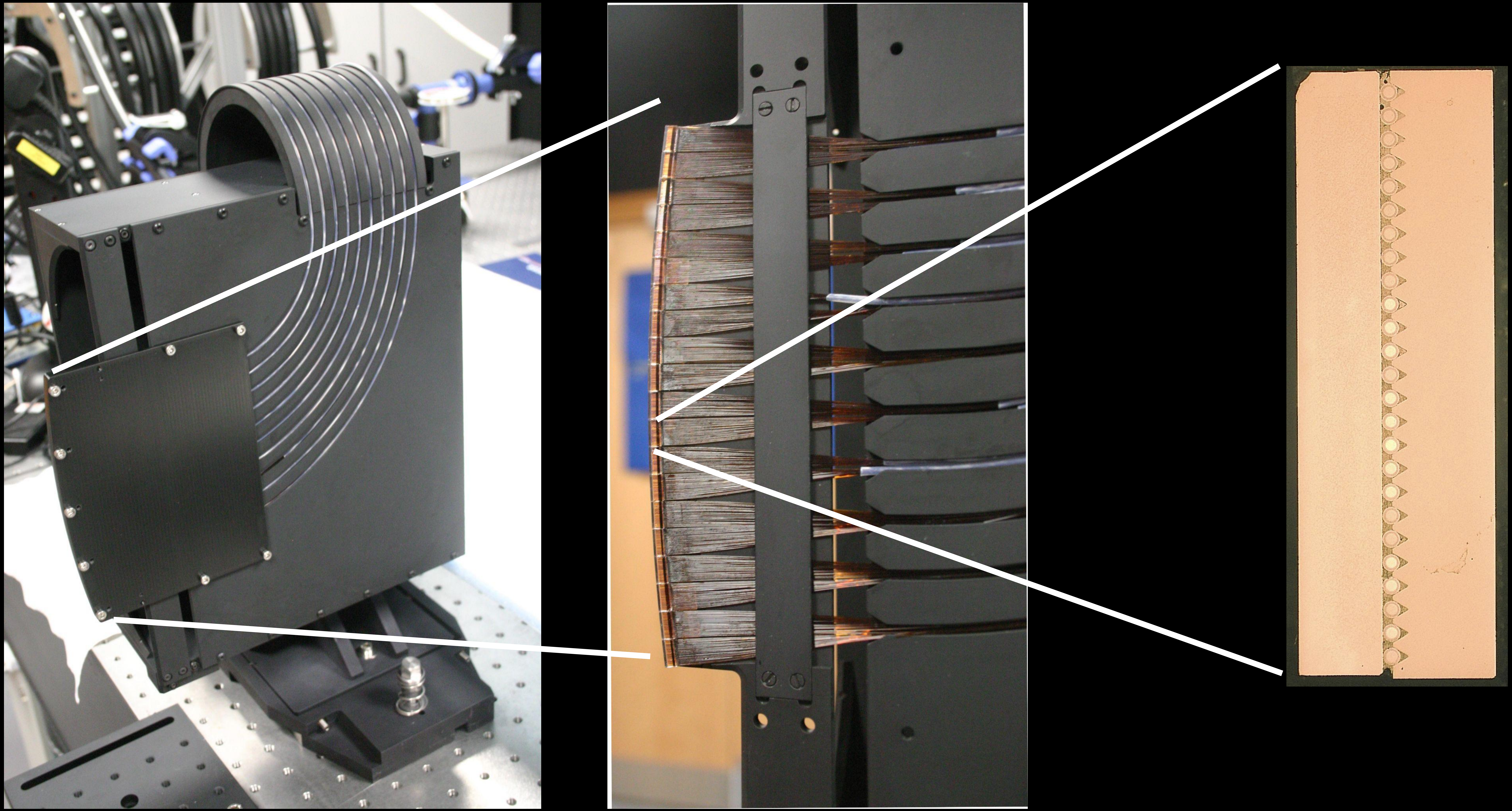


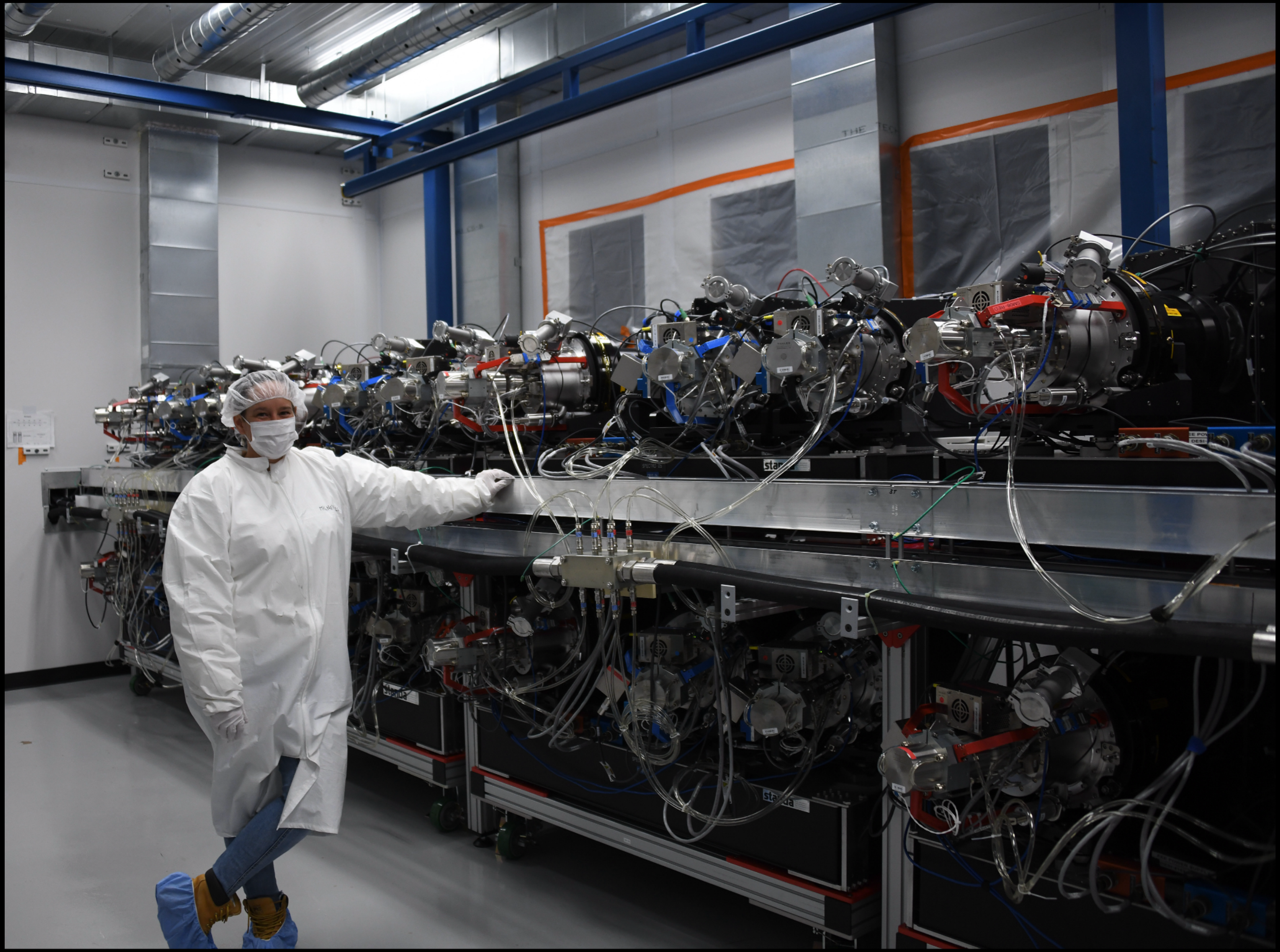


50m of optical fiber transport the captured light to the spectrographs

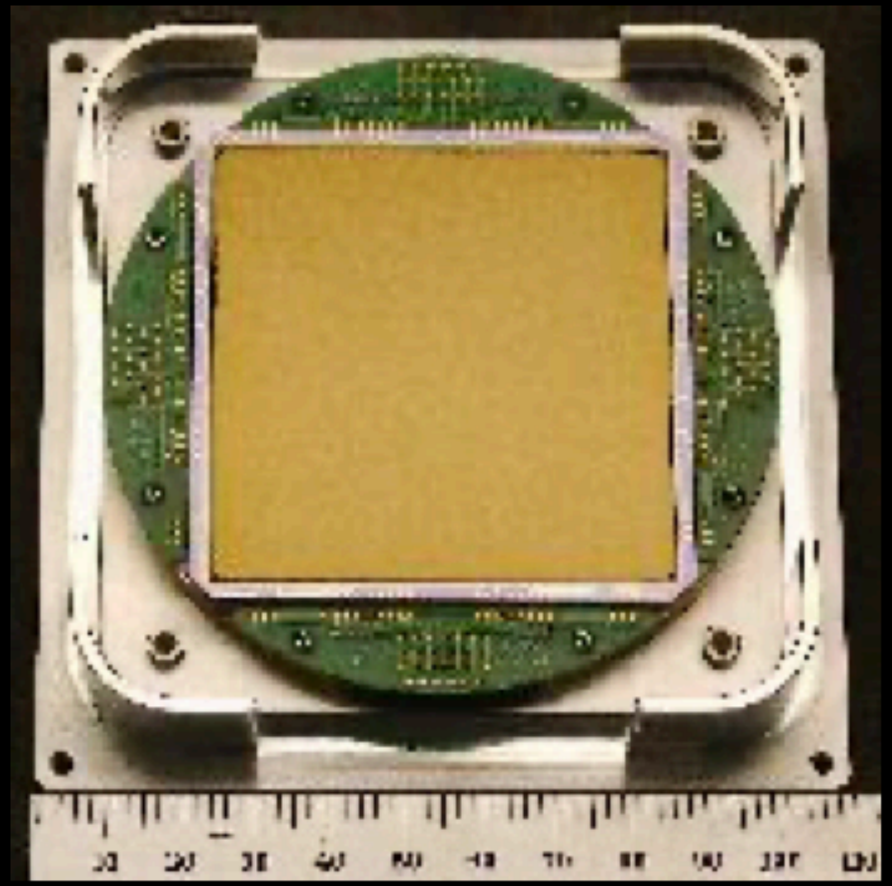
Fibers terminate in a fiber slit



Fiber slits feed the DESI spectrographs

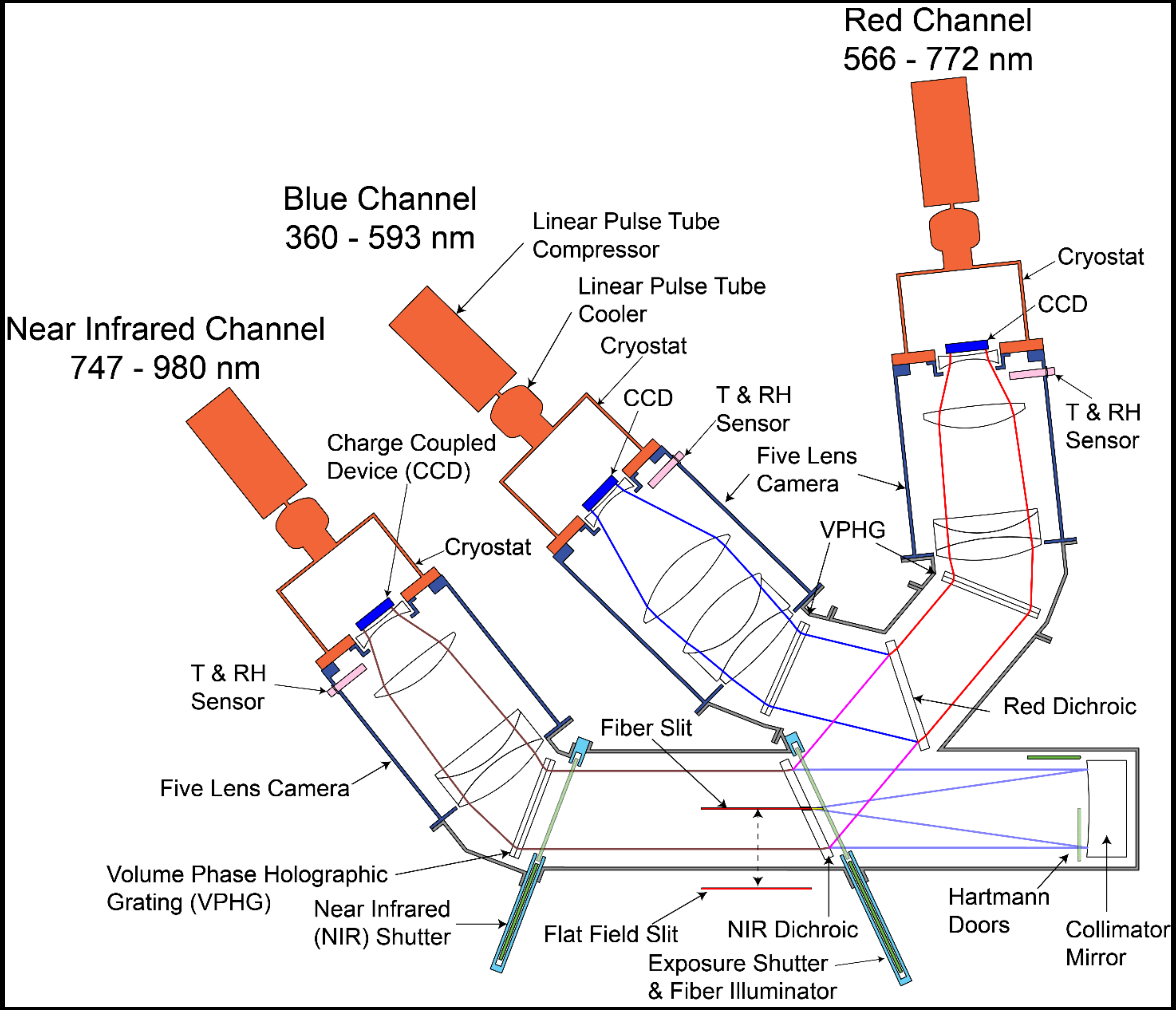


Optical layout of the DESI spectrographs

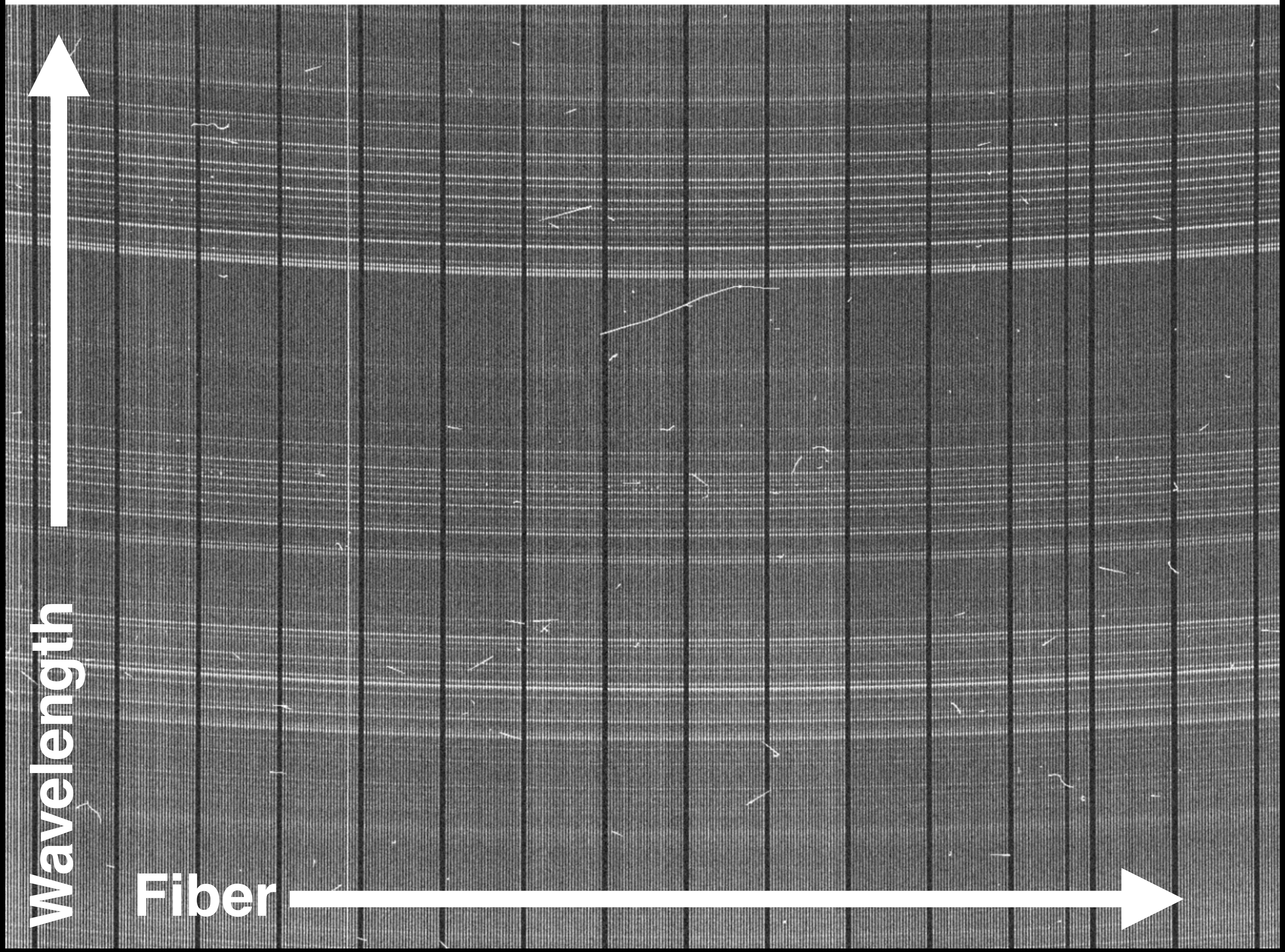


4kx4k detector

Red VPH Grating



4. Read the fingerprint



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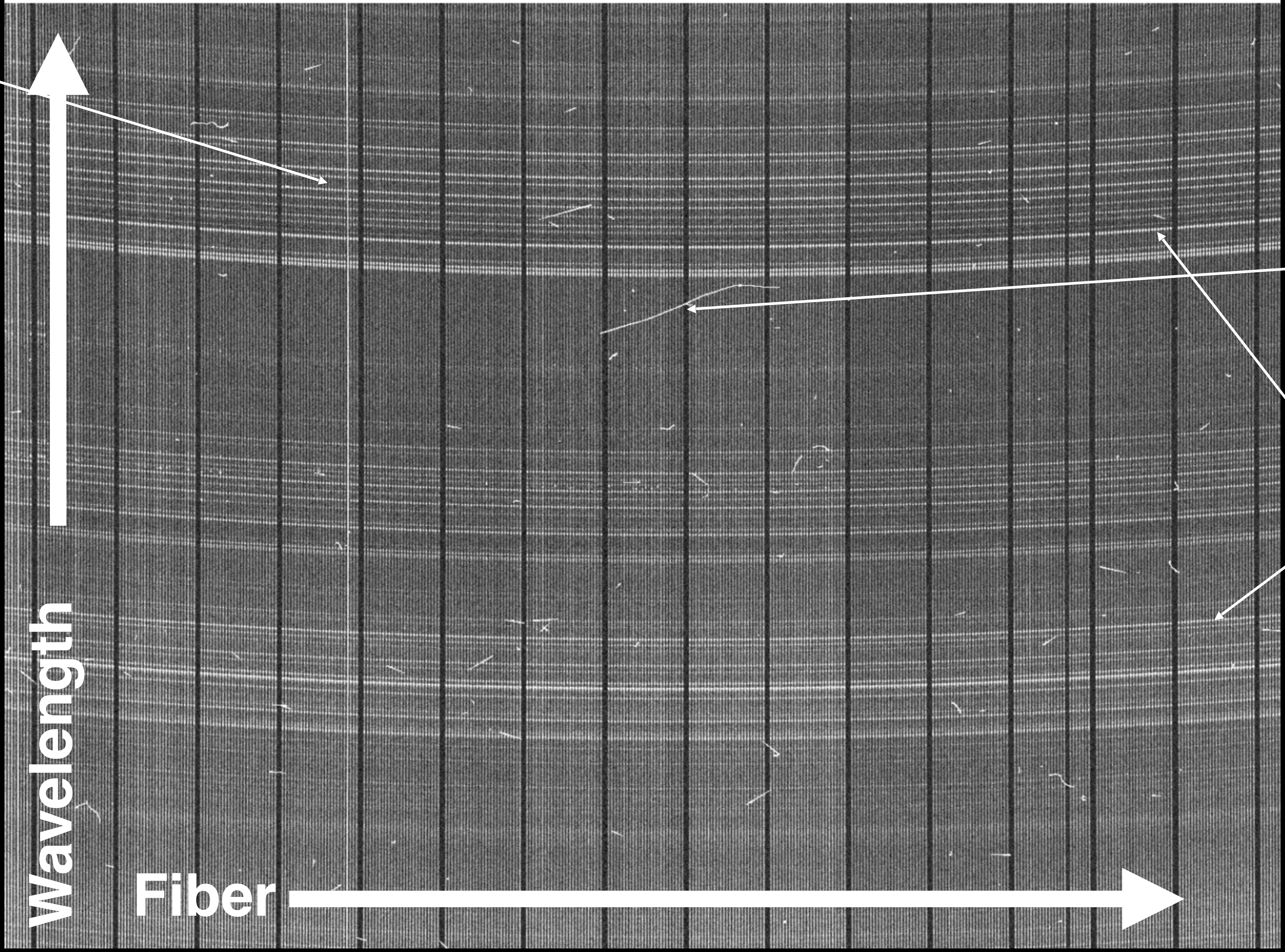

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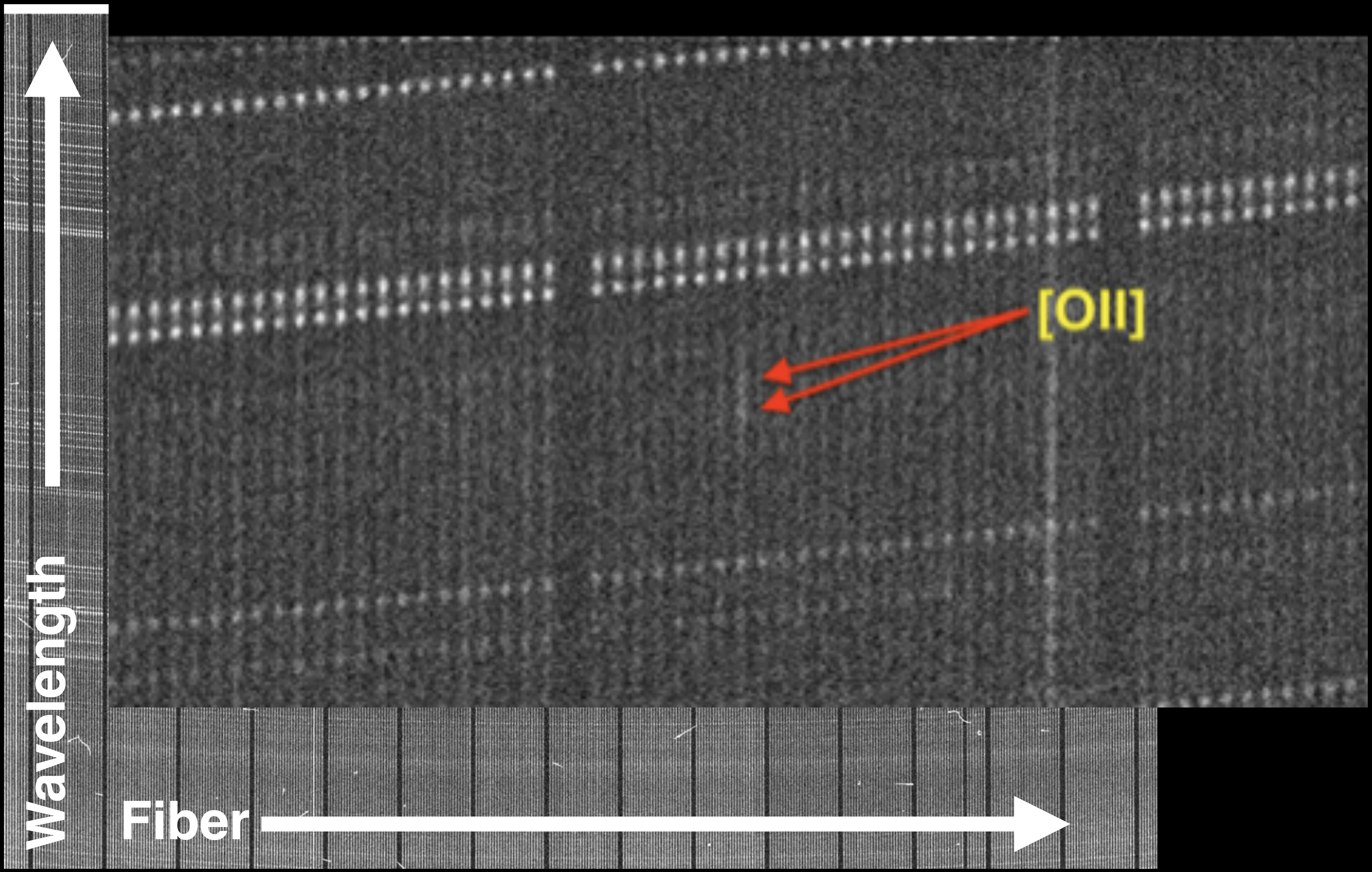
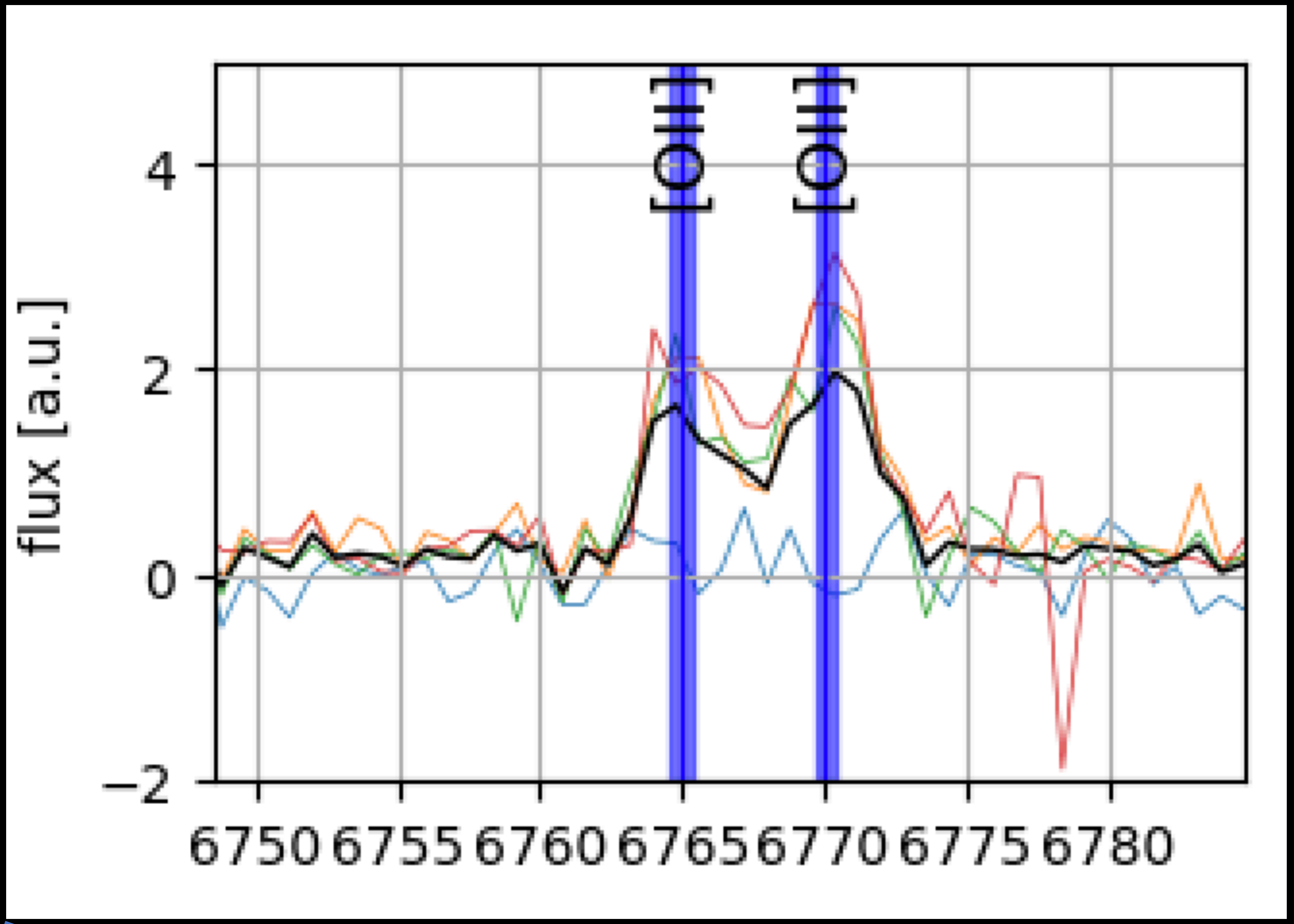
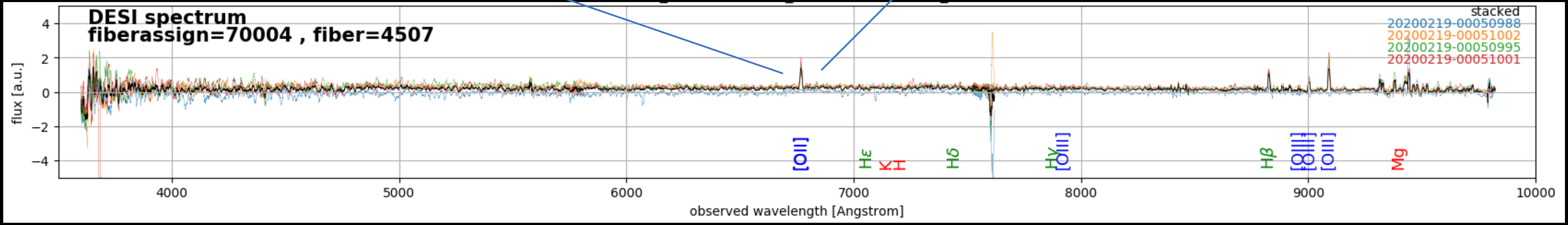


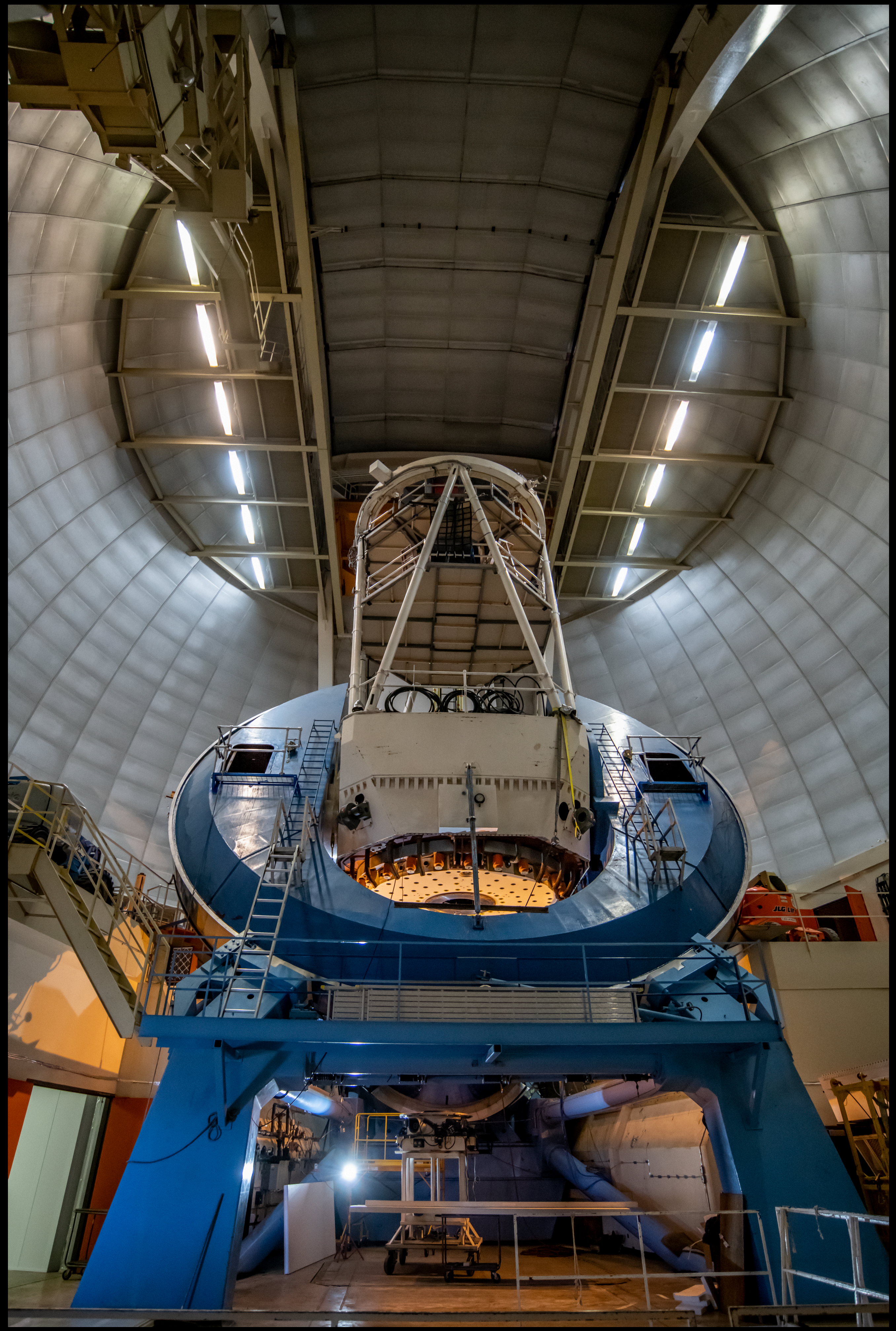
4. Read the fingerprint

DESI spectrum of a faint z=0.8 galaxy





DESI installed on the Mayall Telescope



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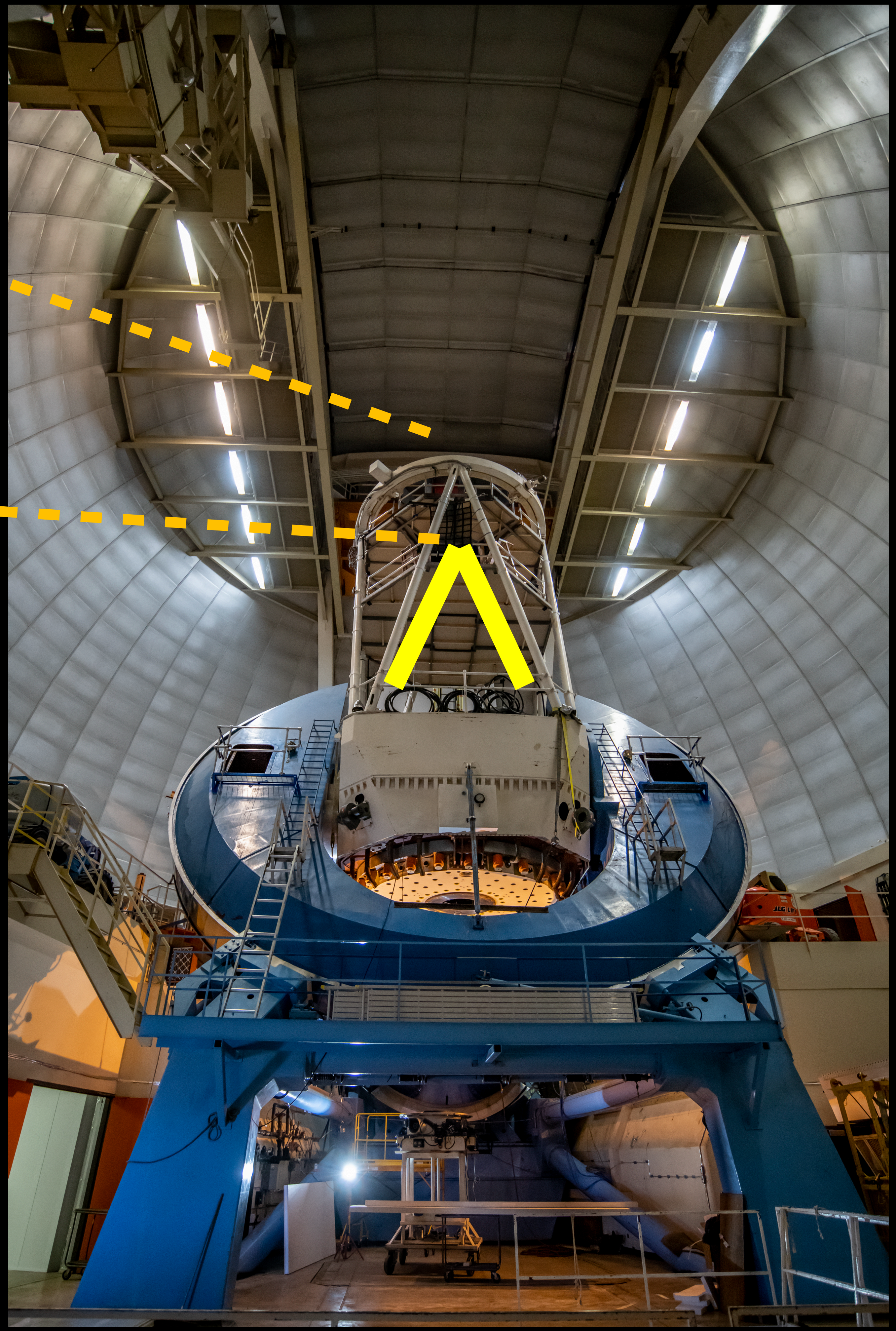

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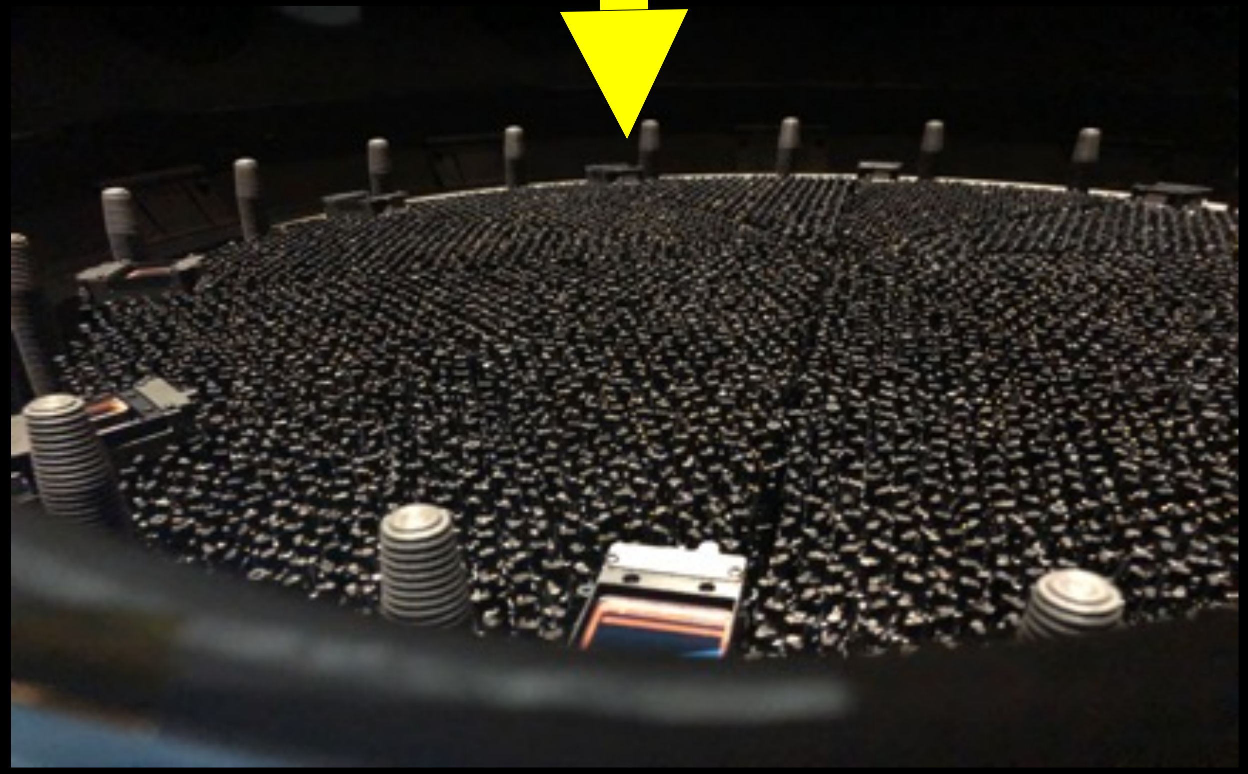
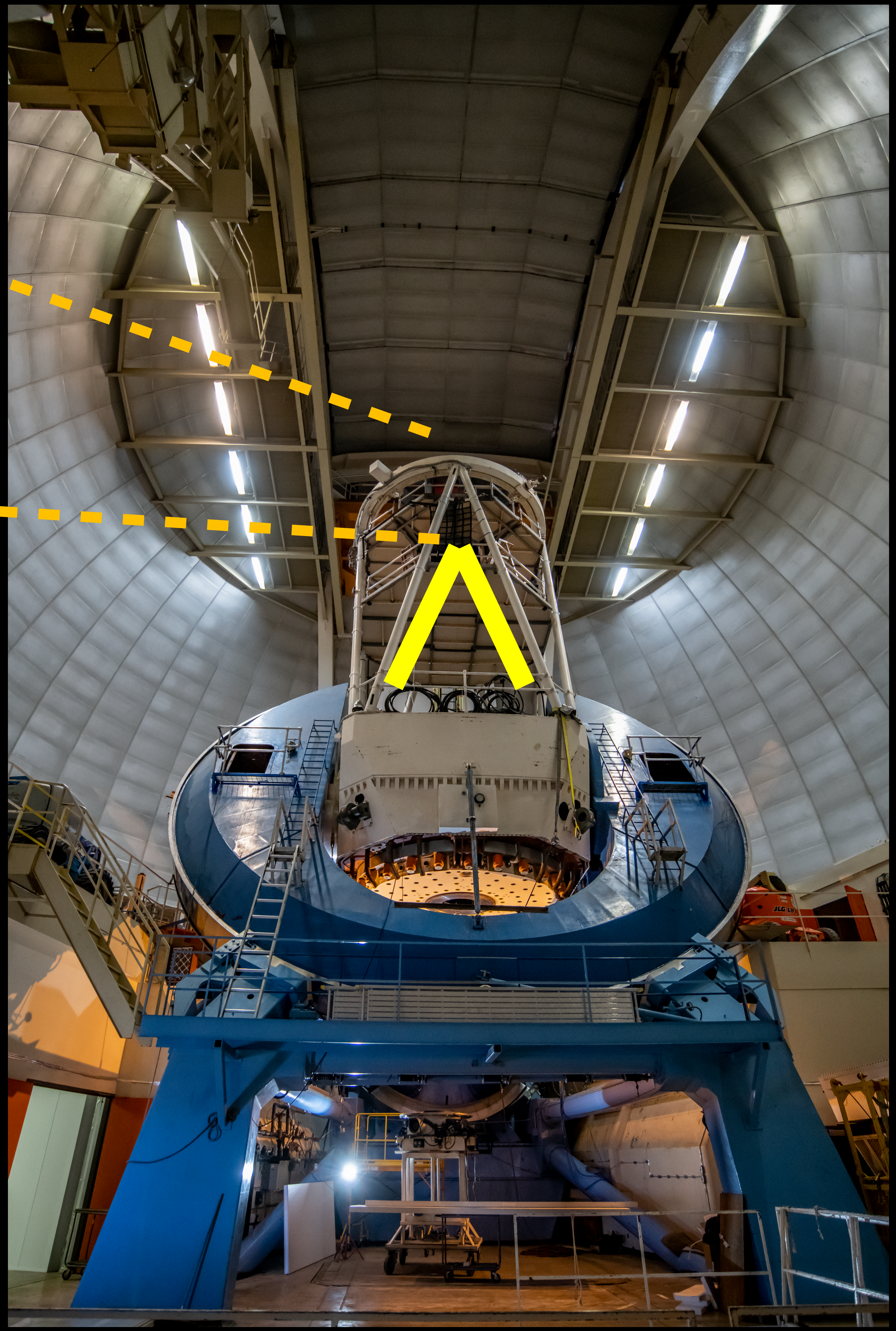
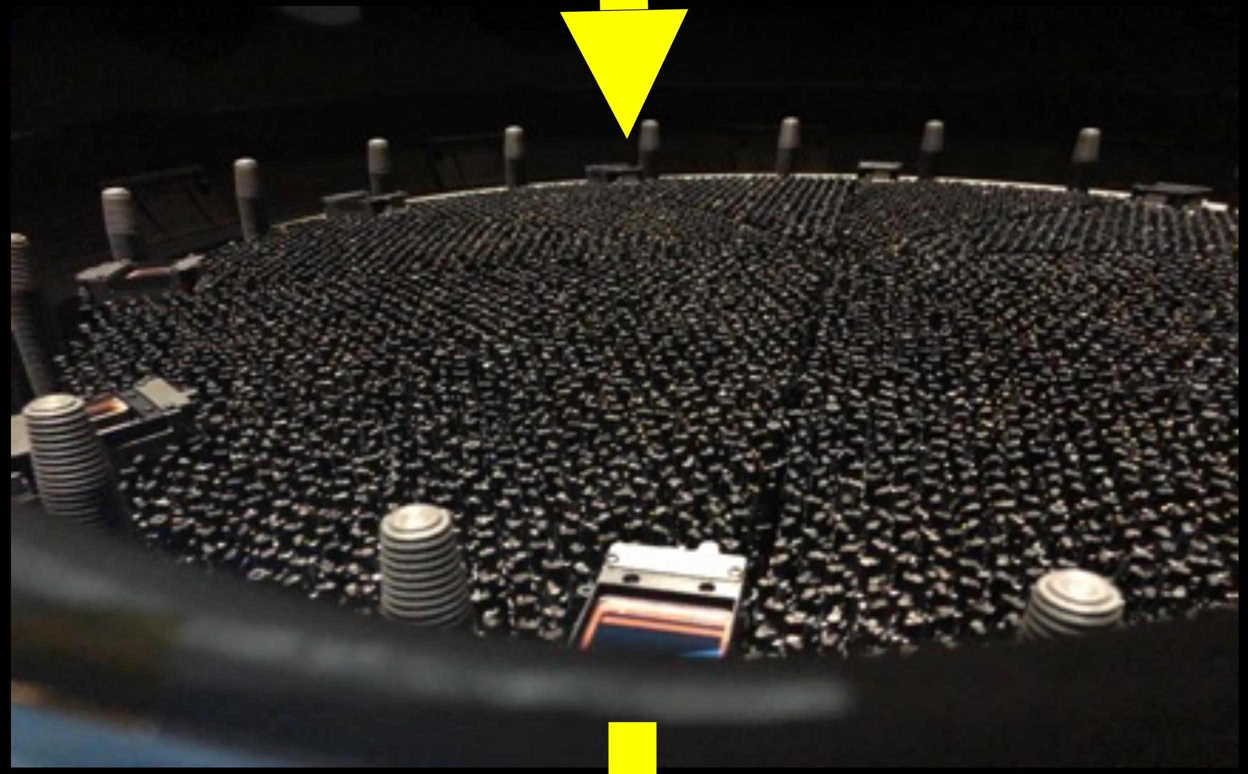
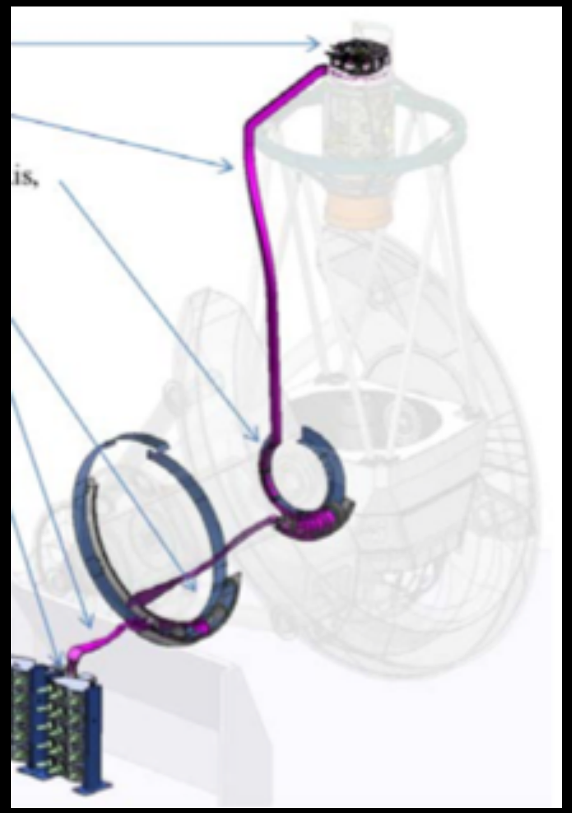
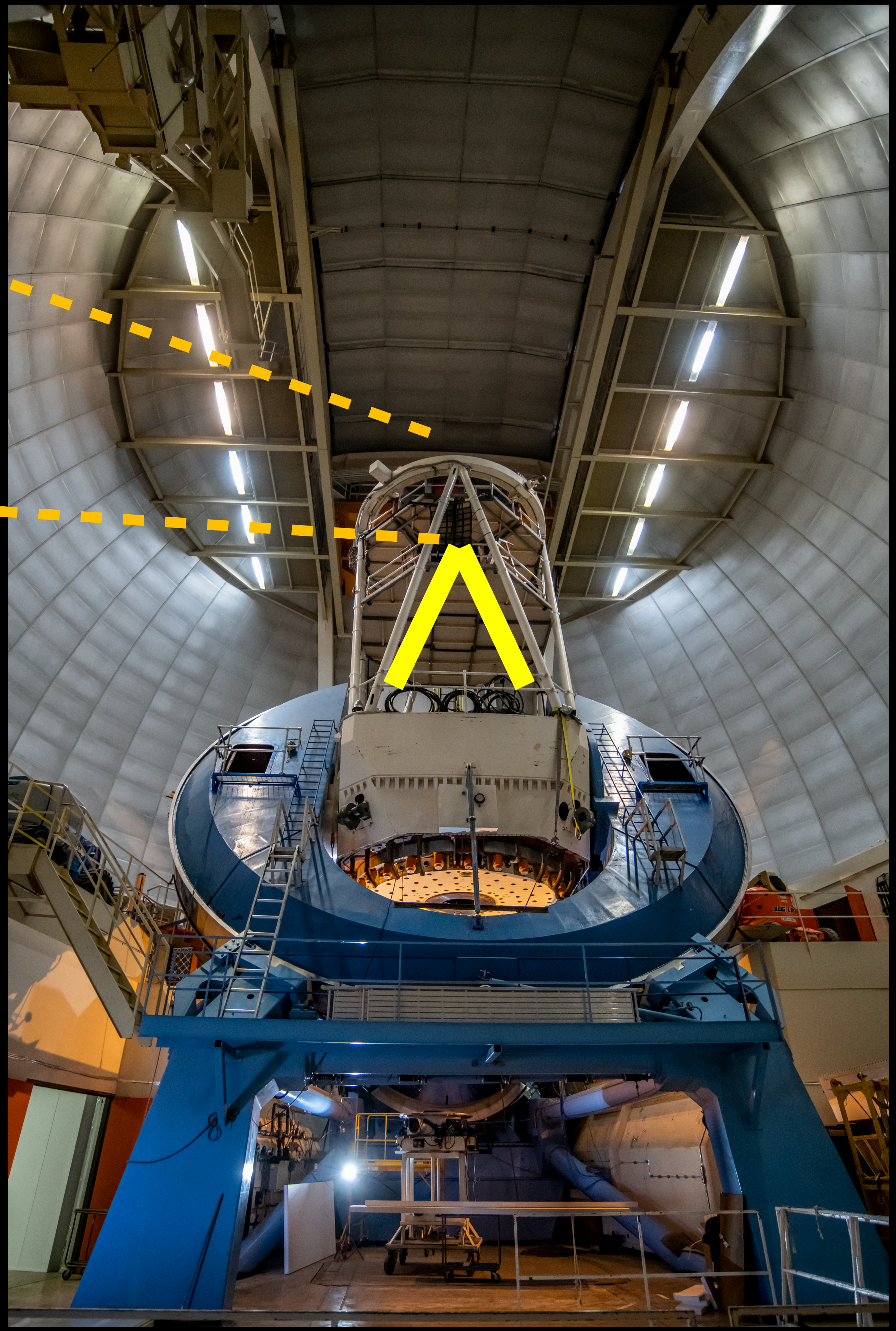




DESI installed on the Mayall Telescope







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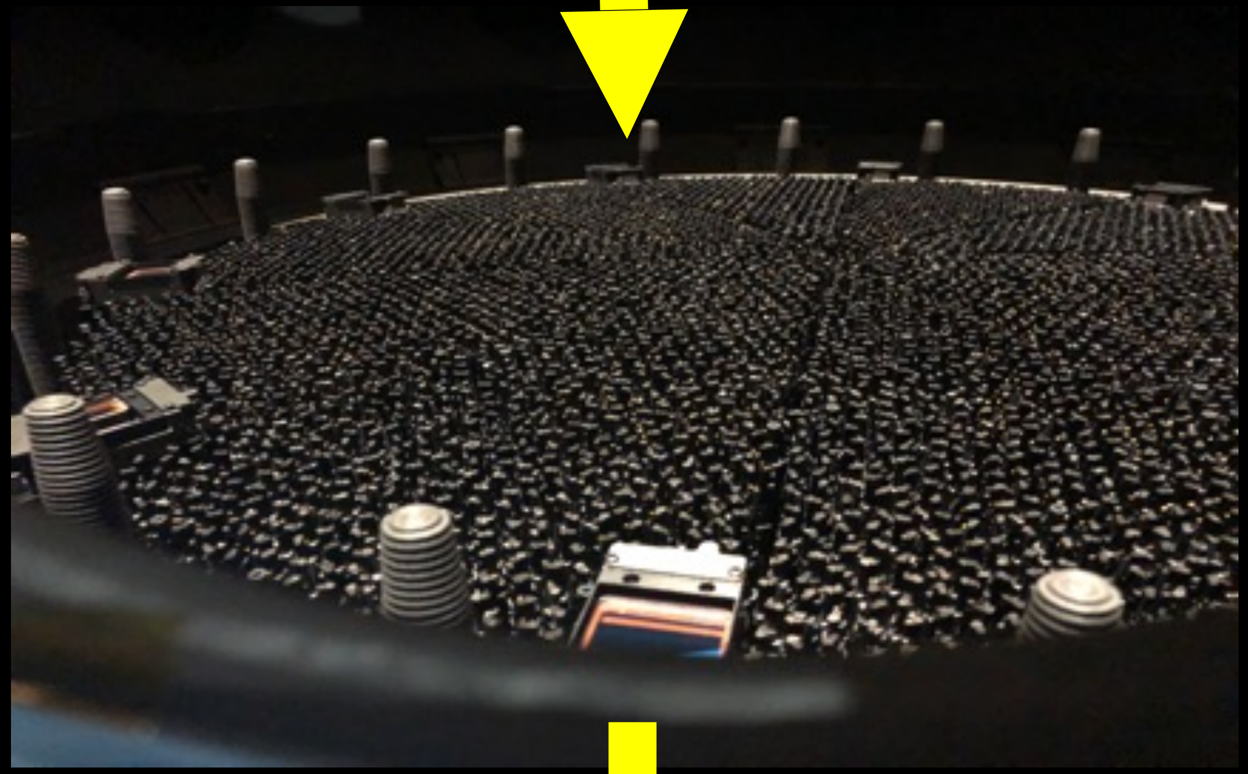

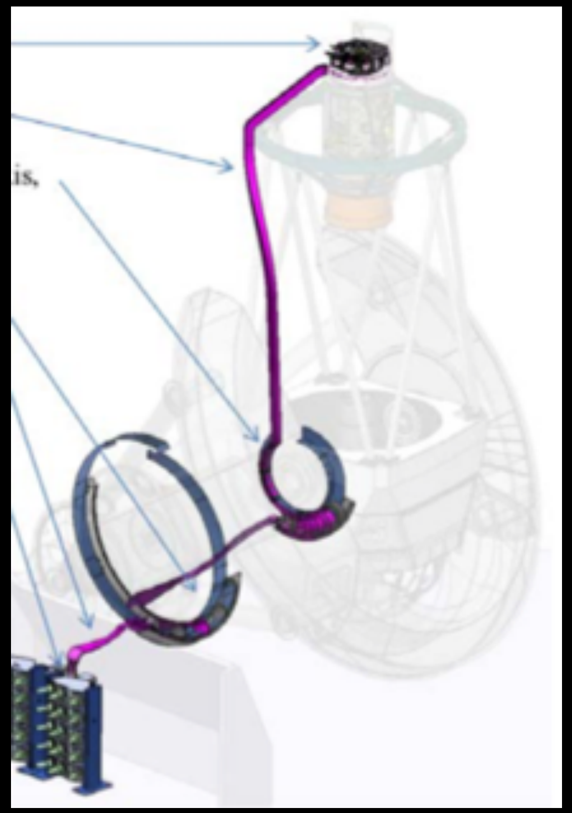

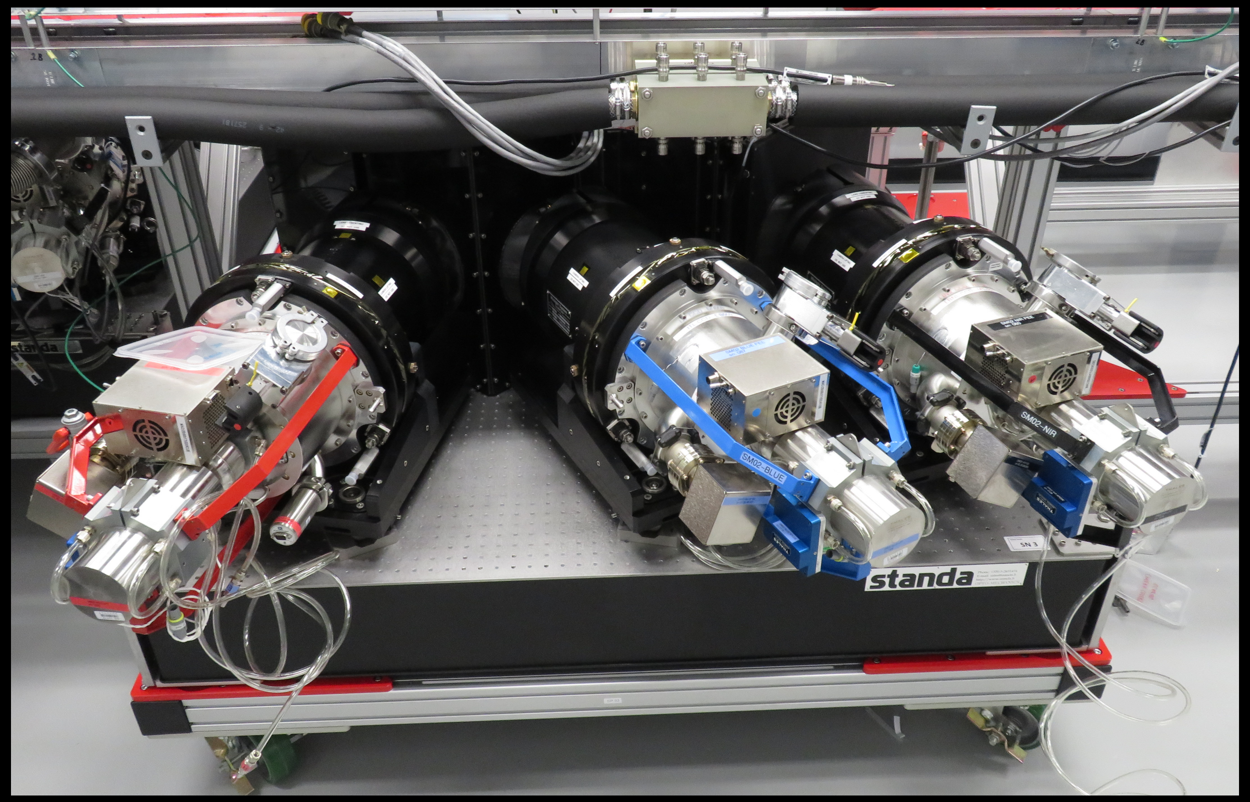

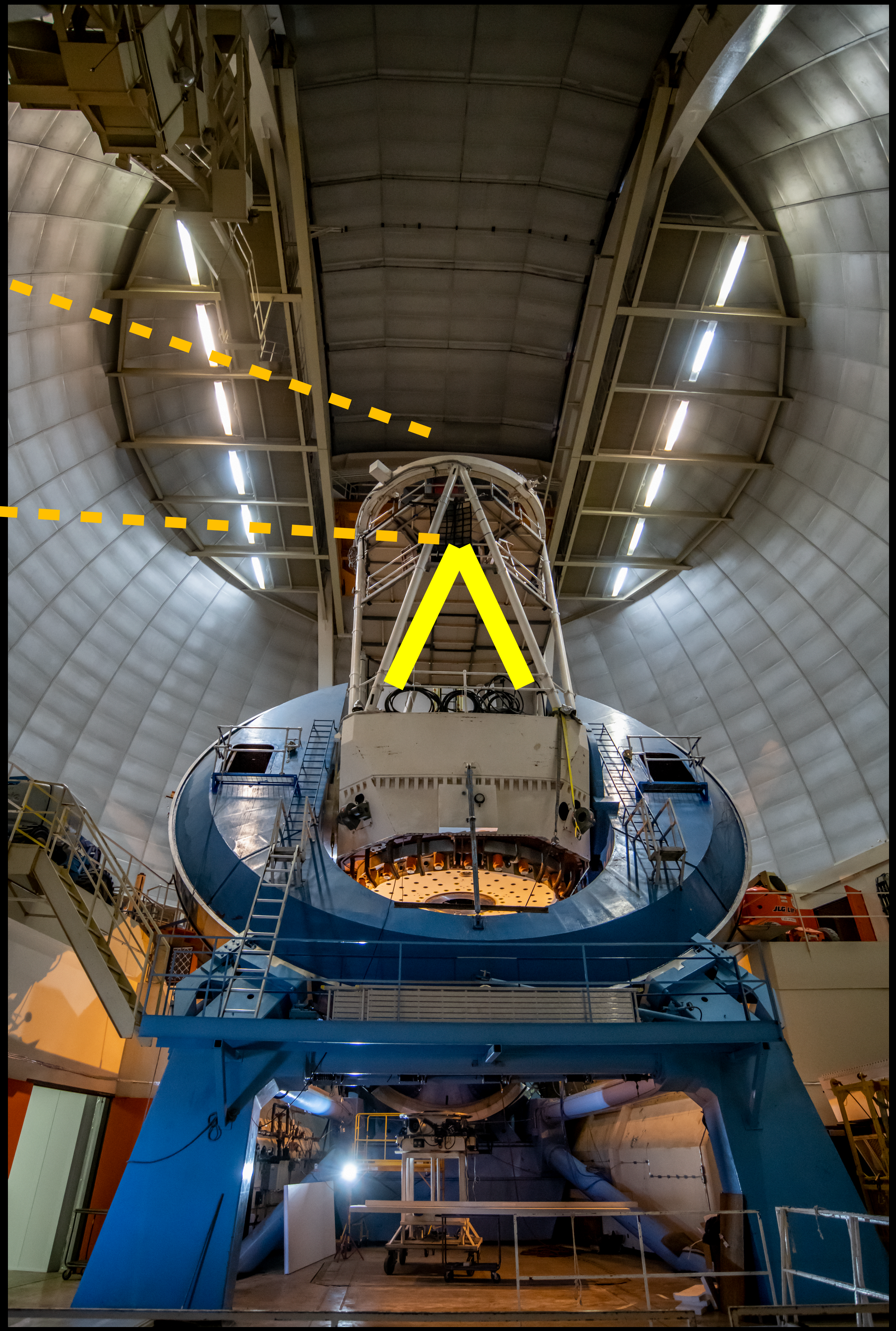

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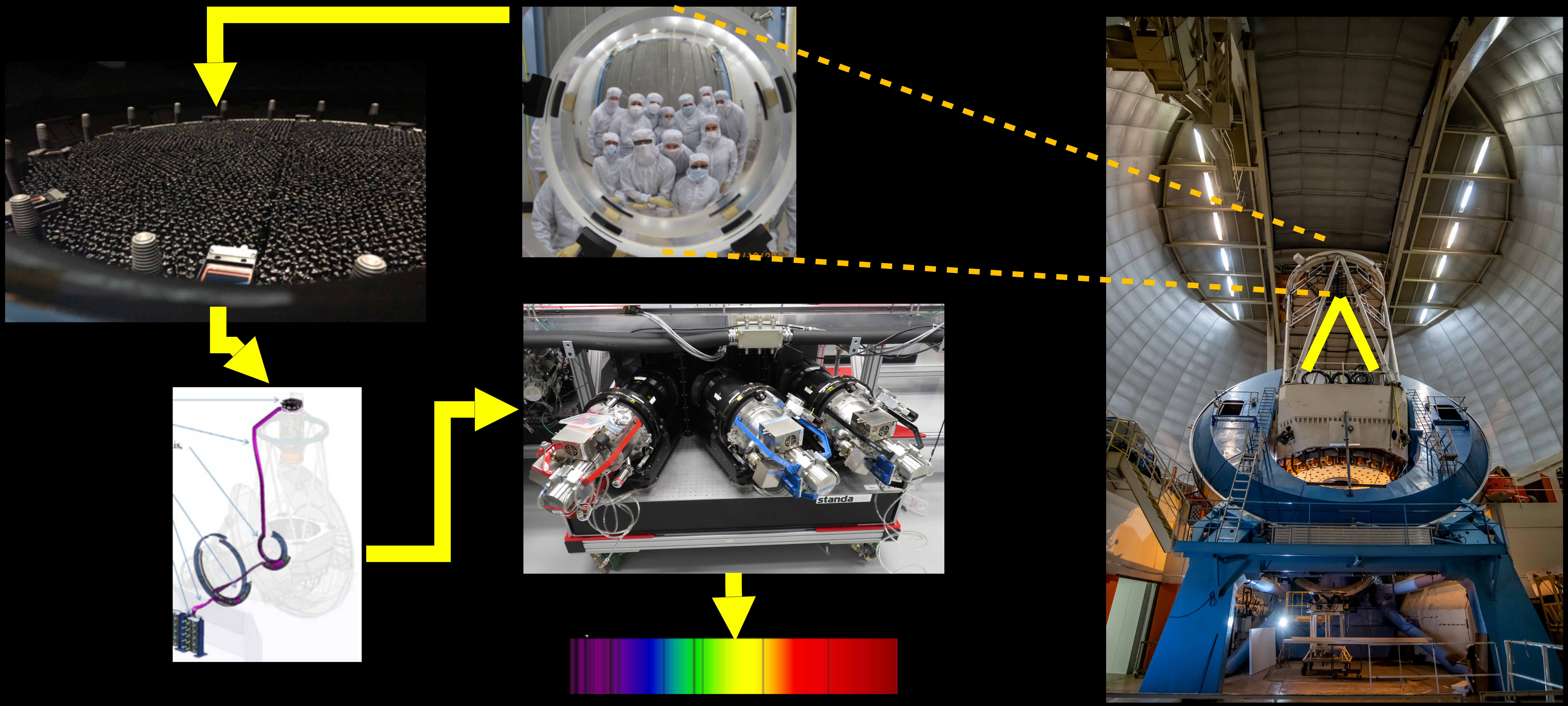


Dark Energy S

DESI Creates Largest
Detailed Map of Univ

Jan 17, 2022 by News Staff

Published in
Astronomy
Featured

Tagged as
DESI

The Dark Energy Spectroscopic Ins
spectrograph installed on the Nicho
National Observatory, has cataloged
3D redshift surveys combined, mea

Dark Energy Spectroscopic Instrument (DESI) Creates Largest 3-D Map of the Cosmos

13 January 2021 | Press release

t-Ever
rk

Astrophysicists Release the Biggest Map of the Universe Yet

A powerful astronomy instrument called DESI charts millions of galaxies in the night sky. Can it help scientists finally figure out what dark energy is?

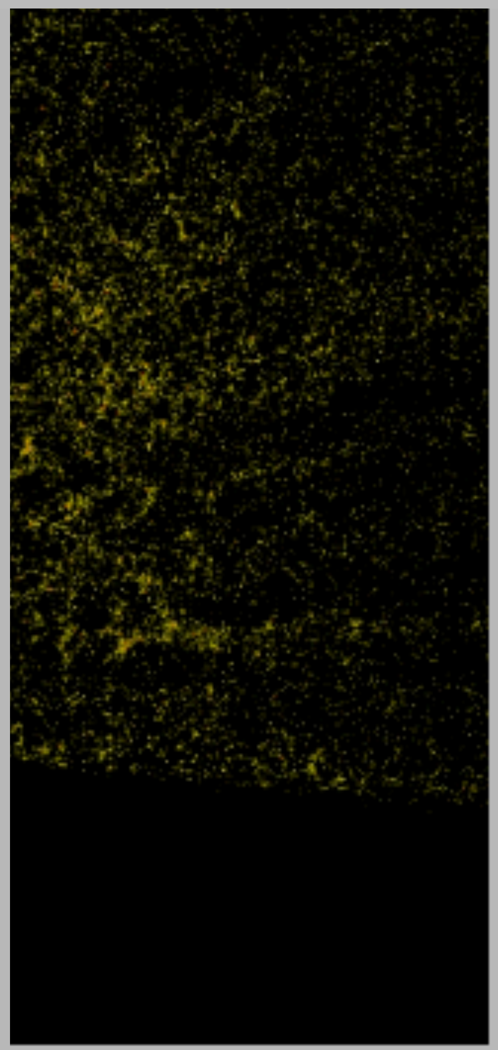
DESI has already mapped out more

Disculogic
YouTube · 1.6K+ views · 1 year ago

DESI: The Largest & Most Detaile

DESI: the largest &
discussing the larg

Kitt Peak National Observatory, near Tucson, Arizona.



ith the furthest galaxies
only about 800,000 of

MNRAS 000, 1–17 (2023) Preprint 18 April 2023 Compiled using MNRAS LaTeX style file v3.0

First Detection of the BAO Signal from Early DESI Data

Jeongin Moon,[1,2]★ David Valcin,[3] Michael Rashkovetskyi,[4] Christoph Saulder,[5] Jessica Nicole Aguilar,[6] Steven Ahlen,[7] Shadab Alam,[8] Stephen Bailey,[6] Charles Baltay,[9] Robert Blum,[10] David Brooks,[11] Etienne Burtin,[12] Edmond Chaussidon,[12] Kyle Dawson,[13] Axel de la Macorra,[14] Arnaud de Mattia,[12] Govinda Dhungana,[15] Daniel Eisenstein,[4] Brenna Flaugher,[16] Andreu Font-Ribera,[17] Cristhian Garcia-Quintero,[18] Julien Guy,[6] Malik Muhammad Sikandar Hanif,[19] Klaus Honscheid,[20,21] Mustapha Ishak,[18] Robert Kehoe,[22] Sumi Kim,[23] Theodore Kisner,[6] Anthony Kremin,[6] Martin Landriau,[6] Laurent Le Guillou,[24] Michael Levi,[6] Paul Martini,[25,21] Patrick McDonald,[6] Aaron Meisner,[10] Ramon Miquel,[17,26] John Moustakas,[27] Adam Myers,[28] Seshadri Nadathur,[29] Richard Neveux,[30] Jeffrey A. Newman,[31] Jundan Nie,[32] Nikhil Padmanabhan,[9] Nathalie Palanque-Delabrouille,[6,12] Will Percival,[33,34] Alejandro Pérez Fernández,[14] Claire Poppett,[35,6] Francisco Prada,[36] Ashley J. Ross,[25,21] Graziano Rossi,[1]† Hee-Jong Seo,[3] Gregory Tarlé,[19] Mariana Vargas Magana,[14] Andrei Variu,[37] Benjamin Alan Weaver,[10] Martin J. White,[38] Sihan Yuan,[39] Cheng Zhao,[37] Rongpu Zhou,[6] Zhimin Zhou,[32] and Hu Zou[32]

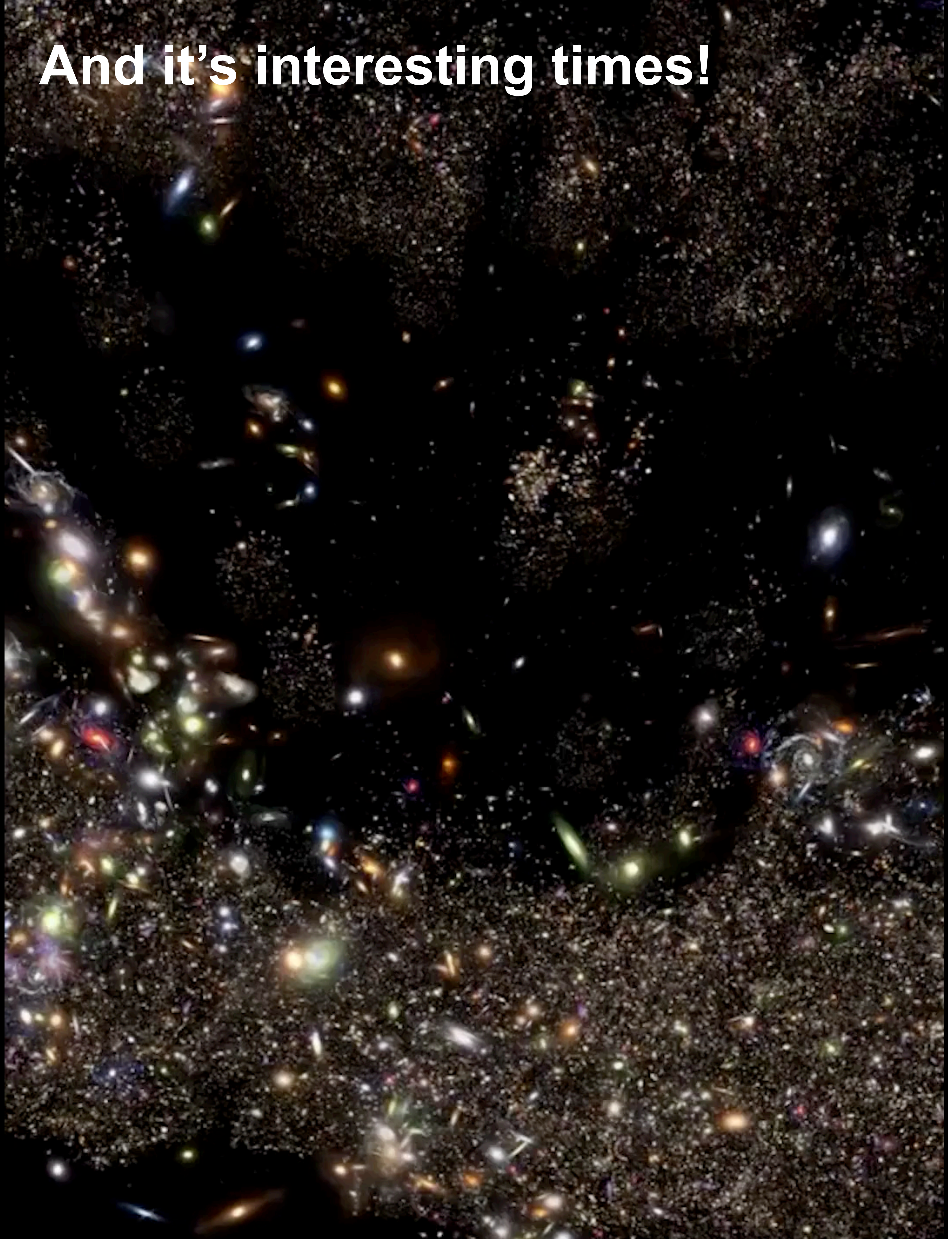
Affiliations are listed at the end of the paper

Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT

We present the first detection of the baryon acoustic oscillations (BAO) signal obtained using unblinded data collected during the initial two months of operations of the Stage-IV ground-based Dark Energy Spectroscopic Instrument (DESI). From a selected sample of $261,291$ Luminous Red Galaxies spanning the redshift interval $0.4 < z < 1.1$ and covering 1651 square degrees with a 57.9% completeness level, we report a $\sim 5\sigma$ level BAO detection and the measurement of the BAO location at a precision of 1.7%. Using a Bright Galaxy Sample of $109,523$ galaxies in the redshift range $0.1 < z < 0.5$, over 3677 square degrees with a 50.0% completeness, we also detect the BAO feature at $\sim 3\sigma$ significance with a 2.6% precision. These first BAO measurements represent an important milestone, acting as a quality control on the optimal performance of the complex robotically-actuated, fiber-fed DESI spectrograph, as well as an early validation of the DESI spectroscopic pipeline and data management system. Based on these first promising results, we forecast that DESI is on target to achieve a high-significance BAO detection at sub-percent precision with the completed 5-year survey data, meeting the top-level science requirements on BAO measurements. This exquisite level of precision will set new standards in cosmology and confirm DESI as the most competitive BAO experiment for the remainder of this decade.

And it's interesting times!



The New York Times

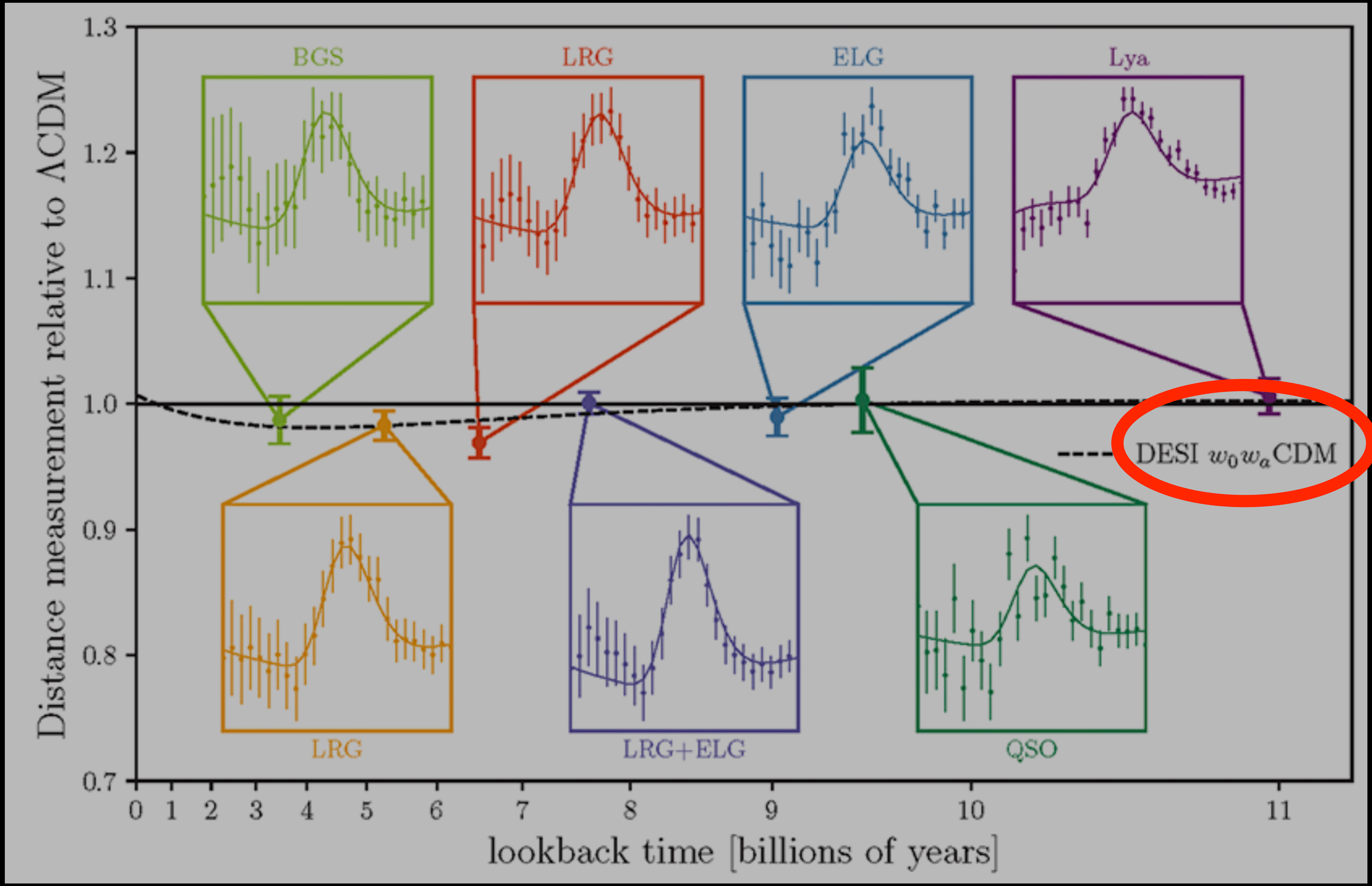
April 4, 2024

A Tantalizing 'Hint' That Astronomers Got Dark Energy All Wrong

Scientists may have discovered a major flaw in their understanding of that mysterious cosmic force. That could be good news for the fate of the universe.

2024: https://arxiv.org/abs/2404.03002
2025: https://arxiv.org/abs/2503.14738

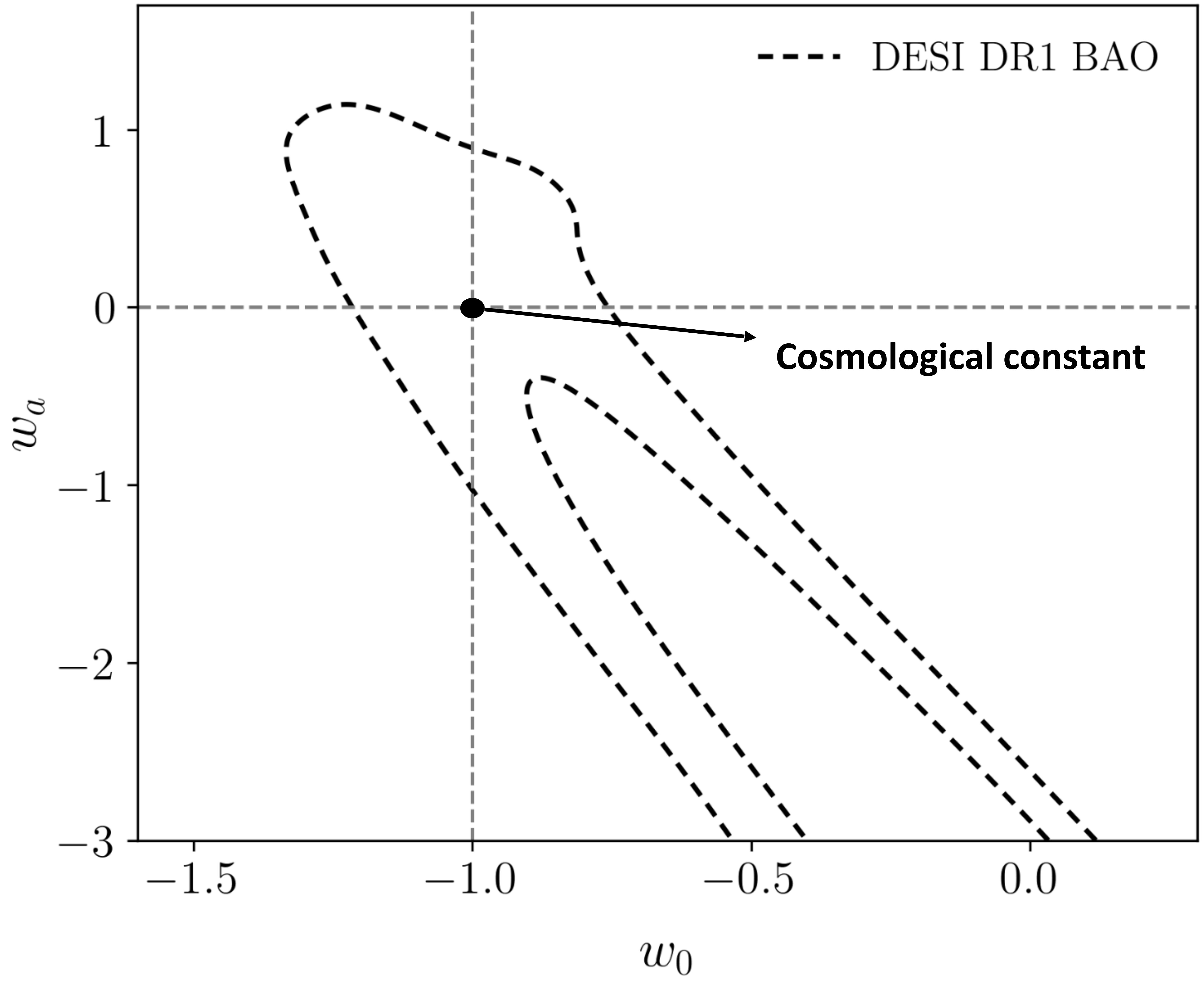
What exactly did we get wrong?



Evolving Dark Energy

DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

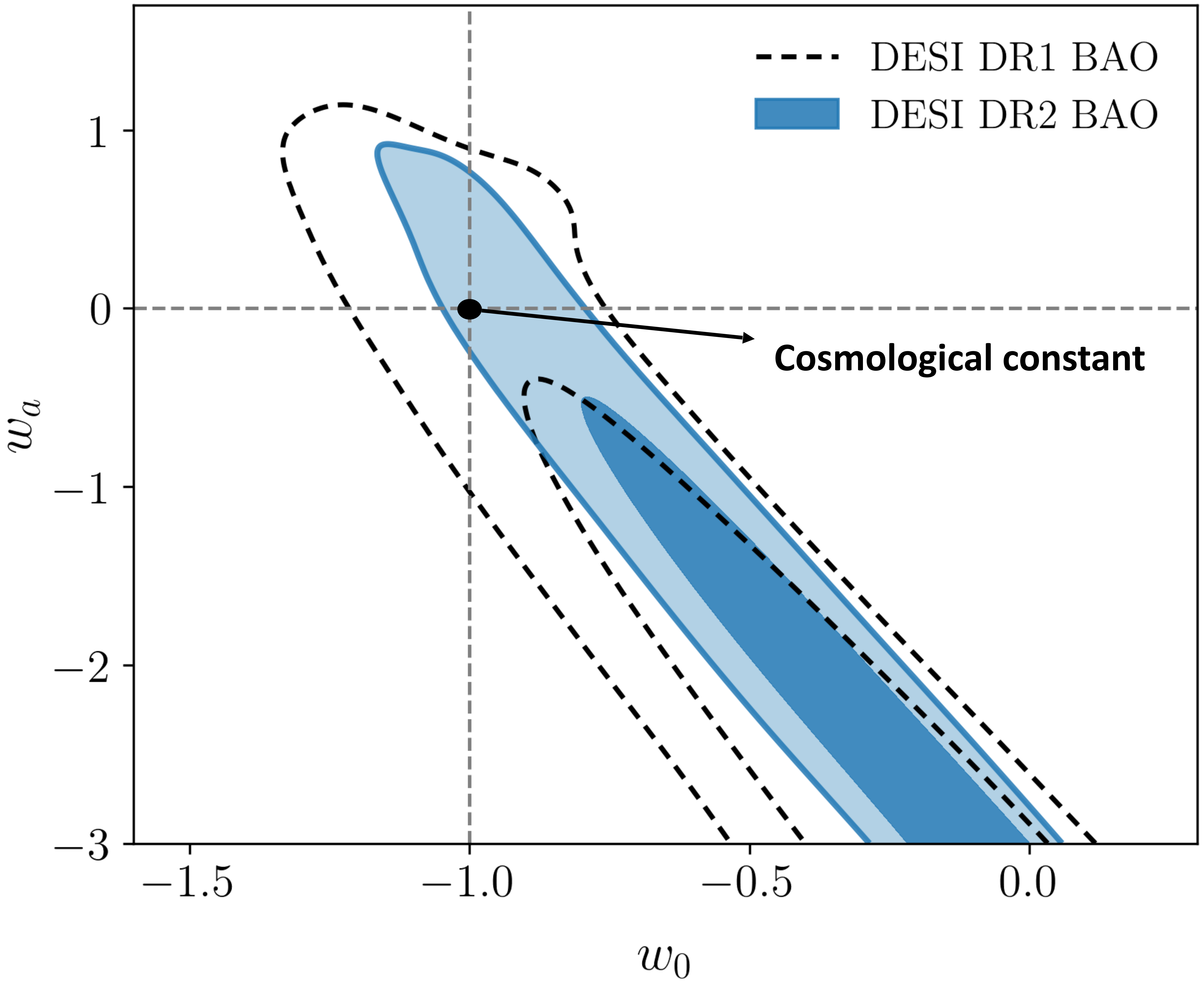
- BAO data define a degeneracy direction in the $w_0 - w_a$ plane



Evolving Dark Energy

DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

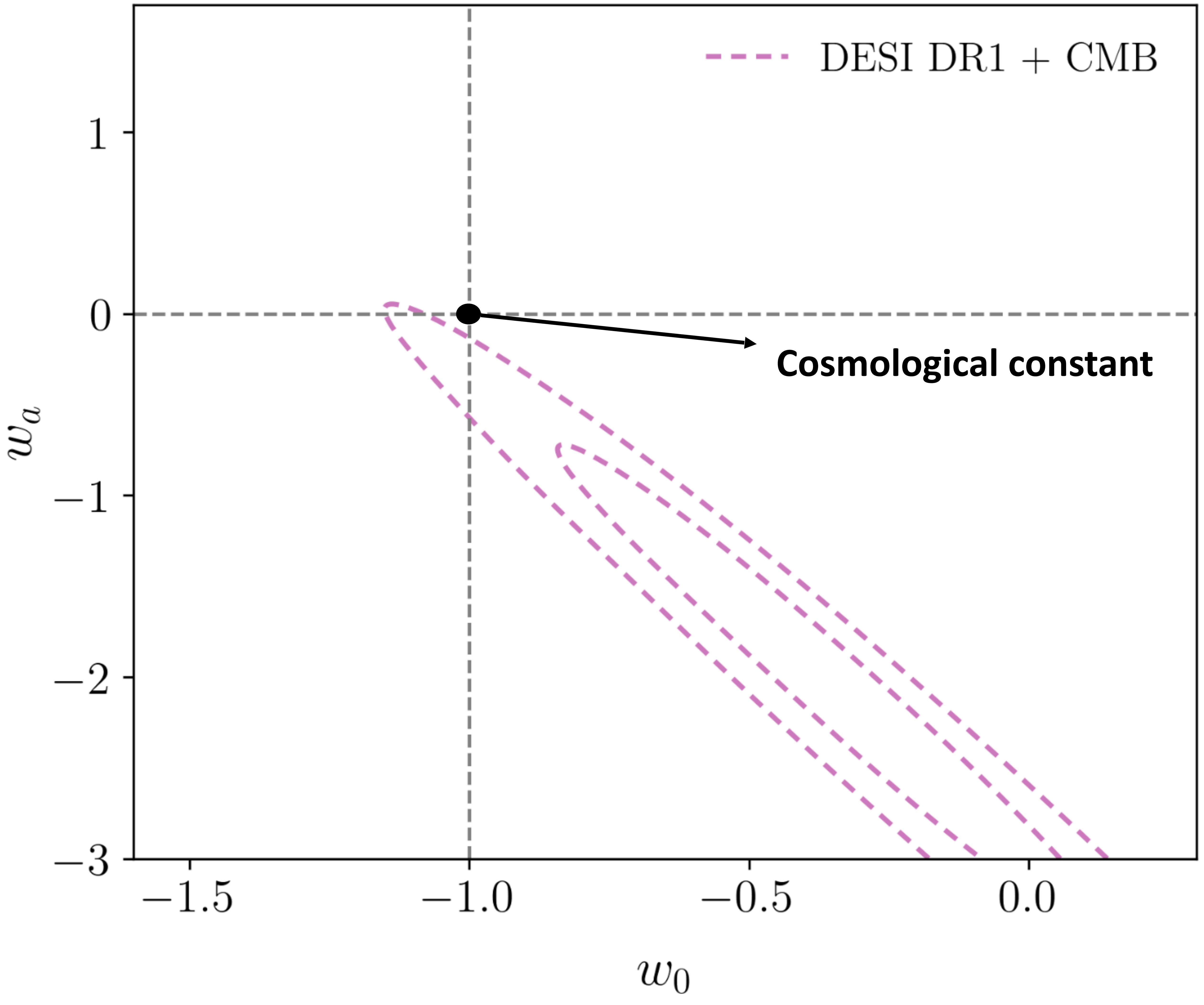
- BAO data define a degeneracy direction in the $w_0 - w_a$ plane
- DESI DR2 still within 2σ of ΛCDM
- Need to combine with other probes to break this degeneracy



DESI DR2 Results II: BAO measurements and Cosmology

Evolving Dark Energy

- DESI DR1 + CMB: 2.6σ from ΛCDM



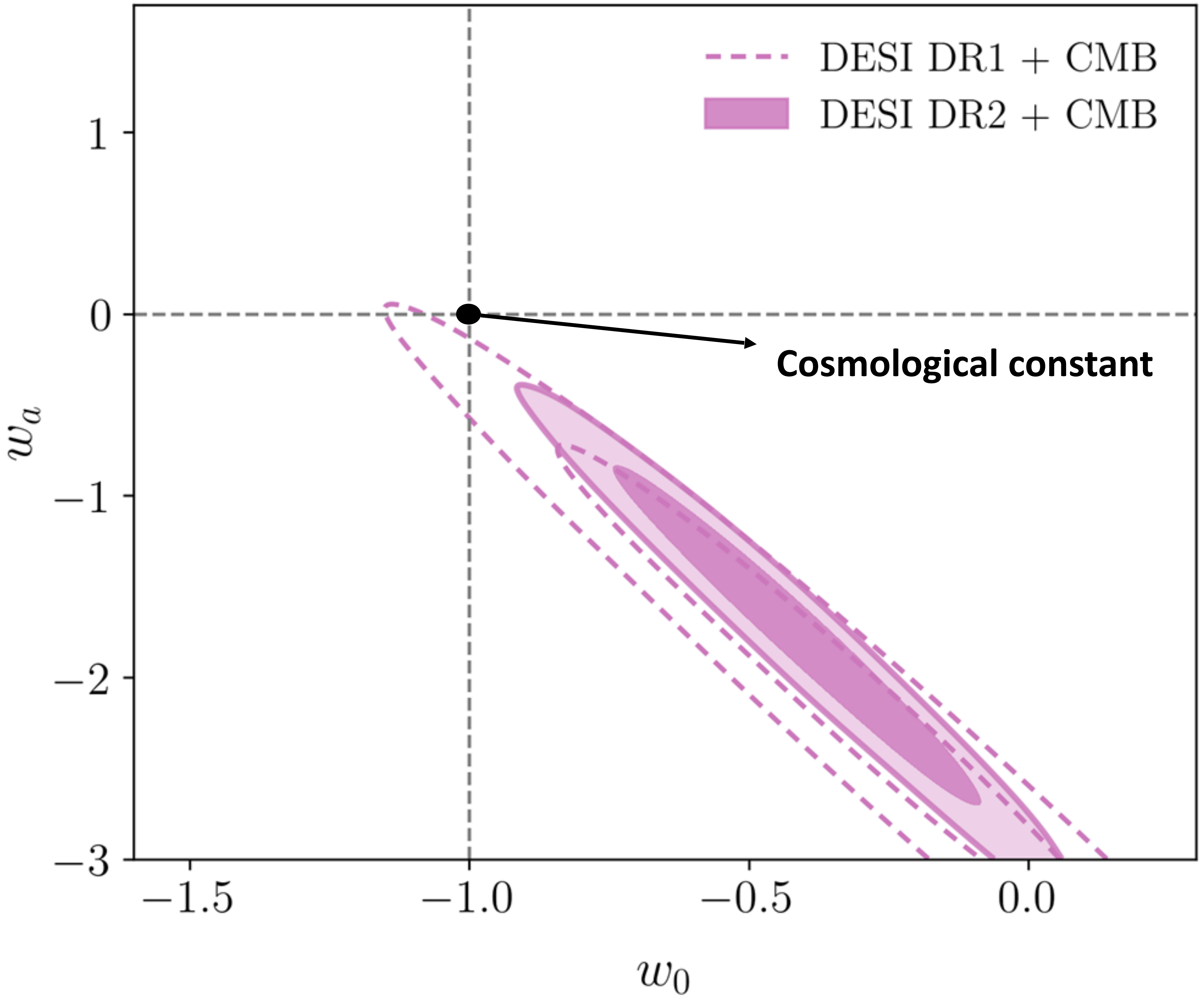
DESI DR2 Results II: BAO measurements and Cosmology

DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

Evolving Dark Energy

- DESI DR1 + CMB: 2.6σ from ΛCDM
- **3.1σ** preference for evolving dark energy with DESI DR2 + CMB

$$\left.\begin{aligned} w_0 &= -0.42 \pm 0.21 \\ w_a &= -1.75 \pm 0.58 \end{aligned}\right\} \textbf{DESI + CMB}$$



DESI DR2 Results II: BAO measurements and Cosmology

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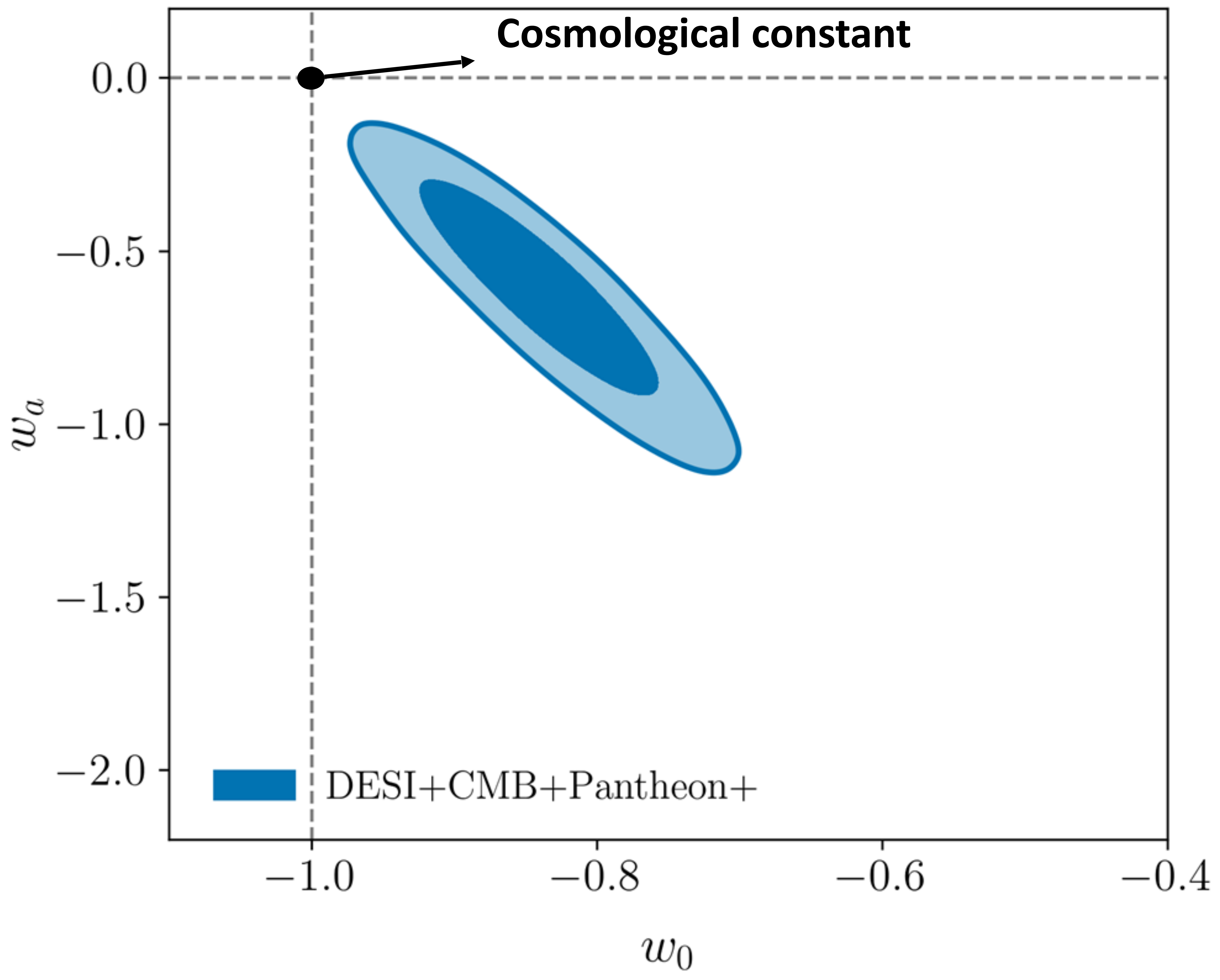
Evolving Dark Energy

Combining all DESI + CMB + SN

$$\underbrace{w_0 = -0.838 \pm 0.055 \qquad w_a = -0.62^{+0.22}_{-0.19}}_{}$$

DESI + CMB + Pantheon+ $\Longrightarrow$ 2.8σ



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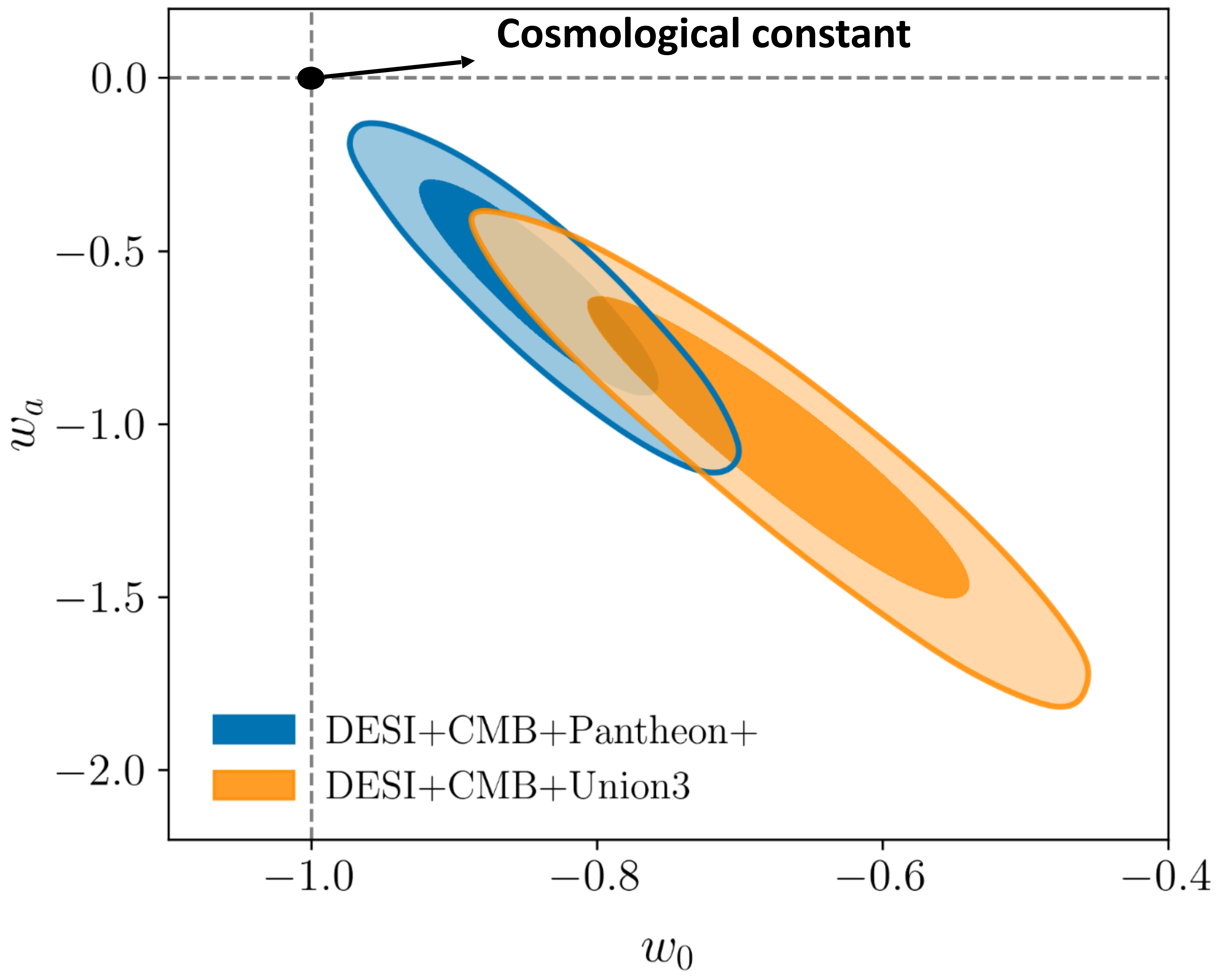
$$\underbrace{w_0 = -0.667 \pm 0.088 \qquad w_a = -1.09^{+0.31}_{-0.27}}$$

DESI + CMB + Union3 $\Longrightarrow$ 3.8σ



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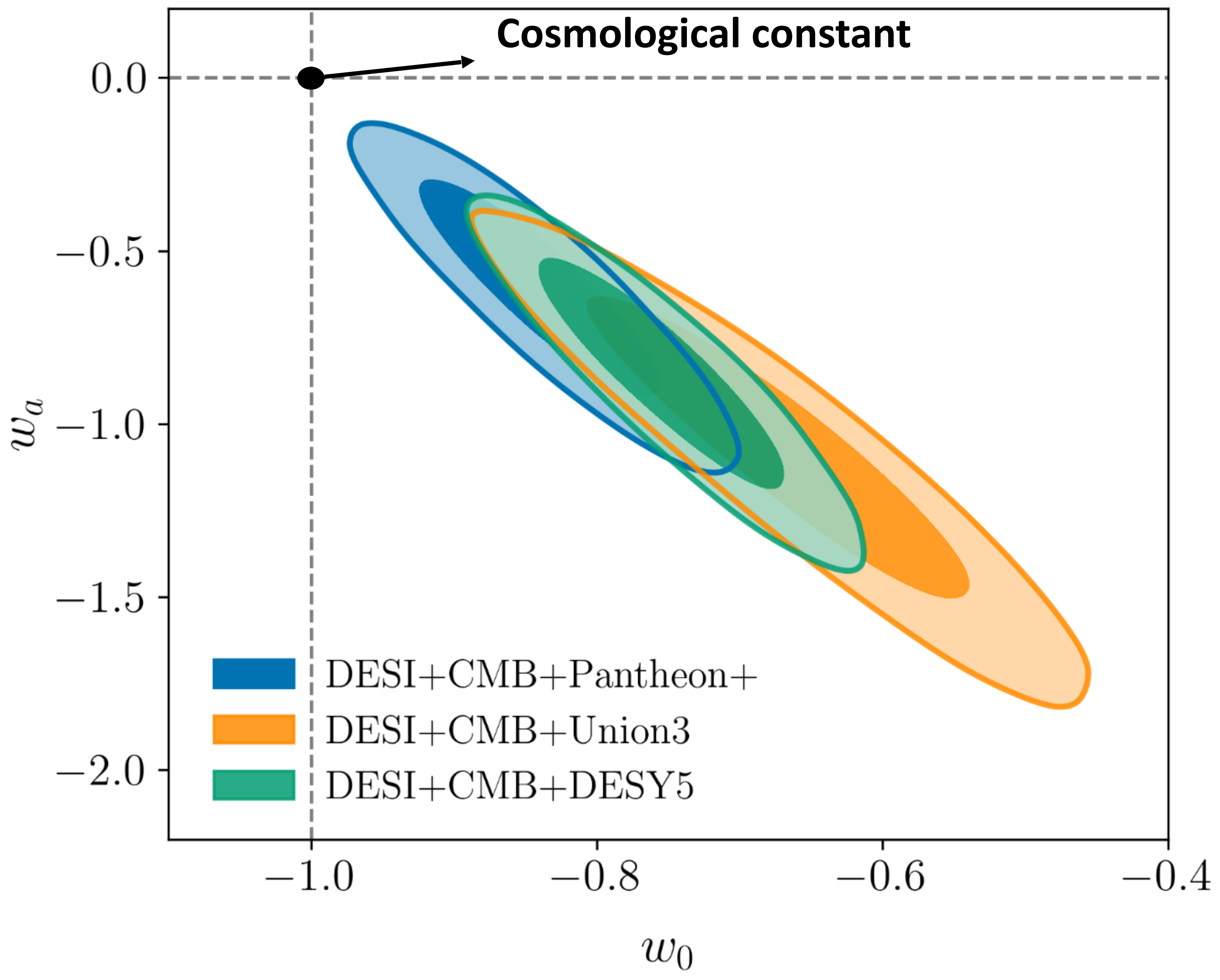
DESI + CMB + Union3 $\Longrightarrow$ 3.8σ

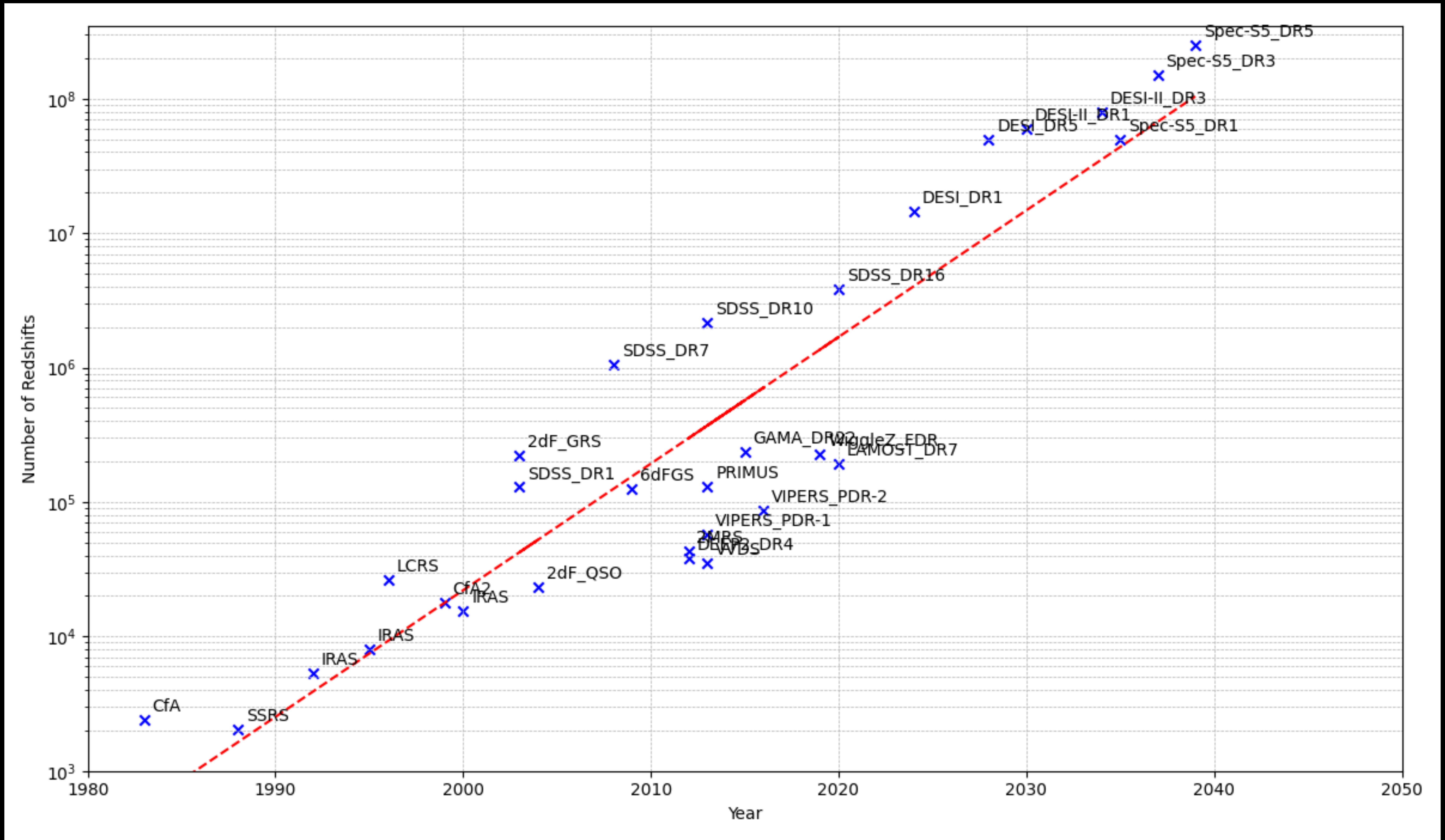
$$\underbrace{w_0 = -0.752 \pm 0.057 \qquad w_a = -0.86^{+0.23}_{-0.20}}$$

DESI + CMB + DESY5 $\Longrightarrow$ 4.2σ

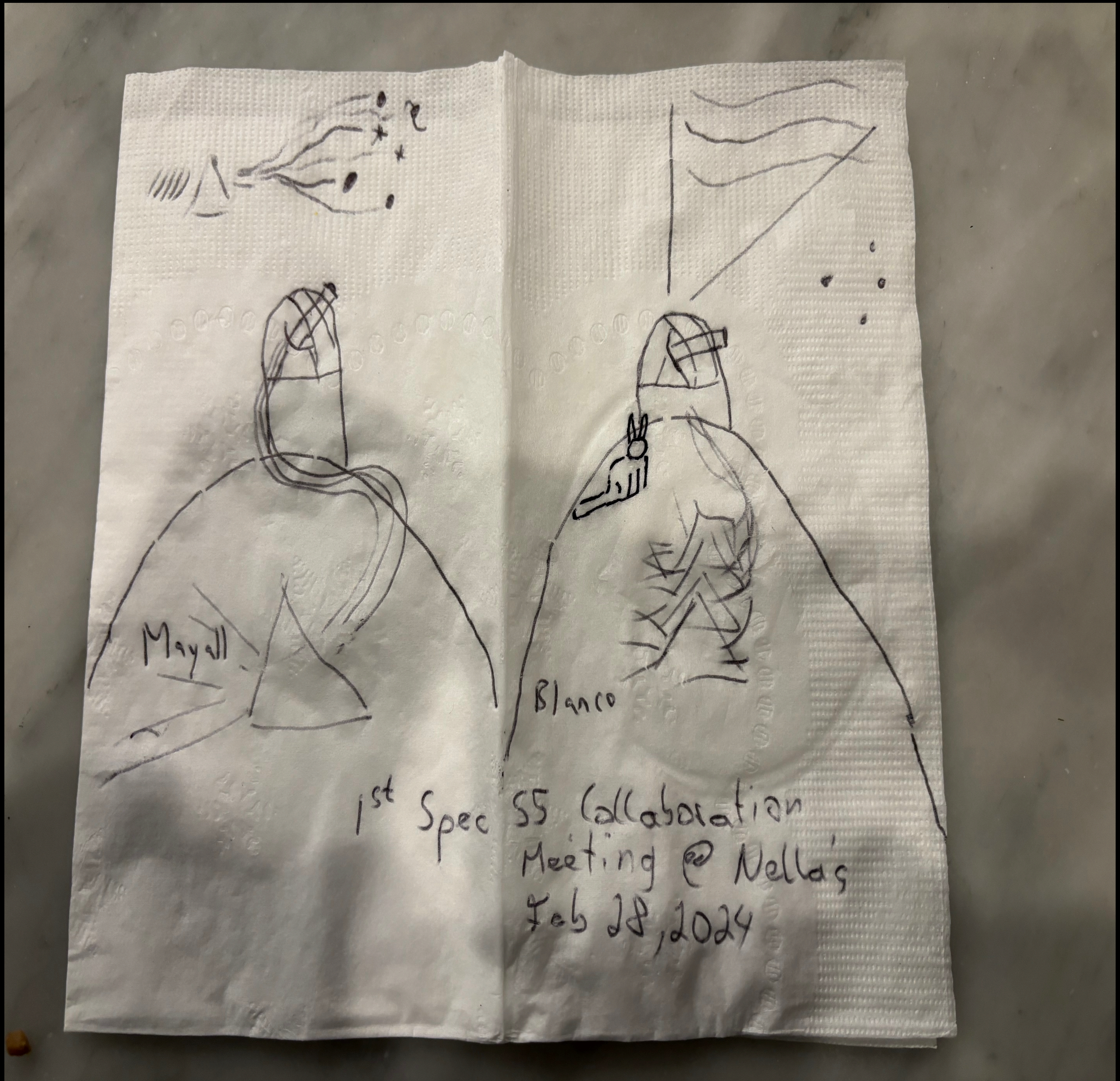


DESI DR2 Results II: BAO measurements and Cosmology

How will we learn more?



Spec-S5 is at a conceptual design stage



Spec-S5 rebuilds two existing telescopes to be 15X faster than DESI

Spec-S5 baseline design is to upgrade 2 existing telescopes (the Mayall & the Blanco) to each have a 6-meter collecting mirror, to have 26,000 fiber robots in total, and to have 46 spectrographs in total

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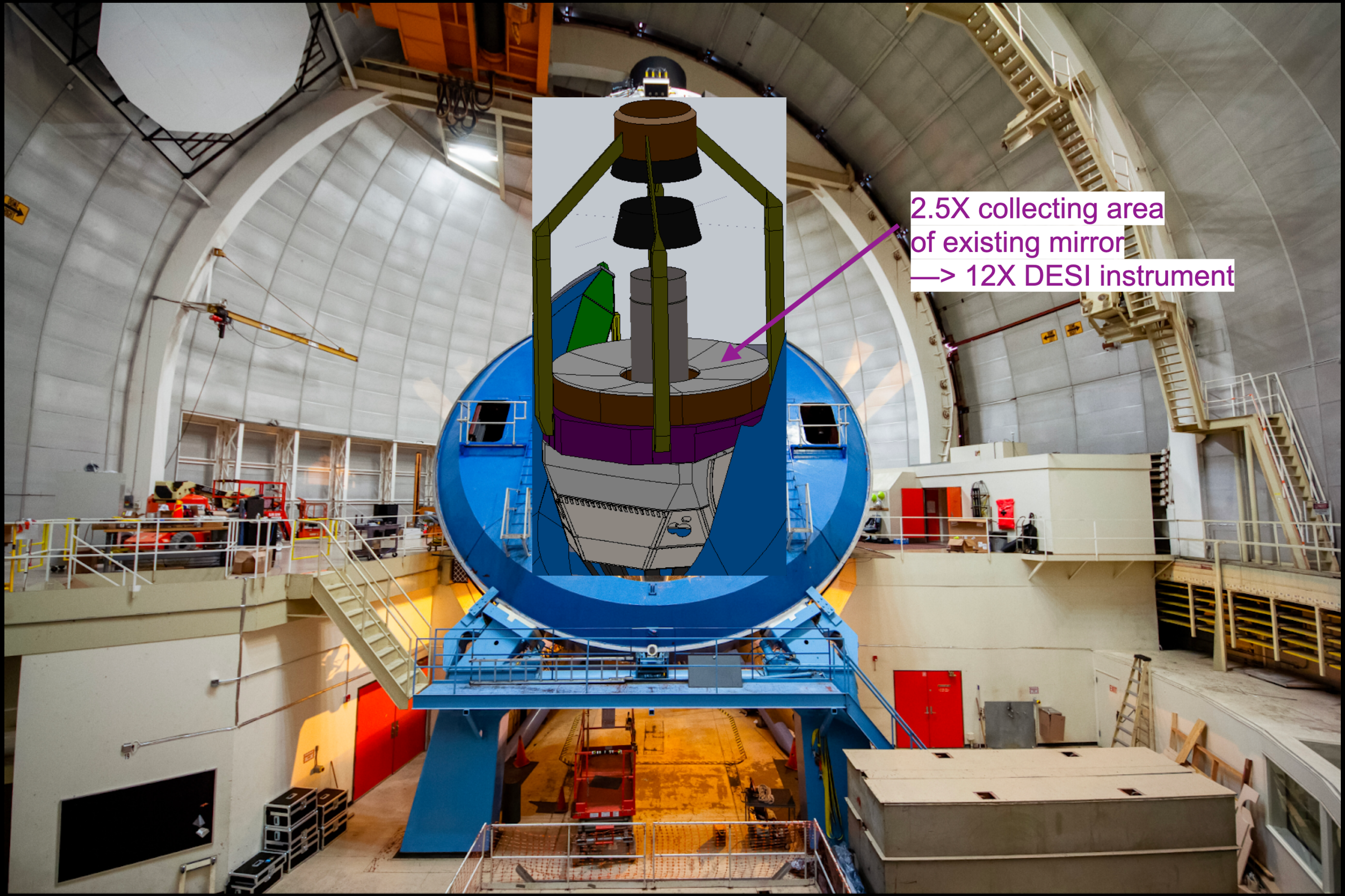
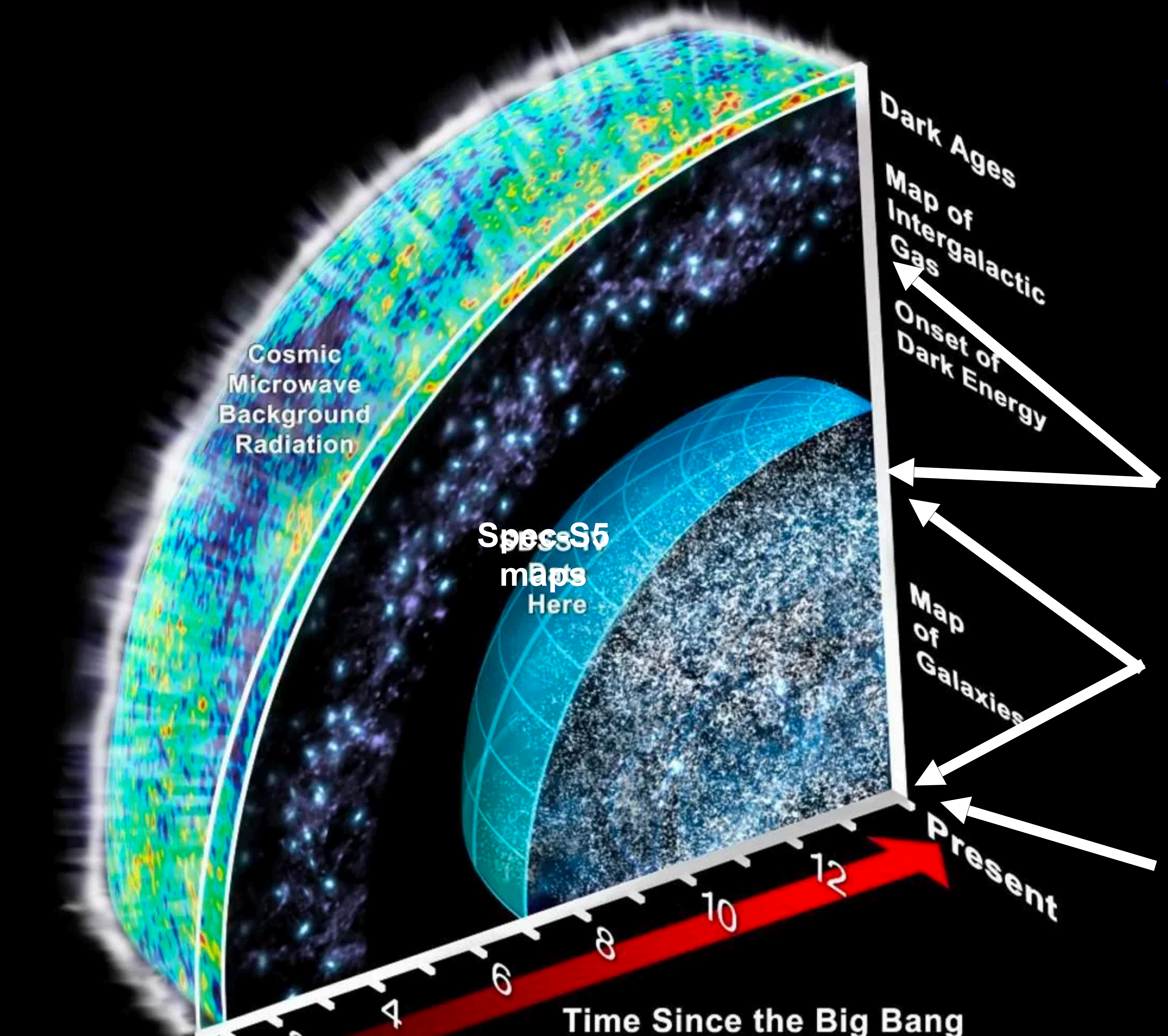


Spec-S5 Reference Design explores physics Beyond the Standard Model (BSM)

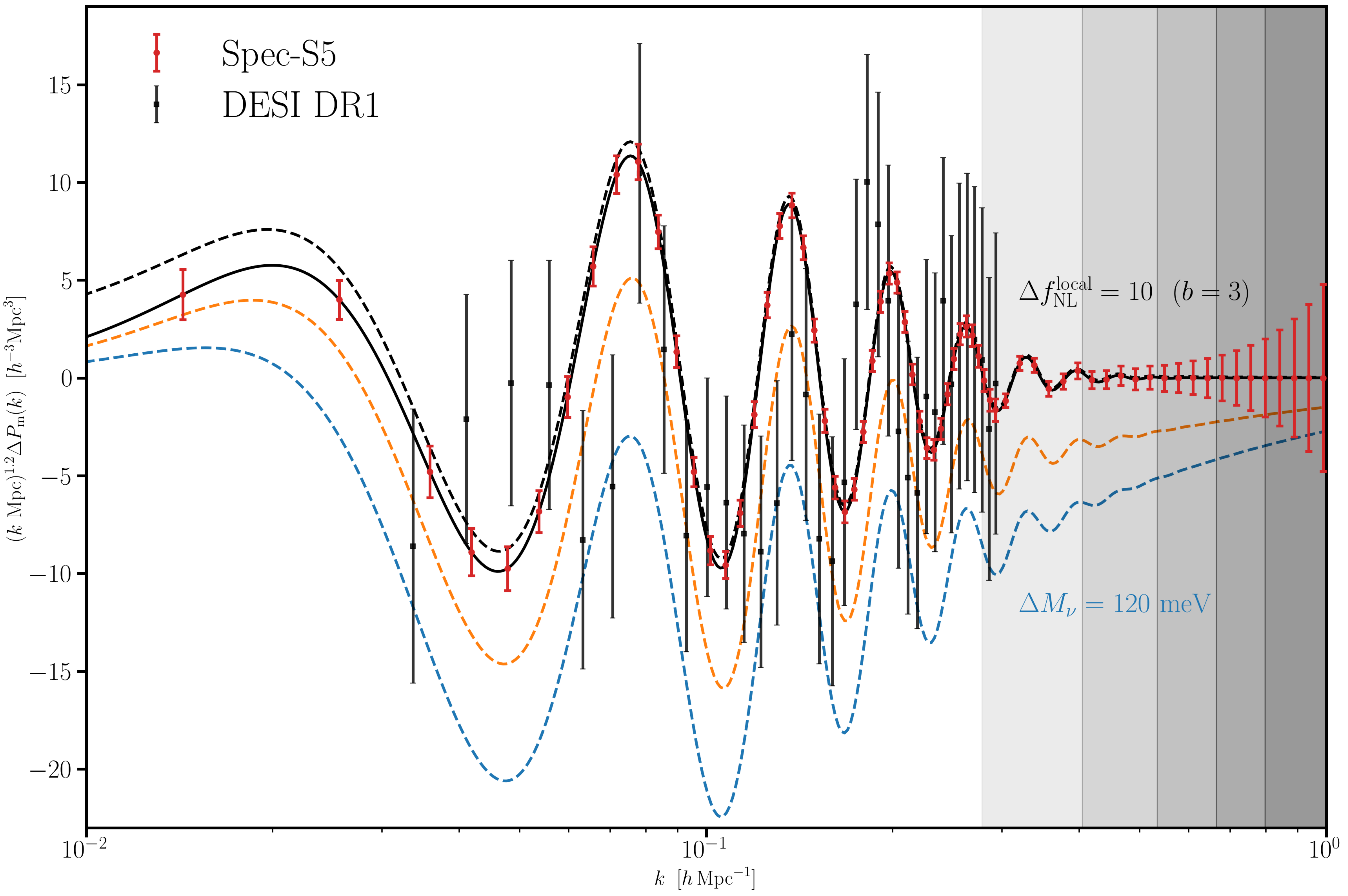


https://arxiv.org/abs/2503.07923

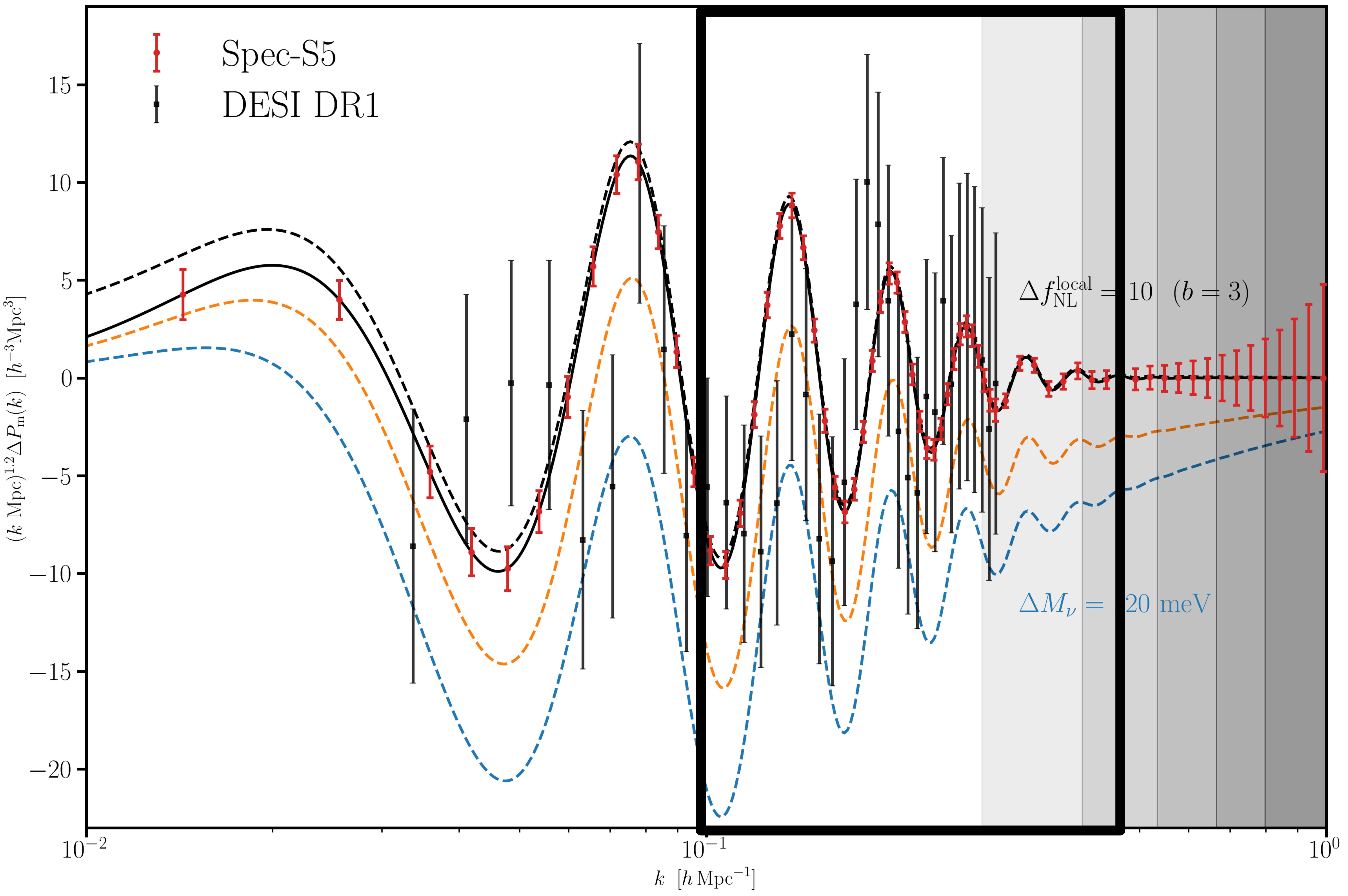
Spec-S5 will map **62 million galaxies** at $z > 2$ to study inflation + dark energy

Spec-S5 will map **130 million galaxies** at $z < 2$ to study late-time dark energy

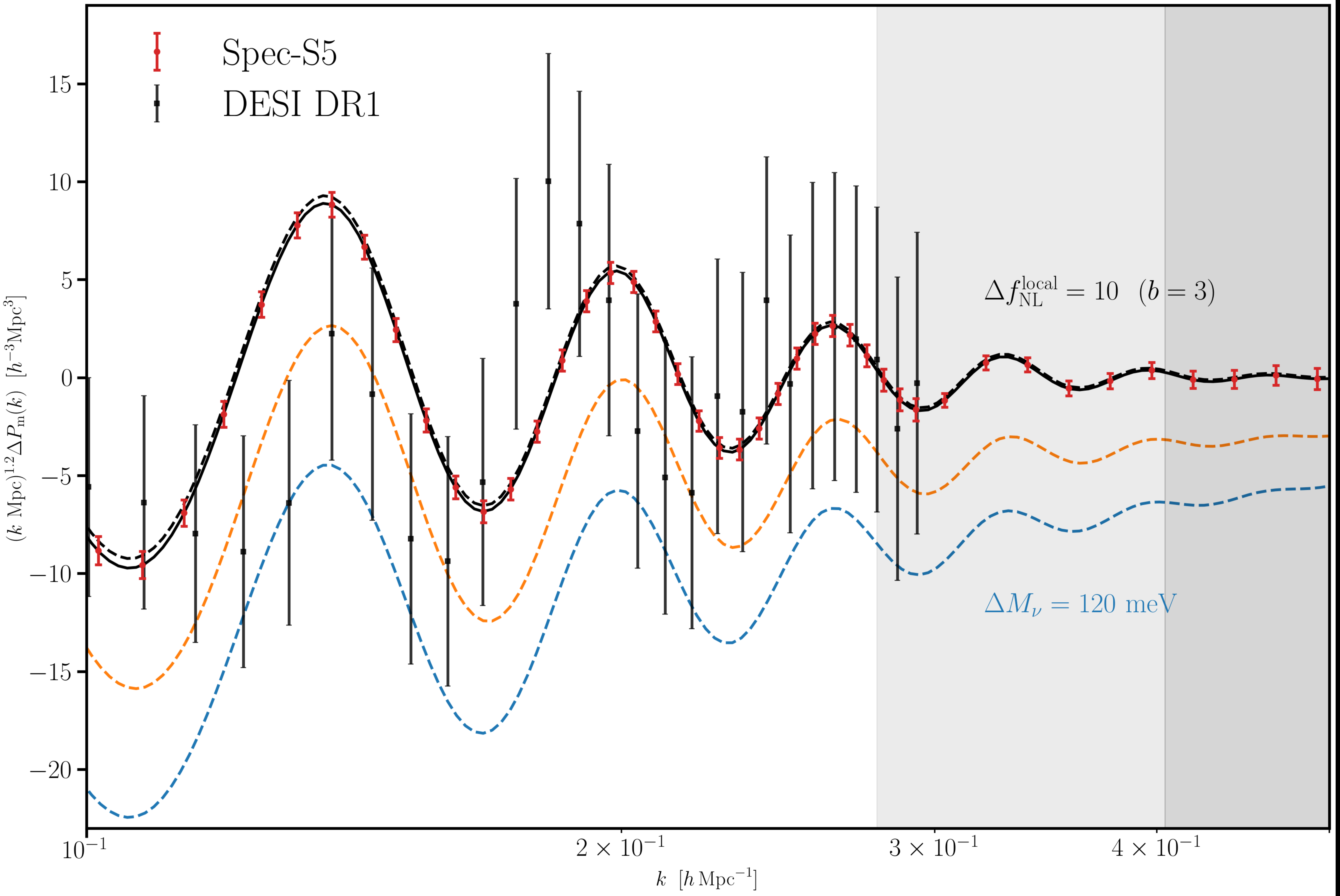
Spec-S5 will map **200 million stars** to study dark matter physics (+ dust maps!)



Spec-S5
DESI DR1
$\Delta f_{\rm NL}^{\rm local} = 10 \quad (b = 3)$
$\Delta M_\nu = 120$ meV
$(k\ \mathrm{Mpc})^{1.2} \Delta P_{\rm m}(k)\ [h^{-3}\mathrm{Mpc}^3]$
$k\ [h\,\mathrm{Mpc}^{-1}]$
15
10
5
0
−5
−10
−15
−20
10^{-2}
10^{-1}
10^{0}



Spec-S5
DESI DR1
$\Delta f_{\rm NL}^{\rm local} = 10 \quad (b = 3)$
$\Delta M_\nu = $ 20 meV
$(k \ \mathrm{Mpc})^{1.2} \Delta P_{\rm m}(k) \ [h^{-3}\mathrm{Mpc}^3]$
$k \ [h\,\mathrm{Mpc}^{-1}]$
15
10
5
0
−5
−10
−15
−20
10^{-2}
10^{-1}
10^{0}



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$k\ [h\,\mathrm{Mpc}^{-1}]$
15
10
5
0
−5
−10
−15
−20
10^{-1}
2×10^{-1}
3×10^{-1}
4×10^{-1}