

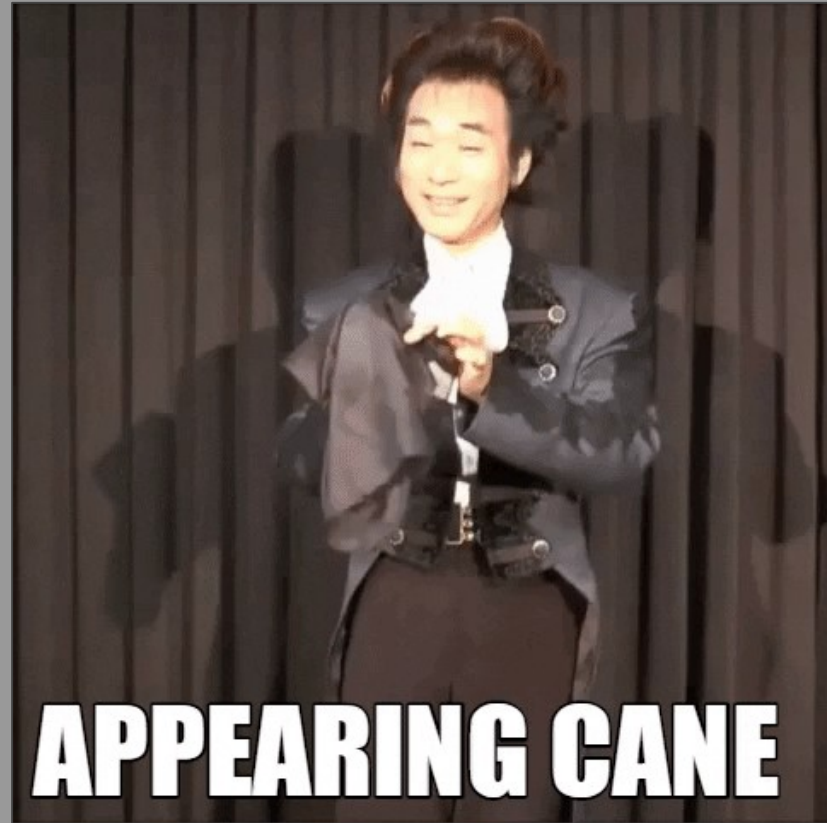
**Want to map the cosmos?  
Build yourself a tiny robot army!**

**Joe Silber**

**Mechanical Engineer @ Lawrence Berkeley National Lab  
QuarkNet, 2023-06-29**

# Pop quiz is this...

- A. Magic??
- B. Science!?
- C. Recklessly dangerous technology?!?\*?



TBLISI, 1988

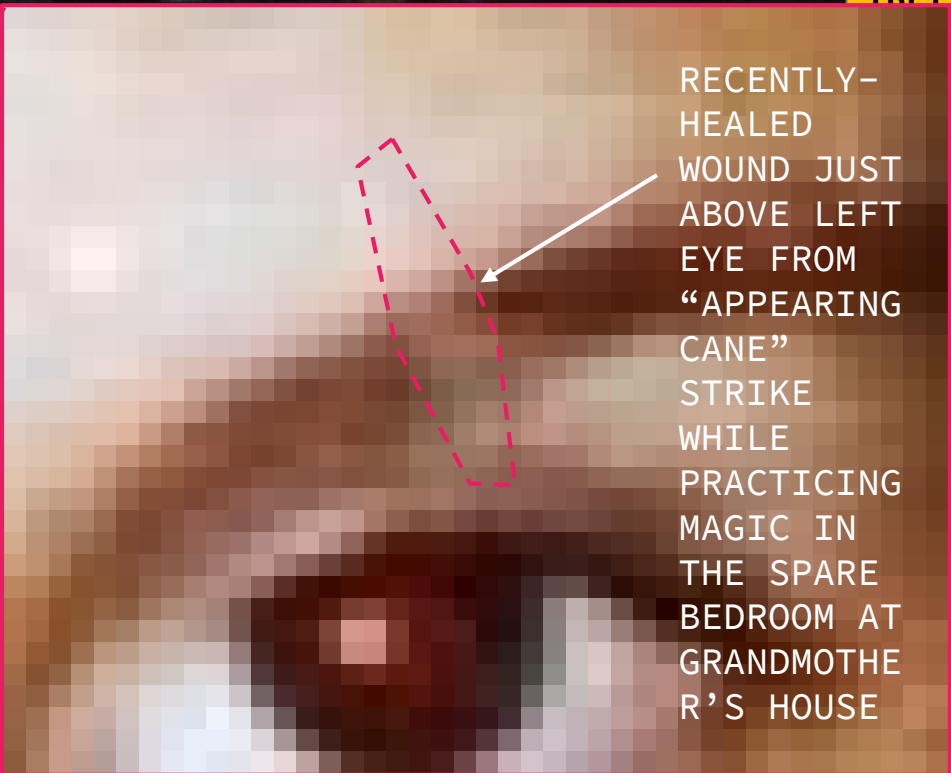
MY BROTHER  
STEVE

ME



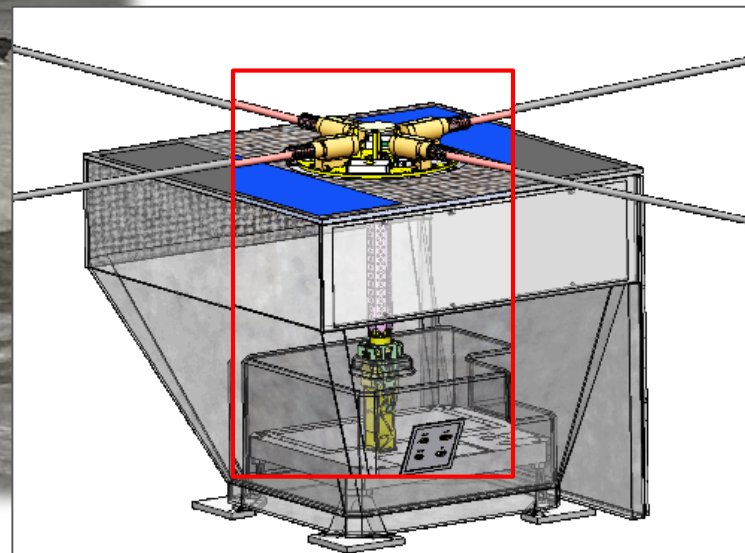
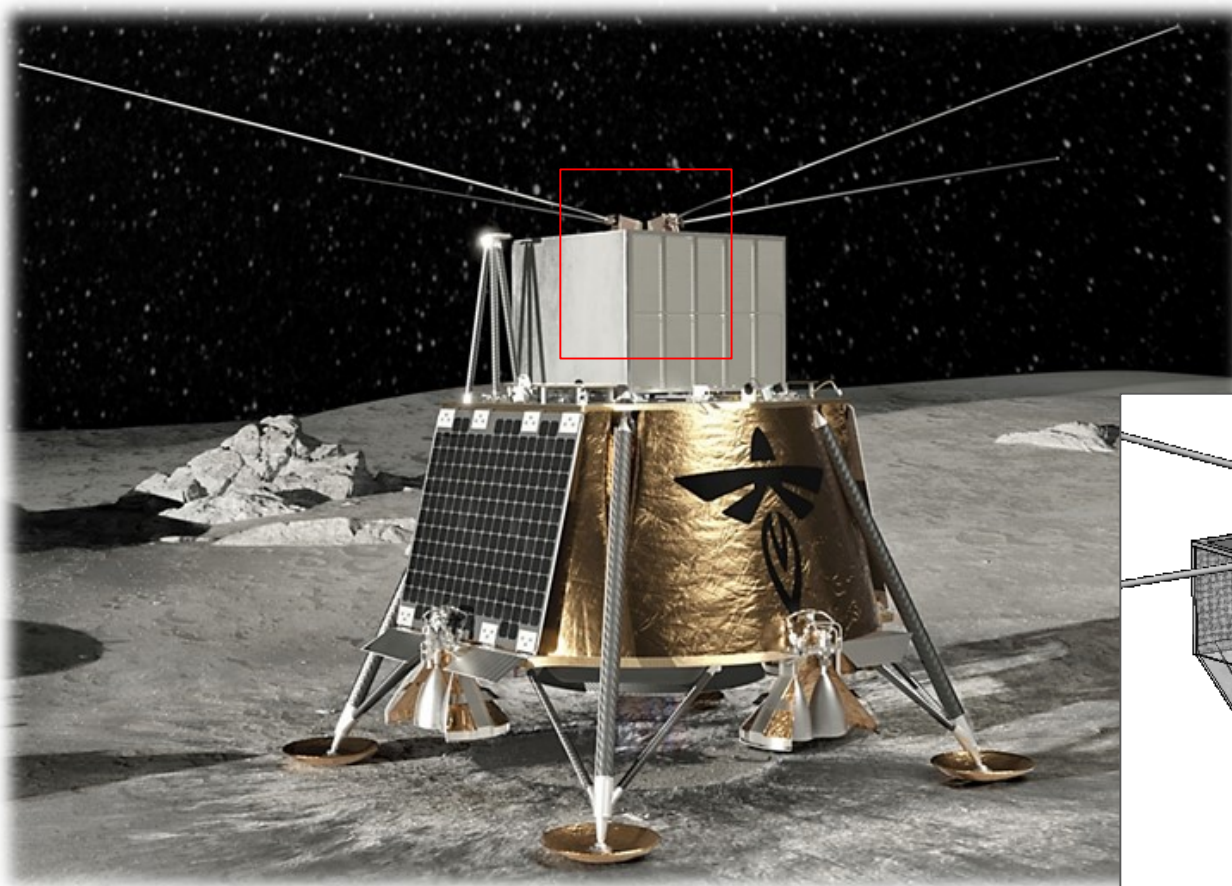
MY BRO  
STEVE

ME



RECENTLY-  
HEALED  
WOUND JUST  
ABOVE LEFT  
EYE FROM  
"APPEARING  
CANE"  
STRIKE  
WHILE  
PRACTICING  
MAGIC IN  
THE SPARE  
BEDROOM AT  
GRANDMOTHE  
R'S HOUSE

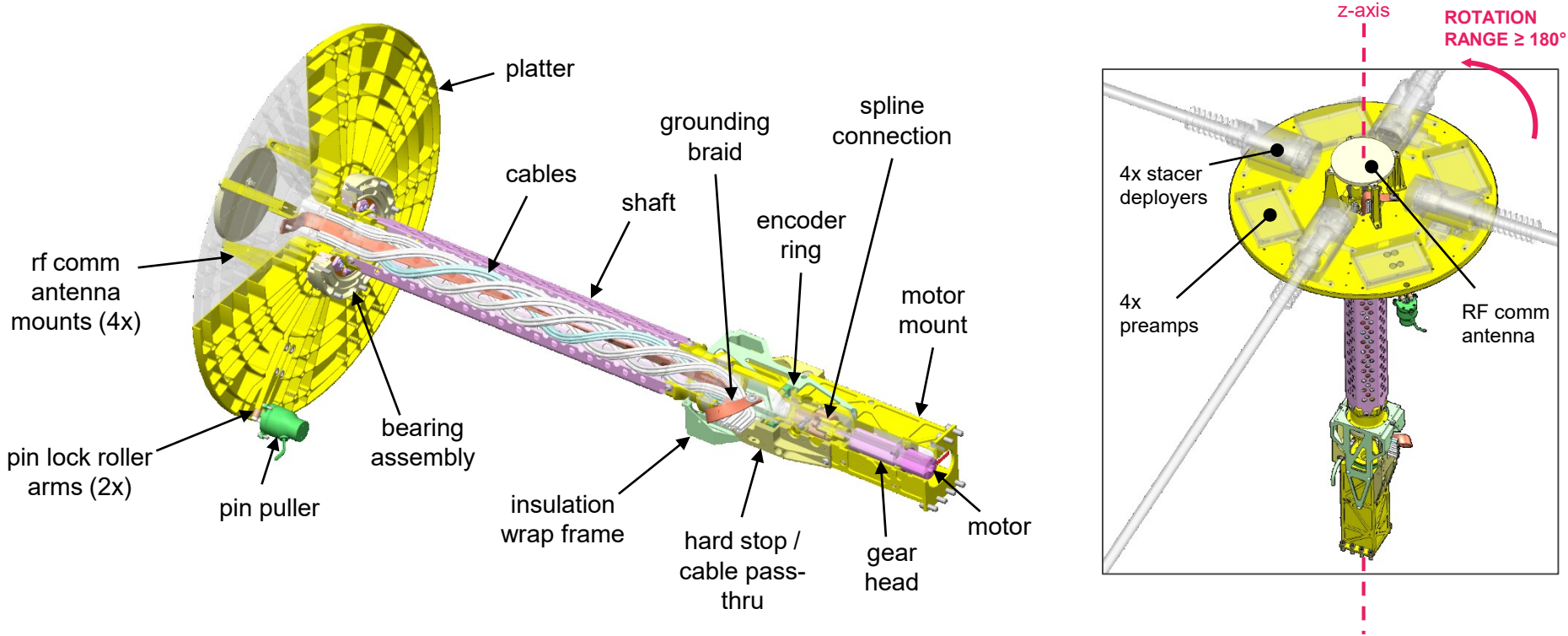
# The Lunar Surface Electromagnetics Experiment “LuSEE-Night”



**ROTATING “STACERS” ANTENNA ARRAY**

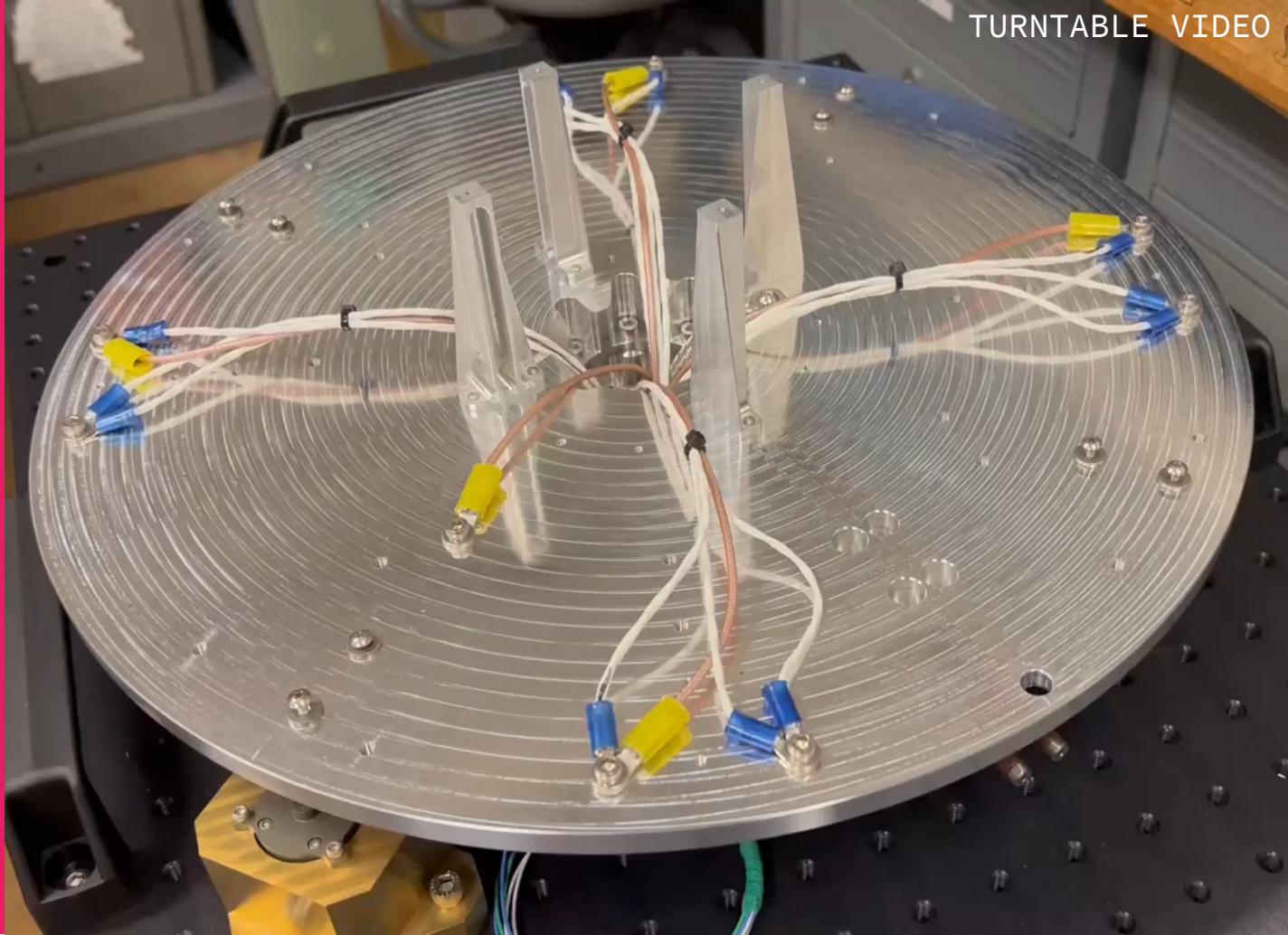


# LuSEE-Night "Carousel" design



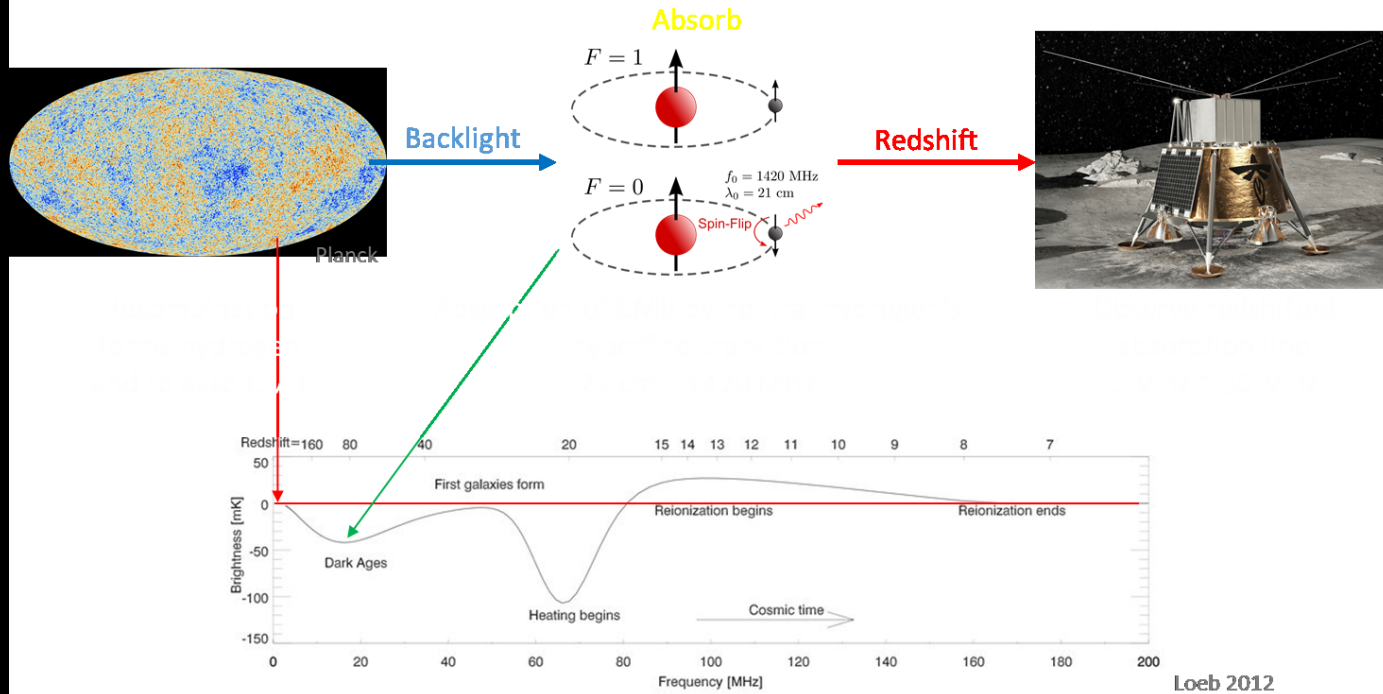
# Action shot

prototype  
LuSEE-Night  
carousel





# How can we observe **THE DARK AGES**



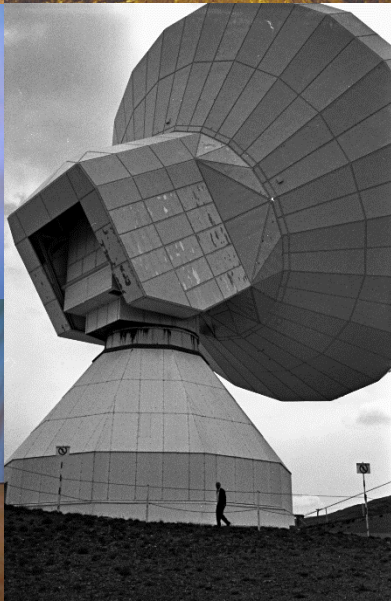
- No luminous source during the Dark Ages.

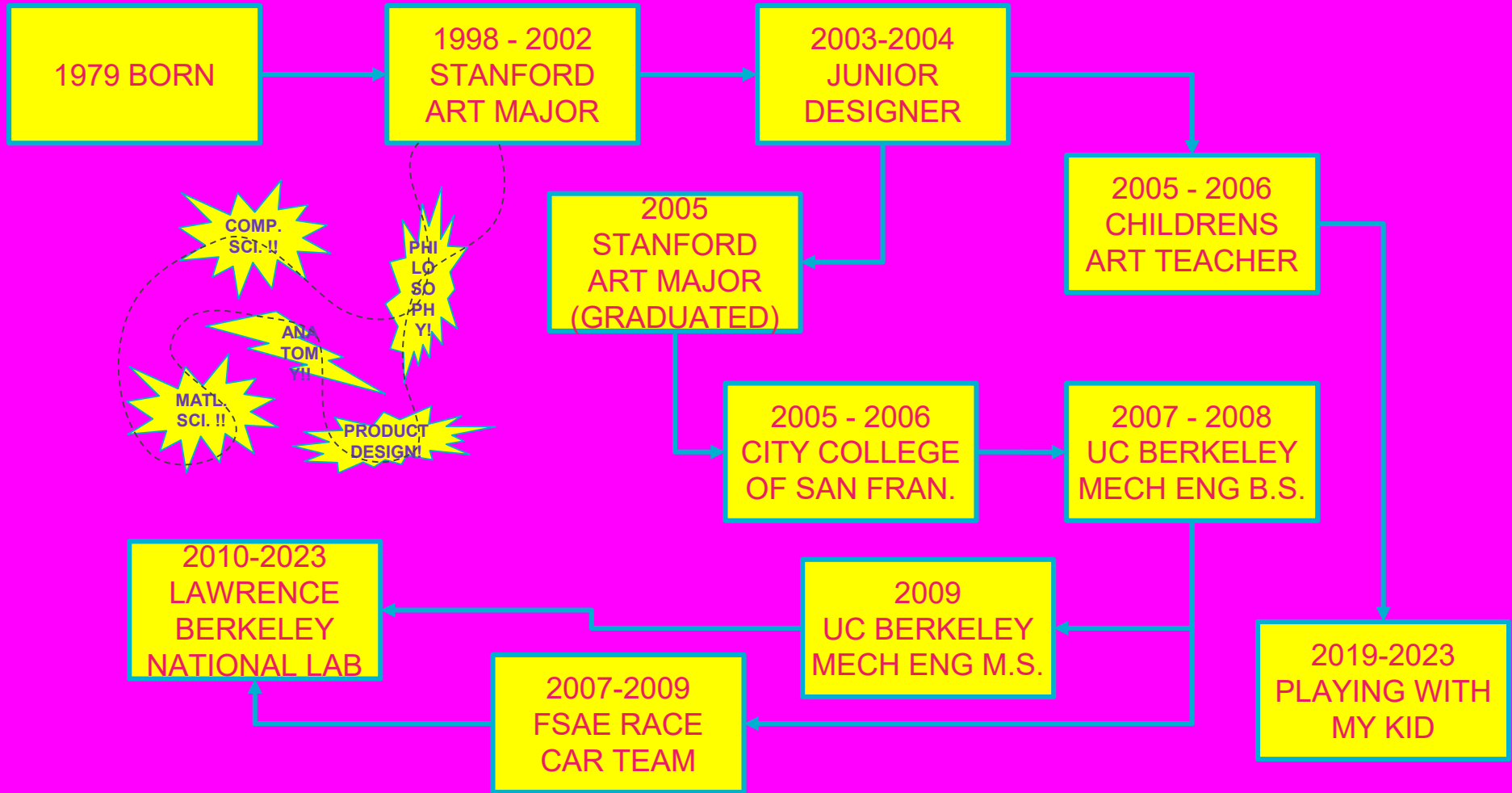
1 MHz ~ 50 MHz today

Slide credit:  
Aritoki Suzuki











B21 - UC BERKELEY FORMULA S.A.E. - 2008



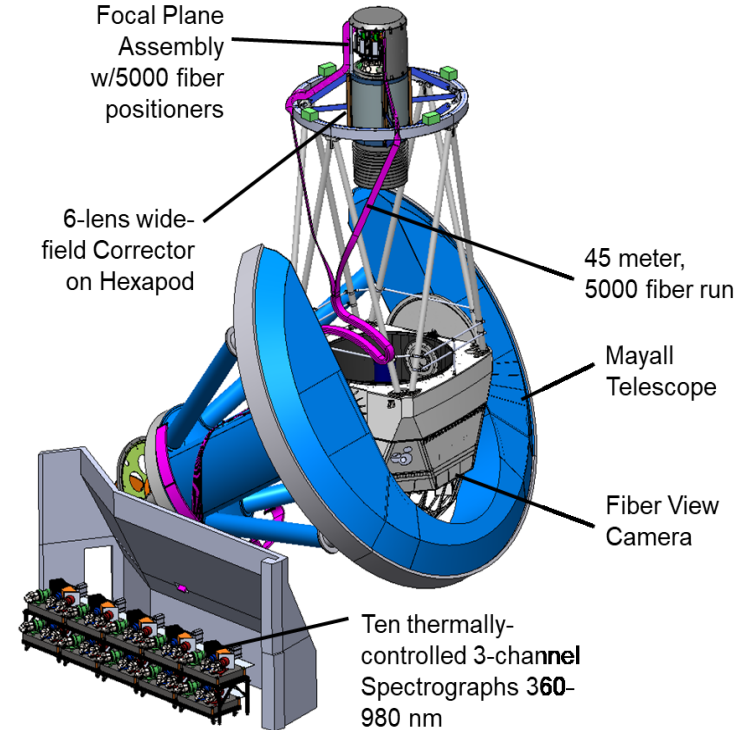
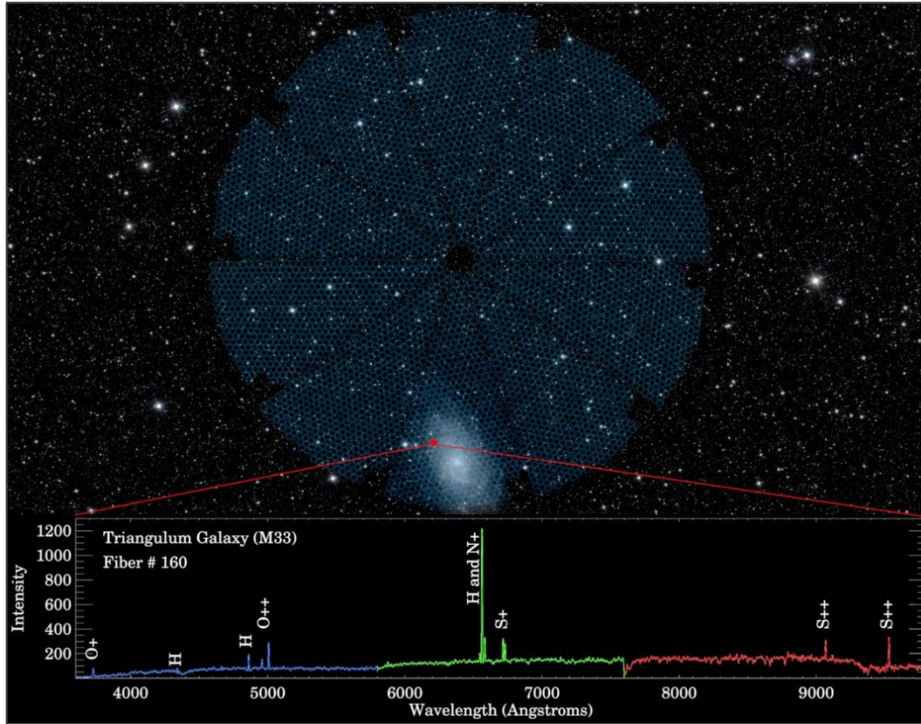
# Questions?



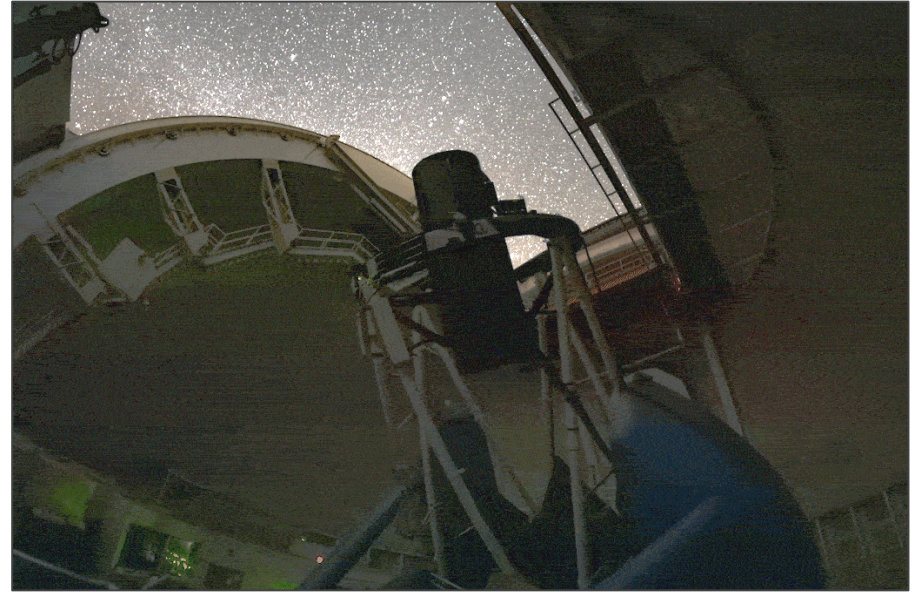
# ROBOT ARMY

# Dark Energy Spectroscopic Instrument = "DESI"

## Measure dark energy expansion of universe to < 1% accuracy

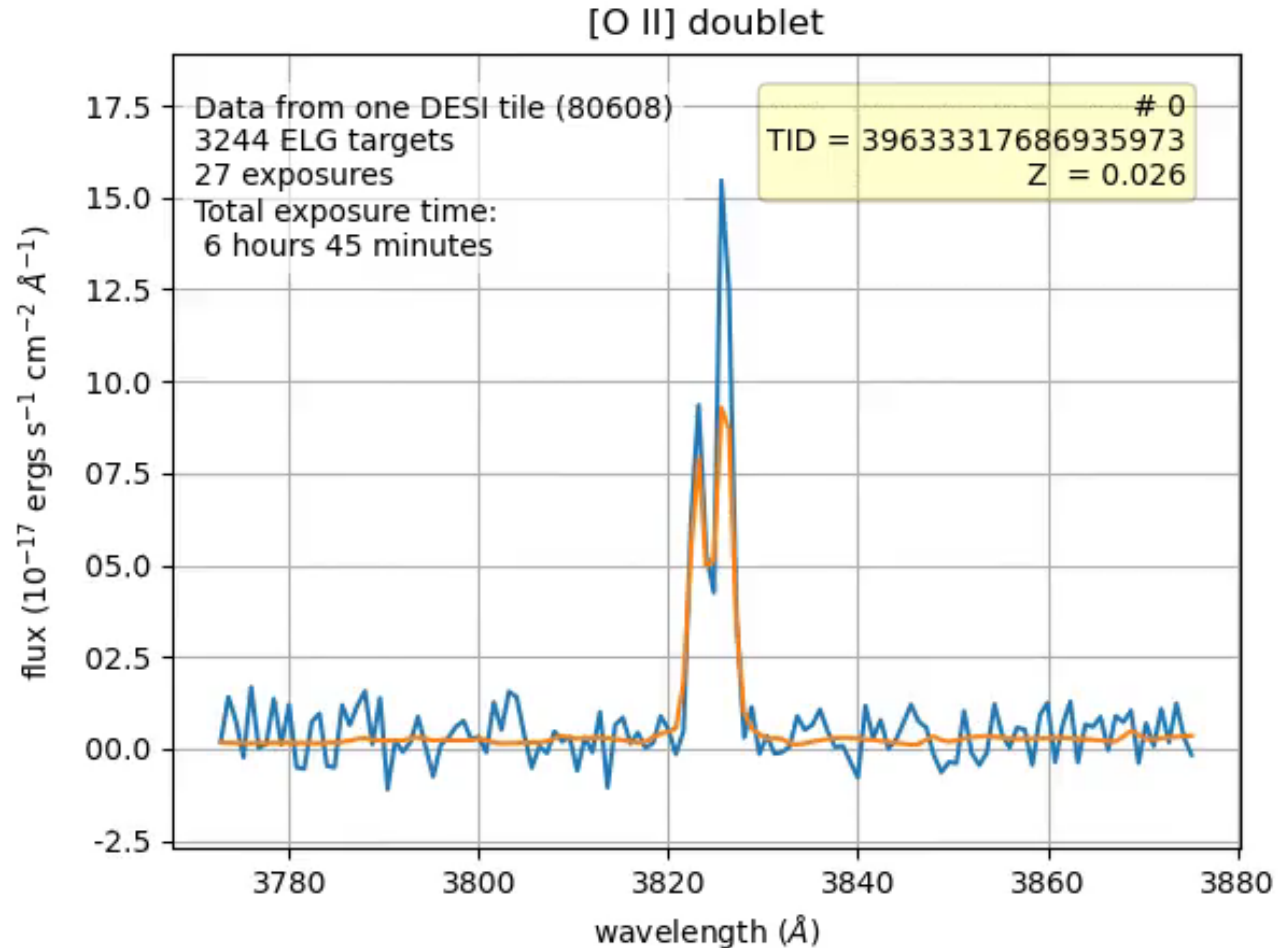


64,000-stars-and-galaxies-per-night-machine. 5 years.  
Goal: **35+ million** high resolution galaxy spectra

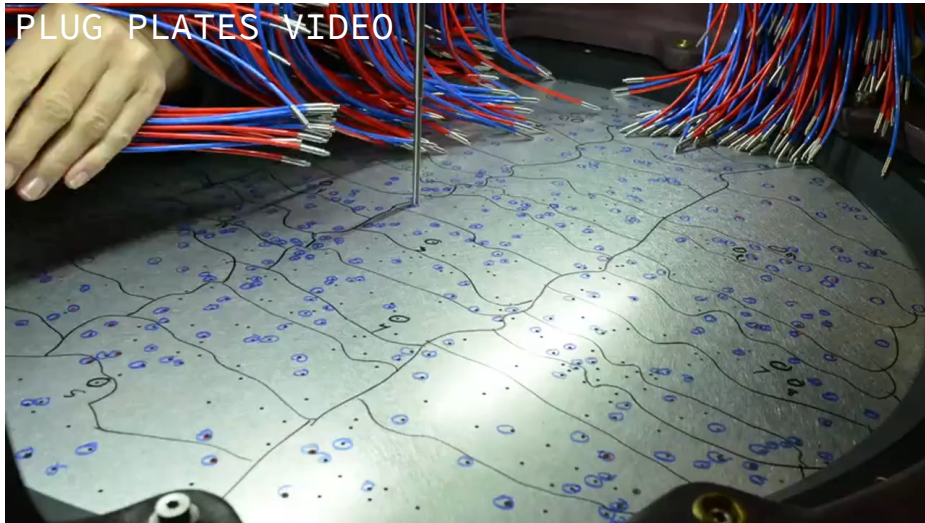
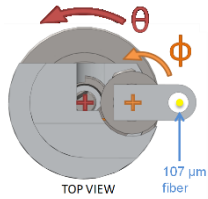


# Data example

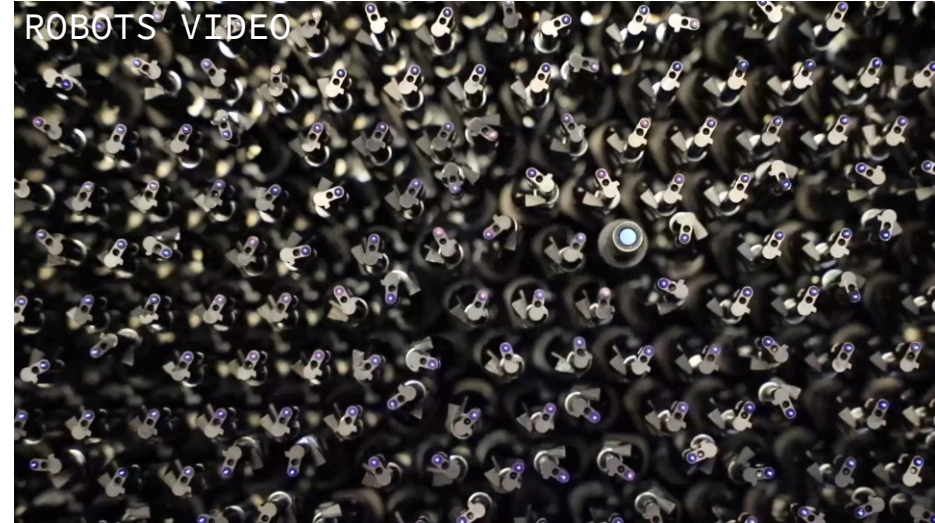
- Movie compiles one field of galaxies
- Each frame is data from a single DESI fiber on a different galaxy
- Spectra are centered on the OII doublet



# Why robots?

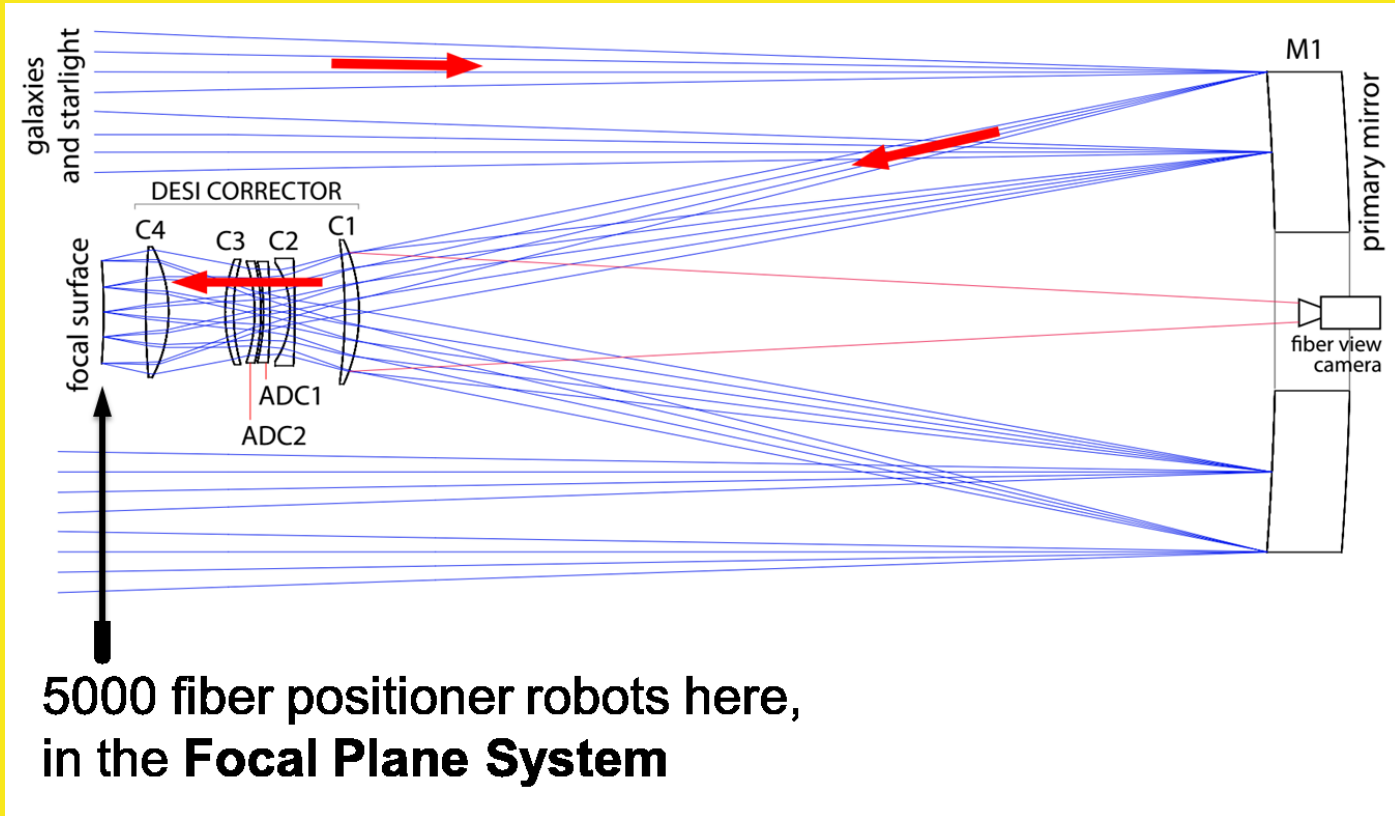


**20 years** of Sloan Digital Sky Survey  
→ **3.8 million redshifts**



**Initial year** of DESI operations  
→ **9.2 million redshifts**

# How light from the galaxies gets to the robots...



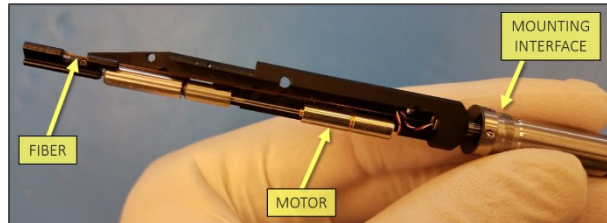
# DESI Focal Plane

R&D → Build → Install: 2012-2019

5,000 fiber positioning robots to gather spectra of 35 million galaxies.

Largest ever multi-object fiber-fed spectrograph, for dark energy cosmology.

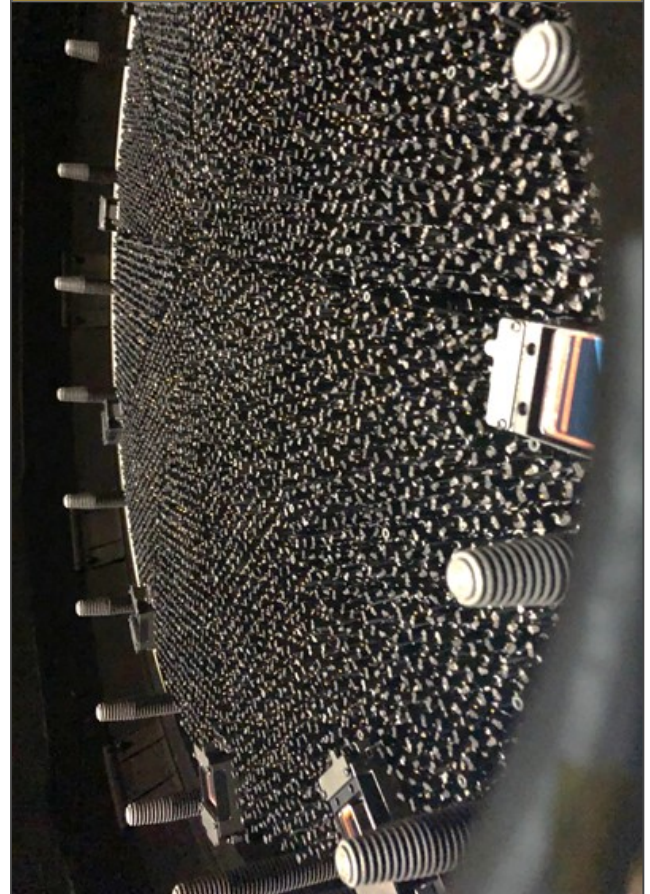
**(I was the lead engineer, designer, and project manager of building the focal plane system.)**



DESI FIBER ROBOTS ARRAY, 10.5 mm PITCH, OVERLAPPING PATROL RADIUS

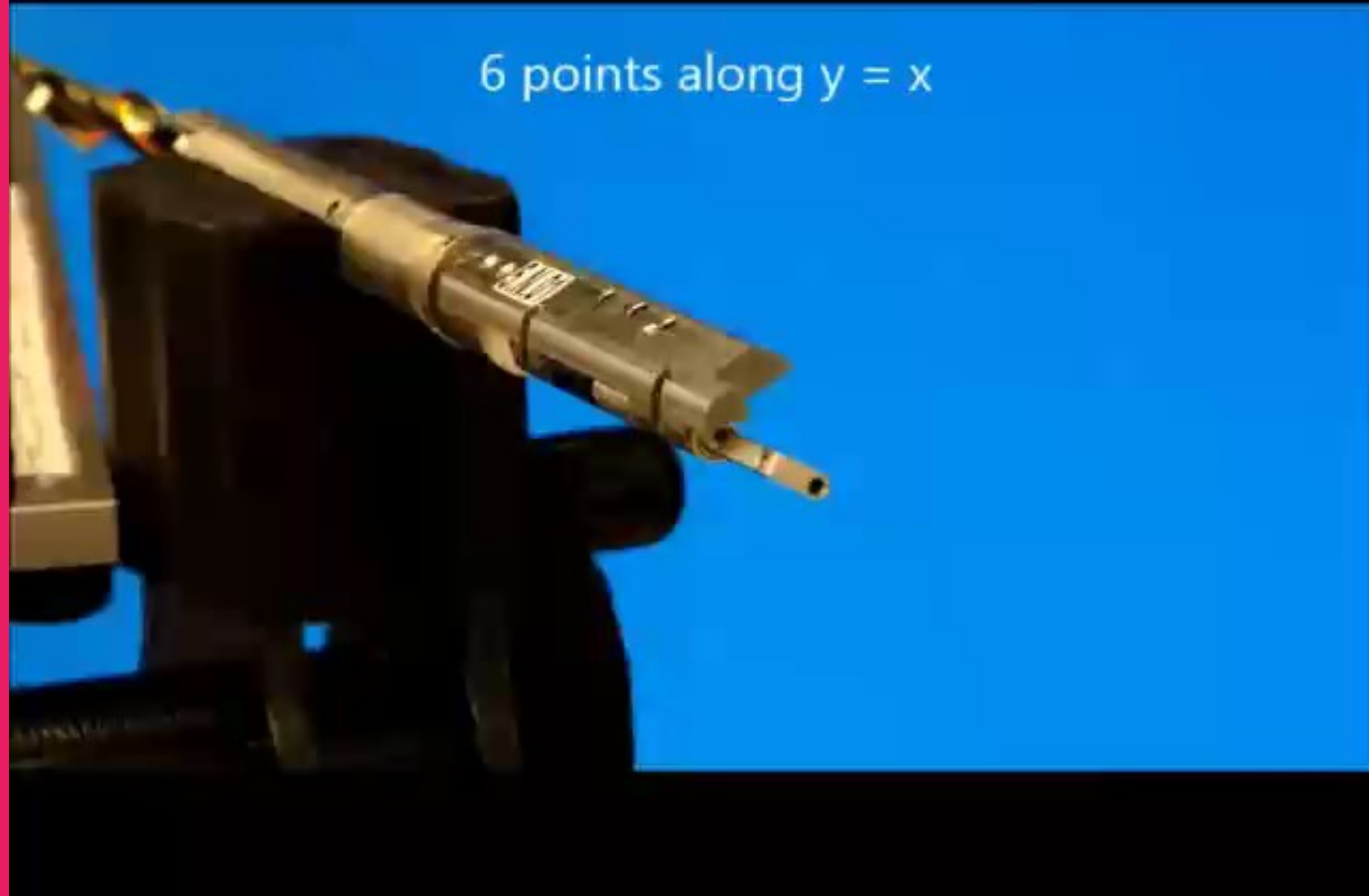


VIEW THROUGH SIDE PORTHOLE OF DESI FOCAL PLANE, AS-INSTALLED AT MAYALL TELESCOPE



# Fiber robot motion

2 rotational  
axes  $\rightarrow$  patrol a  
circular zone

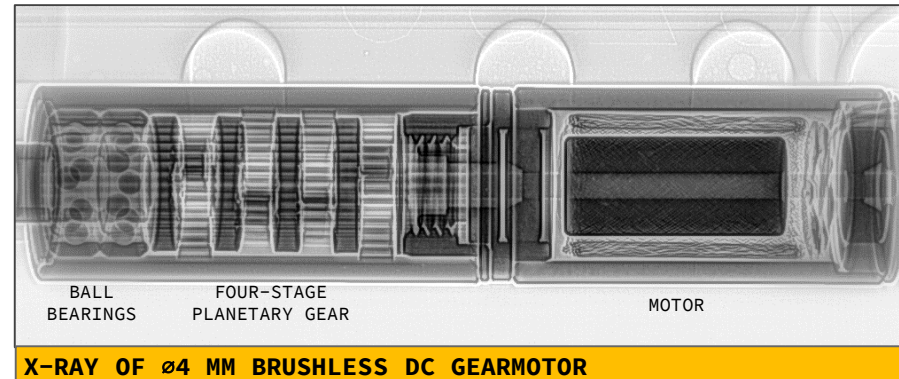
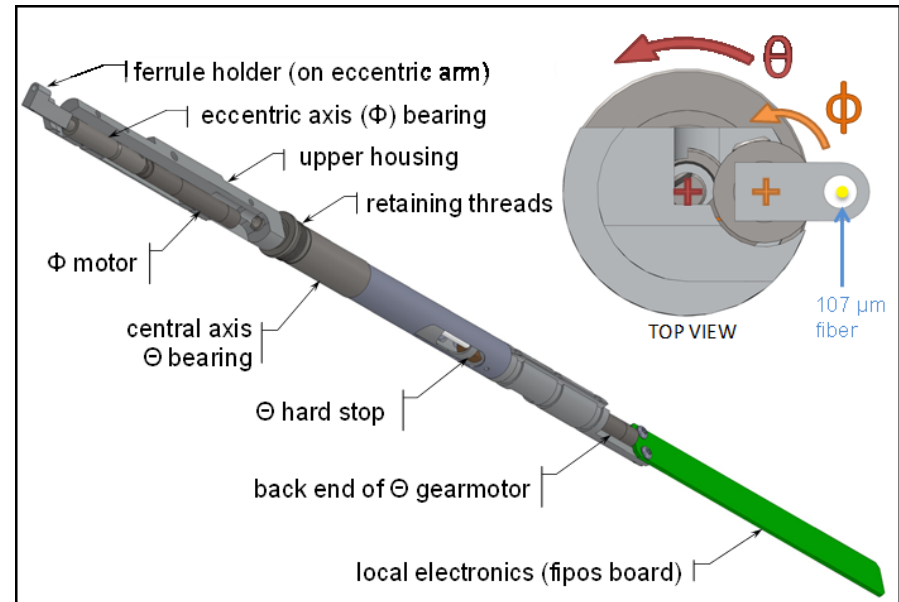


6 points along  $y = x$

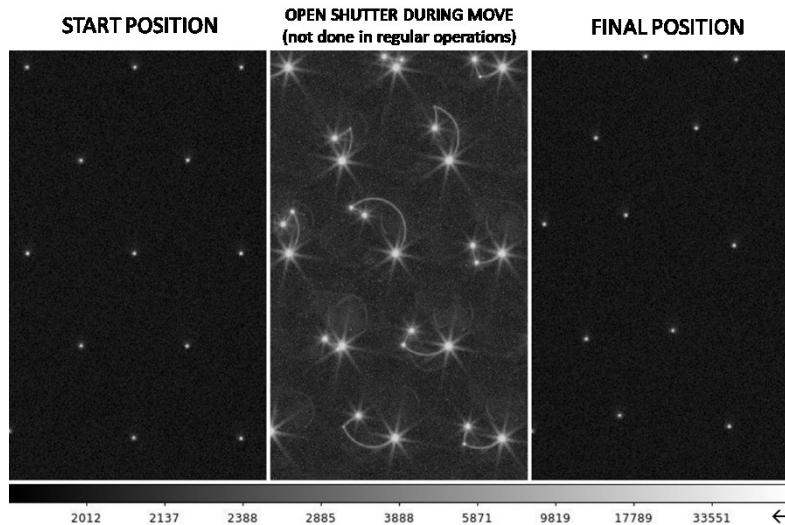
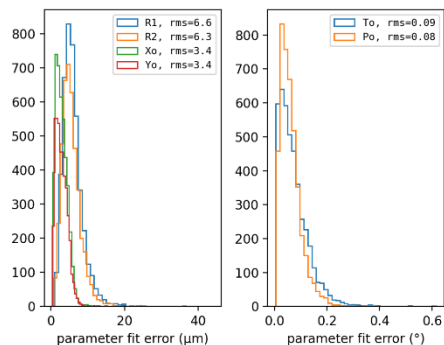
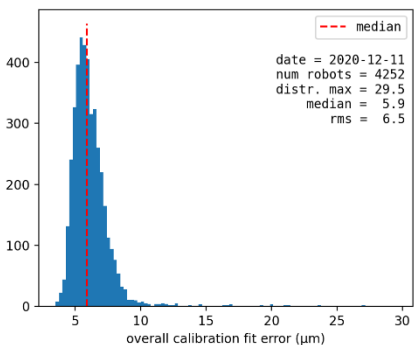
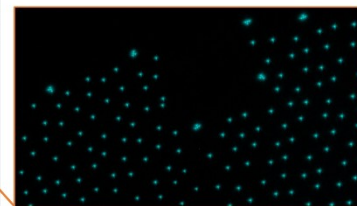
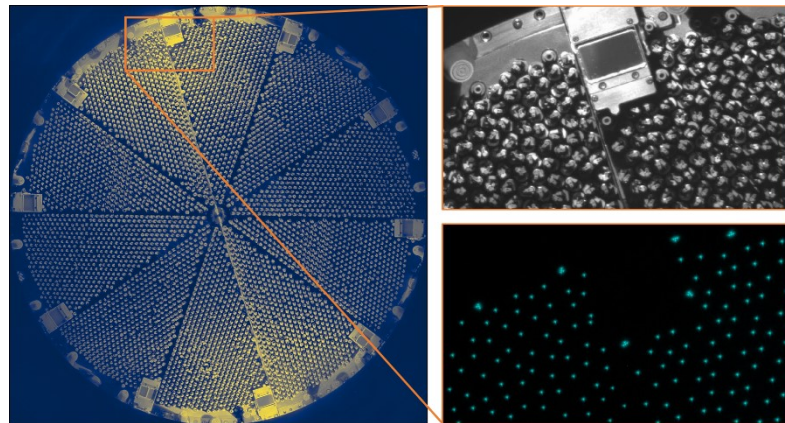
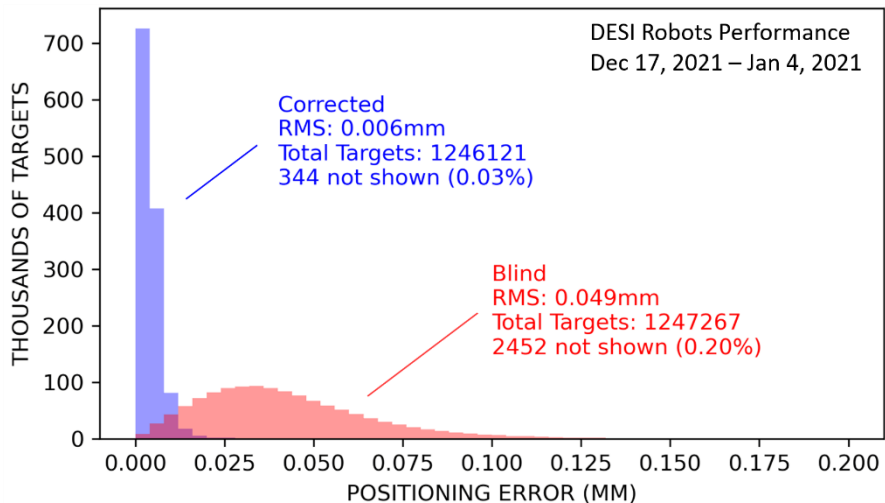


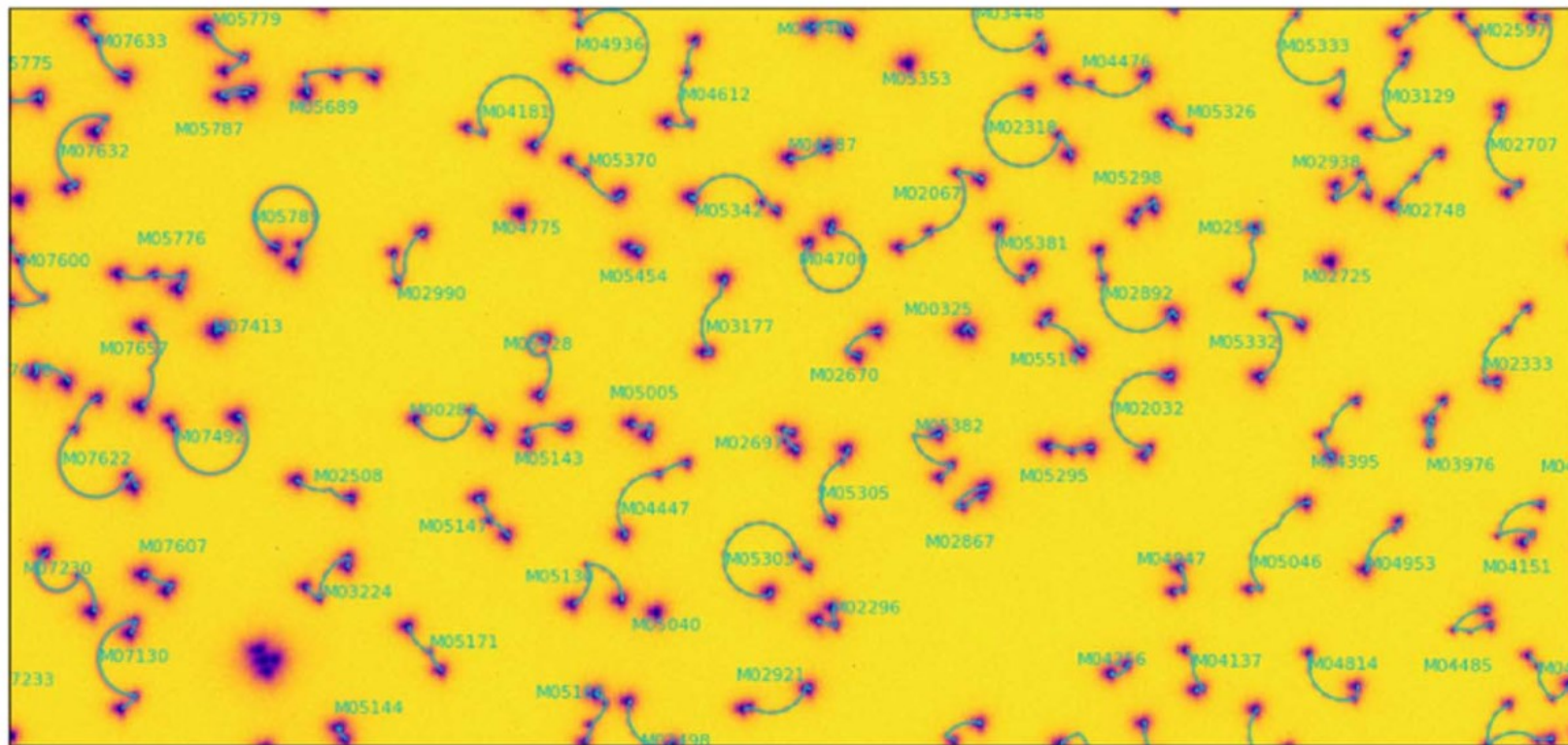
# FIBER ROBOTS

- 2 rotational axes
- Driven by independent  $\varnothing 4$  mm 337:1 gear motors
- 10.5 mm avg pitch between neighboring units
- Integrated drive electronics
- 22 parts + 10 fasteners
- Developed by Berkeley
- Production by University of Michigan (UM)
- 7148 complete units produced



# Positioning accuracy (req't = 10 $\mu\text{m}$ RMS)





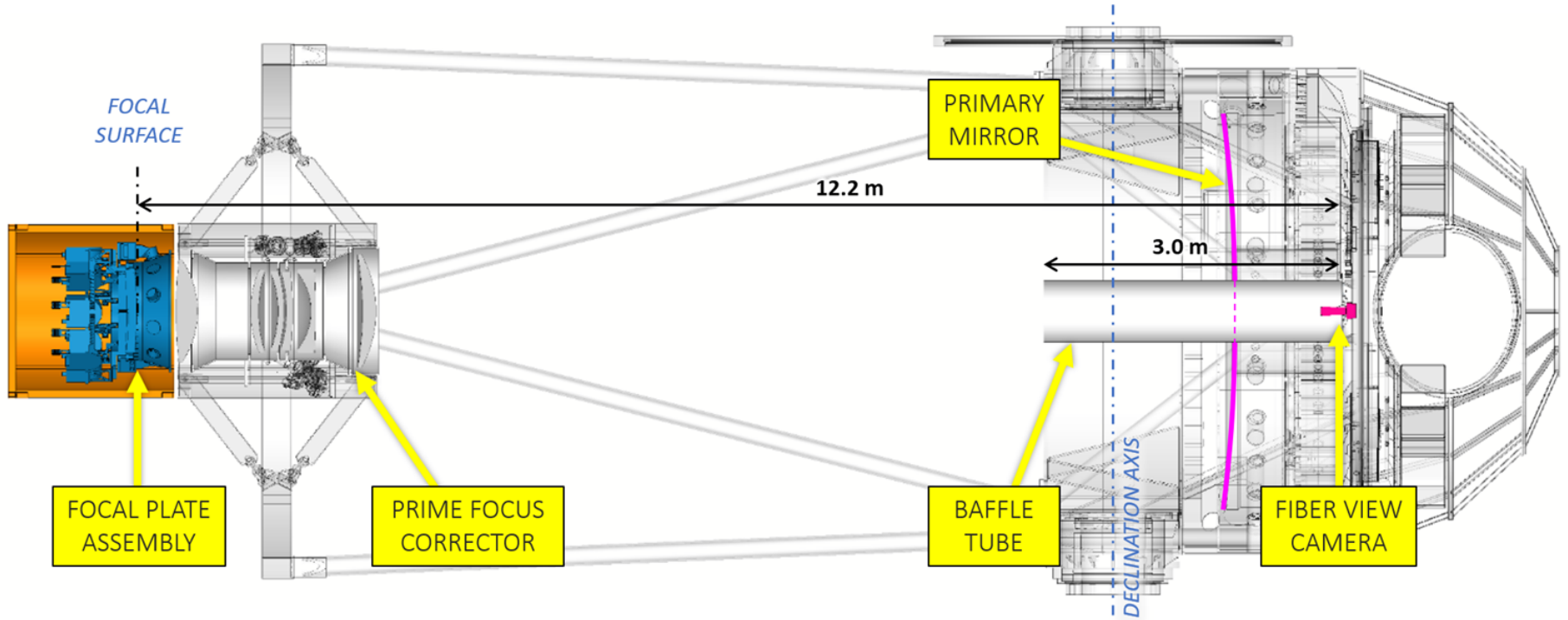
**Figure 25.** Motion paths of positioners, imaged by leaving the FVC shutter open and the fiber backlit during the move. Higher image saturation occurs at pause points during the path. Arcs of motion are naturally dashed due to pulse-width modulation of the fiber backlight source. Positioner id numbers and motion paths (thin solid lines) are overlaid.



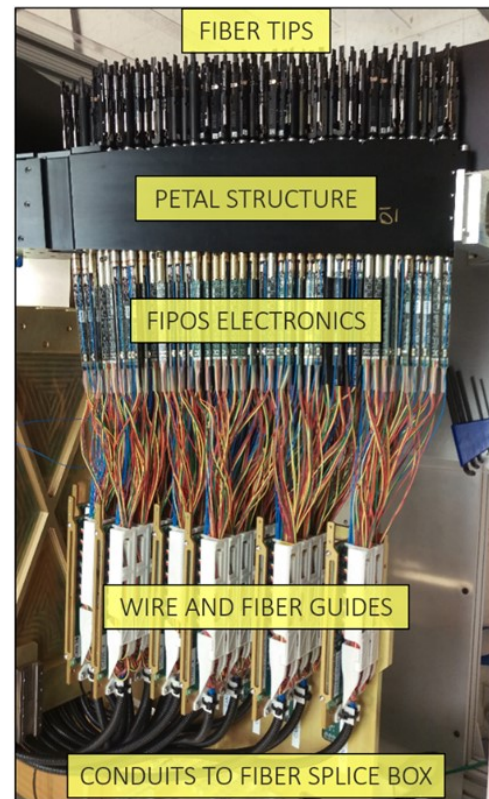
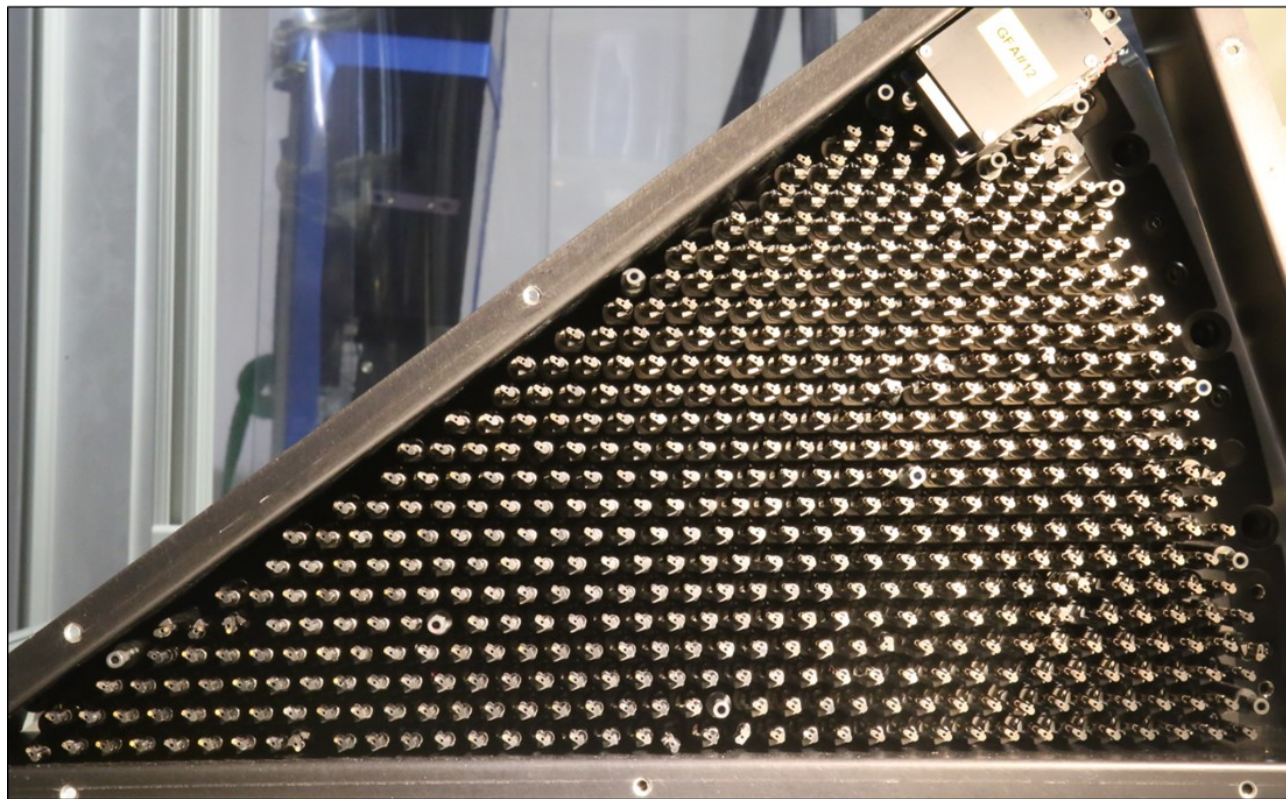
# Robot assembly

at the  
University of  
Michigan

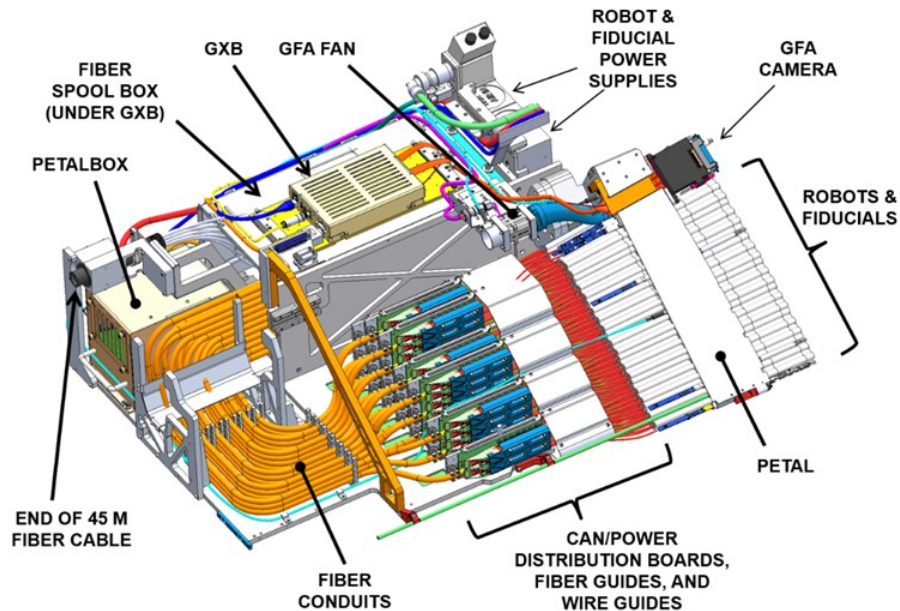
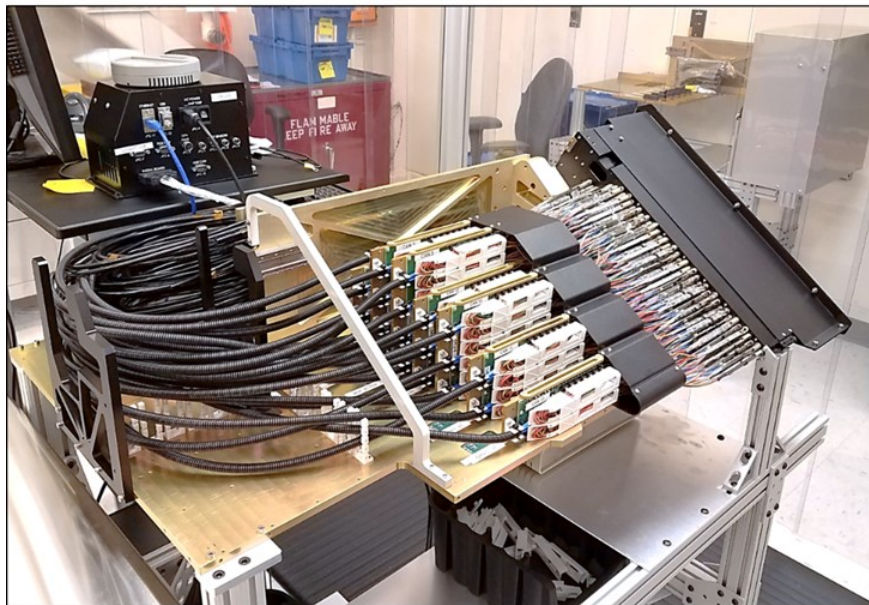
# DESI Focal Plane is installed on the Mayall Telescope's declination axis



We divided the focal plane architecturally into  $10 \times 36^\circ$  “petals”.  
502 robots, 12 fiducial sources, 1 CCD camera per petal.



# Each petal is a complete instrument, and delivers light via a 45 m, fusion-spliced fiber cable, to one of 10 spectrographs off-telescope



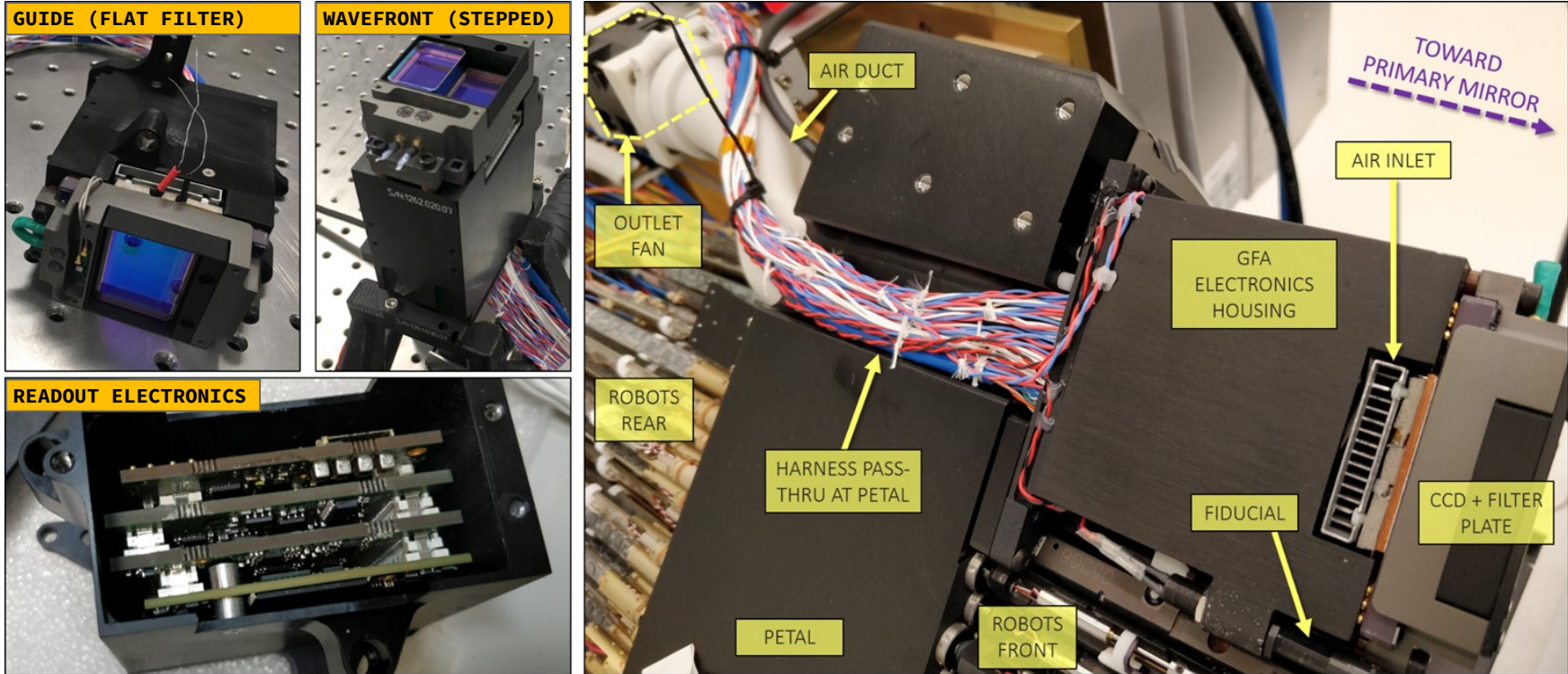
# Assembly of a Petal

Takes ~ 1  
month

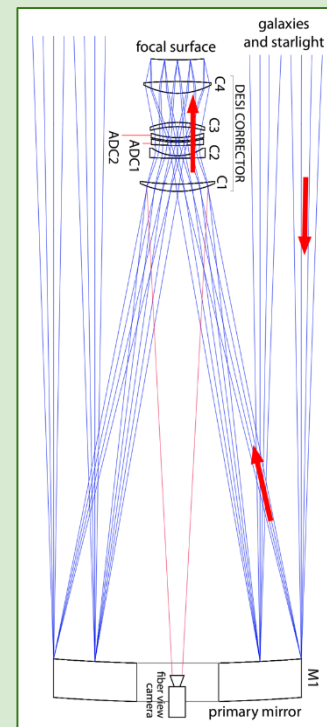
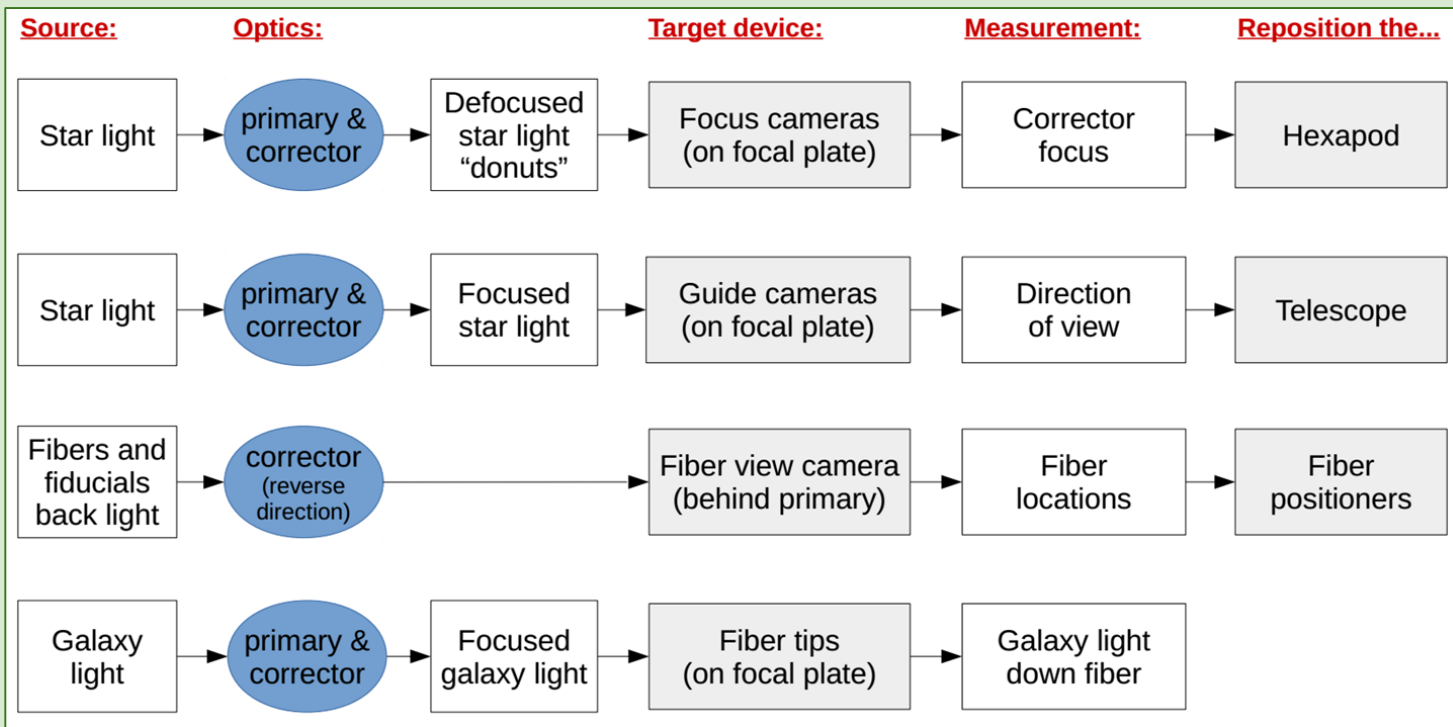




# Guide and wavefront custom CCD cameras

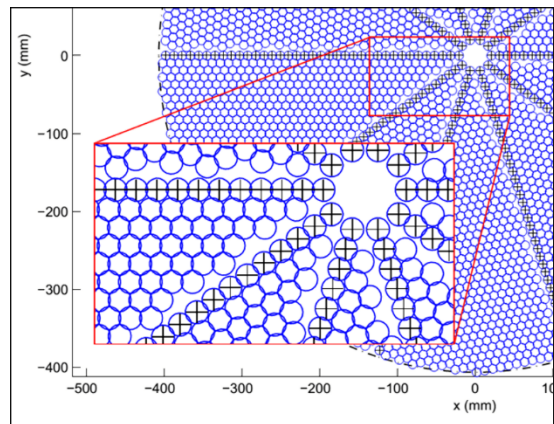
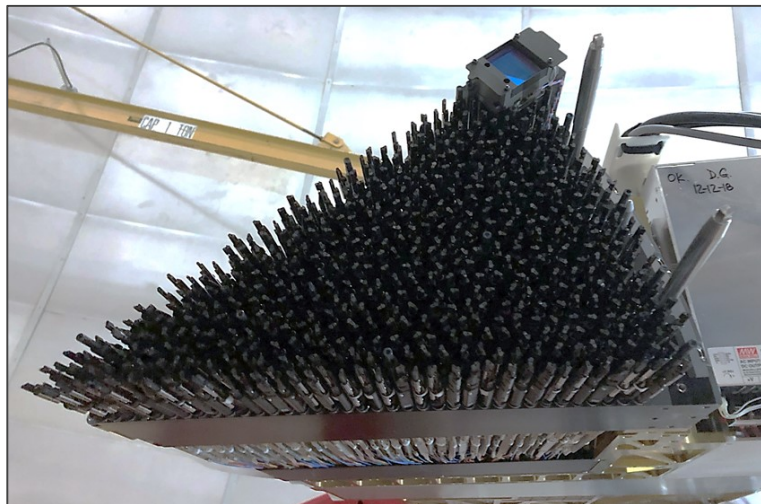
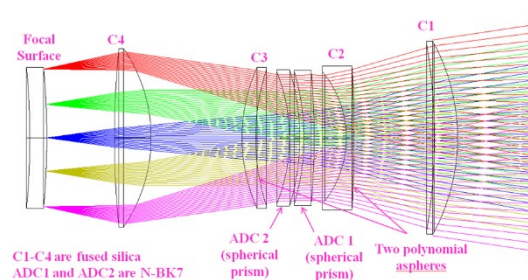
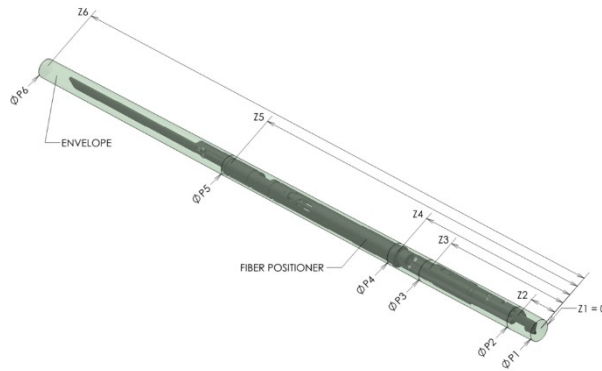


# How we position the fibers on galaxy targets to such accuracy...

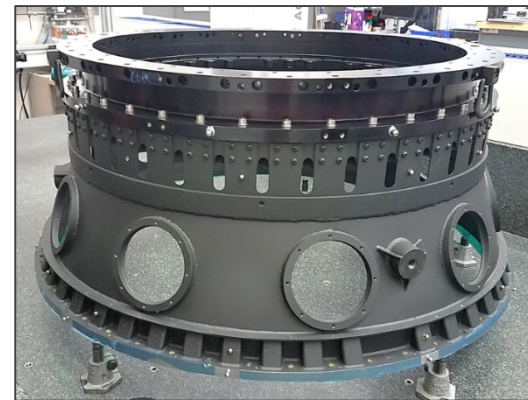
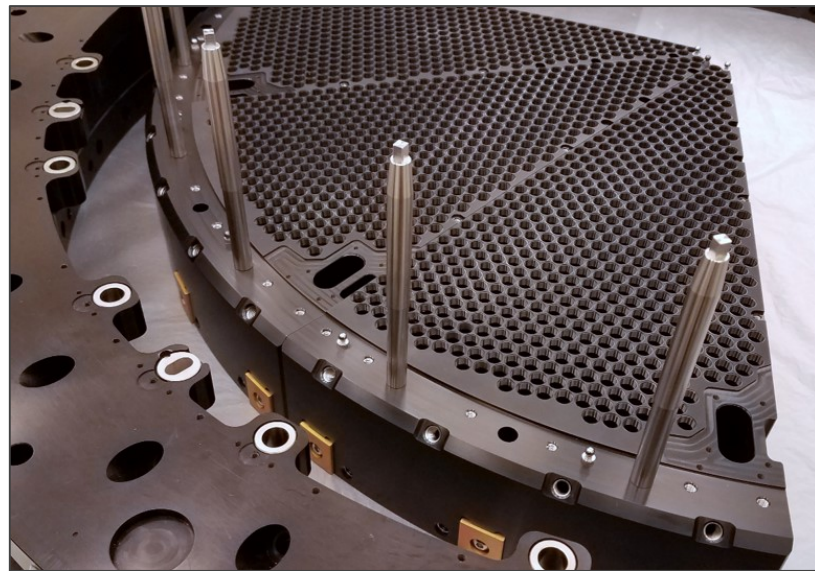
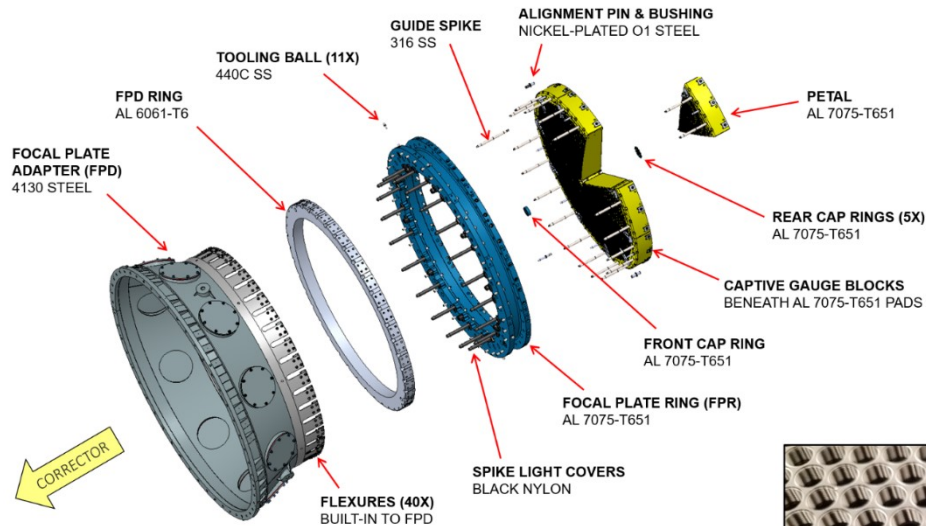


# Focal plane layout:

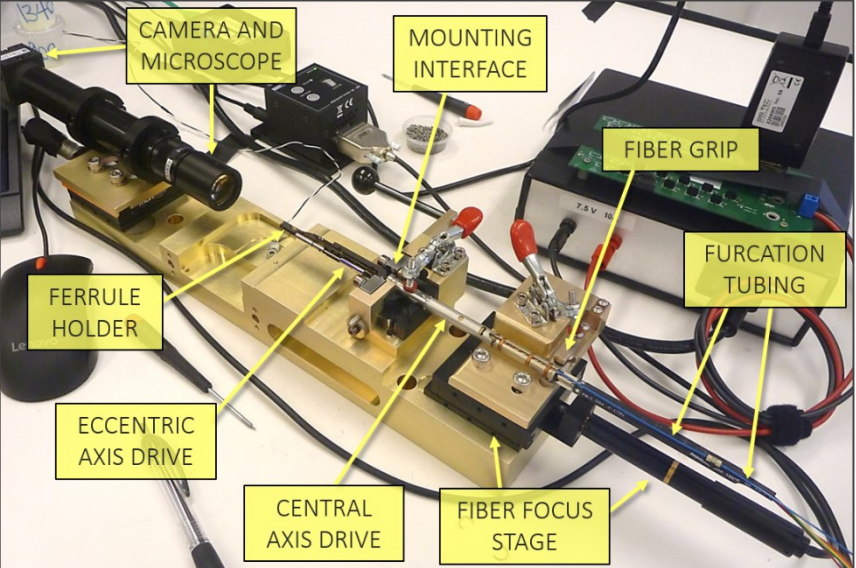
1. Monte Carlo tolerance analysis  
→ Robot envelope
2. Iterative layout code  
→ Close-pack envelopes on aspheric focal surface



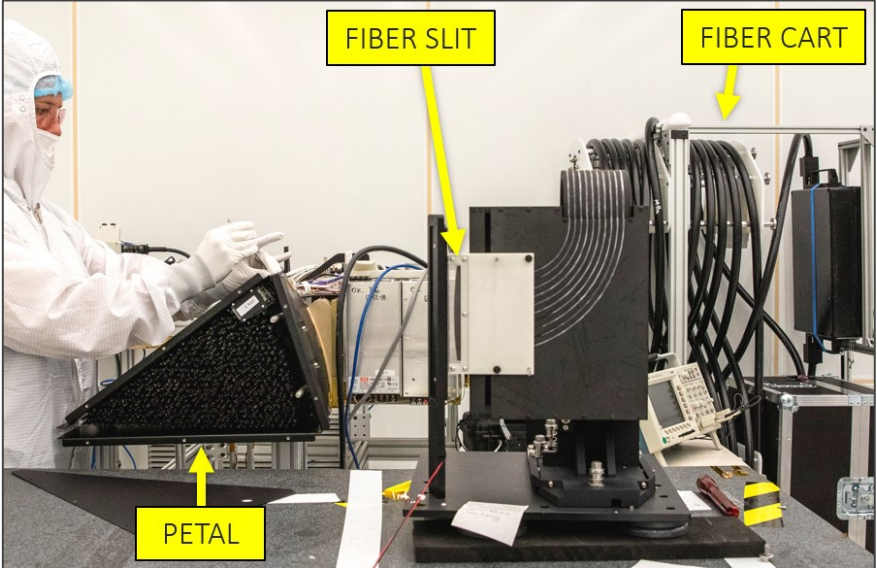
# Focal plate structure



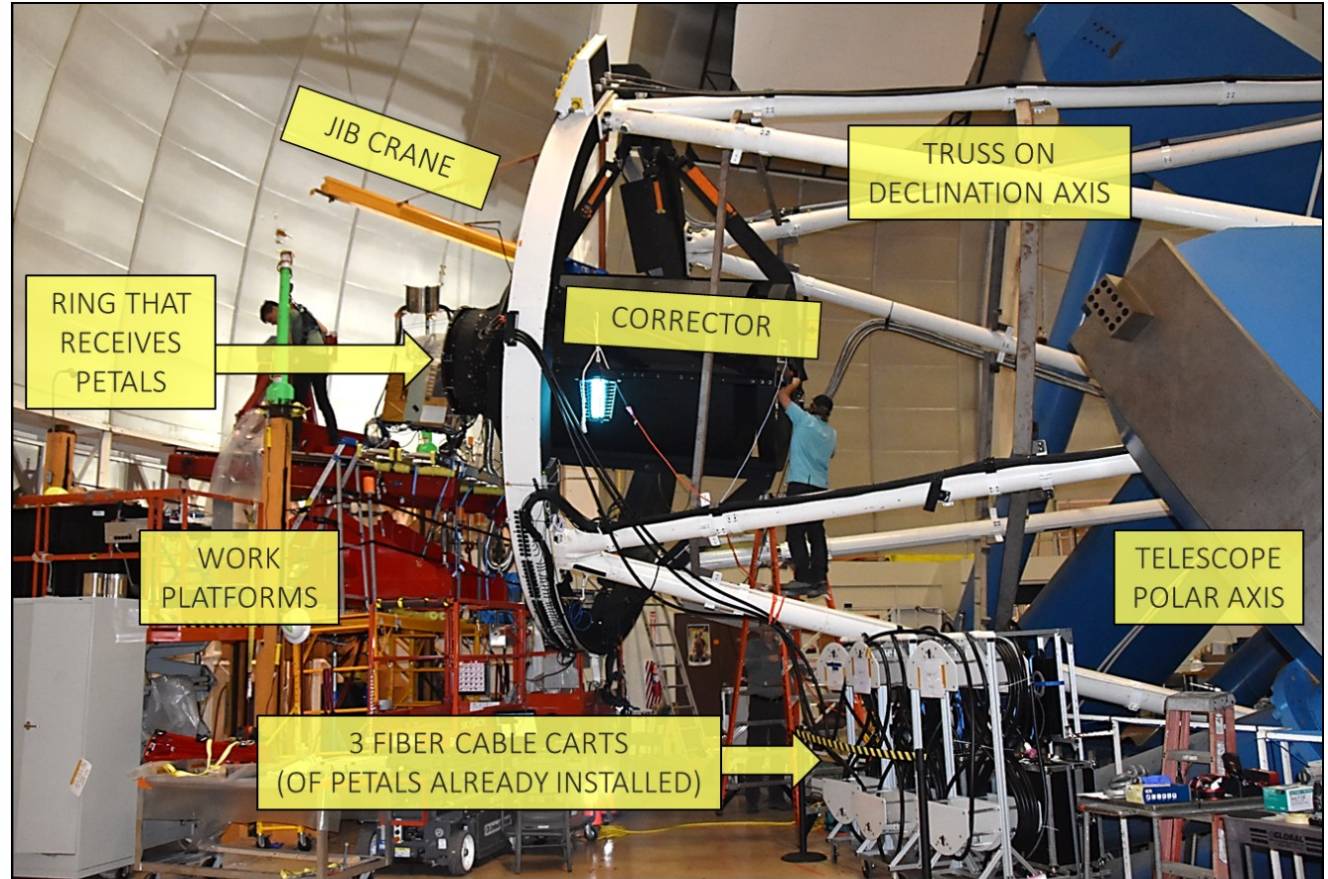
# Fiber alignment in robot



# Fusion spliced to cable + slit



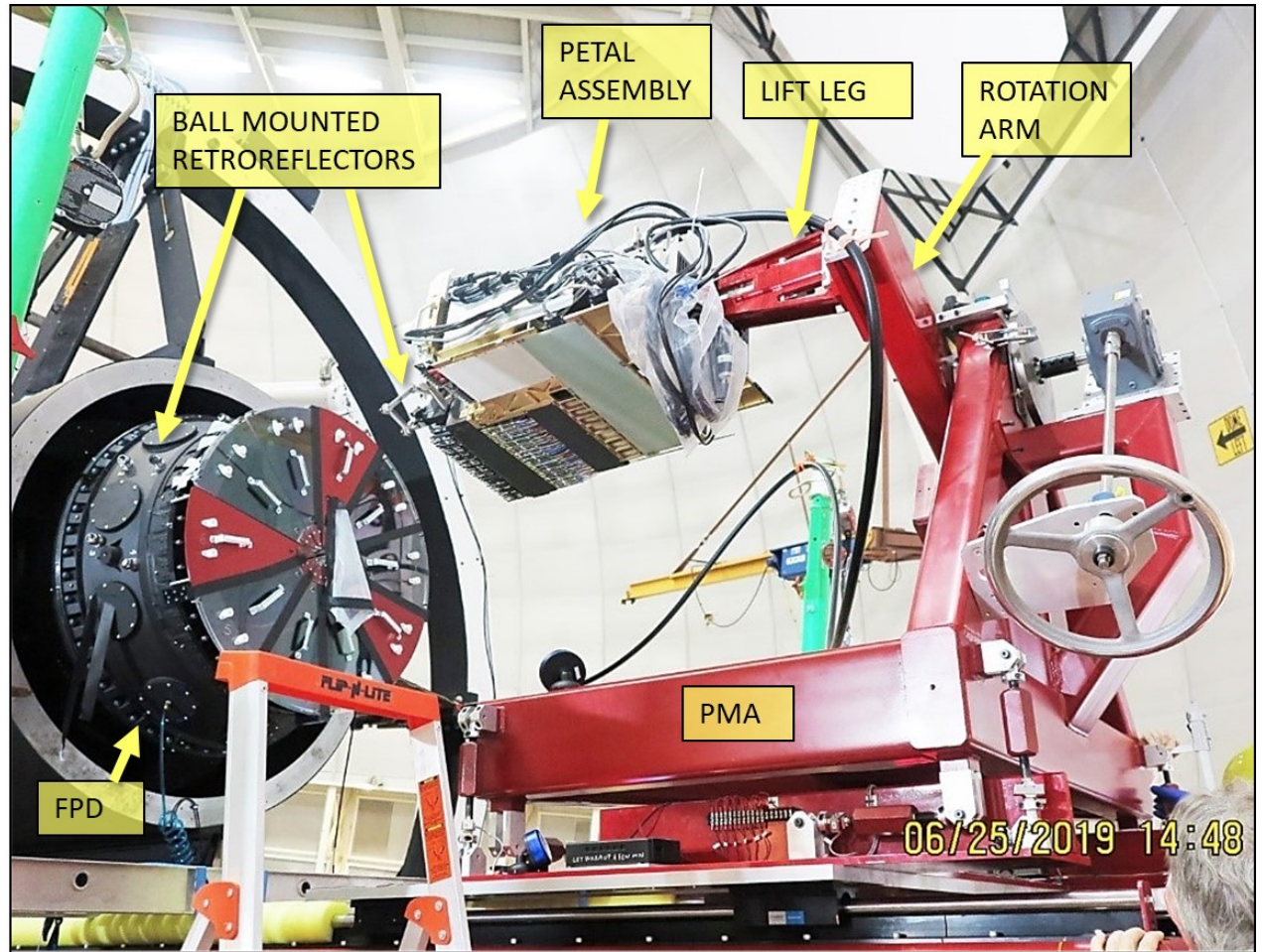
# Installation at Mayall Telescope



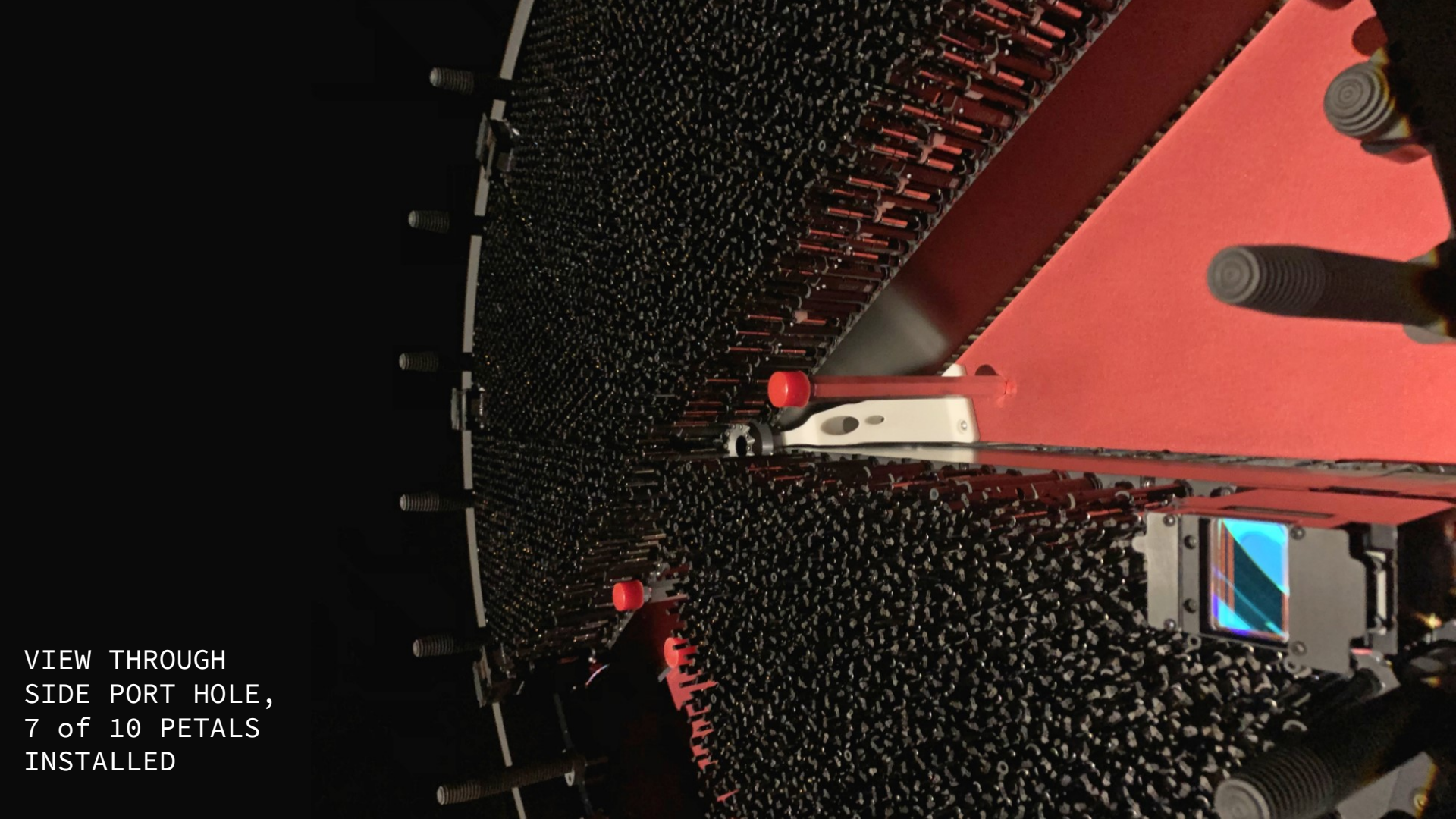


PETAL INSERTION  
INTO OPTICAL  
CORRECTOR AT  
MAYALL TELESCOPE  
(VIDEO)

# Petal insertion into telescope

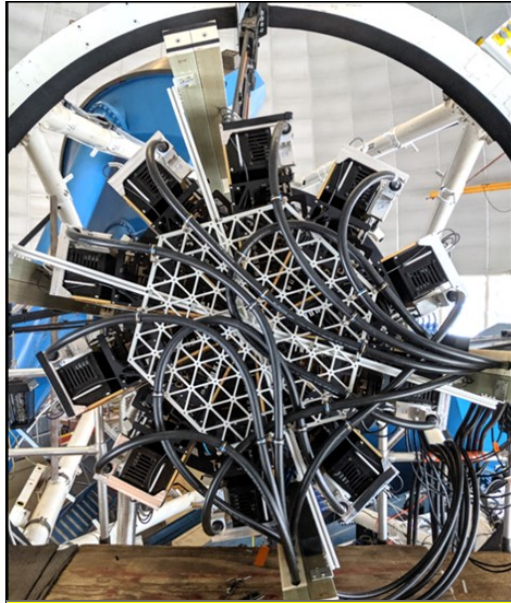
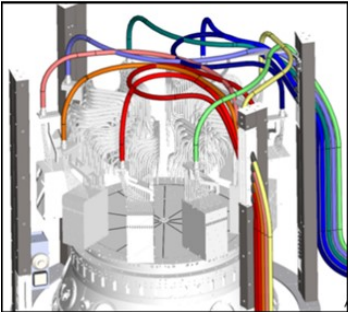
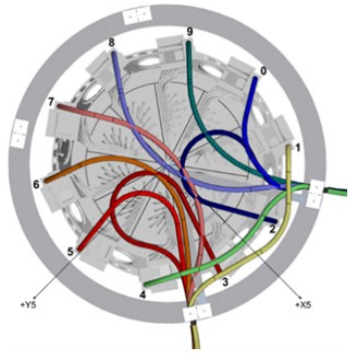




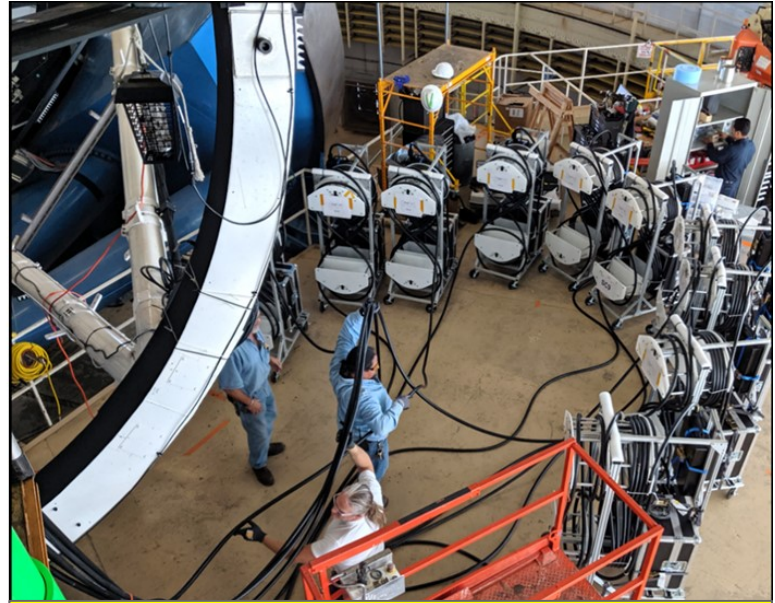


VIEW THROUGH  
SIDE PORT HOLE,  
7 of 10 PETALS  
INSTALLED

# Dressing DESI fiber cables down the telescope



**CABLES DRESSED TO FOCAL PLANE REAR HEX GRID**

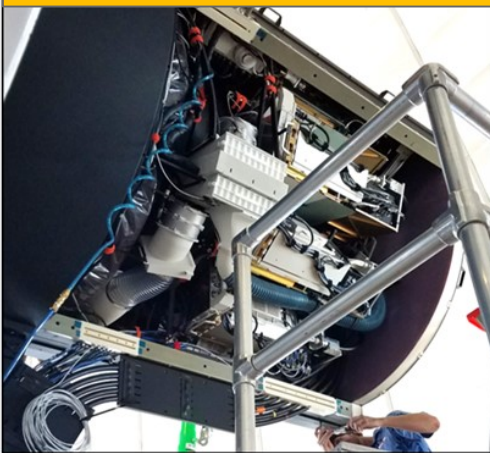


**FIBER CABLES LAID OUT ON C-FLOOR BEFORE DRESSING DOWN THE TELESCOPE**

**THERMAL ENCLOSURE ASSEMBLY AROUND FP SYSTEM**



**HEAT EXCHANGER AND FILTRATION I**



**THERMAL ENCLOSURE SEALED**



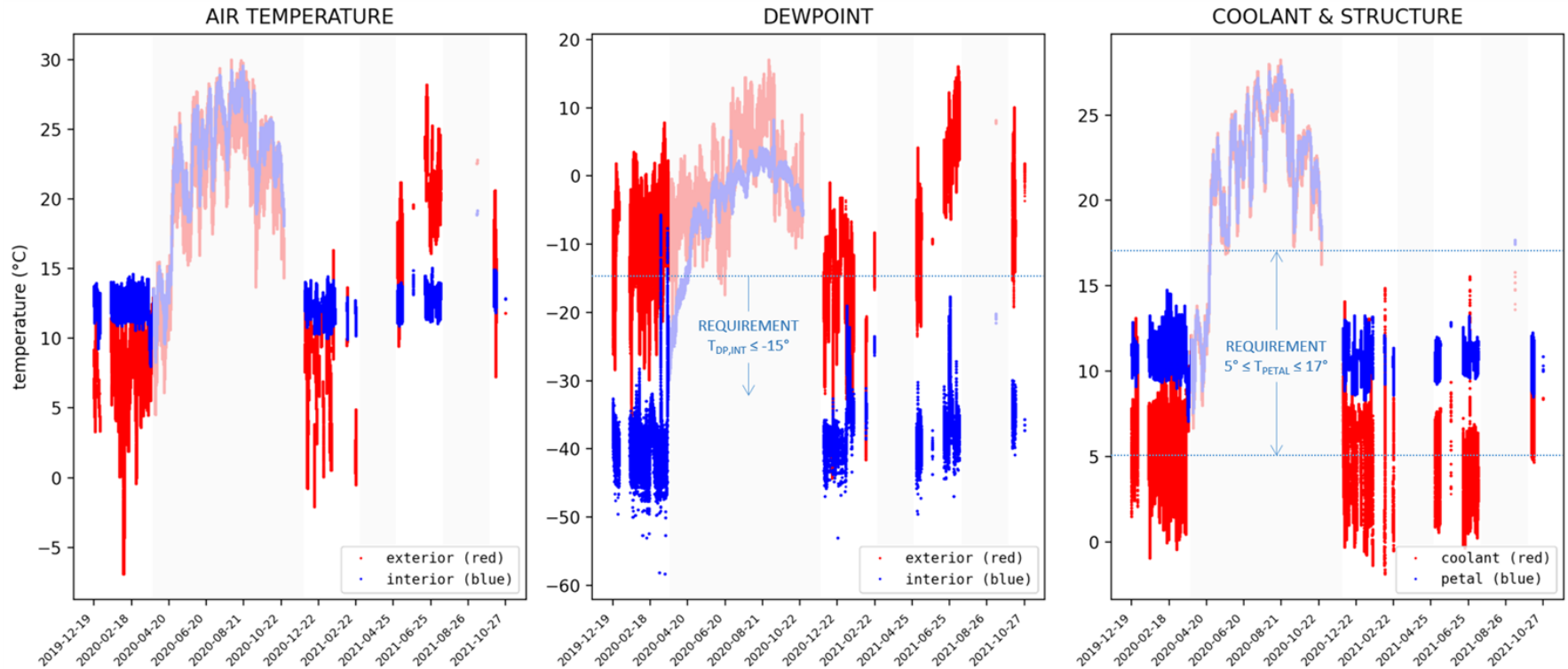
**FPD INPUT PORT & FILTRATION II**



**FIBER CABLES AND SERVICE PENETRATIONS**



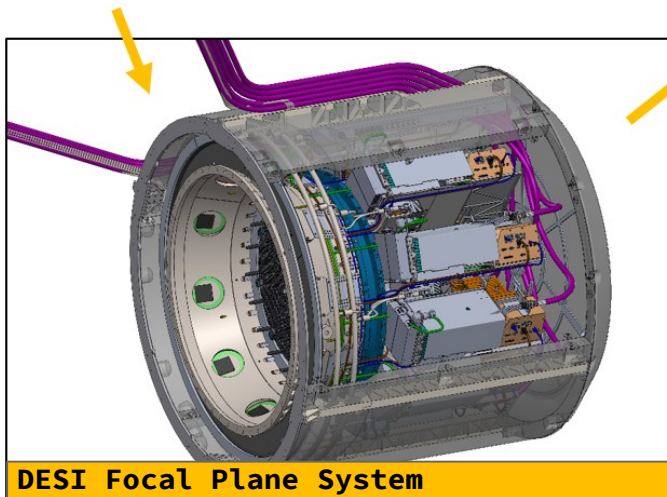
# Thermal system performance (first 22 months of operations)



Grayed zones: Seasonal, maintenance, and COVID-19 shutdown times.

Filter	Total Qty
Individual parts	675,194
Items we integrate	313,769
Unique items	459
Moving parts	416,730
Wires or fibers	61,148
PCBs	5,371
Fasteners	58,086
Electrical connectors	11,609

**Mayall Telescope, atop Iolkam Du'ag (Kitt Peak) in the Tohono O'odham Nation (near Tucson, Arizona)**



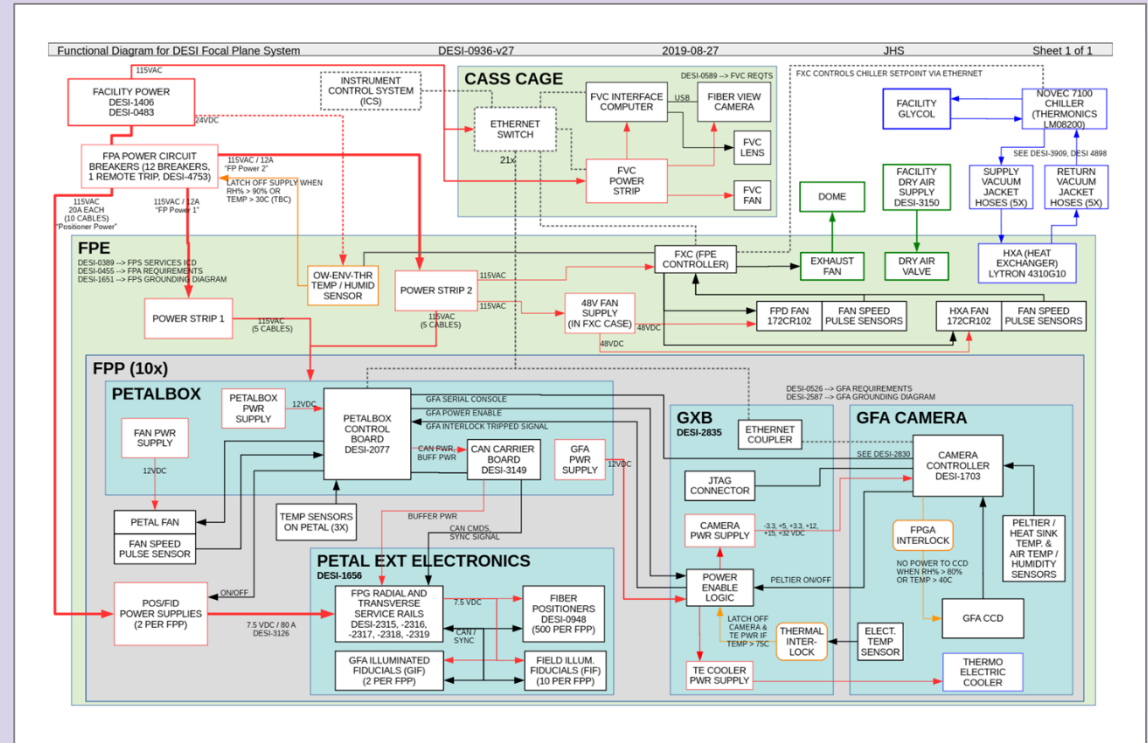
**DESI Focal Plane System**

# Powerful concept:

Summarize your “complex thing”

in

1 PAGE.



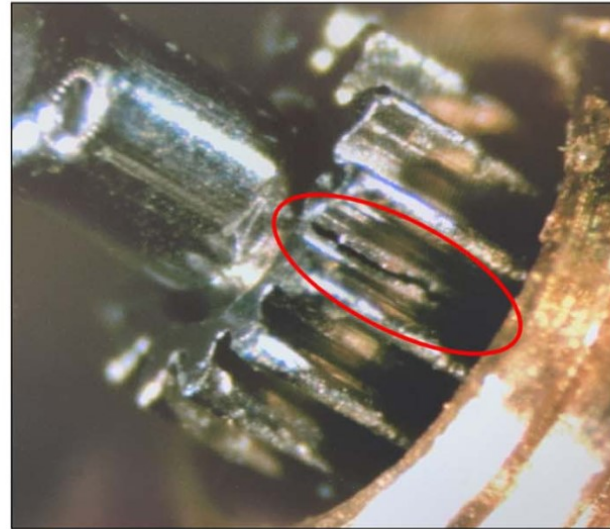
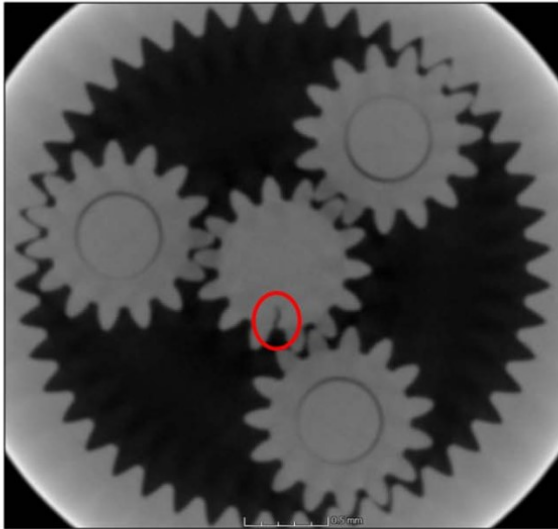
# Things fail, too...

Status	Count	
Nominal	4280	! ? * @ * ! ! (85.3%)
Improper motion	649	(12.9%)
Communication failure	70	(1.4%)
Damaged fiber	21	(0.4%)

**Note.** Counts are as of 2021 December 18.

THE ASTRONOMICAL JOURNAL, 165:9 (40pp), 2023 January

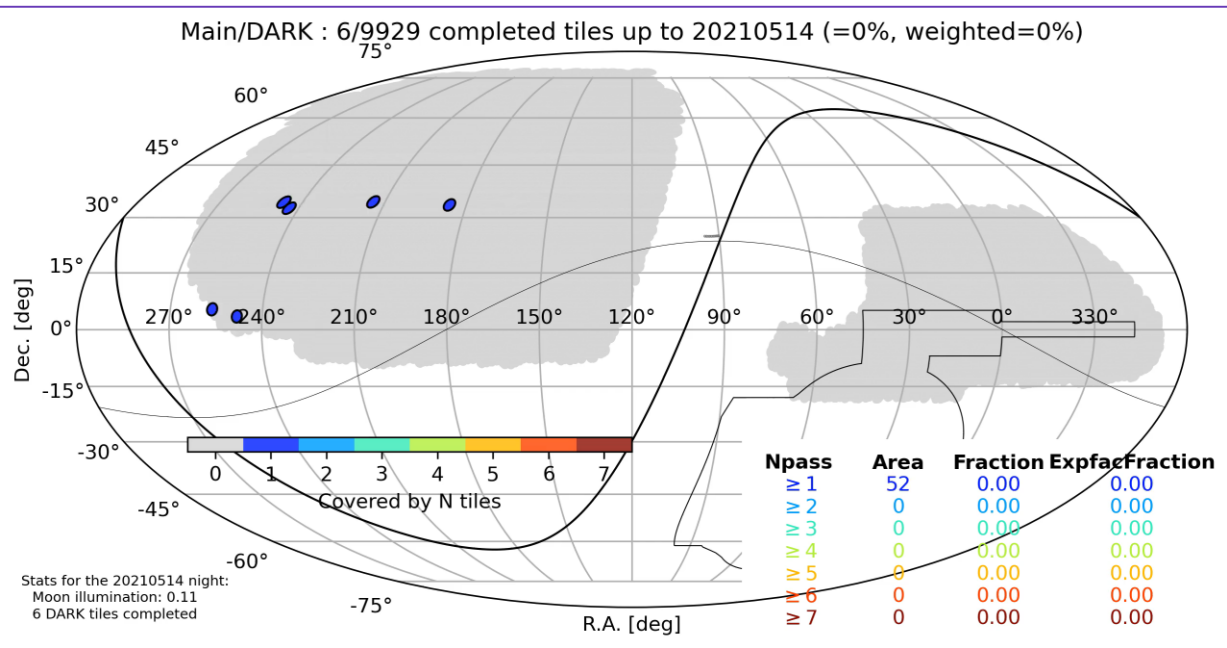
Silber et al.



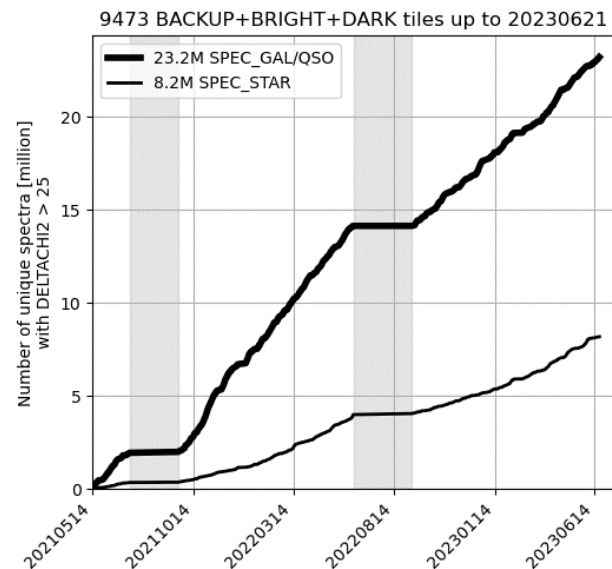
**Figure 37.** X-ray (left) and optical (right) views of a typical cracked pinion gear. In the right-hand view, one can see how the pinion has slipped down the shaft (normally it would be flush to the shaft tip, in the upper corner left of the image).

# Nonetheless...

May 2021 - June 2023: **31.4 million** spectra measured (so far)



SKY COVERAGE TO DATE (VIDEO)





MOSCOW, 1988



MY BROTHER DAVID

ME