

# Zwicky Transient Facility

Roger Smith

Caltech

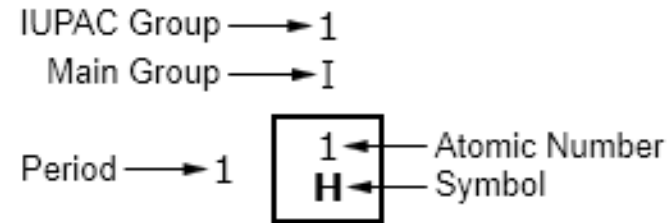
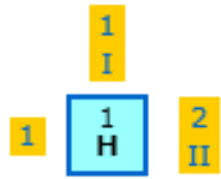
Funded by the National Science Foundation in partnership with



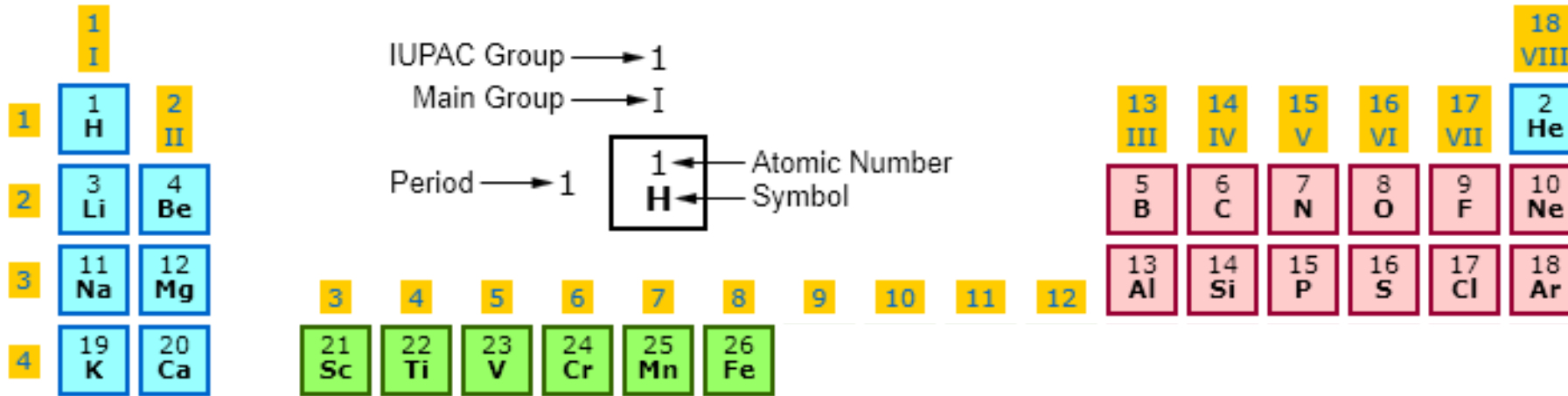
# Why does Astronomy matter ?

- Calendar, in ancient times.
- Navigation and time keeping on earth. (latitude and longitude).
- Exploration: mapping our universe. Could life exist elsewhere?
- History of creation. ← **today's story.**
- Physics laboratory. Study the laws of nature at the extremes.

# Periodic table for the infant universe



# Nuclear fusion in stars makes new elements



Energy is released by fusion, but only up to Iron.

Beyond Fe energy *input* is required.

Stars aren't hot enough to make heaviest elements.

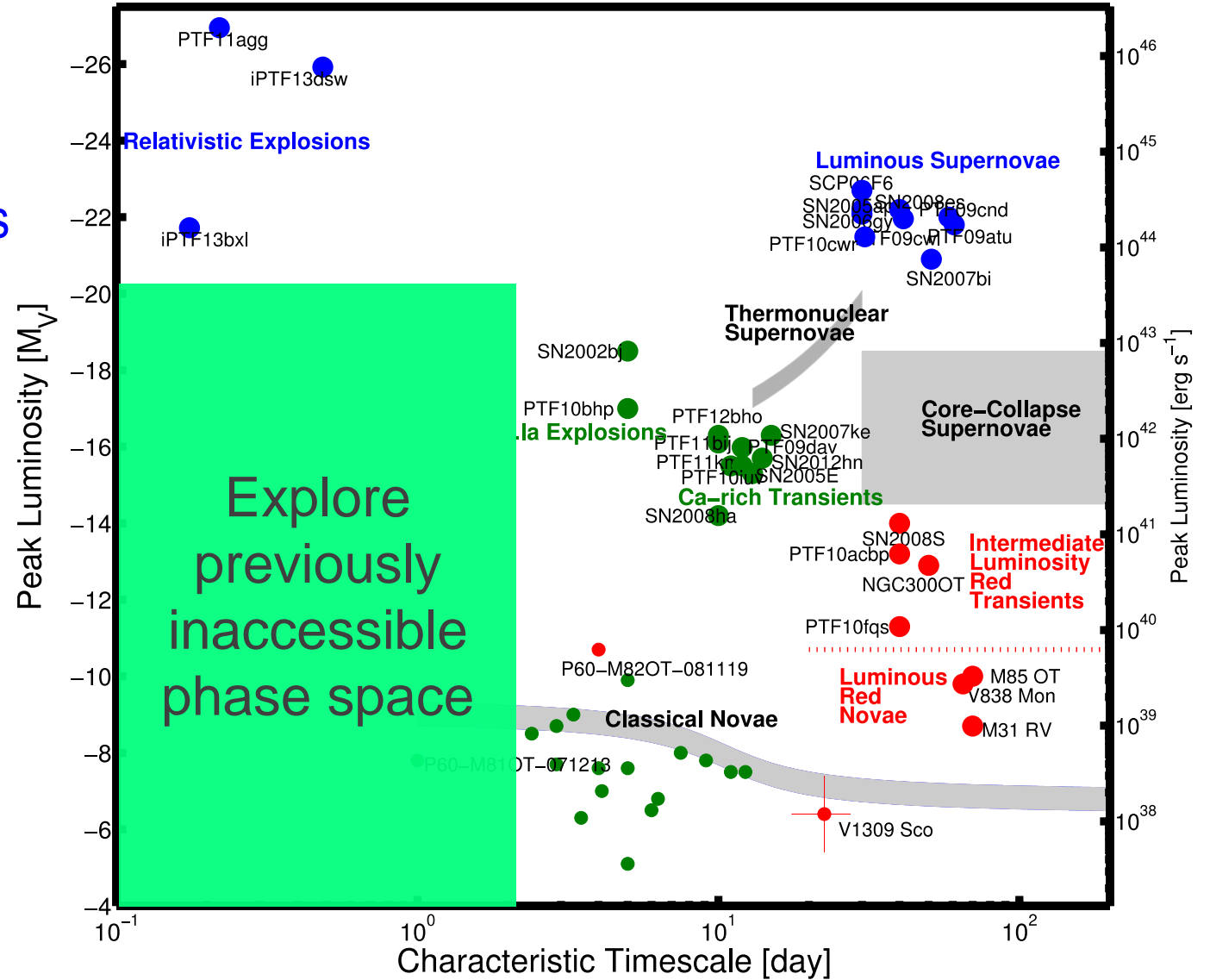
....We need supernovae or neutron star mergers.



# Science objective

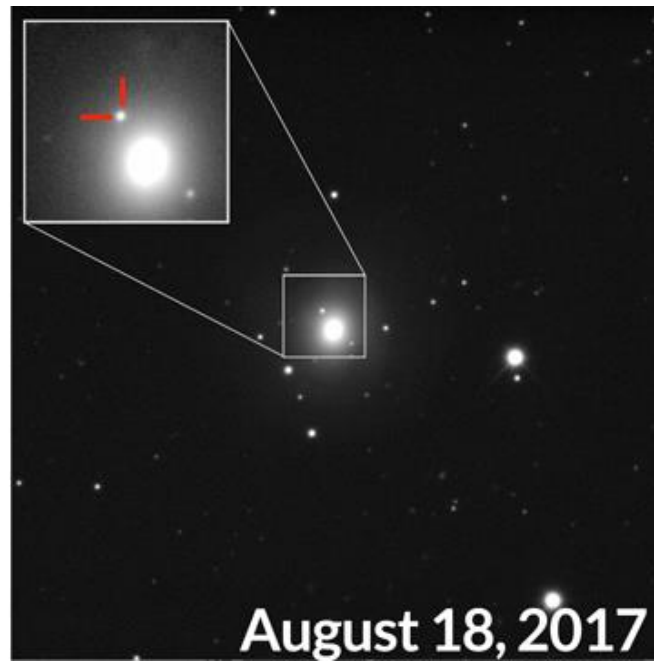
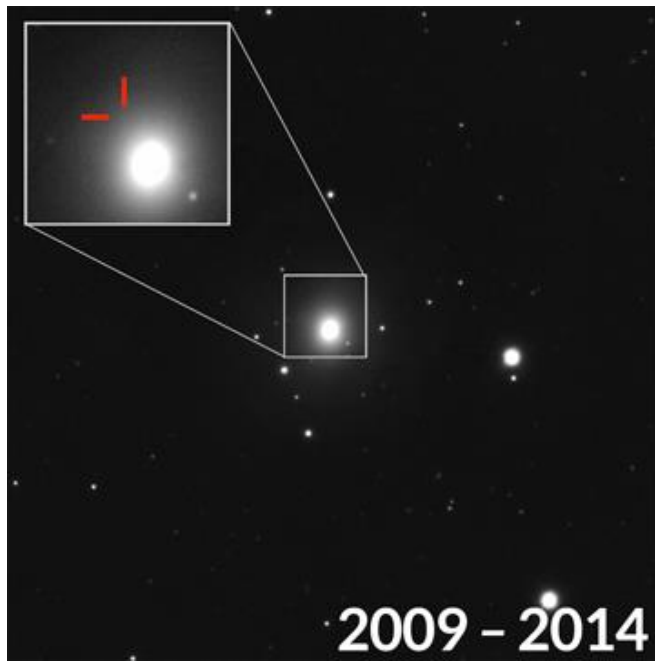
## Transients on time scales down to few hours

- Rare so must record large volume, quickly.
- Bright enough for follow up spectroscopy.



# Recent example – neutron star merger

- 1) LIGO detects gravity waves and approximate direction
  - 2) Wide field telescope(s) (e.g. ZTF) search for optical counterpart to localize events.
  - 3) Large telescopes (narrow field; larger aperture) record spectra to analyze physical processes:
    - Elements present
    - Temperature
    - Pressure
    - Velocity
- } versus time



- To find rare events ZTF will compare most of the sky to reference images every night.
- An array of computers will detect a million things that change, then classify these to automatically identify ~10 interesting events.
- Alerts will be issues to larger telescopes within minutes of discovery.

# NSF and DOE are investing in LSST

<https://gallery.lsst.org/bp/#/folder/2689925/64565141>

ZTF is stepping stone to LSST,  
with complementary capability

Current construction in Northern Chile





# Zwicky Transient Facility is LSST precursor



**Fritz Zwicky**, 18" schmidt telescope

- Neutron stars
- Supernova
- Dark matter
- Gravitational lensing
- 50 patents in rocketry and jet engines



Edwin Hubble, **48" schmidt telescope**

- Galaxies beyond Milky Way
- Expanding universe: velocity-distance relation

Uses same telescope as

National Geographic all-sky  
photographic survey.

1949-1956

Photographic plates manually  
loaded.

Telescope manually pointed.

# Field of view comparison

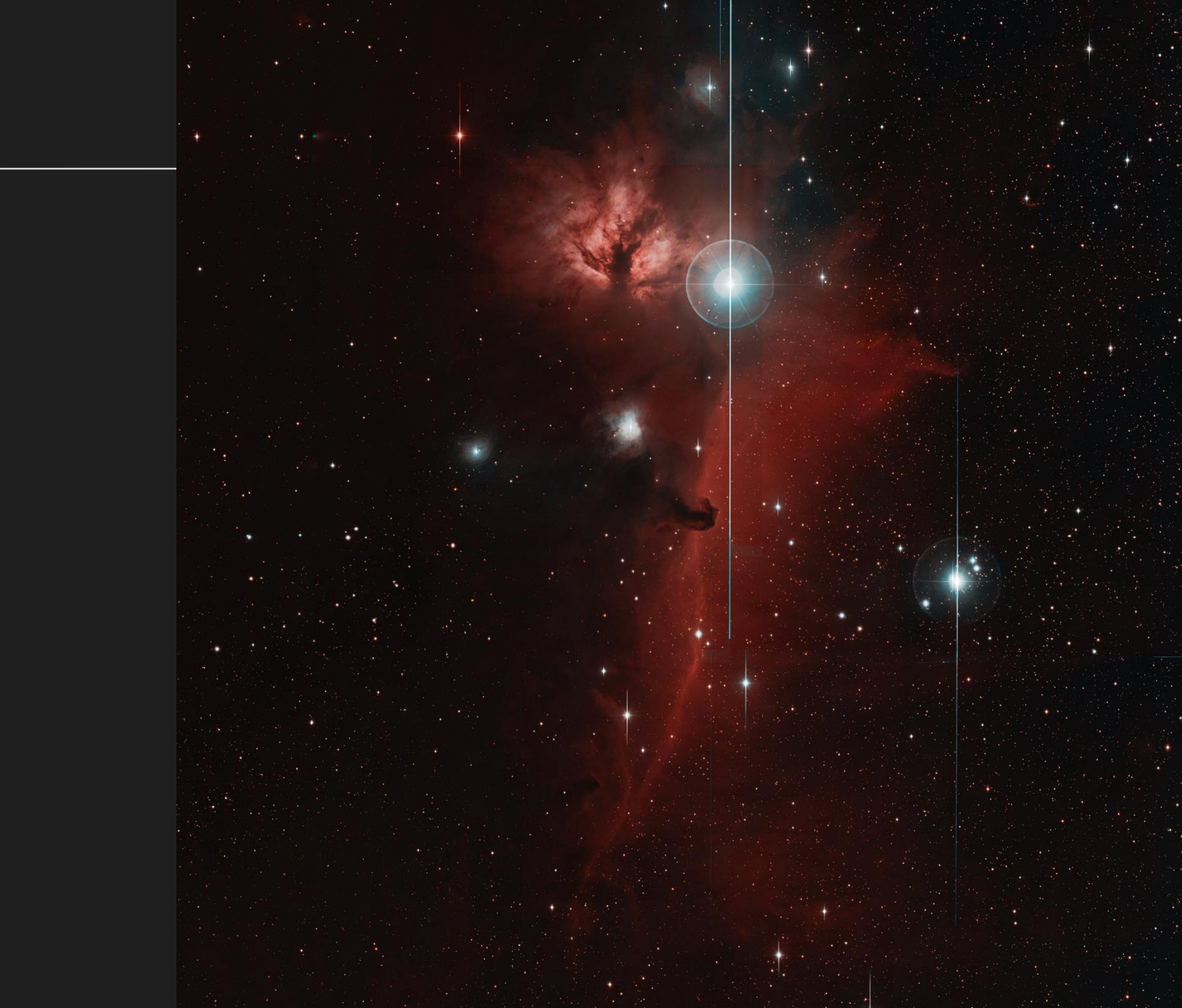


ZTF goes widest though with coarser angular resolution.



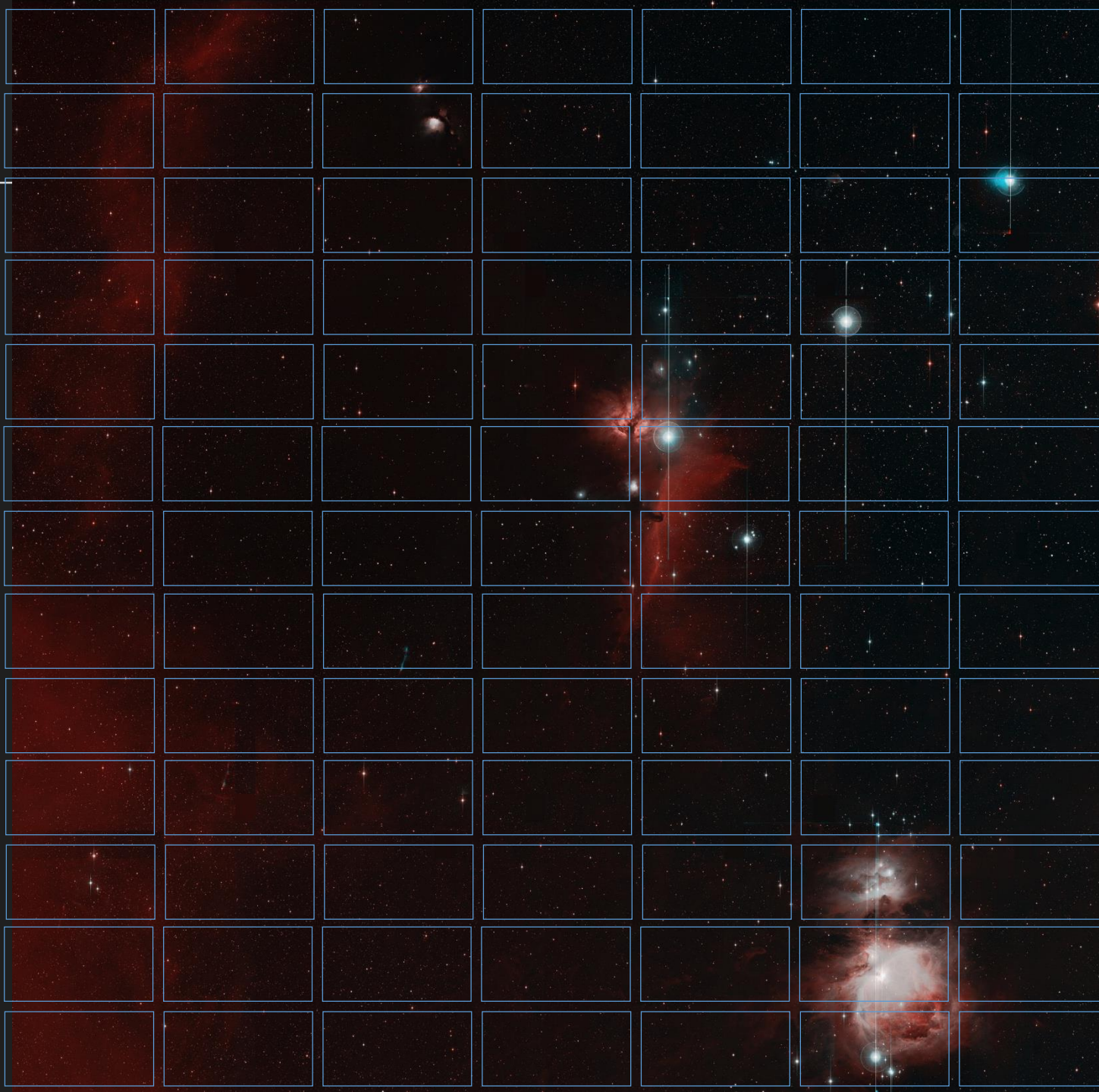
**M42**

cyan and red filters combined



# Flame and Horsehead nebulae in Orion

cyan and red filters combined

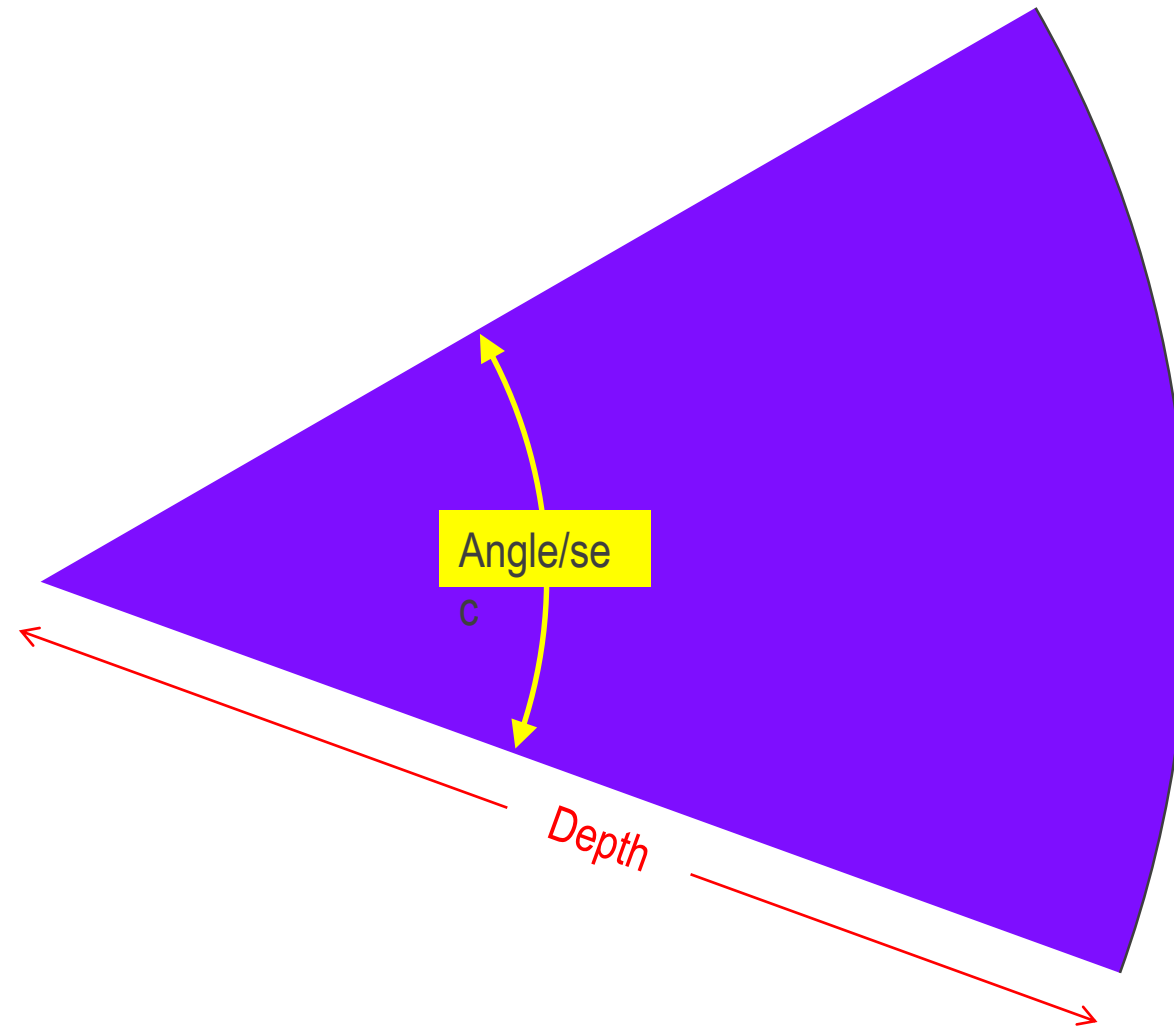


91 Ultra HD (4K) monitors  
to display at full resolution

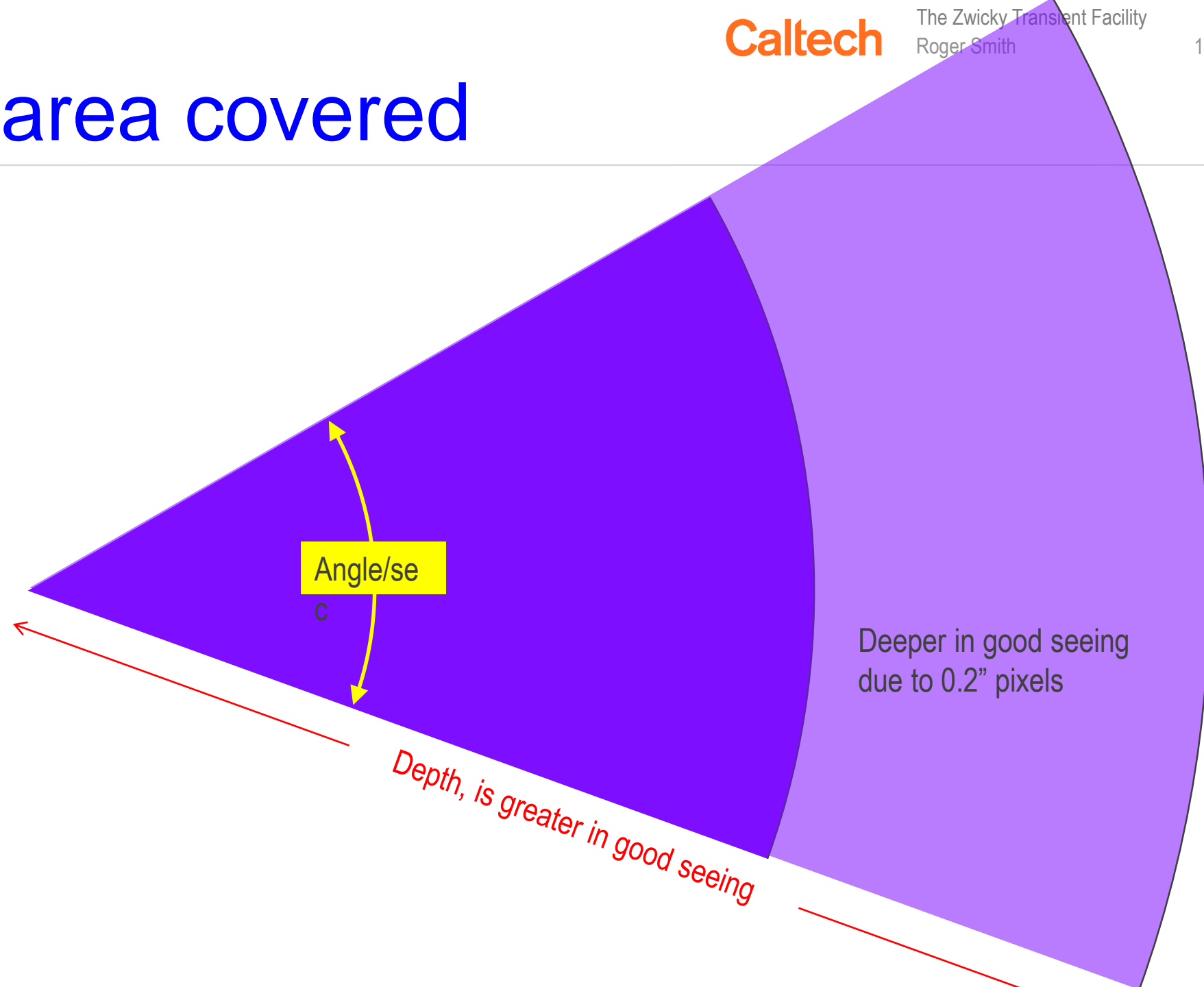
## Full frame

Slightly dithered to fill in gaps  
between sensors

# Depth and area covered

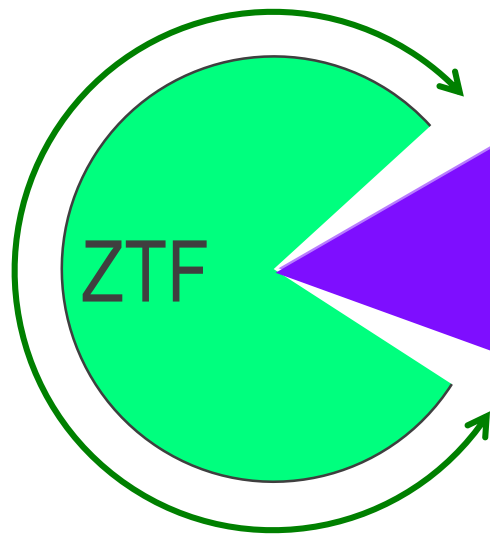


# Depth and area covered



# Complement to LSST

ZTF 5 times as wide  
per second  
@ 1"/pixel



Angle/se

c

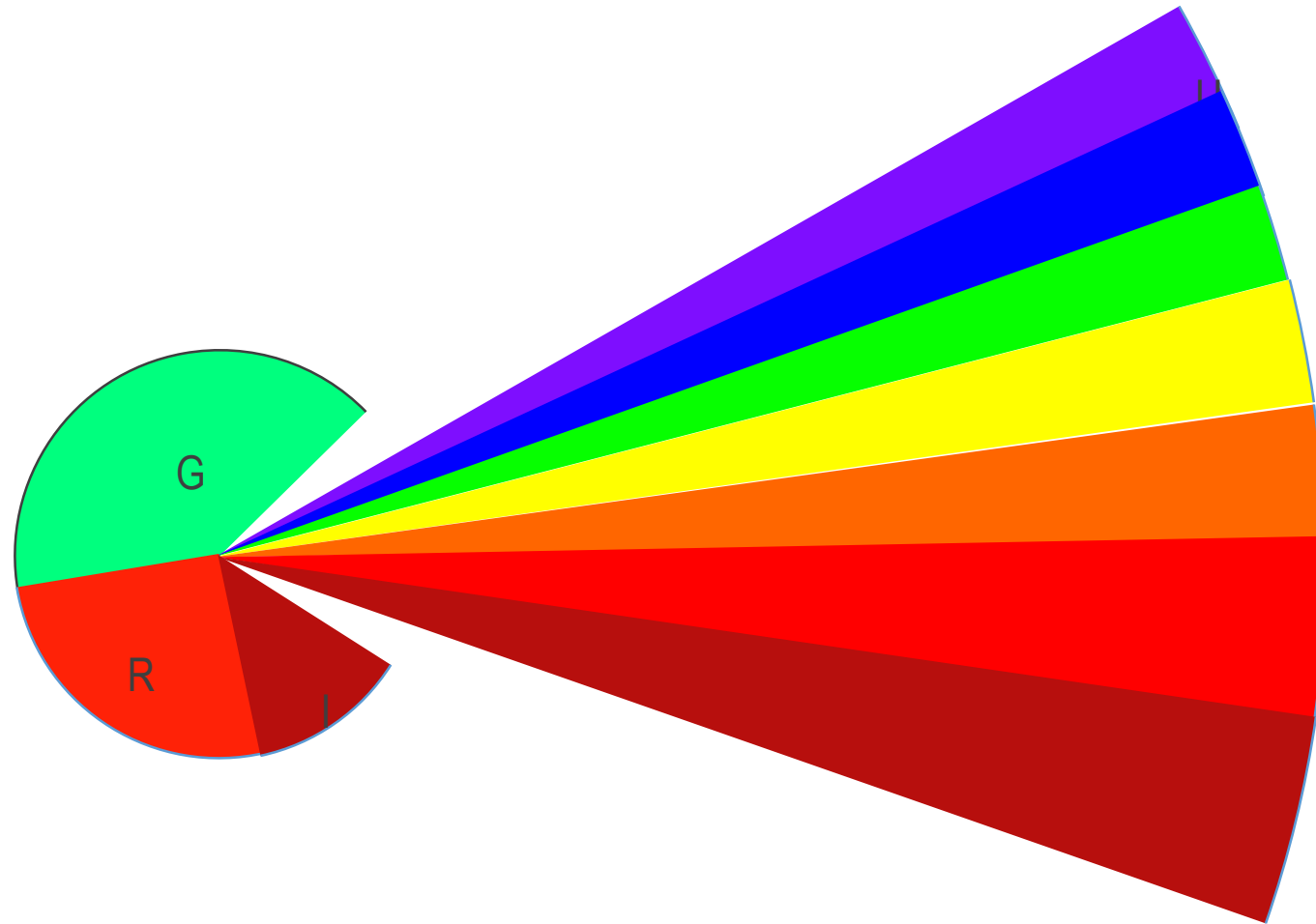
LSST

LSST goes 6.3 times  
deeper per sec than ZTF  
or more in good seeing  
due to 0.2" pixels



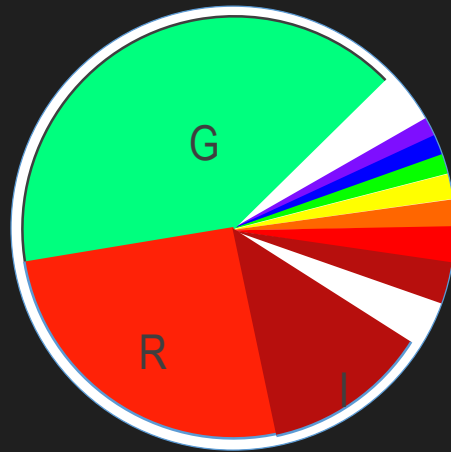
# Complement to LSST

ZTF typically observes in only one or two colors depending on moonlight or nature of target.



LSST observing time is shared between more colors to get photometric redshifts, so survey rate is proportionally lower

ZTF depth is matched to reach of  
medium resolution spectrographs  
on large telescopes



With current telescopes  
most transients found by  
LSST will be too faint for  
detailed follow up  
spectroscopy.

Follow up spectroscopy  
on larger telescopes has  
much greater wavelength  
resolution than LSST  
filter set.

# Top ZTF requirements

- Wide field of view 47 deg<sup>2</sup> ....Nyquist sampling with median seeing.
- Fast cadence 25 s expose, 10 s overhead for read out and slew
- High throughput 23% beam obstruction, great QE, fast readout and slew.
- 1% photometry improve flat fielding; baffling, keep optics clean, reduce ghosting
- G, R, I filters

# 1950 Bugatti

~125 mph



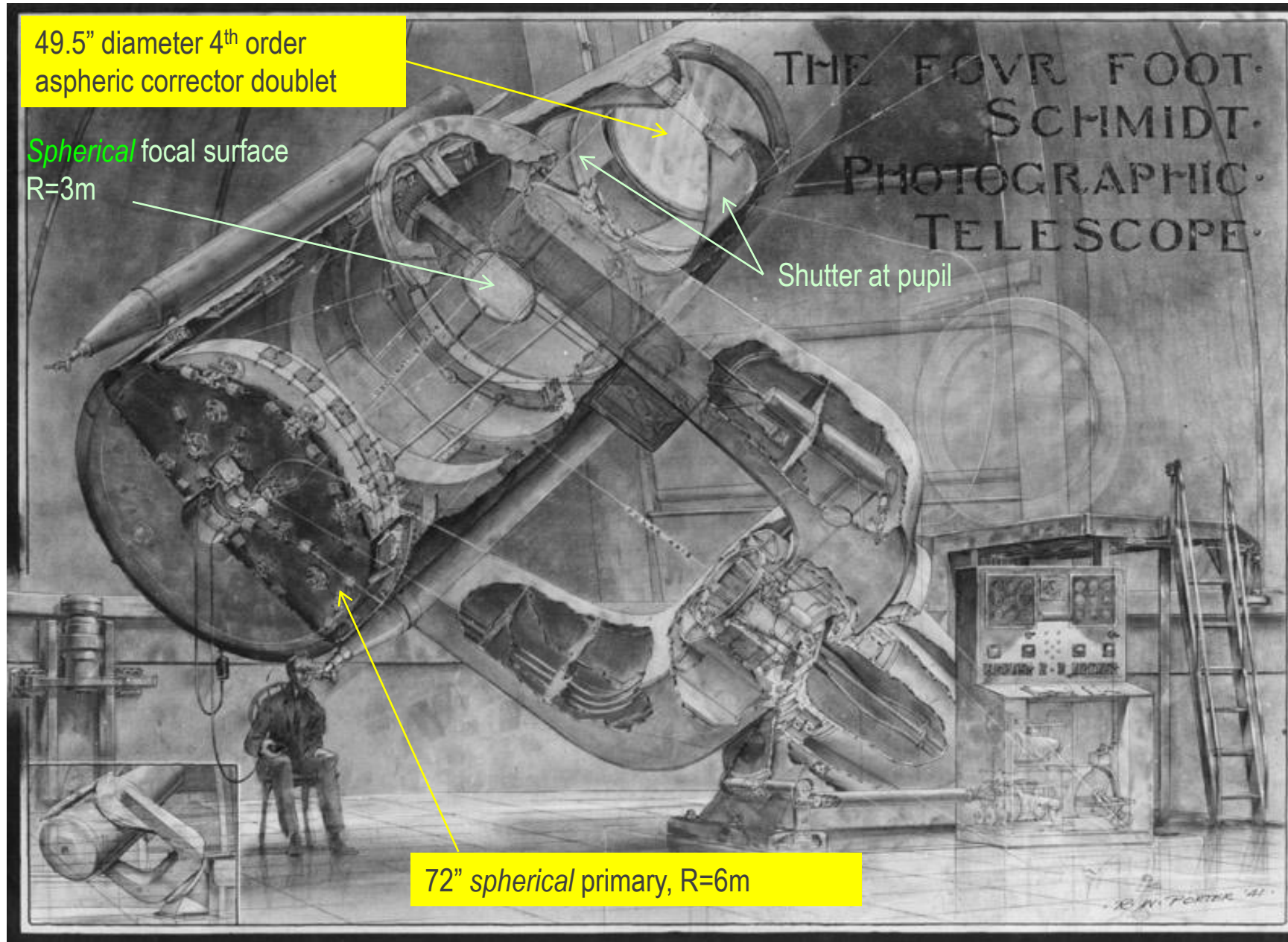
# 2018 Bugatti Chiron

260 mph

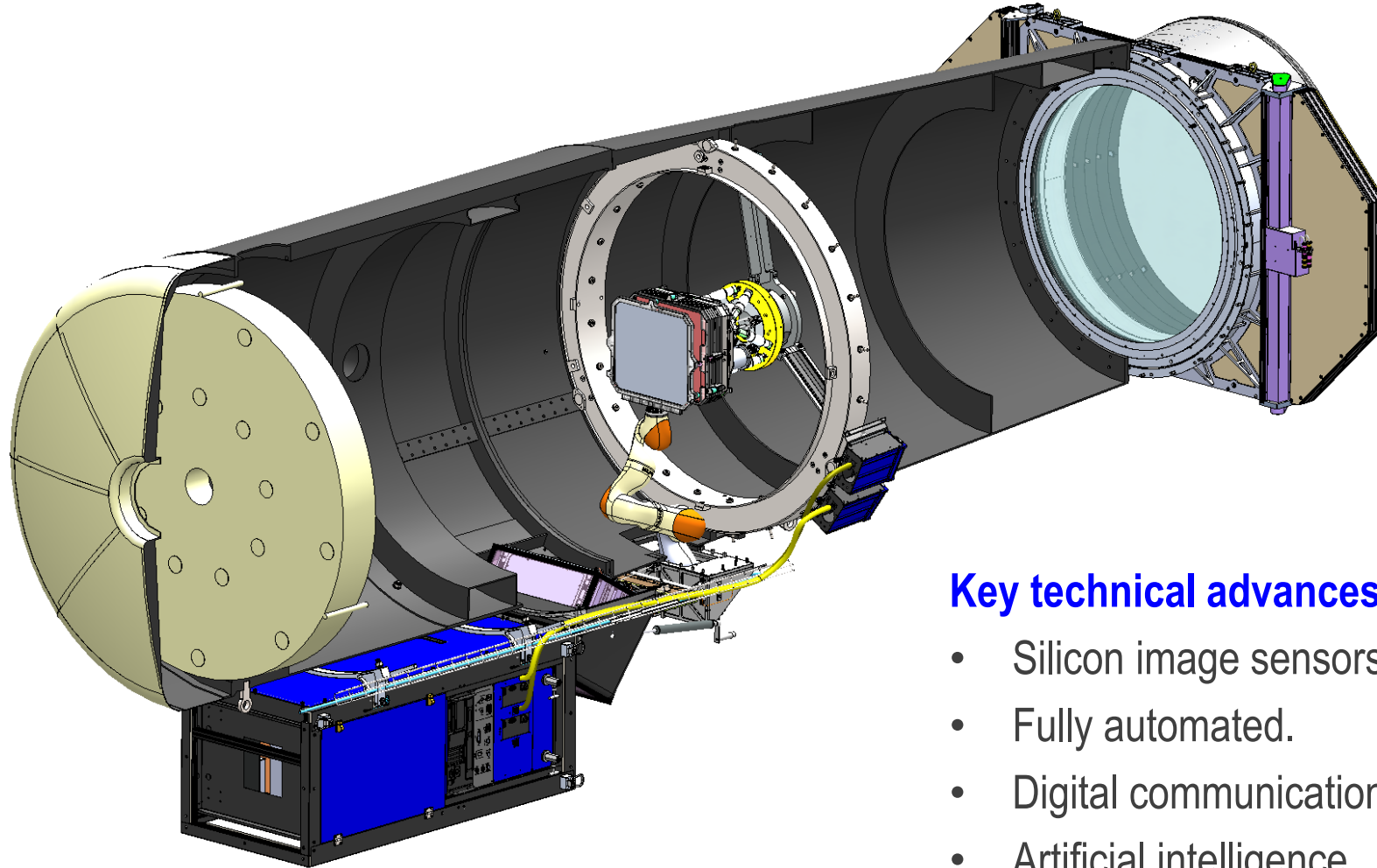
Factor of 2 improvement in 70 years



# 1949 – 1956 Palomar All Sky Survey



# ZTF is 1300x faster using same telescope!



## Key technical advances:

- Silicon image sensors
- Fully automated.
- Digital communication & processing.
- Artificial intelligence.

# Mosaic of large silicon sensors

6Kx6K CCDs tiled on spherical focal surface

→ 605 megapixels every 35 s

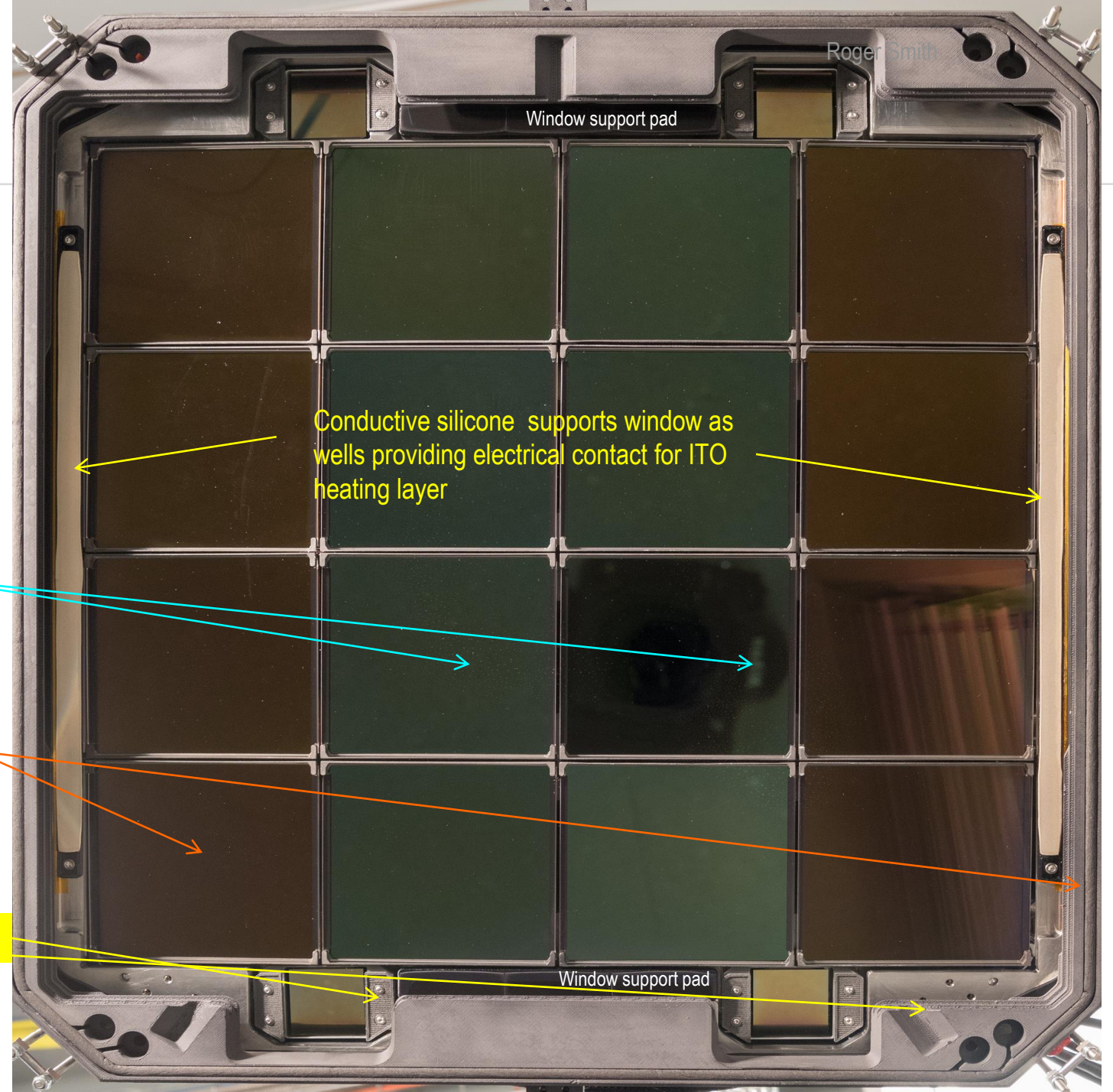


Image from focus test in May 2017

Without trim plate



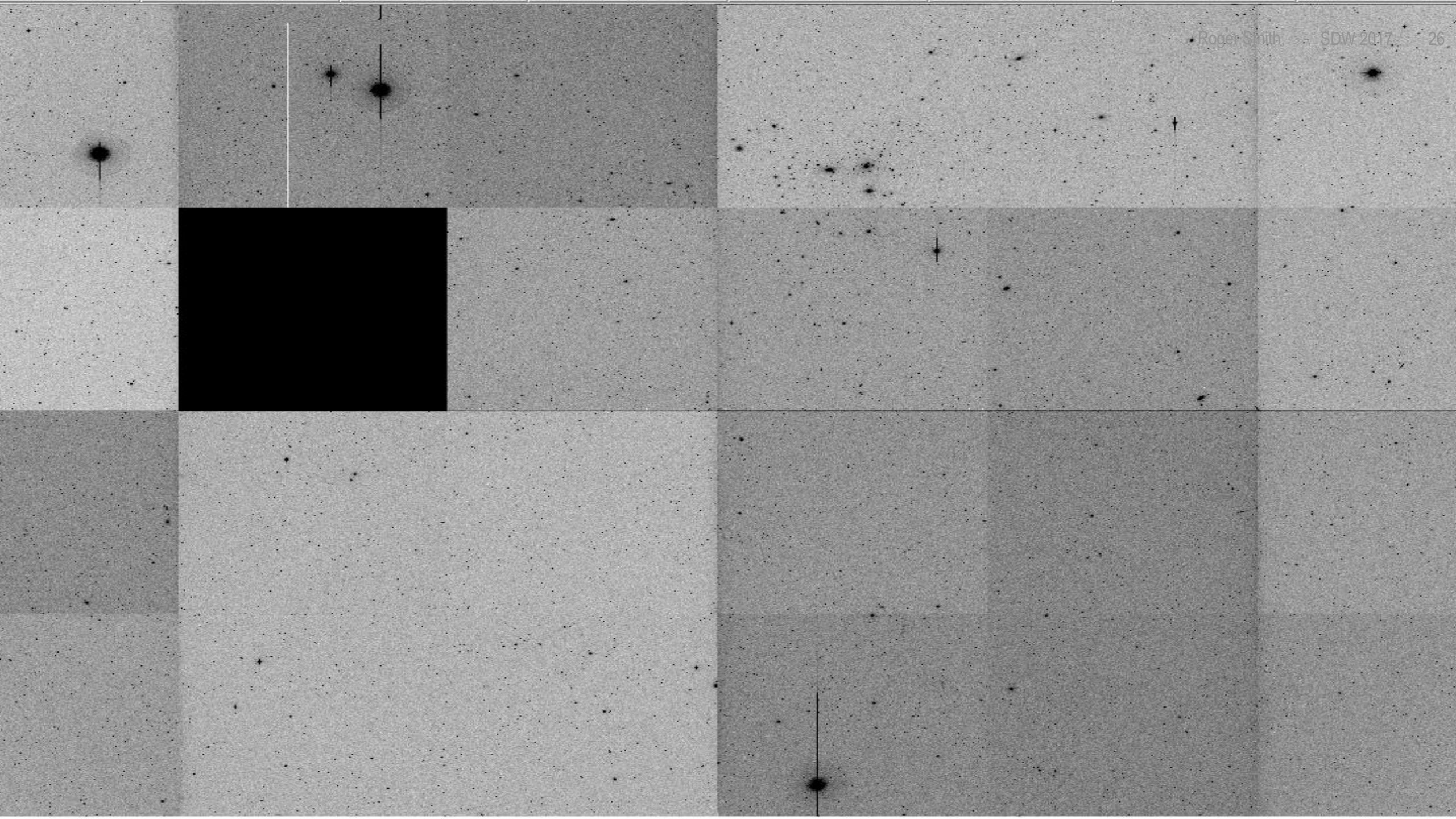
Very few  
cosmetic  
defects

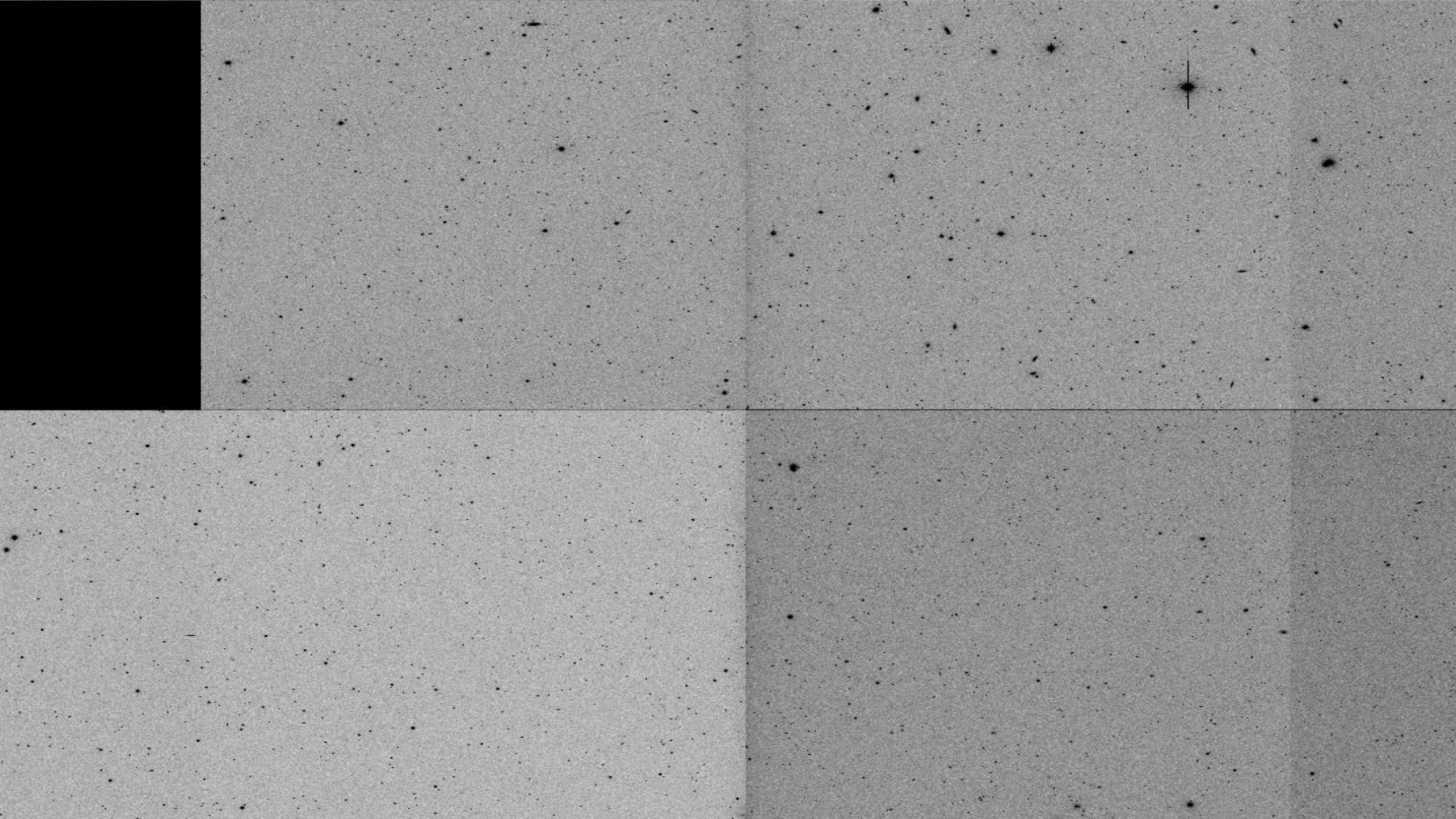
This quadrant  
works but gain  
is different

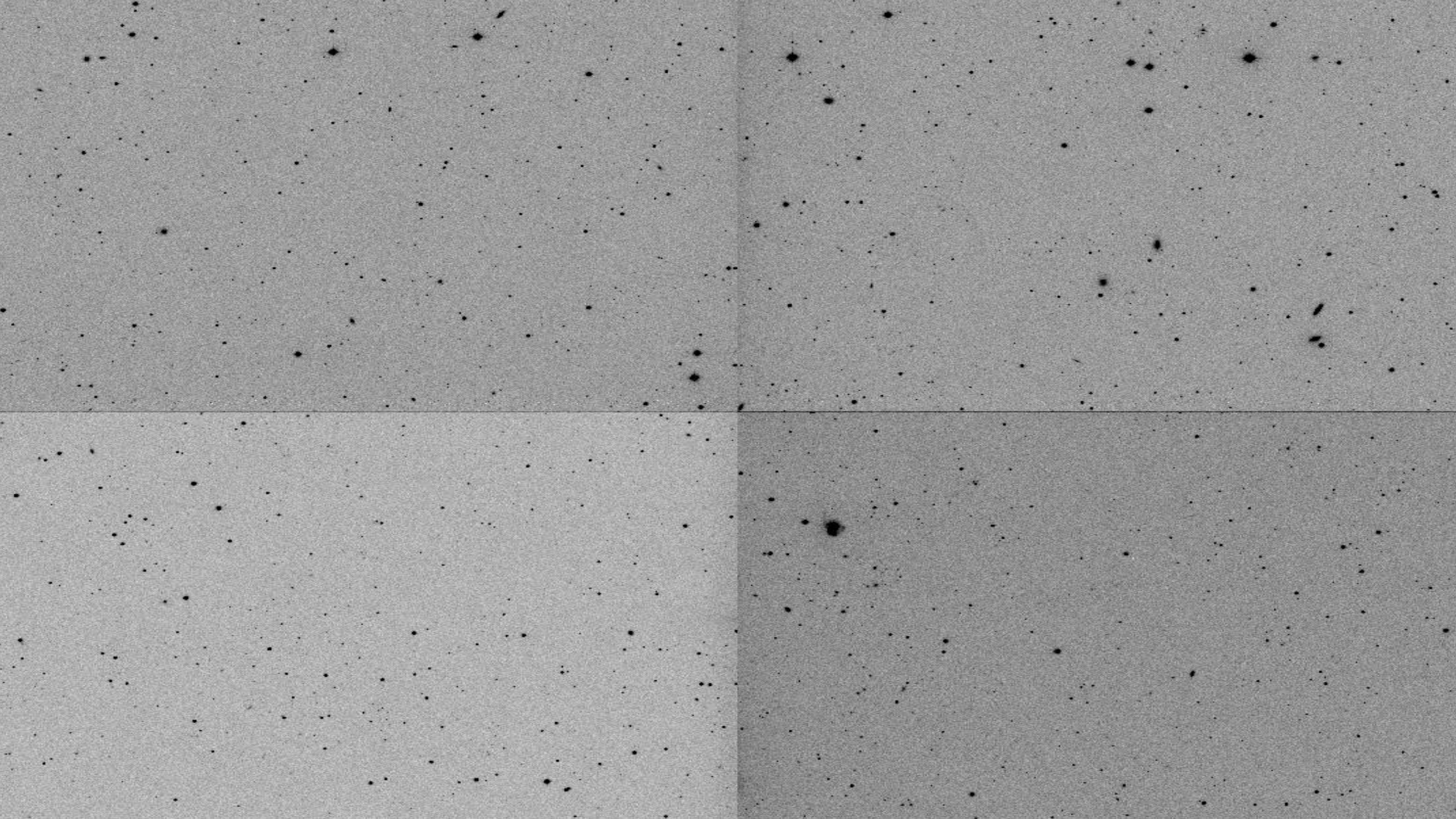
Some line  
start transient  
to fix.

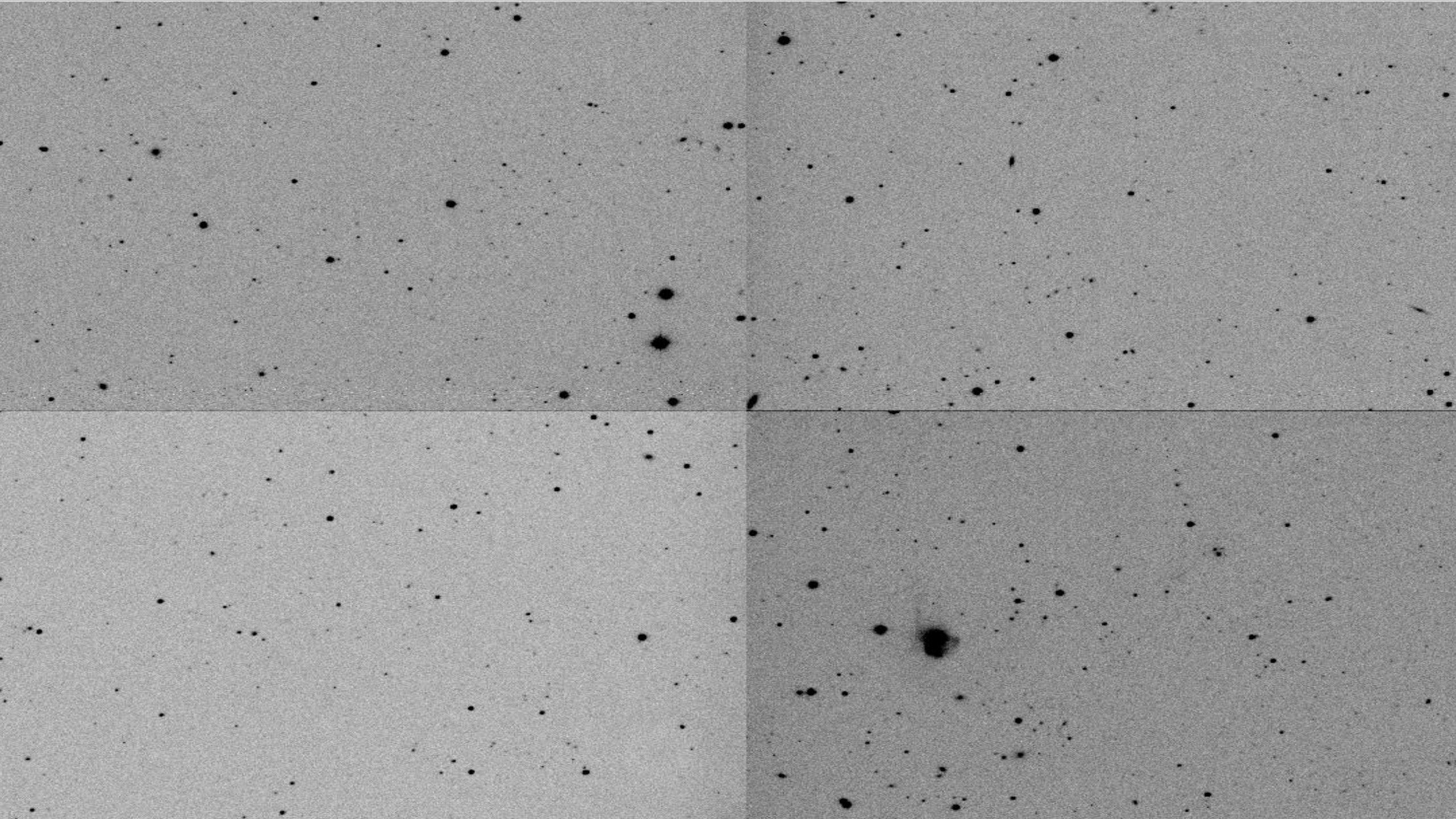
Space junk  
rotating ?

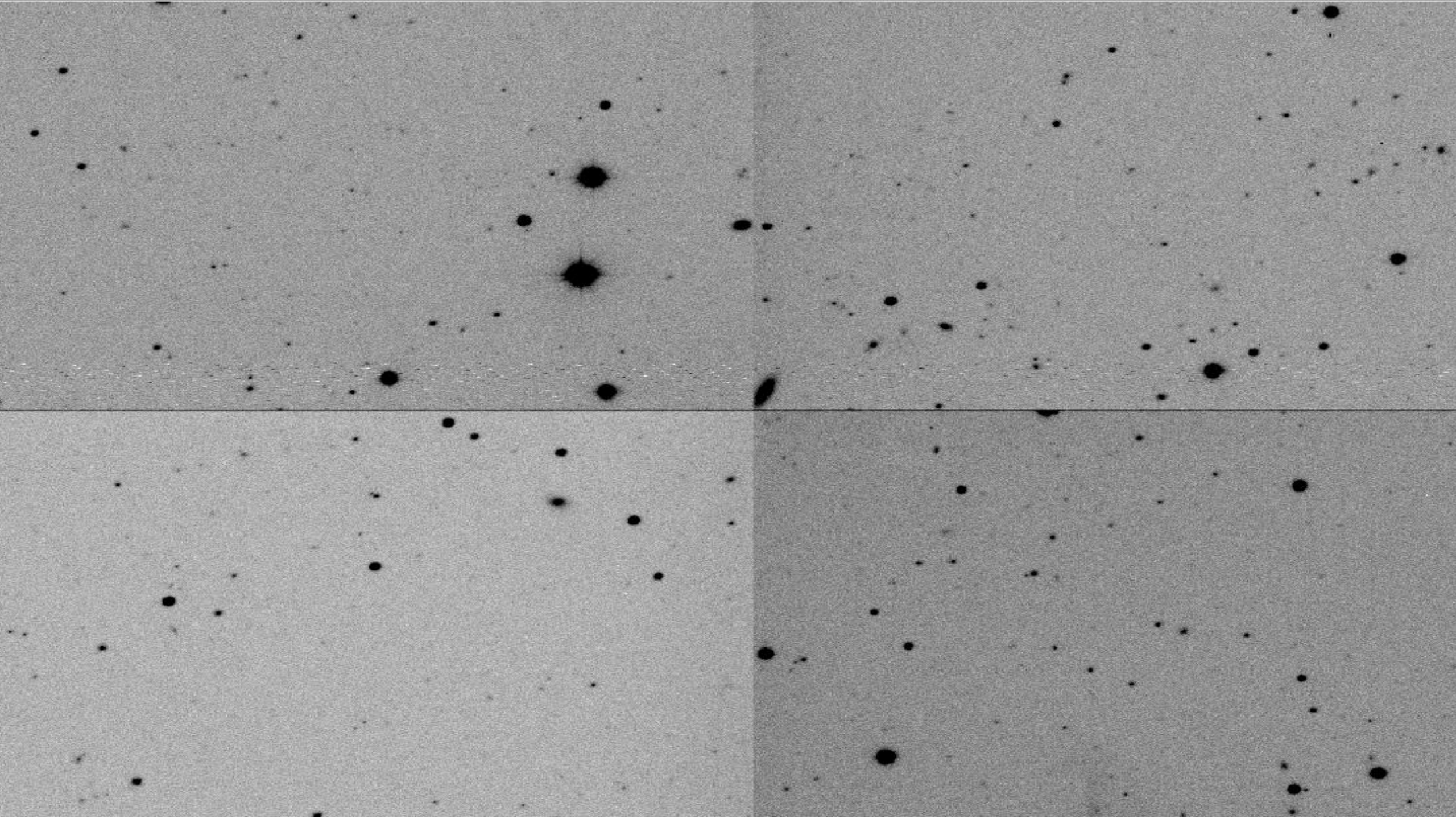


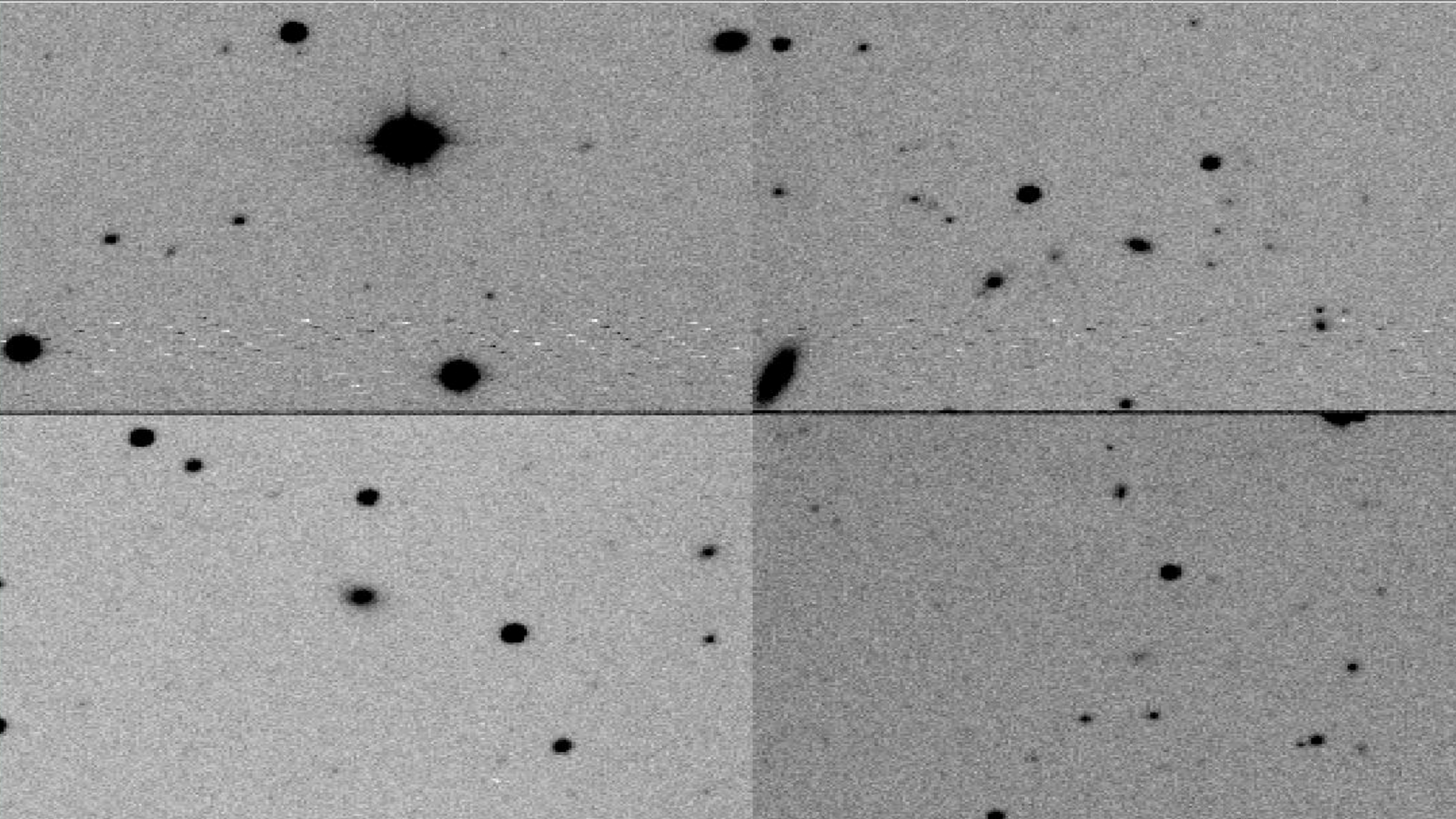












RAW DATA





$10^{11}$  stars per galaxy





$10^{11}$  galaxies

# Up to 10% of all stars have planets in “habitable zone”



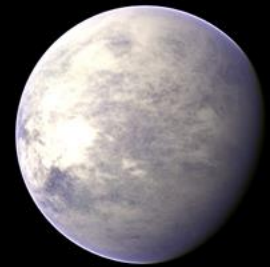
Earth



Gliese 667C c



Kepler-62 e



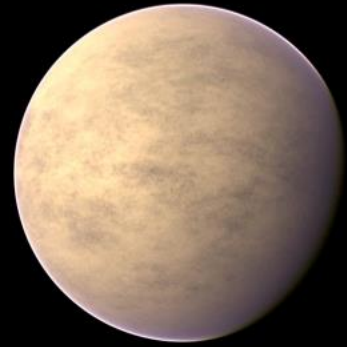
Tau Ceti e\*



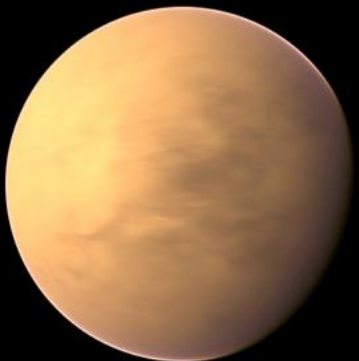
Gliese 581 g\*



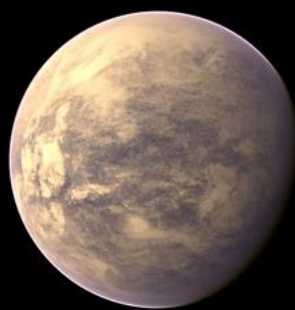
Gliese 667C f



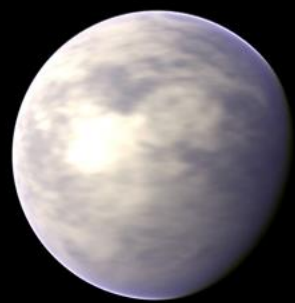
HD 40307 g



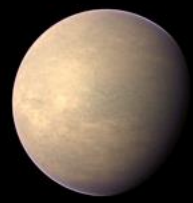
Gliese 163 c



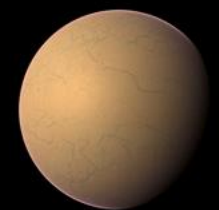
Kepler-61 b



Kepler-22 b



Kepler-62 f



Gliese 667C e



Gliese 581 d

\*planet candidates

# $10^{21}$ habitable planets

A billion trillion planets .... for ten billion years

# How to survey faster?

- All automated

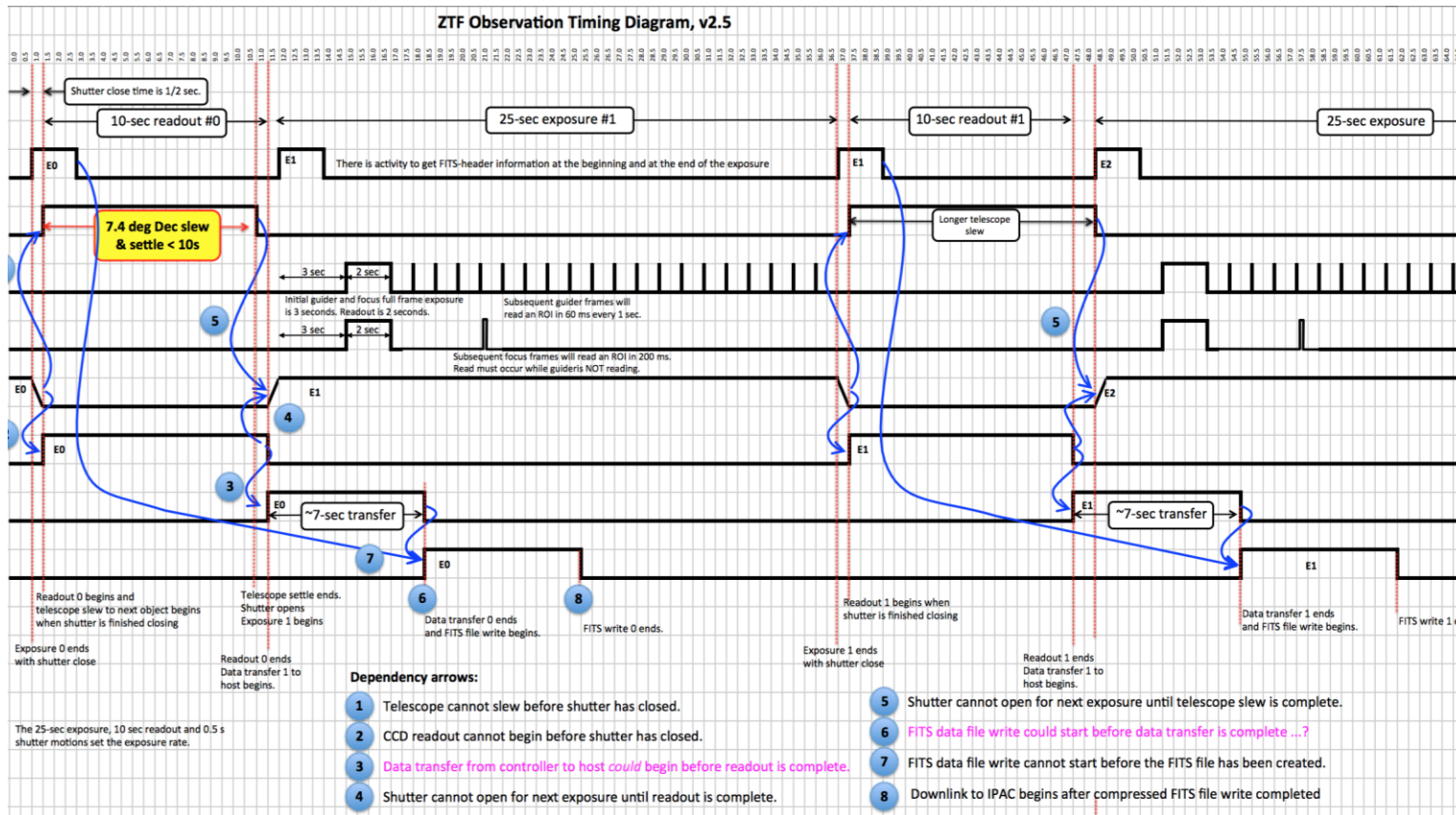
telescope control → image recording → data transfer → analysis

- High sensitivity

Semiconductor sensors record nearly every photon

- Wide field of view

# High duty cycle ...all automated

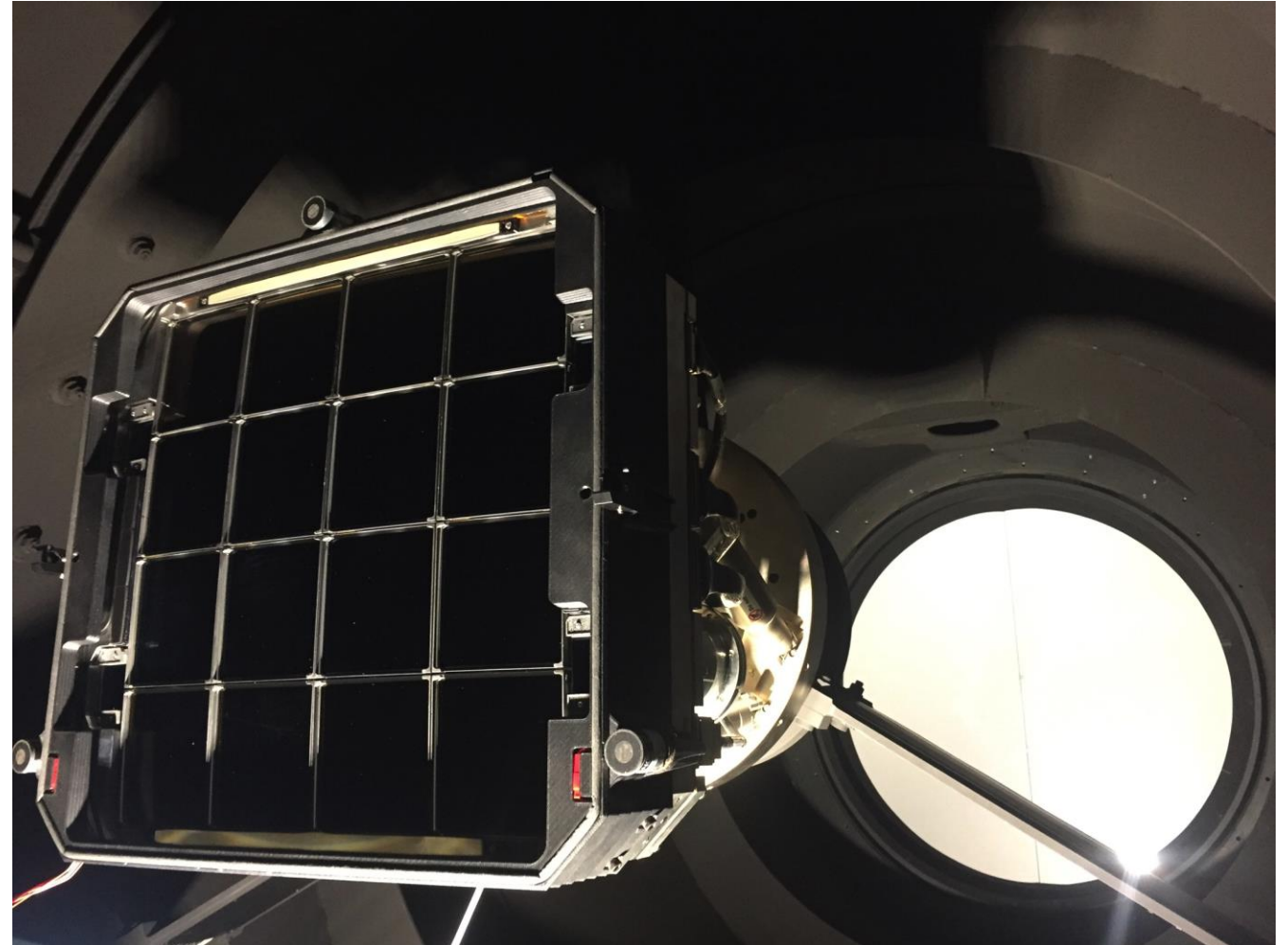


Every 10 ms counts

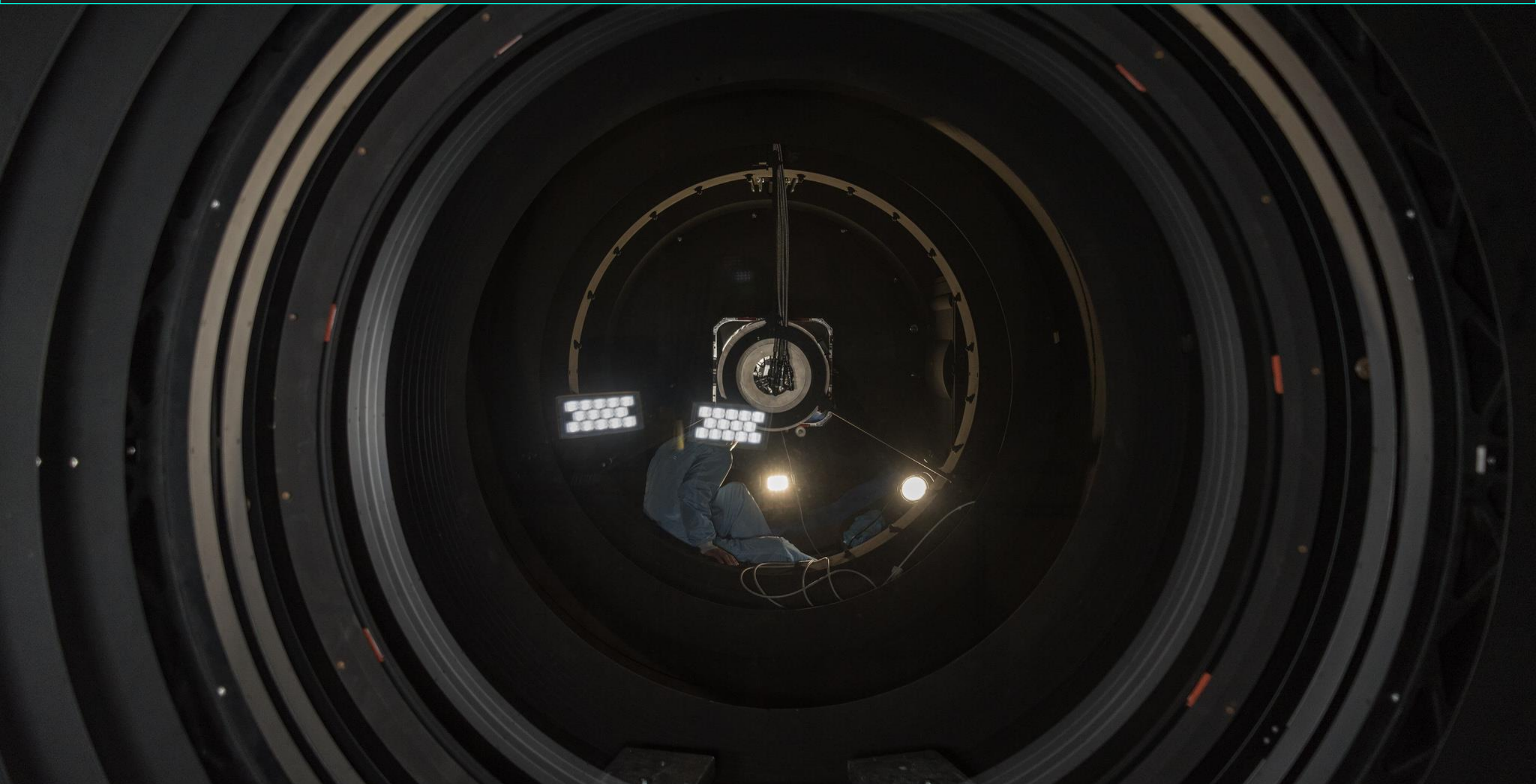
- 25 s exposure
- 1 exposure per pointing
- 8.2 s to read
- Slew and settle while reading
- RA & DEC; 0.5 deg/s<sup>2</sup> to 3 deg/s
- 90 s per filter exchange.

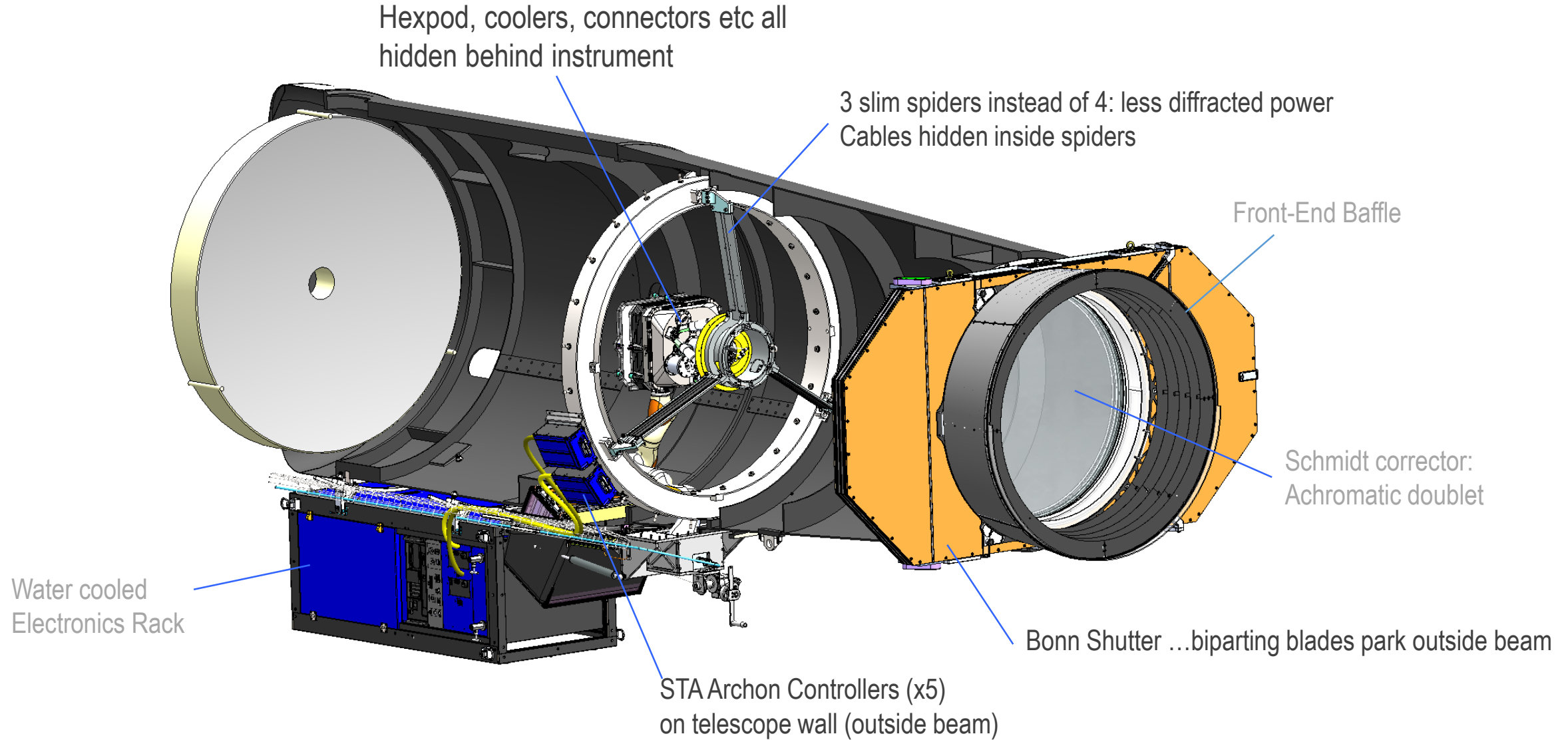
# Silicon Sensors 100x more sensitive

- CCD mosaic: 46.7 deg<sup>2</sup>, 606 Mpixel
- 1 arcsec/pixel → nyquist in median seeing
- 16 \* e2v CCD231-C6, 6K\*6K, 15μm
- 64 readouts at 1 MHz,
- 10 e- read noise << 25 e- min. sky noise
- 3 extra-focal imagers (STA 2K\*2K, 15 μm)
  - Delta doped by JPL
  - 100 μm thick fully depleted n-channel
  - with broadband 2 layer AR
  - 4 side buttable package by JPL
- 1 guider (same as focus)
- 400mm \* 400 mm mosaic
- 498 mm \* 457 mm dewar

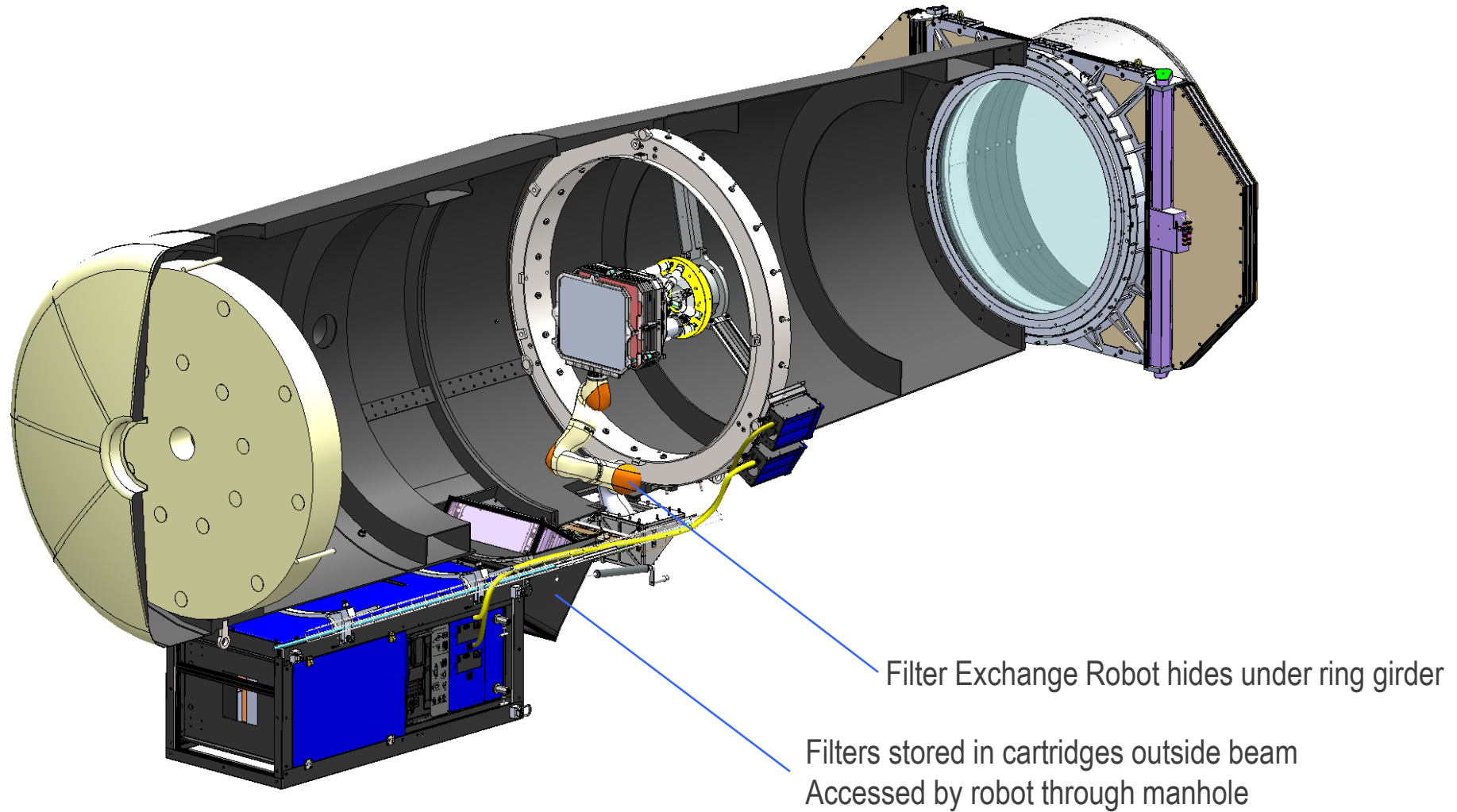


THE CHALLENGE: Big instrument in small beam.



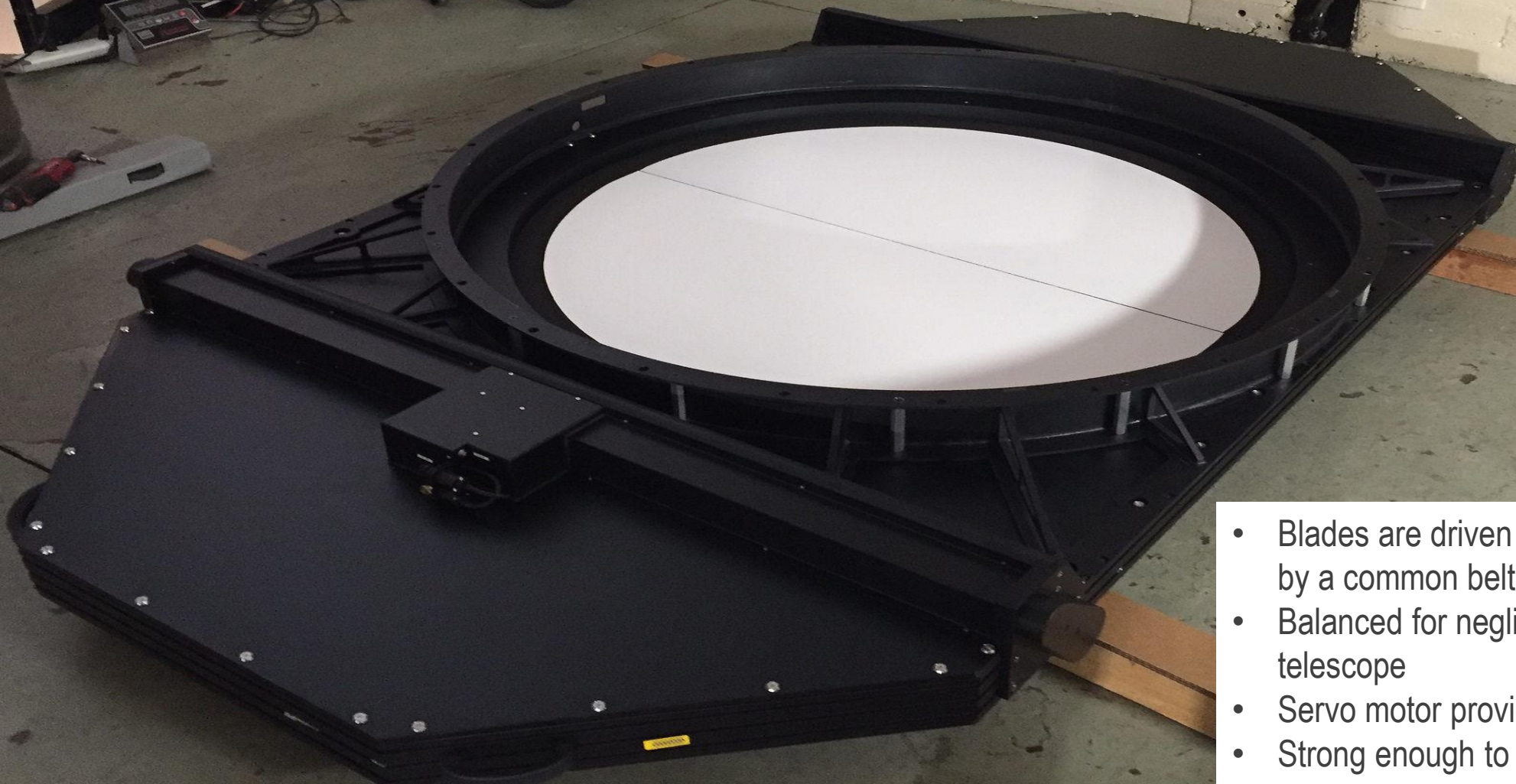






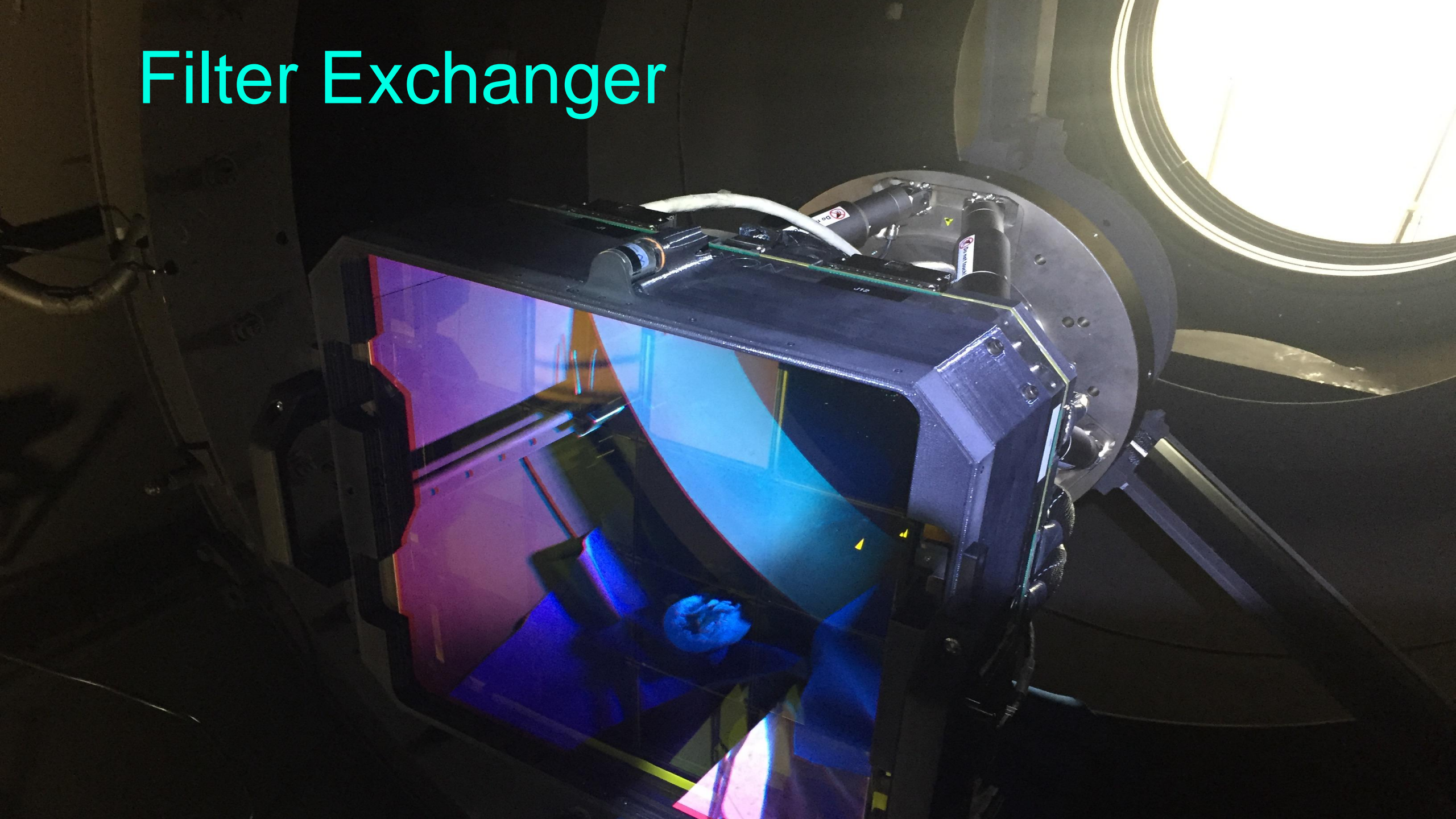
# Bonn Shutter on dome floor

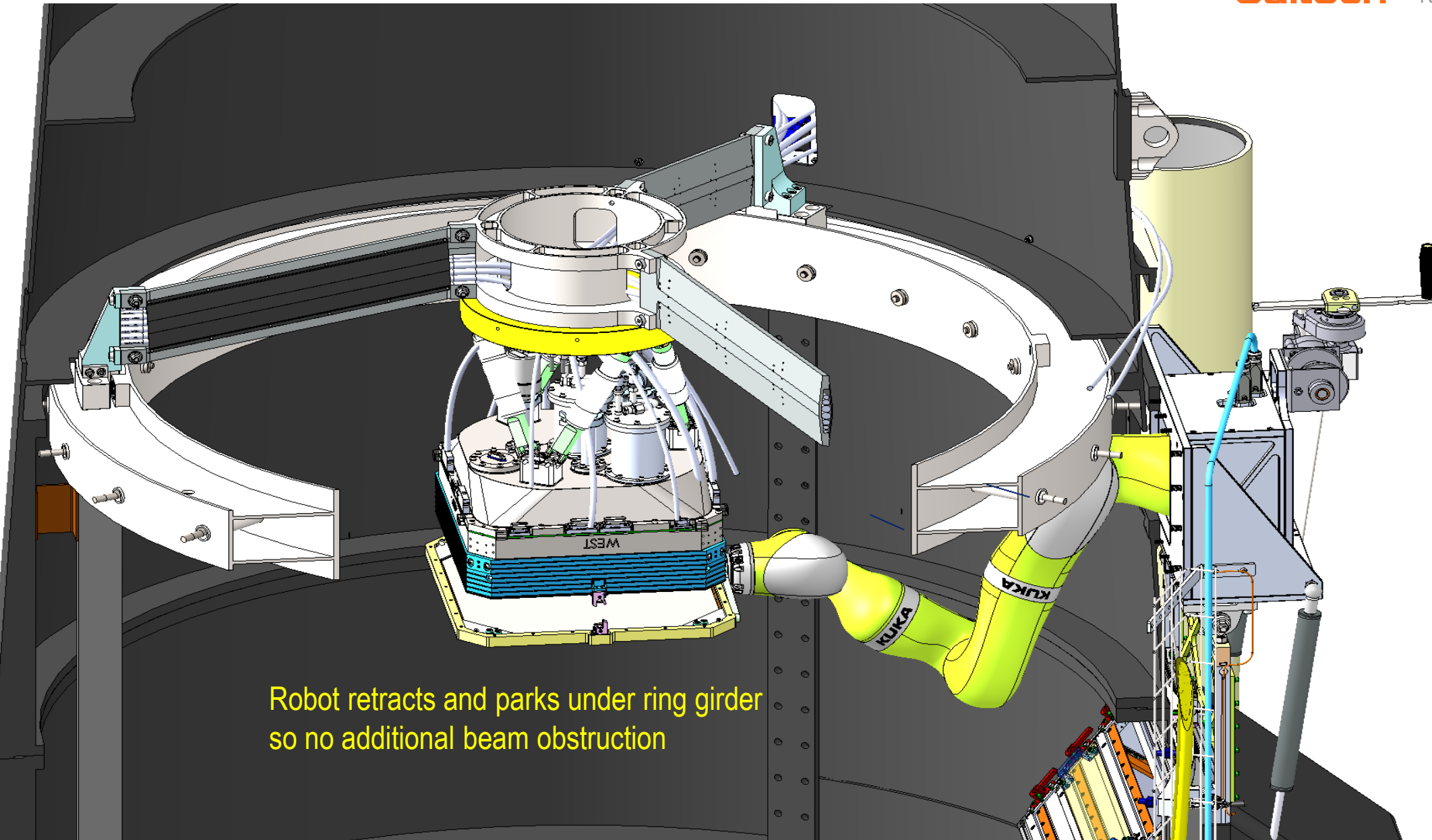
Bi-parting 1.35 m aperture. Open/close in 0.5 s



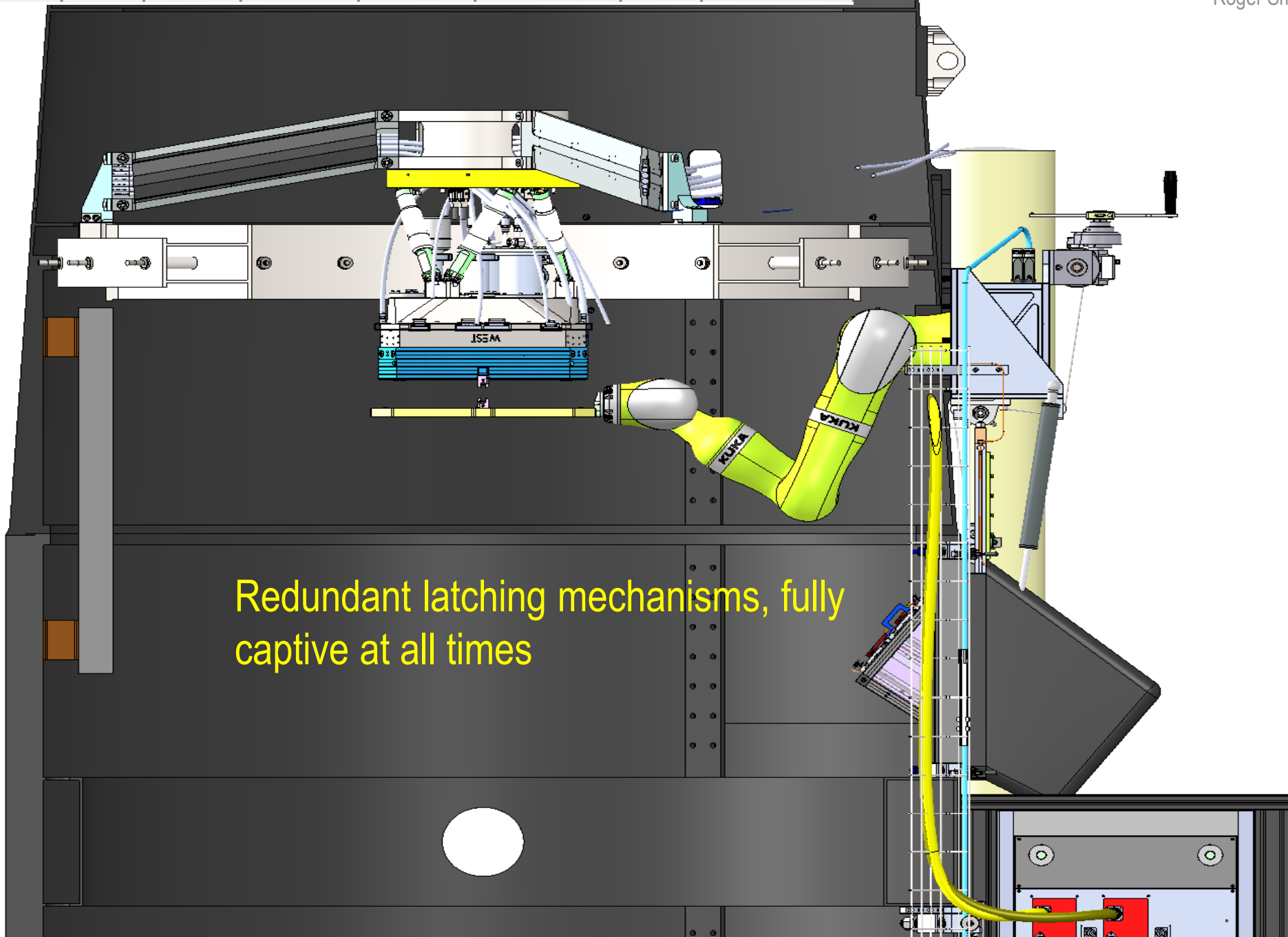
- Blades are driven in opposite directions by a common belt.
- Balanced for negligible force into telescope
- Servo motor provides tunable profiles.
- Strong enough to survive 35 mph winds.

# Filter Exchanger

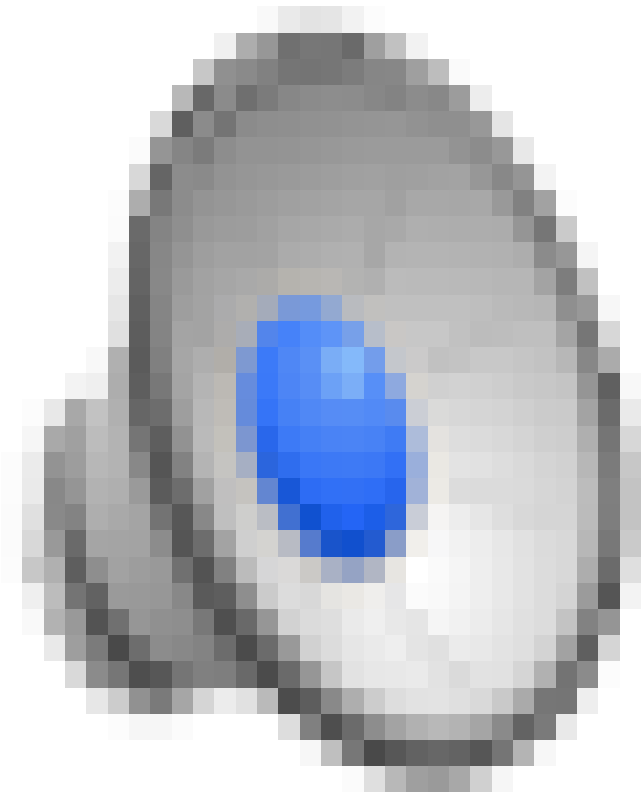




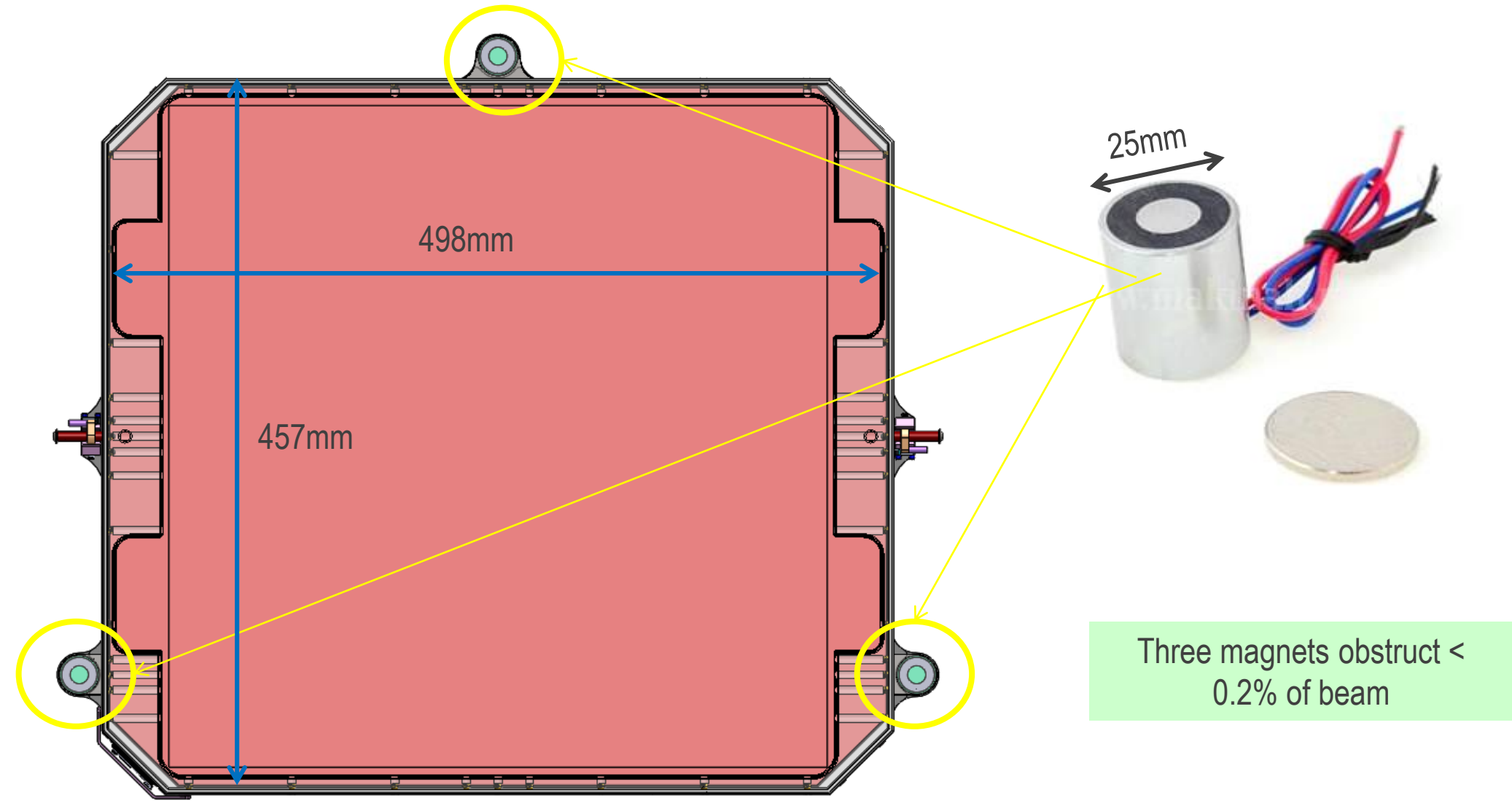
Robot retracts and parks under ring girder  
so no additional beam obstruction



Redundant latching mechanisms, fully captive at all times

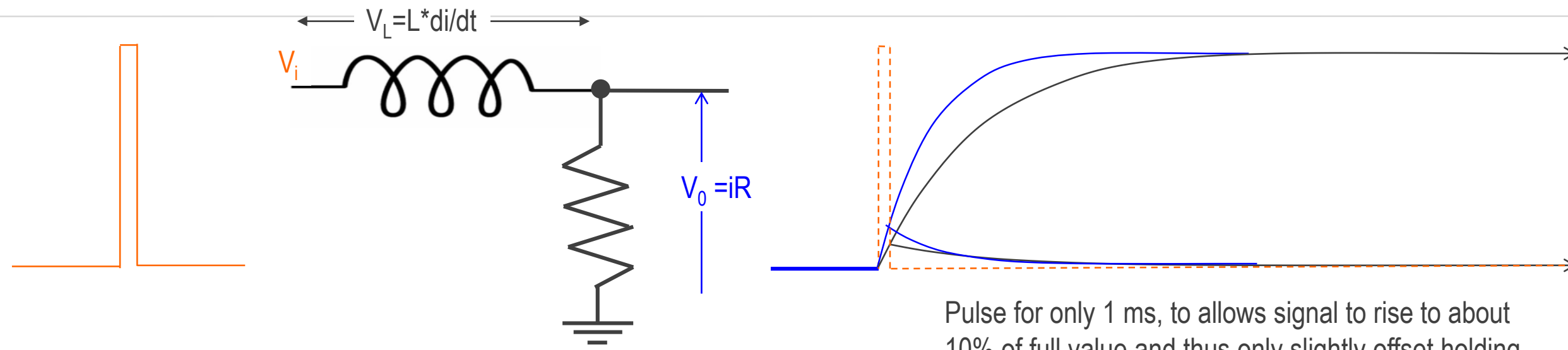


# Filters held by Electro-Permanent Magnets



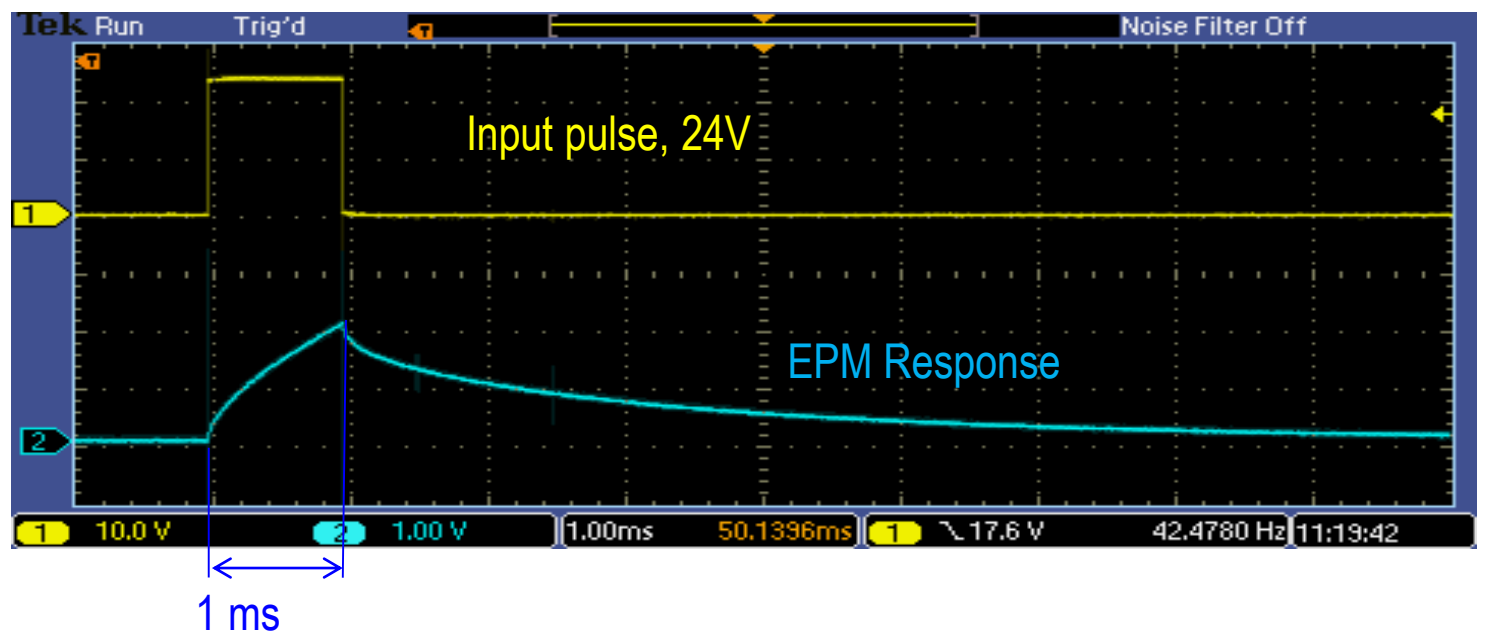
Three magnets obstruct < 0.2% of beam

# Magnet is self encoding latch



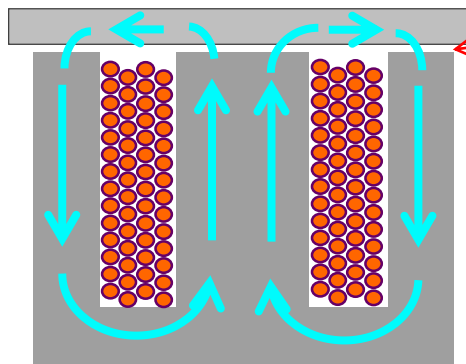
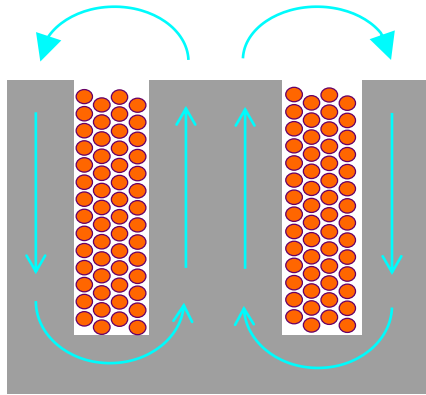
Pulse for only 1 ms, to allows signal to rise to about 10% of full value and thus only slightly offset holding force.

... but enough to pull core out of saturation so inductance depends on air gap.

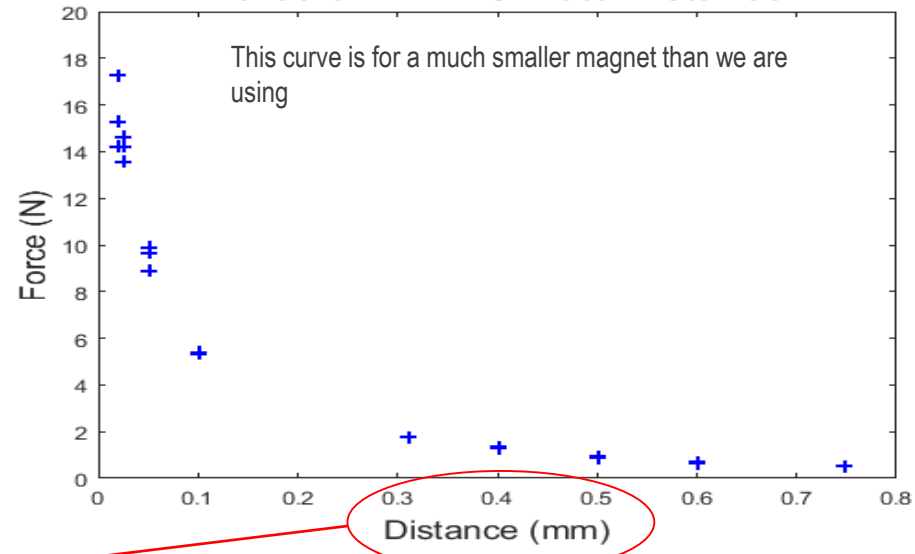




# Rise time reflects air gap



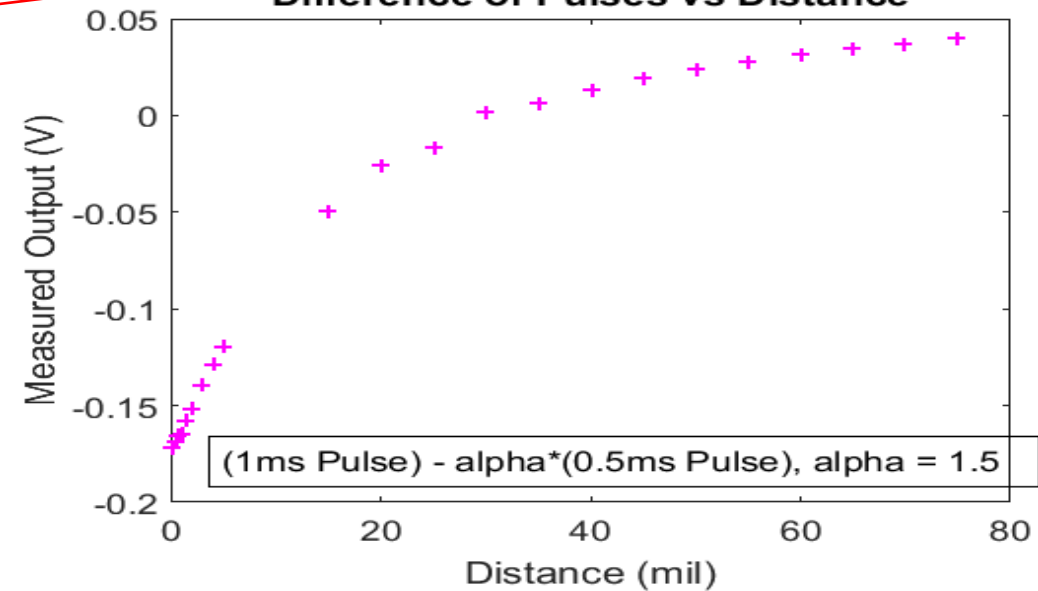
**Force of EPM vs Plate Distance**



Force rolls off steeply with air gap

... need sensing to protect against metal particles on surface

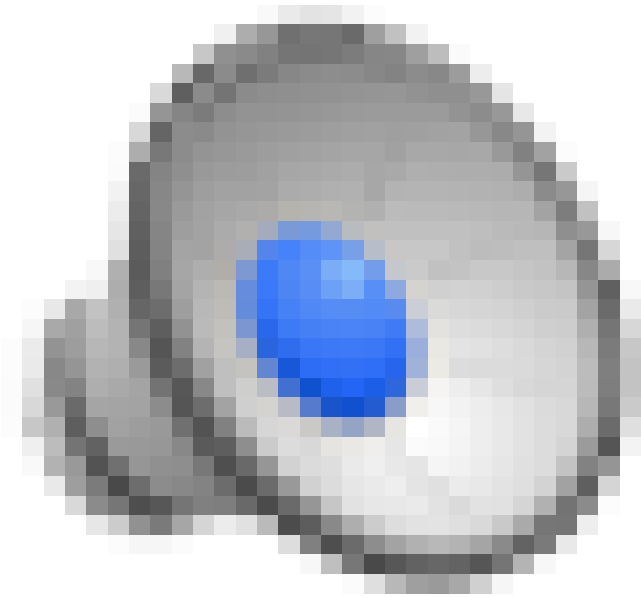
**Difference of Pulses vs Distance**



Sensing works

...after dealing with non-linearity of permanently magnetized core

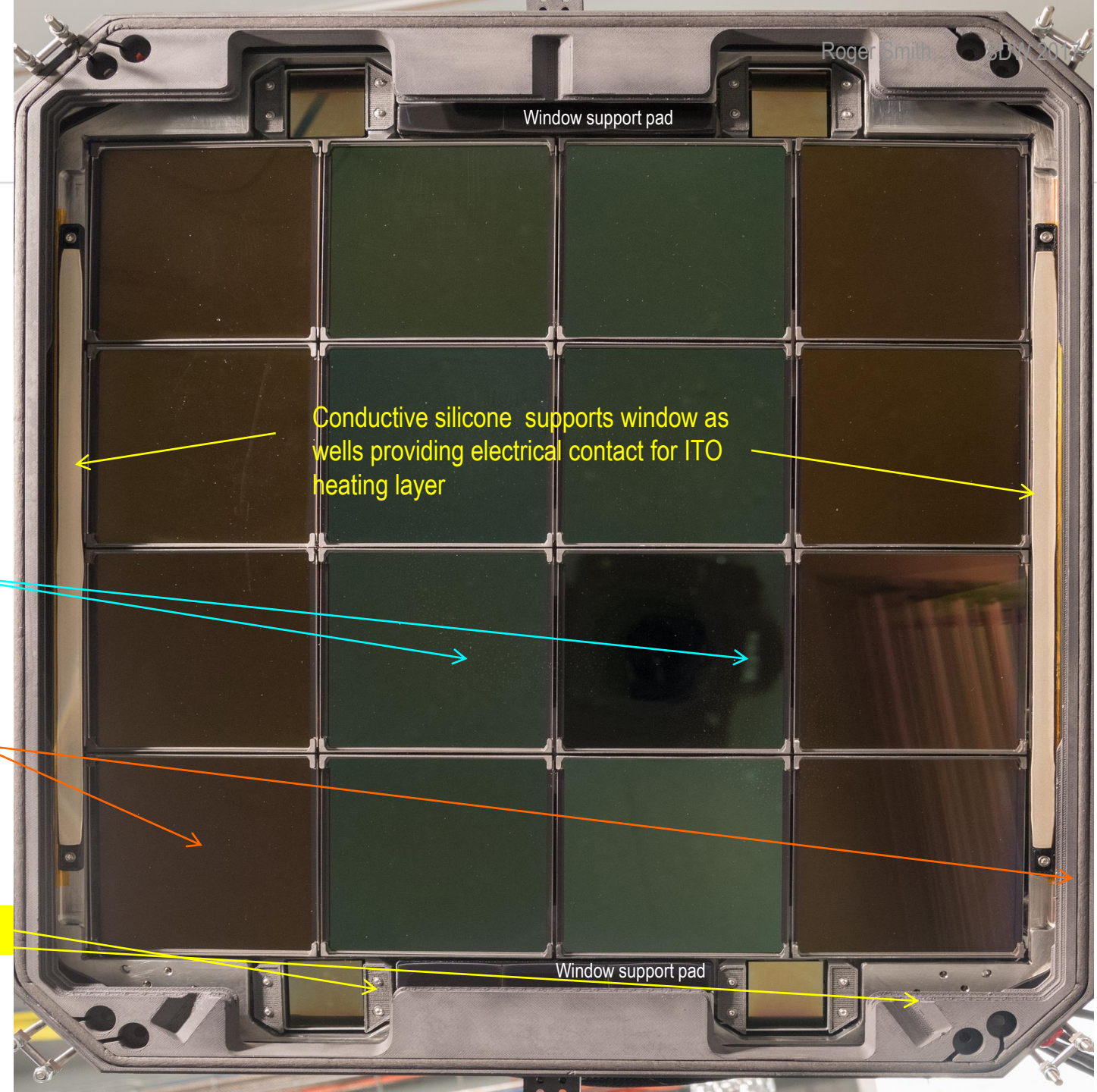
# Secondary Latch close up



# Cryostat

Sensors must operate at -100 C,  
so thermally isolated in vacuum chamber.

# Front view



Window support pad

Conductive silicone supports window as wells providing electrical contact for ITO heating layer

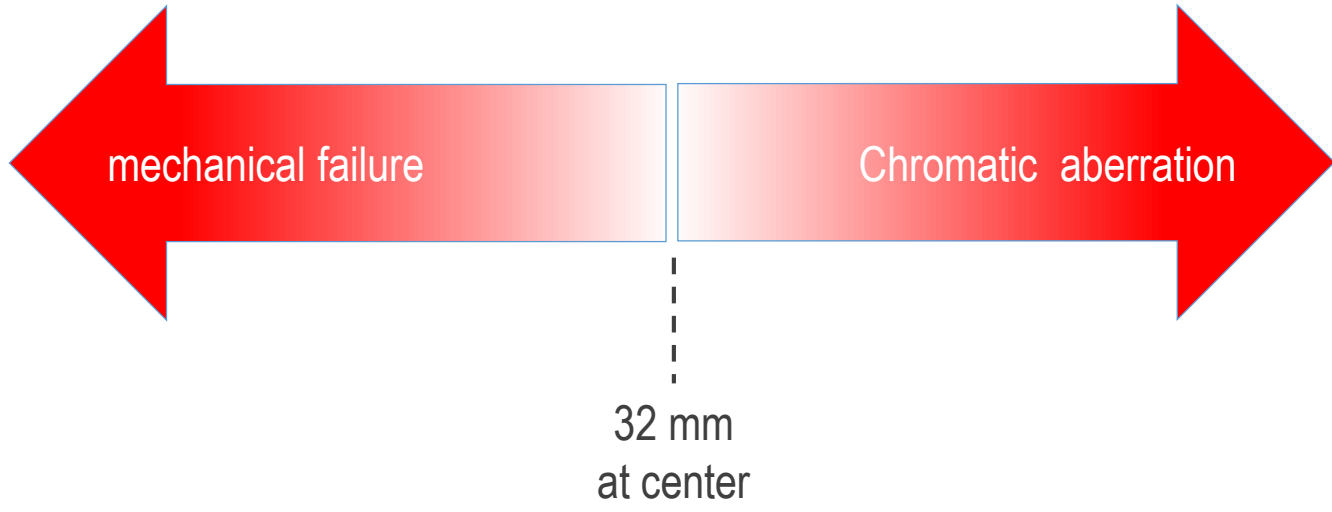
2 layer AR coating

Single layer AR coating

Delta doped, multi-layer AR coating, fully depleted thick CCDs

Window support pad

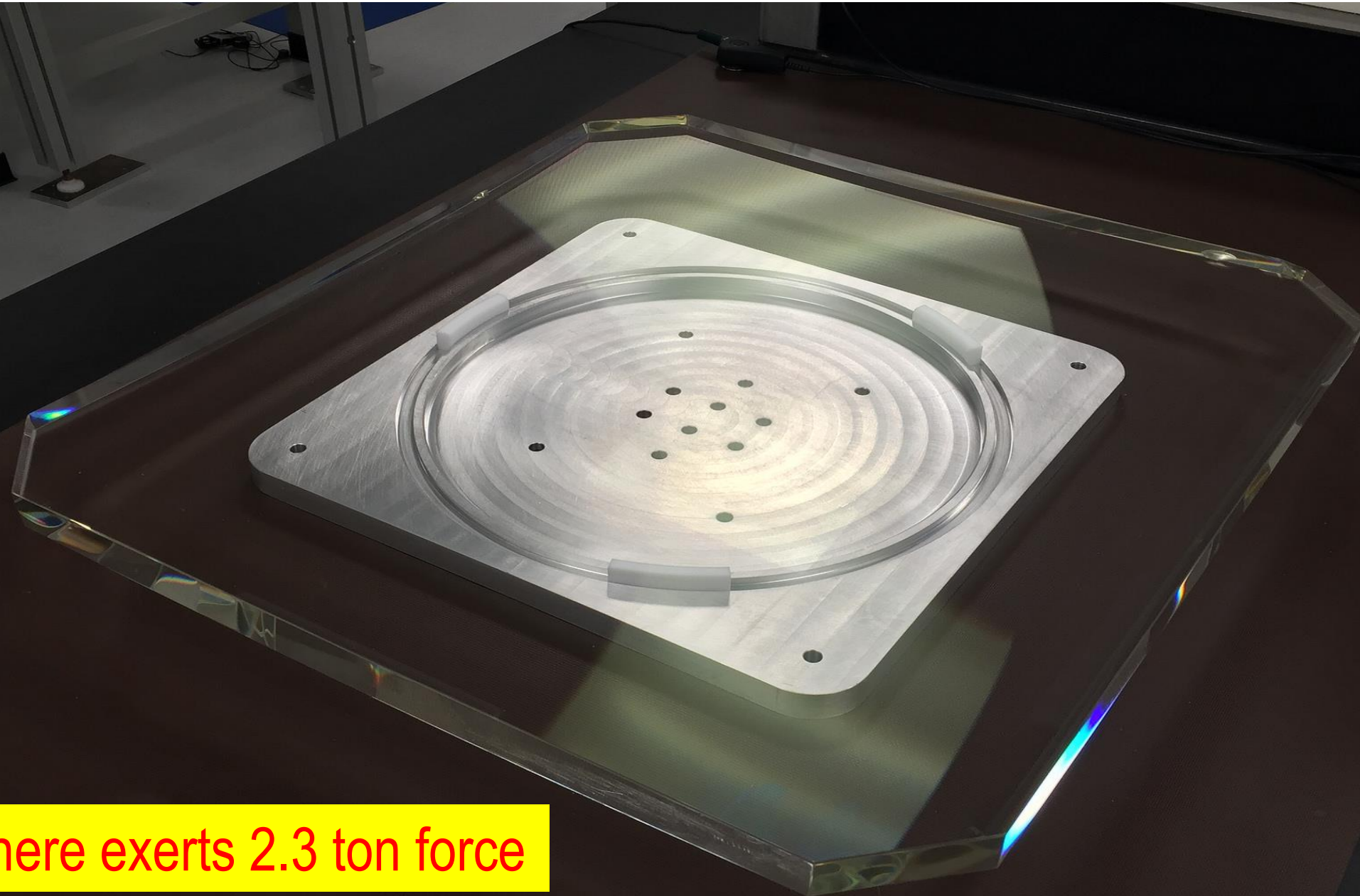
# Window Thickness





Window covers entire front of dewar

32 mm @ center, 22 mm at corner



Atmosphere exerts 2.3 ton force

# Window Factor of Safety improvements

- Increase thickness from 28 mm to 32 mm.
- Move O-rings as close to beam footprint as possible
- Add elastomeric supports at center of each side to resist bowing
- Polish edges and bevels to minimize crack growth
- Test without CCDs installed.

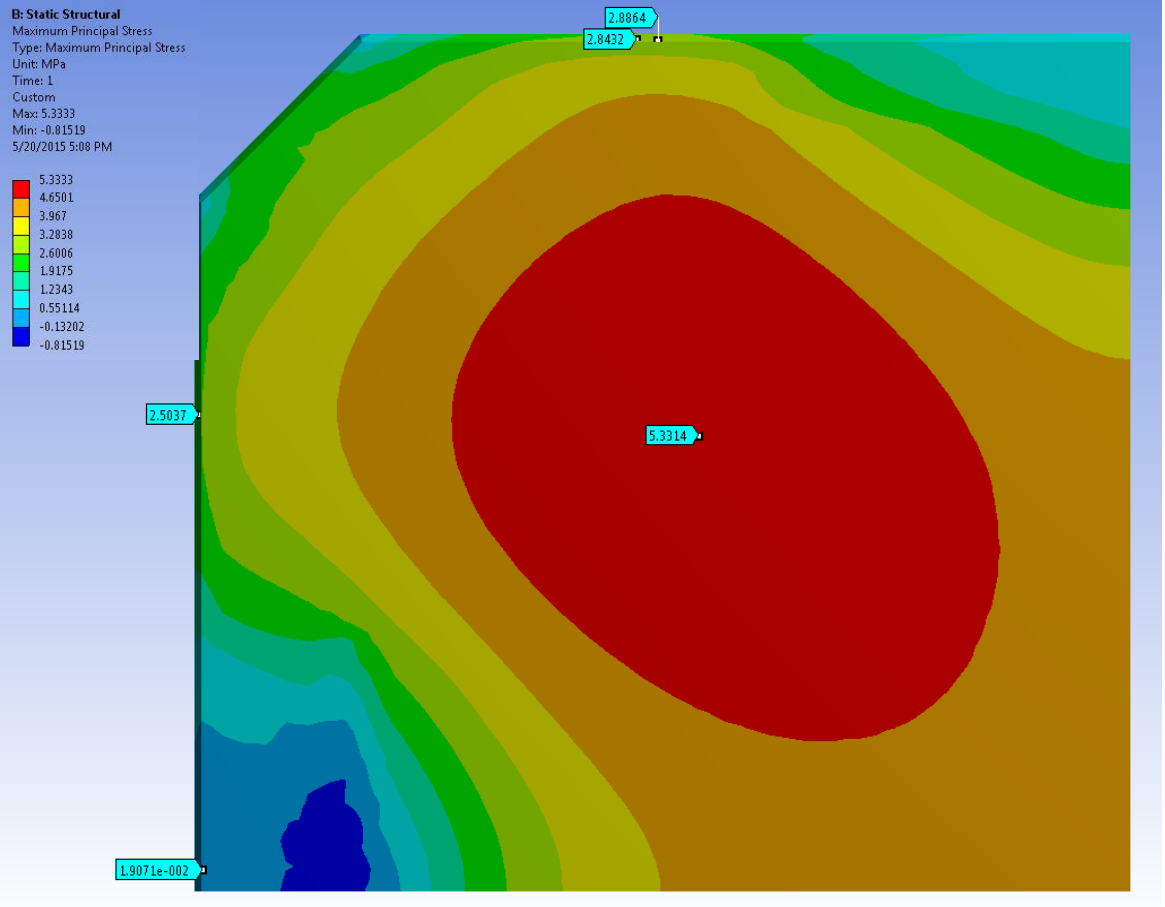




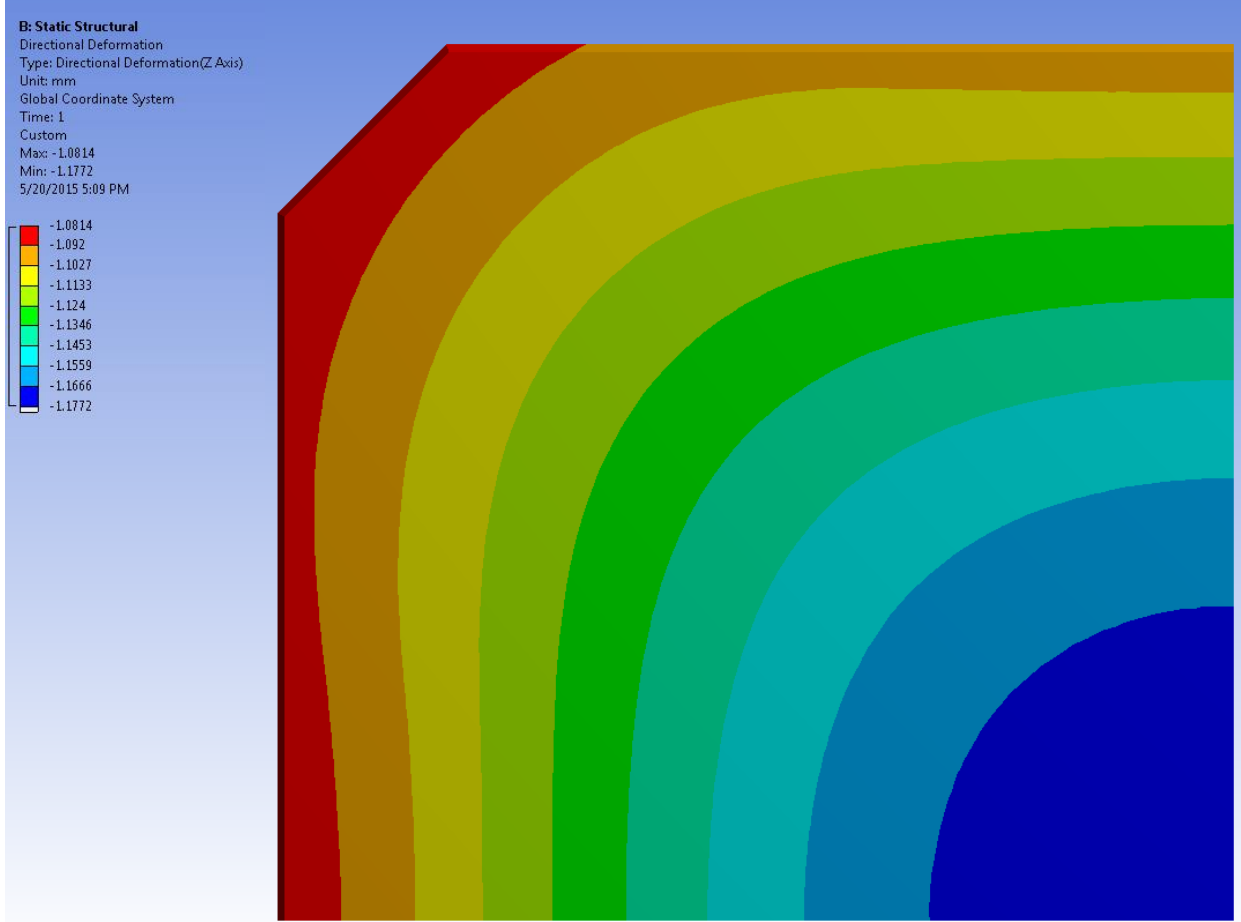
Edges polished to suppress crack initiation

# 32mm Thick

$E_{\text{O-Ring}}$  50 Durometer [360psi] Linear  
 $E_{\text{Gasket}}$  60 Durometer [520psi] Linear  
 Elongated Gasket 185mm



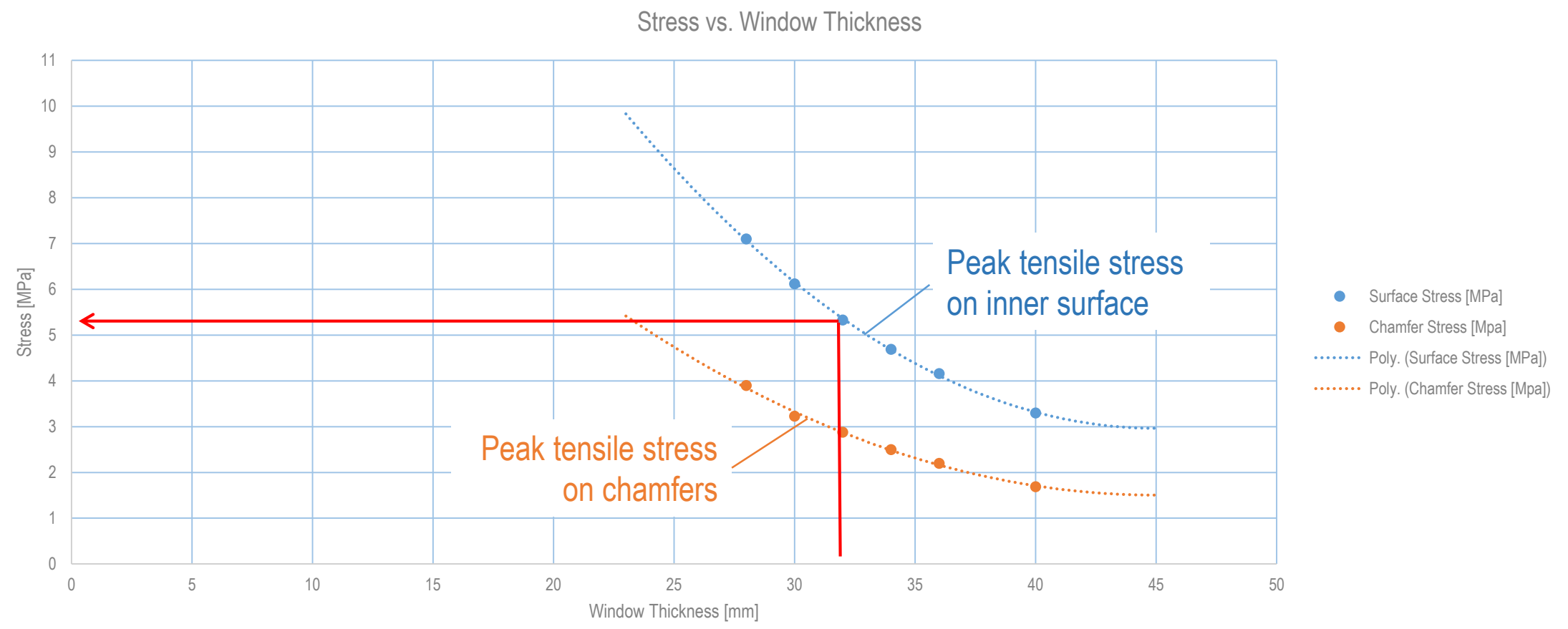
$\sigma_{\text{surface}} = 5.3\text{MPa}$  [768psi]



Vertical Deformations: 96um

# Stress vs. Window Thickness

Key innovation: vary *area* of supporting gasket to counteract bending along perimeter



# Probability of Survival $\sigma_{\max} = 5.3\text{MPa}$

Definition of Factor of Safety and behavior of brittle materials is confusing and widely misunderstood.  
See me later if you would like to know more. ....

- The actual Factor of Safety can now be calculated:

$$\sigma_{\max} := \sigma_c \cdot \left( \frac{\ln(P_s)}{-k_2 \cdot \frac{A_{\text{window}}}{A_{\text{sample}}}} \right)^{\frac{1}{\lambda}} = 35.999\text{MPa}$$

$$\text{FS}(\sigma, P_s) := \frac{\sigma_{\max}(P_s)}{\sigma}$$

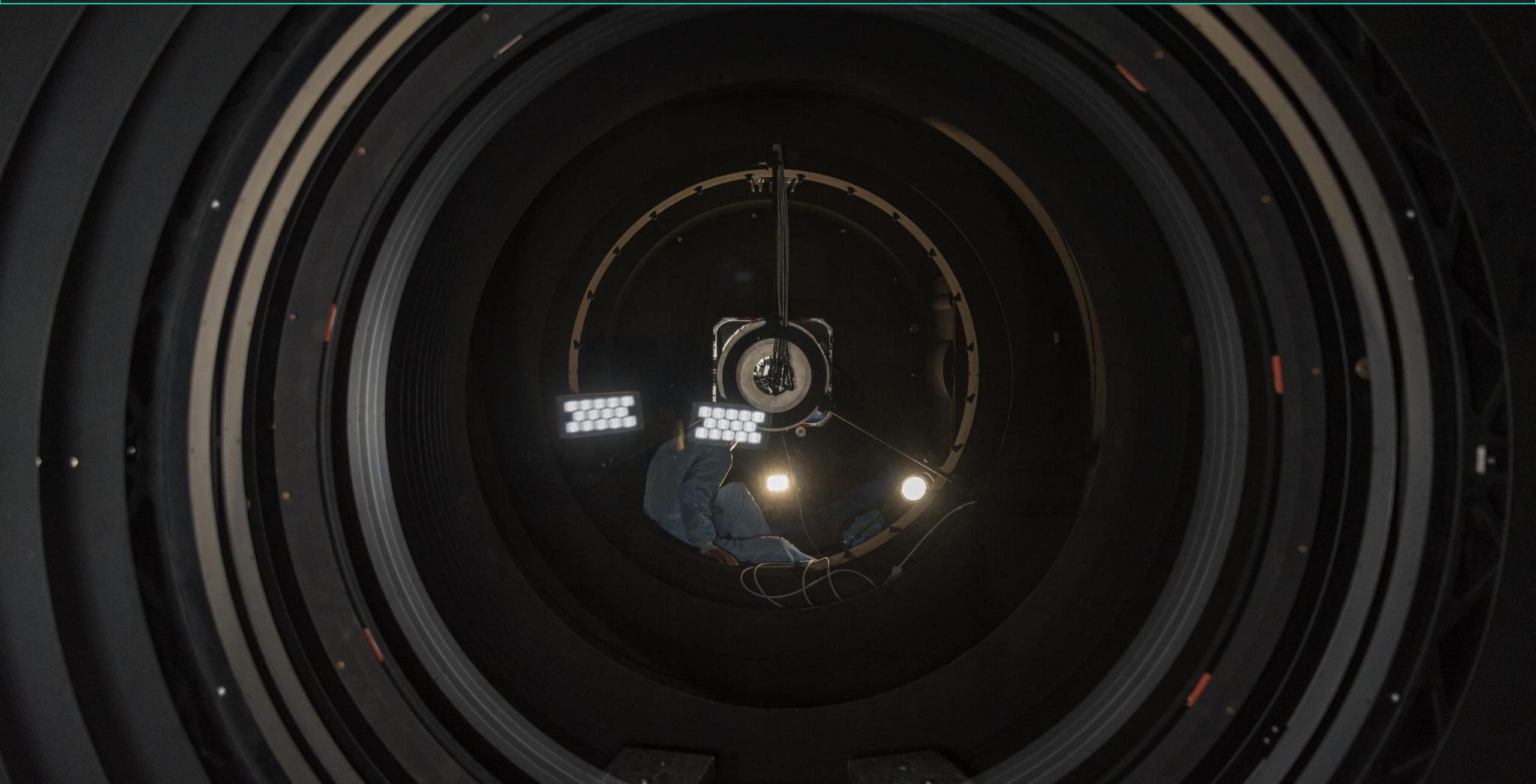
$$\text{FS} := \frac{\sigma_{\max}}{\sigma} = 6.792$$

**FoS(5.3MPa, 0.99) = 6.8**

**Probability of Survival,**

$$P_s := e^{-\frac{A_{\text{effective}}}{A_{\text{sample}}} \left( \frac{\sigma}{\sigma_c} \right)^\lambda} = 0.99999999999951907$$

THE CHALLENGE: Big instrument in small beam.





# ZWICKY TRANSIENT FACILITY

Roger Smith,

### INSTRUMENT BACKPLATE

THE INSTRUMENT BACKPLATE IS THE SINGLE LARGEST AND HEAVIEST COMPONENT OF THE INSTRUMENT. MADE FROM 300 SERIES STAINLESS STEEL, THE BACKPLATE CONTAINS ONE OF THE TWO O-RING SEALS THAT SANDWICH THE VIB AND SUPPORTS ROUGHLY 5000LBS OF FORCE FROM VACUUM. THE BACKPLATE IS A LARGE SUBASSEMBLY THAT CONTAINS MANY COMPONENTS INCLUDING, THE PCC CRYO COOLERS, COPPER THERMAL STRAPS, CRYO REFRIGERANT LINE FIXTURES, CHARCOAL GETTERS, ZEOLITE GETTERS, VACUUM PRESSURE GAUGE, VACUUM PUMPING VALVE, PRESSURE RELIEF VALVE, THERMAL SENSORS, AND HEATING RESISTORS. LASTLY, THE BACKPLATE PROVIDES AN INTERFACE FOR THE HEXAPOD.

### HEXAPOD

MANUFACTURED BY PHYSIK INSTRUMENTE, THE HEXAPOD IS A DEVICE THAT PROVIDES ZIF WITH 6DOF ADJUSTMENT AND CAN SUPPORT UP TO 150KG (TRANSLATIONAL: +/-10mm; ROTATIONAL: +/-5DEG). THE HEXAPOD HANDLES THE ENTIRE 100KG PAYLOAD OF THE INSTRUMENT AND COMPENSATES FOR ANY GRAVITATIONAL SAG OR FOCUS SHIFT.

### BACK THERMAL SHIELD

JUST LIKE THE SIDE THERMAL SHIELD, THE BACK THERMAL SHIELD REDUCES THE RADIATIVE LOAD ON THE COLDPLATE AND CCDS FROM THE REAR PART OF THE INSTRUMENT. IT IS COMPRISED OF 3 HIGHLY POLISHED ALUMINUM SHEETS THAT PROVIDE A MULTILAYER LOW EMISSIVITY REFLECTIVE SURFACE. THE BACK THERMAL SHIELDS HAVE A SLIDING FEATURE THAT CLOSES UP THE ACCESS PORTS AFTER CCD INSTALLATION.

### SIDE THERMAL SHIELD

THE SCIENCE CCDS INSIDE ZIF ARE MAINTAINED AT 165K (-108C). TO ACHIEVE THIS TEMPERATURE, THE INSTRUMENT MUST BE THERMALLY INSULATED FROM THE OUTSIDE WORLD. THE BIGGEST THERMAL LOAD ON THE SENSORS IS THROUGH RADIATION. THE SIDE THERMAL SHIELD IS MADE FROM HIGHLY POLISHED BENT ALUMINUM SHEET METAL AND NESTS INSIDE THE SIDE ENCLOSURE WITH INSULATIVE 3D PRINTED FRAMES. THE SHINY SURFACE OF THE ALUMINUM REDUCES THE EMISSIVITY AND CUTS DOWN ON THE RADIATIVE LOAD FROM THE SIDE ENCLOSURE.

### INSTRUMENT SIDE ENCLOSURE

THE INSTRUMENT SIDE ENCLOSURE ENCASES THE SCIENCE CCDS AND HOLDS UP AGAINST THE FORCES OF VACUUM. IT IS MANUFACTURED FROM 300 SERIES STAINLESS STEEL AND REQUIRED AXIS MACHINING DUE TO THE SPHERICAL O-RING INTERFACE WITH THE WINDOW. THE SIDE ENCLOSURE ALSO CONTAINS 3 BIPODS (THAT SUPPORT THE SENSOR PLANE COLDPLATE) AND THE ELECTRICALLY CONDUCTIVE GASKETS (THAT HEAT THE WINDOW).

### SCIENCE CCDS

ZIF'S FOCAL PLANE IS A MOSAIC OF SIXTEEN E2V231-C6 (4K X 4K) CCDS. WITH A FOCAL PLANE THIS LARGE, ZIF CAN CAPTURE THE ENTIRE NORTHERN SKY IN JUST 3 DAYS. WITH ALL OF THE SENSORS COMBINED, THE TOTAL RESOLUTION IS 24,000X24,000 PIXELS, WHICH EQUATES TO 576 MEGAPIXELS!

### GUIDE-FOCUS CCDS

THERE ARE A TOTAL OF FOUR 2KX2K DELTA DOPED GUIDE FOCUS CCDS PROVIDED BY JPL. AS THE NAME IMPLIES, THE GUIDE FOCUS CCDS HELP KEEP THE SCIENCE CCDS STAY IN FOCUS AND TRACK PROPERLY.

### VACUUM INTERFACE BOARD (VIB)

THE VACUUM INTERFACE BOARD PROVIDES THE SIGNAL PATHWAY FROM THE CCDS INSIDE VACUUM TO THE CAMERA CONTROLLERS OUTSIDE OF VACUUM. RATHER THAN USING SEVERAL HERMETIC BULKHEAD CONNECTORS, ALL OF THE SIGNALS FROM THE 20X CCDS EXIT THE VACUUM THROUGH A PRINTED CIRCUIT BOARD (PCB). EACH CCD HAS 2 FLEX CABLES THAT PLUG INTO 2 CONNECTORS ON THE VIB. ALL 32 OF THESE CONNECTORS ROUTE TO THE PERIMETER OF THE VIB WHERE THEY ARE COMBINED INTO LARGER 100 PIN CONNECTORS. THE VIB IS SANDWICHED BETWEEN TWO O-RINGS (ON THE FRONT AND REAR GOLD PLATED SURFACES) WHICH SEPARATE THE PERIMETER CONNECTORS FROM VACUUM. THE ONLY PATHWAY FOR LEAKS IS THROUGH THE CROSS-SECTION OF THE PCB (WHICH IS IMPOSSIBLE).

### COLDPLATE

ALL 16X SCIENCE CCDS AND 4X GUIDE-FOCUS CCDS MOUNT TO A MONOLITHIC, 5-AXIS MACHINED ALUMINUM BLOCK, BETTER KNOWN AS THE COLDPLATE. THE COLDPLATE CONTAINS 16X PLANAR FACETS THAT ARE TANGENTIAL TO THE SPHERICAL FOCAL SURFACE DEFINED BY THE P48 SCHMIDT TELESCOPE'S OPTICAL PRESCRIPTION. THESE FACETS POSITION THE SCIENCE CCDS WITH THE OPTIMAL TILT ANGLES FOR BEST FOCUS. THE SCIENCE CCDS INTERFACE TO THE FRONT OF THE COLD PLATE WHILE THE COPPER THERMAL STRAPS BOLT ON THROUGH THE BACK. THE COLD PLATE IS MAINTAINED AT 163K.

### WINDOW SUPPORT O-RING

### CONDUCTIVE RUBBER GASKET (2X)

### WINDOW

THE WINDOW IS A LARGE RECTANGULAR MENISCUS 448 X 489.5 X 32mm (17.6 X 19.3 X 1.26IN). IT HOLDS BACK THE 5000LB FORCE OF VACUUM AND SEPARATES THE CCDS FROM THE OUTSIDE WORLD. THE WINDOW HAS AN INDIUM-TIN-OXIDE COATING WHICH ENABLES IT TO BE HEATED FROM INSIDE THE INSTRUMENT BY ELECTRICALLY CONDUCTIVE RUBBER GASKETS (TO ELIMINATE CONDENSATION).

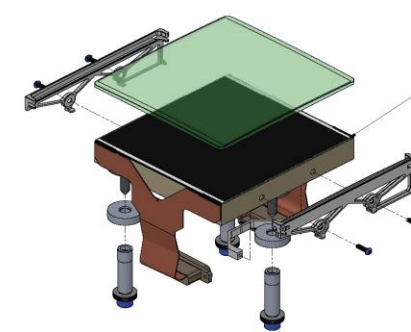
### WINDOW FRAME

THE WINDOW FRAME IS A SINGLE 3D PRINTED COMPONENT (ULTEM 9085 BLACK). IN ADDITION TO RETAINING THE INSTRUMENT WINDOW, THE WINDOW FRAME PROVIDES AN INTERFACE FOR THE EXCHANGEABLE FILTERS (WITH THE USE OF ELECTRO PERMANENT MAGNETS AND FERROUS TARGETS). THE WINDOW IS INHERENTLY CONSTRAINED TO THE INSTRUMENT WITH THE FORCE OF VACUUM, BUT THE WINDOW FRAME IS THERE TO PROTECT THE EDGES OF THE GLASS AND RETAIN THE WINDOW IN THE EVENT OF A LOSS OF VACUUM.

### FERROUS TARGET AND ELECTRO-PERMANENT MAGNET (3X)

### EXCHANGEABLE FILTER + FILTER FRAME

MADE FROM ULTEM 9085 BLACK (3D PRINTED), THE FRAME ENCASES THE EDGES OF THE FILTER GLASS FOR PROTECTION AND PROVIDES USEFUL INTERFACES FOR HANDLING/FILTER EXCHANGES. THERE ARE A TOTAL OF 3 FILTERS FOR ZIF (R, G, I BANDS) THAT WILL BE SWAPPED PERIODICALLY THROUGH OUT OBSERVATIONS.

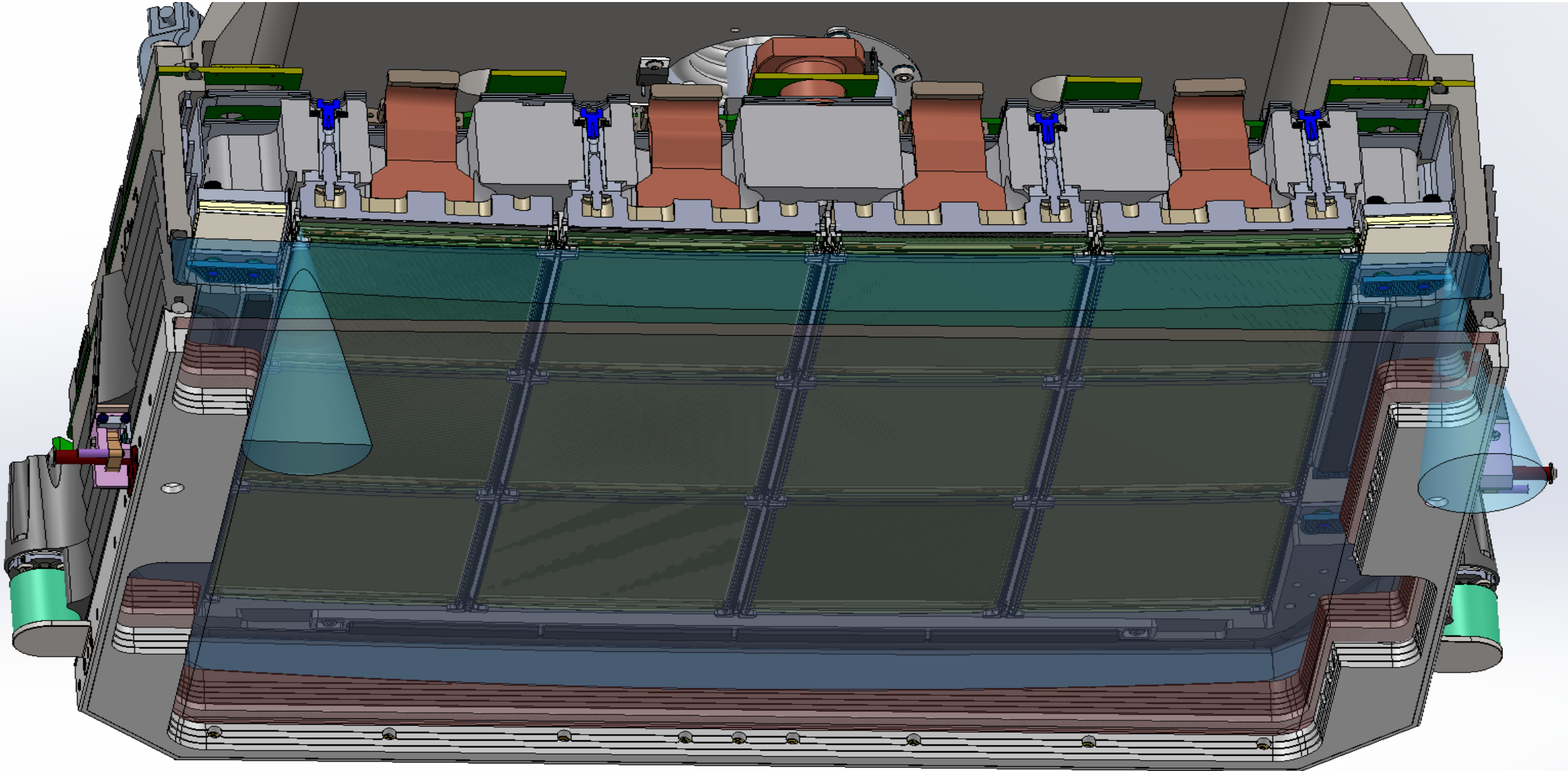


### CCD ASSEMBLY (16X)

CLOSE UP VIEW OF A SINGLE CCD SUB-ASSEMBLY. THIS DETAIL VIEW REVEALS ANOTHER OPTIC IN THE SYSTEM—THE FIELD FLATTENER, FLANKED BY 2X 3D PRINTED TITANIUM FRAMES. THE FIELD FLATTENER SITS DIRECTLY ABOVE THE SILICON SURFACE OF THE CCD AND HELPS FOCUS THE INCOMING LIGHT. ALSO SHOWN IN THIS VIEW ARE THE CCD MOUNTING STUDS, PRECISION SPACERS, AND THE FLEX CABLES.

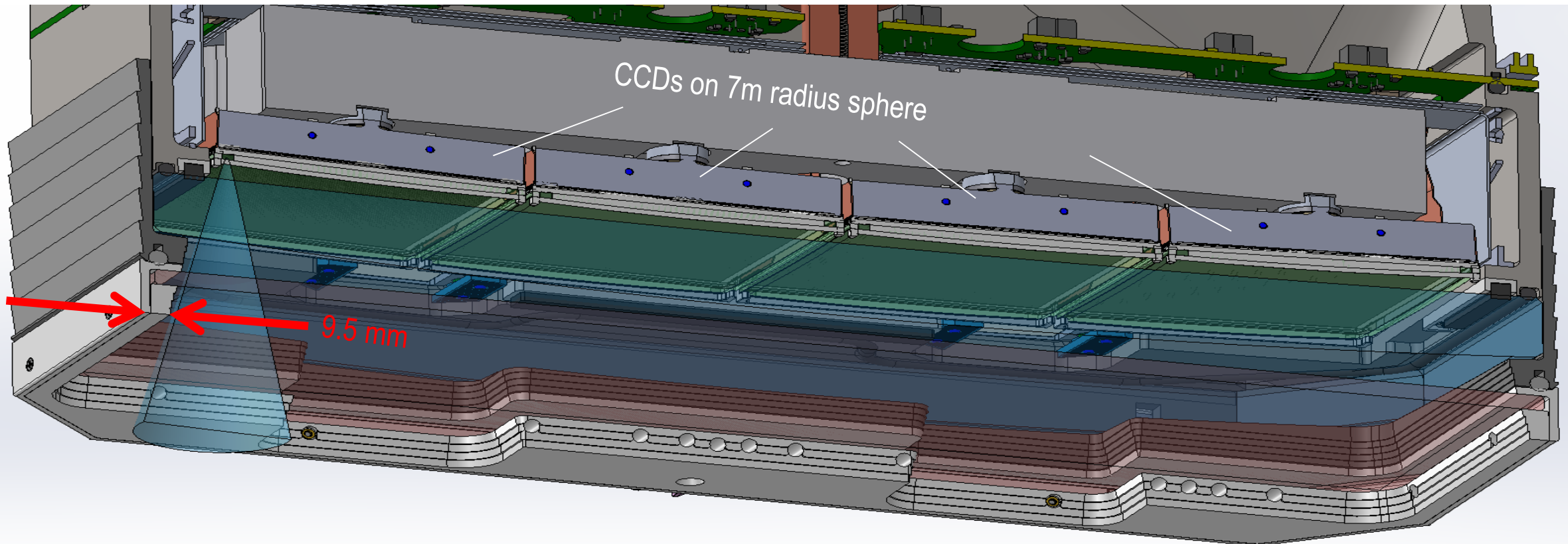
UNLESS OTHERWISE SPECIFIED:	DESIGNED BY	DATE	NAME	PROJECT OBSERVATORY
DIMENSIONS ARE IN INCHES	DR/APP	07/2017	ROGER SMITH	Zwicky Transient Facility CALTECH OPTICAL OBSERVATORIES
MACHINED RILET RACE R0.40 P	ENG APPR			TITLE:
357 FRAZIO FOR CHANGES	REC APPR			
MACHINED RACE V1.01				
RODINETS RACE V1.01				
GENERAL DIMENSIONS				
0.4 MIN	0.1	MACH 20.07		
0.1 MIN	0.02	MACH 20.07		
>0.120	0.03	MACH 20.07		
1:100-1:500	0.05	MACH 20.07		
>1000	0.12	MACH 20.07		
DO NOT SCALE DRAWING				
THIRD ANGLE PROJECTION				
APPLICATION	MATERIAL	SCALE: 1:20	WT: 98.9kg	SHEET 1 OF 1

# Window defines size of instrument



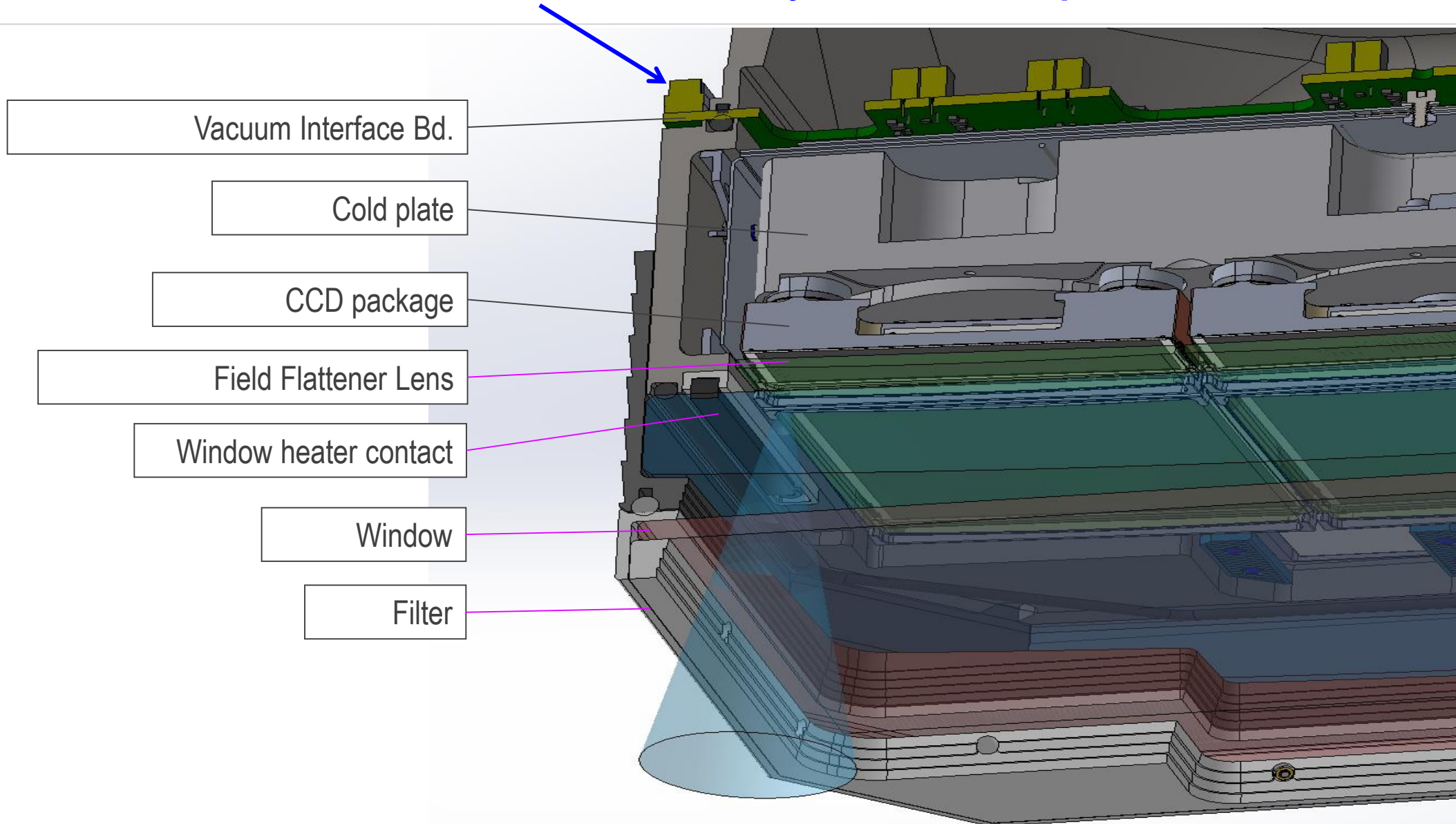
# Dewar is hidden behind filter

Filter frame adds only 9.5 mm to each side of beam footprint

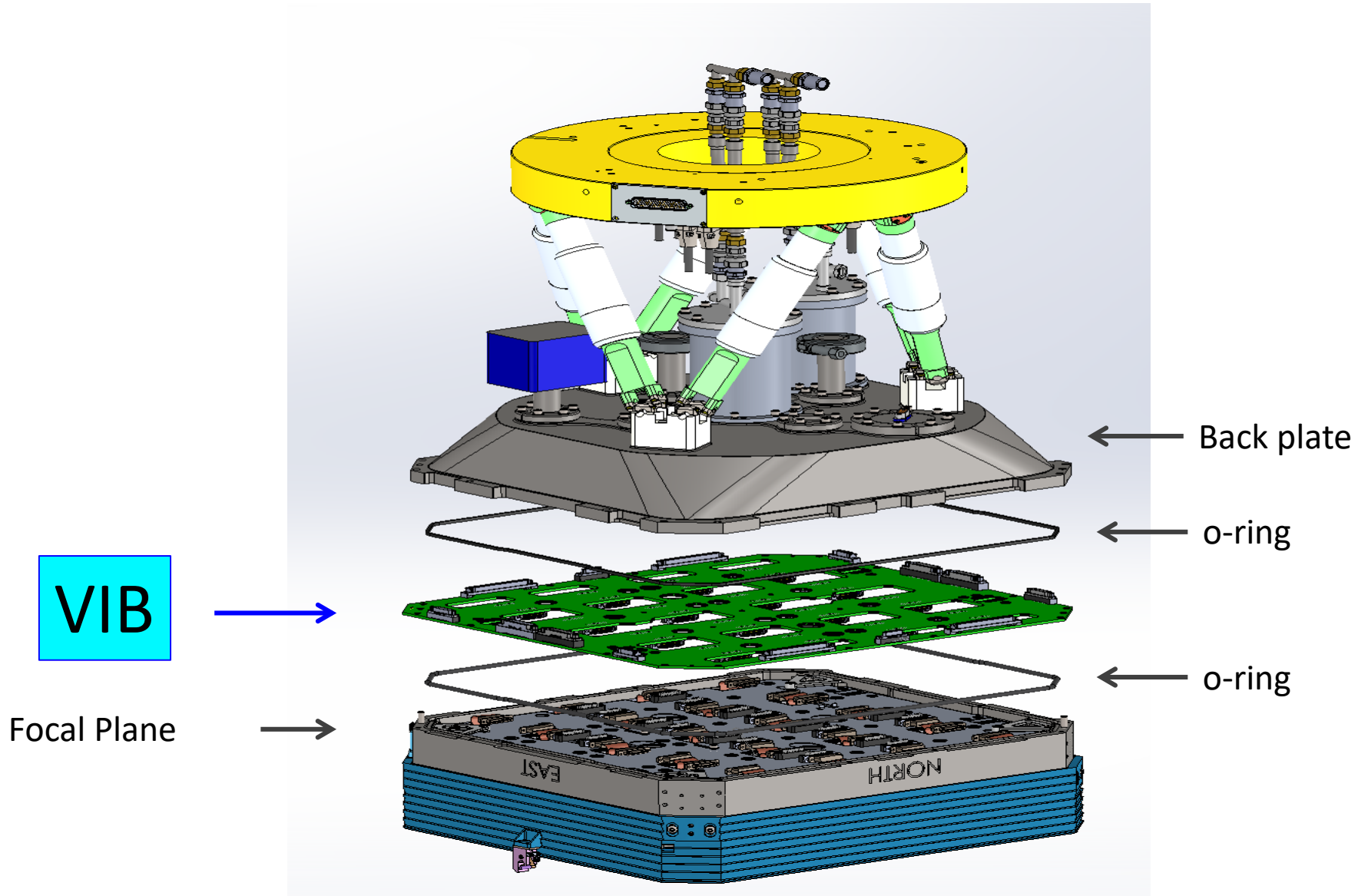




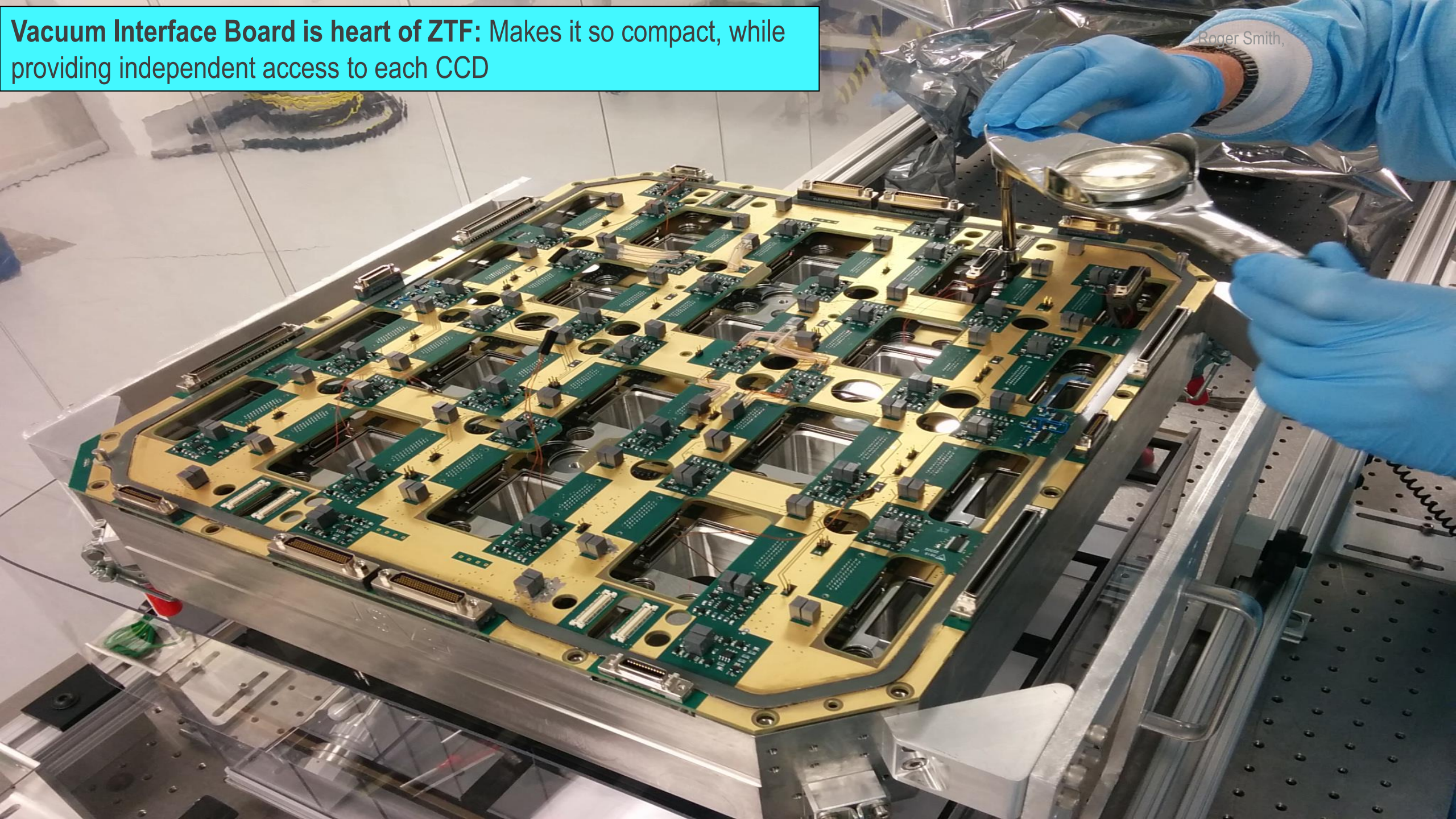
# Walls, connectors hidden by beam expansion



# VIB is trapped between two O-rings



**Vacuum Interface Board is heart of ZTF: Makes it so compact, while providing independent access to each CCD**



Roger Smith,

Line of vacuum seal, reworked

CCD fastener access

Sliding radiation shield

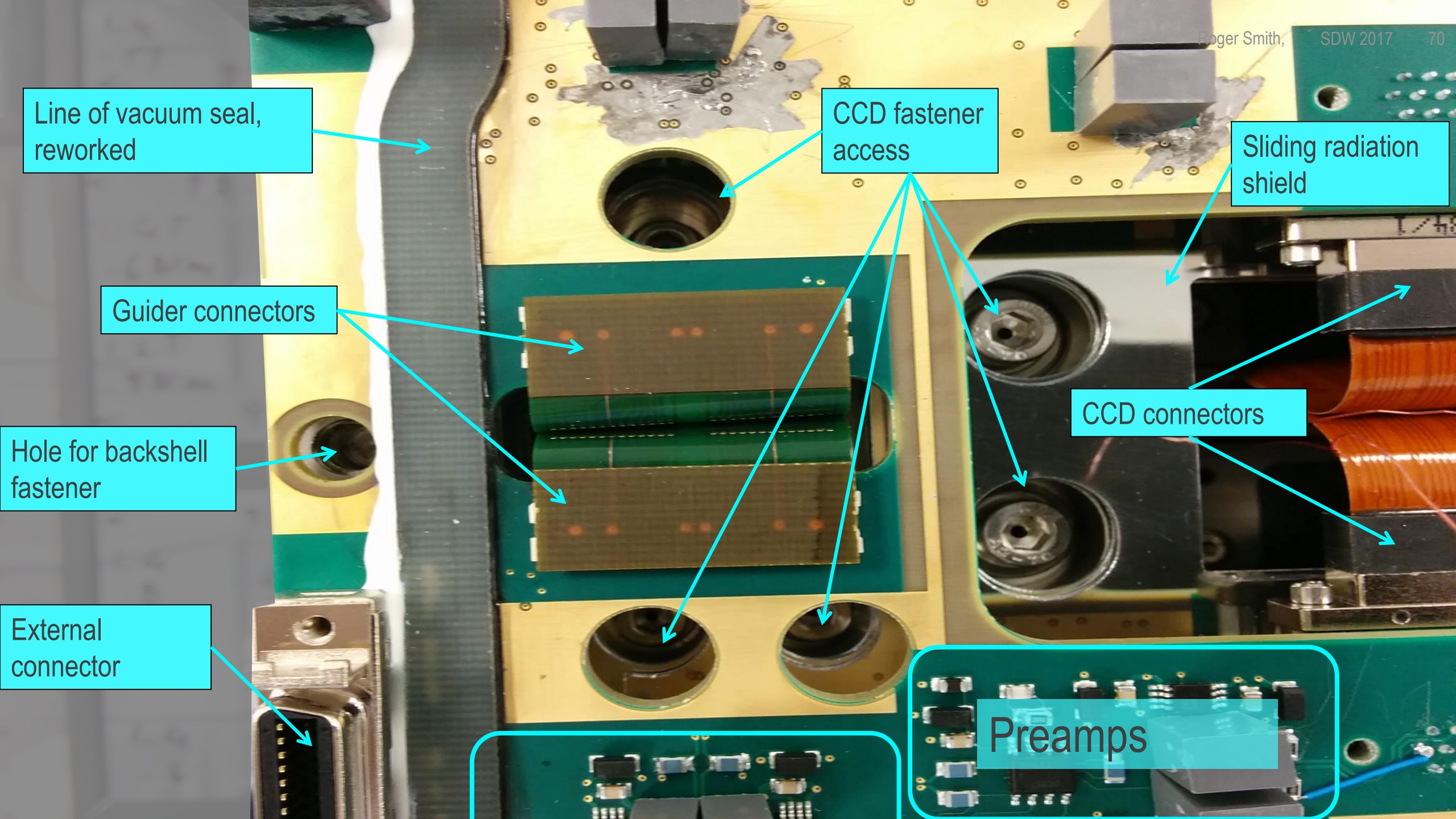
Guider connectors

CCD connectors

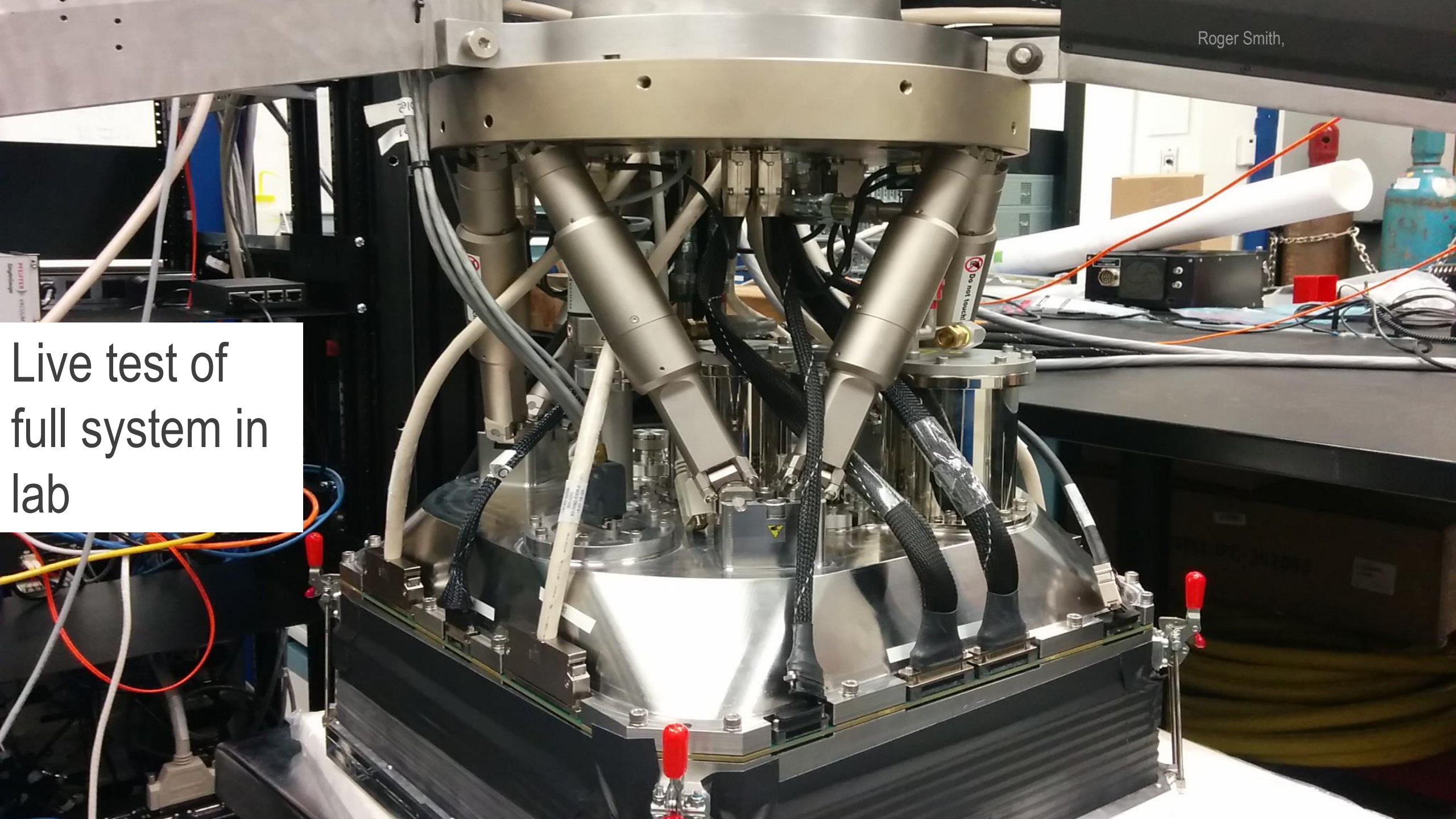
Hole for backshell fastener

External connector

Preamps



Live test of  
full system in  
lab



# Thermal Management

# Refrigeration

- Radiation from large window dominates  
→ Halved by thermally isolating flattener lenses
- CCD power dissipation is unusually large due to fast readout
- Cooled by dual 35W Polycold JT coolers with PT16 refrigerant @ 275 psi.
- Getters directly mounted on cold head get to 130 K.

Charcoal getter to back of cold head

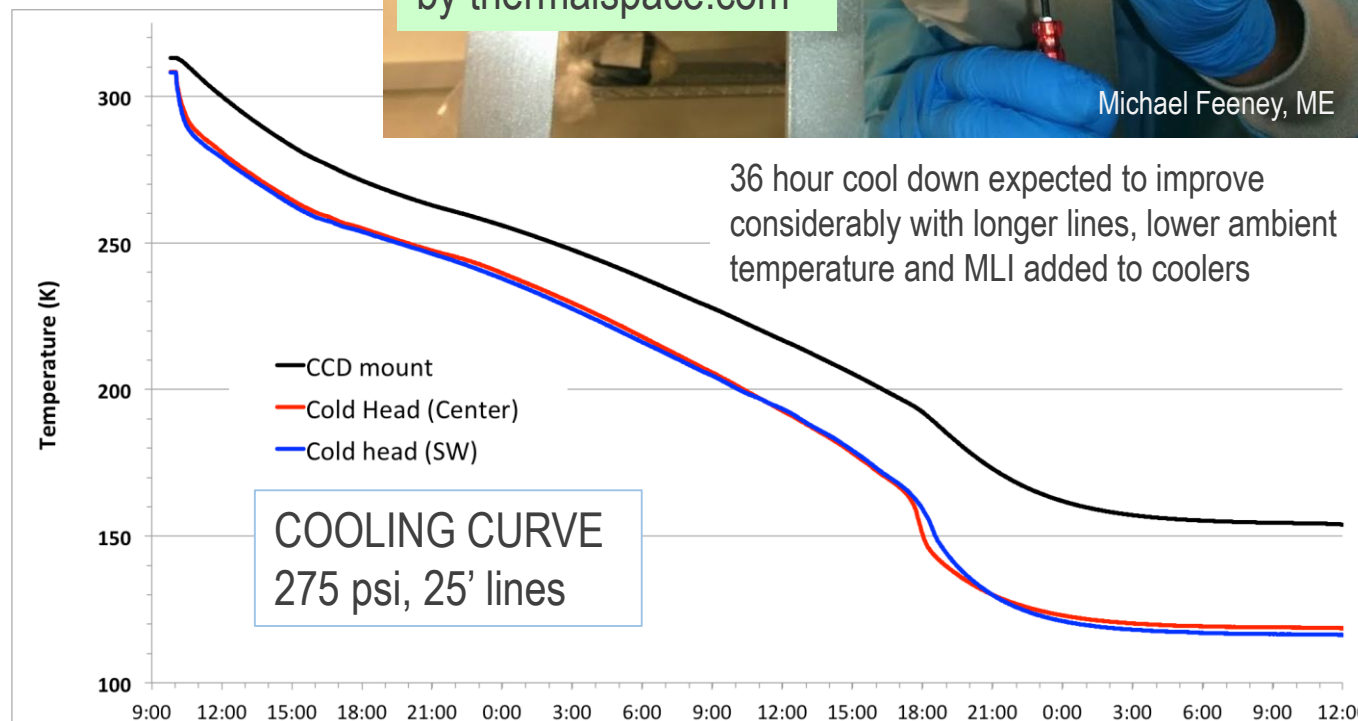
Cold strap attaches to front

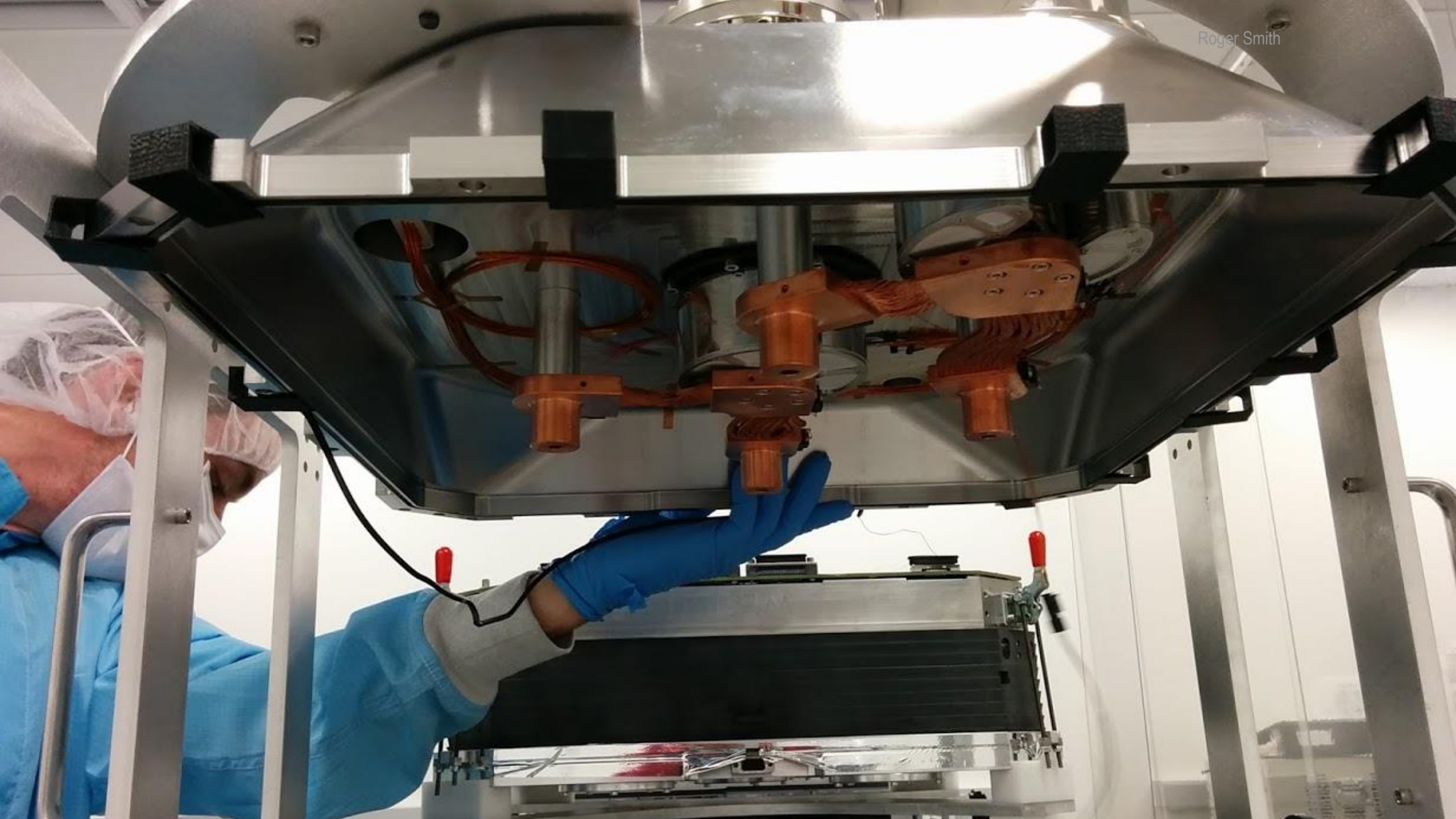
Swaged copper links by thermalspace.com



Michael Feeney, ME

Radiation	Window-CCD	29 W	Field flattener lenses act as floating shield
Radation	Window-gaps	5 W	
Radiation	Back and sides	2.6 W	Bare Aluminum shields, mirror polish
Dissipation	CCD output amps	4 W	5K loads, signal & ref
Dissipation	CCD clocking	1.5 W	Electrode resistance
Dissipation	CCD Heater	3W	
Conduction	CCD Flex cables	4.4W	
Conduction	Cold-plate bipods	1 W	DMLS Titanium
	<b>Total</b>	<b>52 W</b>	

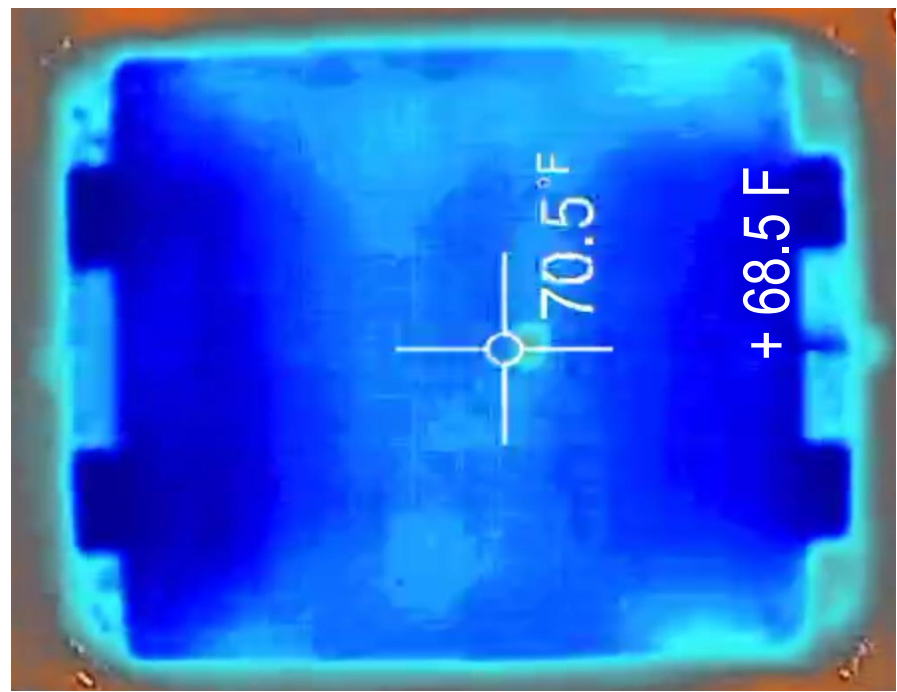






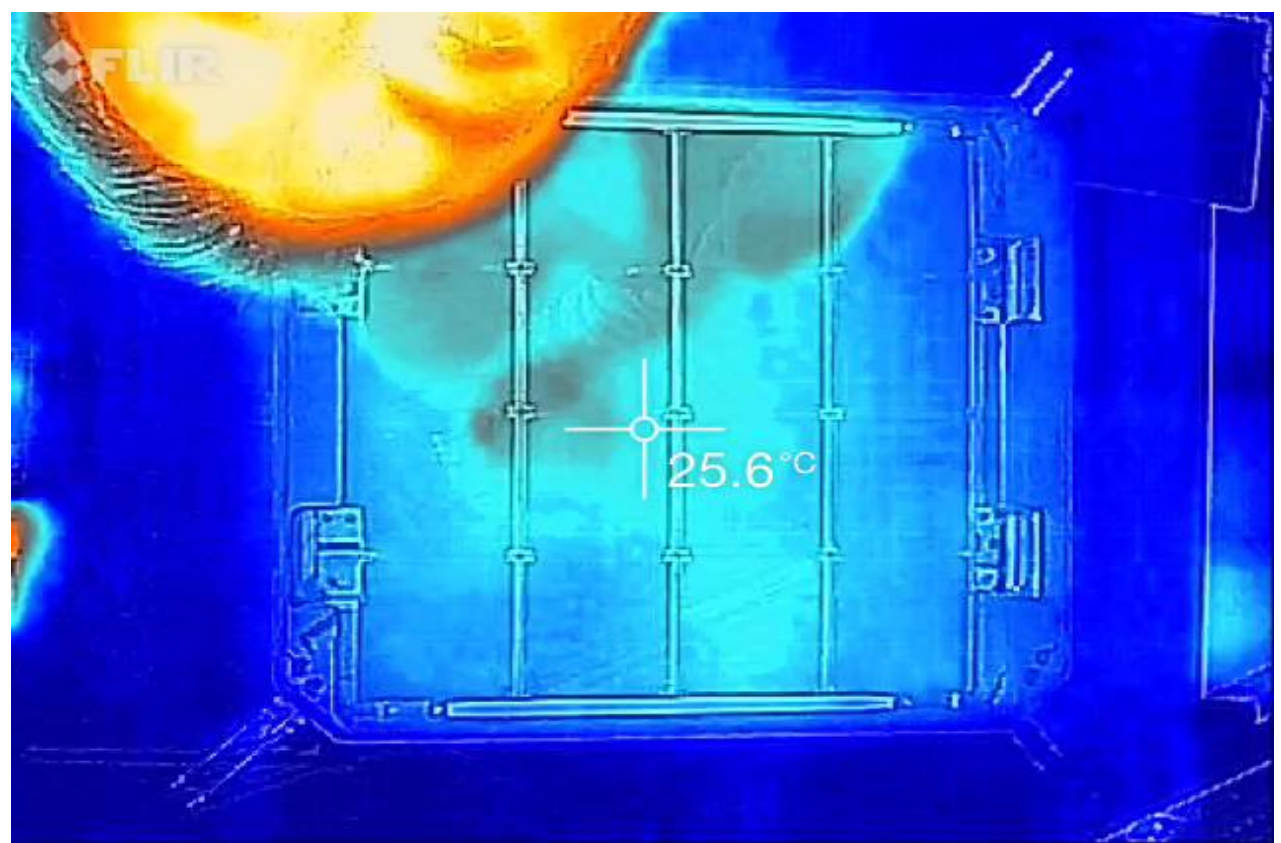
# ITO window heater

CCDs cold, ~20W heat



Only 1 C gradient,  
Power as expected

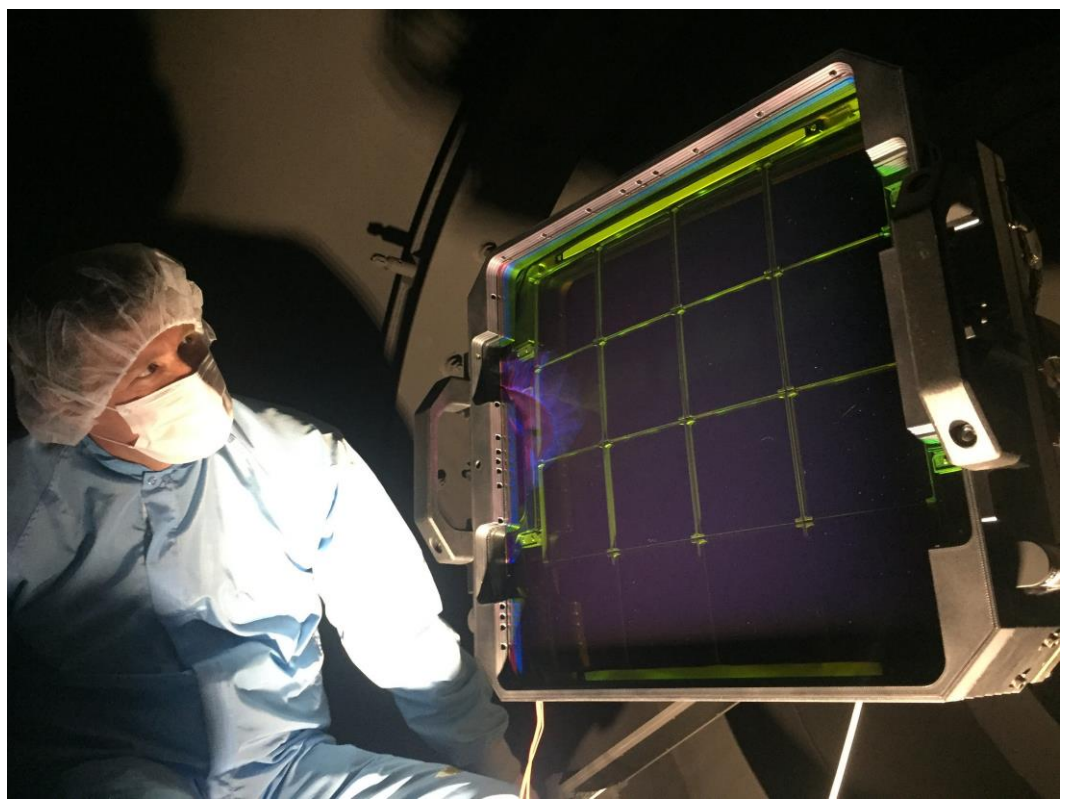
CCDs warm



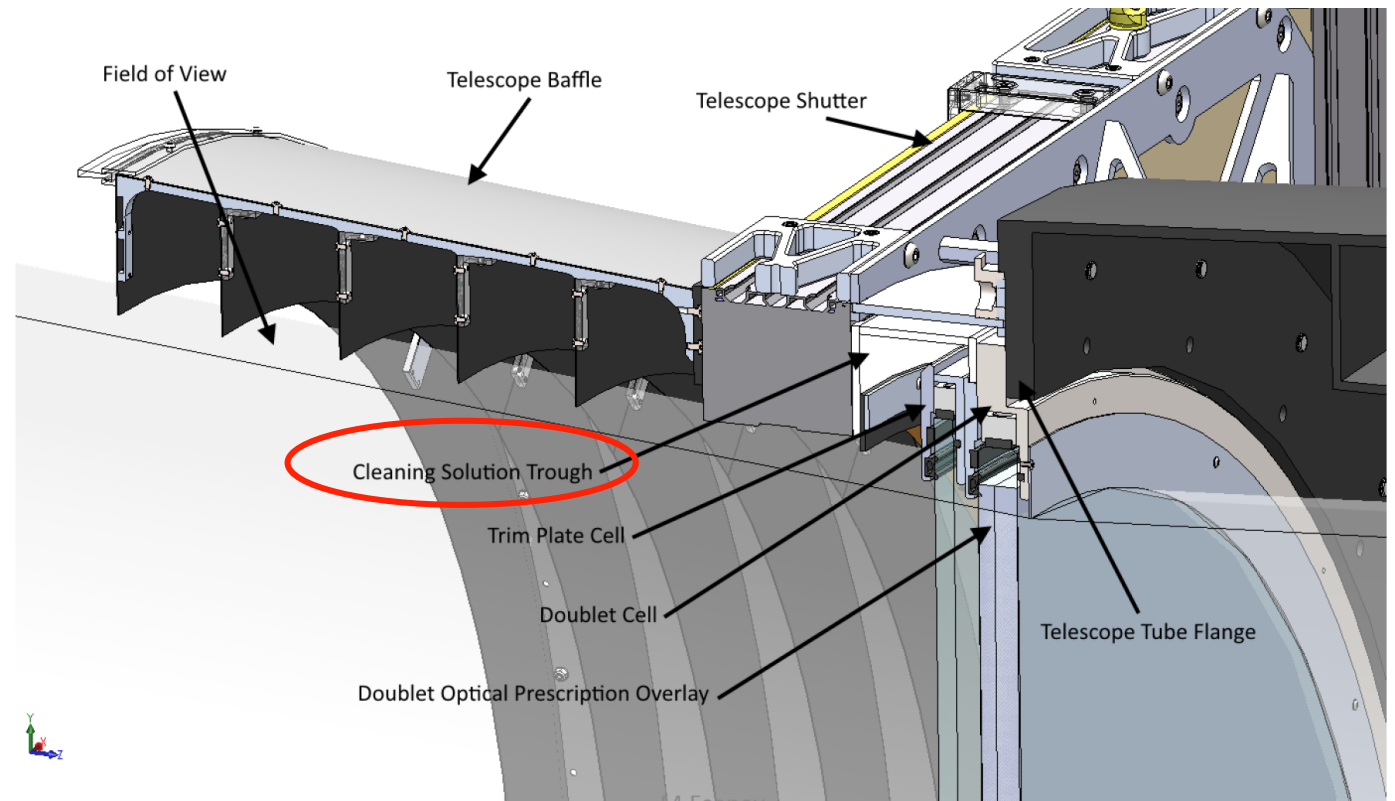
# Scattering (clean optics)

- Closed telescope tube treated as clean room

- Trim plate cell design supports washing with plentiful solvent



Tube painted with Avian Black (3% reflective)



# Assembly story boards

**ZTF CCD Assembly procedure**

**PART II**  
Assembling the Science CCD using the setup

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Assembling the Science CCD using the setup

**Back-up plan**

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Assembling the Science CCD using the setup

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Assembling the Science CCD using the setup

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Assembling the Science CCD using the setup

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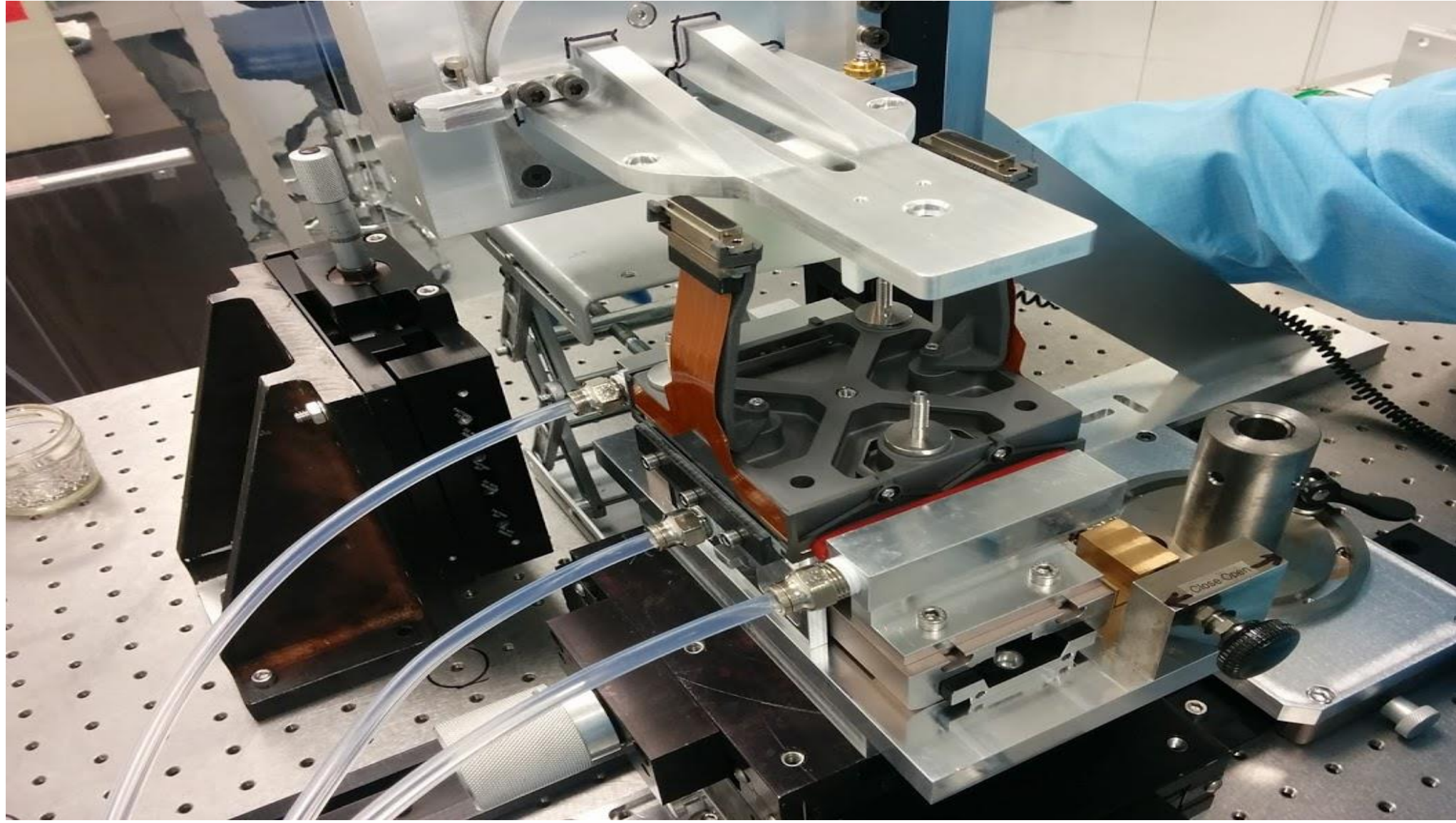
Assembling the Science CCD using the setup

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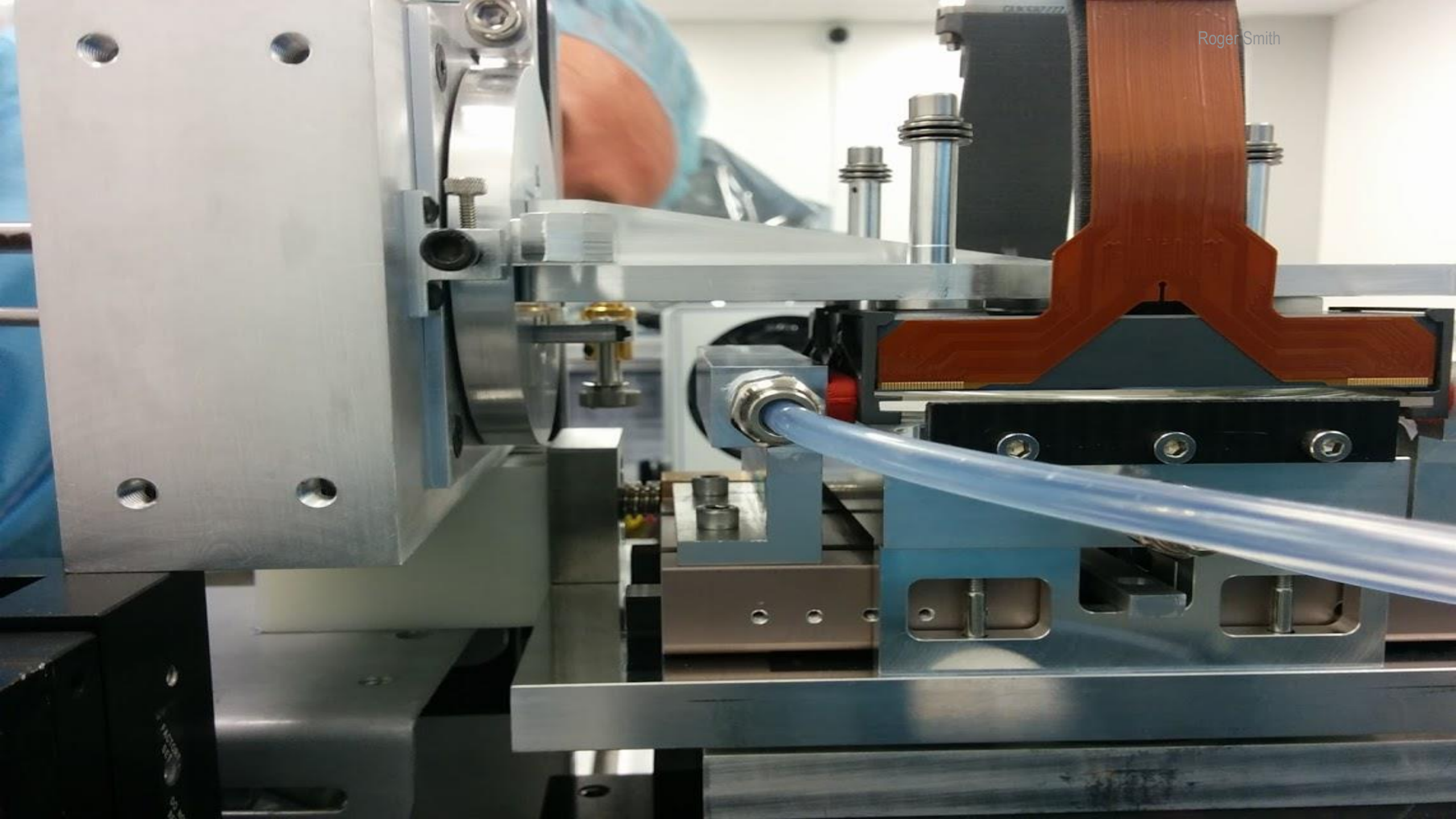
Assembling the Science CCD using the setup

59

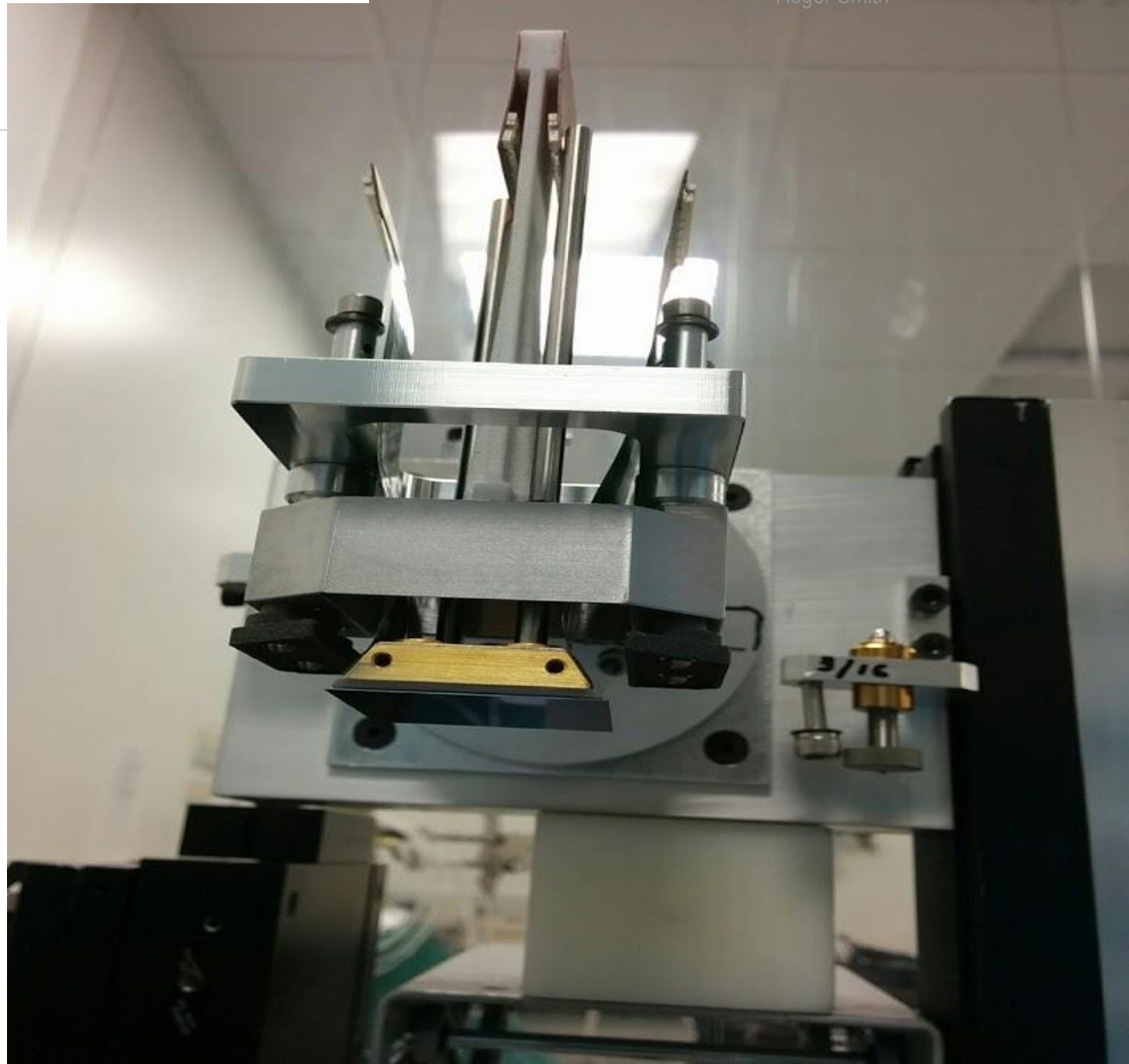
# Field flattener installation on CCD





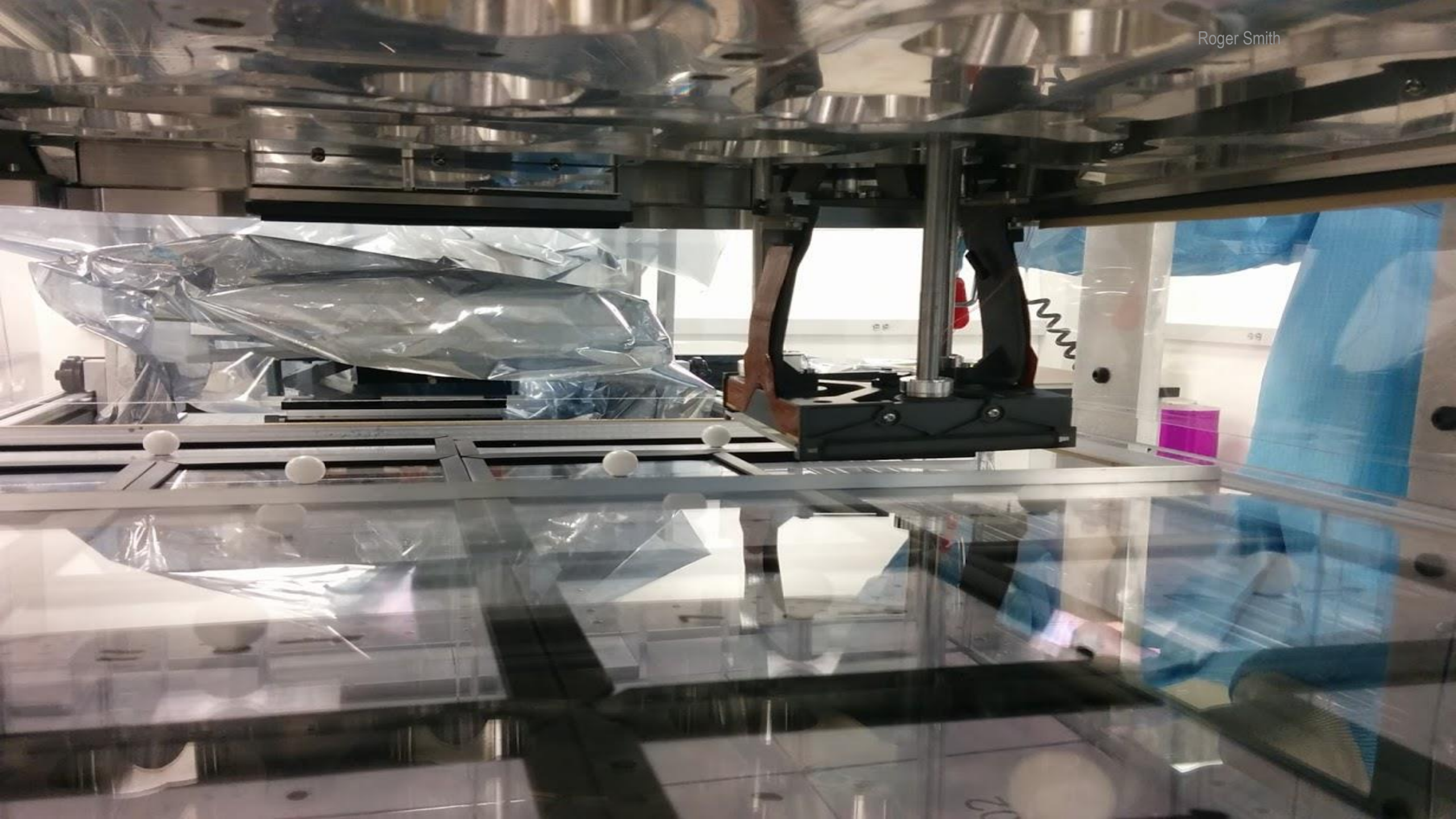


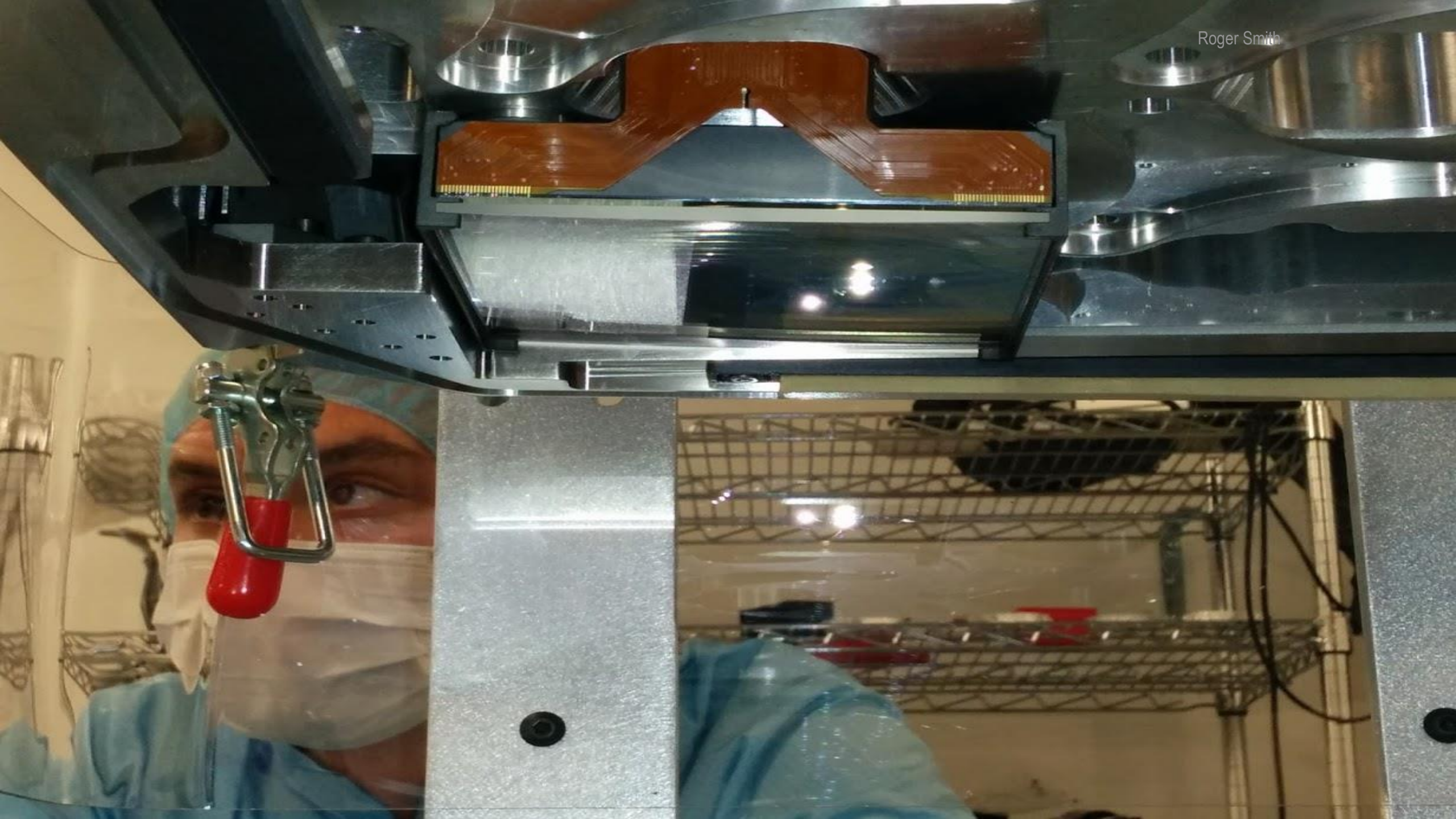
Guider part way  
into its housing











# Making CCDs Parfocal