Zwicky Transient Facility

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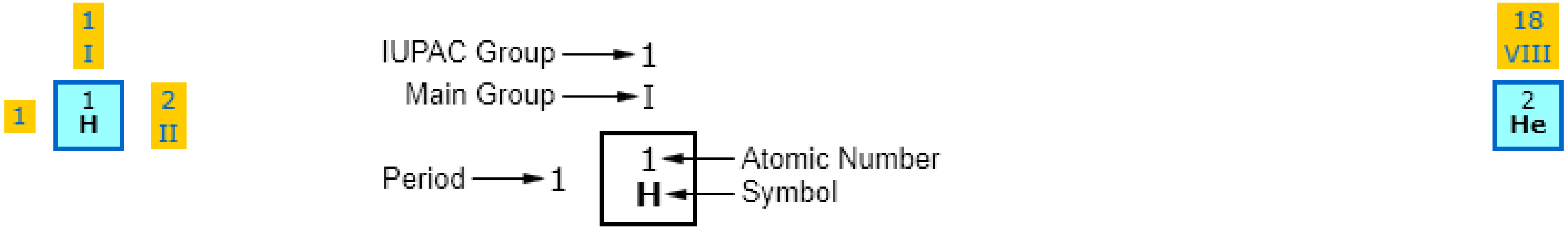
Caltech

Funded by the National Science Foundation in partnership with

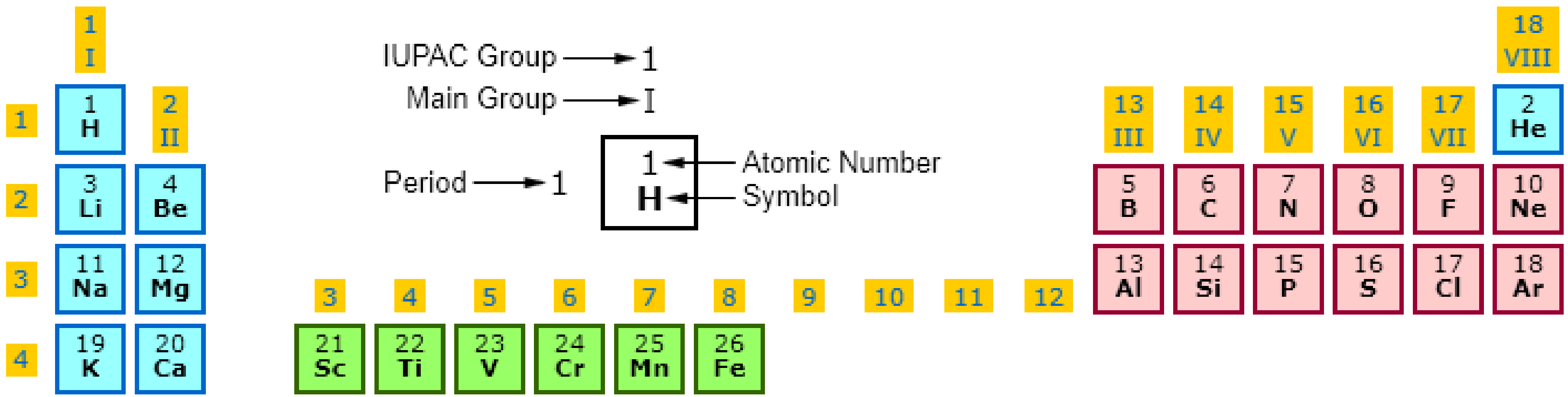
Why does Astronomy matter ?

- 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



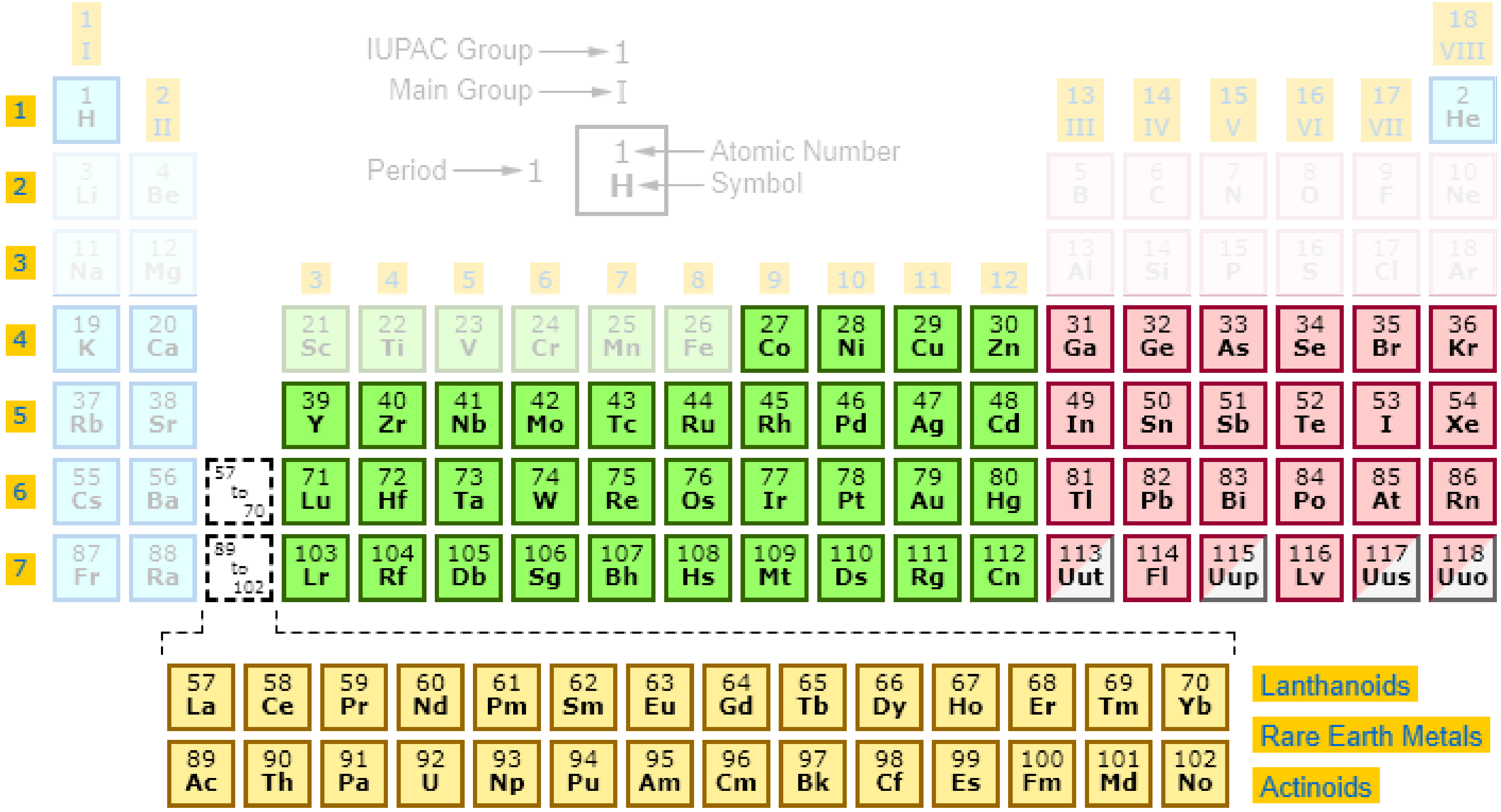
Energy is released by fusion, but only up to Iron.

Beyond Fe energy ***input*** is required.

Stars aren't hot enough to make heaviest elements.

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

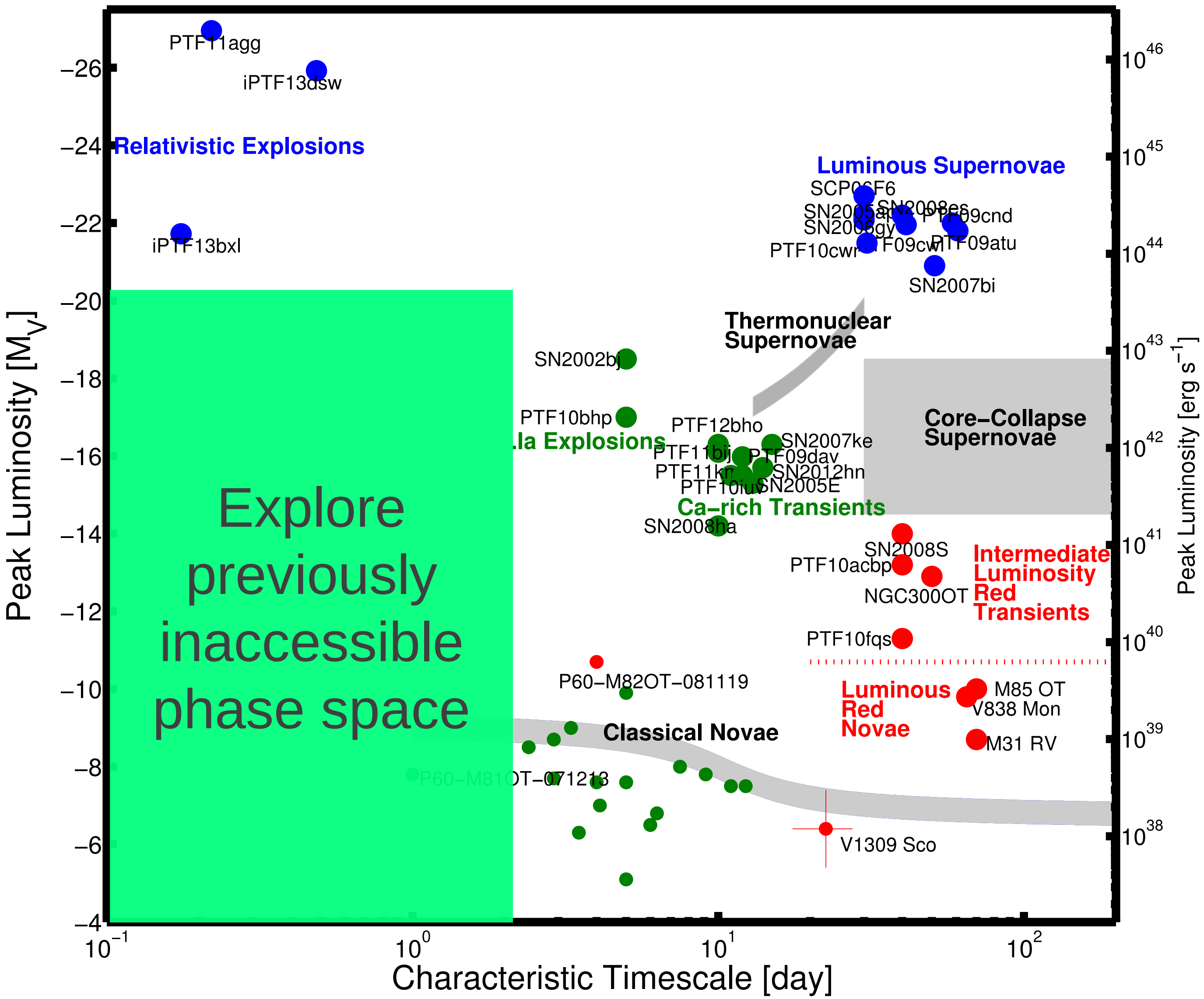
Created in supernovae or neutron star mergers



Science objective

Transients on time scales down to few hours

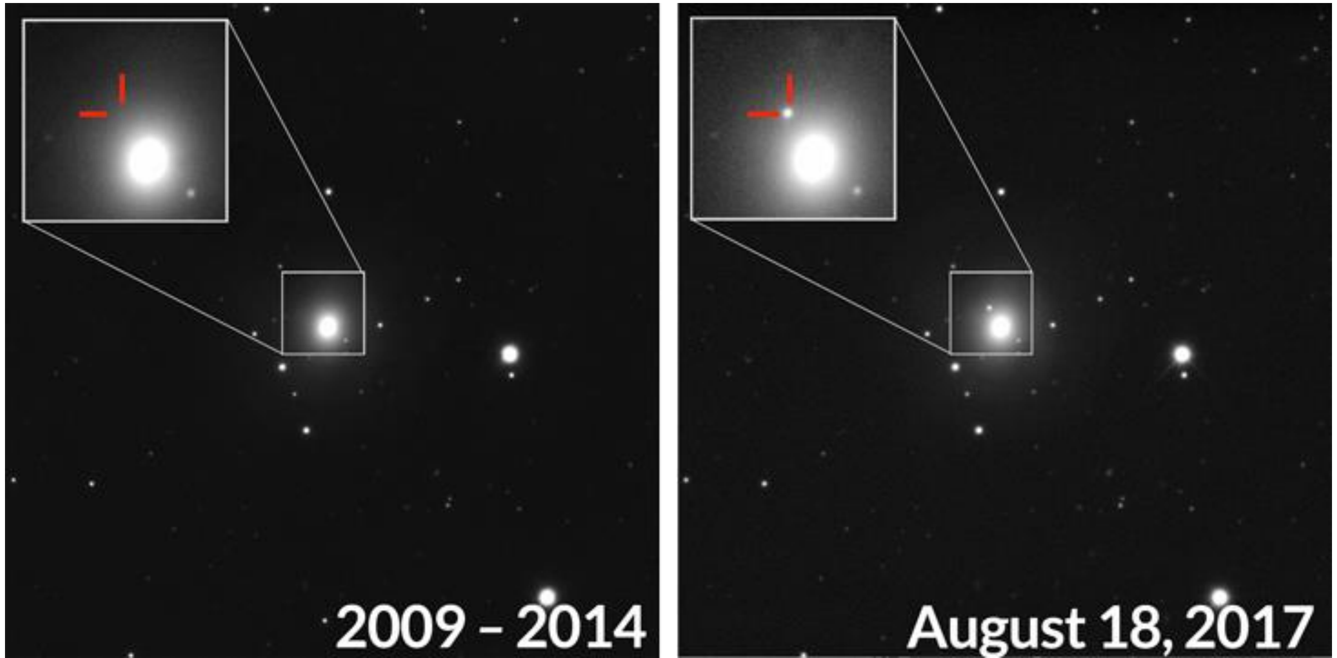
- Rare so must record large volume, quickly.
- Bright enough for follow up spectroscopy.



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

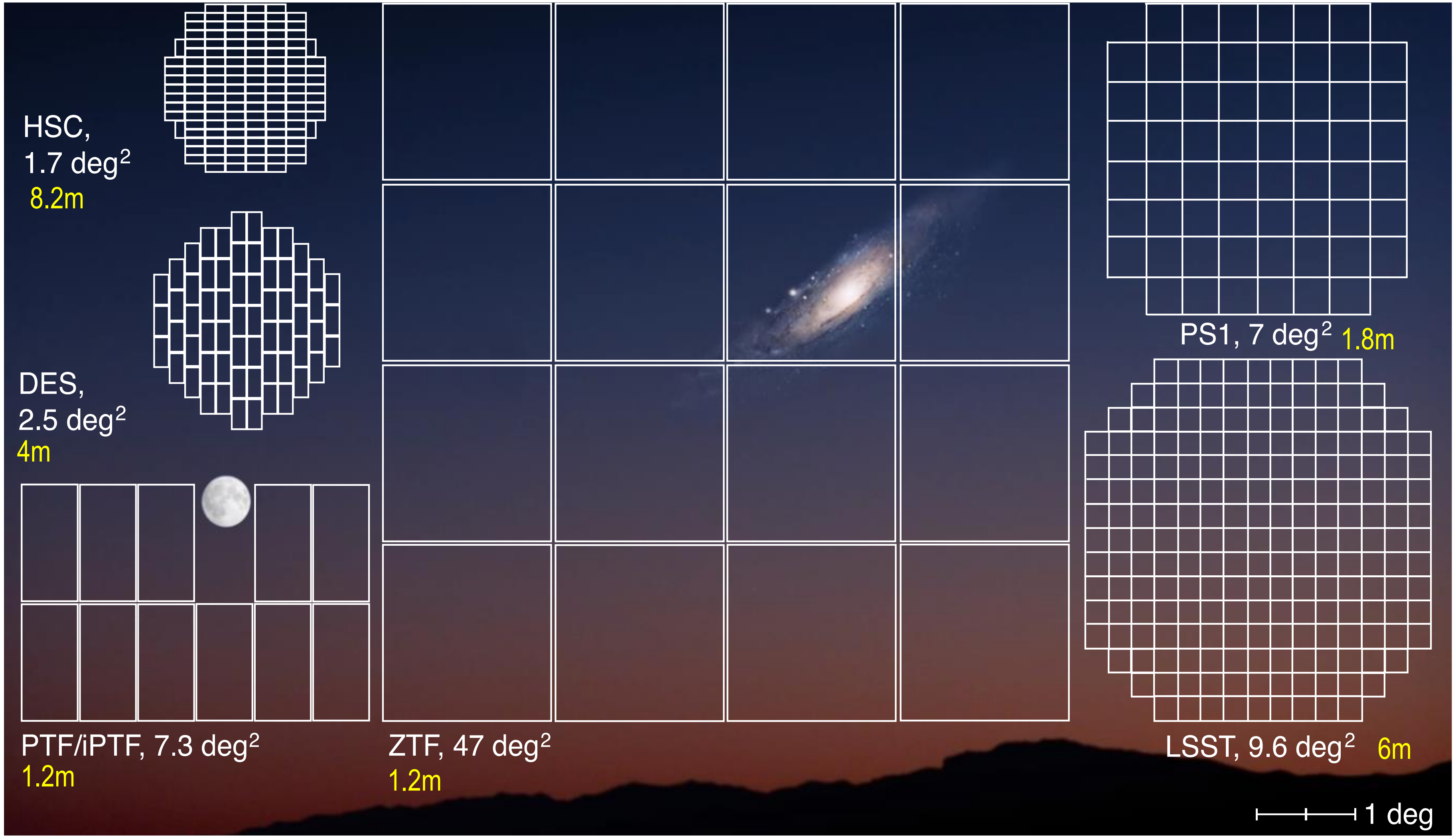
National Geographic all-sky photographic survey.

1949-1956

Photographic plates manually loaded.

Telescope manually pointed.

Field of view comparison

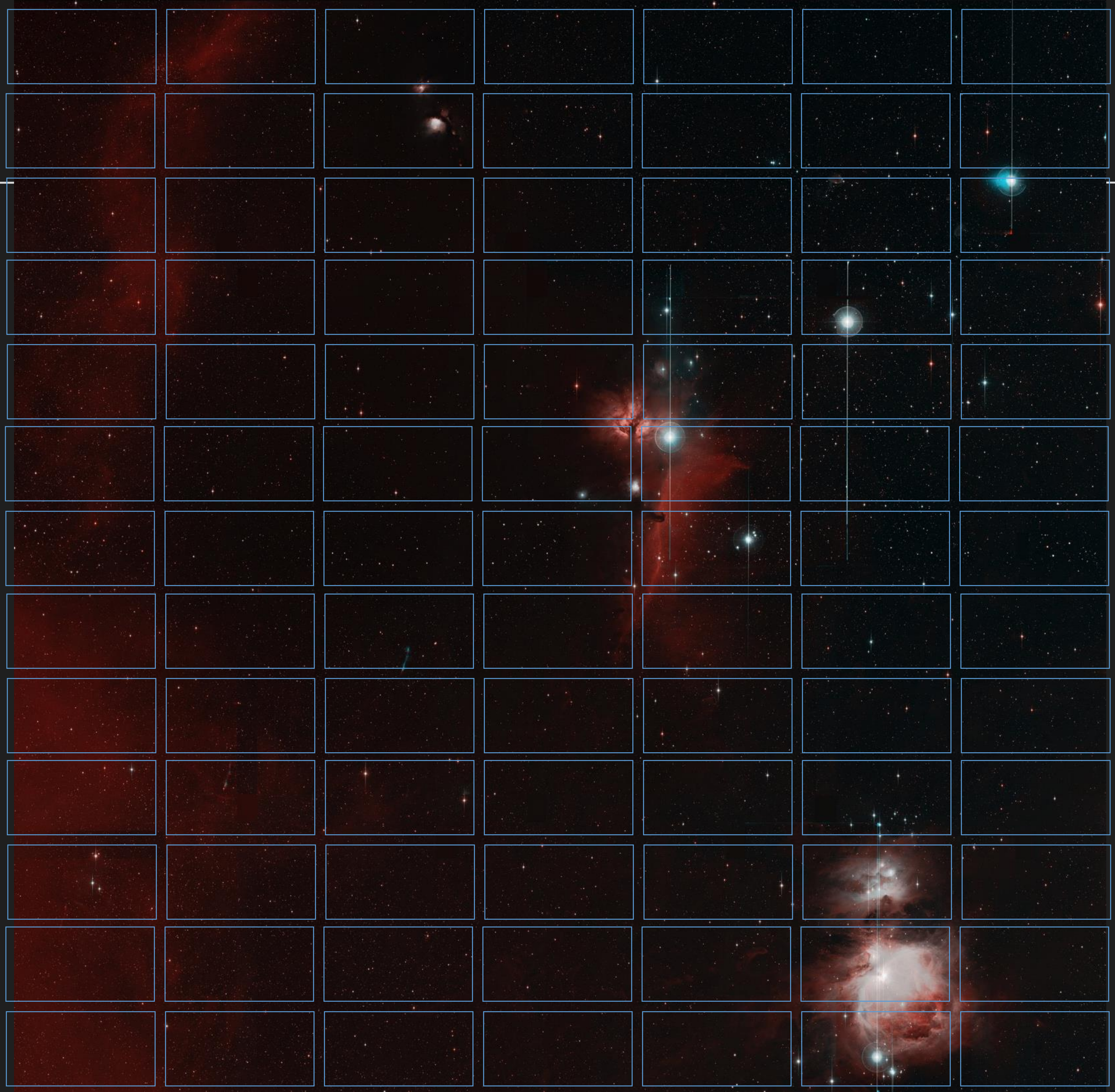


ZTF goes widest though with coarser angular resolution.


M42
cyan and red filters combined

Flame and Horsehead nebulae in Orion

cyan and red filters combined

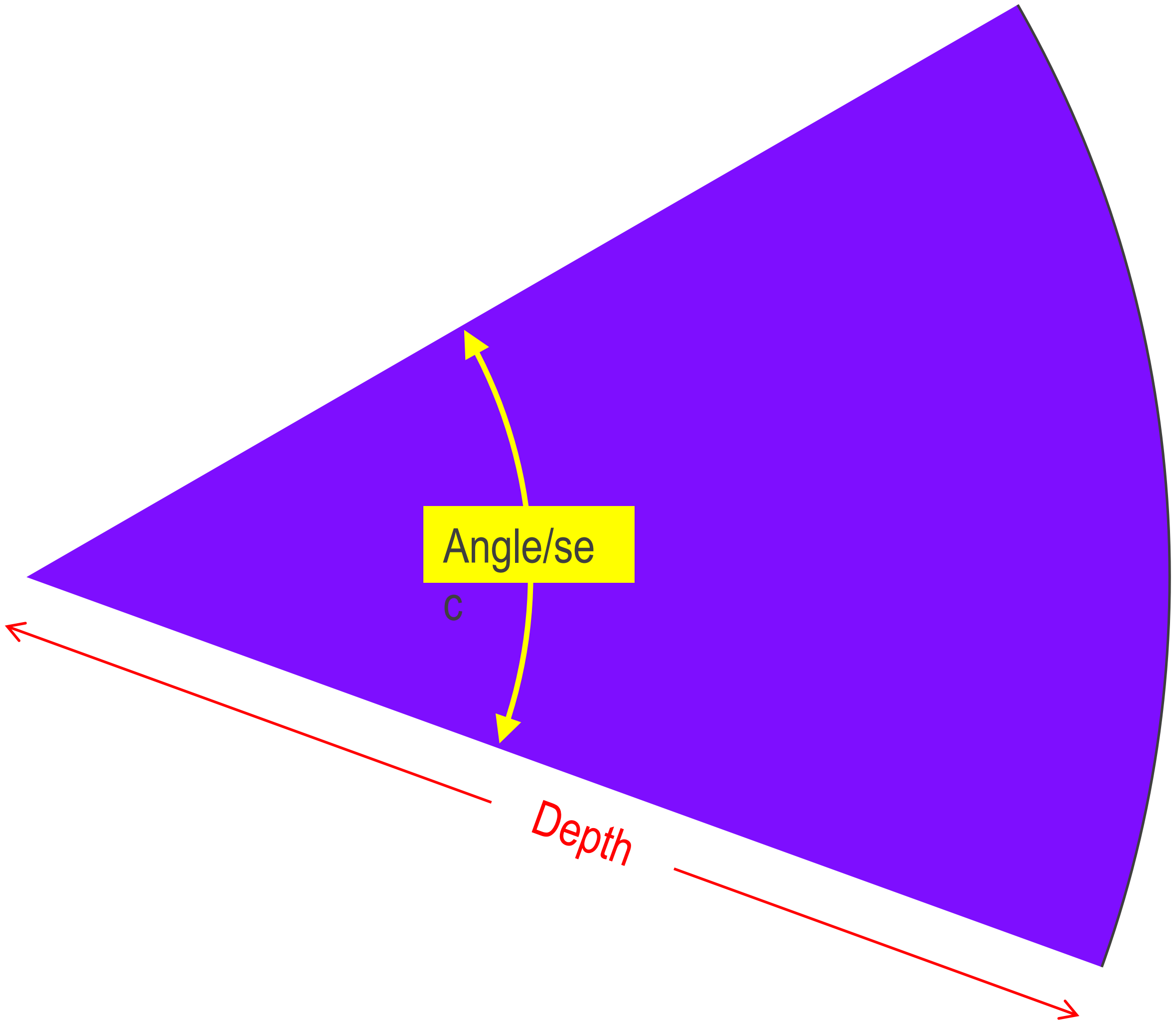


91 Ultra HD (4K) monitors
to display at full resolution

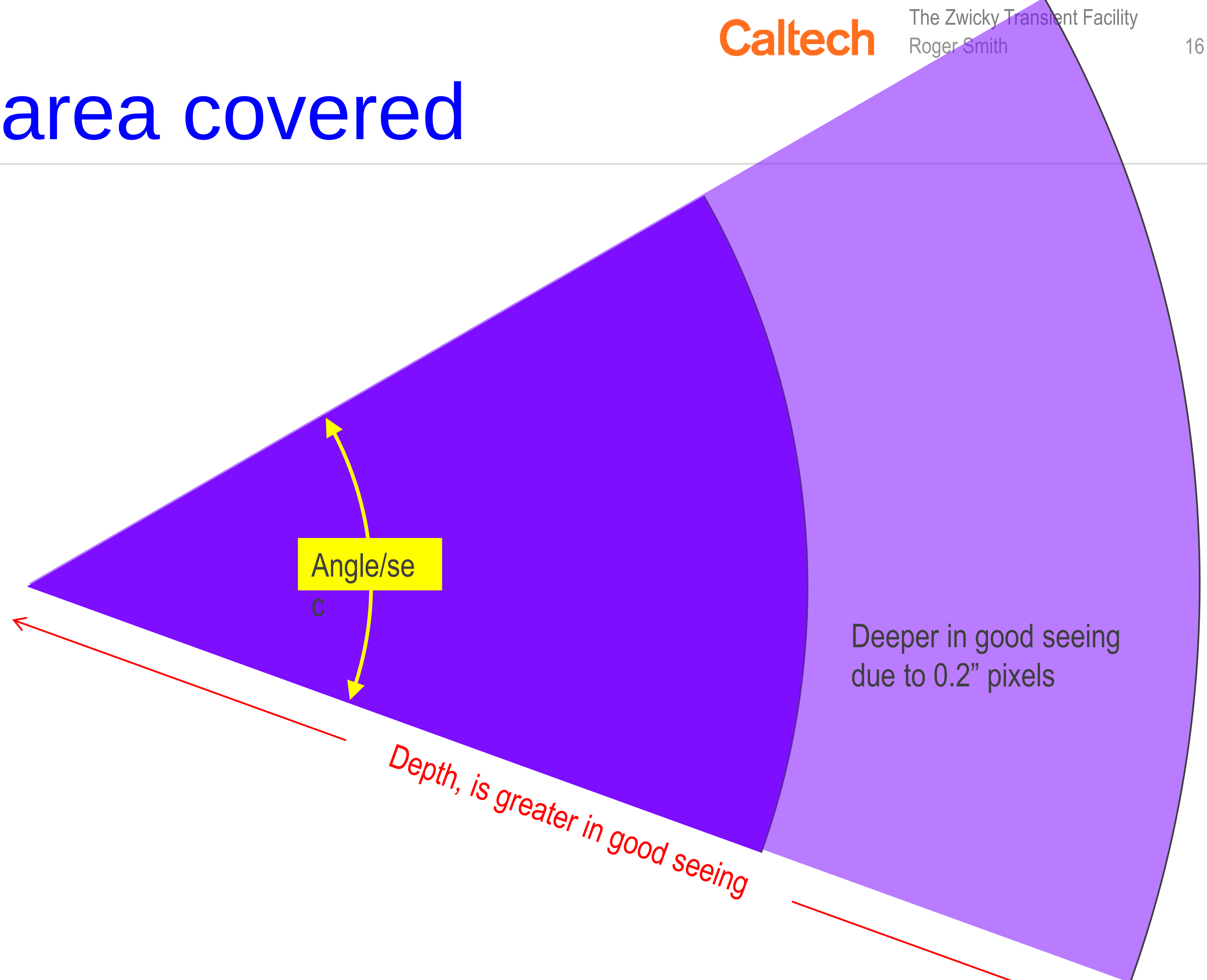
Full frame

Slightly dithered to fill in gaps between sensors

Depth and area covered

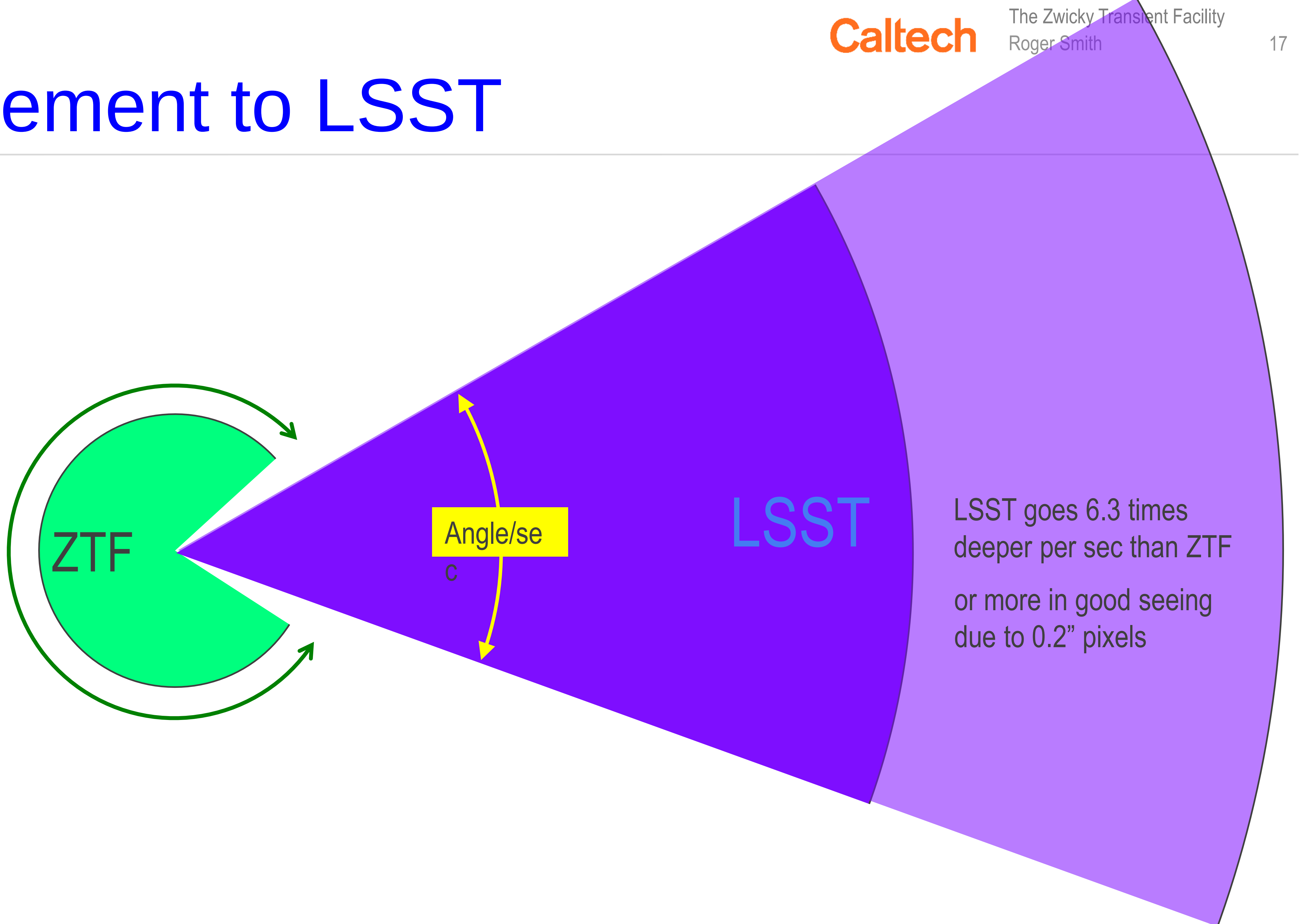


Depth and area covered



Complement to LSST

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

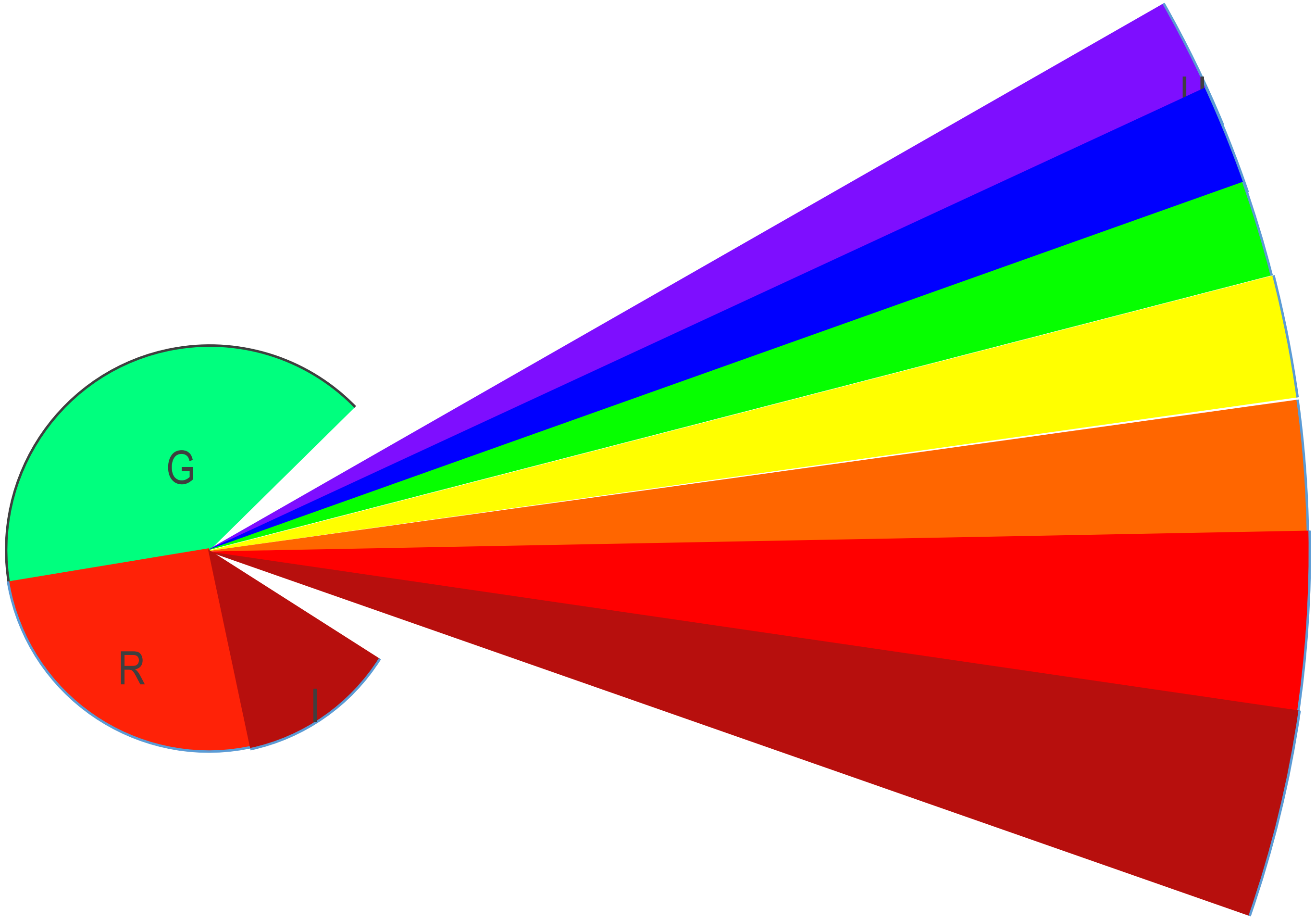


LSST goes 6.3 times deeper per sec than ZTF

or more in good seeing due to 0.2” pixels

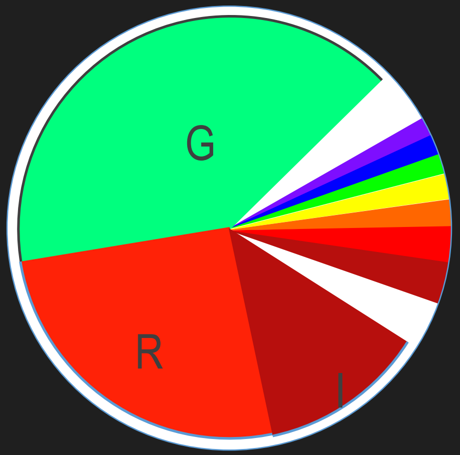
Complement to LSST

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^2 ....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	

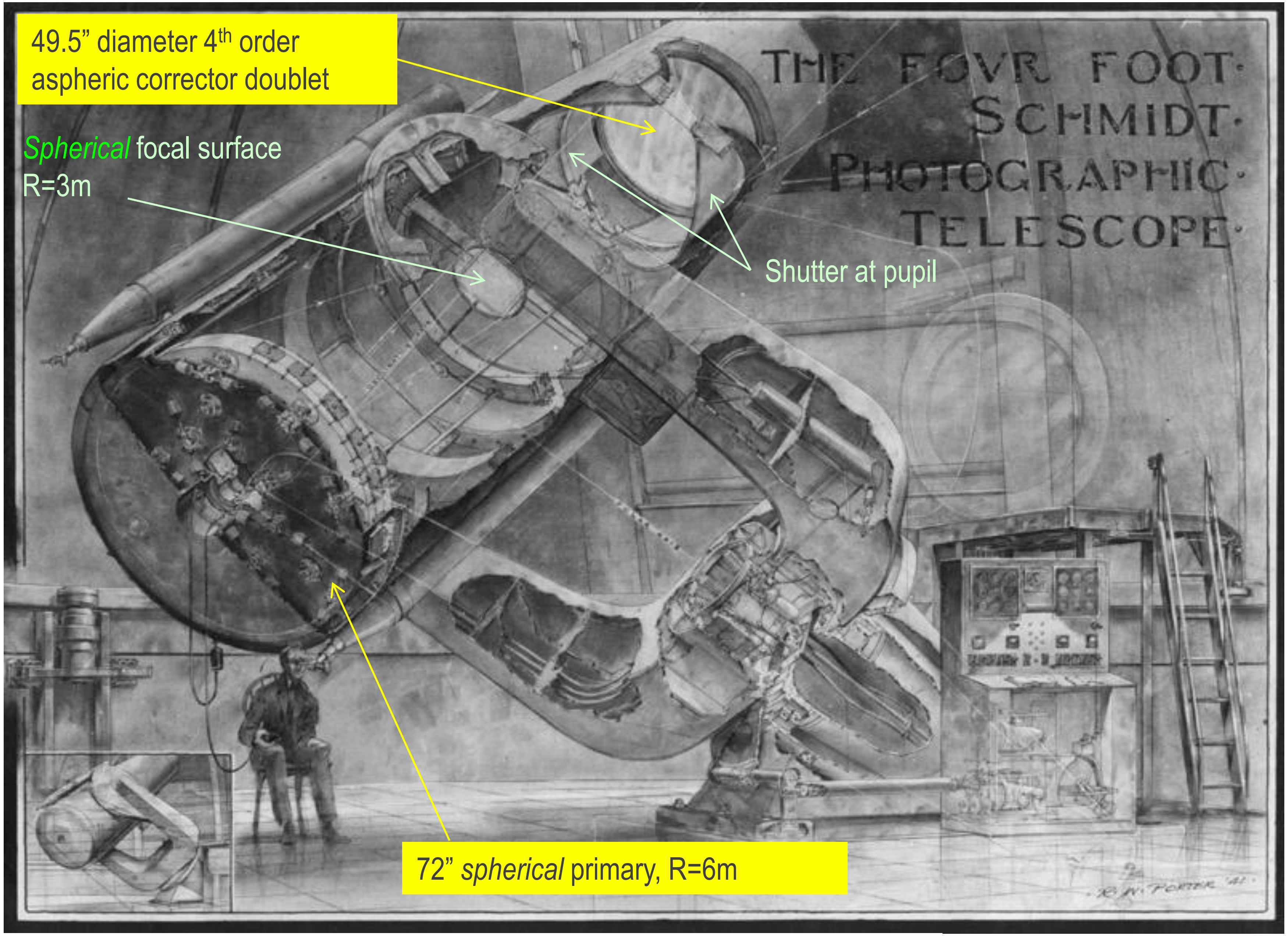
1950 Bugatti

~125 mph

2018 Bugatti Chiron

260 mph

Factor of 2 improvement in 70 years

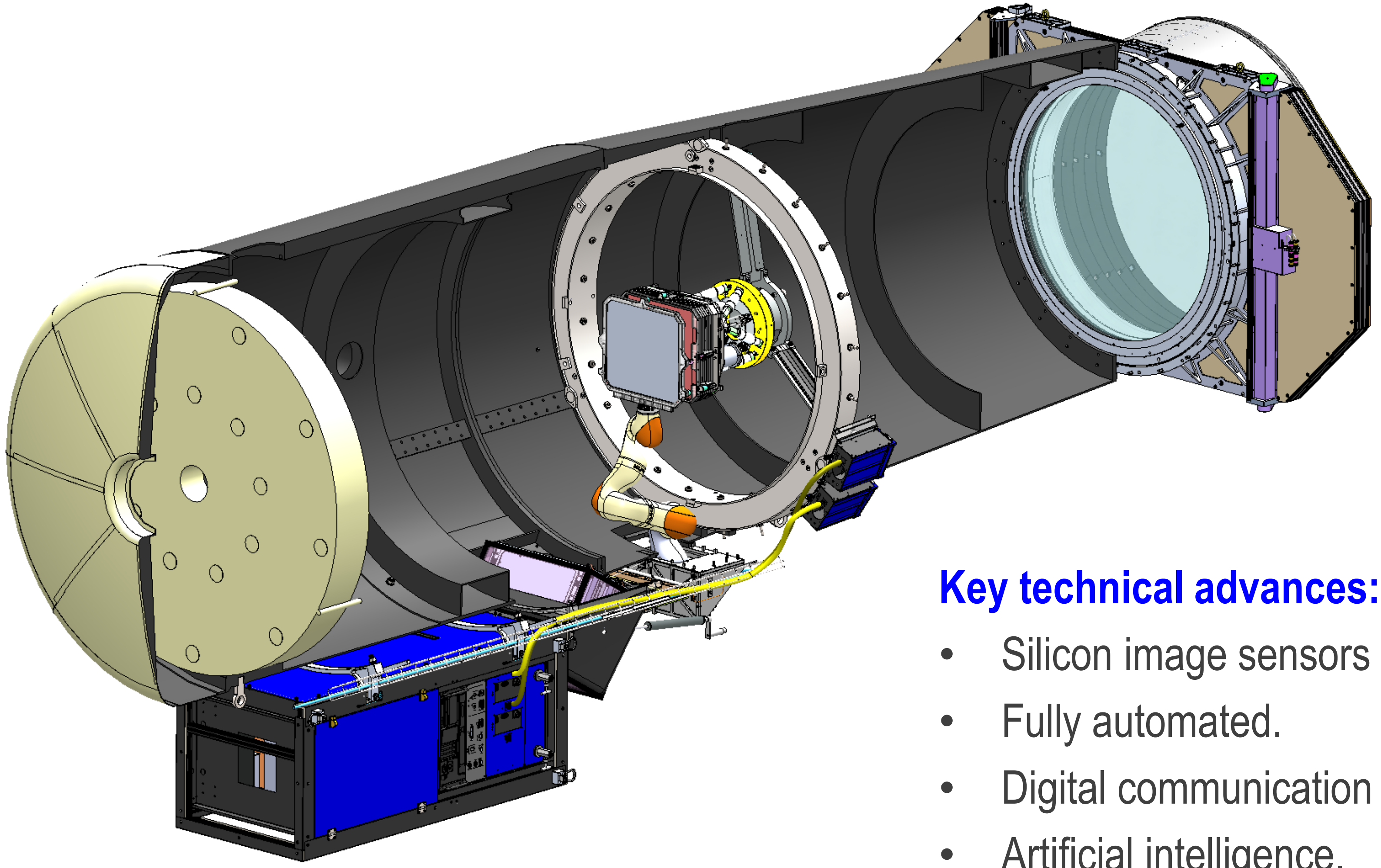


1949 – 1956 Palomar All Sky Survey

Drawing by Russell Porter, illustrator, arctic explorer and amateur astronomer, and designer of domes

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

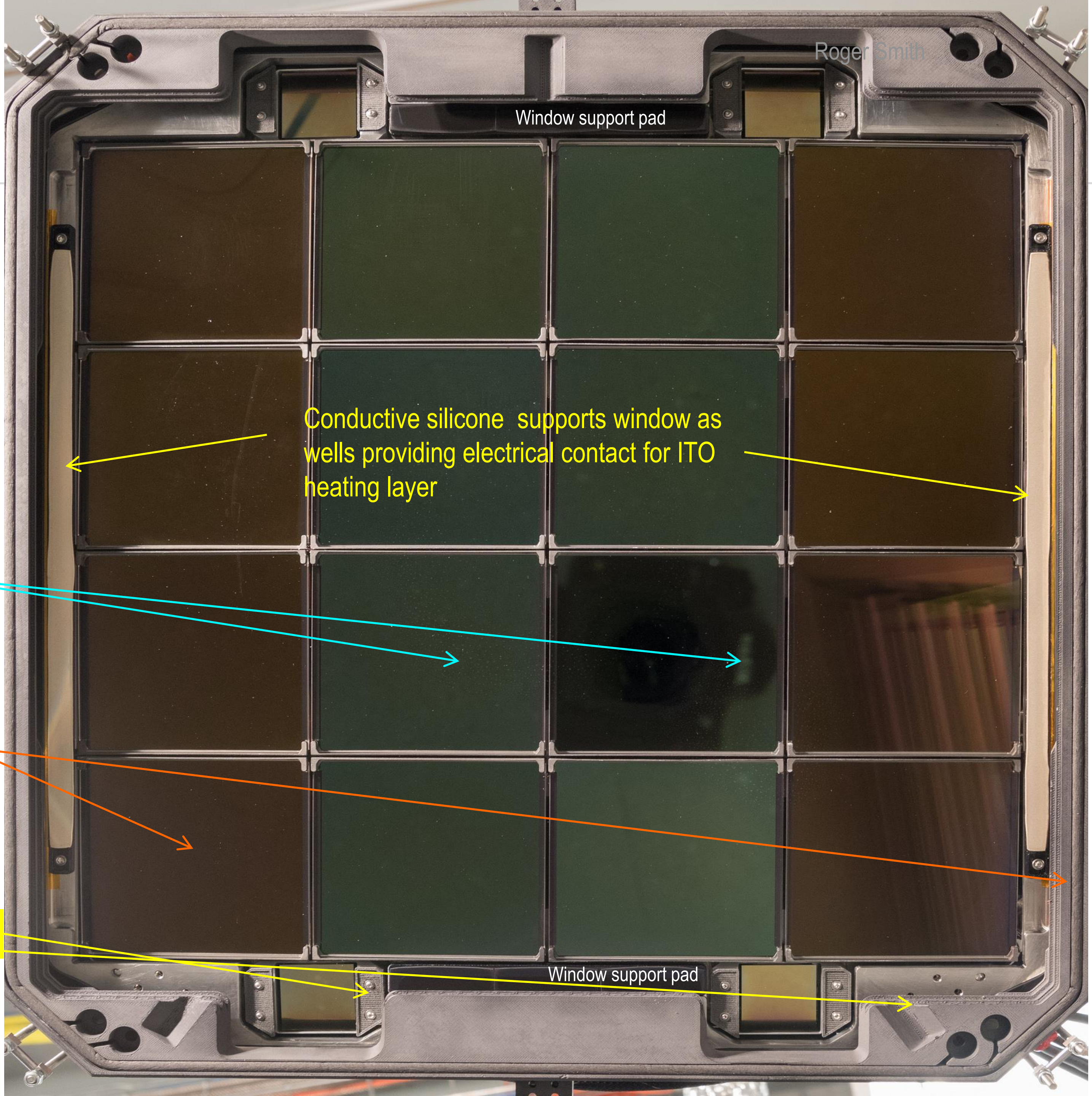
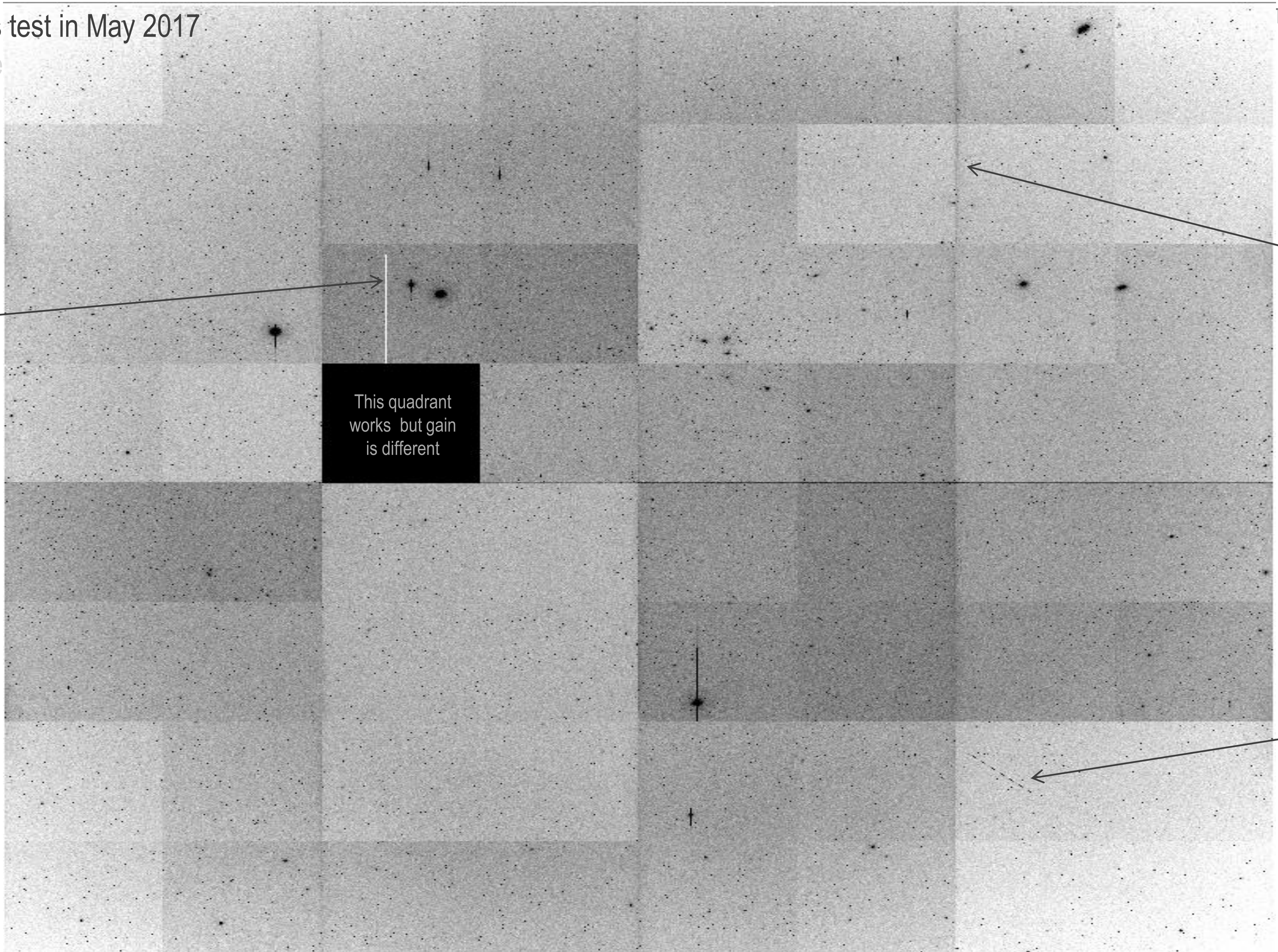


Image from focus test in May 2017

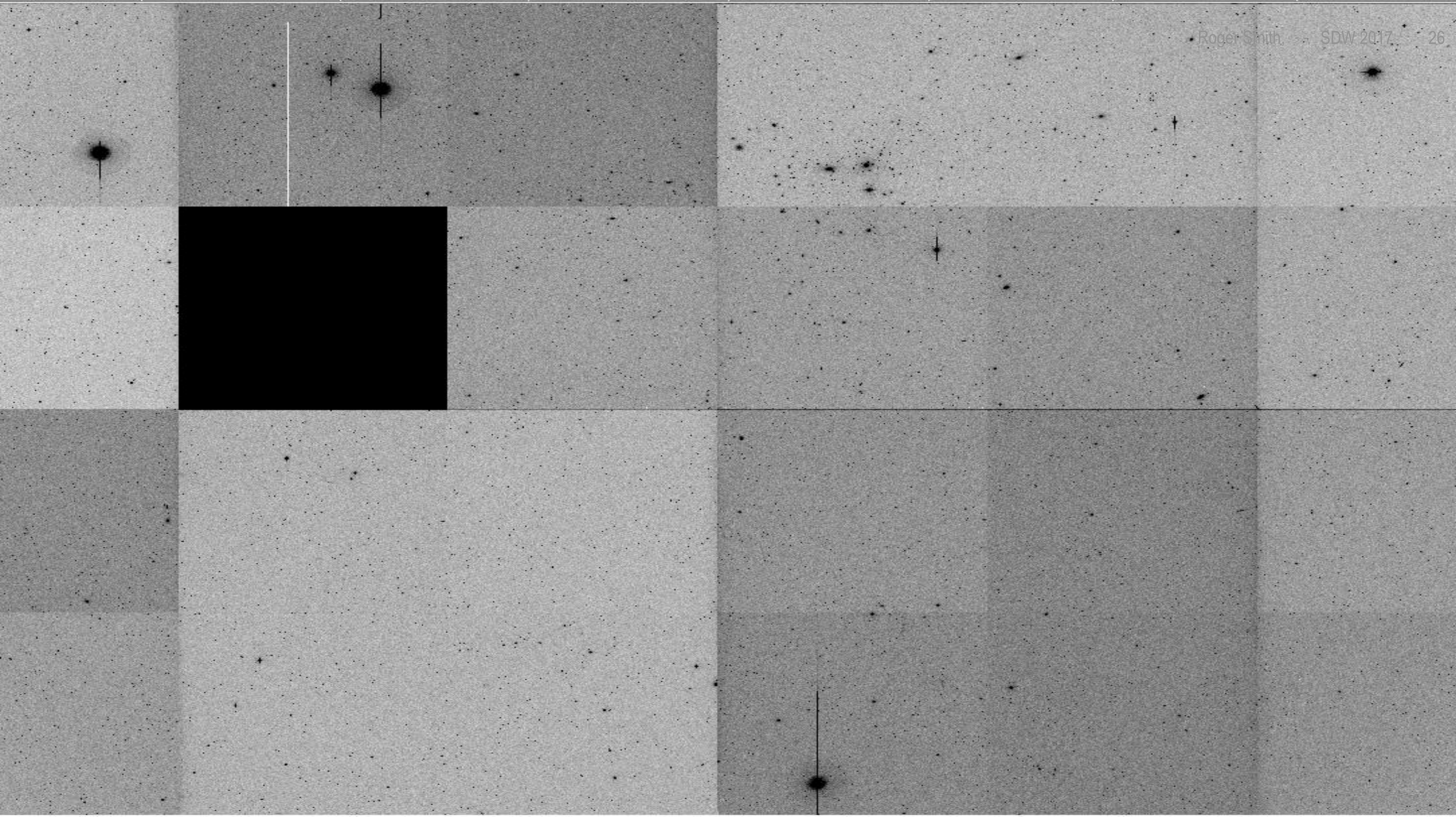
Without trim plate

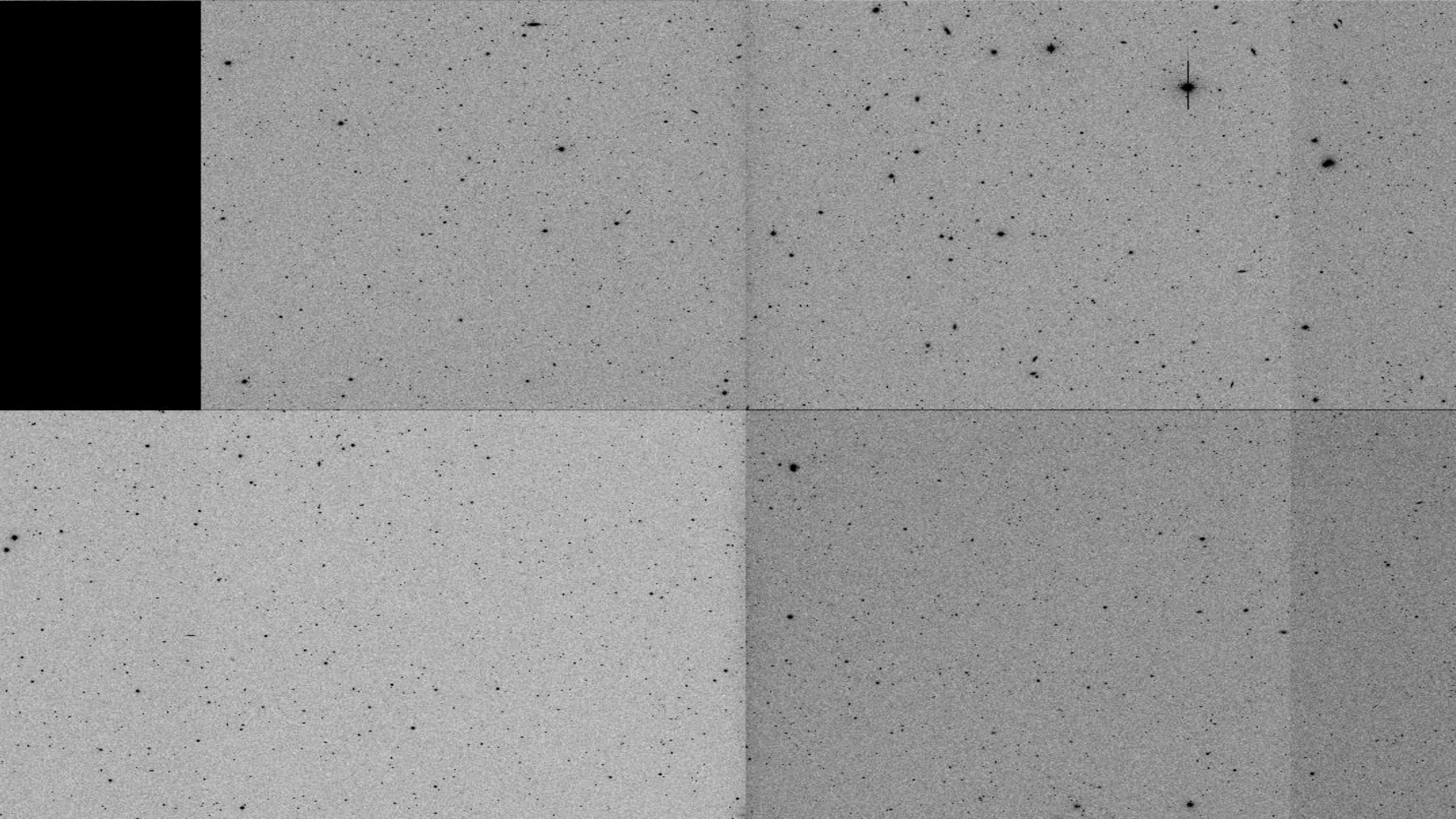


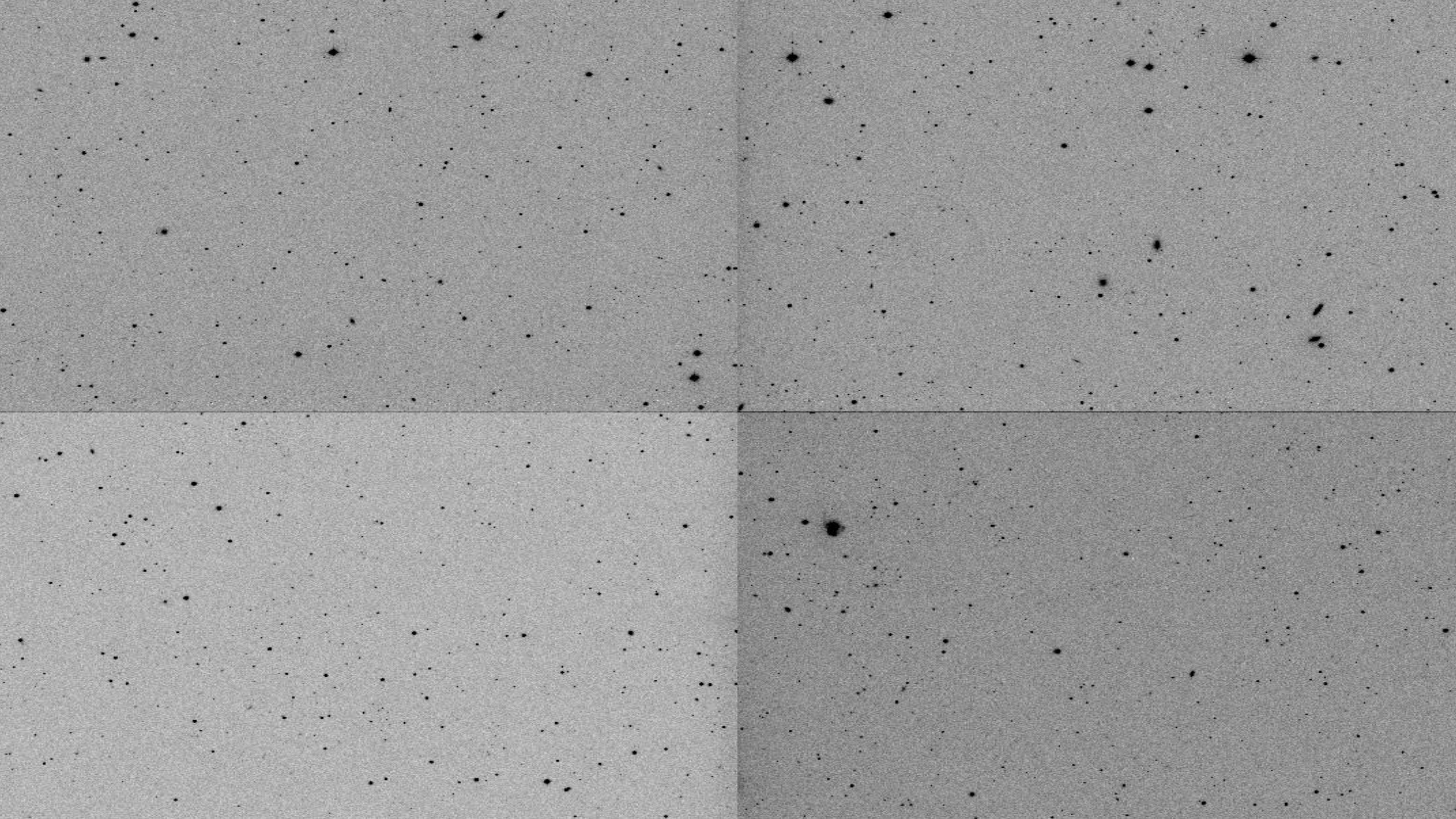
Very few cosmetic defects

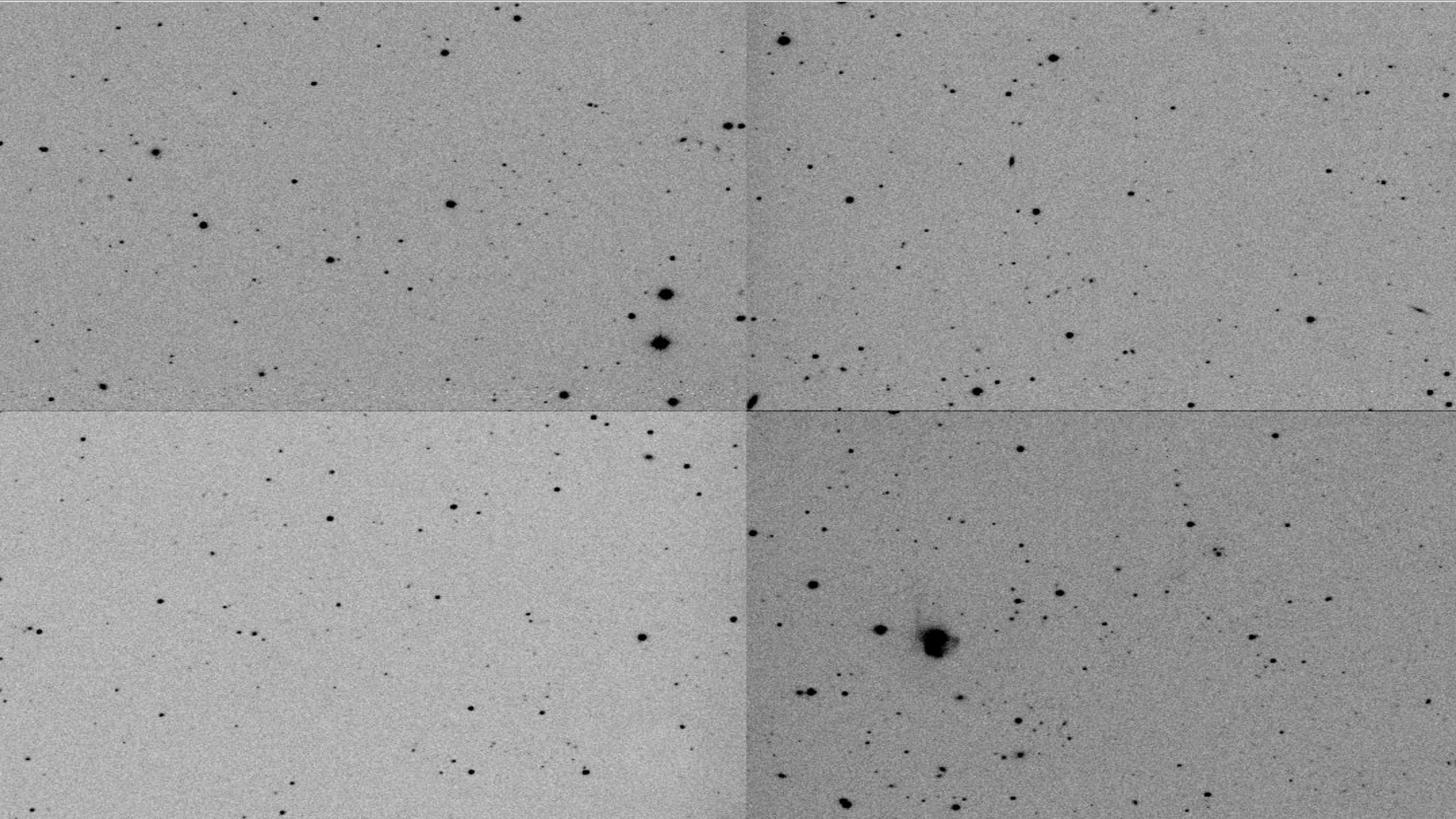
Some line start transient to fix.

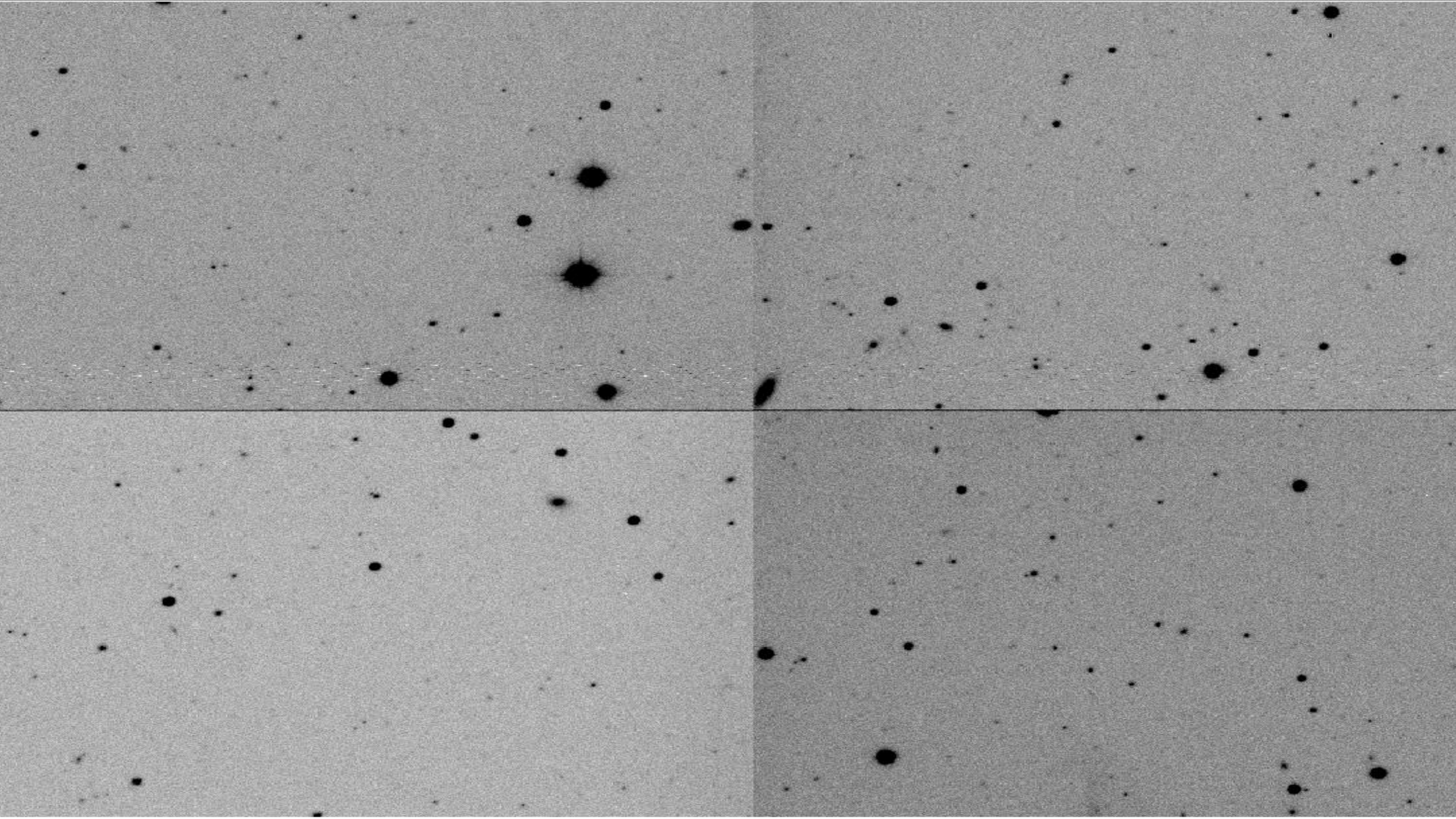
Space junk rotating ?

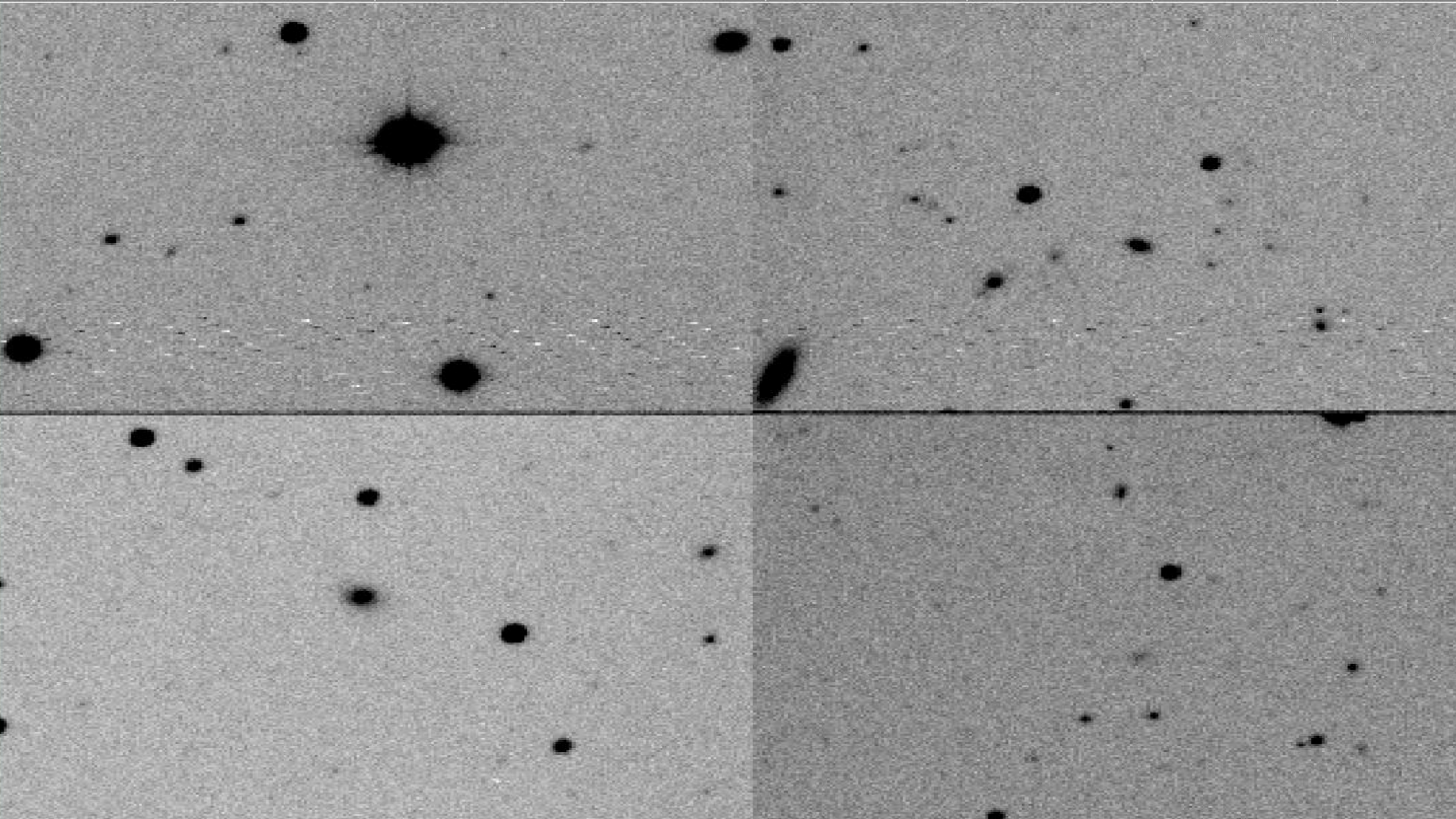


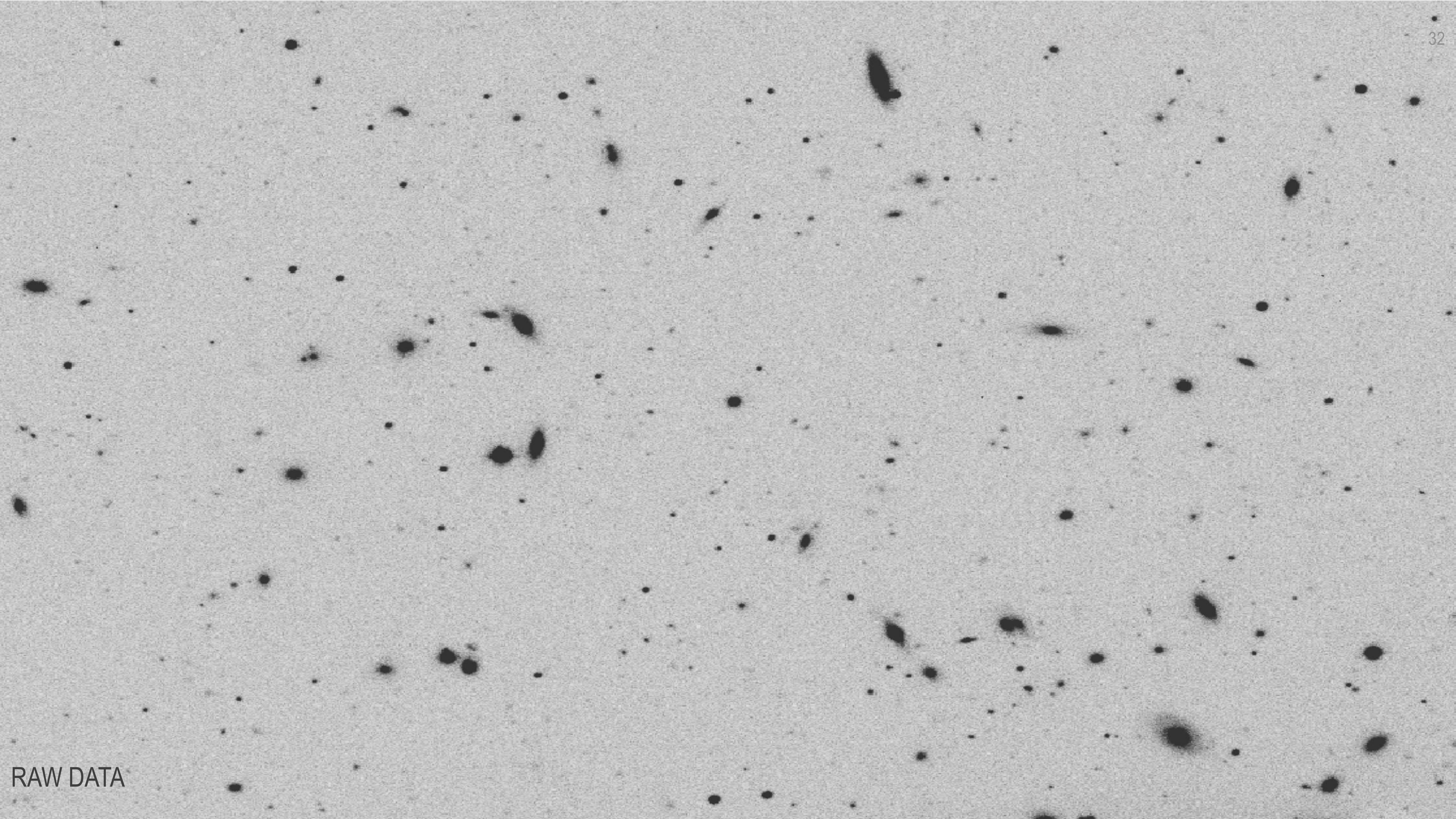


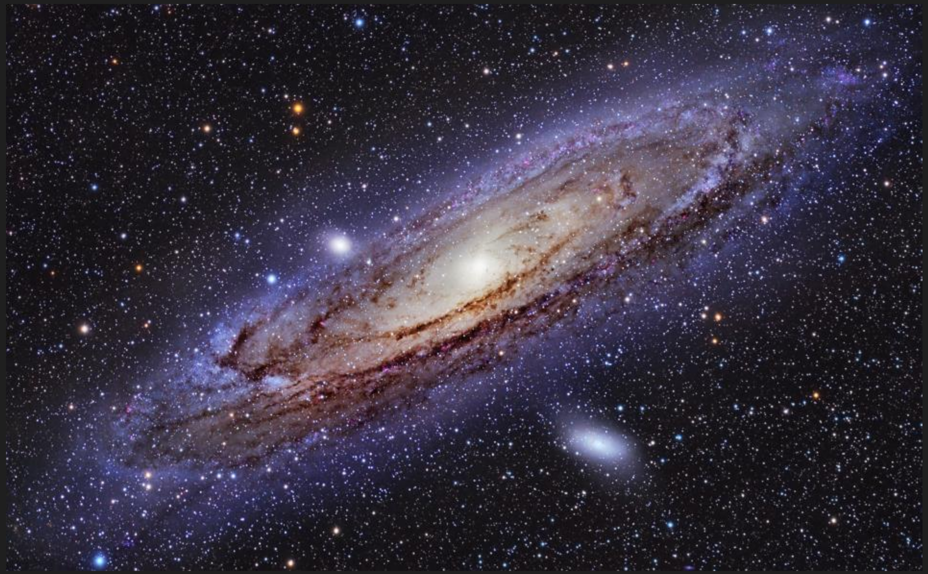








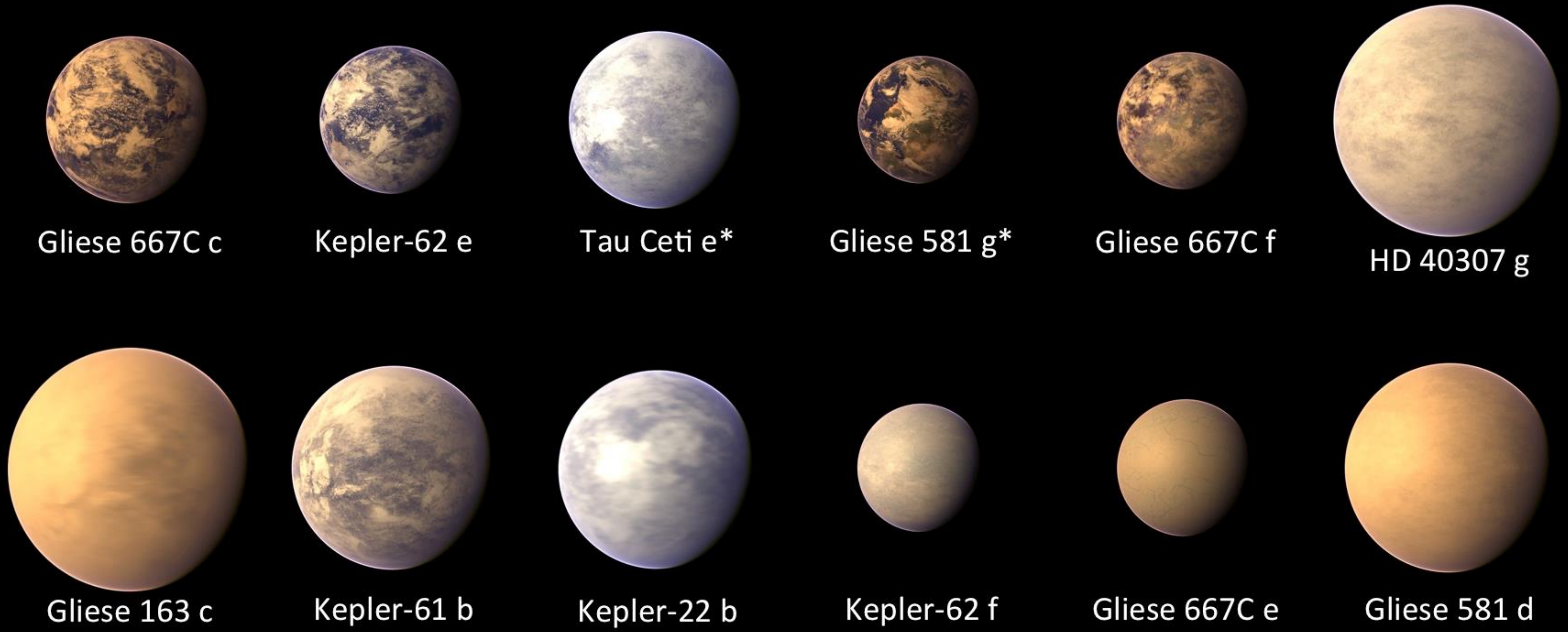

RAW DATA



10^{11} stars per galaxy


10^{11} galaxies

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



*planet candidates

CREDIT: PHL @ UPR Arecibo (phl.upr.edu) December 5, 2013

10^{21} habitable planets

A billion trillion planets …. for ten billion years

How to survey faster?

- All automated

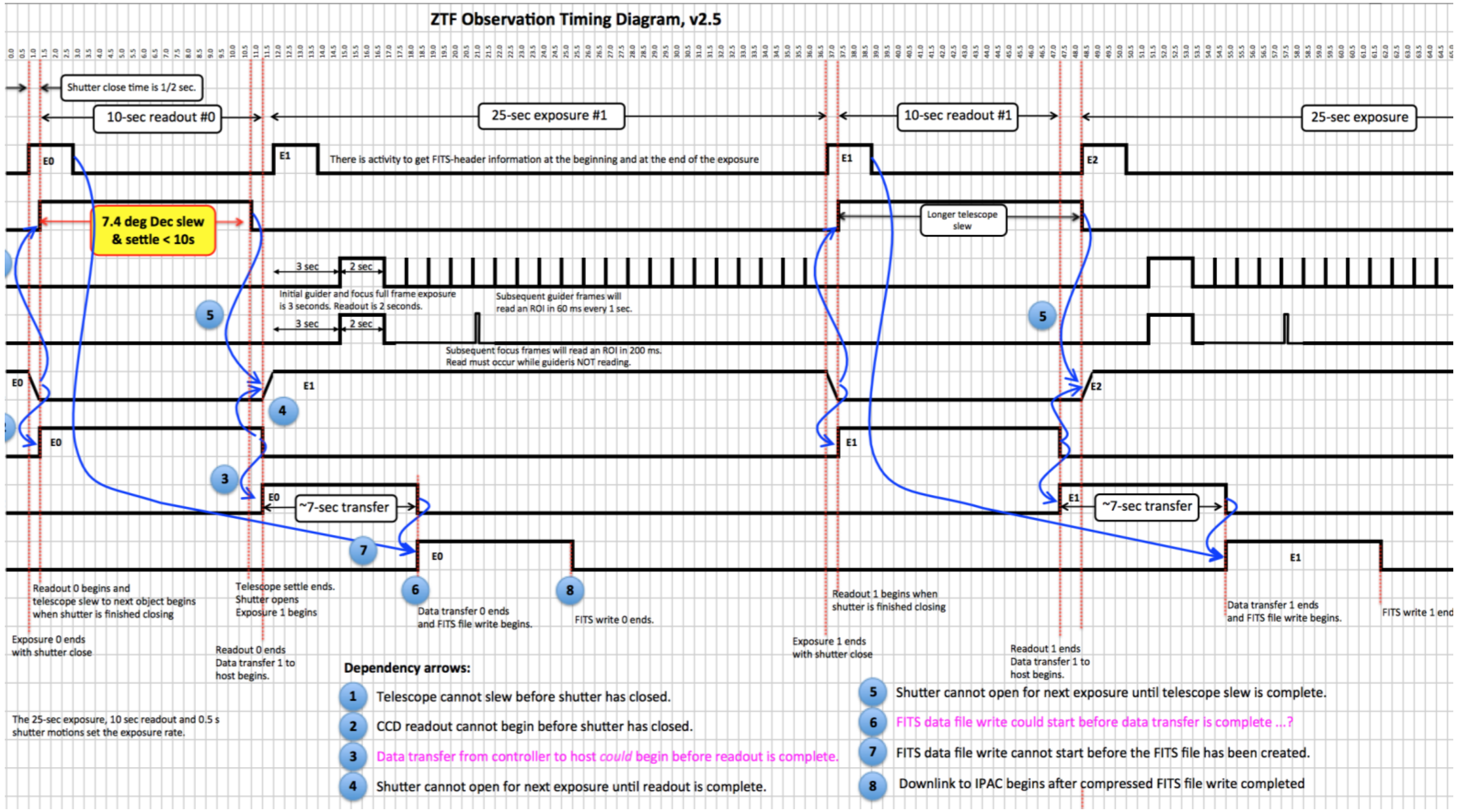
  telescope control → image recording → data transfer → analysis

- High sensitivity

  Semiconductor sensors record nearly every photon

- Wide field of view

High duty cycle …all automated

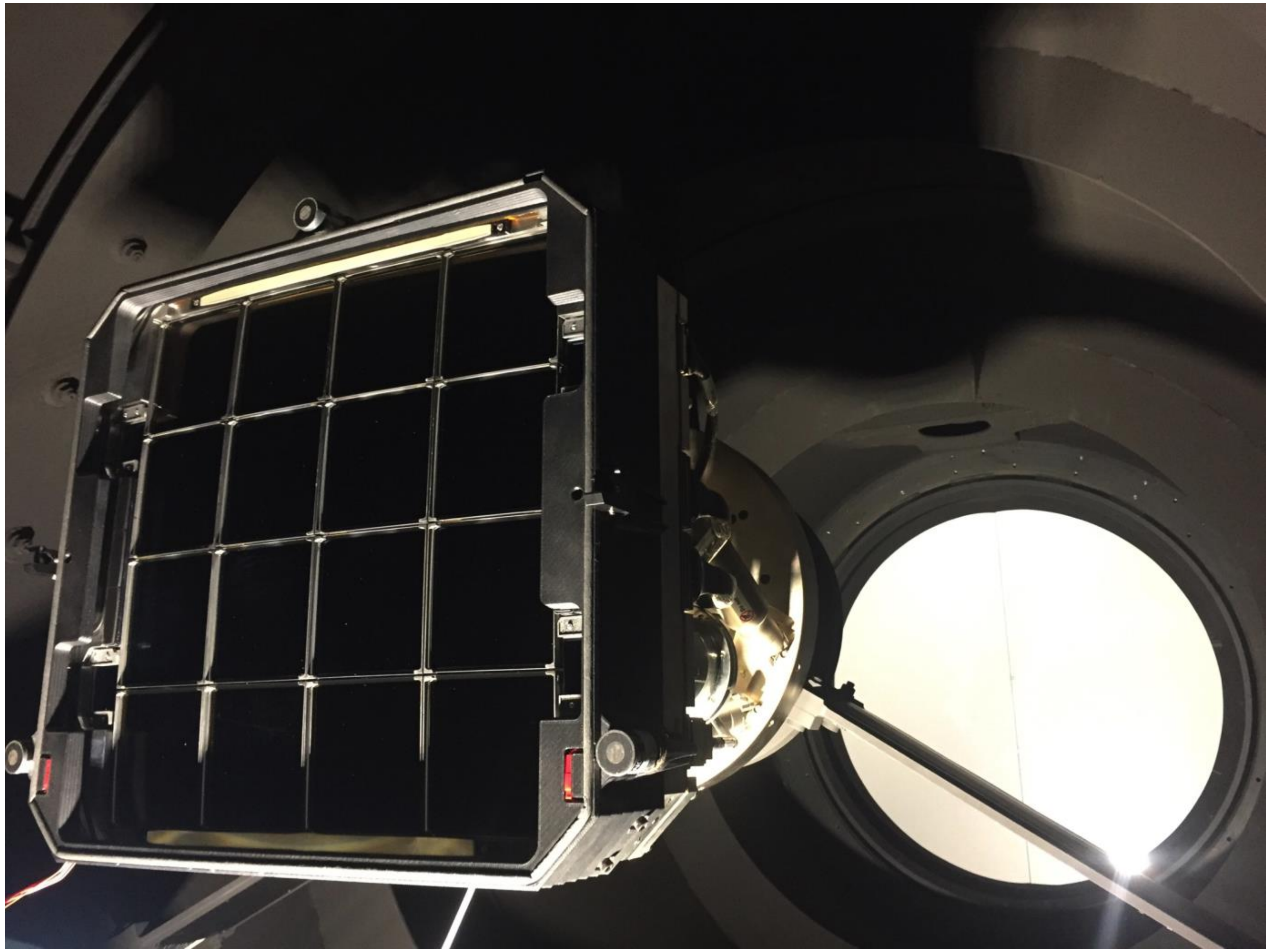


Every 10 ms counts

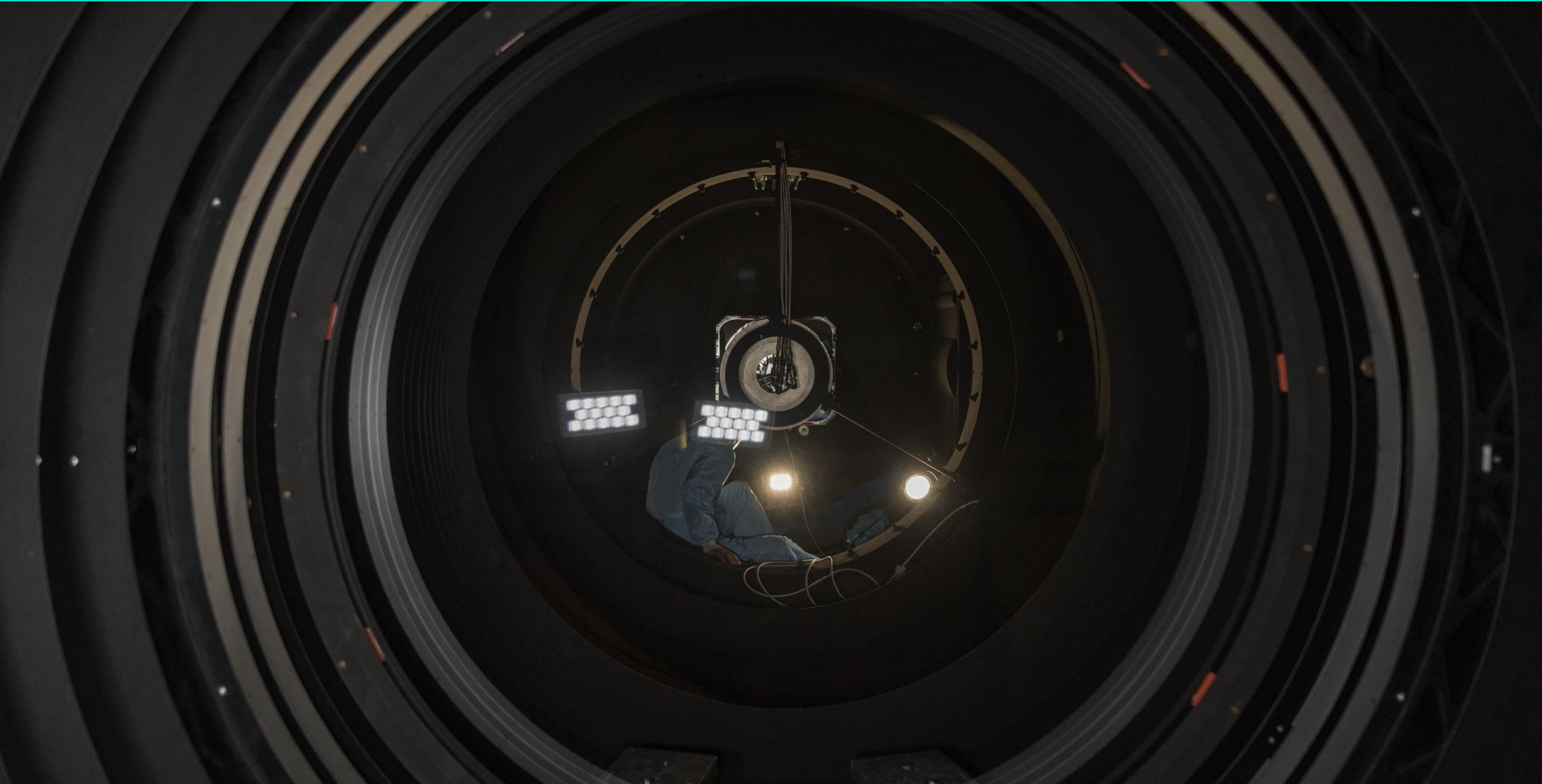
- 25 s exposure
- 1 exposure per pointing
- 8.2 s to read
- Slew and settle while reading
- RA & DEC; 0.5 deg/s^2 to 3 deg/s
- 90 s per filter exchange.

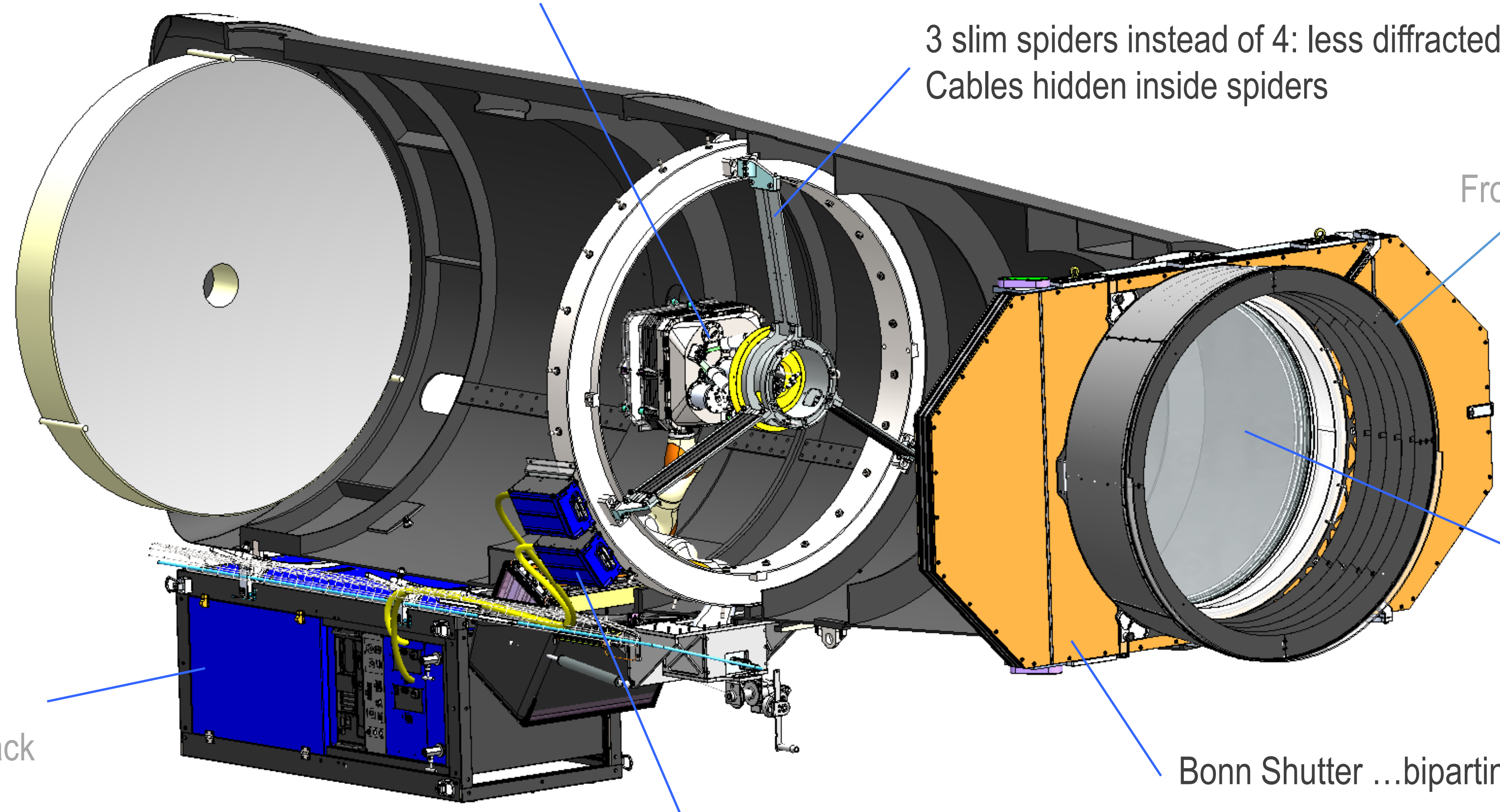
Silicon Sensors 100x more sensitive

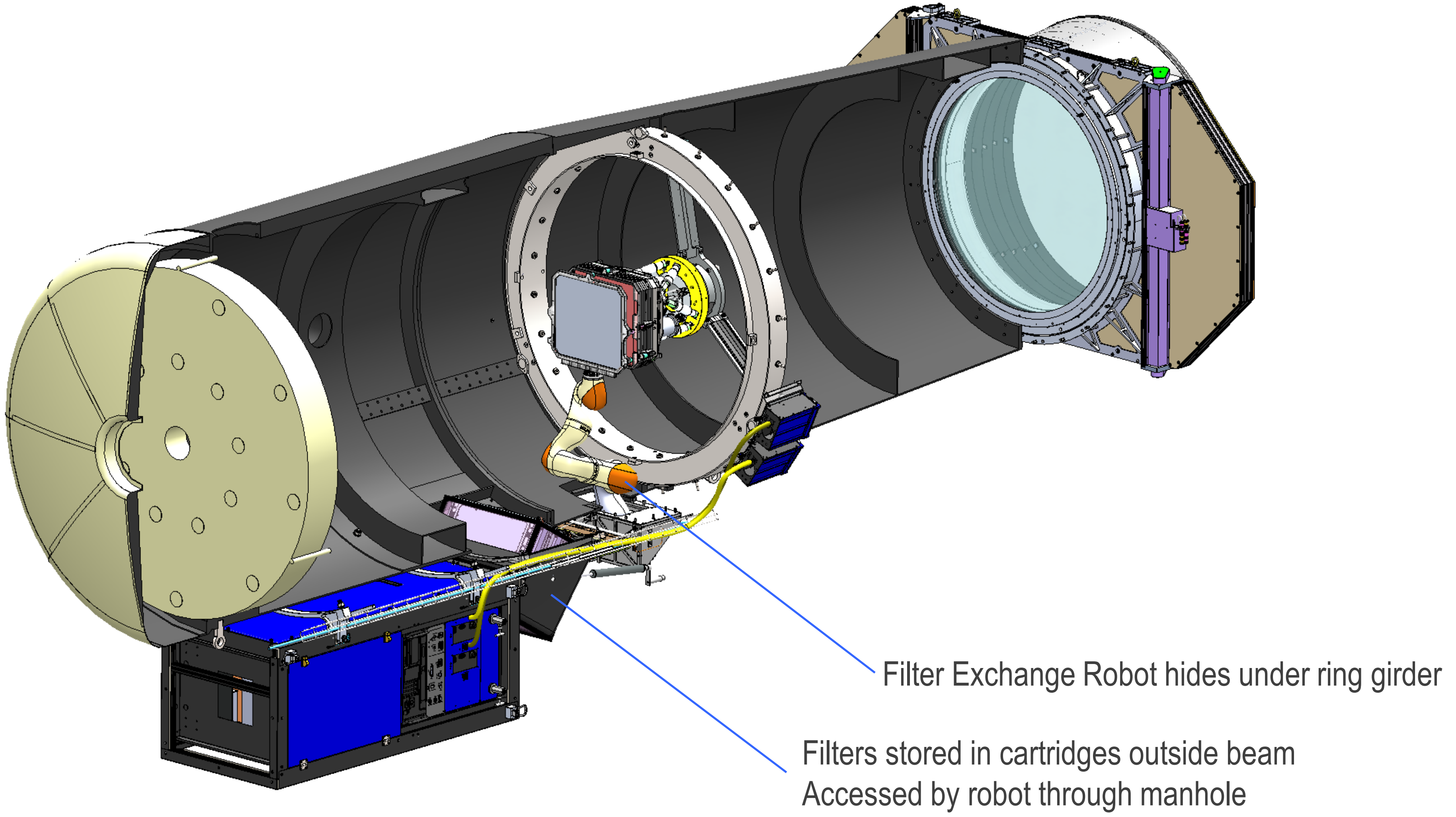
- CCD mosaic: 46.7 deg^2, 606 Mpixel
- 1 arcsec/pixel → nyquist in median seeing
- 16 * e2v CCD231-C6, 6K*6K, 15µm
- 64 readouts at 1 MHz,
- 10 e- read noise << 25 e- min. sky noise
- 3 extra-focal imagers (STA 2K*2K, 15 µm)
  - Delta doped by JPL
  - 100 µm thick fully depleted n-channel
  - with broadband 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.




Hexpod, coolers, connectors etc all
hidden behind instrument
3 slim spiders instead of 4: less diffracted power
Cables hidden inside spiders
Front-End Baffle
Schmidt corrector:
Achromatic doublet
Water cooled
Electronics Rack
Bonn Shutter …biparting blades park outside beam
STA Archon Controllers (x5)
on telescope wall (outside beam)

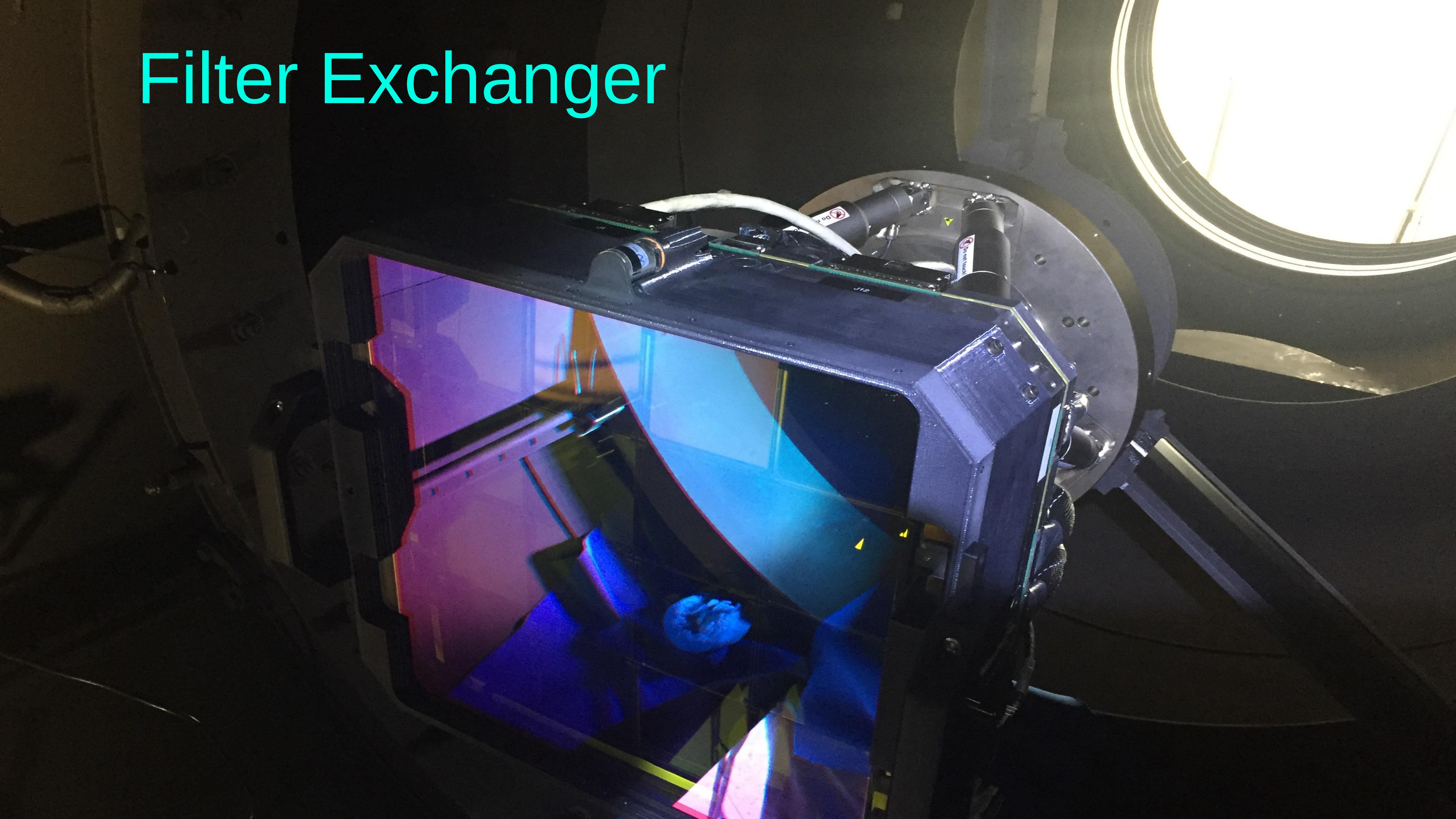

Filter Exchange Robot hides under ring girder
Filters stored in cartridges outside beam
Accessed by robot through manhole

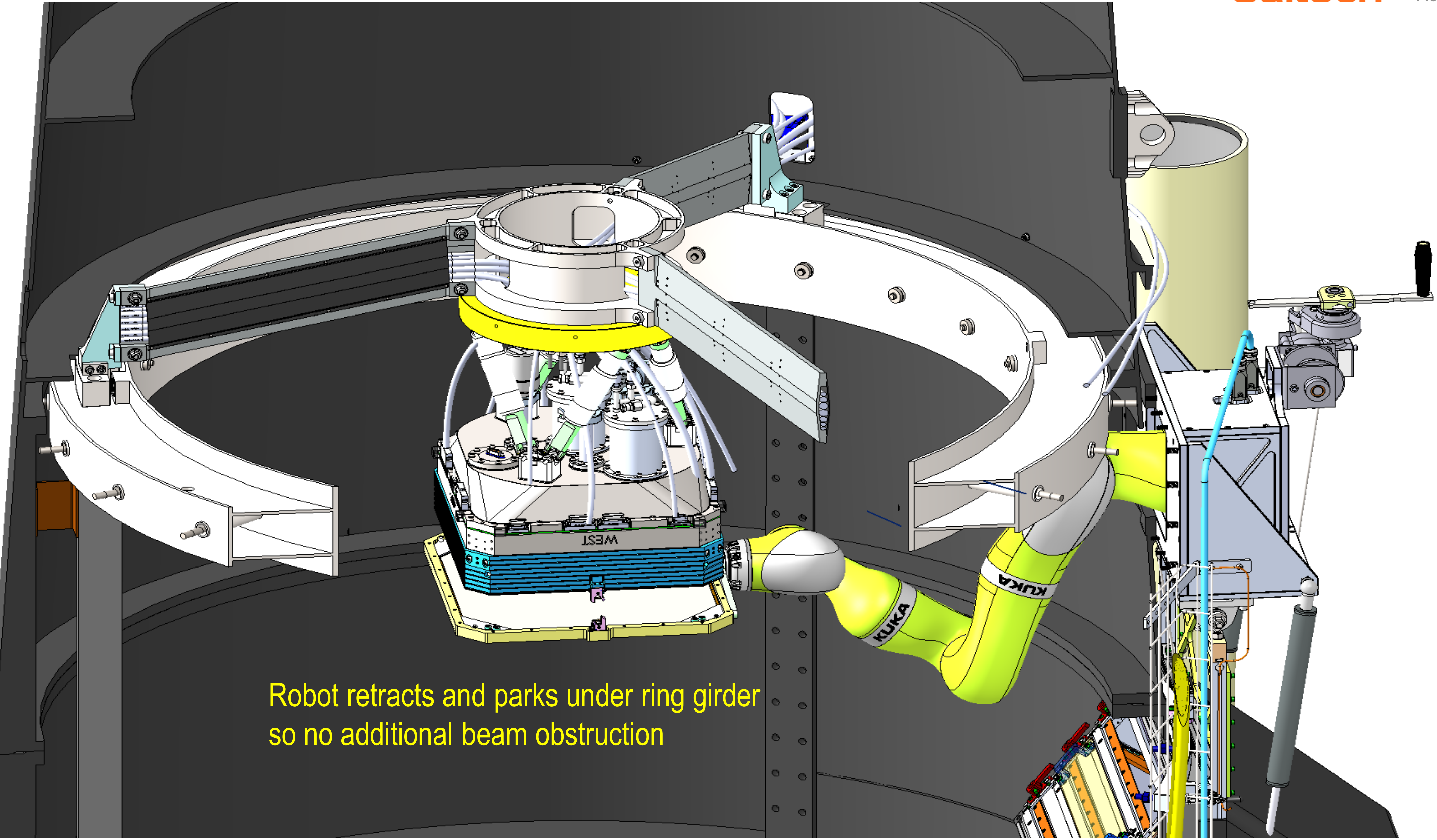
Bonn Shutter on dome floor

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

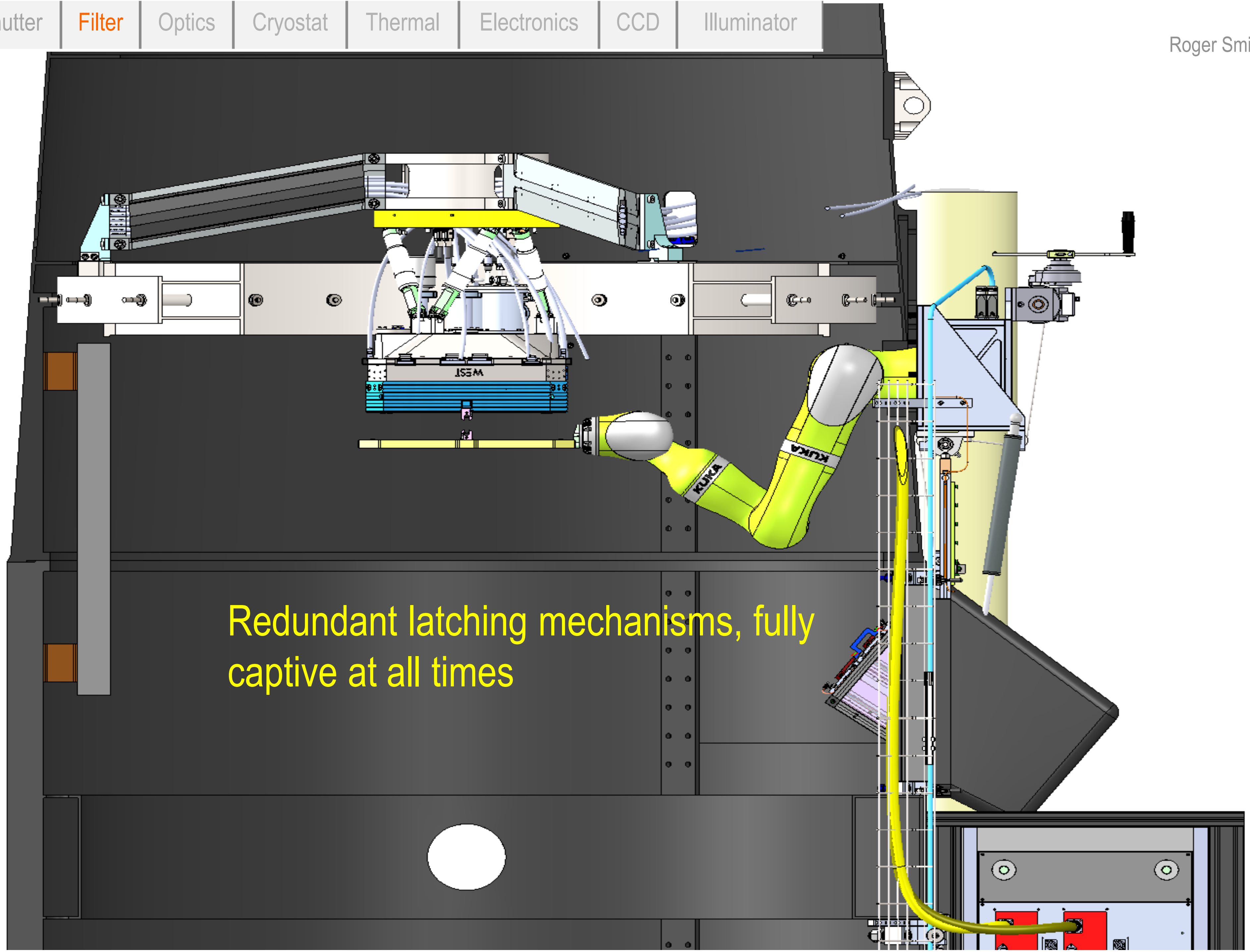
- Blades are driven in opposite directions by a common belt.
- Balanced for negligible force into telescope
- Servo motor provides tunable profiles.
- Strong enough to survive 35 mph winds.

Filter Exchanger

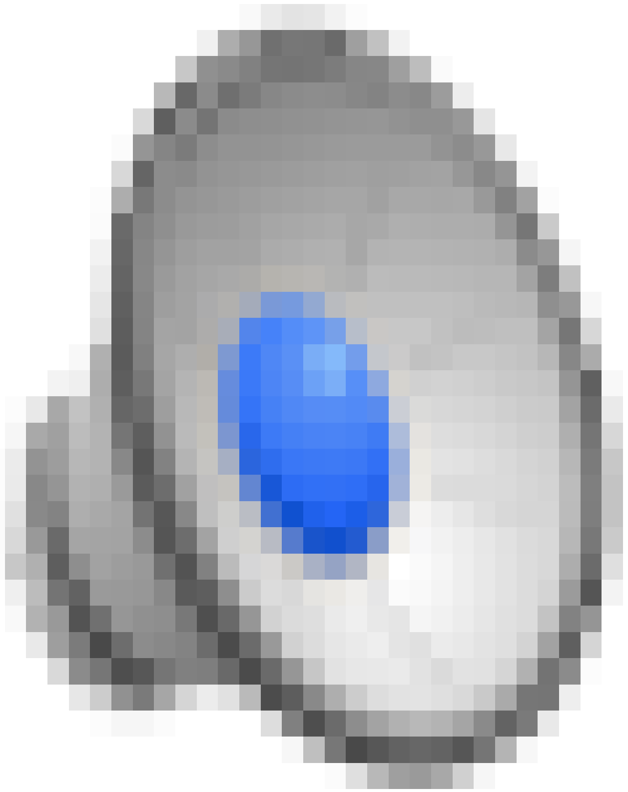




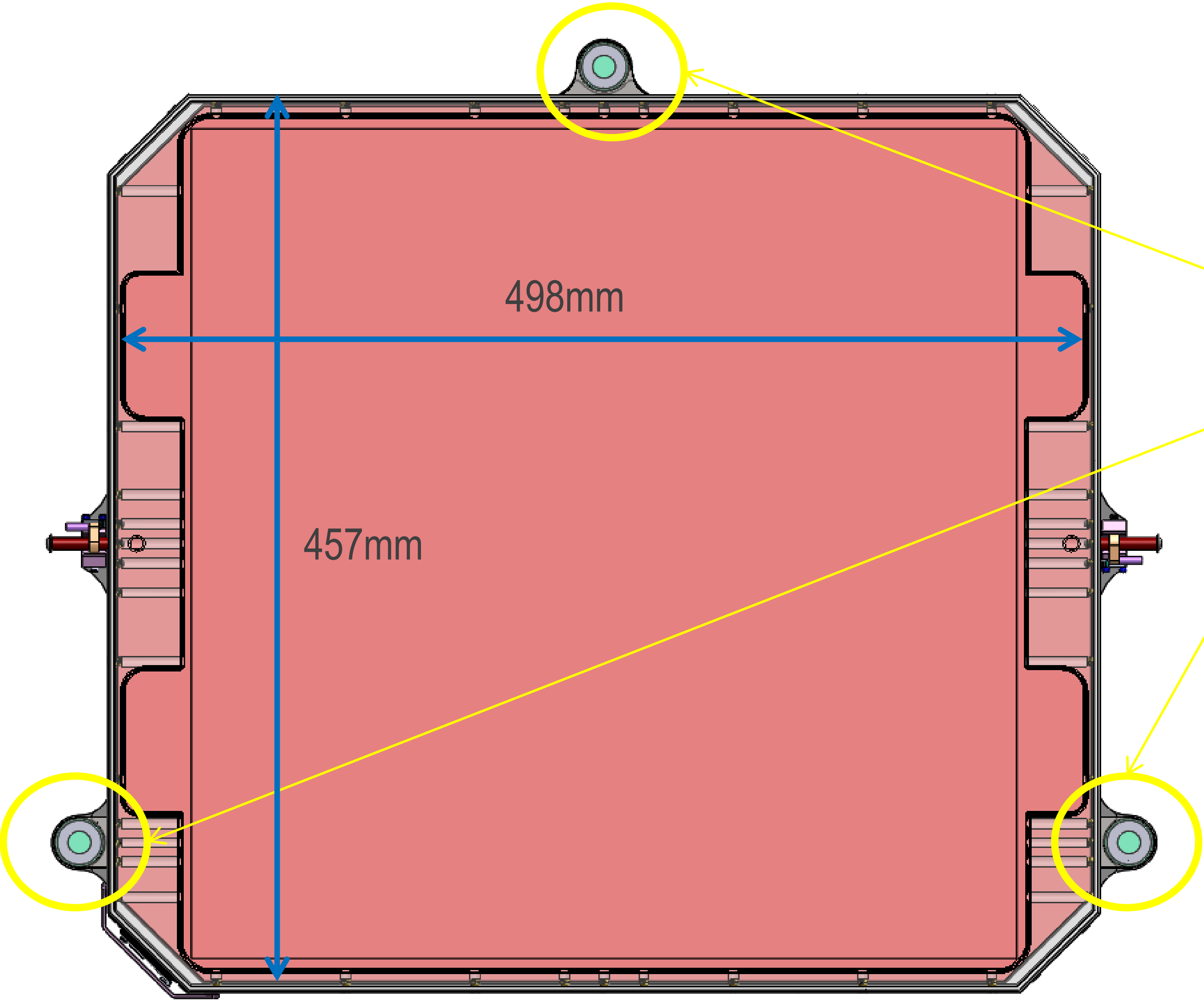
Robot retracts and parks under ring girder
so no additional beam obstruction



Redundant latching mechanisms, fully captive at all times

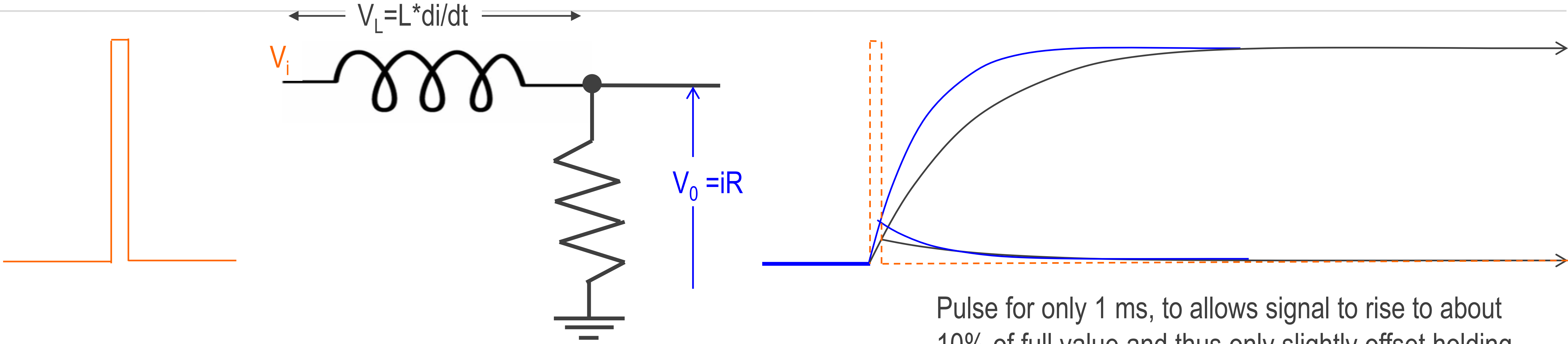


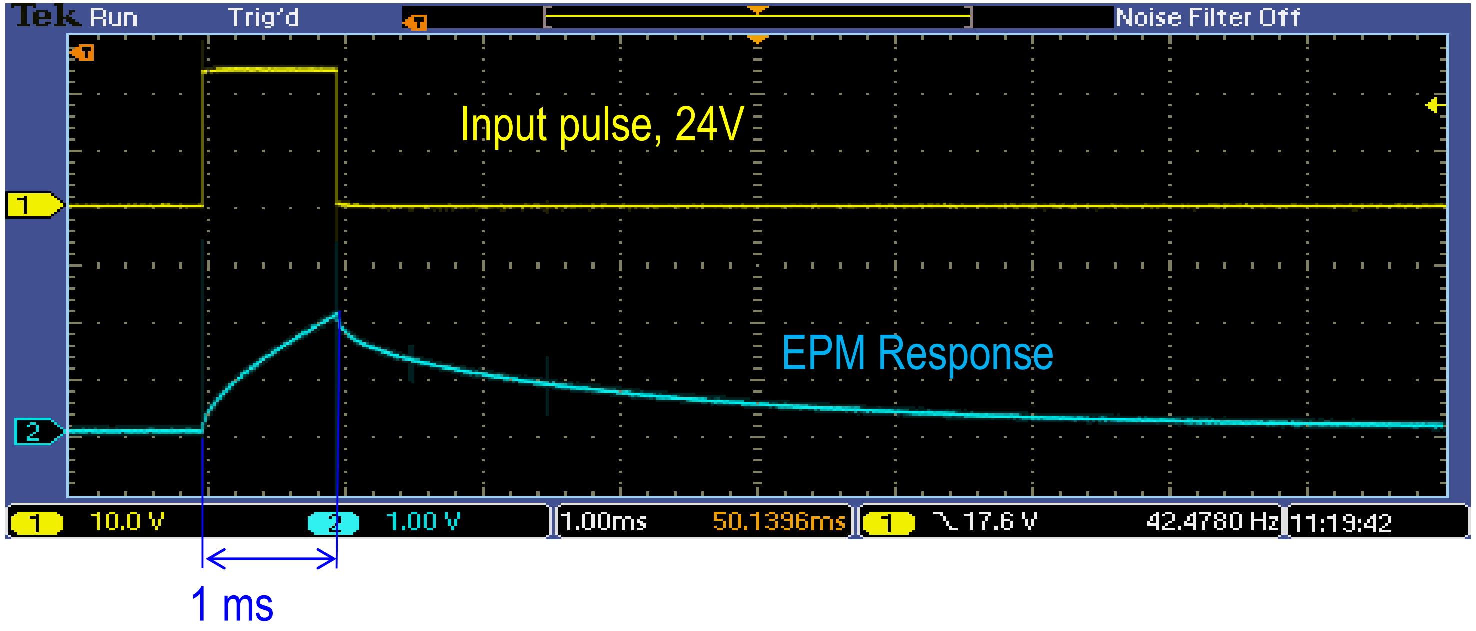
Filters held by Electro-Permanent Magnets



Three magnets obstruct < 0.2% of beam

Magnet is self encoding latch

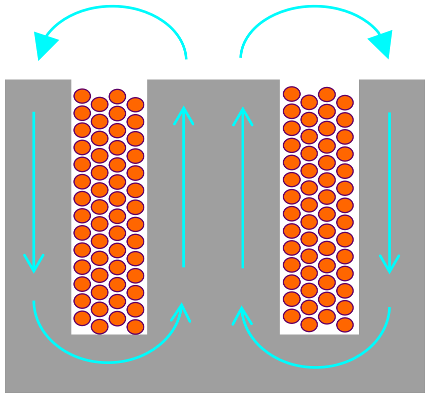


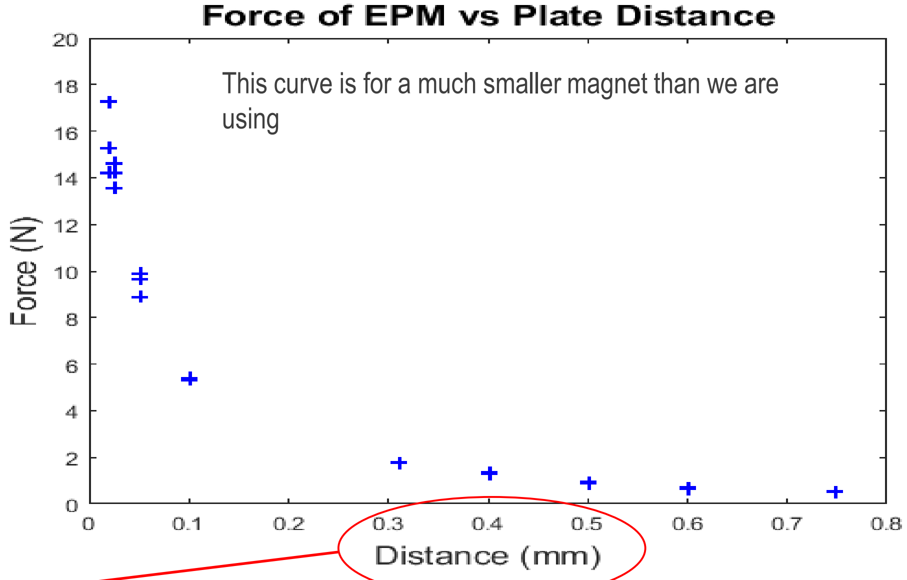


Pulse for only 1 ms, to allows signal to rise to about 10% of full value and thus only slightly offset holding force.

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

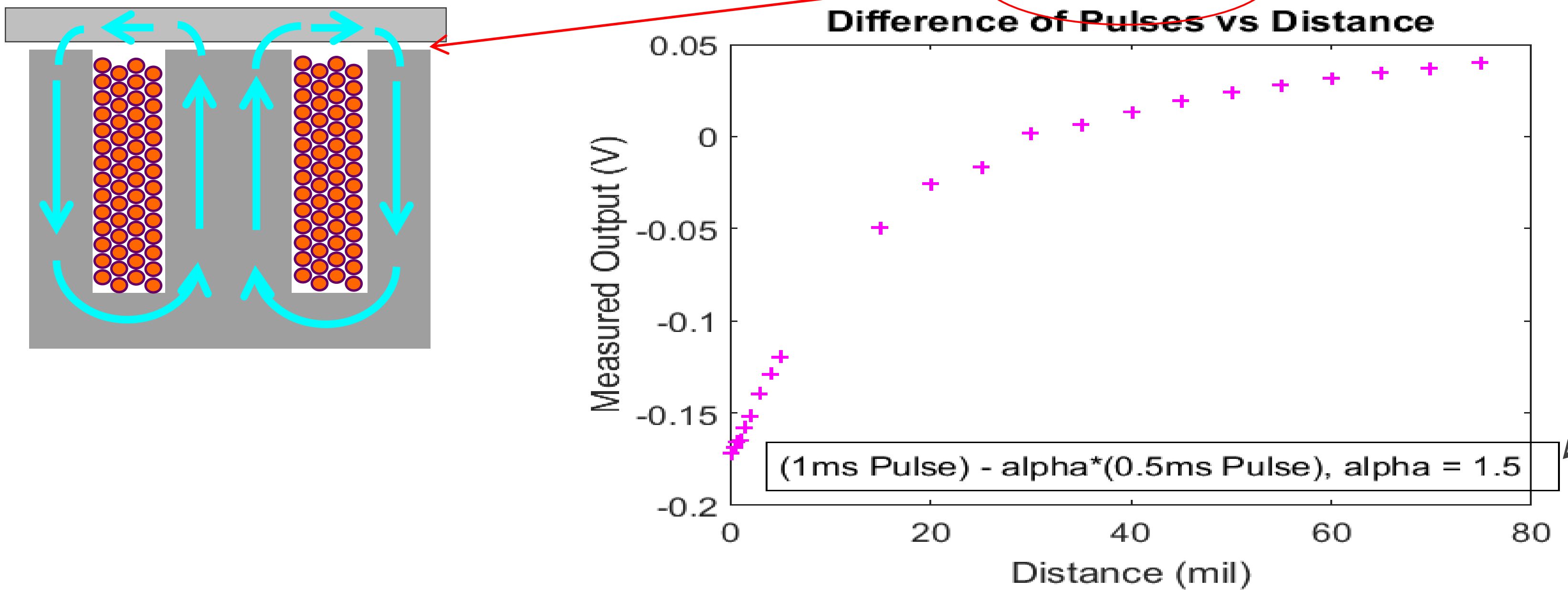
Rise time reflects air gap





Force rolls off steeply with air gap

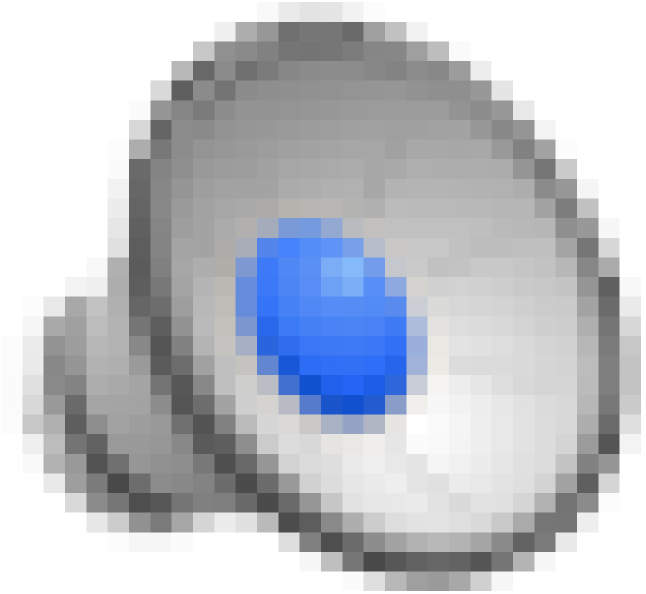
… need sensing to protect against metal particles on surface



Sensing works

…after dealing with non-linearity of permanently magnetized core

Secondary Latch close up



Cryostat

Sensors must operate at -100 C,

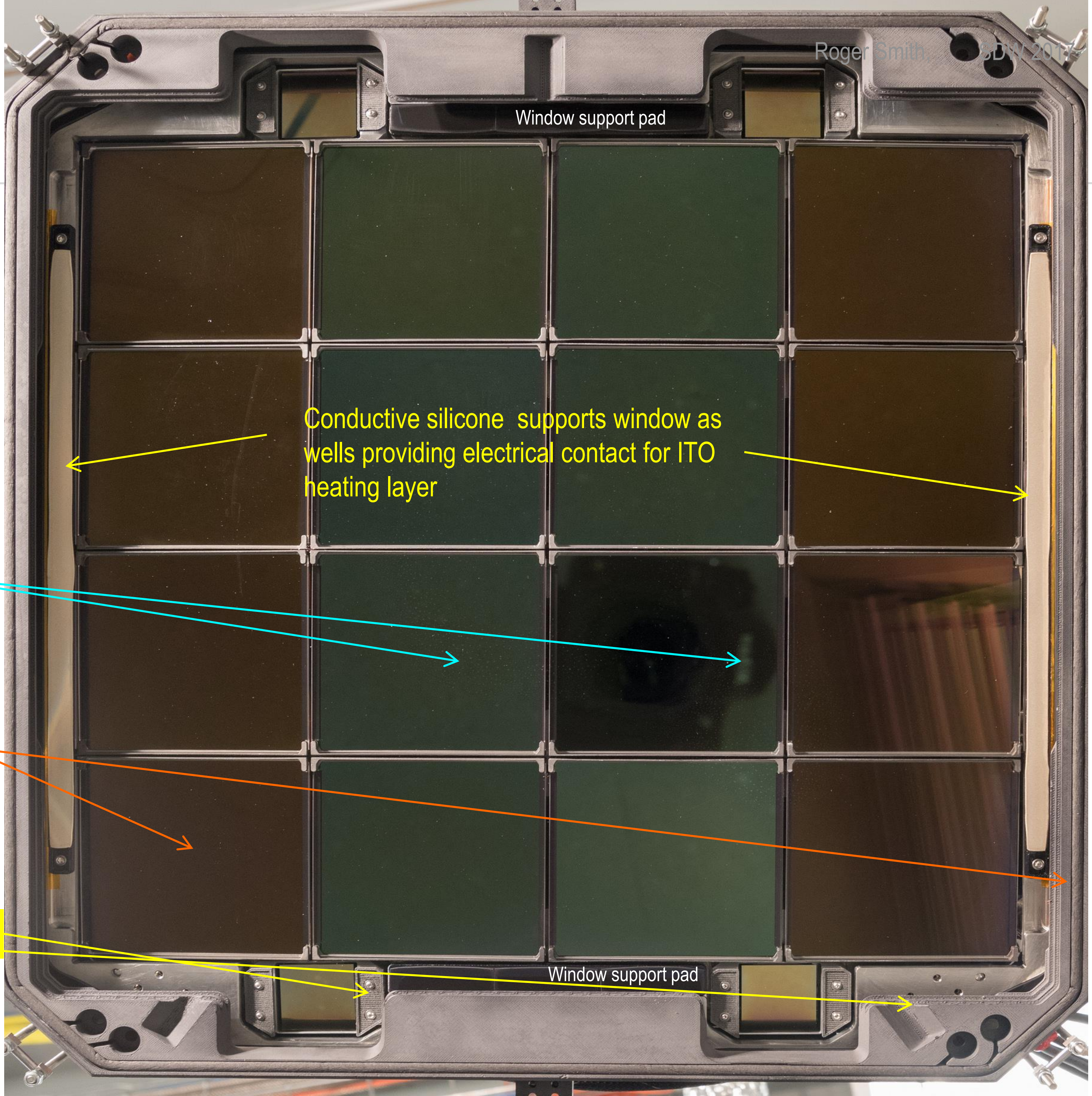
so thermally isolated in vacuum chamber.

Front view

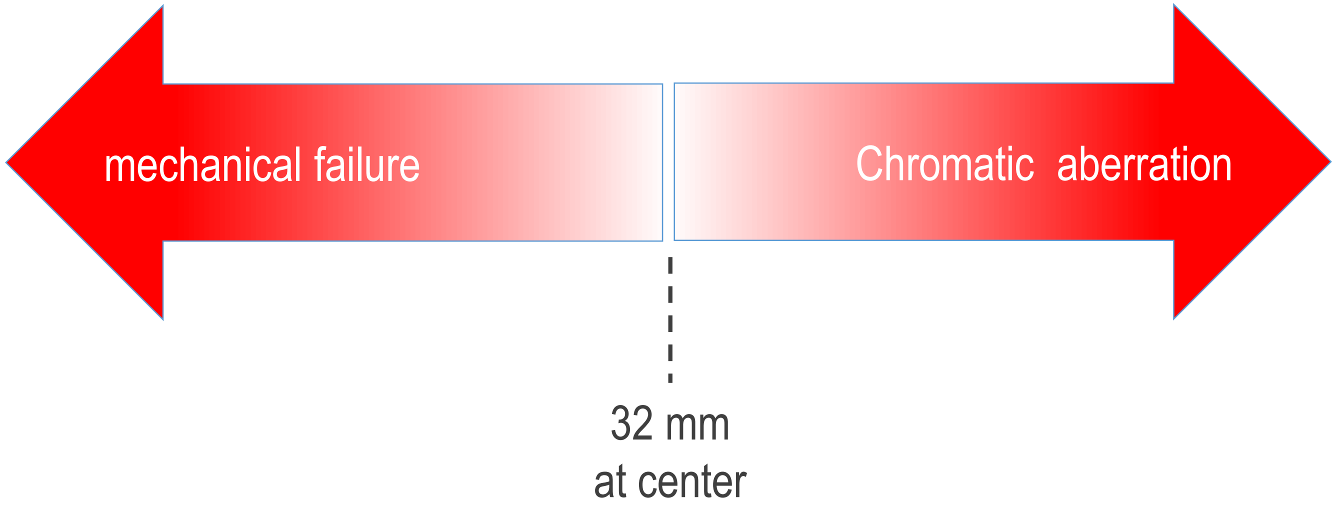
2 layer AR coating

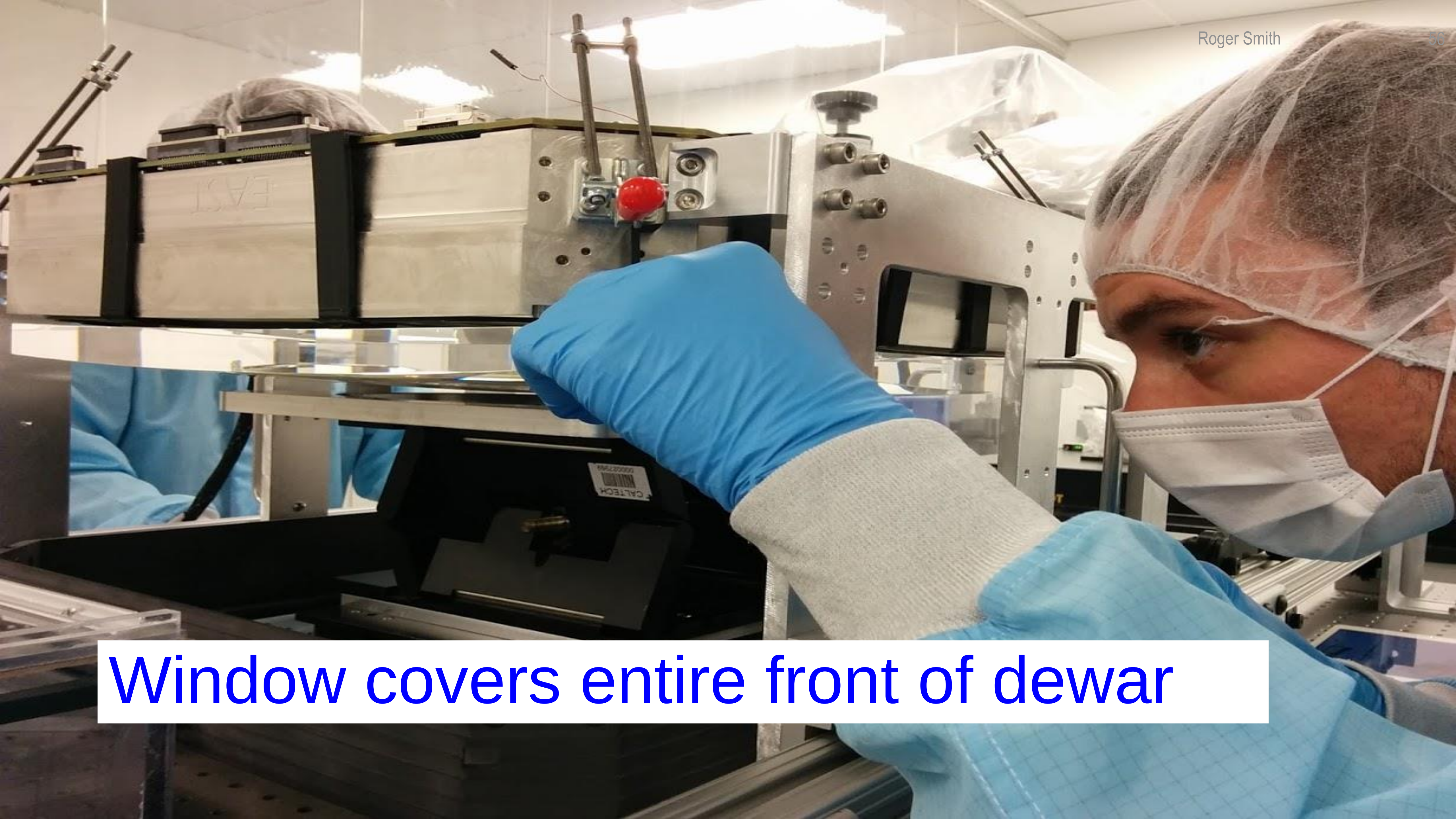
Single layer AR coating

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



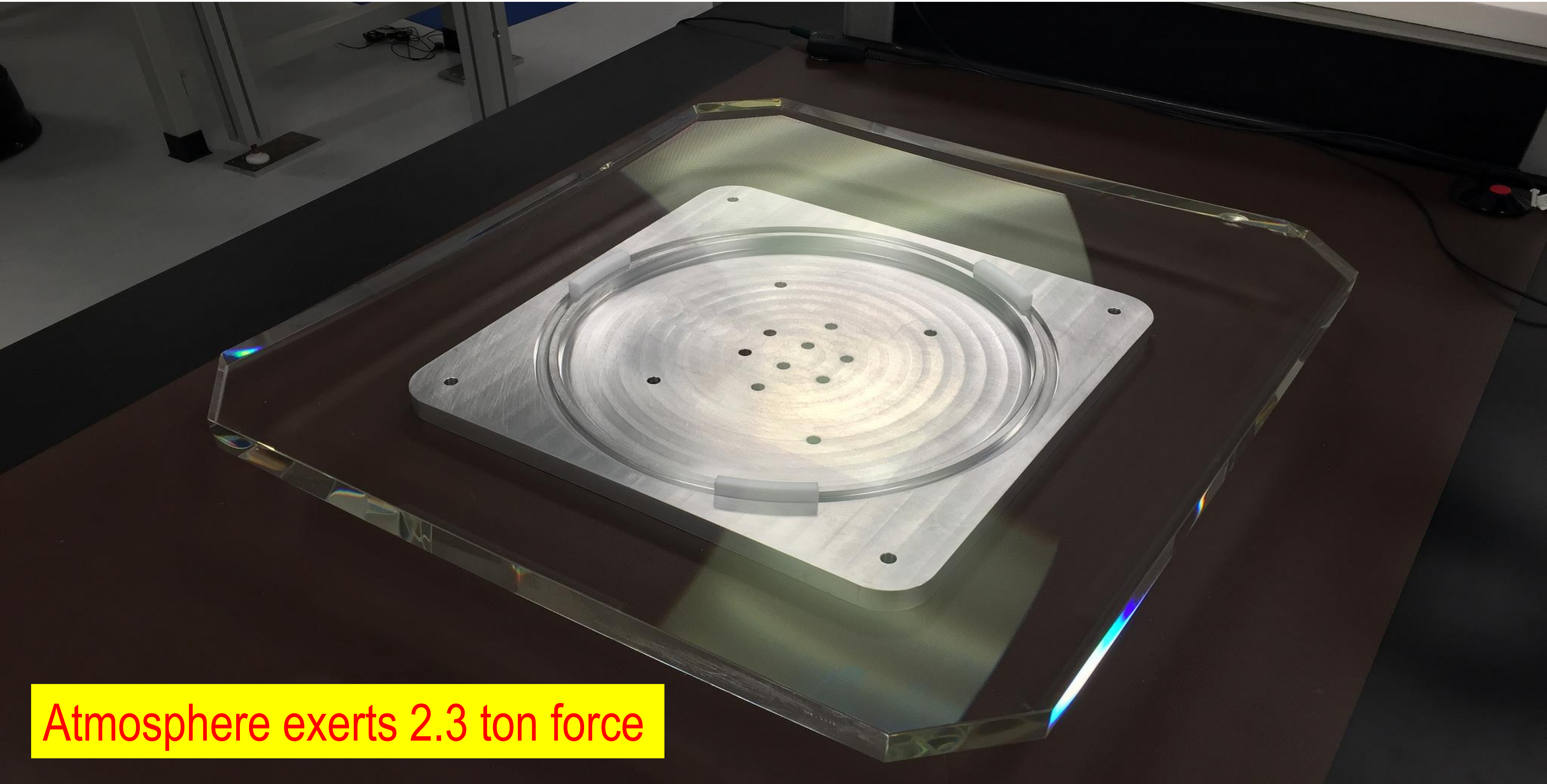
Window Thickness





Window covers entire front of dewar

32 mm @ center, 22 mm at corner



Atmosphere exerts 2.3 ton force

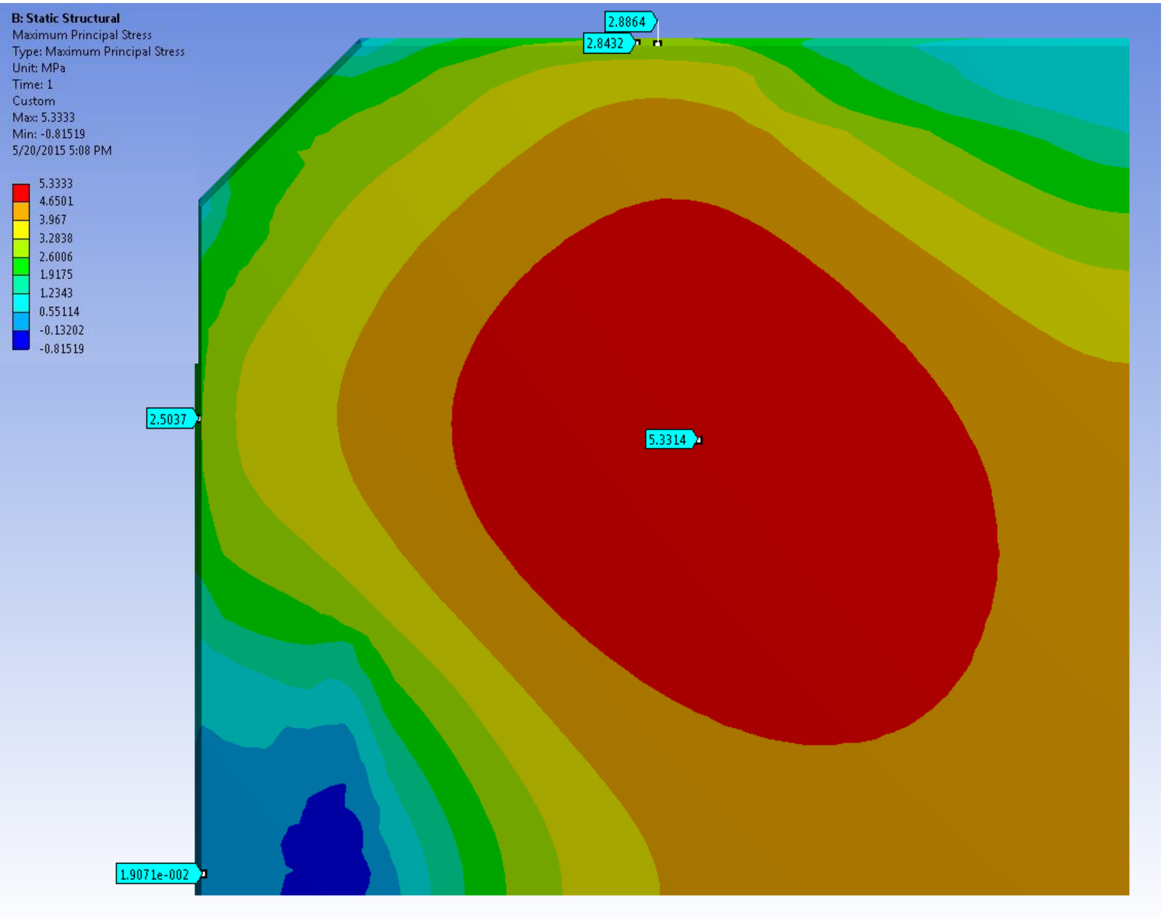
Window Factor of Safety improvements

- 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.

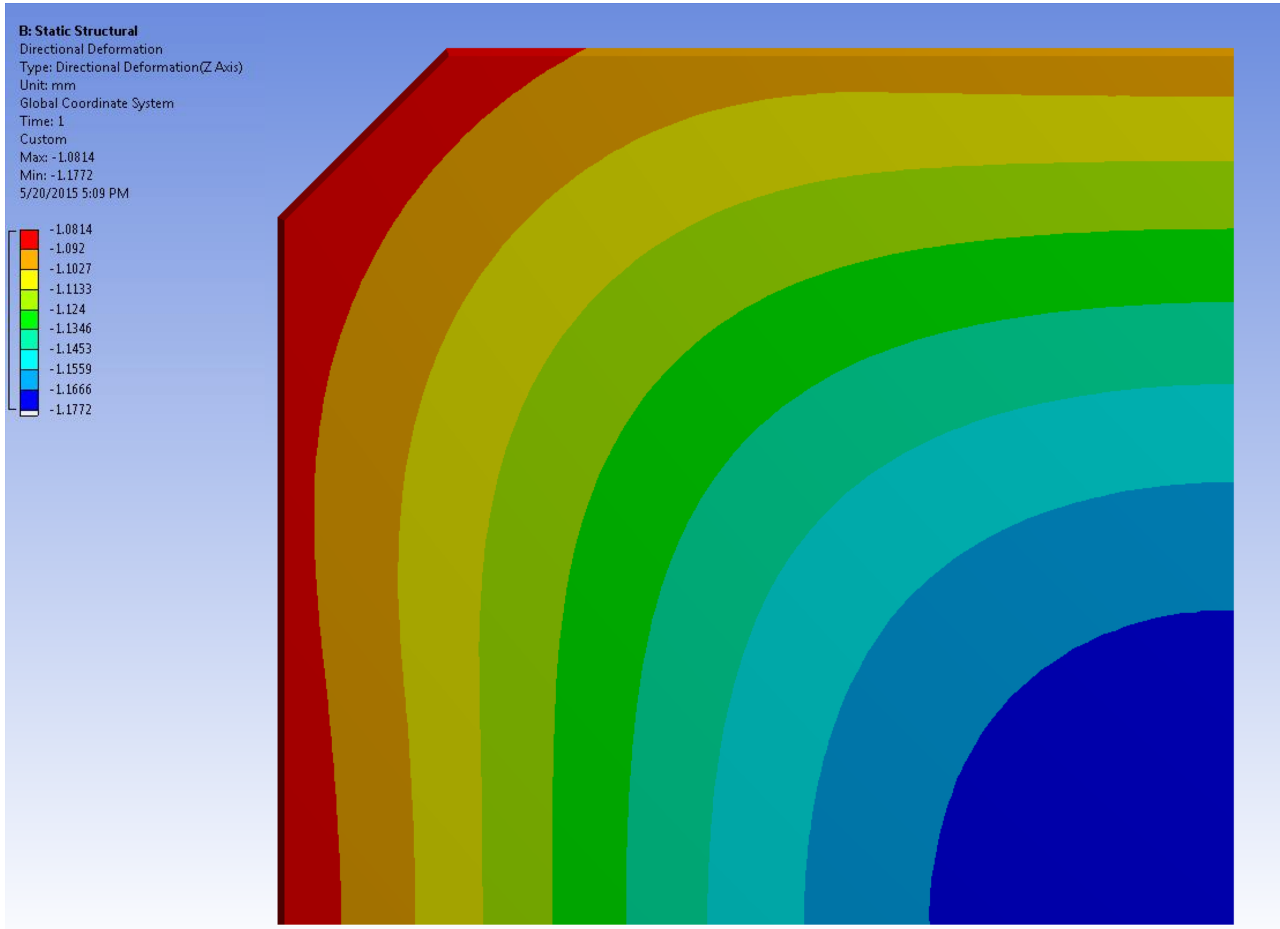
Edges polished to suppress crack initiation

32mm Thick

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



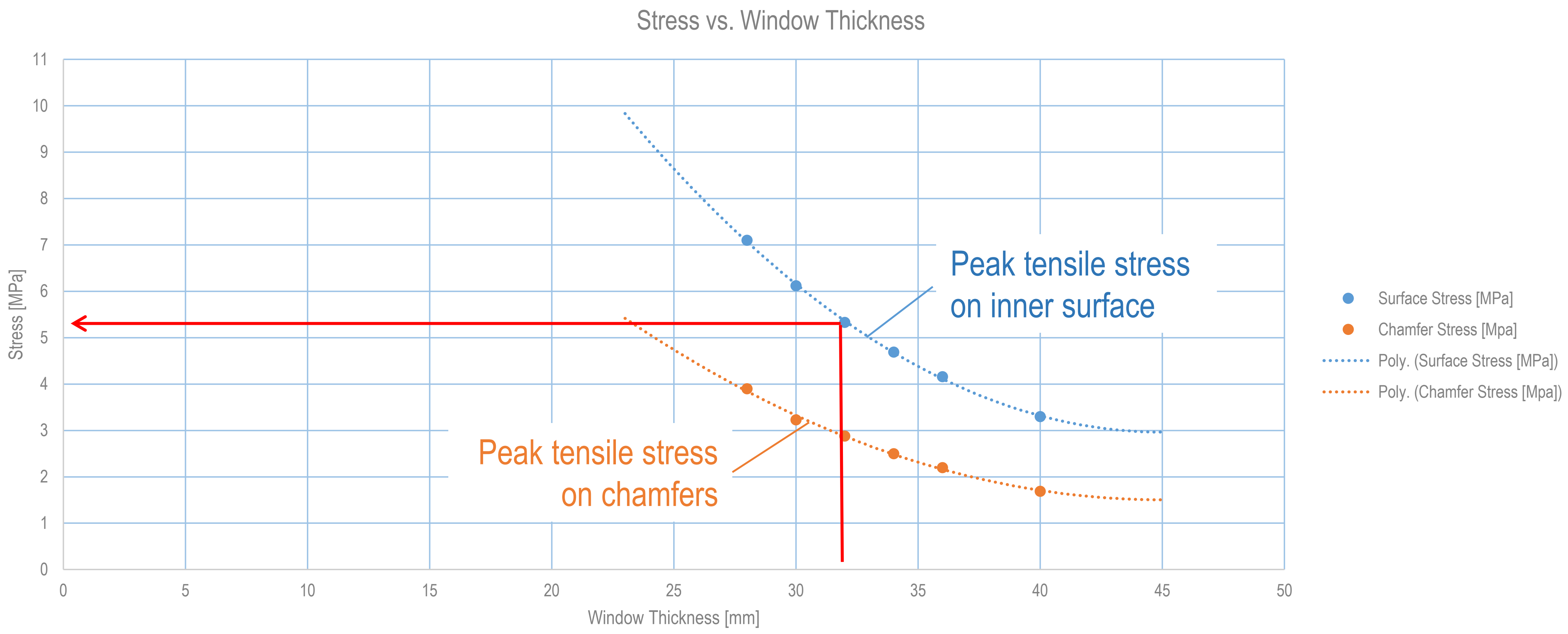
$\sigma_{surface}$ =5.3MPa [768psi]



Vertical Deformations: 96um

Stress vs. Window Thickness

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



Probability of Survival σ_{max} = 5.3MPa

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:

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

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

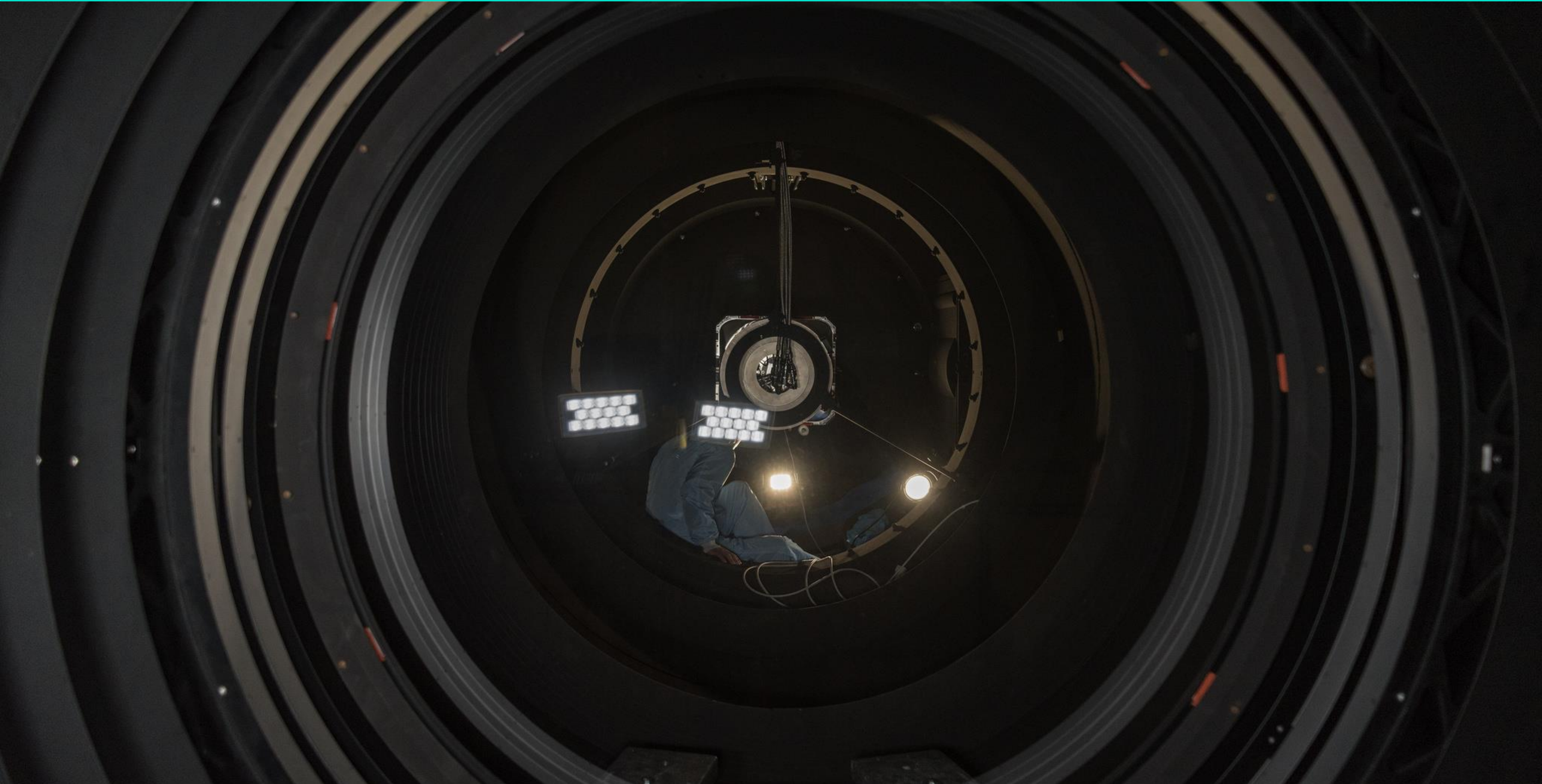
$$FS := \frac{\sigma_{max}}{\sigma} = 6.792$$

FoS(5.3MPa,0.99) = 6.8

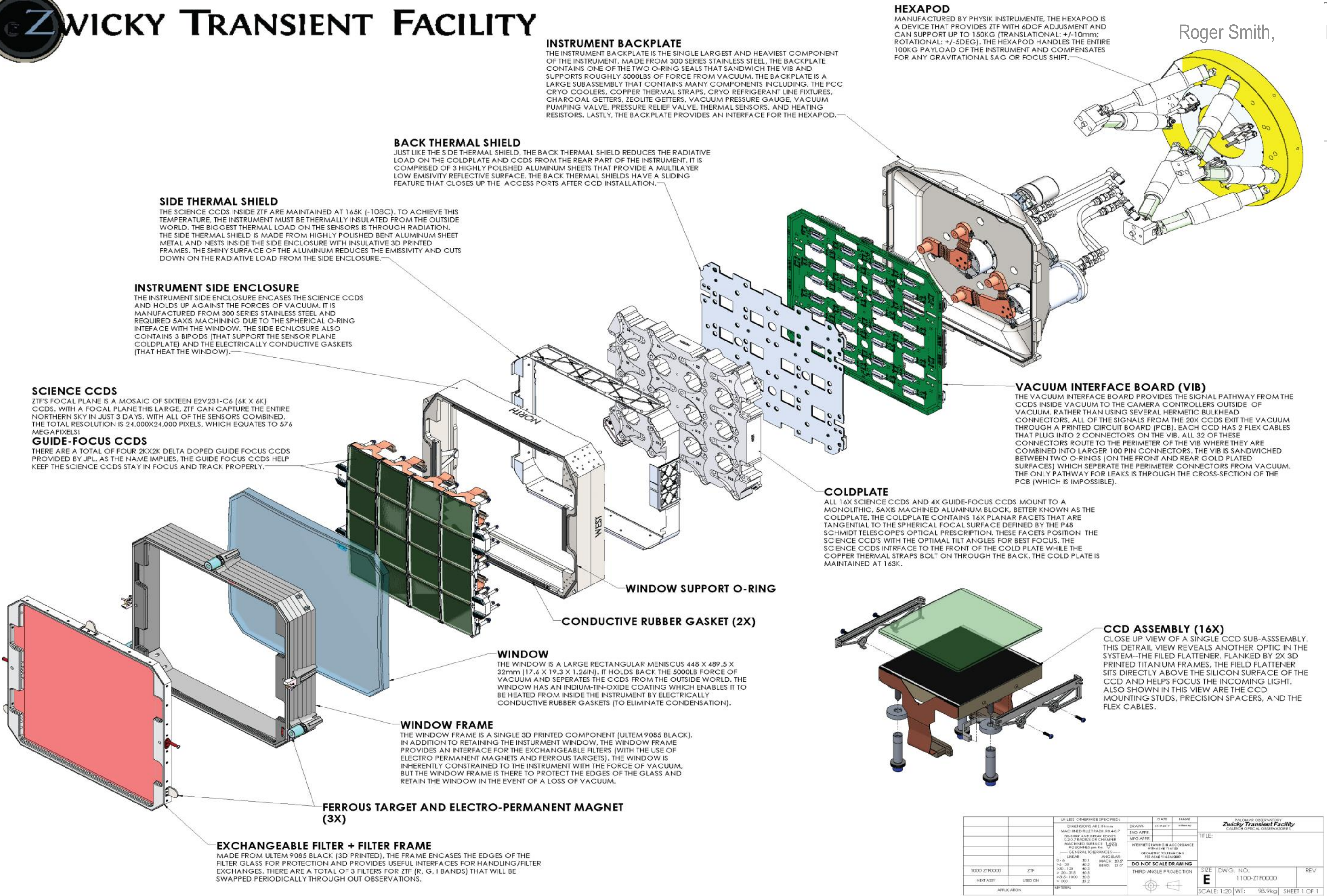
Probability of Survival,

$$P_s := e^{\frac{-A_{effective}}{A_{sample}} \cdot \left(\frac{\sigma}{\sigma_c} \right)^{\lambda}} = 0.99999999951907$$

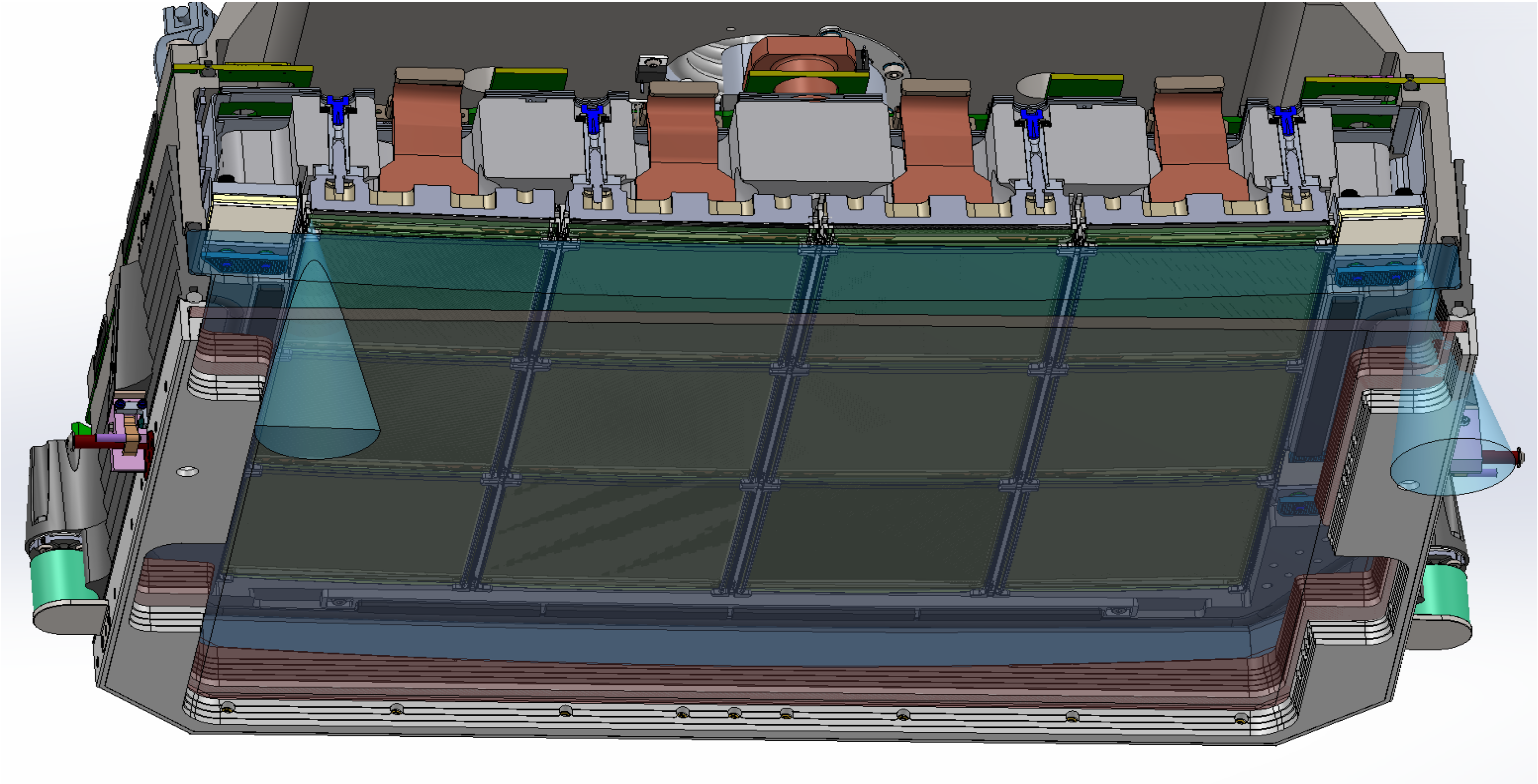
THE CHALLENGE: Big instrument in small beam.



ZWICKY TRANSIENT FACILITY

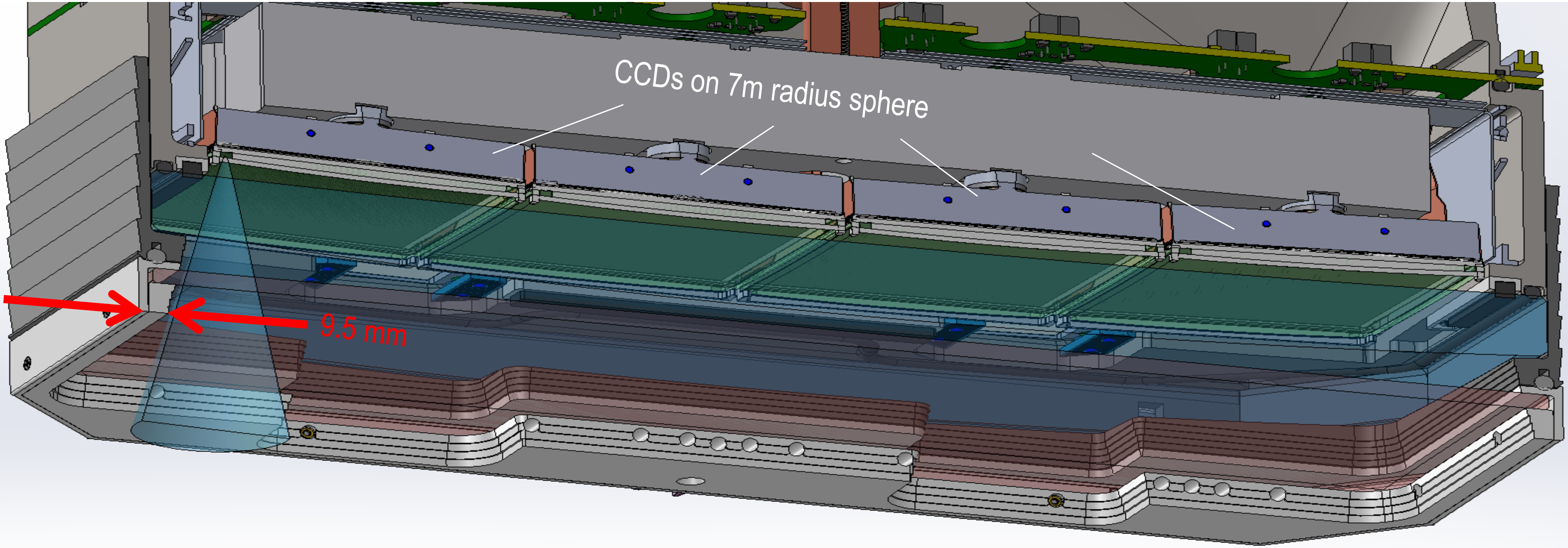


Window defines size of instrument

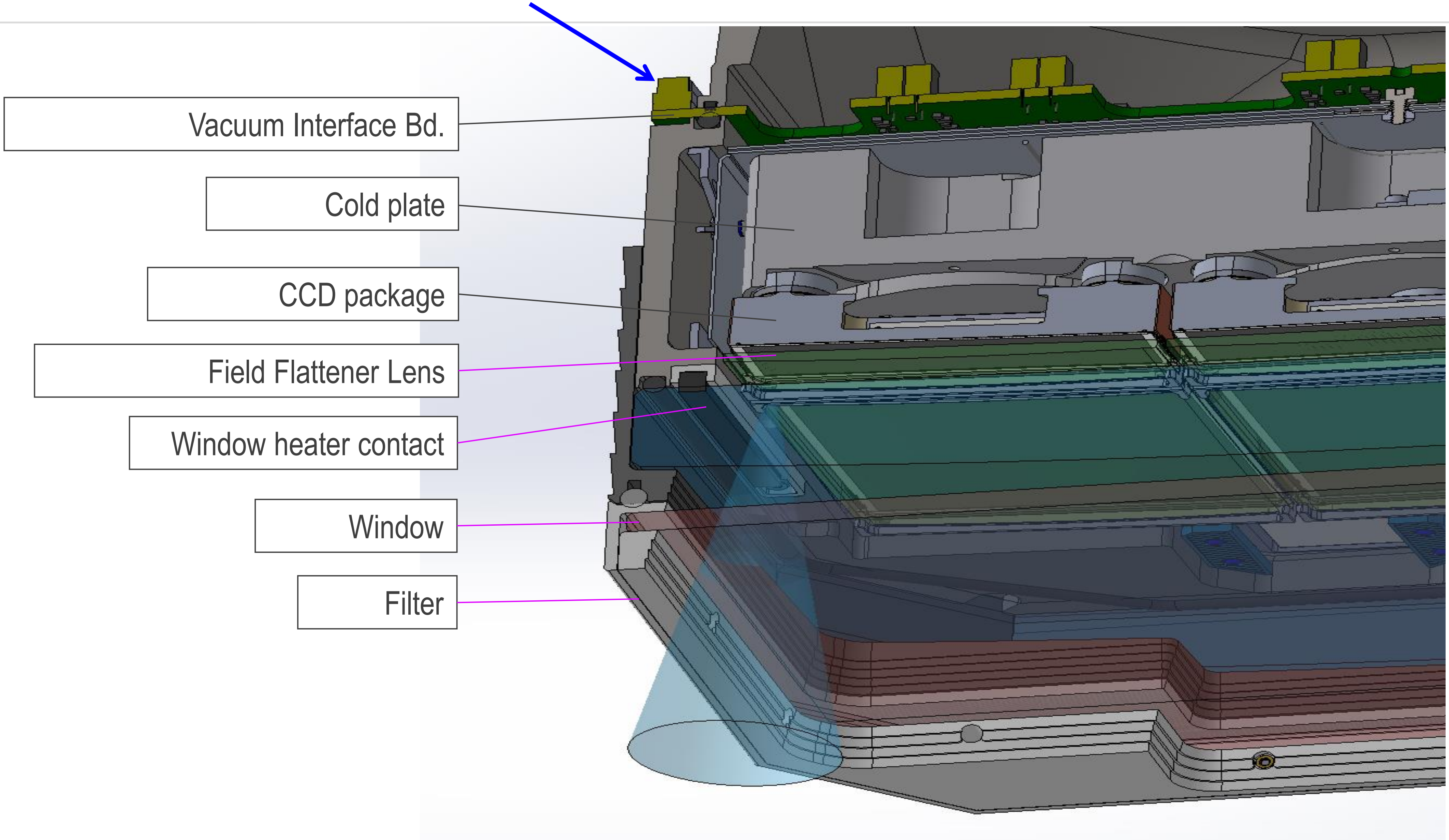


Dewar is hidden behind filter

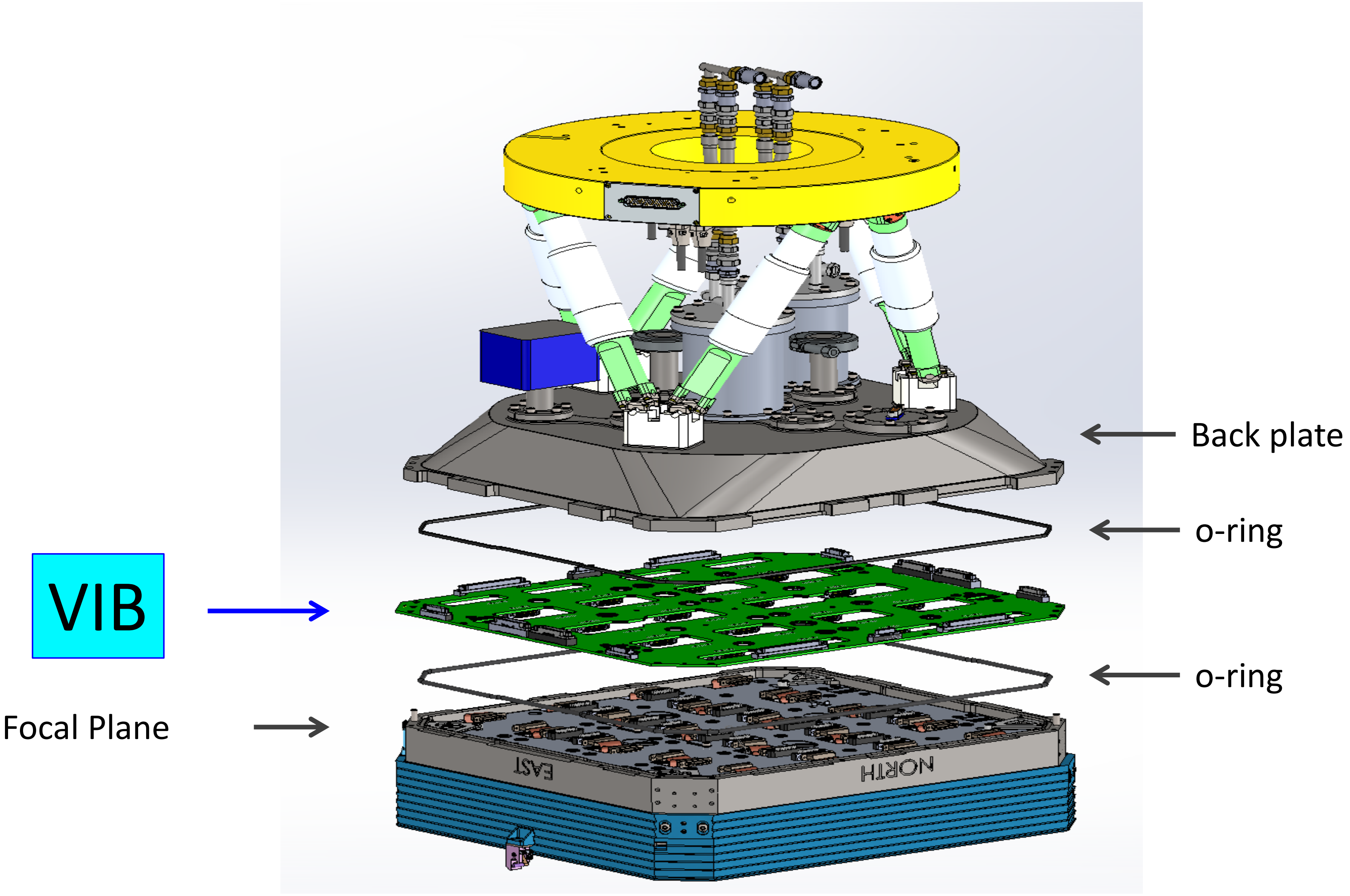
Filter frame adds only 9.5 mm to each side of beam footprint



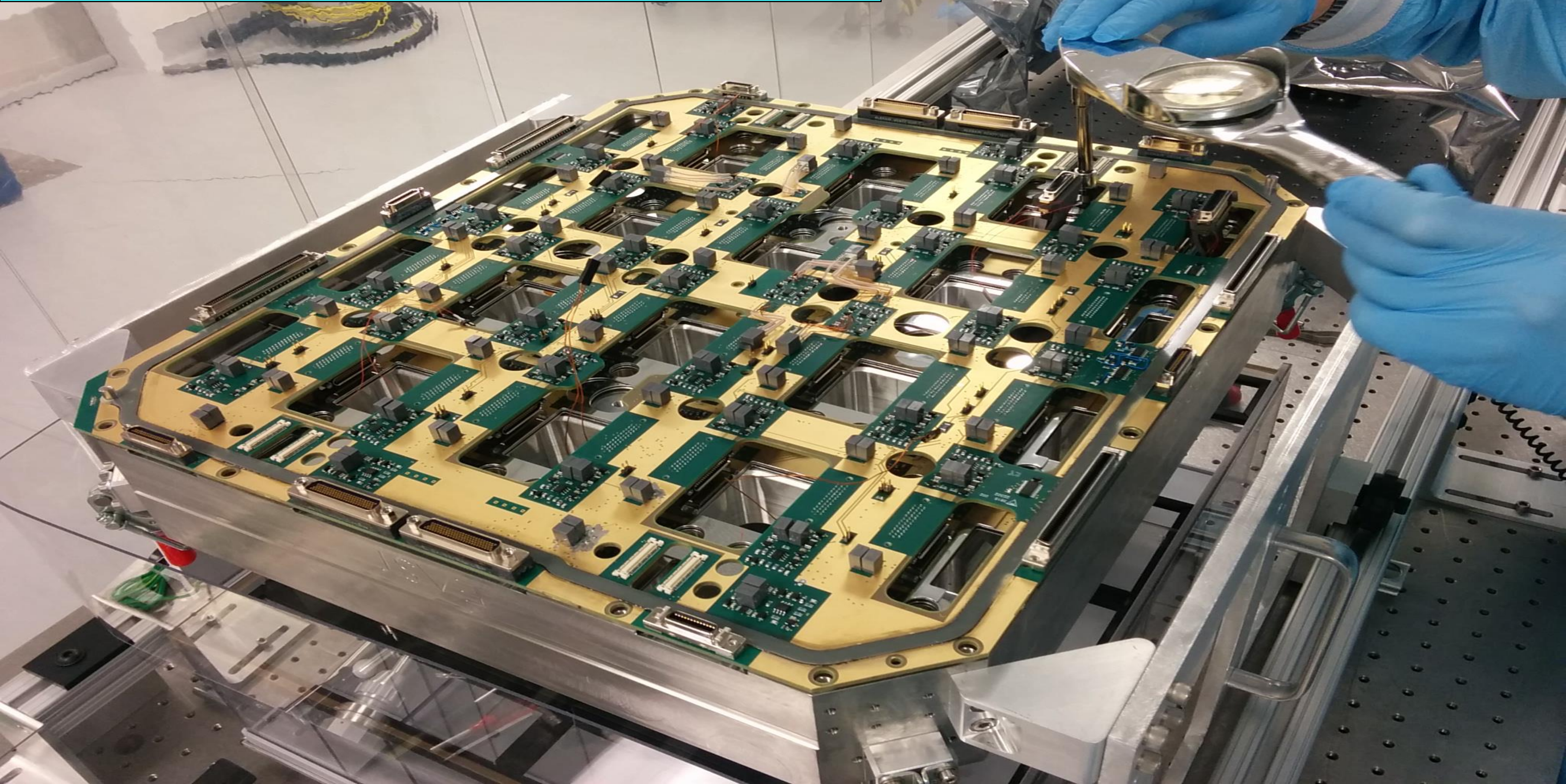
Walls, connectors hidden by beam expansion

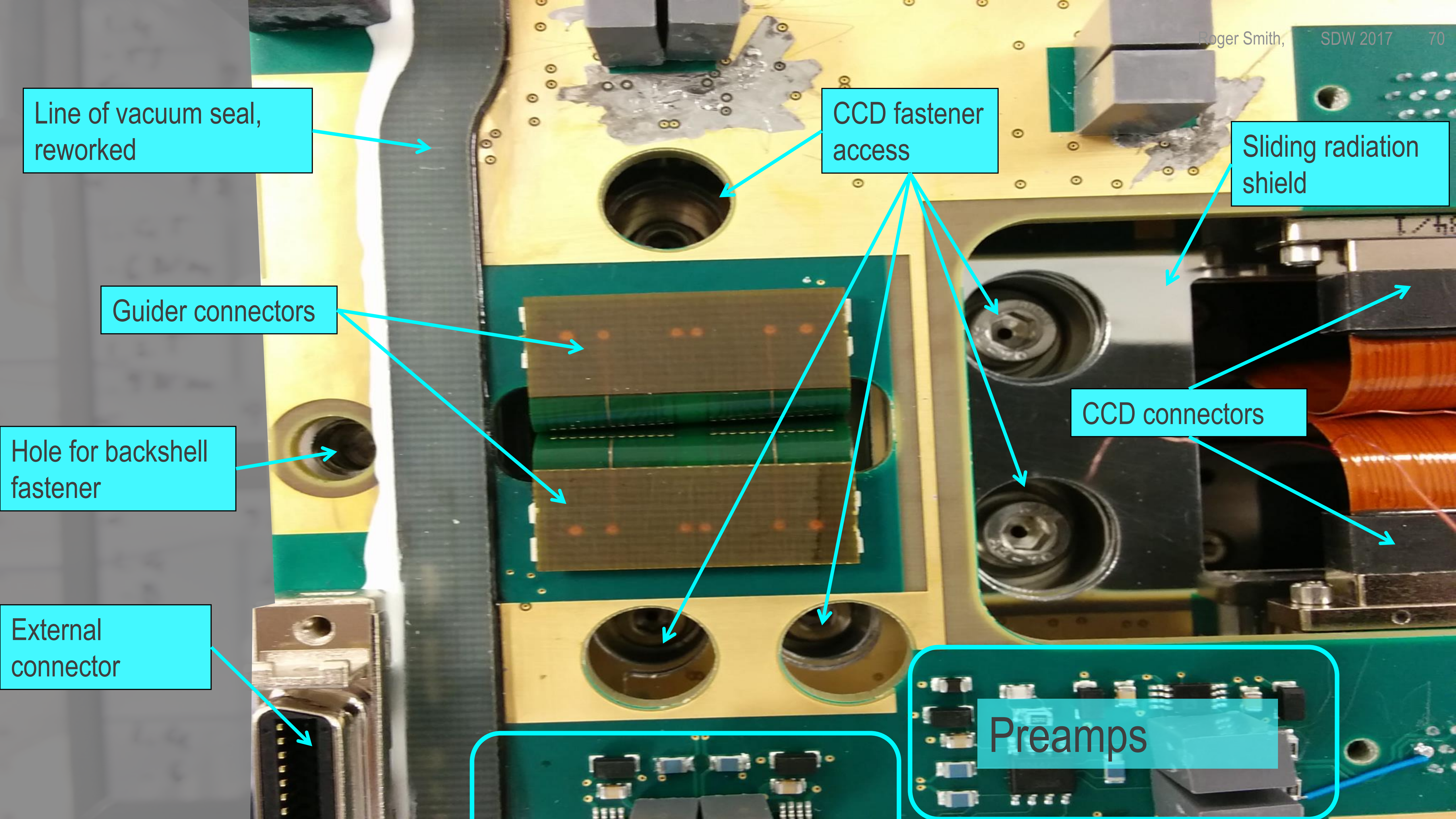


VIB is trapped between two O-rings



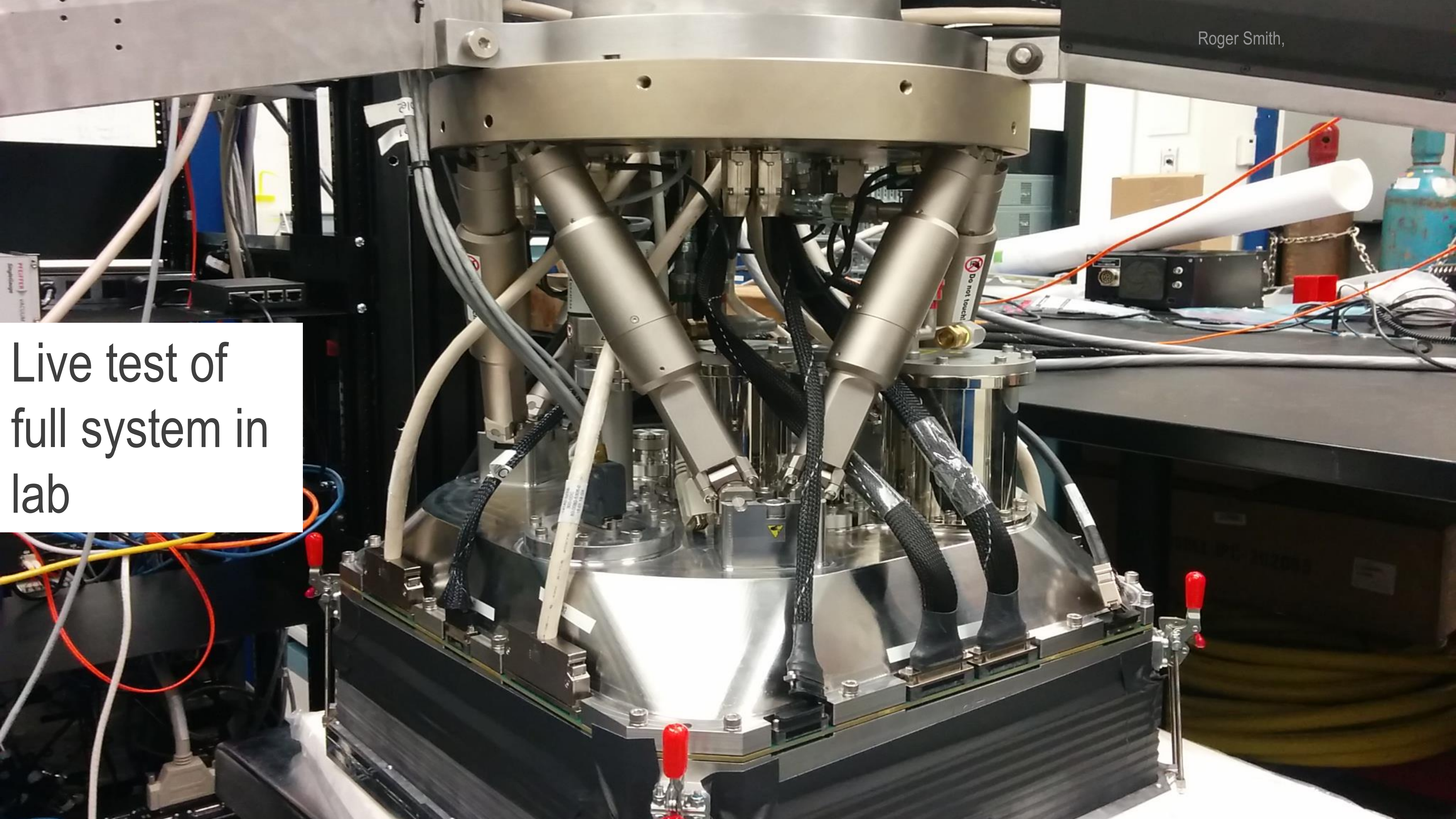
Vacuum Interface Board is heart of ZTF: Makes it so compact, while providing independent access to each CCD




Line of vacuum seal, reworked
CCD fastener access
Sliding radiation shield
Guider connectors
CCD connectors
Hole for backshell fastener
External connector
Preamps

Roger Smith,

Live test of full system in lab



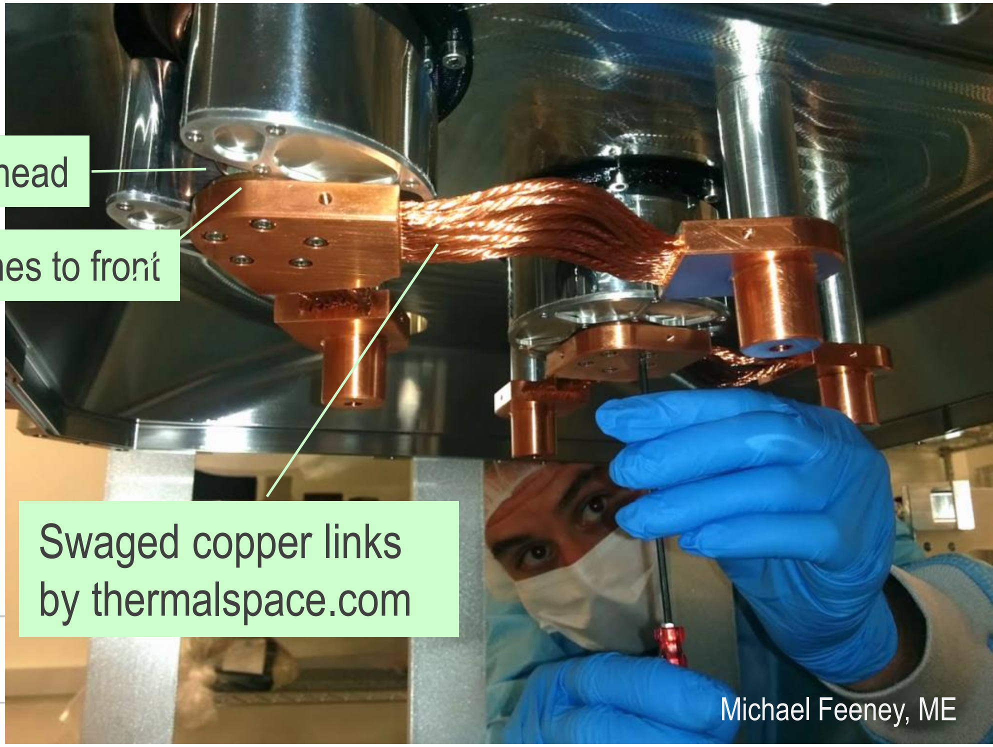
Thermal Management

Refrigeration

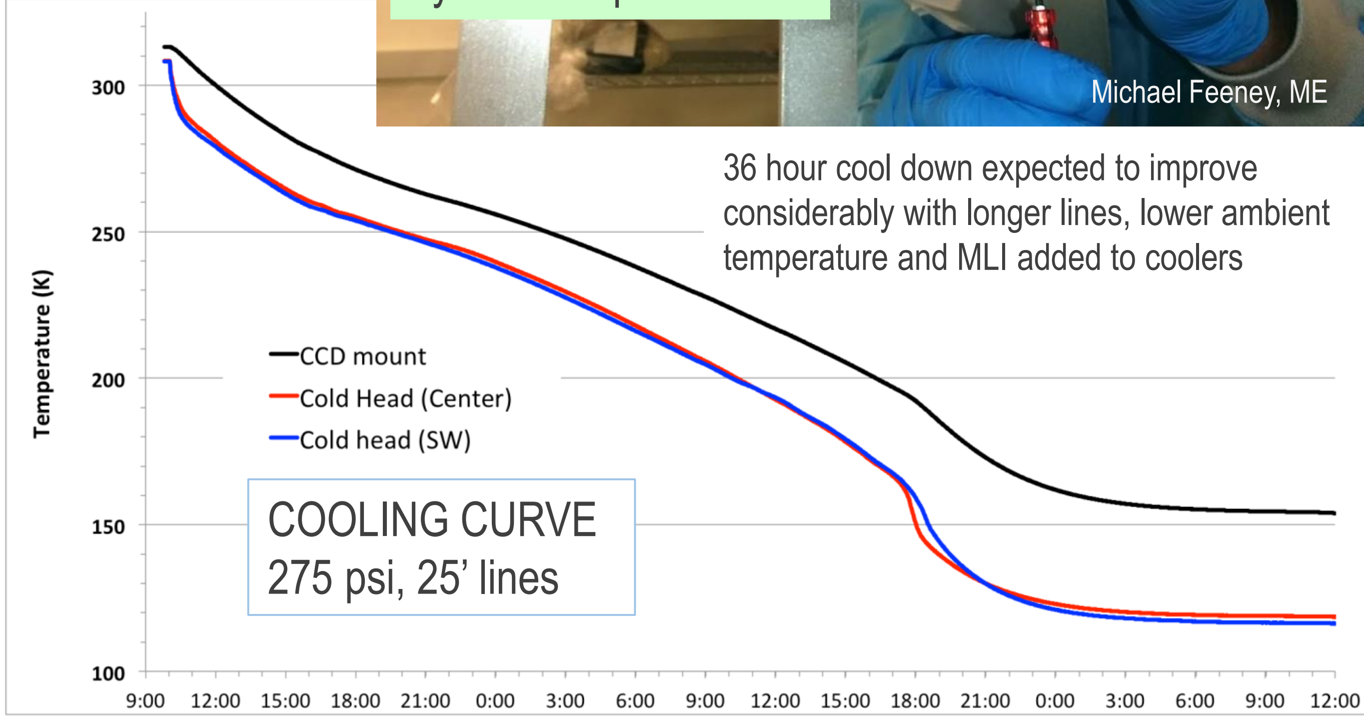
- Radiation from large window dominates

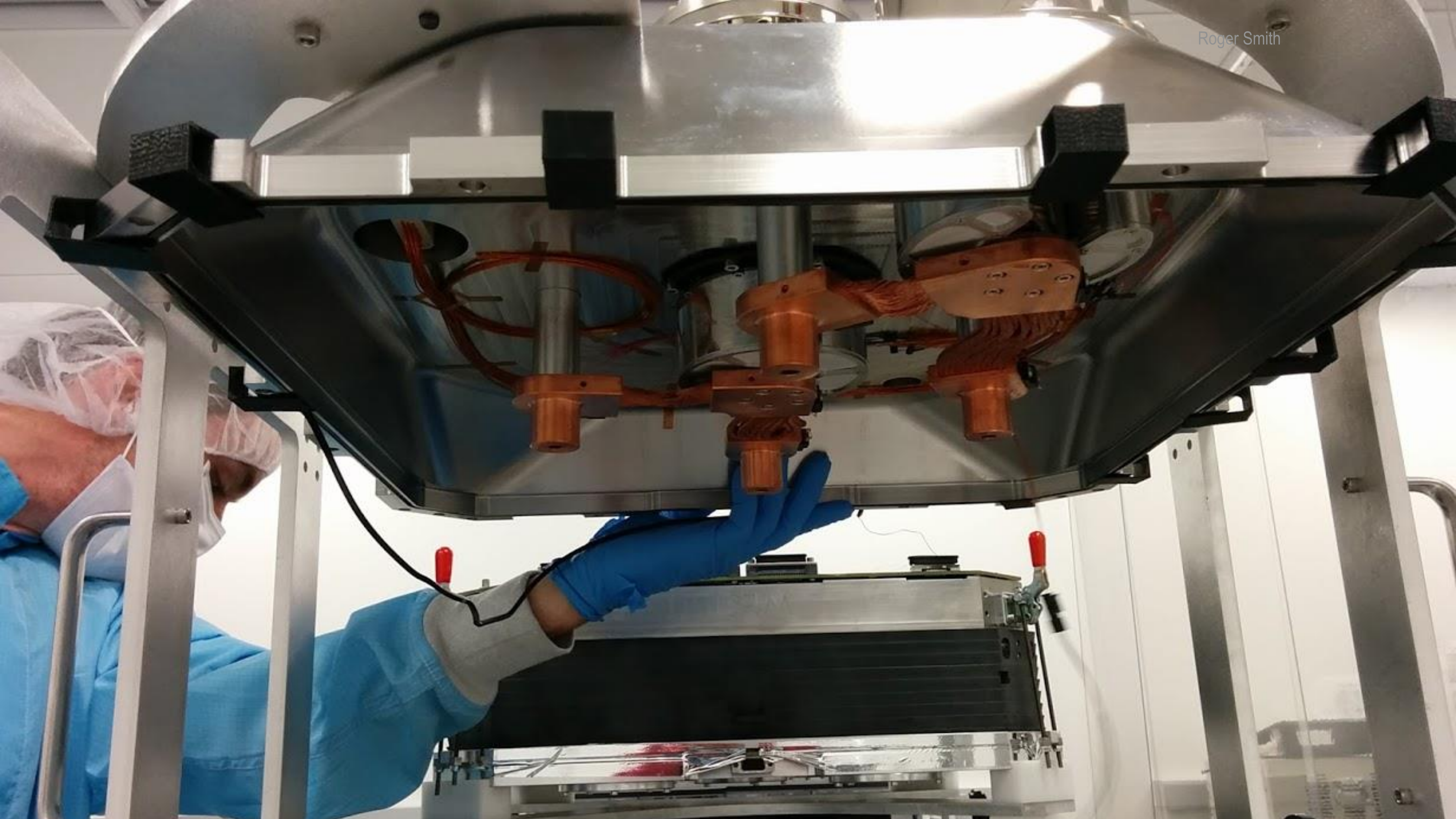
→ Halved by thermally isolating flattener lenses

- 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.



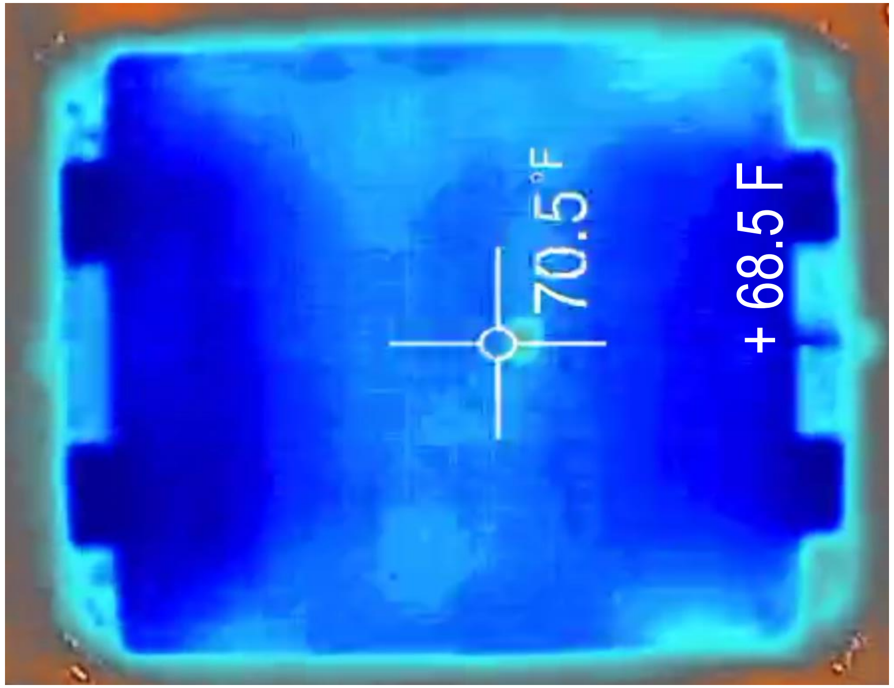
Radiation	Window-CCD	29 W	Field flattener lenses act as floating shield
Radation	Window-gaps	5 W	
Radiation	Back and sides	2.6 W	Bare Aluminum shields, mirror polish
Dissipation	CCD output amps	4 W	5K loads, signal & ref
Dissipation	CCD clocking	1.5 W	Electrode resistance
Dissipation	CCD Heater	3W	
Conduction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




Roger Smith

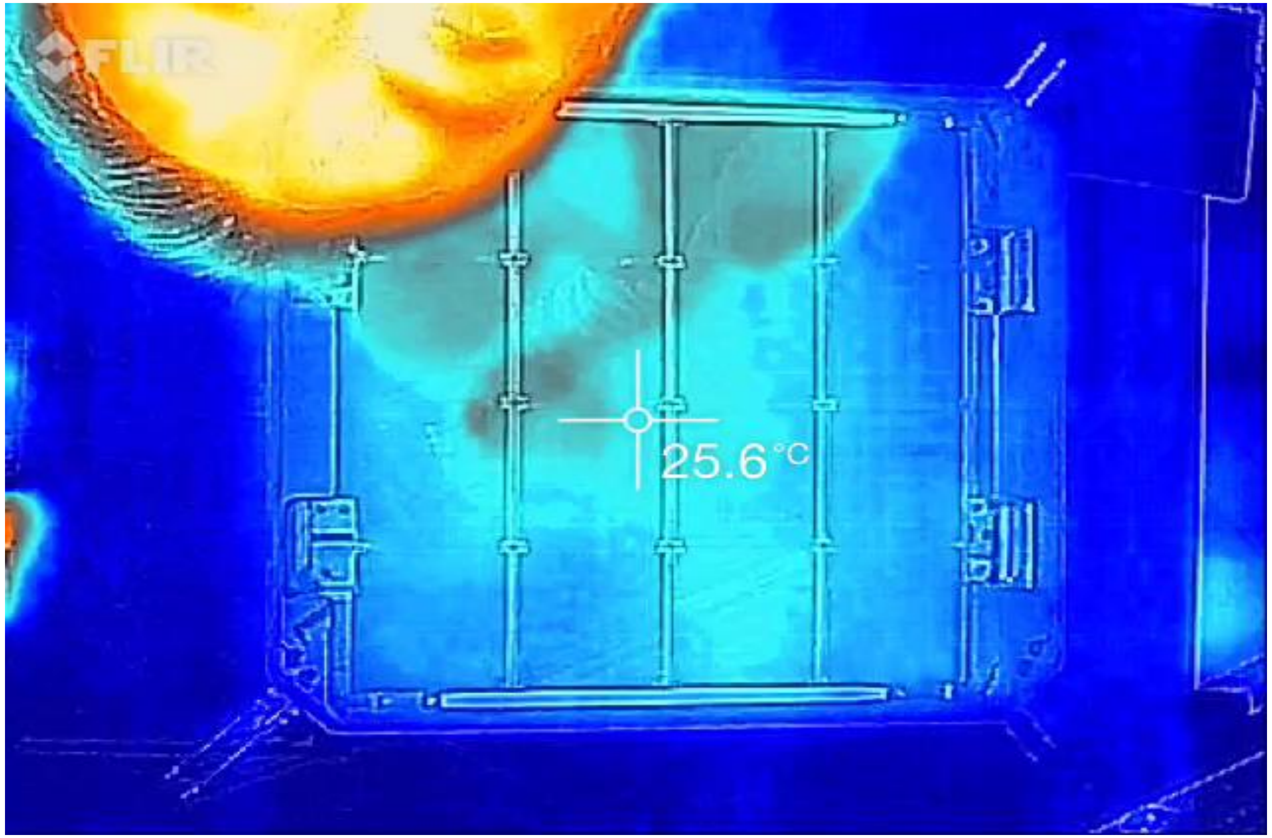
ITO window heater

CCDs cold, ~20W heat



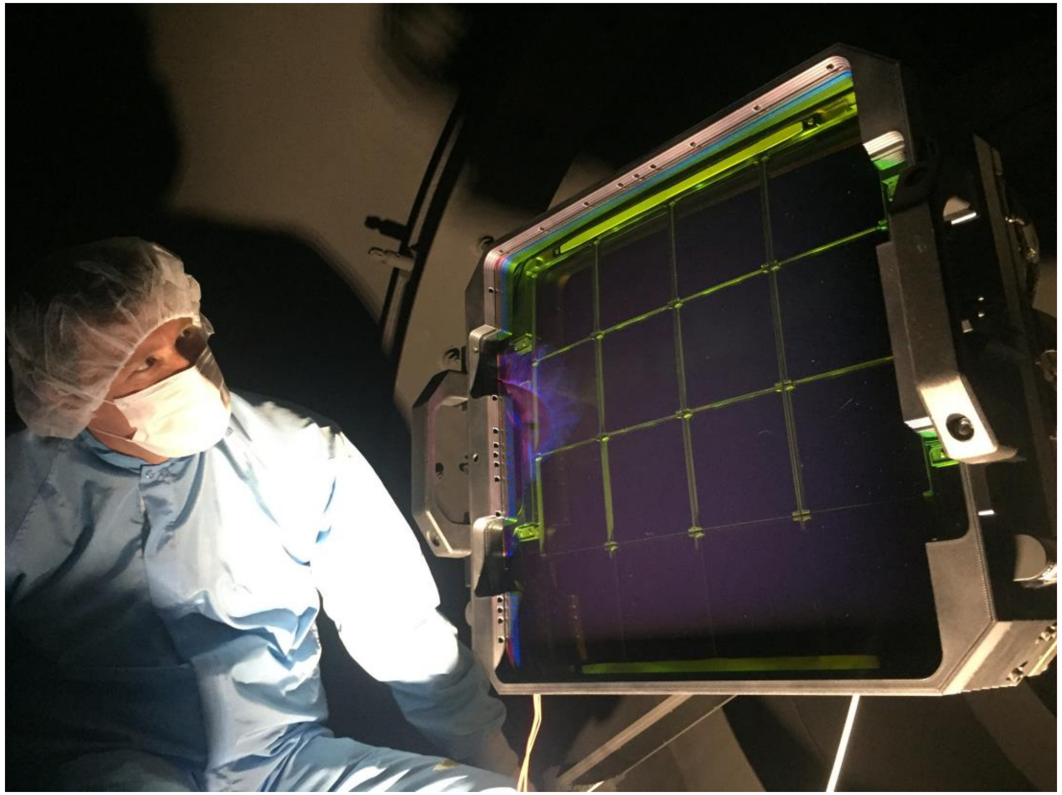
Only 1 C gradient,
Power as expected

CCDs warm



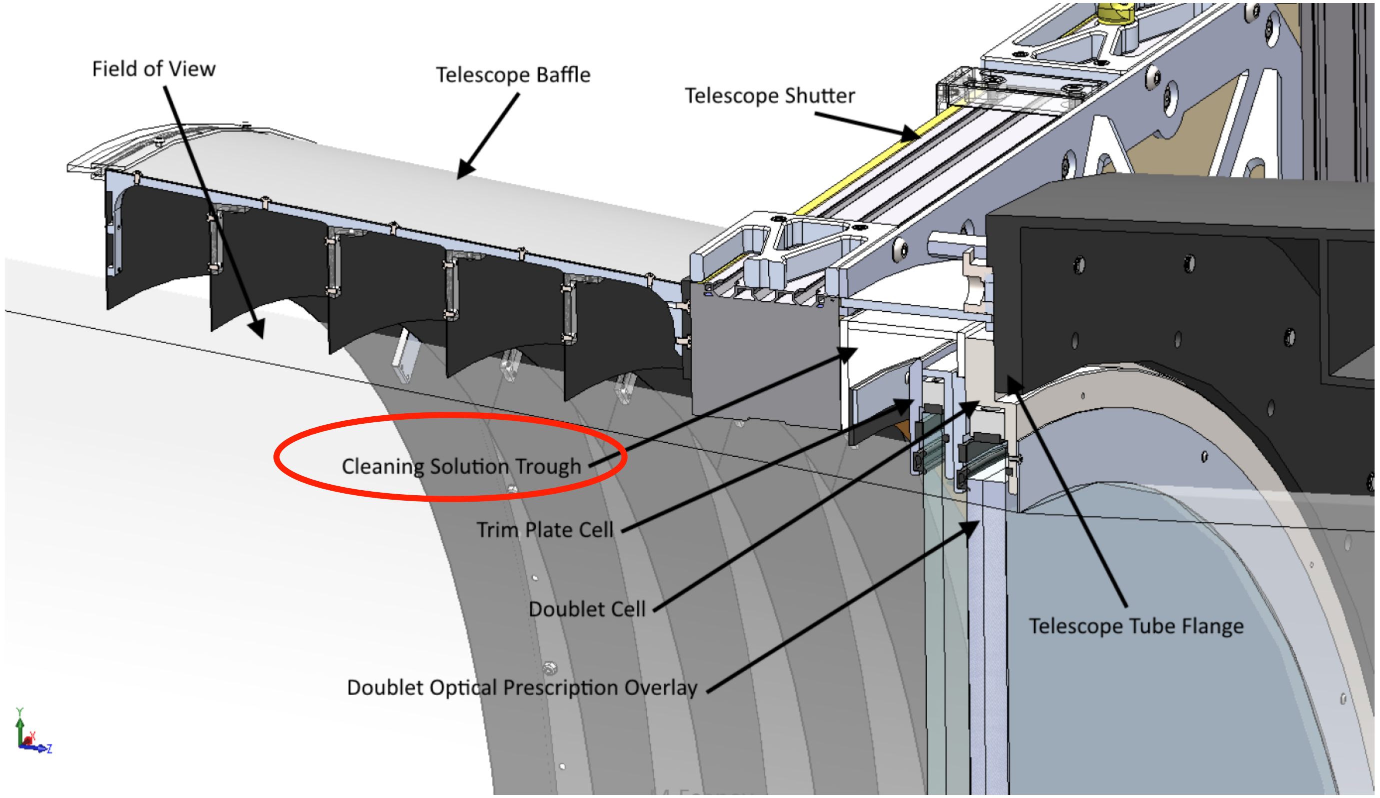
Scattering (clean optics)

- Closed telescope tube treated as clean room



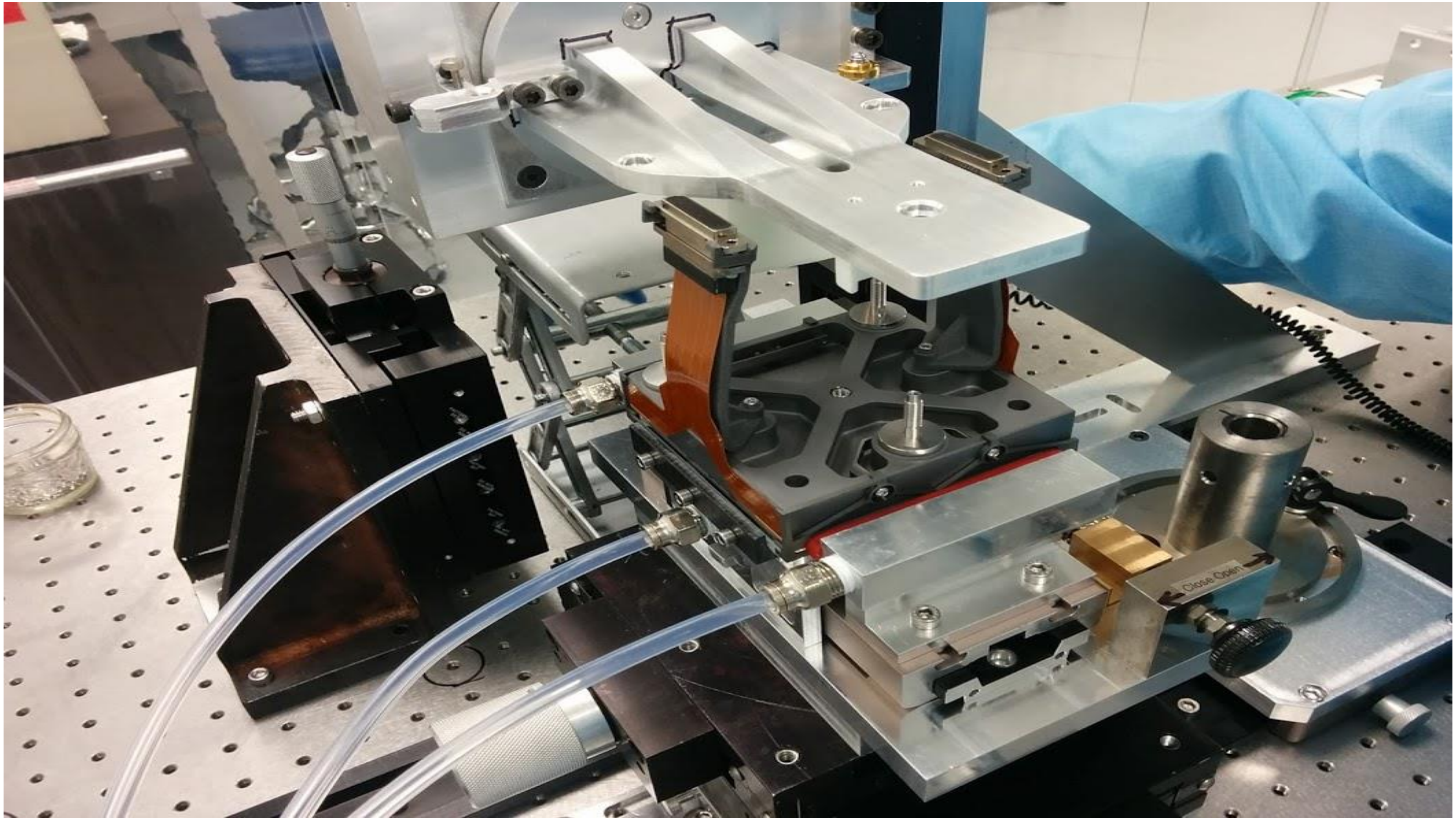
Tube painted with Avian Black (3% reflective)

- Trim plate cell design supports washing with plentiful solvent



Assembly story boards

Field flattener installation on CCD



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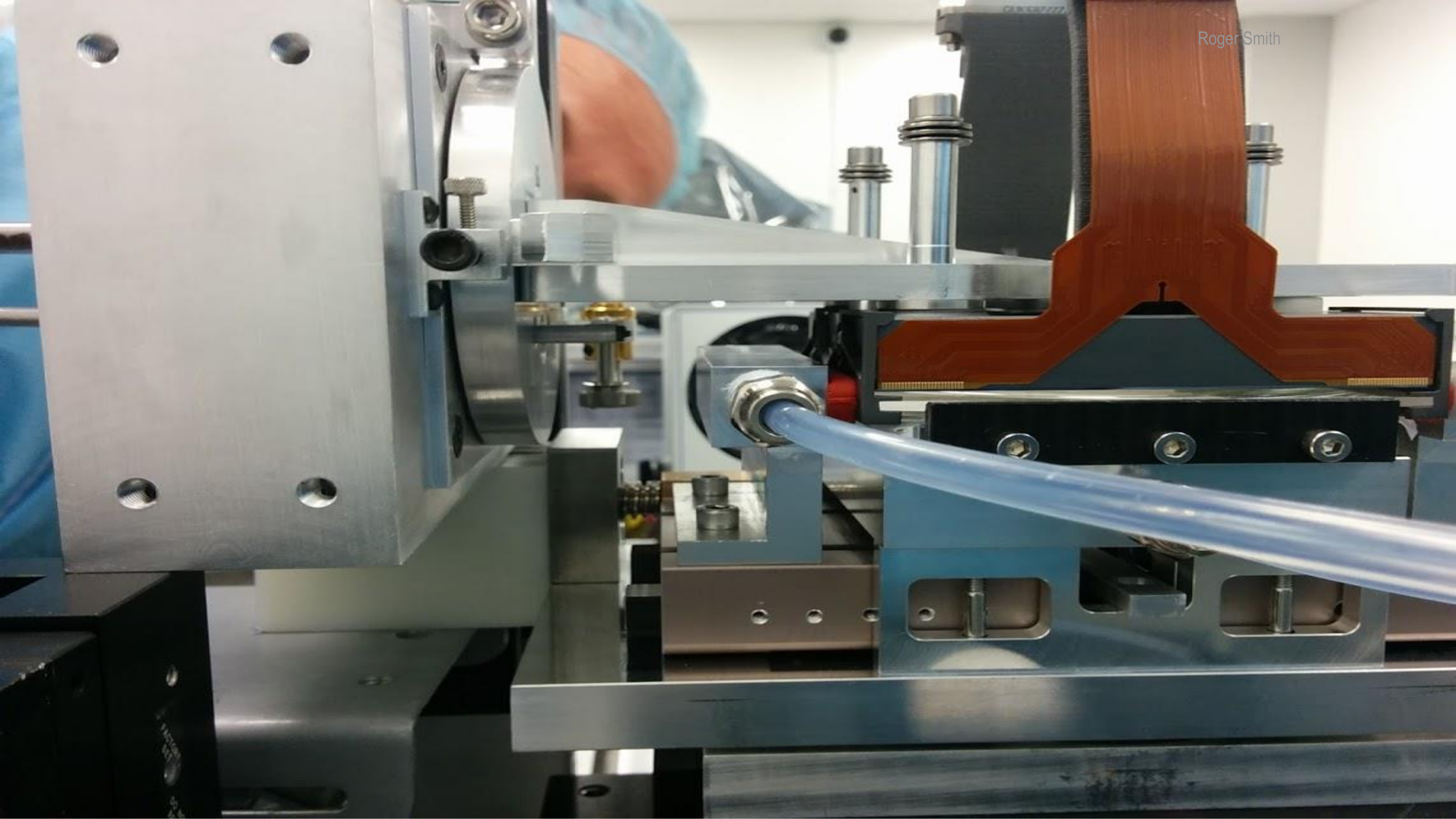
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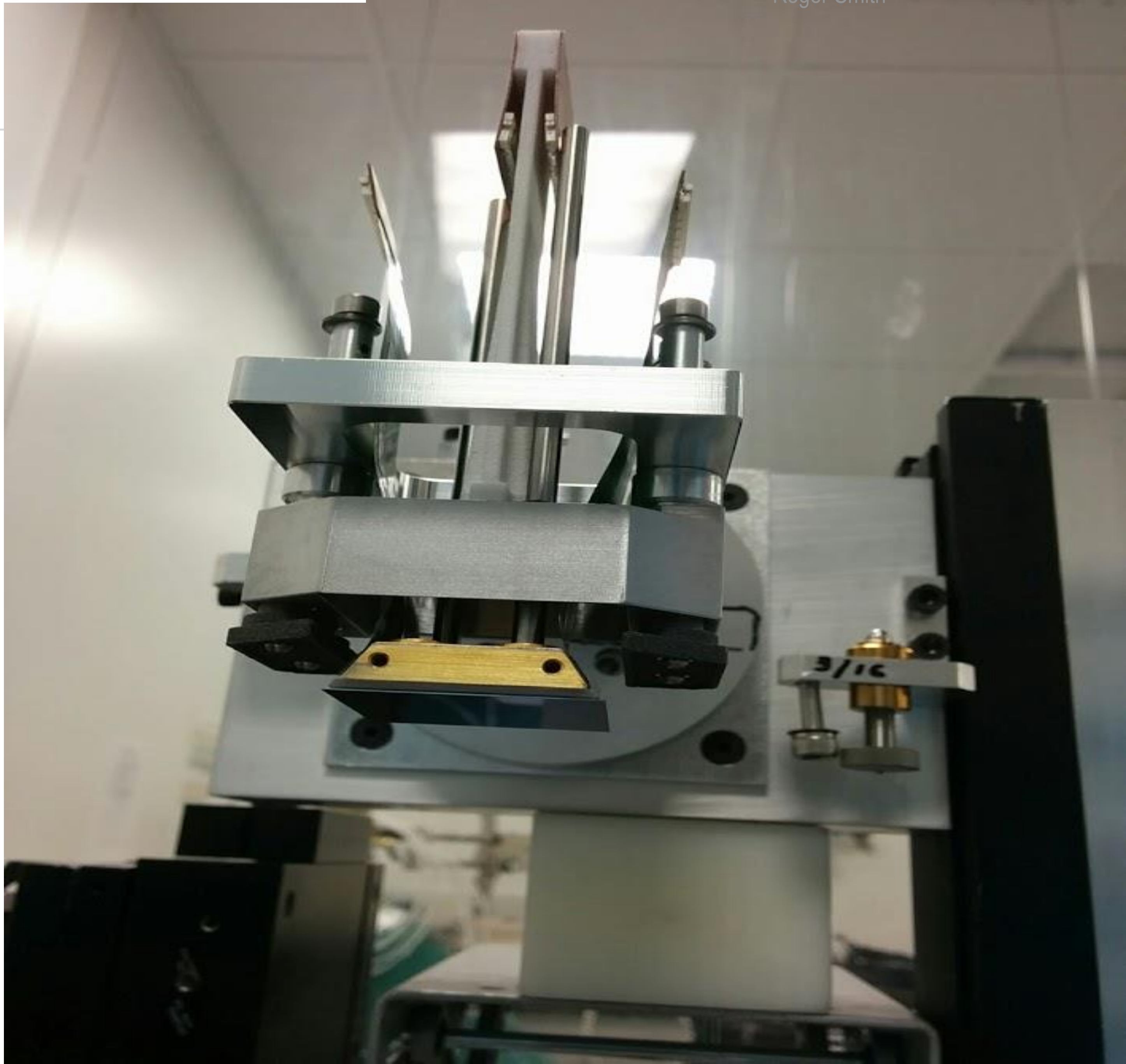
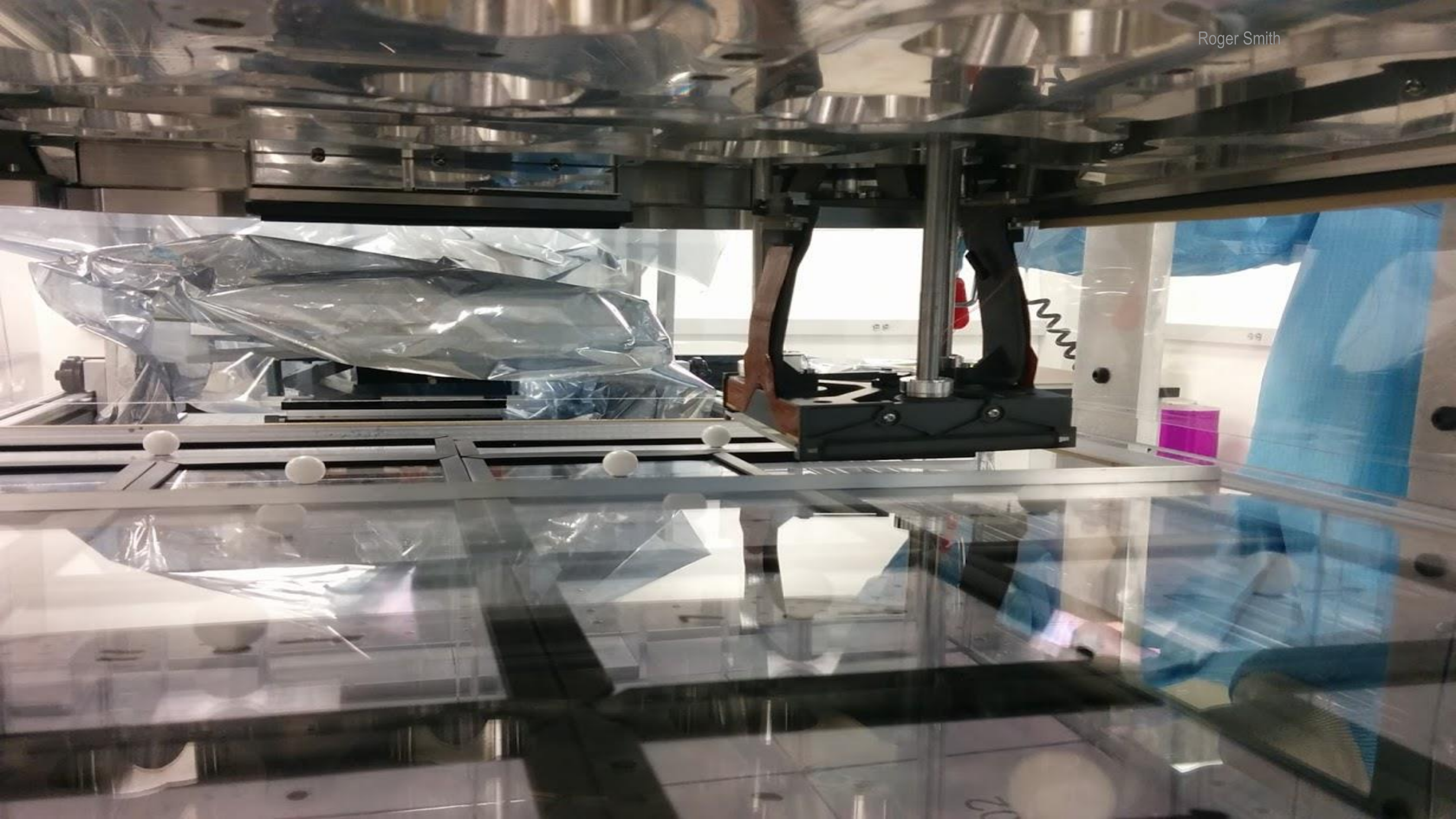
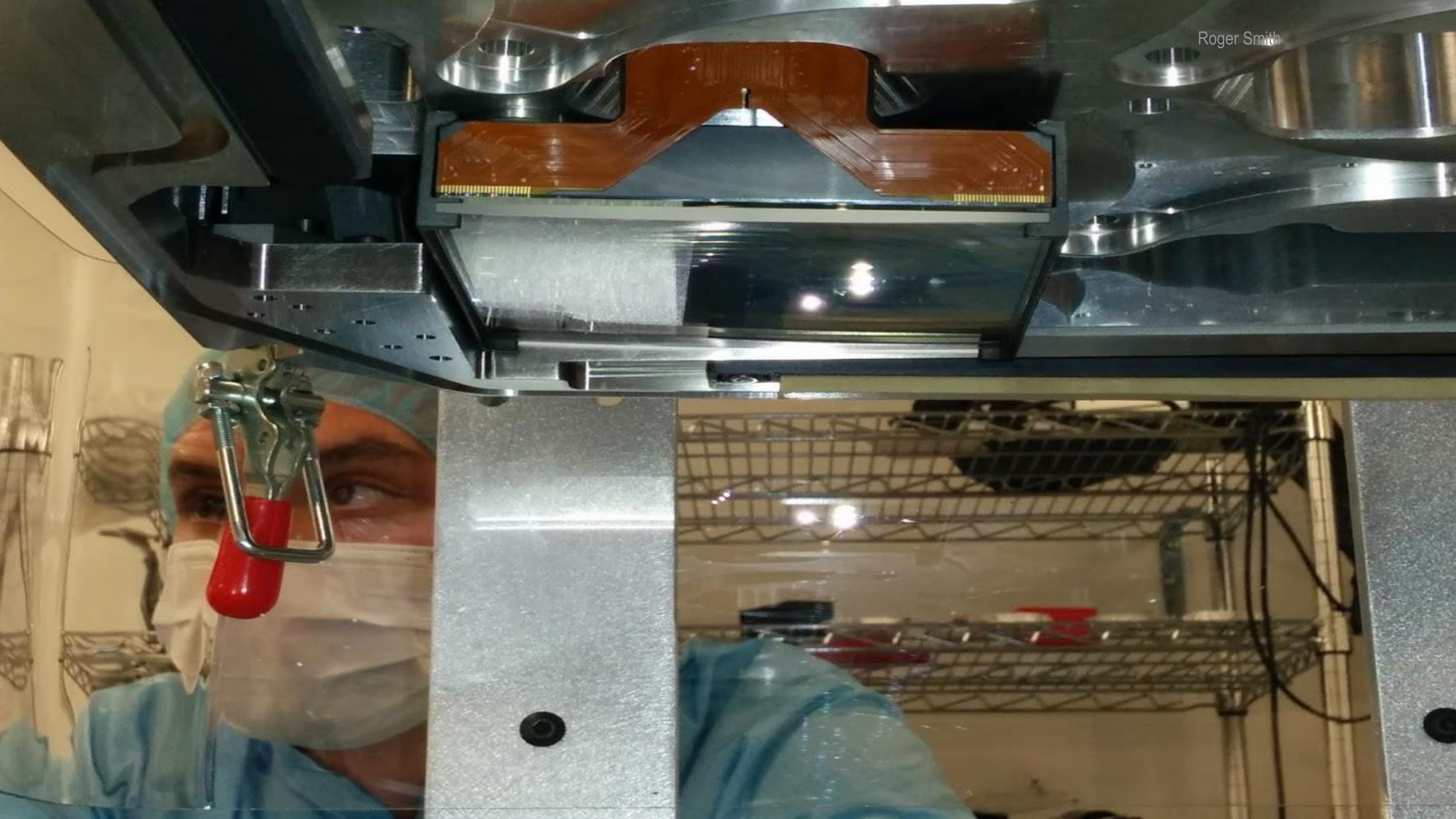
Guider part way into its housing




Roger Smith

Roger Smith





Roger Smith

Making CCDs Parfocal