

Precision Astrophysics with JWST and TOLIMAN space telescopes

Prof Peter Tuthill
University of Sydney



nature astronomy

The fingerprints of mass-loss

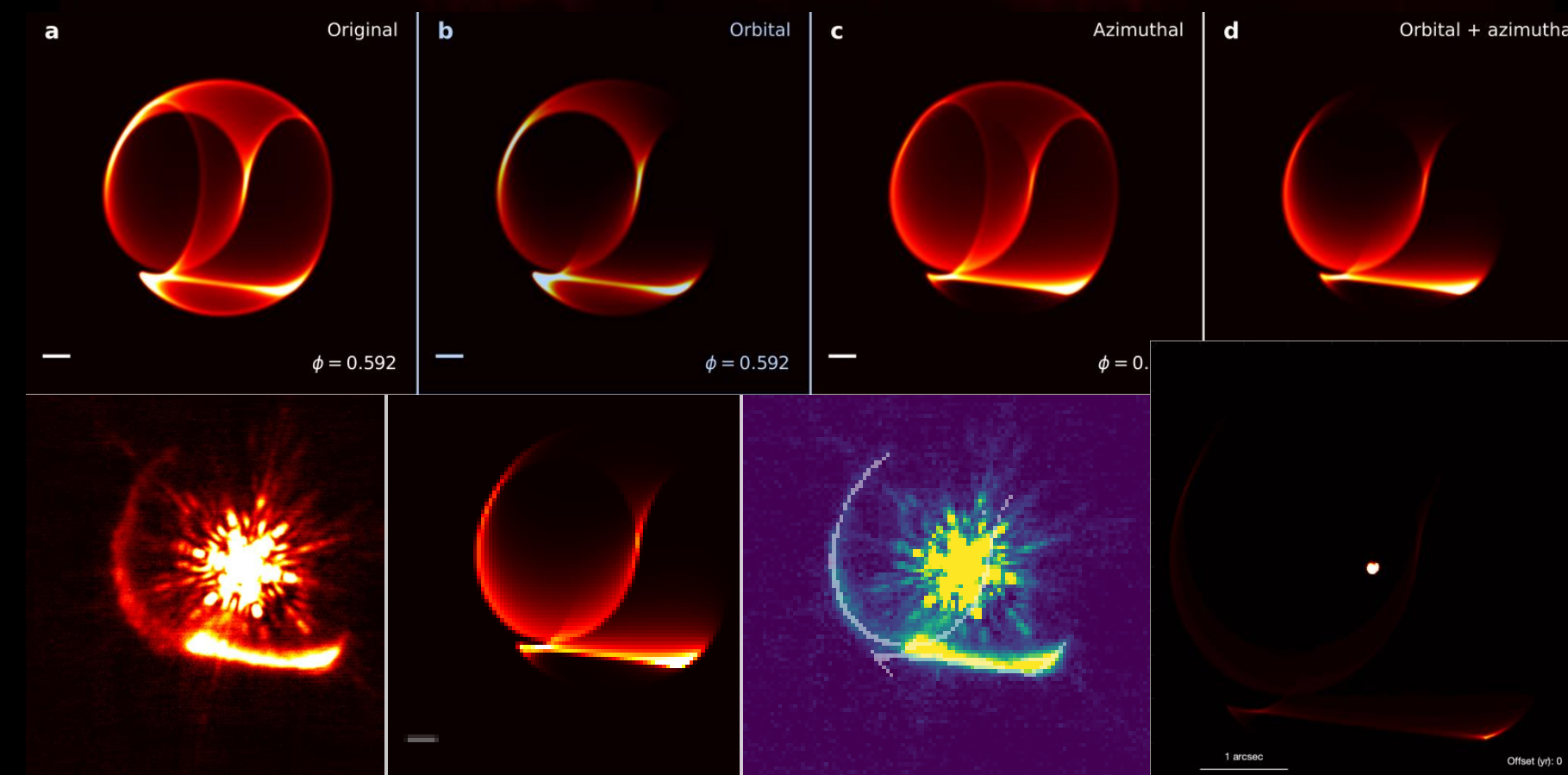
Lau et al NatAst 2022

nature

A PUSH FROM LIGHT

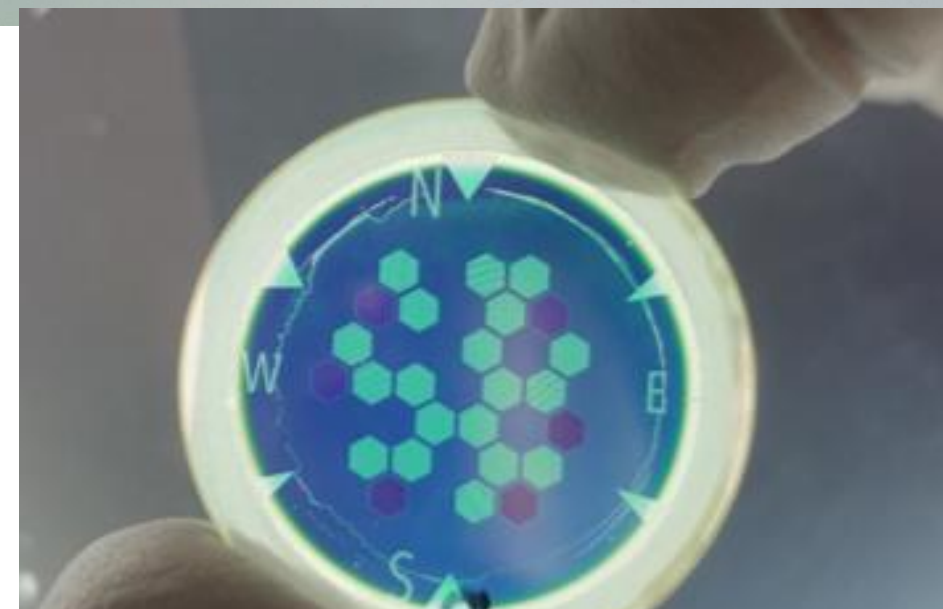
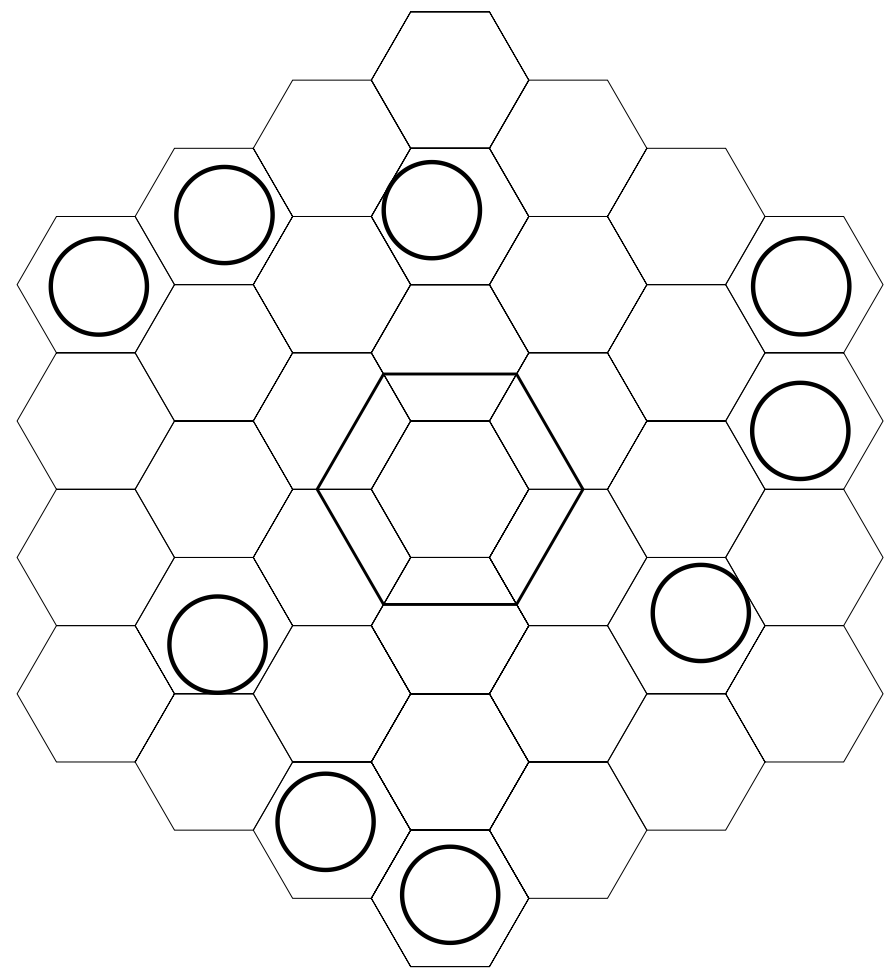
Expansion of dust shell harvests momentum from starlight.

Han, Tuthill et al Nature 2022

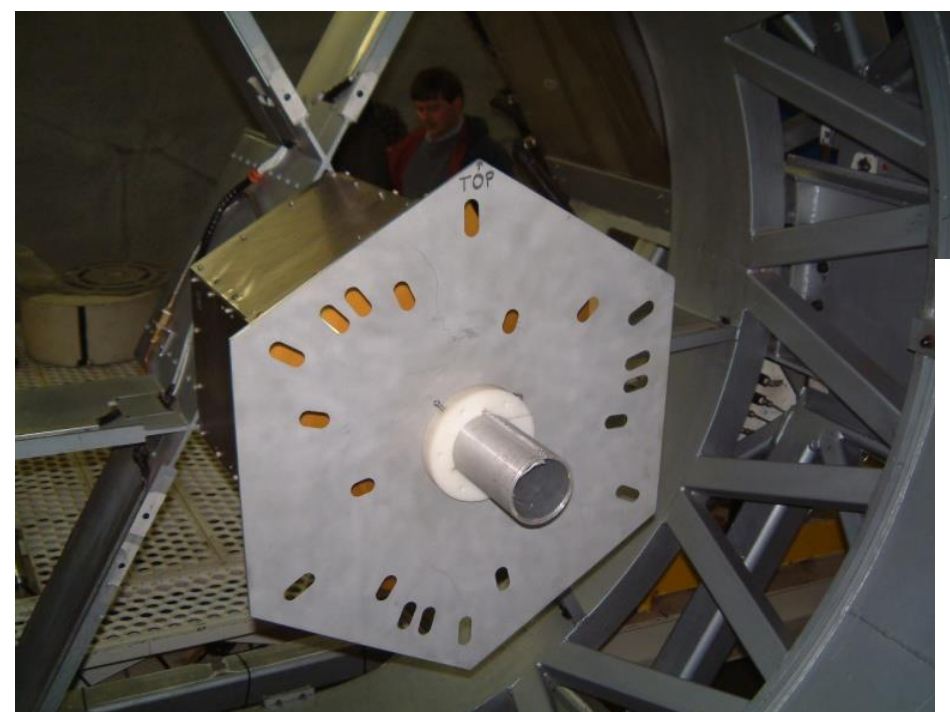
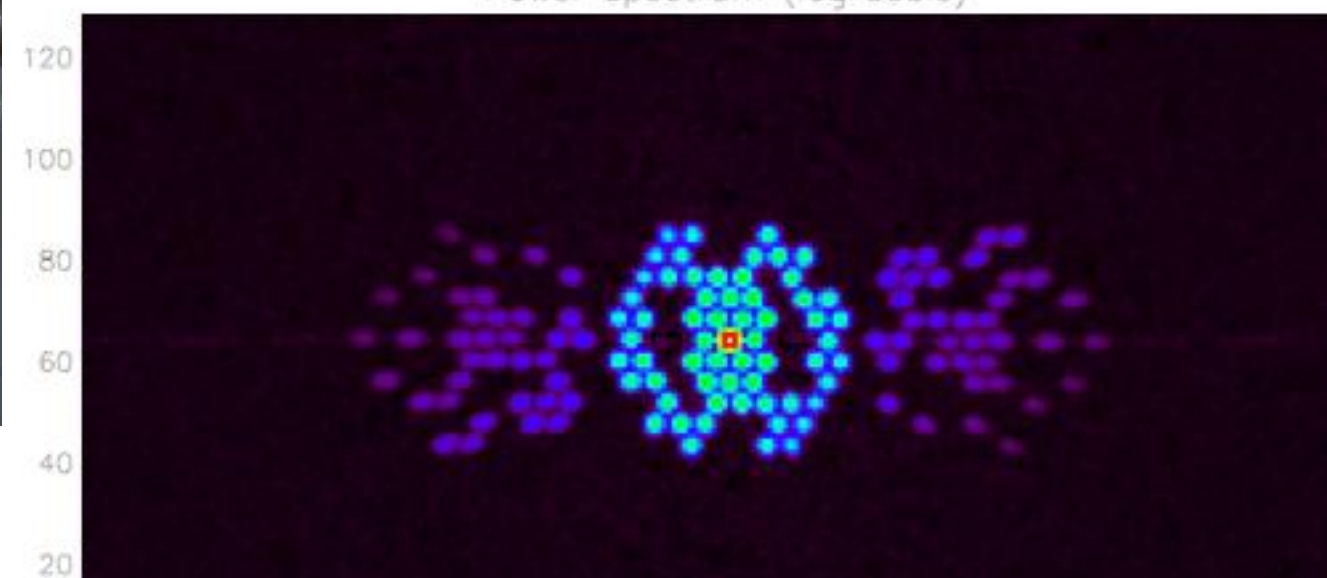


Firstly, start with leading edge, physically principled approaches...

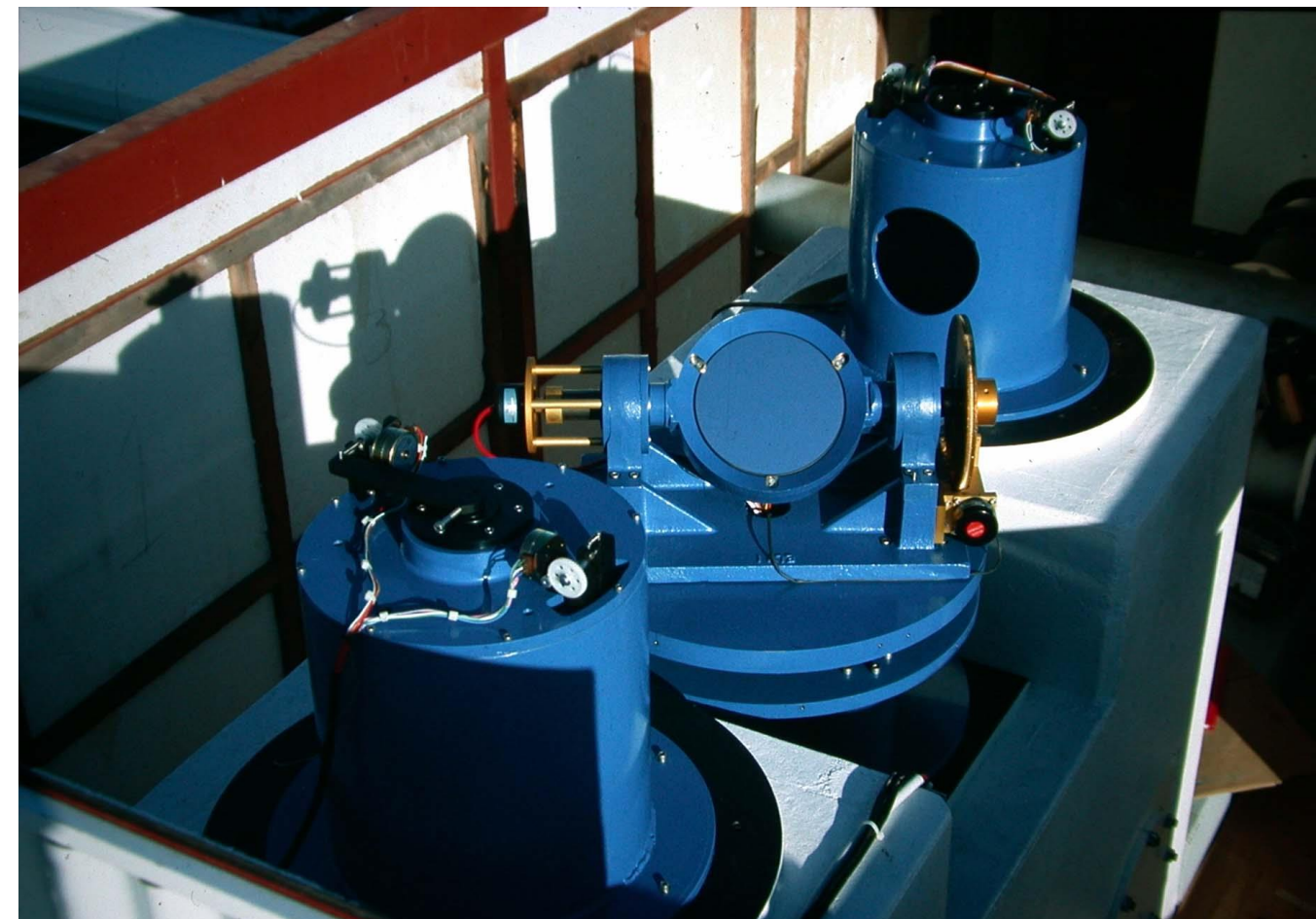
Sparse Aperture Interferometry



Power spectrum (log scale)



Long Baseline Interferometry



Lkha 101

IRC +10216

WR 104

WR 98a

WR 140

Mira A&B

WR140
1999 Jul

MWC 349a

WR 112

GCS4

GCS 3-2

CIT 6

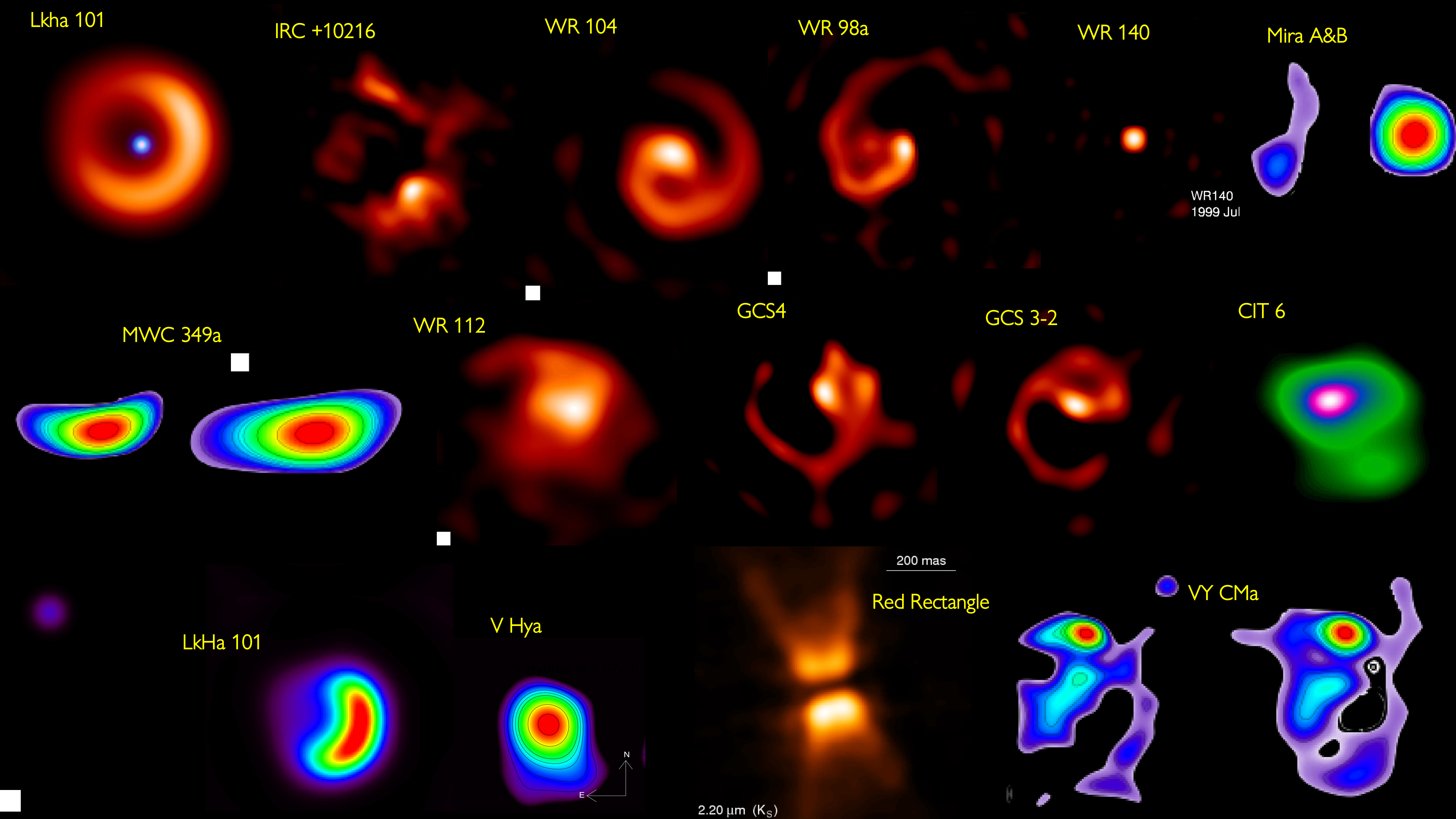
LkHa 101

V Hya

Red Rectangle

VY CMa

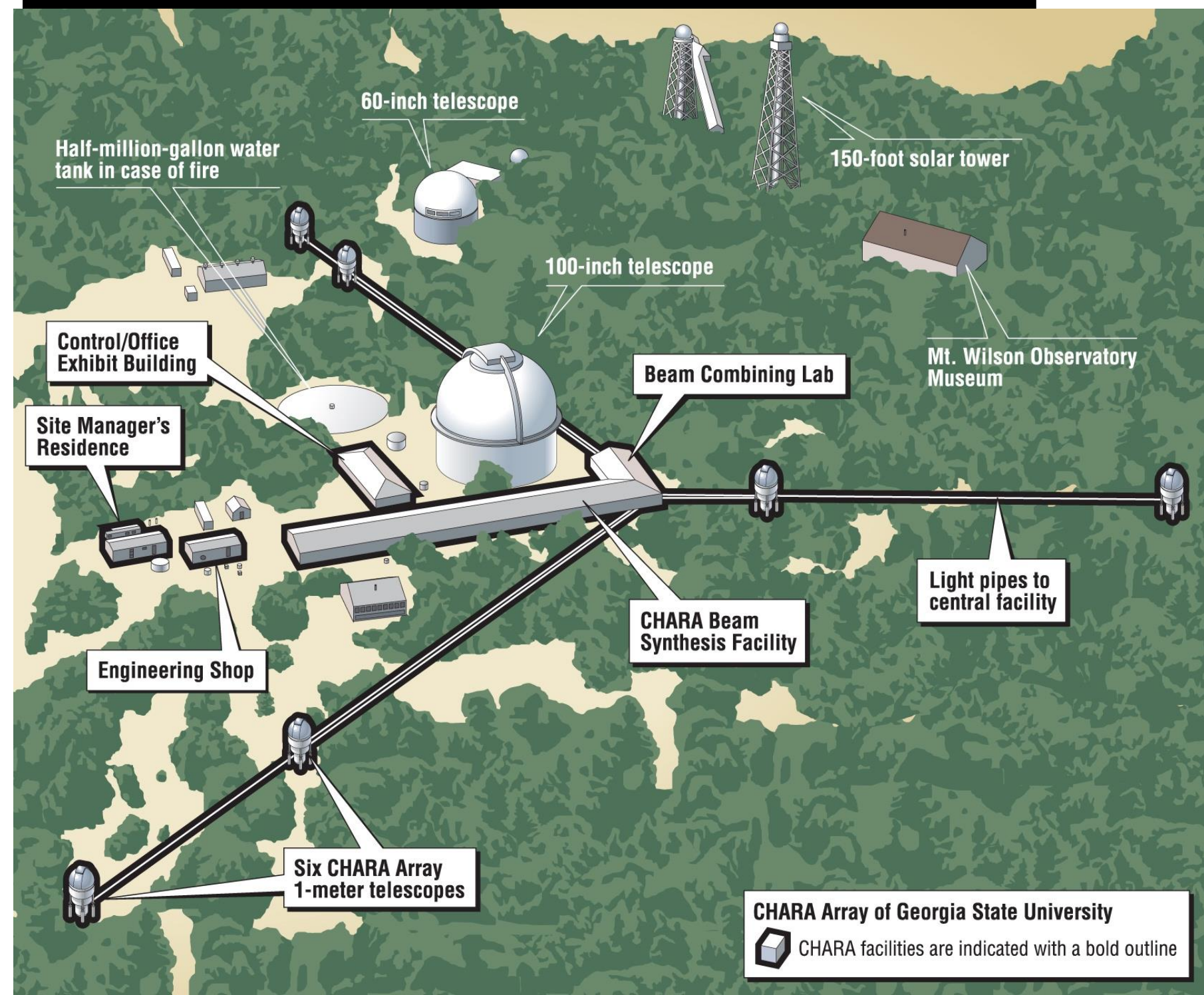
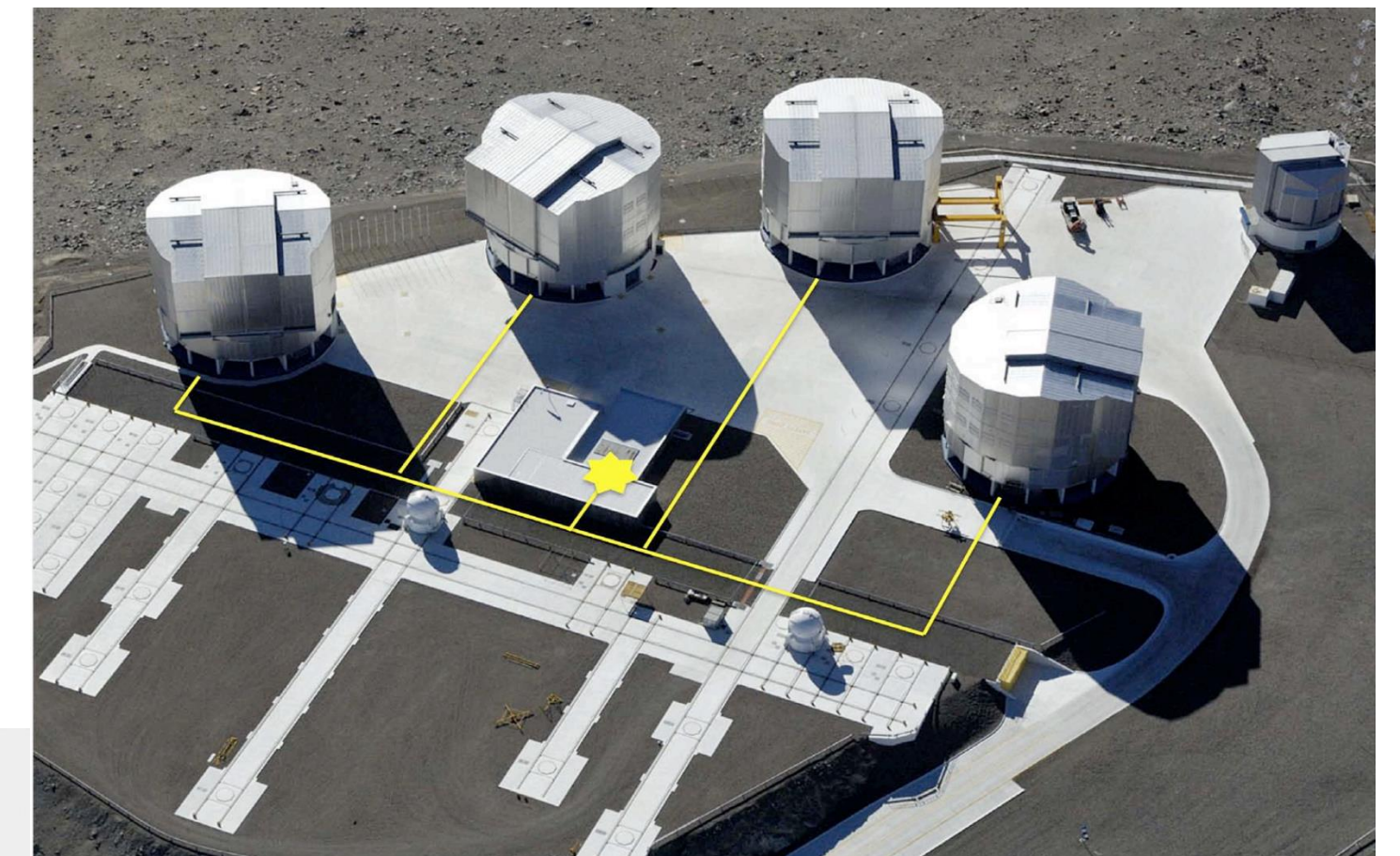
2.20 μm (K_S)



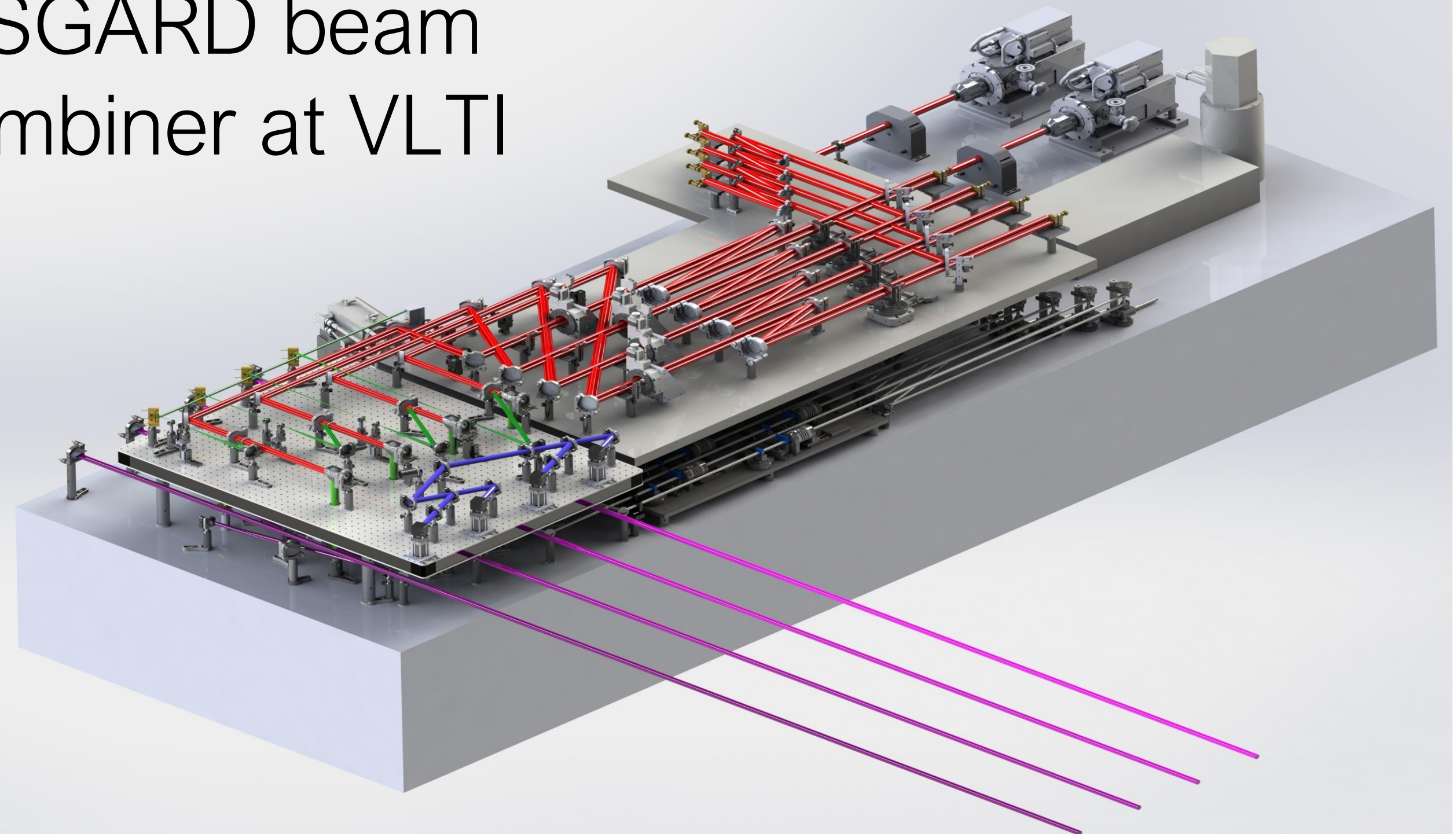
... and this can take you places.



SILMARIL at CHARA

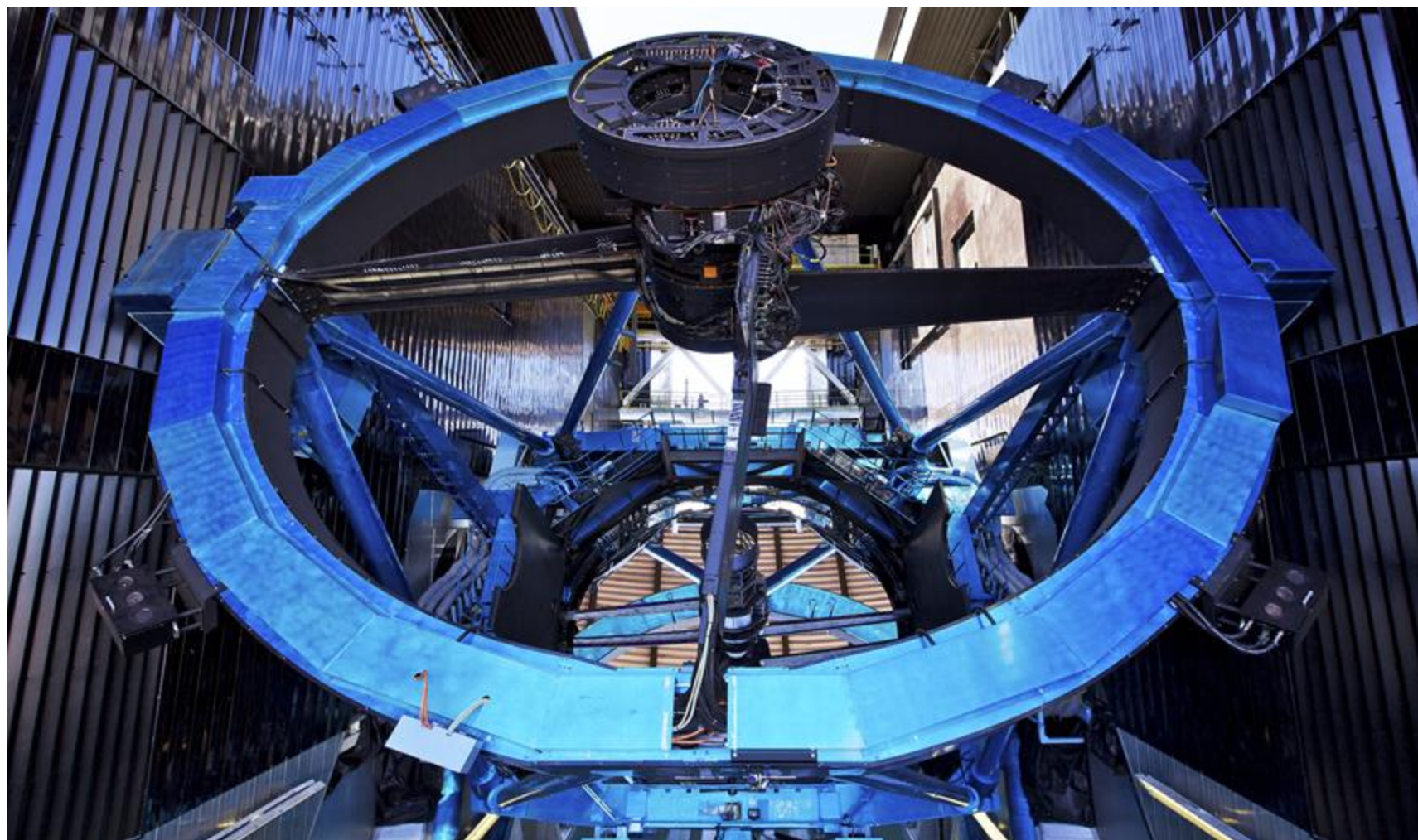
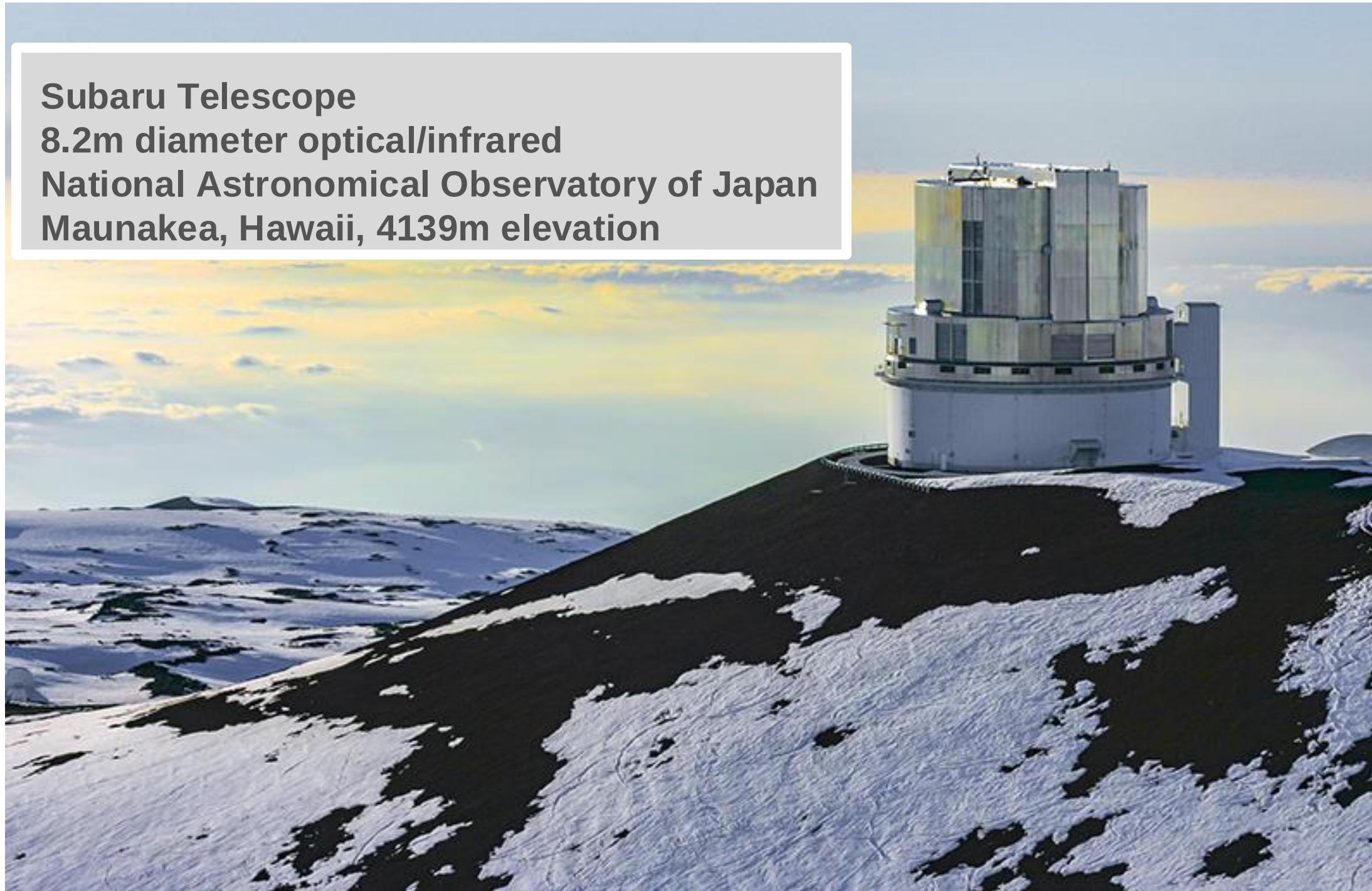


ASGARD beam combiner at VLT

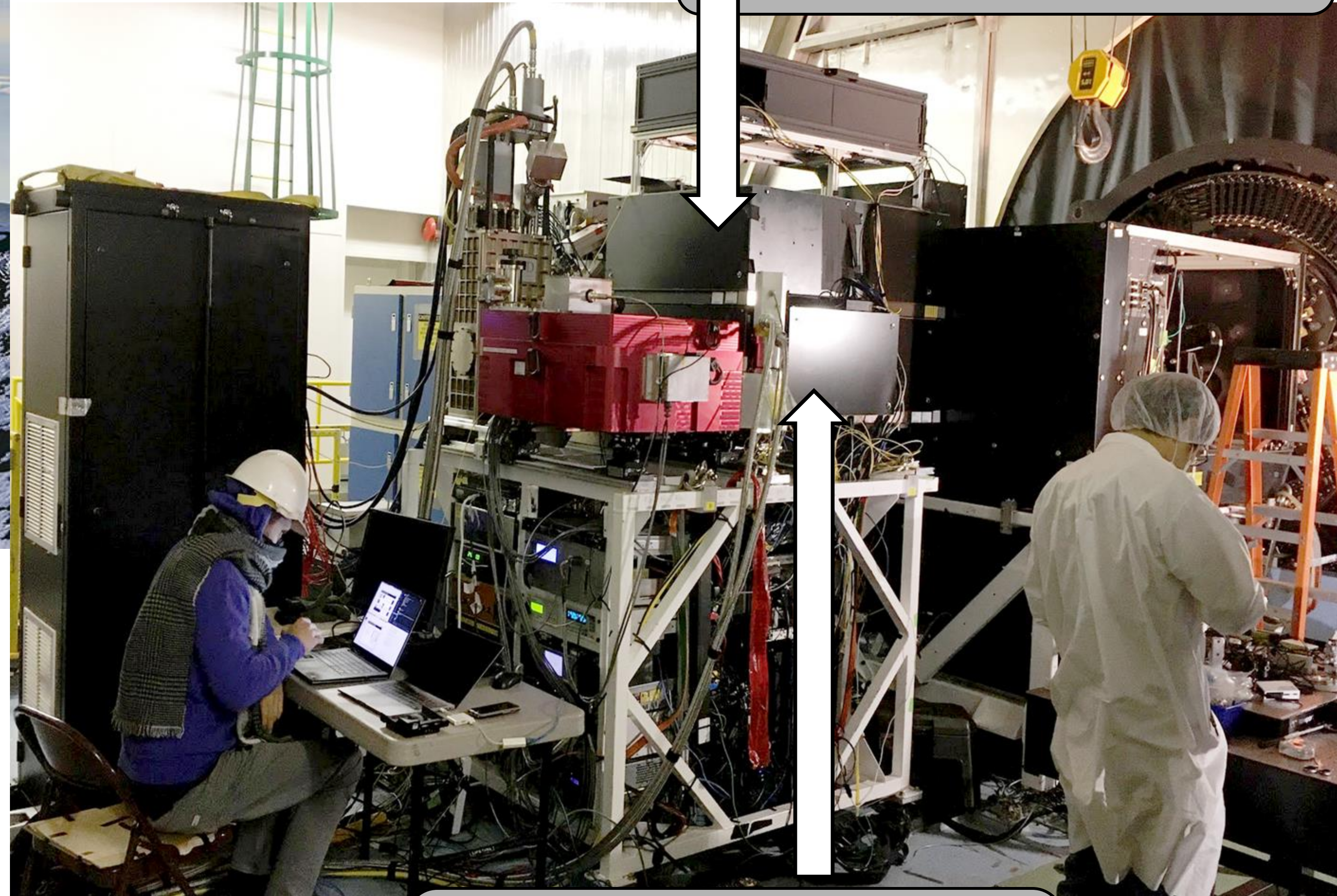


VAMPIRES and GLINT at Subaru telescope

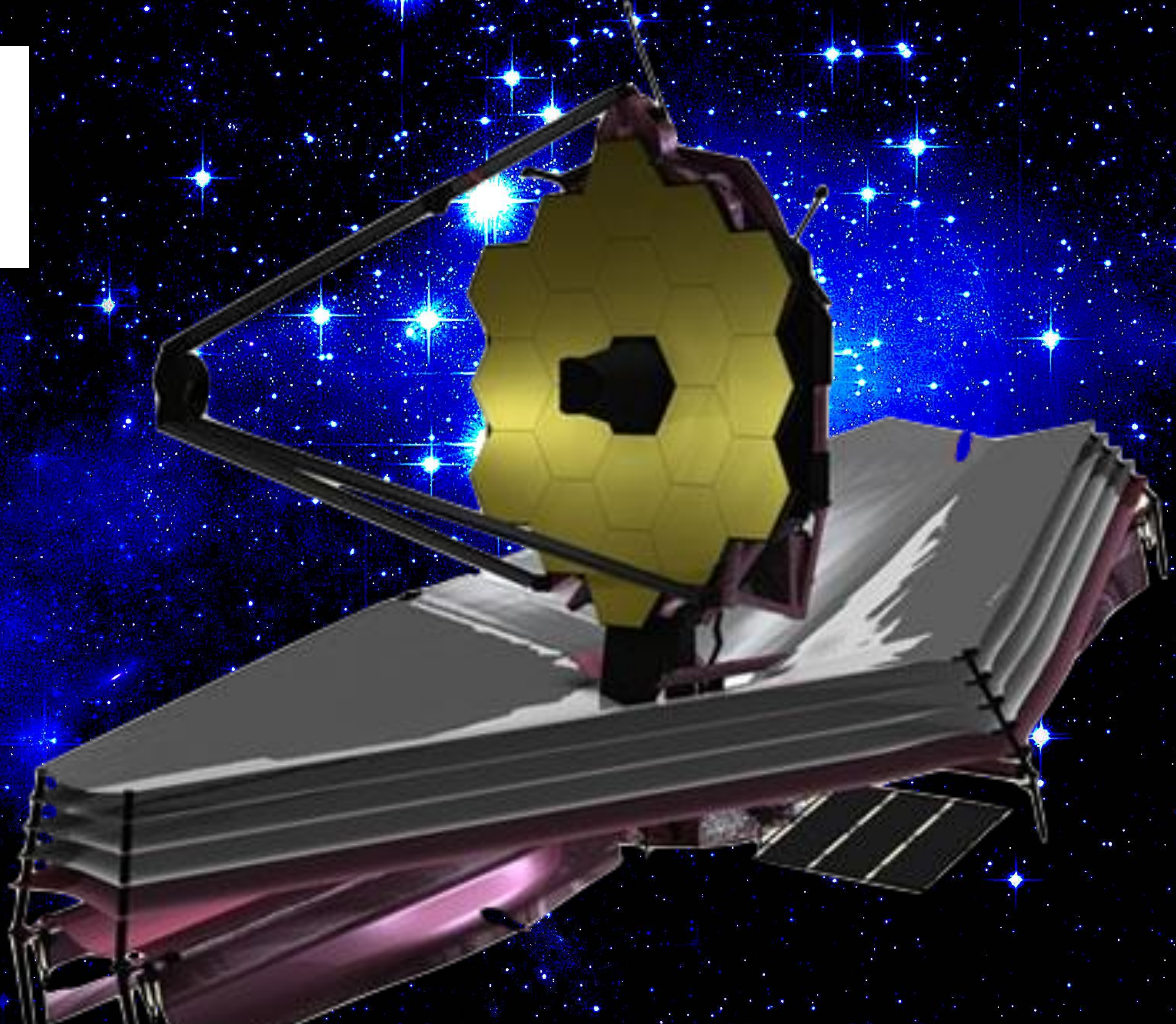
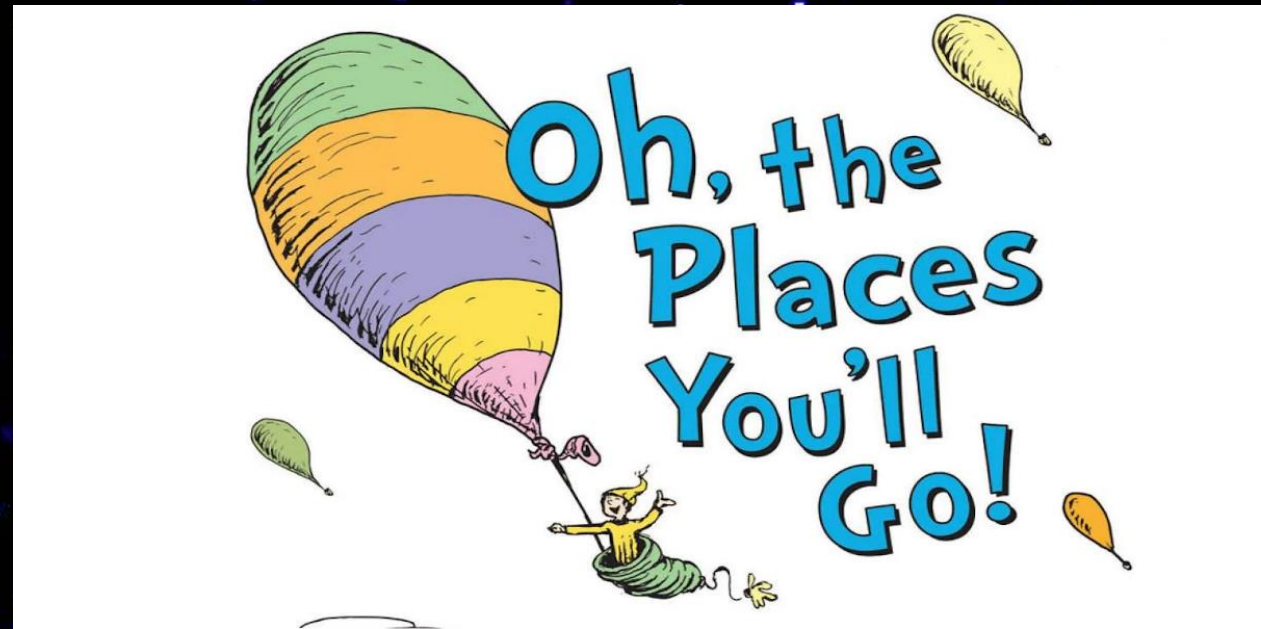
Subaru Telescope
8.2m diameter optical/infrared
National Astronomical Observatory of Japan
Maunakea, Hawaii, 4139m elevation



VAMPIRES (USyd)
Vis Imager

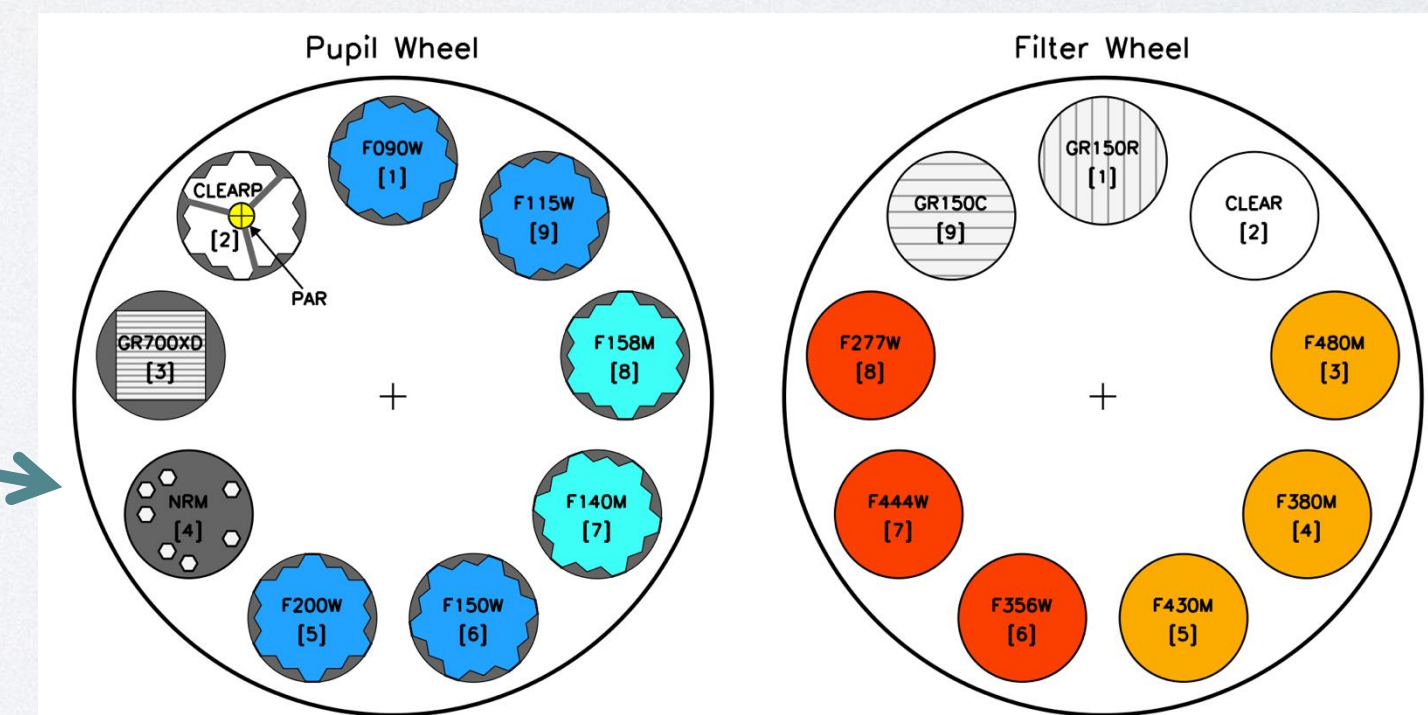
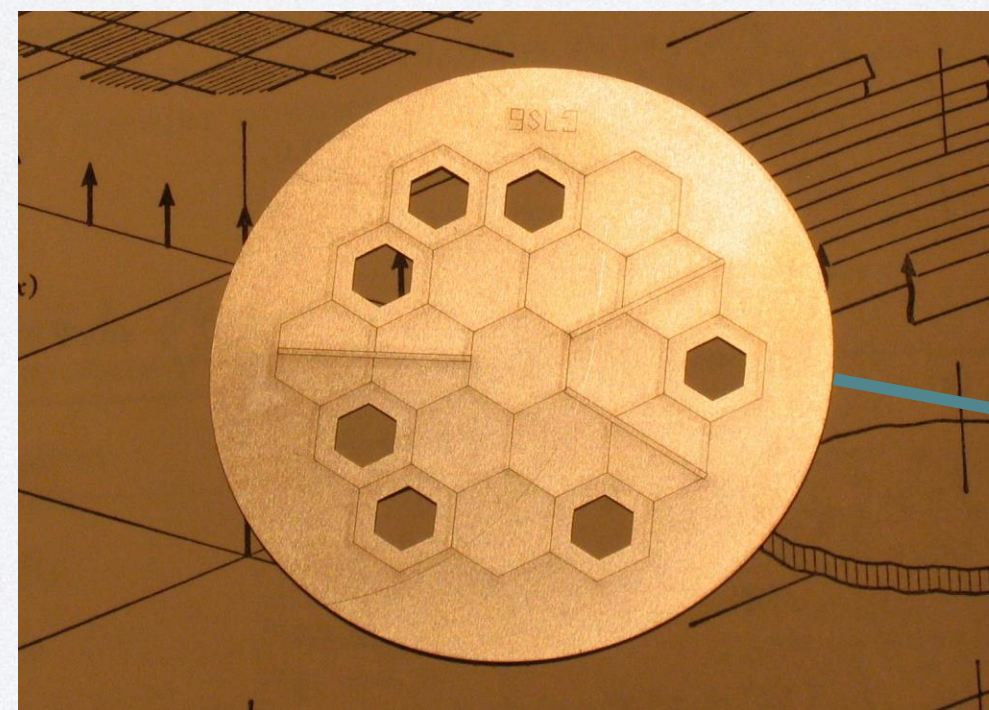
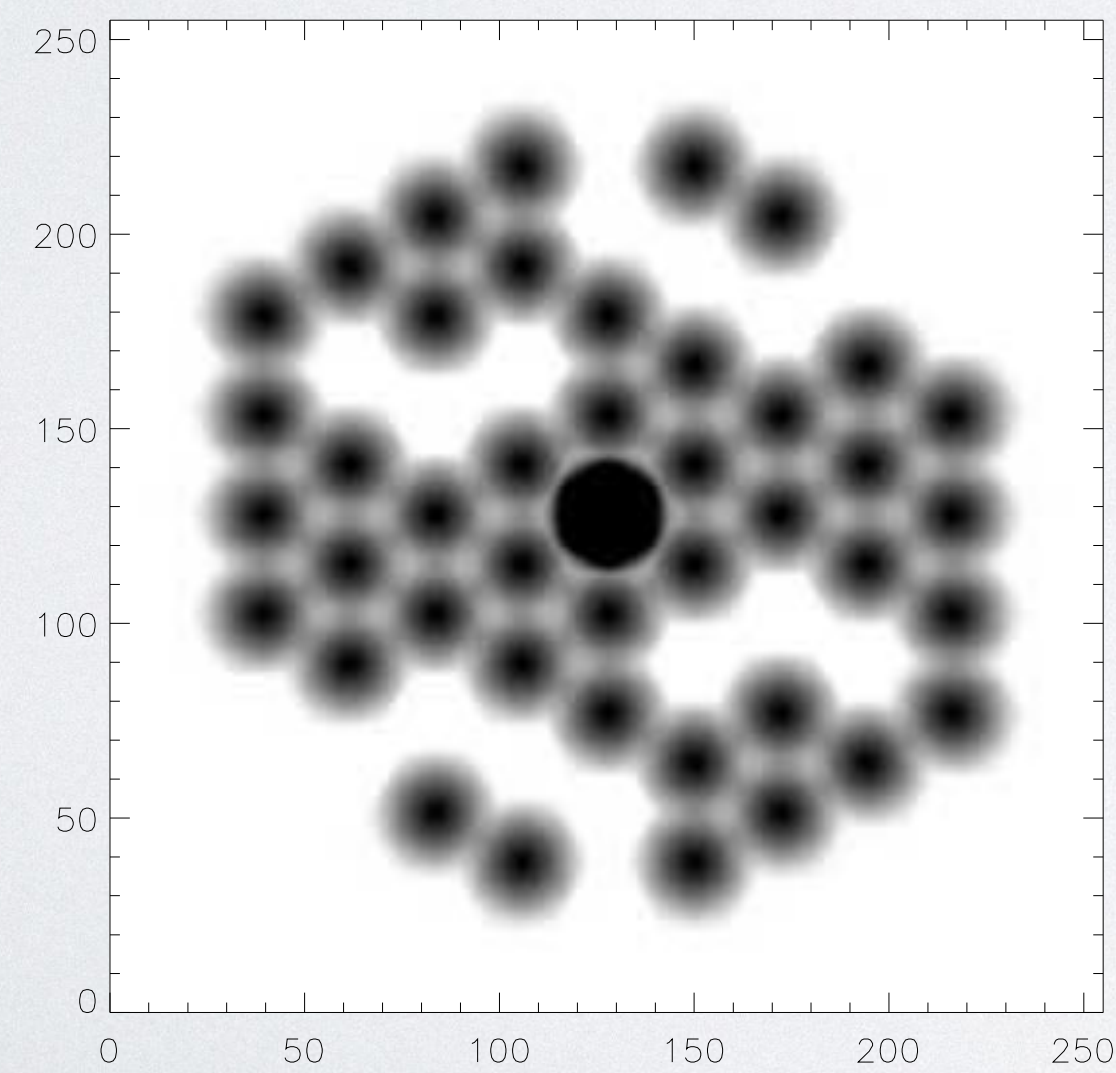
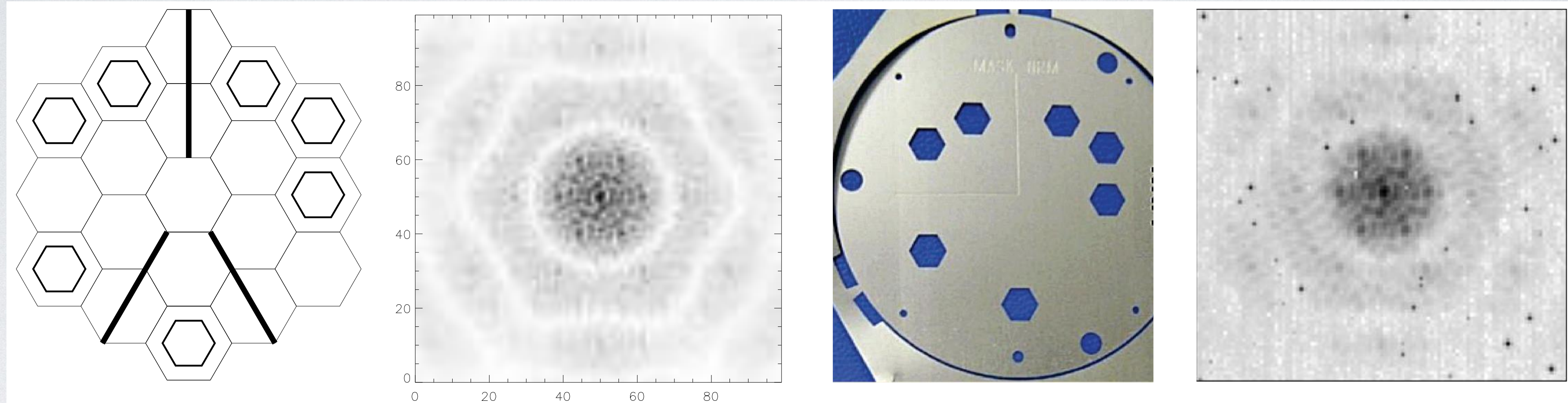


GLINT (USyd)
Nulling interferometer

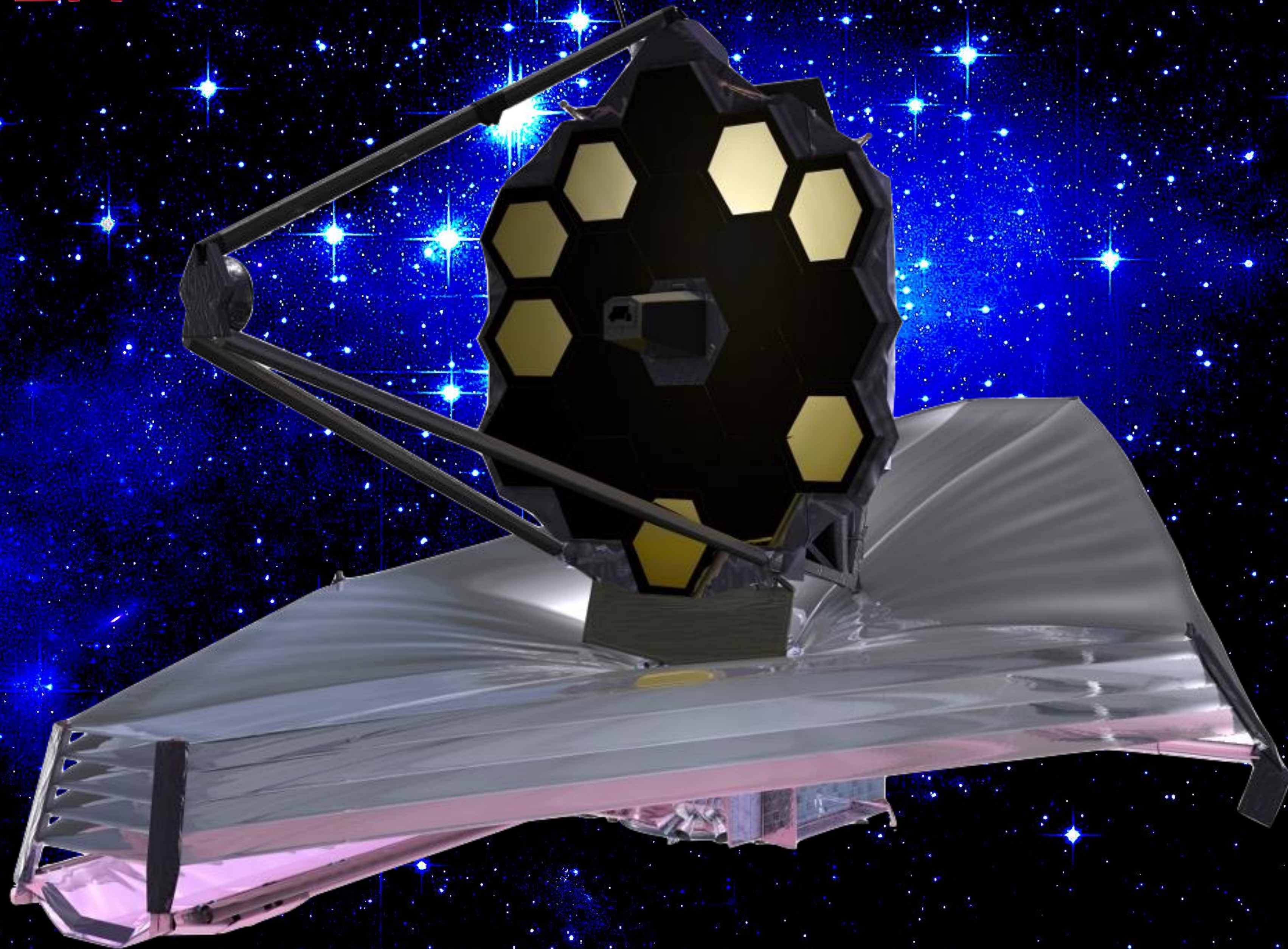


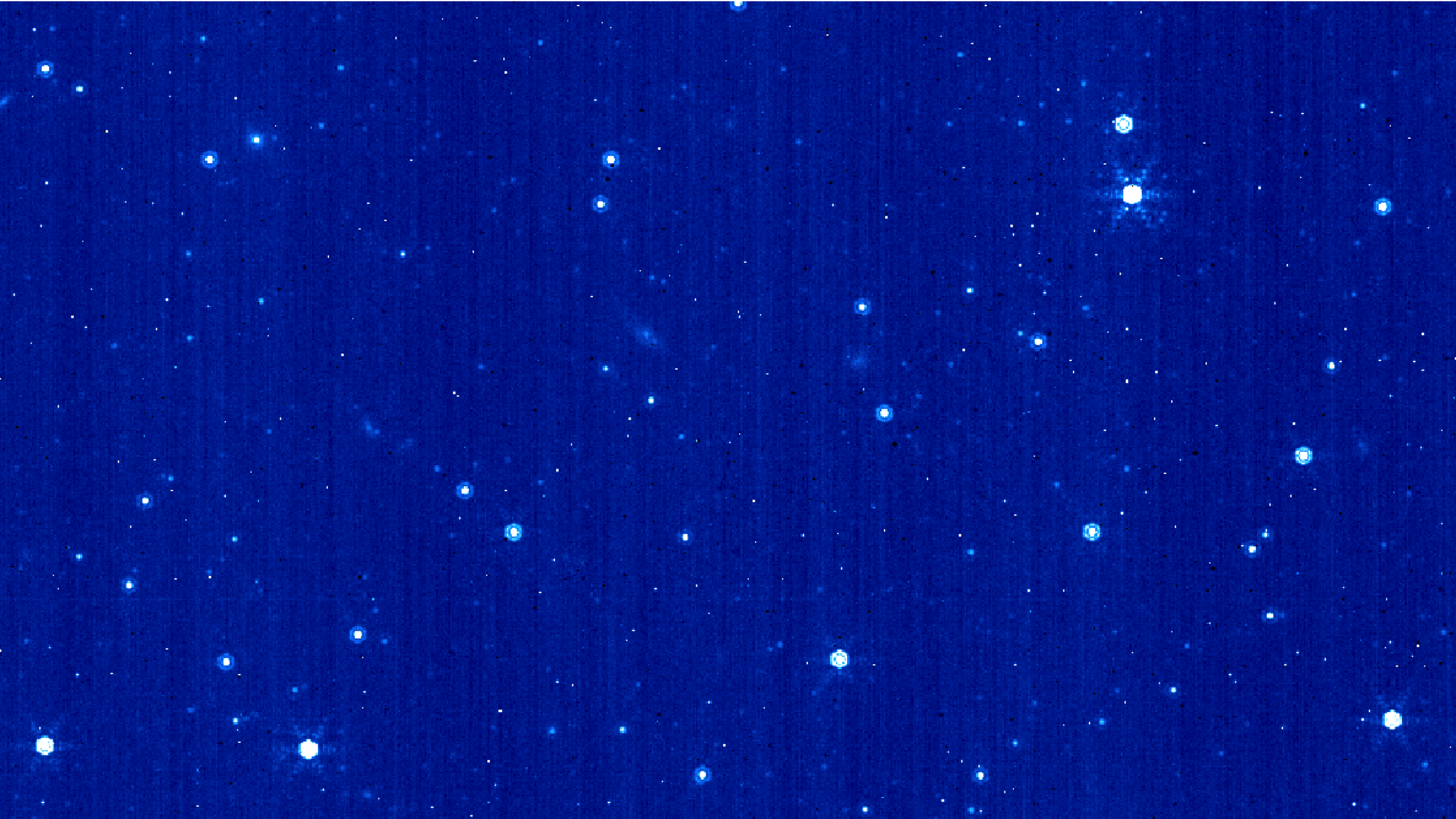


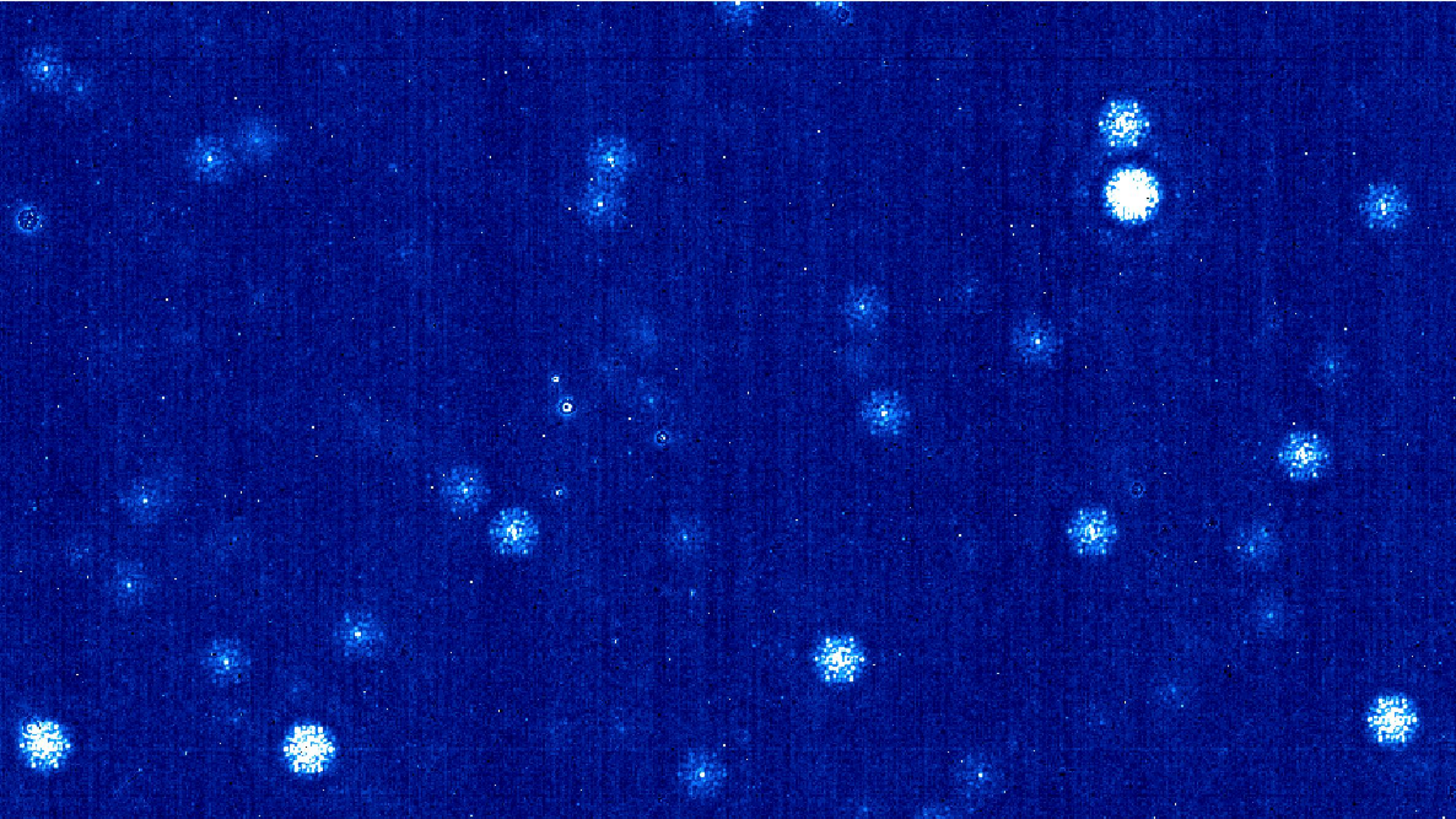
NIRISS AMI: THE JWST INTERFEROMETER



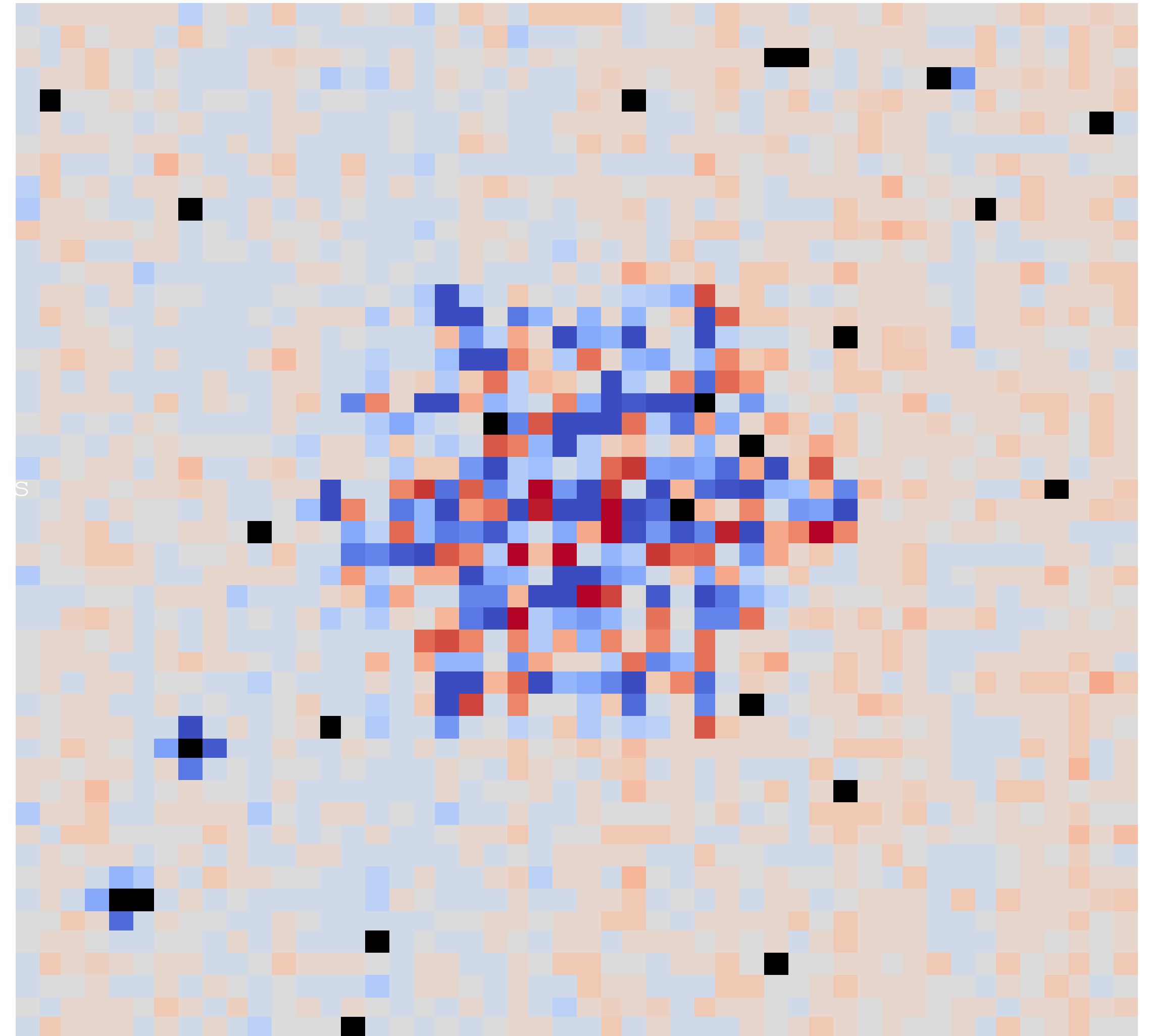
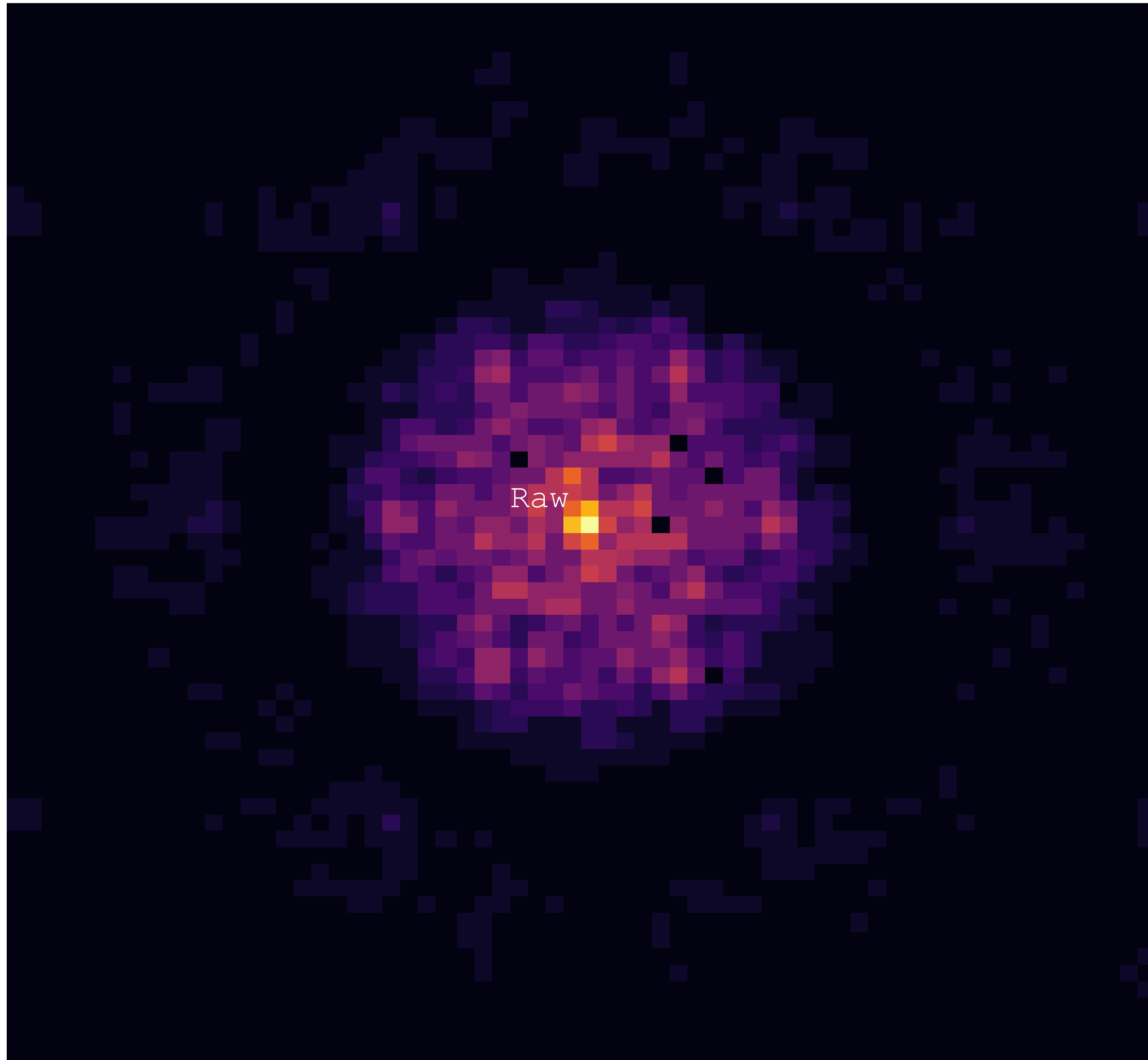
Thanks @ **NASA**



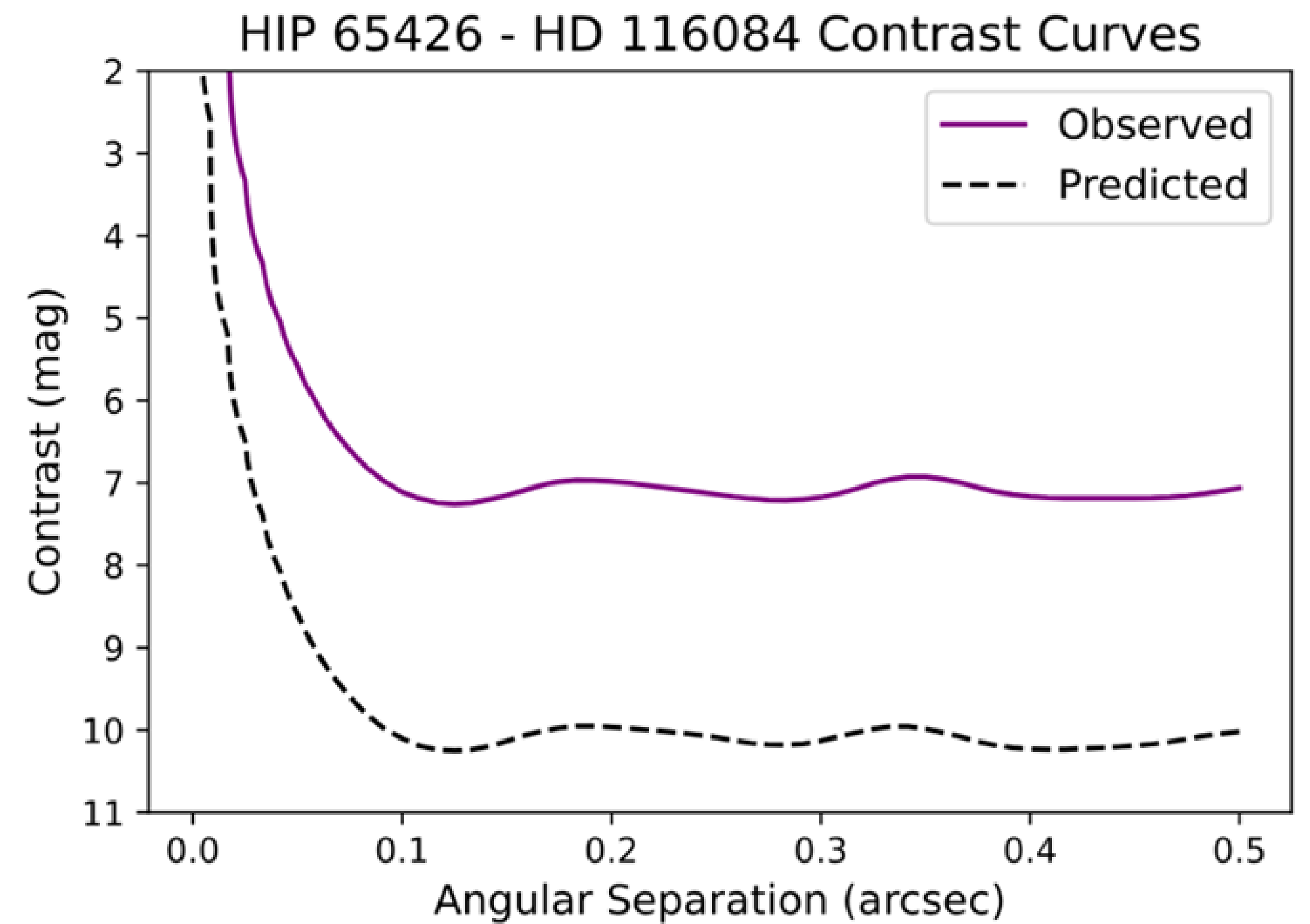
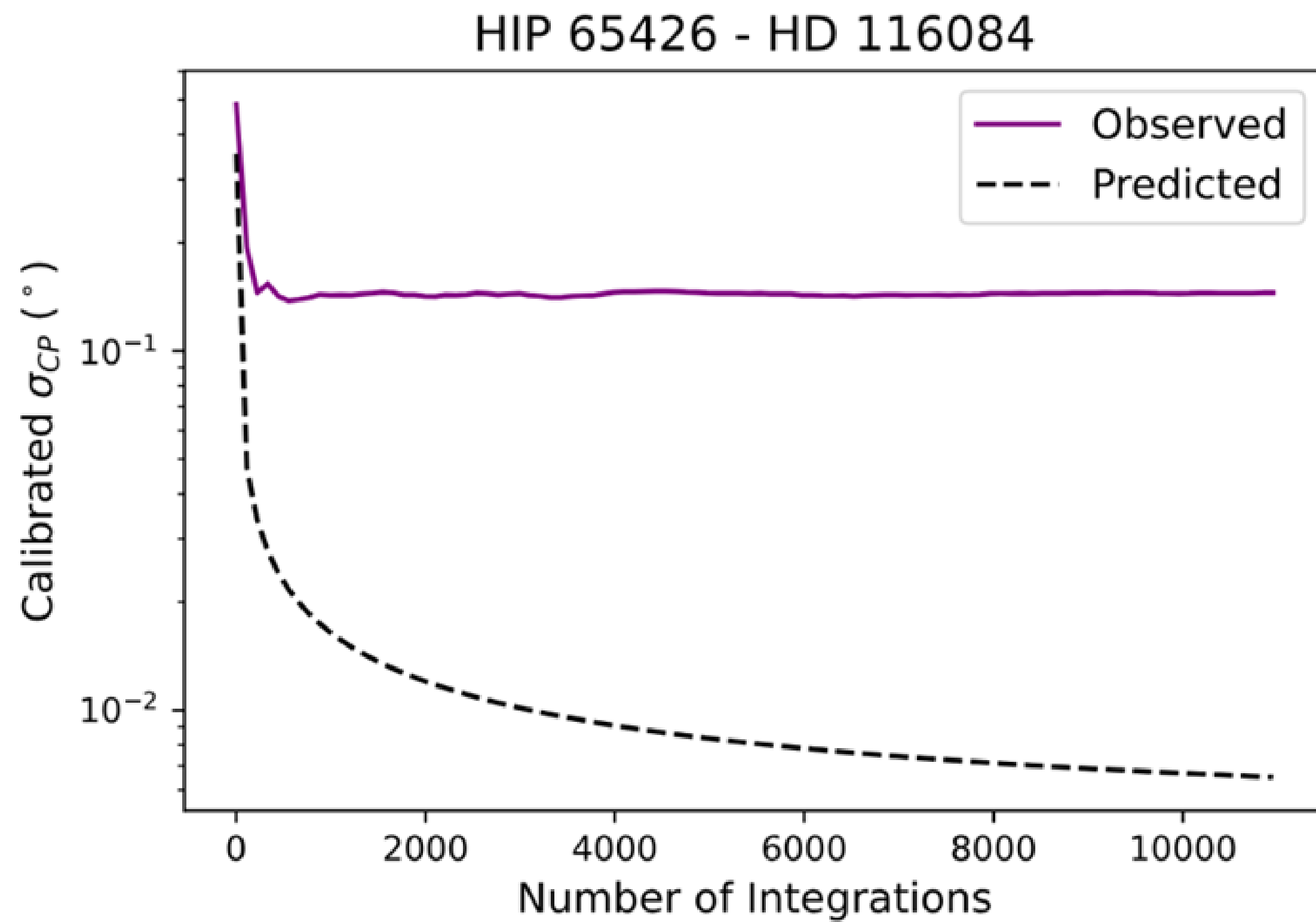




NIRISS AMI: RAW DATA

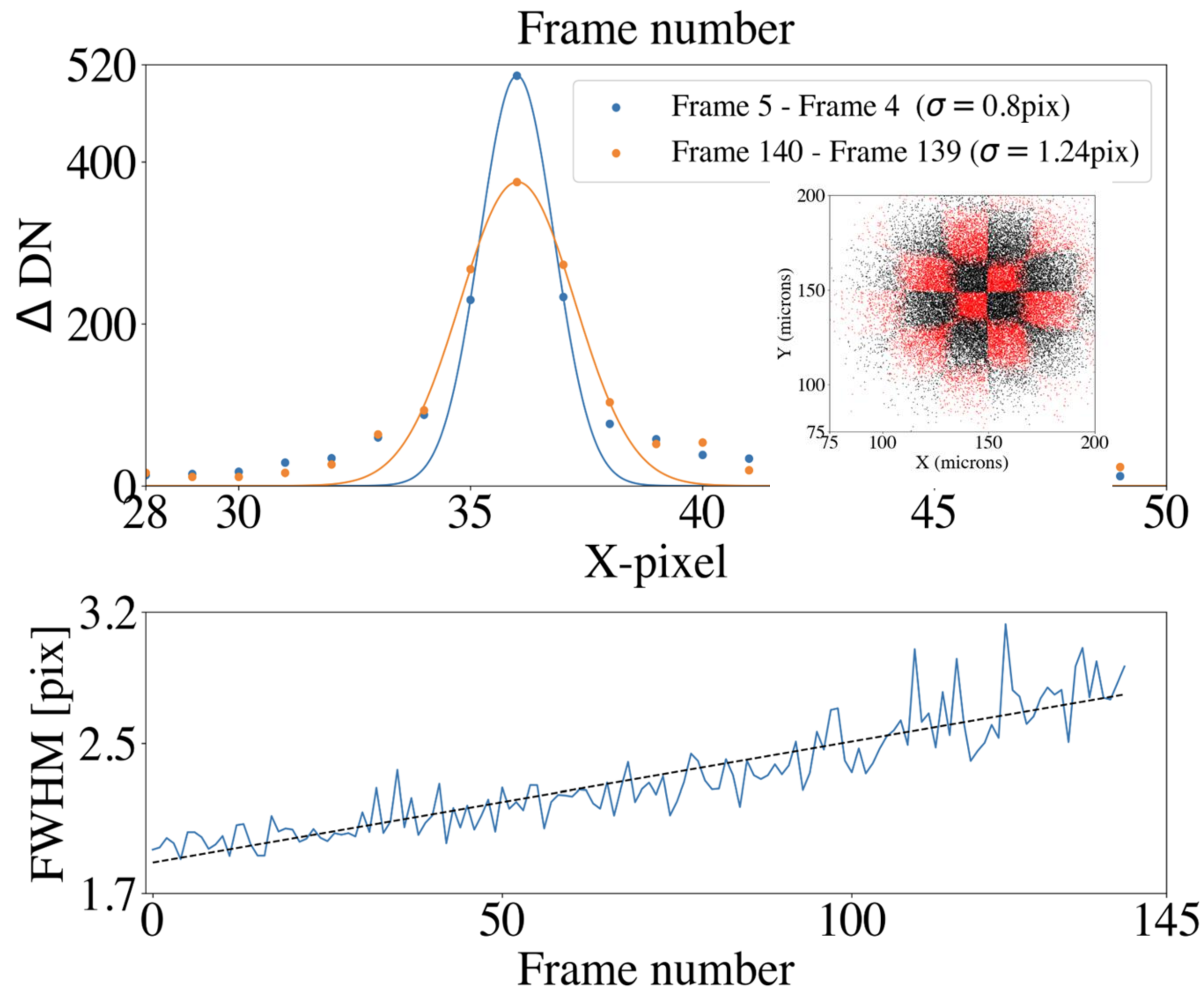
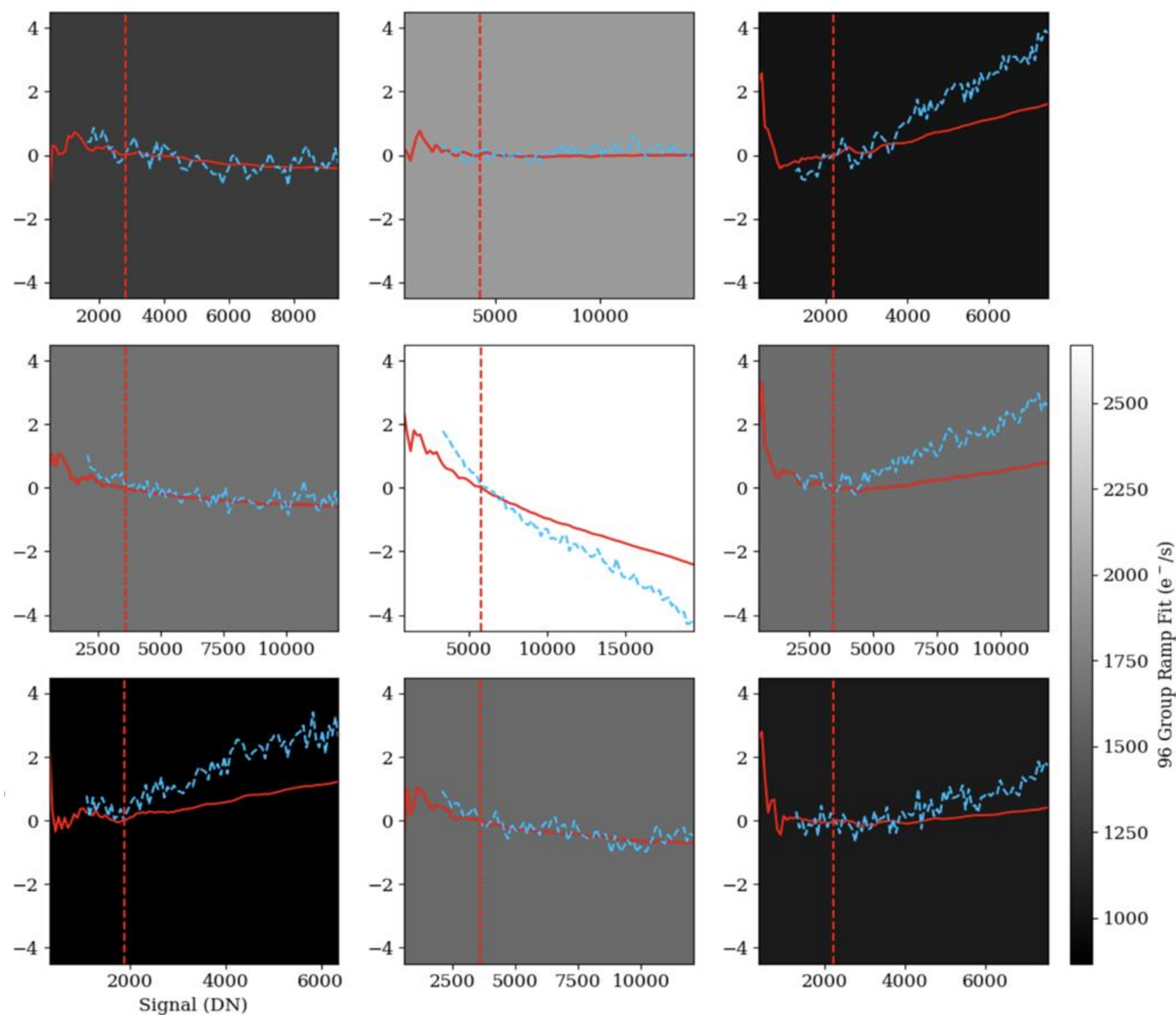


SPHERICAL (HOLY?) COW IN VACUO ...



THERE'S MANY A SLIP TWIXT THE CUP AND THE LIP ...

25h GTO program: charge bleeds out of the central pixel





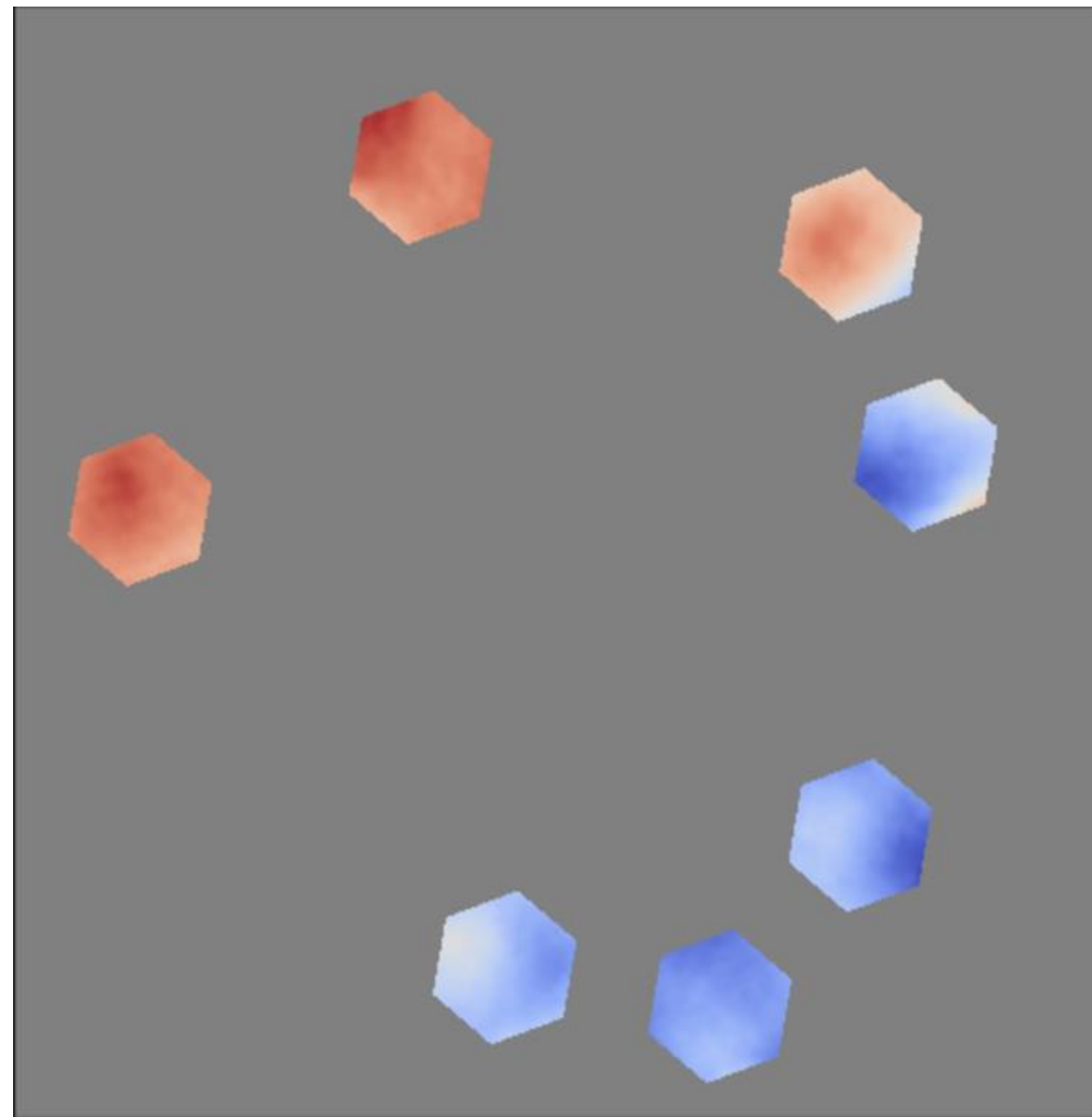
Louis Desdoigts



Ben Pope

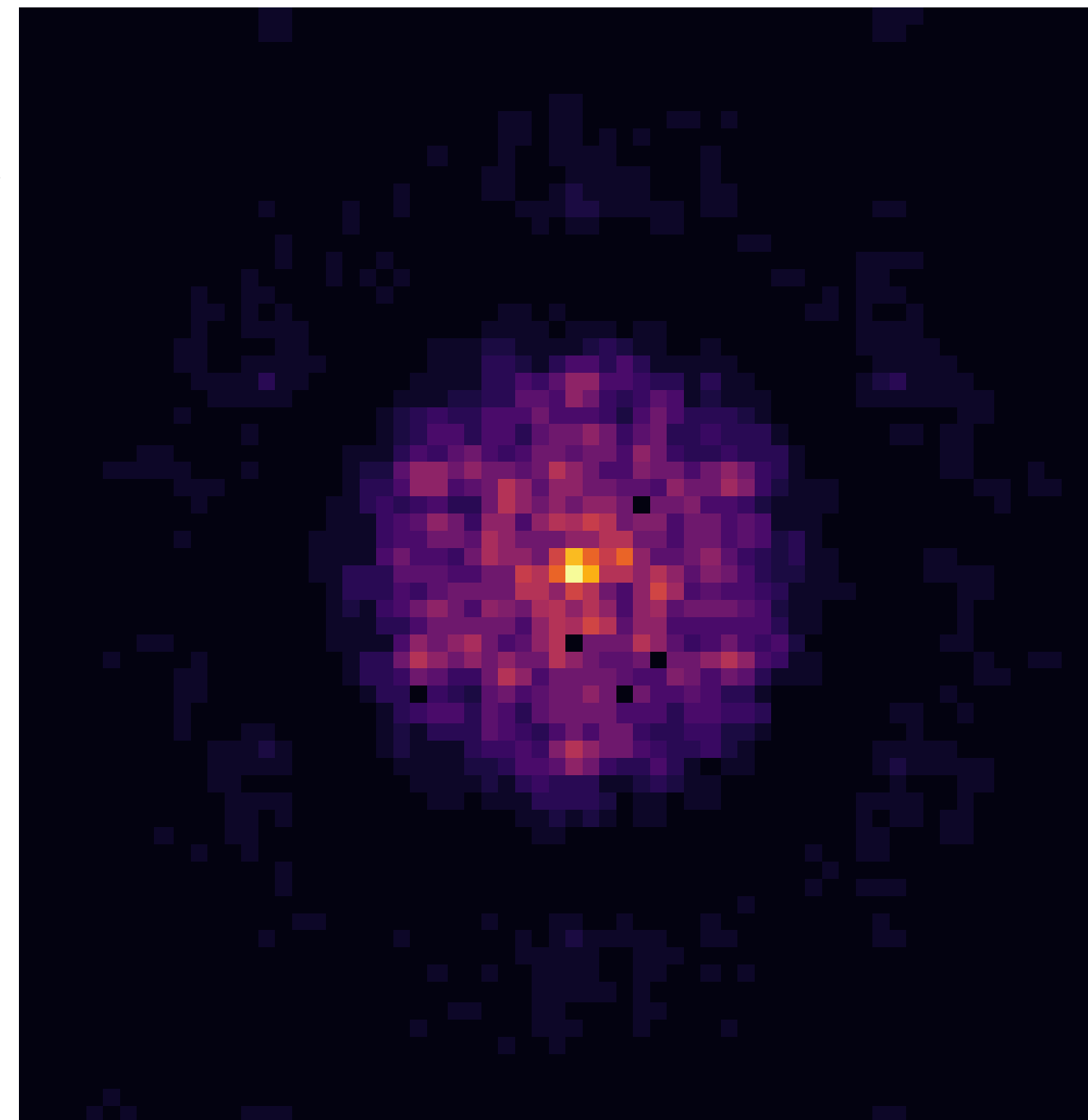
ALUX

DIFFERENTIABLE PHYSICS + STATISTICS



James Webb
Physics Model

Physics
Model
Inference
(HMC,
SGD)



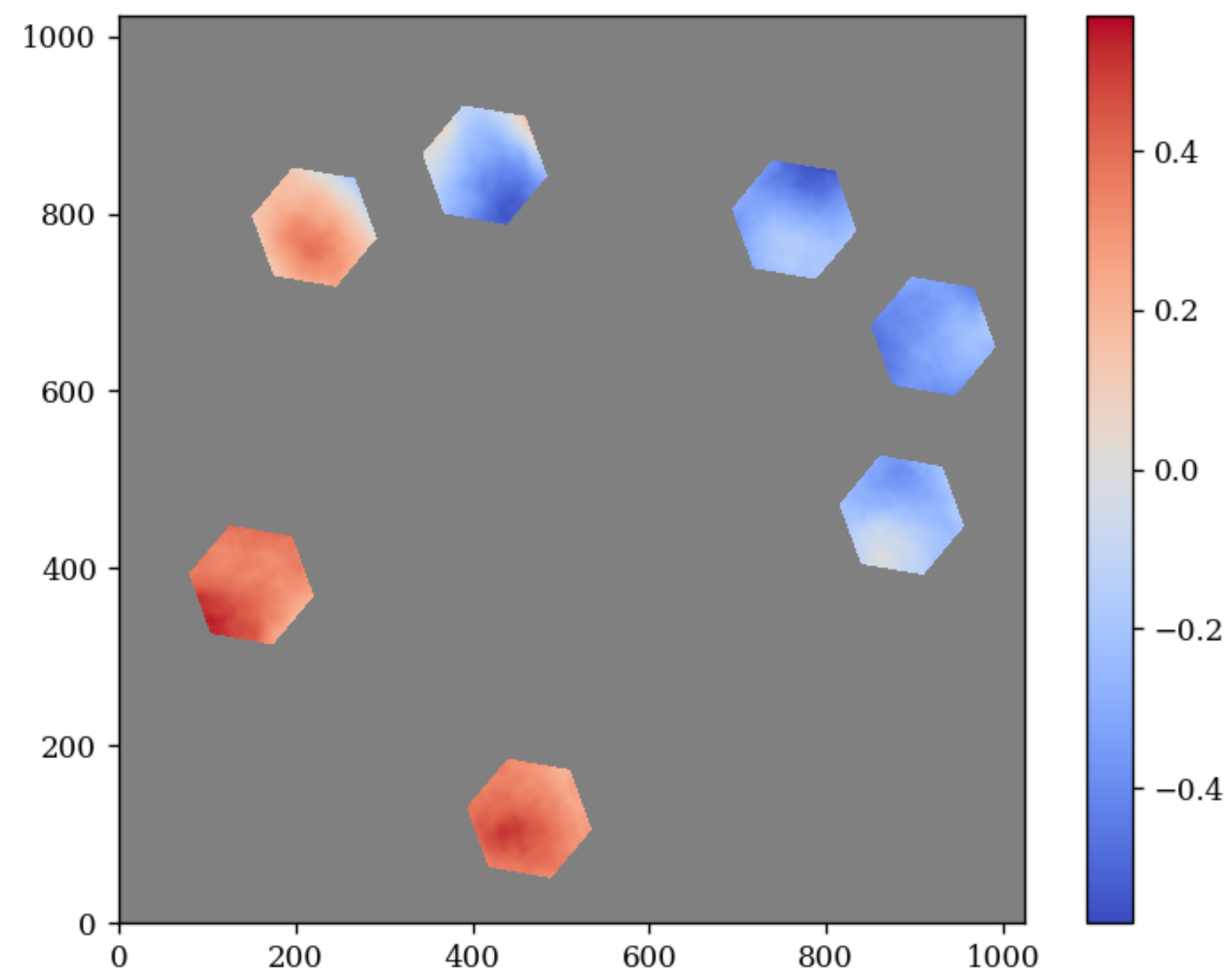
Simulate
Data

Write simulation in Jax
(/PyTorch/Julia), get
**exact gradients by
automatic
differentiation**

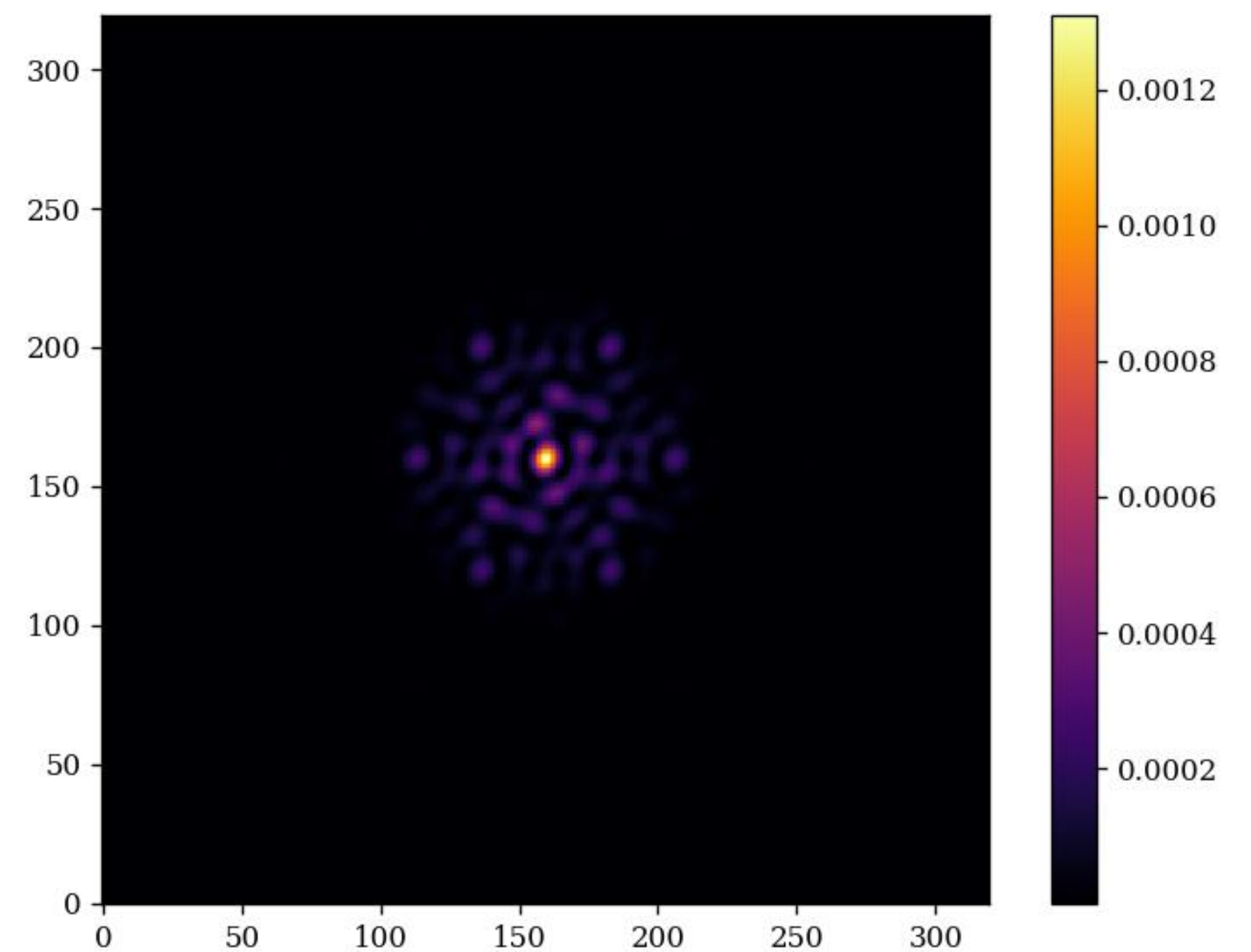
Train deterministic
physics models in
conjunction with NNs,
use HMC, variational
inference, diffusion
models...

FORWARD MODELING JWST/AMI

Pupil

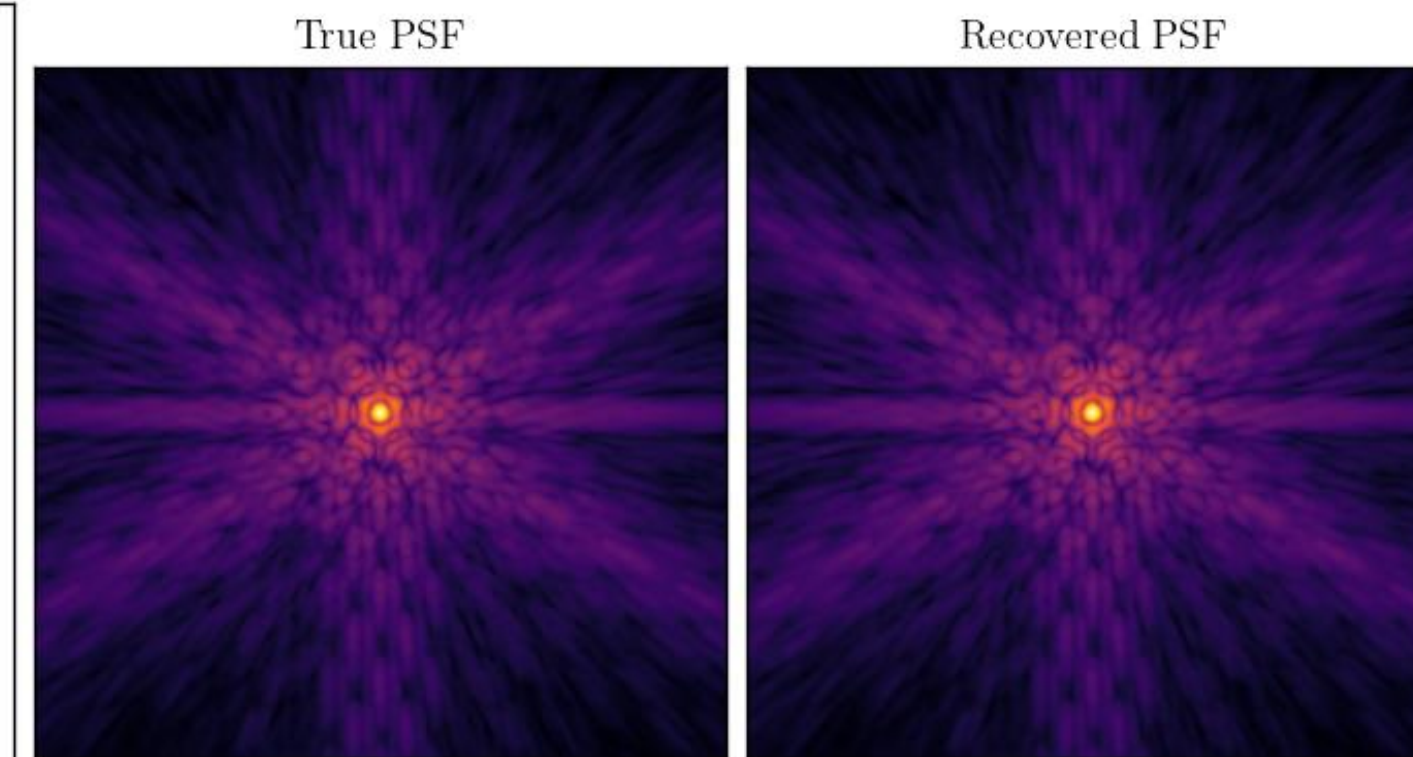
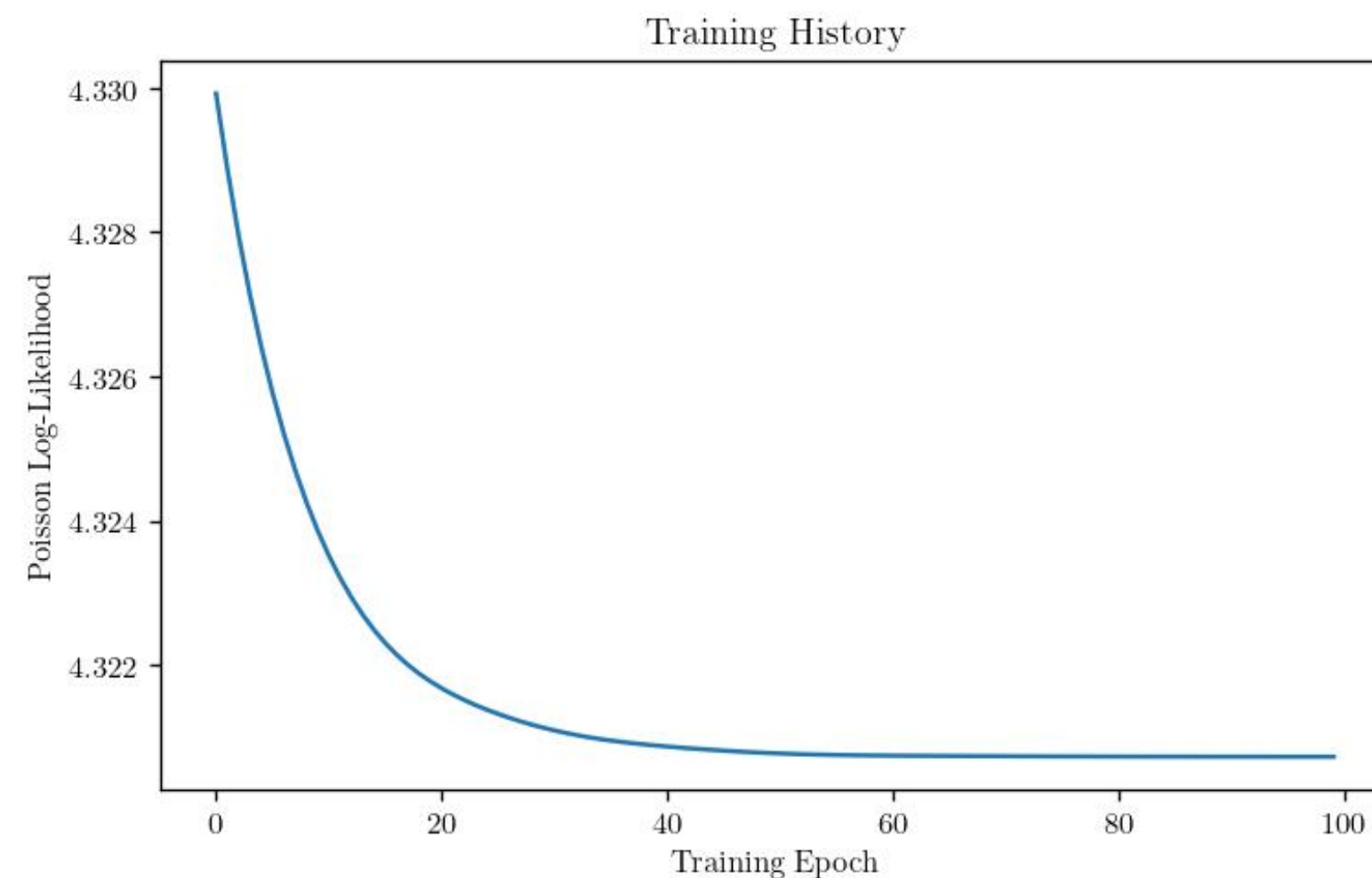


Simulated PSF

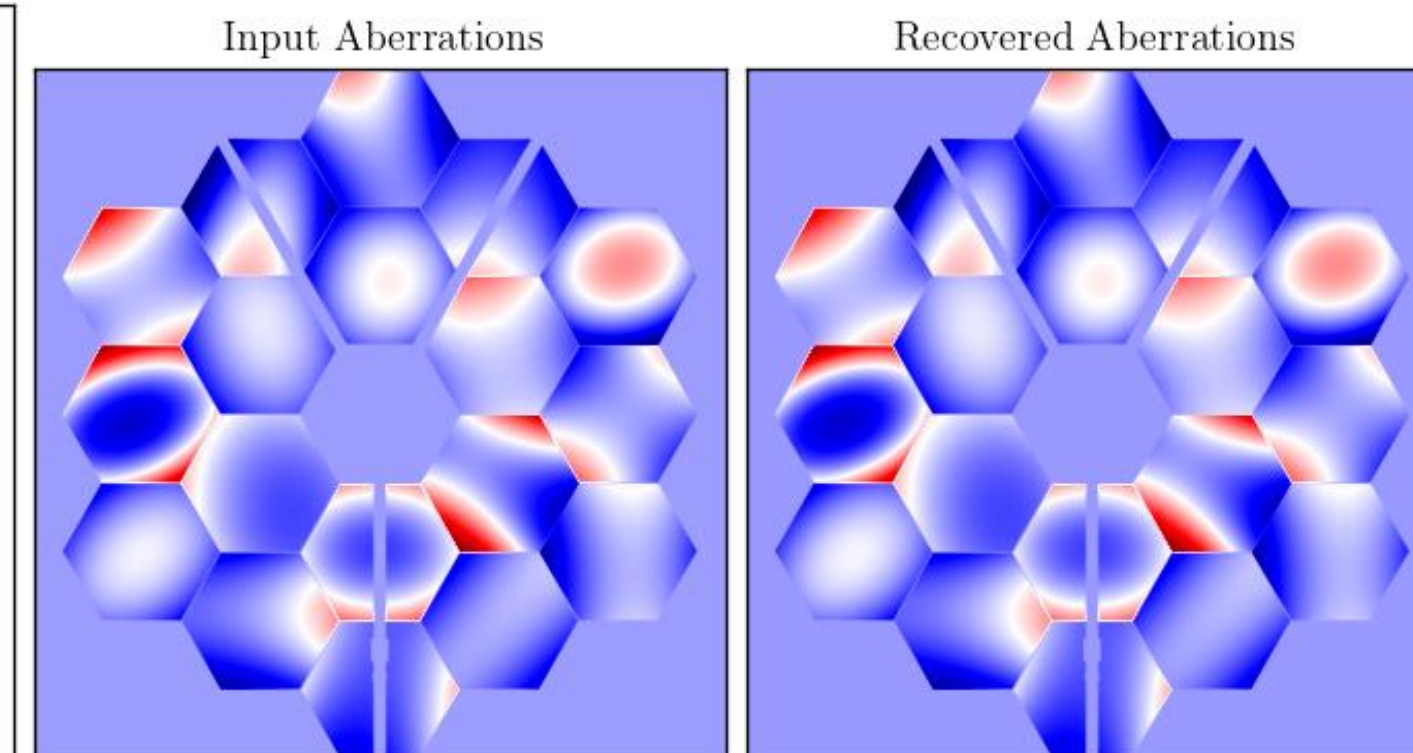
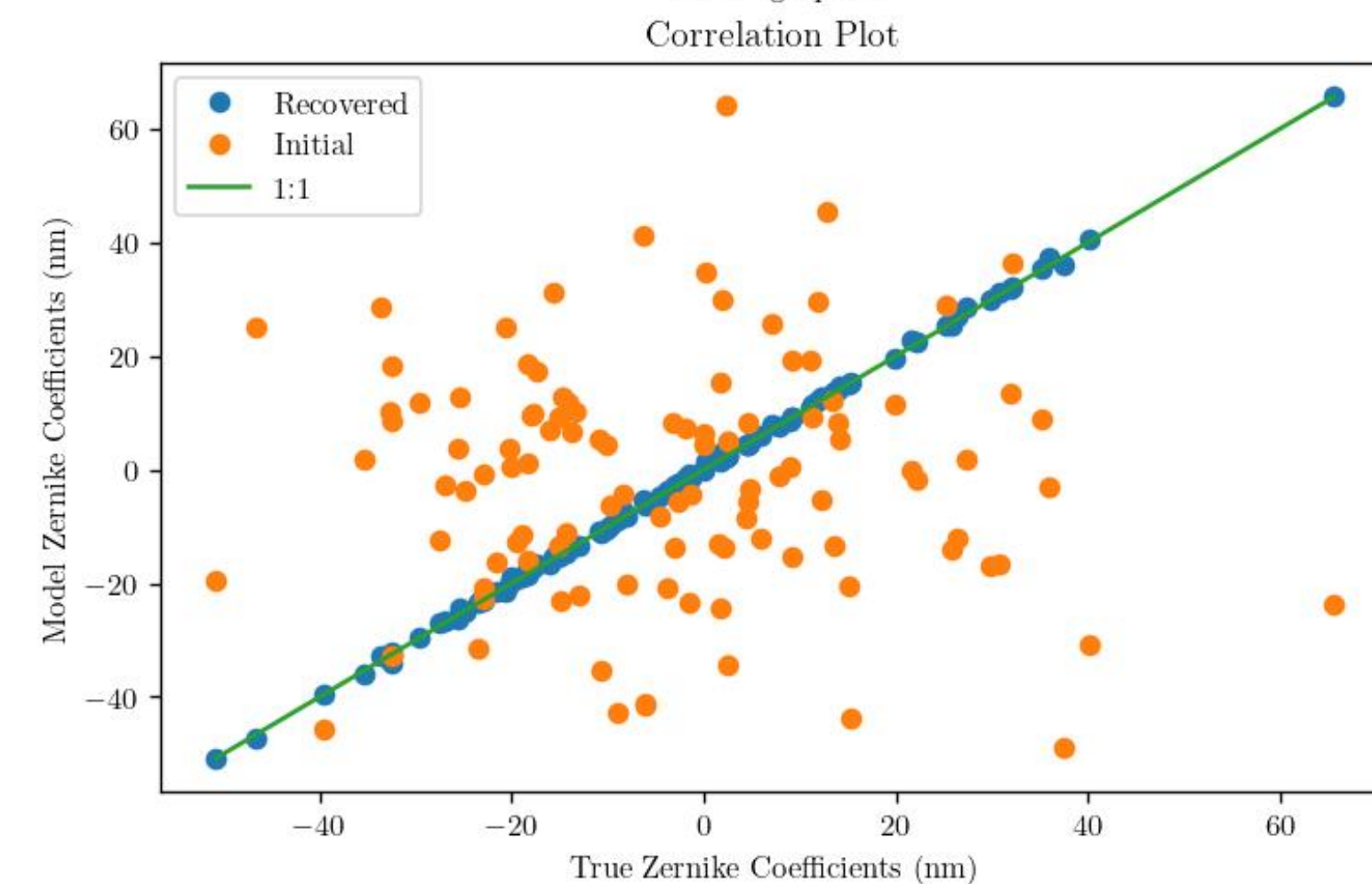


PHASE RETRIEVAL WITH ∂ LUX

- Desdoigts, Pope, Dennis & Tuthill, 2023



JWST has a whole hardware wavefront sensor used every two days to measure & correct the mirror alignment



With ∂ Lux it is straightforward to do phase retrieval *and* detector calibration simultaneously

NOISE FLOORS ALL THE WAY DOWN....



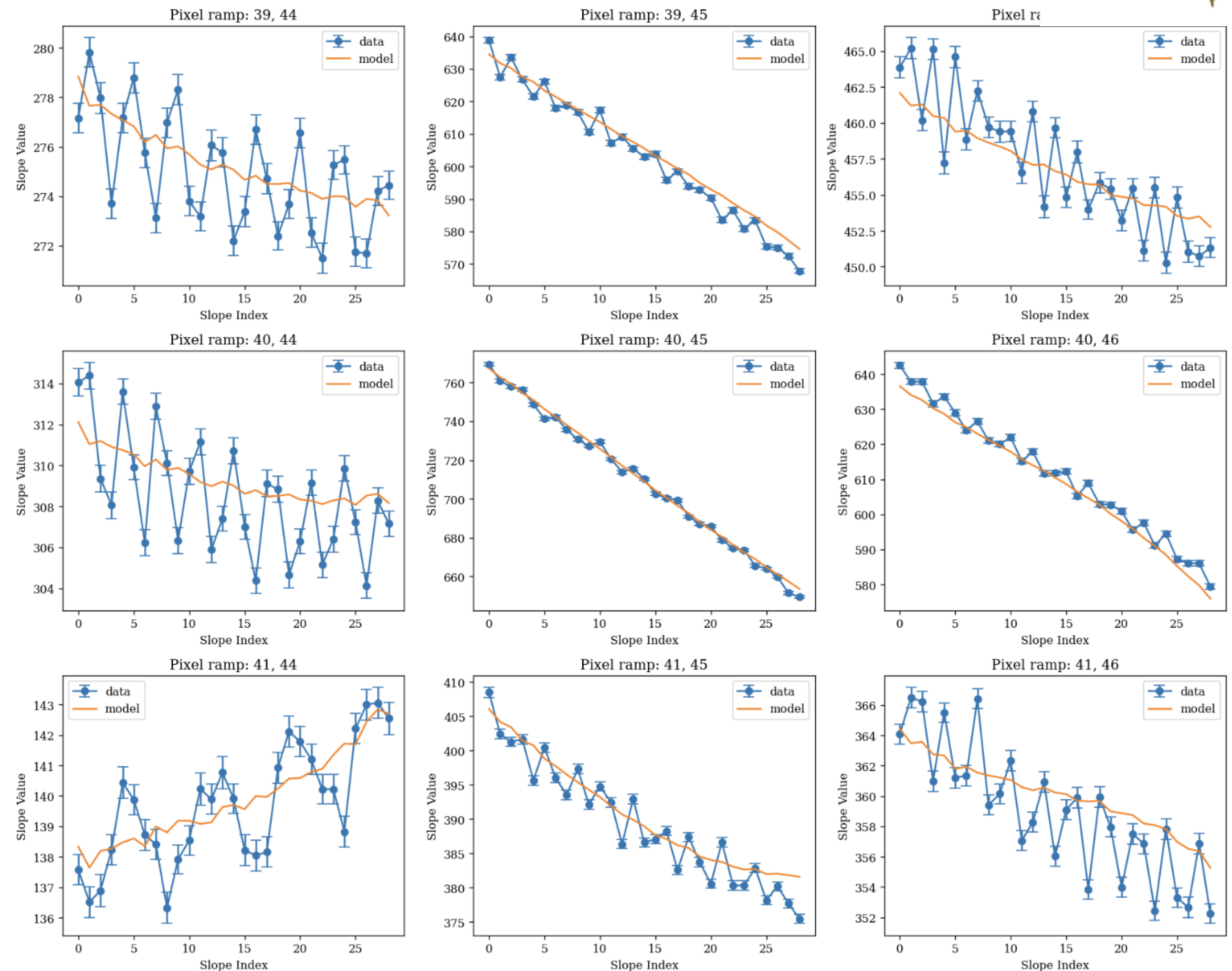
MAJOR NOISE FLOORS

(All now modelled in ∂ Lux by Louis)

- The STSCI Pipeline adds noise
- Incorrect optical data in pipeline
- Fine tuning of optical figure
- Brighter Fatter Effect
- Other nonlinear effects
- THIS ???



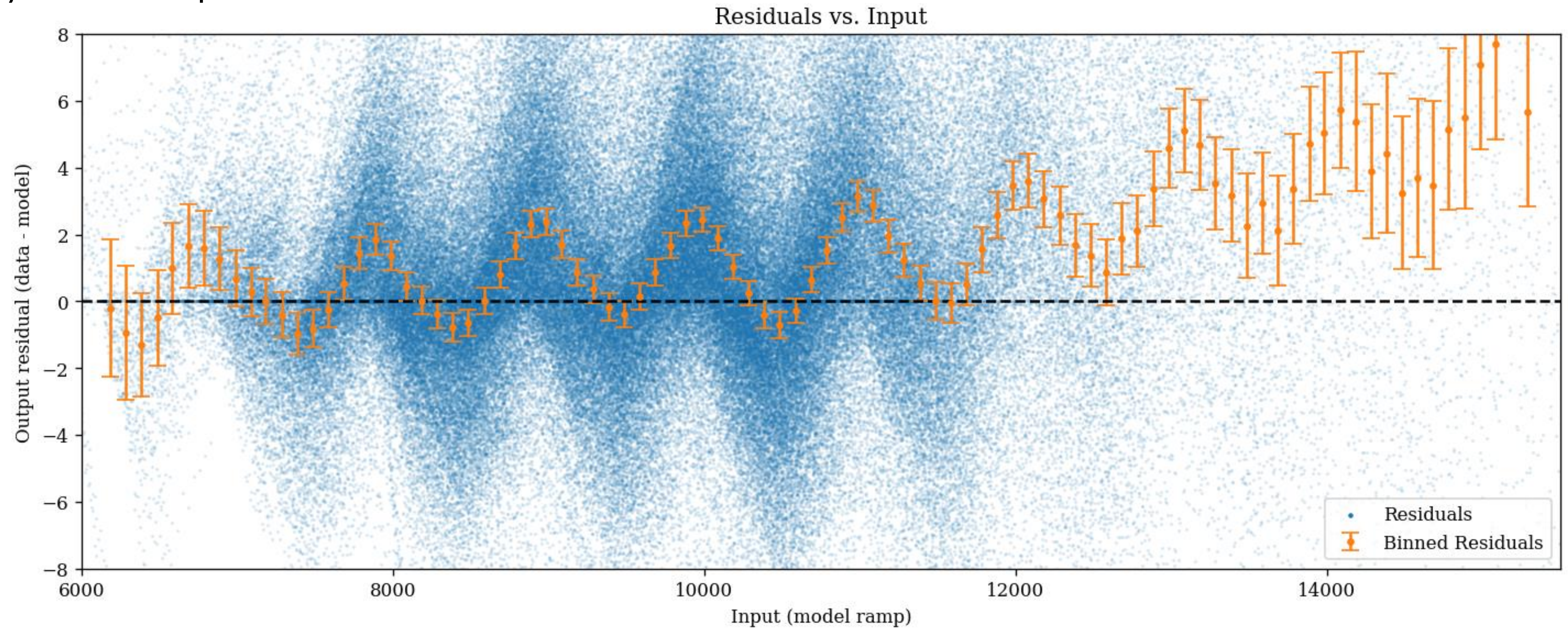
Some kind of periodic jitter as you read the detector out up the ramp?



ELECTRONIC BUG

Periodic model with a few harmonics of 1024 fits beautifully

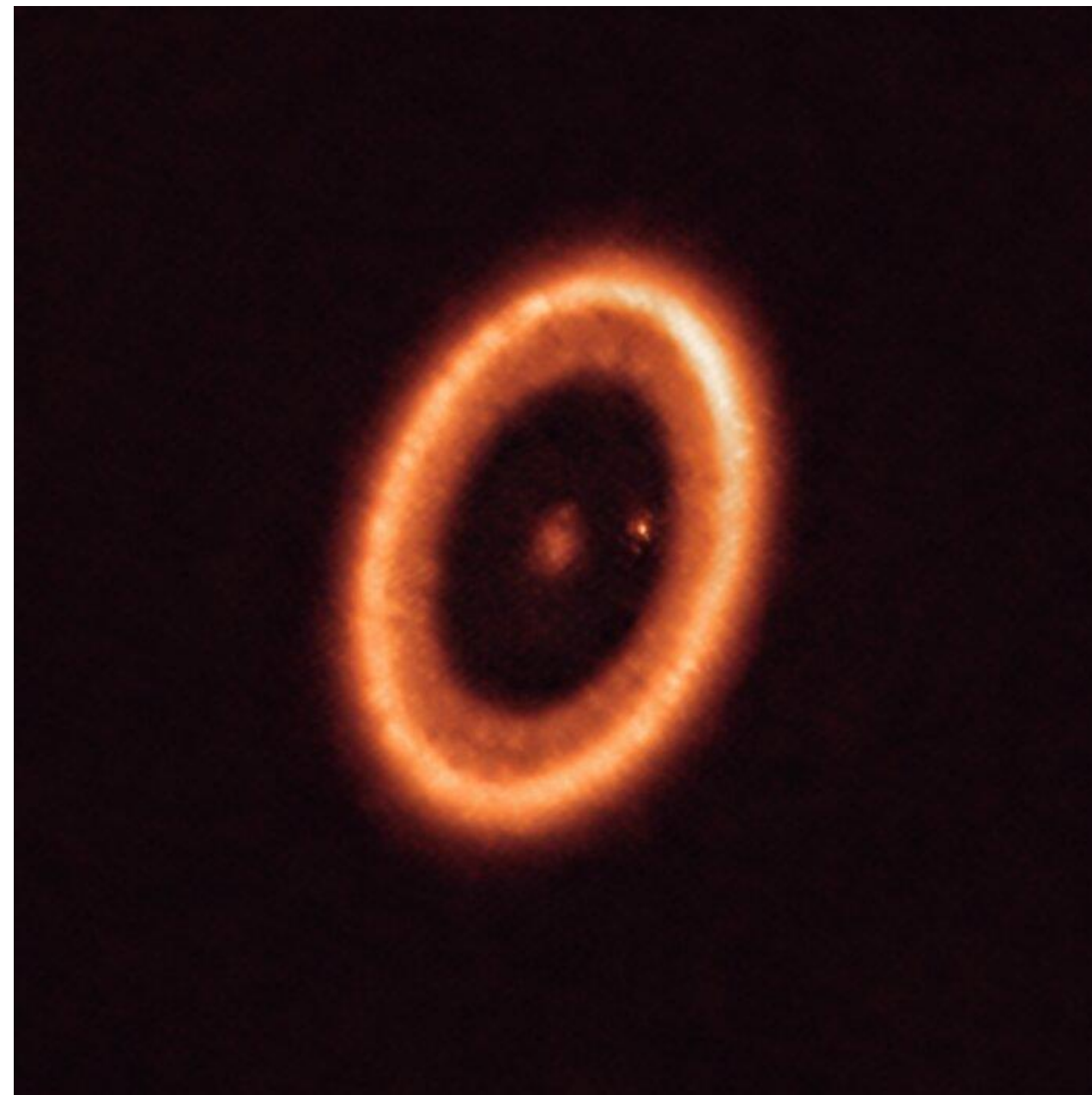
Finally now at the photon noise limit for AMI!



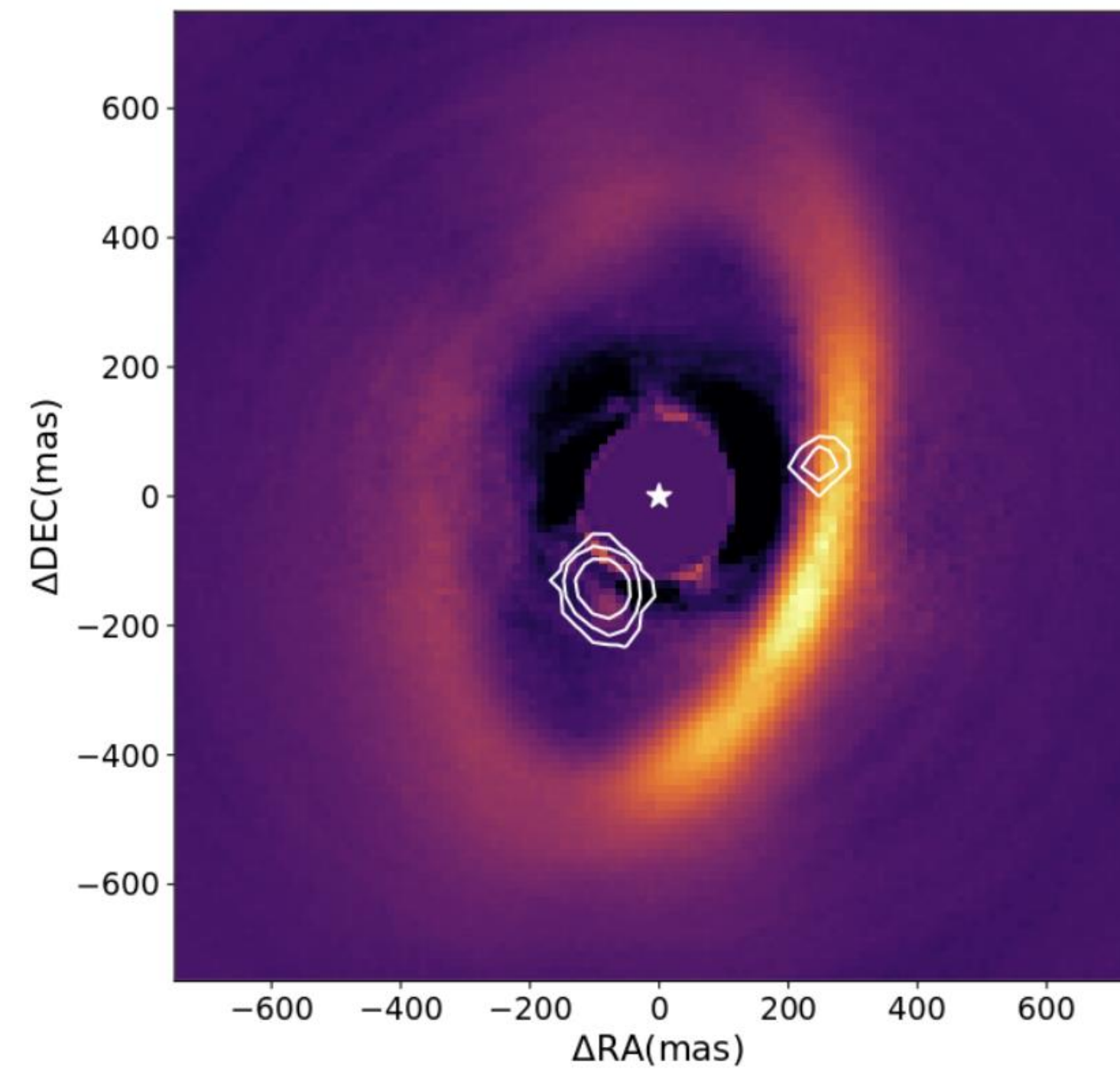
BOTTOM OF THE RABBIT HOLE?

PDS 70!

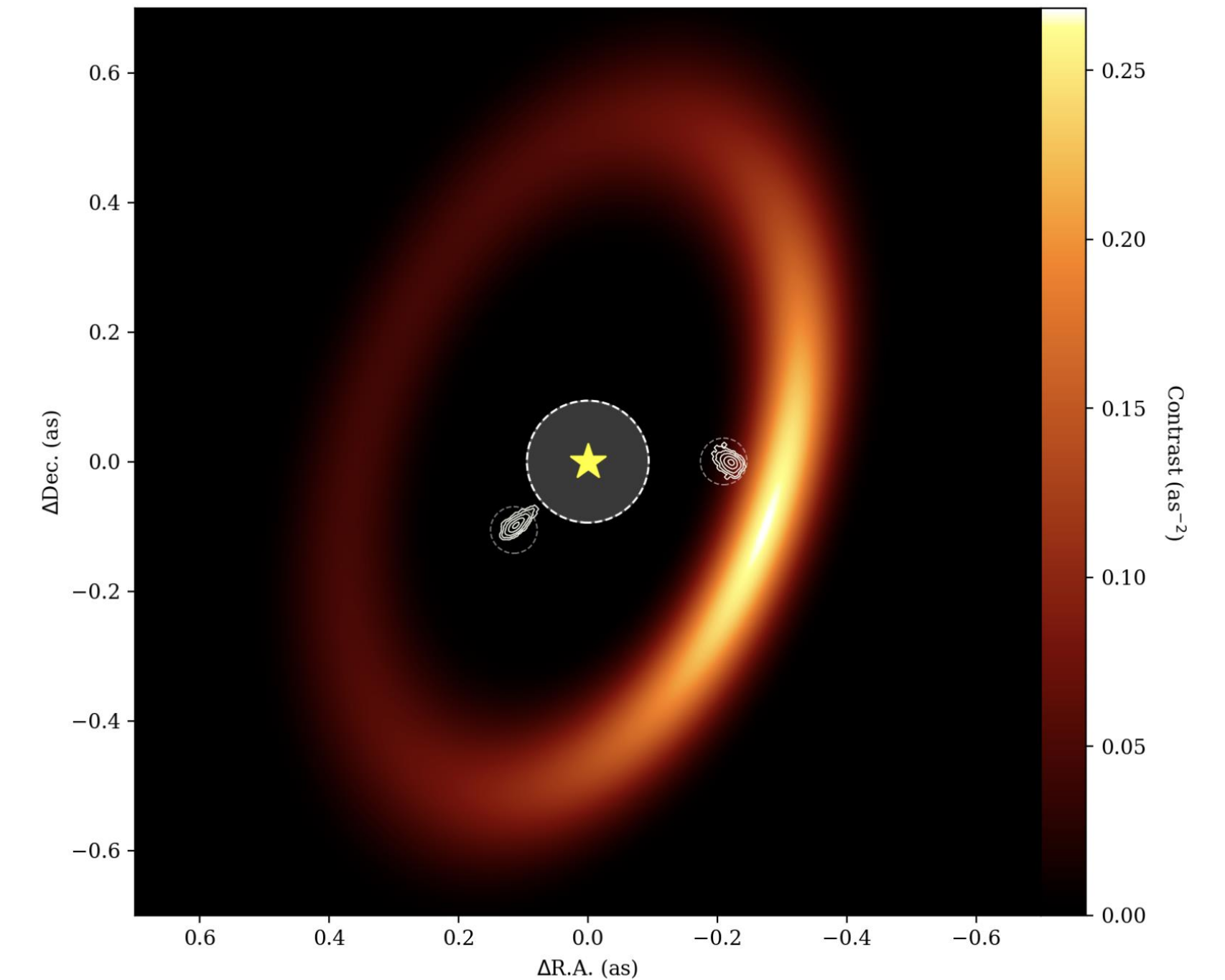
- Dori Blakely (UVic), priv comm – unpublished!



ALMA (Benisty et al, 2021)



VLT/SPHERE (Haffert et al, 2019)



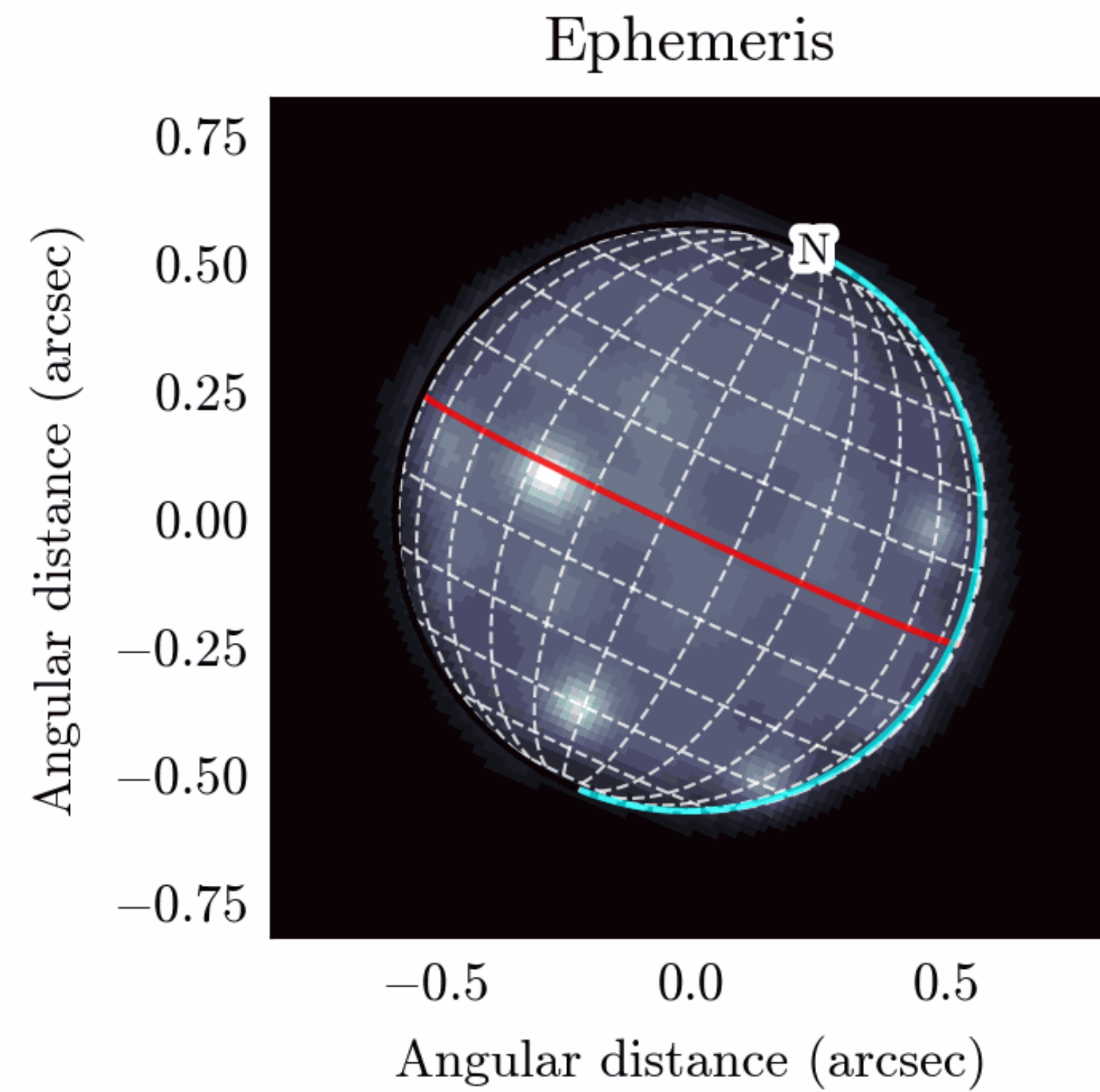
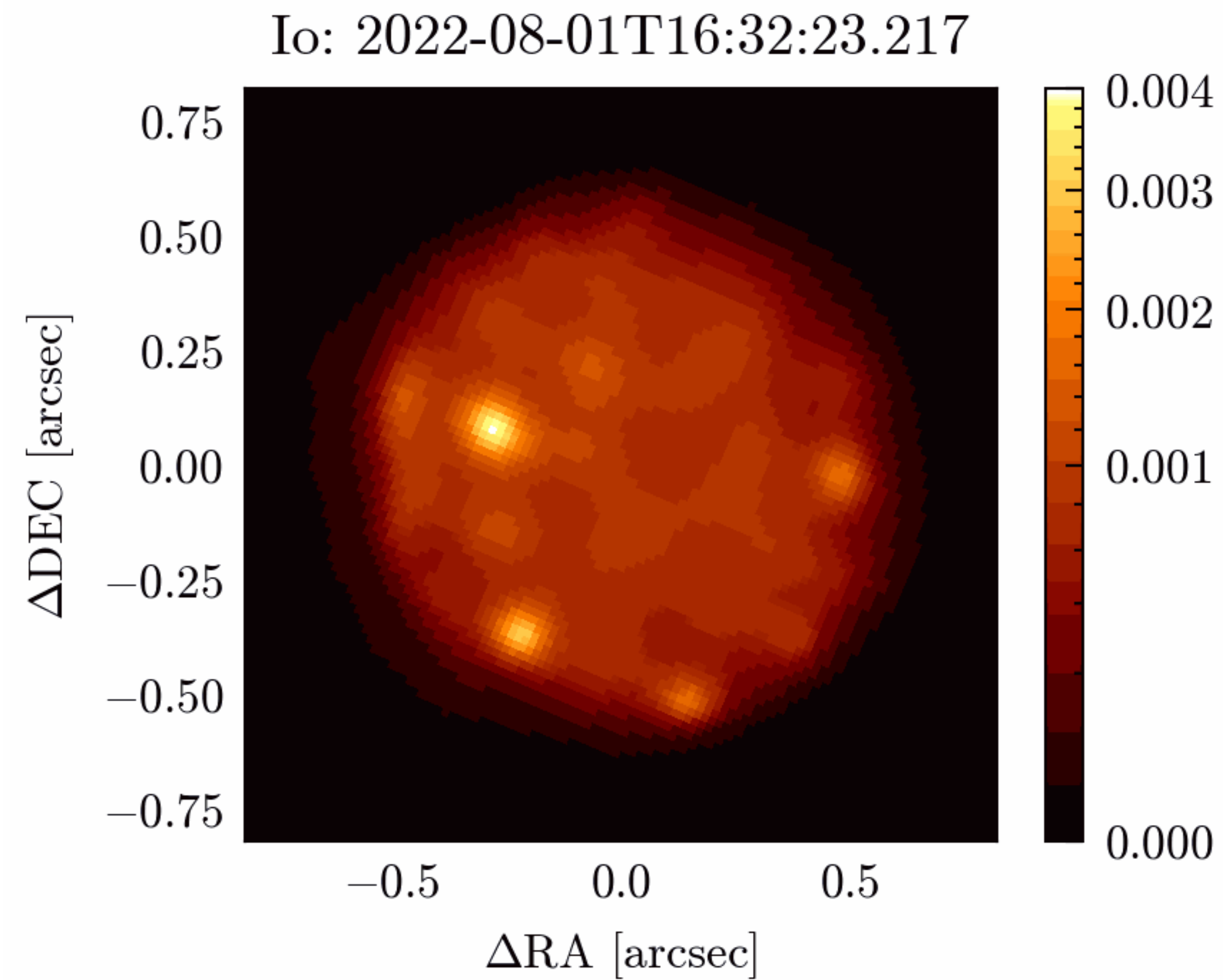
JWST/AMI – Blakely et al,
2024 (our data).
arXiv:2404.13032

IMAGING IO

Max Charles,
PhD student



- Max Charles et al, unpublished





TOLIMAN

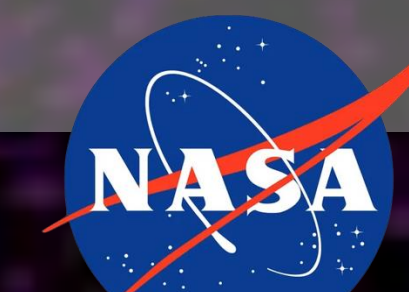
Getting to know the neighbours: Earth analogues in Alpha Centauri with the TOLIMAN space telescope

Peter Tuthill
Chris Betters
Connor Langford
Karel Valenta
Fred Crous
Louis Desdoigts
Max Charles
Grace Piroscia
Conaire Deagan
Redyan Ahmed

Pete Worden
Olivier Guyon
Pete Klupar
Kyran Grattan

Ben Pope
Ben Montet

Kieran Larkin
Gautam Vashisht
Frans Snik
David Doelman



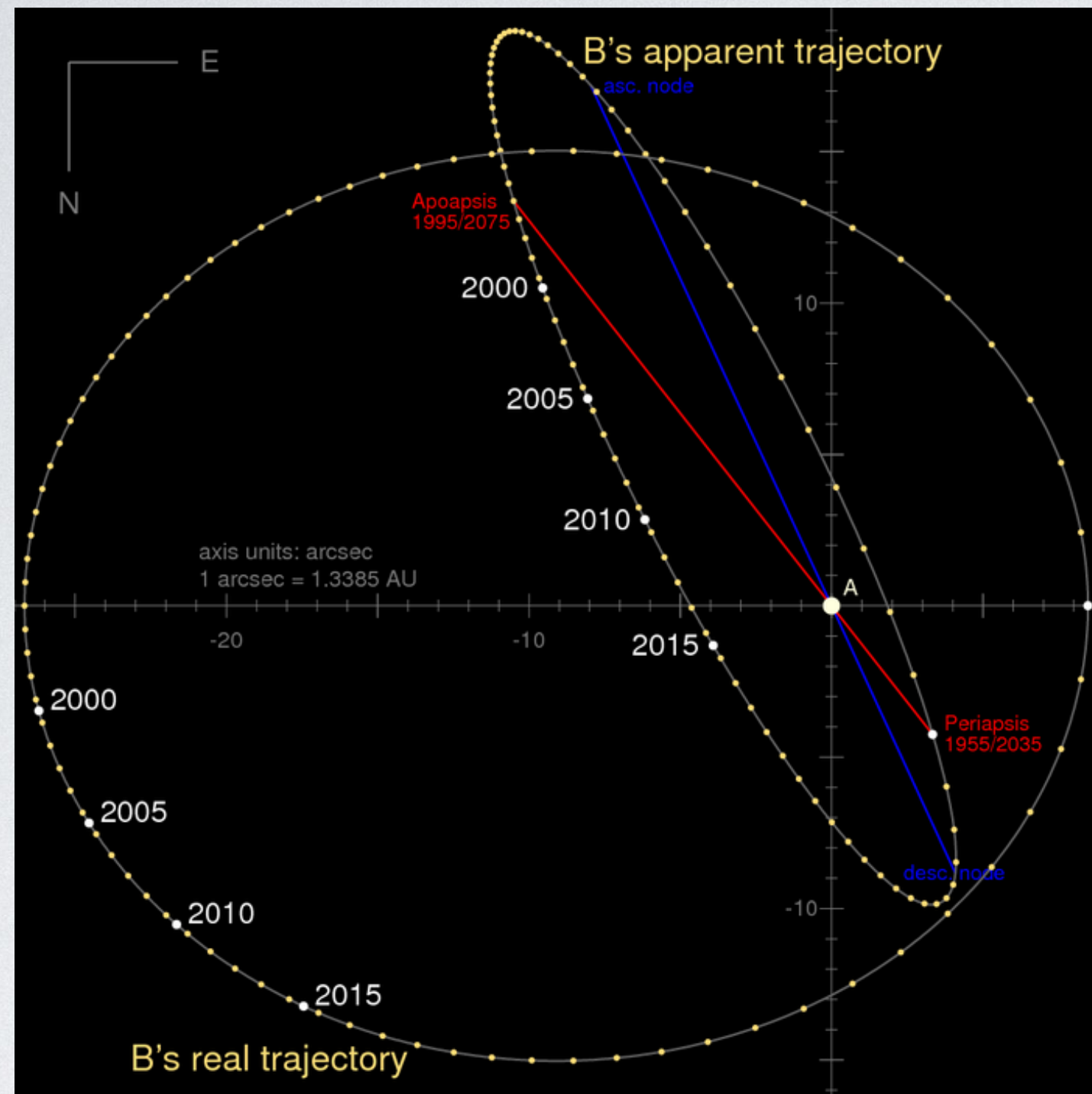


TOLIMAN

Telescope for Orbit Locus Interferometric Monitoring of our Astronomical Neighborhood

- Is there an Earth Analog in Alpha Cen?
- 1 Earth Mass, 0.5-2yr orbit, A or B
 - Secondary Target: 61 Cygni (+others?)
 - 12.5cm pathfinder for a 30cm space telescope
 - Technology demonstrator for Astrometry

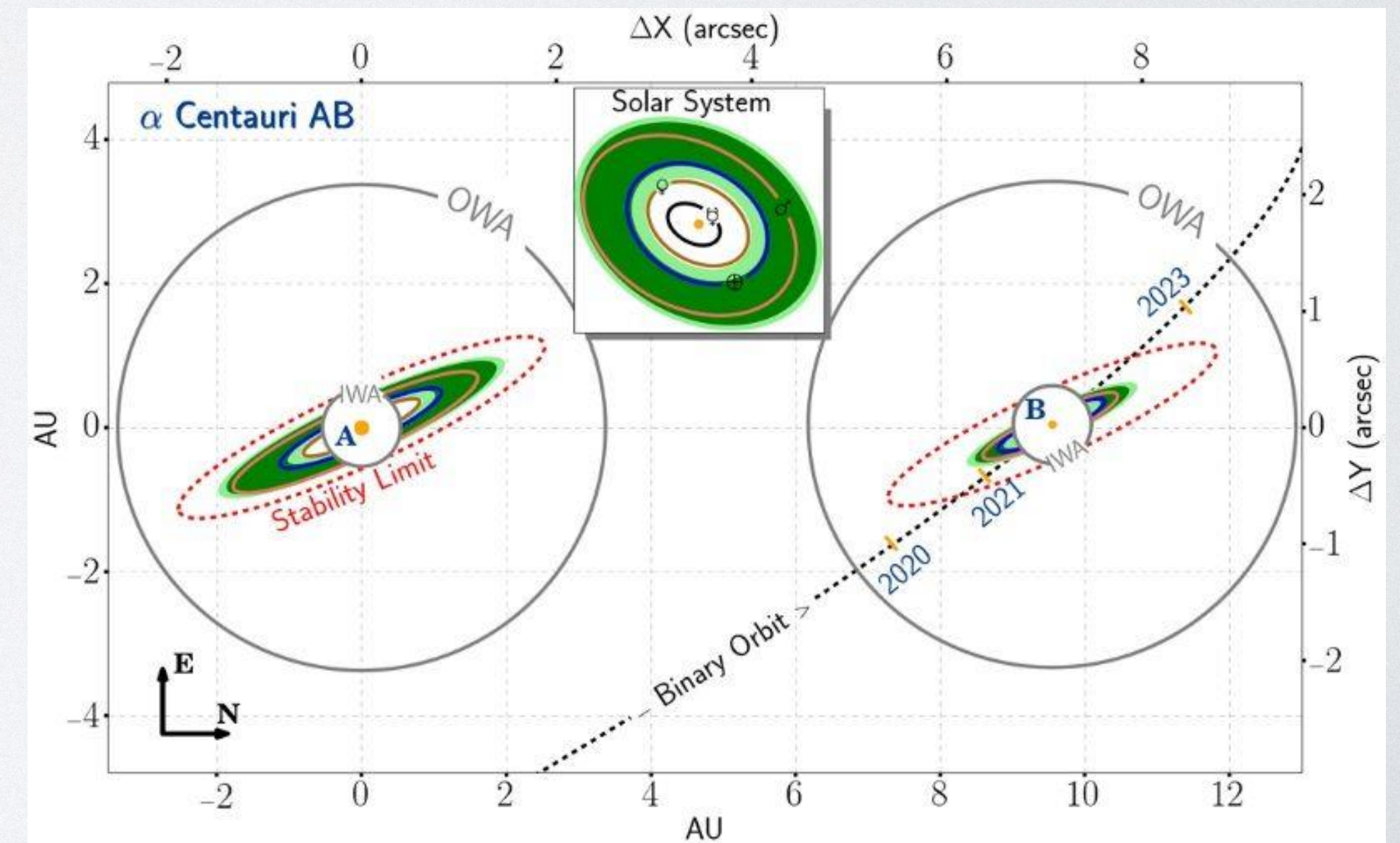




Alpha Cen AB (= Rigel Kent + Toliman)

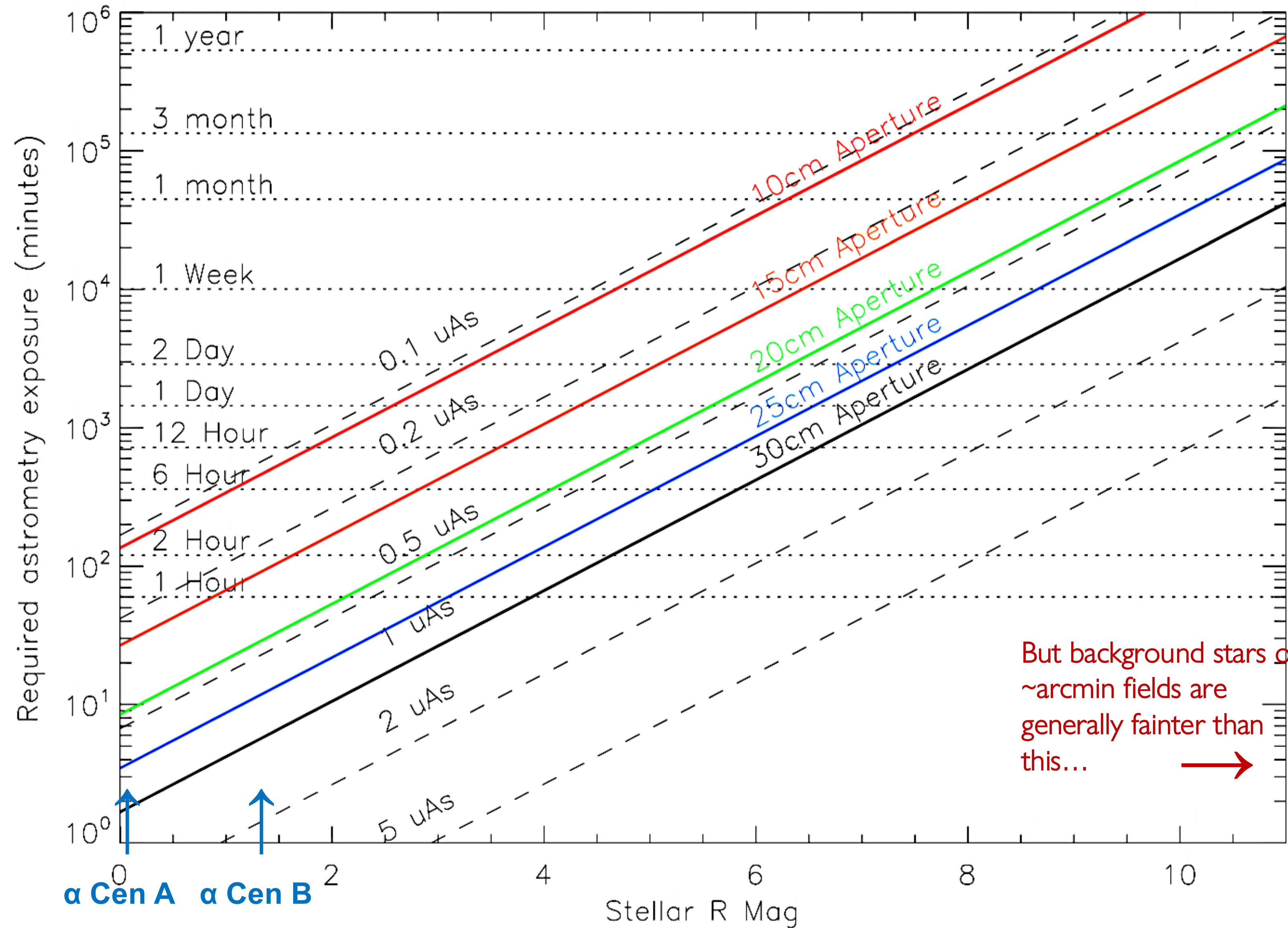
- Componets A, B (+ distant Proxima)
- Bright: 0 Mag + 1.3 Mag
- Nearest sun-like stars (more than factor 2!)
- Apparent 4" close approach: RV problematic
- 1 Earth Mass – 2.4 μ As for A; 1.2 μ As for B
- With .3m area needs ~hours of integration (compared to ~months for 12th mag ref star)
- Binary is near-equal (no contrast problem!)
- Unusual and Unique to have this system so close!

Habitable zones of Alpha Cen A (left) and B (right) in green, along with dynamical stability boundary (red dashed line)





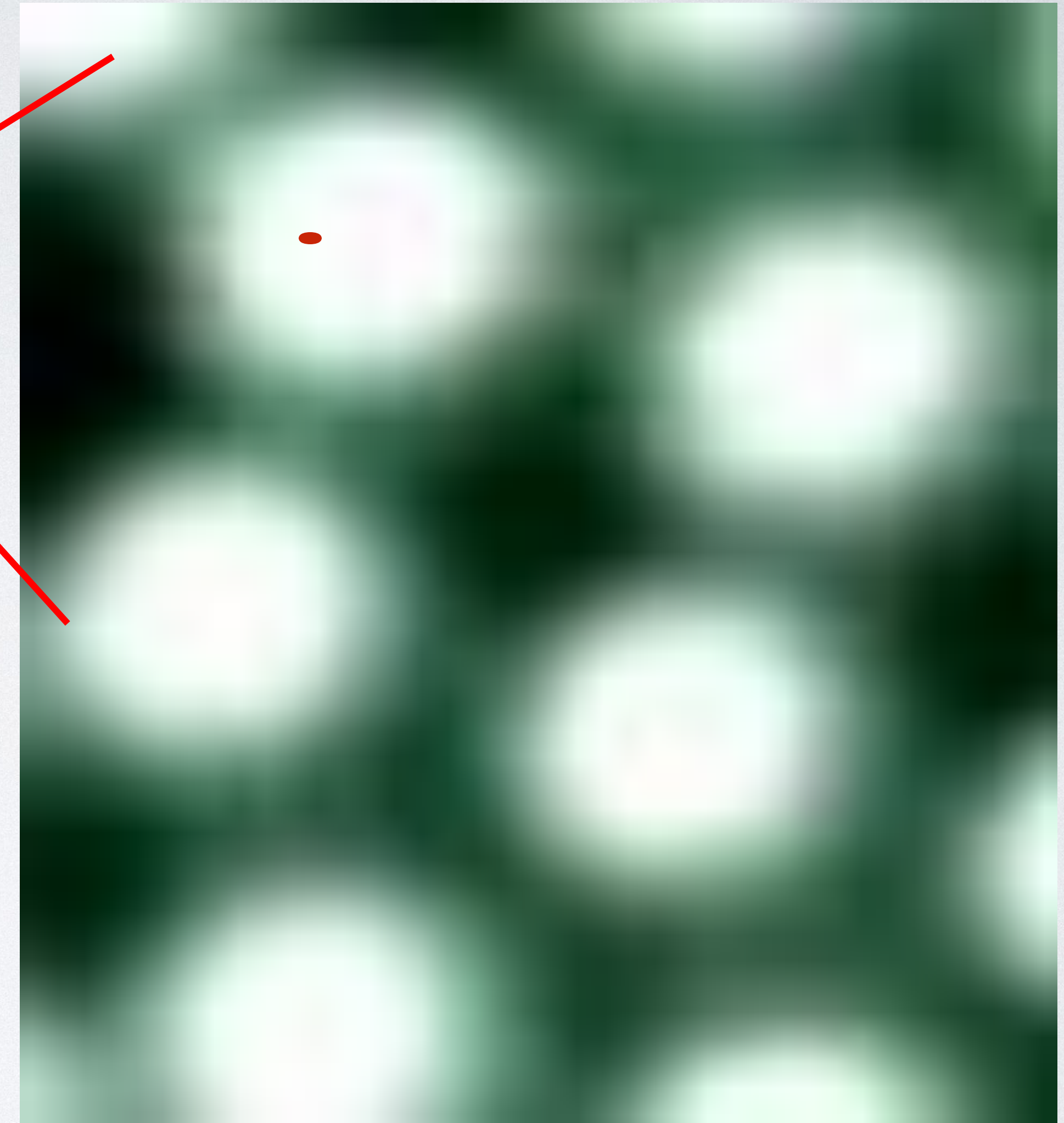
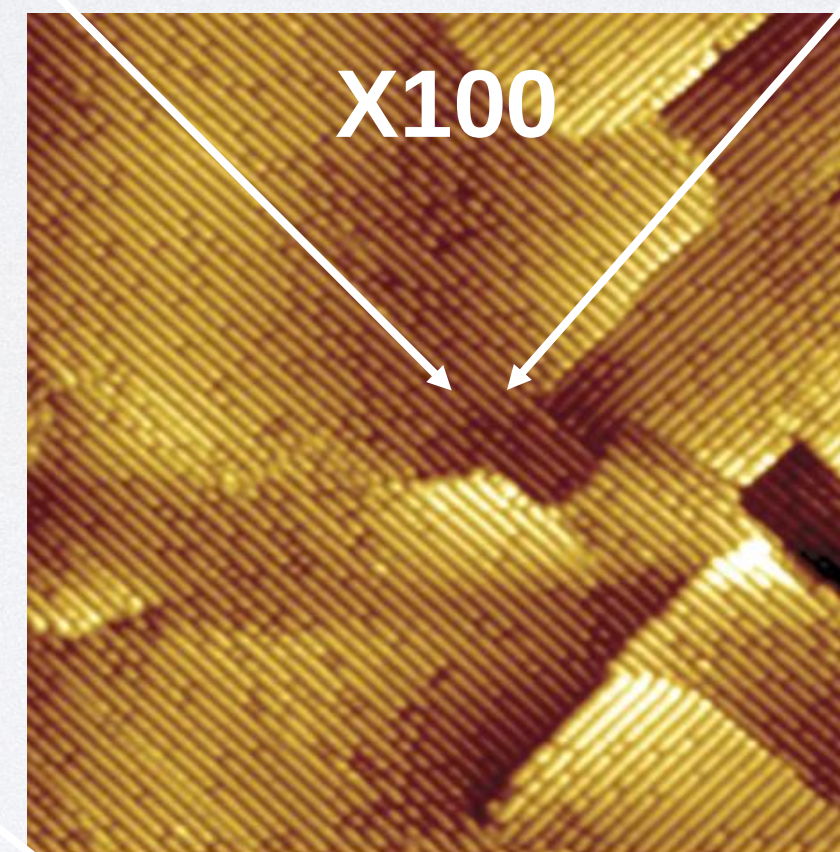
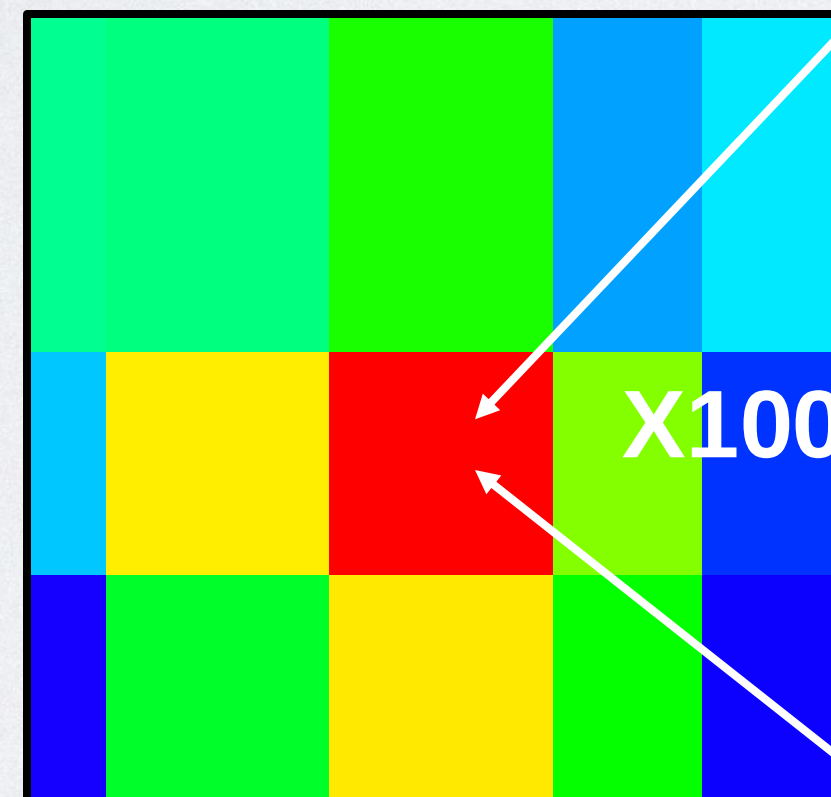
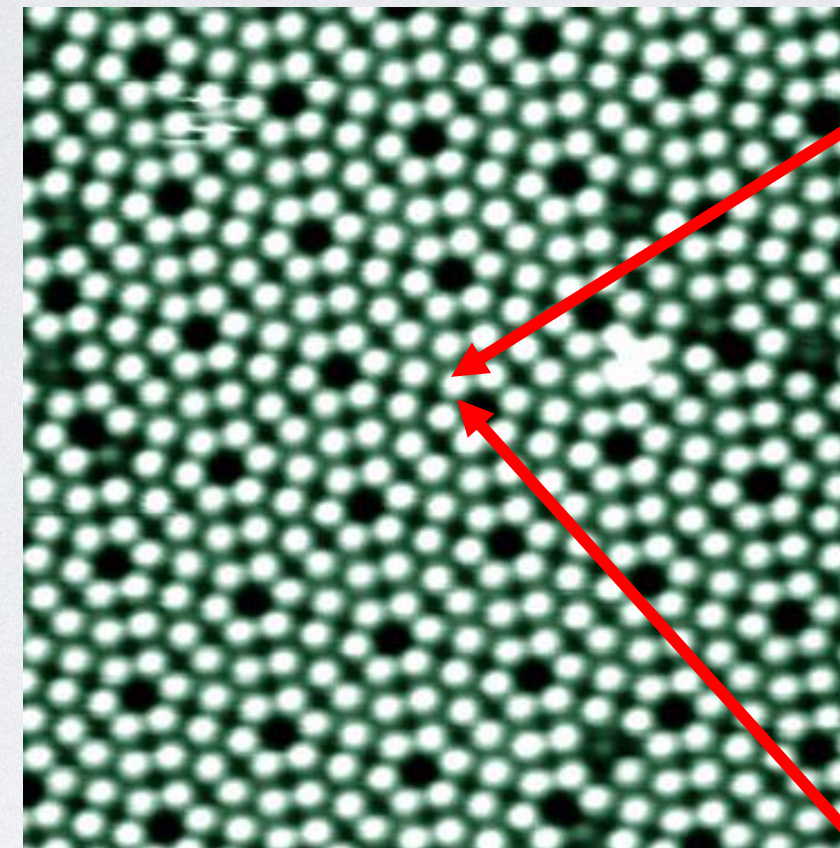
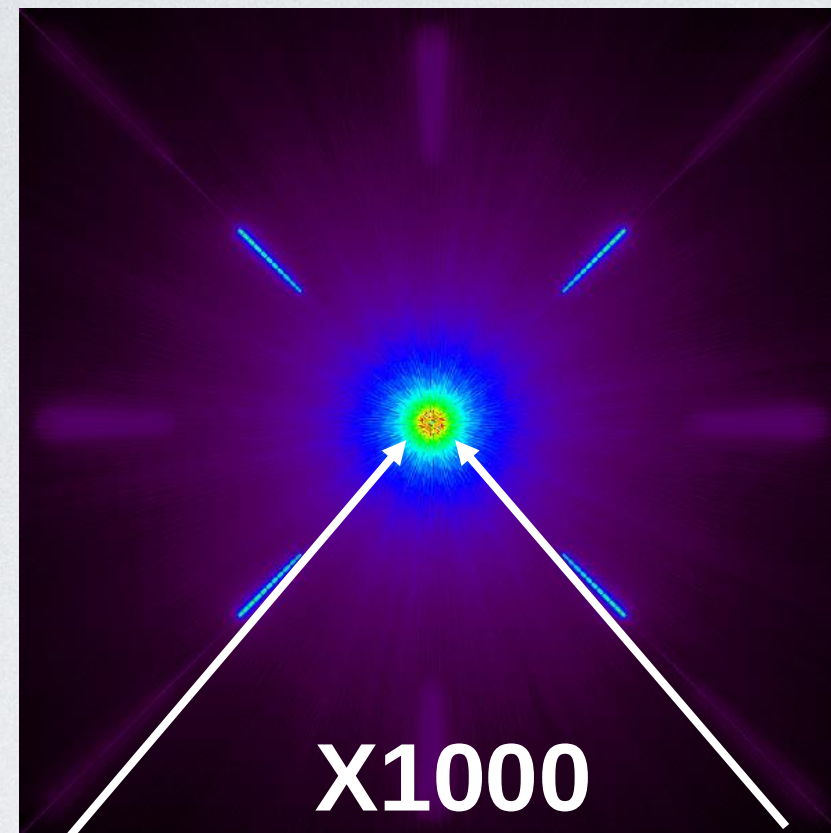
10cm Telescope fundamental (photon noise) limit: integration time required to obtain a given astrometric noise



But background stars on
~arcmin fields are
generally fainter than
this... →



The scale of the Instrumental Challenge





HOW CAN WE MAKE THIS MEASUREMENT ?

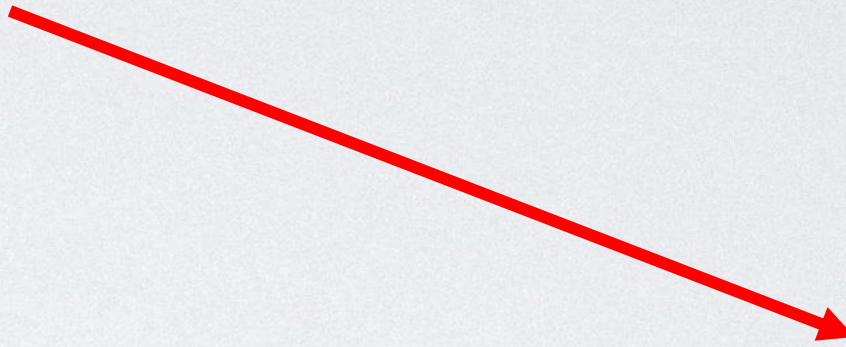
(WITHIN A CUBESAT FORM FACTOR)



Hardware

VERY unorthodox optical system
Stable, high performance telescope

- Excellent pointing (low jitter – better than 1" per second image drift)
- Extreme mechanical and thermal stability required
- Challenges also for on-board data processing, downlink.
- Everything must fit within a cubesat form factor



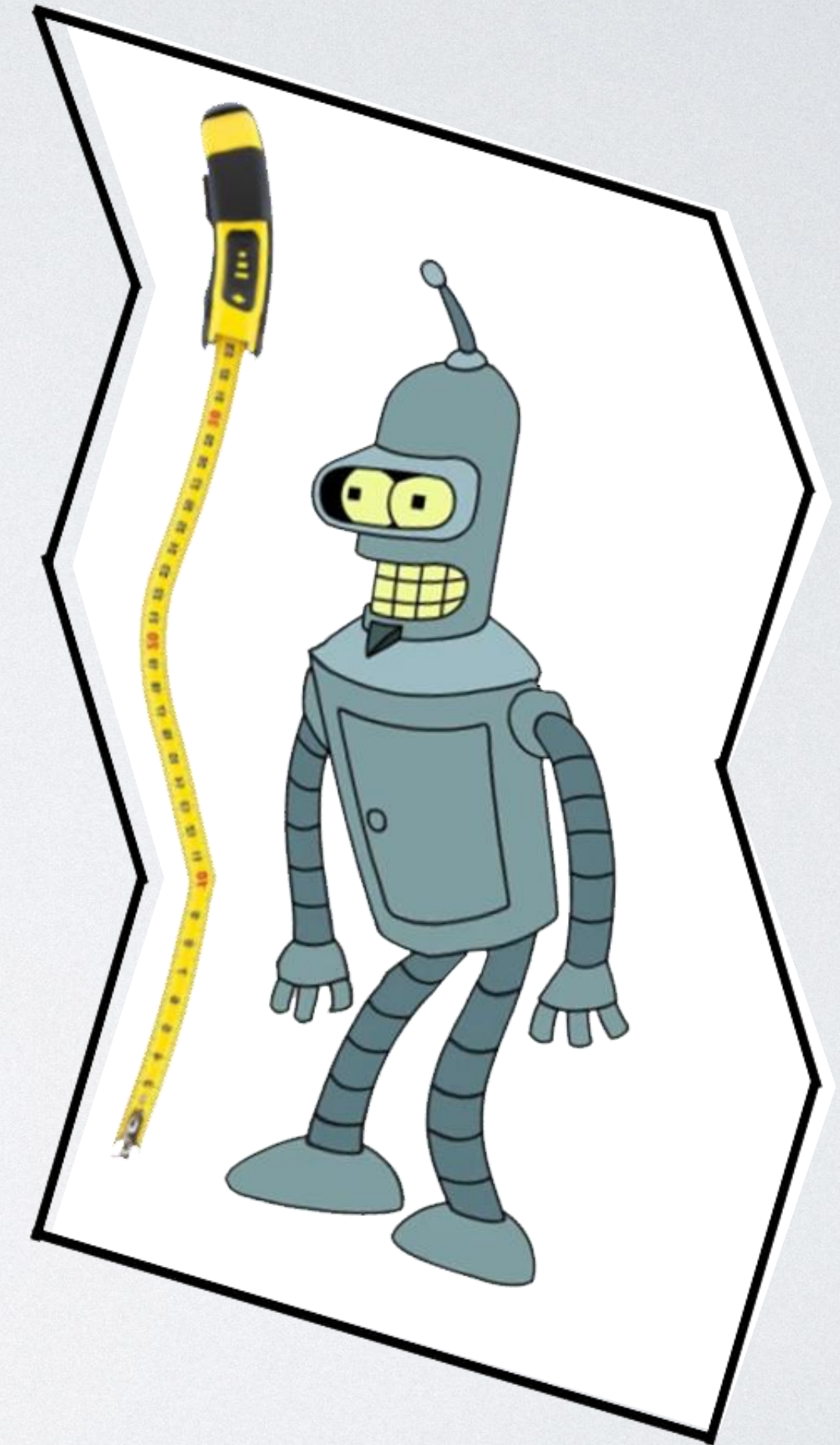
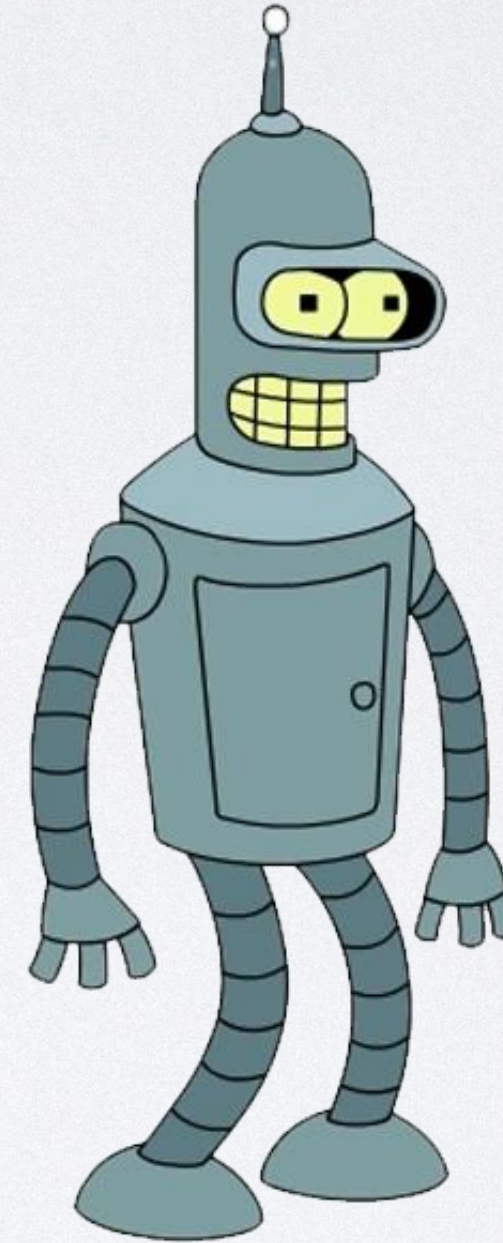
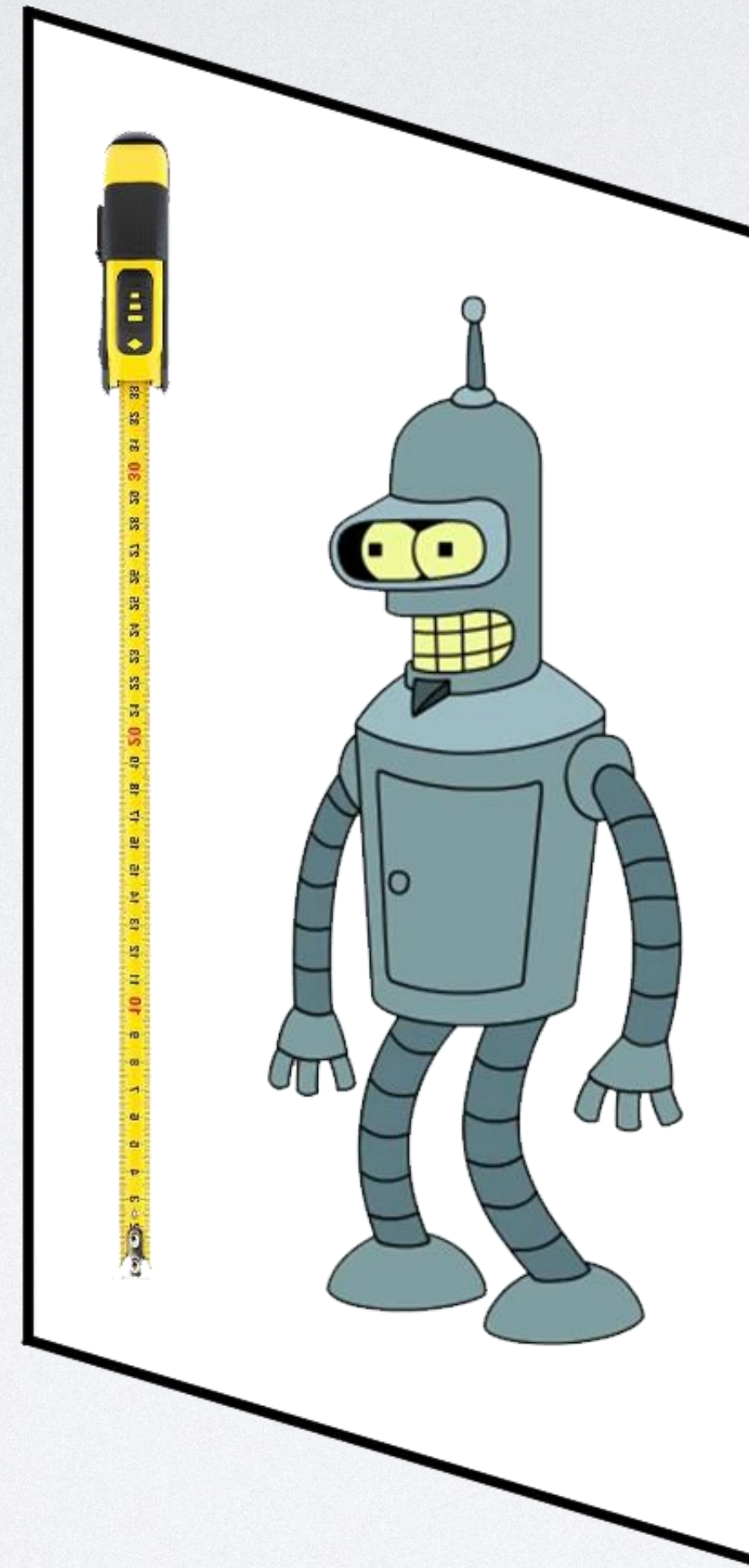
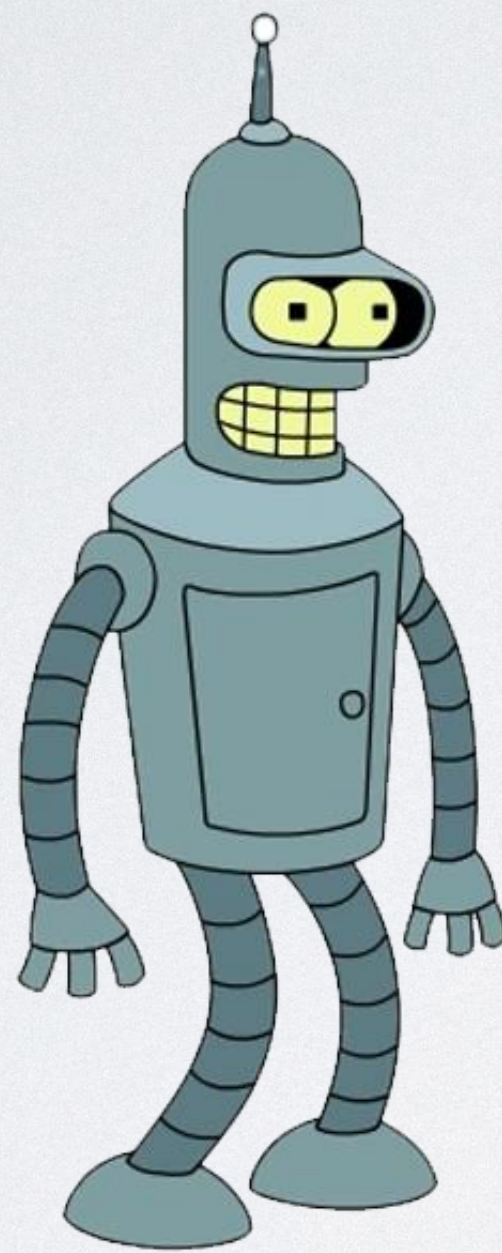
Software

VERY unorthodox data handling
Extreme performance
Statistically principled

- Data handling to extract signal from and tease out (many) systematics.



Optical distortions don't matter if they bend
both your ruler and your object...





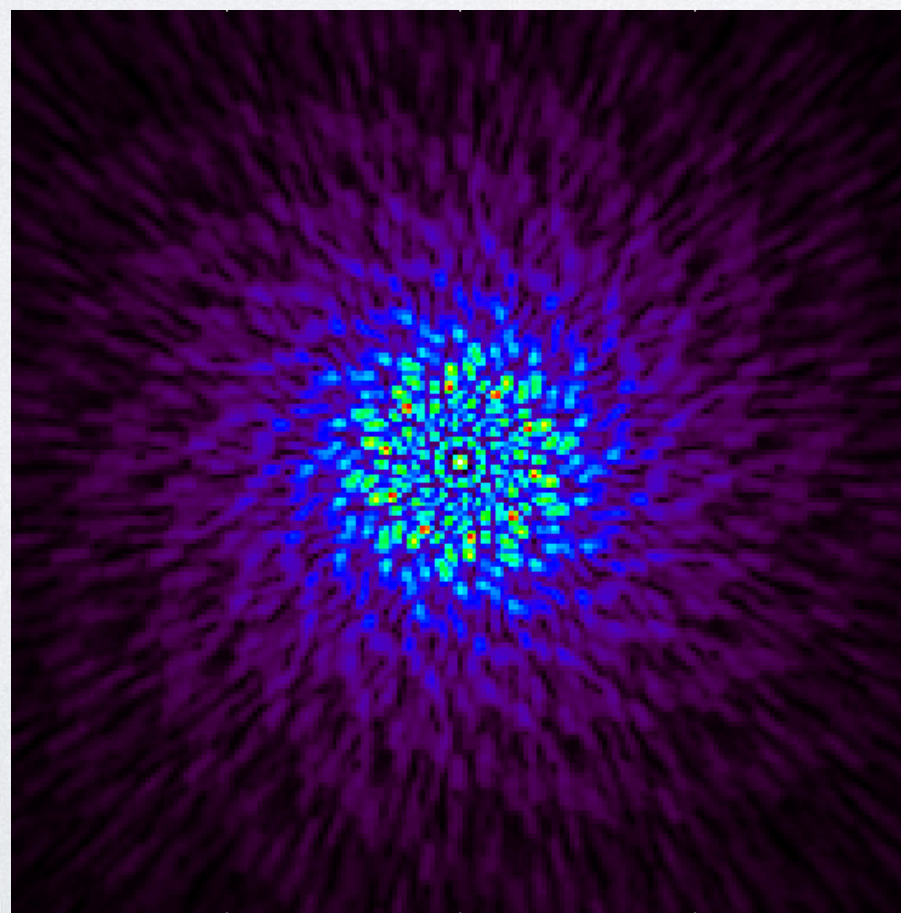
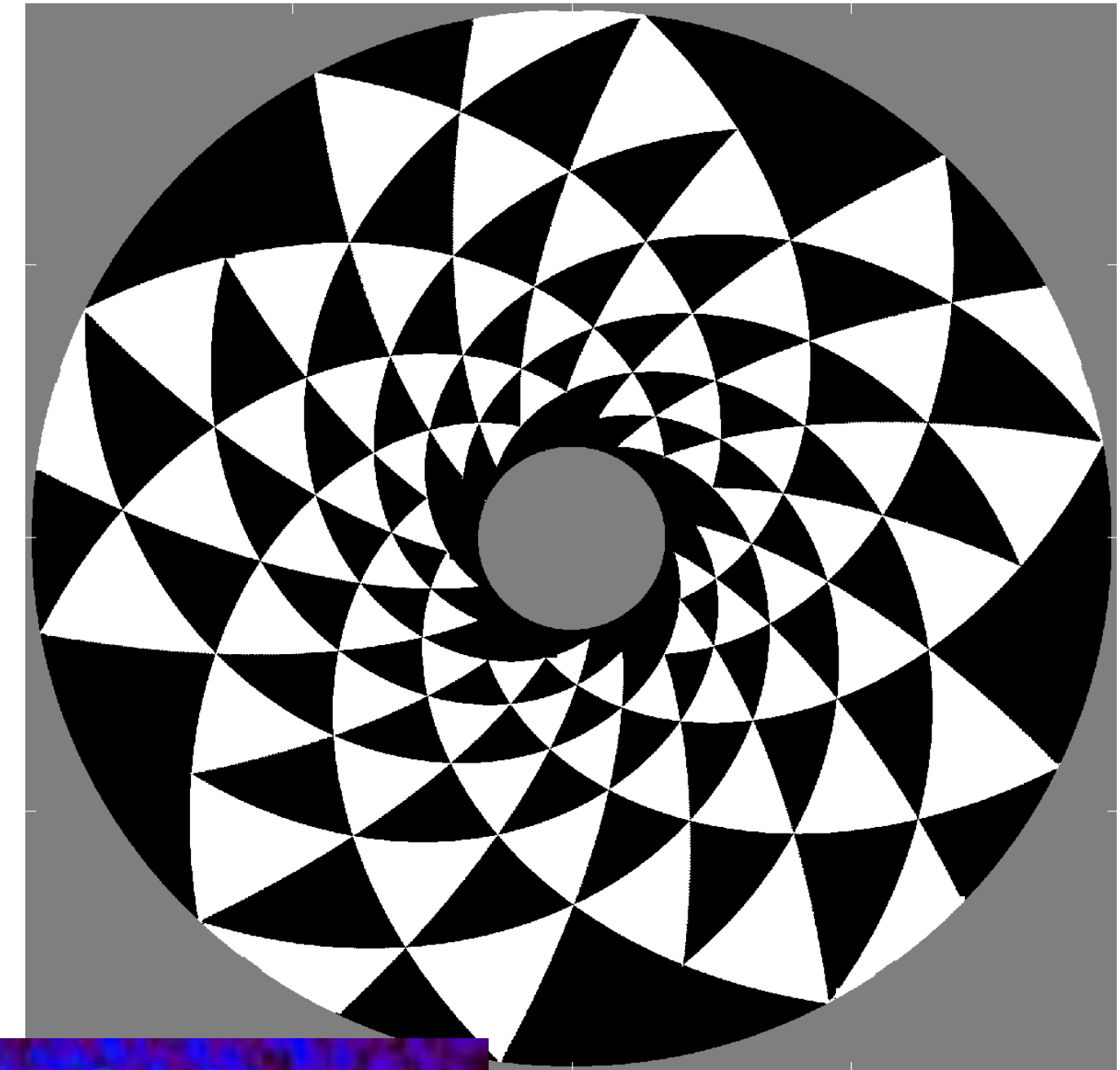
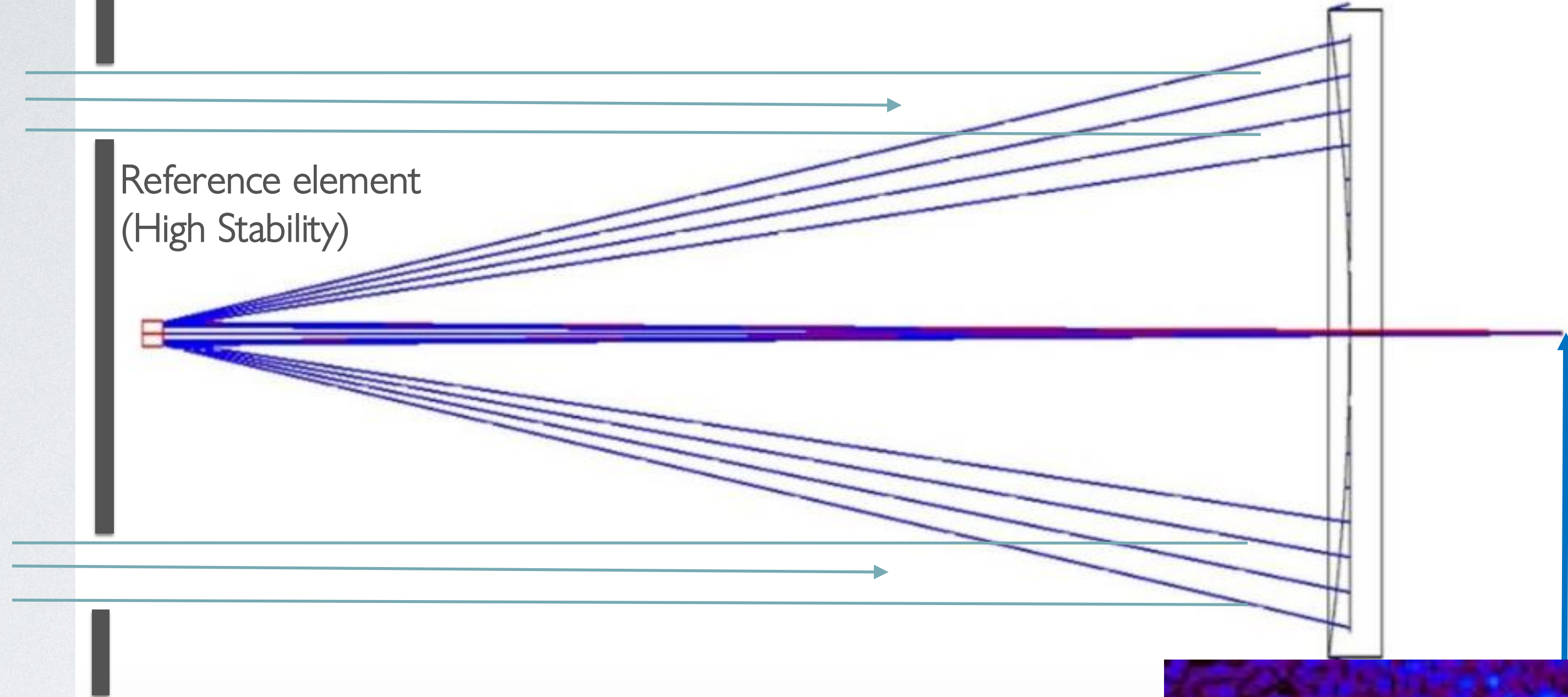
Optical concept empowering TOLIMAN

Diffractive-pupil pupil mask

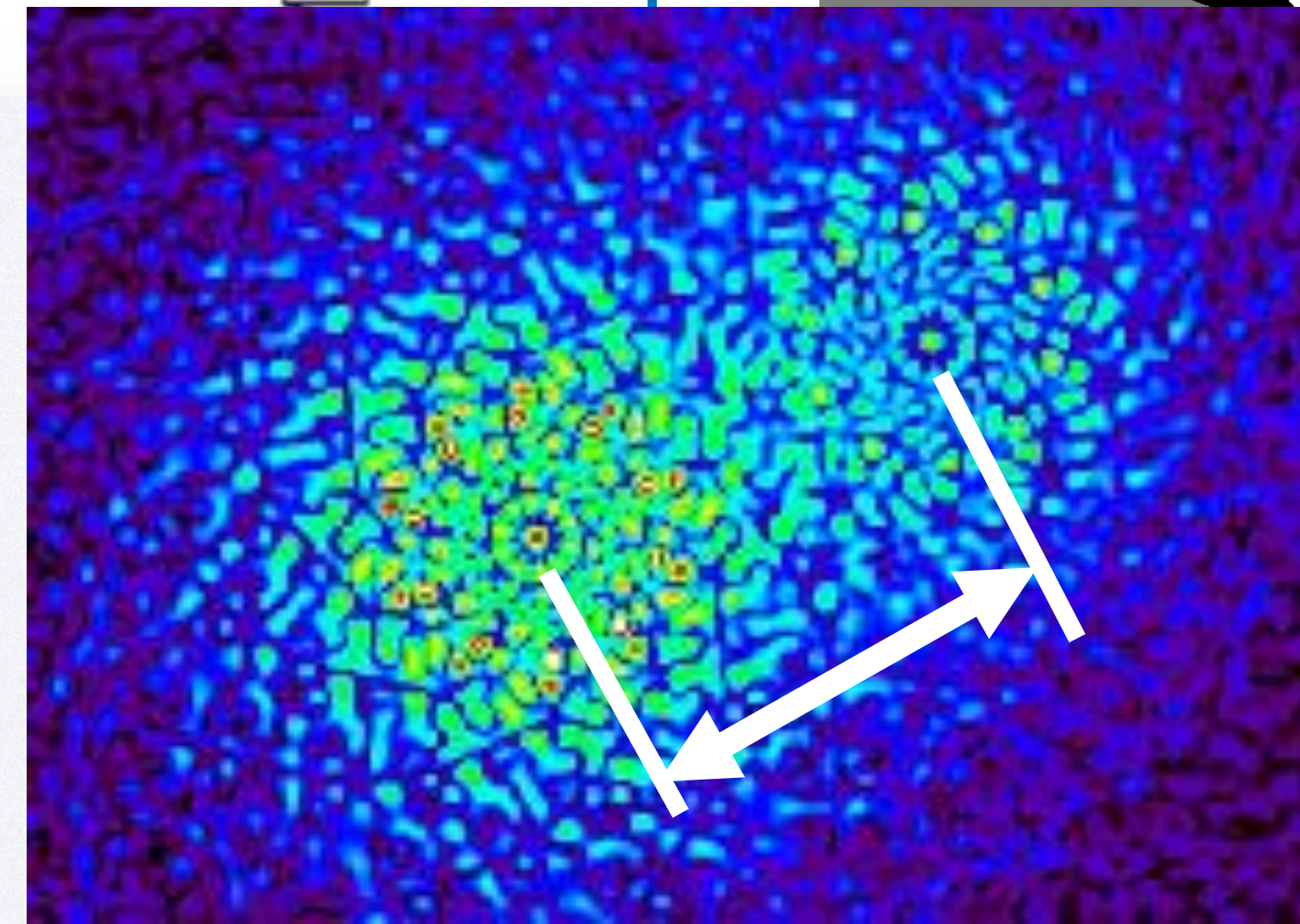
Monitor the binary with a diffractive ruler made of starlight!



Reference element
(High Stability)

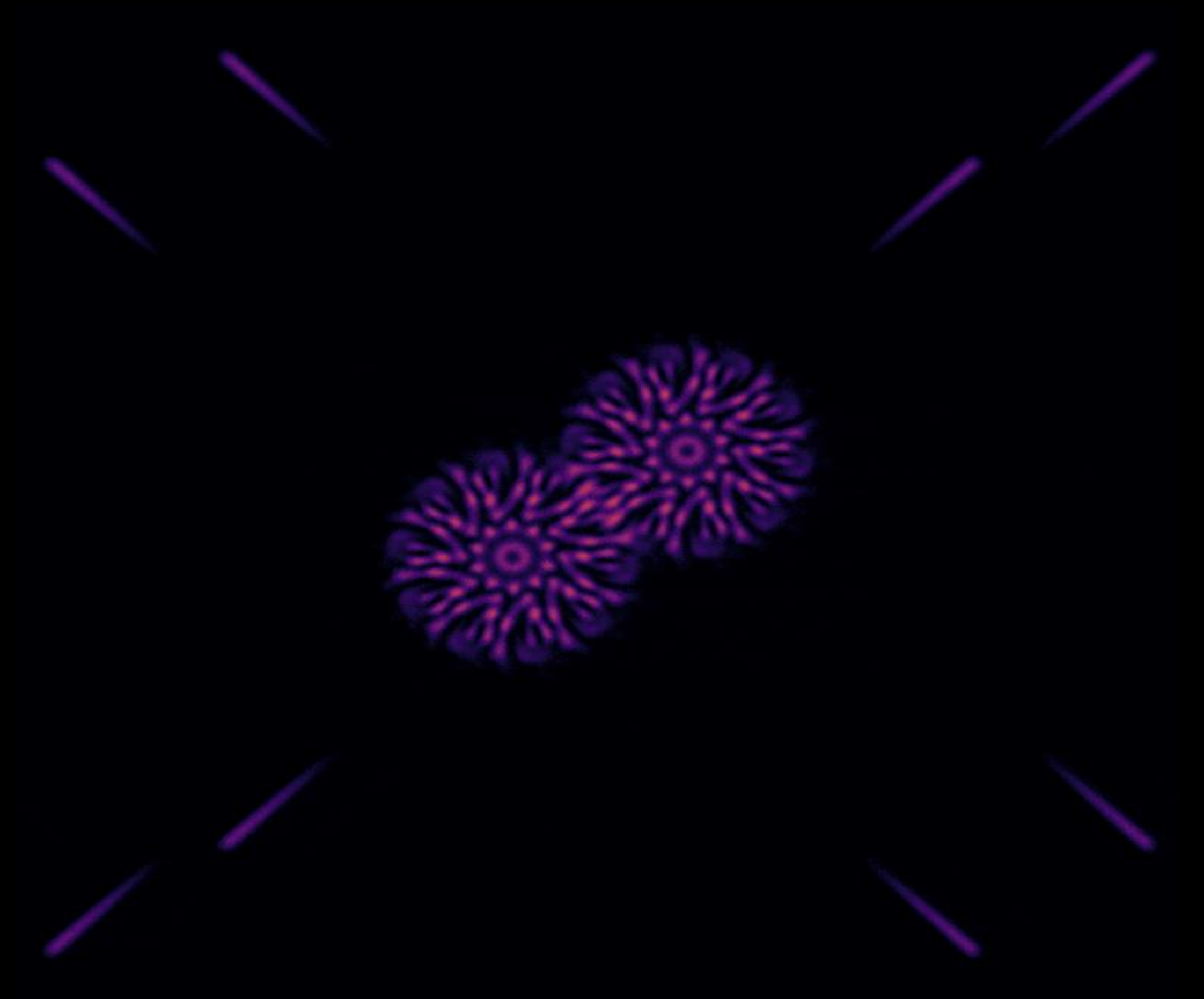
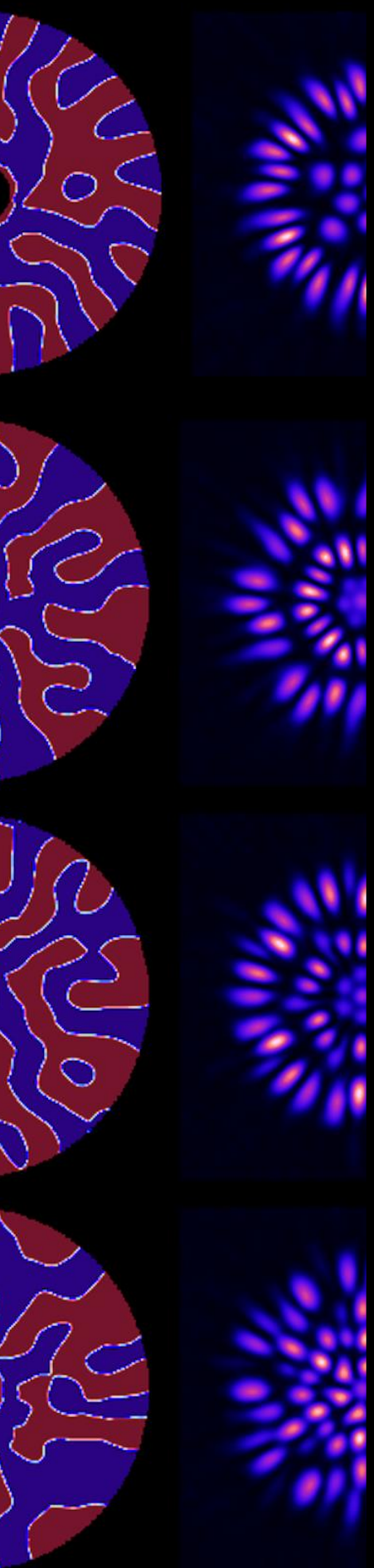


Point
Spread
Function



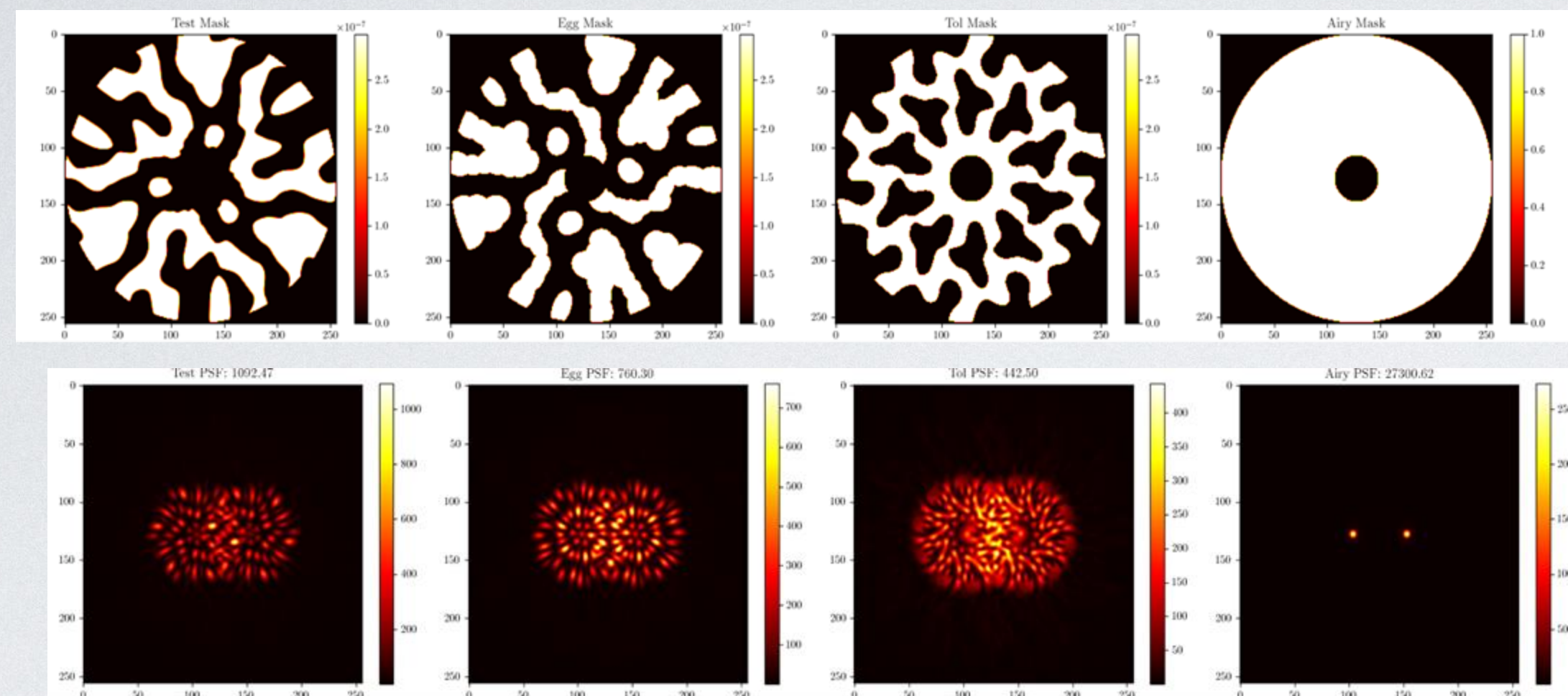


2LUX





Posteriors: Separation, field angle, flux ratio

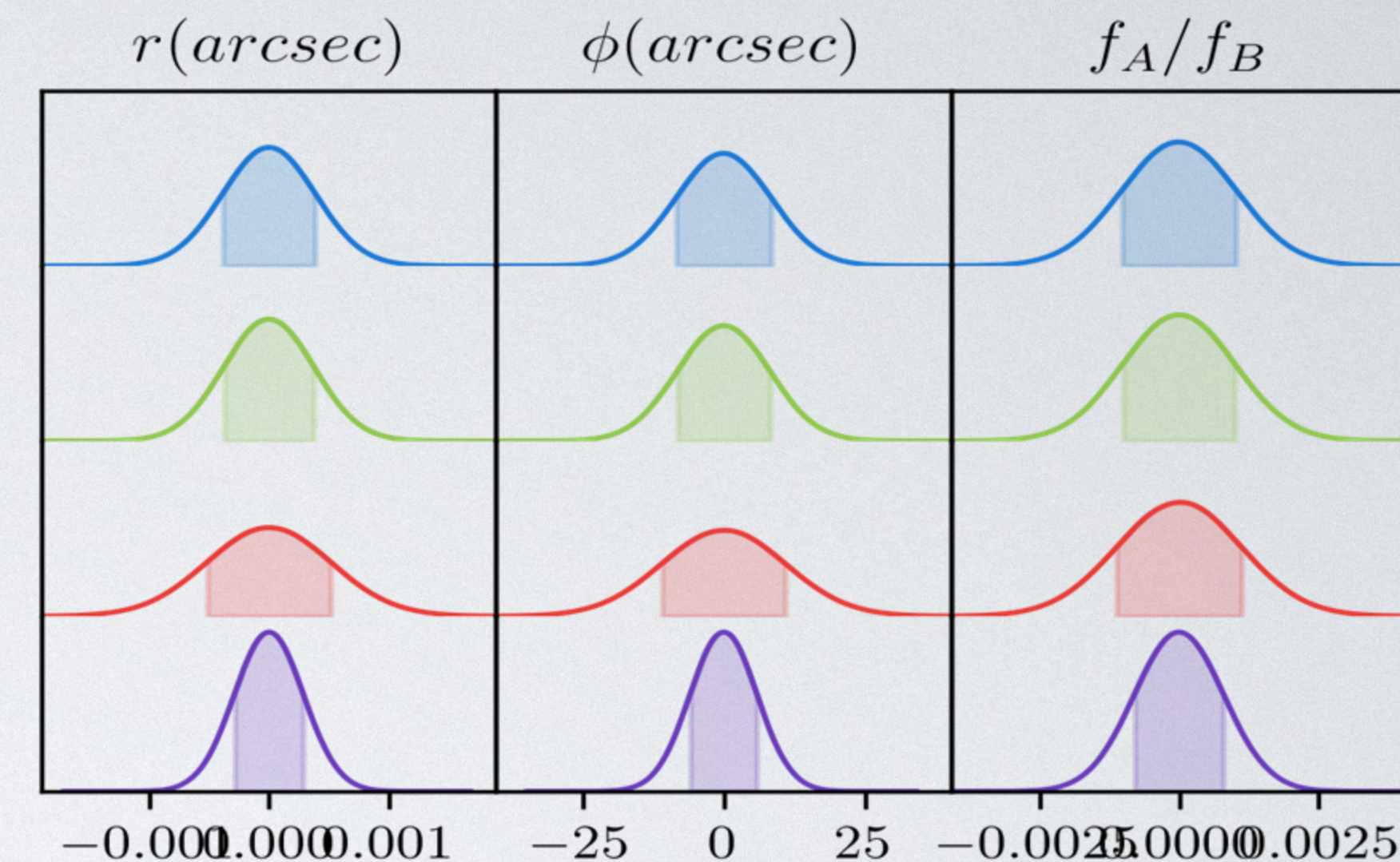


Test

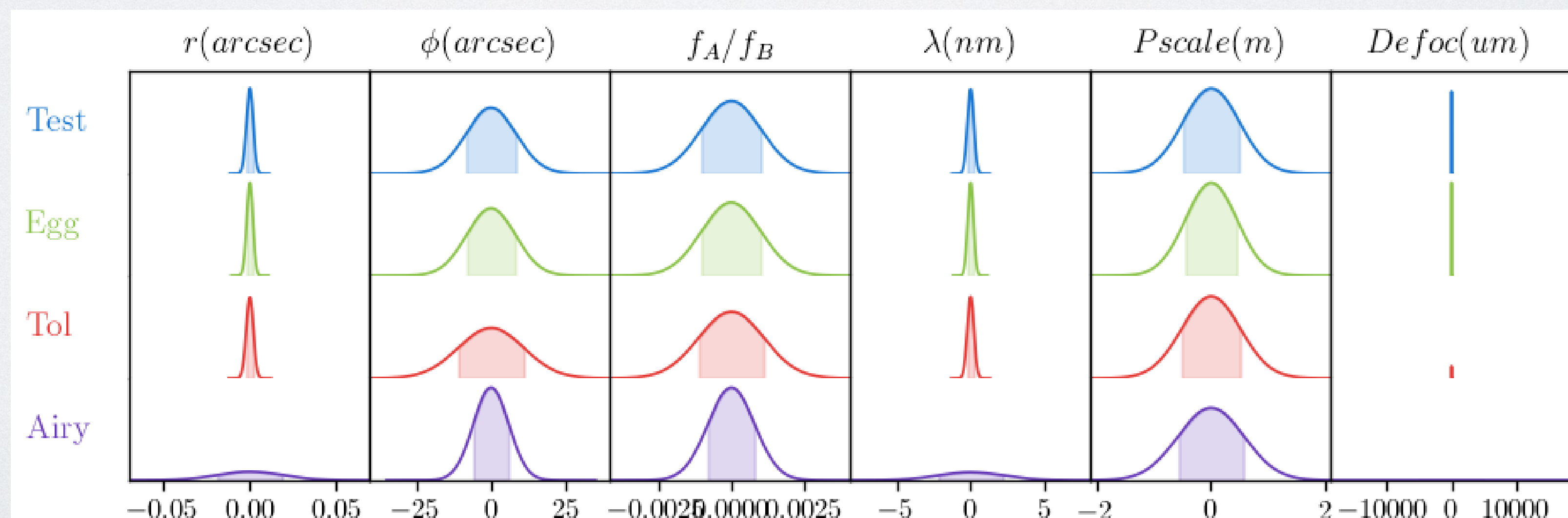
Egg

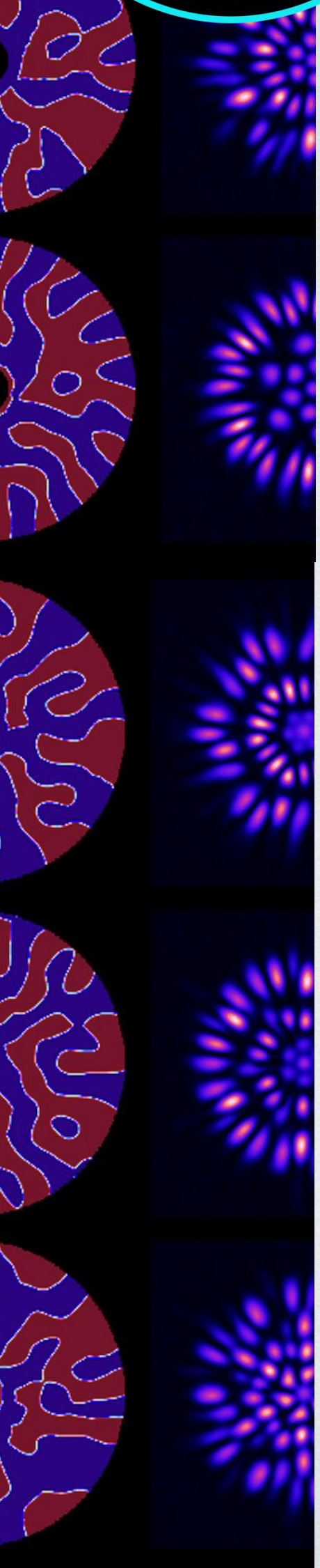
Tol

Airy



POSTERIOR: ADDING WAVELENGTH, PLATE SCALE,

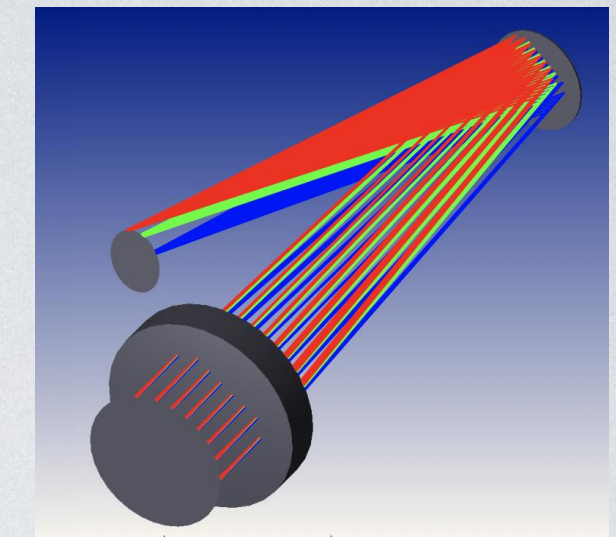
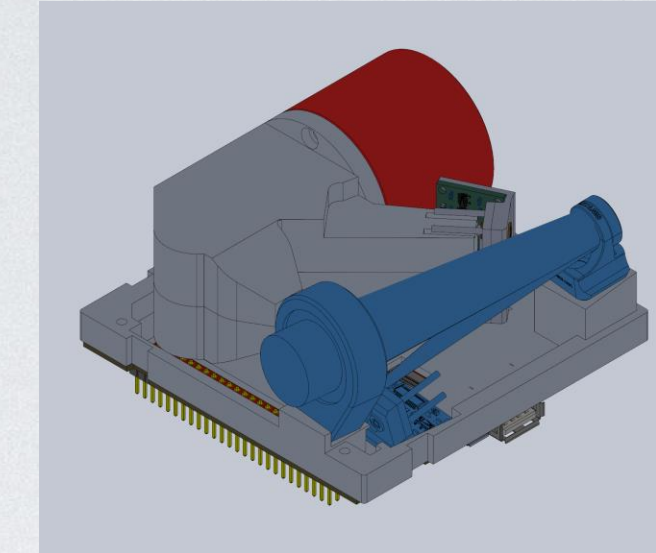




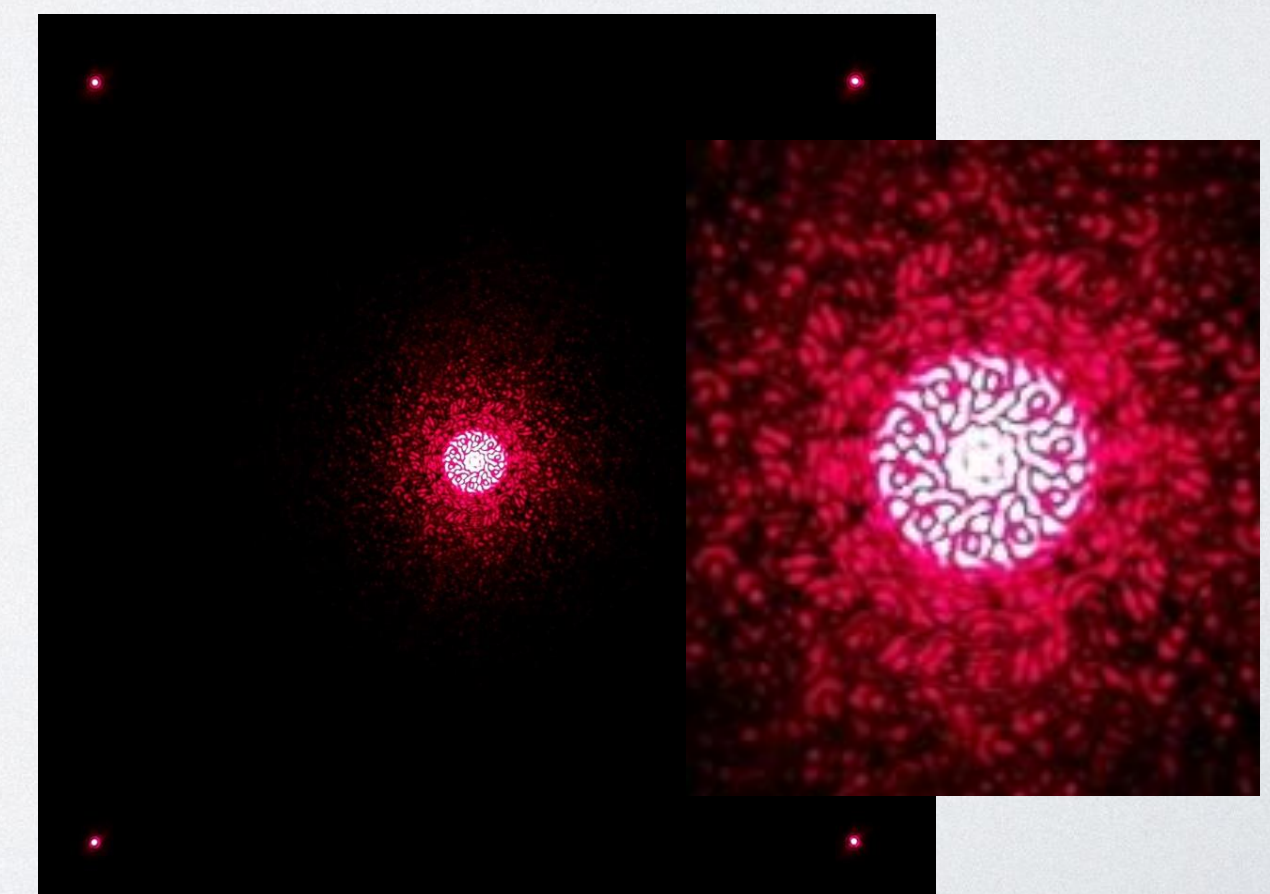
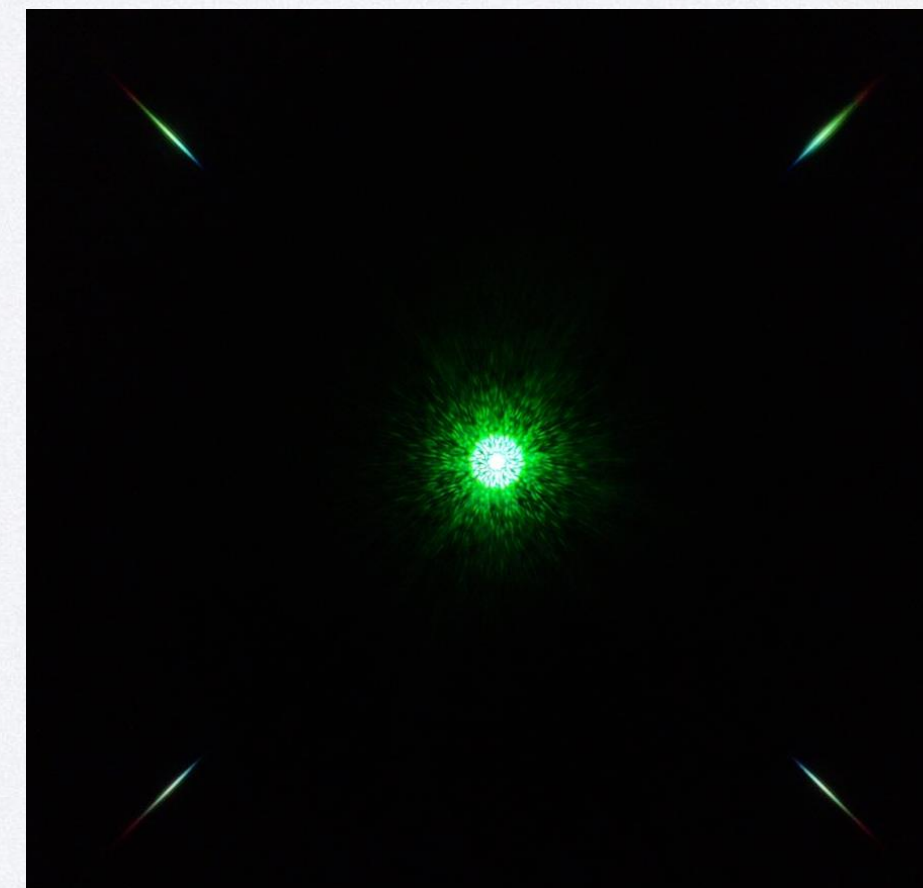
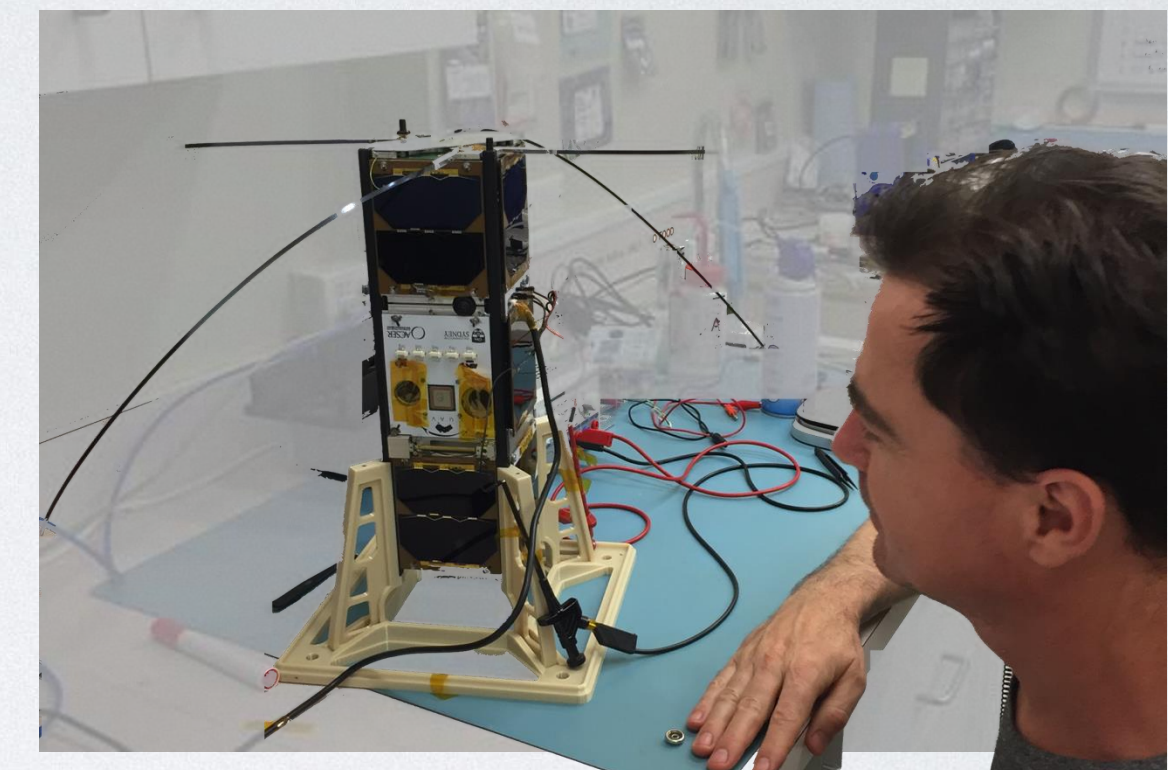
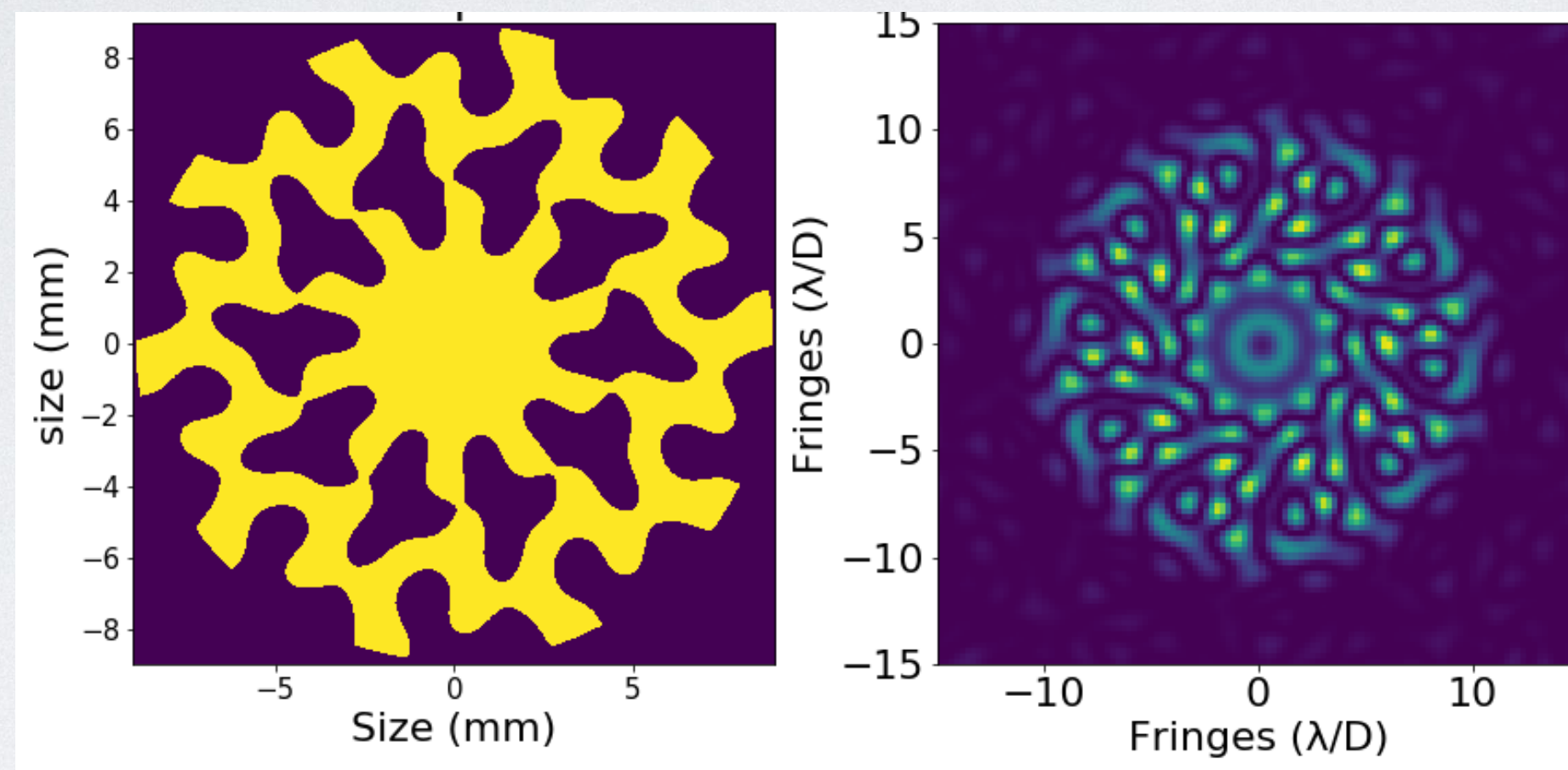


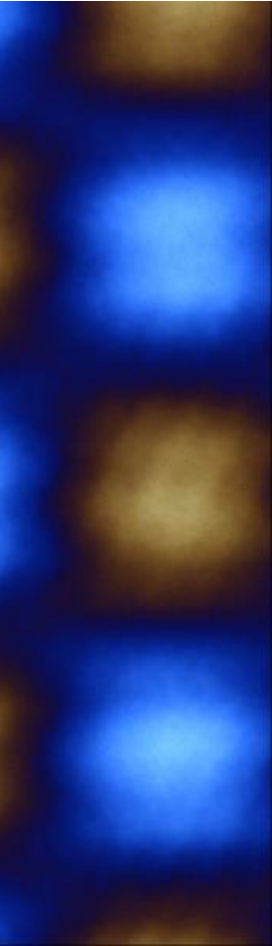
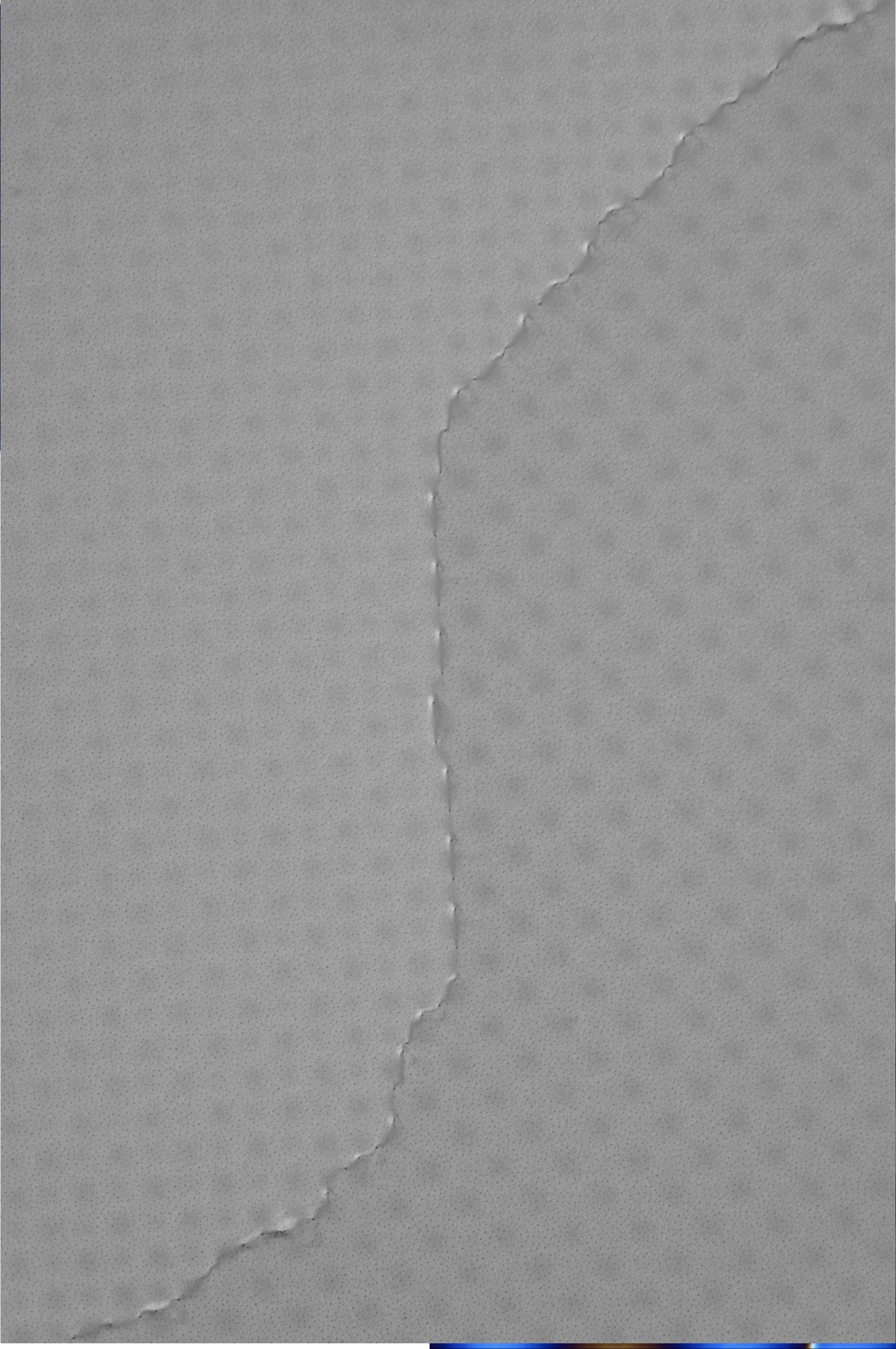
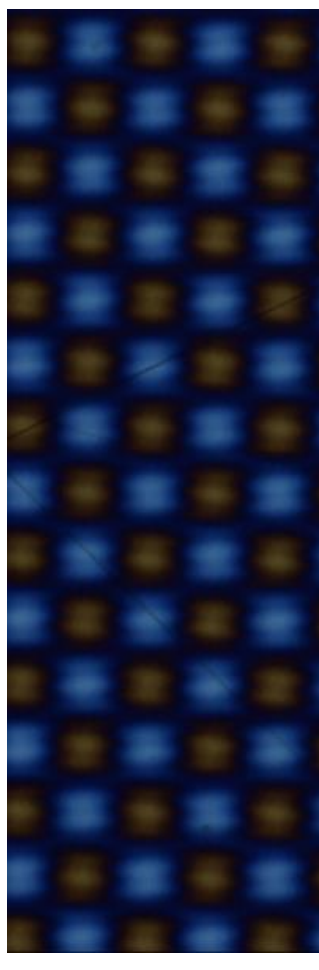
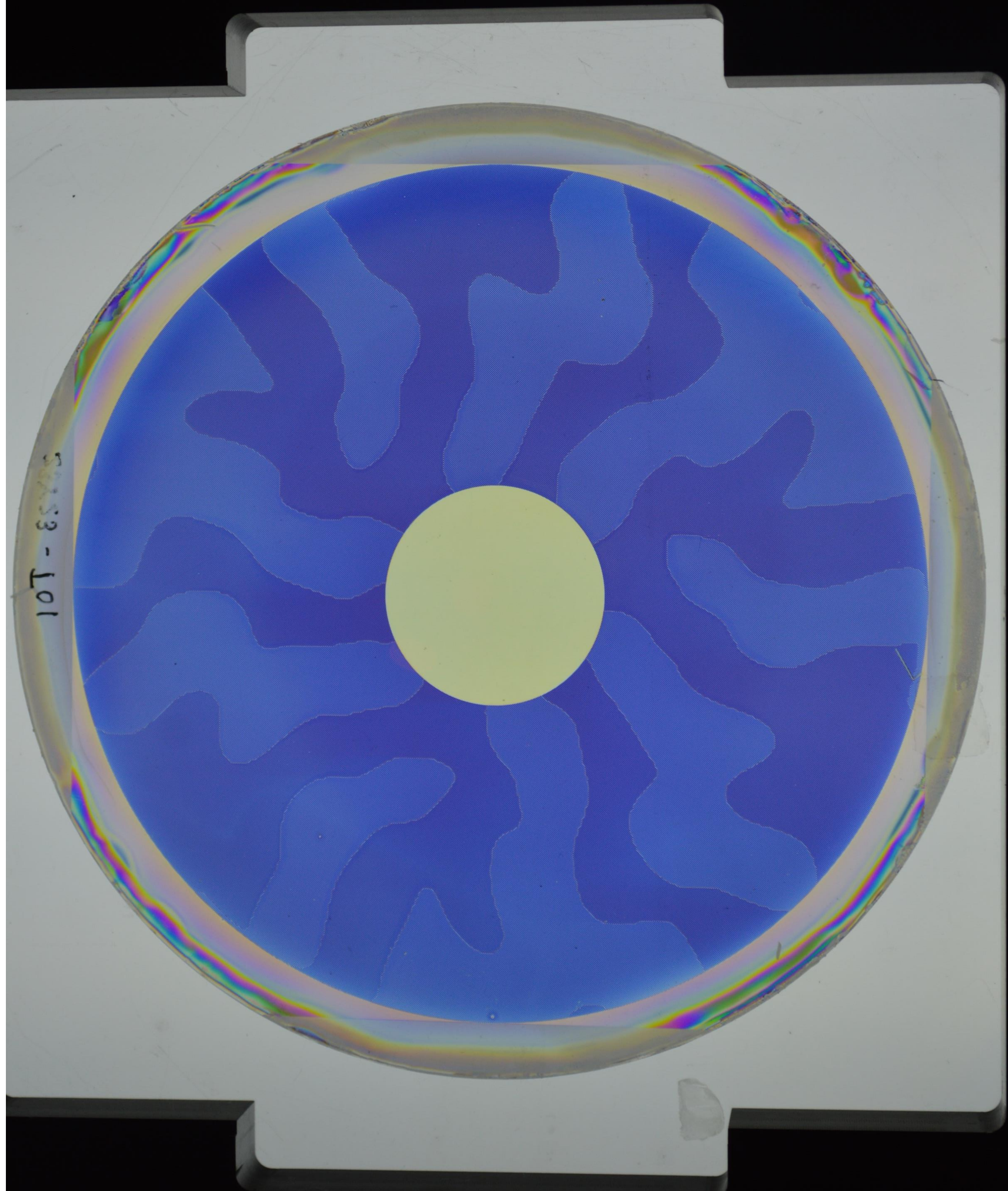
Program: TinyTol, Toliman, ...

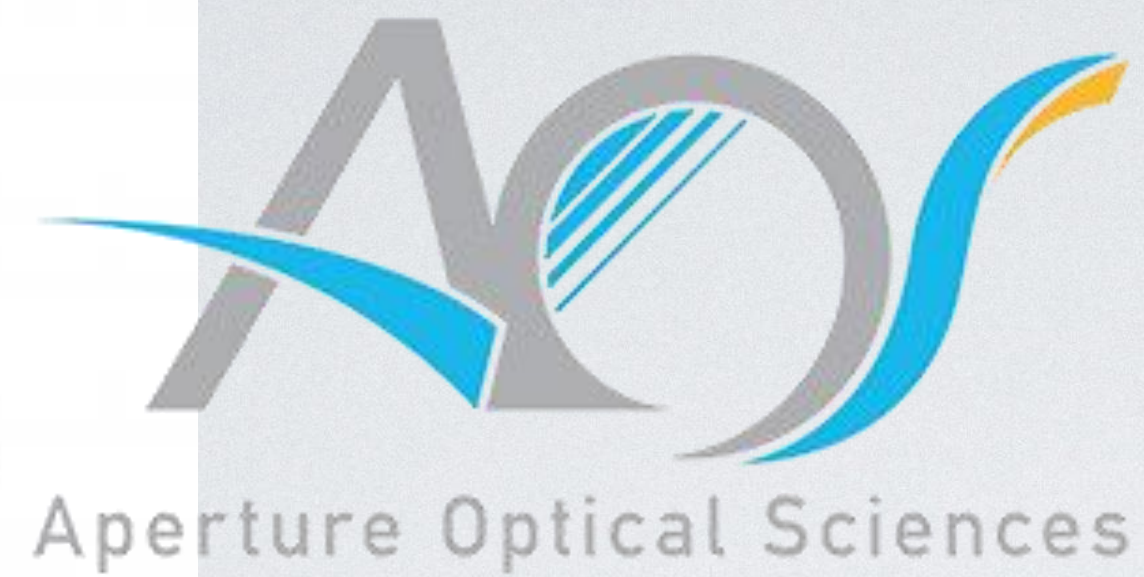
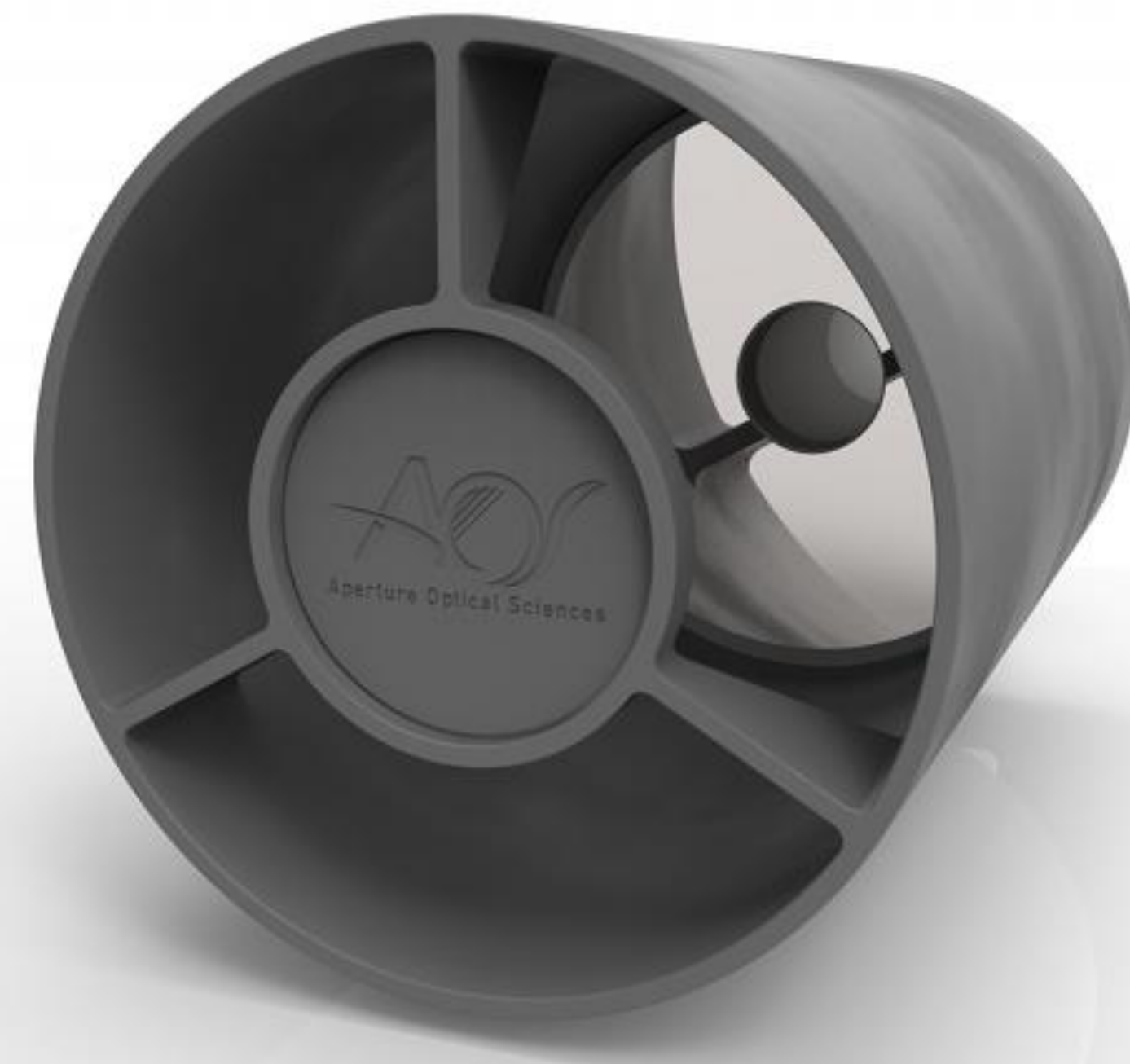
- TinyTol flew aboard CUAVA1
 - 3U cubesat. ISS resupply deployed 2020
 - 20mm aperture, $f=15\text{cm}$, 1 deg FoV
 - Consumer-grade electronics
 - Built, deployed, flown. No data.



TT instrument / Ray Trace

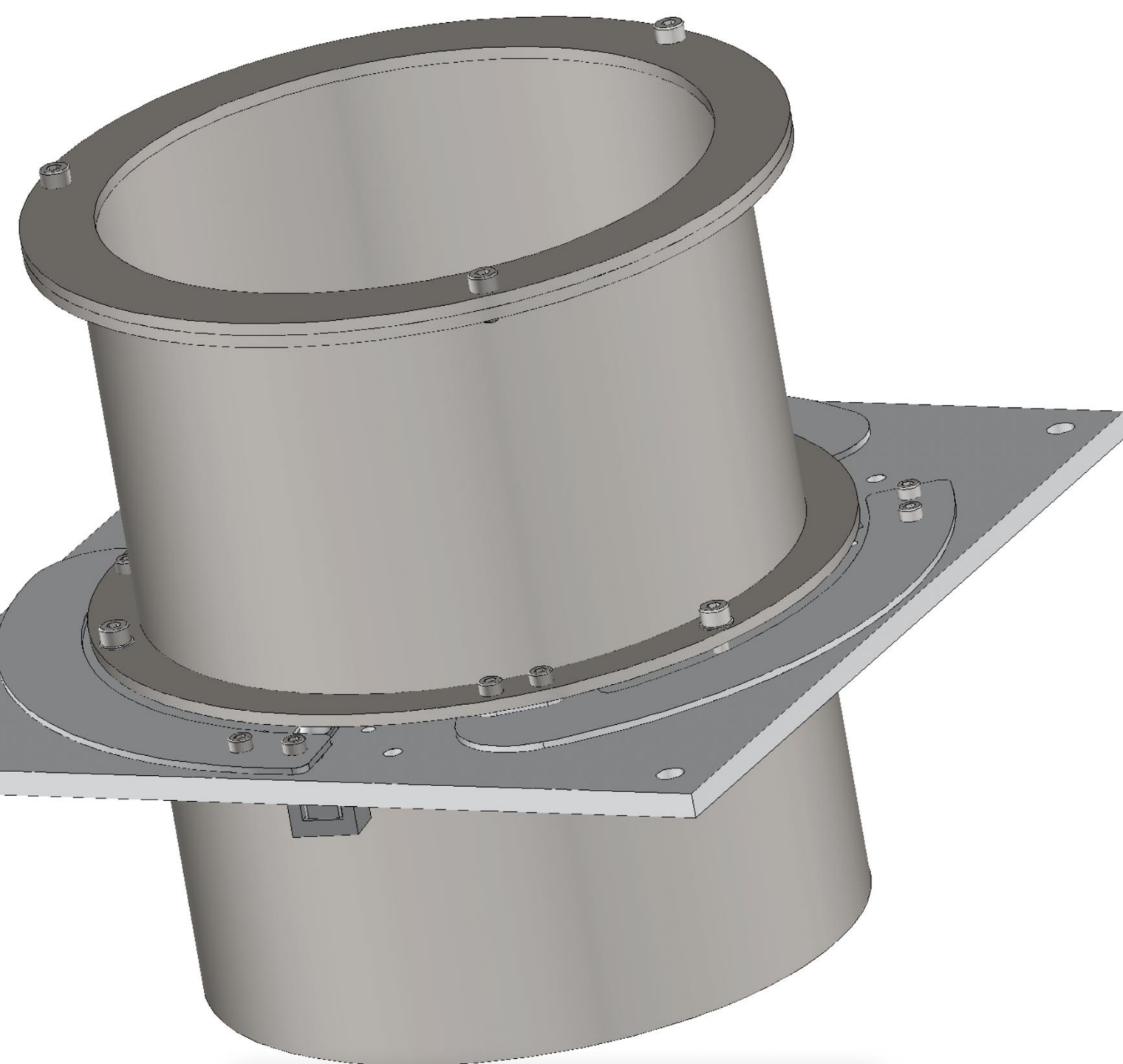




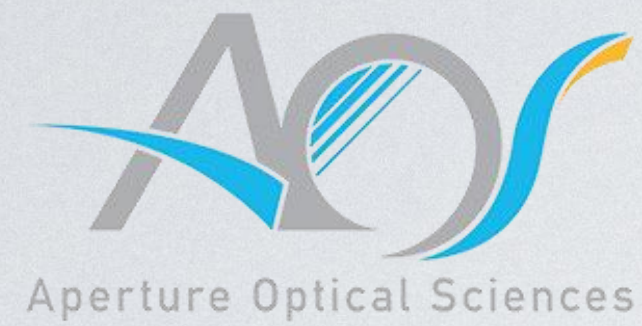


SiC Telescope

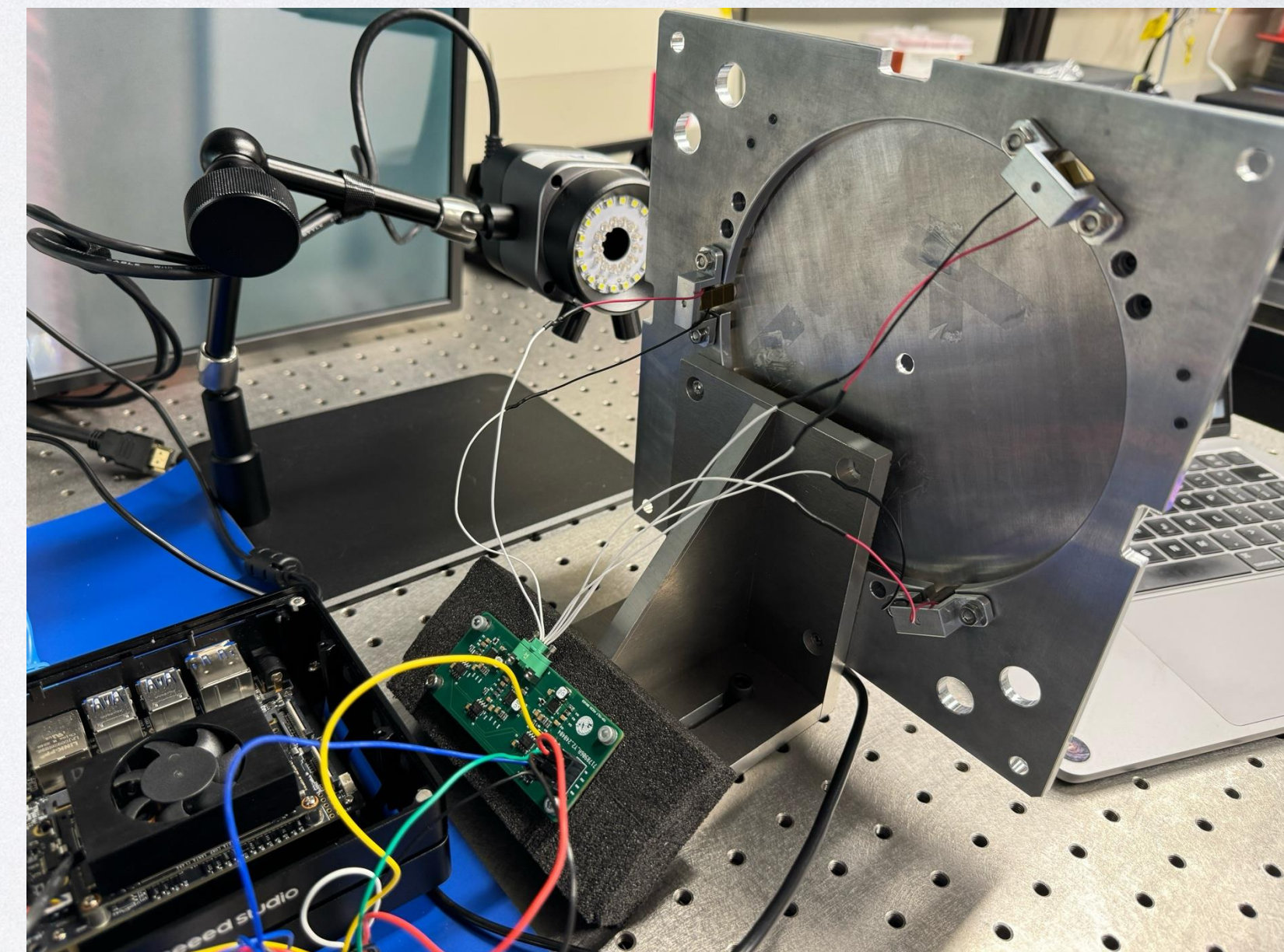
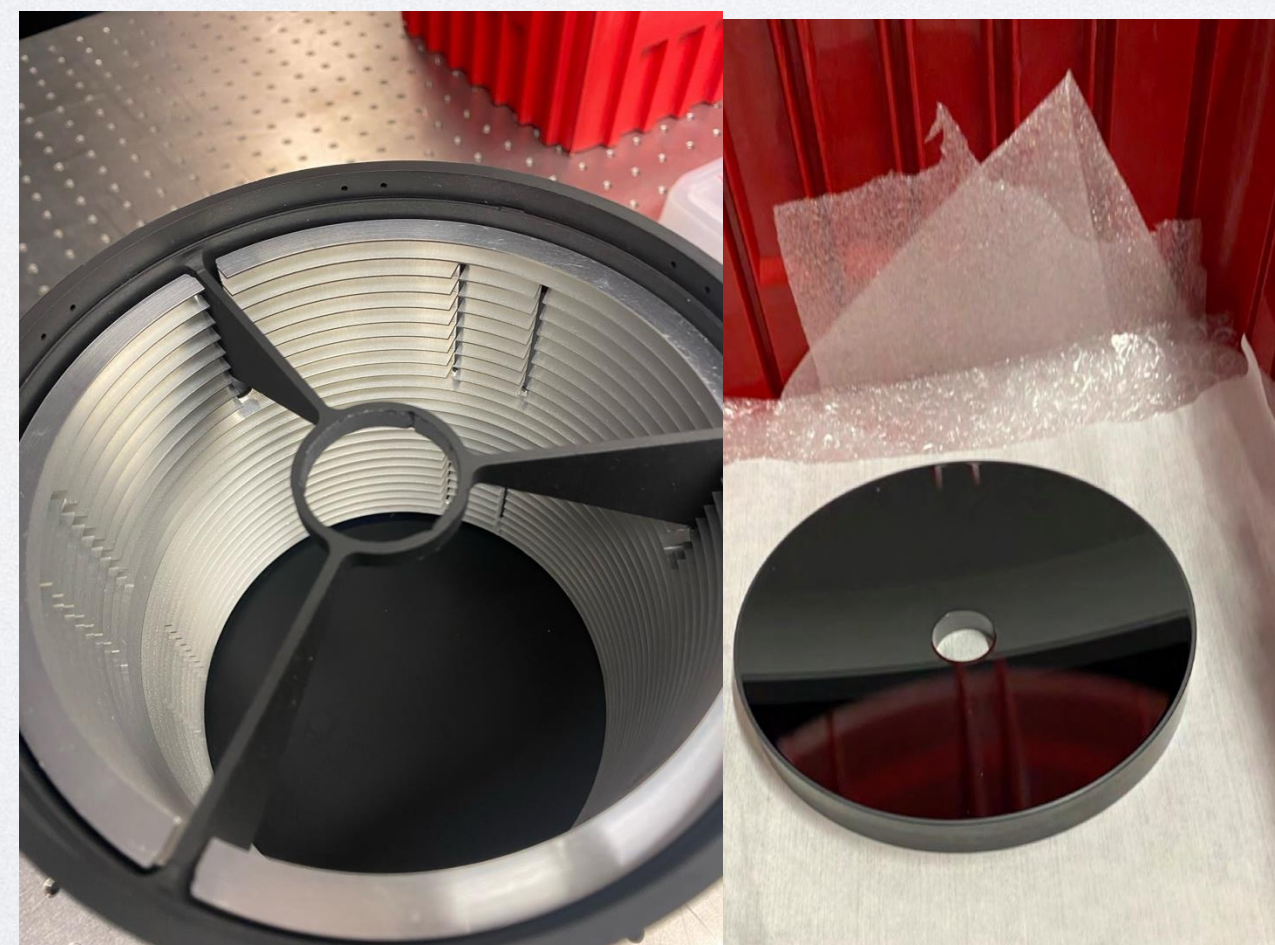
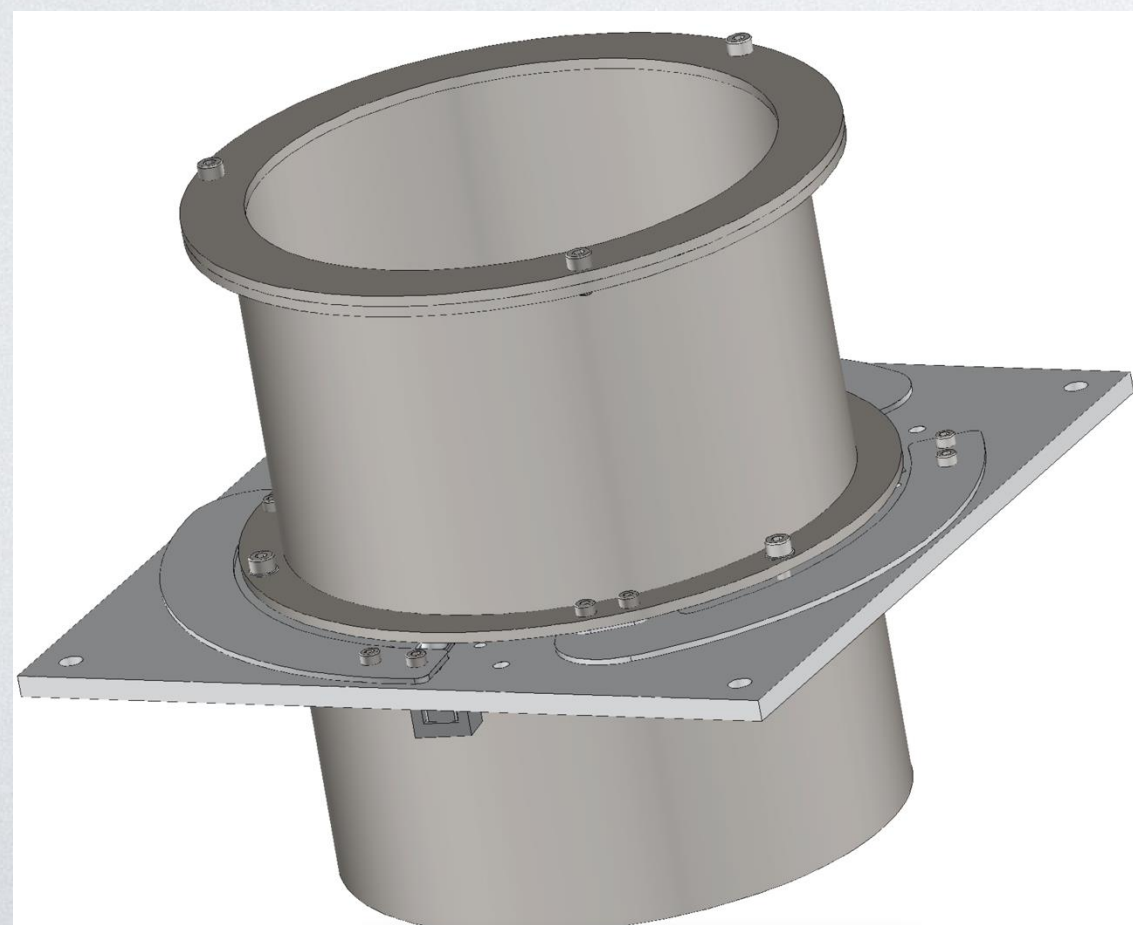
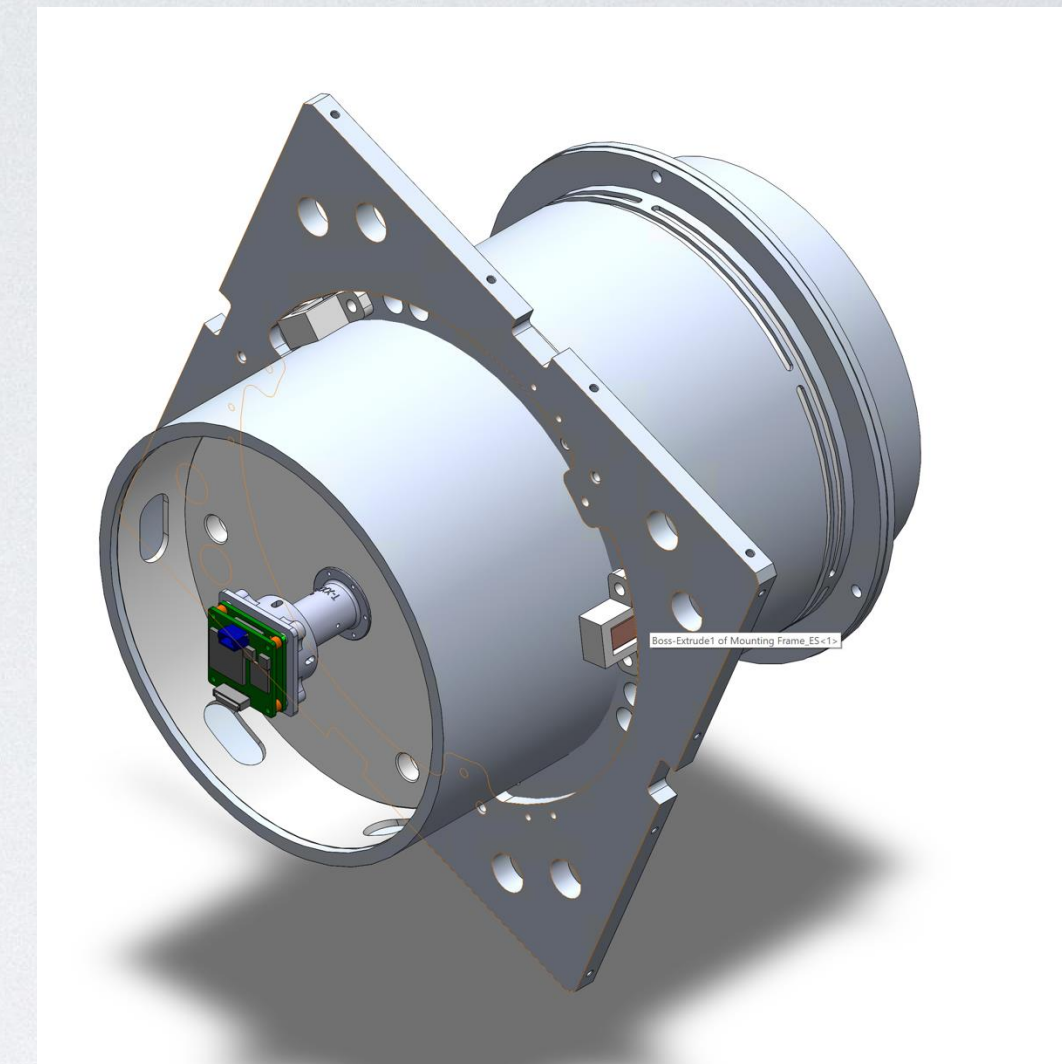
- Design has space heritage
- 130cm Primary Mirror
- F/10 custom prescription to match detector
- Pure Silicon Carbide structure
 - Low CTE, ideal for Toliman
- Deliver Q4 2024
- USYD developing mounting interface with piezo based tip-tilt system for fine pointing



MECHANICAL INTERFACE & TIP TILT



Connor Langford

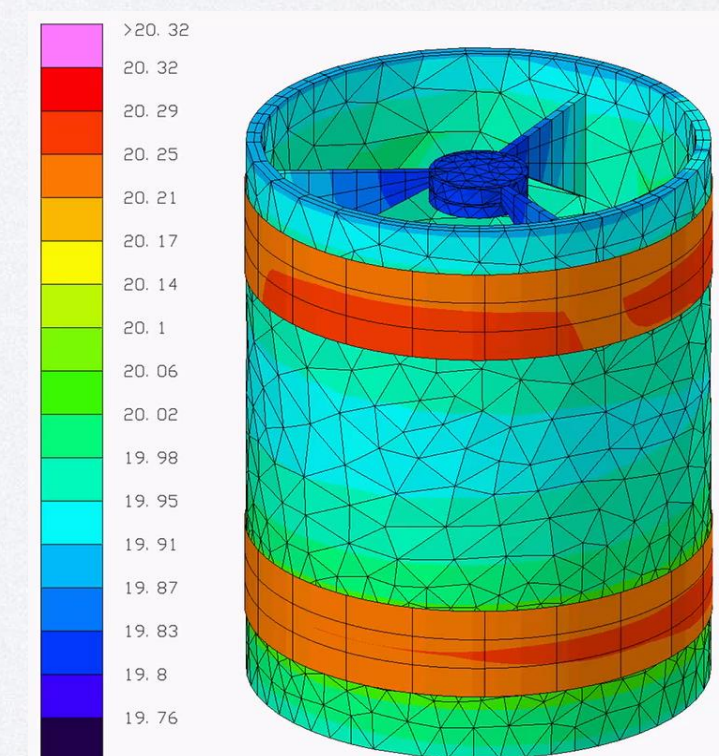
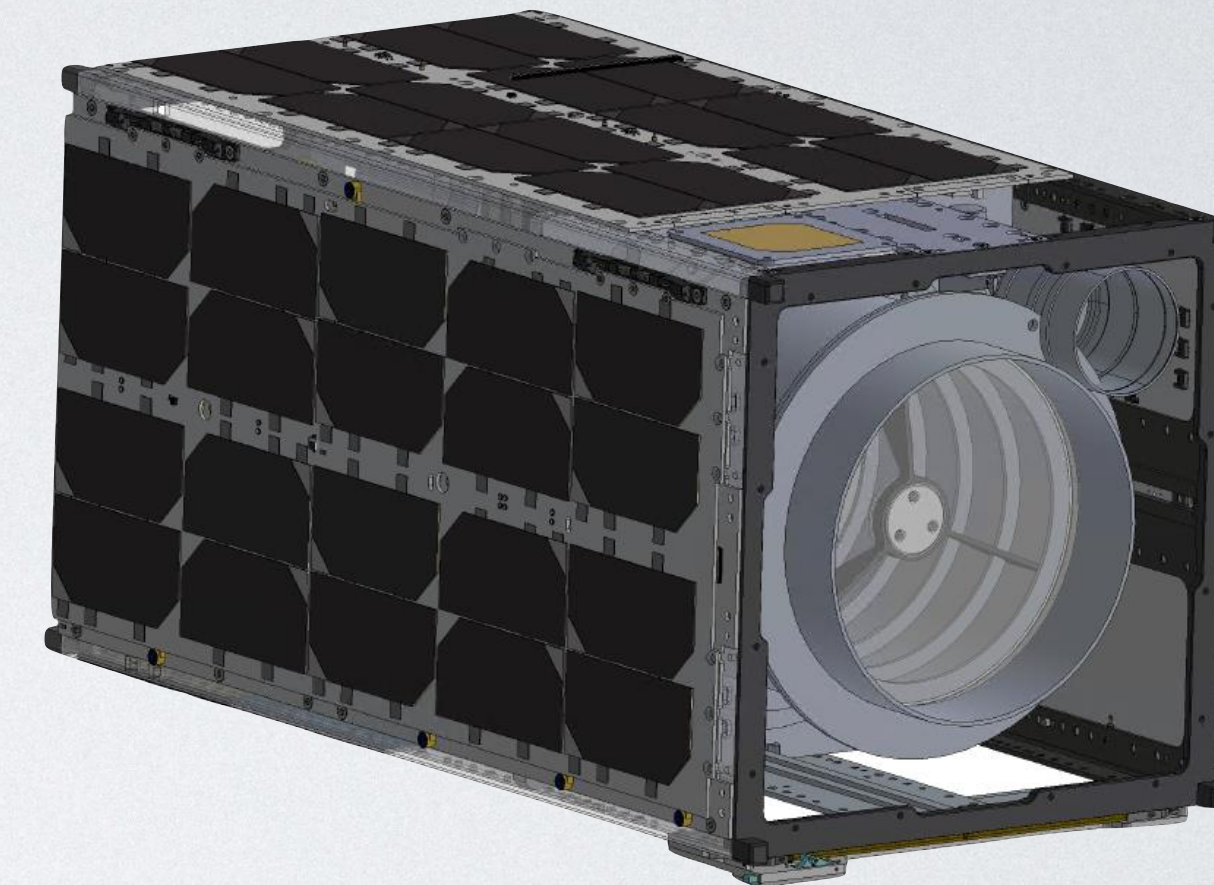
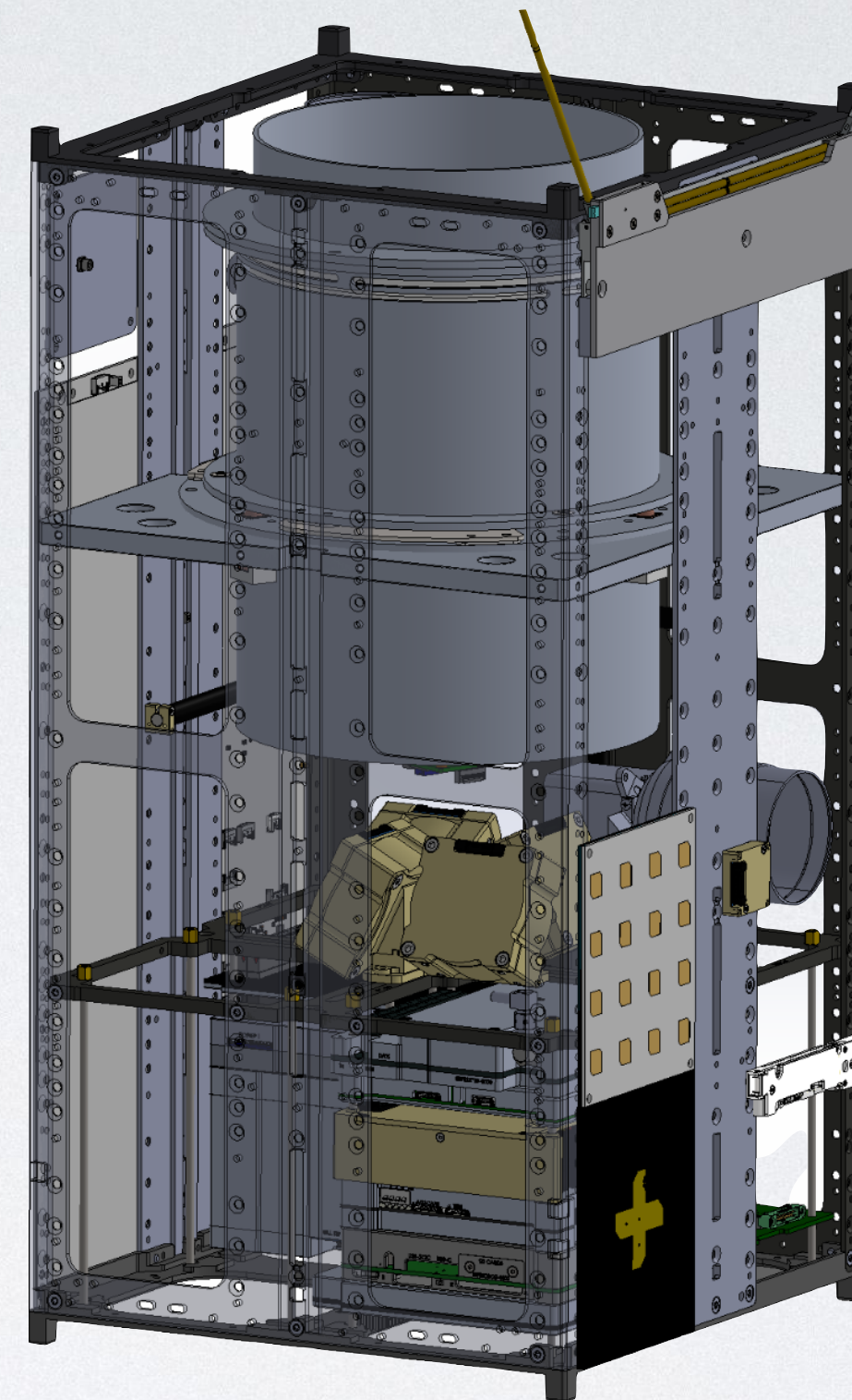
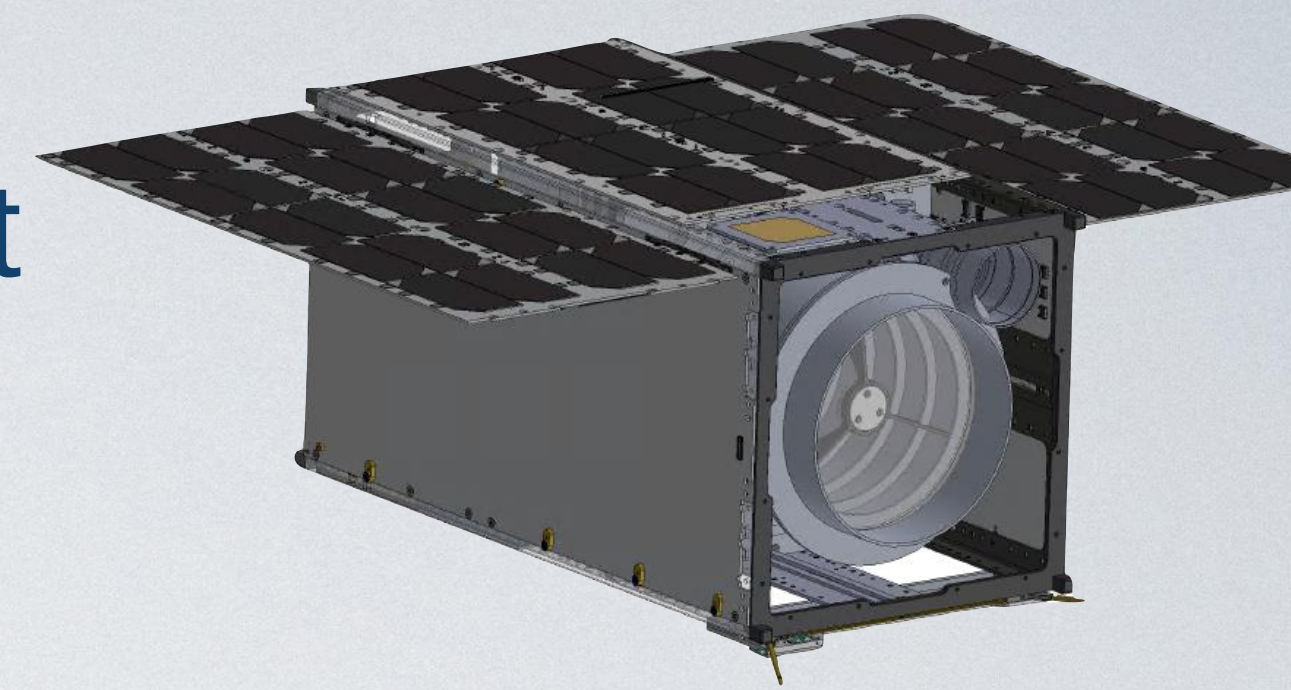




ENDUROSAT

16U Spacecraft

- 16U spacecraft
- X-Band downlink
- Plenty of power
- Advanced ADCS system*
- Full CubeSat as a service model, to be integrated with Saber systems
- Contract signed Dec 22
- Biggest challenges
- are pointing and thermal control





Mission: basic parameters & status

This program aims for Flagship ultra-high precision science outcomes on a CubeSat budget. Despite innovative design, specifications are demanding.

Mission Specs (all in LEO):

- (1) Launch 2026, 16 U cubesat SSO orbit in 2-3 year mission
- (2) Target astrometry (narrow-angle) is <1 micro-arcsec
- (3) Simultaneous Photometry (10hz) and Spectroscopy ($R \sim 200$)
- (4) All hardware components fabricated or in process
- (5) Integration into Bus in Sofia 2025

University of Sydney TOLIMAN team



Peter Tuthill



Chris Betters



Connor Langford



Karel Valenta



Fred Crous



Louis Desdoigts



Max Charles

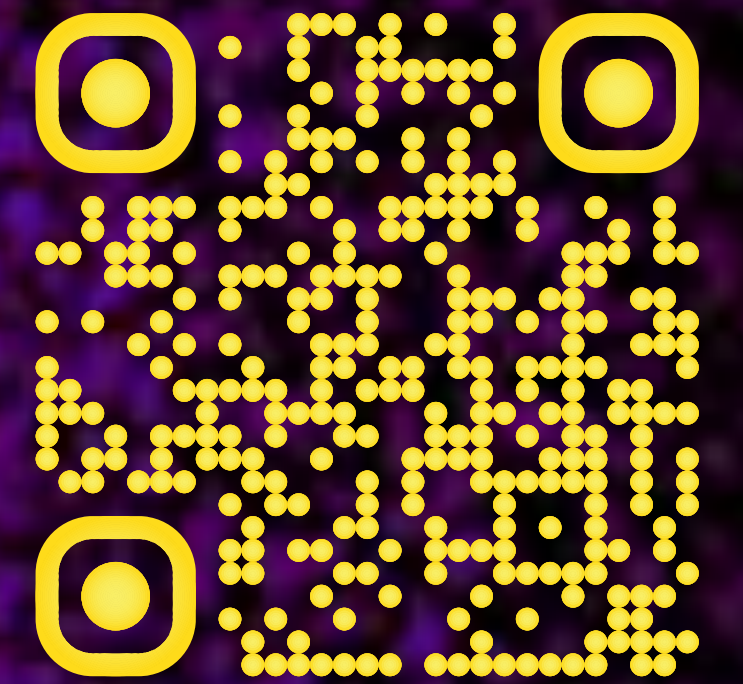


Grace Piroscia

TOLIMAN



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