THE UNIVERSITY OF SYDNEY

TOLIMAN

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

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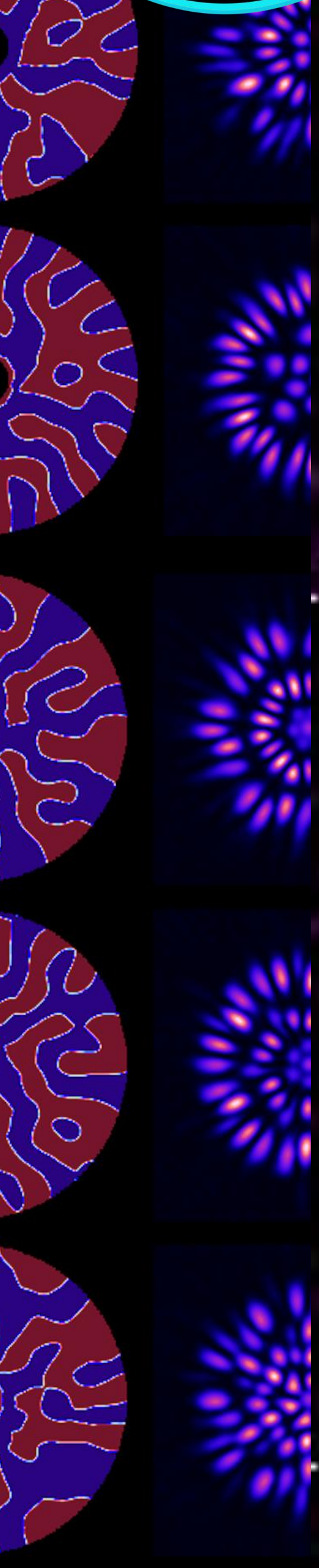
SAIL Sydney Astrophotonic Instrumentation Laboratory
The University of Sydney
The University of Queensland Australia
Universiteit Leiden
The Breakthrough Prize
NASA

TOLIMAN

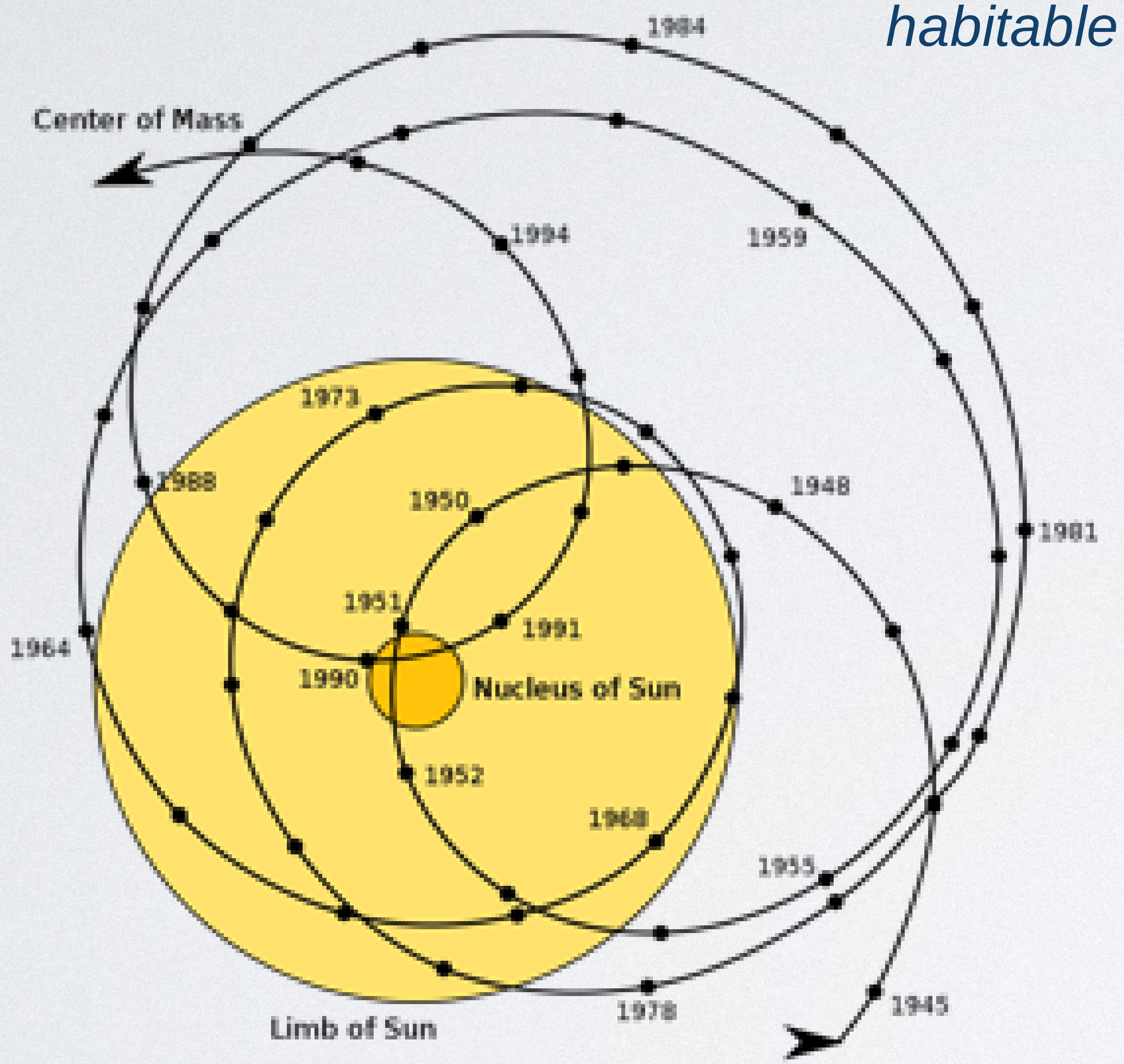
Telescope for Orbit Locus Interferometric Monitoring of our Astronomical Neighborhood



- 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

How do we find rocky temperate zone planets around stars within ~ 10 Pc?

- ✗ Transits? - Sample too small to get lucky
- ✗ Doppler RV? - Signals very small for terrestrial mass temperate planet orbiting FGK star
- ✓ Astrometry ? - *"Astrometry is the only technique technologically ready to detect planets of Earth mass in the habitable zone (HZ) around solar-type stars within 20 pc."* Shao et al 2010



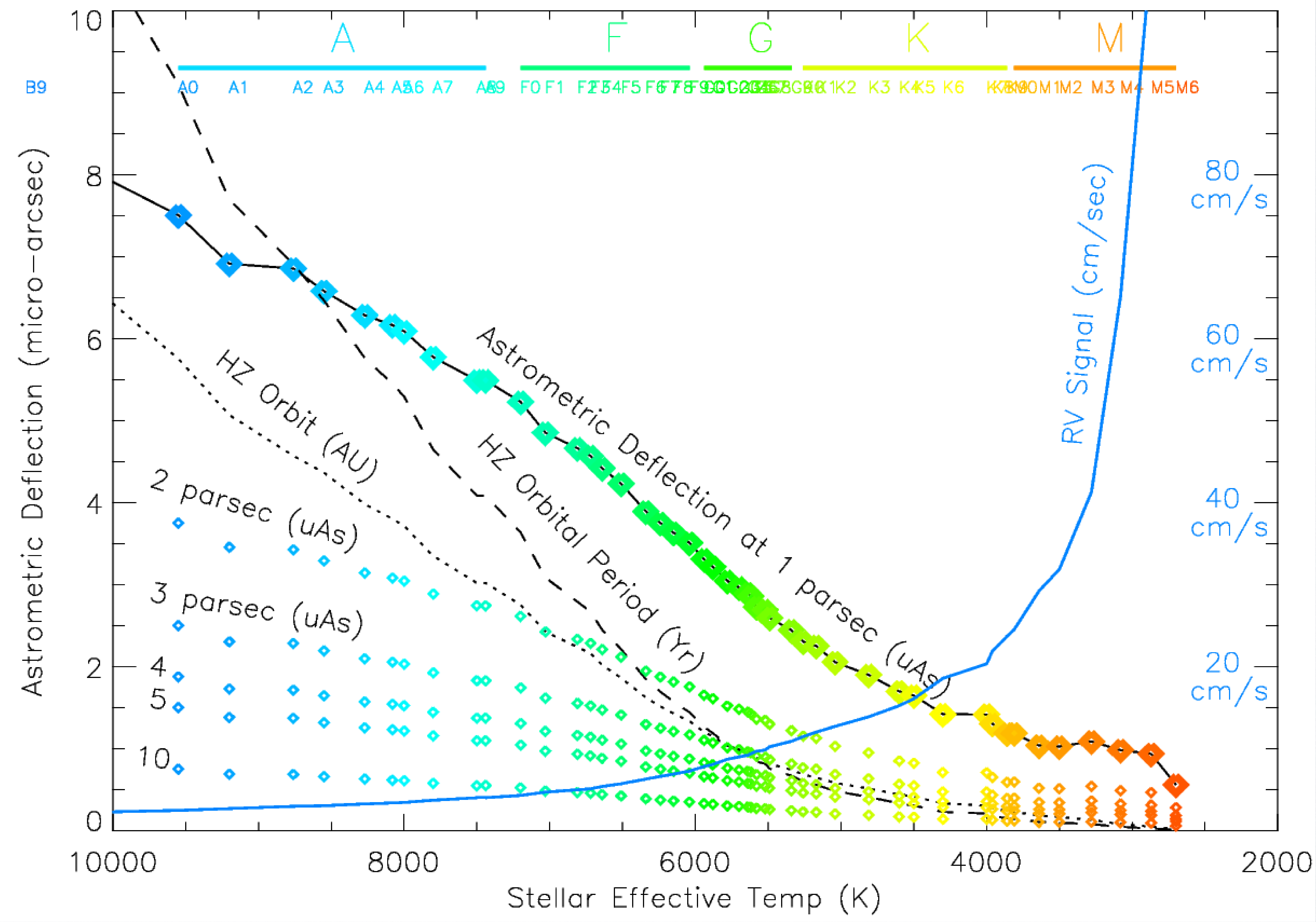
Locus of the Sun's motion due to planets (mainly Jupiter)

True Earth Analogs

What is the stellar (and projected HZ rocky planet) population within 10 PC?

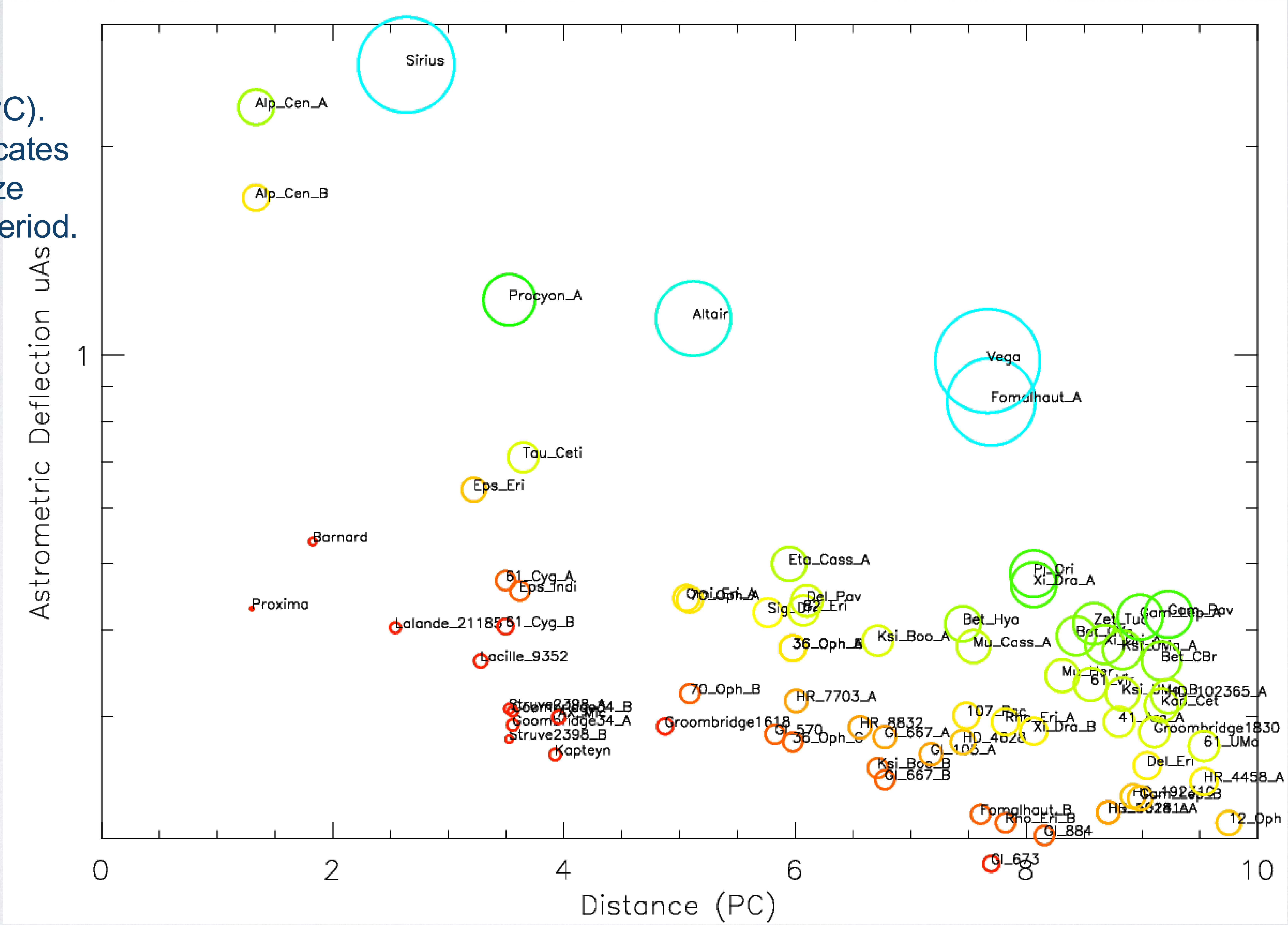
- 5 A-type Stars. likely 0 (or 1) HZ rocky planet
- 69 FGK-type Stars. Likely about a dozen HZ rocky planets
- 273 (+) M-type stars. Likely 140 HZ rocky planets

Astrometric signal of a 1 M_earth planet in the HZ assuming 1PC distant from star of given Sp. type.

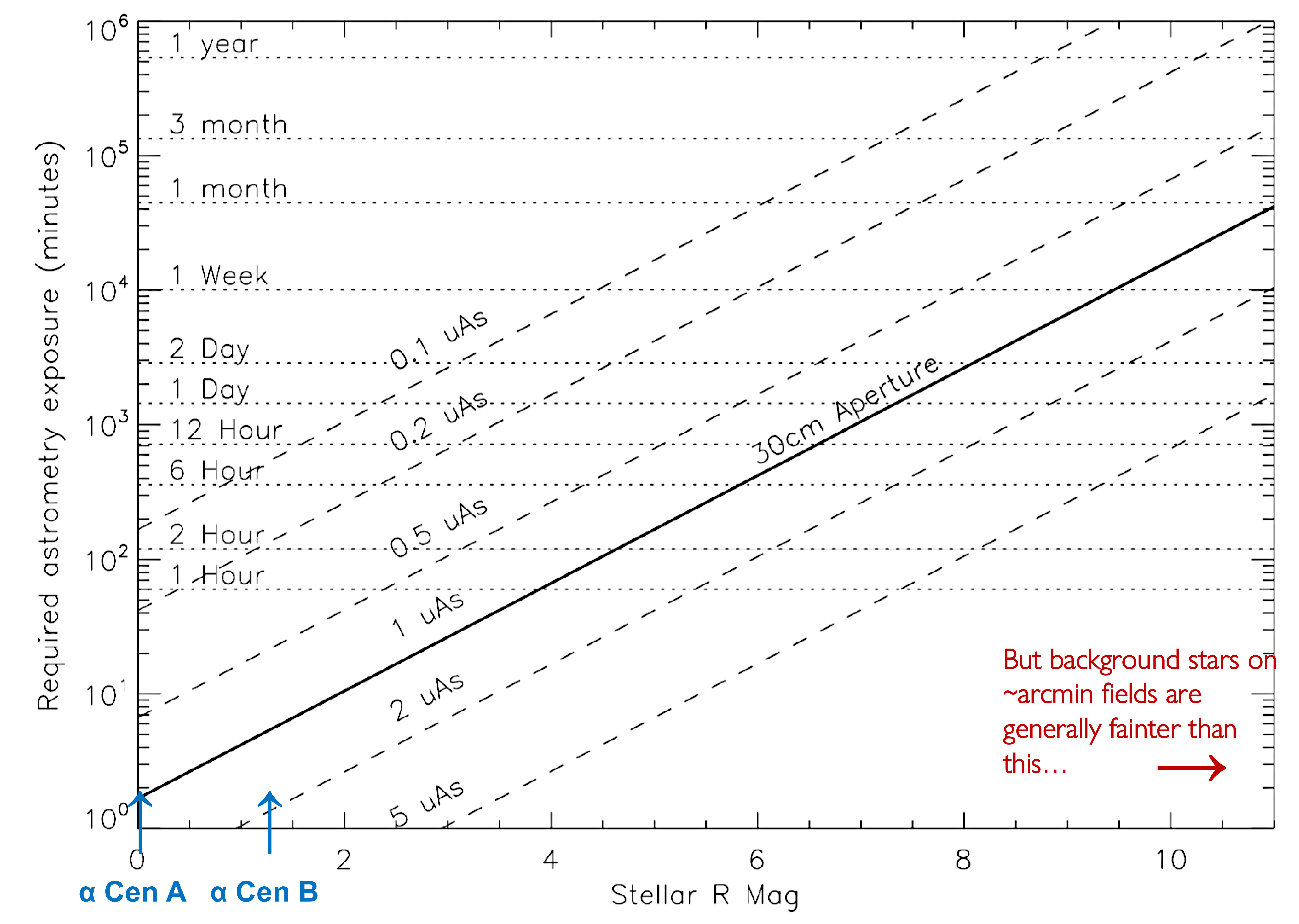


Astrometric signal for HZ Earth mass for all FGK stars to 10PC

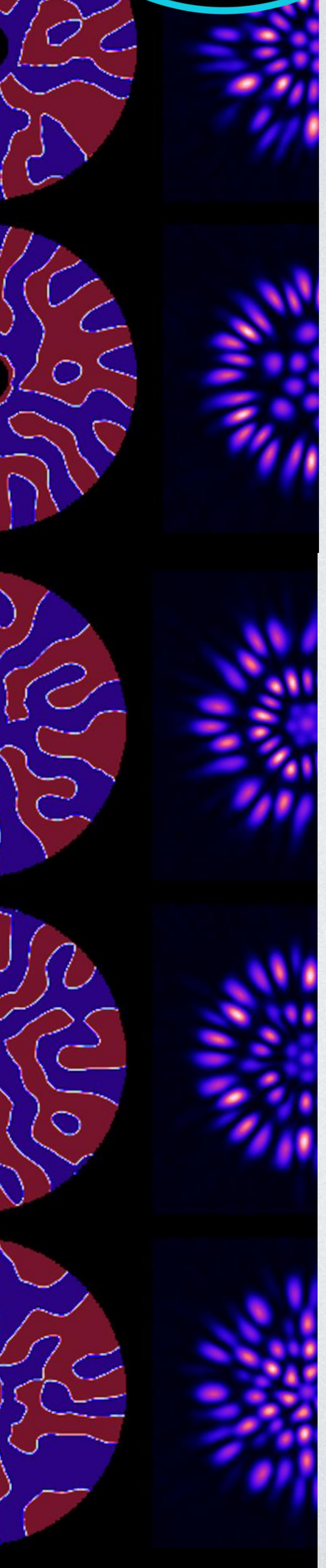
Also M stars (<5PC). Symbol color indicates host spectrum, size indicates orbital period.



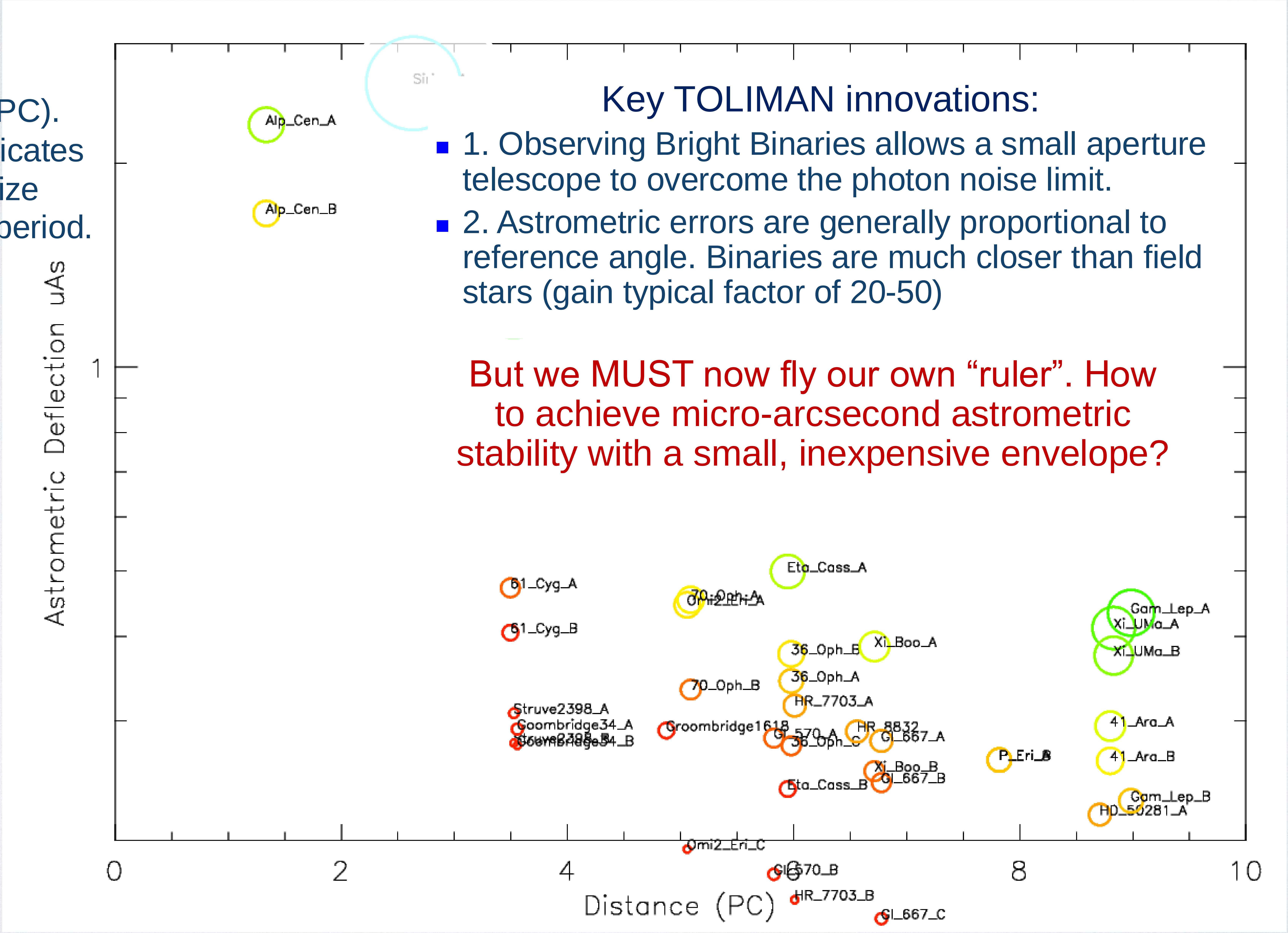
30cm Telescope fundamental (photon noise) limit: integration time required to obtain a given astrometric noise



Astrometric signal for HZ Earth mass for all FGK stars to 10PC Binaries ONLY!



Also M stars (<5PC). Symbol color indicates host spectrum, size indicates orbital period.

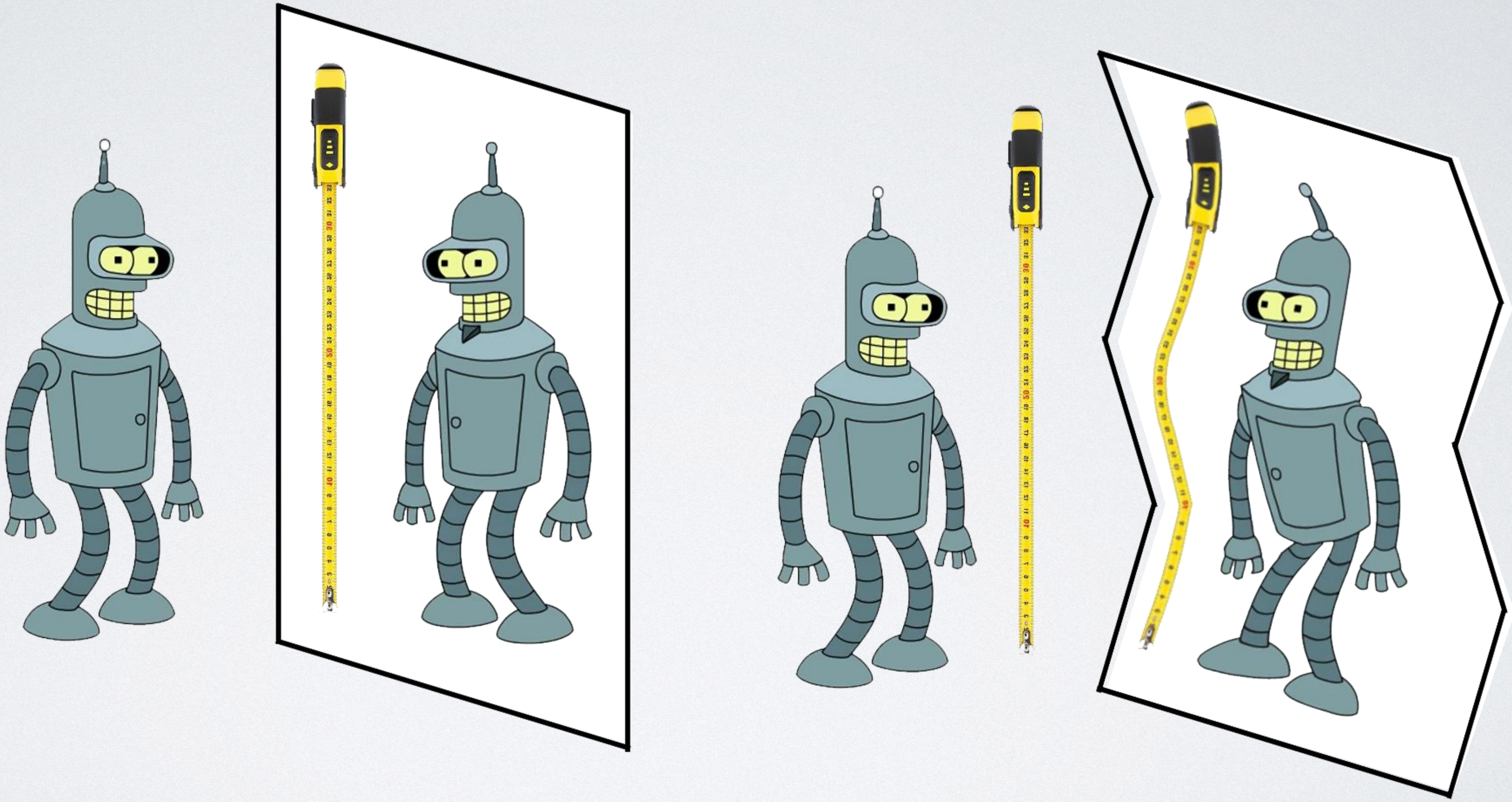


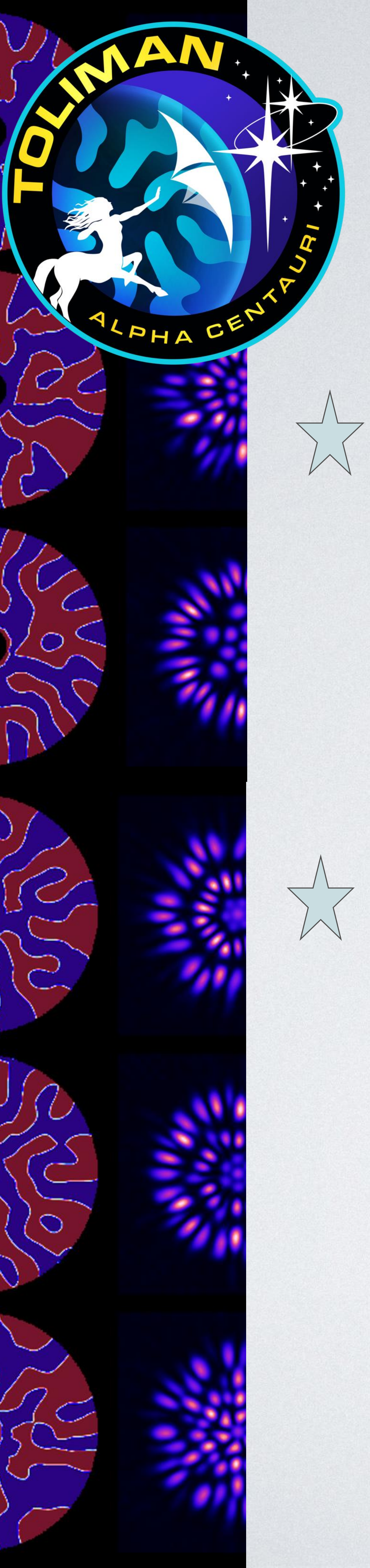
Key TOLIMAN innovations:

- 1. Observing Bright Binaries allows a small aperture telescope to overcome the photon noise limit.
- 2. Astrometric errors are generally proportional to reference angle. Binaries are much closer than field stars (gain typical factor of 20-50)

But we MUST now fly our own "ruler". How to achieve micro-arcsecond astrometric stability with a small, inexpensive envelope?

Optical distortions don’t matter if they bend both your ruler and your object…

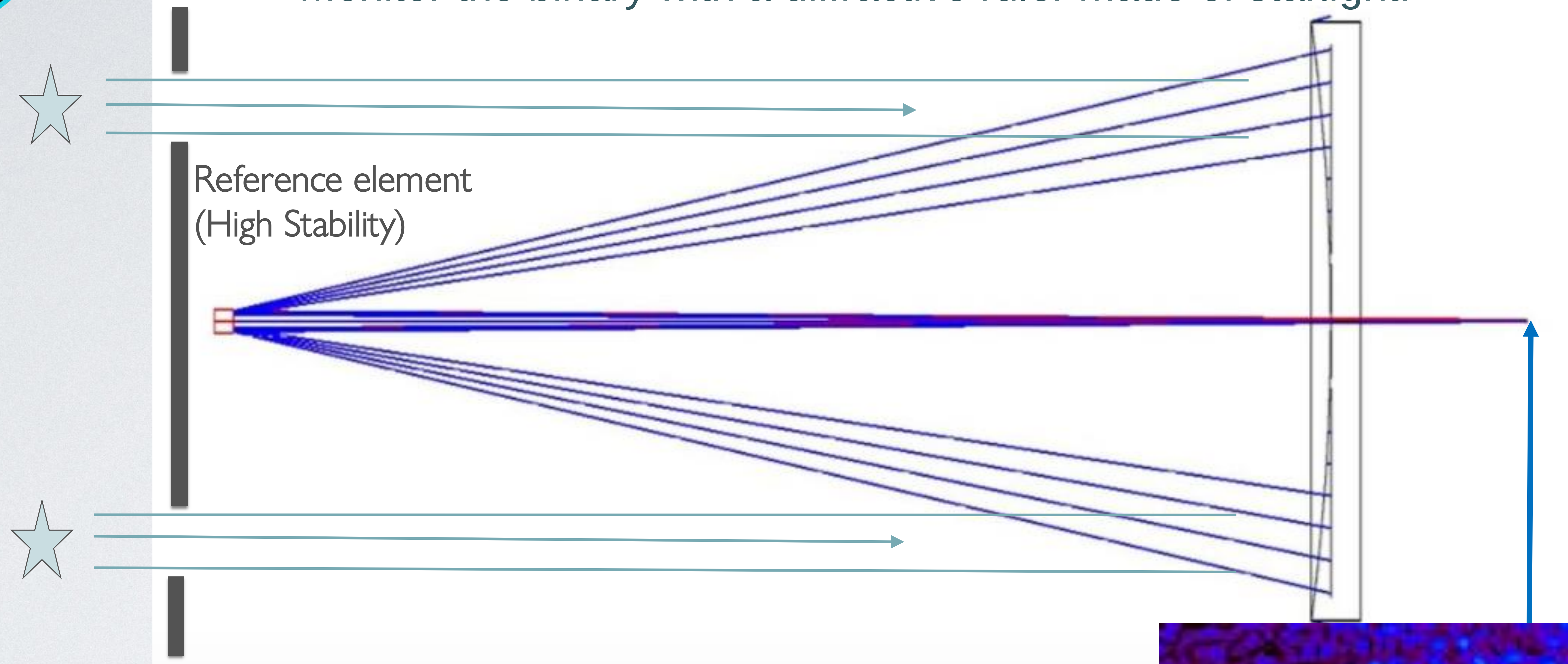


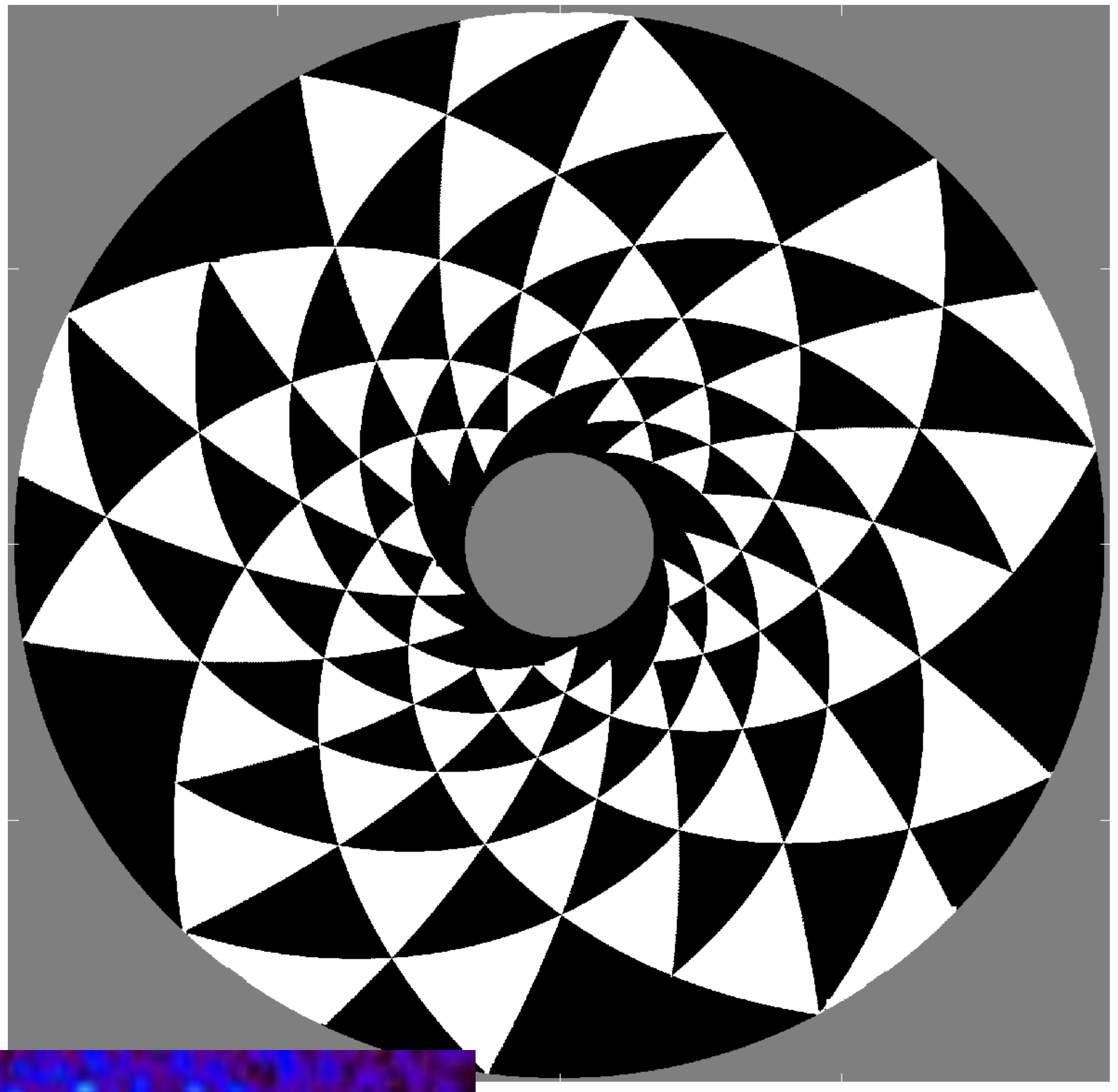


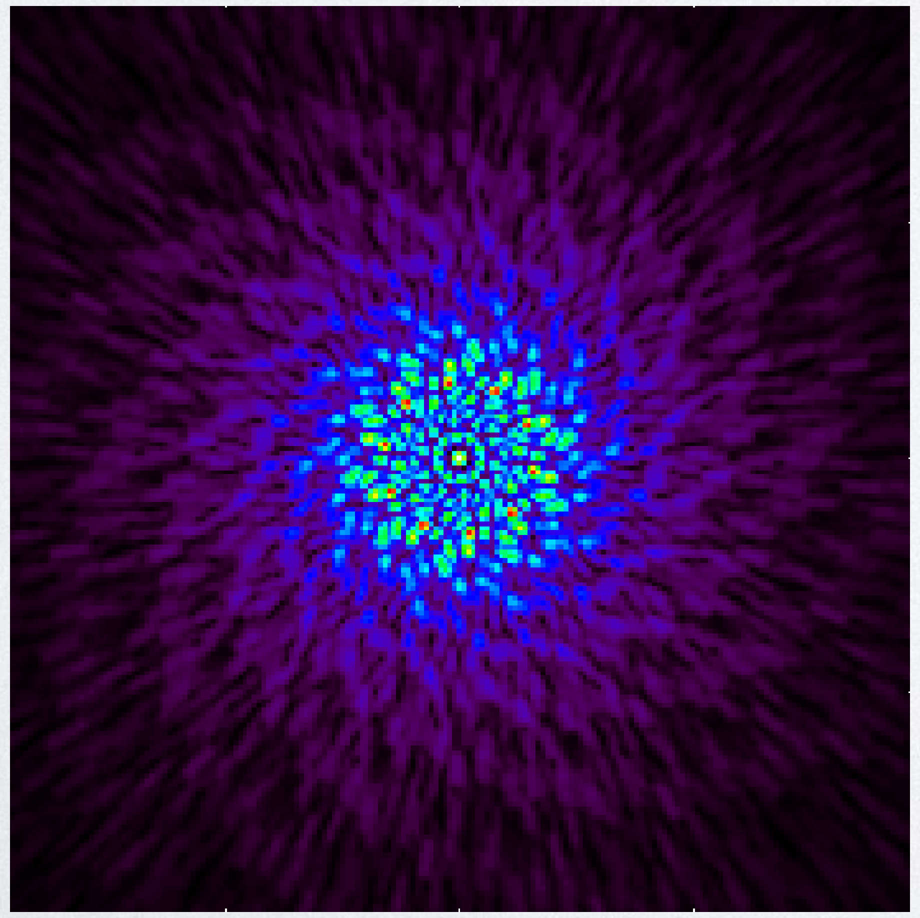
Optical concept empowering TOLIMAN

Diffractive-pupil pupil mask

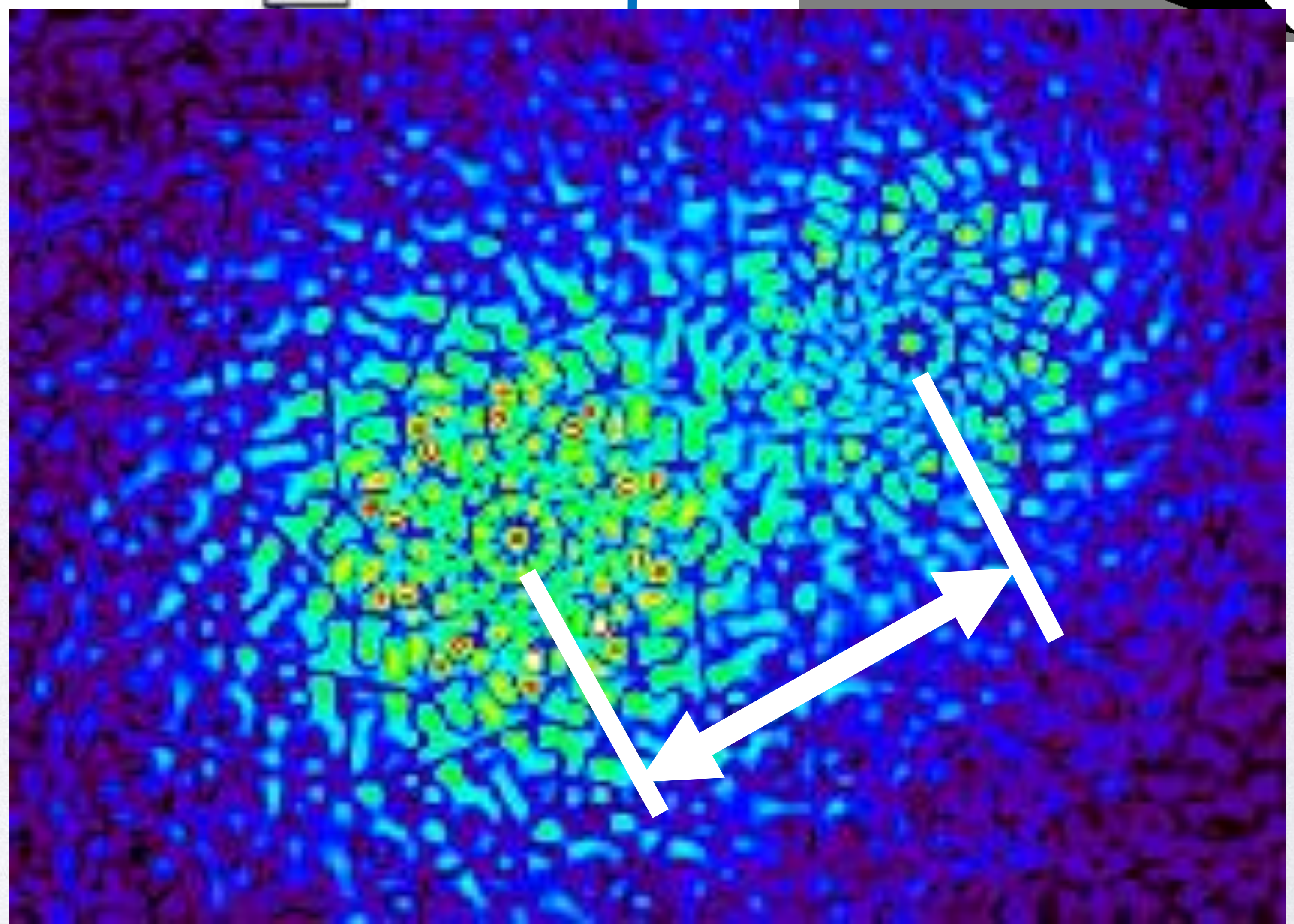
Monitor the binary with a diffractive ruler made of starlight!



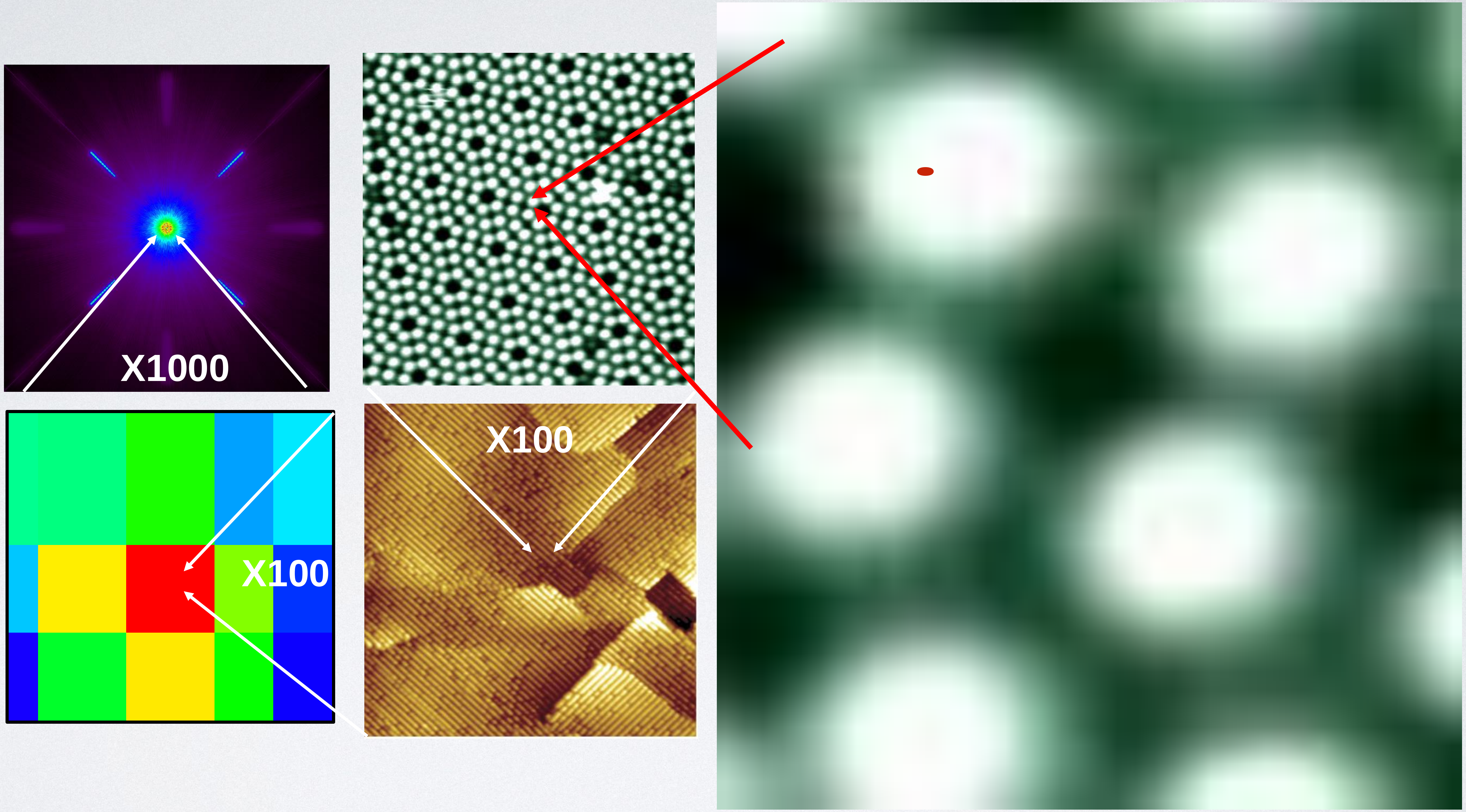


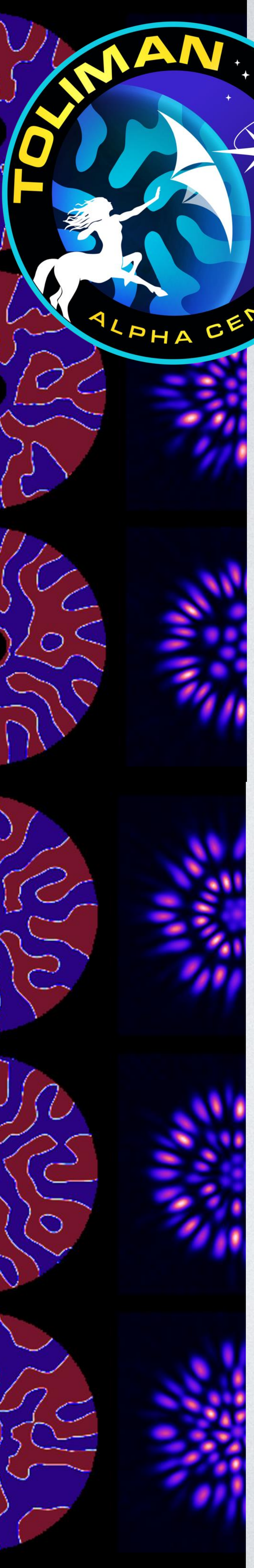


Point Spread Function



The scale of the Instrumental Challenge





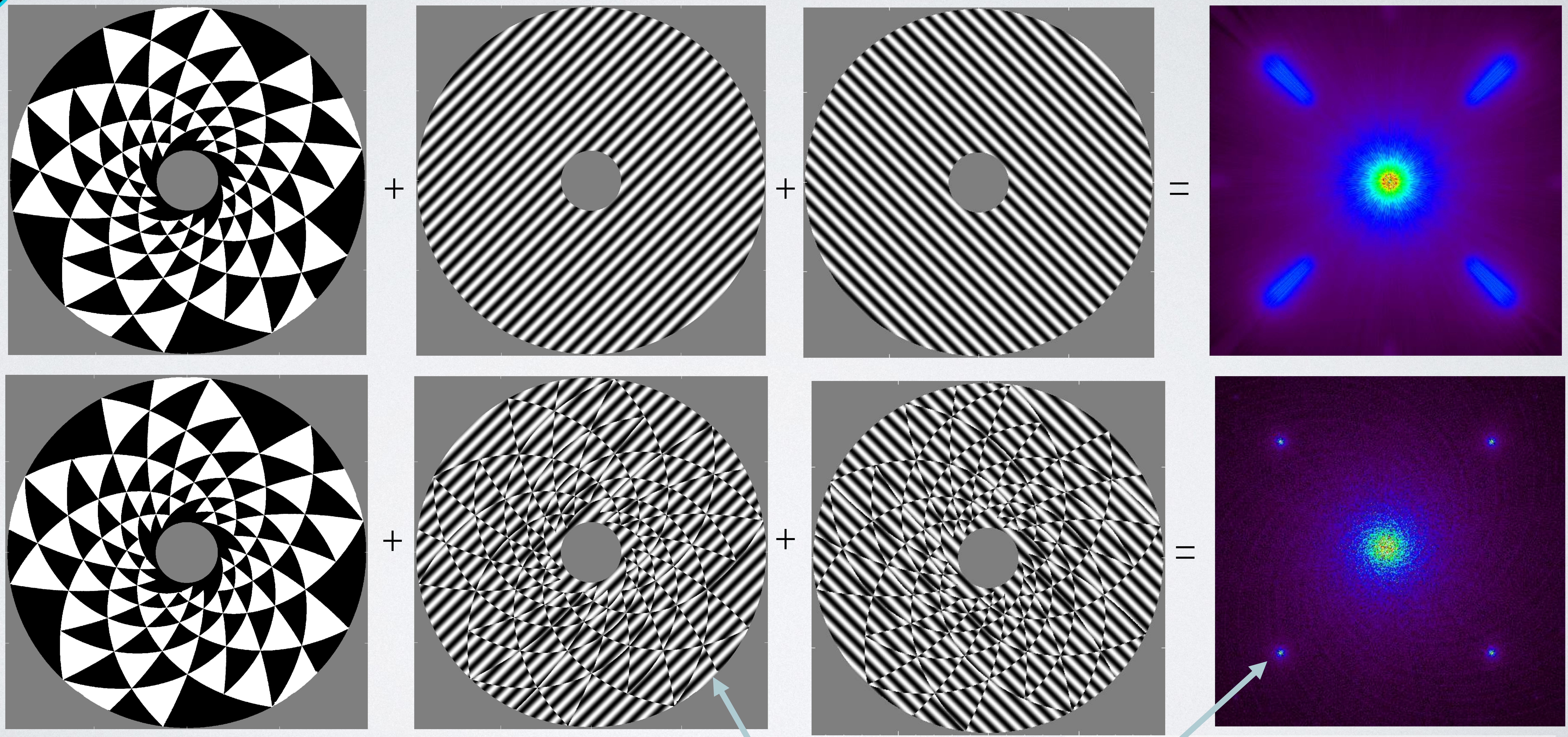
Key TOLIMAN innovations:

- 1. Observing Bright Binaries allows a small aperture telescope to overcome the photon noise limit.
- 2. Astrometric errors are generally proportional to reference angle. Binaries are much closer than field stars (gain typical factor of 20-50)
- 3. The Diffractive Pupil removes most error terms arising from distortion in the optical train. The fundamental ruler element can be made monolithic, thermally stable, and precisely monitored.
- 4. Naturally spreads the starlight over many pixels, preventing detector saturation and at the same time giving major statistical benefits in beating down noise

But there is a flaw!

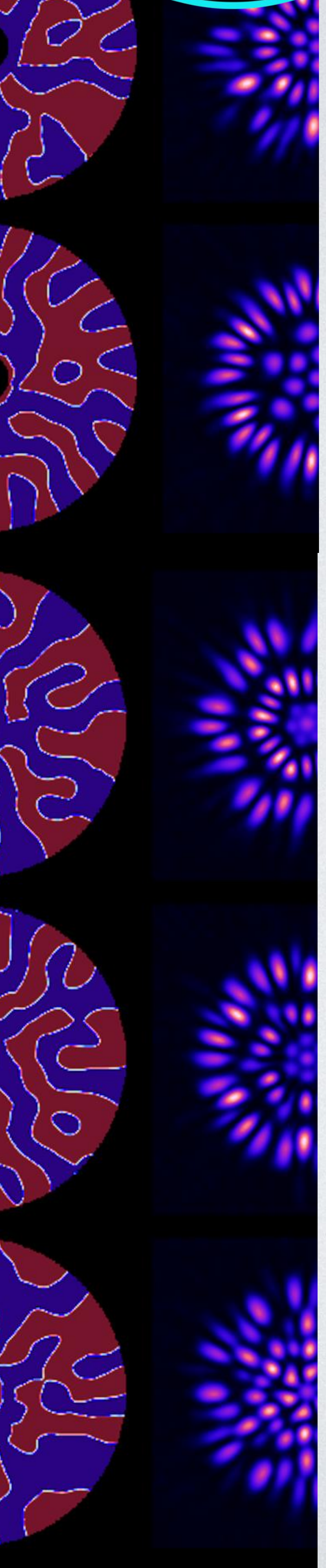
Our ruler is made of light (fringes) depends on the effective wavelength of the starlight – which varies with star Teff!

Nailing down the wavelength: adding a spectrometer (… and Jedi Fourier mind tricks)

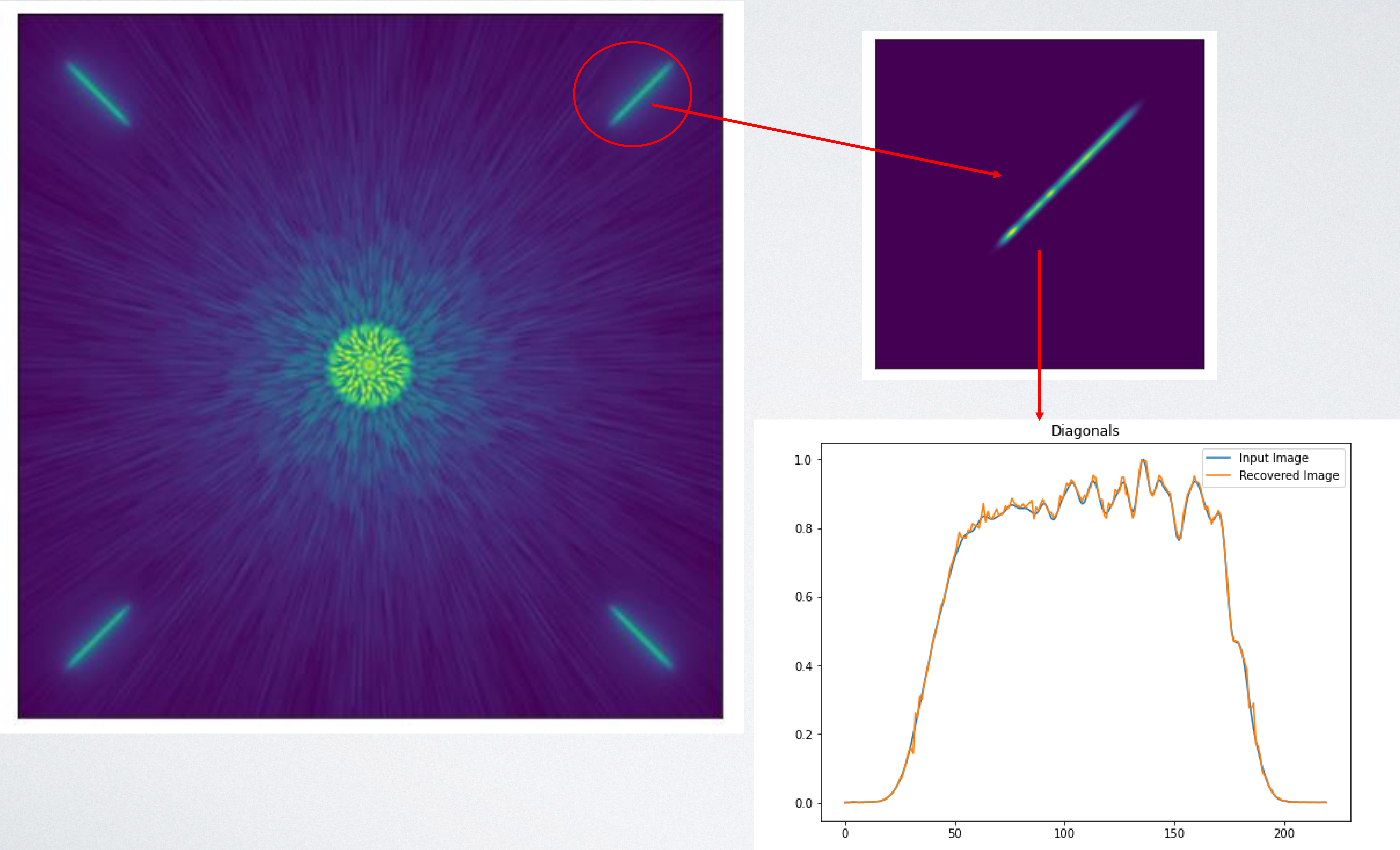


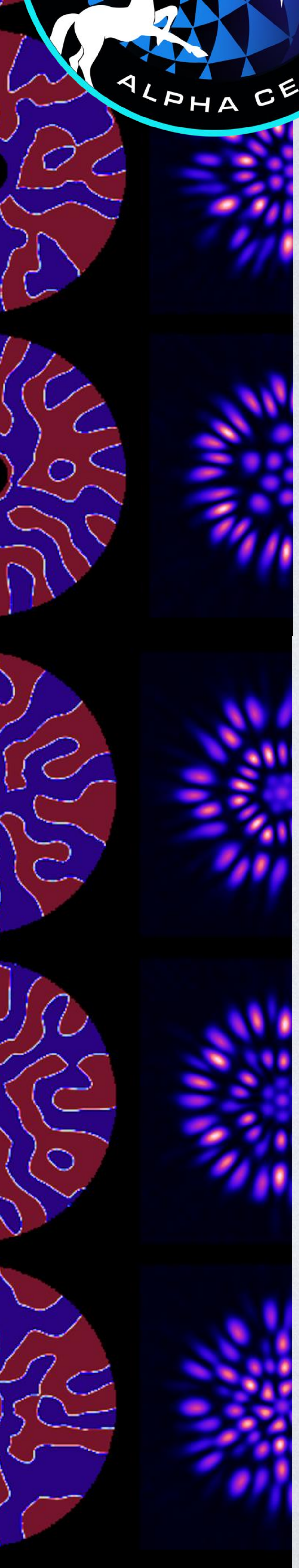
Inverted phase grating

Ideal Spectrometer “slit” function



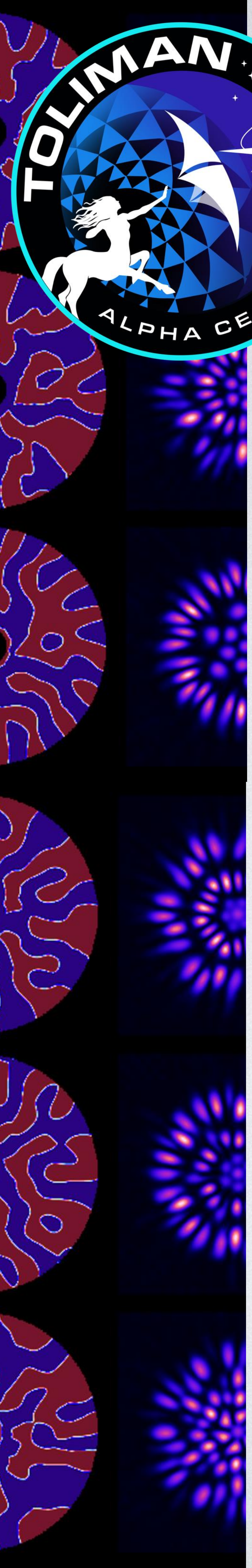
IN-BUILT SPECTROMETER





HOW DO WE BUILD ALL THIS?

- Implement the novel optical principles in hardware
- 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
- Hardest of all - fit within a very aggressive budget!



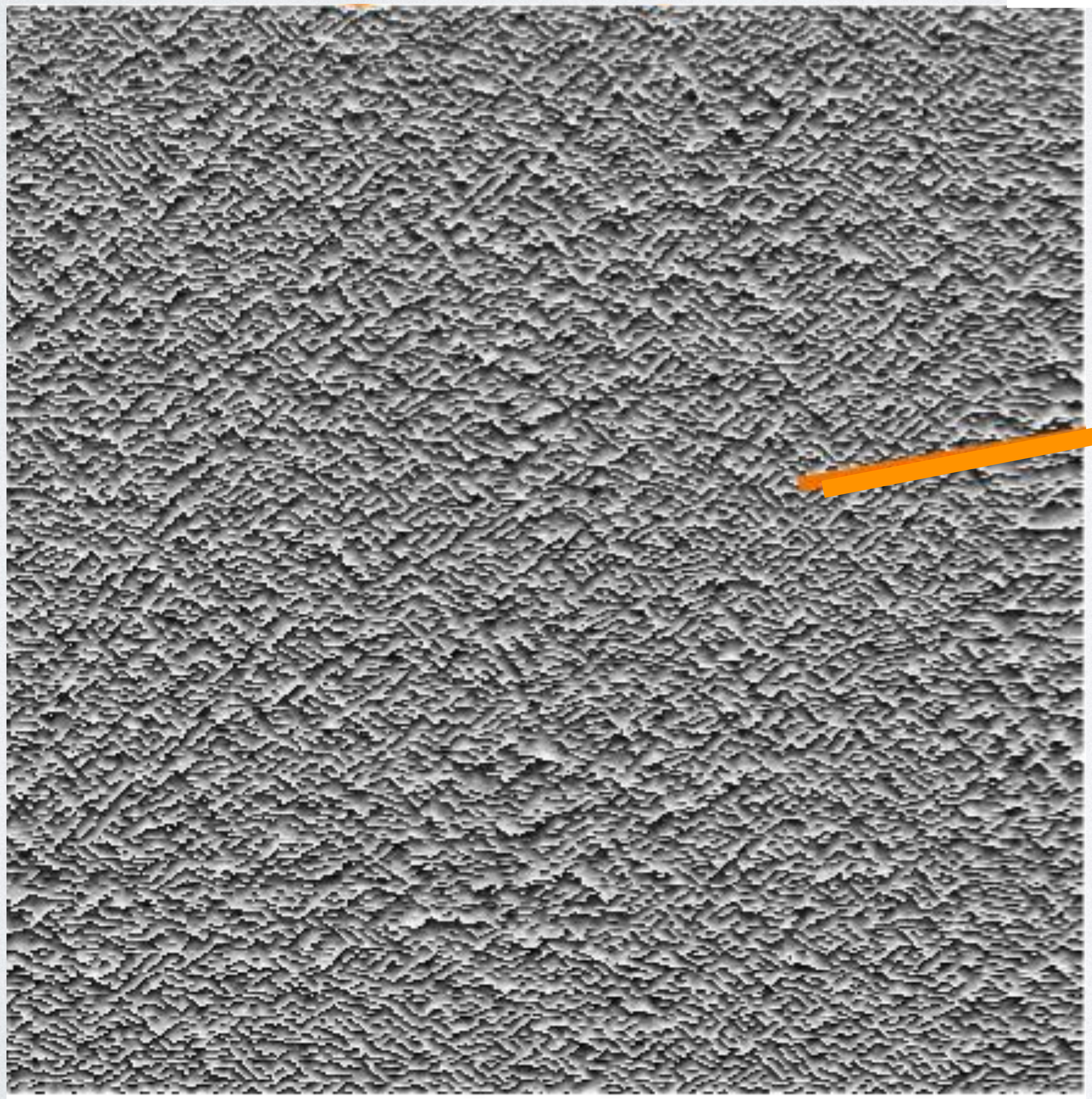
Liquid Crystal Phase Holograms

Frans Snik

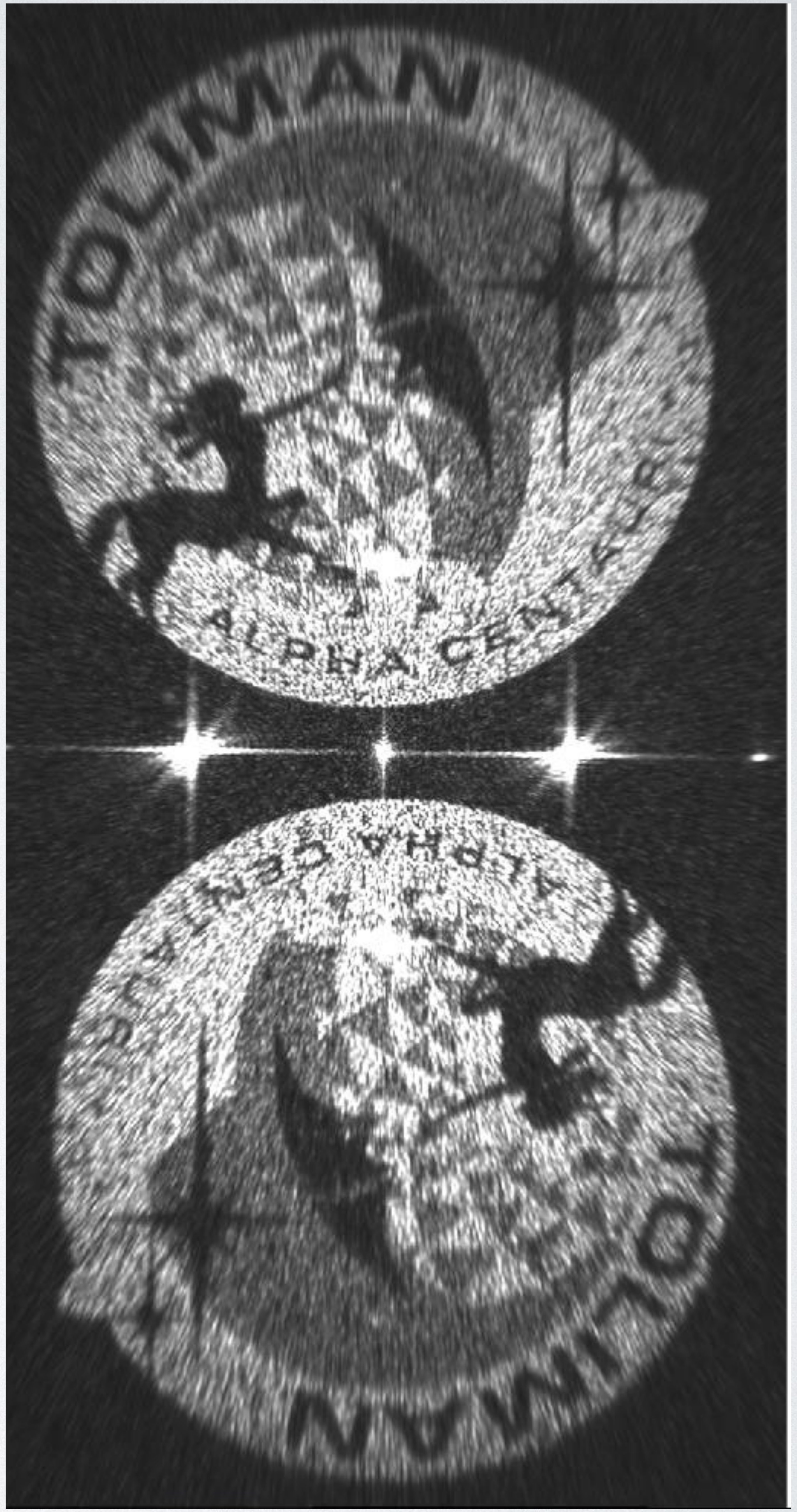
David Doelman

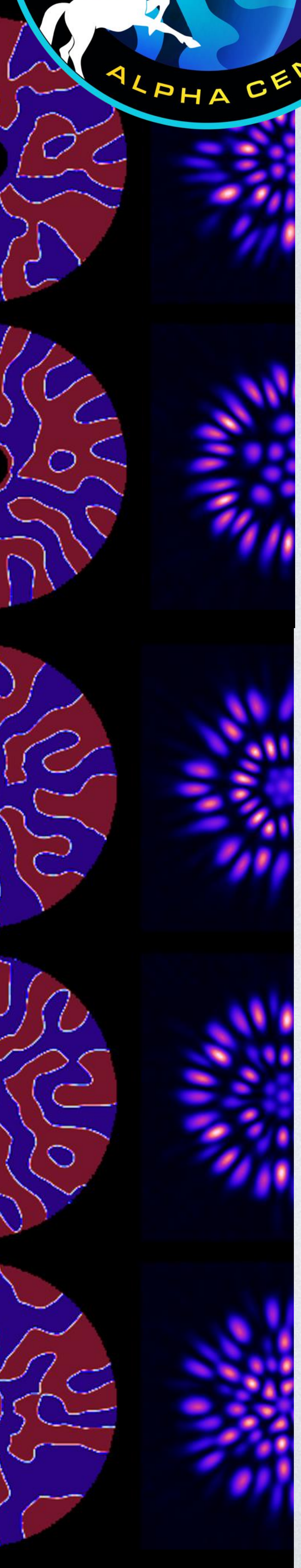
Universiteit Leiden

ColorLink Japan



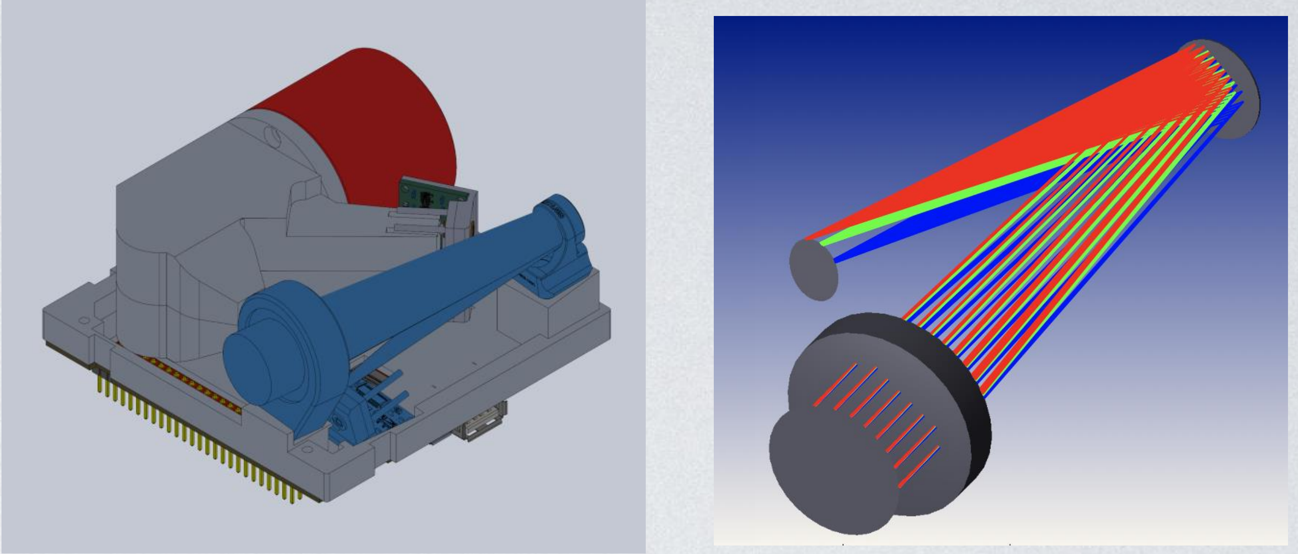
Measured PSF



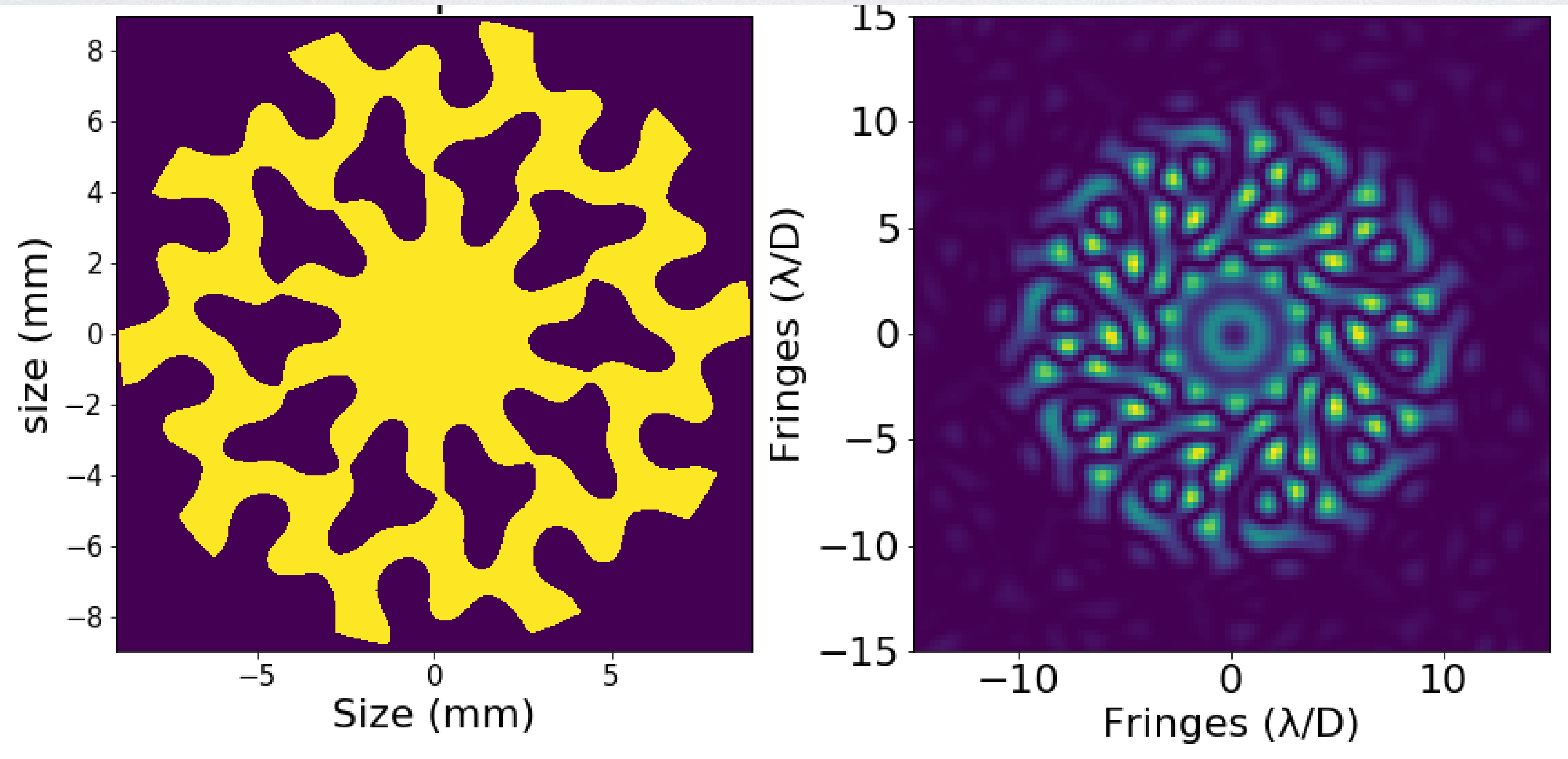


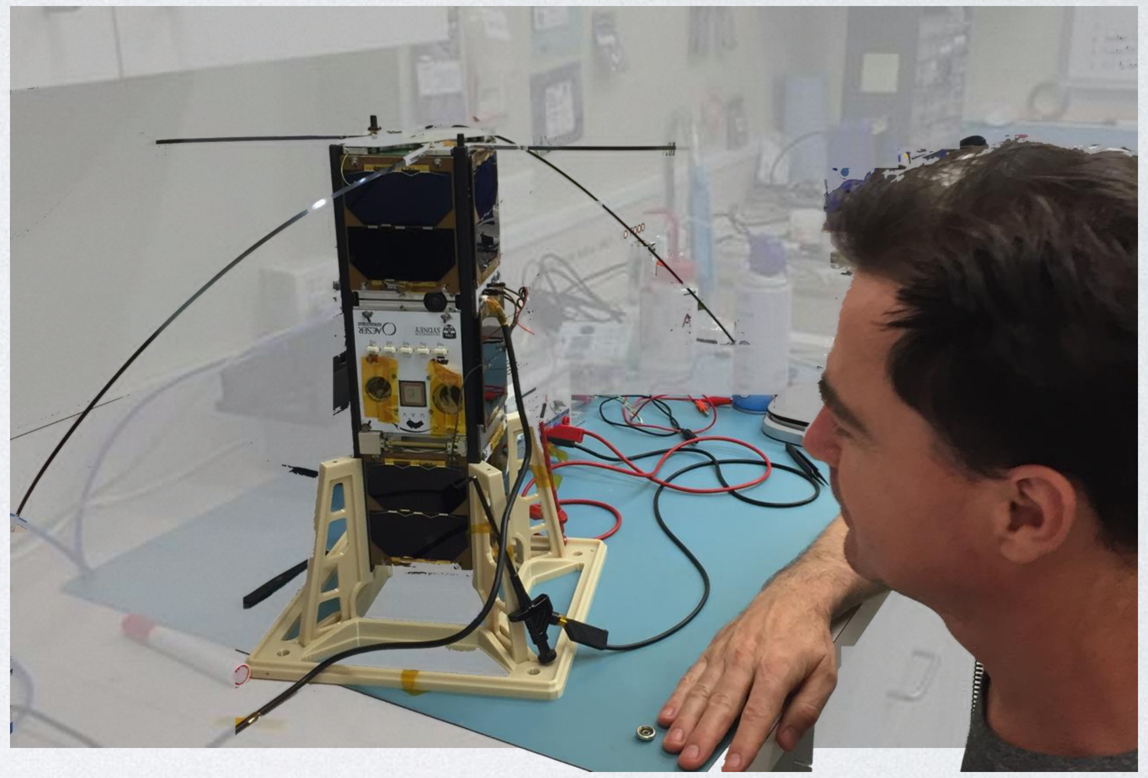
Program: TinyTol, Toliman, …

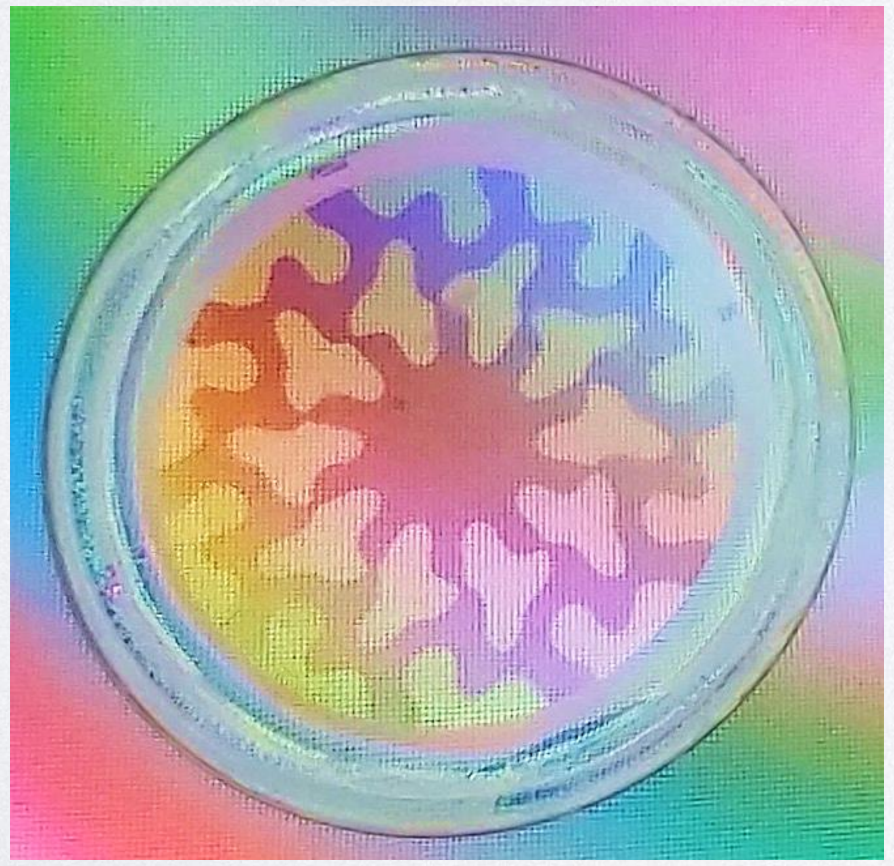
- TinyTol flew aboard CUAVA1
  - 3U cubesat. ISS resupply deployed 2020
  - 20mm aperture, f=15cm, 1 deg FoV
  - Consumer-grade electronics
  - Built, deployed, flown. No data.

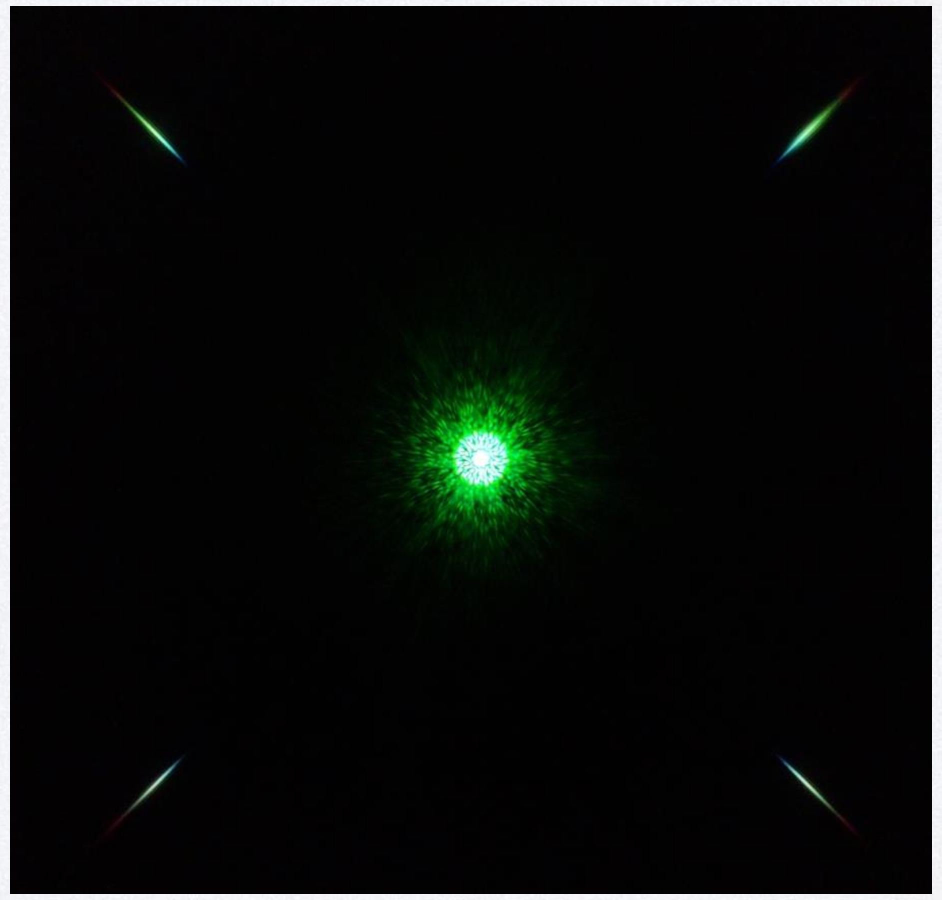


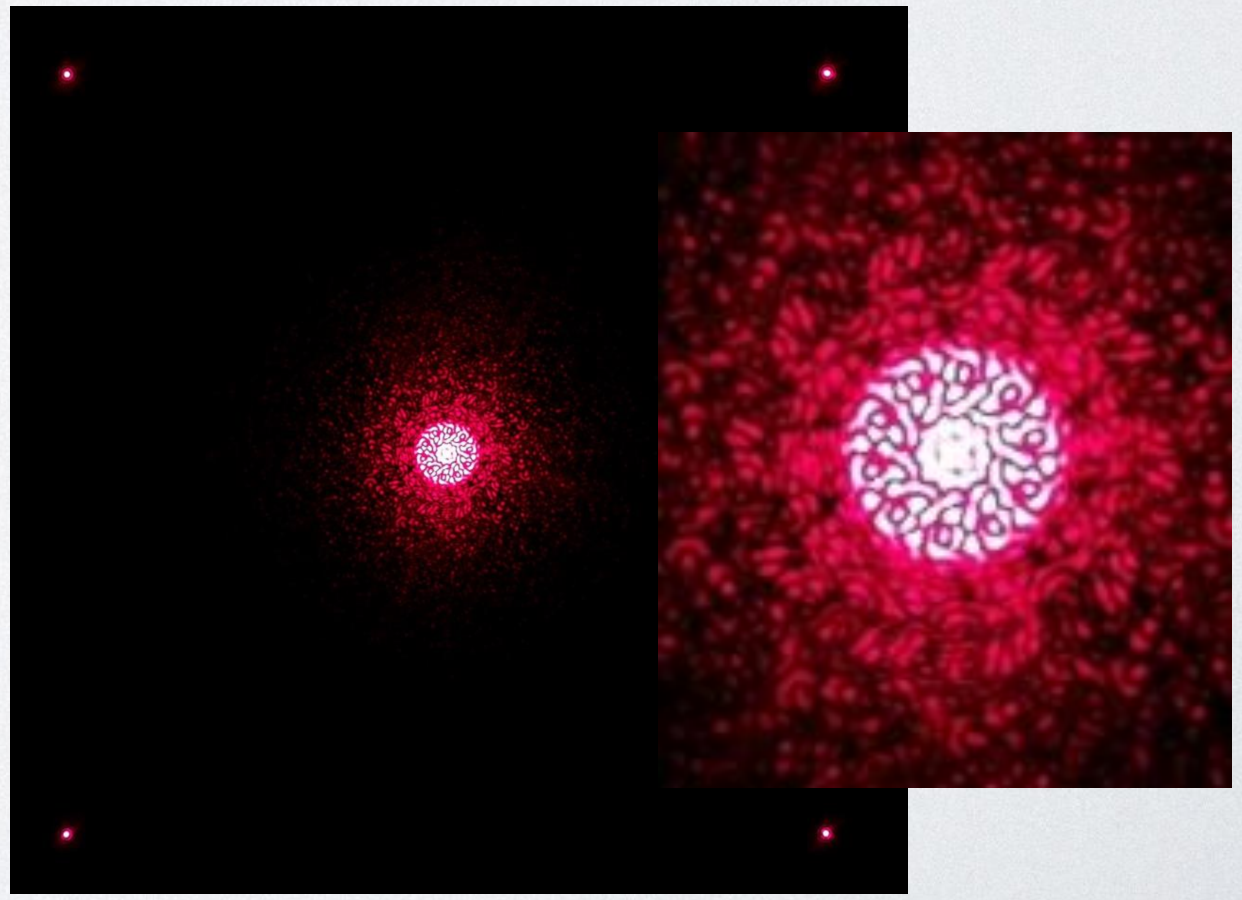
TT instrument / Ray Trace



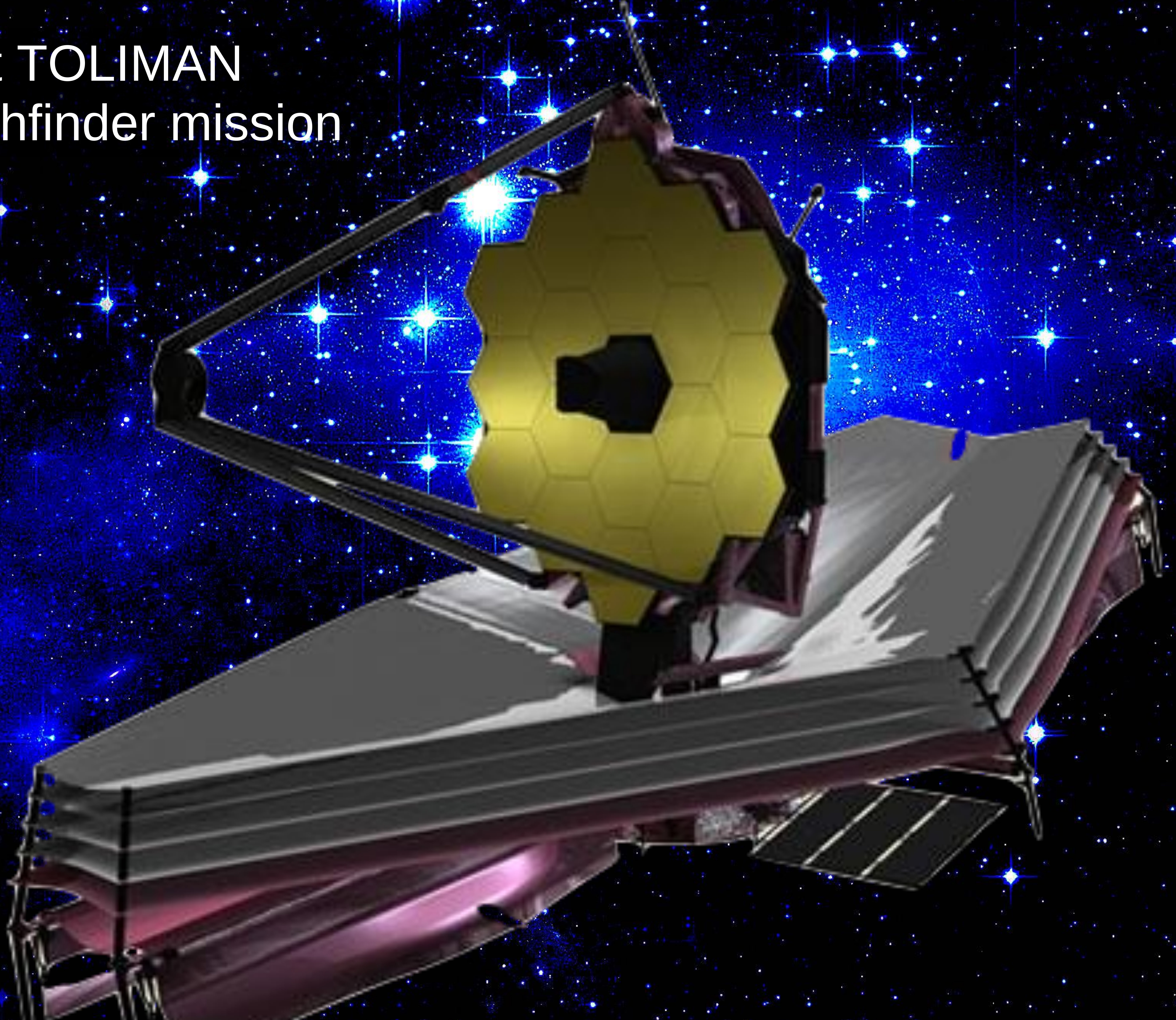




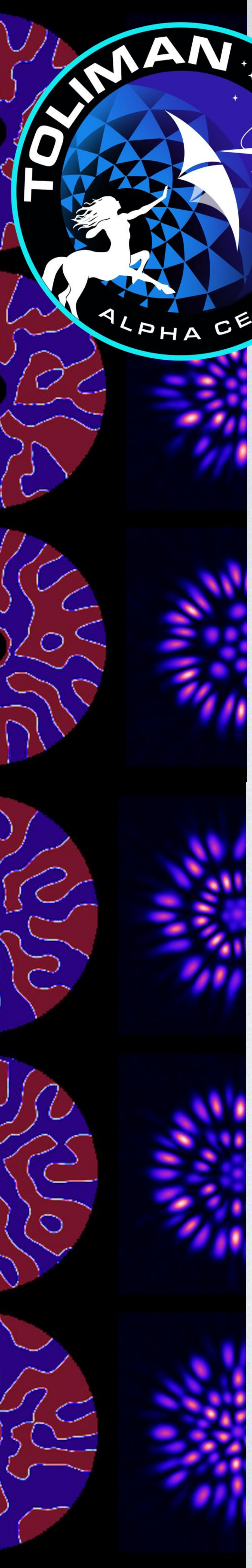


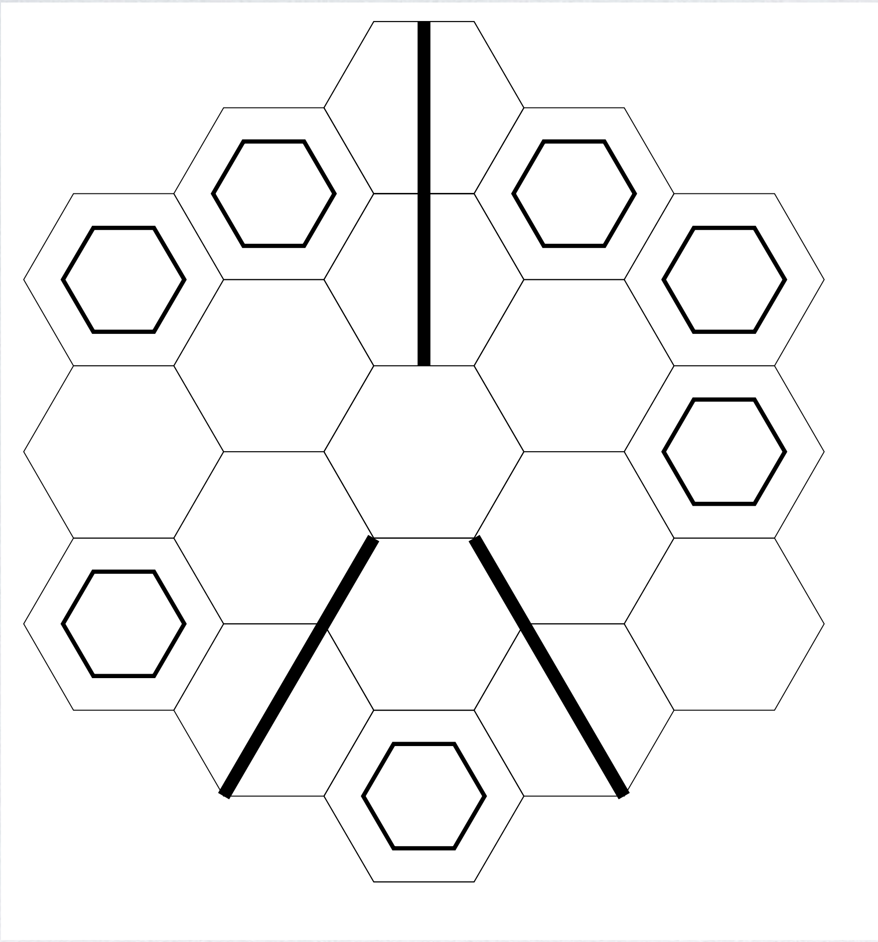


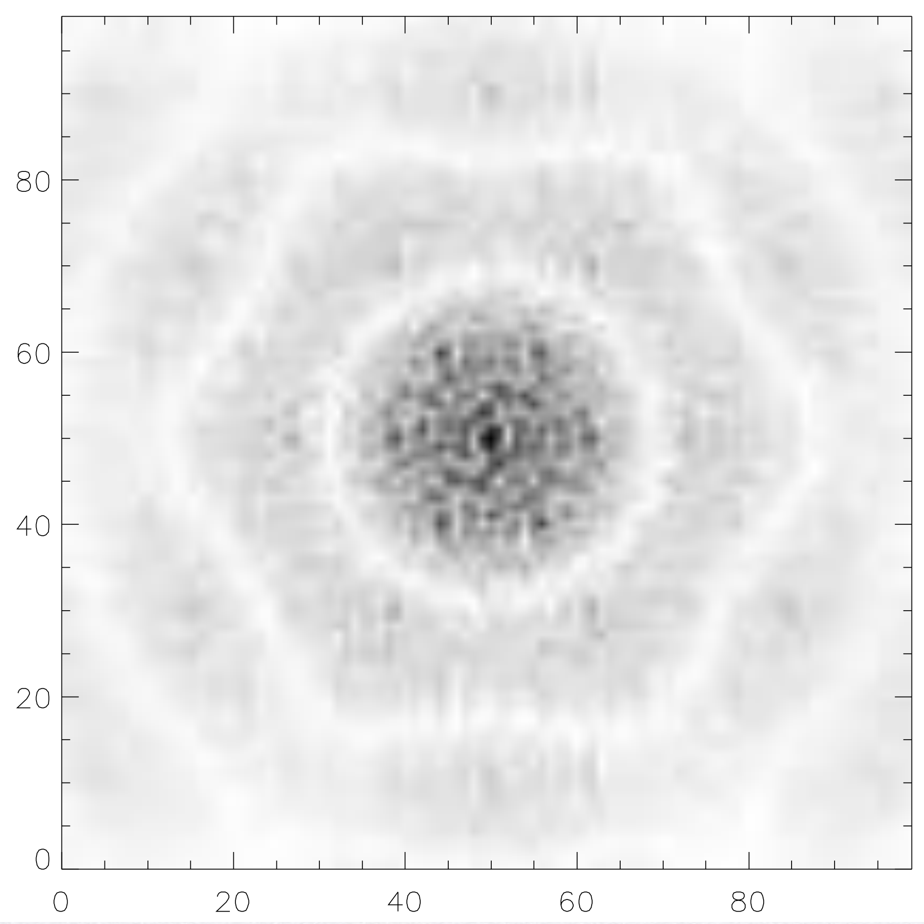
A Modest TOLIMAN Precursor/Pathfinder mission

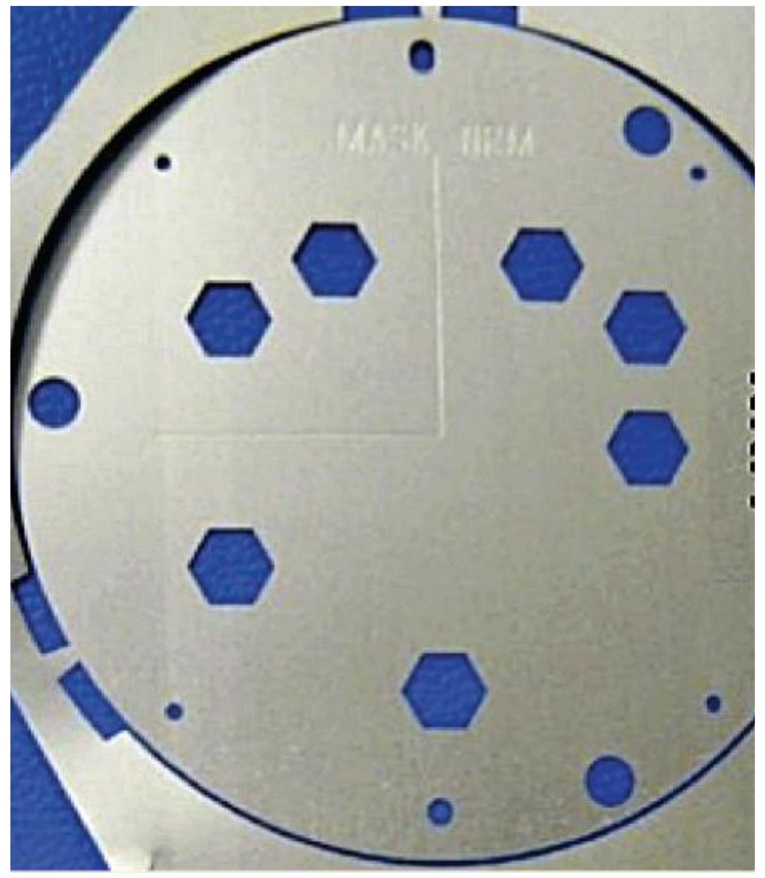


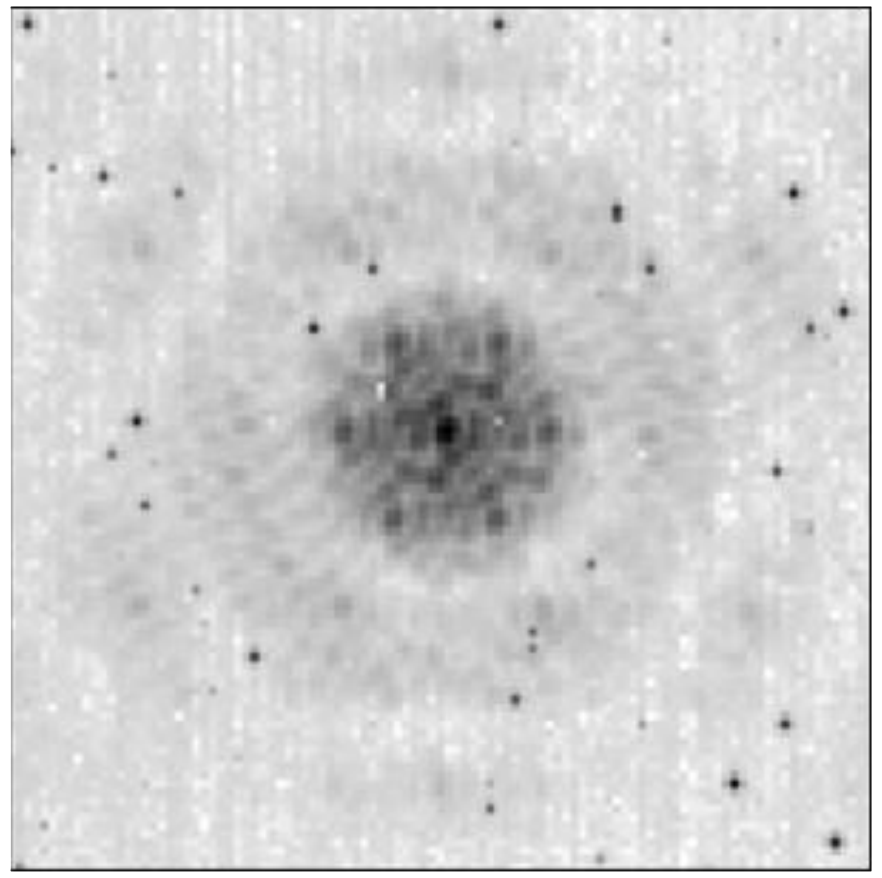
NIRISS AMI: THE JWST INTERFEROMETER

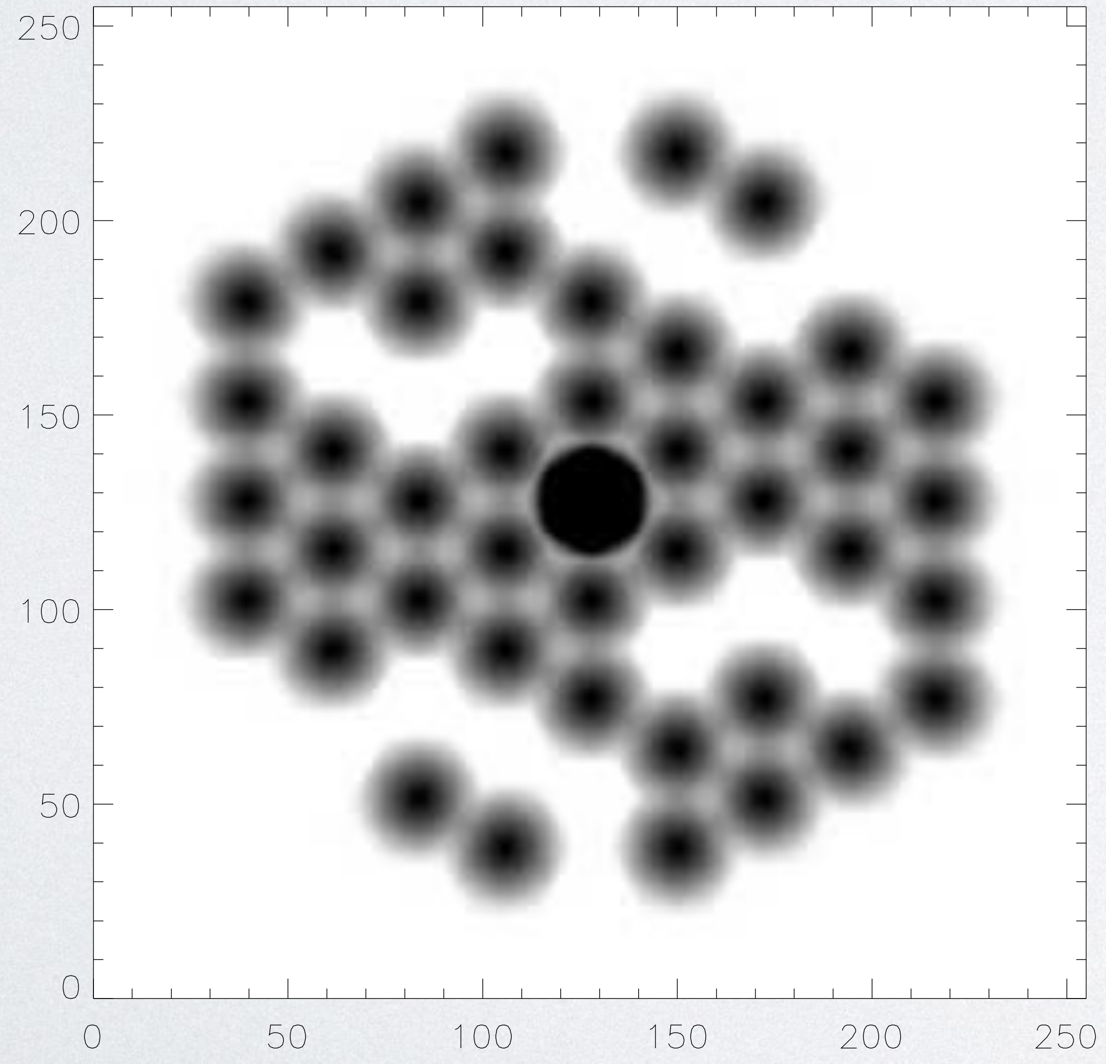


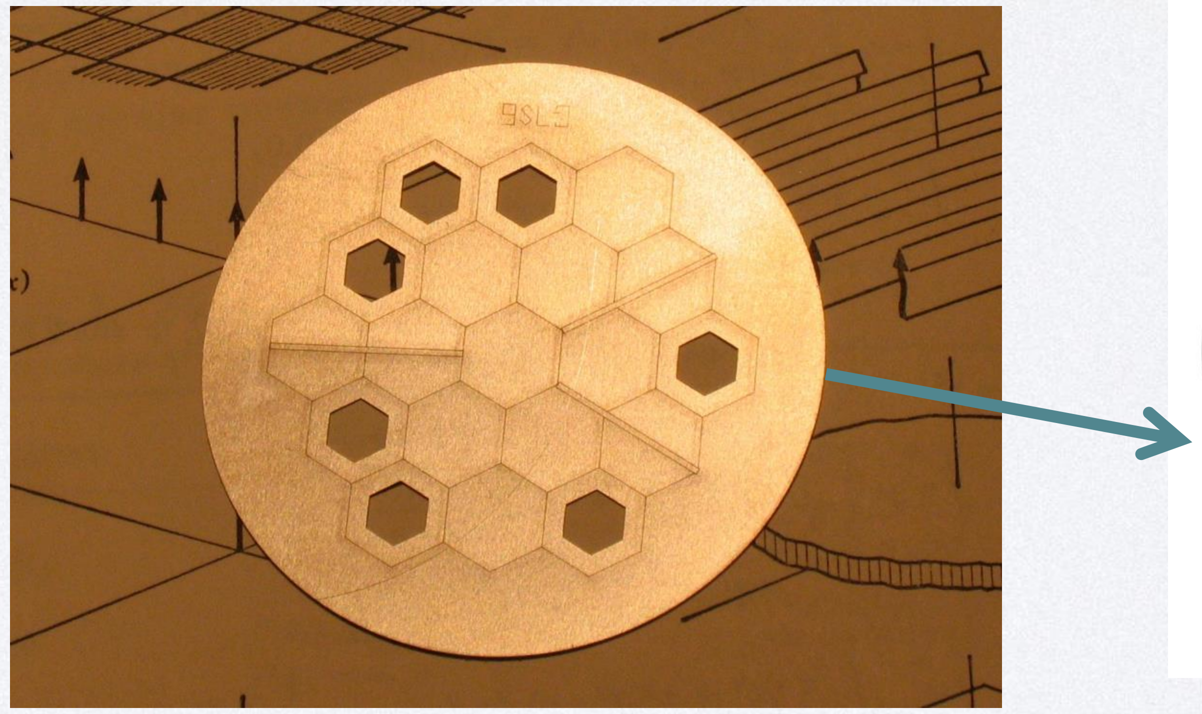


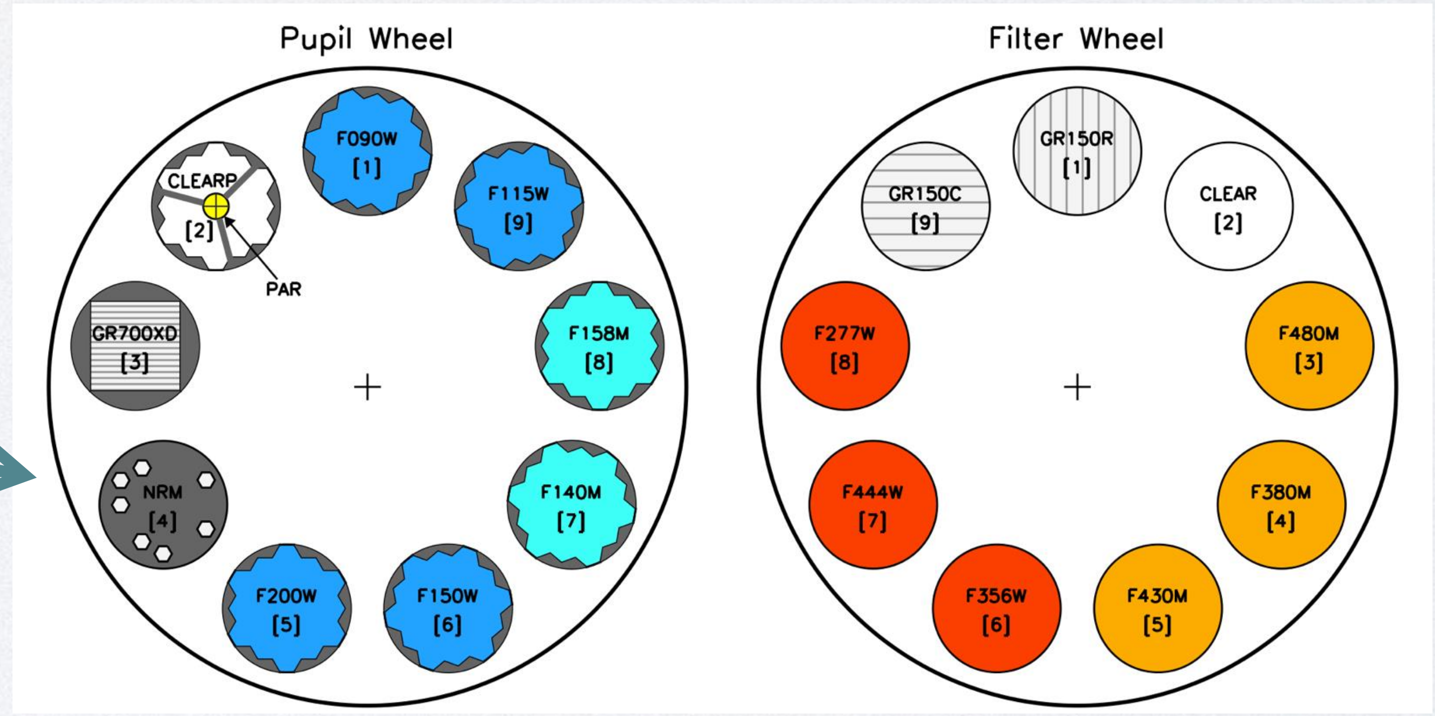




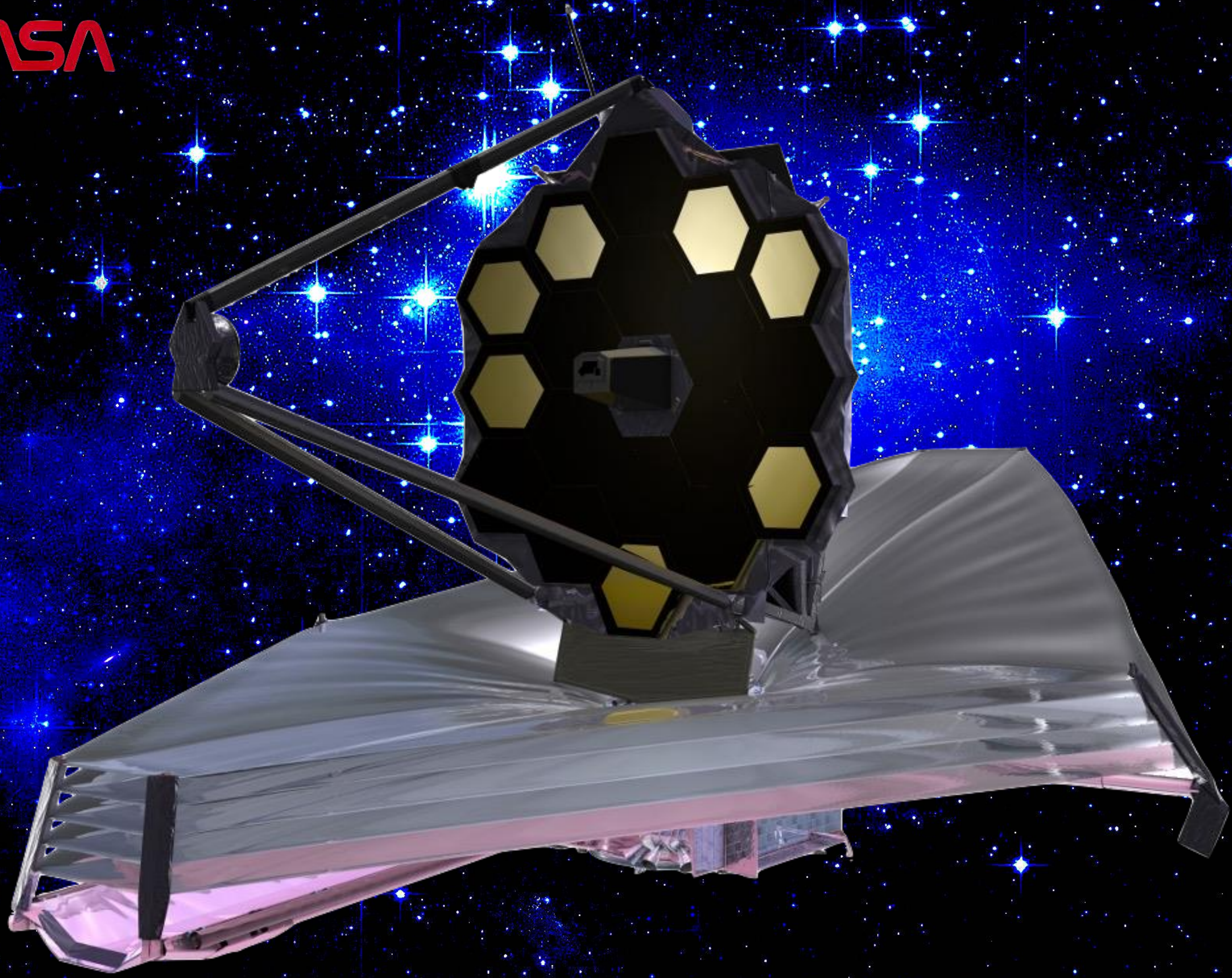






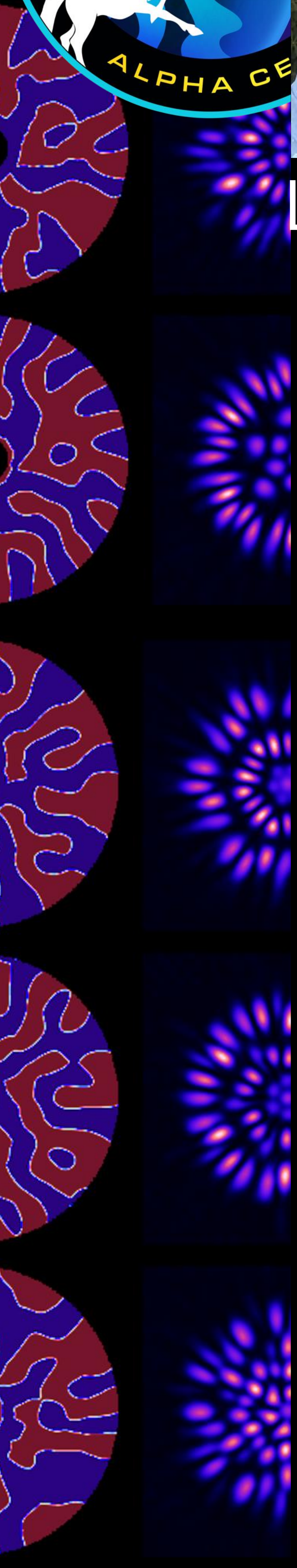


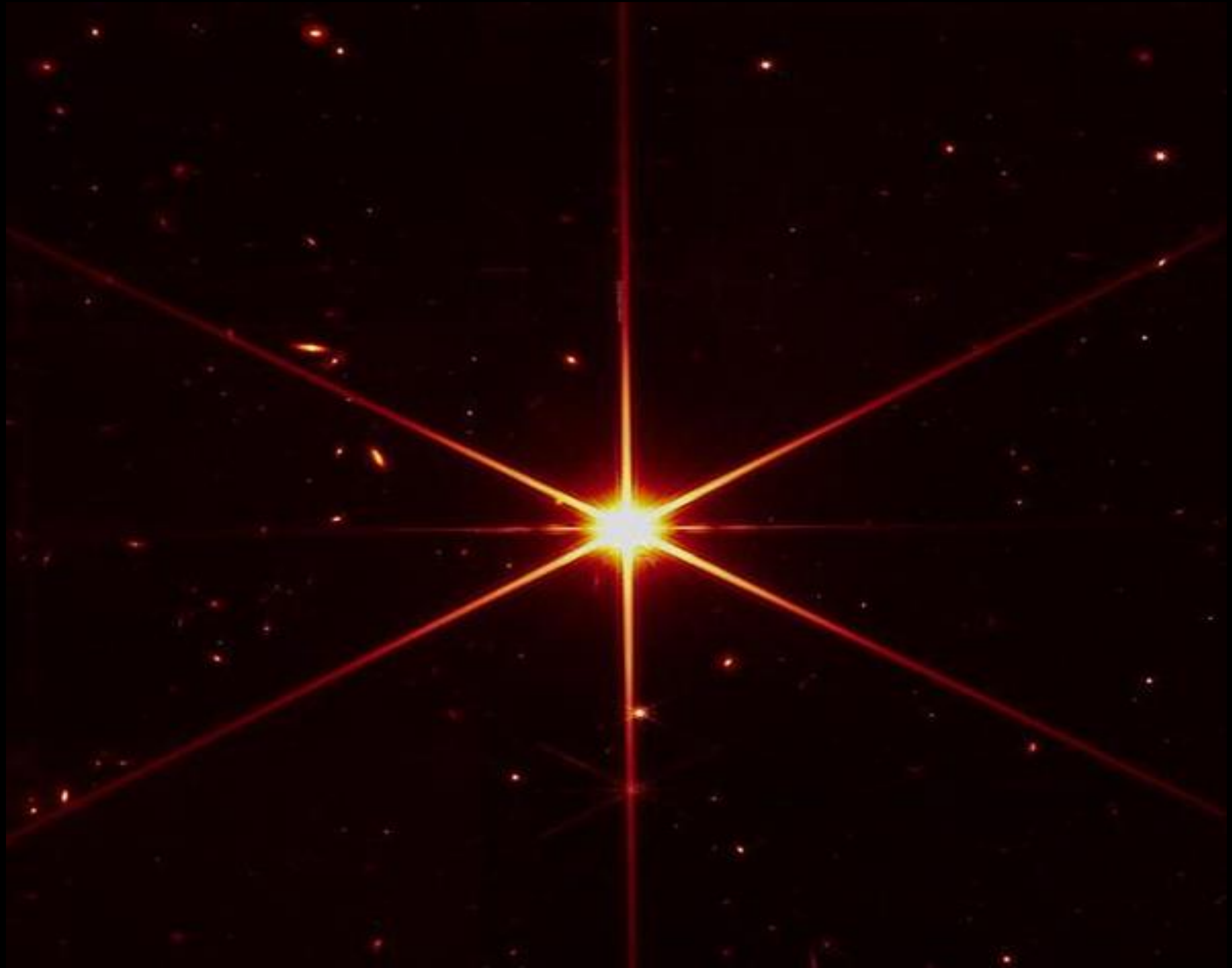
Thanks @ NASA

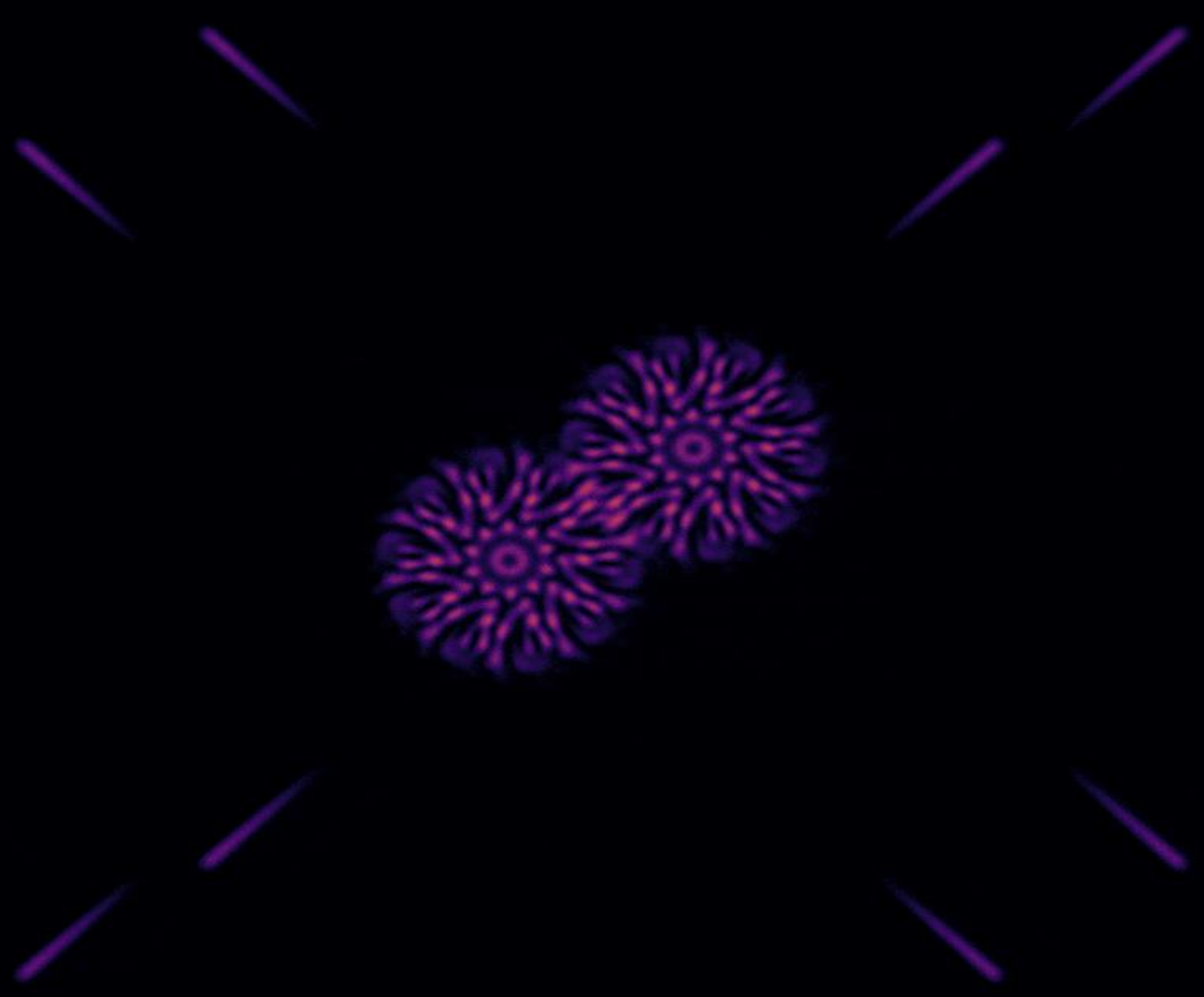



Louis Desdoigts

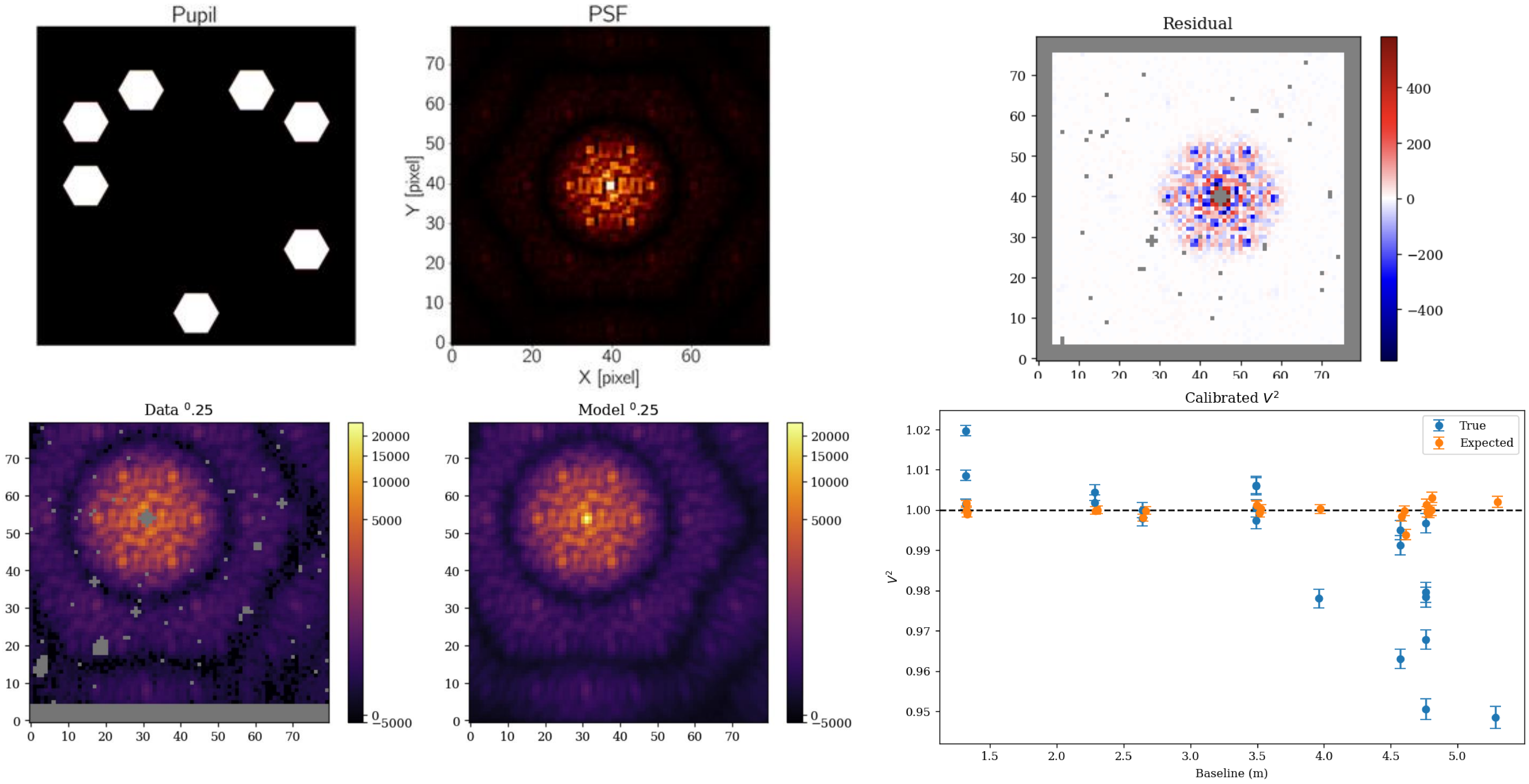

Ben Pope

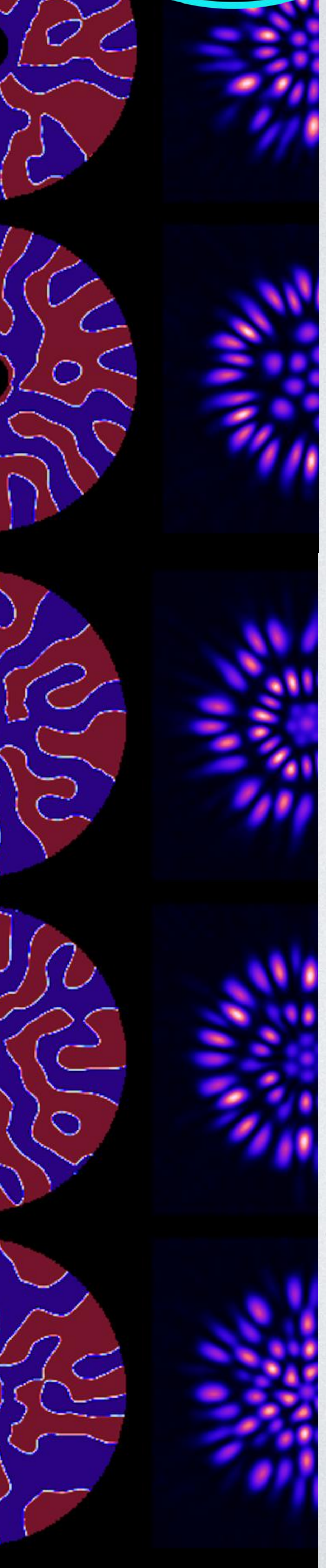




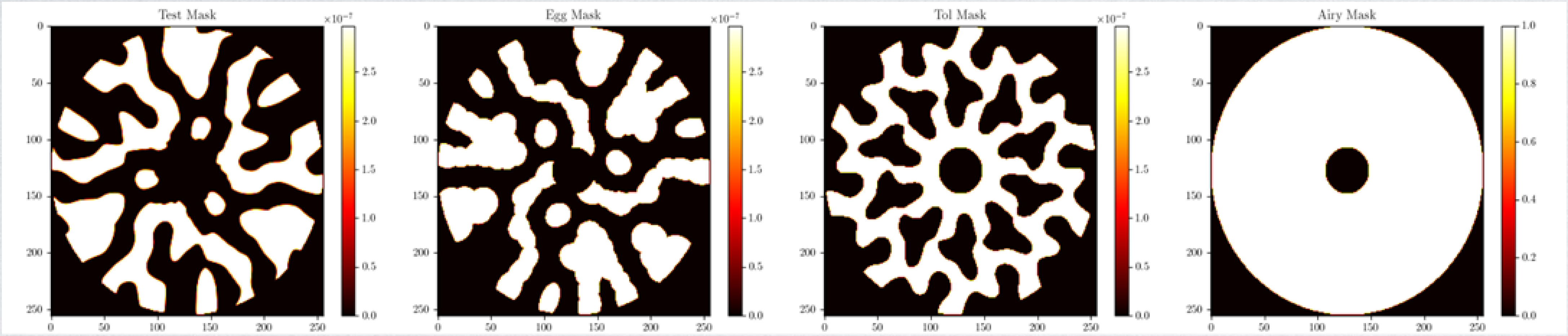


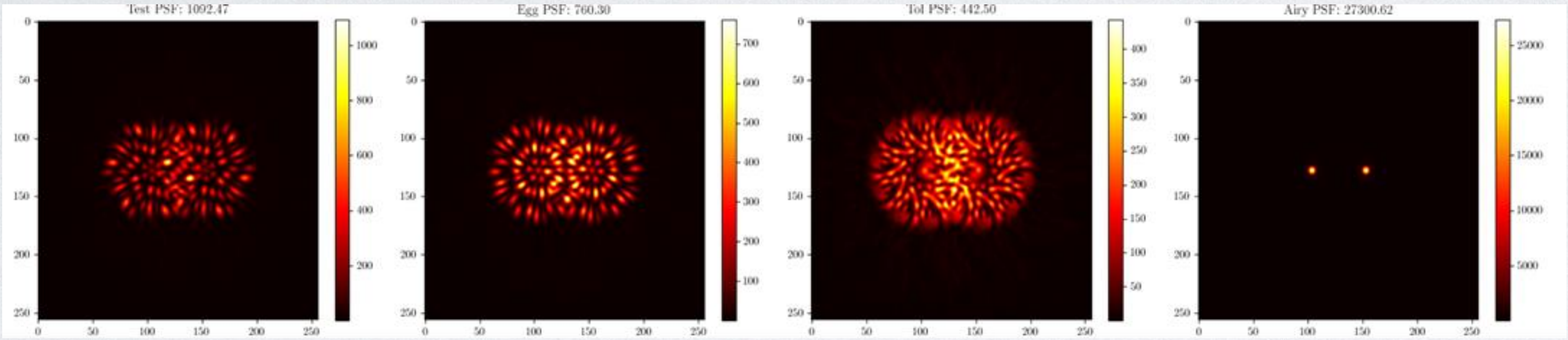
NIRISS AMI: THE JWST INTERFEROMETER

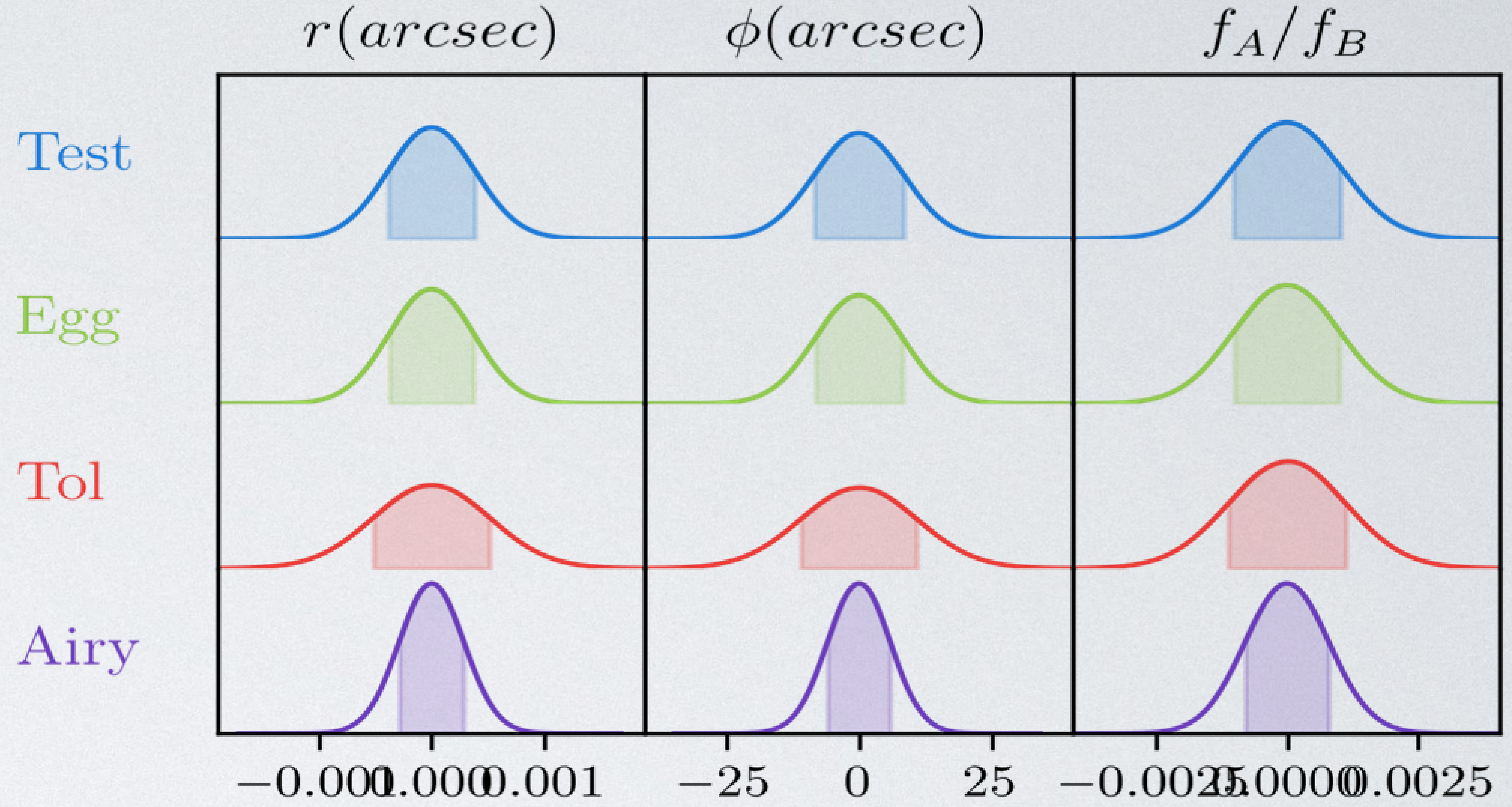




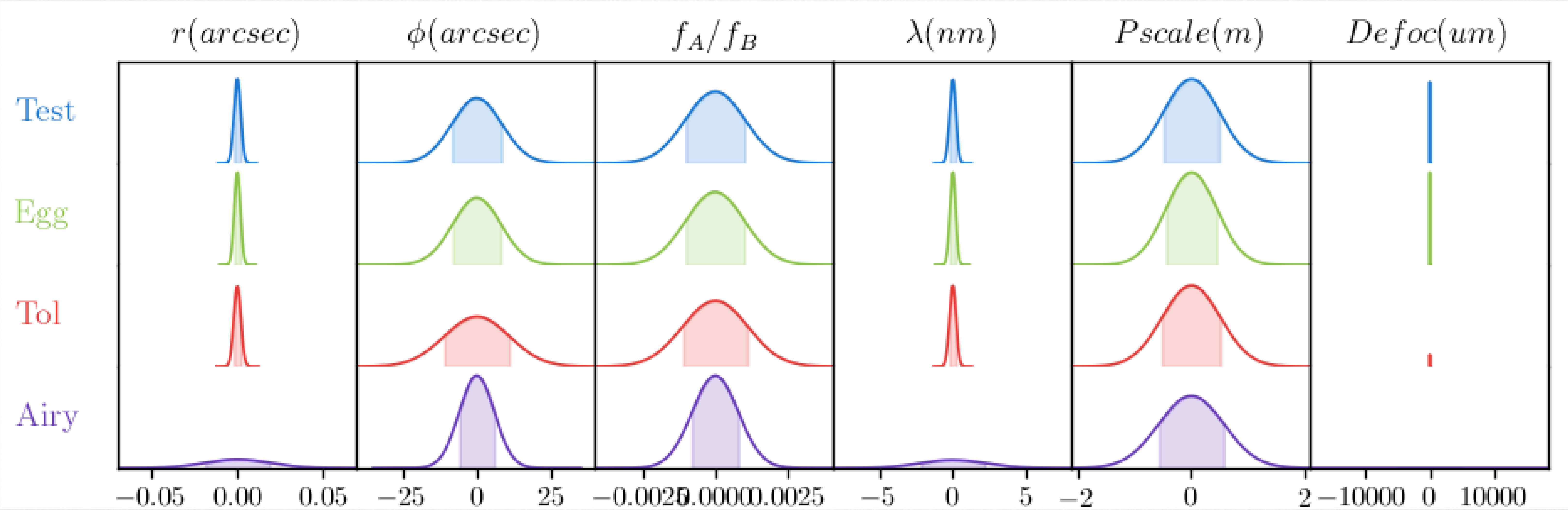
Posteriors: Separation, field angle, flux ratio

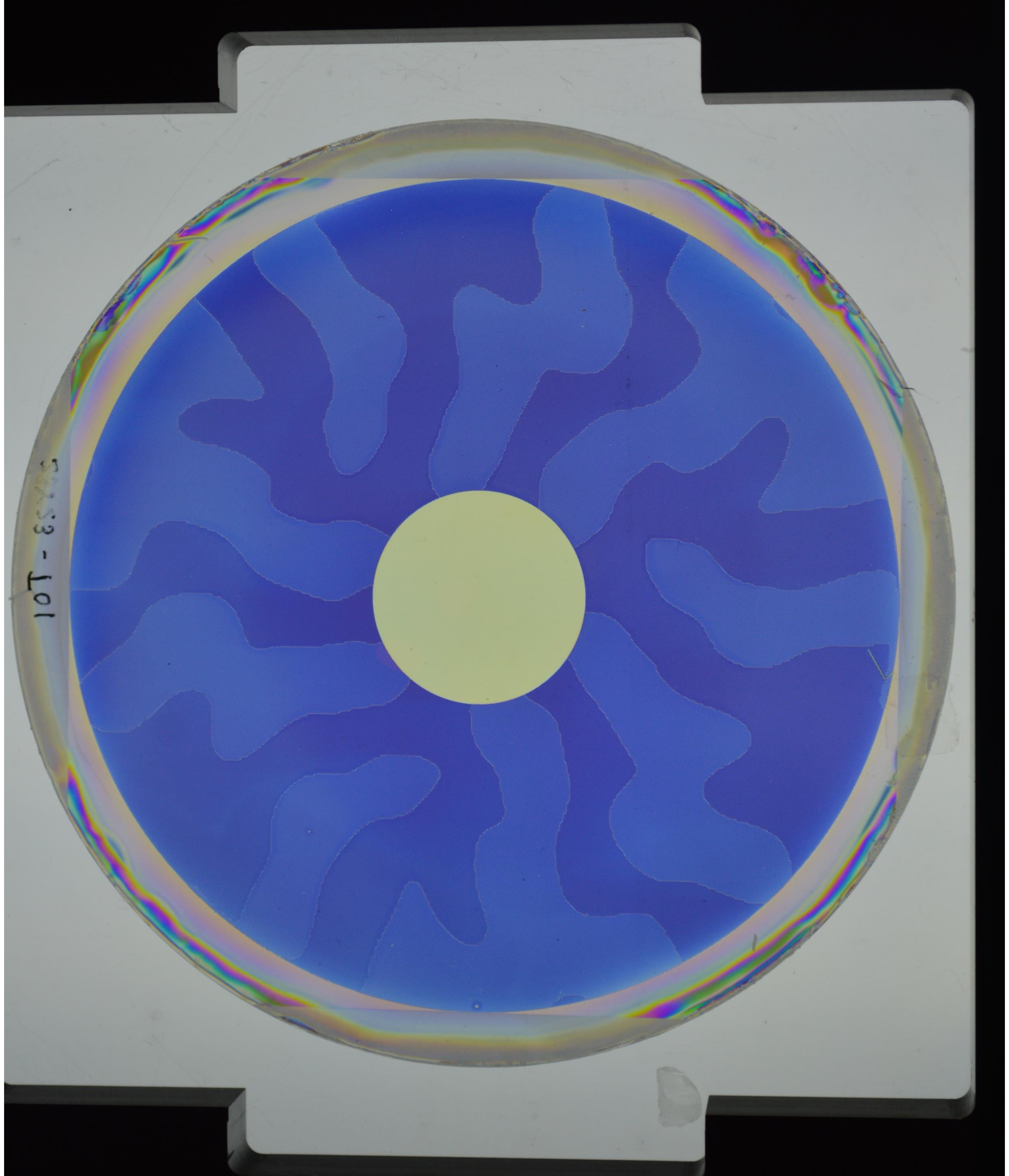


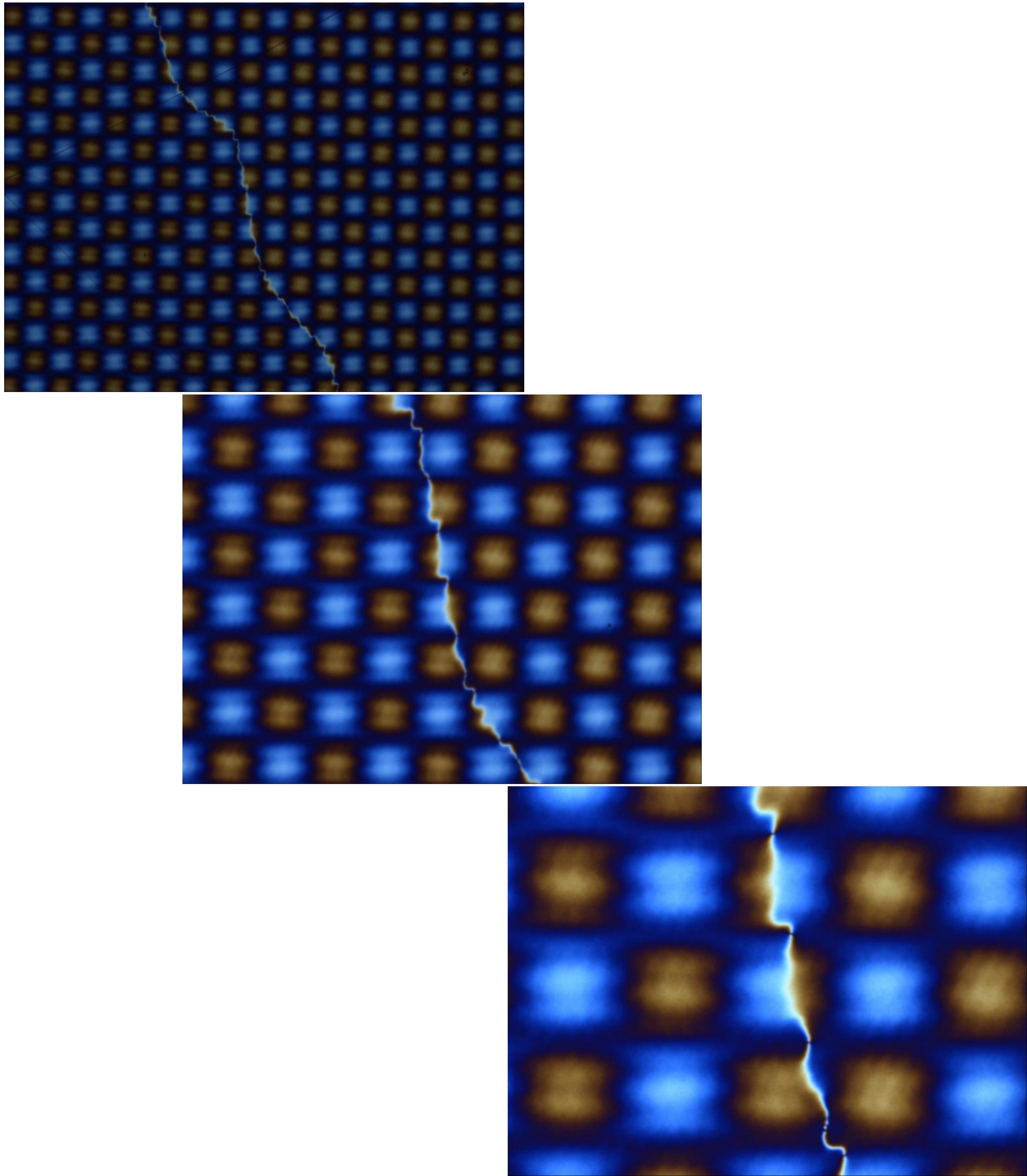




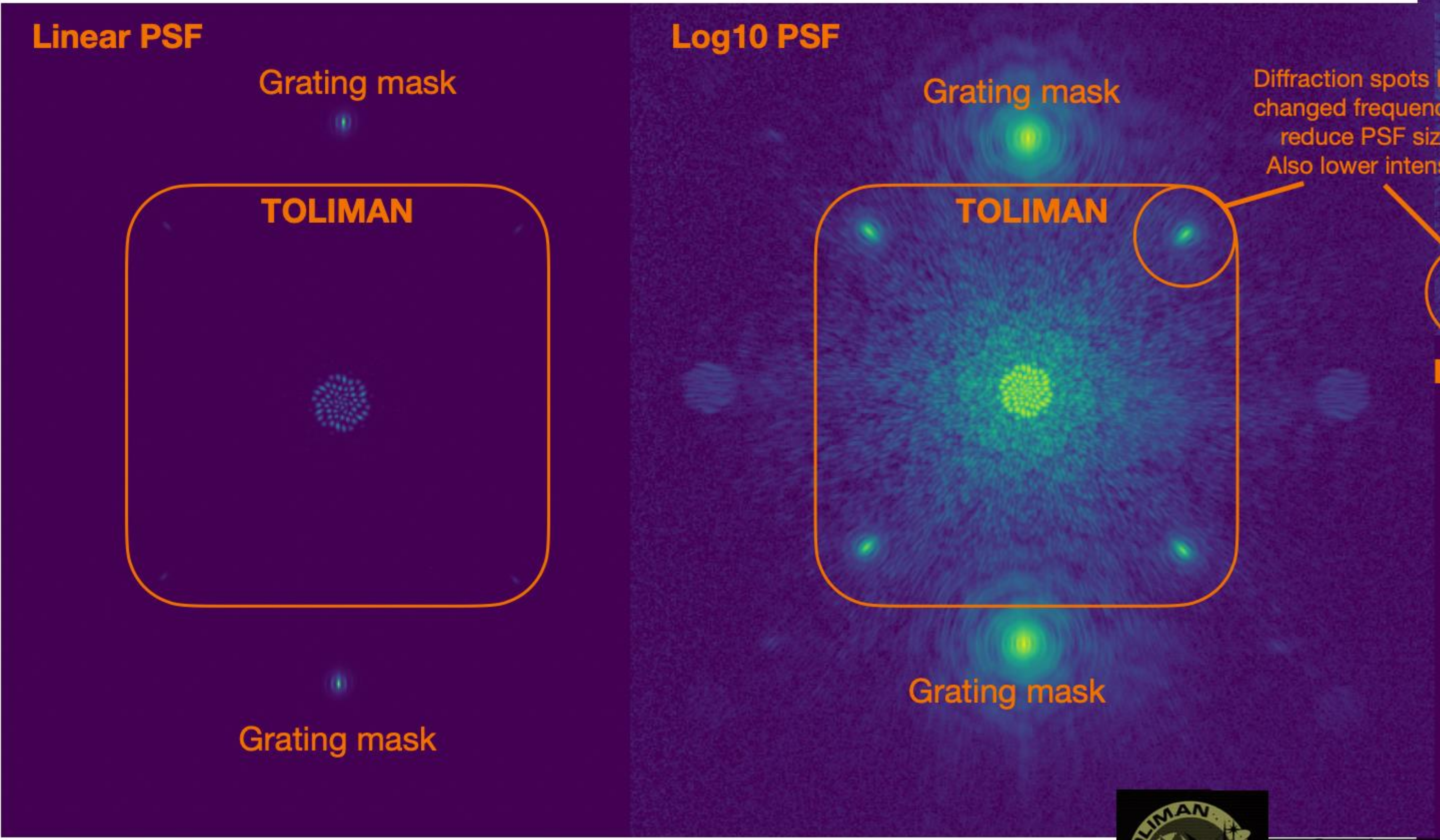
POSTERIORS: ADDING WAVELENGTH, PLATE SCALE,

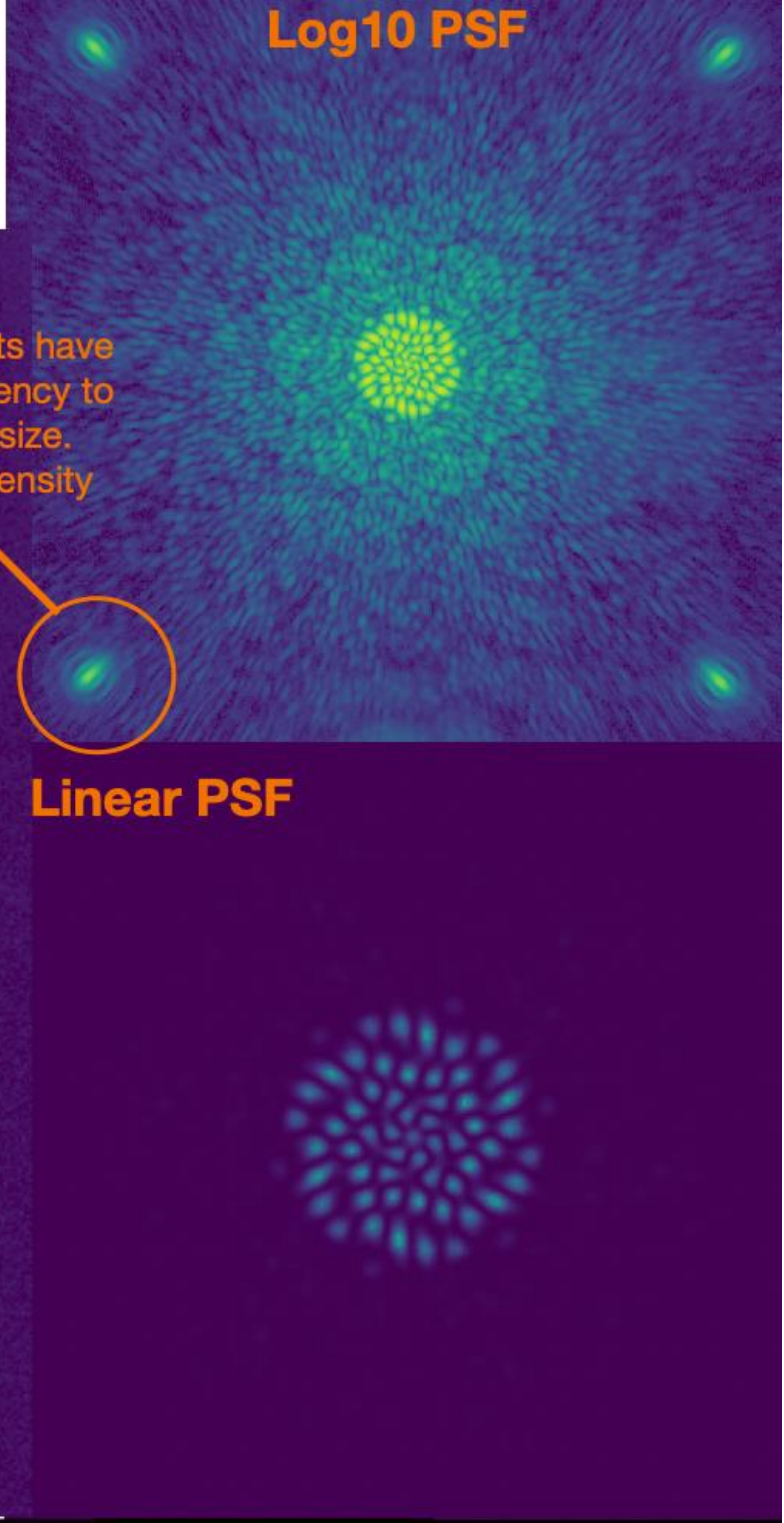




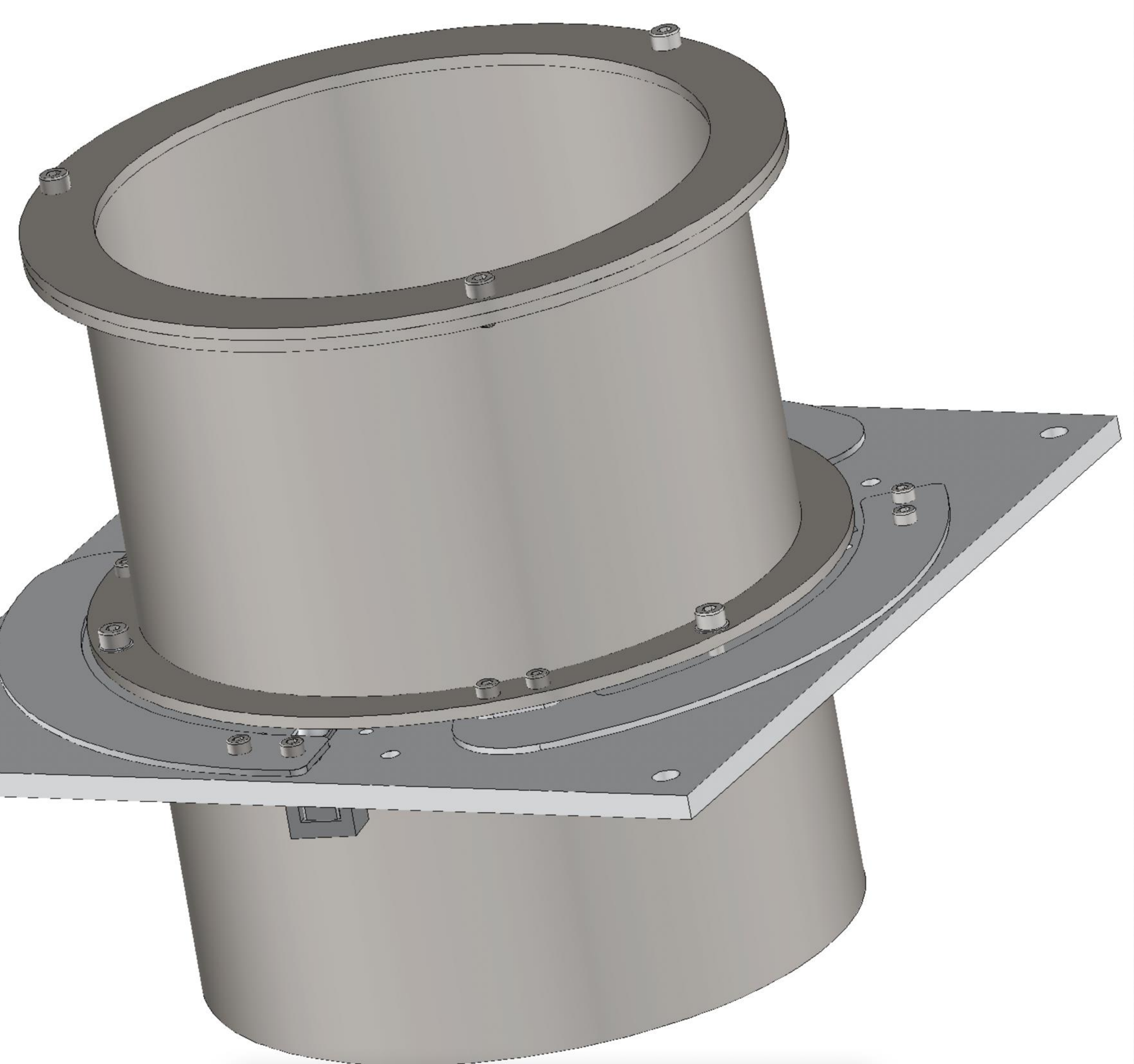


TOLIMAN PSF images





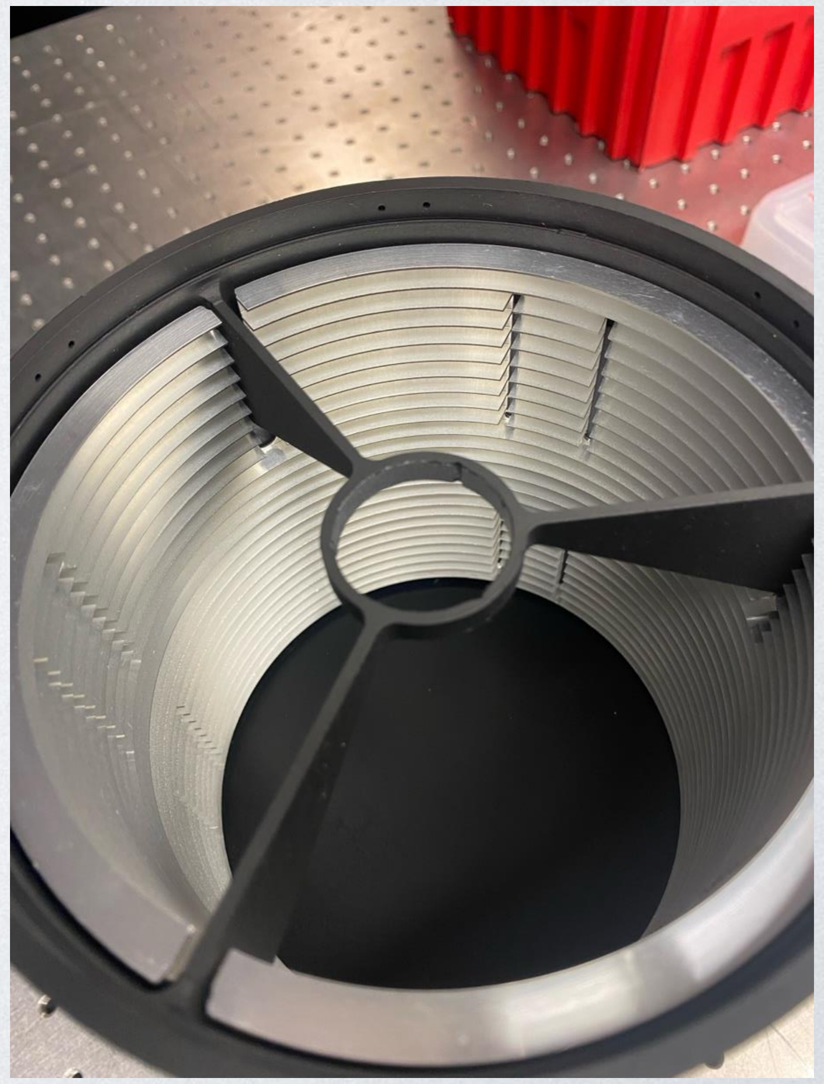
David Doelman 11-11-2023

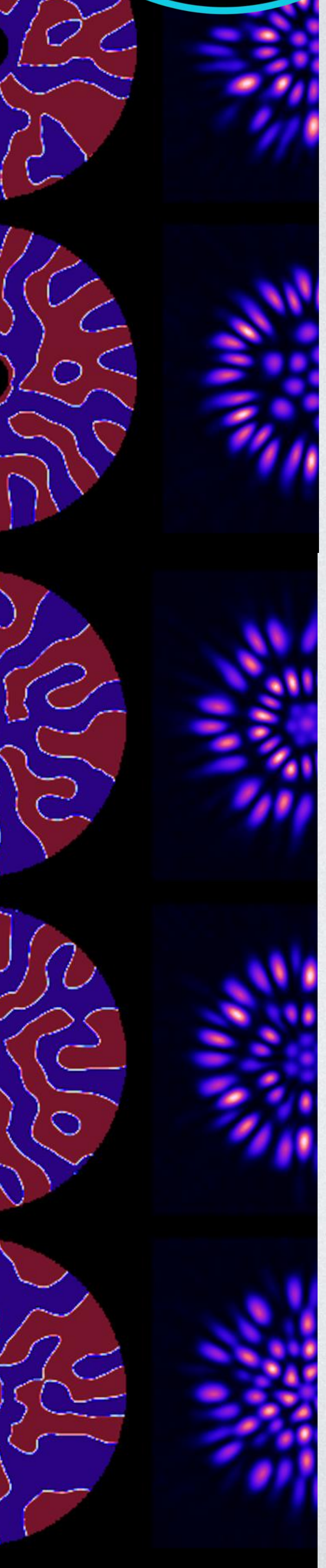


Aperture Optical Sciences

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

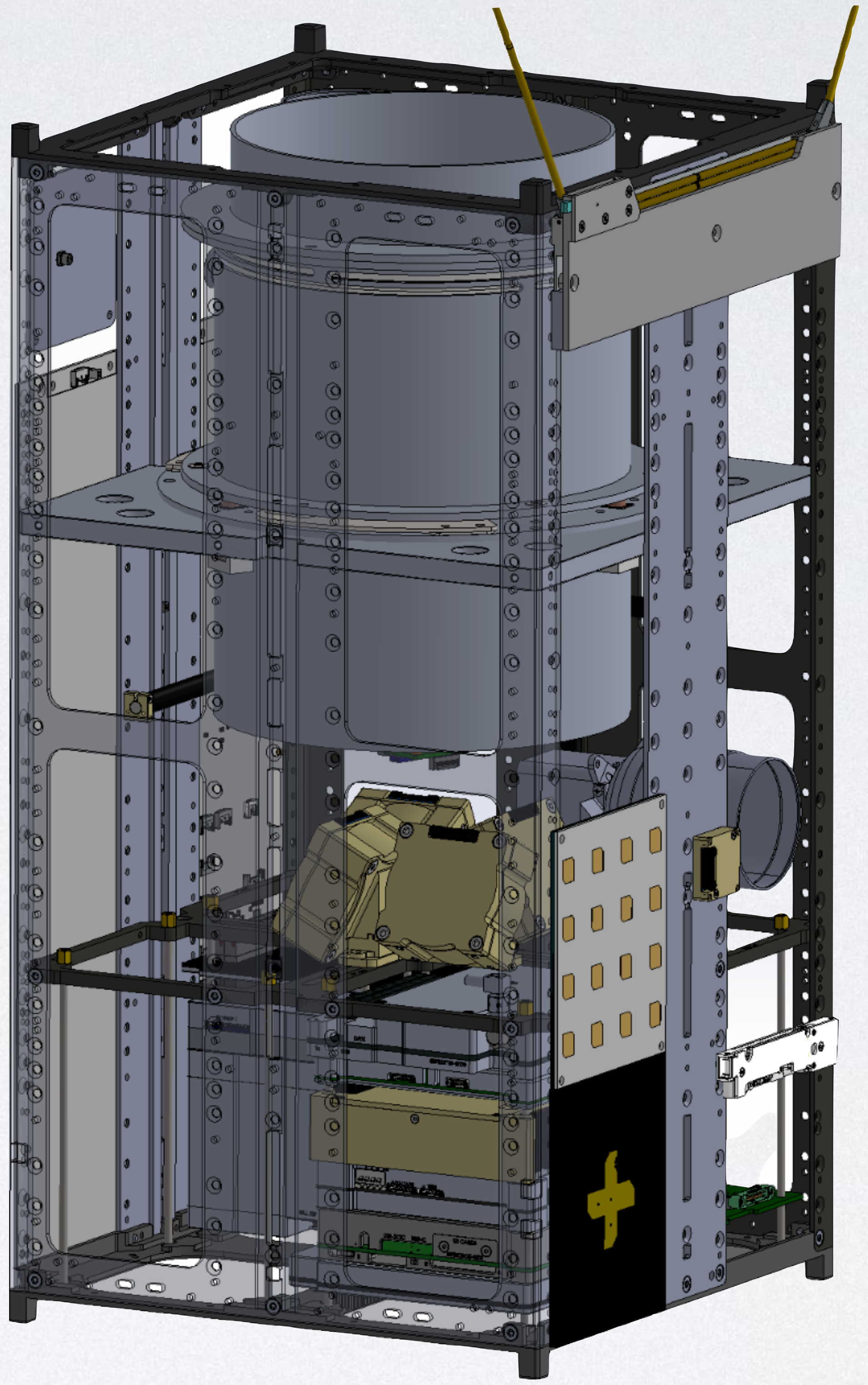


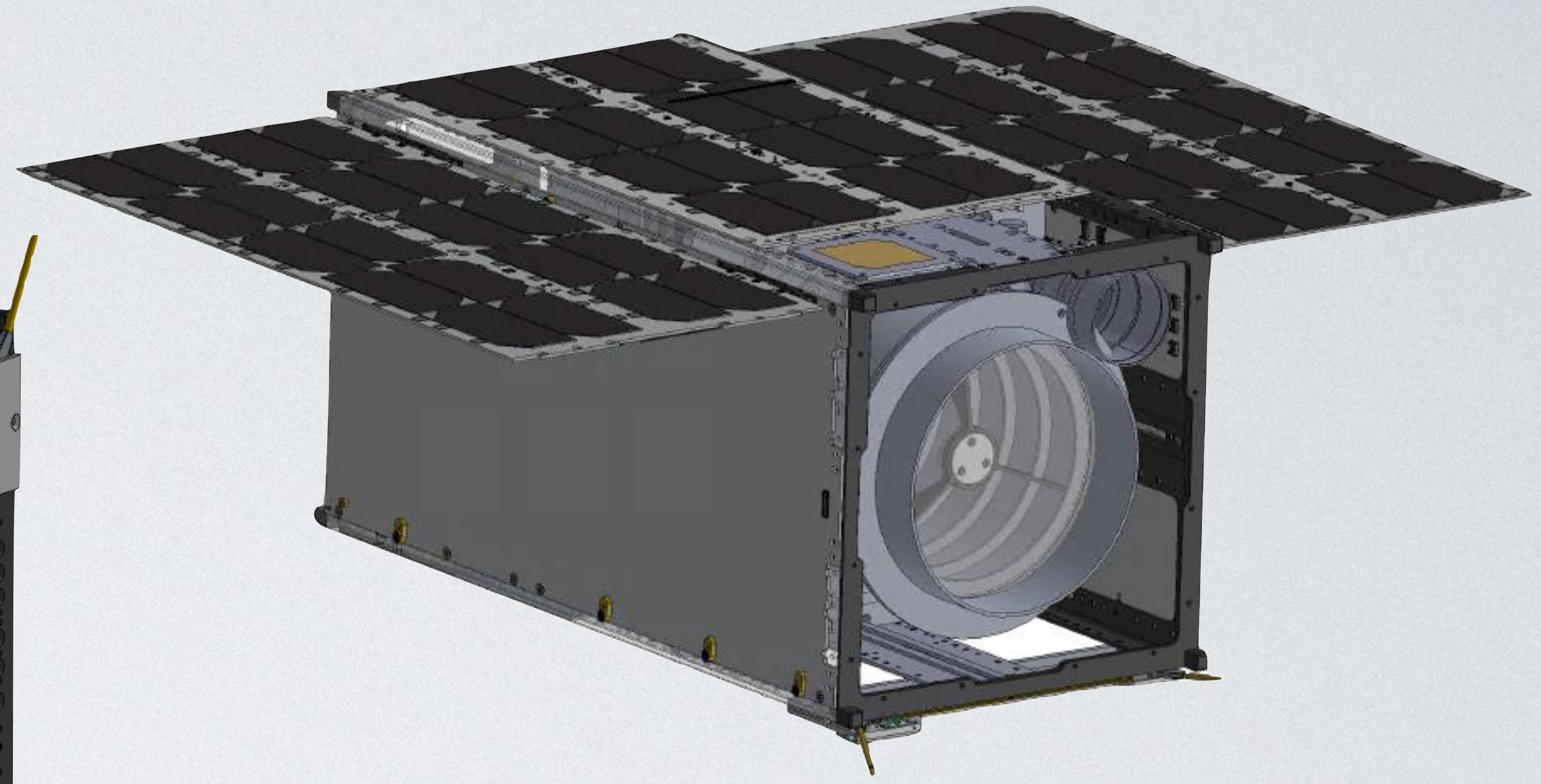


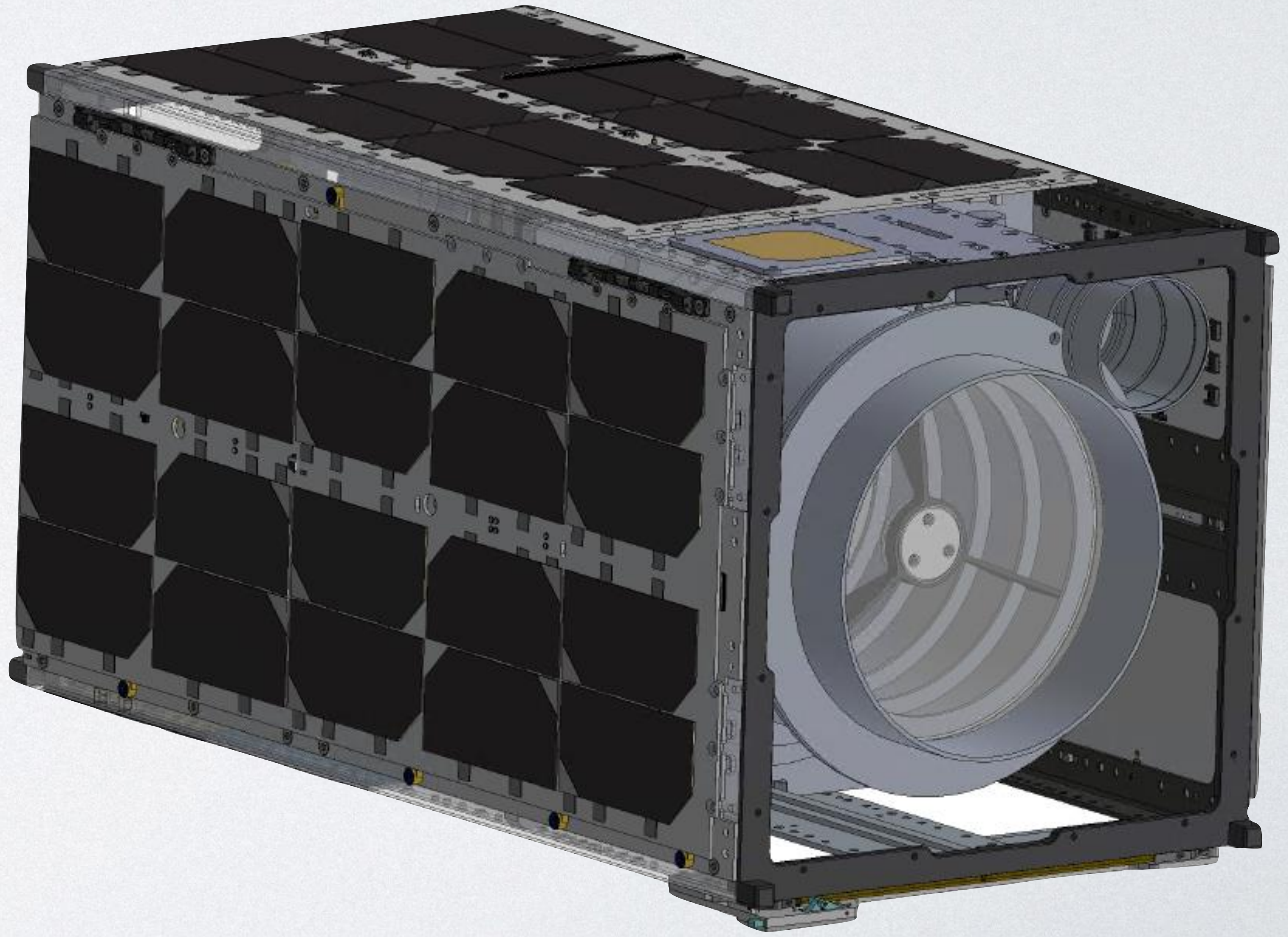
ENDUROSAT

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.

Major Mission Challenges (all in LEO):

(1) Launch 2026, 16 U cubesat SSO orbit in 2-3 year mission

(2) Target astrometry (narrow-angle) is <1micro-arcsec

(3) Simultaneous Photmetry (10hz) and Spectroscopy (R~200)

(4) All hardware components fabricated or in process

(5) Integration into Bus in Sofia 2025

Key Take Aways:

- Sydney team welcomes science/instrument collaborations. See me or Karel Valenta!
- Success is *at least* as dependent on principled reduction of data as on optics. Differentiable forward modelling with ∂Lux has been a gamechanger (public on github).
- Unothodox (coded-aperture) imaging systems might have reach / application to YOUR mission (Talk to me – have ideas!)

University of Sydney TOLIMAN team

Peter Tuthill

Chris Betters

Connor Langford

Karel Valenta

Fred Crous

Louis Desdoigts

Max Charles

Grace Piroscia

TOLIMAN

THE UNIVERSITY OF SYDNEY

TOLIMAN
ALPHA CENTAURI

SAIL
Sydney Astrophotonic Instrumentation Laboratory

The University of Queensland
Australia

Universiteit Leiden

The Breakthrough Prize

NASA