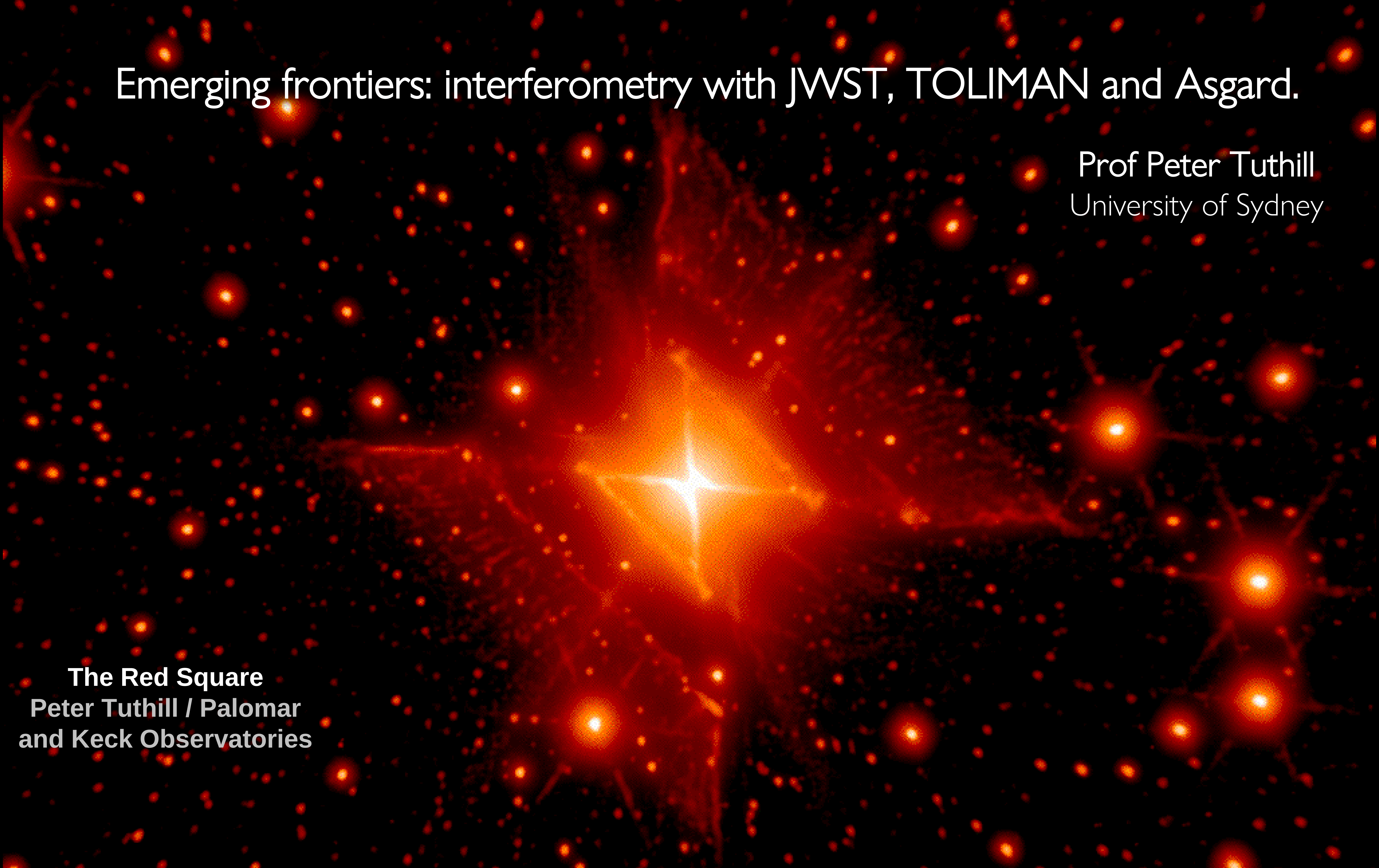
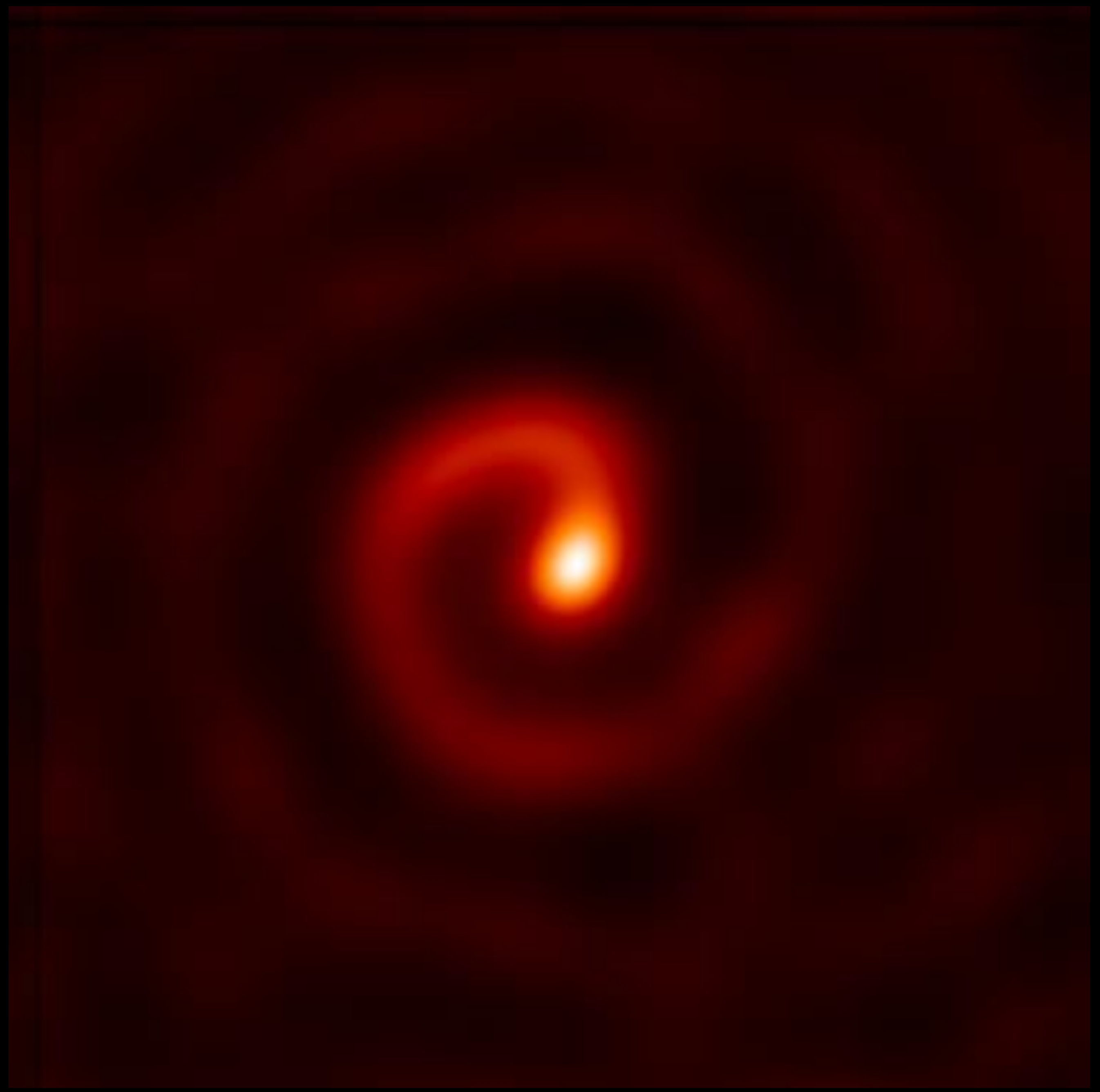
Emerging frontiers: interferometry with JWST, TOLIMAN and Asgard.

Prof Peter Tuthill
University of Sydney

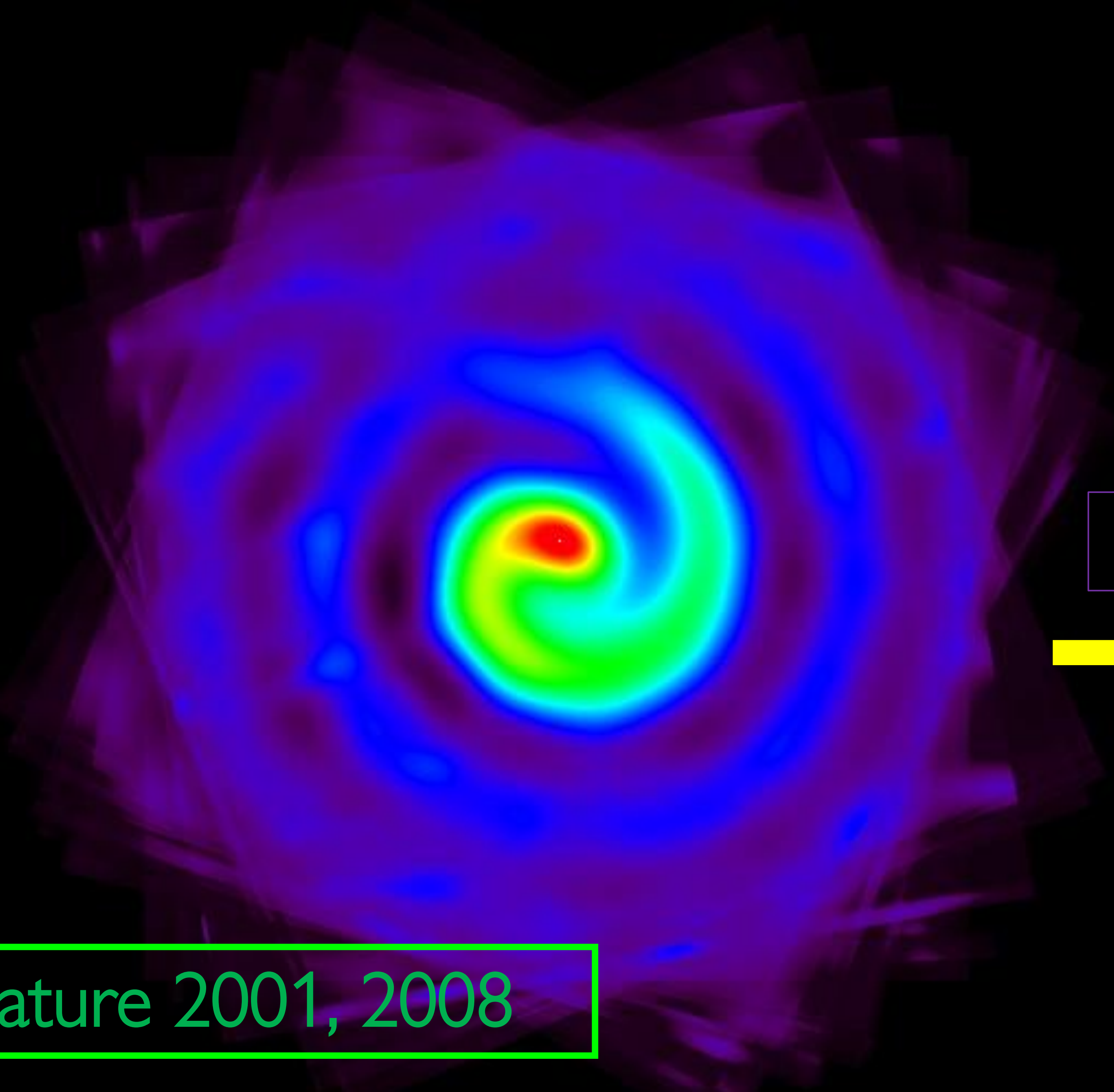


The Red Square
Peter Tuthill / Palomar
and Keck Observatories

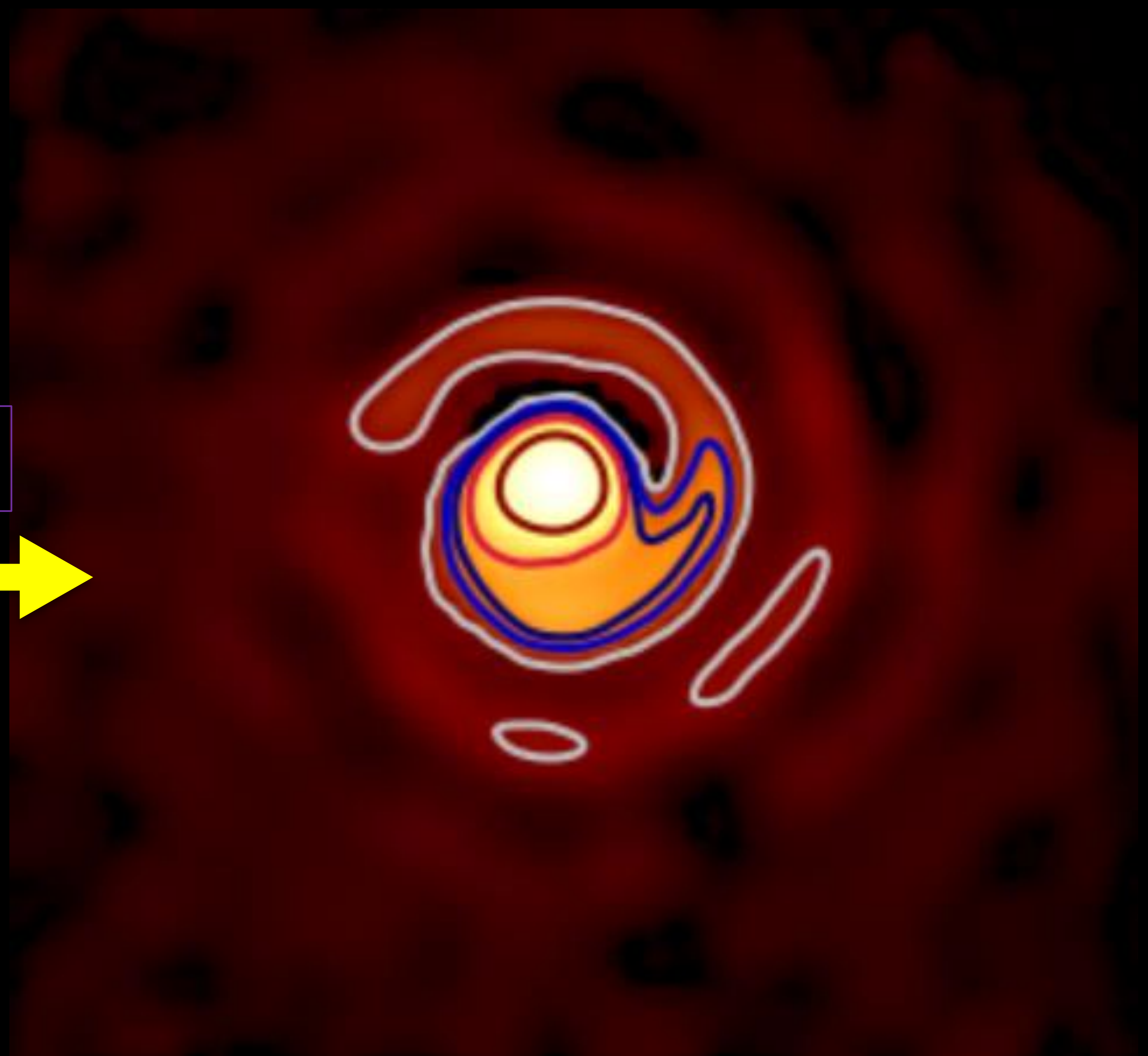
WR 104
11 epochs
K-band
Keck Masking



Stacked image
Keck Masking



17 years

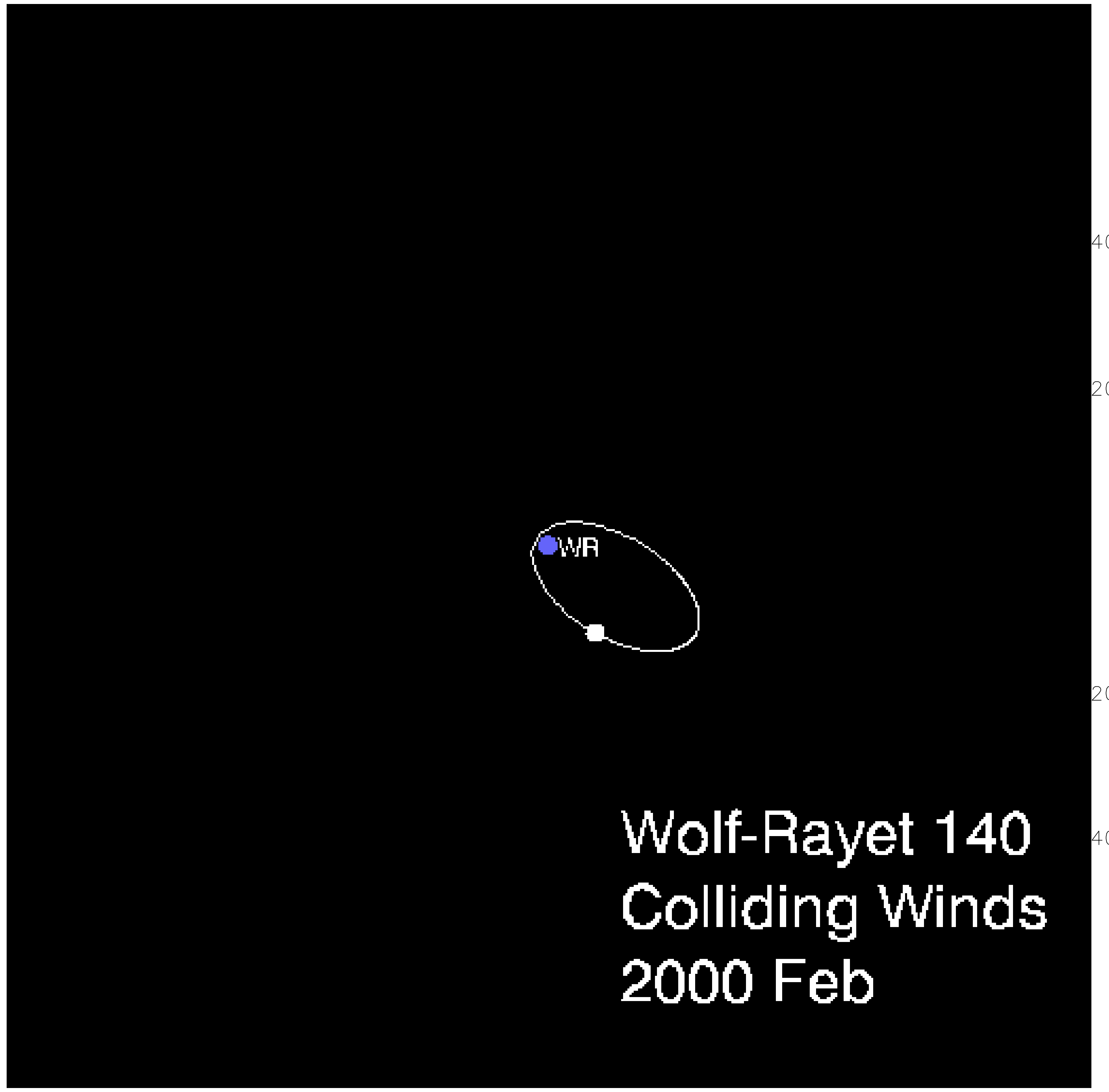


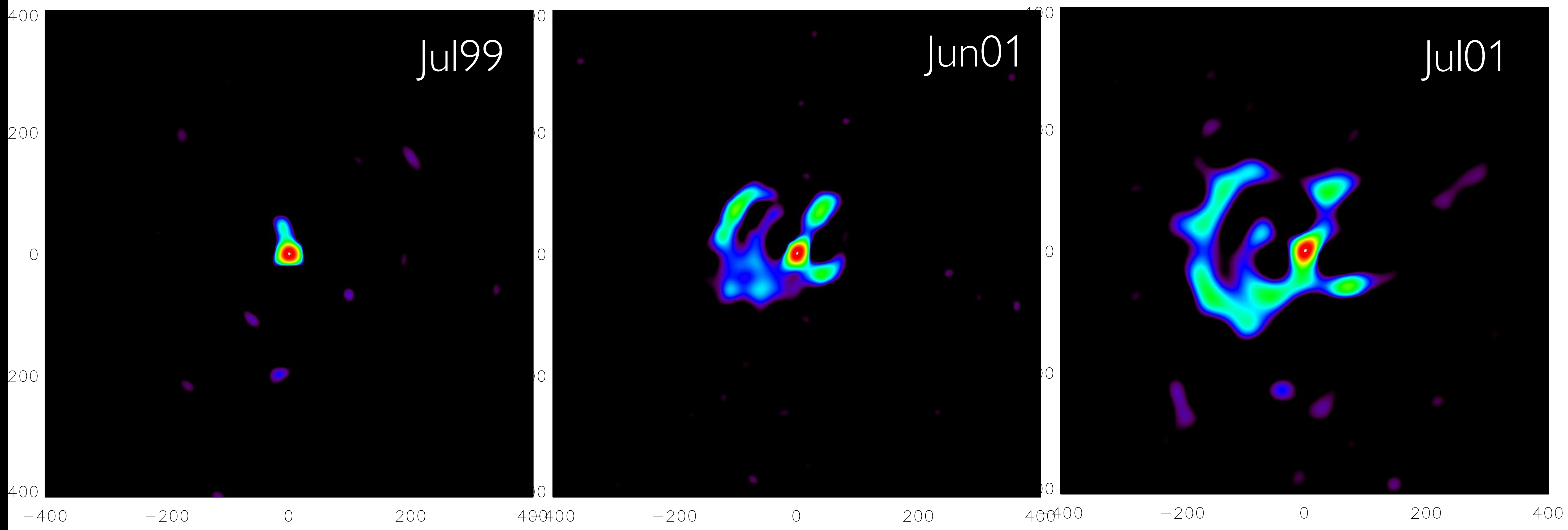
WR 104
Adaptive Optics, SPHERE/ESO

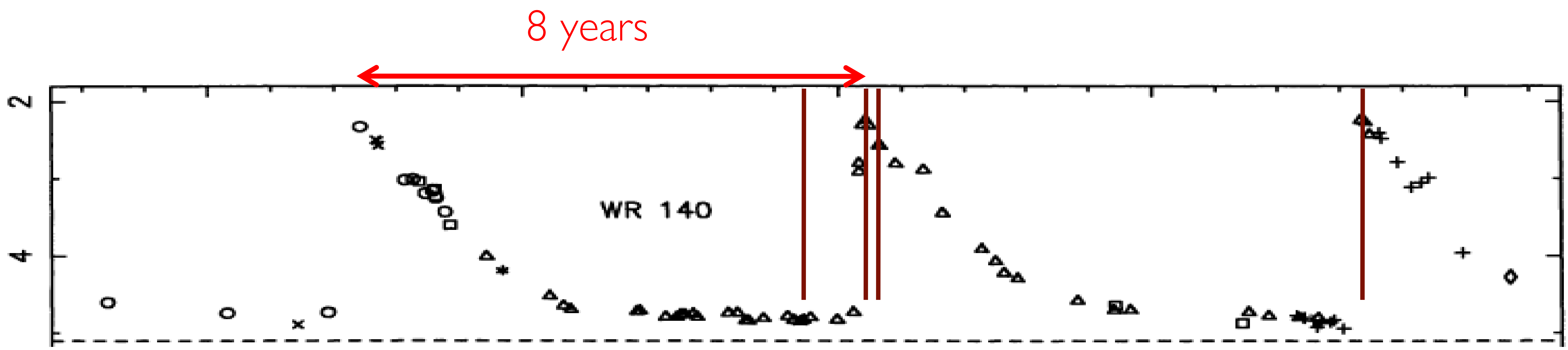
Soulain et al A&A 2016

Tuthilll et al Nature 2001, 2008

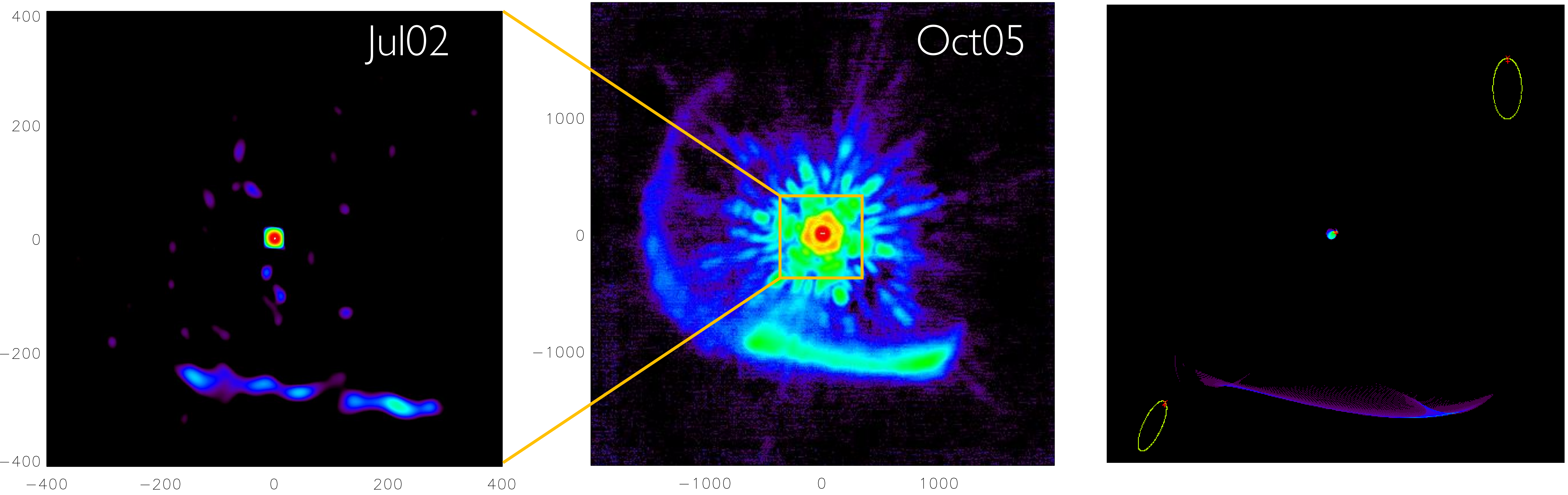
Wolf-Rayet 140 (dusting for God's thumbprint)



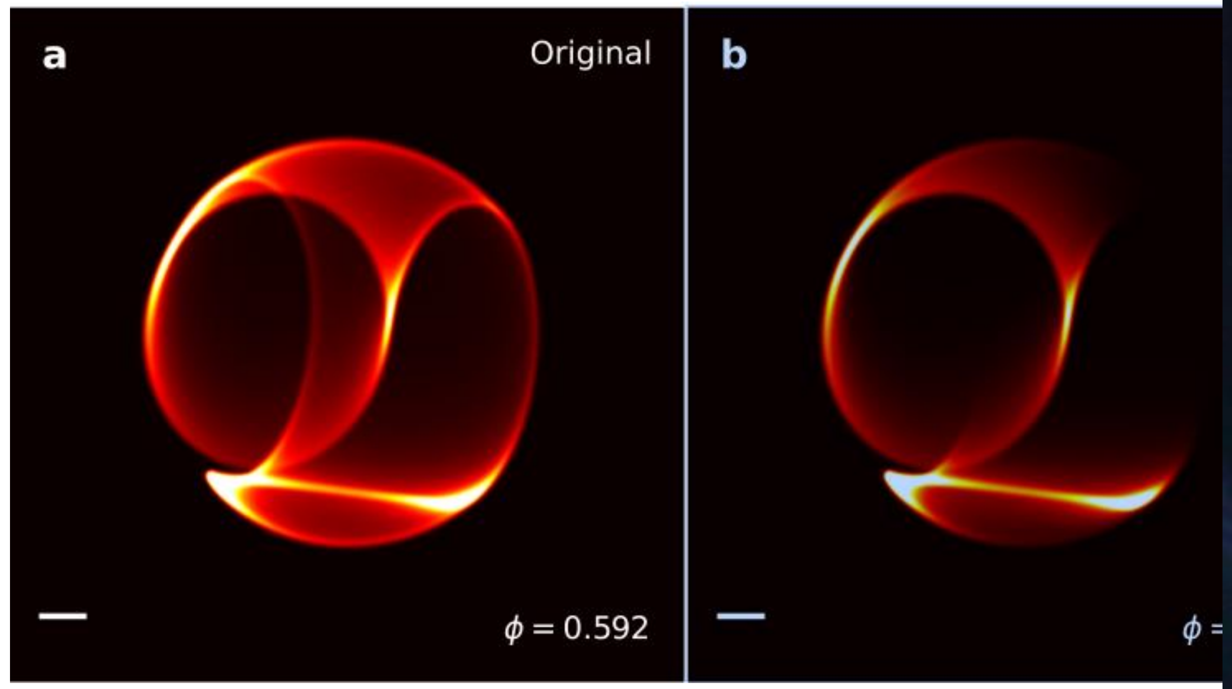


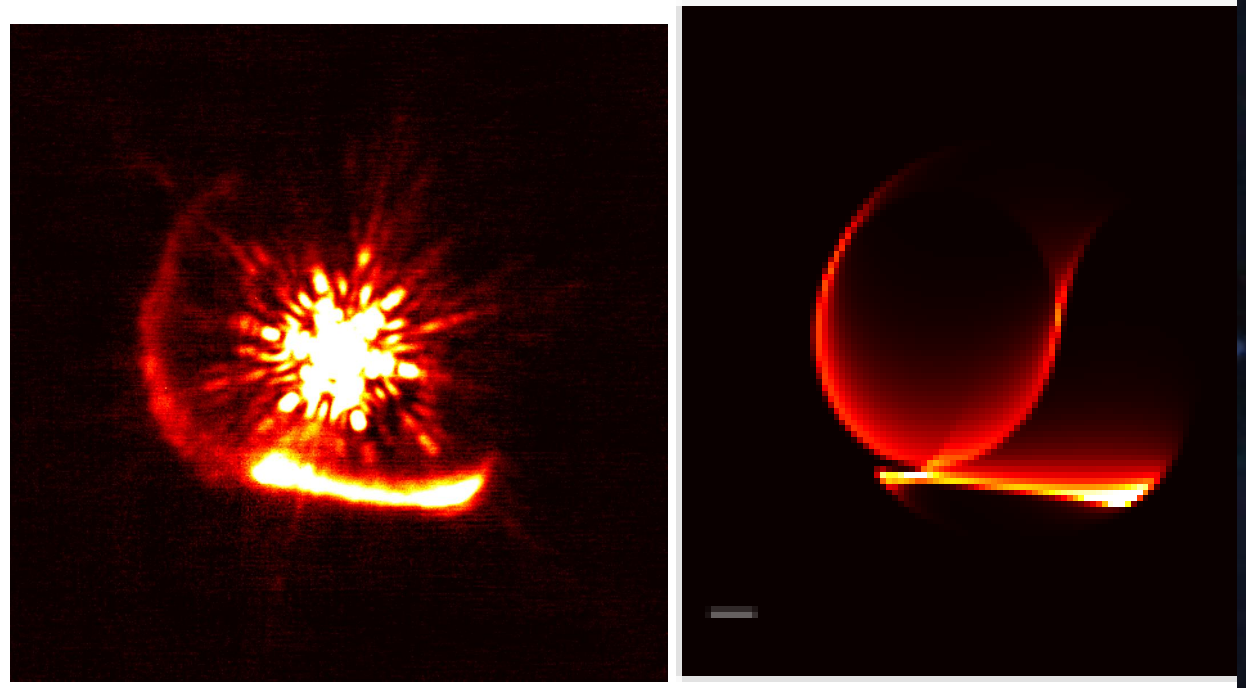


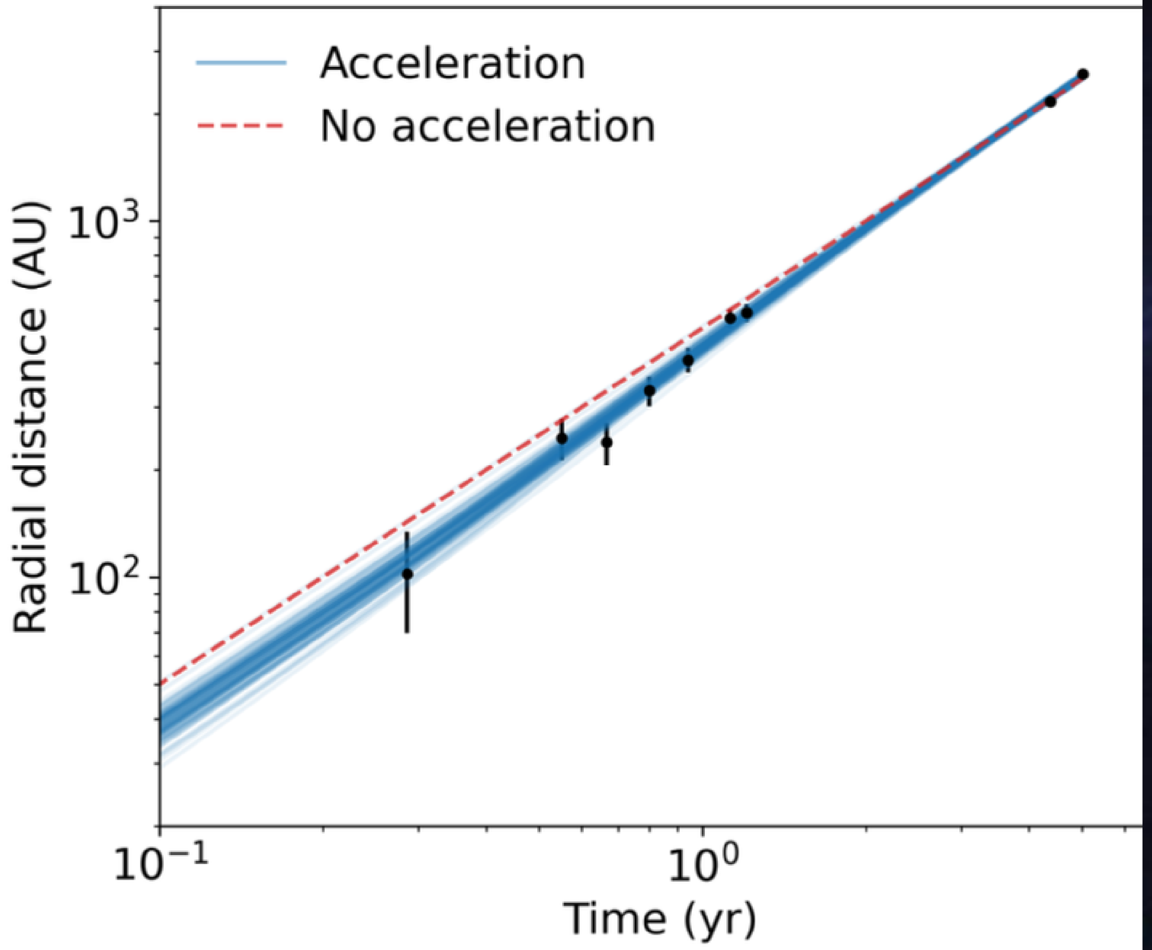
Wolf-Rayet 140 (dusting for God's thumbprint)

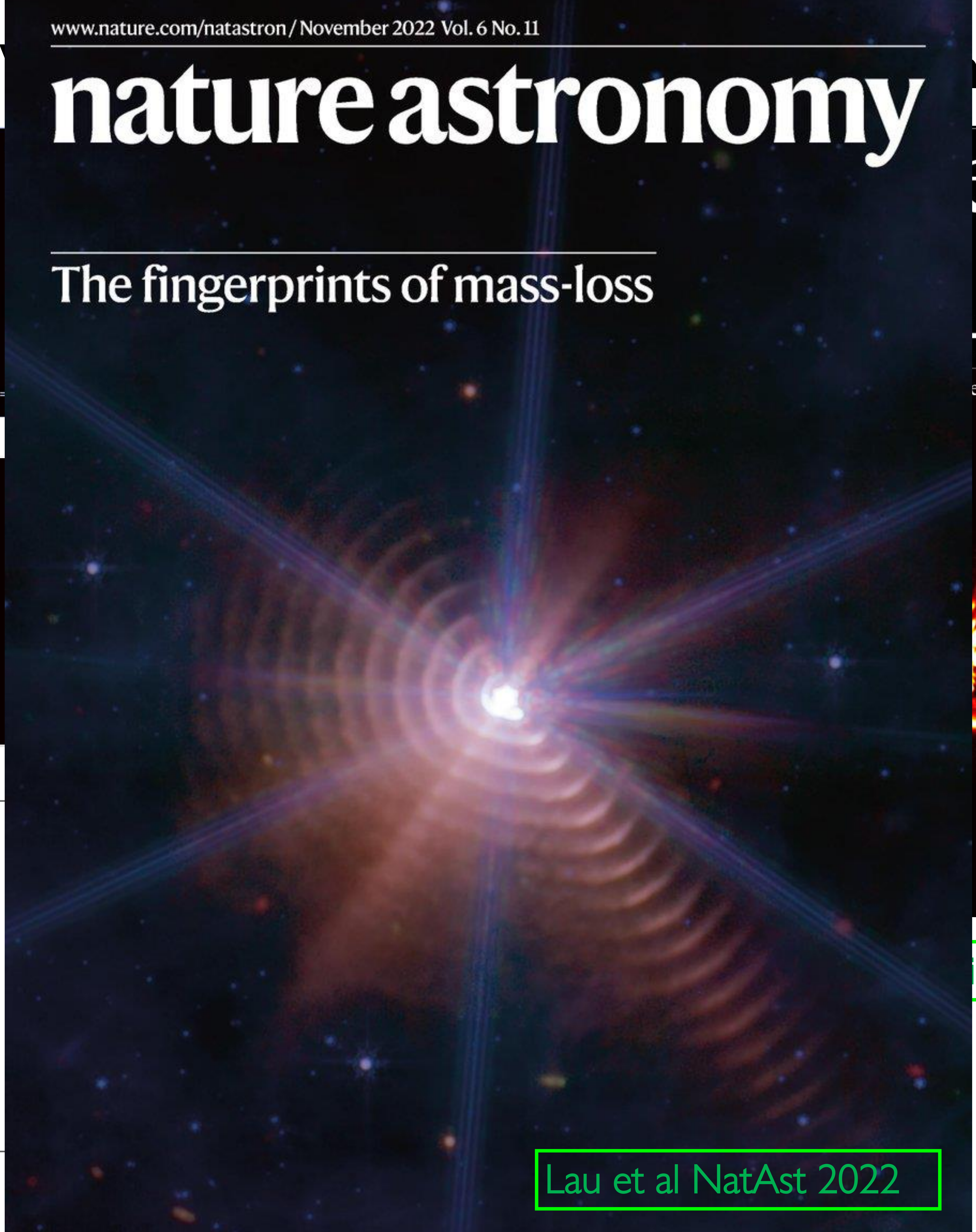


bprint)

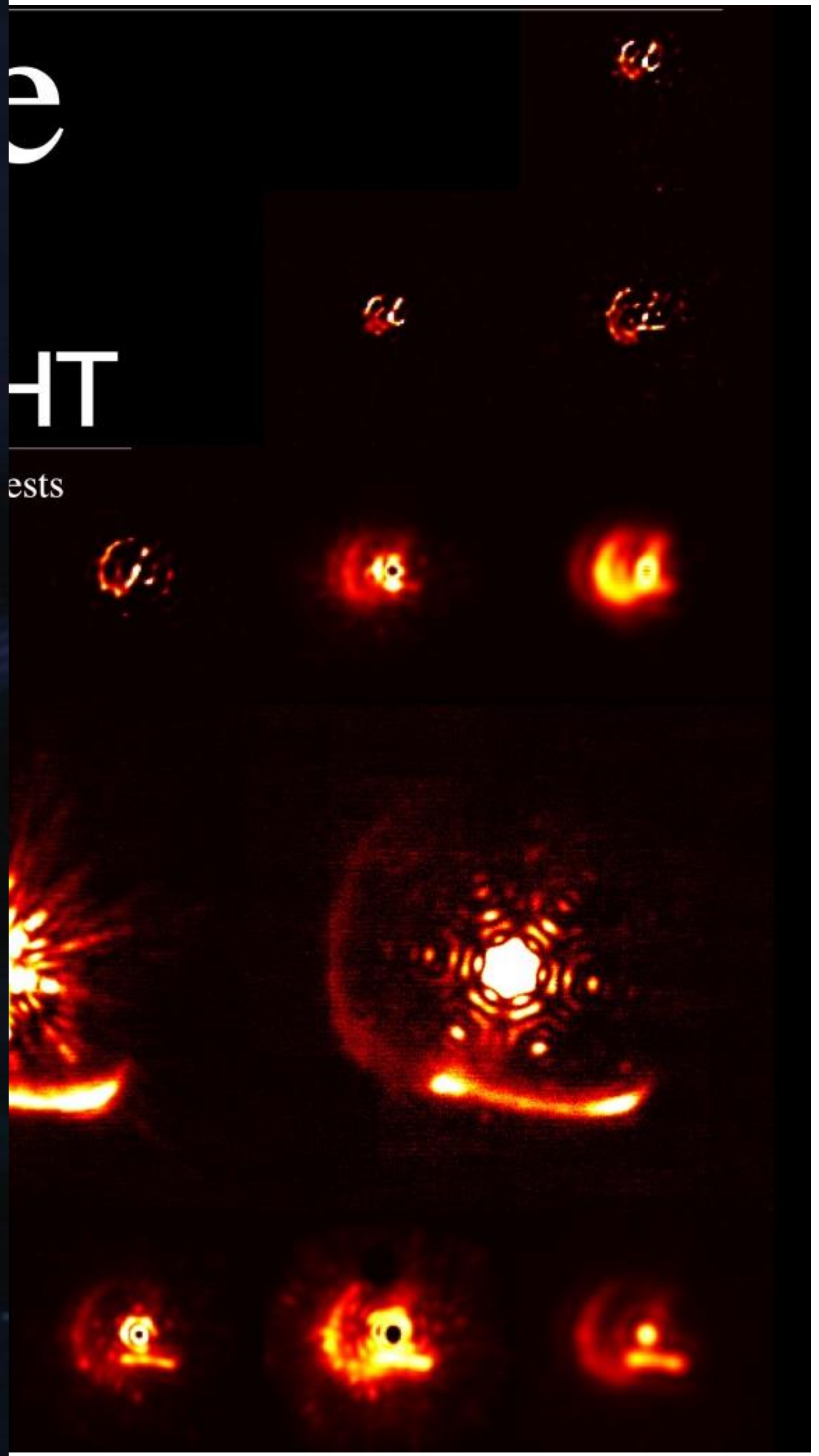








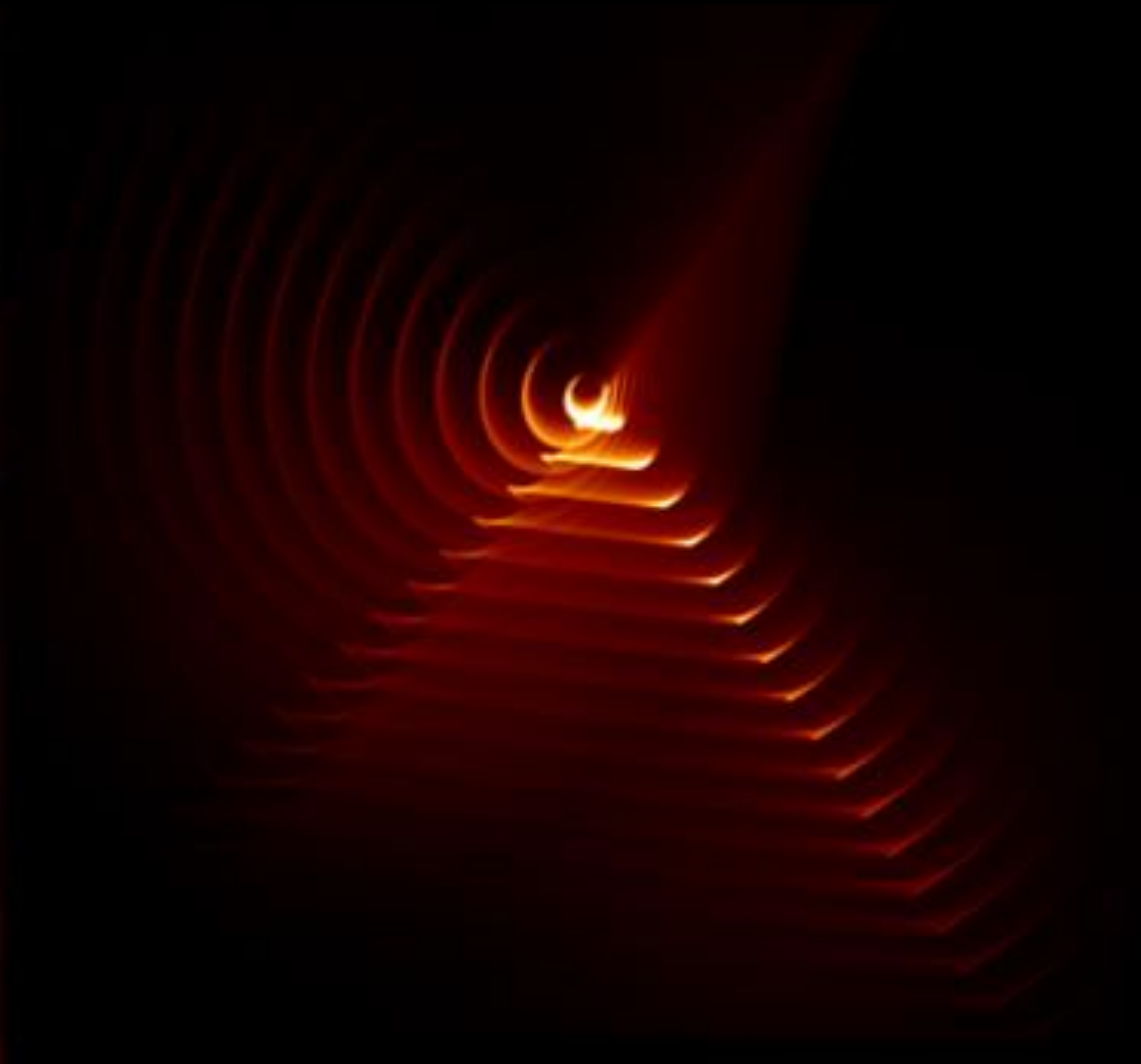
Lau et al NatAst 2022



ill et al Nature 2022

~160yr of orbit-modulated dust

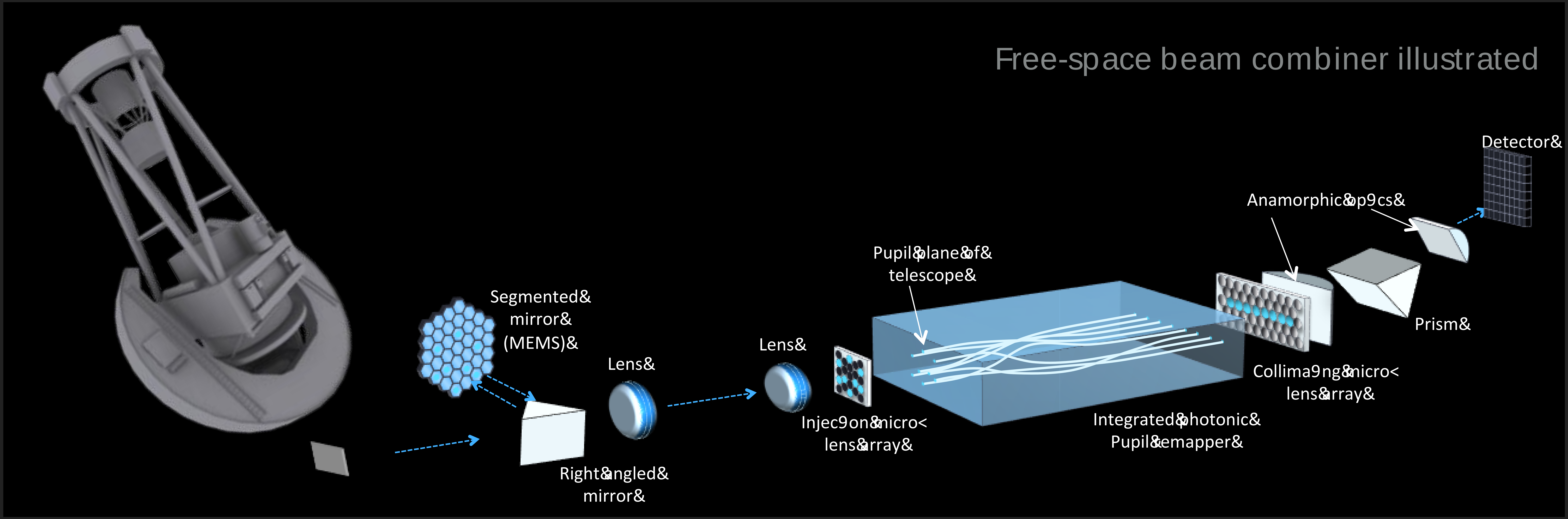
Image from MIRI



Model from Keck mask/AO

‘CLASSIC’ DRAGONFLY: PHOTONIC PUPIL REMAPPER

compare to Non Redundant Masking (aka Sparse Aperture Masking)

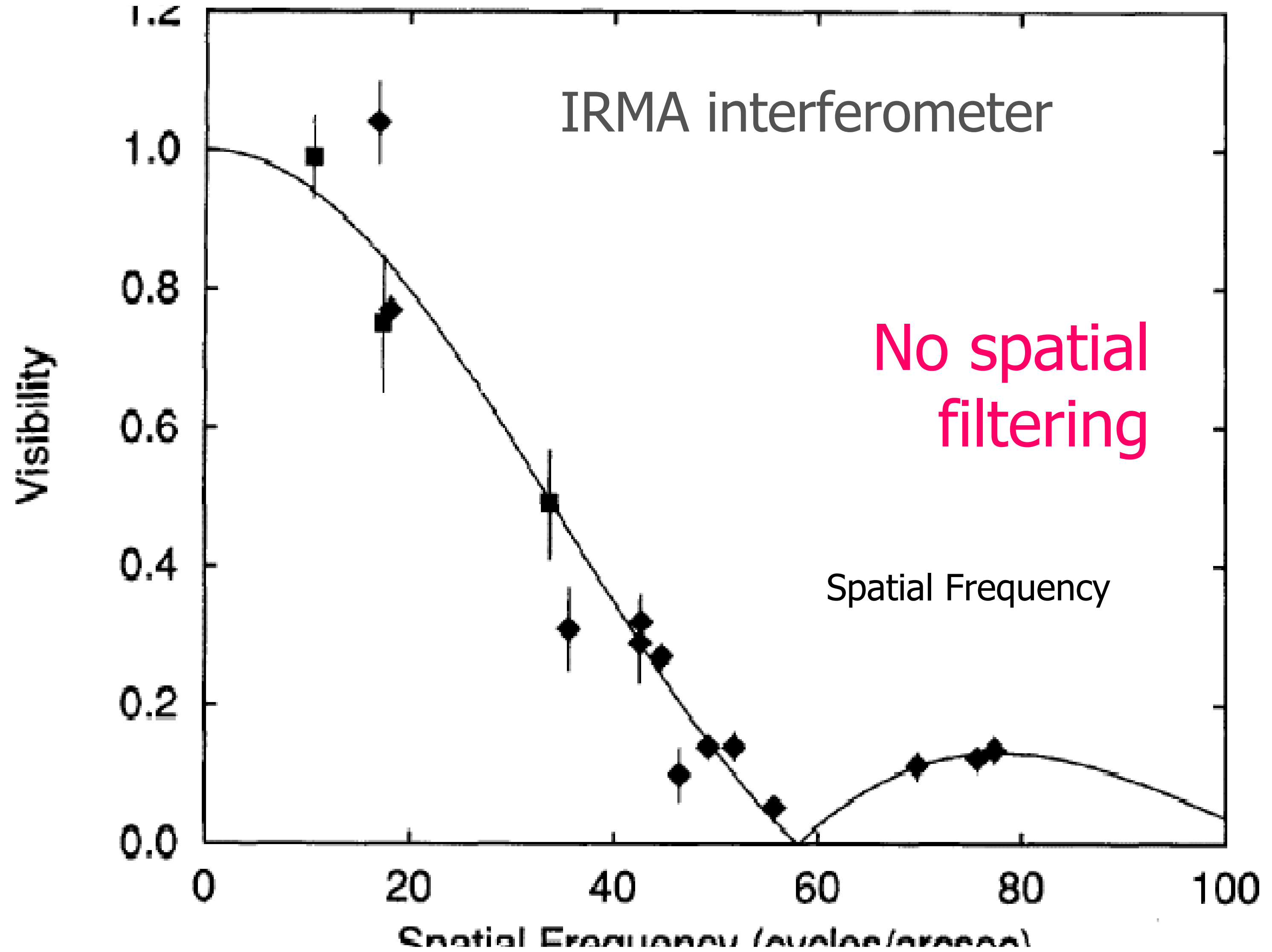


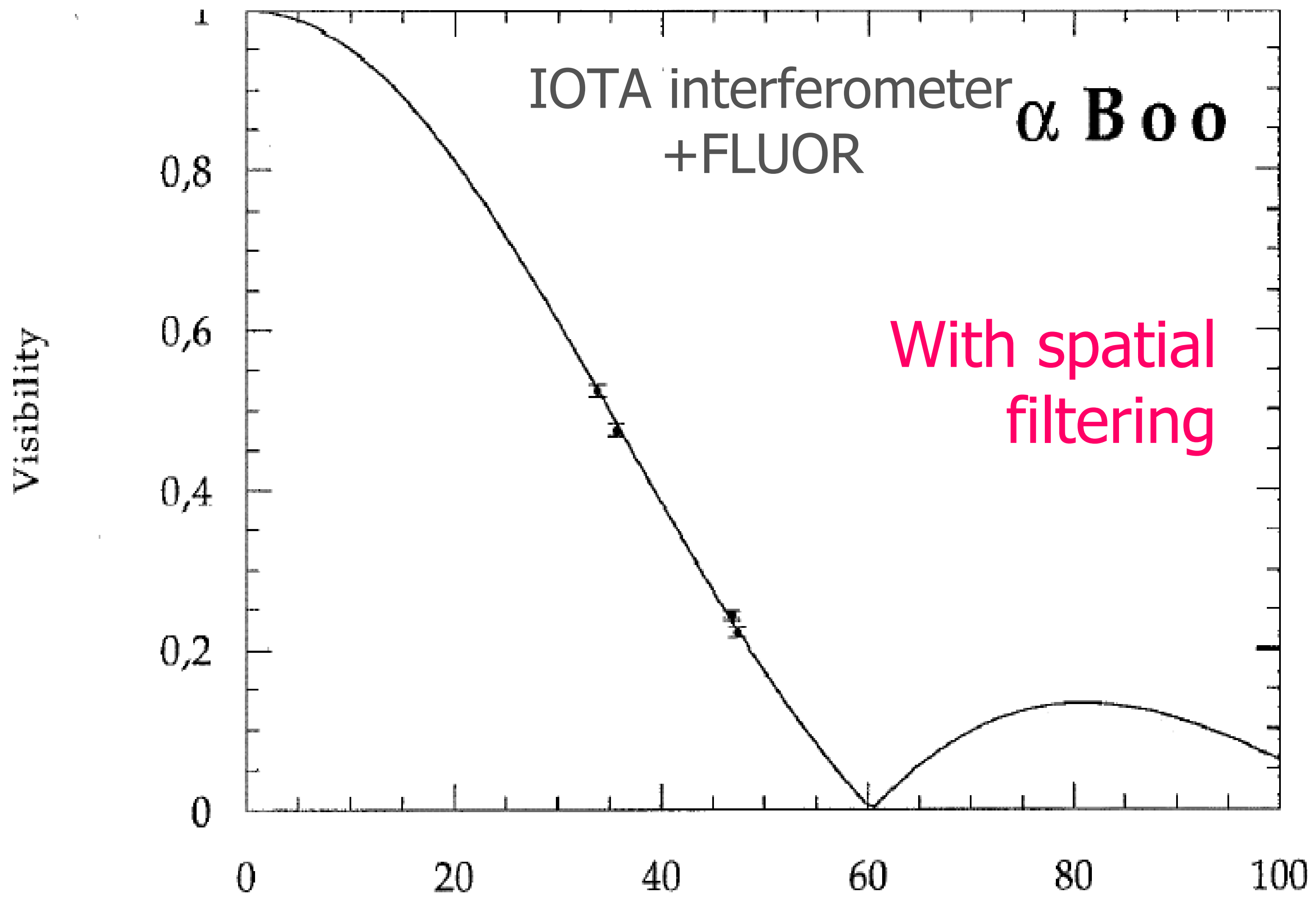
Photonic pupil remapper (NIR) - Remaps arbitrary 2D pattern into 1D

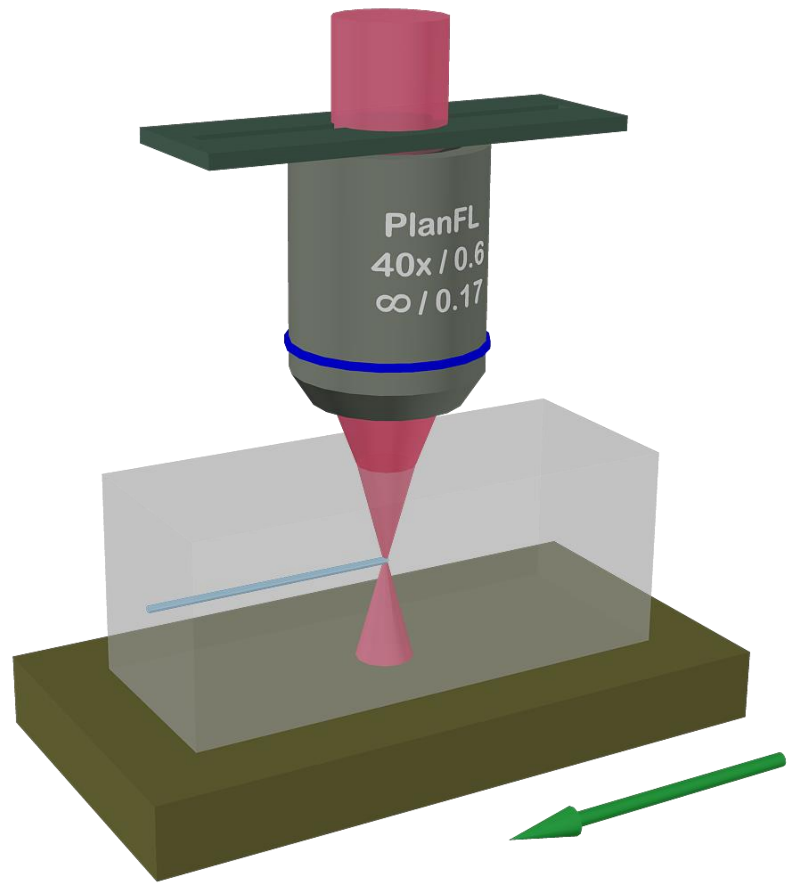
- Redundant (full pupil coverage) → non-redundant
- 1D → can be spectrally dispersed

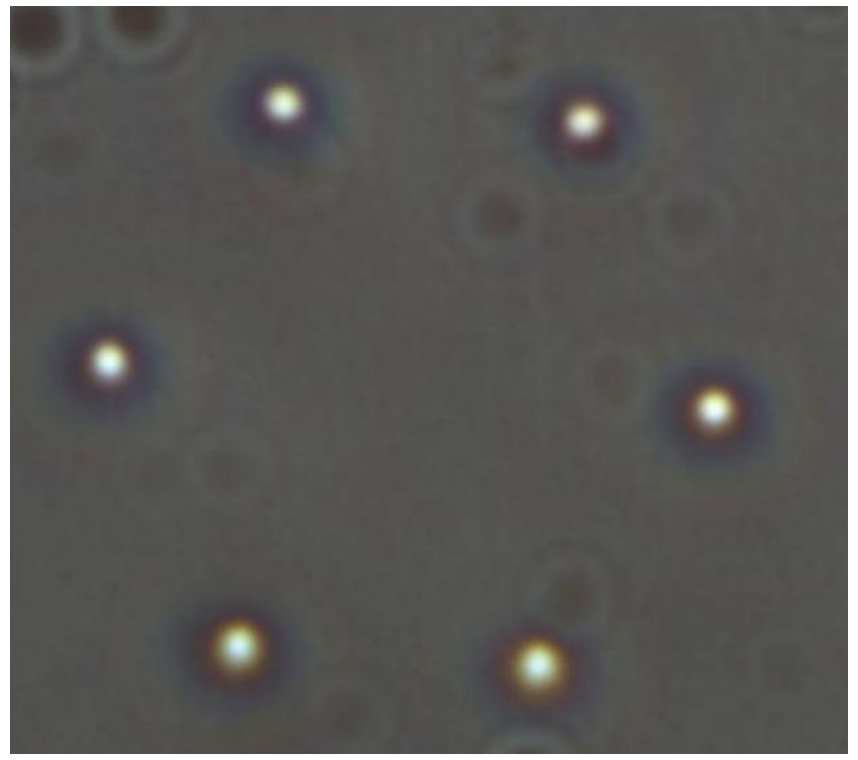
Dragonfly: the first photonic pupil remapping interferometer

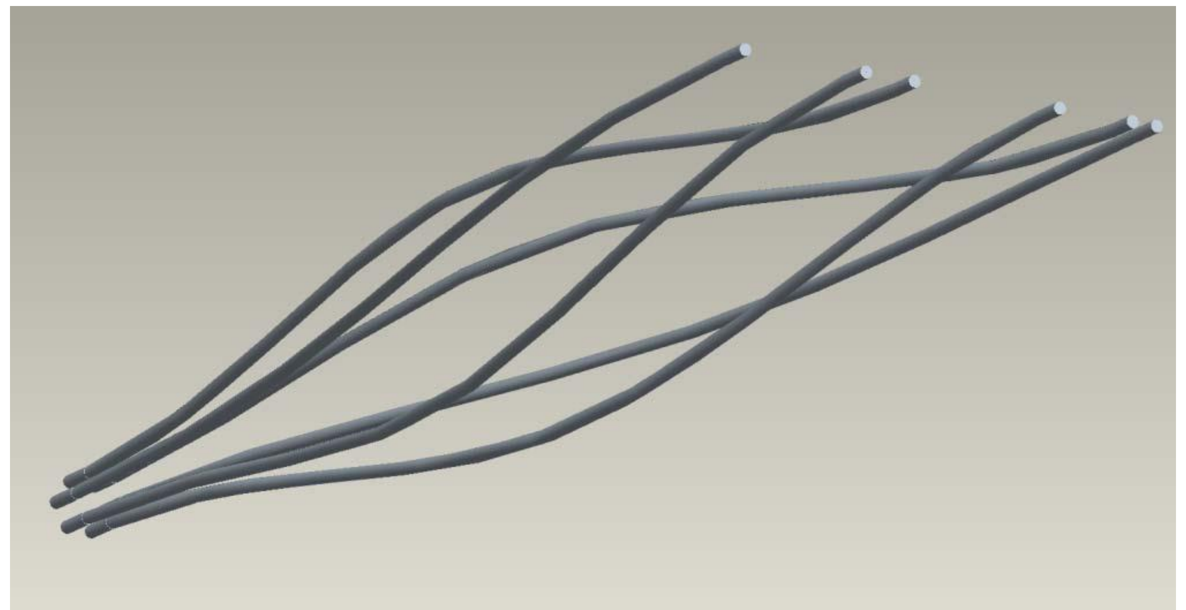
Non-redundant beam combination + single-mode spatial filtering + 3-D waveguides + cross-dispersion

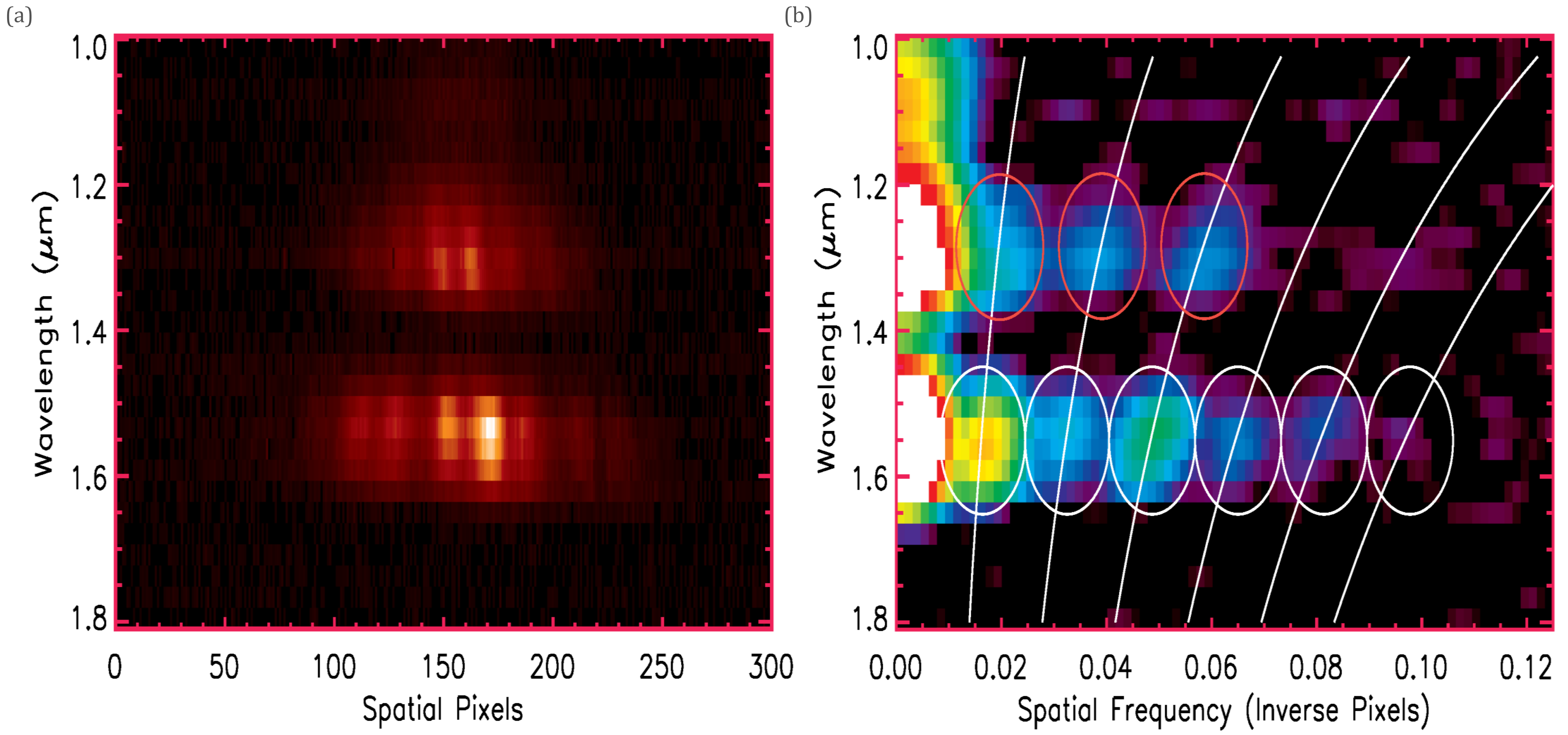


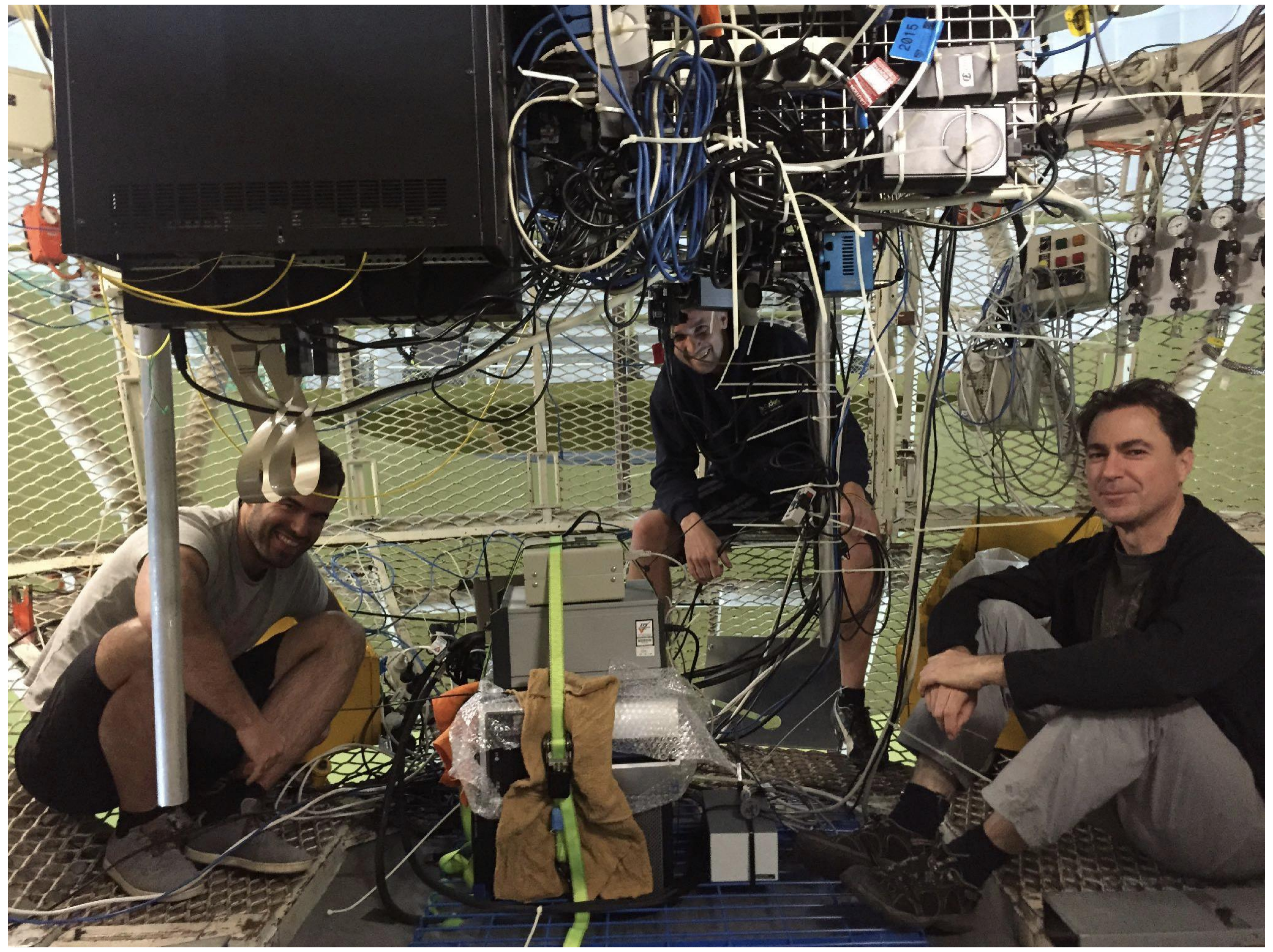






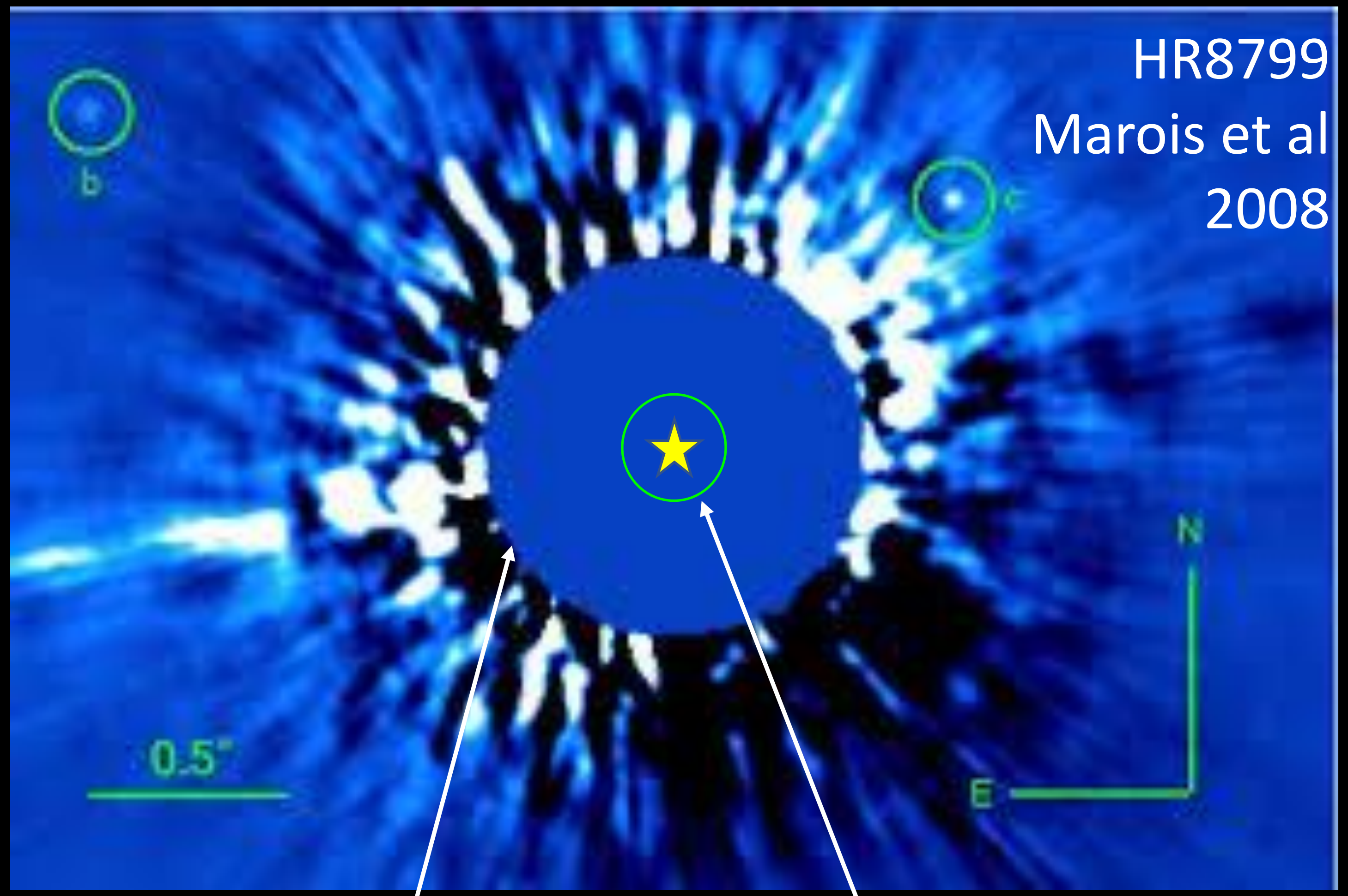






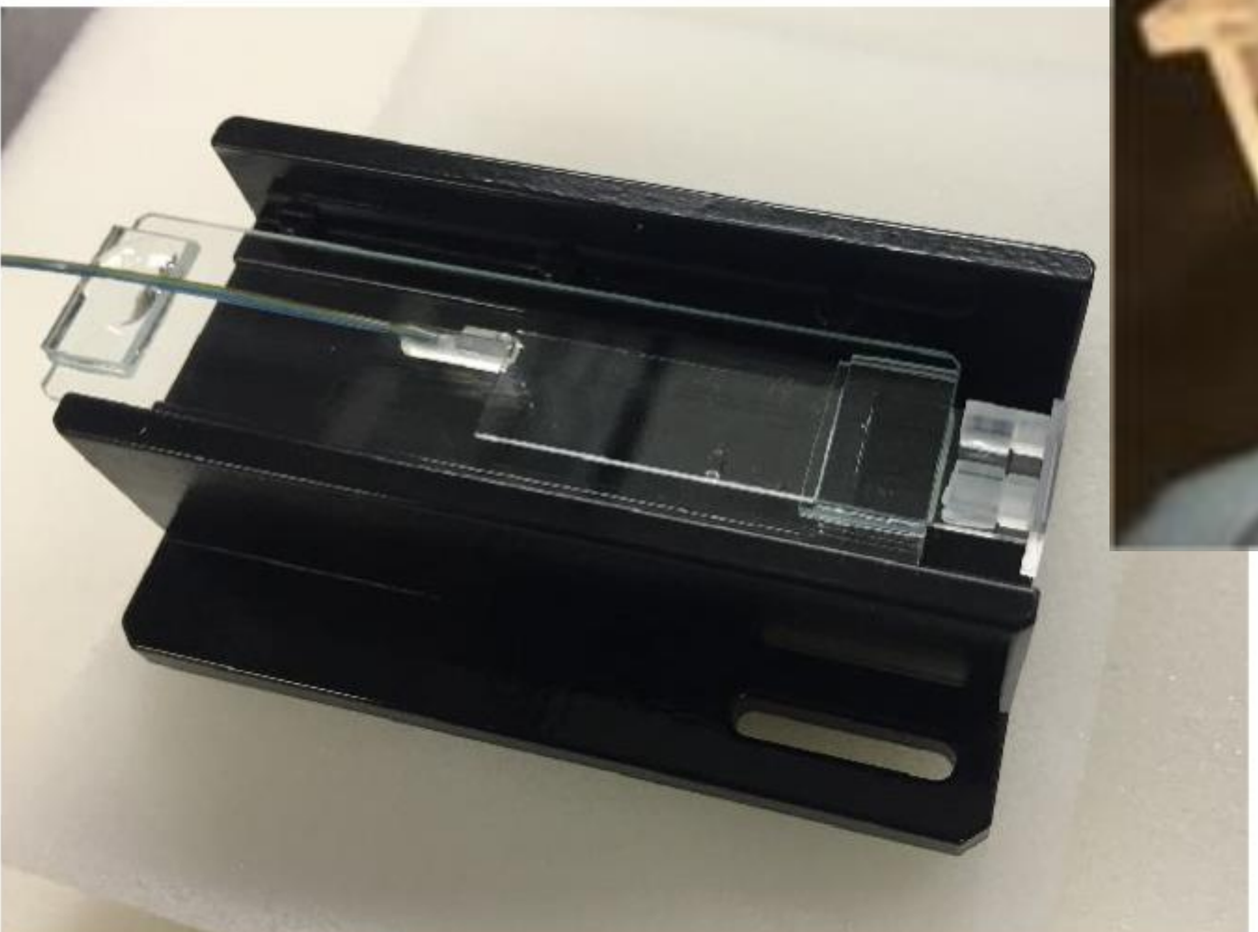
GLINT

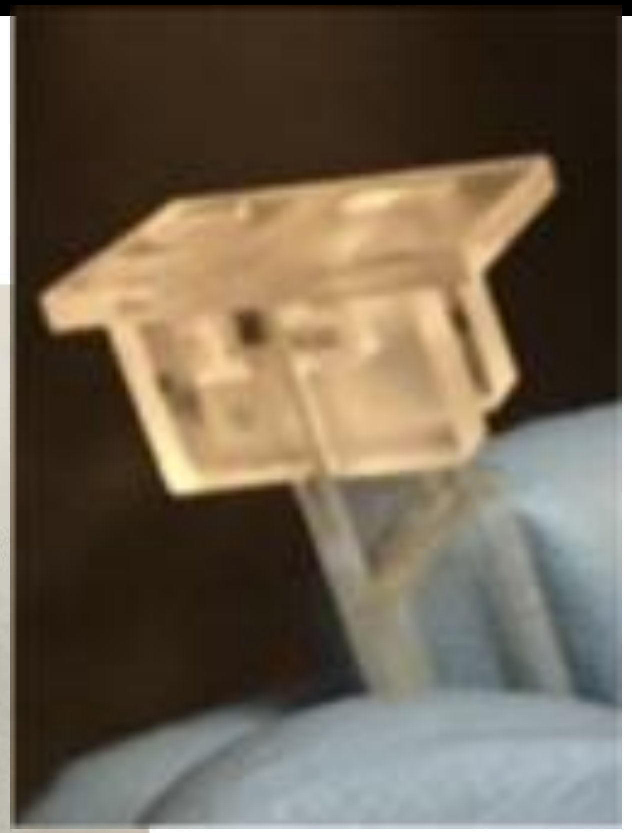
GLINT: photonic nuller at Subaru / SCExAO

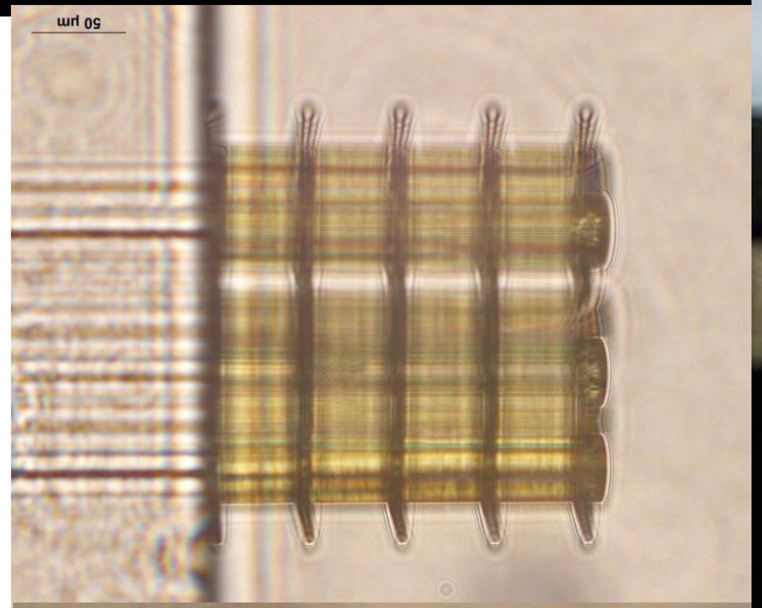


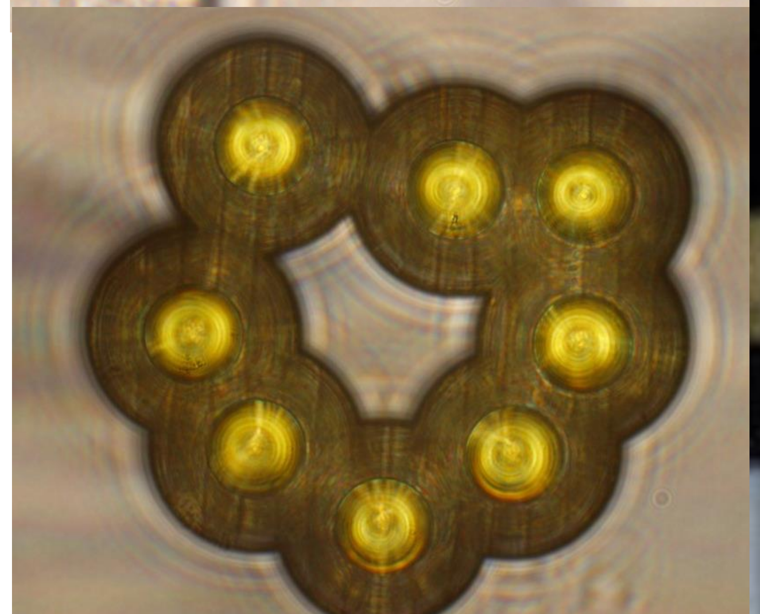
Diameter of effective region of Coronagraph light suppression

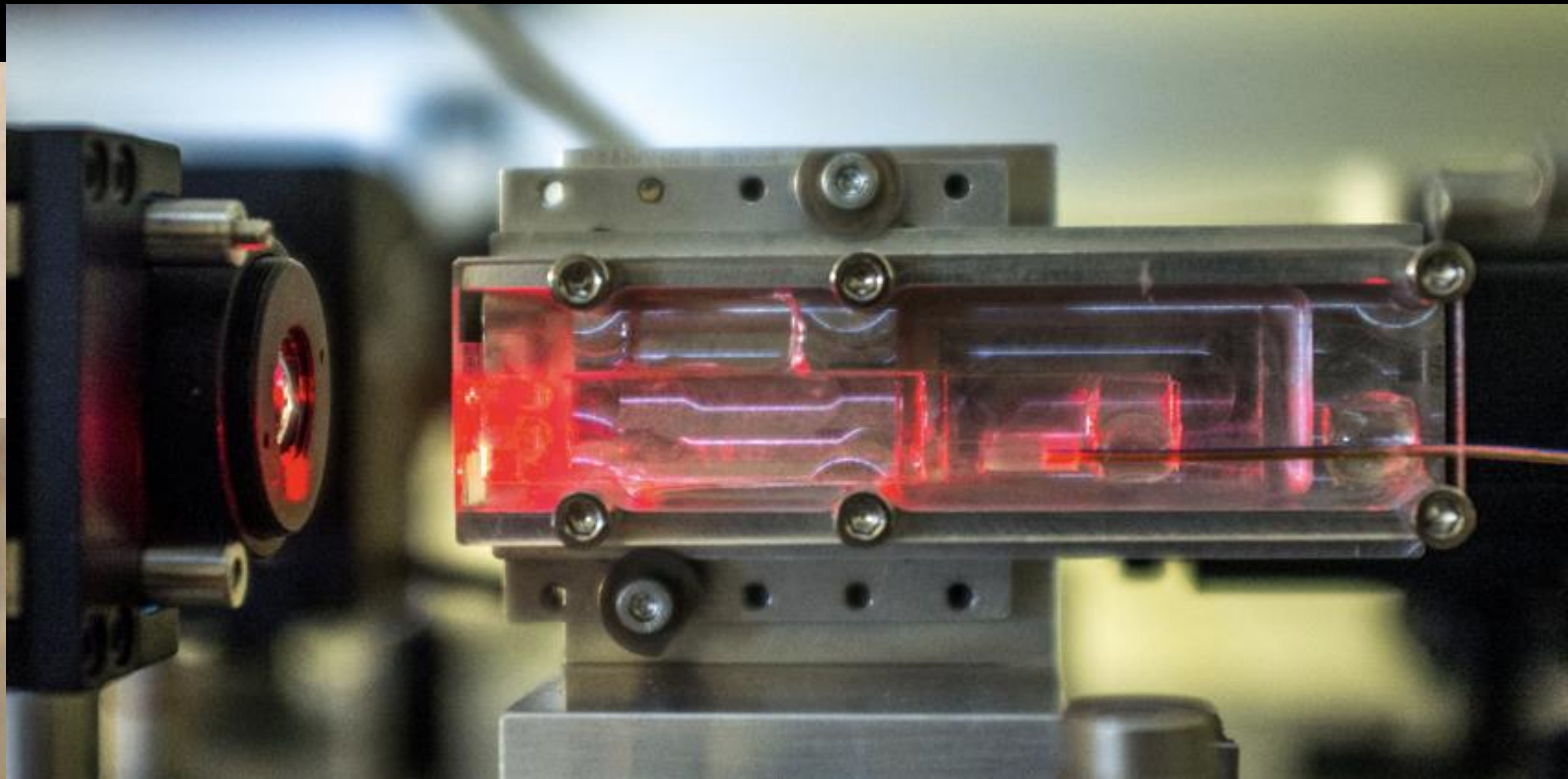
Size of HZ orbit for a G star in the local solar neighborhood (at 15 parsecs)



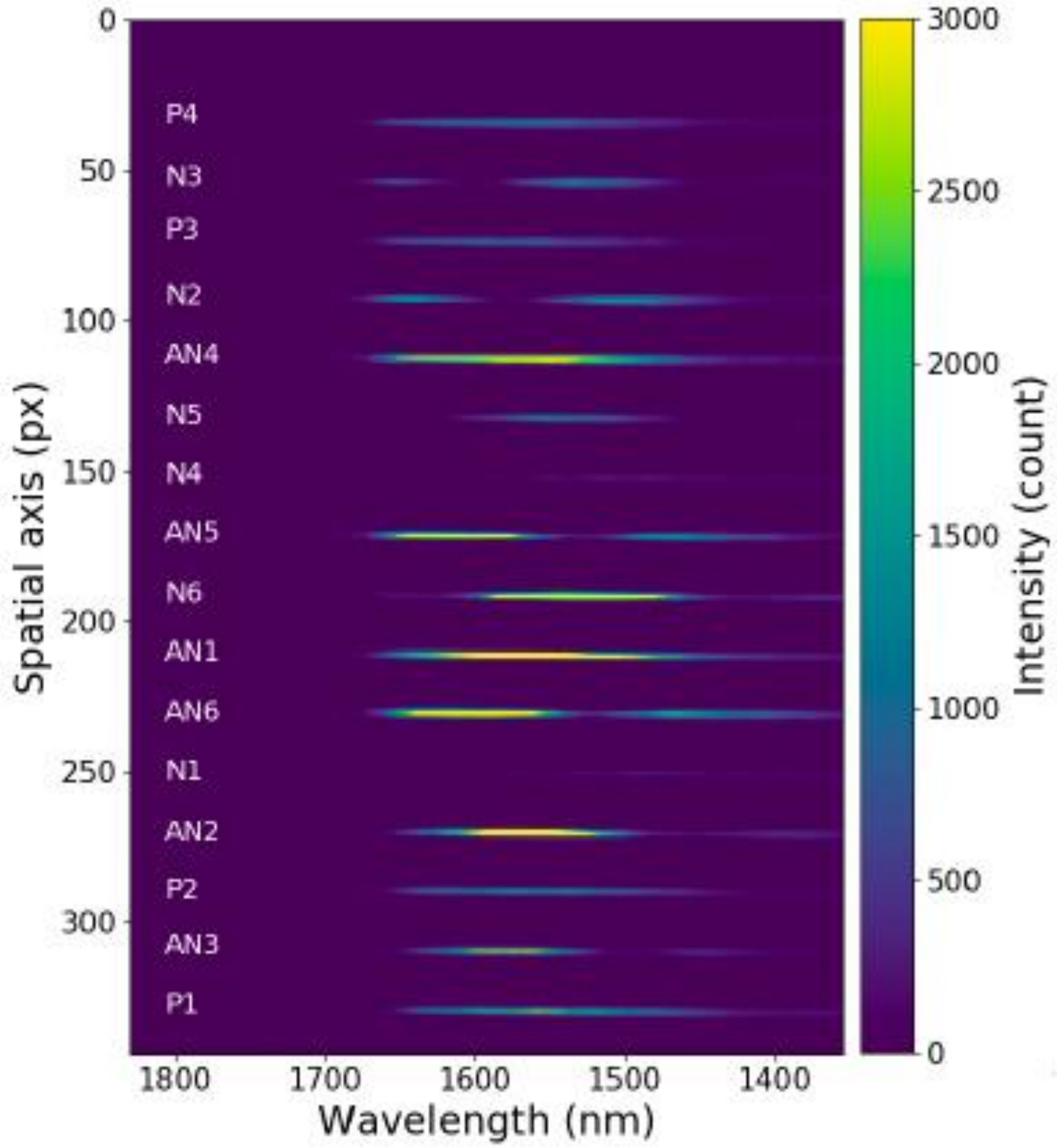




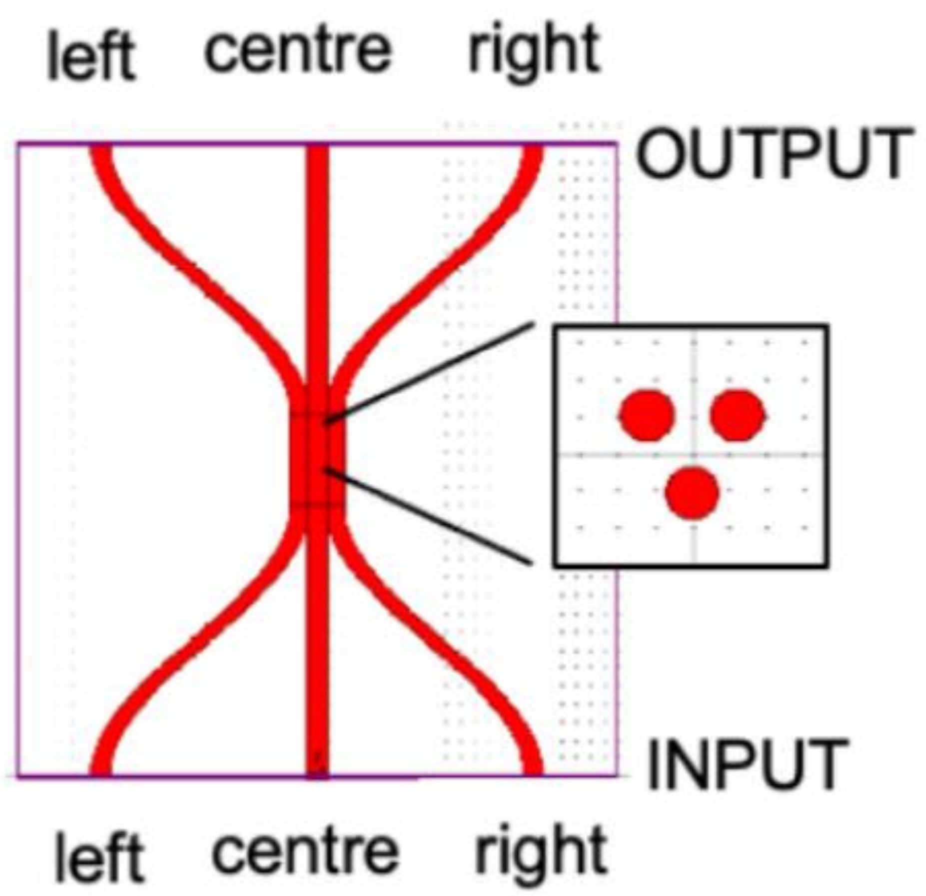


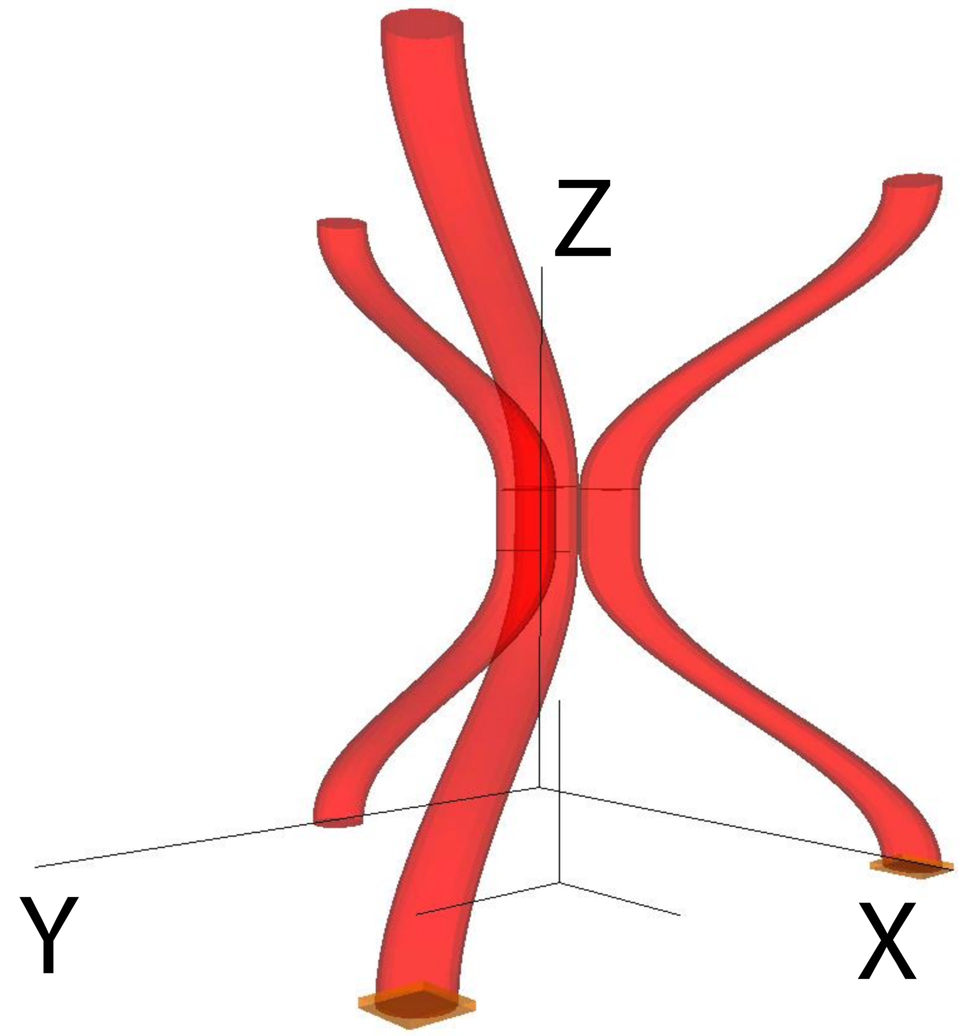


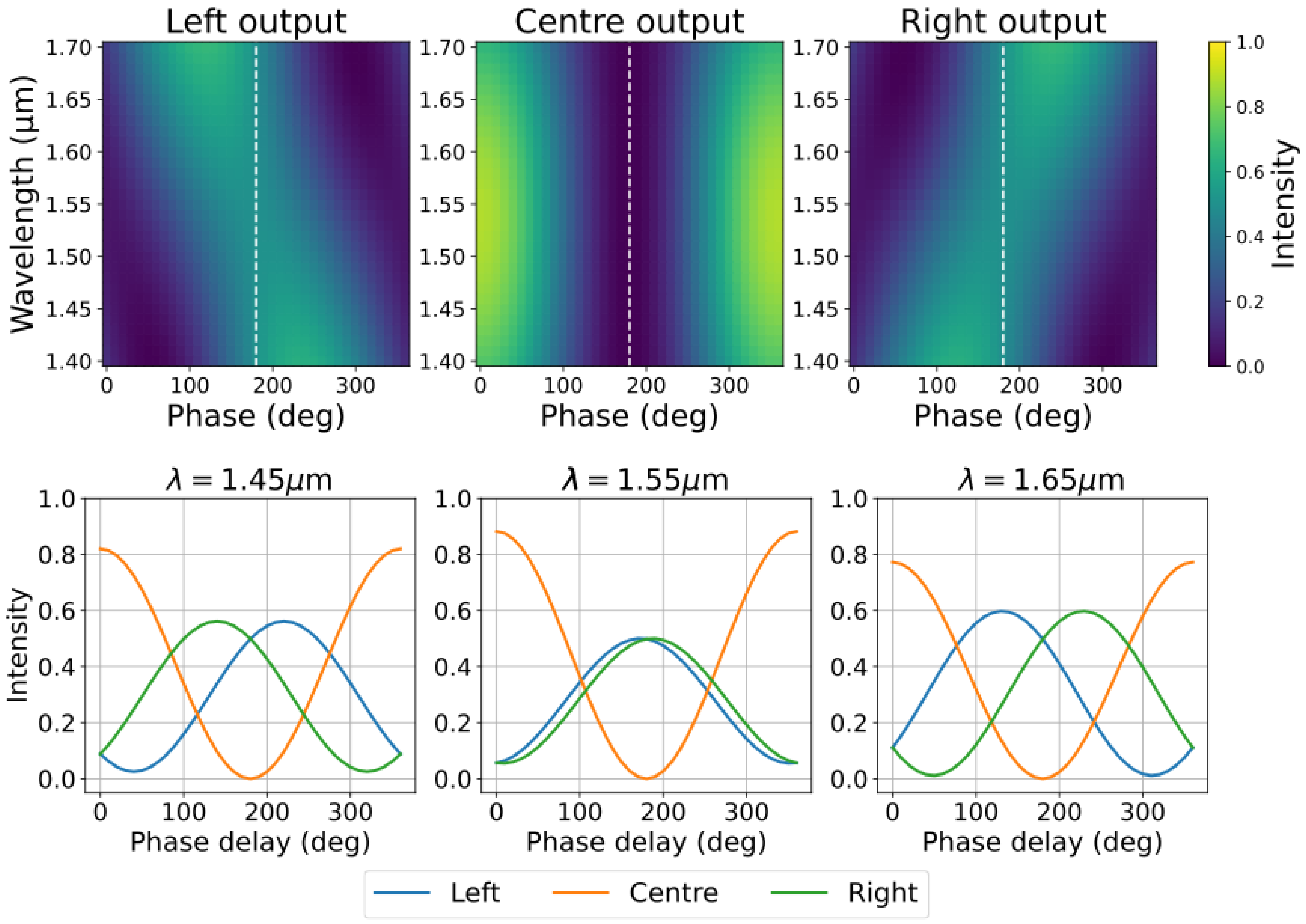
GLINT

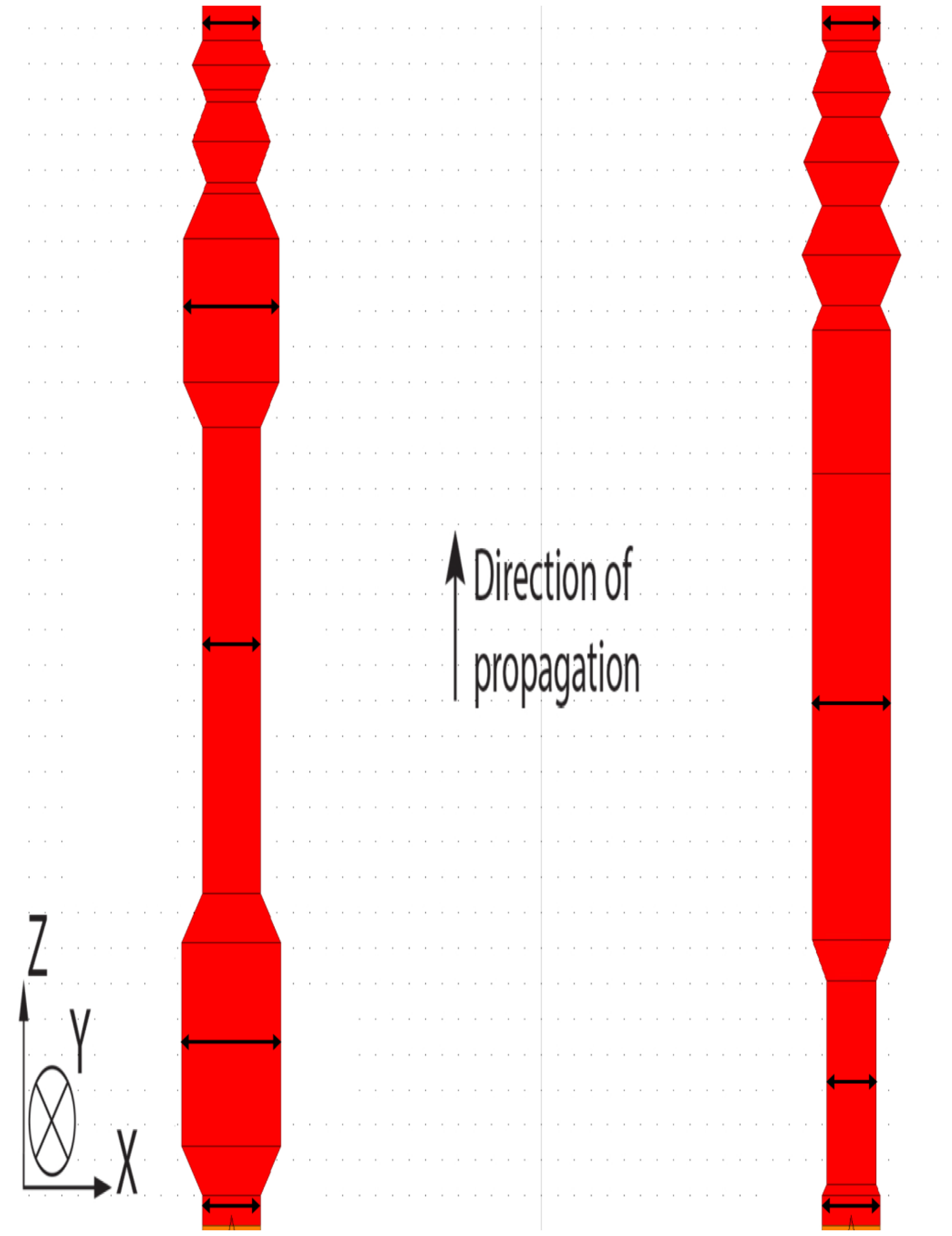


Tricoupler





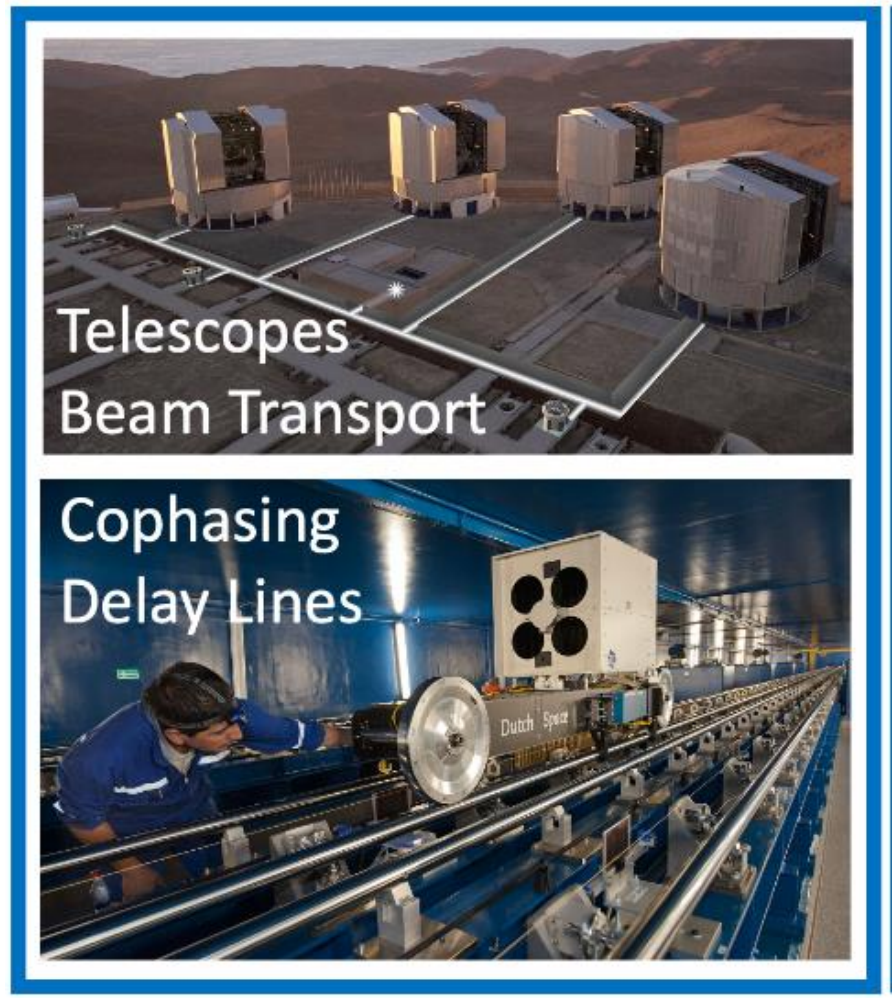




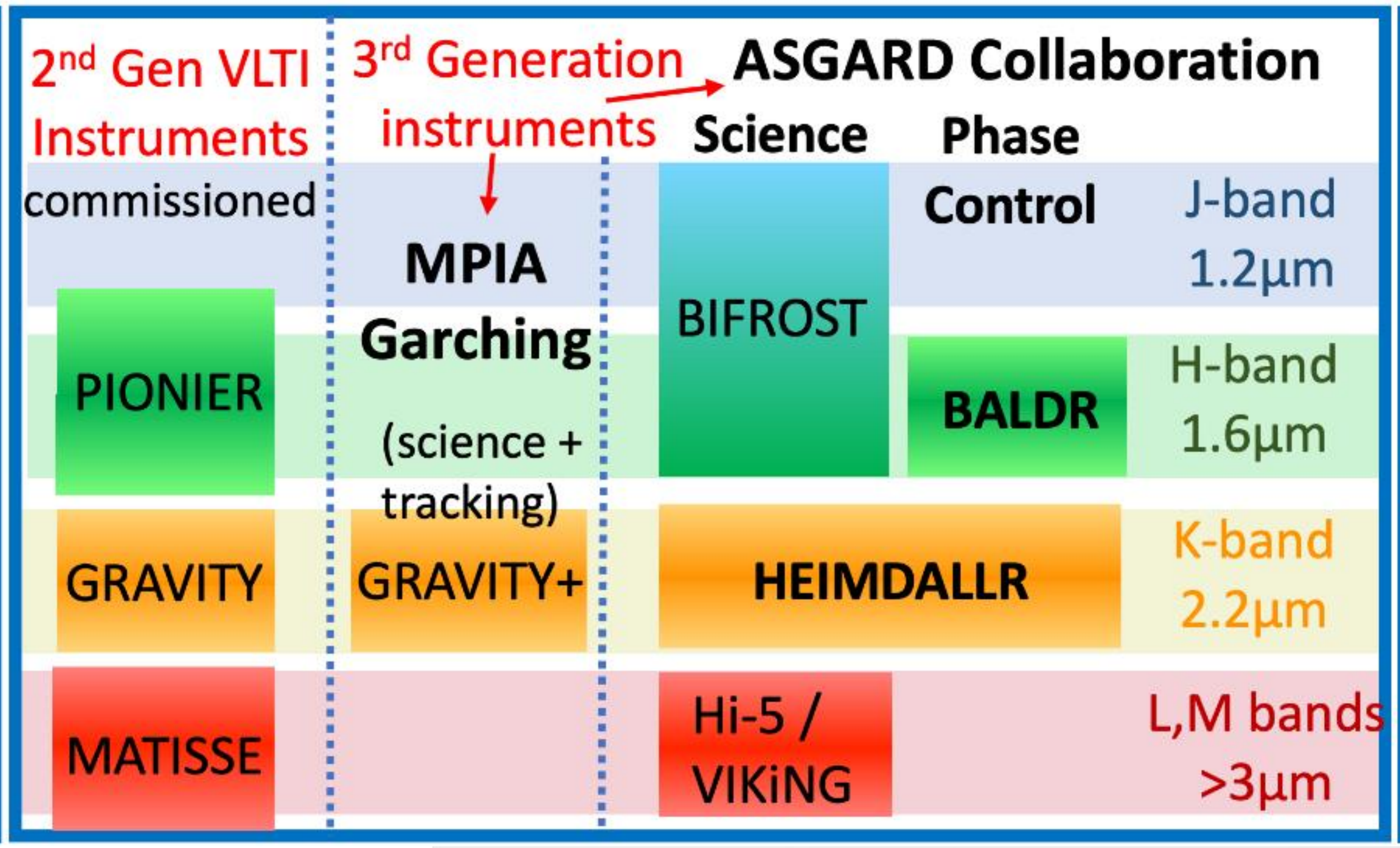
Achromatic phase shifter

ASGARD suite of beam combiners at VLTI

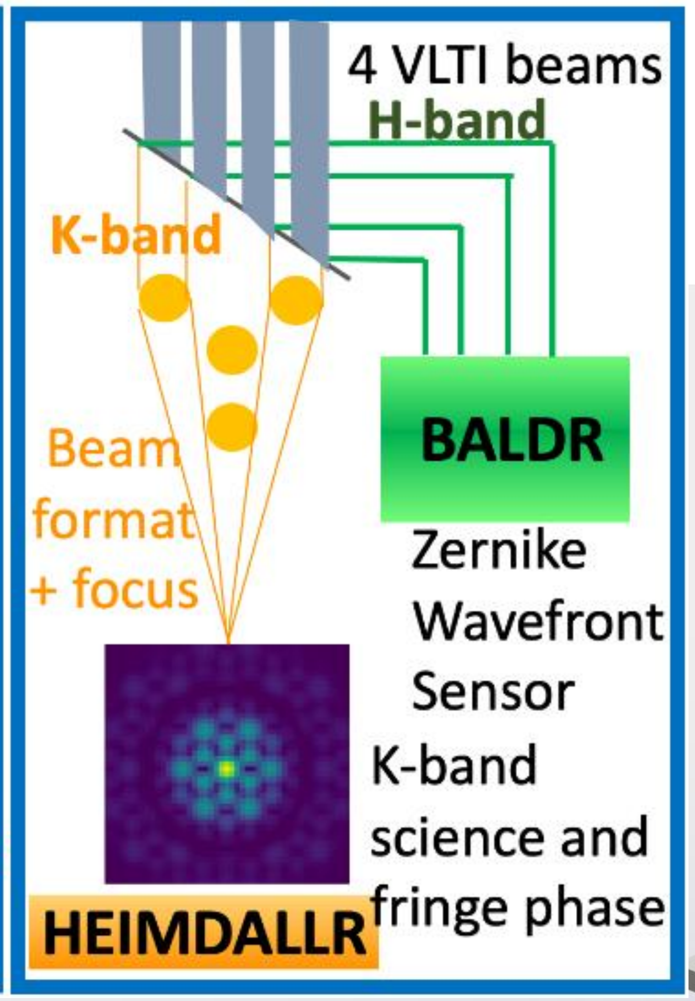
VLT Interferometer

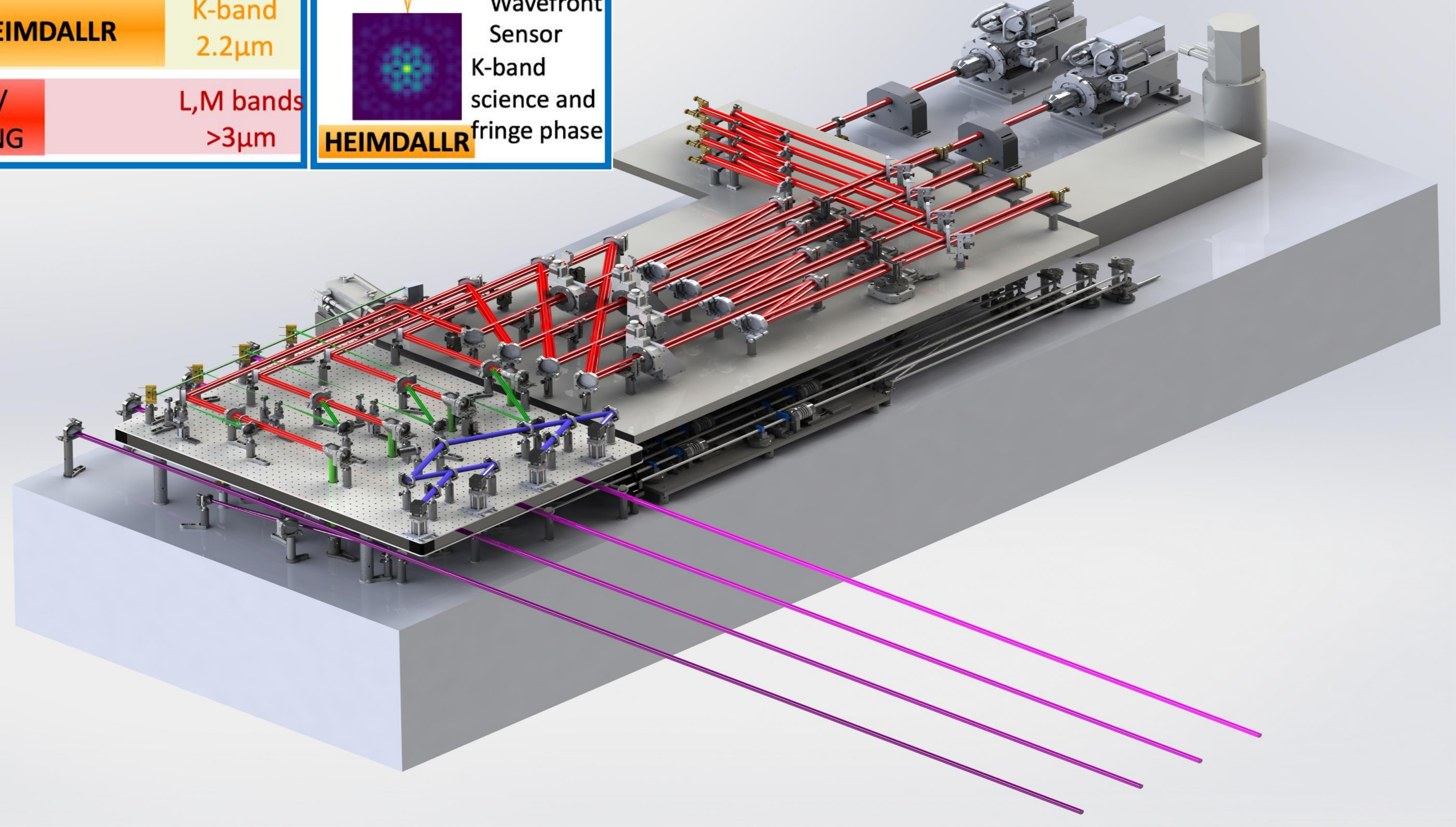


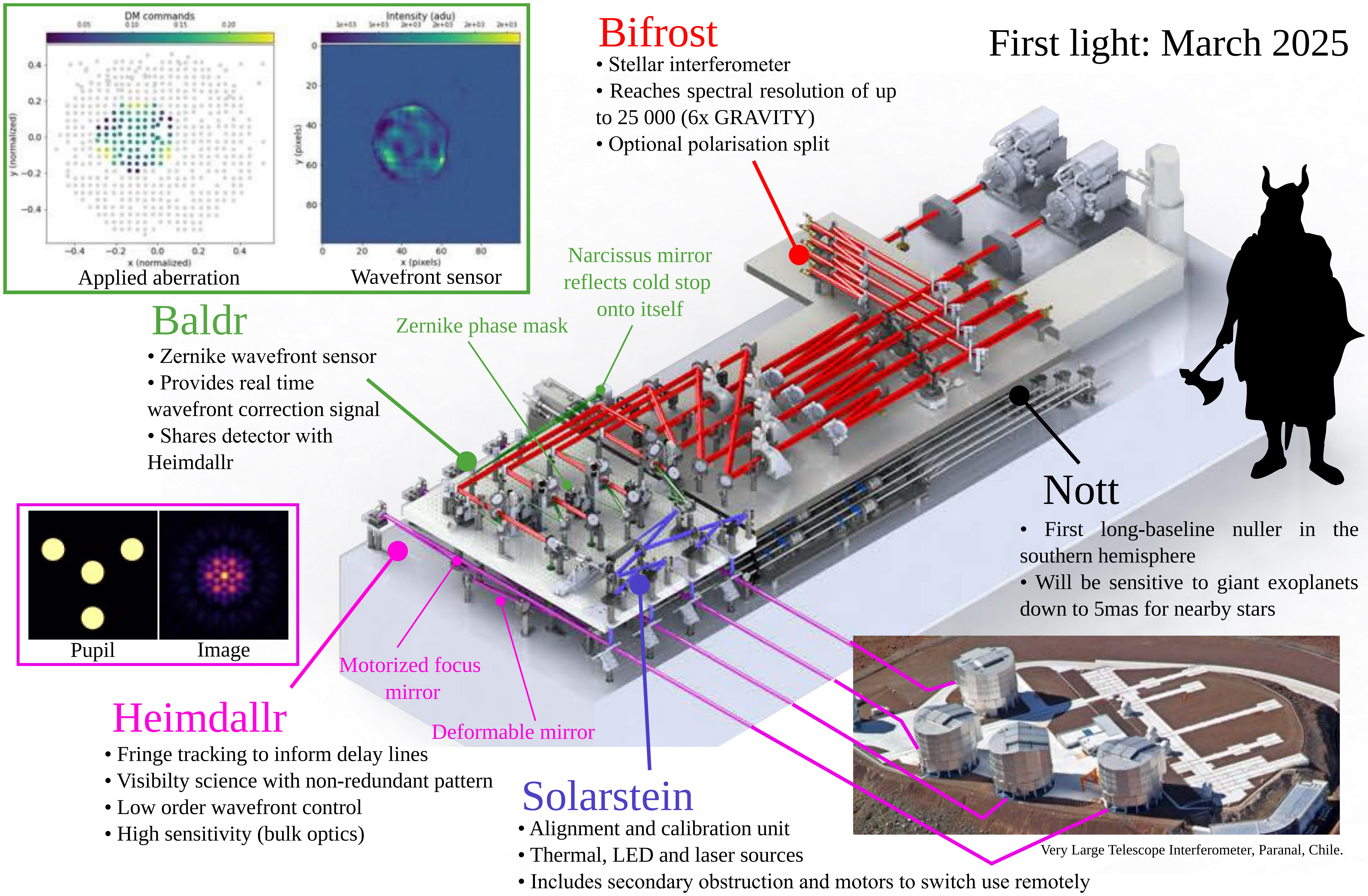
Beam Combiners



Heimdallr + Baldr







First light: March 2025
DM commands
y (normalized)
x (normalized)
Applied aberration
Intensity (adu)
y (pixels)
x (pixels)
Wavefront sensor
Bifrost
• Stellar interferometer
• Reaches spectral resolution of up to 25 000 (6x GRAVITY)
• Optional polarisation split
Narcissus mirror reflects cold stop onto itself
Zernike phase mask
Baldr
• Zernike wavefront sensor
• Provides real time wavefront correction signal
• Shares detector with Heimdallr
Nott
• First long-baseline nuller in the southern hemisphere
• Will be sensitive to giant exoplanets down to 5mas for nearby stars
Pupil
Image
Motorized focus mirror
Deformable mirror
Heimdallr
• Fringe tracking to inform delay lines
• Visibilty science with non-redundant pattern
• Low order wavefront control
• High sensitivity (bulk optics)
Solarstein
• Alignment and calibration unit
• Thermal, LED and laser sources
• Includes secondary obstruction and motors to switch use remotely
Very Large Telescope Interferometer, Paranal, Chile.

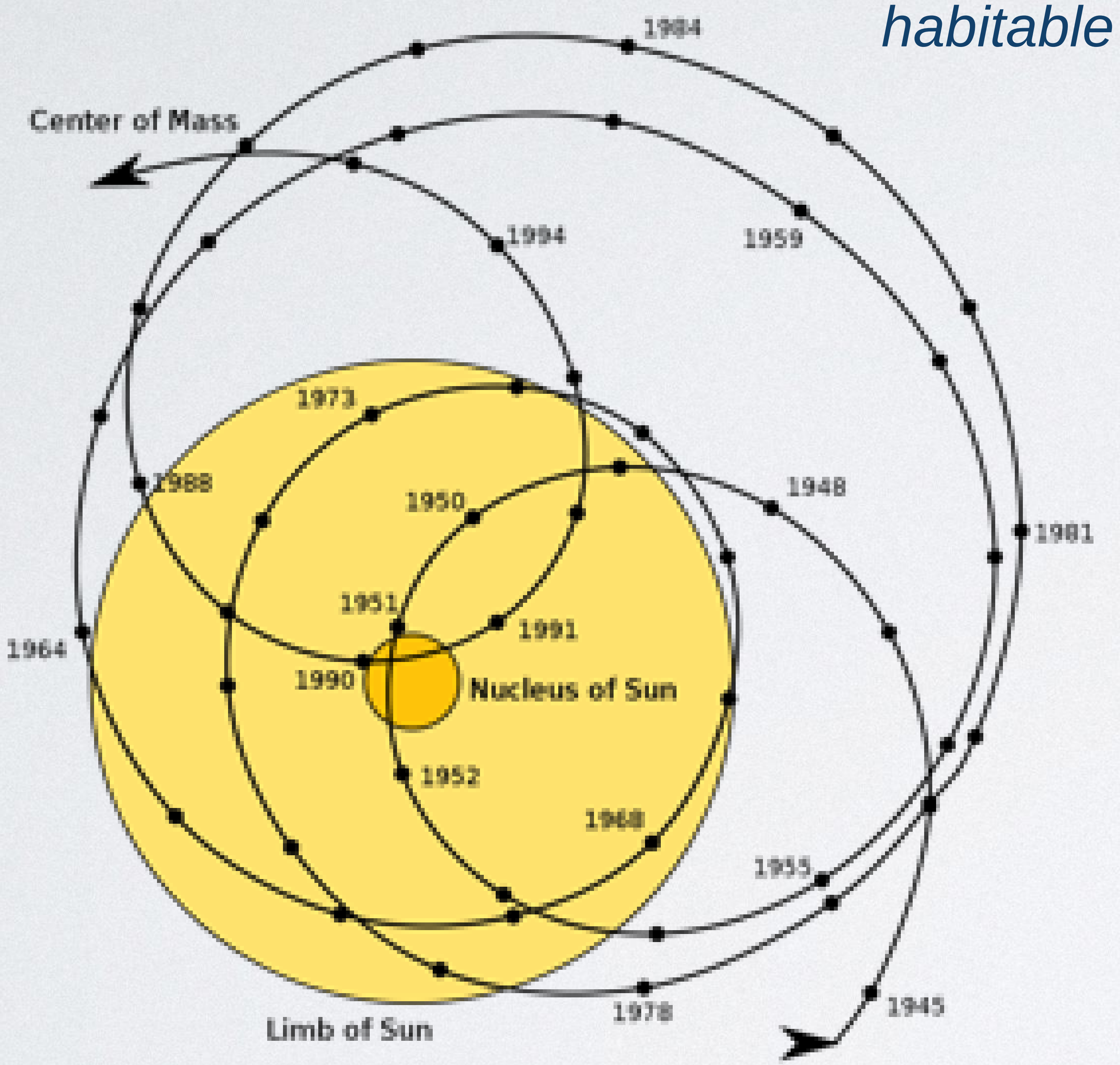
TOLIMAN

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 FGK stars
- ✓ 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



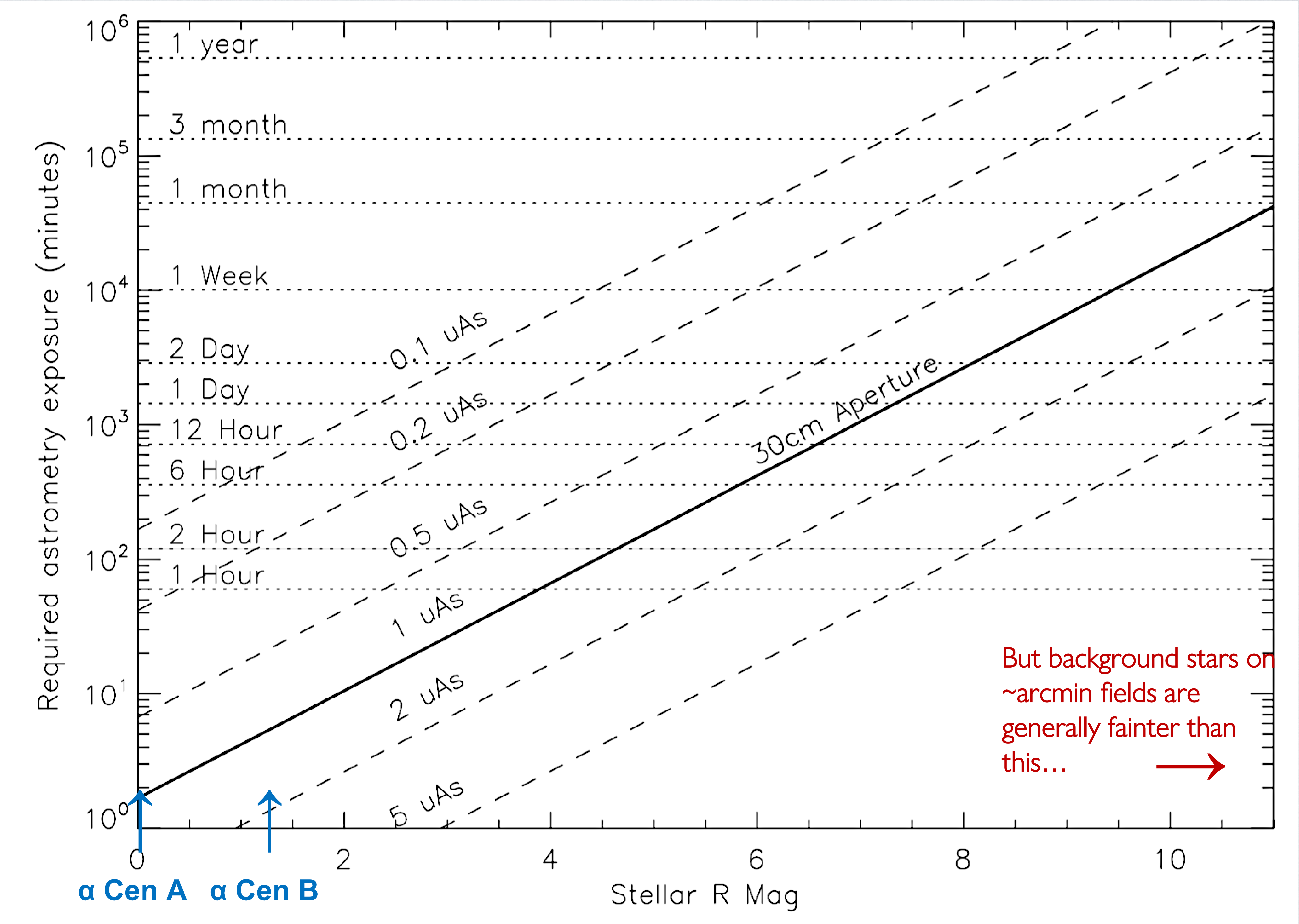
Locus of the Sun's motion due to planets (mainly Jupiter)

True Earth Analogs

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

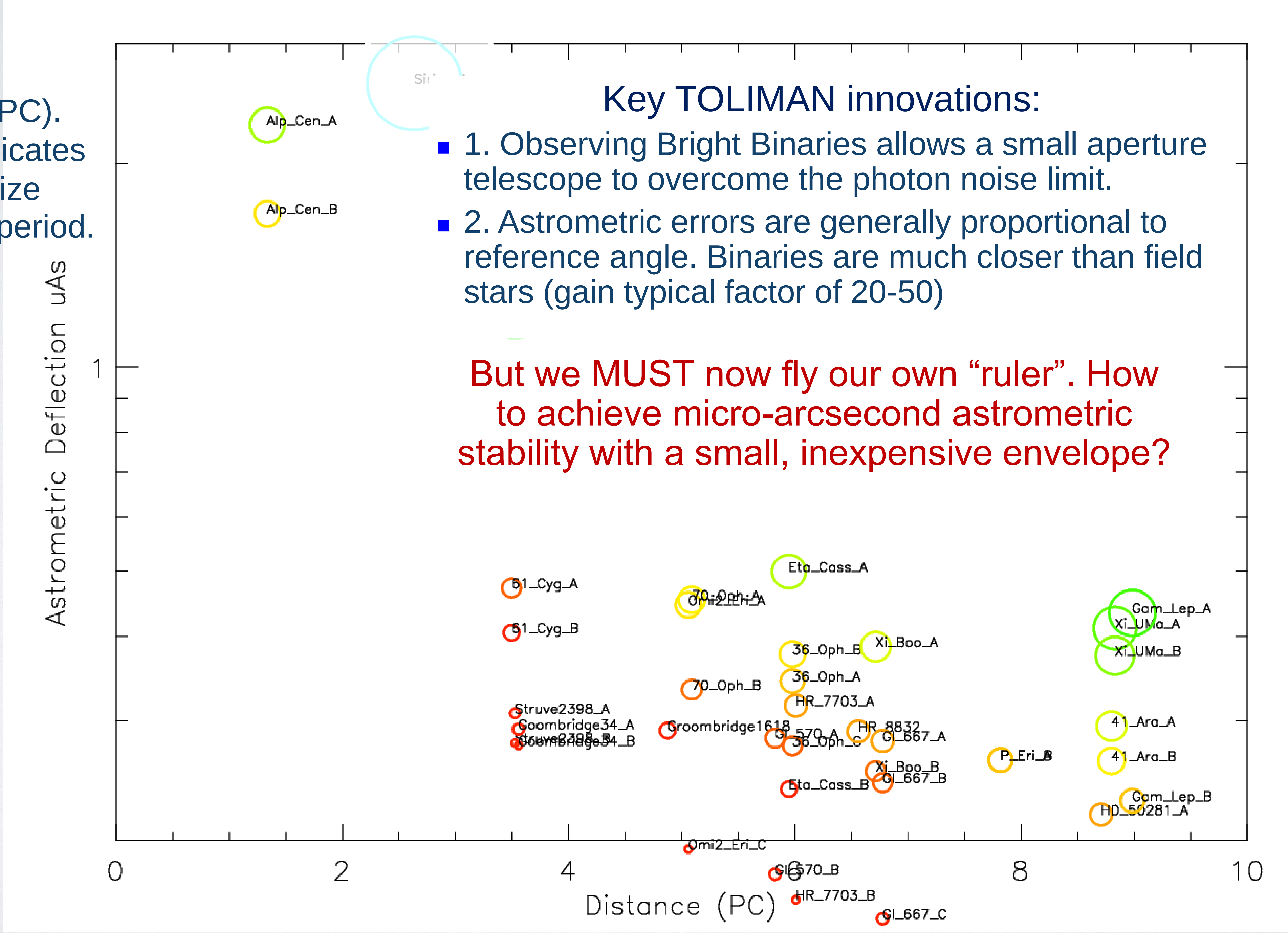
- 5 A-type Stars, likely 0 (or 1) HZ rocky planet
- 69 FGK-type Stars. Likely about a dozen HZ rocky planets
- 273 (+) M-type stars. Likely 140 HZ rocky planets

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:

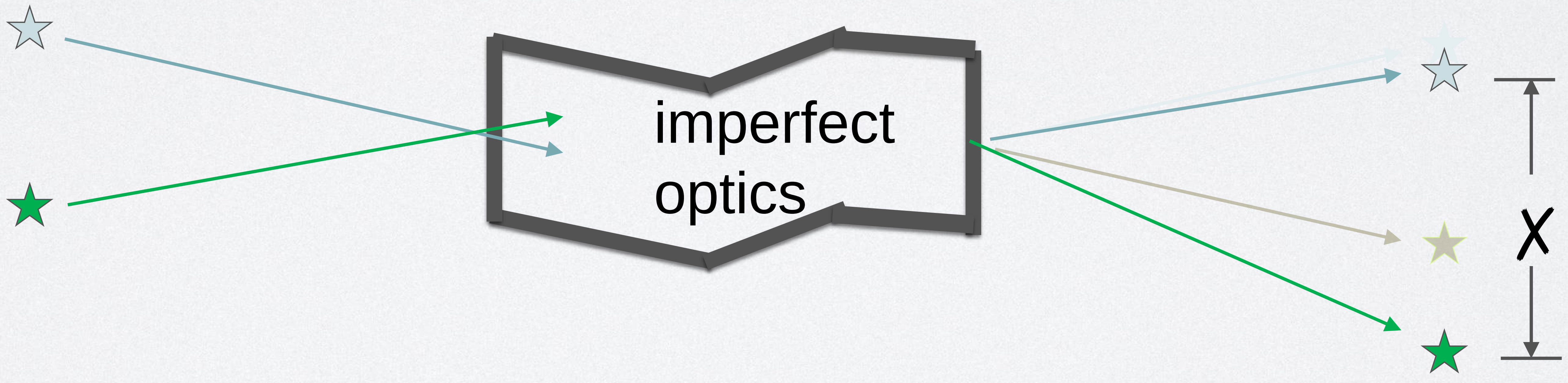
- 1. Observing Bright Binaries allows a small aperture telescope to overcome the photon noise limit.
- 2. Astrometric errors are generally proportional to reference angle. Binaries are much closer than field stars (gain typical factor of 20-50)

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

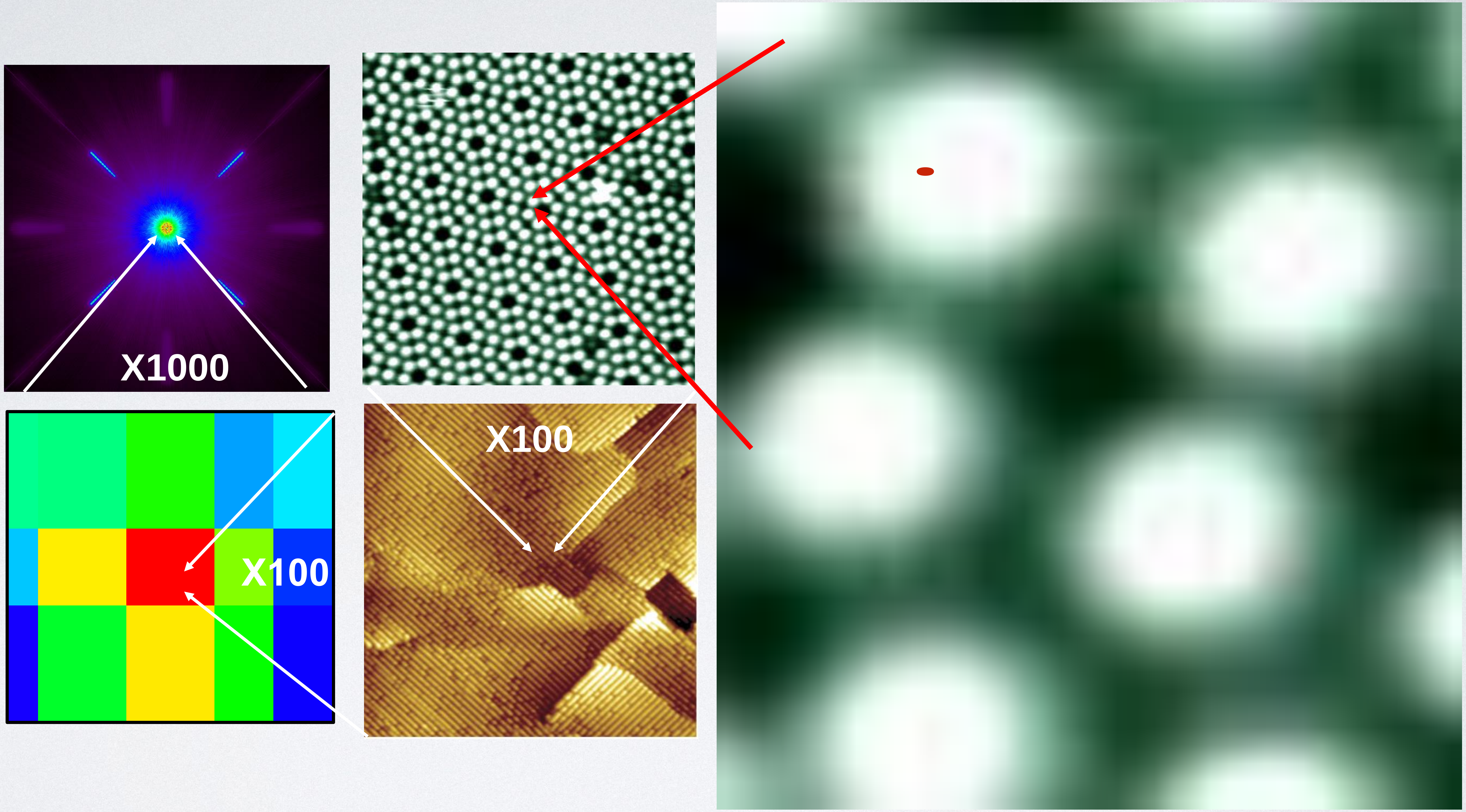
Fundamental principle: Diffractive Pupils

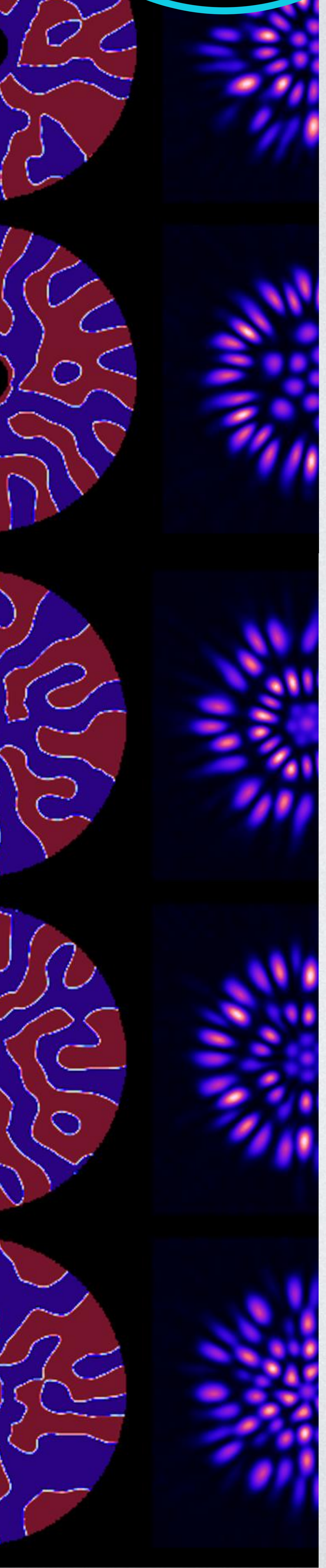
1. The basic problem

Distortion in the image field caused by unstable optical errors causes us to register the wrong apparent separation for the binary



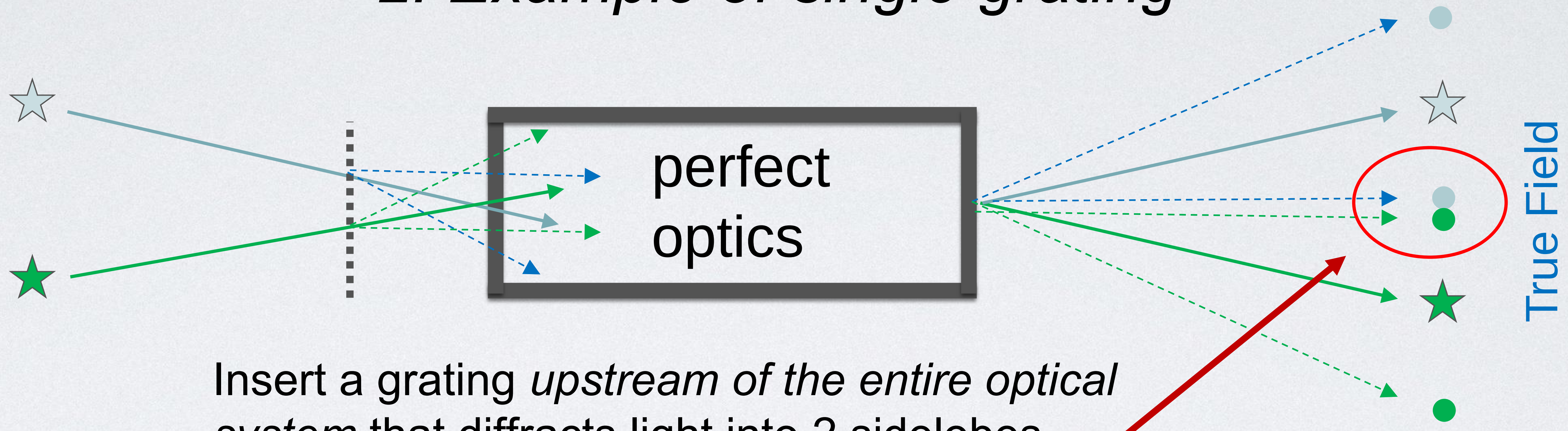
The scale of the Instrumental Challenge





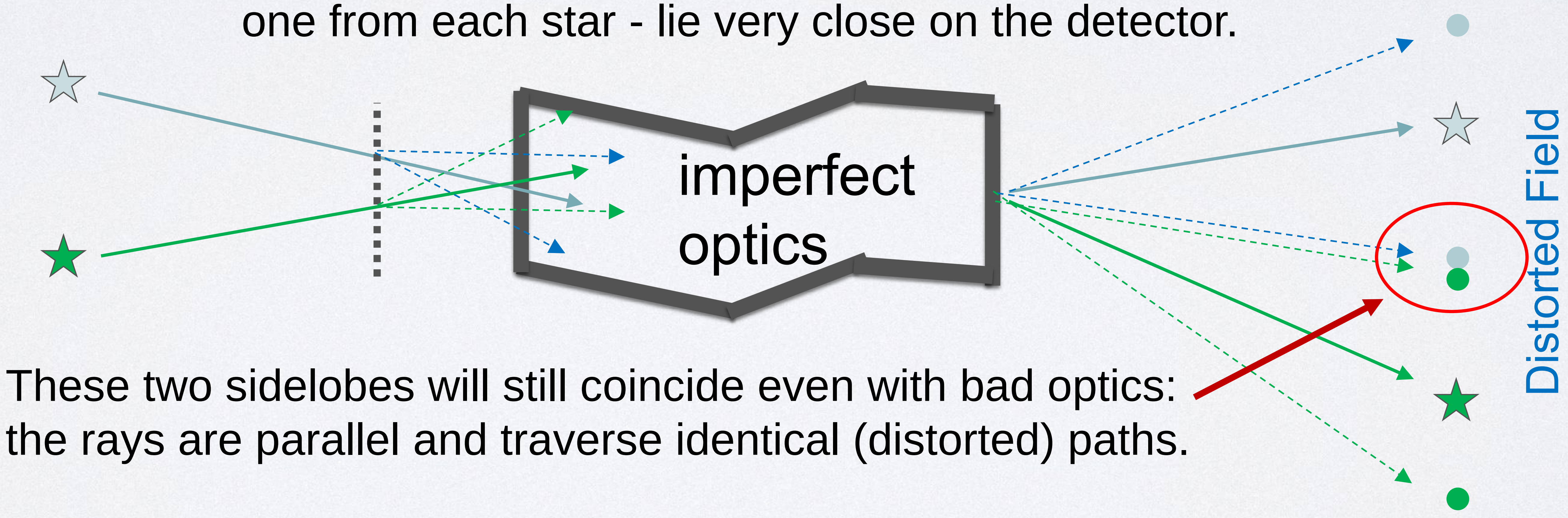
Fundamental principle: Diffractive Pupils

2. Example of single grating

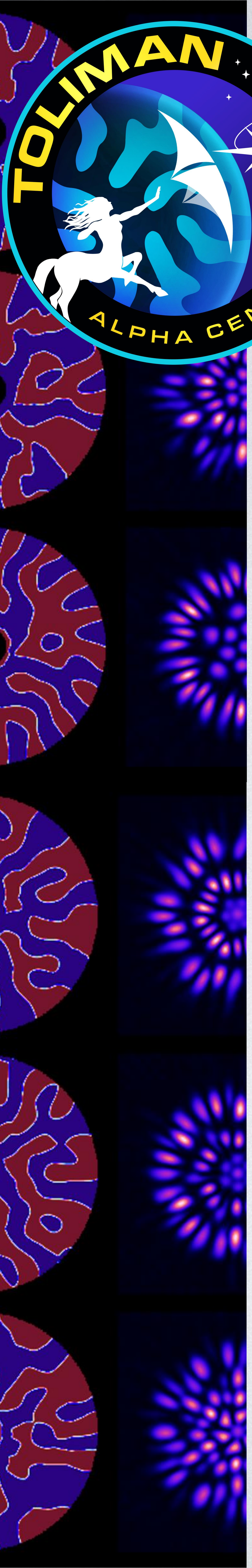


Insert a grating *upstream of the entire optical system* that diffracts light into 2 sidelobes.

The grating spacing is chosen so that two sidelobes – one from each star - lie very close on the detector.



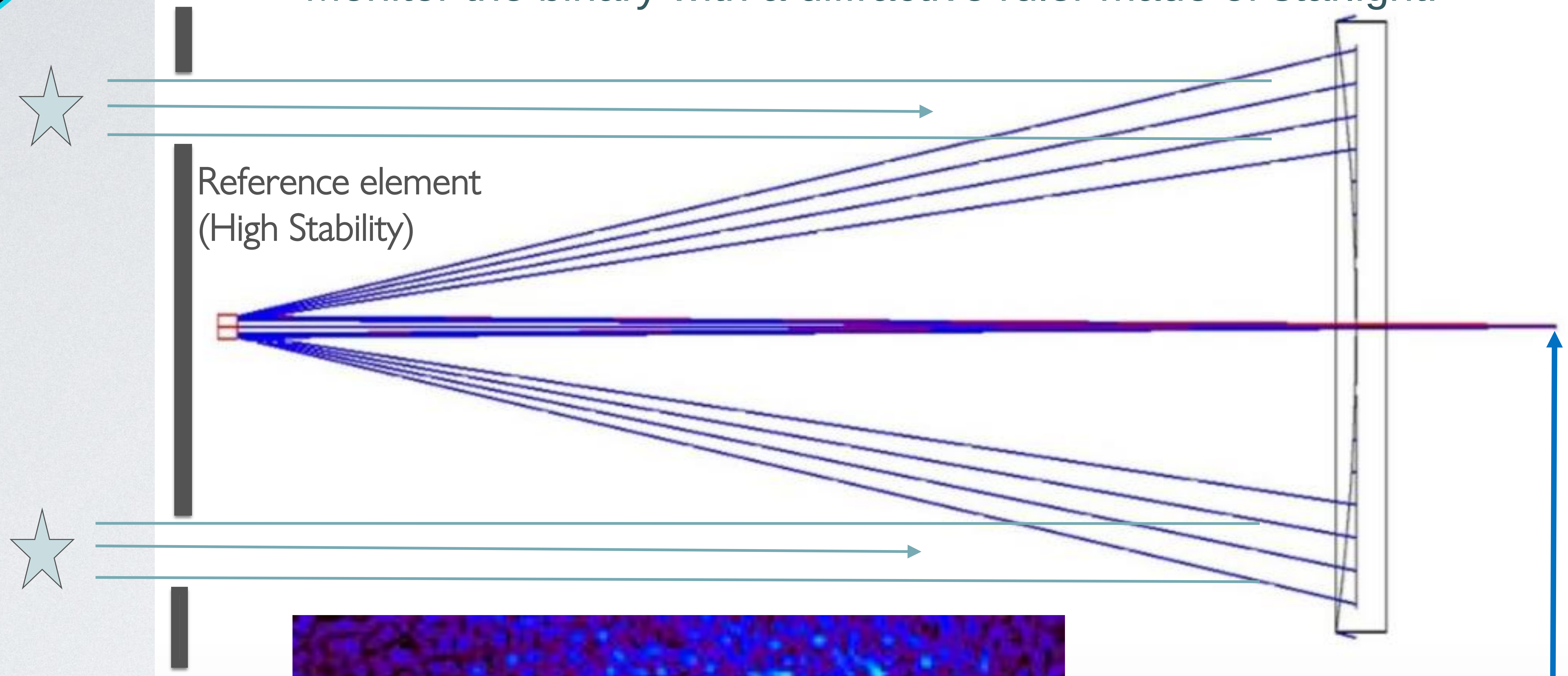
These two sidelobes will still coincide even with bad optics: the rays are parallel and traverse identical (distorted) paths.

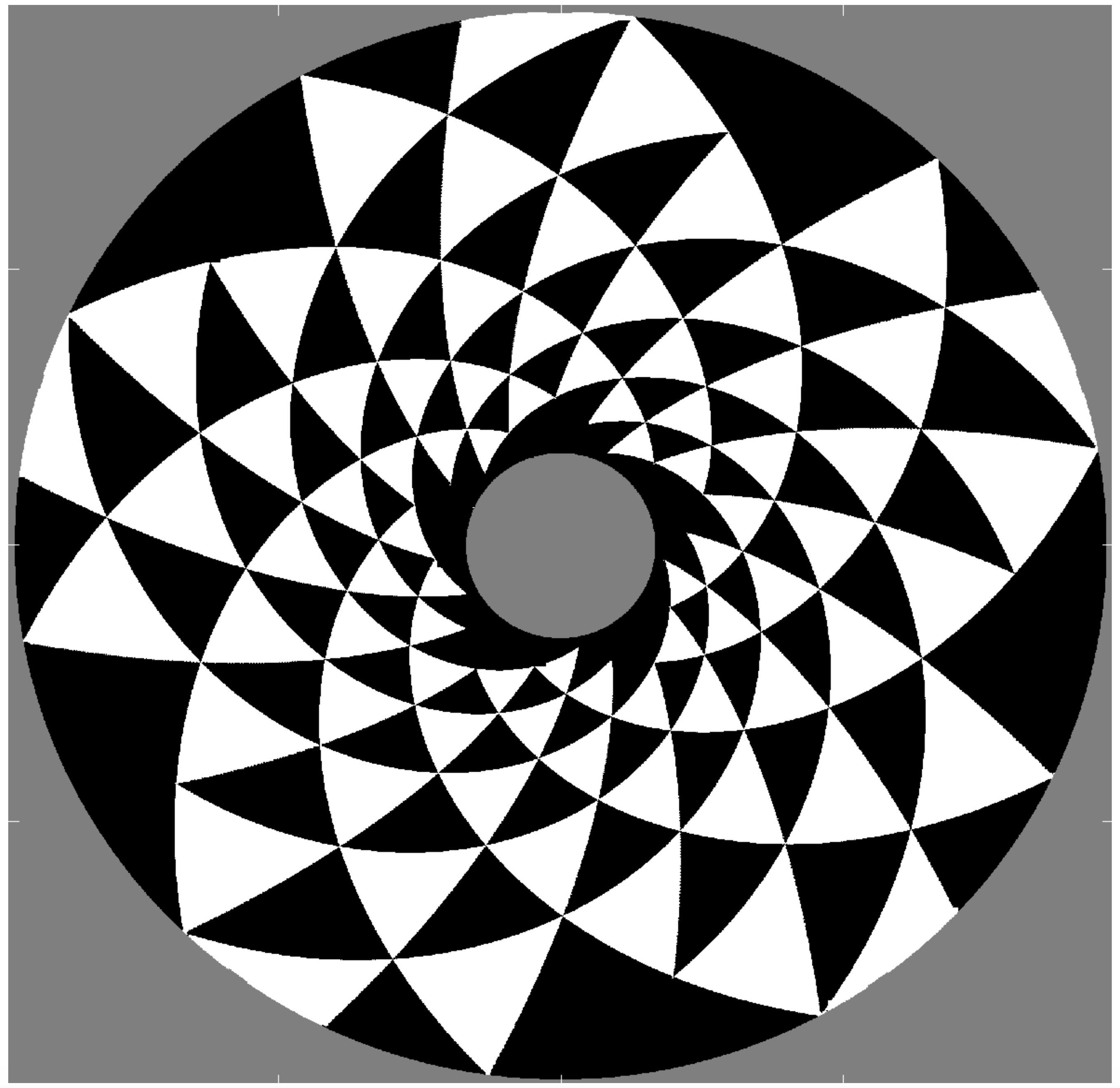


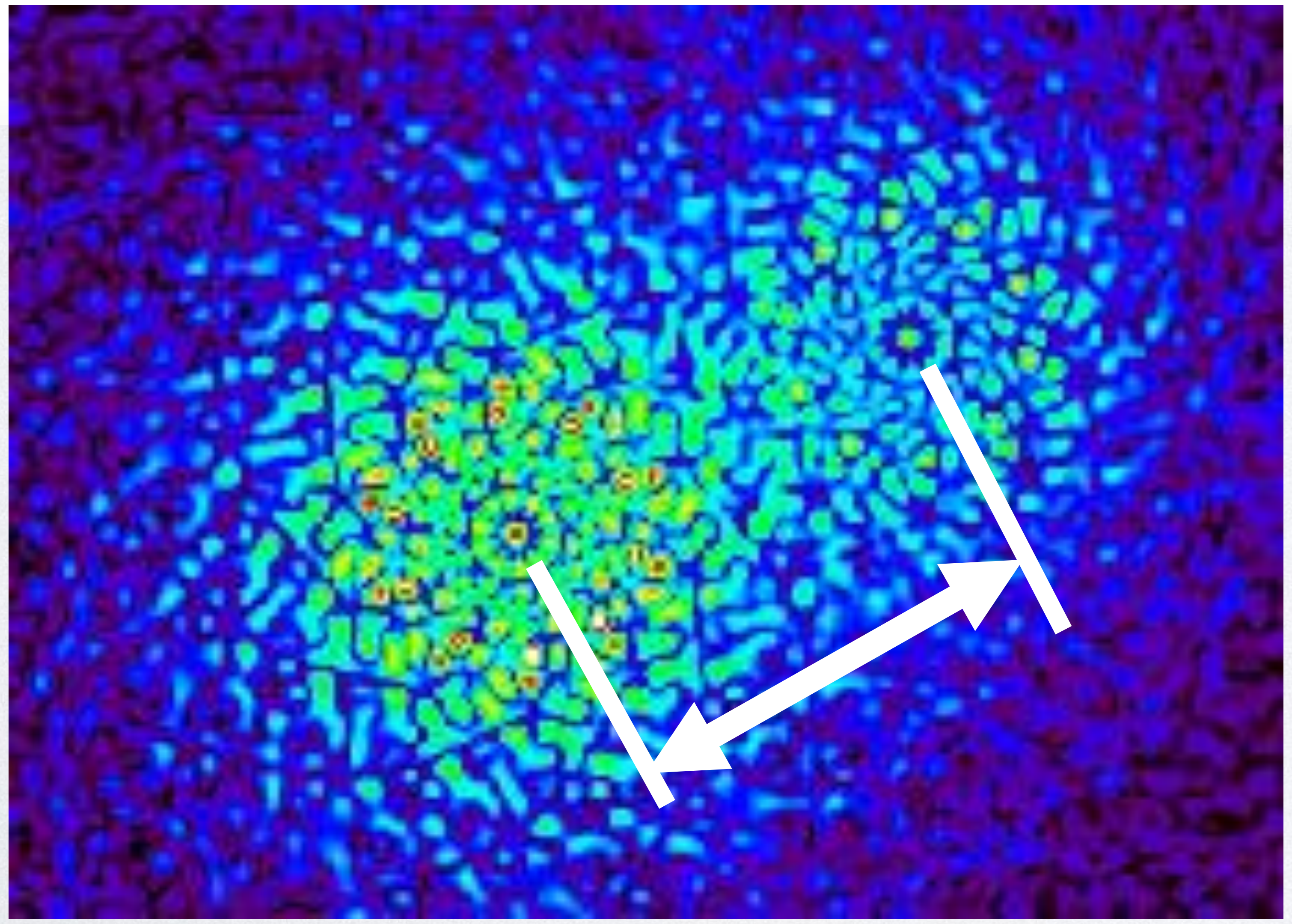
Optical concept empowering TOLIMAN

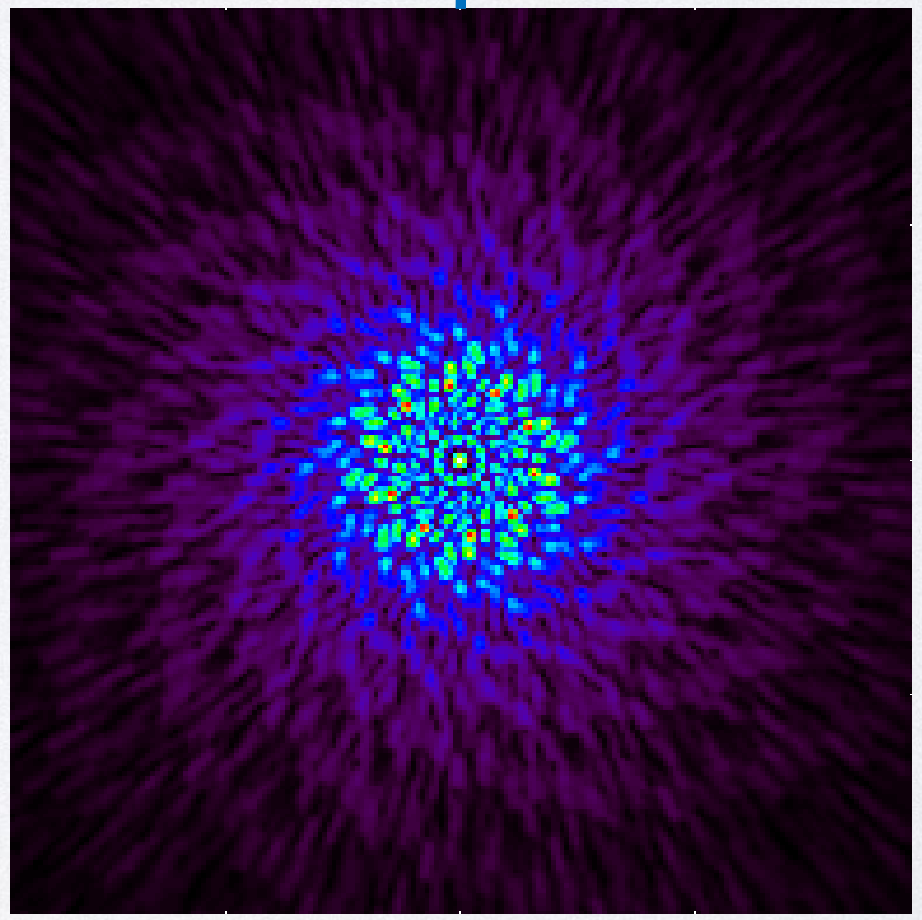
Diffractive-pupil pupil mask

Monitor the binary with a diffractive ruler made of starlight!

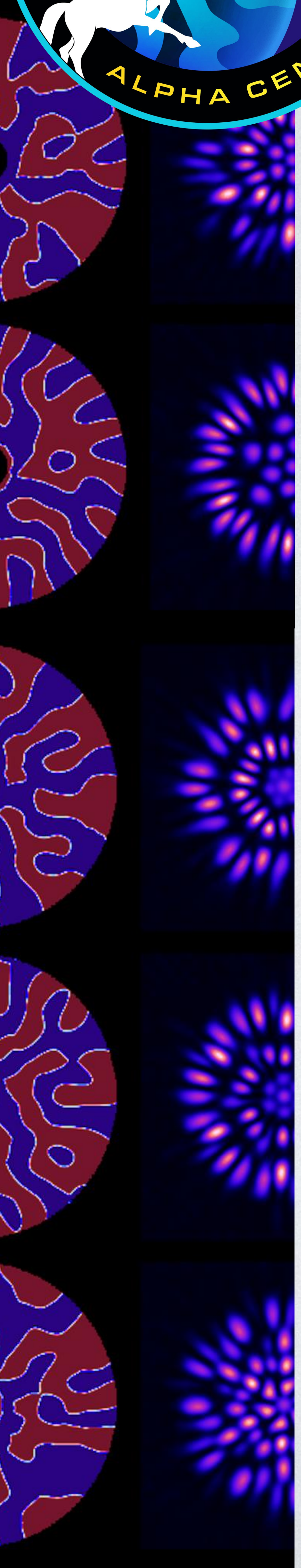








Point Spread Function



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

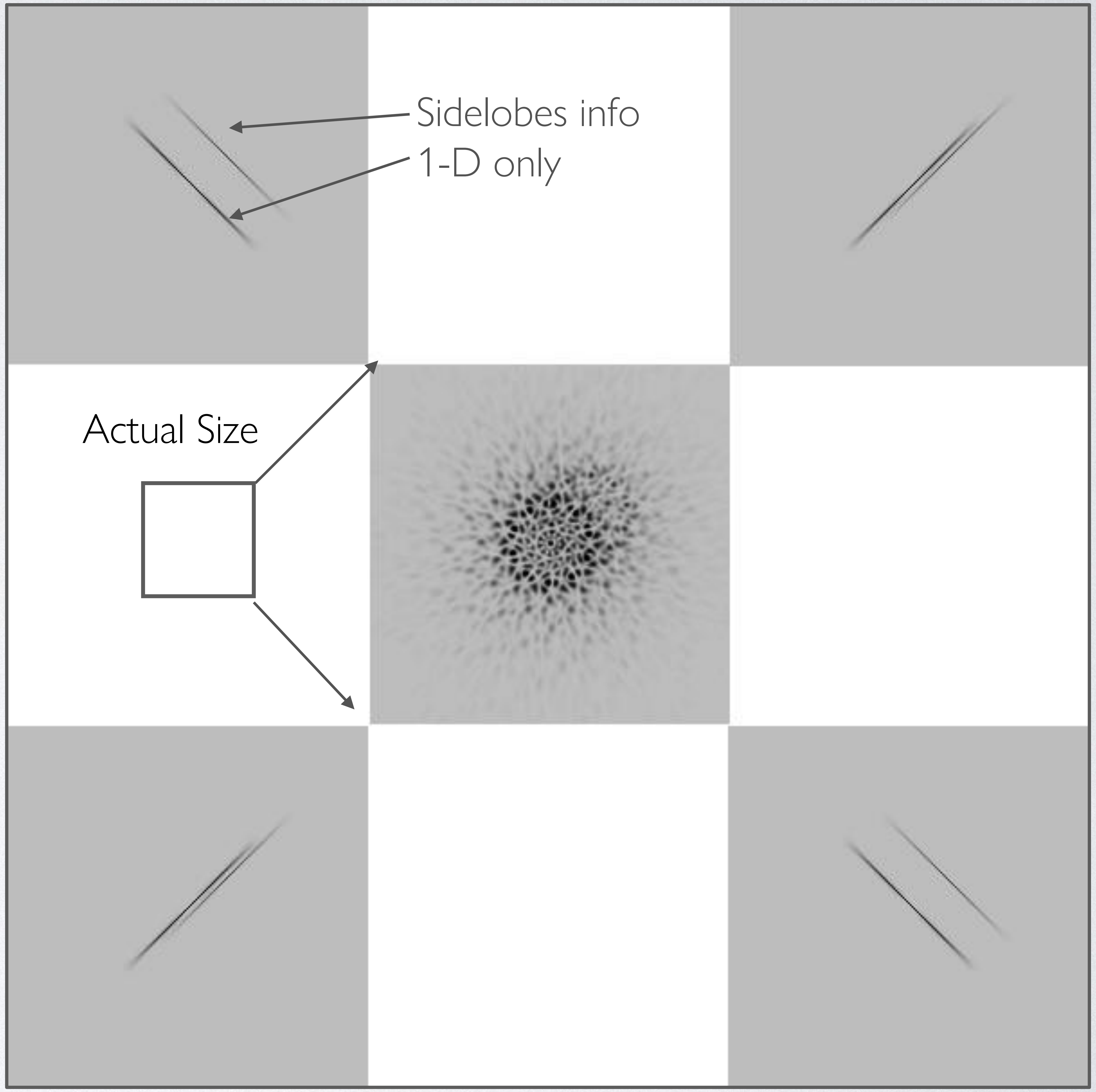
But there is a flaw! Our ruler (fringes) depends on the effective wavelength of the starlight – which varies with star Teff!

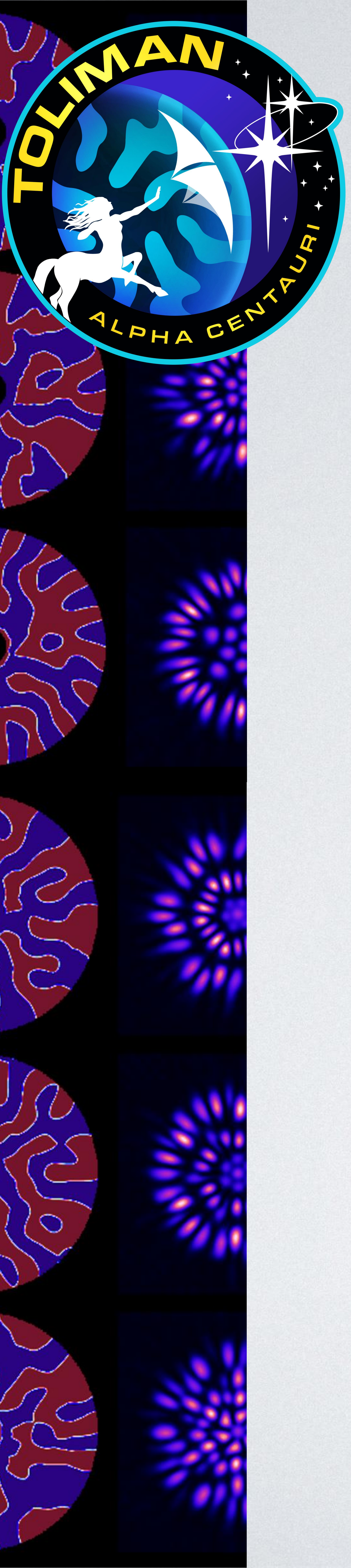
Data rates, compression, Downlink

- E2V Sirius sensor numbers (GSENSE similar)
- 7.5fps x 256x256 x 12bit = 1Mbyte/sec ~few GBytes/hr or 10 GB/Day
- + extra data from sidelobes, sensors, metering etc (small).
- Potential for data truncation, compression
- On-board processing
- NEEDED: signal to send to onboard bespoke Attitude Control system (later)

Max Charles

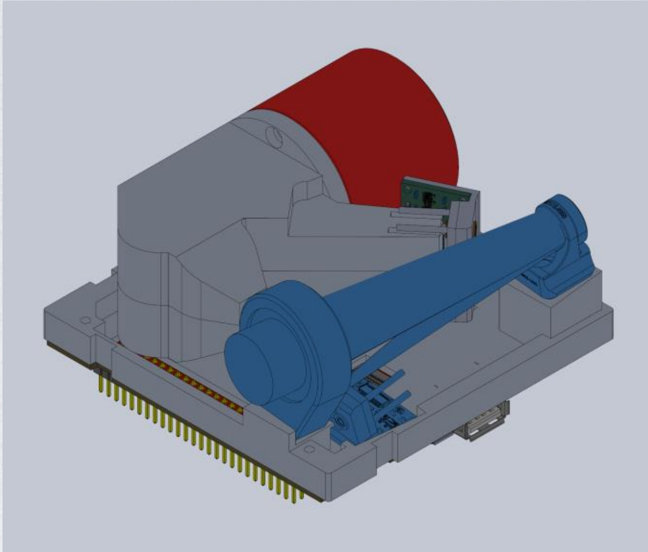
Raw Data Frame

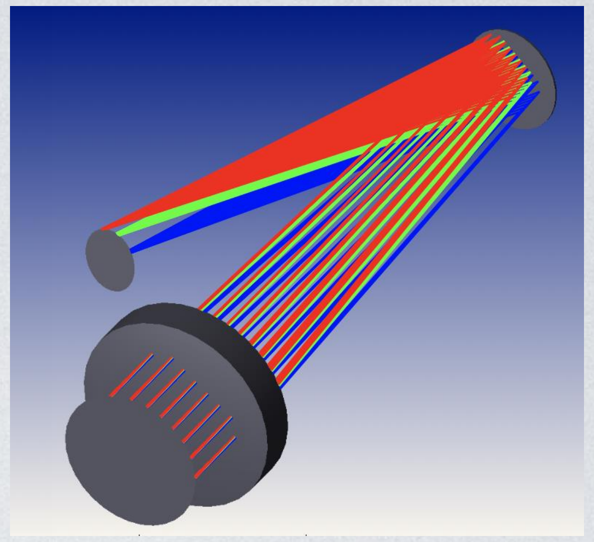




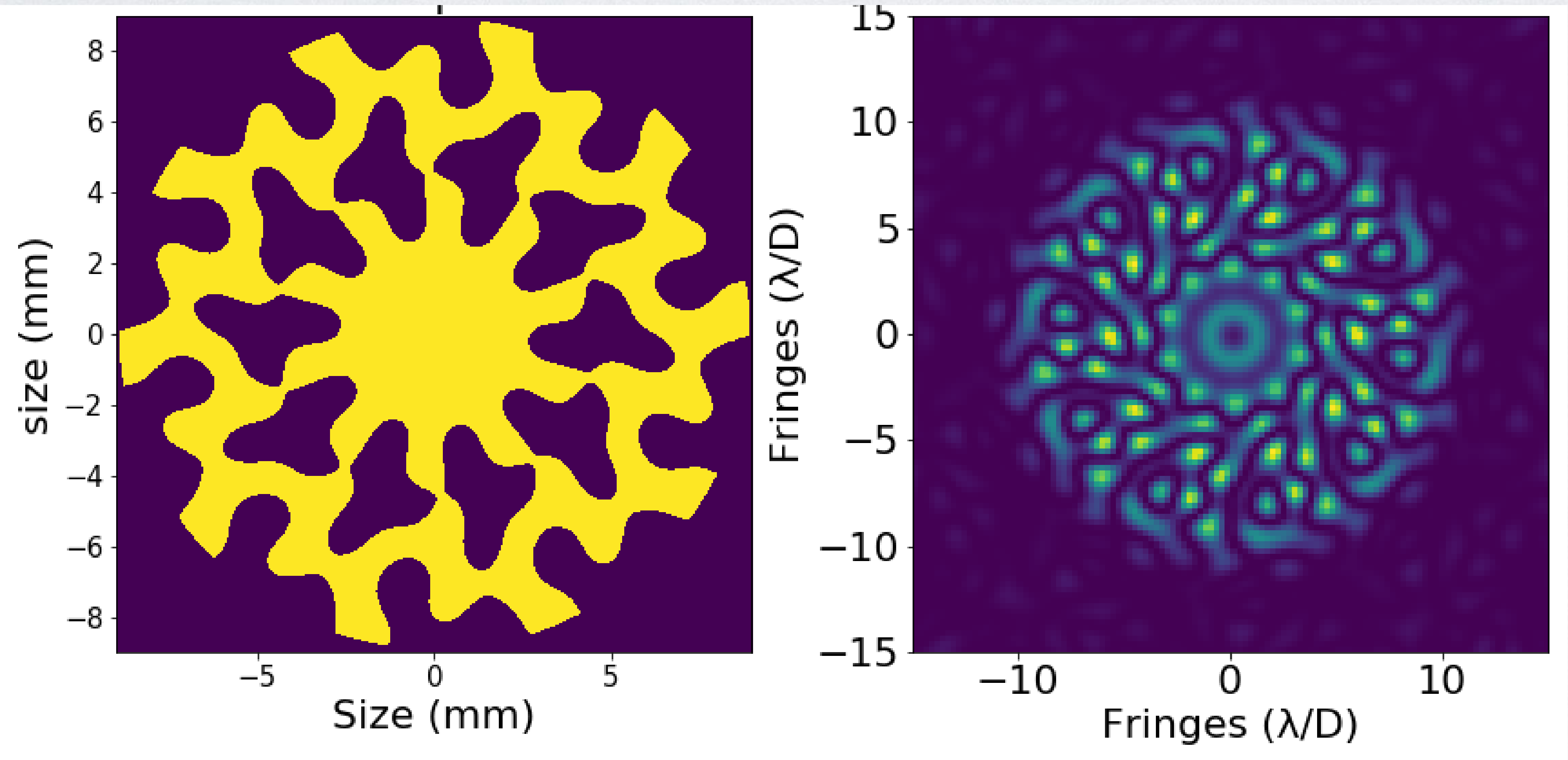
Program Genealogy: TinyTol, Toliman, Toliman+

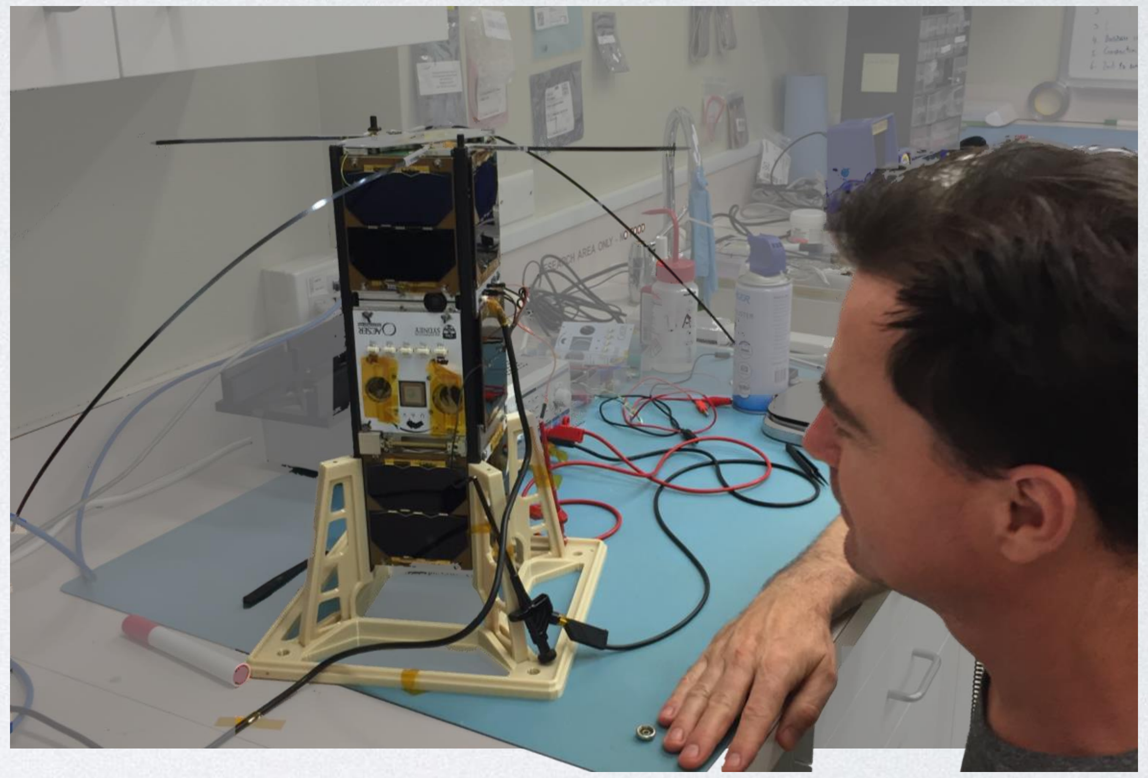
- TinyTol flew aboard CUAVA1
  - 3U cubesat. ISS resupply deployed 2020
  - 20mm aperture, f=15cm, 1 deg FoV
  - Consumer-grade electronics
  - Built, deployed, flown. No data.

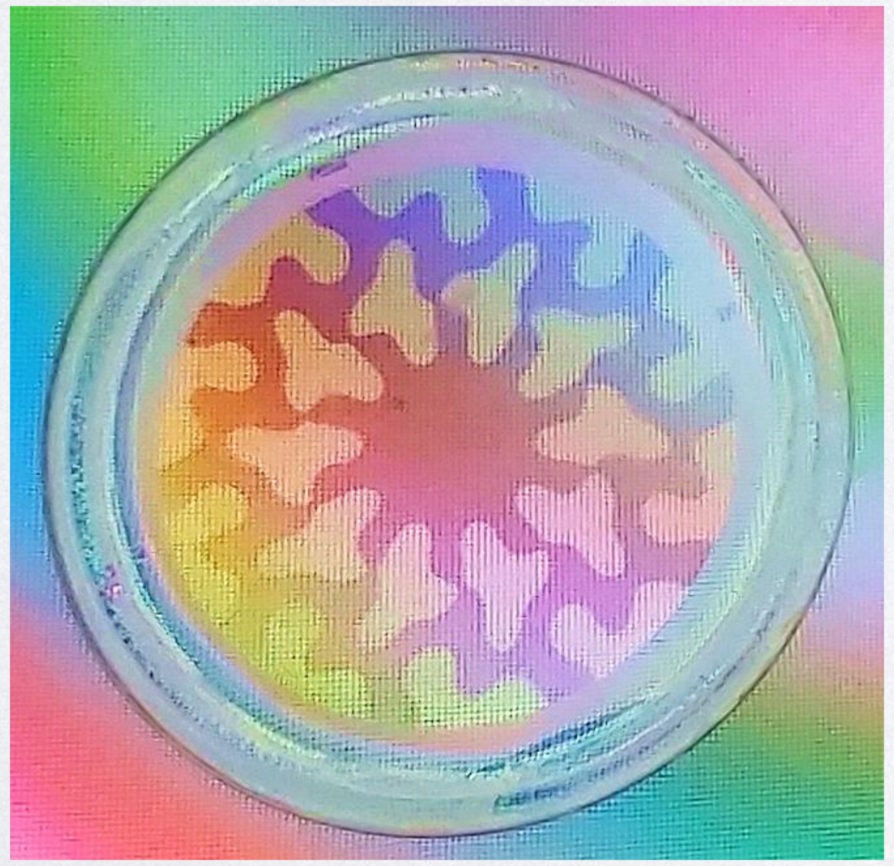


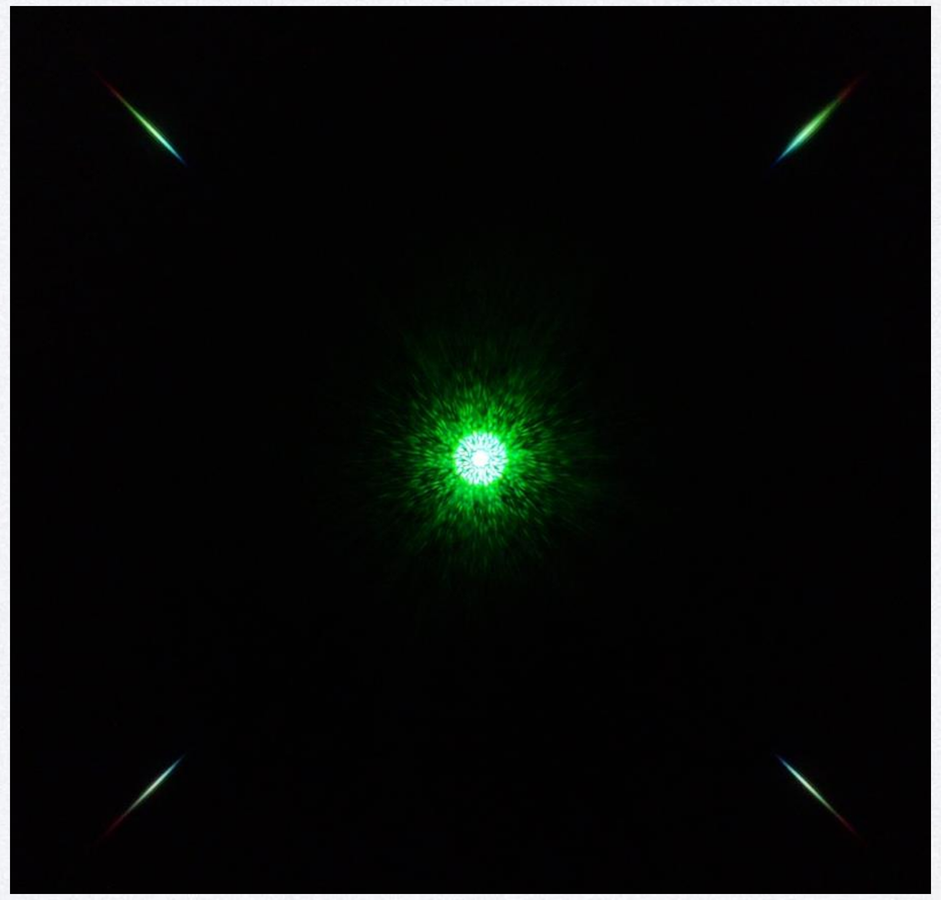


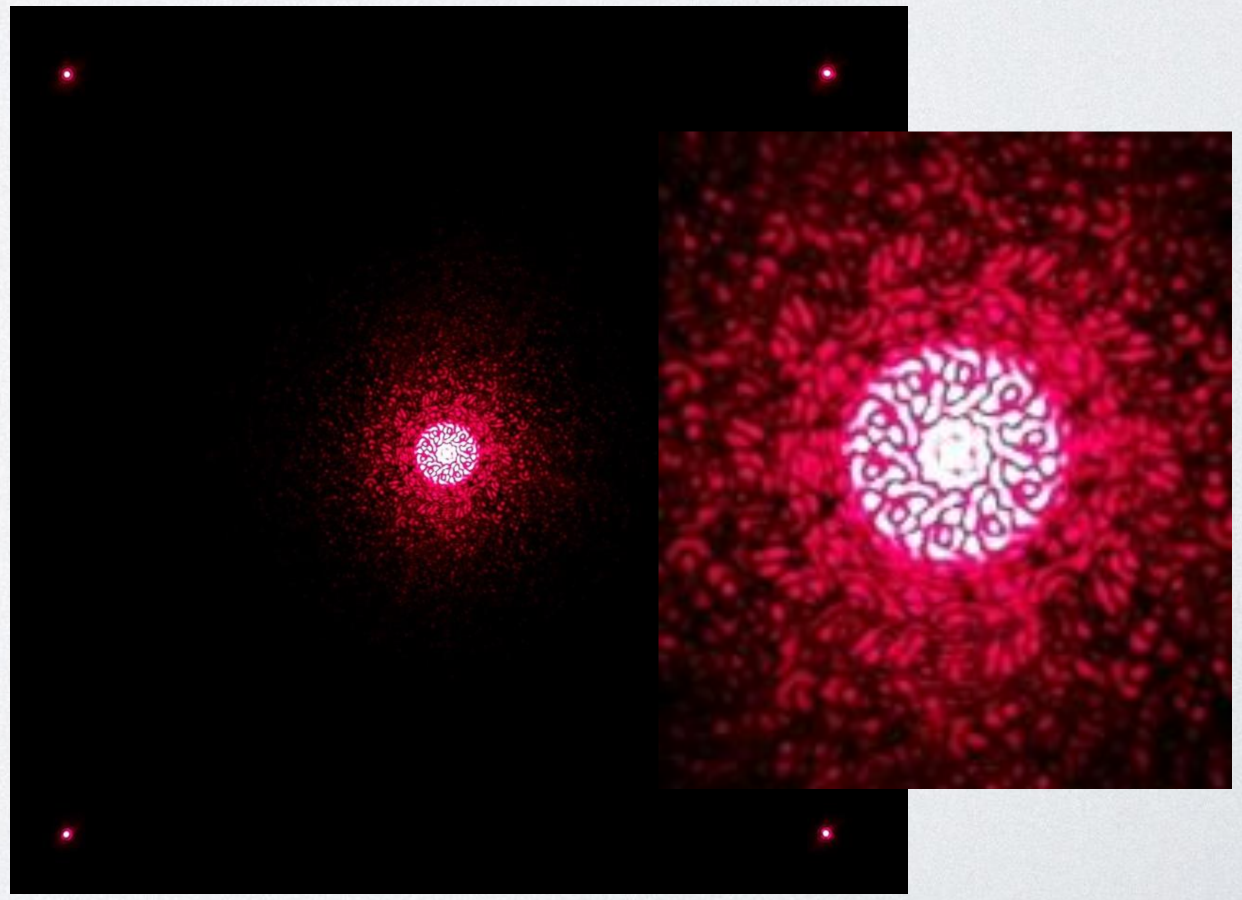
TT instrument / Ray Trace



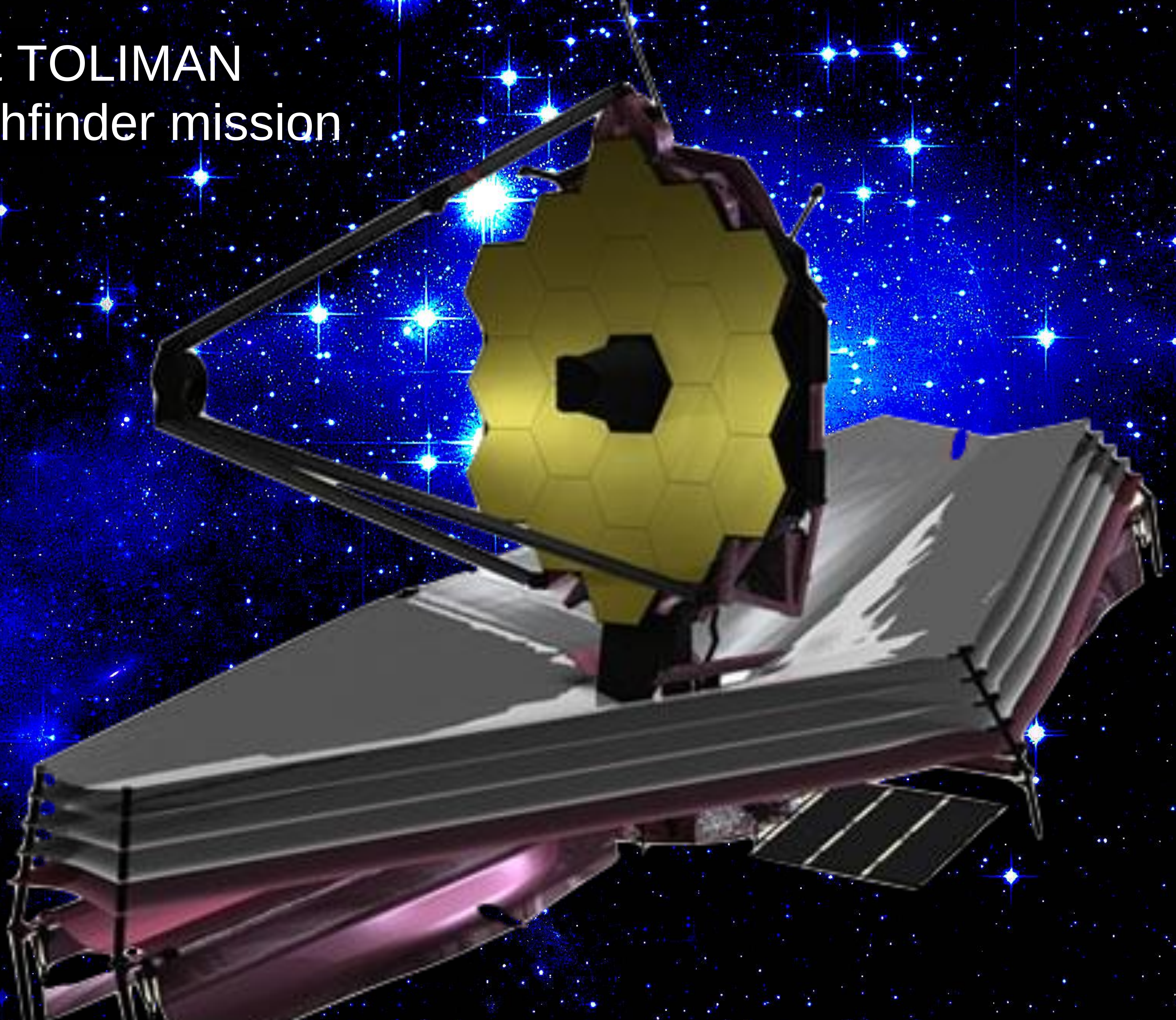




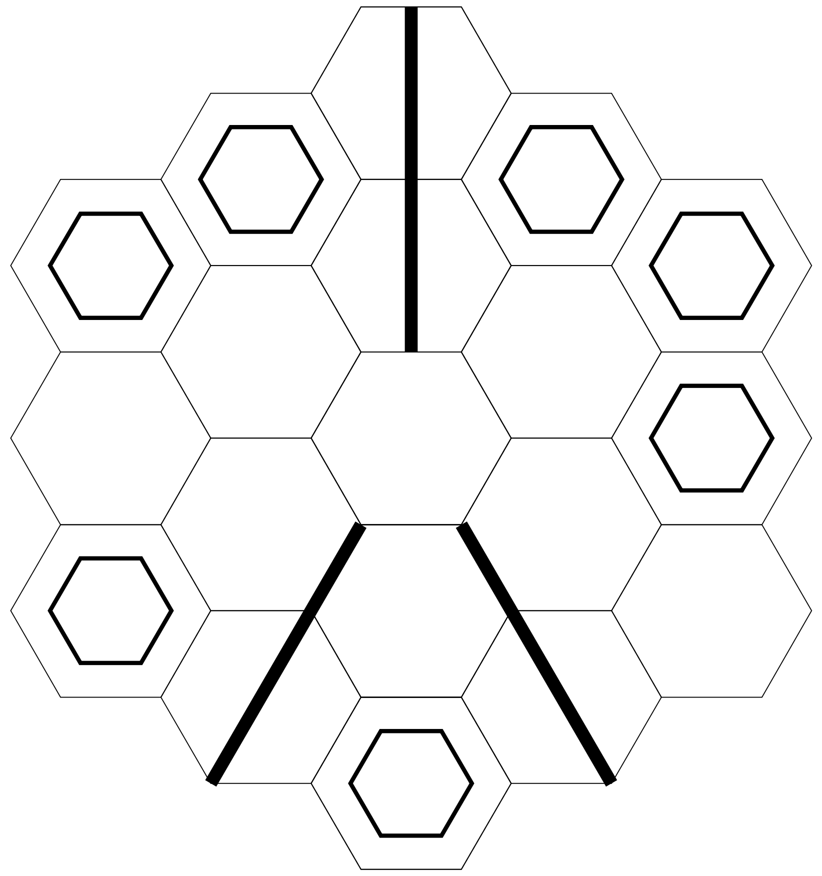


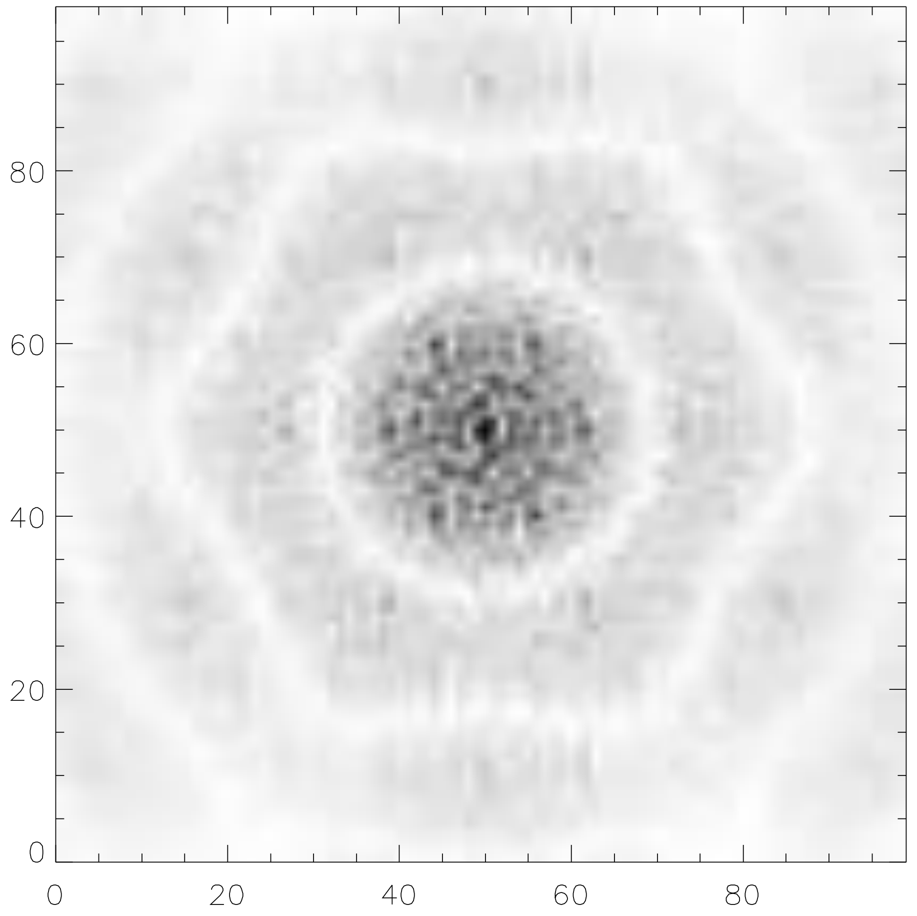


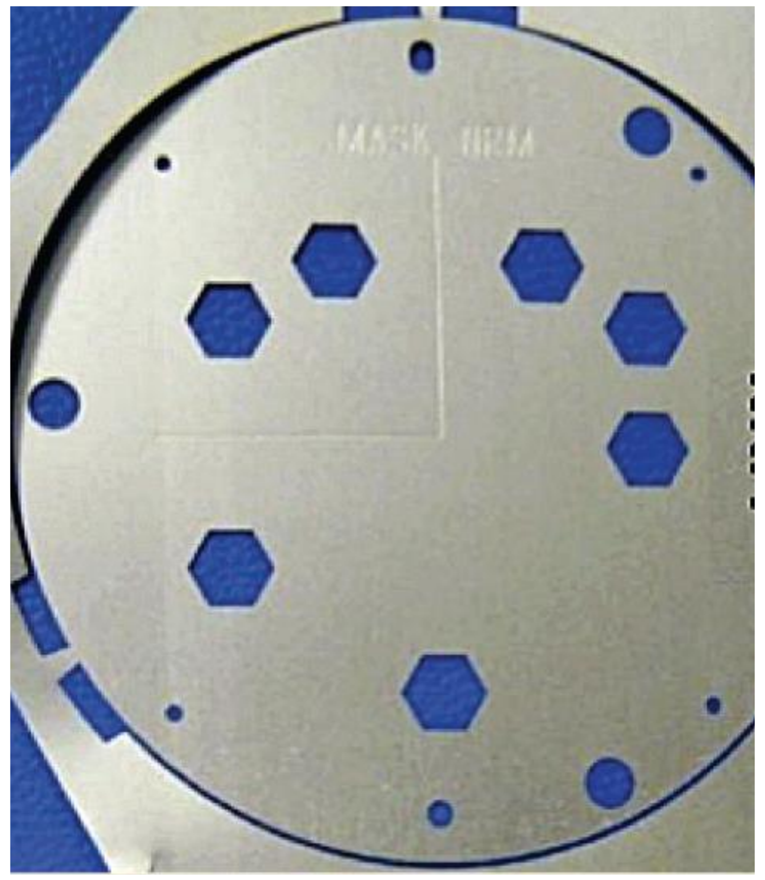
A Modest TOLIMAN Precursor/Pathfinder mission

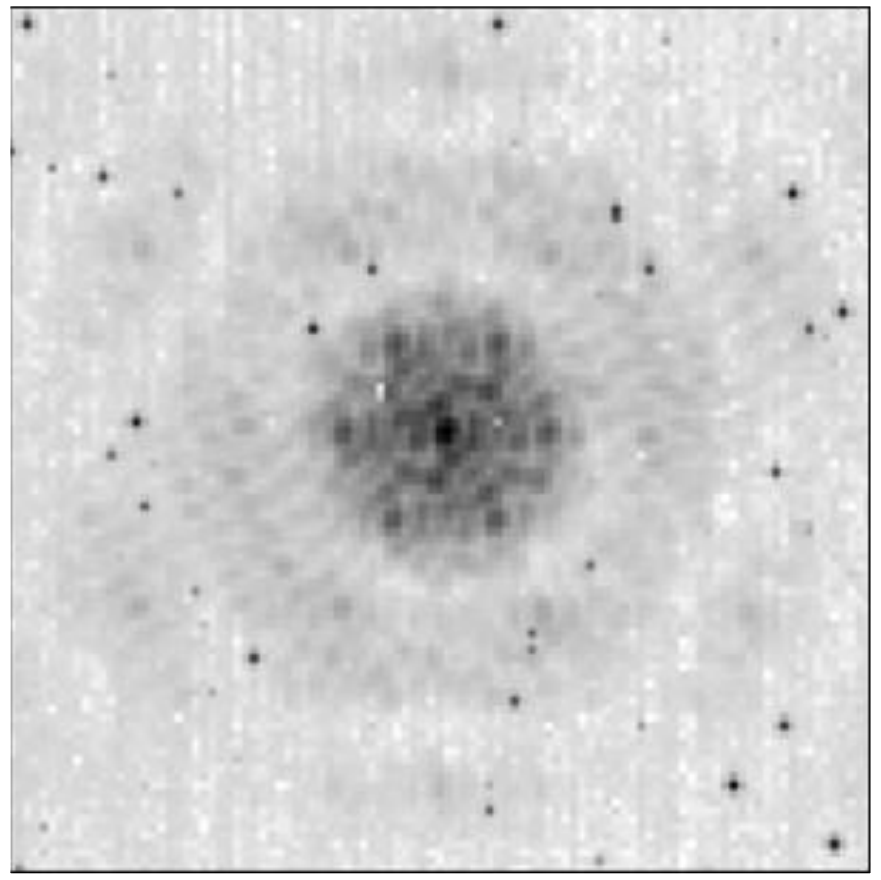


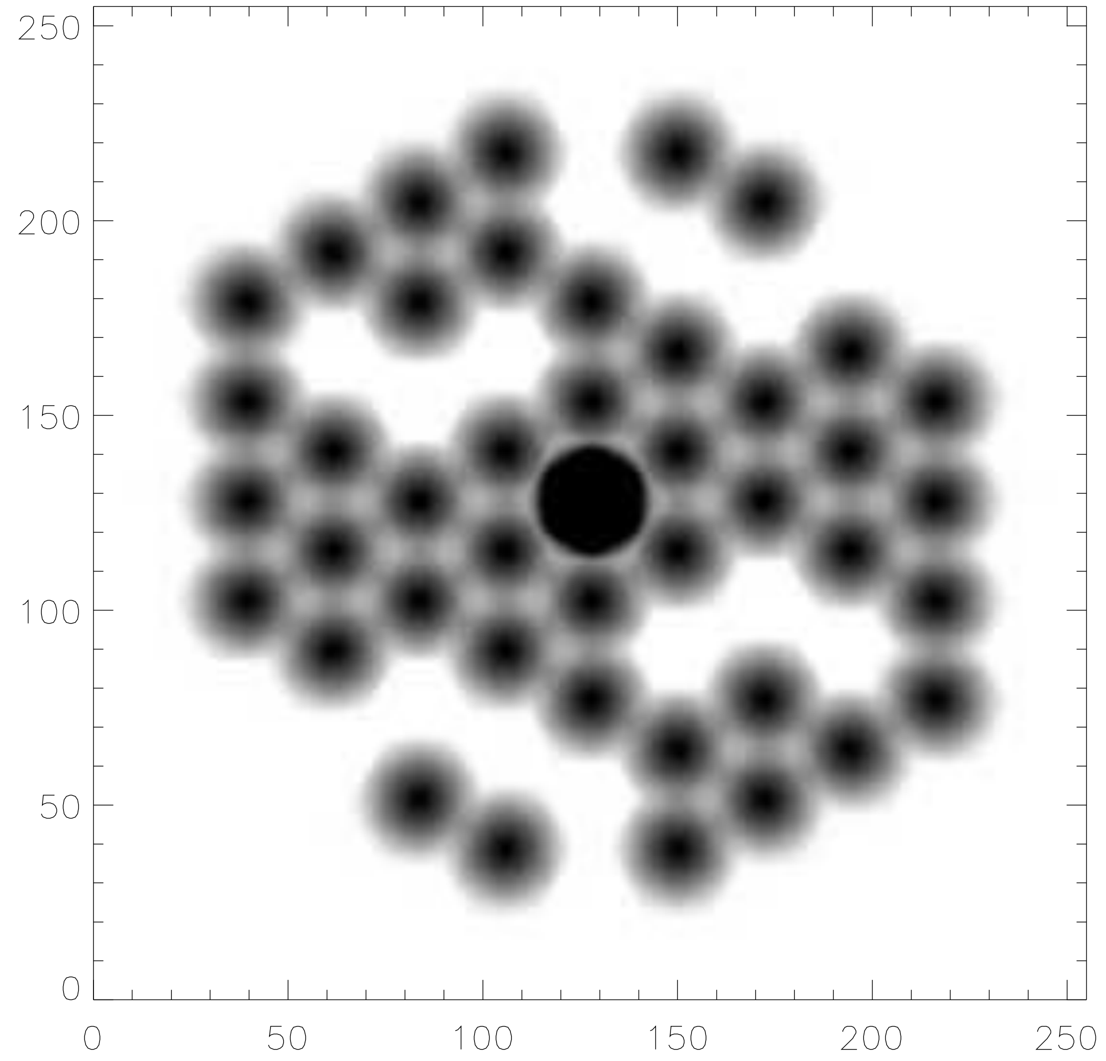
NIRISS AMI: THE JWST INTERFEROMETER

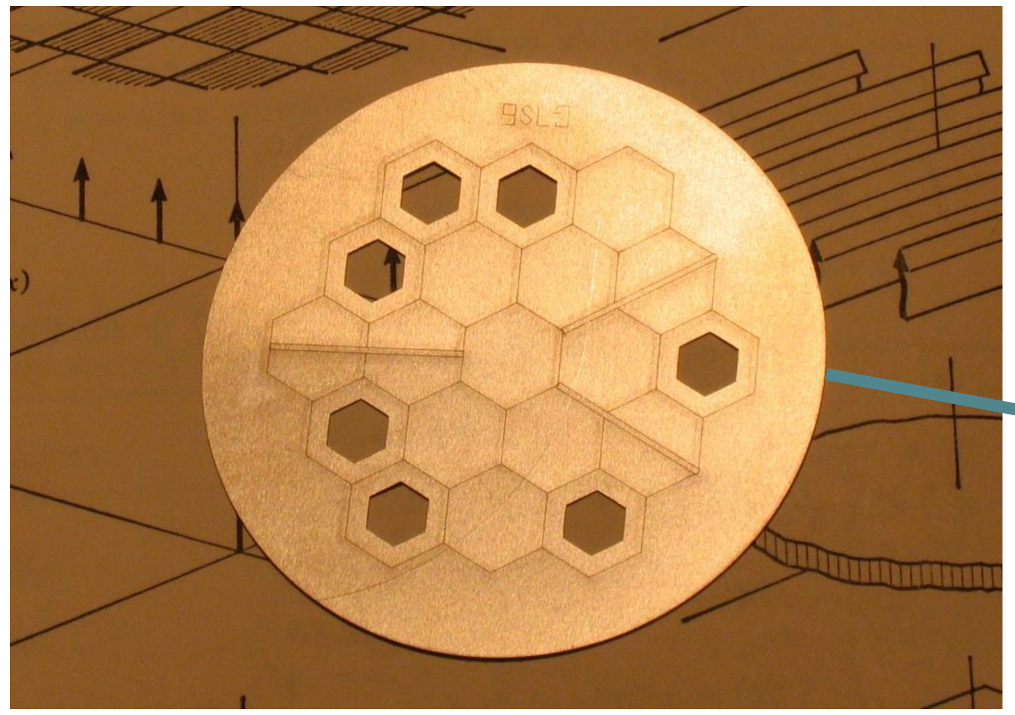


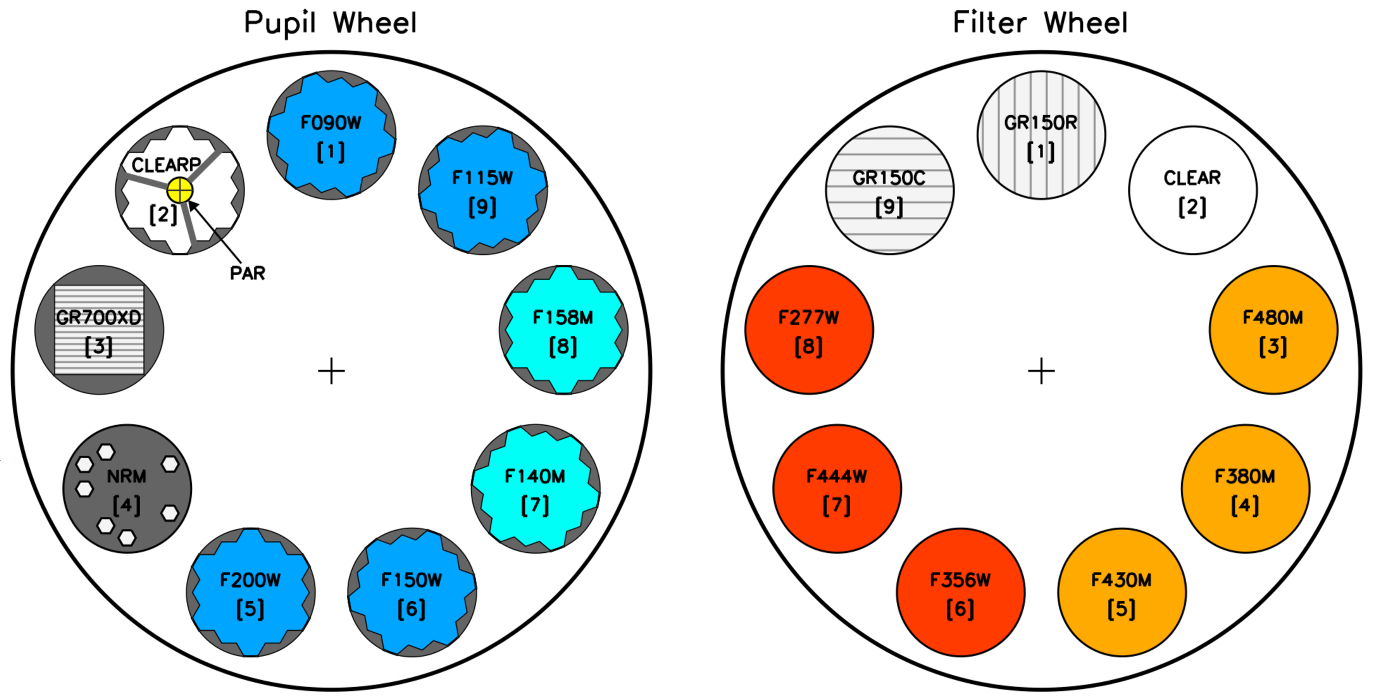






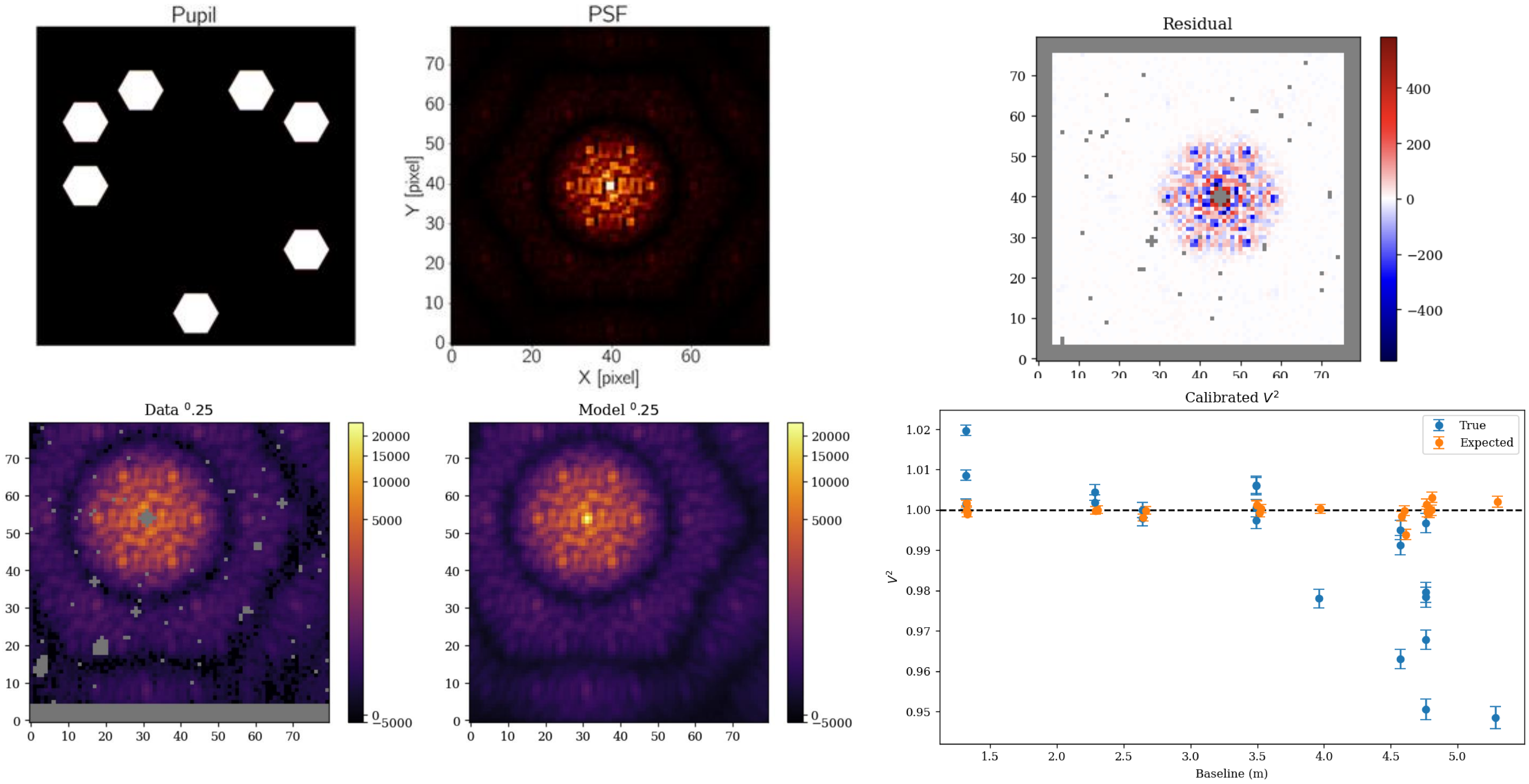






Thanks @ NASA

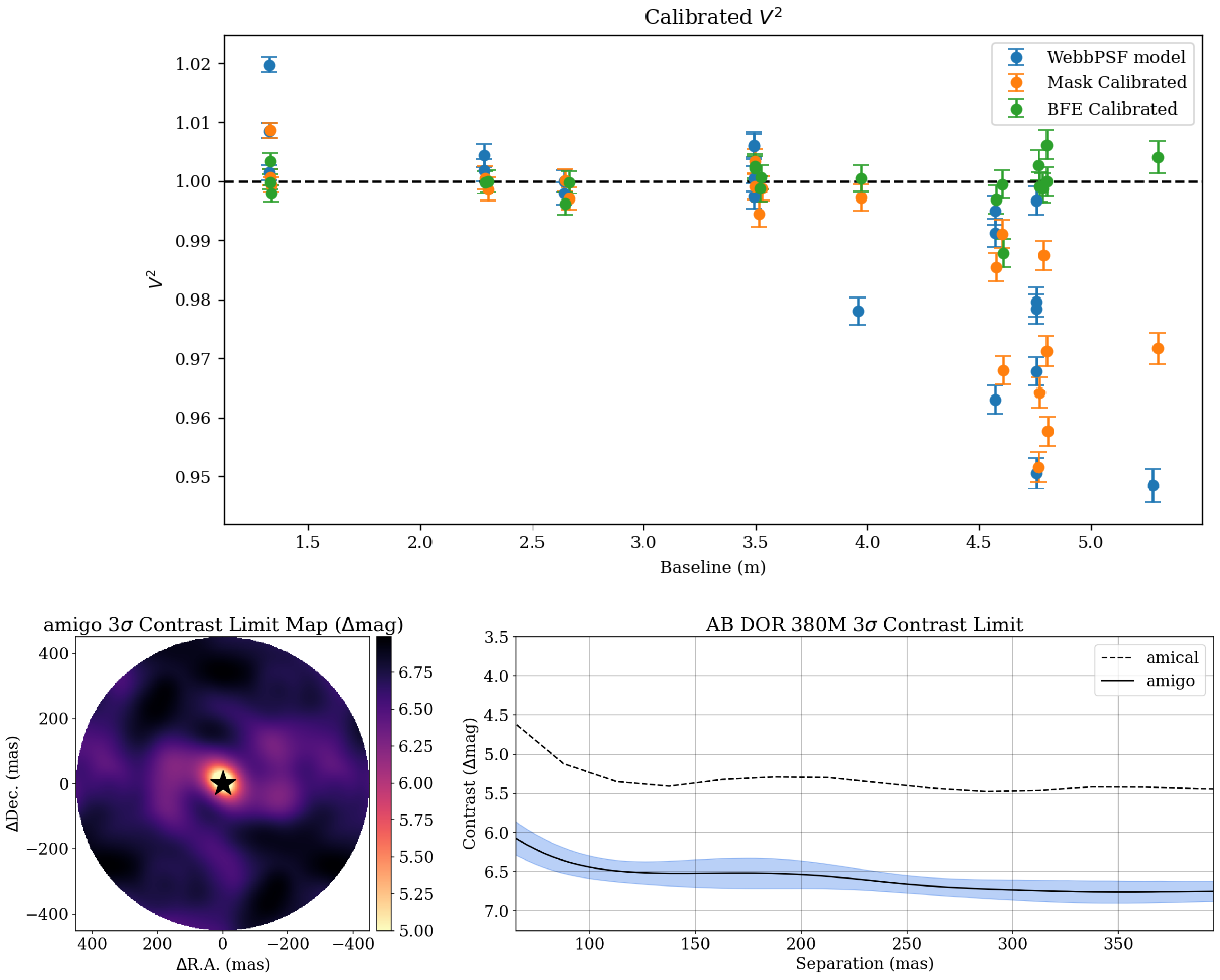
NIRISS AMI: THE JWST INTERFEROMETER

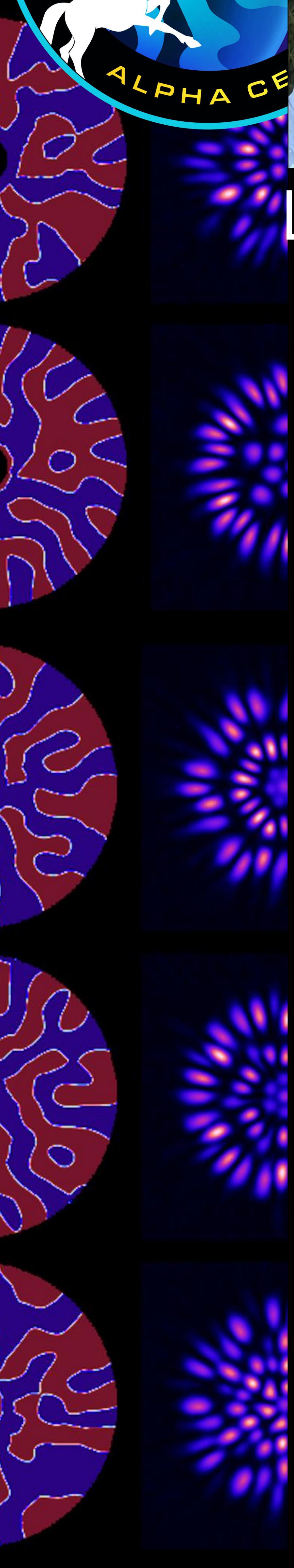



Louis Desdoigts


Ben Pope

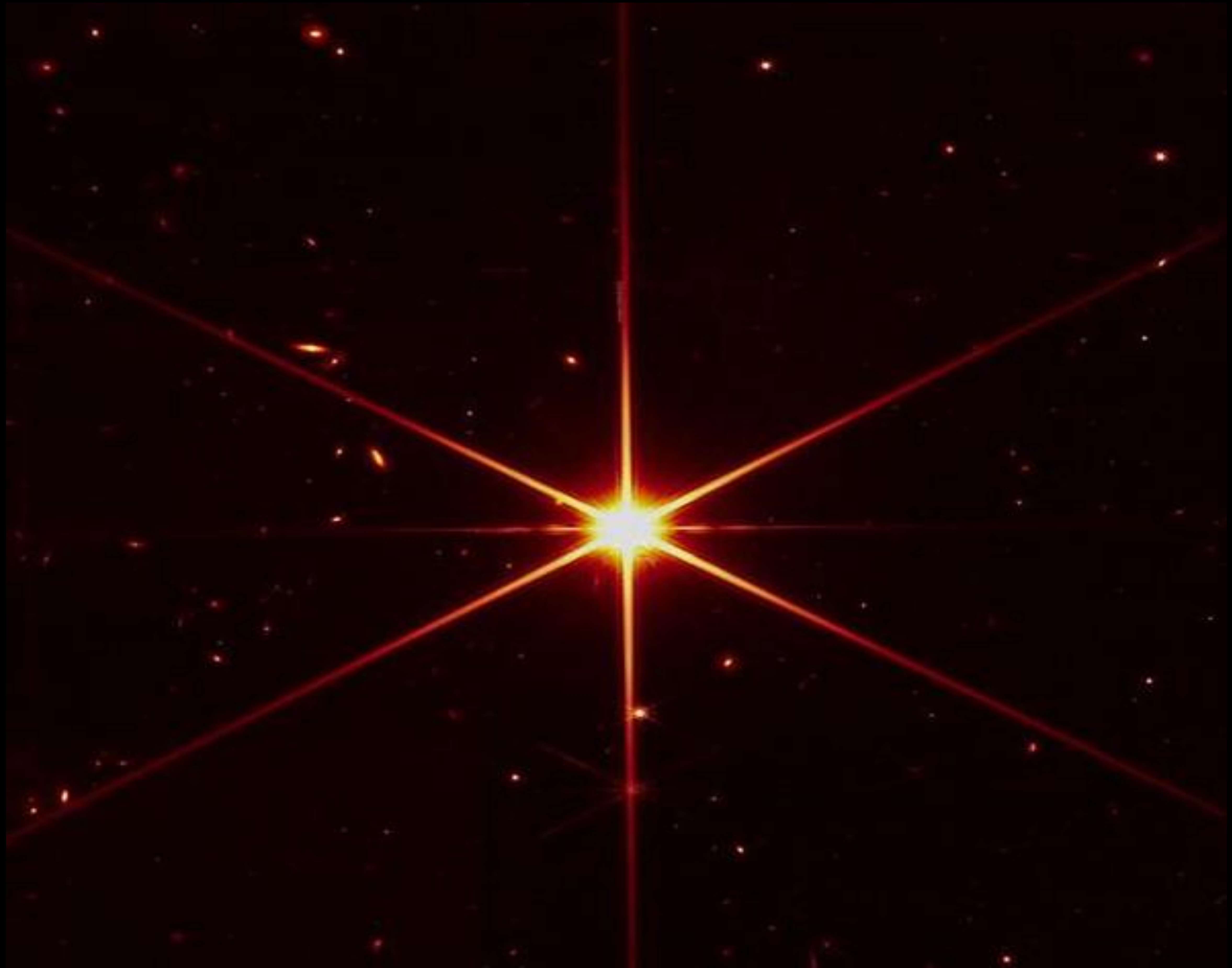
Very promising performance from dLux image plane modeling

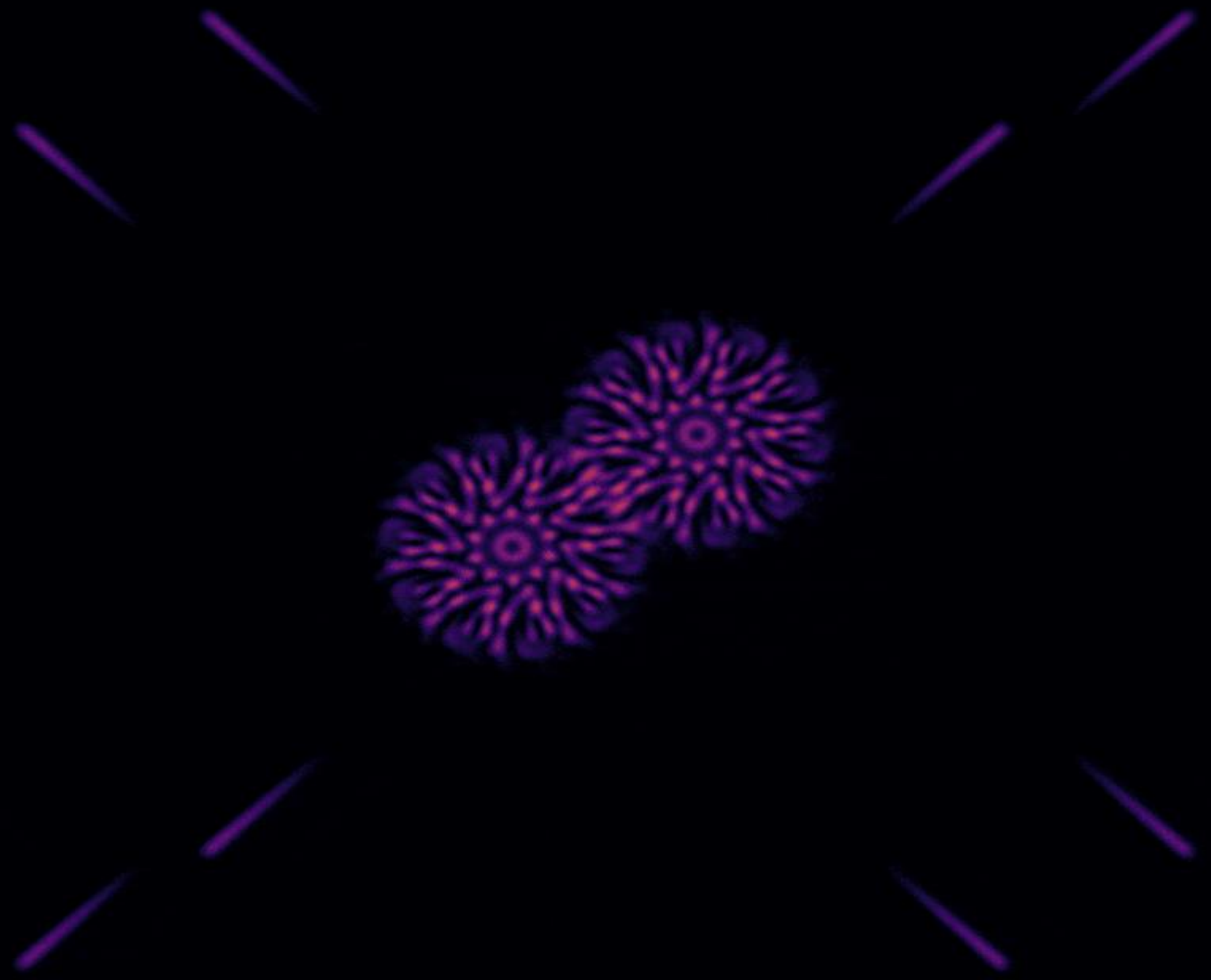


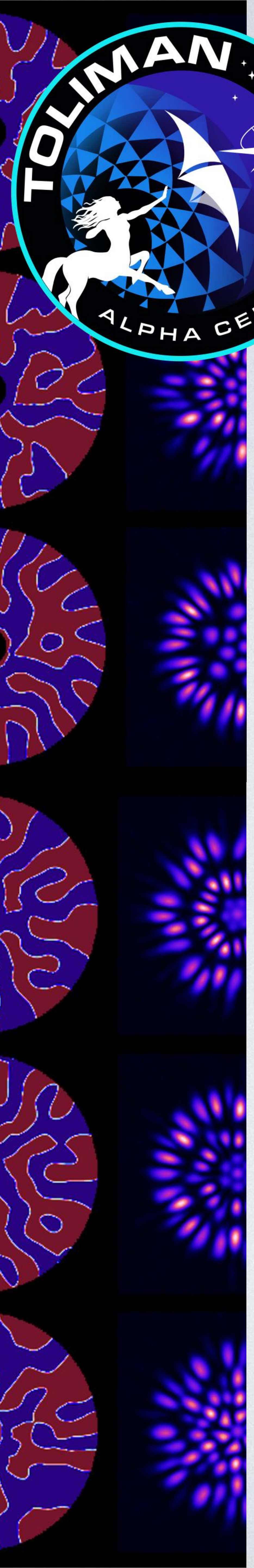


Louis Desdoigts

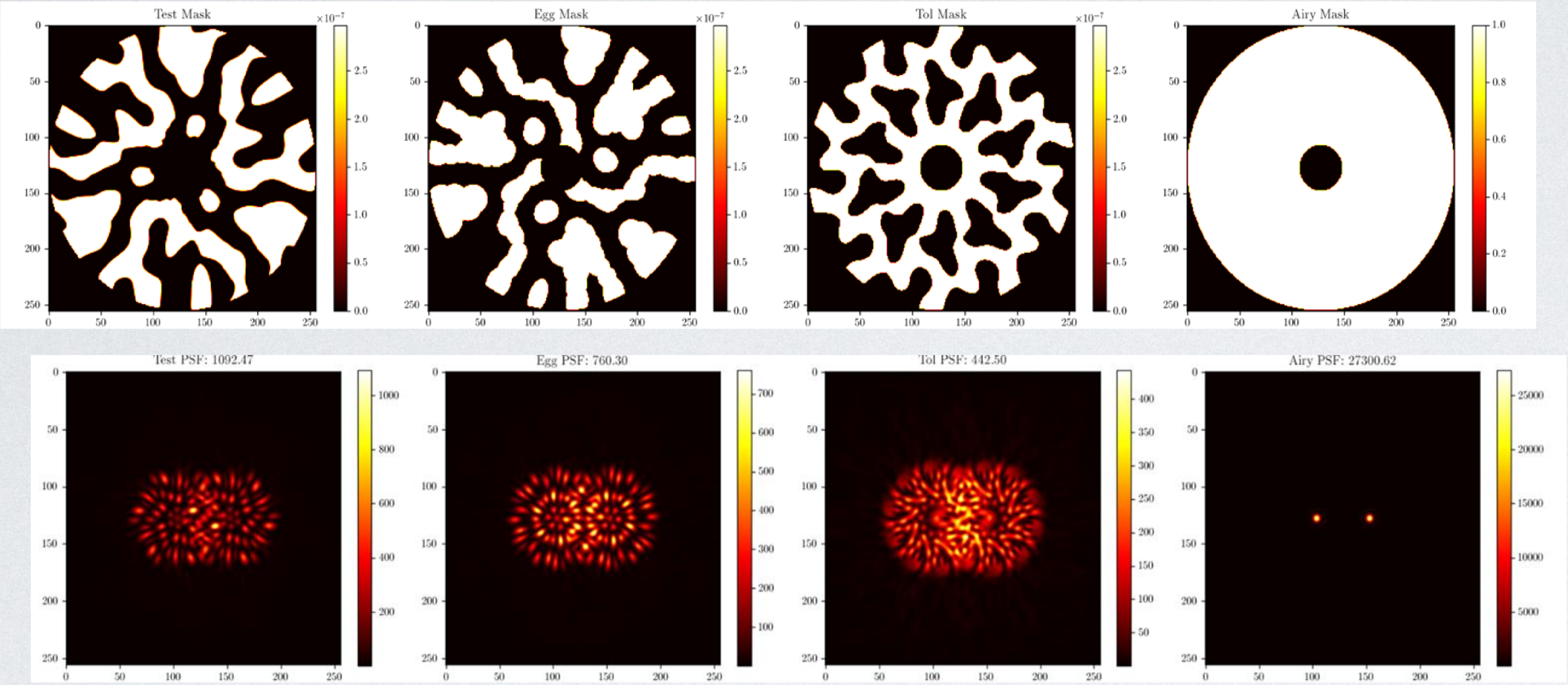
Ben Pope

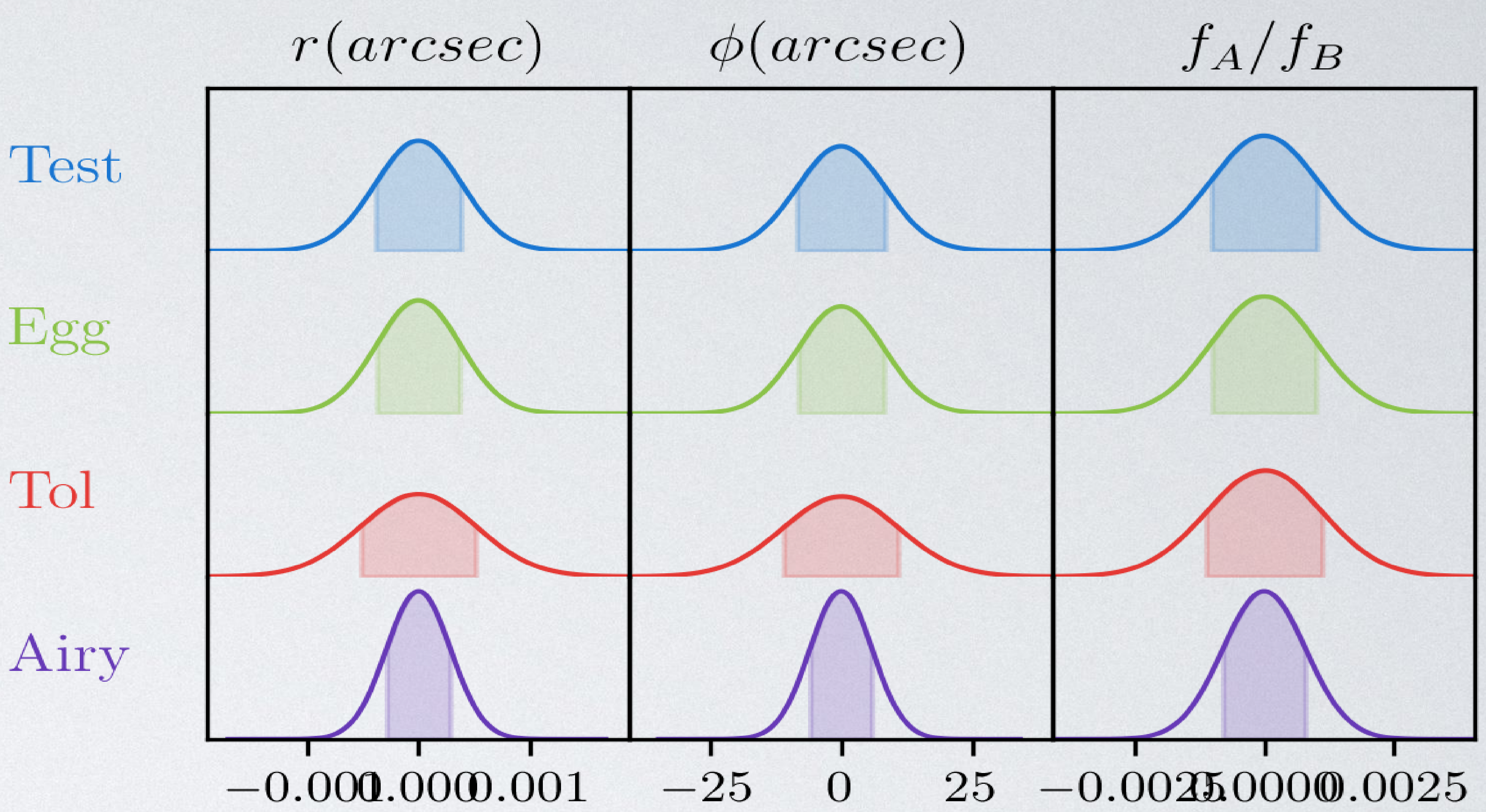




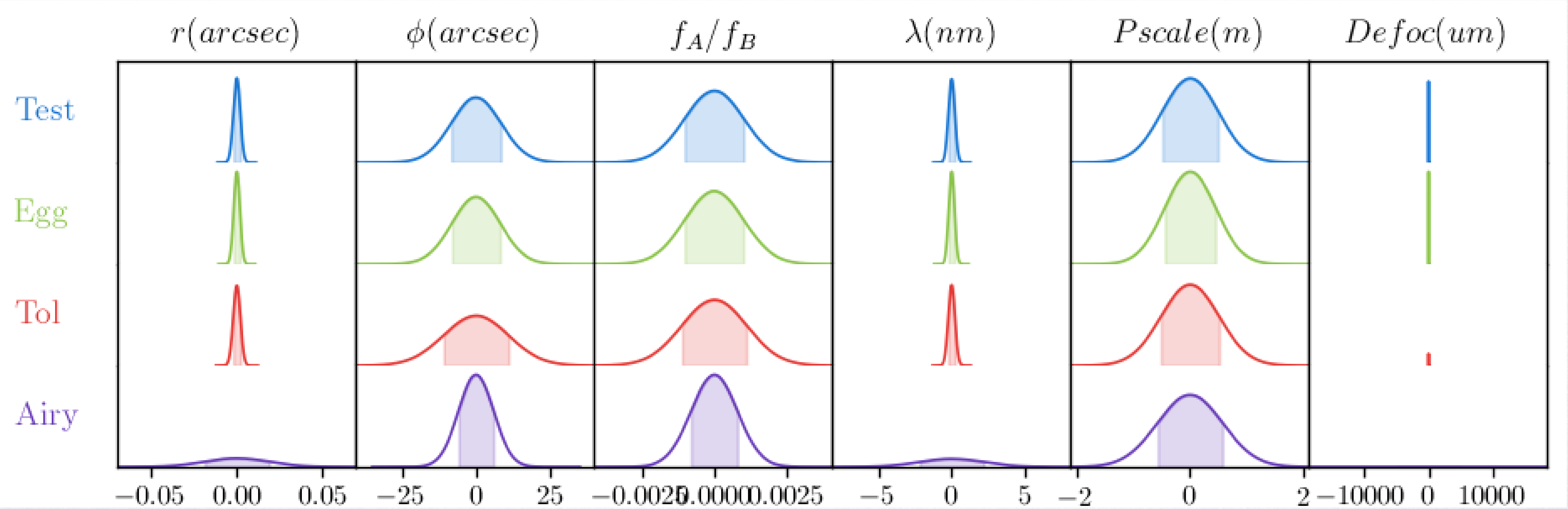


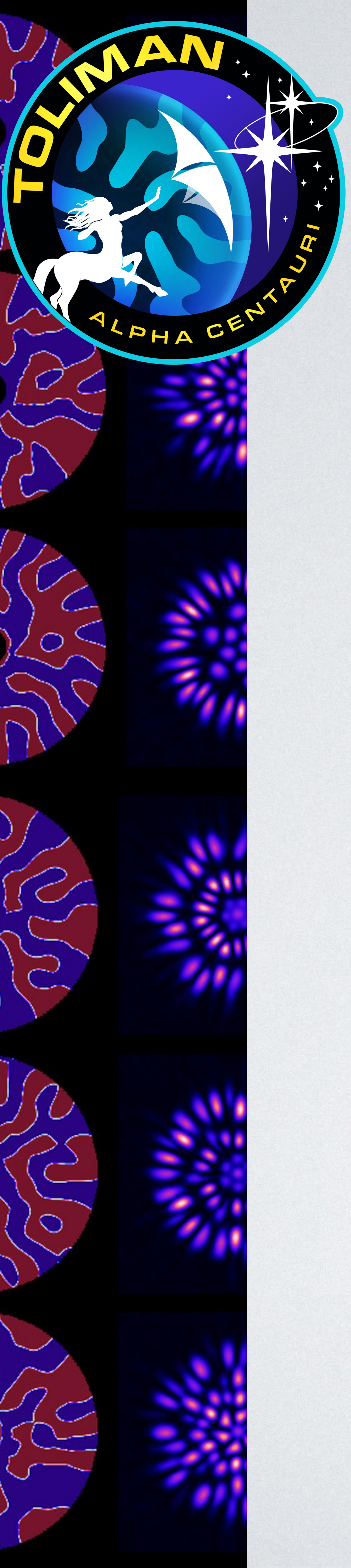
Posteriors: Separation, field angle, flux ratio





POSTERIORS: ADDING WAVELENGTH, PLATE SCALE,

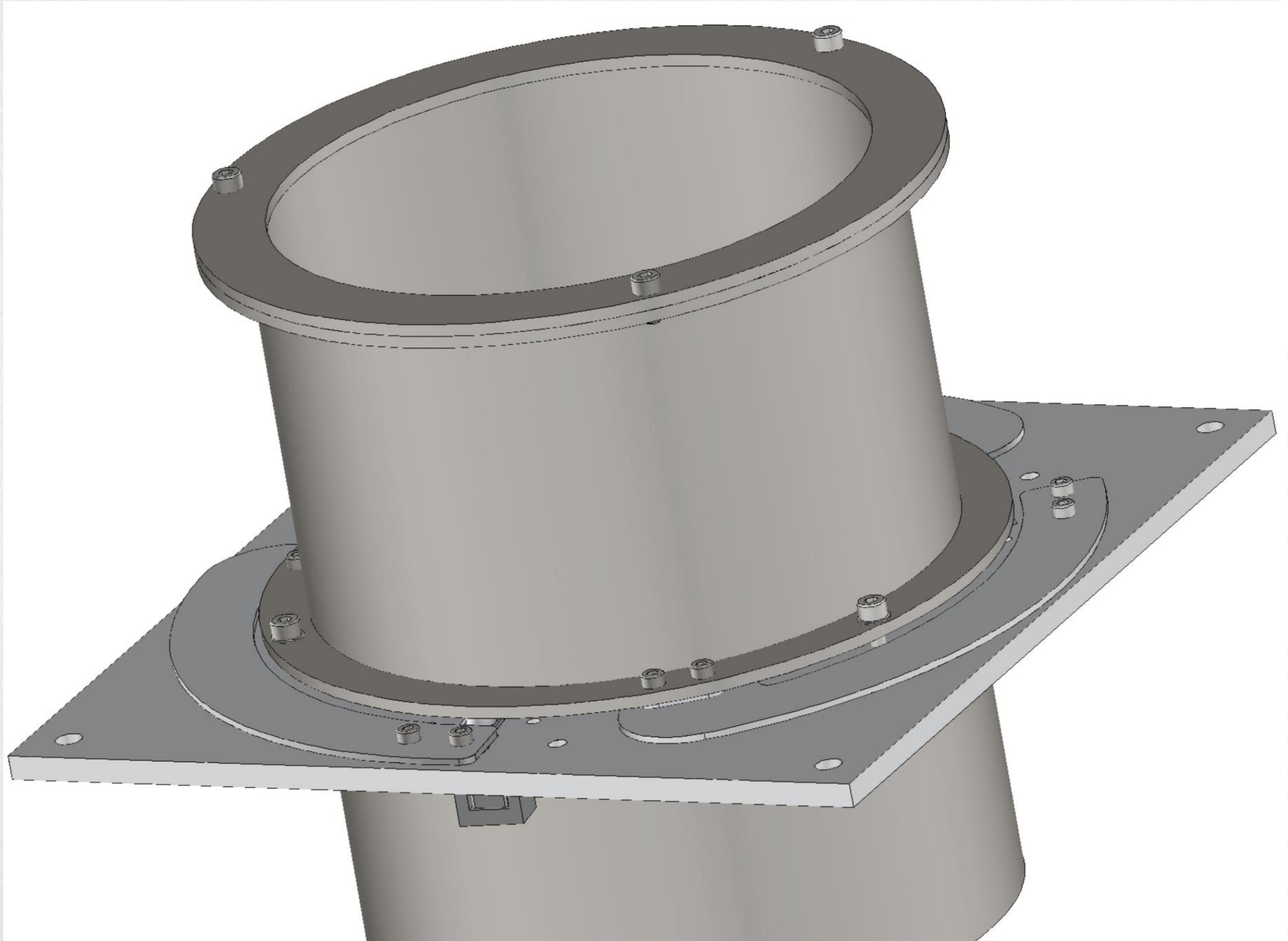


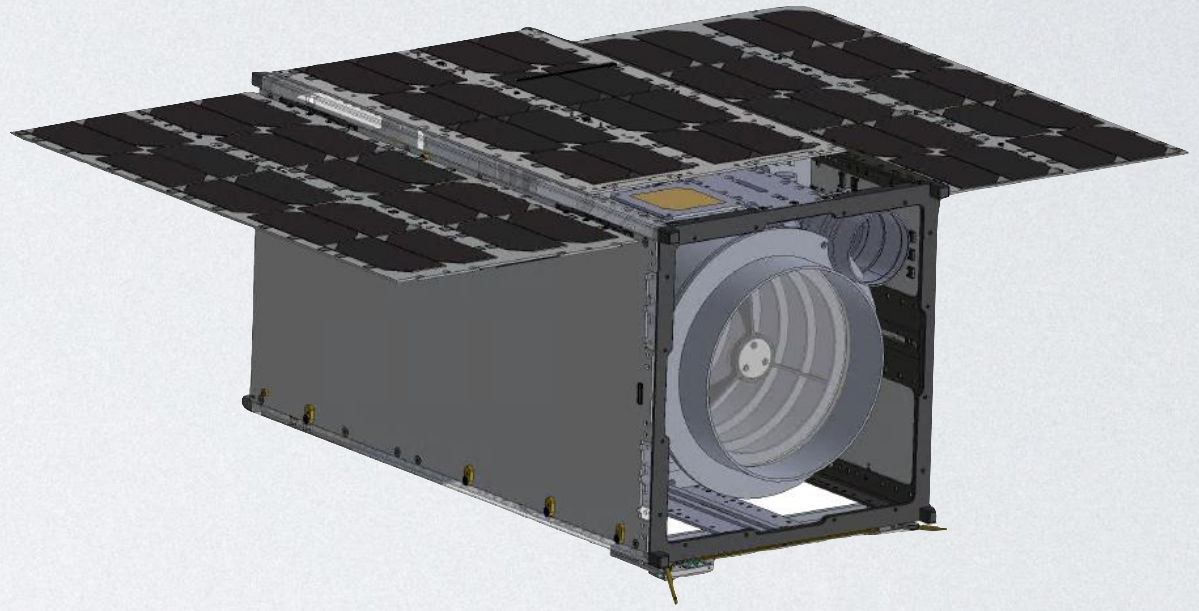


SiC Telescope

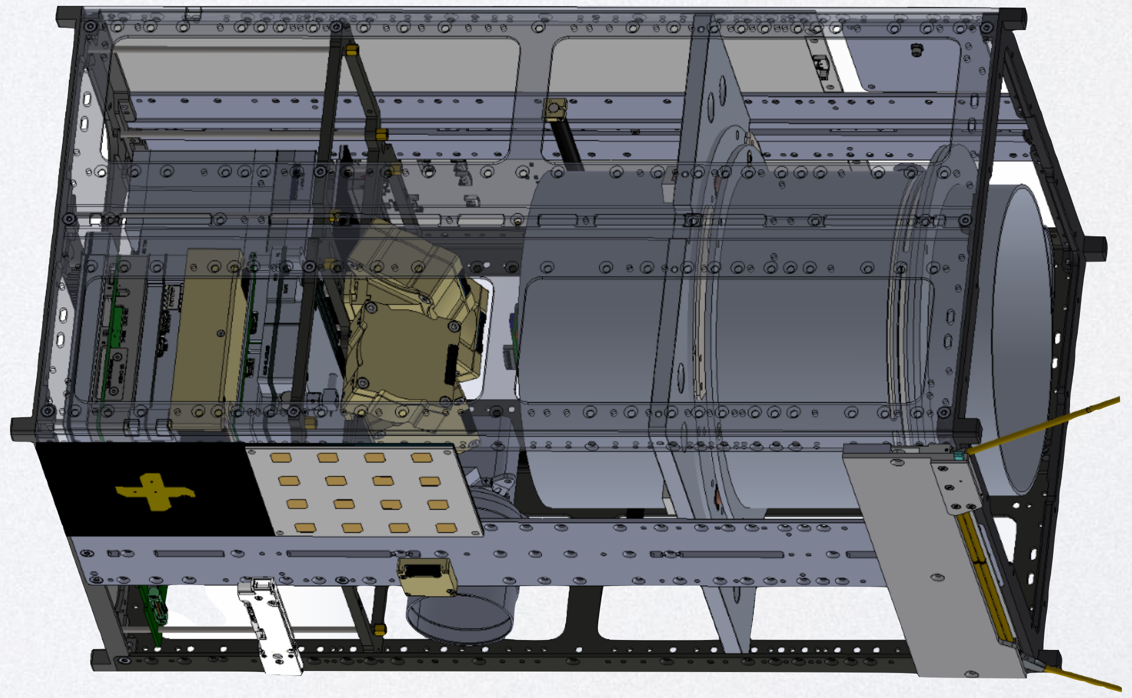
Chris Betters

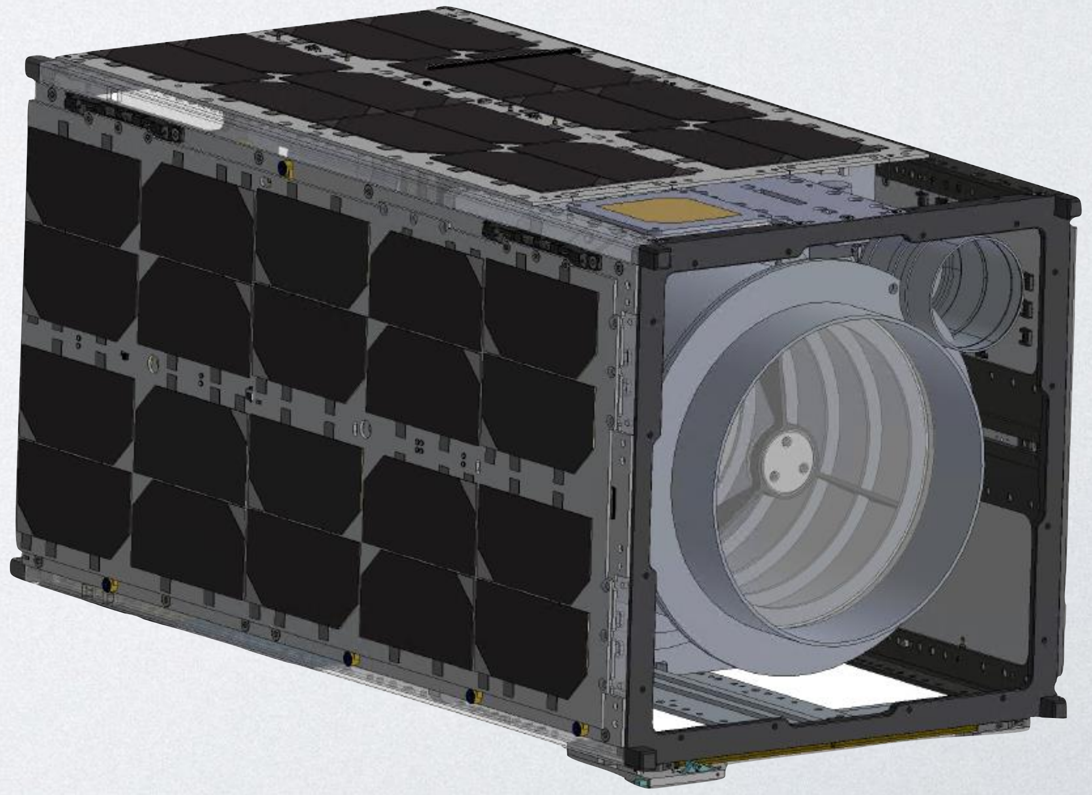
Connor Langford



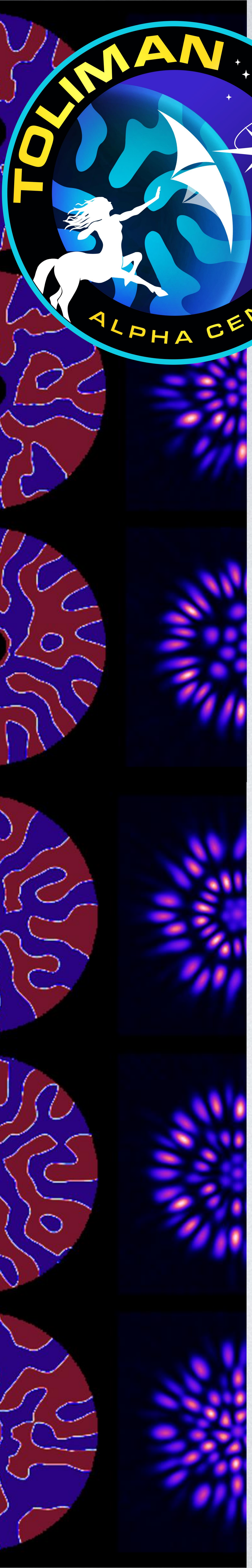


16U Spacecraft

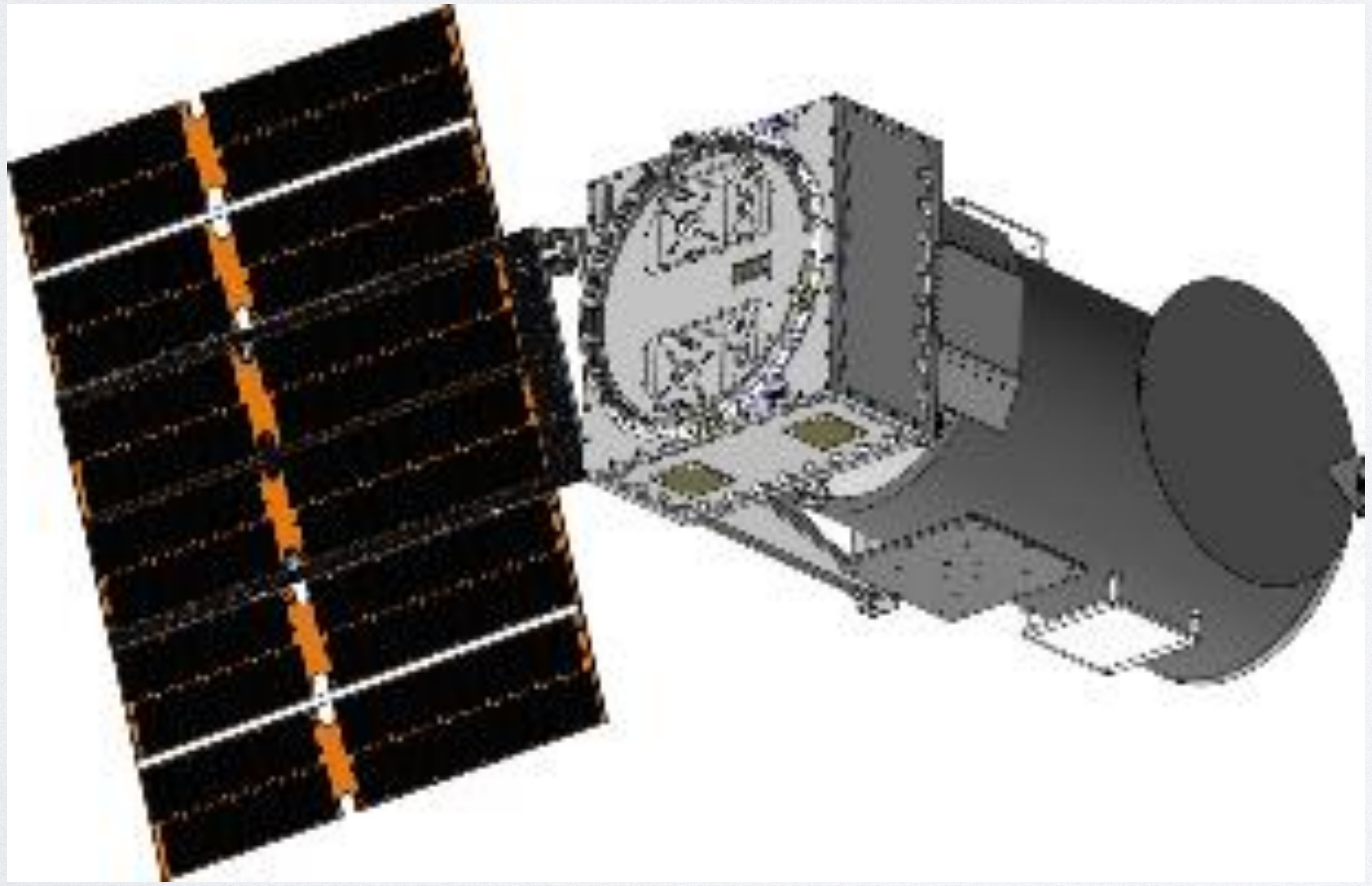




Program Genealogy: TinyTol, Toliman, Toliman+ ?



- Toliman+ ($20m – class?)
  - Aperture in the range of 30-50 cm (?)
  - About ~10 good binaries accessible (e,g, 61 Cygni, 70 Oph) for Earth Mass HZ planets
  - What about single stars? Guyon Dots-pupil?
  - Partners: Breakthrough, JAXA, IAS, NASA, ASA



SMEX ($50-90M ?)

Jet Propulsion Laboratory
California Institute of Technology

Team event, Sydney University, May 2023

TOLIMAN

TOLIMAN

ALPHA CENTAURI

SAIL
Sydney Astrophotonic Instrumentation Laboratory

The University of Sydney

The University of Queensland
Australia

UNSW Sydney

NASA
Jet Propulsion Laboratory
California Institute of Technology

BREAKTHROUGH WATCH

“And the inner fire of the Silmarils Fëanor made of the **blended light** of the Trees of Valinor..”.

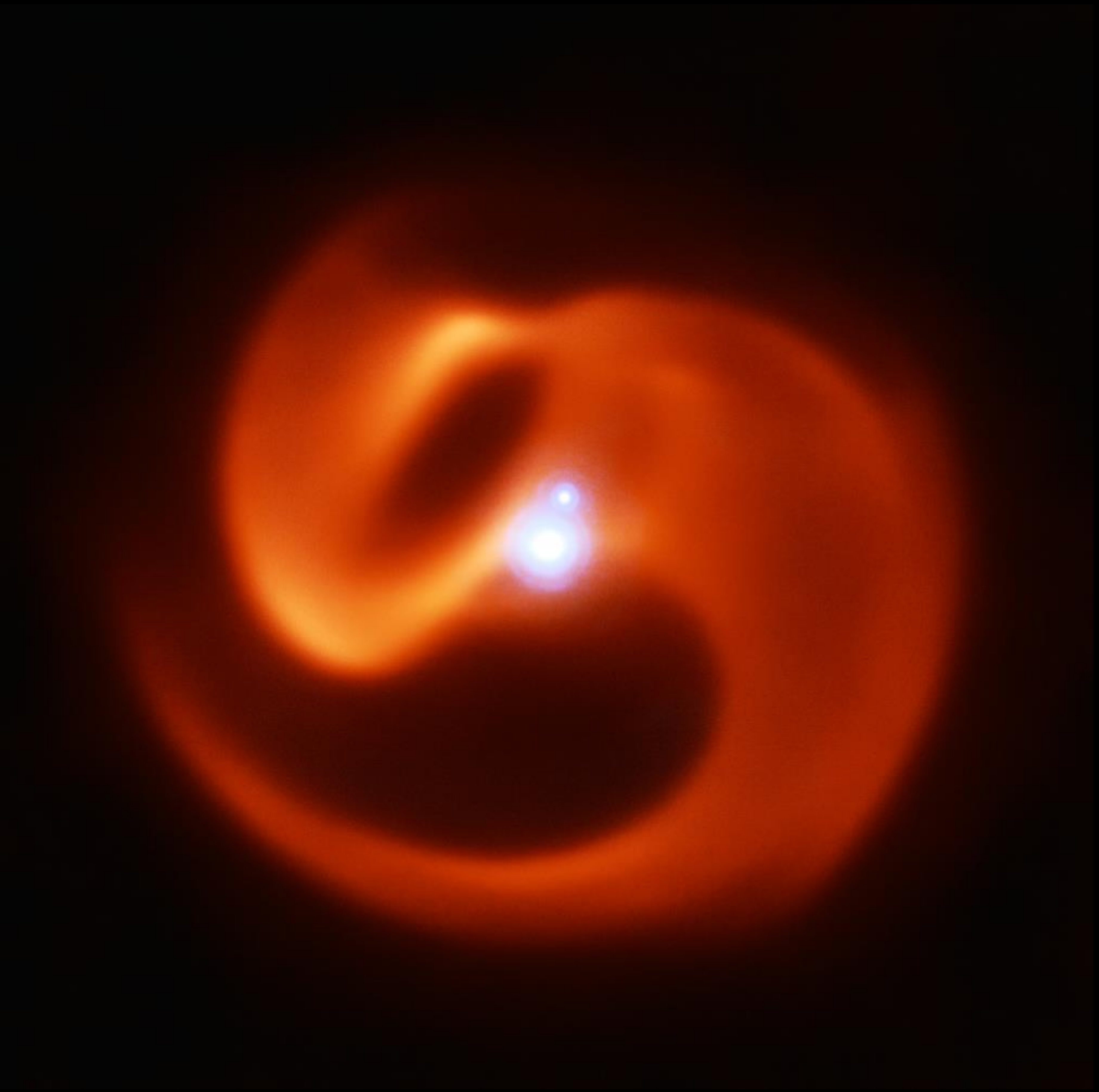
“Thus in Valinor .. their gold and silver **beams were mingled**.”

"they rejoiced in light and received it and
gave it back in hues more marvellous than before”

The Silmarillion
J.R.R. Tolkien

THANK YOU!

Prof Peter Tuthill
University of Sydney



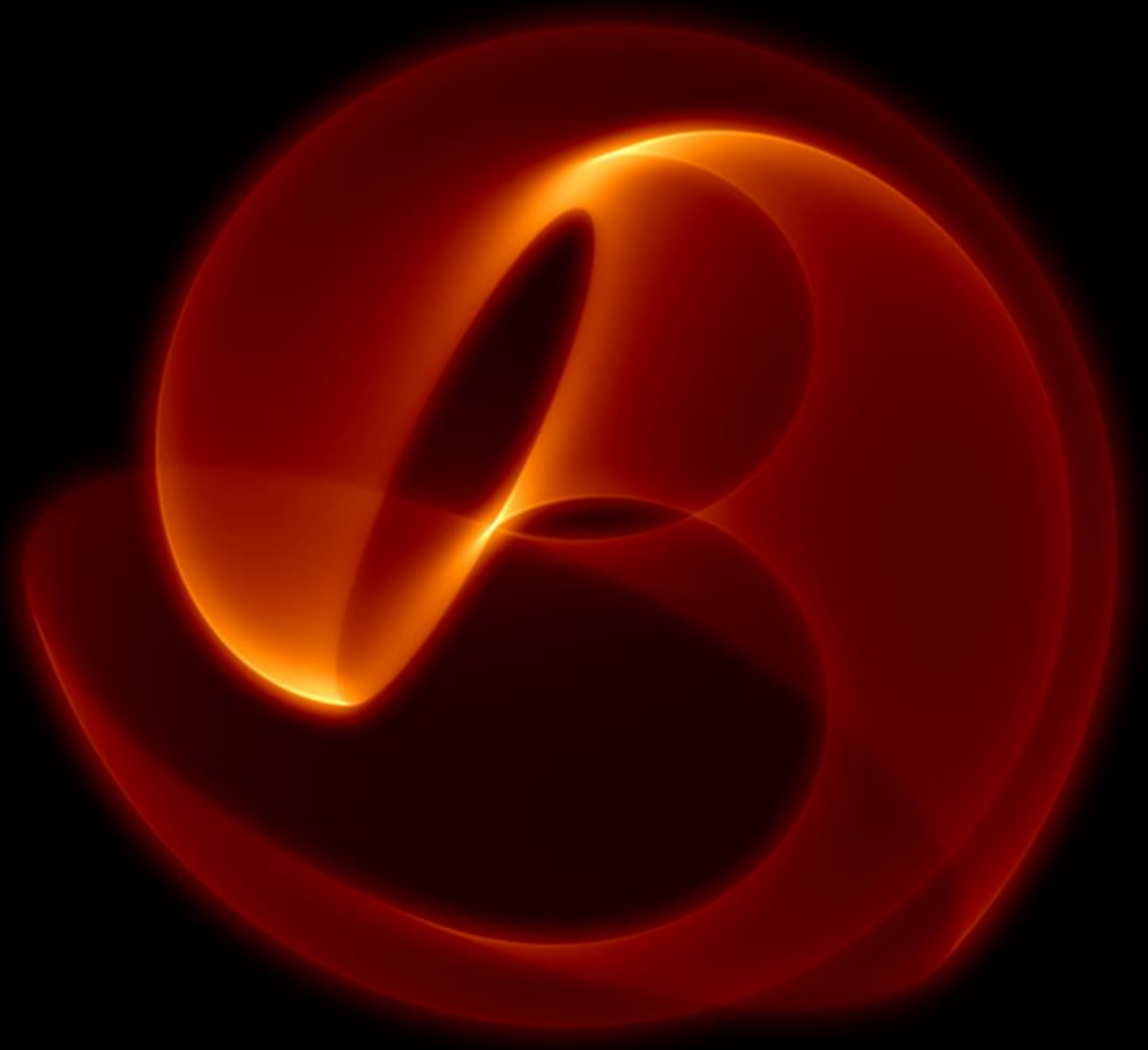
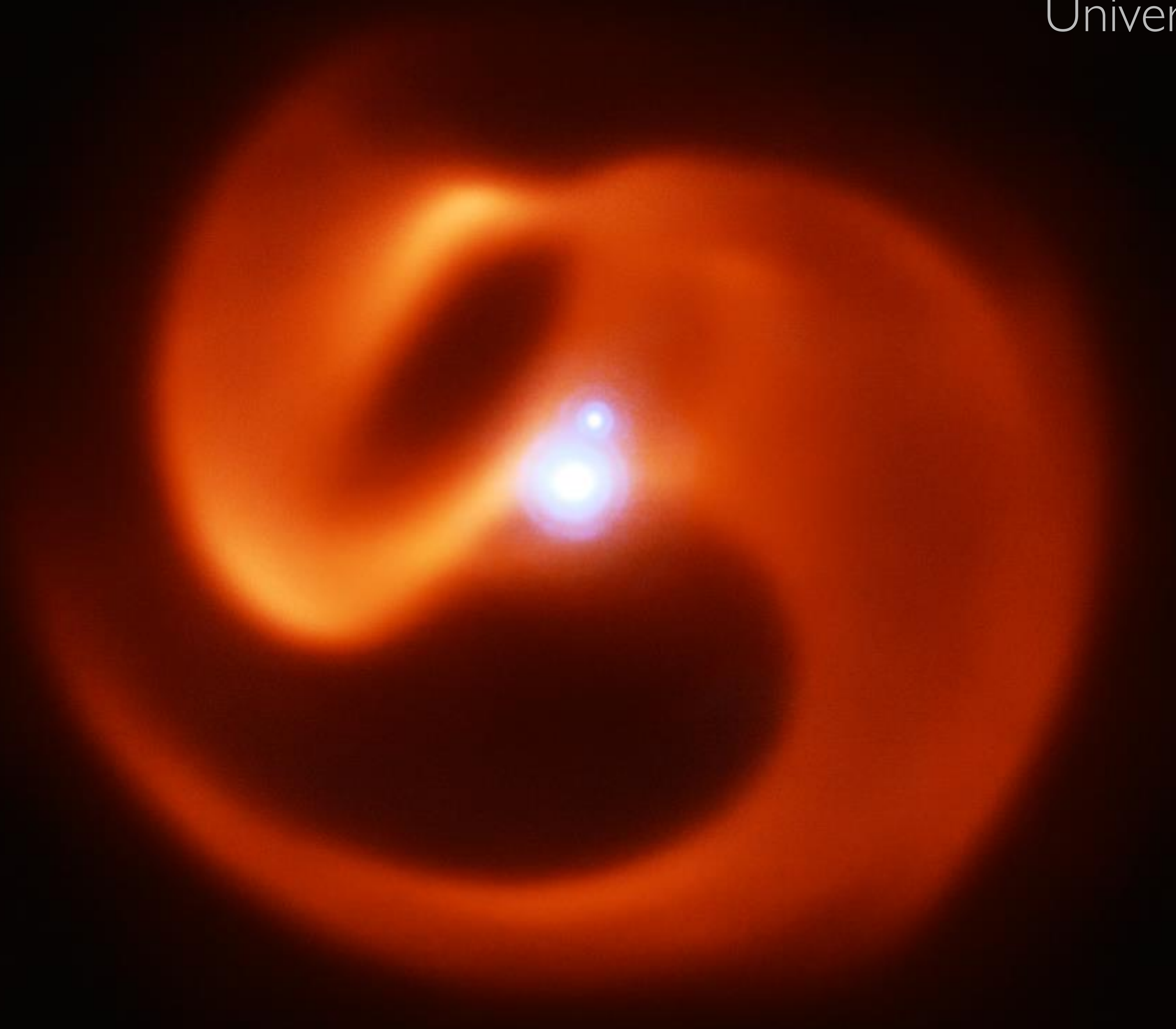


Image: Peter Tuthill / ESO

The quest for coherence: astrophysical imaging from interferometry to photonics

Prof Peter Tuthill
University of Sydney



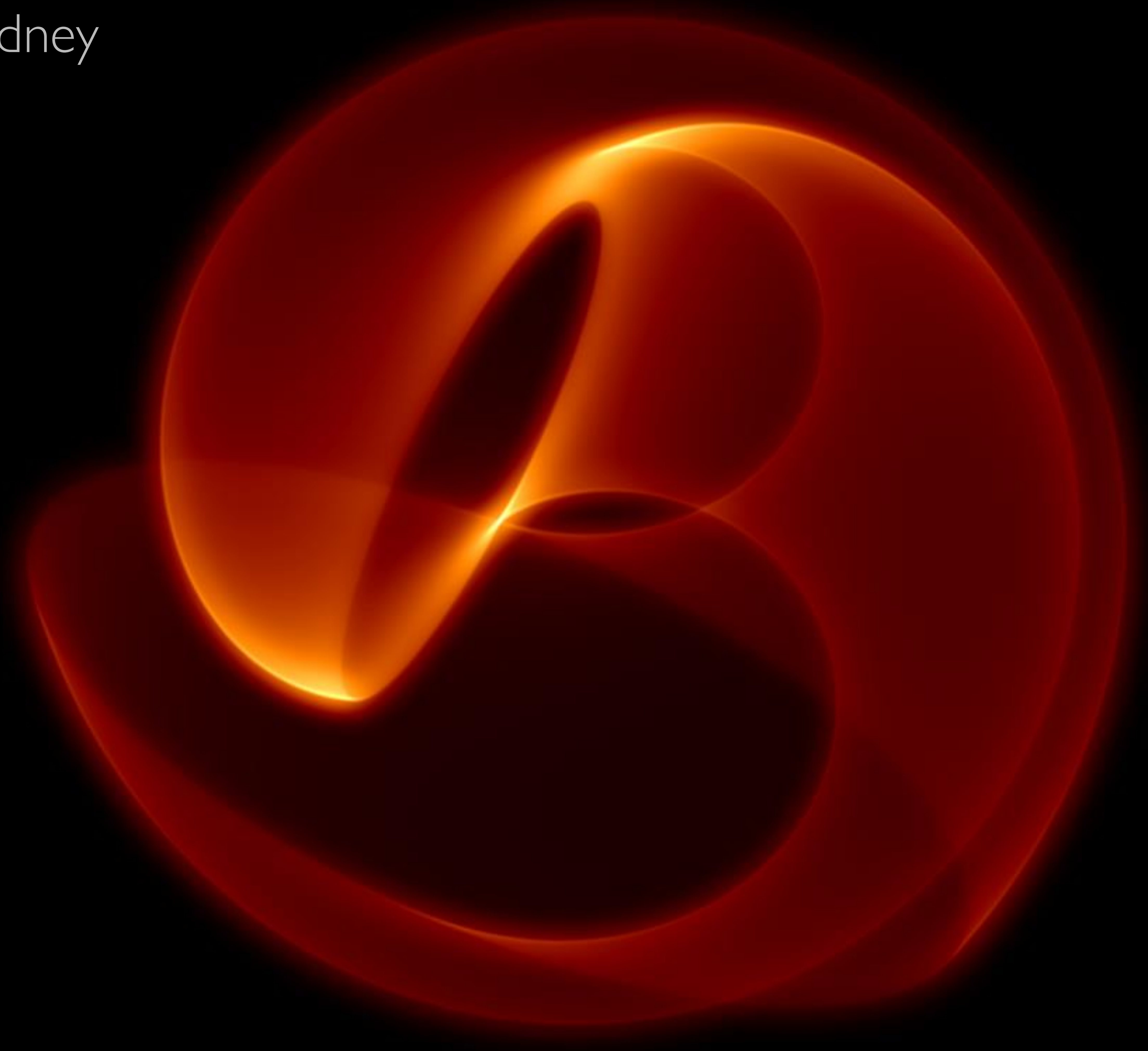


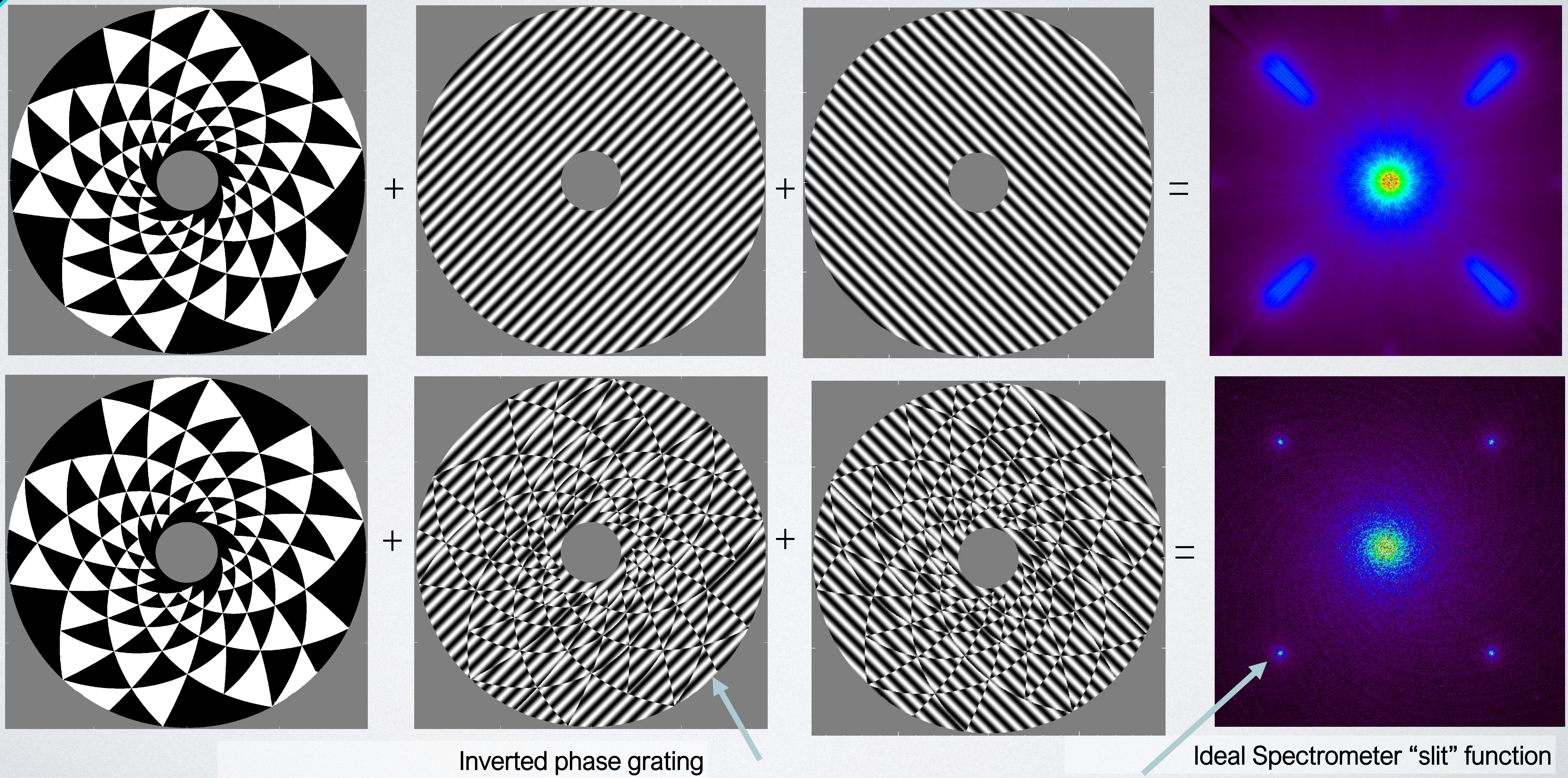
Image: Peter Tuthill / ESO

The quest for coherence:
astrophysical imaging from interferometry to photonics

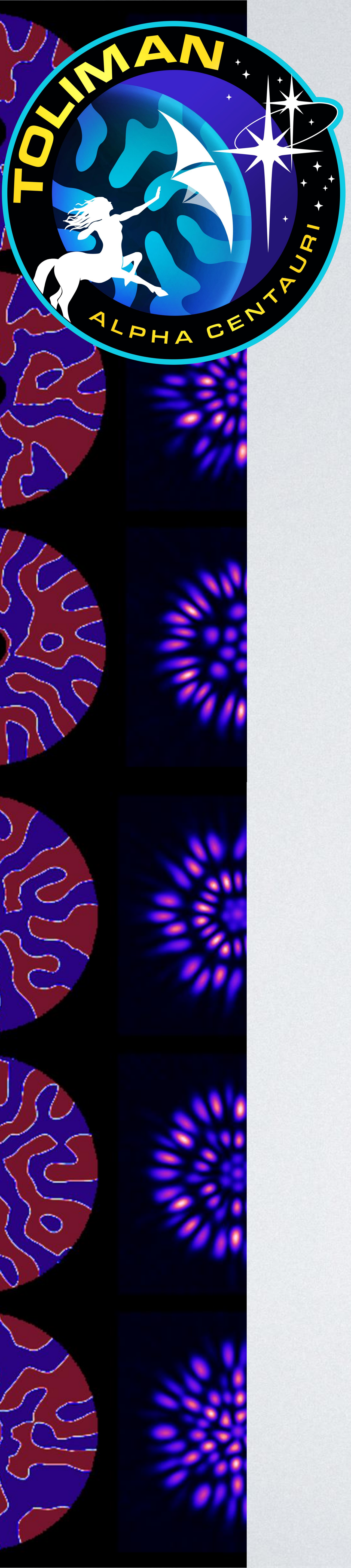
Prof Peter Tuthill
University of Sydney

The Red Square
Peter Tuthill / Palomar
and Keck Observatories

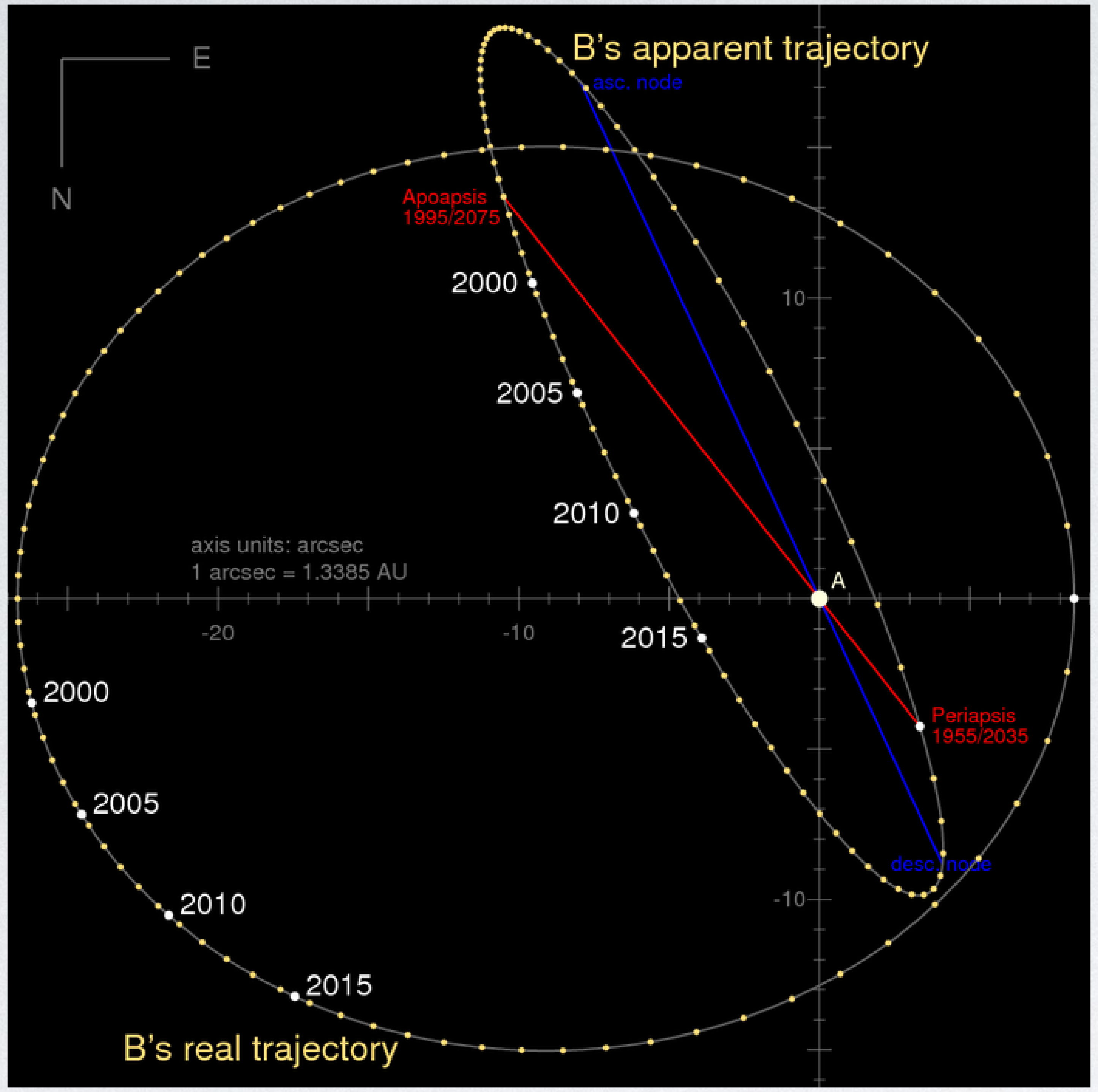
Nailing down the wavelength: adding a spectrometer
(… and Jedi Fourier mind tricks)




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
200 mas
Red Rectangle
VY CMa
LkHa 101
V Hya
N
E
2.20 μm (K$_S$)

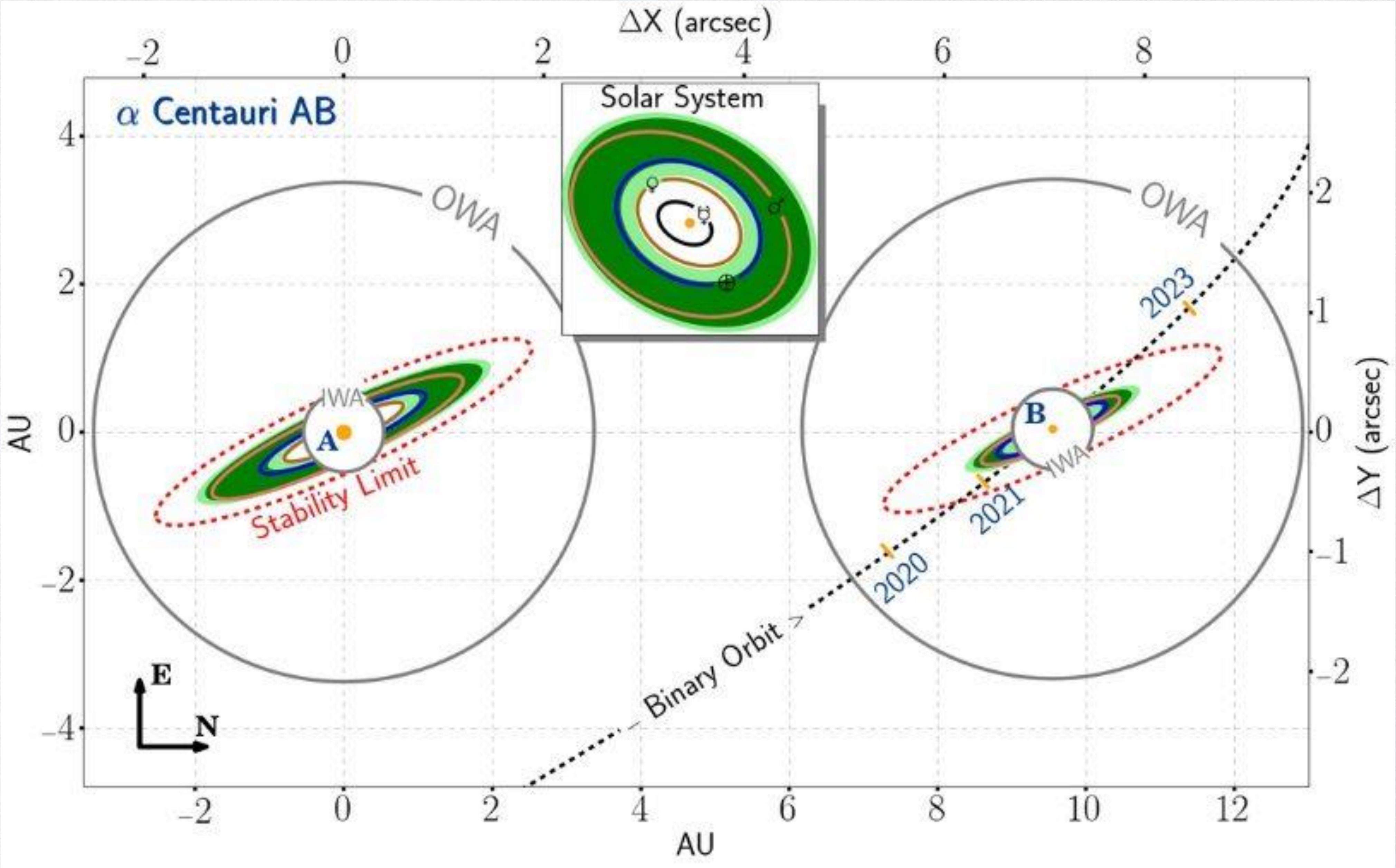


Alpha Cen AB (= Rigel Kent + Toliman)

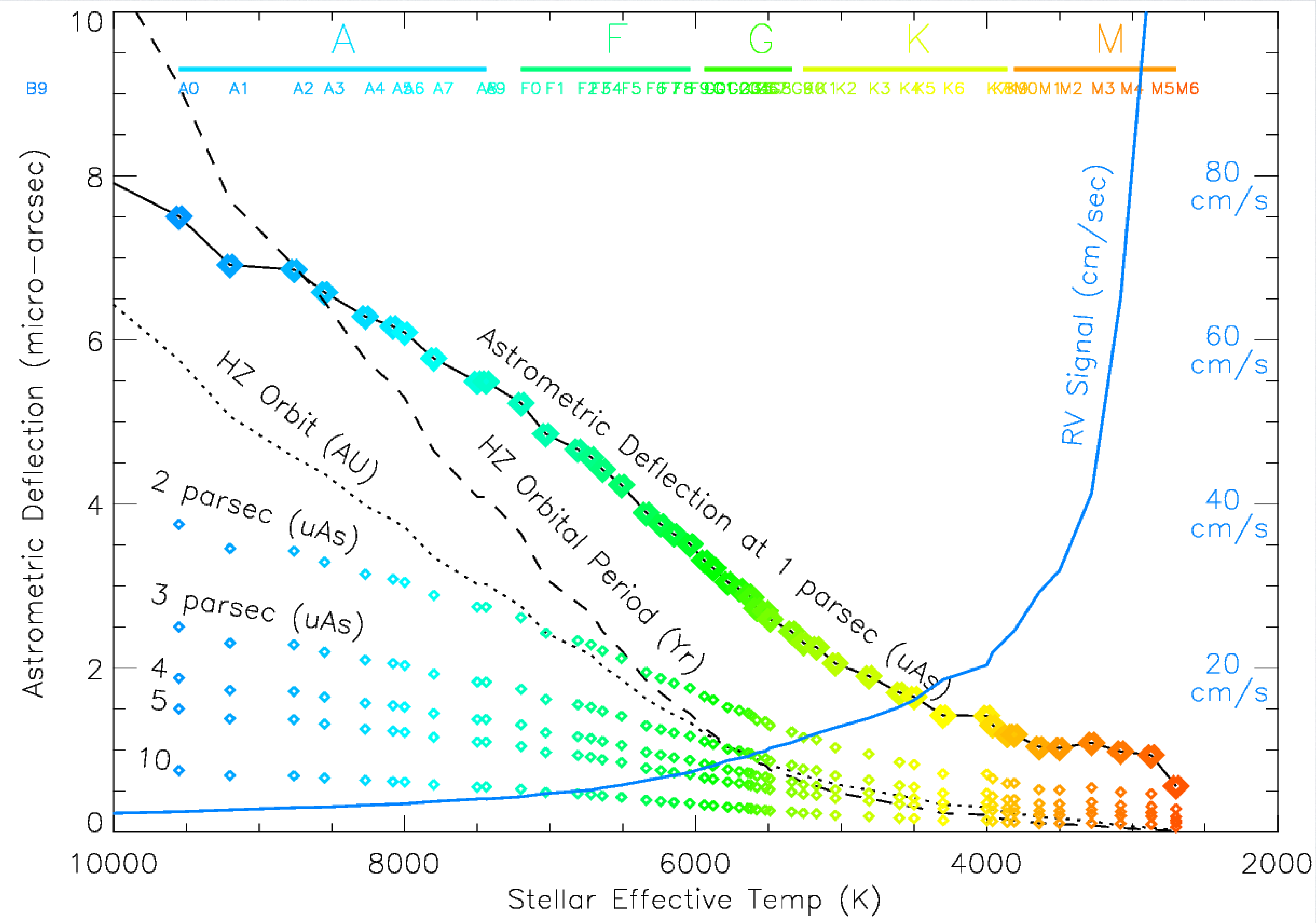


- Componets A, B (+ distant Proxima)
- Bright: 0 Mag + 1.3 Mag
- Nearest sun-like stars (more than factor 2!)
- Apparent 4" close approach: RV problematic
- 1 Earth Mass – 2.4 μAs for A; 1.2 μAs for B
- With .3m area needs ~hours of integration (compared to ~months for 12th mag ref star)
- Binary is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

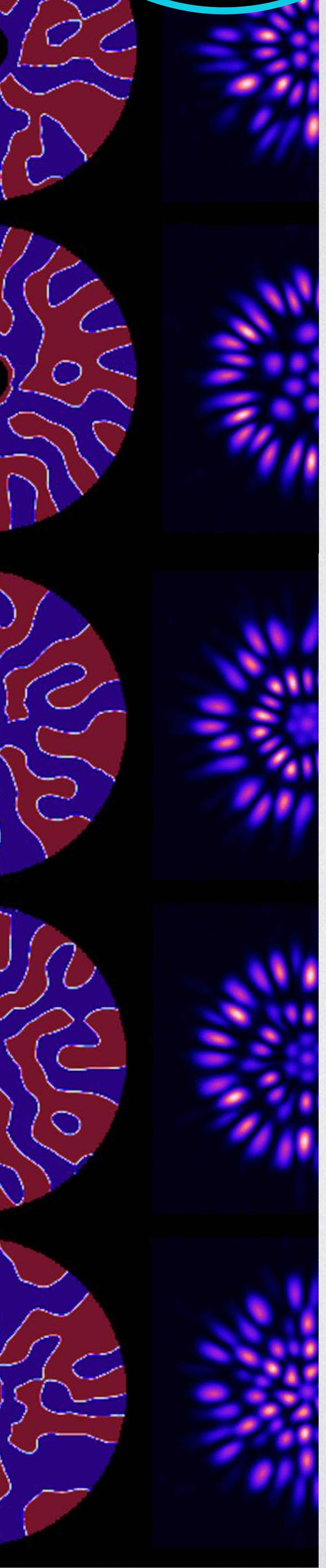
Habitable zones of Alpha Cen A (left) and B (right) in green, along with dynamical stability boundary (red dashed line)



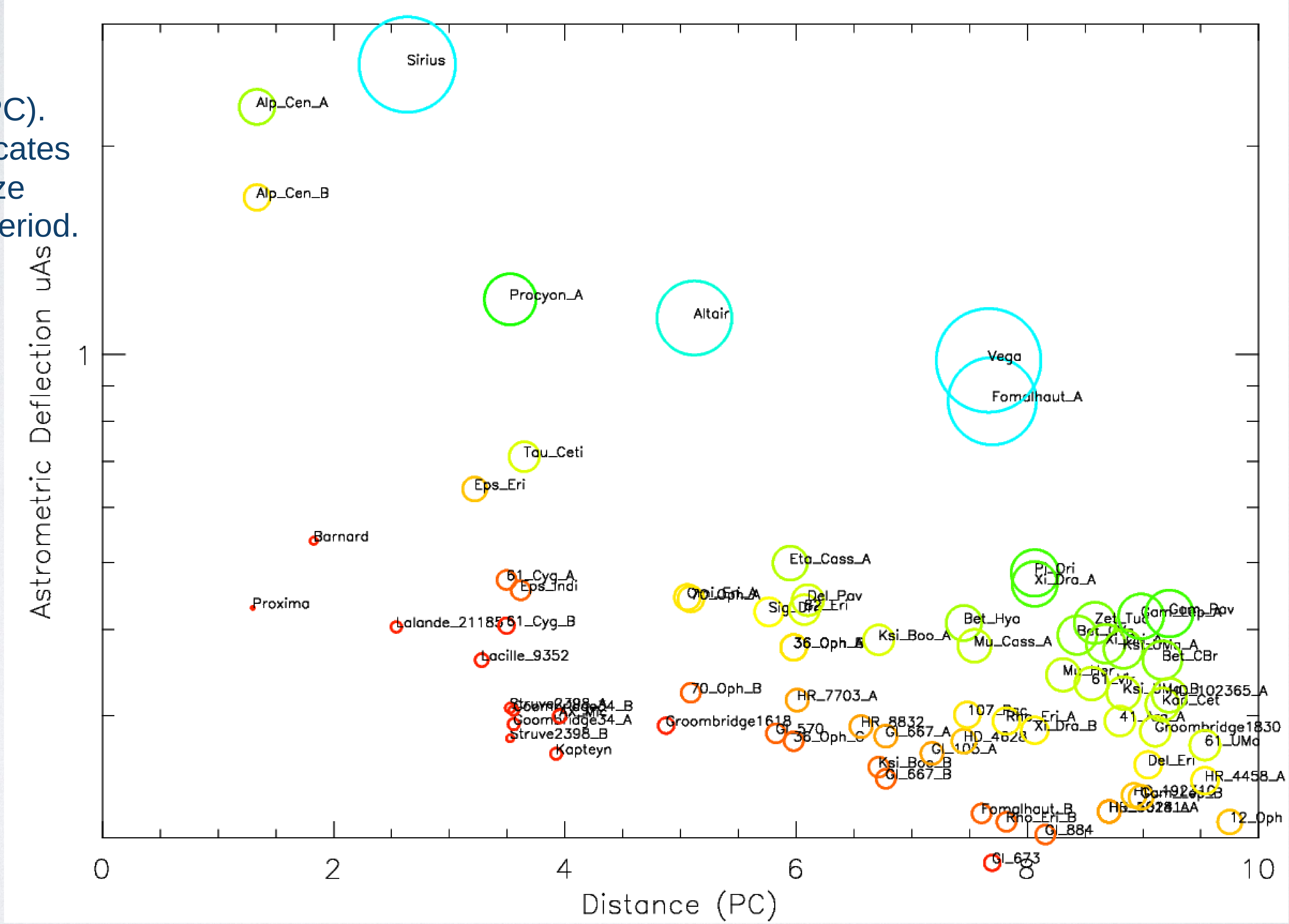
Astrometric signal of a 1 M_earth planet in the HZ assuming 1PC distant from star of given Sp. type.



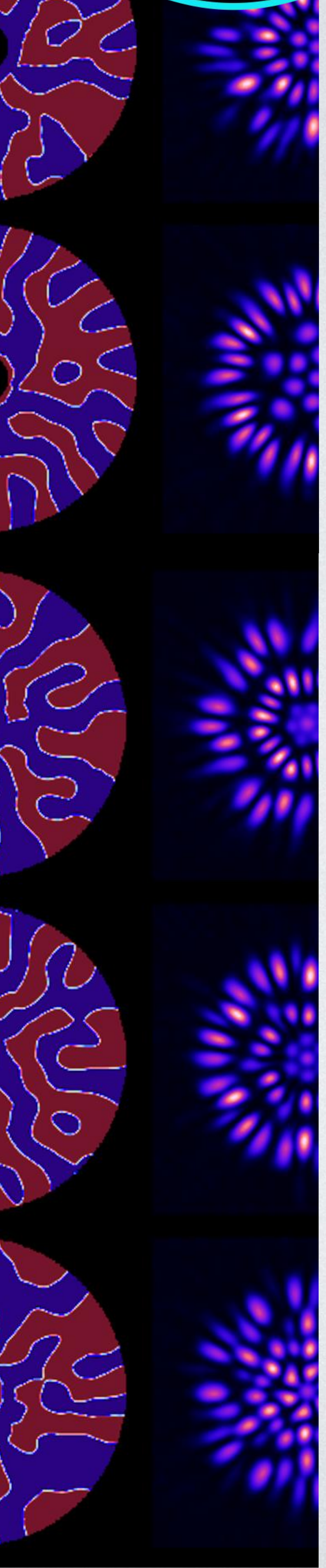
Astrometric signal for HZ Earth mass for all FGK stars to 10PC

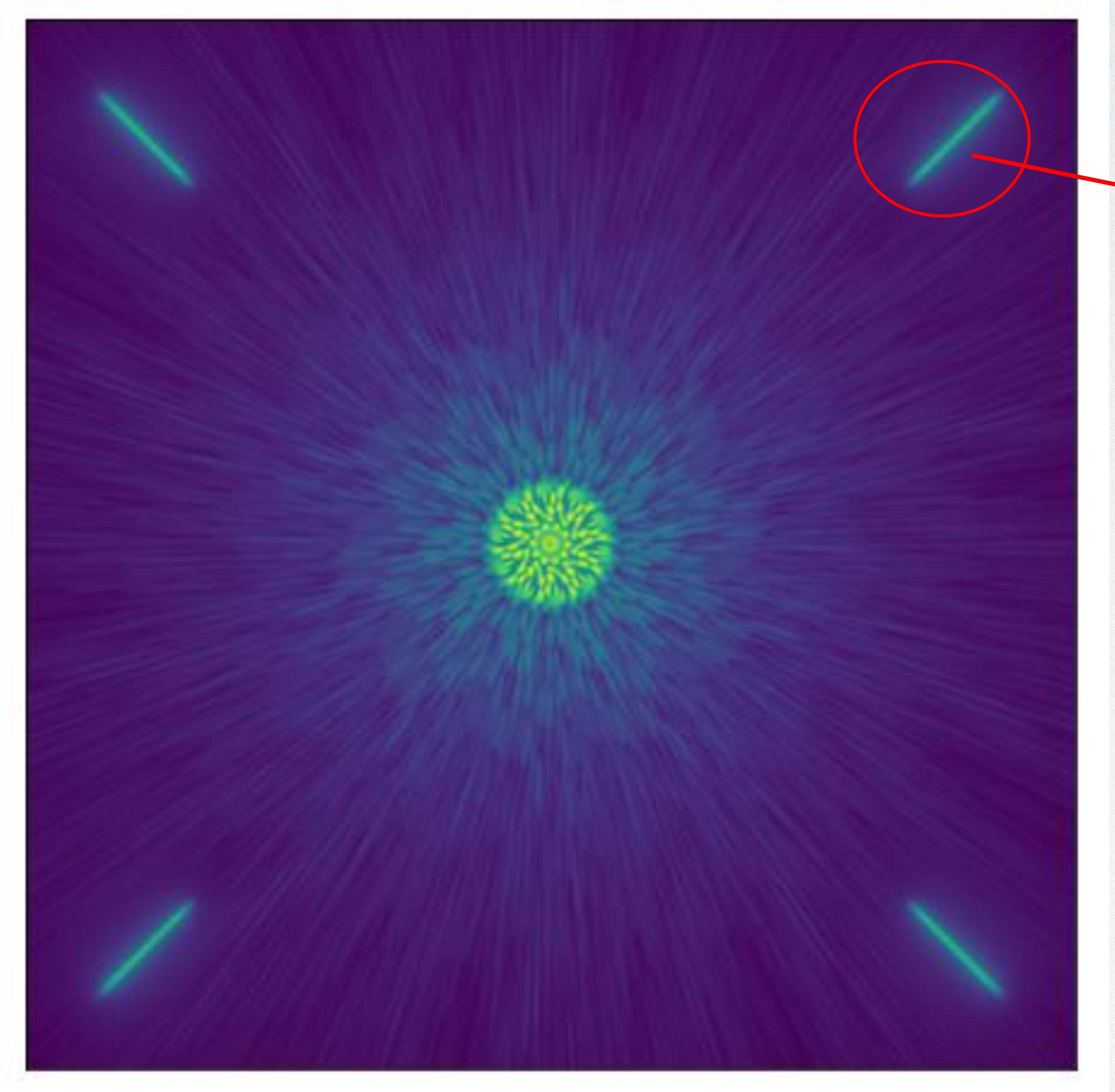


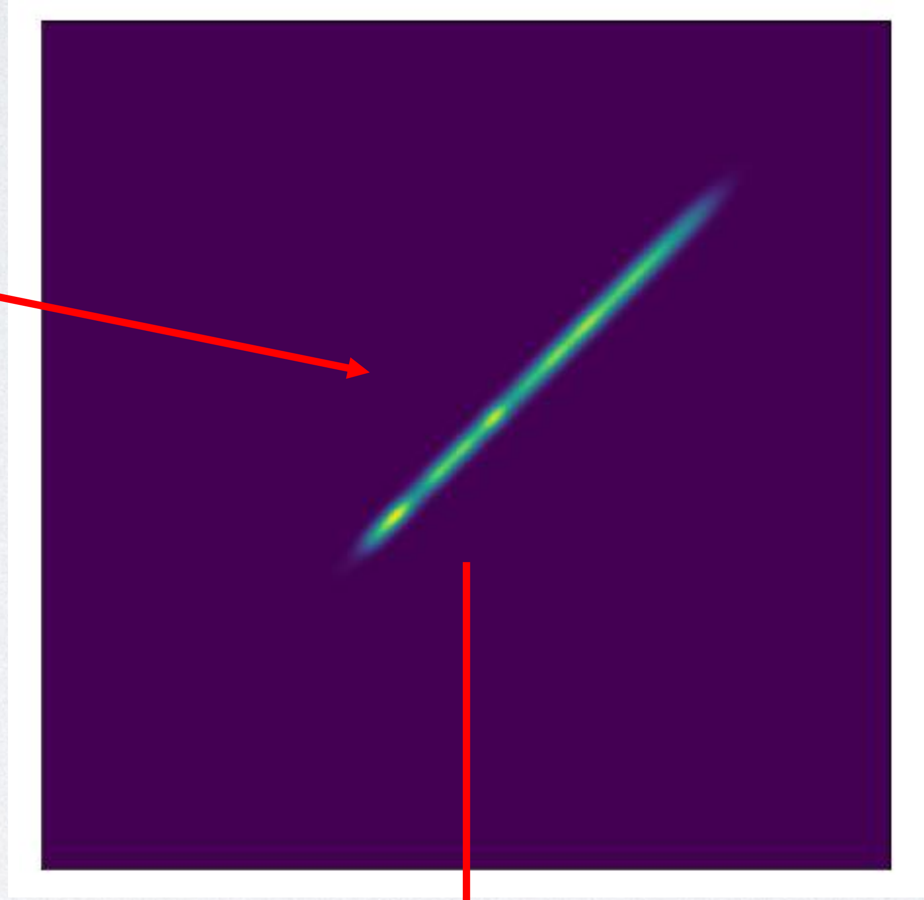
Also M stars (<5PC). Symbol color indicates host spectrum, size indicates orbital period.

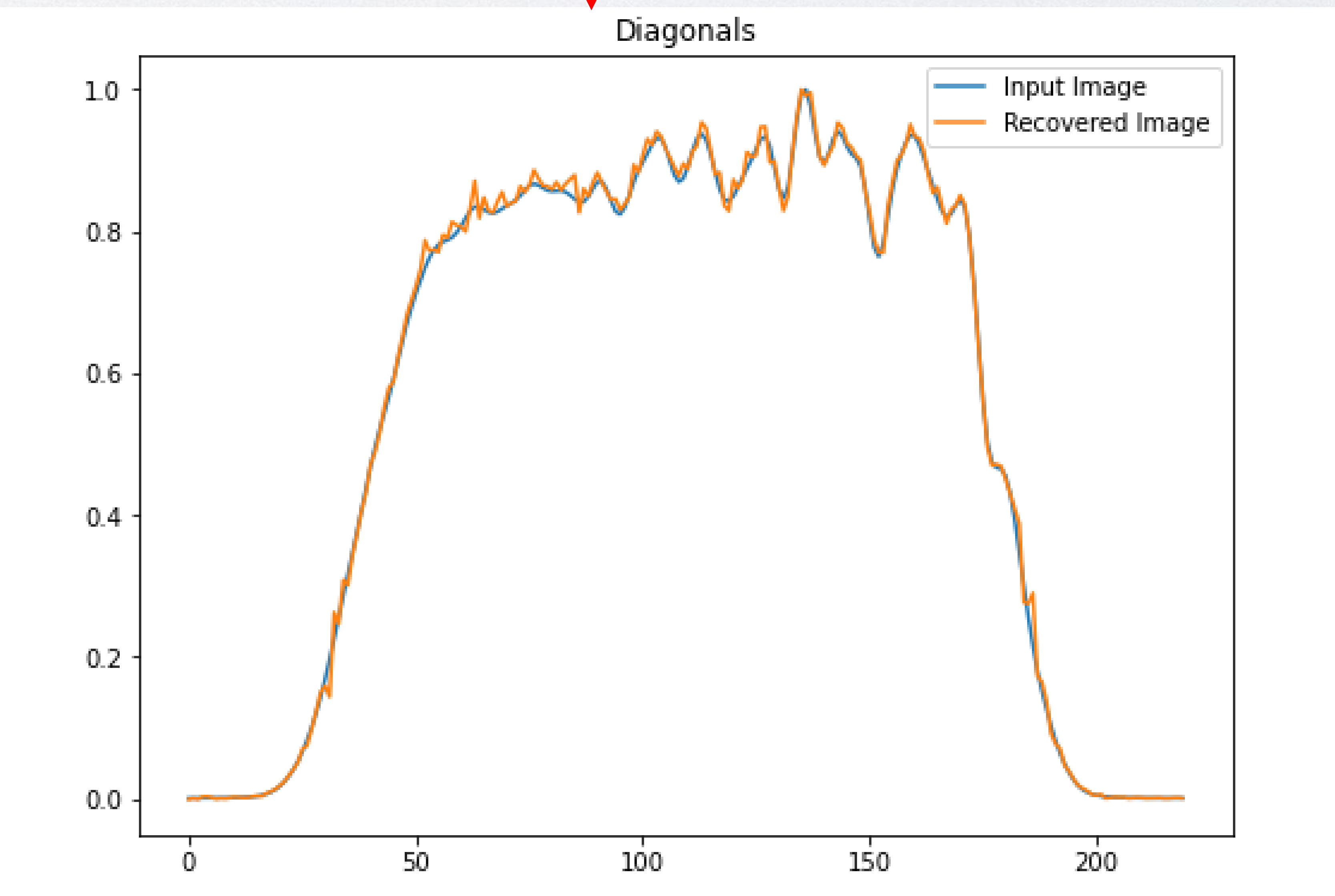


IN-BUILT SPECTROMETER









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BSc Hons Physics
2022