Partner institutes:

SAM: A promising AMi (friend) for the James Webb Space Telescope

Lagrange seminar - January, 24th 2023

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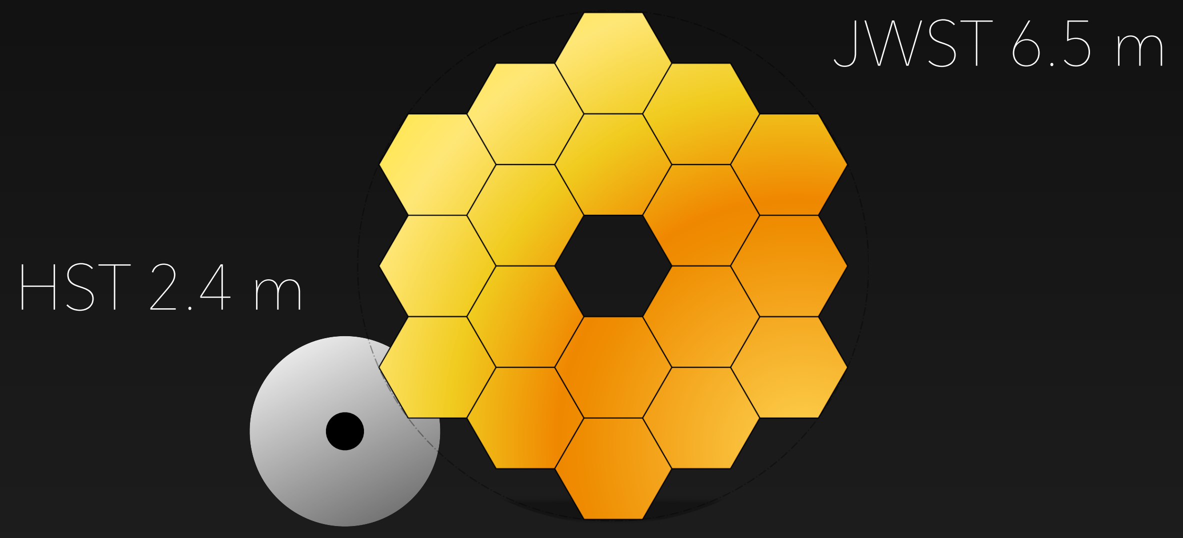
Collaborators: P. Tuthill, A. Sivaramakrishnan, L. Albert, D. Thatte, T. Vandal, among others

An important new challenger: JWST

Largest telescope ever operating in space

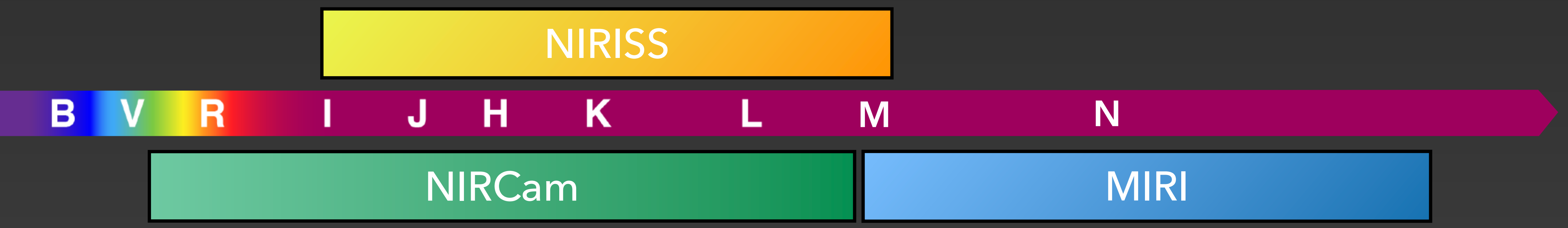


Most expensive NASA/ESA mission

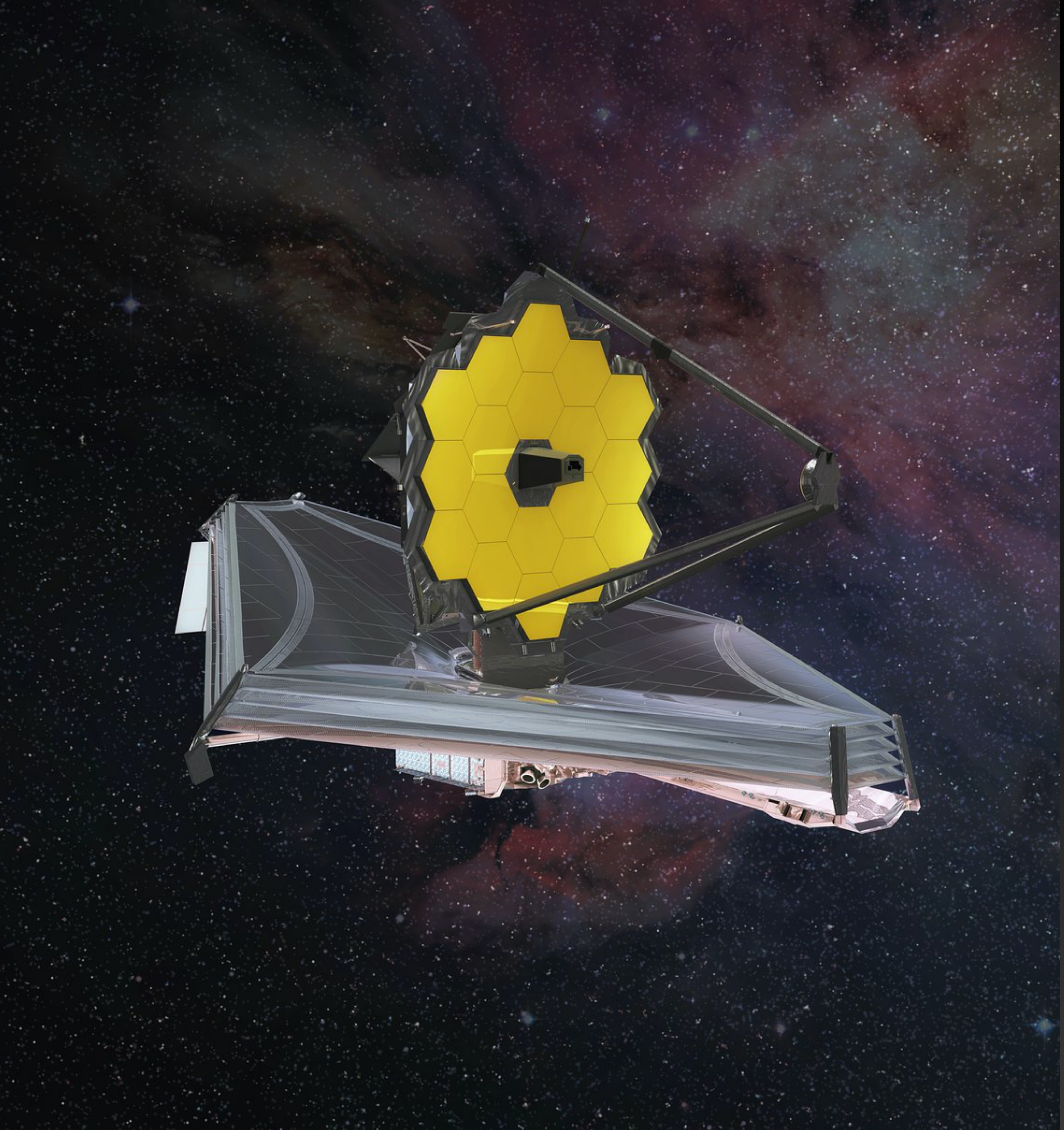
10+ Billion dollars

Large wavelength domain

0.6 to 28.5 μm

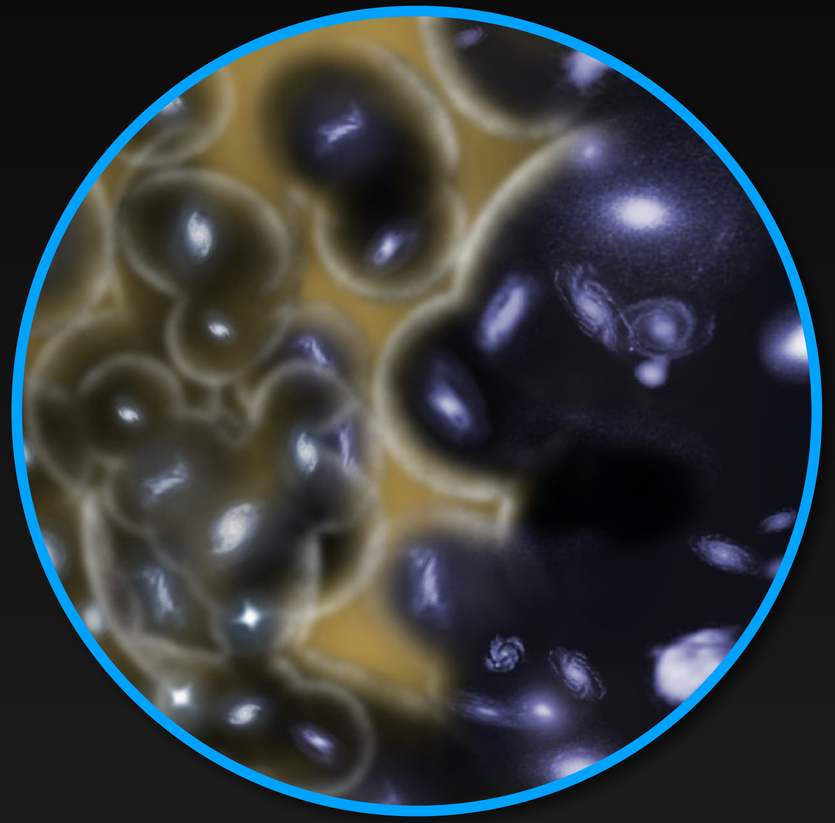


Credit: NASA

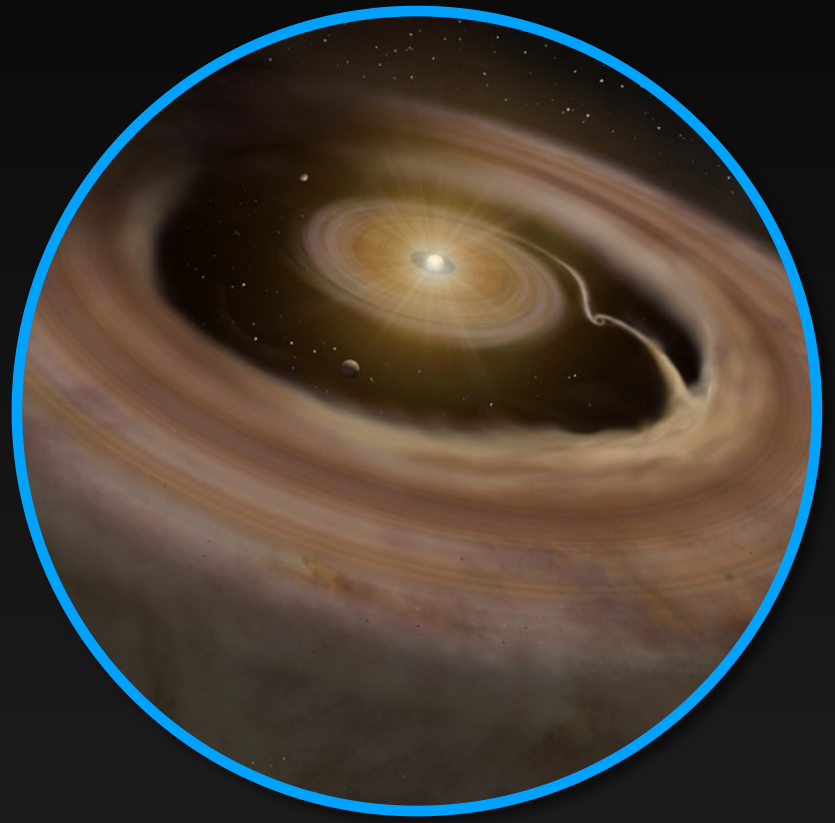


Credit: NASA

Webb Telescope science themes



First light & reionisation



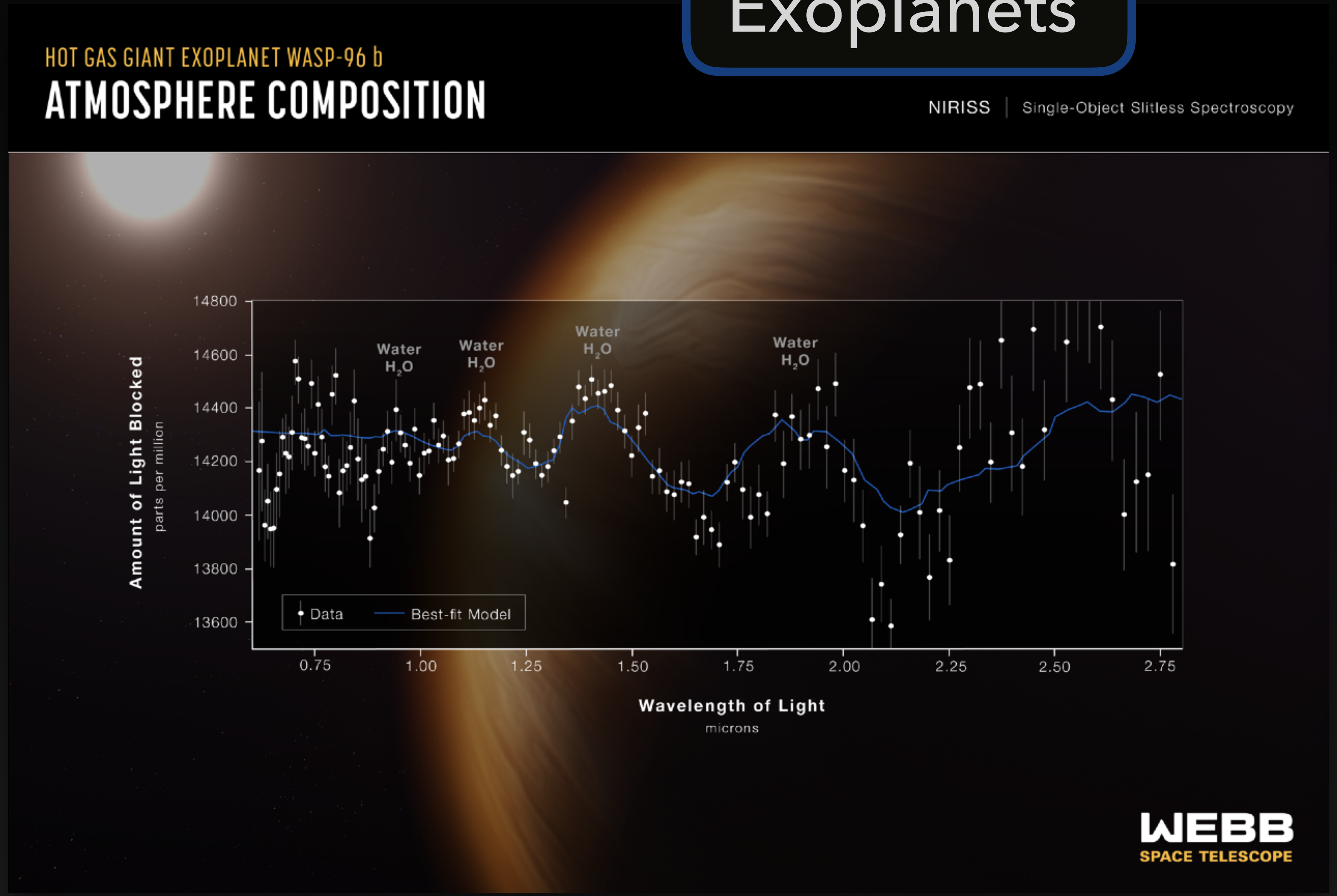
Stars & planets births

Assembly of galaxies

Planets & origins of life

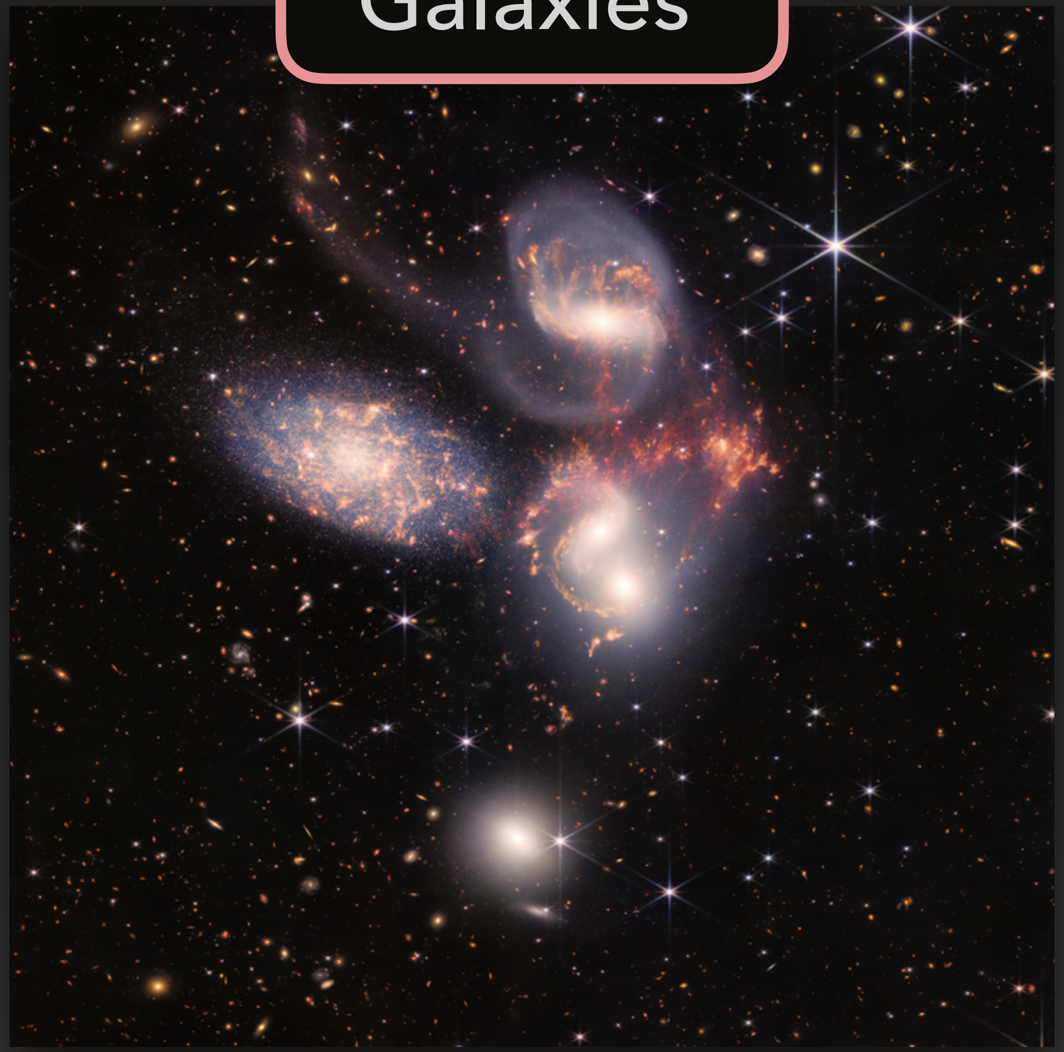
Few months of discoveries and astonishing images

Exoplanets

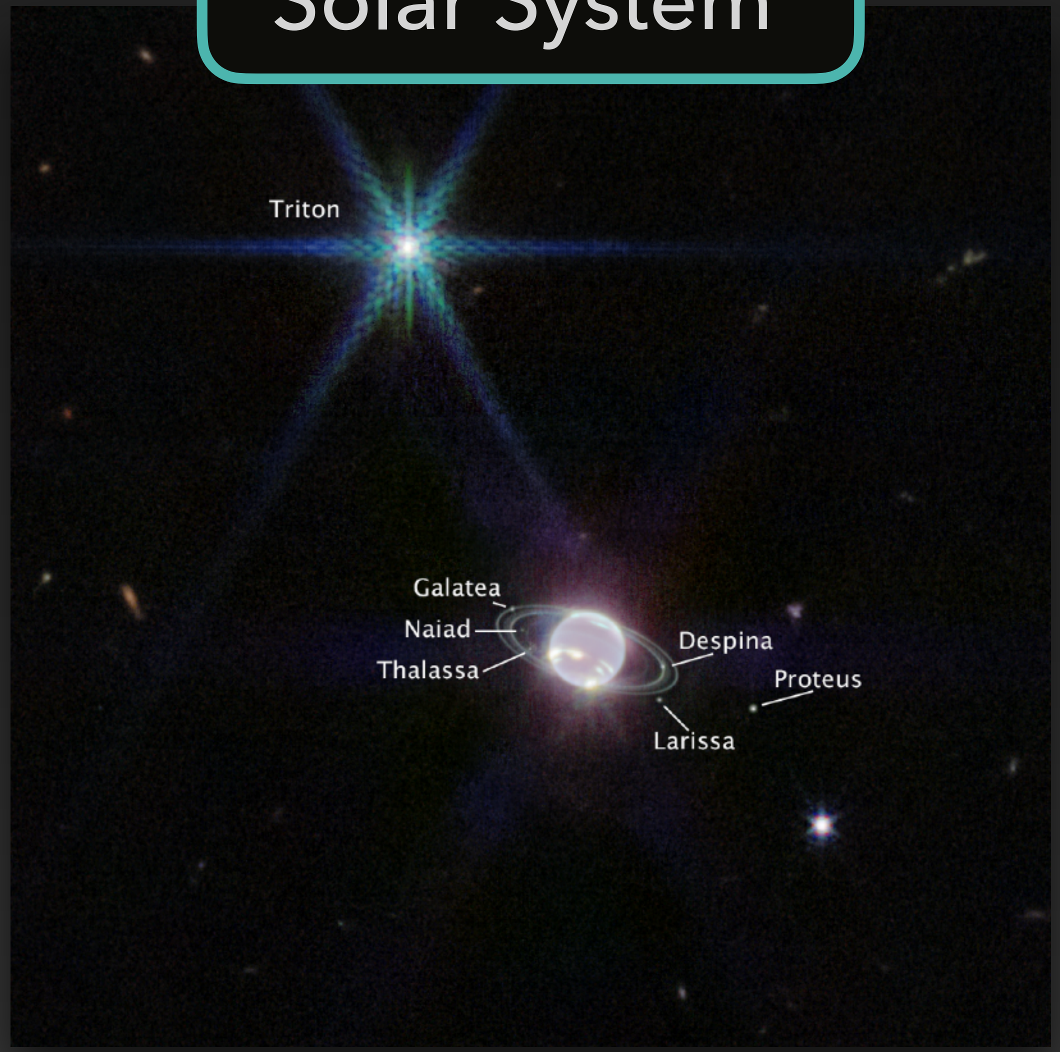


Evolved massive stars

Galaxies



Solar System

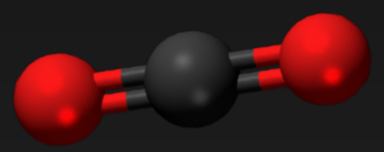


Planetary Nebula

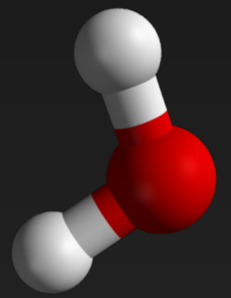
Credit: NASA

Near Infrared Imager and Slitless Spectrograph (NIRISS)

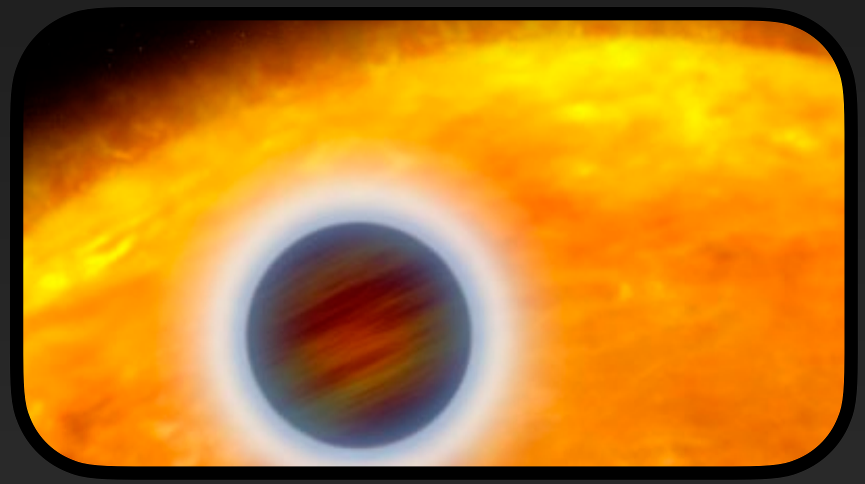
- Canadian contribution to the JWST (PI: R. Doyon, Montréal)
- 1 of the 4 instruments on board



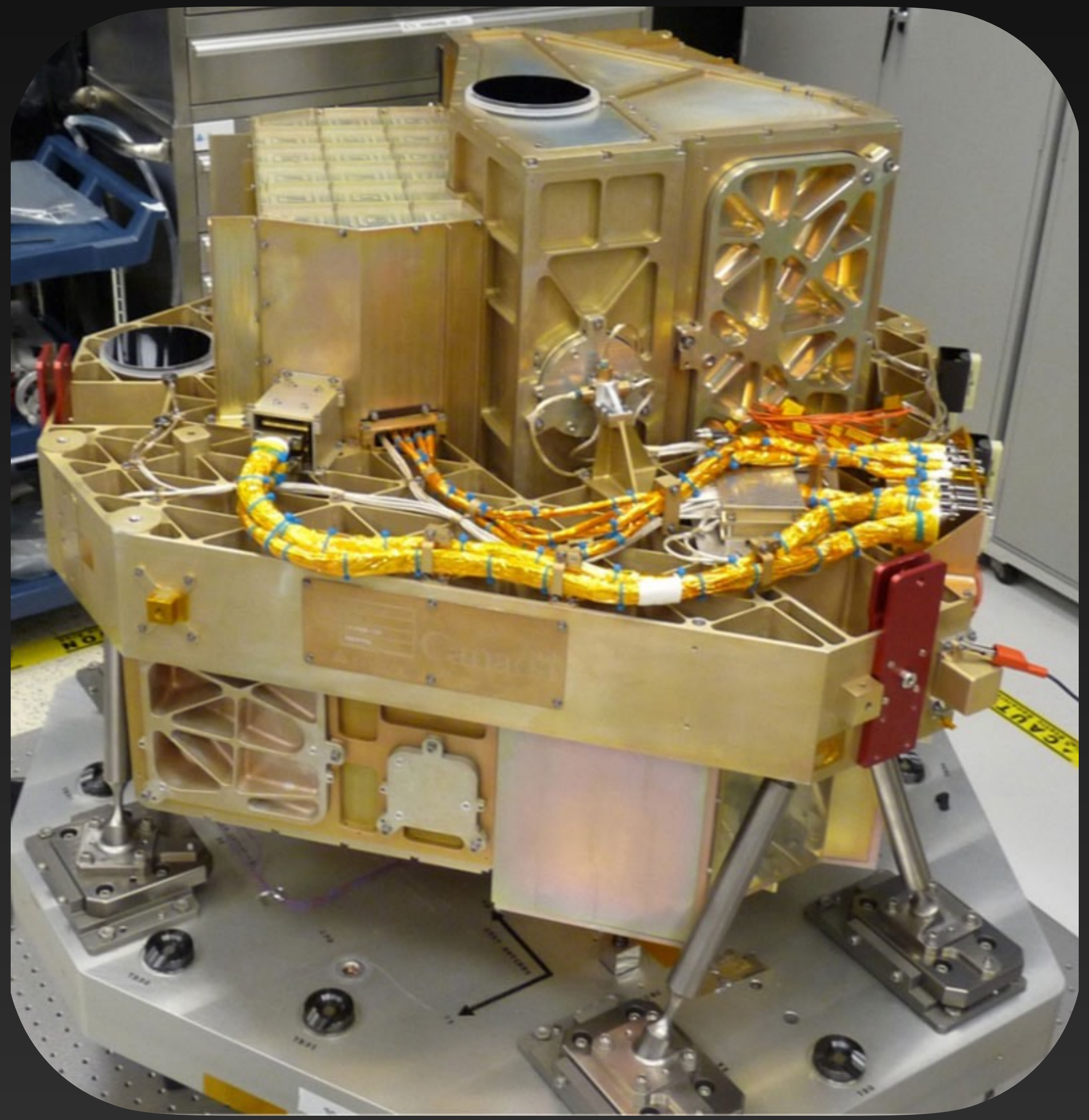
- Operates from 0.6 to 5 µm: CO^2, CO and water signatures



- Focused on exoplanet atmospheres



- 3 modes : imaging, spectroscopy and **Aperture Masking Interferometry** or AMI (friend in French 😉)



Fine Guidance Sensor (FGS) and NIRISS combined instruments (credit: COM DEV Canada)

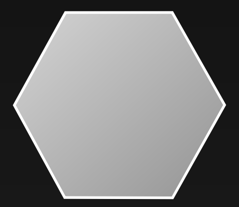
The first interferometer ever placed in space*

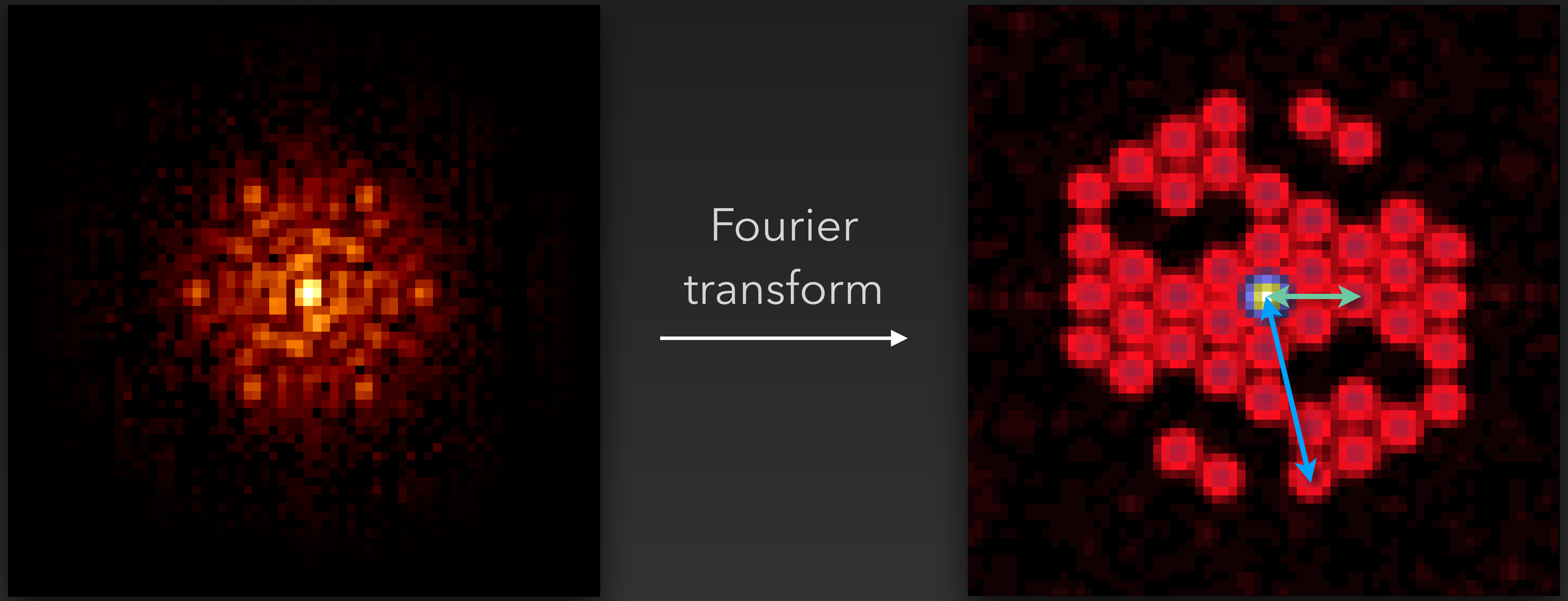
Probe inside the Rayleigh criterion

(Not completely true: for the use of scientific purposes only, HST was equipped with an interferometer-like mode for calibration processes)

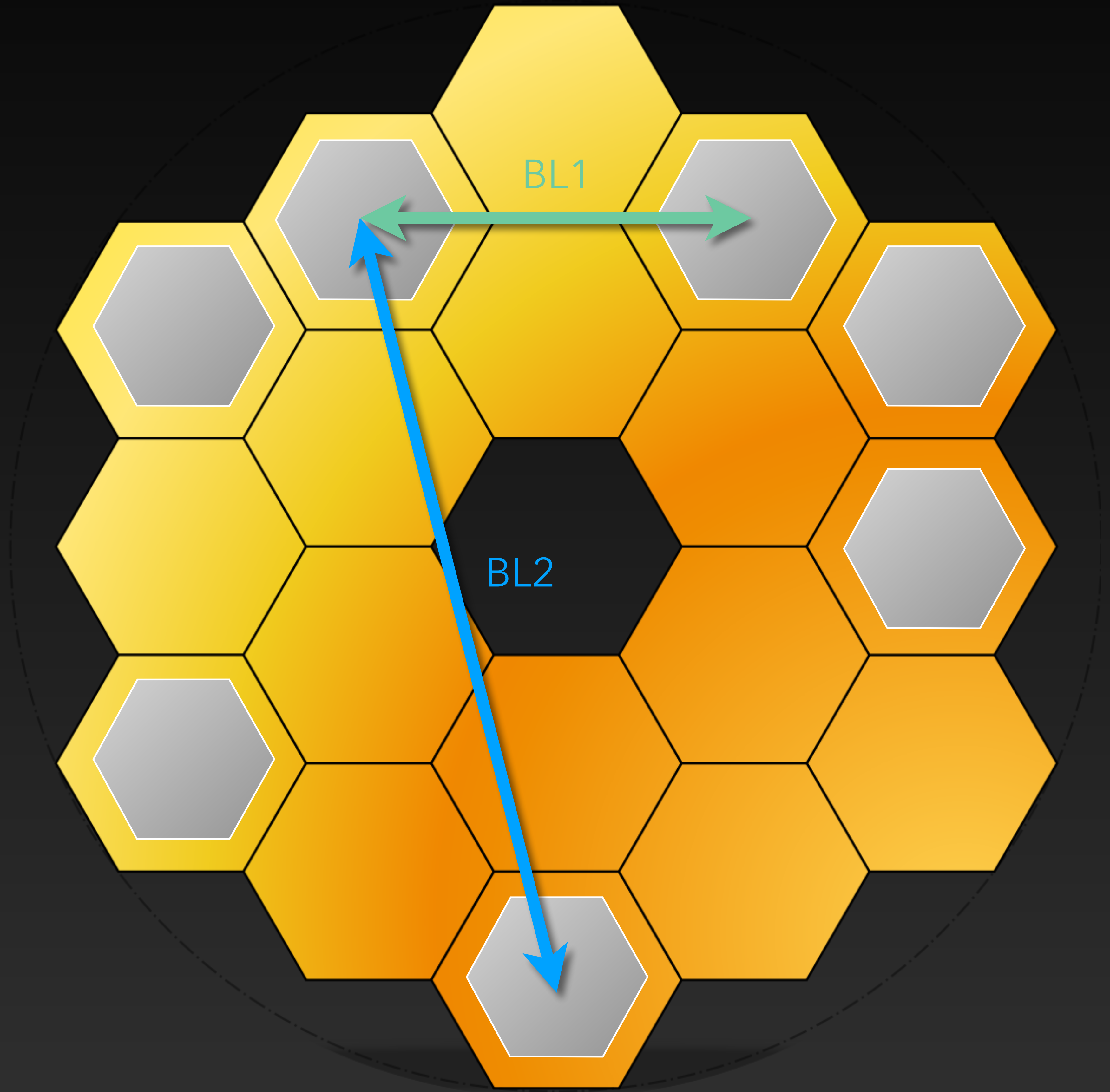
**thanks Anand*

Aperture Masking Interferometry - NIRISS

- Turn the telescope to an interferometric array
- Collect light only from sub-apertures 
- Each aperture interferes to create a fringe pattern



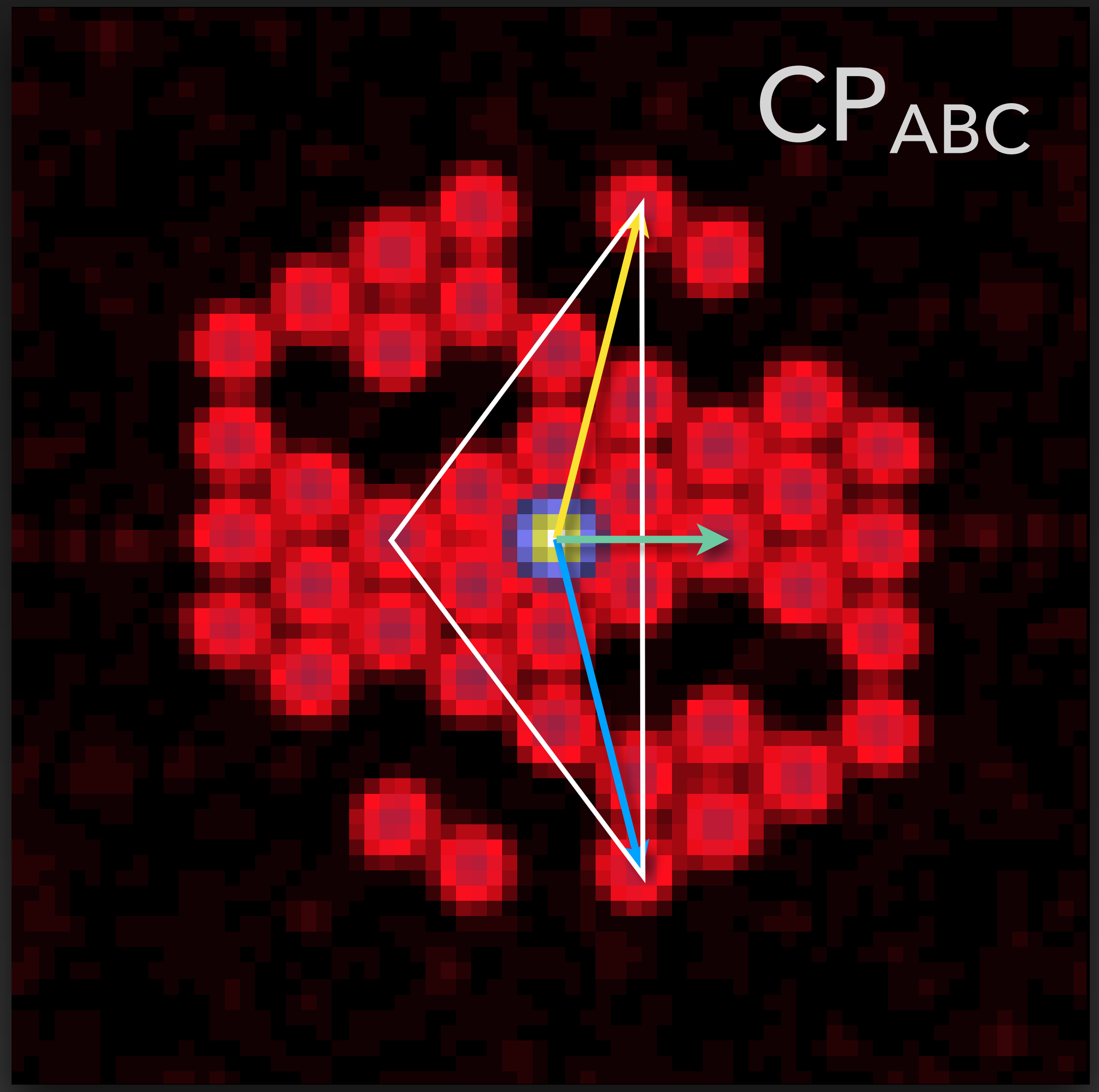
- Each baselines probe a part of the Fourier space



Primary mirror (6.5 m)

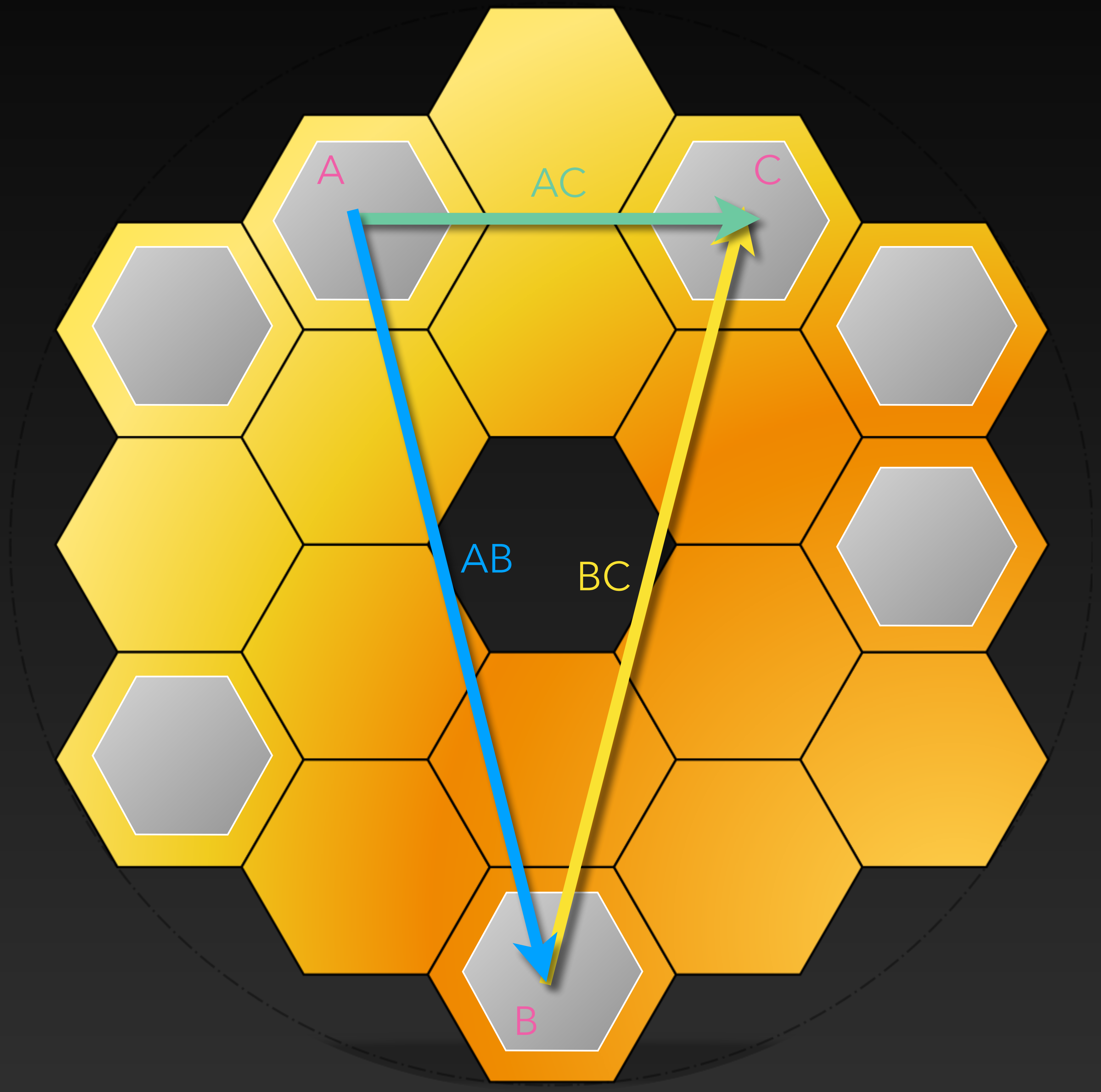
Aperture Masking Interferometry - NIRISS

- Fourier amplitudes are called visibilities
- Fourier phases are atmosphere/optics dependant: only closure phases (CP) are used
- CP are the sum of Fourier phases from 3 holes (ABC)



3 different baselines:

- AB
- AC*
- BC



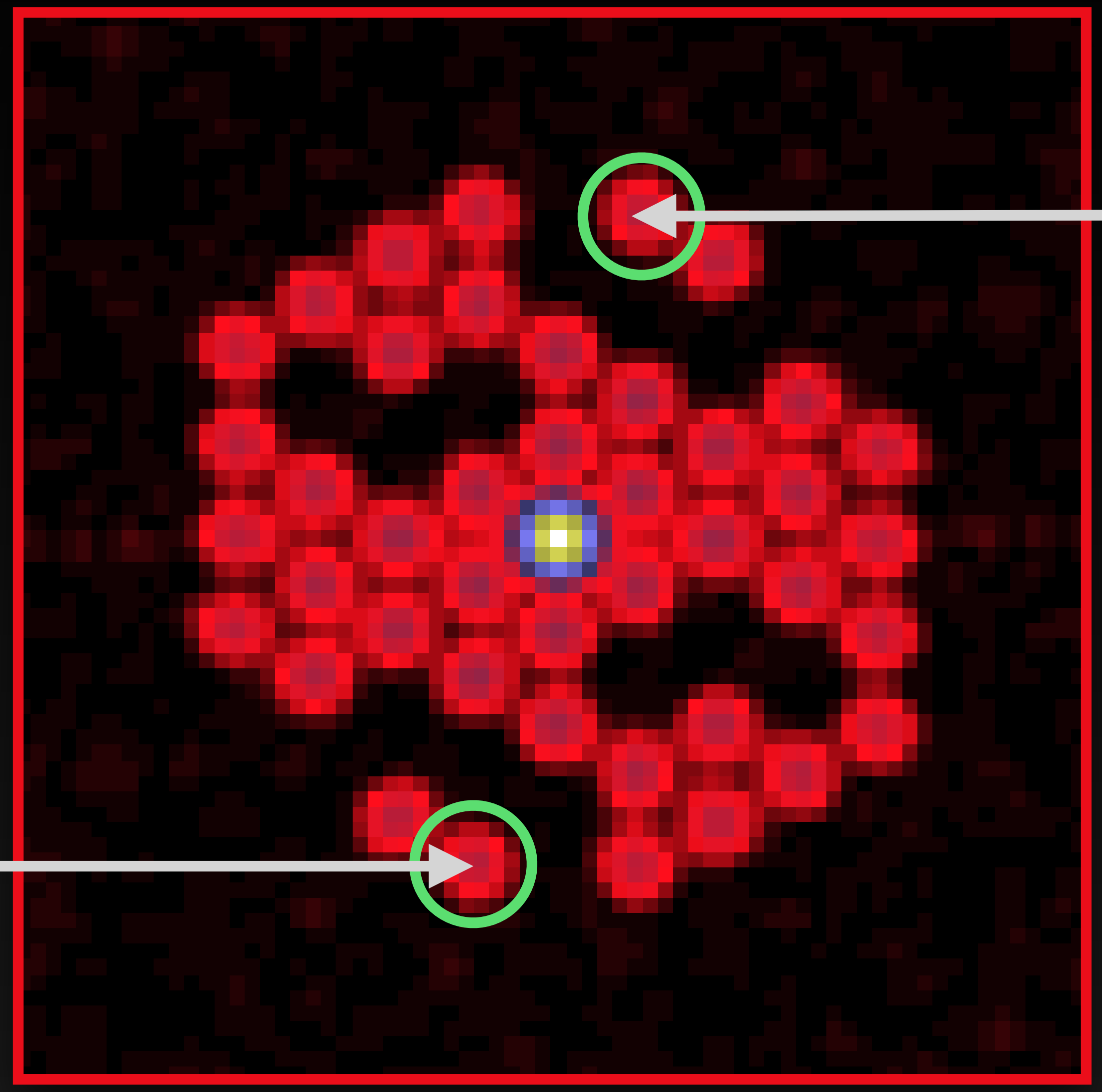
Primary mirror (6.5 m)

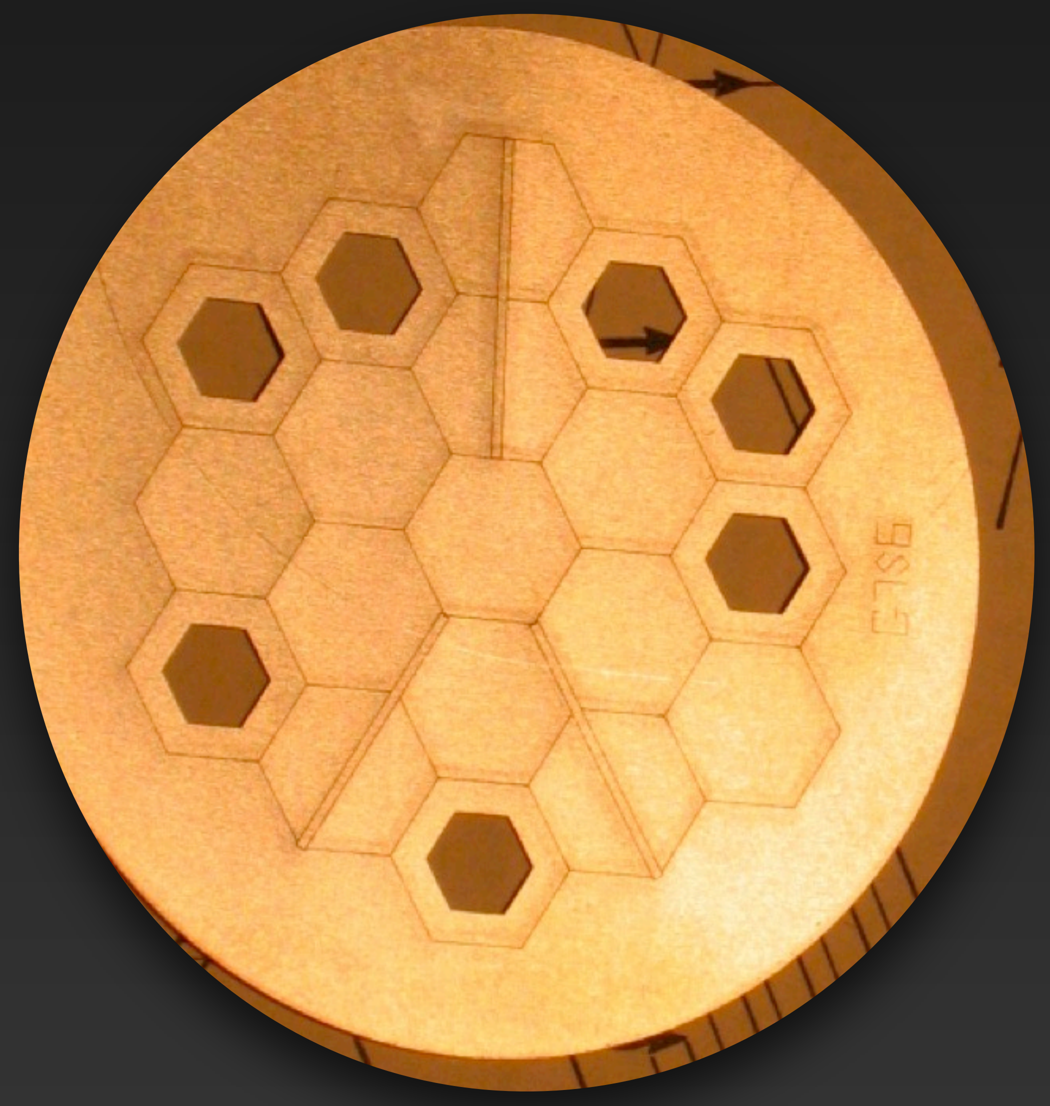
Aperture Masking Interferometry - NIRISS

- Designed to probe unique Fourier informations: Non-Redondant Mask or NRM
- Each Fourier peaks are well isolated
- Generates sharpest core PSF (Michelson criterion 0.5 λ / D or better)
- 7-holes mask probes :

21 baselines (N(N-1)/2)

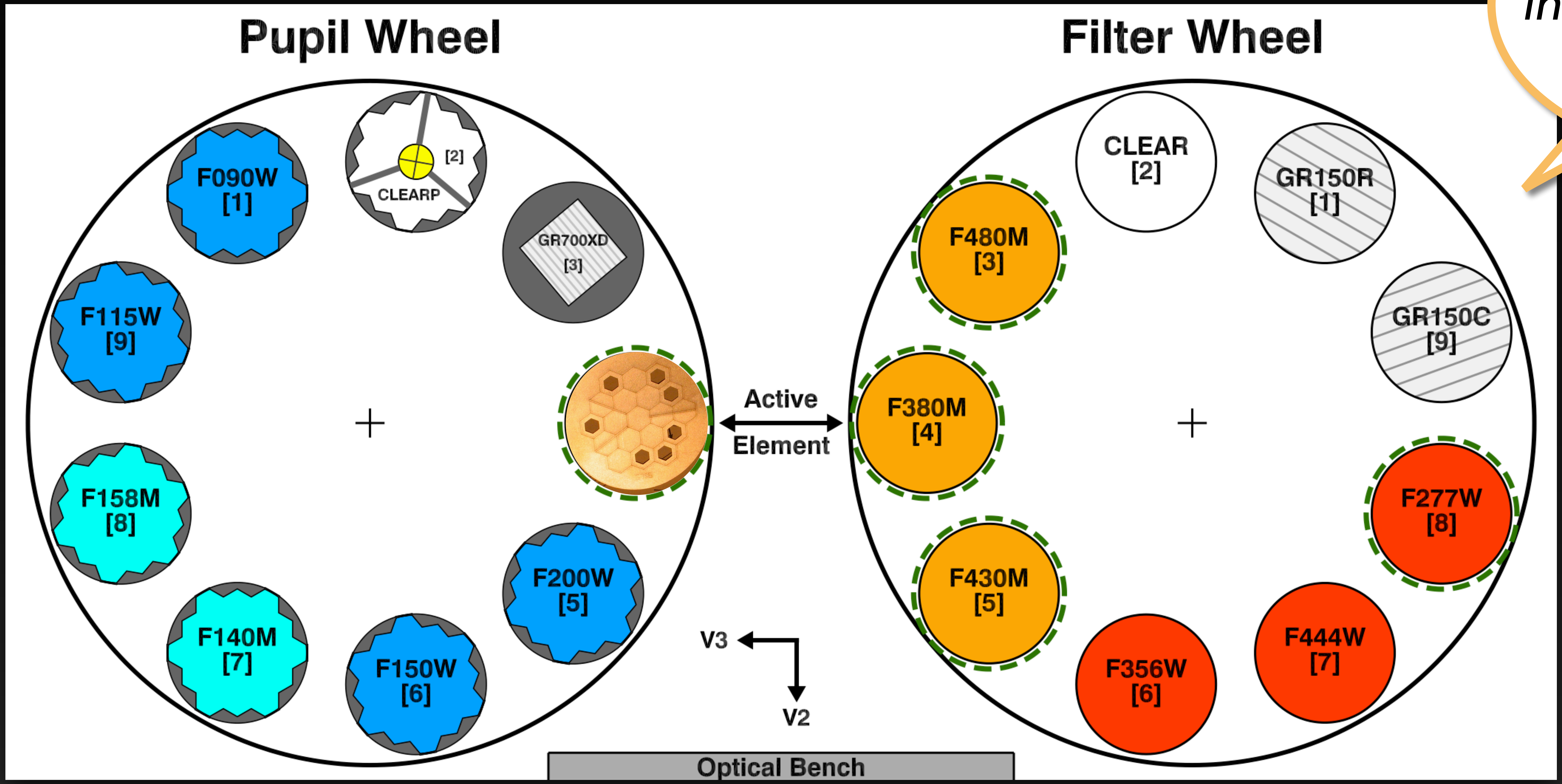
35 closure phases (N(N-1)(N-2)/6)
(71% phase recovery)





7-holes mask of NIRISS

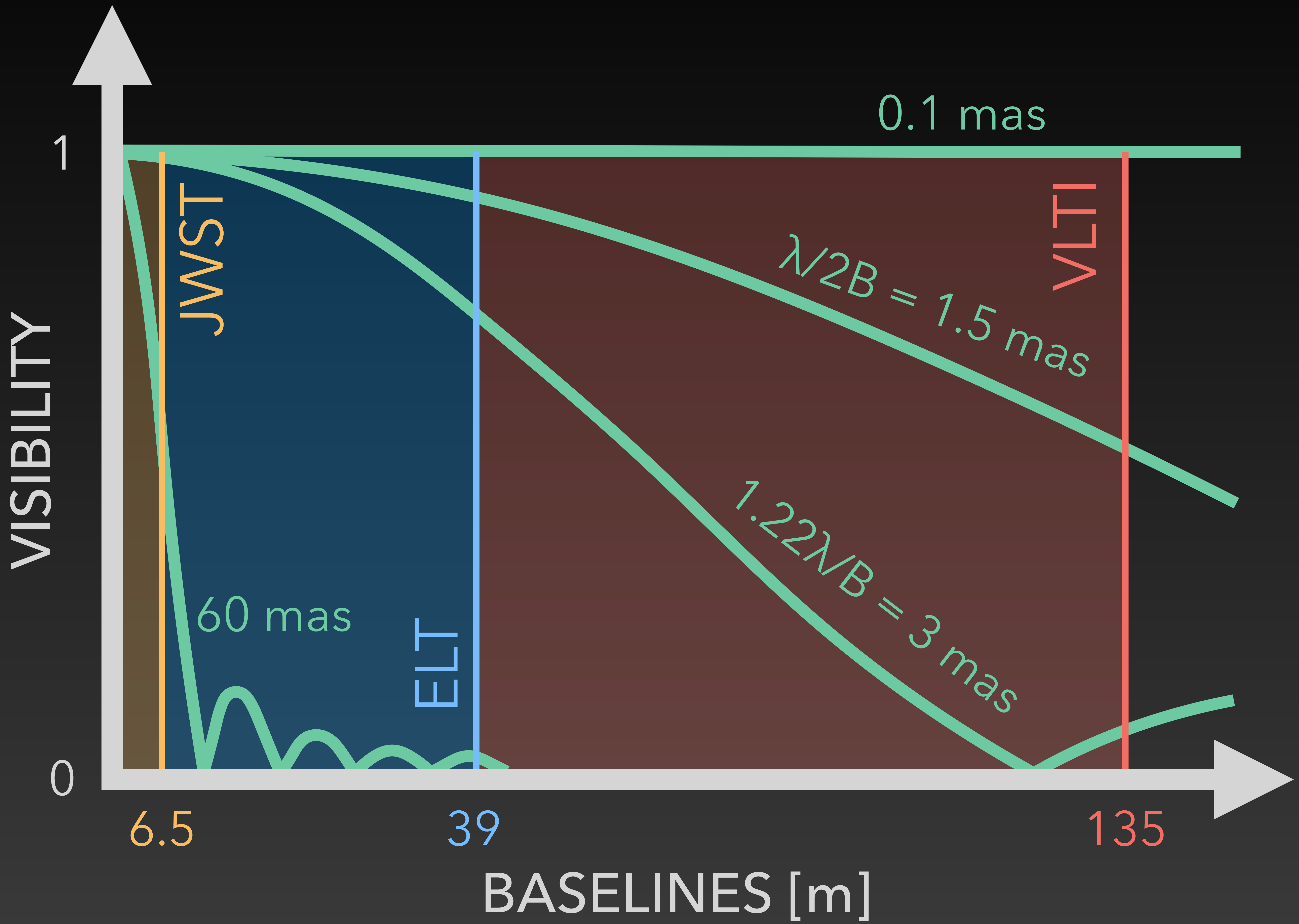
Aperture Masking Interferometry - NIRISS

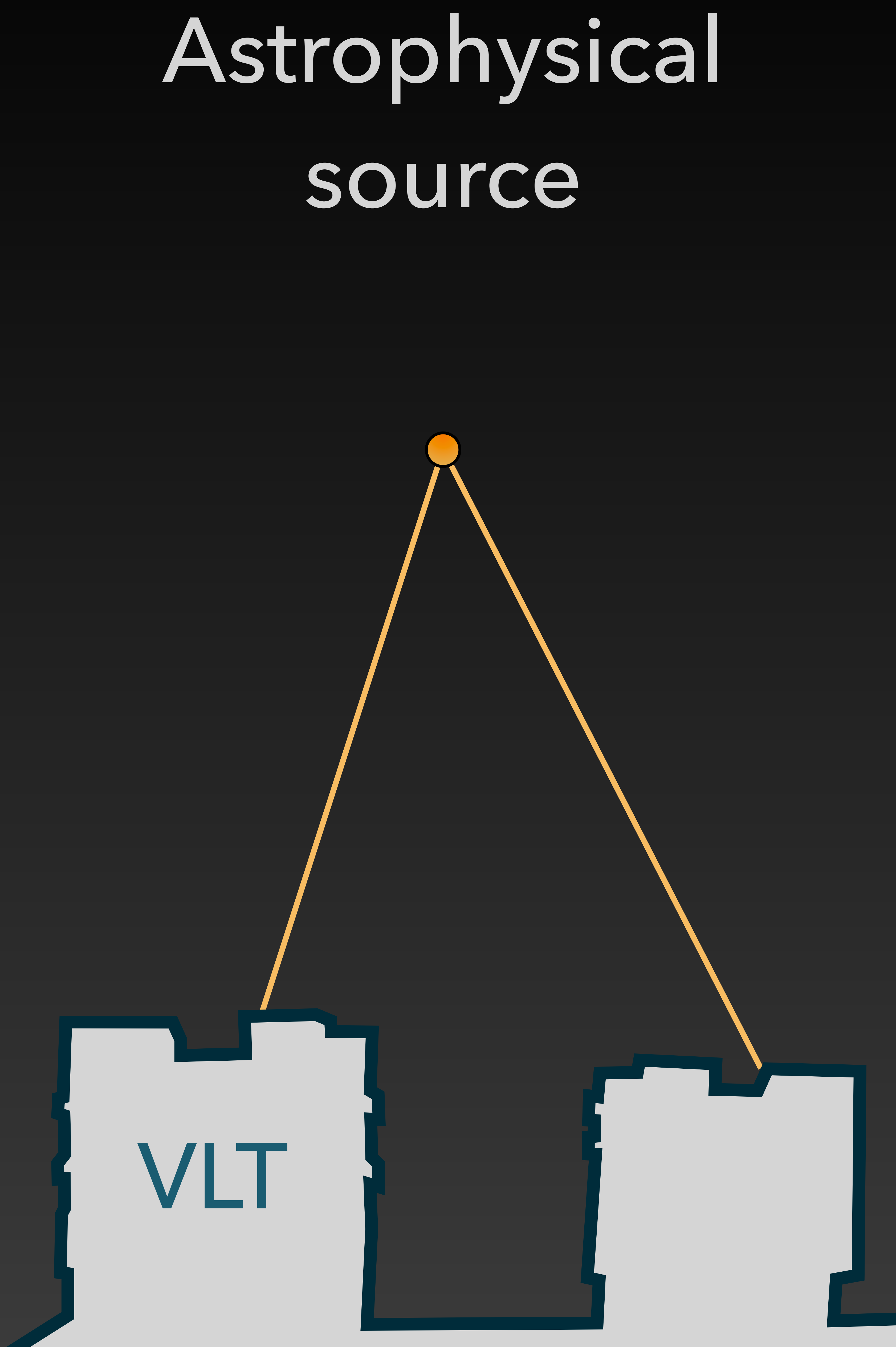


NIRISS can be used with 3 medium bandwidth filters:
3.8 μm, 4.3 μm and 4.8 μm

3 wavelengths can increase the Fourier coverage (u-v coordinates)

Some basics of interferometry (if needed)





Some basics of interferometry (if needed)

Advantages of AMI-NIRISS ?

~4 @ 3.8 μm

~3 @ 4.8 μm

Interferometry can resolve objects as close as

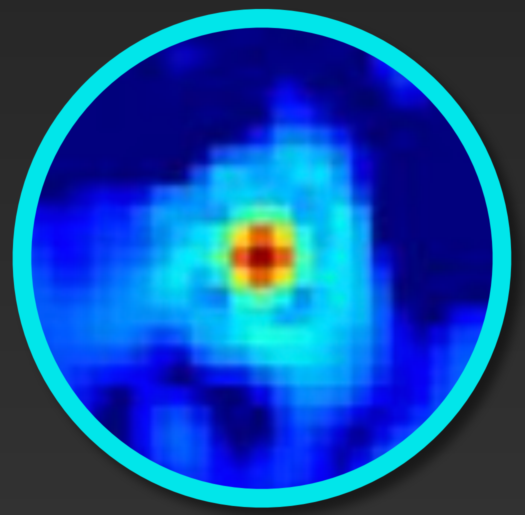
$\delta\theta = 0.5\ \lambda / D$

Study of close and bright stars

Higher saturation limits of the JWST between 3 and 5 μm (peak dust emission)

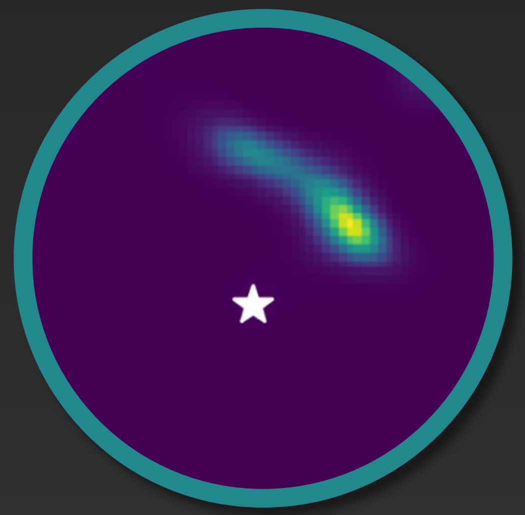
Detect companions up **10** magnitudes fainter than their host star where coronagraphic techniques are blind

Image reconstruction of extended sources



Active Galactic Nuclei
(Ford et al. 2014)

Evolved Stars
(Hankins, **Soulain** et al. in prep)



Transition disks
(Sallum et al. 2016)

And beyond…

Data simulator for AMI-NIRISS

Two main softwares currently exist: MIRAGE (official JWST, STScI) and ami-sim (developed by A. Sivaramakrishnan, available on GitHub)

MIRAGE

- Creates raw datacube (before JWST pipeline) from the Astronomer's Proposal Tools (APT)
- Includes more realistic noises (jitter, flat-field, darks, dither, bad pixels, etc.) and the last simulated PSF (Webb-PSF)

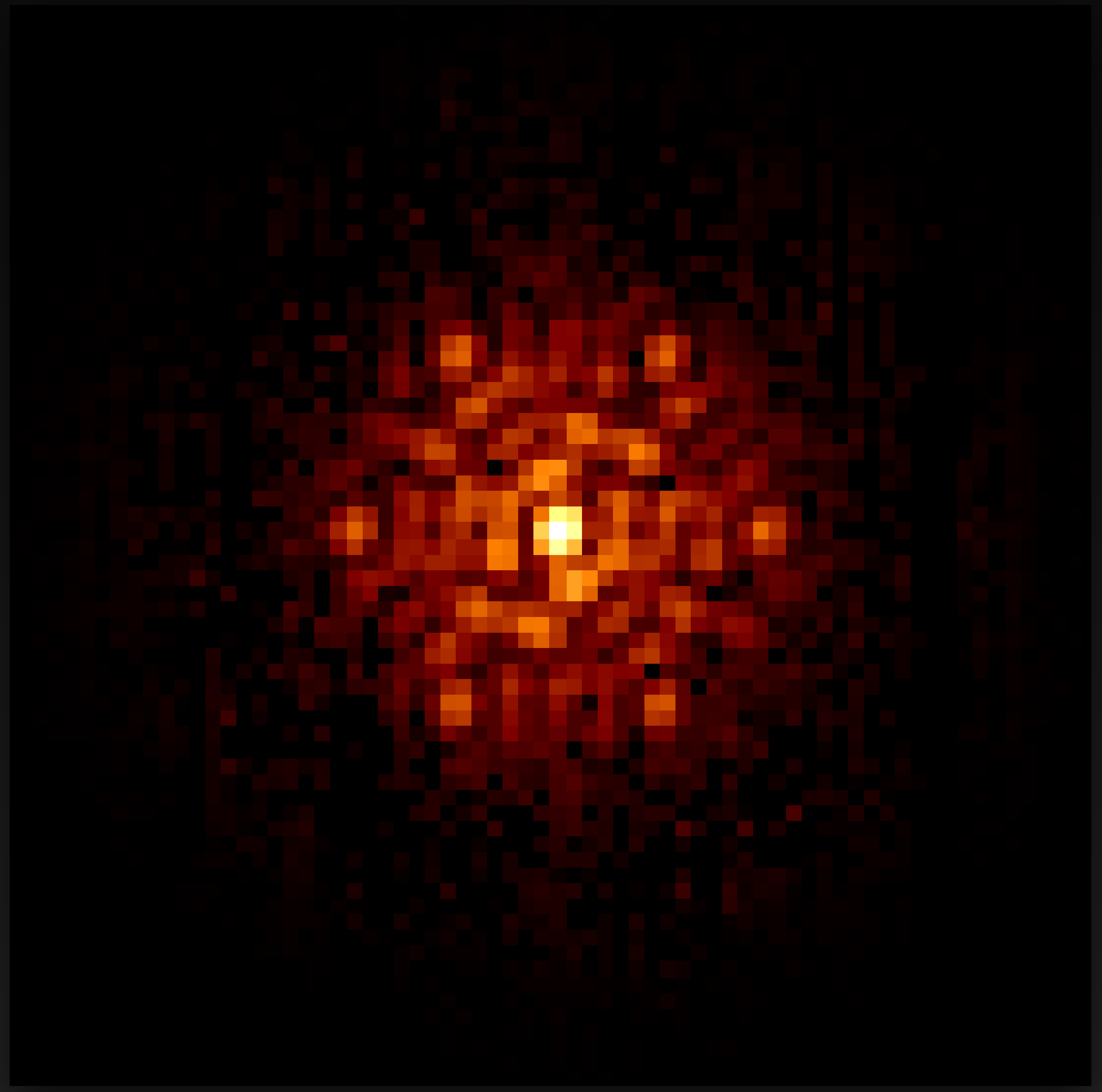
Accurate noise and better for testing JWST pipeline

ami-sim

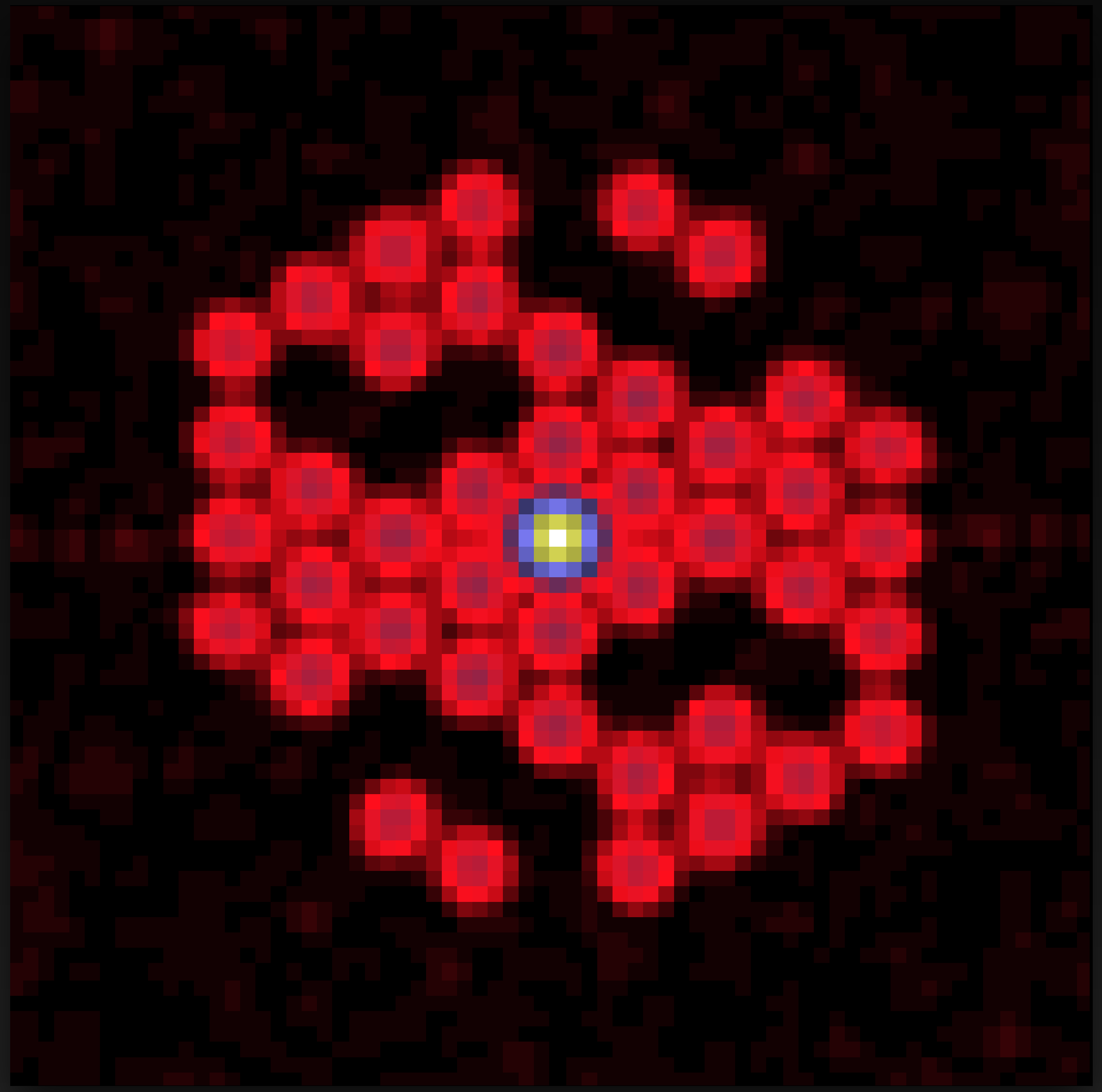
- Creates post-pipeline datacube from astronomical scene (.fits) and ETC informations (N_{grp}, integration, CR)
- Includes basic noises (jitter, photon noise, flat-field, darks, etc.) and customizable realistic PSF

More versatile and easy to use

Aperture Masking Interferometry - NIRISS



Fourier
transform



Fringes on the detector

Observables coded in the Fourier space

How to extract interferometric quantities ?

How to extract interferometric quantities ?

Soulain et al. 2020

- AMICAL : Aperture Masking Interferometry Calibration and Analysis Library (available on GitHub)
- Based on the « famous » IDL Sydney code developed by Peter Tuthill, John Monnier and Mike Ireland among others…
- Python user-friendly interface to extract AMI data
- Versatile all-in-one package compatible with major facilities (SPHERE, ERIS?, NIRISS, VAMPIRES, and more to come (ELT/METIS))

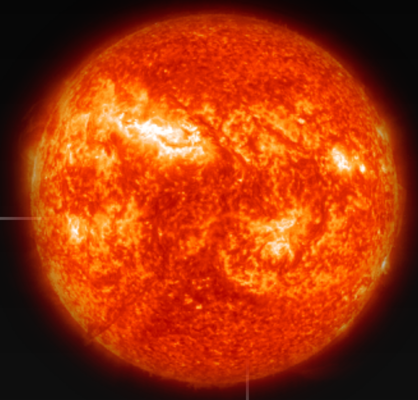
Data cleaning : centering, windowing, sky, bad pixels

Data selection

Complex quantities extraction: Fourier sampling

Data calibration

AMICAL application: AMi-NIRISS performances



Most realistic PSF used (new mask dimension, R. Cooper)

Accuracy = 0.17%

Sun-like star (G2V) of 6 mag (3.8 µm)

Number of group, integrations and countrate computed with the official ETC

We simulate different accuracy regimes represented by the total number of collected photons : 1e7 to 1e10

Astronomical scene is a faint binary with CR = 20 mags

We performed the simulation with ami-sim including all possible noise sources

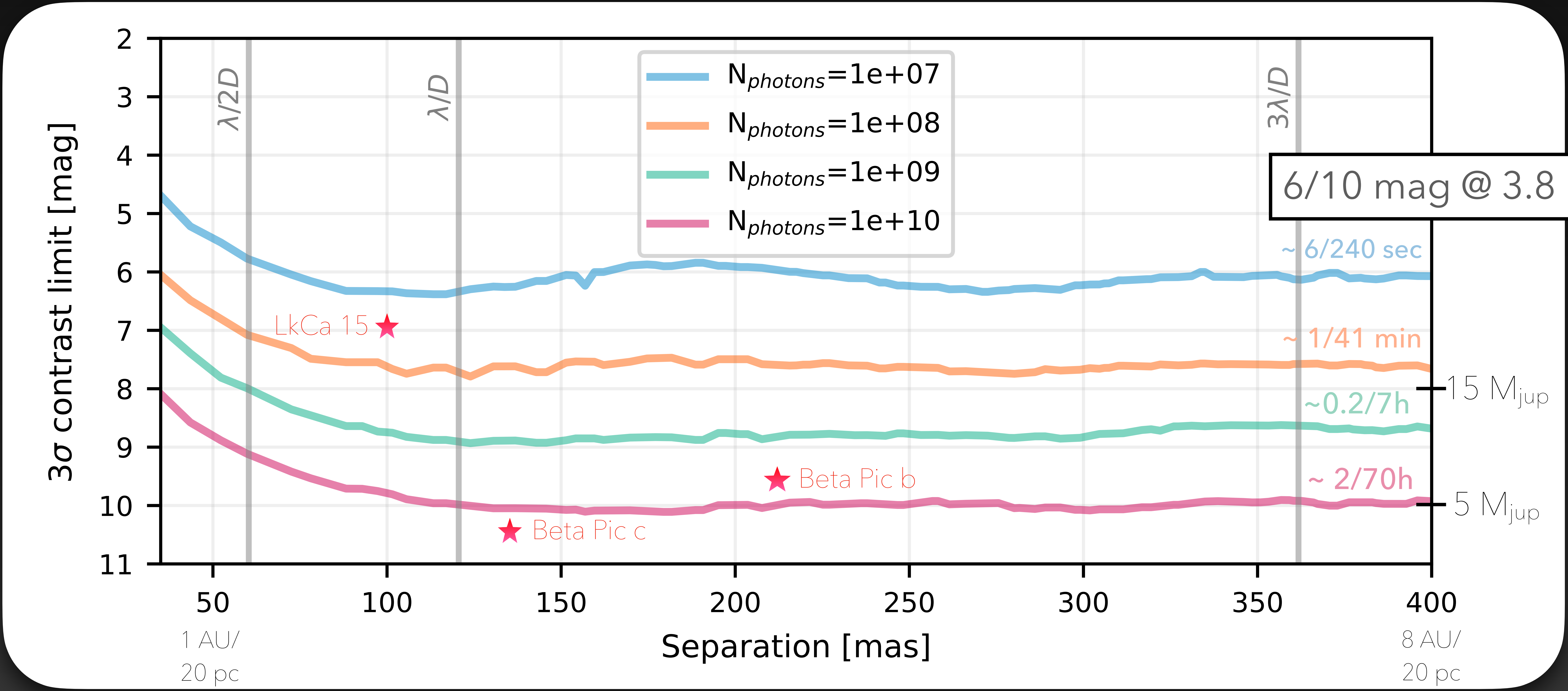
Extraction and analysis are performed using AMICAL software being focused on the interferometric quantities themselves

AMi-NIRISS performances in contrast

- Contrast limits computed using companion injection method from Absil et al. 2014

Breaking news: commissioning and GTO suggest a ~0.5/1 mag contrast poorer than the theoretical prediction

Soulain et al. 2020



Interferometry/spectroscopy

Coronagraphy

AMi-NIRISS : exoplanet (sub-stellar) science case

HD114082, AB Pic
(Proposal cycle 2)

- Example for a close-by system (Palma et al. 2022)
- Planetary model (Ray et al. 2022)
- Complementary detection range
- Gaia companion detection?

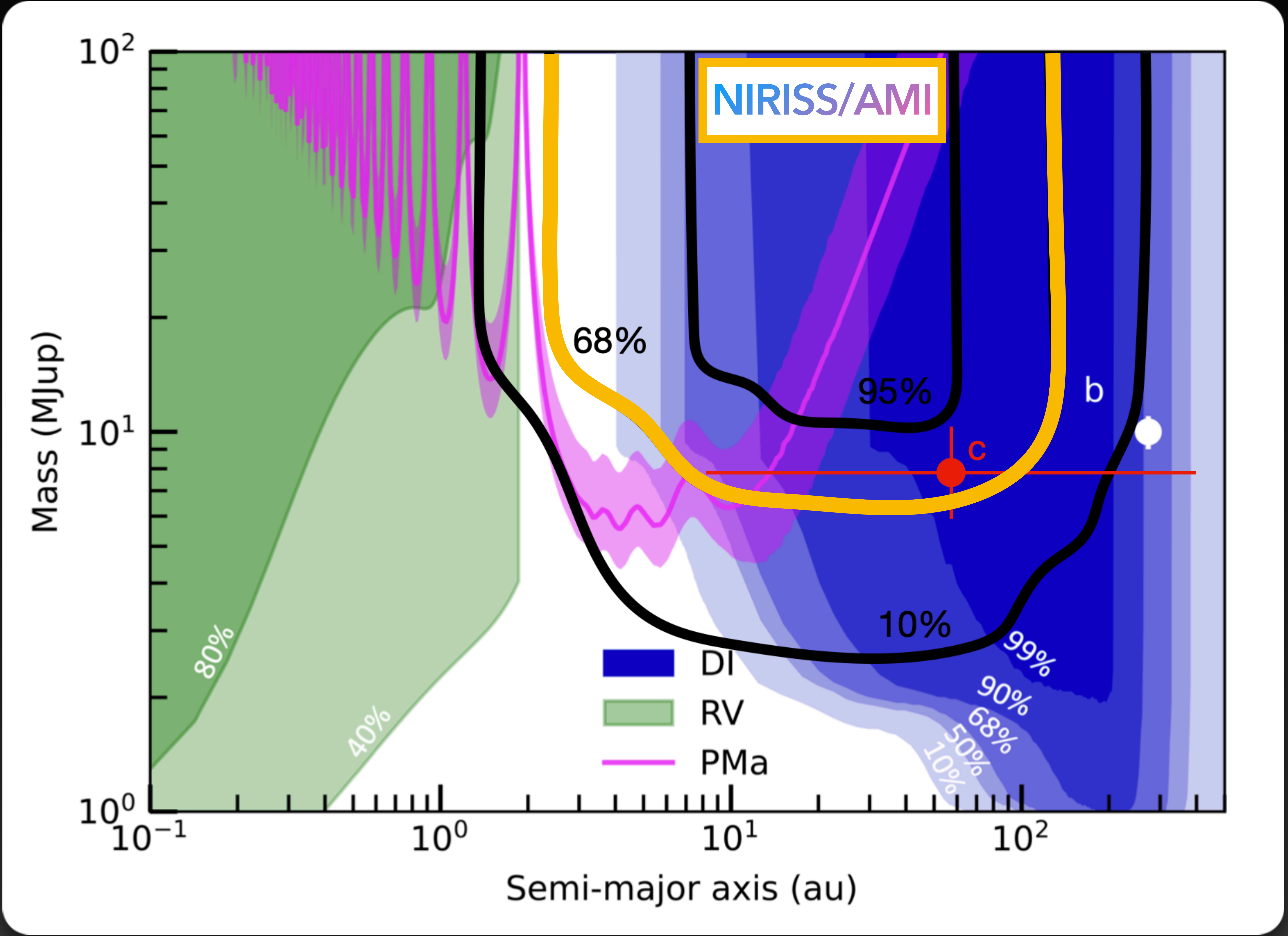
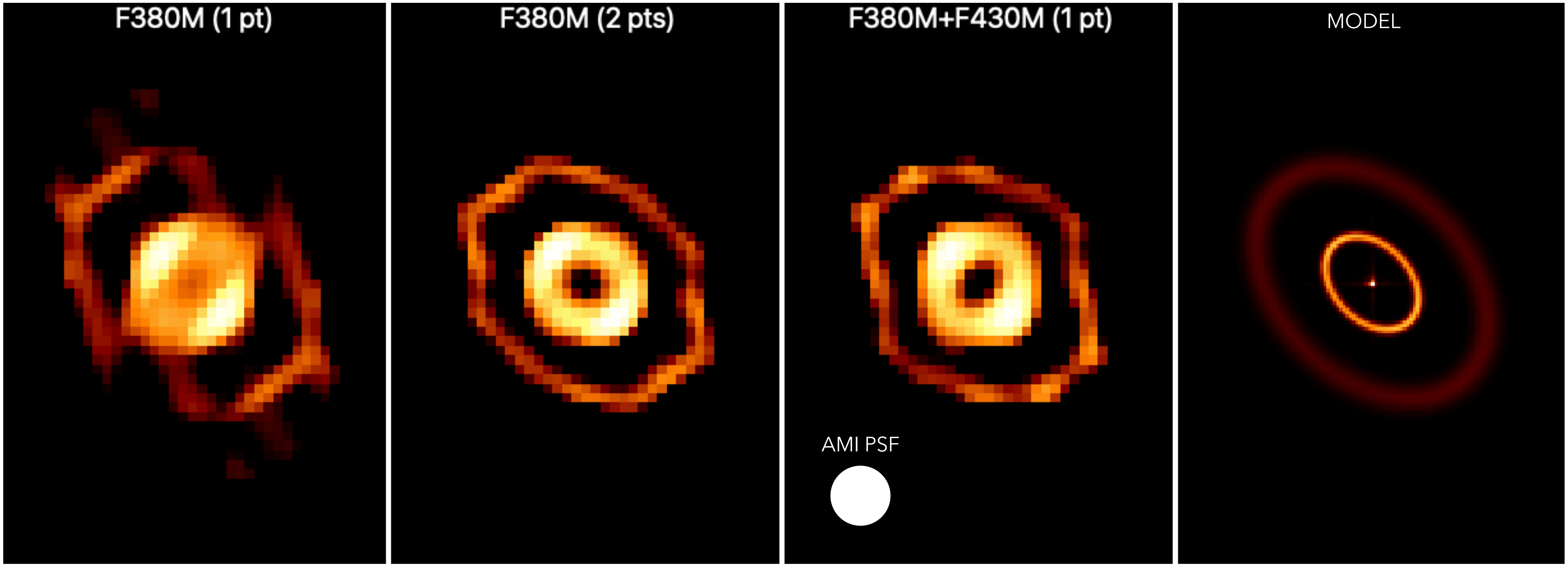


Image reconstruction possibilities



- Synthetic disk ring model, or more complex ones…
- A reasonable amount of photons (1e9) for a 6 magnitude star (3.8 μm)

After years of simulation: first ERS data (summer-2022)

Early **R**elease **S**cience program (PI: R. Lau) on Wolf-Rayet stars

Dying star Dust producers

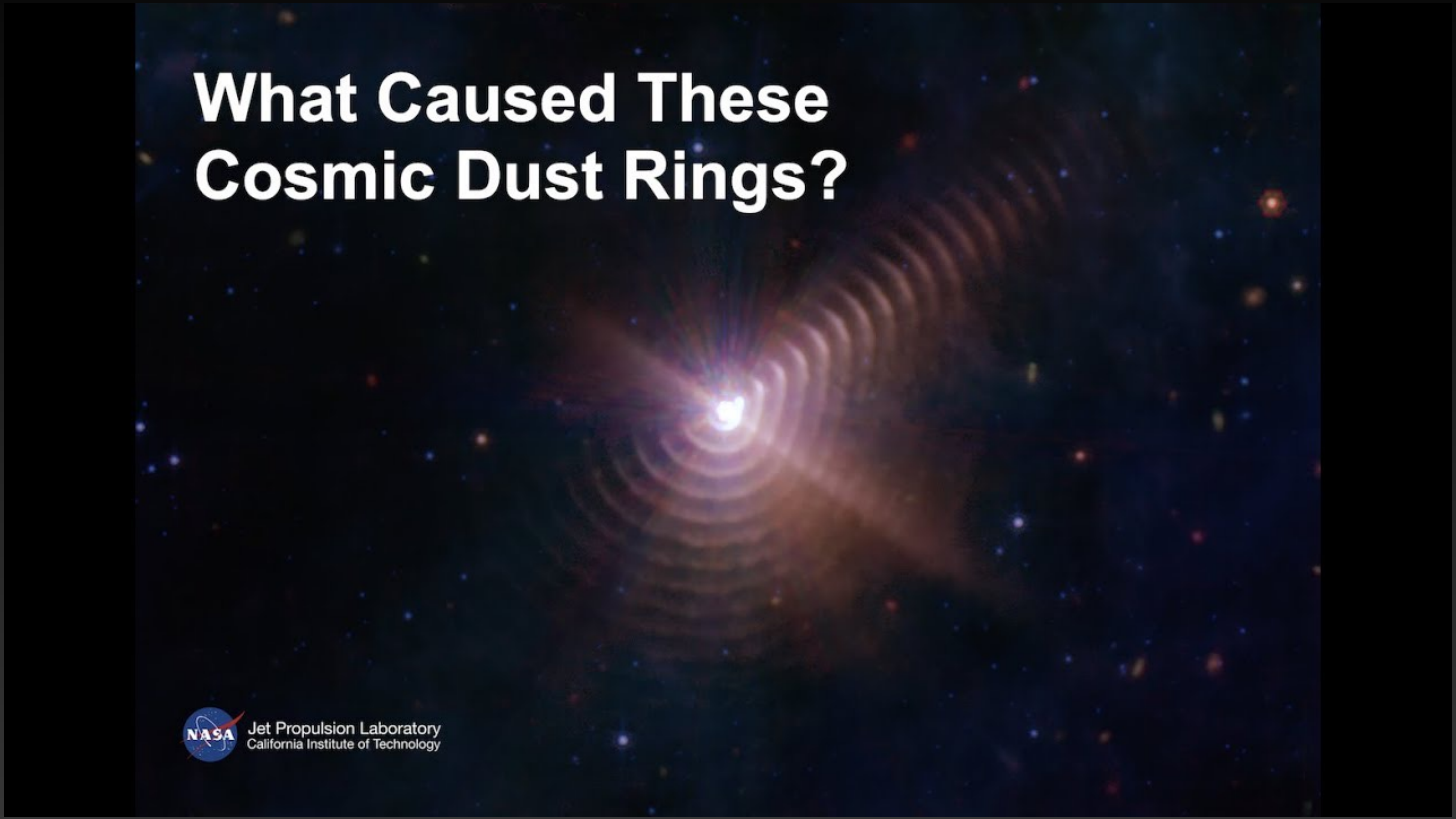
Two targets: the Eccentric system **WR140** and the mysterious system **WR137**

Synergy between JWST instruments: **MIRI** imaging, MIRI IFS and **AMI-NIRISS**

Ground-based telescopes simultaneous observing campaigns

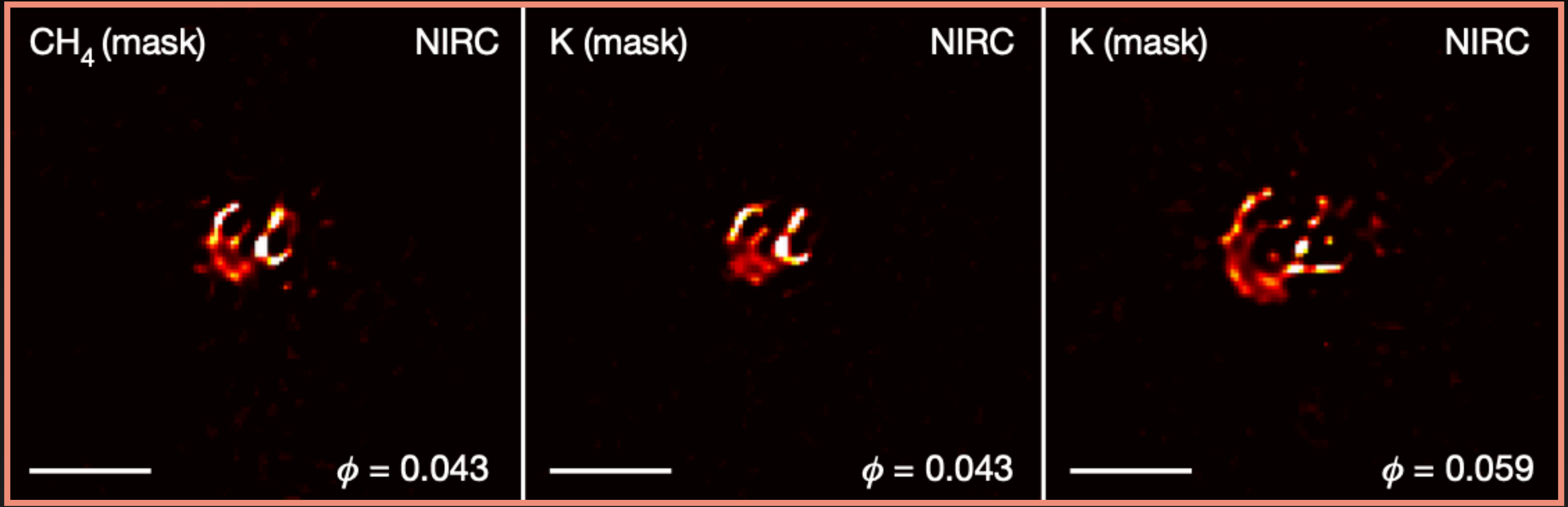
An international group of experts of Wolf-Rayet or interferometry techniques

ERS data: the exquisite view of WR140



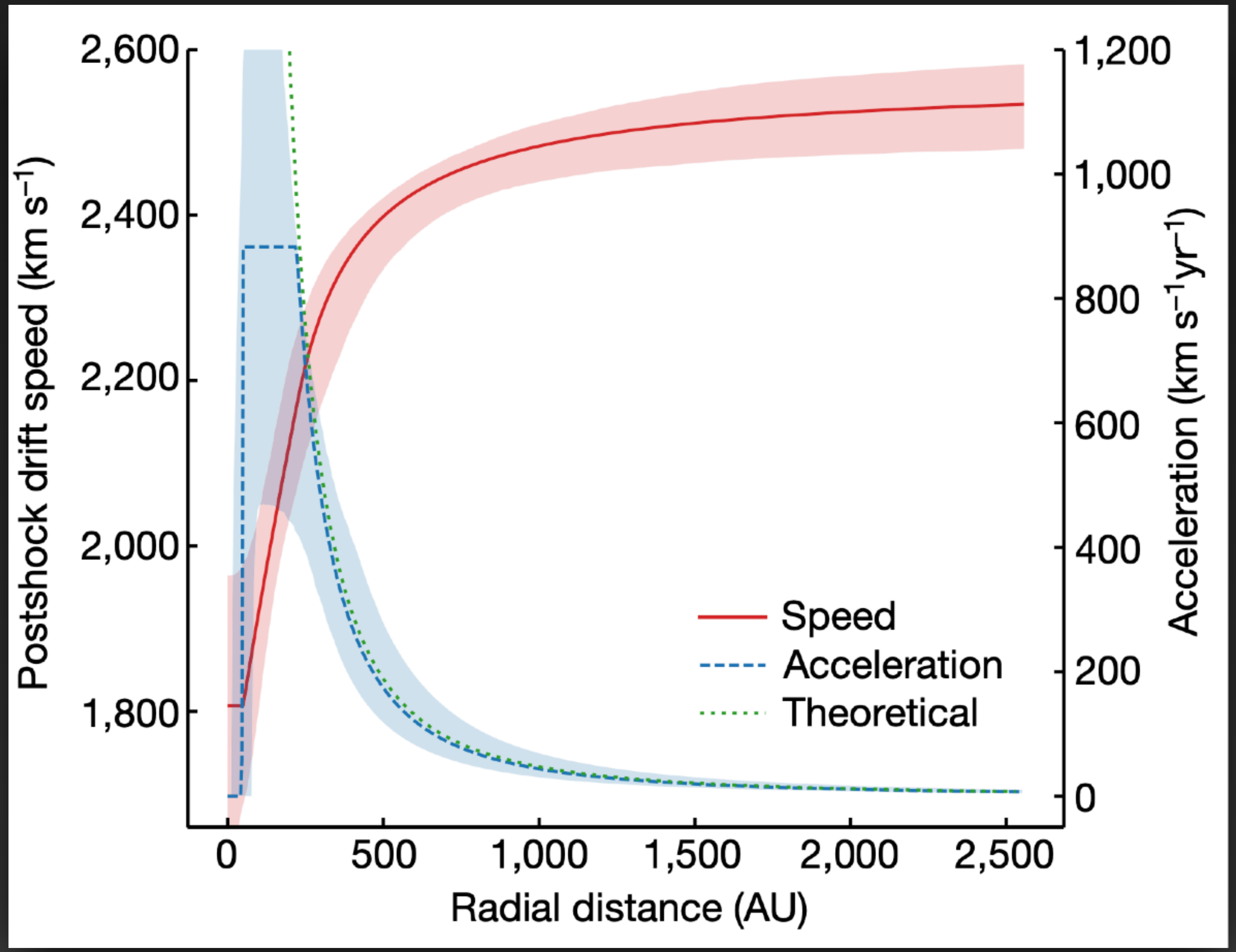
ERS data: the exquisite view of WR140

Han, Tuthill, Lau and Soulain 2022



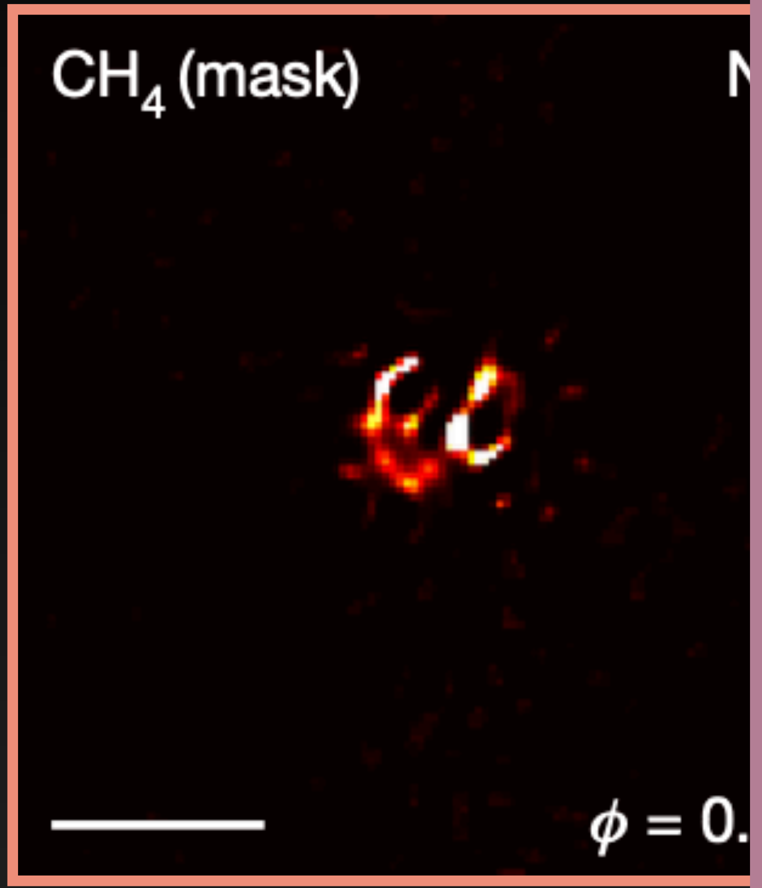
Simultaneous publication in Nature

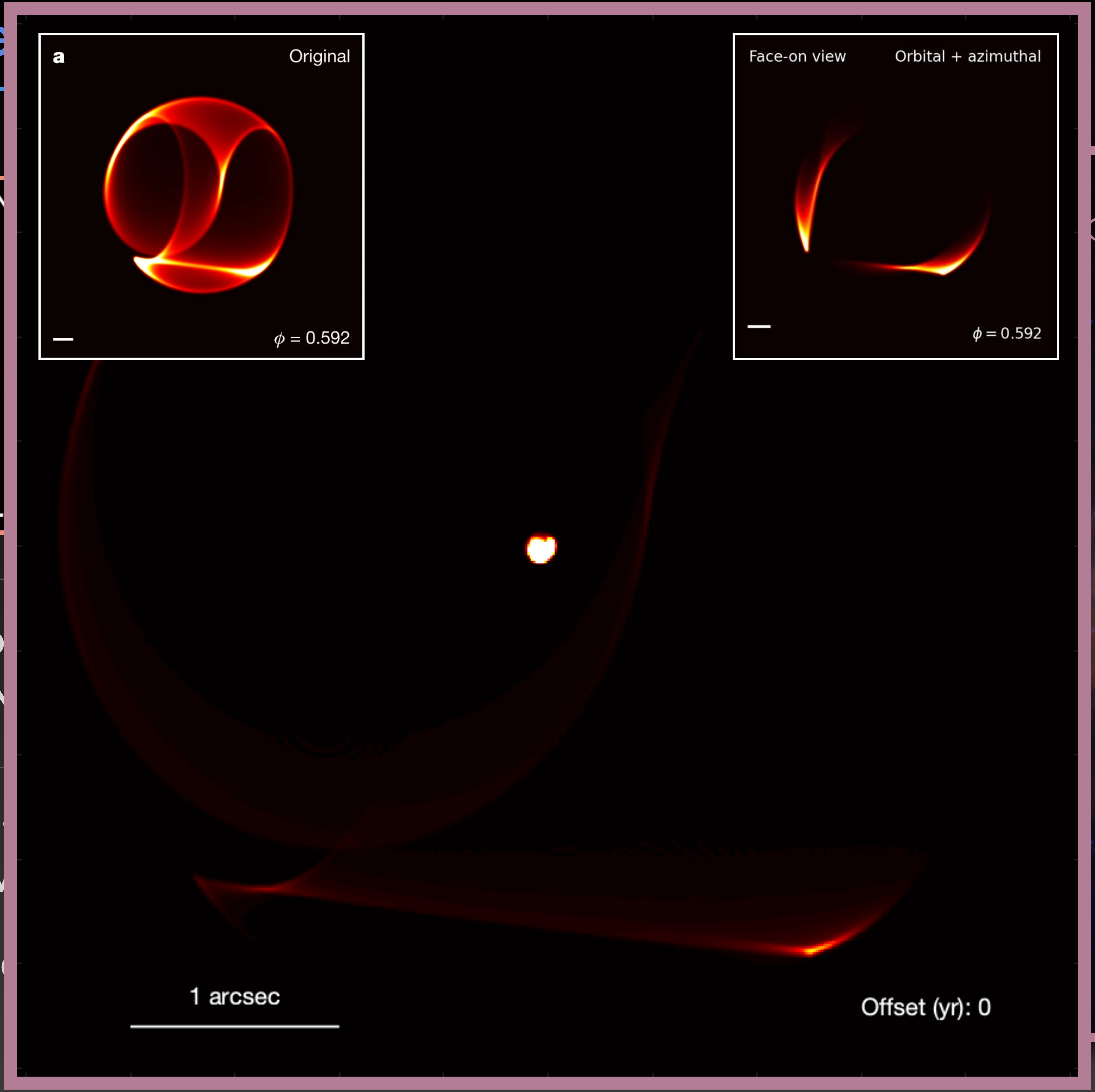
- 20 years of data including SAM
- First observed dust acceleration



Lau, ..., Soulain et al. 2022

ERS data: the e





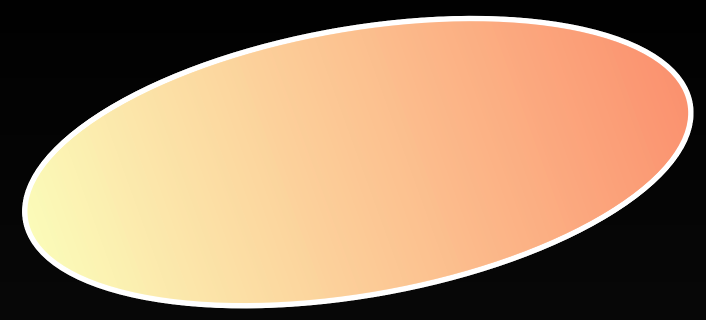
Simultaneo
publication in N

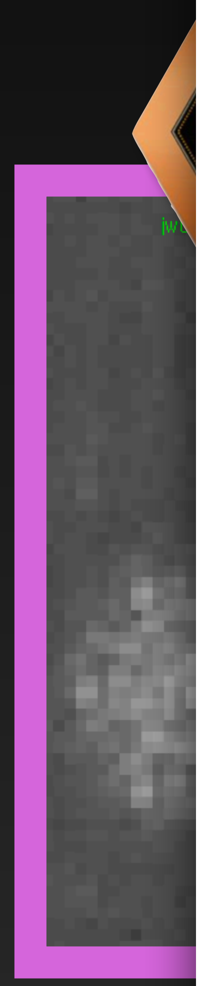
- 20 years of d
  including SAM
- First observe
  acceleration

Lau, ..., Soulain et al. 2022

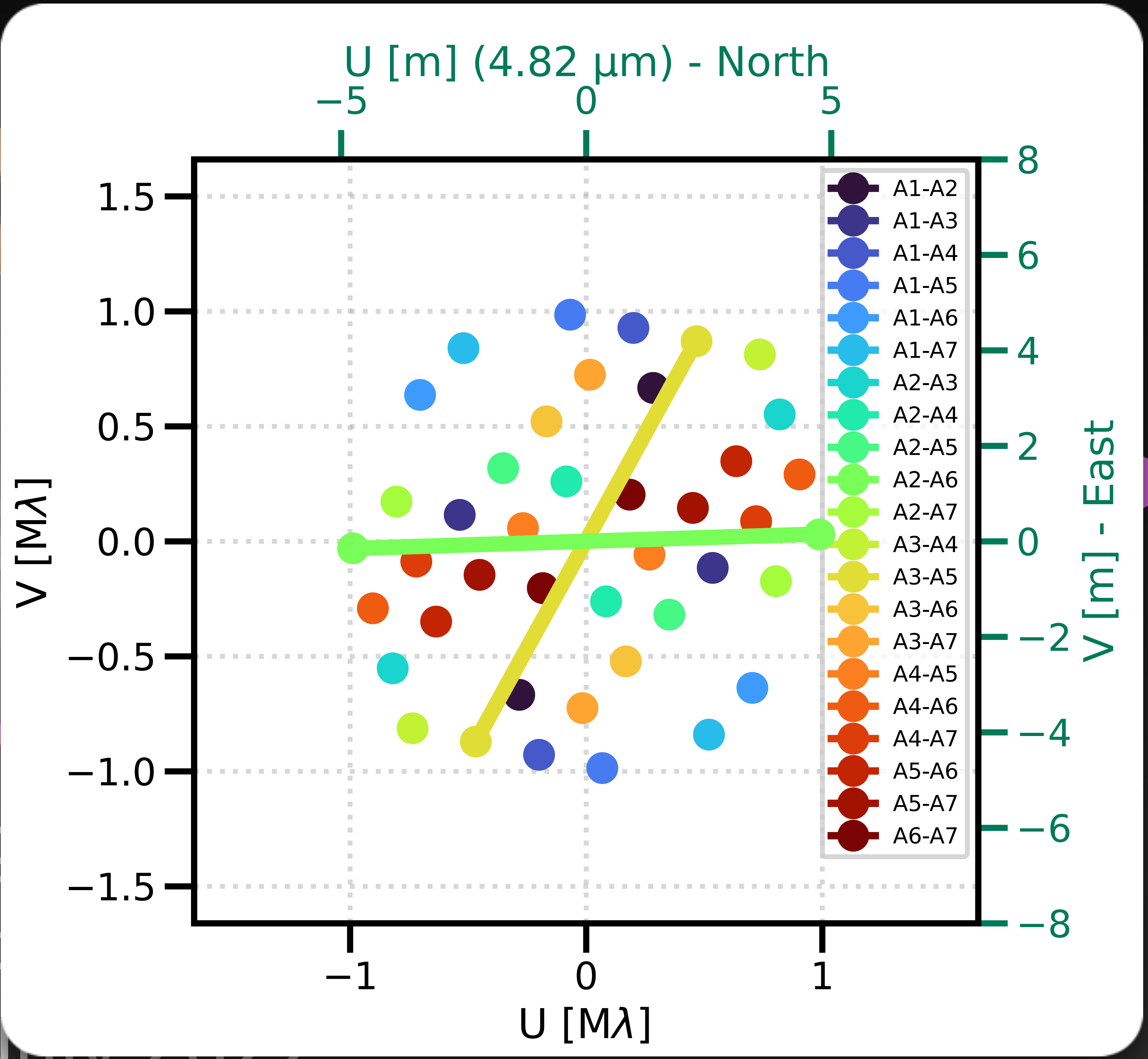
ERS data: the surprising view of WR137

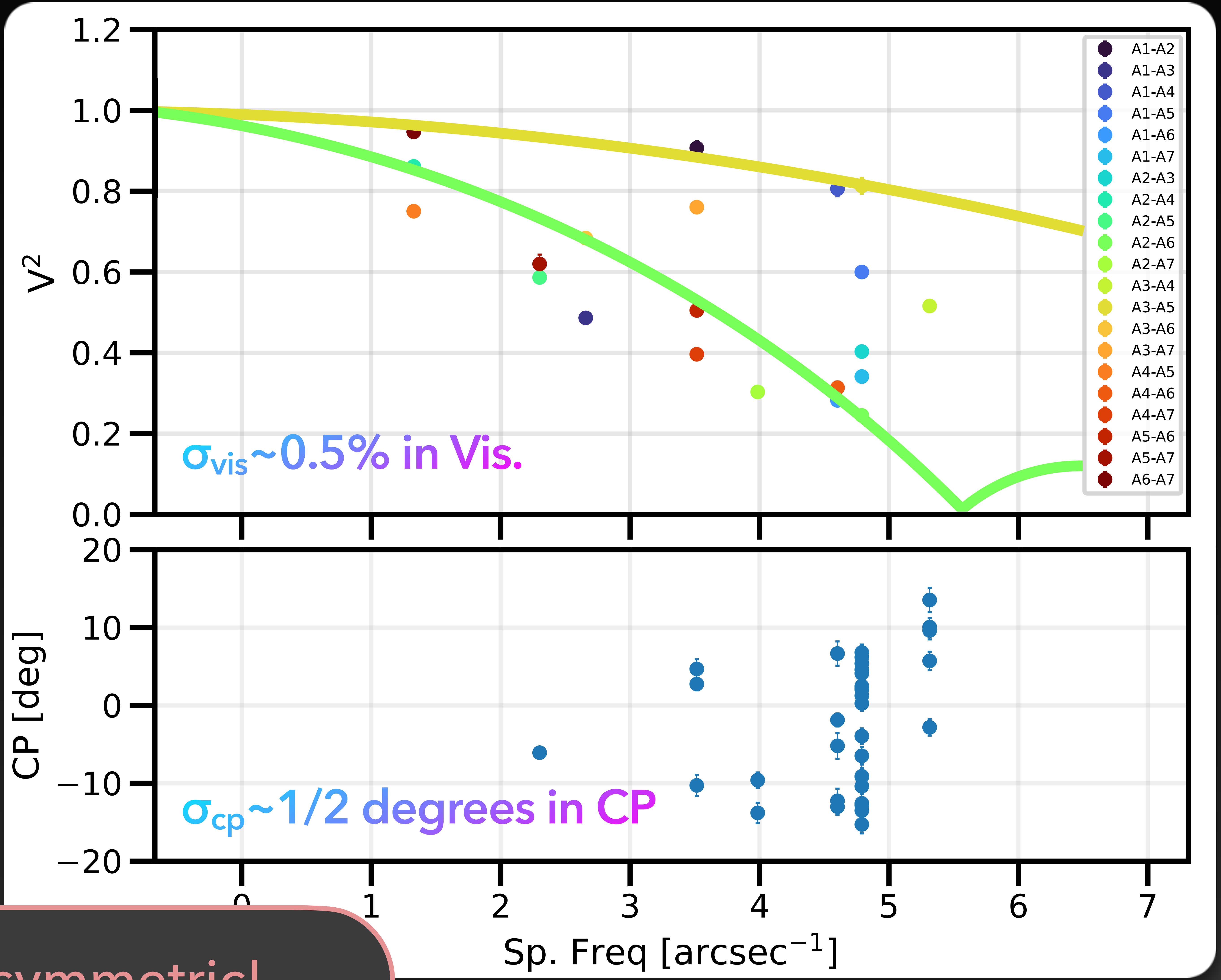
Source brightness distribution ?





Fring
wit
July 2022





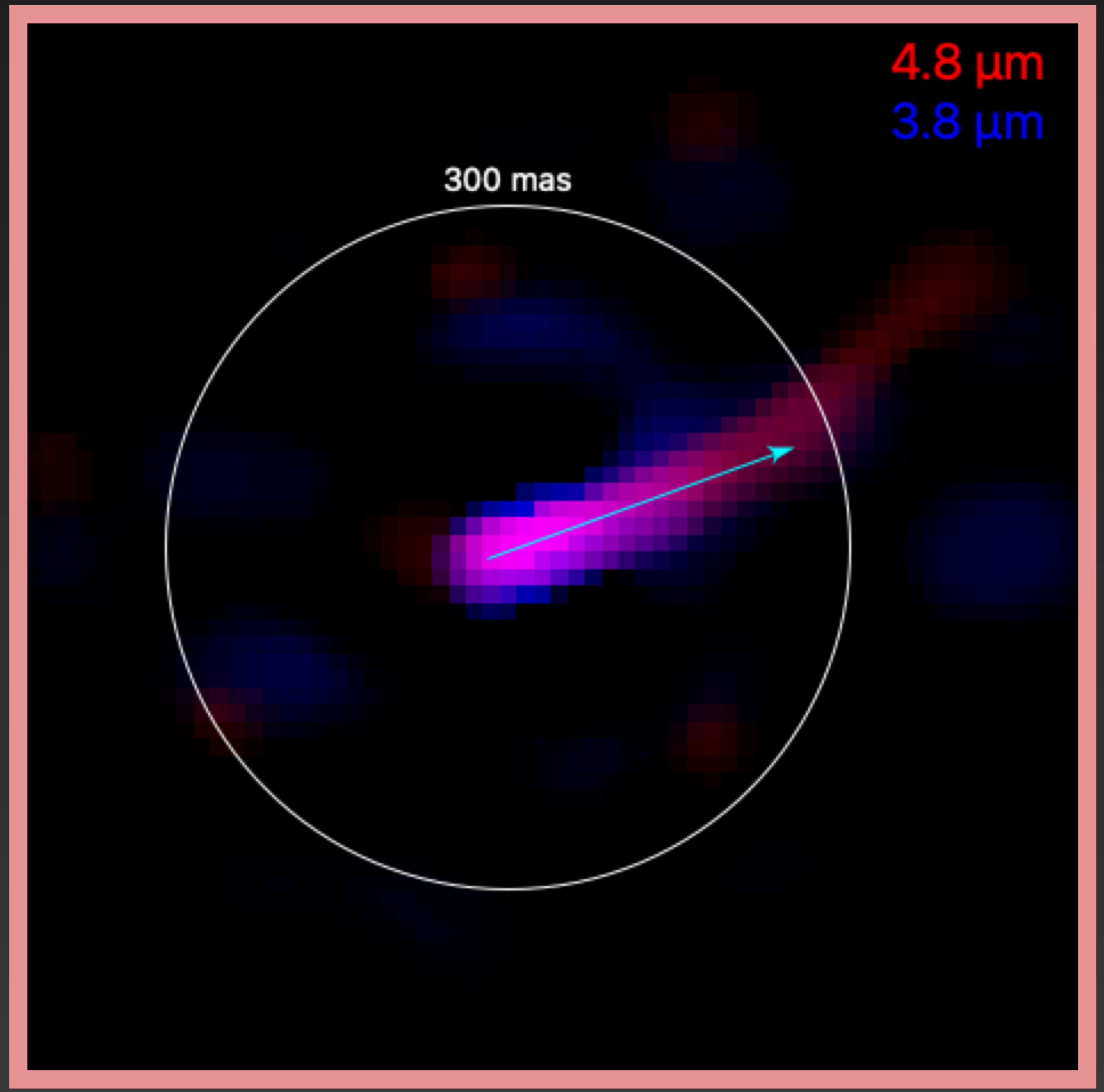
Resolved, elongated and asymmetric!

ERS data: the surprising view of WR137

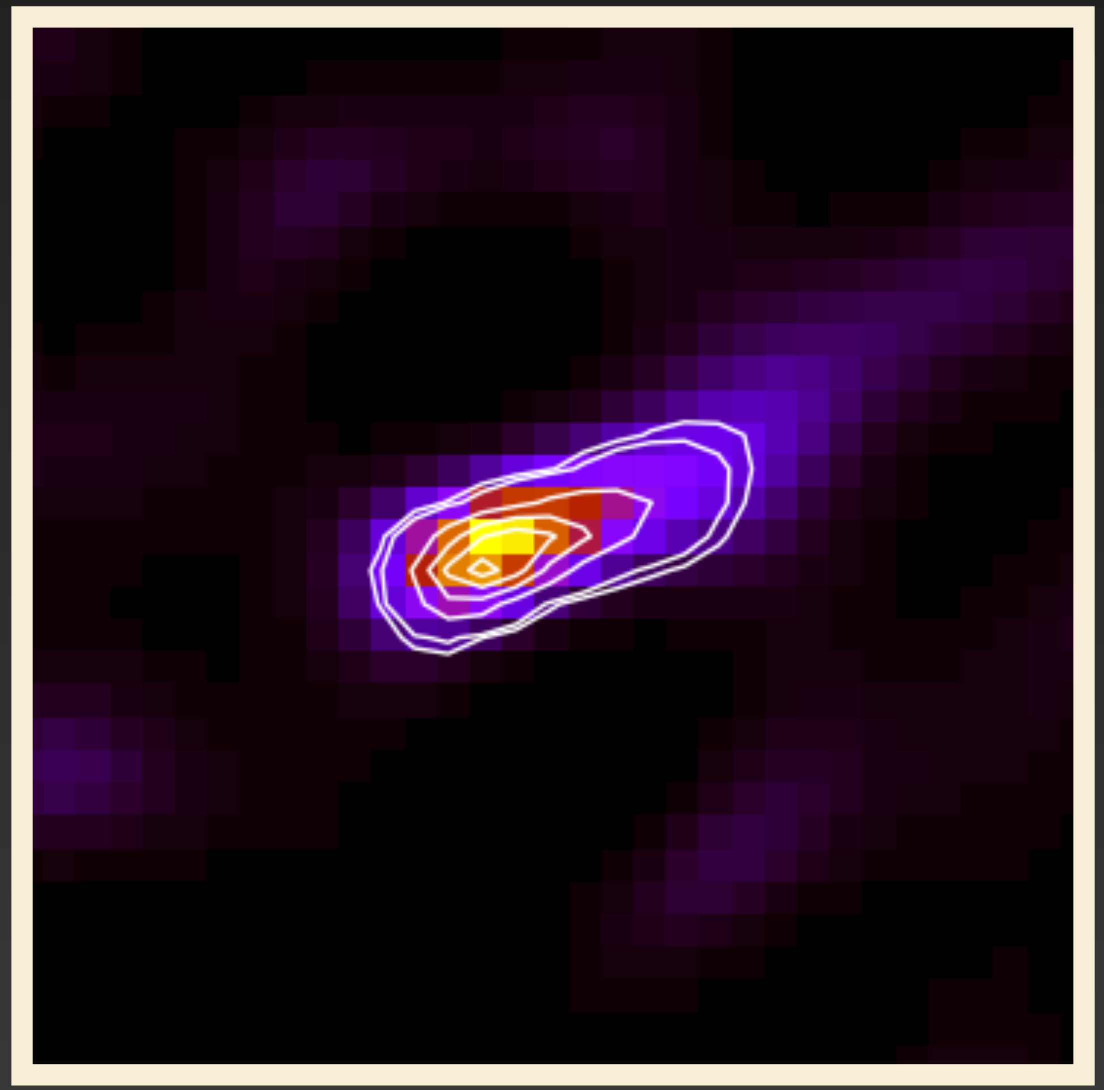
Don’t be afraid by Fourier’s realm: image reconstruction exists!

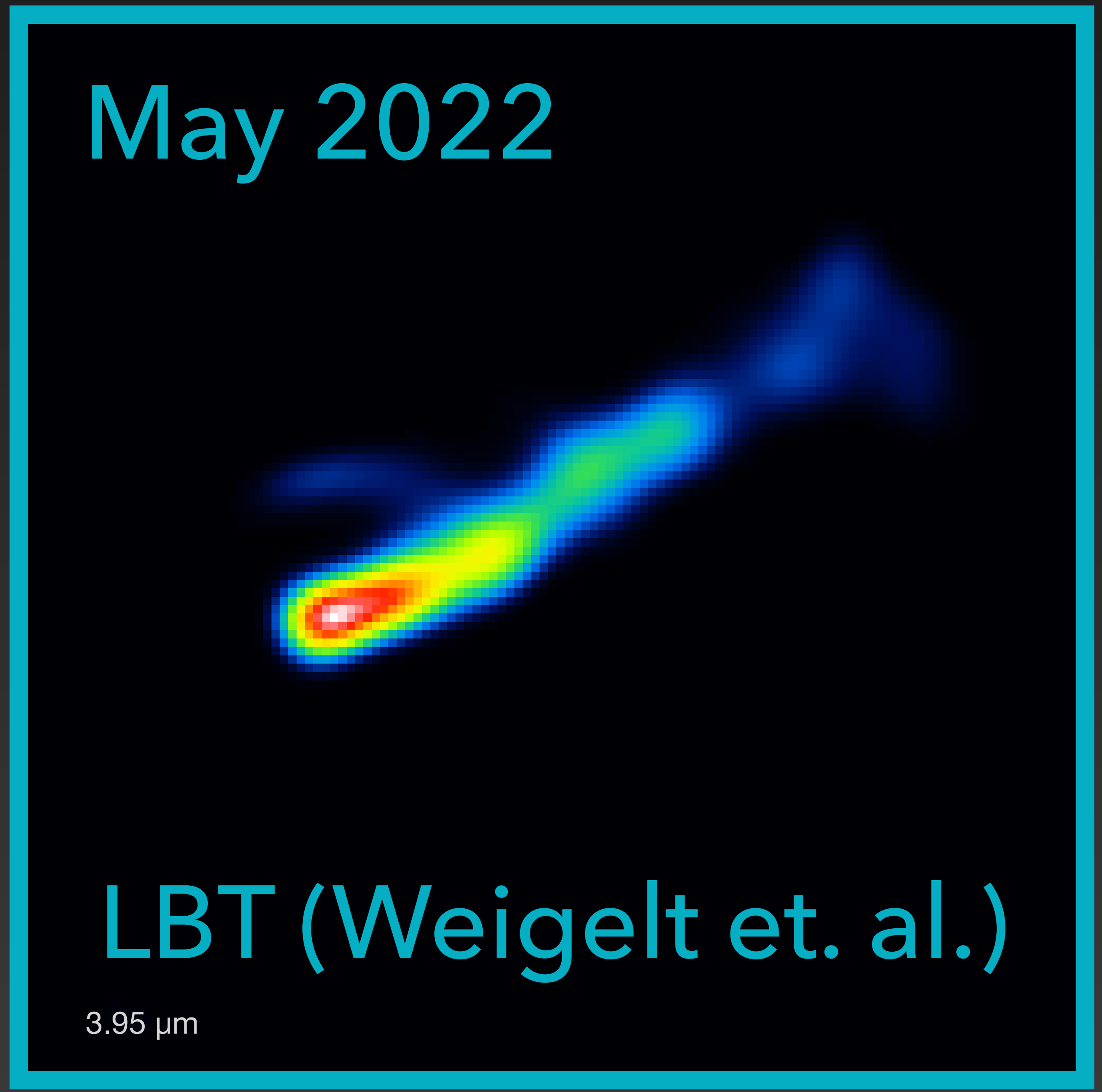
Different algorithms exist to transform visibility/CP into images:
IRBis, Squeeze, MIRA, Sparco, etc.

AMiCAL + IRBis
(Hofmann et al.)



SAMpip + Squeeze
(Sanchez et al., Mexico)





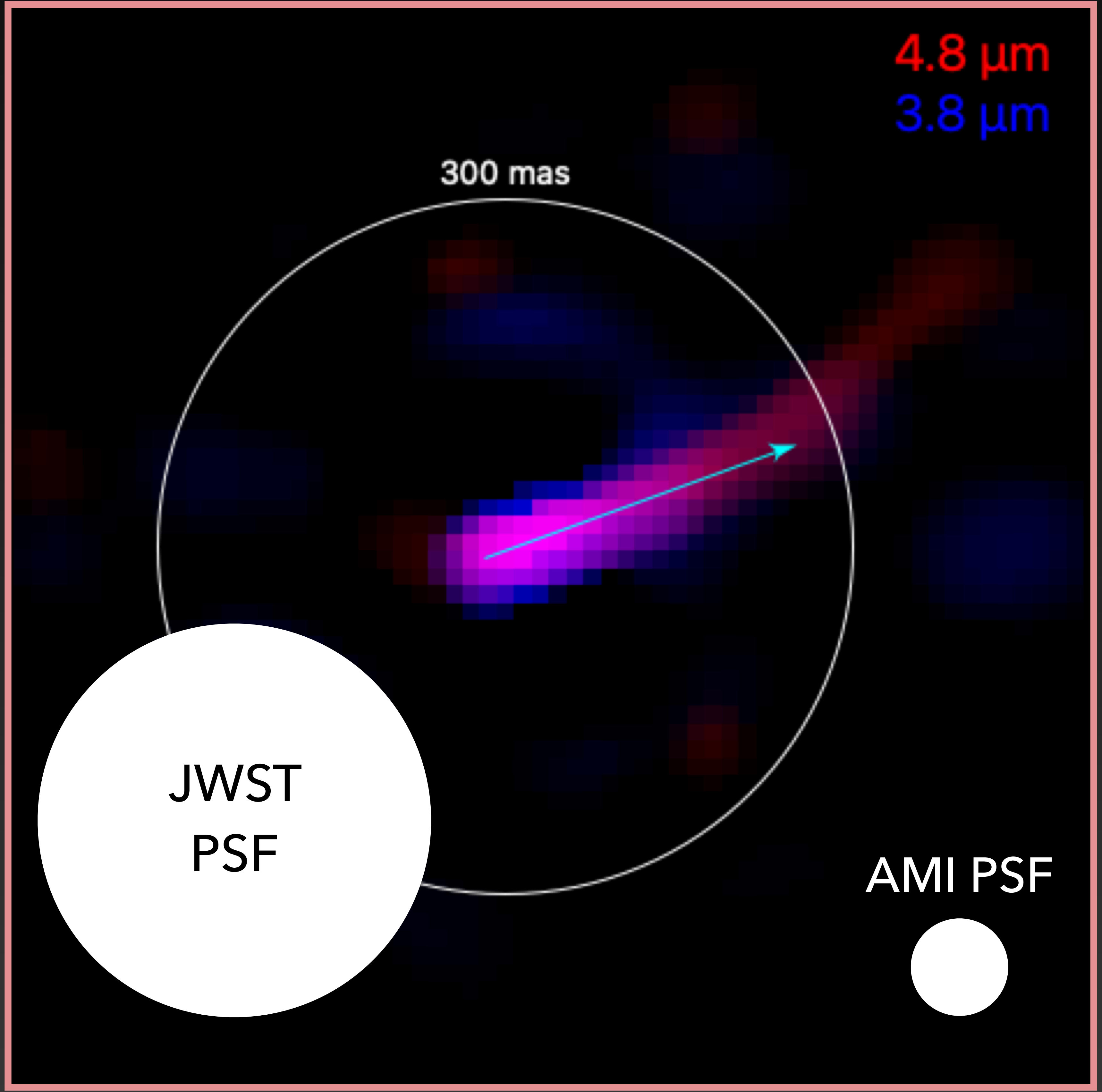
ERS data: the surprising view of WR137

- Super-resolution x4 thanks to the astonishing precision of the JWST

Preliminary results :

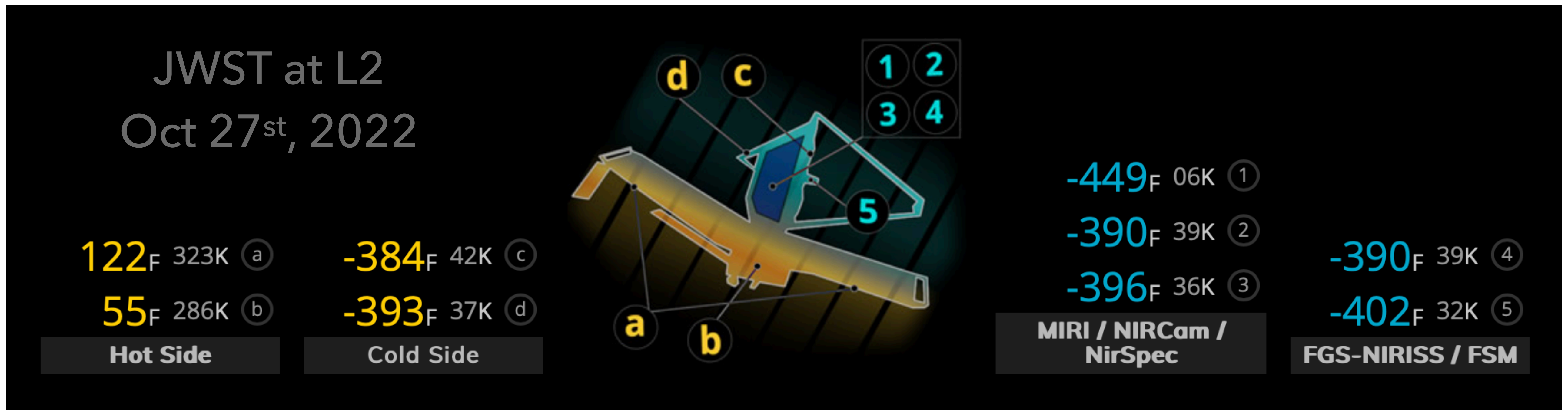
- Extremely collimated dust ejection detected
- Probable curvature after 300 mas: theoretical issue?
- Not standard colliding wind binary? = more complex dust production
- Anisotropic winds + inner dusty disk can create such a collimated dusty jet (<u>to be confirmed!</u>)

AMI-NIRISS + AMICAL + IRBis



Hankins, Soulain et al. in prep

Conclusion and take away



- The first interferometer ever operating in space will overcome all Adaptive Optics (AO) assisted instruments in both accuracy and sensitivity

- AMI-NIRISS offers a unique capability to probe inside the PSF's core of the JWST (70-400 mas) at the peak emission of hot/warm dust (3-5 μm)

- The synergy with ground-based interferometry offers real opportunities

- The 10 magnitudes contrast limitation allows detecting Few Jupiter mass planets and faint companions around nearby stars at a few AU scale

AMI is now fully available for the community, and ready for YOUR science!

Beyond this project…

Future of AMI with JWST

Do you want to know more about our « dusty » origin?

WR pinwheel nebulae and galaxy dust budget

Soulain et al. 2018

Hydrodynamical simulations of Dusty Wolf-Rayet stars

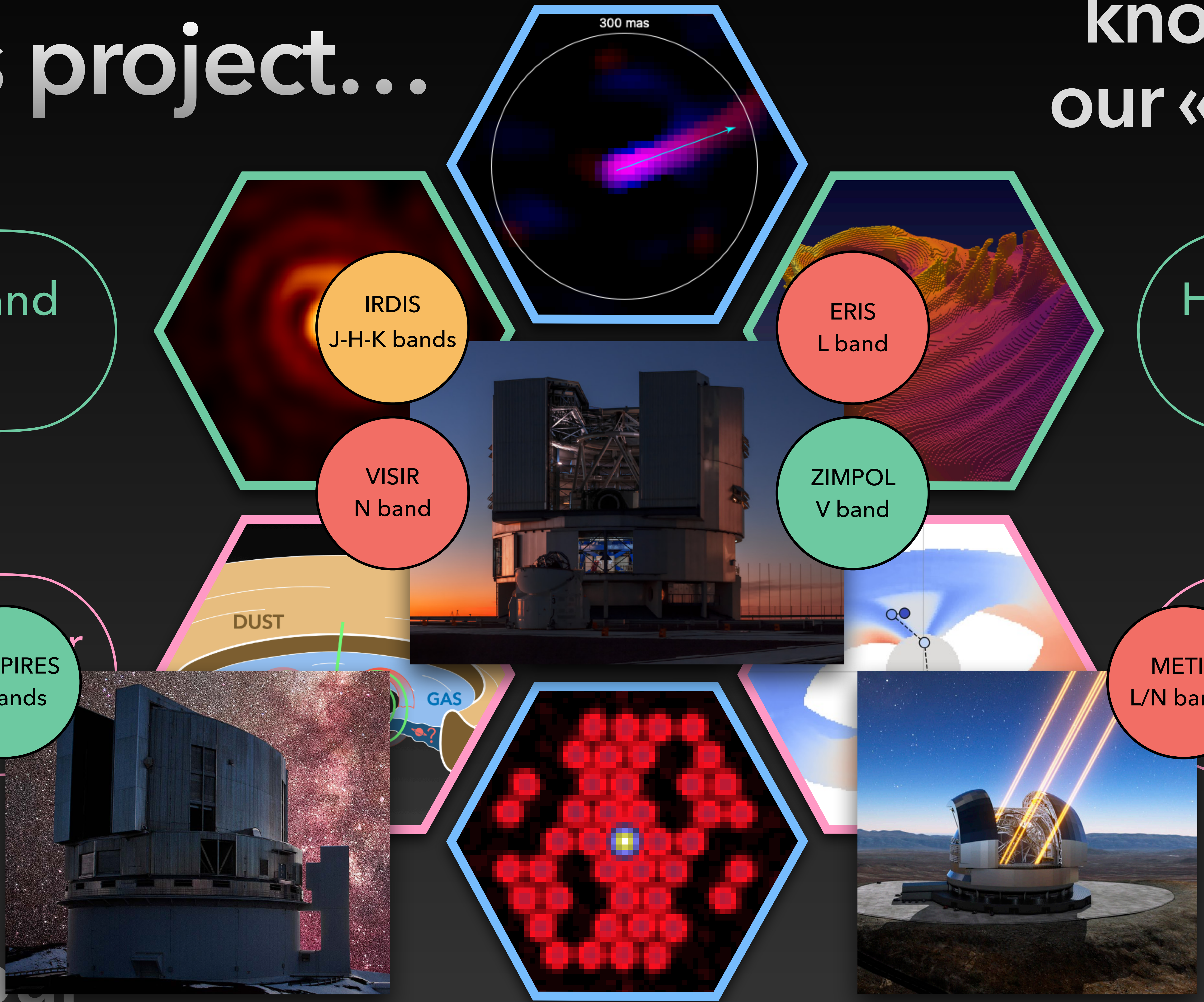
Soulain et al. 2023a

Inner region of Young
Object with GRAV

Soulain et al. 2023b

agnetospheric accretion
n young sun-like stars

Tessore, Soulain et al. 2023



Thanks for yo
attention

Develop AMI from the ground to space

Questions?