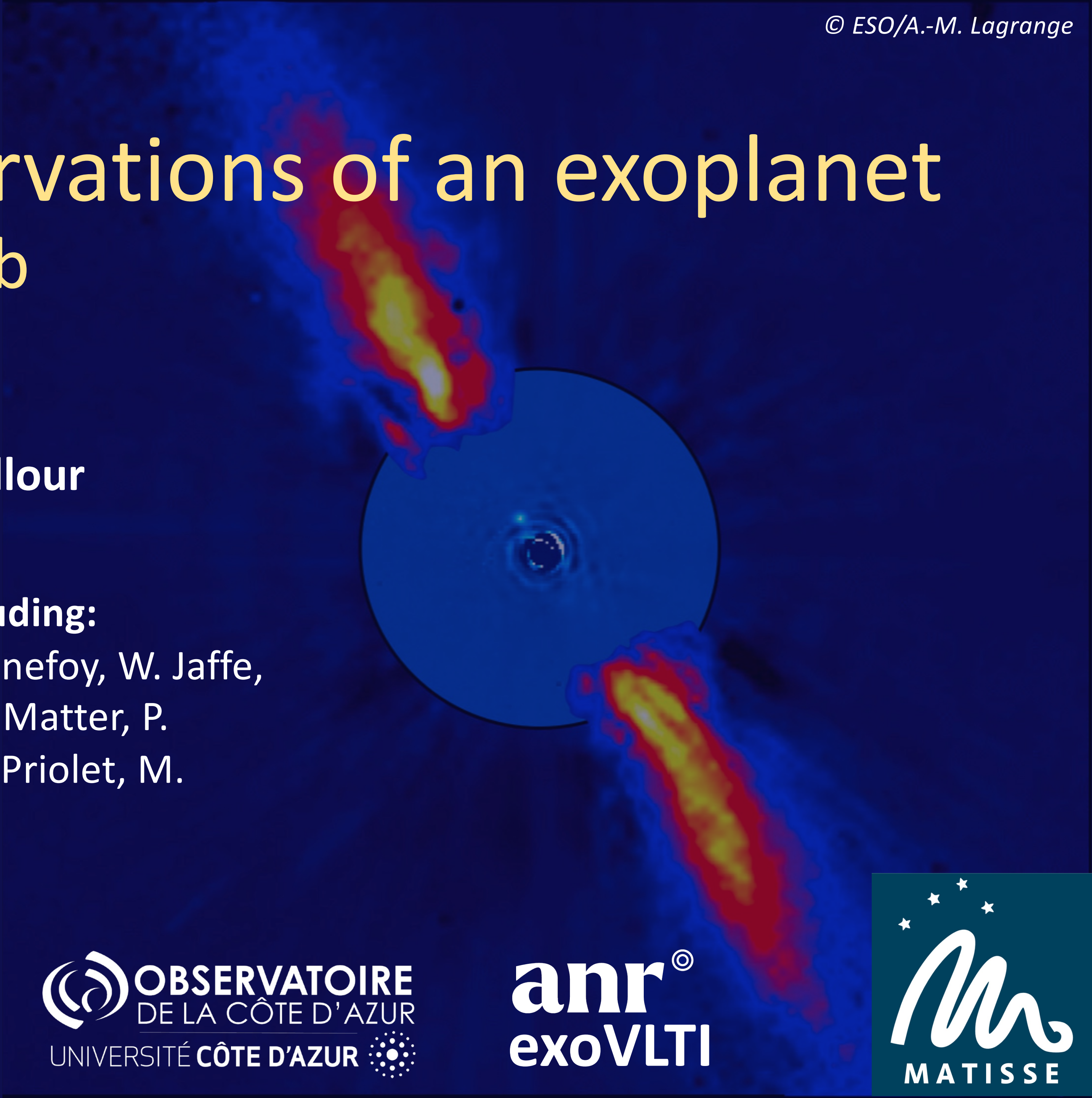


First MATISSE observations of an exoplanet
Demonstration on β Pic b

~~Matisse~~ Mathis Houllé – Florentin Millour
Observatoire de la Côte d'Azur

& the MATISSE & ExoGRAVITY teams, including:
F. Allouche, J.-C. Augereau, P. Berio, M. Bonnefoy, W. Jaffe, S. Lacour, S. Lagarde, J. Leftley, B. Lopez, A. Matter, P. Mollière, M. Nowak, E. Pantin, R. Petrov, P. Priolet, M. Ravet, J. Scigliuto, J. Woillez…

MATISSE Science Days – 06/11/2024

OBSERVATOIRE DE LA CÔTE D'AZUR
UNIVERSITÉ CÔTE D'AZUR
anr exoVLTI
MATISSE

How to collect exoplanet photons?

- Easy! Point at a star.

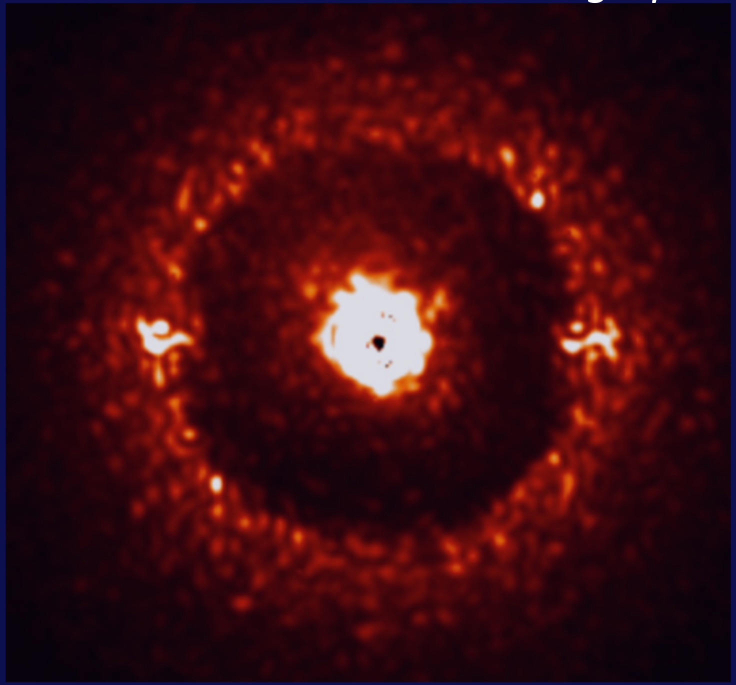
How to collect exoplanet photons?

- Easy! Point at a star.

How to disentangle planet and star photons?

- This is the challenge
  - 1 planet photon for 10^4 (brown dwarfs/super-Jupiters) to 10^{10} (Earth) star photons
  - Diffraction limit

Stellar PSF with AO + coronagraph



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- Easy! Point at a star.

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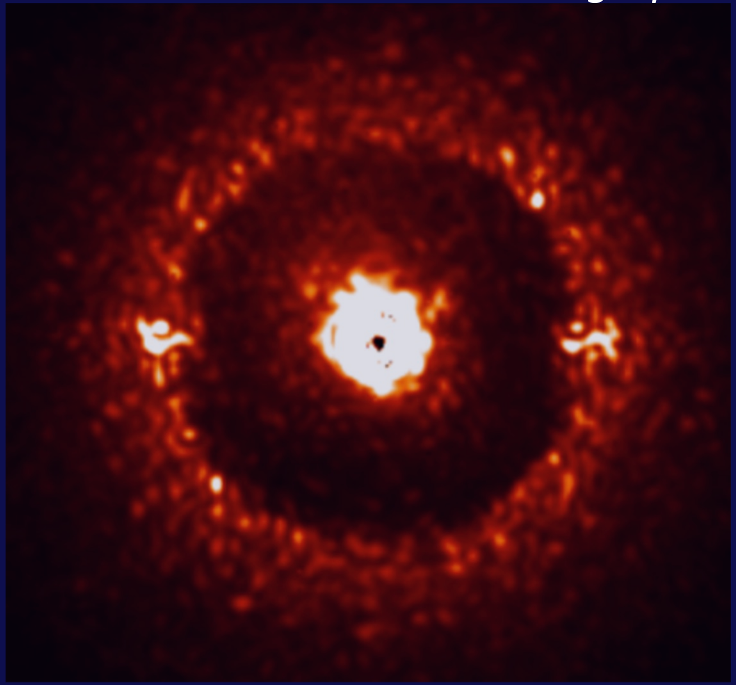
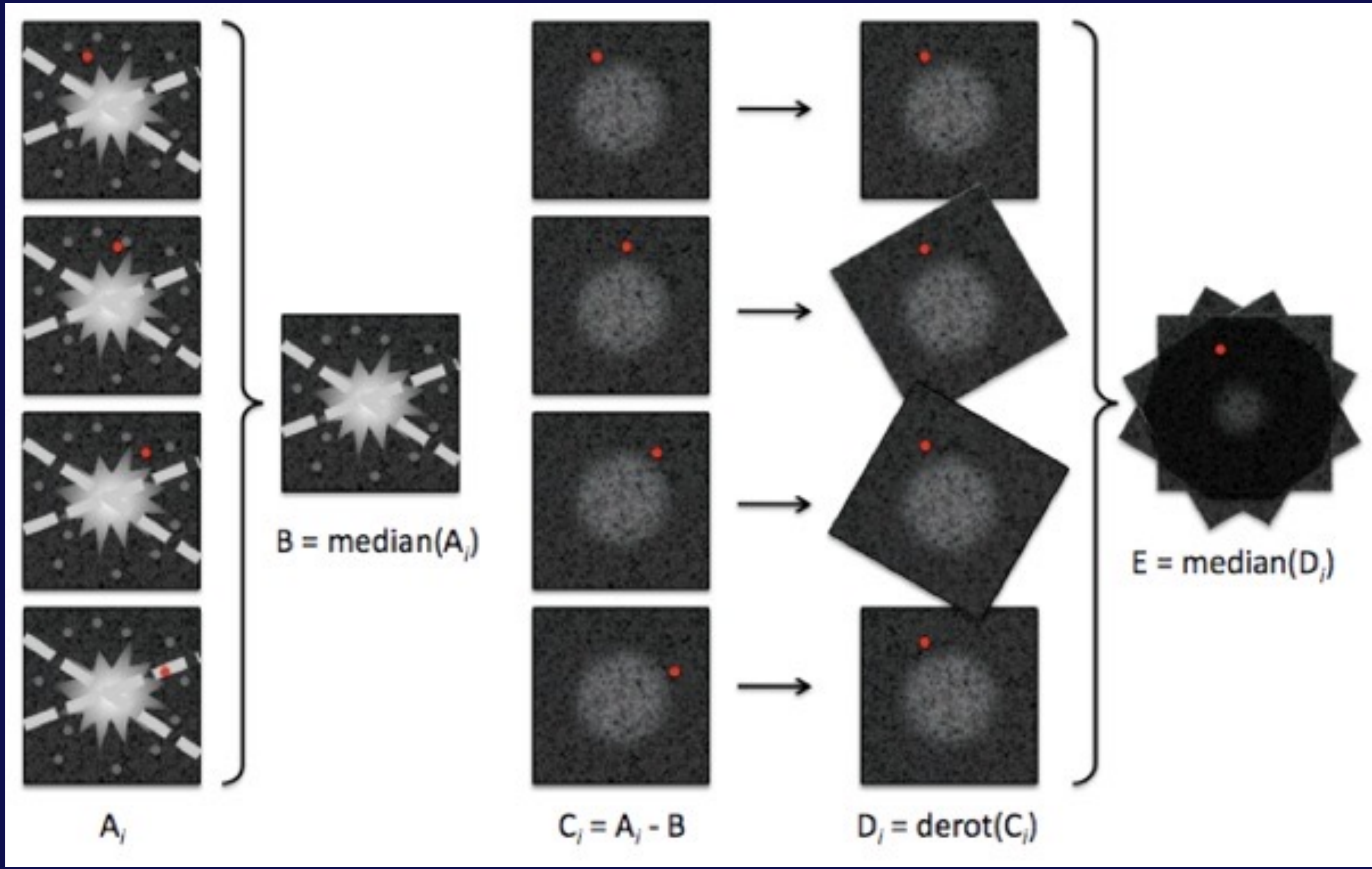
- This is the challenge
  - 1 planet photon for 10^4 (brown dwarfs/super-Jupiters) to 10^{10} (Earth) star photons
  - Diffraction limit
- Has to rely on some kind of *diversity*
  - Observations where the planet moves with respect to the stellar speckles
  - Can be field rotation, wavelength, polarization, time…

Stellar PSF with AO + coronagraph



Disentangling photons in direct imaging

- Angular differential imaging

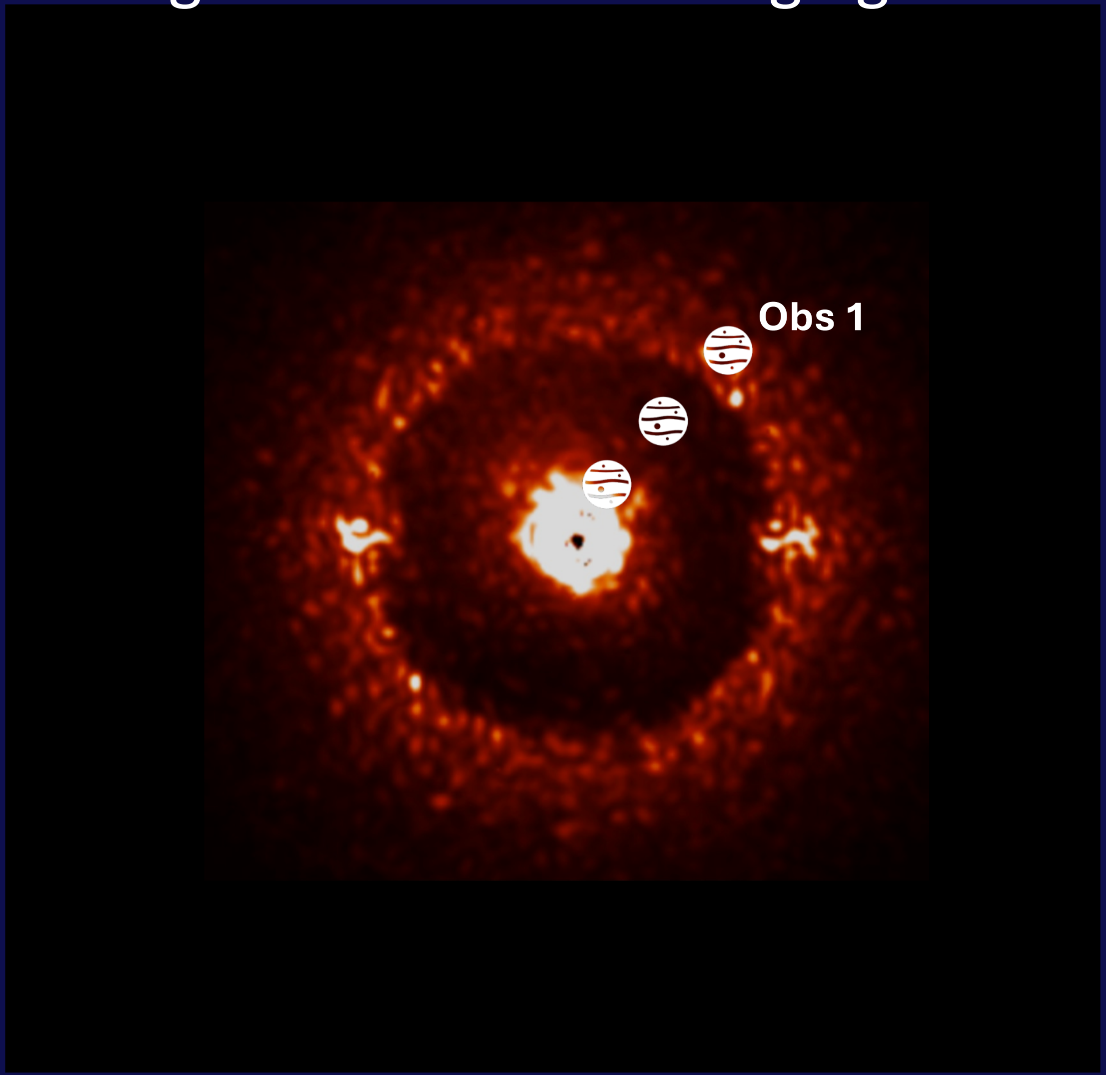


Field of view (including planets) rotate during the night, while the pupil (including speckles) stays fixed.

The two can then be disentangled.

Disentangling photons in direct imaging

- Angular differential imaging



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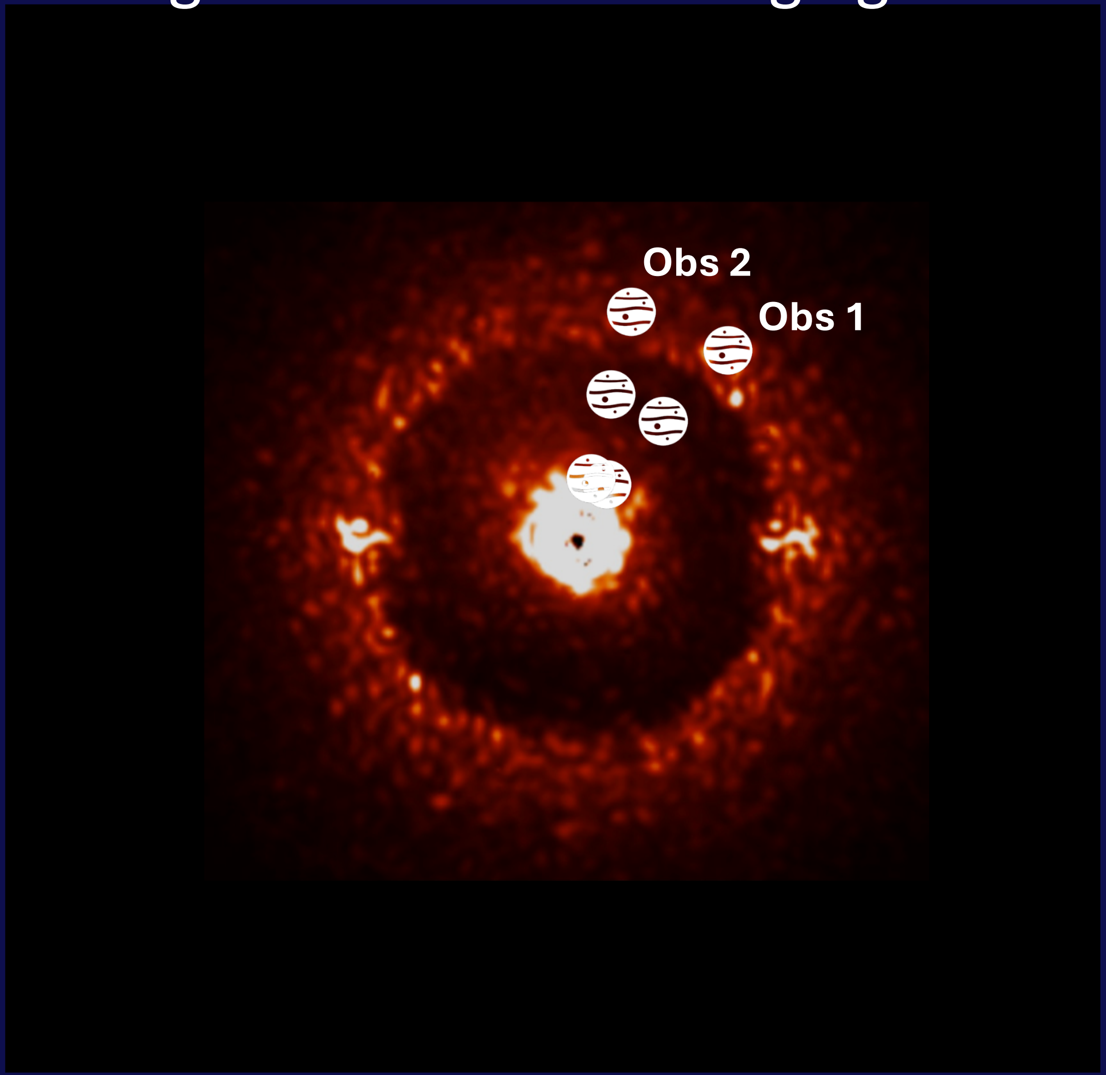

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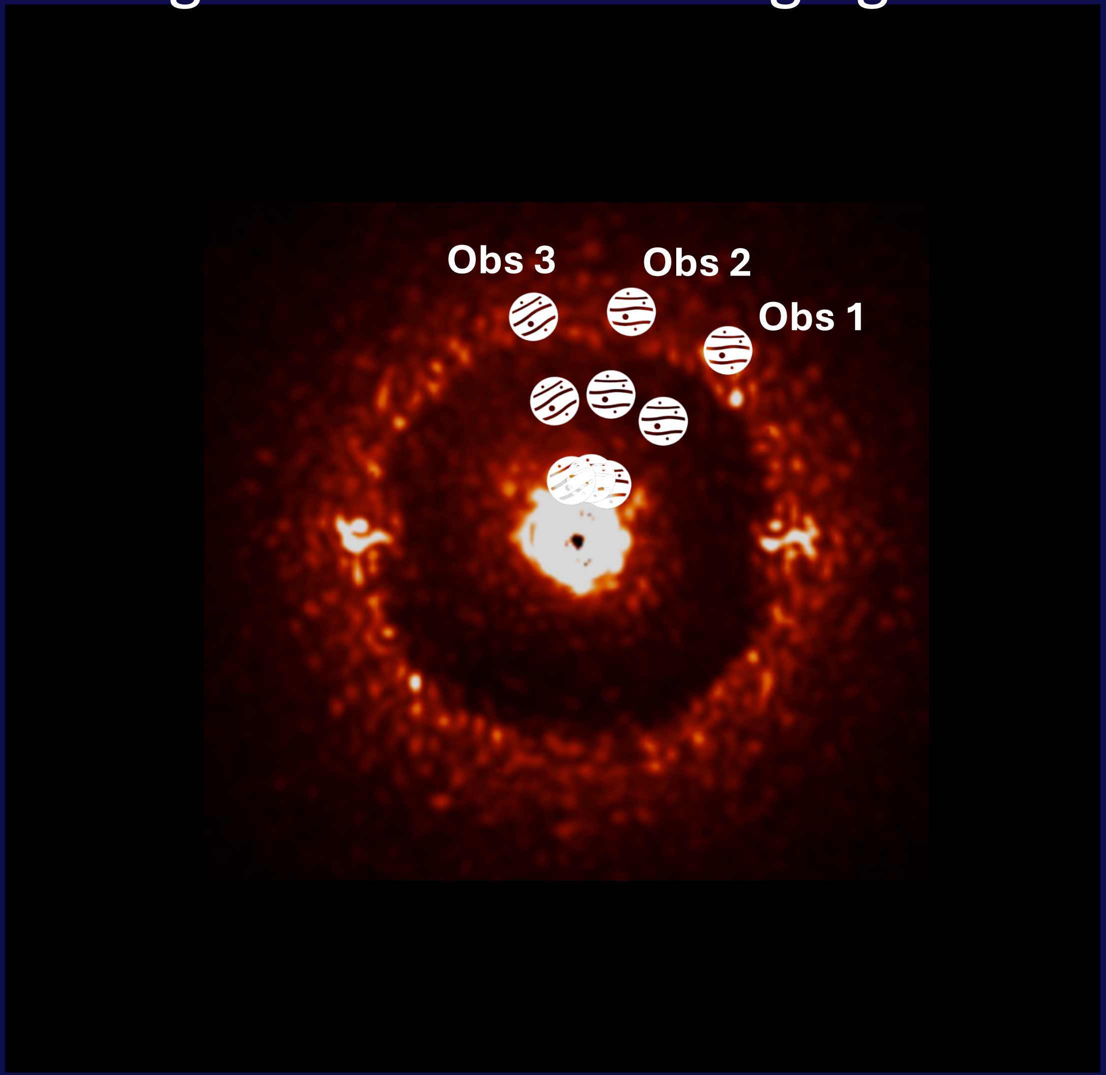

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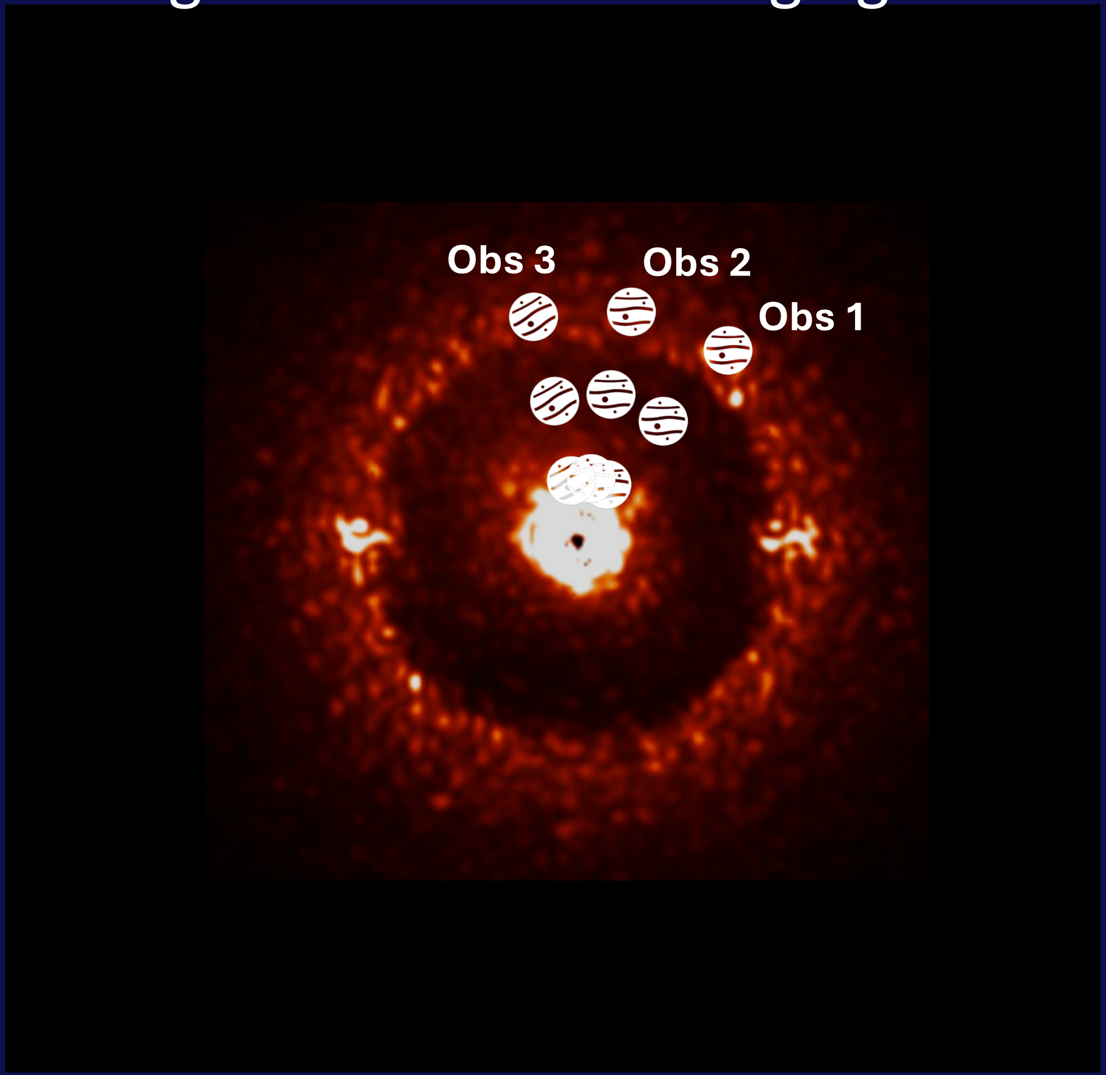
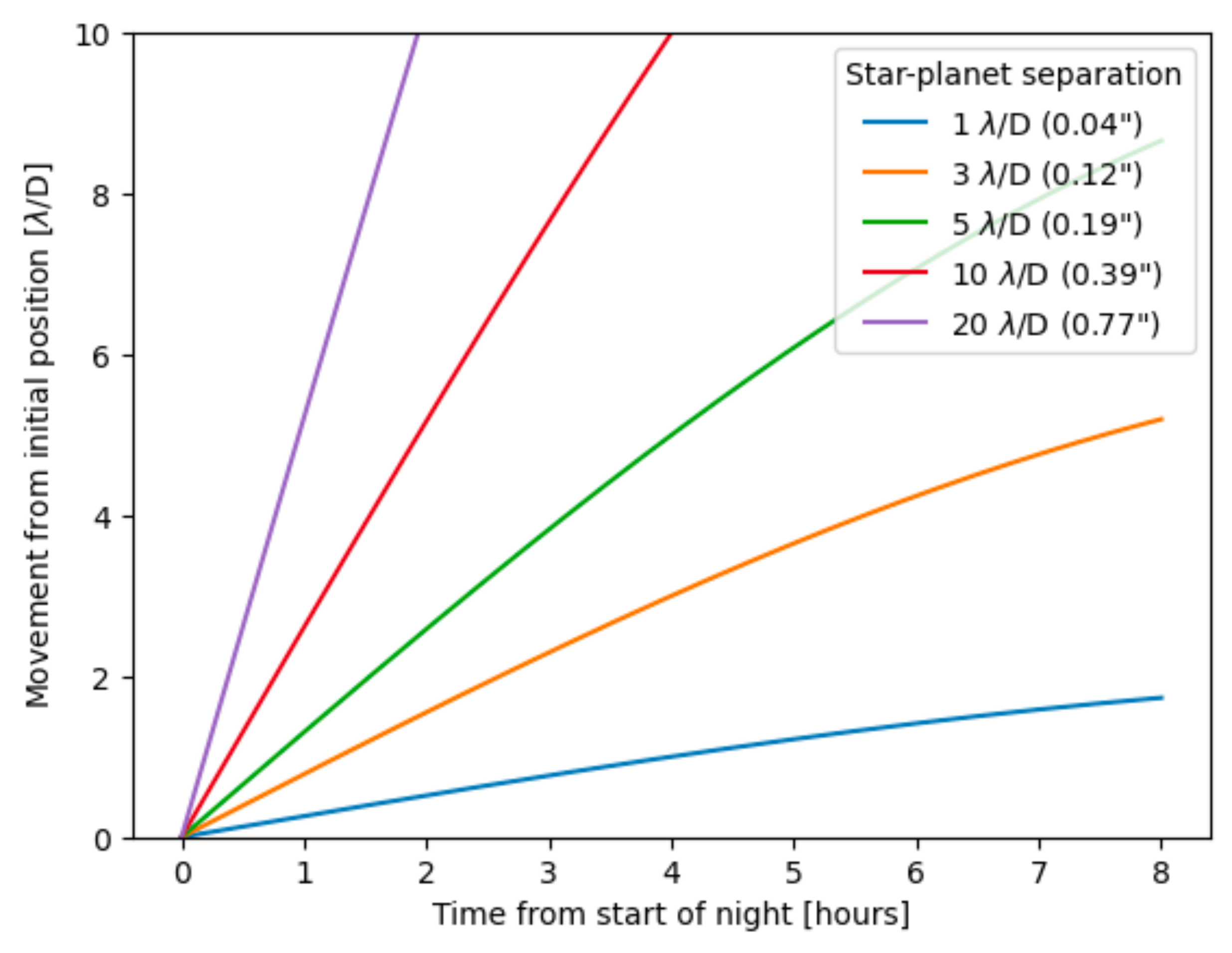


Few uncorrelated exposures at low separation
- self-subtraction

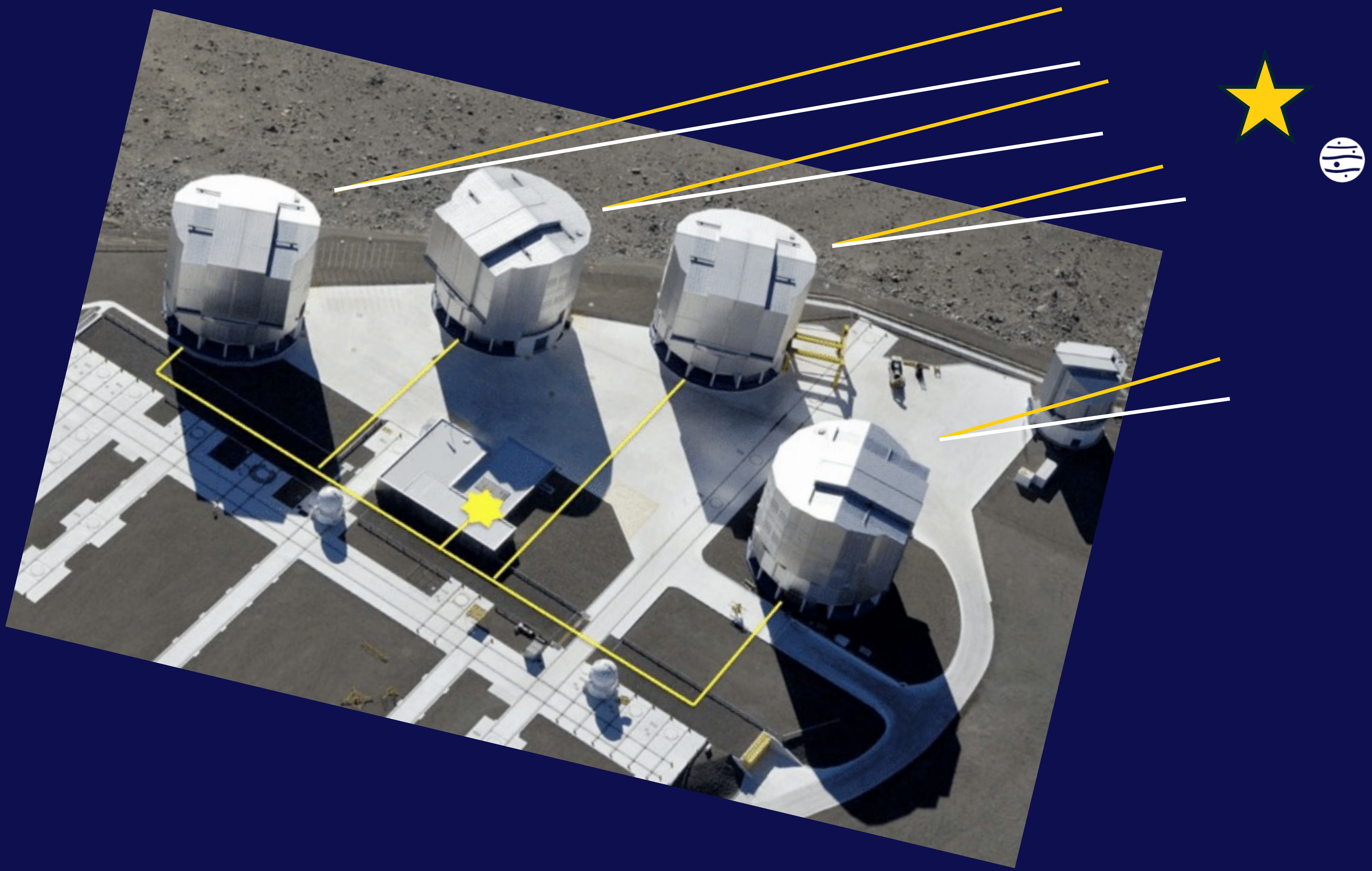


Disentangling photons in interferometry

- VLTI baselines rotate during the night

Disentangling photons in interferometry

- VLTI baselines rotate during the night



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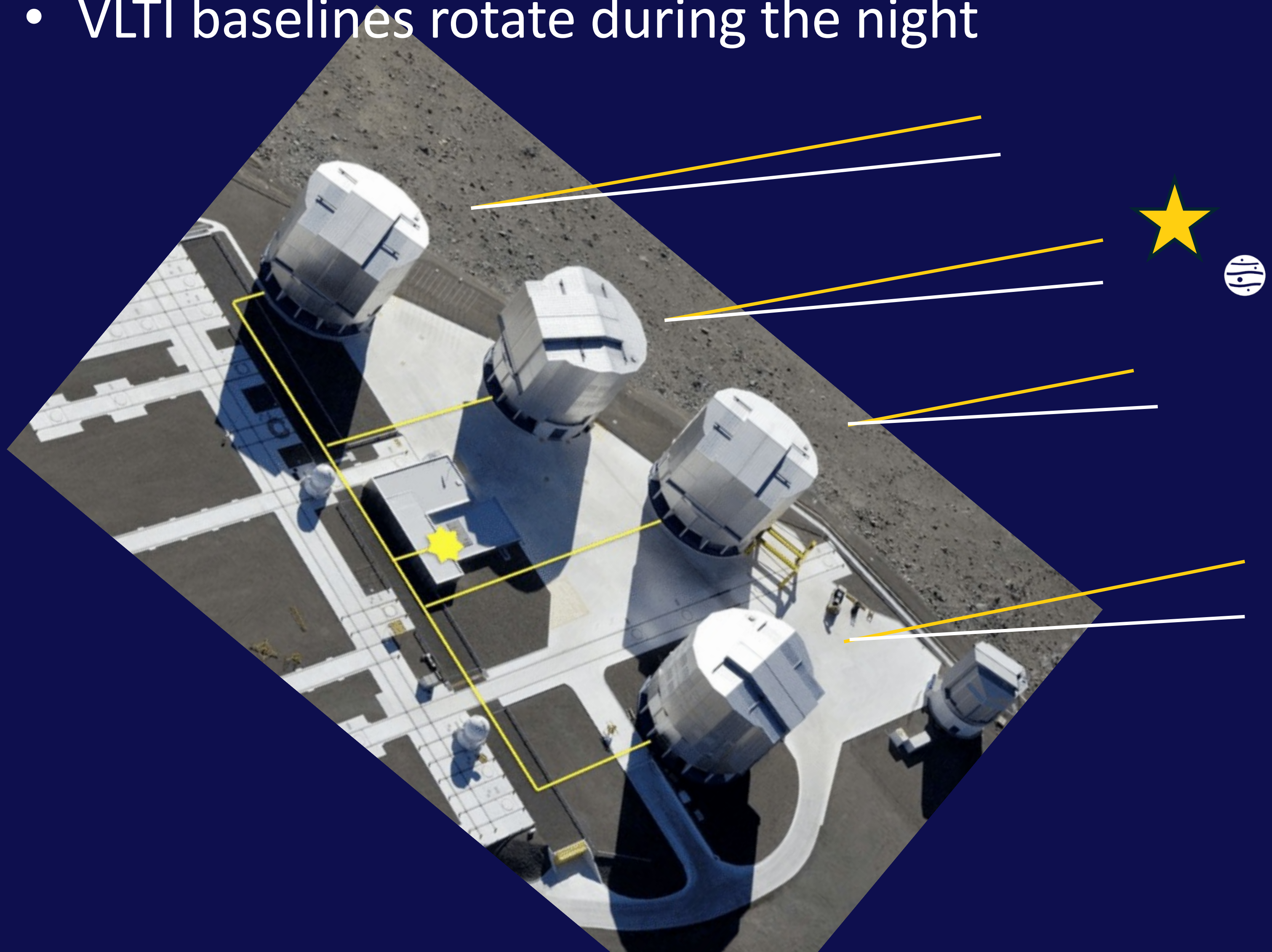
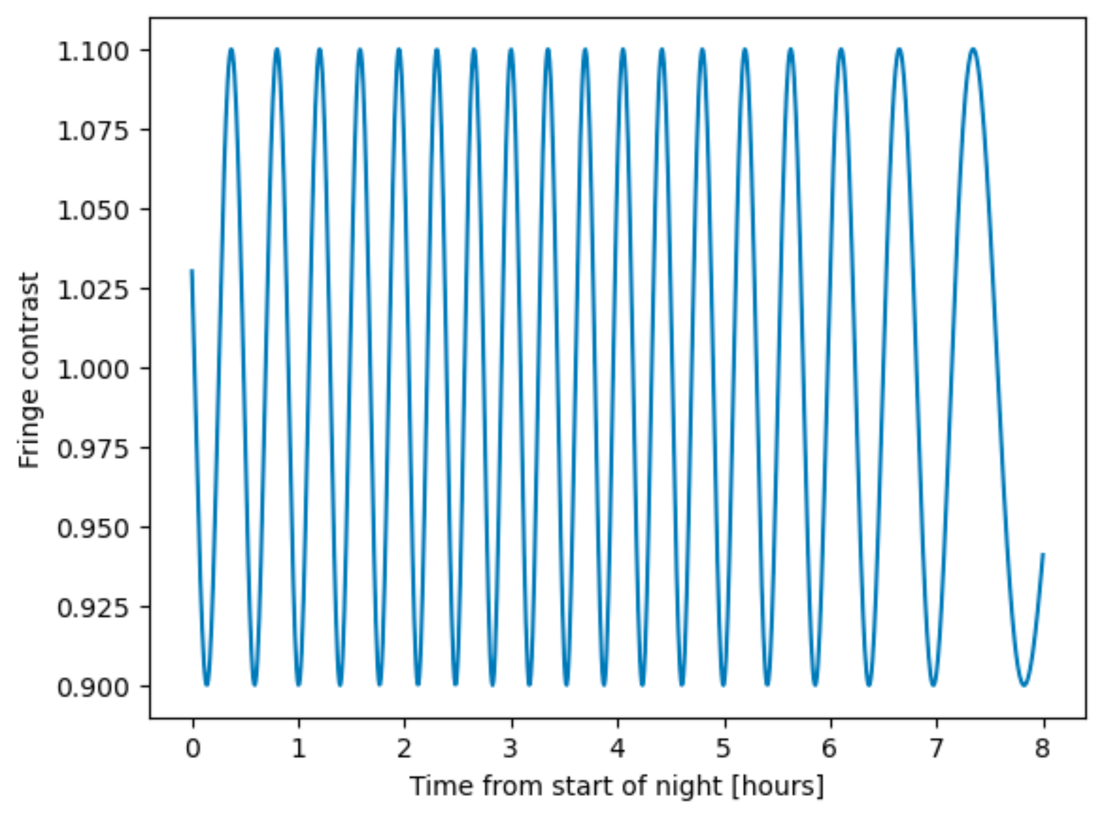


Disentangling photons in interferometry

- Two telescopes interfering make fringes
- The fringes amplitude and phase is related to the Fourier transform of the target spatial distribution
- For a star and planet:
    - Fringe envelope $= S_p + R\ S_* \exp i \frac{2\pi\vec{\alpha}\vec{u}}{\lambda}$
    - $\vec{u}$: baseline vector
    - $\vec{\alpha}$: star-planet separation
    - S_*, S_p: stellar & planetary spectra
    - R: stellar speckle chromaticity

Fringe amplitude for a planet at 0.05" separation and baseline of 100 m



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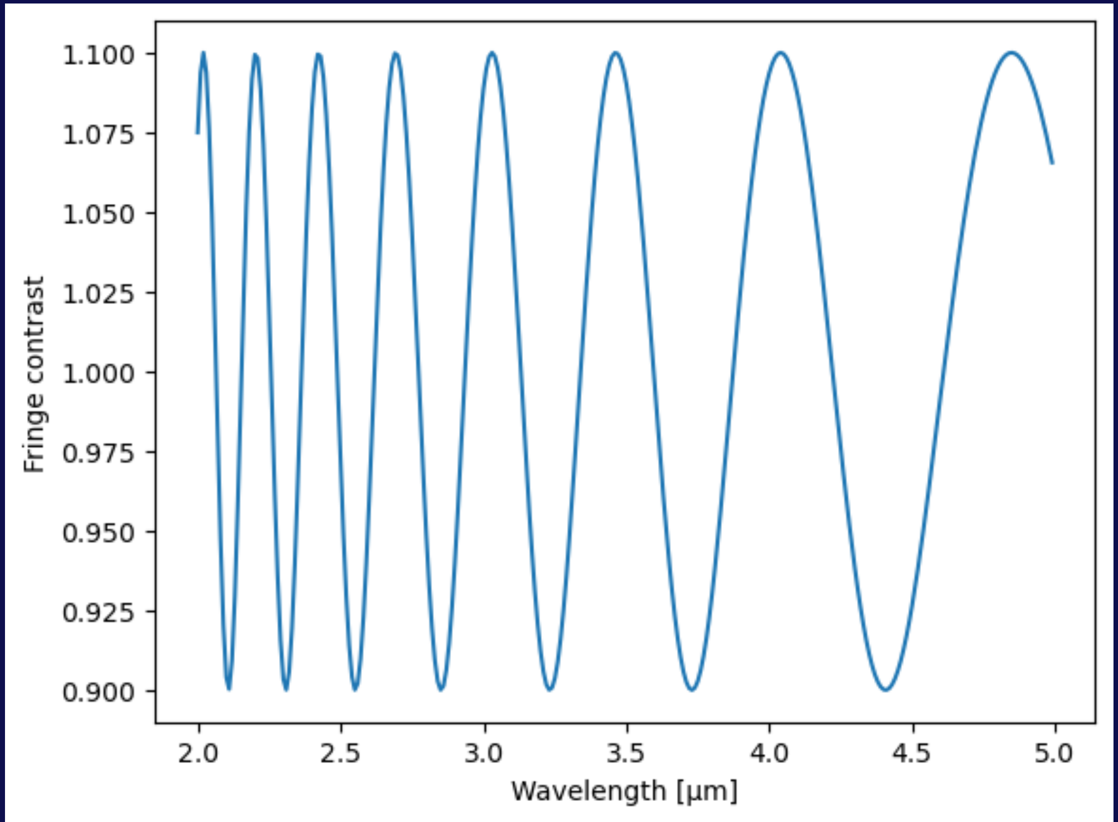
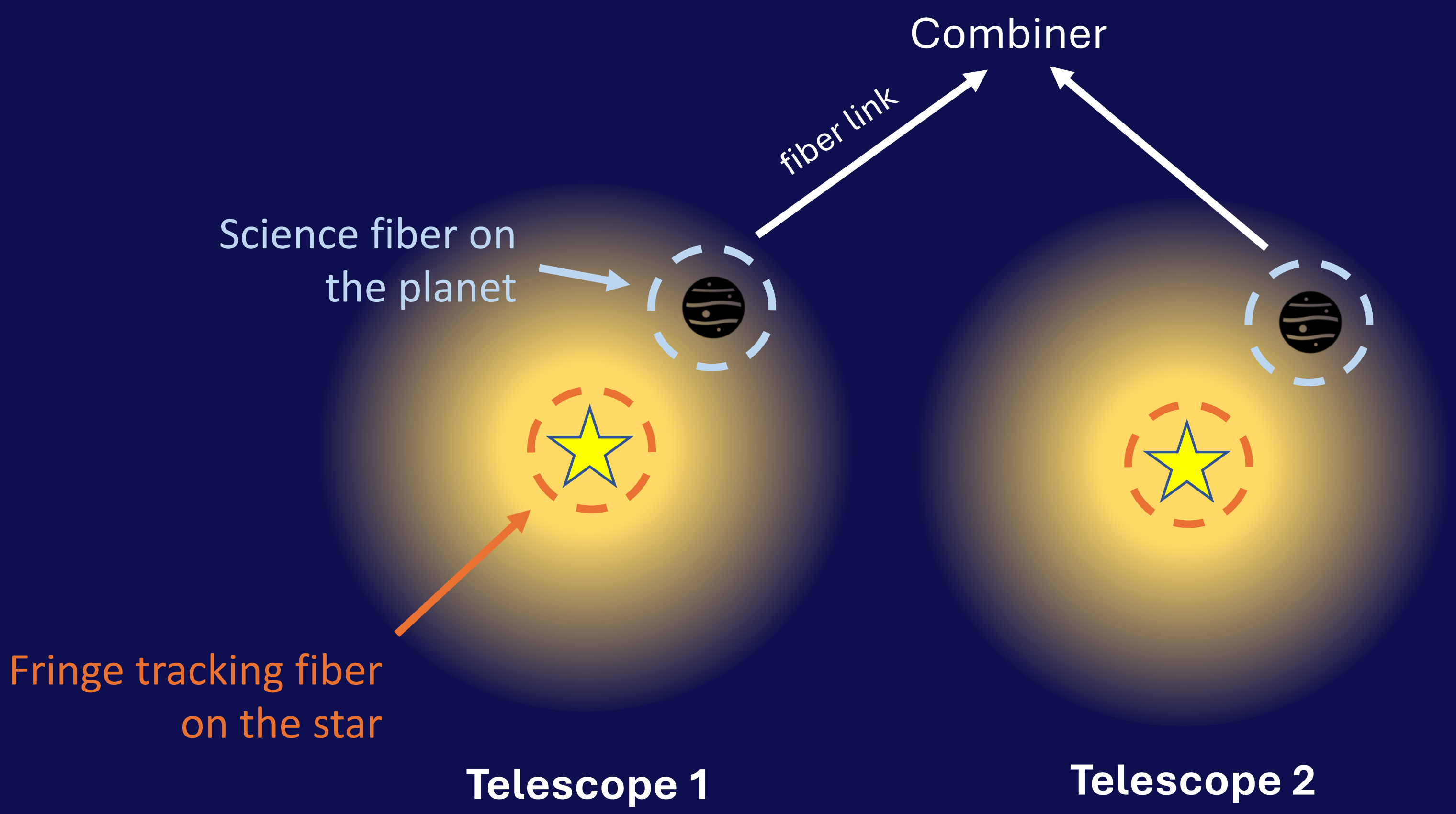


Disentangling photons in interferometry

GRAVITY exoplanet observations



Adaptive optics
MACAO / GPAO

+

Spatial filtering
The monomode fiber filters most of the stellar flux, acting similarly as a coronagraph.

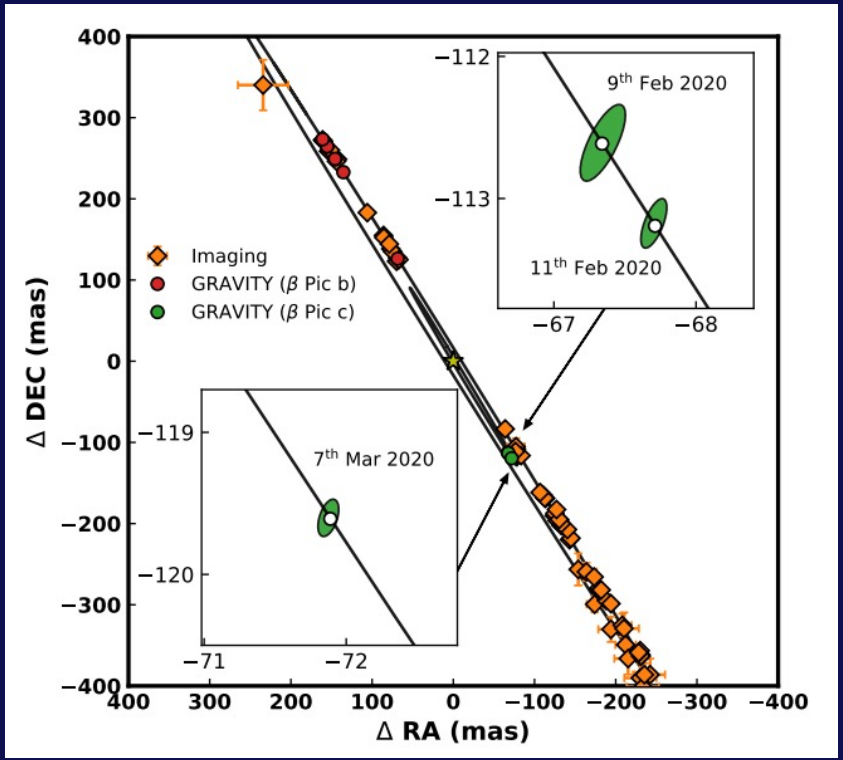
+

Post-processing
Decoupling stellar and planetary signals

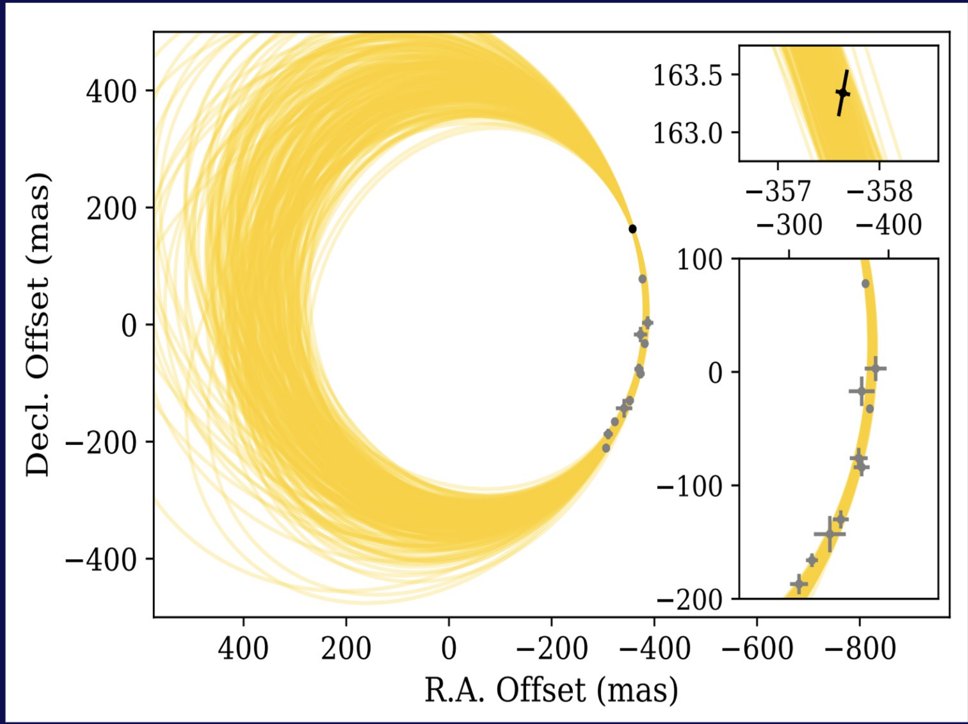
Exoplanet interferometry with GRAVITY

- Ultra-precise **planet astrometry**
  - orbital fitting
  - gives **dynamical masses** (vs. model-dependent "photometric" masses in direct imaging)

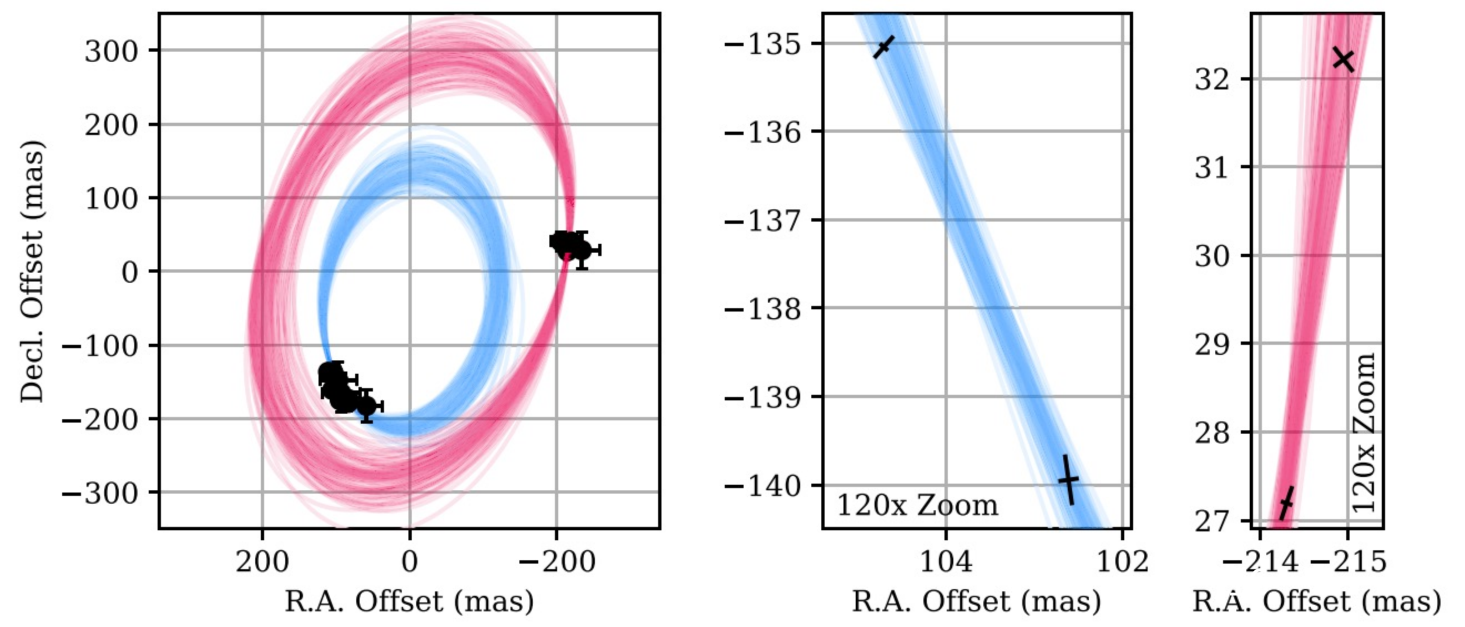
β Pic b & c (Nowak+ 2020)



HR 8799 e (GRAVITY Collab.+ 2019)



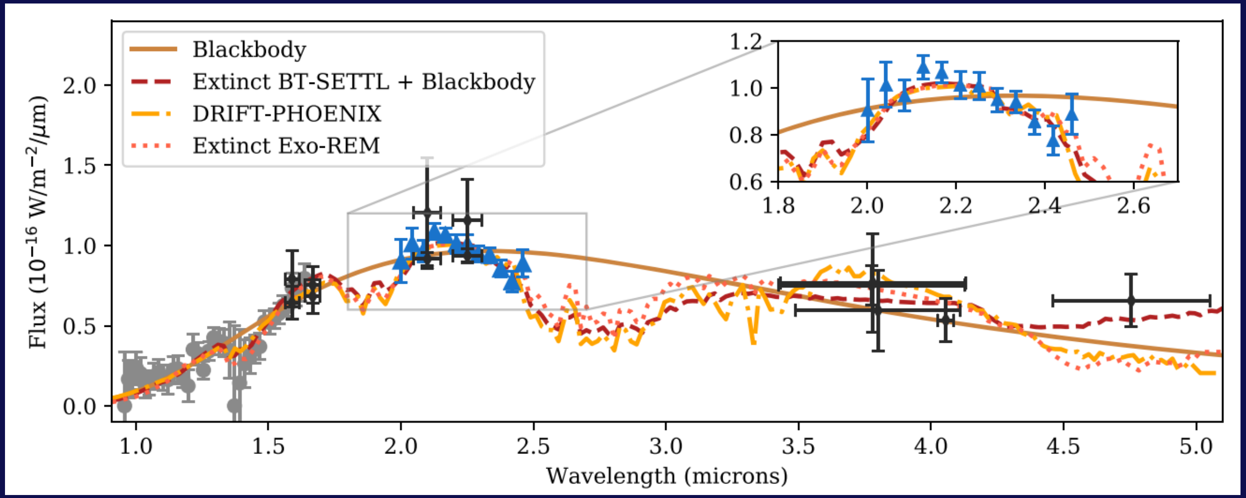
PDS 70 b & c (Wang+ 2021)

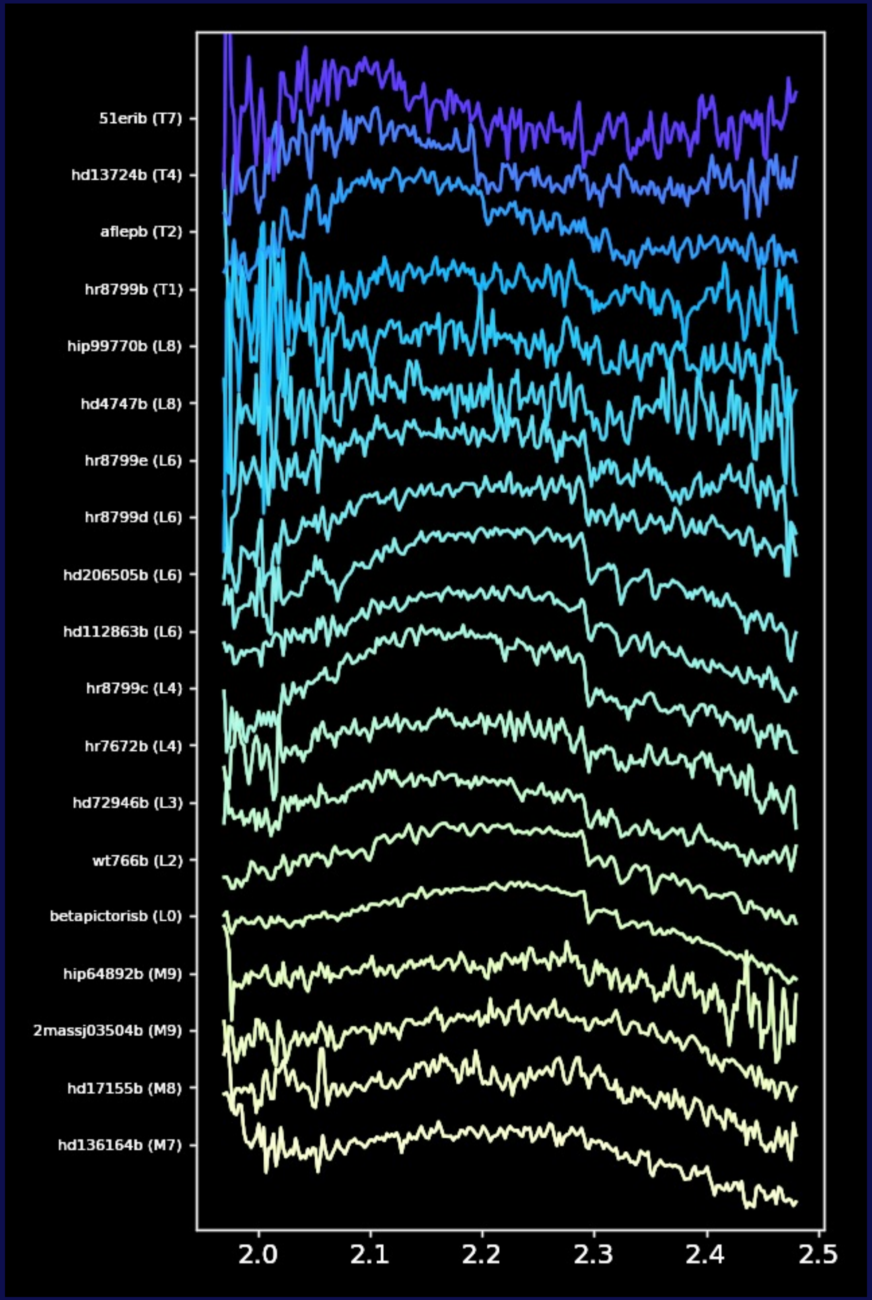


Exoplanet interferometry with GRAVITY

- High-quality **near-infrared spectra**
  - medium spectral resolution (R=500)
  - constrains atmospheric parameters: temperature, surface gravity, C/O, metallicity…
  - C/O linked to planet birthplace and formation mechanism

PDS 70 b (Wang+ 2021)

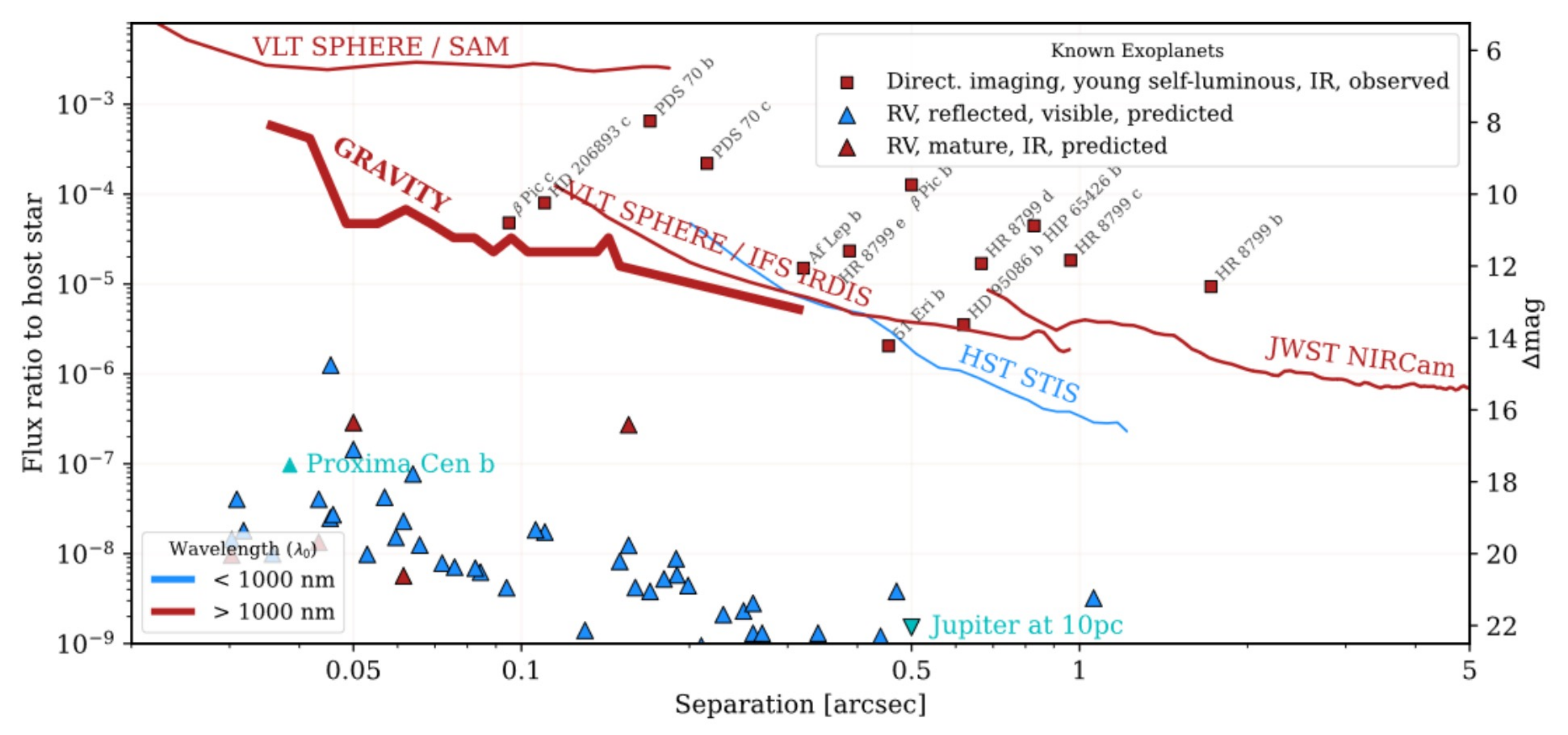




Lacour/Kammerer/ExoGRAVITY

Interferometry & direct imaging

Pourré et al. 2024

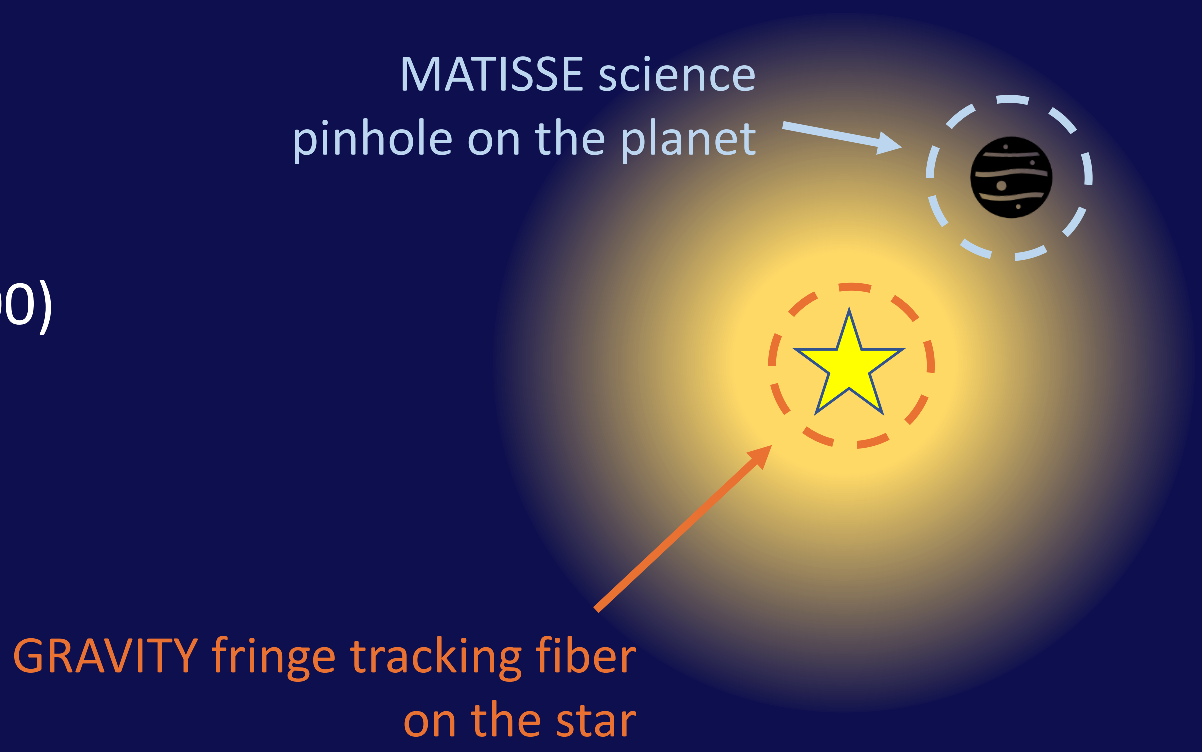


MATISSE & GRA4MAT

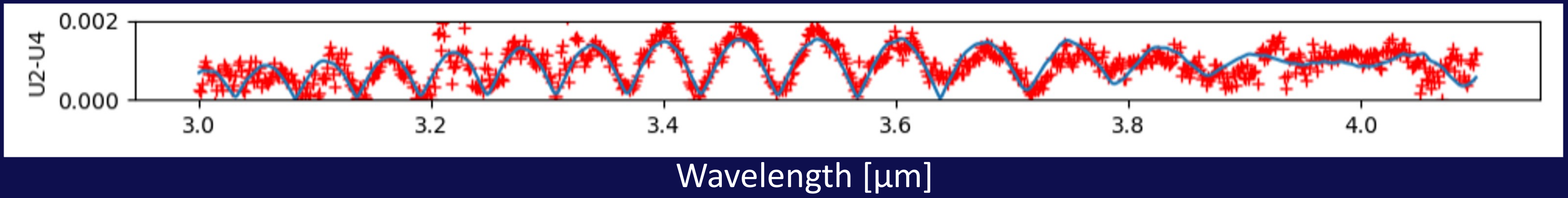
- **MATISSE**: L, M and N band spectro-interferometer
- The GRAVITY fringe tracker can now assist MATISSE observations:
  - This is **GRA4MAT** (Woillez et al. 2024)
  - Greatly improves MATISSE sensitivity: $t\text{exp} = 100 \text{ ms} \Longrightarrow 10 \text{ s}$
  - Now limited to background noise instead of detector noise
  - In addition: narrow off-axis mode: Fringe tracker on star, MATISSE on planet

First demonstration on β Pictoris b

- First demonstration:
  - $\boldsymbol{\beta}$ Pictoris b (Nov. 2022)
  - 4 UTs
  - Medium spectral resolution (R = 500)
  - 45 min on planet
    15 min on star

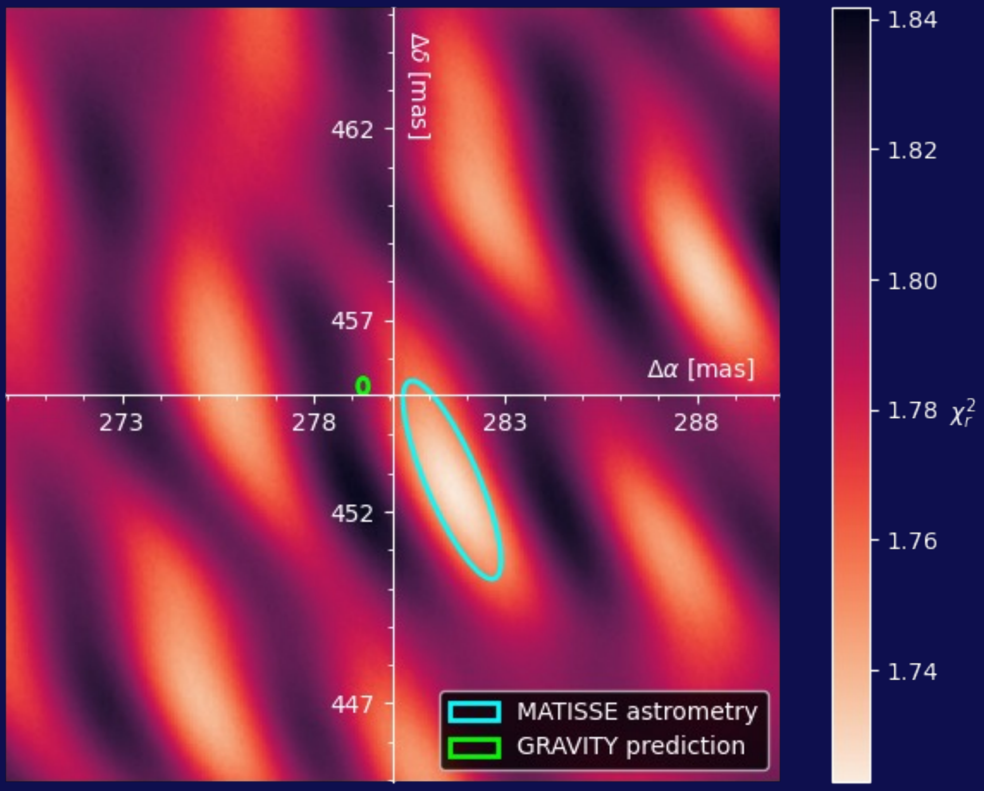


Fringe amplitude

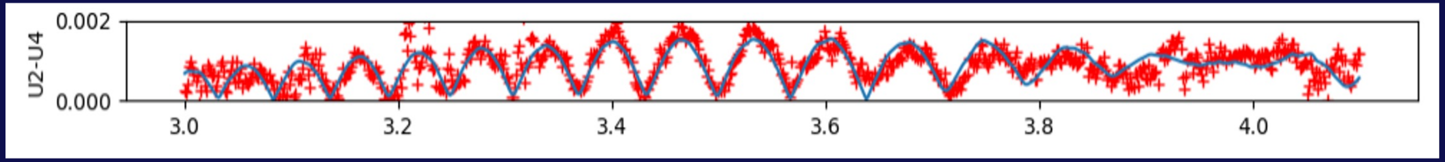


1st step: astrometry & stellar contamination

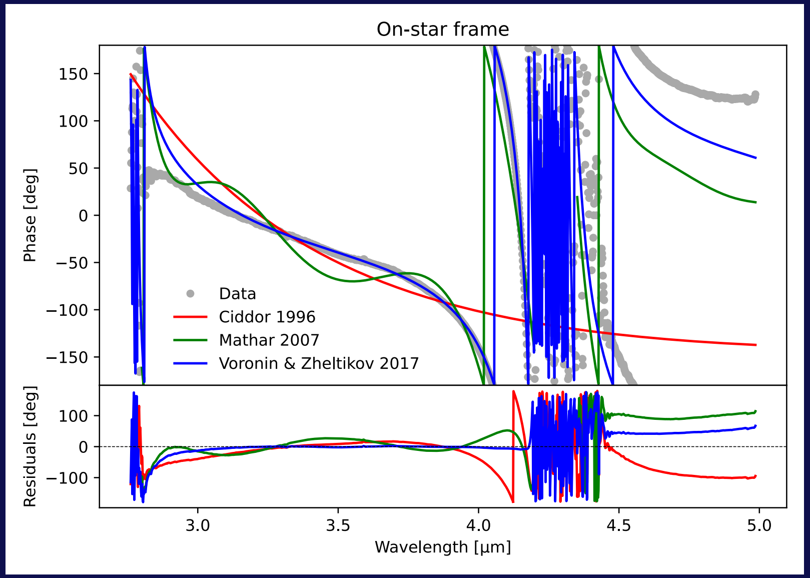
Fitting the planet astrometry & stellar contamination

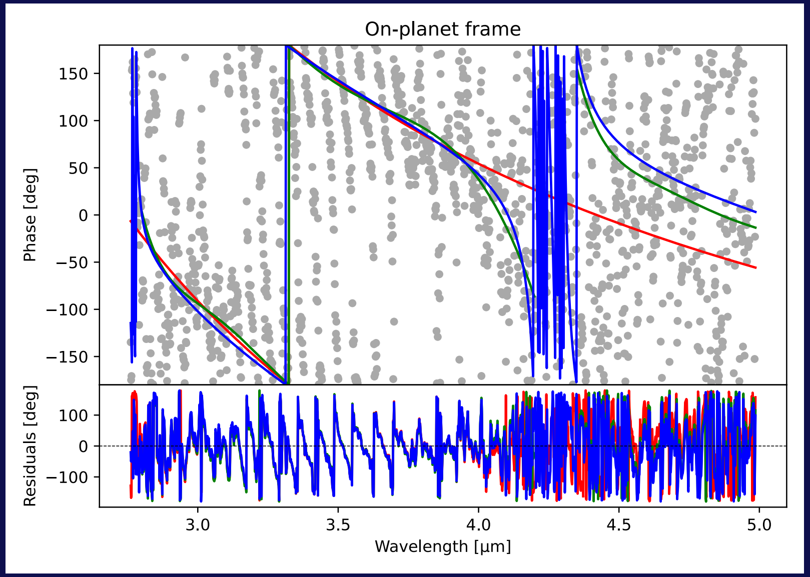


- Planet found ~3.5 mas away from GRAVITY predictions.
- GRAVITY astrometry more reliable thanks to its internal metrology.



Testing several air refractive index models to correct the fringe phase

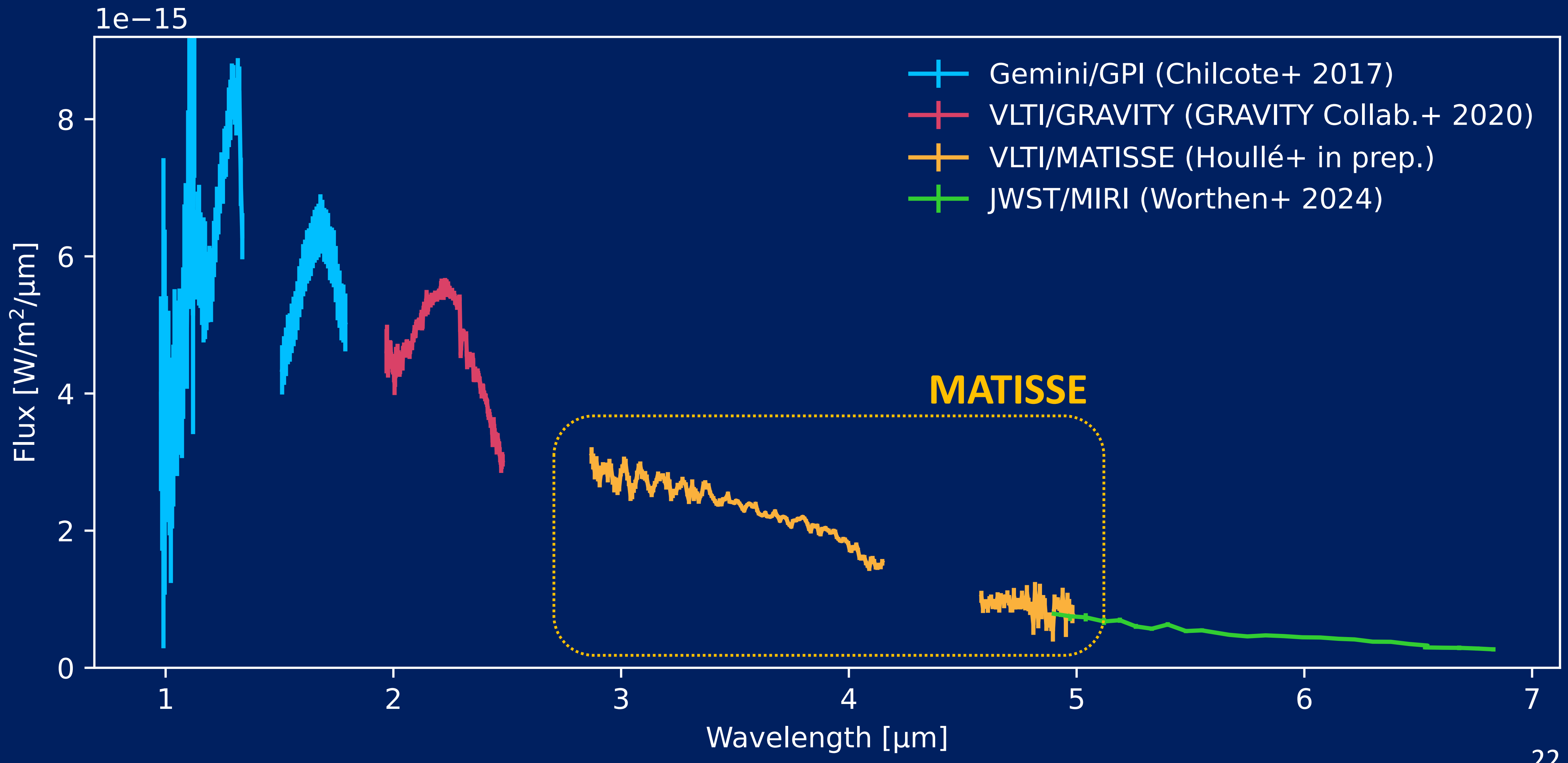




2^{nd} step: the spectrum!

$$S_p(\lambda) = C(\lambda) \times S_*(\lambda)$$

β Pic b spectra now covers a range of 1 to 7 µm!



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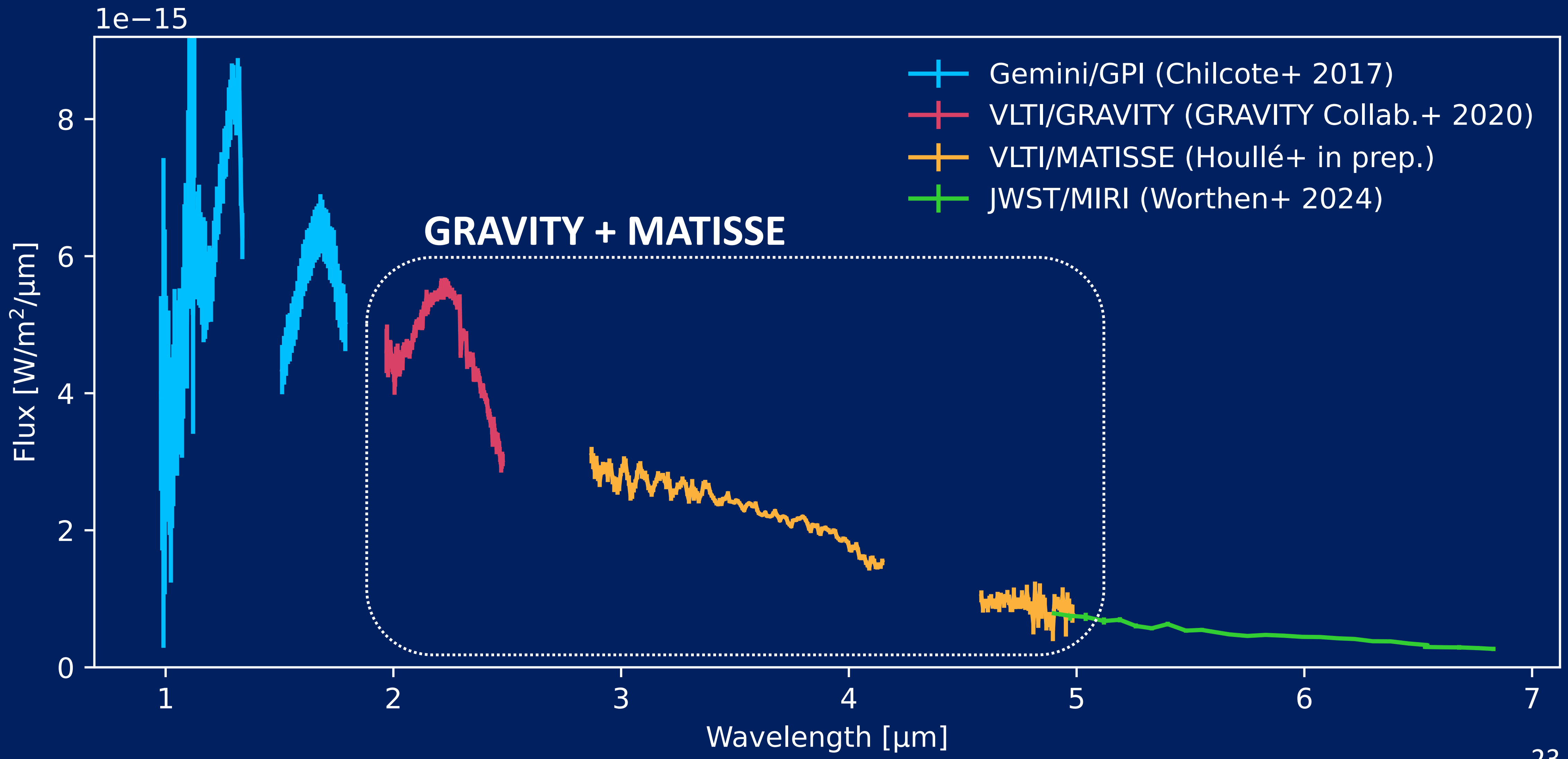
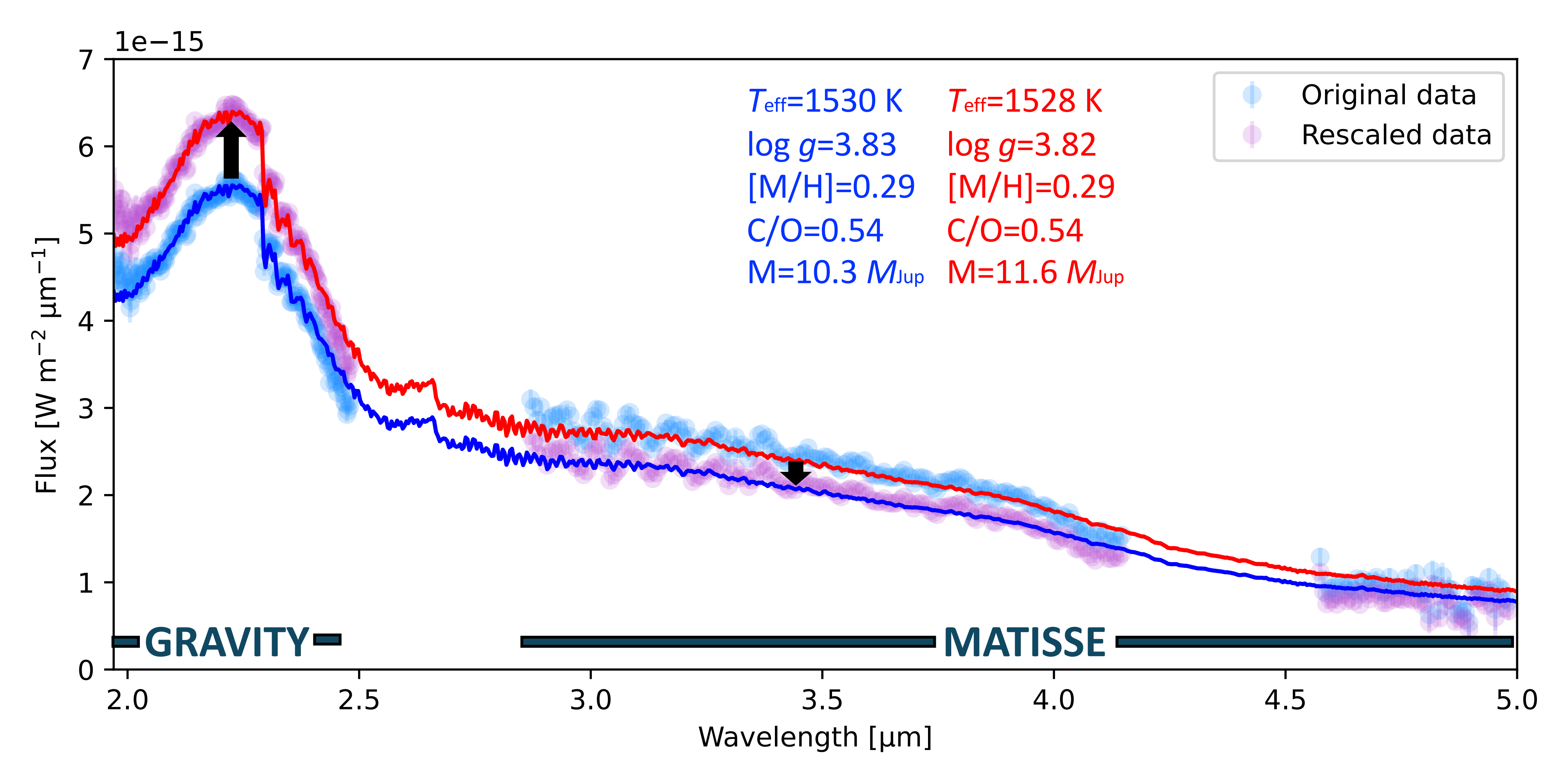


Atmospheric modelling

ForMoSA fitting code (Petrus+23)

ExoREM model grid (Charnay+18)



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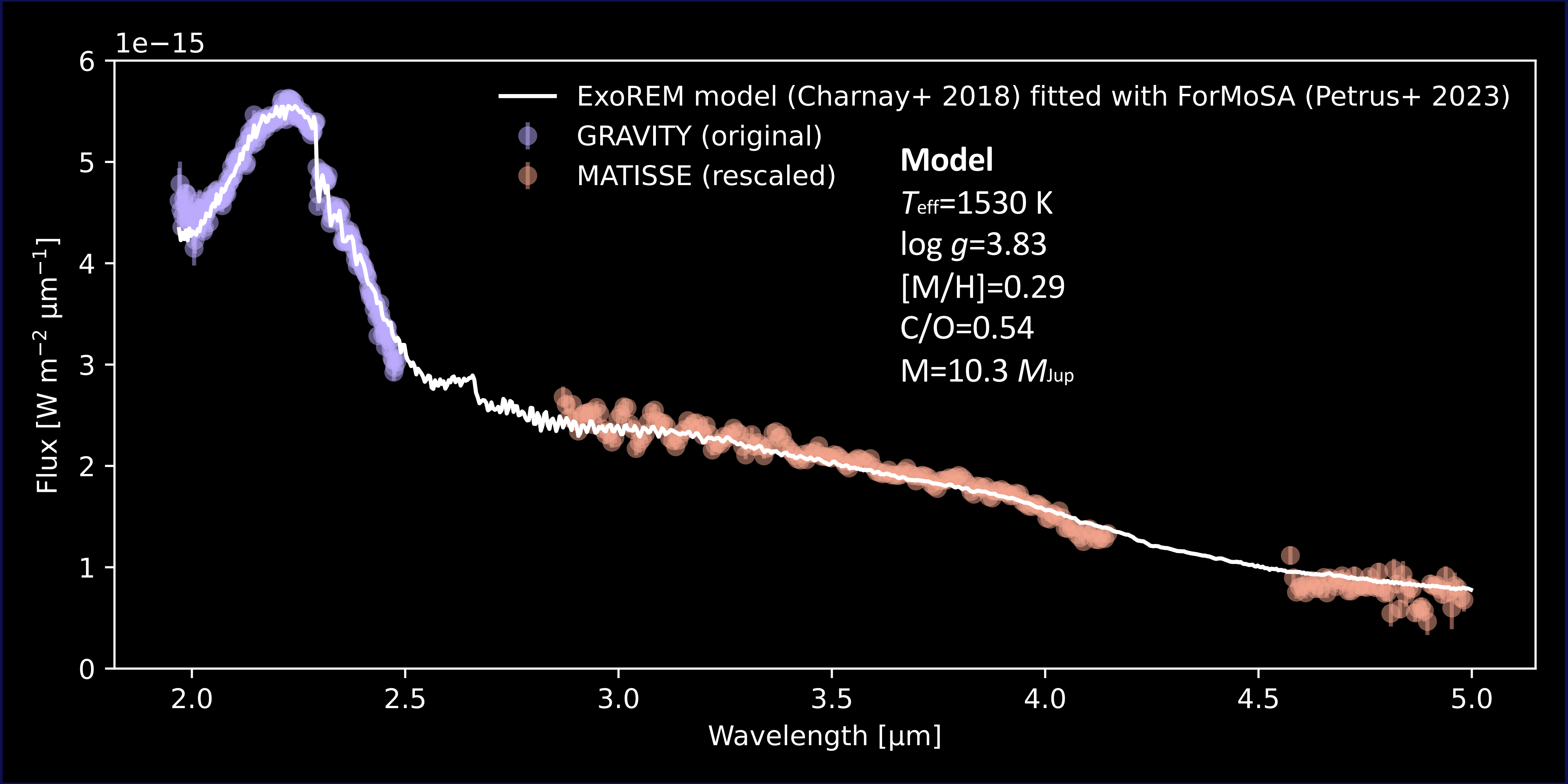

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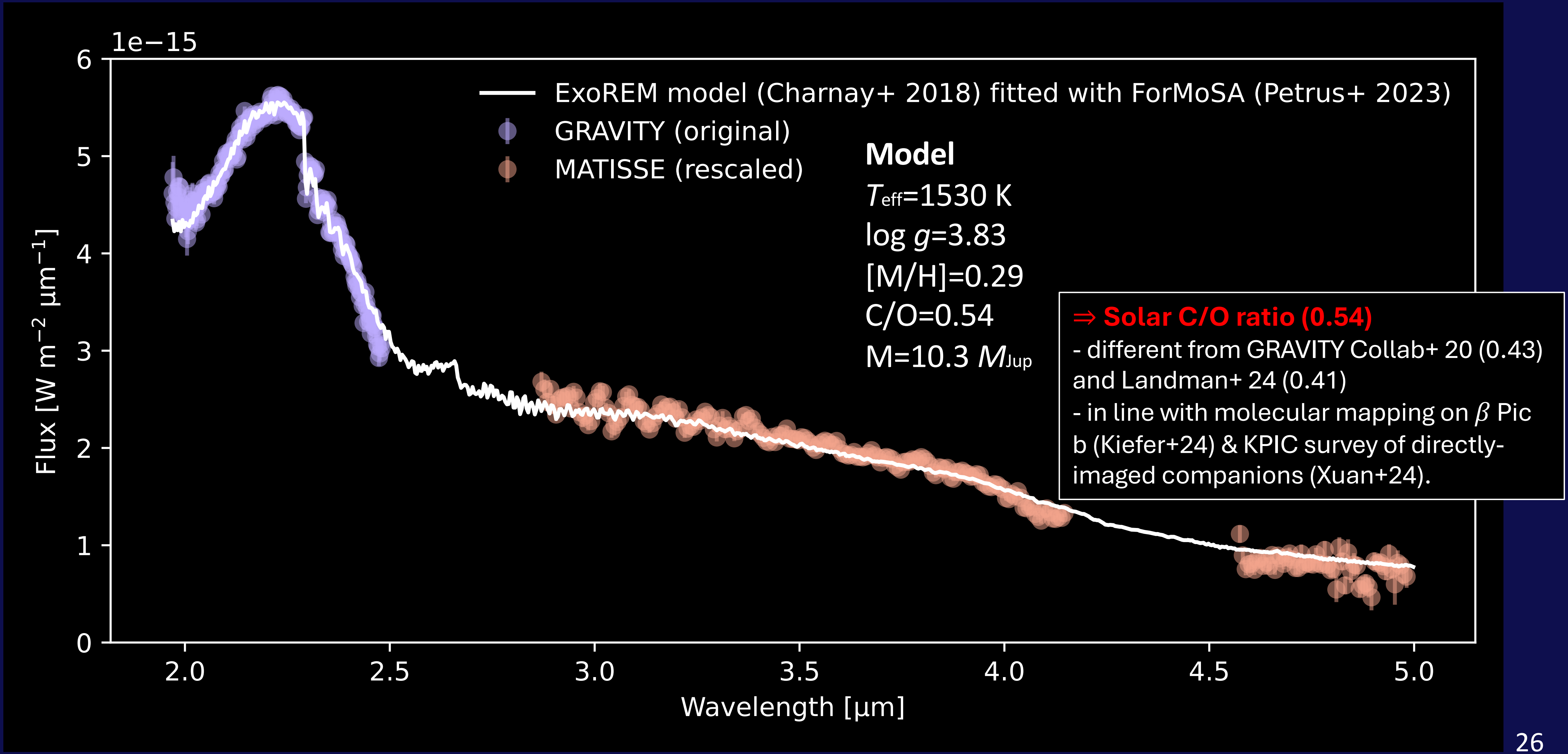

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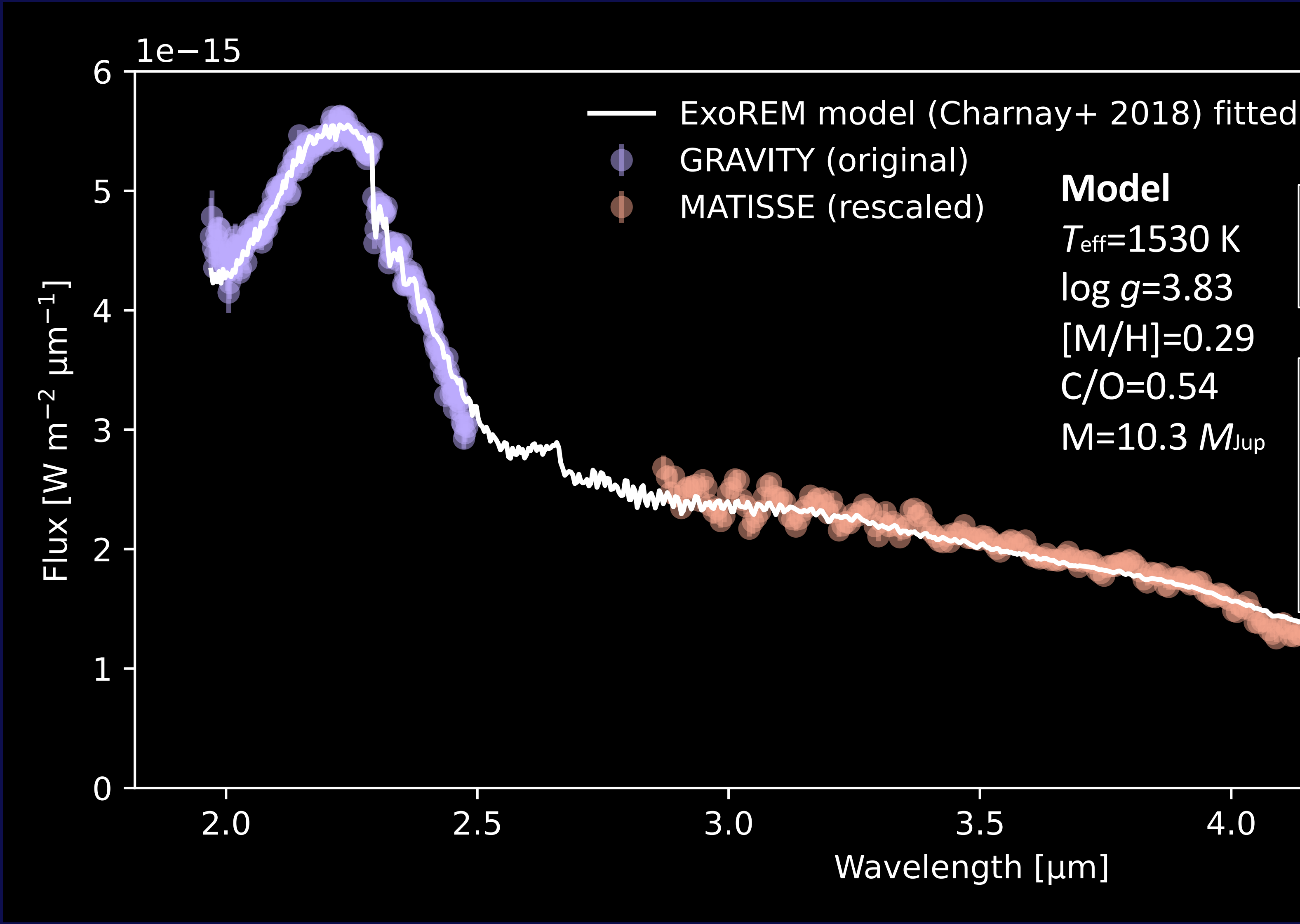


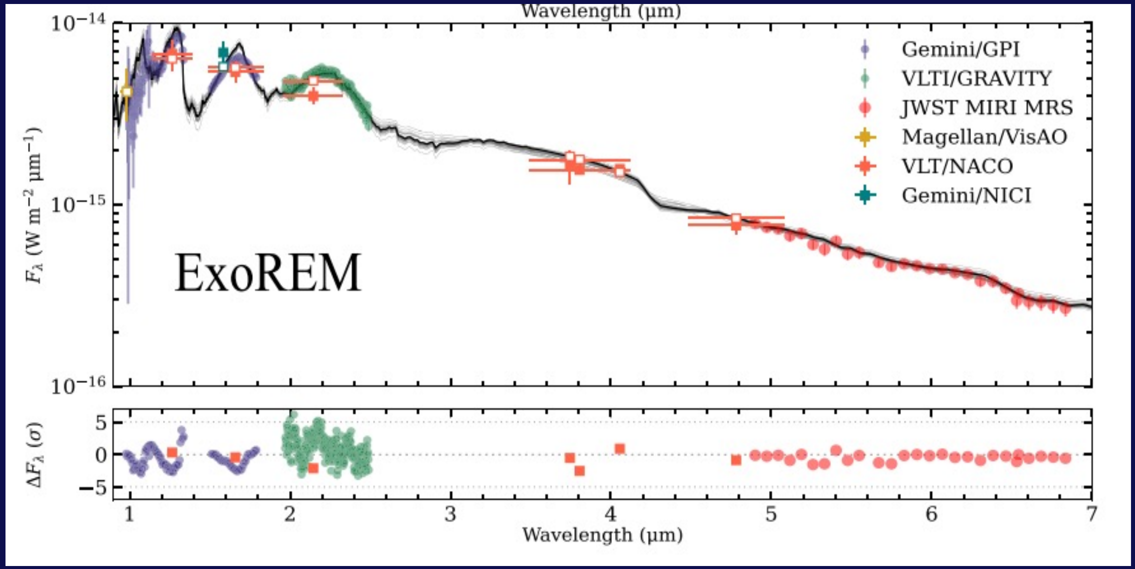
Study in prep. including all β Pic b data with scale factors by Ravet et al.

⇒ Solar C/O ratio (0.54)

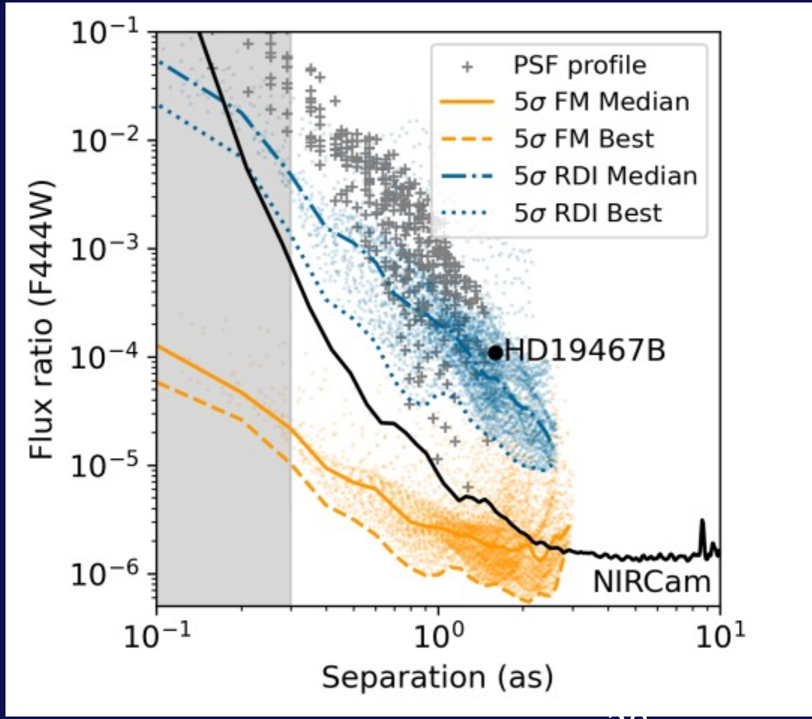
- different from GRAVITY Collab+ 20 (0.43) and Landman+ 24 (0.41)
- in line with molecular mapping on β Pic b (Kiefer+24) & KPIC survey of directly-imaged companions (Xuan+24).

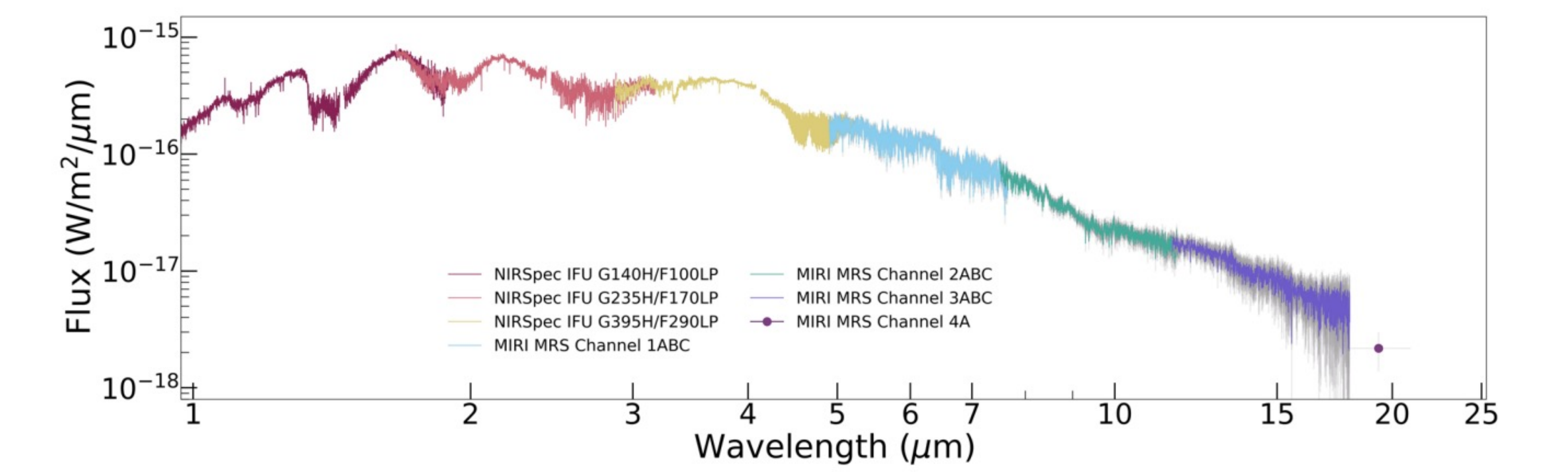
Exoplanets in the mid-infrared

- **Few mid-IR spectra**
  (Janson+2010, Wang+2018, Doelman+2022)
- **JWST** starting to deliver
  - But sensitivity still unclear at low separations
  - No coronagraphy on the spectroscopic modes of the JWST



Worthen+ 2024
β Pic b



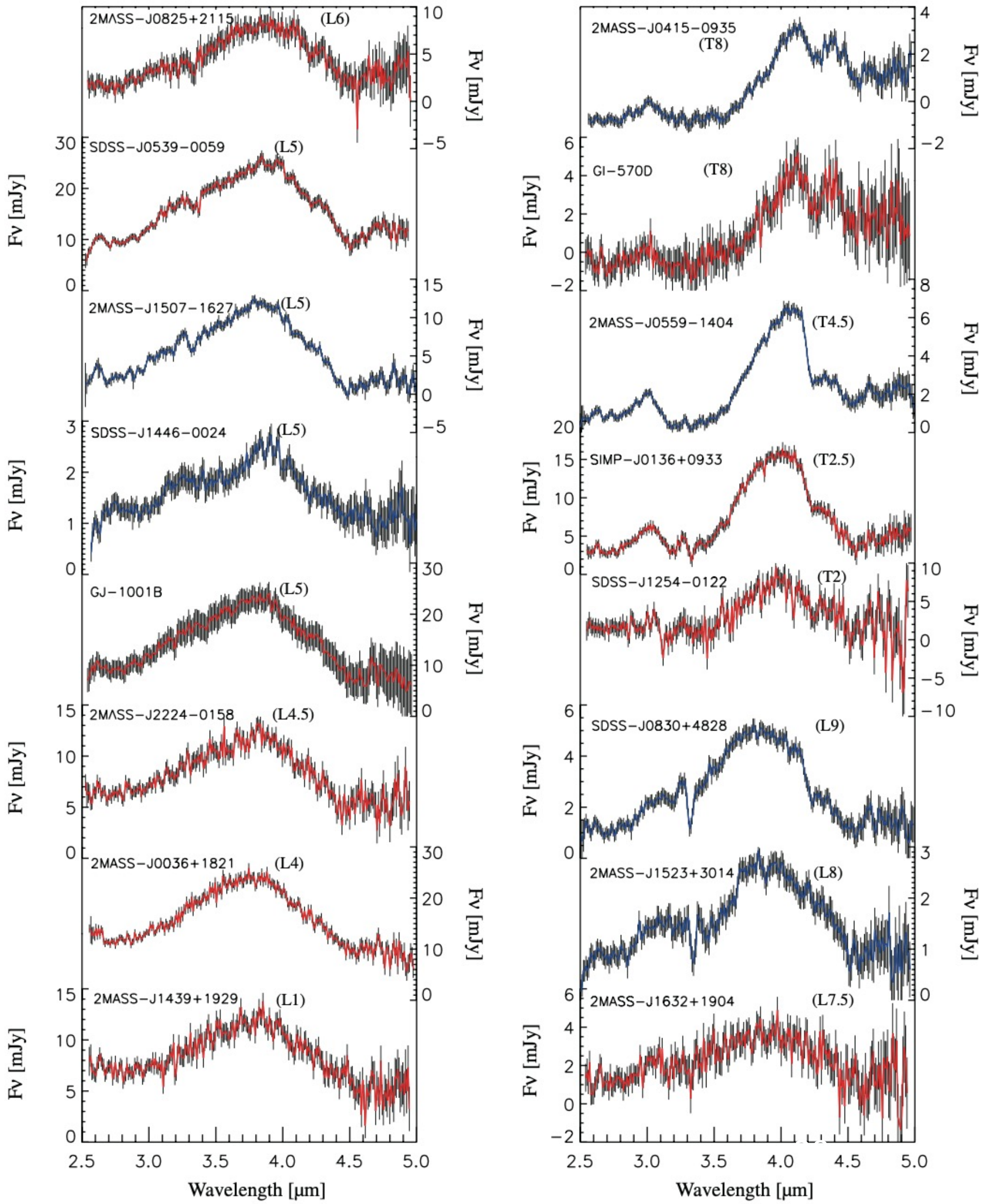


Miles+ 2023, VHS 1256 1257 b

Ruffio+ 2024

The mid-infrared potential

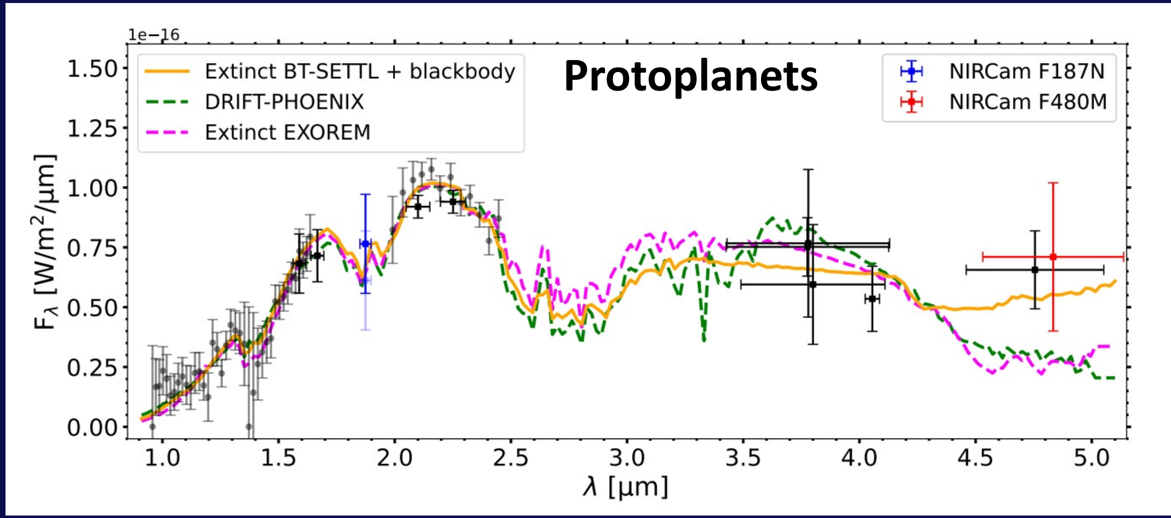
- Rich in spectral lines (CH_4, CO_2, CO…)



Sorahana+ 2012, isolated brown dwarfs

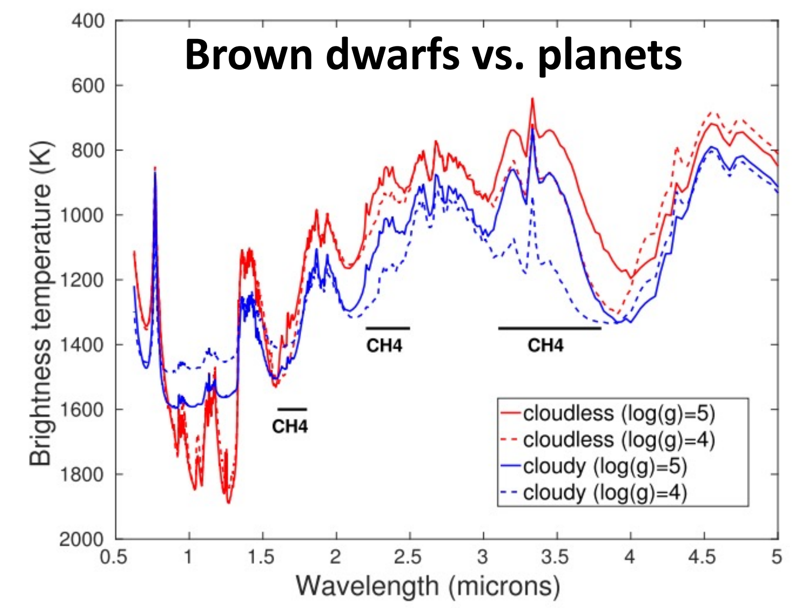
The mid-infrared potential

- Rich in spectral lines (CH_4, CO_2, CO…)
- Science cases:
  - **cloud scattering** (Mollière+ 20) & **patchiness** (Currie+ 14)
  - **vertical mixing** (Phillips+ 20)
  - **protoplanets** (Christiaens+24)
  - **auroral** methane emission? (Faherty+ 24)



Christiaens+24, PDS 70 b spectrum

Charnay+18, ExoREM atmospheric models



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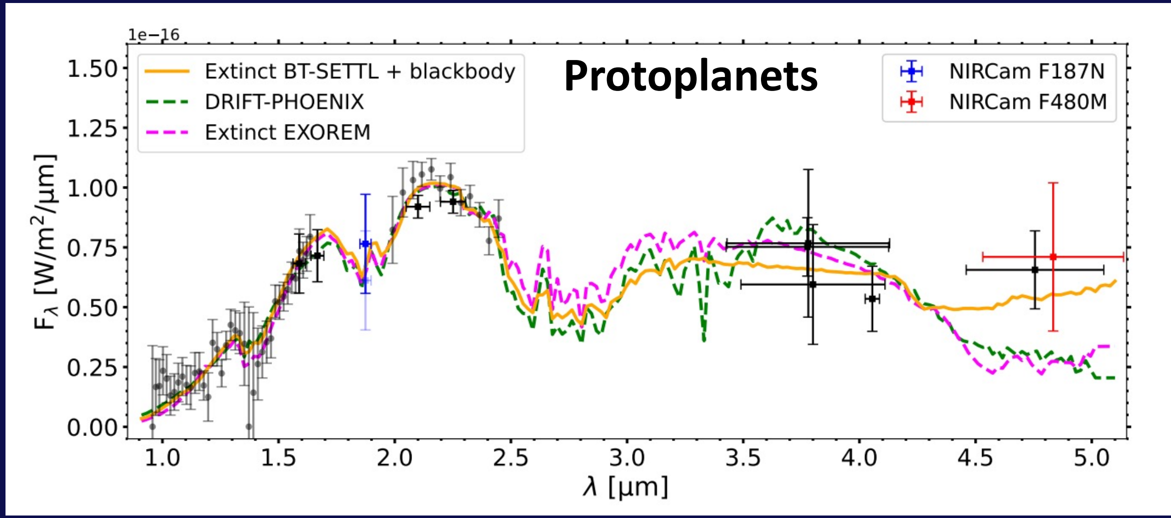
  - **vertical mixing** (Phillips+ 20)
  - **protoplanets** (Christiaens+24)
  - **auroral** methane emission? (Faherty+ 24)

- **MATISSE complementarity with the JWST** at close separations (< 0.4'')

- Ongoing MATISSE programs:
  - β Pic c and HR 8799 e analysis in progress
  - PDS 70 b and c observed in March 2025



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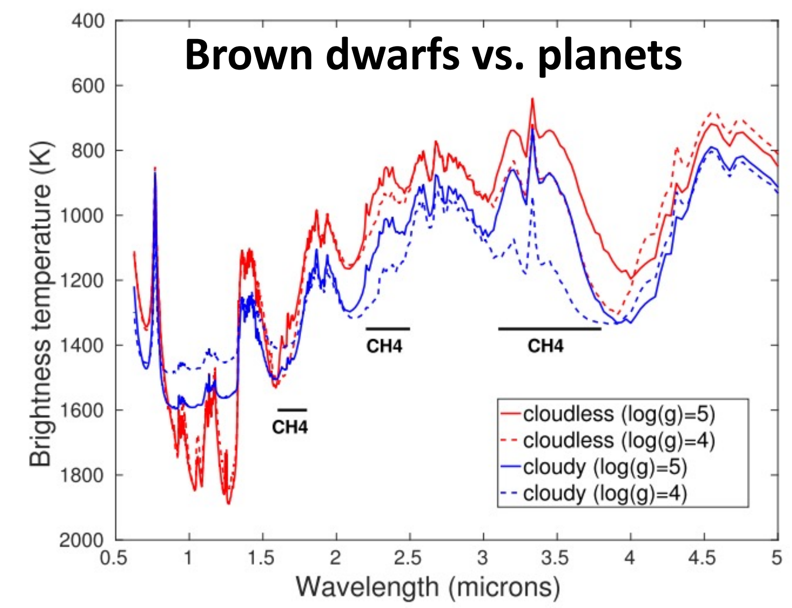
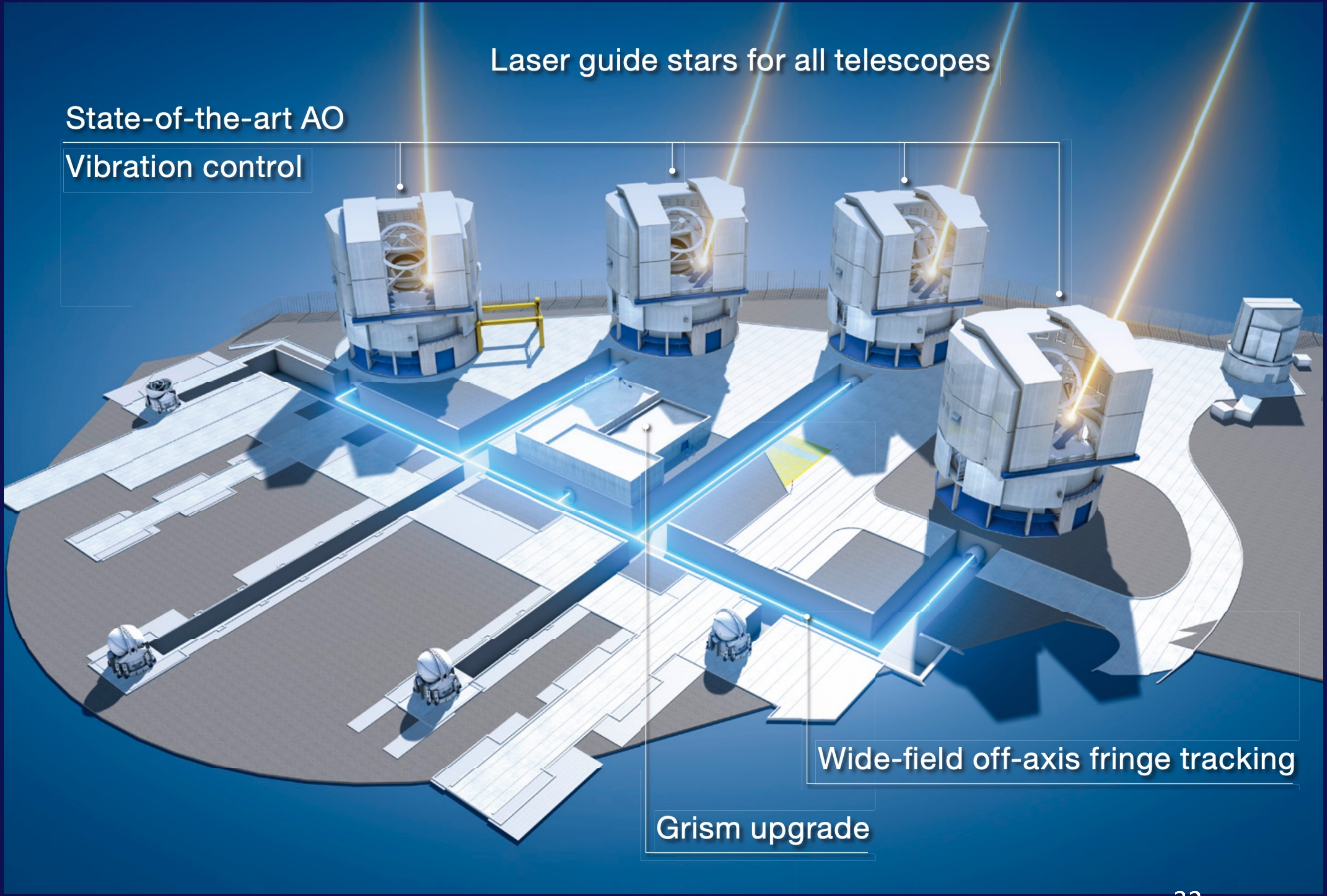


The ongoing VLTI upgrade: GRAVITY+



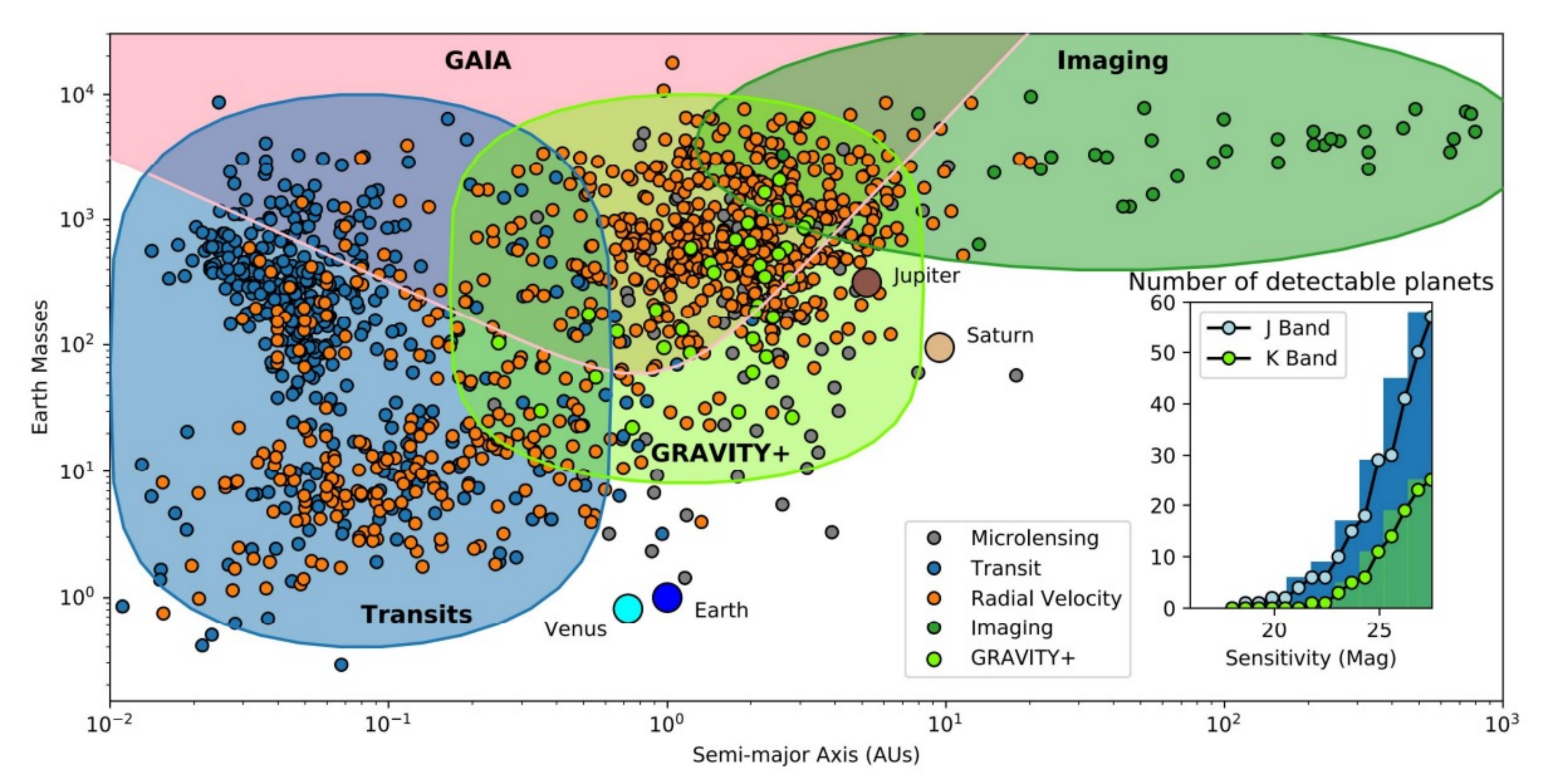
GRAVITY+ Collaboration, ESO Messenger

The GRAVITY+ AO (GPAO)

- Will replace MACAO and benefit all VLTI instruments
- Ongoing commissioning in Paranal: first fringes obtained in September

GRAVITY+ white paper

- Higher performances in Shrehl ratio
- Provides access to lower separations and deeper contrasts
- Bridges the gap with other techniques and access planets within snowlines



Summary

- **Interferometry** is now a **robust technique of exoplanet characterization**
  - ultra-precise astrometry (GRAVITY)
  - medium-resolution spectra in *K* (GRAVITY), *L* and *M* bands (MATISSE)
- **MATISSE** observed an exoplanet for the first time thanks to **GRA4MAT**
  - High S/N obtained on β Pic b in 36 min
- The **GRAVITY+ upgrade** will provide access to deeper contrasts and lower separations
  - **bridging the gap with Gaia astrometry, radial velocities, transits**

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