Hunting exoplanet spectra with MATISSE

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Philippe Berio, Bruno Lopez
& the MATISSE, GRAVITY+ consortia, and exoGRAVITY collaboration

How VLTI + LGS will look like

How it started

2003: Freshly obtained « DEA » (master) in astrophysics
Exoplanets spectroscopy with interferometry looks promising!
A new instrument is being integrated for the VLTI… AMBER!

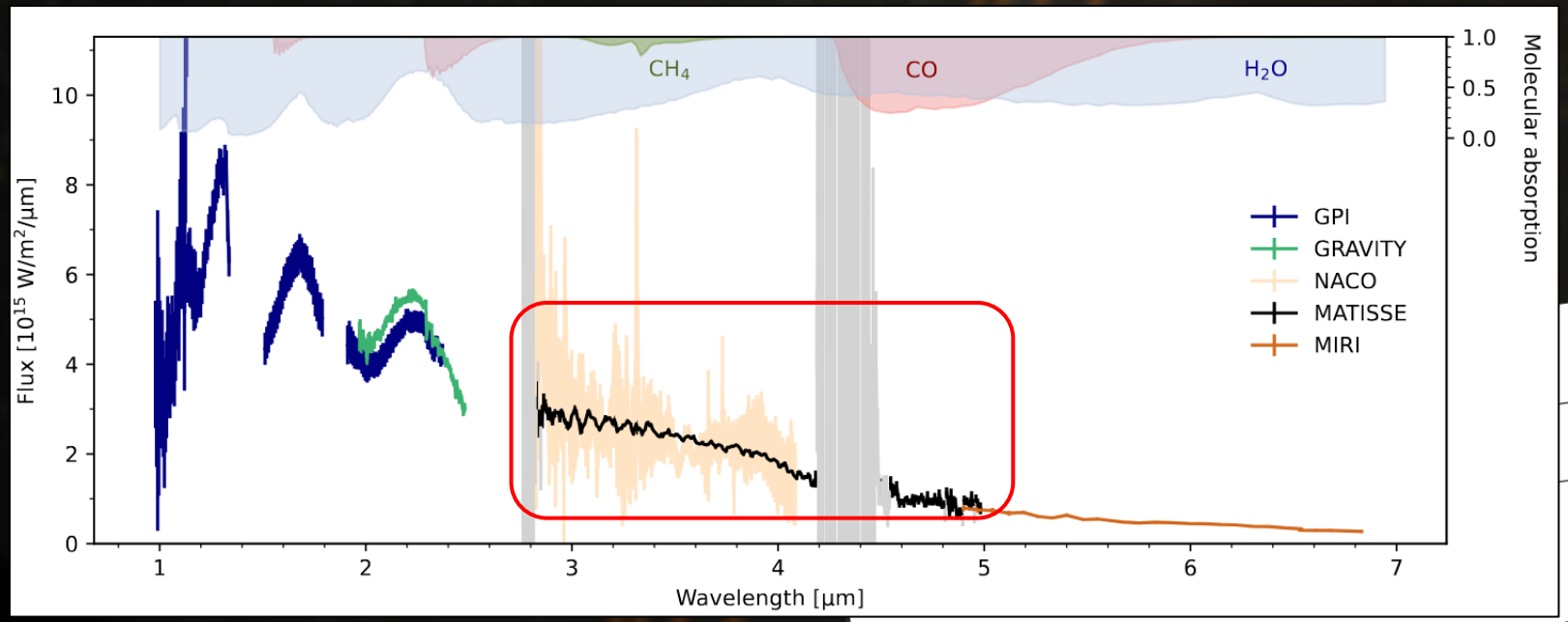
- **Directeur de thèse : Romain G. Petrov**, Directeur de Recherche 2C, « PI » du projet AMBER
- **Lieu de thèse : UMR 6525 « Astrophysique » de l'Université de Nice – Sophia Antipolis**, Parc Valrose, 06108 Nice Cedex 2. Téléphone : 04 92 07 63 47. Télécopie : 04 92 07 63 22. E_mail : petrov@unice.fr
- **Collaborations** : La phase précédente de ce travail (thèse de Martin Vannier) s'est fait en collaboration avec Bruno Lopez (Dpt. Fresnel, OCA). Une poursuite de cette collaboration sera proposée. Par ailleurs, ce travail se fera en liaison avec le groupe « planète extra solaires » qui se met en place pour exploiter AMBER dans ce domaine. Une participation aux essais en laboratoire à Grenoble puis aux essais et observations à l'Observatoire de Paranal (Chili) est à prévoir.
- **Sujet : Caractéristiques physiques de planètes extra solaires géantes chaudes avec l'instrument AMBER du VLTI.**

1. Context e de la thèse

AMBER est l'instrument proche infrarouge du mode interférométrique du Very Large Telescope
Cet instrument est en cours d'intégration et devrait être installé sur le VLTI au deuxième
projet est à la charge d'un Consortium constitué notamment de l'Observatoire de la
avec l'UMR 6525 de l'UNSA, de l'Observatoire de Grenoble
nomie (MPIfR) de Bonn et l'Osservatorio Astrofisico
PACA, le MPIfR, l'OAA et l'ESO.

How it is going

2025: spectroscopy of beta Pic b using the MATISSE instrument! brings new constraints on C/O ratio



The mid-infrared spectrum of β Pictoris b

First VLTI/MATISSE interferometric observations of an exoplanet ⋆

M. Houllé[1,2], F. Millour[1], P. Berio[1], J. Scigliuto[1], S. Lacour[3,4], B. Lopez[1], F. Allouche[1], J.-C. Augereau[2], D. Blain[5], M. Bonnefoy[2], M. Carbillet[1], G. Chauvin[1,5], J. Leftley[1], A. Matter[1], J. Milli[2], P. Mollière[5], E. Nasedkin[5], M. Nowak[3,6], P. Palma-Bifani[1,3], É. Pantin[7], P. Priolet[2], M. Ravet[1,2,5], J. Woillez[4], W. Balmer[8,9], P. Boley[5], V. Gámez Rosas[10], J. H. Girard[9], X. Haubois[11], S. Hinkley[12], M. Hogerheijde[10,13], W. Jaffe[10], J. Kammerer[4], L. Kreidberg[5], O. Lai[1], [illegible][11], J.-B. Le Bouquin[2], A. Meilland[1], A. Mérand[4], C. Paladini[11], R. Petrov[1], E. Rickman[14], [illegible] van Boekel[5], J. Varga[15,16], A. Vigan[17], J. J. Wang[18], and G. Weigelt[19]

Are you familiar with interferometry?

Interferometry increases angular resolution

Virtual 130m telescope

VLTI Baseline: 130m

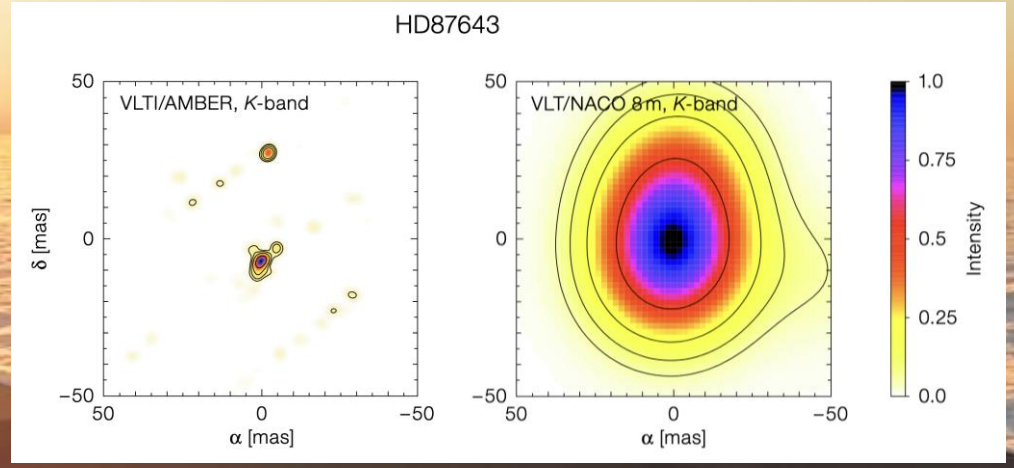
UT: 8m diameter

Focal lab.

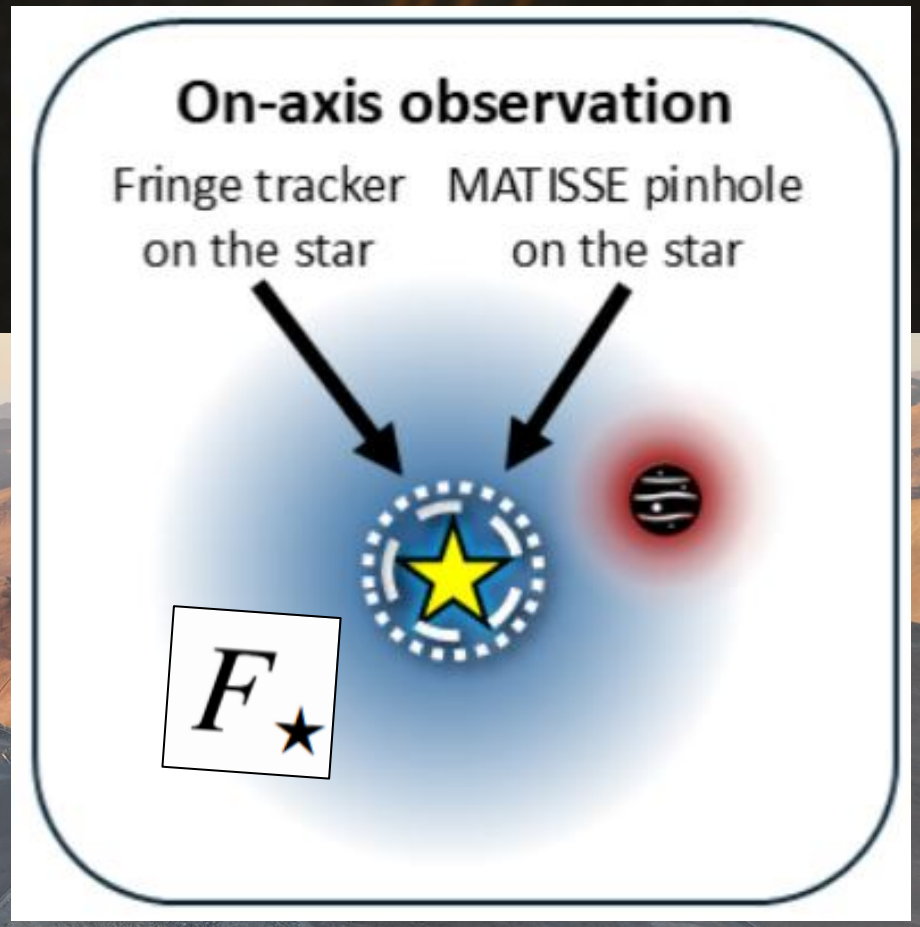
Delay lines

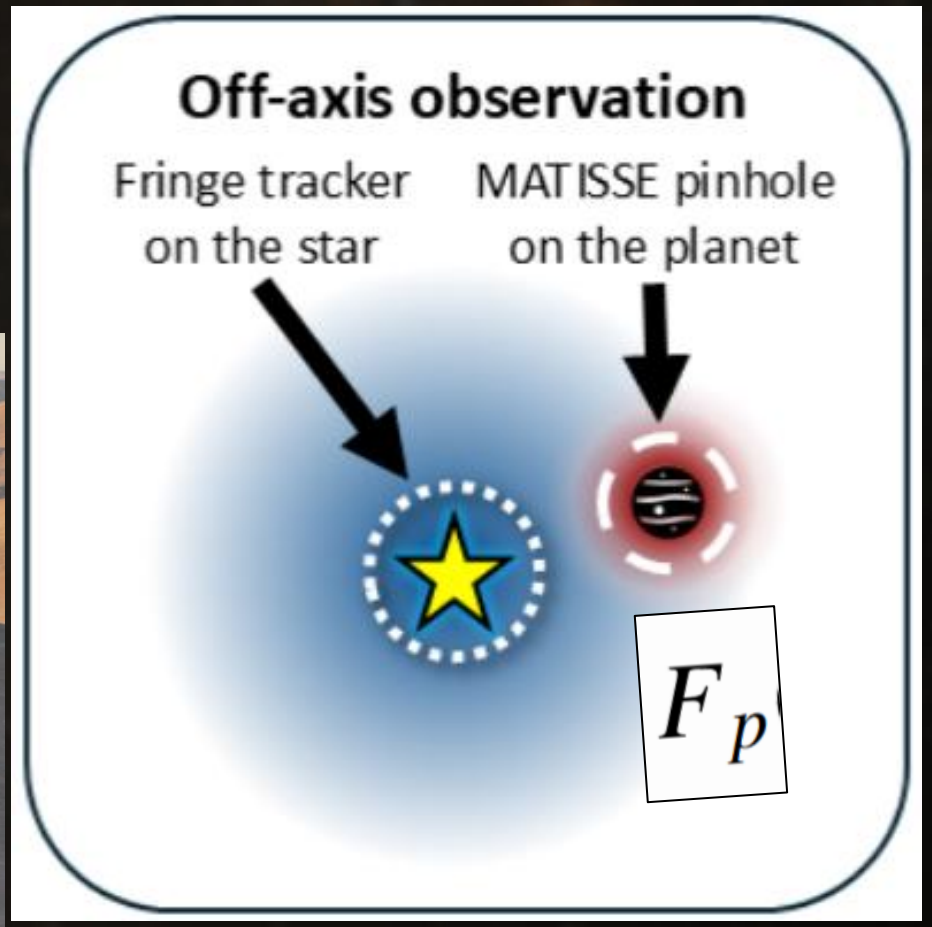
Tunnels

Lebouquin, Millour+2009



How to obtain a mid-IR beta Pic b spectrum?





Houllé, Millour et al. A&A 2025 (accepted)

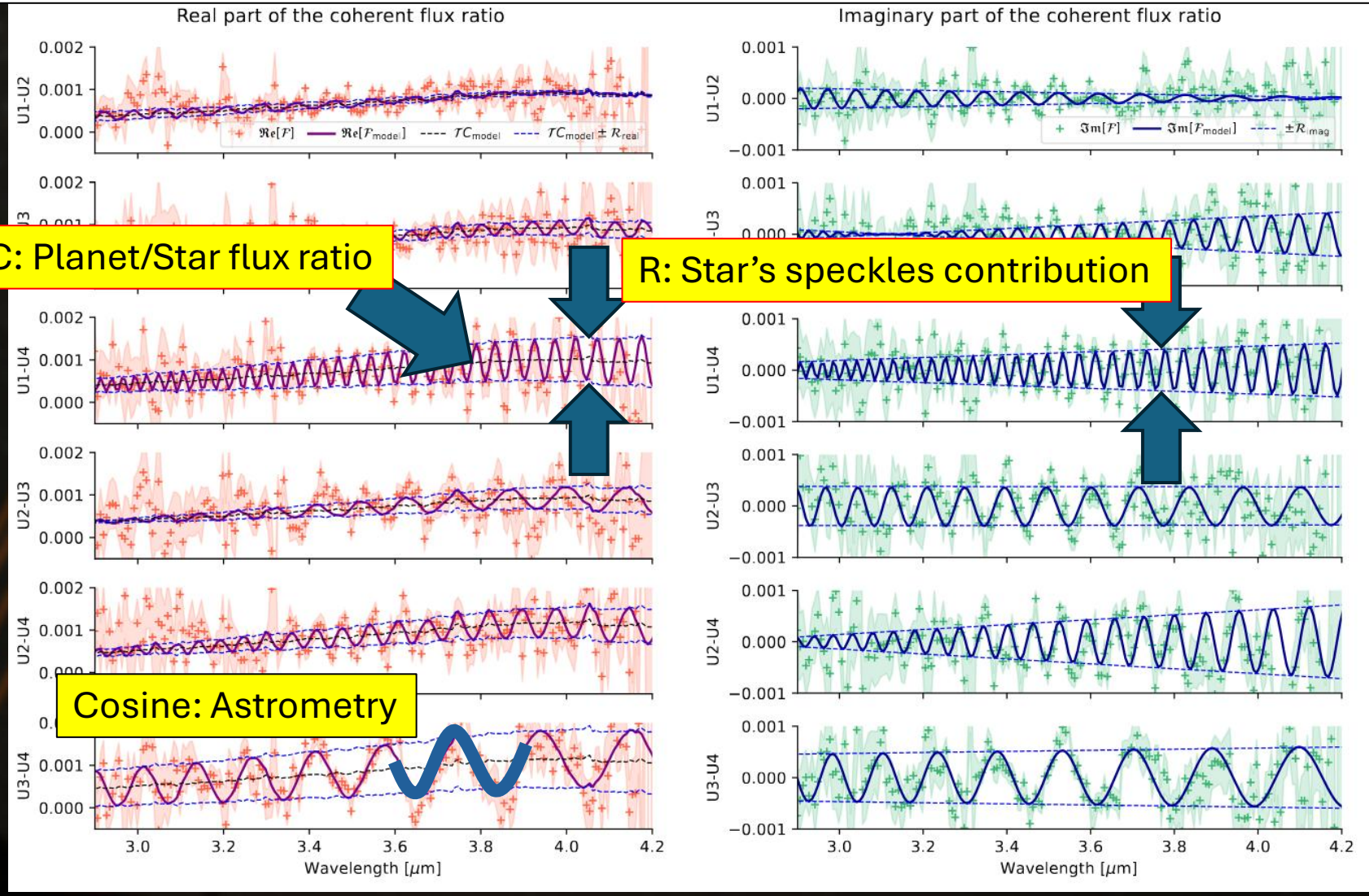
The pla

$$\mathcal{F} = \frac{F_p(\lambda, t_p, \vec{r_p})}{F_\star(\lambda, t_\star, \vec{r_\star})} \approx \tau(\lambda, t_p, t_\star)\left[C(\lambda) + R(\lambda, t_p, \vec{r_p})\, e^{i\frac{2\pi\vec{\alpha}\vec{u}}{\lambda}}\right]$$

$F_\star$

F_p

$$\mathcal{F} = \frac{F_p}{F_\star}$$



pted)

Extracting the planet's astrometry

$$F_\star(\lambda, t_\star, \vec{r_\star}) = T(\lambda, t_\star)\, S_\star(\lambda)\, e^{i\Phi(\lambda, t_\star)}$$

$$F_p(\lambda, t_p, \vec{r_p}) = T(\lambda, t_p) \left[S_p(\lambda) + R(\lambda, t_p, \vec{r_p})\, S_\star(\lambda)\, e^{i\frac{2\pi \vec{\alpha} \vec{u}}{\lambda}} \right] e^{i\Phi(\lambda, t_p)}$$

$$\mathcal{F} = \frac{F_p(\lambda, t_p, \vec{r_p})}{F_\star(\lambda, t_\star, \vec{r_\star})} \approx \tau(\lambda, t_p, t_\star) \left[C(\lambda) + R(\lambda, t_p, \vec{r_p})\, e^{i\frac{2\pi \vec{\alpha} \vec{u}}{\lambda}} \right]$$

$$C(\lambda) = S_p(\lambda) / S_\star(\lambda) \qquad \tau(\lambda, t_p, t_\star) = T(\lambda, t_p) / T(\lambda, t_\star)$$

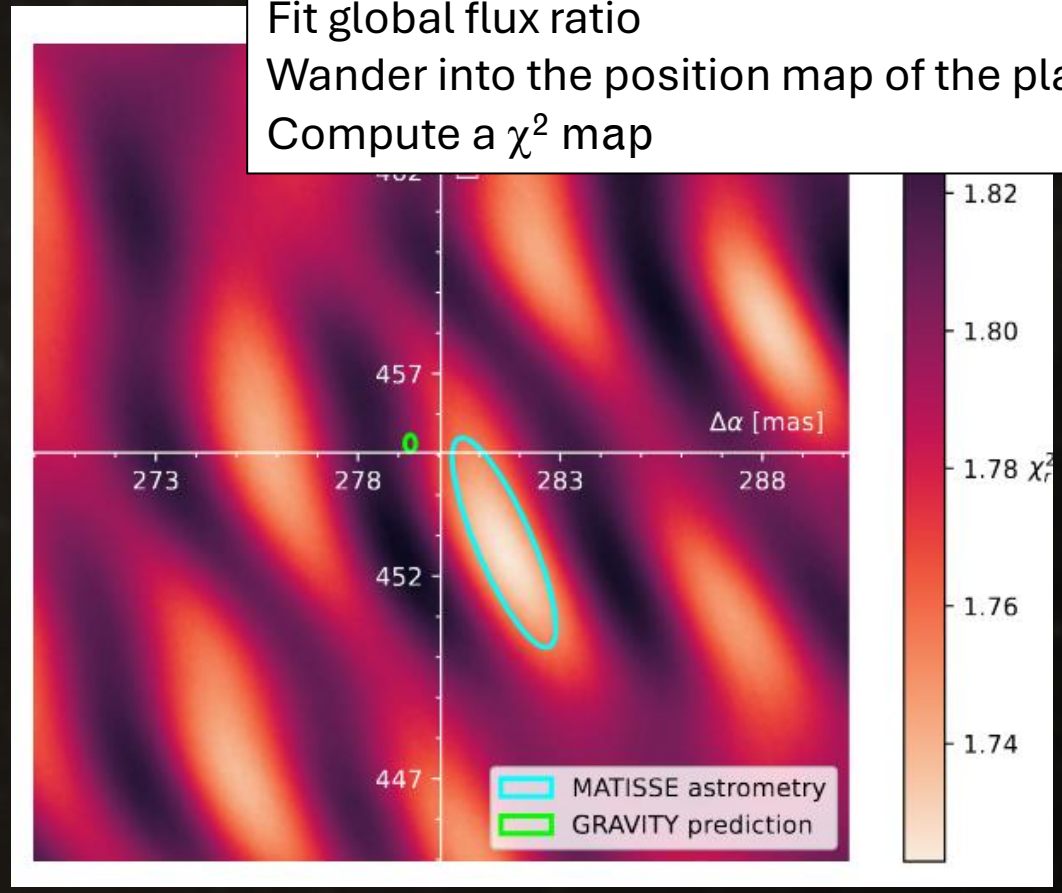
$$\mathcal{F}_{\text{model}}(\lambda) = \mathcal{T}(t_p, t_\star)\, C_{\text{model}}(\lambda) + \mathcal{R}(\lambda, t_p, \vec{r_p})\, e^{i\frac{2\pi \vec{\alpha} \vec{u}}{\lambda}}$$

$$\mathcal{T}(t_p, t_\star) = \gamma\, \tau(t_p, t_\star)$$

$$\mathcal{R}(\lambda, t_p, \vec{r_p}) = \tau(t_p, t_\star)\, R(\lambda, t_p, \vec{r_p})$$

$$\chi^2(t_p, b, \Delta\alpha, \Delta\delta) = \sum_\lambda \frac{\Re e[\mathcal{F}(\lambda) - \mathcal{F}_{\text{model}}(\lambda)]^2}{\sigma^2_{\Re e[\mathcal{F}(\lambda)]}} + \sum_\lambda \frac{\Im m[\mathcal{F}(\lambda) - \mathcal{F}_{\text{model}}(\lambda)]^2}{\sigma^2_{\Im m[\mathcal{F}(\lambda)]}}$$

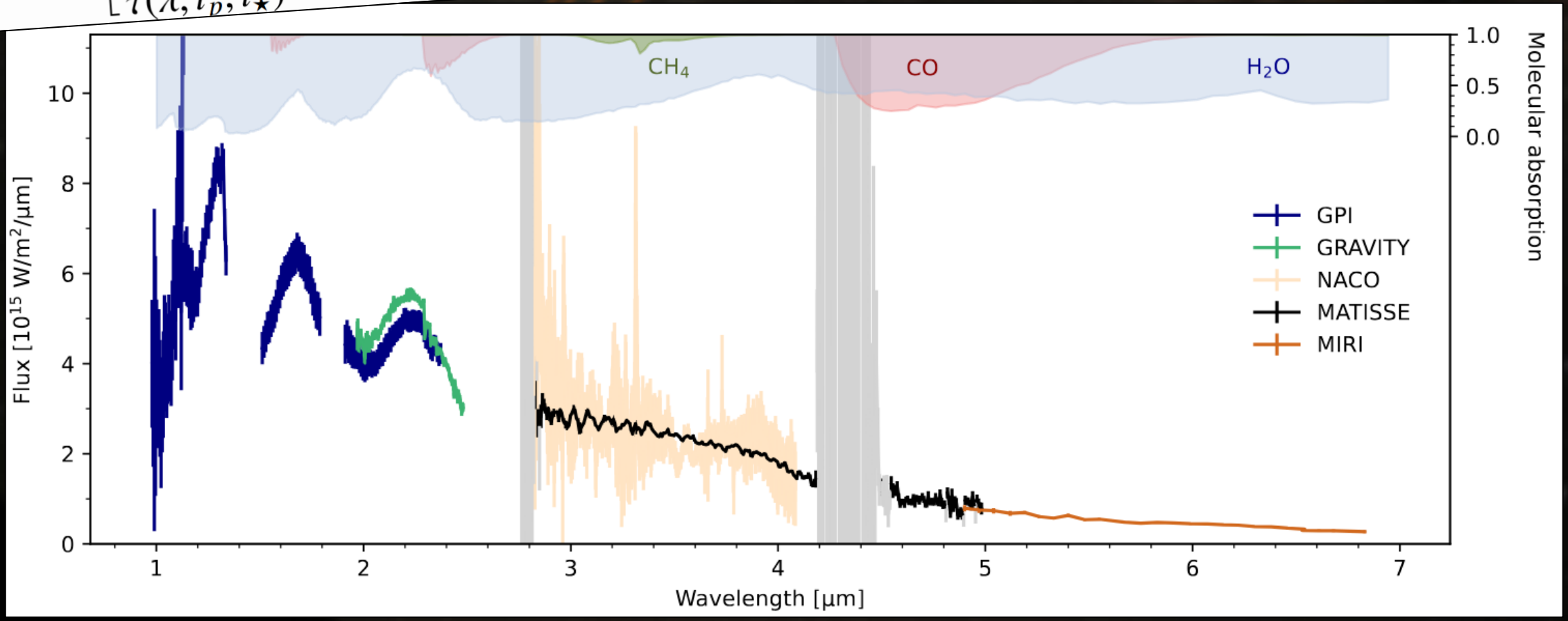
Fix star & planet spectra
Fit global flux ratio
Wander into the position map of the planet
Compute a χ^2 map



Houllé, Millour et al. A&A 2025 (accepted)

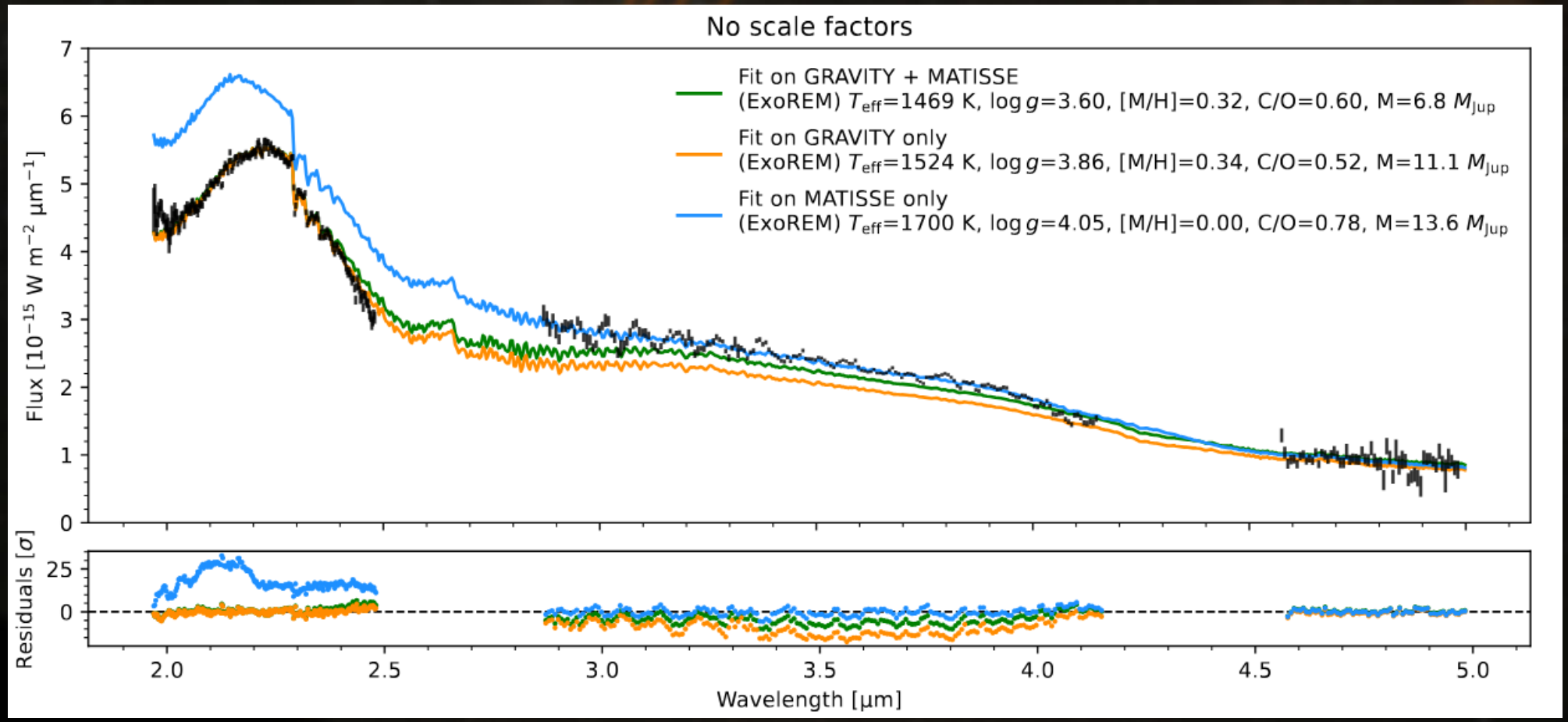
Extracting the spectrum

$$\hat{C}(\lambda, t_p, b) = \Re\mathrm{e}\left[\frac{\mathcal{F}(\lambda, t_p, b)}{\tau(\lambda, t_p, t_\star)} - \hat{\mathcal{R}}(\lambda, t_p, b, \hat{\vec{\alpha}})\, \mathrm{e}^{\mathrm{i}\frac{2\pi\hat{\vec{\alpha}}\vec{u}}{\lambda}}\right]$$



Houllé, Millour et al. A&A 2025 (accepted)

Beta Pic's parameters



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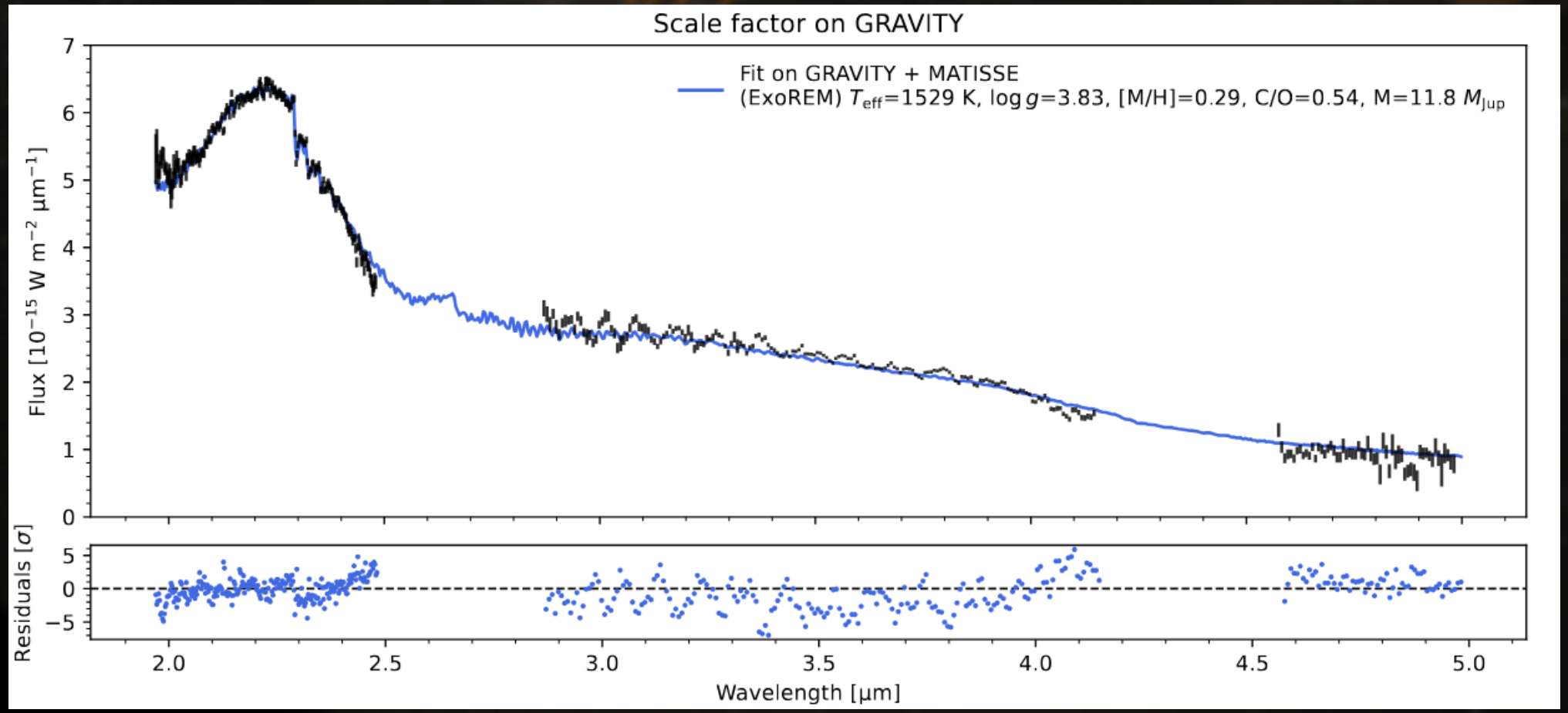

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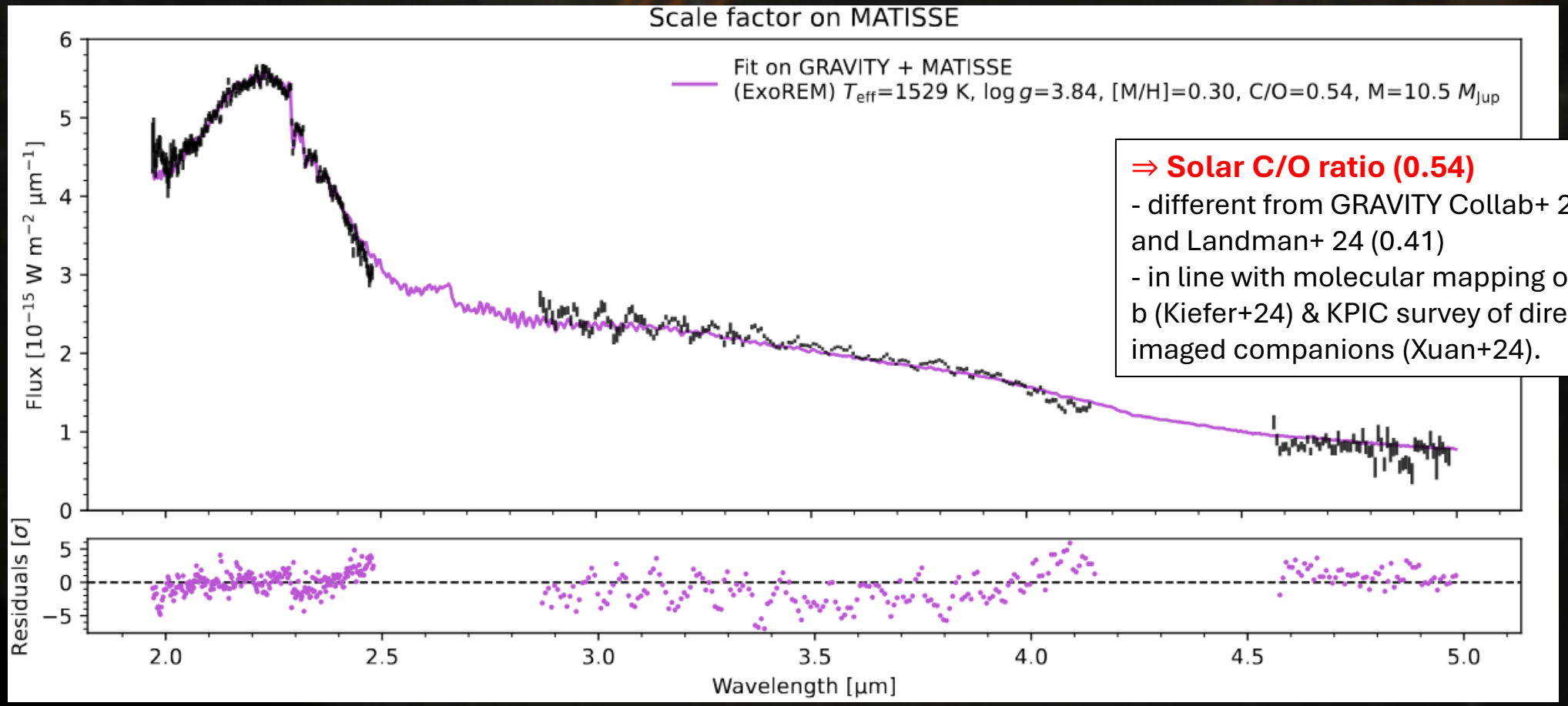


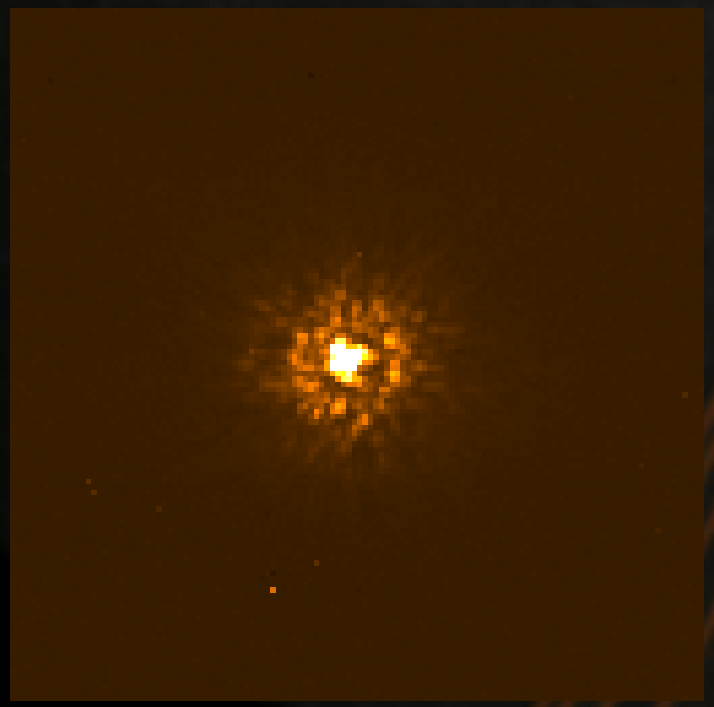
⇒ Solar C/O ratio (0.54)

- 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).

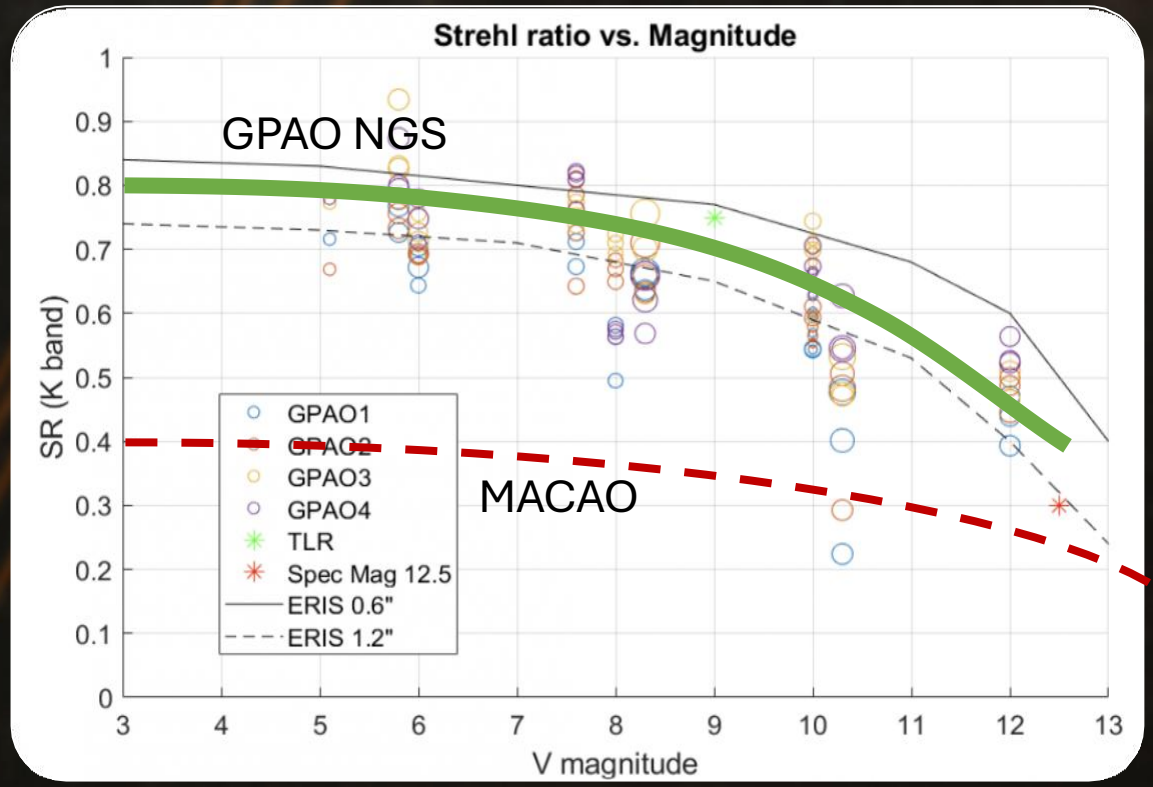
Houllé, Millour et al. A&A 2025 (accepted)

GPAO on the VLTI

MACAO vs. GPAO



GPAO commissionning 2024/2025

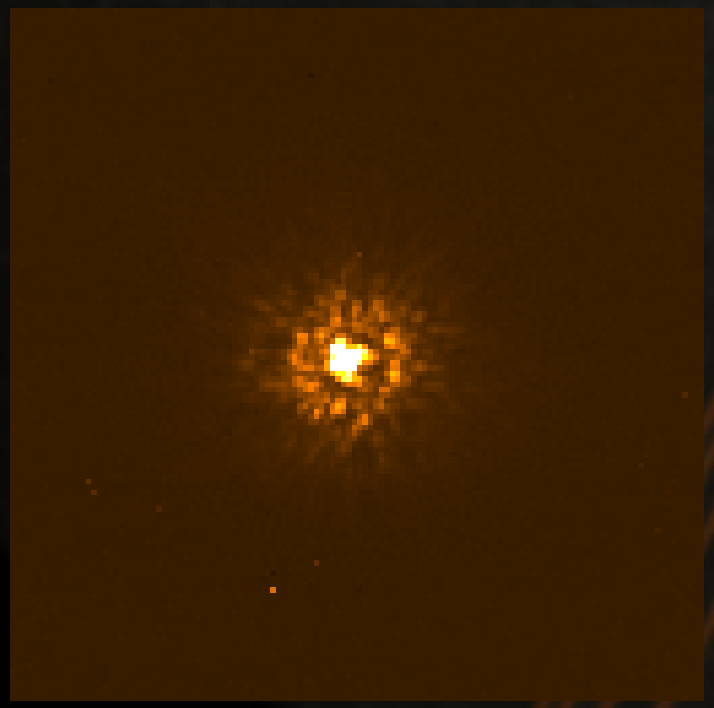


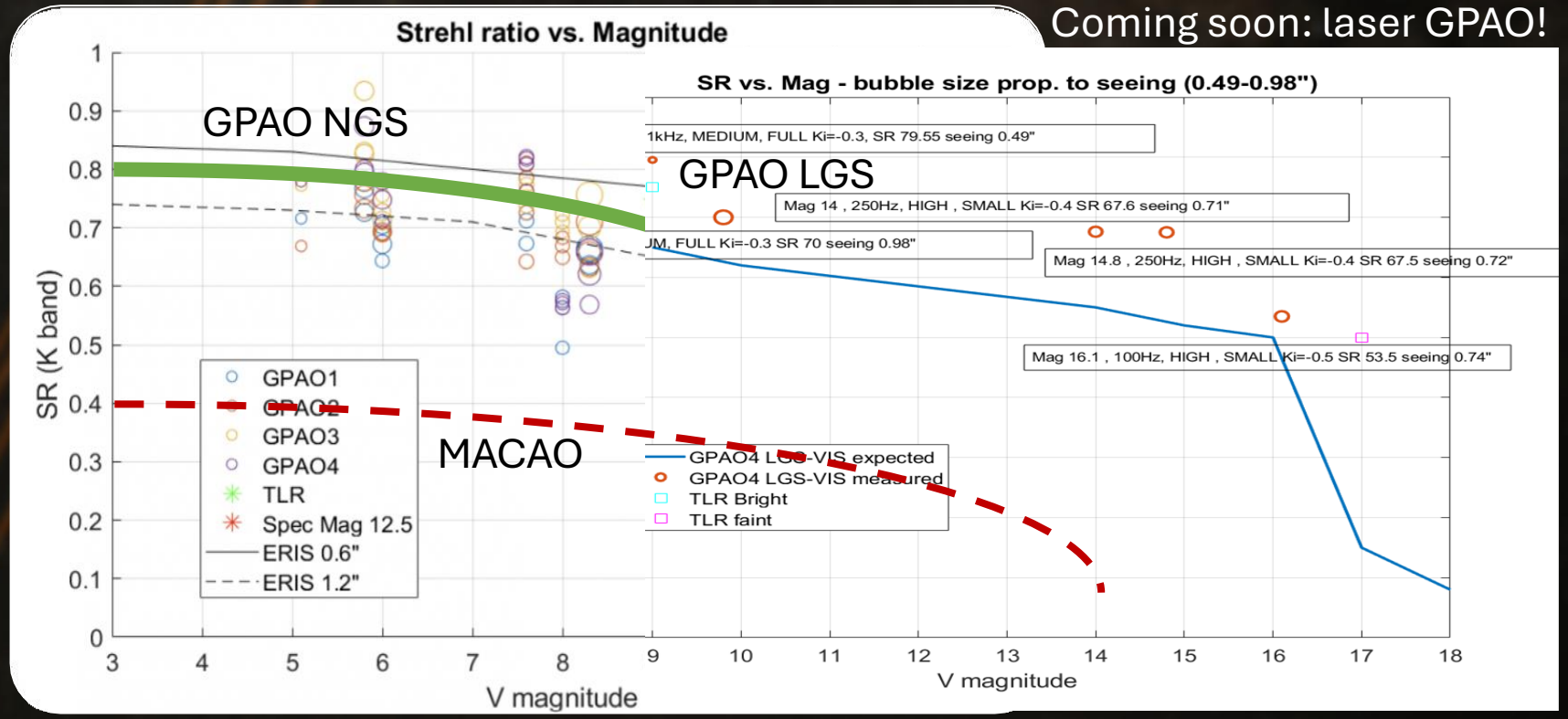
GPAO on the VLTI

GPAO commissionning 2024/2025

Coming soon: laser GPAO!

MACAO vs. GPAO

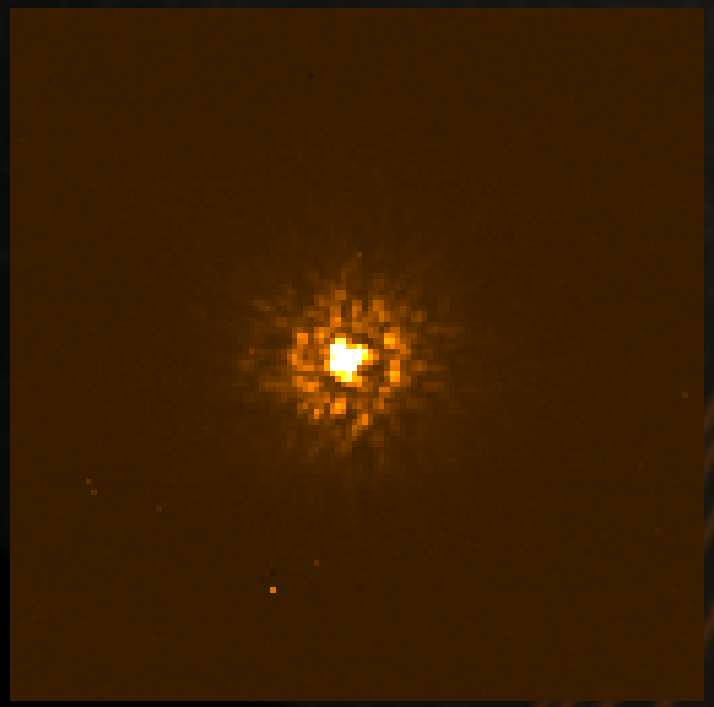


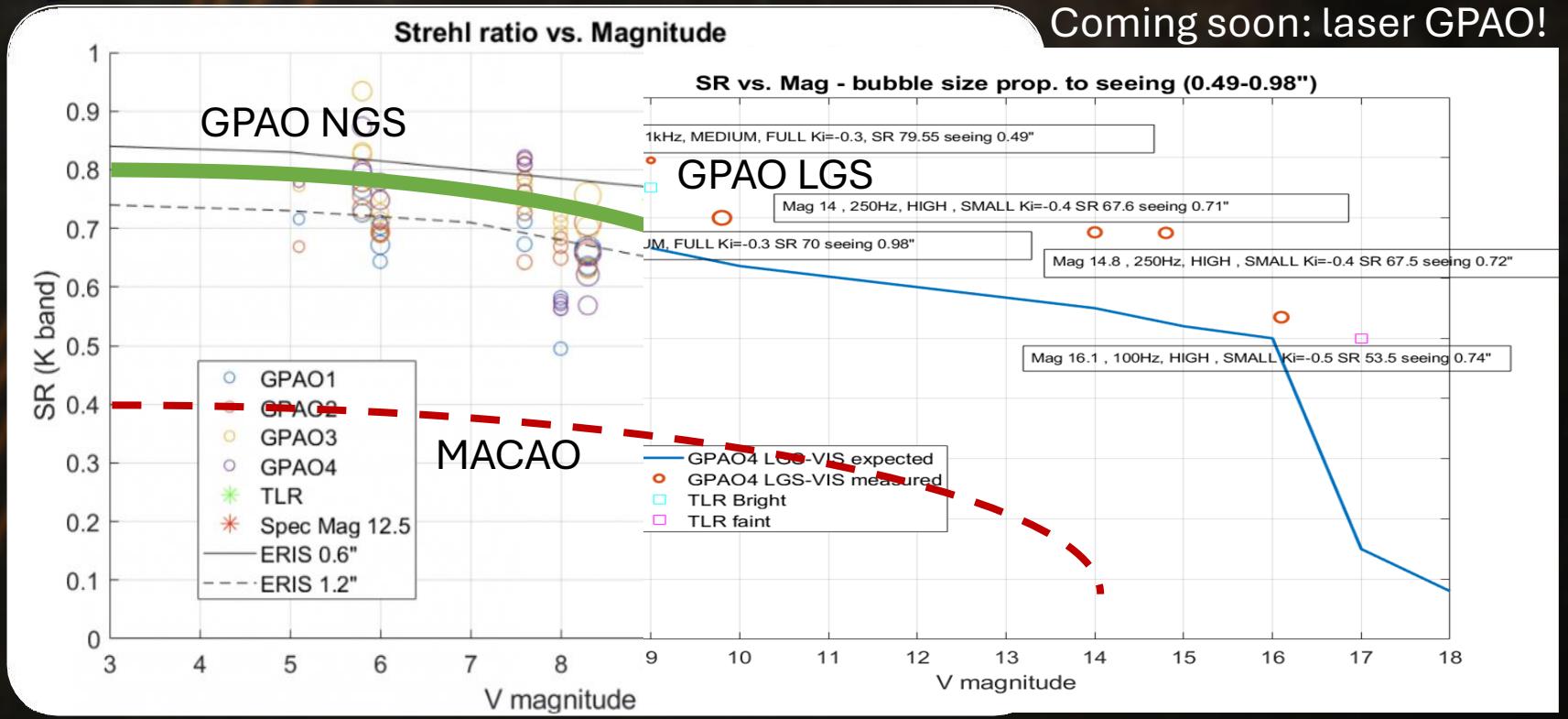


New!
Closing the LGS loop
on UT1 (08/10/2025)

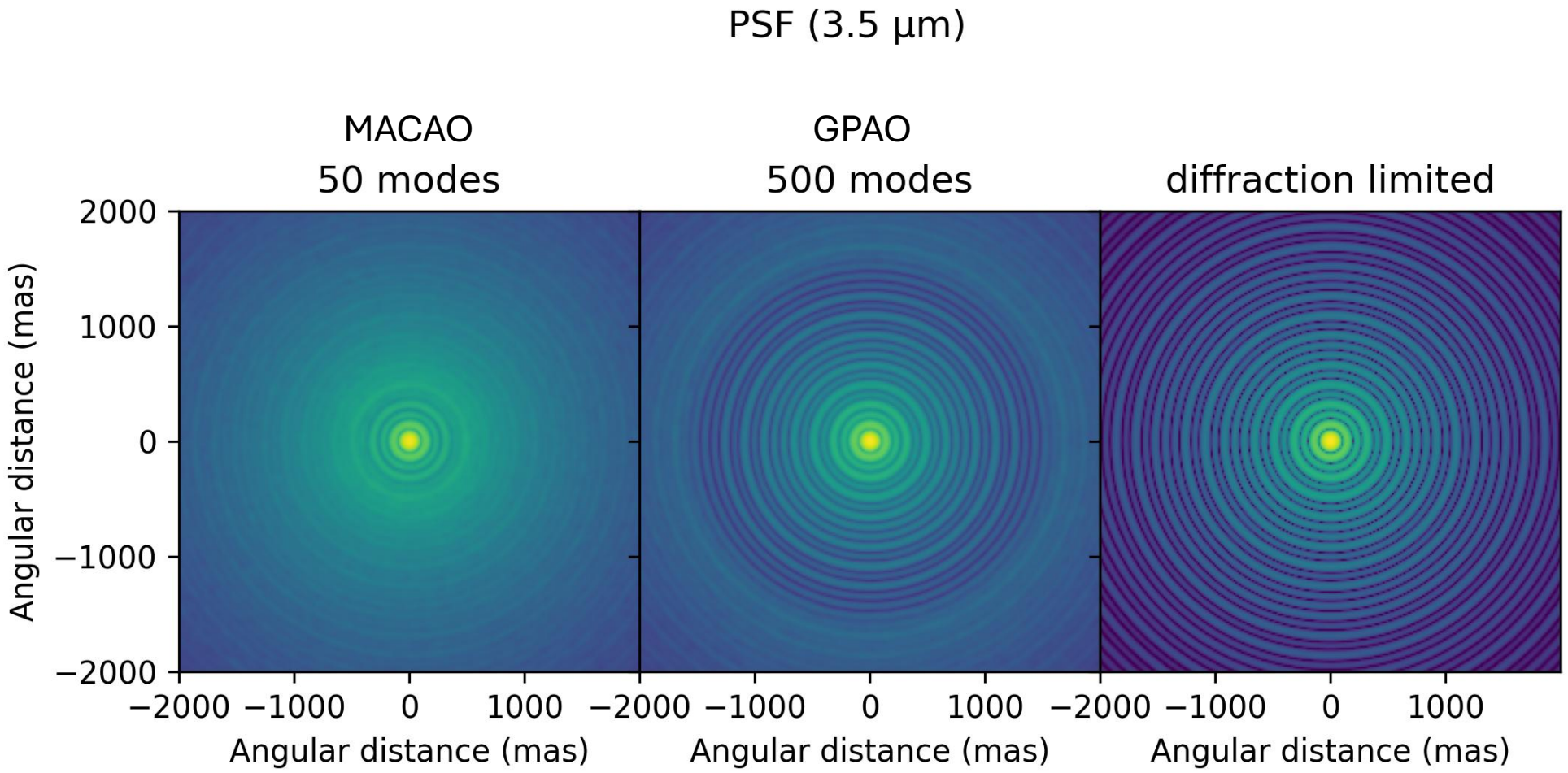
Coming soon: laser GPAO!

MACAO vs. GPAO





What impact has GPAO on MATISSE?



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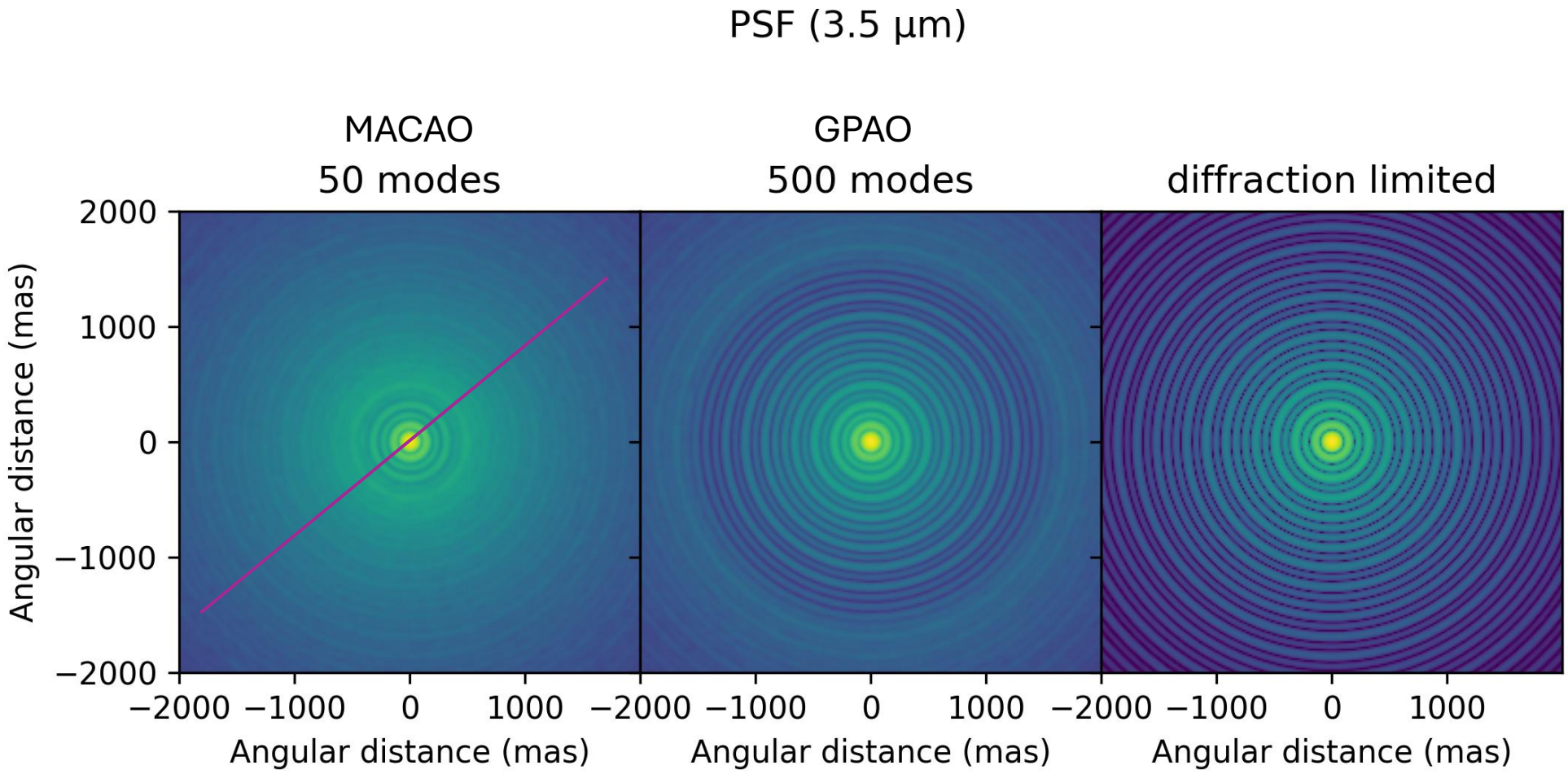

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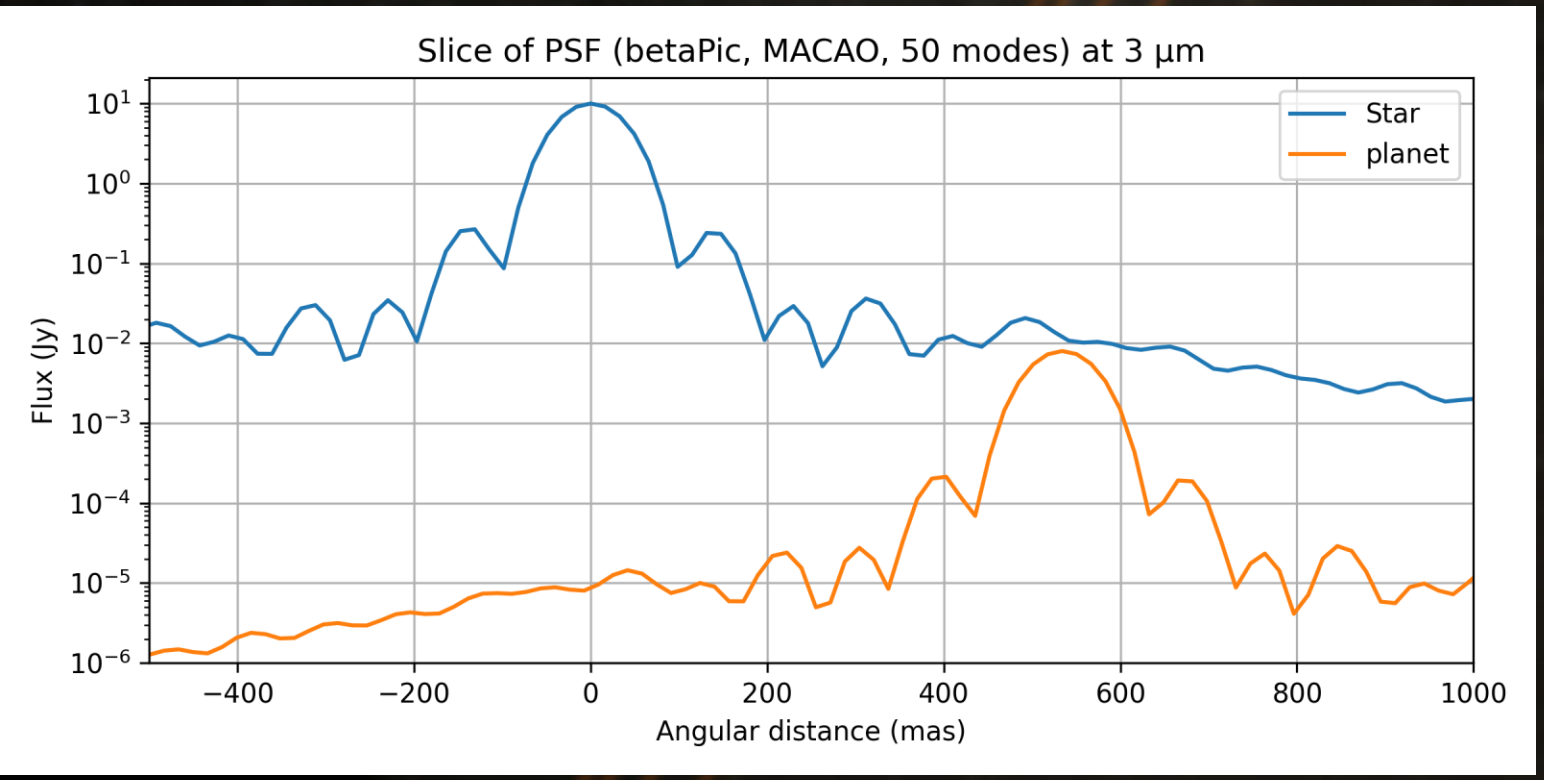

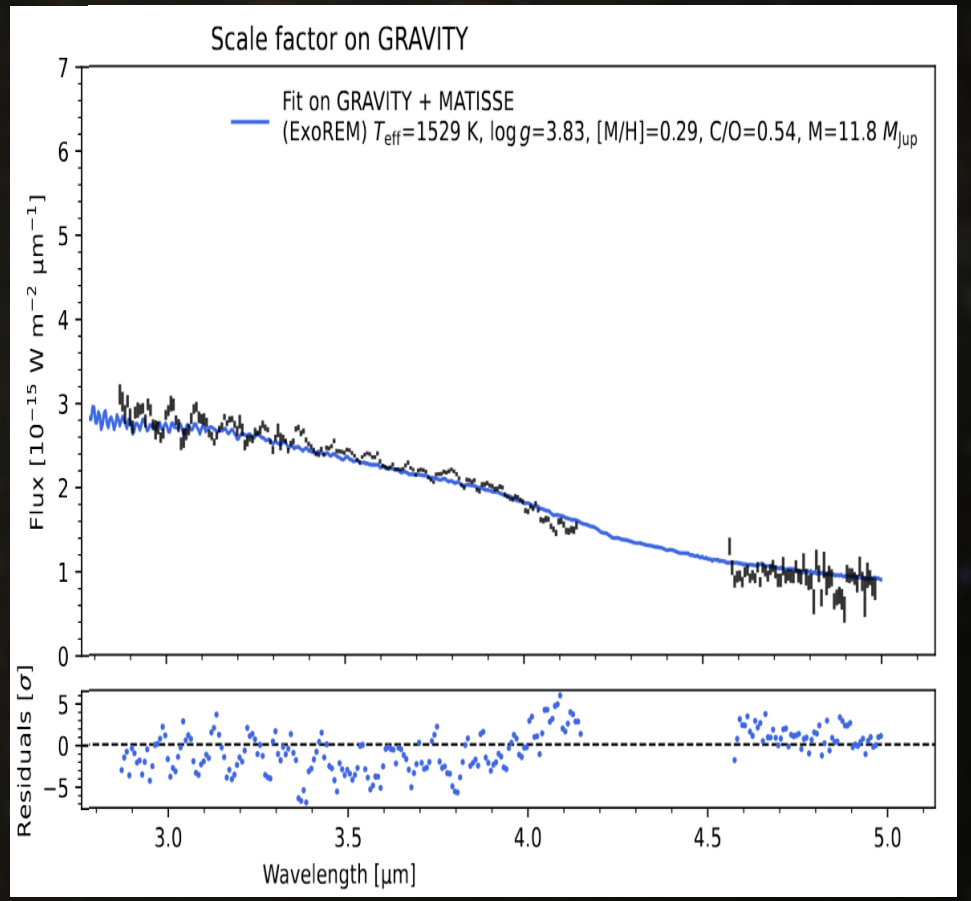

Houllé, Millour et al. A&A 2025, accepted

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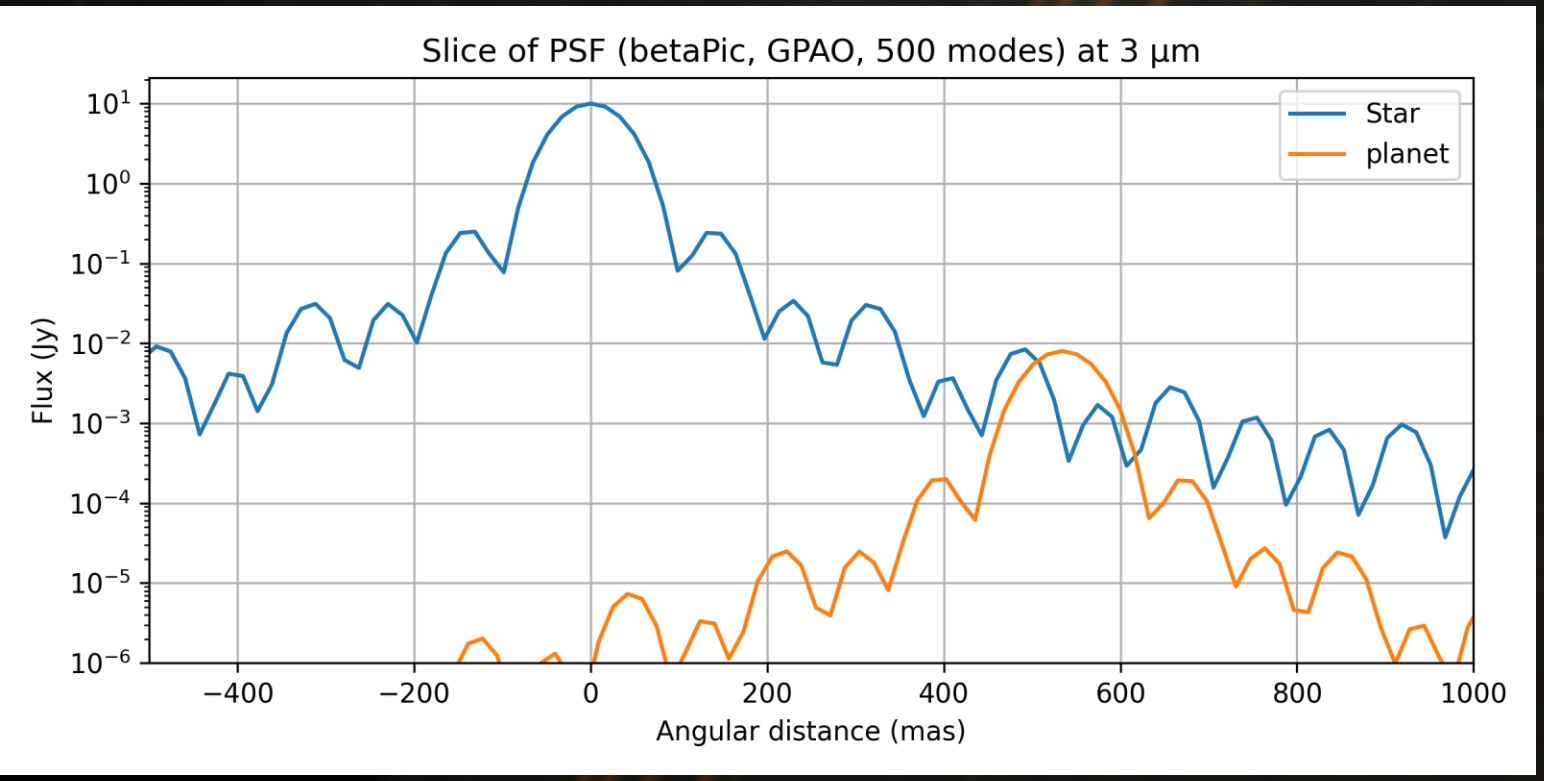
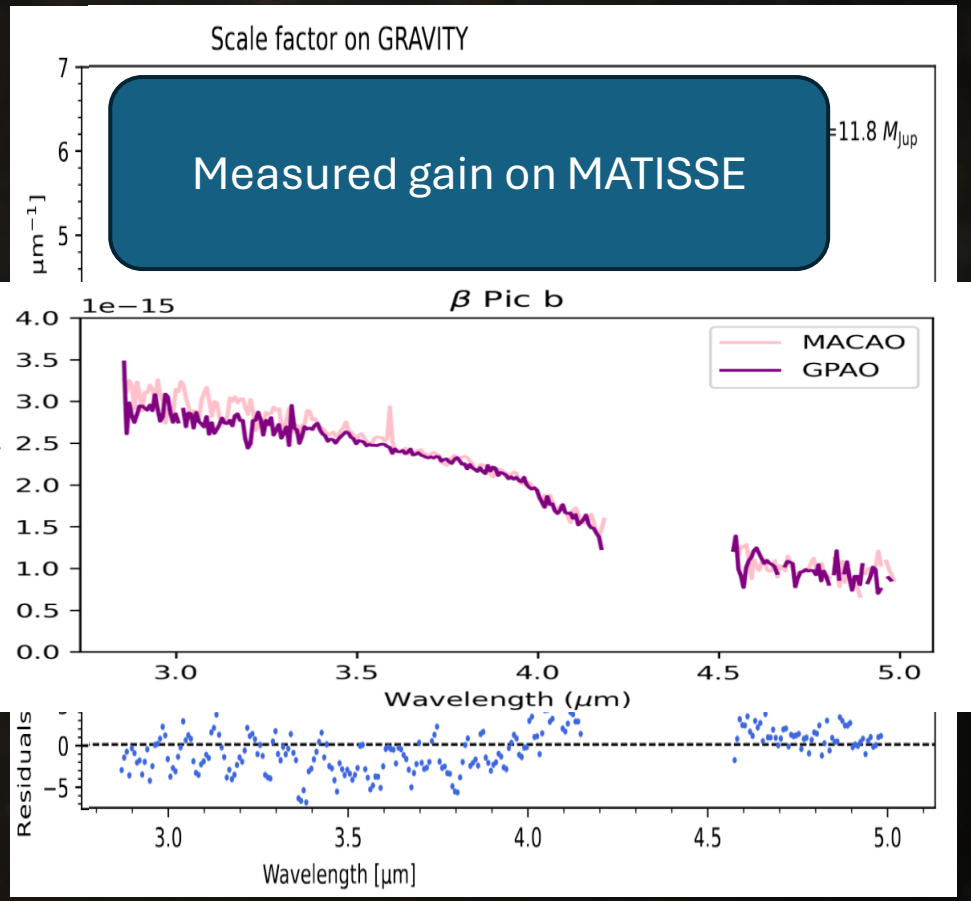
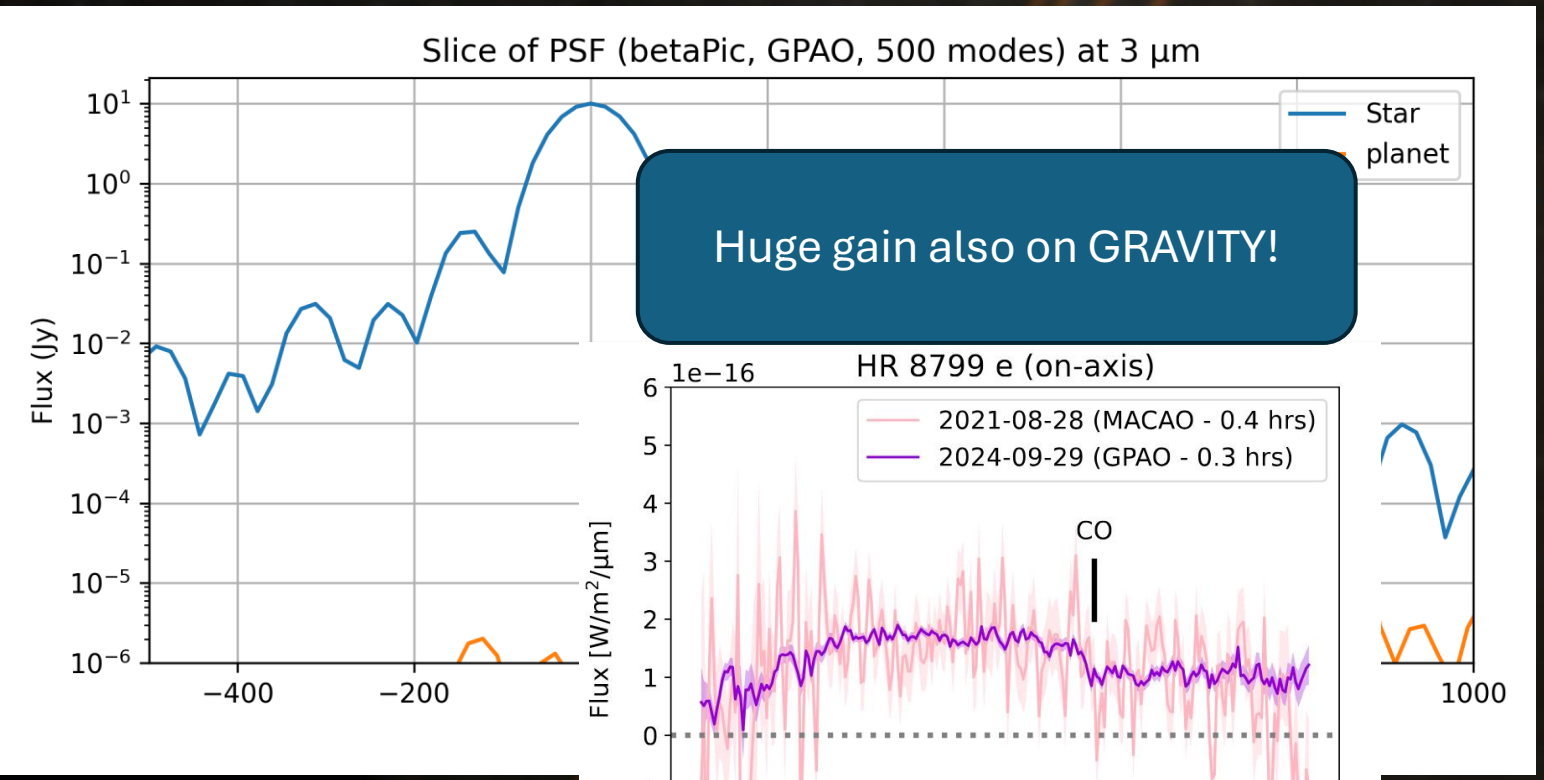


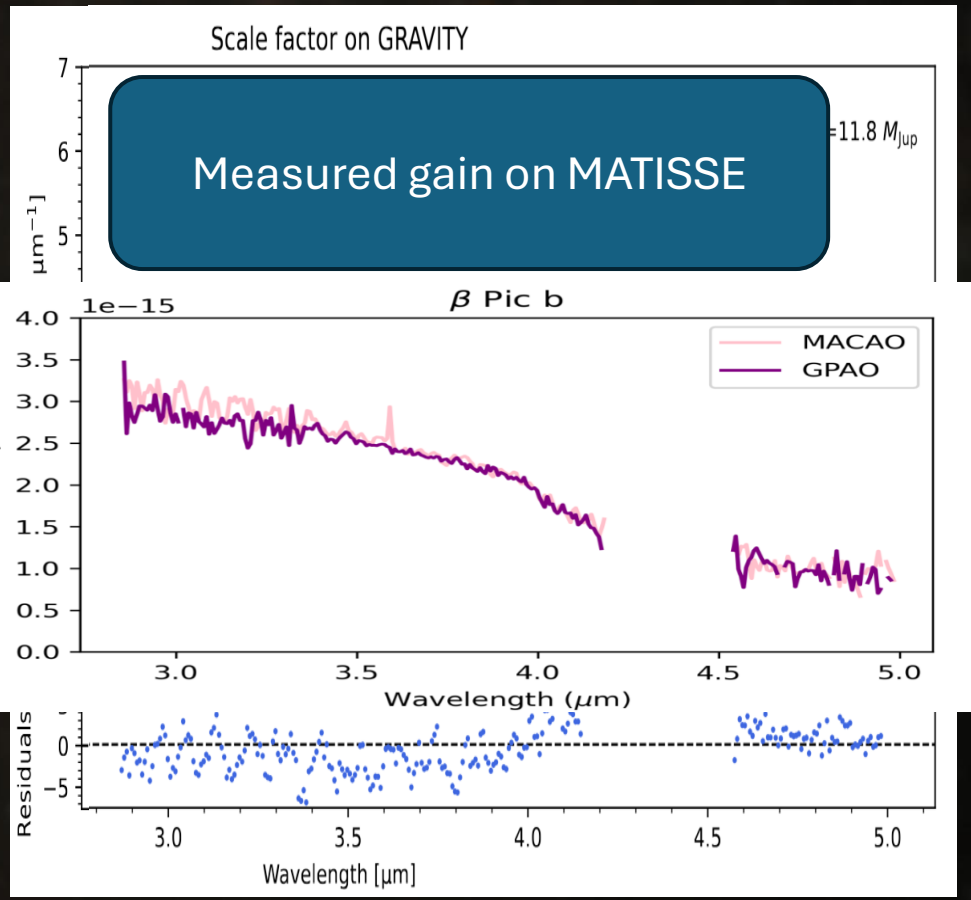


GRAVITY+ collaboration et al. A&A 2025 (accepted)

What impact has GPAO on MATISSE?



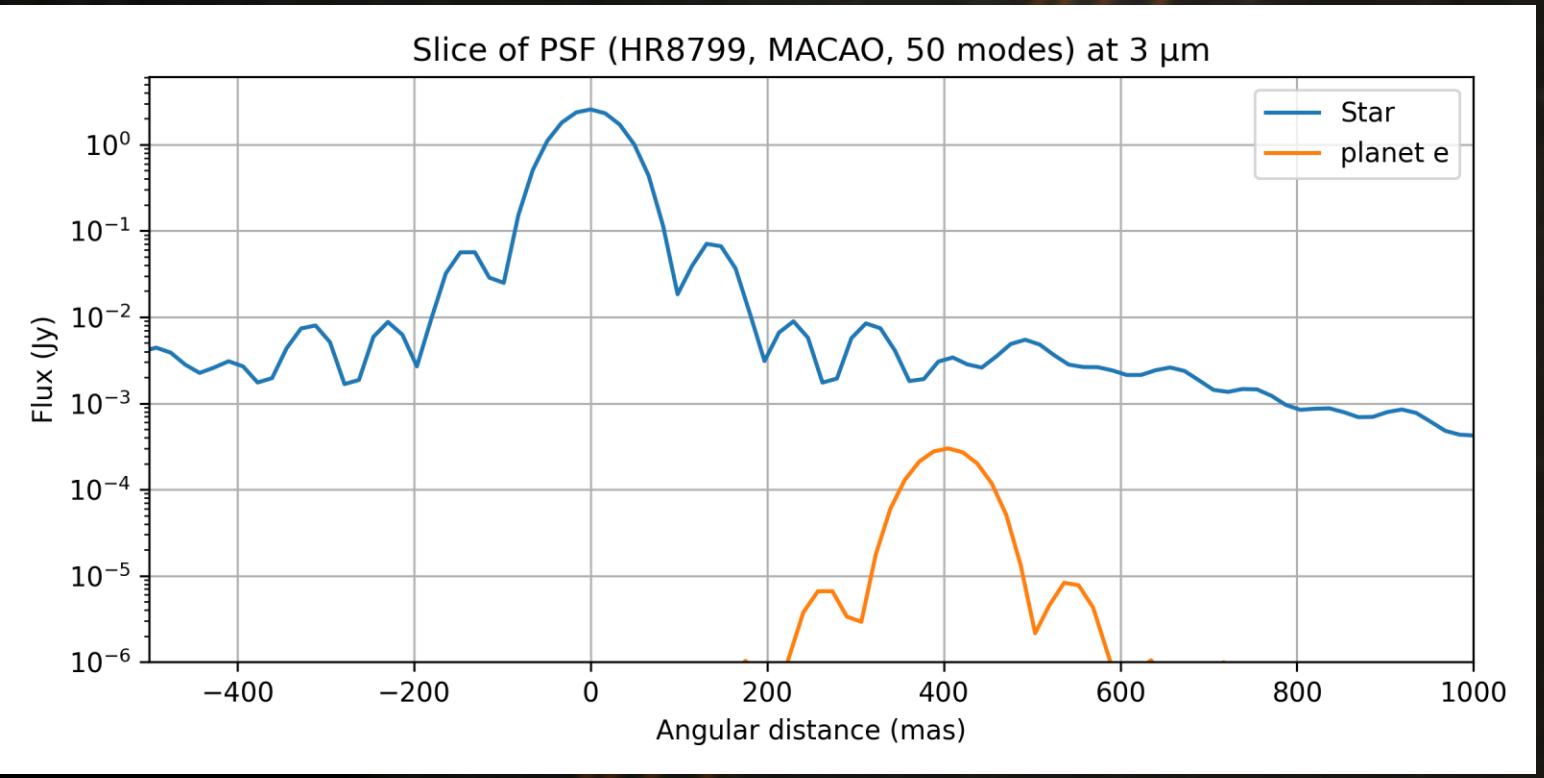
Huge gain also on GRAVITY!



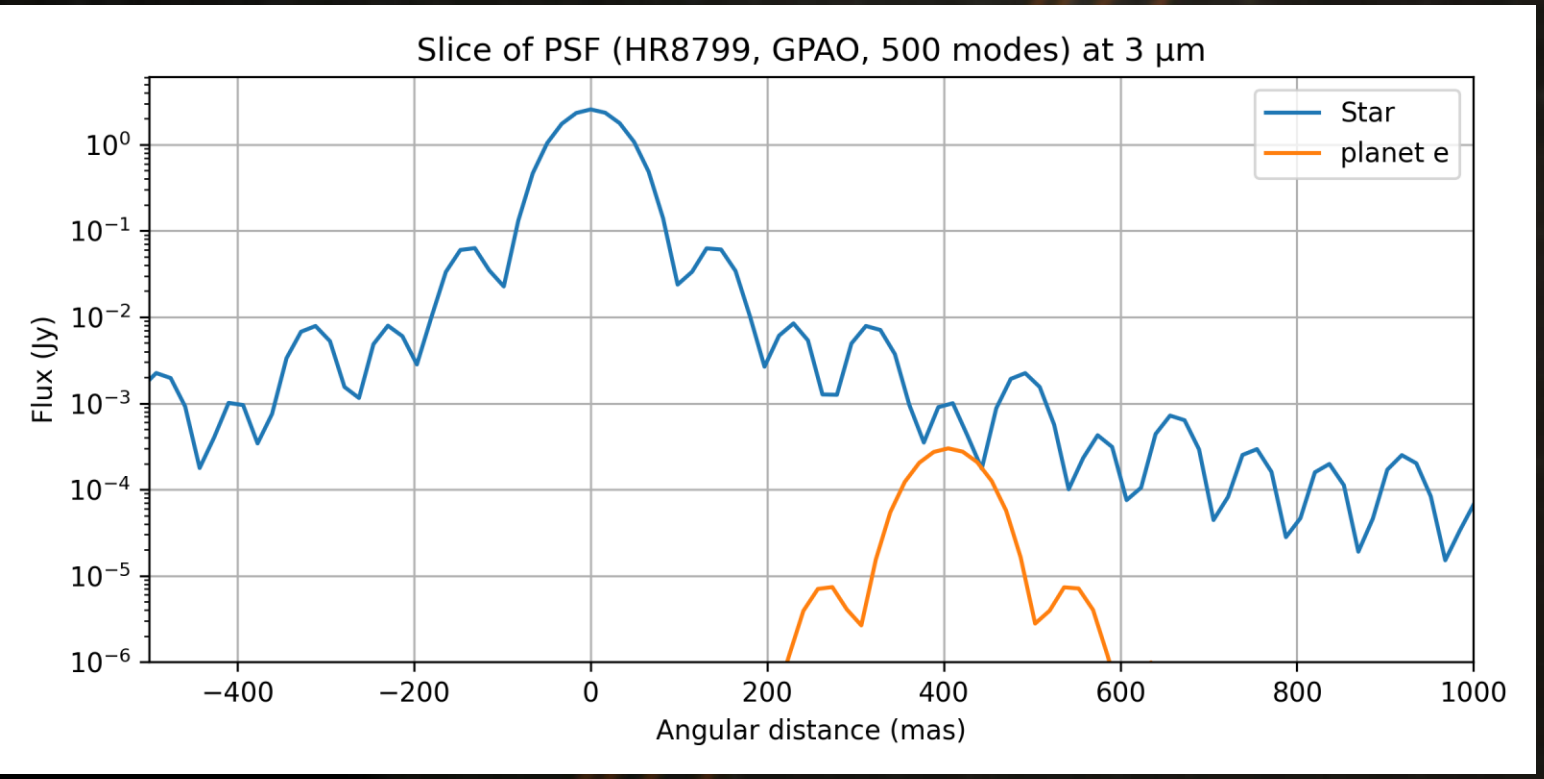
Measured gain on MATISSE

GRAVITY+ collaboration et al. A&A 2025 (accepted)

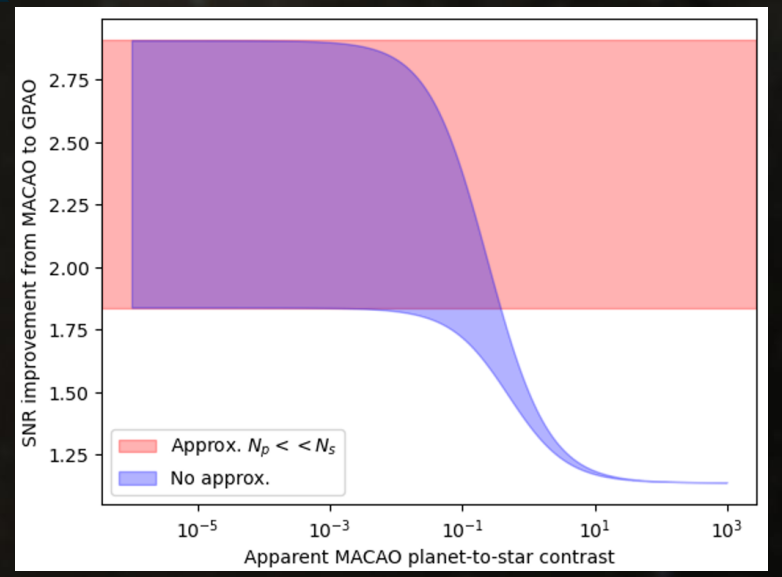
What impact has GPAO on MATISSE? Fainter planets (example of HR8799e)



What impact has GPAO on MATISSE? Fainter planets (example of HR8799e)



Higher SNR gain

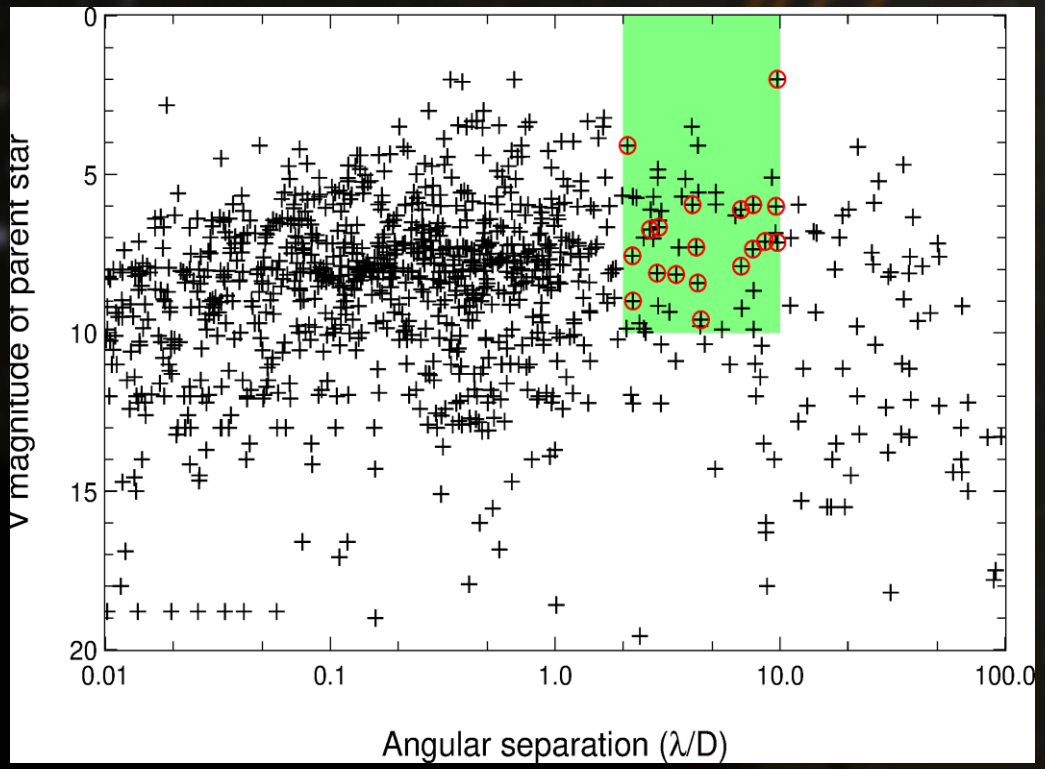


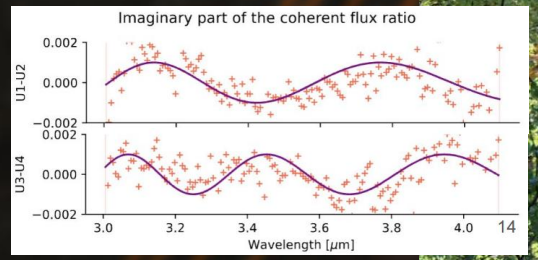
Fainter planet

More to come !

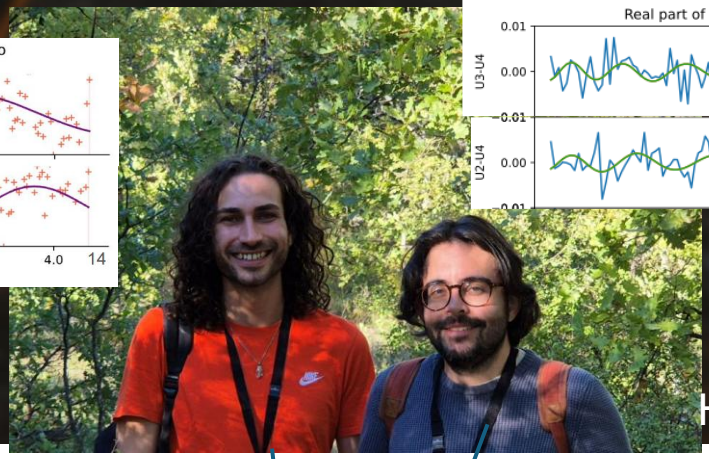
How many candidates for G+M?
Source: exoplanet.eu catalog
Filter by:

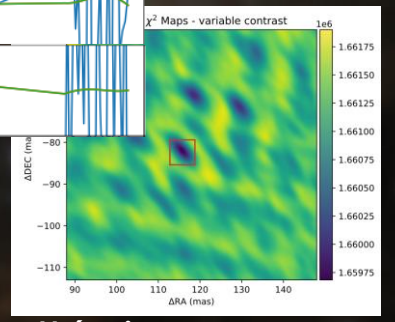
- Mass > $1M_{jup}$
- Mag V_{star} < 10
- Angular separation between 1.5 and 10 λ/D (λ=3.5 microns, D=8m)



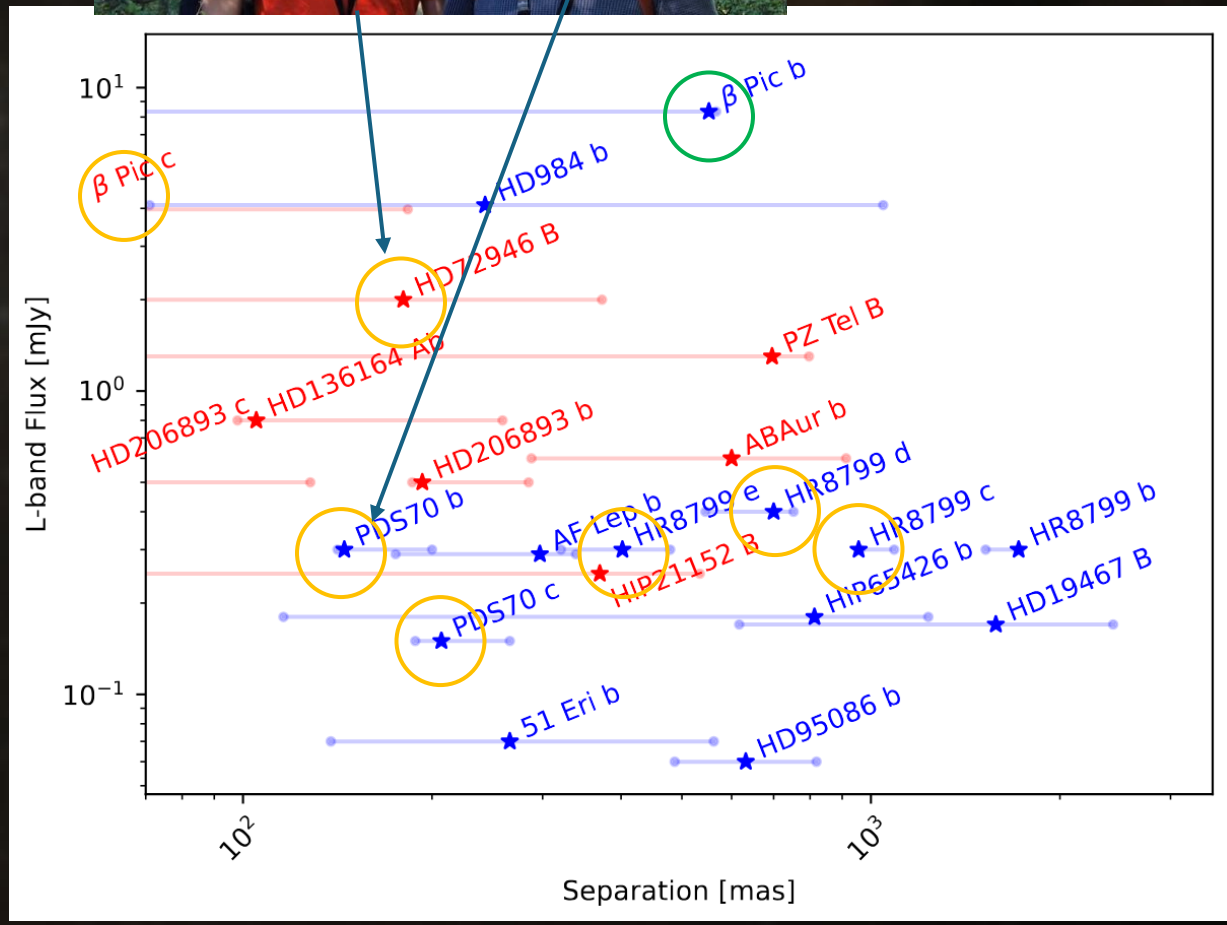


Scigliuto+ in prep





Houllé+ in prep



What's next?

- Gaia DR4 planets to target with MATISSE
- Get to lower wavelength
- Higher spectral resolution
  → See Ravet et al. A&A 2025 (just accepted)
- Add more telescopes !