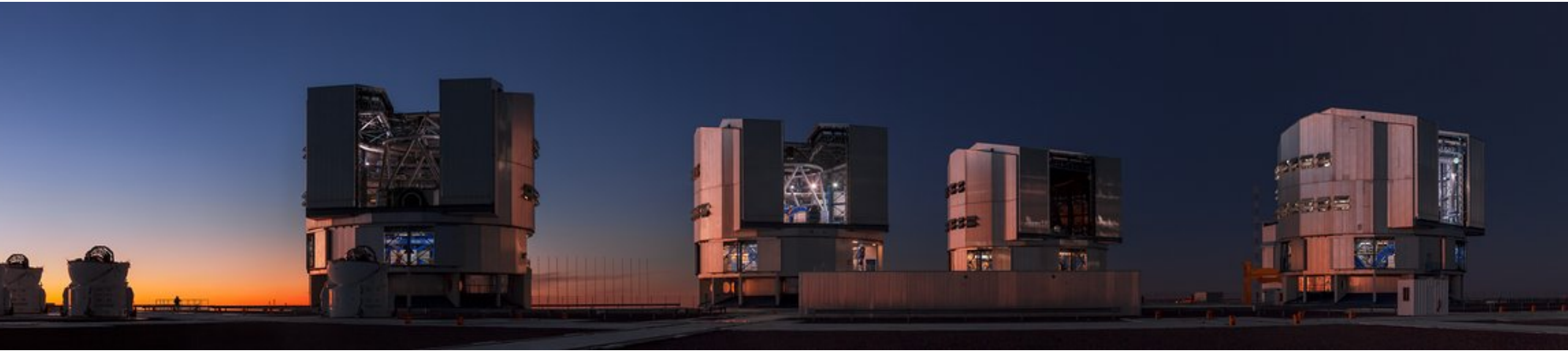
Dark hole + interferometry: a winning combo enabled by GRAVITY+

Sylvestre Lacour, **Mathias Nowak**, Jens Kammerer, Jean-Baptiste Le Bouquin

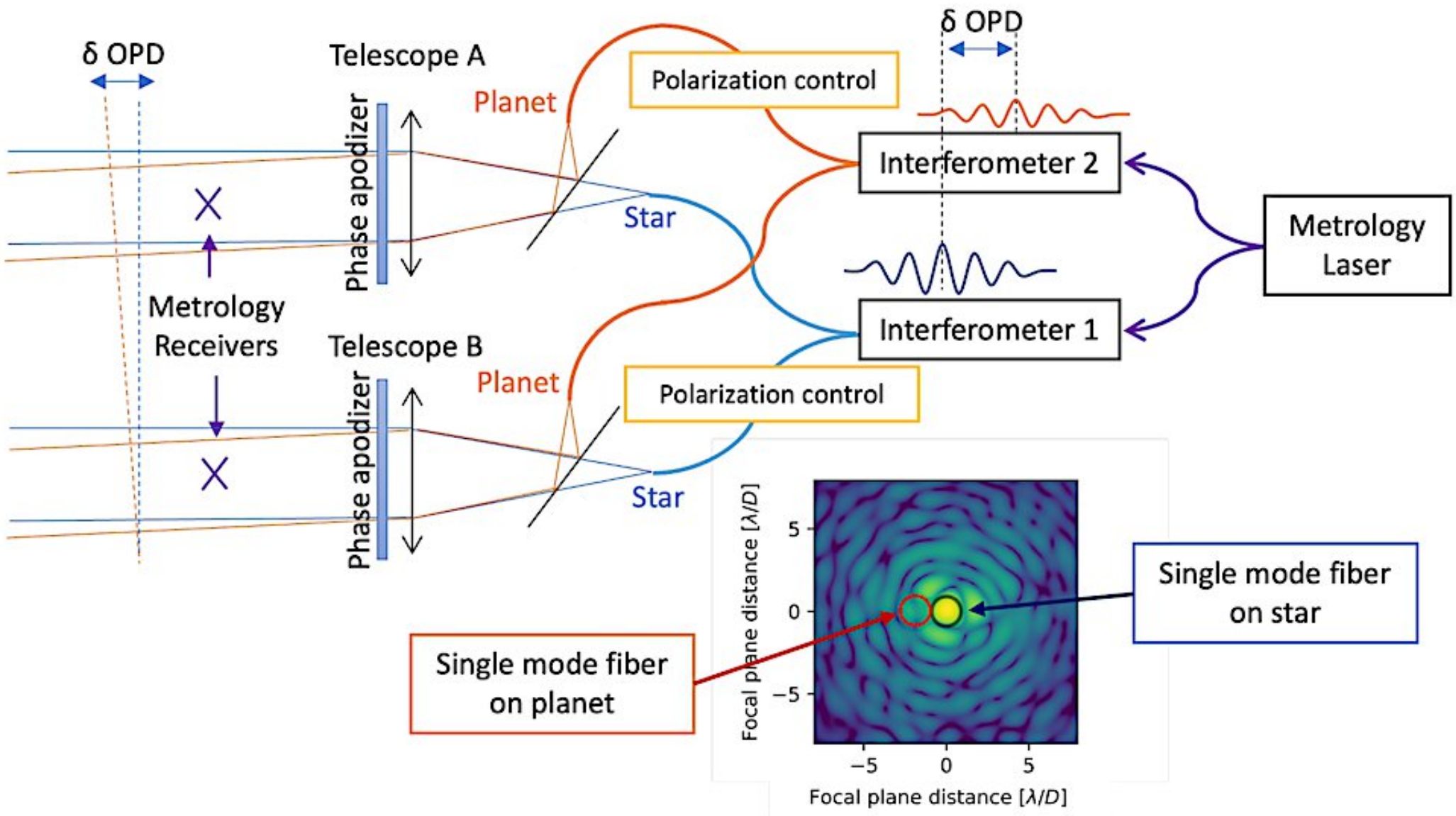
and the GRAVITY+ collaboration



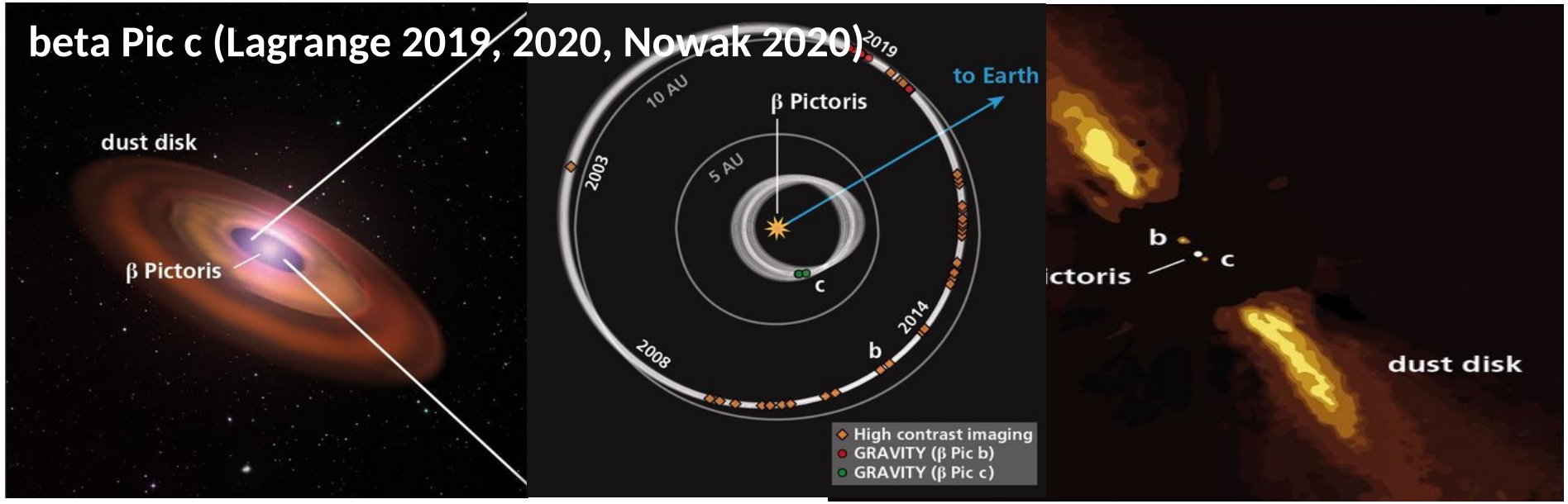
51 Pegasi b - Cool Giant planets and their systems

October 7th, Observatoire de Haute-Provence

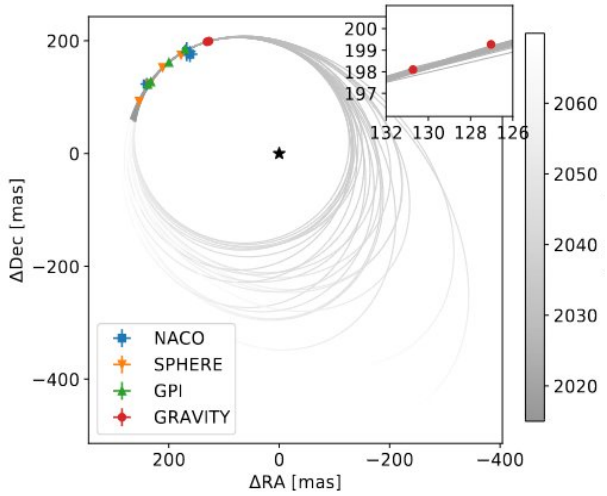
High contrast dual-field interferometry

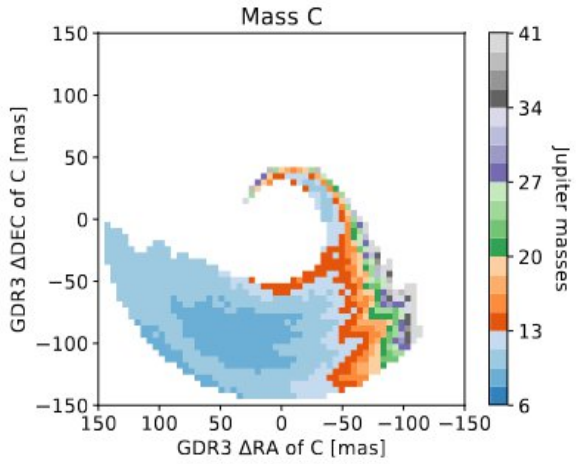


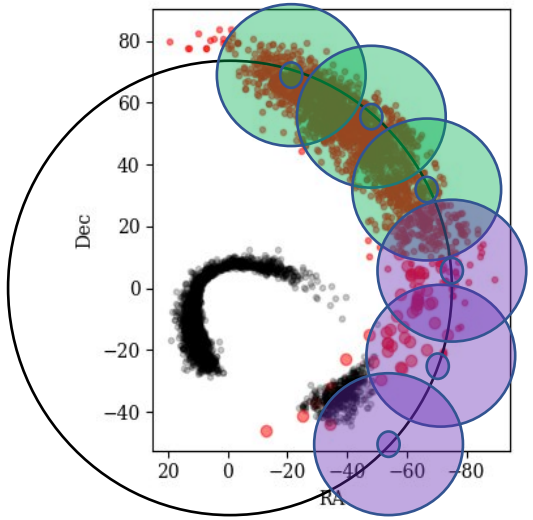
Direct detection of HD206893 c (2023)



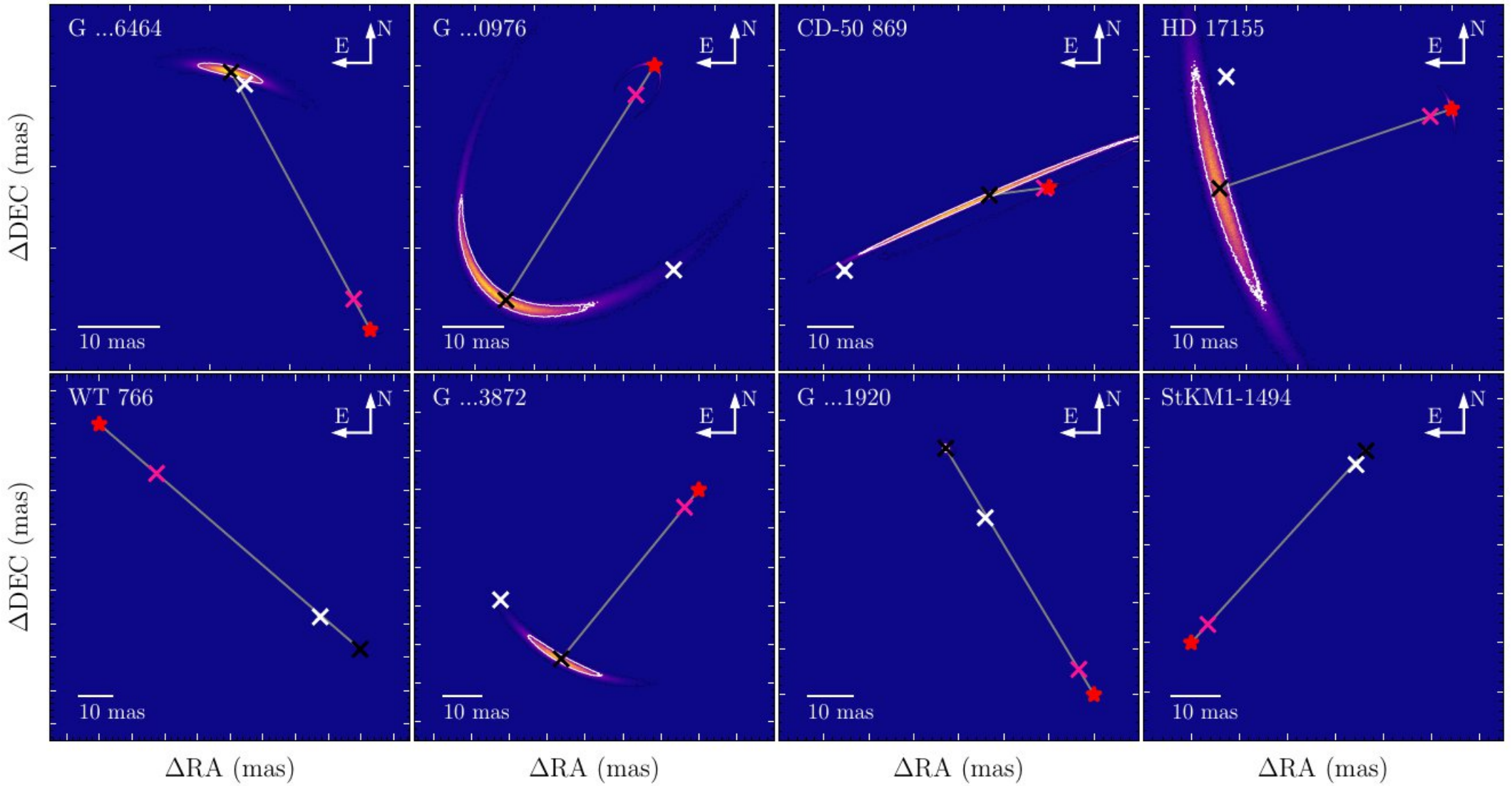
HD206893 c (Kammerer 2021, Hinkley 2023)







Going after the Gaia substellar companions



Winterhalder 2024

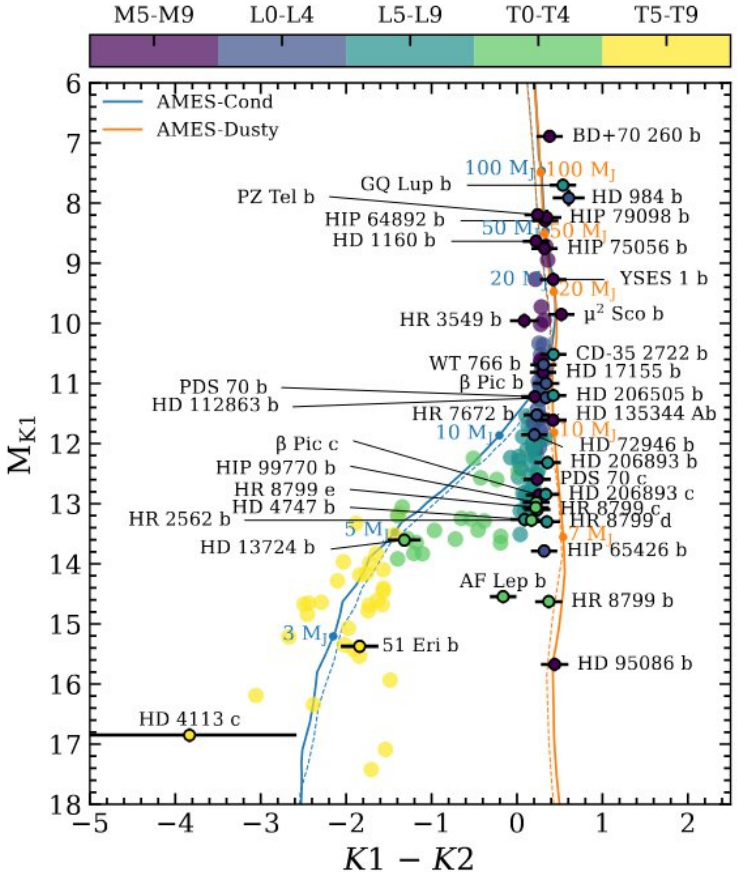
The ExoGRAVITY Large Programme

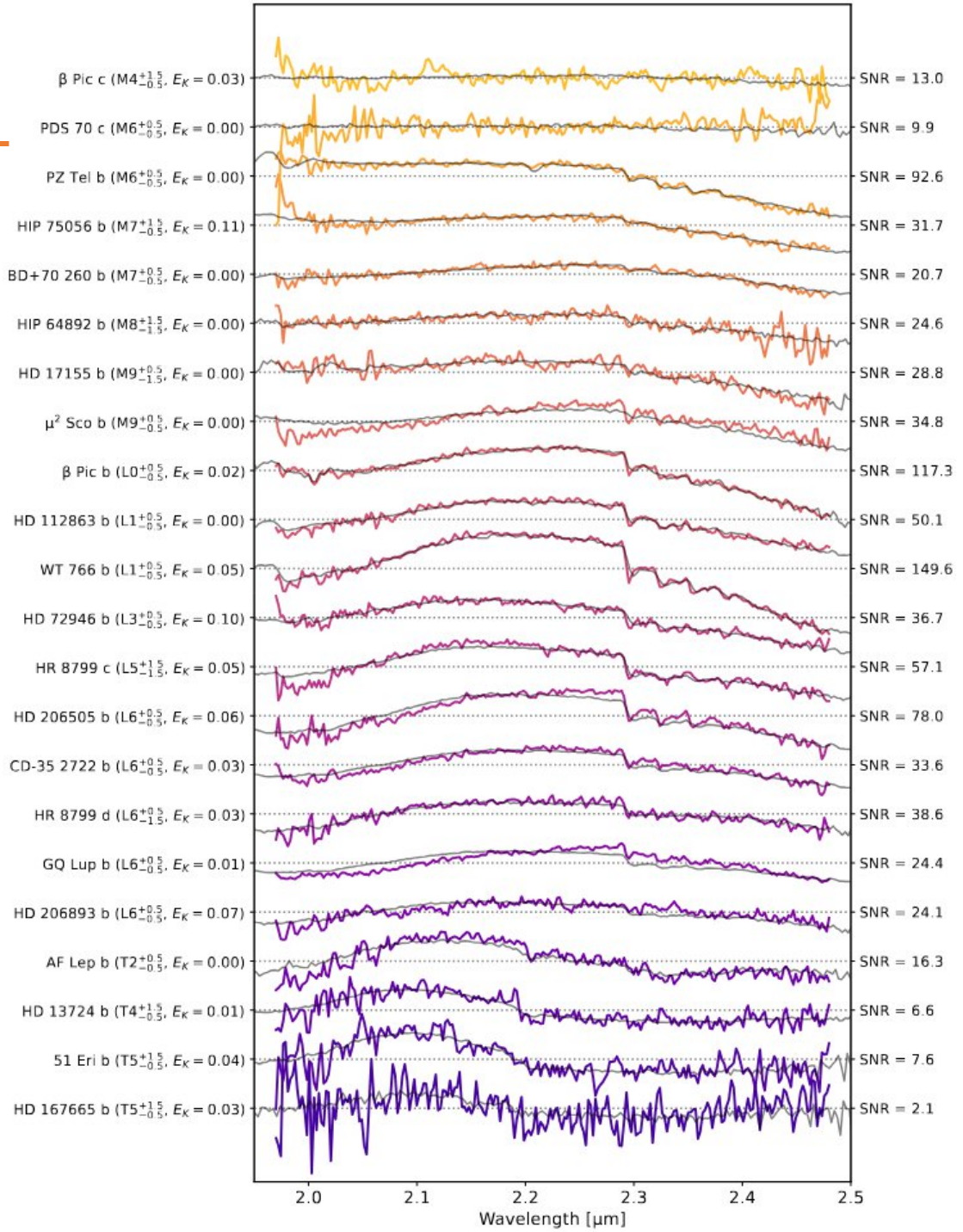
Kammerer et al. (in prep):

- Homogeneous reduction of 39 substellar companions observed during the ExoGRAVITY LP
- K-band library illustrating the L-T transition, with a shift from CO-dominated late M- and L-type dwarfs to CH4-dominated T-type dwarfs
- Soon available online!

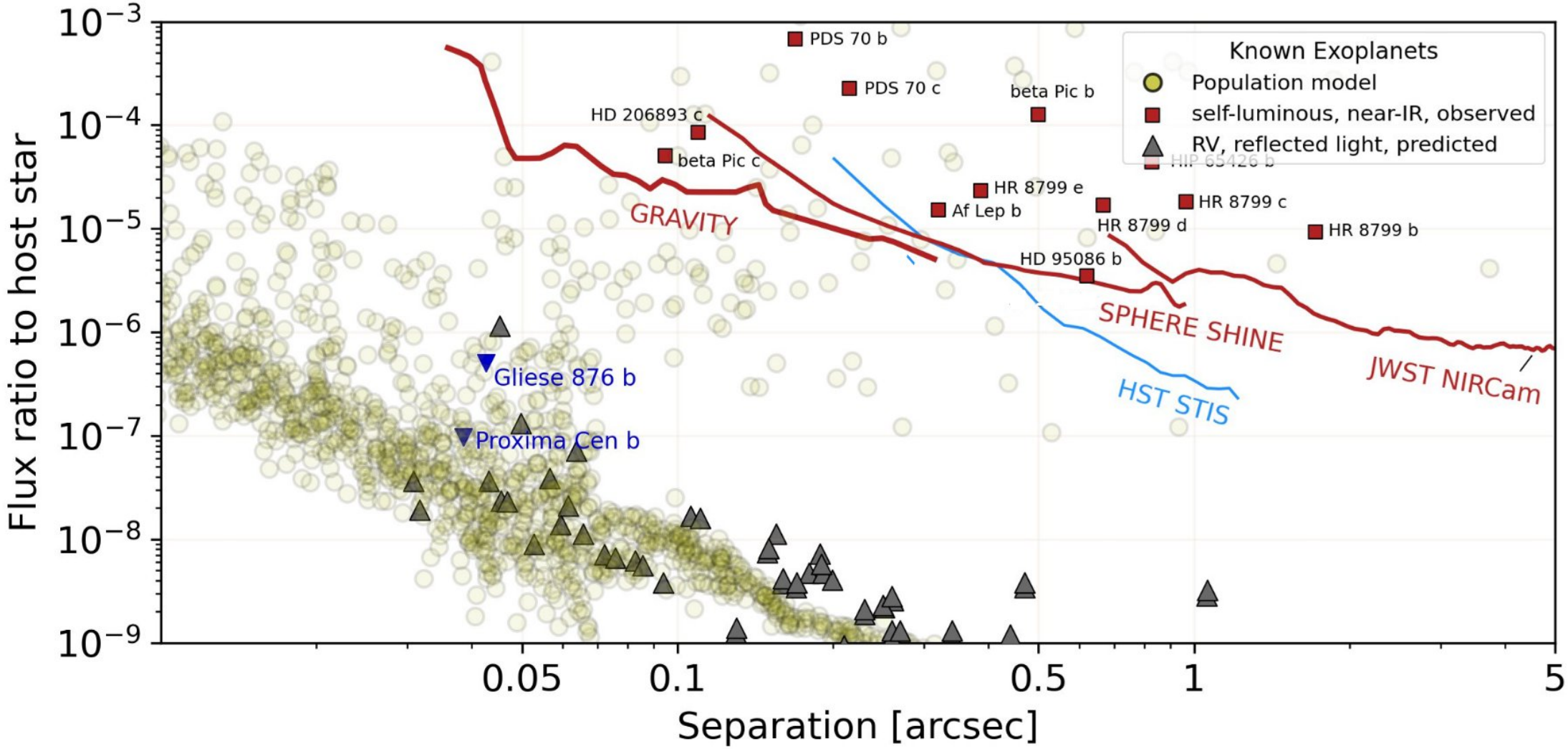
See also:

- orbital characterization (J. Wang, this afternoon)
- MATISSE in mid-IR (M. Houllé, Thursday; F. Millour, Friday)



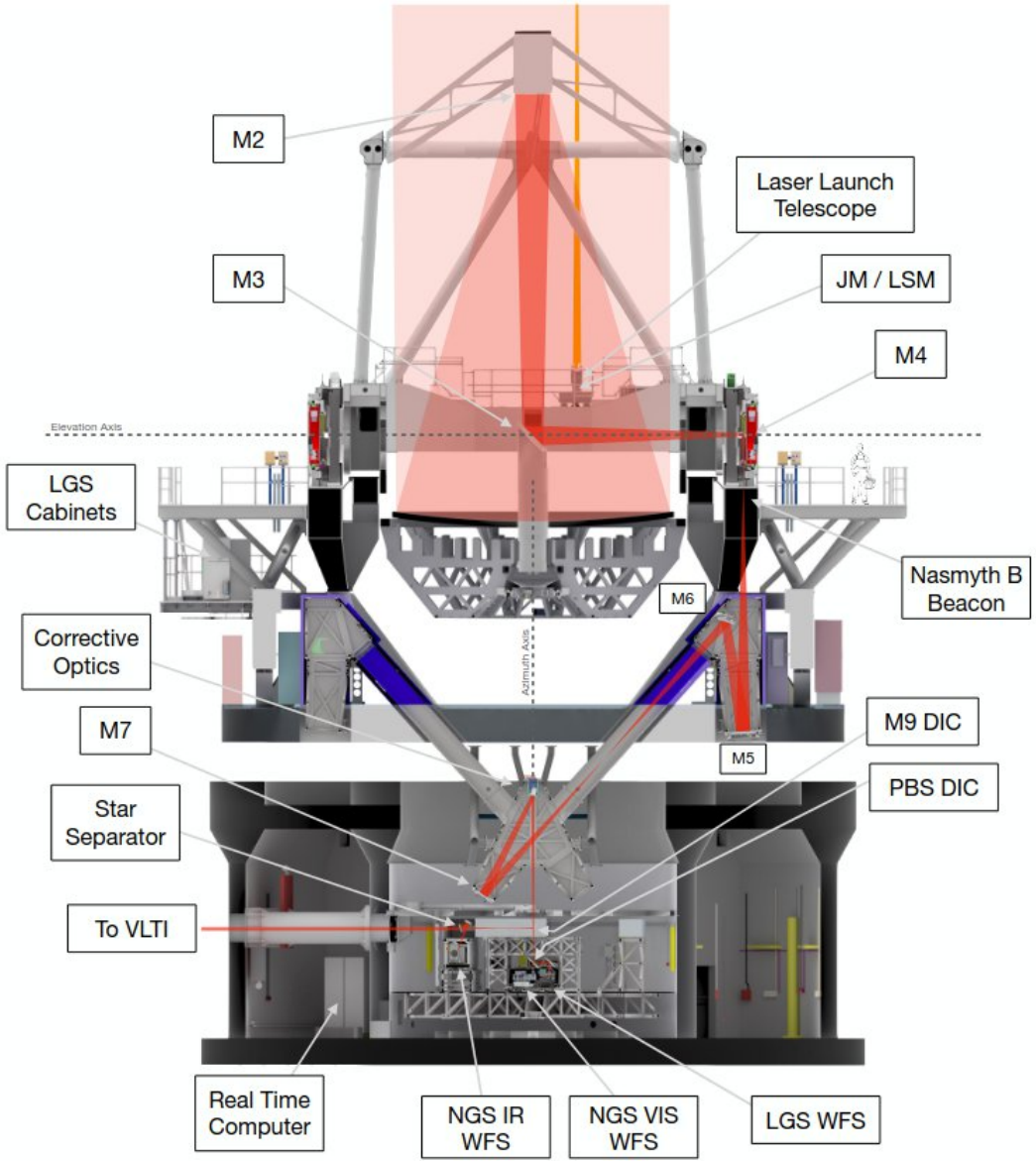


Where do we stand?

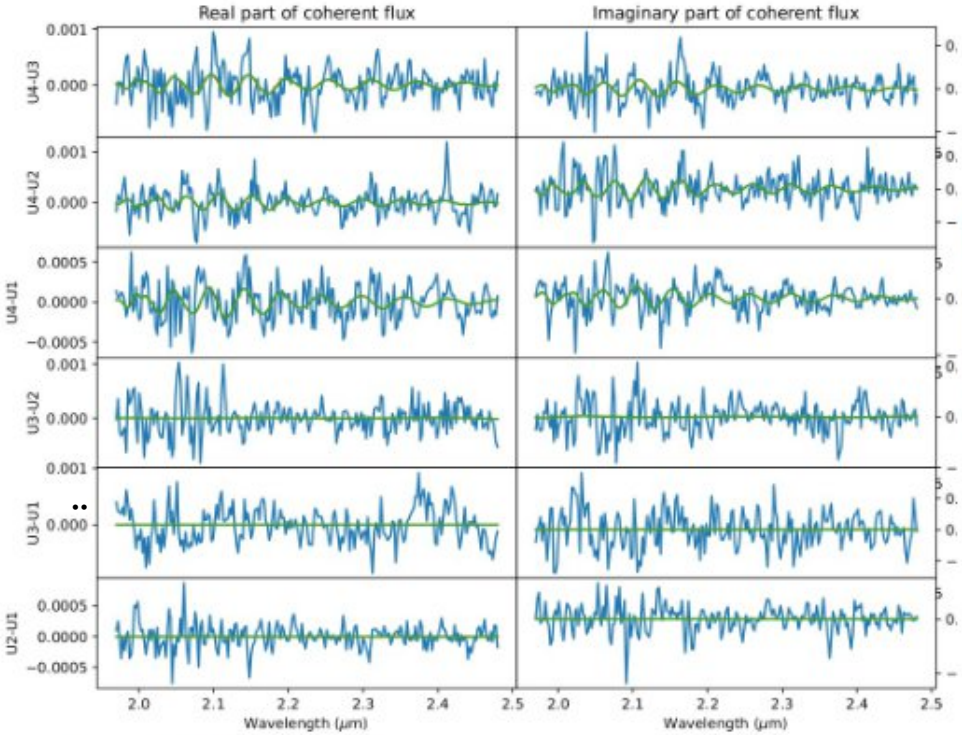


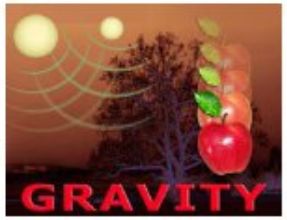
GPAO and GRAVITY+

GRAVITY+ Collaboration (2025)



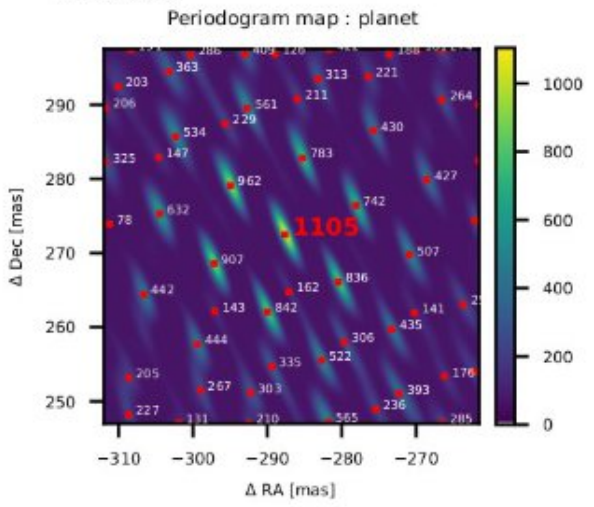
MACAO 2021-09-28 Seeing 0.8", Tau0=3.3ms
Total 20 min integration / 50 min time base





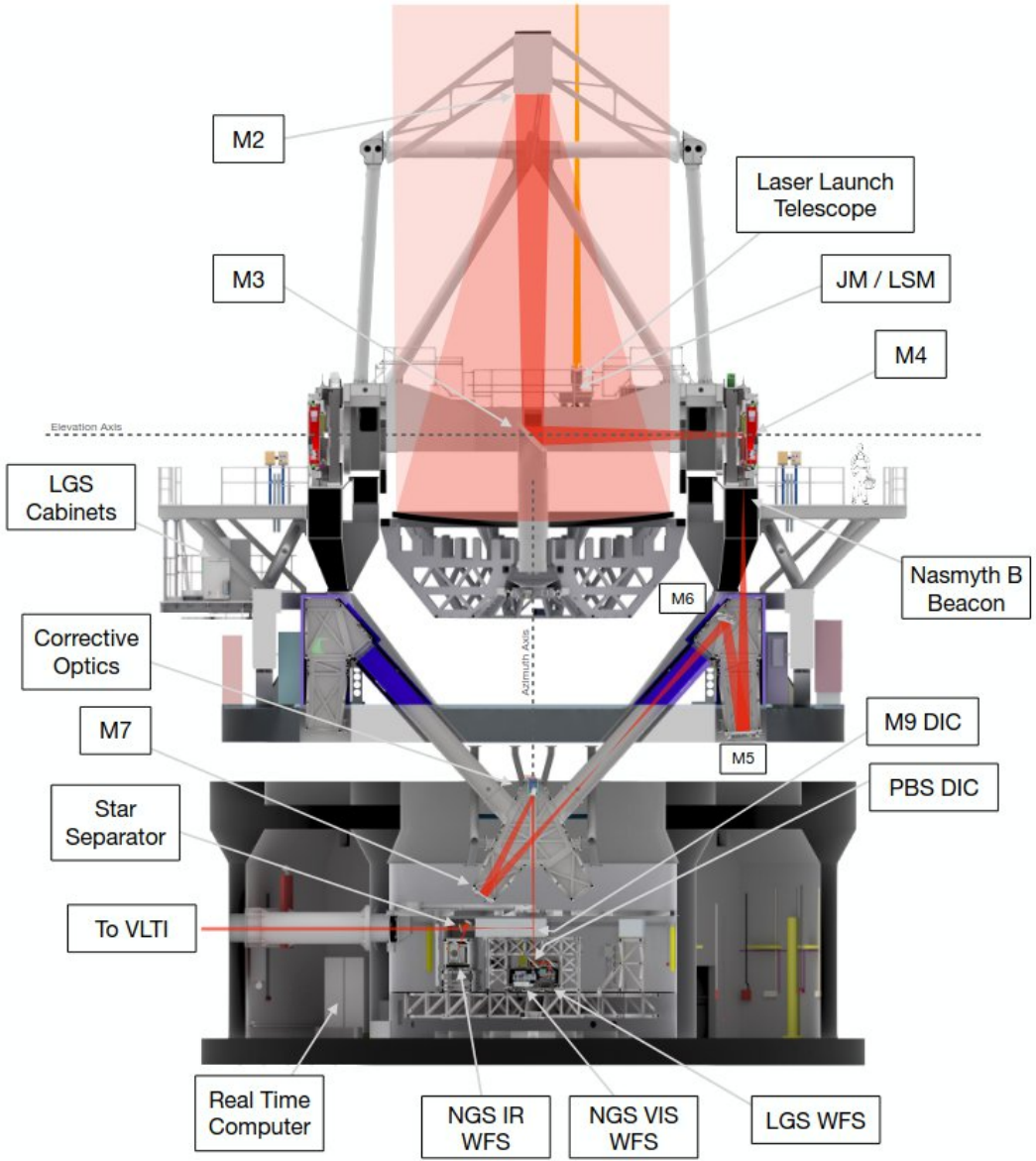
Planet fit

SNR detection = 3.3

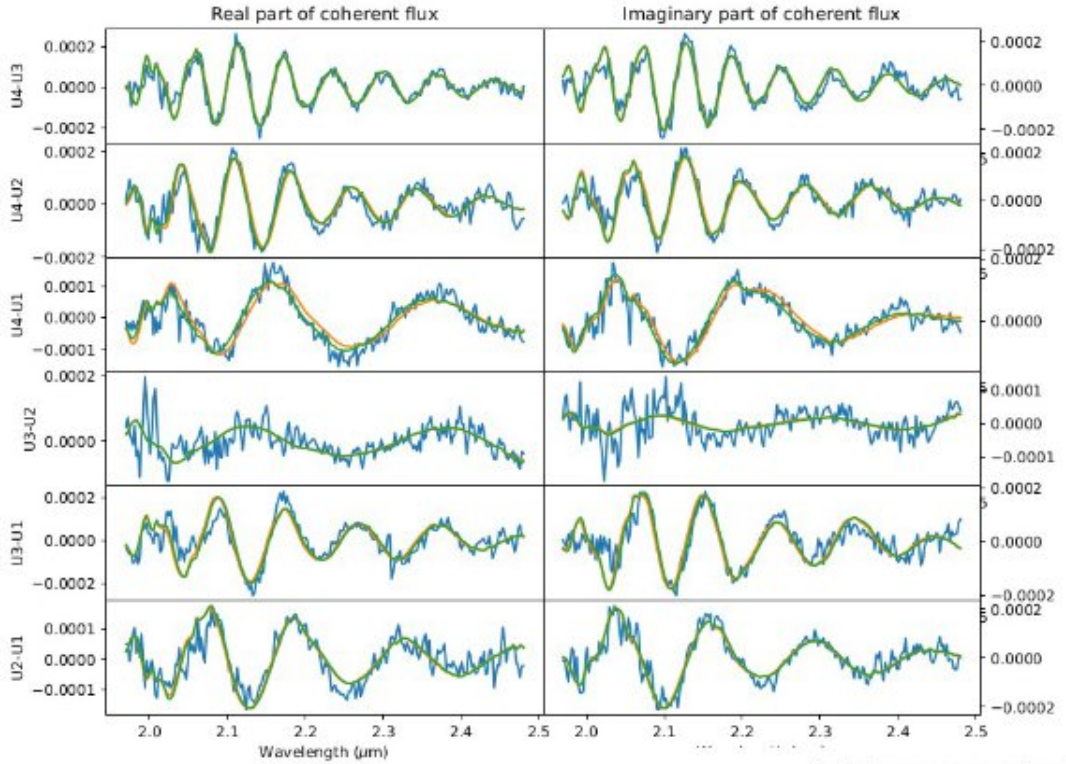


GPAO and GRAVITY+

GRAVITY+ Collaboration (2025)

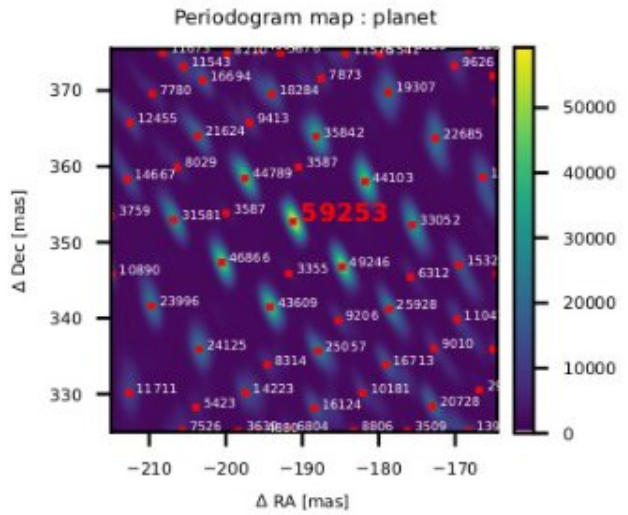


GPAO 2024-09-29 Seeing 0.7", Tau0=5ms
Total 20 min integration / 65 min time base



Planet fit

SNR detection = 14

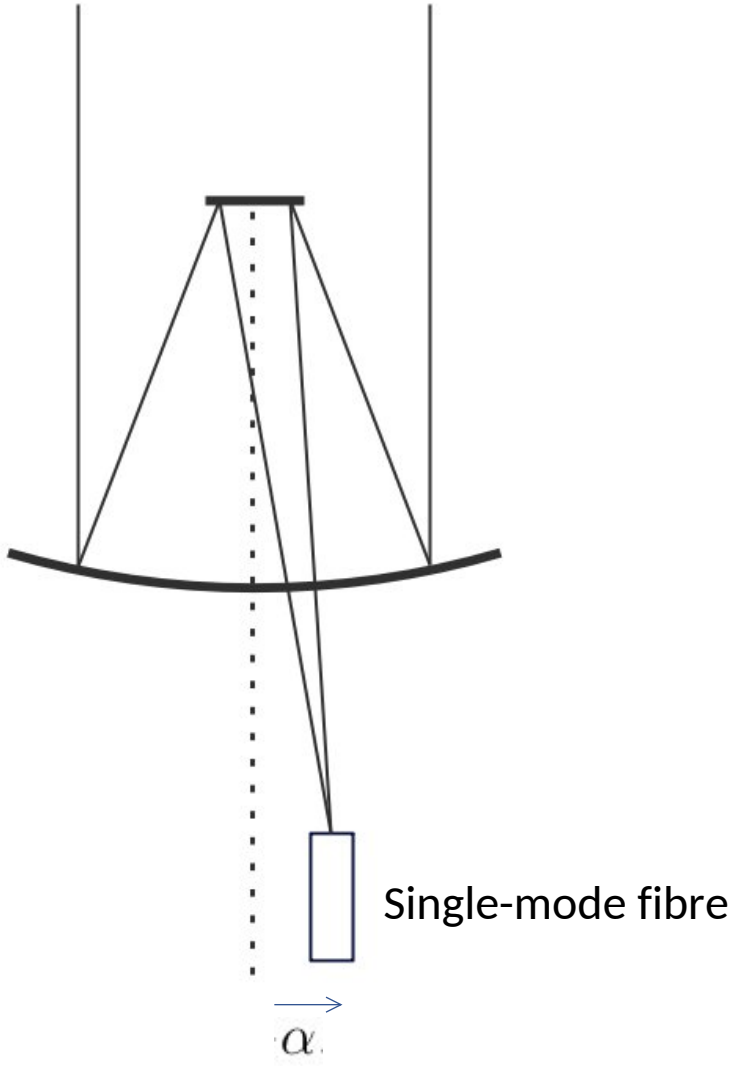


GRAVITY+ dark hole in theory

Fibre mode Fibre position

$$E_{\text{inj}} \propto \iint_{\text{pupil}} H(\mathbf{u}) e^{-i\frac{2\pi}{\lambda}\alpha.\mathbf{u}} \times 1$$

On-axis star



GRAVITY+ dark hole in theory

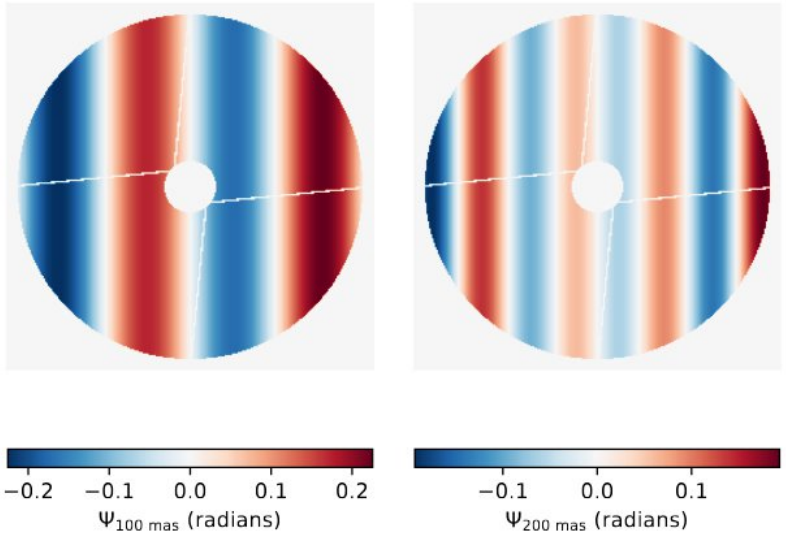
Fibre mode

Fibre position

AO dark-hole modes

$$E_{\text{inj}} \propto \iint_{\text{pupil}} H(\mathbf{u}) e^{-i\frac{2\pi}{\lambda}\alpha.\mathbf{u}} \times 1 \times e^{-i\left[A\cos\left(-\frac{2\pi}{\lambda}\alpha.\mathbf{u}\right)+B\sin\left(-\frac{2\pi}{\lambda}\alpha.\mathbf{u}+\phi\right)\right]} d\mathbf{u}$$

On-axis star



GRAVITY+ dark hole in theory

Fibre mode Fibre position AO dark-hole modes

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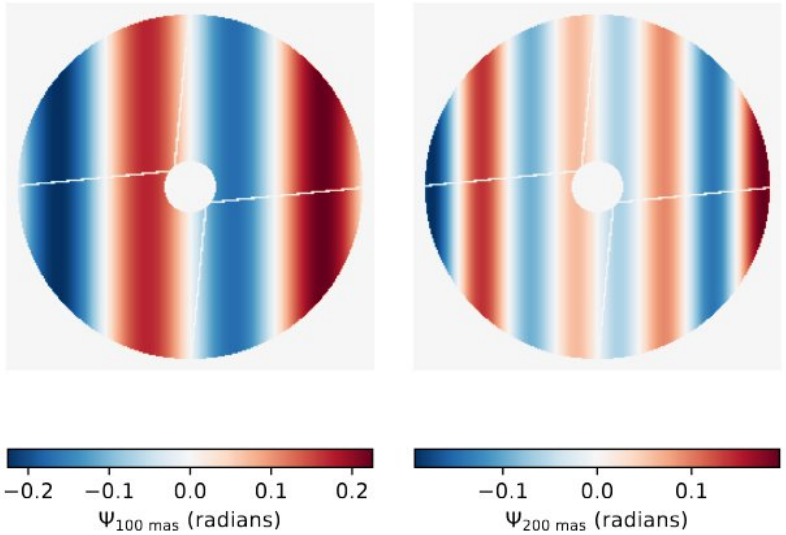
$$\propto \iint_{\text{pupil}} H(\mathbf{u}) e^{-i\frac{2\pi}{\lambda}\alpha.\mathbf{u}} \left[1 - iA\cos\left(-\frac{2\pi}{\lambda}\alpha.\mathbf{u}\right) + iB\sin\left(-\frac{2\pi}{\lambda}\alpha.\mathbf{u}\right)\right] d\mathbf{u}$$

$$\propto E_0 + [iA - B]$$

$$\propto E_0 + U$$



GRAVITY+ dark hole in theory

Fibre mode Fibre position AO dark-hole modes

$$E_{\rm inj} \propto \iint_{\rm pupil} H(\mathbf{u}) e^{-i\frac{2\pi}{\lambda}\alpha.\mathbf{u}} \times 1 \times e^{-i\left[A\cos\left(-\frac{2\pi}{\lambda}\alpha.\mathbf{u}\right)+B\sin\left(-\frac{2\pi}{\lambda}\alpha.\mathbf{u}+\phi\right)\right]} d\mathbf{u}$$

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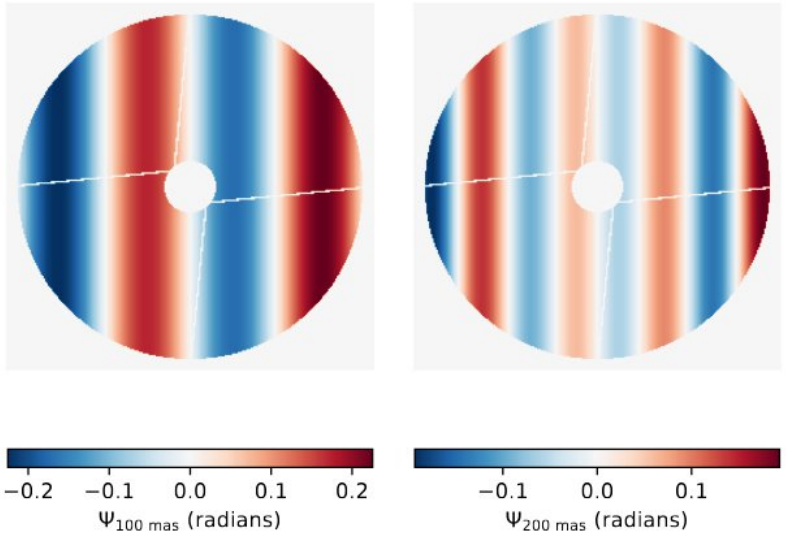
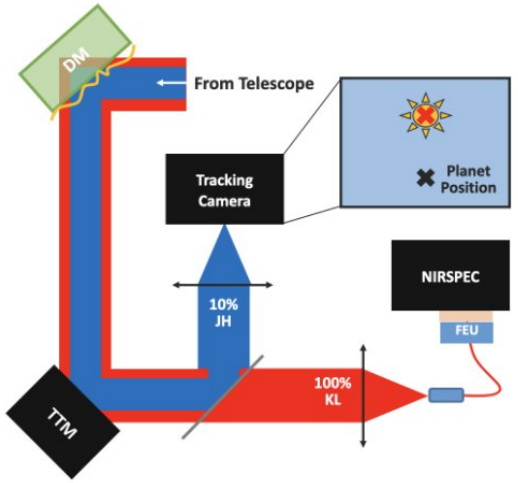
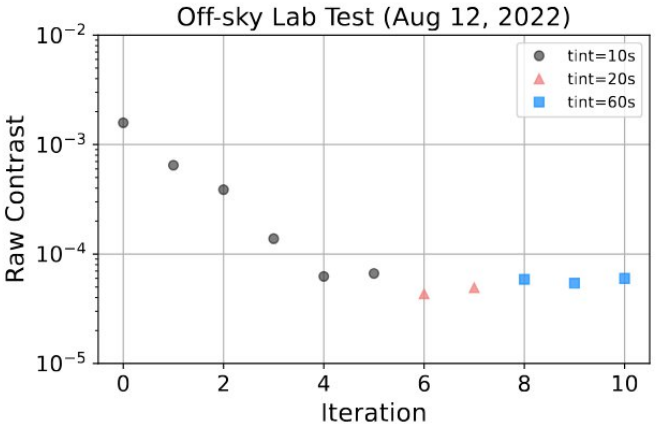


Single telescope: (ex: "nulling" at KPIC, Xin+2023)

$$F = |E_0 + U|^2$$





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Fibre mode | Fibre position | AO dark-hole modes

$$E_{\rm inj} \propto \iint_{\rm pupil} H(\mathbf{u}) e^{-i\frac{2\pi}{\lambda}\alpha.\mathbf{u}} \times 1 \times e^{-i\left[A\cos\left(-\frac{2\pi}{\lambda}\alpha.\mathbf{u}\right)+B\sin\left(-\frac{2\pi}{\lambda}\alpha.\mathbf{u}+\phi\right)\right]} d\mathbf{u}$$

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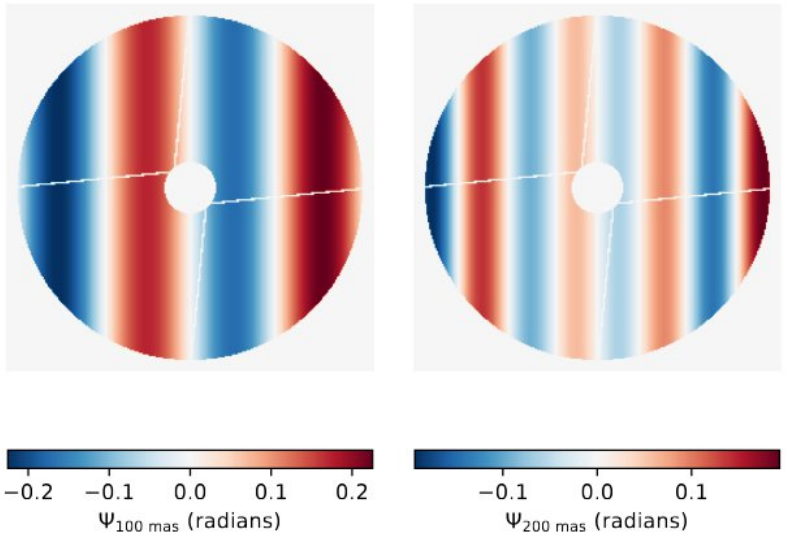

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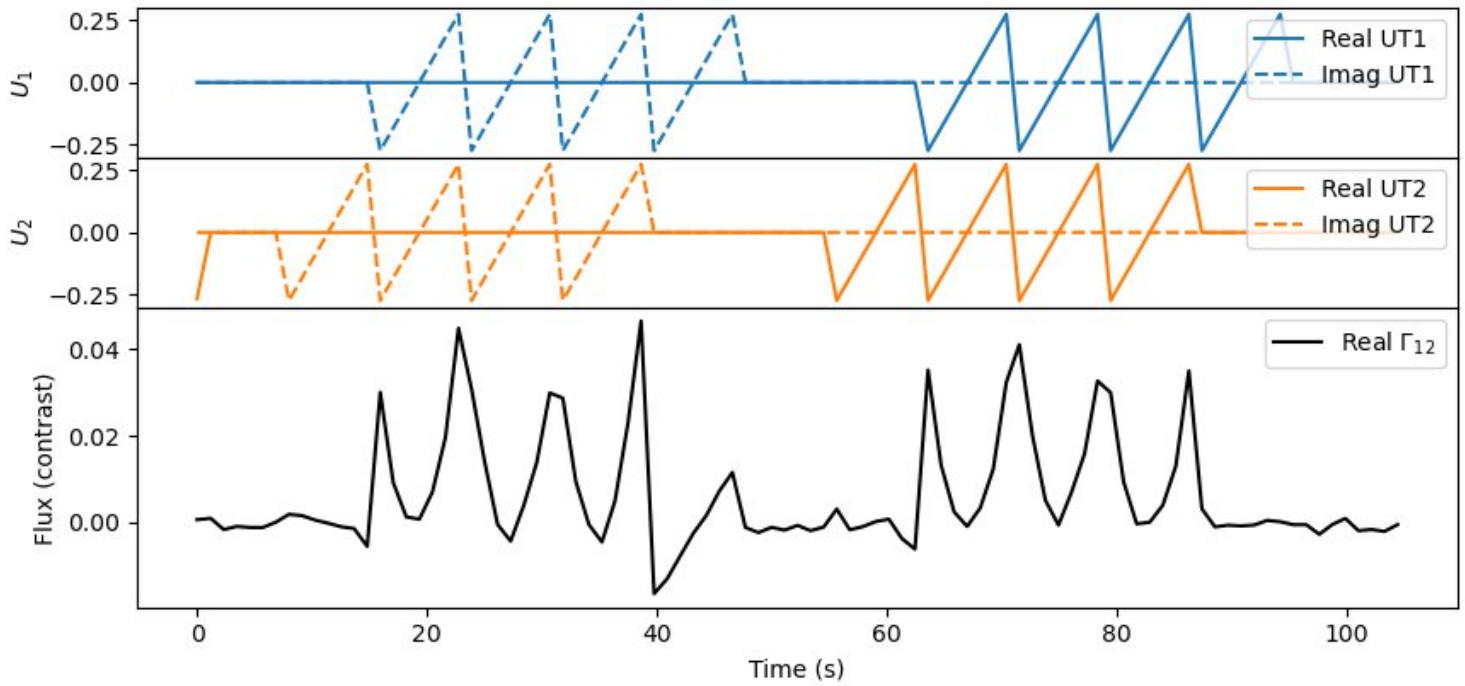
Two-telescope baseline :

$$\Gamma_{12} = (E_1 + U_1)(E_2 + U_2)^*$$
$$= E_1 E_2^* + E_1 U_2^* + E_2^* U_1 + U_1 U_2^*$$



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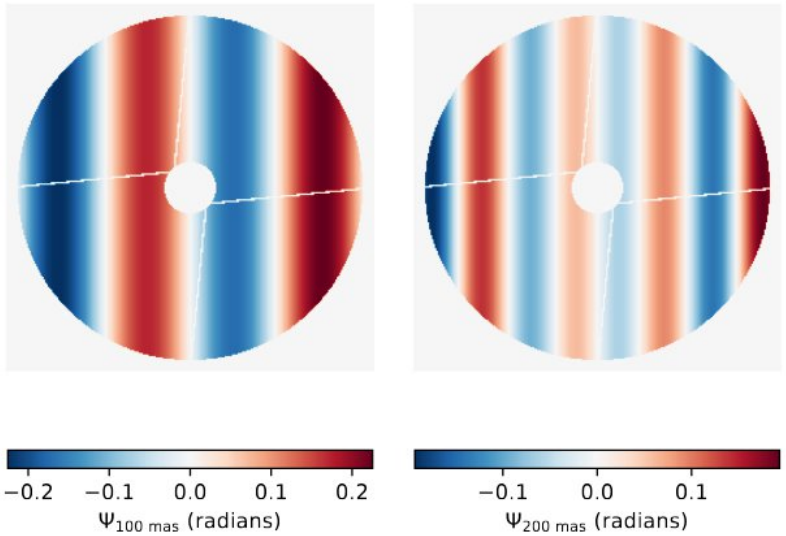

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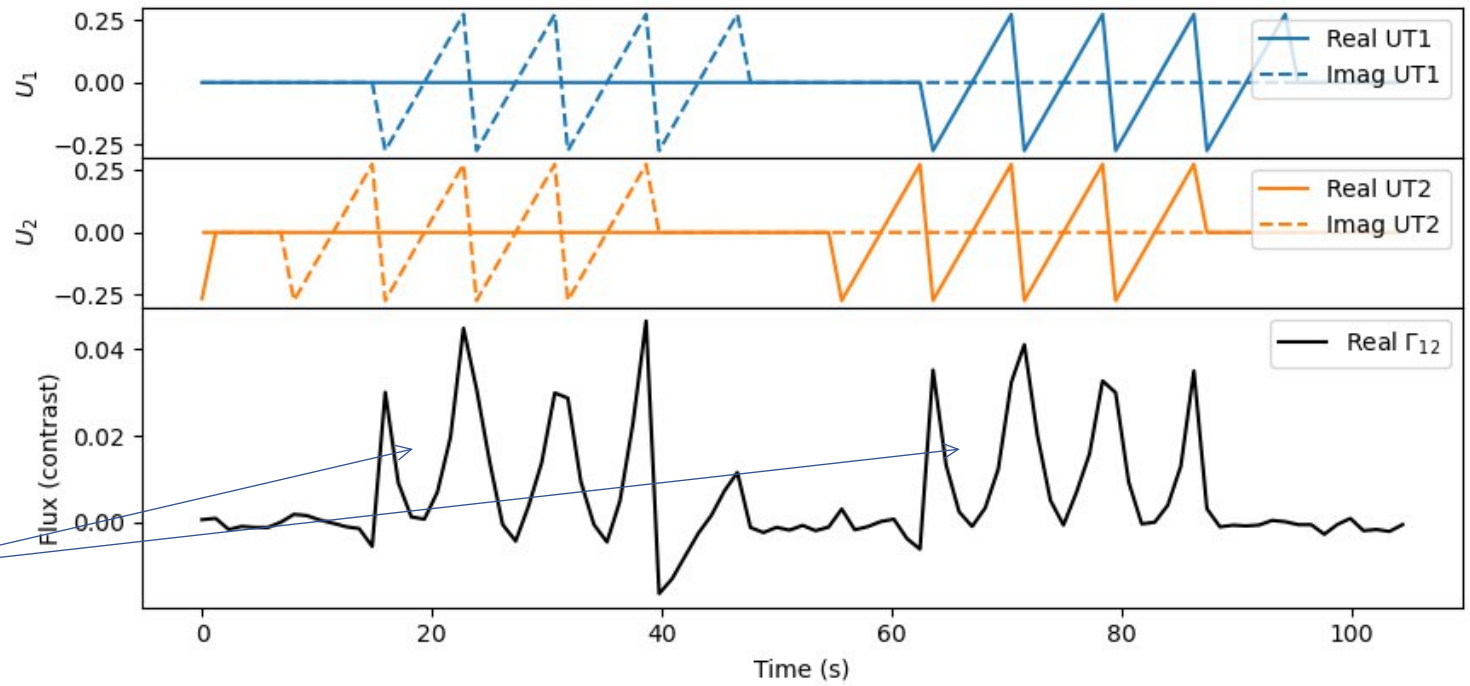

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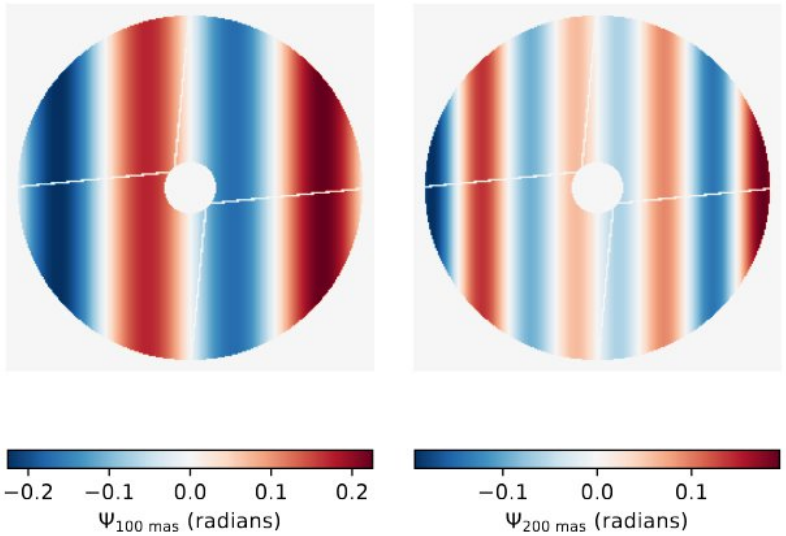

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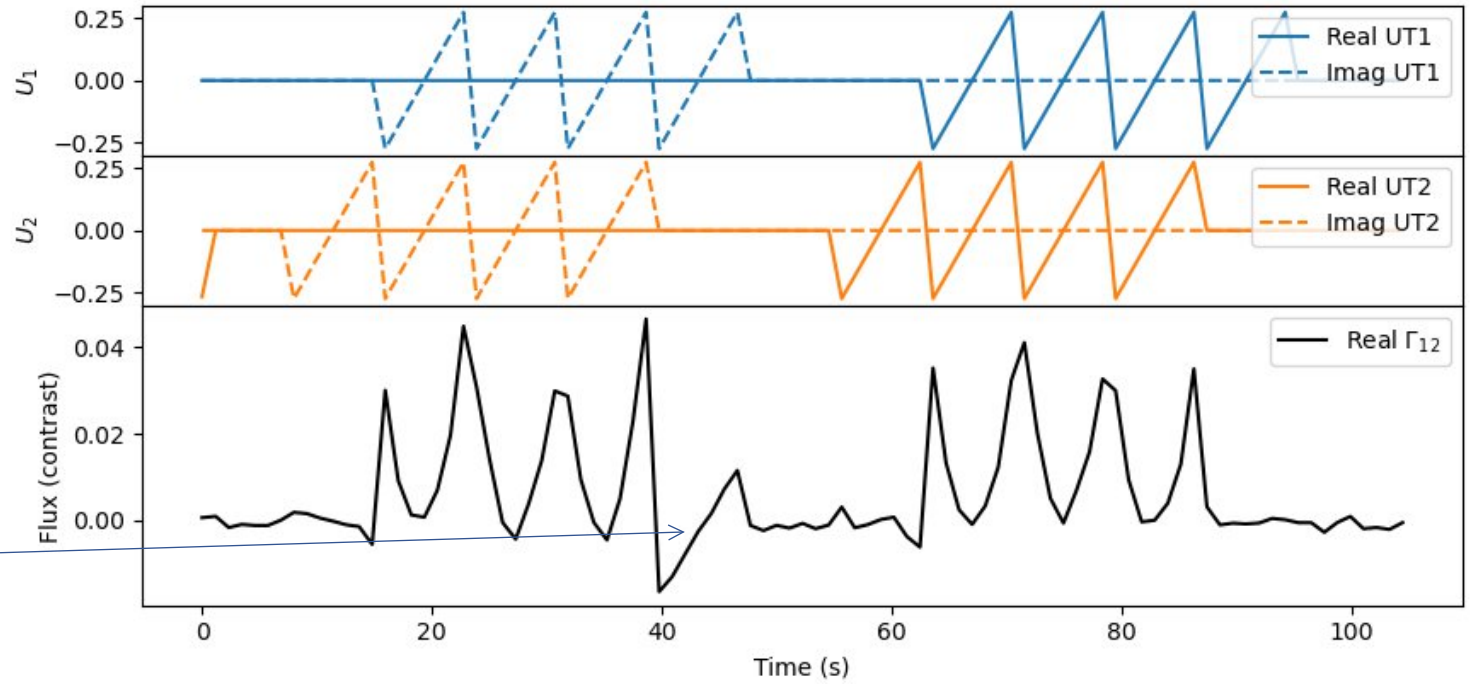
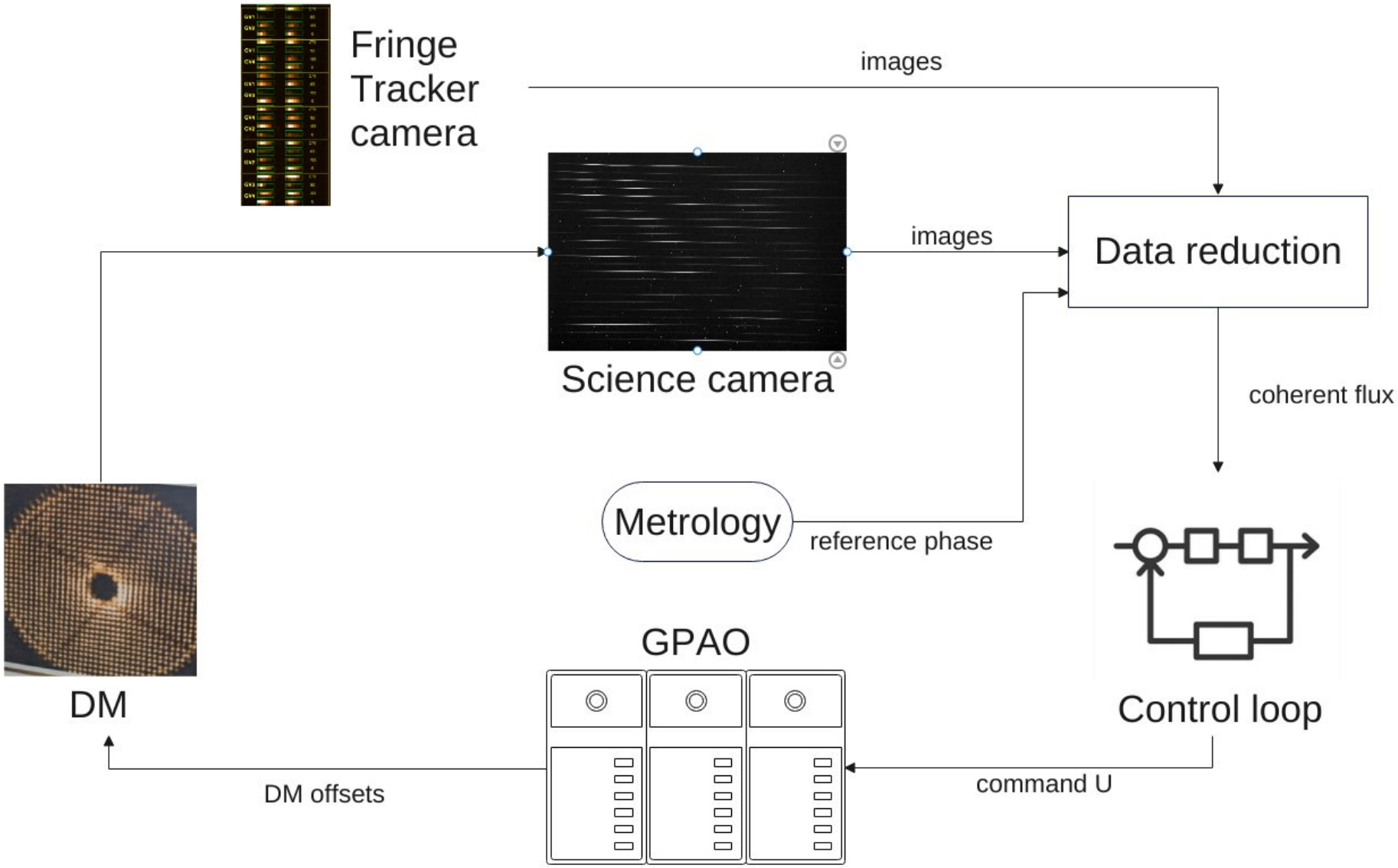
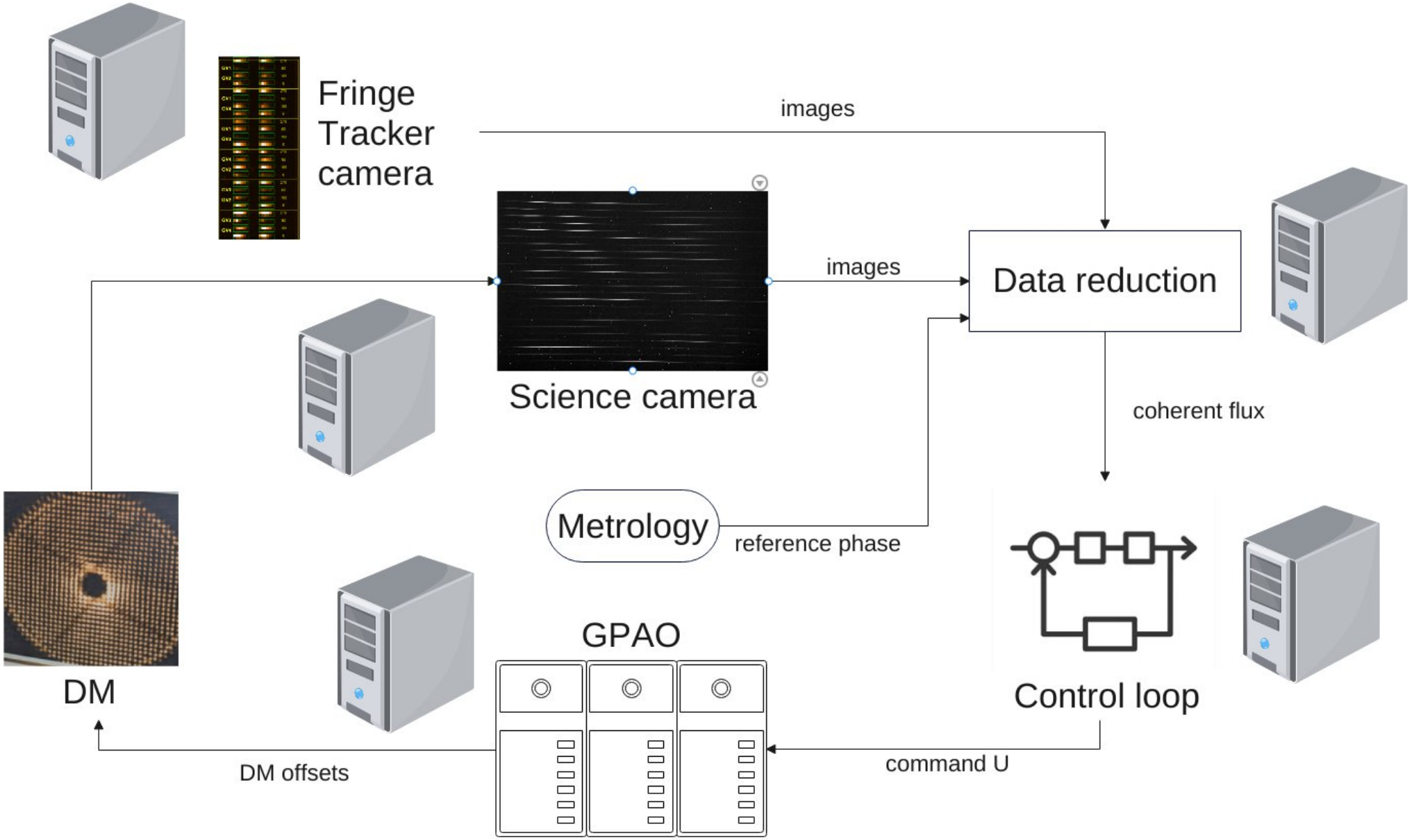


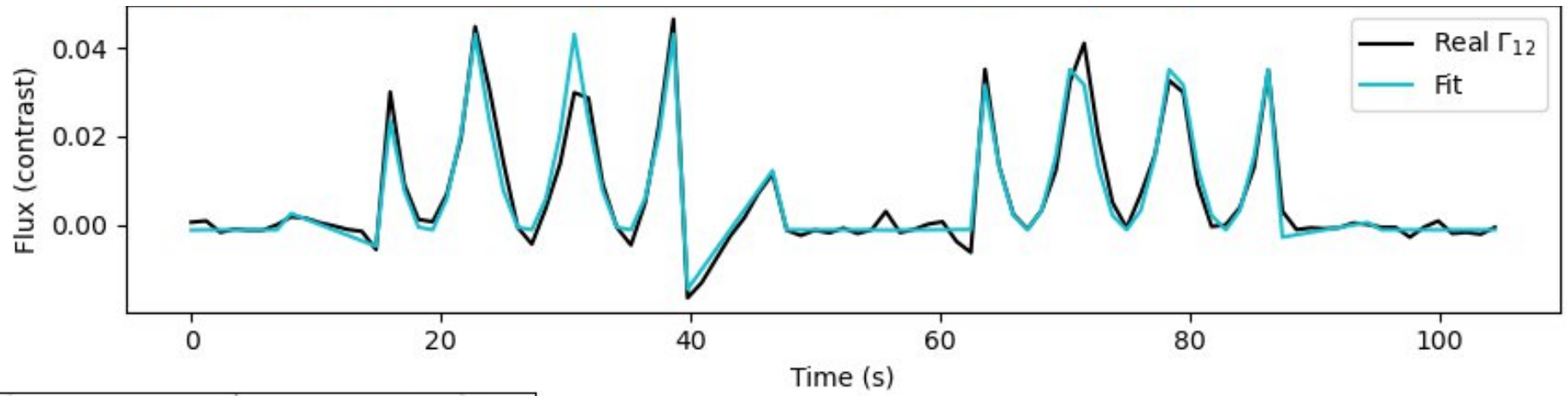
GRAVITY+ dark hole in practice

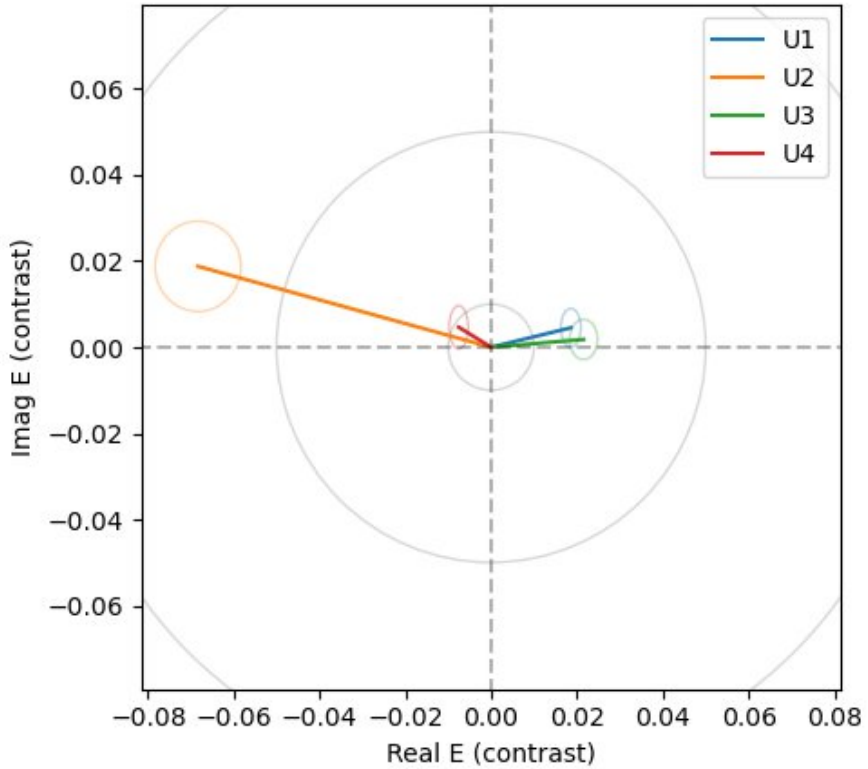


GRAVITY+ dark hole in practice



GRAVITY+ dark hole in practice





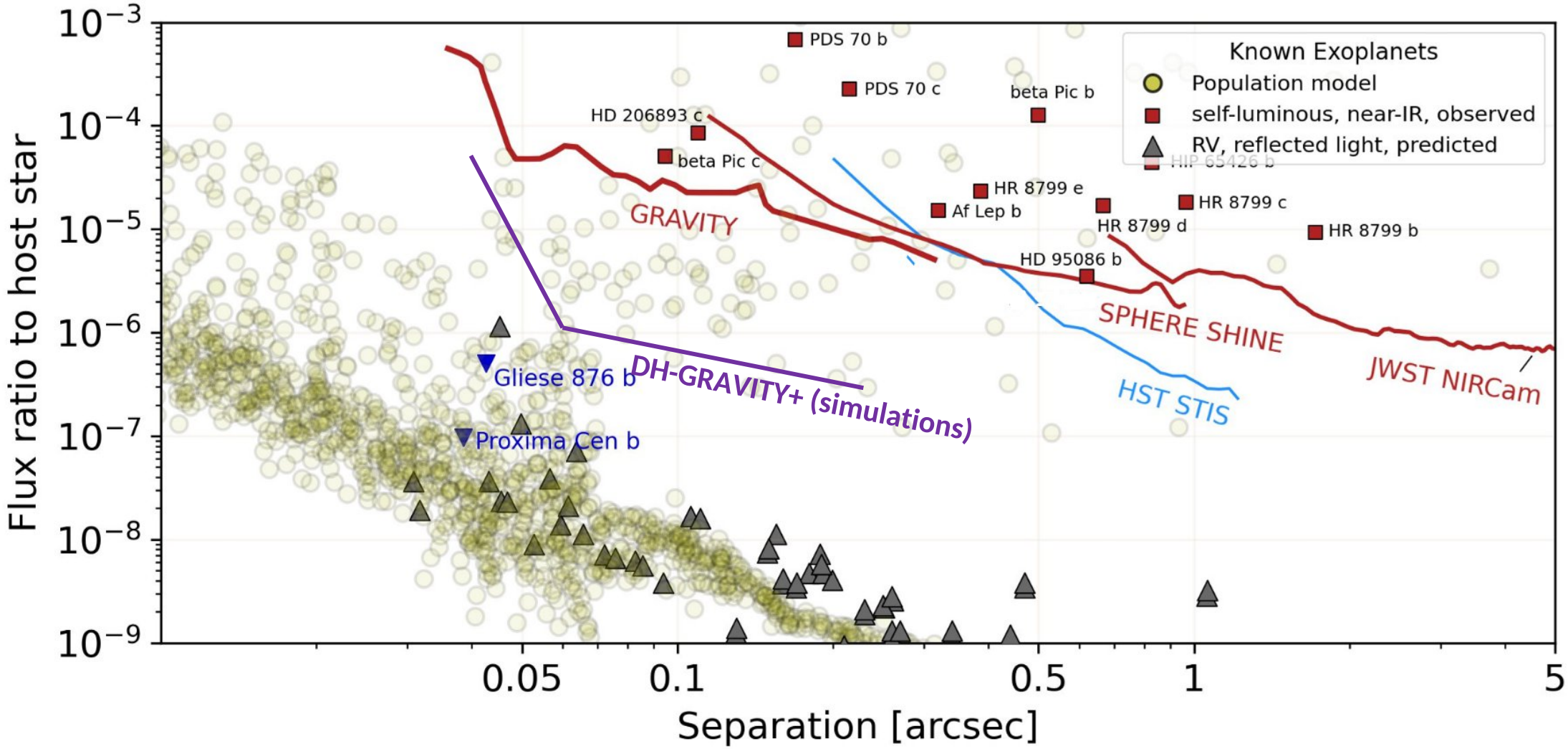
At 100 mas:

- Typical speckle 0.01 to 0.1
- Typical uncertainty of 0.01
- Gain of 10 in E contrast

At 100 mas:

- Stellar Residuals after DH of 10^{-4}
- Gain of 10 in photon noise
- Gain of 10 to 100 in instrumental residuals

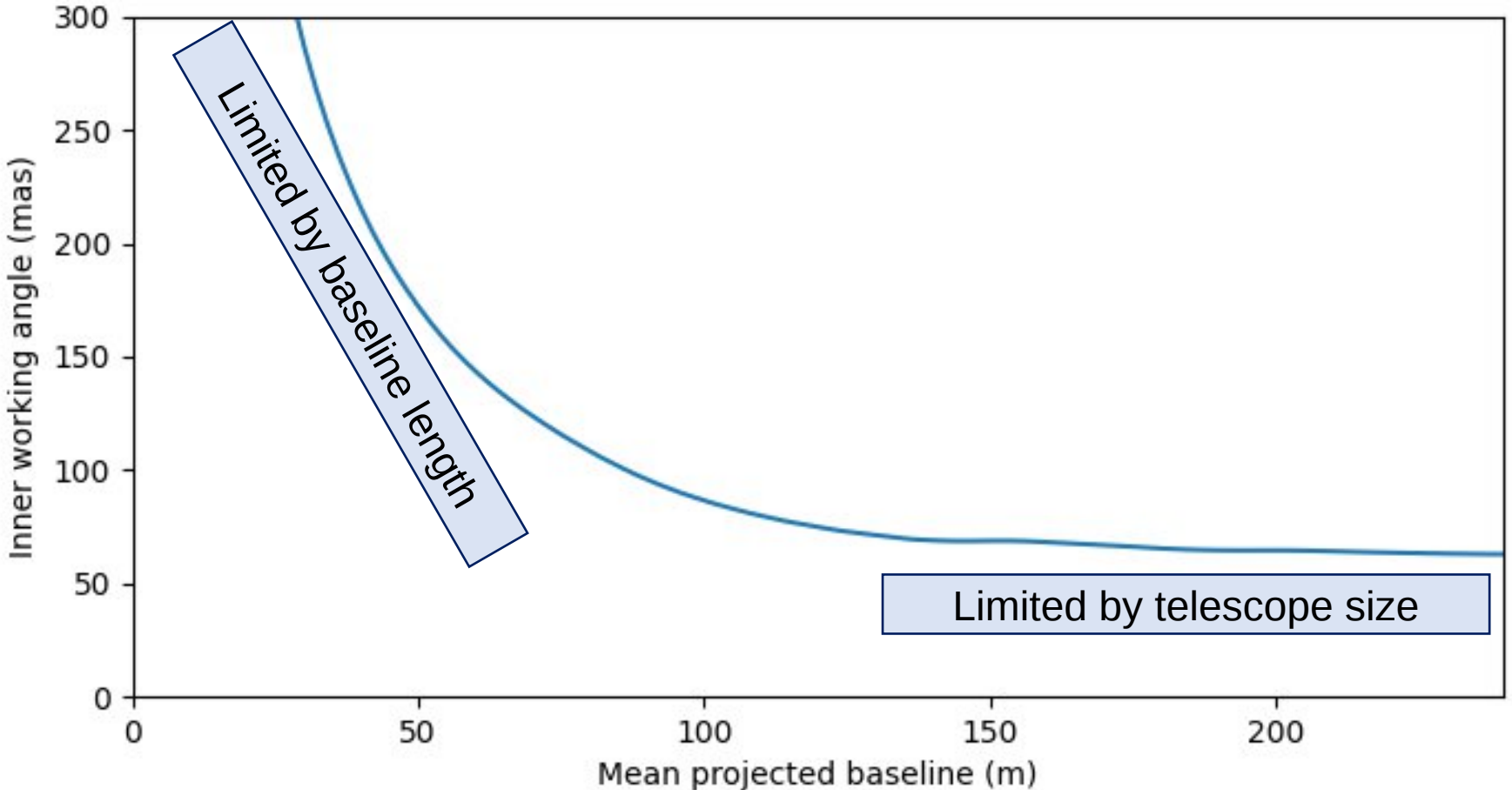
GRAVITY+ Dark-hole (available next year?)



Beyond GRAVITY+: IWA in High Contrast interferometry

IWA in dual-field interferometry is set by:

- Telescope size (AO, dark-hole, raw contrast)
- Baseline length (stellar light filtering, post-processed contrast)



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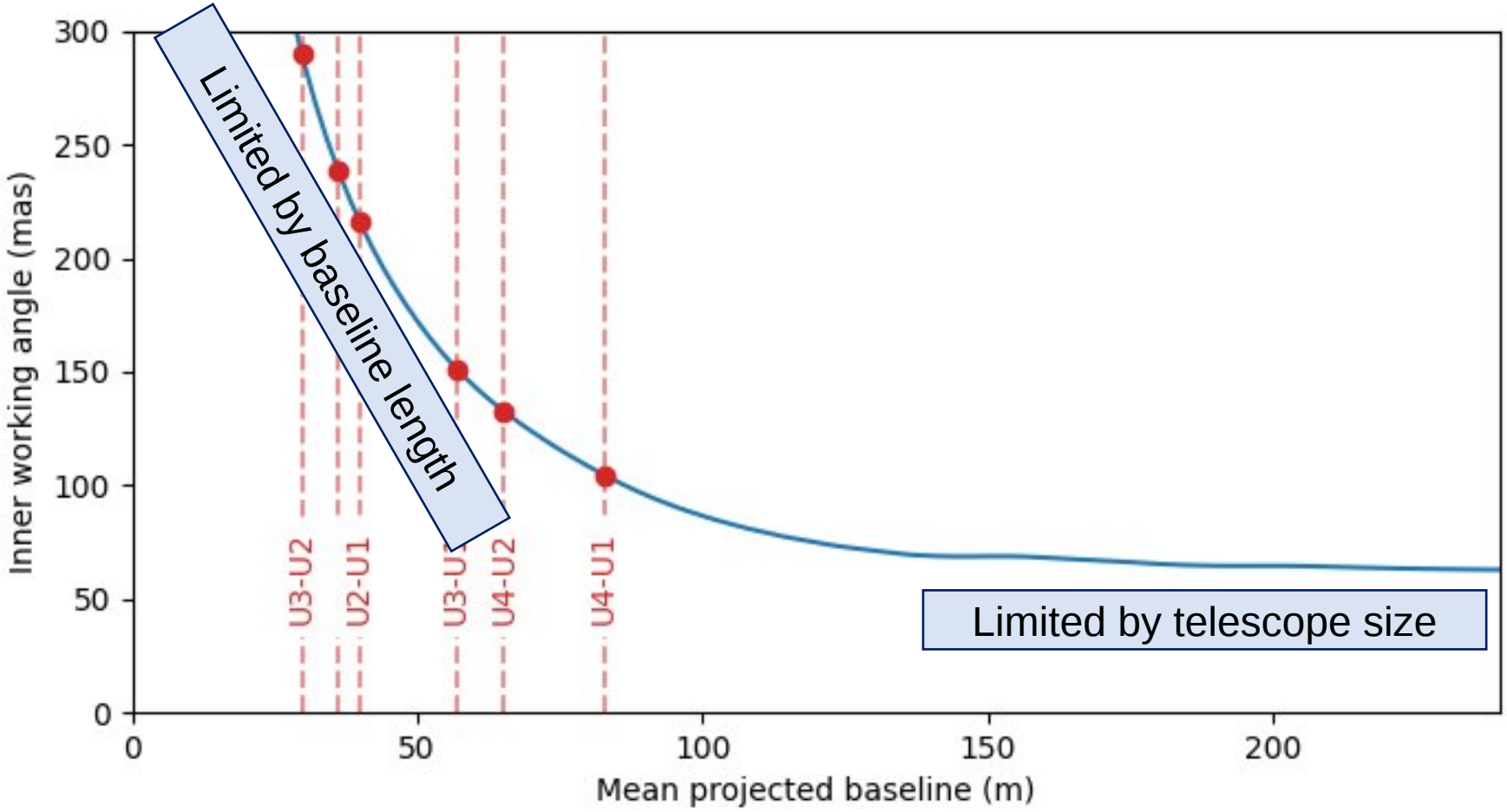
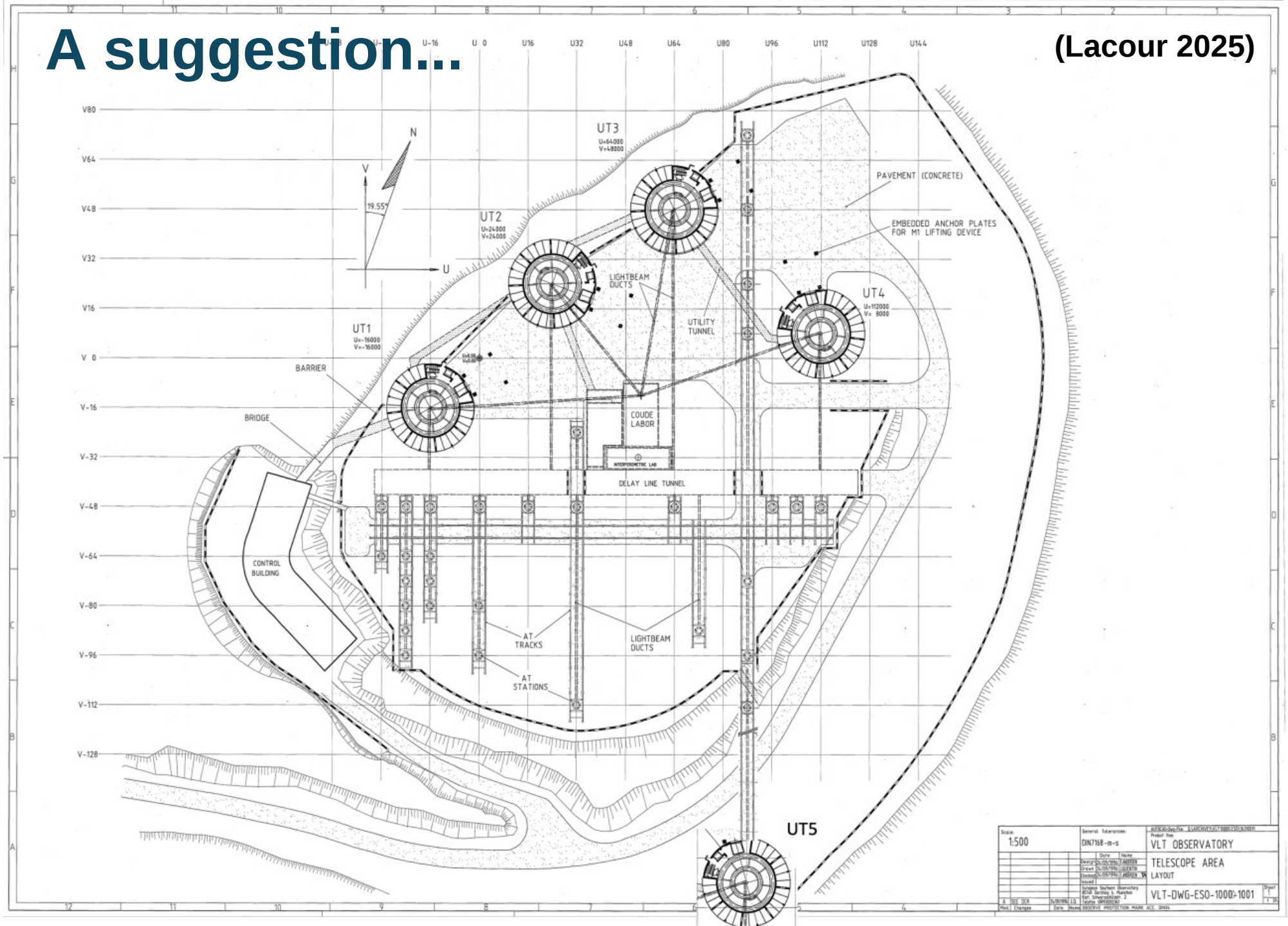


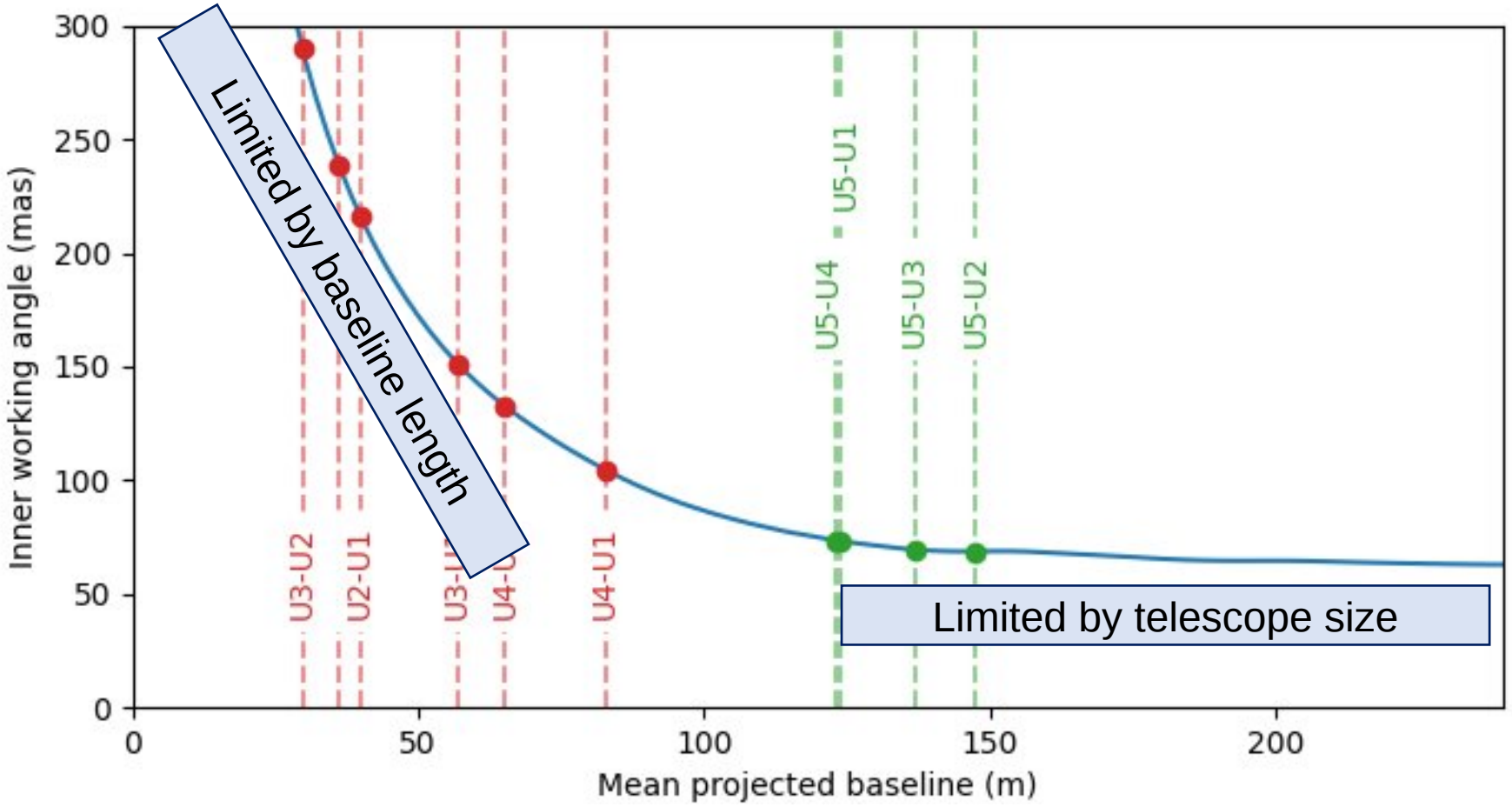
A suggestion...

A suggestion...

(Lacour 2025)



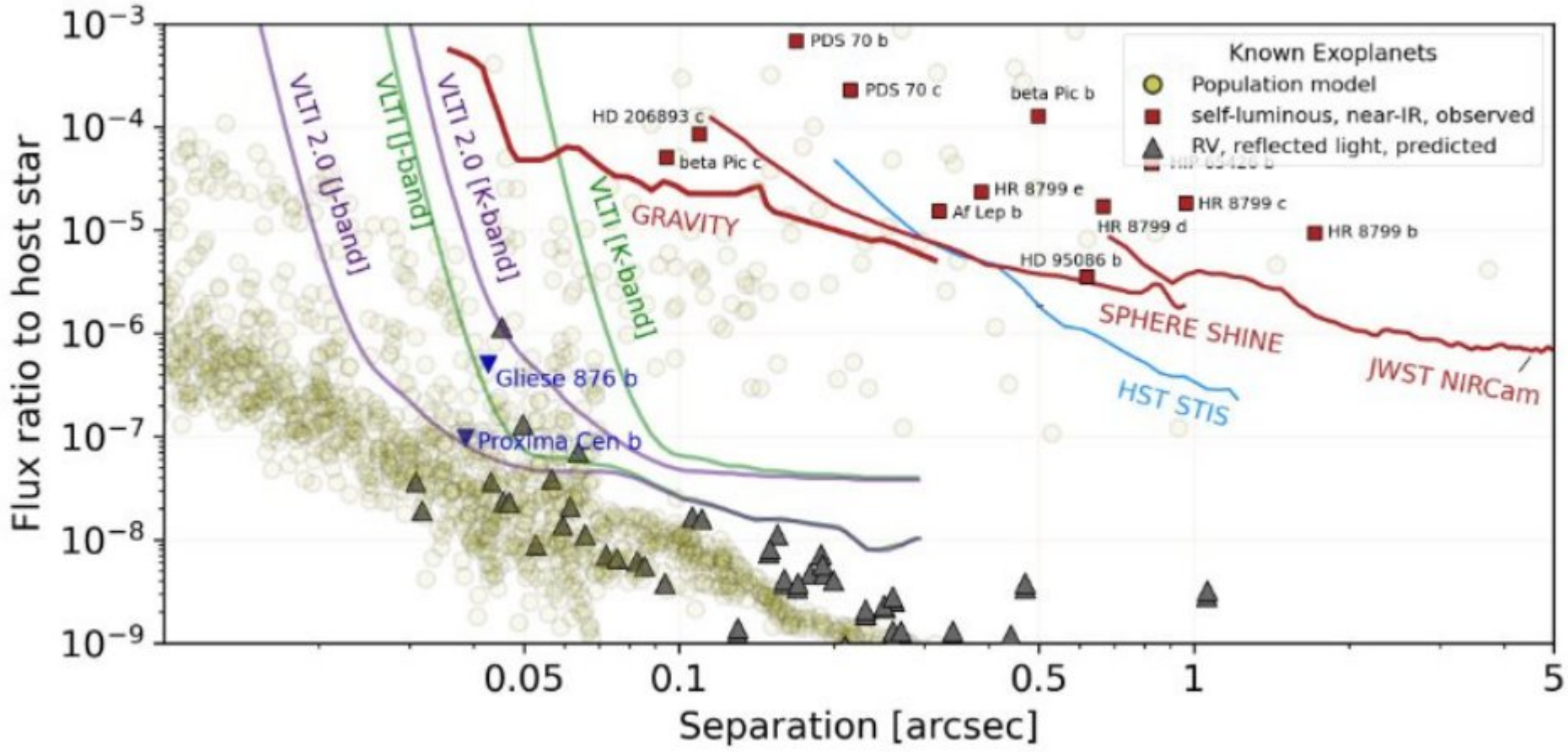
A suggestion...



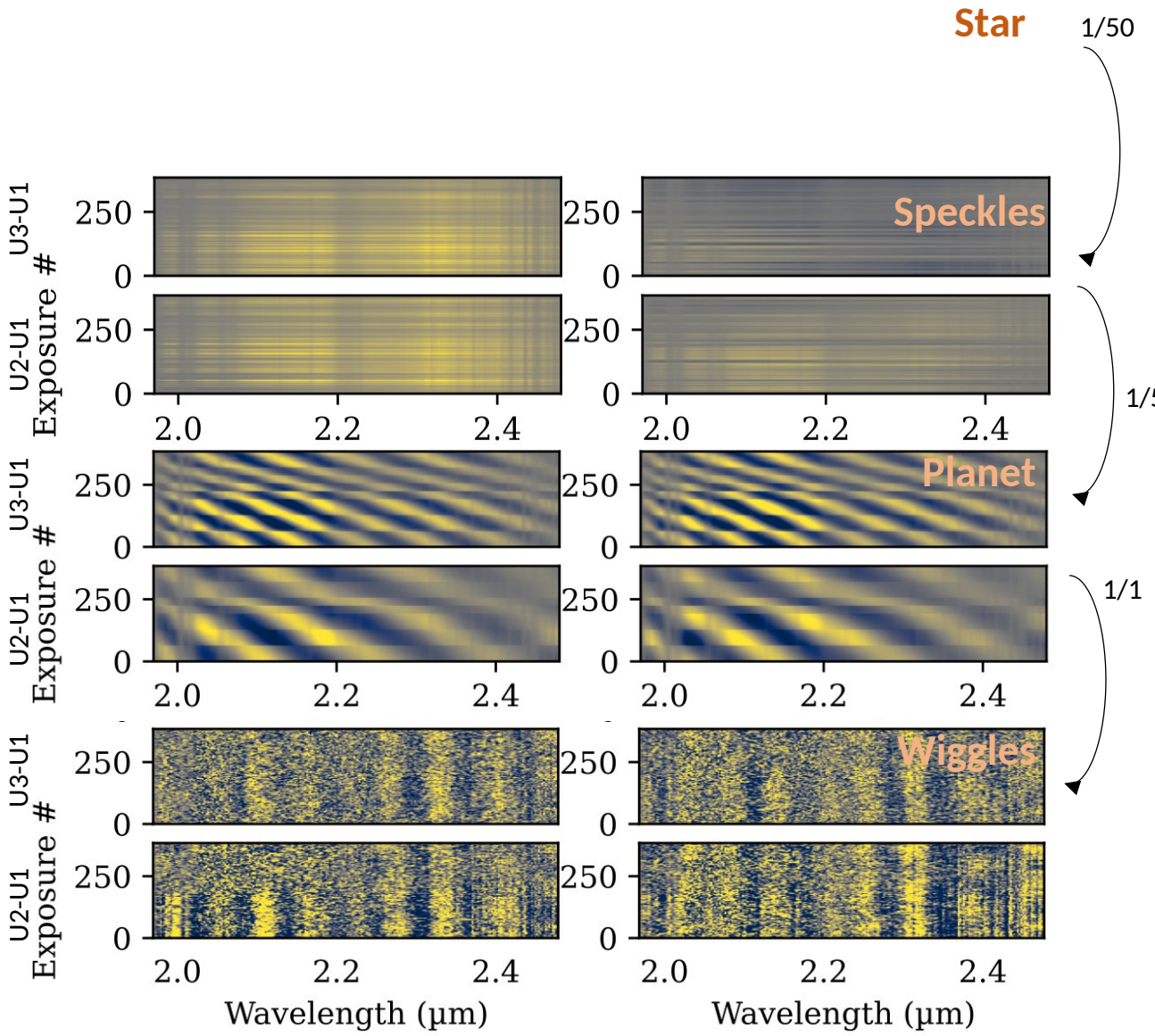
What's next?

Can we reach (some) reflected light planets?

1. Improve the starlight rejection (dark hole)
2. Use longer baselines!
3. Work at shorter wavelengths (better astrometry, smaller separations)



Wiggles in the residuals



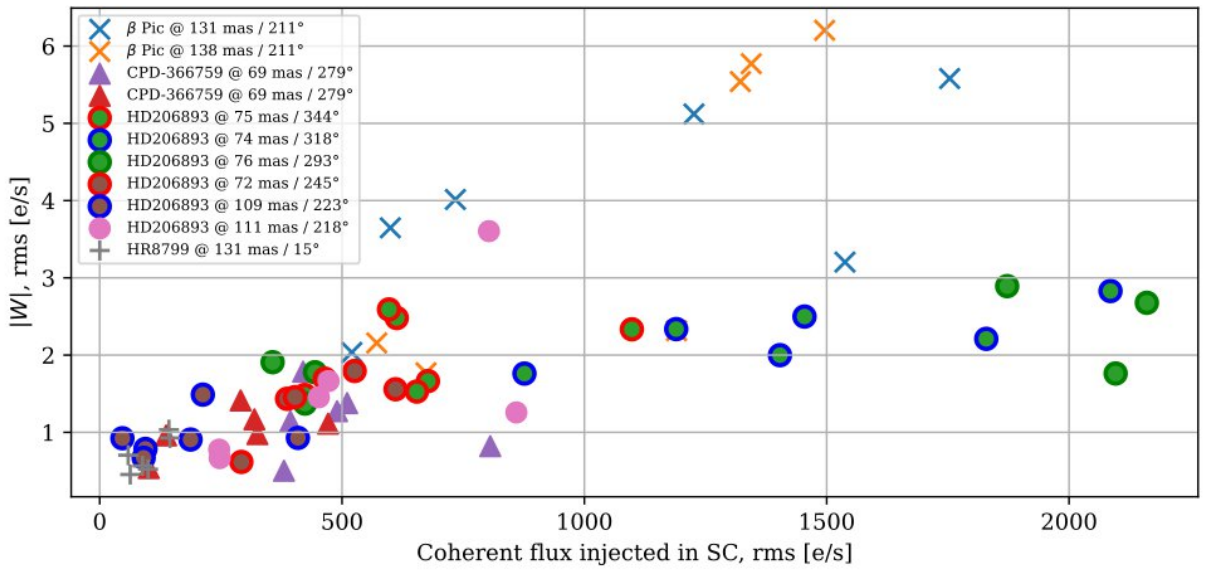
<150 mas:

Current high-contrast limit of GRAVITTY is **instrumental**

- Polarisation cross-talk?
- Parasitic reflection?

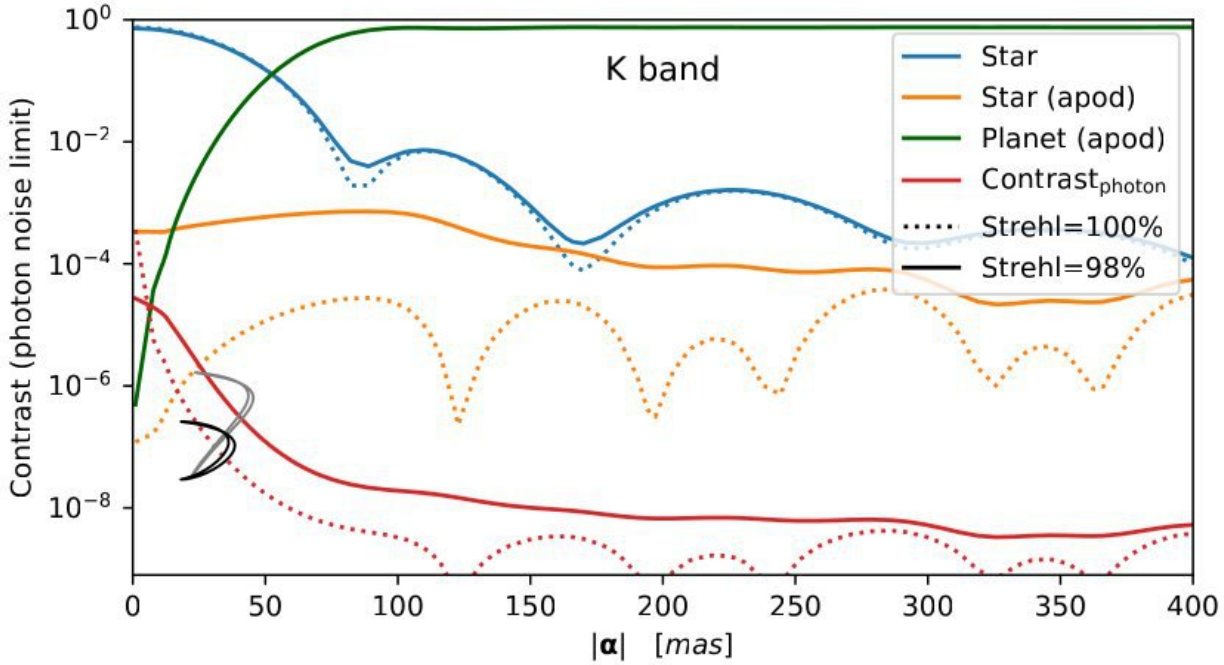
No mitigation strategy has been found, despite efforts

— But we know that these "wiggles" scale with residual flux



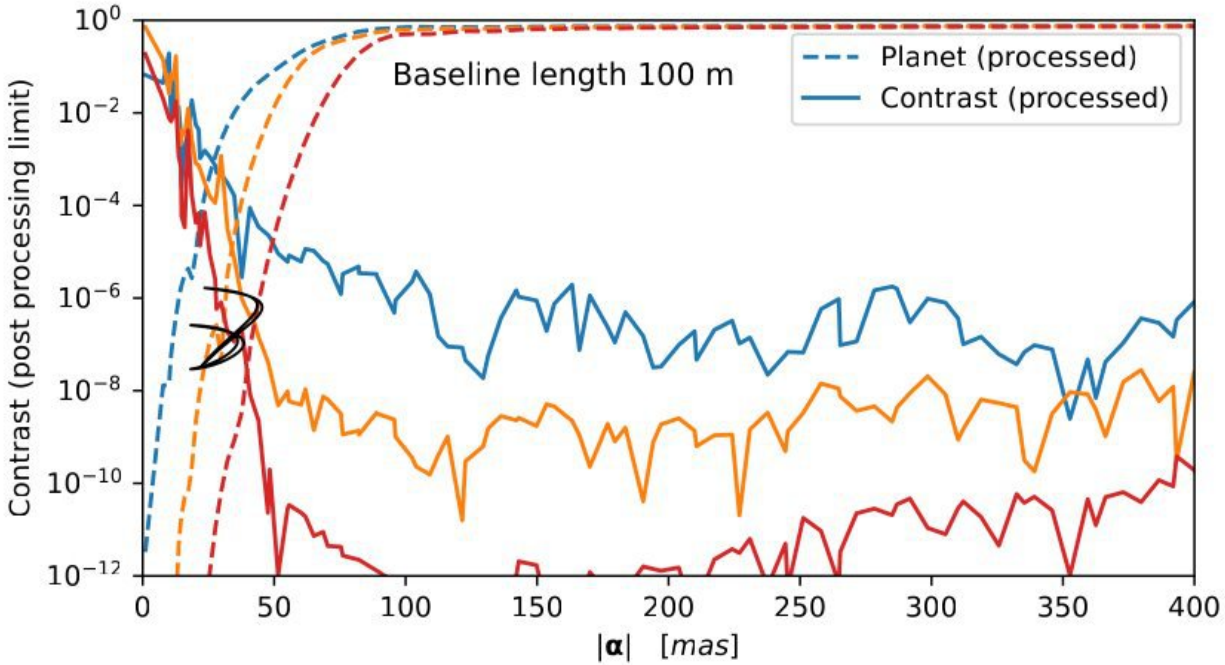
Beyond GRAVITY+: IWA in High Contrast interferometry

Apodization for an 8 m telescope



Driven entirely by the telescope size

High-order filtering for a 100 m baseline

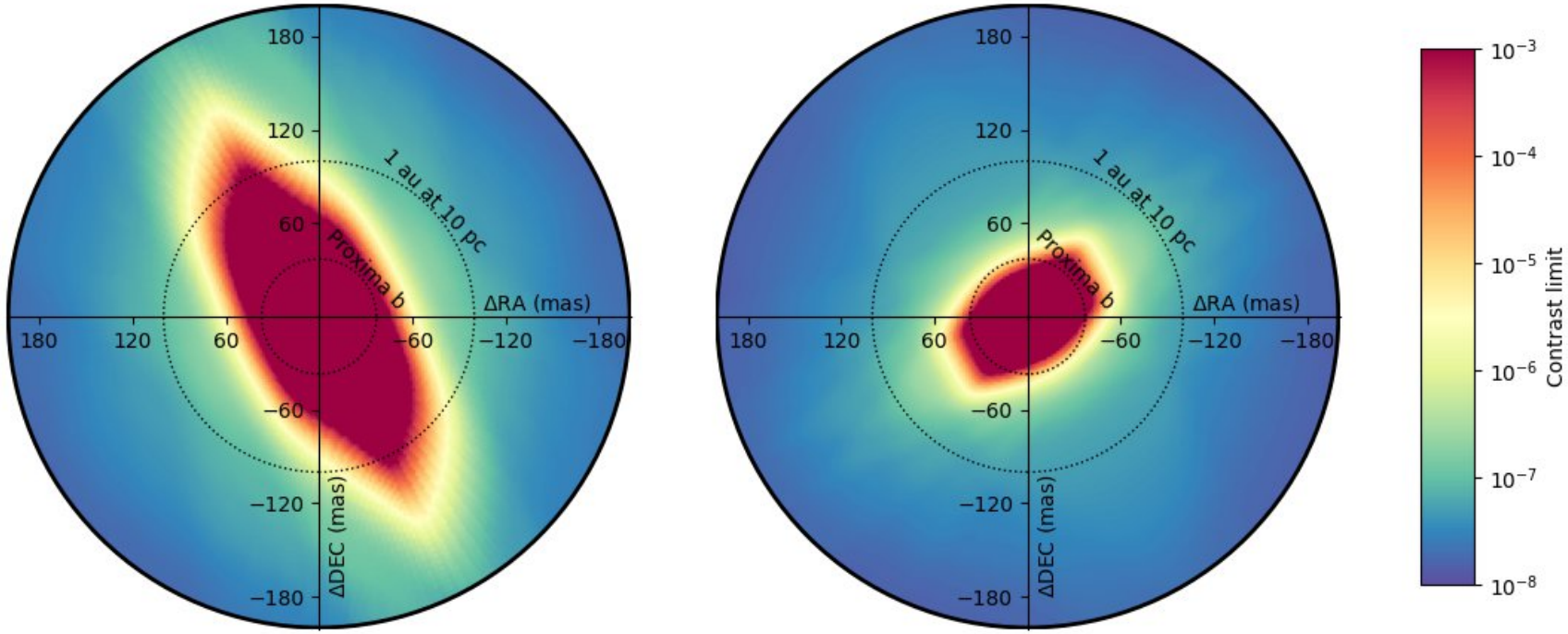


Driven entirely by the baseline length

A suggestion...

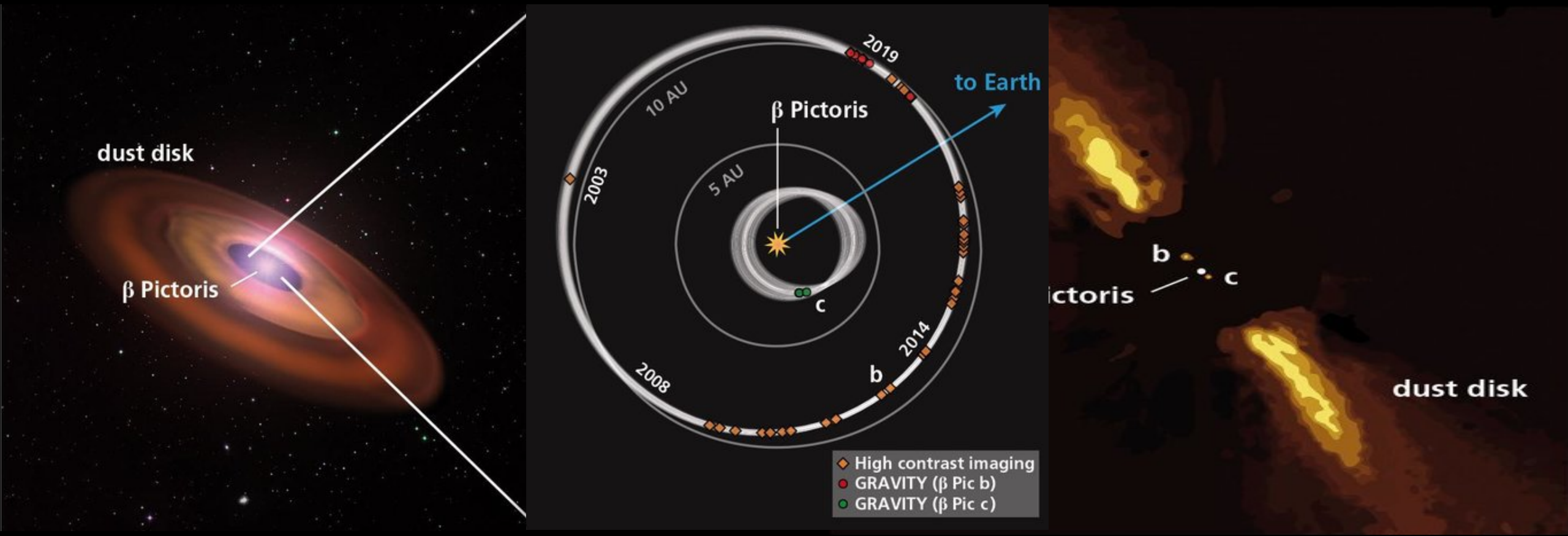
Current VLTI [K-band]

VLTI 2.0 [K-band]



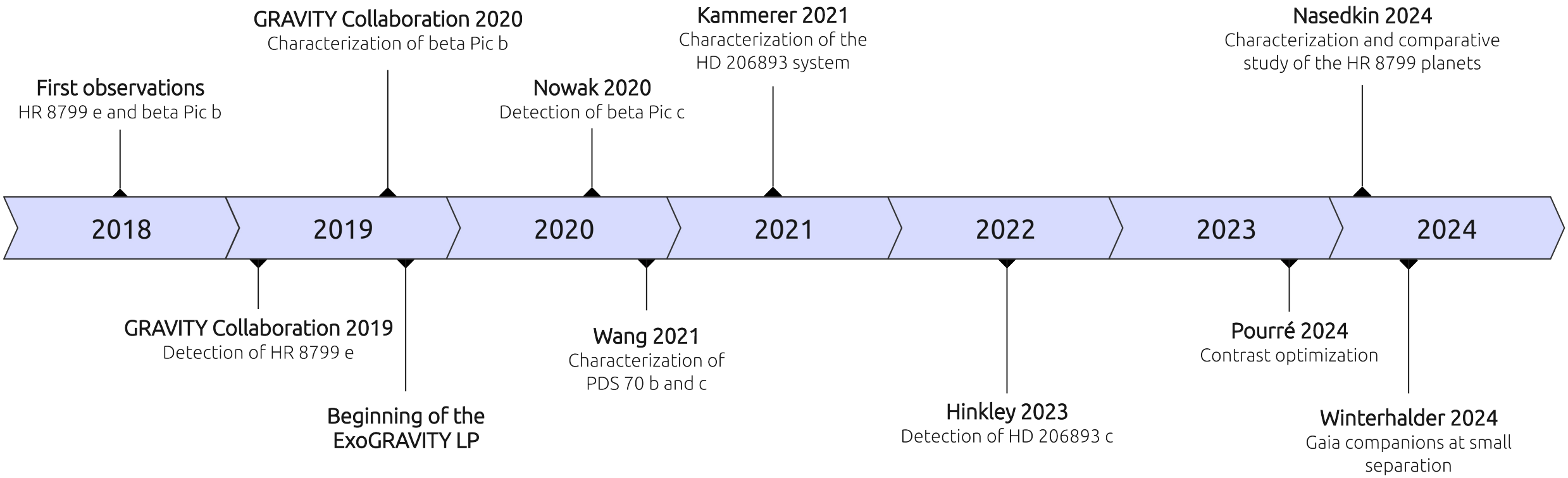
Noise sources included: detector, thermal, speckles, photon noise

Combining interferometry and radial velocity



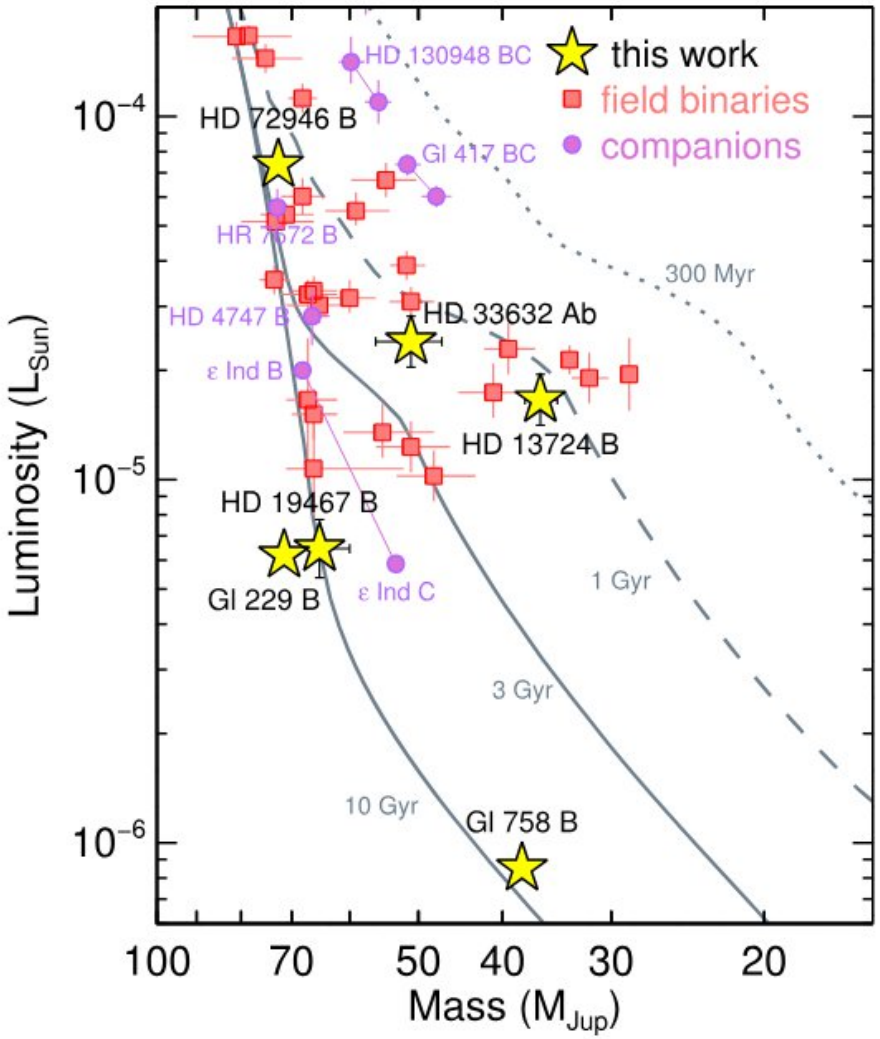
Lagrange et al. (2019, 2020), Nowak et al. (2020), etc.

A timeline of the ExoGravity project

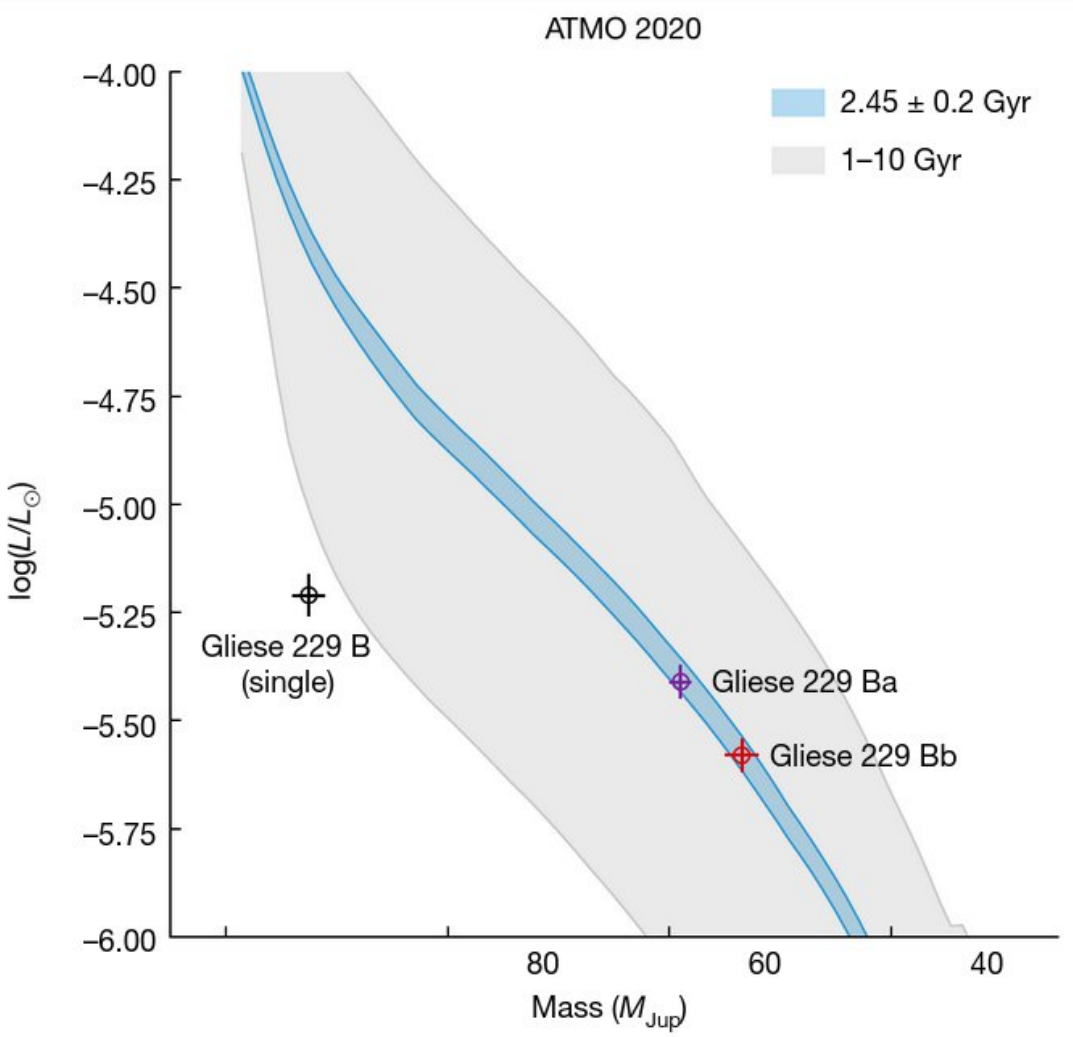


And also: Balmer 2023, 2024, Blunt 2023, Lacour 2021, 2024, Mollière 2020, Maire 2024, etc.

Solving the "underluminous brown dwarf mystery"

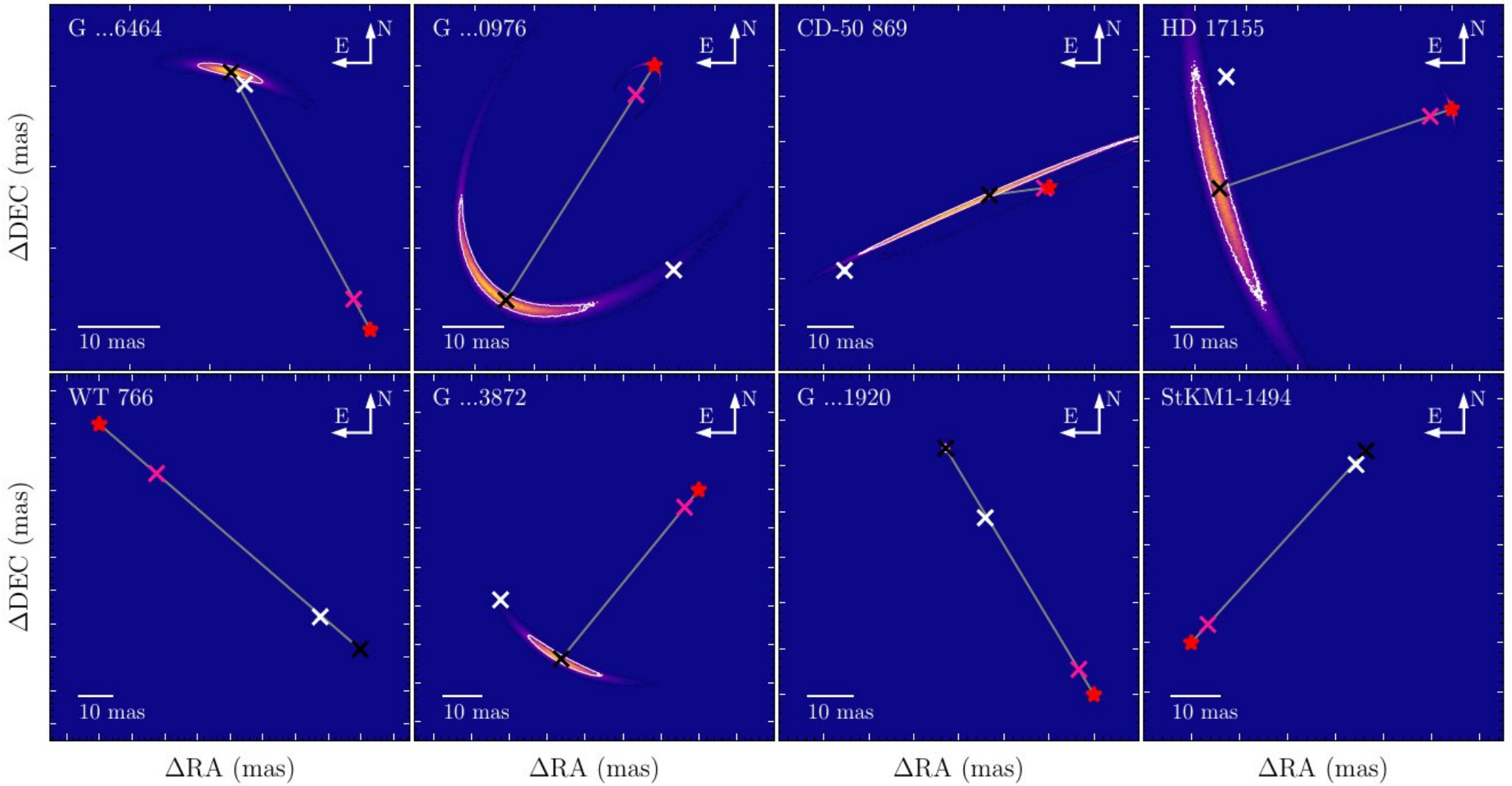


Brandt 2021



Xuan 2024

Going after the Gaia companions

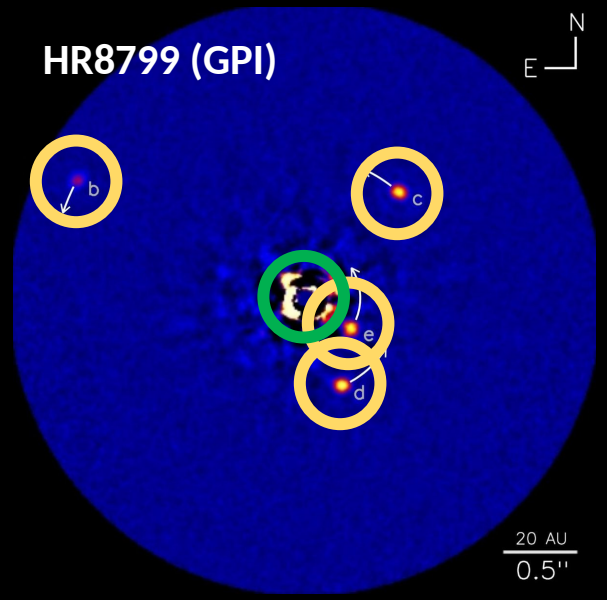


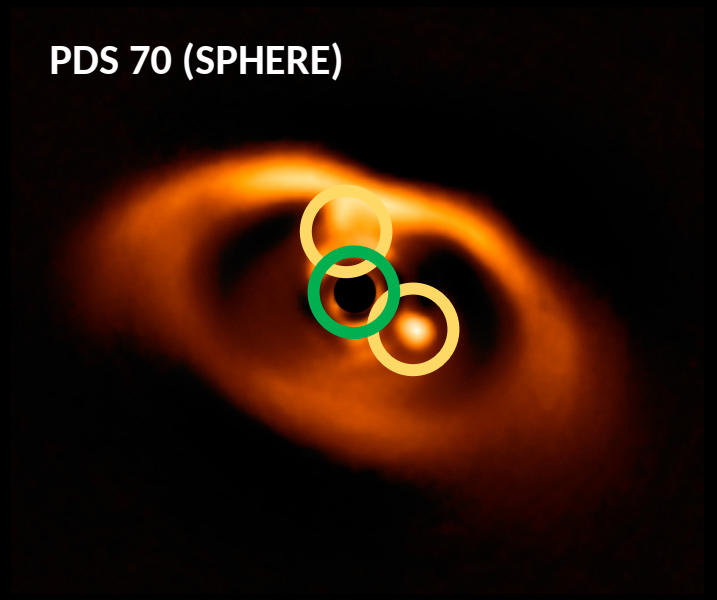
Winterhalder 2024

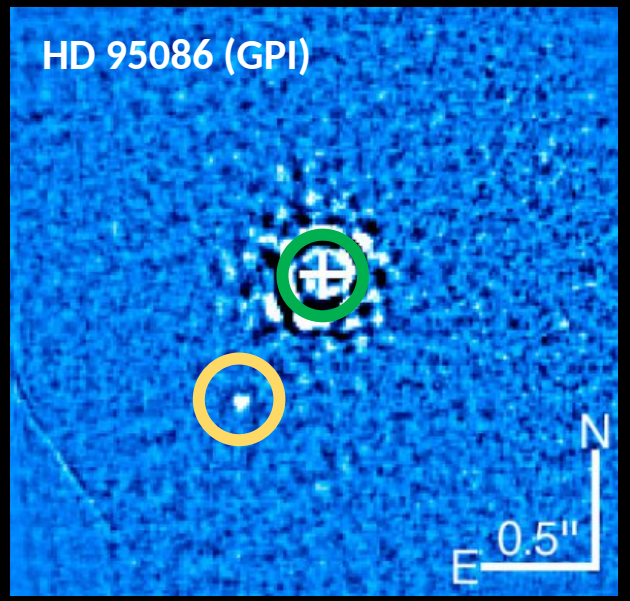
The ExoGravity Large Program

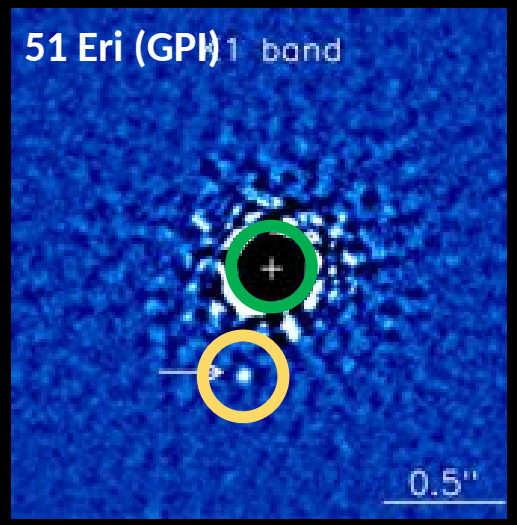
Fringe tracking fibre

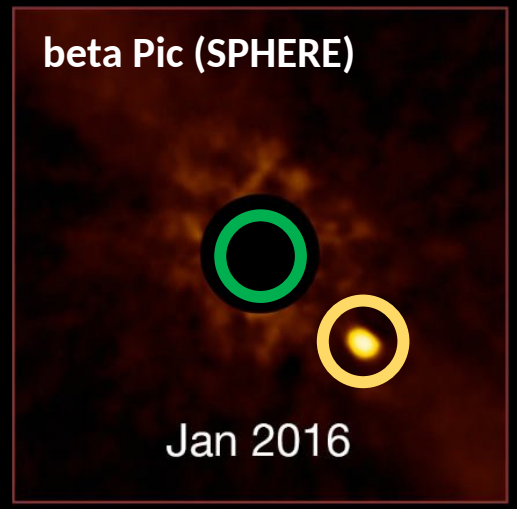
Science fibre

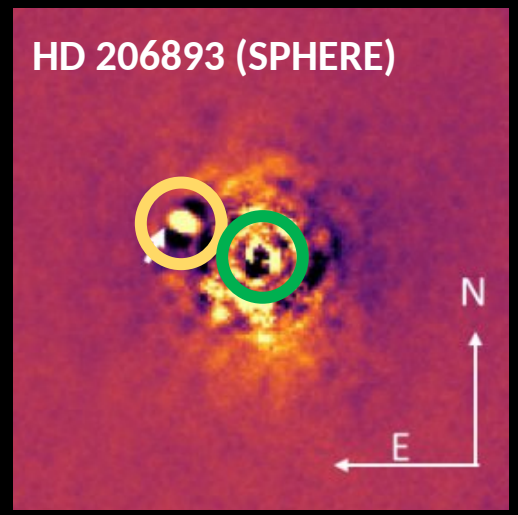


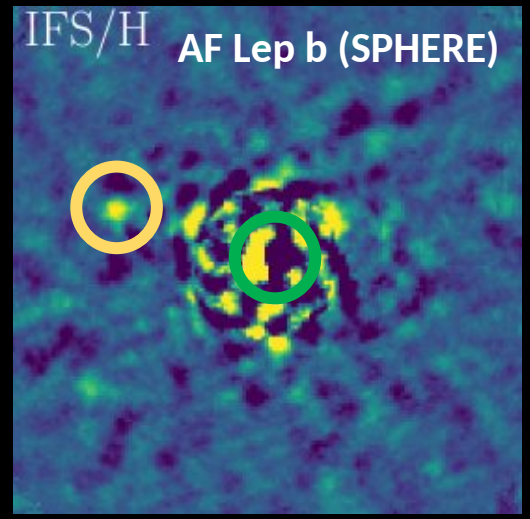






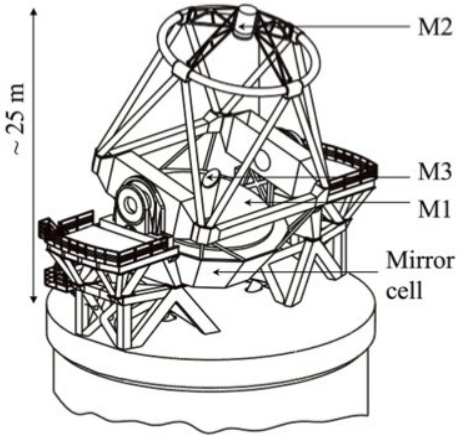






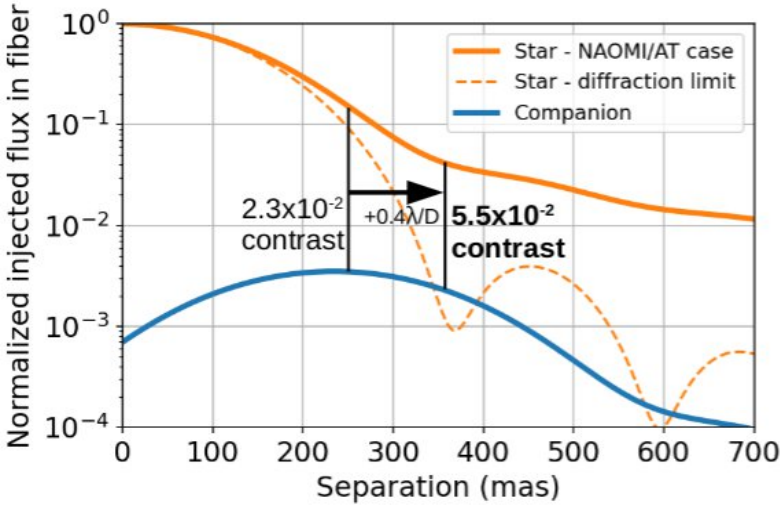
High contrast dual-field interferometry

Adaptive Optics



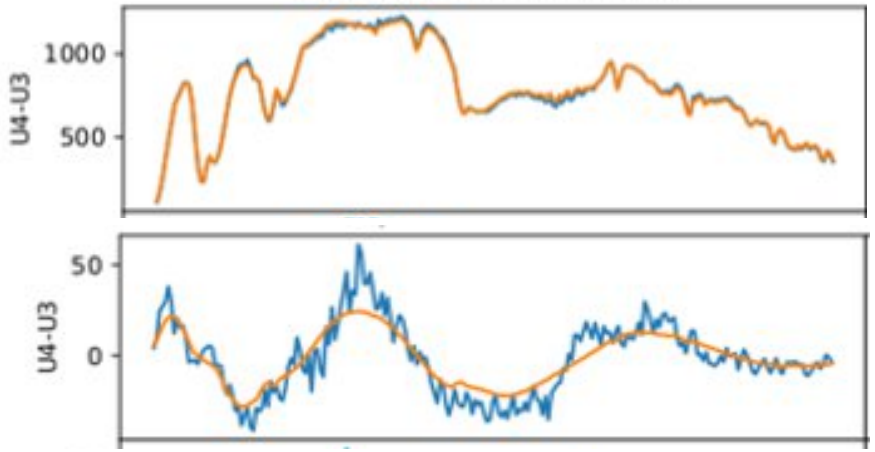
AO
Improve the Strehl ratio to decrease off-axis light

Single-mode filtering



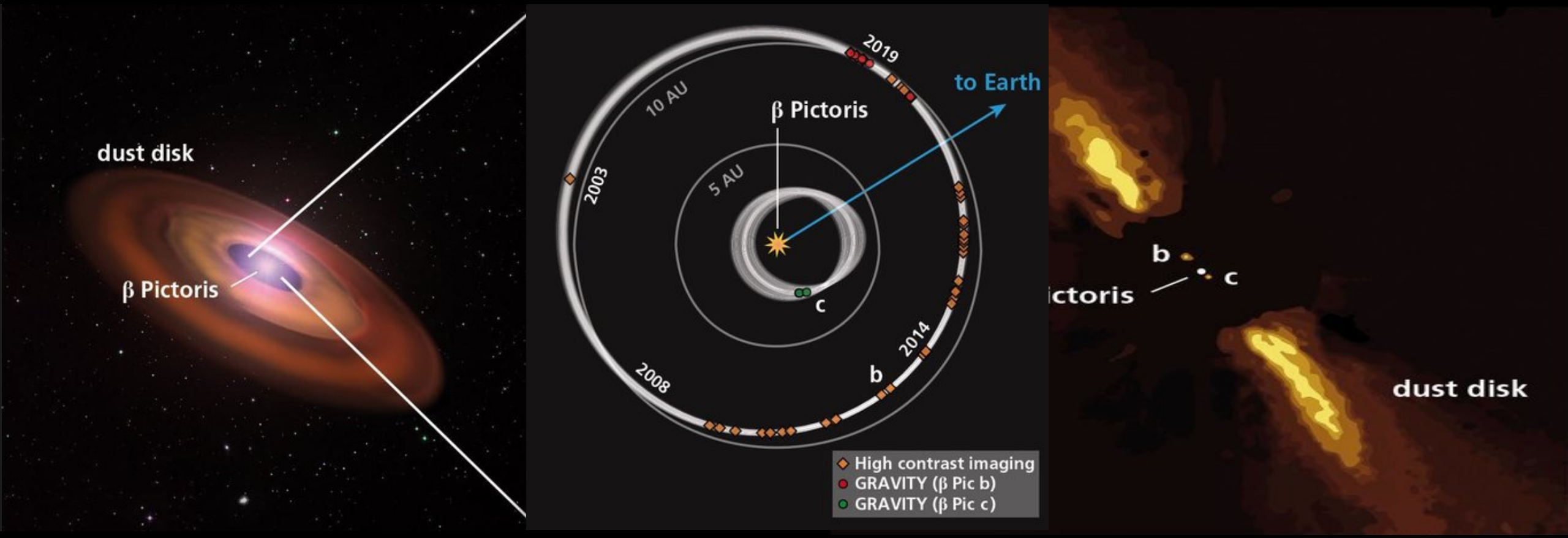
Star rejection
using the single-mode fibre, possibly in combination with dark-hole techniques

Metrology and phase referencing



Speckle filtering
using low-order polynomials

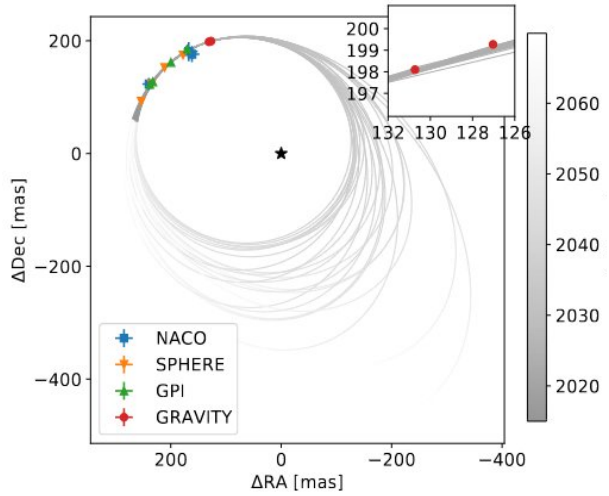
Direct detection of beta Pic c (2020)

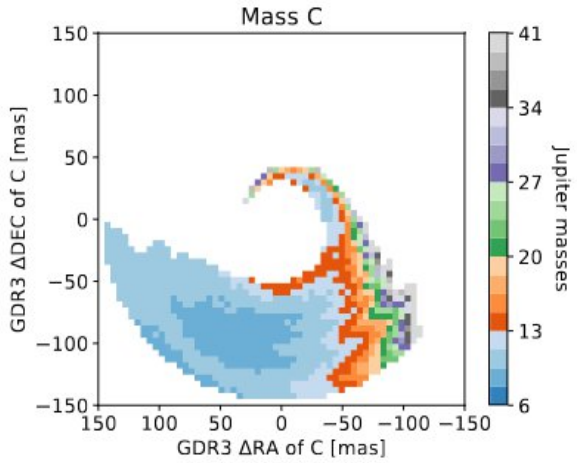


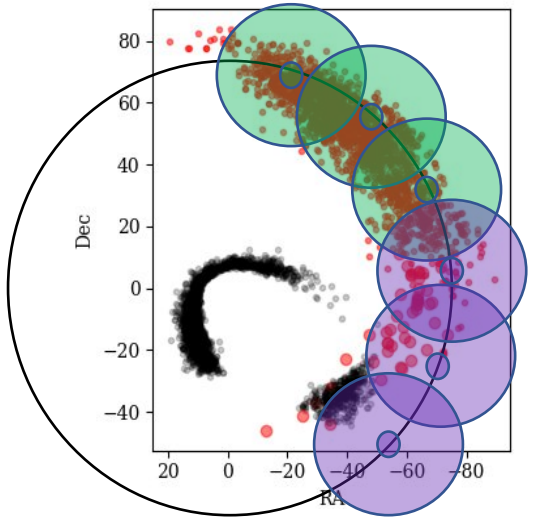
Lagrange et al. (2019, 2020), Nowak et al. (2020)

Direct detection of HD206893 c (2023)

Prediction (Kammerer 2021)







Detection (Hinkley 2023)