Optical interferometry from the Moon

Astrophysics at very high angular resolution

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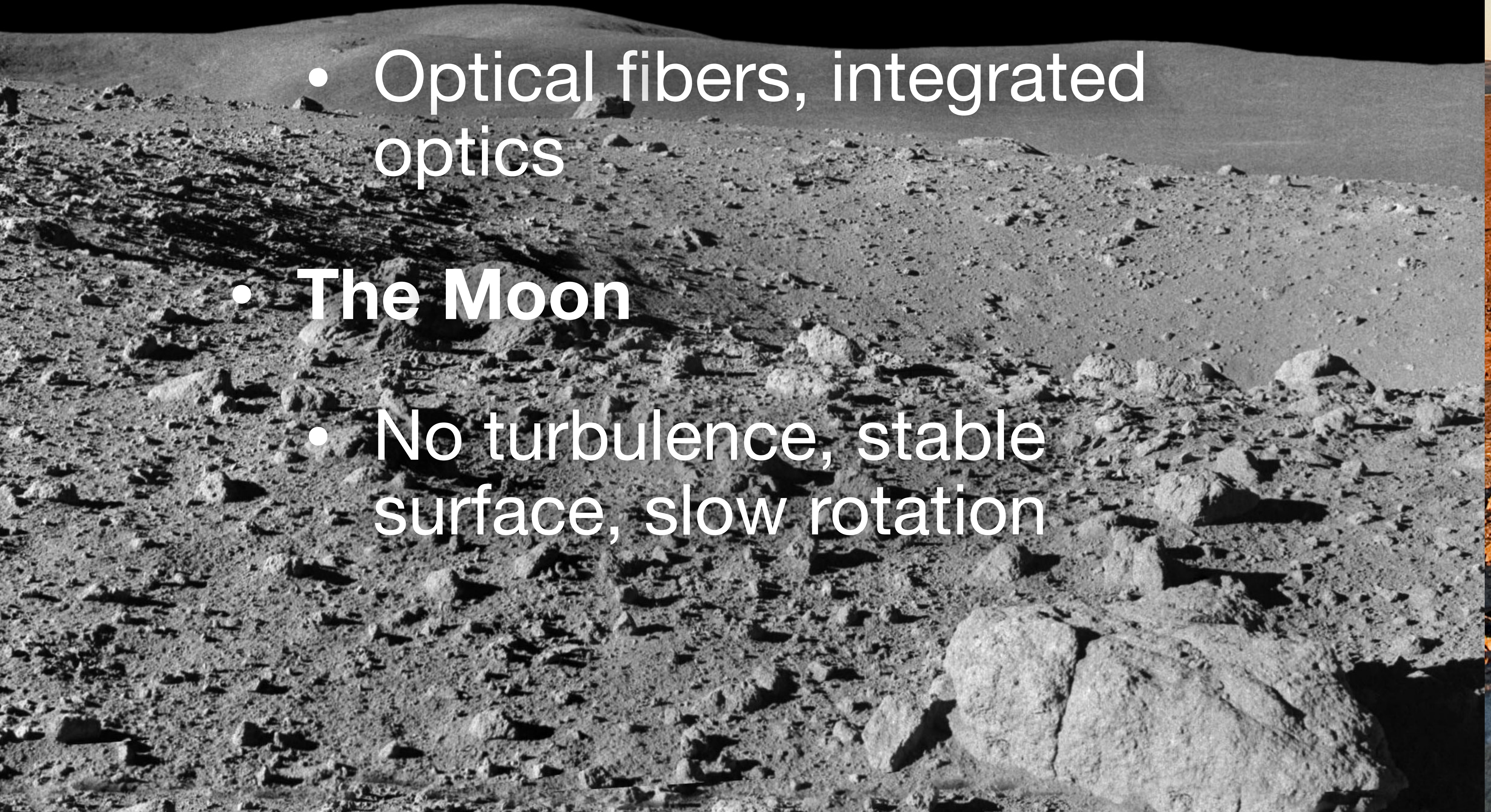
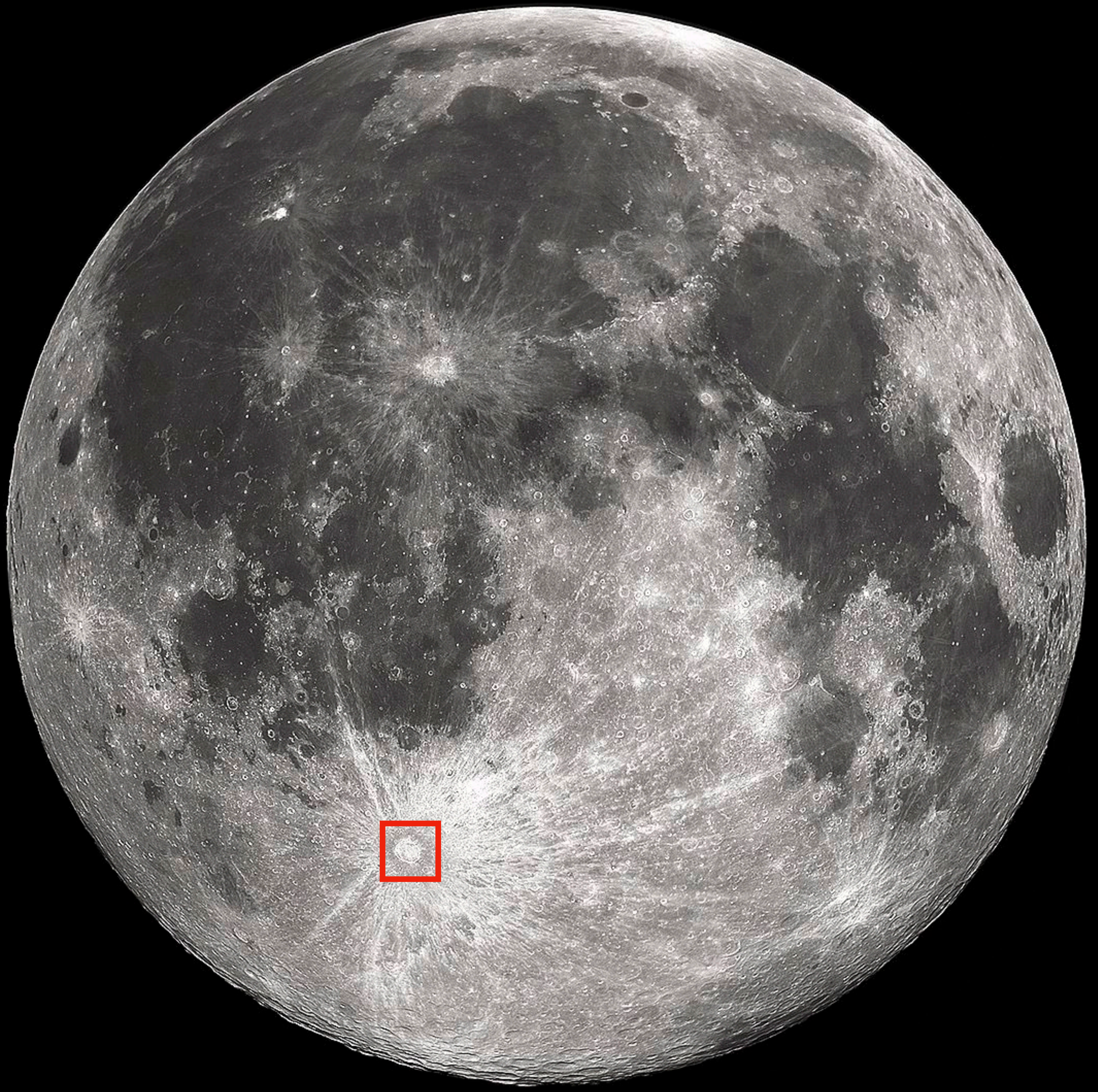
ESO/Y. Beletsky

Overview

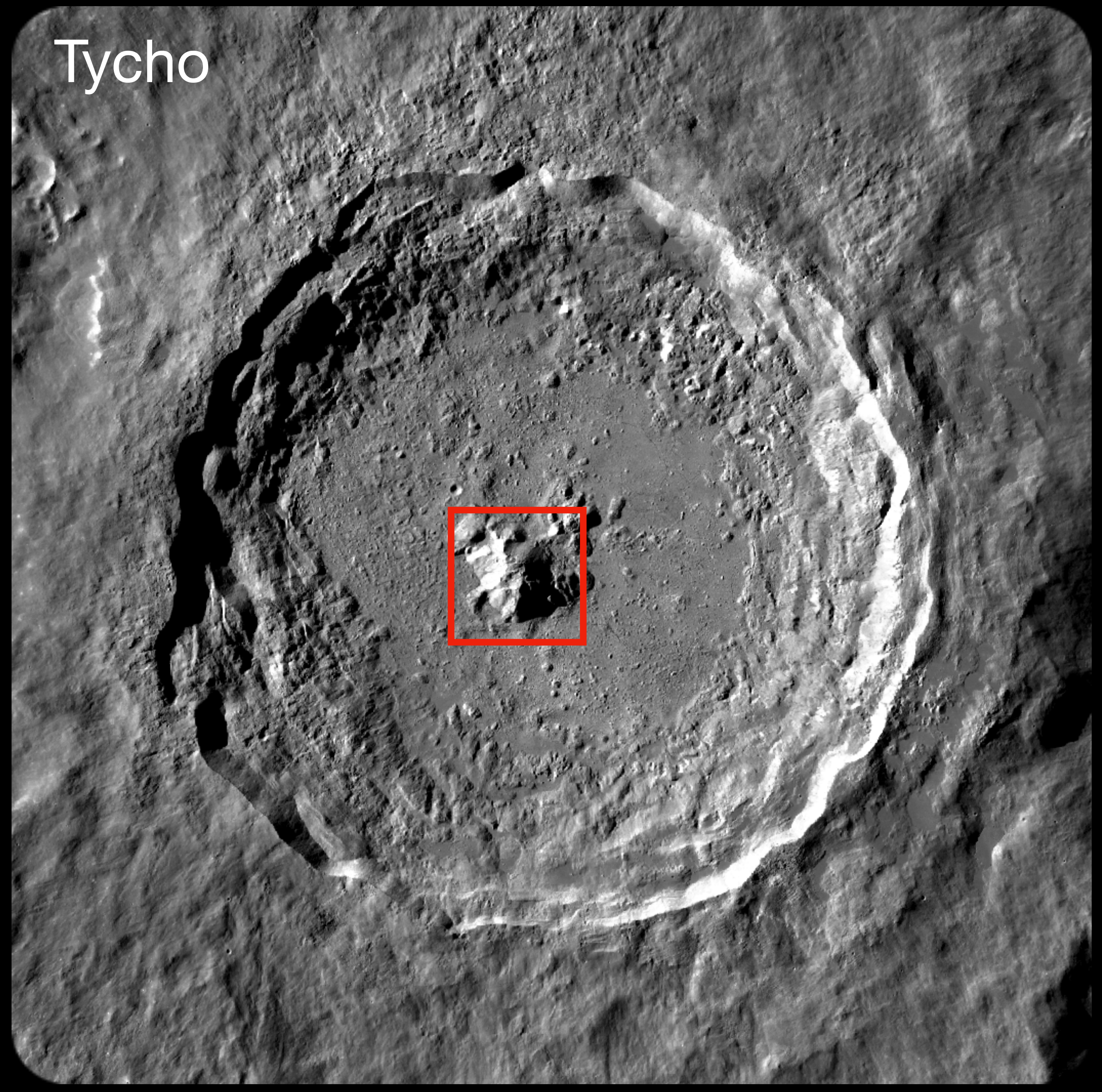
- **Science cases**
  - Black hole Sgr A*, Quasars, Exoplanets
- **Technology**
  - Optical fibers, integrated optics
- **The Moon**
  - No turbulence, stable surface, slow rotation



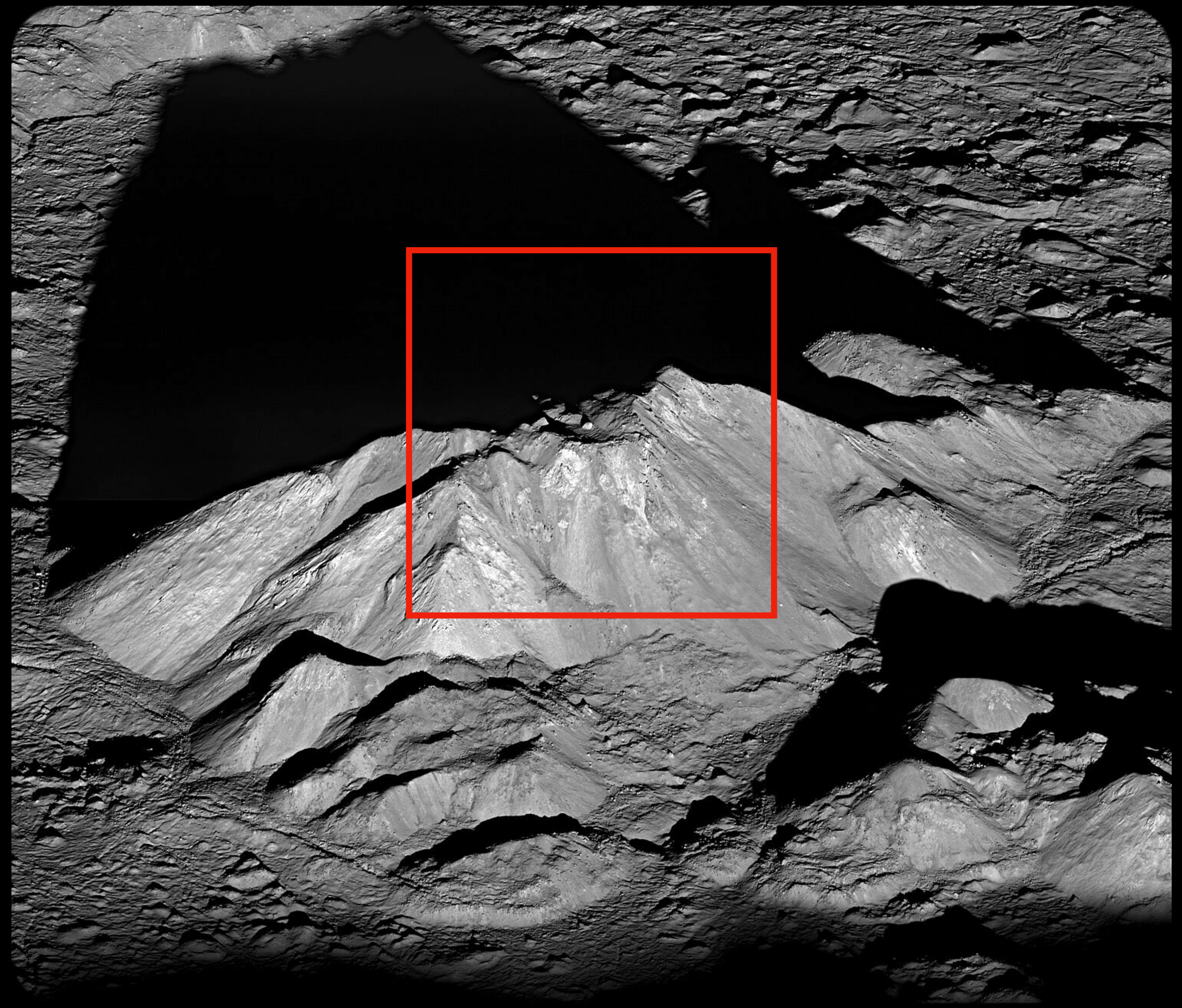
Why interferometry ? Angular resolution !



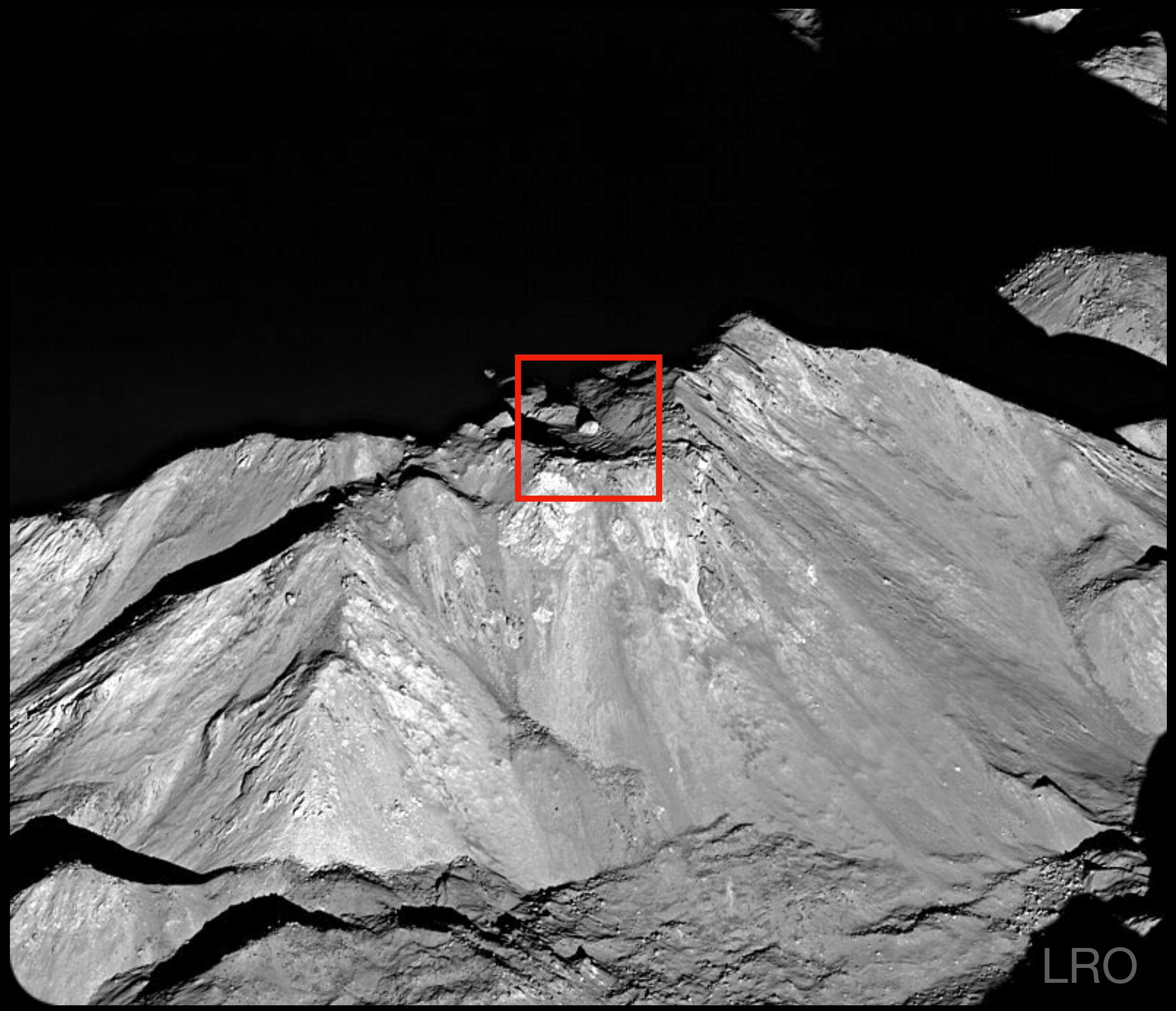
32 arcmin = 1900 arcsec

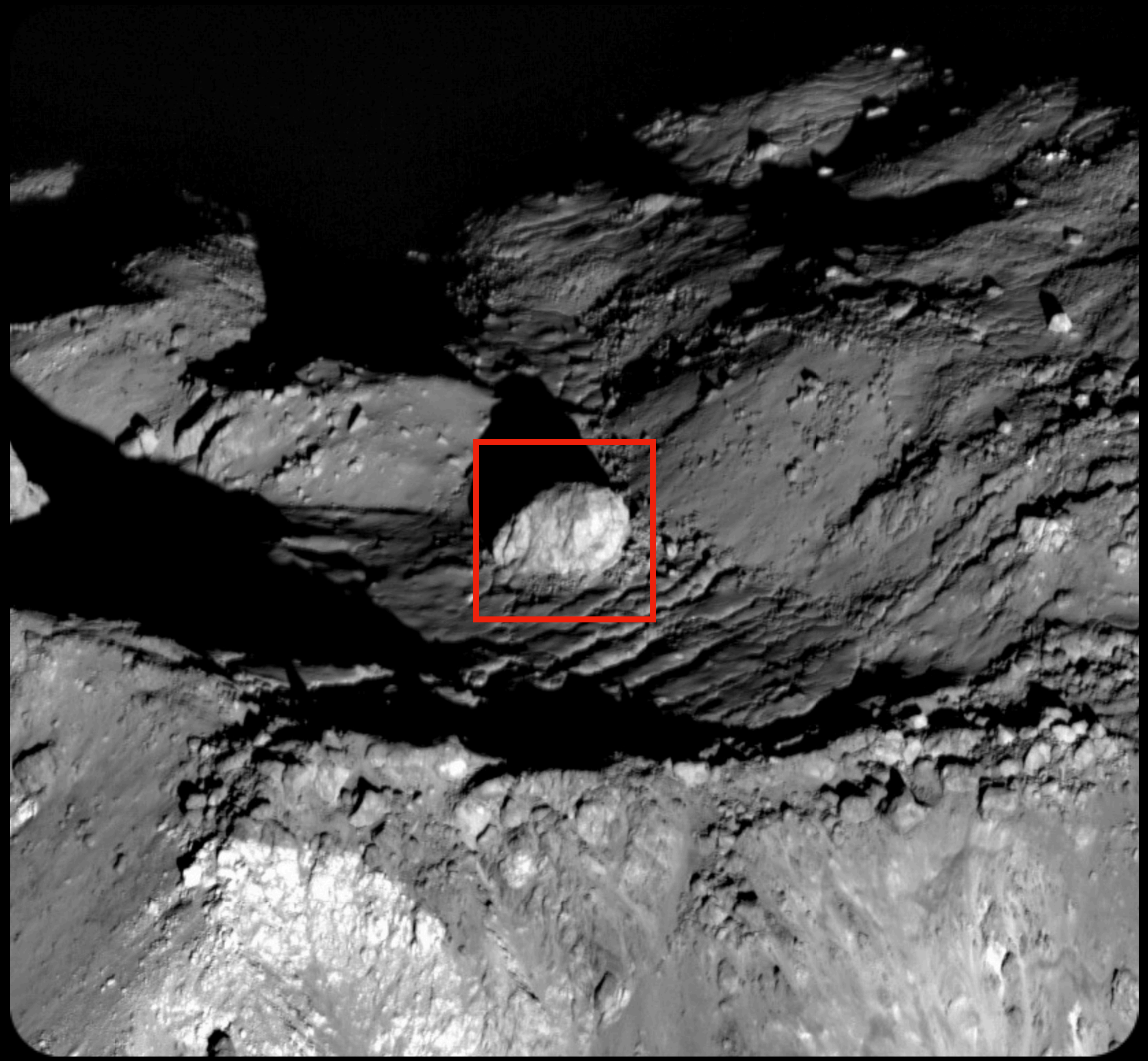


45”



2”



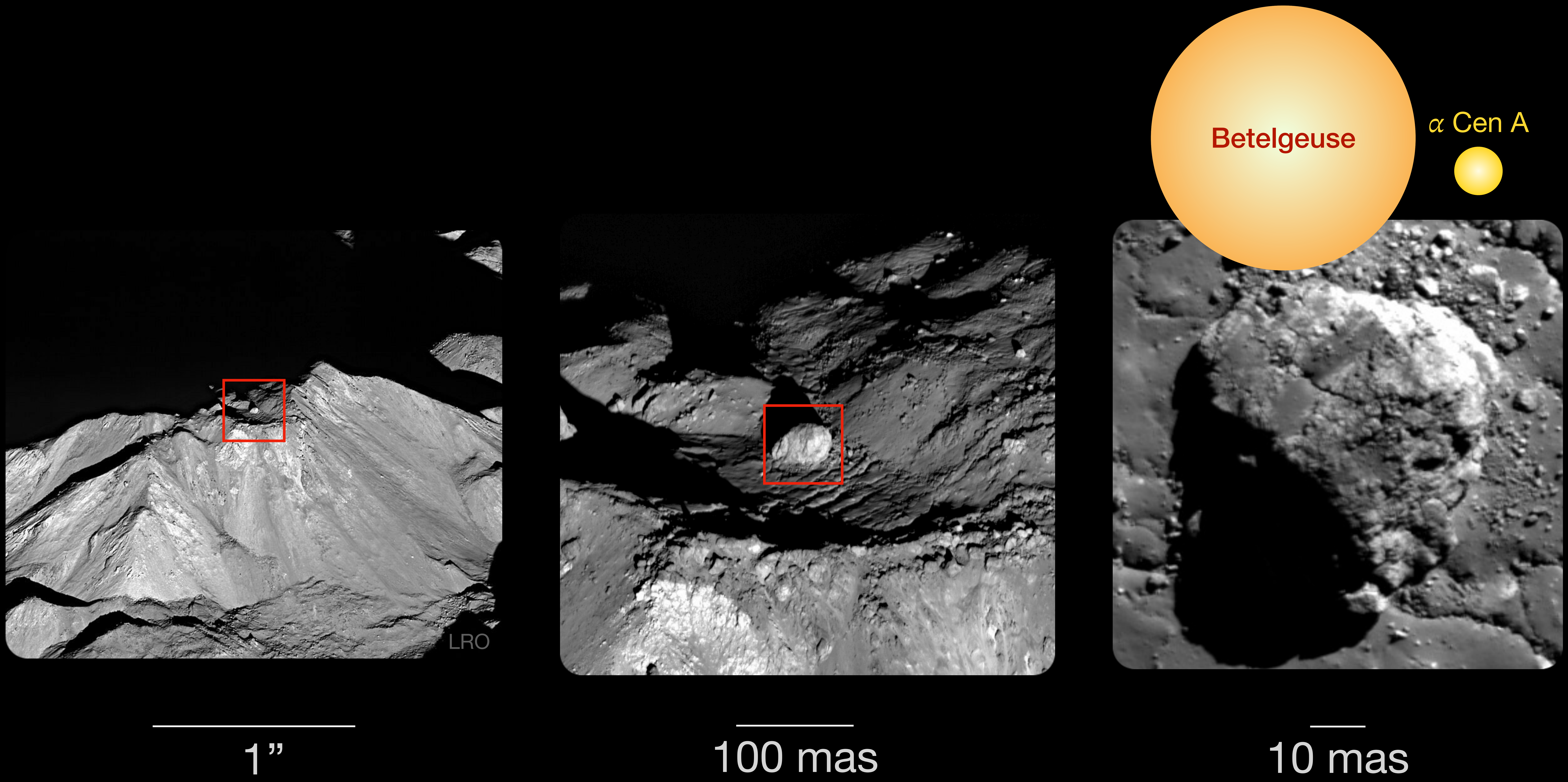


1”

100 mas

10 mas

1 mas ~ 2 meters on the Moon



1 mas ~ 2 meters on the Moon


GRAVITY
l'Observatoire de Paris
PSL
IPAG
Institut de Planétologie et d'Astrophysique de Grenoble
and on GRAVITY+
OBSERVATOIRE DE LA CÔTE D'AZUR
UNIVERSITÉ CÔTE D'AZUR
CRAL
Centre de Recherche Astrophysique de Lyon
ESO
Credit: ESO/G. Hudepohl


Supermassive black holes
NGC 300 (credit: ESO)


Credit: ESO/P. Horálek

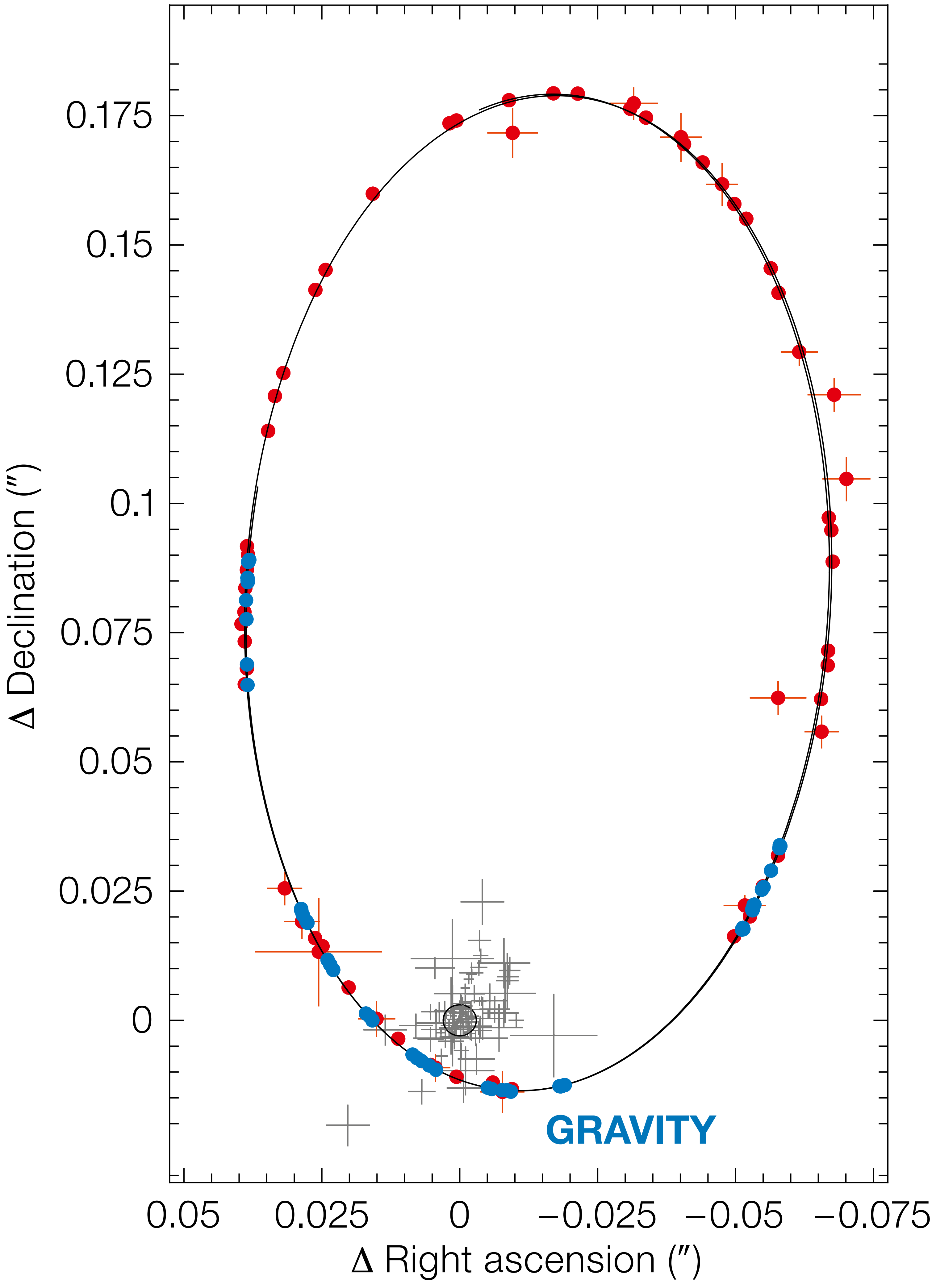

Credit: ESO

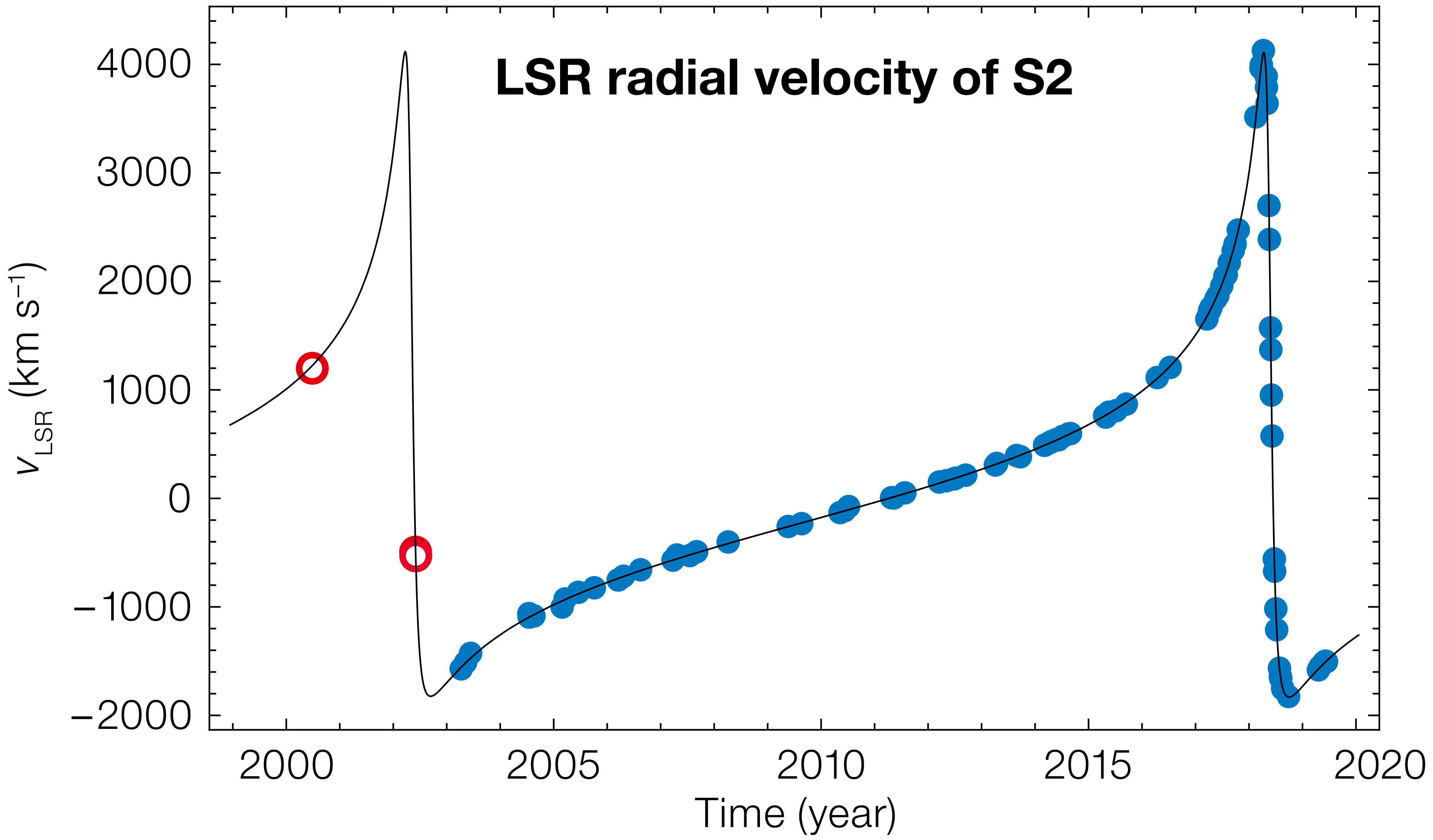

Credit: ESO

Orbit of S2 around Sgr A*

- 4 million solar mass BH


Nobel prize 2020





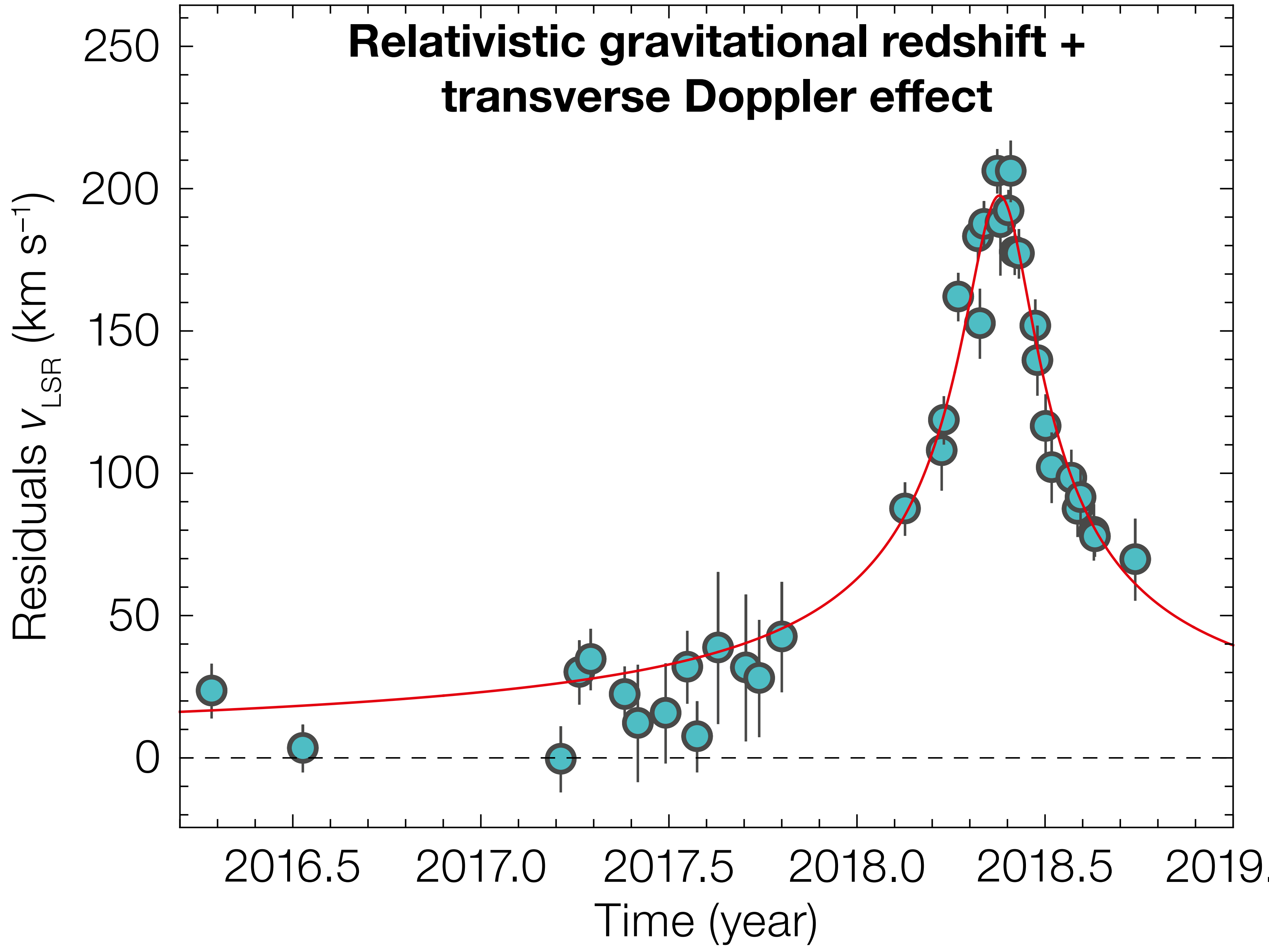
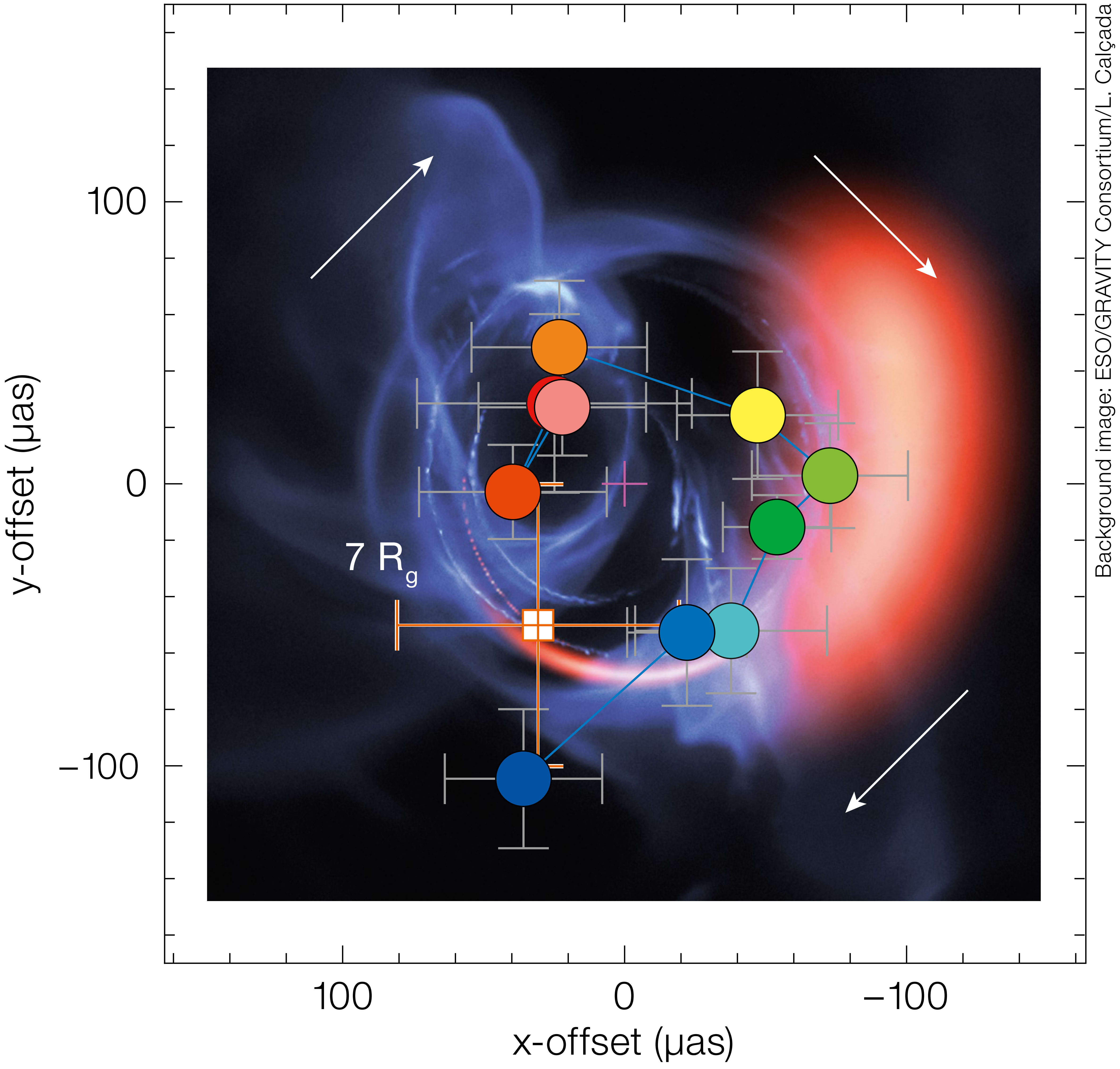


Figure 2. Orbit of S2. Astrometric data from GRAVITY (blue), NACO and SHARP (red). The black ellipse is the best-fit orbit and the black circle shows the position of Sgr A*. Flare positions are marked by grey crosses. Top right: S2 radial velocity (along our line of sight) measured over more than one orbit. Bottom right: The combined gravitational redshift and relativistic transverse Doppler effect manifest in an excess in the radial velocity of 200 km s^{-1}.

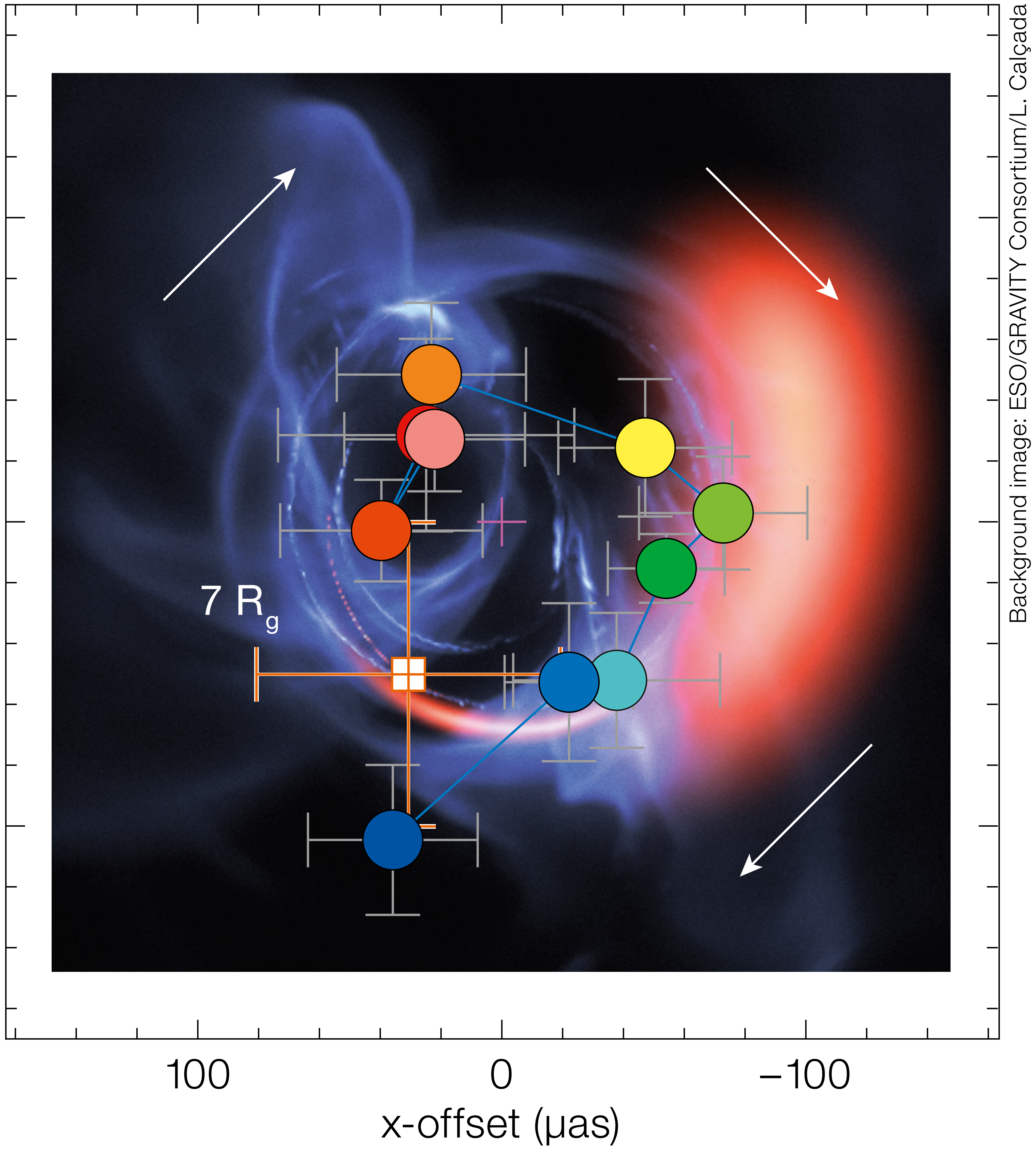
GRAVITY Collaboration 2019, A&A, 625, A10
Heißel et al. 2022, A&A, 660, A13

Accretion on Sgr A*

- Projected orbit of the flare recorded on 22 July 2018
- 30-minute duration

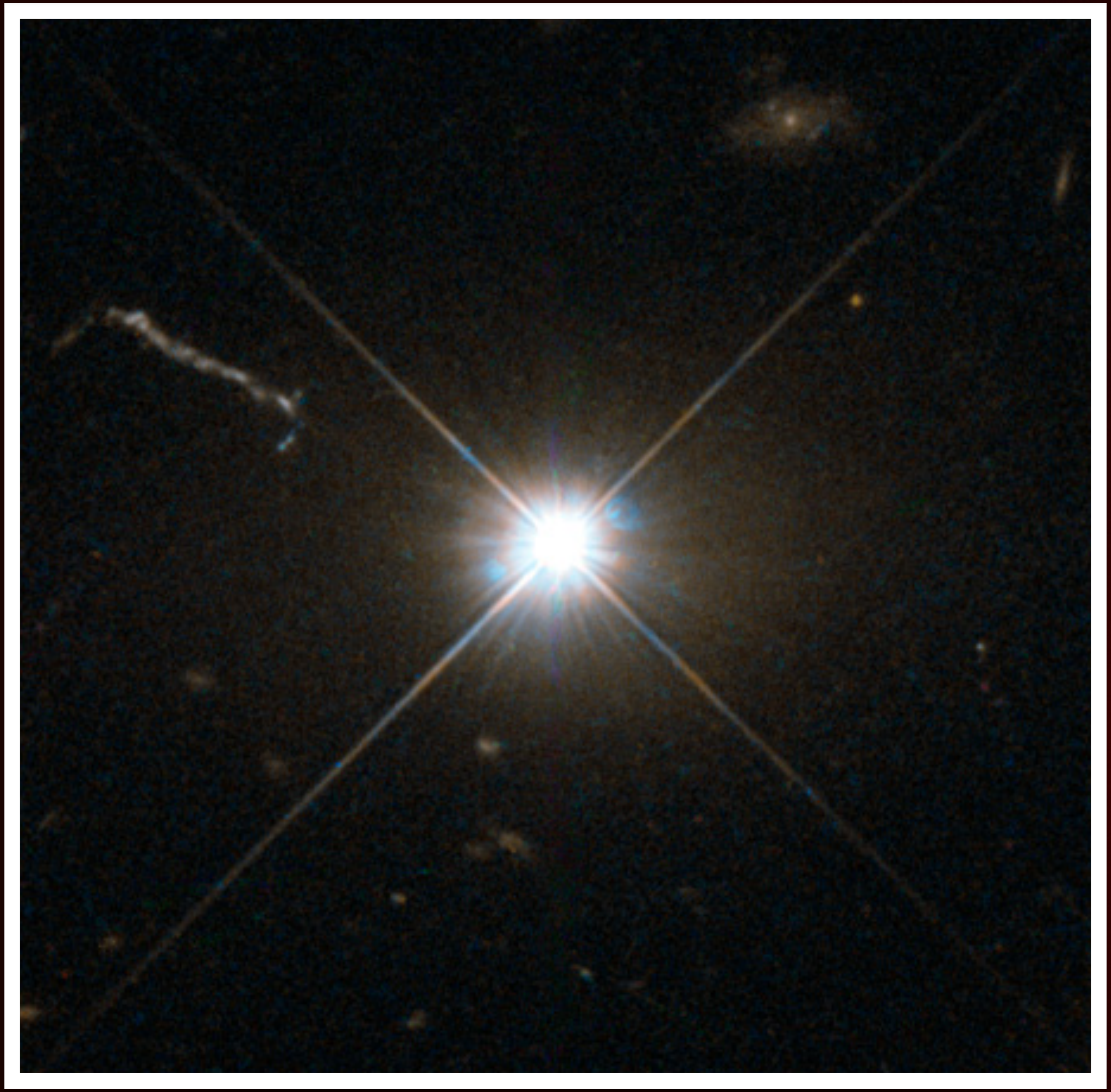


GRAVITY Collaboration, Paumard et al. 2018, A&A, 618, 15



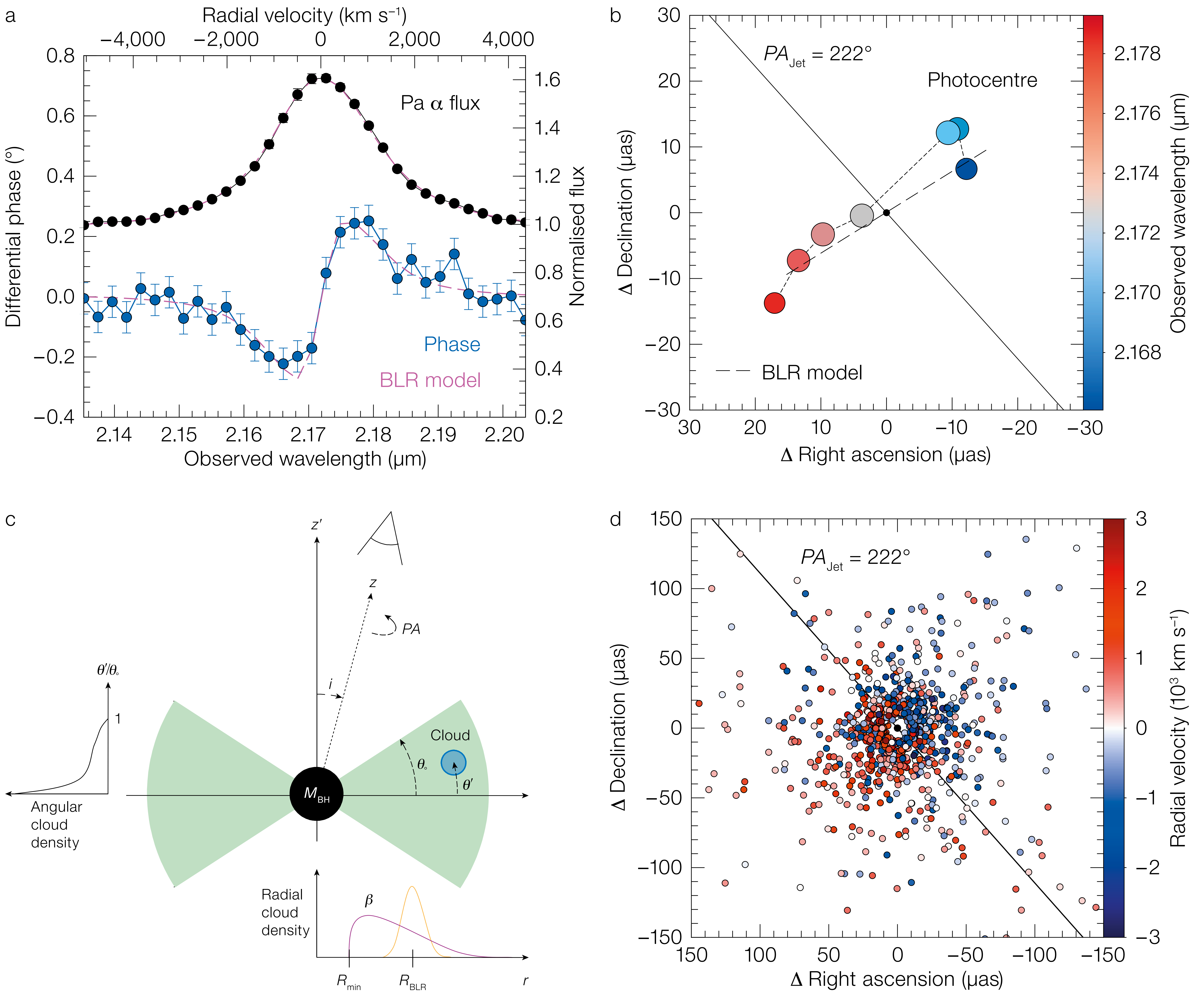
GRAVITY Collaboration, Paumard et al. 2018, A&A, 618, 15

Quasar 3C 273



Quasar 3C 273

- 40 μas photocenter displacement in spectral line
- Dynamics of the material close to the BH (broad line region)
- 300 million solar mass BH



GRAVITY Collaboration 2018, Nature, 563, 657

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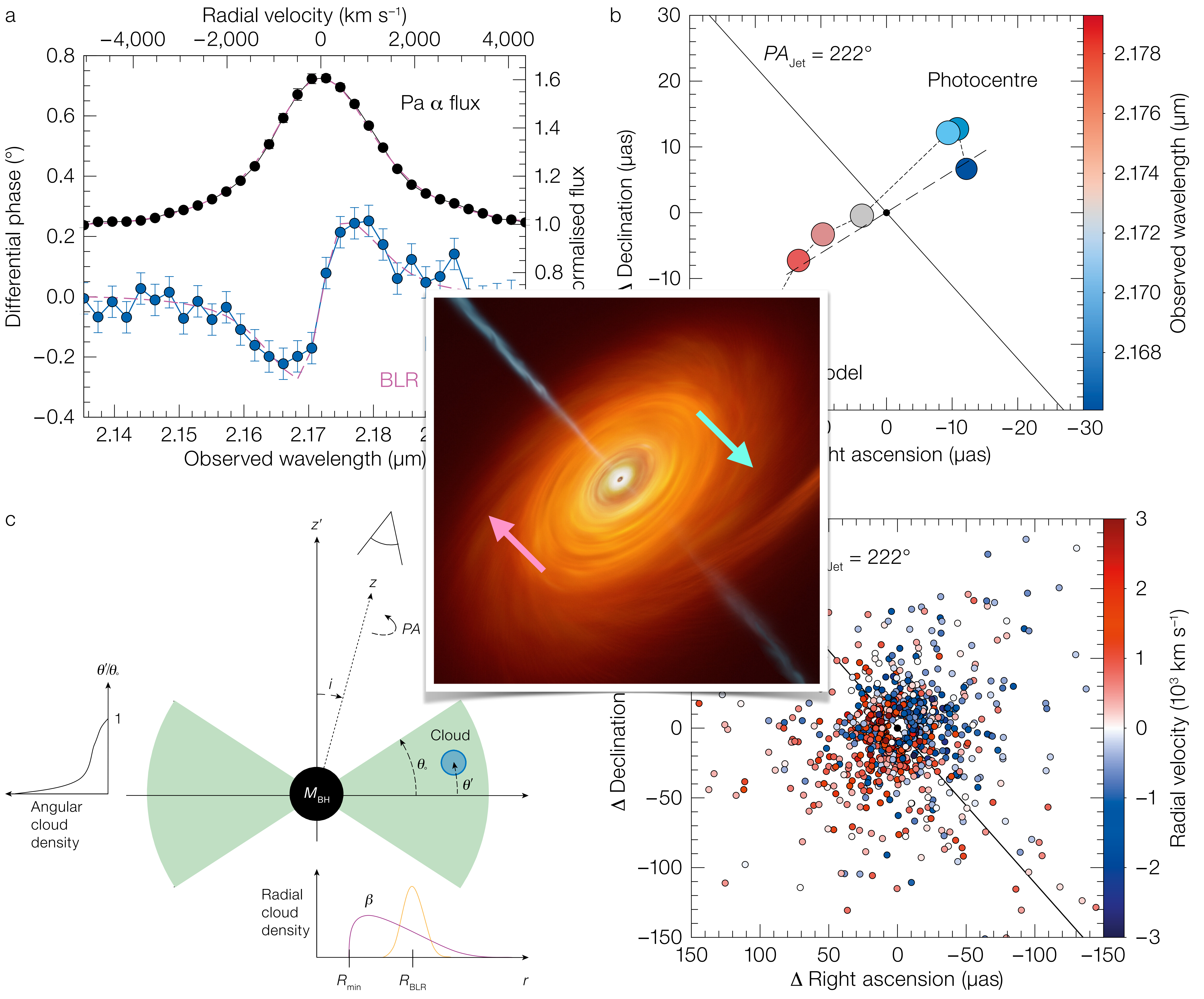
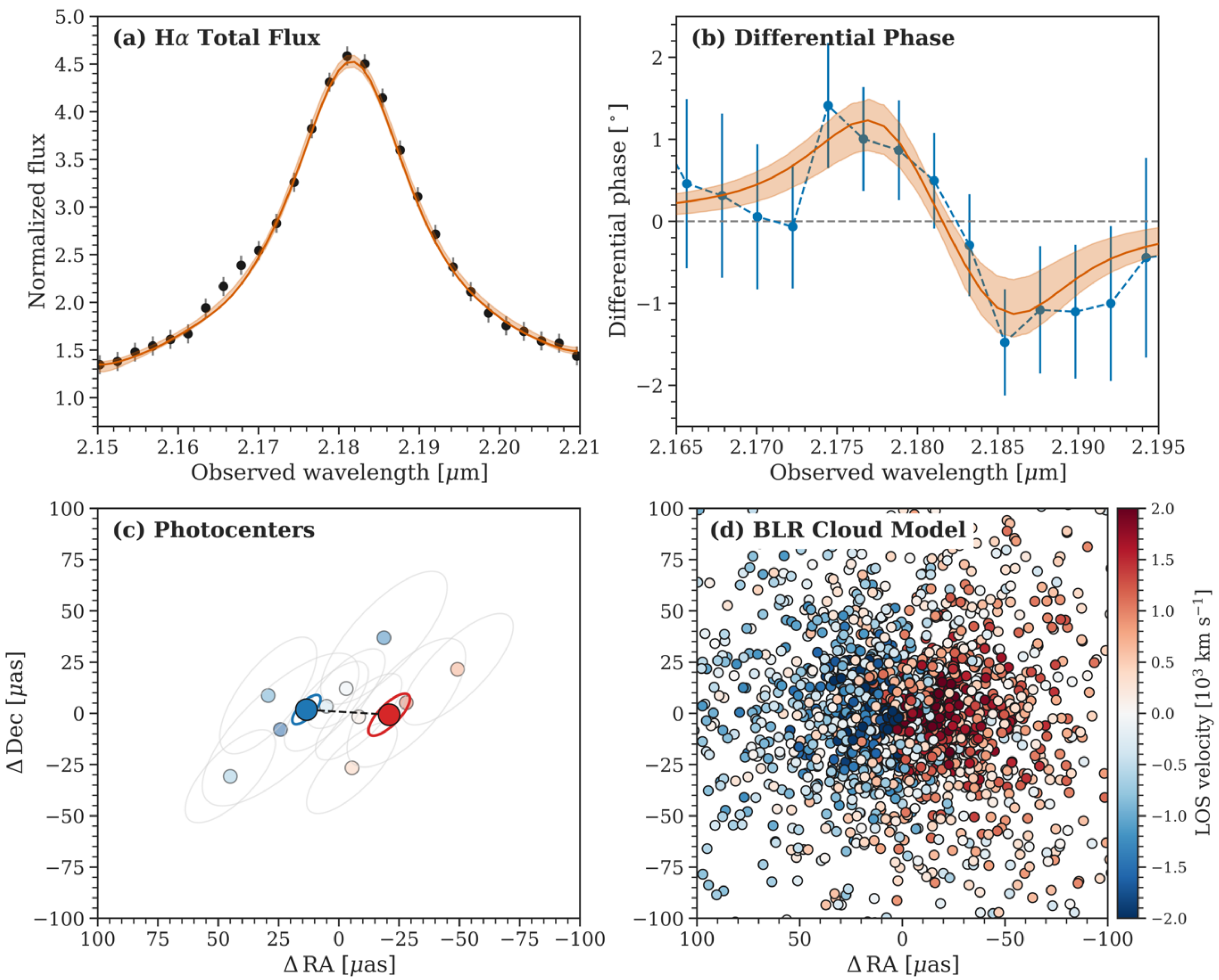


GRAVITY Collaboration 2018, Nature, 563, 657

z=2 quasar SDSS J092034.17+065718.0



- 11 Gyr ago, 320 million solar masses.

GRAVITY Collaboration (2024, Nature, https://doi.org/10.1038/s41586-024-07053-4)

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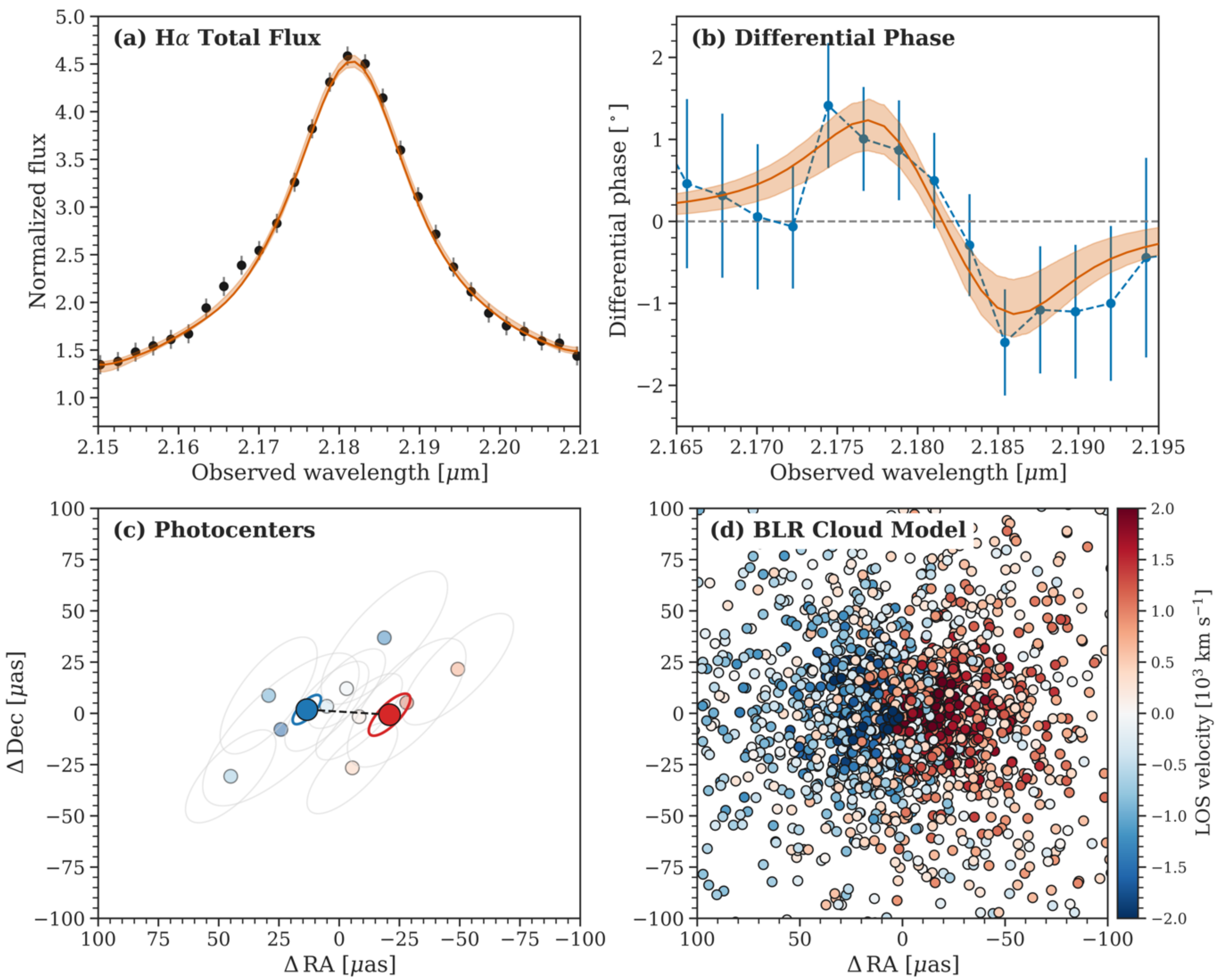

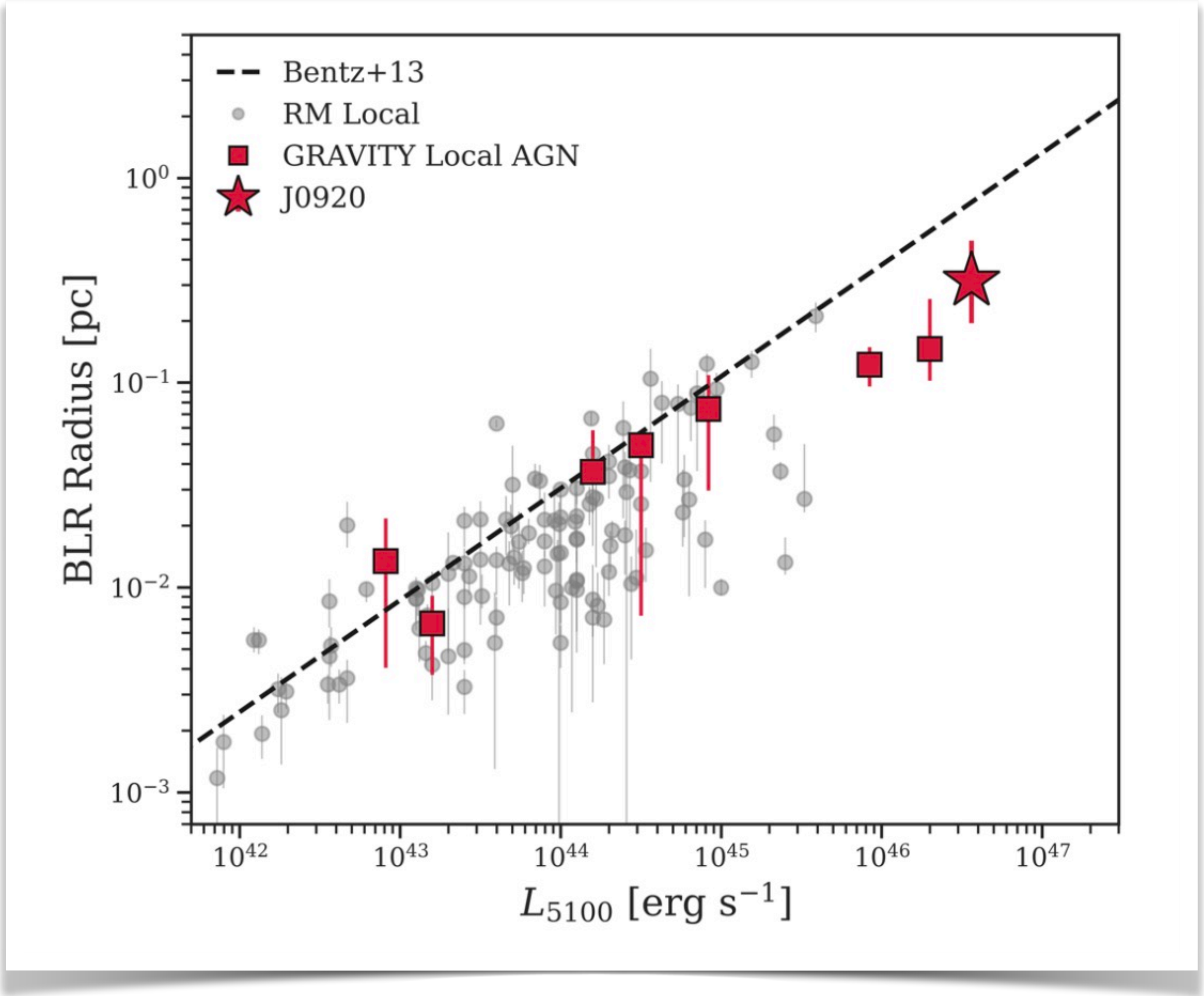

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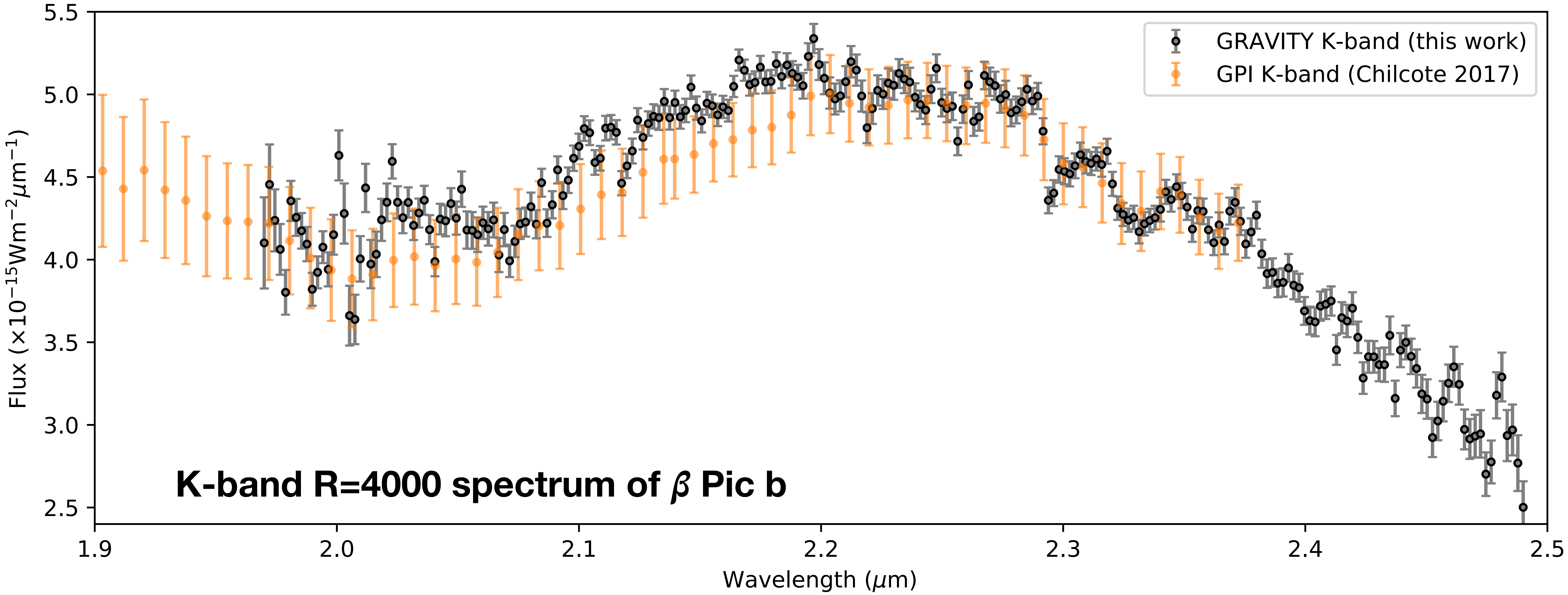
Exoplanets

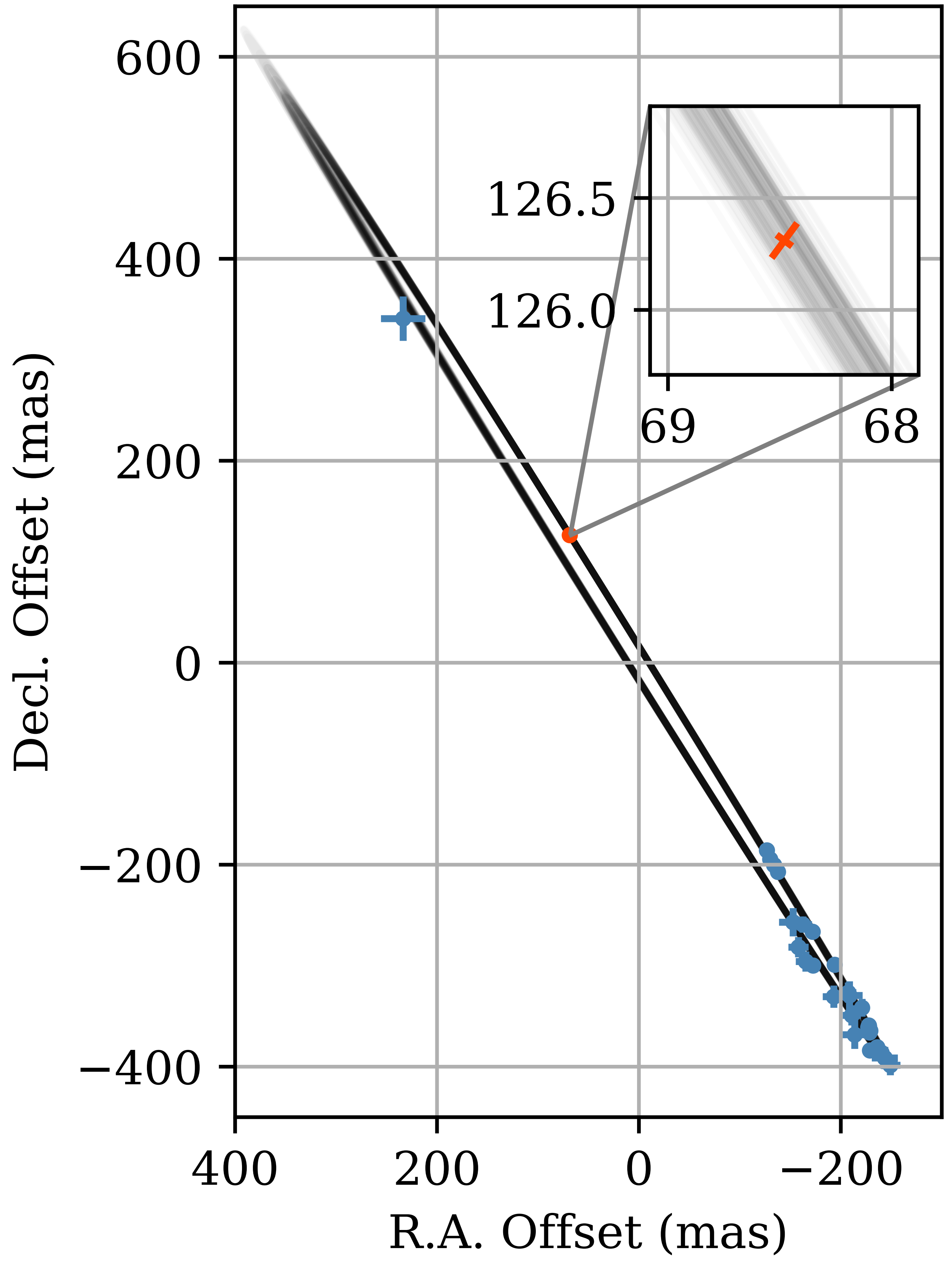
β Pictoris and GRAVITY

Credit: ESO / A.-M. Lagrange

β Pictoris b and GRAVITY

- Astrometric accuracy of GRAVITY position ~ 70 μas from 1.5 hour of VLTI with 4 UTs





GRAVITY Collaboration, Nowak et al. 2020, A&A 633, A110

Astrometric search for exomoons

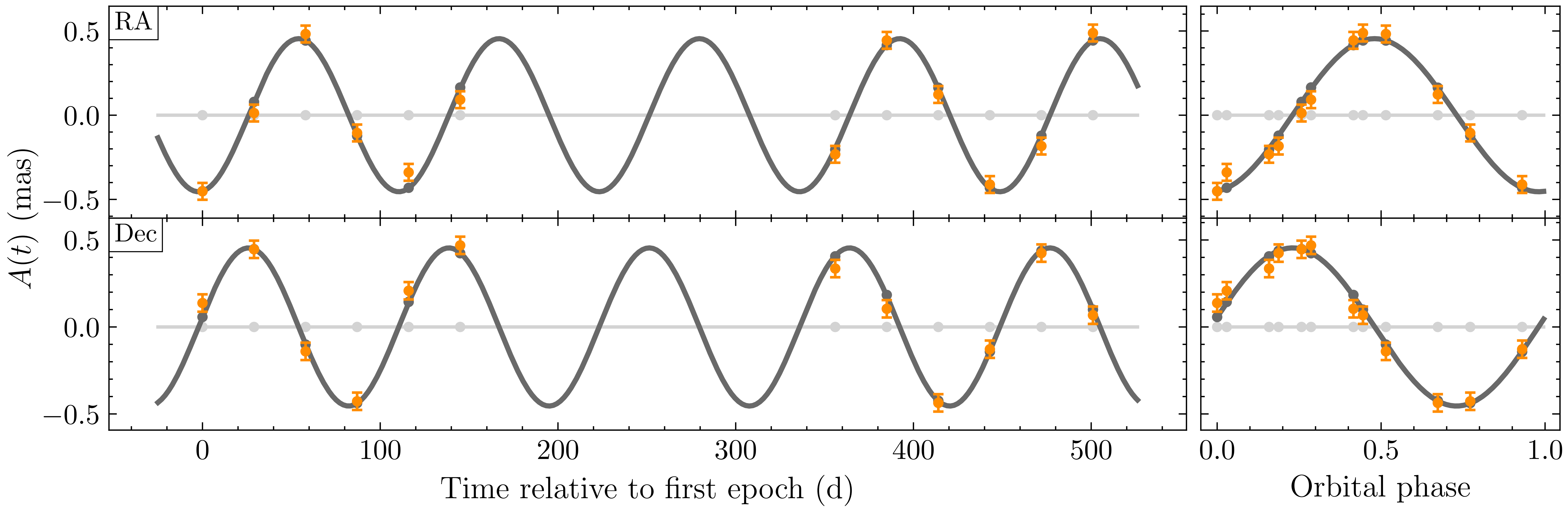


Fig. 3. Fiducial astrometric signal in RA and Dec as a function of time for an exemplary system configuration ($M_s = 1.5\,M_\odot$, $M_{pl} = 10\,M_{Jup}$, $a_{pl,0} = 10$ AU, $M_m = 1\,M_{Jup}$, $\varpi = 50$ mas, $a_{m,0} = 0.1$ AU, $i_m = 0°$, $e_m = 0$; see caption of Fig. 1 for index definitions). The dark grey curve indicates the fiducial signal computed using the star–planet–moon model described in Sect. 2.2.2, while the light grey line shows the zero-signal expected in the absence of a moon. The light and dark grey circles show the fiducial momentary signals in RA and Dec when employing the 12 epoch strategy defined in Sect. 4.1. In orange we indicate the associated GRAVITY mock epochs generated according to the procedure outlined in Sect. 4.2. The right hand panels show the same data but phase-folded by the fiducial orbital period.

Winterhalder et al. 2025, A&A, in press, arXiv:2509.15304v1

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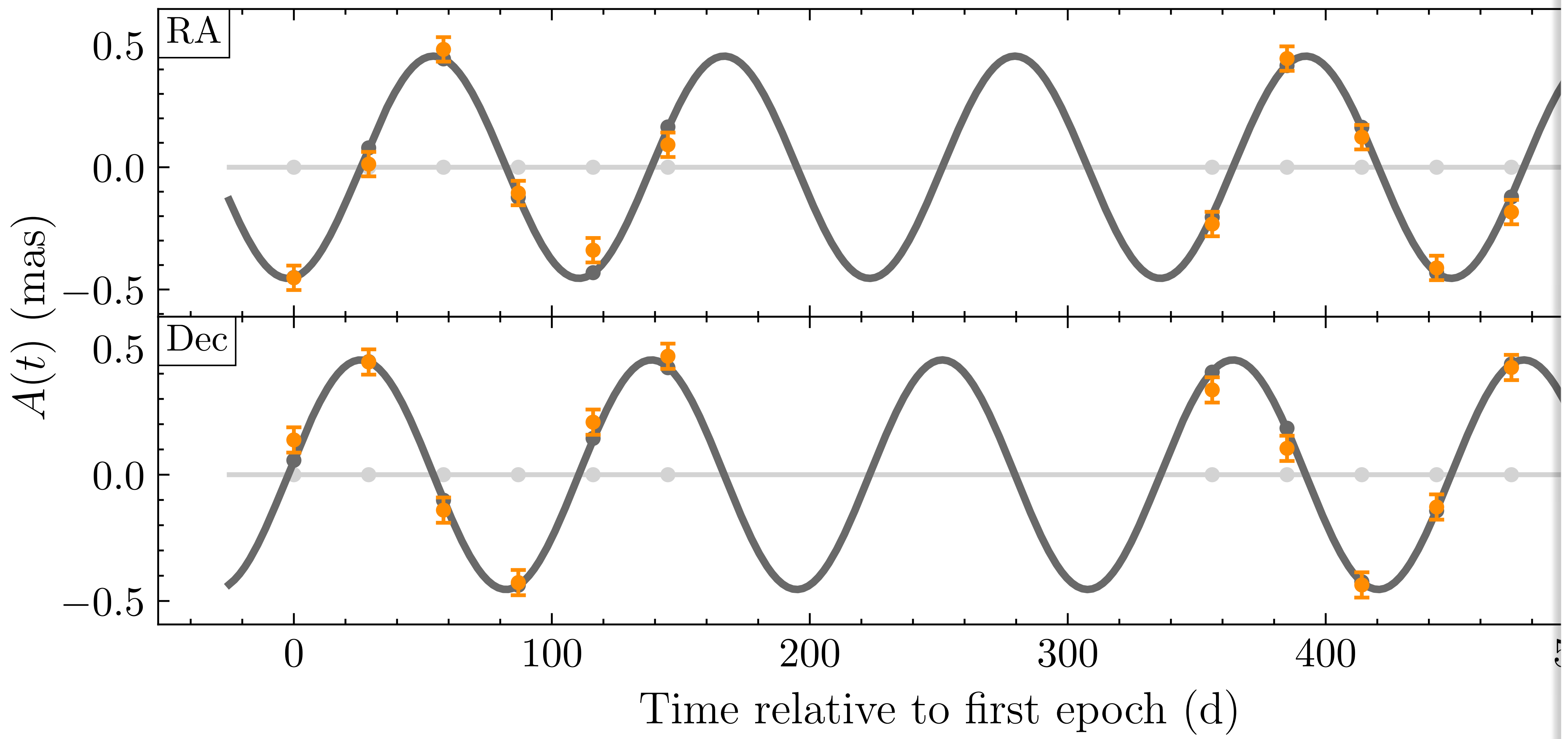

Fig. 3. Fiducial astrometric signal in RA and Dec as a function of time for an exemplary system
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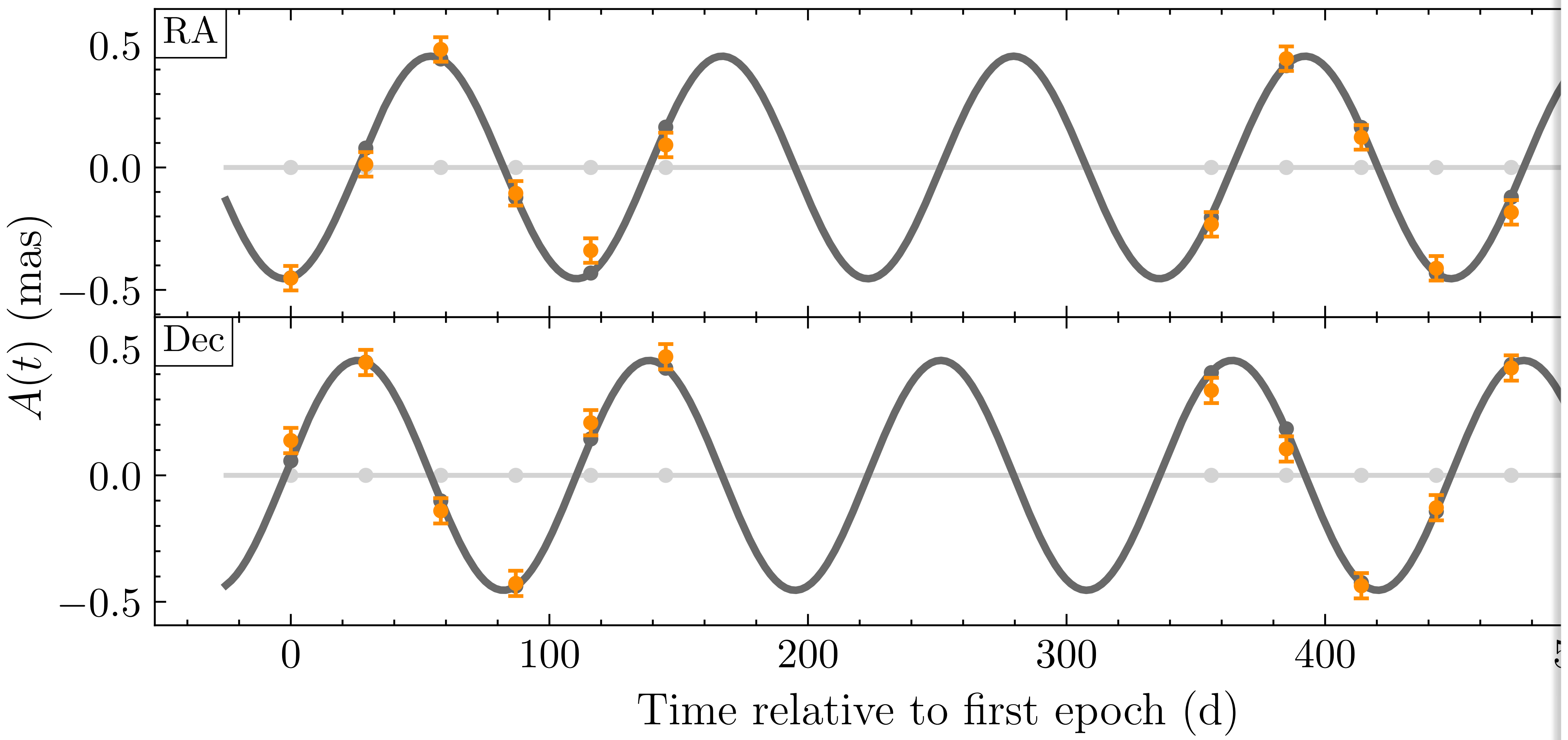
Table 1. Astrometric signal amplitudes for different case examples in the *top* and the approximate astrometric measurement precision of different current and future instruments in the *bottom*.

Planet	System parameters	M_m (M_{Jup})	χ	A (µas)
β Pic b	ϖ = (50.93 ± 0.15) mas [1]	1.0	0.5	3000 ± 600
	M_s = (1.83 ± 0.04) $M_\odot$ [2]		0.1	600 ± 130
	M_{pl} = $9.3^{+2.6}_{-2.5}$ M_{Jup} [2]	0.1	0.5	330 ± 70
	a_{pl} = (10.26 ± 0.10) AU [2]		0.1	65 ± 15
	$R_{Hill,pl}$ = (1.20 ± 0.11) AU	0.01	0.5	33 ± 8
			0.1	6.6 ± 1.5
HR 8799 d	ϖ = (24.46 ± 0.05) mas [1]	1.0	0.5	3800 ± 900
	M_s = $1.51^{+0.38}_{-0.24}$ $M_\odot$ [3]		0.1	770 ± 180
	M_{pl} = (10 ± 3) M_{Jup} [4]	0.1	0.5	420 ± 110
	a_{pl} = (26.97 ± 0.73) AU [3]		0.1	80 ± 20
	$R_{Hill,pl}$ = (3.5 ± 0.4) AU	0.01	0.5	42 ± 11
			0.1	8 ± 2
HD 206893 c	ϖ = (24.53 ± 0.04) mas [1]	1.0	0.5	460 ± 30
	M_s = $1.32^{+0.07}_{-0.05}$ $M_\odot$ [5]		0.1	92 ± 7
	M_{pl} = $12.7^{+1.2}_{-1.0}$ M_{Jup} [5]	0.1	0.5	49 ± 4
	a_{pl} = $3.53^{+0.08}_{-0.06}$ AU [5]		0.1	9.8 ± 0.7
	$R_{Hill,pl}$ = (0.51 ± 0.02) AU	0.01	0.5	5.0 ± 0.4
			0.1	0.99 ± 0.07

	SPHERE	GPI	GRAVITY	PLANETES*	MICADO†	KBI††
σ_A (µas)	1500 [6]	1000 [7]	50 [8]	10 [9]	400 [9]	< 1 [10]

Winterhalder et al. 2025, A&A, in press, arXiv:2509.15304v1

Astrometric search for exomoons



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Winterhalder et al. 2025, A&A, in press, arXiv:2509.15304v1

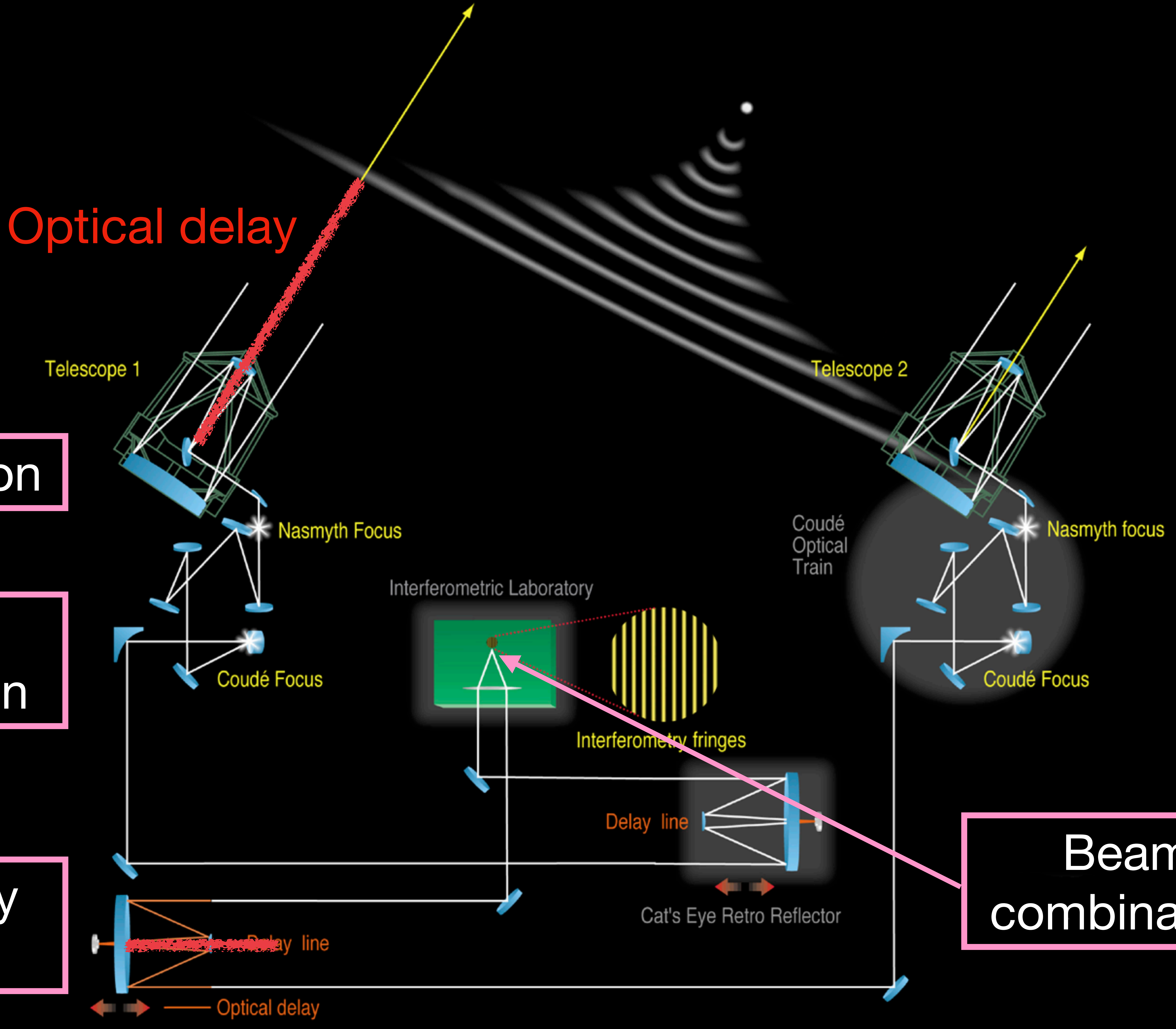
Technology

Credit: ESO

Light collection

Beam transportation

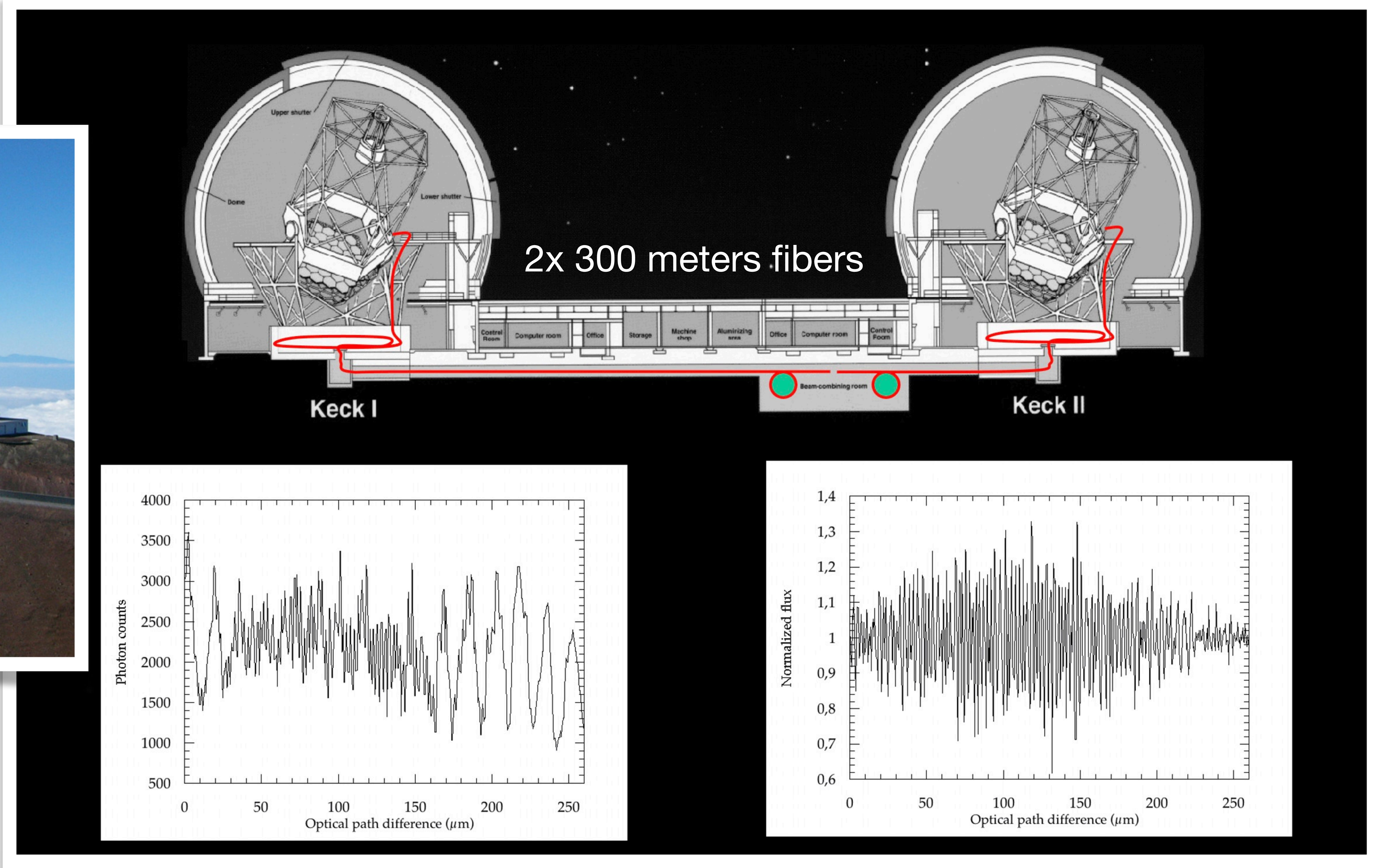
Optical delay cancelation



Beam combination

Beam transportation by optical fibers

The OHANA experiment



Perrin et al. 2006, Science , 31, 194

ESO/B.Tafreshi (twanight.org)

Optical delay cancelation

Typical 3 hour observation:

~ **30 meters delay** at VLTI

~ **1 meter delay** on the Moon

6 mm pure fibered delay lines
in operation in GRAVITY

10 to 1000m delay in fibers
plausible with R&D

Integrated optics beam combiner

GRAVITY's heart

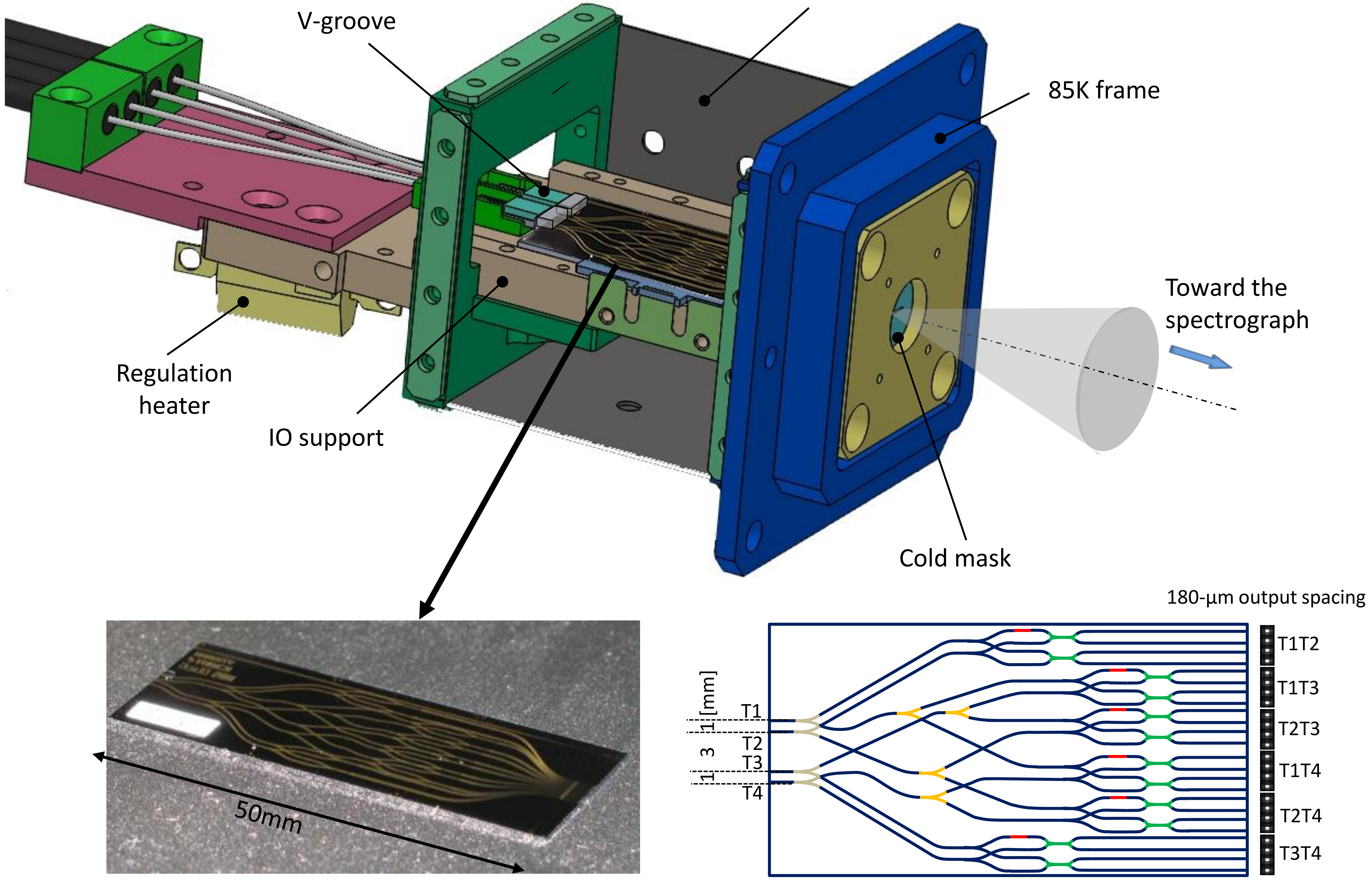


Fig. 3. Description of the IO assembly. *Top*: mechanical mount including the IO beam combiner and the fibre array. *Bottom*: photograph of an IO beam combiner manufactured by silica-on-silicon etching (*left*) and scheme of the beam combiner principle (*right*): 66/33 couplers (in red), Y-junctions (in grey), achromatic $\pi/2$-phase shifters (in light blue), and 50/50 couplers (in green). See text for details.

Perraut et al. A&A 614, A70 (2018)

The Moon: a dream environment for interferometry

- **No turbulence !** + all wavelengths are accessible
- **Stability of the surface** is an advantage compared to free flying telescopes
- **Slow sidereal rotation period of 27 days:** optical delay variation is slow and easier to track with compact modulators +14 days long continuous nights
- **Examples of sciences cases:**
  - Galactic nuclei at high redshift with milliarcsecond angular resolution
  - Surface and close environment of stars at high spatial and spectral resolution
  - Visible/IR high-resolution spectroscopy of exoplanets
  - Wide-angle microarcsecond differential astrometry of faint objects (binary compact objects, exoplanetary systems, exomoons…)

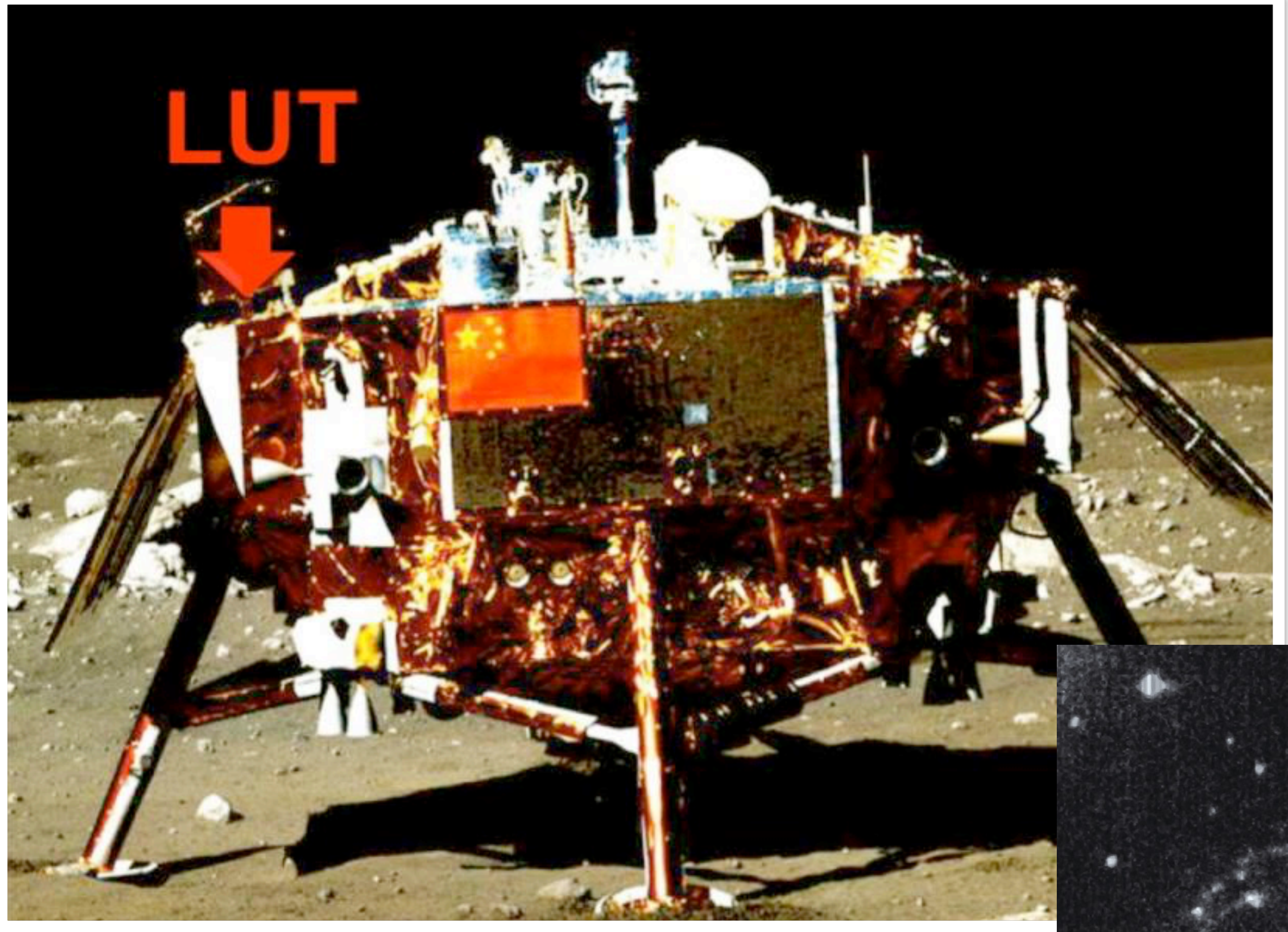
Summary

- Long-baseline optical interferometry is a **mature technique** with broad applicability in astrophysics. The expertise is available in Europe and in the United States.
- All-sky **interferometric astrometry** is extremely appealing
- Possible **modular design** of an interferometric array, with flexible telescope usage in interferometric and single aperture modes (e.g., VLT/VLTI)
- (Sub-)**milliarcsecond angular resolution** at optical and infrared wavelengths
- **Key benefits** of operation from the Moon surface: no atmosphere, stable surface, slow rotation

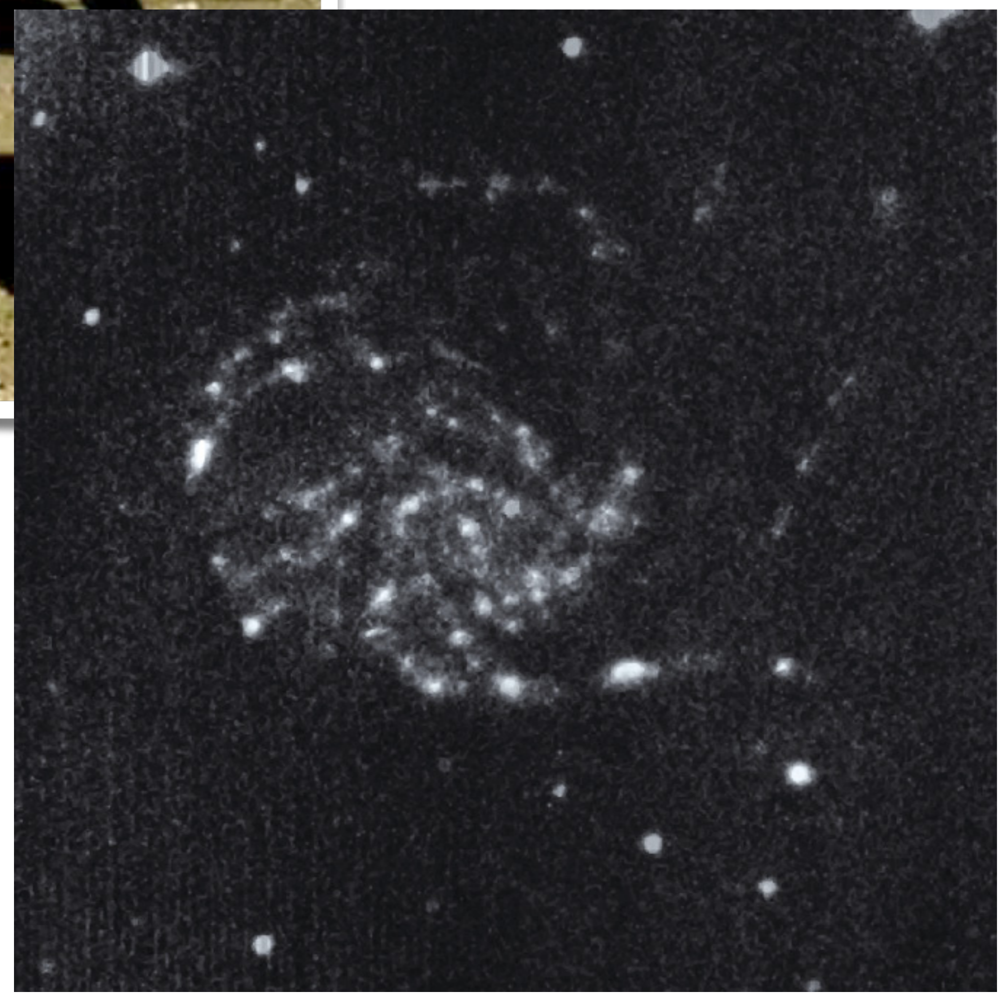

ESO/G. Hudepohl

Light collection

The Lunar-based Ultraviolet Telescope (LUT) on Chang’e-3 lunar lander (2013-2015, 18 months)



Credit: National Astronomical Observatories, Chinese Academy of Sciences



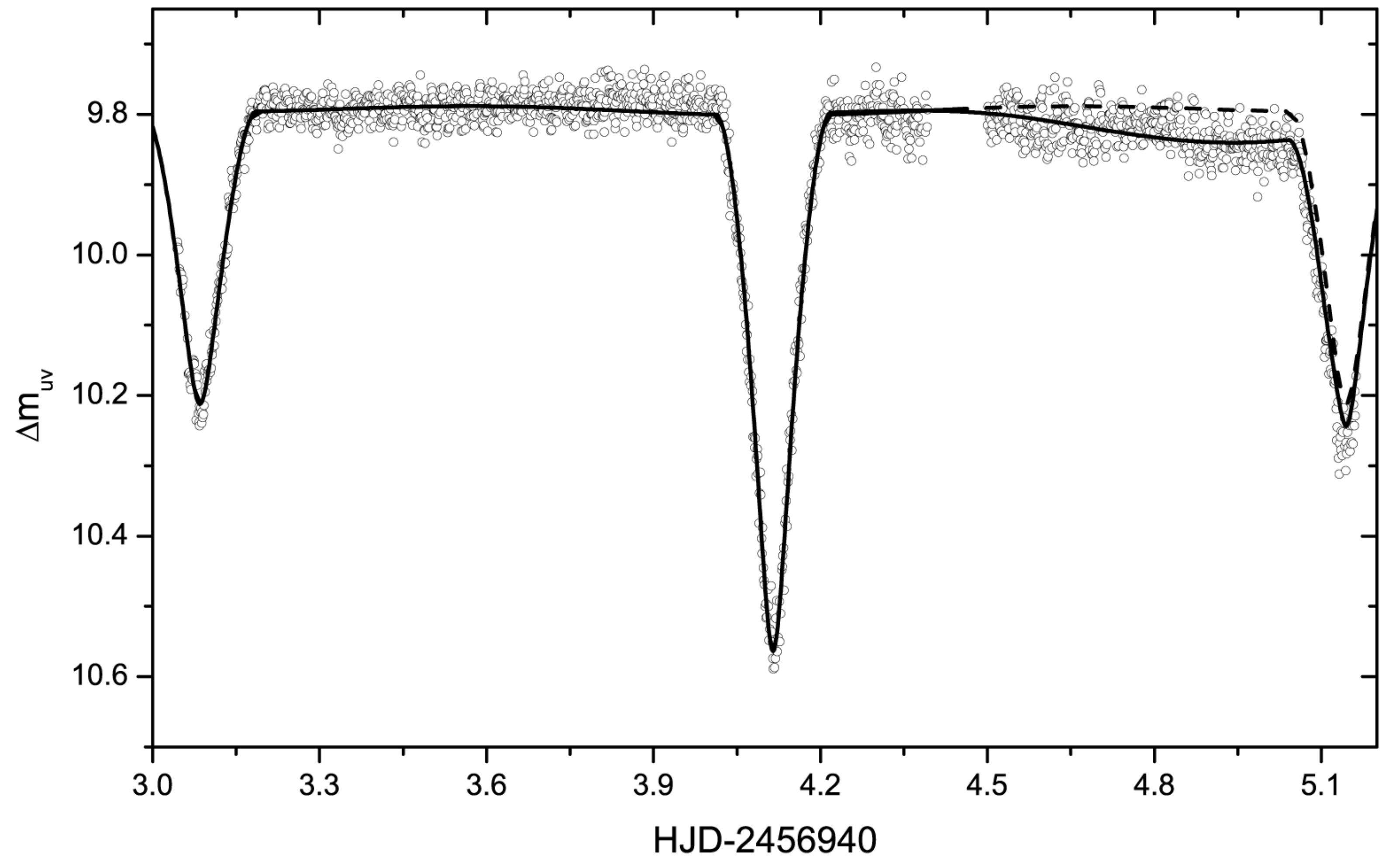
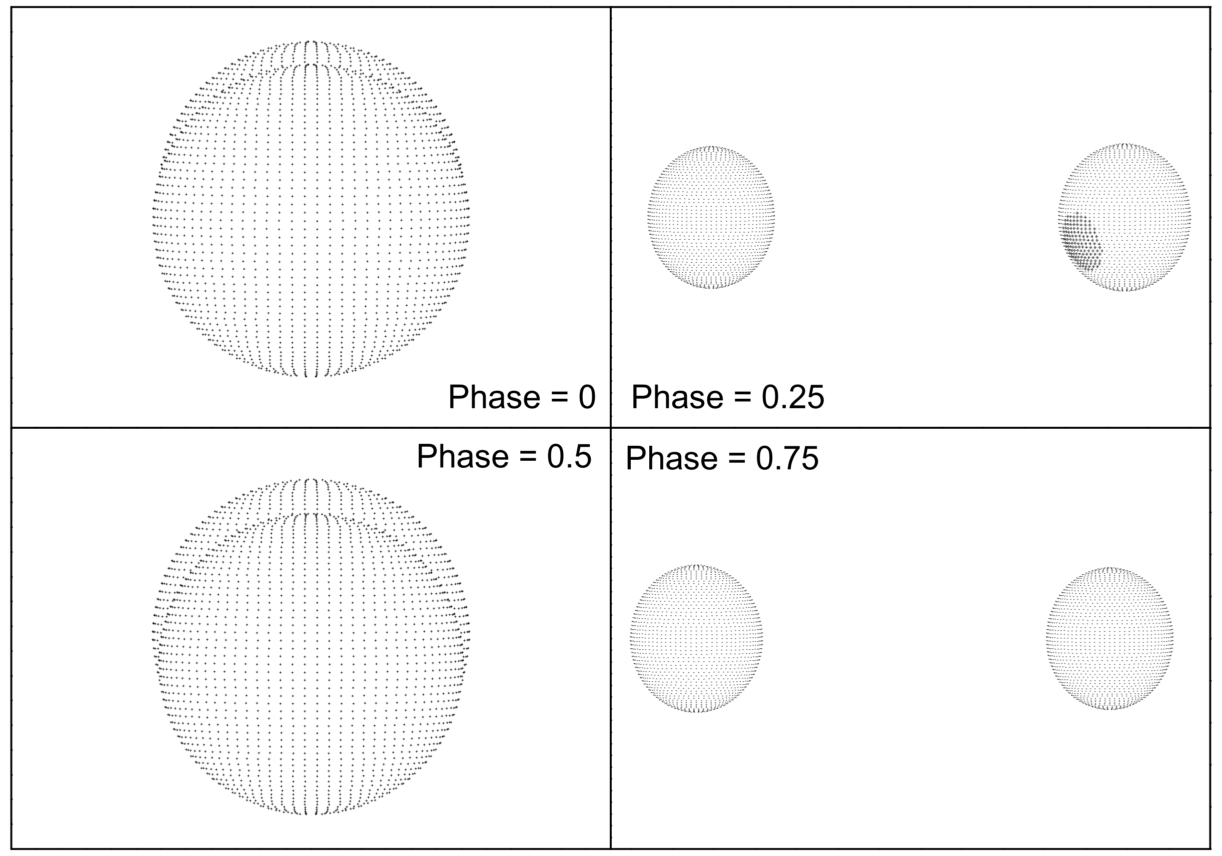


Fig. 1 Light curve of TX Her obtained by LUT from the Moon. *Open circles* refer to observations in the UV band, while the *solid line* to the theoretical light curve with a dark spot on the secondary star and the *dashed line* to the theoretical light curve without the spot.



Zhu et al. (2019, Res. Astron. Astrophys. 19, 094)