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Frank Eisenhauer
(PI)

Découverte des ondes radio

- Heinrich Hertz, 1887. Pense qu’il n’y aura jamais d’utilisation pratique.
- 1895: premier télégraphe sans fil (Guglielmo Marconi)
- Années 30: laboratoires Bell veulent établir une liaison hertzienne transatlantique.

First astronomical radio source

Karl Jansky, 1933, New York Times

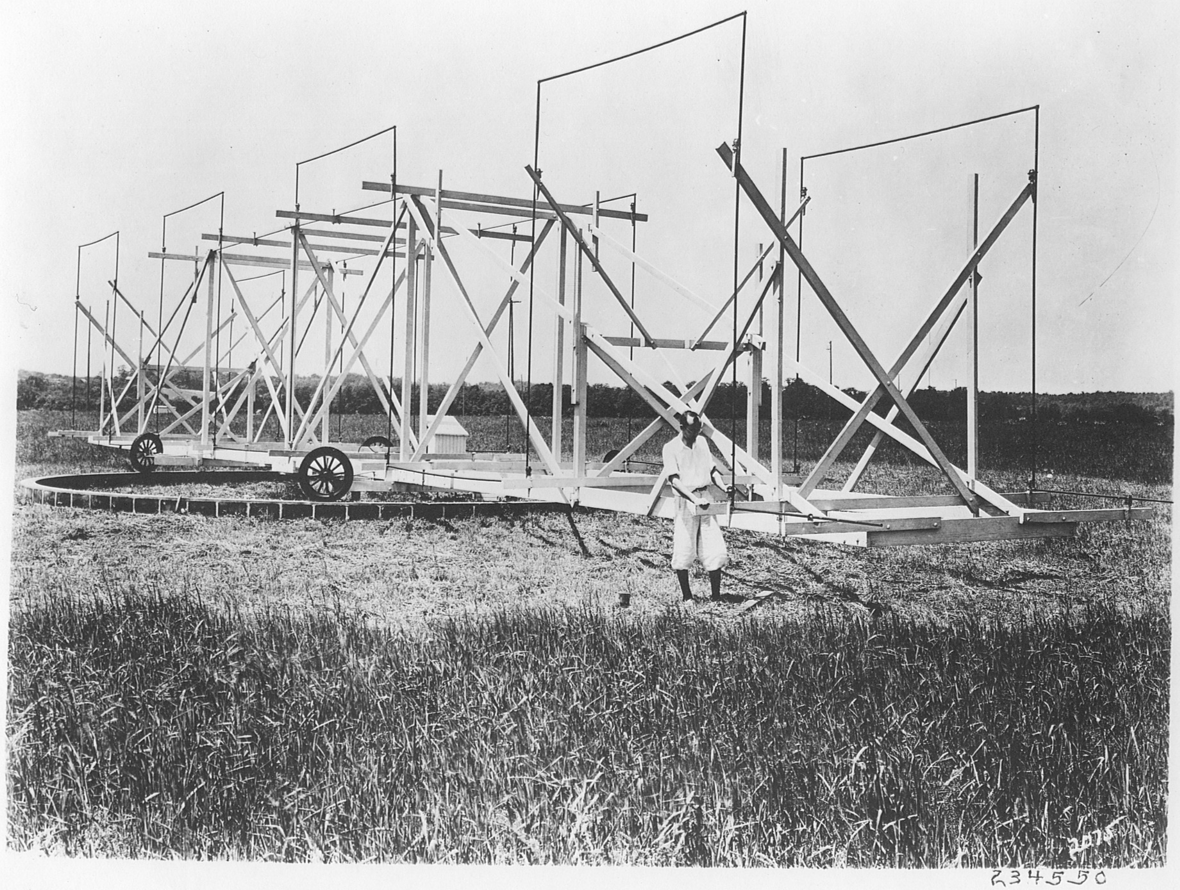
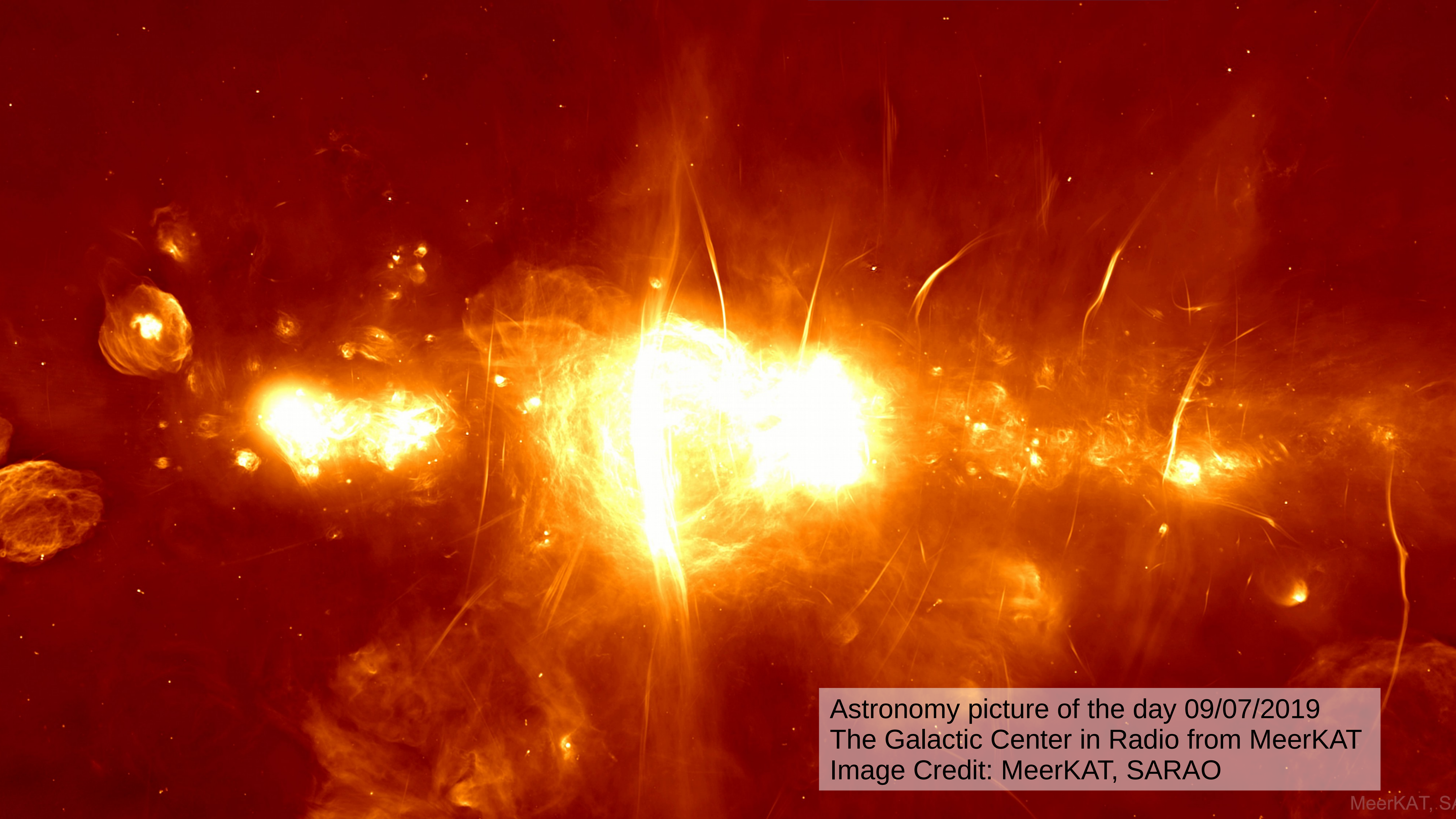
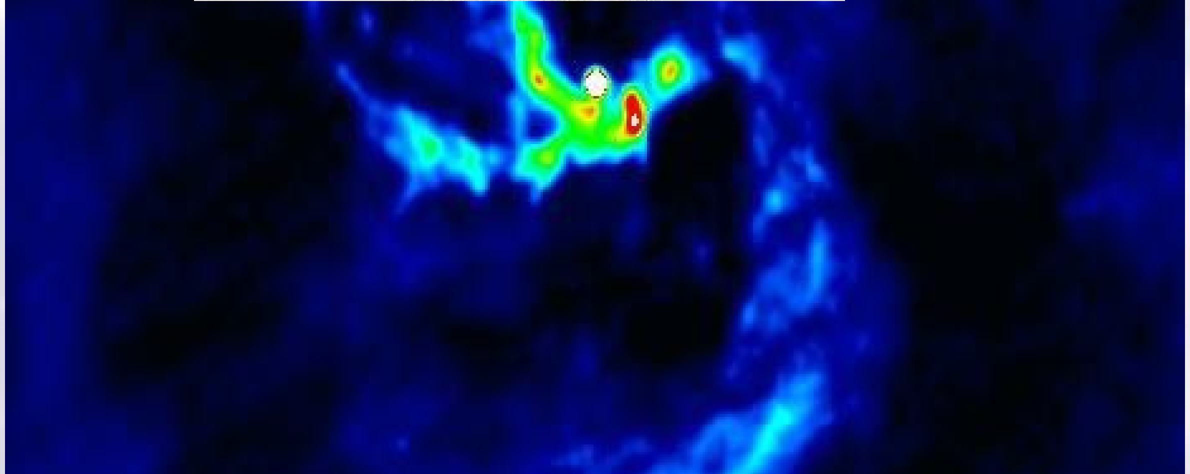
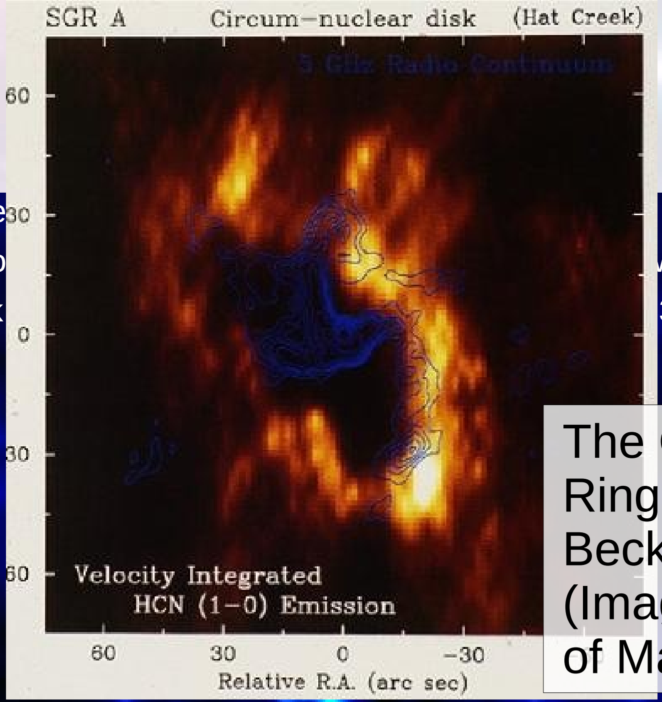


FIG. 8


Astronomy picture of the day 09/07/2019
The Galactic Center in Radio from MeerKAT
Image Credit: MeerKAT, SARAO

In the seventies





The Circumnuclear Disk or Ring: molecules and dust, Becklin et al. 1982 (Image: Leo Blitz, University of Maryland)

2-pc wide VLA radio continuum image of Sgr A, Roberts, Yusef-Zadeh et Goss en 1992, Image courtesy of NRAO/AUI.

The “Infrared Sources” (IRS), Mono-pixel, seeing-limited maps, Becklin & Neugebauer (1975)

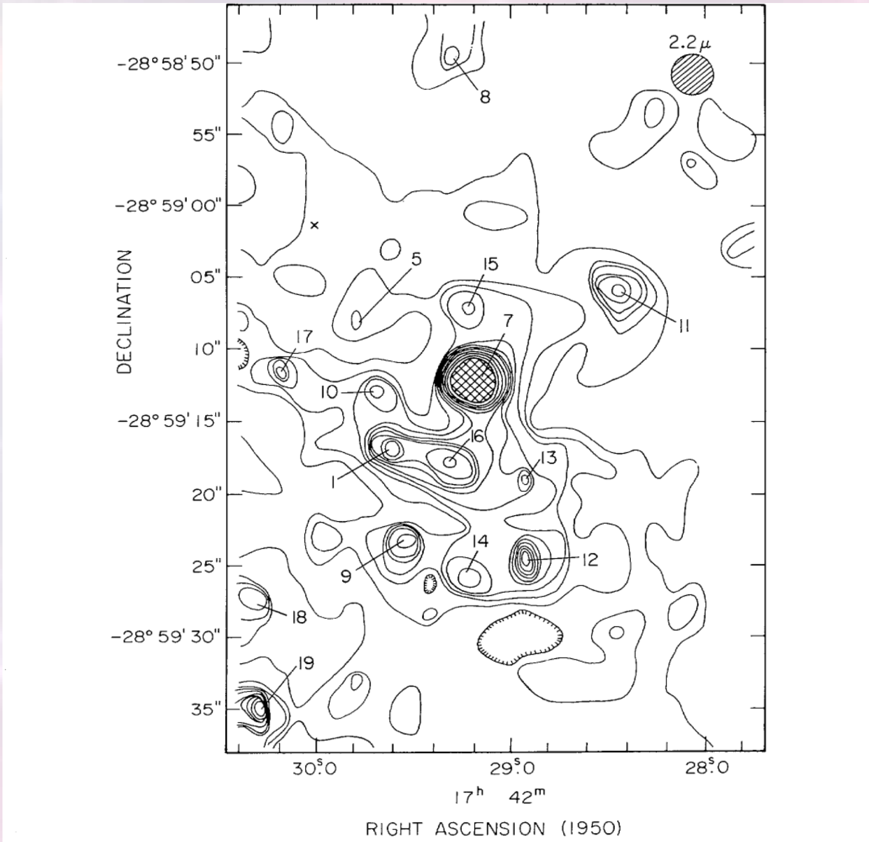


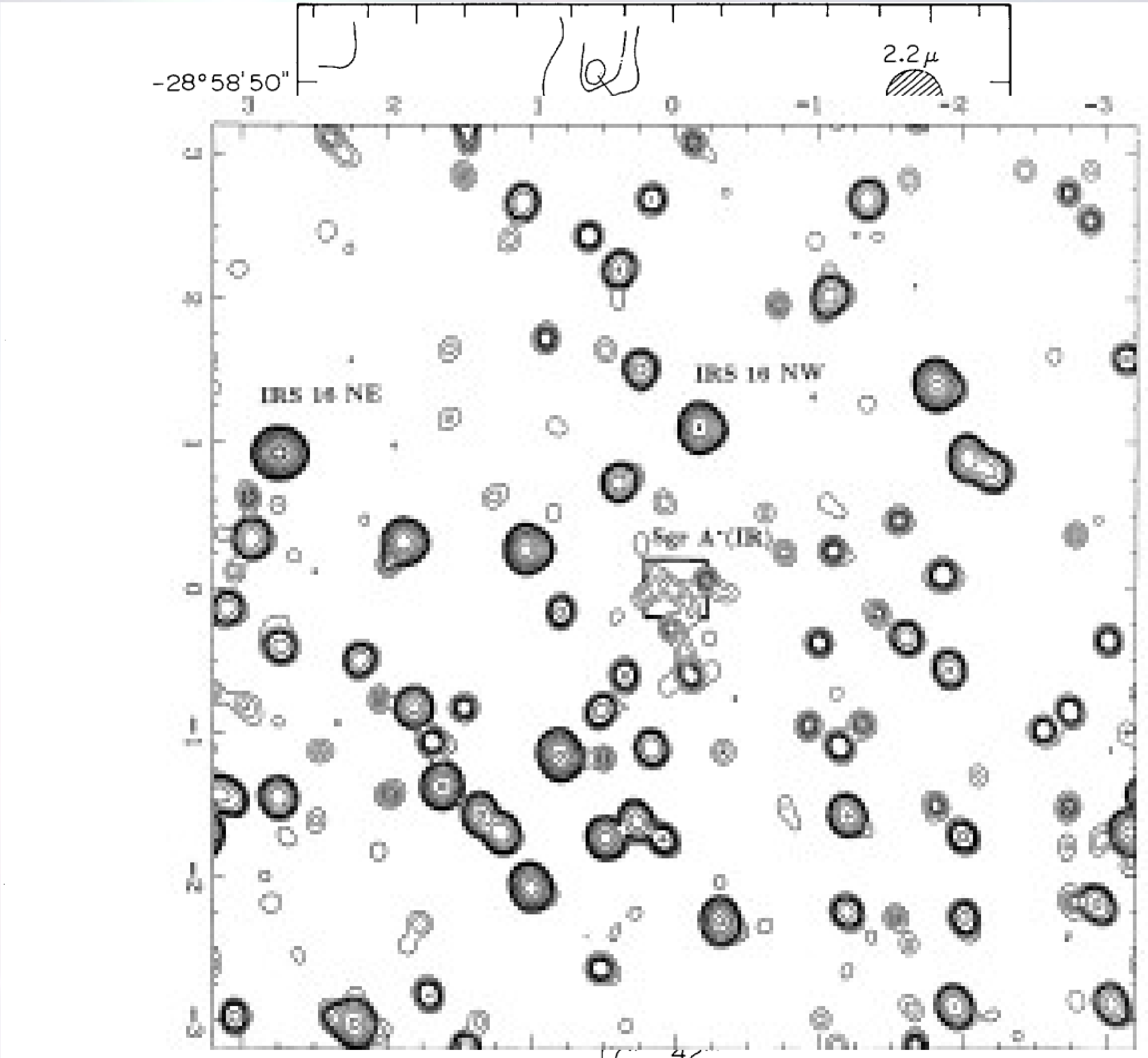
Fig. 1.—Map of the central 1′ of the galactic center at 2.2 μ made with a 2″5 circular aperture. The × denotes a visible field star. The contour levels each correspond to 2.5 × 10⁻¹⁸ W m⁻² Hz⁻¹ s⁻¹. The crosshatching corresponds to 35 contour levels. The numbers refer to the source numbers in Table 1. The angular resolution is shown by the circle in the upper right corner.

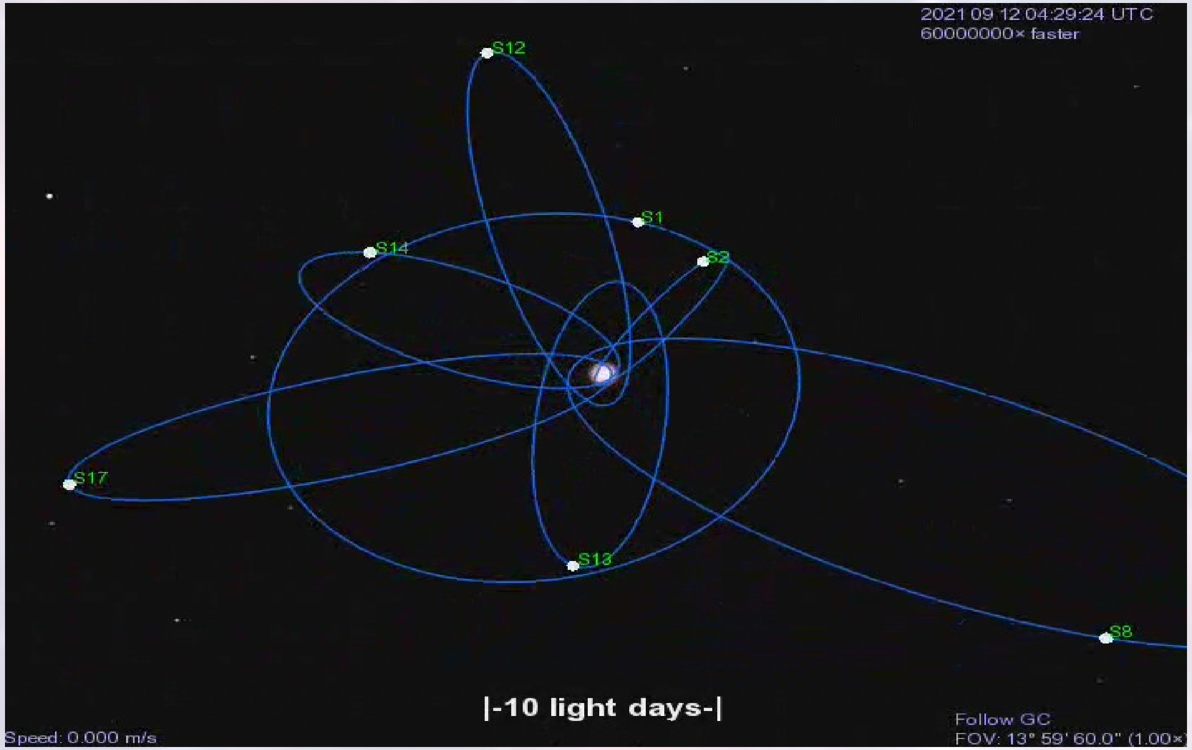
Speckle imaging: the S stars (Eckhart et al. 1995)

Still only stars, no counterpart to Sgr A*.

First fit of S2 orbit: Schödel et al. 2002:

- Central compact object
- 4 x 10^6 $M_\odot$
- R_0 = 8 kpc





2002:

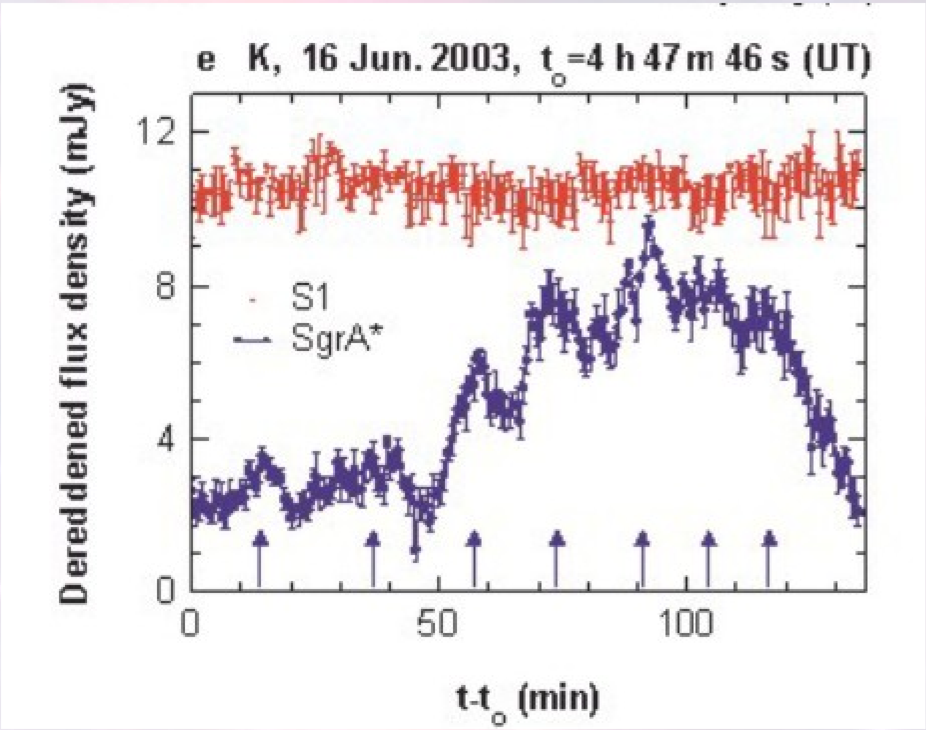
Présence du trou noir trahie par son influence gravitationnelle

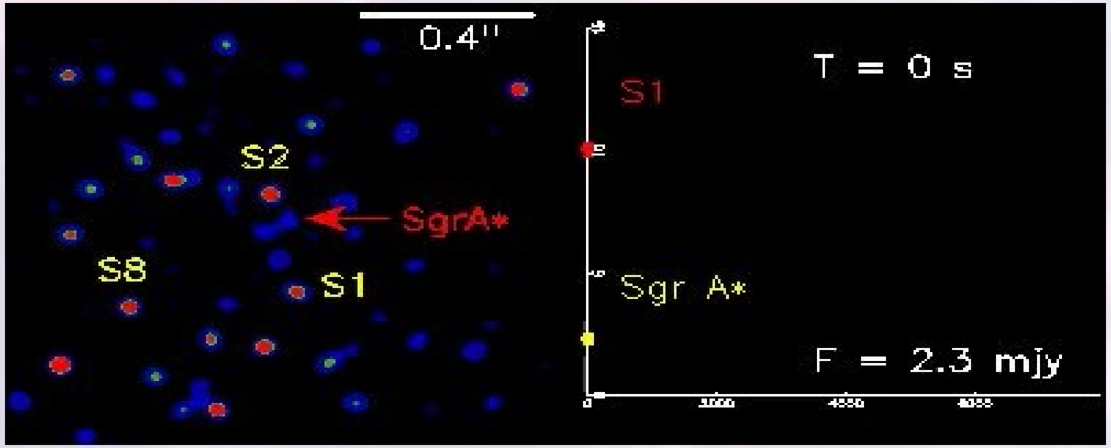
Toujours pas de détection infrarouge

Orbites parfaitement képlериennes

2003: at last a non-stellar (flaring) point source

- Genzel et al. (2003)
- Duration: ~140min
- Pseudo-period: ~20min





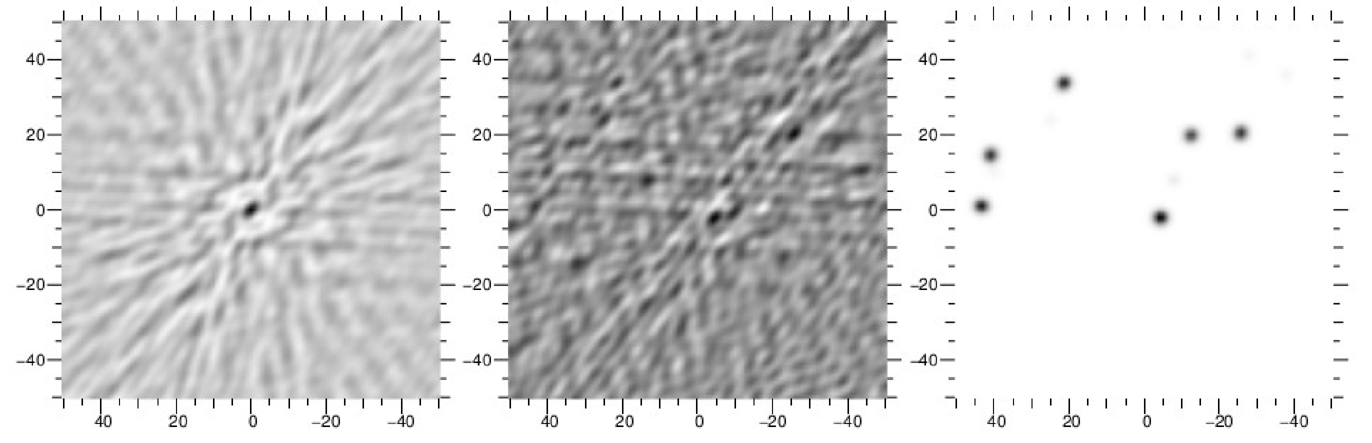


Fig. 1. One-night simulated observation of a model cluster containing six stars with a dynamical range of 1 magnitude. Left: synthesised beam. Middle: raw synthesised image. Right: reconvolved CLEANed image (axes in mas)

Provided with the right instrument, the VLTI should be able to detect general-relativistic effects in the orbital motion of close stars (S2 or new, to-be-discovered stars).

Paumard et al. (2005-2008)
Eisenhauer et al. (2005-2008)

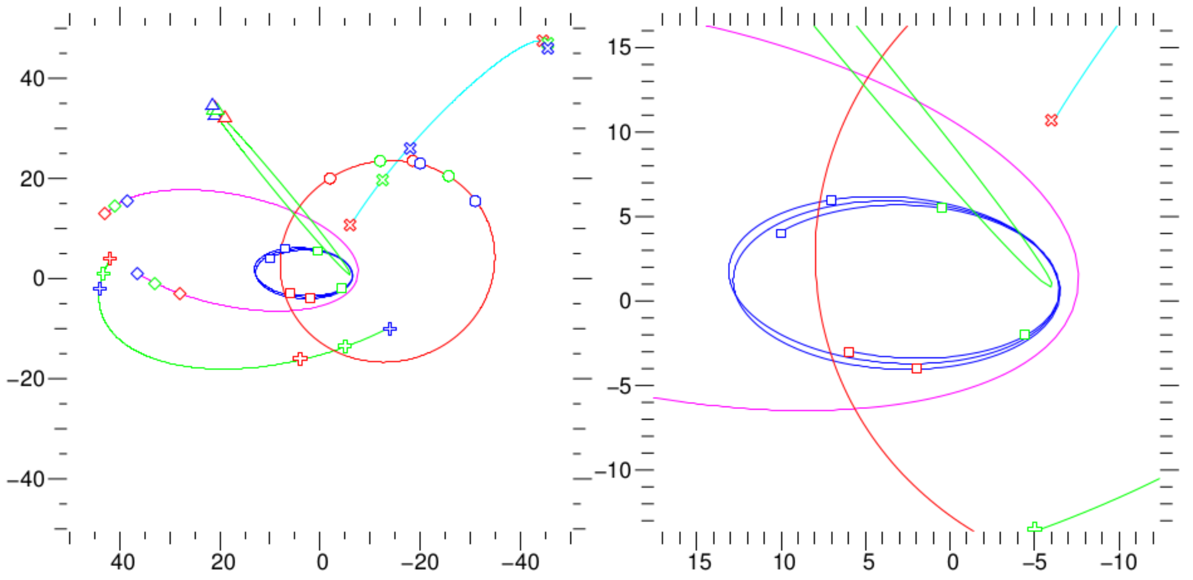
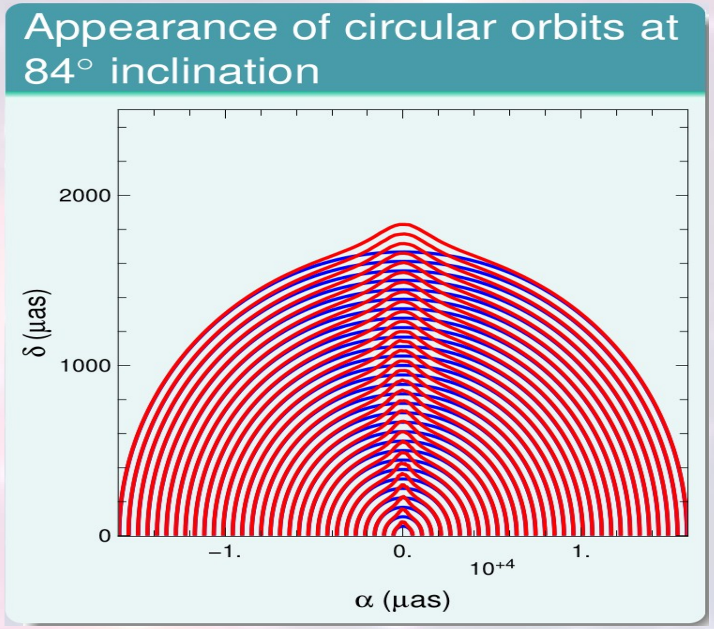
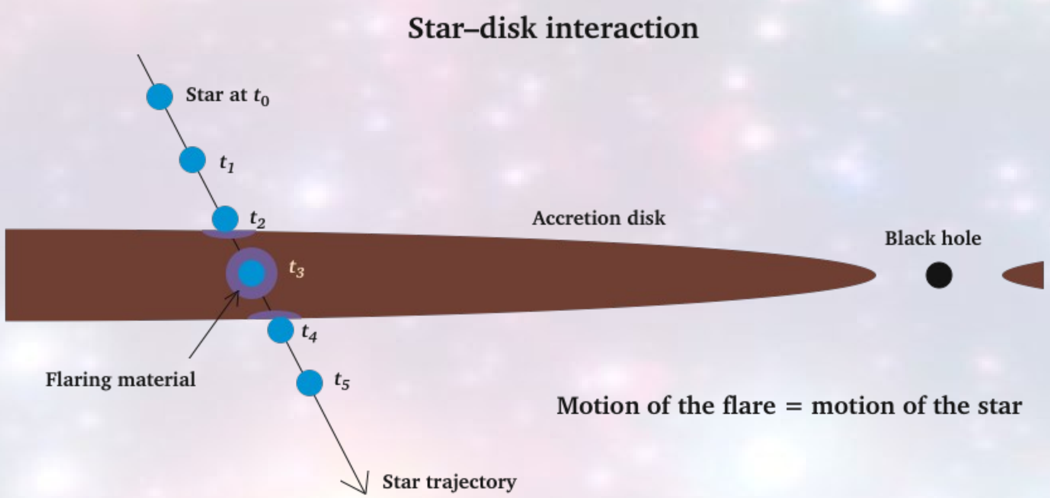
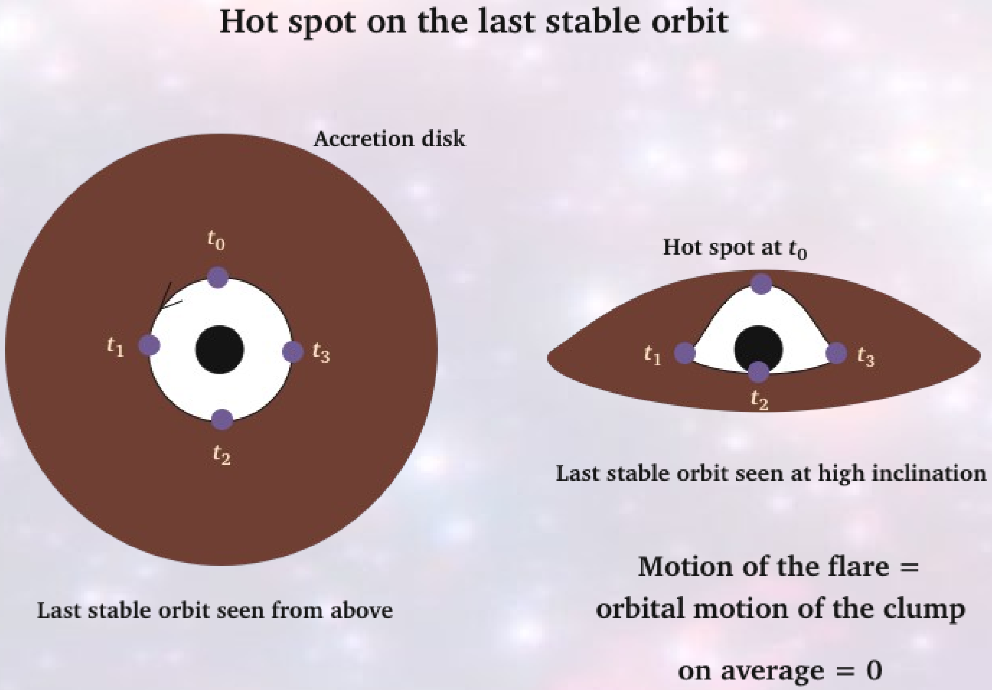


Fig. 2. Orbits of six stars in the relativistic potential well of Sgr A*, over 15 months (axes in mas). The (initial) orbital parameters are those of S-stars, 10 times down-scaled. The symbols represent the crude astrometry retrieved from the simulated observations (brightest pixel on a mas grid): the precession is already significant



Beware of lensing effects
(Grould et al. 2016, 2017)



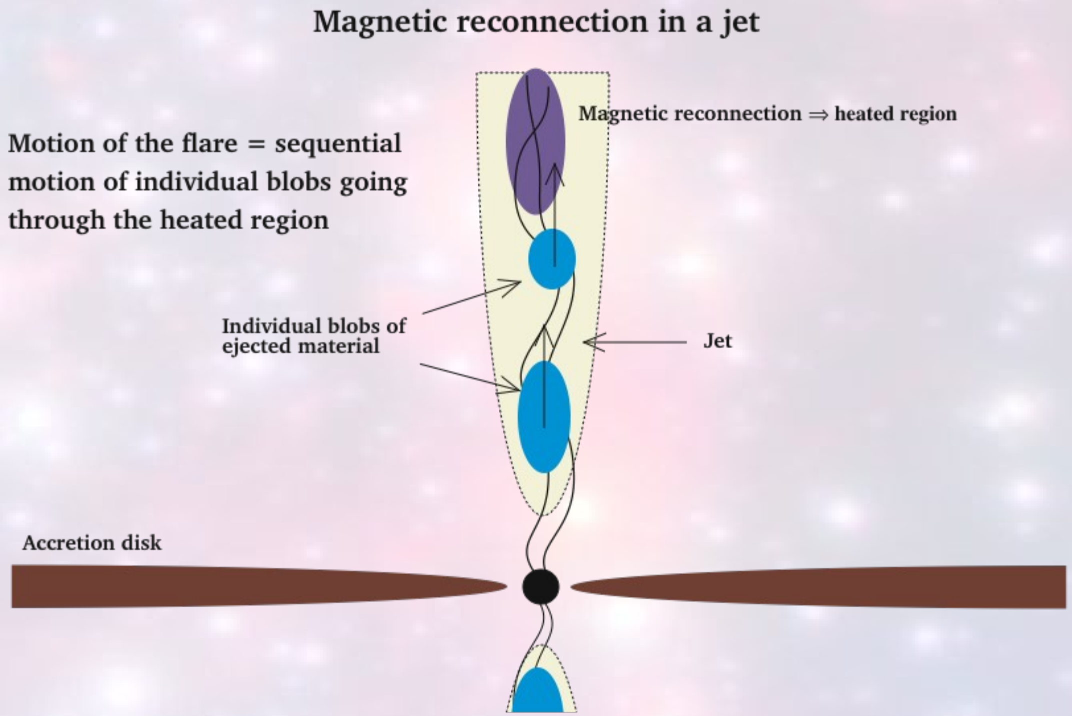


Flares have to be moving at near the speed of light.

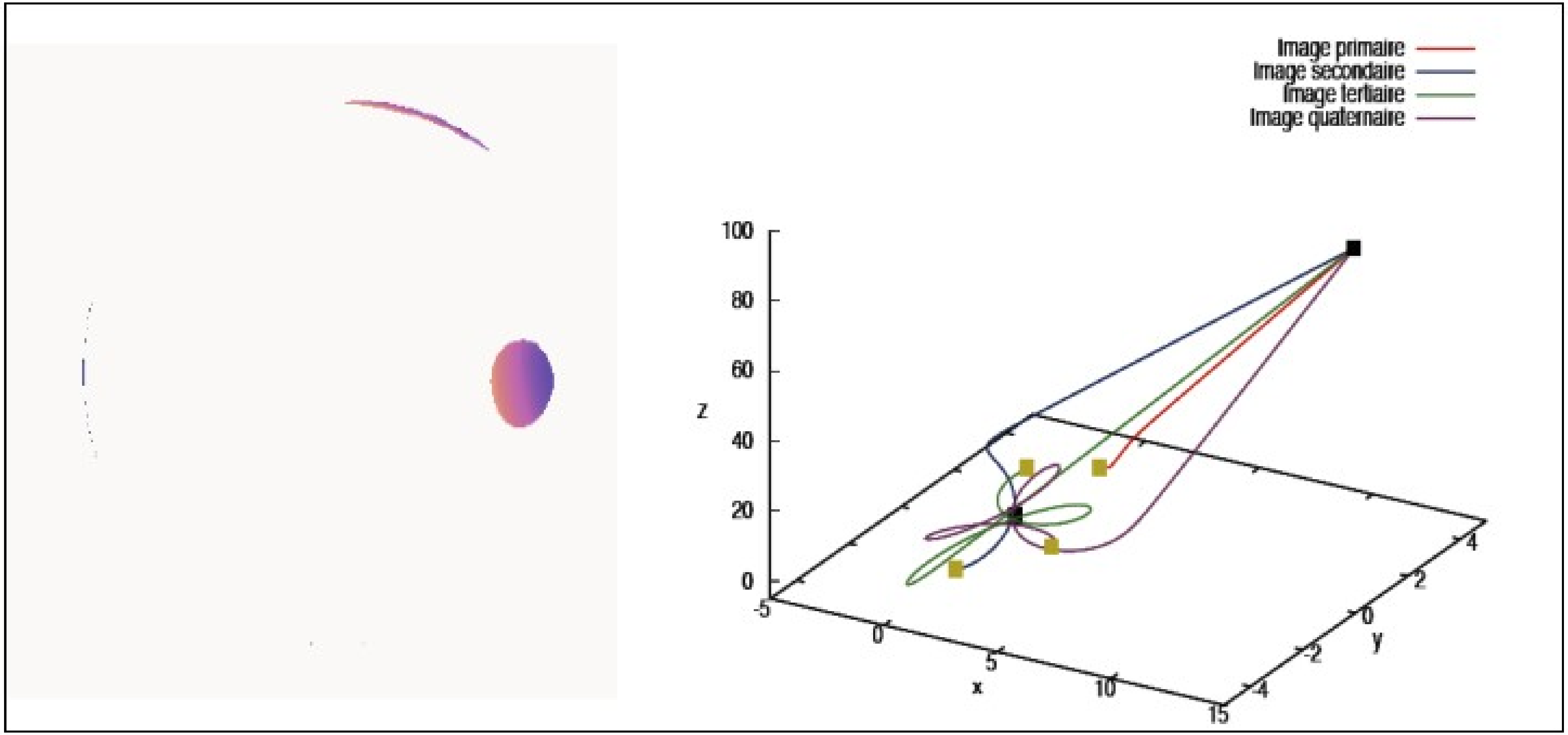
Need an instrument that can measure position at 10 µas within 5 min. Calls for interferometric differential astrometry.

Atmospheric differential piston averages out within minutes for separations near 1”.

In hot spot model, room for lensing effects.

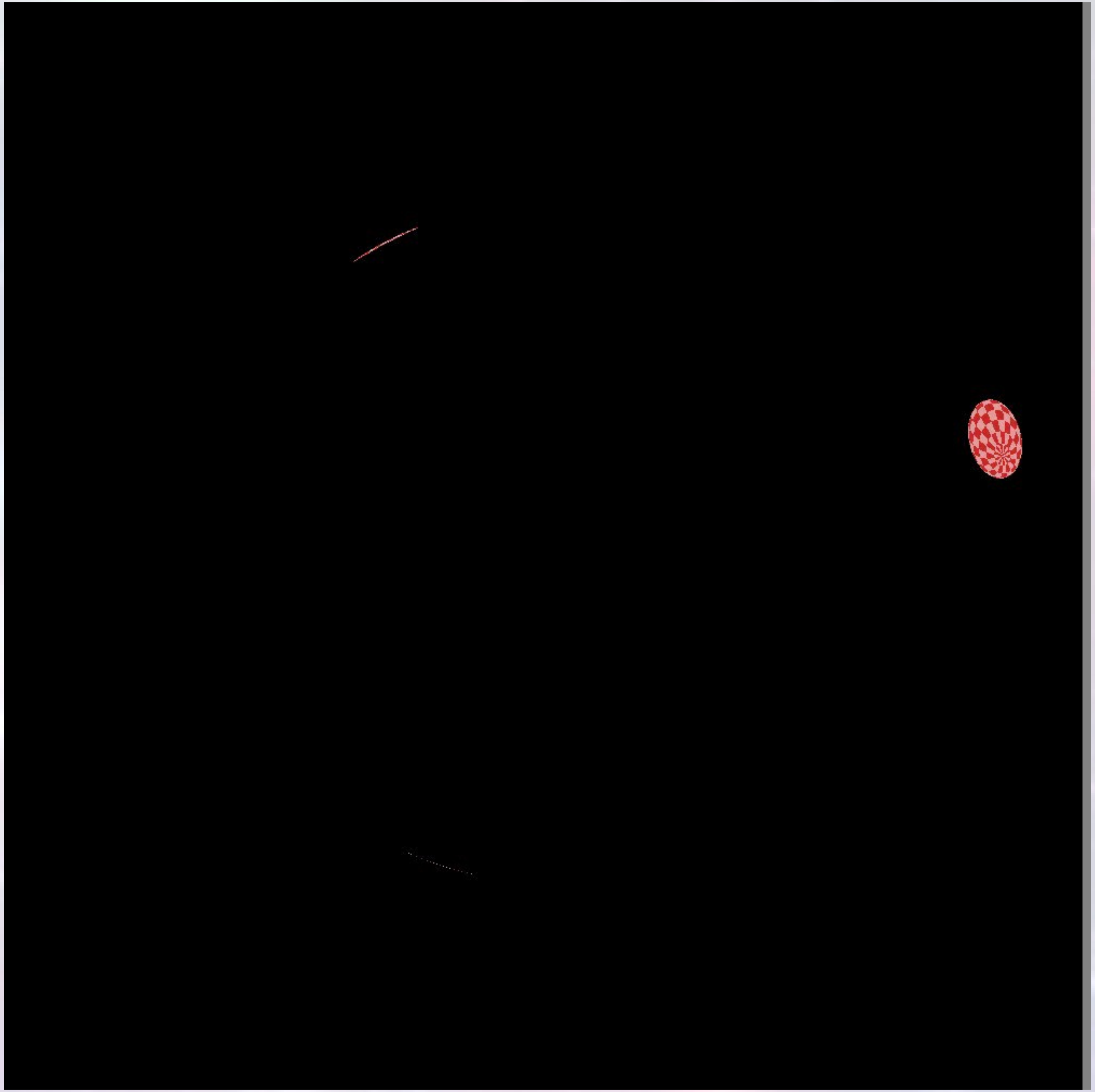


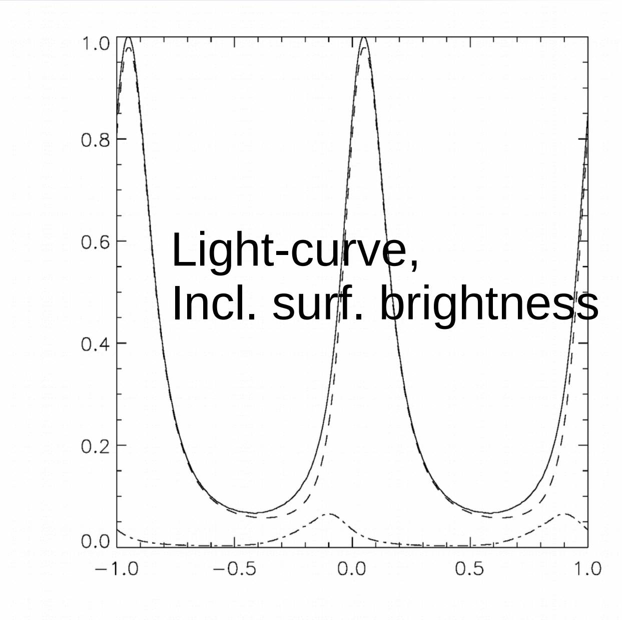
Basics of strong lensing and ray-tracing



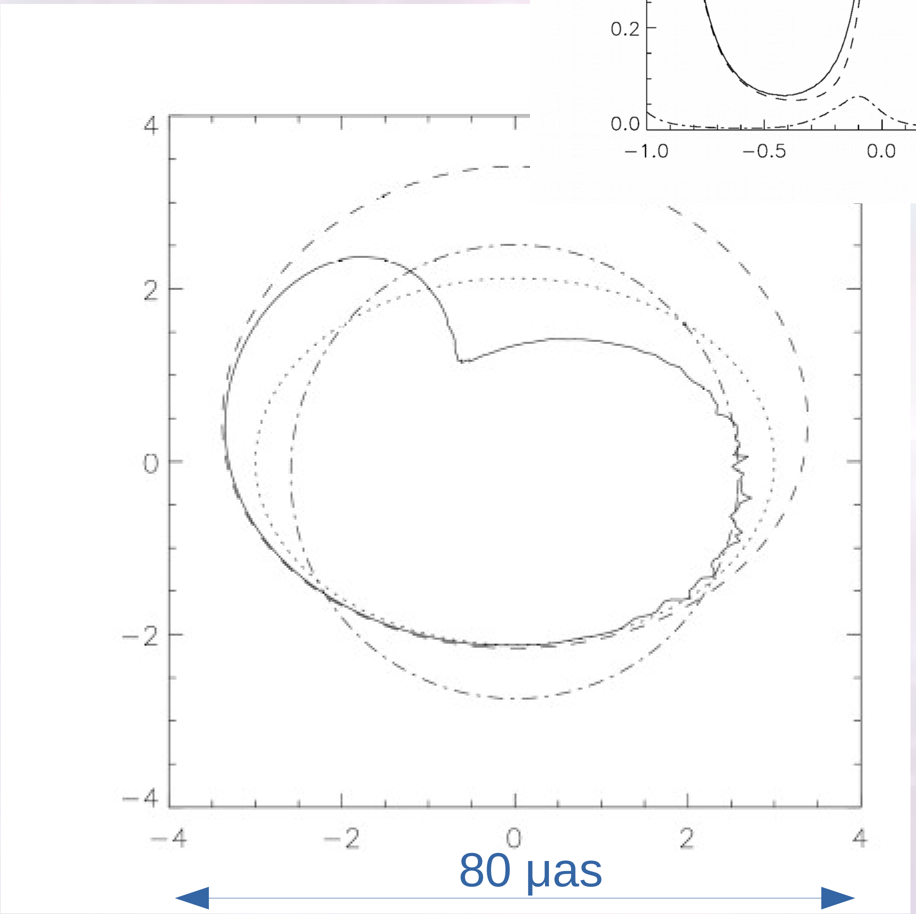
Lensing effects of a moving star on the ISCO with ā=0.9(PhD of Frédéric Vincent).

Orbiting blob on the last stable orbit





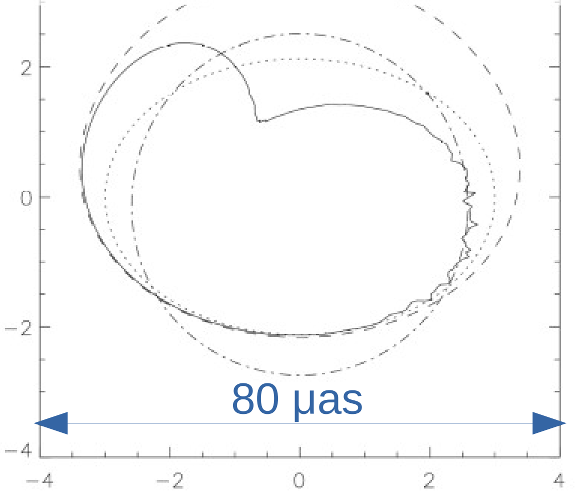
track



- Flat space image of orbit: an ellipse
- Primary image: distorted, enlarged ellipse
- Secondary image: almost a circle
- Image centroid track, lensing only (i.e. uniform apparent surface brightness)
- Image centroid track, incl. beaming and Doppler (color dependent)

Depending on physical and orbital parameters, motion can be detected with a single observation @10µas. Lensing effects require stacking observations together.

Paumard et al. (2005)

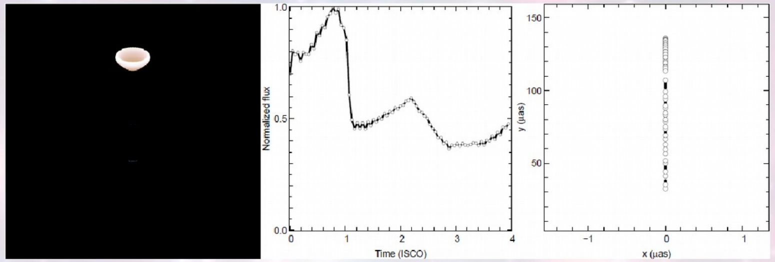


Flares have to be moving at near the speed of light.

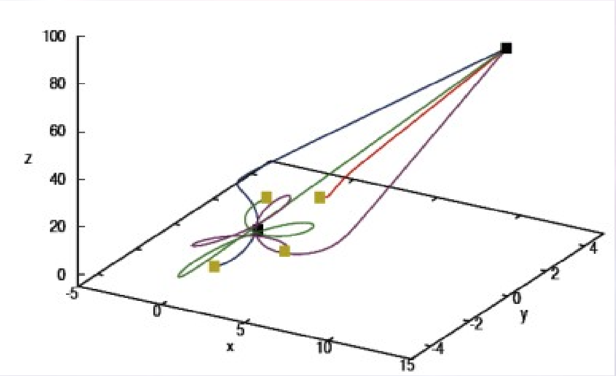
In hot spot model, room for lensing effects.

Need an instrument that can measure position at 10 µas within 5 min. Calls for interferometric differential astrometry.

Ejected plasmon

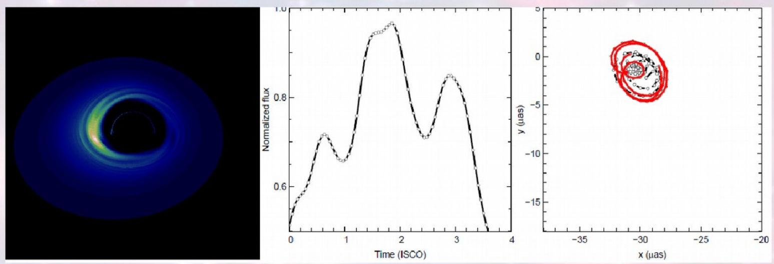


- Like spot-in-jet;
- In jet, not in disk;
- Axial motion.



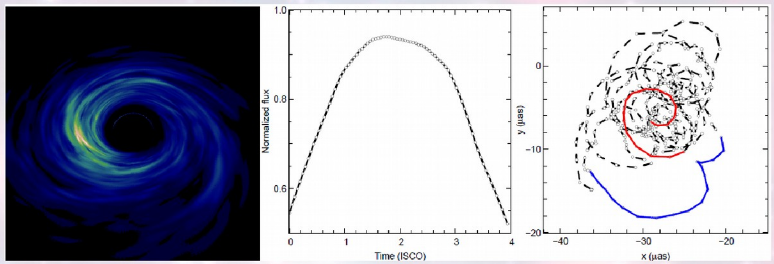
Frédéric Vincent (PhD, 2011)

Rossby wave instability



- Like little-contrasted hot-spot;
- Contained in disk;
- Orbital motion.

Red noise (a.k.a. disk meteorology)



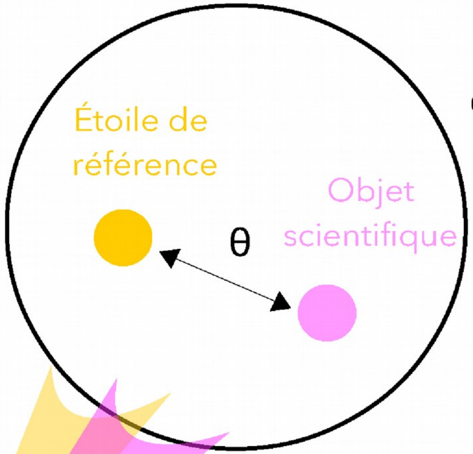
- Like many random hot-spots;
- Contained in disk;
- Orbital motion.

GRAVITY: MPE, LESIA, IPAG, MPIA, UoC, SIM

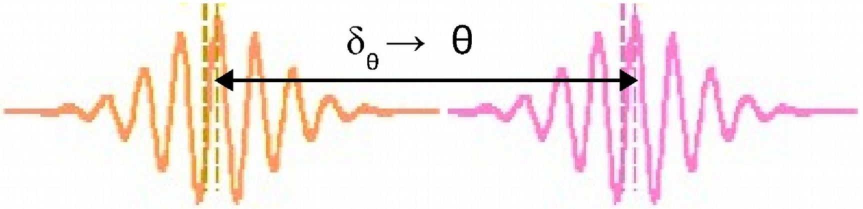
- 2004: first ideas when working on PRIMA reference missions
- 2005: proposed during VLTI workshop
- 2007: successful answer to call-for-proposal
- 2009: preliminary design review
- 2011: final design review
- 2015: preliminary acceptance in Europe + shipment to Paranal
- 2016: science verification
- 2018: S2 peripassage, preliminary acceptance Chile

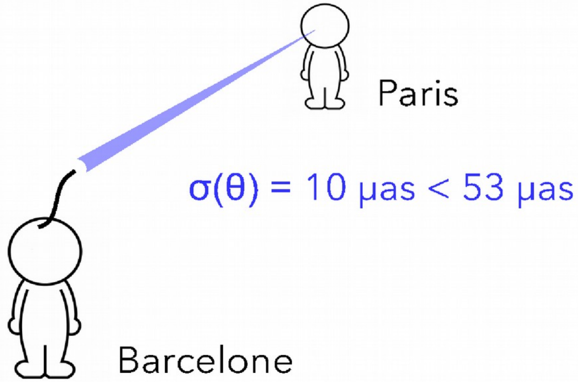
Marion Grould (2016, PhD)

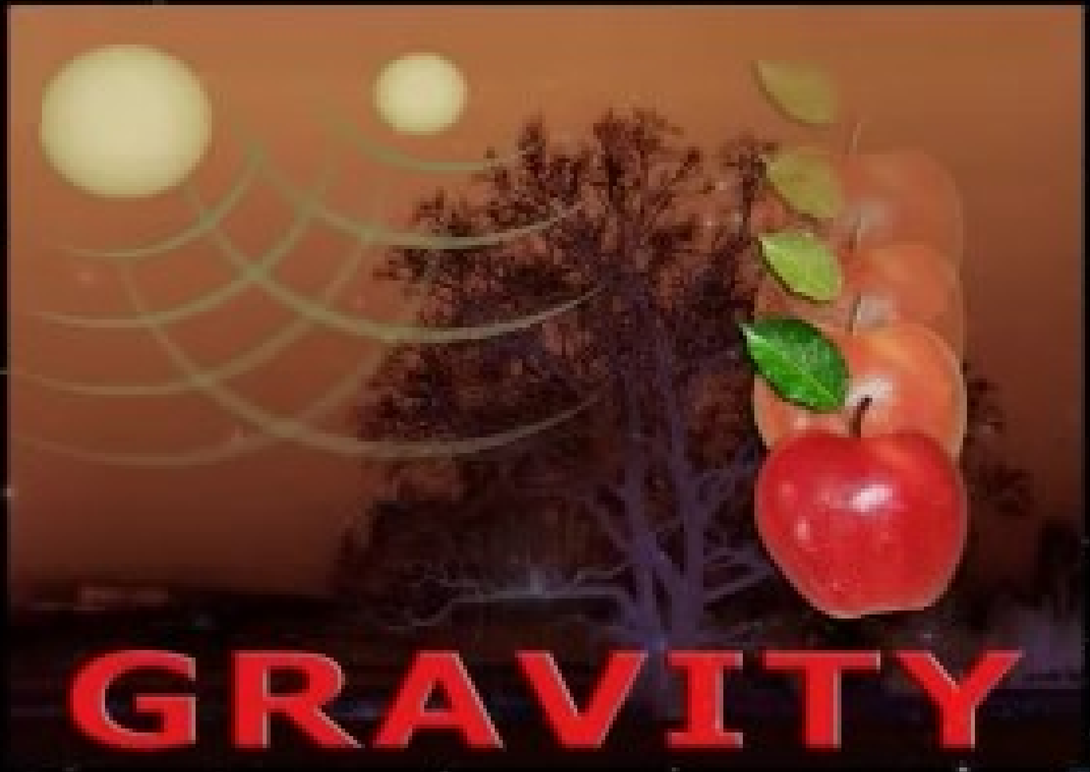
Illustration de la mesure astrométrique avec 2 télescopes



CDV *VLT* = 2''



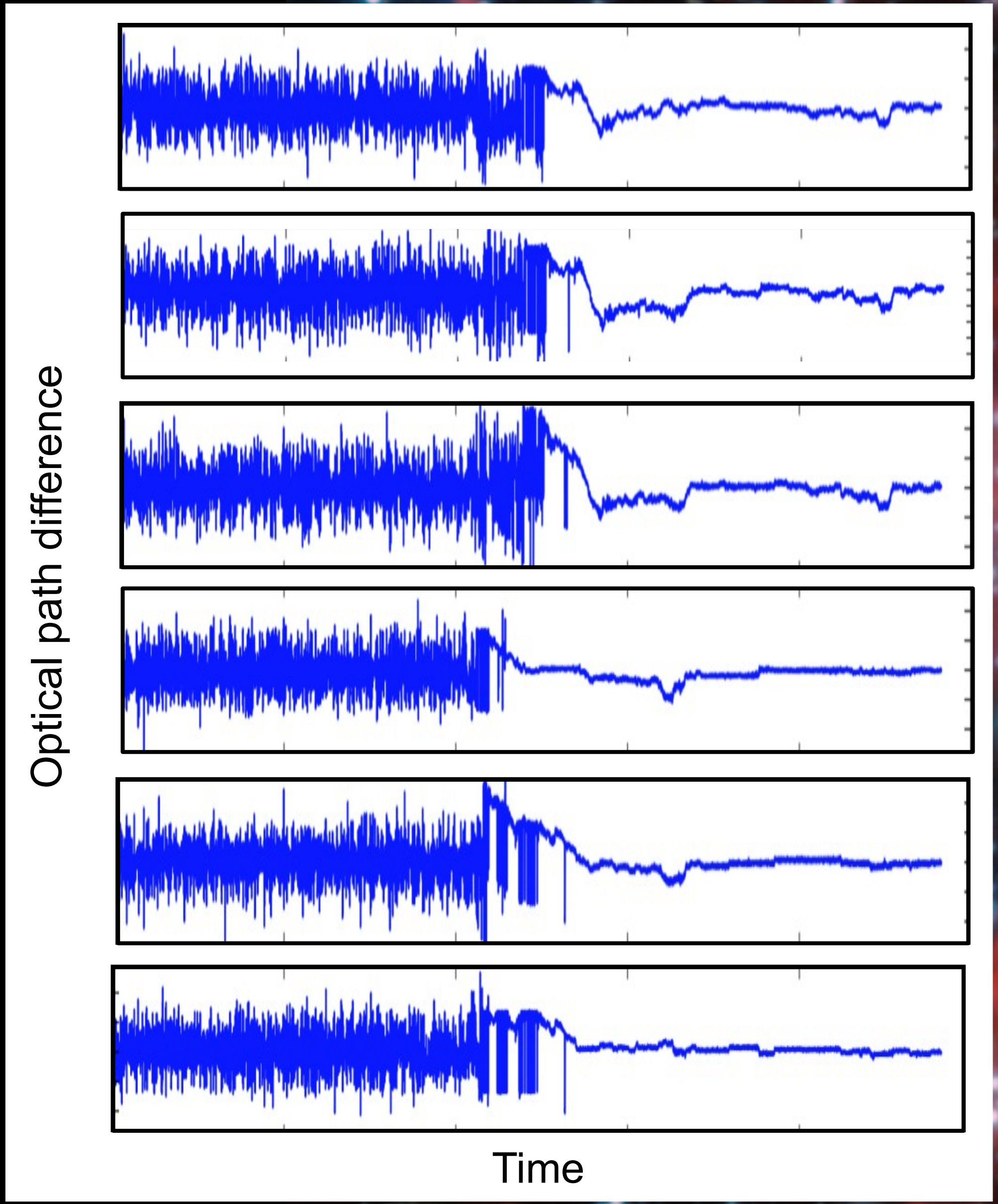


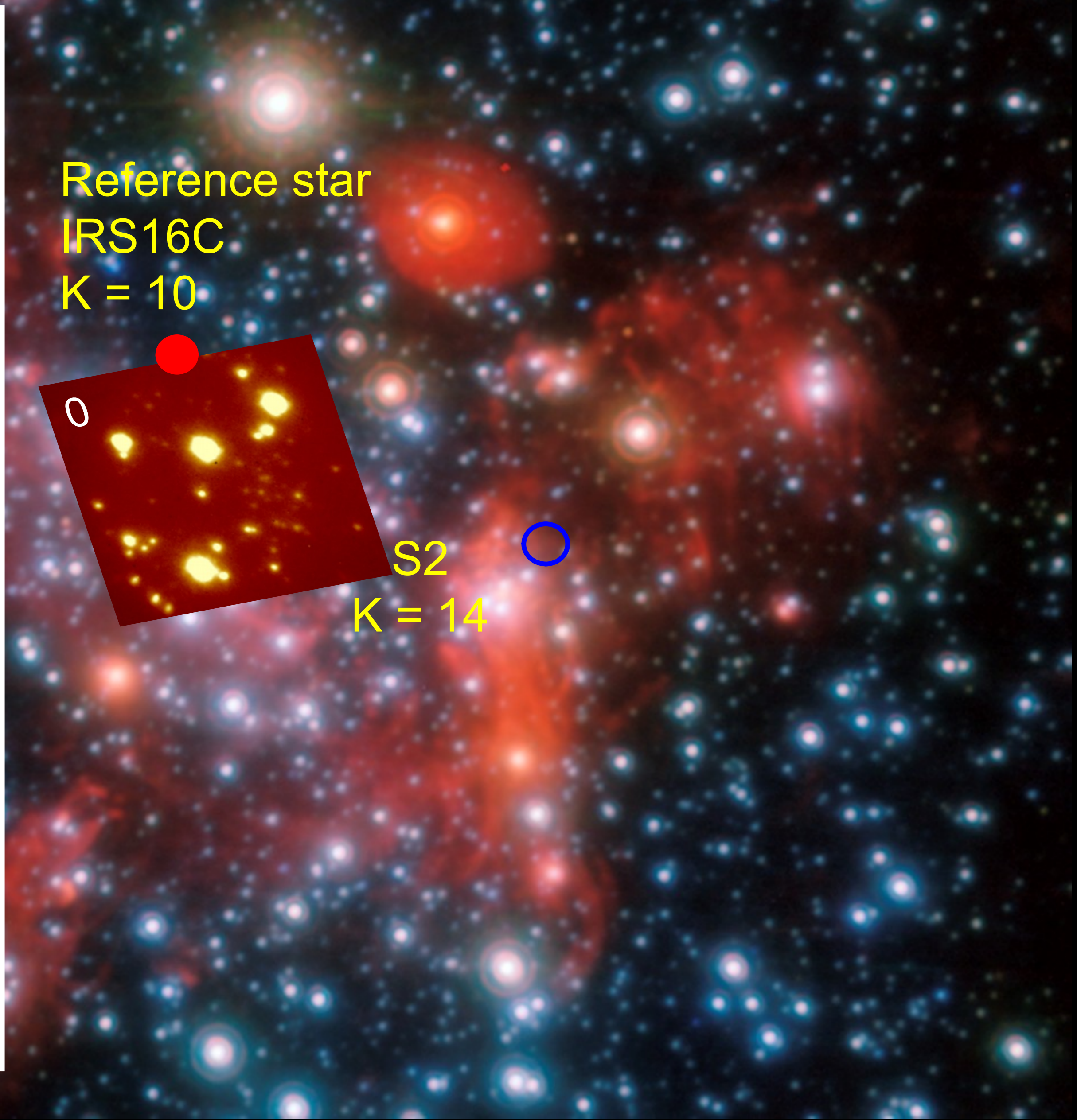

GRAVITY

First Galactic Center observations

(17 May 2016)

Fringe tracking on IRS16C (λ/10 rms)





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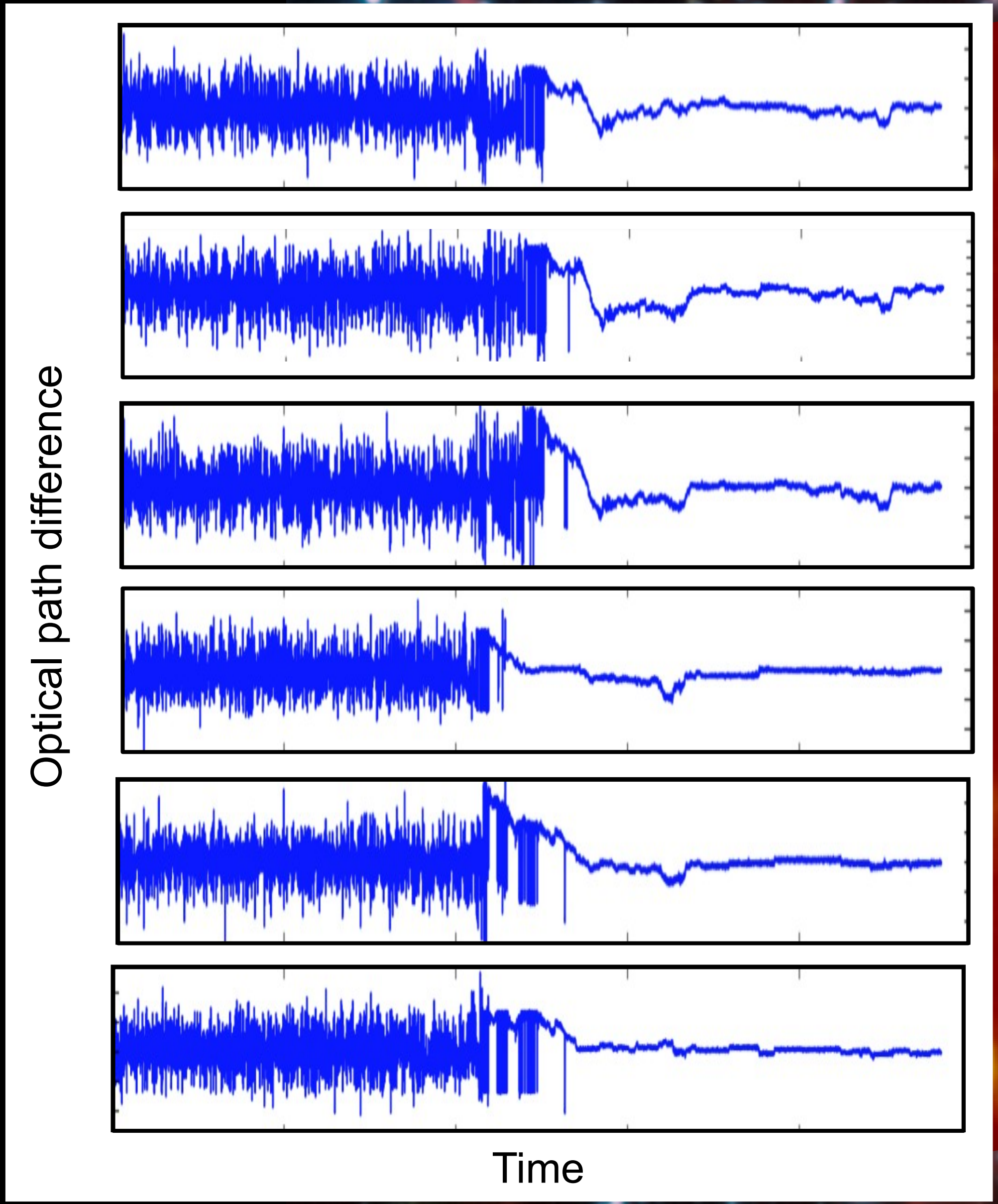
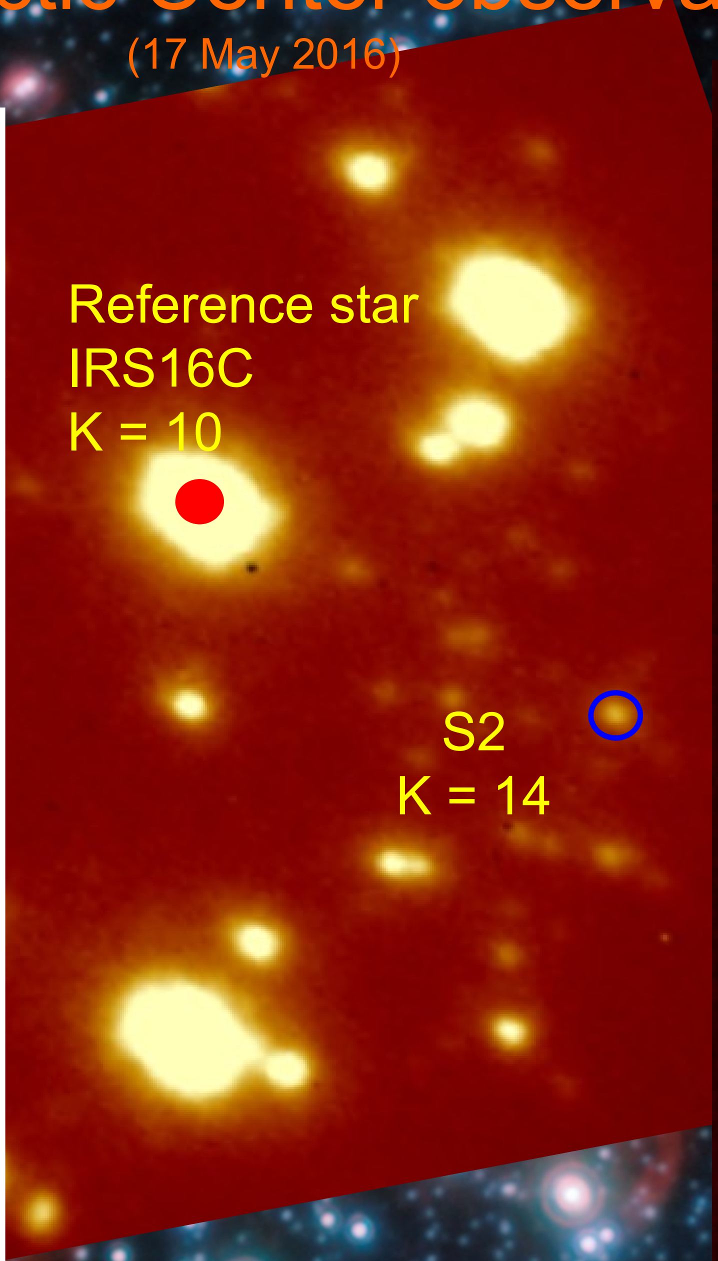
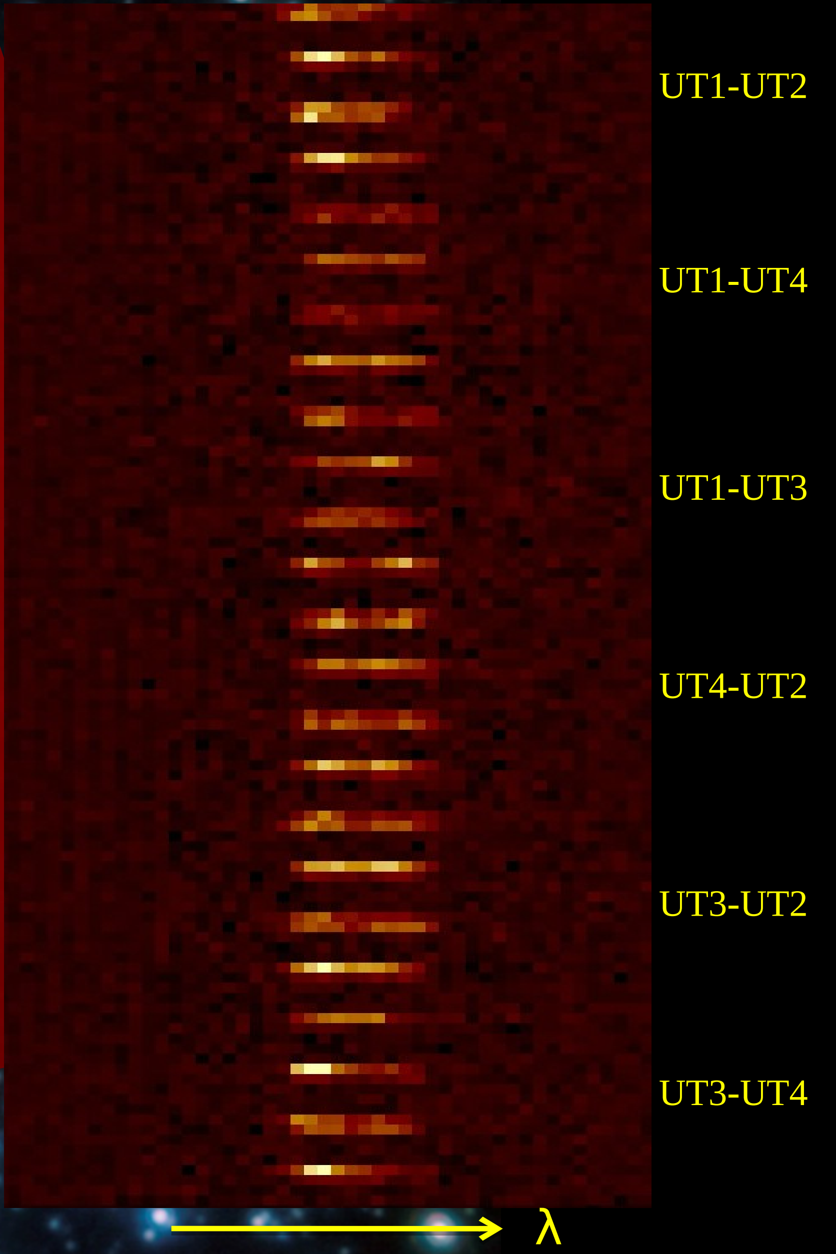
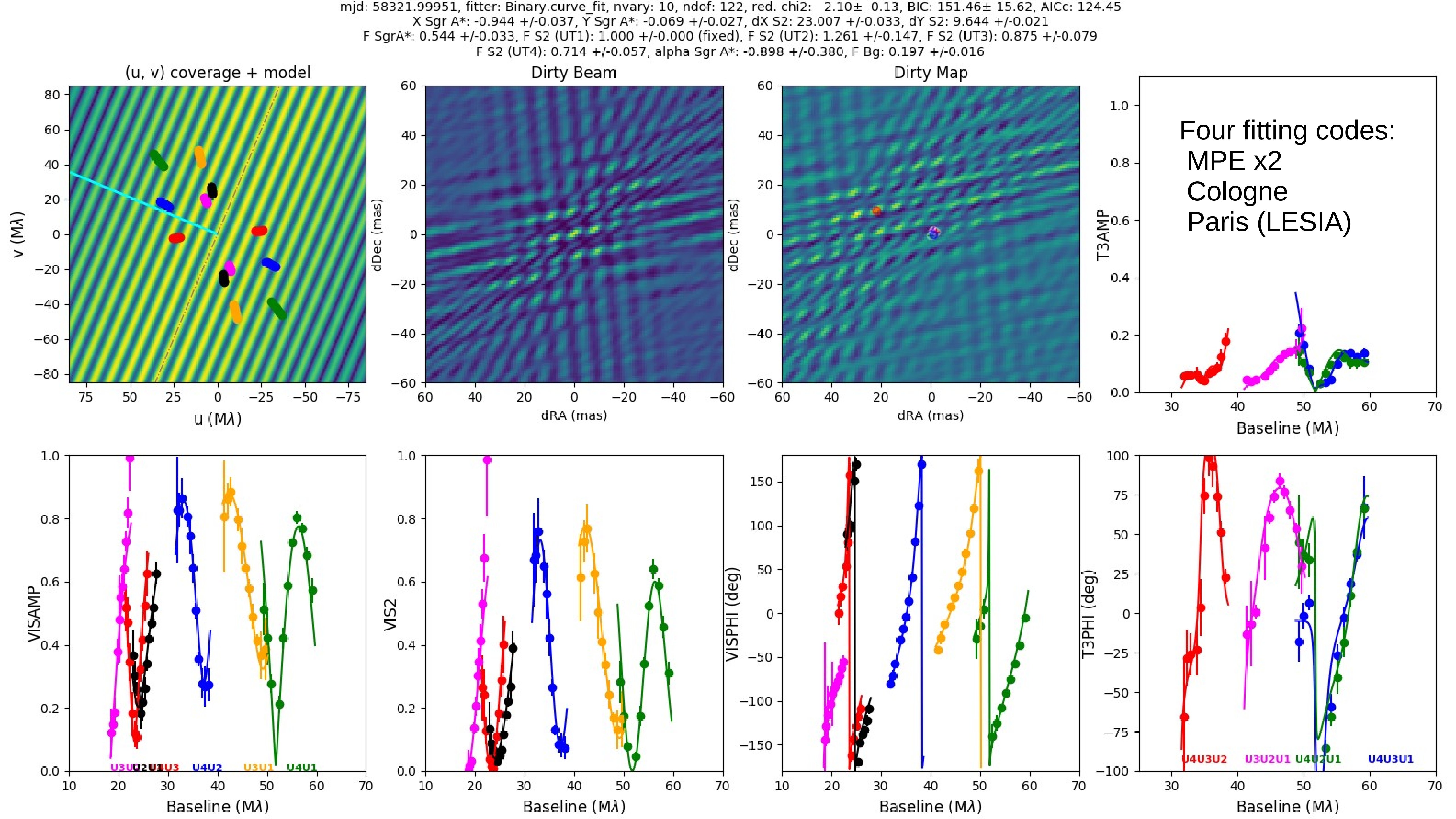
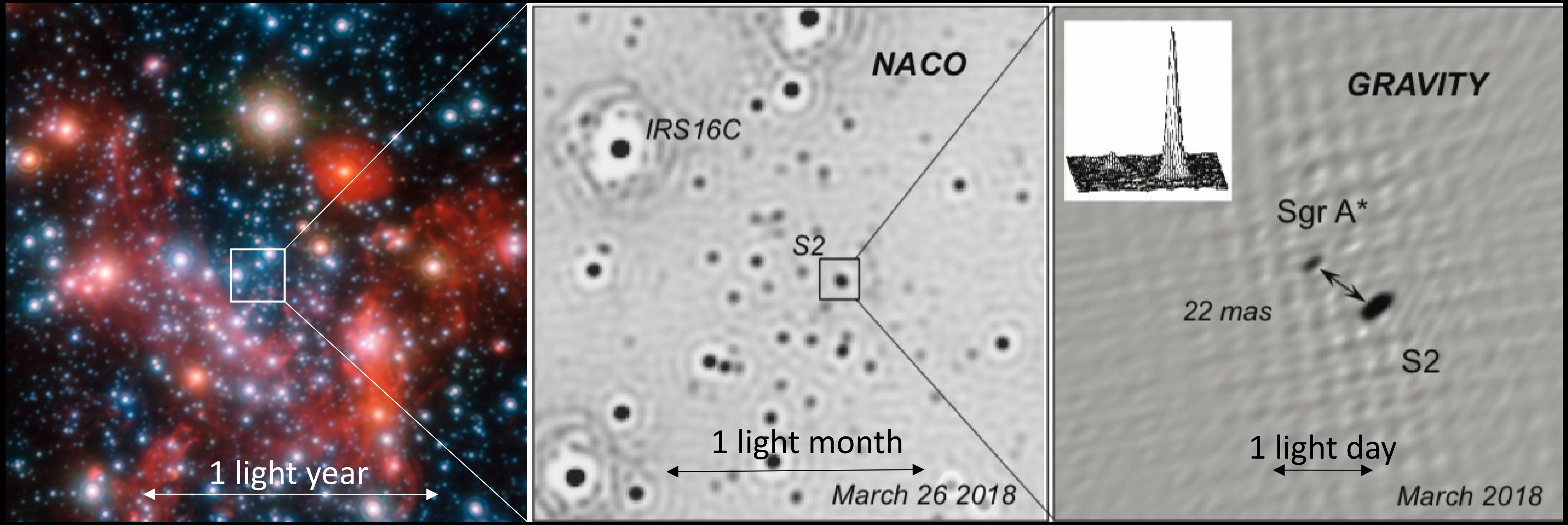




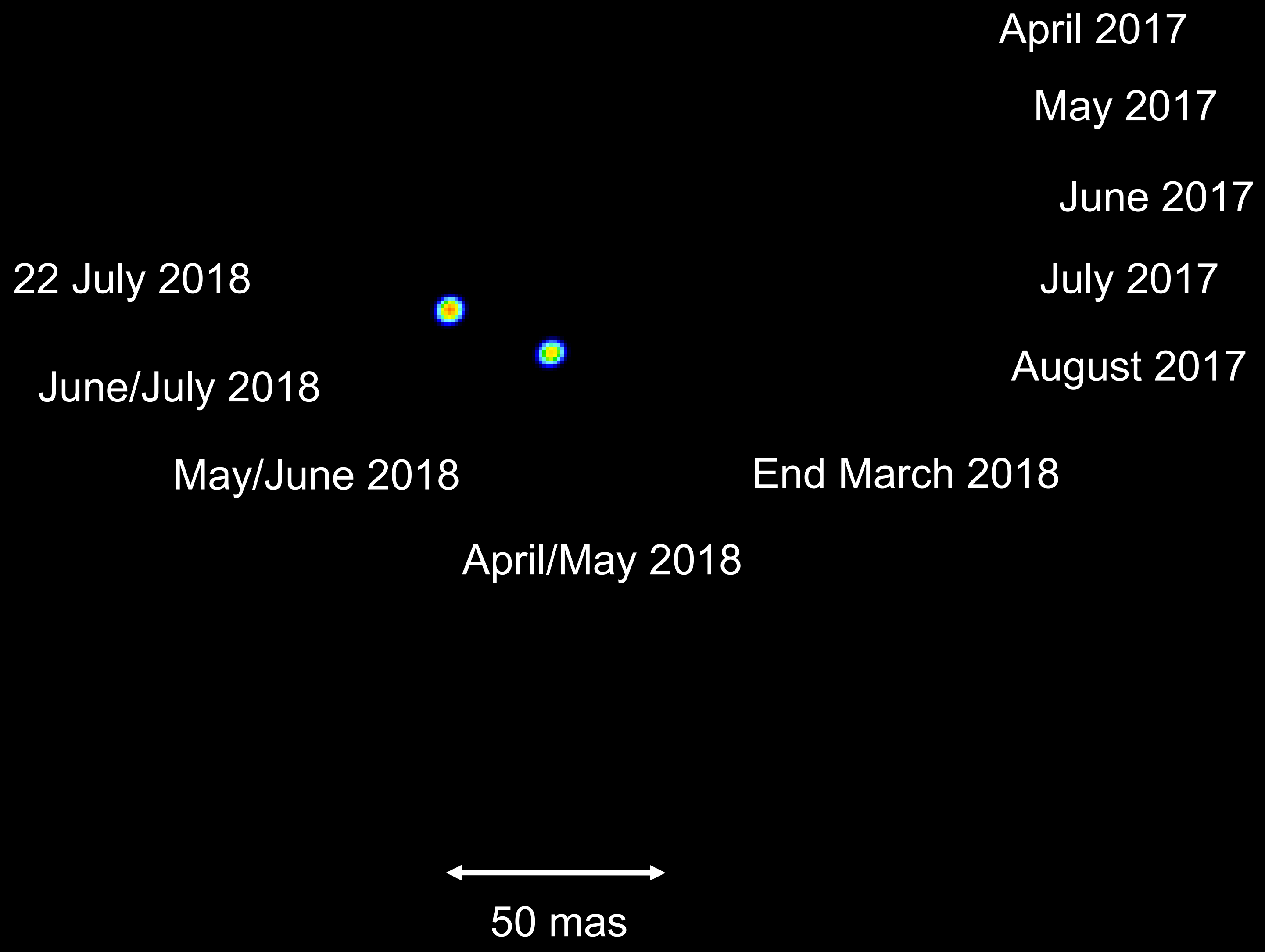



mjd: 58321.99951, fitter: Binary.curve_fit, nvary: 10, ndof: 122, red. chi2: 2.10± 0.13, BIC: 151.46± 15.62, AICc: 124.45
X Sgr A*: -0.944 +/-0.037, Y Sgr A*: -0.069 +/-0.027, dX S2: 23.007 +/-0.033, dY S2: 9.644 +/-0.021
F SgrA*: 0.544 +/-0.033, F S2 (UT1): 1.000 +/-0.000 (fixed), F S2 (UT2): 1.261 +/-0.147, F S2 (UT3): 0.875 +/-0.079
F S2 (UT4): 0.714 +/-0.057, alpha Sgr A*: -0.898 +/-0.380, F Bg: 0.197 +/-0.016
(u, v) coverage + model
v (Mλ)
u (Mλ)
Dirty Beam
dDec (mas)
dRA (mas)
Dirty Map
dDec (mas)
dRA (mas)
Four fitting codes:
MPE x2
Cologne
Paris (LESIA)
T3AMP
Baseline (Mλ)
VISAMP
Baseline (Mλ)
VIS2
Baseline (Mλ)
VISPHI (deg)
Baseline (Mλ)
T3PHI (deg)
Baseline (Mλ)
U4U3U2
U3U2U1
U4U2U1
U4U3U1
U4U2
U3U1
U4U1

Zooming in with GRAVITY

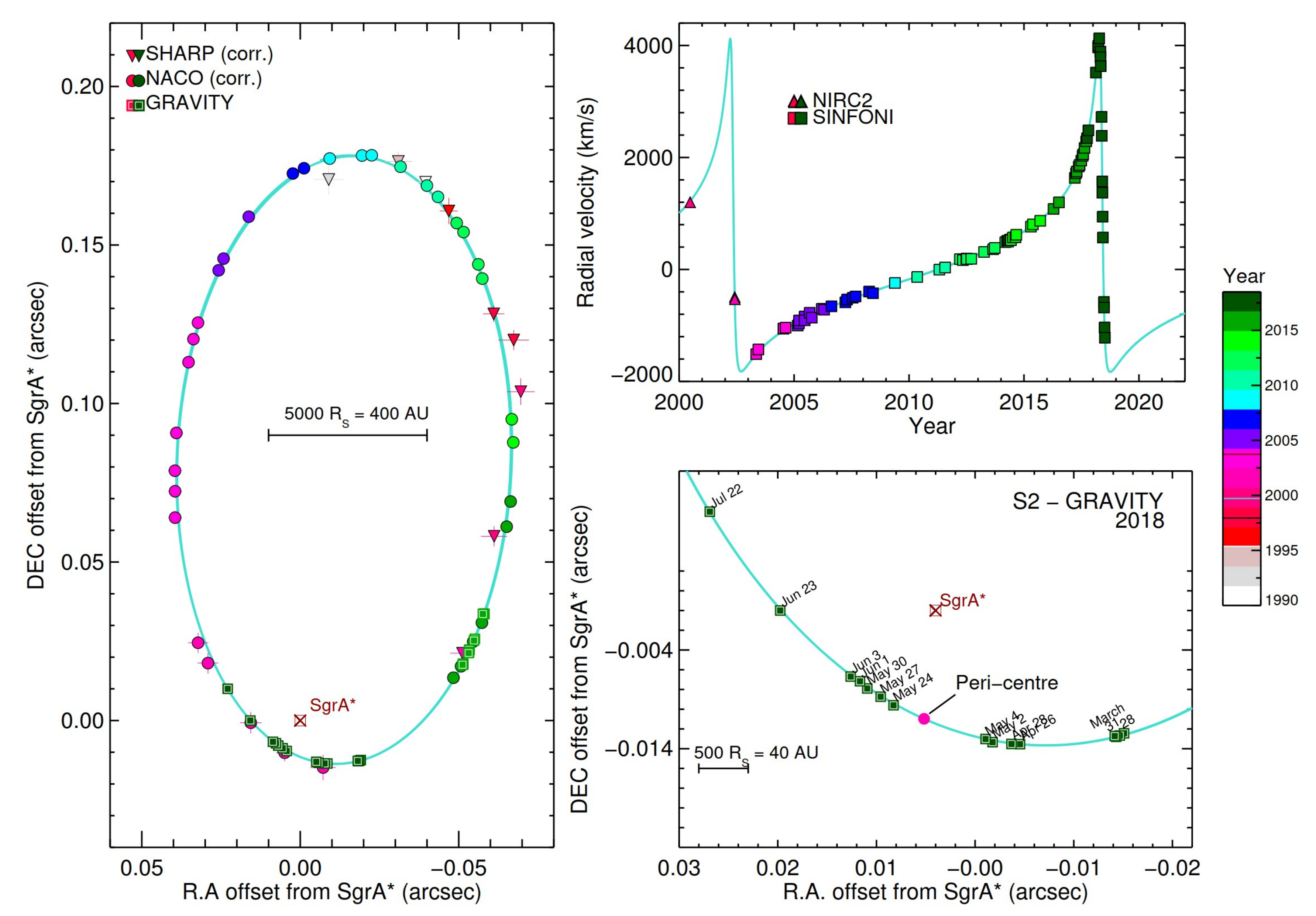


Routine Faint Milli-arcsec Imaging with GRAVTIY



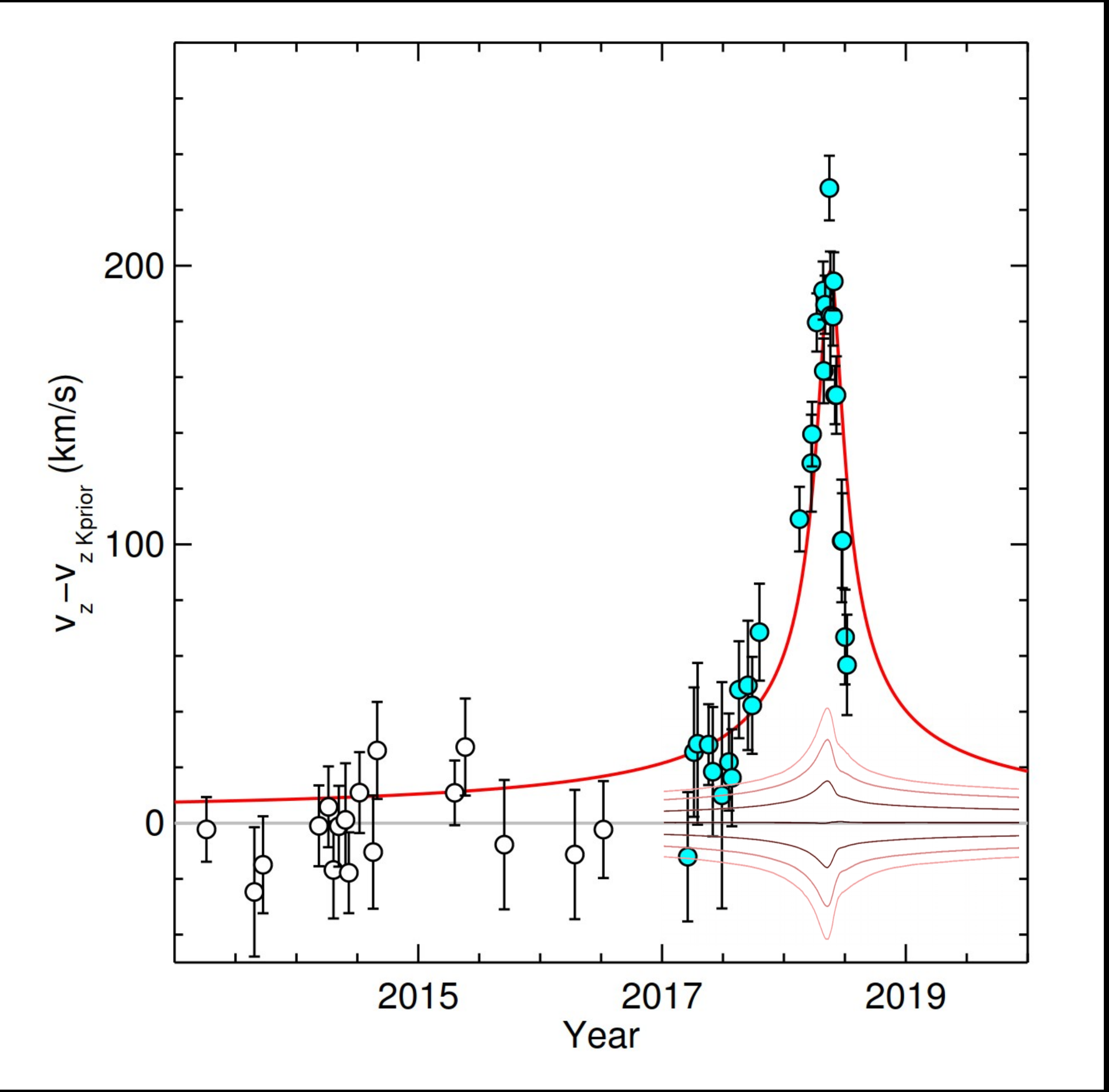
GRAVITY collaboration+18

Gravitational Redshift in S2 Orbit



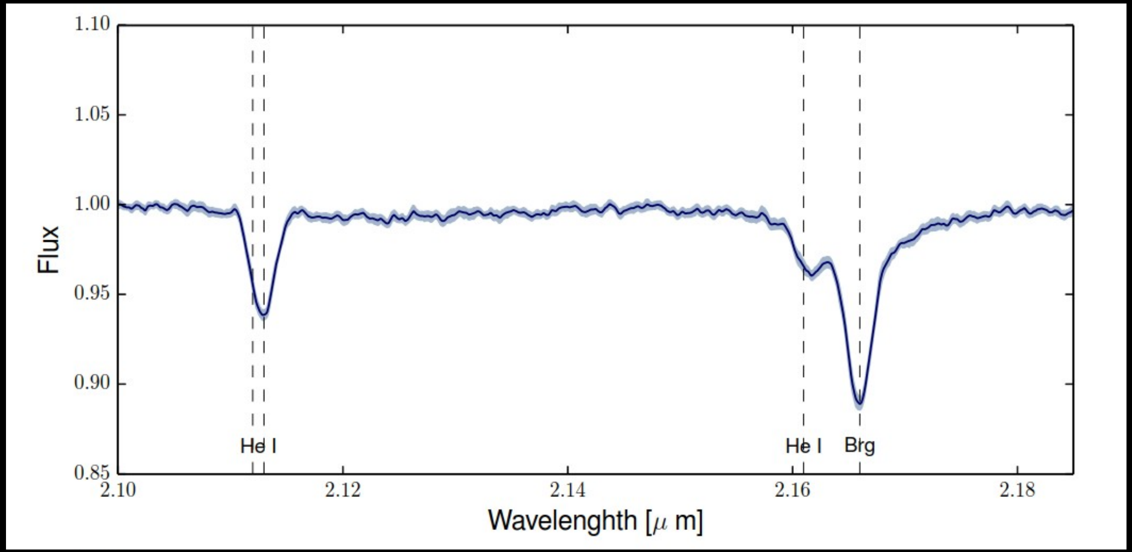
GRAVITY collaboration+18

A Priori Analysis



GRAVITY collaboration+18

GRAVITY + High SNR spectroscopy



Habibi+17

Measured radial velocities - Kepler fit to data excluding 2017/18 radial velocities

⟶ Excludes prior Newtonian orbit

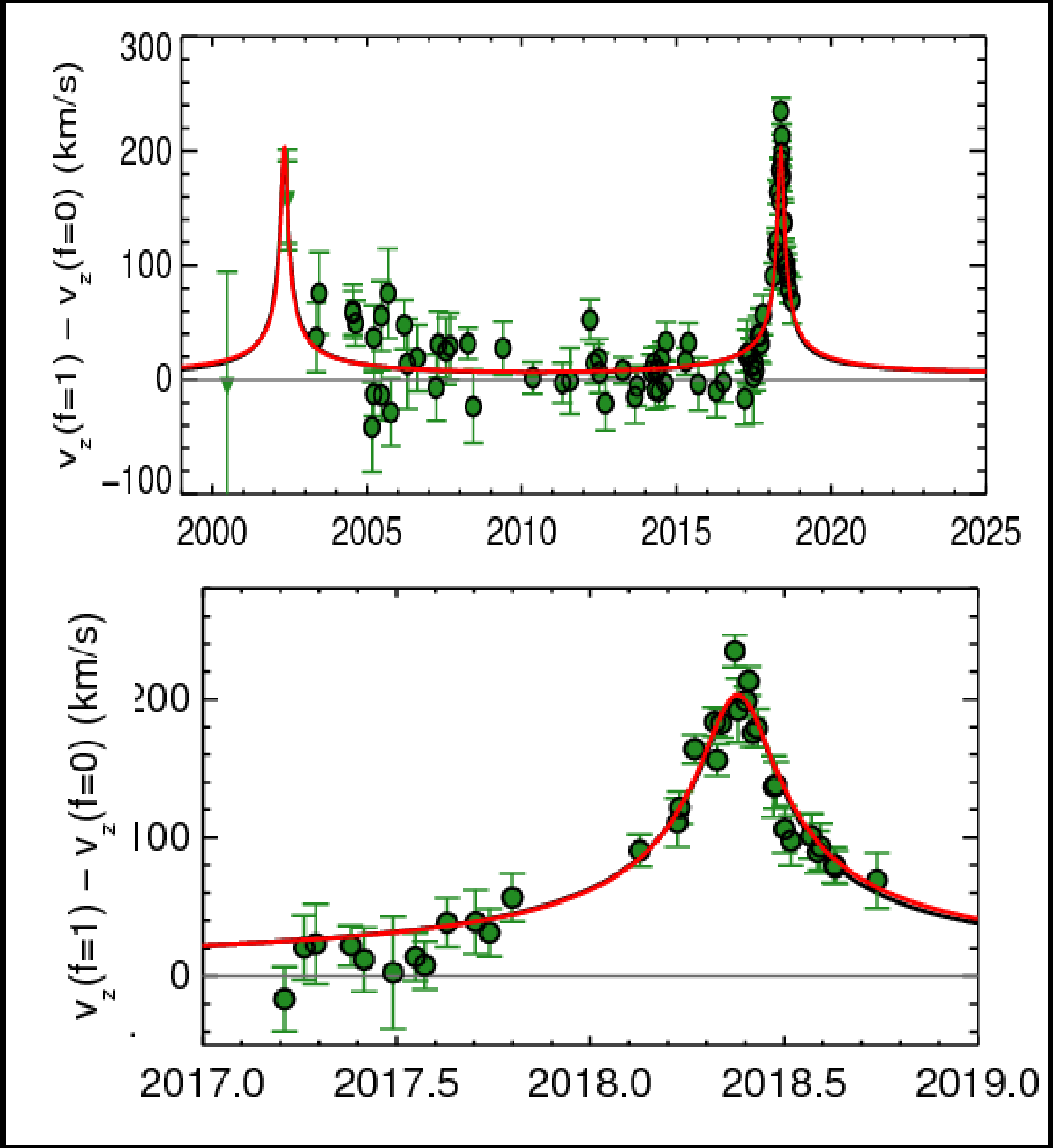
Uncertainty of the radial velocity prediction

Still possible to fit reasonable Keplerian orbit a posteriori → require exquisite astrometry

A Posteriori Analysis: Parameterizing ß² Term with Parameter *f*

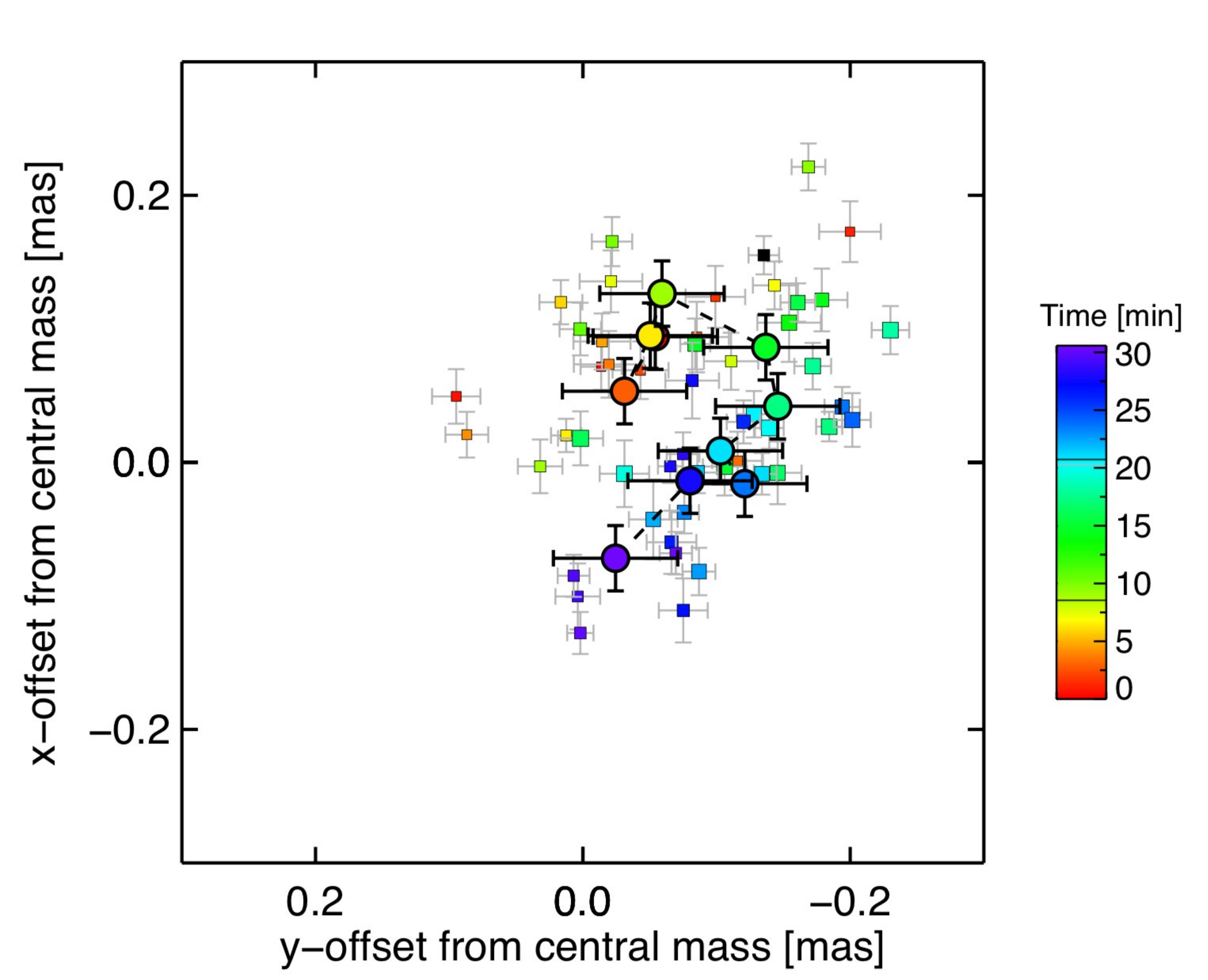
f = 0: Newton
f = 1: General Relativity

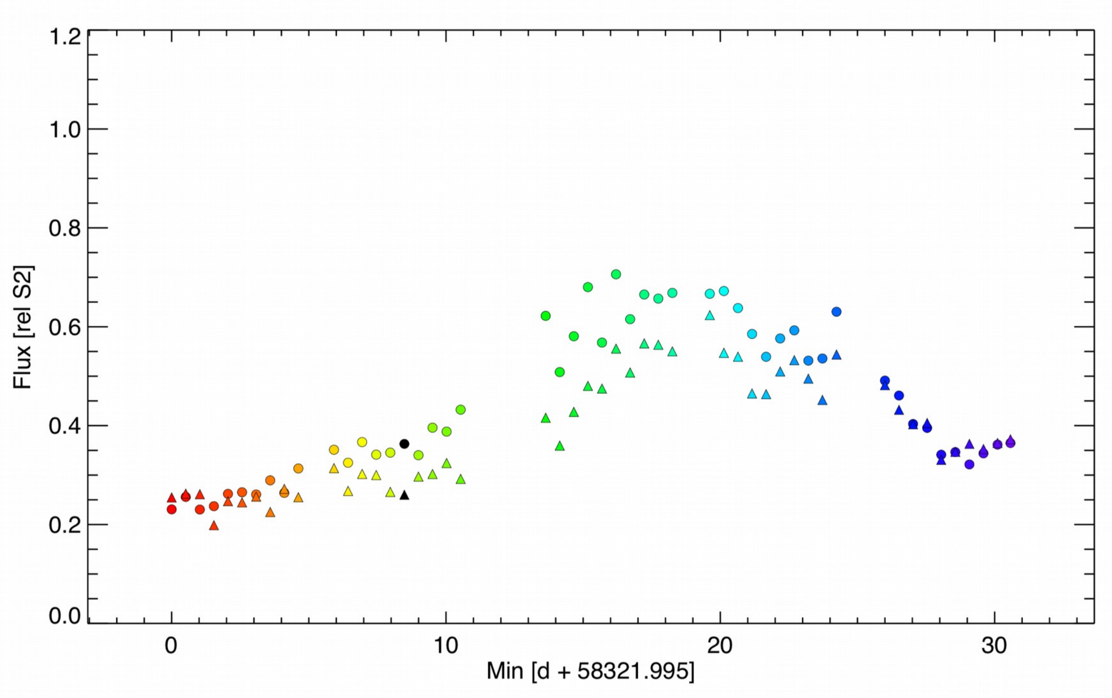
→ f = 1.027±0.044
Kepler/Newton is excluded at >20 σ

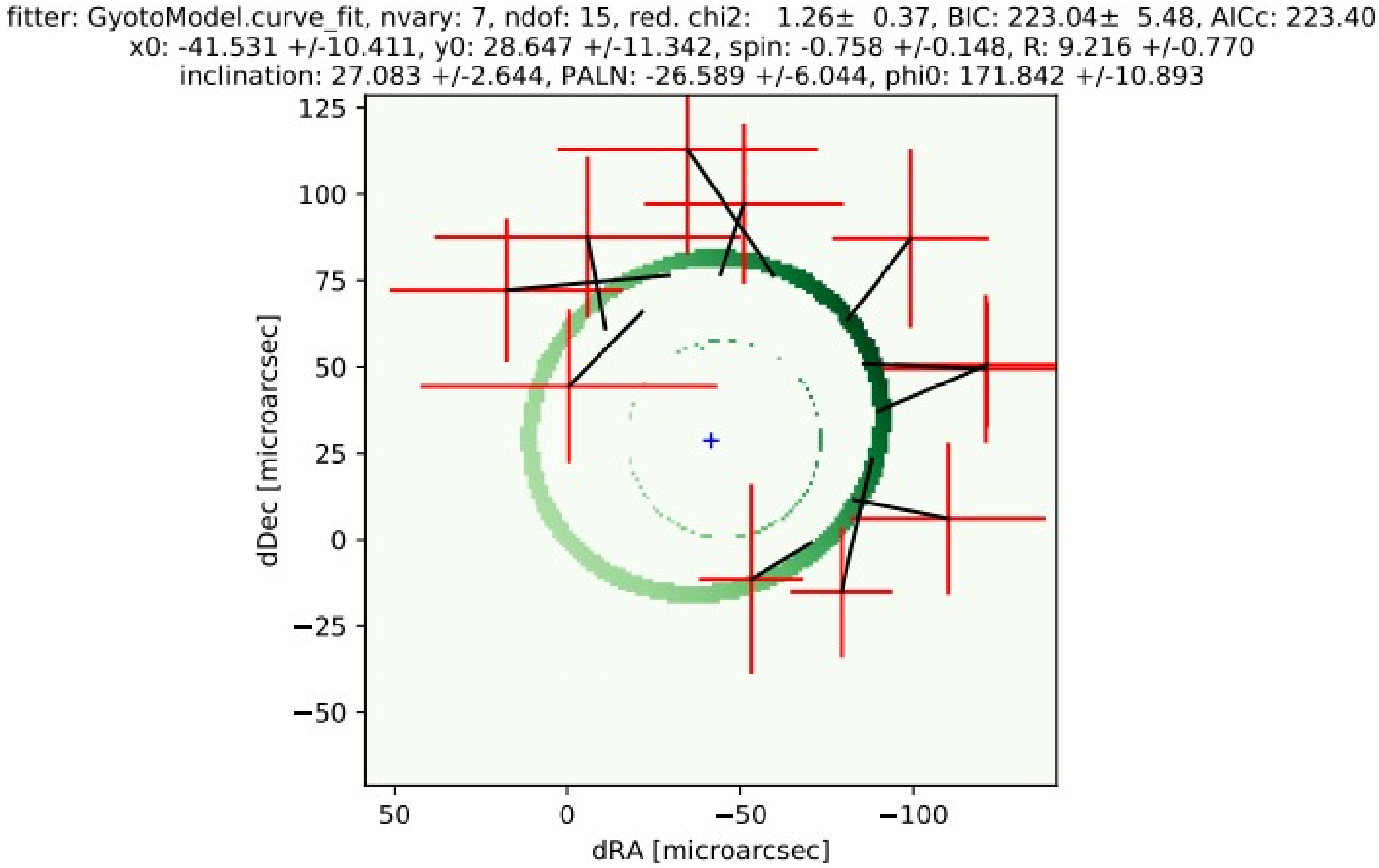


GRAVITY collaboration+18

July 22 flare

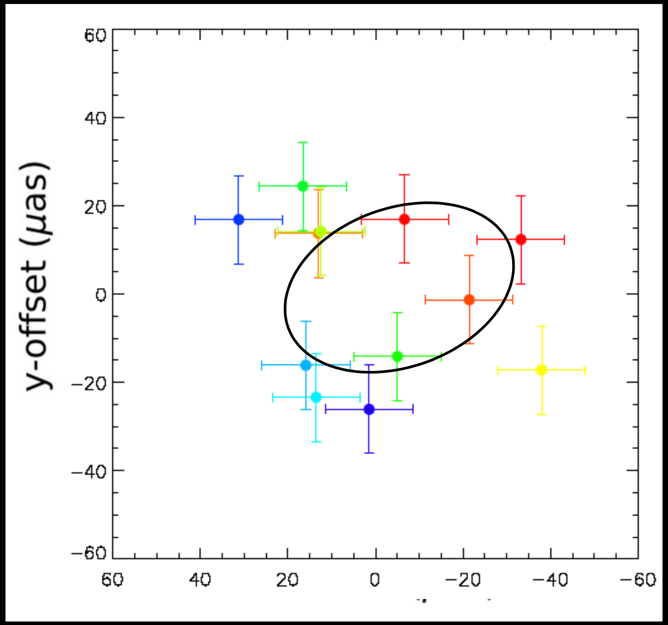




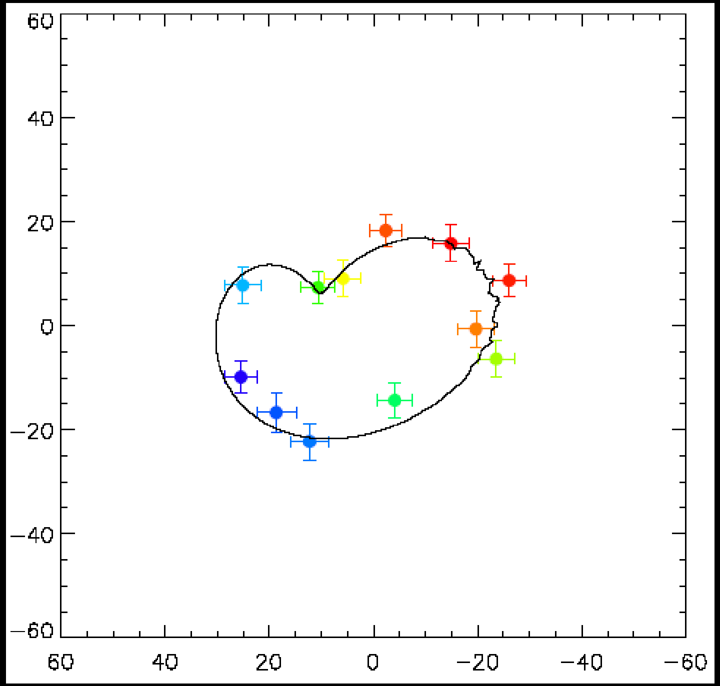

fitter: GyotoModel.curve_fit, nvary: 7, ndof: 15, red. chi2: 1.26± 0.37, BIC: 223.04± 5.48, AICc: 223.40
x0: -41.531 +/-10.411, y0: 28.647 +/-11.342, spin: -0.758 +/-0.148, R: 9.216 +/-0.770
inclination: 27.083 +/-2.644, PALN: -26.589 +/-6.044, phi0: 171.842 +/-10.893
125
100
75
50
25
0
−25
−50
dDec [microarcsec]
50
0
−50
−100
dRA [microarcsec]

Future: Probing the spin with GRAVITY

Model from 2005,
Data from 2018,
single flare



Model from 2005,
co-adding flares:



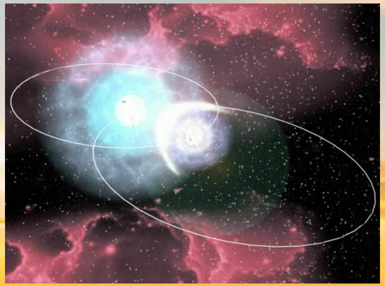
- Improve precision
- “Coherently” add flares
- Super flare
- Is there a zoo of flares?

GRAVITY is Truly Exceptional

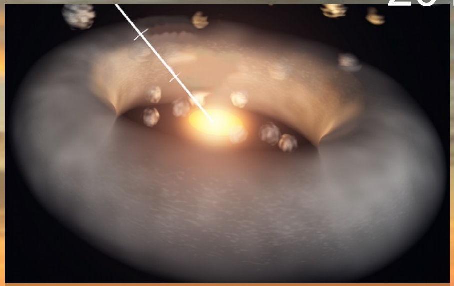
GRAVITY collaboration
2018d, Nature, accepted

GRAVITY collaboration
2018, A&A, accepted
arXiv180802141G

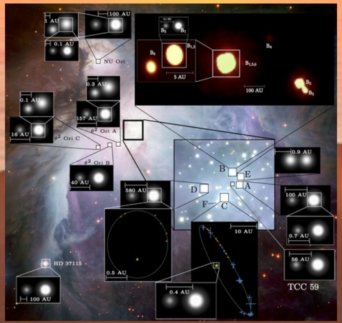
2



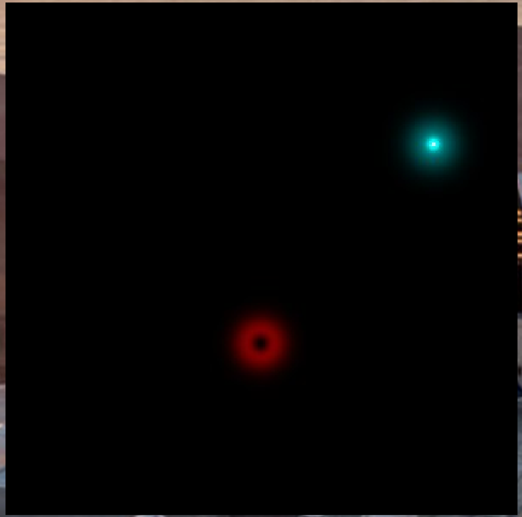
^{2} collecting
area



s

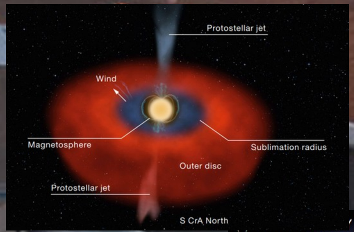


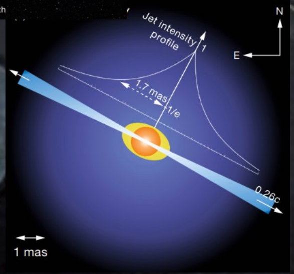
2 x 4 milli-arcsec
resolution imaging



Micro-acrsec

astrometry





19+ mag limiting
magnitude

GRAVITY collaboration
2018, A&A, accepted
arXiv180910376G

<50 μas imaging
astrometry

70 km/s spectral
resolution
spectroscopy

GRAVITY collaboration
2017, A&A, 602L, 11

GRAVITY collaboration
2018, A&A, accepted

Credit: ESO, Huedepohl