GRAVITY: first results on Sgr A*
(thanks to PNHE & PNGRAM!)

Semaine de l'astrophysique française 2019

Nice

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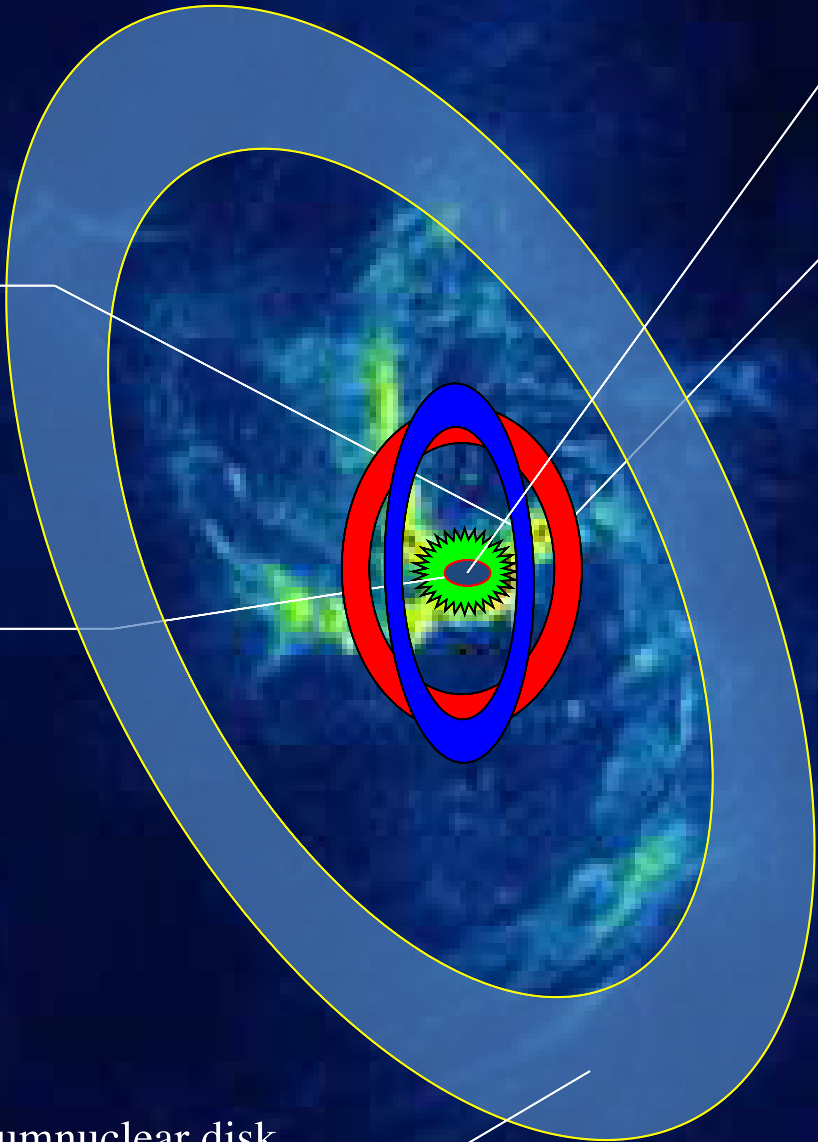
Laboratoire d'Études Spatiales et d'Instrumentation en Astrophysique

Thursday 16 May 2019

The Galactic Center



Sgr A*

R_s=10 μas = 0.1 ua

Dist. 8 k pc

Mini spiral, HII region

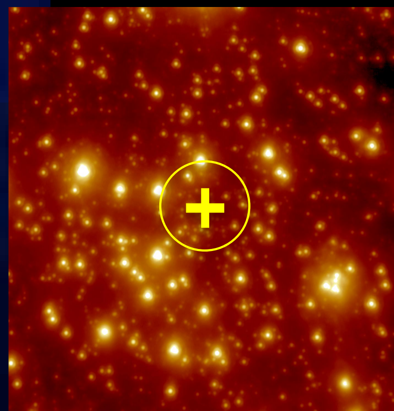
(2 pc/~ 50”)

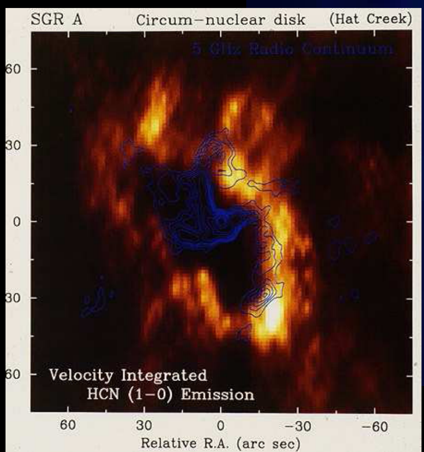
2-disk central cluster
90 massive OB and Wolf-Rayet stars

(0.5 pc/12.5”)

S star cluster
50 massive main sequence stars

(0.5-20 mpc/12-400 mas)





Circumnuclear disk
Molecular gaz and dust

(1.5-7 pc/~100”)

(Balick & Brown 1974, Becklin et al. 1982, Roberts, Yusef-Zadeh & Goss 1992, Eckart et al. 1995, Paumard et al. 2004, 2006)

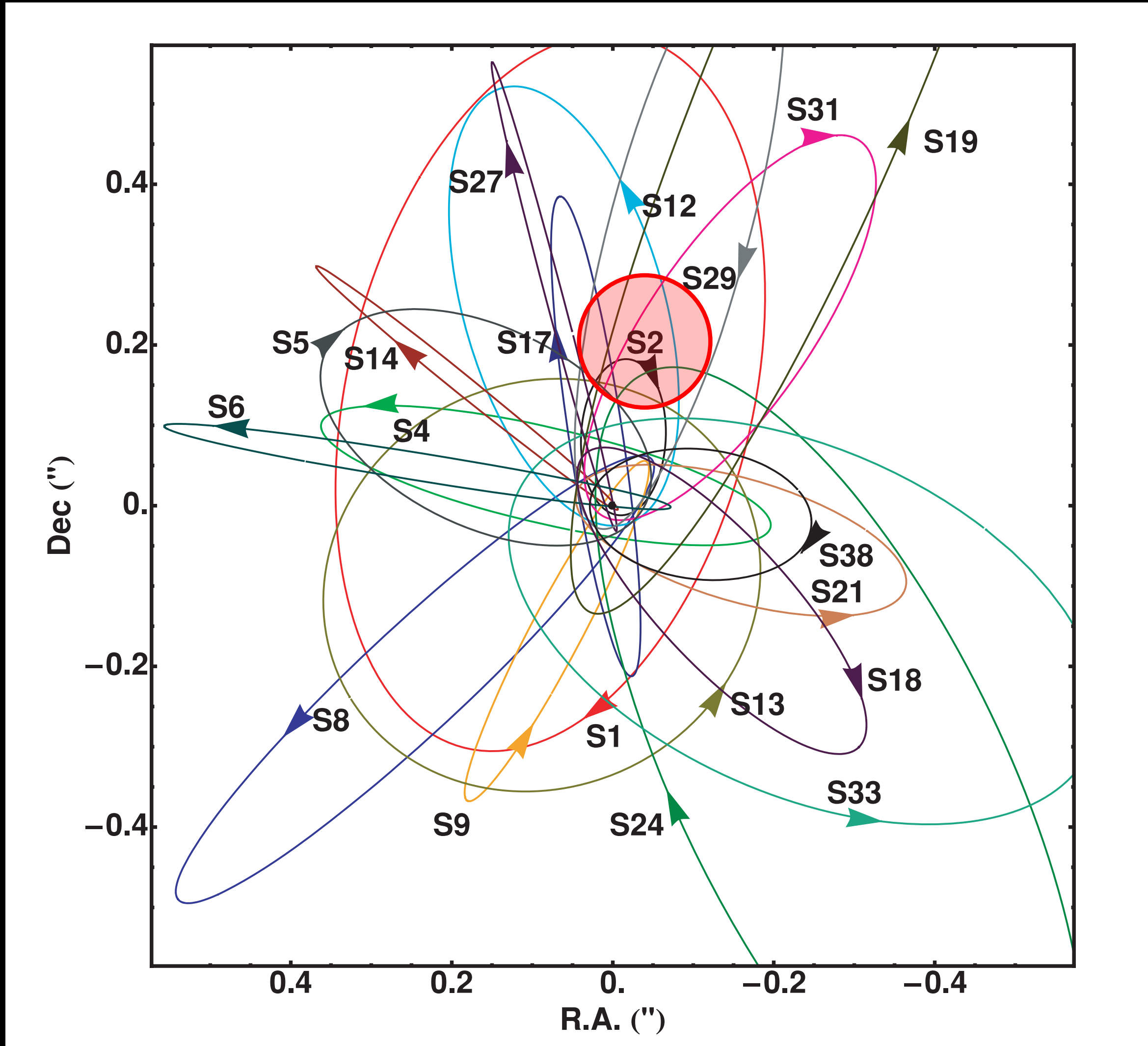
AO+radial velocities
Accurate mass estimate for Sgr A*

3rd Kepler law:

$$\frac{a^3}{T^2} = \frac{GM_{Sgr\,A^*}}{4\pi^2}$$

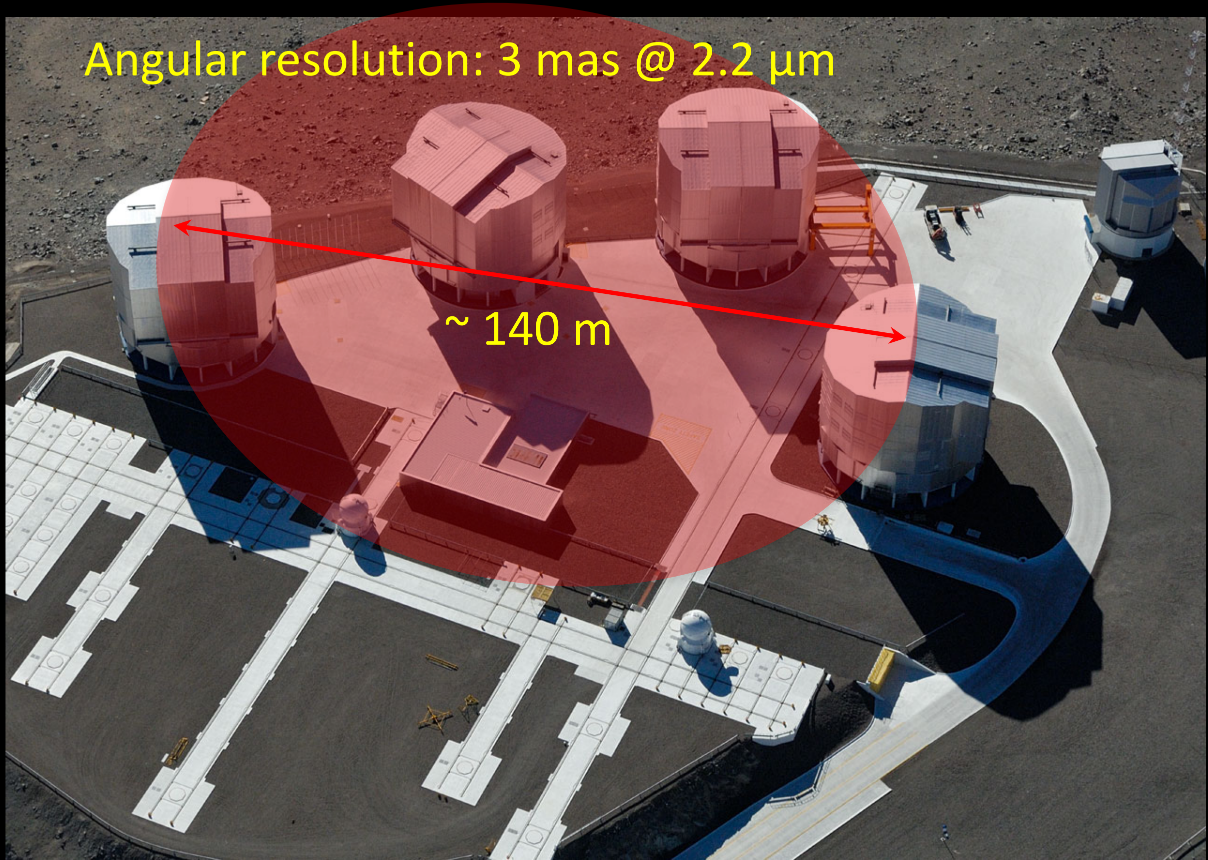
$M_{Sgr\,A^*} = 4.31 \pm 0.42 \times 10^6\ M_\odot$

(d = 7.62±0.32 kpc)



Gillessen et al. (2009)

GRAVITY combines the 4 UTs (8 m) or the 4 ATs (1.80 m) of the VLTI




The GRAVITY family
ESO
IPAG
SIM
l'Observatoire de Paris

What increasing angular resolution in the IR brings

S stars

- Potentially discover new and closer S stars, understand their nature and distribution — IR
- Probe gravity near a super massive black hole with point masses — IR

Scale ~ 100 R_s 1 mas (gain of 50)

Sgr A*

- Understand the nature of the flares — IR & mm ?
- Probe general relativity in the strong field regime with point masses — IR & mm ?
- Bring the evidence that Sgr A* is a black hole exploring the horizon scale — IR & mm

Scale ~ 1 R_s 10 µas (gain of 5000)

GRAVITY: a distributed instrument on the VLTI

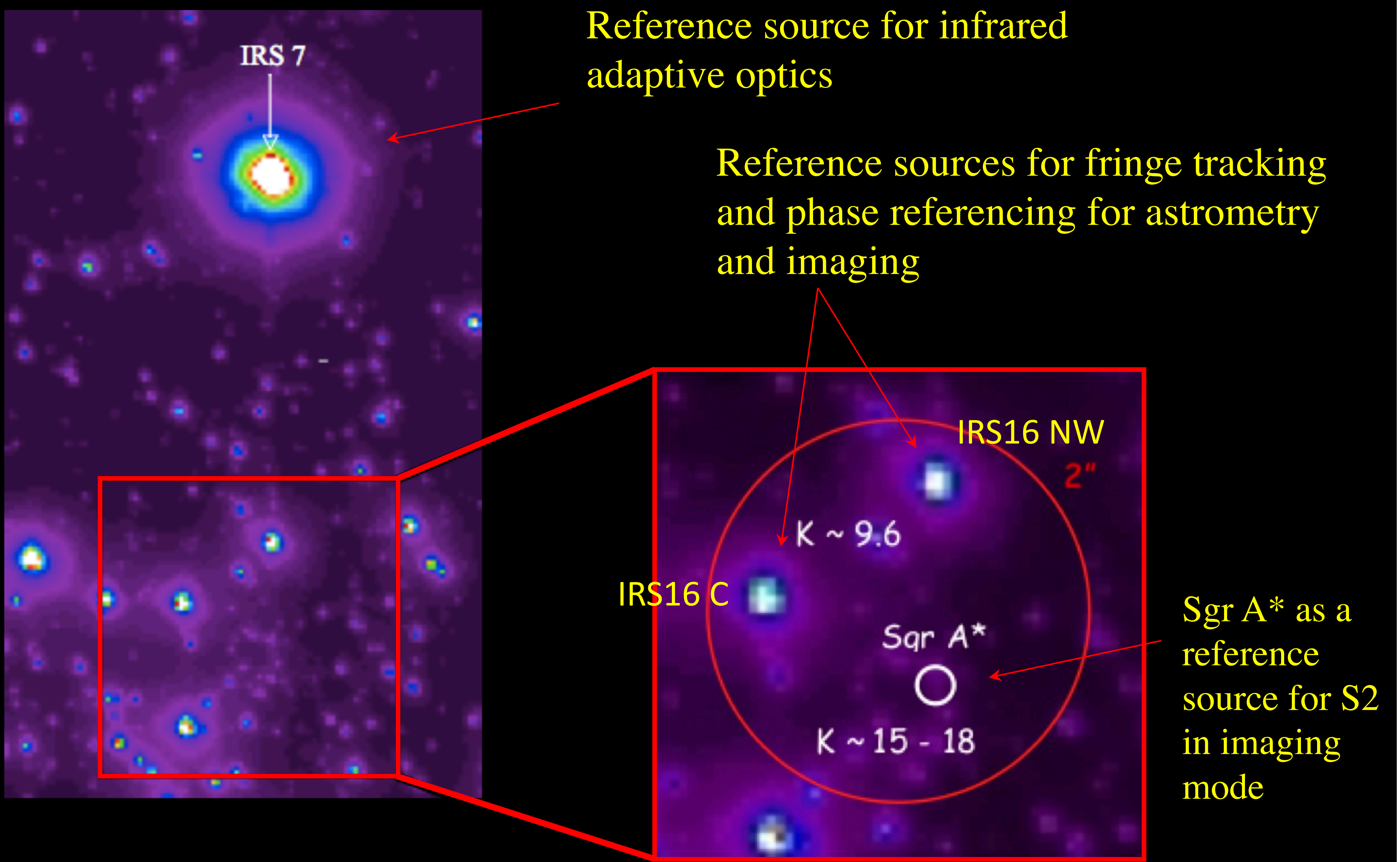
2-field beam combiner

In addition to the beam combiner:

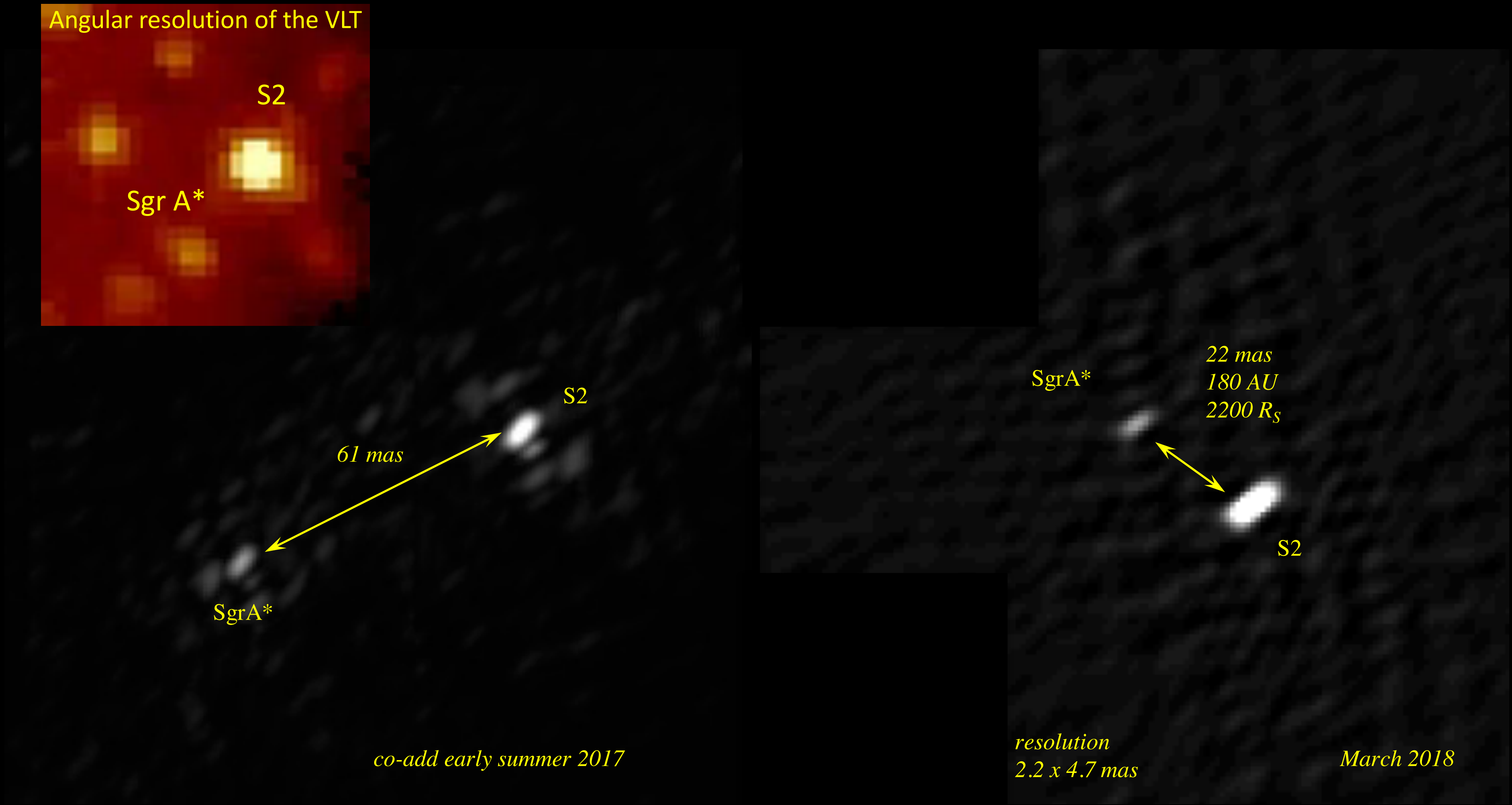
- 4 infrared adaptive optics (UT)
- Metrology probes on the telescopes (UTs and ATs) for high precision astrometry

Eisenhauer+ 05,11, 17

Principle of the GRAVITY measurements



Imaging the Galactic Center with GRAVITY



Interferometric astrometry

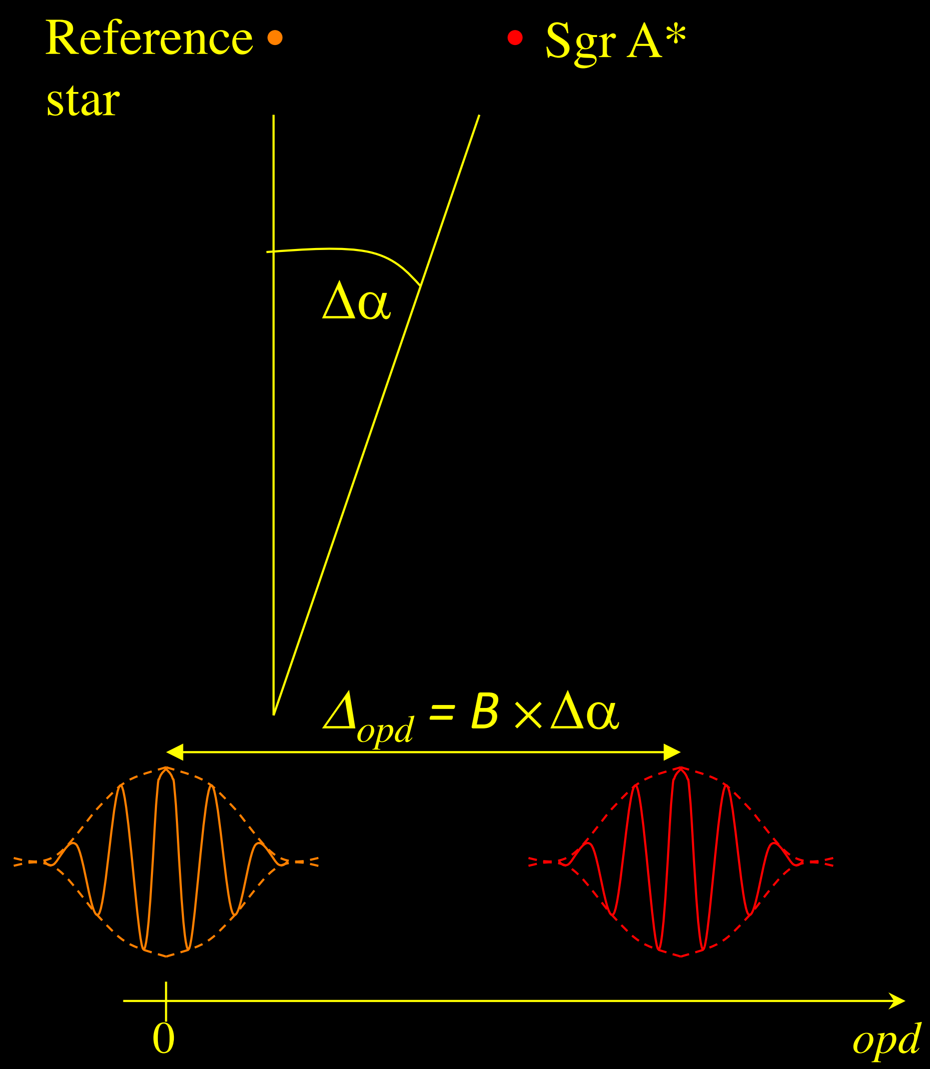
Distance between interferograms:

$$\Delta_{opd} = B \times \Delta\alpha$$

Hence:

$$\Delta\alpha = \Delta_{opd} / B$$

An accuracy of 5 nm on Δ_{opd} with a 100 m baseline yields an accuracy of 10 μas on $\Delta\alpha$.



Detection of gravitational redshift with S2

A&A 615, L15 (2018)
https://doi.org/10.1051/0004-6361/201833718

Astronomy & Astrophysics

LETTER TO THE EDITOR

Detection of the gravitational redshift in the orbit of the star S2 near the Galactic centre massive black hole★

GRAVITY Collaboration★★: R. Abuter[8], A. Amorim[6,14], N. Anugu[7], M. Bauböck[1], M. Benisty[5], J. P. Berger[5,8], N. Blind[10], H. Bonnet[8], W. Brandner[3], A. Buron[1], C. Collin[2], F. Chapron[2], Y. Clénet[2], V. Coudé du Foresto[2], P. T. de Zeeuw[12,1], C. Deen[1], F. Delplancke-Ströbele[8], R. Dembet[8,2], J. Dexter[1], G. Duvert[5], A. Eckart[4,11], F. Eisenhauer[1,★★★], G. Finger[8], N. M. Förster Schreiber[1], P. Fédou[2], P. Garcia[7,14], R. Garcia Lopez[15,3], F. Gao[1], E. Gendron[2], R. Genzel[1,13], S. Gillessen[1], P. Gordo[6,14], M. Habibi[1], X. Haubois[9], M. Haug[8], F. Haußmann[1], Th. Henning[3], S. Hippler[3], M. Horrobin[4], Z. Hubert[2,3], N. Hubin[8], A. Jimenez Rosales[1], L. Jochum[8], L. Jocou[5], A. Kaufer[9], S. Kellner[11], S. Kendrew[16,3], P. Kervella[2], Y. Kok[1], M. Kulas[3], S. Lacour[2], V. Lapeyrère[2], B. Lazareff[5], J.-B. Le Bouquin[5], P. Léna[2], M. Lippa[1], R. Lenzen[3], A. Mérand[8], E. Müler[8,3], U. Neumann[3], T. Ott[1], L. Palanca[9], T. Paumard[2], L. Pasquini[8], K. Perraut[5], G. Perrin[2], O. Pfuhl[1], P. M. Plewa[1], S. Rabien[1], A. Ramírez[9], J. Ramos[3], C. Rau[1], G. Rodríguez-Coira[2], R.-R. Rohloff[3], G. Rousset[2], J. Sanchez-Bermudez[9,3], S. Scheithauer[3], M. Schöller[8], N. Schuler[9], J. Spyromilio[8], O. Straub[2], C. Straubmeier[4], E. Sturm[1], L. J. Tacconi[1], K. R. W. Tristram[9], F. Vincent[2], S. von Fellenberg[1], I. Wank[4], I. Waisberg[1], F. Widmann[1], E. Wieprecht[1], M. Wiest[4], E. Wiezorrek[1], J. Woillez[8], S. Yazici[1,4], D. Ziegler[2], and G. Zins[9]

(Affiliations can be found after the references)

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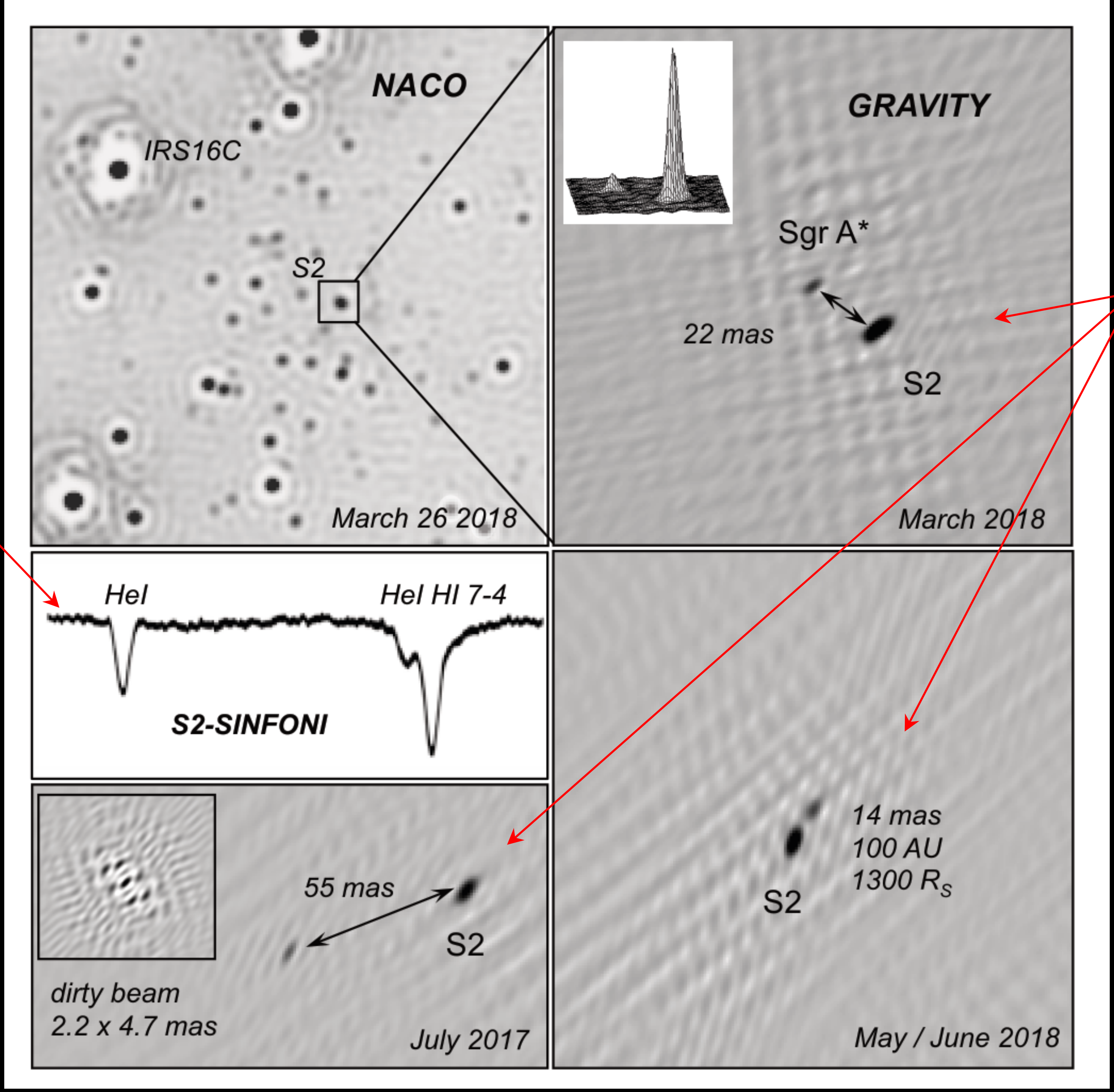
Detection of gravitational redshift with S2

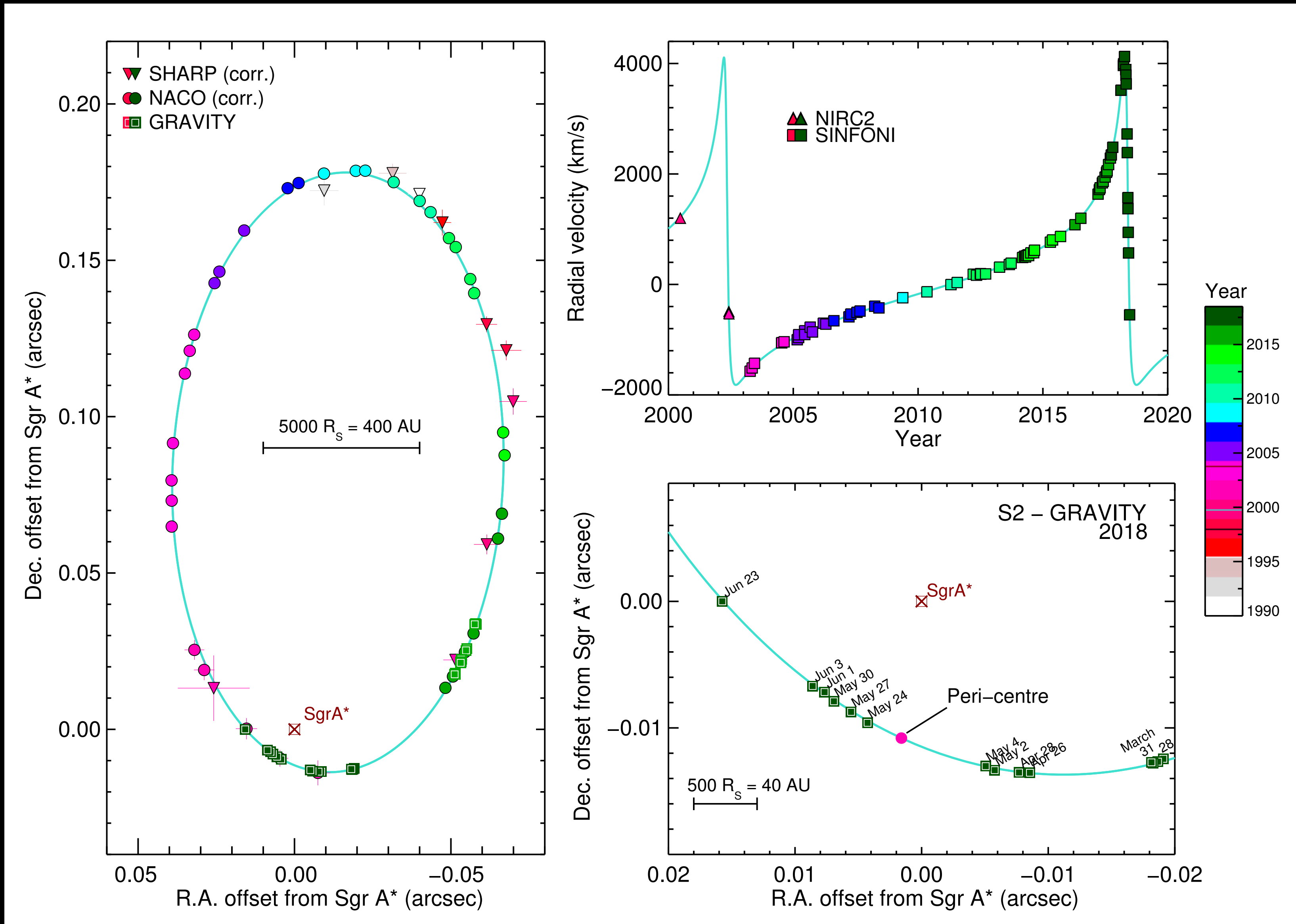
Spectroscopy
(velocities)



Imaging and
relative astrometry
to Sgr A*

GRAVITY Collaboration, A&A 615, L15 (2018)

The S2 dataset



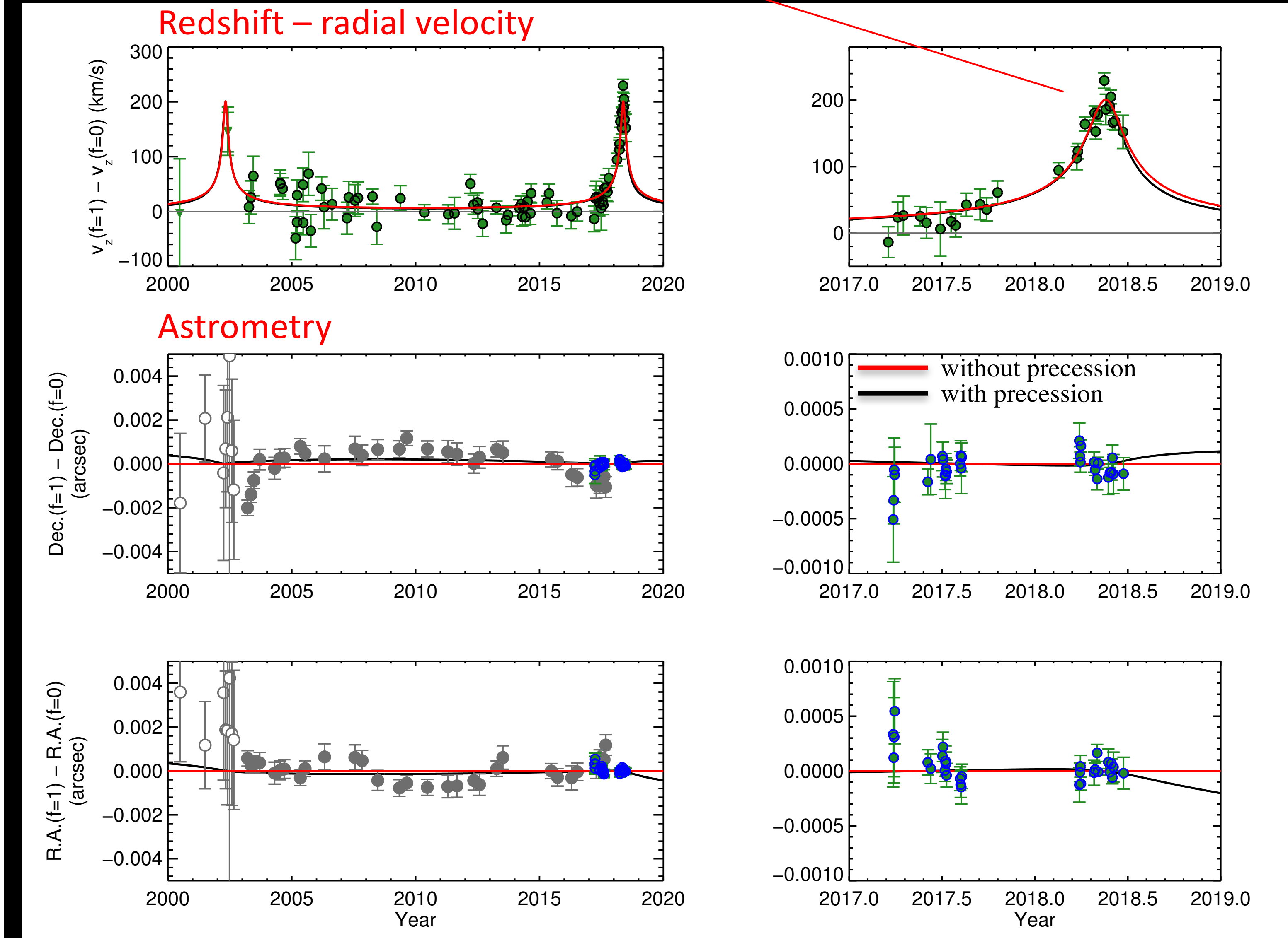
GRAVITY Collaboration, A&A 615, L15 (2018)

Fitting with a relativistic orbit

PPN (1) terms: $z = \frac{\Delta\lambda}{\lambda} = B_0 + B_{0.5}\beta + B_1\beta^2 + \mathcal{O}(\beta^3)$

$B_1 = B_{1,\mathrm{tD}} + B_{1,\mathrm{gr}}$

$z_{\mathrm{tot}} = z_{\mathrm{K}} + f\,(z_{\mathrm{GR}} - z_{\mathrm{K}})$



$f = 0$: Kepler orbit

$f = 1$: GR orbit (post-newtonian approximation)

GRAVITY result: $f = 0.94 \pm 0.09$ (wih precession)

Mass of Sgr A*: $4.11 \pm 0.03 \times 10^6\ M_\odot$ (precision of 6×10^{-3})

Distance to Sgr A*: 8127 ± 31 pc (precision of 4×10^{-3})

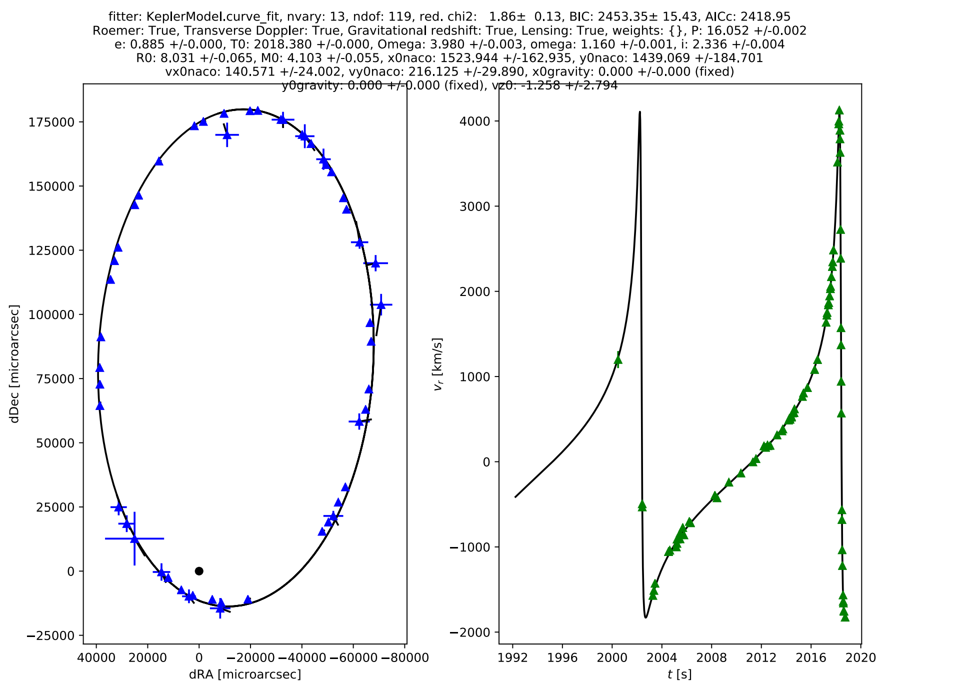
GRAVITY Collaboration, A&A 615, L15 (2018)

The power of the GRAVITY data

NACO+SHARP+spectroscopic data

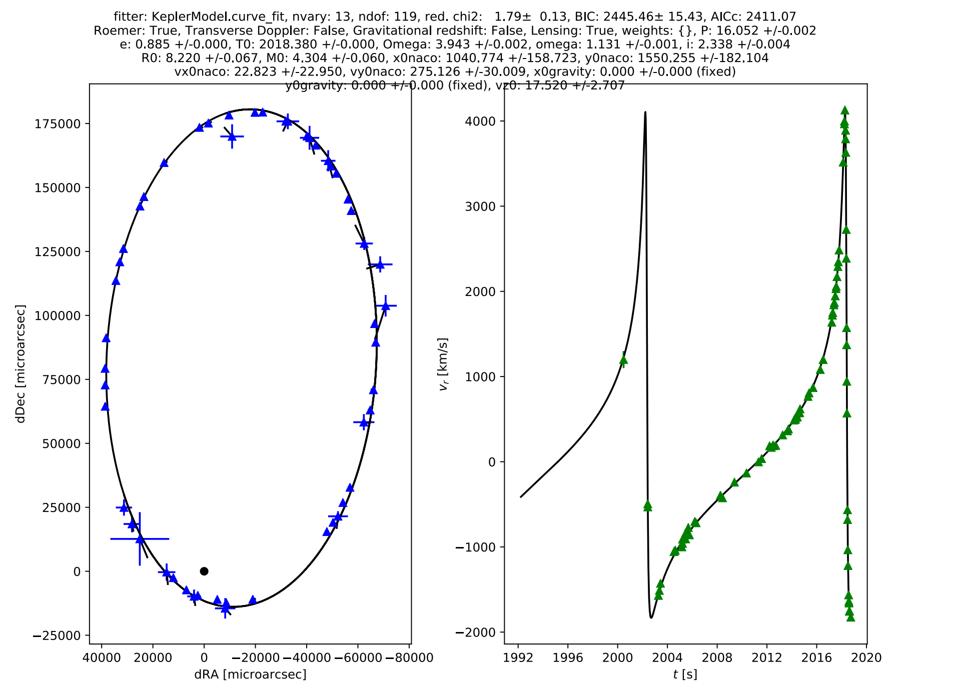
General relativity

χ^2=1.86



Newton including the Rømer effect

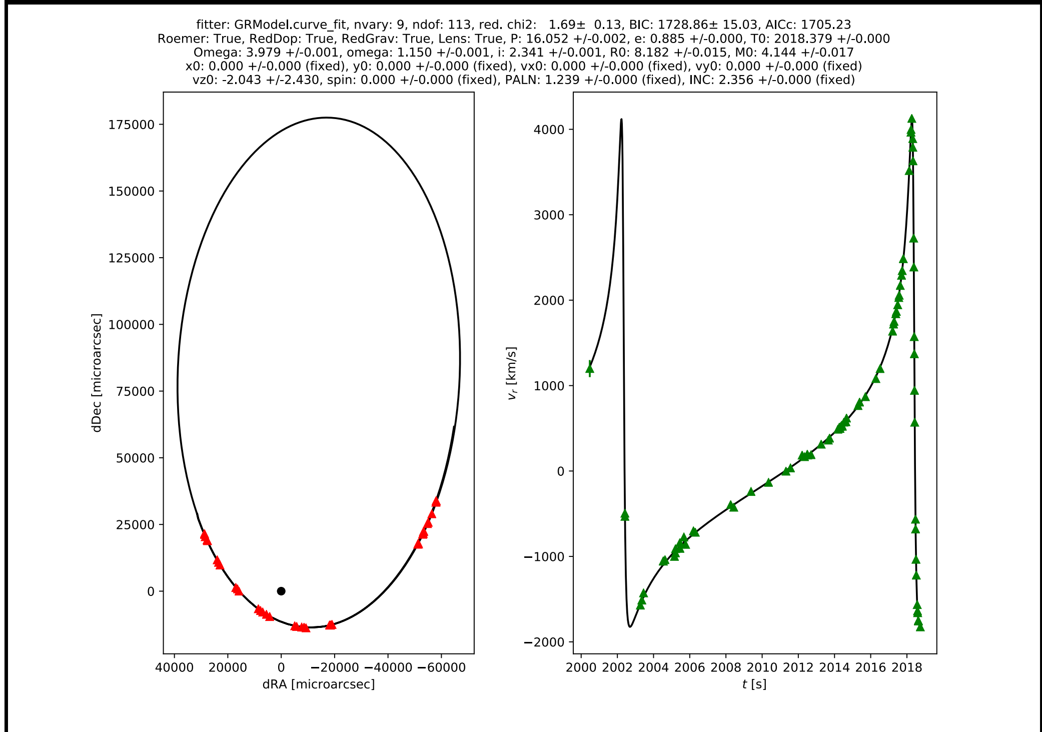
χ^2=1.79



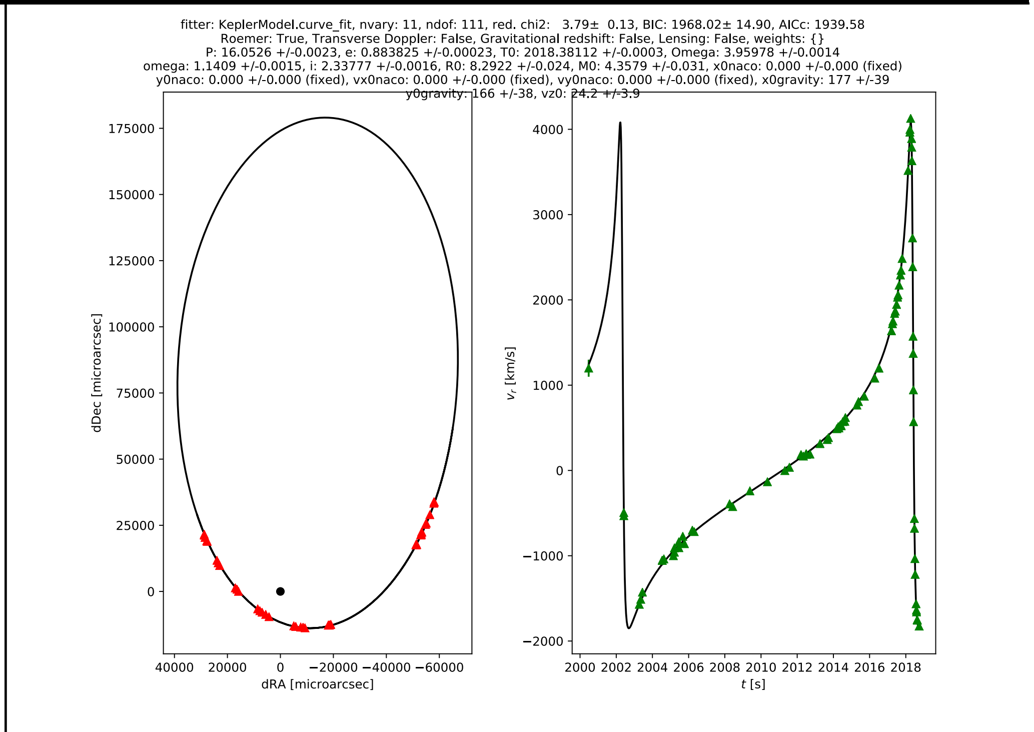
The power of the GRAVITY data

GRAVITY+spectroscopic data

General relativity
χ^2=1.69



Newton including the Rømer effect
χ^2=3.79



With all 2017 & 2018 data:
$f = 1.04 \pm 0.06$
Newton excluded at 16 σ

GR orbit computed with GYOTO, Vincent et al. (2011)

Flares near the innermost stable circular orbit

A&A 618, L10 (2018)
https://doi.org/10.1051/0004-6361/201834294

Astronomy & Astrophysics

Letter to the Editor

Detection of orbital motions near the last stable circular orbit of the massive black hole SgrA*★

GRAVITY Collaboration★★: R. Abuter[8], A. Amorim[6,14], M. Bauböck[1], J. P. Berger[5], H. Bonnet[8], W. Brandner[3], Y. Clénet[2], V. Coudé du Foresto[2], P. T. de Zeeuw[10,1], C. Deen[1], J. Dexter[1,★★★], G. Duvert[5], A. Eckart[4,13], F. Eisenhauer[1], N. M. Förster Schreiber[1], P. Garcia[7,9,14], F. Gao[1], E. Gendron[2], R. Genzel[1,11], S. Gillessen[1], P. Guajardo[9], M. Habibi[1], X. Haubois[9], Th. Henning[3], S. Hippler[3], M. Horrobin[4], A. Huber[3], A. Jiménez-Rosales[1], L. Jocou[5], P. Kervella[2], S. Lacour[2,1], V. Lapeyrère[2], B. Lazareff[5], J.-B. Le Bouquin[5], P. Léna[2], M. Lippa[1], T. Ott[1], J. Panduro [3], T. Paumard[2,★★★], K. Perraut[5], G. Perrin[2], O. Pfuhl[1,★★★], P. M. Plewa[1], S. Rabien[1], G. Rodríguez-Coira[2], G. Rousset[2], A. Sternberg[12,15], O. Straub[2], C. Straubmeier[4], E. Sturm[1], L. J. Tacconi[1], F. Vincent[2], S. von Fellenberg[1], I. Waisberg[1], F. Widmann[1], E. Wieprecht[1], E. Wiezorrek[1], J. Woillez[8], and S. Yazici[1,4]

(Affiliations can be found after the references)

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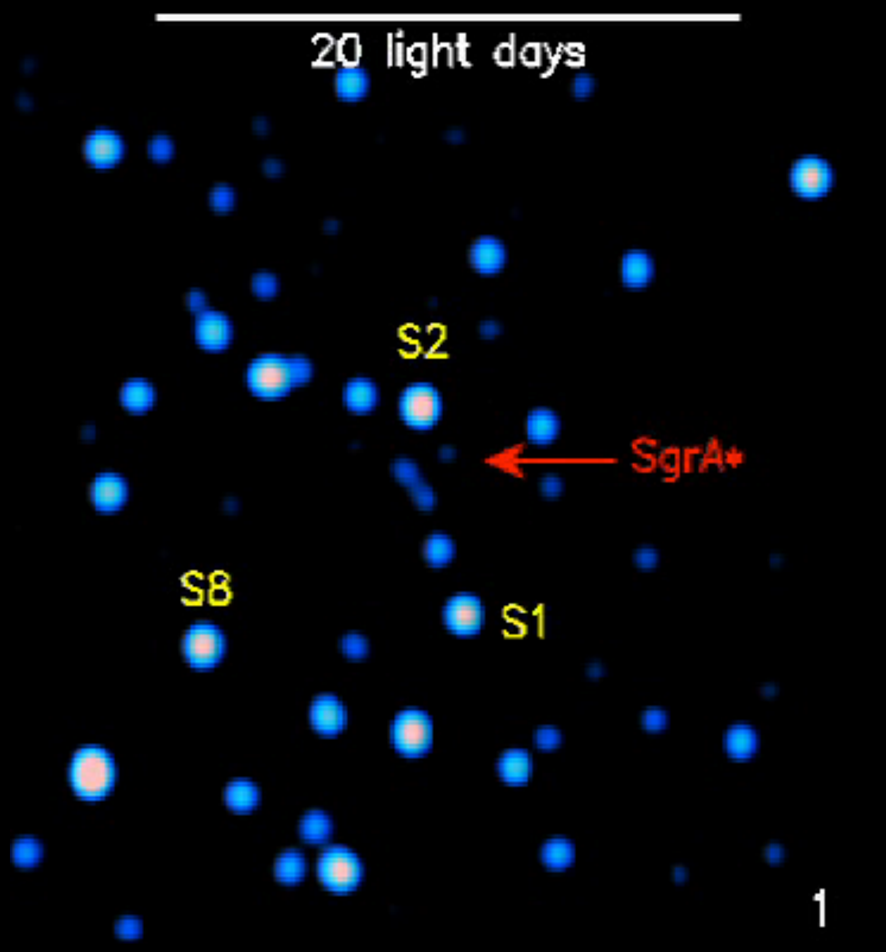
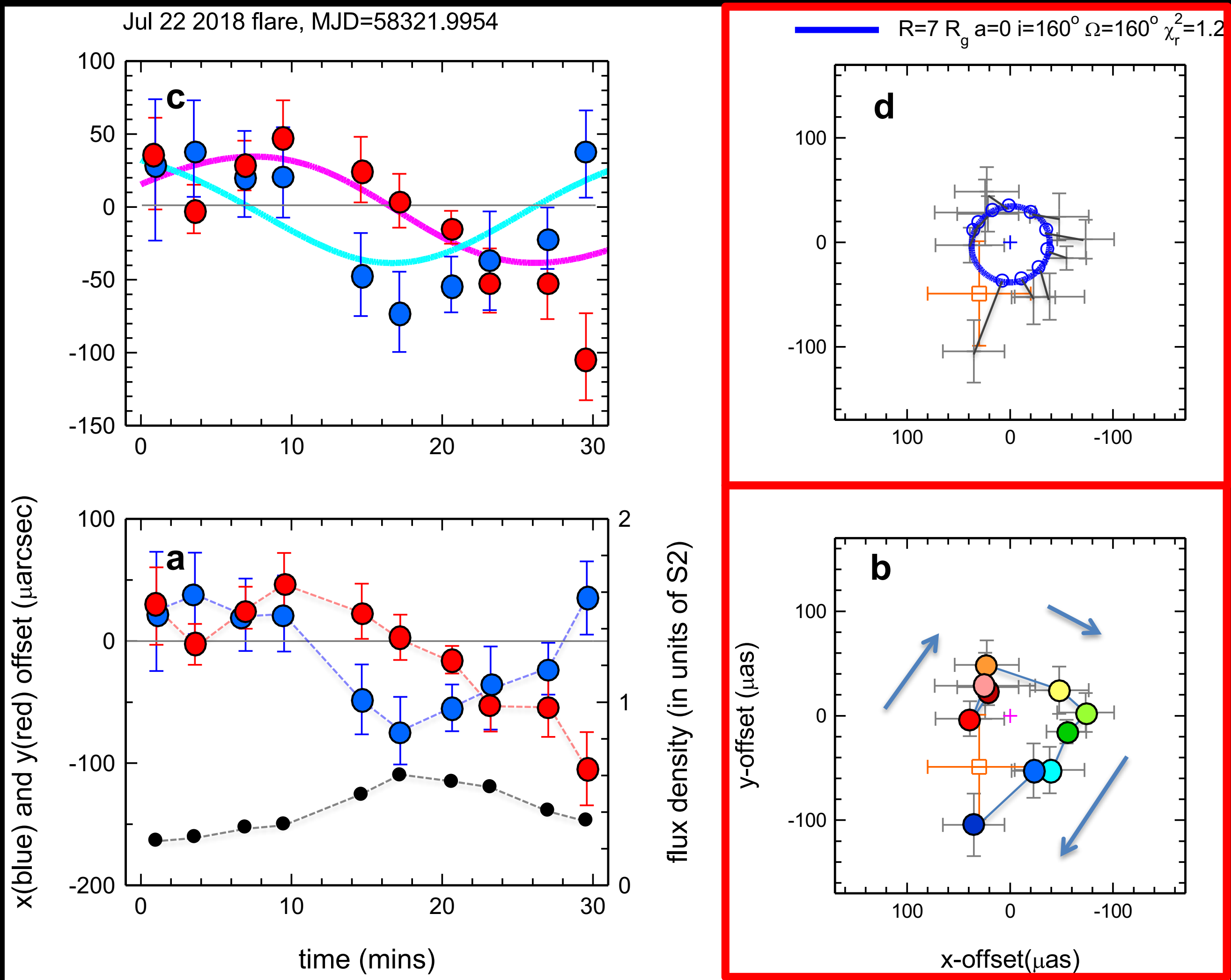
Flares at the Galactic Center



Genzel et al. (2003)

Flares near the innermost stable circular orbit



3 flares observed on May 27, July 22 and 28 2018

Model fitting with a relativistic hot spot model (NERO, GYOTO)

Schwarzschild case (a=0):

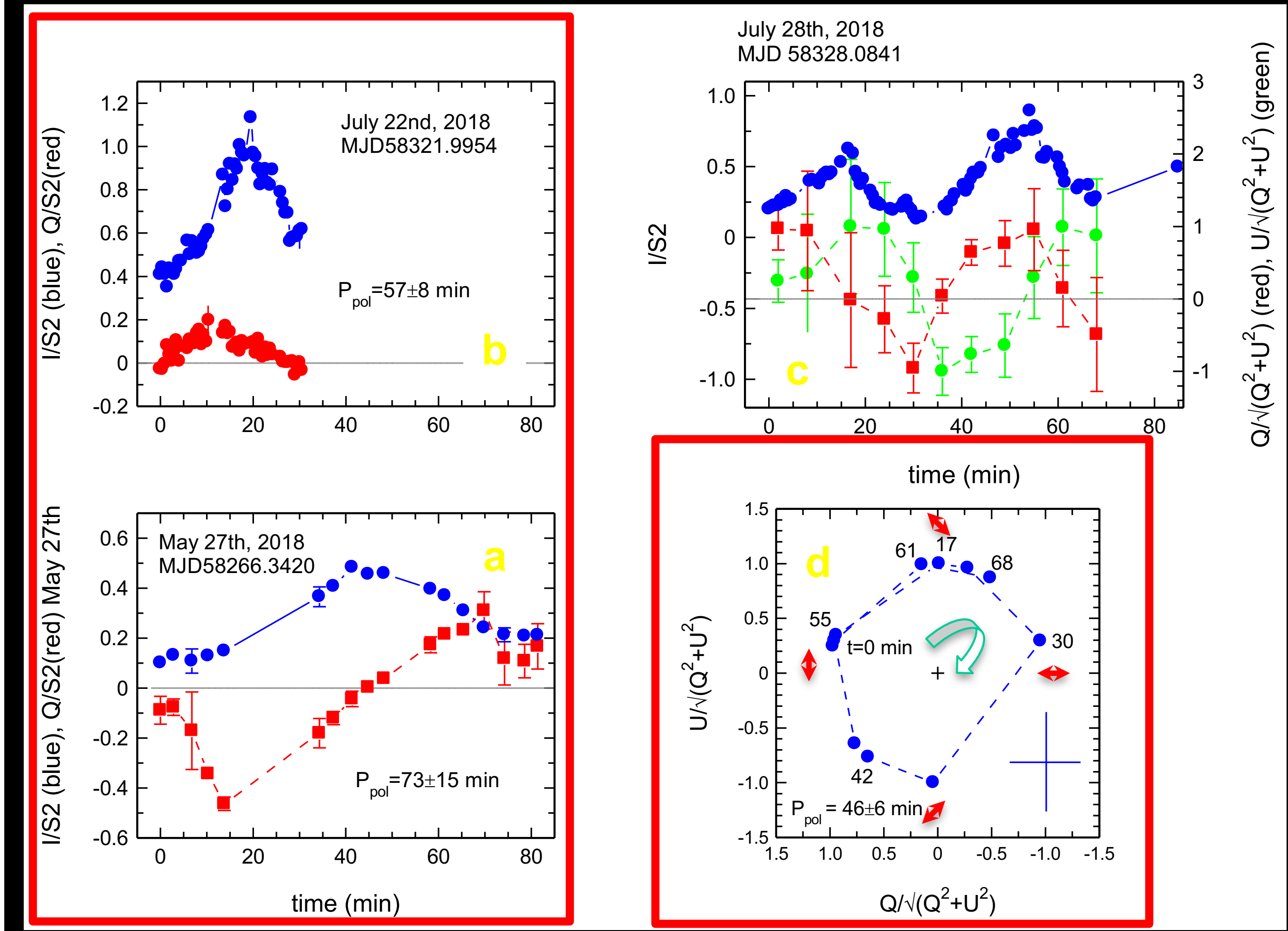
$R = 7.3 \pm 0.5\ R_g$

$P = 40 \pm 8$ min

=> $v_{orb} \sim 0.3$ c

GRAVITY Collaboration, A&A 618, L10 (2018)

Polarization loops



Poloidal magnetic field (perpendicular to orbital plane)

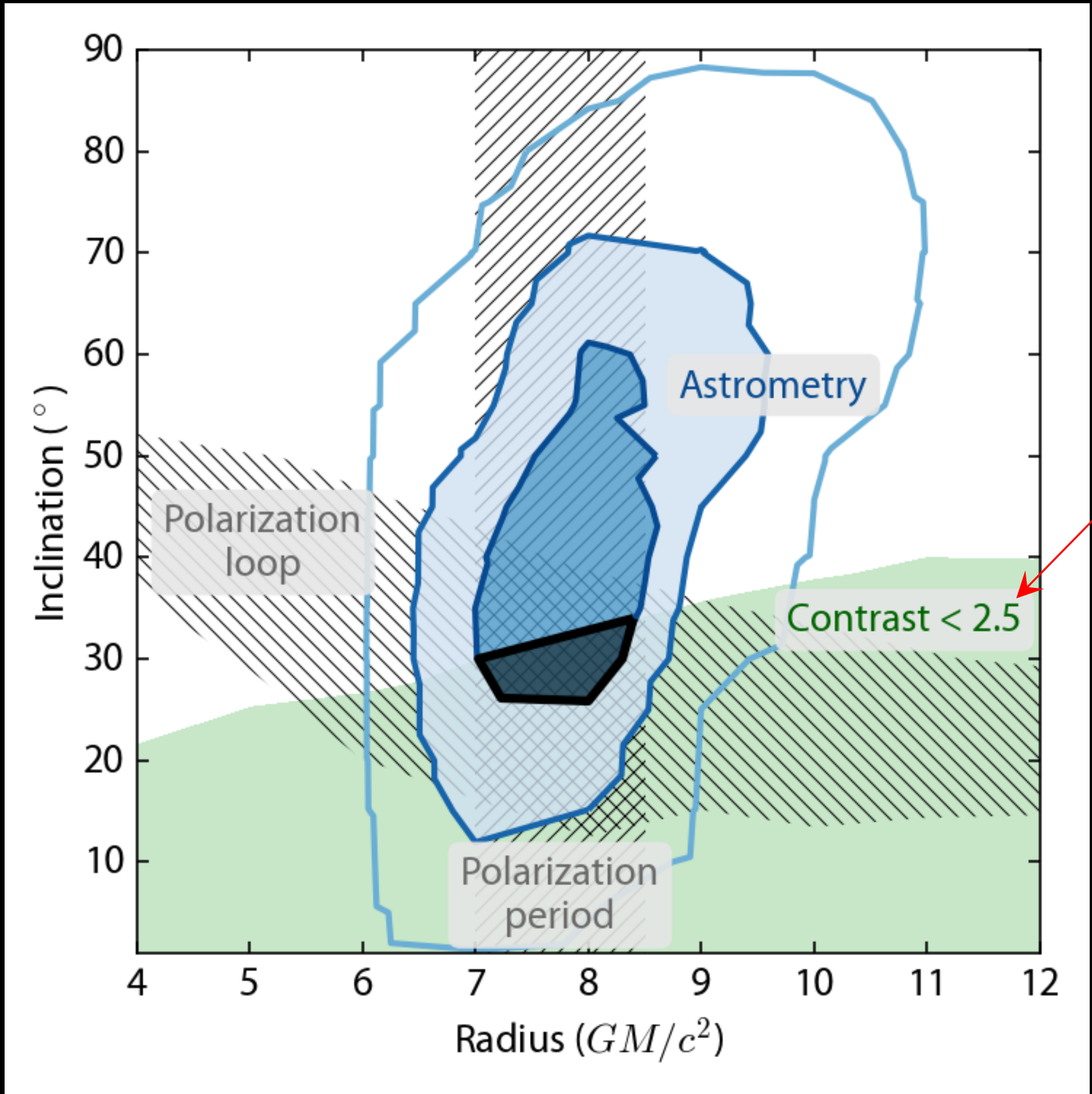
Flare of July 28: $P_{pol} = 48 \pm 6$ min

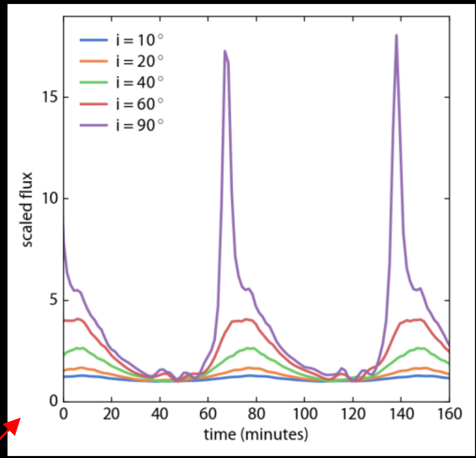
Light bending by Sgr A* adds an azimutal component to polarization with an orbit-like motion

Compatible with a low inclination (15-30°) and a 7-8 R_g orbital radius.

GRAVITY Collaboration, A&A 618, L10 (2018)

Constraint on inclination and orbital radius

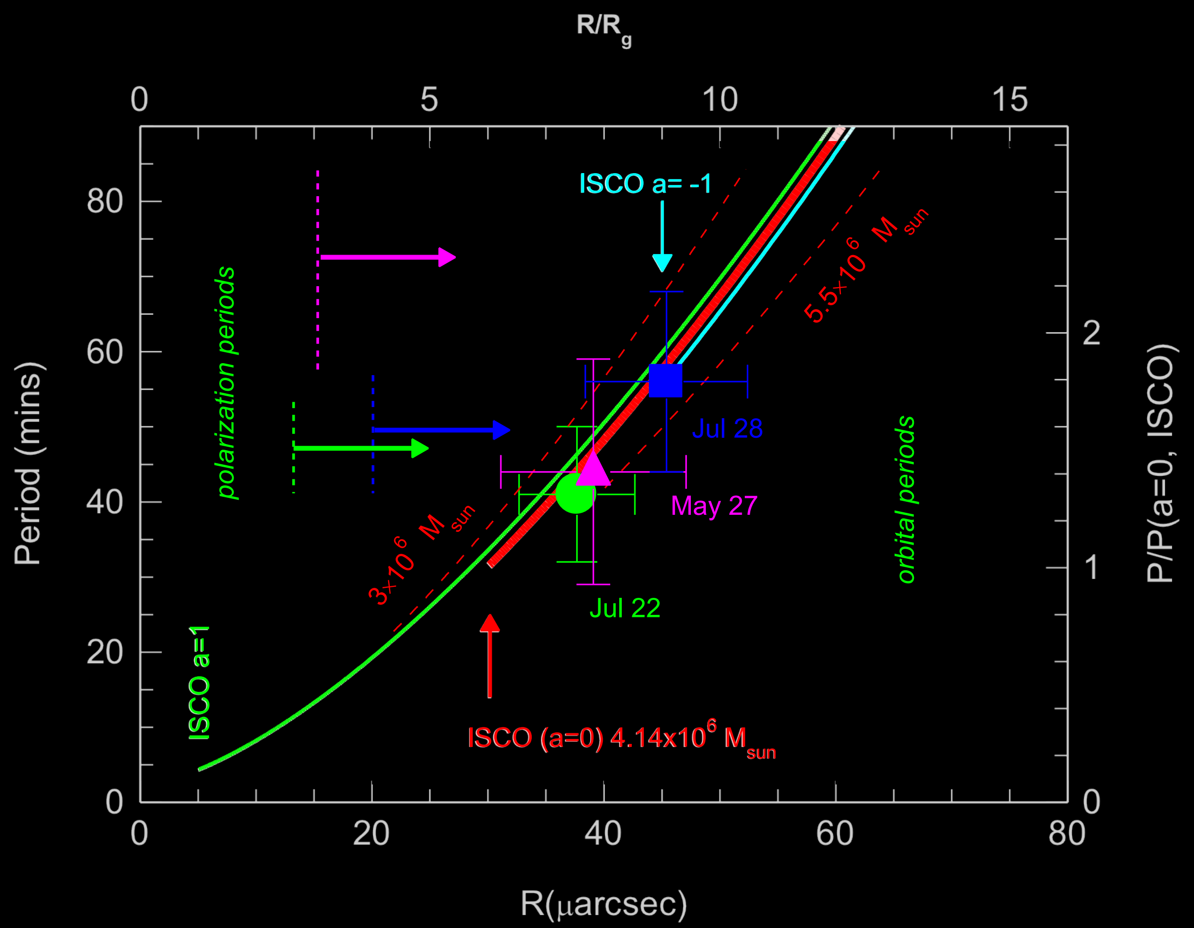




R = 7.6 ± 0.5 *Rg* and inclination 15-30°

GRAVITY Collaboration, A&A 618, L10 (2018)

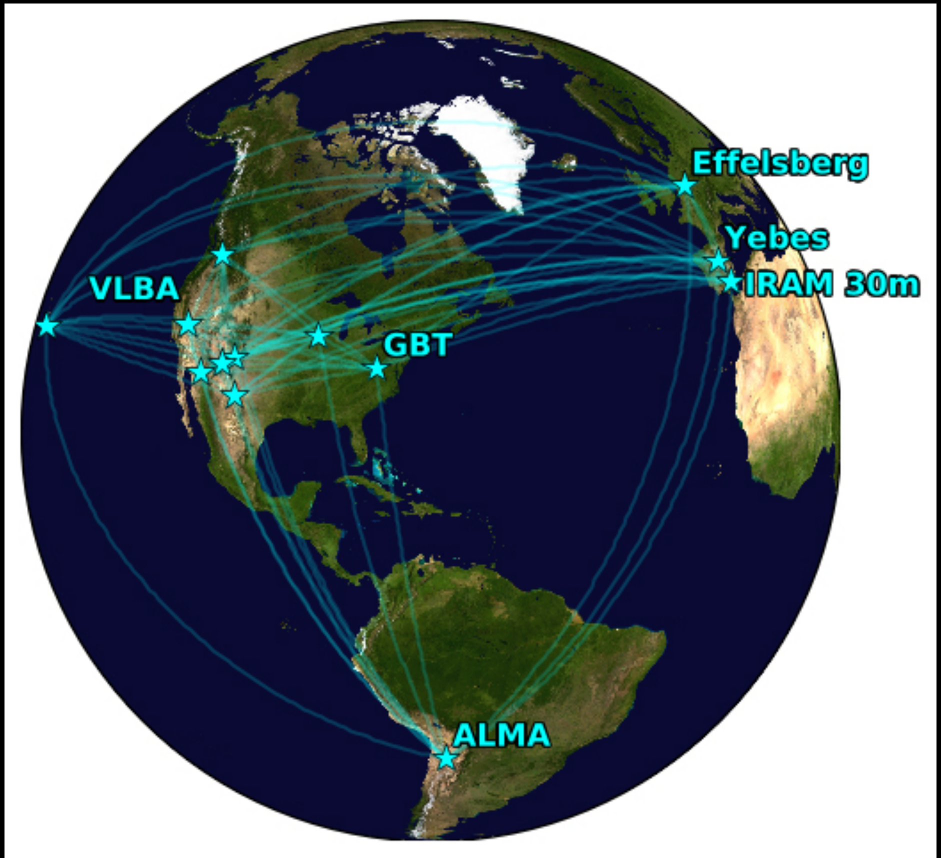
Orbital motions are fully compatible with a 4 million solar mass black hole



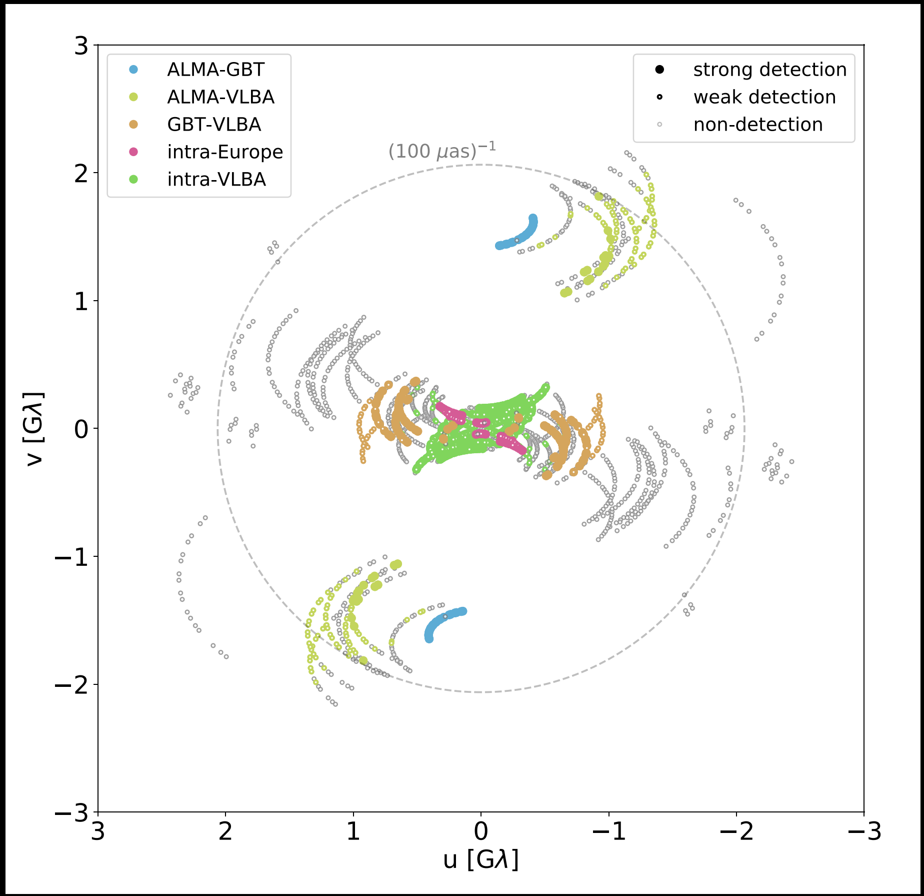
GRAVITY Collaboration, A&A 618, L10 (2018)

Complementary measurements at millimeter wavelengths

First image of Sgr A* at 86 GHz (3.5 mm)

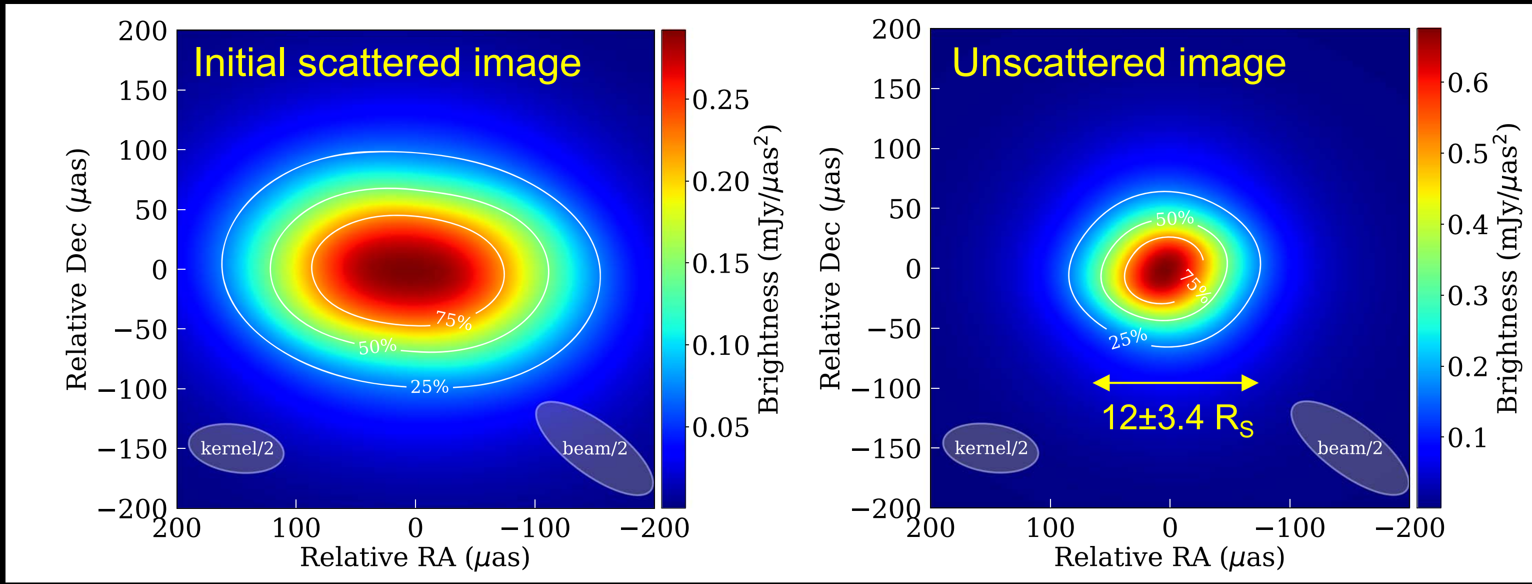


(u,v) coverage



Issaoun et al., ApJ, 871:30 (2019)

First image of Sgr A* at 86 GHz (3.5 mm)



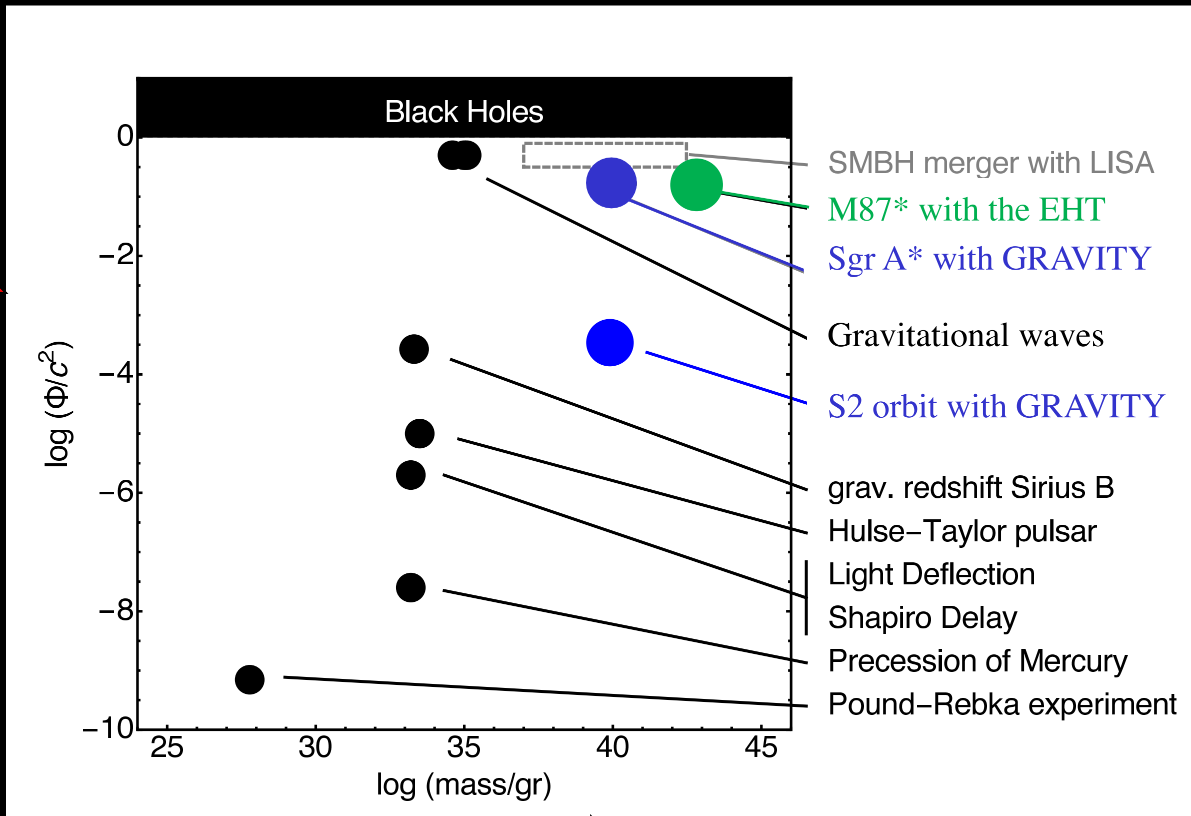
Modeling: only disks at moderate viewing angles and jet with viewing angles ≤ 20° are consistent with 1 and 3mm sizes and asymmetry constraints

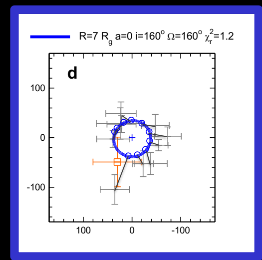
=> Fully compatible with the constraints derived from the GRAVITY data

Issaoun et al., ApJ, 871:30 (2019)

Contributions of GRAVITY and the EHT to tests of general relativity

Potential



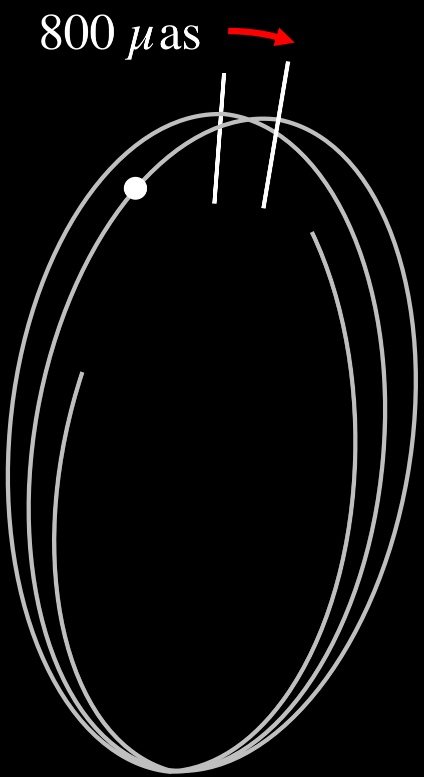


Central mass

Inspired from Psaltis (2004)

More with GRAVITY?

Measuring the relativistic precession of S2



$$\Delta\Phi_{per\ orbit} = f_{SP} \times 3\pi \left(\frac{R_s}{a(1-e^2)} \right) + f_{LT} \times 2\chi \left(\frac{R_s}{a(1-e^2)} \right)^{3/2}$$

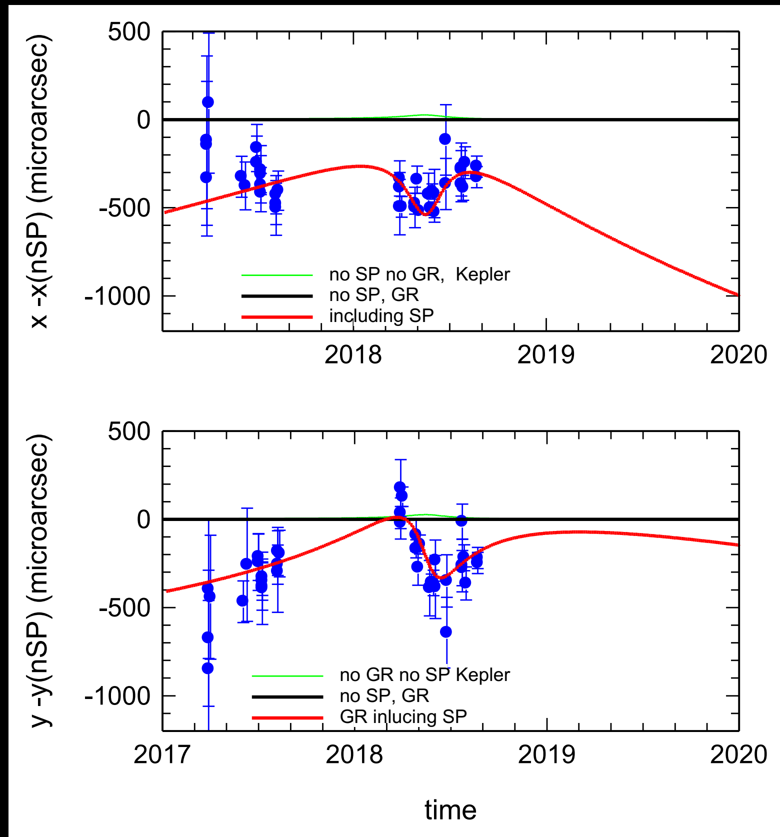
$PPN(1)_\Phi$: Schwarzschild Precession

$S2 : 11.9'$

With the current data
(up to Sep 2018):

f_{SP}=1.3±0.8

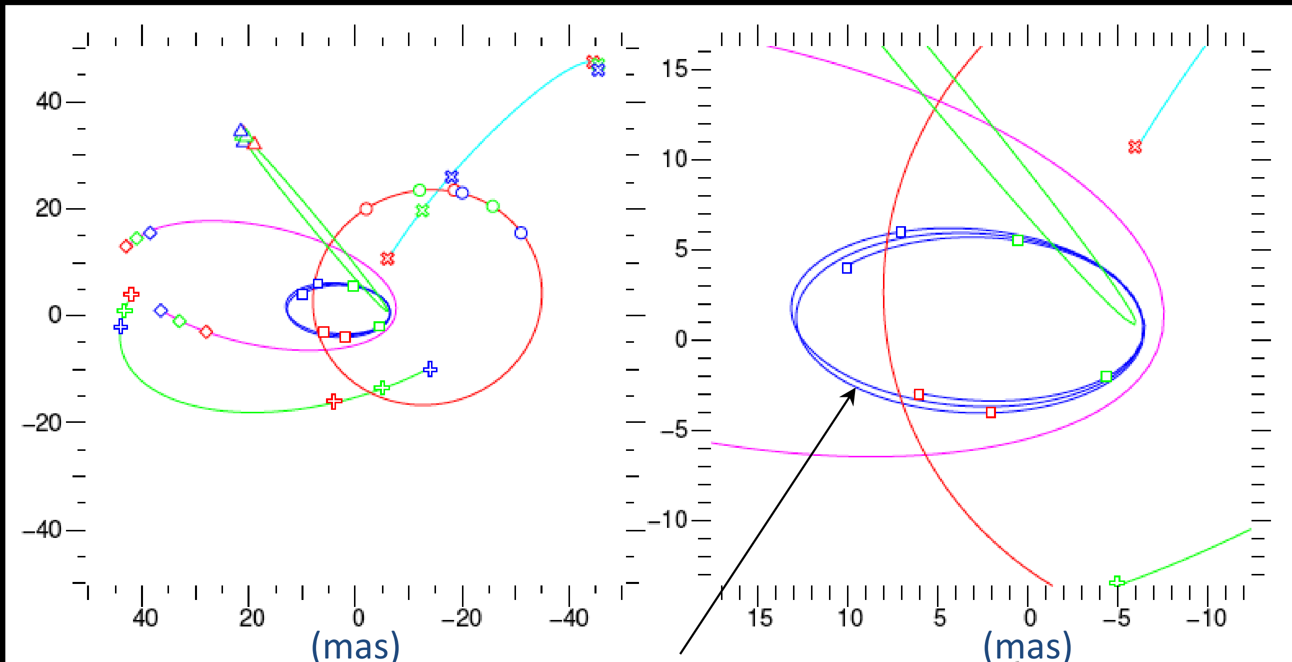
Robust detection in 2019



Orbits of nearby stars

Imaging of the central 100 mas (one night)

After 15 months of observing:



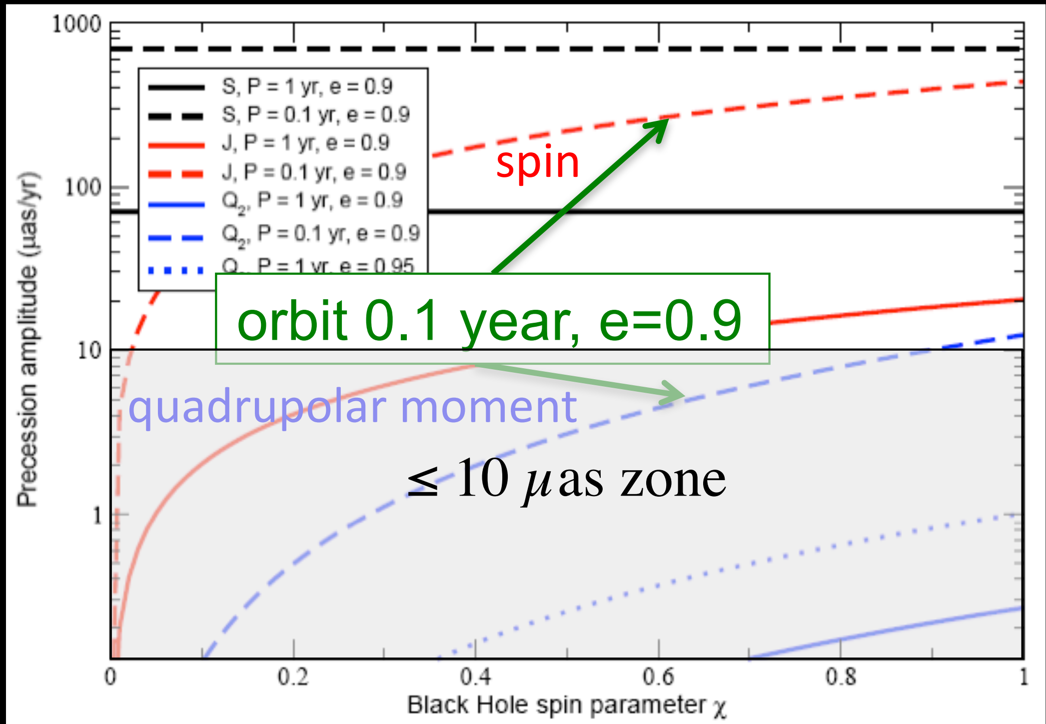
Simulation of the S star cluster downscaled to 100 mas

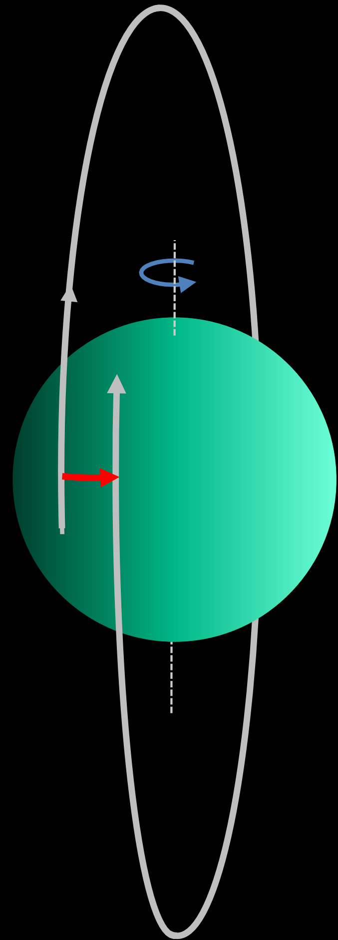
Schwarzschild precession
Kerr precession and spin measurement
Measurement of the quadrupolar moment?

Paumard et al. (2005)

Lense-Thirring effect and precession of the quadrupolar moment

Precession of the orbital plane (precession of the angular momentum vector around the BH spin vector)





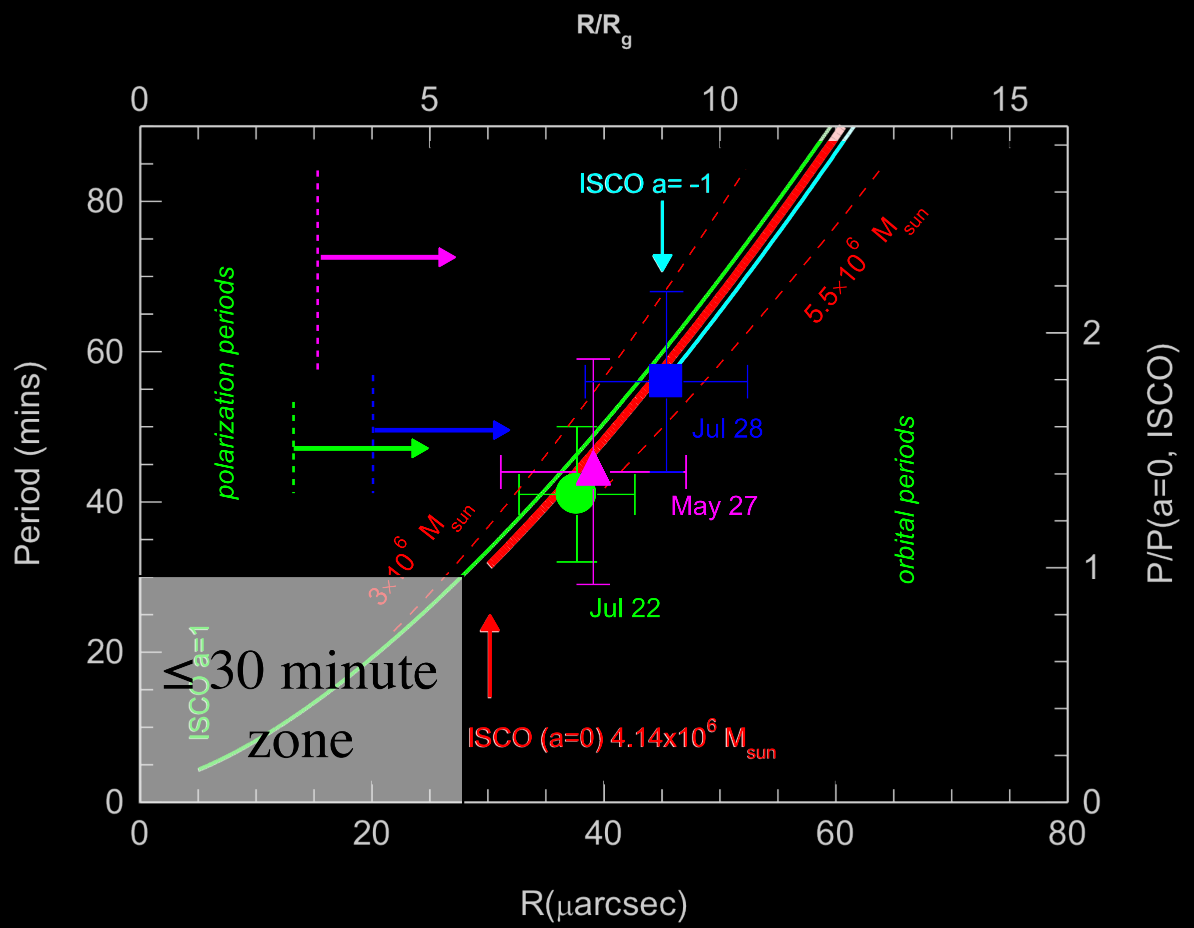
No-hair theorem: only 3 parameters describe a black hole: mass M, spin J, electric charge
Quadrupolar moment: $Q_2 = -J^2 / M$

The measurement of precession due to frame dragging in a few years with orbits of size 0,2 - 1 mpc (5 - 25 mas)

Will (2008)

Merritt et al. (2010)

A flare with ≤ 30 minute period to constrain the spin?



GRAVITY Collaboration, A&A 618, L10 (2018)

Thank you for your attention!

Special thanks to Thibaut Paumard, Frédéric Vincent, Reinhard Genzel, Oliver Pfuhl, Frank Eisenhauer and the members of the GRAVITY consortium!