First explorations of Sgr A* at the event horizon scale and first tests of general relativity with GRAVITY

Laboratoire Astroparticules et Cosmologie

Guy Perrin

l'Observatoire de Paris | LESIA
Laboratoire d'Études Spatiales et d'Instrumentation en Astrophysique

Thursday 1st February 2019

The Galaxy as we see it

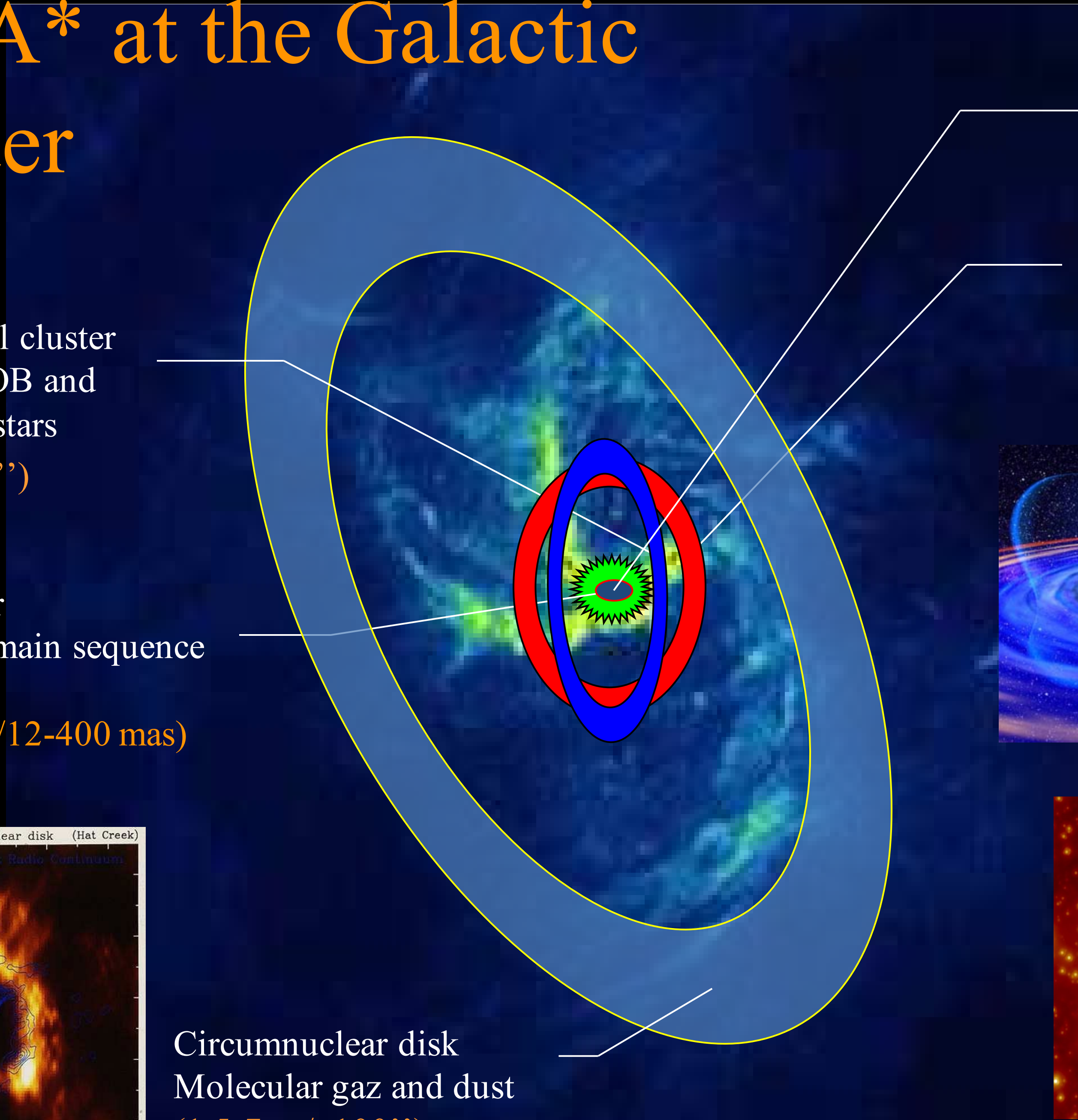
Sgr A* at the Galactic Center

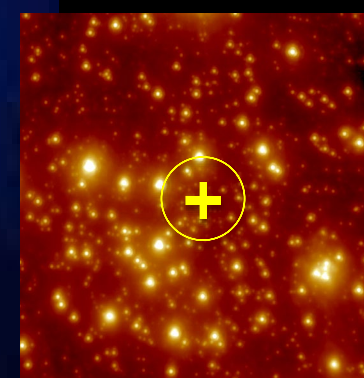
Sgr A*
R_s=10 µas = 0.1 ua
Dist. 8 k pc

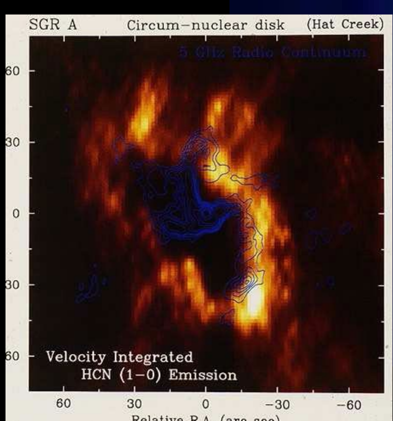
Mini spiral, HII region
(2 pc/~ 50'')

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)





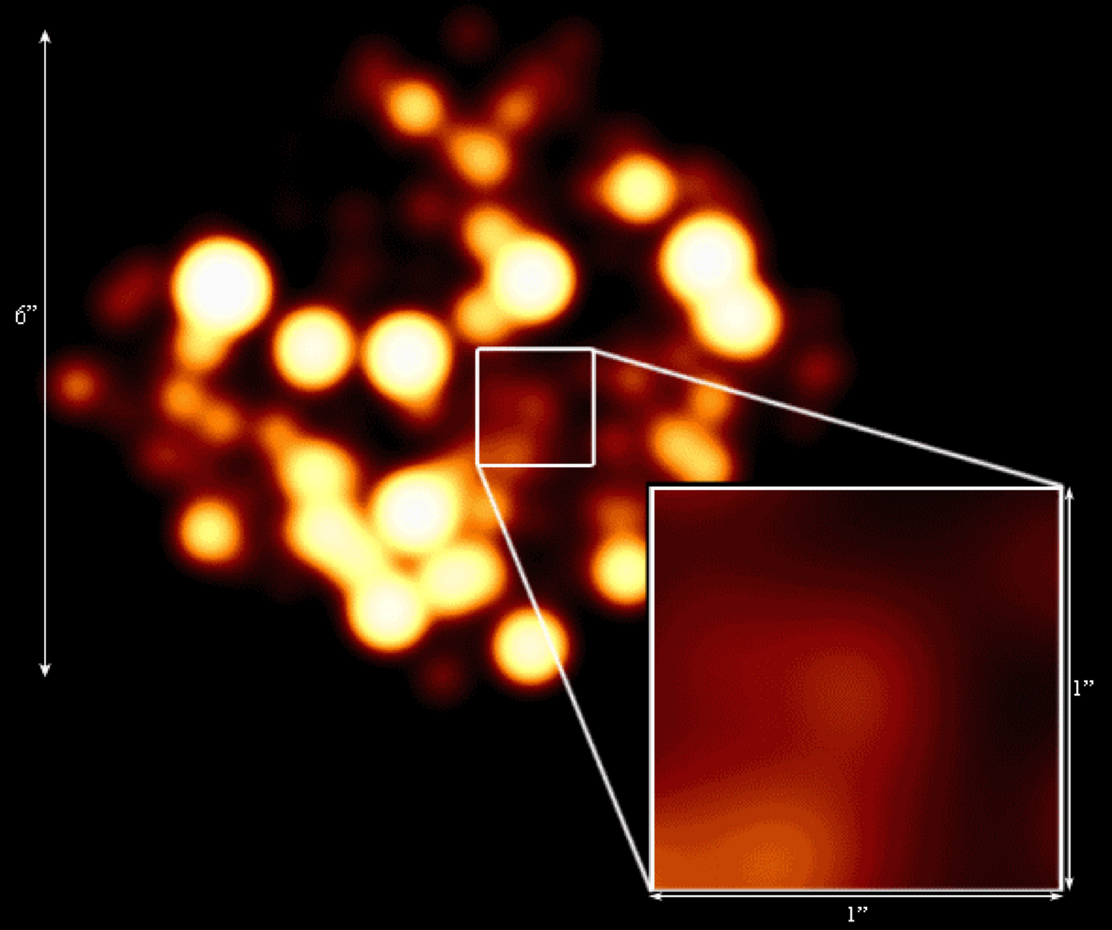


Circumnuclear disk
Molecular gaz and dust
(1.5-7 pc/~100'')

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

Observations in the near infrared

0,25 pc



The VLT, *Very Large Telescope*

Four 8m European telescopes on Mount Paranal in Chili

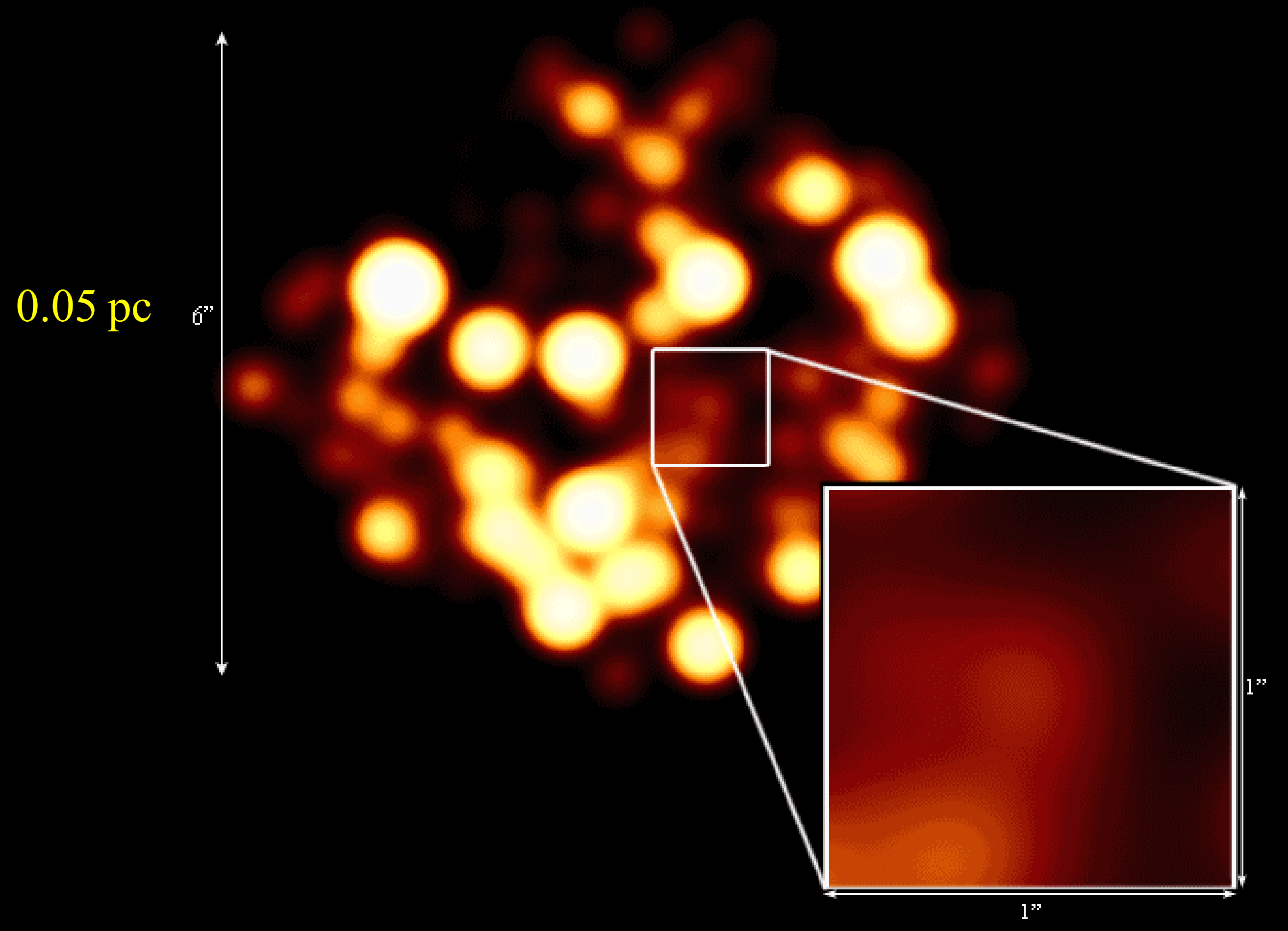
The miracle of adaptive optics
NACO (VLT)

On
Off

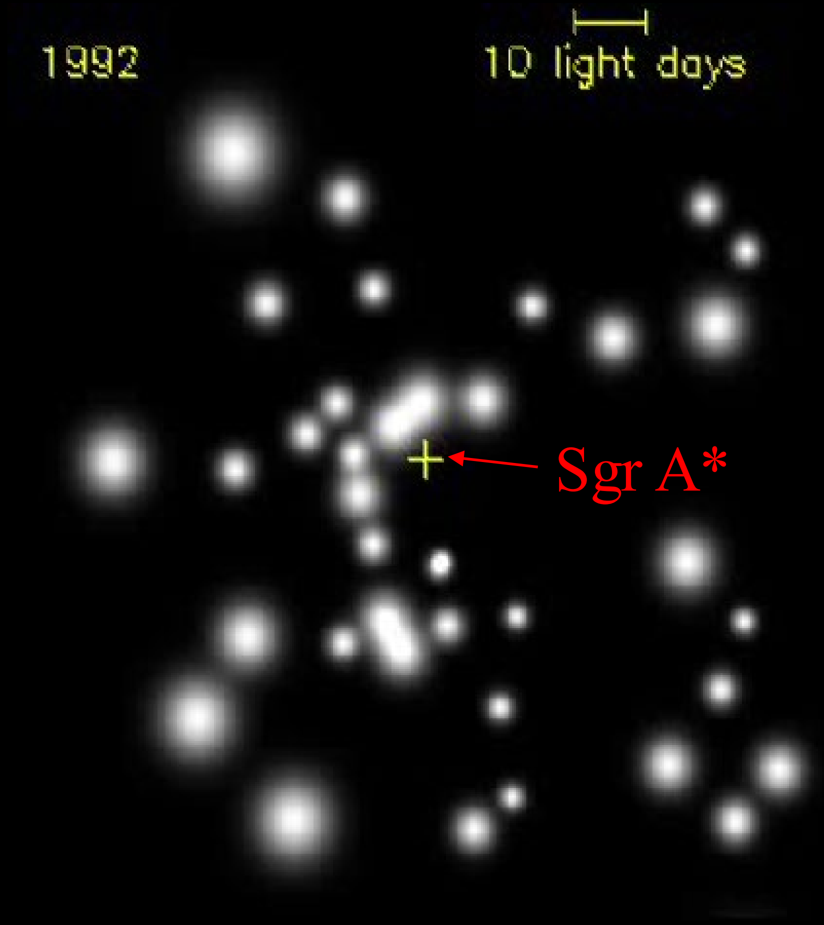
Diffraction-limited angular resolution

Image of a double star

With infrared adaptive optics on the Galactic Center

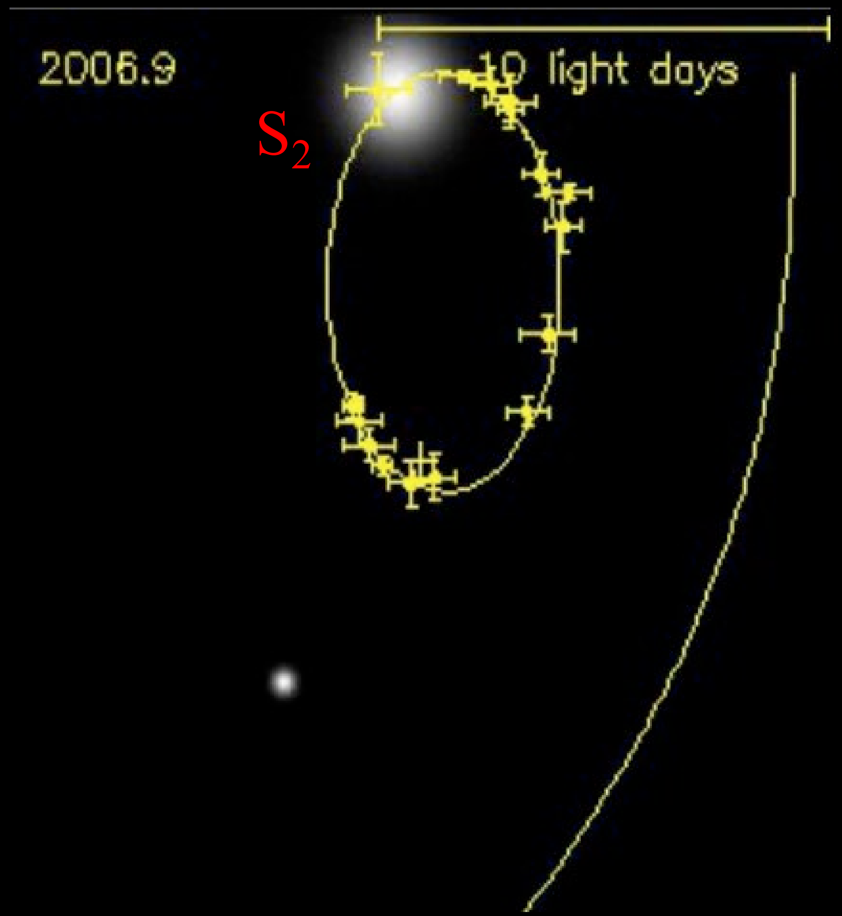


Orbit of the S_2 star observed with the NAOS VLT adaptive optics system



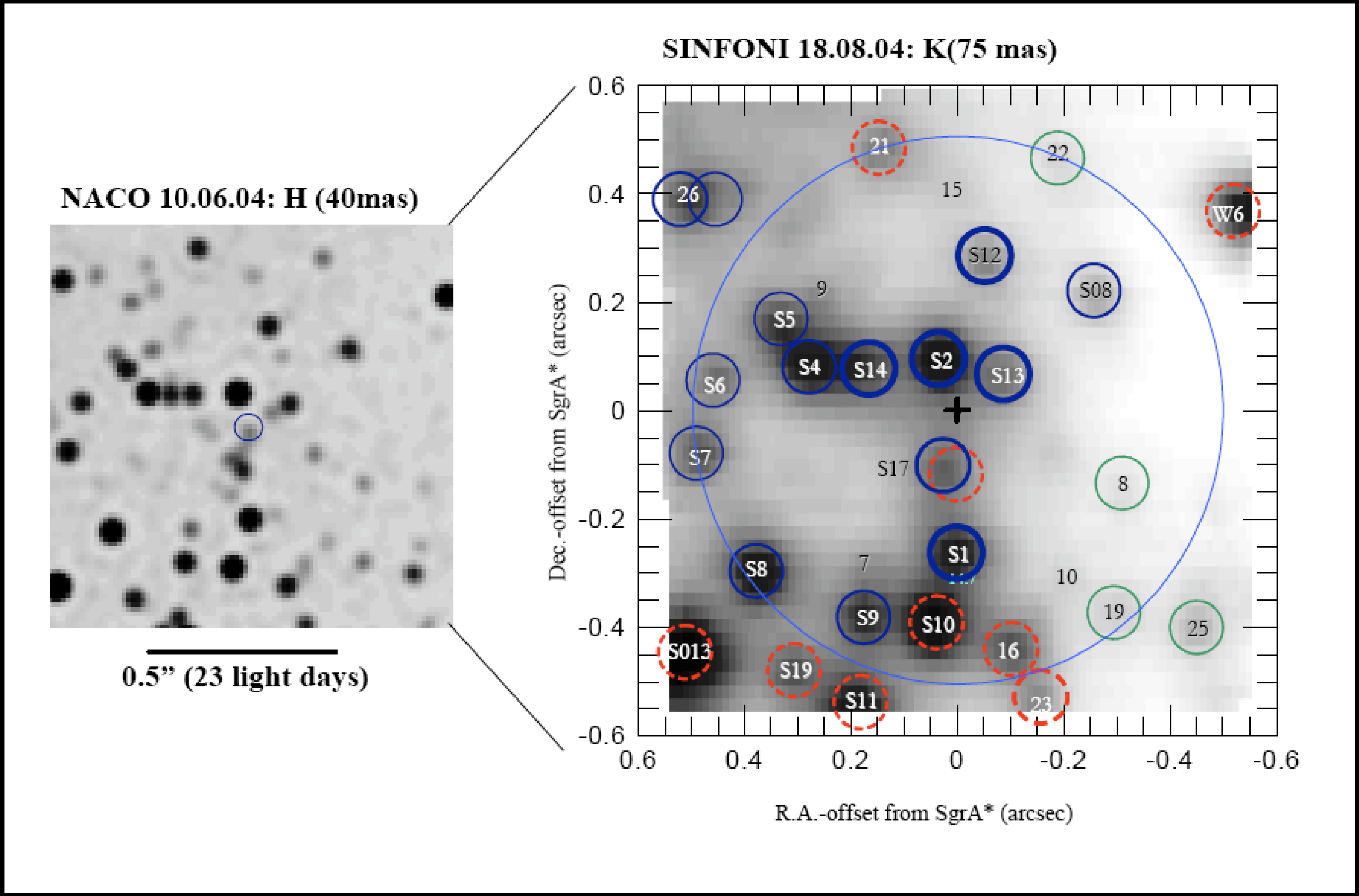
Schödel et al. (2002)

Orbit of the S_2 star observed with the NAOS VLT adaptive optics system

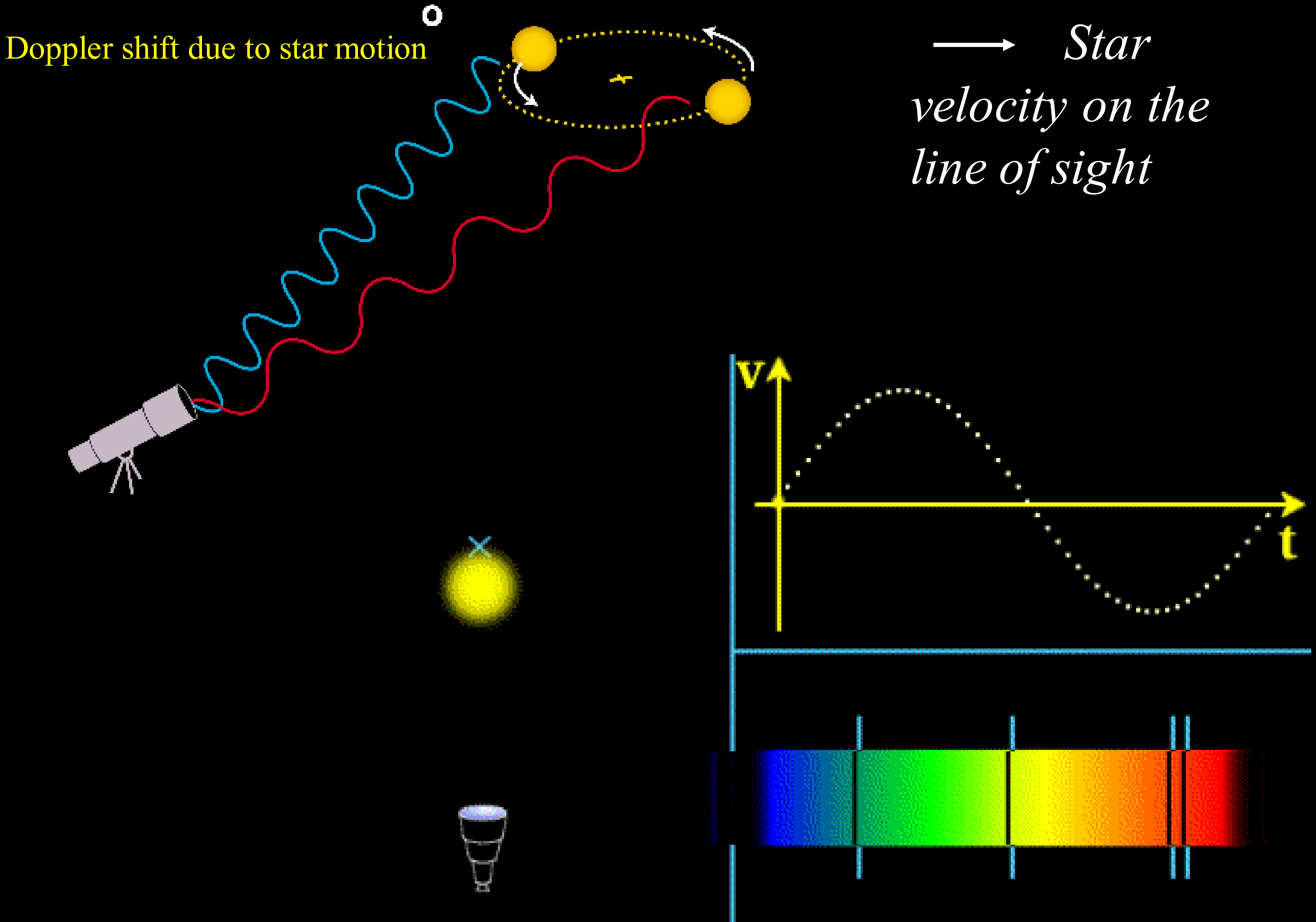


Schödel et al. (2002)

More orbits + spectroscopy



Eisenhauer et al. (2005)


Doppler shift due to star motion
Star
velocity on the
line of sight
v
t

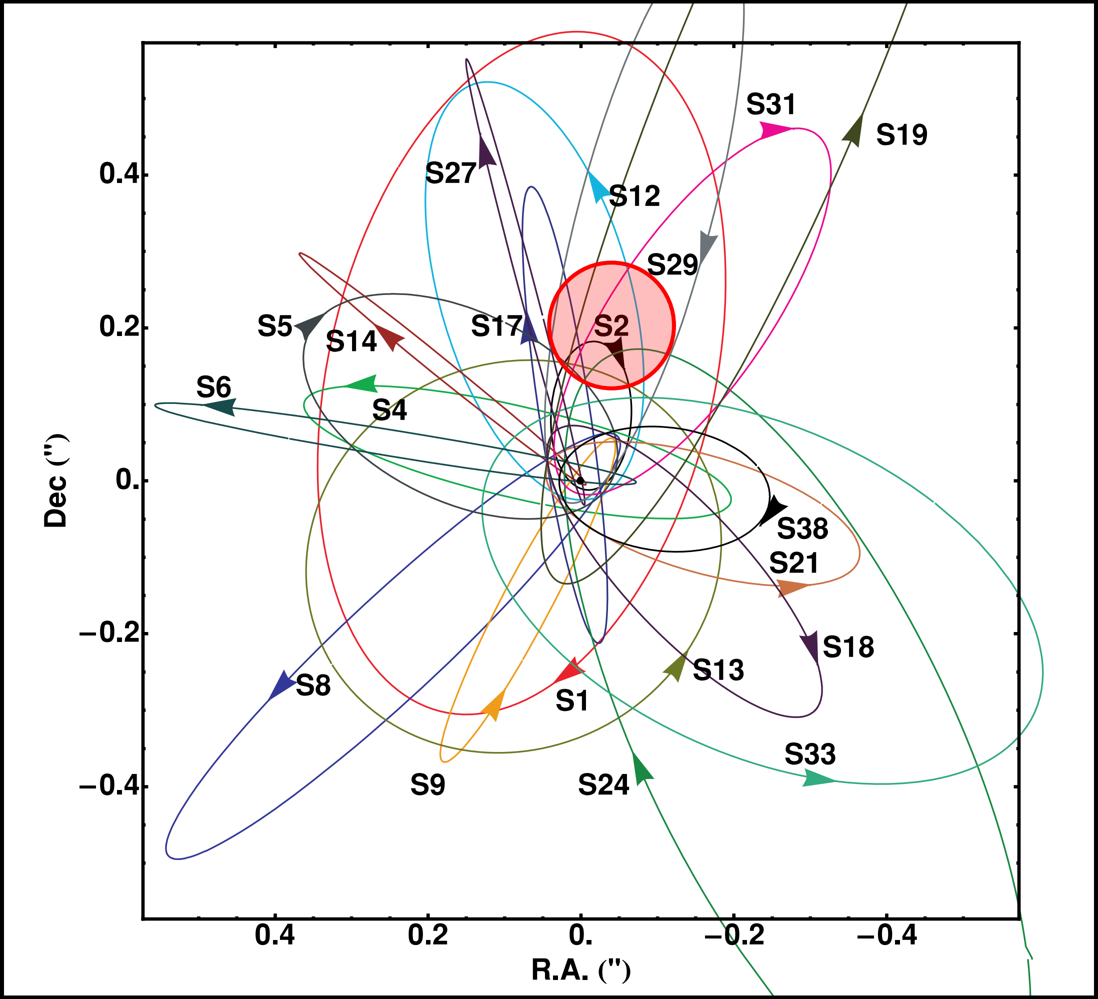
Acurate mass estimate for Sgr A*

3rd Kepler law:

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

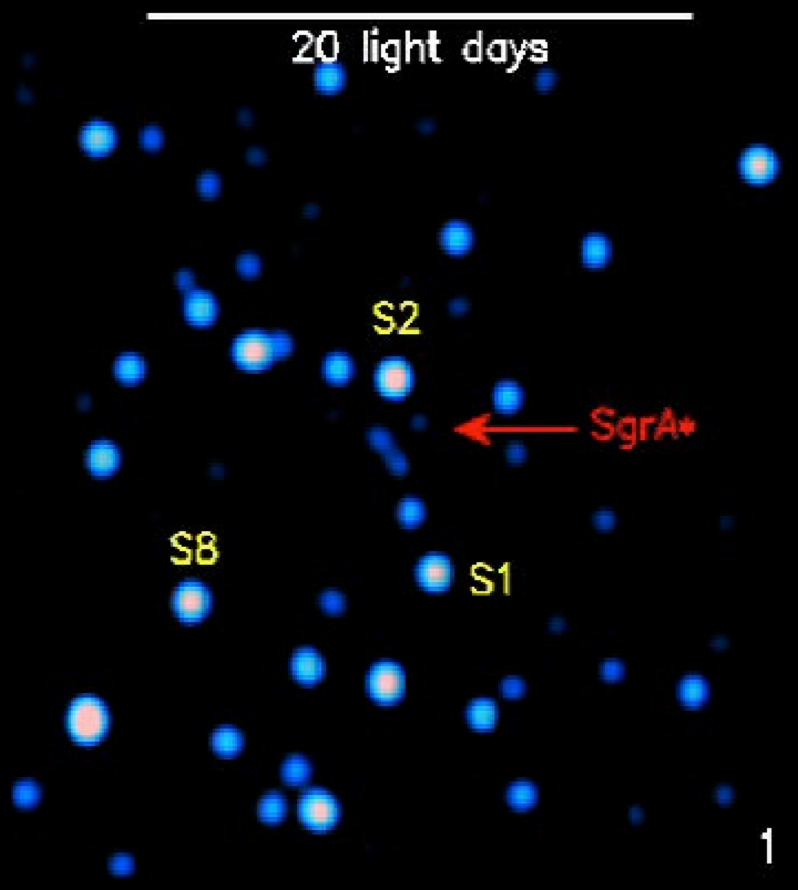
$M_{Sgr\ A^*} = 4.31 \pm 0.42 \times 10^6\ M_\odot$

$(d = 7.62 \pm 0.32\ \mathrm{kpc})$



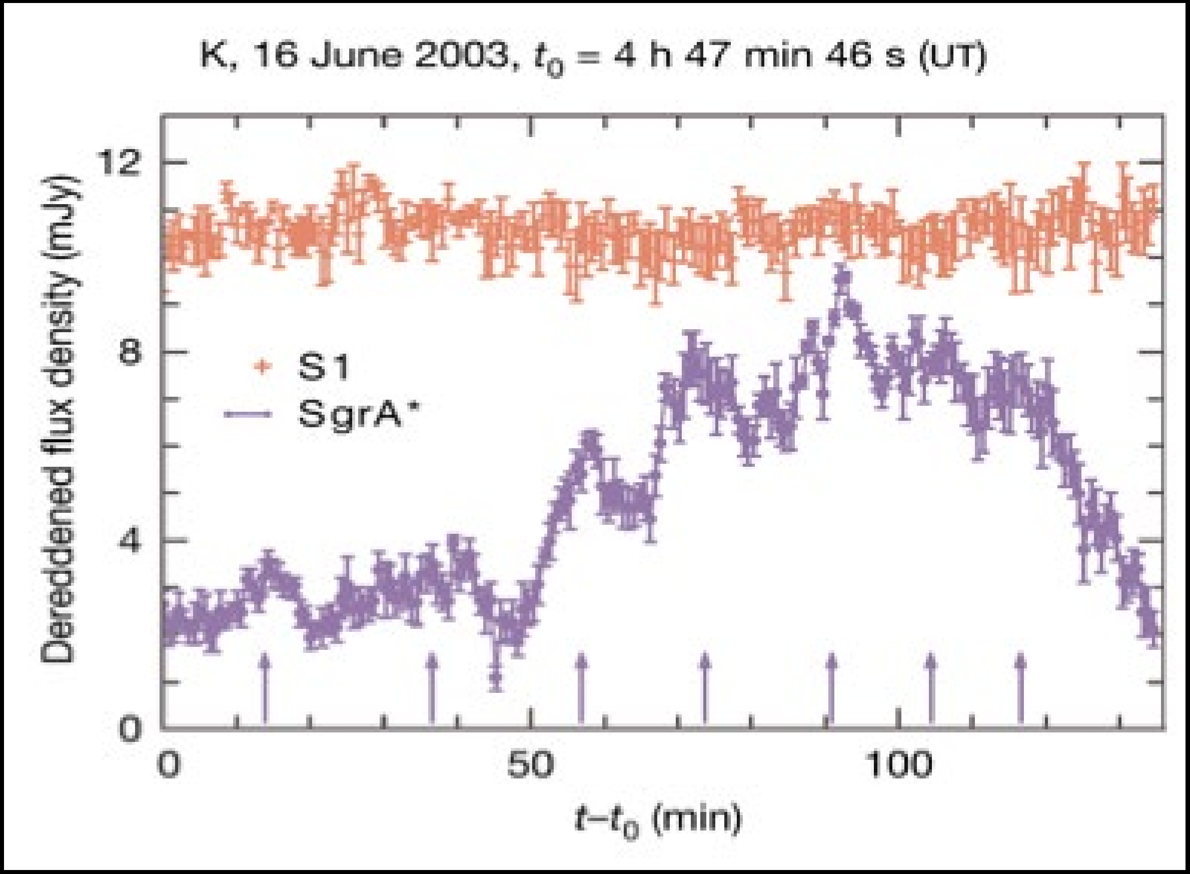
Gillessen et al. (2009)

Flares at the Galactic Center



Genzel et al. (2003)

The luminosity of the 2003 flare

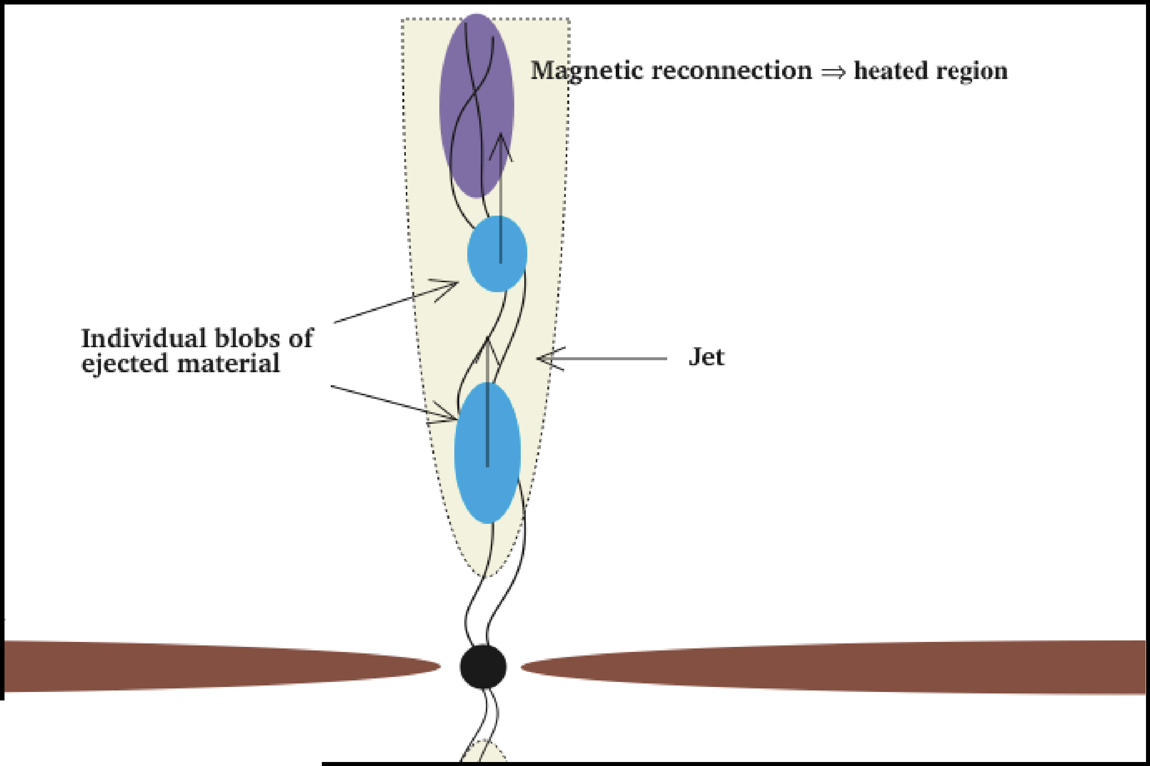


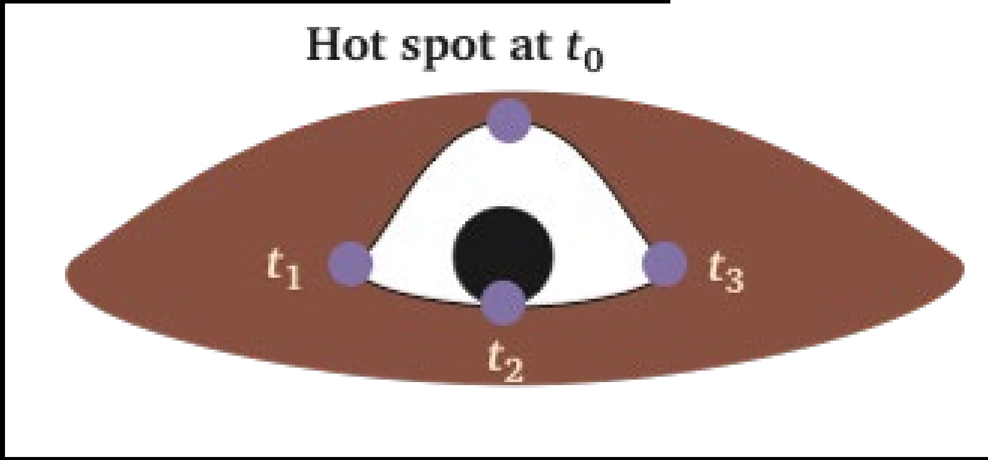
Genzel et al. (2003)

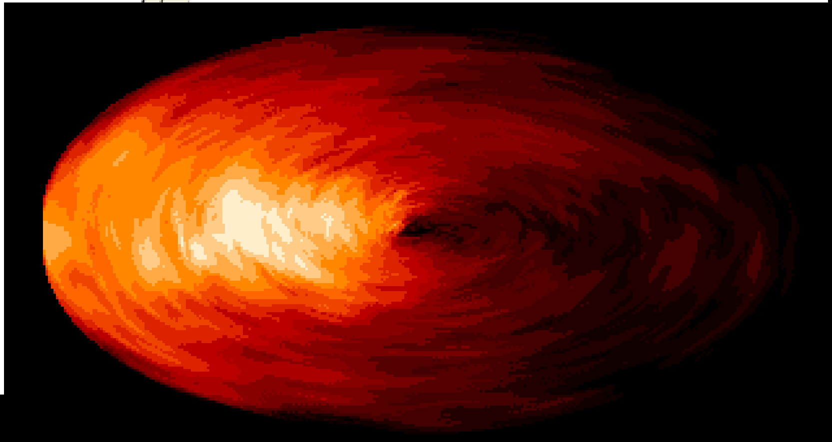
Flares at the Galactic Center

Three examples of scenarios:
- magnetic reconnection in jets
- hot spots (reconnection) at the ISCO
- statistical fluctuations

Characteristic scale: few 10 μas







Going further by increasing angular resolution

Studying relativistic effects with close stellar orbits

Understanding the nature of S stars and their distribution

Scale ~ 100 R_s 1 mas (x50)

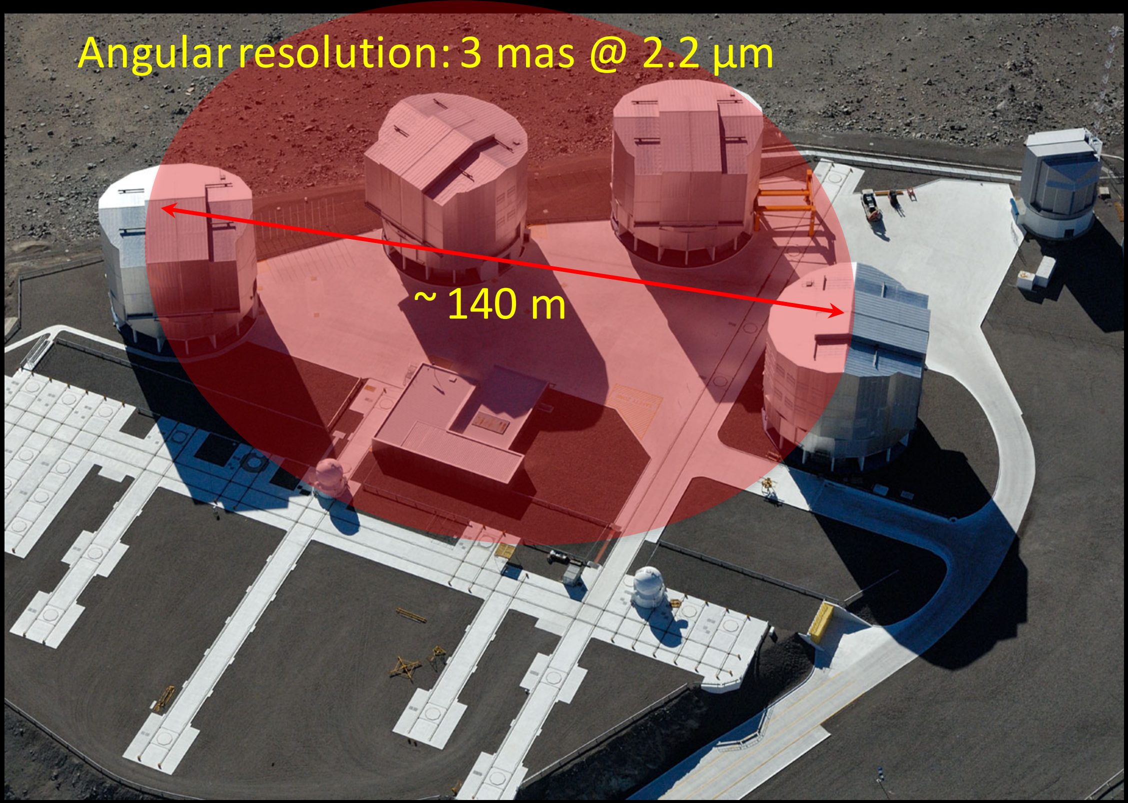
Bringing the evidence that Sgr A* is a black hole

Understanding the nature of the flares

Probing general relativity in the strong field regime

Scale ~ 1 R_s 10 μas (x5000)

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



GRAVITY: a distributed instrument on VLTI

In addition to the beam combiner:

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

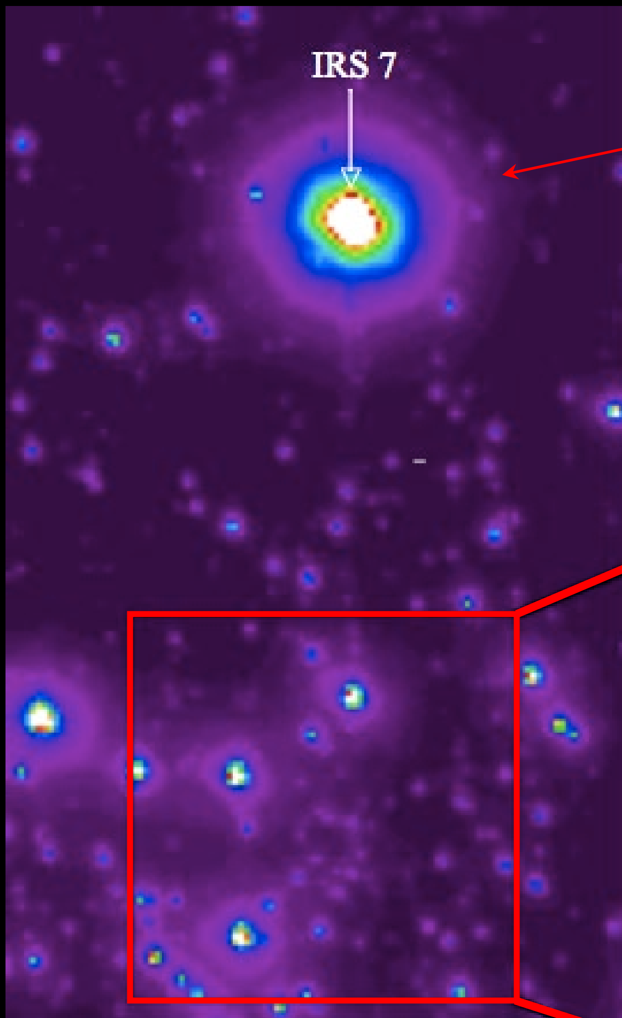
Eisenhauer+ 05,11

The GRAVITY consortium

Frank Eisenhauer, Guy Perrin, Wolfgang Brandner, Christian Straubmeier , Karine Perraut , Antonio Amorim , Markus Schöller, Reinhard Genzel, Pierre Kervella , Myriam Benisty, Sebastian Fischer , Laurent Jocou, Paulo Garcia, Gerd Jakob, Stefan Gillessen, Yann Clénet , Armin Boehm, Constanza Araujo-Hauck, Jean-Philippe Berger, Jorge Lima, Roberto Abuter, Oliver Pfuhl, Thibaut Paumard, Casey P. Deen, Michael Wiest , Thibaut Moulin, Jaime Villate, Gerardo Avila, Marcus Haug, Sylvestre Lacour , Thomas Henning, Senol Yazici , Axelle Nolot , Pedro Carvas, Reinhold Dorn, Stefan Kellner, Eric Gendron, Stefan Hippler, Andreas Eckart , Sonia Anton, Yves Jung, Alexander Gräter, Élodie Choquet , Armin Huber, Narsireddy Anugu , Philippe Gitton, Eckhard Sturm, Frédéric Vincent , Sarah Kendrew, Stefan Ströbele, Clemens Kister, Pierre Fédou, Ralf Klein, Paul Jolley, Magdalena Lippa, Vincent Lapeyrère, Natalia Kudryavtseva, Christian Lucuix, Ekkehard Wieprecht, Frédéric Chapron, Werner Laun, Leander Mehrgan, Thomas Ott, Gérard Rousset , Rainer Lenzen, Marcos Suarez, Reiner Hofmann, Jean-Michel Reess, Vianak Naranjo, Pierre Haguenauer, Oliver Hans, Arnaud Sevin , Udo Neumann, Jean-Louis Lizon, Markus Thiel, Claude Collin , Jose Ricardo Ramos, Gert Finger, David Moch, Daniel Rouan, Ralf-Rainer Rohloff, Markus Wittkowski, Richard Davies, Denis Ziegler , Karl Wagner, Henri Bonnet, Katie Dodds-Eden, Frédéric Cassaing, Pengqian Yang, Florian Kerber, Sebastian Rabien, Nabih Azouaoui, Frederic Gonte, Josef Eder, Vartan Arslanyan, Willem-Jan de Wit, Frank Hausmann, Roderick Dembet, Luca Pasquini, Harald Weisz, Pierre Lena, Mark Casali, Bernard Lazareff, Zoltan Hubert, Jean-Baptiste Le Bouquin

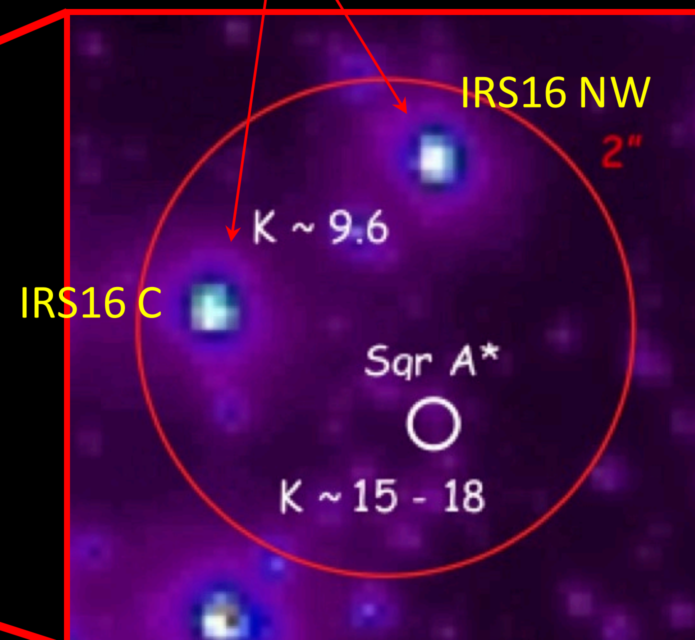
The GRAVITY consortium

Principle of the GRAVITY measurements



Reference source for infrared adaptive optics

Reference sources for fringe tracking and phase referencing for astrometry and imaging



Interferometric astrometry

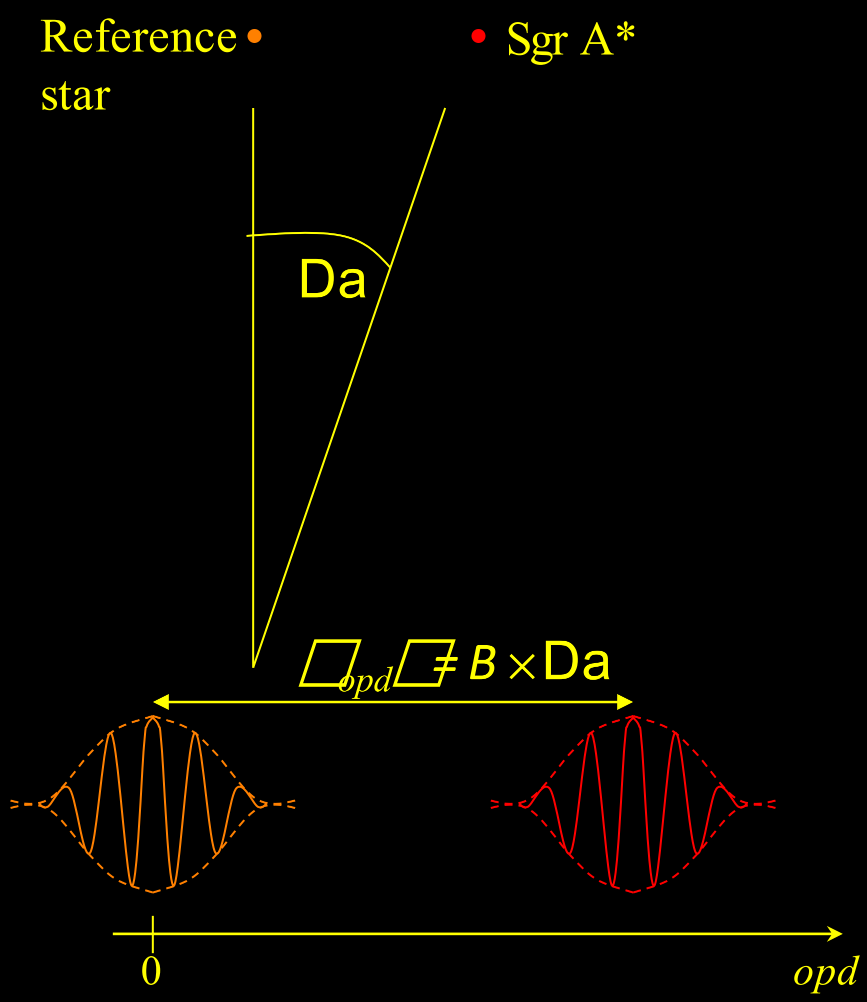
Distance between interferograms:

$$D_{opd} = B \times Da$$

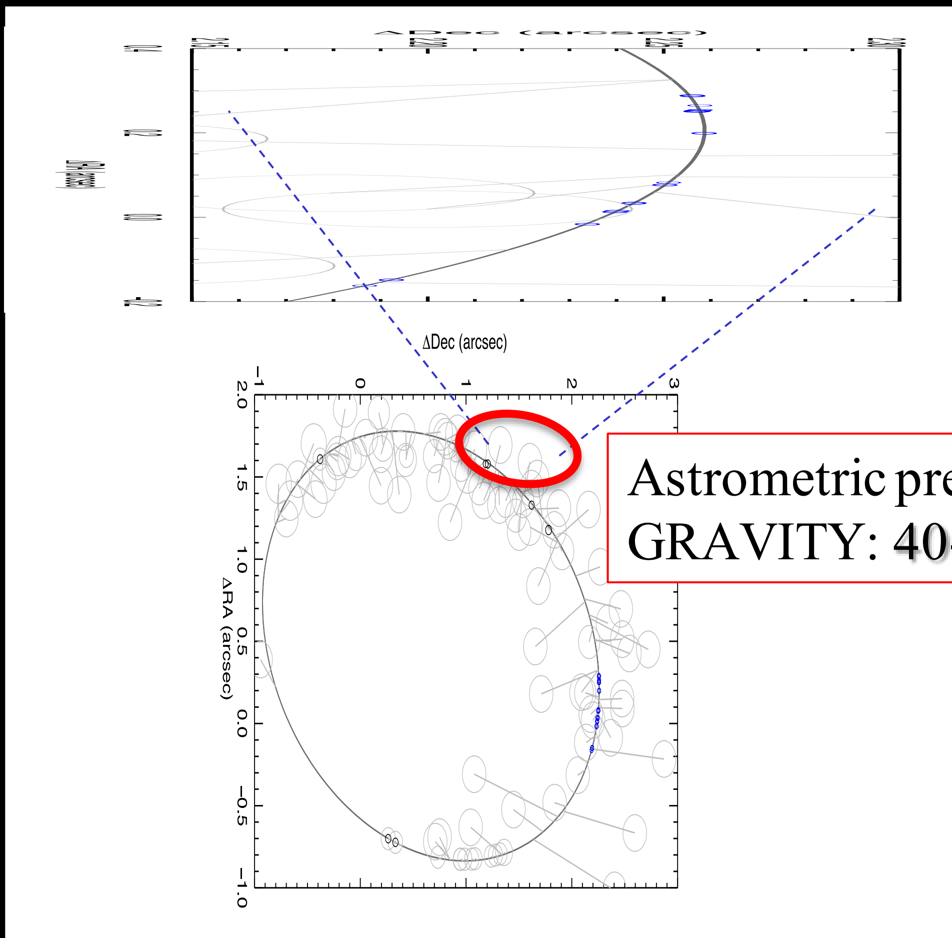
Hence:

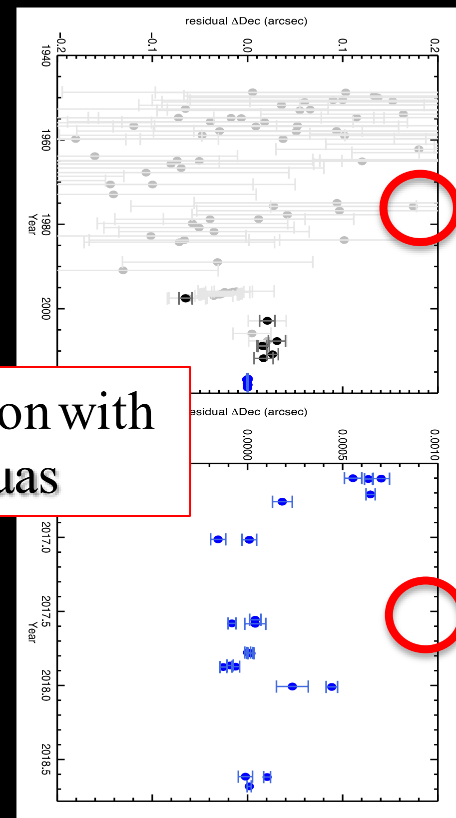
$$Da = D_{opd} / B$$

A precision of 5 nm on D_{opd} with a 100 m baseline yields and accuracy of 10 µas on Da.



Gliese 65AB

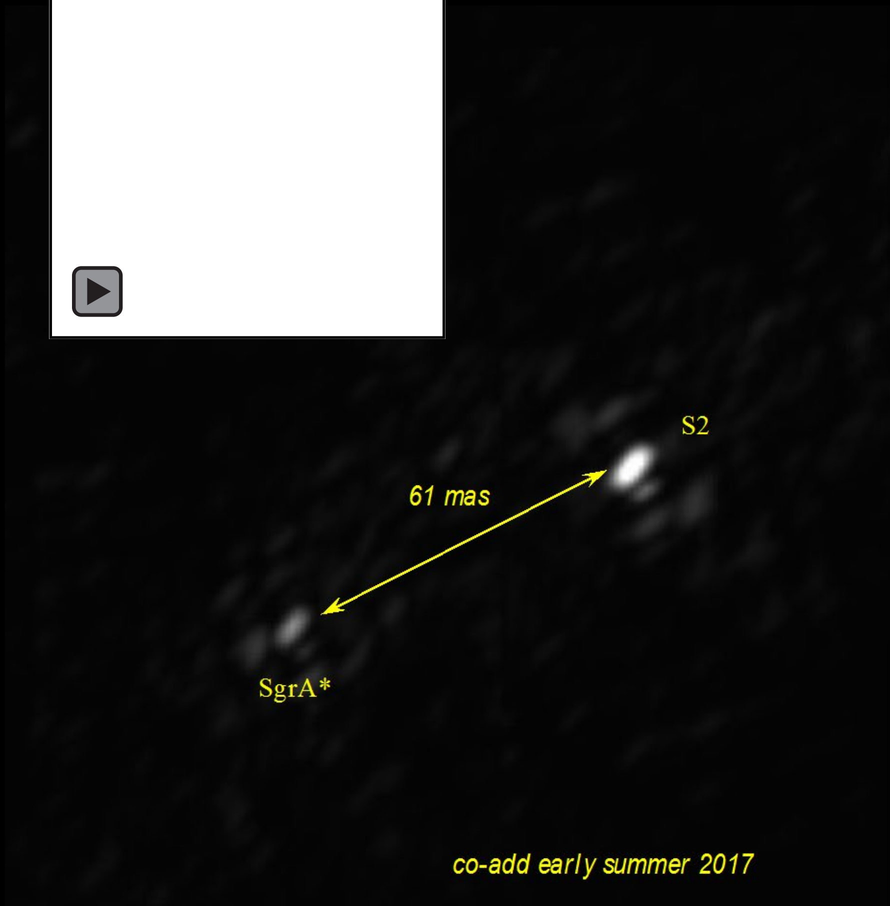


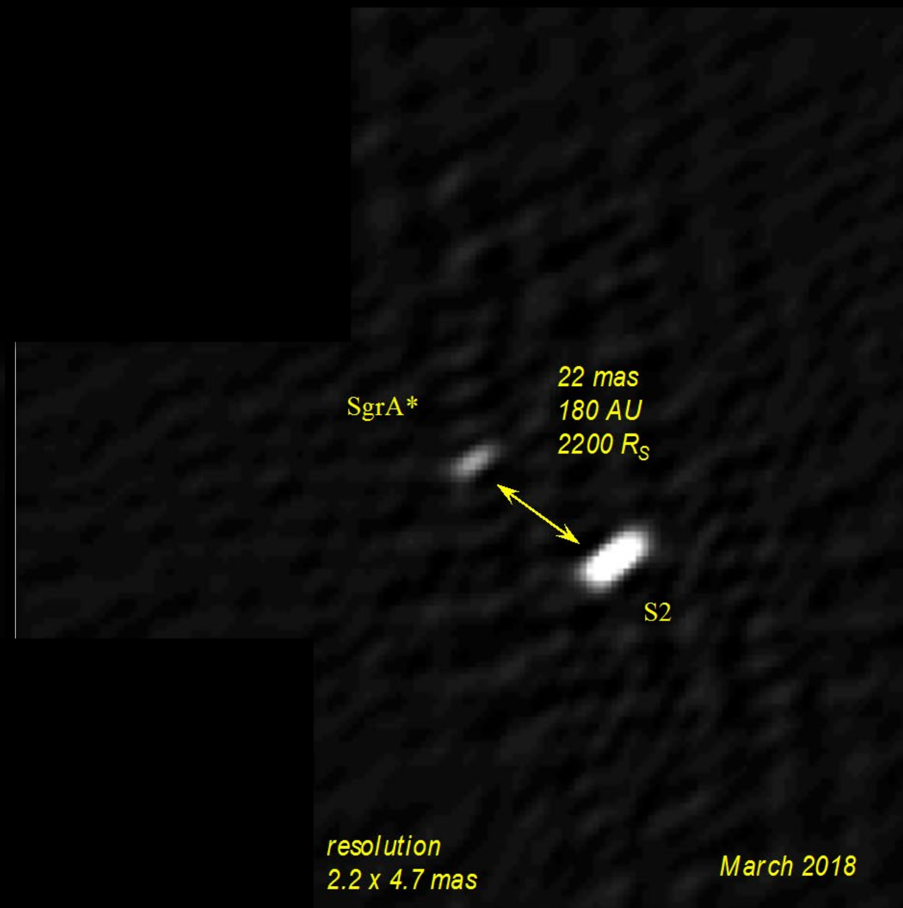


Astrometric precision with GRAVITY: 40-60 μas

GRAVITY collaboration Abuter et al., A&A 602, A94 (2017), GRAVITY collaboration *in preparation*

Reconstructed images of S2 and Sgr A*





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*

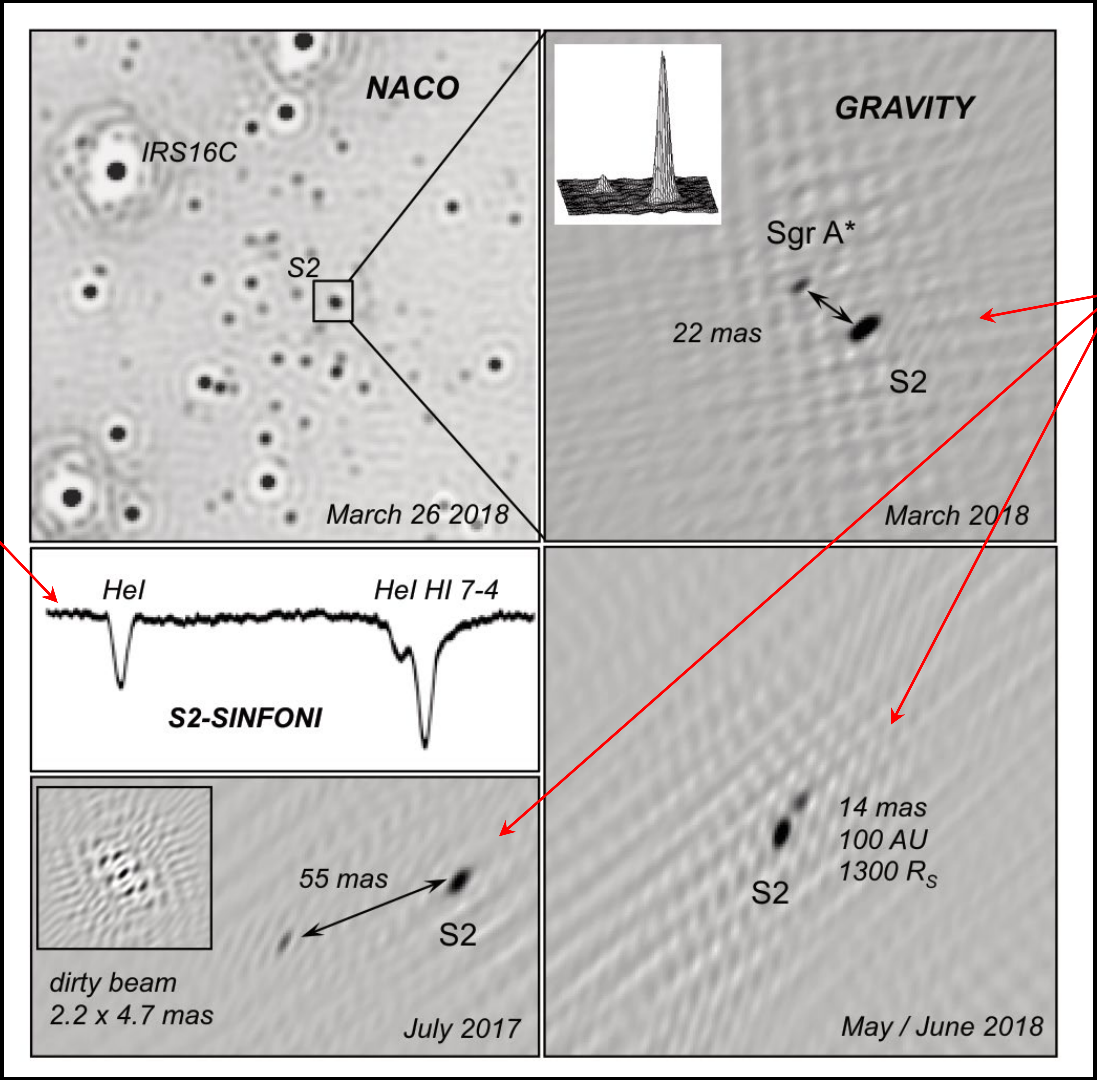
GRAVITY Collaboration**: R. Abuter[8], A. Amorim[6,14], N. Anugu[7], M. Bauböck[1], M. Benisty[5], J. P. Berger[5,8], N. Blind[10], H. Bonnet[8], W. Brandner[3], A. Buron[1], C. Collin[2], F. Chapron[2], Y. Clénet[2], V. Coudé du Foresto[2], P. T. de Zeeuw[12,1], C. Deen[1], F. Delplancke-Ströbele[8], 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)

Received 26 June 2018 / Accepted 29 June 2018

Detection of gravitational redshift with S2

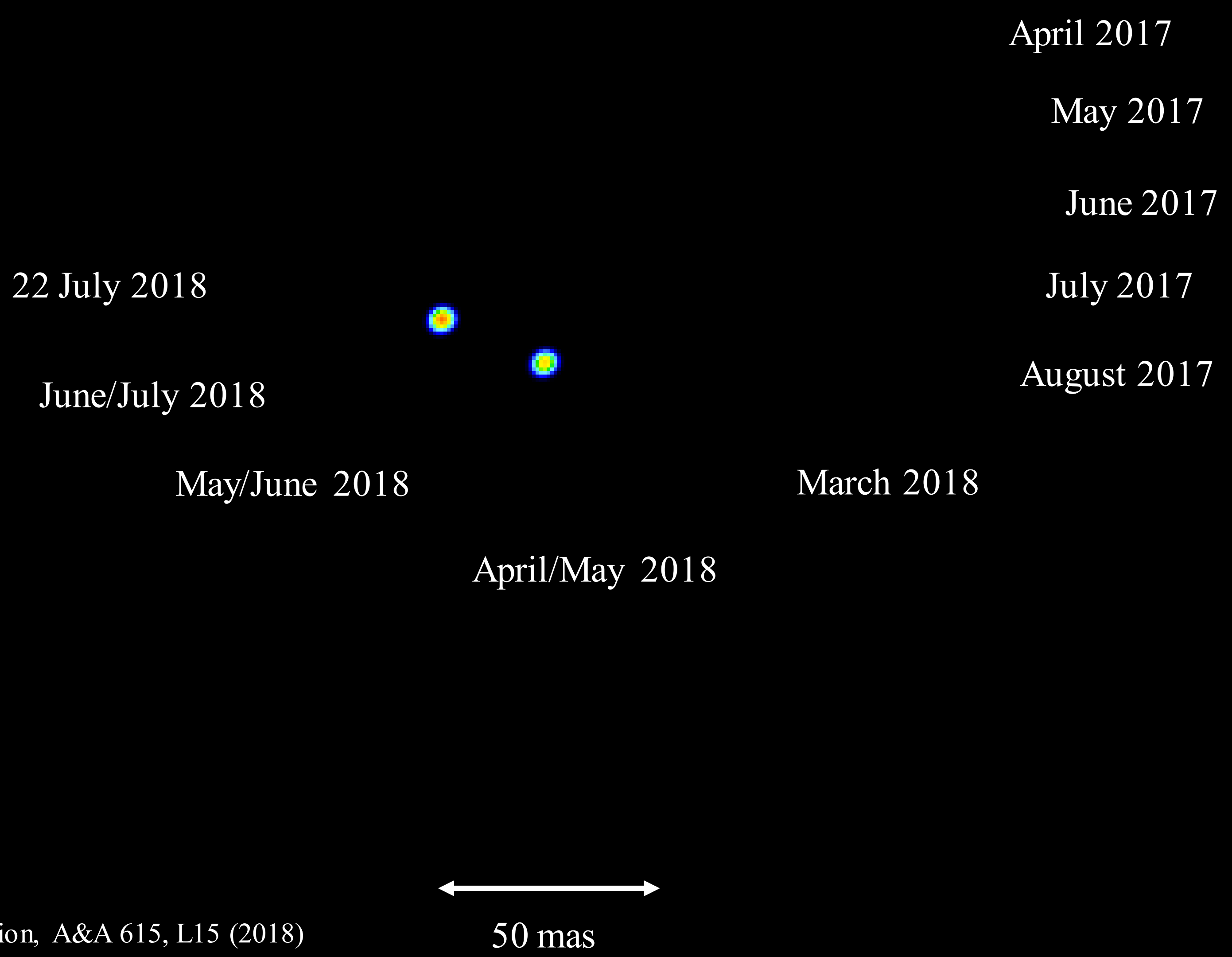
Spectroscopy (velocities)



Imaging and relative astrometry to Sgr A*

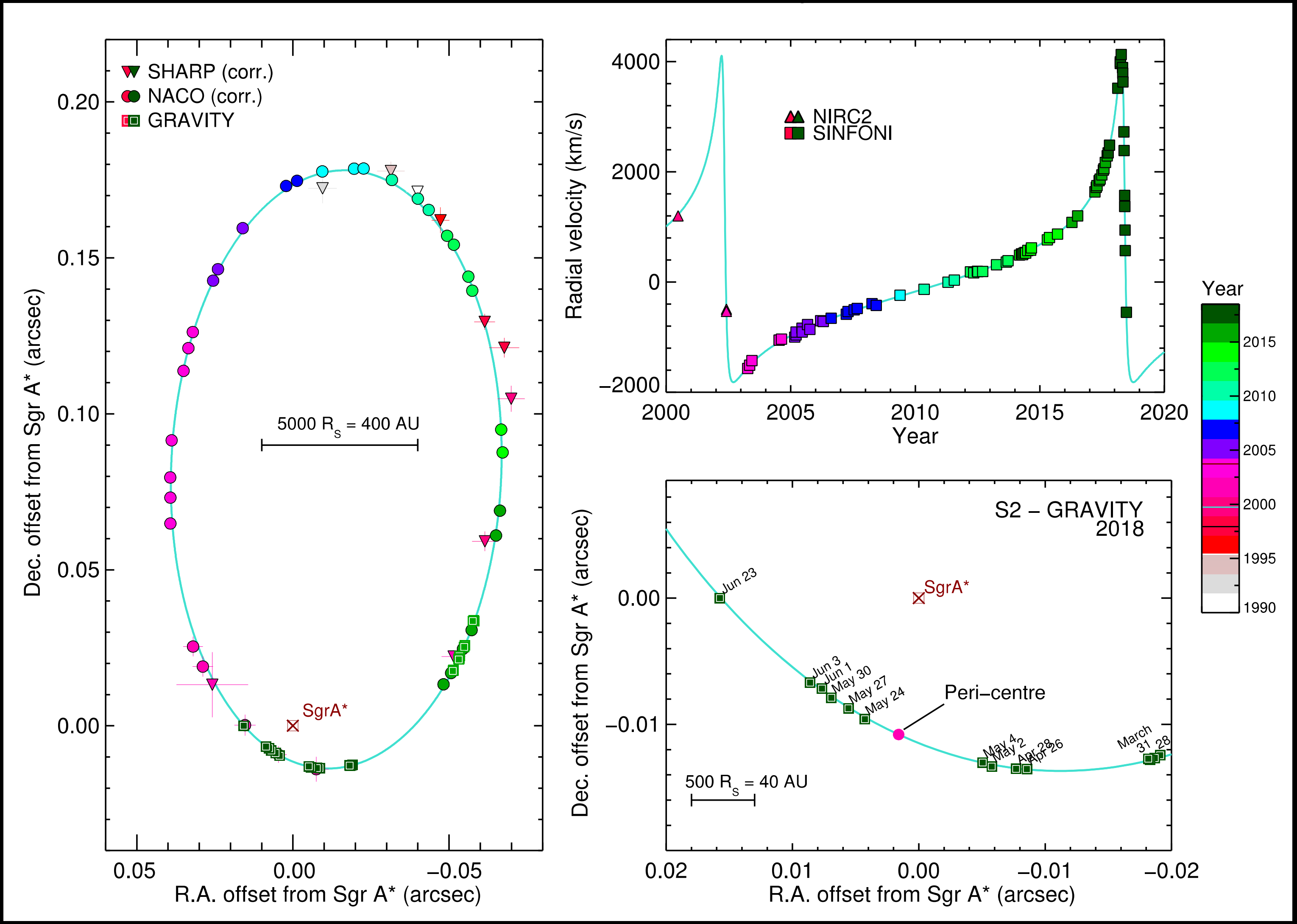
GRAVITY Collaboration, A&A 615, L15 (2018)

Tracking of S2 position with GRAVITY



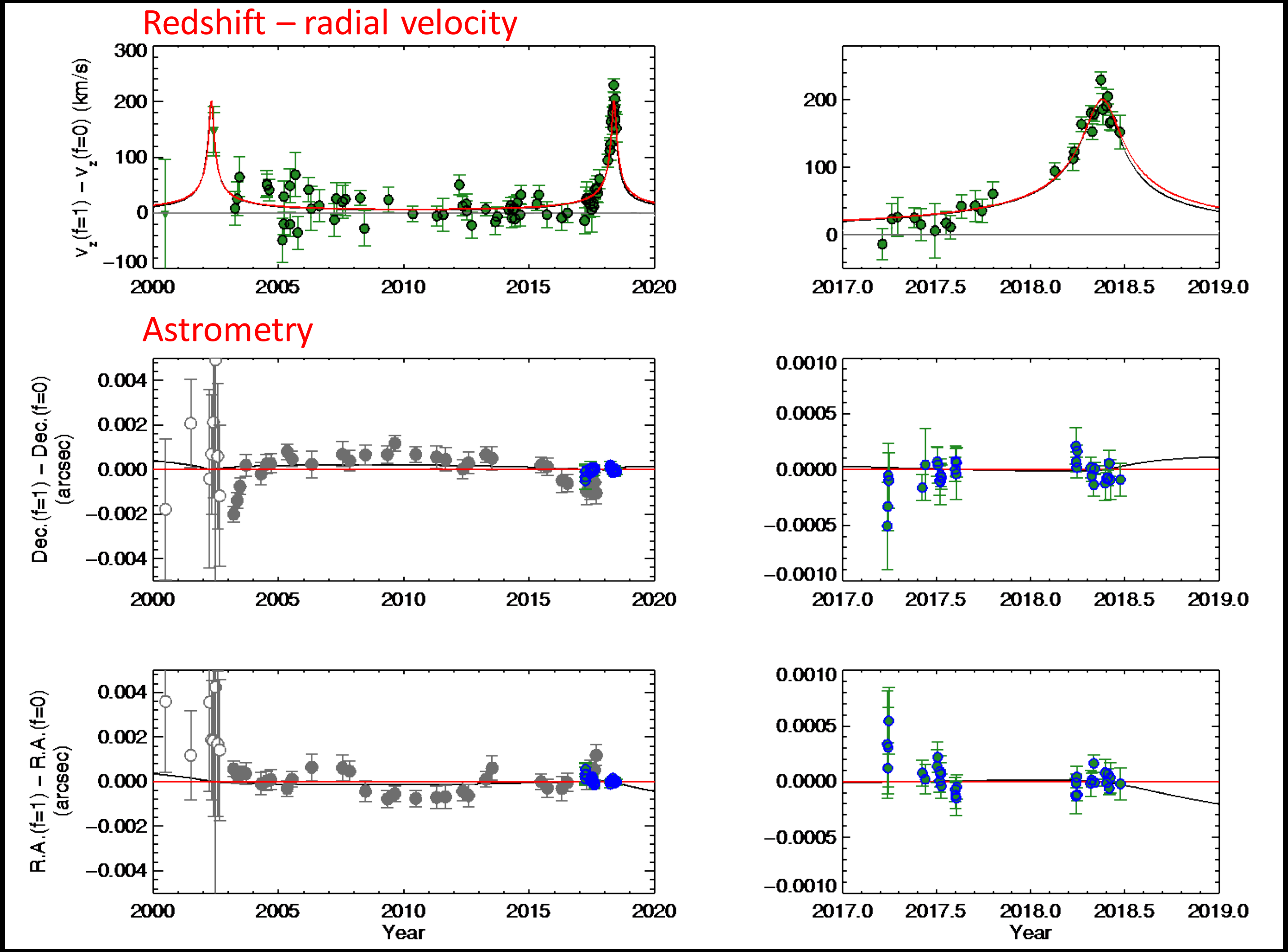
GRAVITY Collaboration, A&A 615, L15 (2018)

The S2 dataset



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

Fitting with a relativistic orbit



$f = 0$: Newton

$f = 1$: Einstein (post-newtonian approximation)

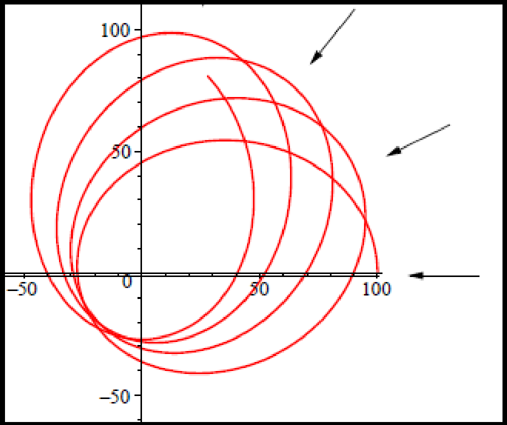
GRAVITY result:
$f = 0.94 \pm 0.09$

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)

Measuring the relativistic precession of S2

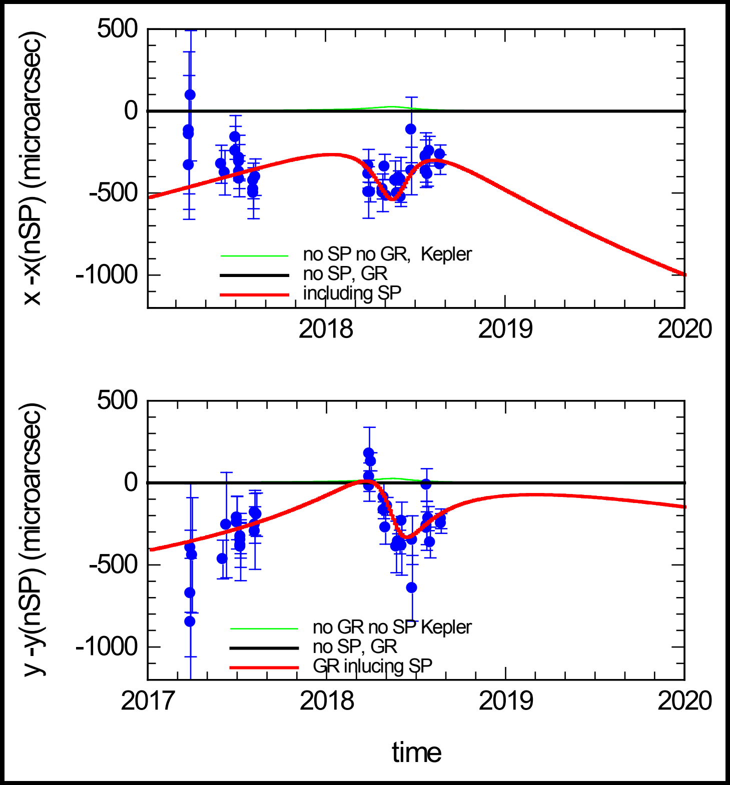


Jaroszynski 98

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

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

$S2 : 11.9'$



With the current data (up to Sep 2018):

f_{SP}=1.3±0.8

Robust detection in 2019

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

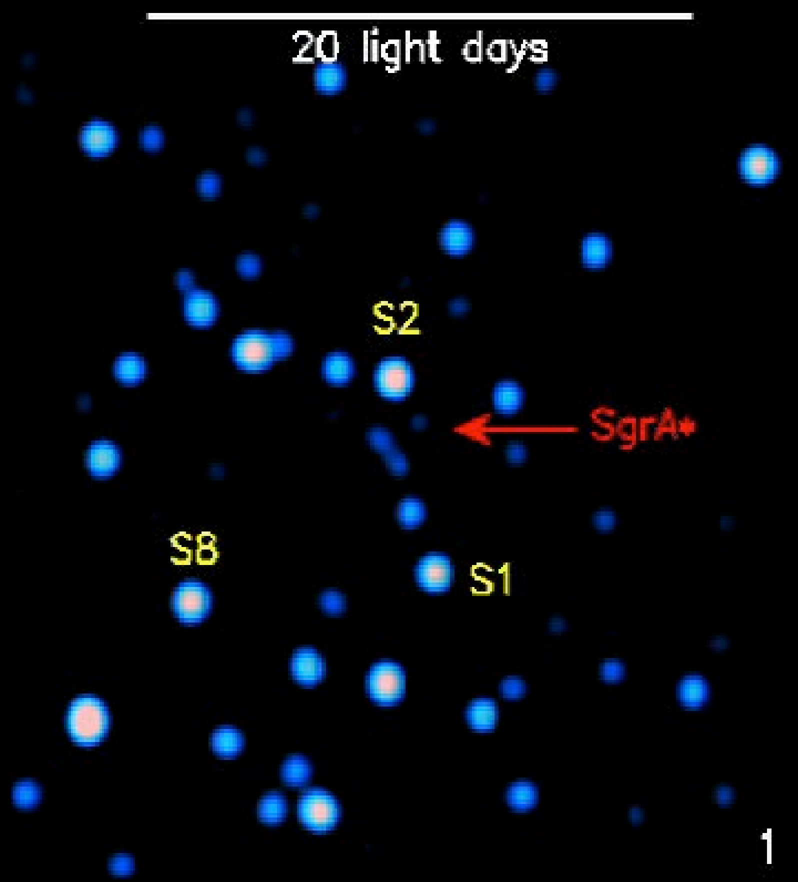
Detection of orbital motions near the last stable circular orbit of the massive black hole SgrA*★

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)

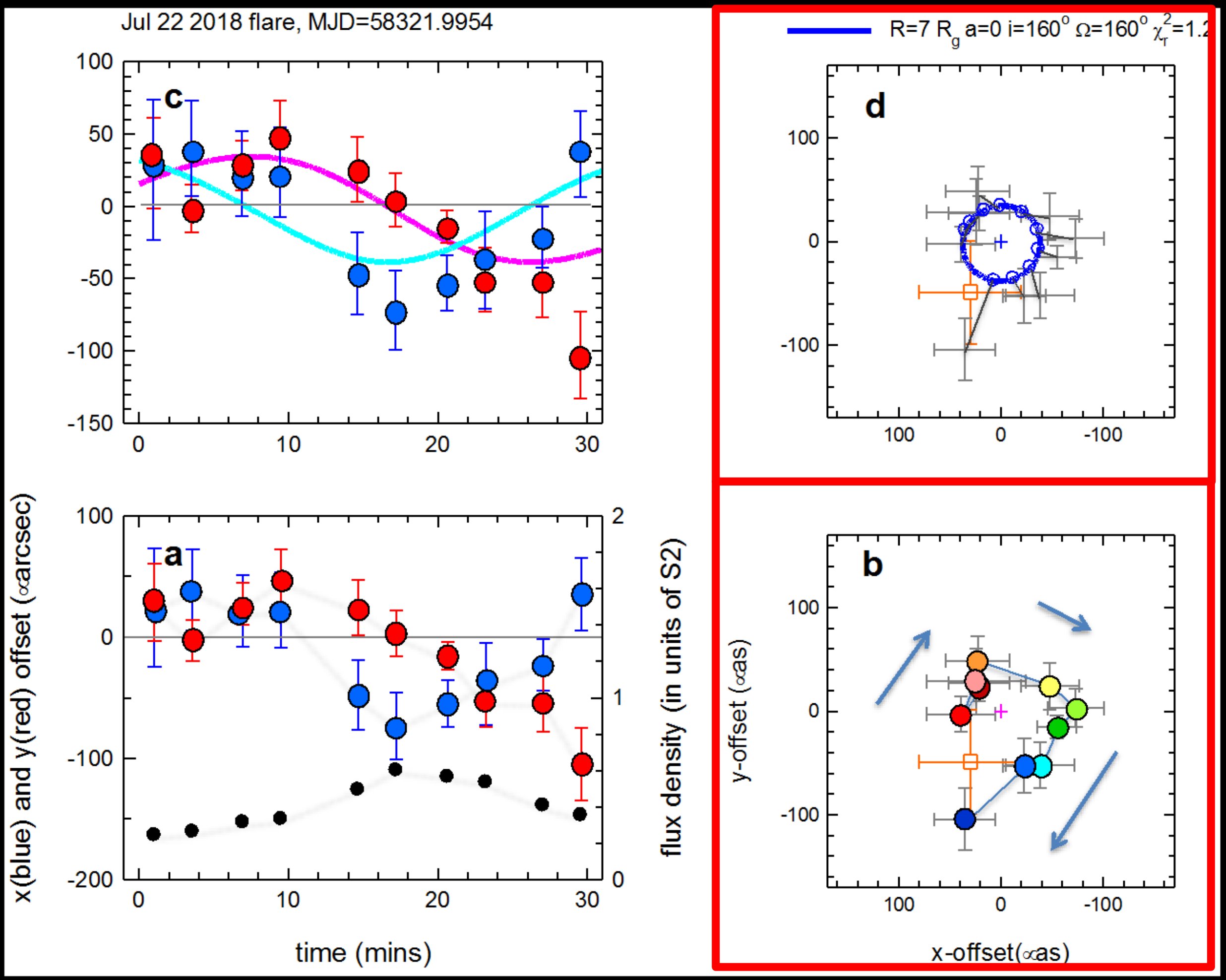
Received 21 September 2018 / Accepted 5 October 2018

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 (GYOTO, Vincent et al. 2011)

Schwarzschild case (a=0):

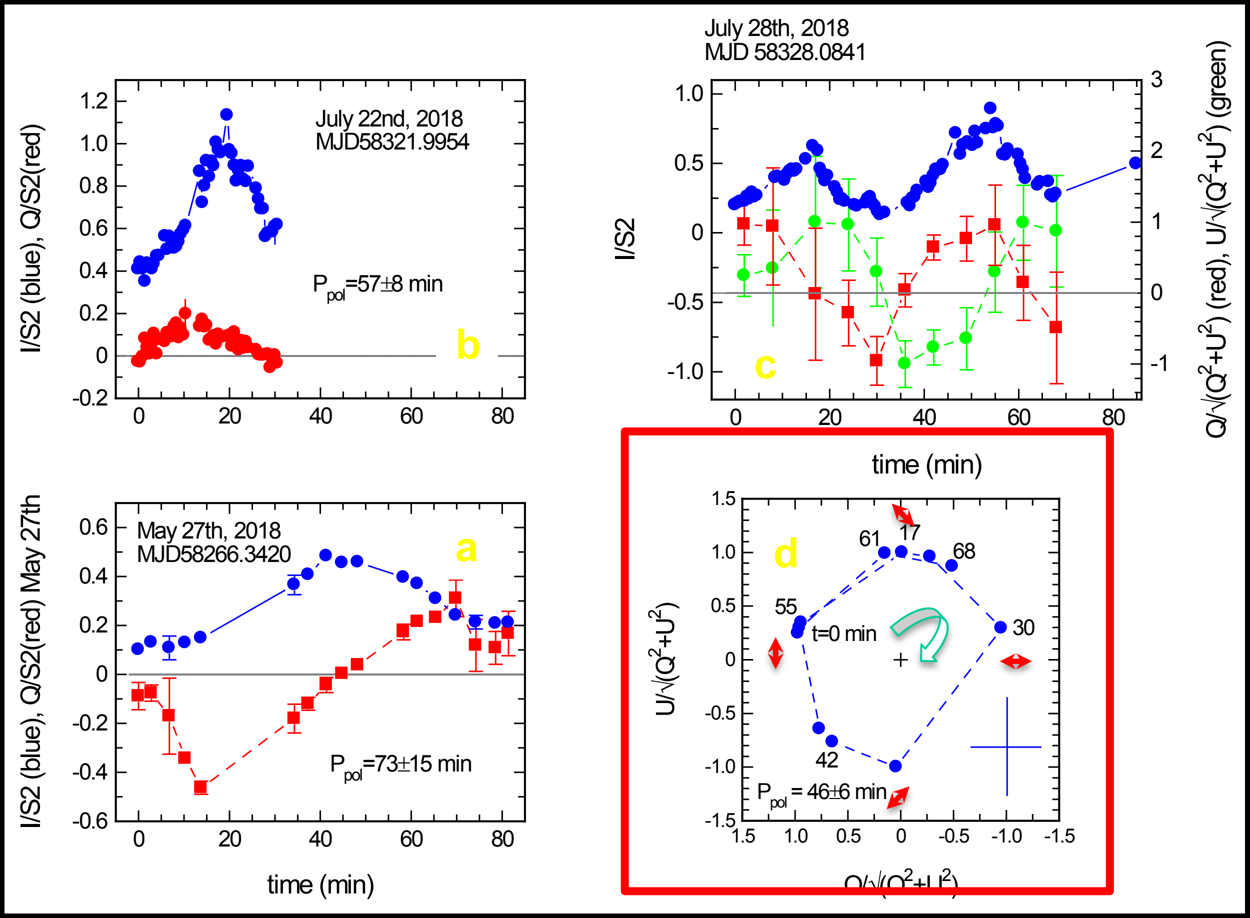
$R = 7.3 \pm 0.5\ R_g$

$P = 40 \pm 8$ min

$\Rightarrow v_{orb} \sim 0.3$ c

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

Polarization loops



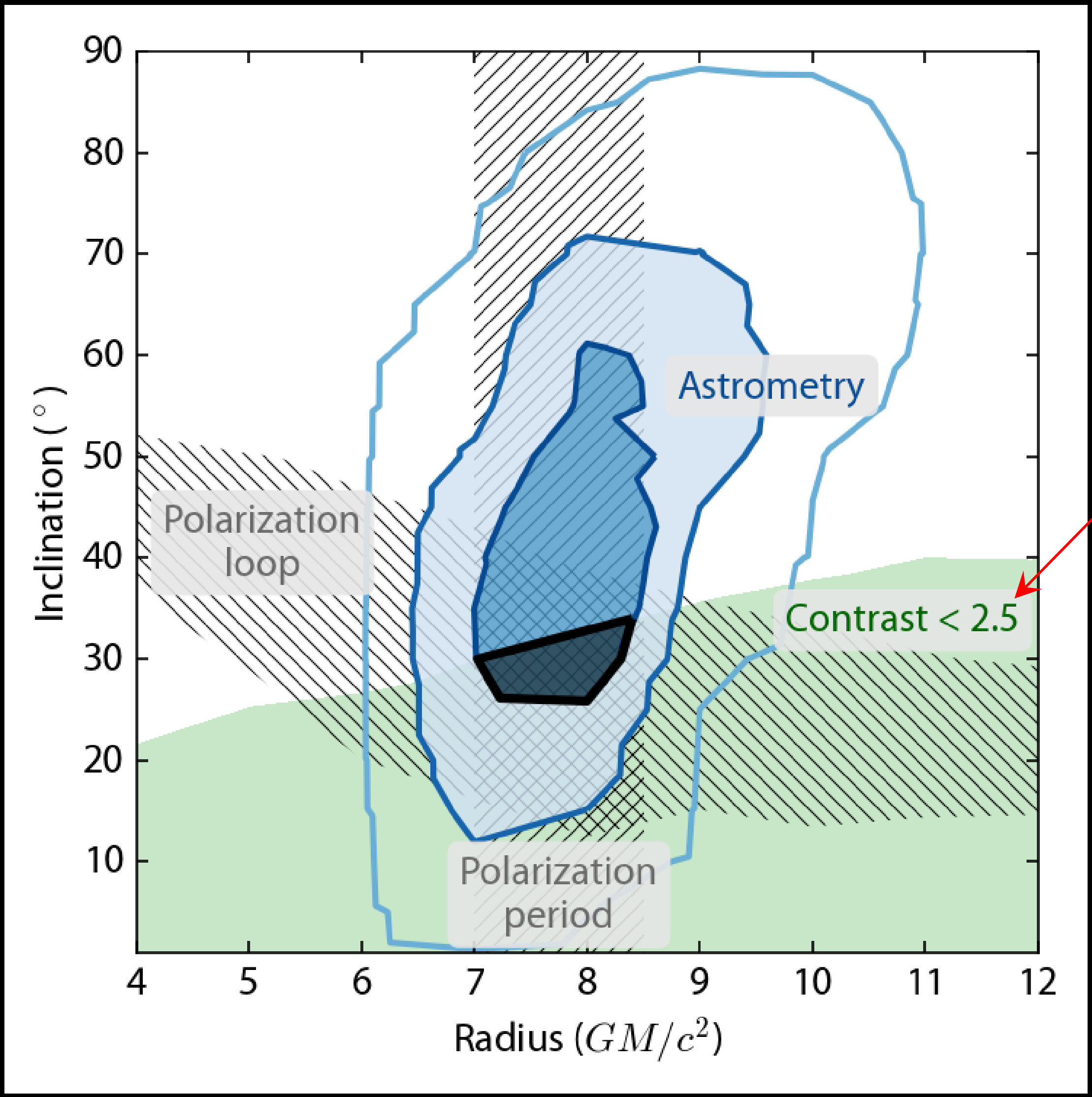
Poloidal magnetic field (perpendicular to orbital plane)

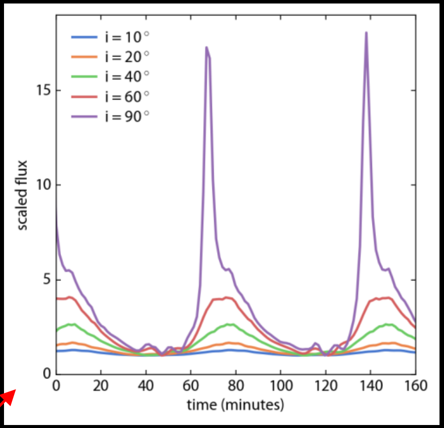
Light bending by Sgr A* adds an azimutal component to polarization with an orbit-like motion

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

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

Constraint on inclination and orbital radius

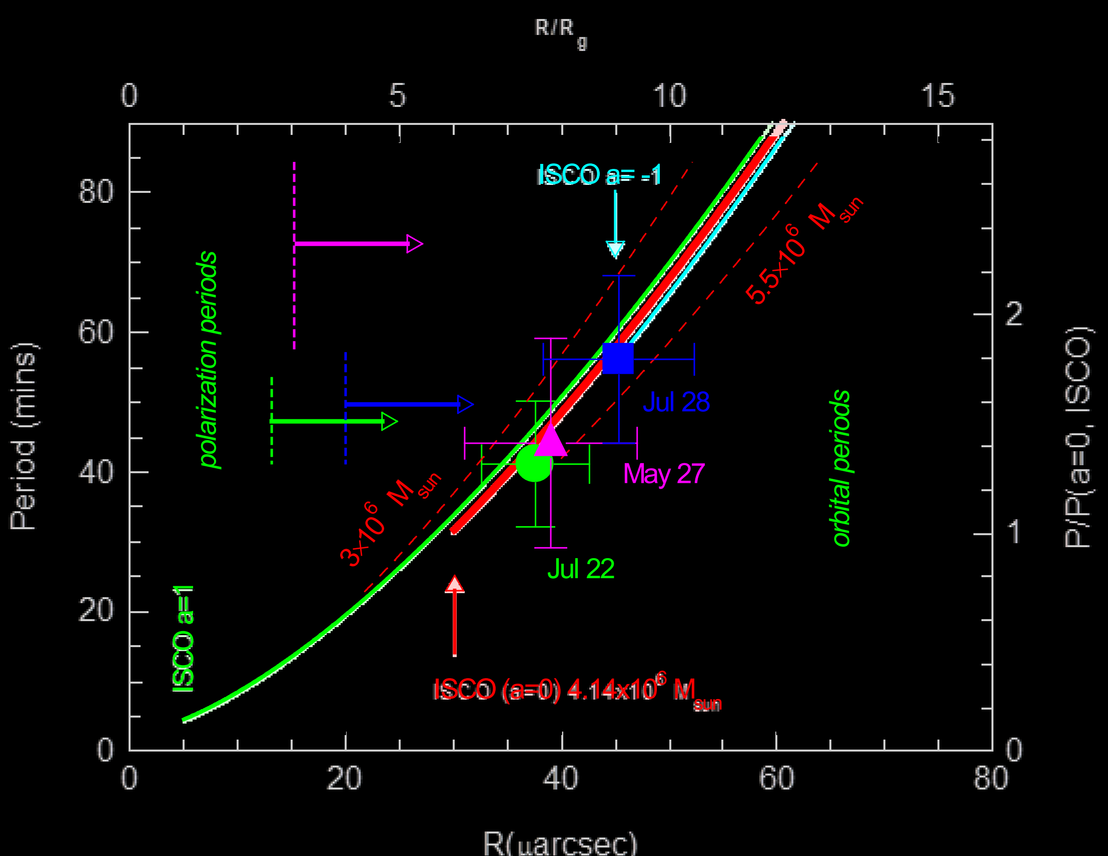




$R = 7.6 \pm 0.5\ Rg$ and inclination $i \leq\ 30$

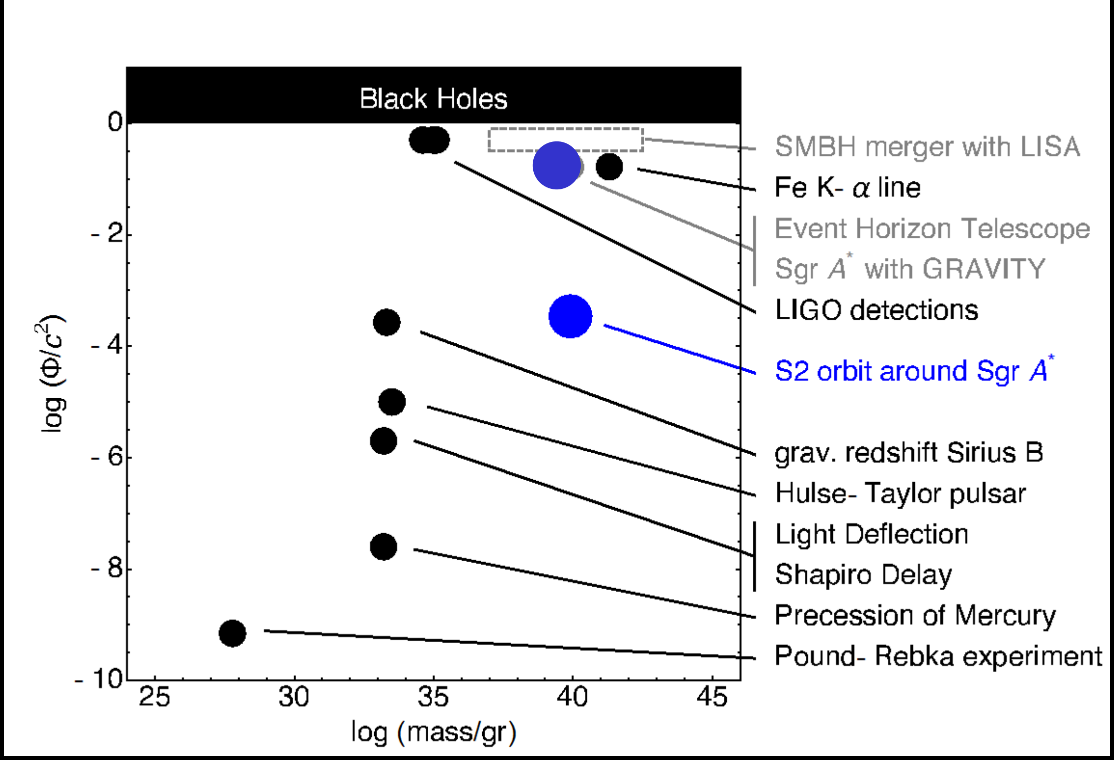
GRAVITY Collaboration, A&A 618, L10 (2018)

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



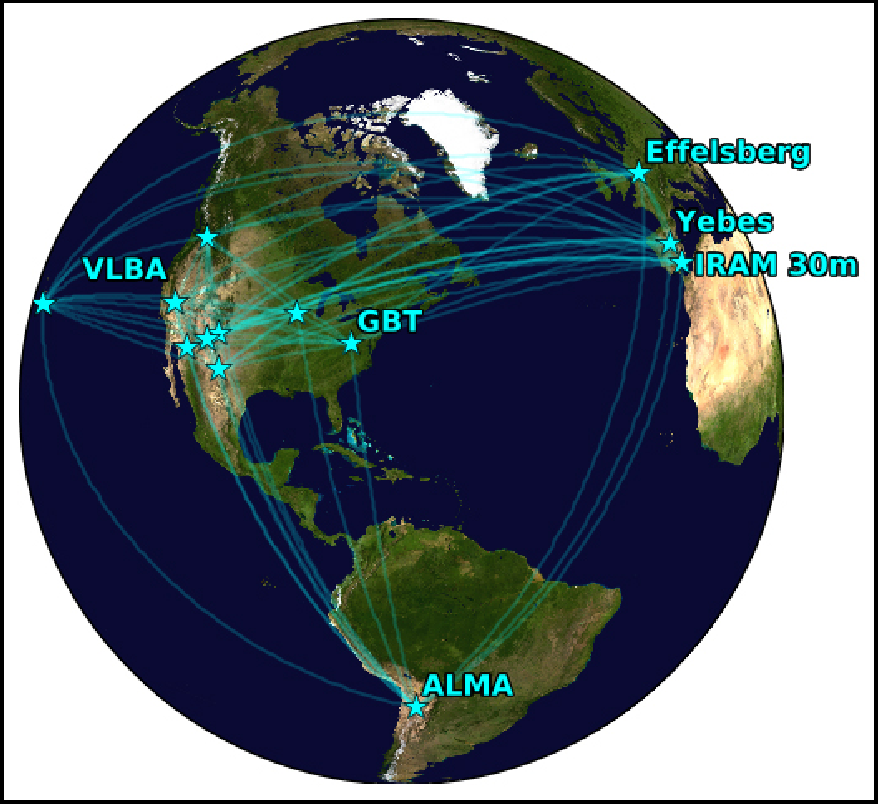
GRAVITY Collaboration, A&A 618, L10 (2018)

Contributions of GRAVITY to tests of general relativity

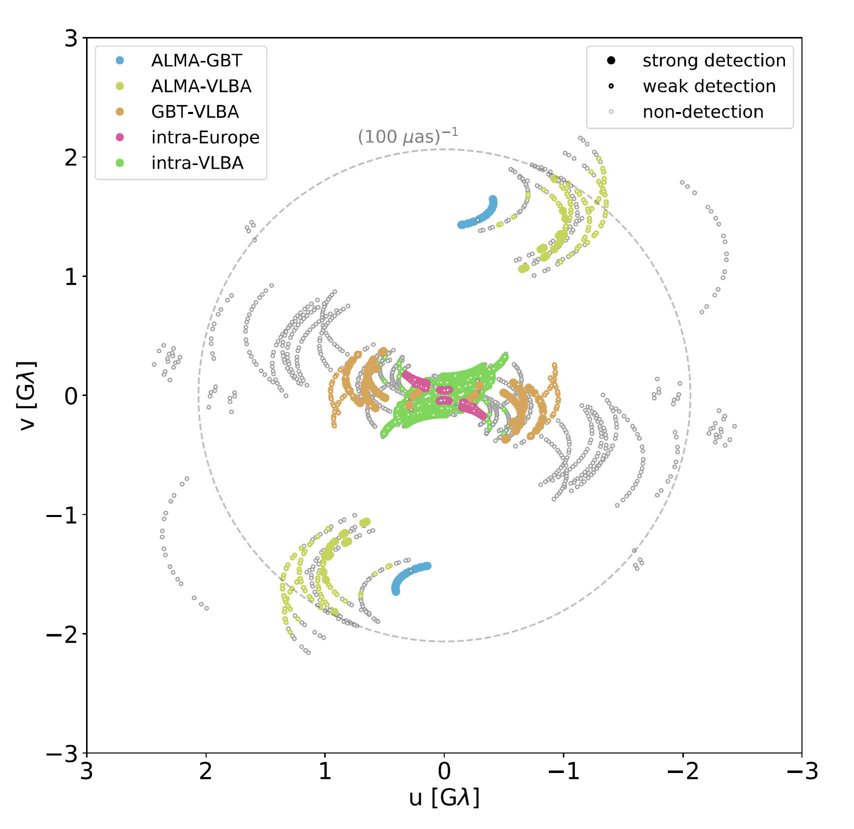


Other measurements?

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



(u,v) coverage



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

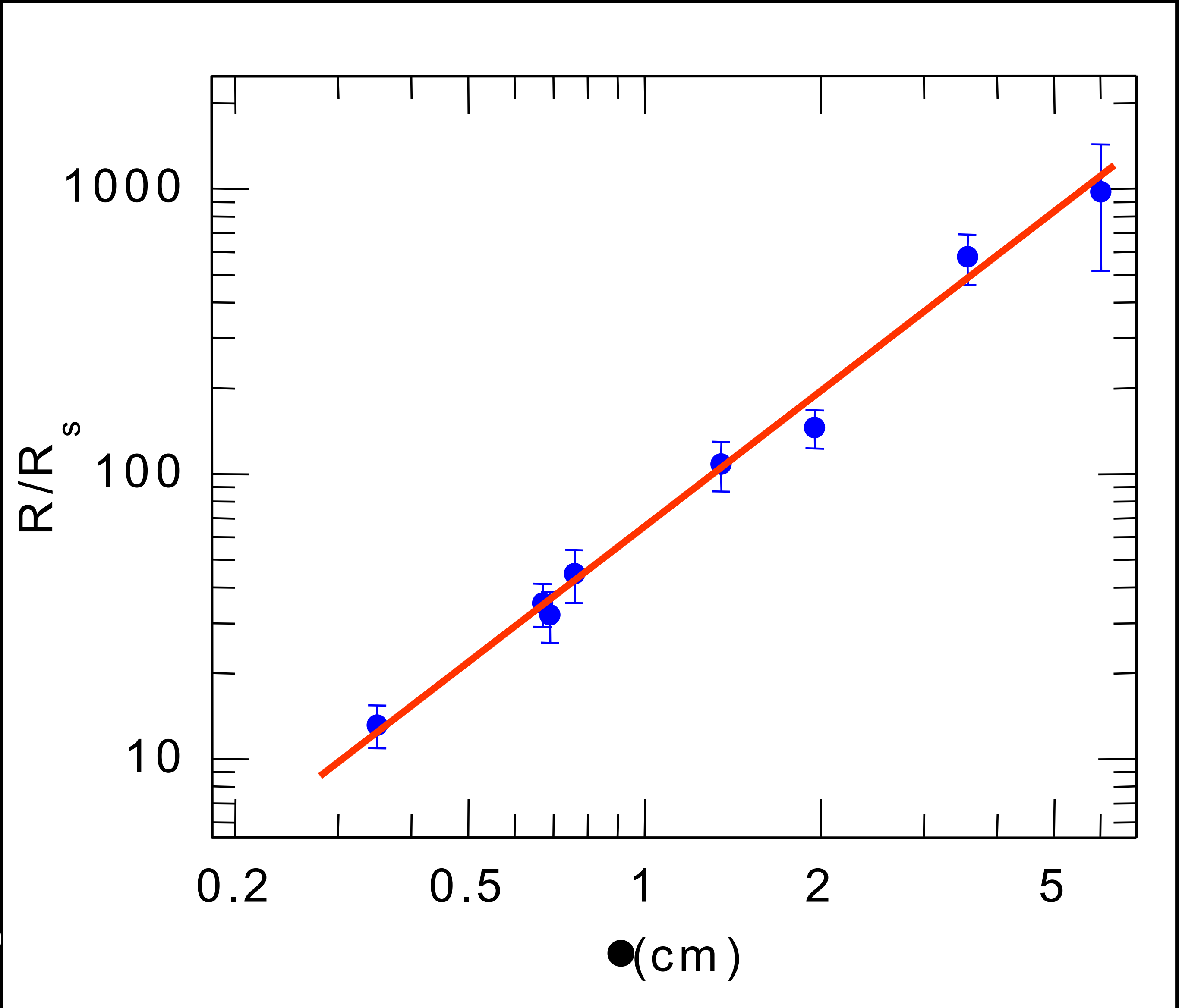
Scattering by plasma

Diameter ~ 20 R_S $(\lambda_{5mm})^{1.3\text{-}1.7}$

@ 3.5 mm

1 ua or 13 R_S

Radiation is scattered by plasma



Bower et al. (2006, 2004)

Shen et al. (2005)

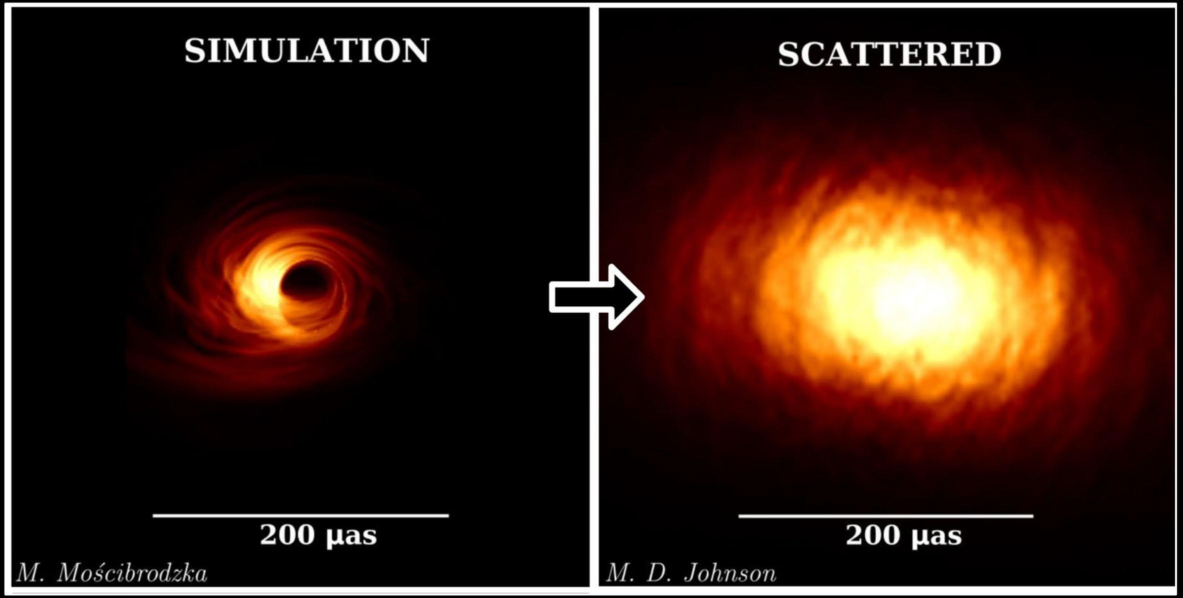
Scattering by plasma

Diameter ~ 20 R_S $(\lambda_{5mm})^{1.3-1.7}$

@ 3.5 mm

1 ua or 13 R_S

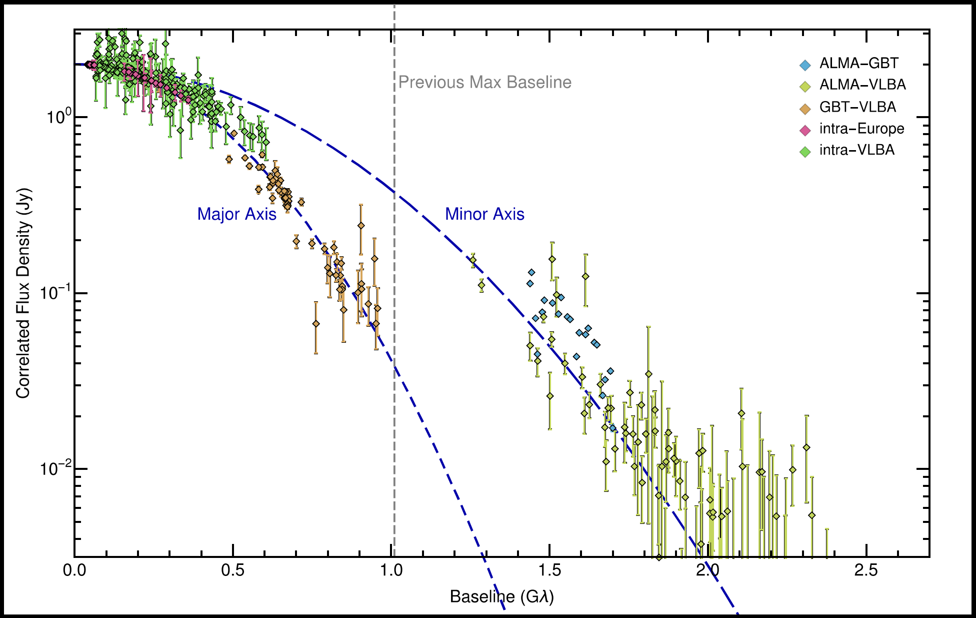
Radiation is scattered by plasma



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

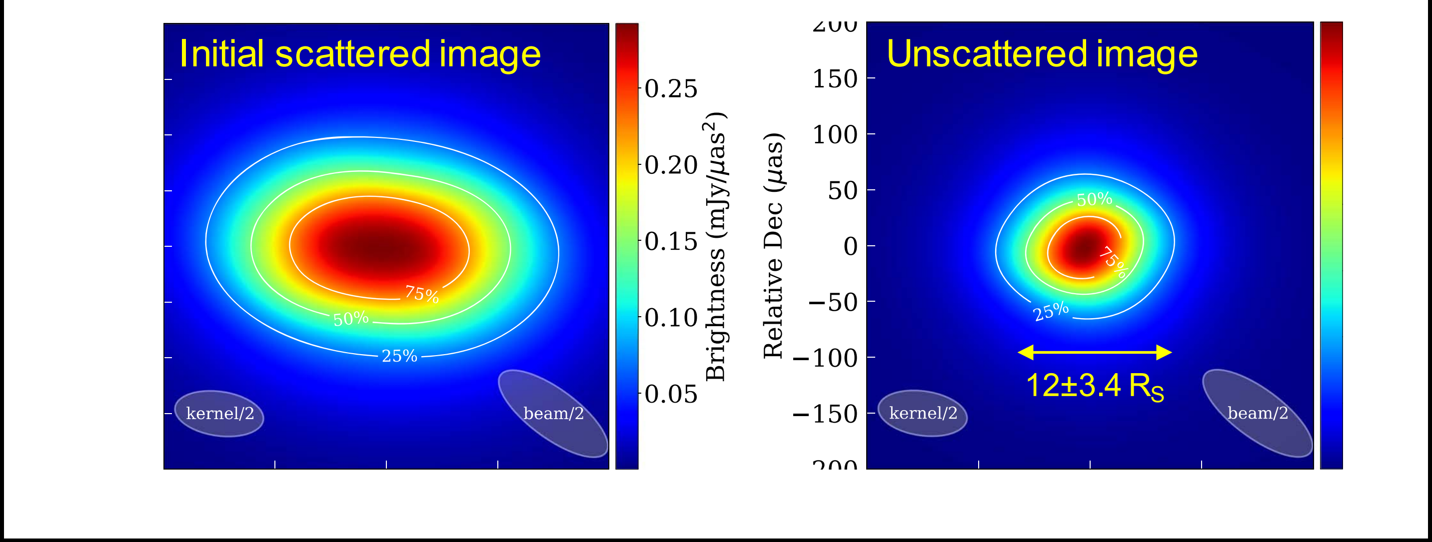
Bower et al. (2006, 2004)
Shen et al. (2005)

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



Measured vsibilities

Reconstructed images

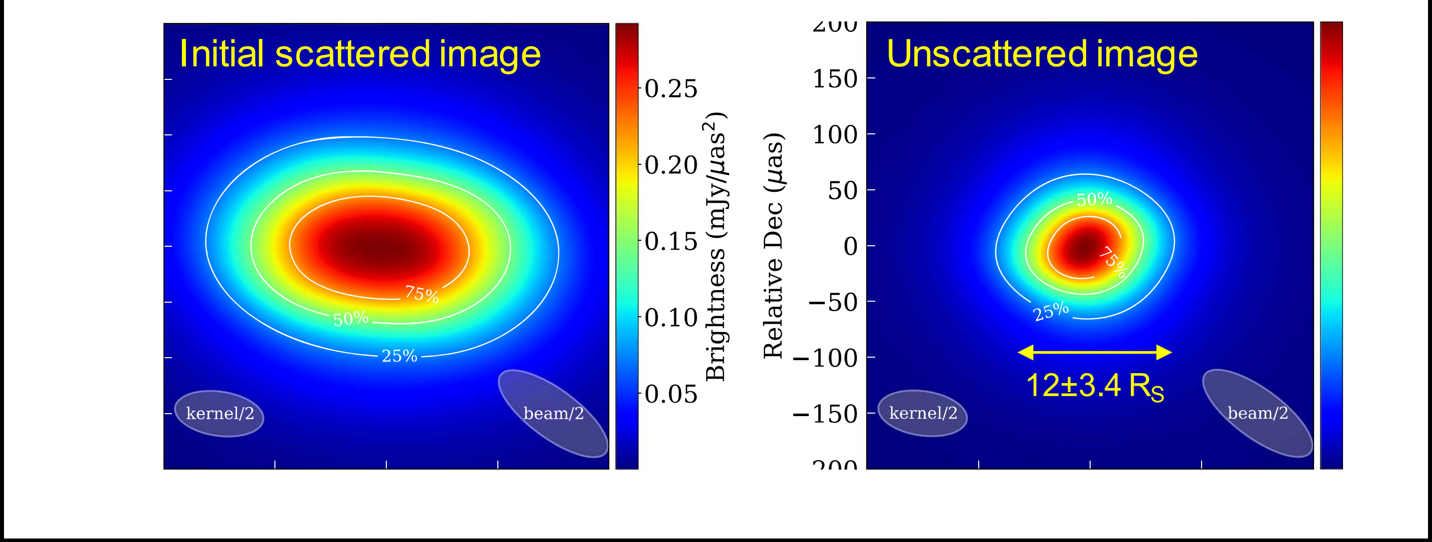


Issaoun et al., ApJ, 871:30 (2019)

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

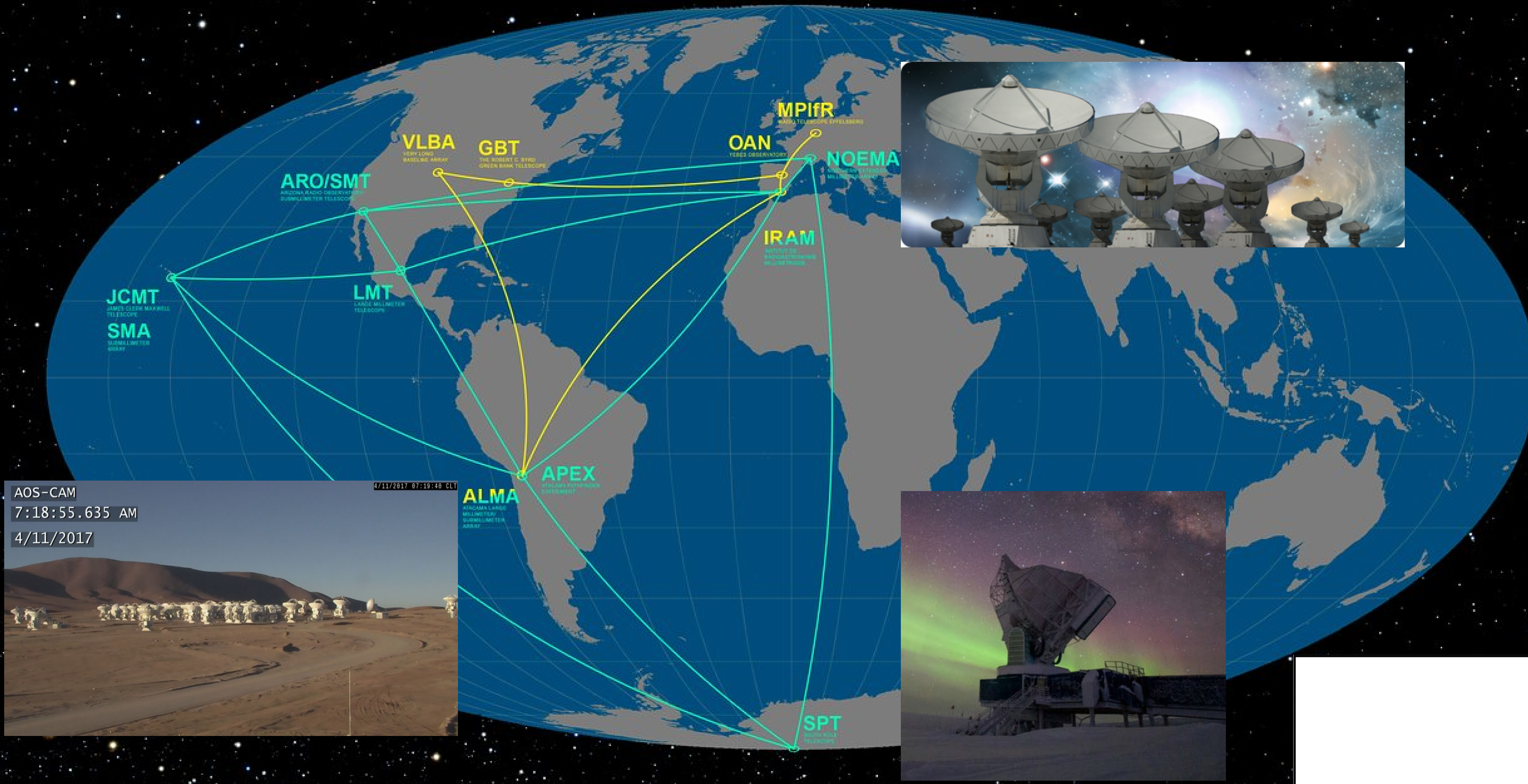
Modeling:
only disks at moderate viewing angles
and jet models with viewing angles ≤ 20°
are consistent with 1 and 3mm sizes and asymmetry constraints

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



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

Event Horizon Telescope

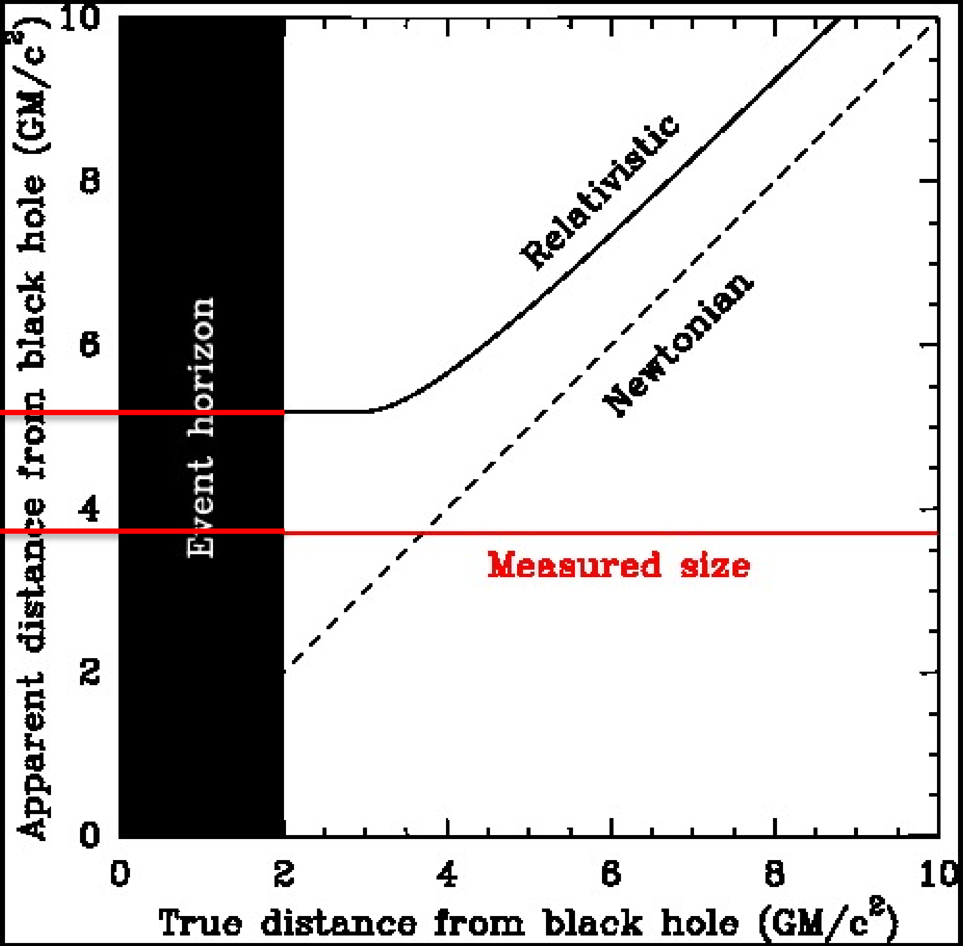


First observations in April 2017 …
results should come soon …

First measurements at ● ~ 1 mm

5.2 GM/c^2

3.7 GM/c^2



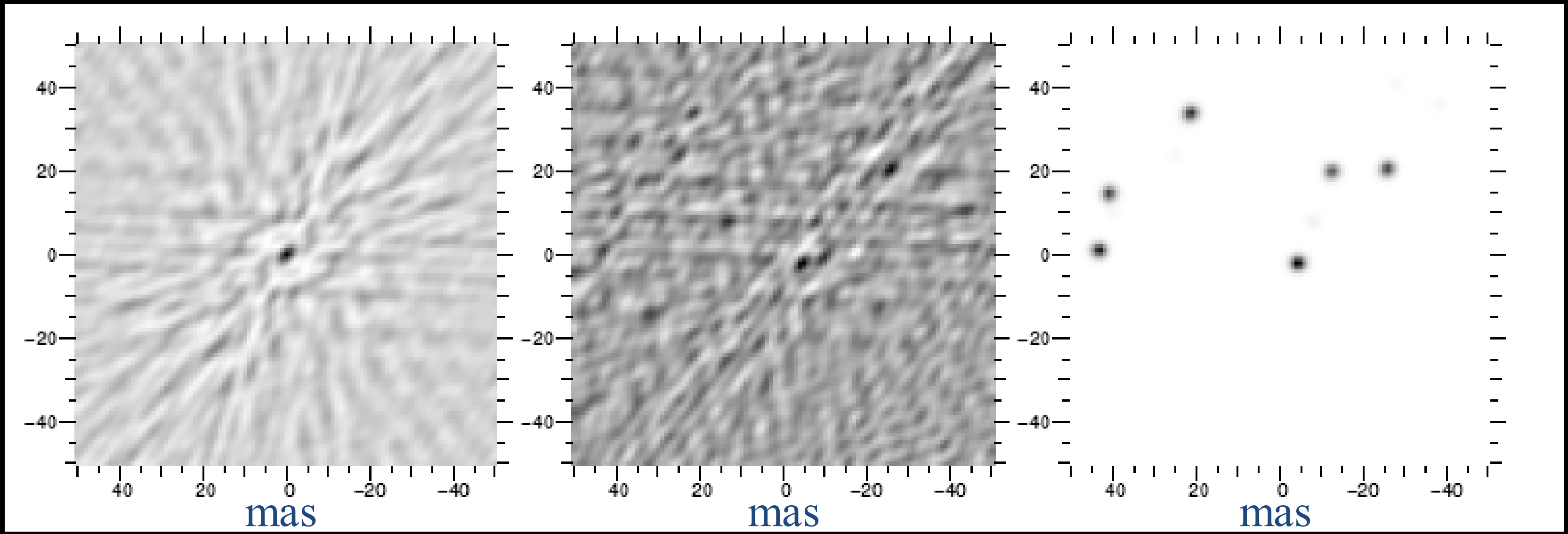
Not the event horizon yet!

Doeleman et al. (2008)

More with GRAVITY?

Orbits of nearby stars

Imaging of the central 100 mas (one night)



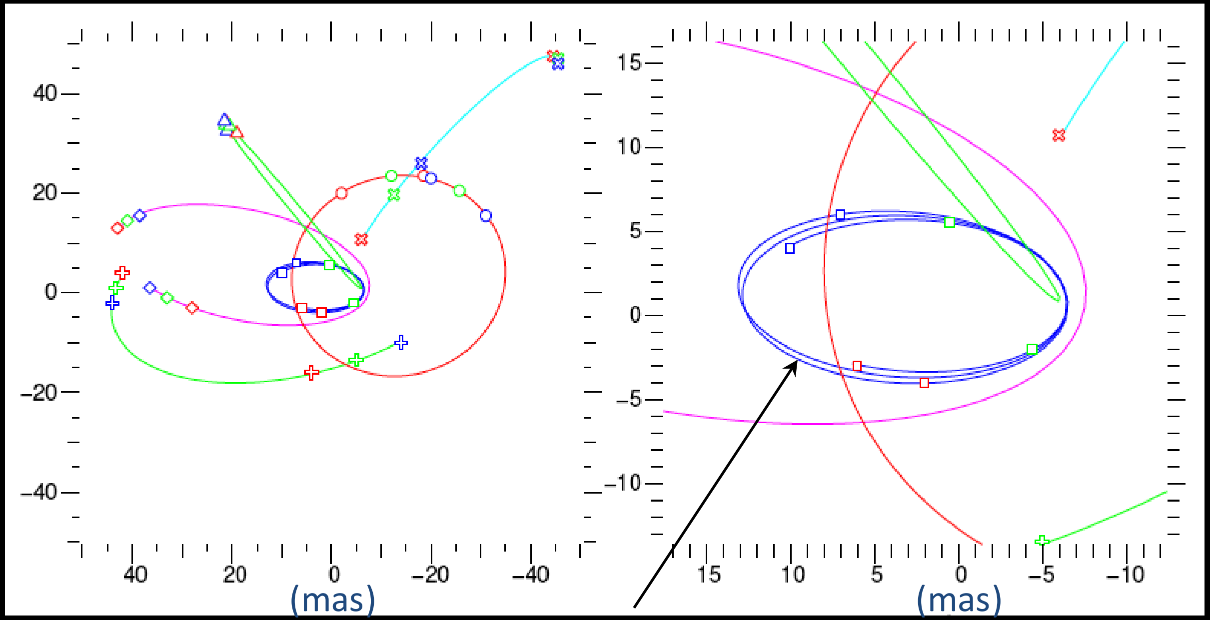
Dirty beam   Dirty image   After deconvolution

Paumard et al. (2005)

Orbits of nearby stars

Imaging of the central 100 mas (one night)

After 15 months of observing:



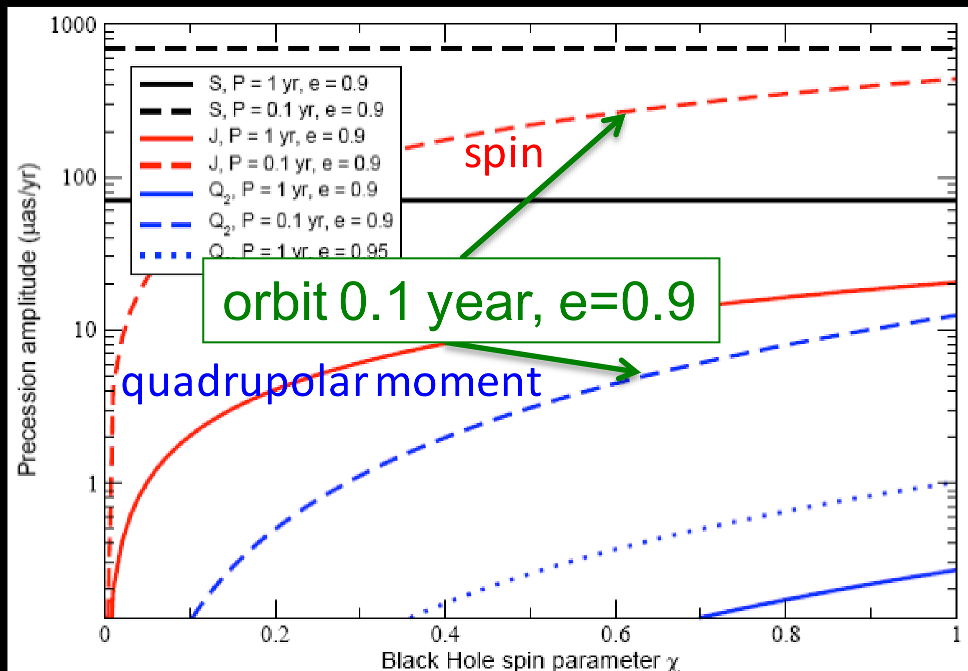
Simulation of the S star cluster downscaled to 100 mas

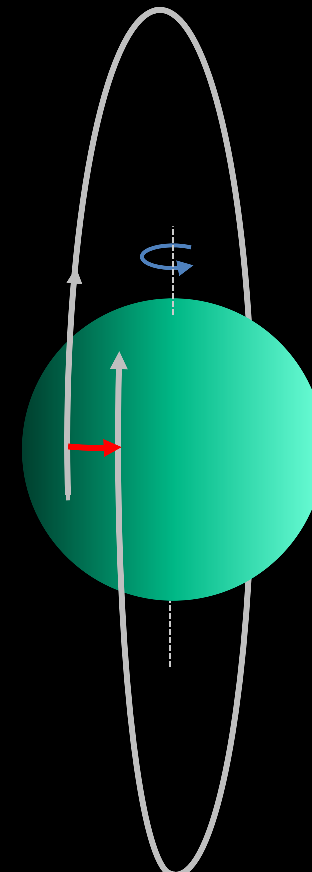
Schwarzschild precession
Kerr precession and spin measurement
Measurement of the quadrupolar moment?

Paumard et al. (2005)

Lense-Thirring effects 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 of Wheeler: only 3 parameters describe a black hole: mass M, spin J, electric charge

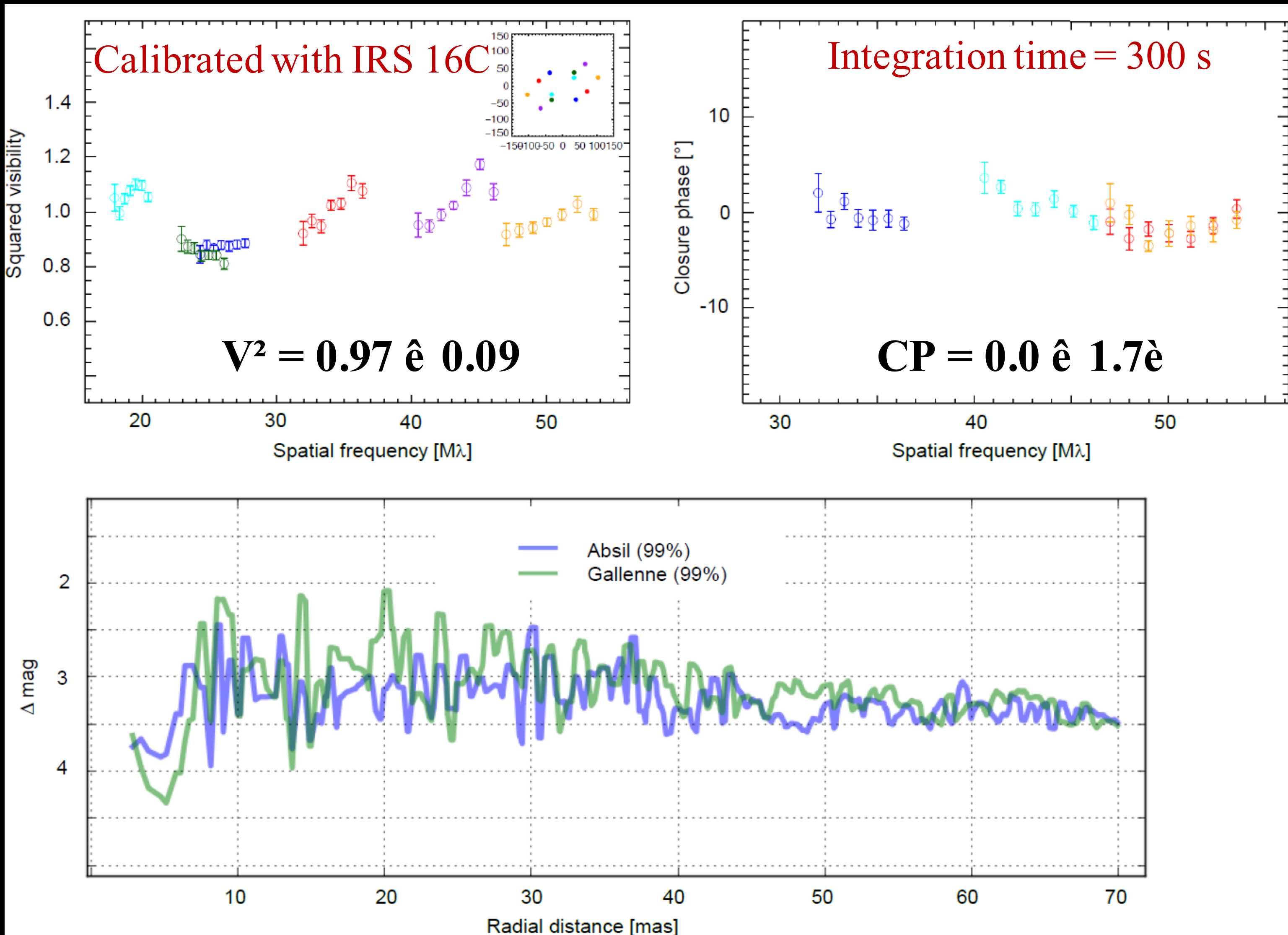
Quadrupolar moment: $Q_2 = -J^2 / M$

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)

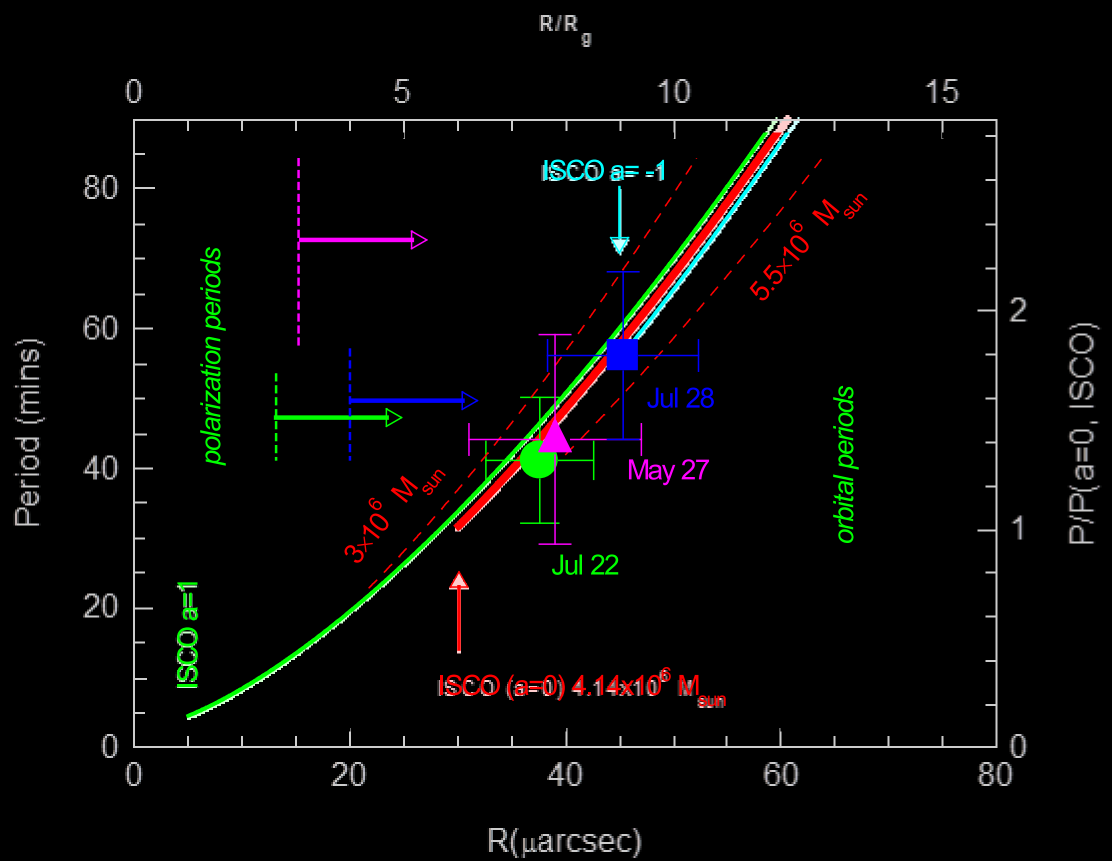
Merritt et al. (2010)

So far: no star brighter than K = 17.1 next to S2 and Sgr A*



GRAVITY Collaboration, A&A 602, A94 (2017)

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

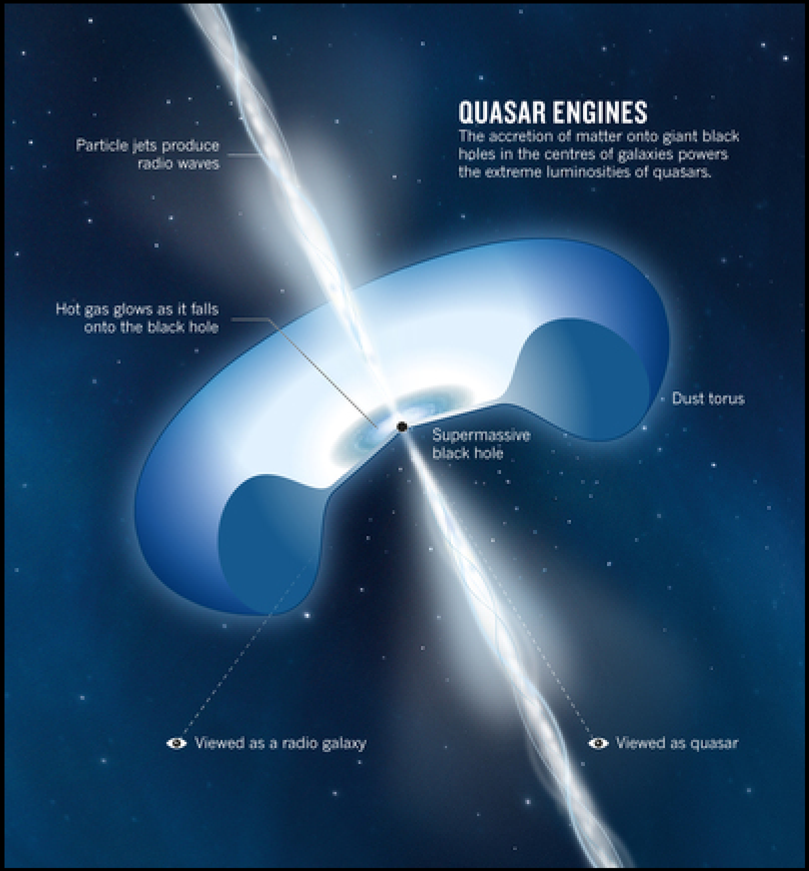


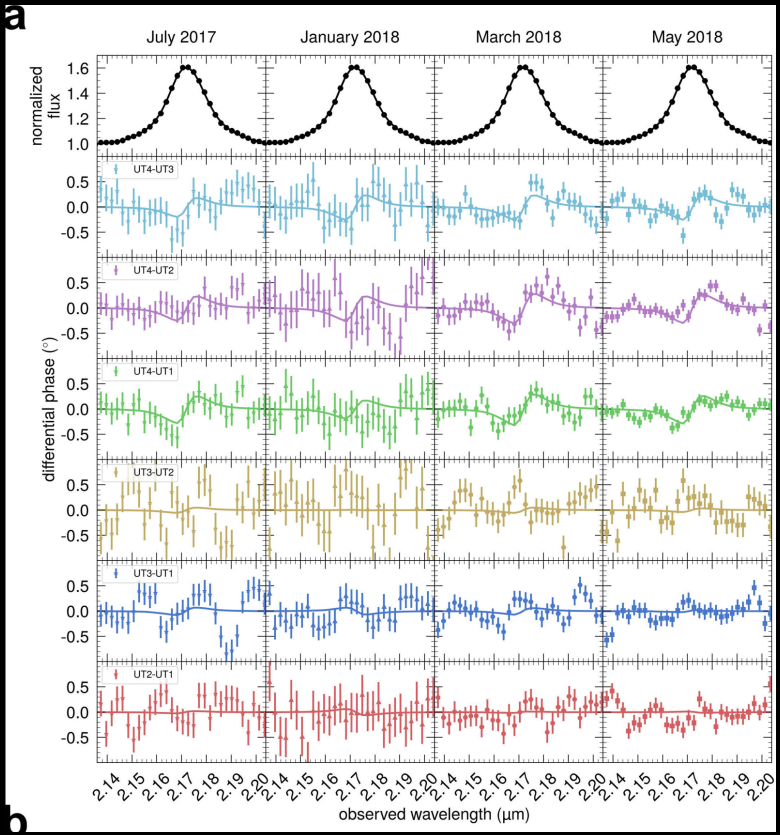
GRAVITY Collaboration, A&A 618, L10 (2018)

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!

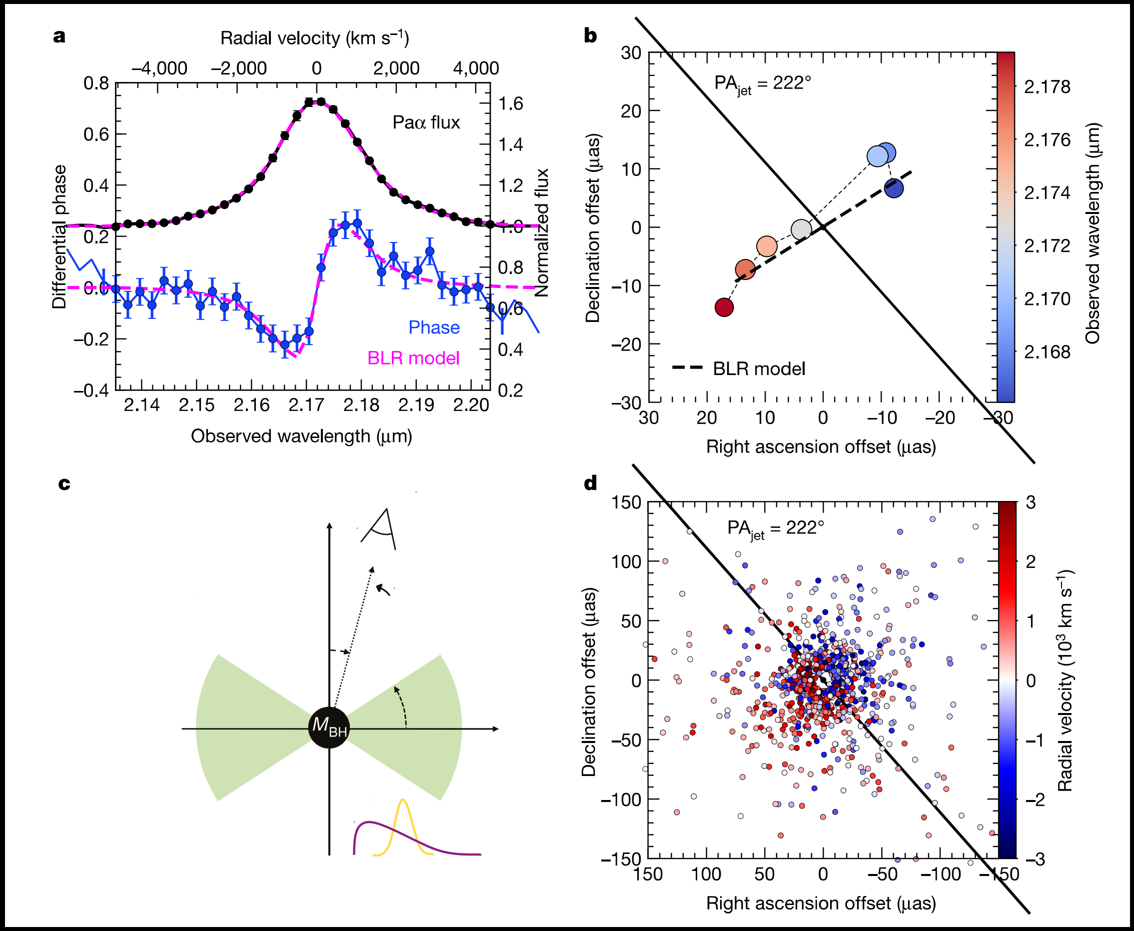
First direct measurement of the mass of a quasar: 3C273





GRAVITY collaboration, Nature 563, 657 (2018)

First direct measurement of the mass of a quasar: 3C273



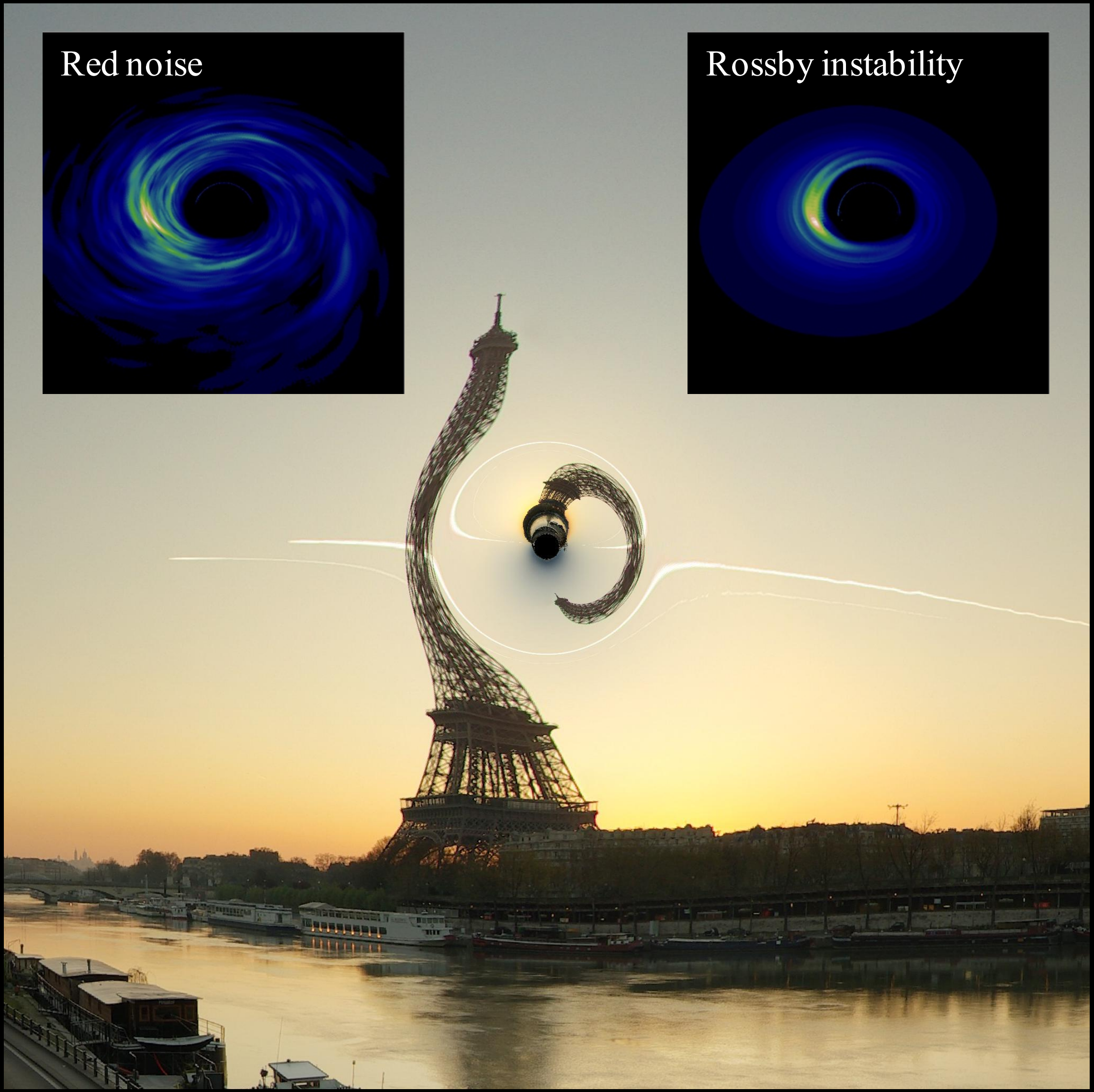
$R_{\mathrm{BLR}} = 46 \pm 10\ \mu\mathrm{as}\ (0.12 \pm 0.03\ \mathrm{pc})$

$R_{\min} = 11 \pm 3\ \mu\mathrm{as}\ (0.03 \pm 0.01\ \mathrm{pc})$

$M_{\mathrm{BH}} = (2.6 \pm 1.1) \times 10^8 M_\odot$

GRAVITY collaboration, Nature 563, 657 (2018)

Relativistic ray tracing code GYOTO



1 Earth mass black hole in the direction of the Eiffel Tower

Vincent et al. *Classical and Quantum Gravity* 28, 225011 (2011)