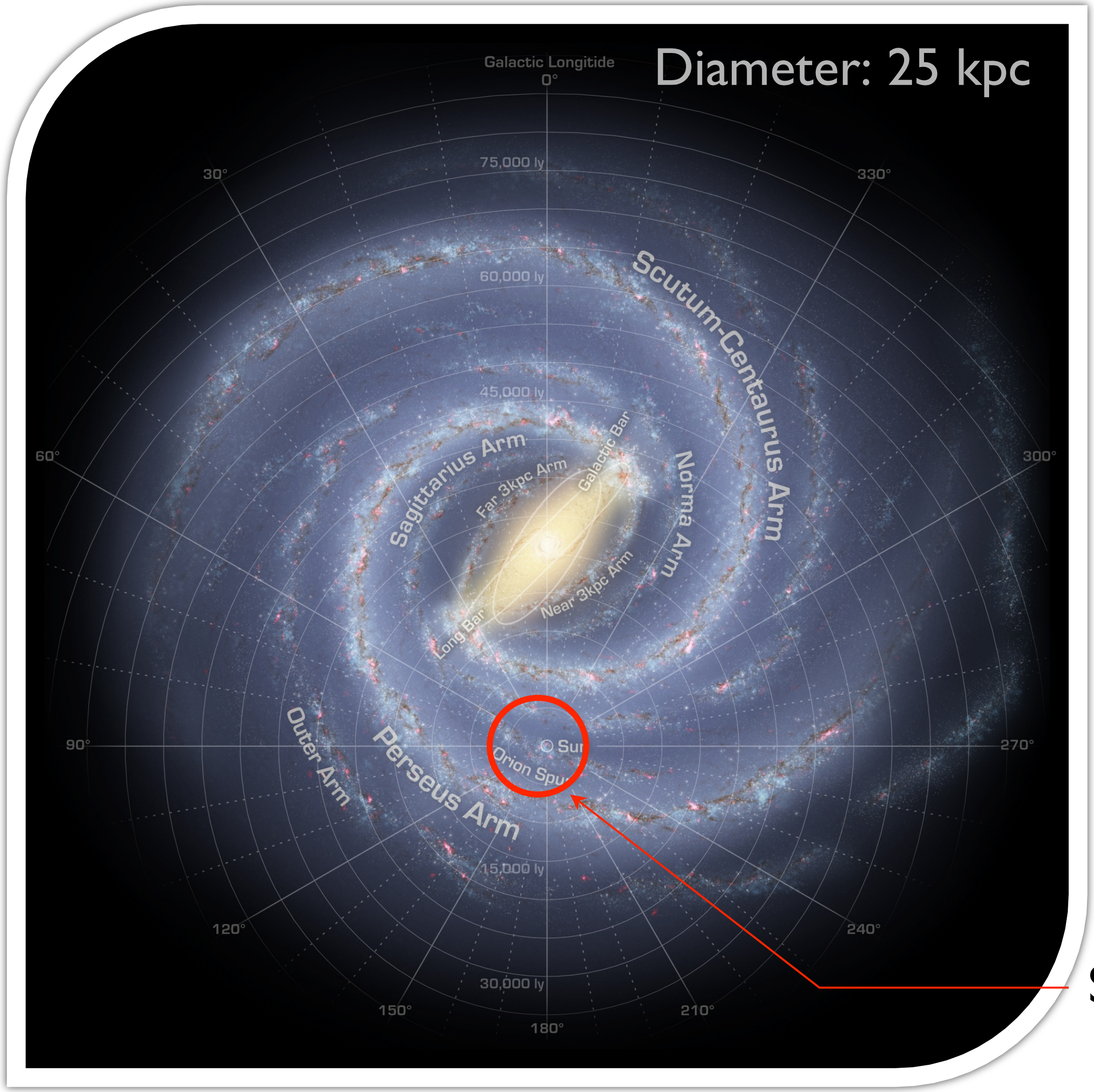
GRAVITY

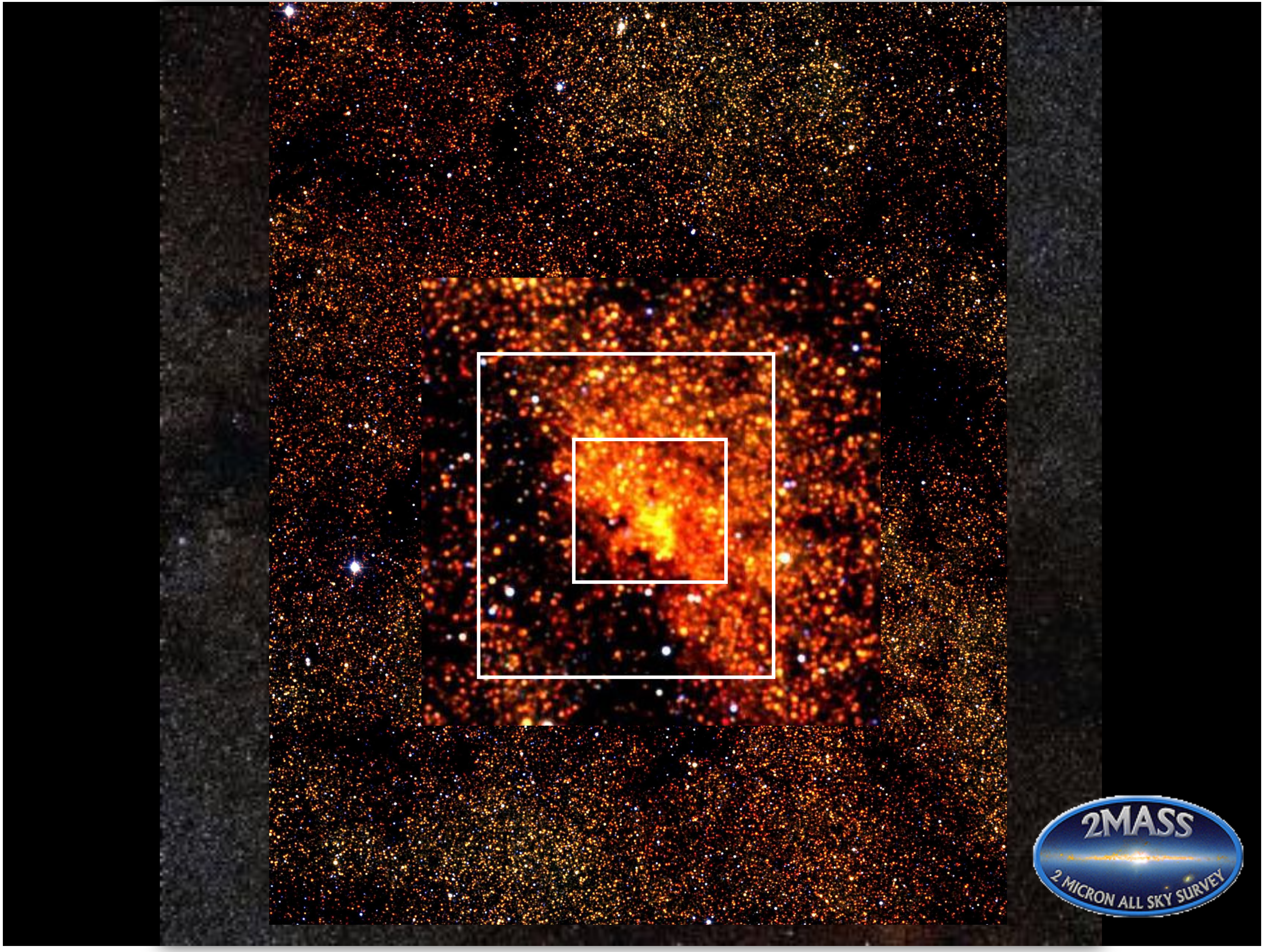
Astrometry and high-resolution imaging of the Galactic Center

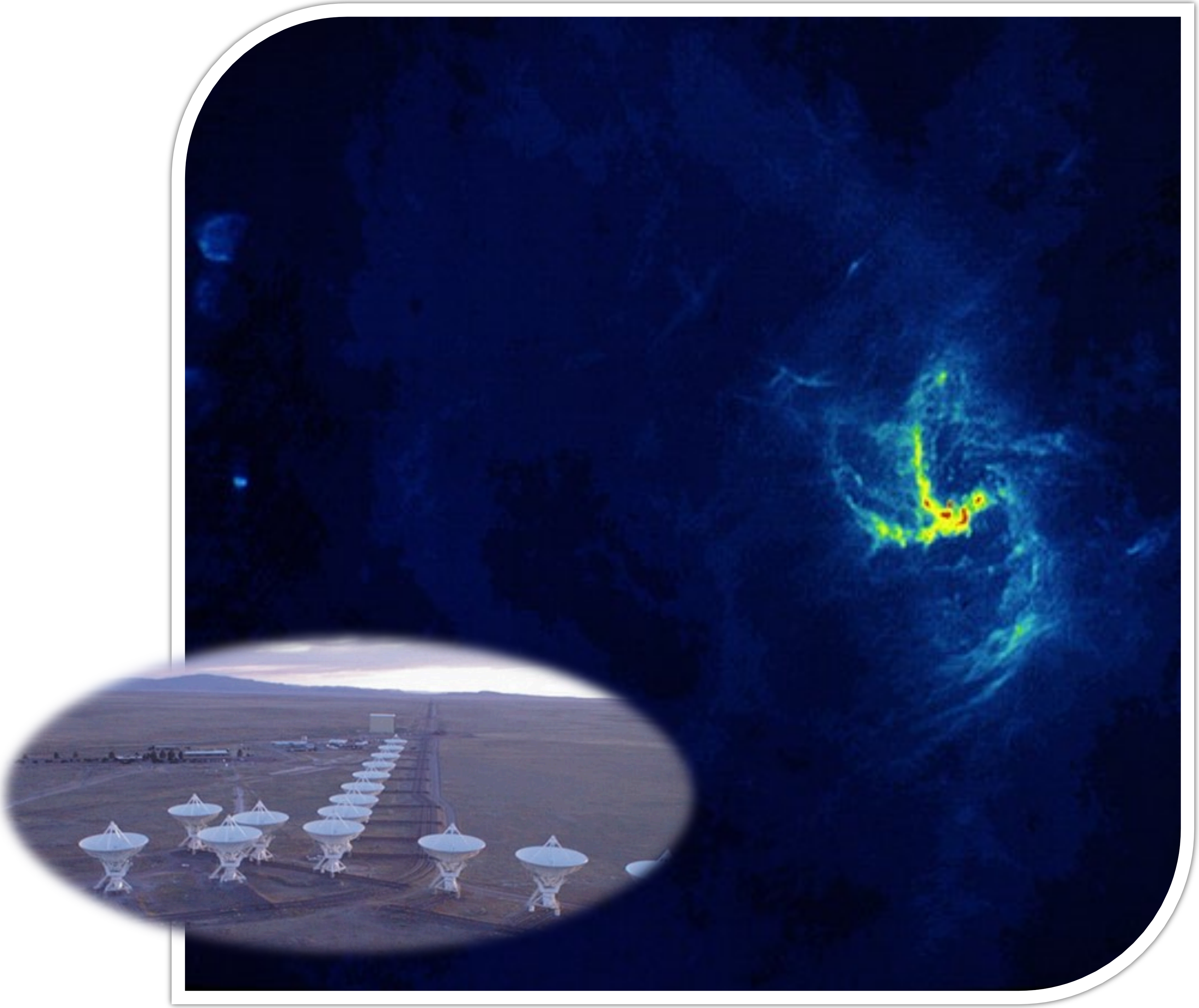
Guy Perrin
Pierre Kervella

Friends spotting us from outside the Galaxy

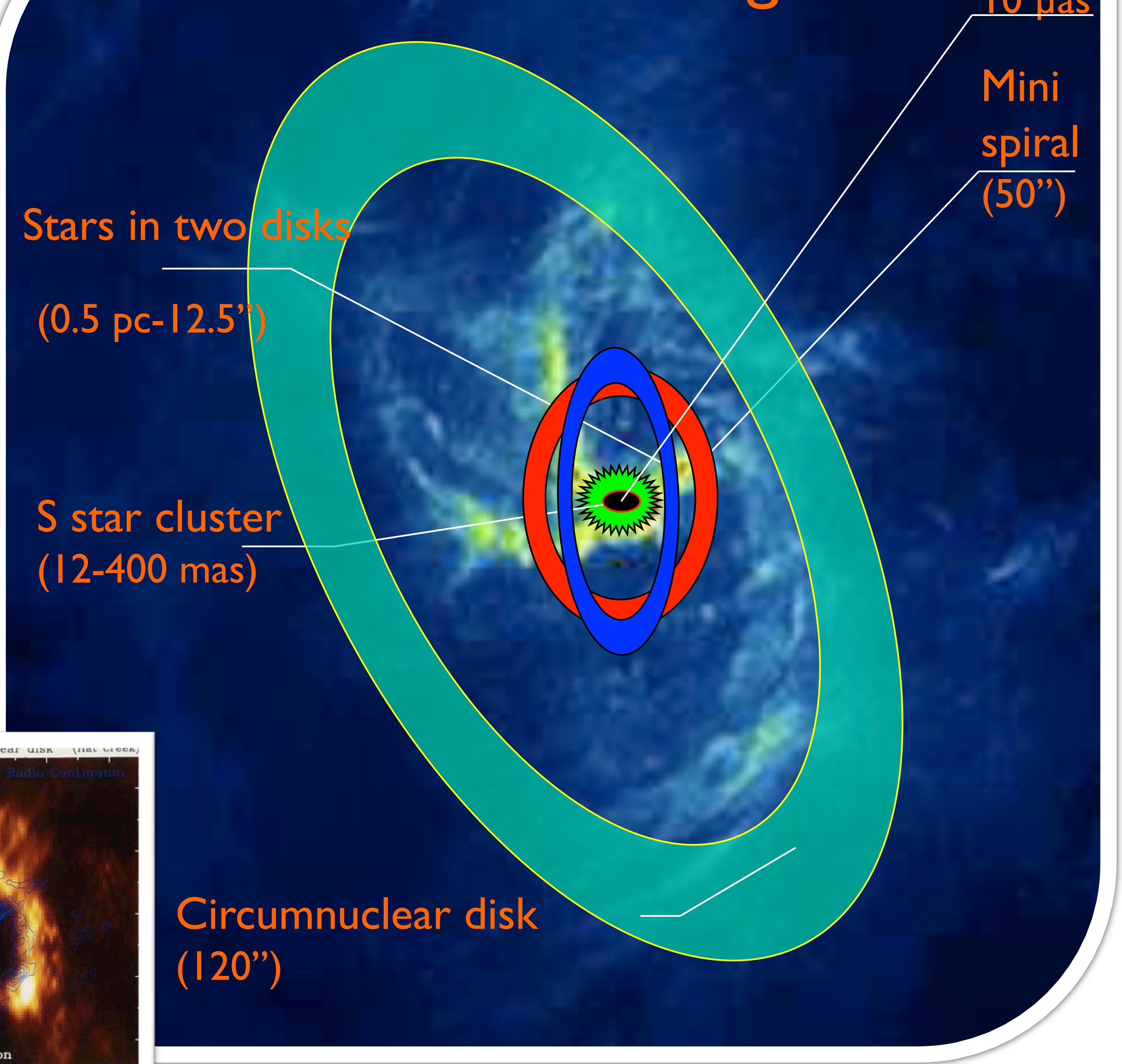


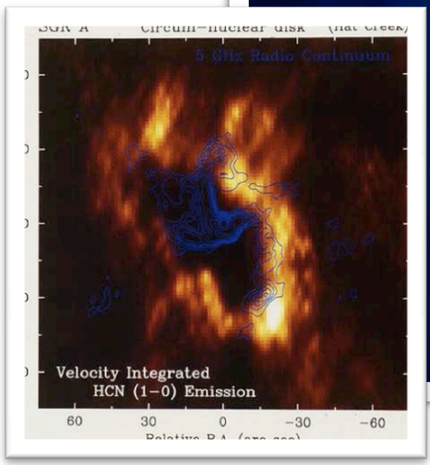
Solar system


2MASS
2 MICRON ALL SKY SURVEY

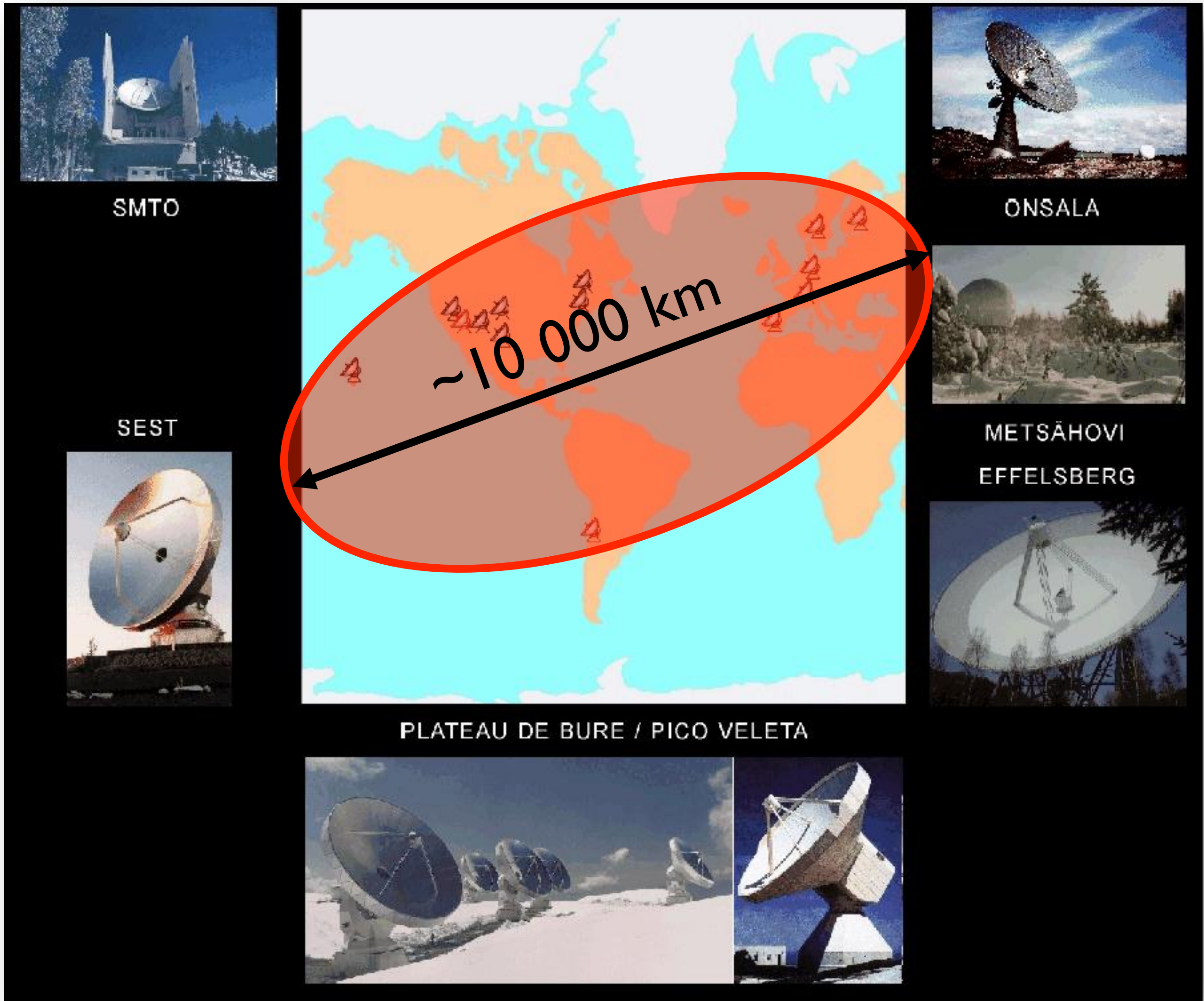


The environment of Sgr A*



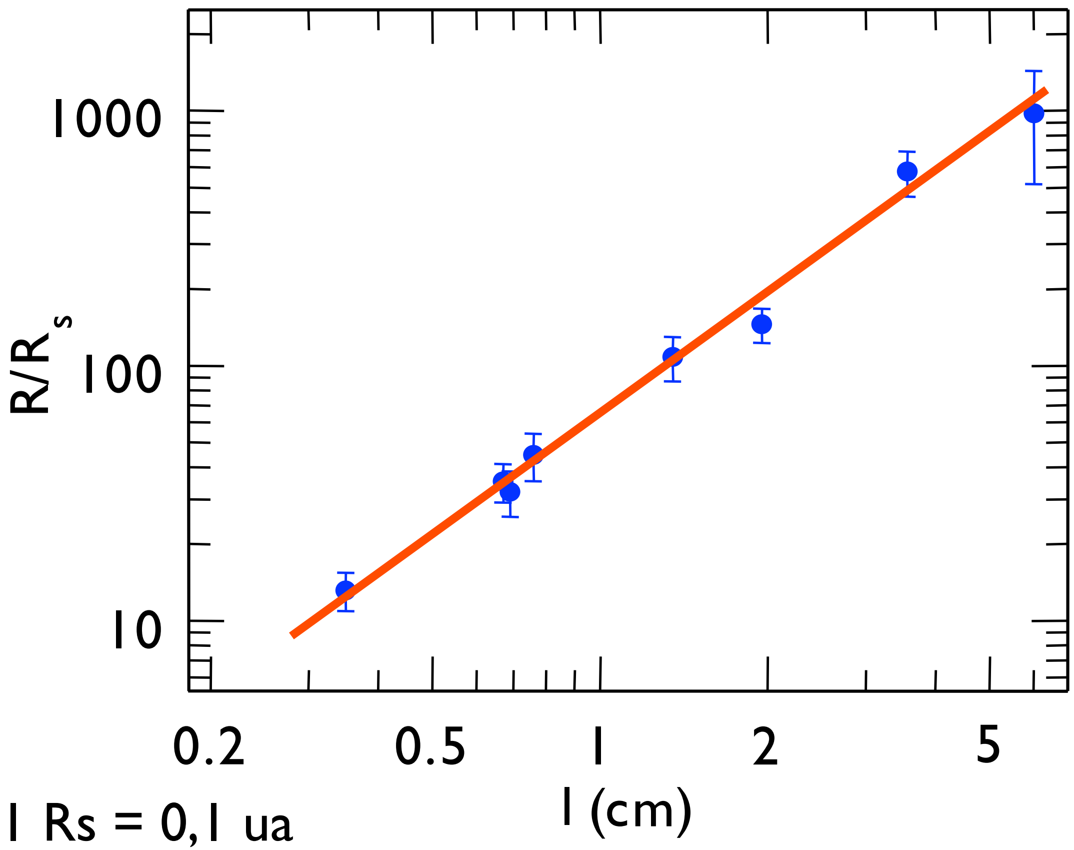


Very Long Baseline Interferometry



The size of Sgr A* at radio wavelengths

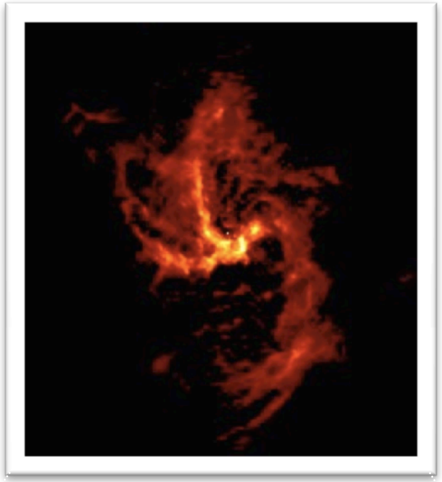
Law due to scattering by hot ionized gas.

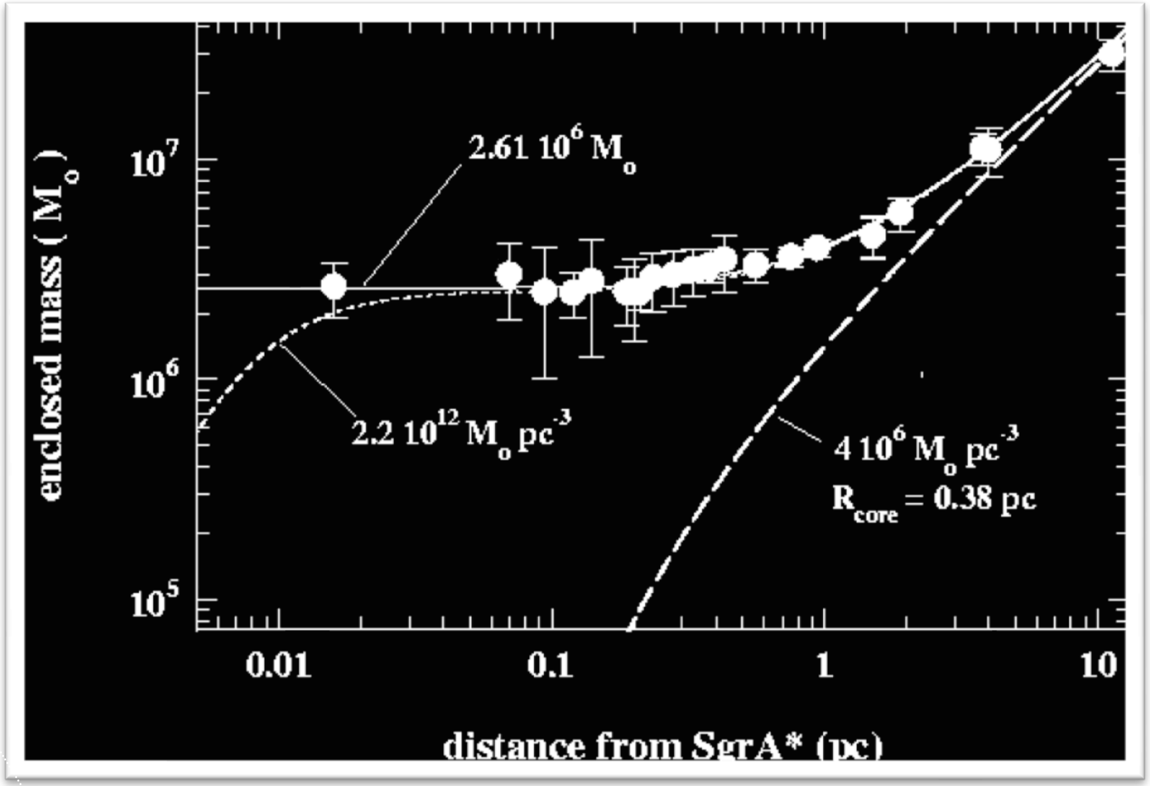


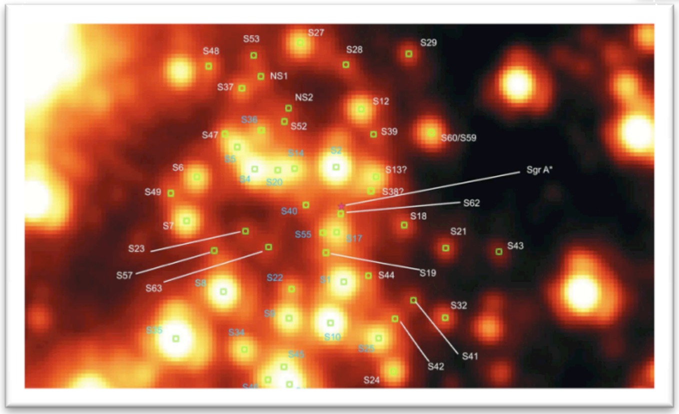
1 Rs = 0,1 ua

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

The mass of Sgr A*

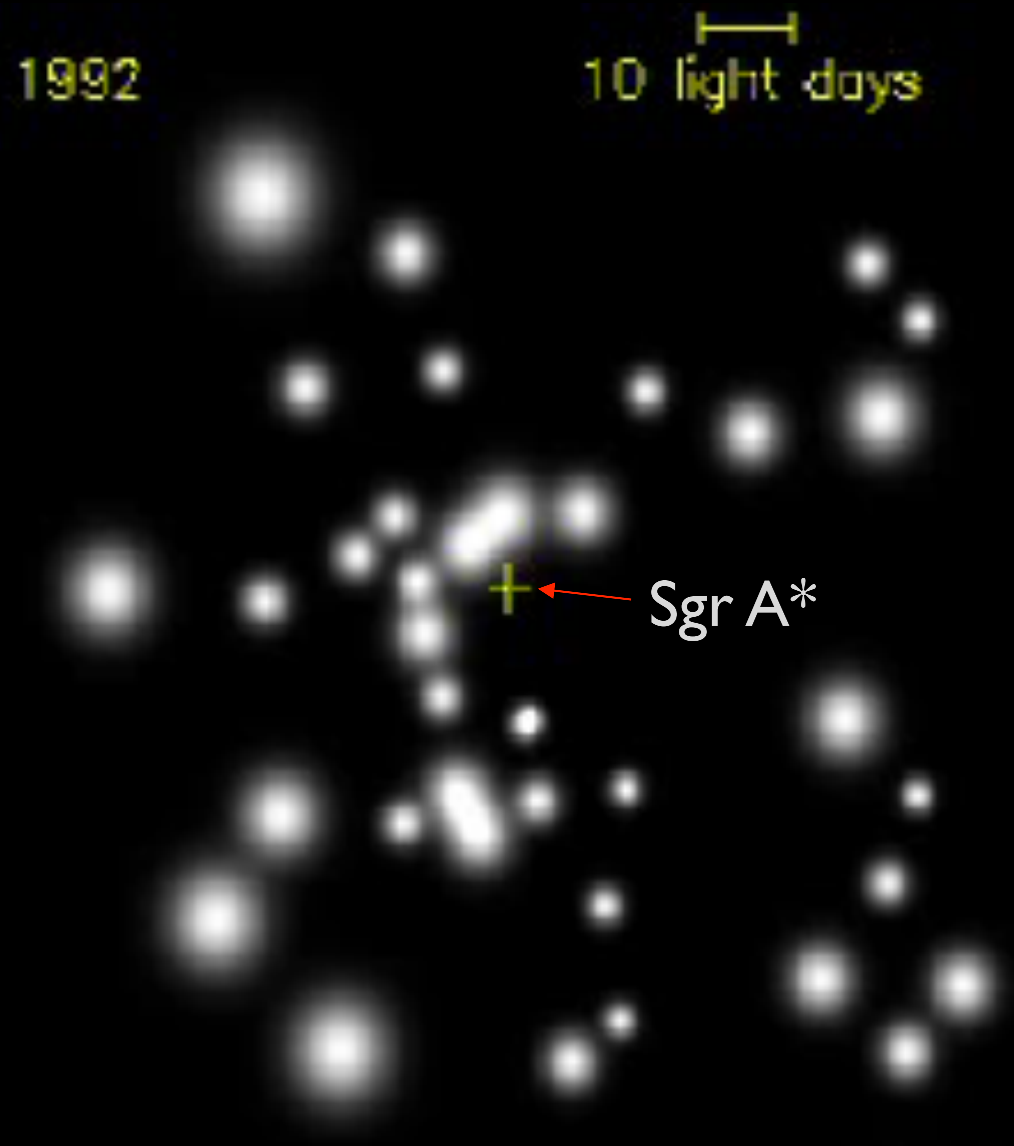




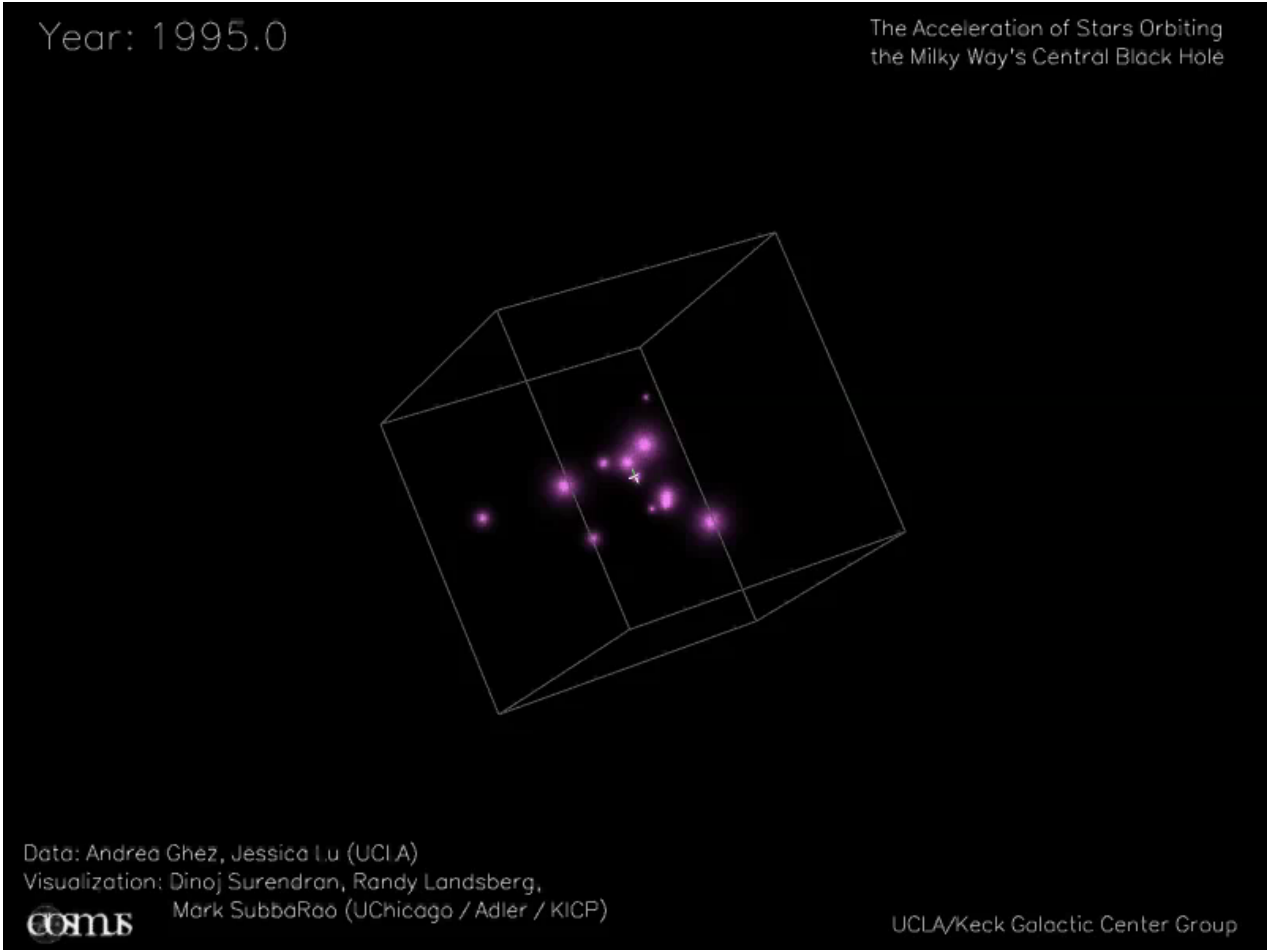


A bit less than 3 million solar masses until recently.

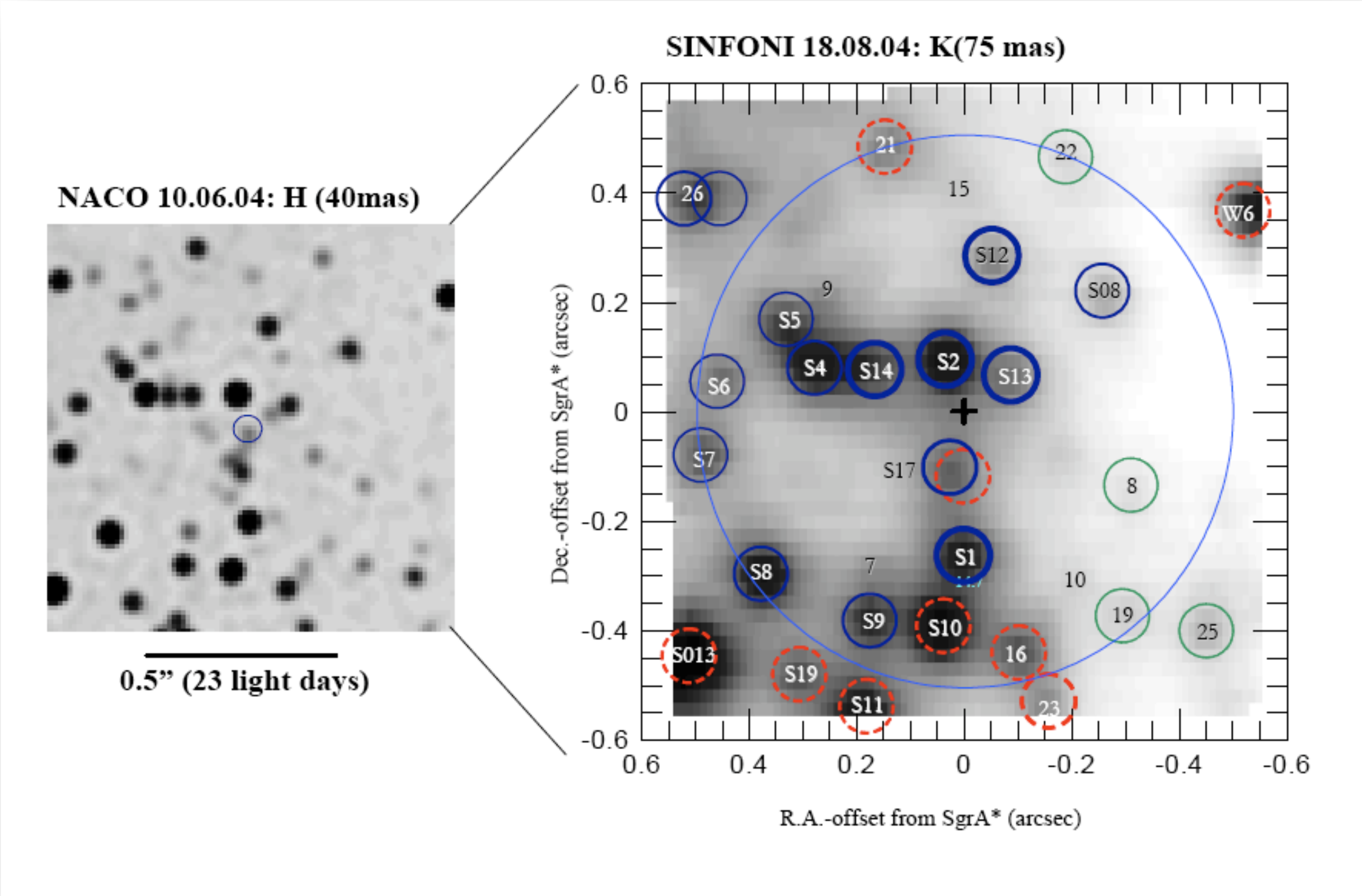
The orbit of S_2 measured with NACO



Schödel et al. (2002)


Year: 1995.0
The Acceleration of Stars Orbiting
the Milky Way's Central Black Hole
Data: Andrea Ghez, Jessica Lu (UCLA)
Visualization: Dinoj Surendran, Randy Landsberg,
Mark SubbaRao (UChicago / Adler / KICP)
UCLA/Keck Galactic Center Group

Orbits of nearby stars measured with SINFONI



Eisenhauer et al. (2005)

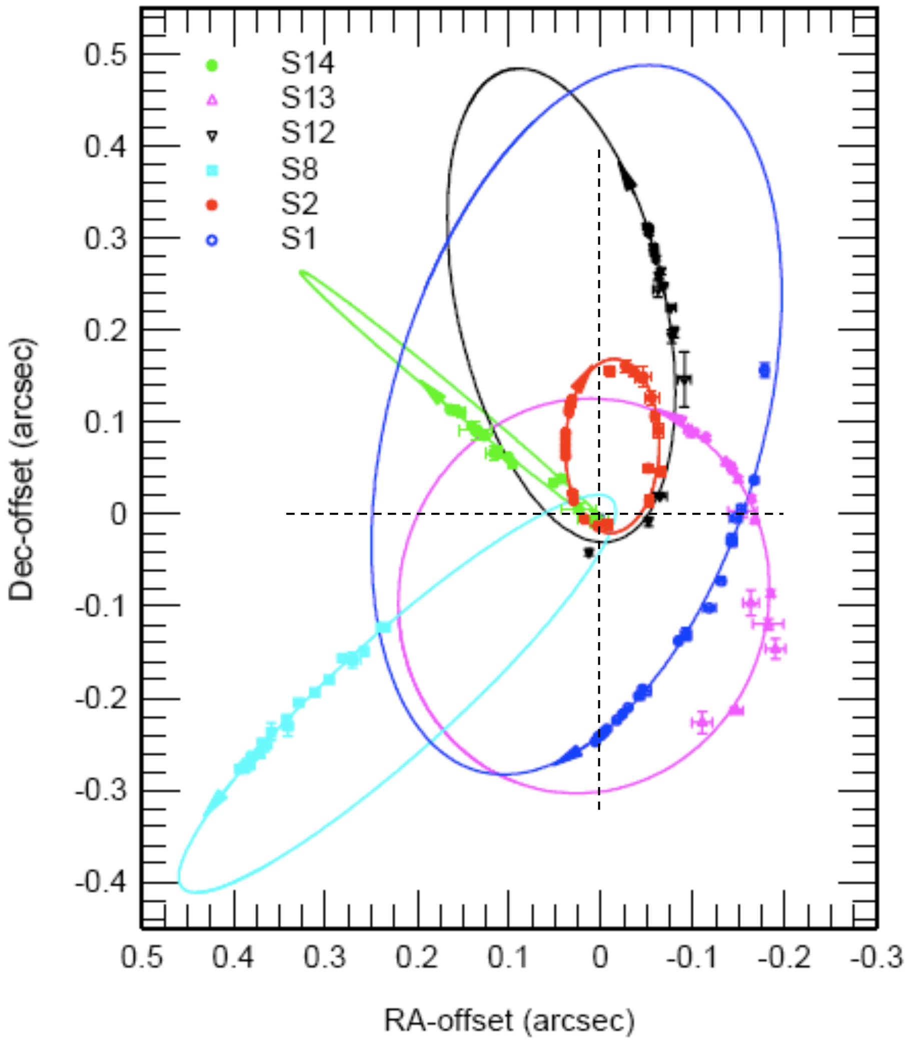
Accurate update of the mass of Sgr A*

3rd Kepler law:

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

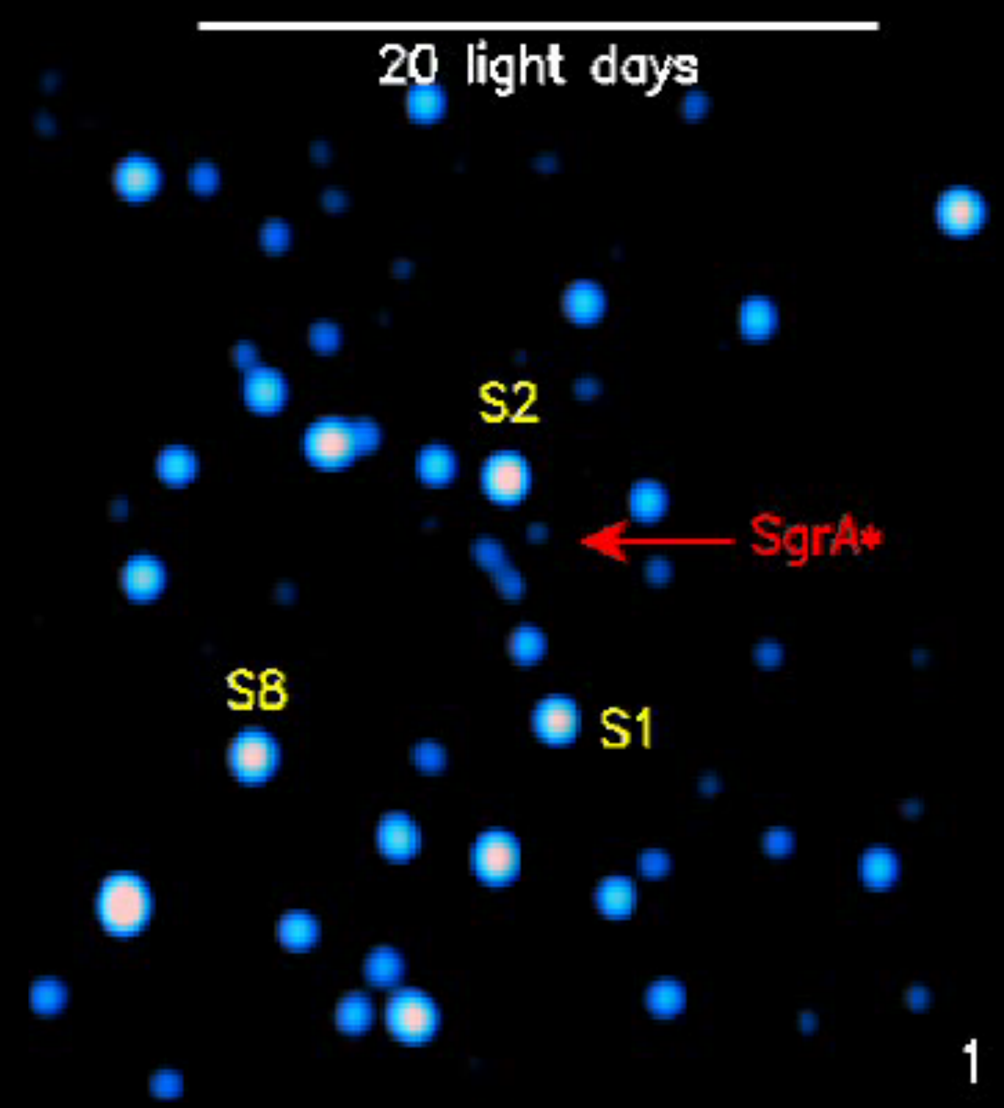
$M_{Sgr\,A*}$= 3.61±0.32 × 10^6 M_{Sun}

(d = 7.62±0.32 kpc)

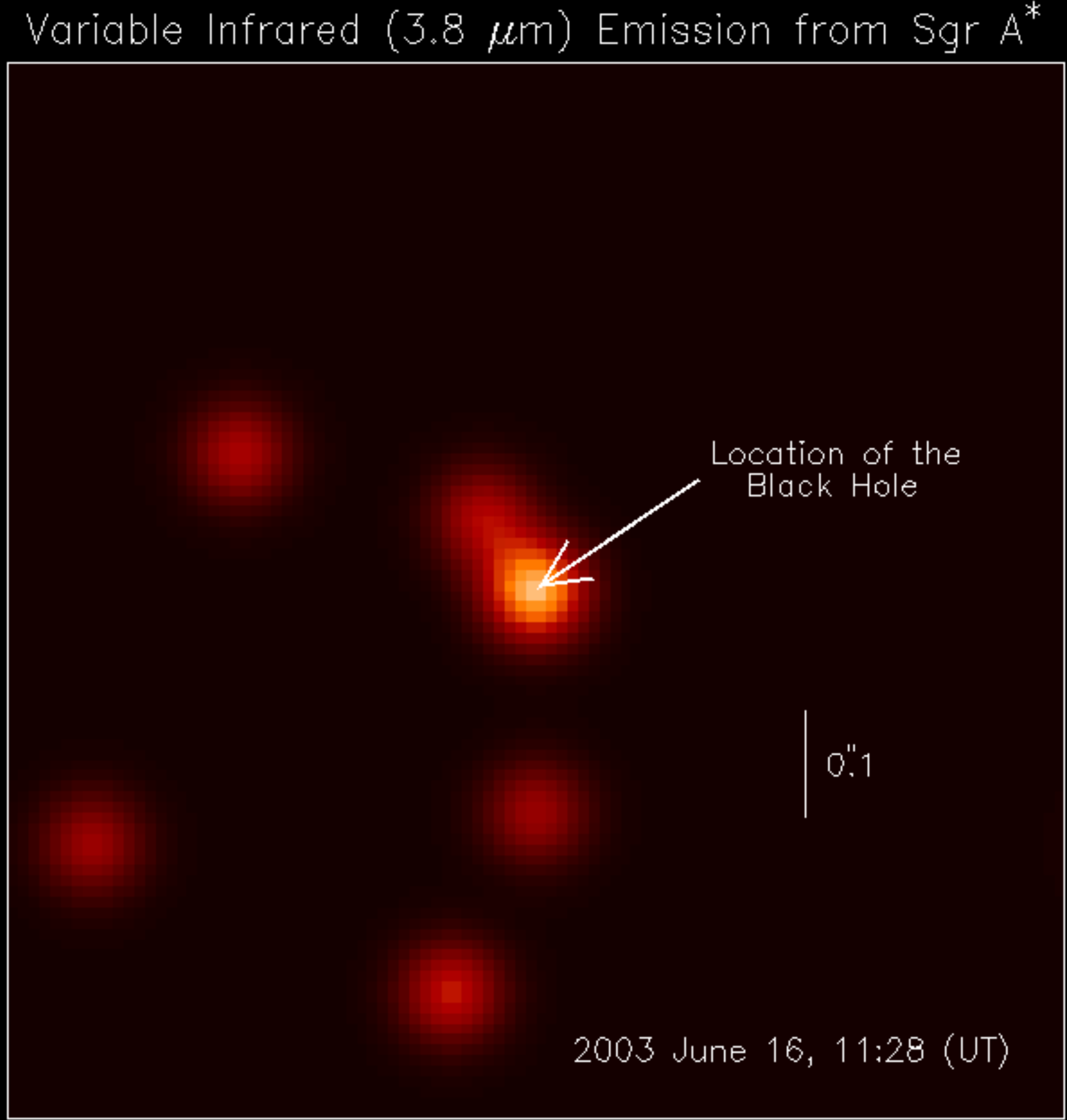


Eisenhauer et al. (2005)

A blinking dark spot !

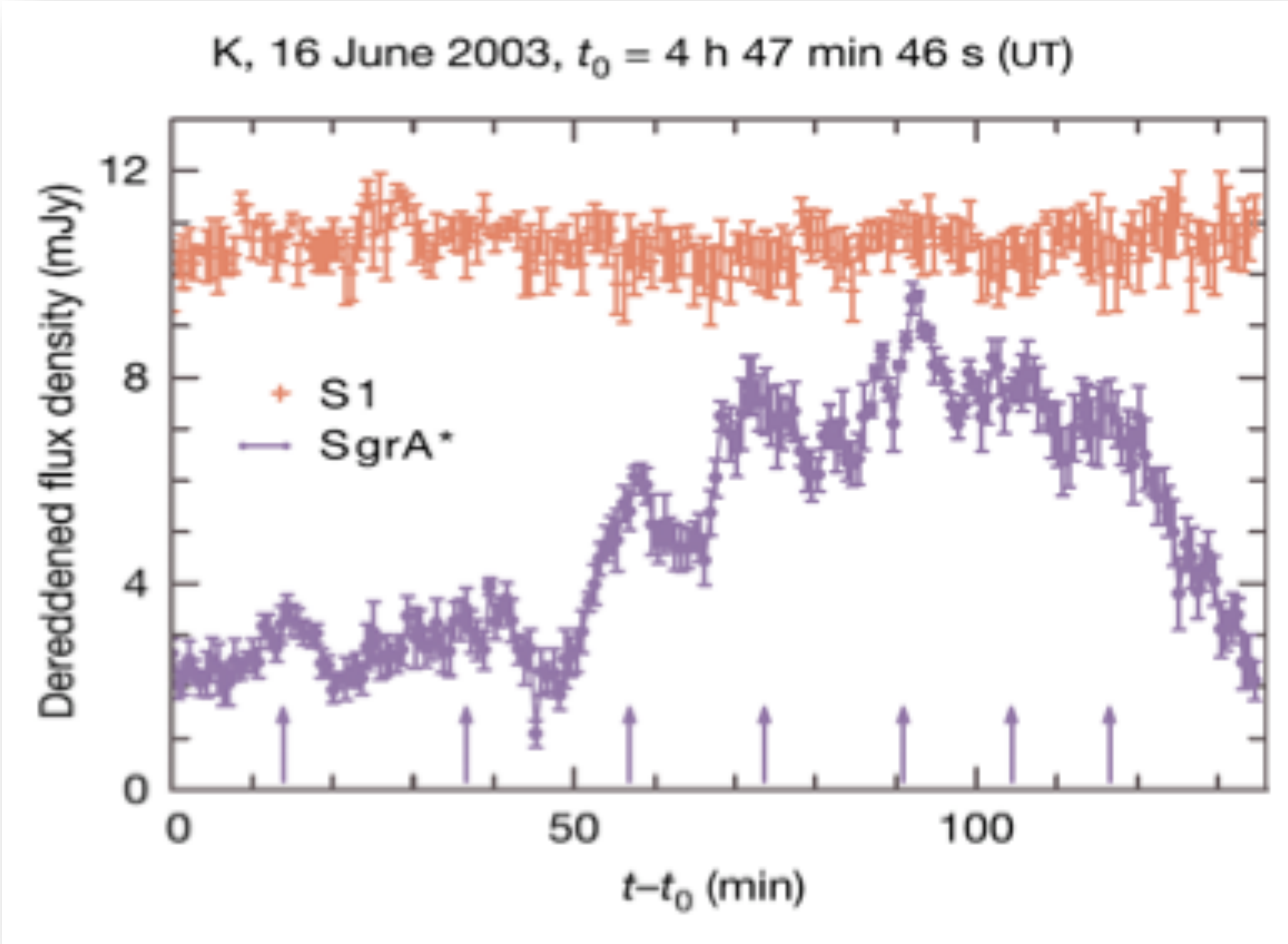


Genzel et al. (2003)


Variable Infrared (3.8 μm) Emission from Sgr A*
Location of the Black Hole
0.″1
2003 June 16, 11:28 (UT)

Ghez et al.

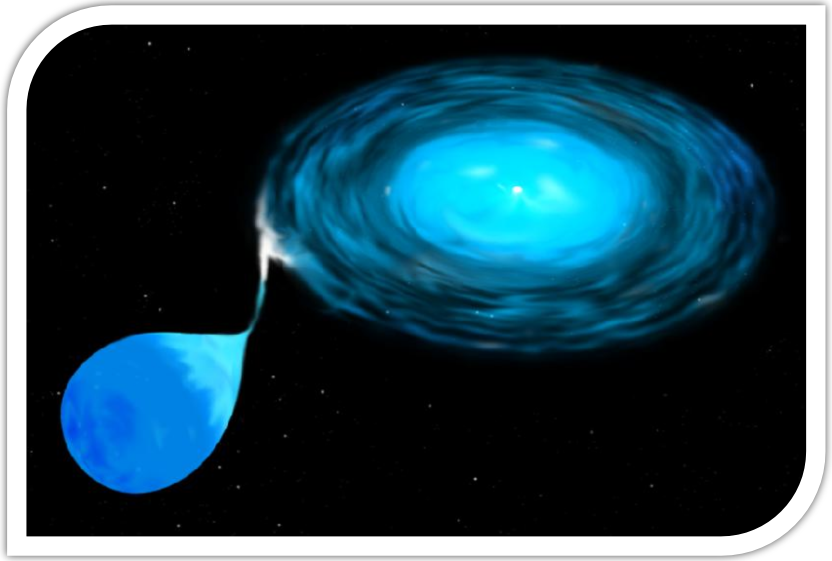
Luminosity of Sgr A* vs. time



Genzel et al. (2003)

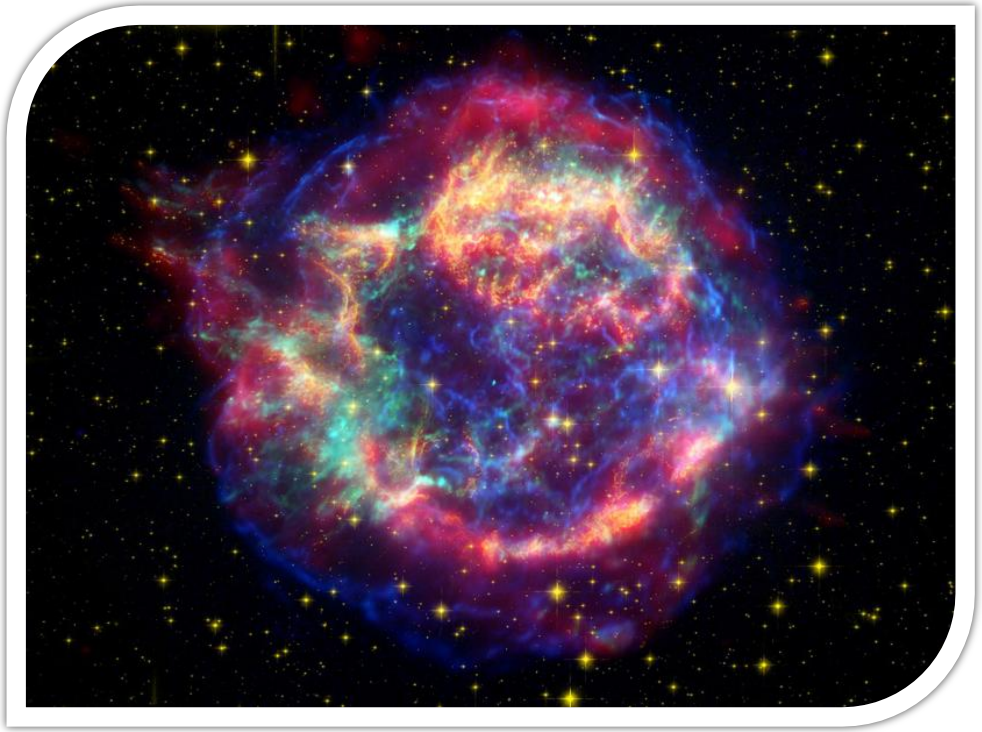
Stellar black holes

Cygnus X-1



Black hole is formed by accretion of the mass lost by the companion (intermediate and low-mass stars)

Cassiopee A



Black hole is formed by implosion of star during supernova collapse (massive stars)

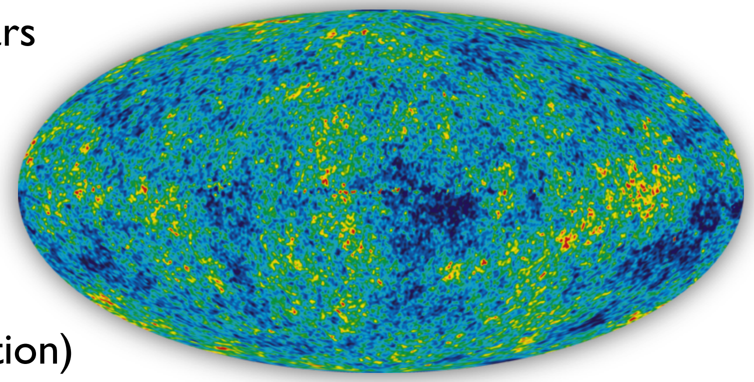
Supermassive black holes (10^6 - 10^9 M_{Sun})

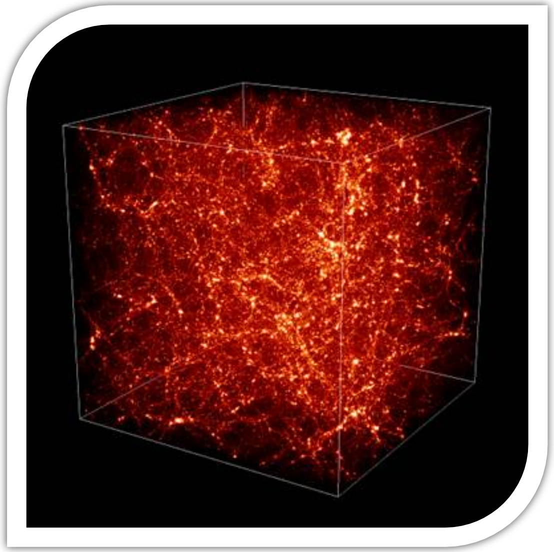
Age of Universe:

380 000 years

(recombination)

Cosmo. Microwave Backd





What is the apparent size of a black hole ?

- Stellar black holes
  tiny: R_{BH} ~ few km
  at 1 parsec : 10^{-10} arcsec (smaller than a human cell seen from the Moon)

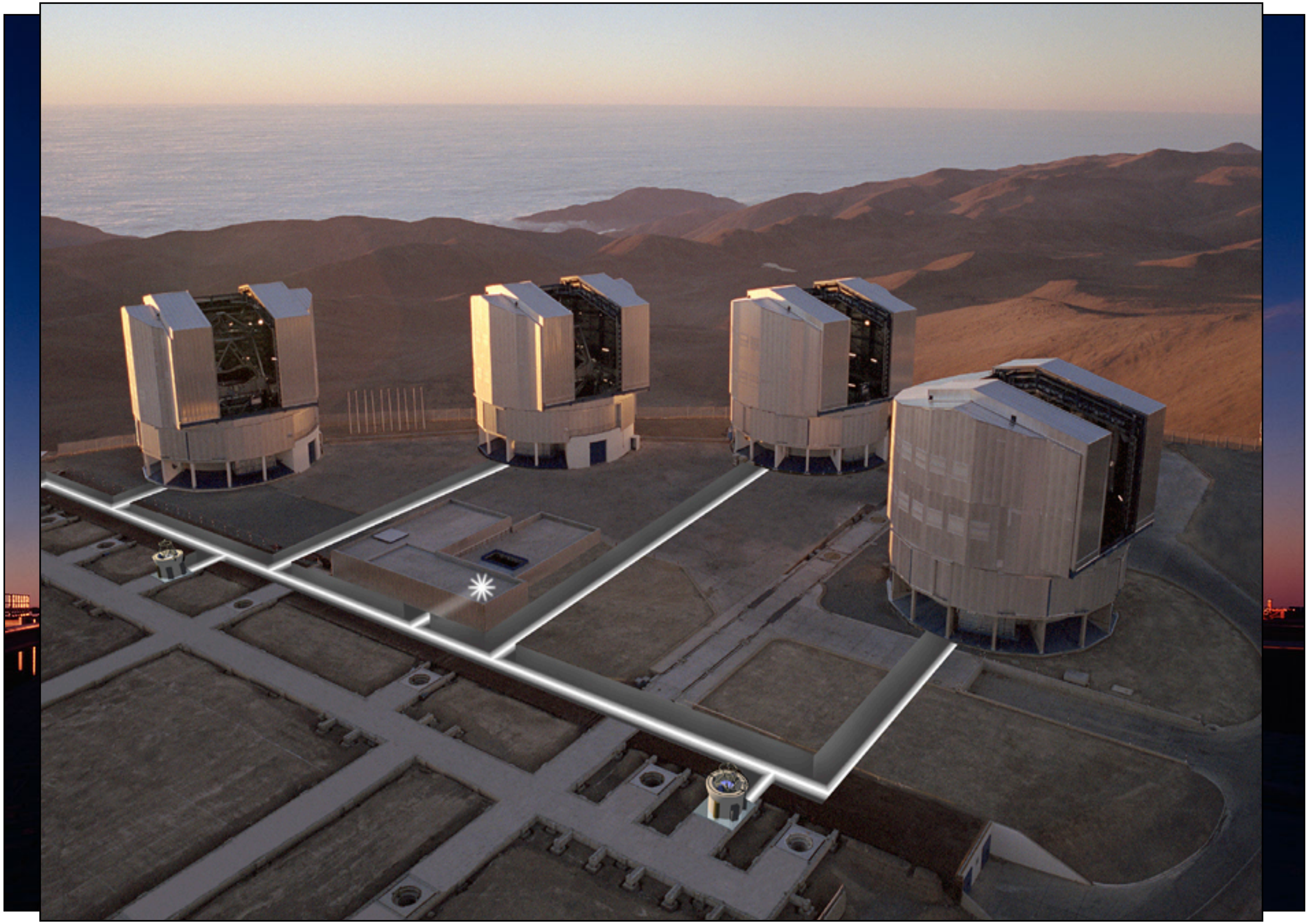
- Supermassive black holes
  huge: R_{BH} ~ few 10^6-10^9 km
  but very far away galaxies

Sgr A* is the largest one angular size-wise
Schwarzshild radius:
10 µas = 1 € coin on the Moon.

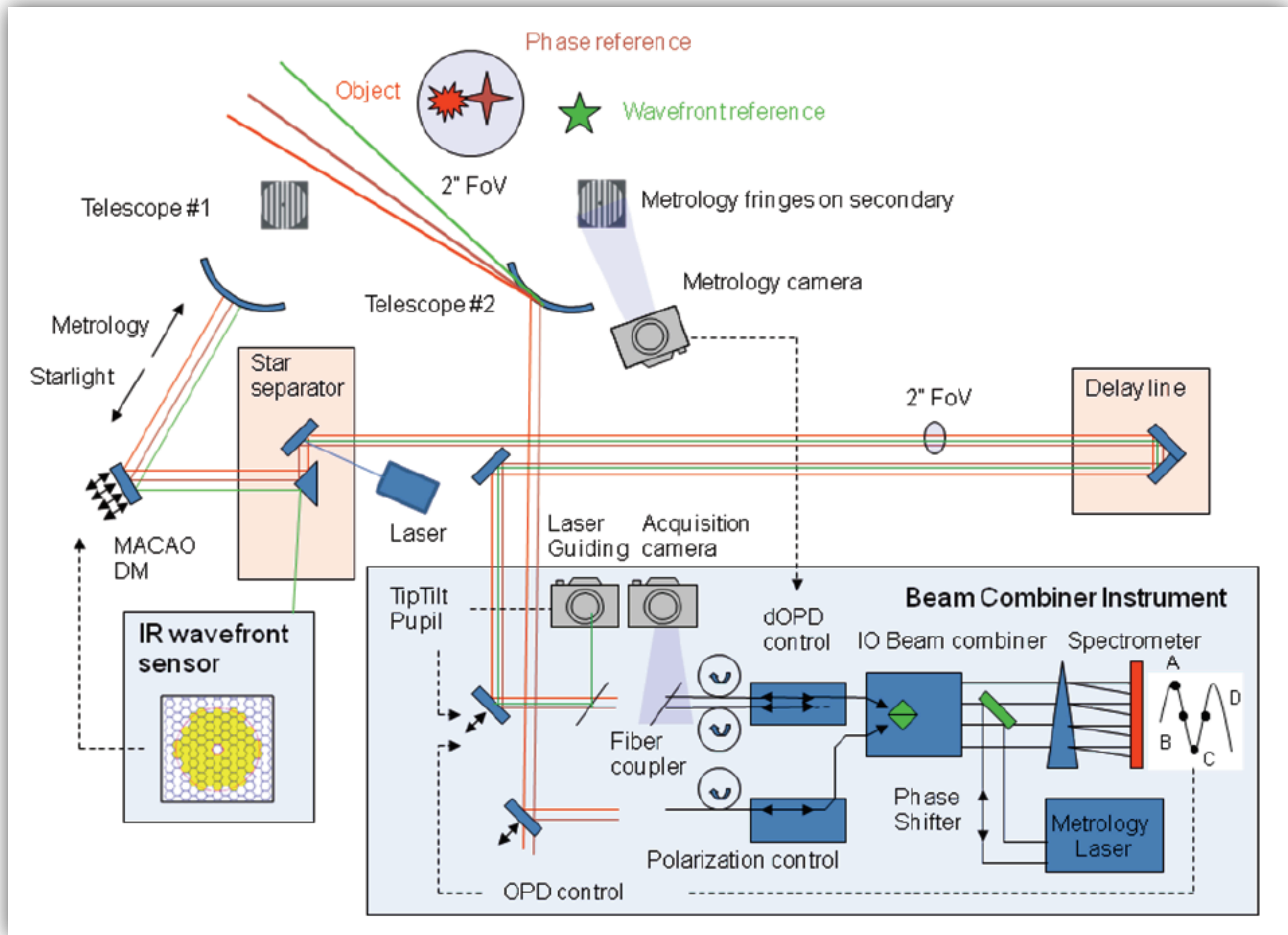
The specifications of GRAVITY

- Wavefront correction (SR=35% at 30° from zenith) at K on a K=7 magnitude star (SR=10% on a K=10 star at zenith).
- OPD stabilization (λ/10) on a K=10 star.
- 100 s exposure times to reach K=17 in wide band.
- Closure phase or phase reference imaging (quick and accurate) with 3 mas résolution with the UTs and 2 mas with the ATs.
- Narrow angle astrometry (2”) with 10 μas accuracy in 5 minutes (primary K=10, secondary K=15 with the UTs).
- R=22, 500, 4000

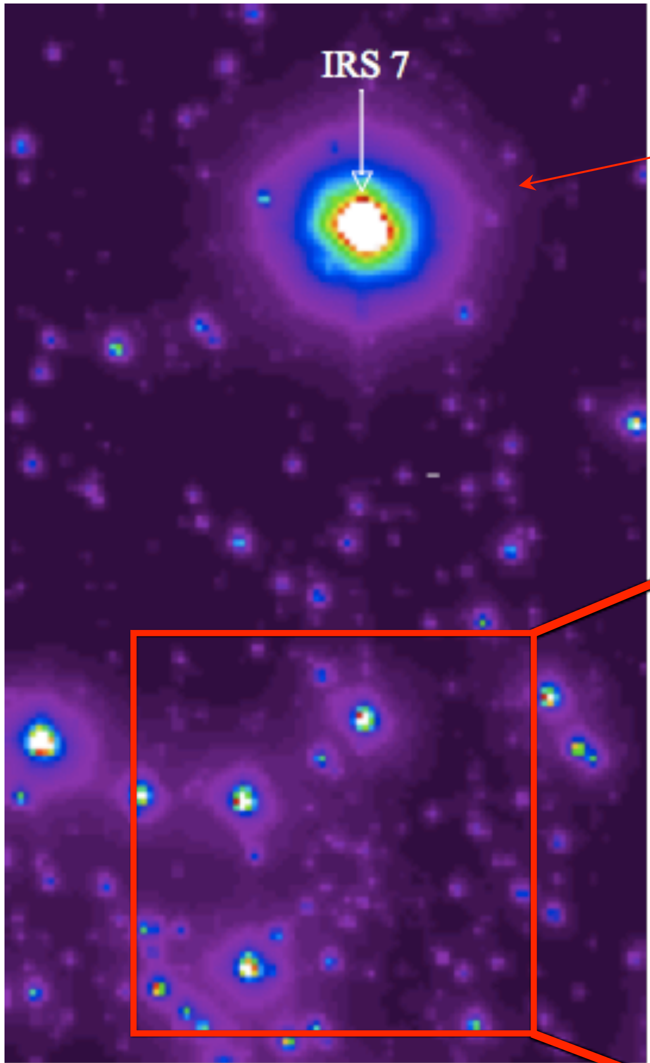
VLTI



Principle of the instrument

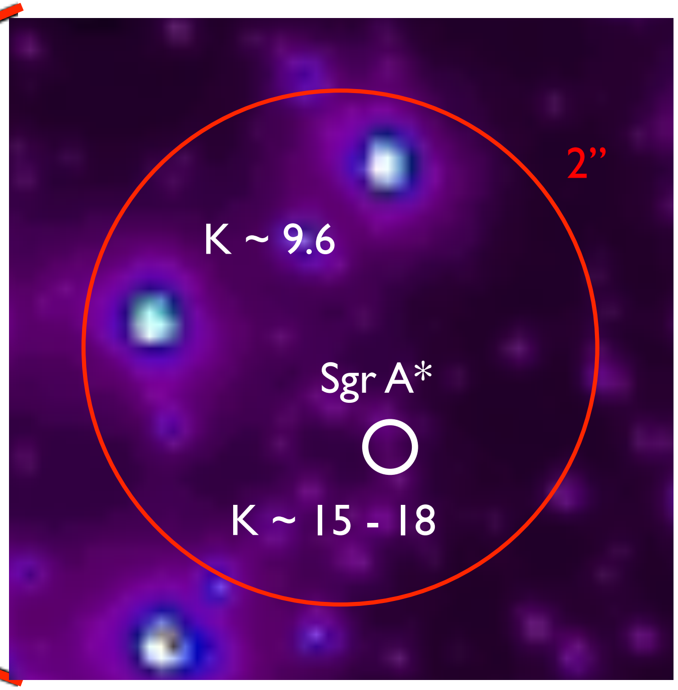


Reference sources for GRAVITY near Sgr A*

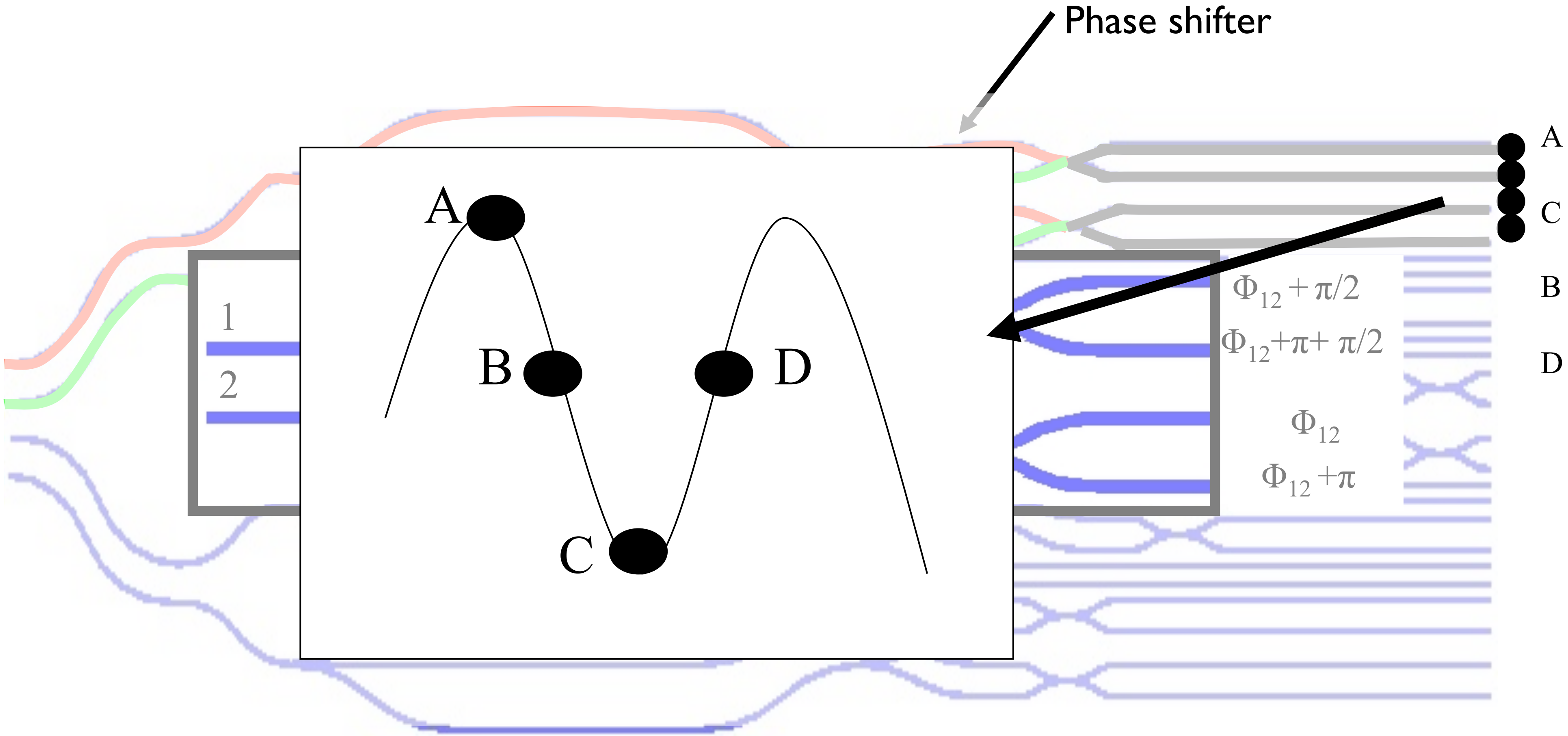


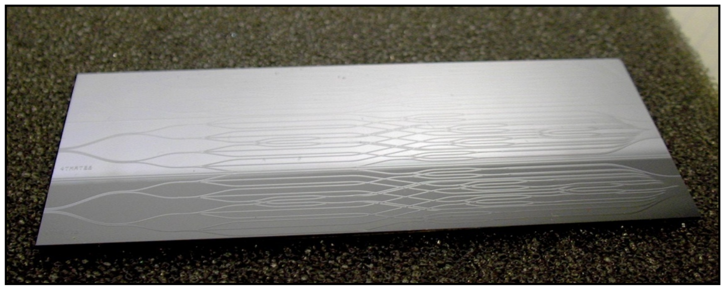
Adaptive Optics reference source

Interferometry reference sources - IRS 16 - (imaging and astrometry)



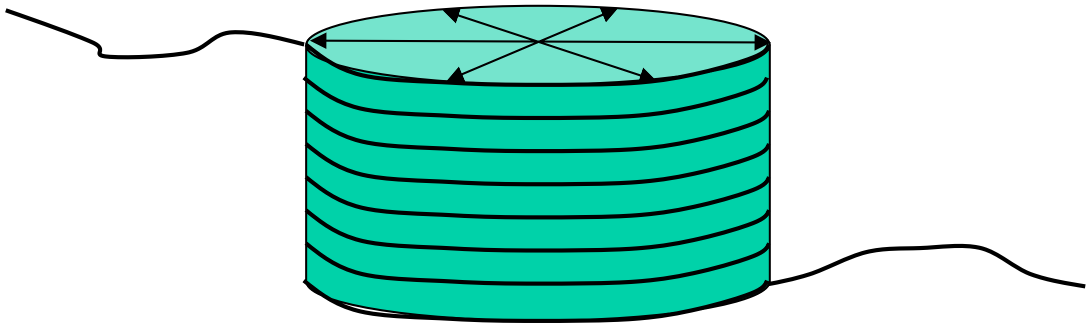
Integrated optics beam combiner





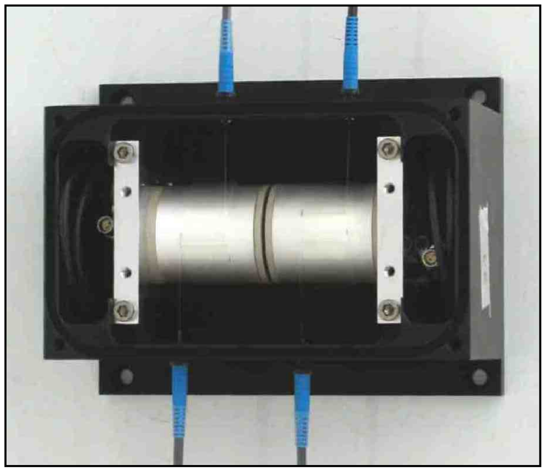
LETI prototype (ANR LAOG/LESIA)

Fibered delay line

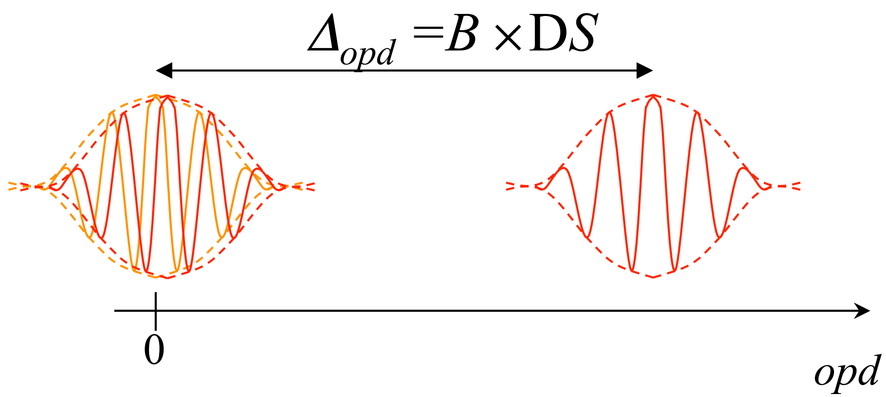


Fiber wrapped on a piezo cylinder.

Applying a voltage changes the fiber length.

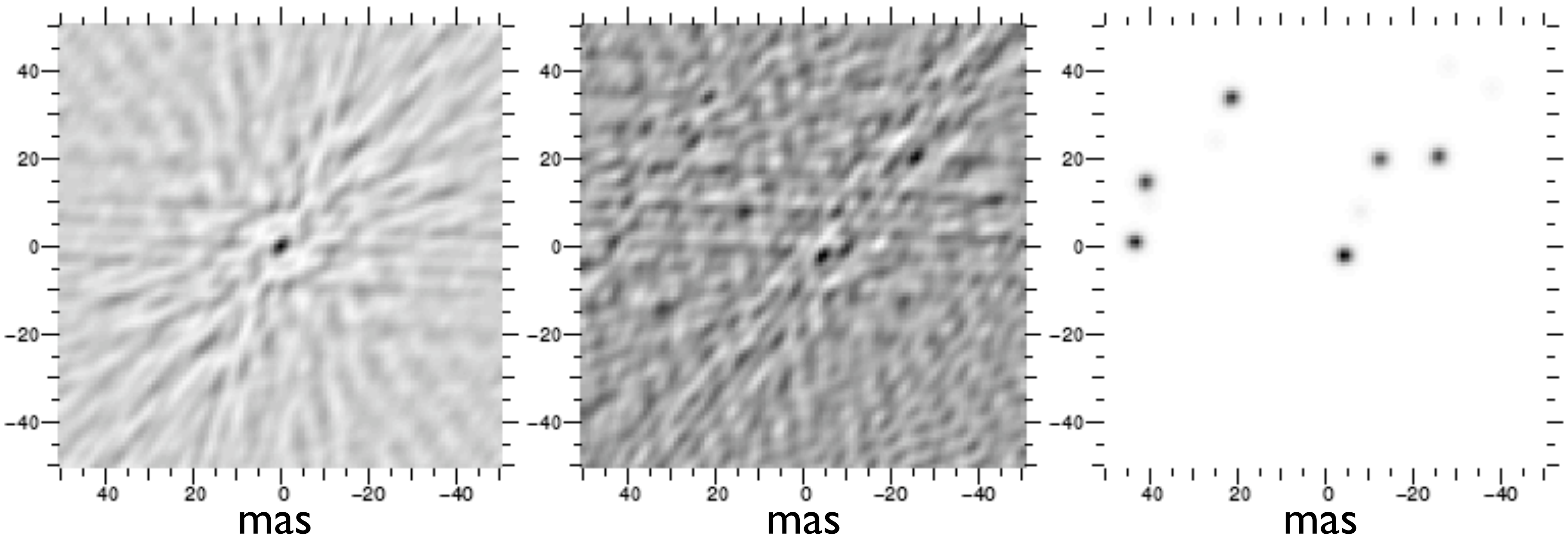


Le Verre Fluoré prototype



Imaging of the closest stars orbiting Sgr A*

Reconstructed image after a one night observation:

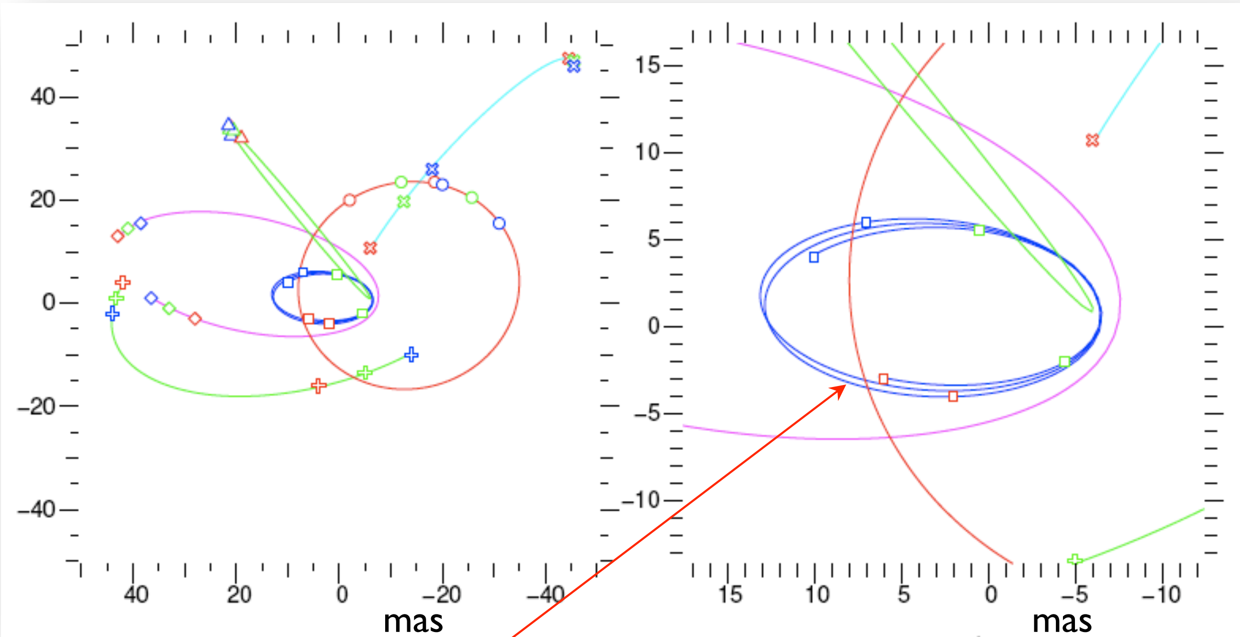


PSF | Raw image | Deconvolved image

Paumard et al. (2005)

Imaging of the closest stars orbiting Sgr A*

Orbits after 15 months of observing:



1 mas = 100 R_{BH}

Detection of the pericenter shift in the Schwarzschild metric

Paumard et al. (2005)

Narrow angle astrometry

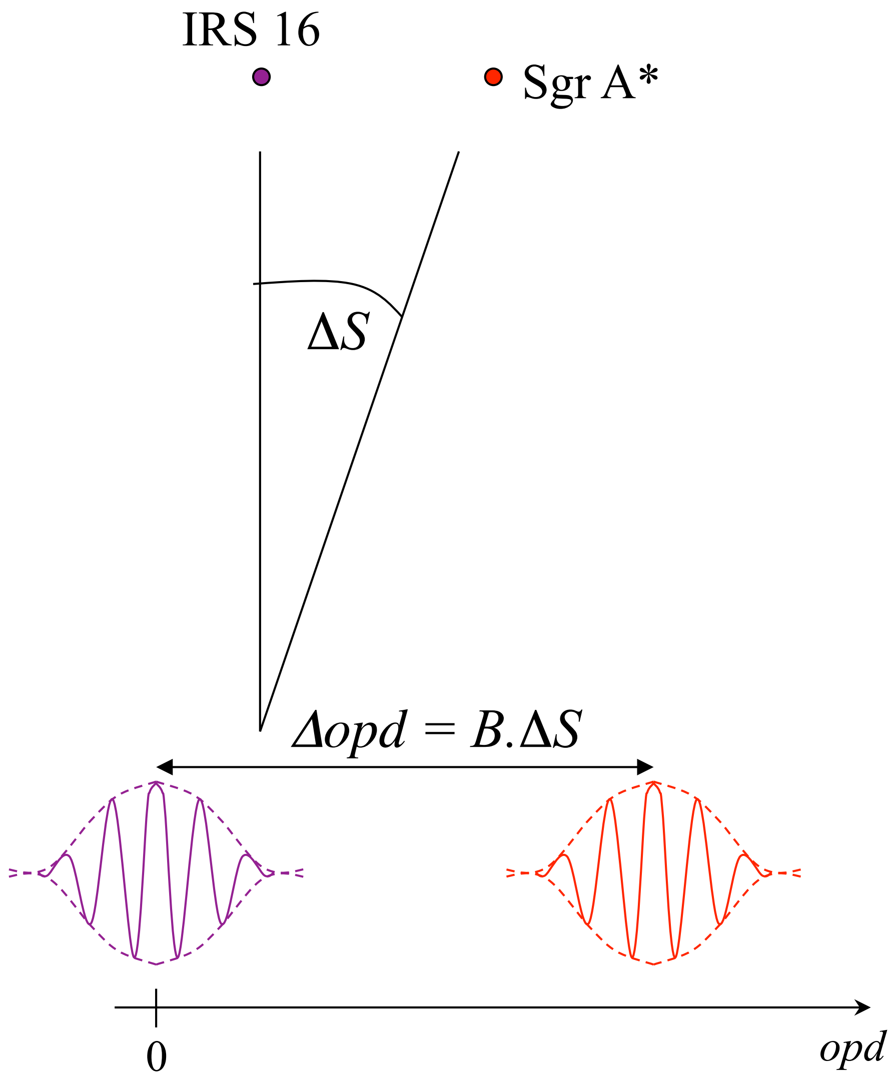
Distance between interferogram:

$$\Delta opd = B.\Delta S$$

Hence:

$$\Delta S = \Delta opd / B$$

A 5 nm accuracy on Δopd with a 100 m baseline yields an accuracy of 10 μas on ΔS.

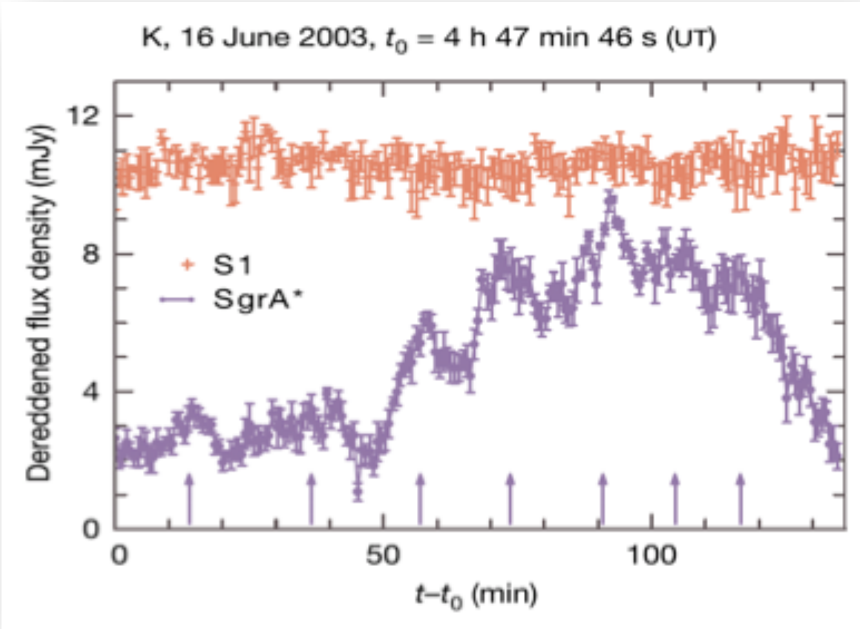


Motion of flares around Sgr A*

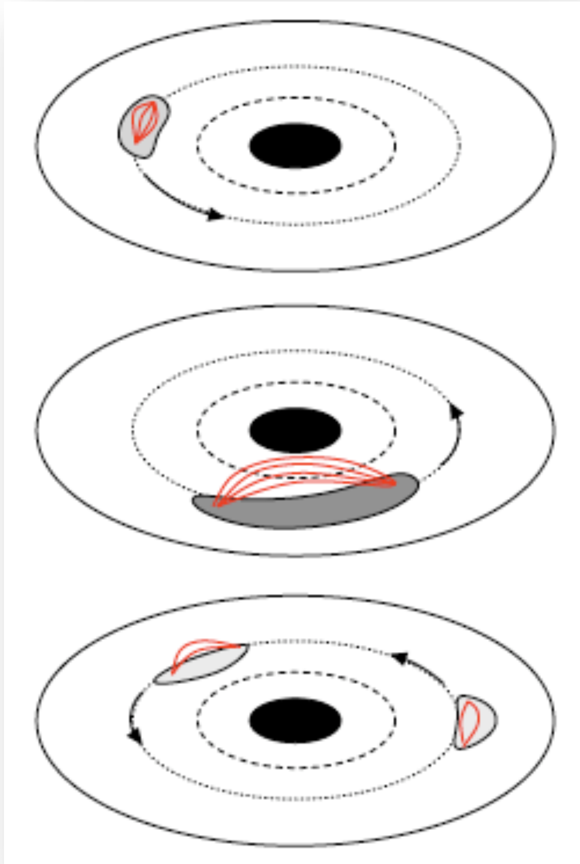
The hot spot as a test particle to explore space-time in a strong field

Scale ~ 1 R_{BH} = 10 μas accuracy

Time scale = 10 min



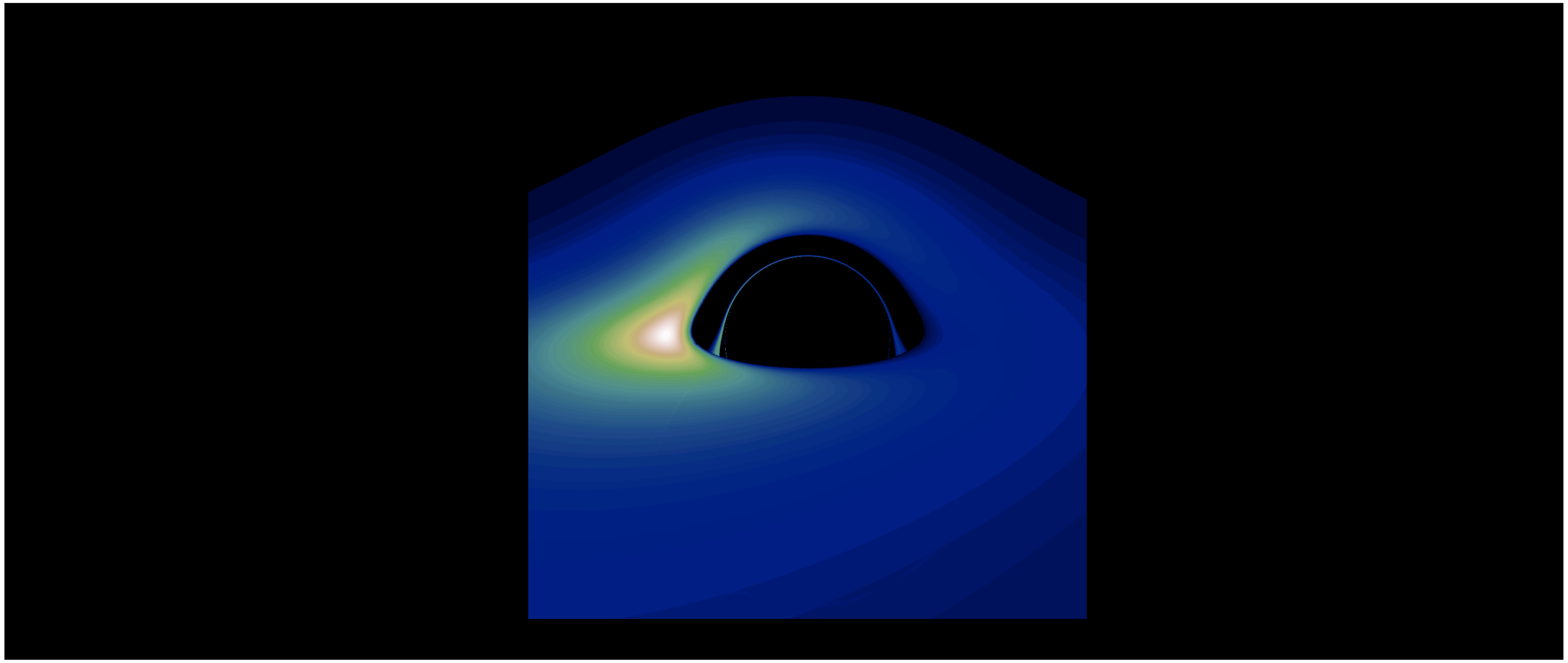
Genzel et al. (2003)



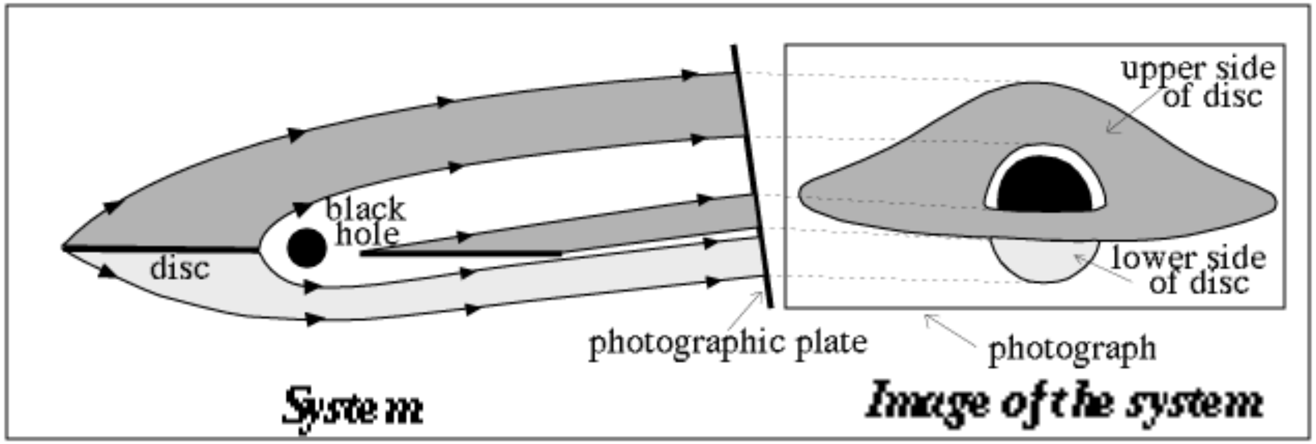
Eckart et al. A&A 500, 935 (2009)

Hot spot model on the last stable orbit.

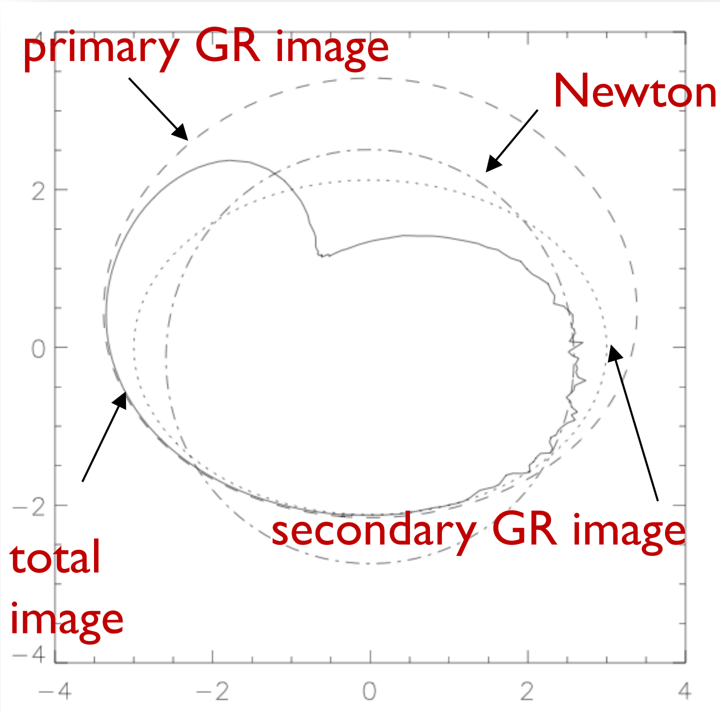
Space-time around a black hole

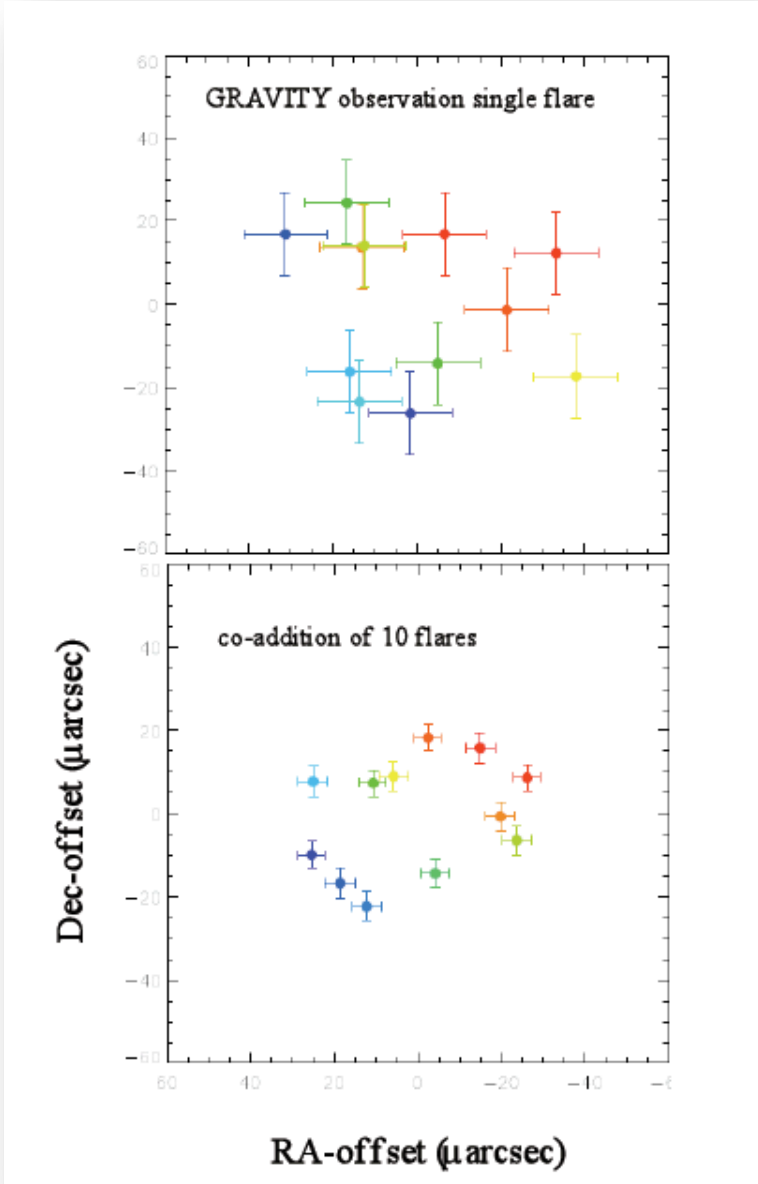


But it looks different around a black hole

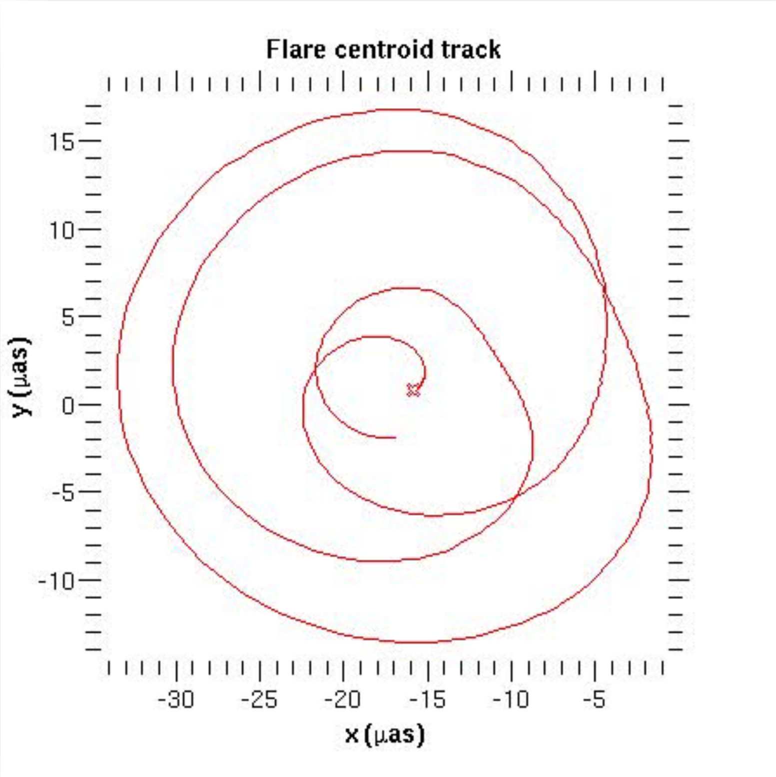


Mesuring the last stable orbit with GRAVITY

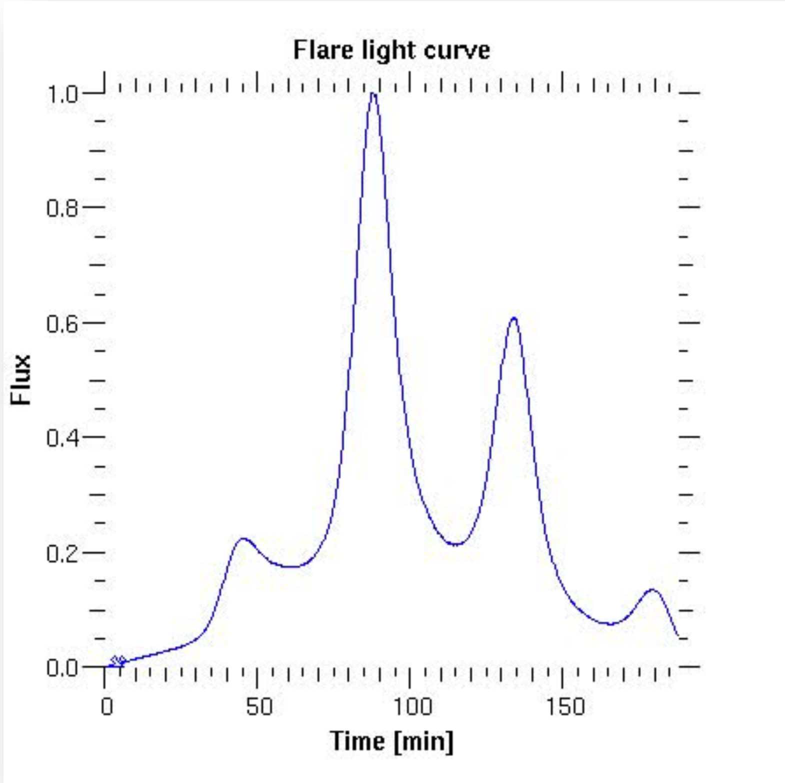




Paumard et al. (2005)



GRAVITY
astrometric
accuracy



Black hole outburst

Orbit inclination = 70°

Schwarzschild black hole (J=0).

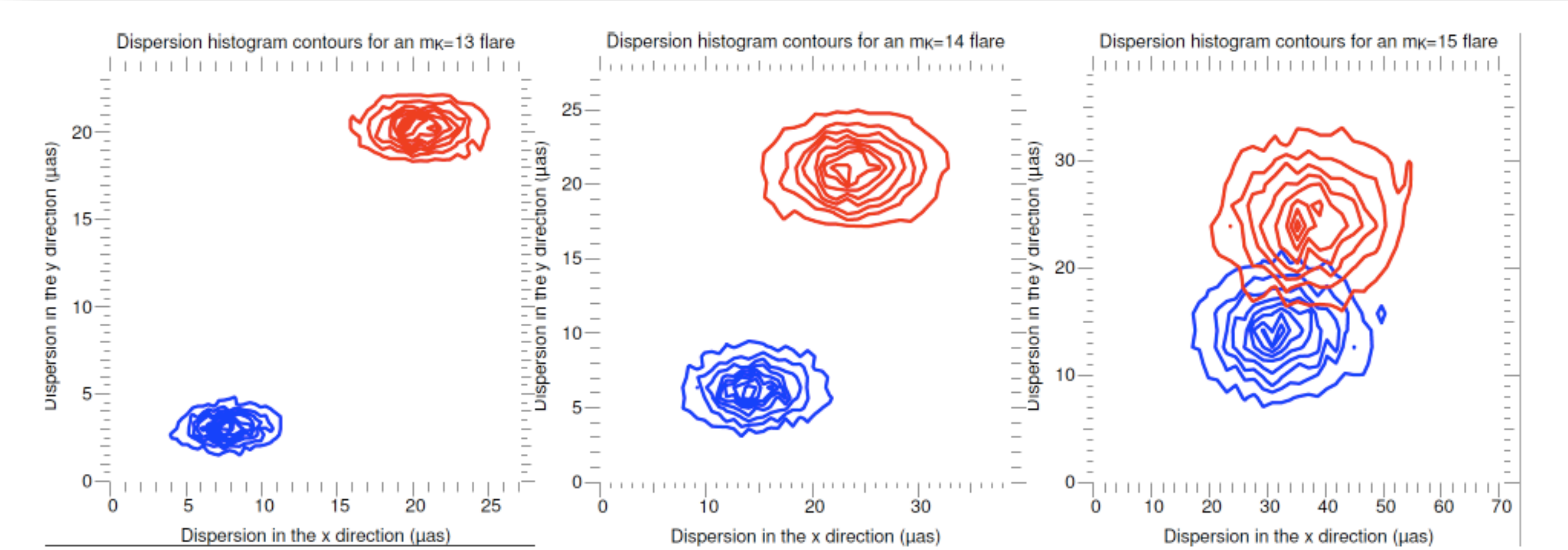
Innermost stable circular orbit.

Distance to observer = 50 R_{BH}

Vincent et al. (2010)

Detection of the hot spot motion on the Innermost stable circular orbit

- Full GRAVITY simulation with *realistic* noises
- 100 s exposure time for individual measurements



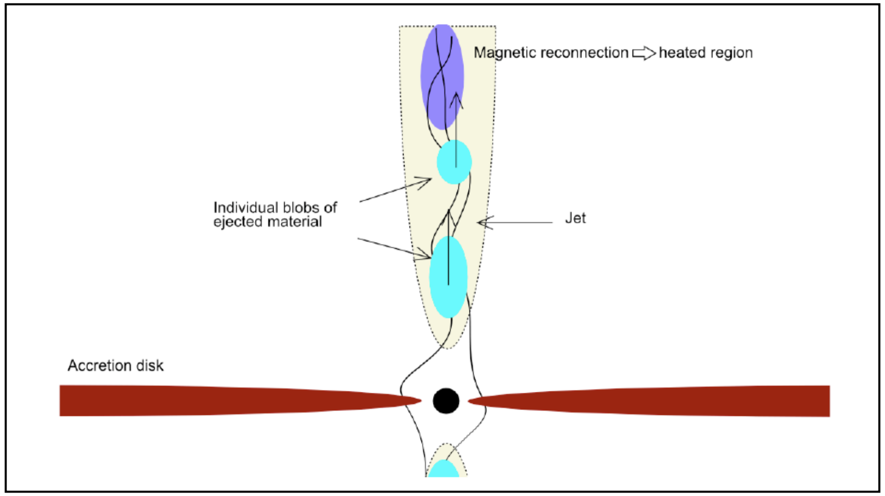
Vincent et al. (2010)

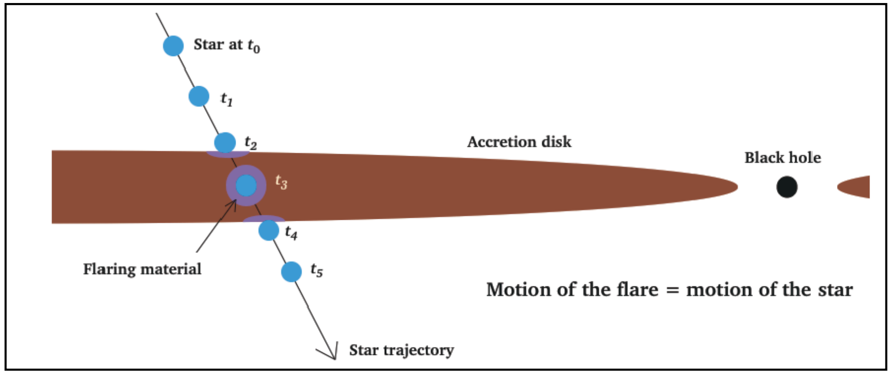
Red: hot spot in motion

Blue: still hot spot

Detection of the hot spot motion on the Innermost stable circular orbit

Alternative scenarios will induce motions even easier to detect (10 μas min^{-1}).





Magnetic reconnection at the base of jets
Falcke & Markoff (2000)

Star-disk interaction
Nayakshin et al. (2004)

GRAVITY schedule

- December 2009: PDR
- ≥ July 2010: δ PDR for adaptive optics
- Mid-2011: Final Design Review
- 2011 - 2013: Construction
- Mid-2013: first light
- ≥ 2014: in operation