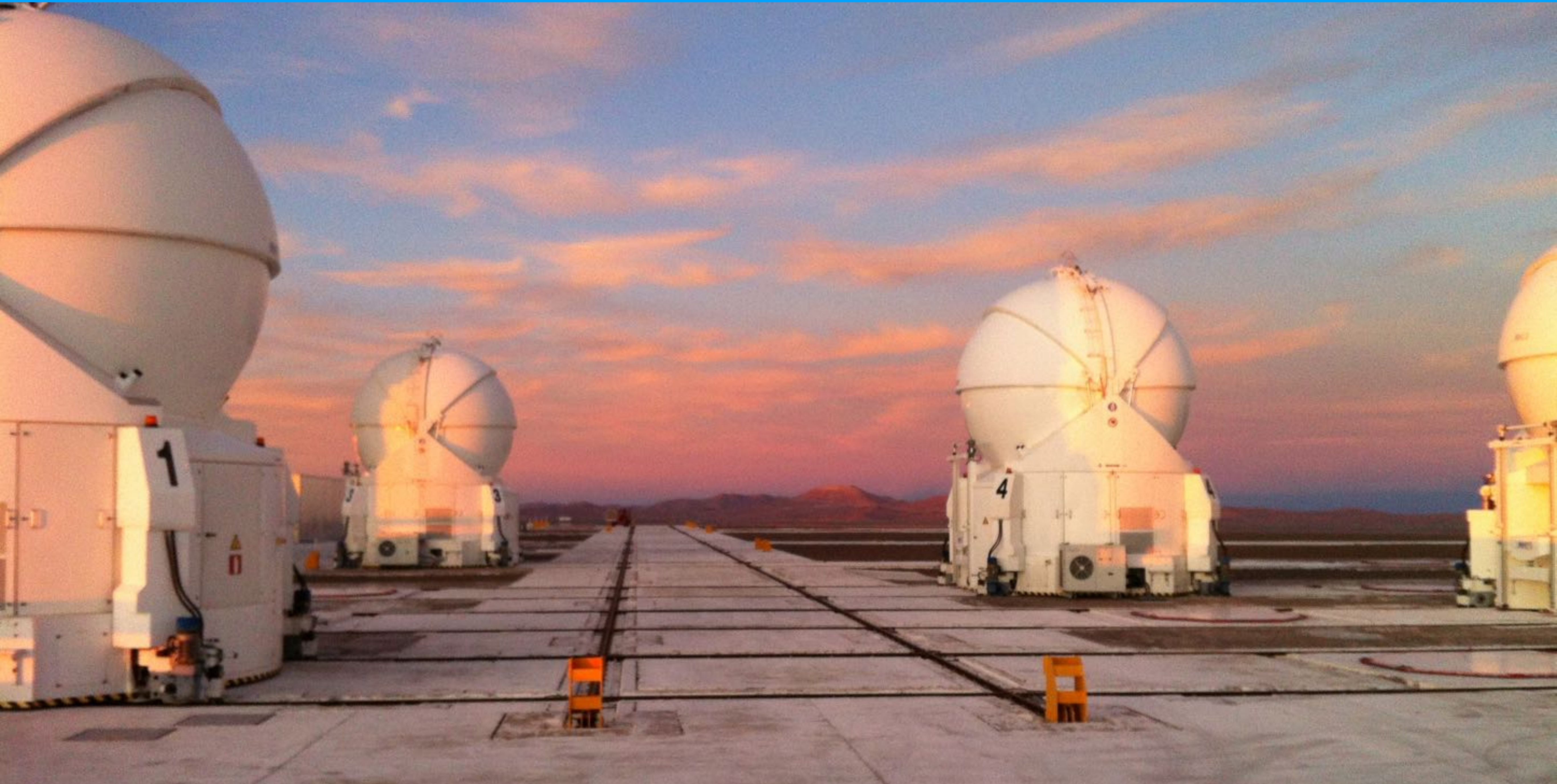
Galactic Center observations with the VLT(I)
Die Vermessung des Zentrums unserer Milchstraße mit dem VLT(I)



SIM

IPAG Institut de Planétologie et d'Astrophysique de Grenoble

Max-Planck-Institut für Astronomie Heidelberg / Max Planck Institute for Astronomy Heidelberg

MPE

l'Observatoire de Paris

1. Physikalisches Institut Universität zu Köln

ESO

Wolfgang Brandner: GRAVITY observations of the Galactic Center Dec 2018

Overview

1. The center of our Milky way - astrophysical questions
2. The measurement tools
    A. Basic methods
    B. VLT+GRAVITY/CIAO
3. S2 orbiting the central blackhole
4. The nature of flares close to the blackhole
5. Outlook

1. The center of our Milky way - astrophysical questions

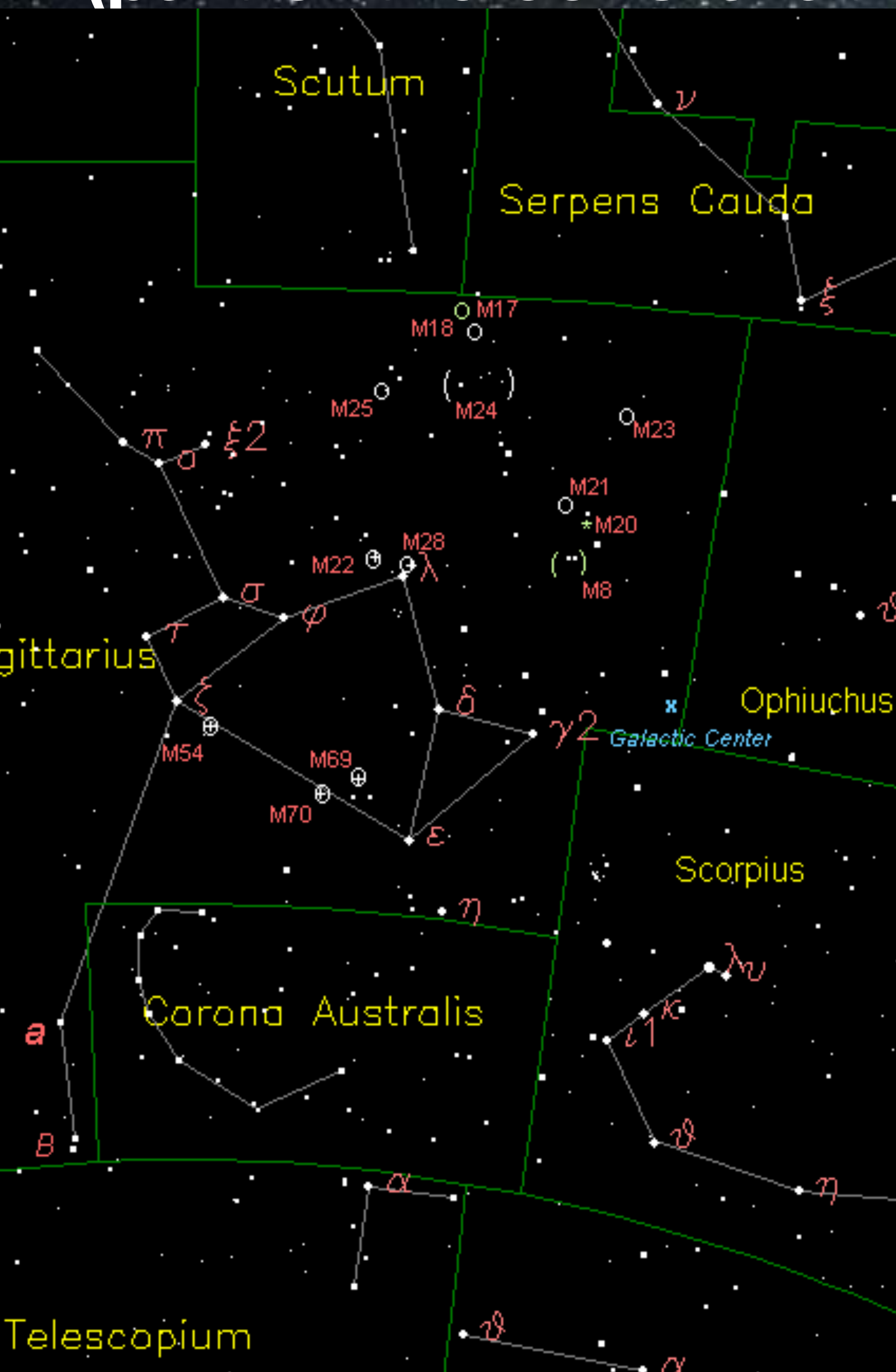
Photo: Henning Avenhaus

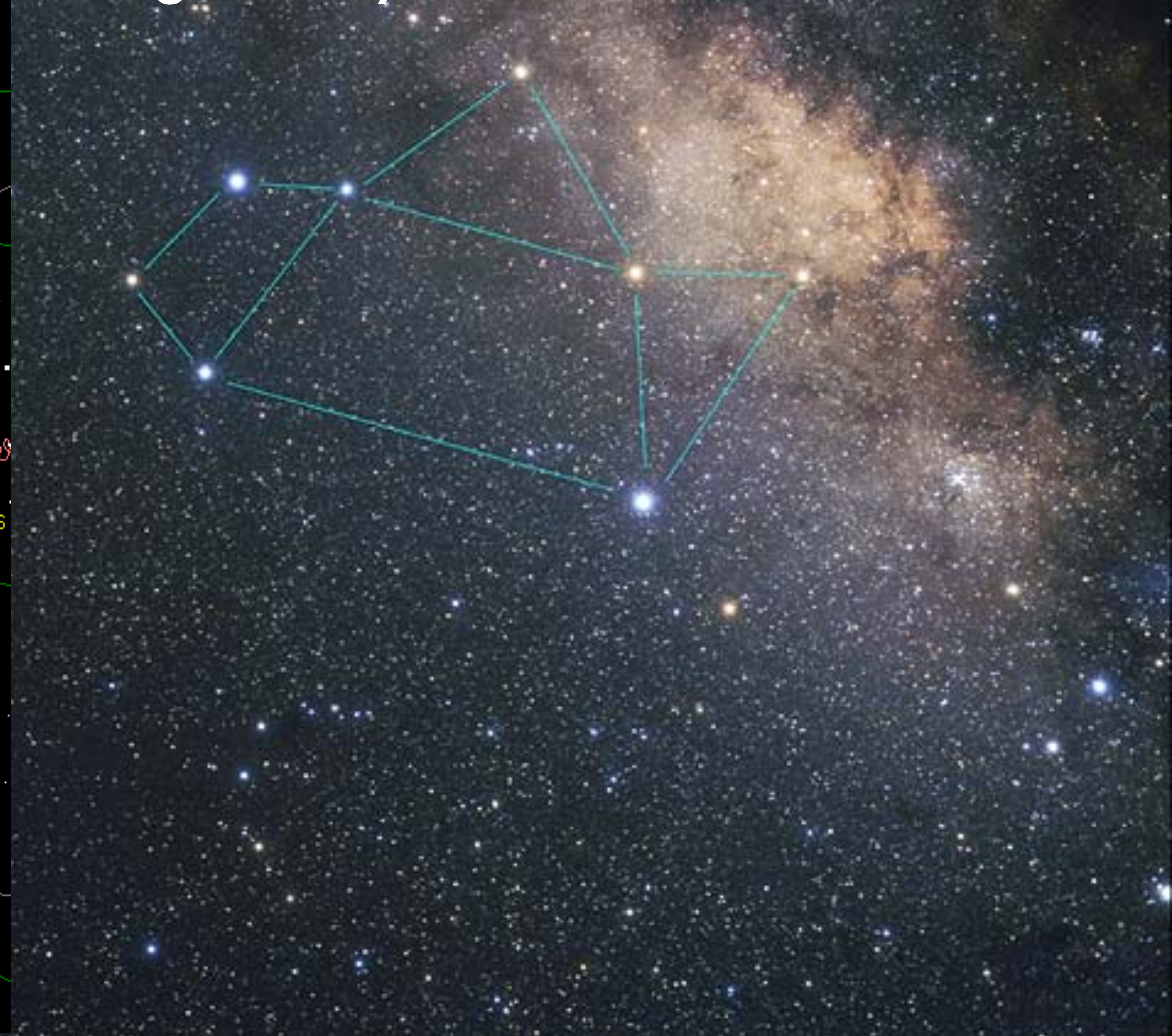
Where is the Galactic center?

How do we observe it?

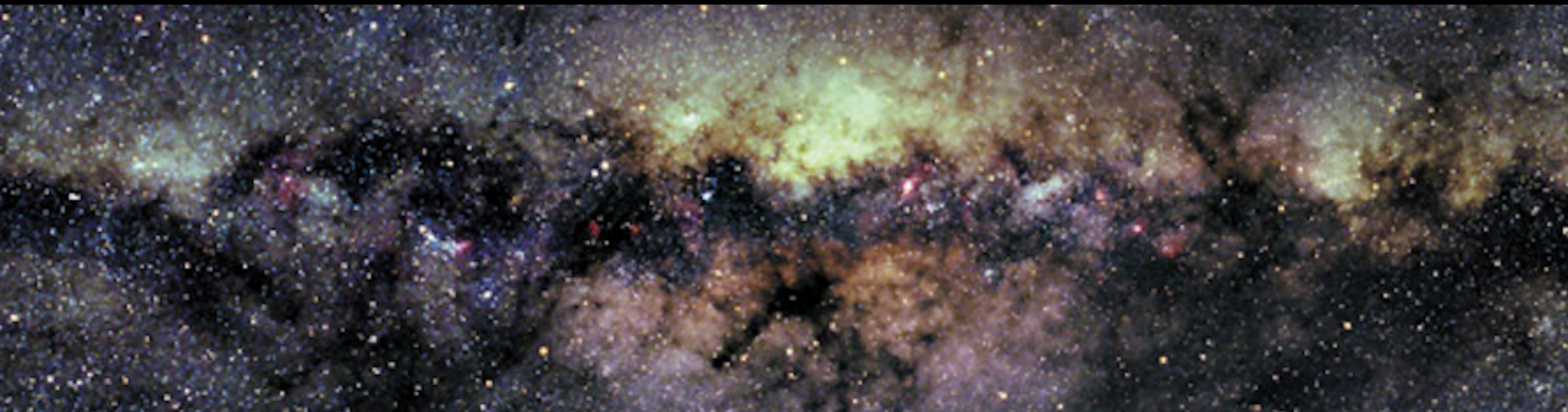
The “teapot”

(part of the constellation Sagittarius)





Dark clouds obscure the Galactic center in the optical



=> need for observations in the infrared, radio, etc.

- **What is the nature of the central bright radio source? Is it a black hole (yes)? What is its mass (~4 million solar masses)?**
- **Which physical processes are involved?**
- **What is the origin of brightness outbursts (“flares”) in the galactic center?**

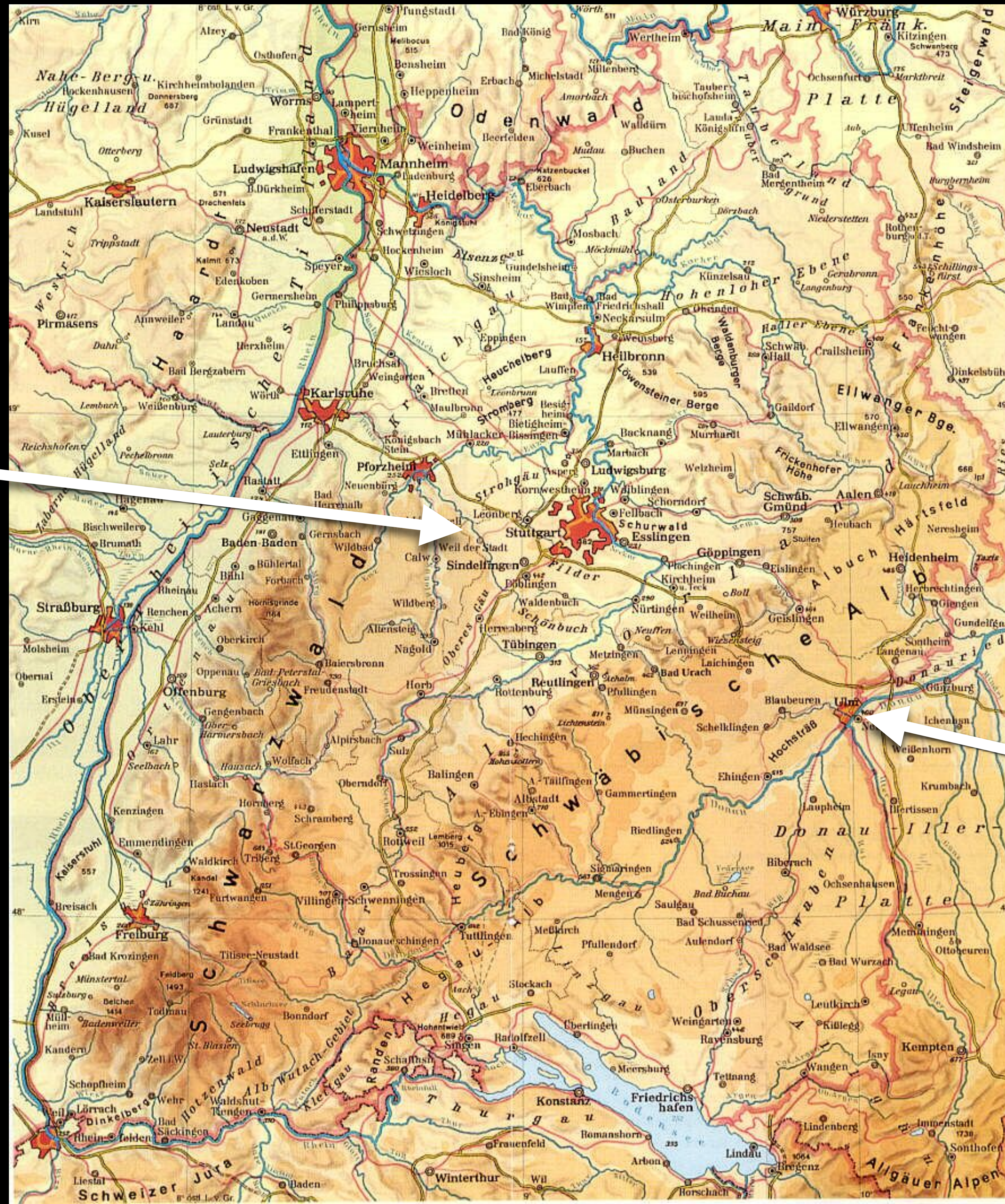
- **What are the stellar populations (age, metalicity, mass function, …) in the central region?**

- **What is the distance from the Sun to the Galactic center (~8 kpc)?**

2. The measurement tools

2A. The basic tools: developed by two “local” scientists

Weil der Stadt



Ulm

Johannes Kepler (** 1571 in Weil der Stadt)

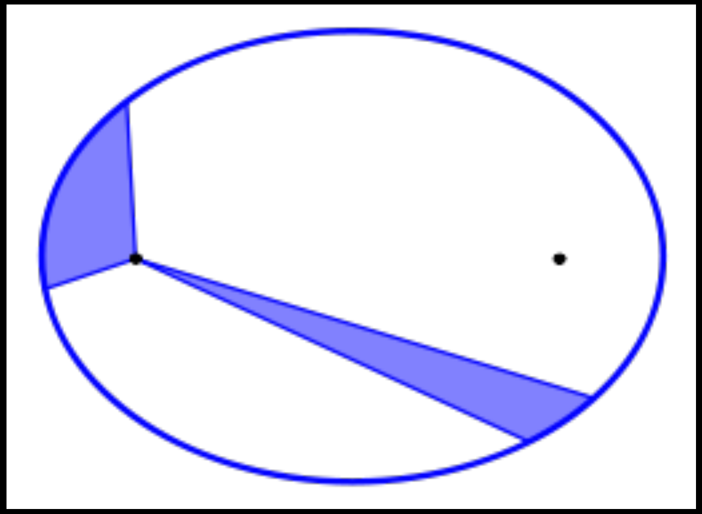
Kepler's laws from 1608, 1618
("solutions" of Isaac Newton's theory of gravity in 1684)

1st law of Kepler

Planets orbit on ellipses. The Sun is in one of the focal points

2nd law of Kepler

In equal time the line joining the Sun and the planet covers equal area.



i.e. closer to the Sun planets move faster than at larger distances
=> Location and velocity of the planet as a function of time

3rd law of Kepler

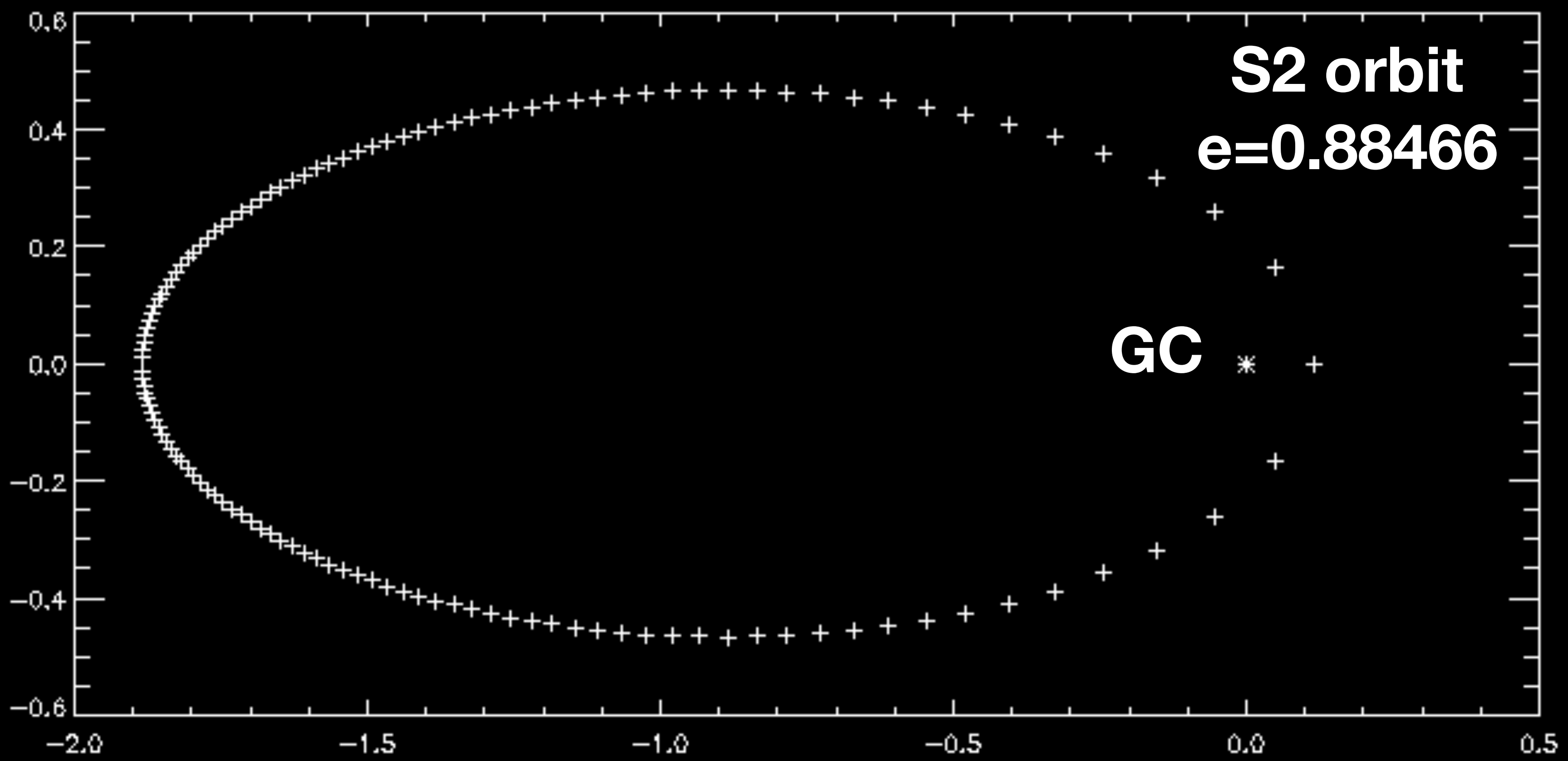
$a^3 = M * P^2$

$M = a^3 / P^2$

a := semi-major axis in AU
M := mass of the central object in solar masses
P := orbital period in years

Examples

2nd law of Kepler



"+" marks the position at equal time intervals

At periastron S2 moves at ~8 times the speed it moved at apastron

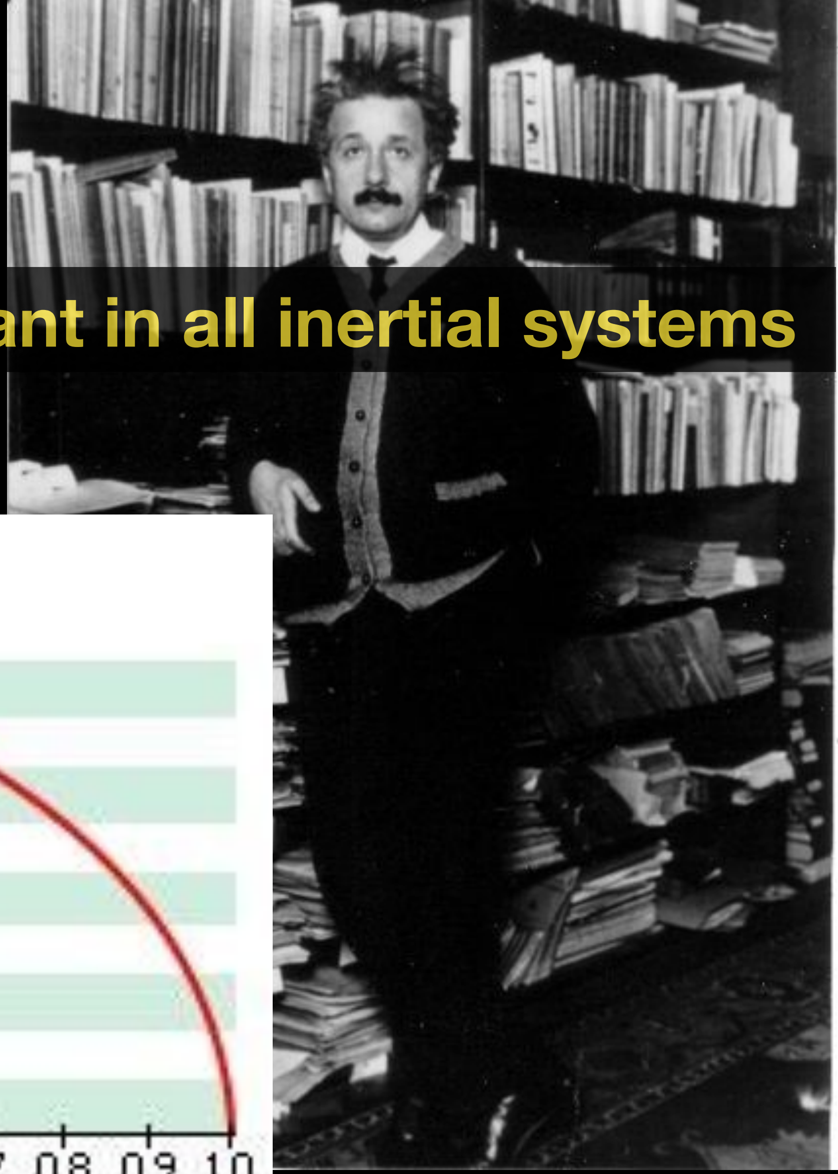
3rd law of Kepler

Earth: P = 1yr, a = 1AU

Jupiter @ P = 11.86yr

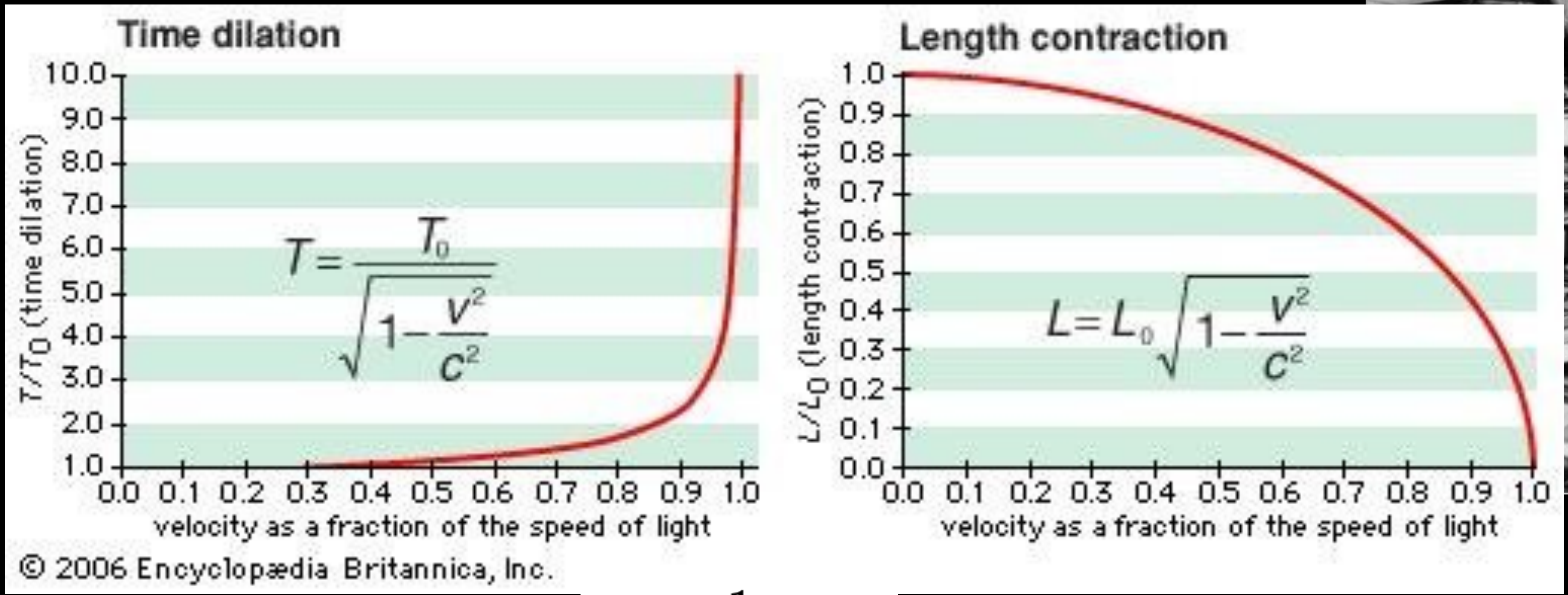
=> a [AU]=$(11.86^2)^{1/3}$ = 5.2

Albert Einstein (** 1879 in Ulm)



special theory of relativity (1905): speed of light is constant in all inertial systems

“Moving clocks tick slower”



Lorentz factor (~1895): $$\frac{1}{\sqrt{1-v^2/c^2}}$$

v := relative velocity between system and observer

c := speed of light = 300 000 km/s

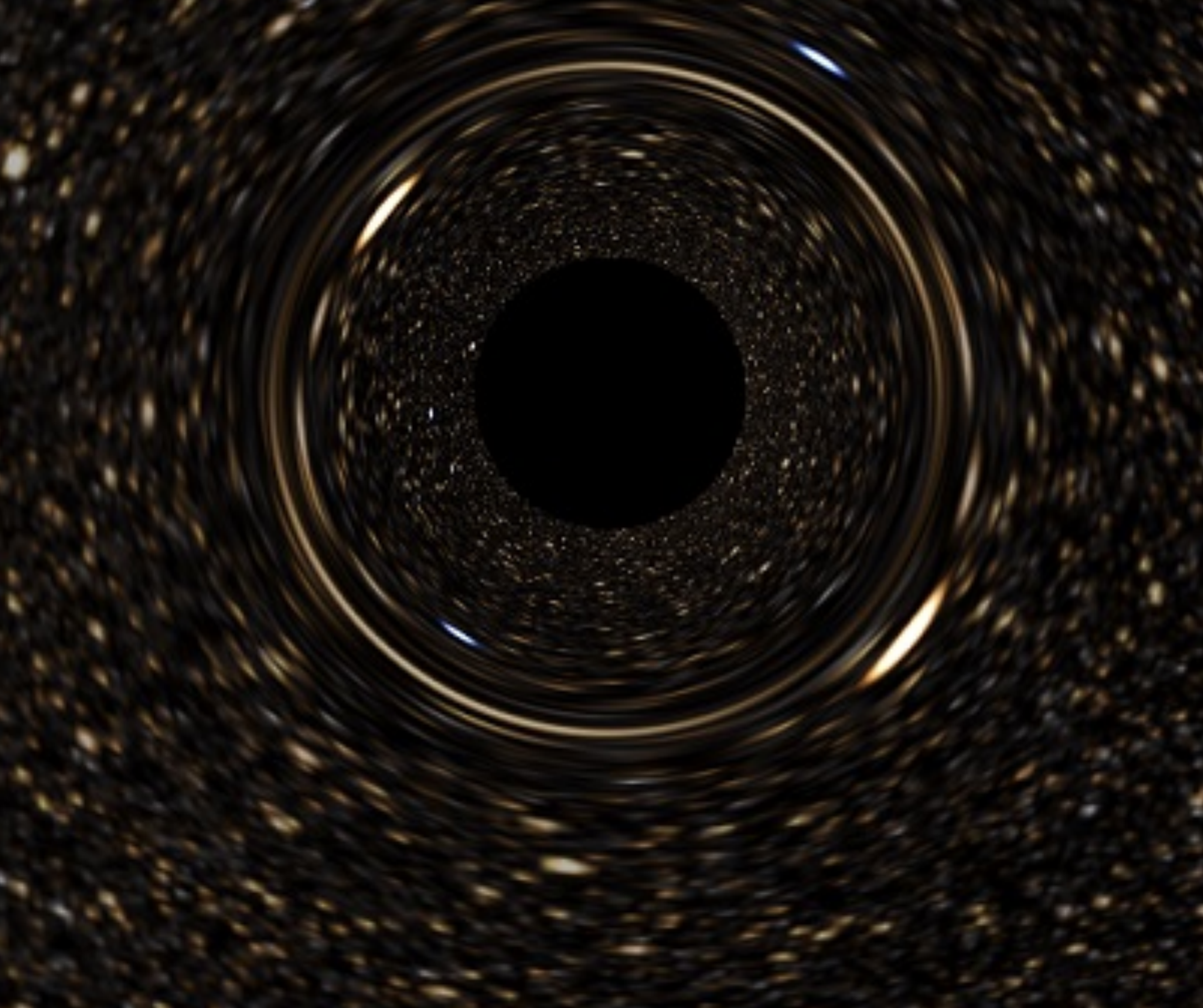
=> in everyday life, Lorentz factor is indistinguishable from 1

Noticeable only when moving at a significant fraction of the speed of light:
v = 0.025*c => Lorentz factor = 1.00033 <=> S2 at GC periastron
v = 0.3*c => Lorentz factor = 1.05 <=> hot spot/flare orbit around GC

Einstein's General theory of relativity

Considers the effects of mass and acceleration

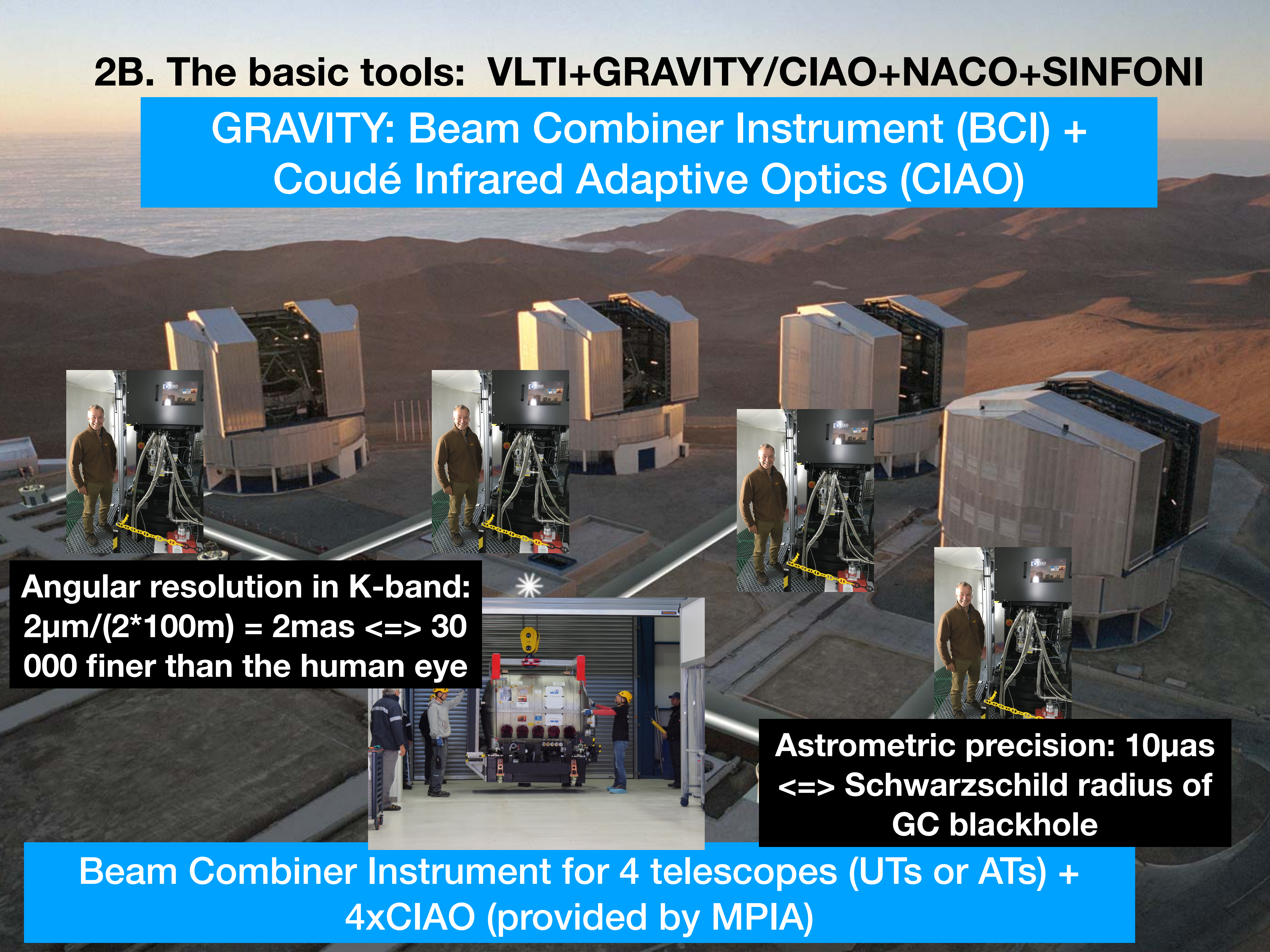
"space is curved" => mass acts as a gravitational lens
=> Karl Schwarzschild in 1916: for very high mass density, space curvature can increase so that space "closes" on itself => "blackhole"



Size of a black hole (Schwarzschild radius): R_s = 3 km * M [M_{Sun}]
Galactic center: R_s = 3 km * 4*10^6 = 12 million km <=> 10 μas

2B. The basic tools: VLTI+GRAVITY/CIAO+NACO+SINFONI

GRAVITY: Beam Combiner Instrument (BCI) +
Coudé Infrared Adaptive Optics (CIAO)



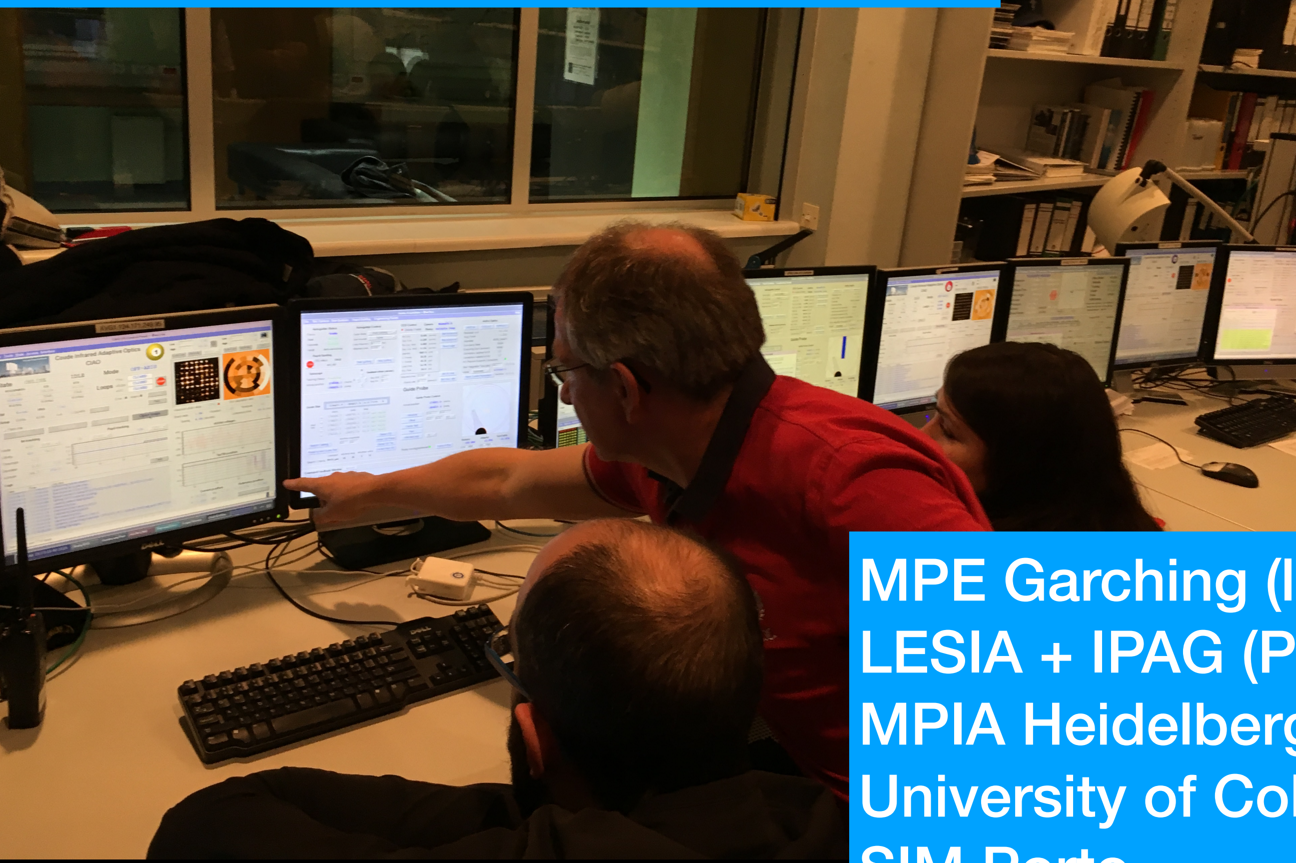
Angular resolution in K-band: 2µm/(2*100m) = 2mas <=> 30 000 finer than the human eye

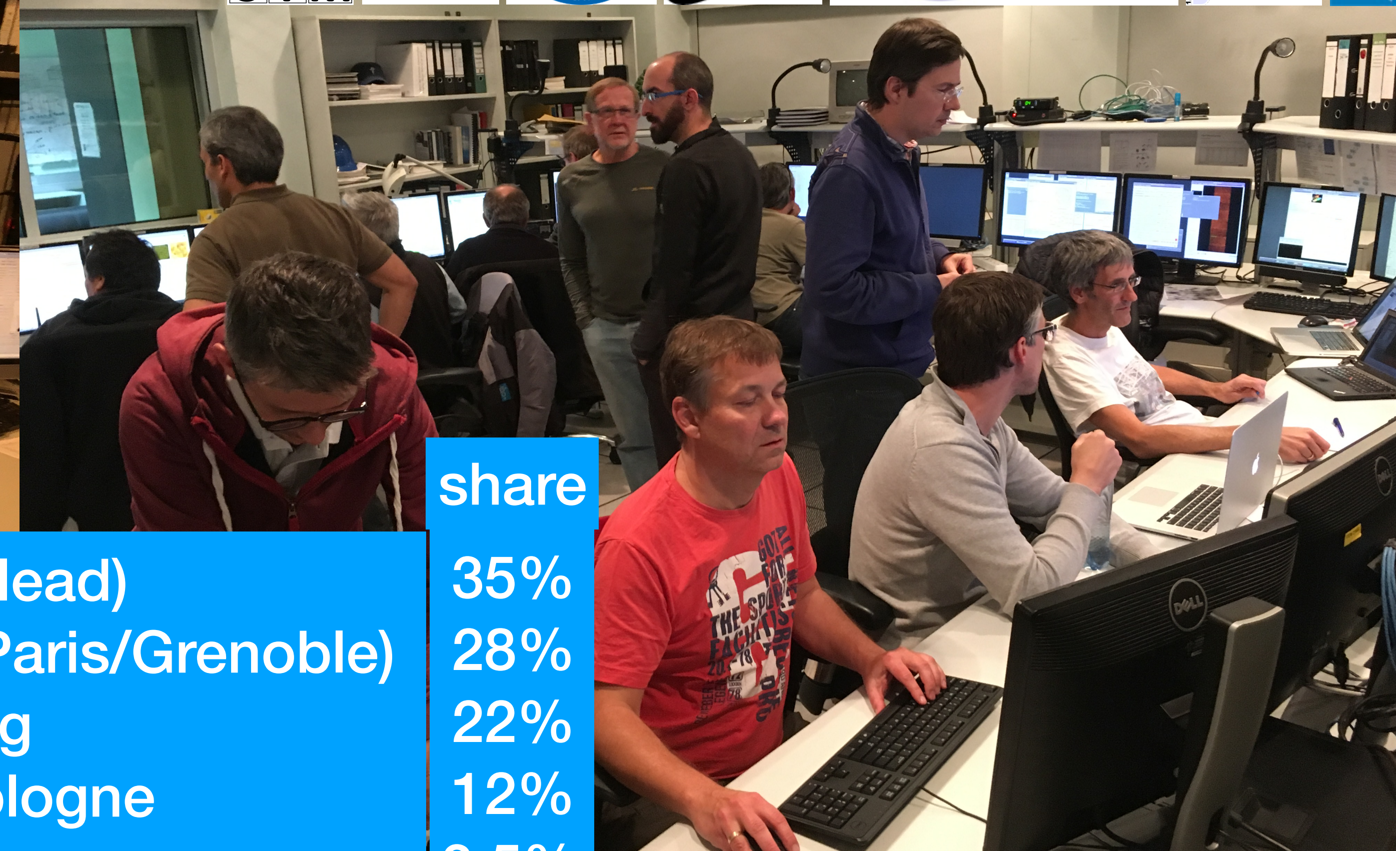
Astrometric precision: 10µas <=> Schwarzschild radius of GC blackhole

Beam Combiner Instrument for 4 telescopes (UTs or ATs) +
4xCIAO (provided by MPIA)

MPIA team on Paranal for CIAO installation

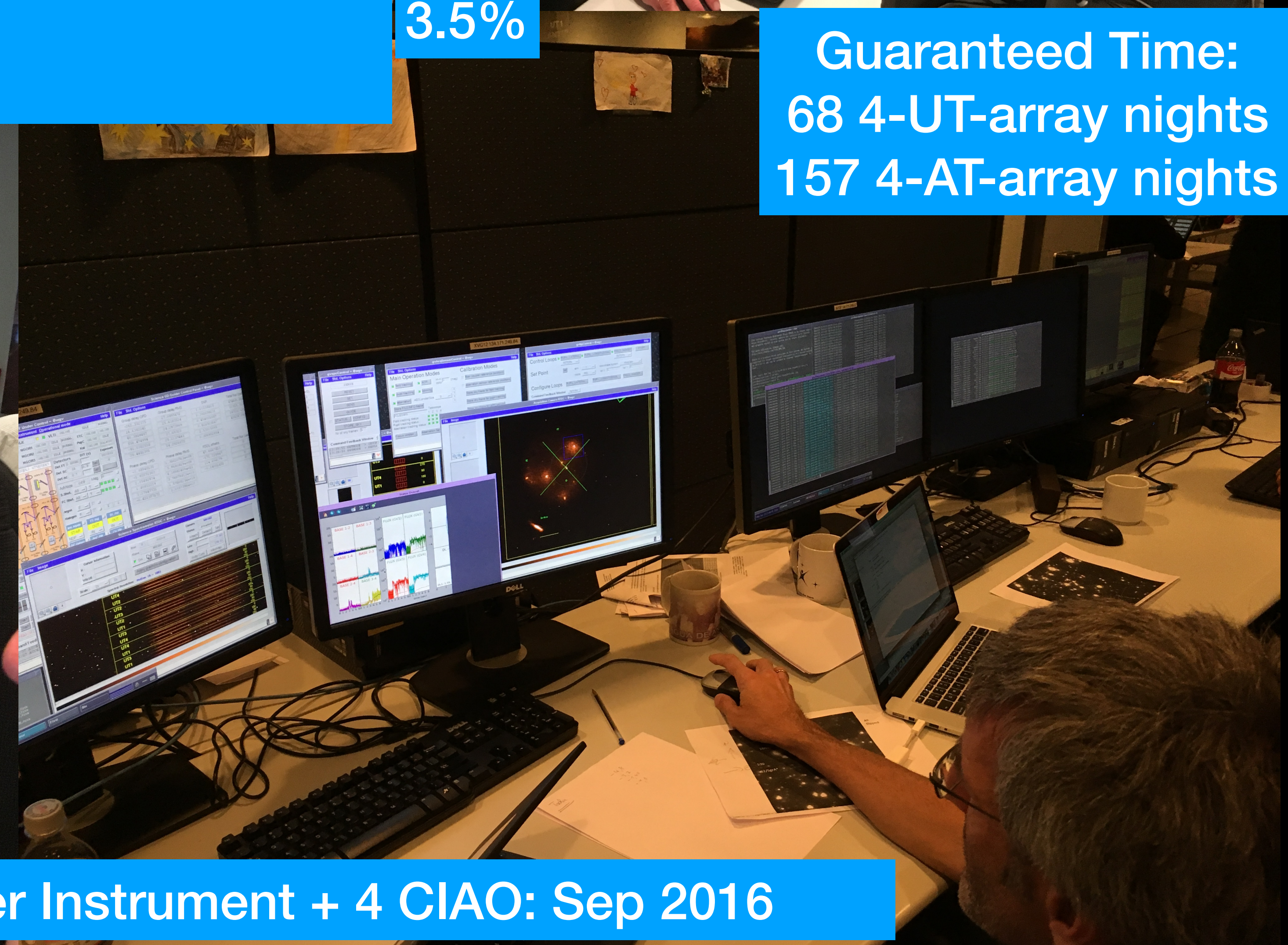
GRAVITY consortium





	share
MPE Garching (lead)	35%
LESIA + IPAG (Paris/Grenoble)	28%
MPIA Heidelberg	22%
University of Cologne	12%
SIM Porto	3.5%
+ESO	

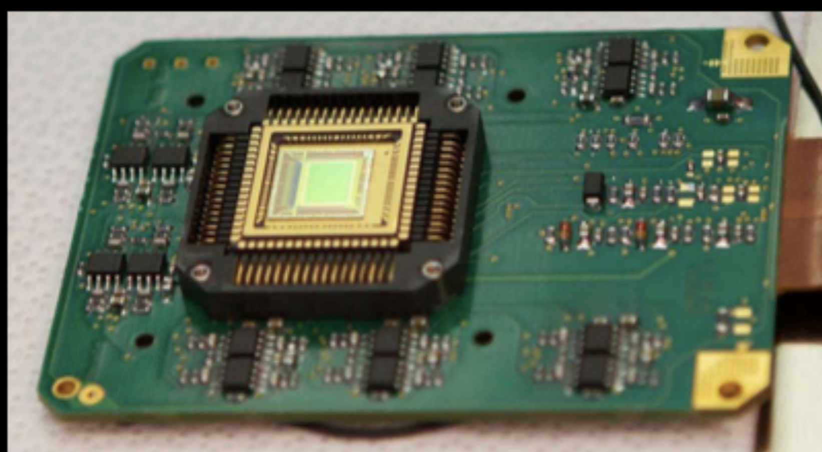
Guaranteed Time:
68 4-UT-array nights
157 4-AT-array nights

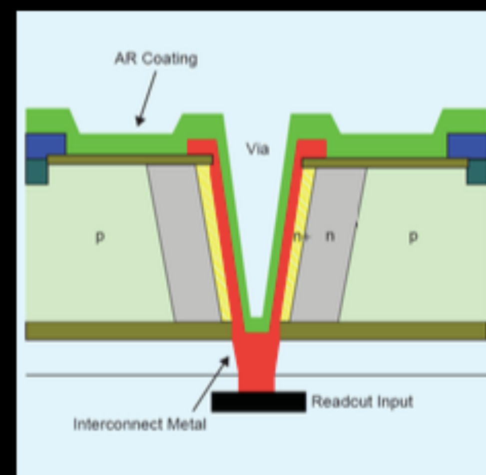


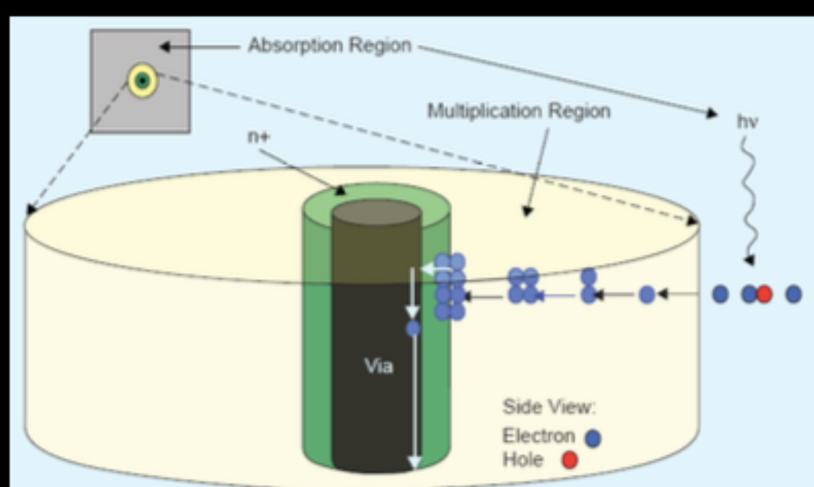
1st light GRAVITY Beam Combiner Instrument + 4 CIAO: Sep 2016

GRAVITY: new key technologies

eAPD SELEX/SAPHIRA infrared detector
- Adaptive Optics in CIAO
- Fringe Tracker in BCI



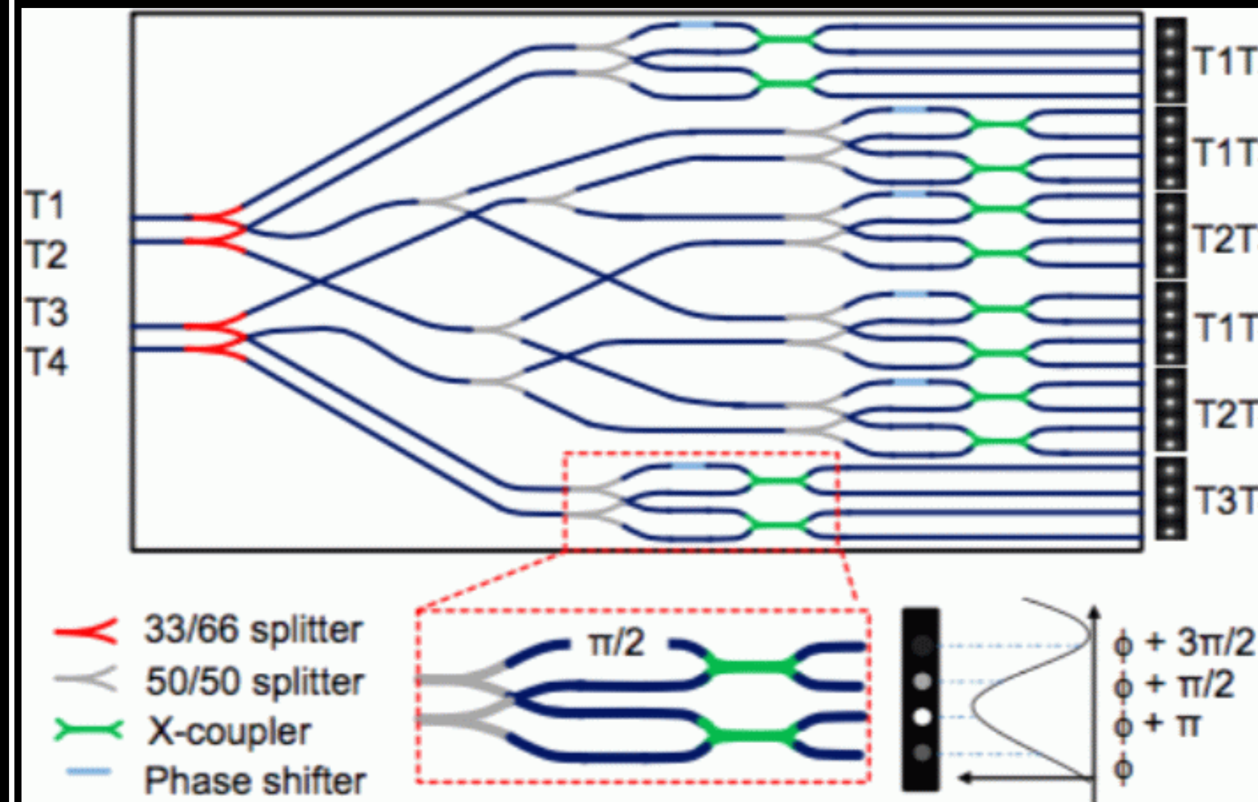


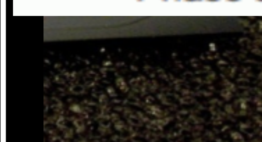


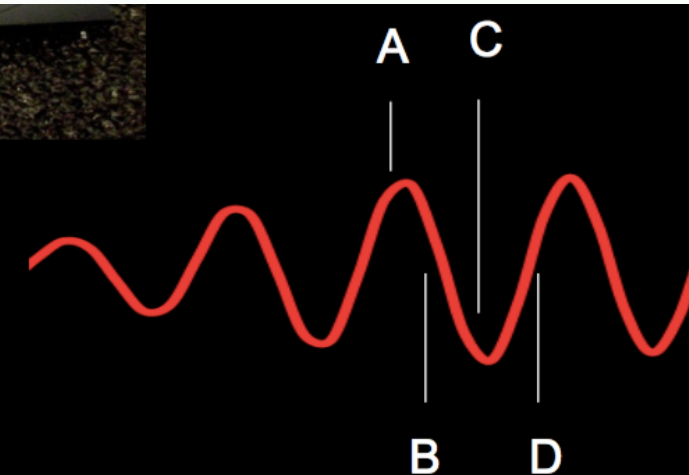
Finger, Baker et al. 2010, 2012

Read-out noise ≈ 1e- @1kHz
close to background noise

K-band integrated optics BCI





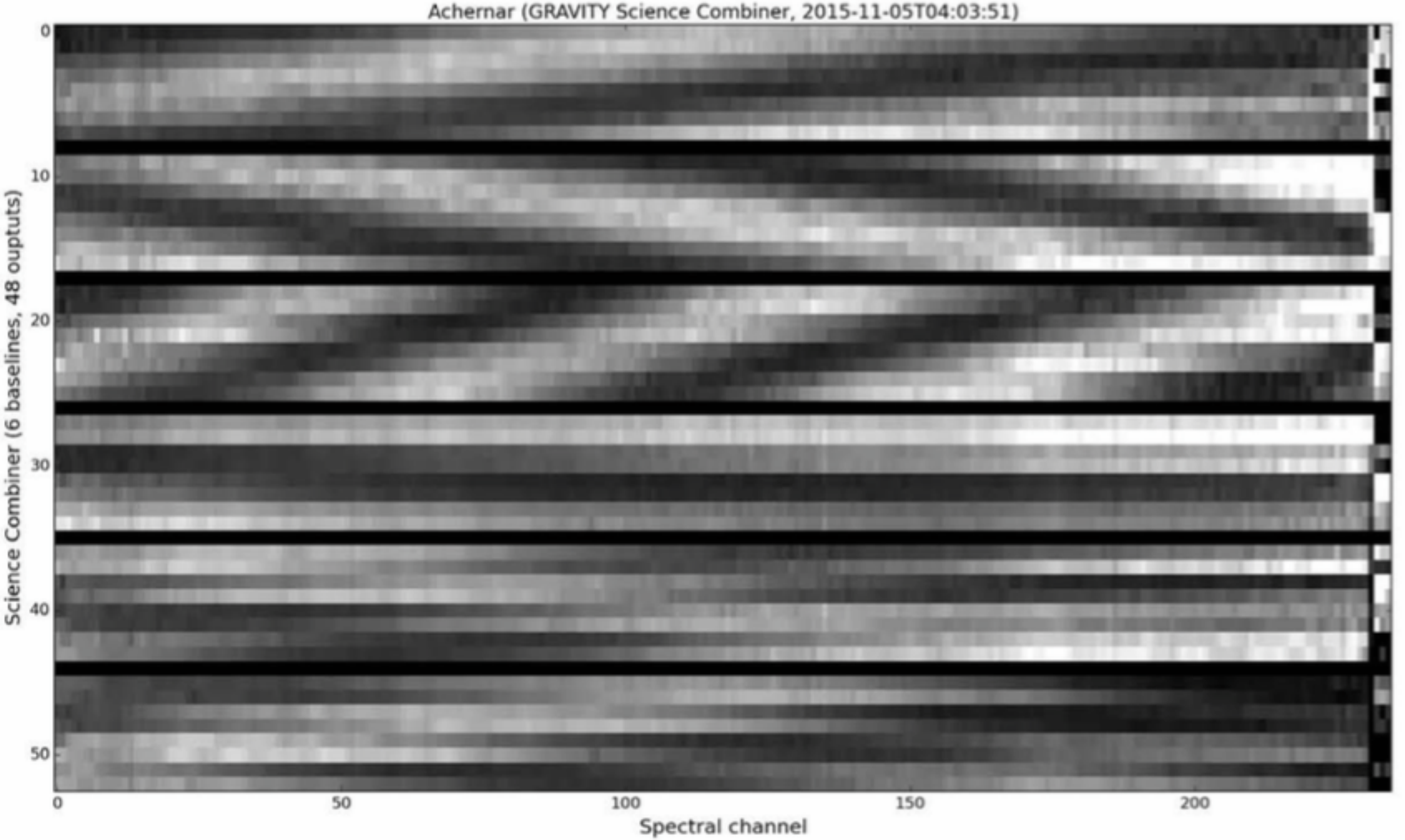


$$\varphi = ArcTan\,\frac{A-C}{B-D}$$

$$V^2 = (A-C)^2 + (B-D)^2$$

Phase + Contrast

GRAVITY science channel (example)

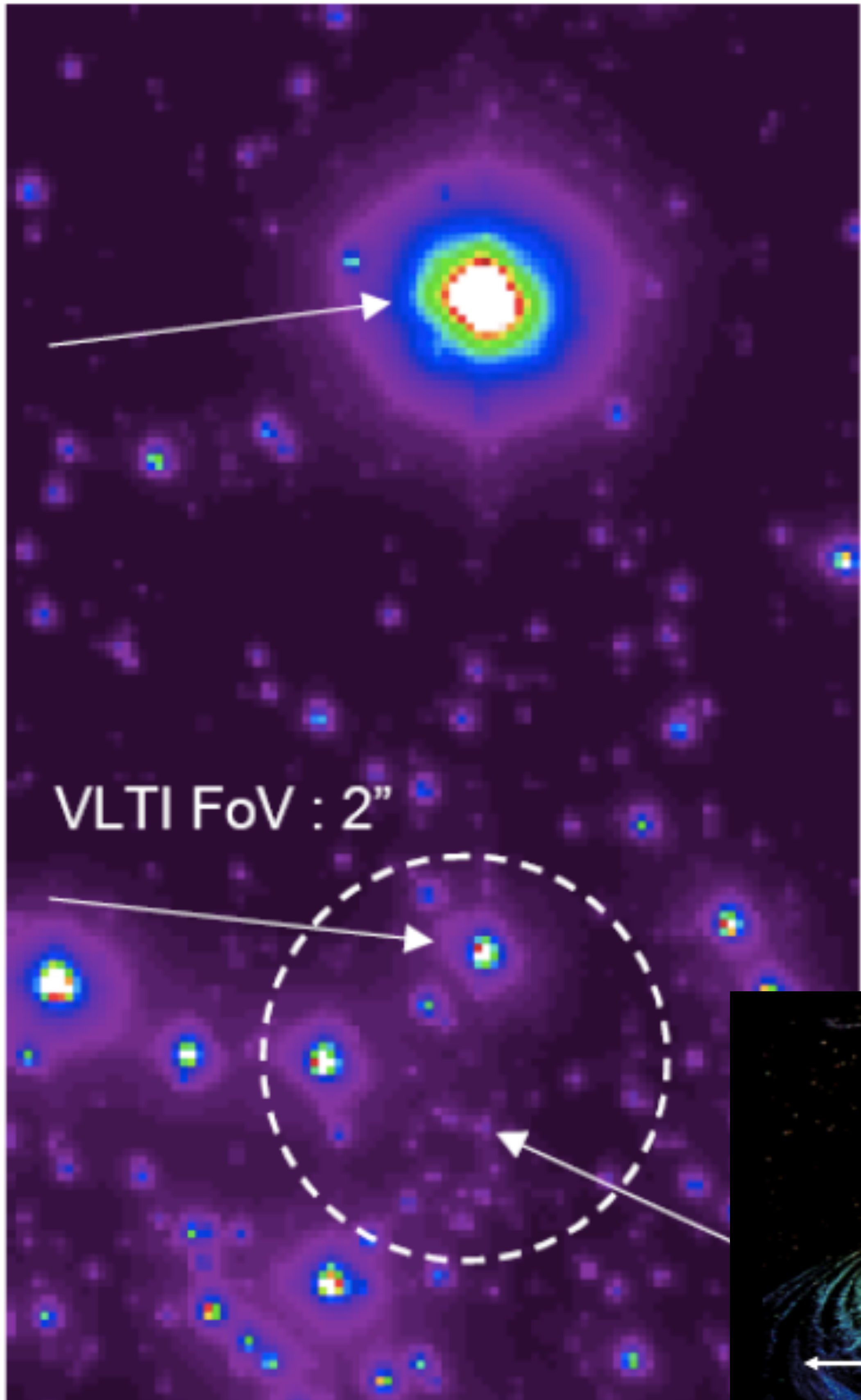


48 spectrally resolved channels: 2 (polarisation) x 4 (ABCD) x 6 baselines

3. Observations of the Galactic Centre

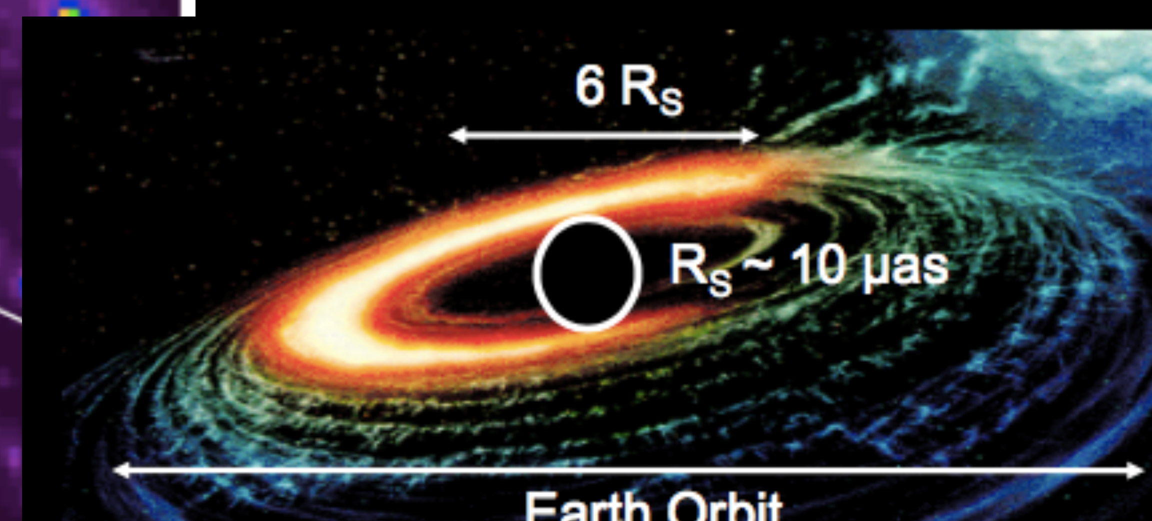
Reference star for GRAVITY infrared **wavefront-sensor** picked by star-separators

Reference star for GRAVITY internal **fringe-tracking**

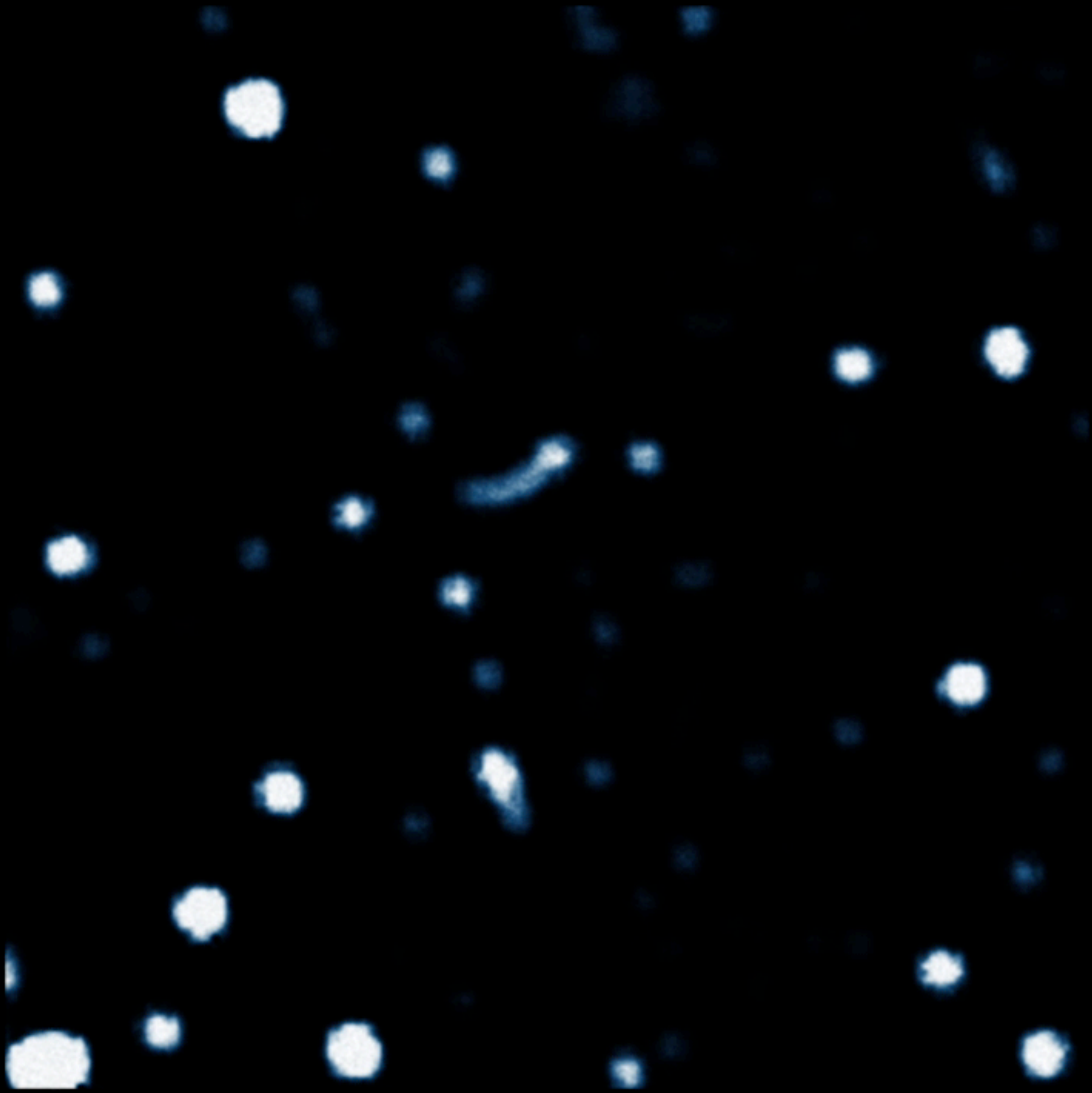


- CIAO on GC IRS7 (M1 supergiant, K=6.5^m to 7^m, ~6 arcsec north of GC)

- Fringe tracking on IRS16NW or IRS16C
- Science-fiber on Sgr A* (GC) or S2



Movie of direct imaging observations (NTT/SHARP, VLT/NACO) of the GC over a period of ~22 years

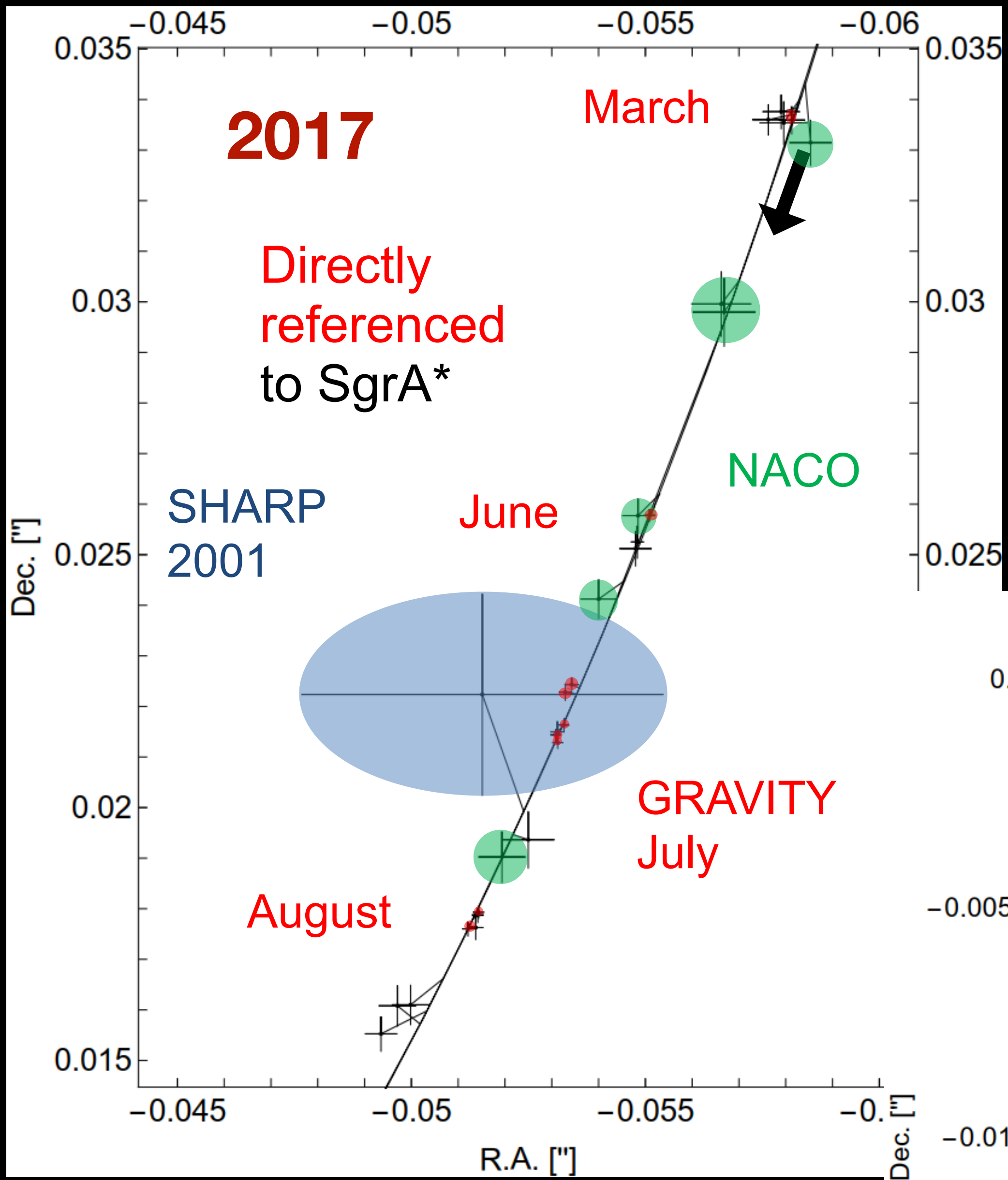


Stars orbit the “flickering” (flaring) Galactic Center

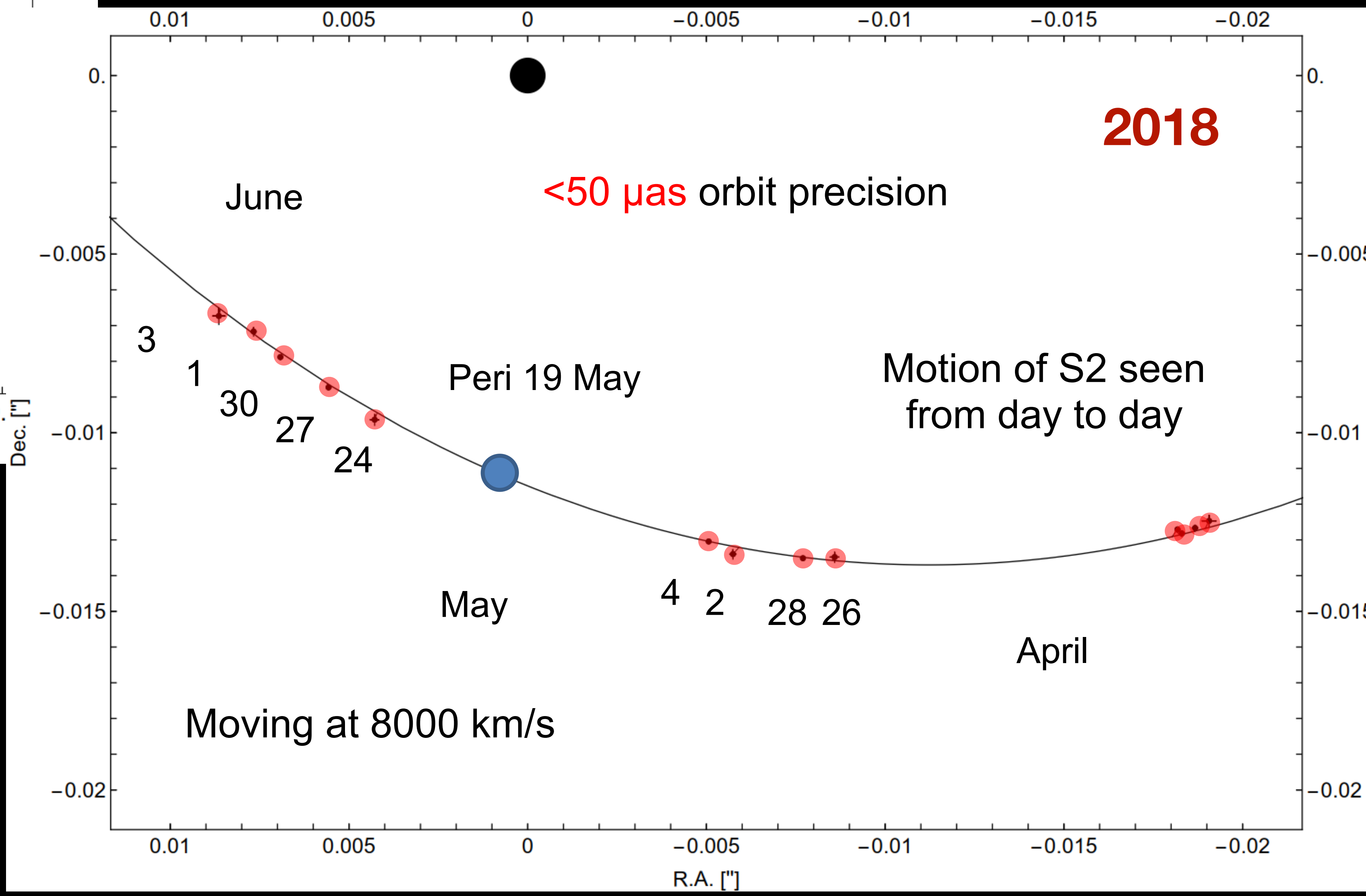
VLTI/GRAVITY+CIAO observations of S2's closest approach to the Galactic Center

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

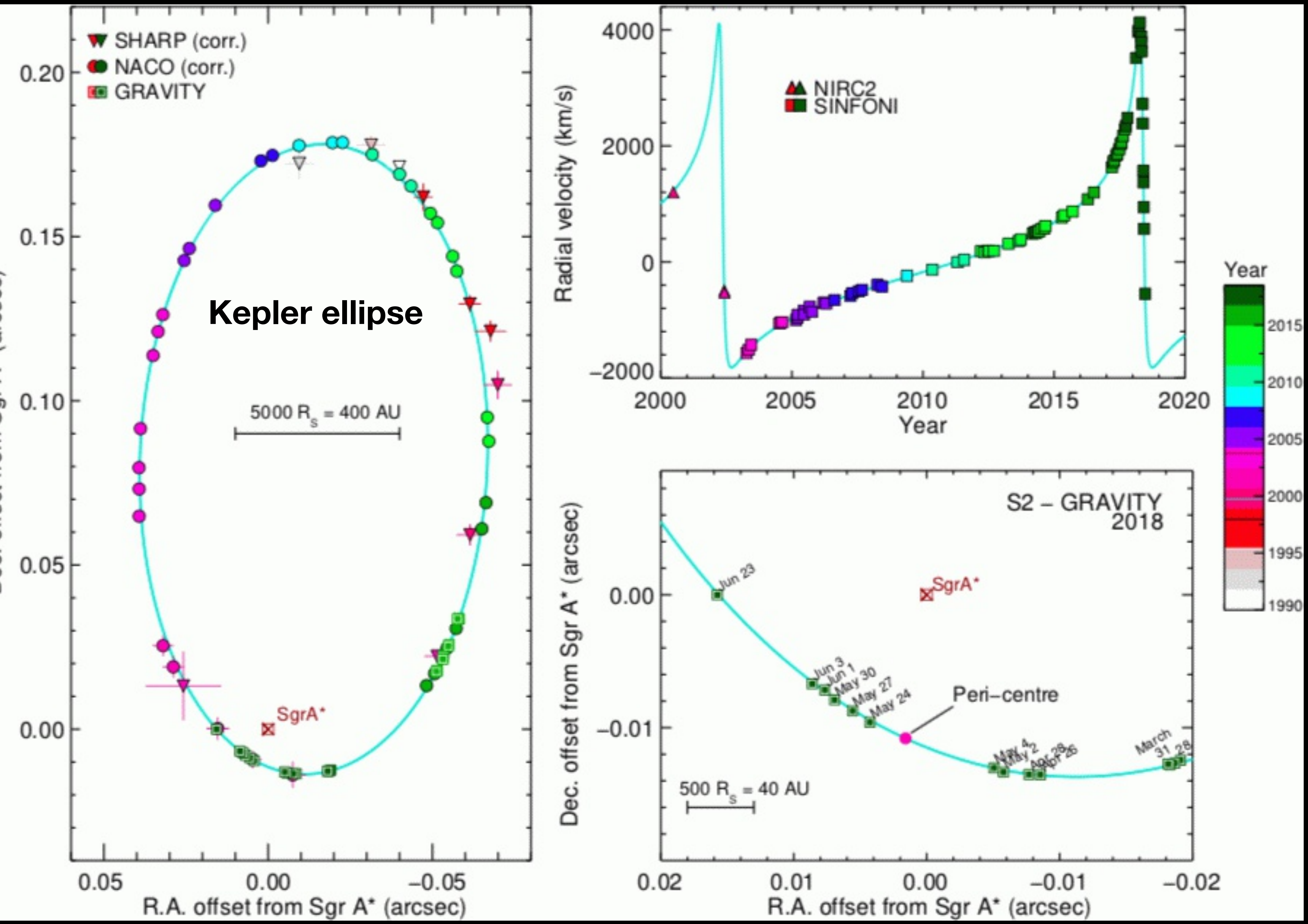
S2 astrometry: comparison of astrometric precision NTT/SHARP, VLT/NACO, and VLTI/GRAVITY



>1000 improvement from 50 mas to <50µas over the past 20 yr

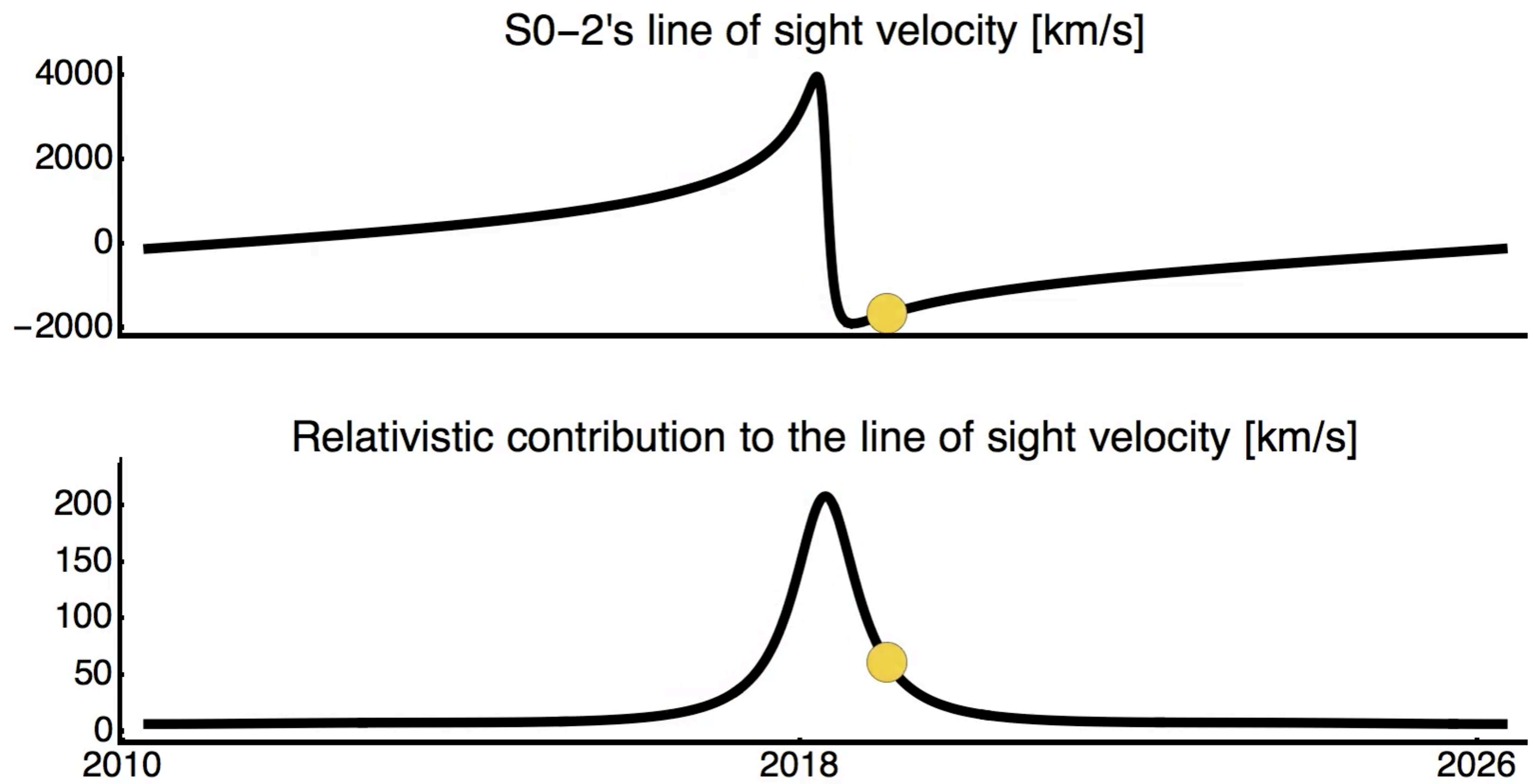


S2 astrometric and radial velocity orbit GRAVITY consortium, A&A 615, L15 (2018)

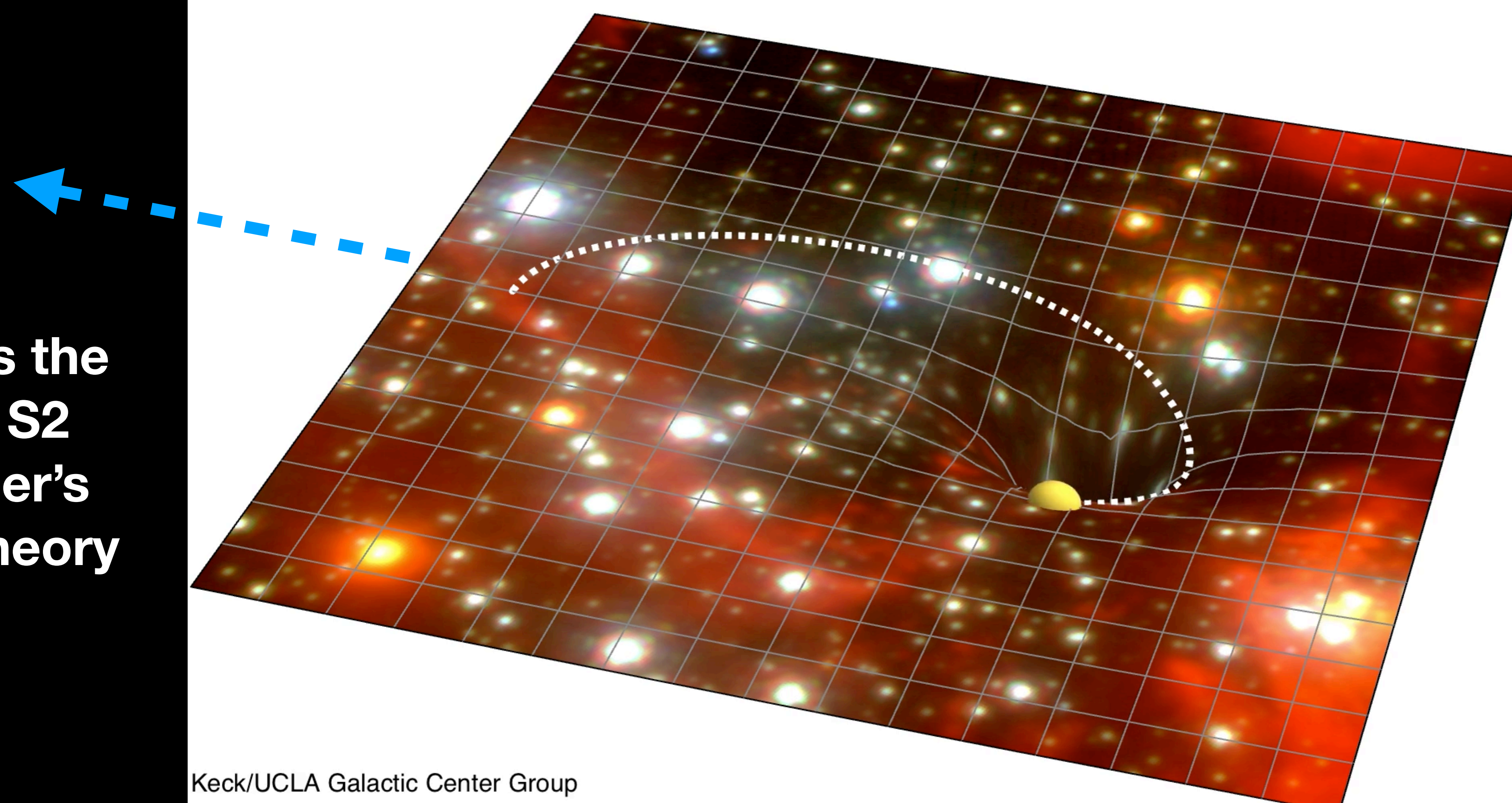


S2 orbit visualization

UCLA GC group



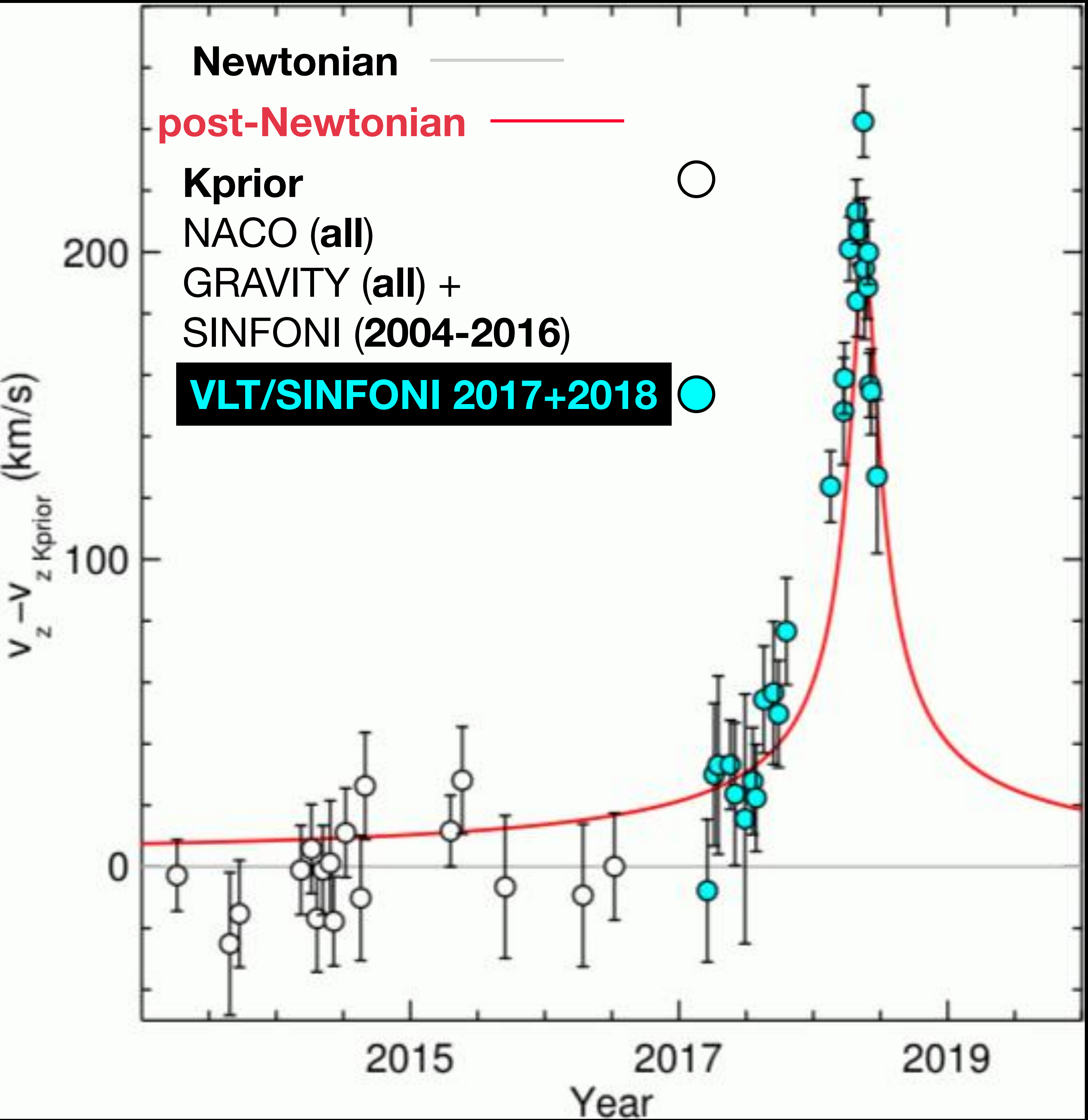
Sun



Keck/UCLA Galactic Center Group

By how much does the orbital motion of S2 deviate from Kepler's 2nd law (Newton theory of gravity)?

S2 radial velocity residuals after subtraction of non-relativistic effects



v_orbit_max = 7650 km/s
~ 2.5% of speed of light

post-Newtonian: 1st order effects (relativistic transverse Doppler shift + gravitational redshift)

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

1st order effects post-Newtonian effects on S2's radial velocity

relativistic transverse Doppler shift:

$$1+z = \frac{1}{\sqrt{1 - v^2/c^2}}$$

v_orbit_max = 7650 km/s

$1+z_{Doppler} = 1.00033$, $z_{Doppler}=0.00033$ => $v_{Doppler} = z * v\_orbit\_max = 100$ km/s

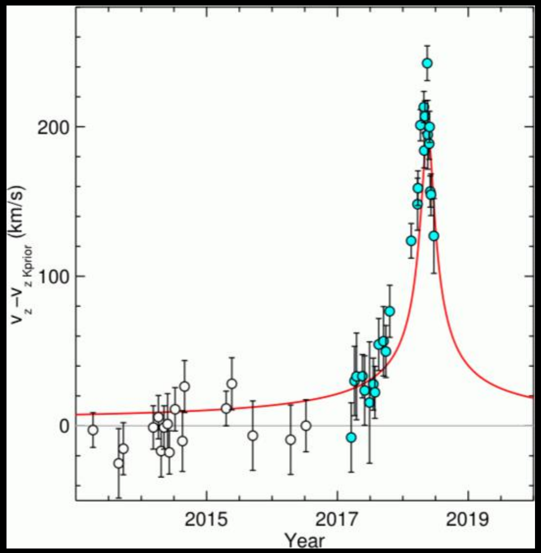
gravitational redshift:

$z_{redshift} = 0.5 * R_{Schwarzschild}/R_{S2\_GC} = 0.00033$

$R_{S2\_GC} = 120$ AU

=> $v_{GravRedshift} = 100$ km/s

$v_{relativistic} = v_{Doppler} + v_{GravRedshift} = 200$ km/s



Clear signature of general relativistic gravitational redshift detected in radial velocity measurements of S2

Observations are in full agreement with the relativistic predictions. They confirm the validity of the theory of relativity at 120 AU distance from a blackhole with 4 million solar masses

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

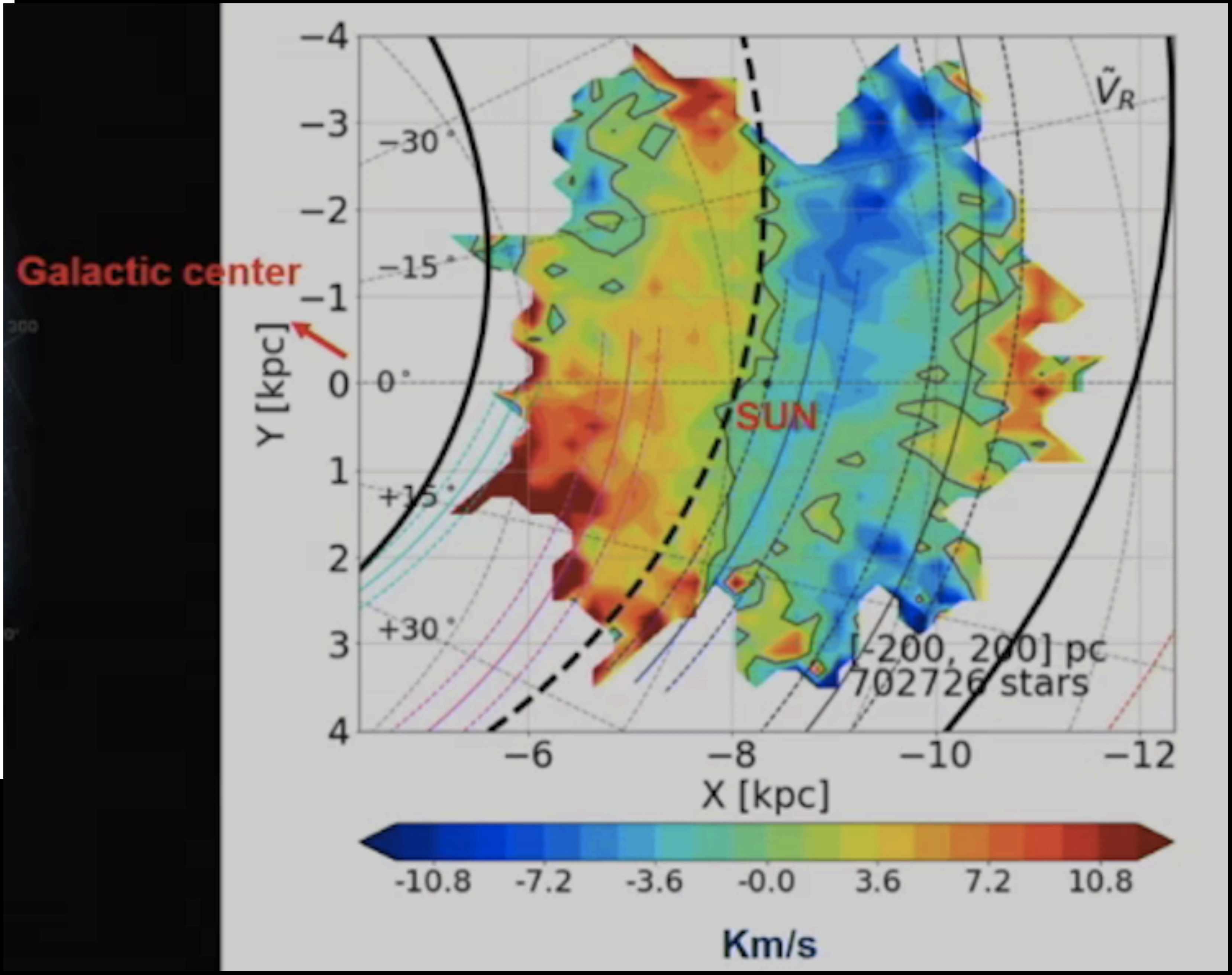
What is means …
Placing the GC+S2 results in context

- **Improved determination of S2 orbital parameters, most precise determination of blackhole mass, Sgr A* velocity, and distance to the Sun**

Parameter	With Schwarzschild precession	Unit
f	0.945 ± 0.090	
$M_\bullet$	4.100 ± 0.034	$10^6\ M_\odot$
R_0	8122 ± 31	pc
a	125.40 ± 0.18	mas
e	0.88466 ± 0.00018	
i	133.818 ± 0.093	°
ω	66.13 ± 0.12	°
Ω	227.85 ± 0.19	°
P	16.0518	yr
t_{peri}	2018.37974 ± 0.00015	yr
	58257.698 ± 0.054	MJD
x_0	-1.00 ± 0.47	mas
y_0	-0.99 ± 0.41	mas
$\dot{x}_0$	0.076 ± 0.031	mas/yr
$\dot{y}_0$	0.178 ± 0.030	mas/yr
$\dot{z}_0$	1.9 ± 3.0	km/s

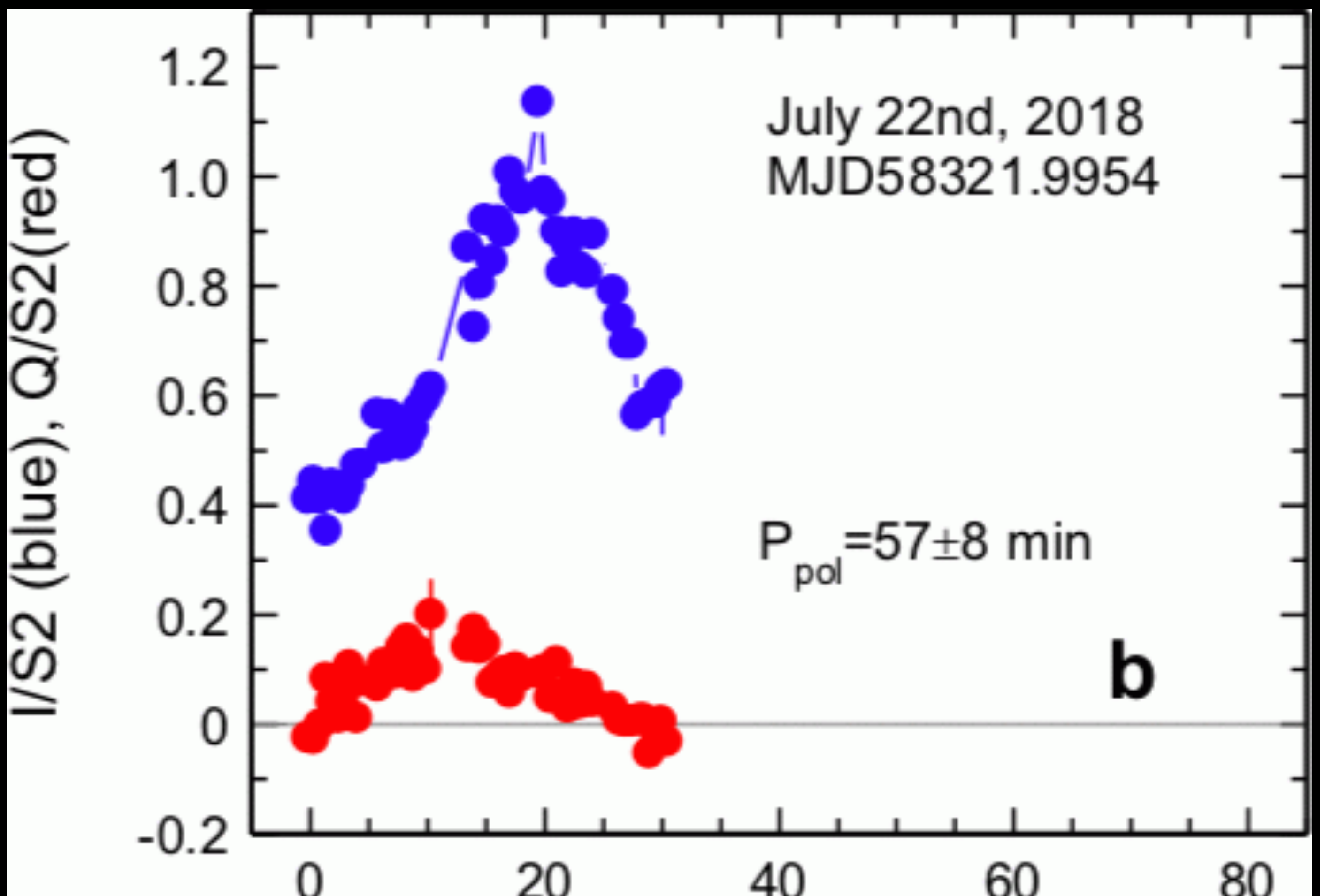
GRAVITY consortium, A&A 615, L15 (2018)

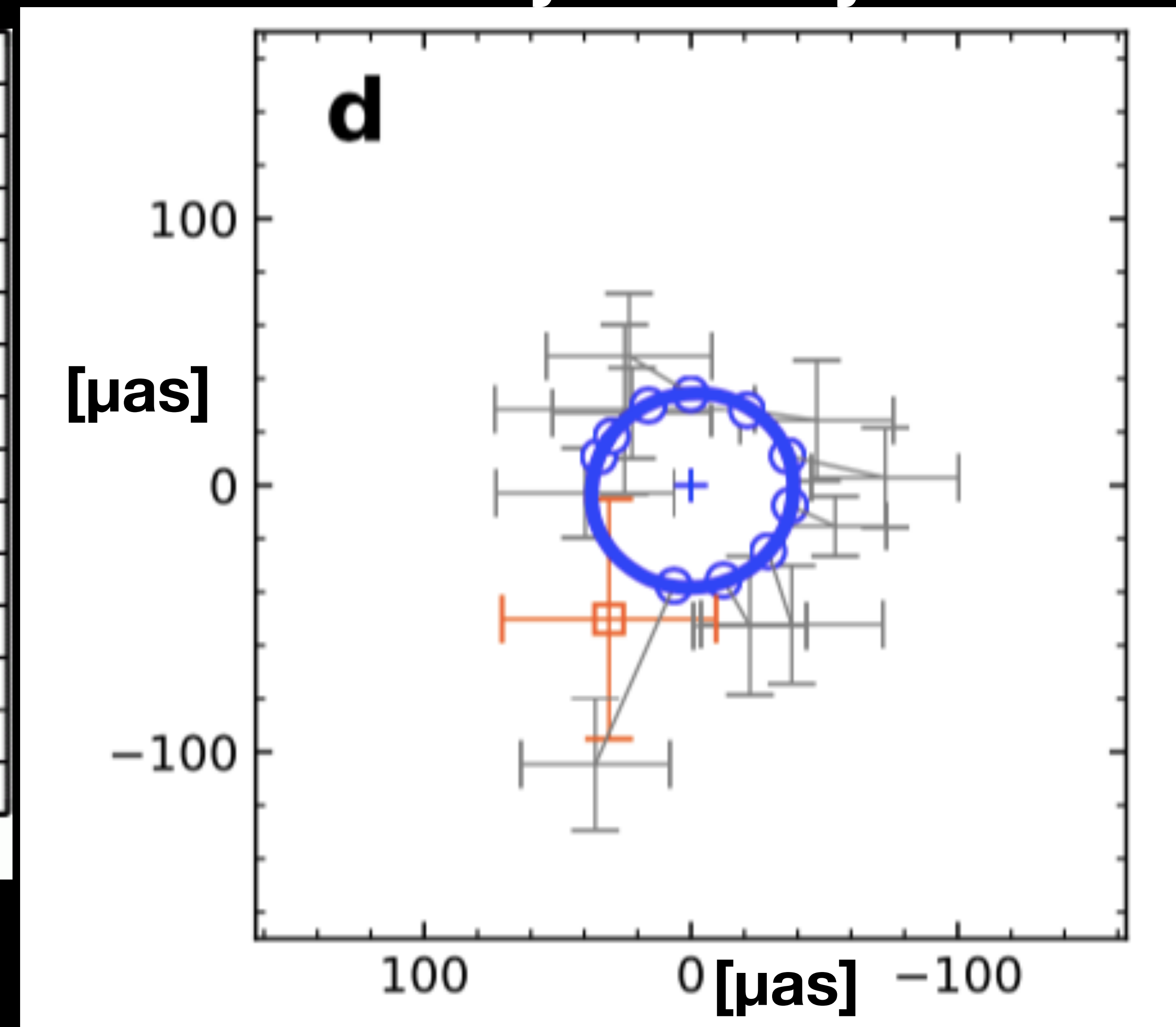
R_0 is relevant, e.g., for interpretation of GAIA findings



4. Flares from the Galactic Center

3 flares observed with VLTI/GRAVITY between May and July 2018



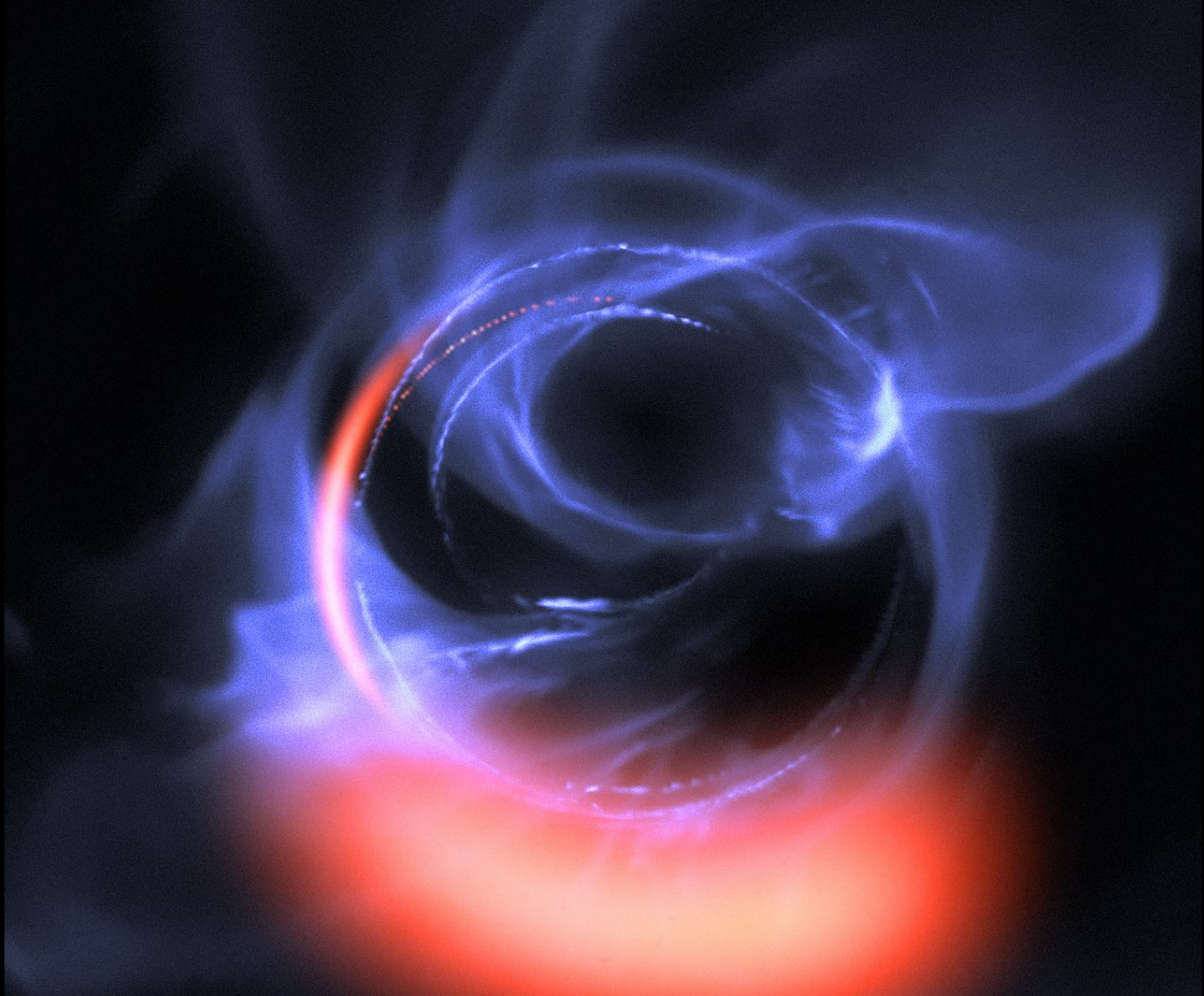


July 22 flare was as bright as S2

astrometric signal can be fitted by a circular orbit with a radius of 3.5 Schwarzschild radii seen face on, and enlarged by gravitational lensing

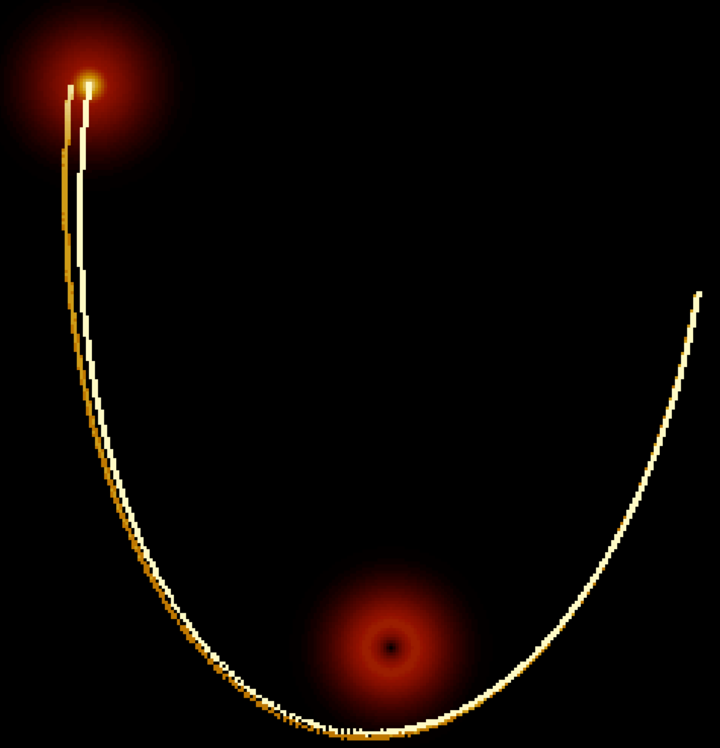
GRAVITY consortium,
A&A 618, L10 (2018)

4. Flares from the Galactic Center



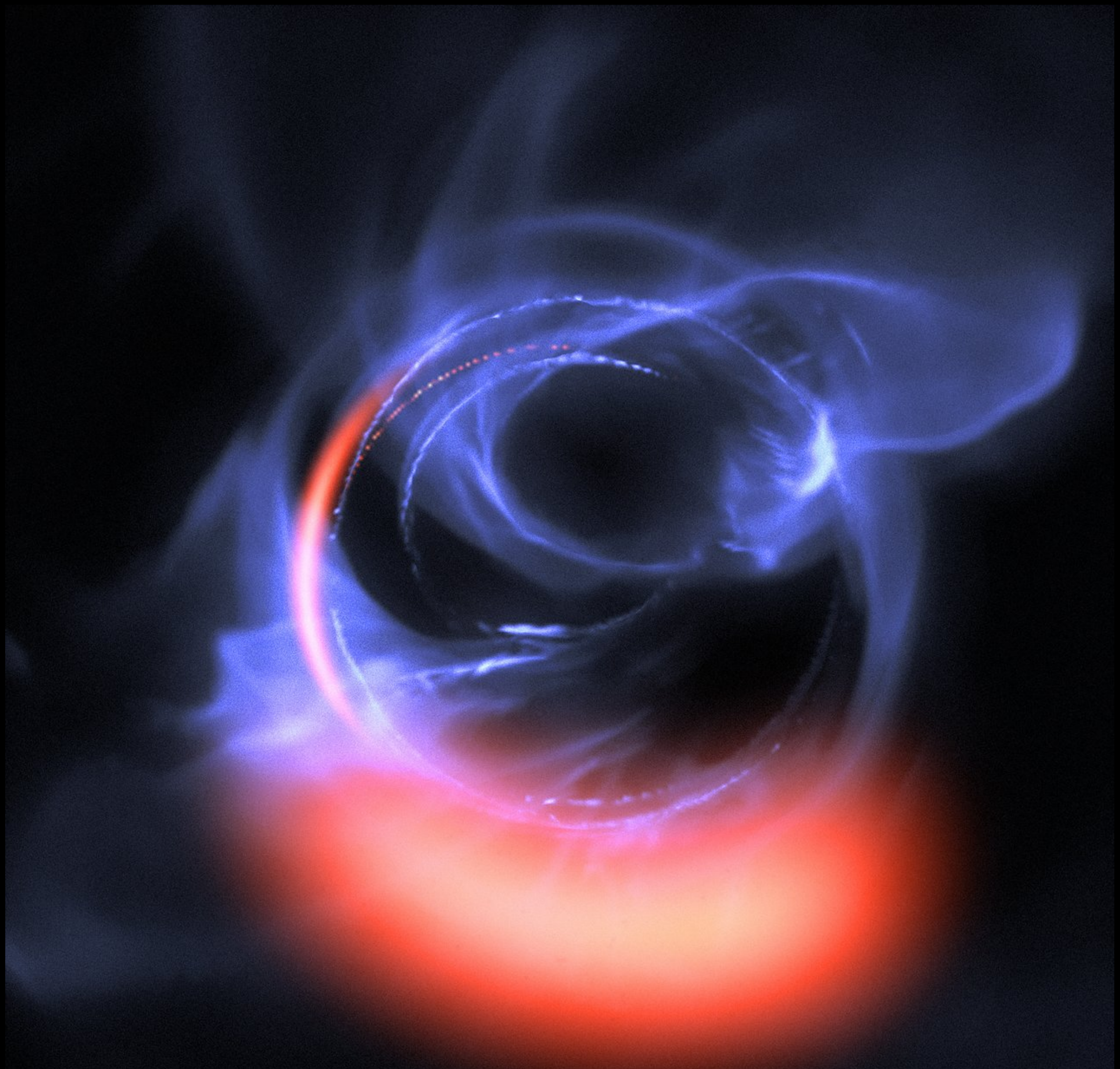
=>Flares originate in plasma disk orbiting the blackhole just outside the innermost stable orbit

5. Outlook: What next?



from 2019 on:

- Schwarzschild precession of S2 orbit
- more astrophysics of GC flaring
- spin of blackhole (Kerr metric, frame dragging)
- lower mass stars in closer orbit around the GC (higher order GR effects)
- …



Movie lightpath of VLTI+GRAVITY/CIAO: http://www.mpe.mpg.de/ir/gravity