May 23, 2019
Sao Tome und Principe

Testing General Relativity in the Galactic Center

GRAVITY Collaboration

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Credit: Gerhard Hüdepohl


GRAVITY Collaboration
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MPE
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Max Planck Institute for Astronomy Heidelberg


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Pfuhl
Genzel
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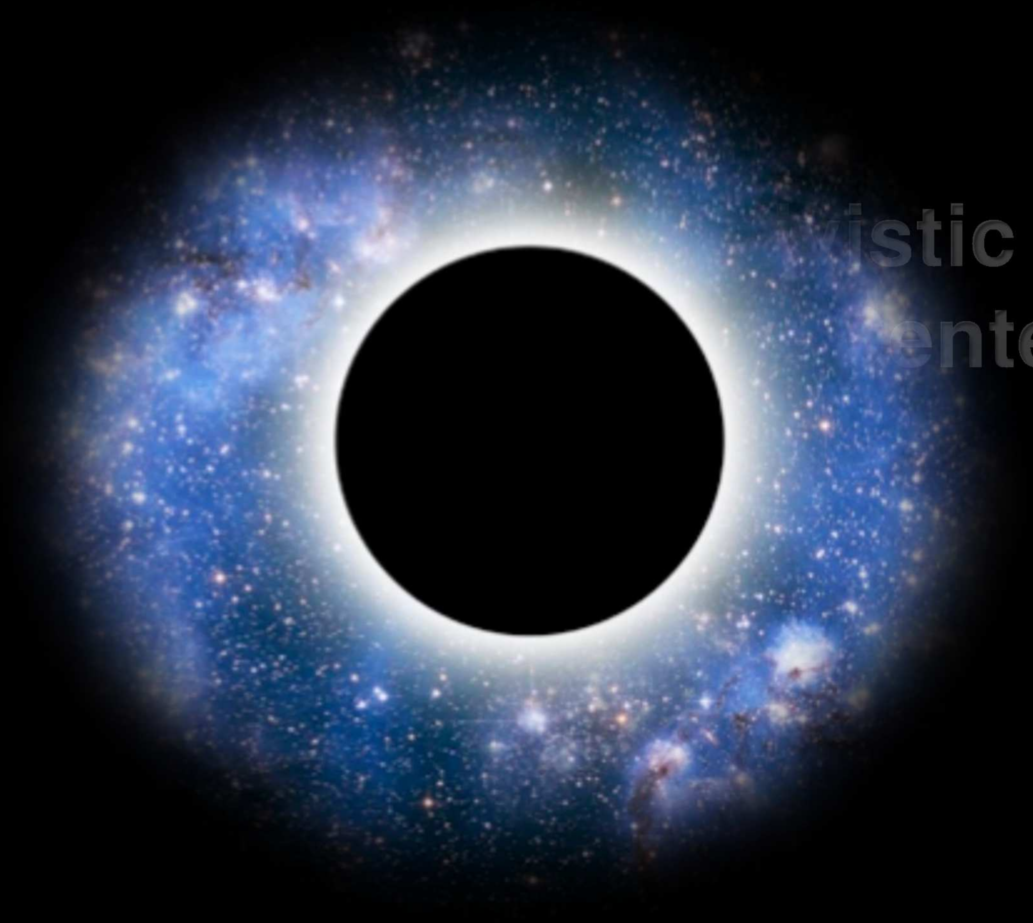
de Zeeuw
Perraut
Dexter
Paumard
Eckart
Lacour
Brandner
Garcia
Straubmeier
Woillez
Bonnet

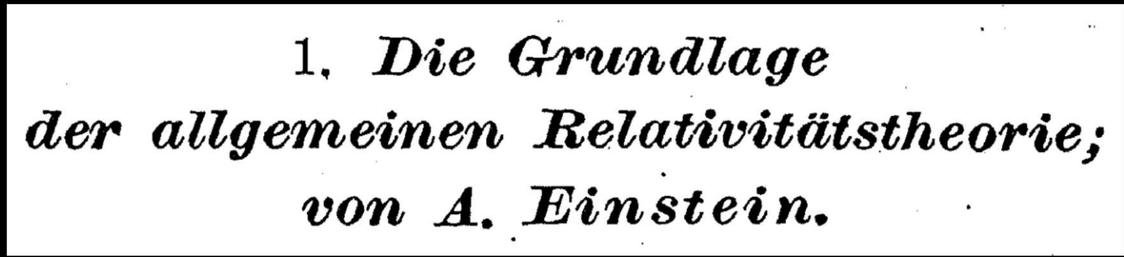
General Relativistic Effects Around the Galactic Center Black Hole

istic Effects Around the
enter Black Hole



Region of Space Time Locked away from Outside World

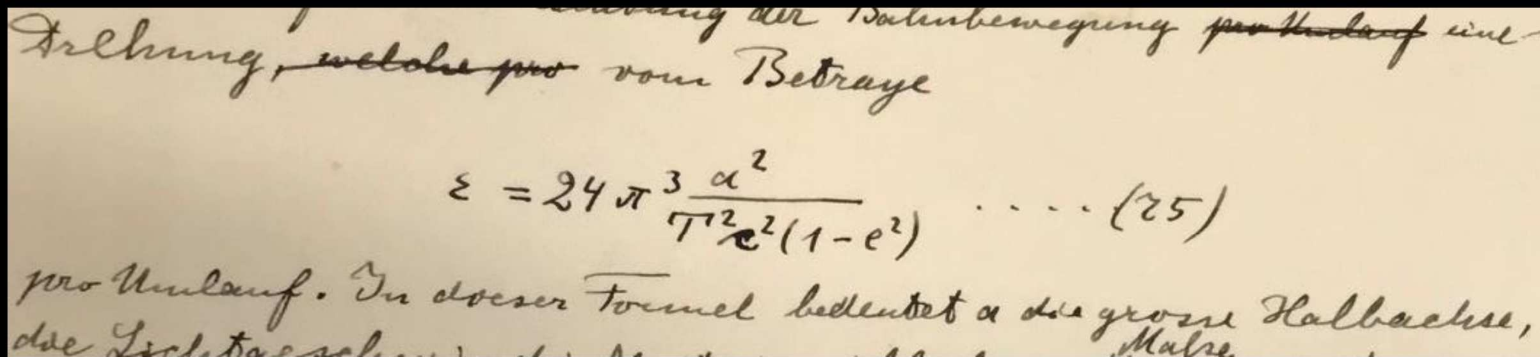
Credit: Victor de Schwanberg/Science Photo Library



1. *Die Grundlage*
der allgemeinen Relativitätstheorie;
von A. Einstein.

General Relativistic Effects Around the Galactic Center Black

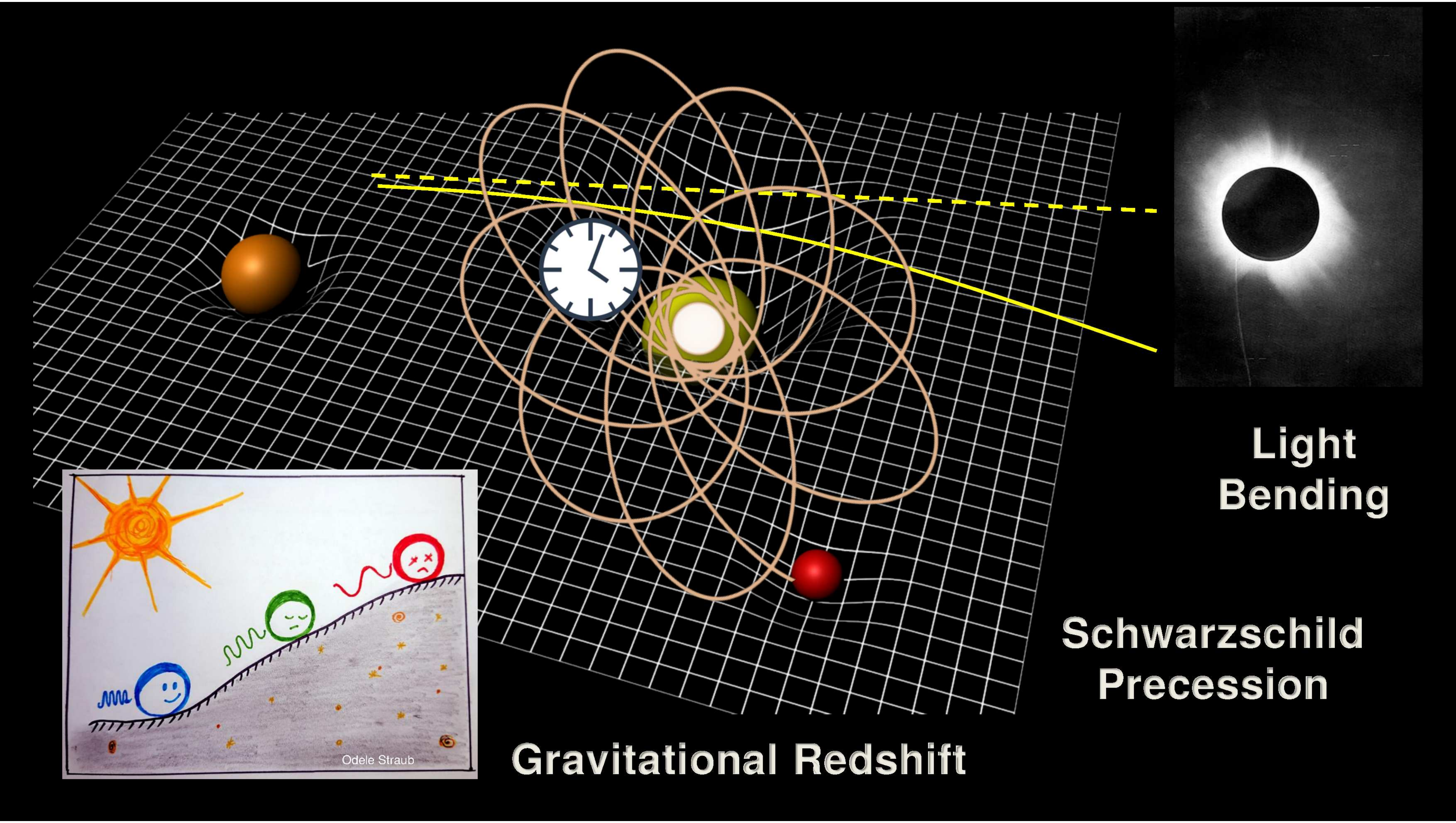
Einstein

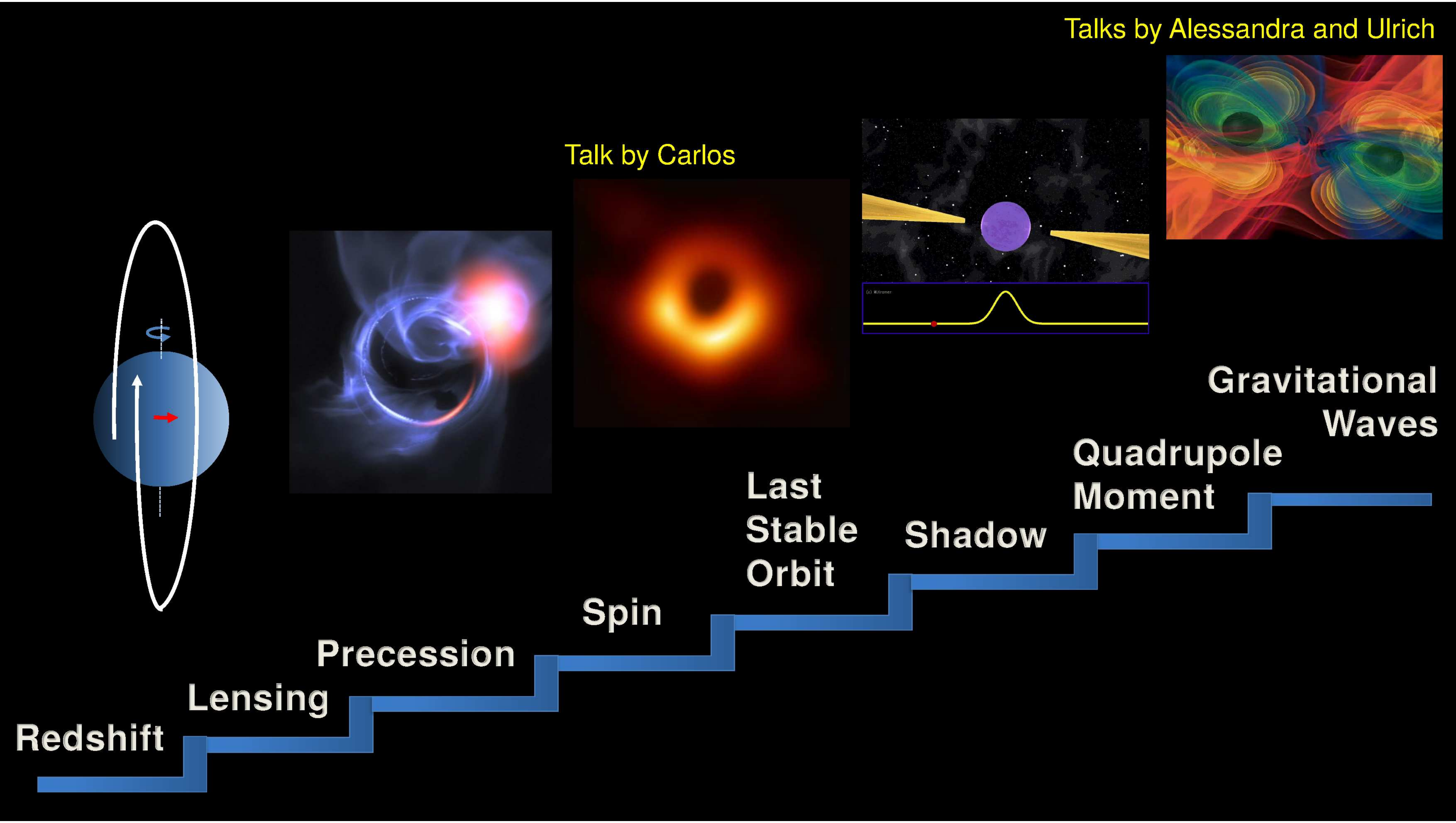


... der Bahnbewegung ~~pro Umlauf~~ eine Drehung, ~~welche pro~~ vom Betrage

$$\varepsilon = 24\pi^3 \frac{a^2}{T^2 c^2 (1-e^2)} \quad \ldots\ldots (25)$$

pro Umlauf. In dieser Formel bedeutet a die grosse Halbachse,


Light
Bending
Schwarzschild
Precession
Gravitational Redshift
Odele Straub


Talks by Alessandra and Ulrich
Talk by Carlos
Gravitational Waves
Quadrupole Moment
Last Stable Orbit
Shadow
Spin
Precession
Lensing
Redshift


General Relativistic Effects Around the
Galactic Center Black Hole
GRAVITY collaboration+18a,b,19, Genzel,Eisenhauer&Gillessen10, Morris,Meyer&Ghez12, Falcke&Markoff13
Eckart&Genzel96, Genzel+97,03, Ghez+98,05,08, Schödel+02, Eisenhauer+03,05, Gillessen+09,17, Paumard+07, Do+09, Meyer+12, Boehle+16, Fritz+16, Witzel+18, ...
Courtesy: ESO / MPE

Black Holes – The Quest for Hard Numbers

Is General Relativity the correct theory ?

Is the mass concentrated within the Schwarzschild radius ?

0.3%

A geometric distance measurement to the Galactic Center black hole with 0.3% uncertainty

arXiv:1904.05721

5%

Test of Einstein Equivalence Principle near the Galactic Center Massive Black Hole

Physical Review Letters, 122, 1102

3-5 R_S

Detection of Orbital Motions Near the Last Stable Circular Orbit of the Massive Black Hole SgrA*

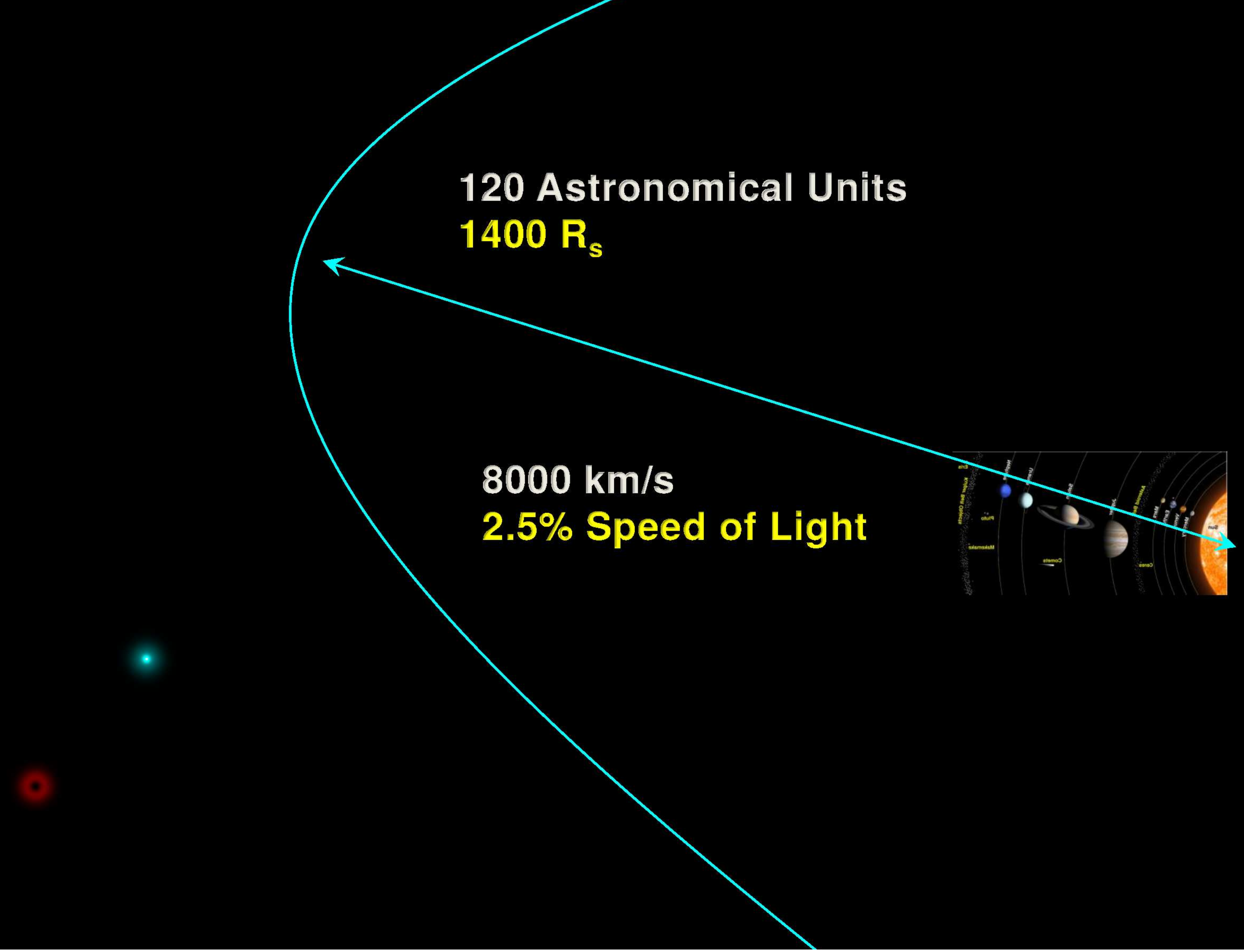
Astronomy & Astrophysics, 618, 10

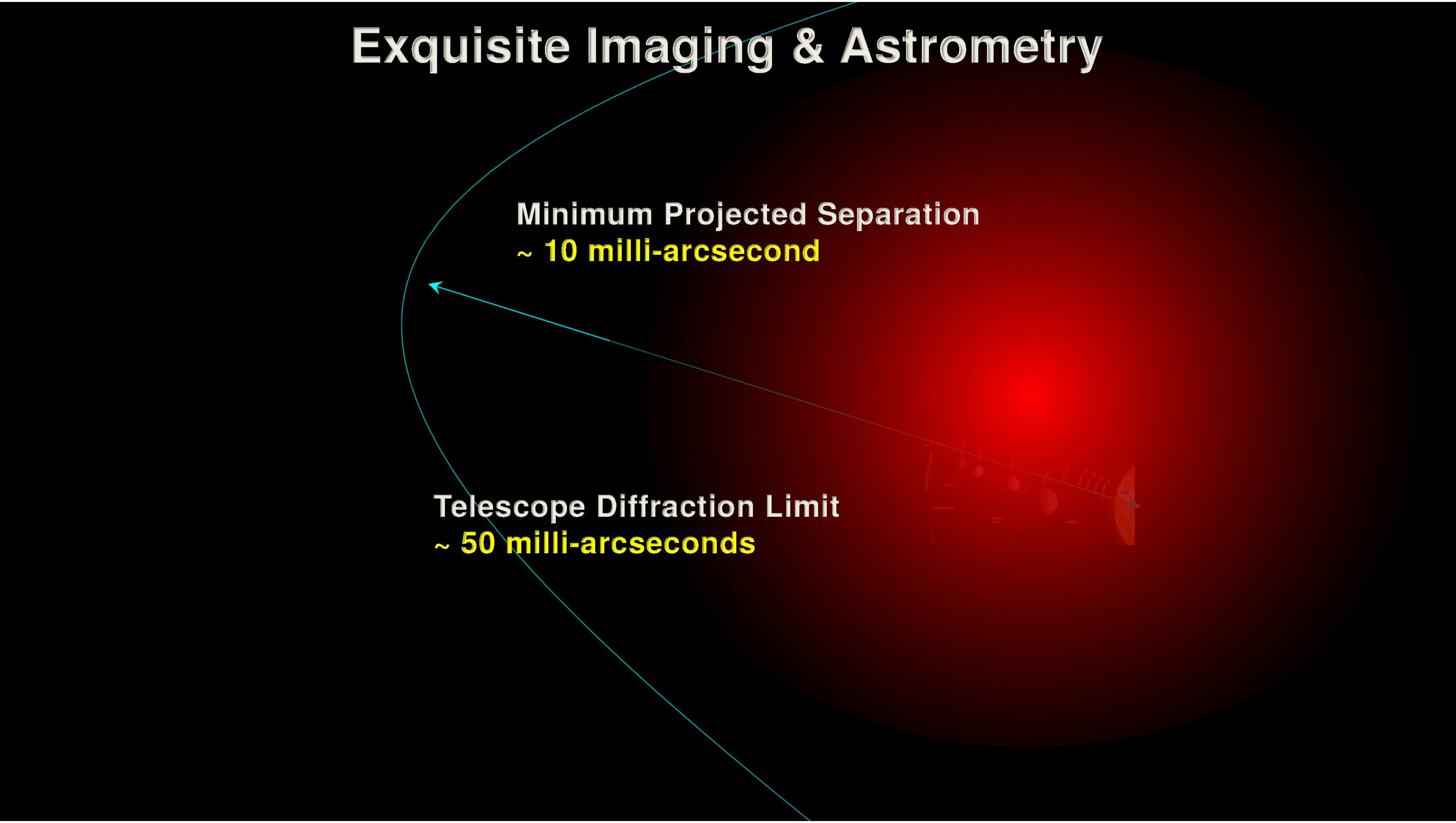
Detection of the gravitational redshift in the orbit of the star S2 near the Galactic centre massive black hole

20σ

Astronomy & Astrophysics, 615, 15

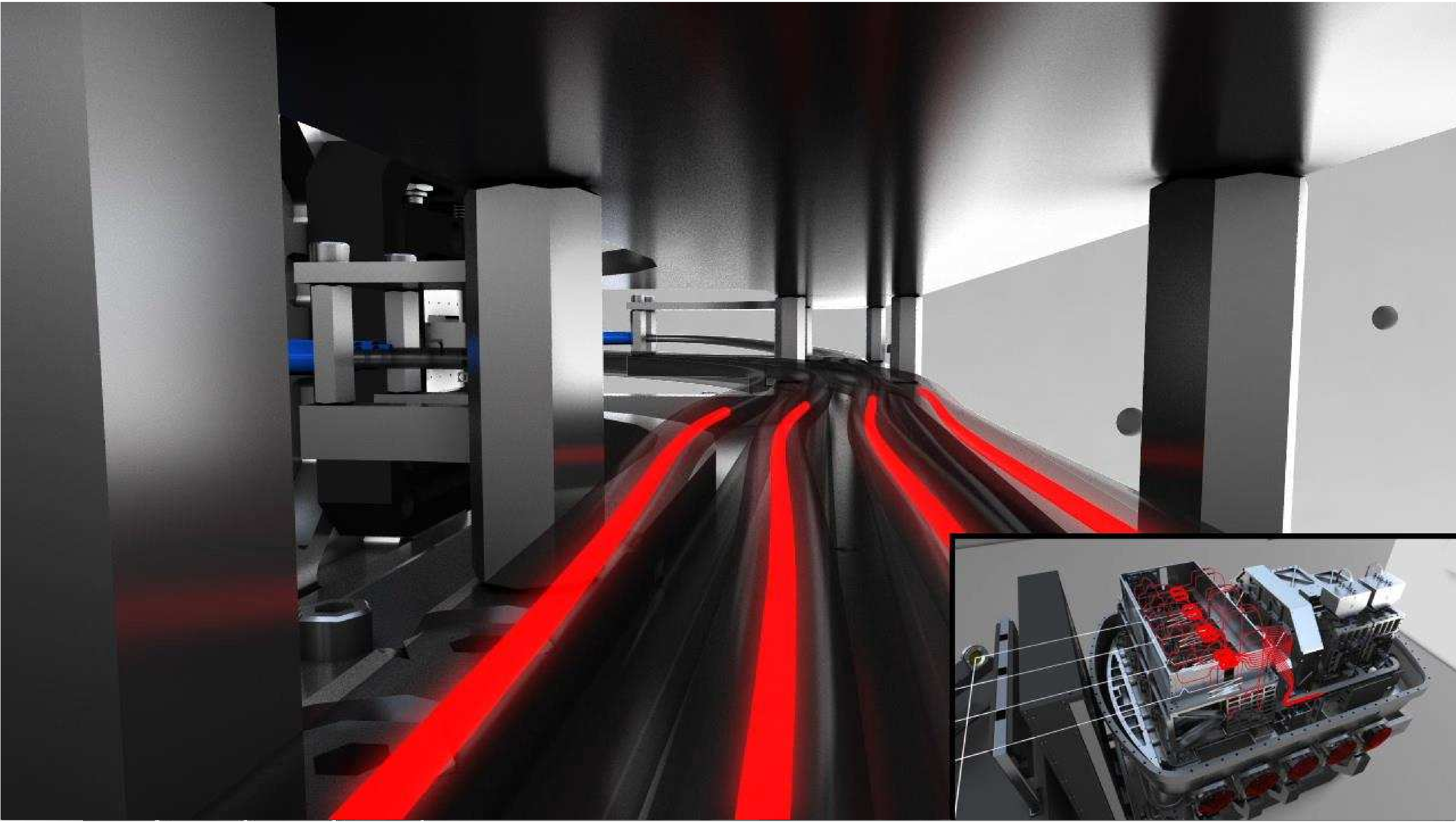
Exquisite Imaging & Astrometry




Exquisite Imaging & Astrometry
Minimum Projected Separation
~ 10 milli-arcsecond
Telescope Diffraction Limit
~ 50 milli-arcseconds

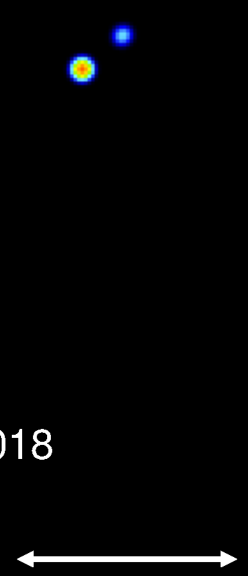
Combining the ESO VLTI to a 200m Super Telescope

ESO / GRAVITY collaboration



Routine Faint Milli-Arcsec Imaging
1000x More Sensitive than Earlier Interferometer

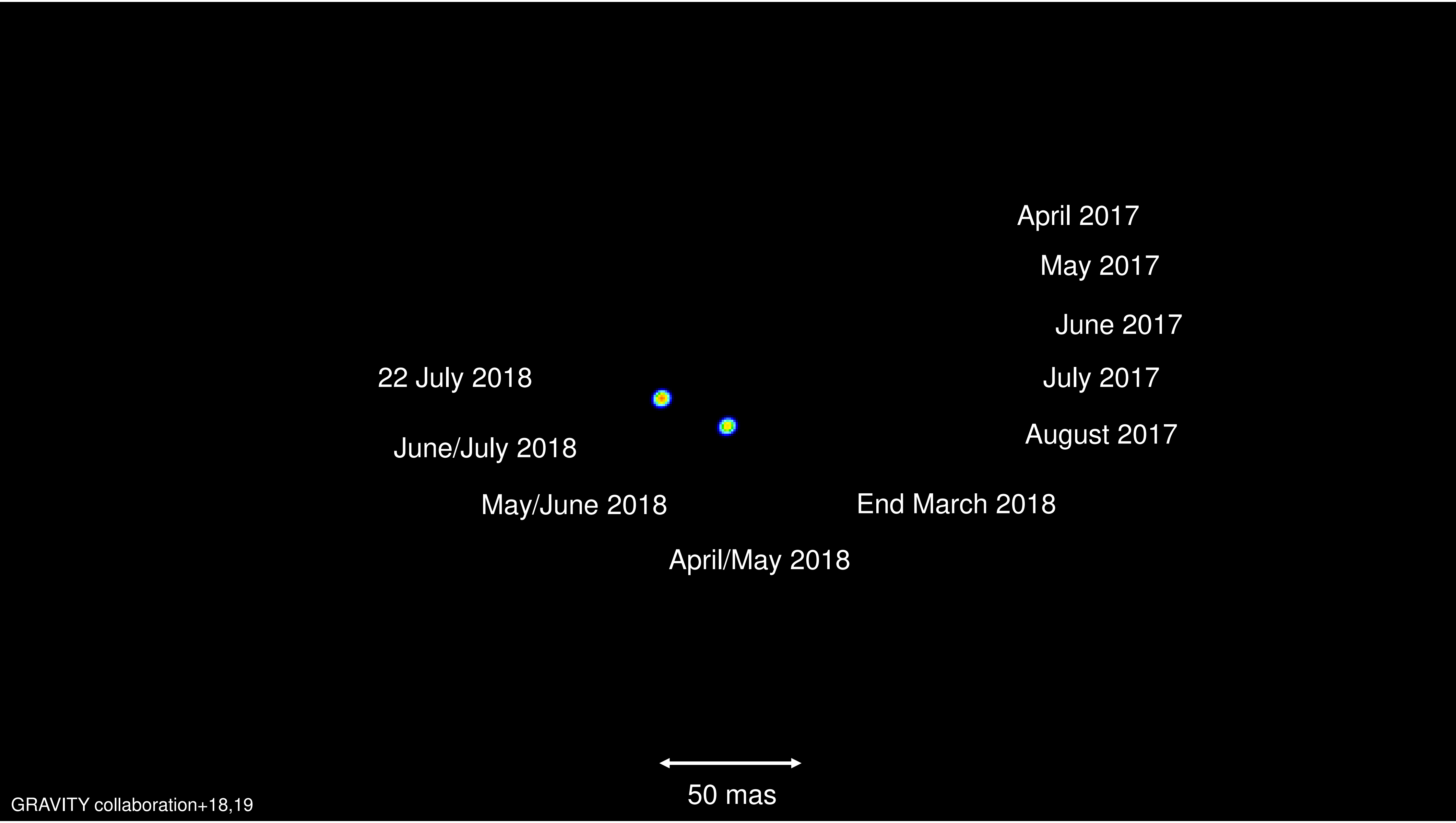
Typically
2 hours
on source



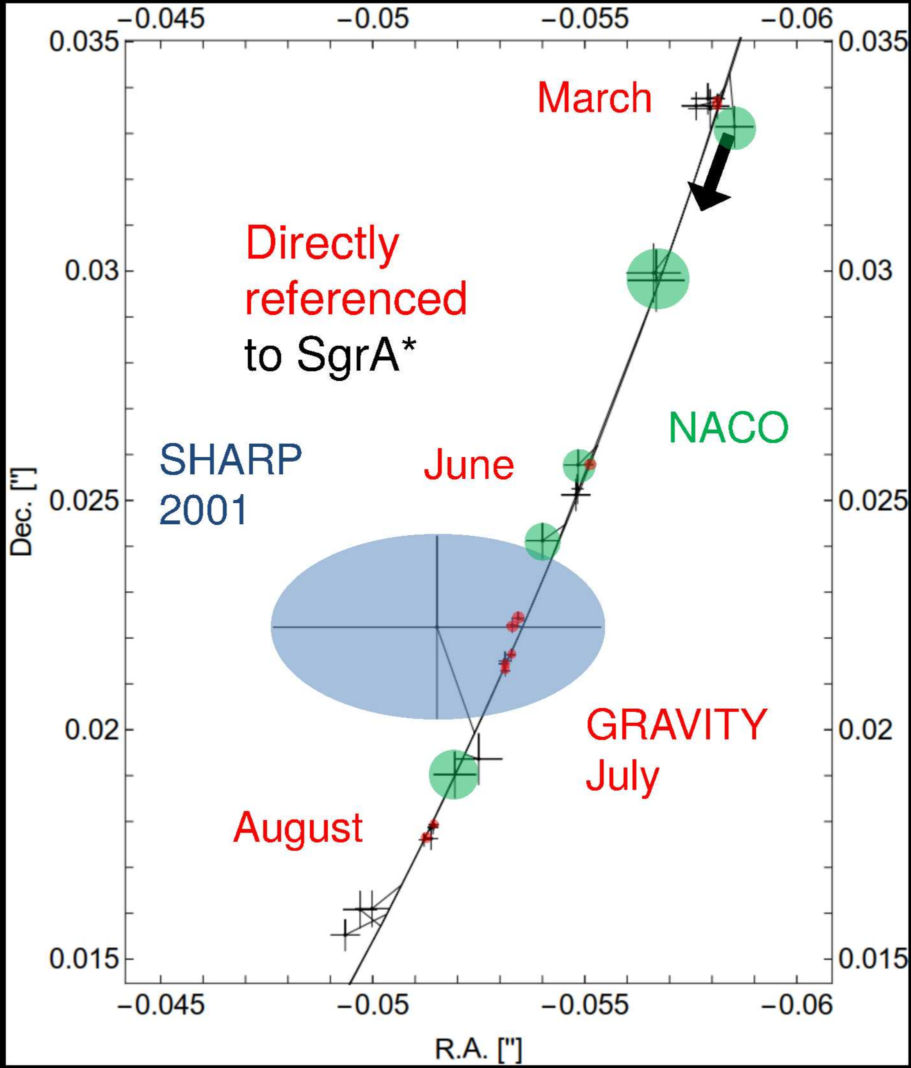
May/June 2018

RMS noise
>20 mag

GRAVITY collaboration+18,19

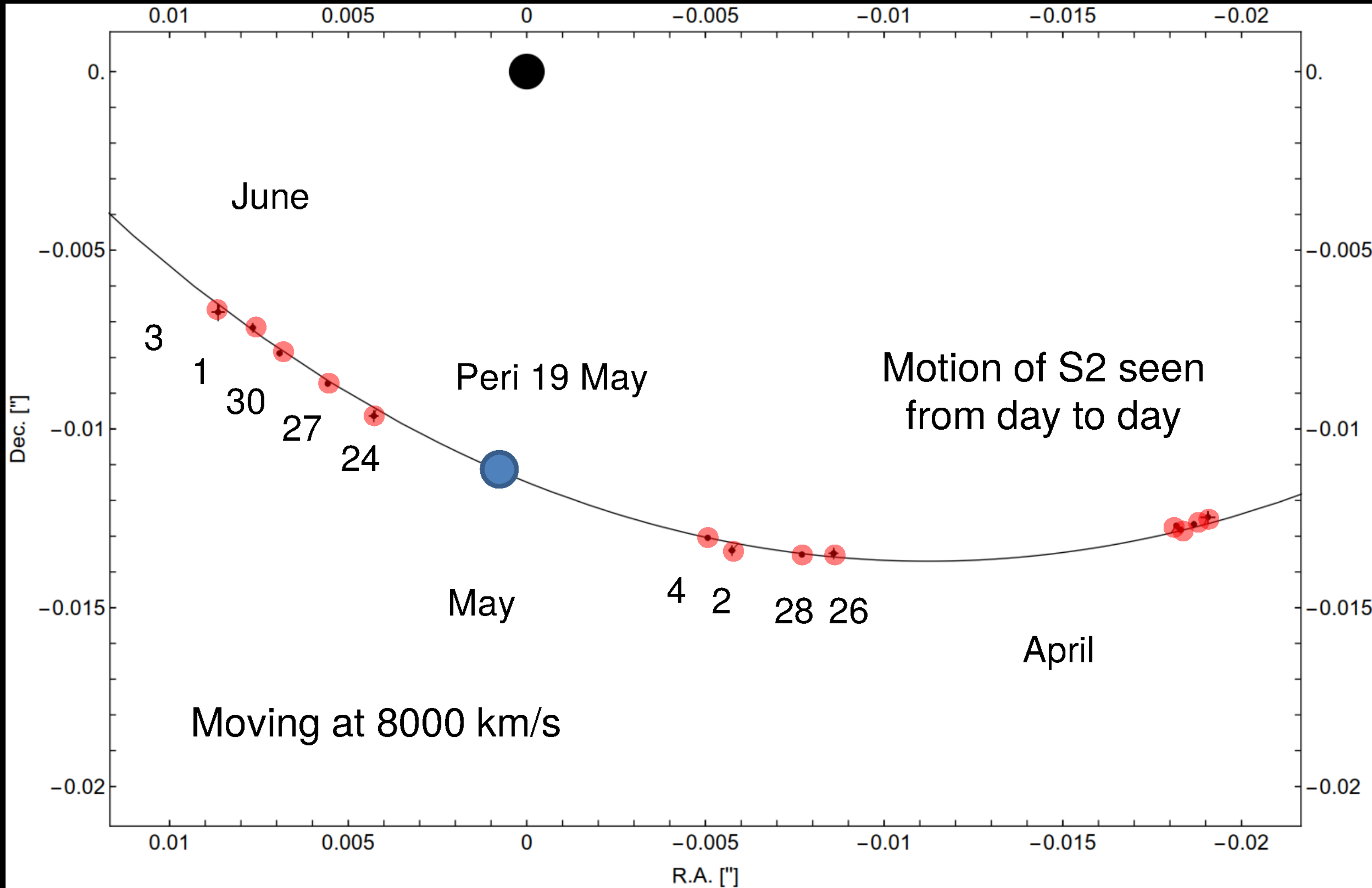

April 2017
May 2017
June 2017
July 2017
August 2017
22 July 2018
June/July 2018
May/June 2018
End March 2018
April/May 2018
50 mas
GRAVITY collaboration+18,19

20 – 100 Micro-Arcsecond Precision Astrometry



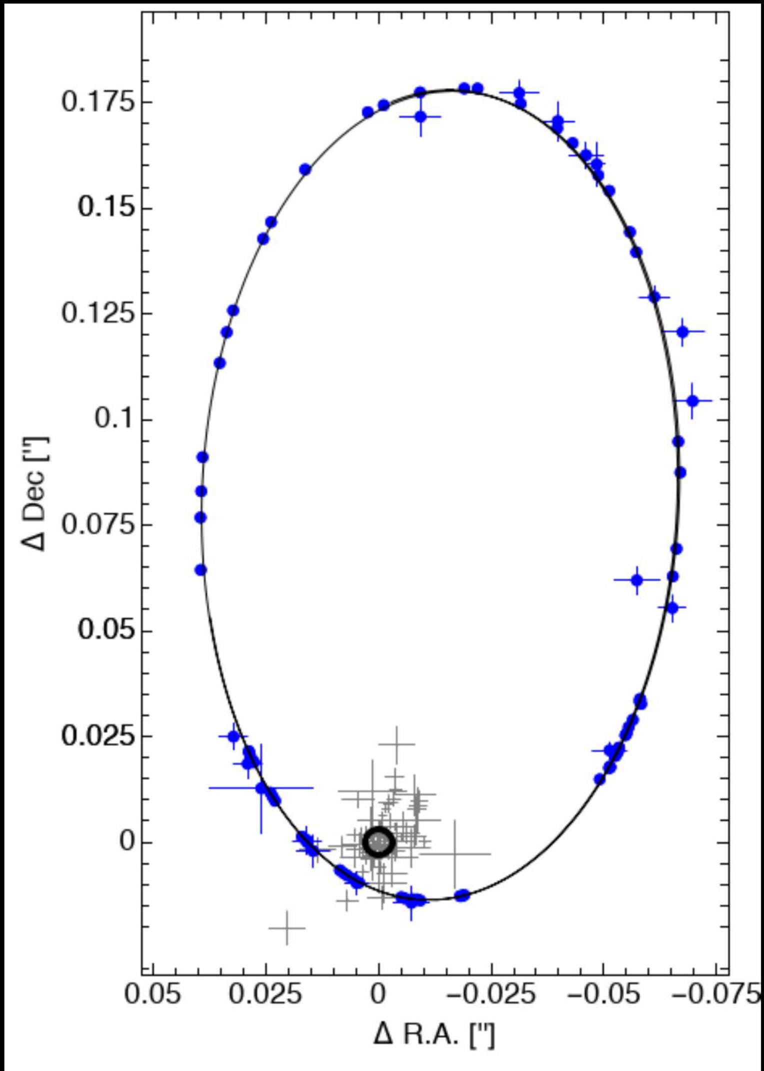
GRAVITY collaboration+18,19

20 – 100 Micro-Arcsecond Precision Astrometry



GRAVITY collaboration+18,19

Precise Mass and Distance of the Galactic Center Black Hole



Motion on sky ("arcsec/yr") ~ Mass / Distance

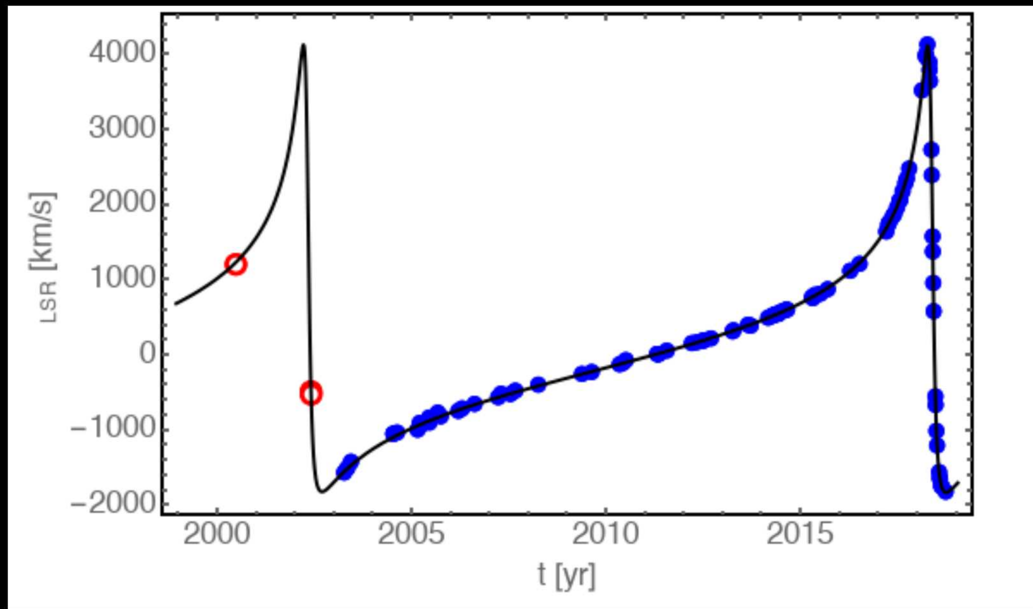
$R_0 = 26673 \pm 42_{stat} \pm 71_{sys}\ ly$

0.33%

$M = 4.152 \text{ x } 10^6\ M_{\text{Sun}}$

$R_S/R_0 = 10022\ \pm 20_{stat} \pm 32_{sys}$ *Nano arcsec*

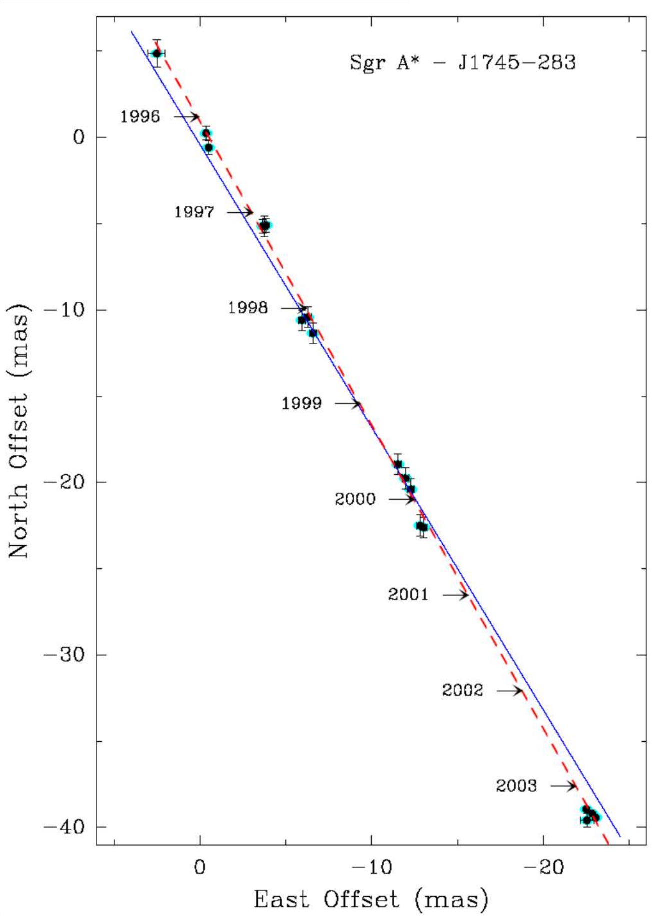
Radial velocity ("km/s") ~ Mass, NOT ~~Distance~~



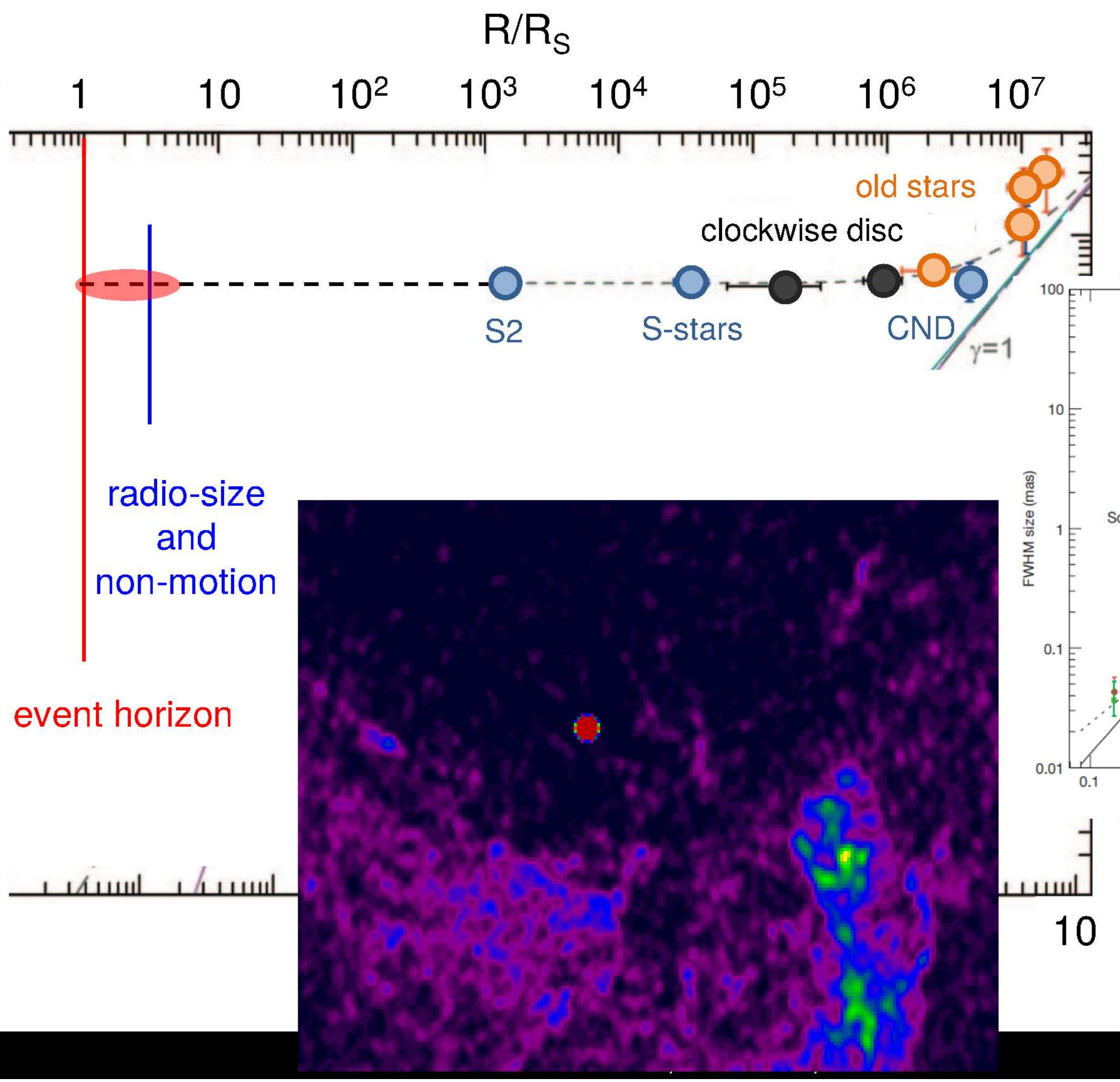
GRAVITY collaboration+18,19

Culmination of 40 Years of Enclosed Mass Measurements

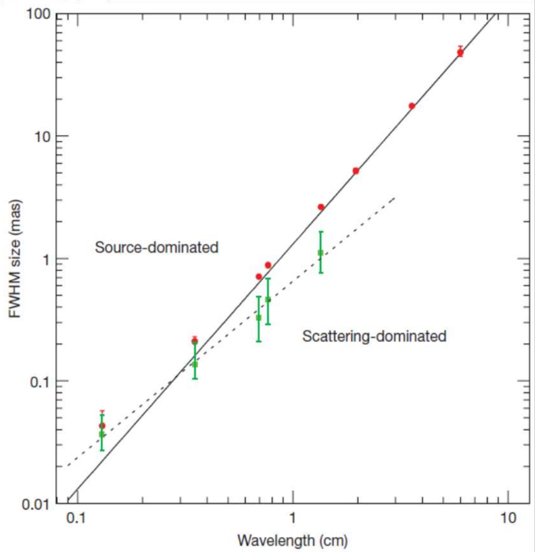
> 400000 M_{Sun}



Reid&Brunthaler04
Reid+08

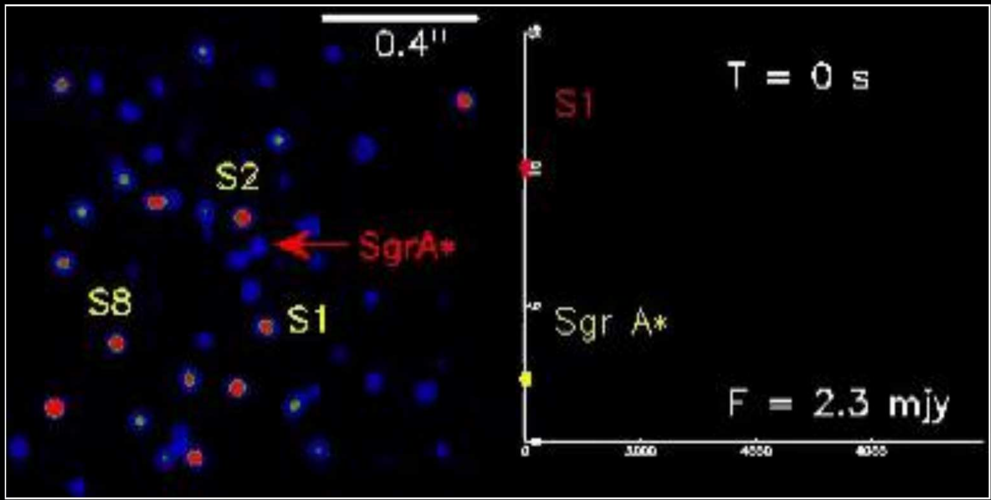


Smaller 3.7 R_S

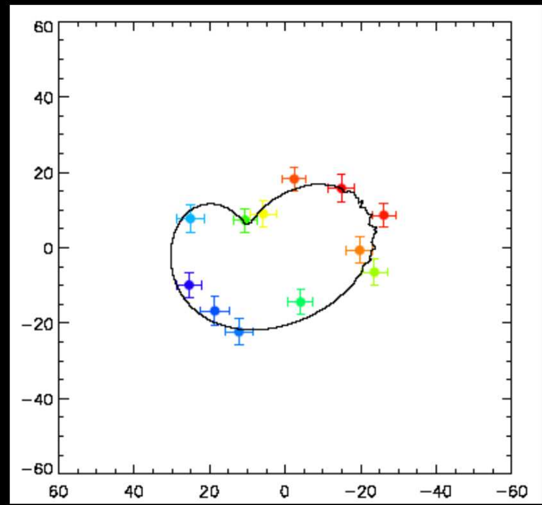


Krichbaum+98, Bower+04,06,
Shen+05, Fish+11, Doeleman+08

Hope for a Dynamical Mass Measurement at R_S Scale ?

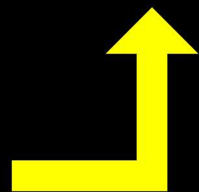


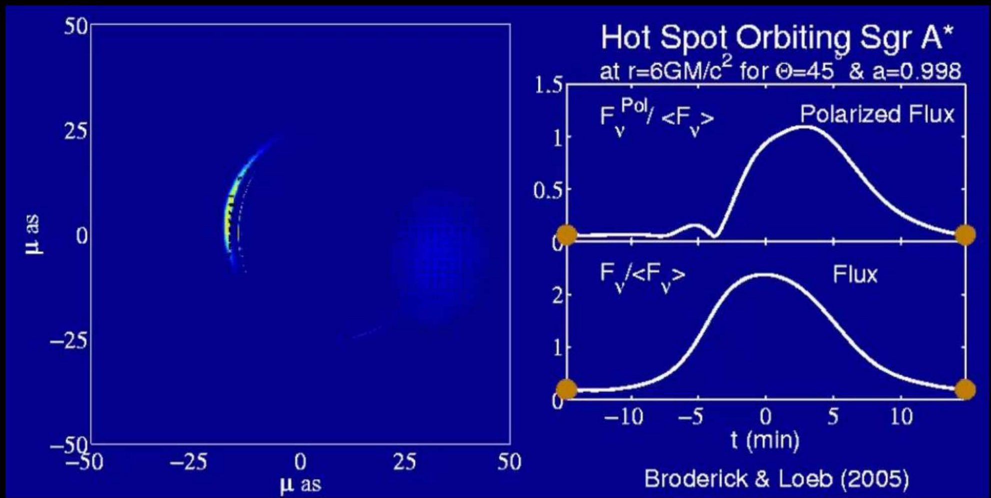
Genzel+03, Meyer+06/7, Trippe+07, Dodds-Eden+09,
Hamaus+09, Zamaninasab+10, Karssen+17



GRAVITY Proposal

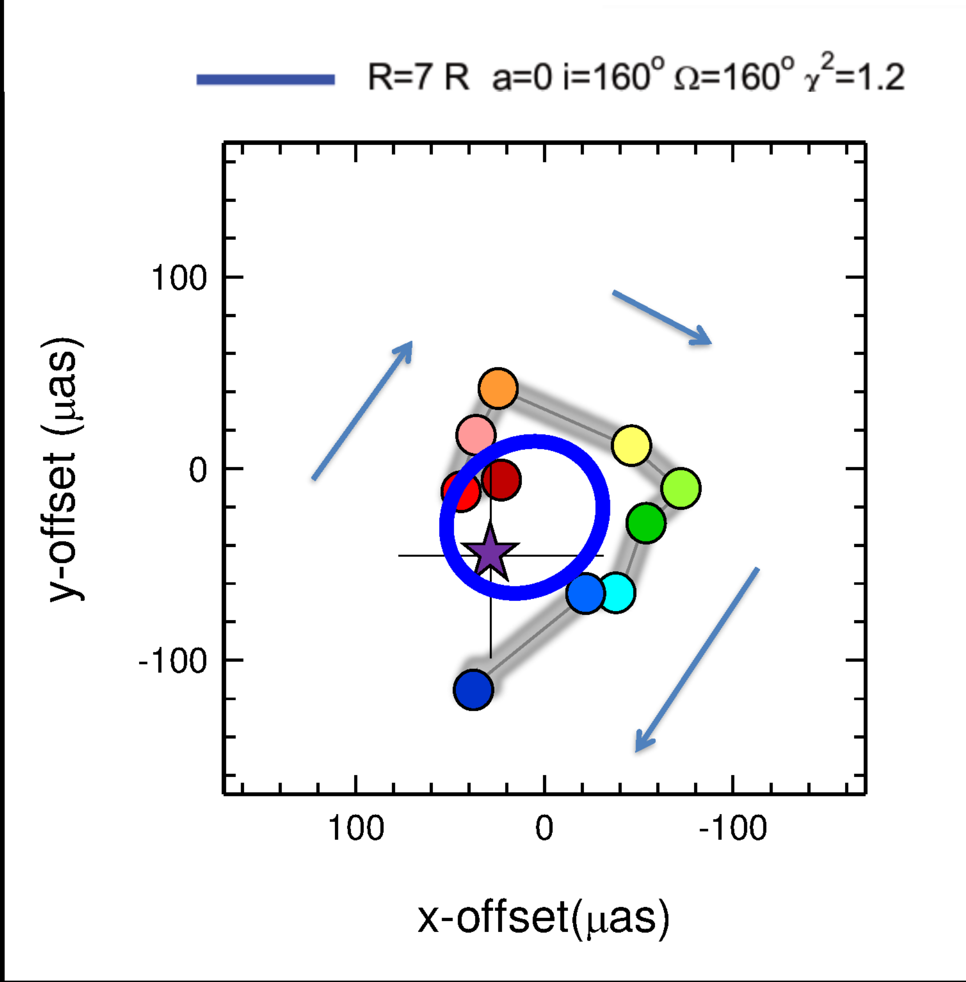
Eisenhauer+05





Broderick&Loeb05, Paumard05

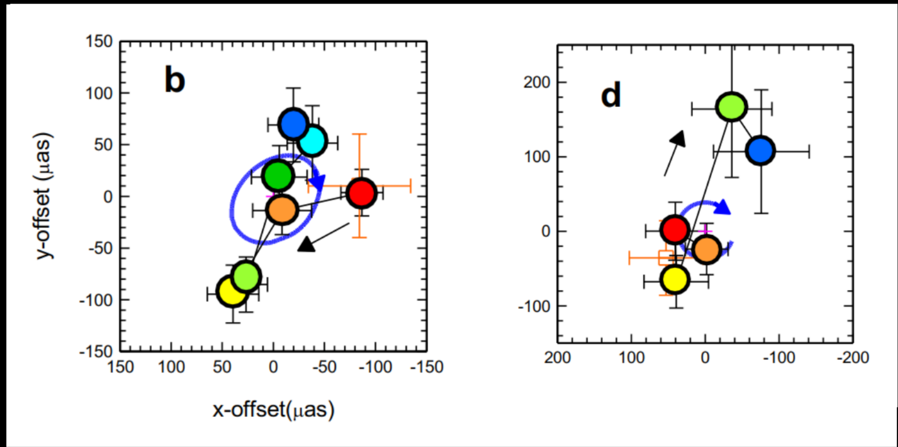
GRAVITY Flare 22 July 2018



- Clockwise, Looped Motion
- 150 as Scale
- Few Ten Minutes

Circular Motion at about
30% Speed of Light

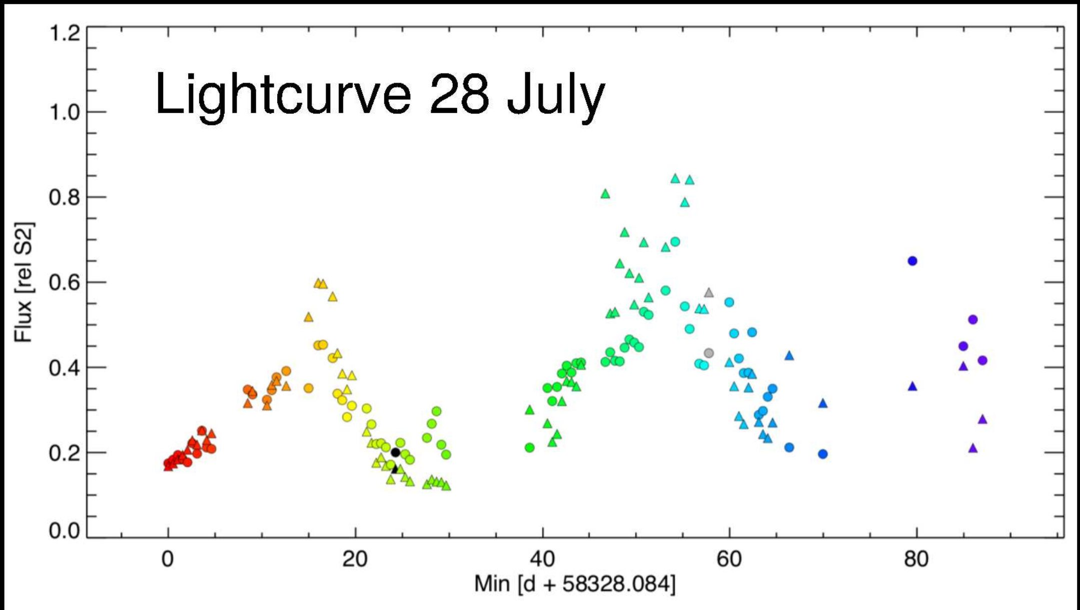
Again on 28 July and back on 27 May



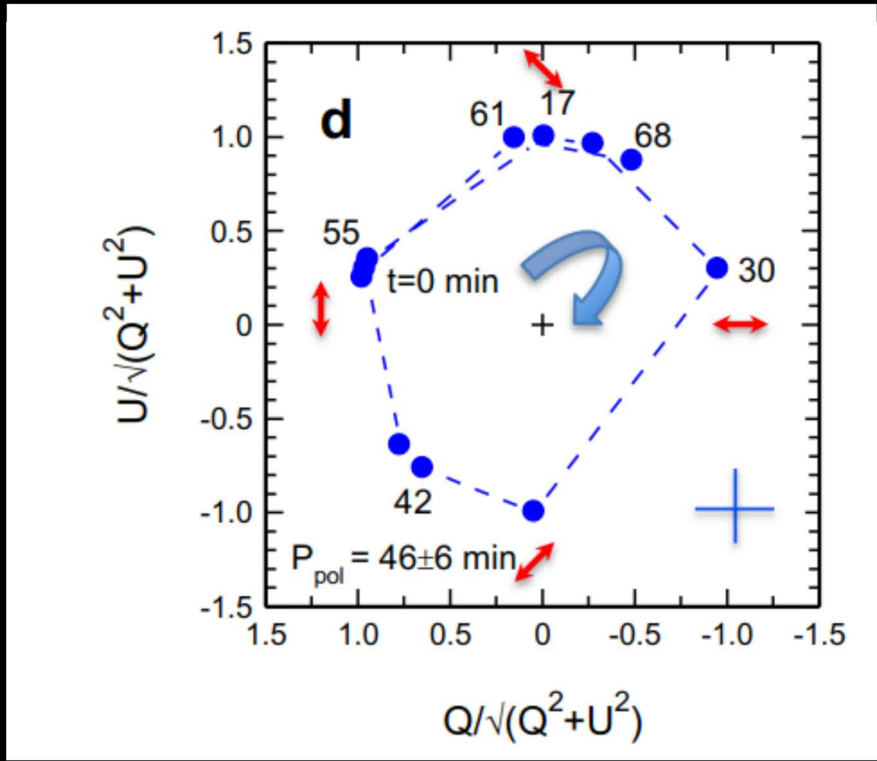
GRAVITY collaboration+18

Low Inclination Circular Orbit Near Last Stable Orbit

Supported by Low Relativistic Beaming Factor

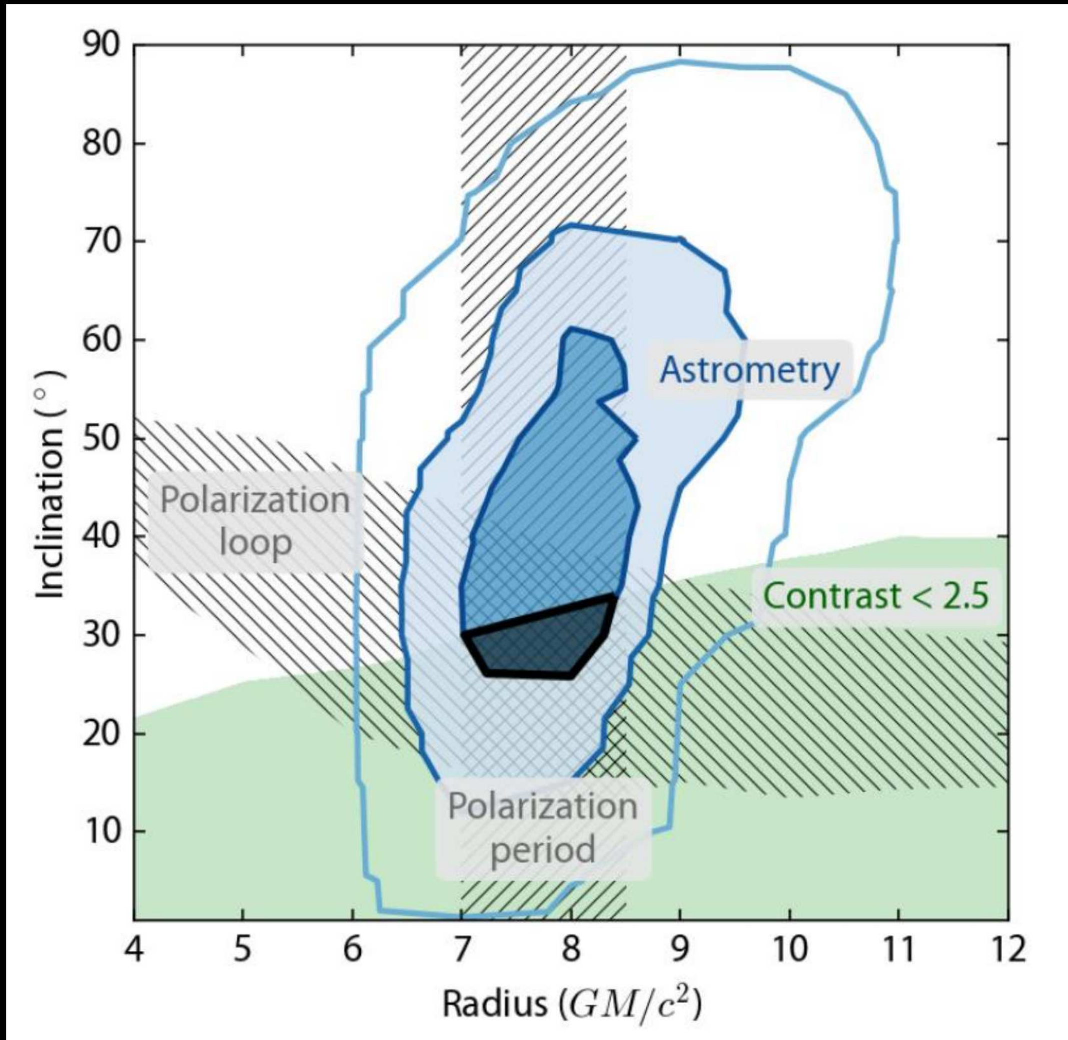


and High Polarization Rotating with Orbit



GRAVITY collaboration+18

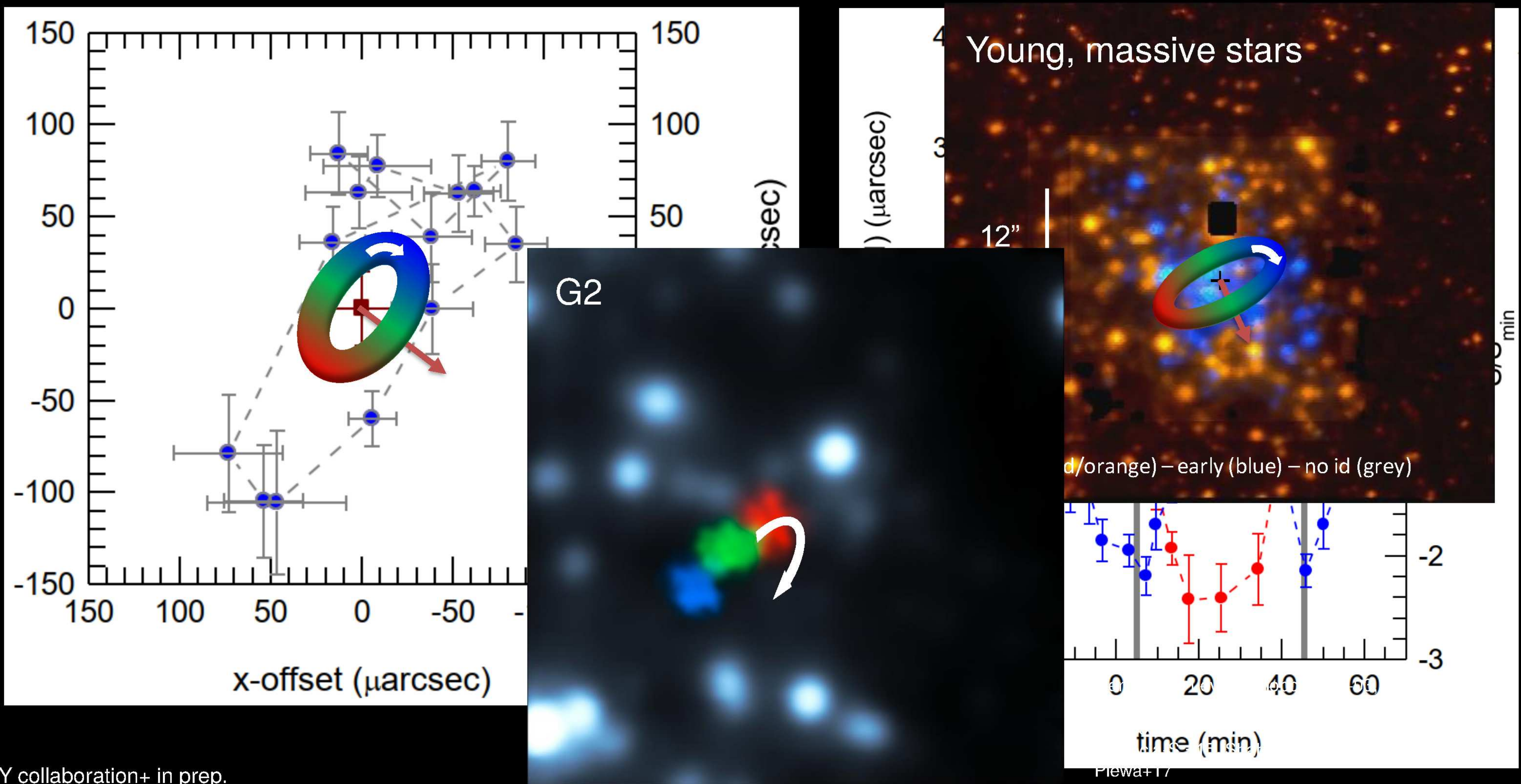
Low Inclination Circular Orbit Near Last Stable Orbit



GRAVITY collaboration+18

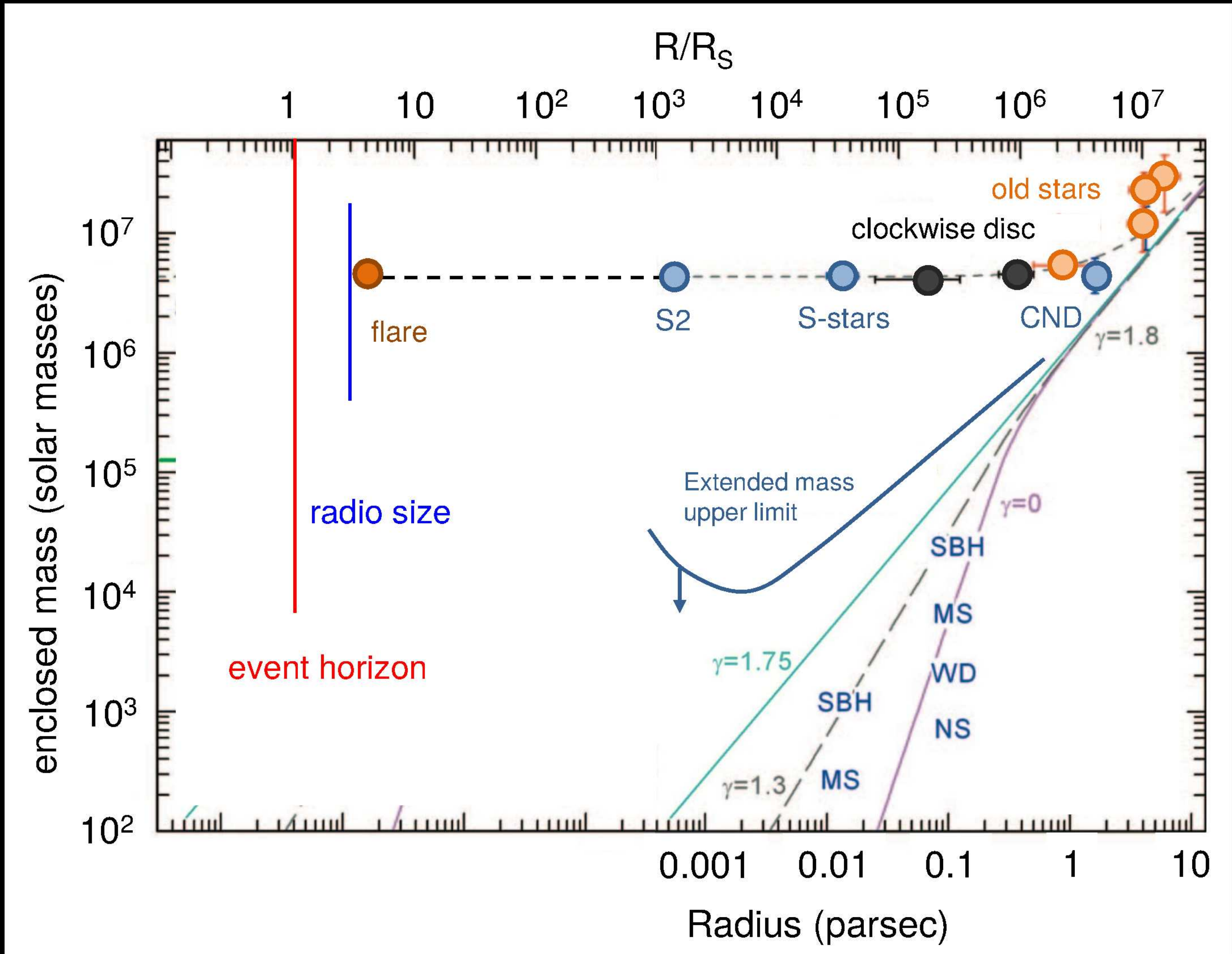
Again in April 2019 – Average of the Best Three Flares

Angular momentum orientation comparable to stellar disc and infalling gas cloud



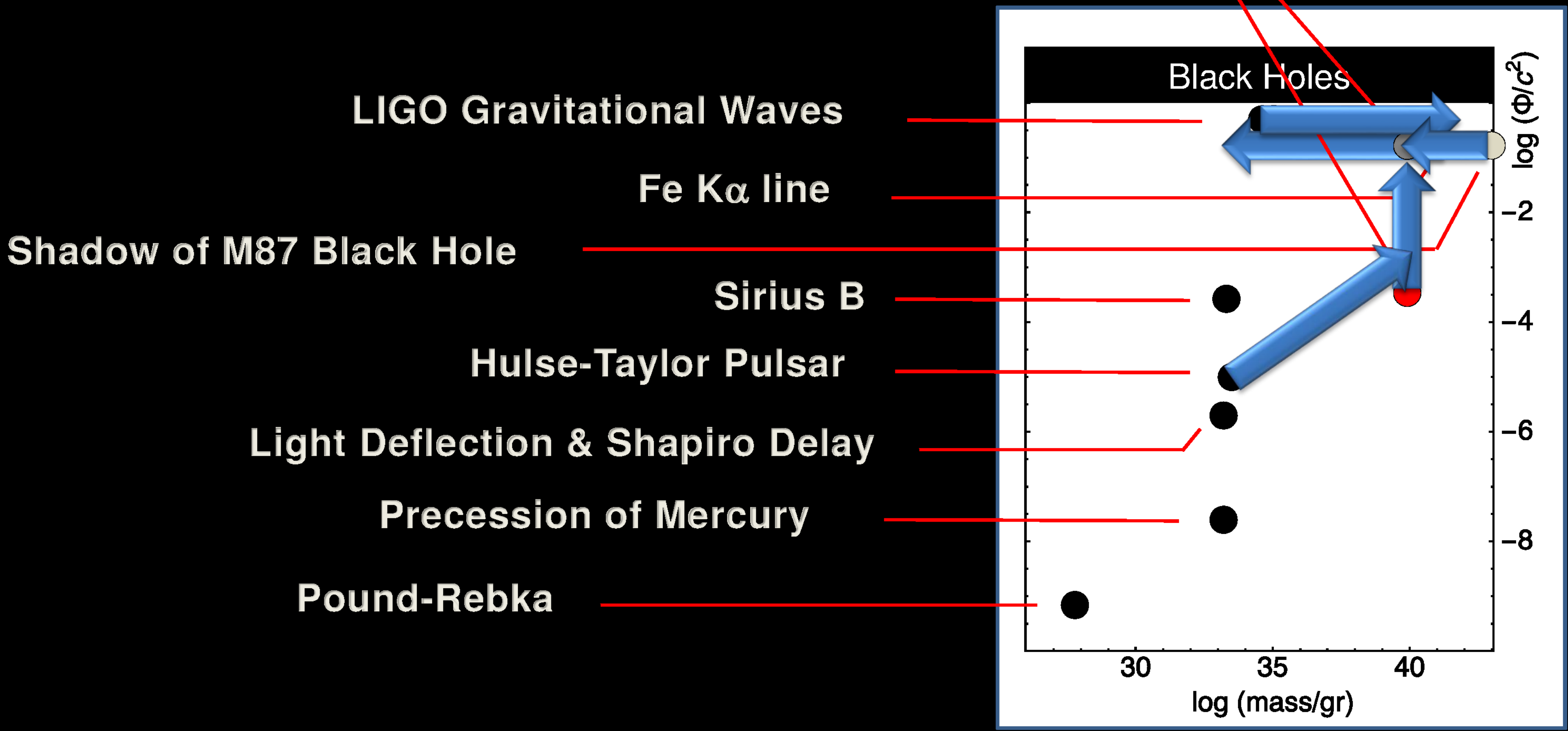
GRAVITY collaboration+ in prep.

Best Model Independent Case for Massive Black Holes



GRAVITY collaboration

Test of General Relativity in the Galactic Center

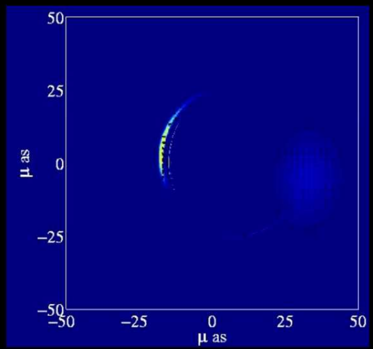


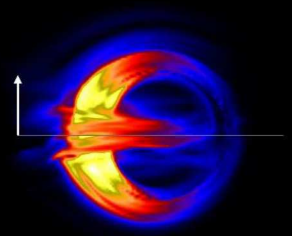
Adapted from Psaltis04

Pound&Rebka59, Einstein1916, Tylor&Weisberg82, Greenstein71, Barstow+05, Abbott+16+, Tanaka+95, Fabian+00, EHT collaboration+19

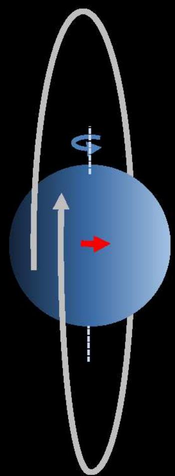
Test of General Relativity in the Galactic Center

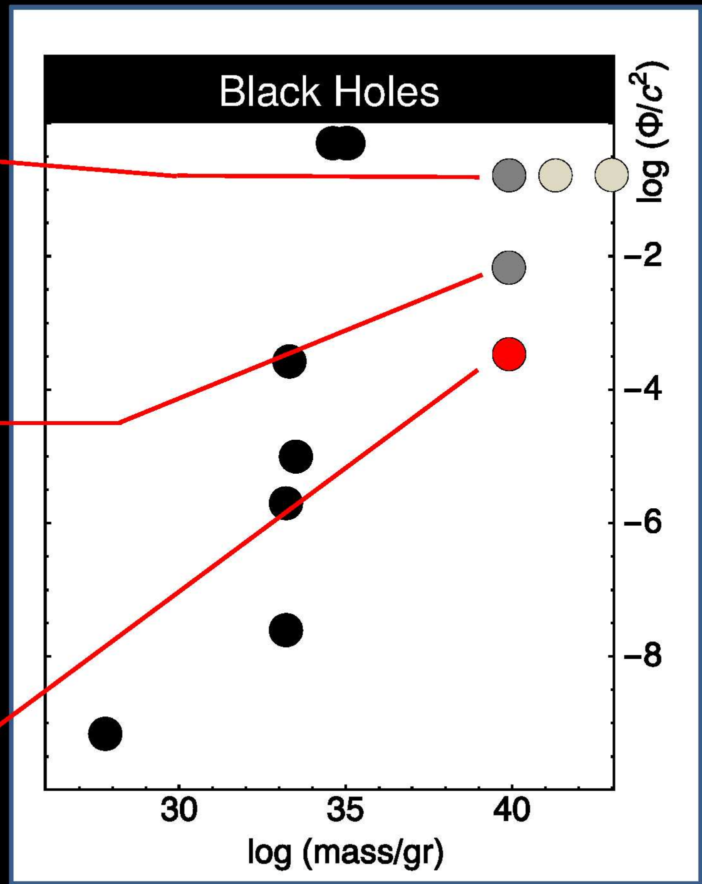
Flares & Shadow from Sgr A*



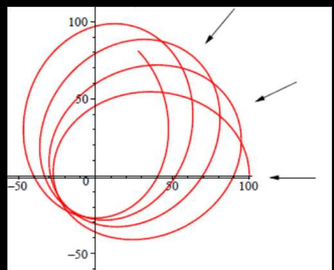


Lense Thirring Precession

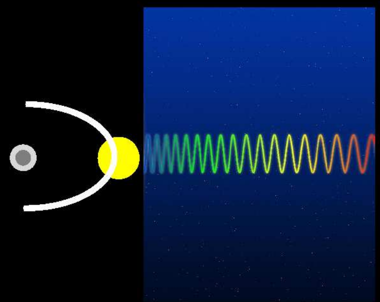




Periastron Shift



Gravitational Redshift



Flares: GRAVITY collaboration+18, Broderick,Loeb+05, Paumard+05, Hamaus+06,Vincent+16,
Shadow: McKinney, Blandford+, Falcke, Dexter, Agol+, Mościbrodzka, Gammie, Dolence+, Broderick, Loeb+, Shcherbakov, Penna+
Lense Thirring: Kraniotis07, Will08, Kannan&Saha09, Merritt+10, Angélil+10,11, Iorio11, Zhang+15,17, Yu+16, Grould+17, Waiserg+18
β^2 effects: Jaroszynski 98, Rubilar&Eckart 01, Fragile&Mathews 00, Alexander 05, Weinberg+05, Zucker+06, Angelil+10, Hees+17, Parsa+17, Grould+17, Nishiyama+18

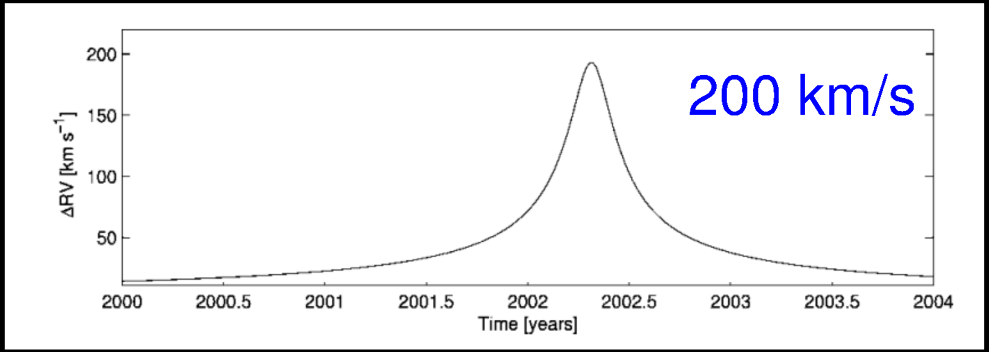
Probing PPN with Stellar Redshifts

Redshift

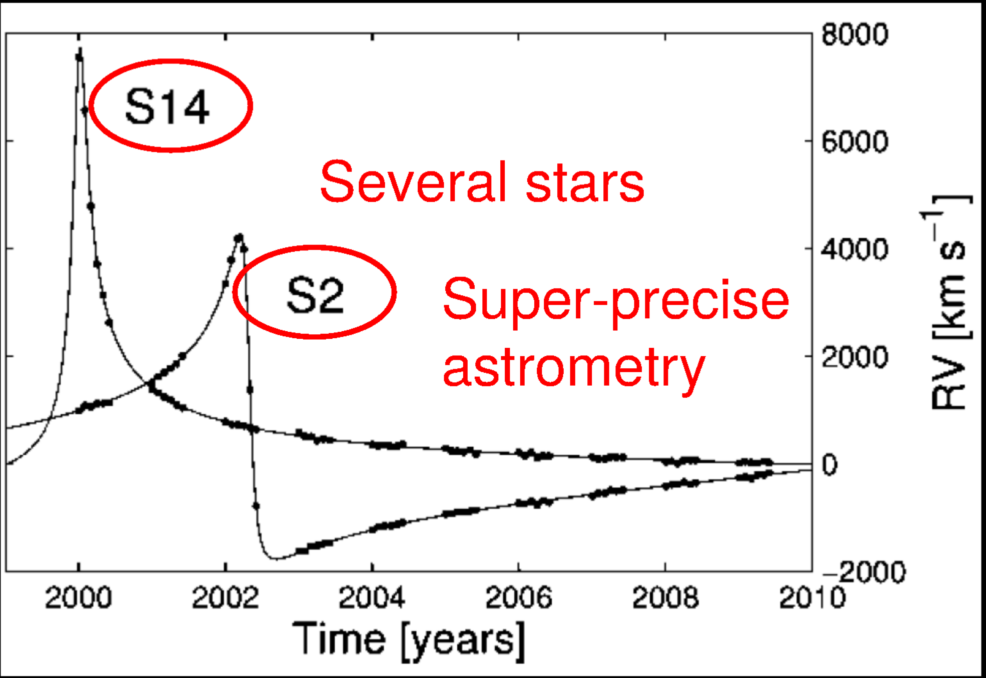
$$z = \Delta\lambda/\lambda = B_0 + B_1\beta + B_2\beta^2$$

$$\mathrm{PPN}(1) \sim \Upsilon(r_p) \equiv r_s/r_p \sim \beta^2$$

$$\sim 6.5\times 10^{-4}$$

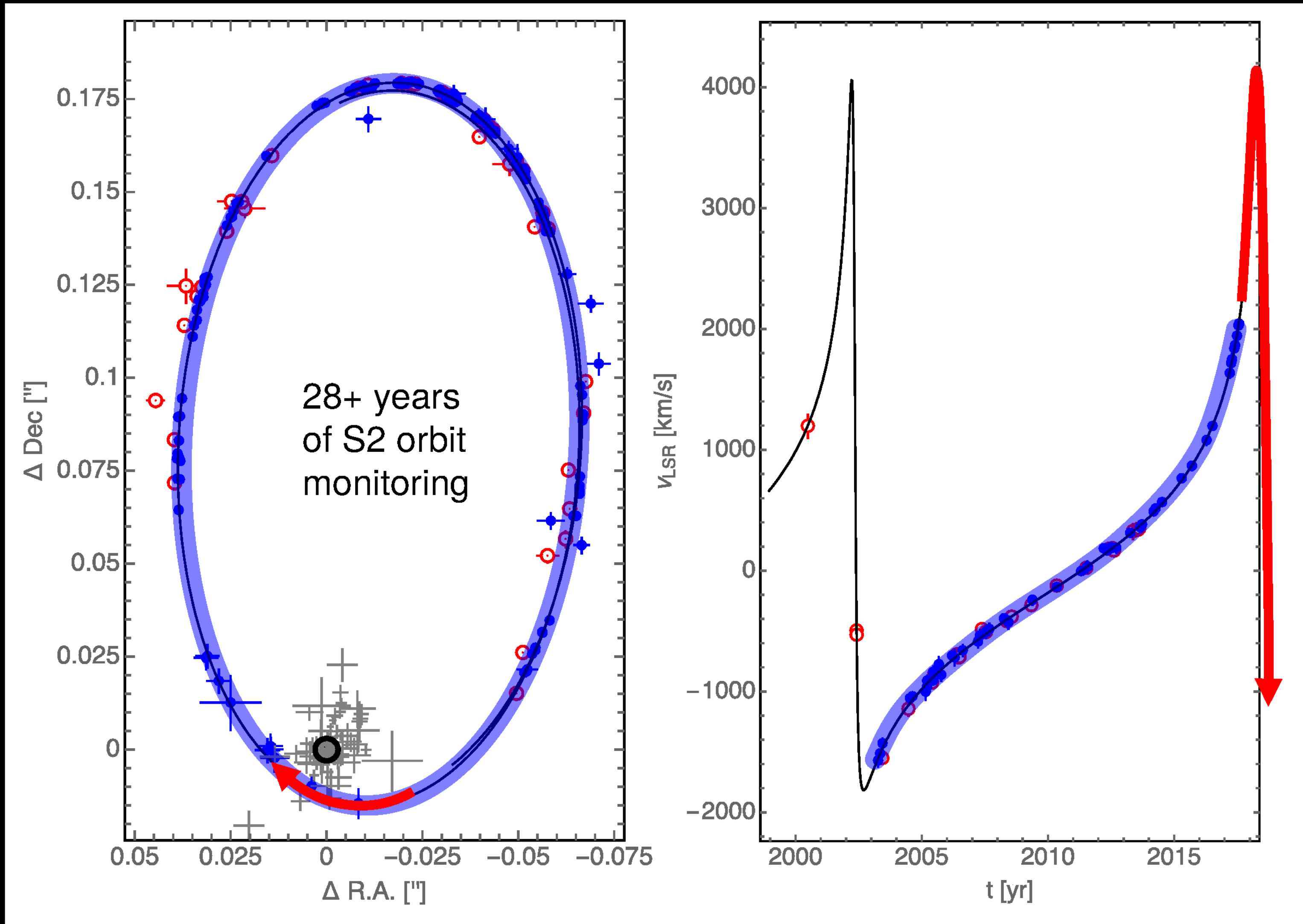


But radial velocity alone not enough, because relativistic effect can be absorbed in Kepler orbital elements



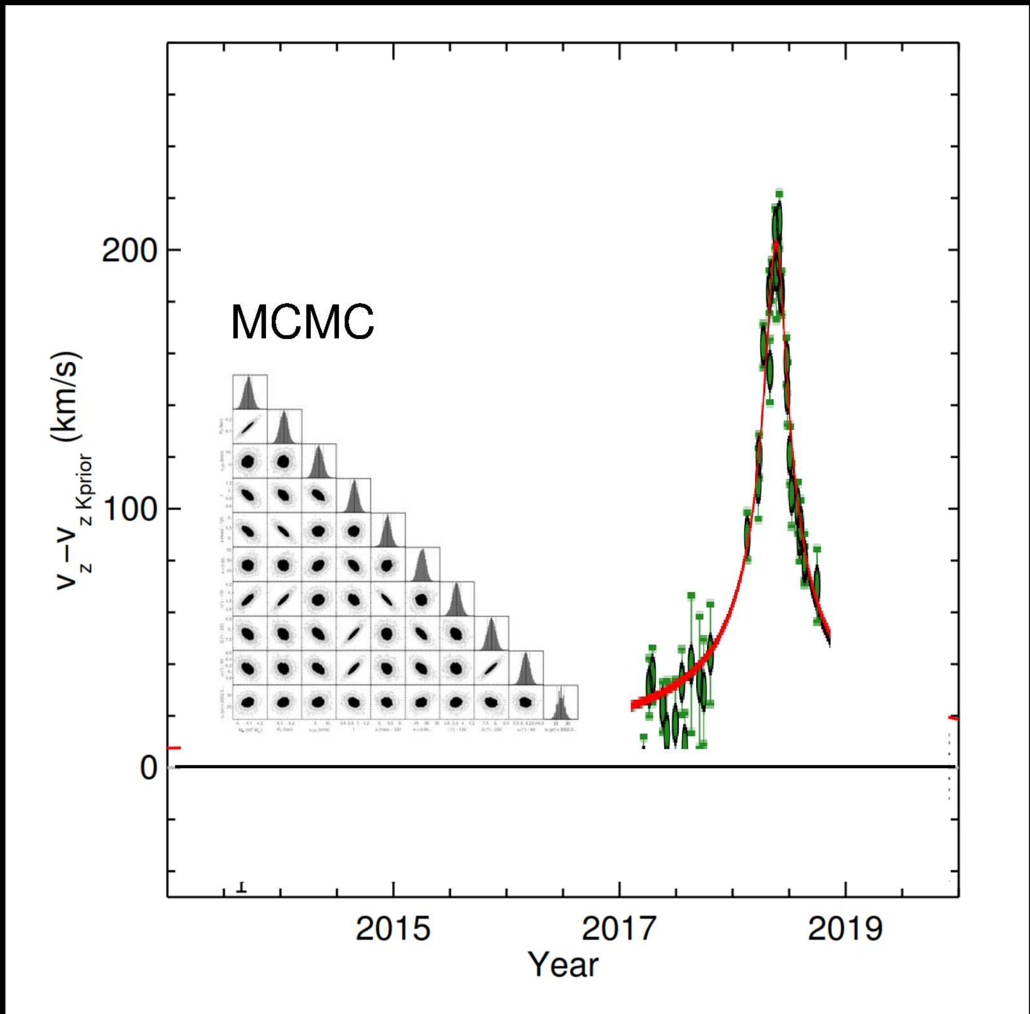
Fragile&Mathews00, Alexander05, Zucker+06

Measuring the Gravitational Redshift at Closest Approach



Schödel+02, Eisenhauer+03,05, Ghez+05,08, Gillessen+09,17, Mayer+12, Boehle+16, Sakha+19, GRAVITY collaboration+18,19

A Posteriori Analysis



f = 0: Newton
f = 1: General Relativity

→ Excludes prior Newtonian orbit
= 1.01 ± 0.05 is excluded at 20 σ

Such high significance **only possible** with **precise knowledge** of **orbital parameters**

Uncertainty of the radial velocity prediction from Kepler fit to data up to 2017

GRAVITY collaboration+18,19, Do+19 submitted

Gravitational Redshift is More Fundamental than GR

f = 0: Newton
f = 1: General Relativity

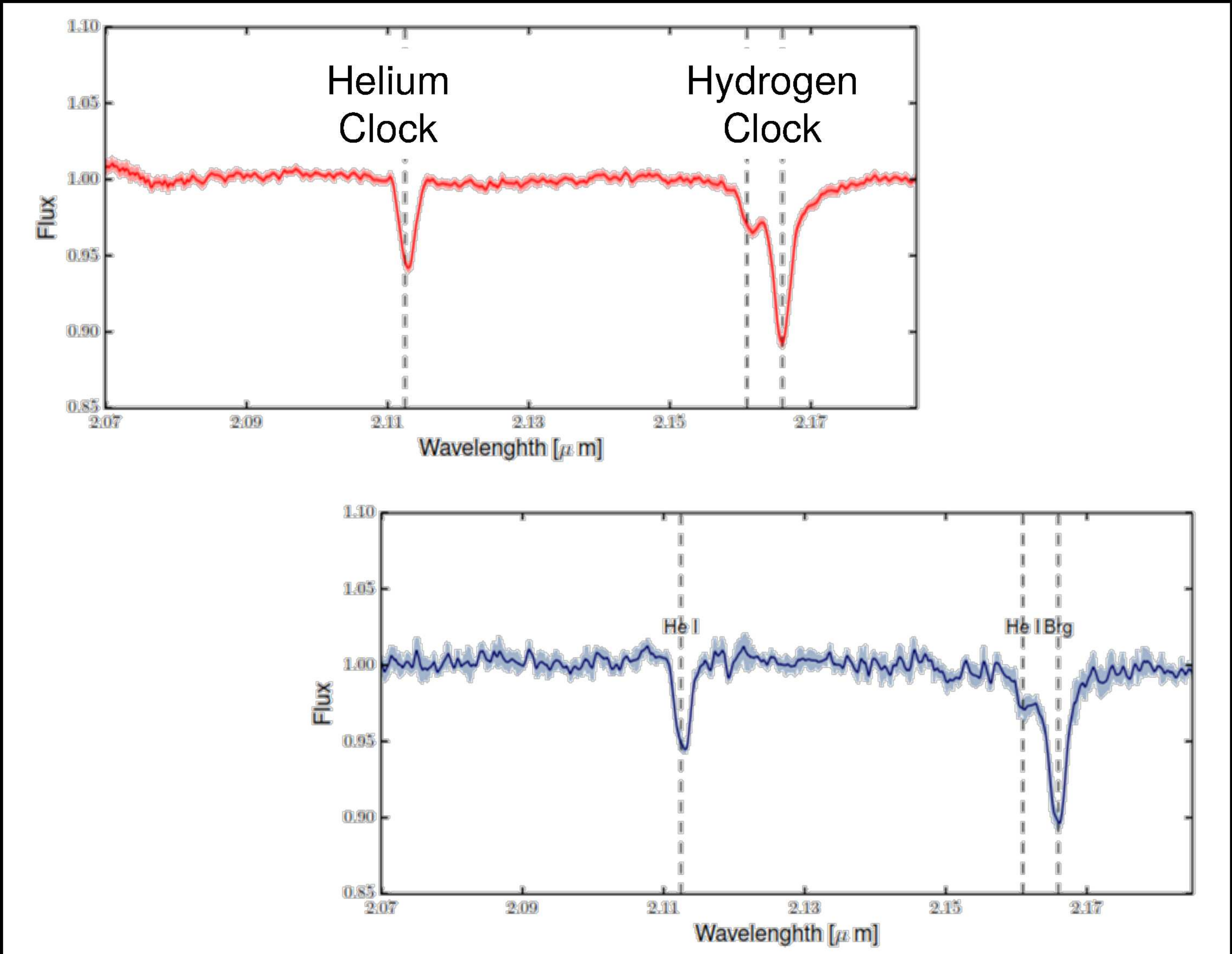
→ f = 1.04±0.05

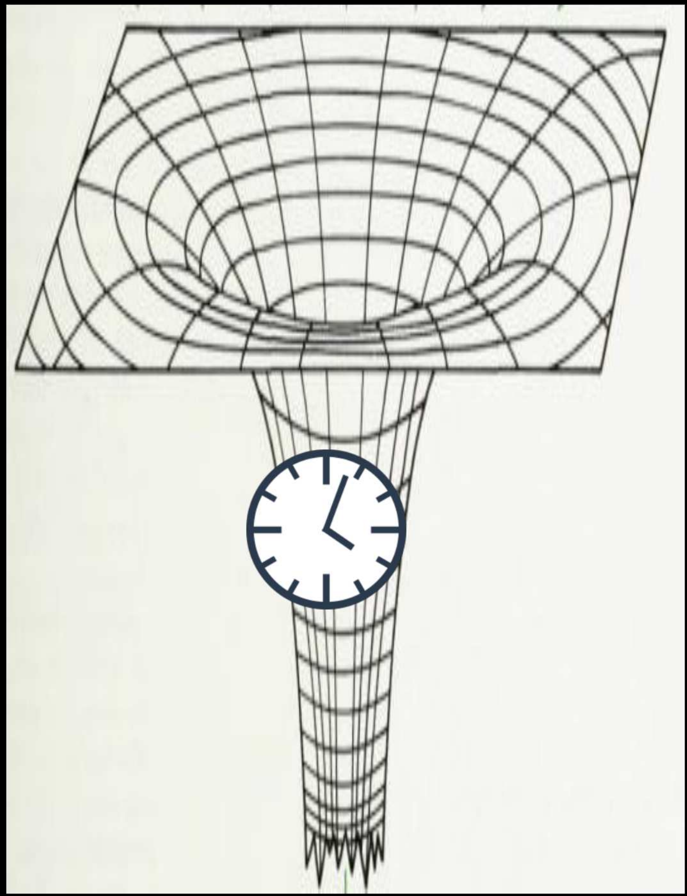
Does not distinguish between GR and any other metric theory of gravity, but is only a test of the Einstein Equivalence Principle

Will 06, Angelil&Saha10

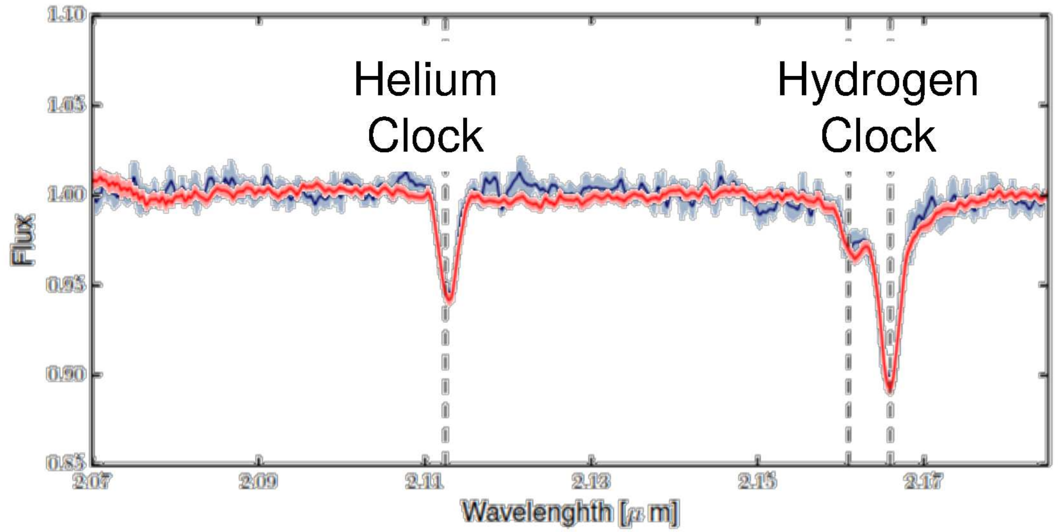
GRAVITY collaboration+19

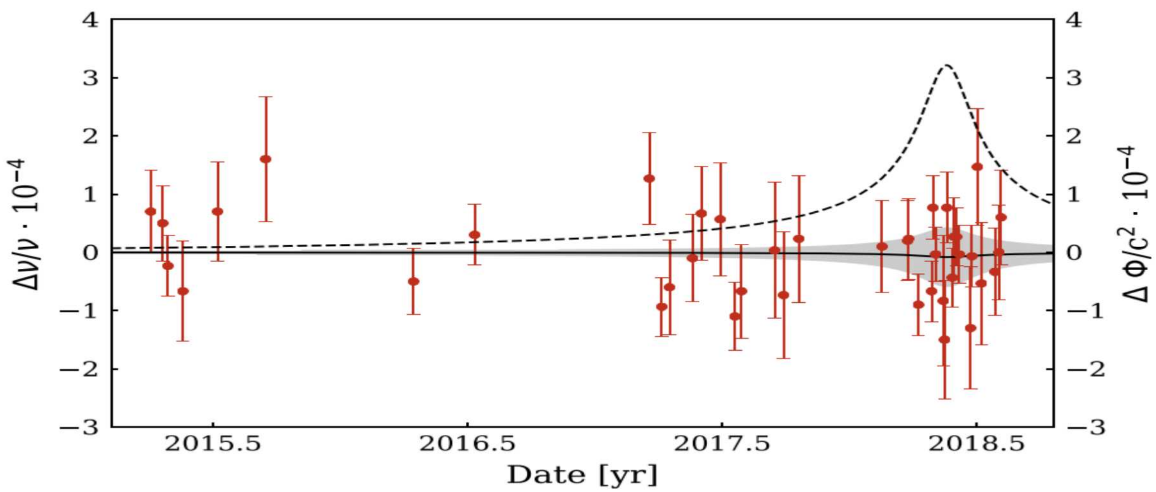
Testing the Local Position Invariance (LPI)





Local Position Invariance for Different Clocks





$$\frac{\Delta f}{f} = \Delta z_{Clock1\,-Clock2} = \frac{\Delta\alpha}{\alpha}\left(\frac{\Delta\Phi}{c^2}\right)$$

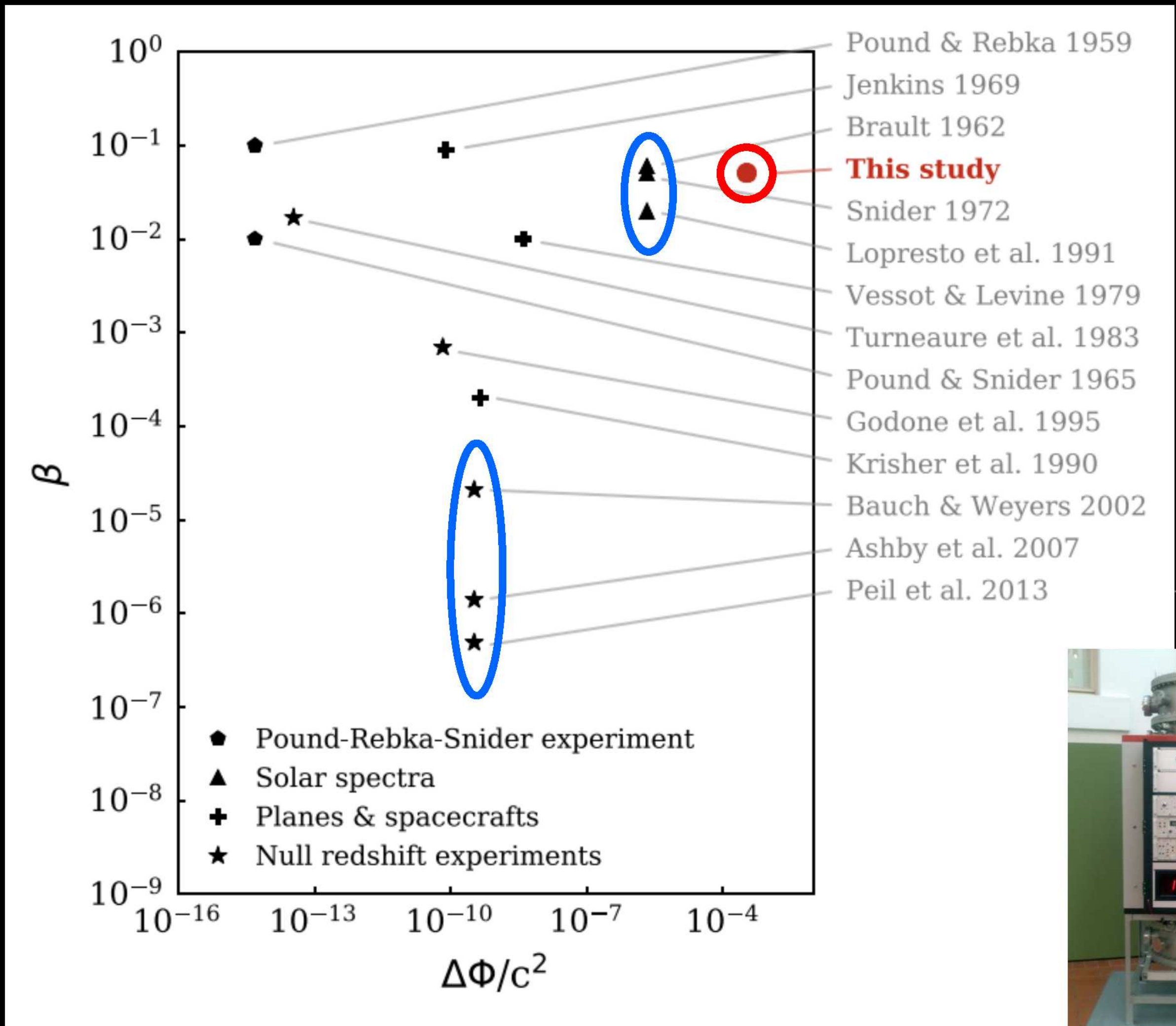
Galactic Center

$$\left(\frac{\Delta\alpha}{\alpha}\right)_{HeI\,-Br\gamma} = 2.4 \pm 5.1\ \%$$

for $\left(\frac{\Delta\Phi}{c^2}\right) = 3 \times 10^{-4}$

GRAVITY collaboration+19

LPI Tested in Orders of Magnitude Stronger Potentials

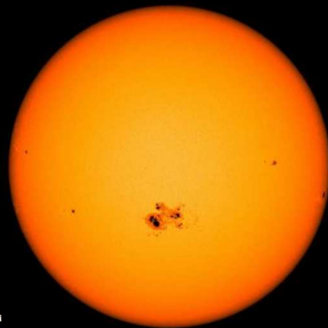


Sun / Infrared Oxygen Triplet

(e.g. Brault63, Snider72, Lopresto+91)

$$\left(\frac{\Delta\alpha}{\alpha}\right)_{O\ \lambda 7772-7775} < 10^{-2}$$

for $\left(\frac{\Delta\Phi}{c^2}\right) = 4 \times 10^{-6}$



Galactic Center

$$\left(\frac{\Delta\alpha}{\alpha}\right)_{HeI\ -Br\gamma} = 2.4 \pm 5.1\ \%$$

for $\left(\frac{\Delta\Phi}{c^2}\right) = 3 \times 10^{-4}$

Atomic Clock vs. H-Masers

(Bauch&Weyers02, Ashby+07, Peil+13)

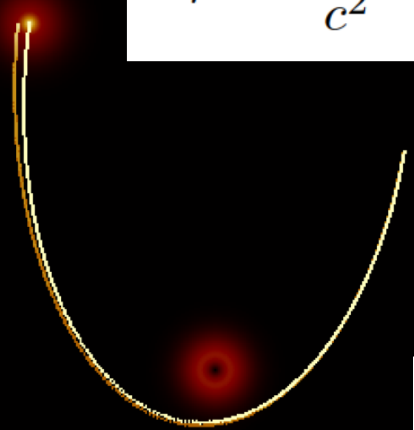
$$\left(\frac{\Delta\alpha}{\alpha}\right)_{Rb-H} < 10^{-6}$$

for $\left(\frac{\Delta\Phi}{c^2}\right) = 3 \times 10^{-10}$

GRAVITY collaboration+19

The Next Step – Schwarzschild Precession

$$\Delta\varphi = \frac{6\pi G}{c^2}\frac{M}{a(1-e^2)}$$ ~ 11.9' ~ 800 µas

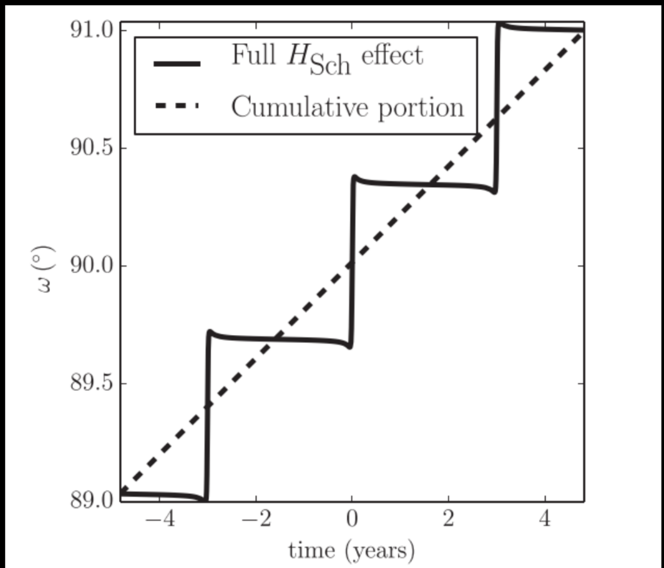


Mar – Aug ΔRA ~ 50 mas

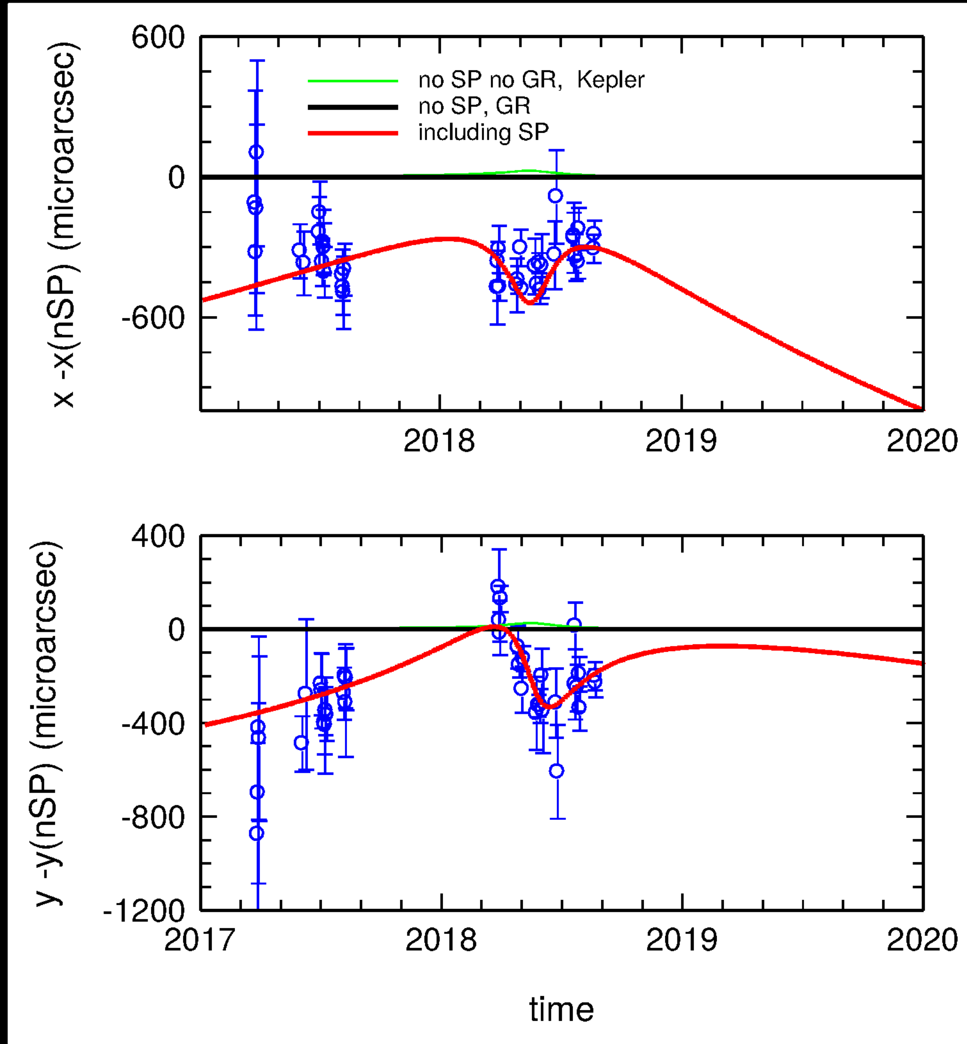
$\rightarrow \Delta\varphi = 200\ \mu as$

Currently about 2σ

Jaroszynski98
Fragile&Mathews00
Rubilar&Eckart01



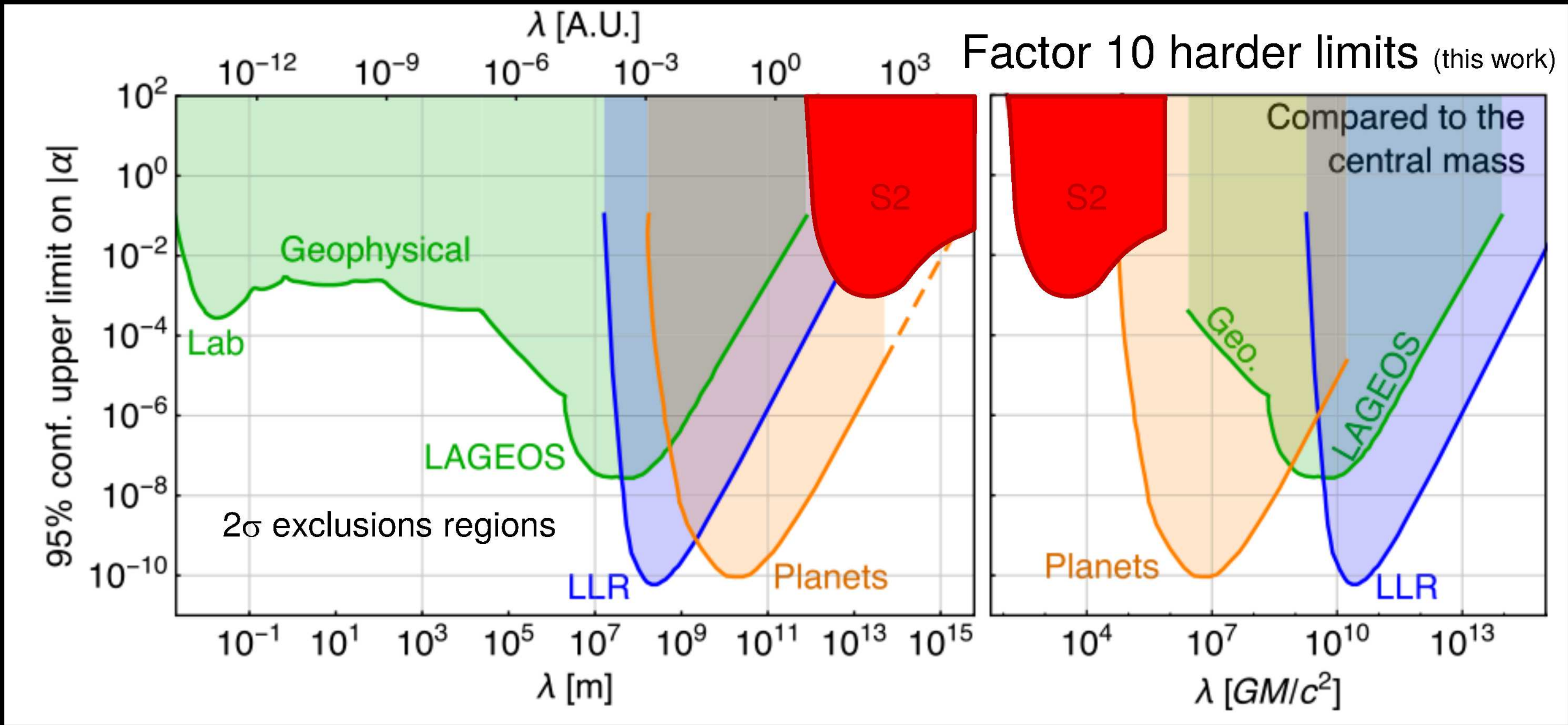
Angelil&Saha14



GRAVITY collaboration

New Physics – Fifth Force ?

Phenomenological via Additional Yukawa Potential $U = \frac{G\,M}{r}\left(1 + \alpha e^{-r/\lambda}\right)$



Scalar Tensor Gravity Gravina+18 Jovanovic+19 **Tidal Charge** Horvat&Gergely13

Hees+17 GRAVITY collaboration+19, in prep.

Grand Quests for the Future

Spin of the Black Hole

$$V_{\text{eff}}(r,e,l) = -\frac{M}{r} + \frac{l^2 - a^2(e^2-1)}{2r^2} - \frac{M(l-ae)^2}{r^3}$$

$$a \equiv \frac{J}{M}$$

Cosmic Censorship

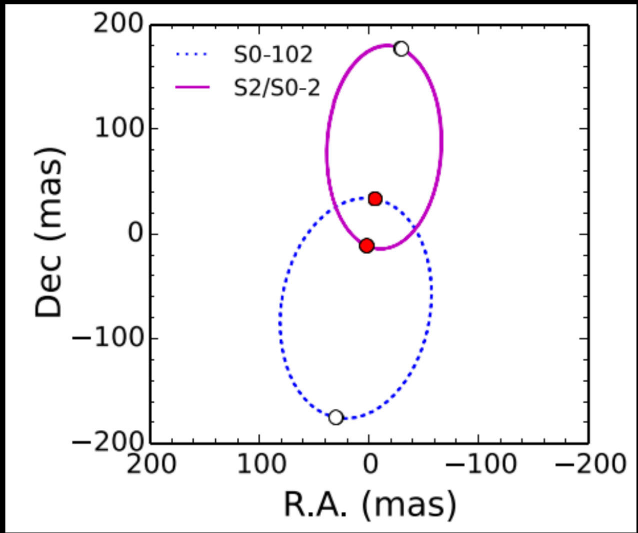
$a > 1$ **Naked Singularity**

No Hair Theorem

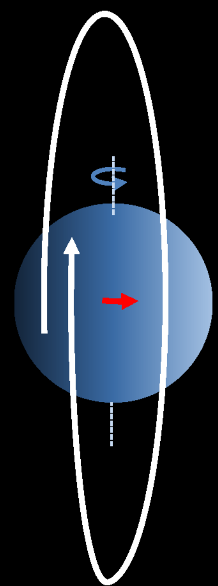
$$Q_2 = -J^2/M$$

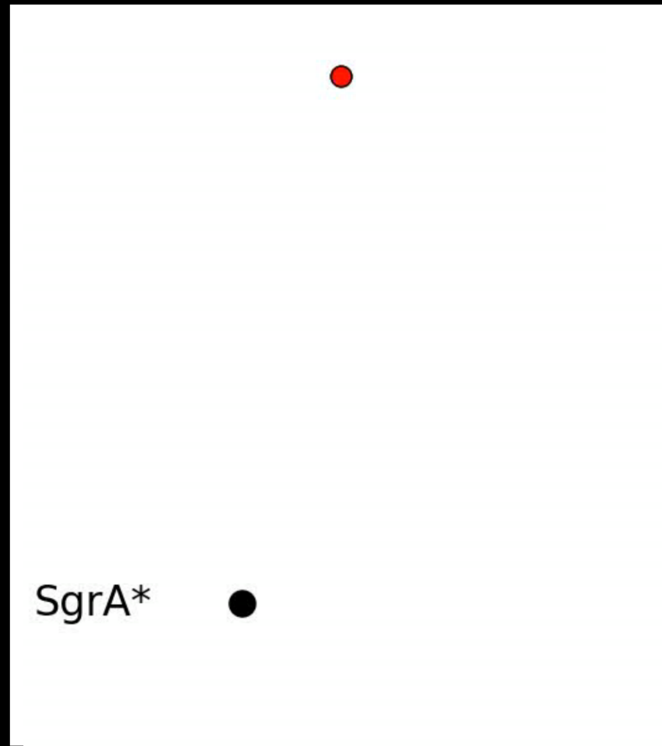
Quadrupole Moment

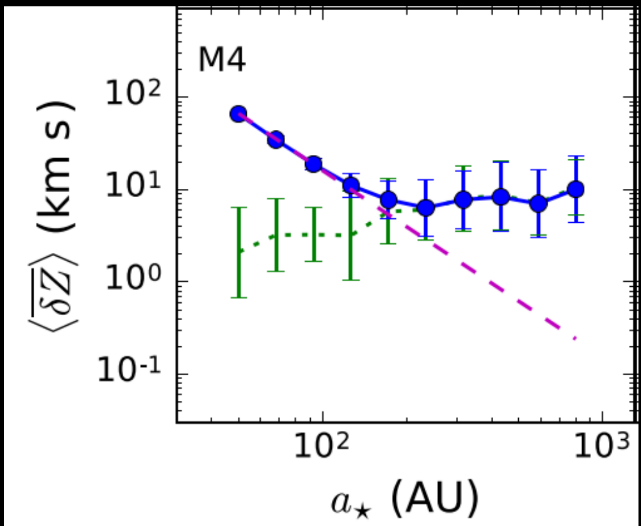
Model Independent Spin Measurement



Already **known stars obscure spin** in S2 orbit







Newtonian Perturbations

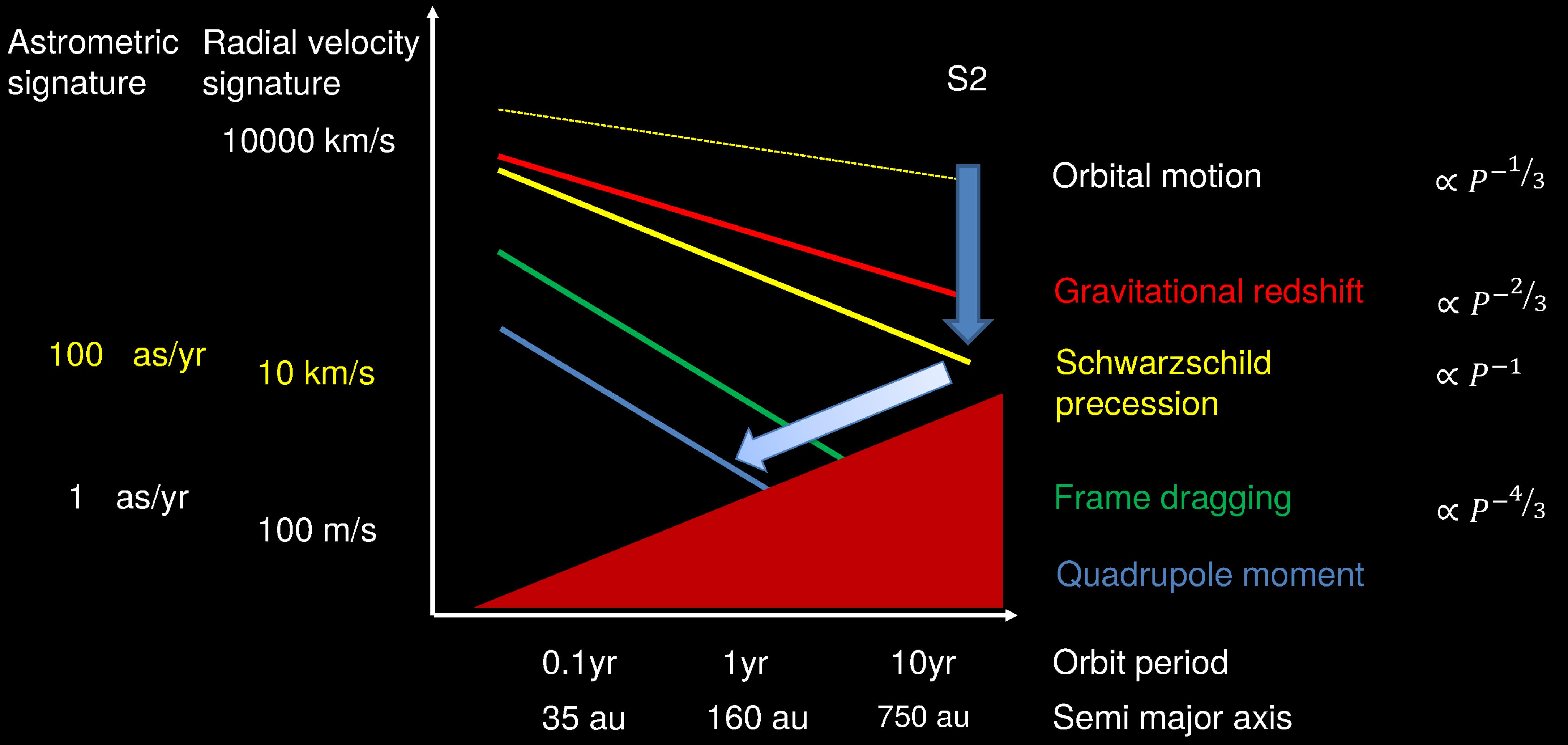
To be on safe side "S2/10"

We should have about $\lesssim$ 1 star

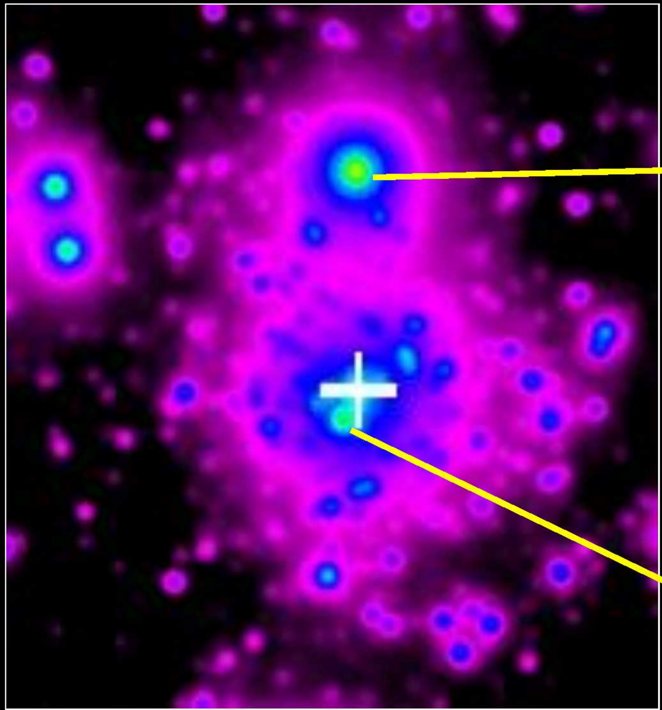
with K~20 fulfilling criteria

Kraniotis07, Will08, Kannan&Saha09, Merritt+10, Angélil+10,11, Iorio11, Zhang+15,17, Yu+16, Grould+17, Waisberg+18

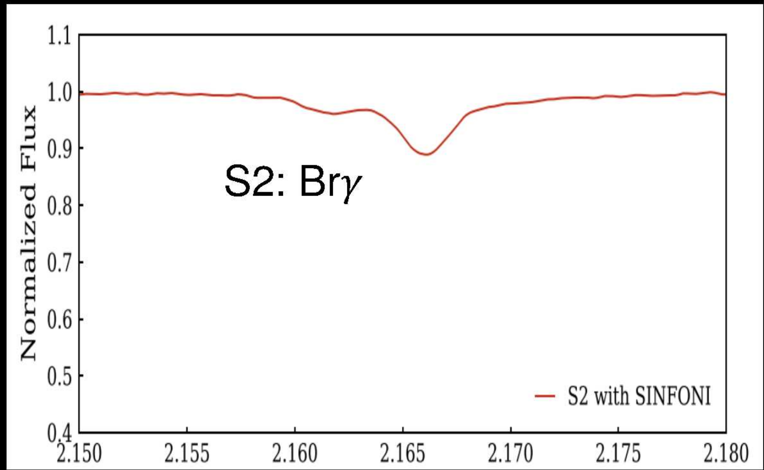
Towards a Spin Measurement – How To Get There

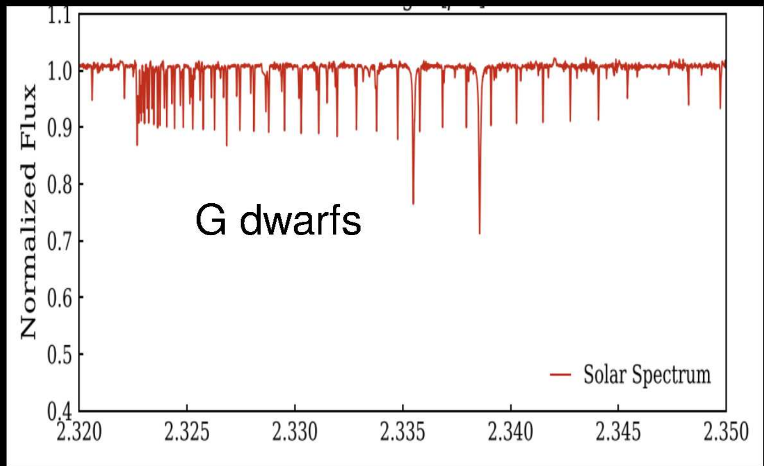


Towards a Spin Measurement – How To Get There



Spectroscopy

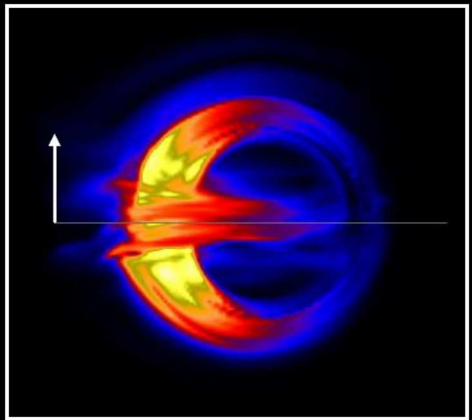




Extremely Large Telescope

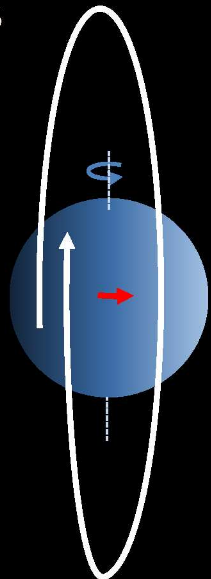
And Bring Together Hard, Independent Numbers

Shadow



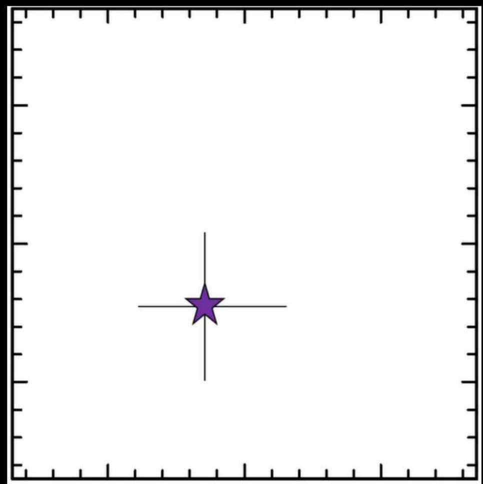
EHT collaboration
Dexter, Agol et al.,
Mościbrodzka, Gammie, Dolence et al.,
Broderick, Loeb et al.,
Shcherbakov, Penna, McKinney

Stellar orbits



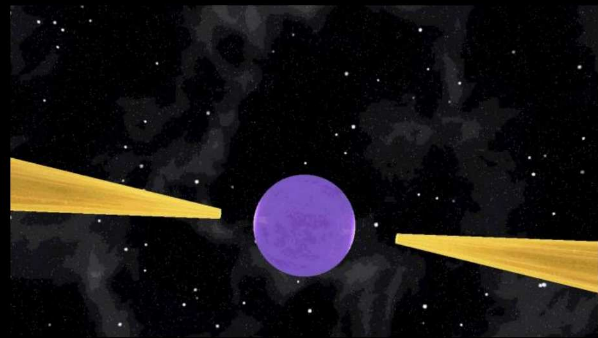
Kraniotis07, Will08,
Kannan&Saha09, Merritt+10,
Angélil+10,11, Iorio11,
Zhang+15,17, Yu+16,
Grould+17, Waiserberg+18

Flares



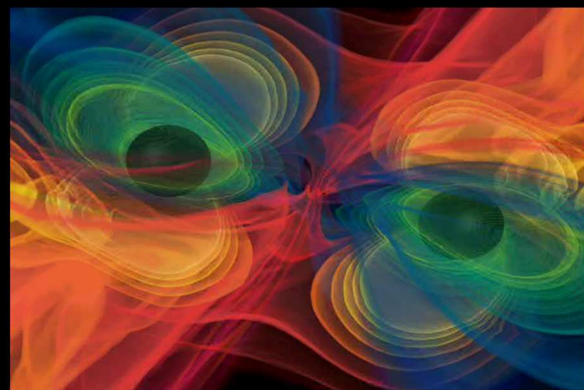
Baganoff+01, Ponti+18, Boyce+19
Genzel+03, Broderick&Loeb05,
Paumard+05, Hamaus+08, Vincent+16
GRAVIY collaboration+18

Pulsars



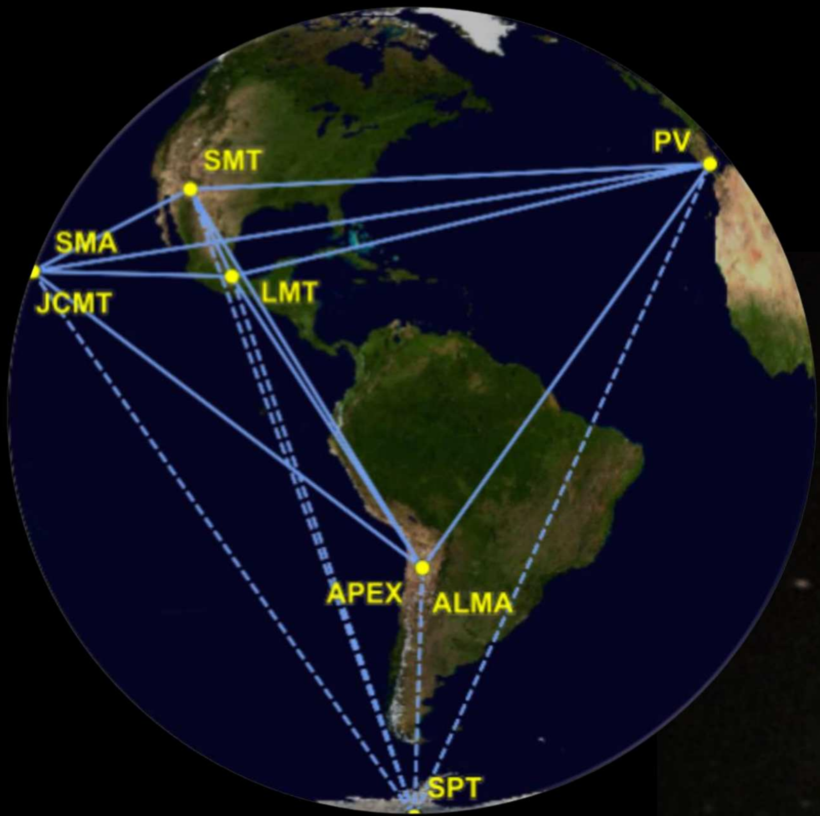
Wex&Kopeikin99, Liu12, Liu+14,
Psaltis,Wex,Kramer16, Eatough+13

Gravitational Waves



For SgrA* e.g. Gourgoulhon+19

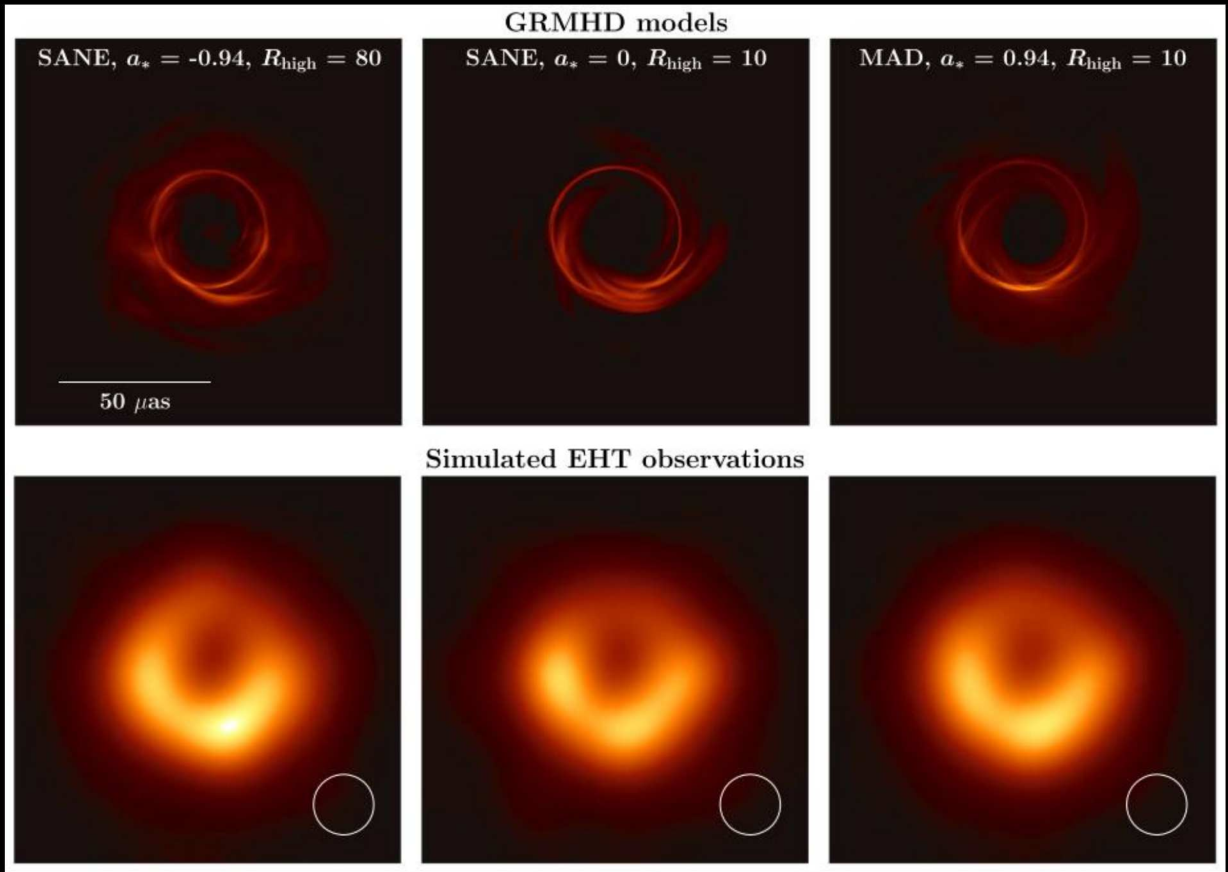
Shadow Experiment – Following the Example of M87

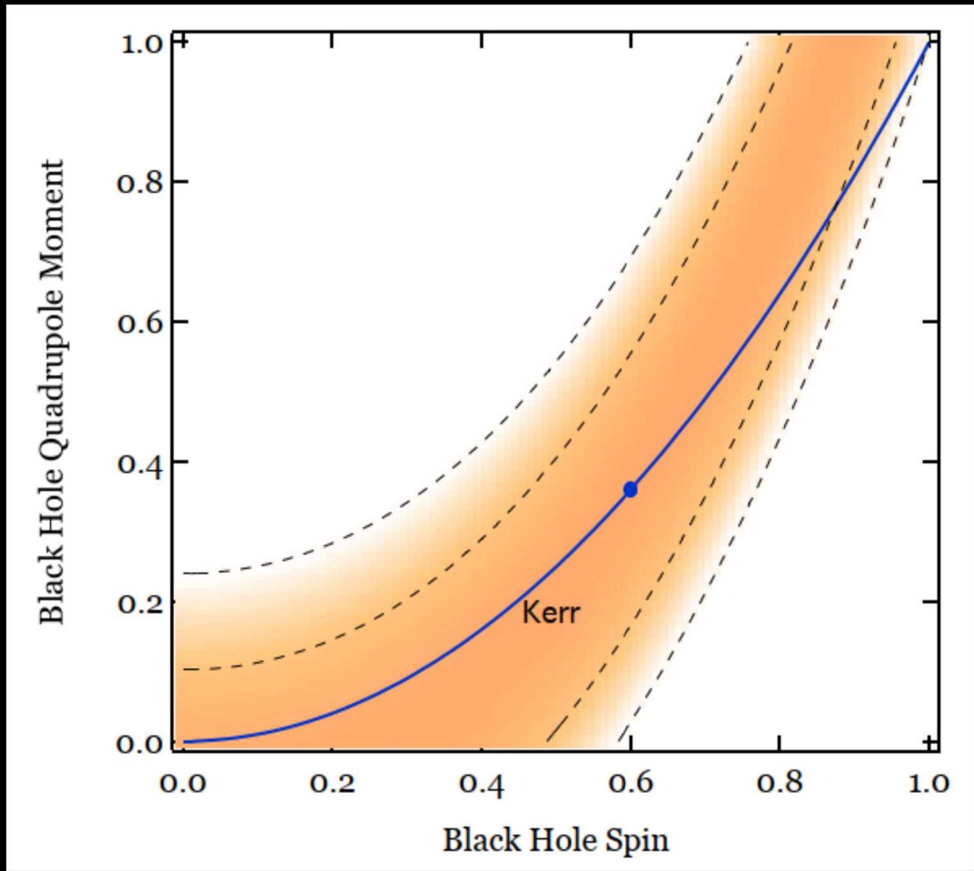


The Event Horizon Telescope Collaboration+19

Shape of Shadow – Tracer of Spin / Quadropole Moment

Ringlike Structure ~ 5 R_G very much Modell Independent



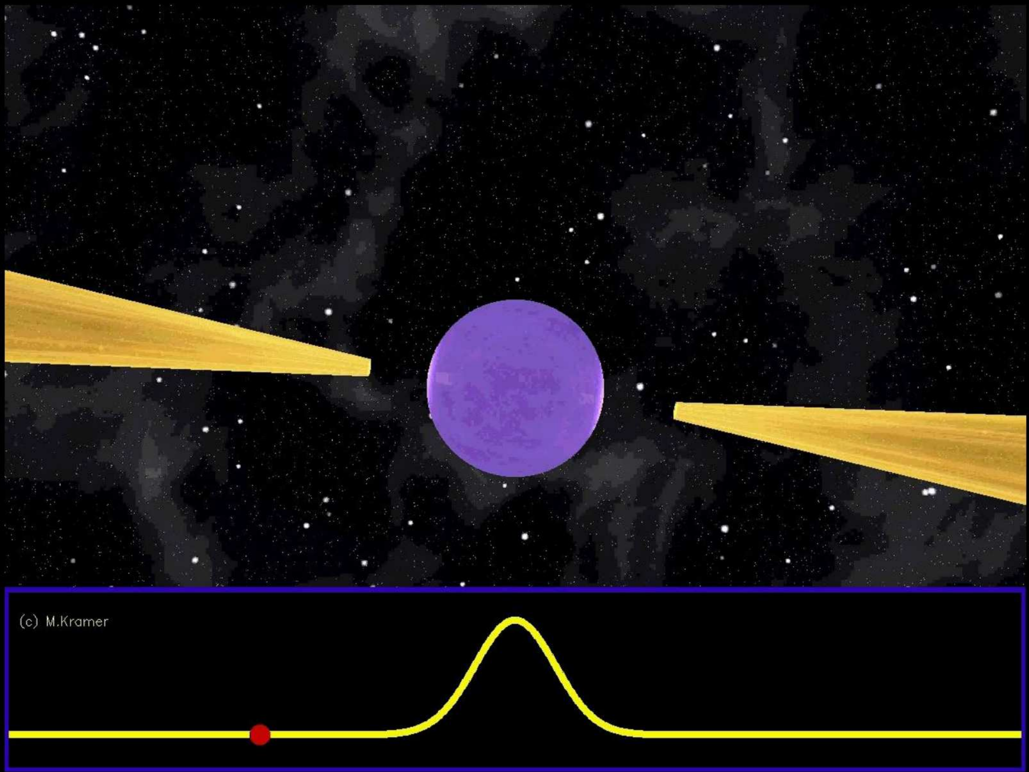


The Event Horizon Telescope Collaboration+19

Bambi&Freese09, Johannsen&Psaltis10, Broderick+14, Psaltis+15, Psaltis,Wex,Kramer18

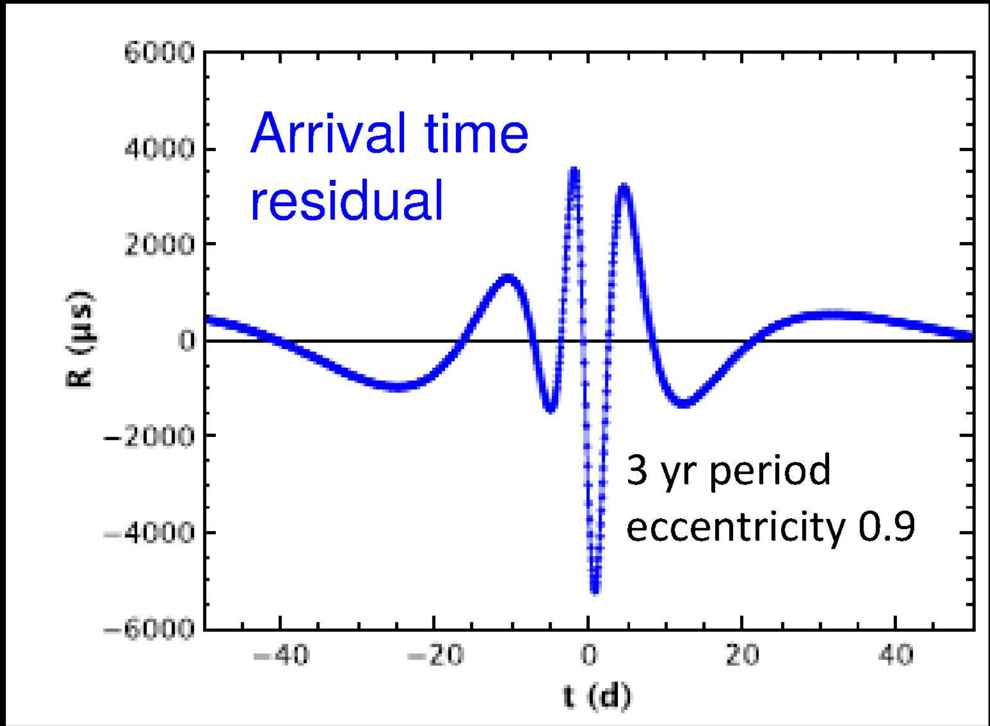
Pulsars – Perfect Timing

Hulse&Taylor76, Kramer+06, Weisberg+10



Exquisite Precision, e.g.
Periastron Advance for Binary Pulsar PSR B1913+16:

4.226598(5) deg/yr



Clean signature of Frame Dragging in Simulated Galactic Center Pulsar

Wex&Kopeikin+99, Liu 2012, Liu+14, Psaltis,Wex&Kramer16

Shadow Imaging and Pulsar Search are Difficult in the GC

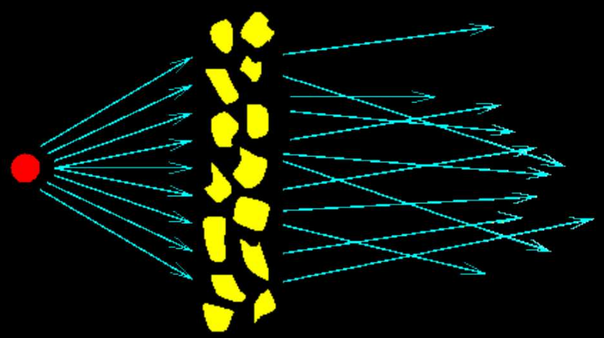
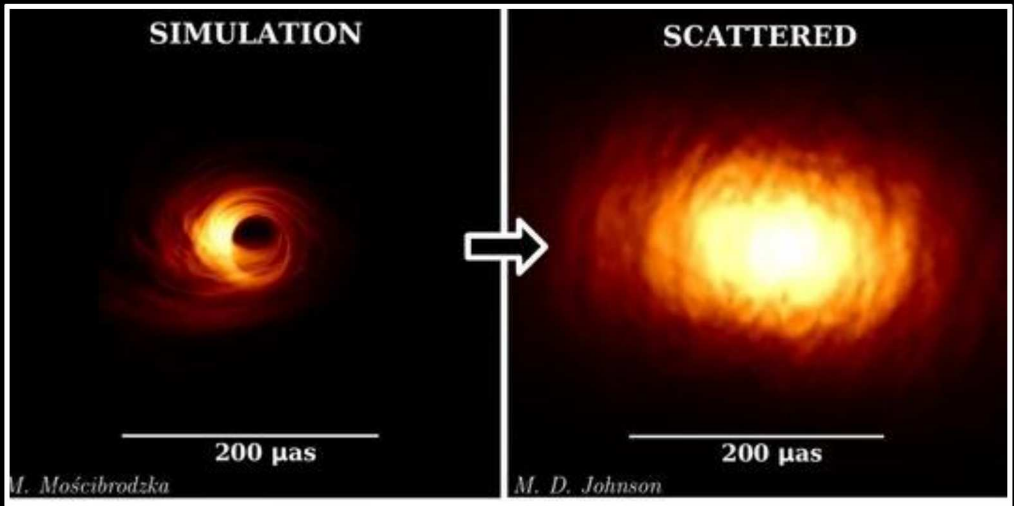
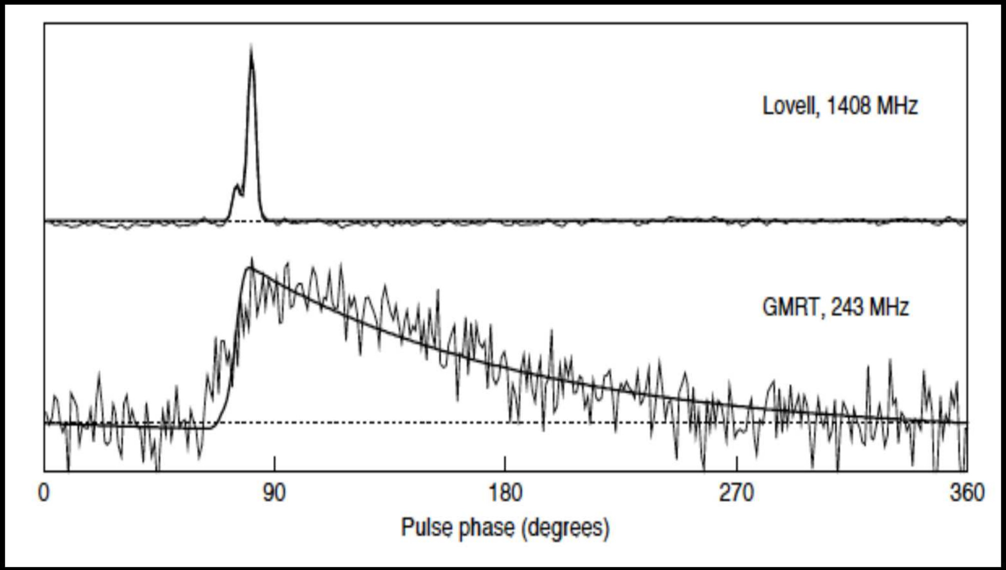


Image Blur



Pulse Smearing



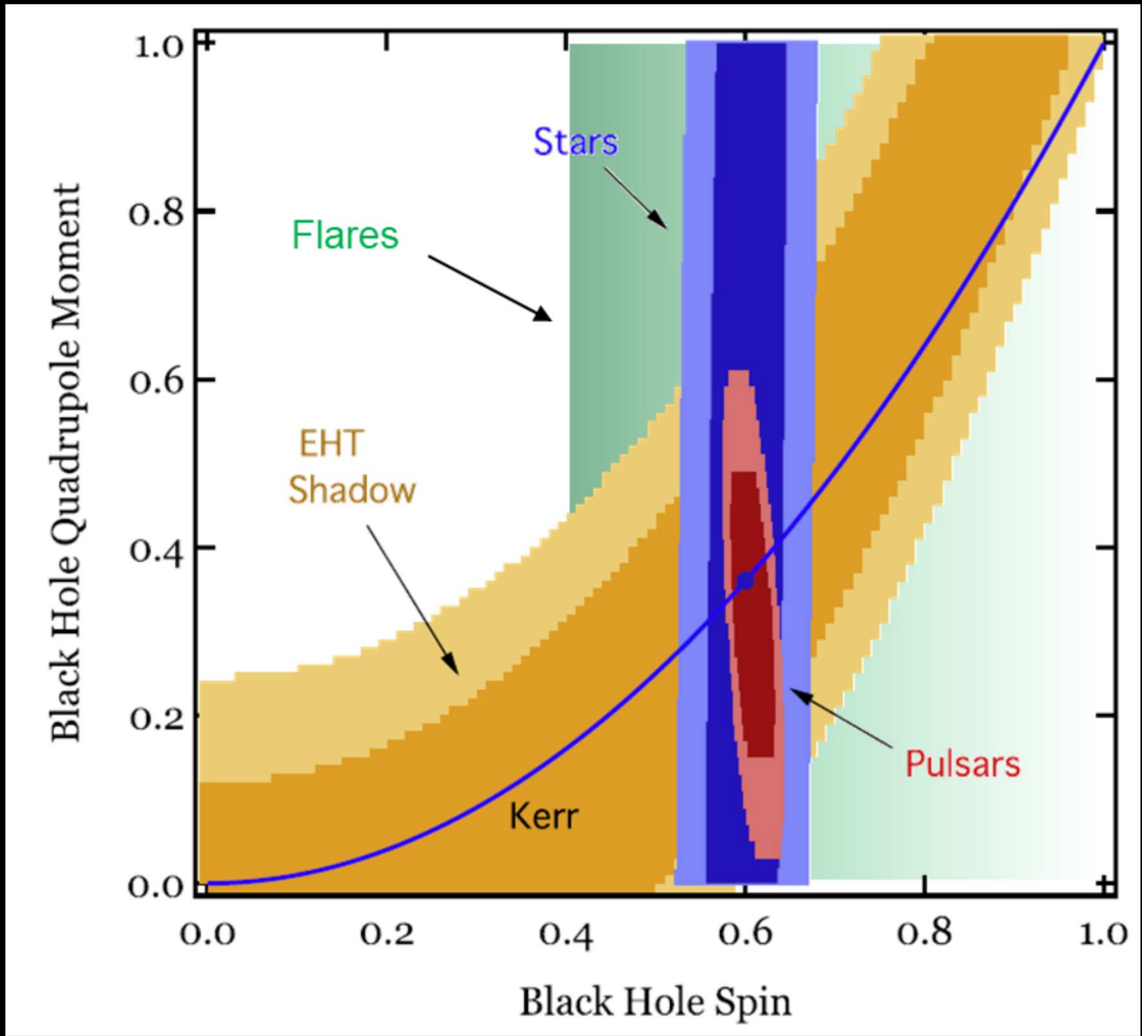
Difficult for Imaging because of Atmosphere

Need for High Frequencies

Pulsars Get Very Faint

Löhmer+01, Issaoun+19

Key will be to Bring Together Hard, Independent Numbers



Adapted from Psaltis,Wex&Kramer16

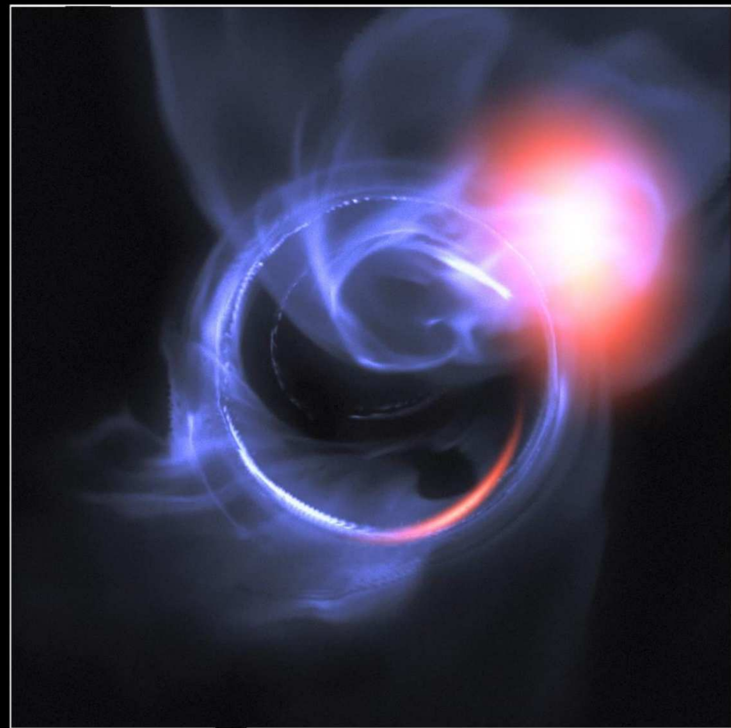
Thank You for Your Attention

Is General Relativity the correct theory ?

General Relativity is so far the correct theory

Is the mass concentrated within Schwarzschild radius ?

The mass is concentrated at least within 3-5 Schwarzschild radii



Credit: ESO/Gravity Consortium/L. Calçada/N. Risinger

Credit: ESO/M. Kornmesser