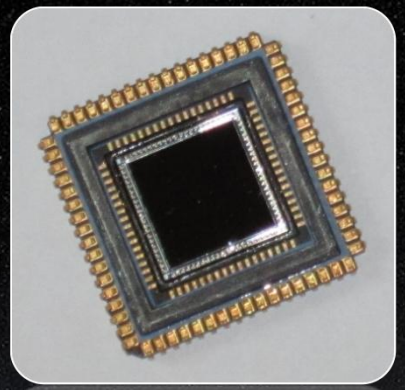
Infrared Observations of the Galactic Center Black Hole

GRAVITY(+) Collaborations

Infrared Observations of the Galactic Center Black Hole

Infrared

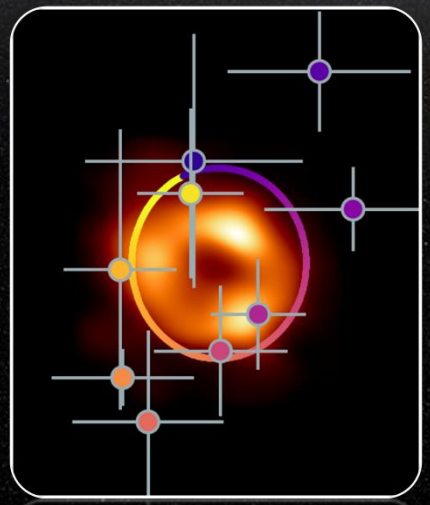


Adaptive Optics

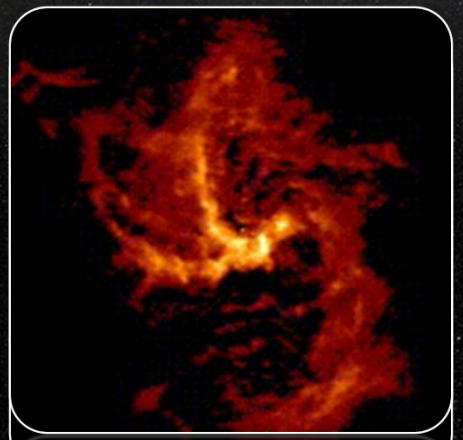
Imaging Spectroscopy

(In)Visible

Black Hole



Radio

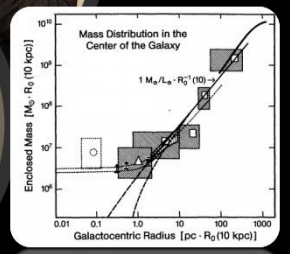


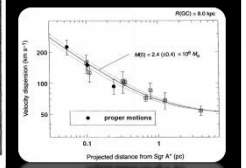
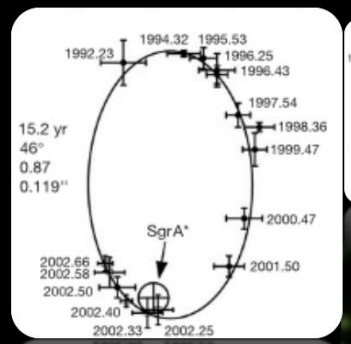
X-Rays

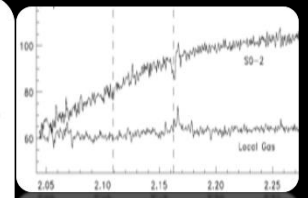
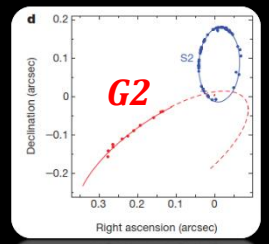
Slide from Nobel Lecture by R. Genzel

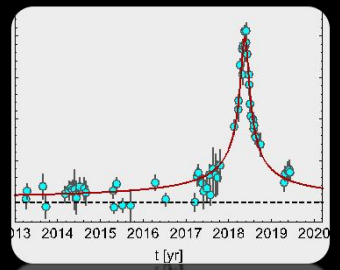
A fourty year Journey

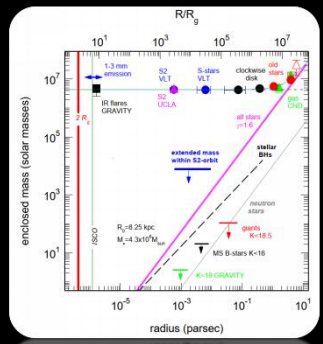


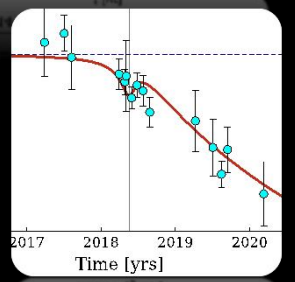


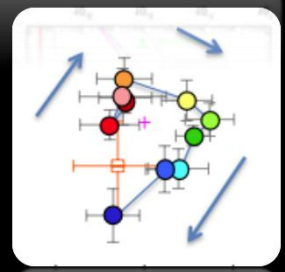
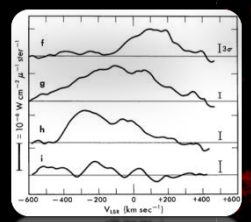
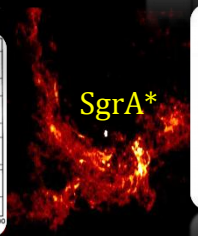



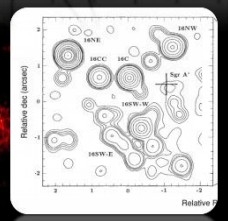
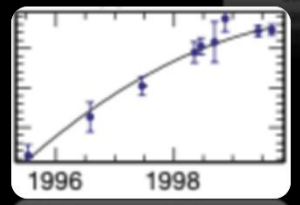



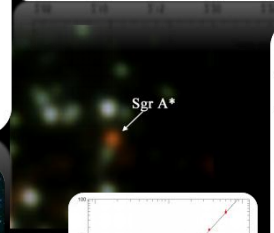


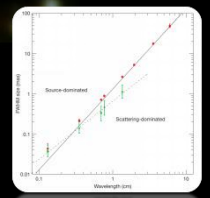
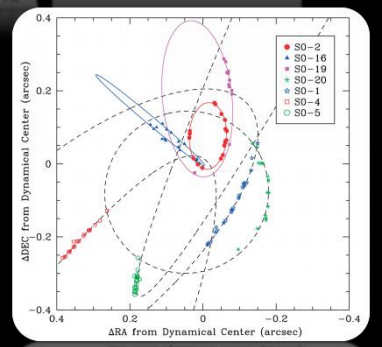


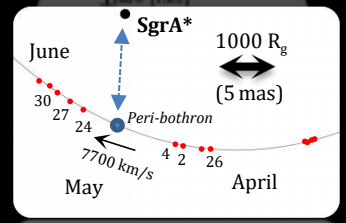




1970 1985 1992 1996-98 2002 2003 2005 ..... 2017 2018 2020

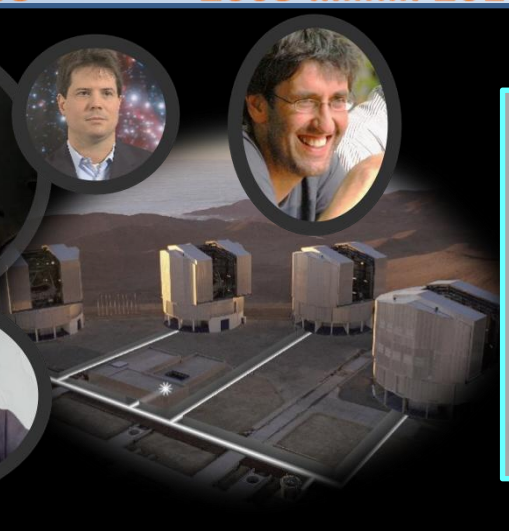
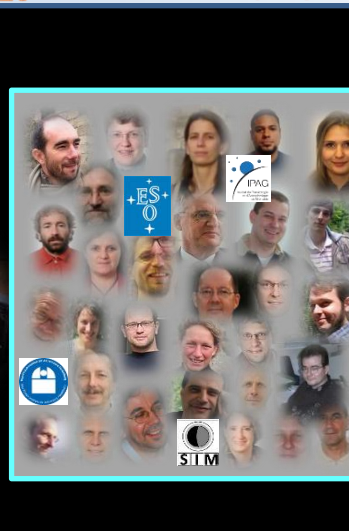


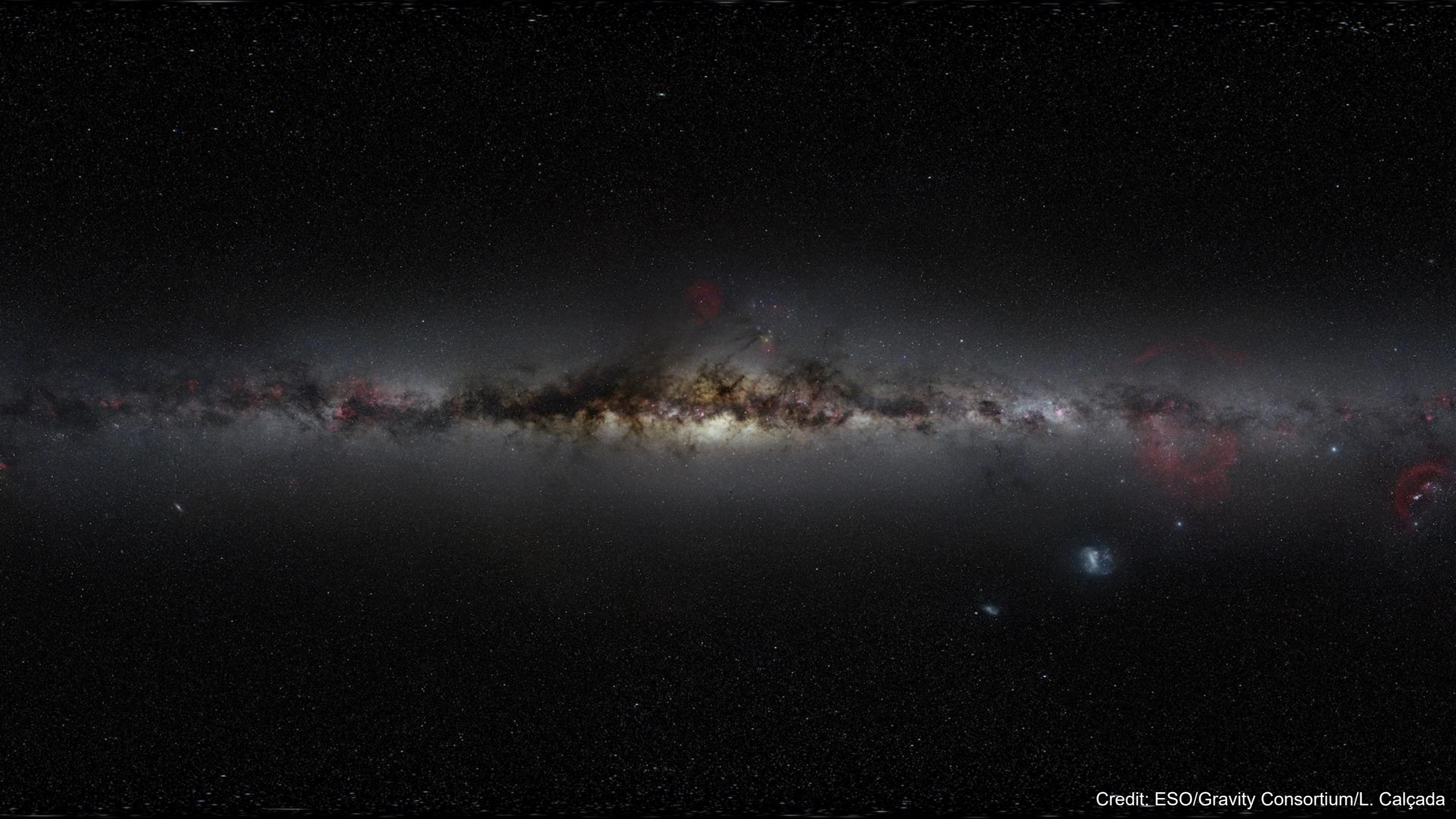




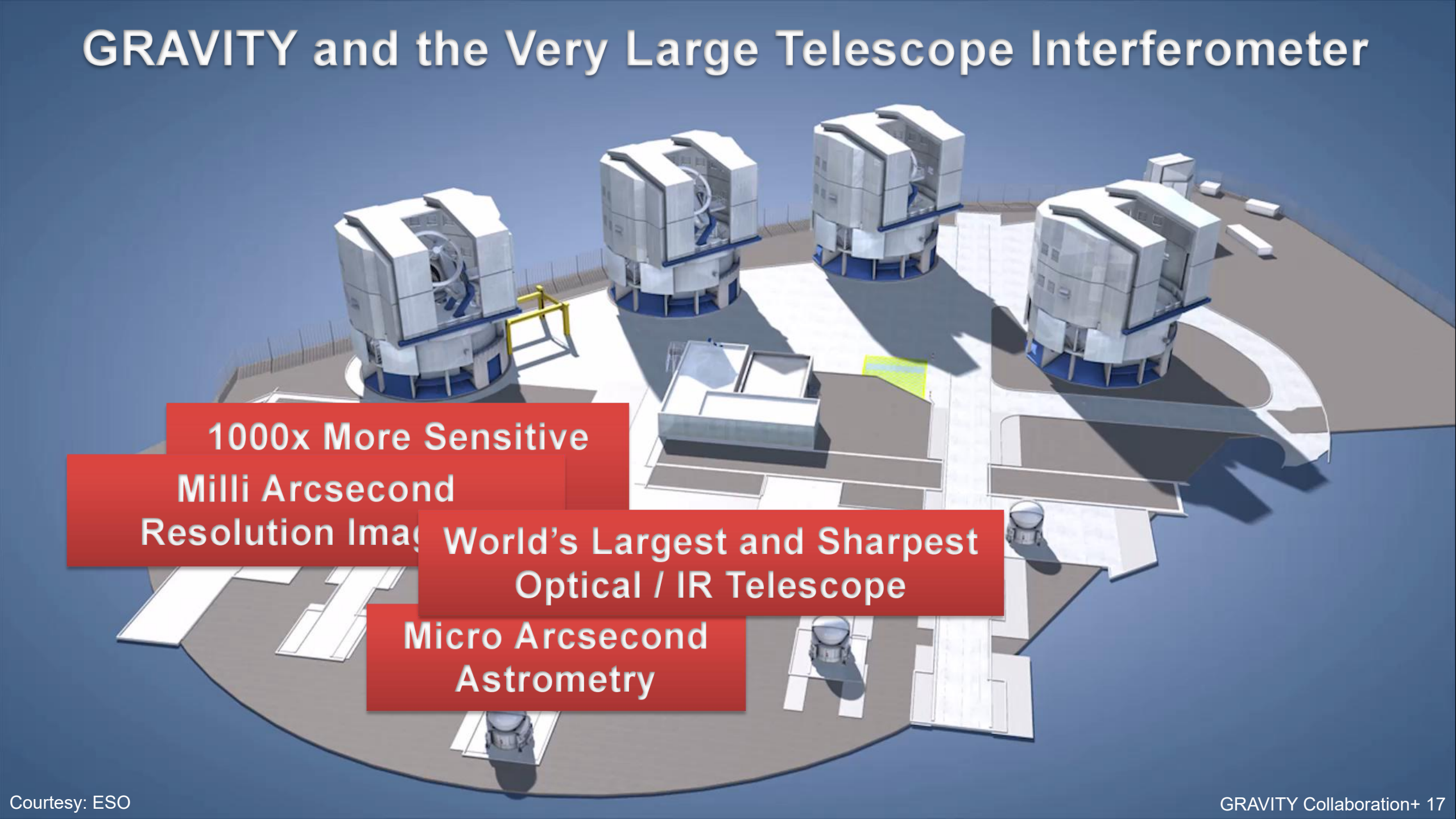




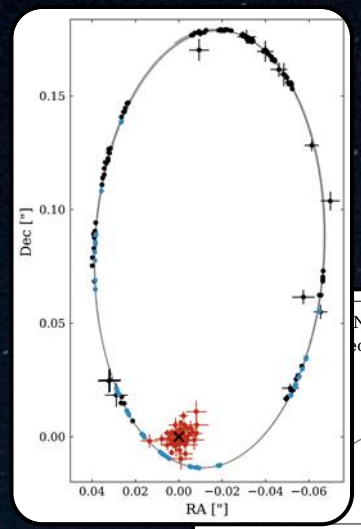


Credit: ESO/Gravity Consortium/L. Calçada

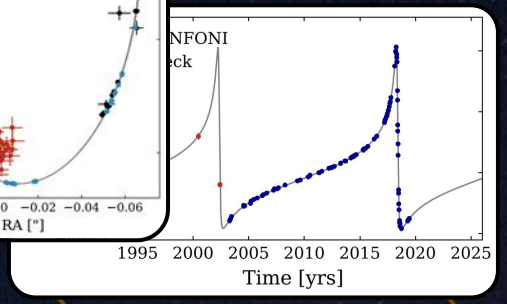
GRAVITY and the Very Large Telescope Interferometer

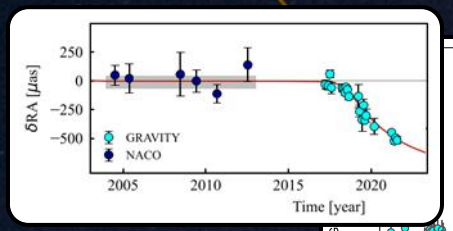


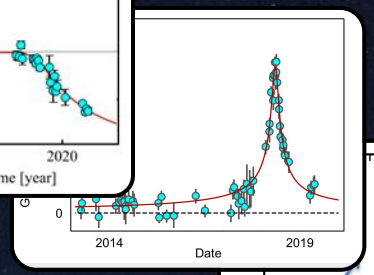
Courtesy: ESO

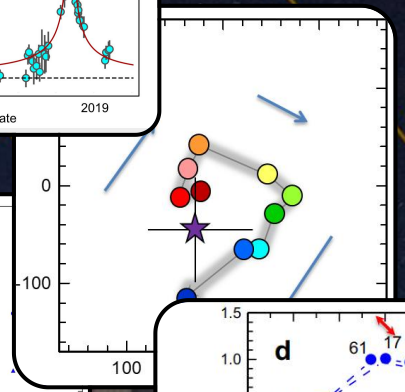
Testing the Black Hole Paradigm for SgrA*

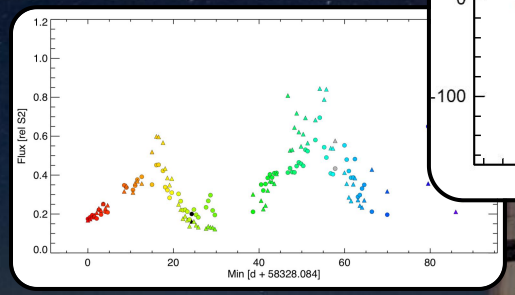


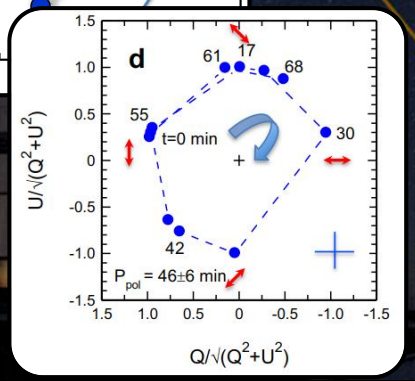












Mass M = 4.30 x 10^6 $M_\odot$

Distance R_0 = 8280 pc
+/- 0.1%$_{stat}$ +/- 0.3%$_{sys}$

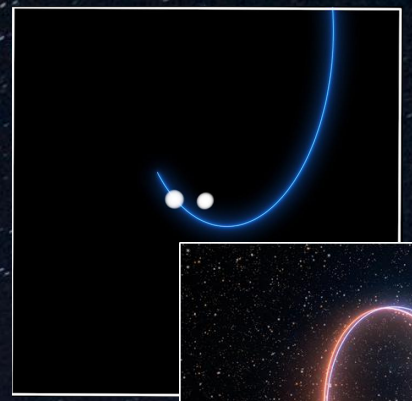
→ Radius R_g/R_0= 5.125 μas
± 0.009$_{stat}$ ± 0.020$_{sys}$

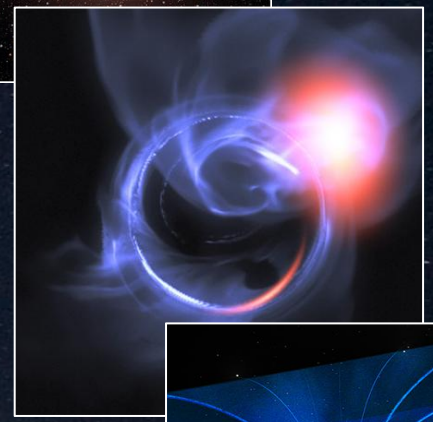
GR f_G = 0.99 ± 0.05
Tests f_{SP} =1.15 ± 0.1

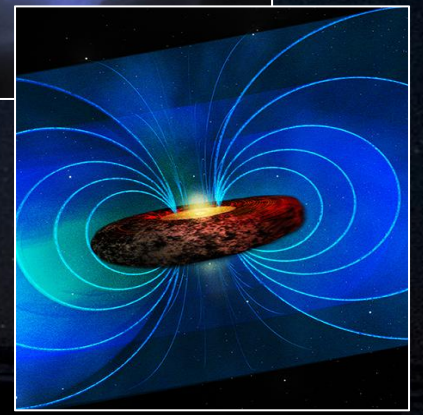
Compactness
Mass within 6-10 R_g

Low inclination ≲ 30°

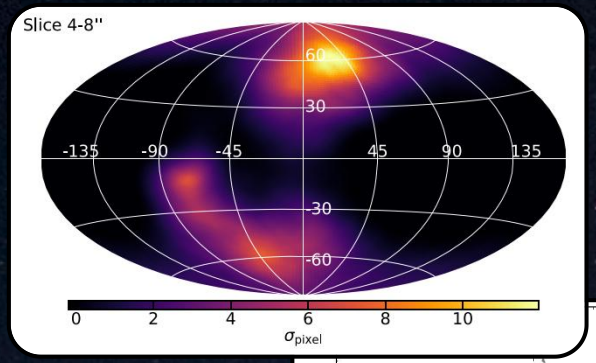
Magnetically dominated MAD

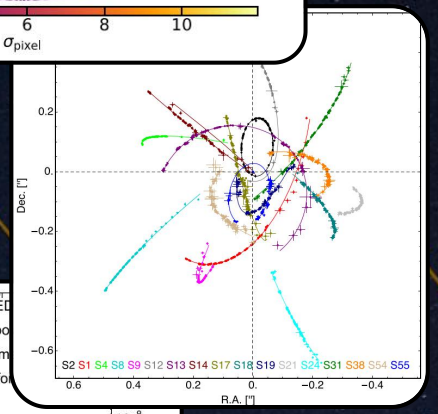


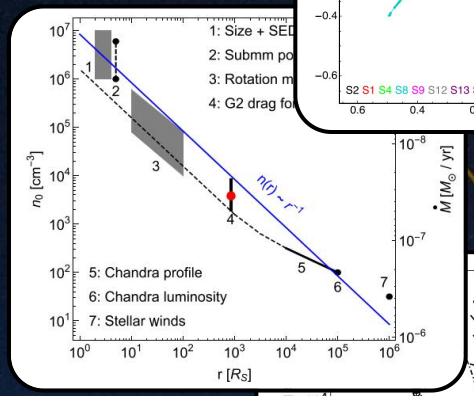


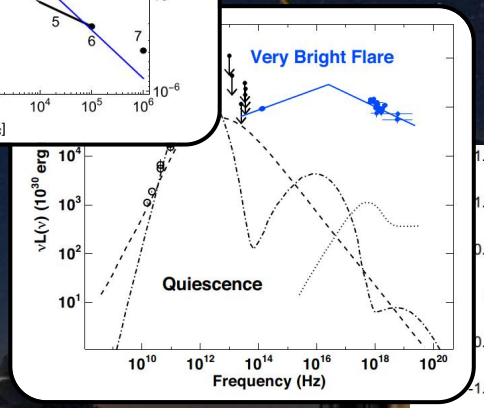


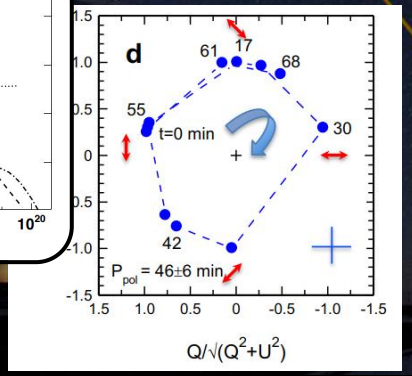
Black Hole Astrophysics

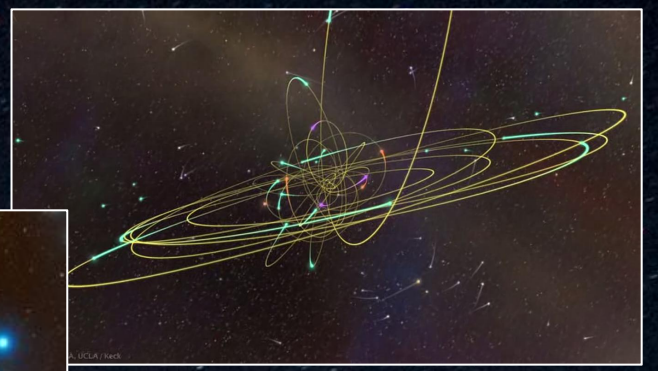


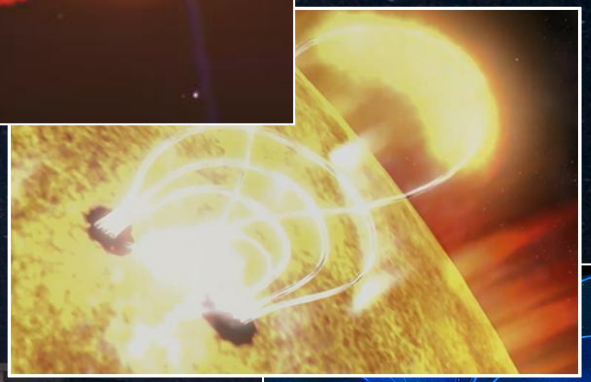


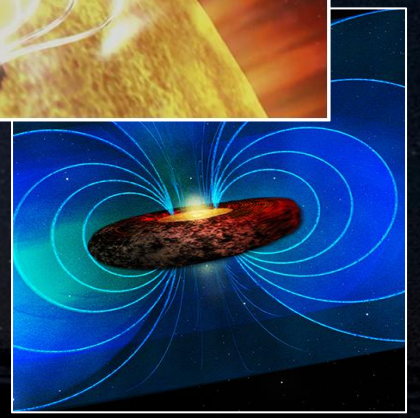












Stellar discs
10^{-3} $M_\odot$ /yr winds
Clockwise motion

S-Stars
Thermalized orbits

Accretion
Fed by gas clouds
few 10^{-8} $M_\odot$ /yr

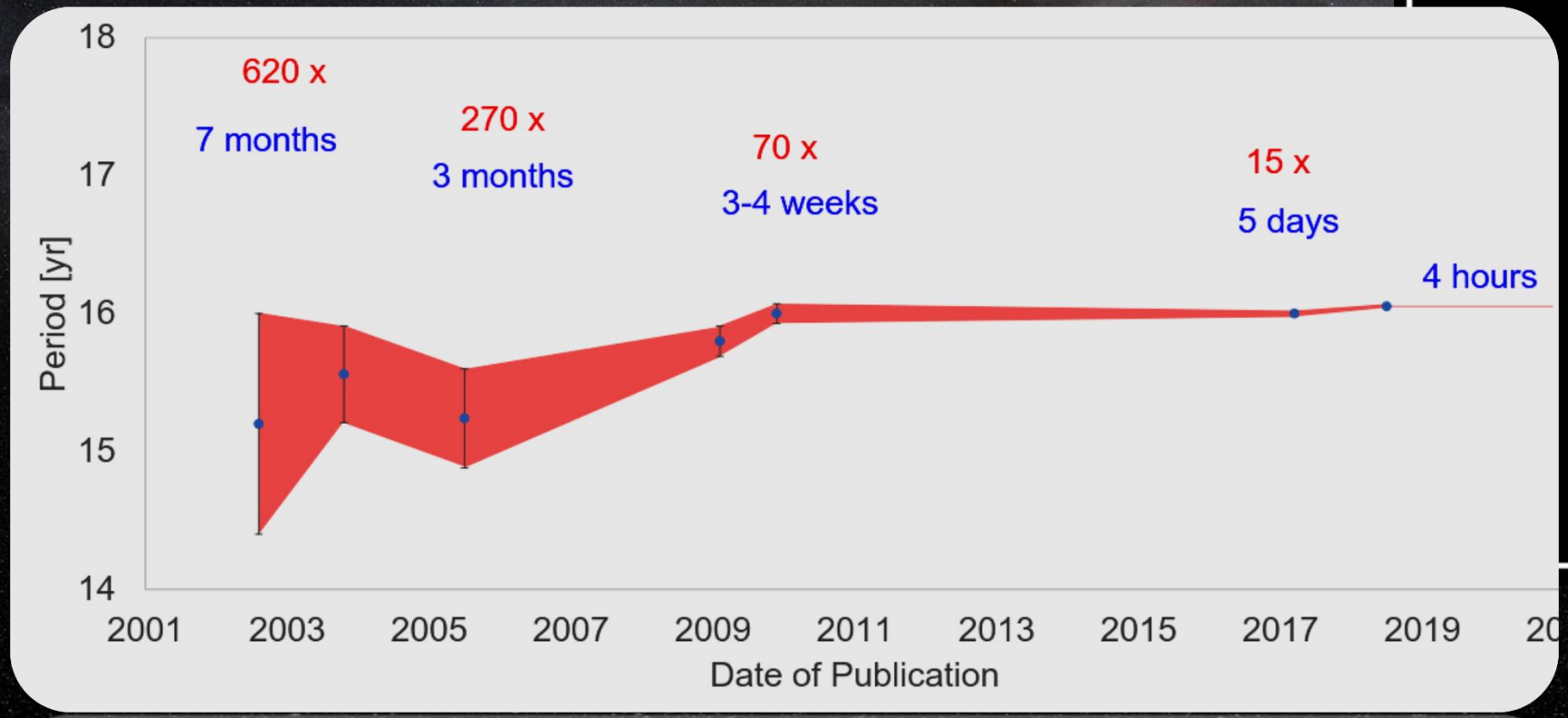
Flare physics
Synchrotron emission
B ~ 30 G, γ ~ up to 10^5

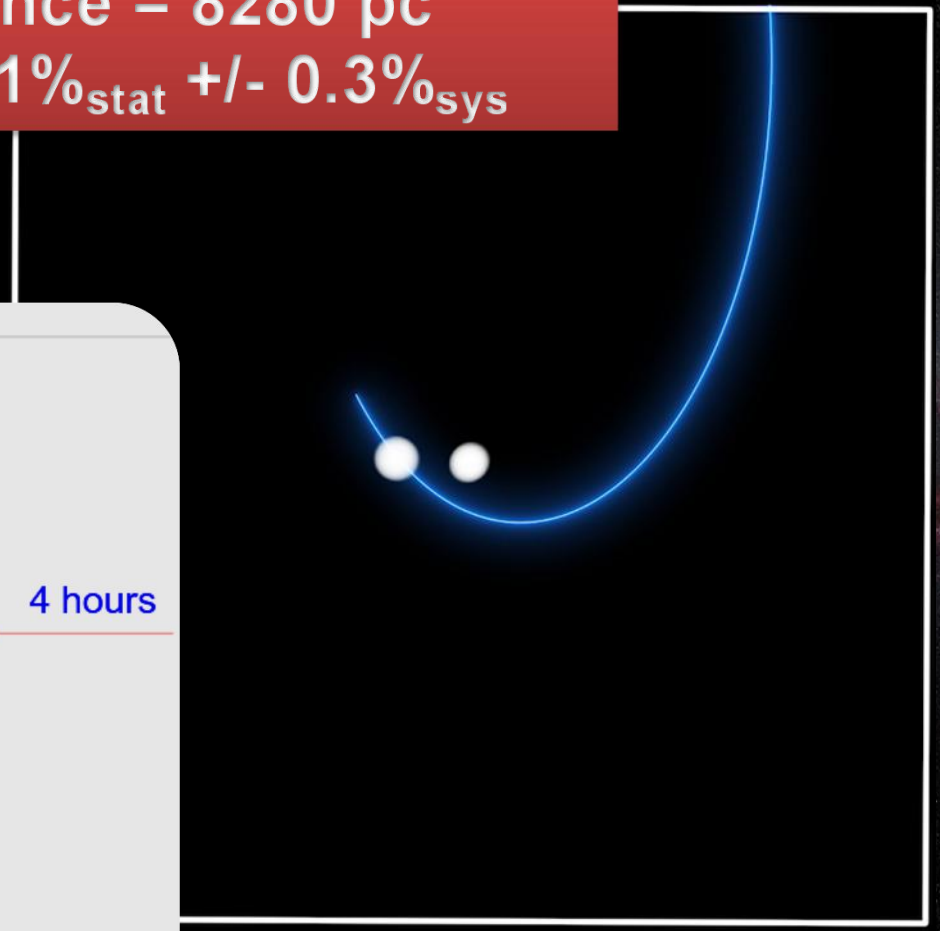
Magnetically dominated MAD

Precision Testing the Black Hole Paradigm

Mass = 4.300 x 10^6 $M_\odot$
Distance = 8280 pc
+/- 0.1%$_{stat}$ +/- 0.3%$_{sys}$

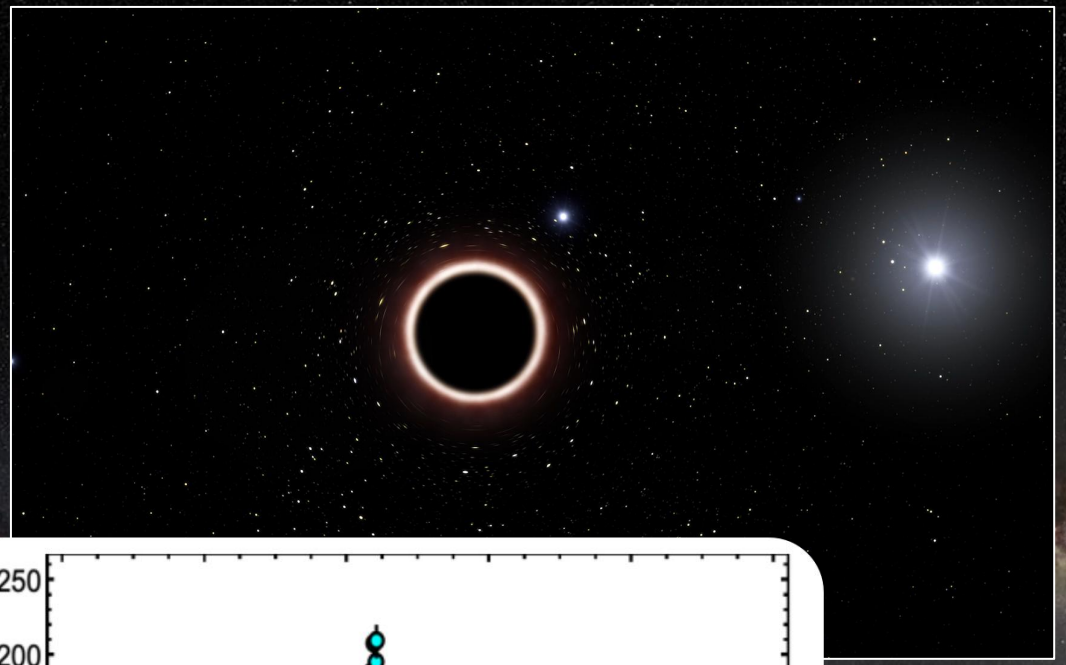
Improvement in orbital period by factor 1000

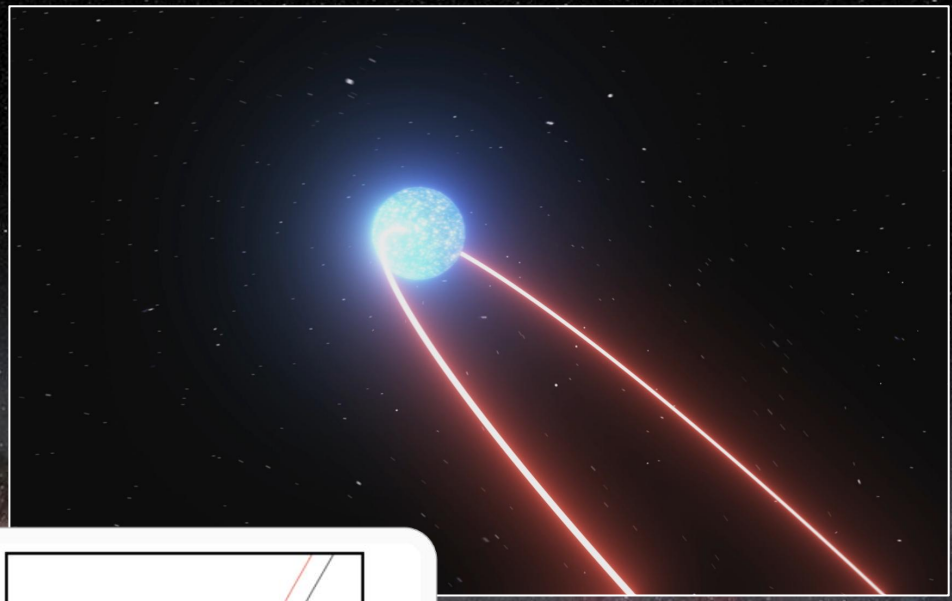


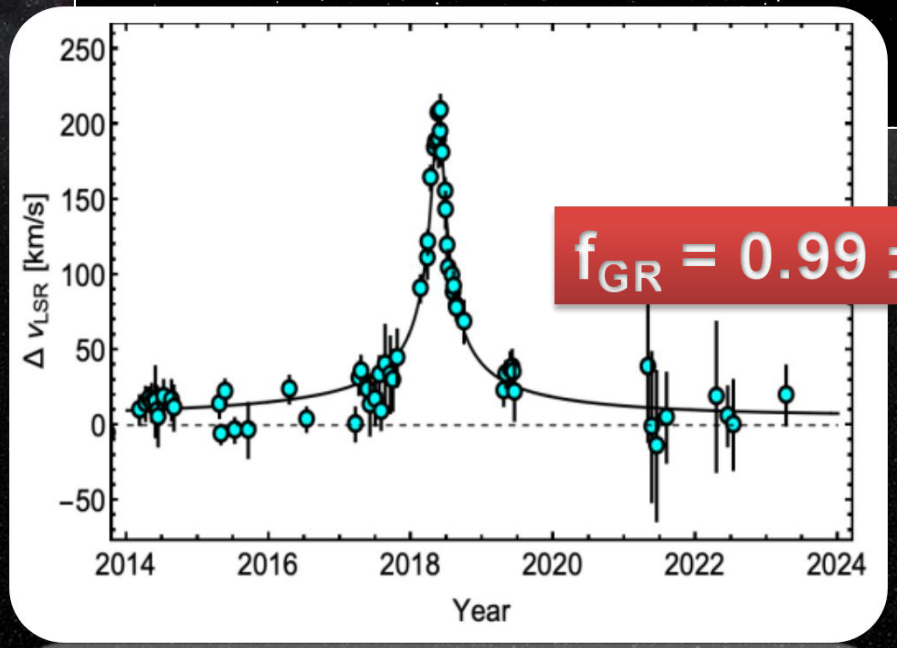


Eckart+ 92, Genzel+ 97, Ghez+ 98,00, Schödel+ 02, Ghez+ 03, Eisenhauer+ 03,05, Gillessen + 09,17, Boehle+ 16, GRAVITY collaboration+ 17…24

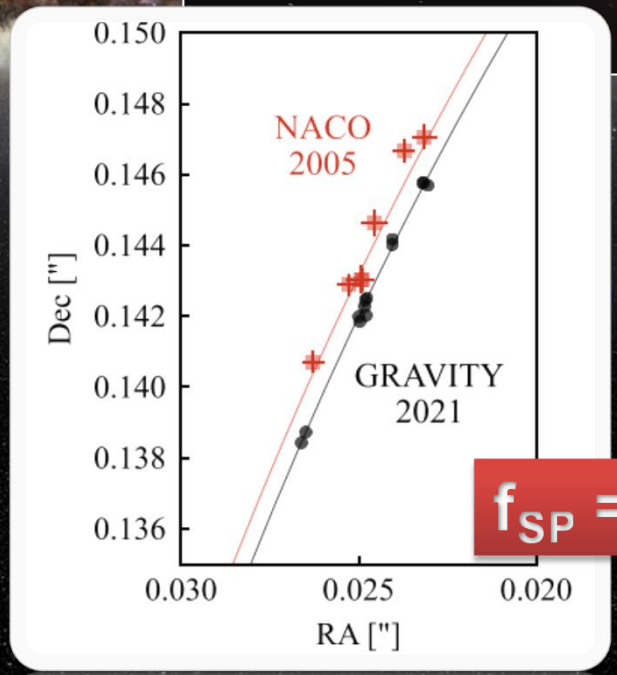
Gravitational Redshift and Schwarzschild Precession







$f_{GR} = 0.99 \pm 0.05$



$f_{SP} = 1.15 \pm 0.1$

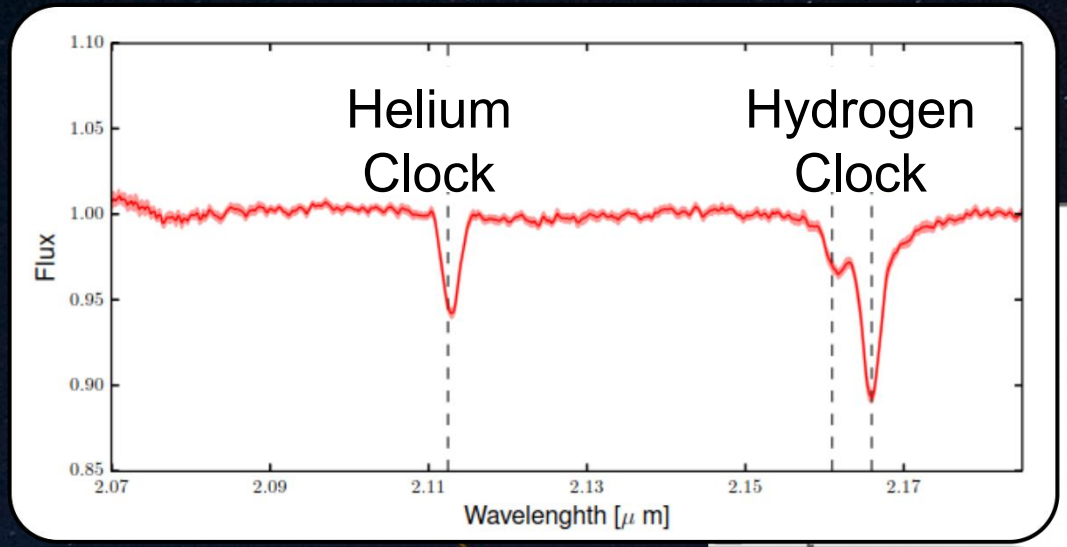
GRAVITY Collaboration+ 18…24, Do+ 19

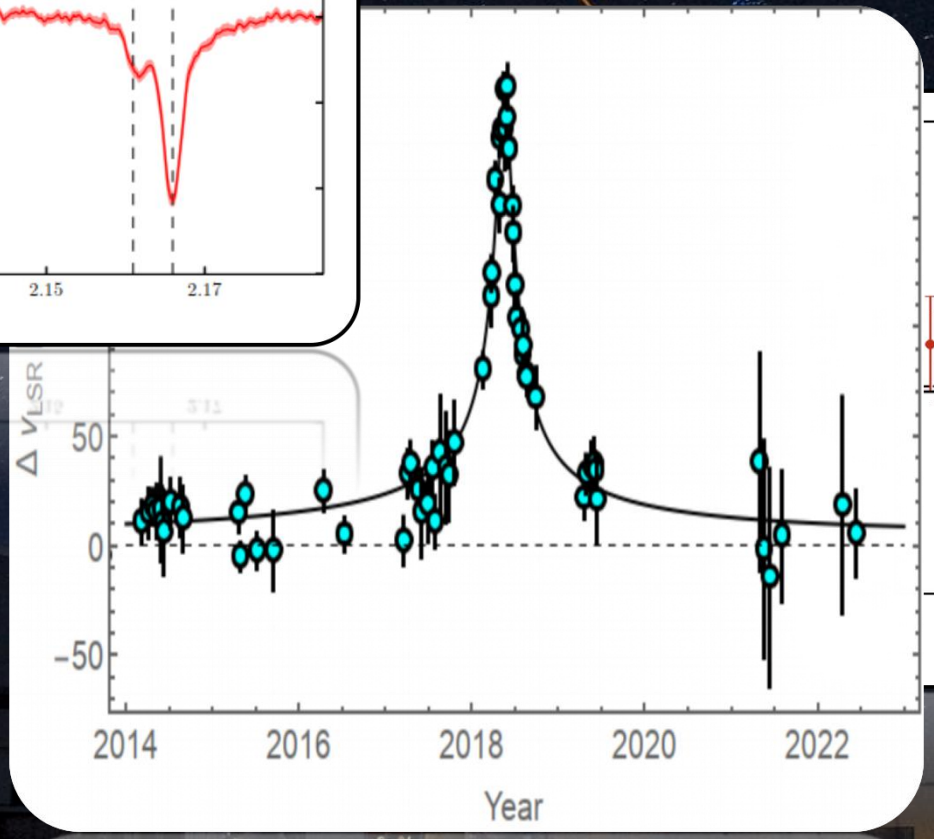
GRAVITY collaboration+ 20…24

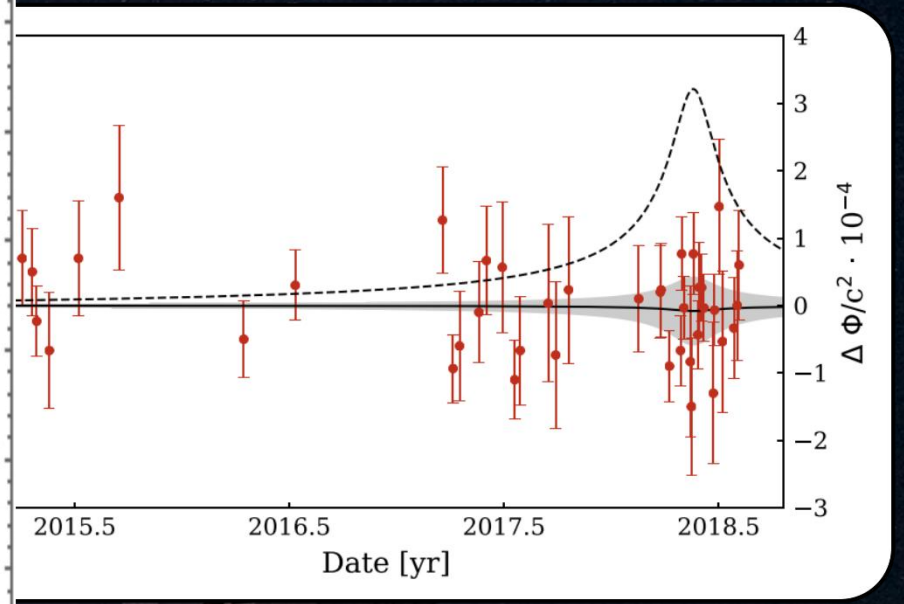
Equivalence Principle

$\Delta\alpha/\alpha = 2.4 \pm 5.1$ %

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







GRAVITY Collaboration+ 19, Hees+ 20 for Limits on Variation of Fine Structure Constant

Constraints on Higher Order Terms and Metrics

Gravitational redshift f_{RS}

Equivalence principle $1+\Delta\beta$

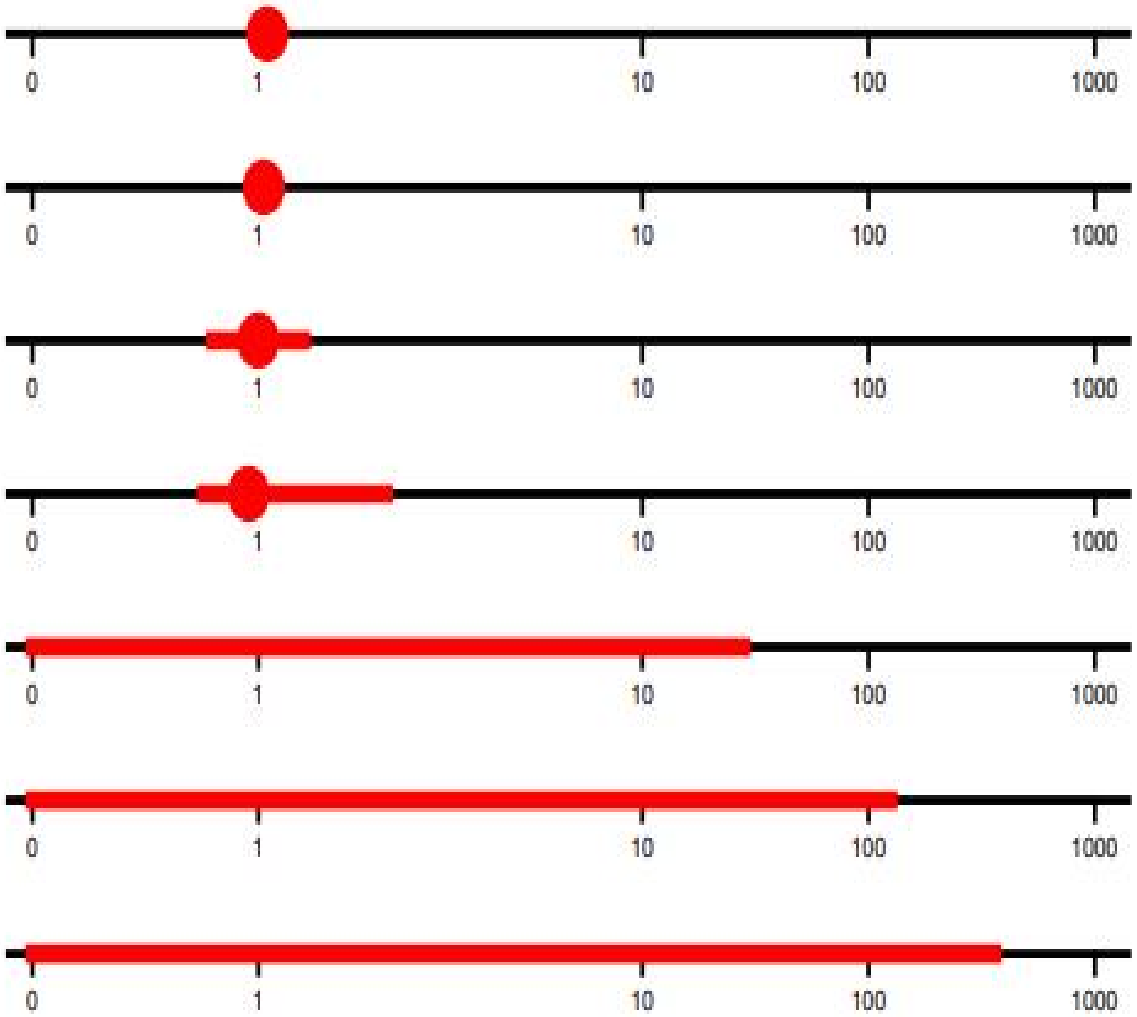
Schwarzschild precession f_{SP}

P_{flare}/P_{Kepler}

White hole metric α_{WH}/R_G

Black hole spin X_{spin}

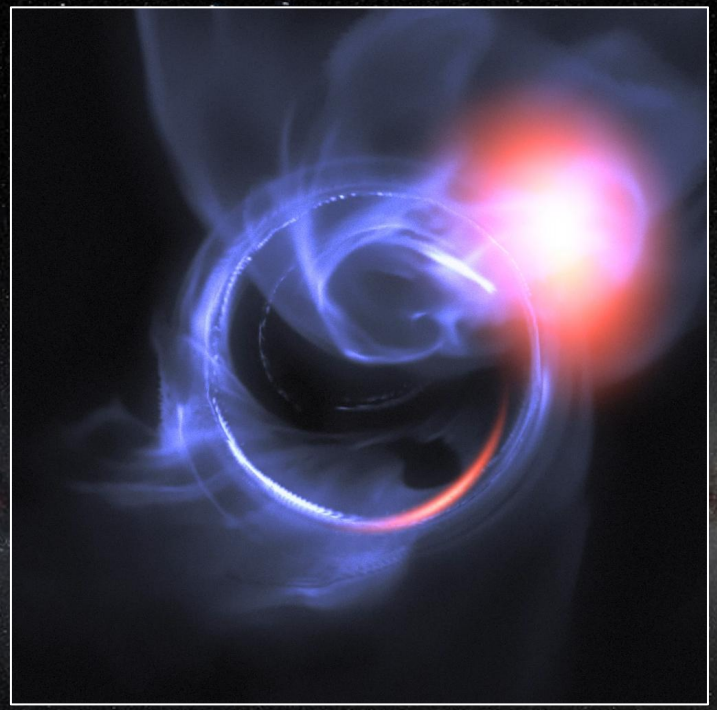
2PN term f_{2PN}



White Hole: Simpson & Visser 19, della Monica & de Martino 21, 2PN order: Valtonen+ 10, Blanchet+ 14, Spin: Faye+ 06, Will 08, Valtone+ 10

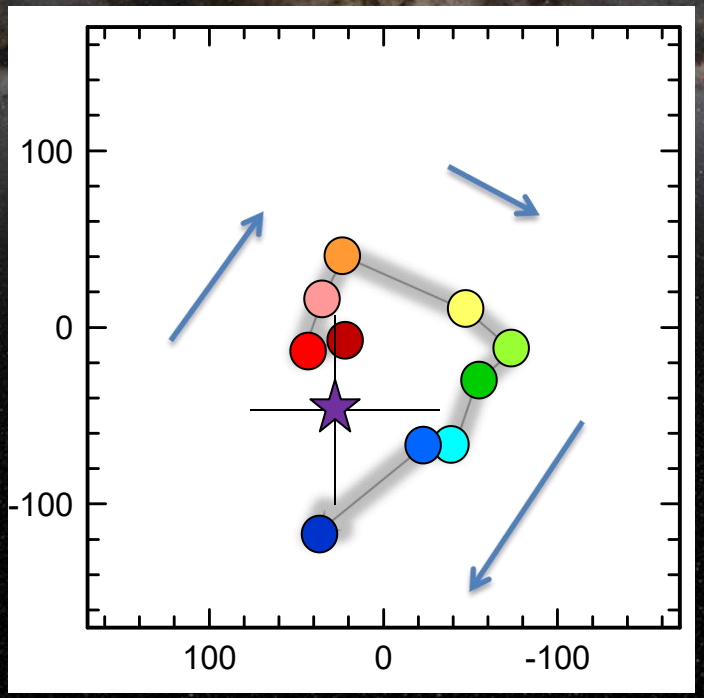
Orbital Motion Close to the Event Horizon

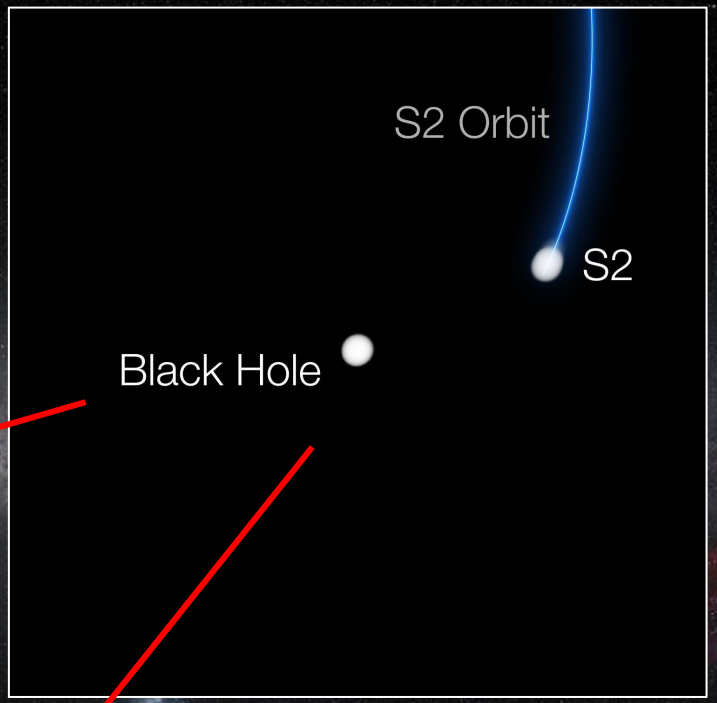
Hot spot



Low inclination
Magnetically dominated accretion

In 45 minutes round the black hole
30% speed of light

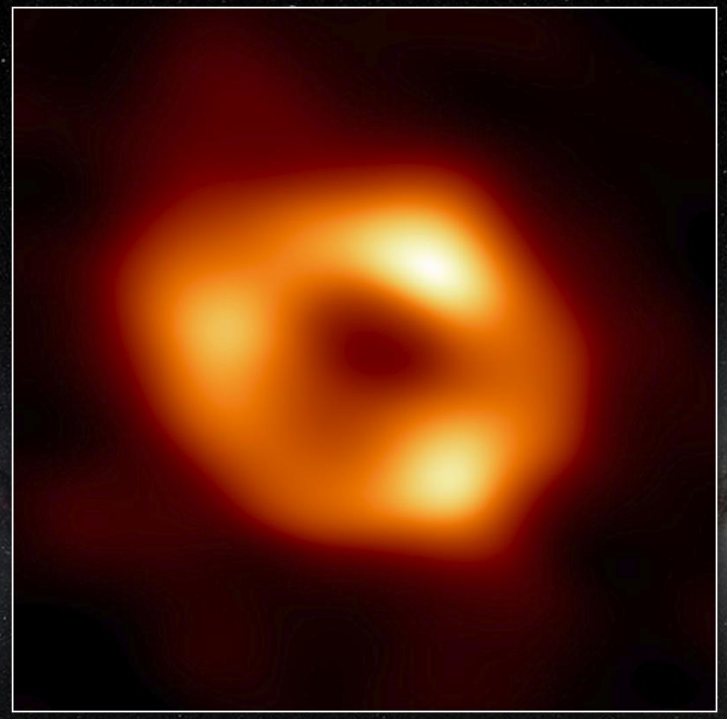




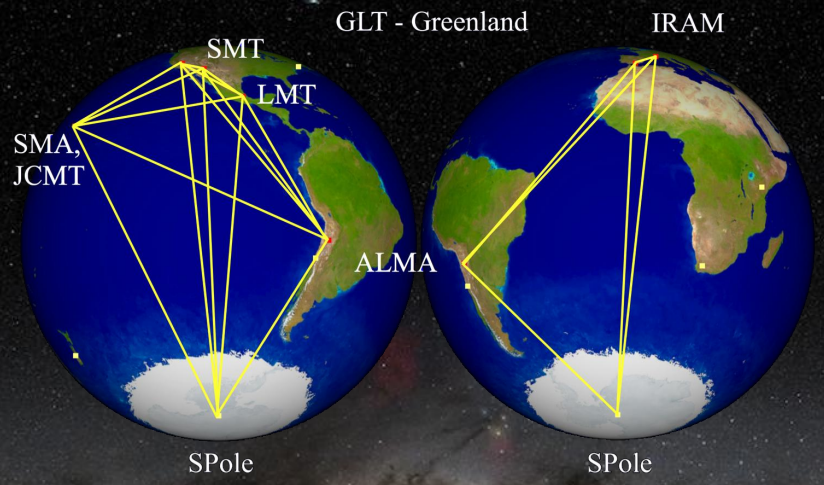
GRAVITY Collaboration+ 18

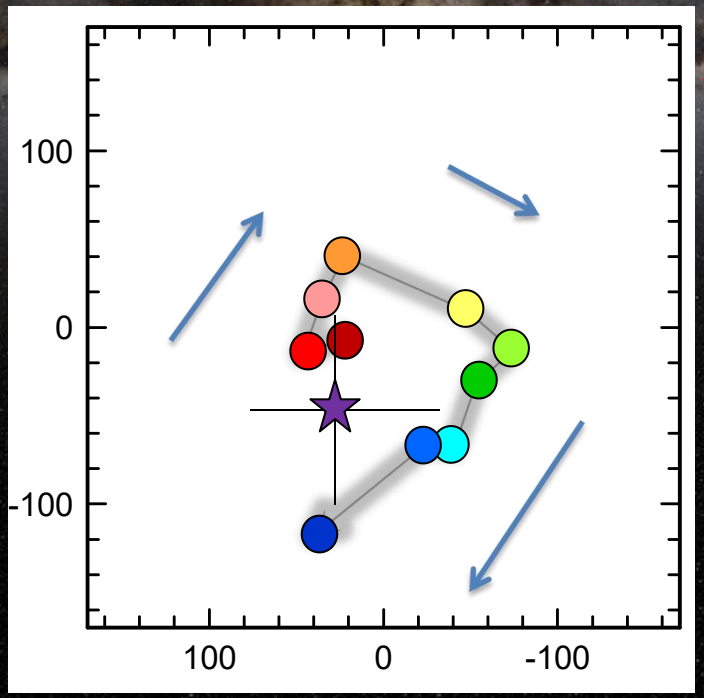
Shadow of the Black Hole

SgrA*

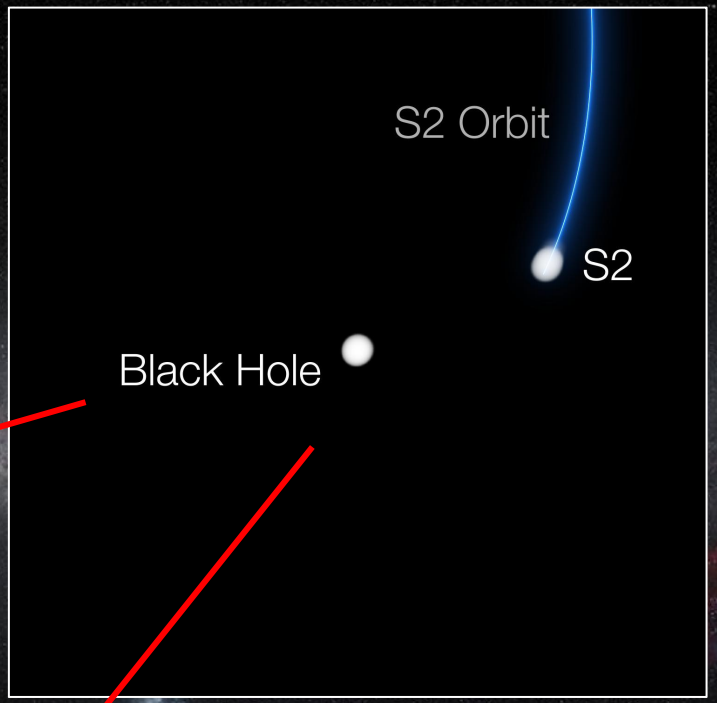


EHT collaboration 22



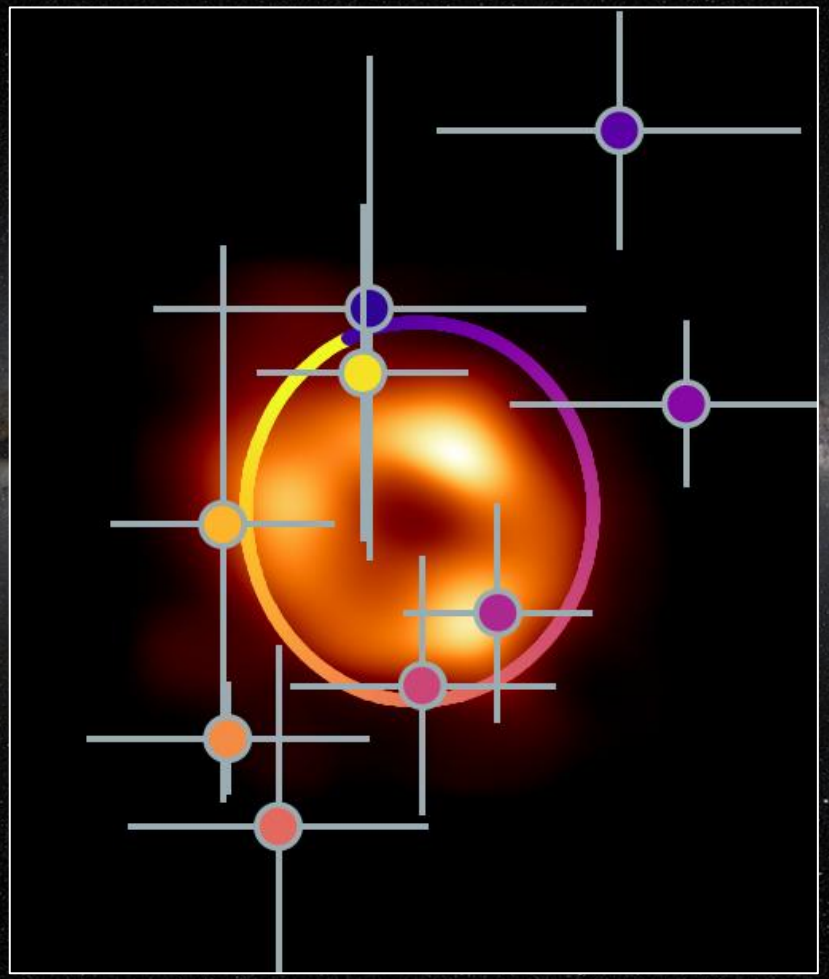


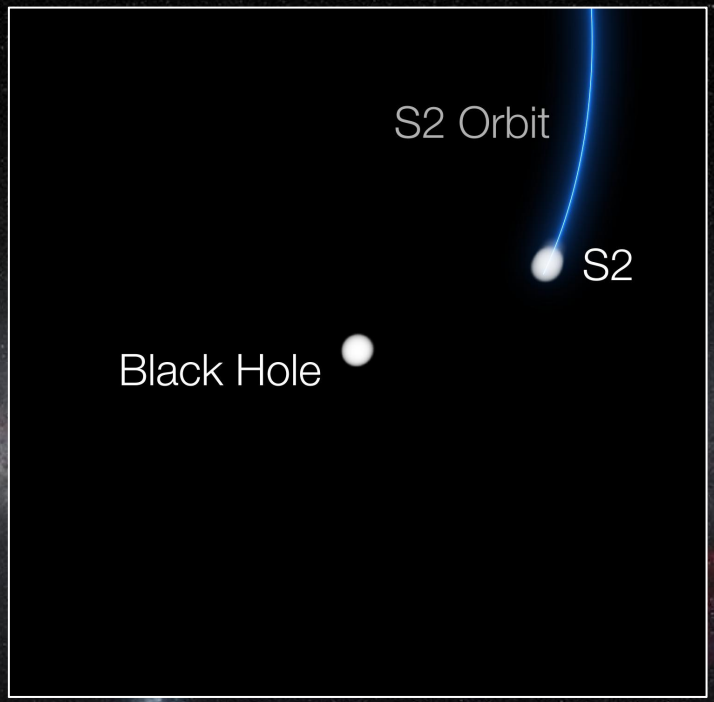
GRAVITY Collaboration+ 18



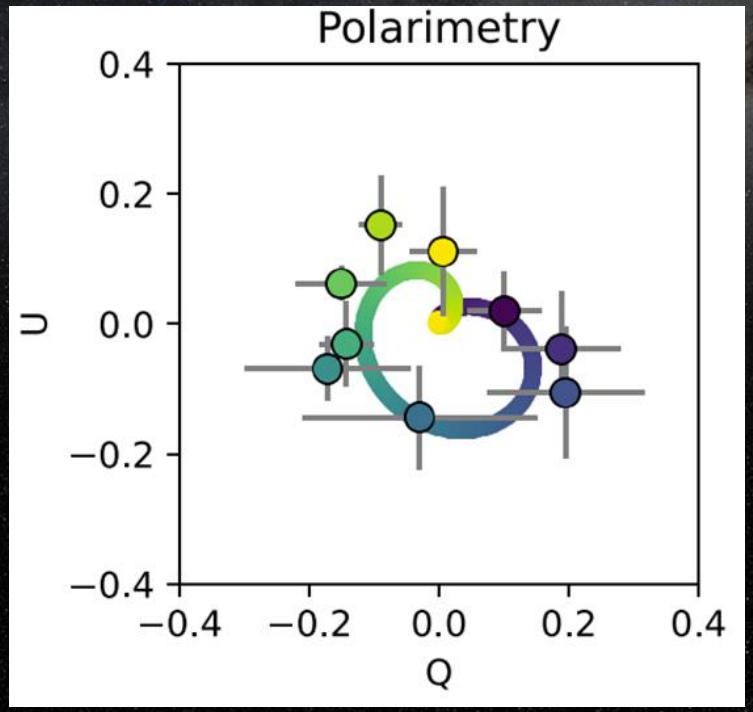
More than Ten Flares with Astrometry or Polarization

4 flares astrometry





6 flares polarisation



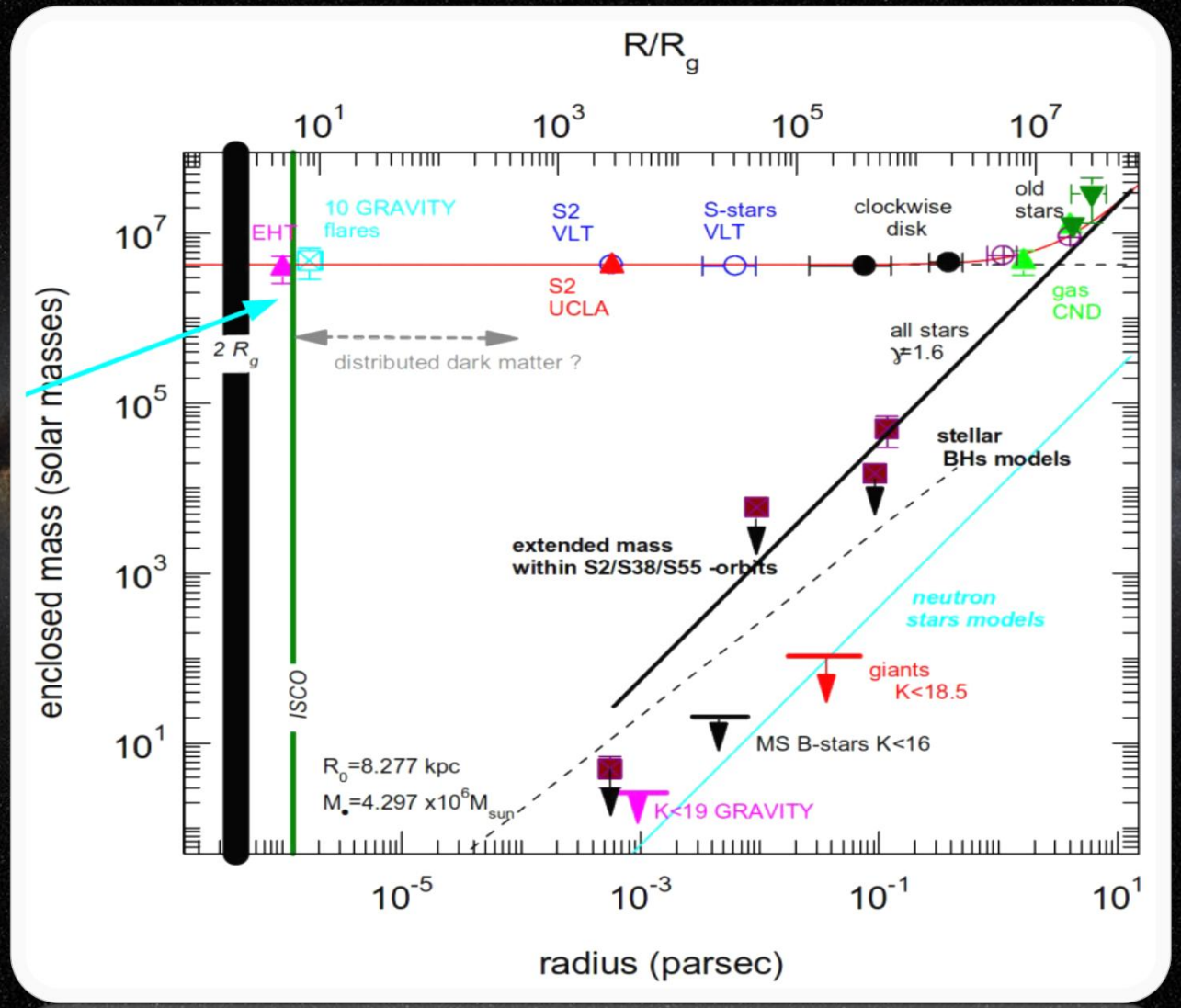
EHT image

GRAVITY Collaboration+ 18 … 23, EHT Collaboration 22+

Mass is Enclosed in 3 – 5 Schwarzschild Radii

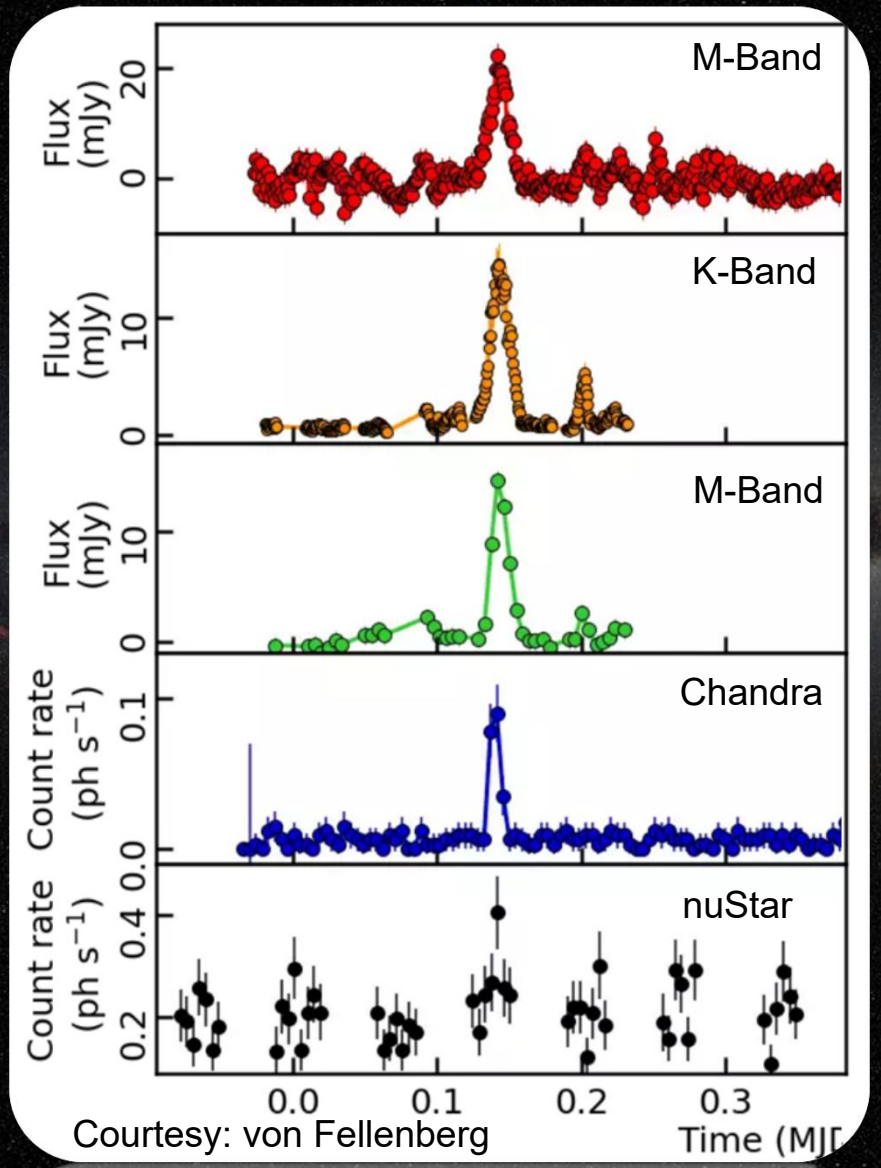
Joint fit

$$M_{enc} = 4.2^{+1.0}_{-0.9} \times 10^6 M_\odot$$
$$R = 8.9^{+1.5}_{-1.2} R_g$$

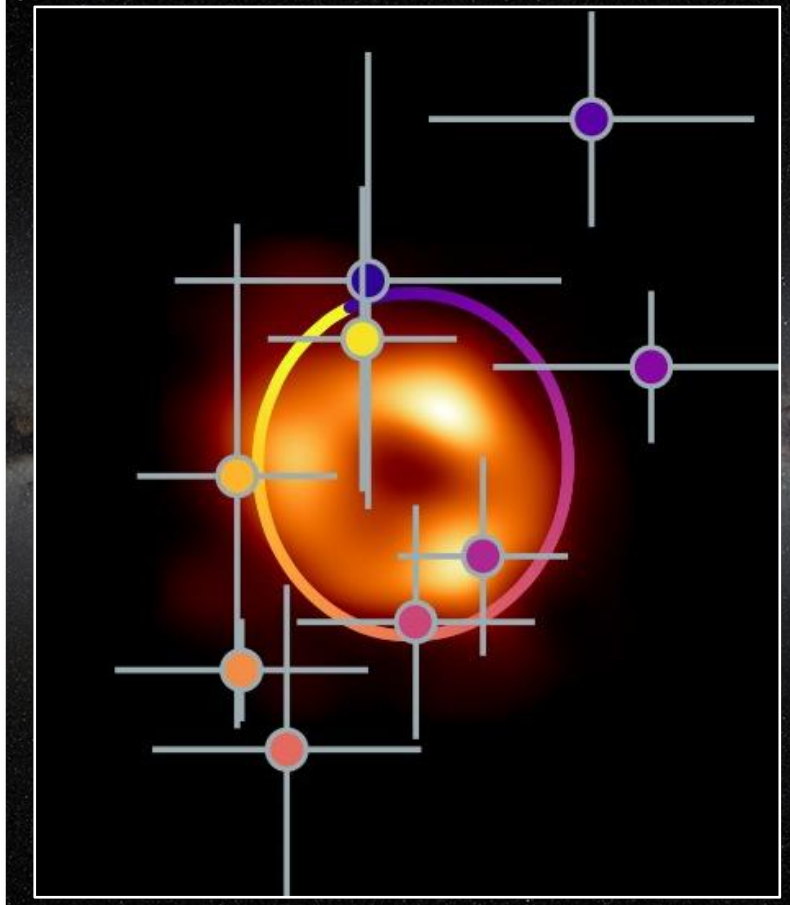


GRAVITY Collaboration+ 18…23, EHT Collaboration 22+

Polarization and Magnetic Field: Accretion Physics

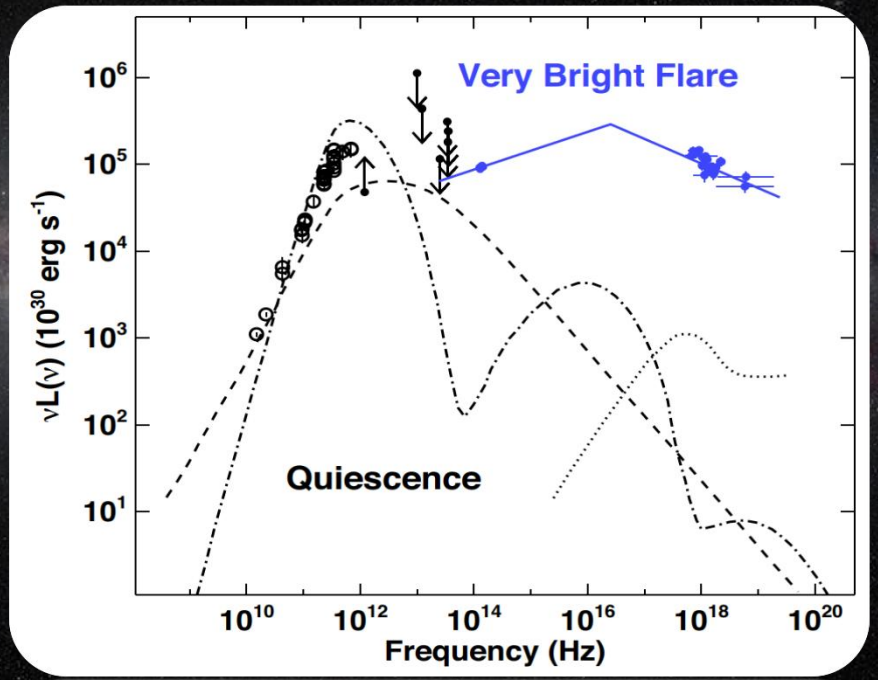


Courtesy: von Fellenberg



GRAVITY Collaboration+ 18,…,23
EHT Collaboration 22,…

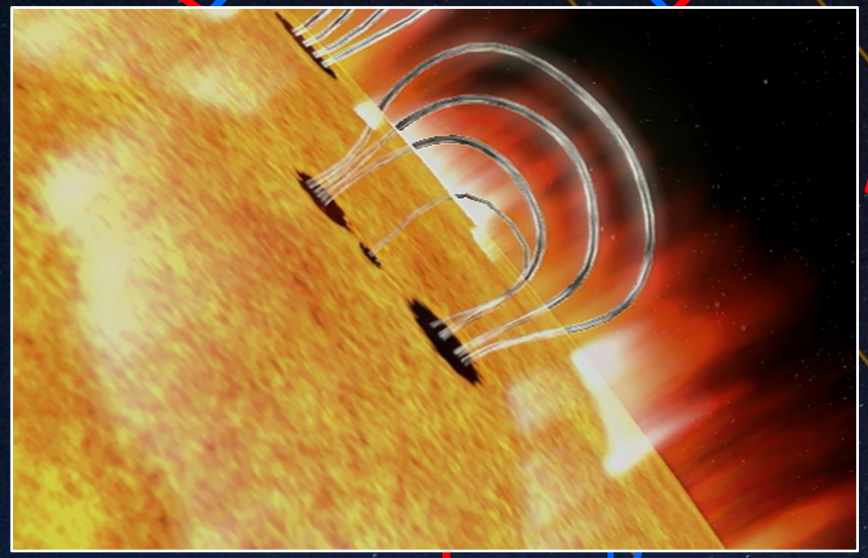
Synchrotron emission
Magnetic field **B ~ 30 G**
Lorenz factor up to **γ ~ 10^5**

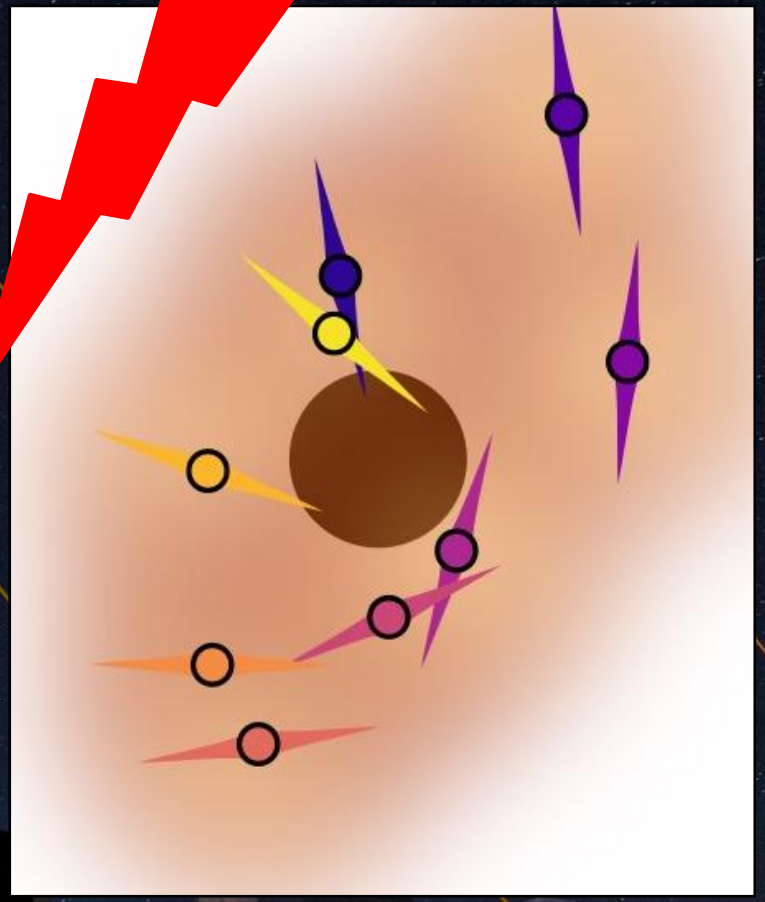


Baganoff+ 01, Genzel+ 03,10, Trippe+ 07, Meyer+ 08, Do+ 09, Dodds-Eden+ 09,10, Witzel+ 12,18, Ponti+ 17, GRAVITY Collaboration+ 20, 21, von Fellenberg+ 23

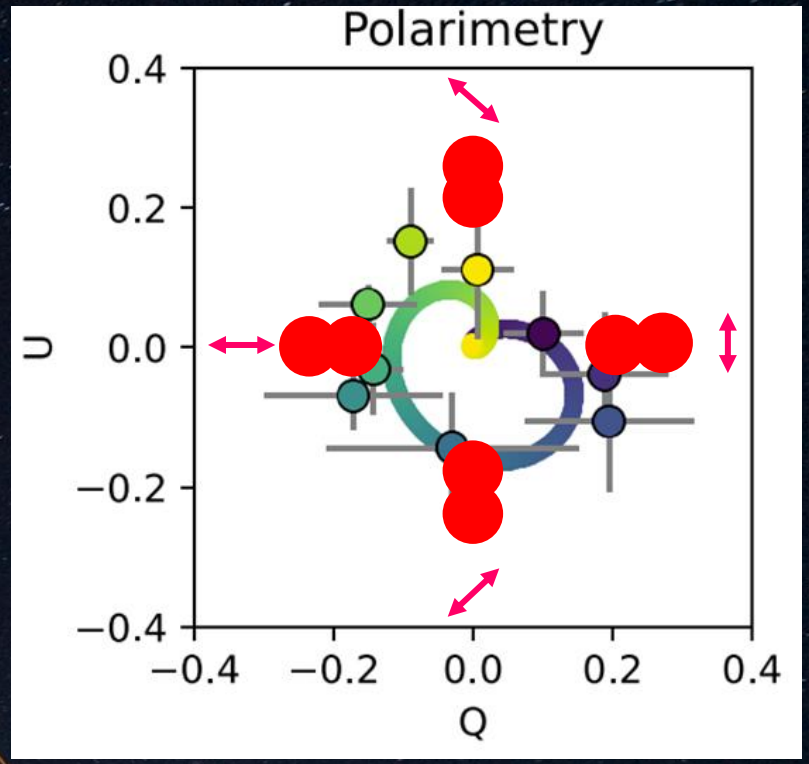
Polarization and Magnet Field Is Not Toroidal

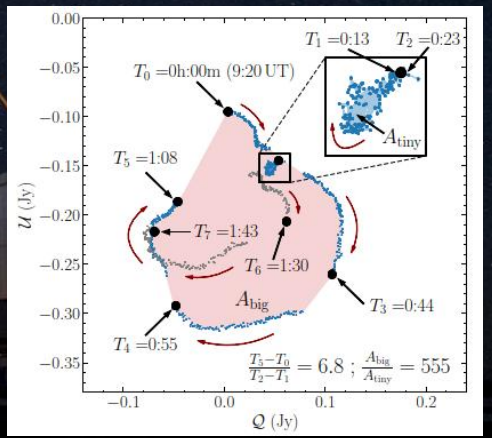
Double Polarization Loop





GRAVITY Collaboration+ 18,…,23



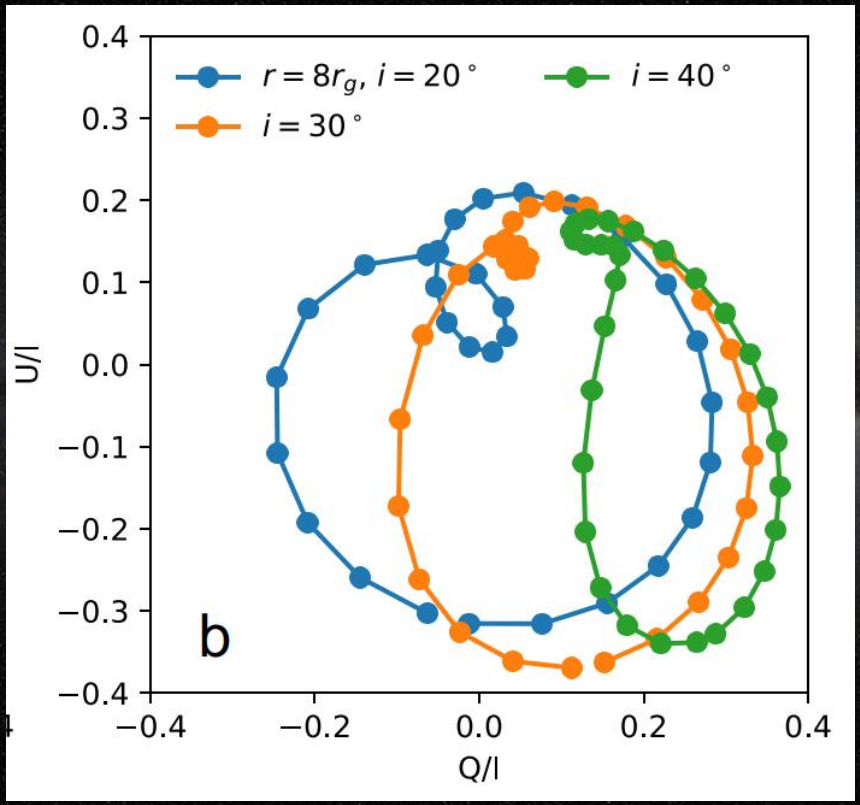


Radio

Marrone+ 06
Wielgus+ 23

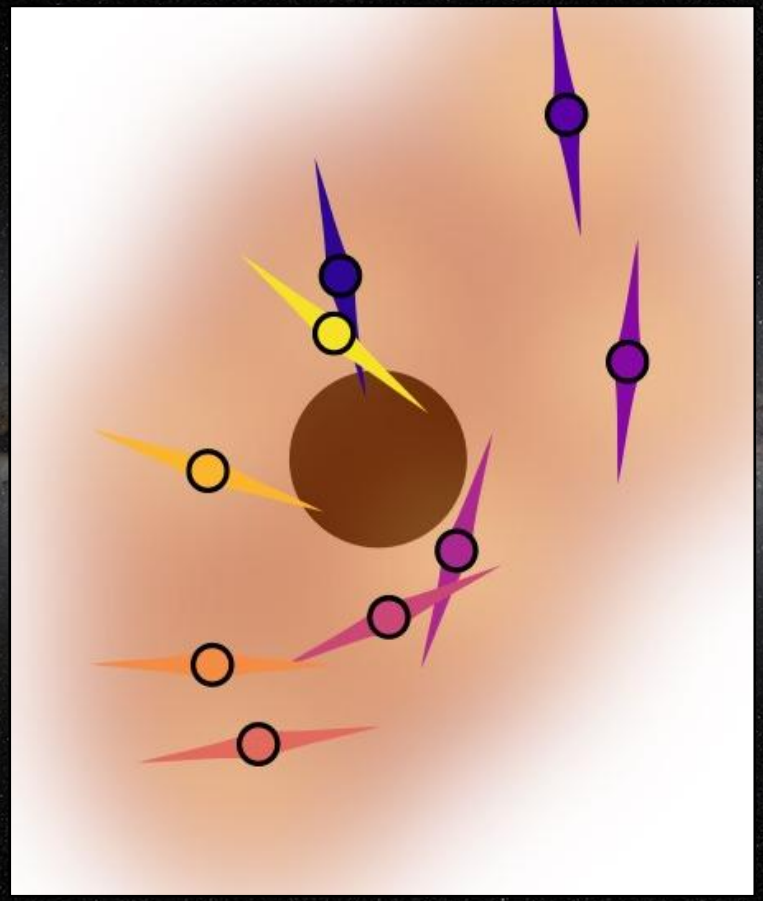
Magnet Field Is Predominantly "Vertical"

Aberration and Bending



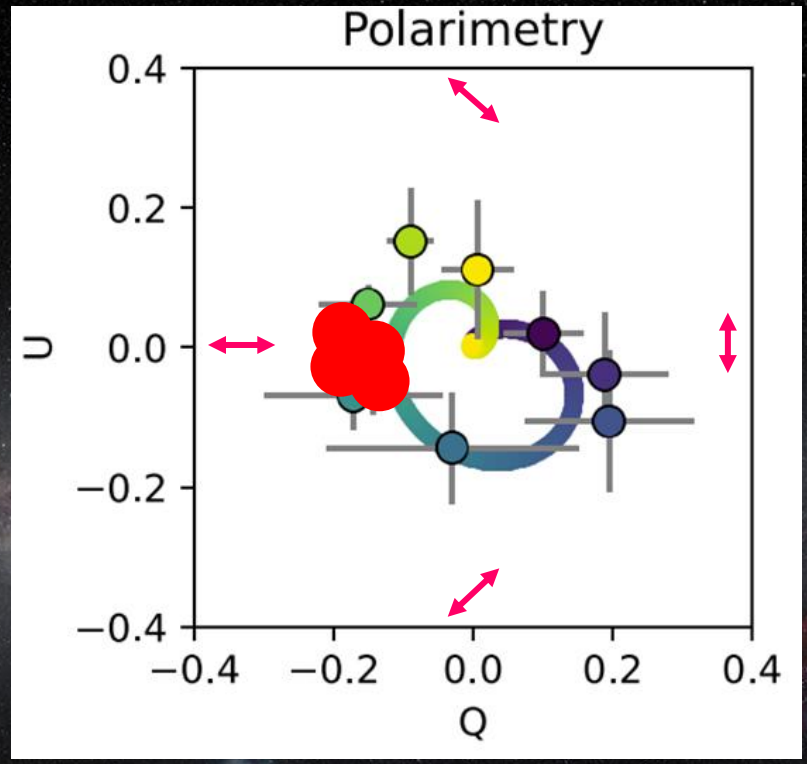
GRAVITY collaboration+18, Gelles+ 21, Vincent+ 23
also e.g. Connors+ 80, Broderick & Loeb 05, Dexter 16

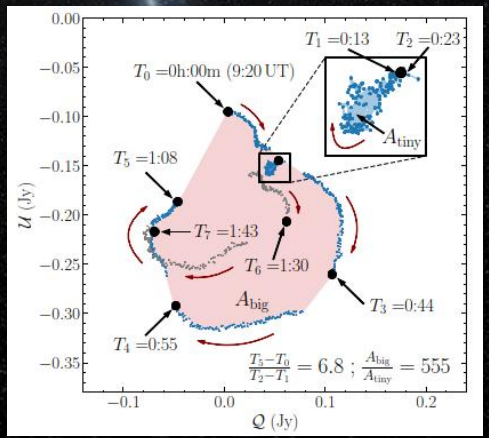
Single Polarization Loop



GRAVITY Collaboration+ 18,…,23

Polarimetry





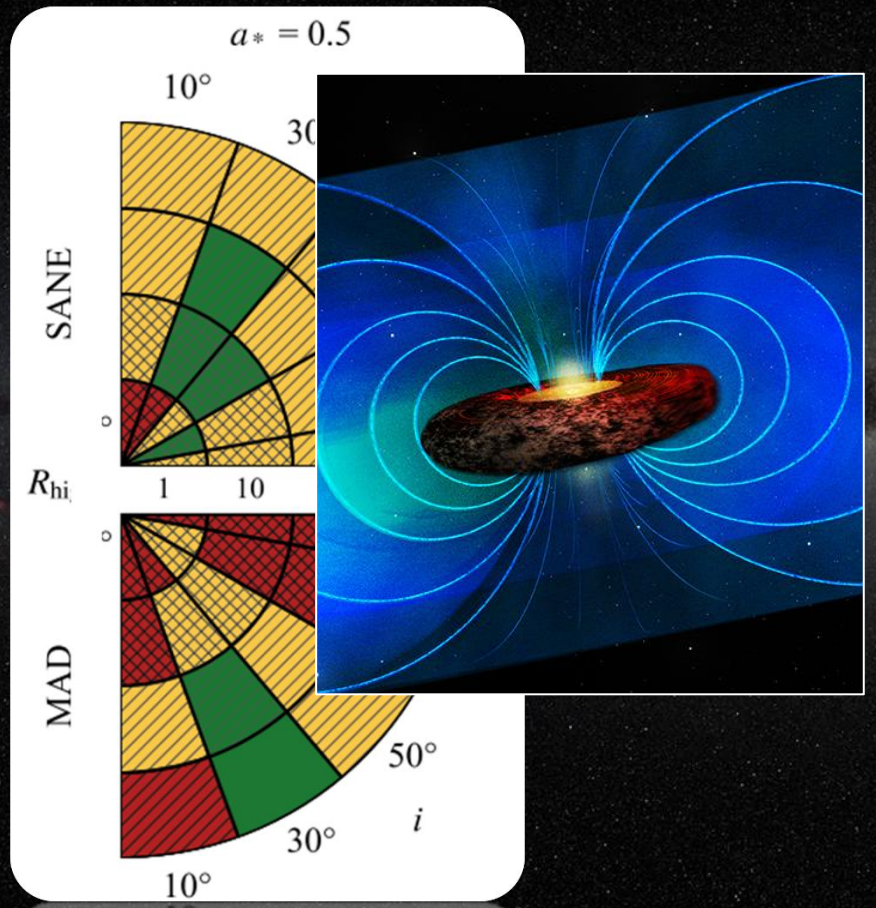
Radio

Marrone+ 06
Wielgus+ 23

Magnet Field Is Predominantly "Vertical"

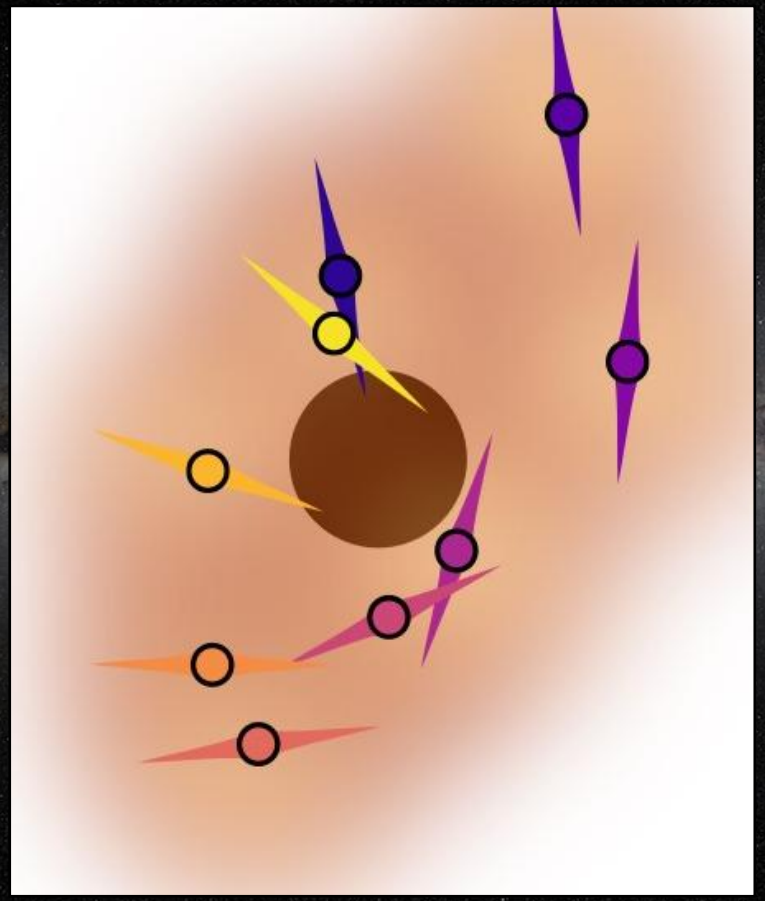
Single Polarization Loop

EHT Image



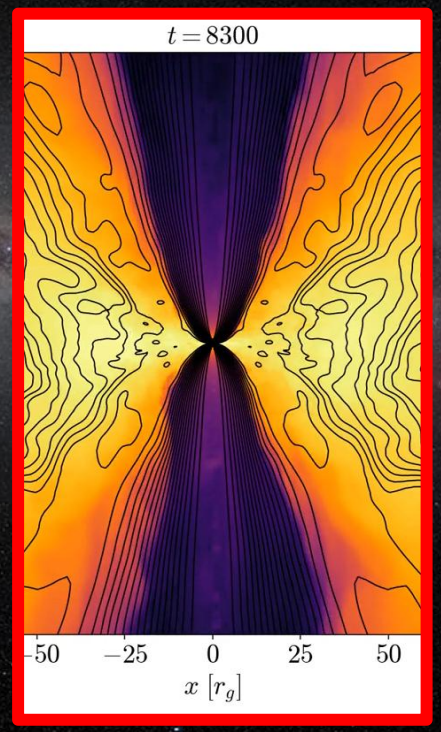
ALMA Polarization

EHT Collaboration 22,
Wielgus+ 23



GRAVITY Collaboration+ 18,…,23

Magnetically Arrested Disk



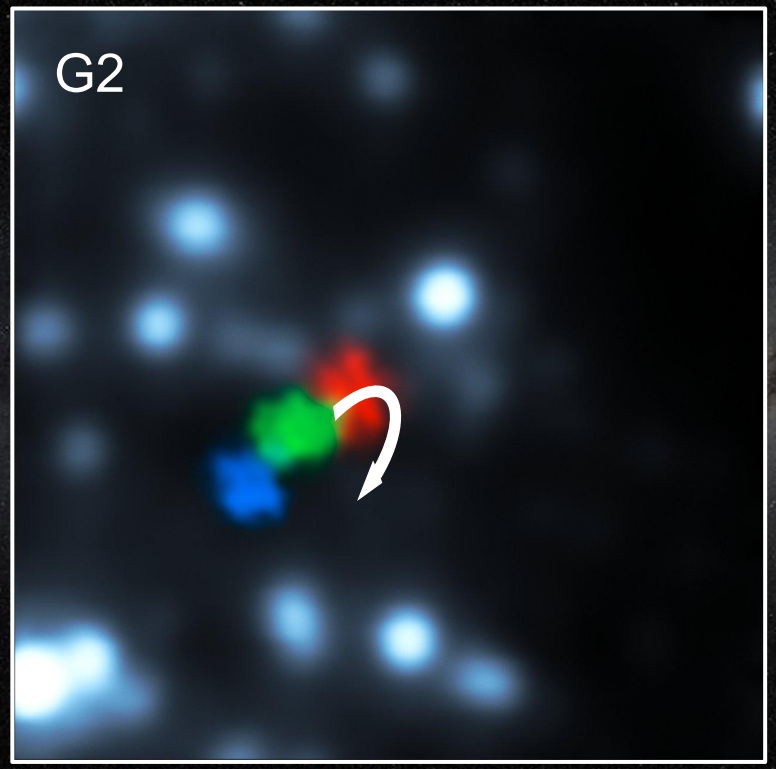
Standard and Normal

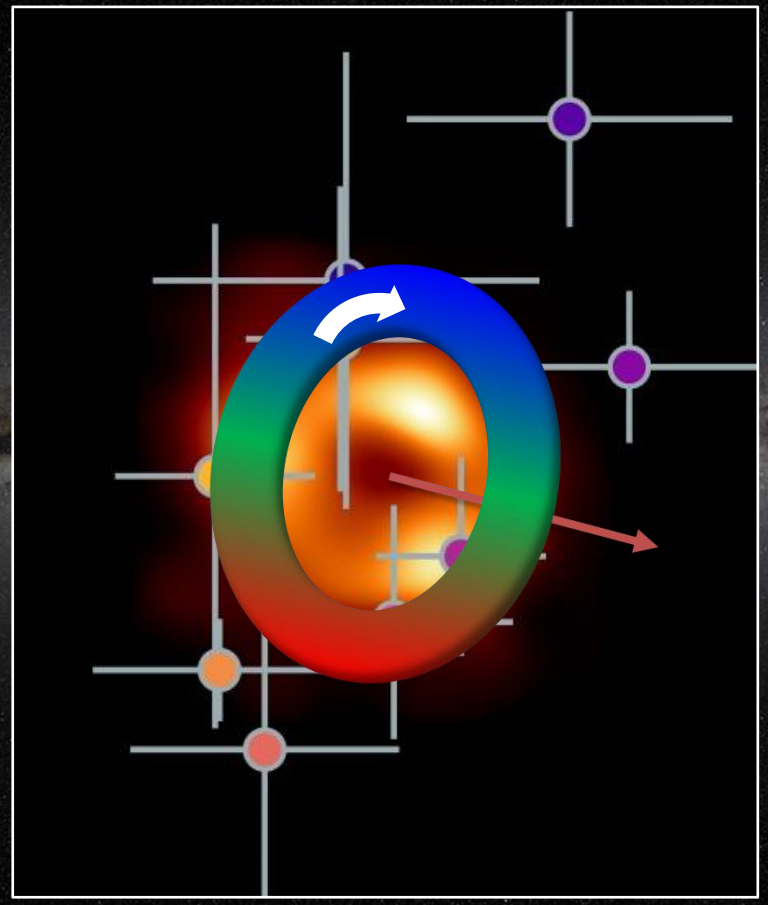
Courtesy: Dexter

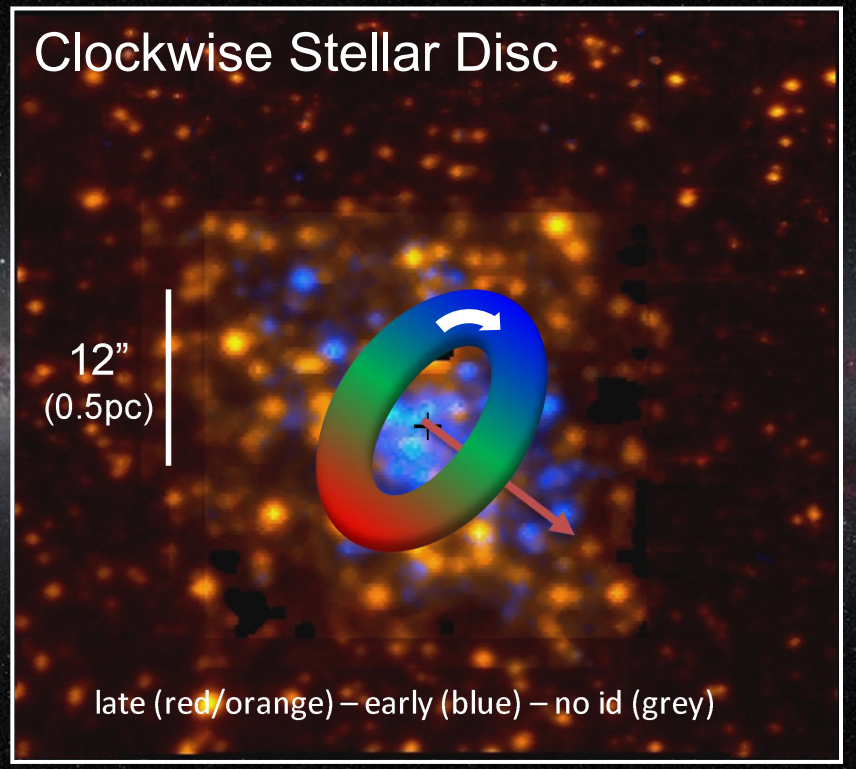
Narayan+ 03, Igumenshchev+ 03,08, McKinney+ 12, see also review Yuan&Narayan 14
Johnson+ 15, Gold+ 17, see also Doeleman+ 08,12, Fish+ 11, Akiyama+ 15, Bower+ 18

Angular Momentum of Accretion

Consistent with Stellar Disc and Clouds



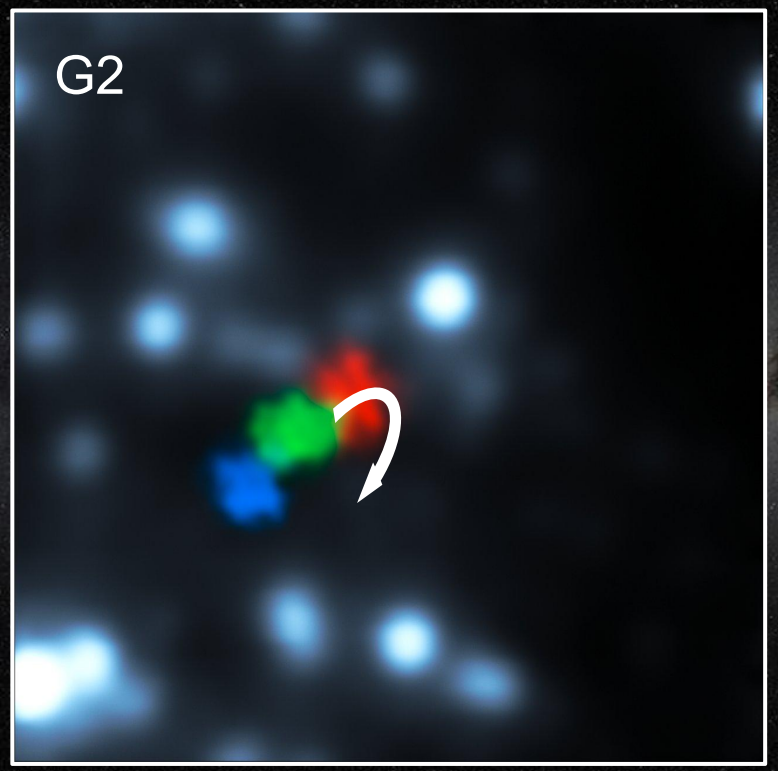




Stellar Disc: Genzel+ 03, Levin&Beloborodov 03, Beloborodov+ 06, Lu+ 06, Paumard+ 06, Bartko+ 09, Lu+ 09, Bartko+ 09,10, Do+ 13, Pfuhl+ 11,14, Yelda+ 14, von Fellenberg+ 22
Clouds: Gillessen+ 12,13,19, Phifer+ 14, Witzel+ 14, Pfuhl+ 15, Valencia-S.+ 15, Shahzamanian+ 16, Zajaček+ 17, Plewa+ 17, Ciurlo+ 20, Peißker+ 20

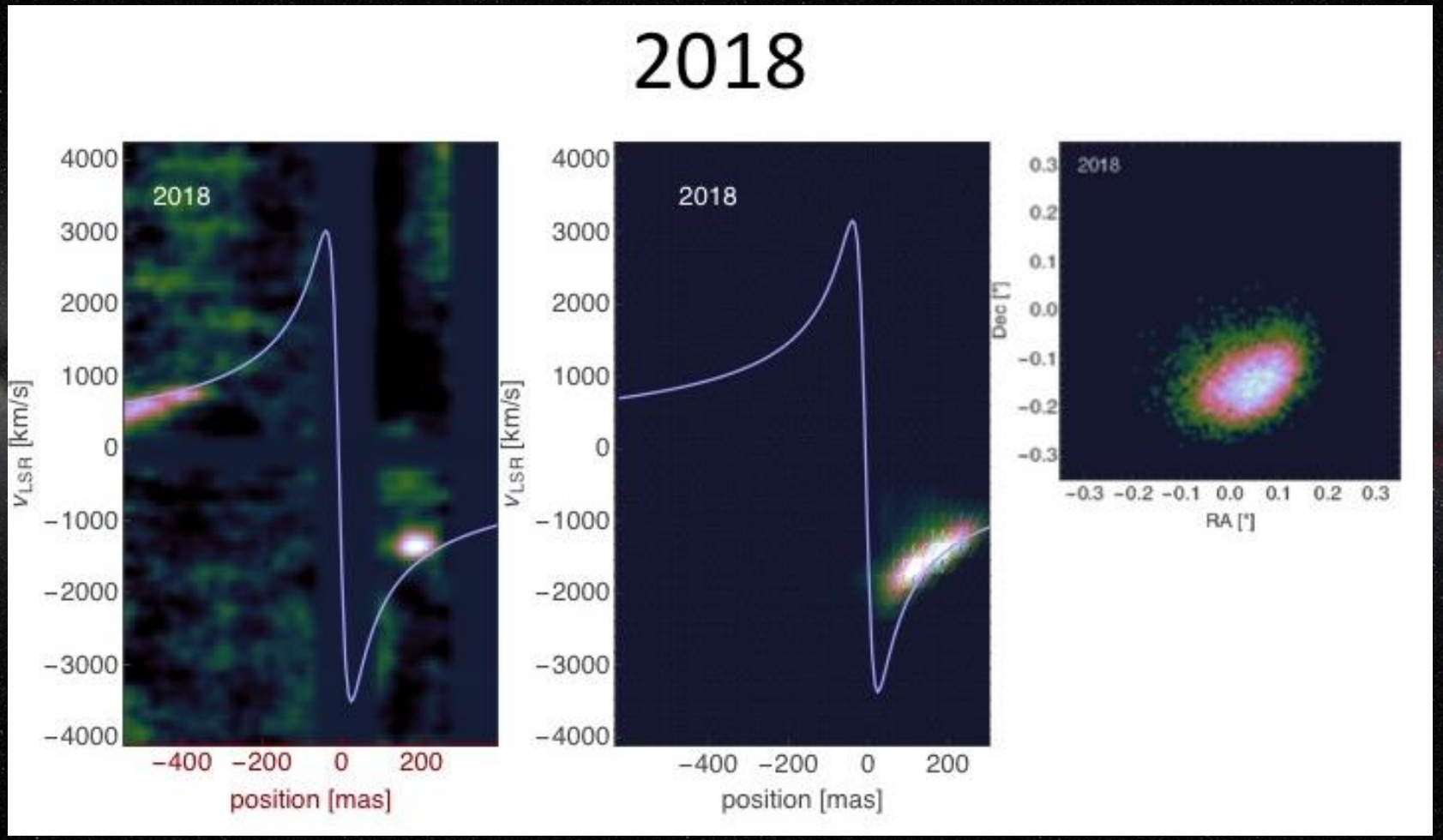
G2 Cloud

Resolved Br-γ emission



Unresolved thermal emission

Highly eccentric (0.98) orbit with peridistance ~1000 R_S



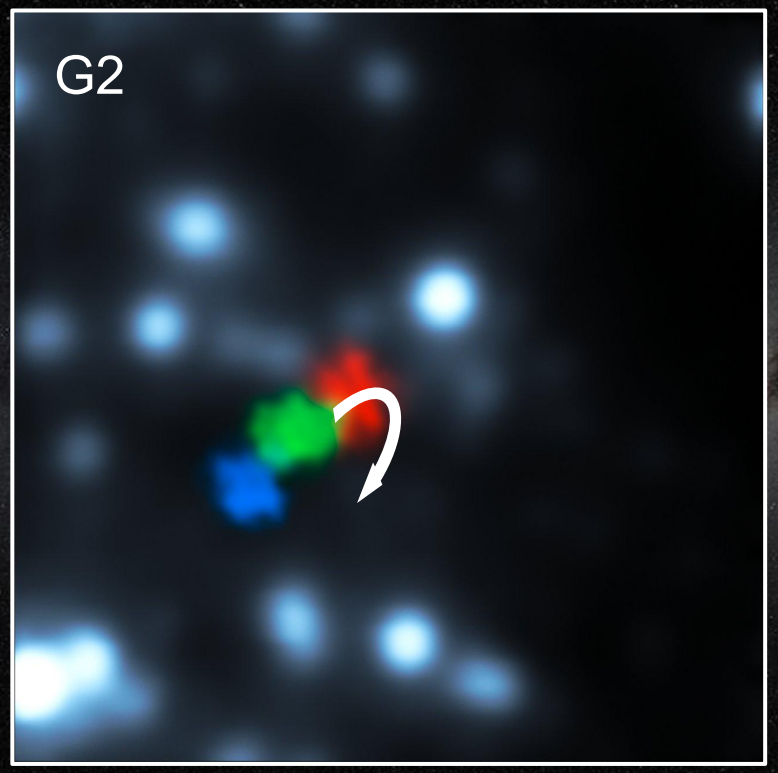
Many possible origins

Gillessen+ 12,13,19, Phifer+ 14, Witzel+ 14, Pfuhl+ 15, Valencia-S.+ 15, Shahzamanian+ 16, Zajaček+ 17, Plewa+ 17, Ciurlo+ 20, Peißker+ 20

Ballone, Burkert, De Colle, Eckart, Gillessen, Guillochon, Miralda-Escude, Meyer, Meyer-H., Murray-Clay, Pfuhl, Prodan, Schartmann, Scoville, Shcherbakov, Valencia-S., Witzel, Calderon, Cuadra

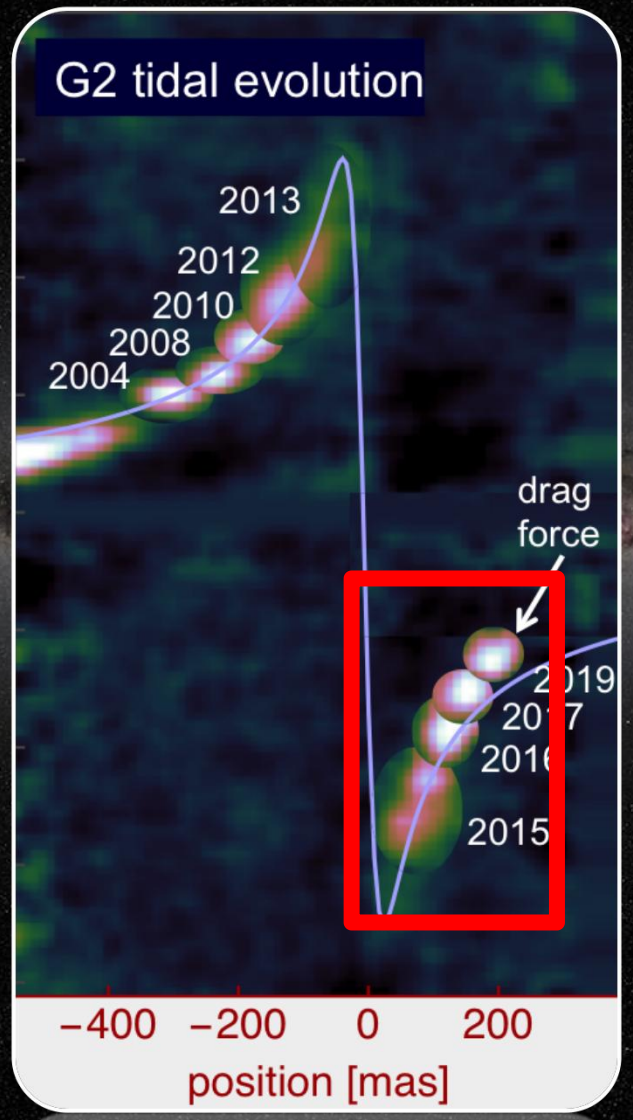
G2 Measuring Density of Accretion Flow

Experiencing Friction

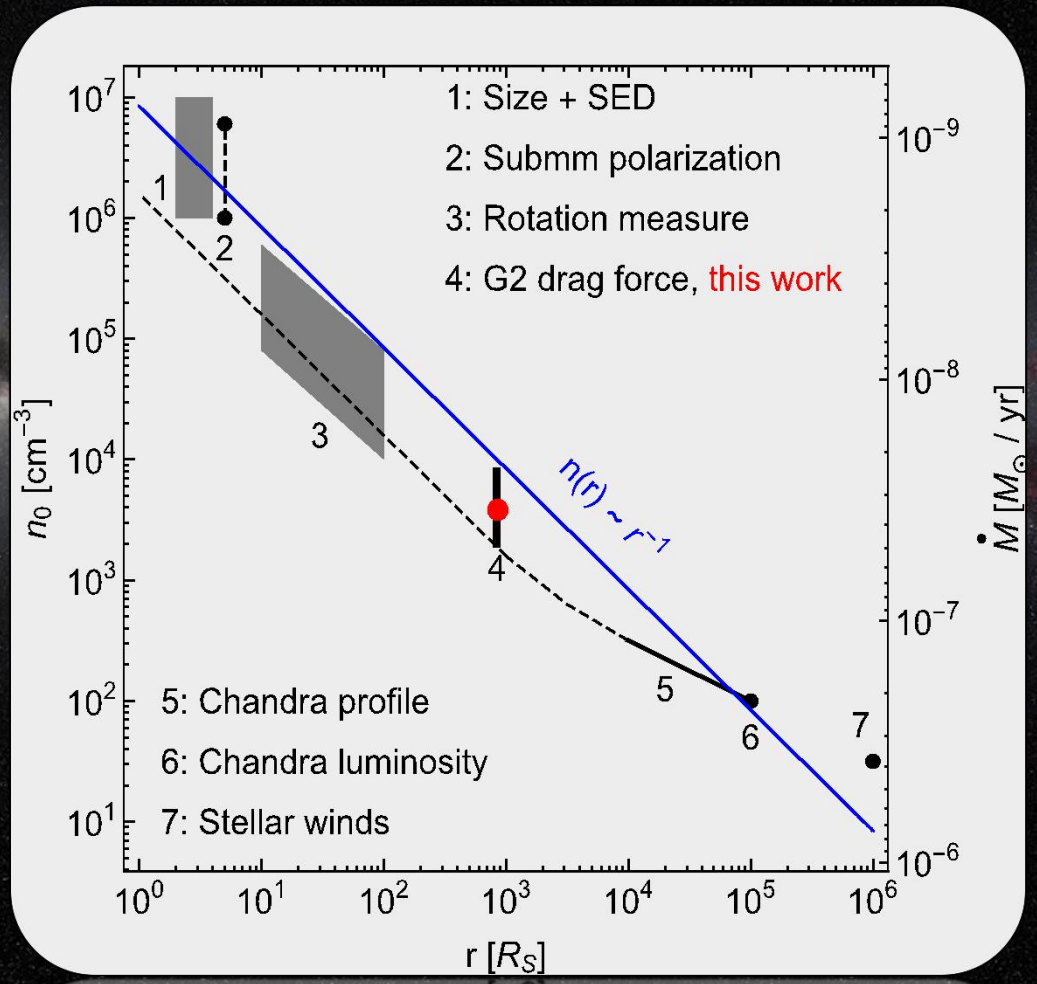


Drag force detected at 14 σ
Confirmed 2022/24

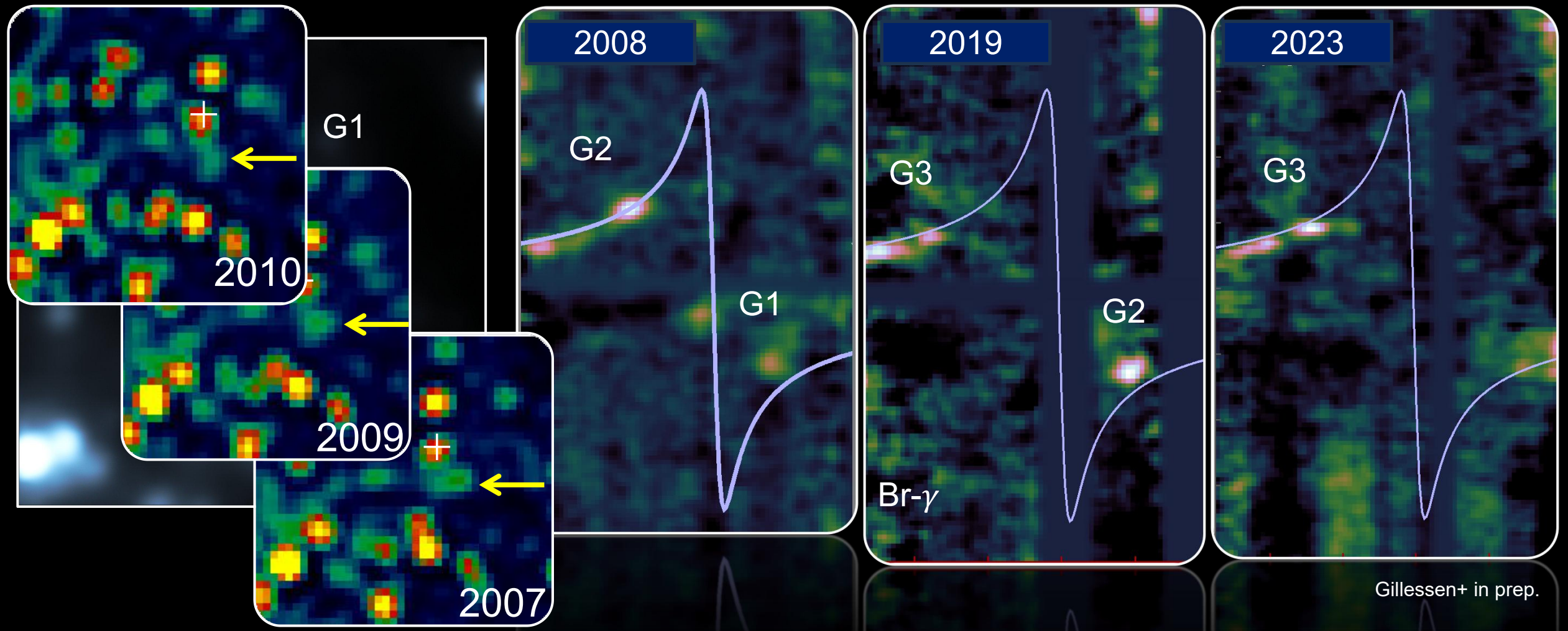
Gillessen+ 12,13,19, Phifer+ 14, Witzel+ 14,
Pfuhl+ 15, Valencia-S.+ 15, Shahzamanian+ 16,
Zajaček+ 17, Plewa+ 17, Ciurlo+ 20, Peißker+ 20



Density n ~ 400 cm³ @ 1000 R_S
Accretion Rate few 10^{-8} $M_\odot$ /yr



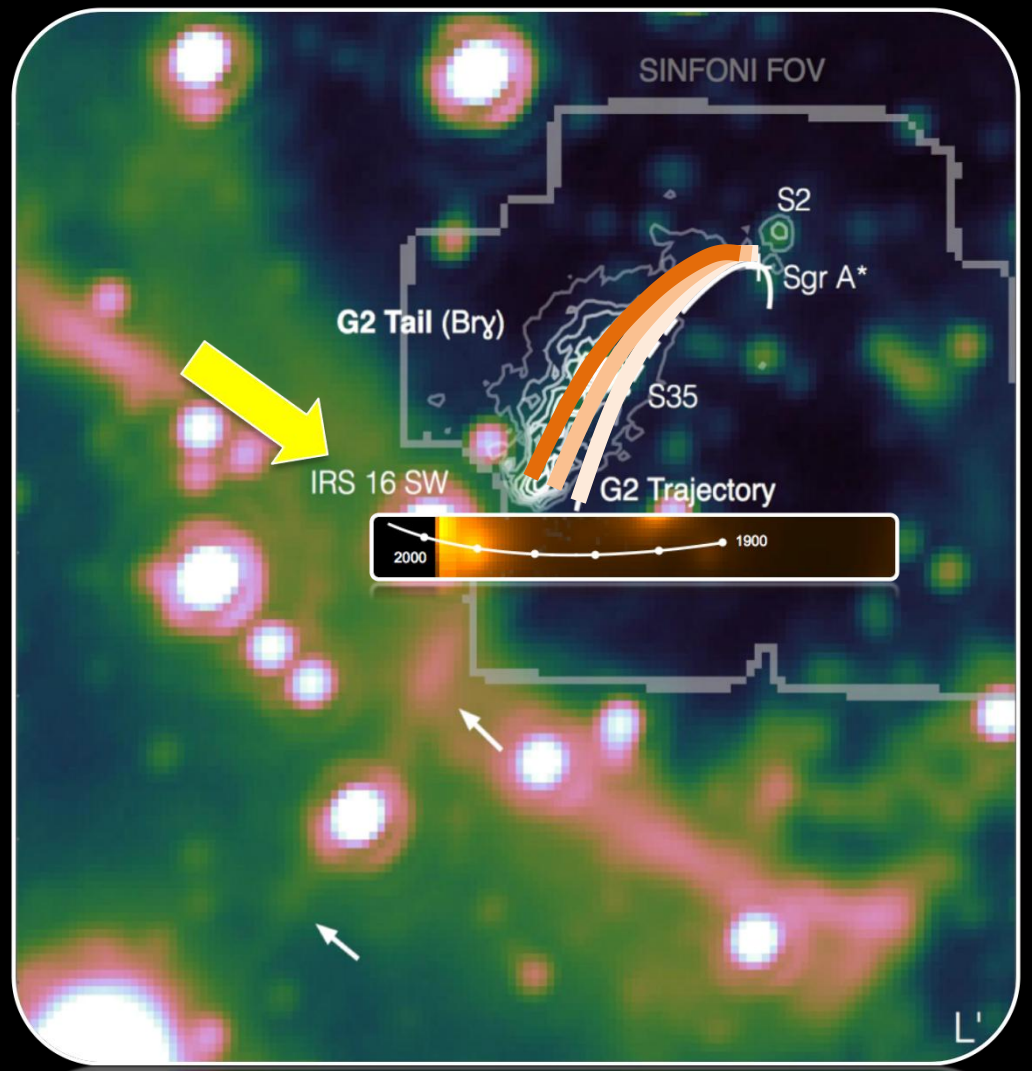
Series of Clouds and Stream: G1, G2, G3



Gillessen+ in prep.

Gillessen+ 12,13,19, Phifer+ 14, Witzel+ 14,
Pfuhl+ 15, Valencia-S.+ 15, Shahzamanian+ 16,
Zajaček+ 17, Plewa+ 17, Ciurlo+ 20, Peißker+ 20

Is IRS16SW Injecting the Clouds and Feeding SgrA*



Gillessen+ 12,13,19, Phifer+ 14, Witzel+ 14, Pfuhl+ 15, Valencia-S.+ 15, Shahzamanian+ 16, Zajaček+ 17, Plewa+ 17, Ciurlo+ 20, Peißker+ 20

Ofpe/WN Eclipsing Contact Binary

Two 50 M_{Sun} stars with period 19.45 days

Orbits following 16SW

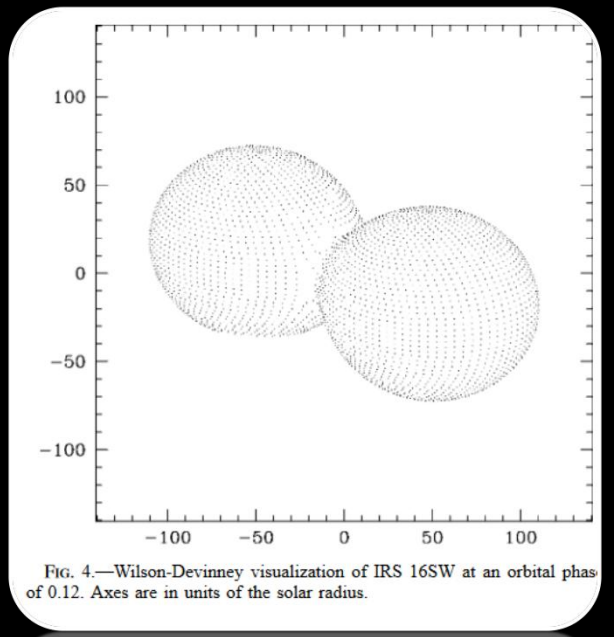
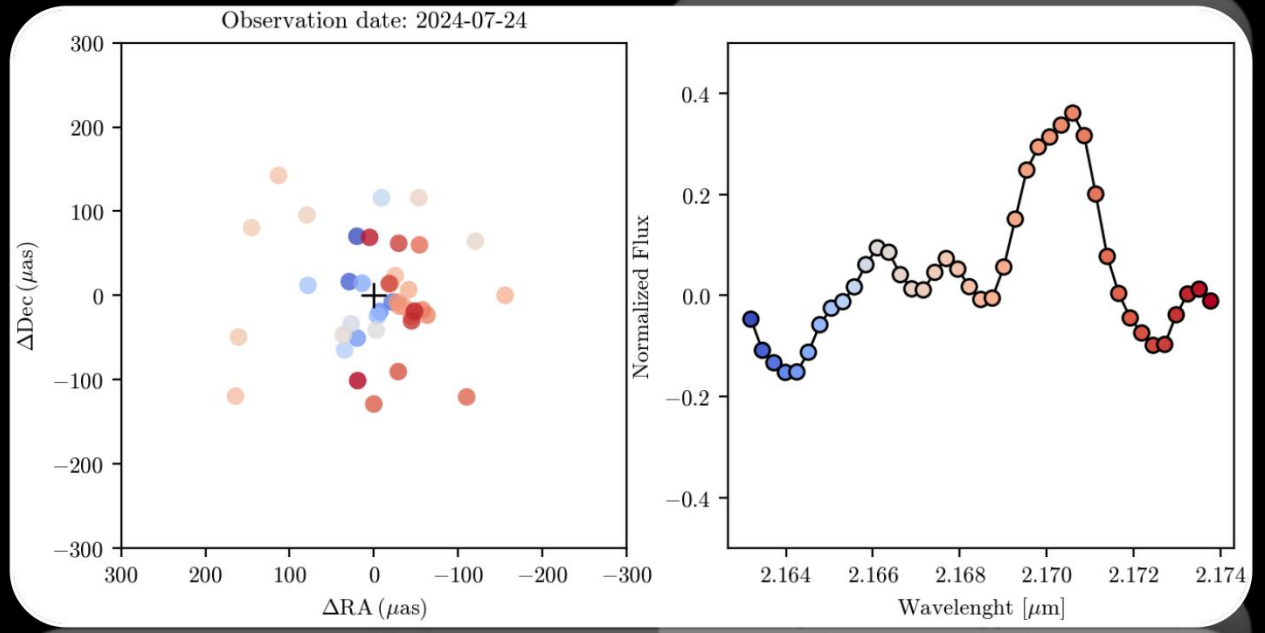


FIG. 4.—Wilson-Devinney visualization of IRS 16SW at an orbital phas of 0.12. Axes are in units of the solar radius.

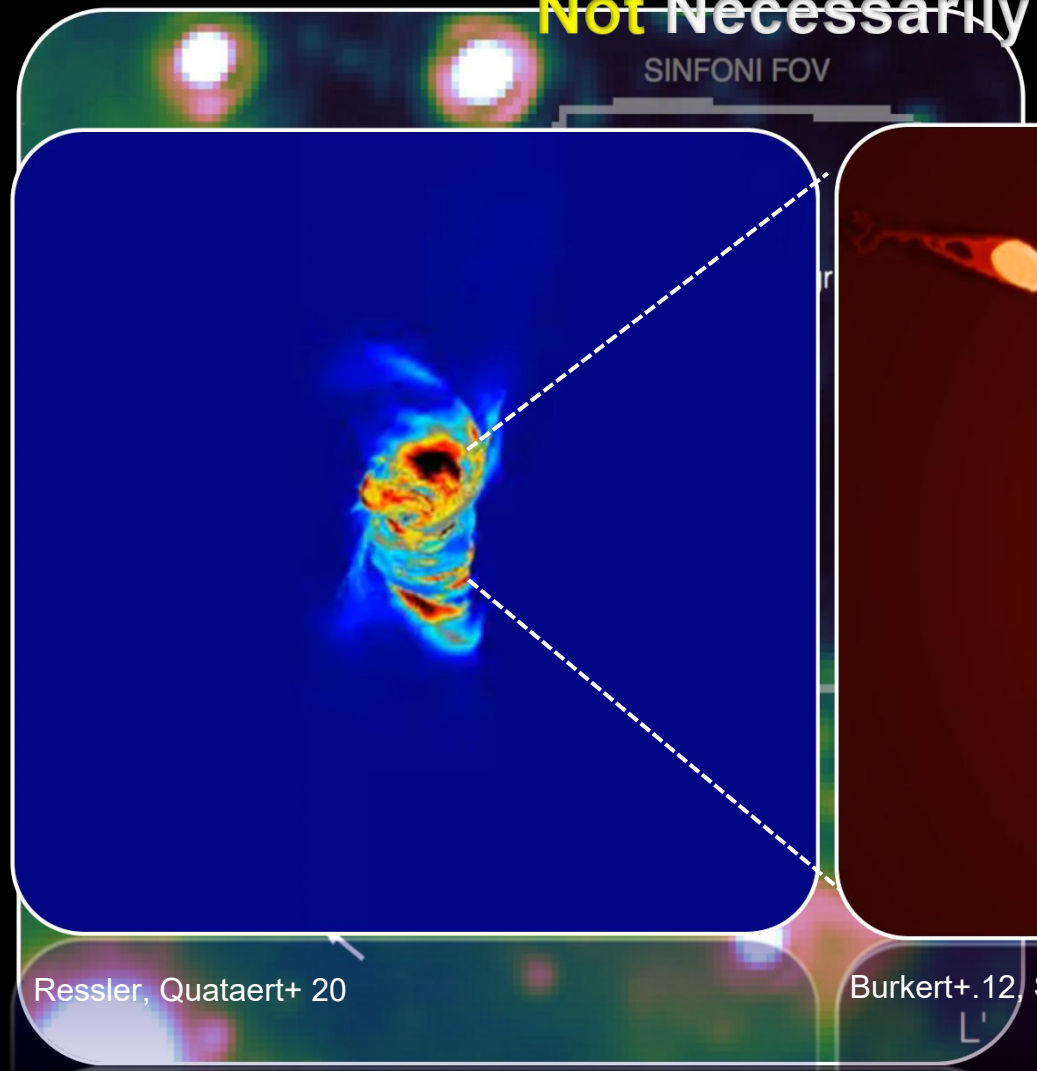
GRAVITY+ Collaboration+, in prep.



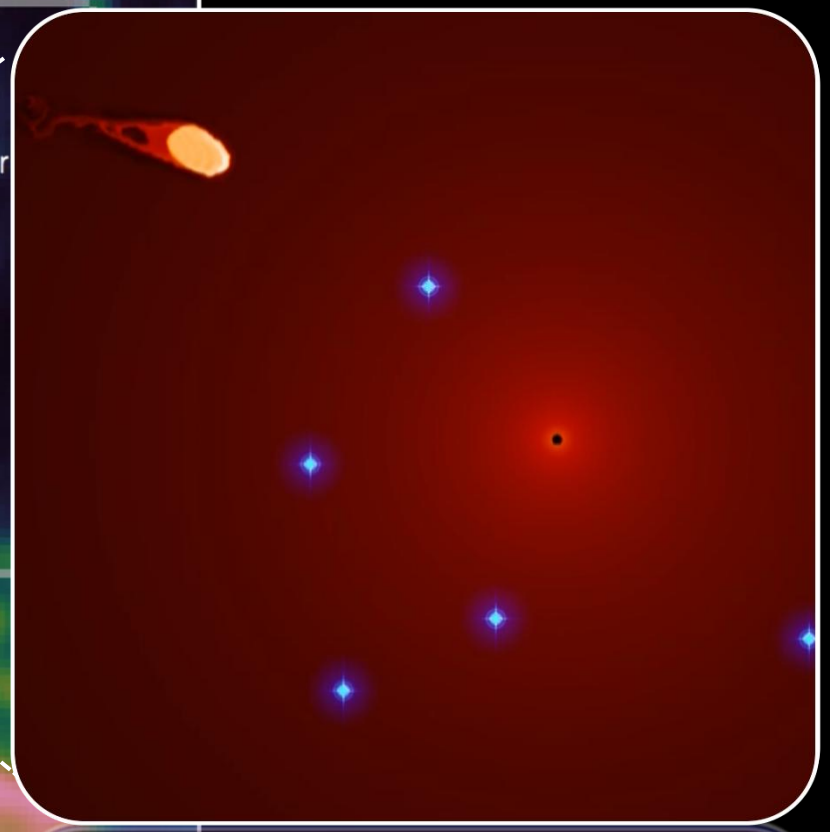
Is IRS16SW Injecting the Clouds and Feeding SgrA*

~~Not~~ Necessarily Driven by Spin

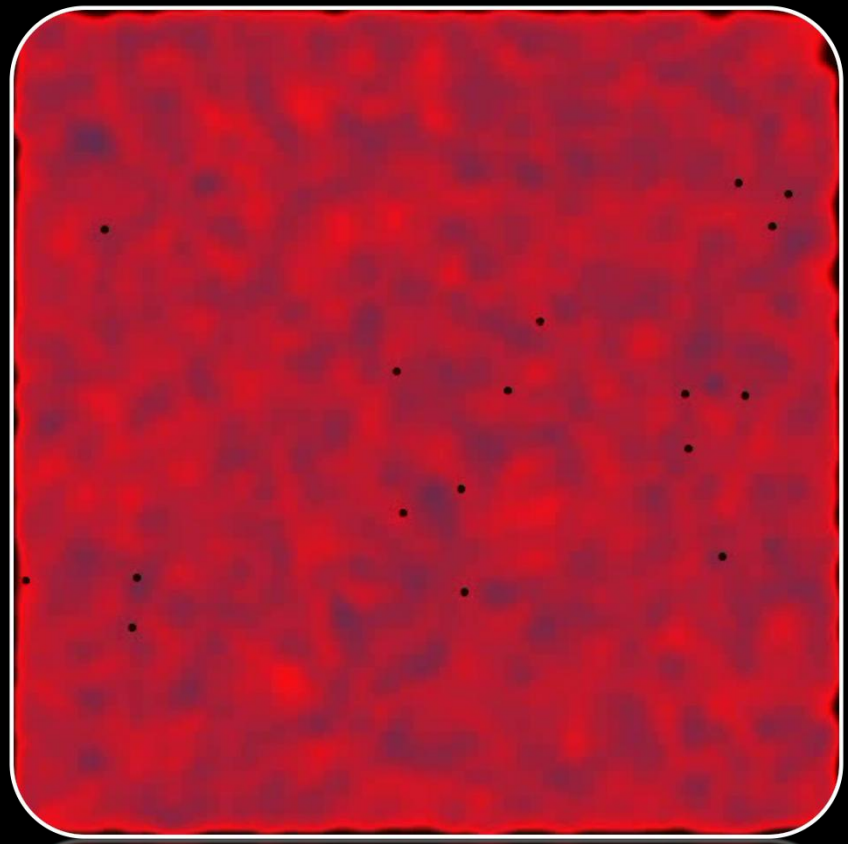
Stellar Winds ~ 10^{-3} $M_\odot$ /yr



Ressler, Quataert+ 20



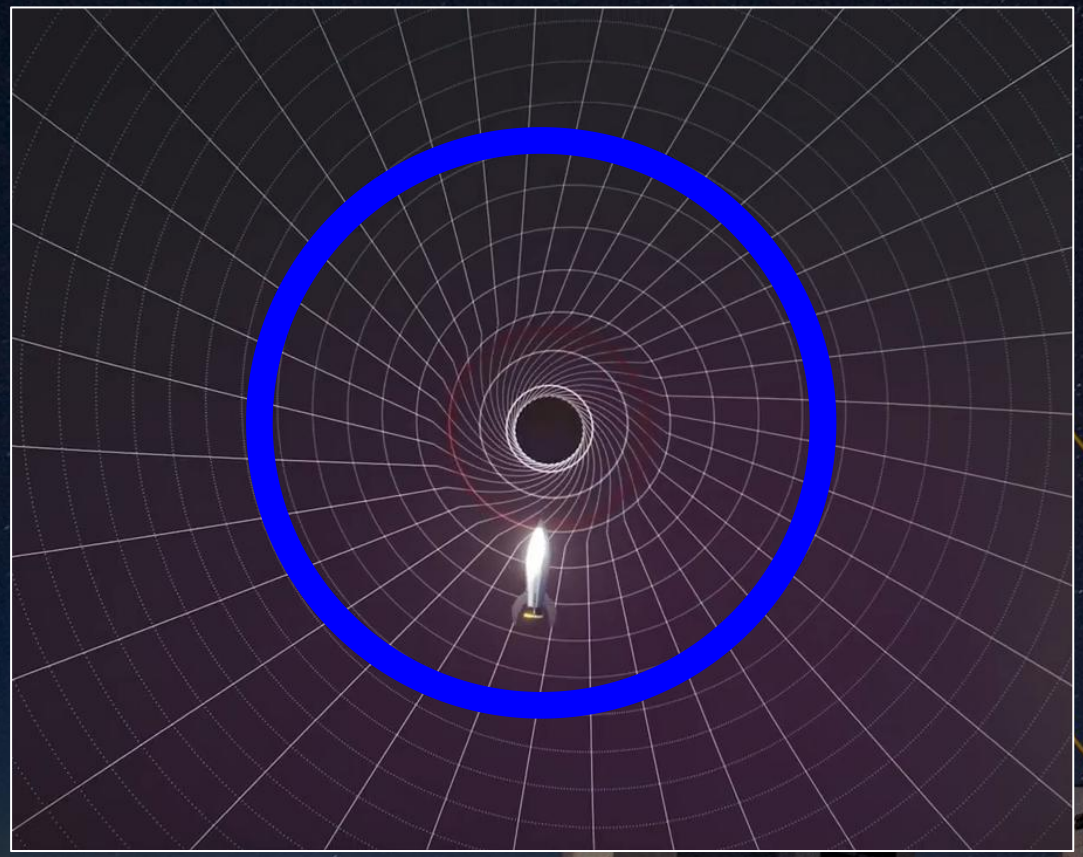
Burkert+.12, Schartmann+ 12,13



Cuadra+ 05,06,08, Calderon+ 16,17,18,19,20, Ressler+ 18,19

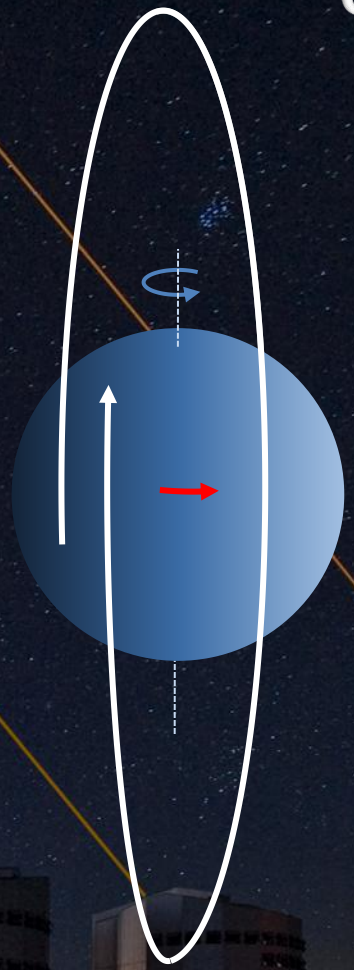
How to Measure the Spin of a Black Hole

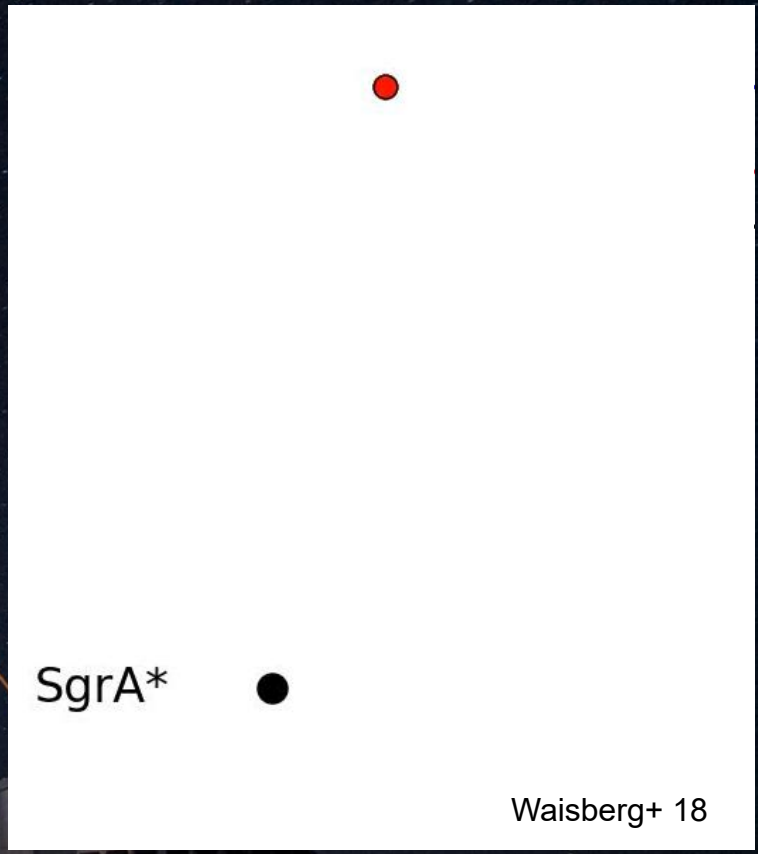
Size, Period, or Redshift Measurement all Degenerate with Mass



PBS Spacetime https://www.youtube.com/watch?v=UjgGdGzDFiM

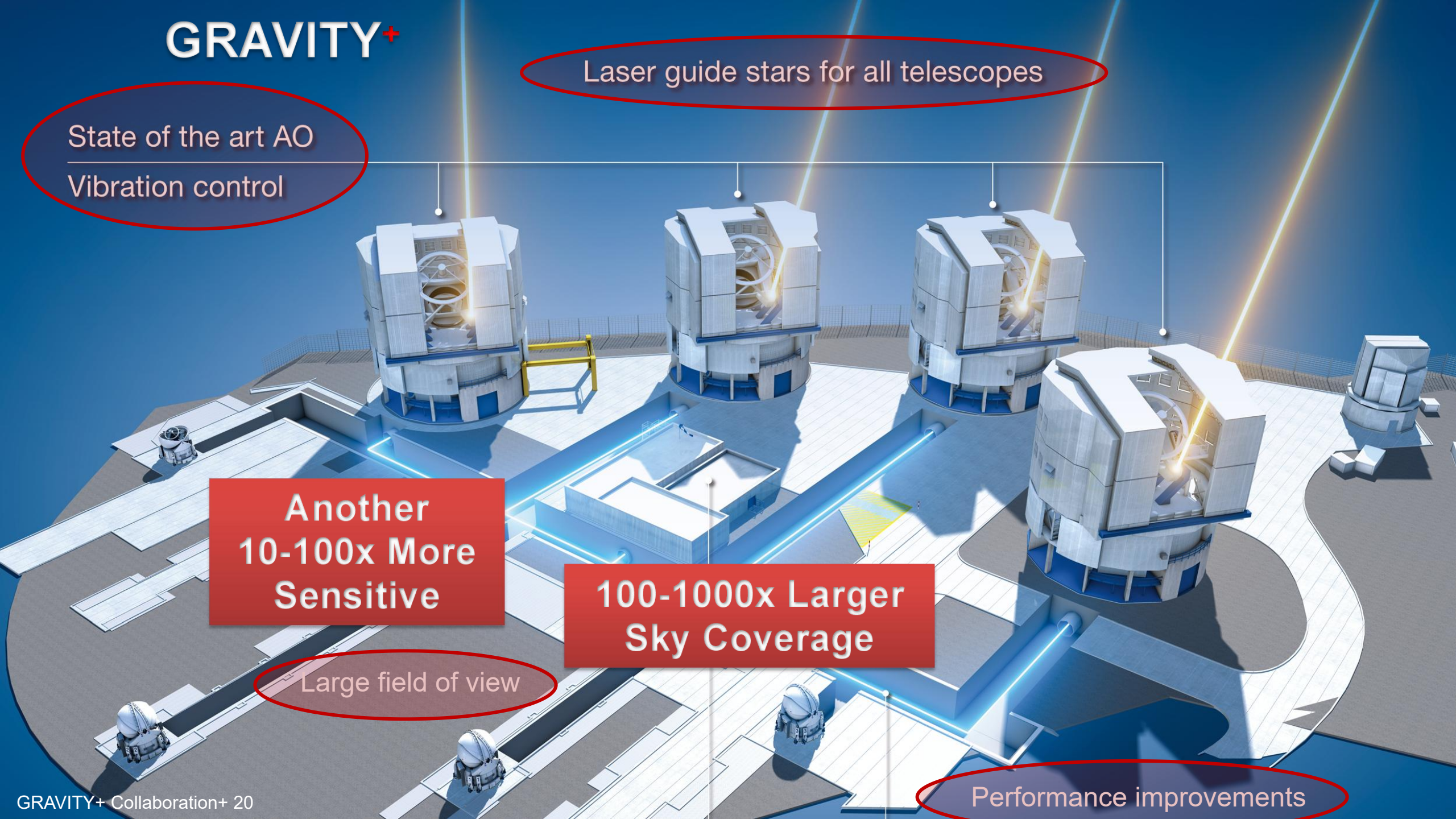
Need Test Particle Out of the Equatorial Plane





Faint, close-in stars will fulfill criteria

Kraniotis 07, Will 08, Kannan&Saha 09, Merritt+ 10, Angélil+ 10,11, Iorio 11, Zhang+ 15,17, Yu+ 16, Grould+ 17, Waisberg+ 18


GRAVITY+
Laser guide stars for all telescopes
State of the art AO
Vibration control
Another 10-100x More Sensitive
100-1000x Larger Sky Coverage
Large field of view
Performance improvements

First GRAVITY+ Results: Ever Fainter Stars in the GC

Five Objects in the Central **Few Ten Mas**

S29: **Closer** than S2

S55: **Shorter Period** than S2

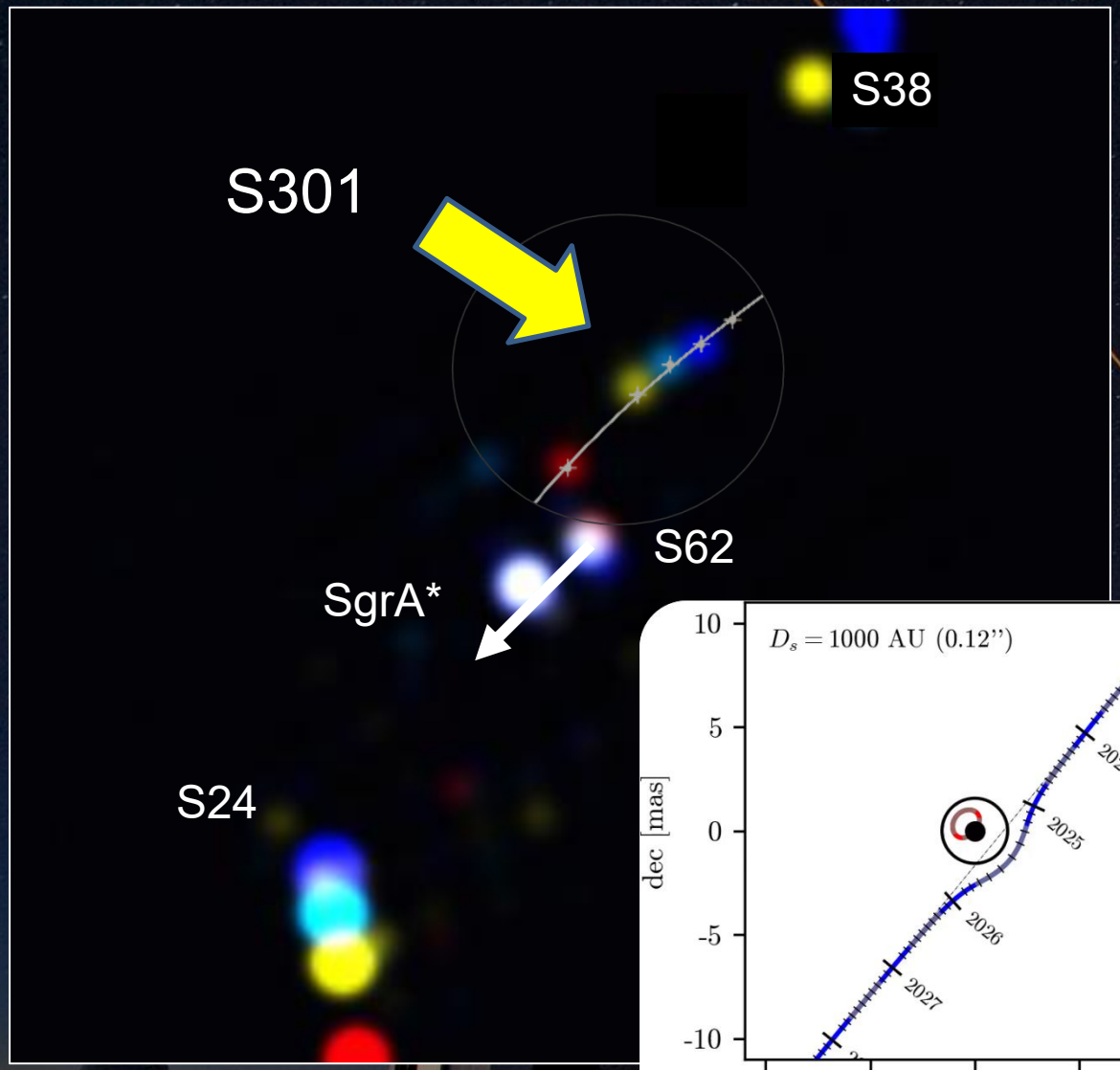
S300: **100x Fainter** than S2

No extended mass or intermediate mass black hole within S2 orbit with more than approx. 1000 $M_\odot$

Bauböck+ 20, Naoz+ 20, Heißel+ 22, Evans+ 23
GRAVITY Collaboration+ 22,23,24

GRAVITY collaboration+ 22

First GRAVITY+ Results: Ever Fainter Stars in the GC



Five Objects in the Central **Few Ten Mas**

- S29: **Closer** than S2
- S55: **Shorter Period** than S2
- S300: **100x Fainter** than S2

And a **candidate star** with even **closer** peri-distance

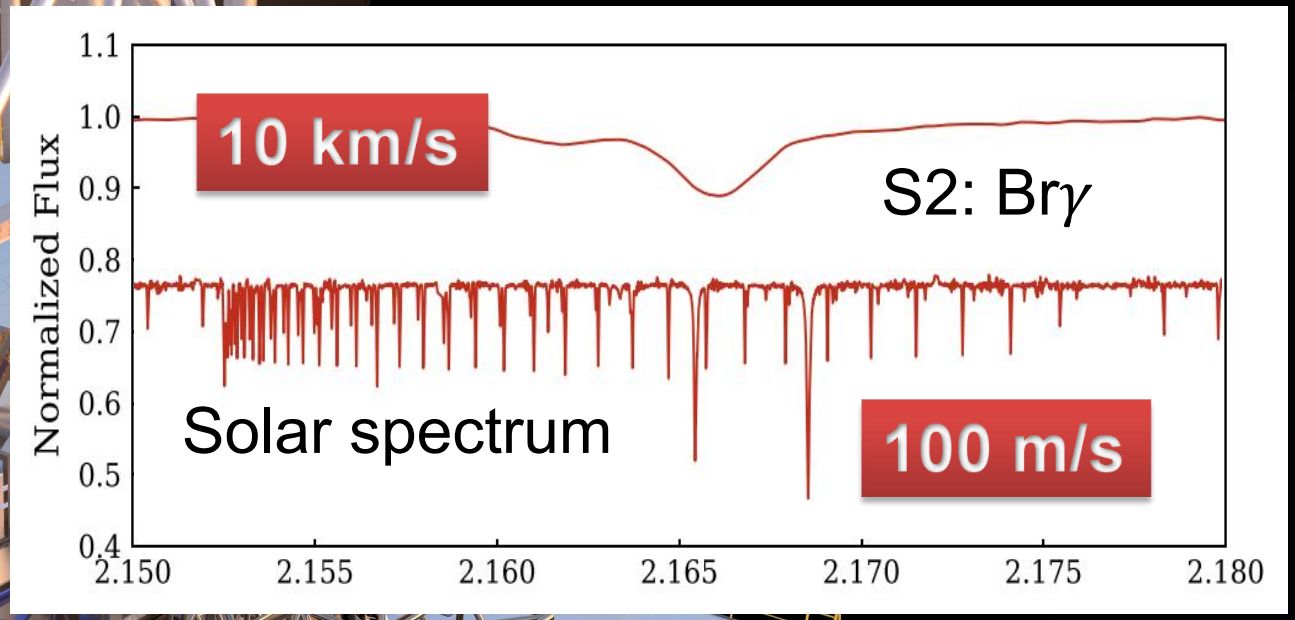
And possibly a **strong lensing** event just ahead

GRAVITY Collaboration+ 24 in prep.

And soon after: Extremely Large Telescope

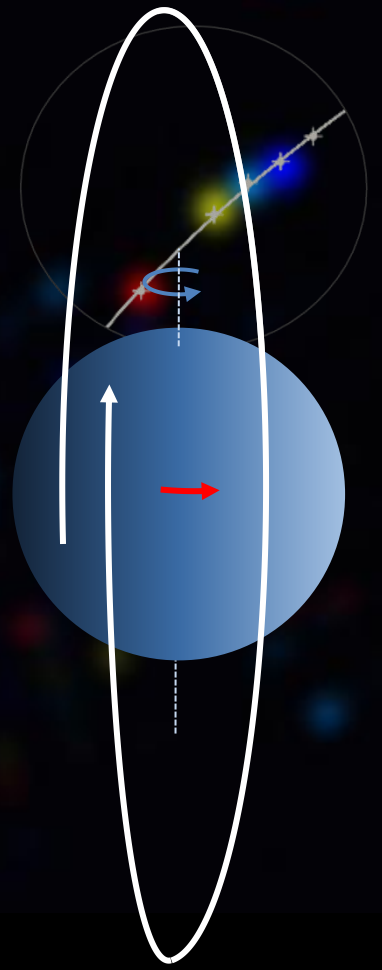
Credit: ESO / MICADO Collaboration

Spectrocsopy with 1000m² Collecting Area



Rad err [km/s]	Schwarz-schild	Lense-Thirring	Lensing & Delay	Quad-rupole
10	0.6%	3%	-	-
1	0.4%	0.7%	35%	-
0.1	0.02%	0.04%	4%	11%

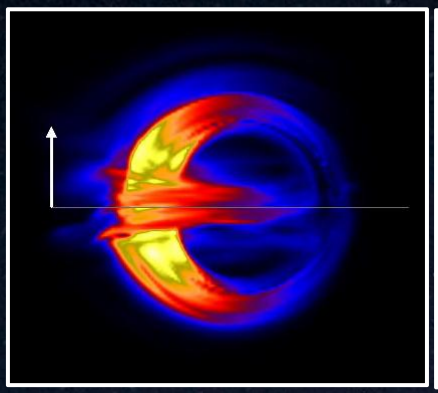
"Pulsar Science"

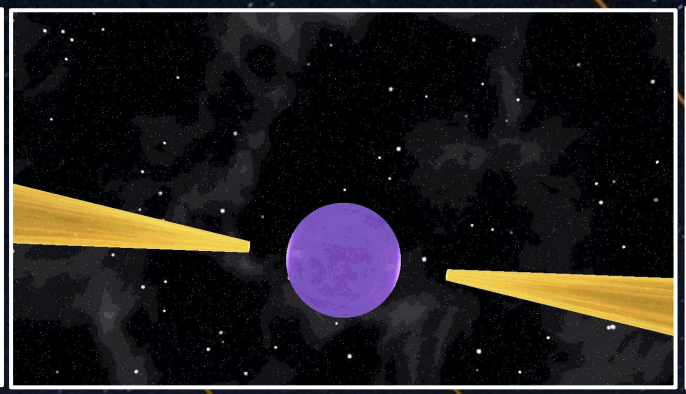


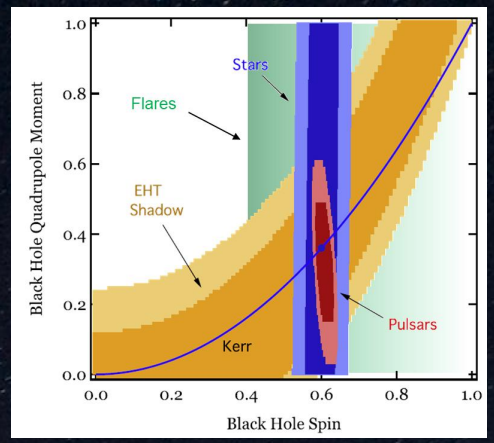
Spin of black hole

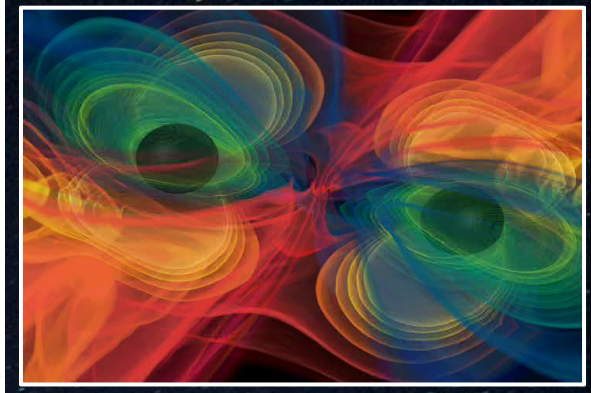
ESO / L. Calçada

Outlook on Testing General Relativity in Strong Field









Event Horizon

$$R_0 = R_g\left(1+\sqrt{1-a^2}\right) \times (1+\varepsilon)$$

No Hair

$$\left(\frac{Q}{M}\right) = -\left(a^2+\varepsilon\right)$$

Following
Cardoso & Pani 2019

Object	Measurement	Limit on ε
AGN	Kα line / reverberation	a few
GW150914	In-spiral / ring down	0.4-0.7
SgrA*	GRAVITY near ISCO	O(1)
SgrA*	EHT ring	O(1)
SgrA*	GRAVITY stars @ 10mas	0.3
SgrA*	GRAVITY & EHT	0.2
SgrA*	Pulsar in central 10 mas	0.1
SgrA*	ELT & GRAVITY+	0.05
Distant MBH	LISA EMR in-spiral	0.01

Johannsen & Psaltis 10, Johannsen 16, Psaltis, Wex & Kramer 16, Zhang+ 15, Waisberg+ 18, GRAVITY collaboration+, EHT collaboration+, Cardoso & Pani 2019, Genzel, Eisenhauer, Gillessen 24

Thank you very much