Testing General Relativity and The Massive Black Hole Paradigm with Infrared Techniques in the Galactic Center

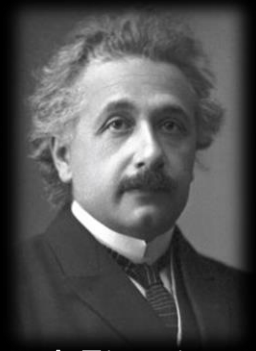
A forty year Journey

Reinhard Genzel, Stefan Gillessen, Andreas Eckart, Frank Eisenhauer, Michi Bauböck, Wolfgang Brandner, Jason Dexter, Sebastiano v. Fellenberg, Paolo Garcia, Feng Gao, Alejandra Jimenez, Antonio Amorim, Pierre Léna, Sylvestre Lacour, Thomas Ott, Thibaut Paumard, Karine Perraut, Guy Perrin, Oliver Pfuhl, Odele Straub, Christian Straubmeier, Idel Waisberg & Felix Widmann

and the GRAVITY Collaboration

Prologue (1915-1965): The Theory of General Relativity

1916: General Relativity & Black Holes

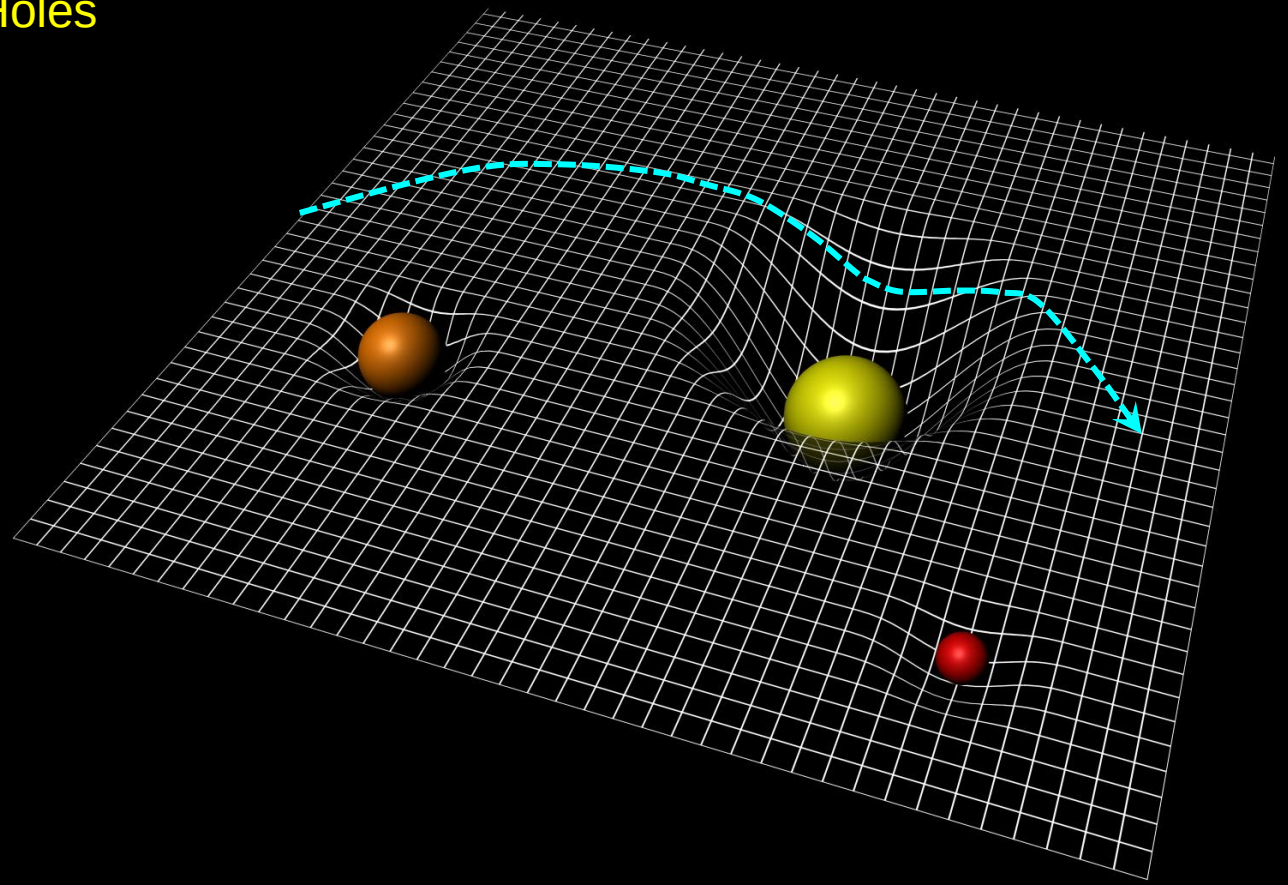


A.Einstein

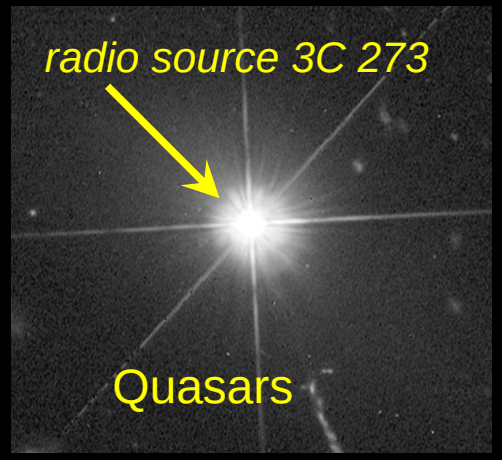
K.Schwarzschild

R.Penrose

R.Kerr



Introduzione (1963-1971): Quasars & the Massive Black Hole Paradigm



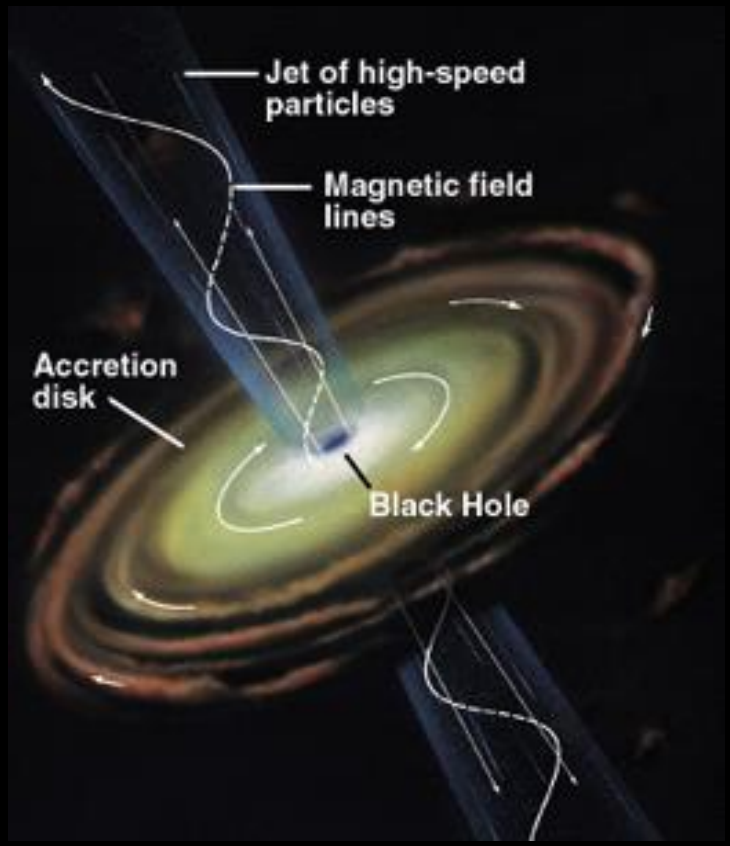
$z=0.16$, $D_L \sim 2.4 \times 10^9$ ly
$L \sim 10^3 L_{MW}$

M. Schmidt
1963

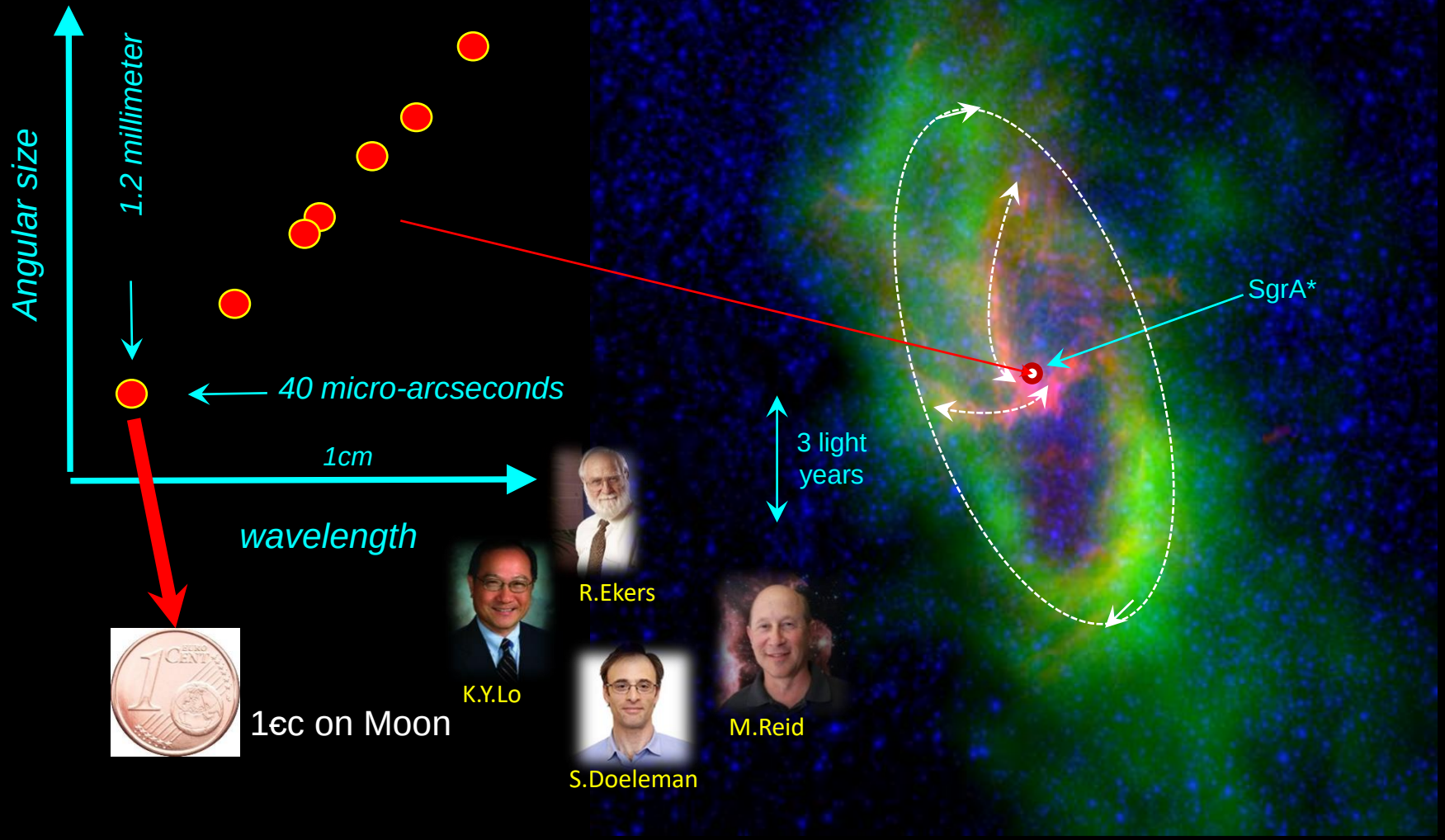
Lynden-Bell Rees

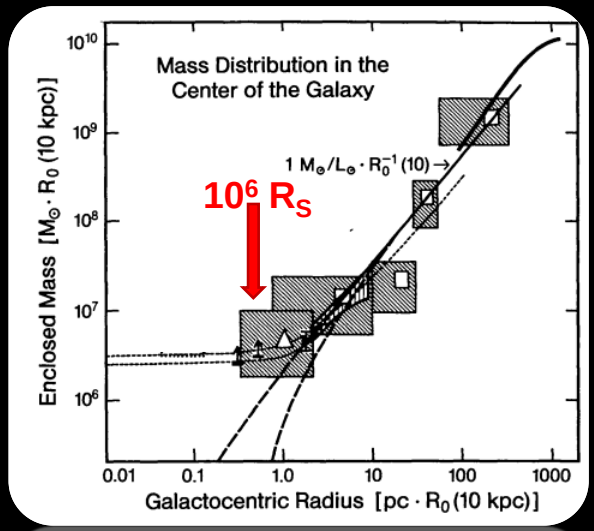
Sunyaev Blandford

E < 0.4 Mc²
variable X- und γ-radiation
relativistic radio jets



Il Primo (1971-1991): SgrA* & Gas Motions

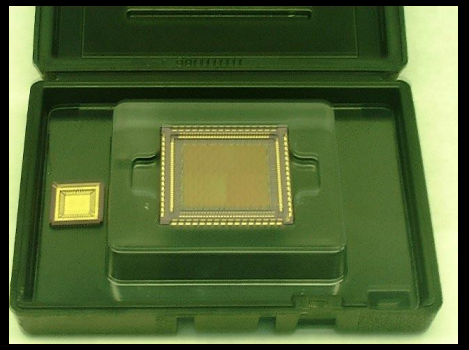




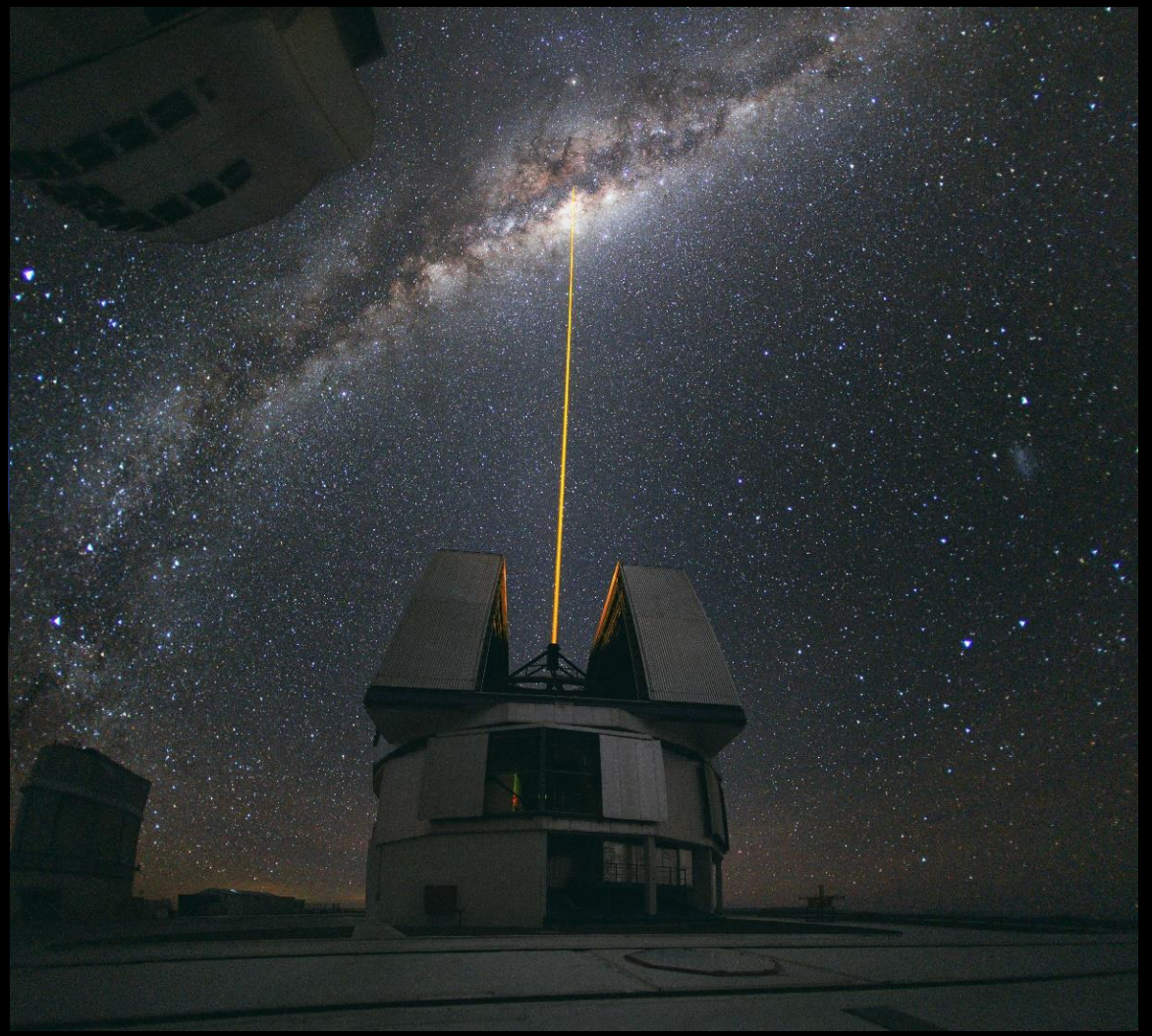
Wollman et al. 1977, Lacy + 1980, Balick & Brown 1974, Serabyn & Lacy 1985, Genzel & Townes 1987, Doeleman +2008, 2013

Intermezzo (1992-1998): Motions of stars: the importance of key new technologies

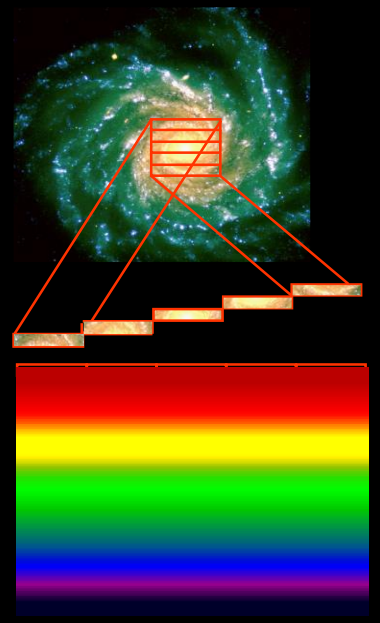
Low-noise IR Imaging Detectors
Adaptive Optics
Fast RTCs
Integral- Feld Spectroscopy
Laser guide stars



NICMOS HgCdTe detector



Modern 10m class telescope with artificial laser guide star



IFU spectrometers

Hofmann +1993, Eckart +1993, 1995, Weitzel +1996, Ghez et al. 1998, 2005, Wizinowich et al. 2005

La Secunda (1992-1998): Motions of stars around SgrA*

1992….
ESO-NTT 3.5m


A.Eckart


R.Schoedel


F.Eisenhauer

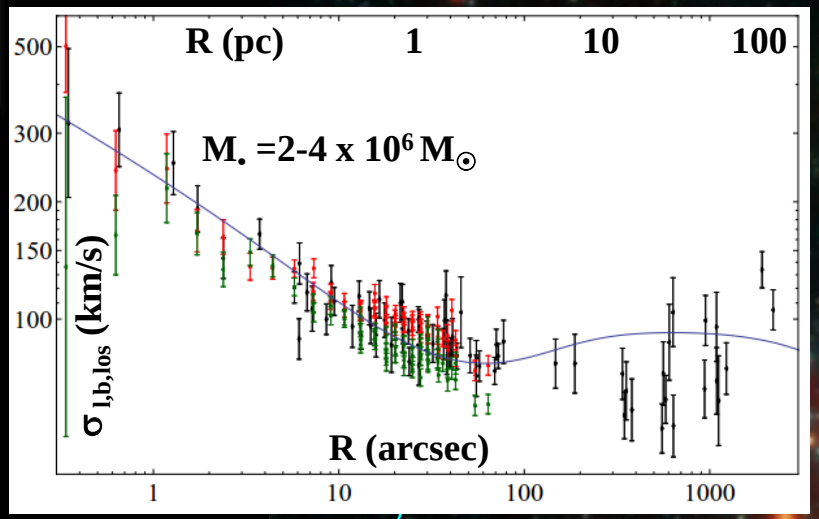

S.Gillessen

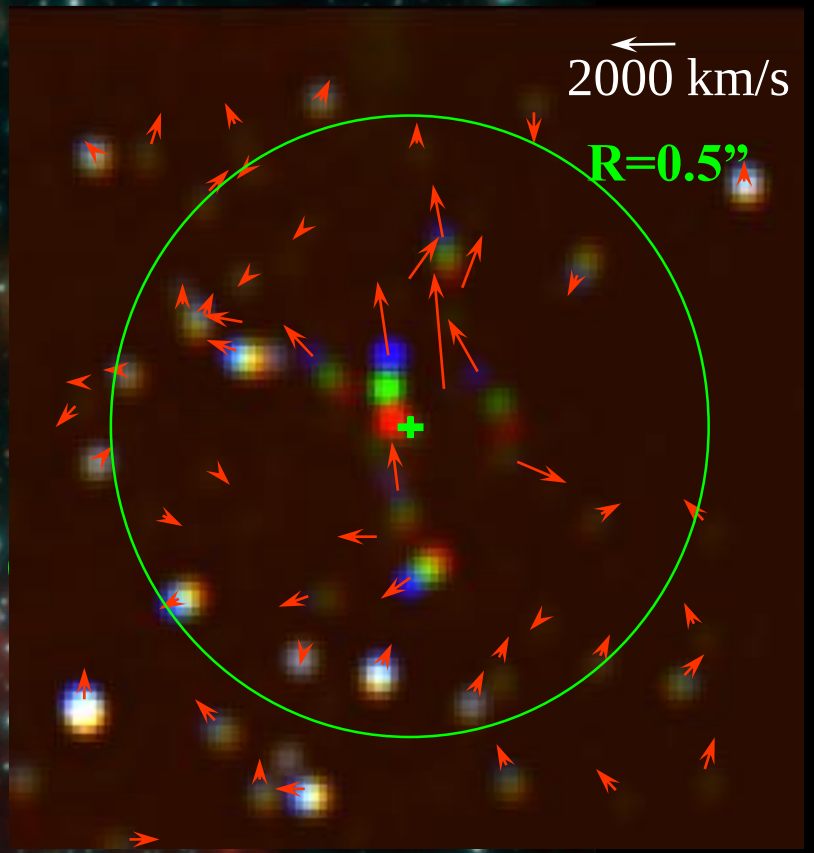
1995….
Keck 10m


A.Ghez


M.Morris


E.Becklin



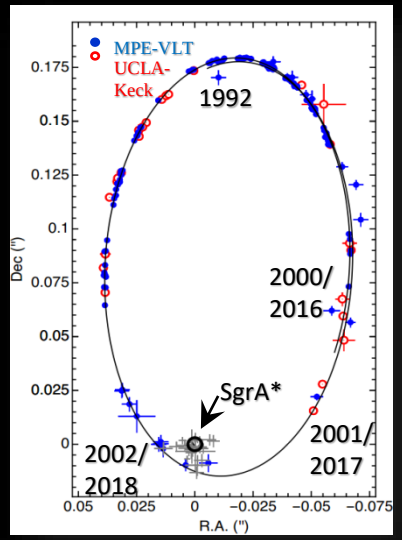


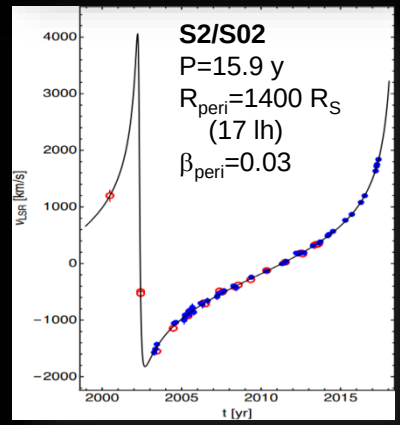
Eckart & Genzel 96, 97, Ghez +98

Tertia: Stellar Orbits (2002-2017)

10m Keck 1 & 2
NIRC2 AO
OSIRIS IFU
LGSF

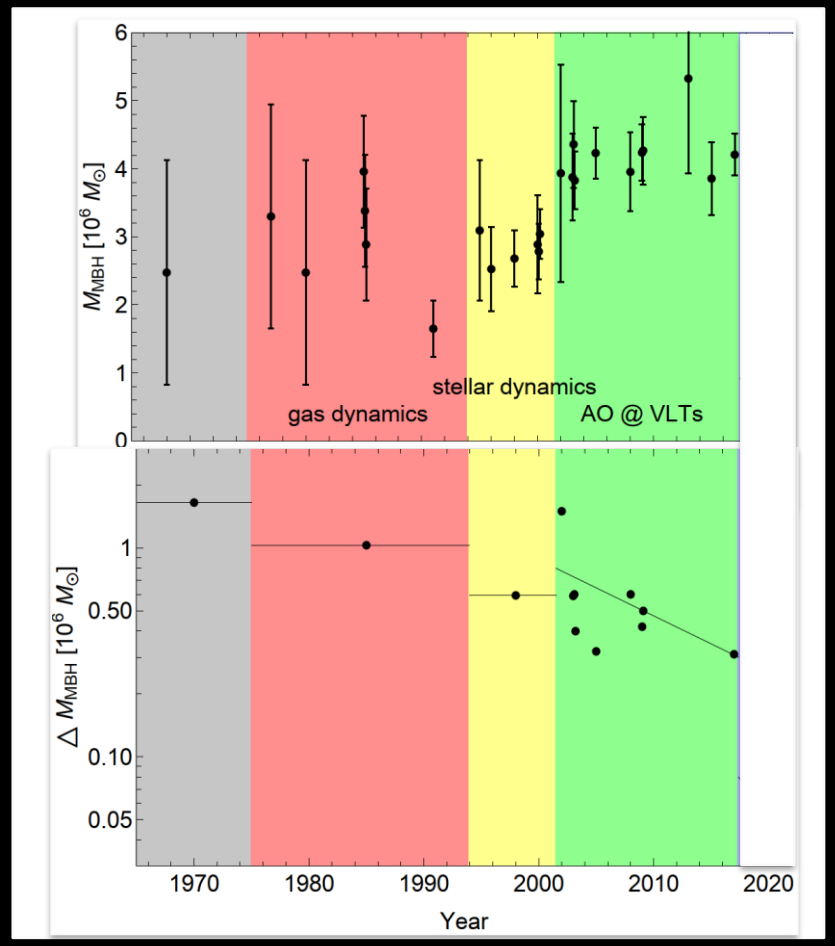
8m VLT UT
NACO AO
SINFONI IFU
PARSEC LGSF

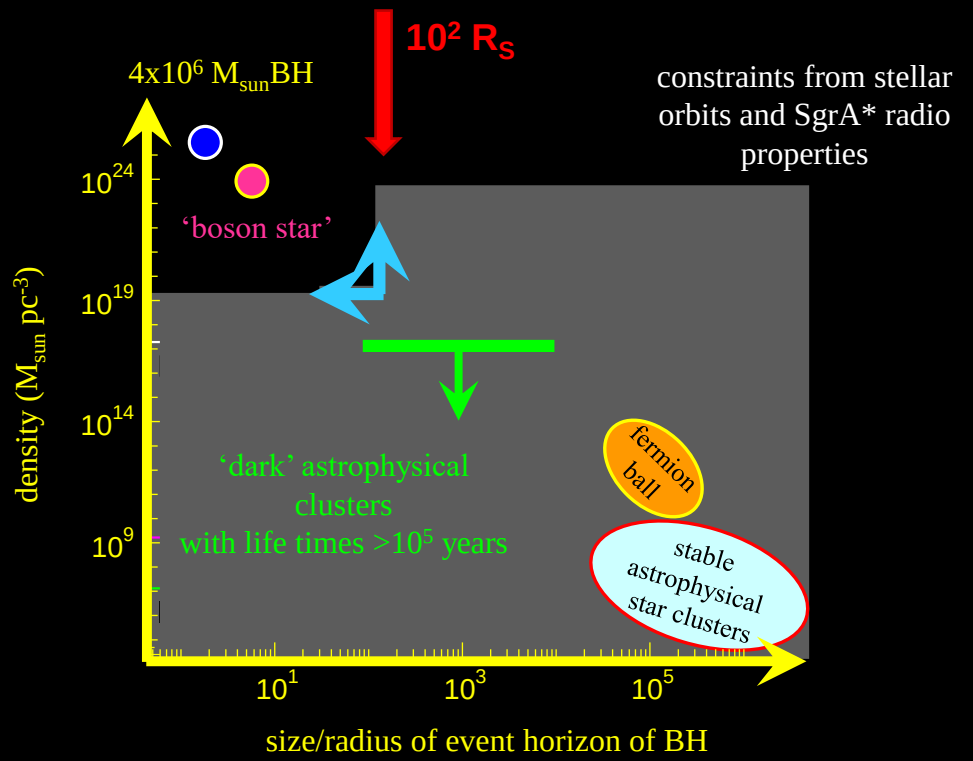




Ghez + 2000, 2003, 2008, Schödel +2002, 2003, Gillessen + 2009a,b, 2017, Meyer +2012, Fritz +2014, Boehle +16

After Phase 3 (2017)





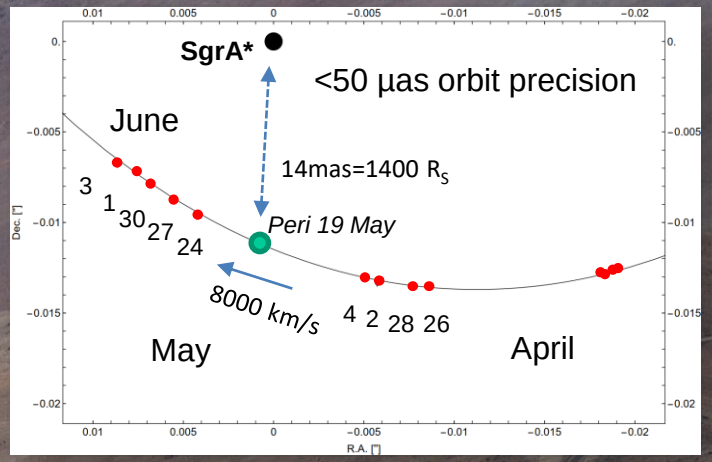
Maoz 1998, Schödel +2003, Ghez + 2005, 2008, Gillessen +2009, 2017, Coleman Miller 2006, Tsiklauri & Viollier 1998, Torres + 2000, Chapline +2001, 2003, Mazur & Mottola 2004, Genzel, Eisenhauer & Gillessen 2010

Phase 4 (2017….): GRAVITY & GR Tests

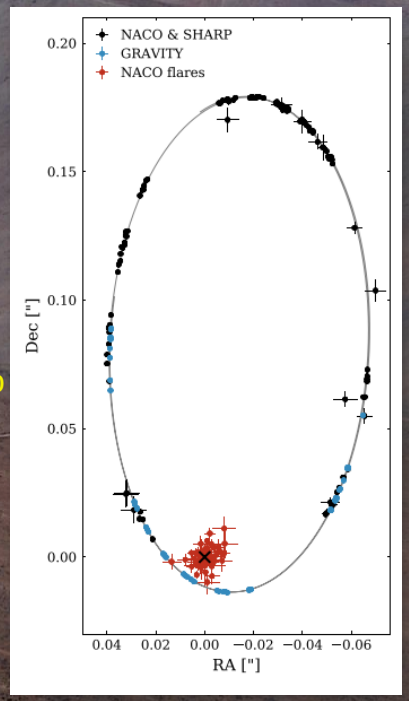
Frank Eisenhauer

Pierre Léna

Guy Perrin



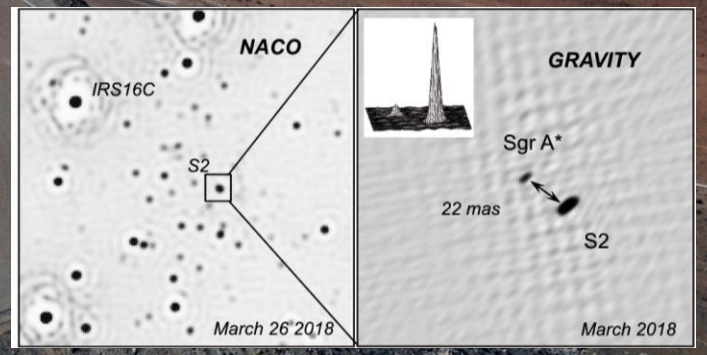
Motion of S2 seen from day to day



The GRAVITY VLTI Beam Combiner:
3 milli-arcsec angular resolution
20-100 micro-arcsecond astrometry
spectroscopy, polarimetry

GRAVITY

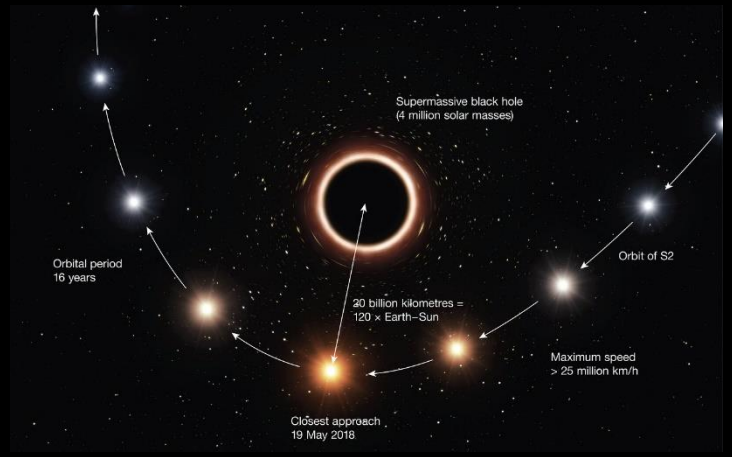
150mas
1.4e4 R_S

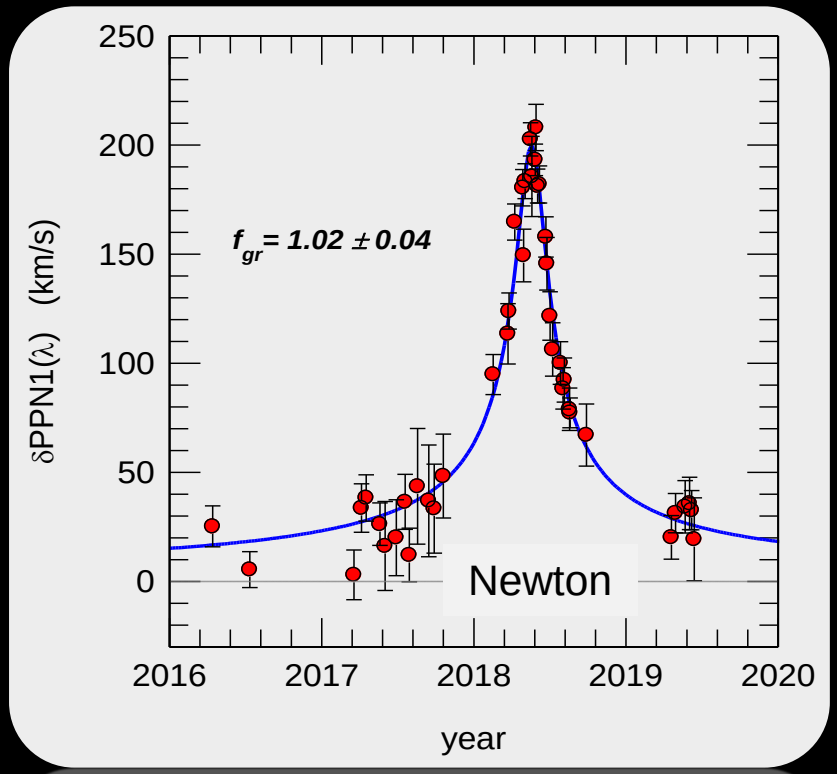


deepest GRAVITY image
to date: 8 hours, May 2018, K_m ~ 21
(10^4 fainter than previous interferometry)

The GRAVITY collaboration 2017

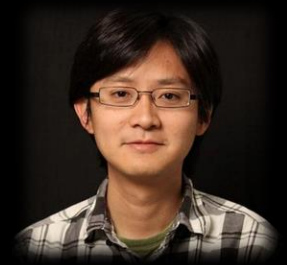
GR Effects in the Orbit of S2: Gravitational Redshift






T.Alexander


F.Eisenhauer

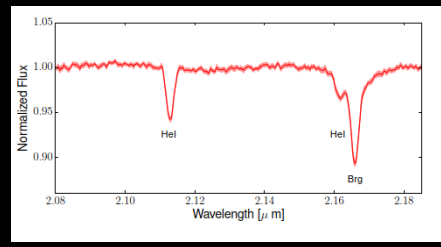

T.Do


F.Widmann

Test of the Local Positional Invariance of Einstein's Equivalence Principle

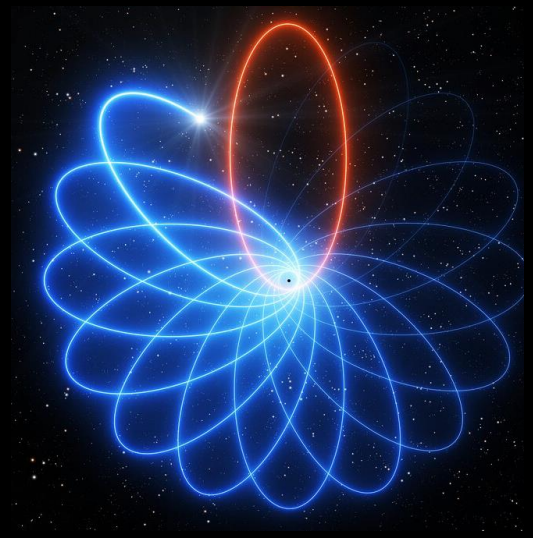
$$\frac{\Delta\nu}{\nu} = (1+\beta)\frac{\Delta\Phi}{c^2}$$

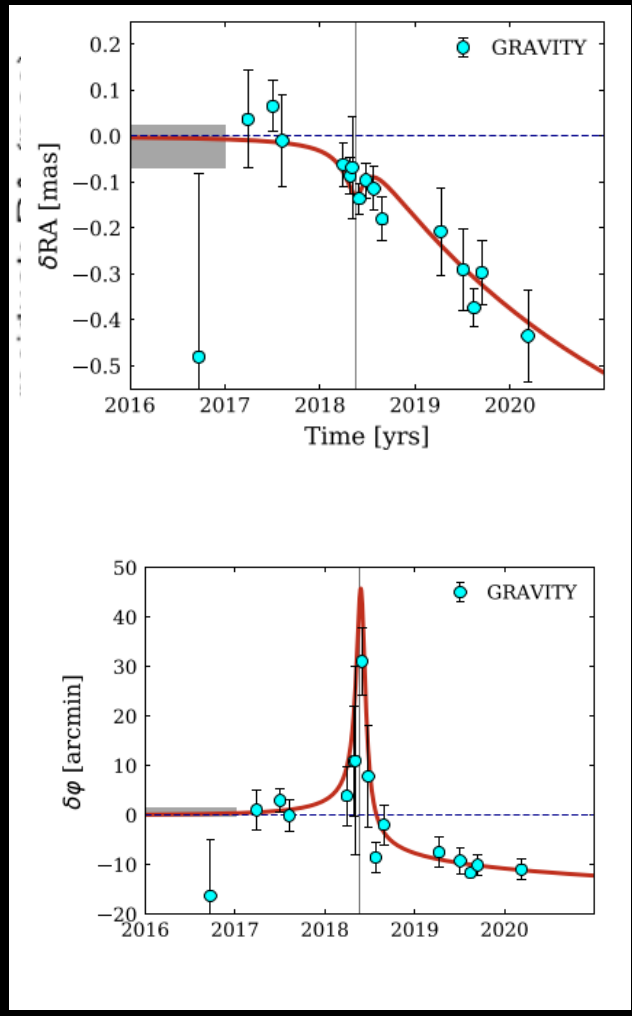
$$\Delta\beta = |\beta_{He} - \beta_H| = (2.4 \pm 5.1) \cdot 10^{-2}$$



GRAVITY collaboration+18a, +19b,+20, Do et al. 2019

GR effects in the orbit of S2: Schwarzschild Precession





S.Gillessen

A.Eckart

GRAVITY collaboration 2020

Detection of Orbital Motions near SgrA*s ISCO


J.Dexter

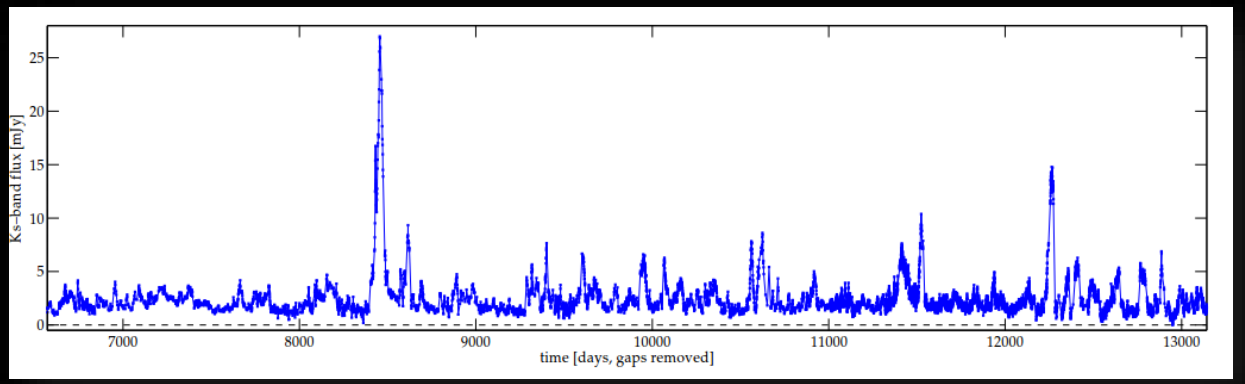

O.Pfuhl

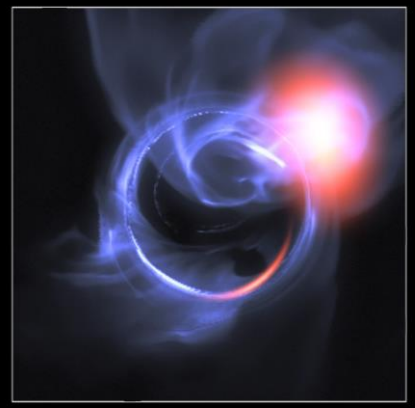

T.Paumard

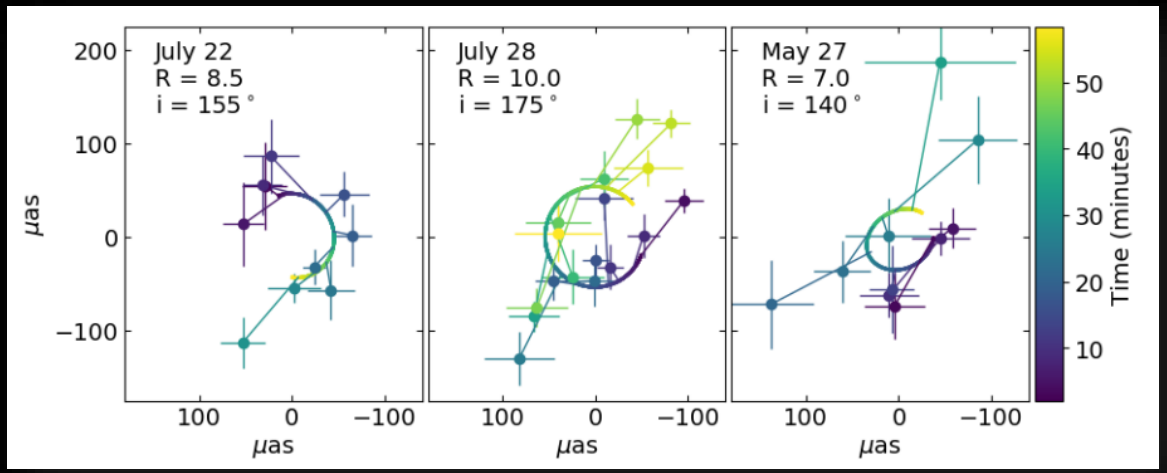

M.Bauboeck


S.Fellenberg


A.Jimenez








K.Dodds-Eden

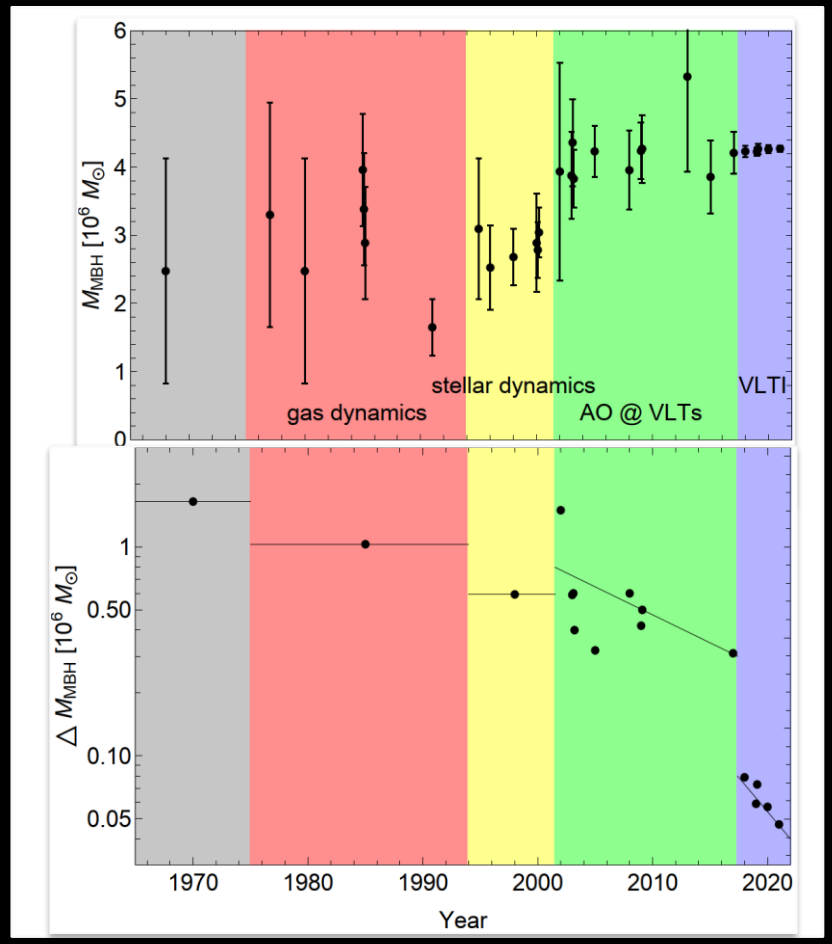

G.Witzel

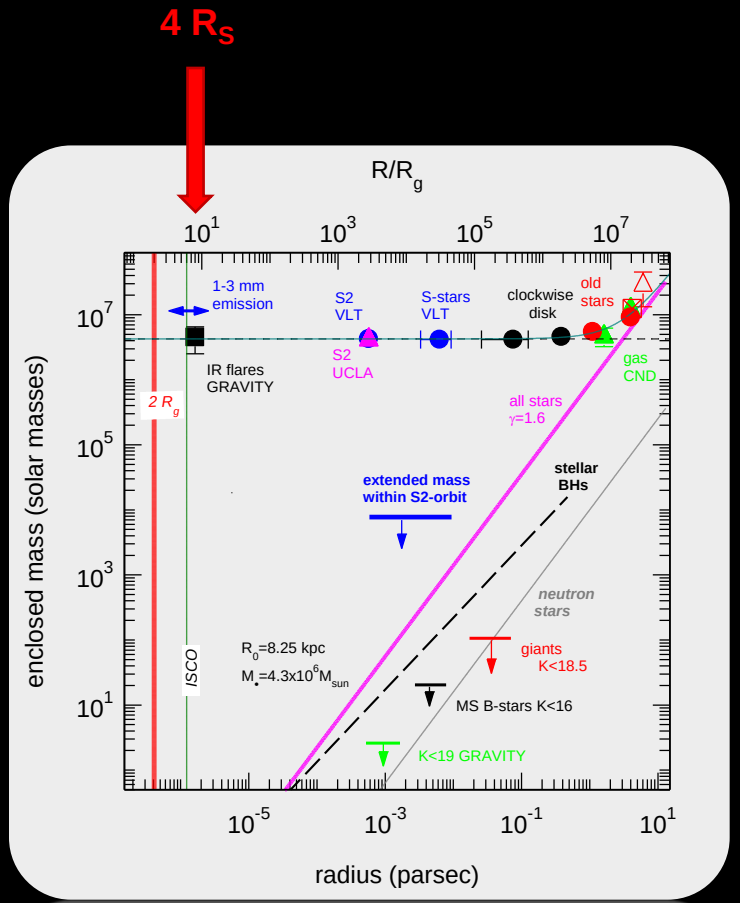

F.Baganoff

→ P_{orb}~40-50 minutes
R_{orb}~6-10 R_g
v_{orb}~0.3 c ~$v_{orb}(4x10^6 M_\odot)$
P_{mag}~P_{orb}→ poloidal B-fields

Baganoff +2001, Genzel +2003, Ghez +2004, Do +2008, Dodds-Eden +2009, 2010, , Witzel +2012. 2018, Ponti +2017, Broderick & Loeb 2005, 2006, Hamaus +2009, Markoff +2001, Yuan +2004, Moscibrodzka +2015, Dexter +2013, Doeleman +2008, Broderick +2011, Johnson +2017, GRAVITY collaboration 2018b, 2020d

After Phase 4 (2020)



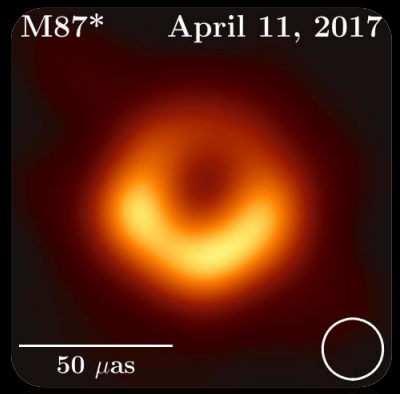


black hole mass: $4.268_{0.012\ [0.03]}\times10^6$
(3×10^{-3} [$7x10^{-3}$] precision)
GC distance: $8252_{8\ [40]}$ pc (10^{-3} [$5x10^{-3}$])

Gravity Collaboration et al. 2018a,b, 2019a,b, 2020a, Do et al. 2019

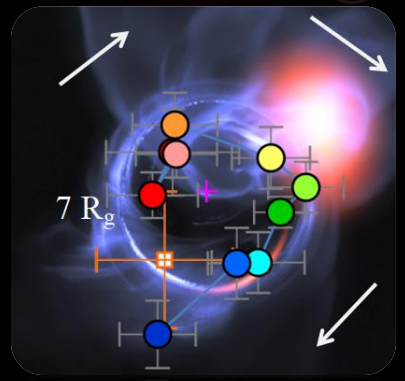
Are we done?

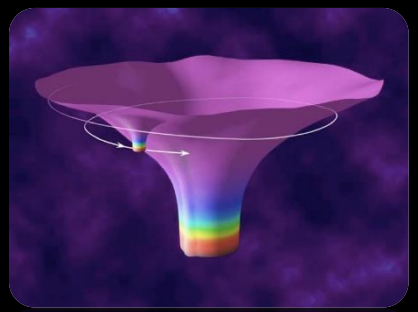
(are black holes described by the Kerr Space-Time and can other theories of gravity, boson-stars, grava-stars etc. be excluded ?)



$$\left(\frac{q}{M}\right) = -\left[a^2 + \varepsilon\right] \quad \text{(no hair)}$$

object	measurement	limit on ε
AGN	Kα line width/reverberation	a few
GW150914	in-spiral/ring down	0.3-0.7
SgrA*	GRAVITY hot spots near ISCO	1
SgrA*	**EHT ring & mass from stars**	**0.5**
SgrA*	**GRAVITY faint star R~10mas**	**0.3**
SgrA*	**GRAVITY & EHT**	**0.1**
SgrA*	**pulsar in central 10 mas**	**0.1**
SgrA*	**MICADO spectroscopy**	**0.05**
distant MBH	**LISA EMR in-spiral**	**0.01**





Johannsen & Psaltis 2010 a,b, Will 2014, Johannsen 2016, Psaltis, Wex & Kramer 2016, Johannsen et al. 2016, Zhang et al. 2015, Waisberg et al. 2018 , GRAVITY collaboration et al. 2018c, EHT collaboration et al. 2019, Cardoso & Pani 2019

The Future

Spin of GC MBH

No-hair theorem
Test from IR+EHT

Faint stars
inside S2 orbit

GRAVITY+

Intermediate mass
Black Holes

Tidal disruption

Measuring BH-masses from resolved BLR studies from z=0 to 2

Binary BHs & the final parsec problem

MICADO @
EELT