The Galactic Center

a laboratory for testing physical processes near massive black holes

Reinhard Genzel, Frank Eisenhauer & Stefan Gillessen, MPE

The GC Legacy Program: Motivation

Mon. Not. R. astr. Soc. (1971) **152**, 461–475.

ON QUASARS, DUST AND THE GALACTIC CENTRE

D. Lynden-Bell and M. J. Rees

(Received 1971 January 5)

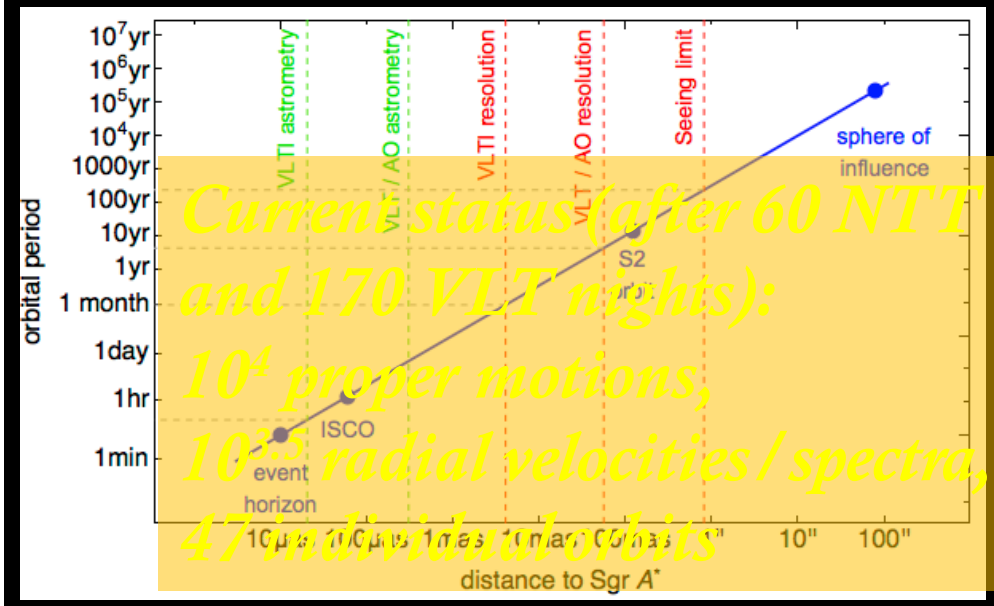
SUMMARY

The black-hole model of galactic nuclei is used to discuss properties of quasars as proto-black-holes in the middle of galaxies. Quasar life-times may be as long as $\sim 10^8$ years and masses will be of the order of $10^8 M_\odot$. Dust in the neighbourhood of black holes is sometimes driven from the accreted gas by radiation pressure. This may cause the dust often seen in exploding nuclei and the infra-red radiation from the galactic centre. Dust models for the galactic centre are considered in detail, and it is suggested that there may be a central black hole currently emitting $\sim 1{\cdot}5 \times 10^8 L_\odot$ in the ultra-violet and blowing away a hot nuclear wind. Emission knots in the central regions probably contain prominent OB stars which would make the Galaxy later than Sb. Finally we list critical observations which could establish the existence of a large central mass in the Galaxy of so small a size that it must be associated with a black hole.

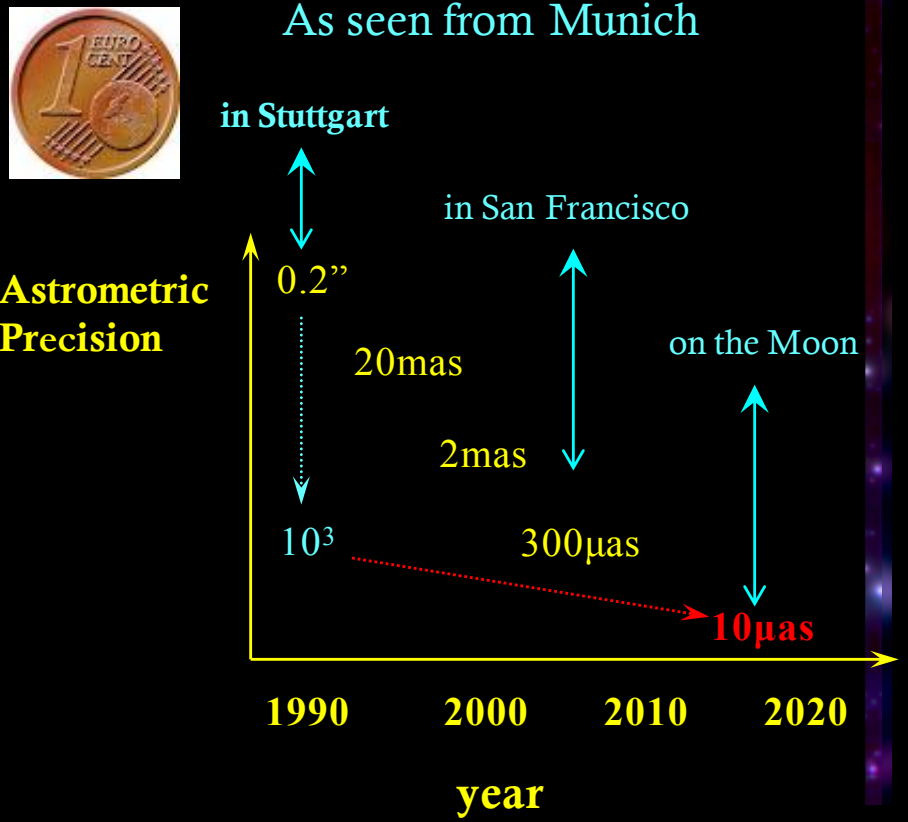
an unambiguous 'proof' for the existence of a black hole requires the determination of the gravitational field/space time metric to the scale of the event horizon.

The GC Legacy Program: high resolution imaging & precision astrometry of stars (as tracers of gravity)

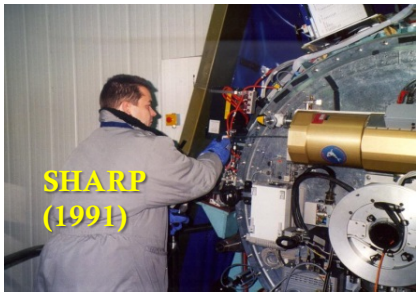
at 8 kpc:, 1mas=1 lh, 1mas/yr = 39 km/s

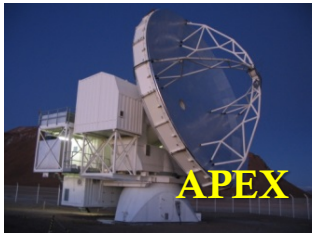


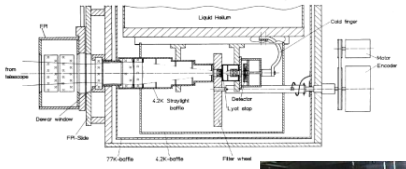
Current status (after 60 NTT and 170 VLT nights):
10^4 proper motions,
$10^{3.5}$ radial velocities / spectra,
47 individual orbits



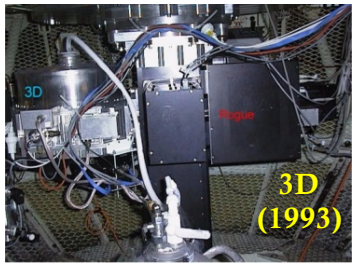
The MPE-ESO Galactic Center Legacy Program

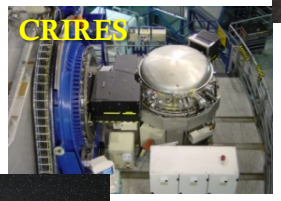


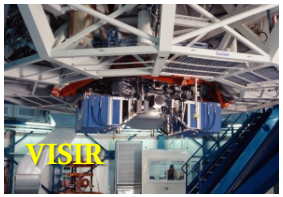


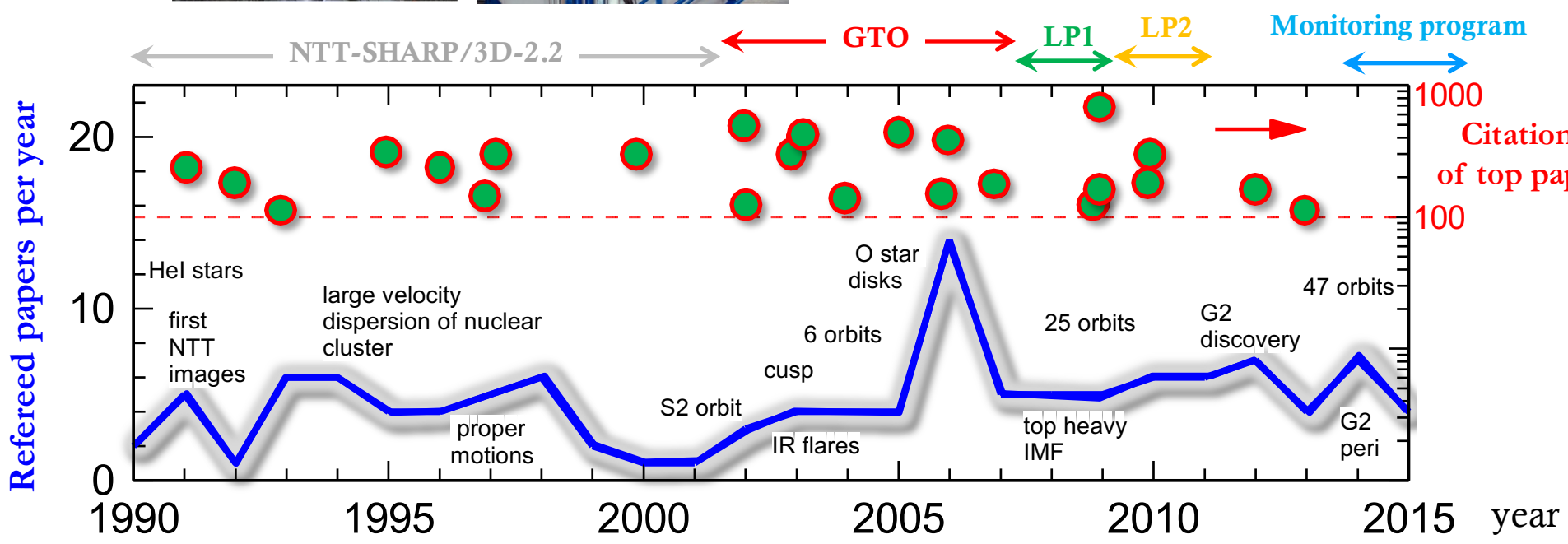


FAST (1990)

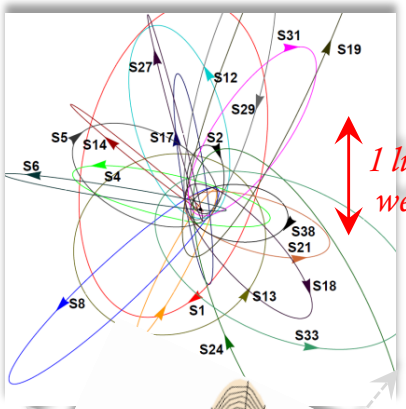


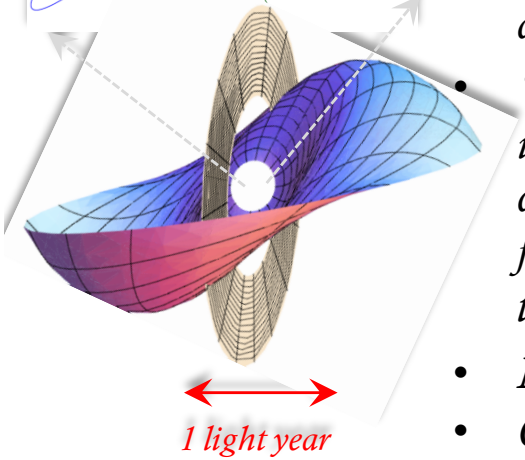


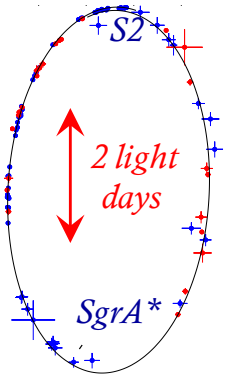




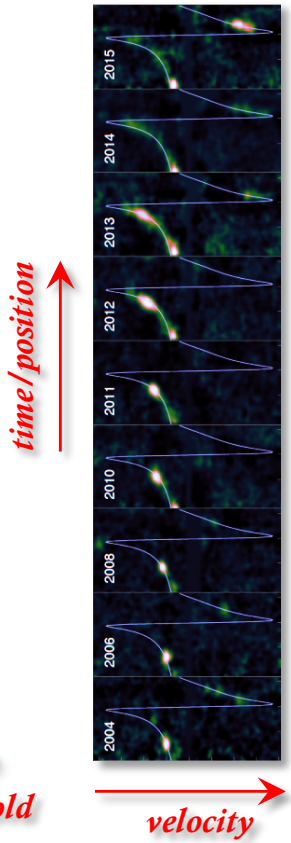
Highlights of the Galactic Center Legacy Program

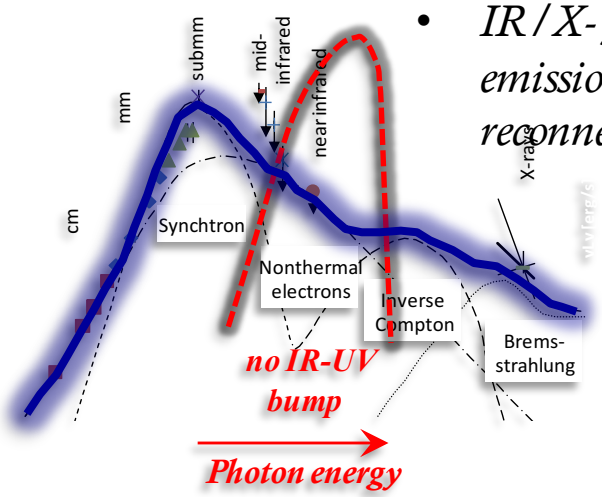


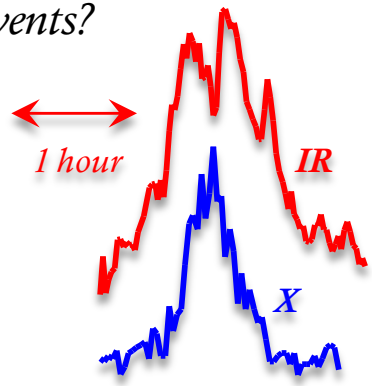


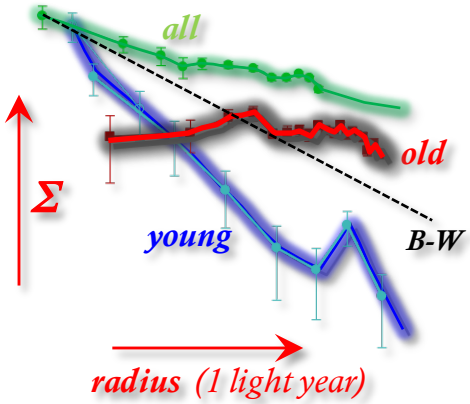


- *Compelling Detection of $4x10^6$ $M_\odot$ Central Mass, which must be a Schwarzschild-Kerr Black Hole, if GR is applicable*
- *'Paradox of Youth': presence of a compact cluster of B/A-stars immediately around the MBH, as well as one or two rotating disks of O/WR stars surrounding it, indicating that episodic star formation and/or fast loss-cone injection/capture is effective near the MBH; the O/WR disk(s) have a top-heavy IMF*
- *No Bahcall-Wolf cusp: nature or nurture?*
- *G2: tidal disruption of gas cloud/envelope in front of our eyes*
- *'feeble' emission and lack of 'Big Blue Bump' from MBH (η_{Edd}~10^{-8} : advection dominated accretion & outflows)*
- *IR/X-flares from inner accretion zone of MBH: synchrotron emission from accelerated (γ~10^3) electrons at ~10 R_S: magnetic reconnection events?*

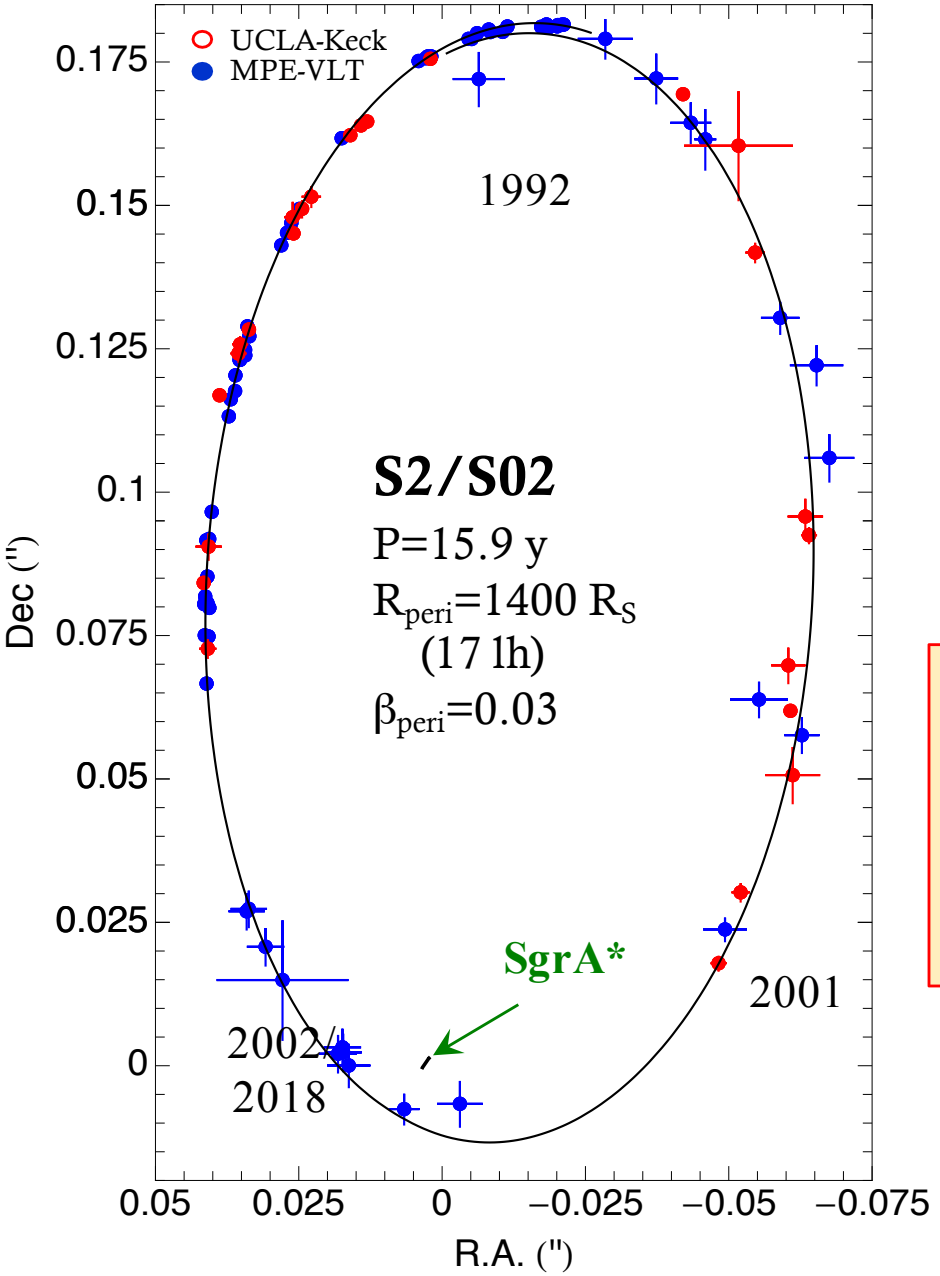








stellar orbits testing the potential: S2



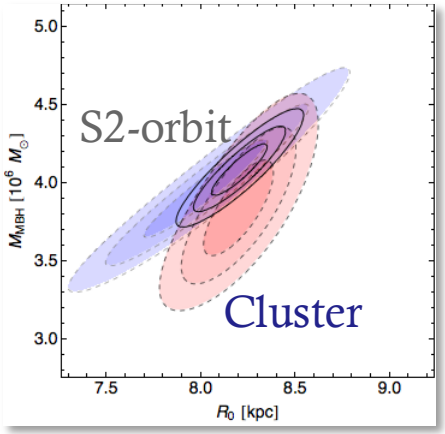
$M_\bullet = 4.26(\pm0.14)_{stat}(\pm0.2)_{sys} \times 10^6\, M_\odot$

$R_0 = 8.36\,(\pm0.1)_{stat}(\pm0.15)_{sys}$ kpc

$\rho_\bullet > 10^{16..19.5}\, M_\odot pc^{-3}$

$M_{extended}/M_\bullet <$ a few 10^{-2}

$M_\bullet$ & SgrA* coincident <0.3mas



Schödel et al. 2002, 2003, Ghez et al. 2003, 2008, Eisenhauer et al. 2003, 2005, Gillessen et al. 2009a,b, Meyer et al. 2012, Chatzopoulos et al. 2015, Fritz et al. 2015, Plewa et al. 2015

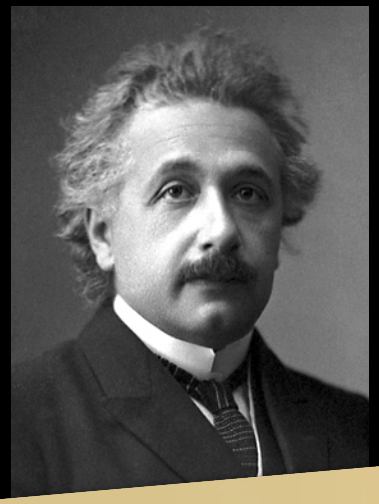
1916. № 7.

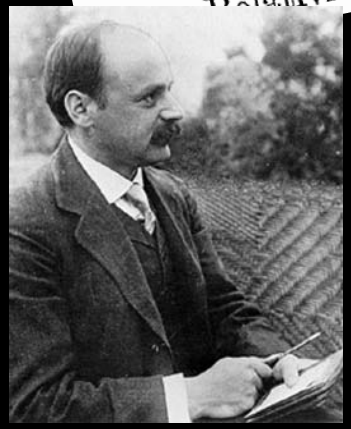
ANNALEN DER PHYSIK.

VIERTE FOLGE. BAND 49.

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

Die im nachfolge
bar weitgehendste Ve
„Relativitätstheorie“
ich im folgenden zur
Relativitätstheorie“





Über das Gravitationsfeld eines Massenpunktes nach der Einsteinschen Theorie.

Von K. Schwarzschild.

(Vorgelegt am 13. Januar 1916 [s. oben S. 42].)

§ 1. Hr. Einstein hat in seiner Arbeit über die Perihelbewegung des Merkur (s. Sitzungsberichte vom 18. November 1915) folgendes Problem gestellt:

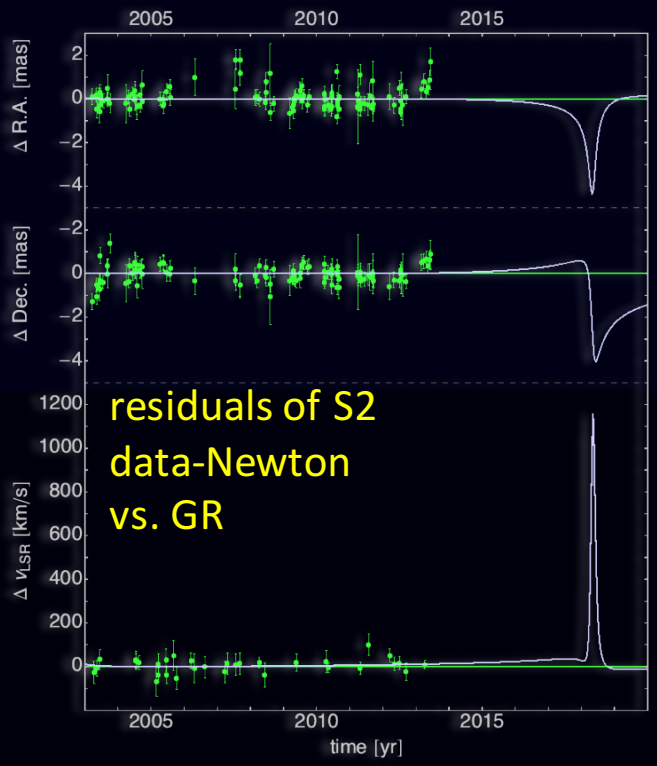
Ein Punkt bewege sich gemäß der Forderung

$$\left.\begin{aligned} &\delta\int ds = 0, \\ &ds = \sqrt{\sum g_{\mu\nu} dx_\mu dx_\nu} \qquad \mu,\nu = 1,2,3,4 \end{aligned}\right\} \quad (1)$$

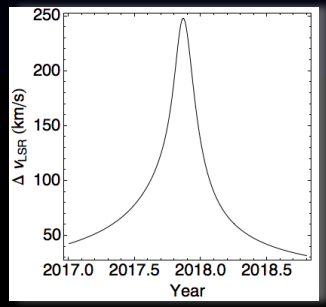
wobei

Inward bound

GRAVITY & submm-VLBI pulsars?

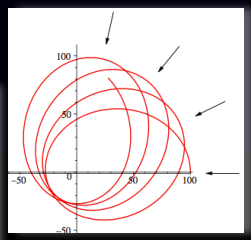


residuals of S2 data-Newton vs. GR



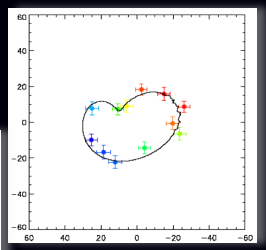
β^2 effects in radial velocities

1



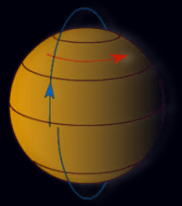
relativistic prograde precession

2



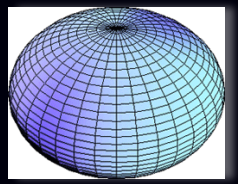
spin from Flares, L-T precession

3



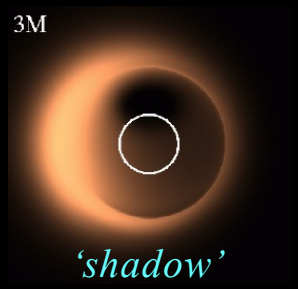
Strong curvature: photon orbit

4

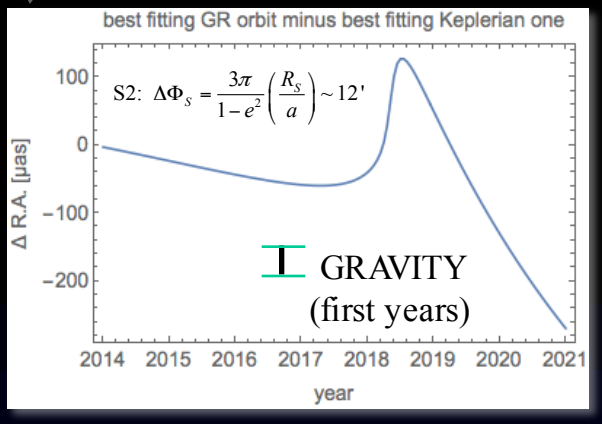


Quadrupole moment of metric, no hair & quantum effects

5



more challenging



Impact of GC Legacy Program

- *Driver of State of the Art Instrumentation Development: FAST, SHARP, 3D, NACO, SINFONI, PARSEC, LABOCA, KMOS, GRAVITY*

- *Education: 29 PhDs, 25 postdocs Europe-wide*
- *Papers: ~100 refereed publications , ~11,000 citations*

- *Remarkable String of (Theoretically) Unexpected Discoveries over 25 Years*
- *A Highlight Result of ESO, in head-to-head competition with Keck*

- *GC as a Physics Laboratory: currently best proof of MBH paradigm*
  : next step PN and strong-curvature tests of GR
- *GC as an Astrophysics Laboratory: gas accretion, star formation and dynamics/structure/evolution of star cluster near MBH*
  : measuring R_0 to percent accuracy
  : guidance on MBH accretion in low-density limit
  : strong participation & stimulation of theory