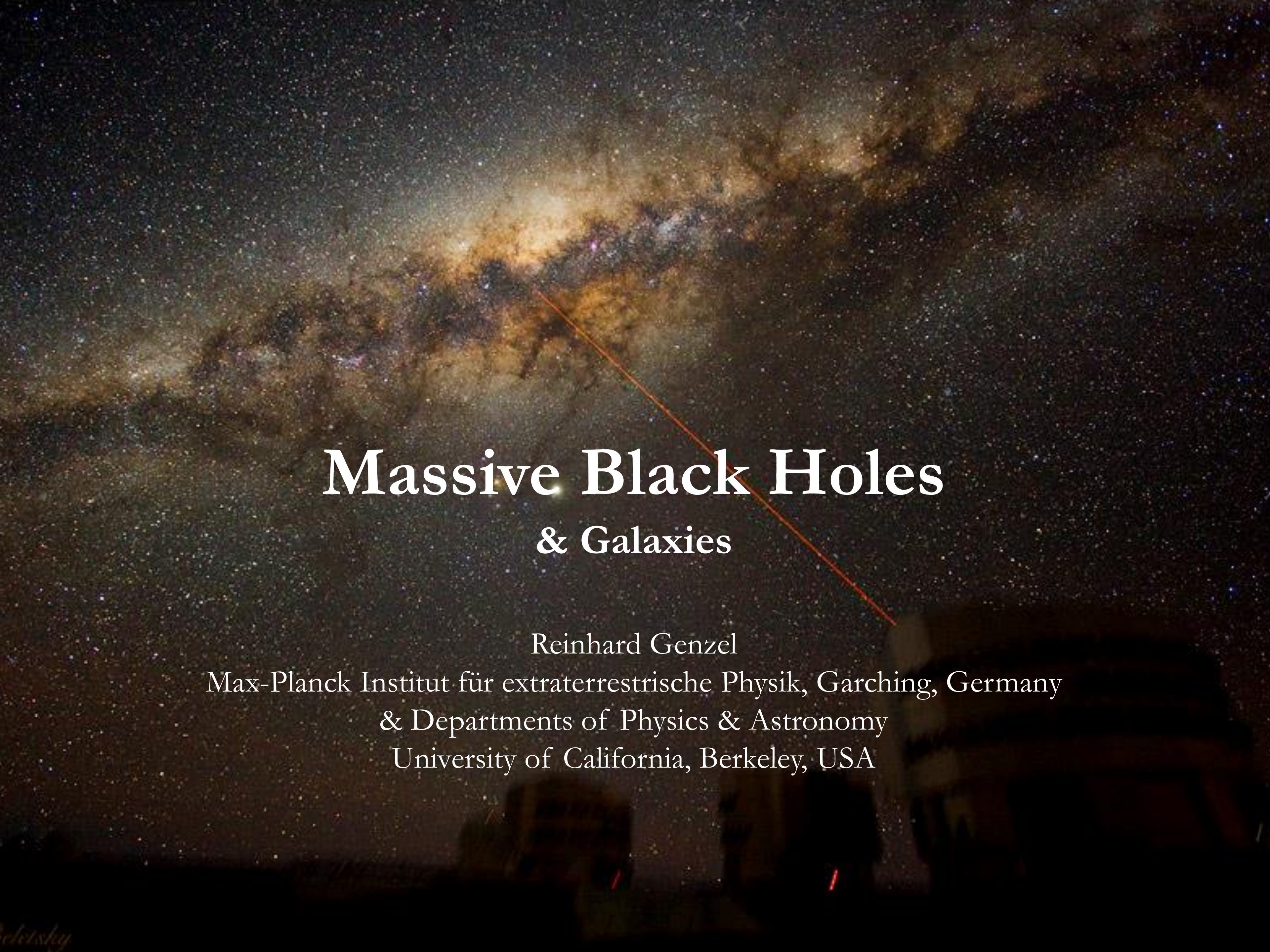


Massive Black Holes

& Galaxies

Reinhard Genzel
Max-Planck Institut für extraterrestrische Physik, Garching, Germany
& Departments of Physics & Astronomy
University of California, Berkeley, USA

Quasars

& the high-z Universe

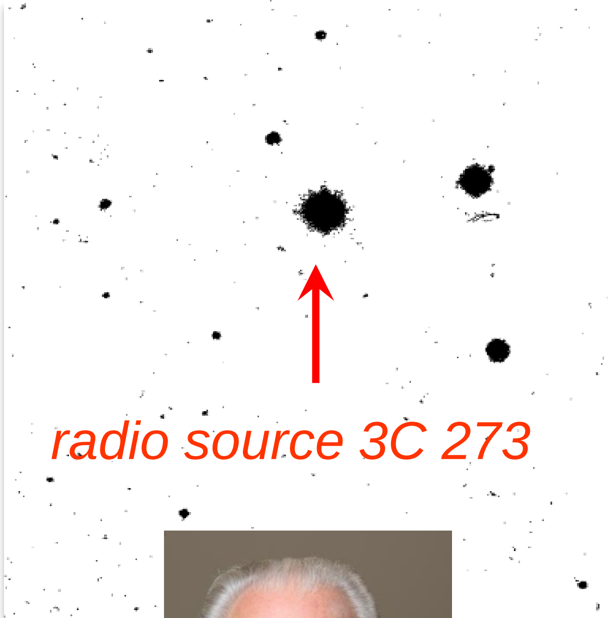


Table 1. Wave-lengths and Identifications

λ	$\lambda/1\cdot158$	λ_0	
3239	2797	2798	Mg II
4595	3968	3970	Hϵ
4753	4104	4102	Hδ
5032	4345	4340	Hγ
5200–5415	4490–4675		
5632	4864	4861	Hβ
5792	5002	5007	[O III]
6005–6190	5186–5345		
6400–6510	5527–5622		

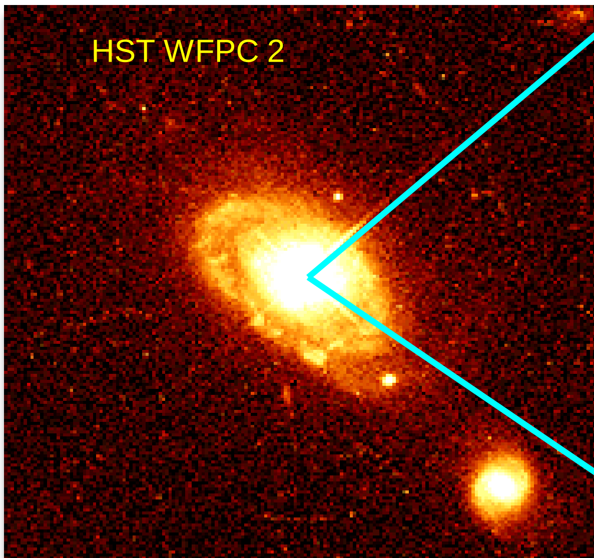
Marten Schmidt
1963

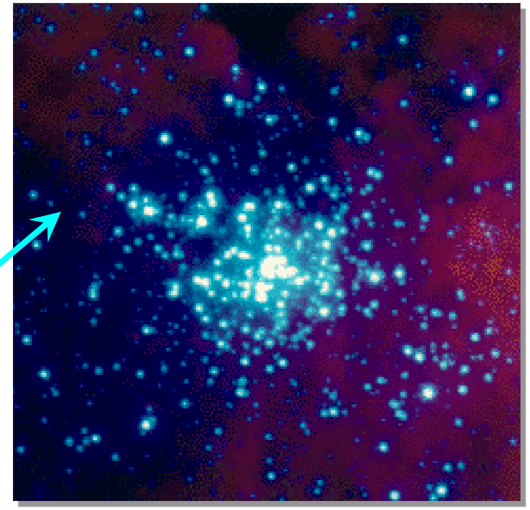
z=0.16, D=2.4 billion light years!
$L \sim 10^3\ L_{\text{milky Way}}$

by 1973: z~3.5 (lookback time 11.6 Gyr), $L \sim 10^5\ L_{MW}$

Burbidge, Greenstein, Hazard, Matthews, Rees, Sandage,Schmidt 1961-1970

what powers Quasars ?



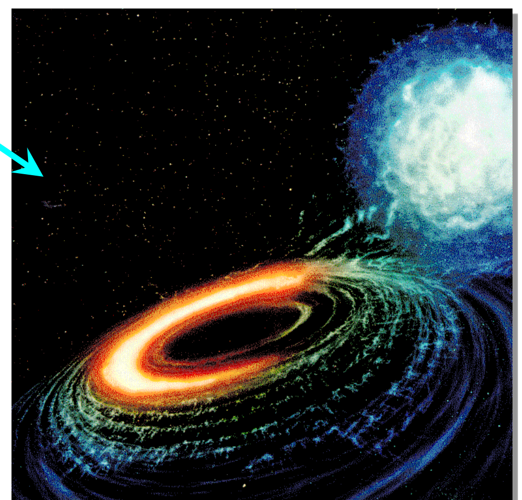


R. Sunyaev

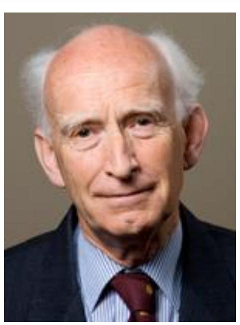
fusion:
$E < 0.005 \ Mc^2$

‘Schwarzschild throat’

(Schwarzschild-Kerr)



accreting BH model:
$E \sim 0.06 \ldots 0.4 \ Mc^2$
variable X- and γ-radiation
relativistic radio jets



D.Lynden-Bell

M. Rees

Salpeter, Lynden-Bell, Rees,
Shakura, Sunyaev 1964 - 1973

How to prove the existence of BHs ?

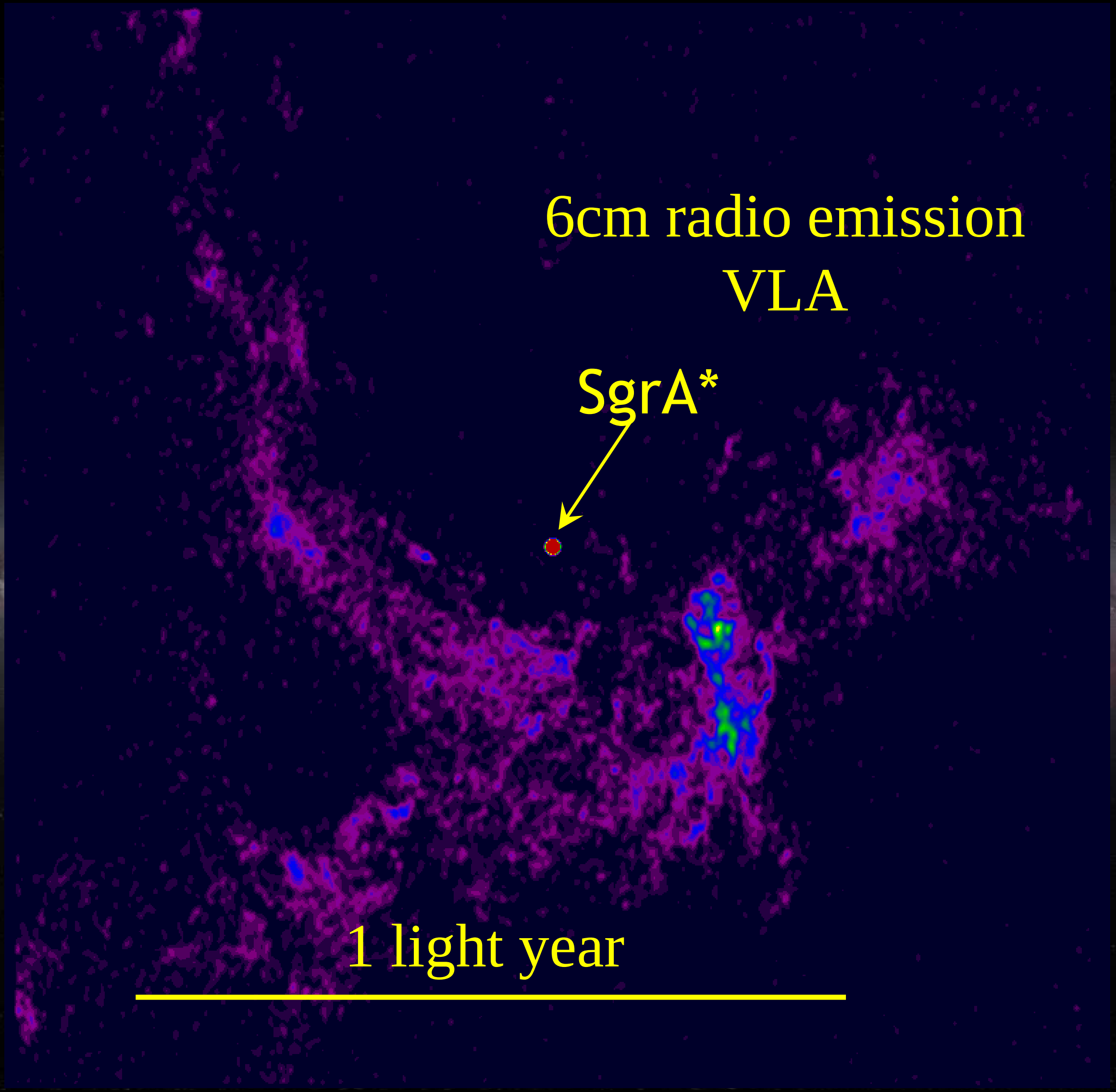
ON QUASARS, DUST AND THE GALACTIC CENTRE

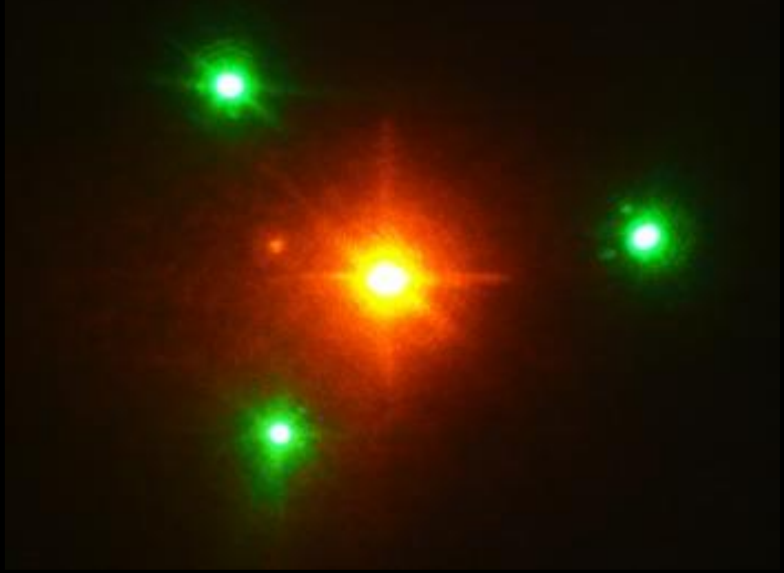
D. Lynden-Bell and M. J. Rees

(Received 1971 January 5)

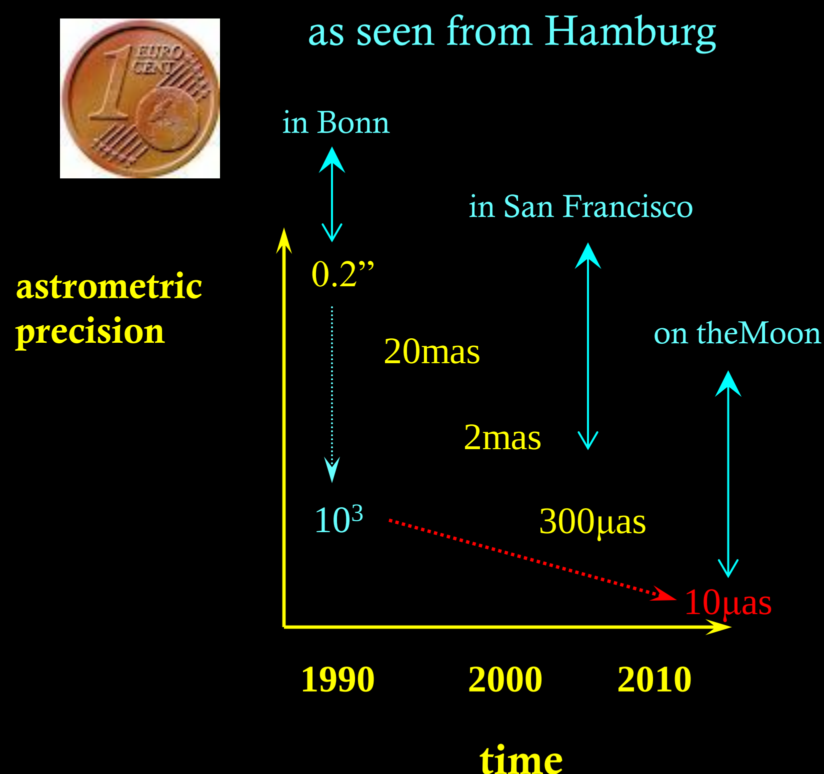
an unambiguous 'proof' for the existence of a black hole requires the determination of the gravitational field/space time metric to the scale of the event horizon.

A Journey to the Center of the Milky Way





The MPE 'ARGOS' GLAO field correction system for the Large Binocular Telescope (LBT)


as seen from Hamburg
in Bonn
in San Francisco
on theMoon
astrometric precision
0.2”
20mas
2mas
10³
300µas
10µas
1990
2000
2010
time

Motions of stars around SgrA*

F.Eisenhauer

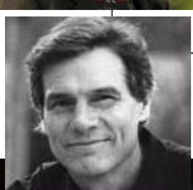
S.Gillessen

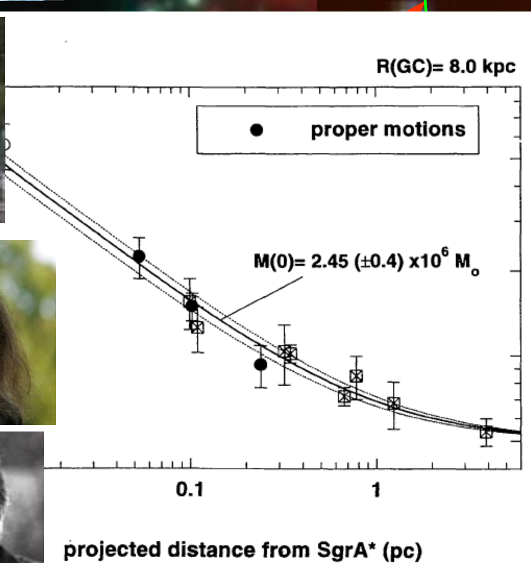
A.Eckart

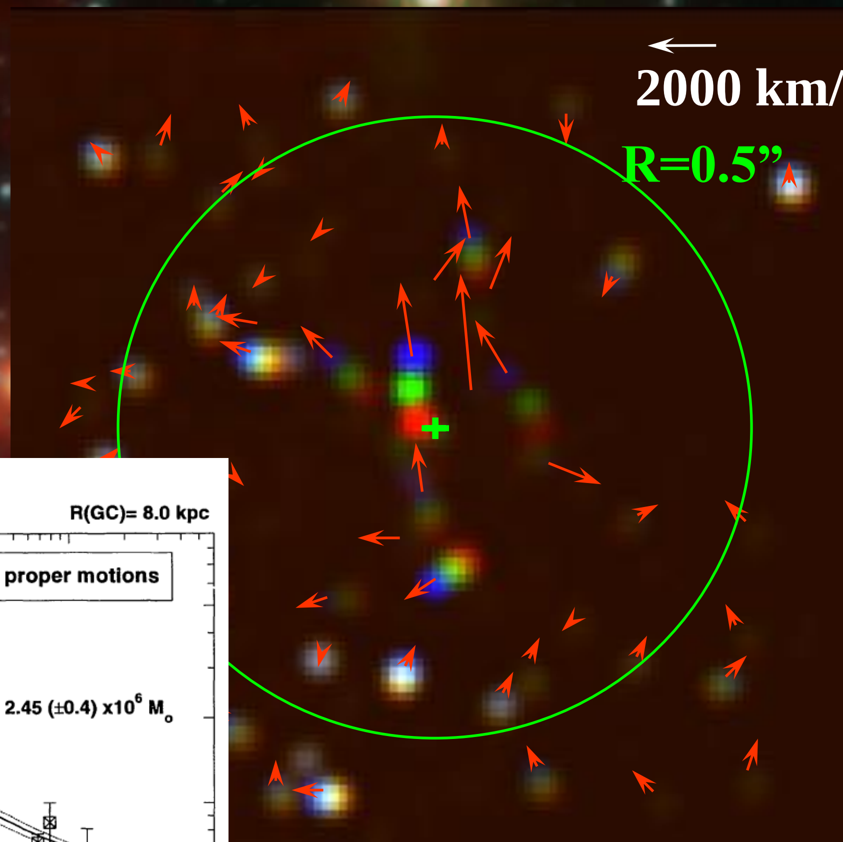
R.Schoedel

A.Ghez

M.Morris

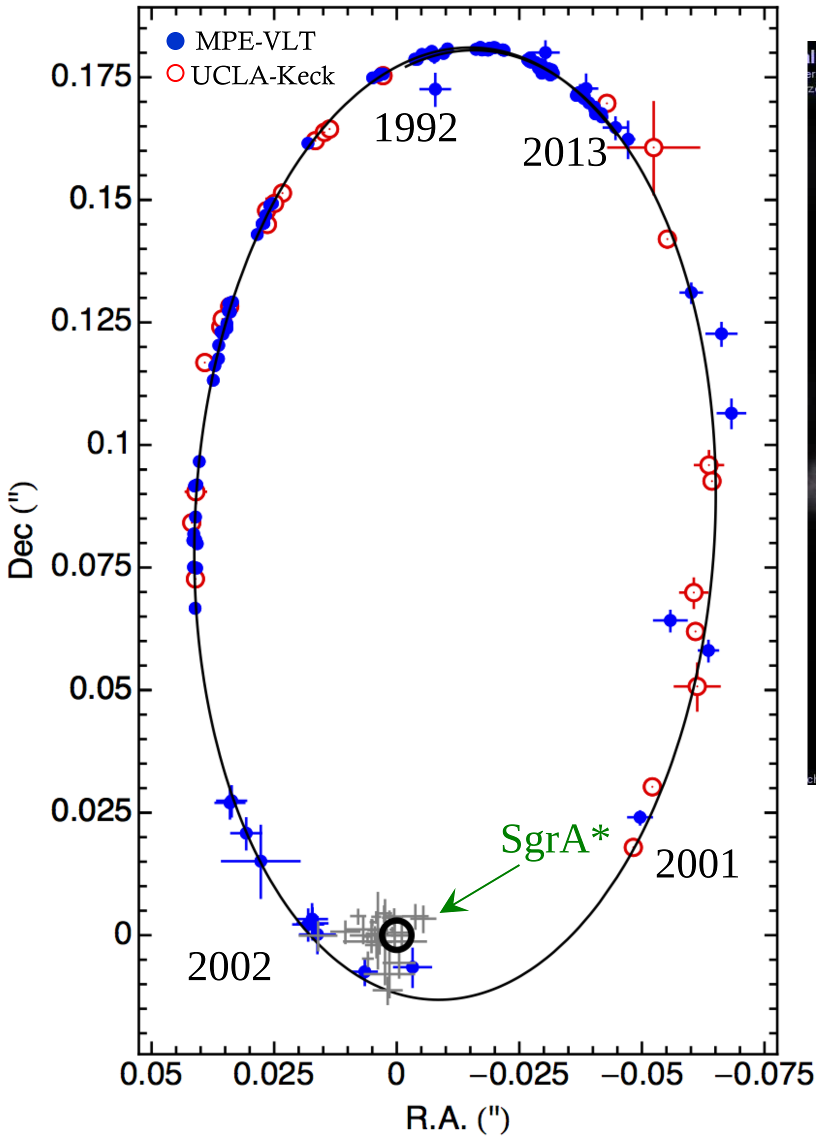


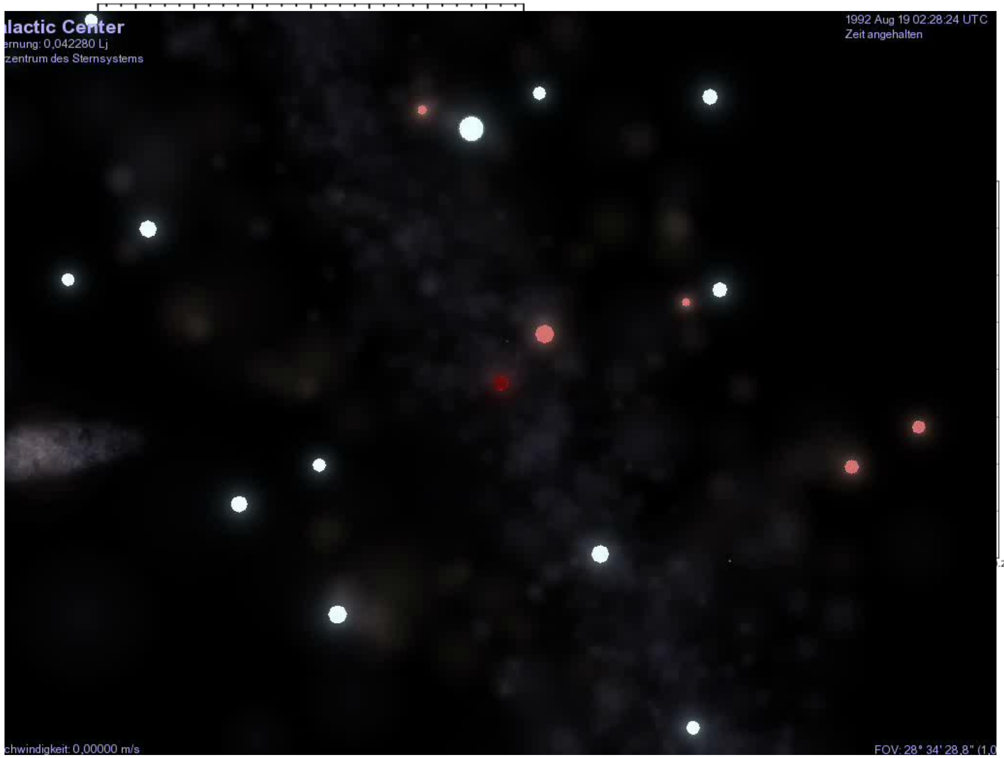




Eckart & Genzel 1996, 1997, Ghez et al. 1998

a complete orbit: S2 (1992-2013)





$M_\bullet$= 4.30(±0.20)$_{stat}$(±0.30)$_{sys}$ x10^6 $M_\odot$

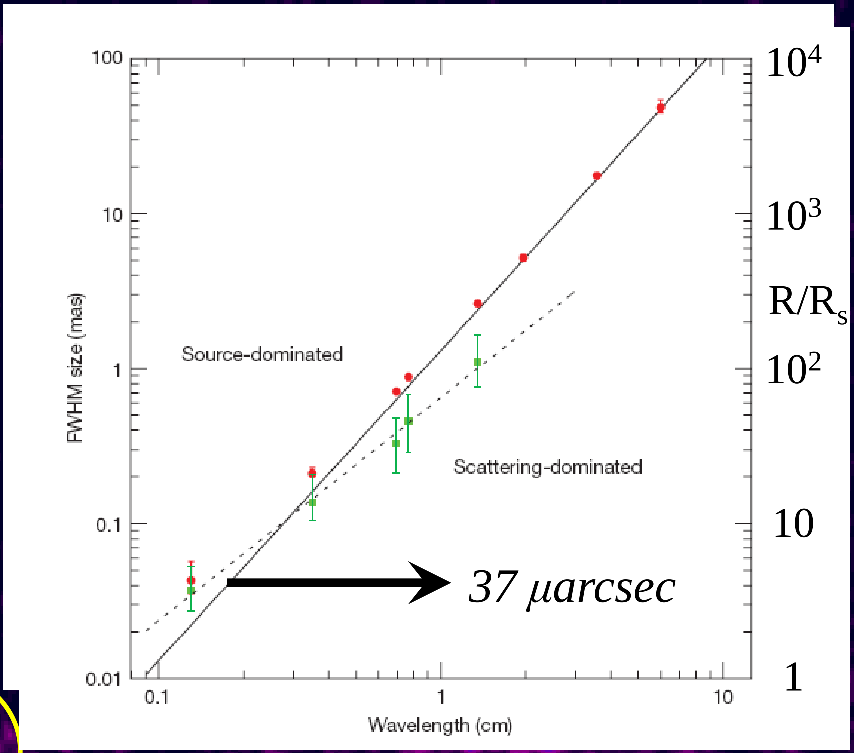
R_0= 8.28 (±0.15)$_{stat}$(±0.29)$_{sys}$ kpc

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

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

Schoedel et al. 2002, Ghez et al. 2003, 2008, Gillessen et al. 2009a,b

SgrA*



4 light months

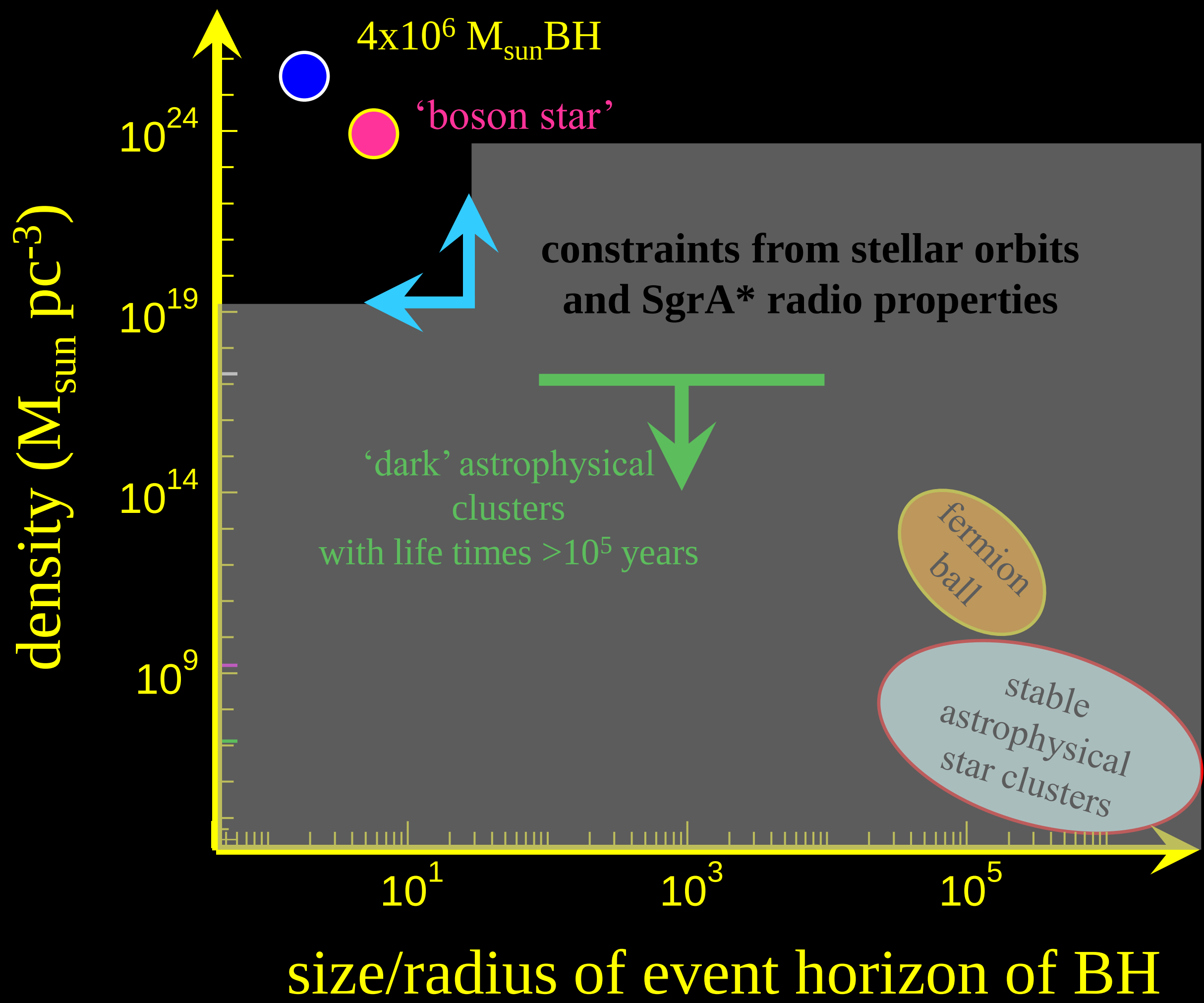
$v_{pm} \leq 2$, 20 km/s

(50 μarcseconds/Jahr !)

Model of 1.3mm Emission from SgrA*

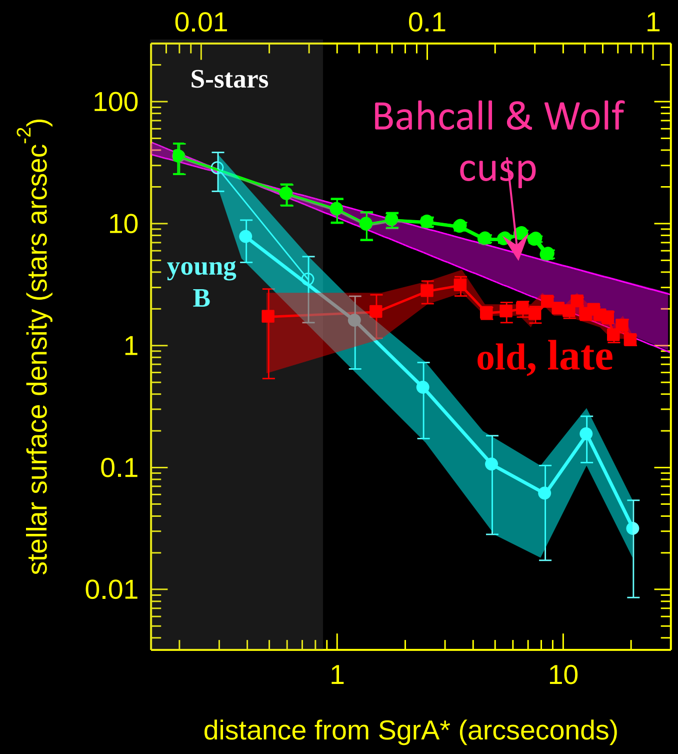
Backer & Sramek 1996, Bower et al. 2003, 2005, Reid & Brunthaler 2004, Shen et al. 2005, Doeleman et al. 2008

Is SgrA* a black hole ?



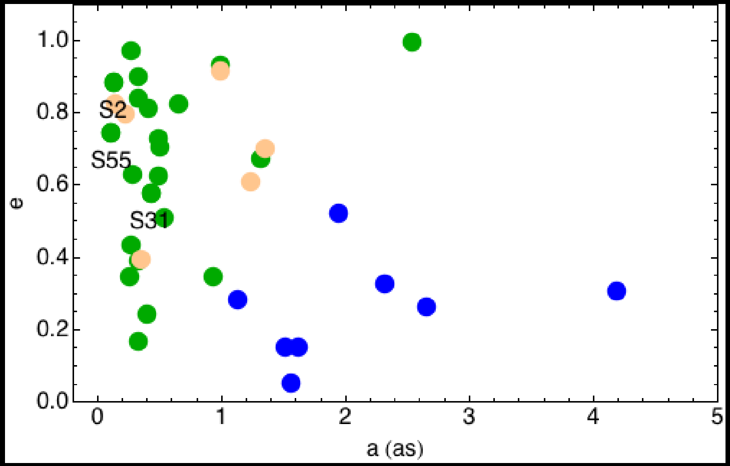
Maoz 1998, Schödel et al. 2003, Ghez et al. 2005, Coleman Miller 2006, Tsiklauri & Viollier 1998, Torres et al. 2000, Chapline et al. 2001, 2003, Mazur & Mottola 2004, Genzel et al. 2010

probing the environment of a massive black hole

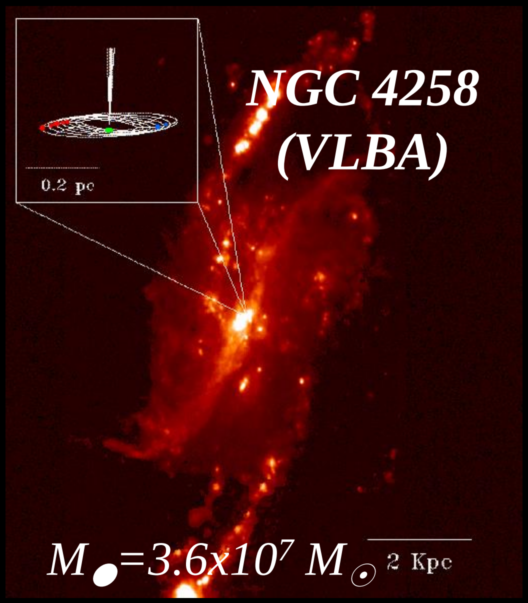


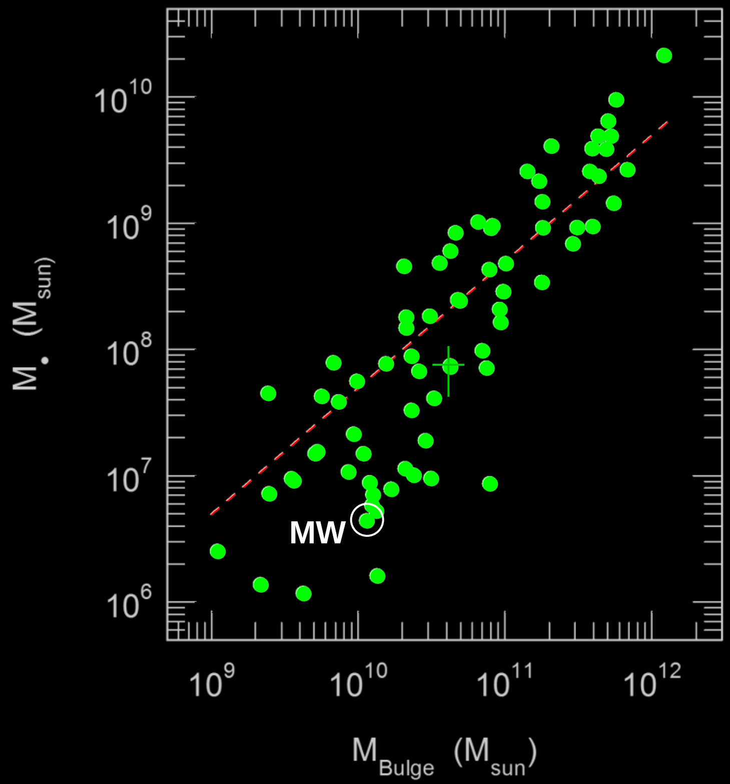
some key theoretical predictions:

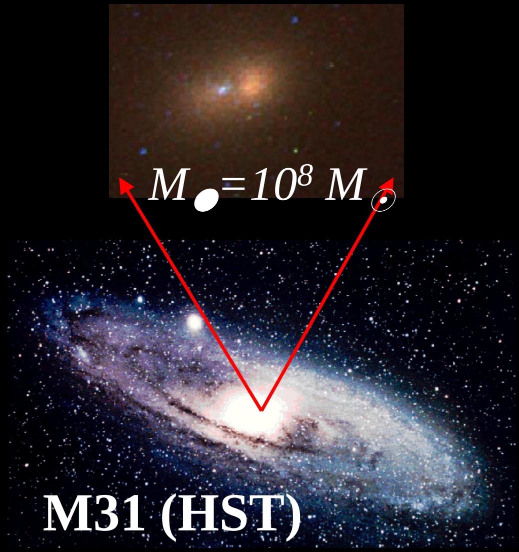
- star formation near BH very difficult if not impossible
- power-law cusp of old stars & remnants centered on BH
- binaries on loss cone orbits get captured and one member ejected out of Galaxy
- $L_{SgrA*} \sim 10^{8\text{-}9}\ L_{\odot}$



Massive black holes in nearby galaxies



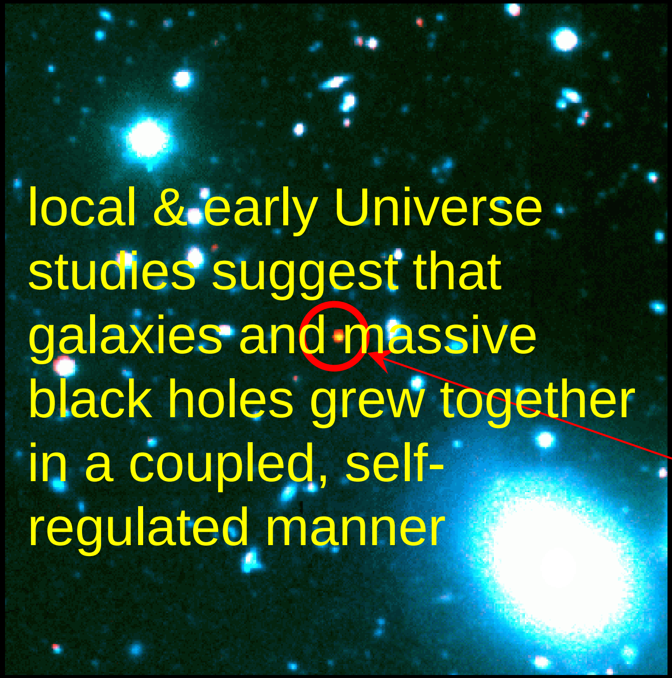




$M_\bullet / M_{bulge} \sim 1\text{-}5\times10^{-3}$

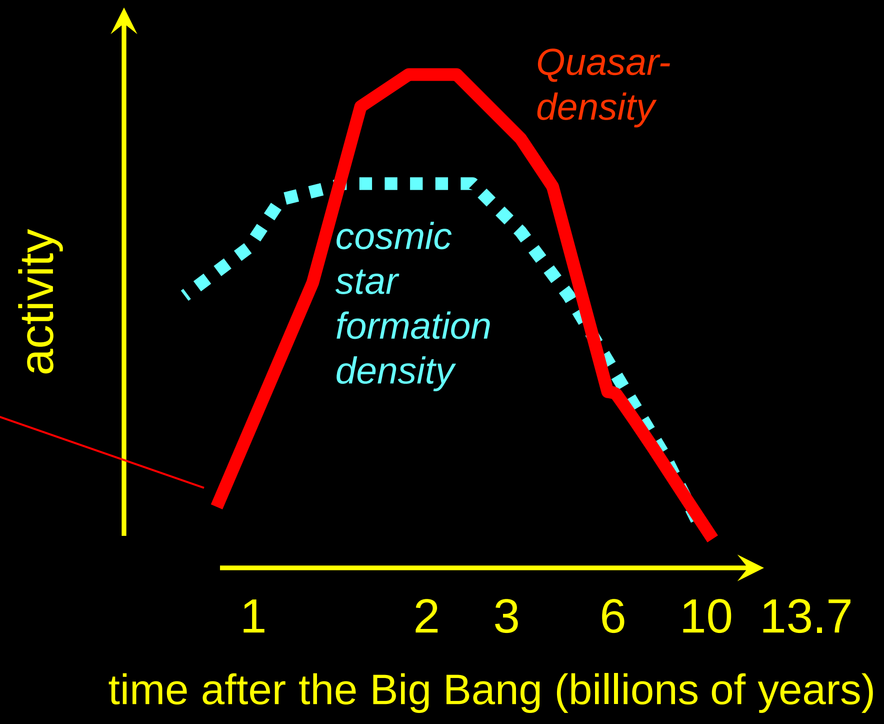
Bender, Fabian, Ferrarese, Ford, Gebhardt, Greenhill, Ho, Kormendy, Nandra, Ma, Moran, Merritt, Tanaka, Tremaine 1995-2013

galaxies and massive black holes in the young Universe



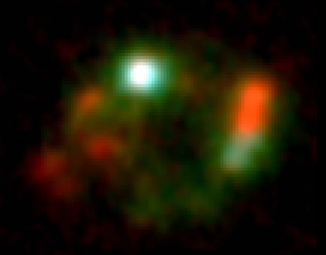
a 3 billion solar mass black hole 800 million years after the Big Bang!

key issue: $M_{BH}(t) < M_0 \exp(t/300\ \mathrm{Myr})$

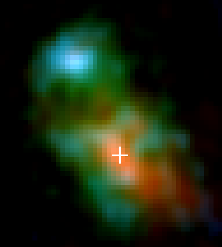
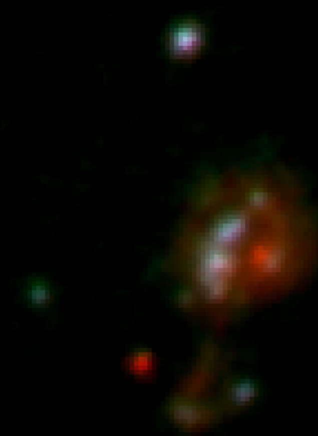
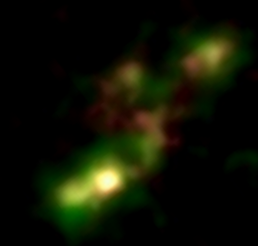


Steidel, Madau, Fan, Hasinger, Ueda, A.Hopkins et al. 1996-2009





Possible growth processes for massive black holes

- formation of $10^{2\ldots3}\ M_\odot$ seed black holes at z~10..12, from super-massive stars, dense clusters or direct collapse

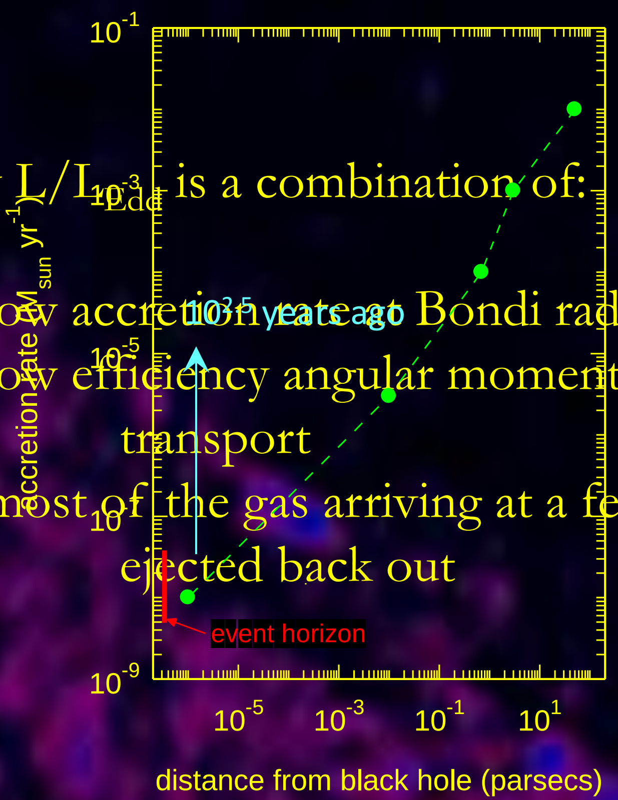
- rapid growth (super-) Eddington triggered by major galaxy mergers

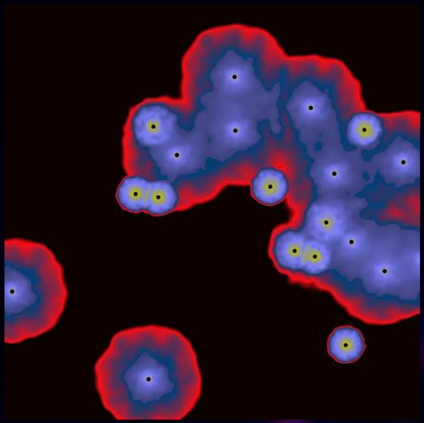
- continuous (sub-)Eddington growth (10 doubling times ~ 1-3 Gyrs) through accretion from the cosmic web and disk instabilities

why is SgrA* so weak ?

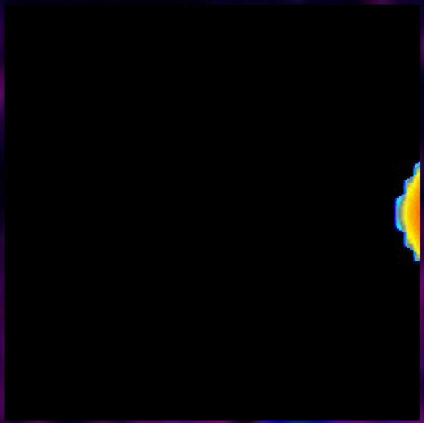
low L/L_{Edd} is a combination of:

- low accretion rate at Bondi radius
- low efficiency angular momentum transport
- most of the gas arriving at a few R_s ejected back out



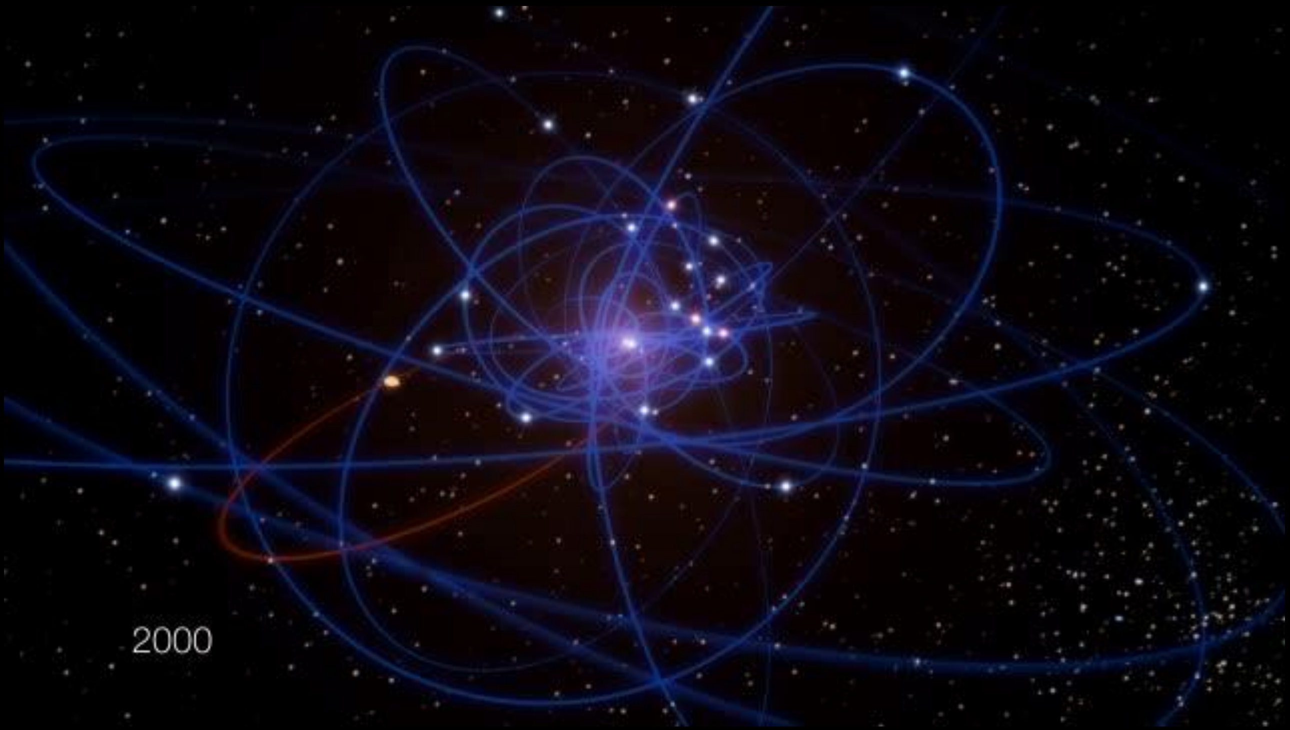


$L_{SgrA*} \sim 10^{35\text{-}36}$ erg/s $\sim 10^{-8}$ L_{edd}, $\eta_{radiation} \sim 10^{-6}$



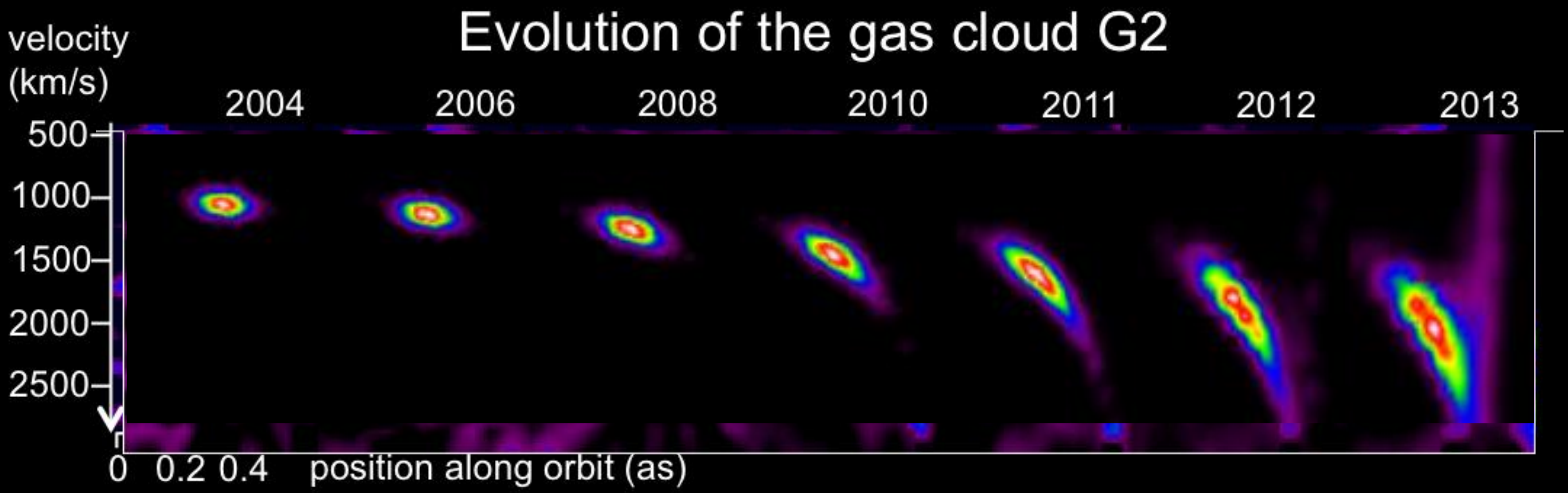
Cuadra et al. 2006, Bower et al. 2005, Marrone et al. 2006, Revnitsev et al. 2005, Begelman, Blandford, De Villers, Hawley, Krolik, Liu, Narayan, Quataert, Melia, Markoff, Rees, Stone, Yuan 1995-2009

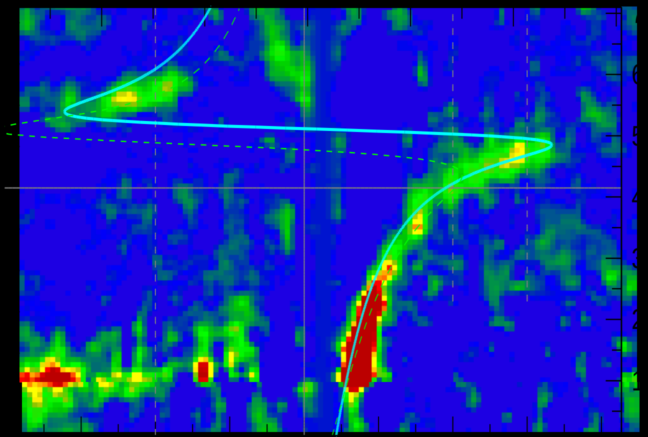
Yet another surprise in the Galactic Center : a gas cloud falling straight into the hole



Gillessen et al. 2012, 2013, theory: Burkert et al. 2012, Schartmann et al. 2012, Murray-Clay & Loeb 2012, Miralda-Escude 2012, Meyer & Meyer-Hofmeister 2012, Moscibrodzka et al. 2012

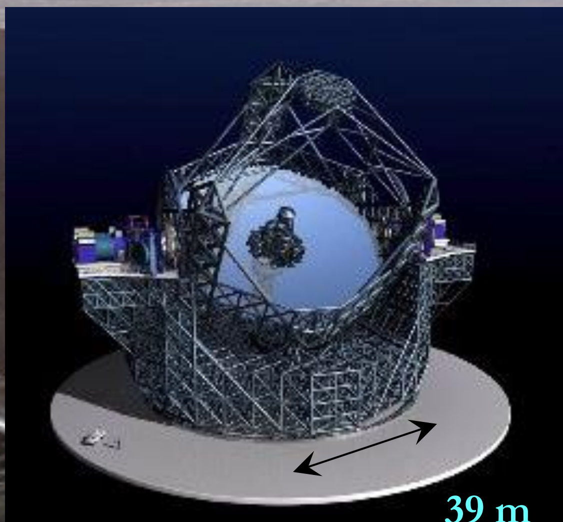
Text book tidal disruption under our eyes





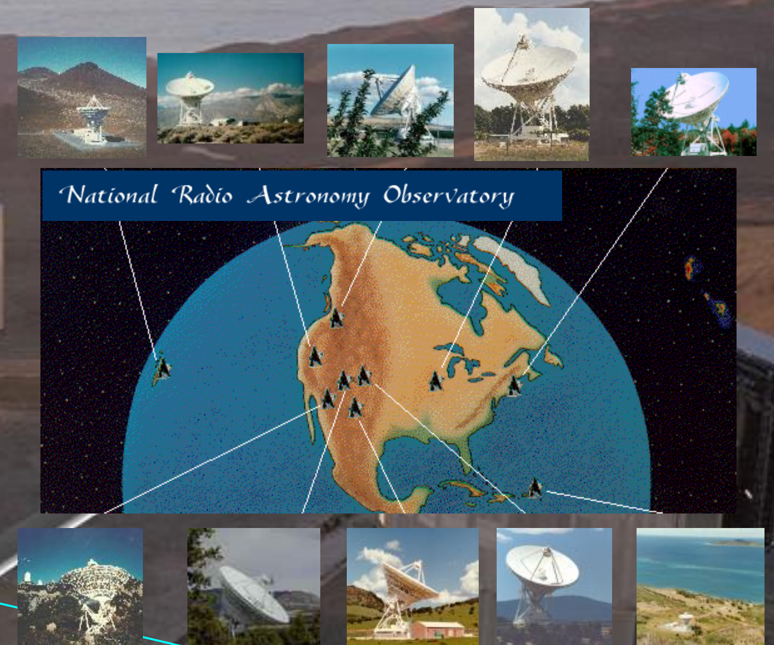
Gillessen et al. 2013b

the future: zooming in on the horizon

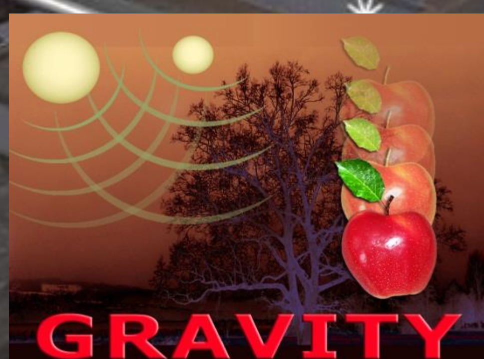


EELT

200m



near-IR precision interferometric astrometry (10μarcsec~R_s, K_s<19)



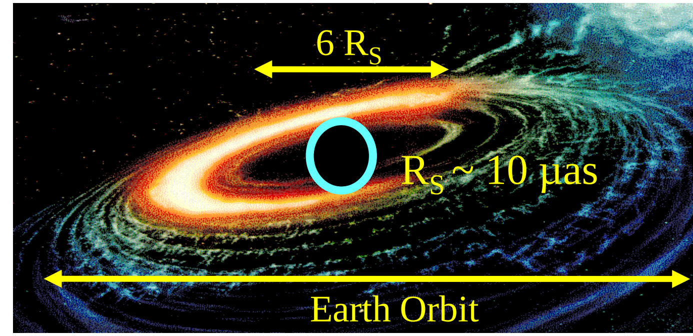
(sub)-millimeter Very Long Baseline Interferometry ('Event Horizon Telescope') (Doeleman et al. 2011)

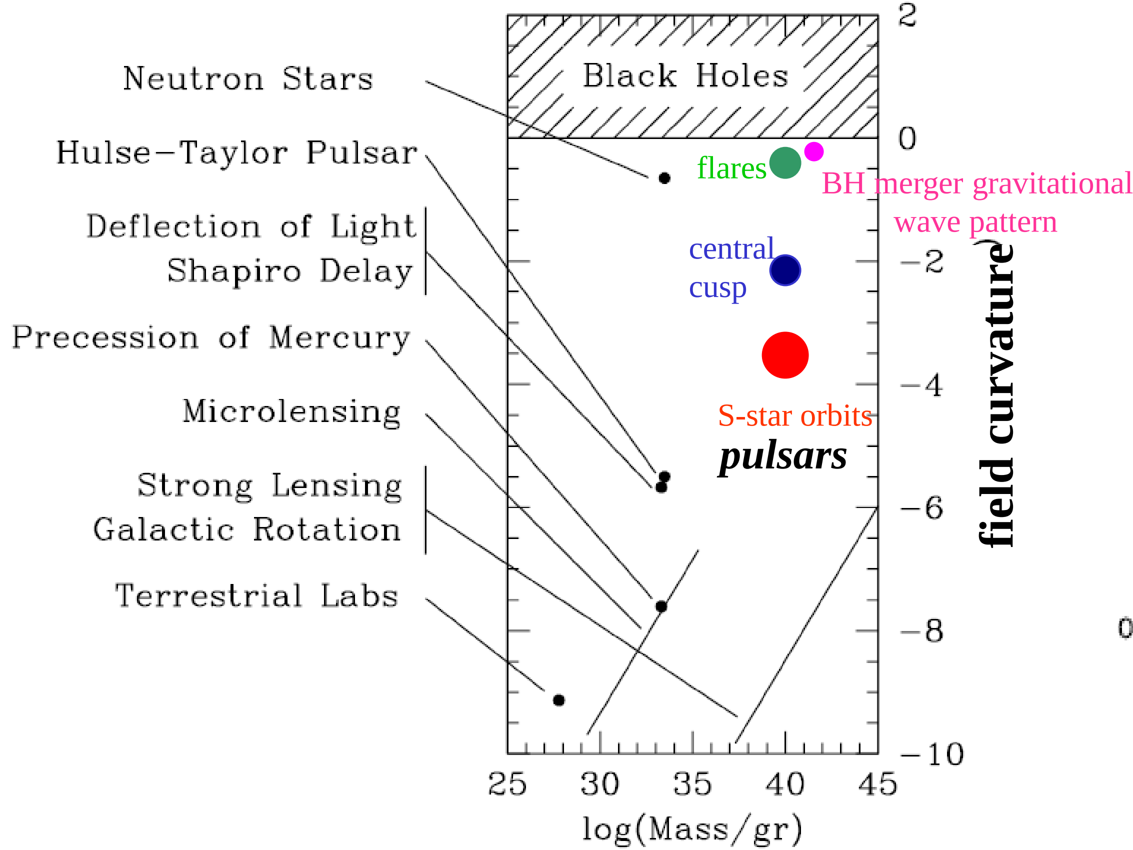
MPE, Paris, Cologne, Grenoble, Lisbon, MPIA

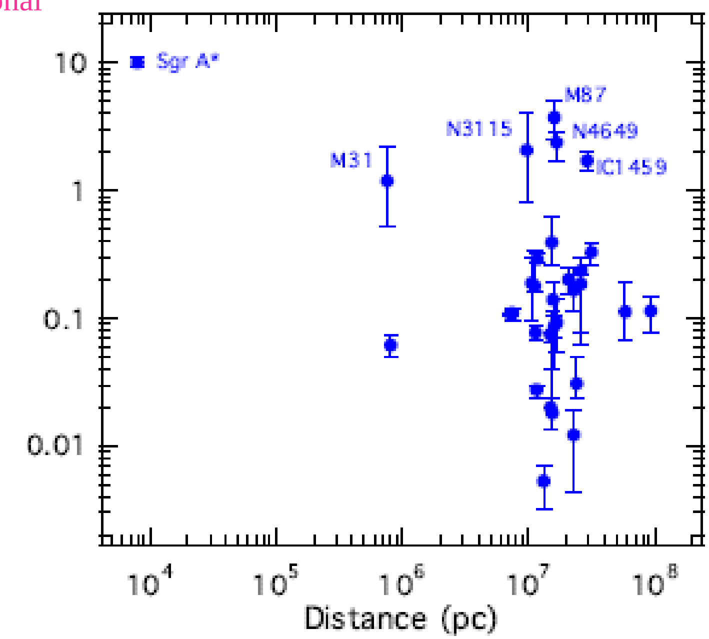
PI Frank Eisenhauer (MPE)

ESO-VLTI

The potential of GC measurements for constraints on GR



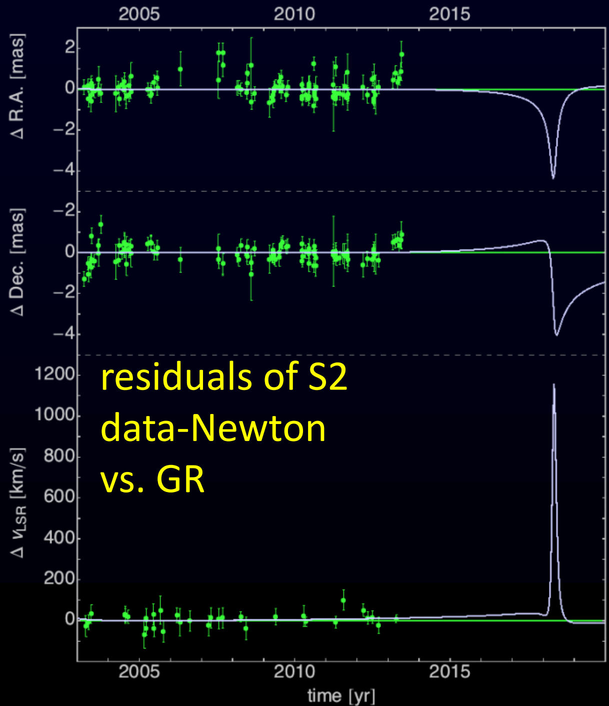


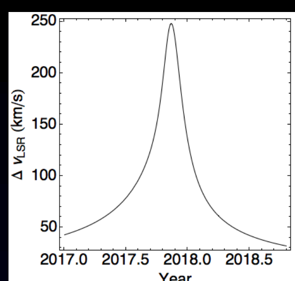


Psaltis 2004, 2012

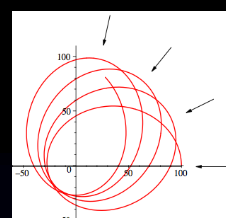
Inward bound

IR & radio instruments

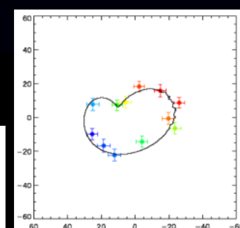




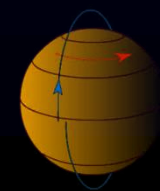
1. β^2 effects in radial velocities



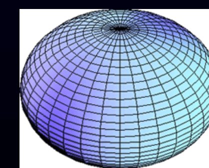
2. relativistic prograde precession



3. black hole spin from flares



4. Lense-Thirring precession



5. Quadrupole moment of metric, no hair & quantum effects

more challenging