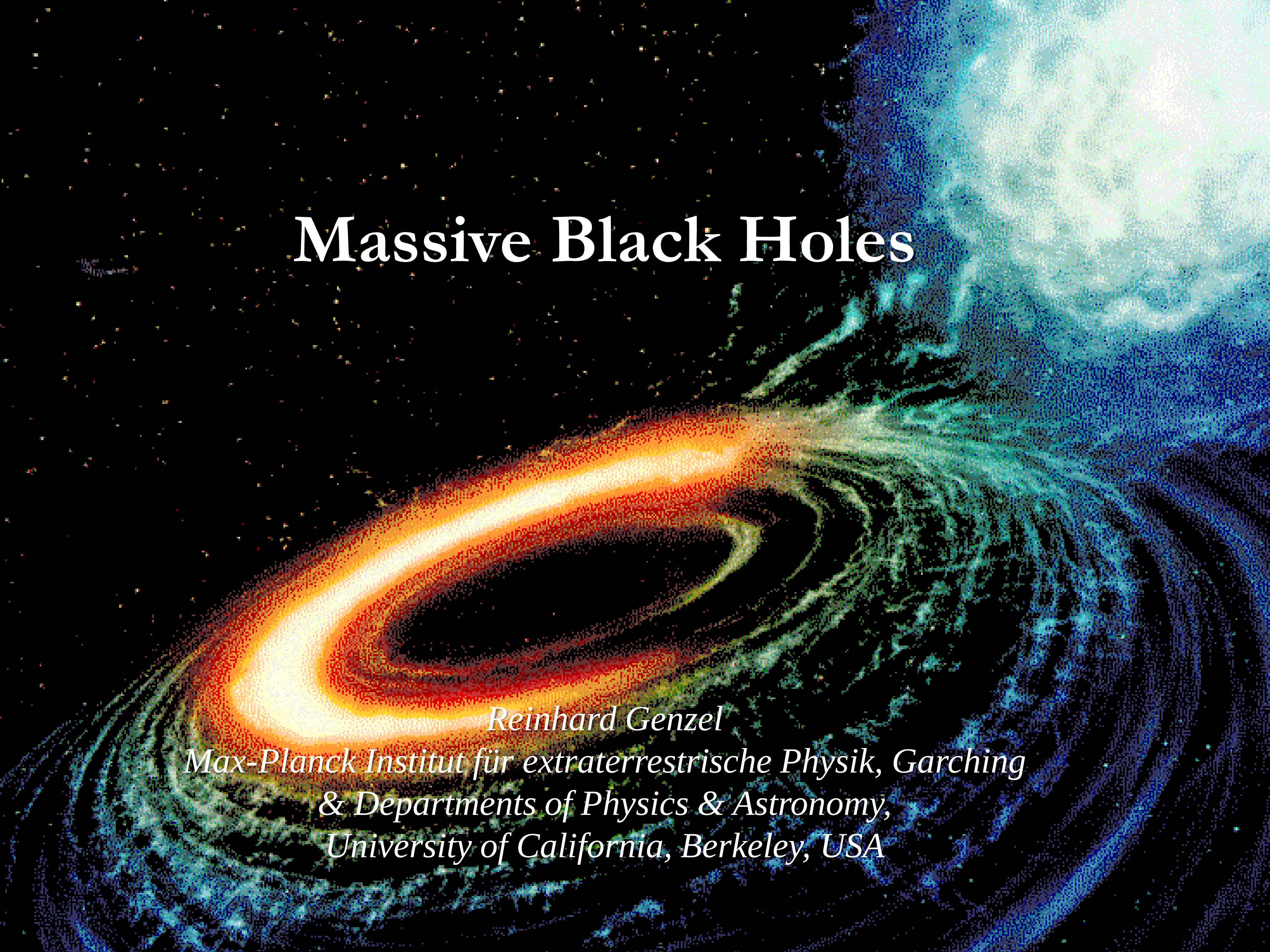


Massive Black Holes

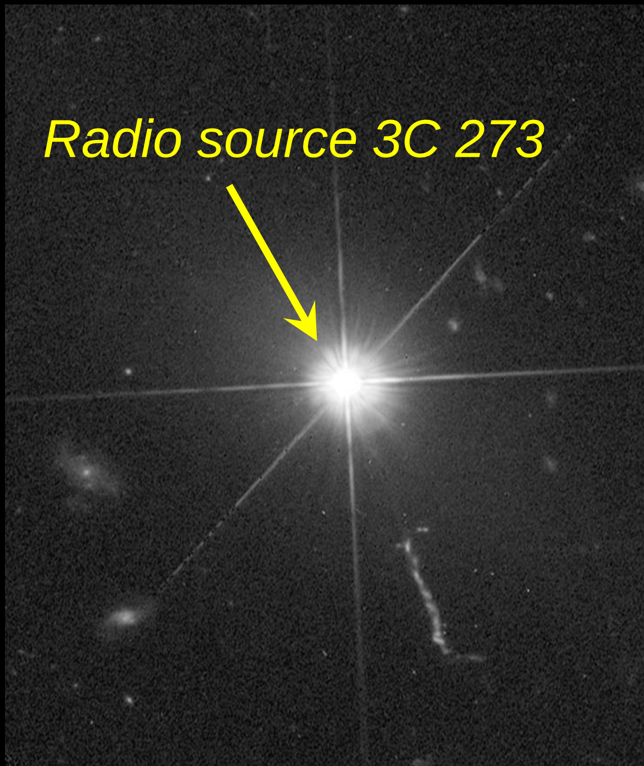
Reinhard Genzel

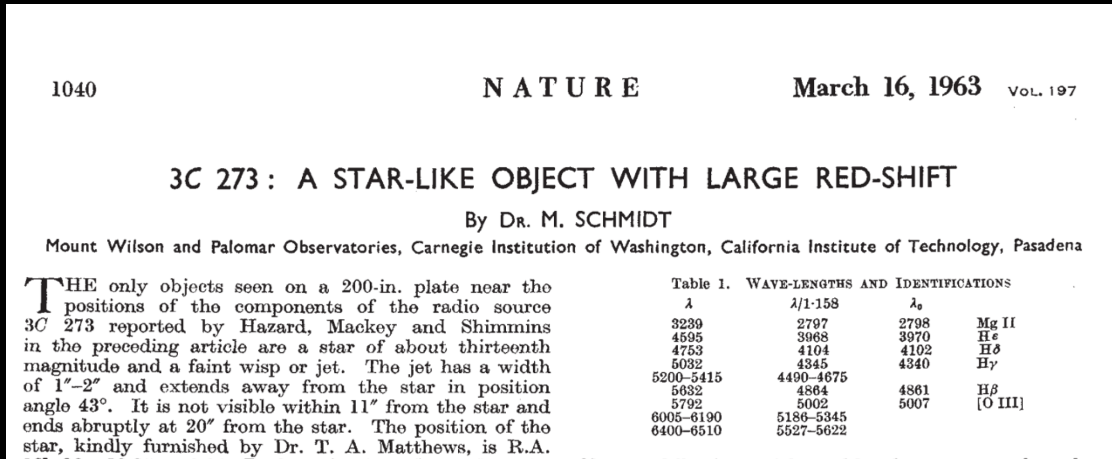
Max-Planck Institut für extraterrestrische Physik, Garching

& Departments of Physics & Astronomy,

University of California, Berkeley, USA

The Discovery of Quasars




1040 NATURE March 16, 1963 VOL. 197

3C 273: A STAR-LIKE OBJECT WITH LARGE RED-SHIFT

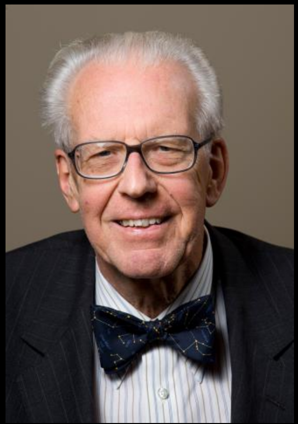
By DR. M. SCHMIDT

Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena

THE only objects seen on a 200-in. plate near the positions of the components of the radio source 3C 273 reported by Hazard, Mackey and Shimmins in the preceding article are a star of about thirteenth magnitude and a faint wisp or jet. The jet has a width of 1″–2″ and extends away from the star in position angle 43°. It is not visible within 11″ from the star and ends abruptly at 20″ from the star. The position of the star, kindly furnished by Dr. T. A. Matthews, is R.A.

Table 1. WAVE-LENGTHS AND IDENTIFICATIONS

λ	λ/1·158	λ_0	
3239	2797	2798	Mg II
4595	3968	3970	$H\varepsilon$
4753	4104	4102	$H\delta$
5032	4345	4340	$H\gamma$
5200–5415	4490–4675		
5632	4864	4861	$H\beta$
5792	5002	5007	[O III]
6005–6190	5186–5345		
6400–6510	5527–5622		

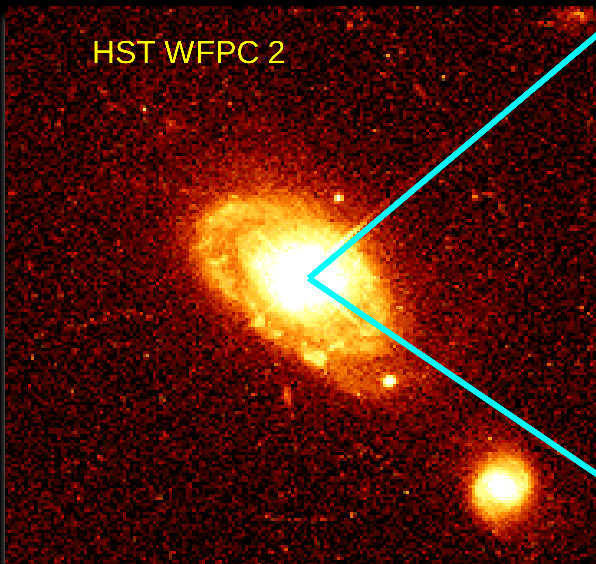


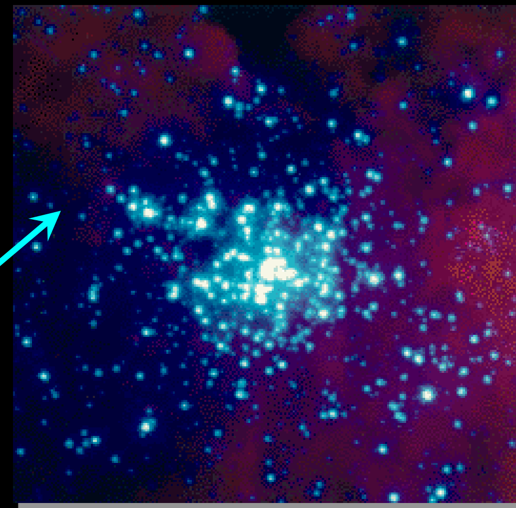
Marten Schmidt
1963

➡ z=0.16, distance 2.4 billion light years!
$L \sim 10^3\ L_{MW}$

1973: $z \sim 3.5$ (t_0=11.6 Gyr), $L \sim 10^5\ L_{MS}$

What powers QSOs?





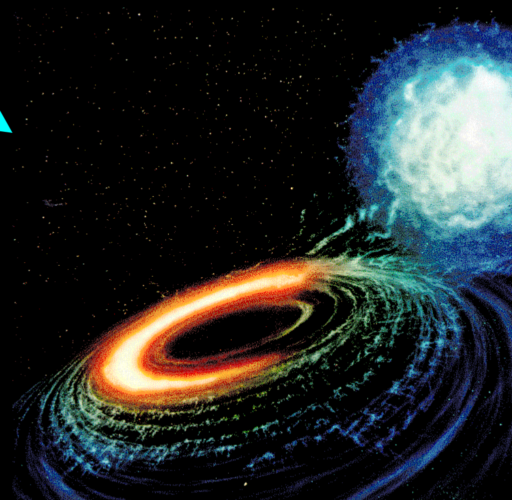
Fusion:
_$E < 0.005\ Mc^2$_

R. Sunyaev

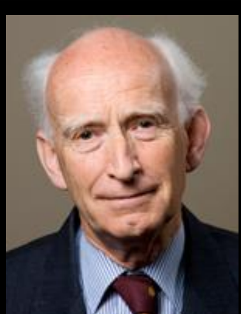
E.Salpeter

‘Schwarzschild throat’

(Schwarzschild-Kerr)



$E < 0.4\ Mc^2$
variable X- und γ-radiation
relativistic radio jets



D.Lynden-Bell

M. Rees

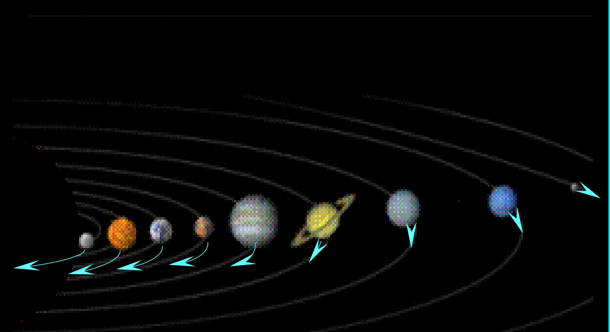
How does one prove the existence of a black hole?

ON QUASARS, DUST AND THE GALACTIC CENTRE

D. Lynden-Bell and M. J. Rees

(Received 1971 January 5)

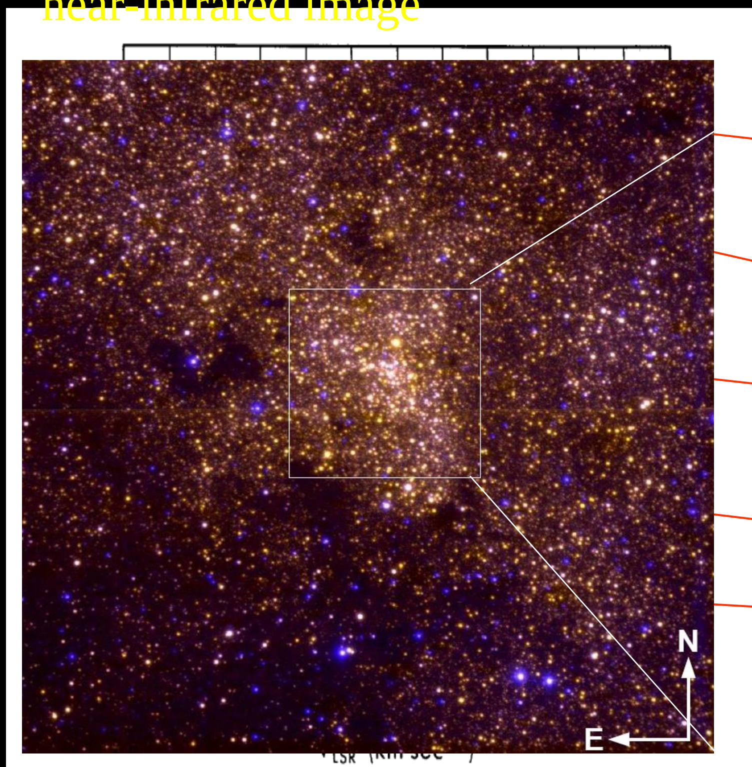
an unambiguous 'proof' of the existence of a black hole requires the determination of the gravitational field/space time metric to the scale of the event horizon.

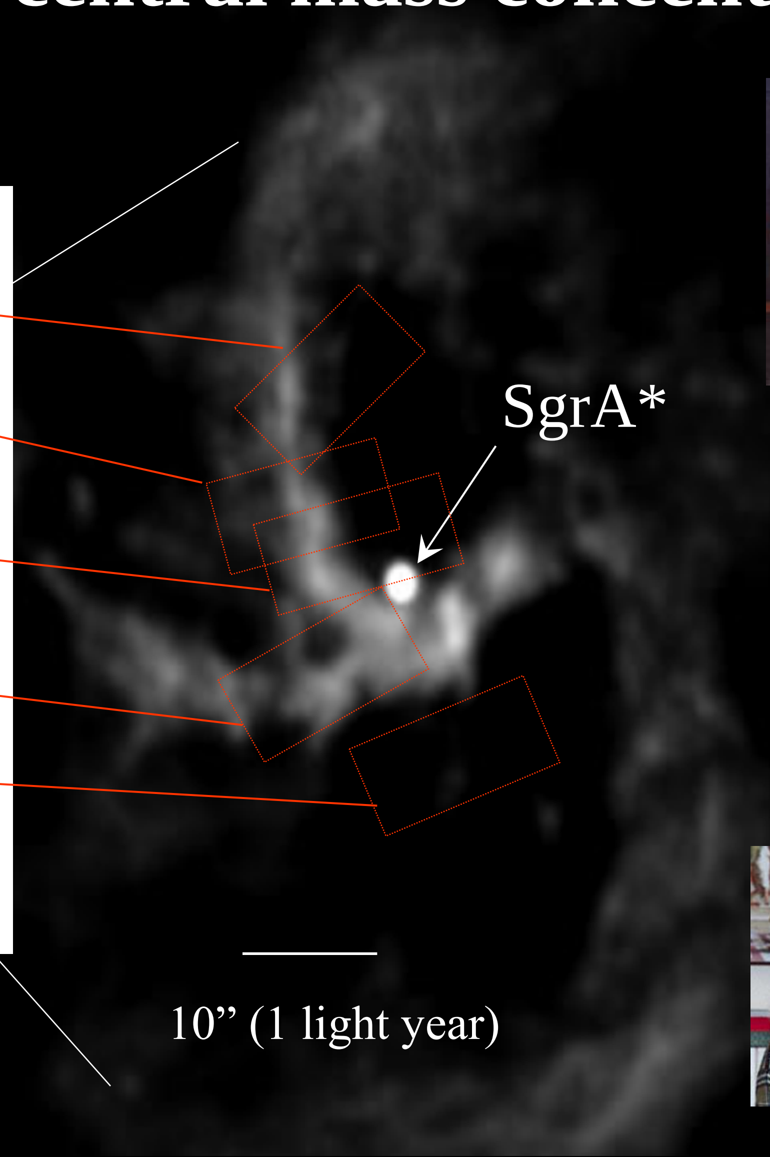


Kepler orbits of the planets
$V \sim 1/\sqrt{R}$

early evidence for a central mass concentration

near-infrared image






C.H.Townes


E.Becklin

Becklin et al. 1971, Balick & Brown 1974, Lo et al. 1975, Wollman et al. 1977, Lacy et al. 1980, 1982

high resolution stellar NIR imaging/spectroscopy

adaptive optics @ the ESO/VLT and Keck

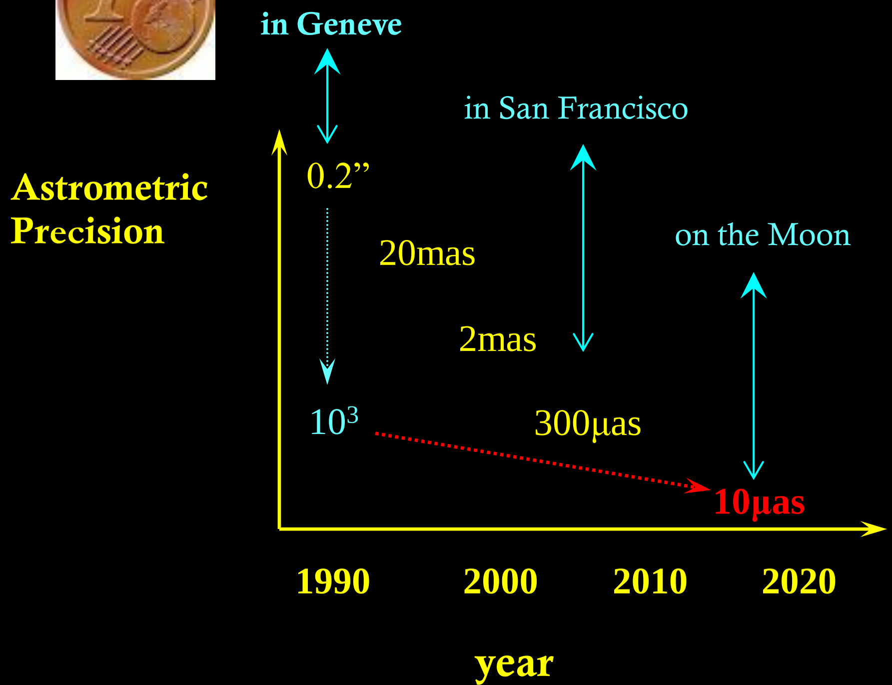
NACO

SINFONI

PARSEC

Lenzen, Hofmann, Eisenhauer, Bonnet, Rabien, Davies, Matthews, McLean, Larkin, Wizinovich 2002-2010

As seen from Zuerich



"Kepler Experiment": motions of stars near SgrA*

F.Eisenhauer

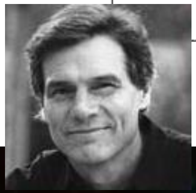
S.Gillessen

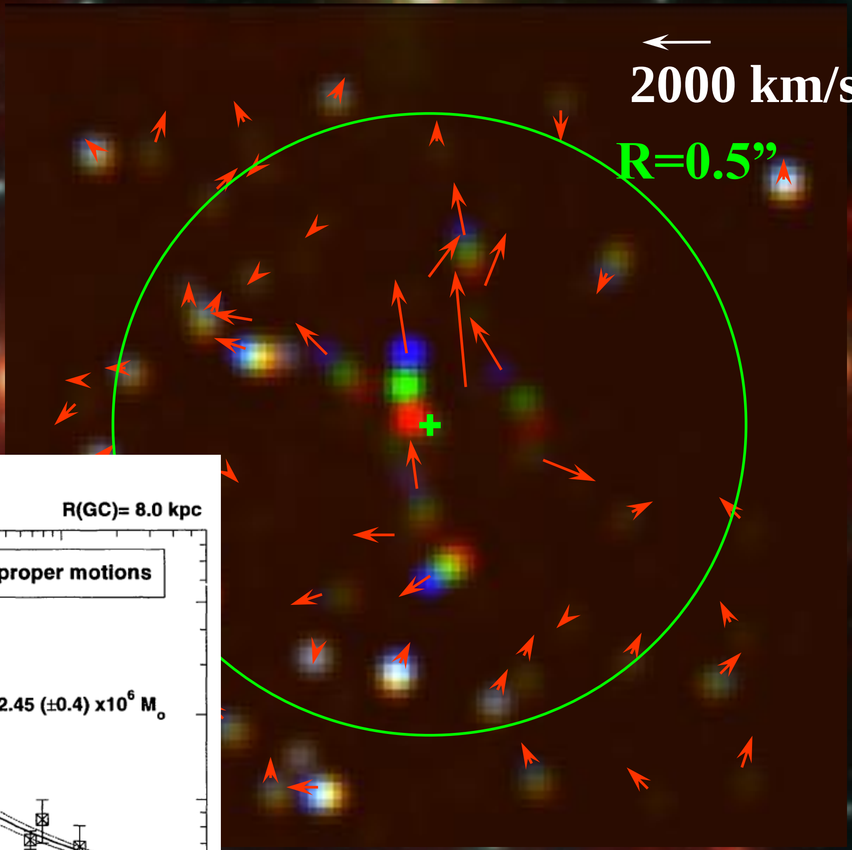
A.Eckart

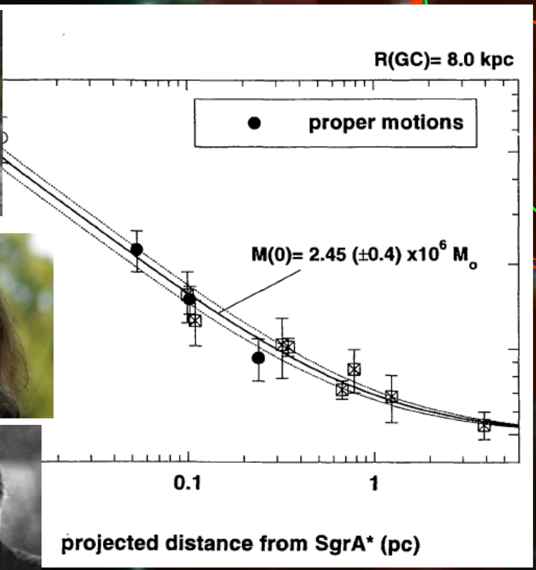
R.Schoedel

A.Ghez

M.Morris

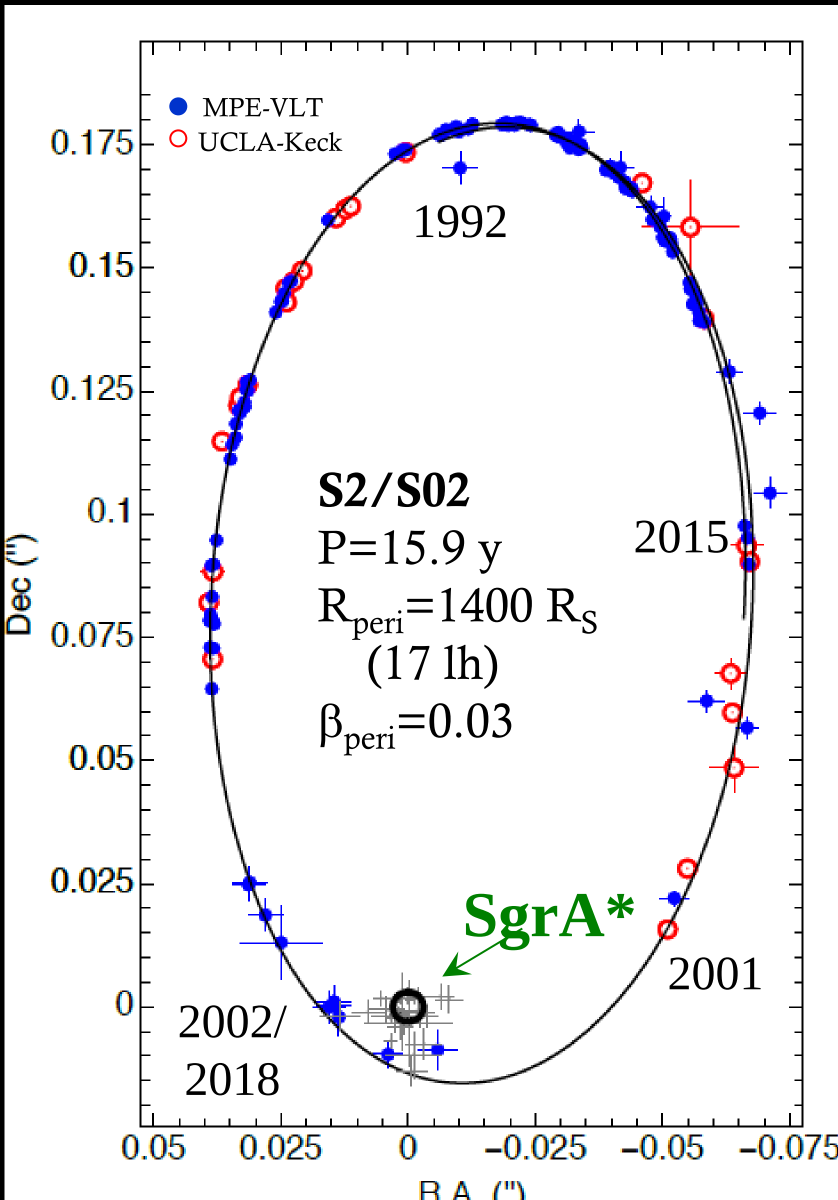


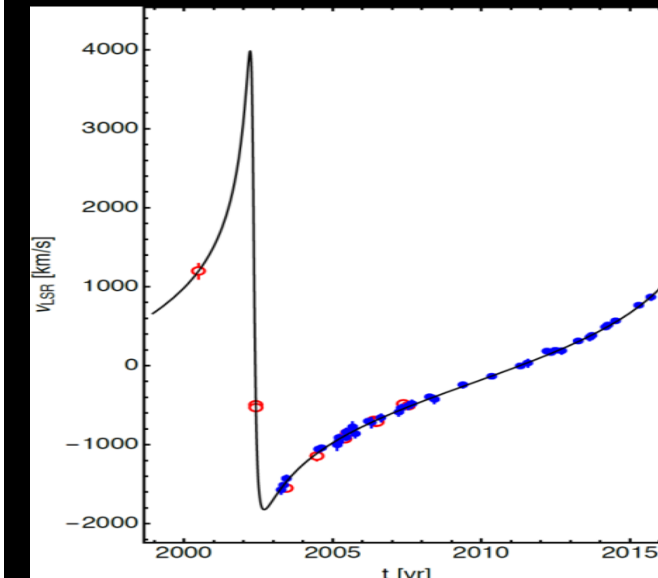




Eckart & Genzel 1996, 1997, Ghez et al. 1998

stellar orbits testing the potential: S2





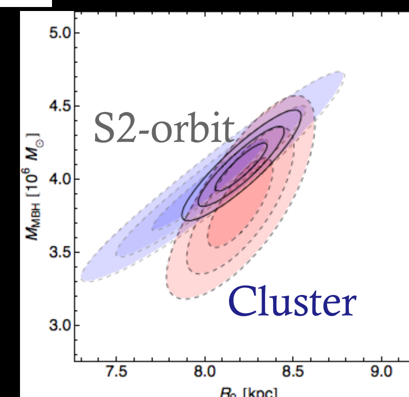
$M_\bullet = 4.26(\pm 0.14)_{stat}(\pm 0.2)_{sys} \times 10^6\ M_\odot$

$R_0 = 8.36\ (\pm 0.1)_{stat}(\pm 0.15)_{sys}$ kpc

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

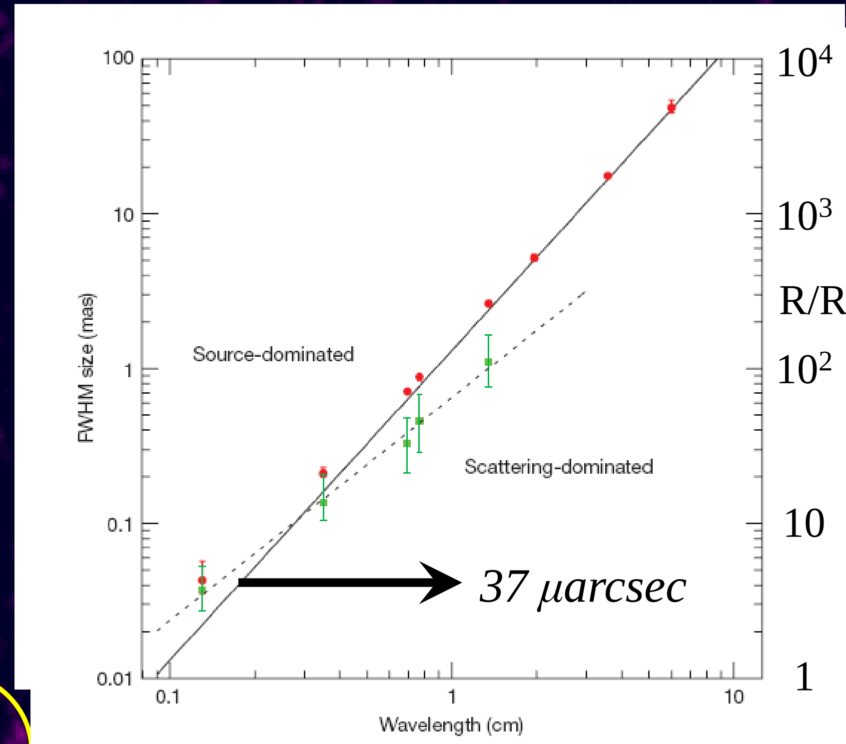
$M_{extended}/M_\bullet <$ a few 10^{-2}

$M_\bullet$ & 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

SgrA*



4 light months

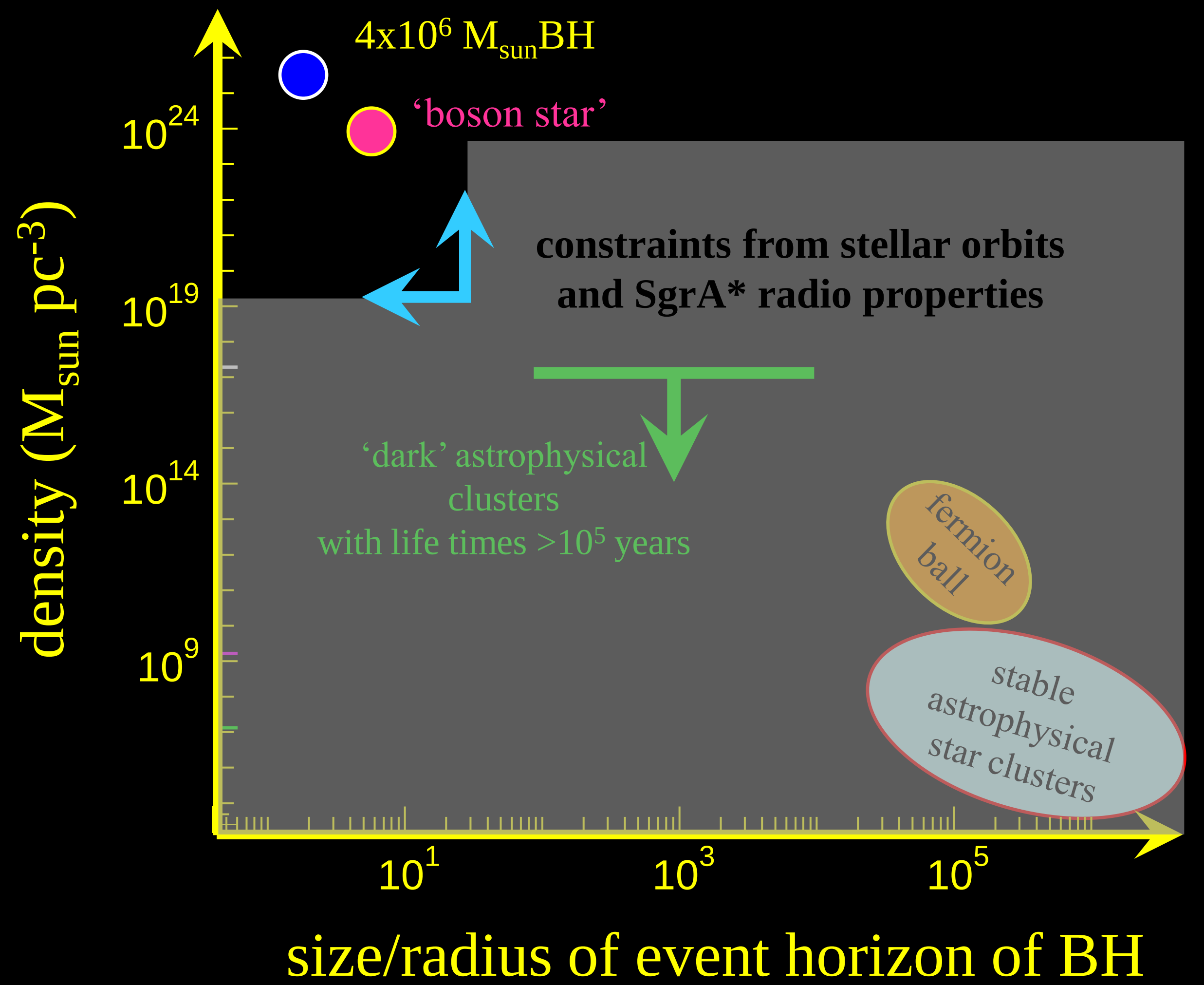
$v_{pm} \leq 2, 20$ km/s

(50 μarcseconds/yr !)

Model of 1.3mm Emission from SgrA*

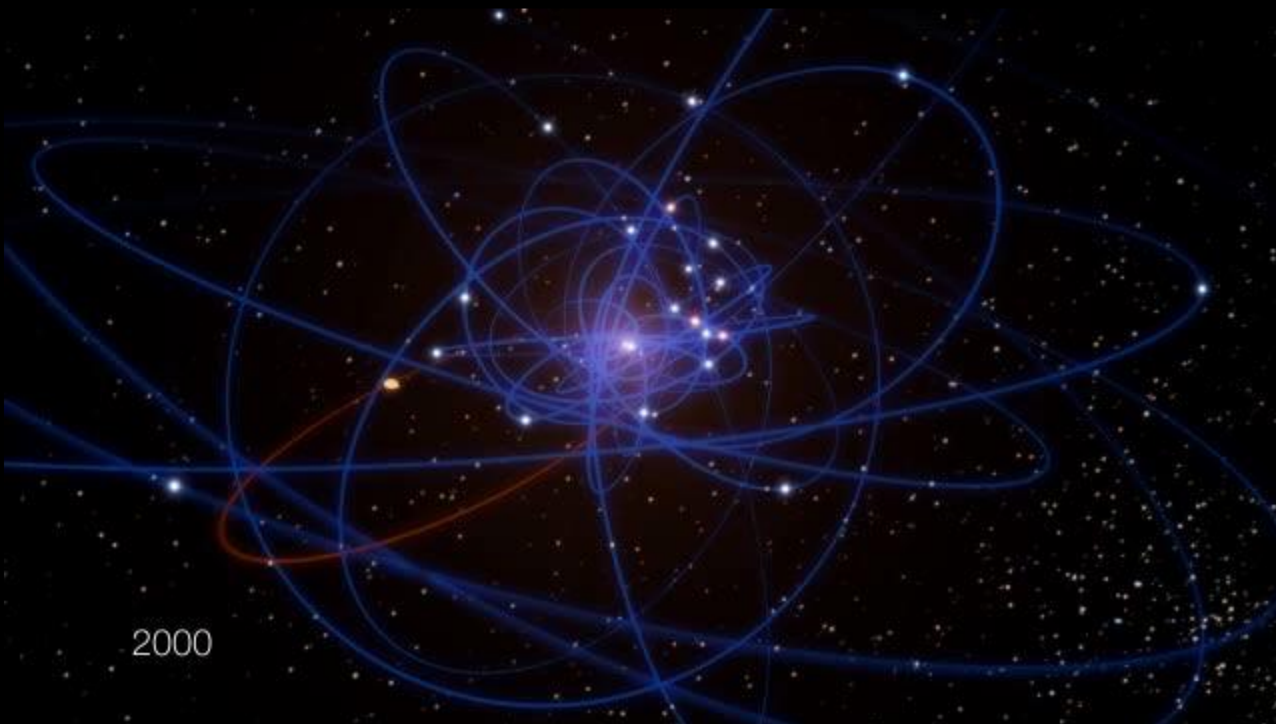
Backer & Sramek 1996, Bower et al. 2003, 2005, Reid & Brunthaler 2004, Shen et al. 2005, Doeleman et al. 2008

Is SgrA* a black hole ?



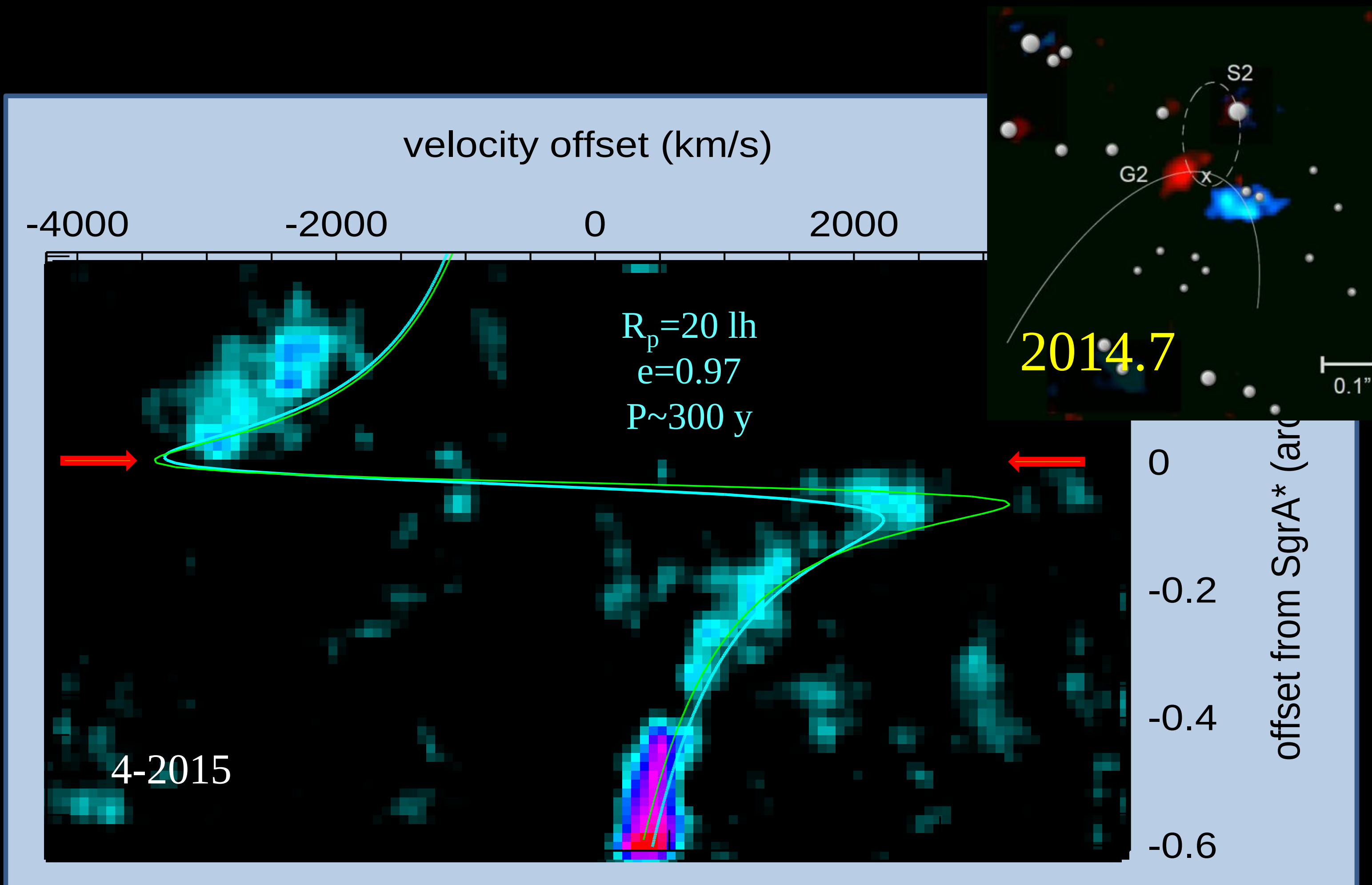
Maoz 1998, Schödel et al. 2003, Ghez et al. 2005, Coleman Miller 2006, Tsiklauri & Viollier 1998, Torres et al. 2000, Chapline et al. 2001, 2003, Mazur & Mottola 2004

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



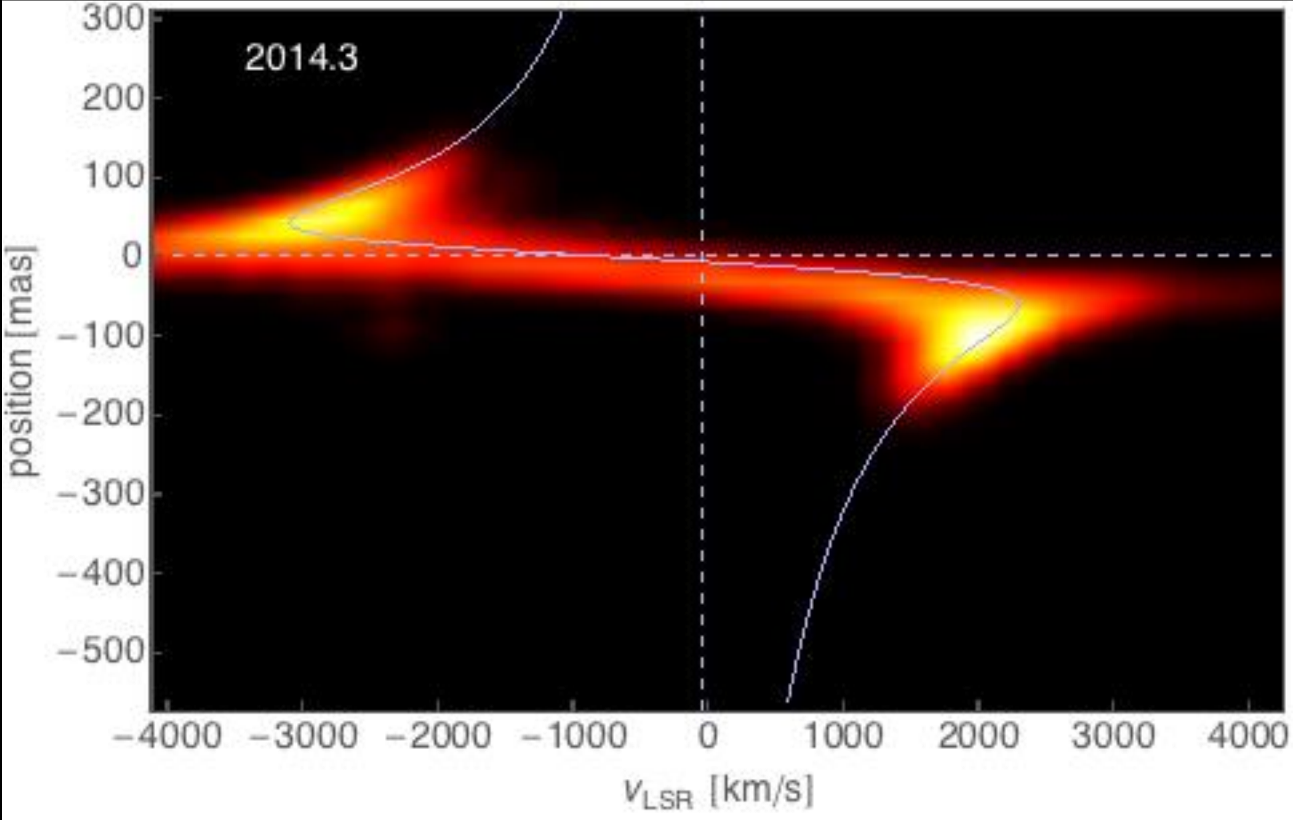
Gillessen et al. 2012, 2013, 2014, Pipher et al. 2014, Pfuhl et al. 2014, Witzel et al. 2014 , Valencia-S et al. 2014, theory: Burkert et al. 2012, Schartmann et al. 2012, 2015, Murray-Clay & Loeb 2012, Miralda-Escude 2012, Meyer & Meyer-Hofmeister 2012, Moscibrodzka et al. 2012, Scoville et al. 2013, Ballone et al. 2014, Guillocjon et al. 20144, Mapelli & Ripamonti 2015

G2: Text book case of tidal shearing



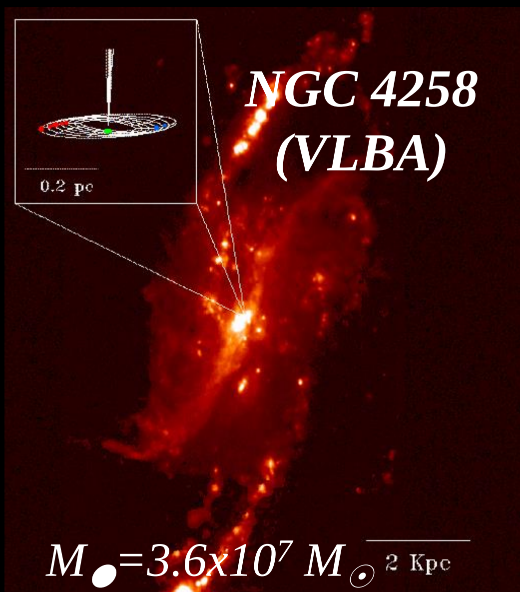
Evolution of pv structure of Brγ-emission in G2 2004-2015
with SINFONI & AO: Gillessen et al. 2012, 2013a,b, Pfuhl et al. 2014

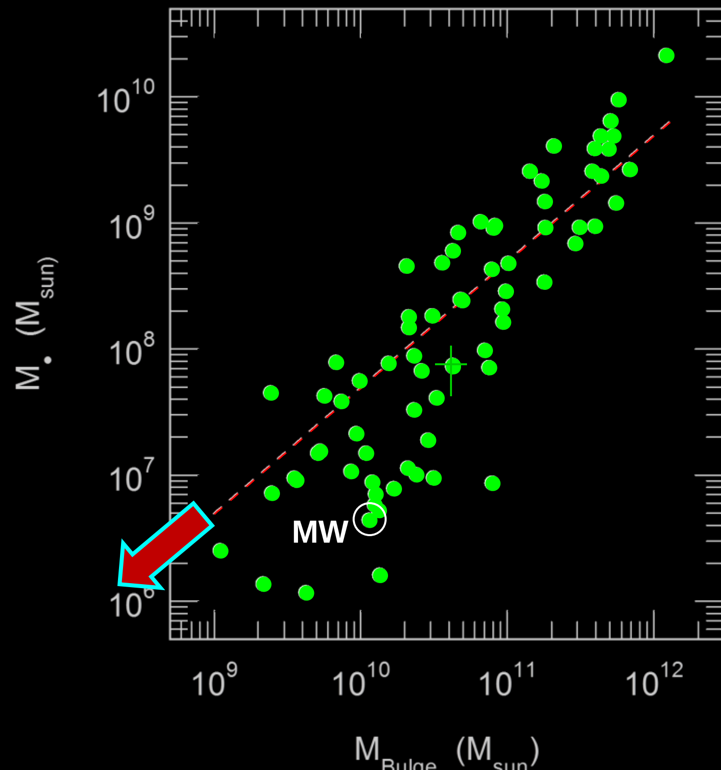
Simulation of tidally disrupting gas cloud

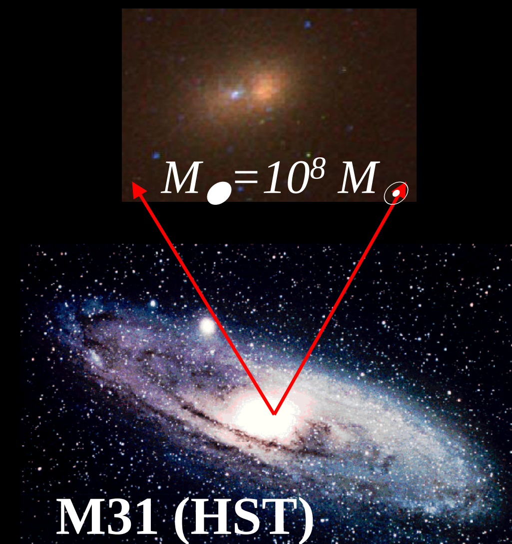


Simulation of a purely ballistic evolution of tidally disrupting gas cloud

Demographics of massive black holes in nearby galaxies



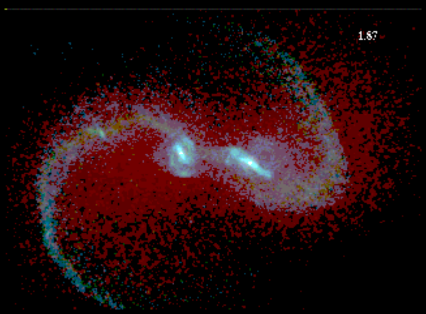




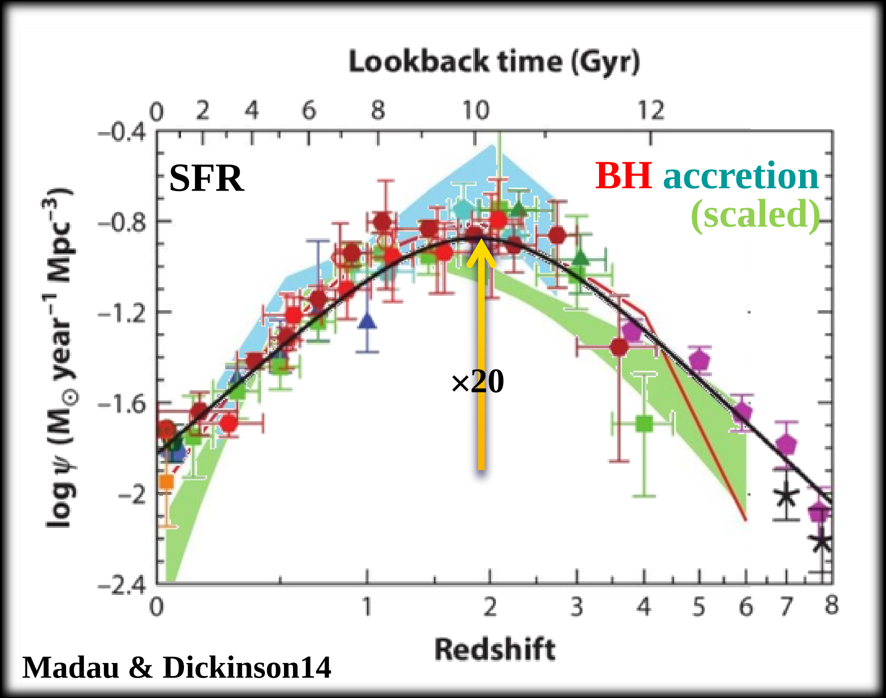
$M_\bullet / M_{bulge} \sim 2\text{-}5\mathrm{x}10^{-3}$

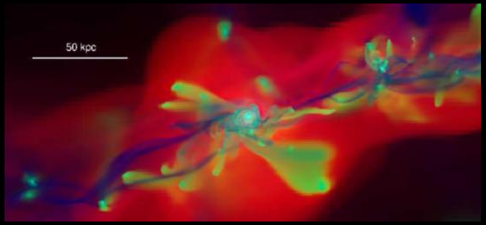
Green, Barth & Ho 2006, Kormendy & Ho 2013, McConnell & Ma 2013

The cosmic evolution of galaxies and massive black holes



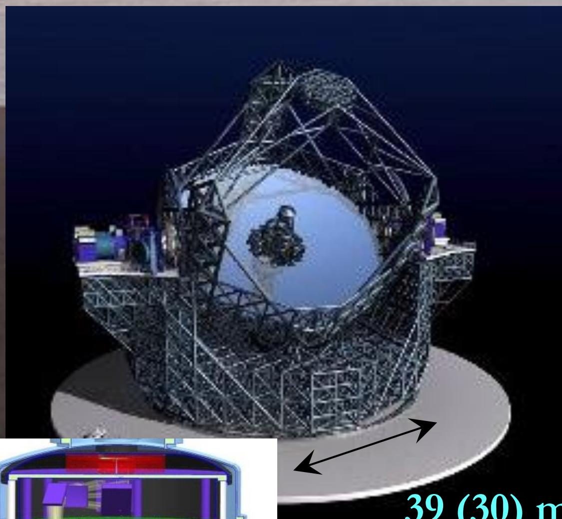
(major) mergers
& starbursts
rate ~ 20-30%

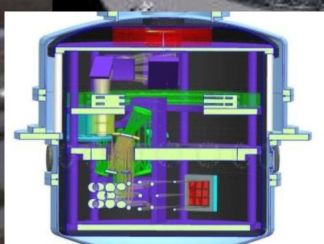




semi-continuous
accretion from halo
(including minor
mergers)
& disk instabilities
rate ~ 60-80 %

The next steps: using the GC-BH to test GR

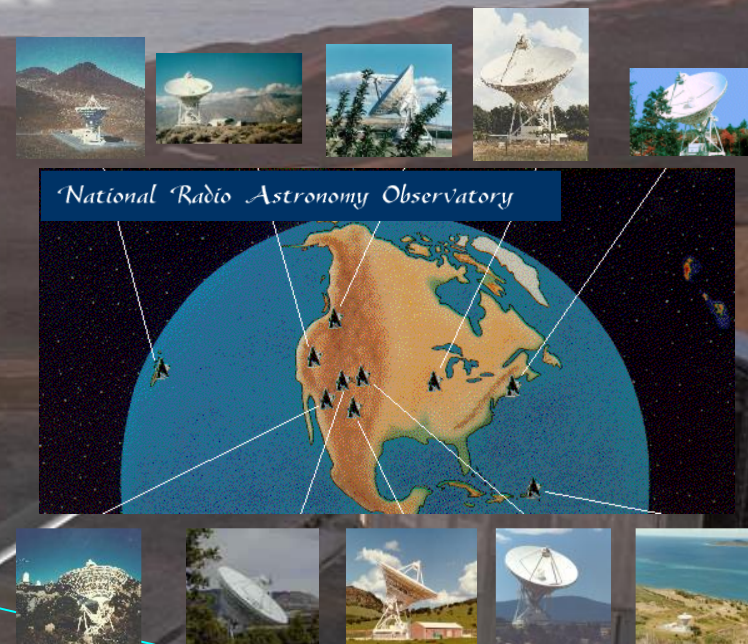




39 (30) m **EELT (TMT)**

MICADO
Astrometric Camera

120m



Inter-Continental Submm-VLBI

'Event Horizon Telescope'
'Black Hole Cam'

Pulsars?

Near-IR Interferometric Astrometry

ESO-VLTI


Fringe Tracker RTDC – @wgv
Help
File
Image
20
Cursor Information
X :
Y :
VALUE :
Scale :
1x
10x
Bias
0
No Image Loaded
Name
On
Camera :
NGCIR3
Status :
Attached
Attach
Detach
Set
Low :
-5.50
High :
2000
Auto Cuts
Min/Max
Apply graphics
Get ref. pixels
AT1
AT2
270
90
180
0
AT1
AT4
270
90
0
180
AT1
AT3
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270
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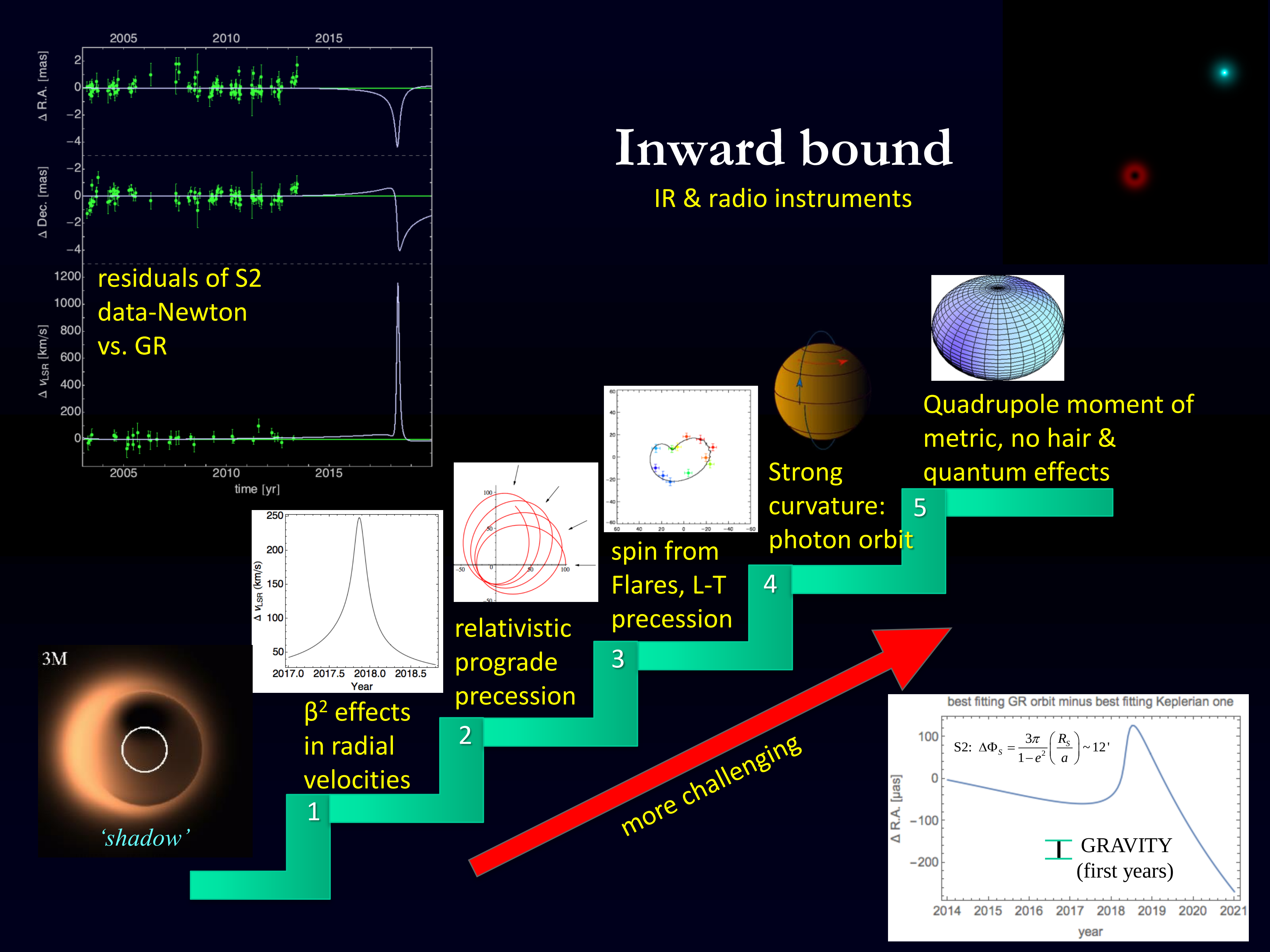
Inward bound
IR & radio instruments
residuals of S2
data-Newton
vs. GR
Δ R.A. [mas]
Δ Dec. [mas]
Δ v_LSR [km/s]
time [yr]
2005
2010
2015
Quadrupole moment of
metric, no hair &
quantum effects
Strong
curvature:
photon orbit
spin from
Flares, L-T
precession
relativistic
prograde
precession
β² effects
in radial
velocities
Δ v_LSR (km/s)
Year
3M
'shadow'
1
2
3
4
5
more challenging
best fitting GR orbit minus best fitting Keplerian one
S2: $\Delta\Phi_S = \frac{3\pi}{1-e^2}\left(\frac{R_S}{a}\right) \sim 12'$
Δ R.A. [μas]
GRAVITY
(first years)
year