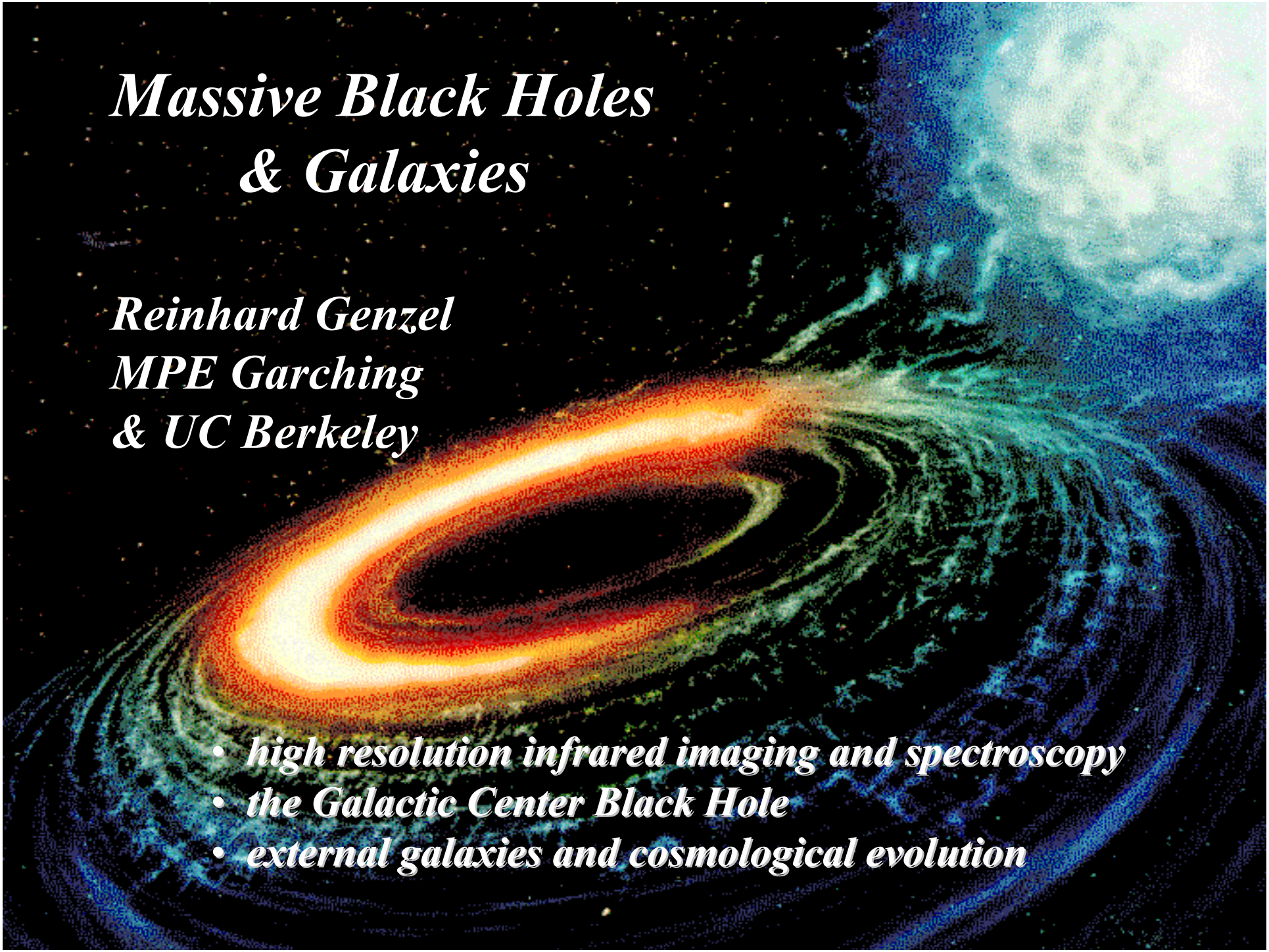
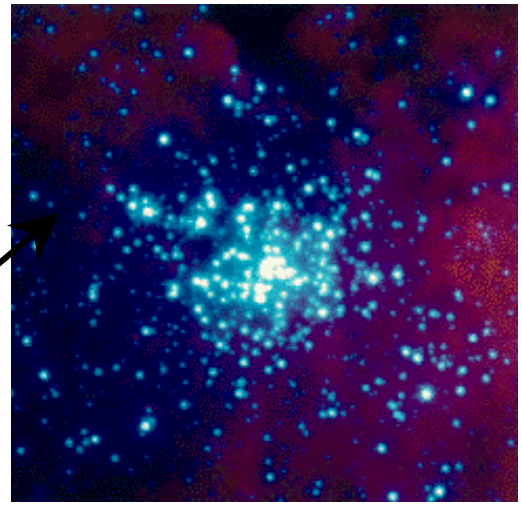
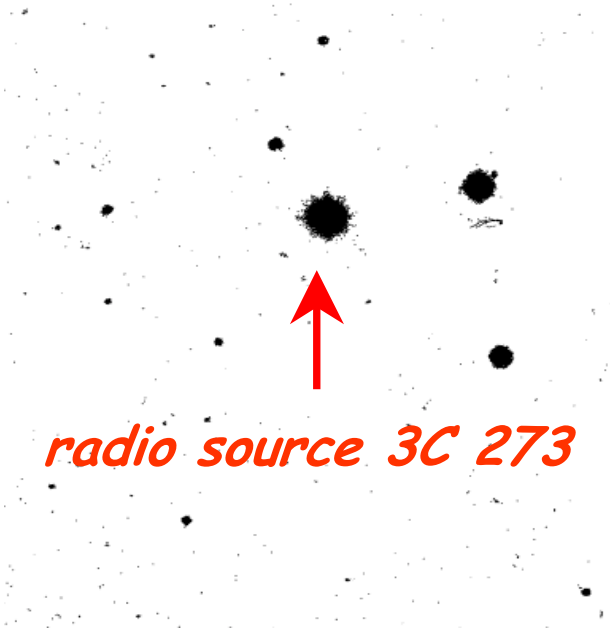

Massive Black Holes
& Galaxies
Reinhard Genzel
MPE Garching
& UC Berkeley
• high resolution infrared imaging and spectroscopy
• the Galactic Center Black Hole
• external galaxies and cosmological evolution

Quasars: stars or black holes ?



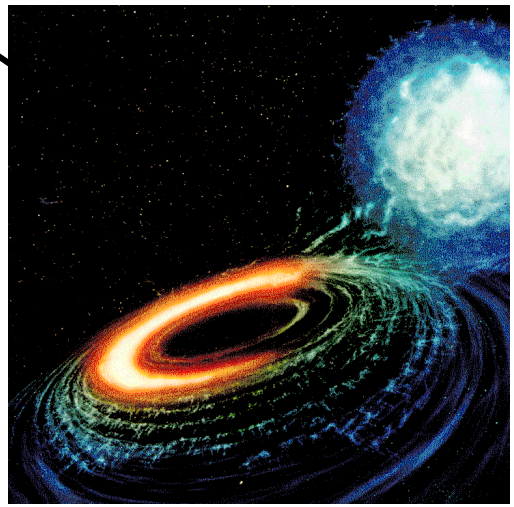
$E < 0.005\ Mc^2$



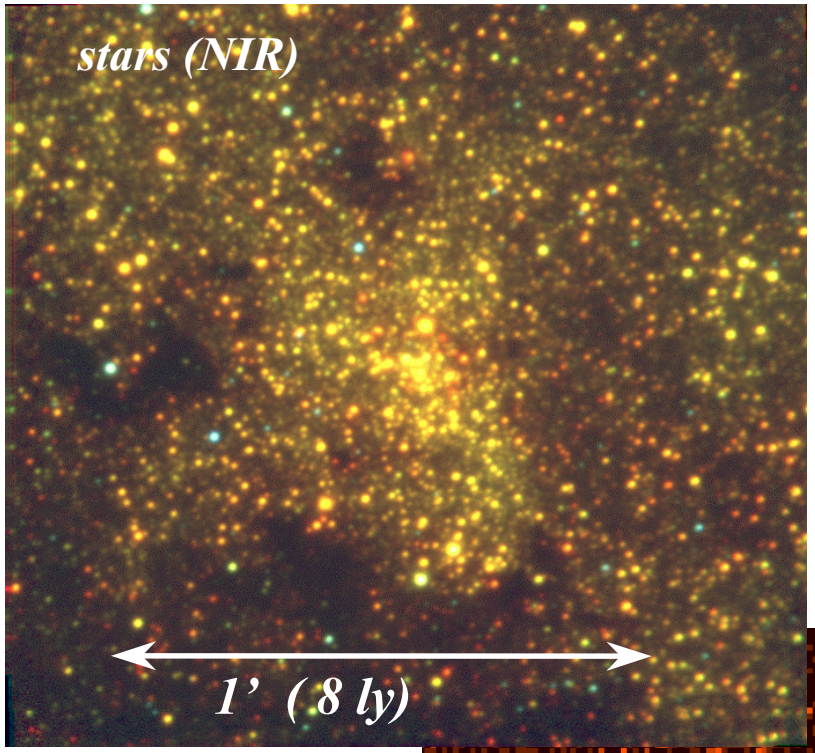
radio source 3C 273

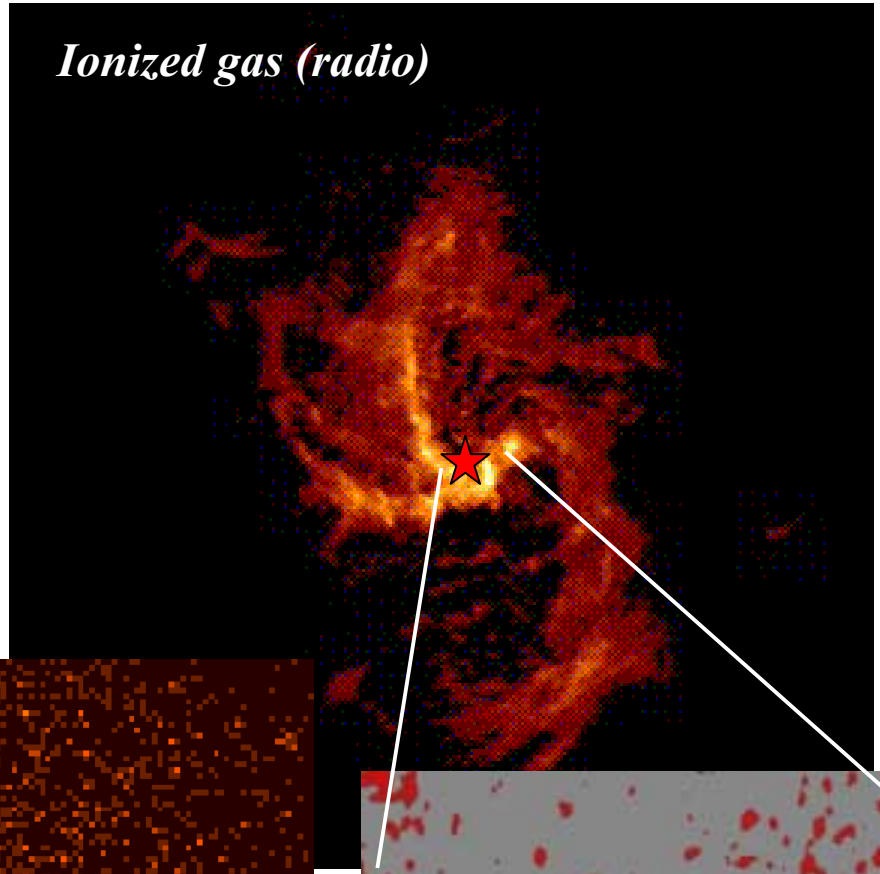
mass distribution

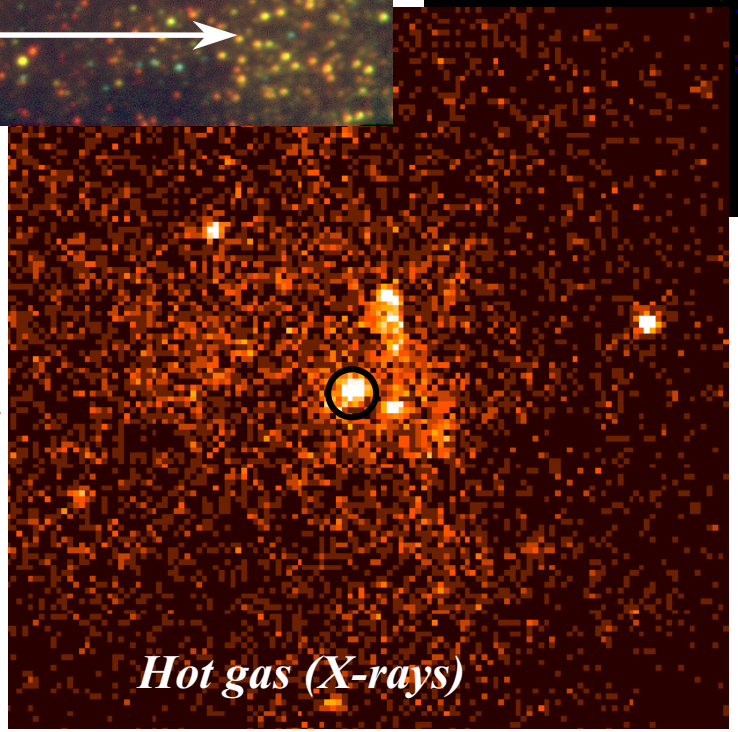
Schmidt, Lynden-Bell, Rees
1963-71

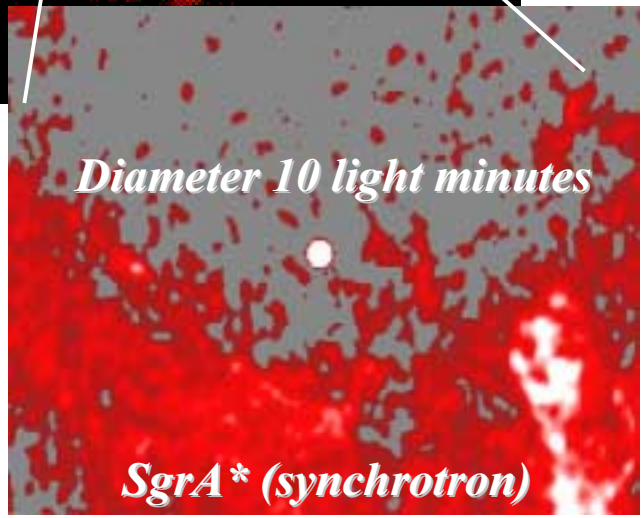


$E \leq 0.4\ Mc^2$
variable X- und γ -
radiation
relativistic radio jets





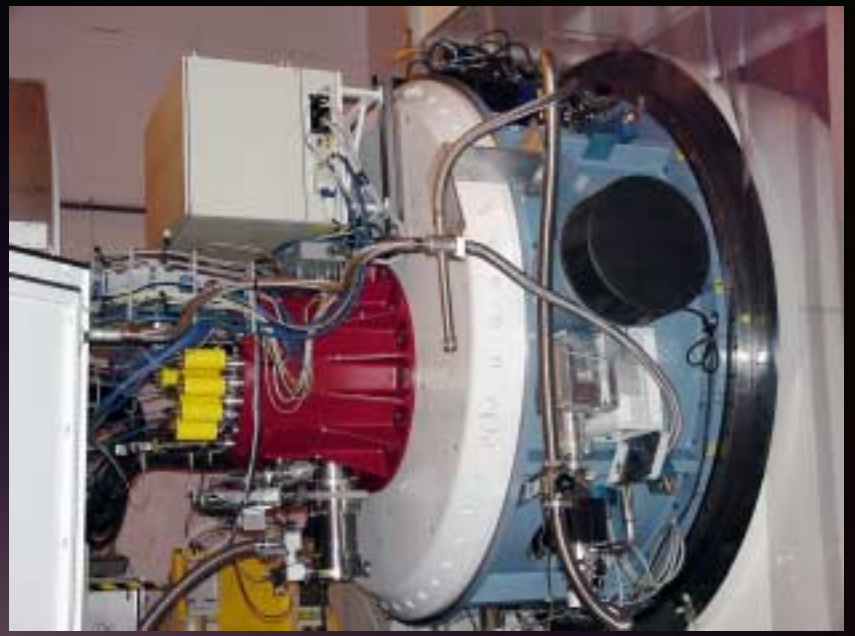




The center of the Milky Way

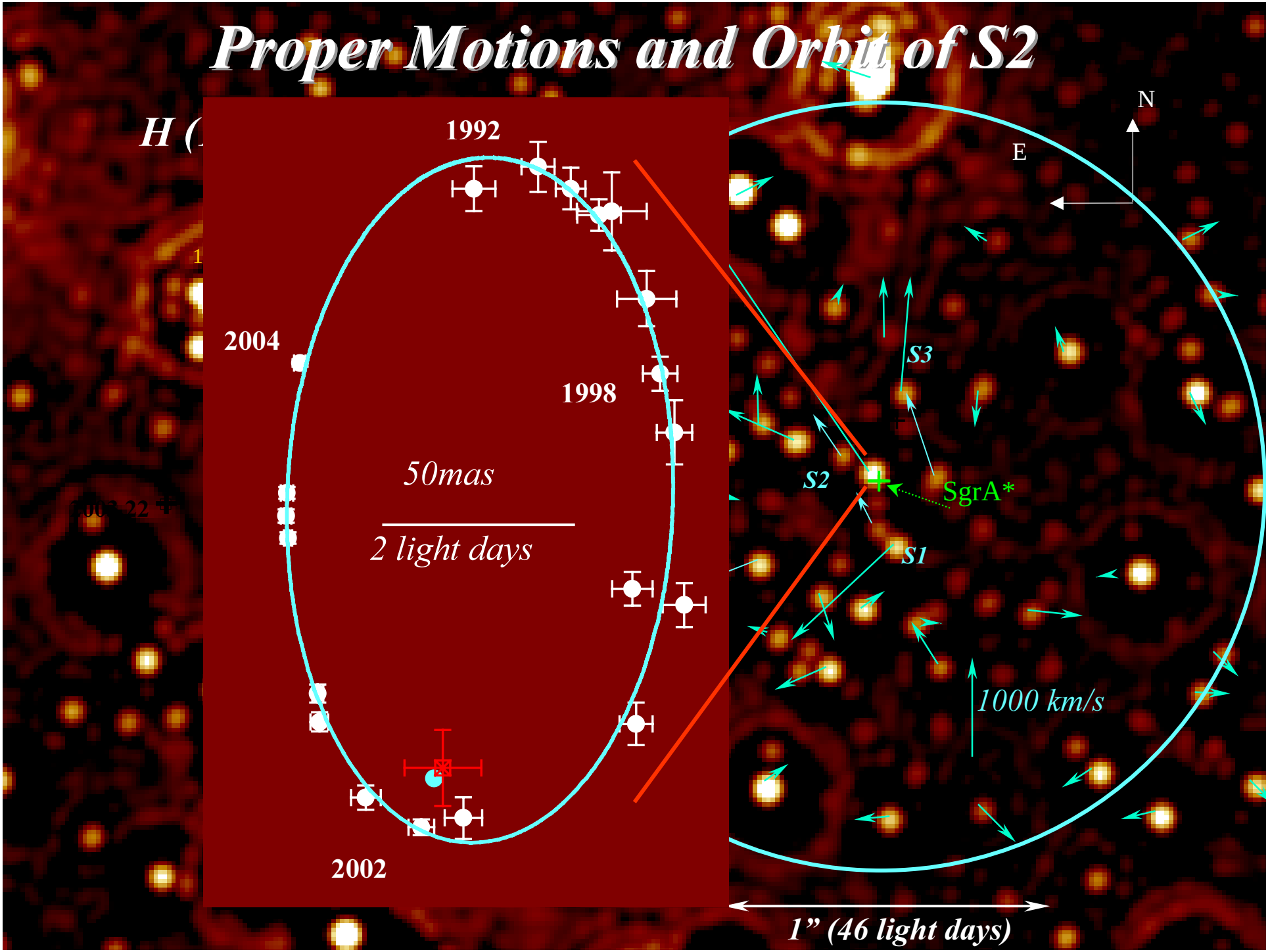

ALFA Calar Alto (MPIA/MPE)

NAOS/CONICA and SPIFFI at the VLT



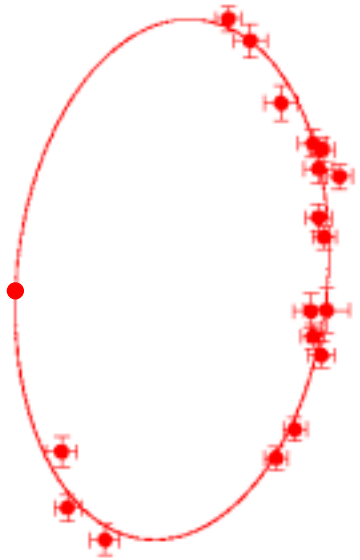
NAOS-CONICA:
Co-PIs: G.Rousset (ONERA), R.Lenzen (MPIA), R.Hofmann(MPE)

SPIFFI/SINFONI:
PIs: F.Eisenhauer & N.Thatte (MPE)

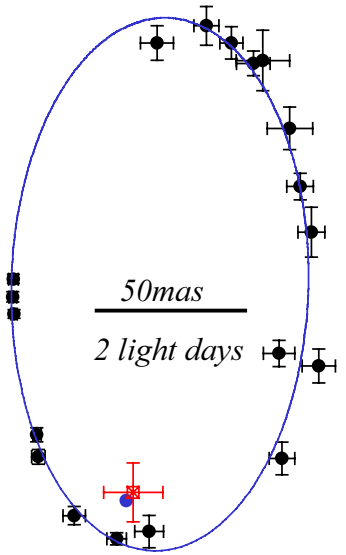

Proper Motions and Orbit of S2
1992
2004
1998
2002
50mas
2 light days
N
E
S3
S2
SgrA*
S1
1000 km/s
1" (46 light days)

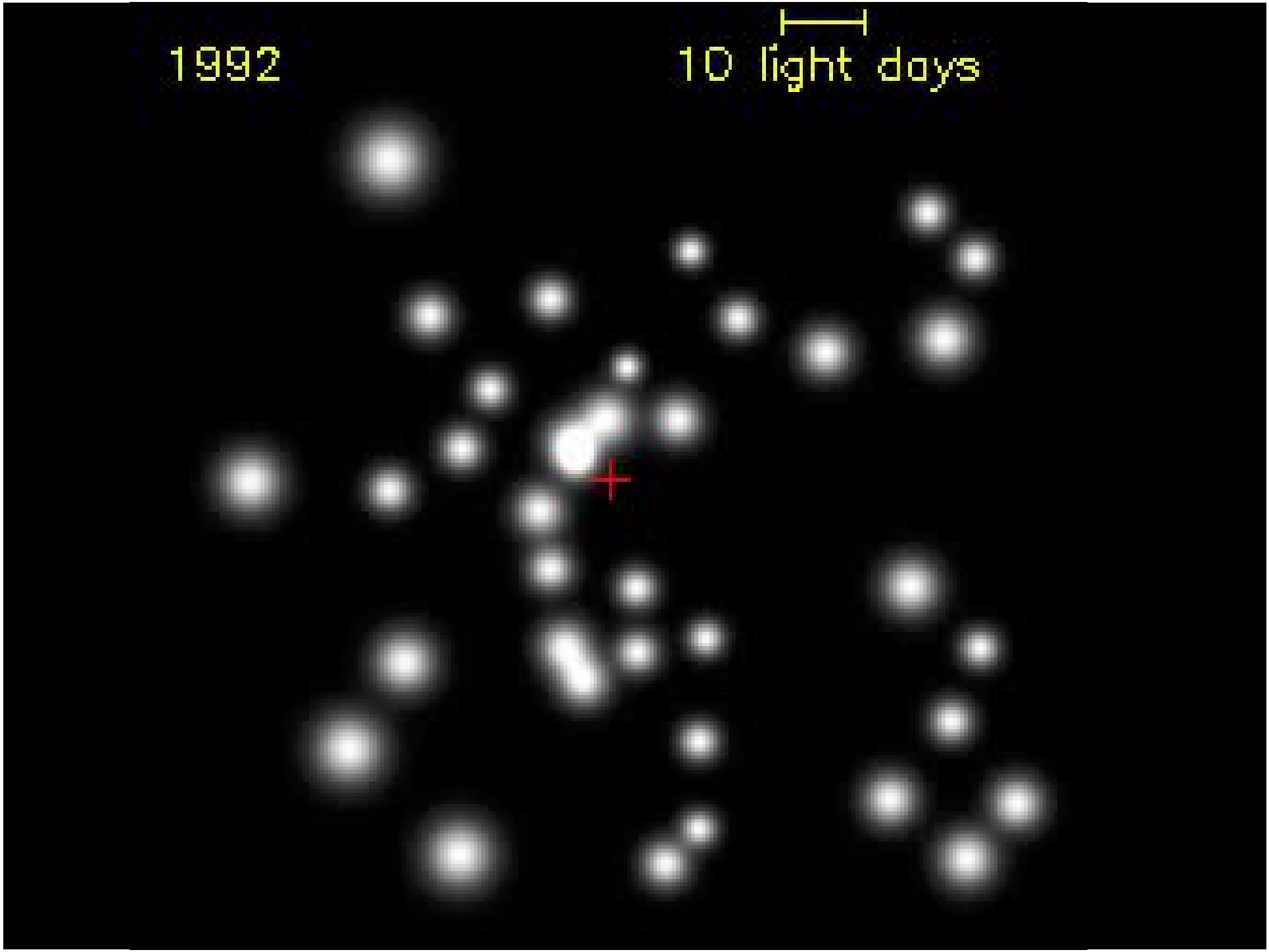
Precision determination of S2 orbit

Schödel et al. 2002, NATURE 419, 694
Schödel, et al. 2003, Ap.J. 596, 1015
Eisenhauer et al., Ap.J.Lett (astro-ph 0306220)
Ghez et al. 2003, ApJ 586, L127, + astro-ph 0306130

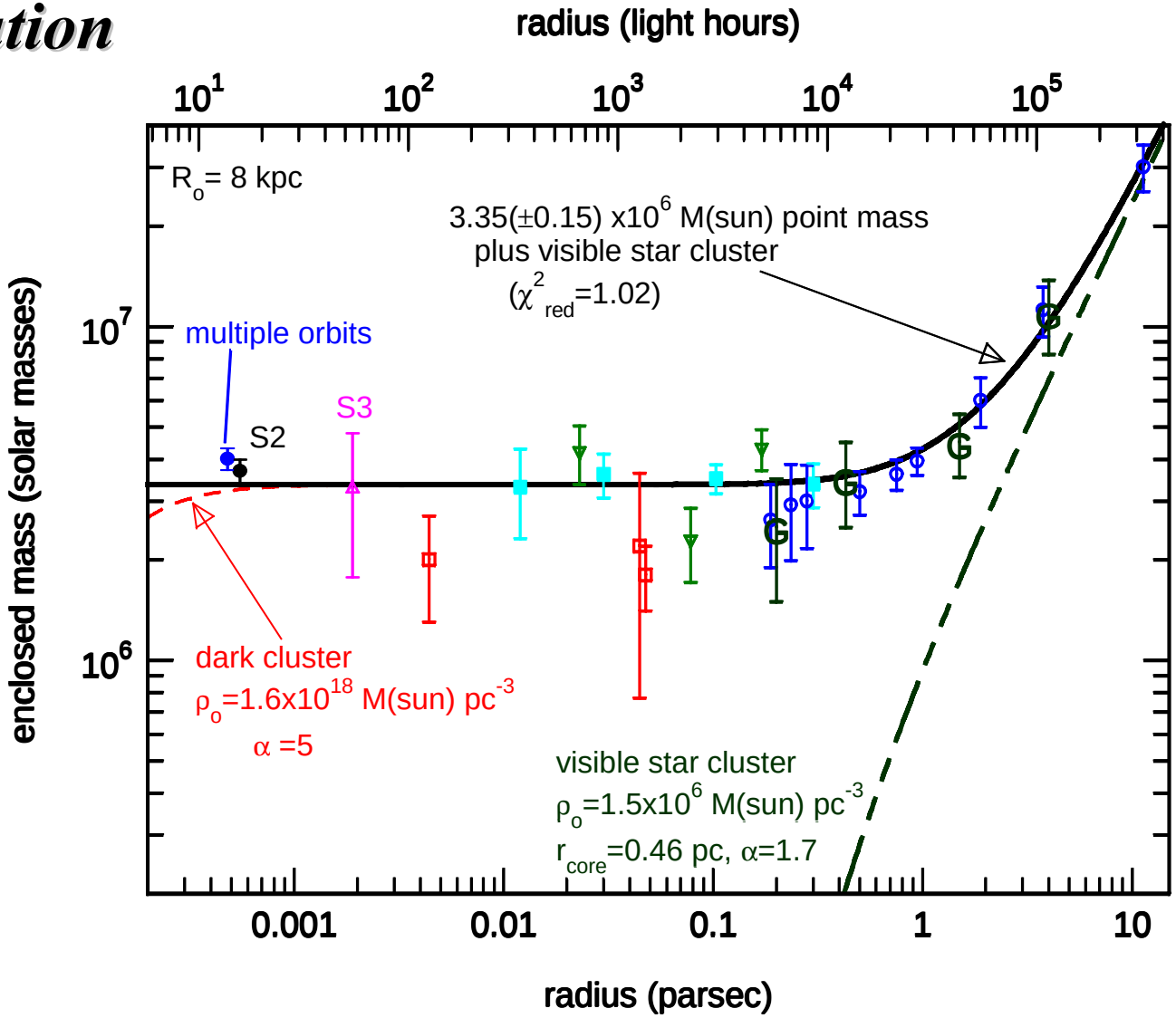


S2 parameters	Eisenhauer et al. 03	Ghez et al. 03
Offset R.A. (mas)	**2.3±1.2**	-2.7 ± 1.9
Offset Decl. (mas)	**-3.1 ±1.2**	-5.4 ± 1.4
Central Mass ($10^6 M_\odot$)	**3.59±0.29(0.59)**	**3.99±0.3**
Period (yr)	**15.56 ±0.35**	**15.02±0.7**
Pericenter Passage (yr)	**2002.33±0.016**	**2002.33±0.013**
Eccentricity	**0.881 ±0.007**	**0.876±0.006**
Angle of line of nodes (deg)	**45.0 ±1.6**	**45.4±1.7**
Inclination (deg)	**-48.1 ±2.3**	**-46.4±1.7**
Angle of node to pericenter	**245.4 ±1.7**	**247.1±2.3**
Semi-major axis (mpc)	**4.63 ±0.10**	**4.63±0.17**
Separation of pericenter (mpc)	**0.551 ±0.010**	**0.573±0.025**
R_o (kpc)	**7.94±0.42**	

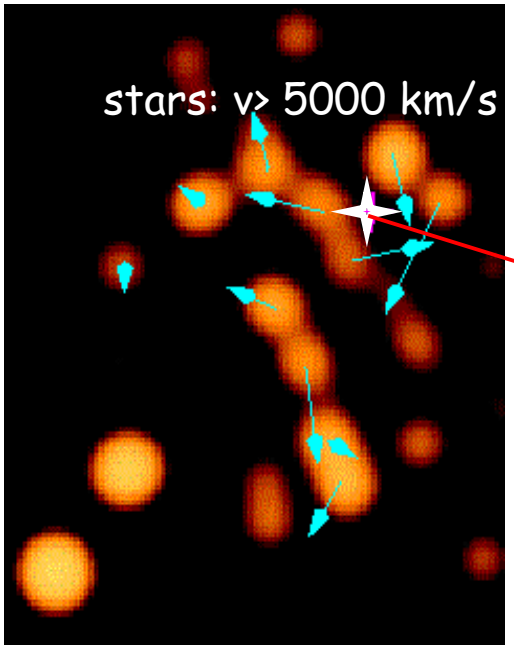



1992
10 light days

mass distribution



Schödel et al., NATURE 2002, 419, 694; 2003, Ap.J. 596, 1015, Ghez et al. 2003, Ap.J. 586, L127, astro-ph 0306130, Eisenhauer et al. 2003, ApJ 597, L121



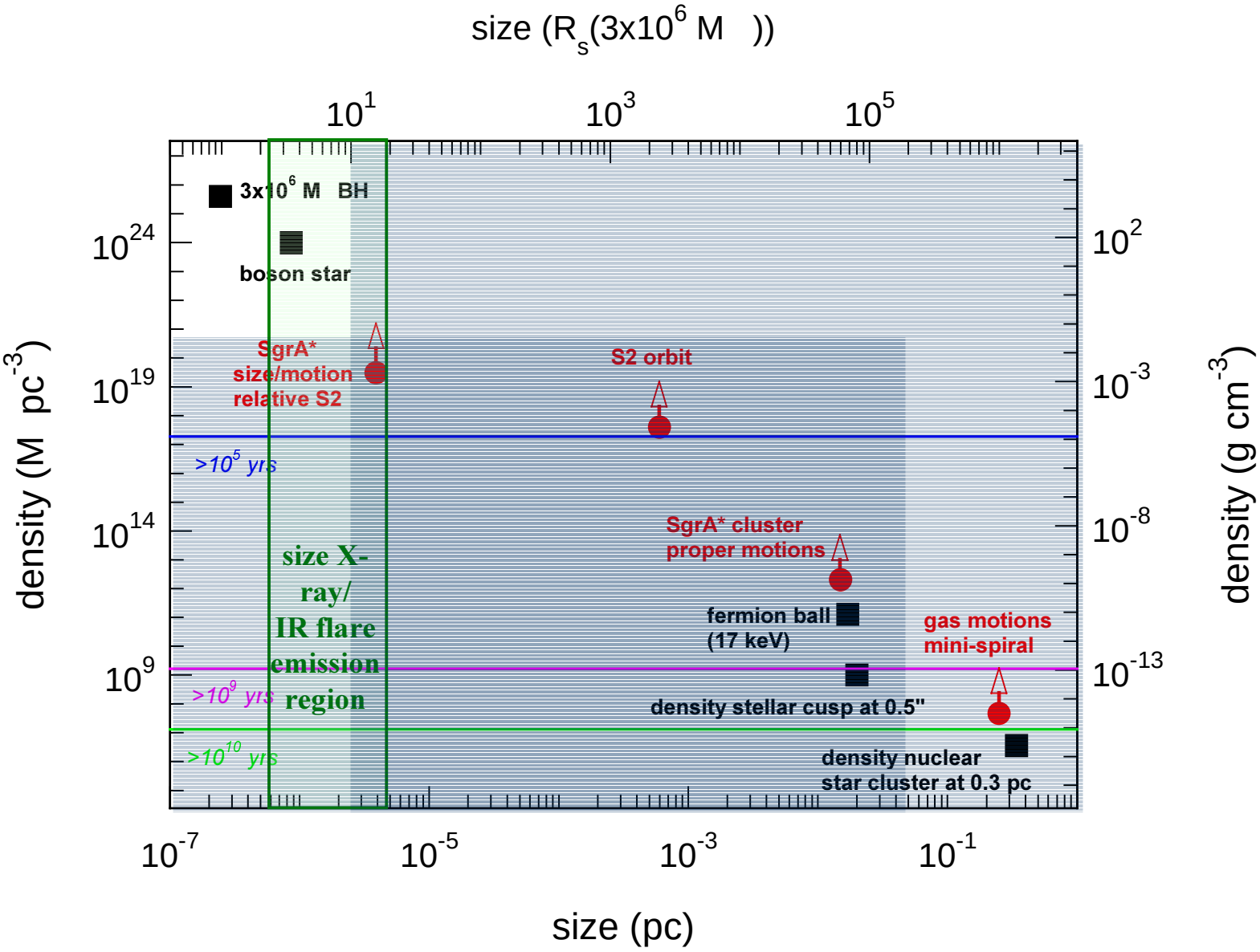
SgrA* does not move

VLBI:
v(SgrA*)<10 (2) km/s
diameter radio source <20 R_s
(Backer, Reid et al. 1999, 2004)

$$M_{SgrA*} > 10^5 M$$

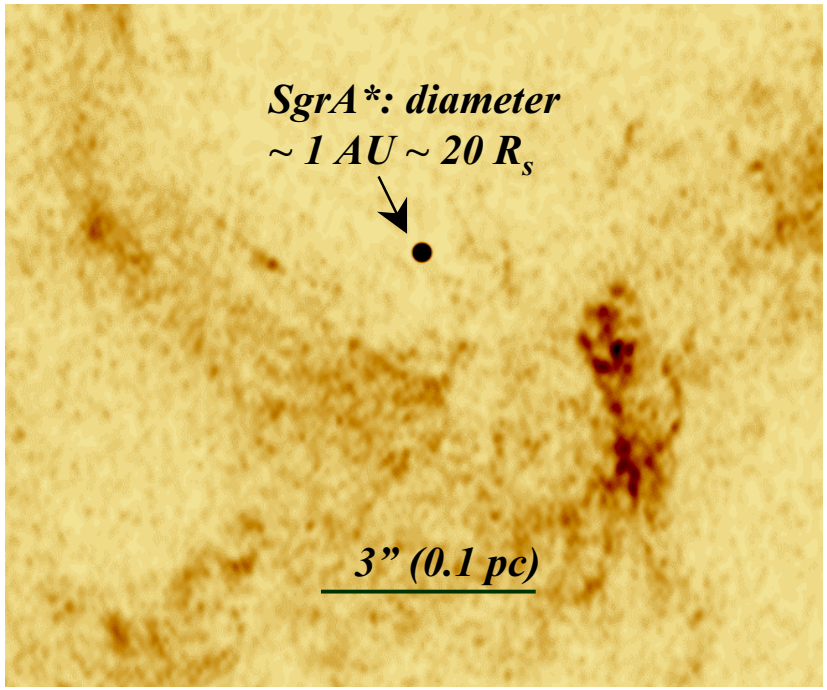
$$?_{SgrA*} > 10^{20.5} M \; pc^{-3} = 10^{-1.7} g \; cm^{-3}$$

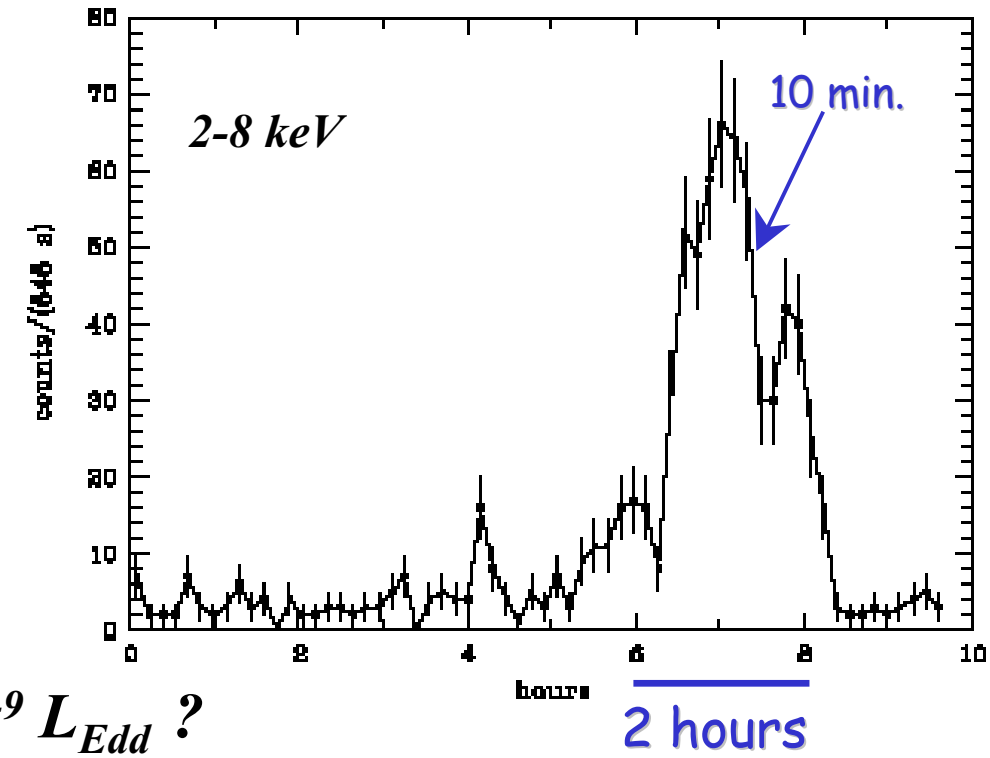
Reid et al. 1999, 2004, Chatterjee et al. 2002, Dorband et al. 2003


size (R_s(3x10^6 M))
10^1
10^3
10^5
3x10^6 M BH
boson star
SgrA*
size/motion
relative S2
S2 orbit
>10^5 yrs
SgrA* cluster
proper motions
fermion ball
(17 keV)
gas motions
mini-spiral
size X-
ray/
IR flare
emission
region
density stellar cusp at 0.5"
>10^9 yrs
>10^{10} yrs
density nuclear
star cluster at 0.3 pc
density (M pc^{-3})
density (g cm^{-3})
10^{24}
10^{19}
10^{14}
10^9
10^2
10^{-3}
10^{-8}
10^{-13}
10^{-7}
10^{-5}
10^{-3}
10^{-1}
size (pc)

Accretion onto the Black Hole

radio/mm





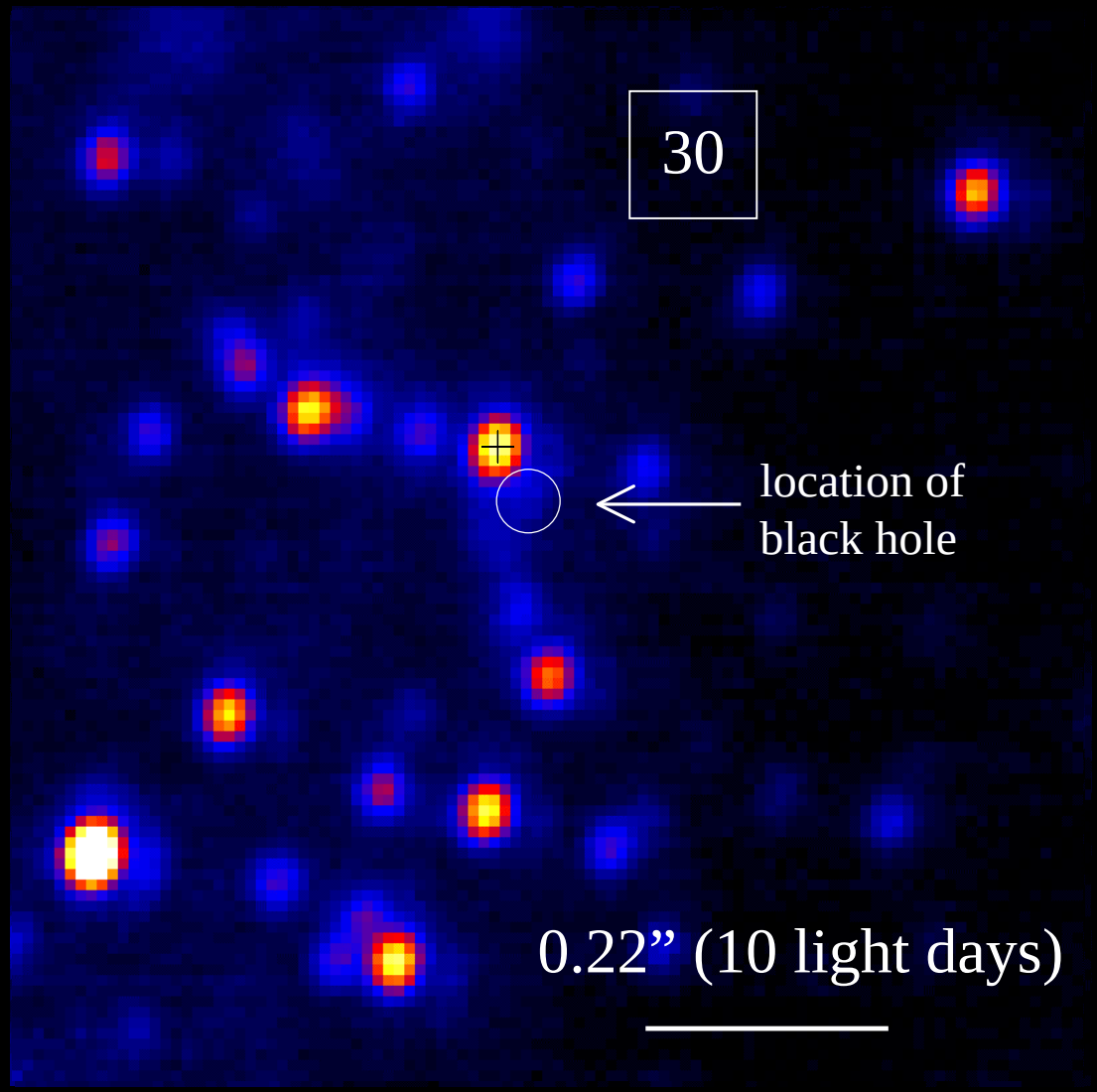
Why is the BH so faint: $L \sim 10^{-9} L_{Edd}$?

- ***low accretion rate***
- ***low conversion efficiency to radiation***
- ***low efficiency of removal of angular momentum***

May 2002 campaign: ~0.6-1.2 flares/day

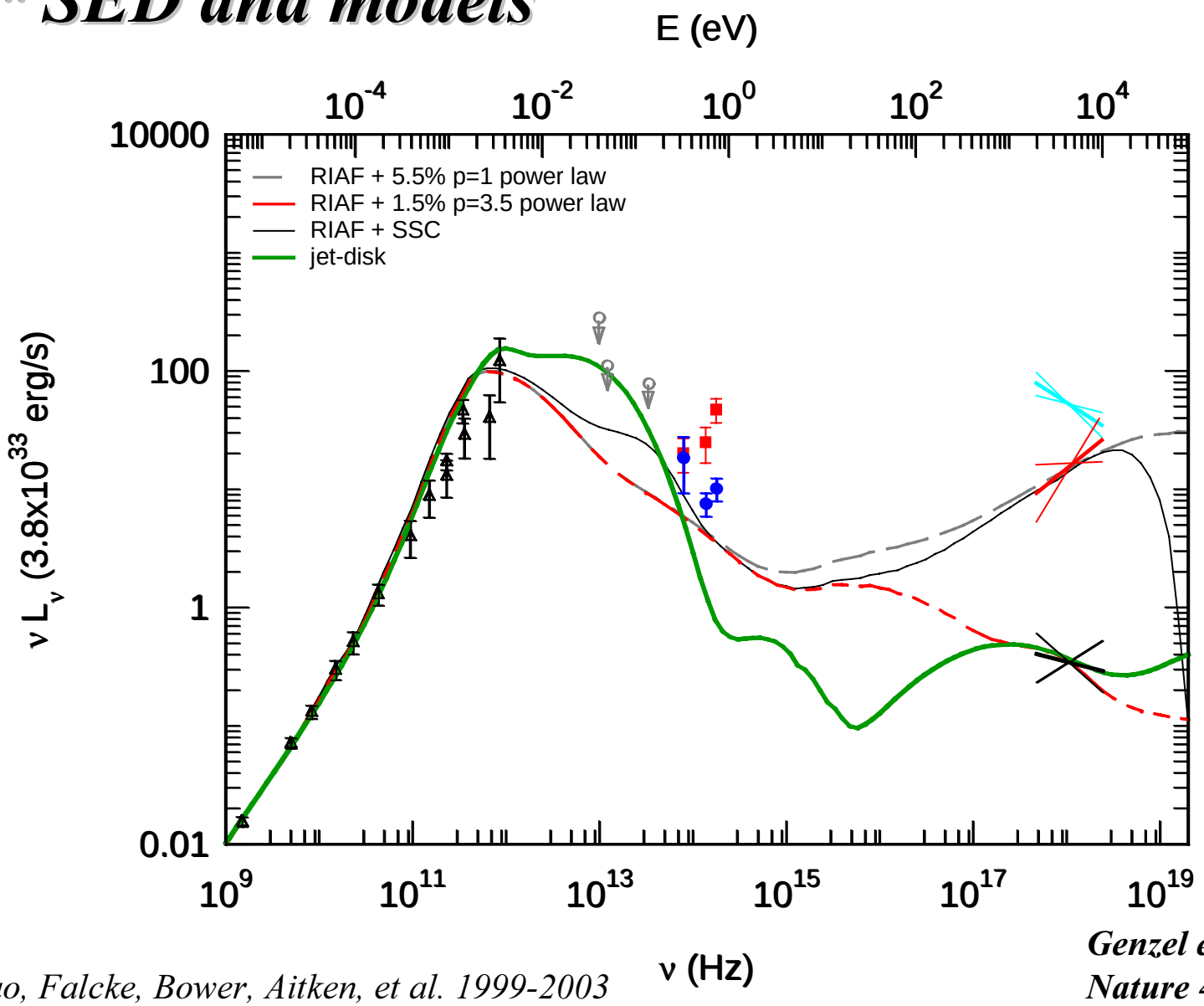
Baganoff et al. 2000, 2001,2003, Porquet et al. 2003, Aschenbach et al. 2004, Yusef-Zadeh, Zhao et al. 2000, 2003,Aitken et al. 99, Bower et al. 2003

Infrared flares & BH spin



May 09, 2003: NACO (VLT) H-band, 40 mas resolution (adaptive optics), 1 min per image

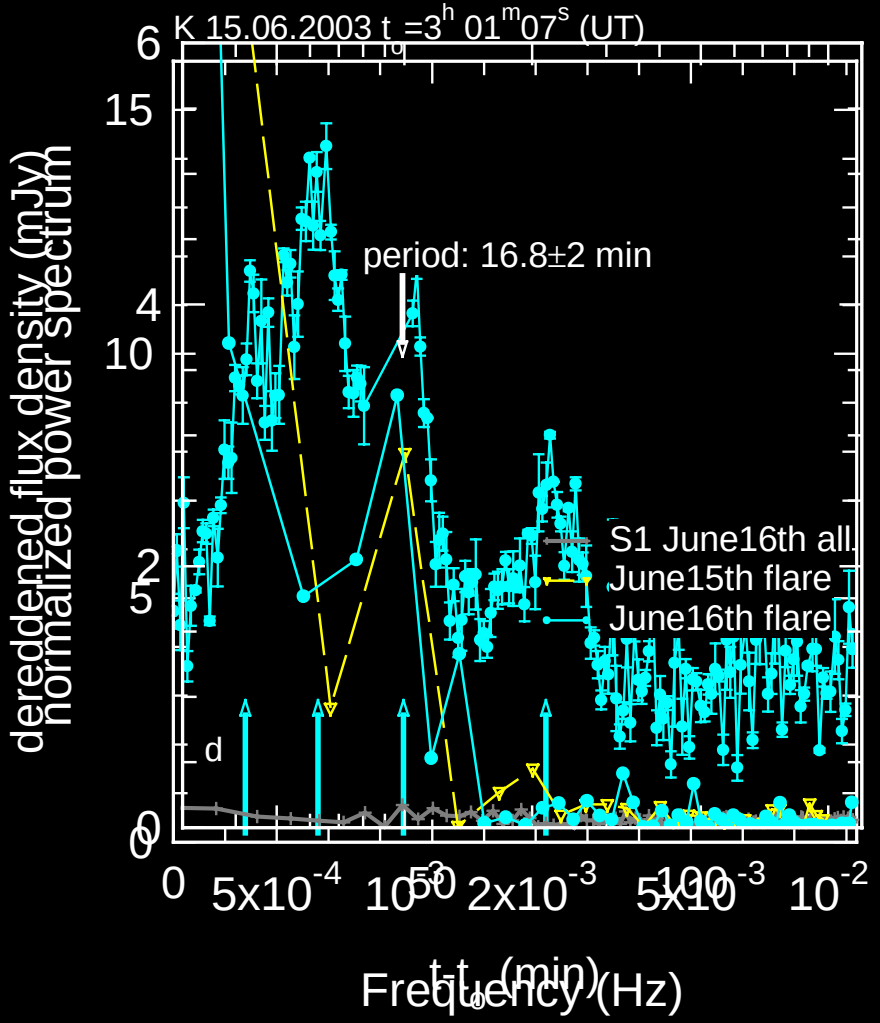
SgrA SED and models*

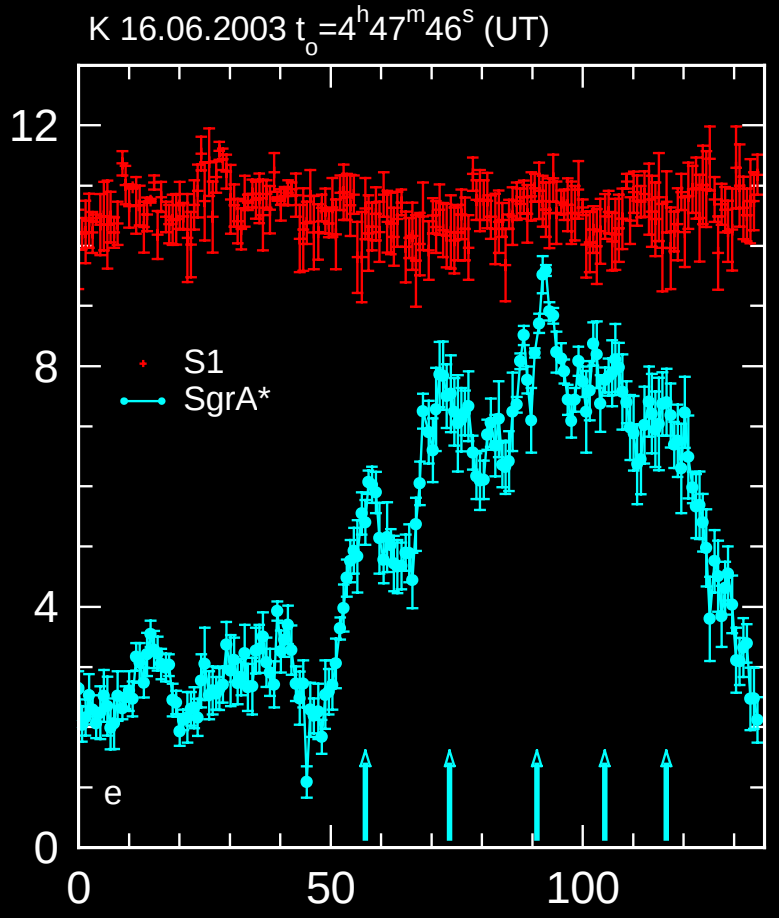


Radio: Zhao, Falcke, Bower, Aitken, et al. 1999-2003
X-ray: Baganoff et al. 2001, 2003, Goldwurm et al. 2003, Porquet et al. 2003,
models: Markoff, Falcke, Liu, Melia, Narayan, Quataert, Yuan et al. 1999-2003

Genzel et al. 2003, Nature 425. 934
Ghez et al. 2004, ApJ 601, L159

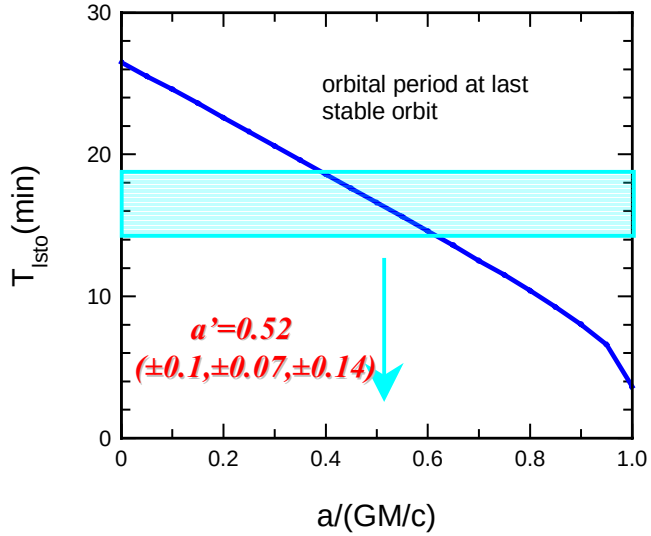
Quasi-periodic oscillations

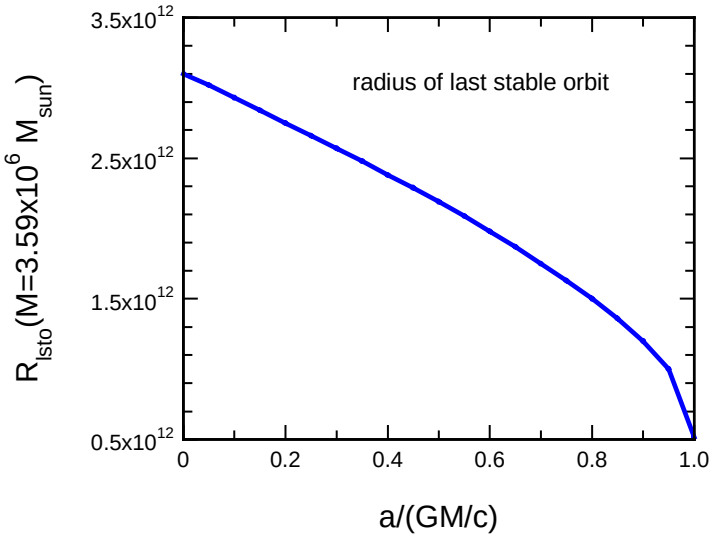


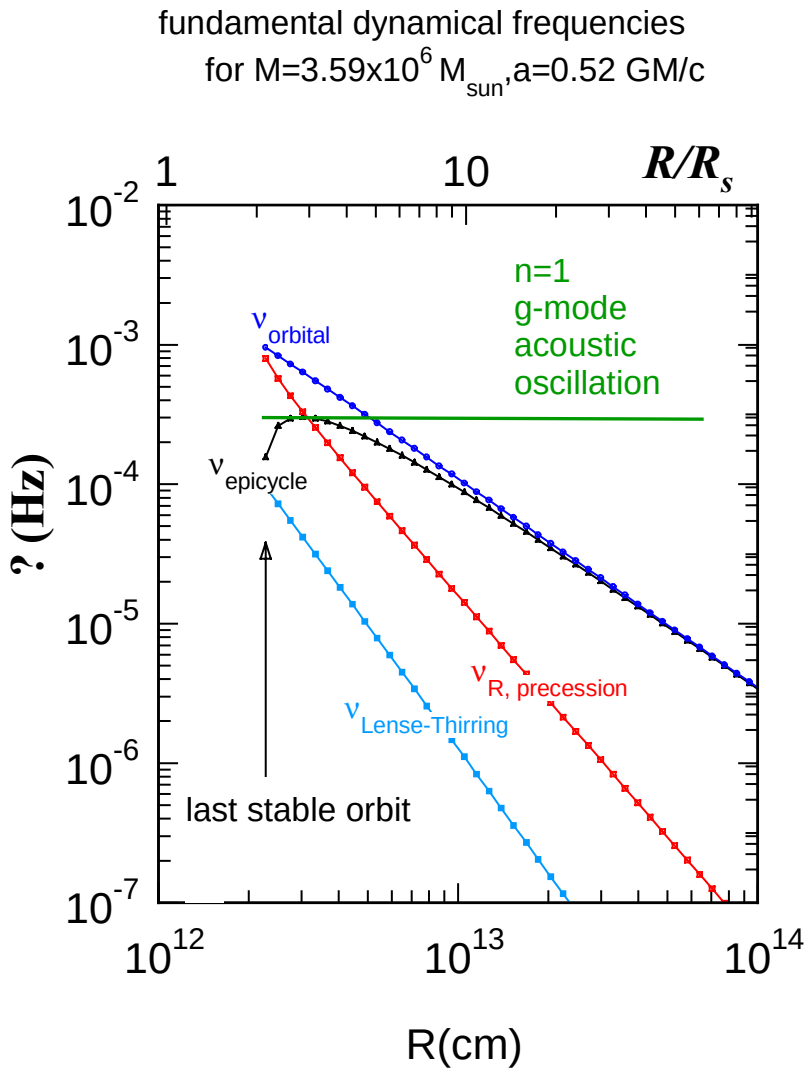


Genzel et al. 2003, Nature 425, 934

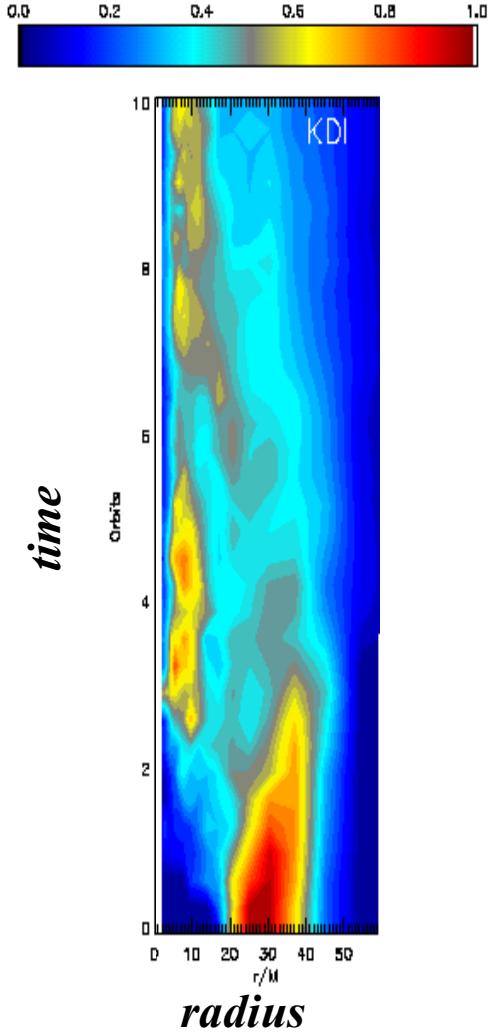
Fundamental dynamical frequencies around a black hole

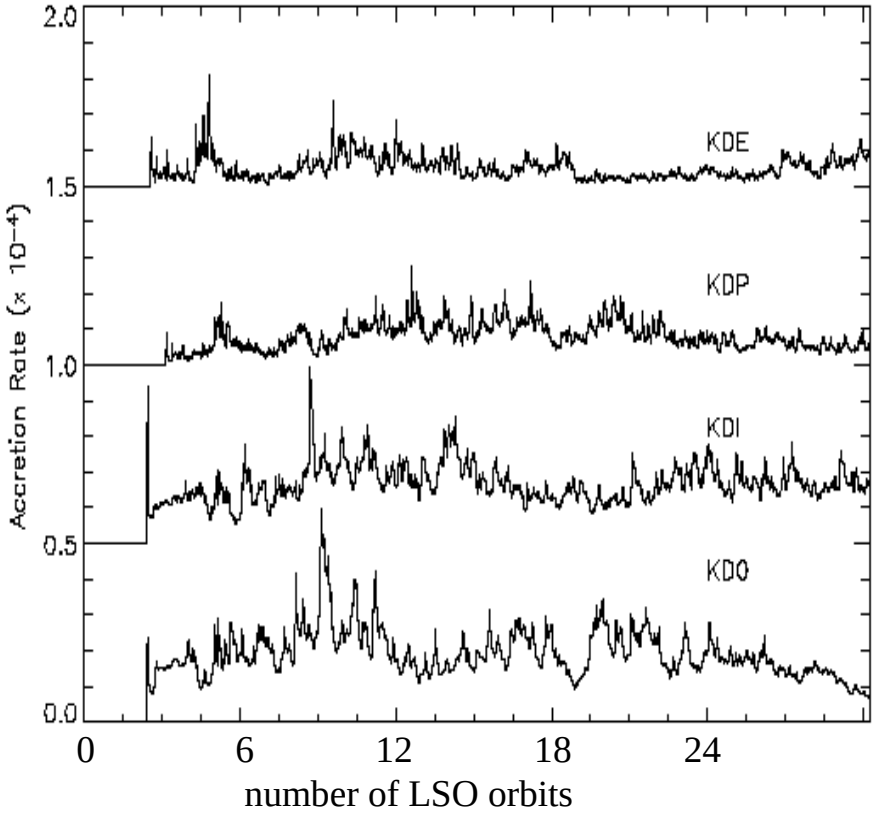






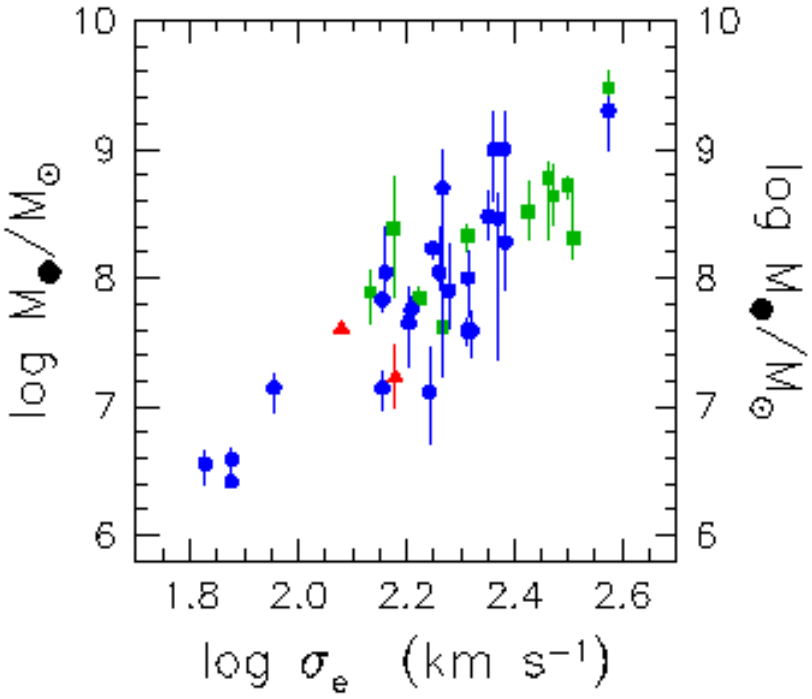
Kerr MHD accretion disk simulation

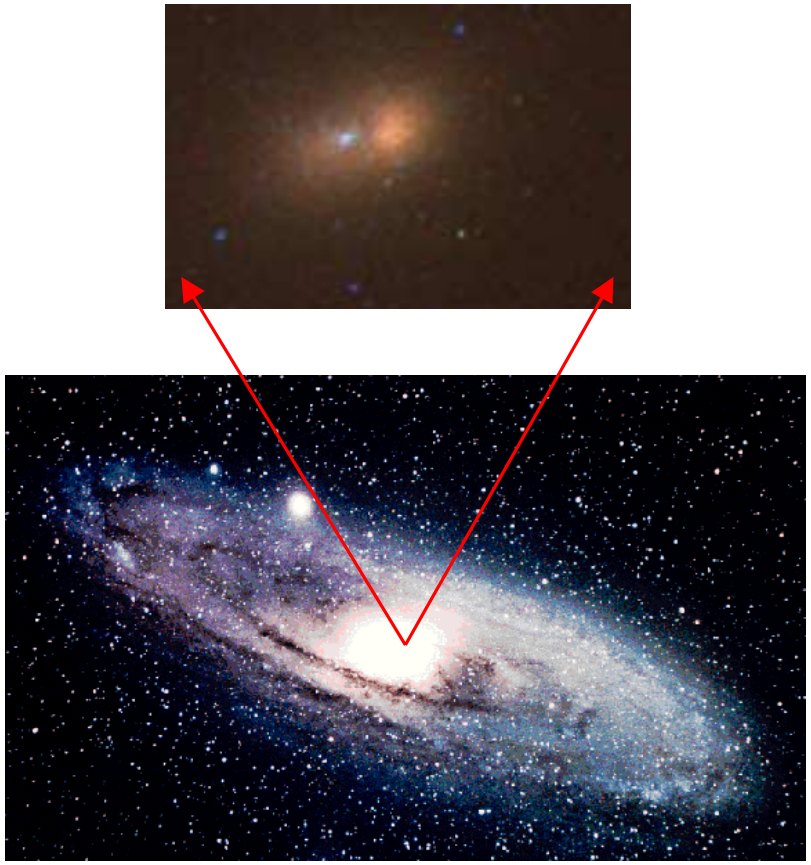




De Villers, Hawley & Krolik, 2003, astroph 0307260

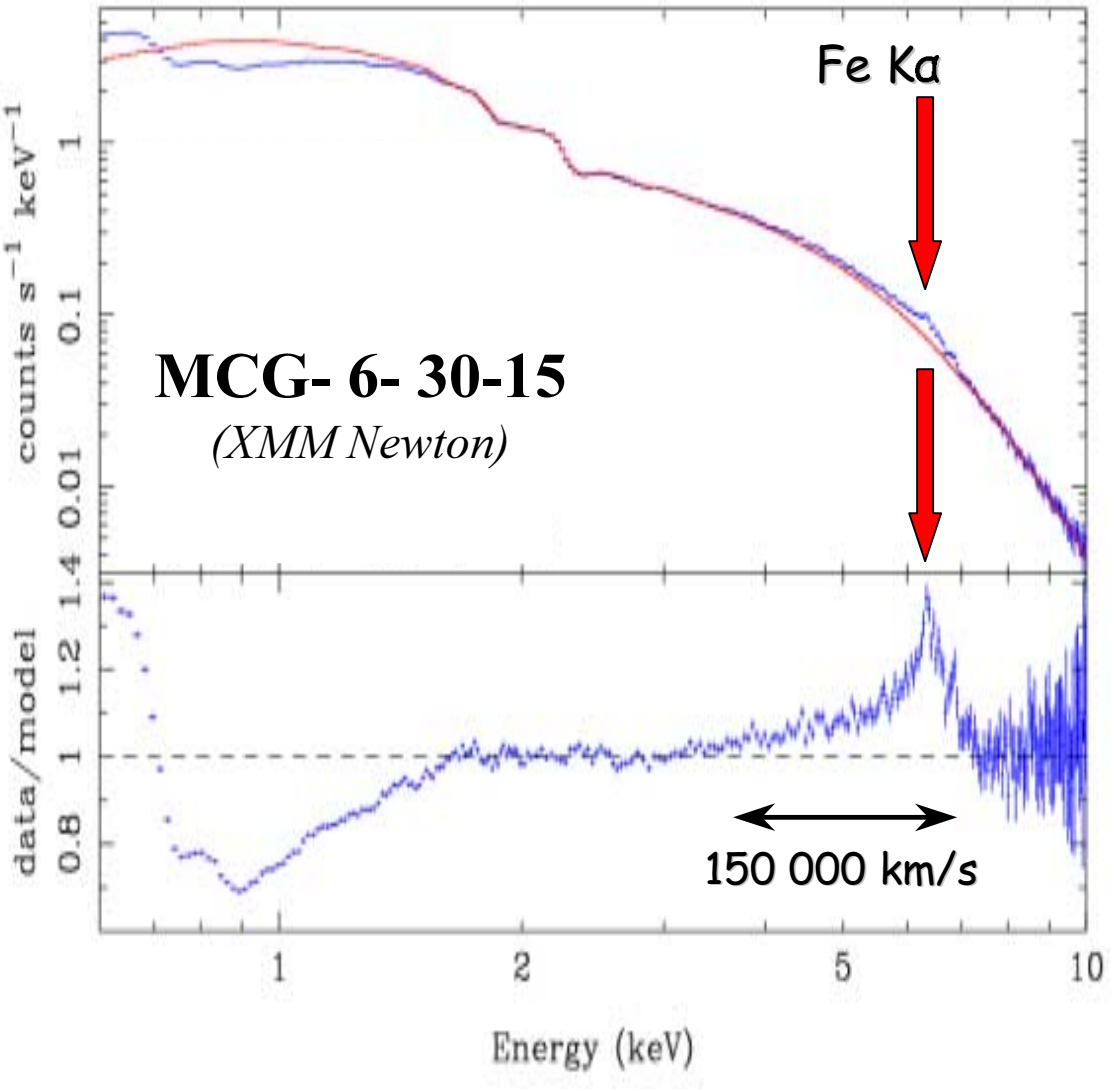
Black Holes in the Local Universe





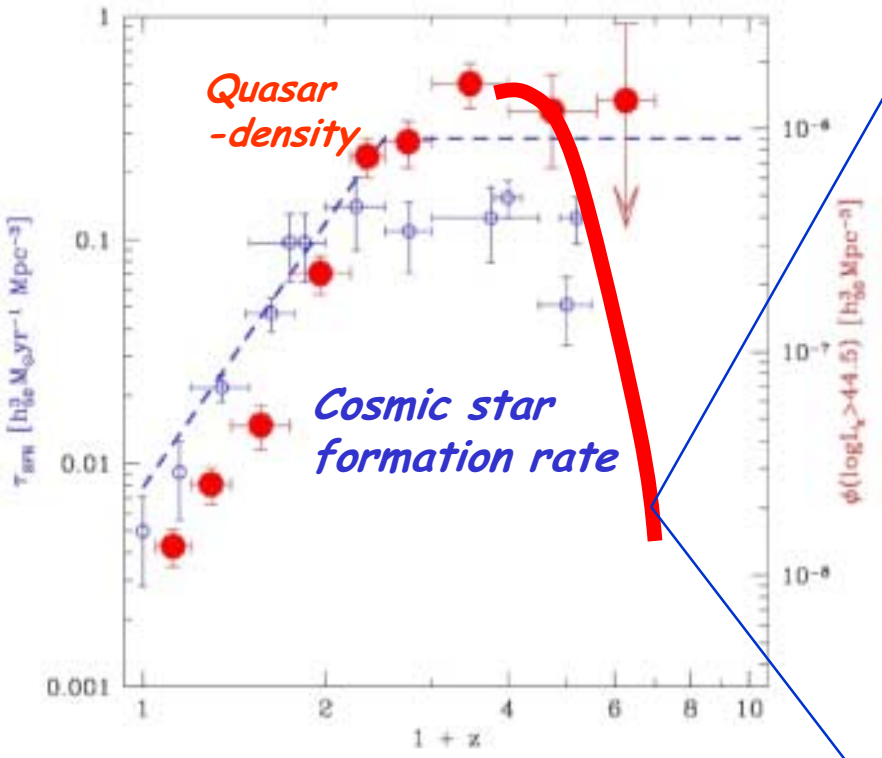
Miyoshi et al. 1995, Kormendy & Richstone 1995, Gebhardt et al. 2000, Merritt und Ferrarese 2000, Tremaine et al. 2002

Relativistic accretion disks

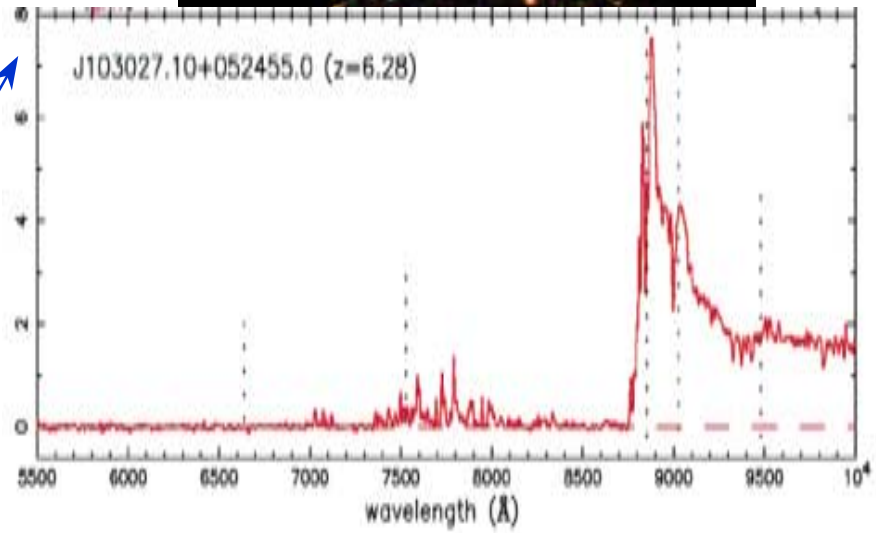


Tanaka, Nandra et al
1997-99
Fabian et al. 2002

Black Holes & Galaxy Formation



ROSAT/XMM/Chandra

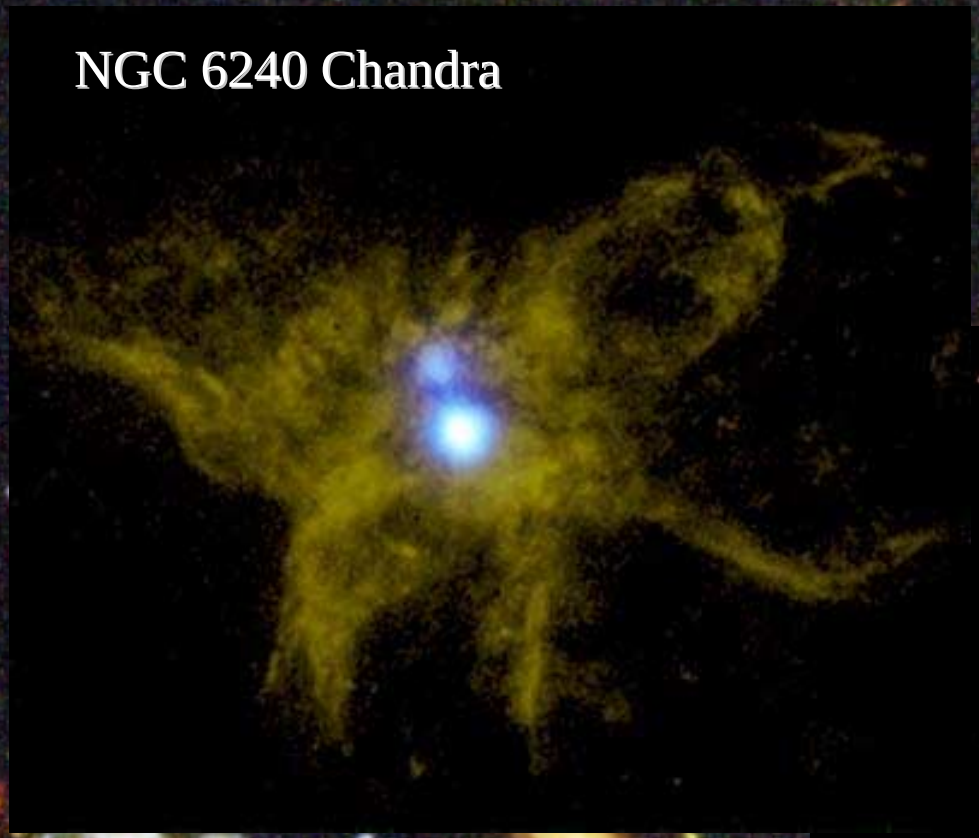


$M_{BH} \sim$ a few $10^9 M_\odot$ at $t \sim 800$ Myrs after Big Bang!

Hasinger et al. 1999, 2002, Steidel et al. 1999, Bender und FORS Team 2002

Fan et al. 2001, Becker et al. 2002

Formation of Quasars



VIRGO Consortium (MPA), White e al.1987-2002, Springel 2001
Binary black hole: Komossa & Hasinger 2003

The future

- **interferometry: relativistic regime**
- **submm VLBI: detection of event horizon**
- **simultaneous radio to ?-emission : accretion flow**
- **TeV emission: dark matter spike?**
- **z~10 QSOs and galaxies**

ESO-VLTI