# *The massive black hole and central star cluster in the Milky Way Center*

+ SgrA*

*R.Genzel*

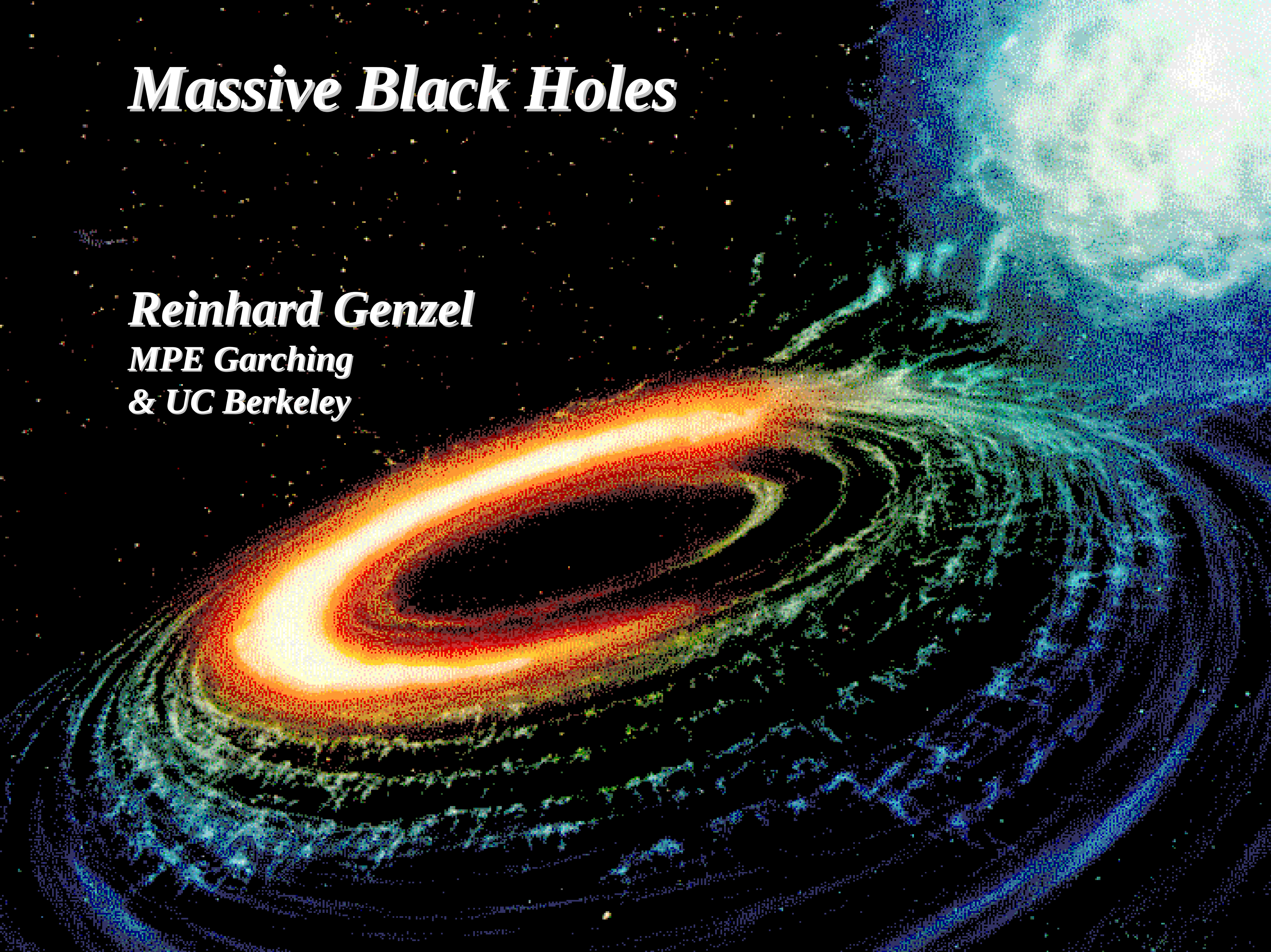
*MPE & UC Berkeley*

- **paradox of youth**
- **testing the BH paradigm with stellar orbits**
- **emission and properties of SgrA***

*F.Eisenhauer, T.Paumard, R.Schödel, T.Ott, A.Eckart, T.Alexander, S.Trippe , R.Abuter, S.Gillessen, F.Martins*

# *Massive Black Holes*

***Reinhard Genzel***
*MPE Garching*
*& UC Berkeley*



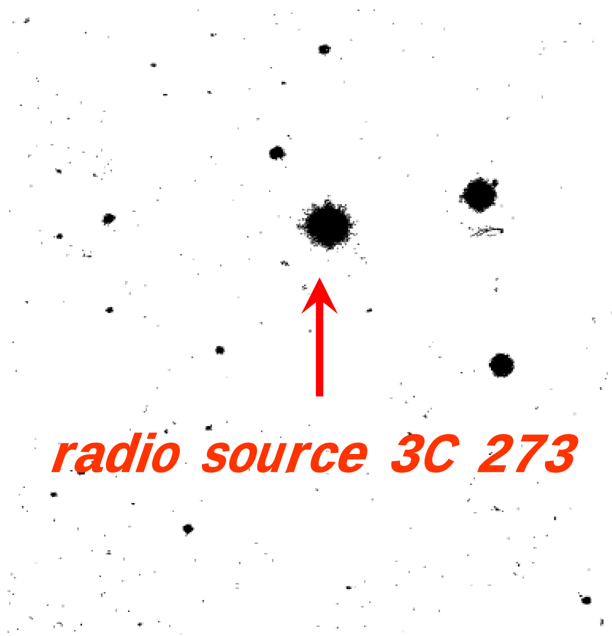
# *New Results in the Galactic Center*

*R.Genzel*
*MPE Garching & UC Berkeley*

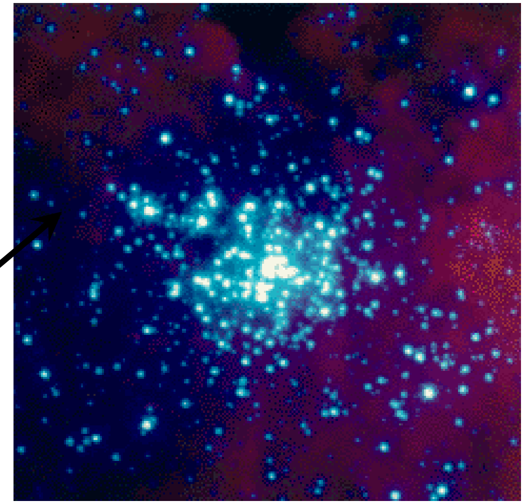
*R.Schödel, T.Ott, A.Eckart, T.Alexander,*
*F.Eisenhauer, R.Abuter, T.Paumard*

- *a paradox of youth*
- *testing the BH paradigm with stellar orbits*
- *accretion, flares & BH spin*

# Quasars: stars or black holes ?

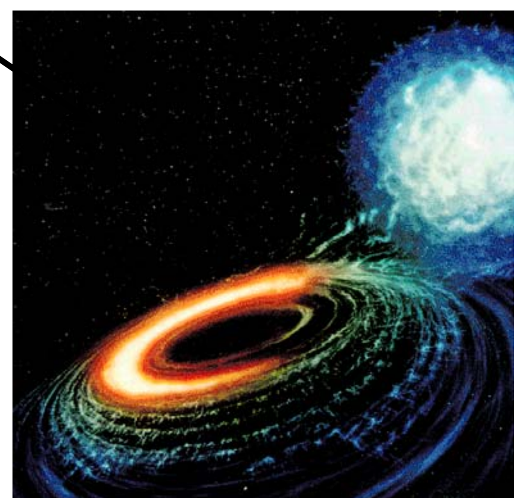


radio source 3C 273



$E < 0.005\ Mc^2$

mass distribution



$E \leq 0.4\ Mc^2$

variable X- und $\gamma$ -radiation

relativistic radio jets

Schmidt, Lynden-Bell, Rees
1963-71

# *The Galactic Center as Laboratory: Expectations*

*(Morris 1993, Genzel, Hollenbach & Townes 1994, Melia & Falcke 2001, Alexander 2002)*

$t_r \tilde{t}_{ms} \geq t_{coll} \sim 150Myr / m_{10}, t_{ms} \sim 20Myr / m_{10}^2$

for R ≤ 1'' ms-ms

$t_{ms} \geq t_r \Rightarrow m \leq 1.3 M_{\odot}$

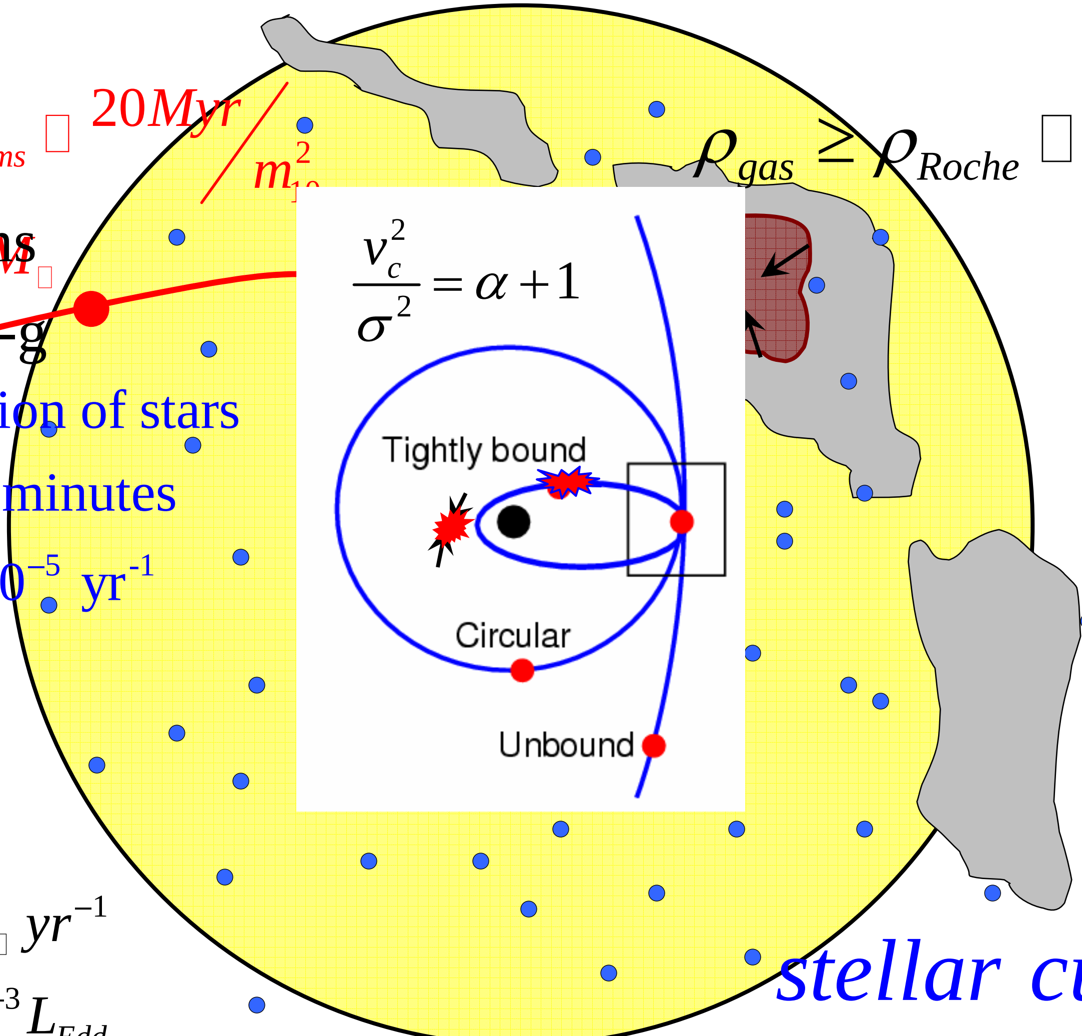
for R ≤ 2.5'' ms-g

tidal disruption of stars

R ≤ 15 light minutes

$1/t_{disruption} \sim 10^{-5}\ yr^{-1}$

$\rho_{gas} \geq \rho_{Roche} \sim 10^{9.5} R_{5''}^{-3} cm^{-3}$




$R_{acc} \sim 1''$

$\dot{M}_{acc} \sim 10^{-4....-5} M_{\odot}\, yr^{-1}$

$L_{acc} \sim 10^{8} L_{\odot} \sim 10^{-3} L_{Edd}$

$observed: L_{SgrA*} \leq 10^{3} L_{\odot}$

*stellar cusp:*

$\rho(R) \propto R^{-\alpha(=0.5...1.85)}$

# *The Galactic Center as Laboratory: Expectations*

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$t_{ms} \geq t_{coll}$

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for R ≤ 2.5" ms-g

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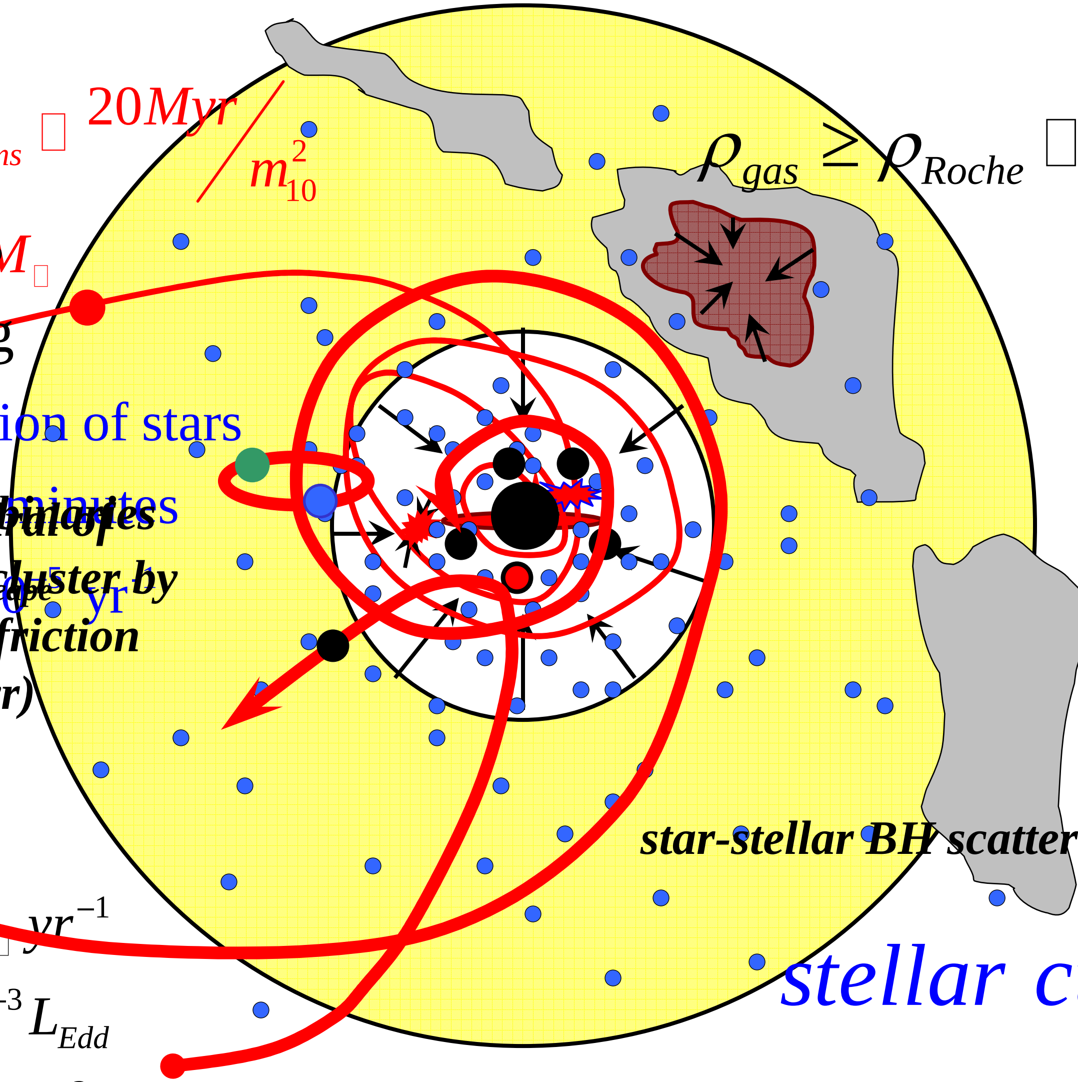


tidal disruption of stars

R ≤ 15 light minutes

$1/t_{disruption} \square 10^{-5}$ yr$^{-1}$

***low abundance of binaries because $t_{cluster} > t_{escape}$***

***rapid in-spiral of dense star cluster by dynamical friction (<a few Myr)***

***star-stellar BH scattering***

$R_{acc} \square 1"$

$\dot{M}_{acc} \square 10^{-4...-5} M_{\square} yr^{-1}$

$L_{acc} \square 10^8 L_{\square} \square 10^{-3} L_{Edd}$

$observed: L_{SgrA*} \leq 10^3 L_{\square}$

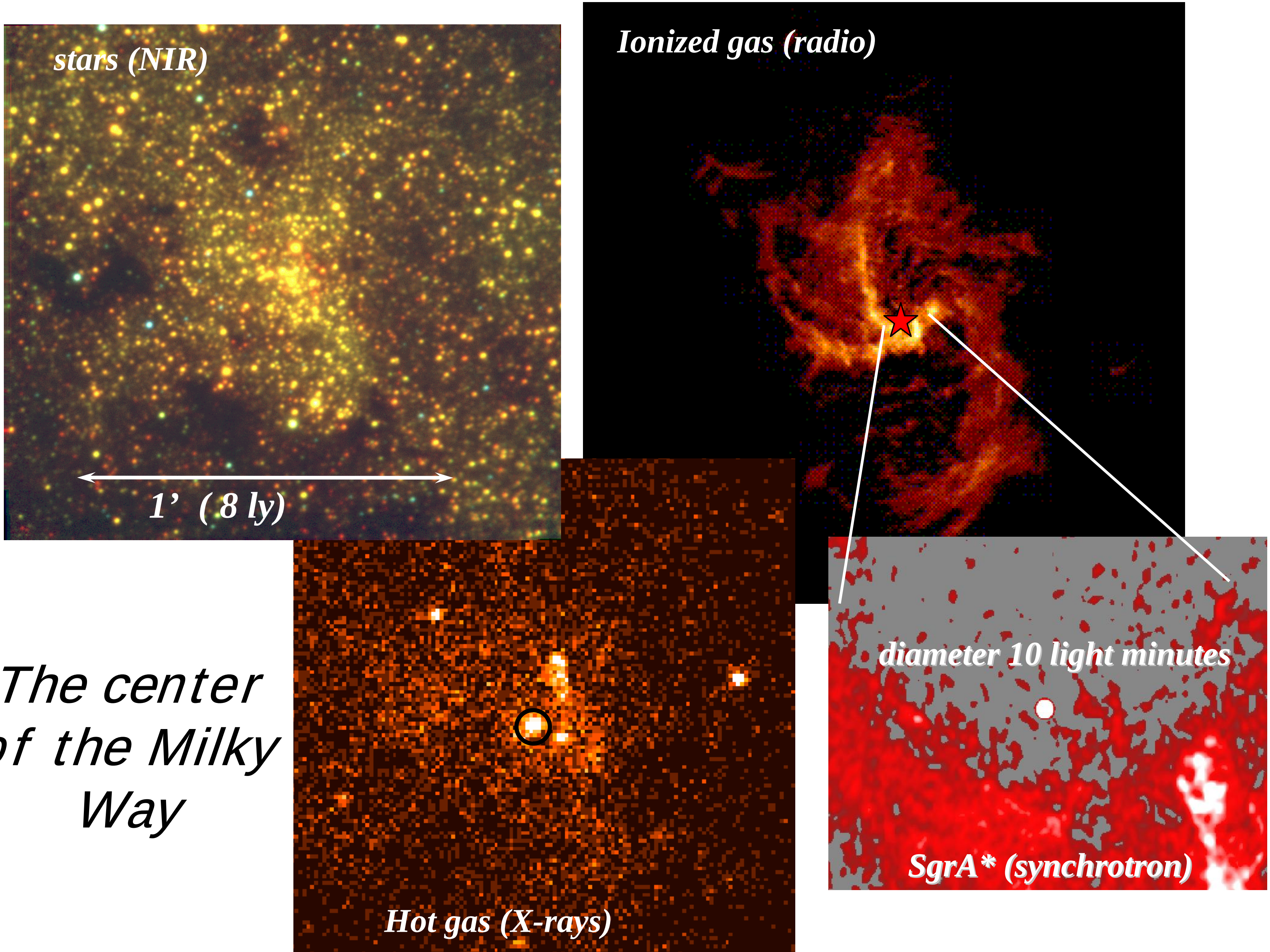
$stellar\ cusp:$

$\rho(R) \propto R^{-\alpha(=0.5...1.85)}$

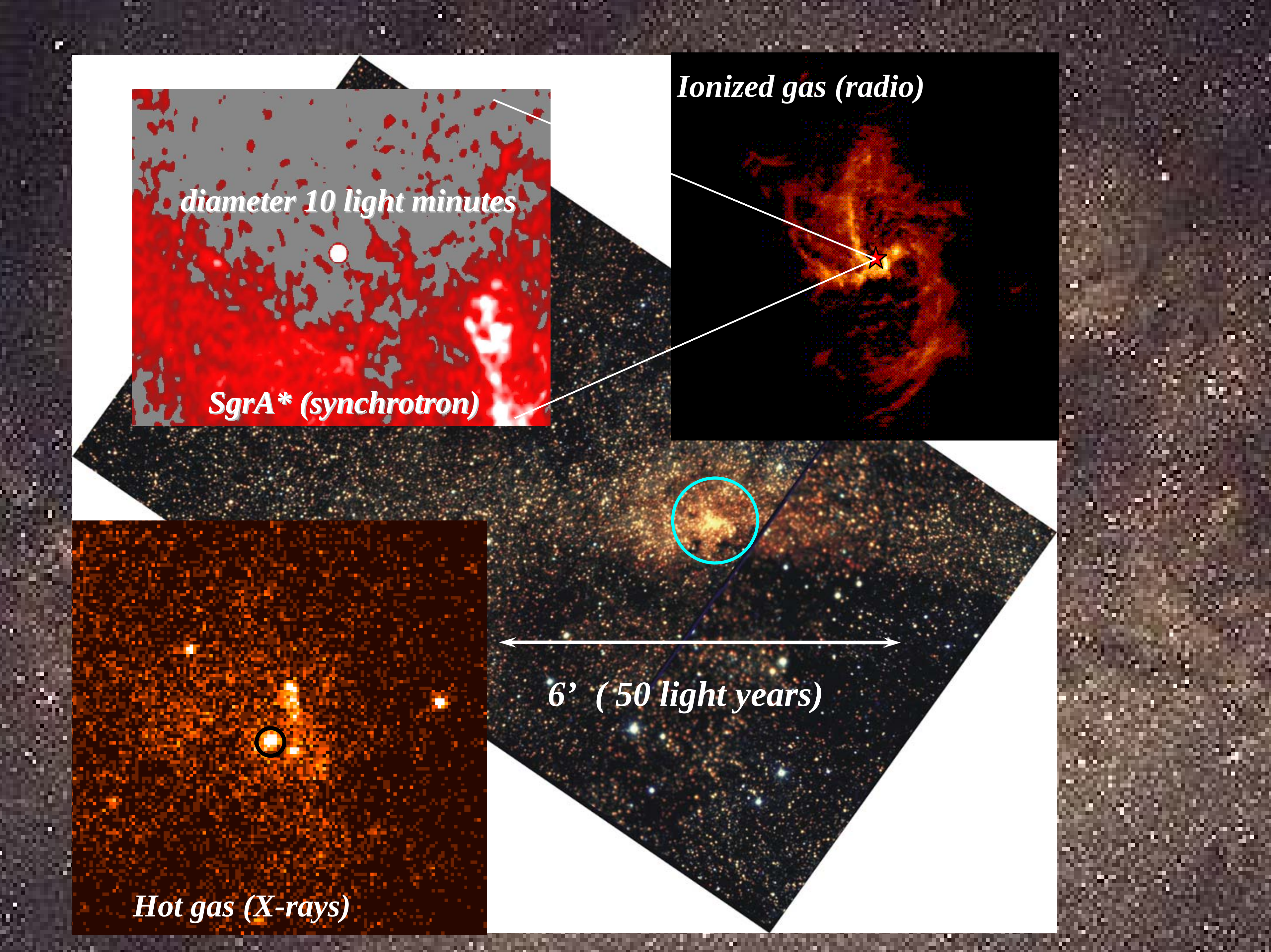
# The MPE G.C.experiments

- *proper motion experiment at the 3.5m ESO NTT (near-IR speckle camera SHARP): since 1991*
- *adaptive optics-assisted (AO) integral field spectroscopy on ESO 2.2m (3D): since 1994*
- *AO camera/spectrometer NAOS/CONICA on 8m ESO VLT: since 2002*
- *AO integral field spectroscopy on VLT (SINFONI/SPIFFI): since Feb 2003*

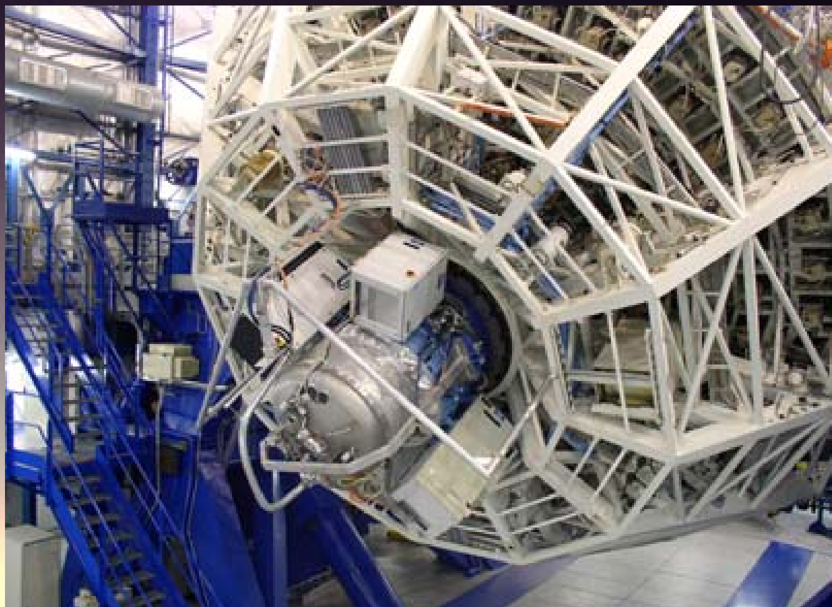
*key people: A.Eckart, F.Eisenhauer, T.Ott, R.Schödel*

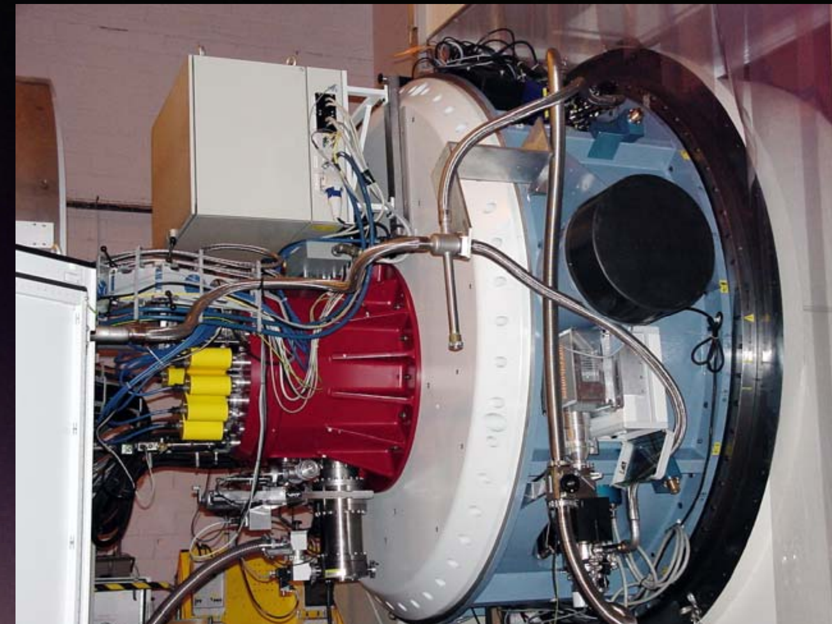



The center of the Milky Way


Ionized gas (radio)
diameter 10 light minutes
SgrA* (synchrotron)
6' ( 50 light years)
Hot gas (X-rays)

# *NAOS/CONICA and SINFONI*



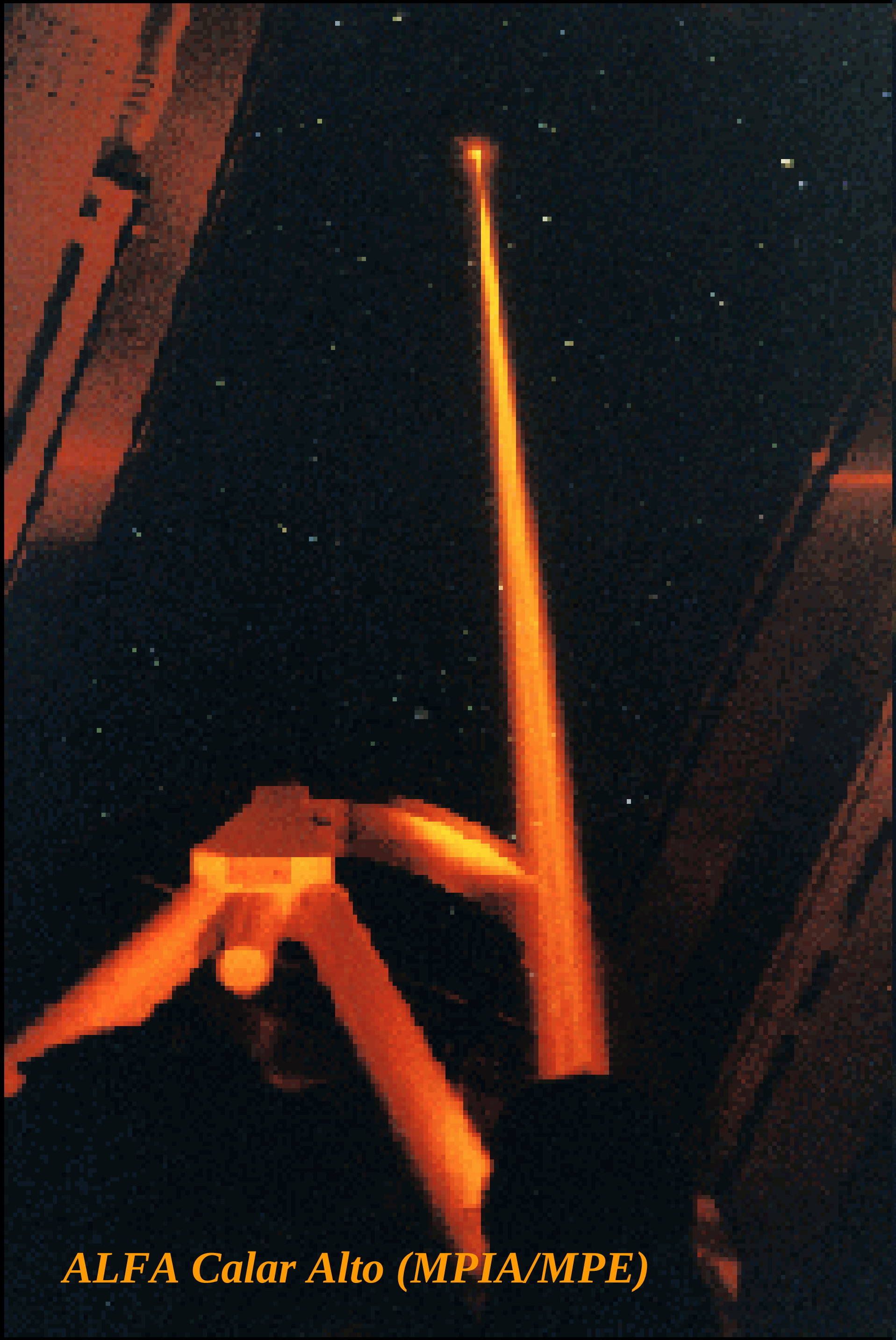


**NAOS-CONICA:**

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

**SPIFFI/SINFONI:**

*PIs: F.Eisenhauer & N.Thatte (MPE)*

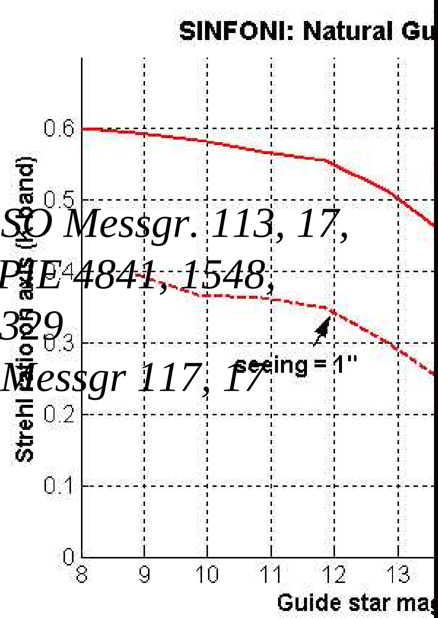

ALFA Calar Alto (MPIA/MPE)

# SINFONI

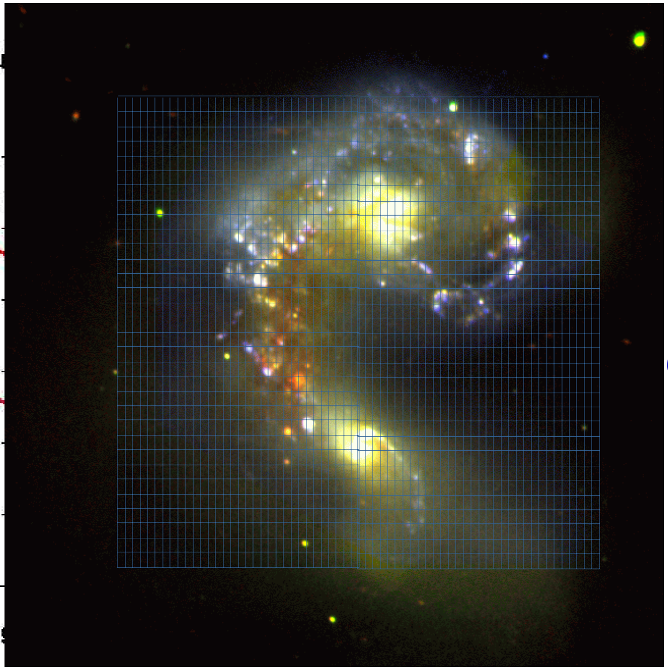
( = SPIFFI (MPE, PI F.Eisenhauer)+MACAO(ESO, PI H.Bonnet))

***Integral field spectrometer with reflective image slicer***
***32x64 spatial pixels (0.0125”, 0.05”, 0.125”) x 2000 spectral pixels (2K Hawaii)***
***spectral resolving power: 2000-5000***
***~40% throughput in J, H and K***

***60 element, curvature sensor AO system/bimorph mirror with APDs***

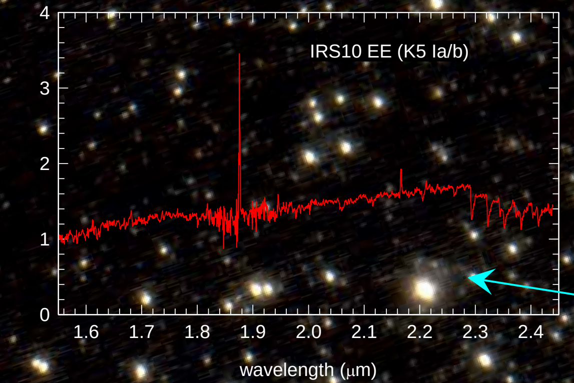


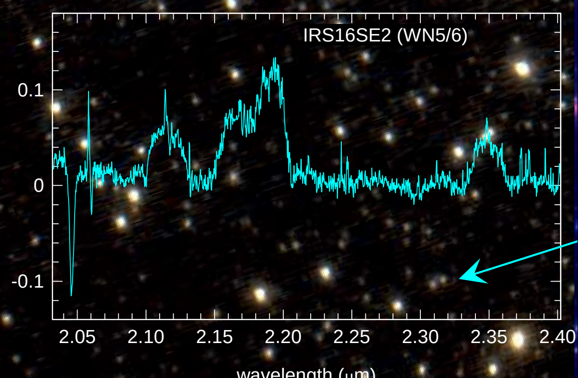

*Eisenhauer et al. 2003, ESO Messgr. 113, 17,*
*Eisenhauer et al. 2003, SPIE 4841, 1548,*
*Bonnet et al. SPIE 4839, 329*
*Bonnet et al., 2004, ESO Messgr 117, 17*

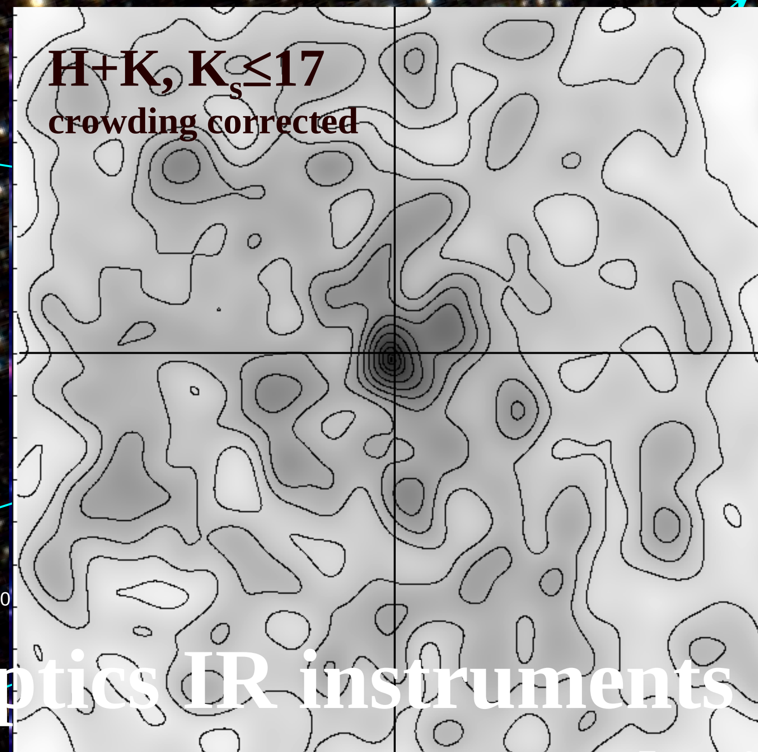


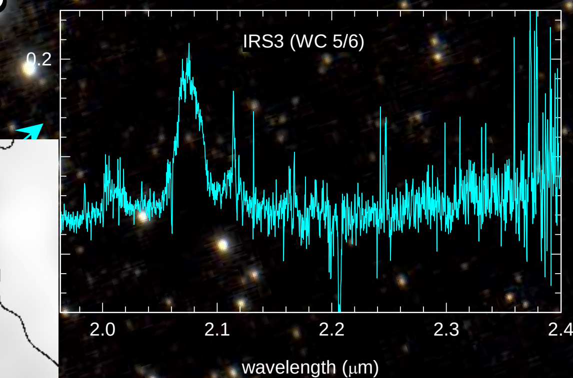
***ance (2005)***

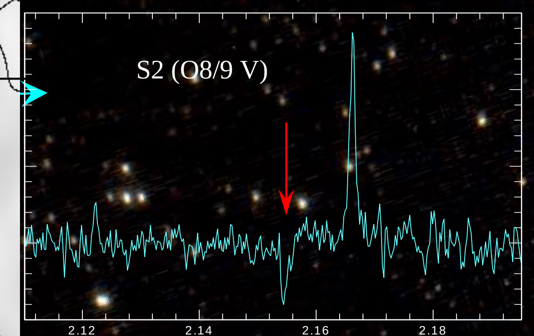
# *stellar cusp and its properties*



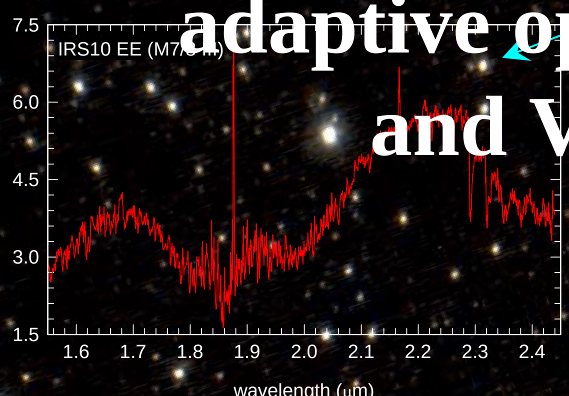



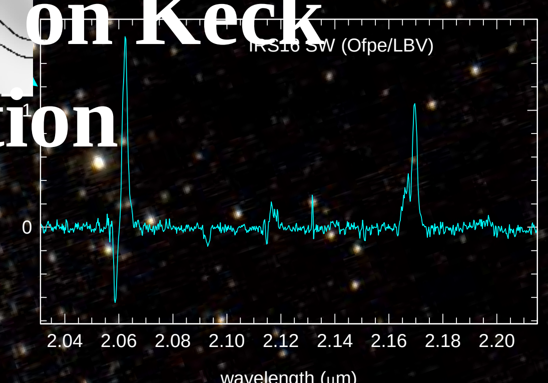




# adaptive optics IR instruments on Keck and VLT: 50 mas resolution



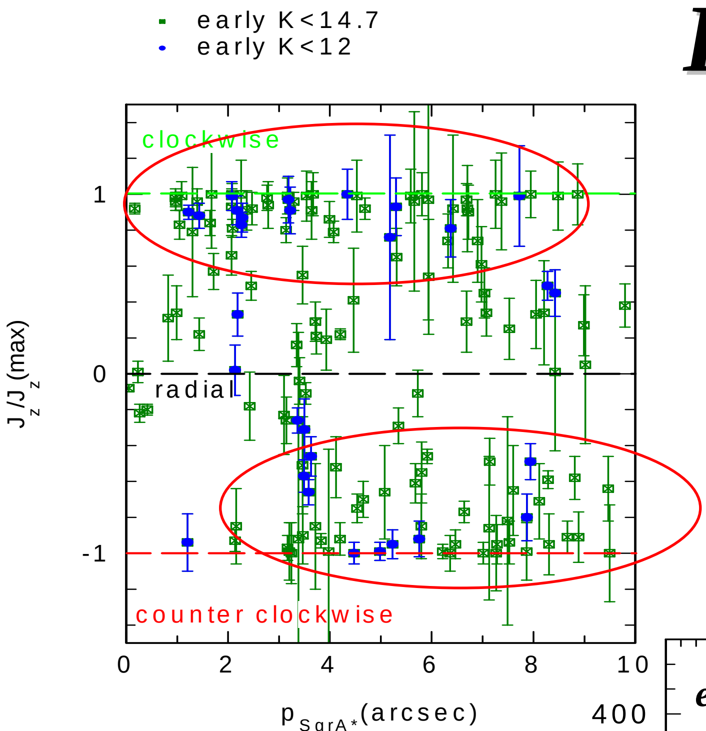

**NACO** **SINFONI**

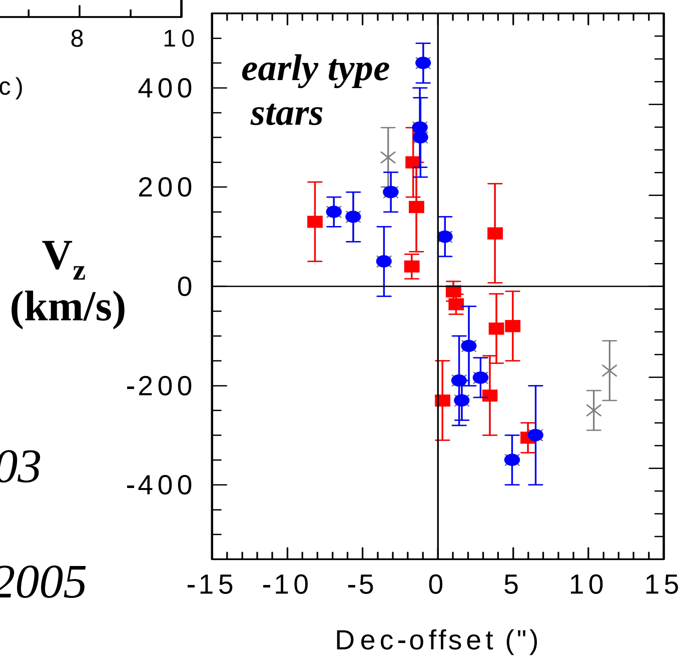
*$H/K_s/L'$*

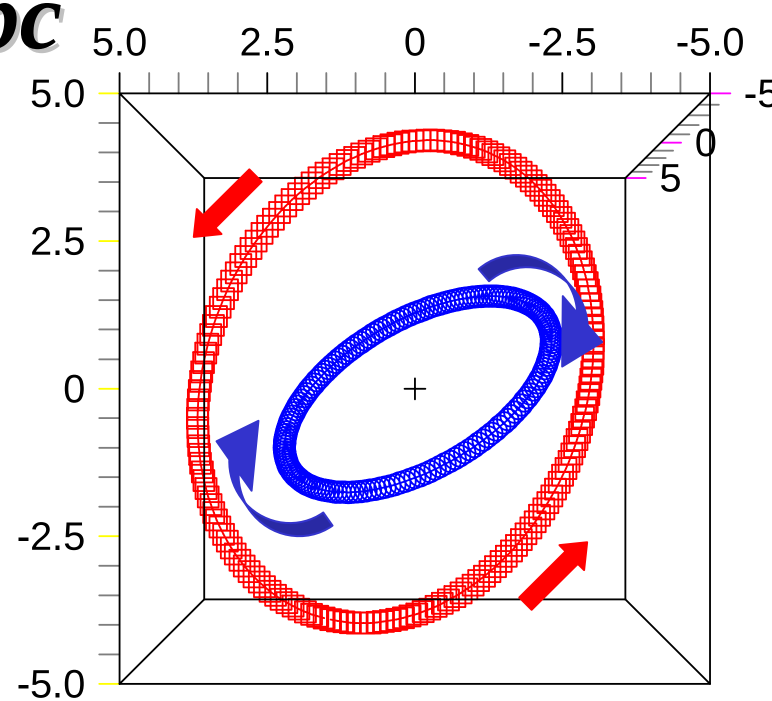
**Ghez et al. 2004, Keck laser guide star AO**

*Genzel et al. 2003, Ott et al. 2004*

# *two coeval, rotating discs of stars at R~0.1-0.5 pc*

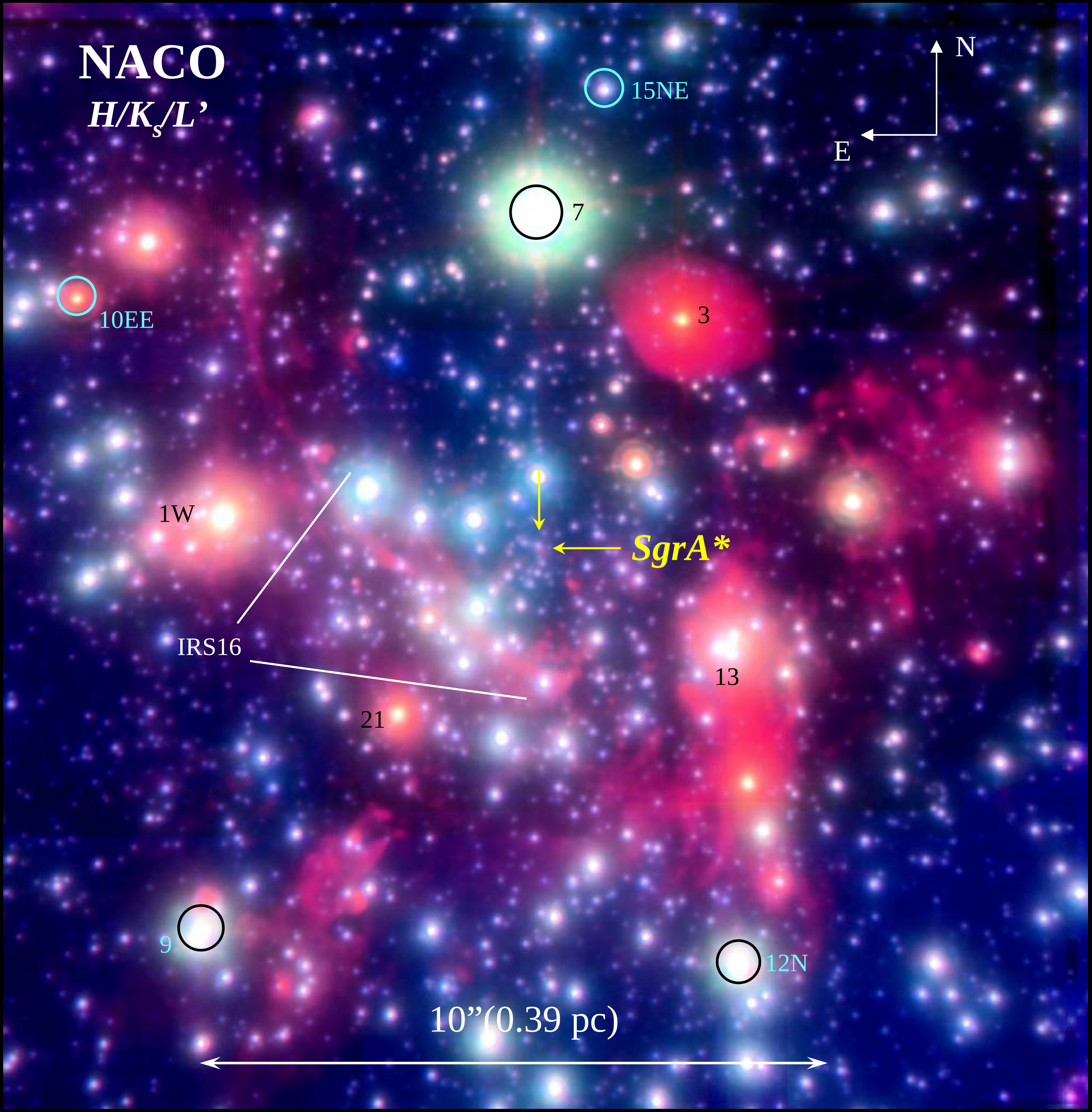


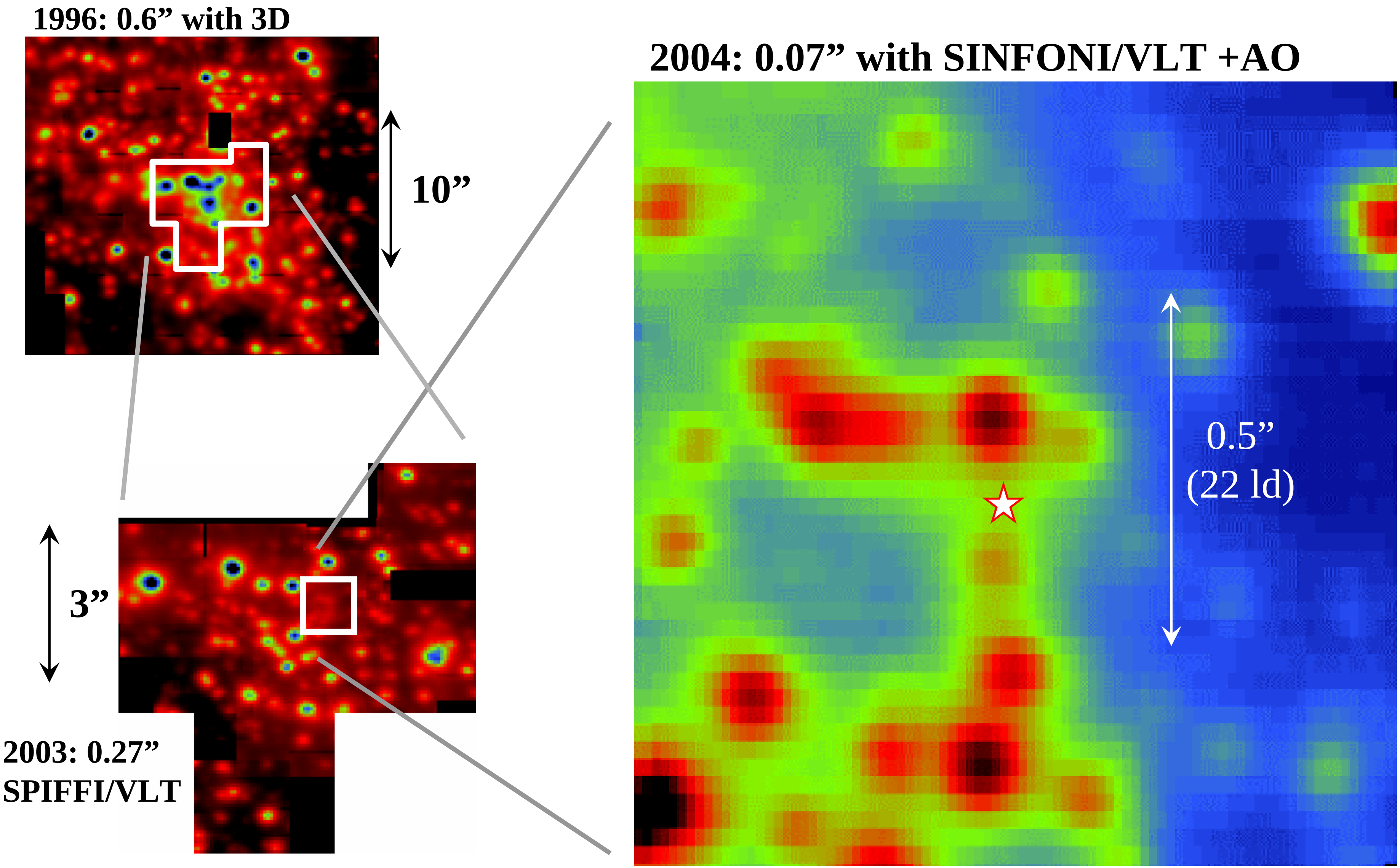




| type | clockwise | counter-clockwise |
|---|---|---|
| LBV/WN10 | 4 | 1 |
| WN9/Ofpe | 4 | 2 |
| WN7/8 | 1 | 1 |
| WN5/6 | 1 | |
| WC8/9 | 5 | 5 |
| WC5-7 | | 1 |
| OB | >5 | >5 |

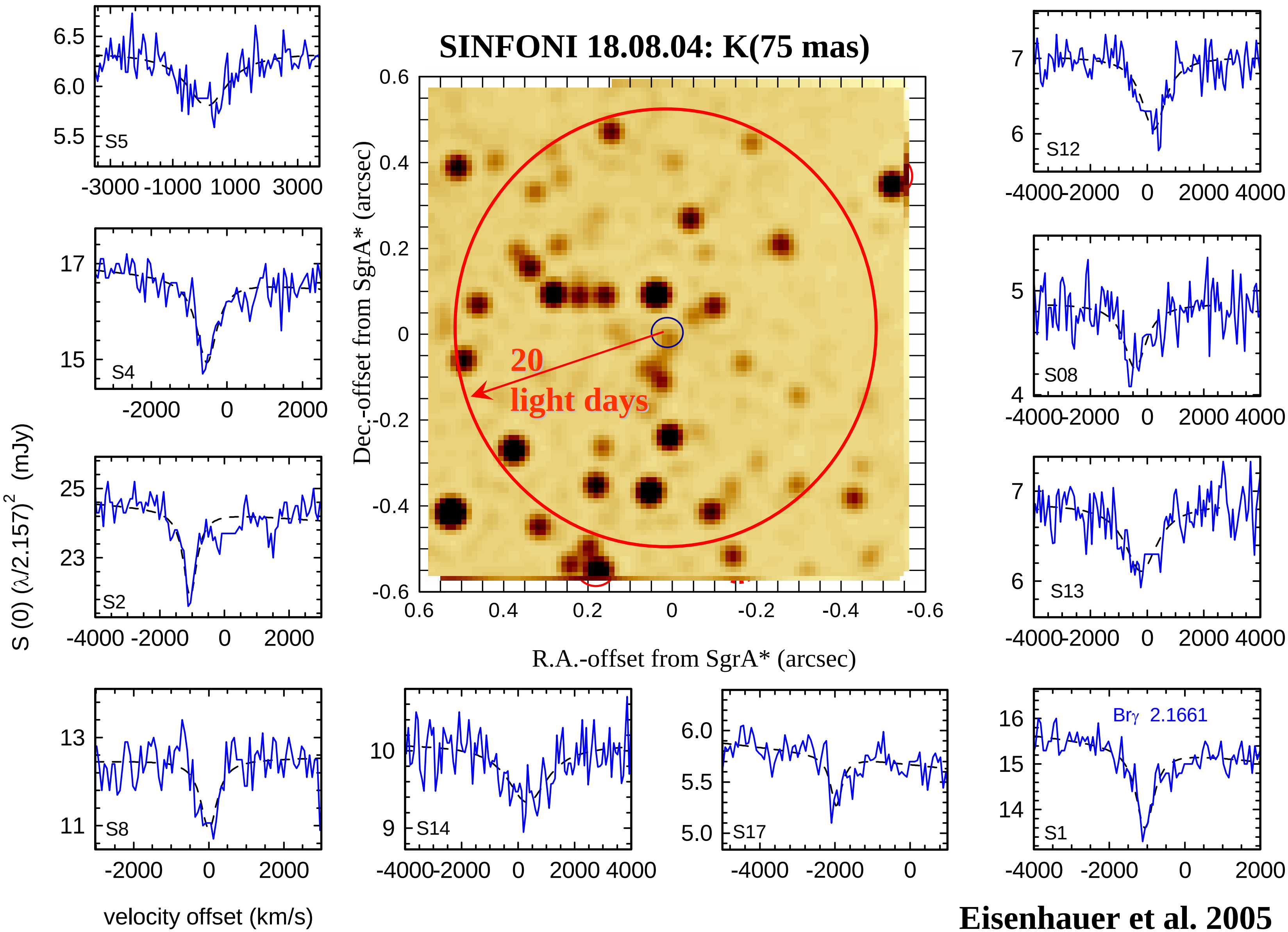
*Genzel et al. 2000, 2003*
*Ott et al. 2004,*
*Paumard et al. 2001, 2005*


NACO
H/Ks/L'
N
E
15NE
7
10EE
3
1W
SgrA*
IRS16
13
21
9
12N
10"(0.39 pc)

# *Integral field spectroscopy*



# *stars in the central 20 light days: a paradox of youth*




Eisenhauer et al. 2005

# *ordinary B main sequence-stars !*

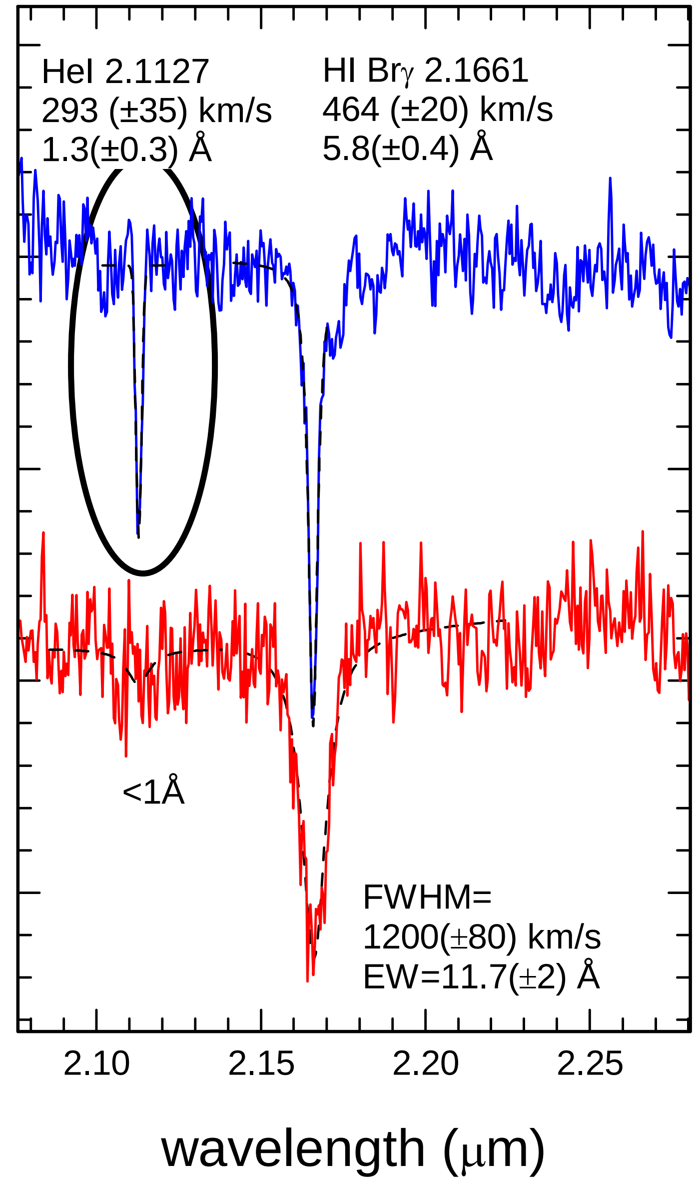
HeI:

$v_{rot}\sin(i) \sim 0.55$ FWHM = 154(±19) km/s.

solar neighborhood early B stars

$<v_{rot}\sin i> \sim 130$ km/s

(Gathier, Lamers & Snow 1981)



# *parodox of youth: two basic scenarios*

- ***in situ formation***
  - from molecular clouds
  - formation in massive disk
  - collision of less massive stars

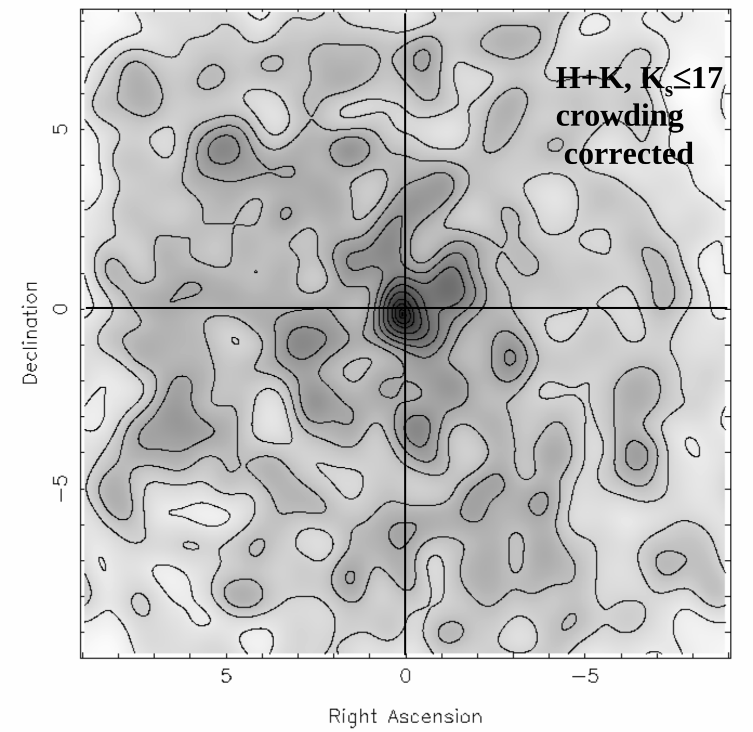
  ***general problem: tidal field***

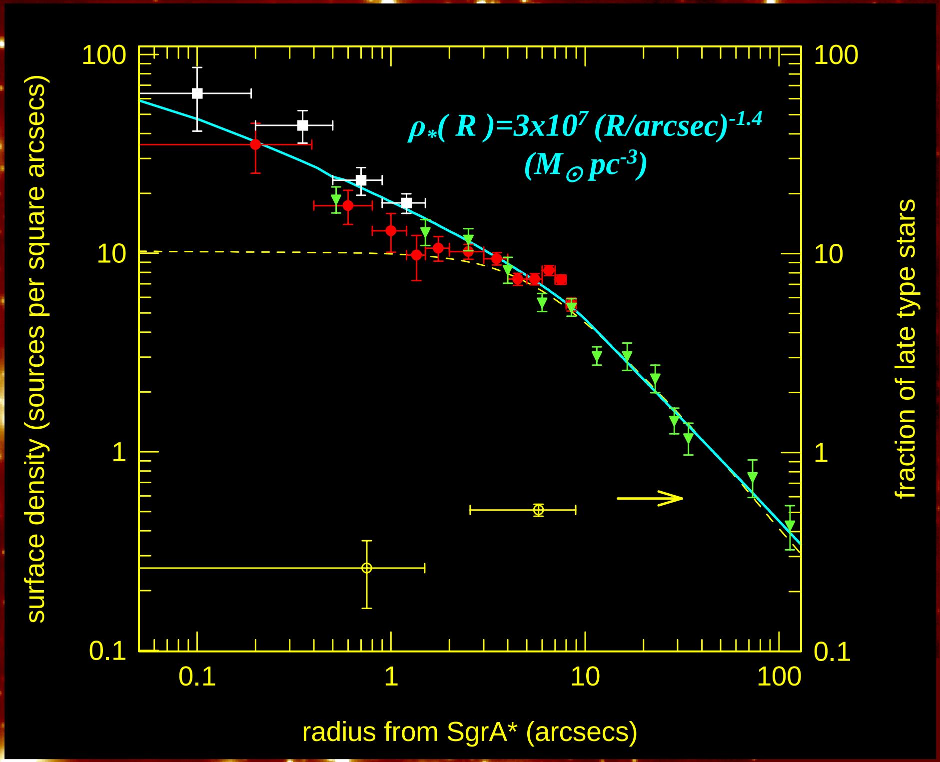
- ***external star formation and migration***
  - mass segregation
  - spiraling in of star cluster
  - scattering

  ***general problem: timescale and efficiency***

*Morris 1993, Genzel, Hollenbach & Townes 1994, Lee 1994, Sanders 1998, Gerhard 2001, Portegies Zwart et al. 2002, Levin & Beloborodov 2003, Nayakshin et al. 2003, 2004, Gould & Quillen 2003, Genzel et al.2003, Hansen & Milosavlevic 2003, Kim & Morris 2003, Alexander 2003, Milosavlevic & Loeb 2004*

# *NACO/VLT AO images*

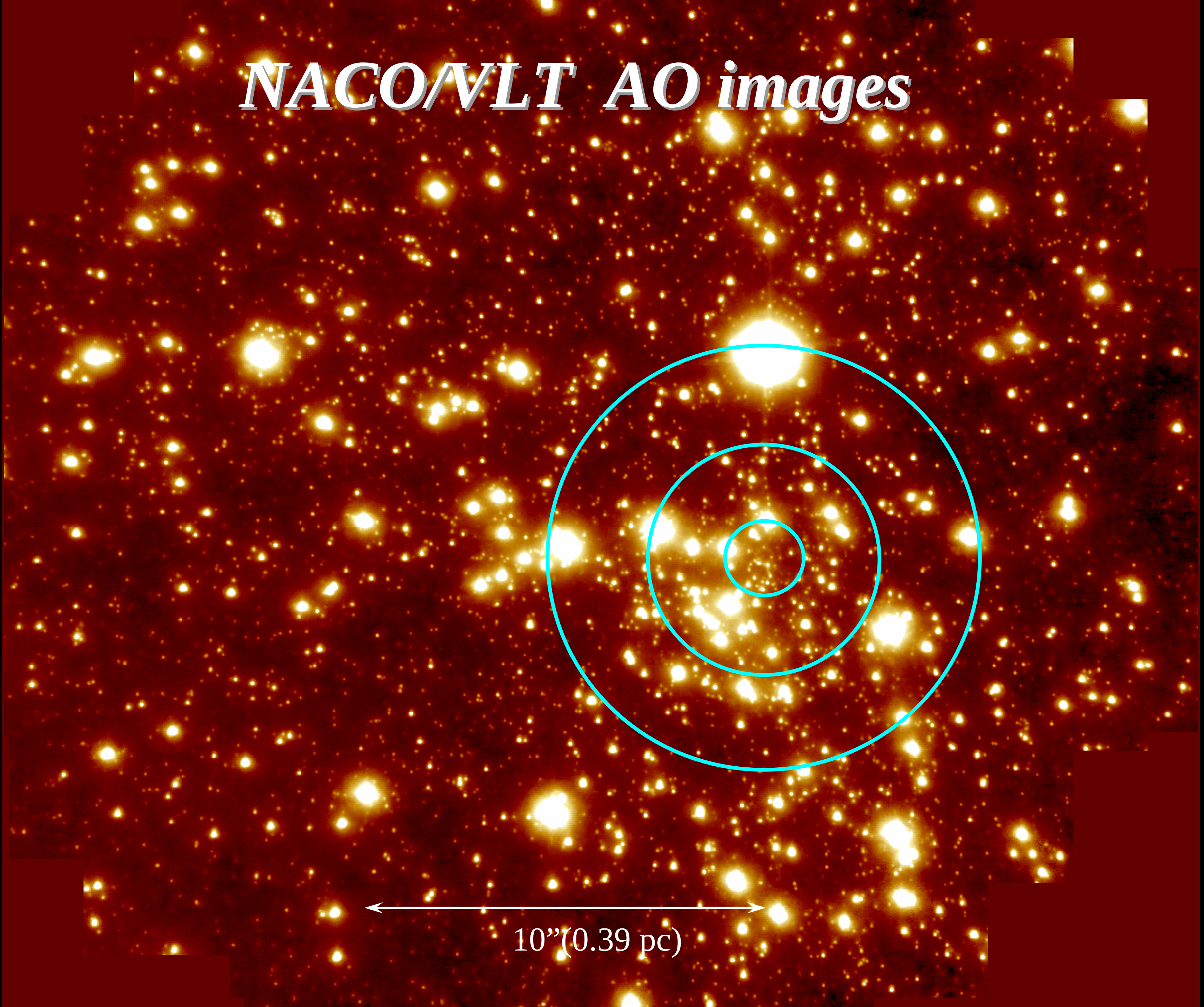


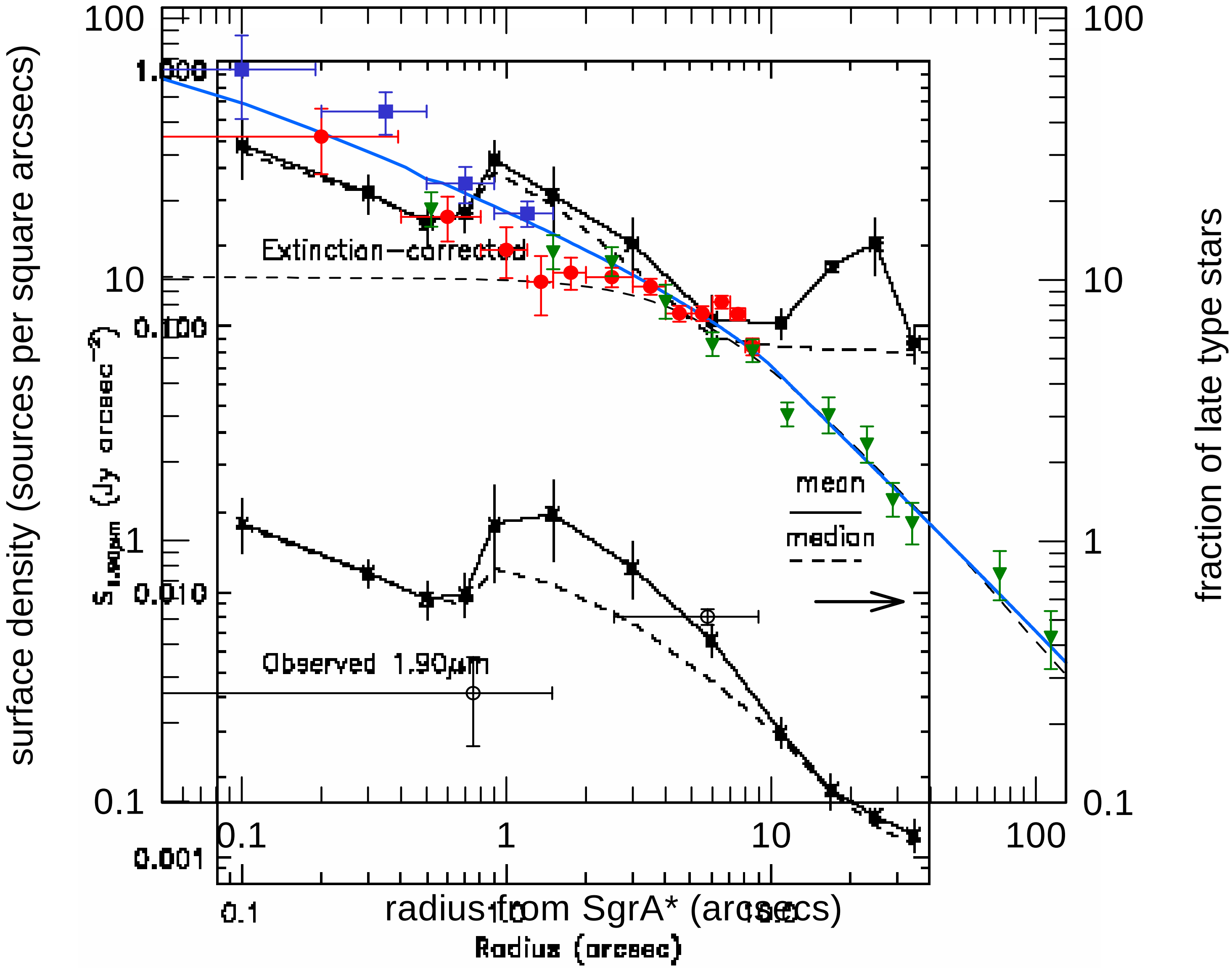




10”(0.39 pc)

*Genzel et al. 2003, Ap.J. 594, 812*

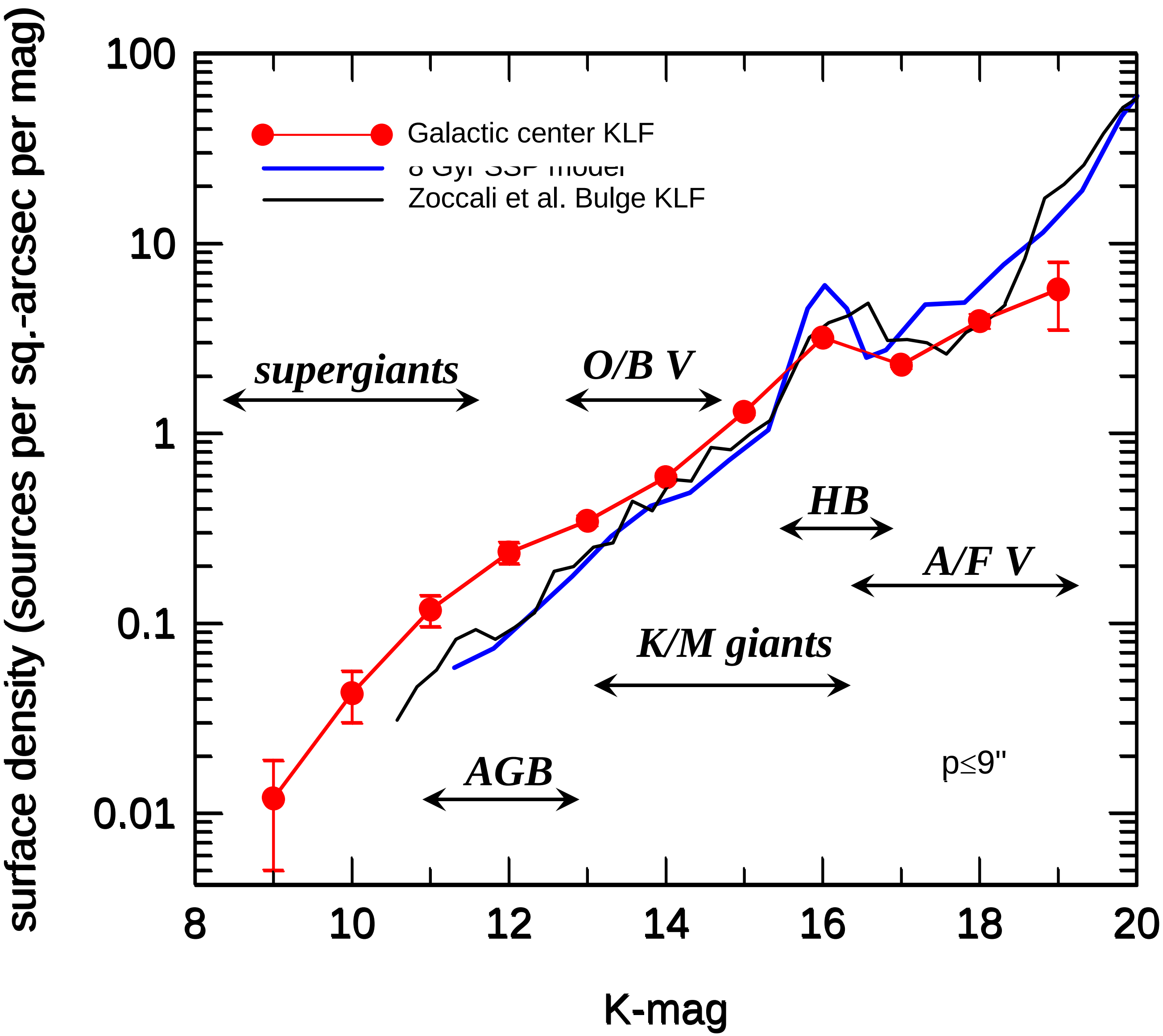
# NACO/VLT AO images





surface density (sources per square arcsecs)
fraction of late type stars
radius from SgrA* (arcsecs)
Extinction−corrected
Observed 1.90μm
mean
median
Radius (arcsec)
100
10
1
0.1
0.1
1
10
100
1.000
0.100
0.010
0.001

# Properties of nuclear star cluster: K-luminosity function




*Best fit:*

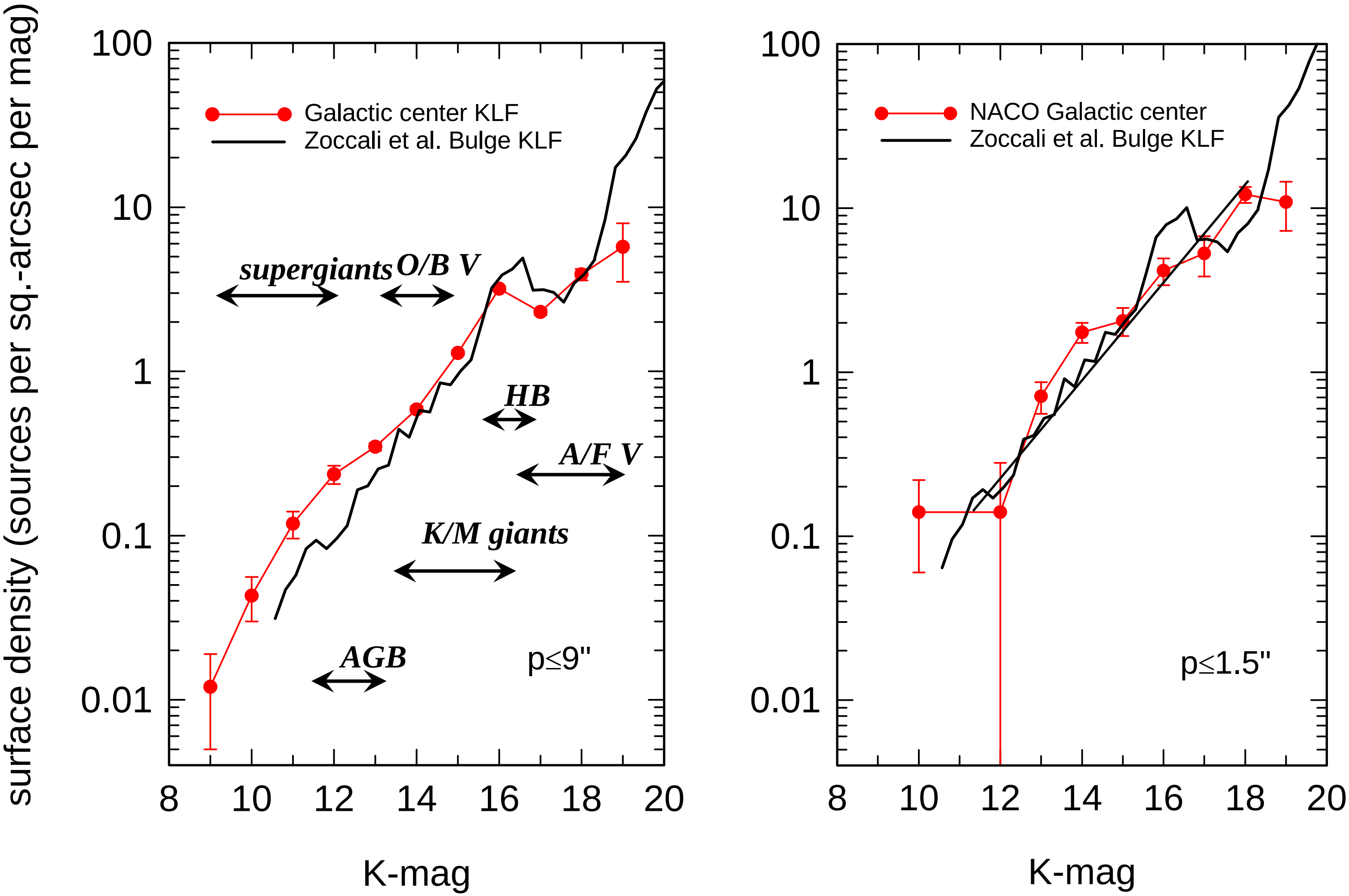
*old metal rich component + young burst population,*

*or*

*constant star formation*

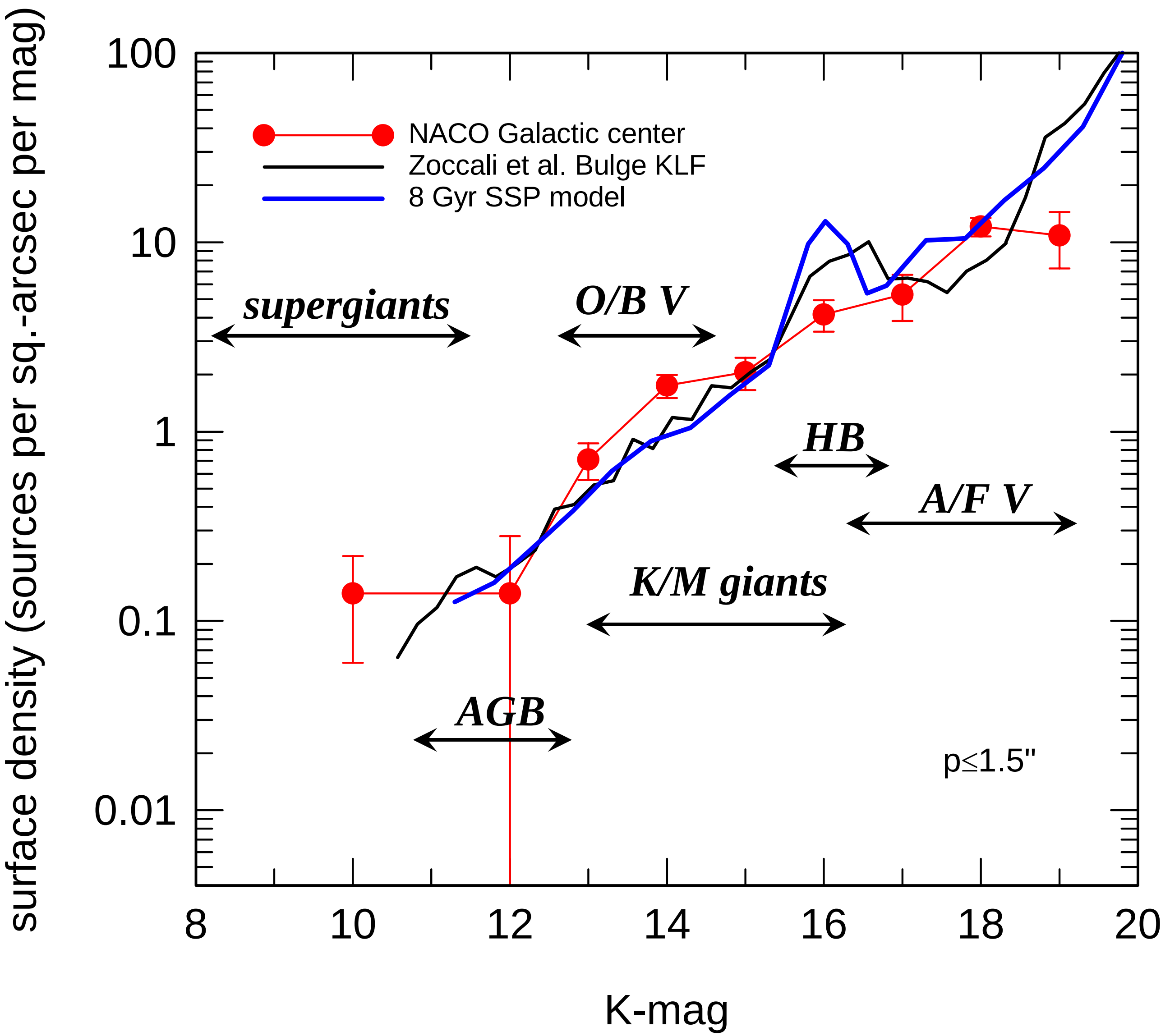
*Genzel et al. 2003, Zoccali et al.2002, Tiede et al. 1995, Figer 2002*

# Properties of nuclear star cluster: K-luminosity function




*Genzel et al. 2003*

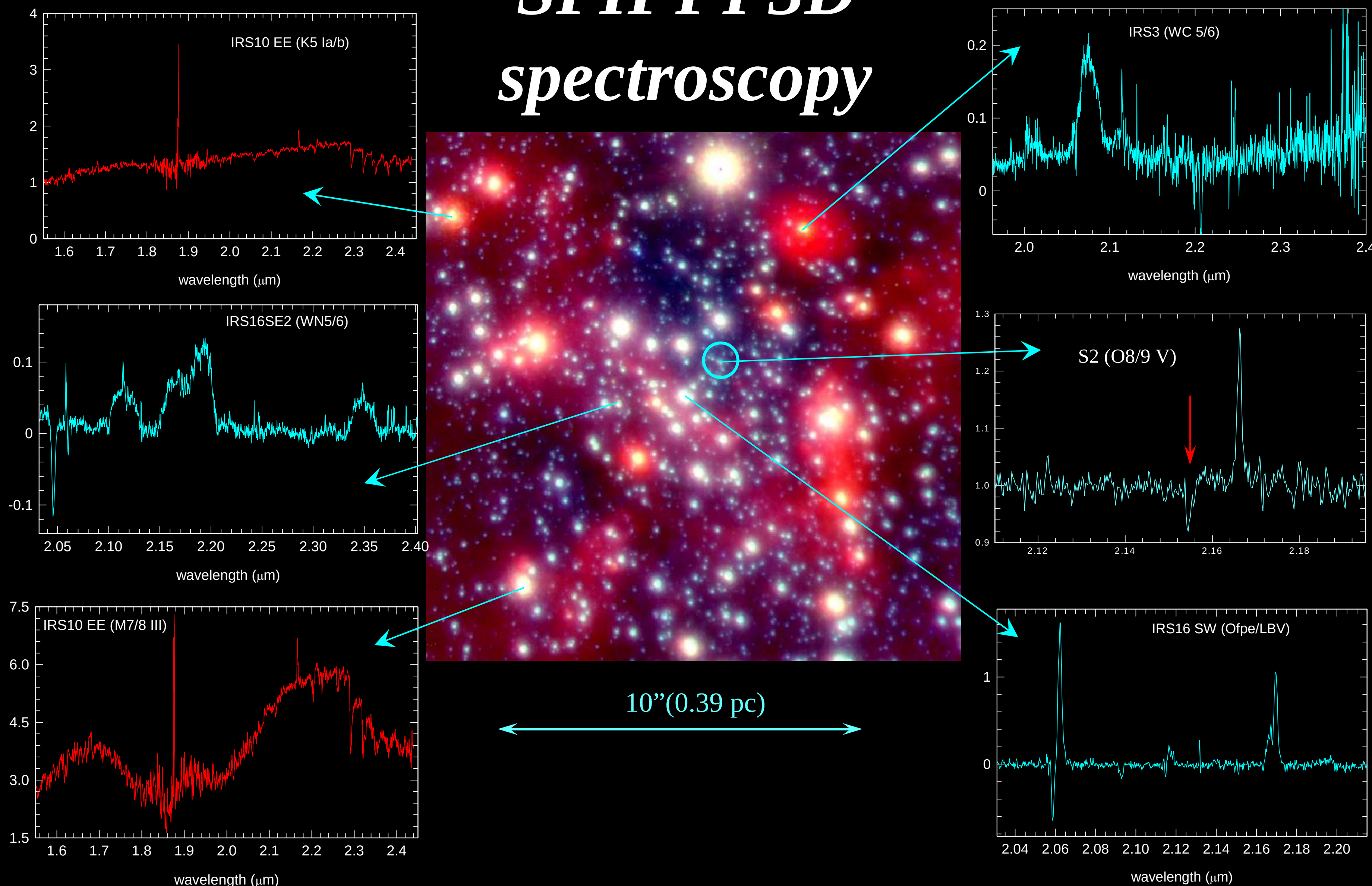
# KLF of cusp




*lack of red clump/HB stars*

*KLF+cusp mass model: either KLF steepens at K>19, or IMF is flatter than Salpeter*

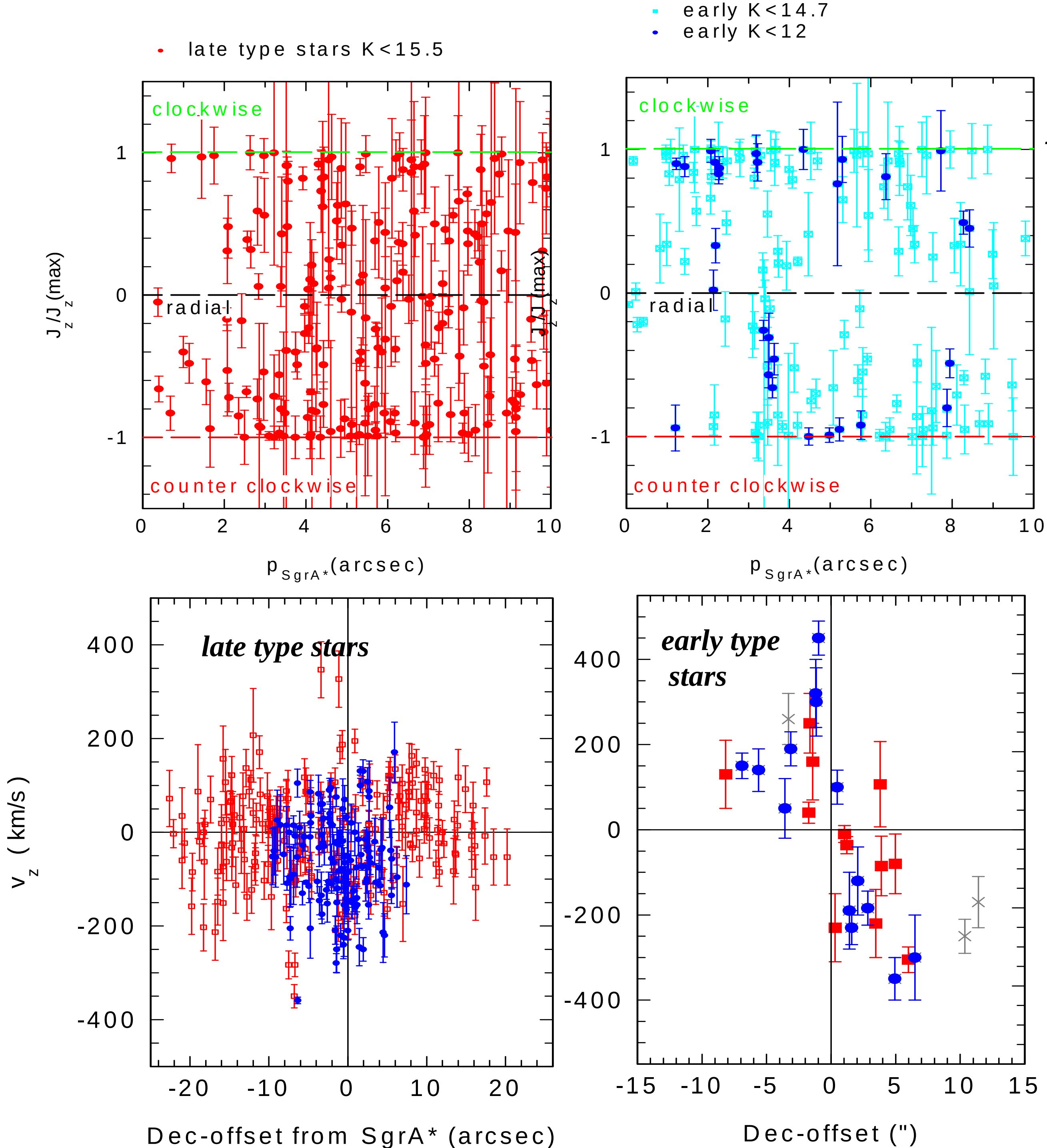
# *SPIFFI 3D spectroscopy*




*Ott et al. 2004, in prep.*

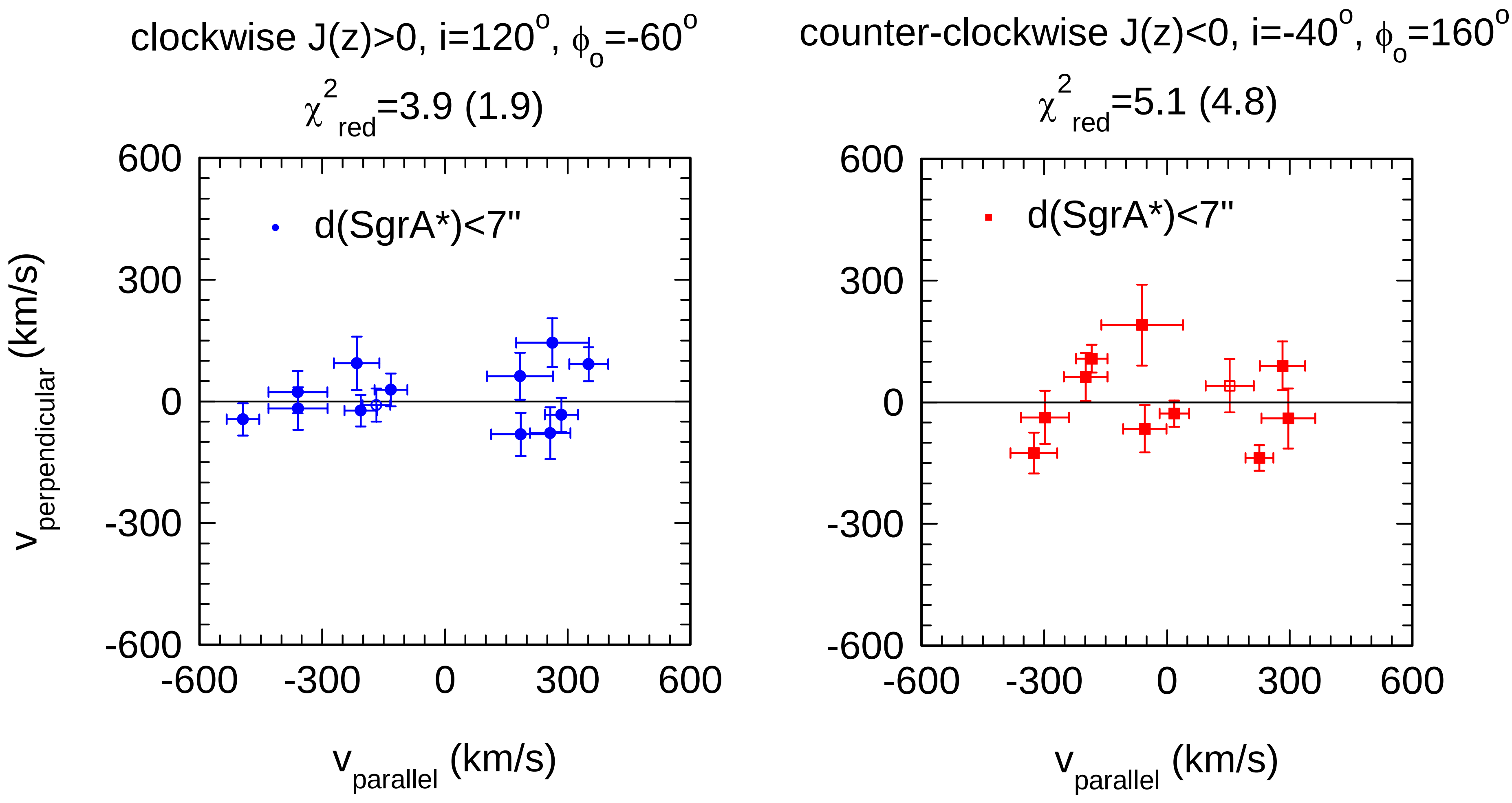
*S2: see Ghez et al. 2003*

# ***Dynamics of stellar components***



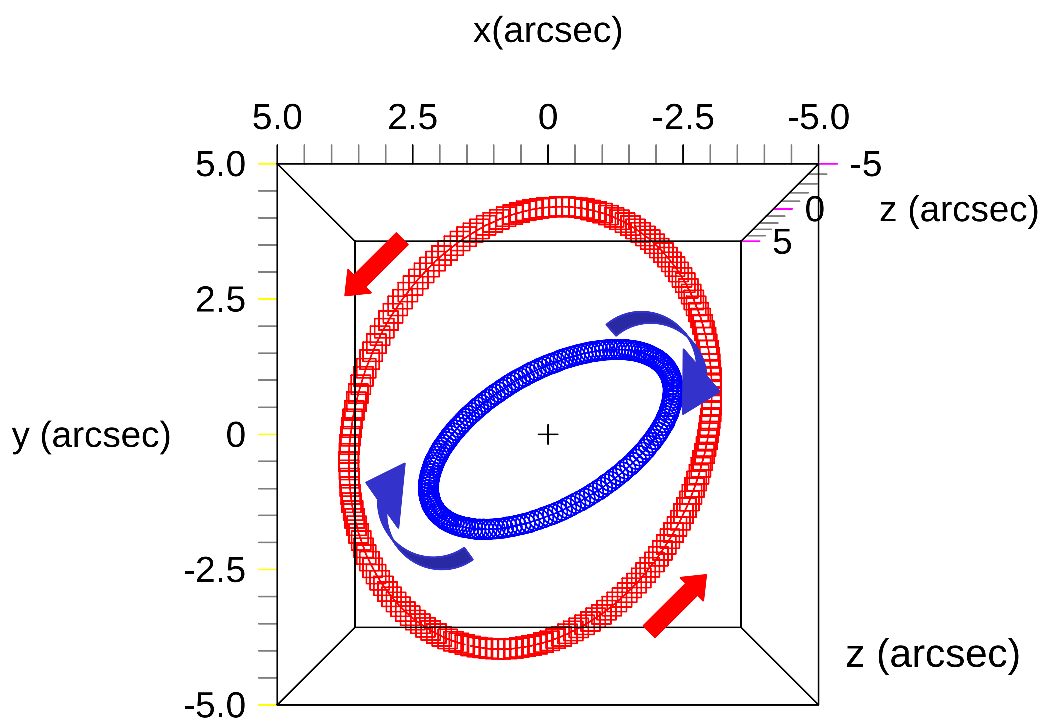

**$10^3$ proper motions and radial velocities (Ott et al. 2004)**

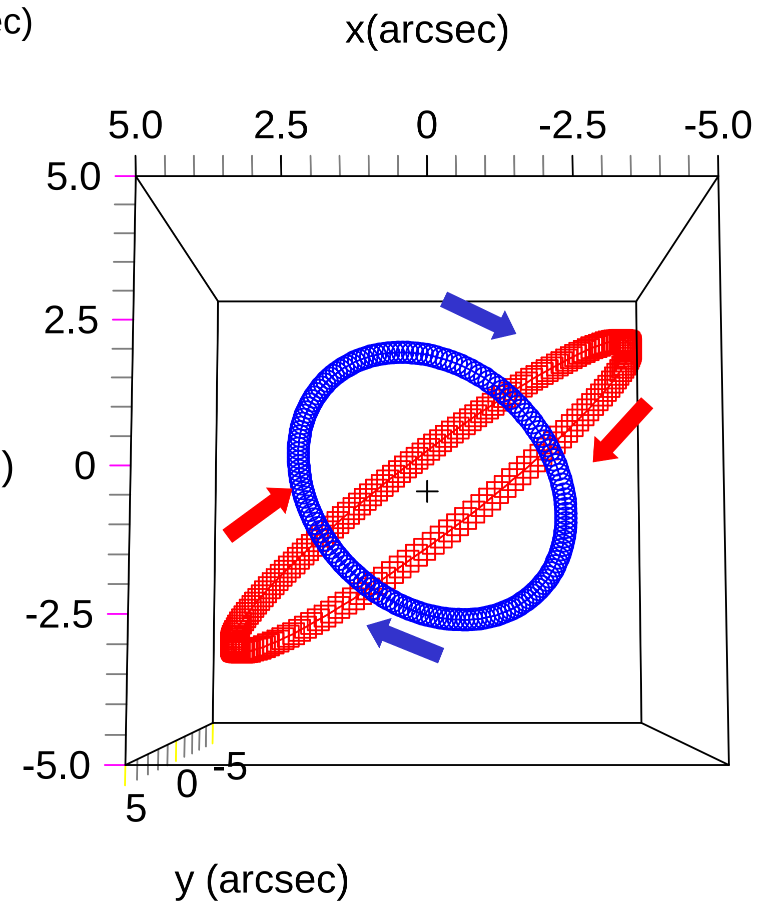
*McGinn et al. 1989, Sellgren et al.1990, Krabbe et al. 1995, Haller et al. 1996, Genzel et al. 2000, 2003, Paumard et al. 2001, Figer et al. 2003*




***Genzel et al. 2003, Ap.J. 594, 812, Levin & Beloborodov, 2003, ApJ, 590, L33***

# *massive stars in two counter-rotating disks*




| type | clockwise | counter-clockwise |
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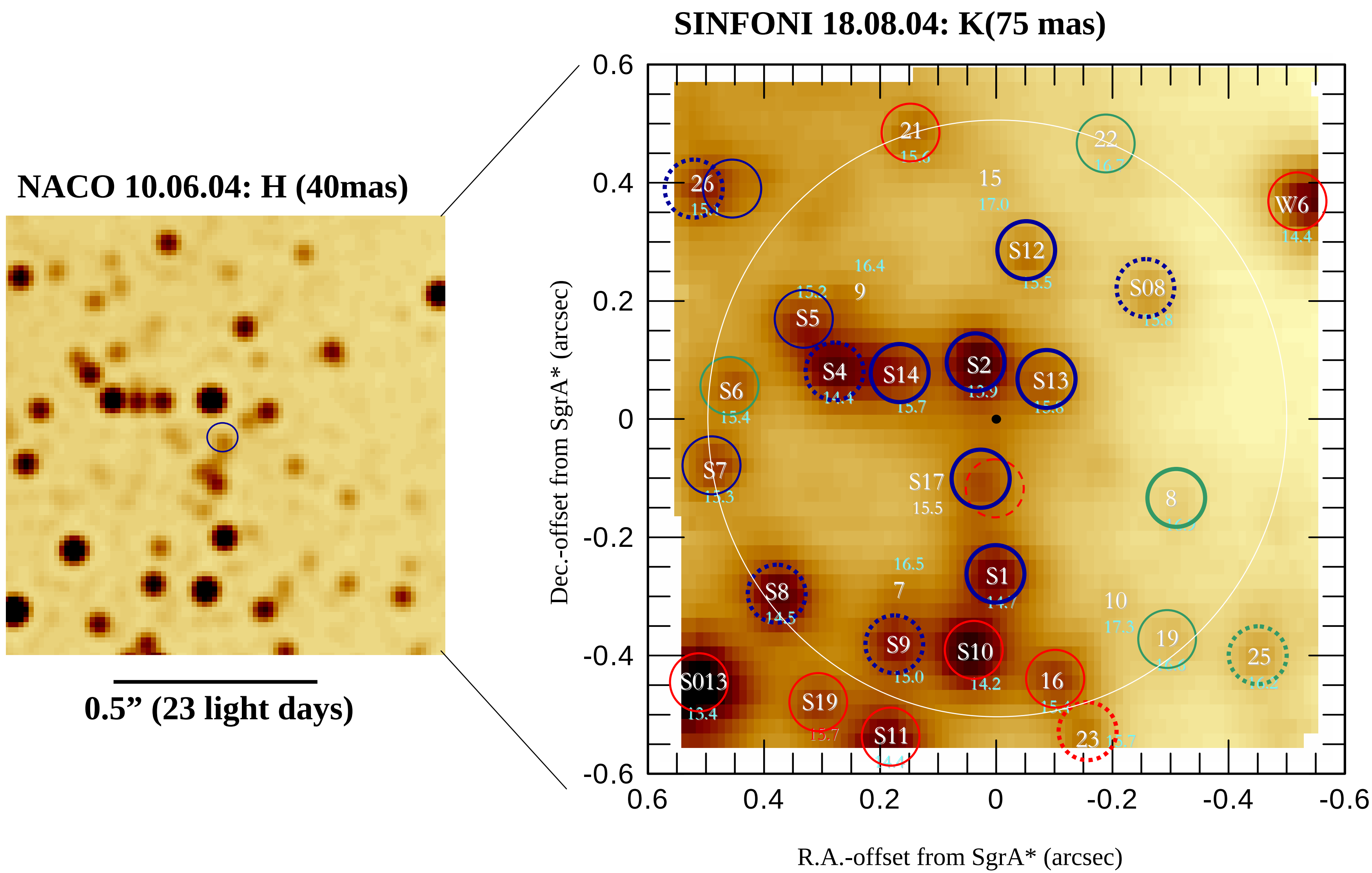
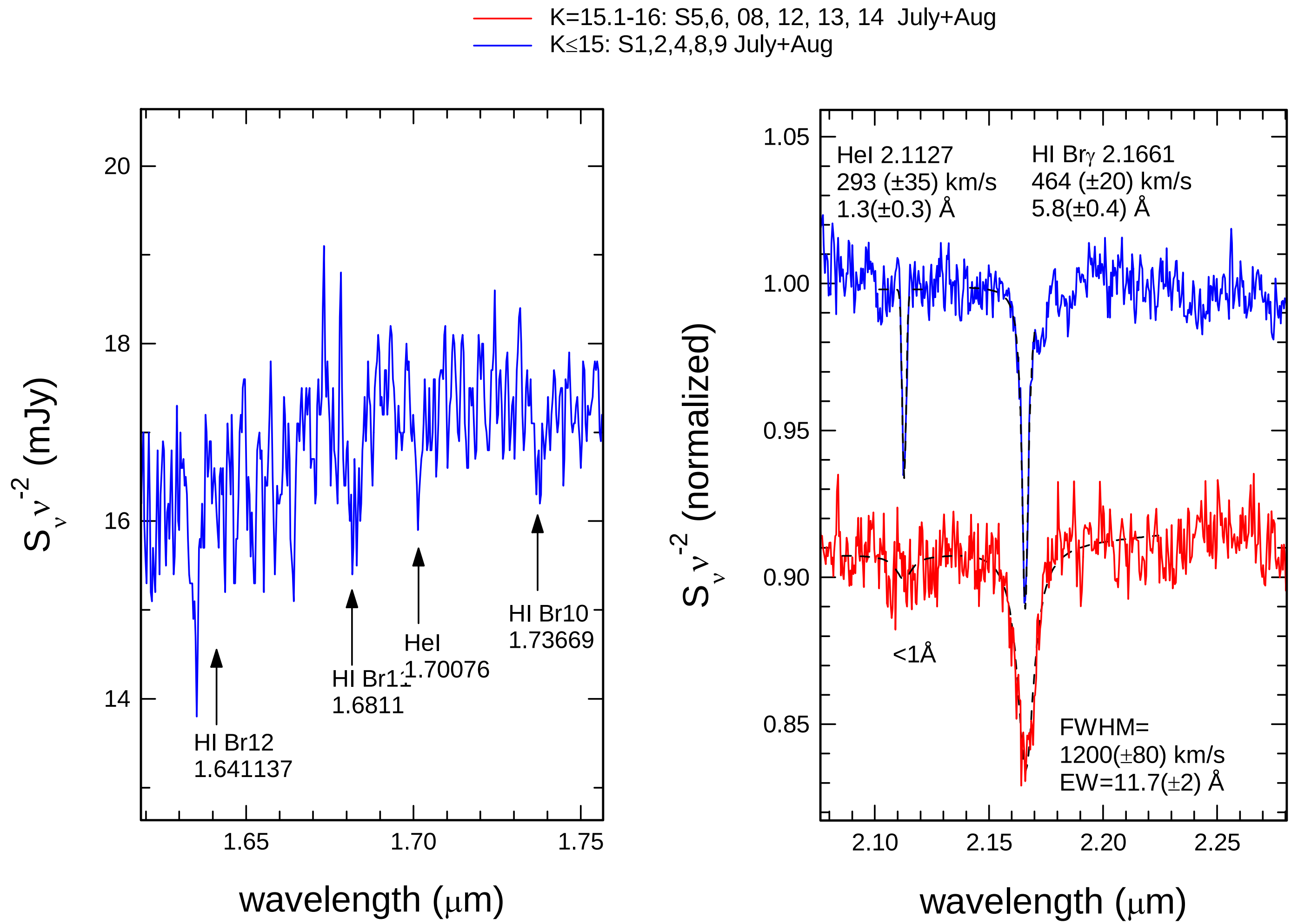

NACO 10.06.04: H (40mas)
0.5” (23 light days)
SINFONI 18.08.04: K(75 mas)
Dec.-offset from SgrA* (arcsec)
R.A.-offset from SgrA* (arcsec)
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
21
22
26
W6
14.4
15
17.0
S12
15.5
S08
16.4
9
S5
S4
14.4
S14
15.7
S2
S13
S6
15.4
S7
15.3
S17
15.5
8
S1
16.5
7
S8
14.5
10
17.3
19
25
S9
15.0
S10
14.2
16
S013
13.4
S19
15.7
S11
23

# S-stars are main sequence B-stars




Eisenhauer et al. 2005

# *'A Paradox of Youth': how did the massive stars get into the cusp?*

- *formation outside and mass-segregation into center: excluded for stars >2 $M_\odot$*
- *in situ formation in extremely dense gas (>$10^9$ $cm^{-3}$): fragmentation of self-gravitating accretion disk, following cloud infall and dissipation, + perhaps cloud-cloud collisions*
- *sinking to the center of a young, very massive ($10^{5...6}$ $M_\odot$) and compact (<0.2pc) cluster formed at R~10 pc*
- *creation of massive stars from collisions and mergers of lower mass stars in the central 0.5" (but not further out)*
- *'shuttling' in of stars by intermediate mass black hole*
- *binary scattering*
- *resonant scattering by stellar black holes near SgrA**

*Morris 1993, Genzel, Hollenbach & Townes 1994, Lee 1994, Sanders 1998, Gerhard 2001, Portegies Zwart et al. 2002, Levin & Beloborodov 2003, Nayakshin et al. 2003, Gould & Quillen 2003, Genzel et al.2003, Hansen & Milosavlevic 2003, Kim & Morris 2003, Alexander 2003, Milosavlevic & Loeb 2004*

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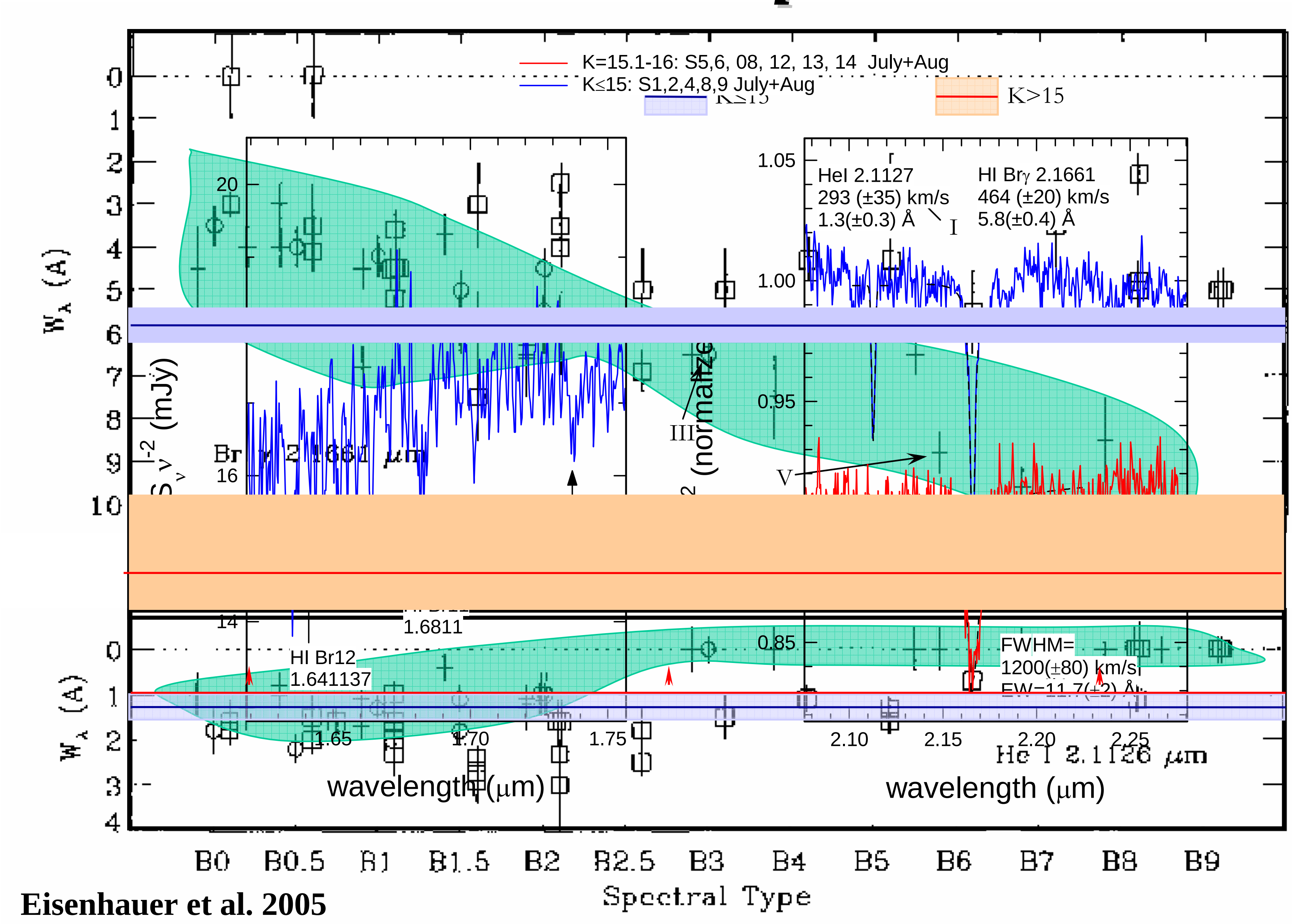
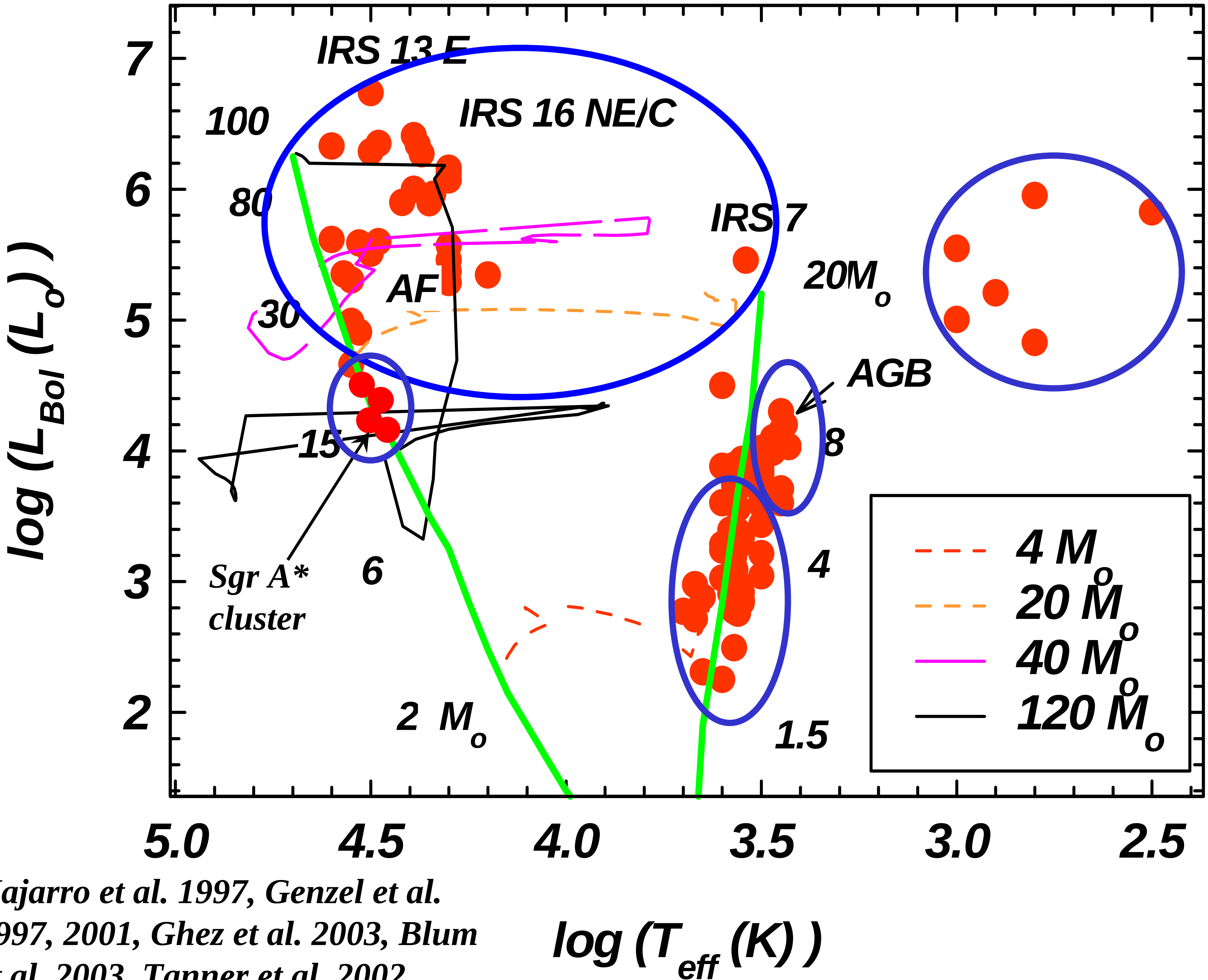
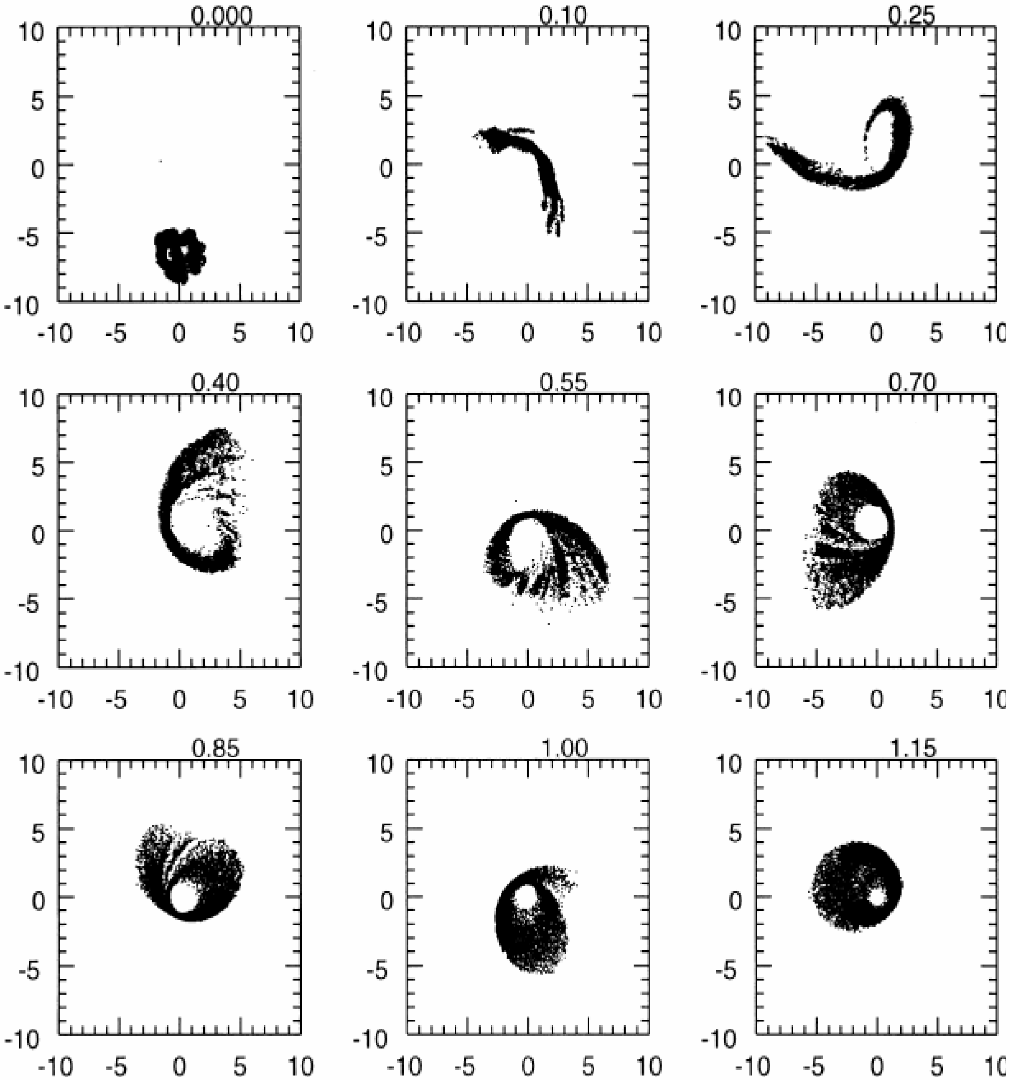


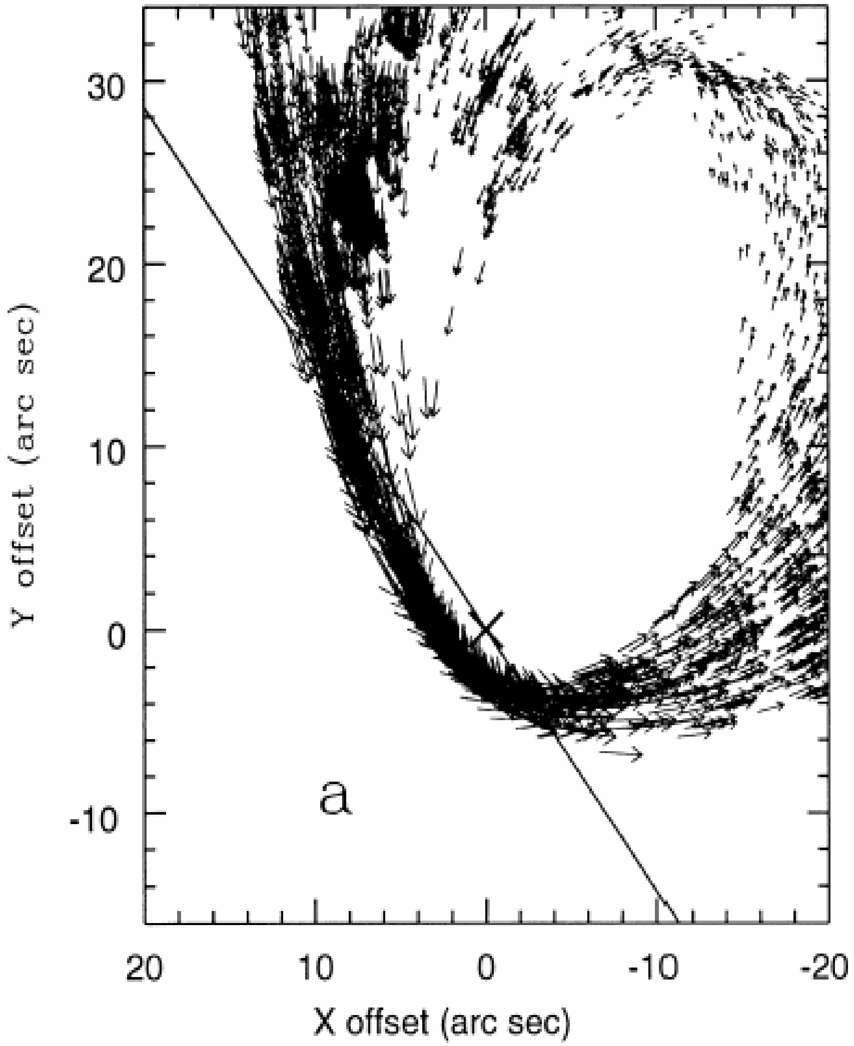

Eisenhauer et al. 2005




*Najarro et al. 1997, Genzel et al. 1997, 2001, Ghez et al. 2003, Blum et al. 2003, Tanner et al. 2002*

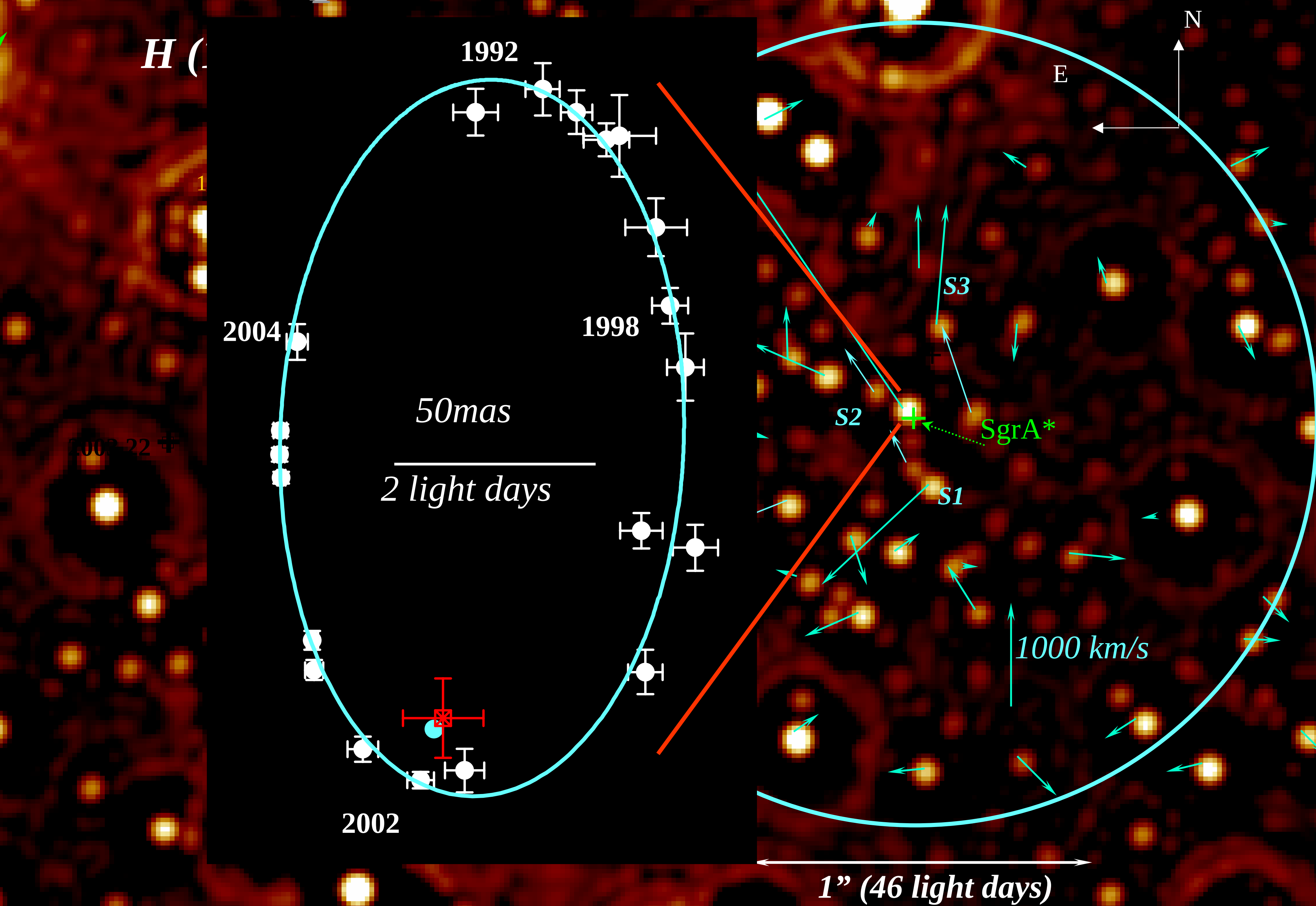
# *Tidally disrupted 'dispersion rings'*



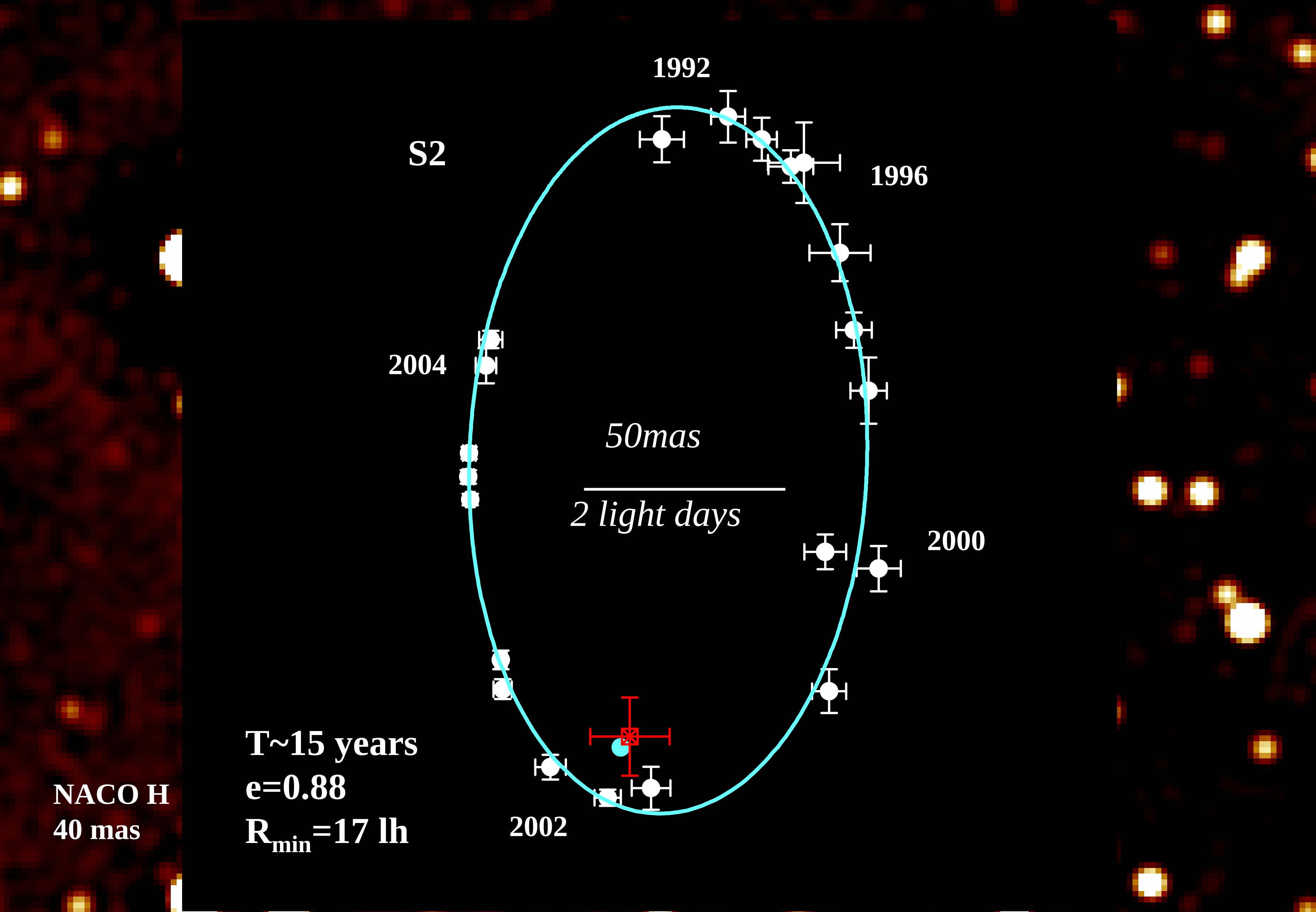



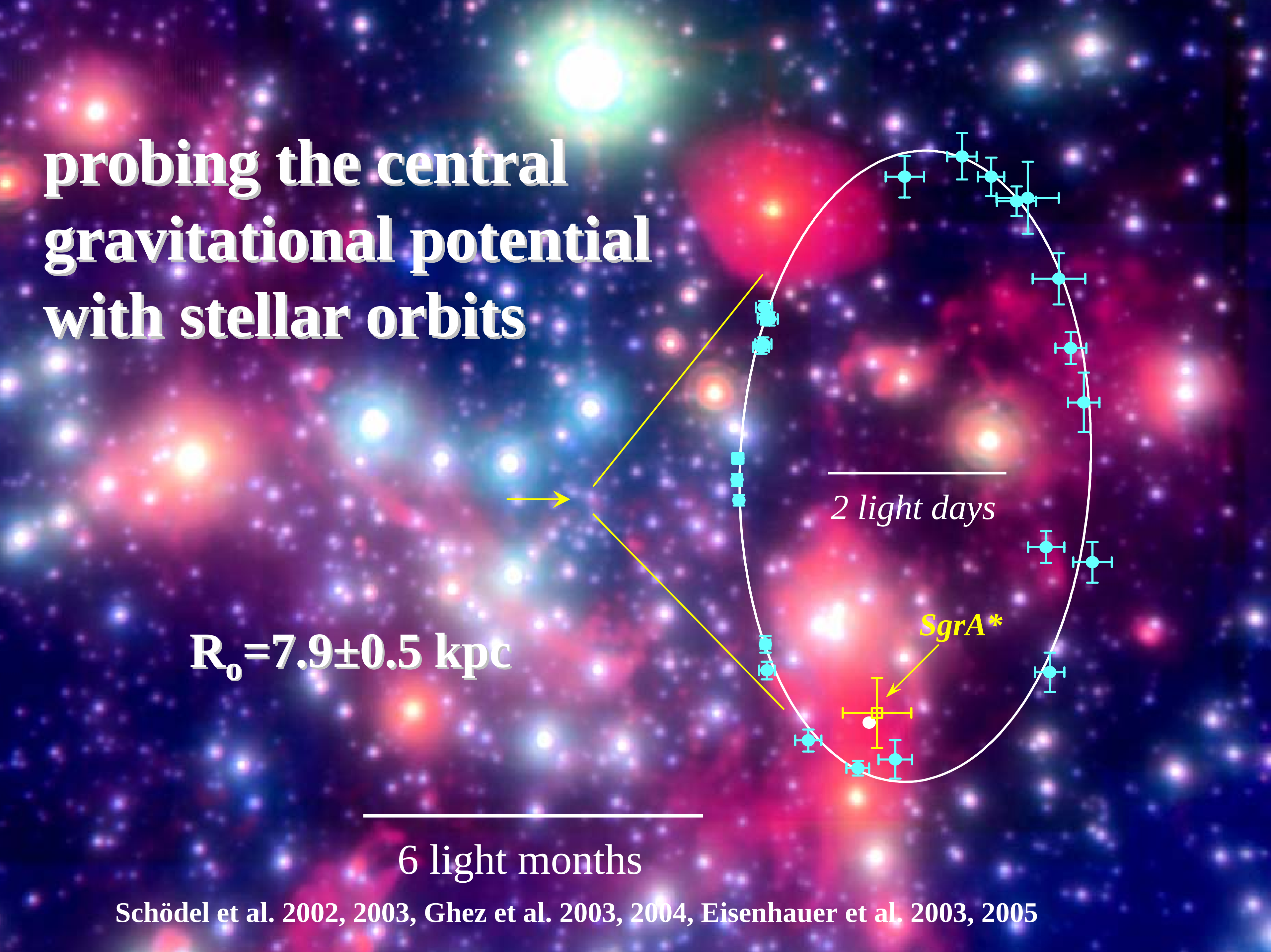

**R. Sanders 1998**

# Proper Motions and Orbit of S2



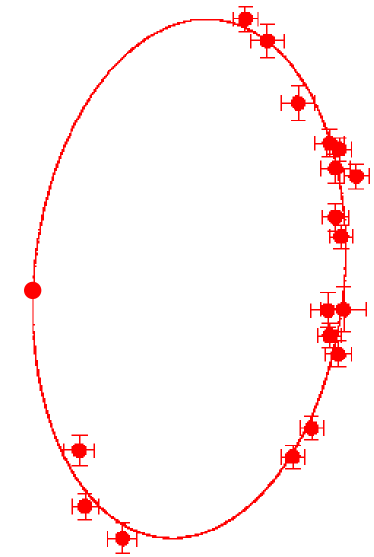
# stellar proper motions in central 45 light days



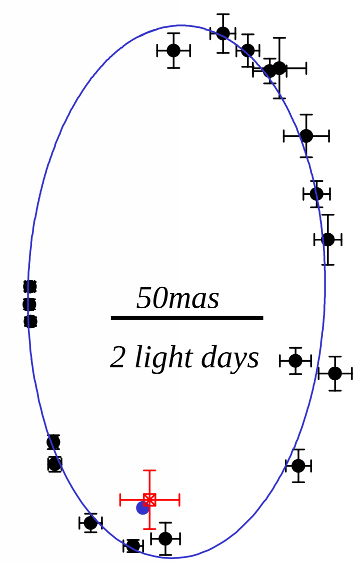

probing the central gravitational potential with stellar orbits
2 light days
SgrA*
$R_0$=7.9±0.5 kpc
6 light months
Schödel et al. 2002, 2003, Ghez et al. 2003, 2004, Eisenhauer et al. 2003, 2005

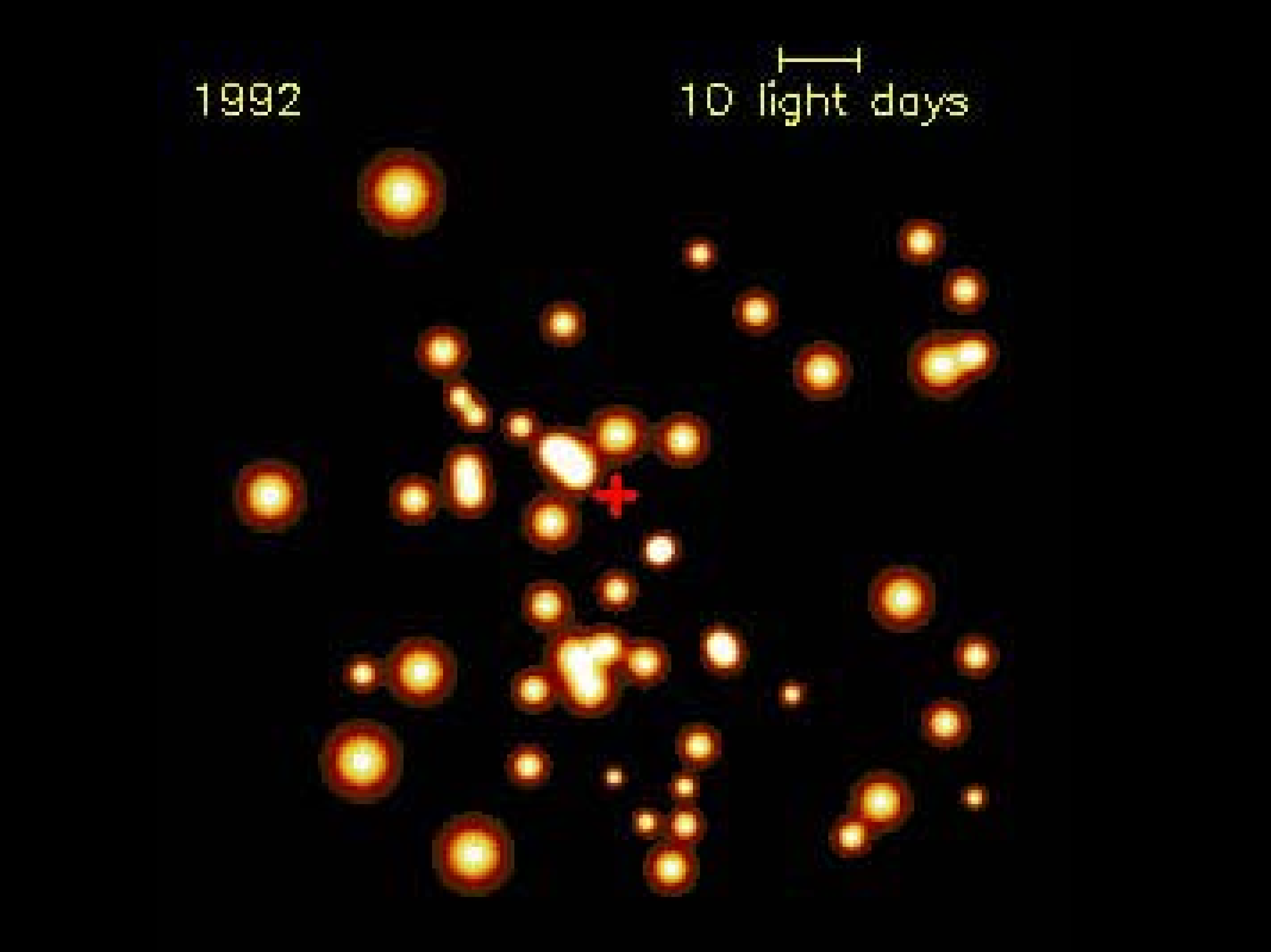
# *precision determination of S2 orbit*

*Schödel et al. 2002, NATURE 419, 694*
*Schödel, et al. 2003, Ap.J. 596, 1015*
*Eisenhauer et al., 2003, Ap.J.Lett 597, L121, 2005 in prep*
*Ghez et al. 2003, ApJ  586, L127, + astro-ph 0306130*

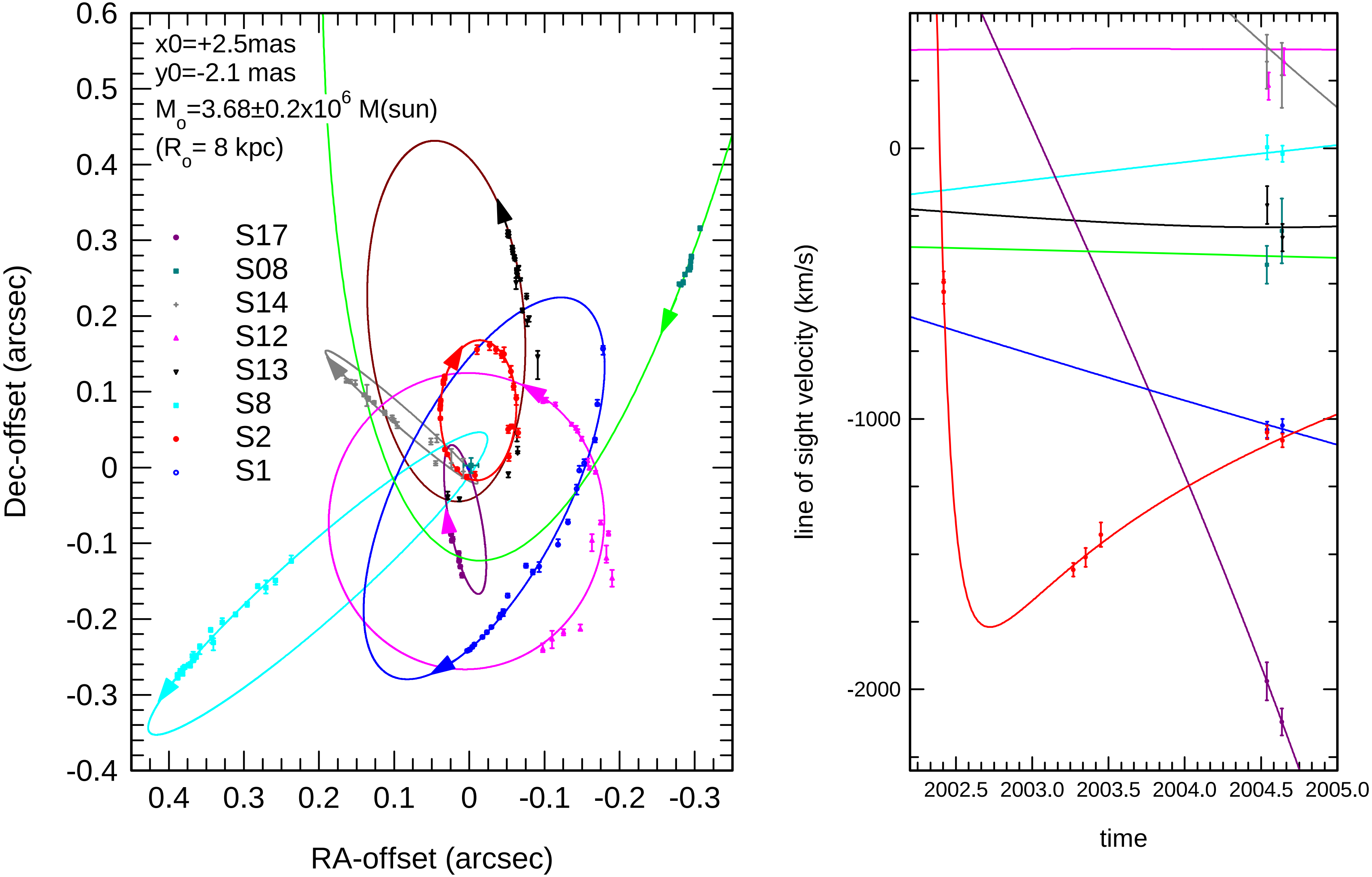


| ***S2 parameters*** | Eisenhauer et al. 05 | Ghez et al. 03 |
|---|---|---|
| Offset R.A. (mas) | **2.3±1.2** | −2.7 ± 1.9 |
| Offset Decl. (mas) | **-3.1 ±1.2** | −5.4 ± 1.4 |
| Central Mass ($10^6 M_\odot$) | **3.59±0.29(0.59)** | **3.99±0.3** |
| Period (yr) | **15.56 ±0.35** | **15.02±0.7** |
| 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** | |

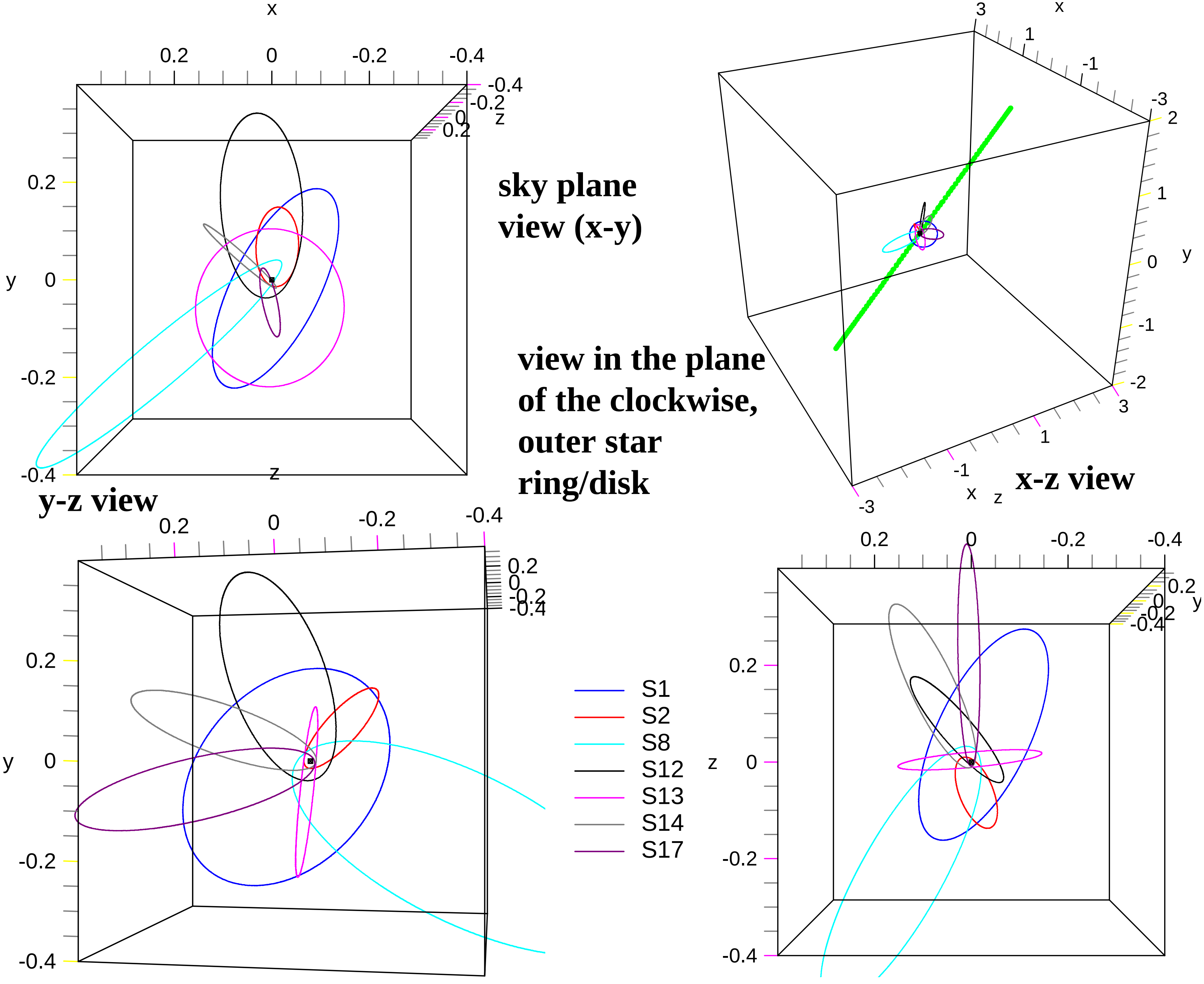


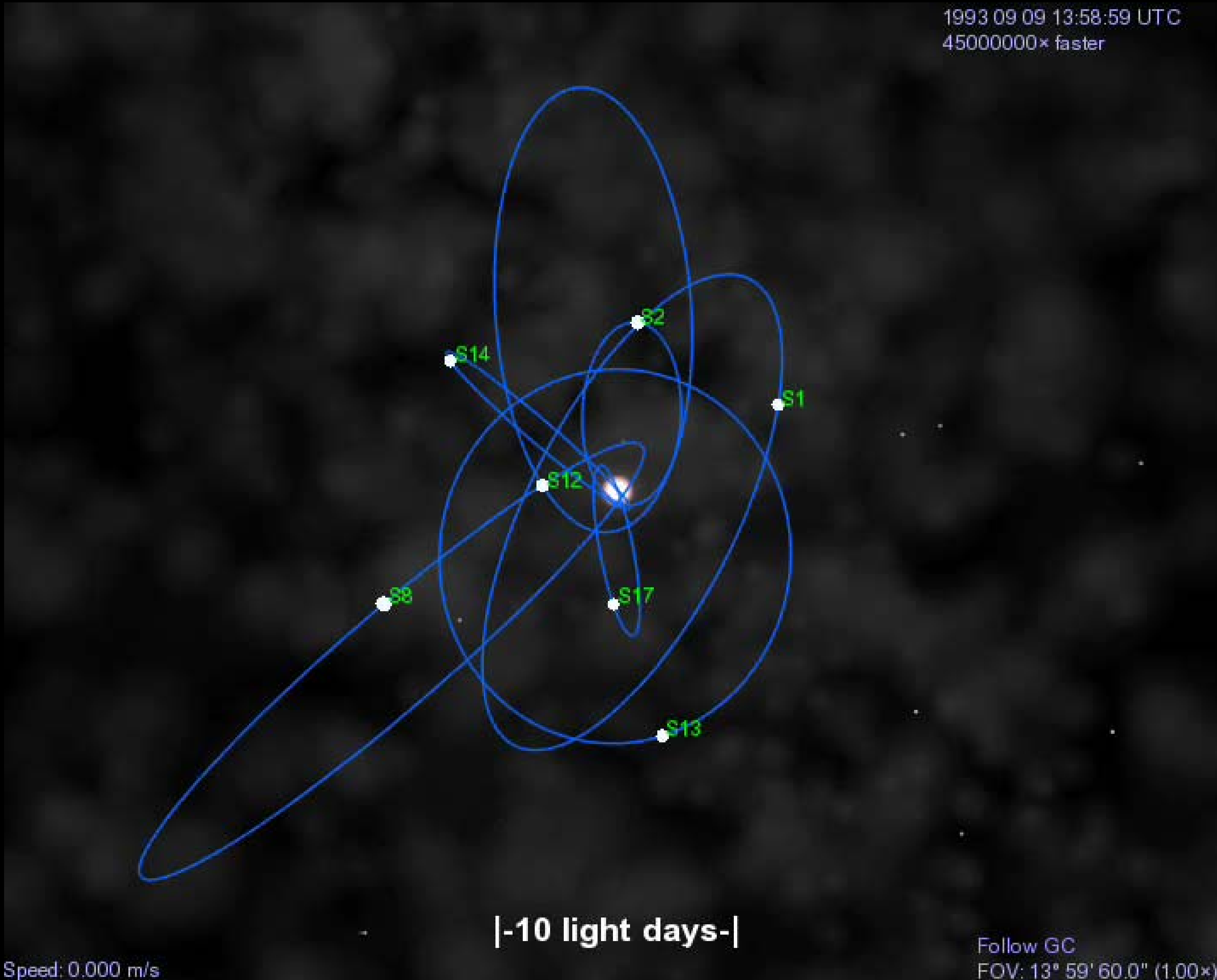

1992
10 light days

# 3D structure of orbits

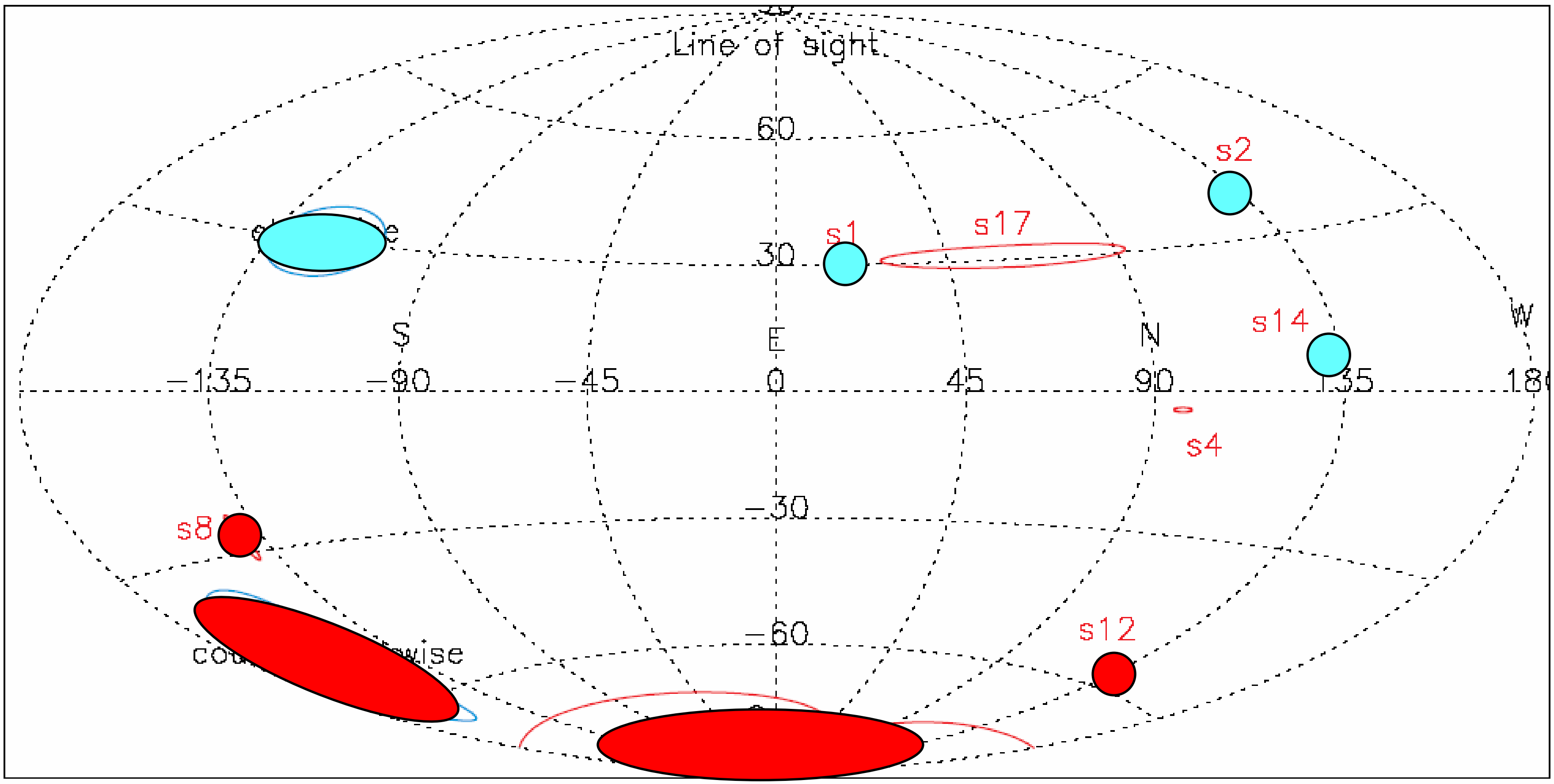



**Schödel et al. 2003, Ghez et al. 2003, Eisenhauer et al. 2005**

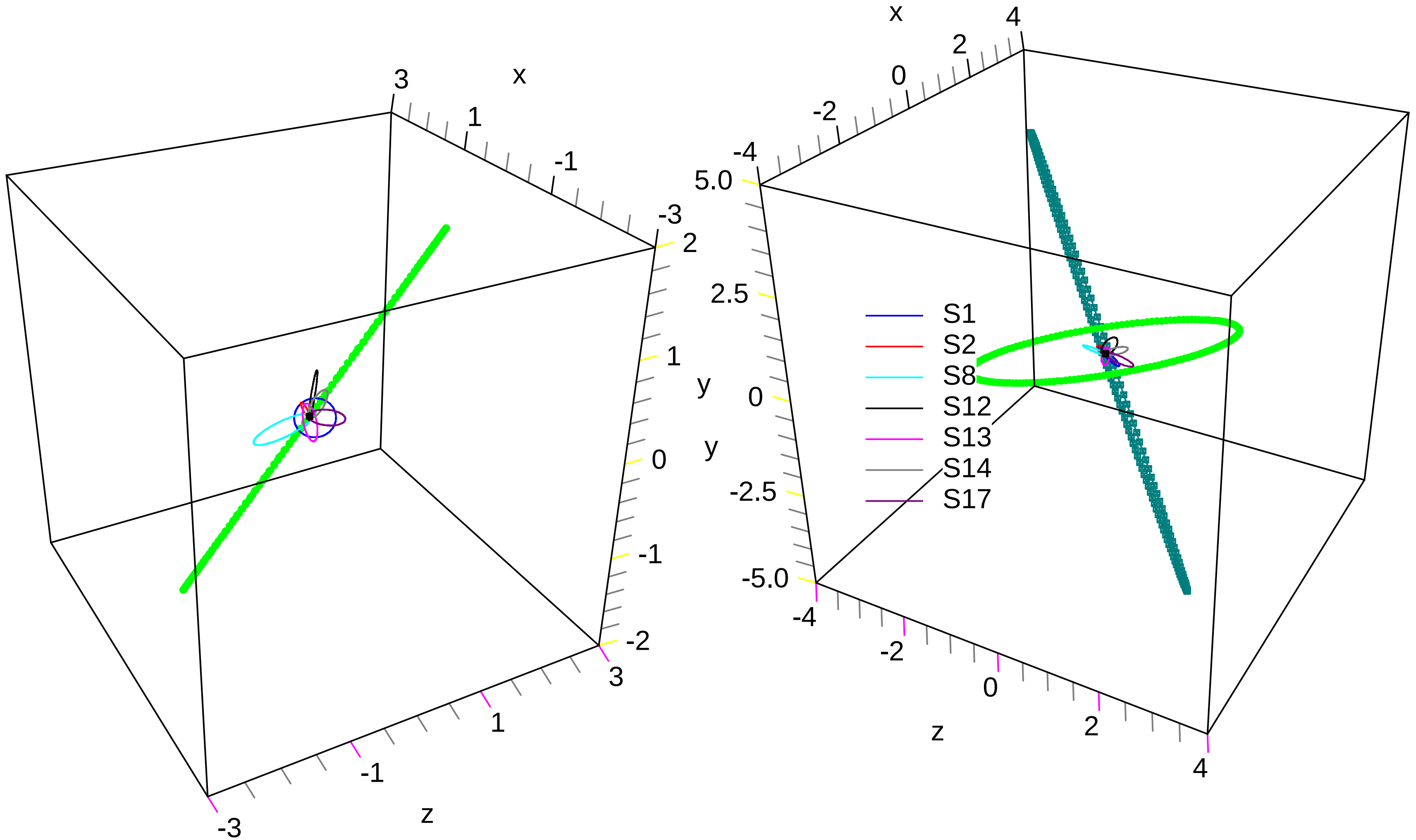

sky plane
view (x-y)
view in the plane
of the clockwise,
outer star
ring/disk
x-z view
y-z view
S1
S2
S8
S12
S13
S14
S17


1993 09 09 13:58:59 UTC
45000000× faster
S2
S14
S1
S12
S8
S17
S13
|-10 light days-|
Speed: 0.000 m/s
Follow GC
FOV: 13° 59' 60.0" (1.00×)

# *orientation of orbital spin directions*

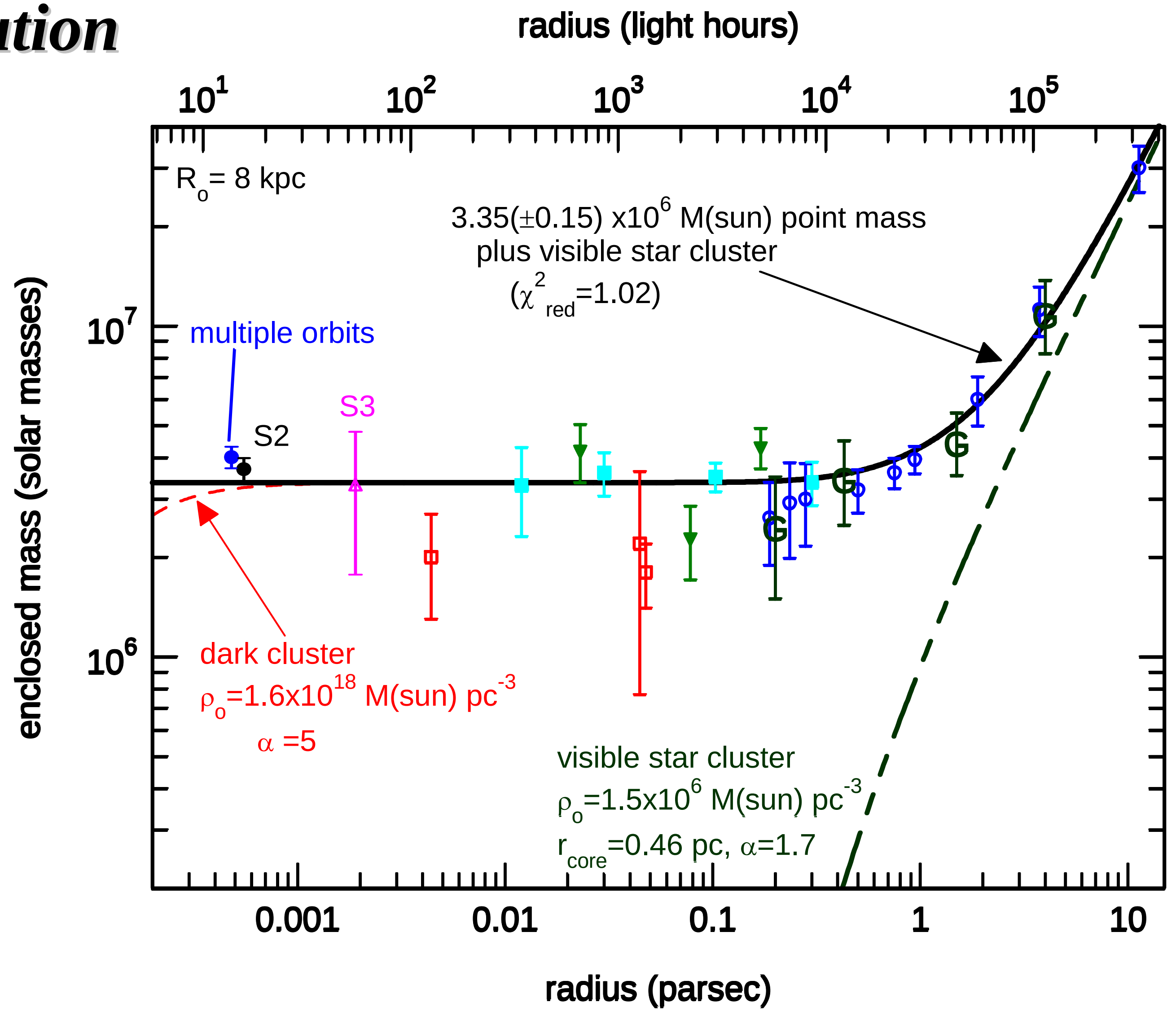



**Eisenhauer et al. 2005**



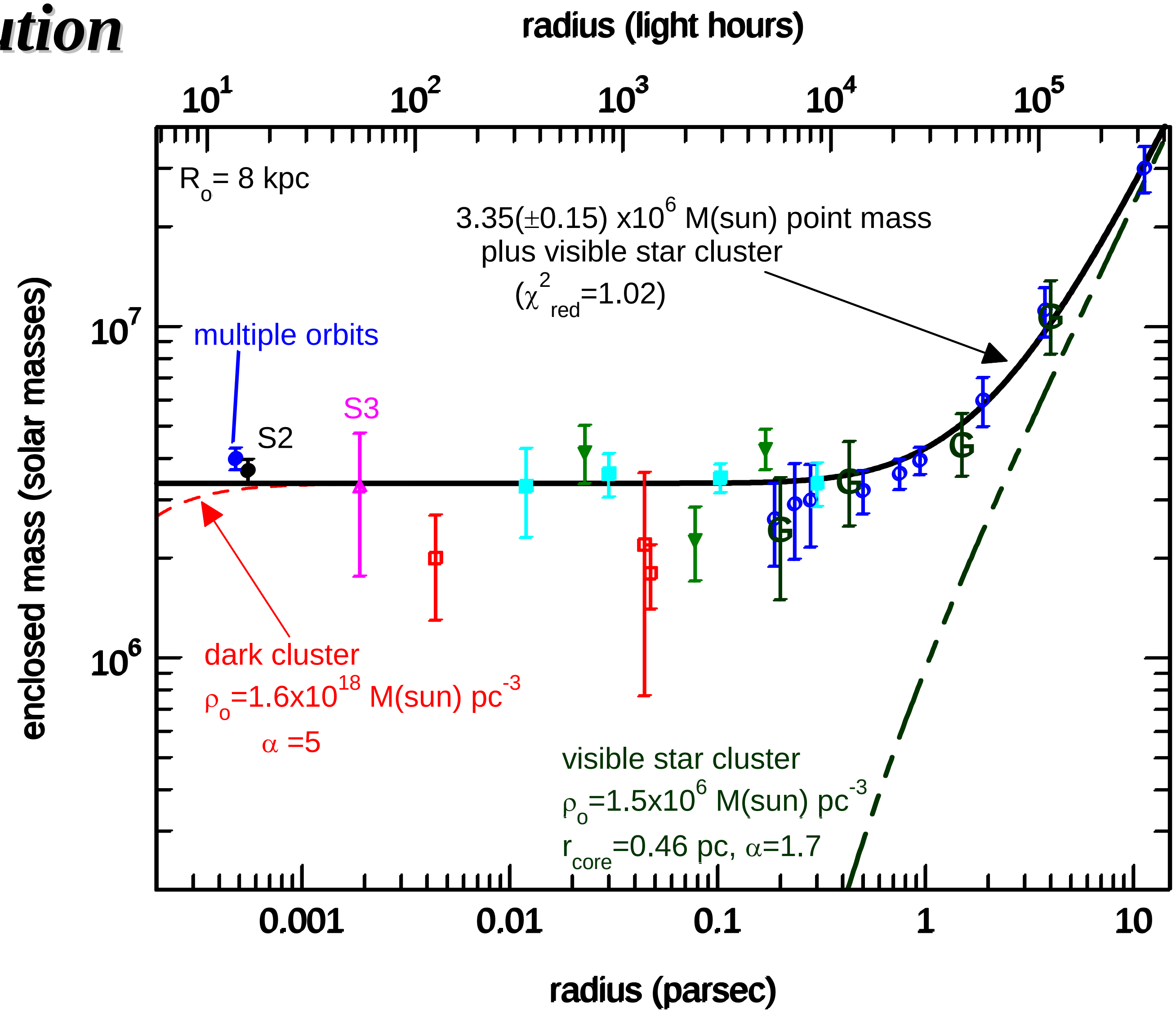

Orientation of S-orbits relative to outer star disks

# mass distribution

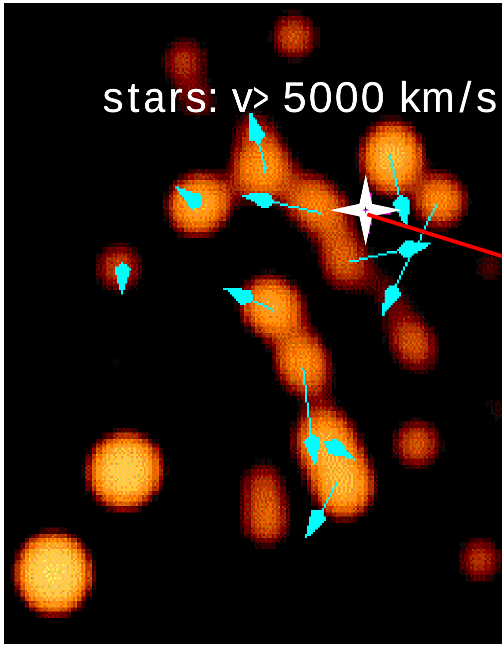



*Schödel et al., NATURE 2002, 419, 694; 2003, Ap.J. 596, 1015, Ghez et al. 2003, Ap.J. 586, L127, astro-ph 0306130, Eisenhauer et al. 2003, ApJ 597, L121*

***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)***

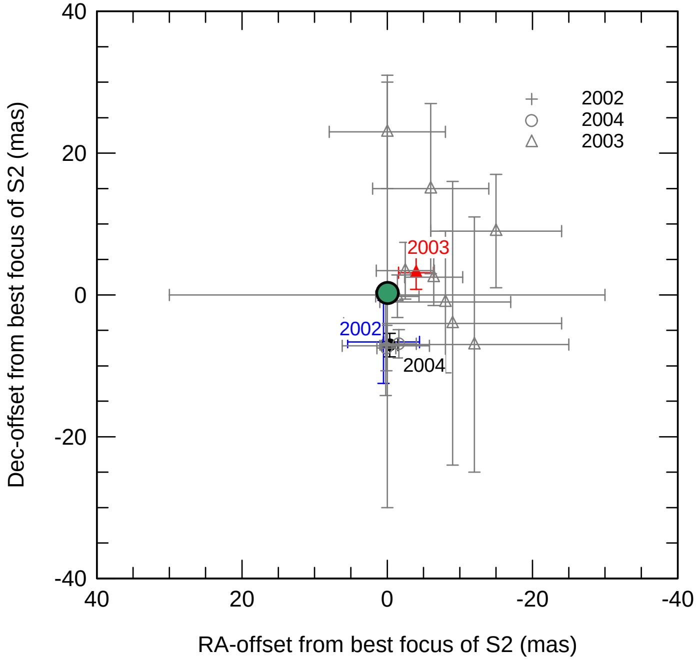
$$M_{SgrA*} > 10^5\, M_{\odot}$$

$$\rho_{SgrA*} > 10^{20.5}\, M_{\odot}\, pc^{-3} = 10^{-1.7}\ g\ cm^{-3}$$

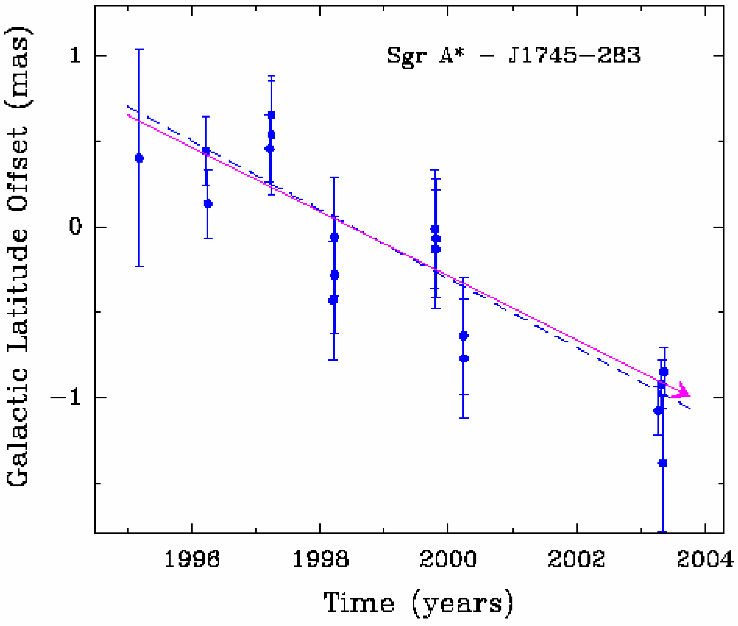
***Reid et al. 1999, 2004, Chatterjee et al. 2002, Dorband et al. 2003***

# *limits to the proper motion of SgrA**

IR




radio

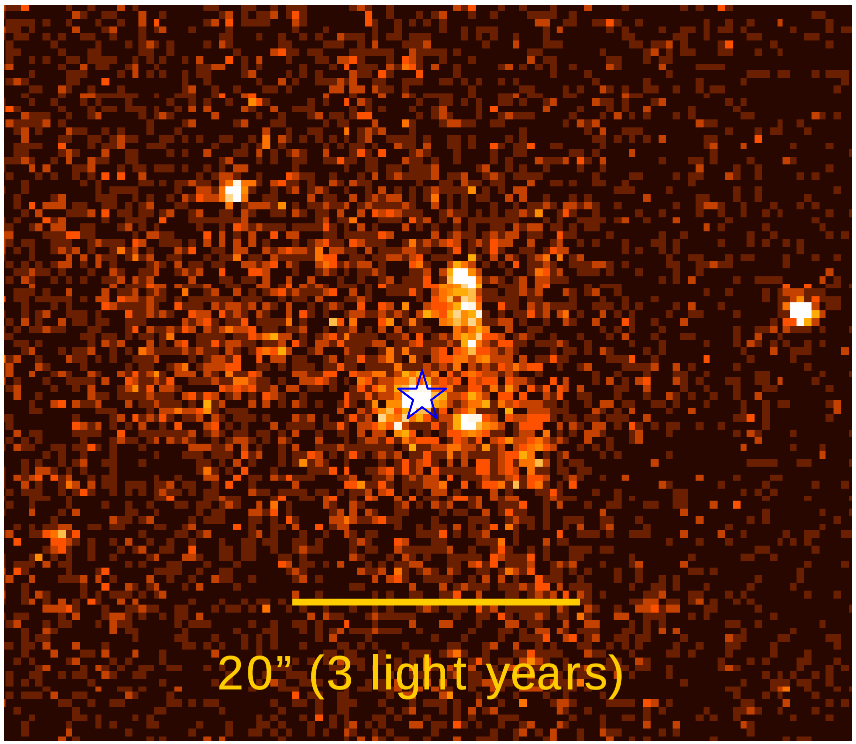


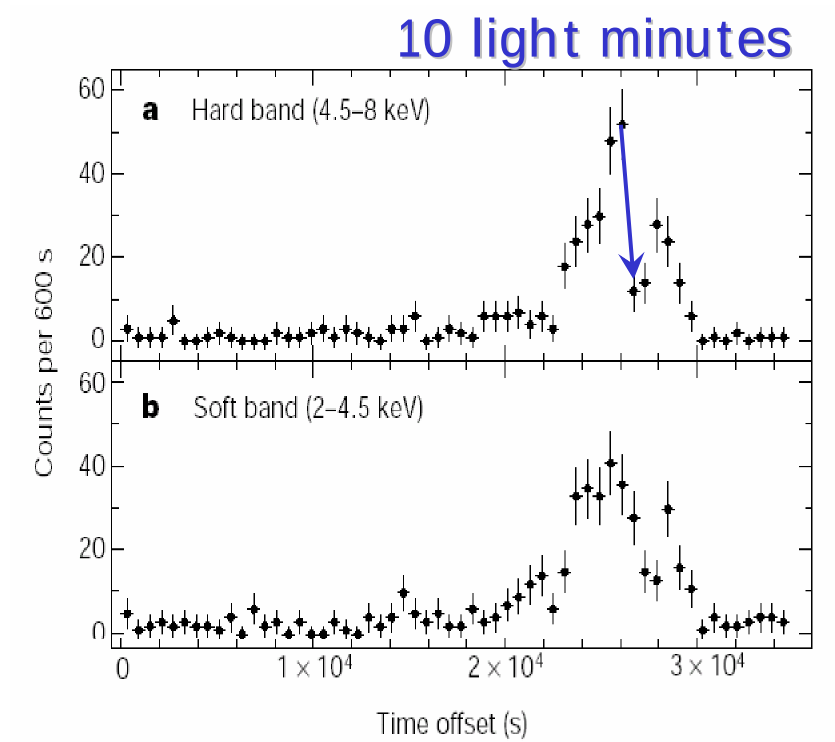

**$v_{IR} \leq 100$ km/s**

**$v_{rad} < 20$ (2) km/s proper motion of SgrA***

**Backer &Sramek 1999, Reid et al. 1999, Genzel et al. 2003, Ghez et al. 2004, Reid et al. 2004**

# *X-ray flares*




***Chandra***

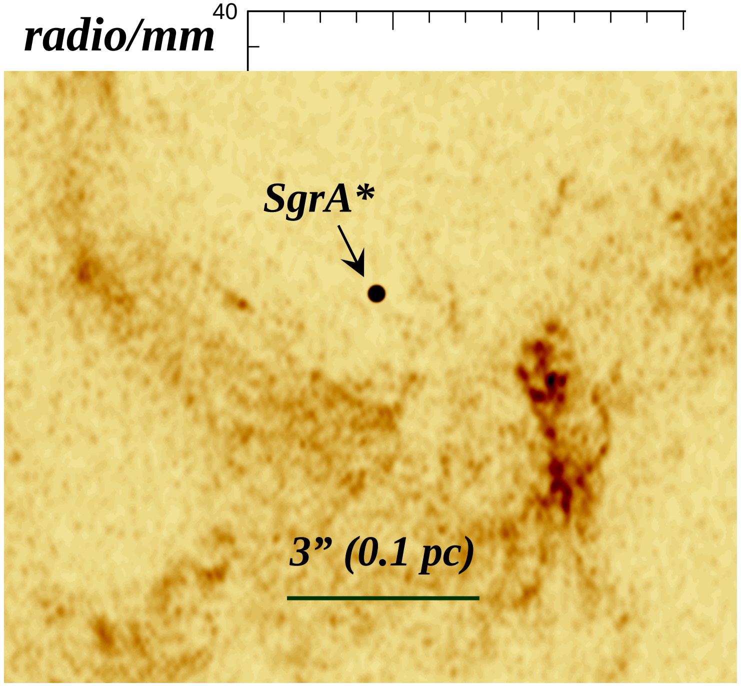
***May 2002 campaign: ~0.5 flares/day***

Baganoff et al. 2000, 2001,2003

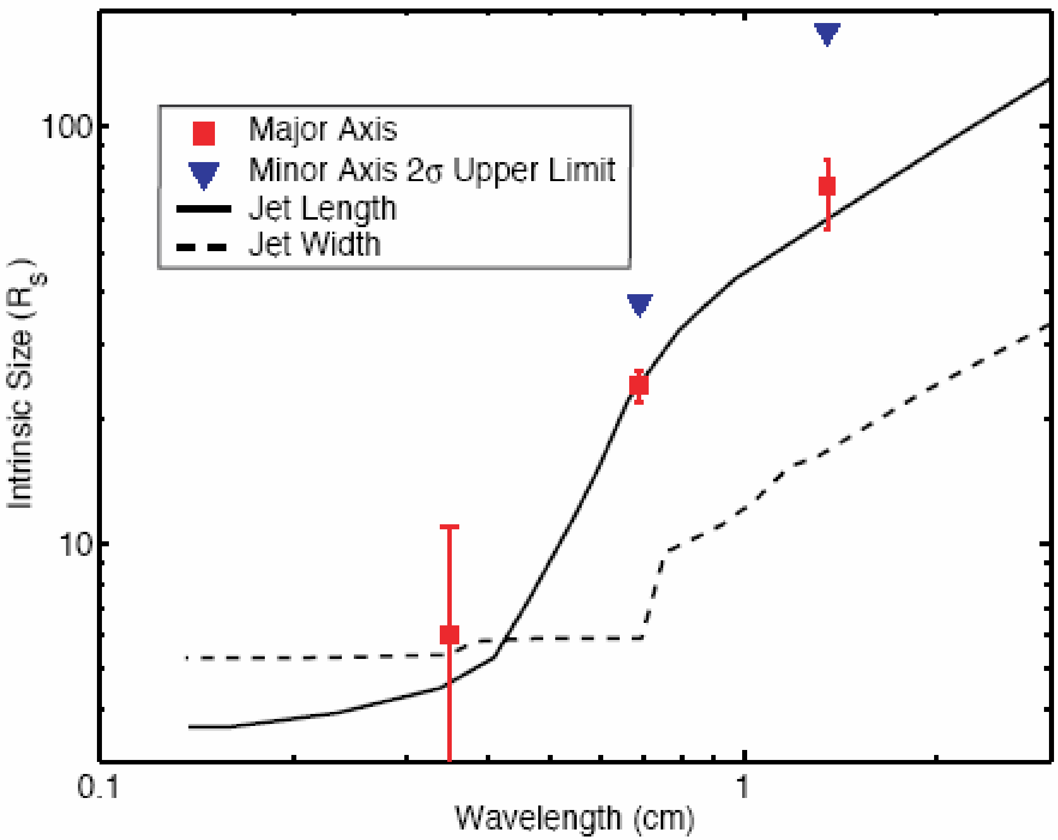
# *properties of SgrA**

IR flares

*radio/mm*

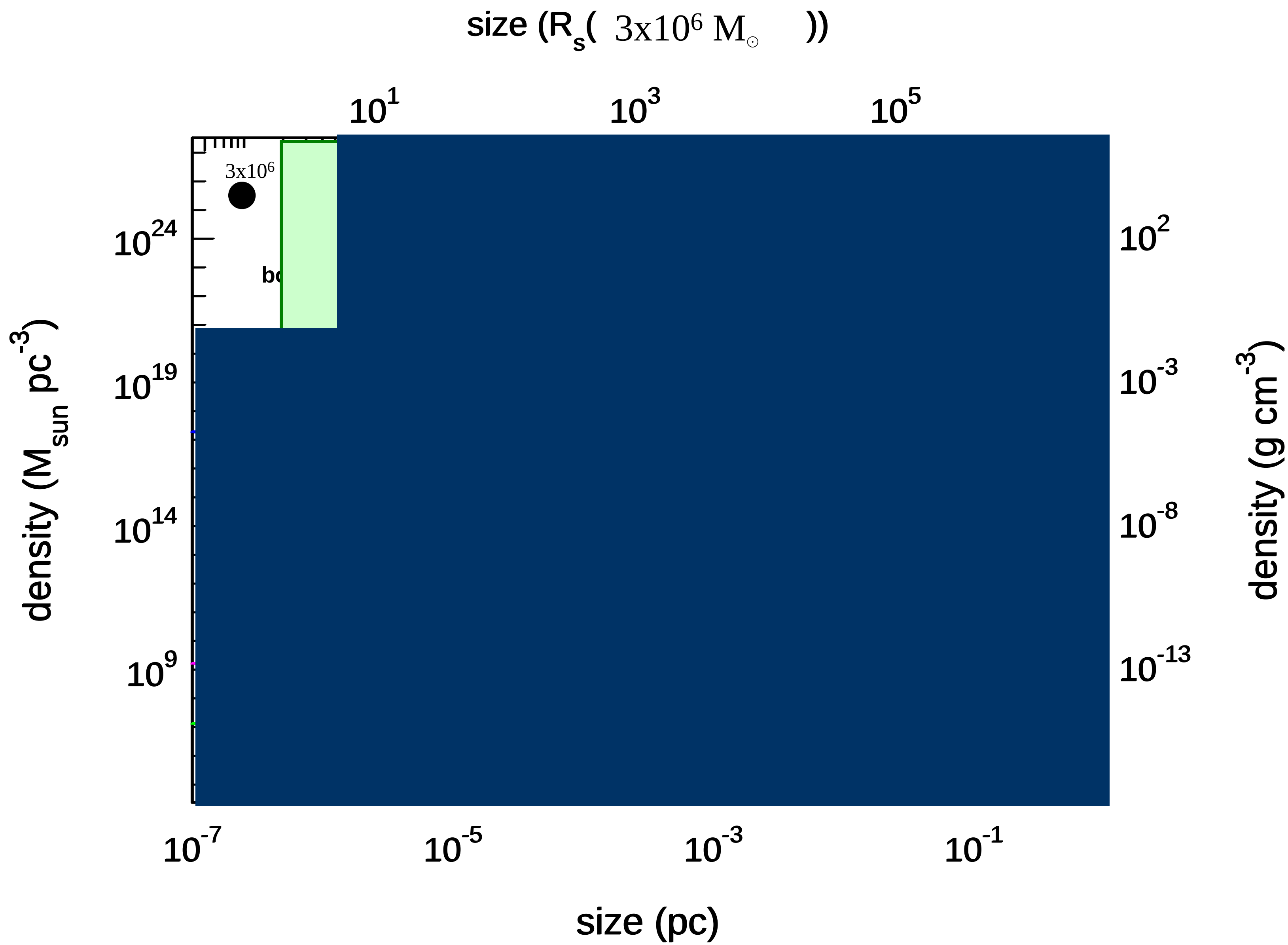



$v_{IR} \leq 100$ km/s

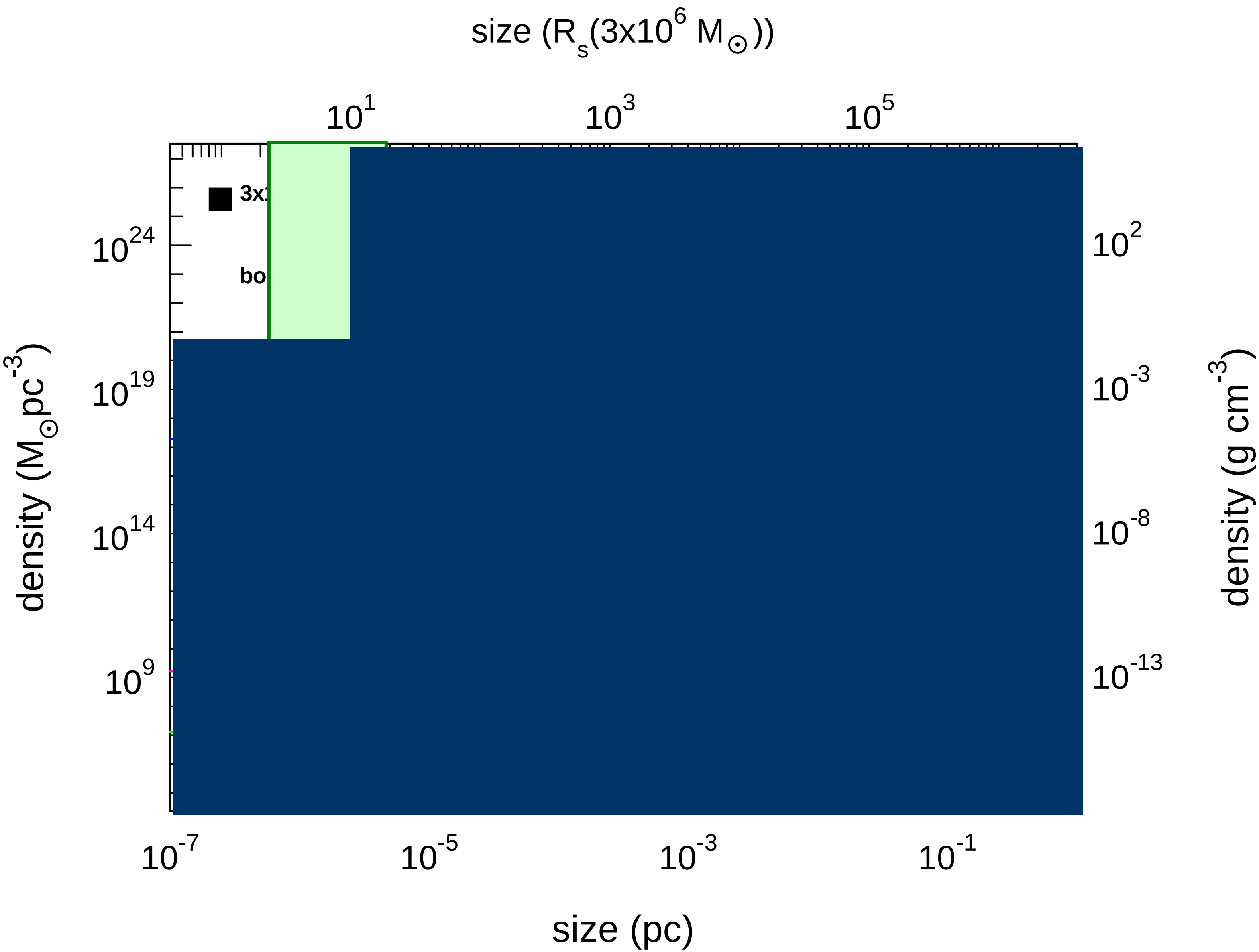



Lo et al. 1998, Zhao et al. 2002, Doeleman et al. 2002, Backer & Sramek 1999, Reid et al. 1999, Genzel et al. 2003, Ghez et al. 2004, Reid et al. 2004, Bower et al. 2004

# *Black hole or not black hole?*

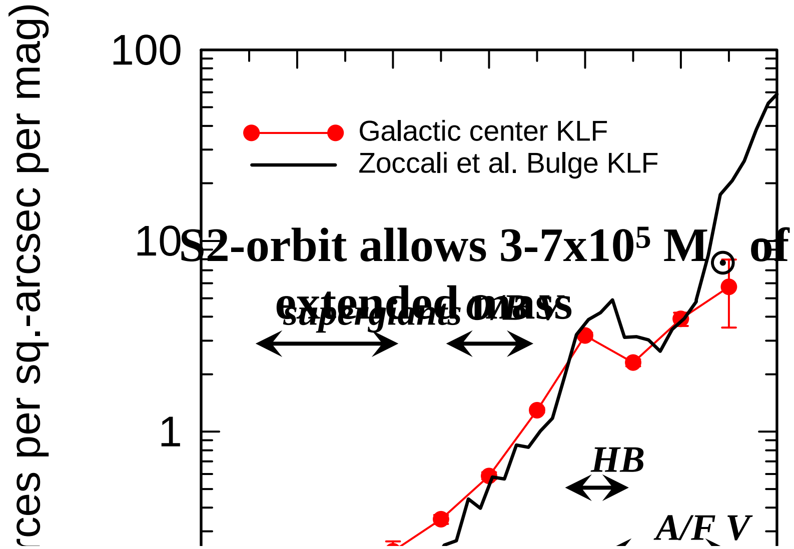


# black hole or no black hole?

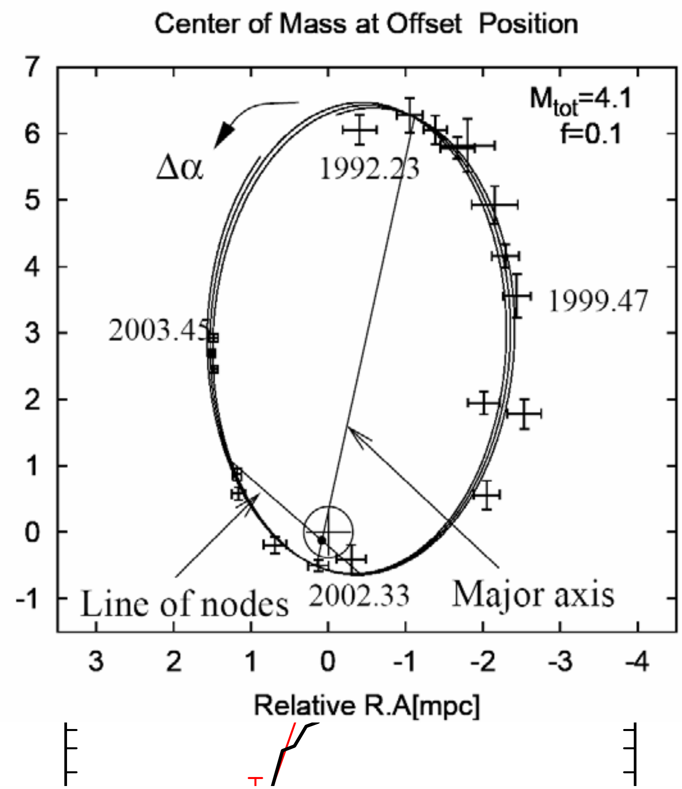


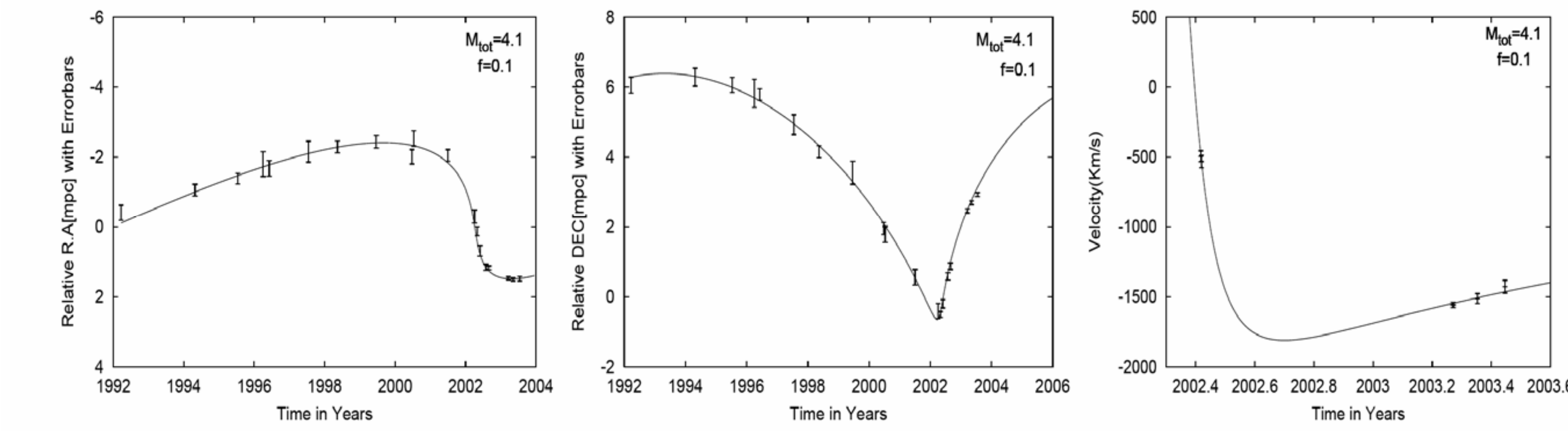

**Schödel et al. 2002, 2003, Ghez et al. 2004, Reid et al. 2004**

# Constraints on cusp properties & mass




**S2-orbit allows 3-7x10$^5$ M$_\odot$ of extended mass**

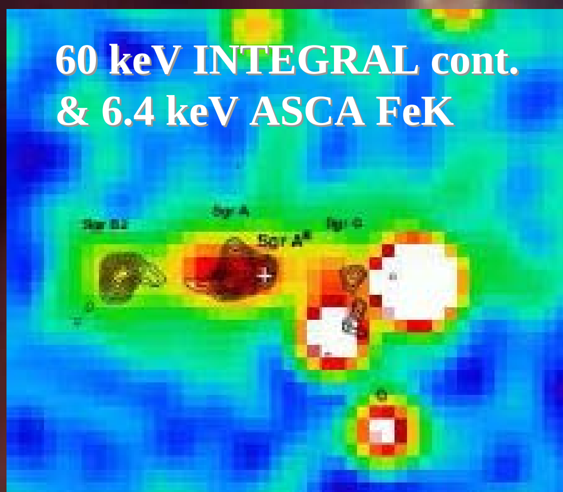


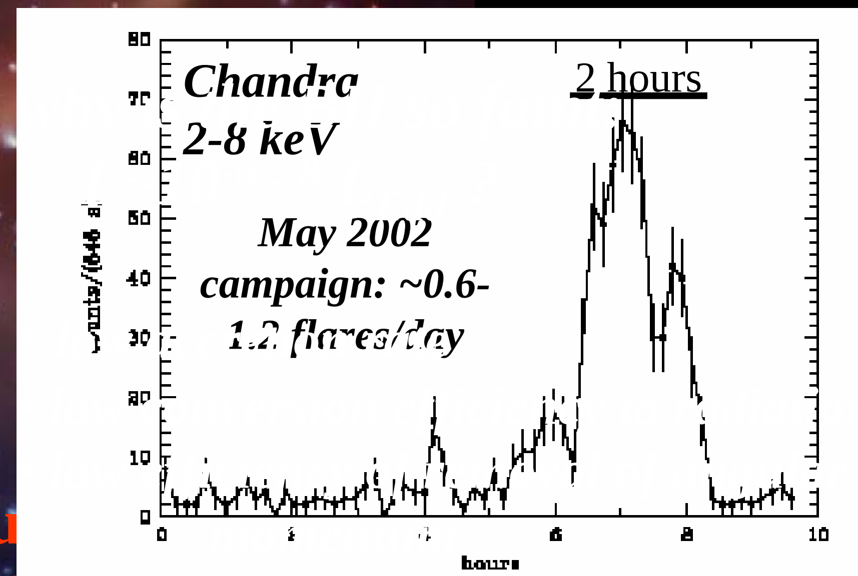

Mouawad et al. 2004, A&A in press (astro-ph 0402338)

Genzel et al. 2003

# *X- and γ-rays from SgrA**




SgrA*



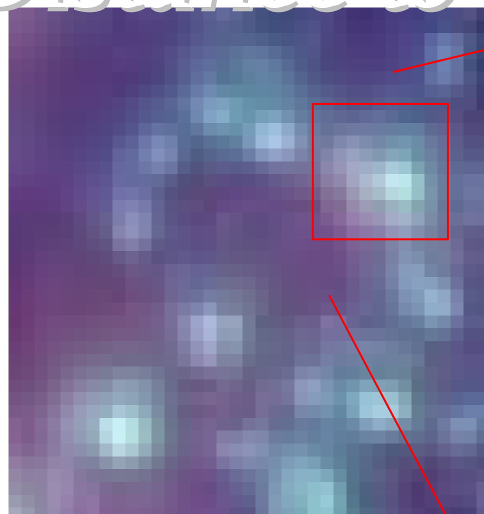

TeV sou[rce]
Aharonian et al. 2004

1.6 '

Baganoff et al. 01, 04, Muno et al. 04, Mayer-Hasselwander et al. 99, Porquet et al. 2003, Goldwurm et al. 1998, 2003, Sunyaev et al. 1993, Koyama et al. 1996, Revnivtsev et al. 2004

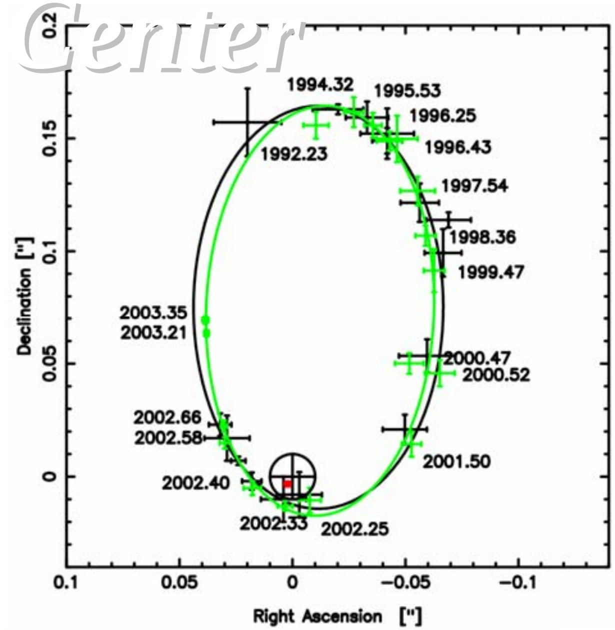
# Distance to Galactic Center

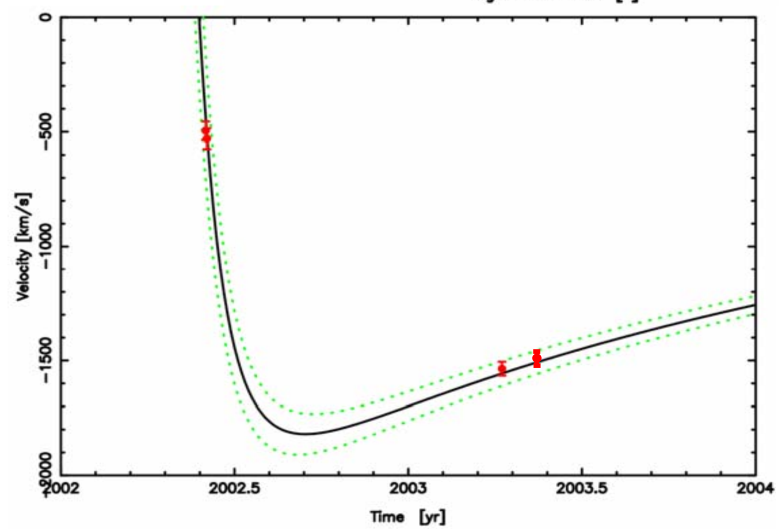
1“



NACO

SPIFFI



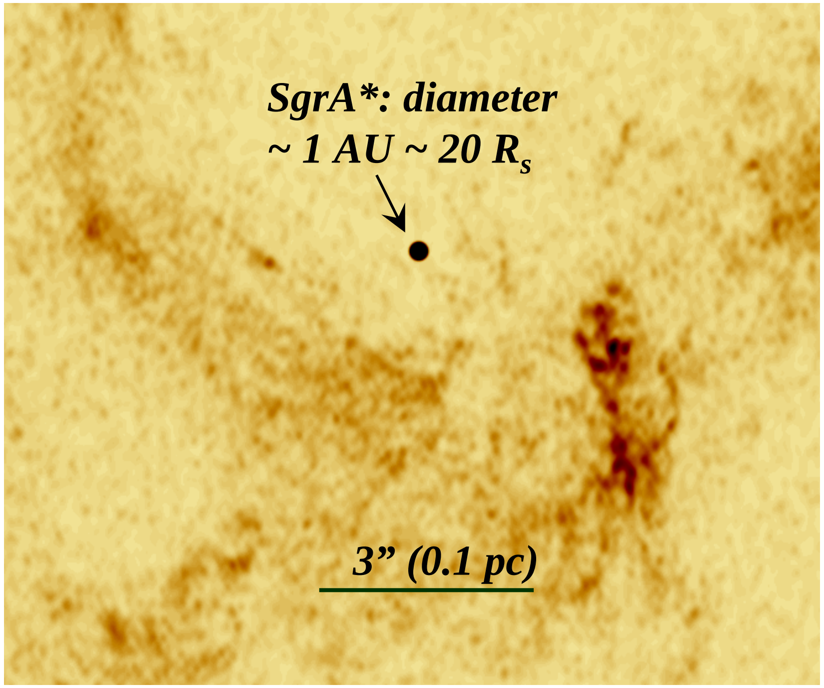



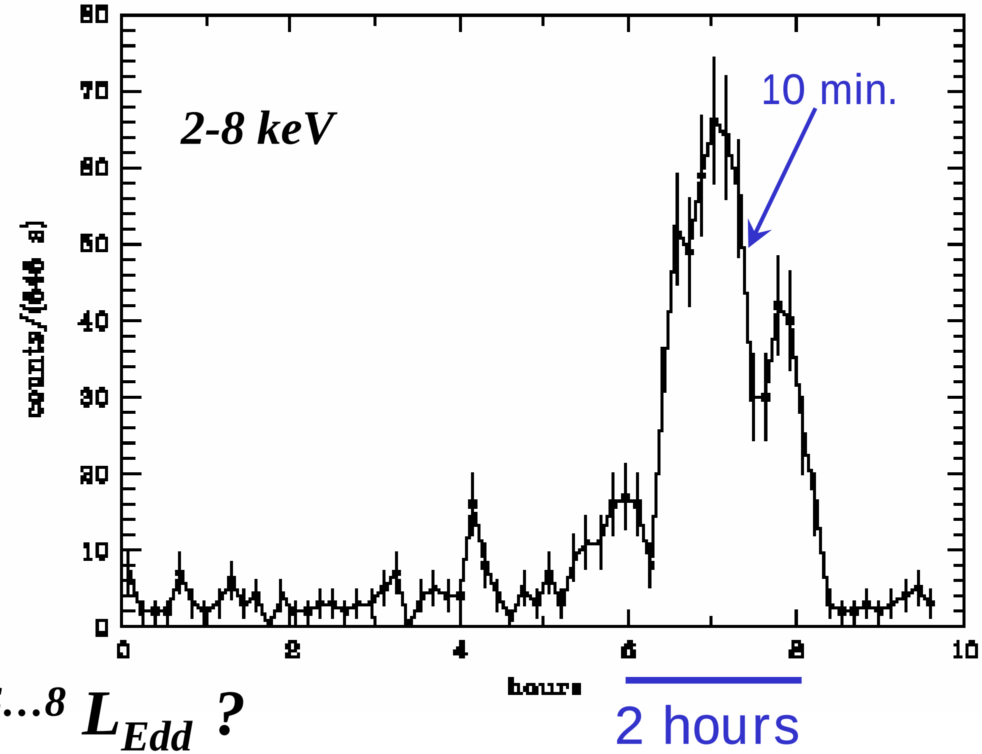

Distance Galactic Center: 7.94±0.42 kpc
Rotation velocity of sun: 220.7+-12.7 km/s

*Eisenhauer et al. 2003*

# *accretion onto the black hole*

***radio/mm***




***why is the BH so faint: $L \sim 10^{-6 \ldots 8} L_{Edd}$ ?***

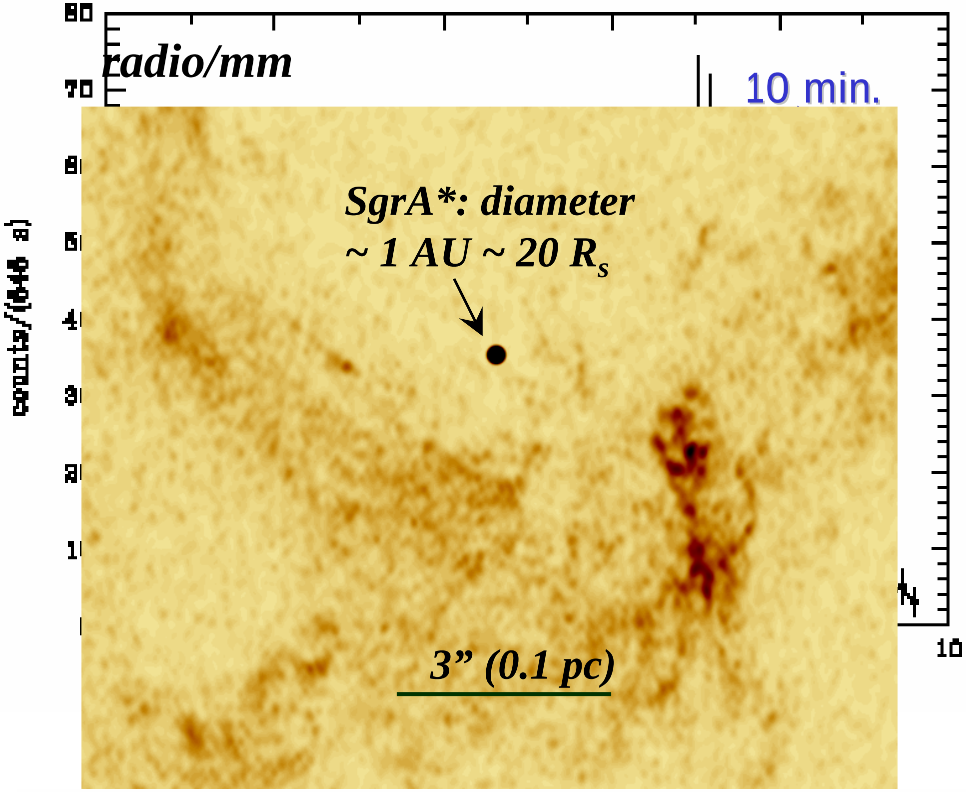
- ***low accretion rate***
- ***low conversion efficiency to radiation***
- ***low efficiency of removal of angular momentum***

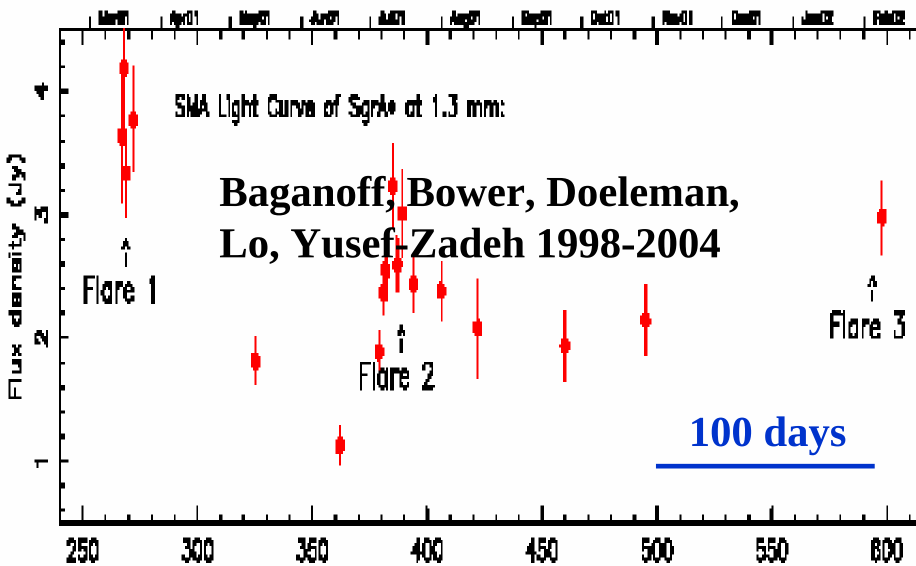
***May 2002 campaign: ~0.6-1.2 flares/day***

*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*

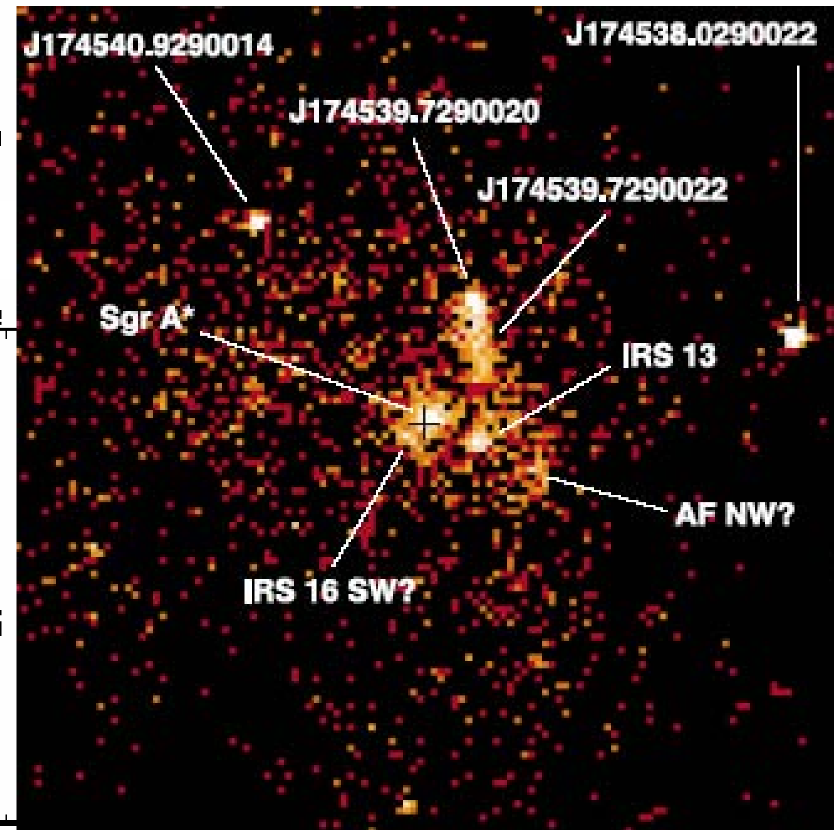
# *Accretion onto the Black Hole*

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

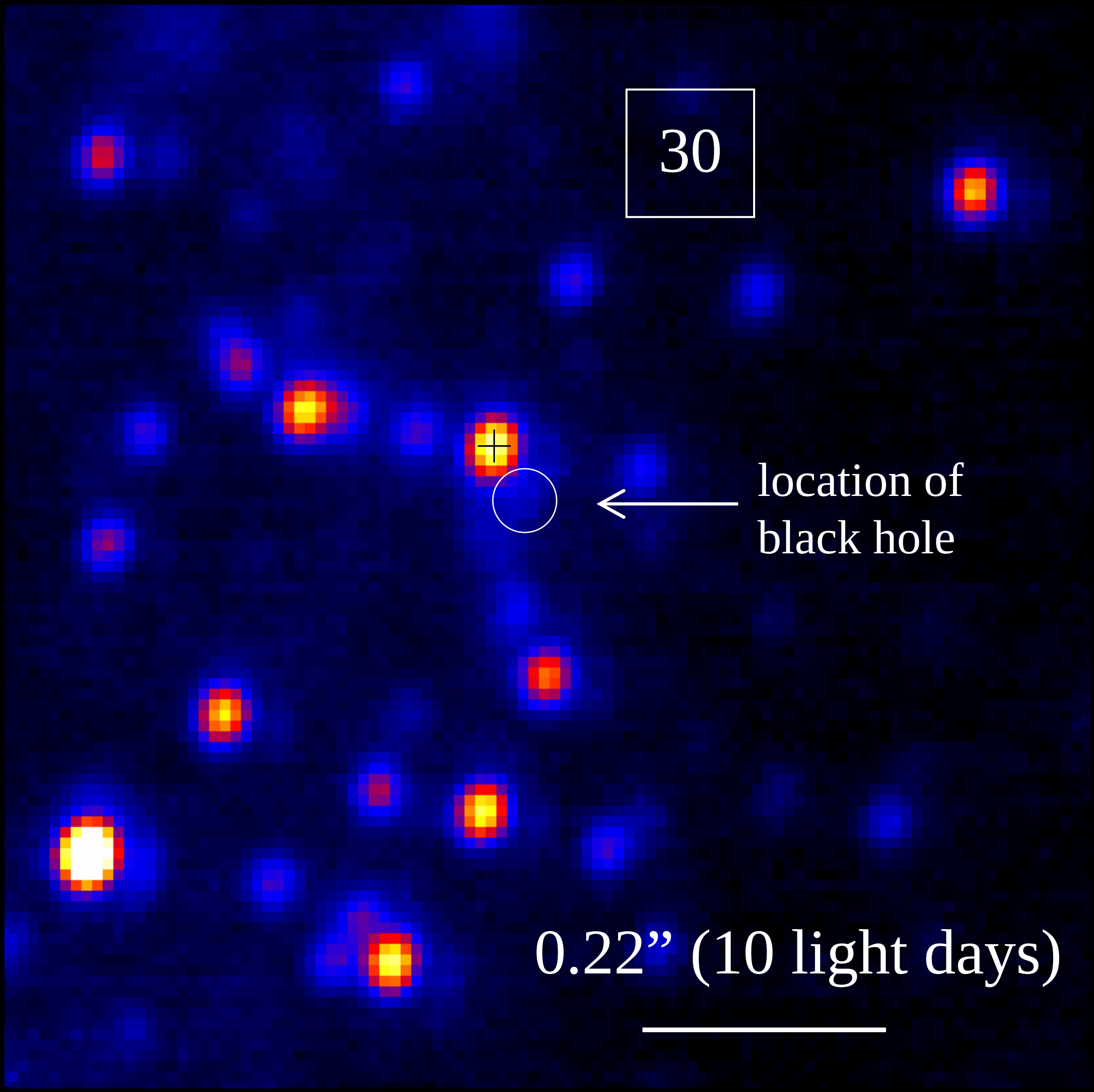



X-rays

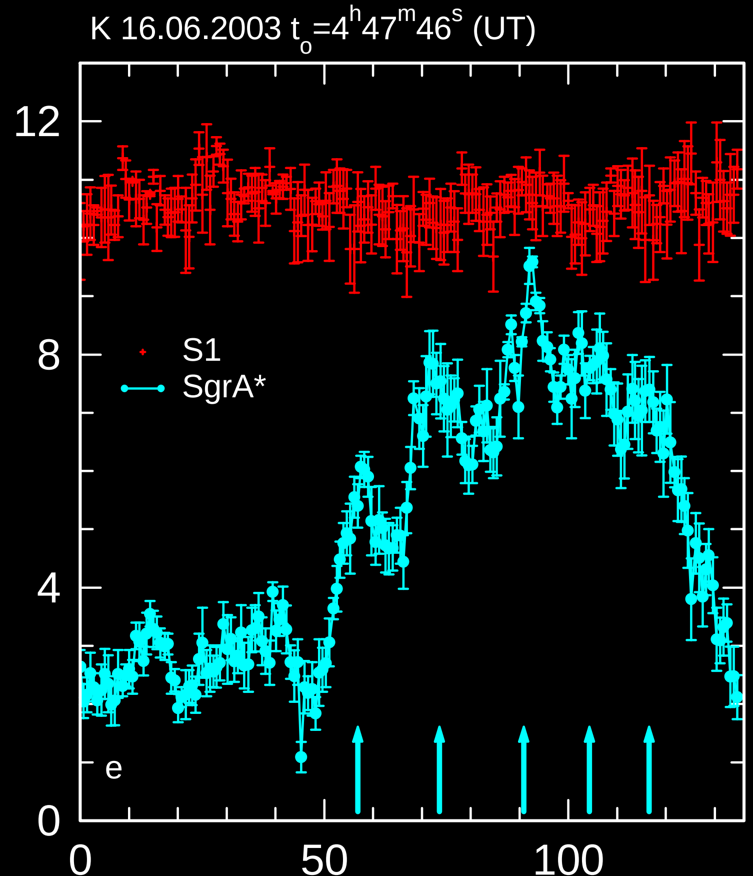


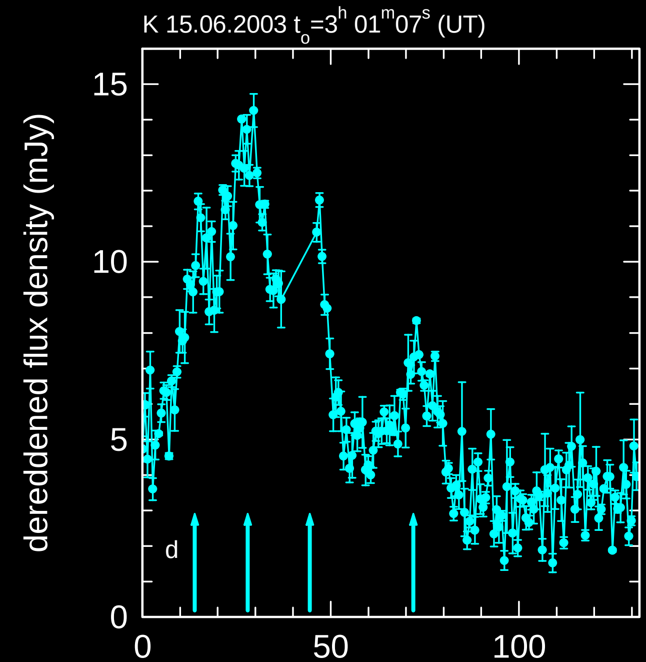
# *infrared flares & BH spin*

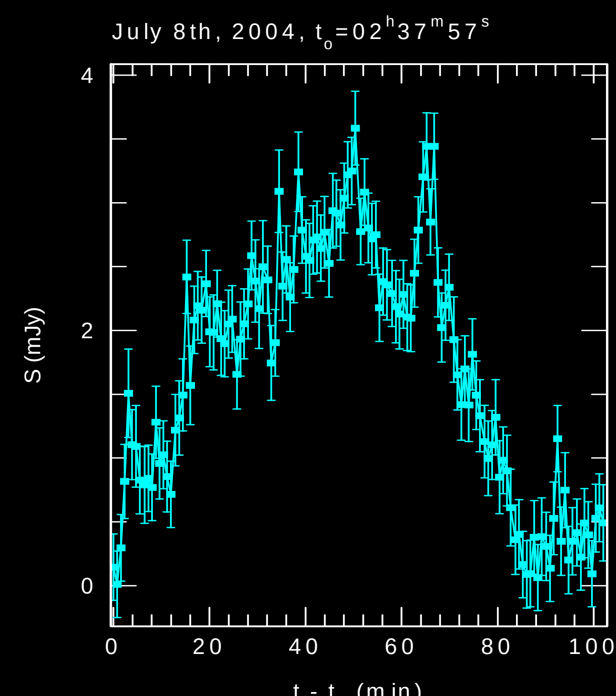



*May 09, 2003: NACO (VLT) H-band, 40 mas resolution (adaptive optics), 1 min per image*

# *infrared flares*

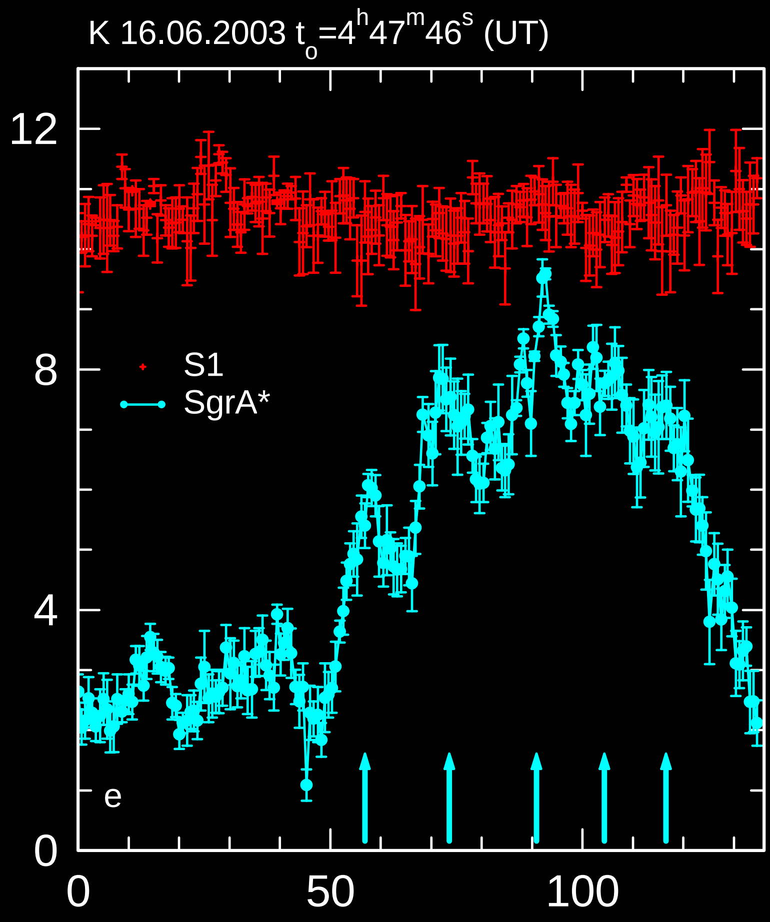


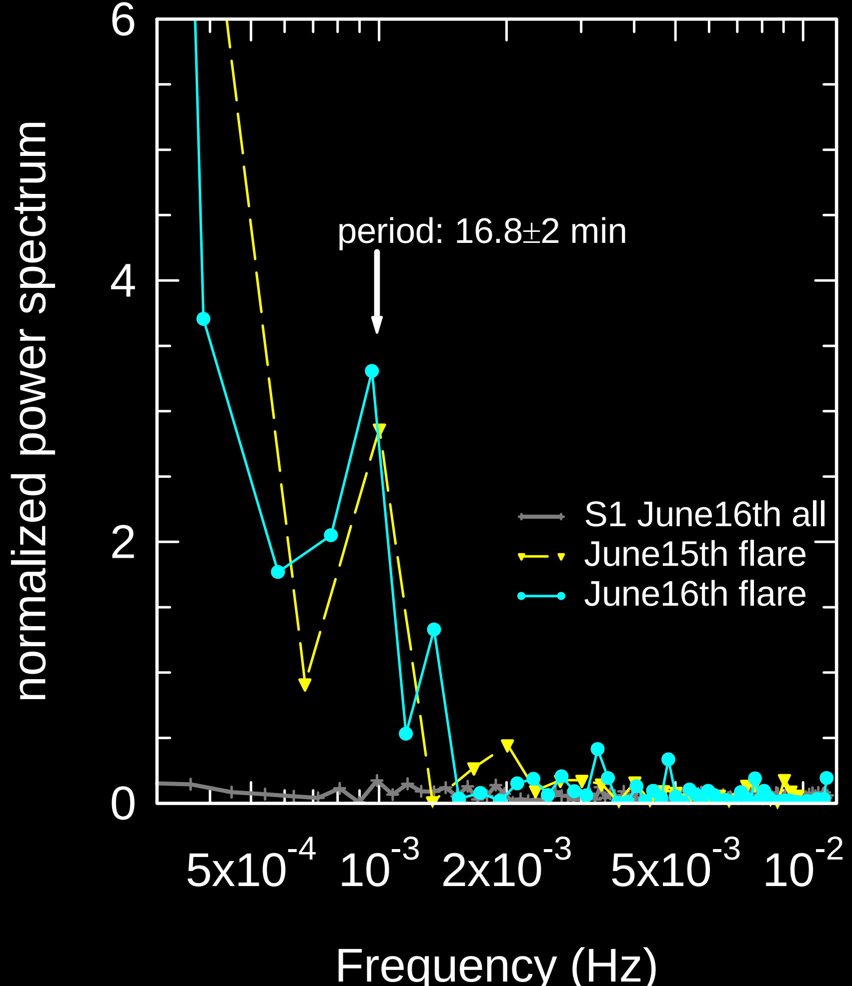




***Genzel et al. 2003, Nature 425, Ghez et al. 2004 ApJL***

# *Infrared flares: quasi-periodicity*

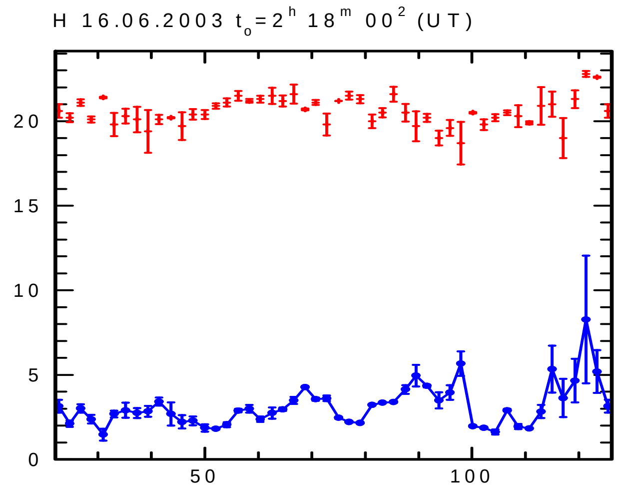


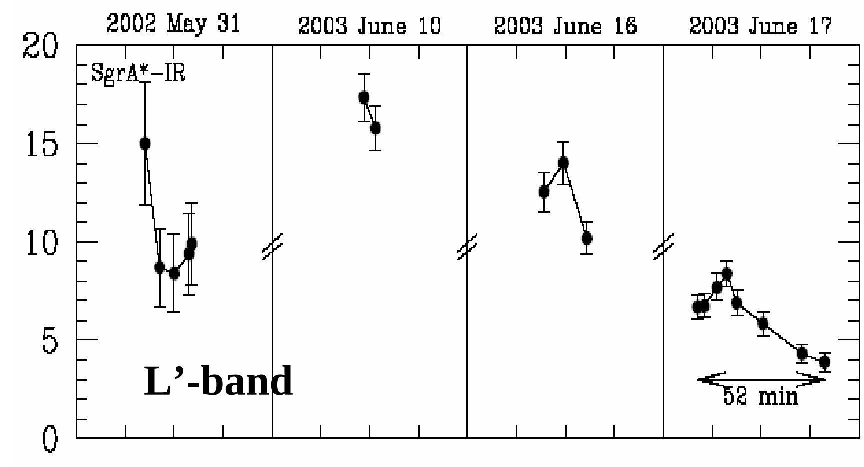




**spin parameter: a=0.52±0.15**

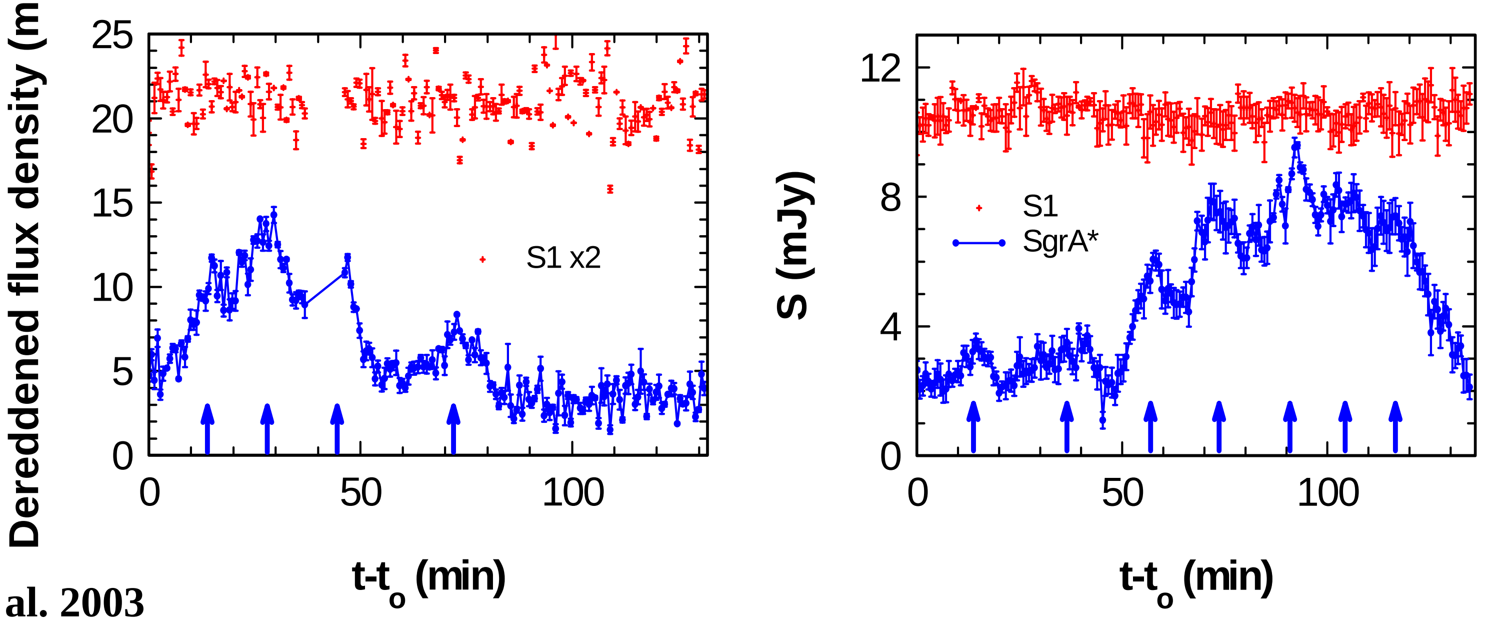
***Genzel et al. 2003, Nature 425, 934***

# *IR variability VLT/Keck*




Ghez et al. 2004, ApJ 601, L159

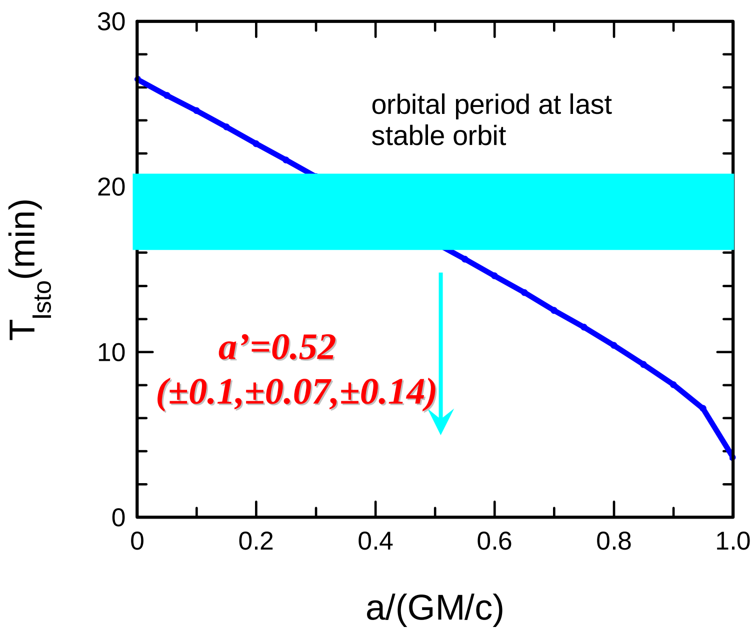


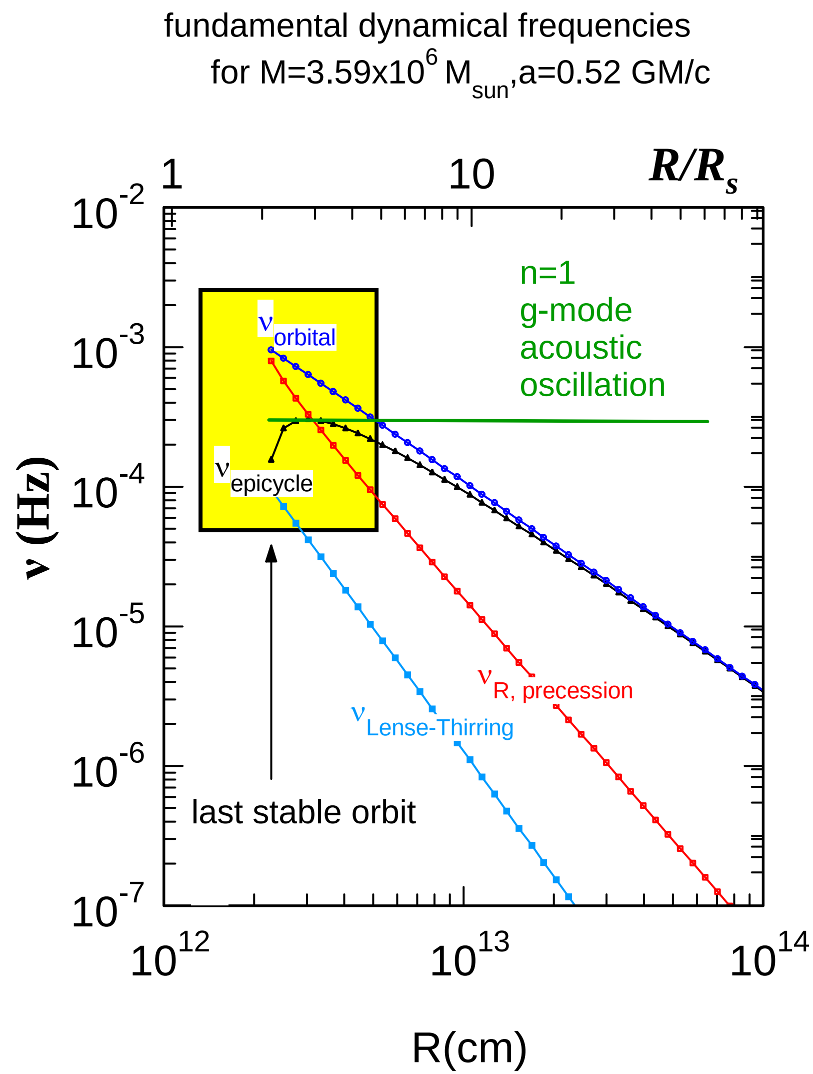

Genzel et al. 2003
Nature 425, 934

K, 15 Jun. 2003, $t_o$=3 h 01 m 07 s (UT)

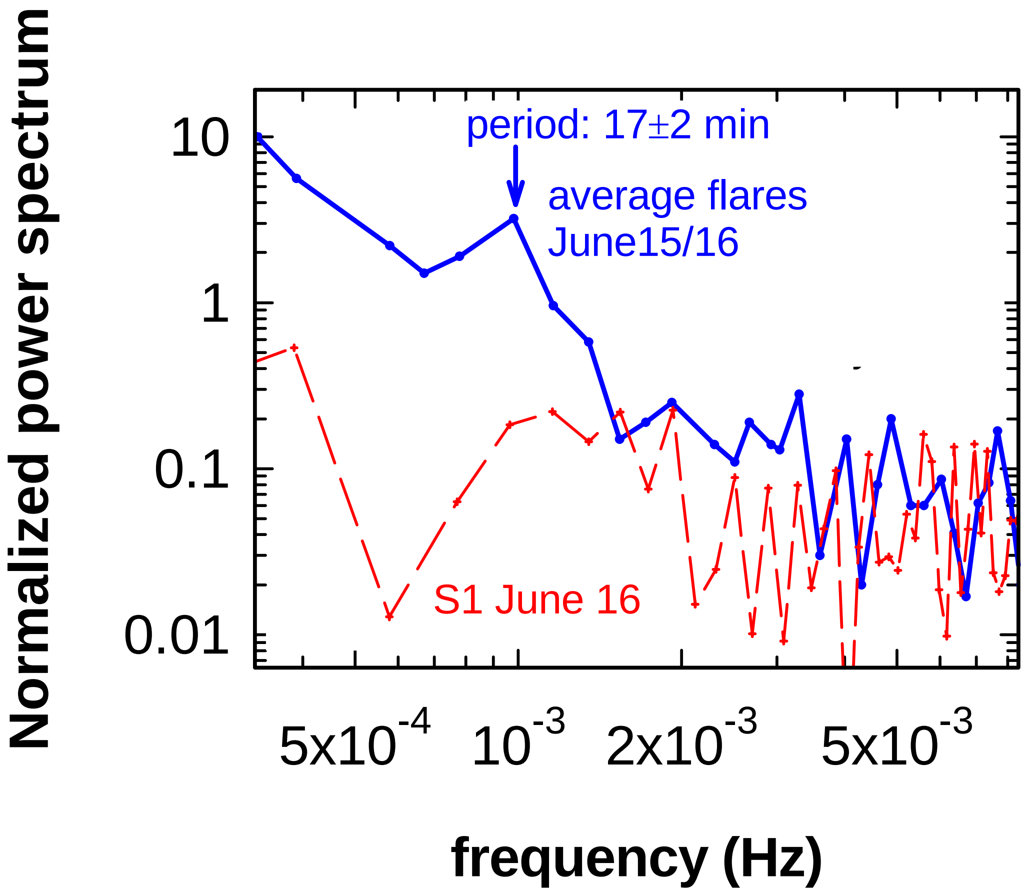
K, 16 Jun. 2003, $t_o$=4 h 47m 46 s (UT)

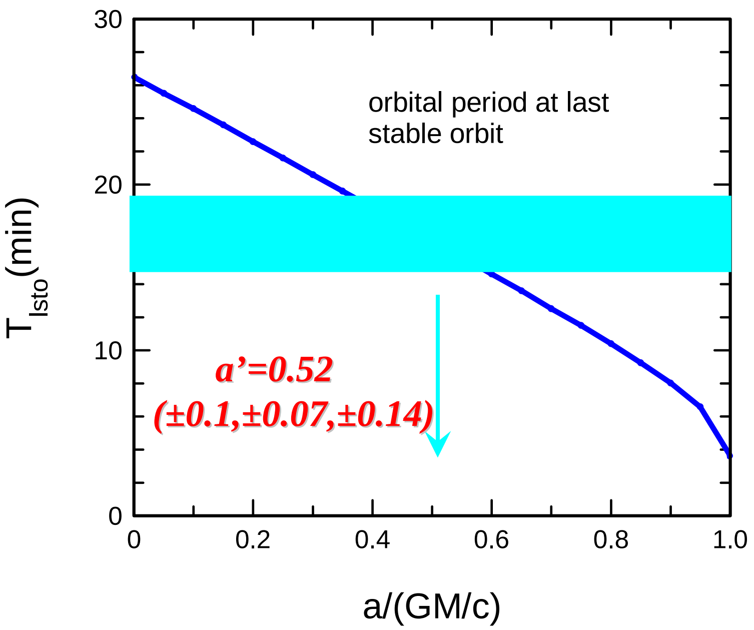
# *Fundamental dynamical frequencies around a black hole*



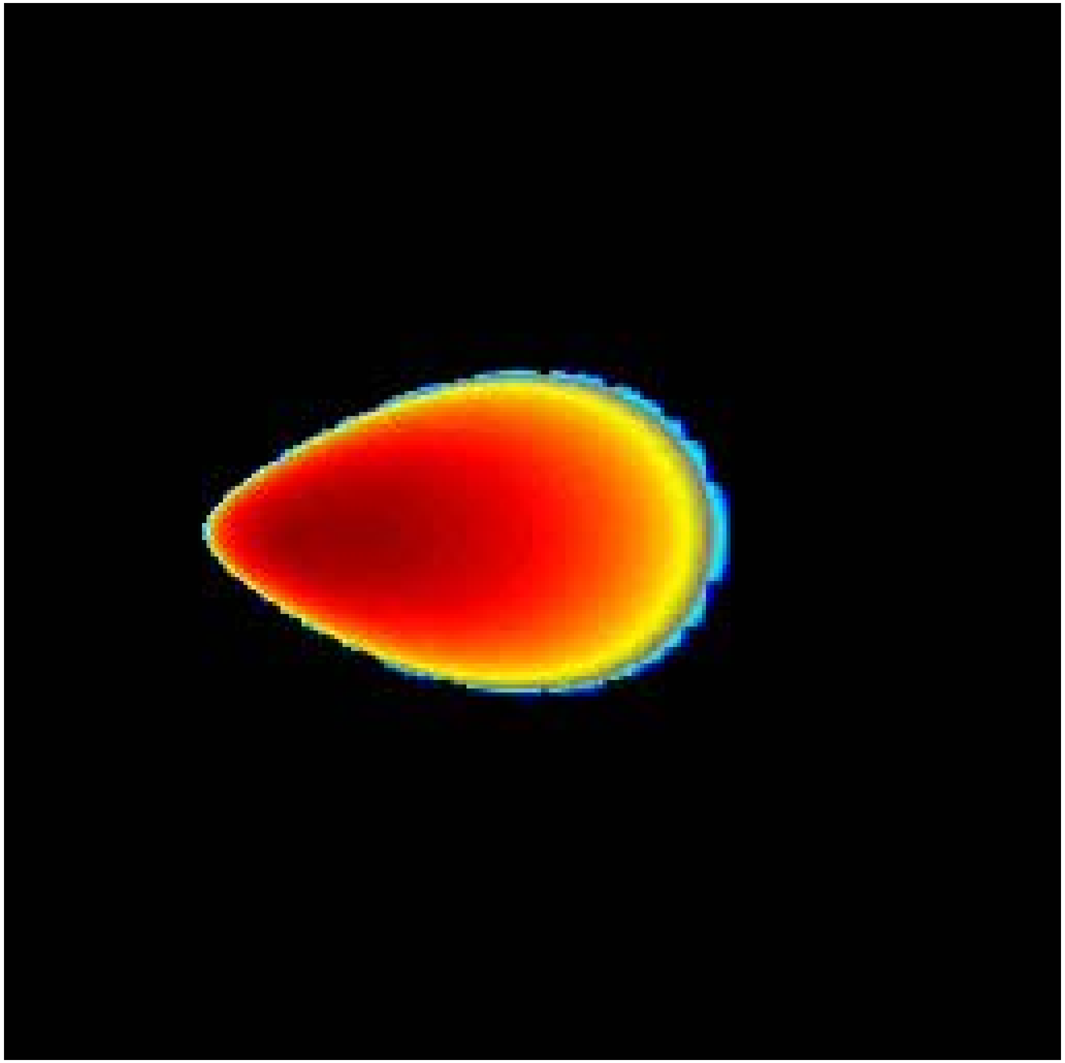
# *SgrA* flare variability and evidence for significant BH spin*



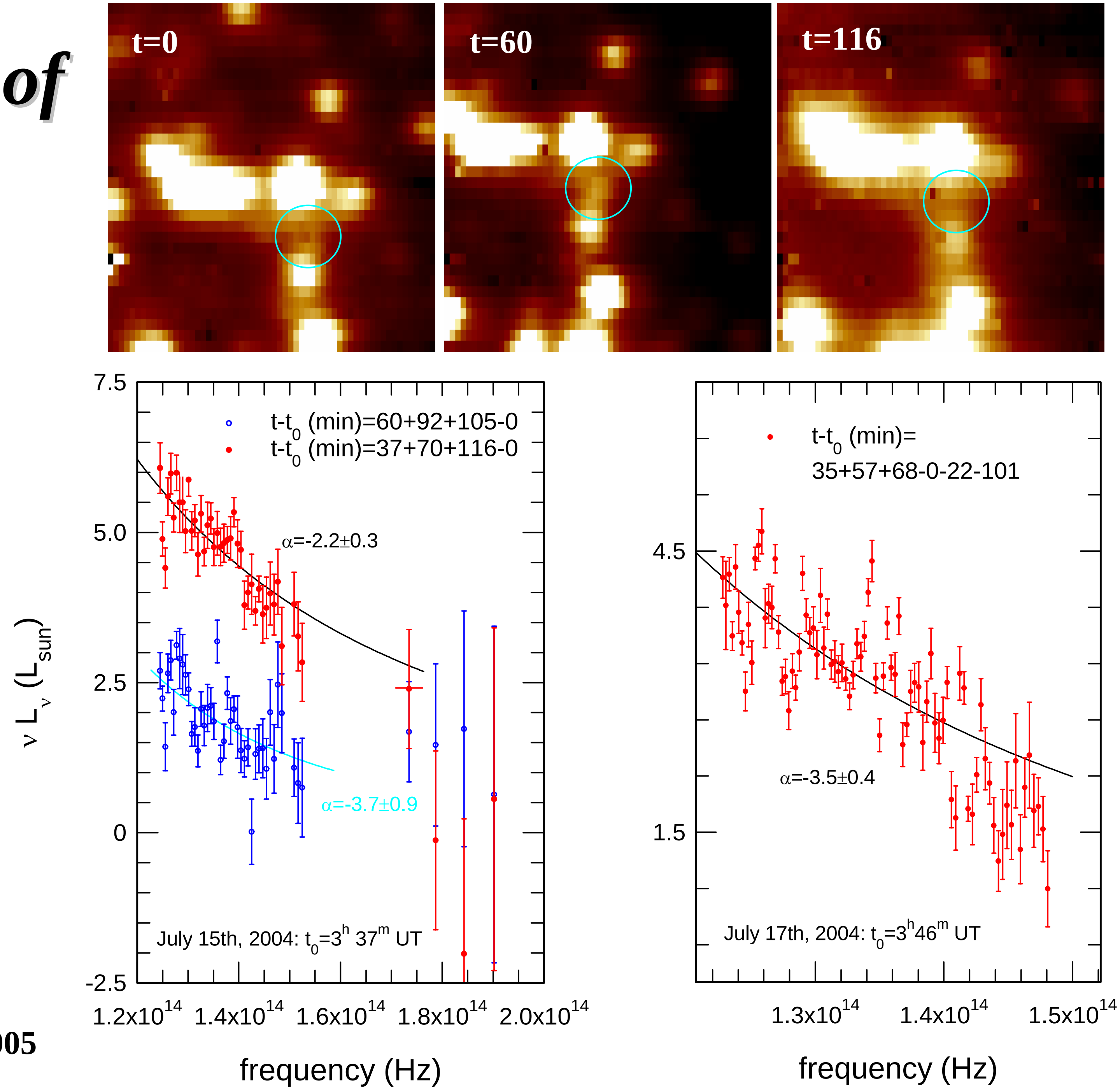

**Genzel et al. 2004, Aschenbach et al. 2004**

# *Kerr MHD accretion disk simulation*



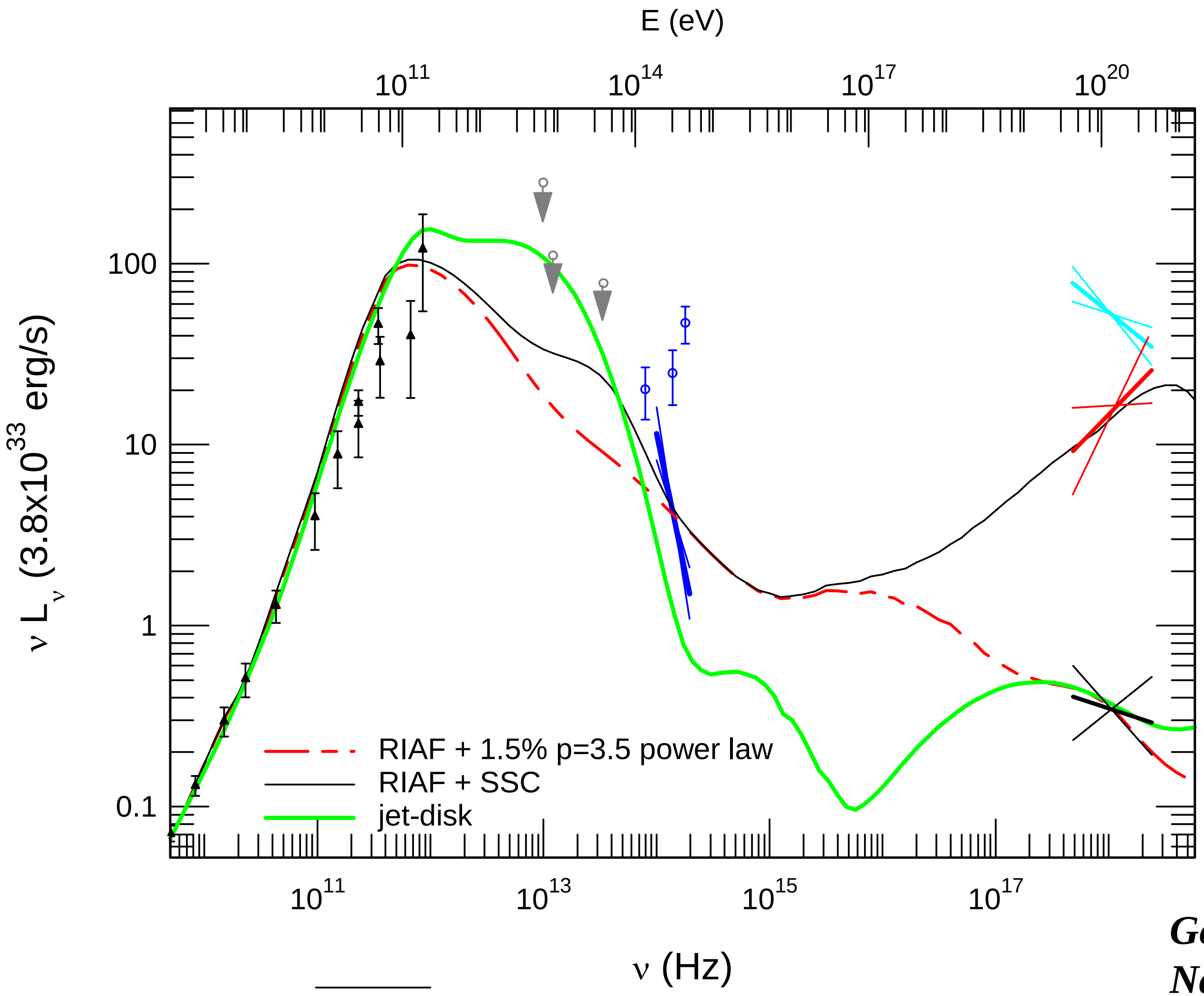
***De Villers, Hawley & Krolik, 2004, Narayan, Quataert, Blandford, Begelman, Balbus, Stone, Gammie 1998-2004***

# *IR SED of flares*




**SINFONI 2004:**
**Eisenhauer et al. 2005**

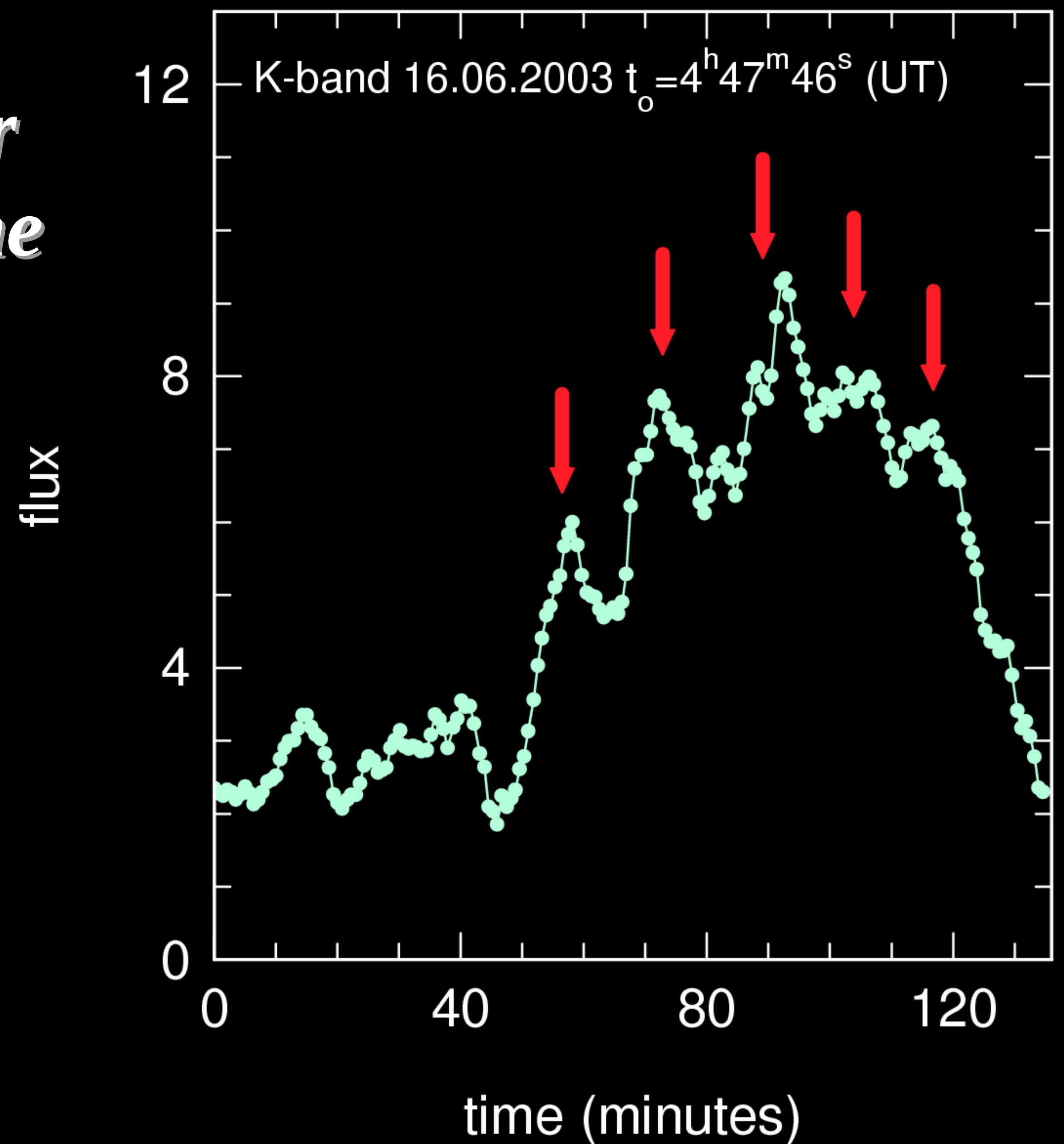
# *SgrA* SED and models*




*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, Eisenhauer et al. 2005***

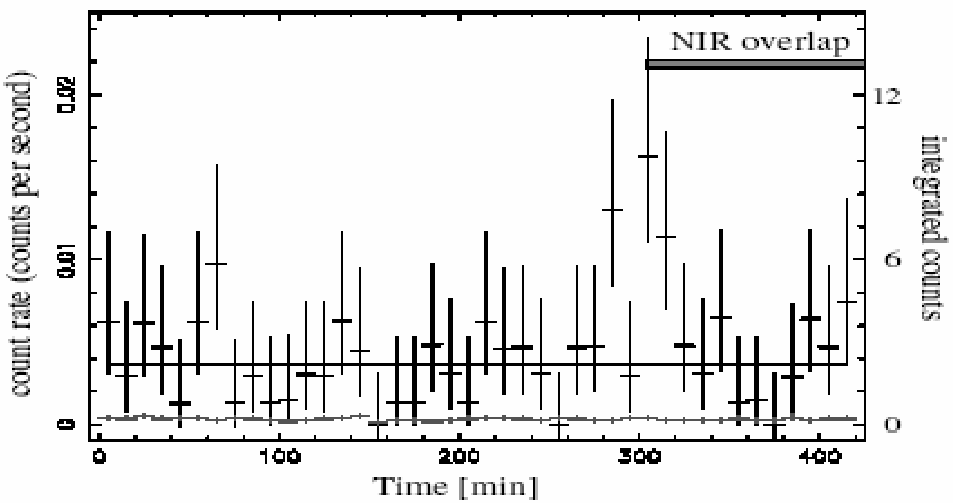
# *Evidence for rotation of the black hole*

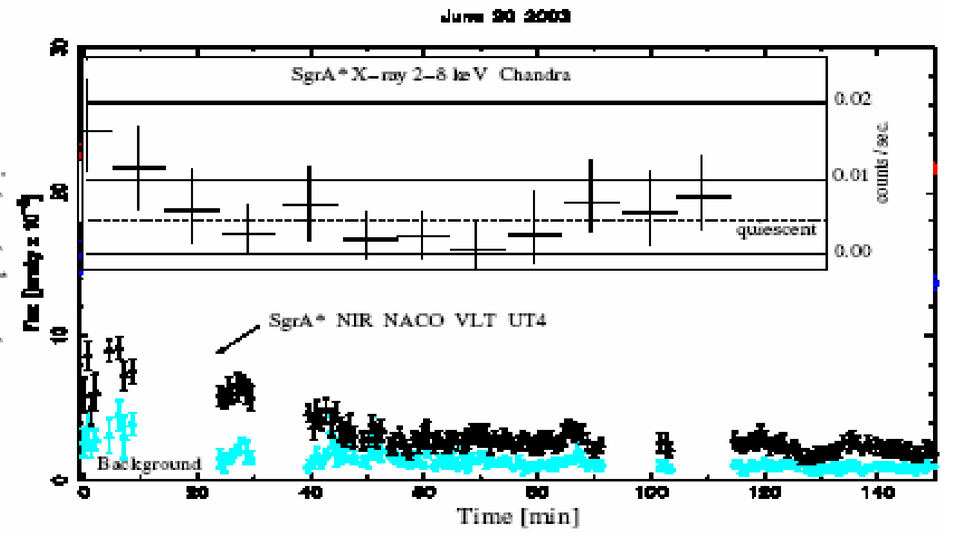



*Genzel et al. 2003, Nature 425, 934*

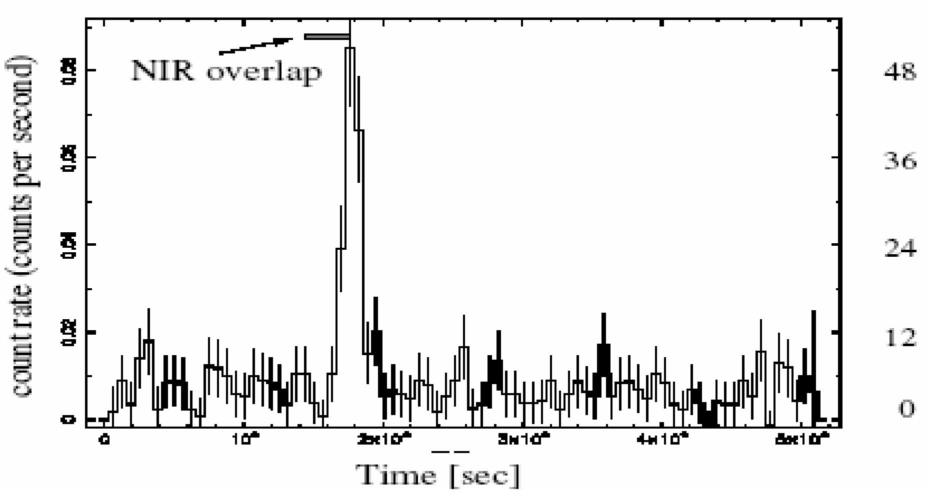
# *Simultaneous X-/IR-Flares*

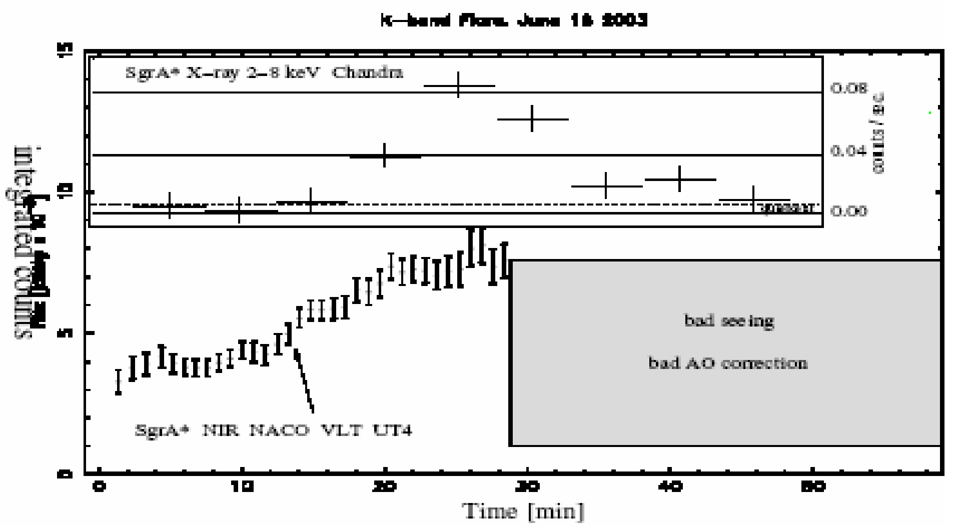
2003



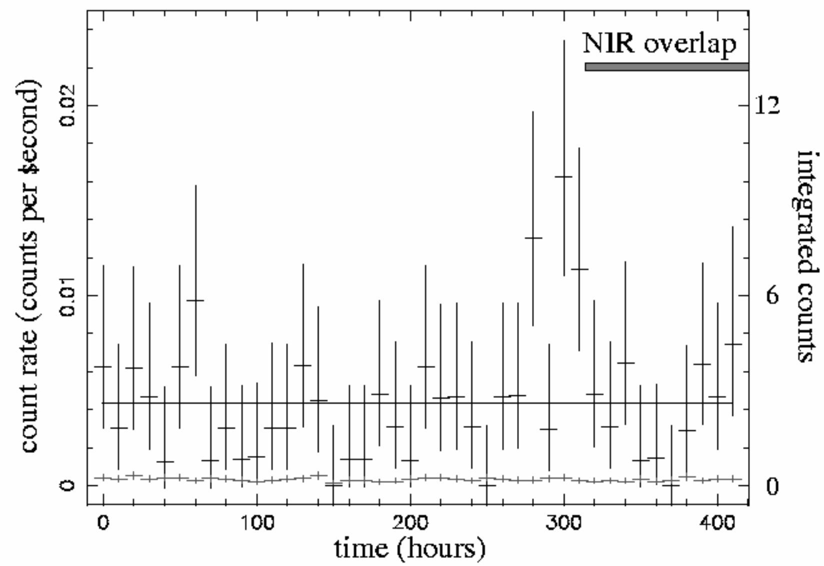



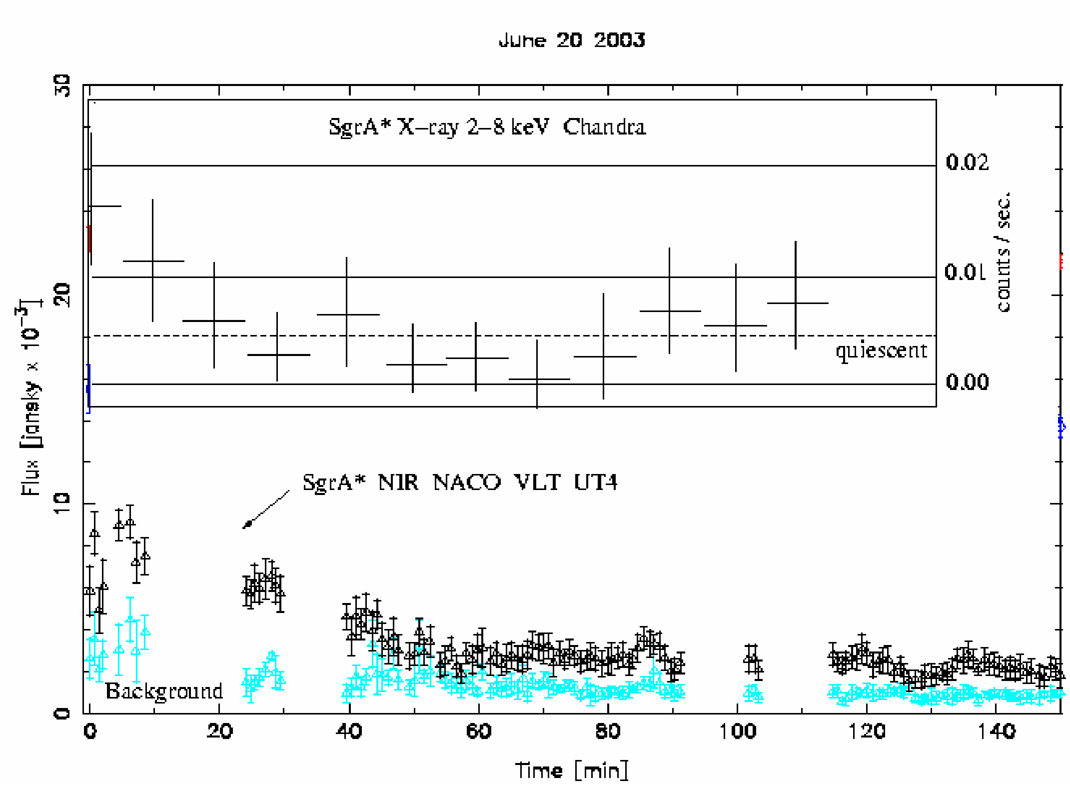

2004



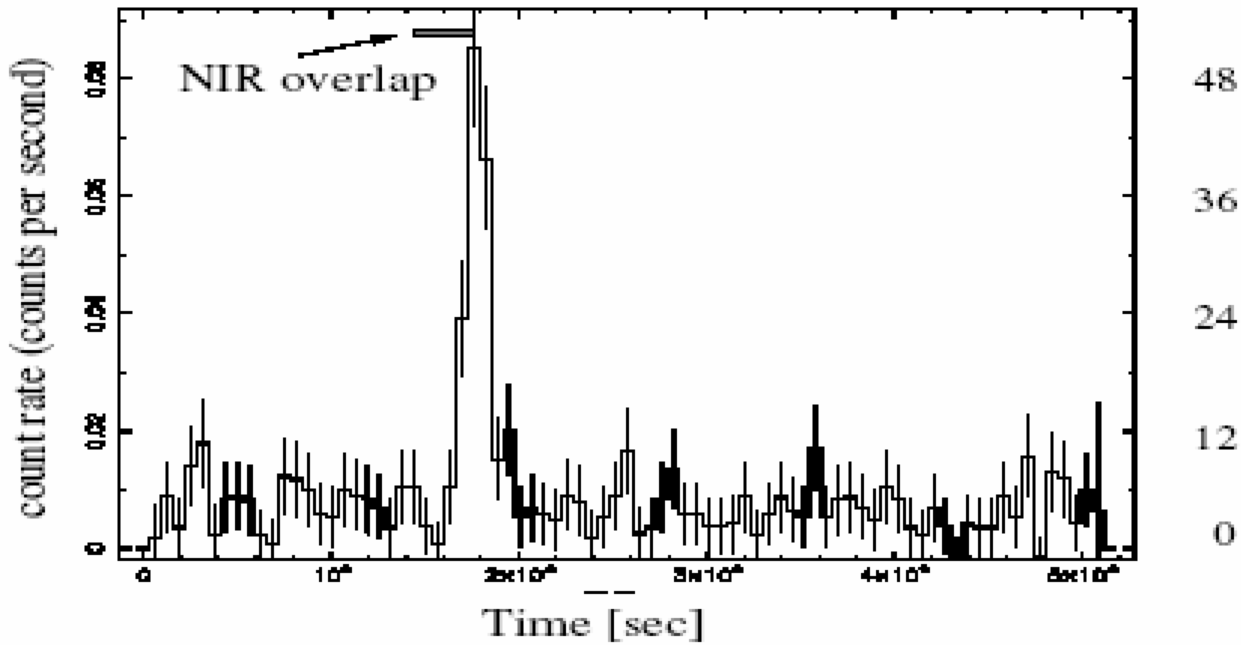




**Eckart et al. 04, 05**

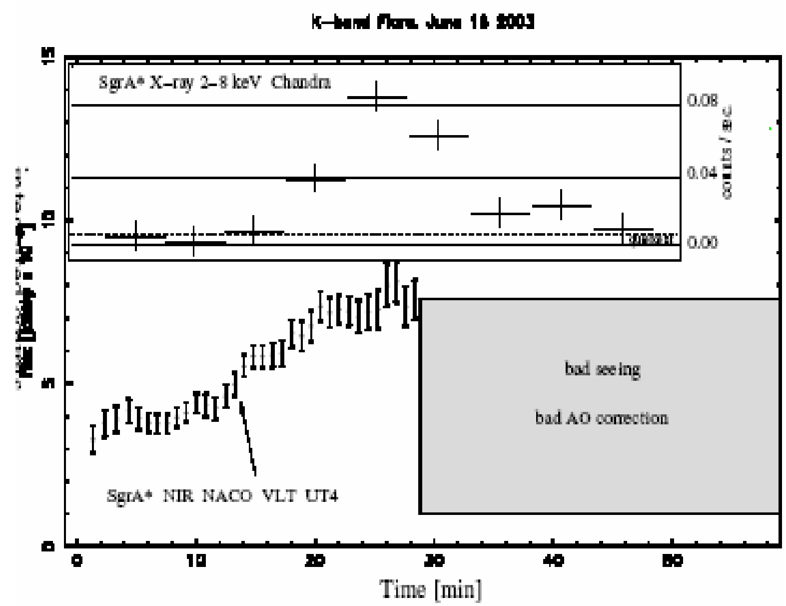

NIR overlap
count rate (counts per second)
integrated counts
time (hours)
0
100
200
300
400
0.02
0.01
12
6


June 20 2003
SgrA* X-ray 2–8 keV Chandra
0.02
0.01
0.00
counts / sec.
quiescent
SgrA* NIR NACO VLT UT4
Background
Flux [jansky x 10$^{-3}$]
Time [min]
0
20
40
60
80
100
120
140
10
30

2004

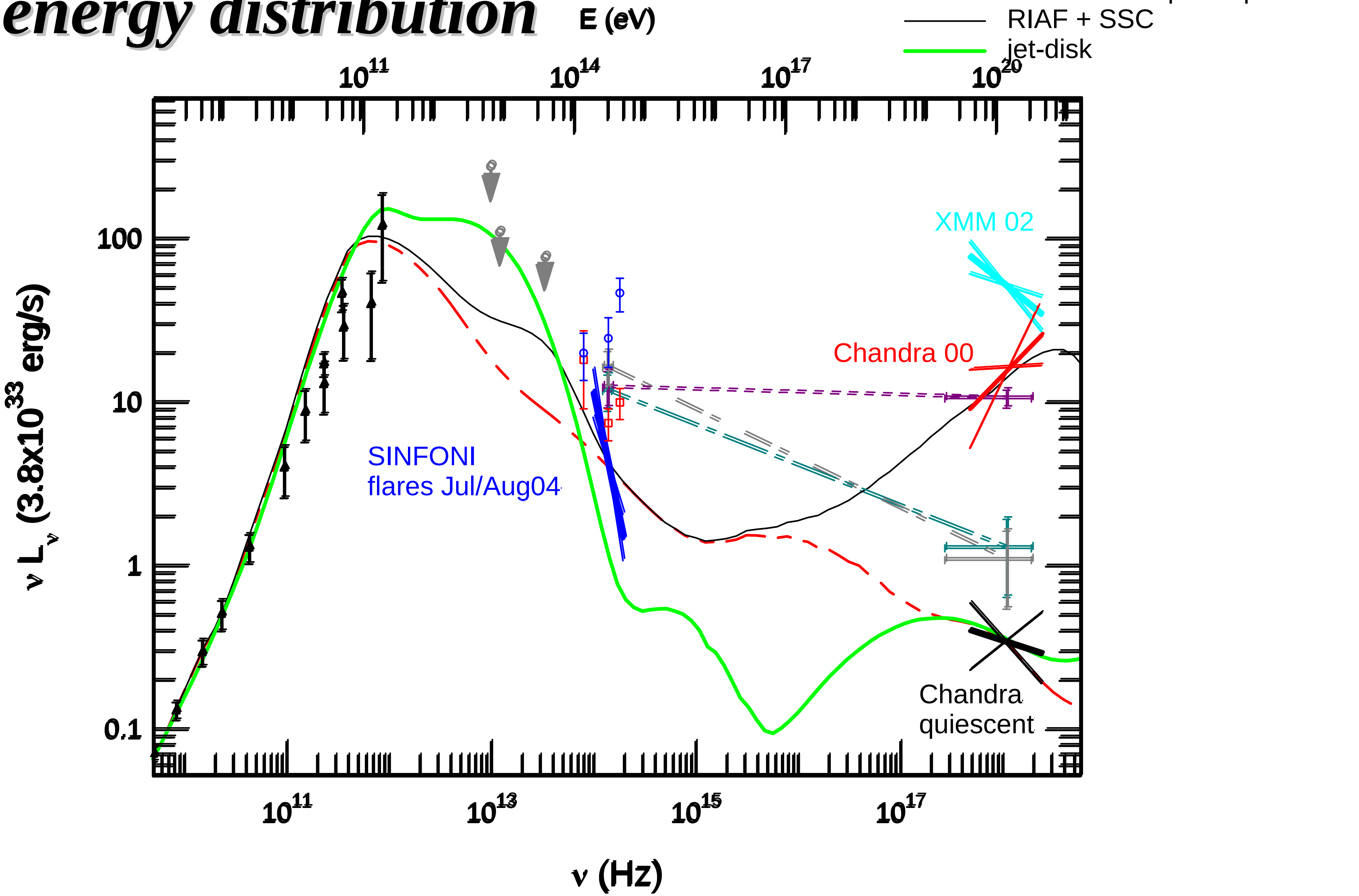


NIR overlap
count rate (counts per second)
Time [sec]
48
36
24
12
0

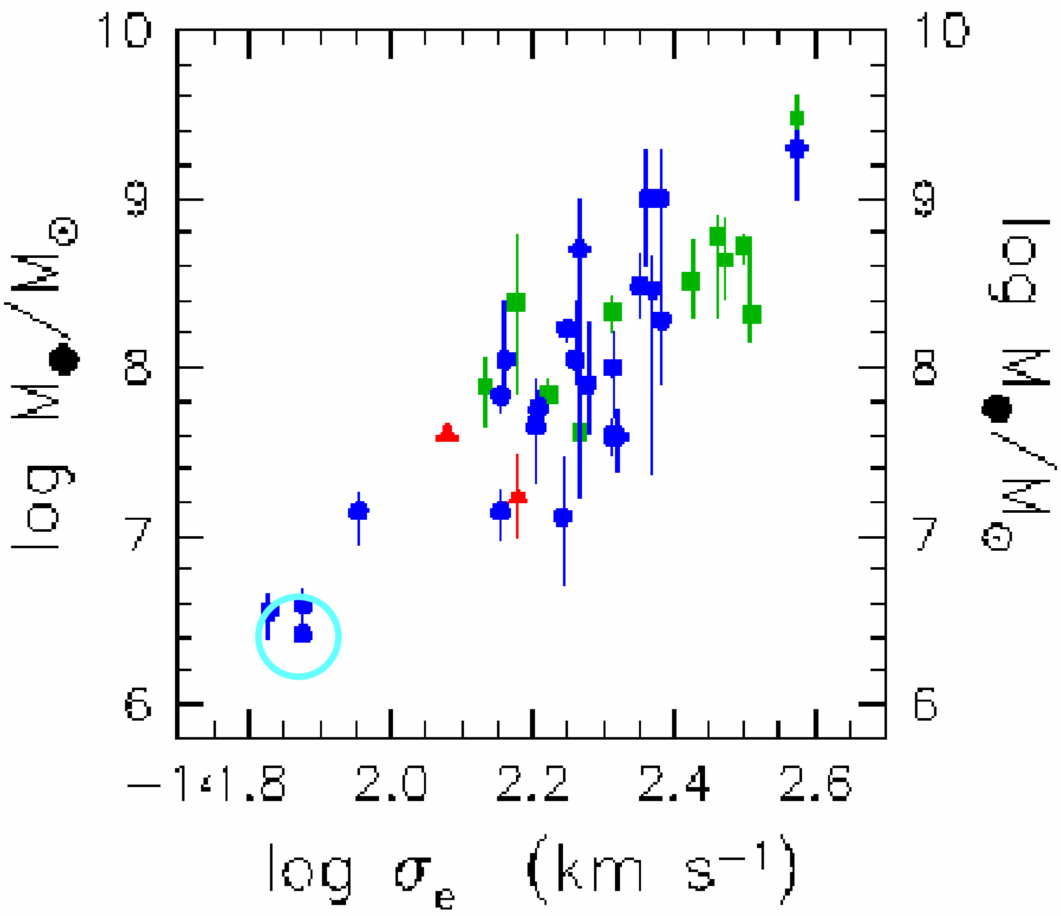
SgrA* X-ray 2–8 keV Chandra
0.08
0.04
0.00
counts / sec
bad seeing
bad AO correction
SgrA* NIR NACO VLT UT4
Time [min]

# overall SgrA* spectral energy distribution



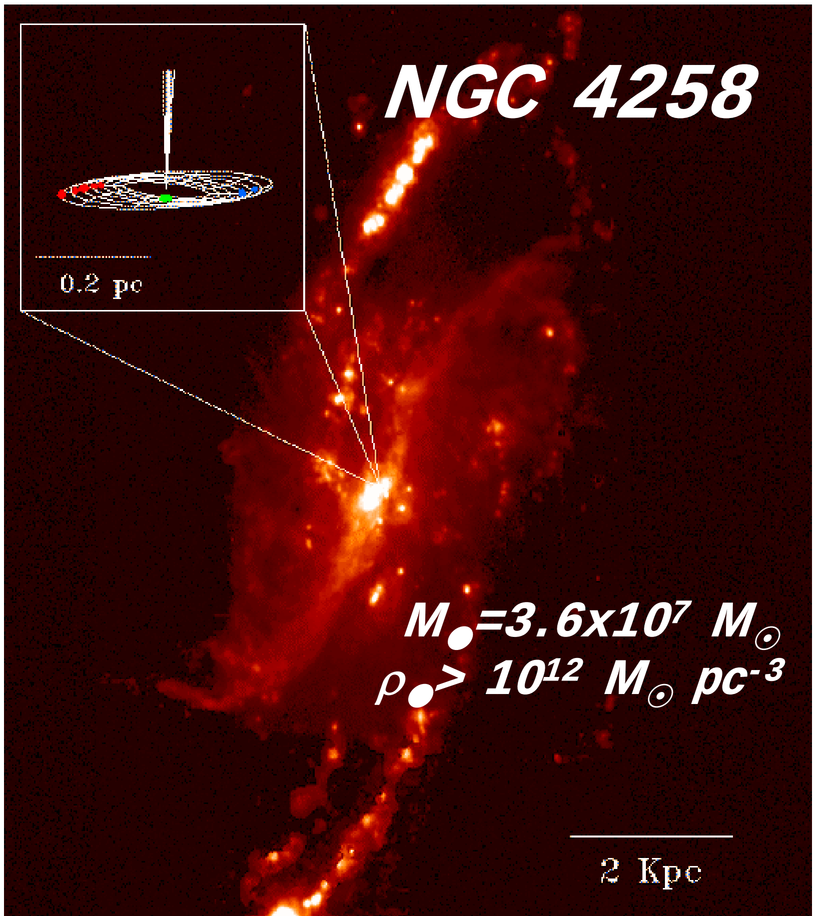

**Falcke et al. 1999, Zhao et al. 2004, Markoff et al. 2001, Genzel et al. 2003, Ghez et al. 2004,Eisenhauer et al. 2005, Baganoff et al. 2001, 2003, Porquet et al. 2003, Eckart et al. 2004, 2005, Yuan et al. 2001, 2003, 2004, Liu et al. 2004**

# *Black hole demographics*



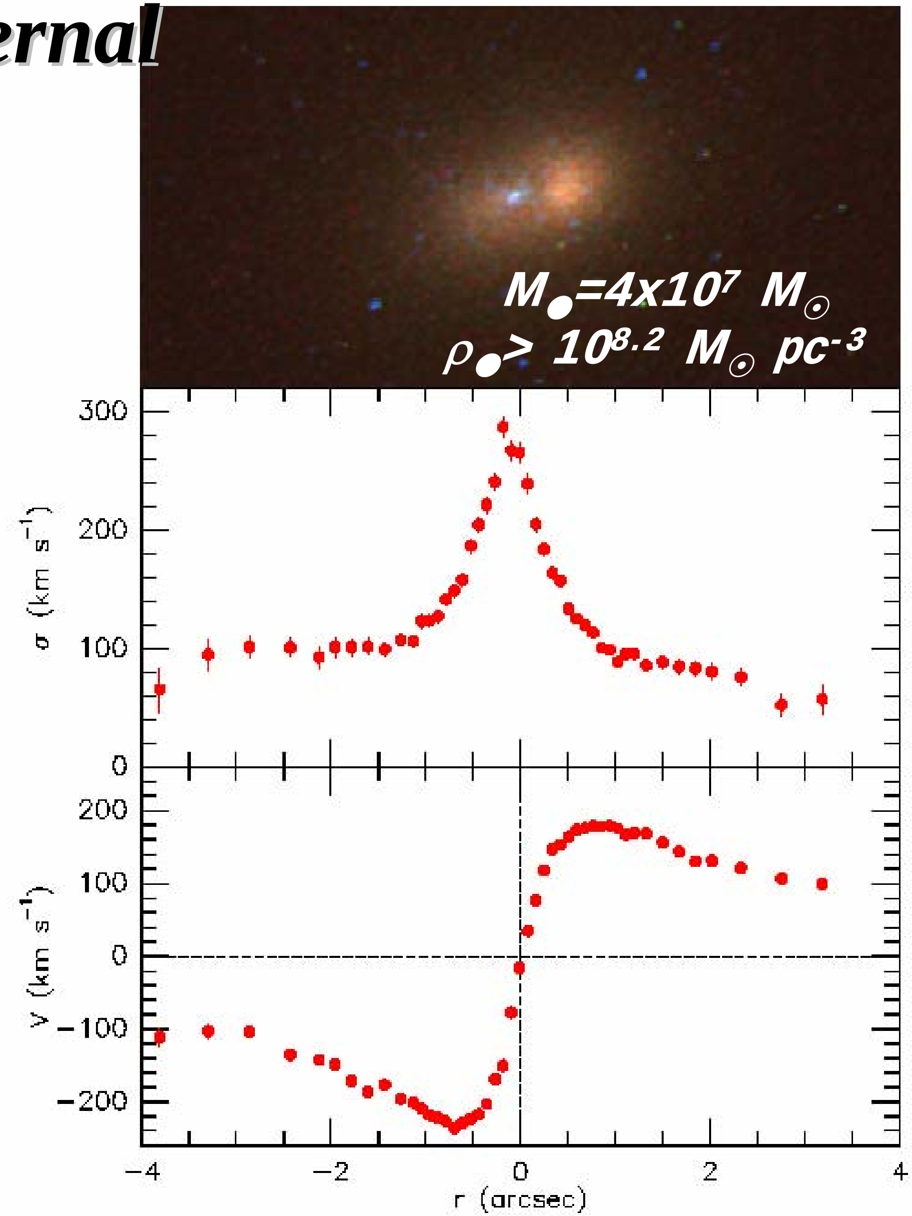

***Kormendy & Ho 2001***

# Dark central masses in external galaxies



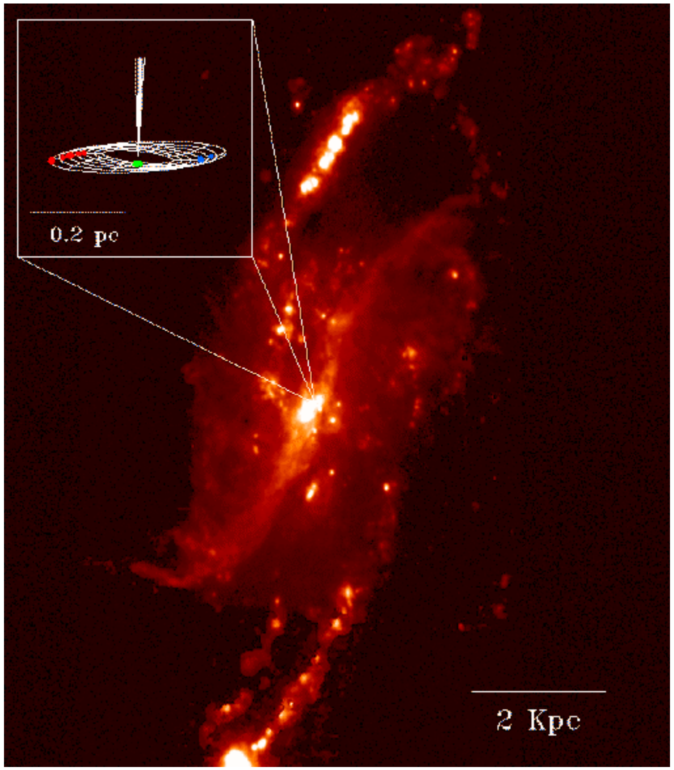

Greenhill, Myoshi, Moran et al 1995-97

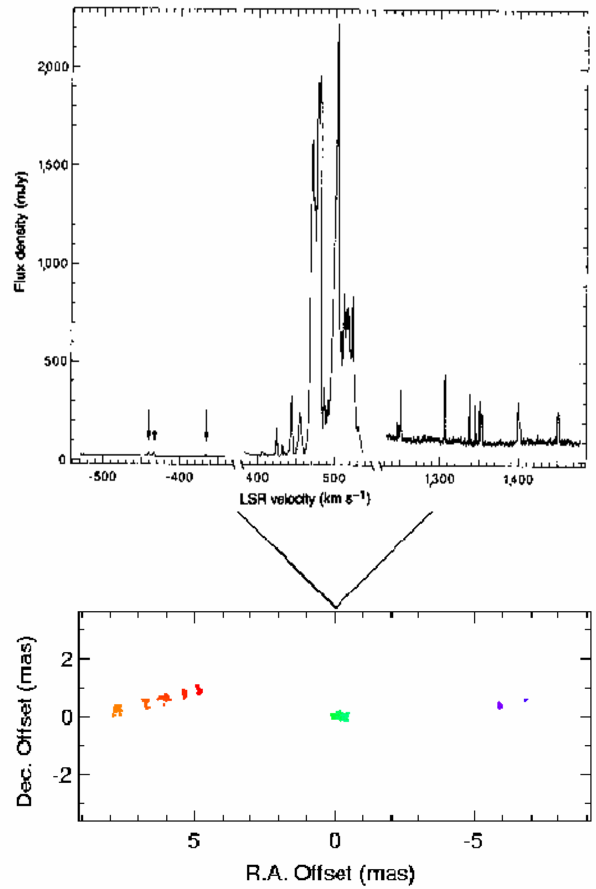
M31

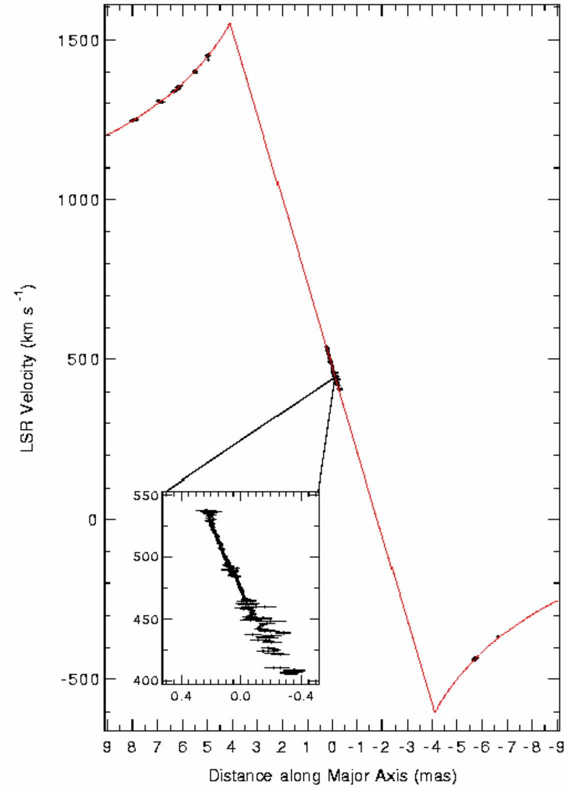



Bacon, Bender, Kormendy, Richstone, Tonry, van der Marel, et al. 1985-2000

# *Dark central masses in external galaxies: $H_2O$ maser disk in NGC 4258*



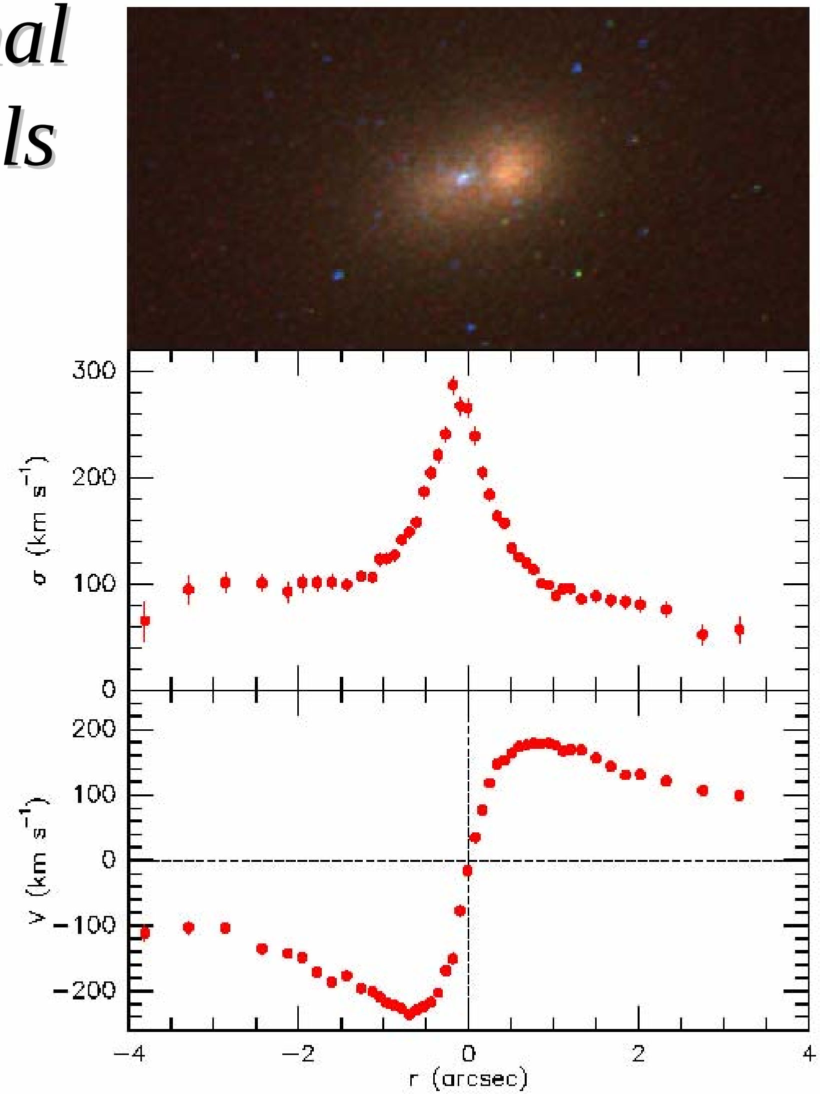

***$M_\bullet = 3.6 \times 10^7\ M_\odot$***

***$\rho_\bullet > 10^{12}\ M_\odot\ pc^{-3}$***

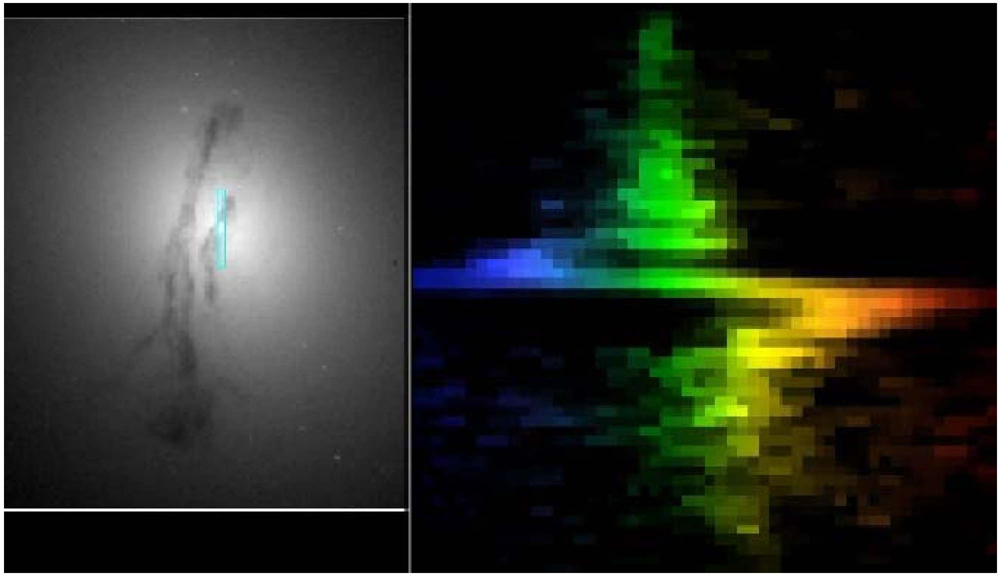
***Greenhill, Herrnstein, Myoshi, Moran et al 1995-97 (e.g. Nature 373, 127)***

# Dark central masses in external galaxies: bulges and ellipticals

**M31** **$M_\bullet = 3\times10^7\ M_\odot$**



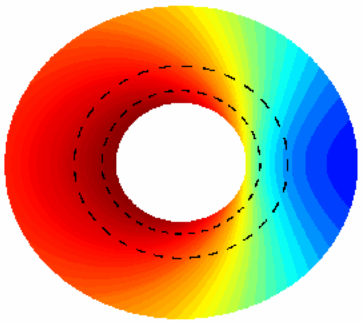

**M84**



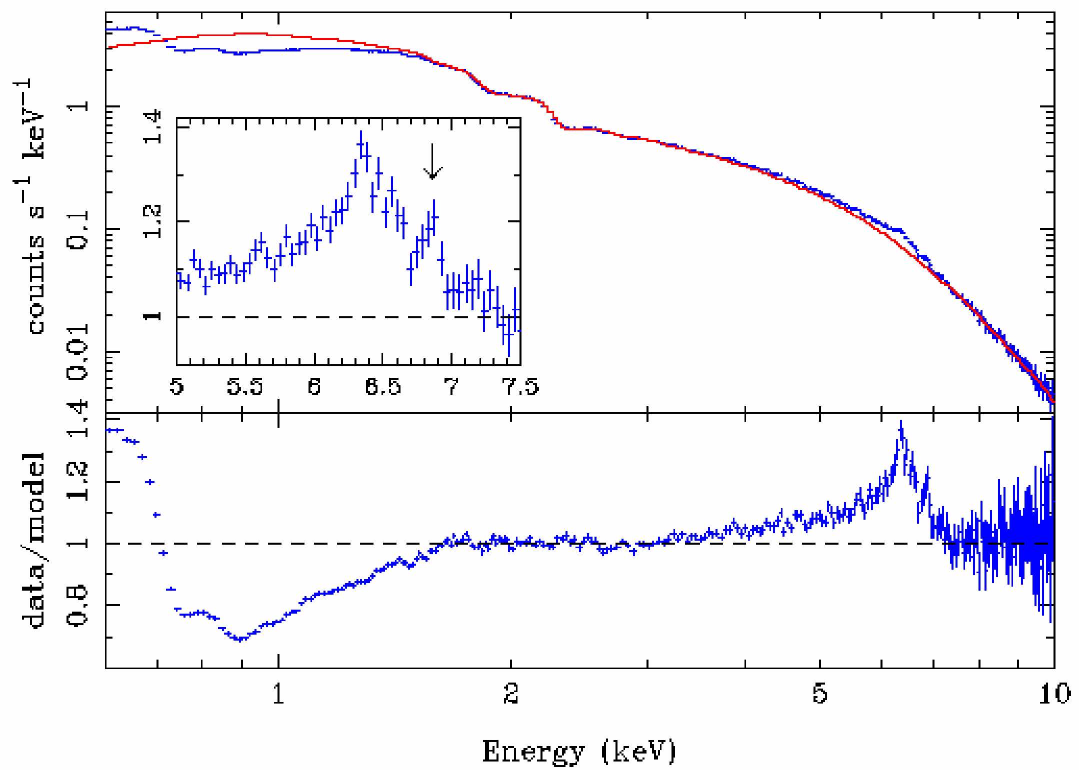
**$M_\bullet = 2\times10^9\ M_\odot$**

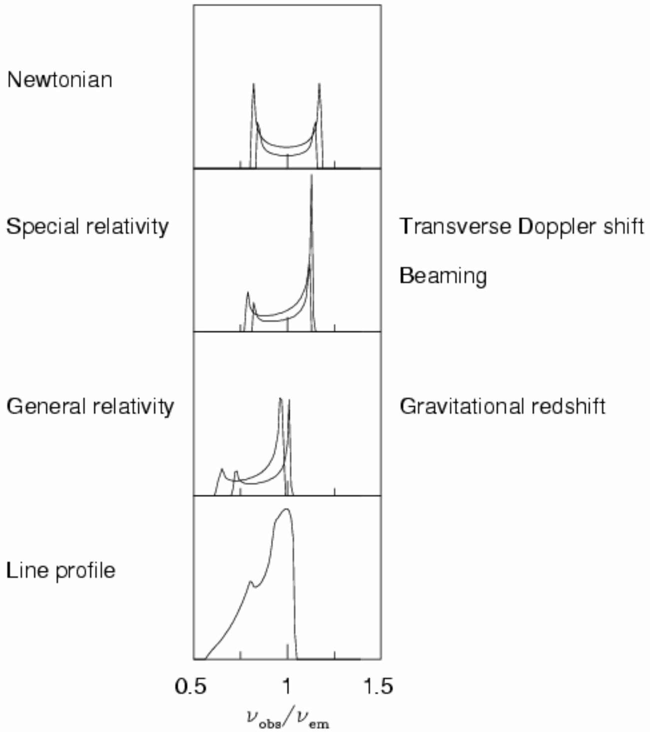
***Bacon, Bender, Bower, Dressler, Kormendy, Richstone, Tonry, van der Marel, et al. 1985-2000***

# X-ray spectroscopy: relativistic accretion disks



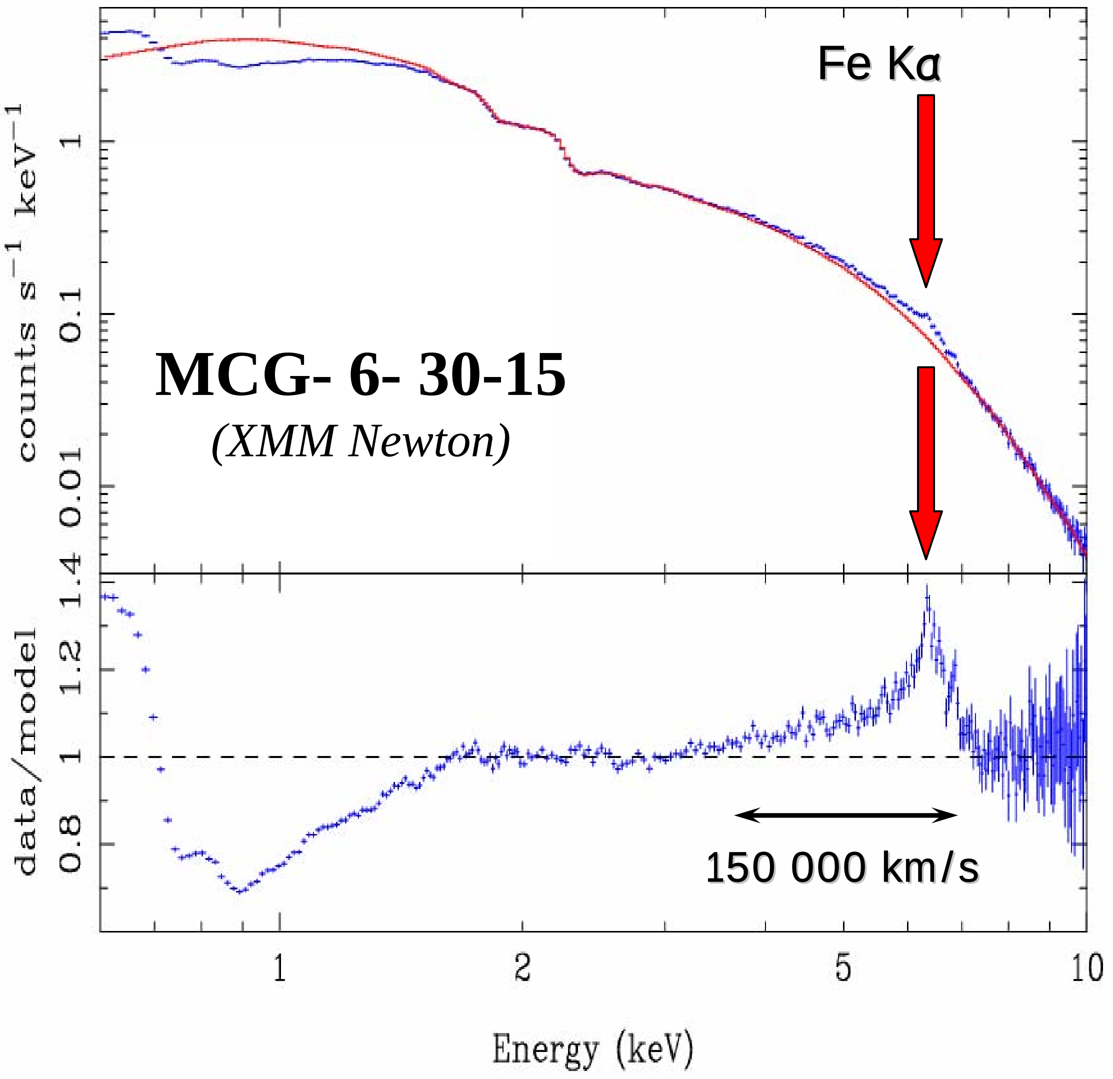
**XMM-Newton MCG-6-30-15**




*Tanaka et al. 95, Nandra et al. 97, Ballantyne and Fabian 2001, Wilms et al. 2001, Lee et al. 2000, Elvis 2000, Fabian et al. 2002*

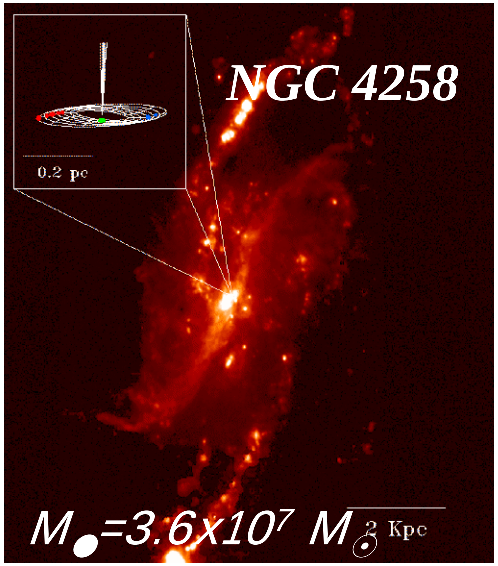
# *Relativistic accretion disks in external galaxies*

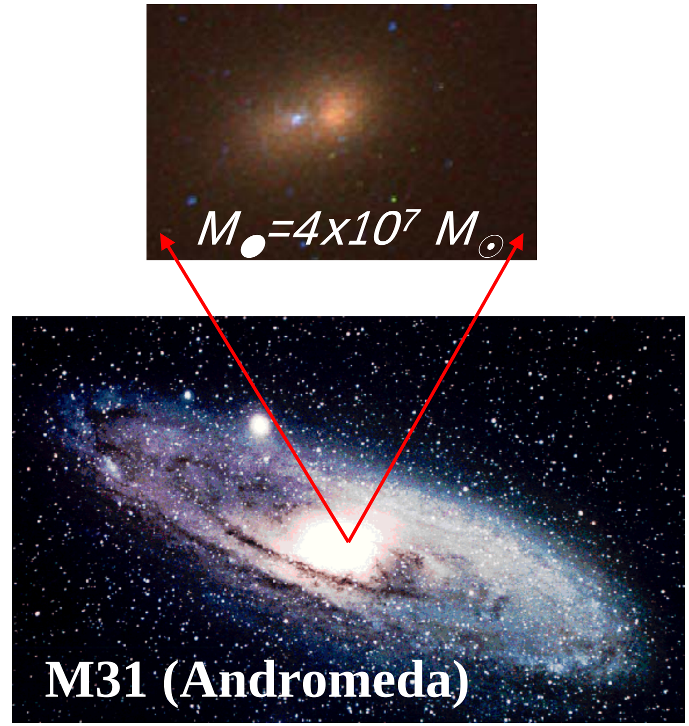


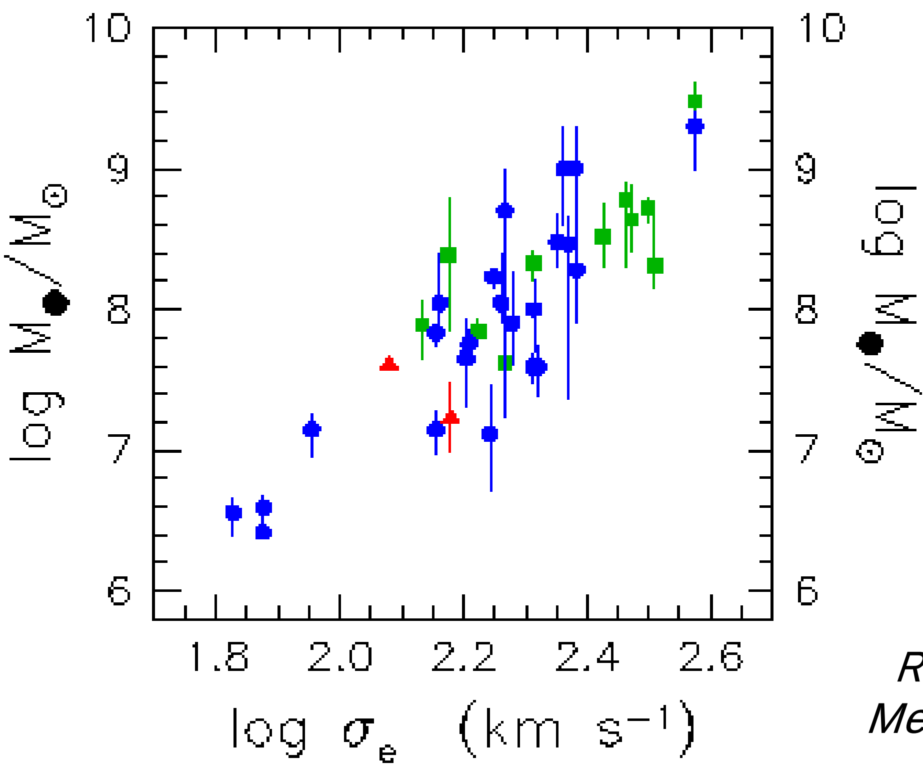

*Tanaka, Nandra et al 1997-99*

*Fabian et al. 2002*

# Black Holes in the Local Universe

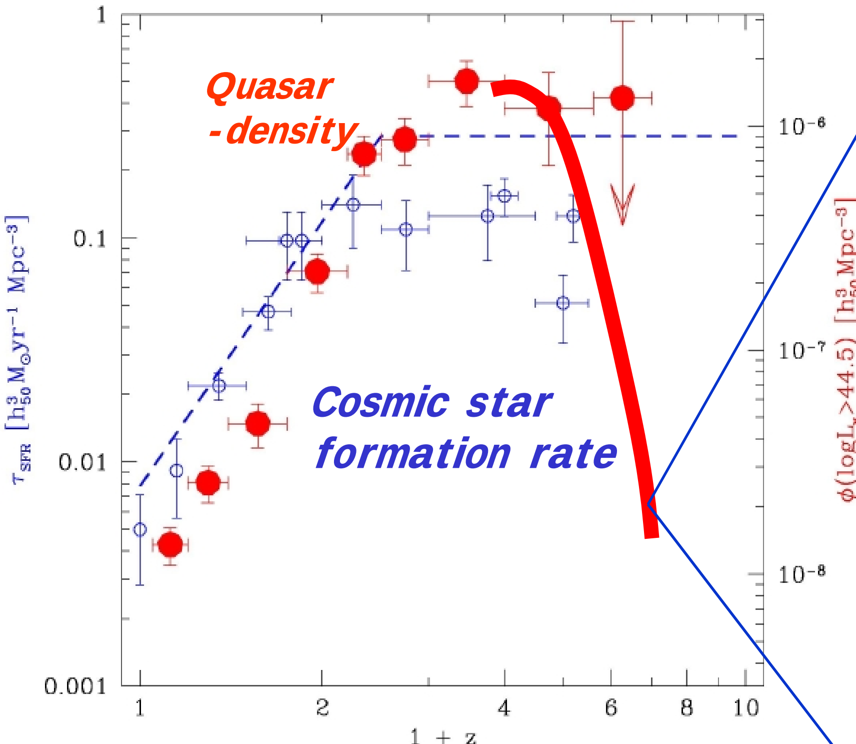


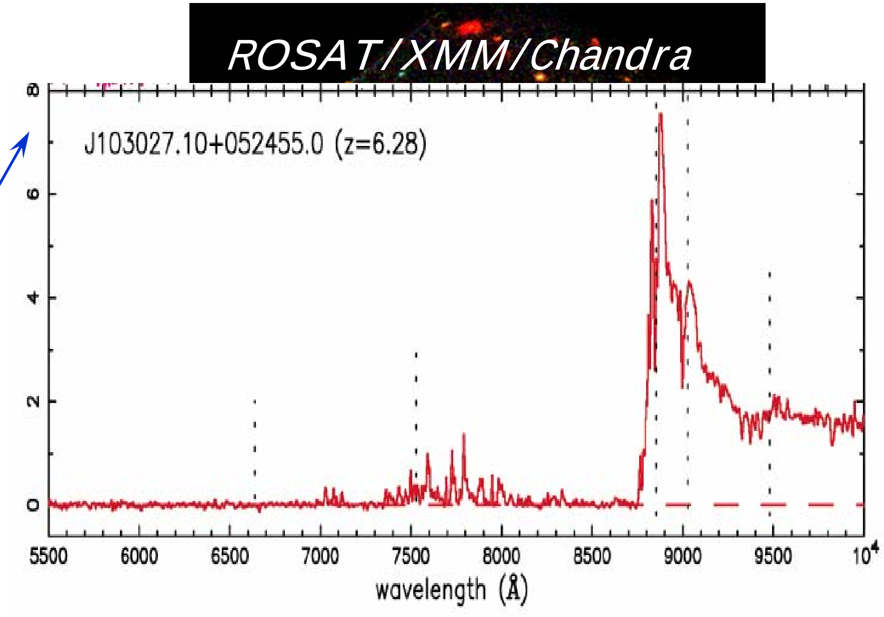




*Miyoshi et al. 1995, Kormendy & Richstone 1995, Gebhardt et al. 2000, Merritt und Ferrarese 2000, Tremaine et al. 2002, Bender et al. 2002, 2005*

# Black Holes & Galaxy Formation



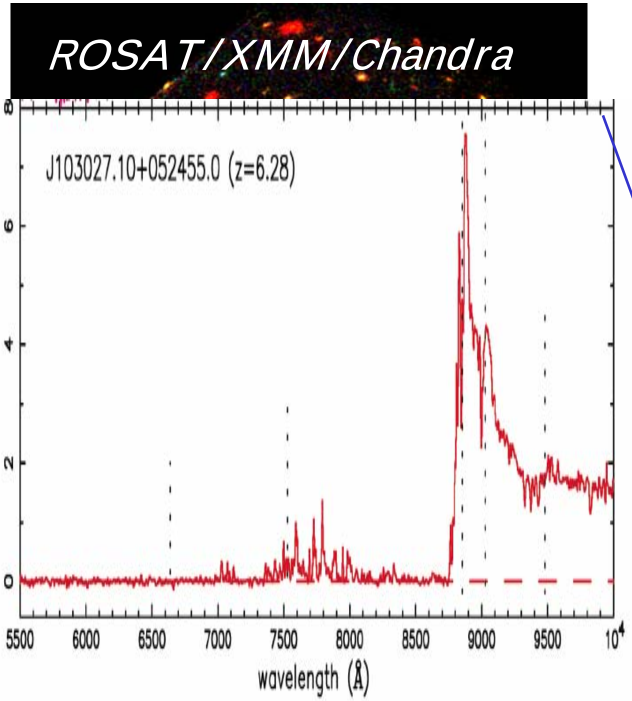




$M_{BH}$ ~ a few $10^9$ $M_\odot$ at t~800 Myrs after Big Bang!

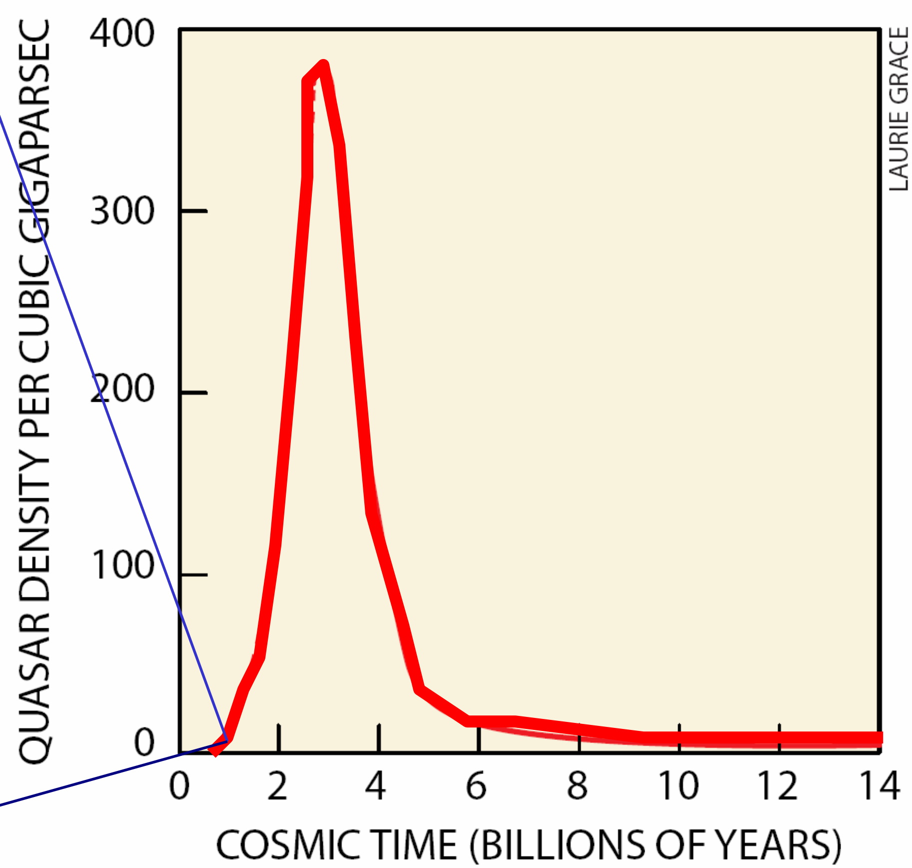
Fan et al. 2001, Becker et al. 2002

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

# Black Holes & Galaxy Formation

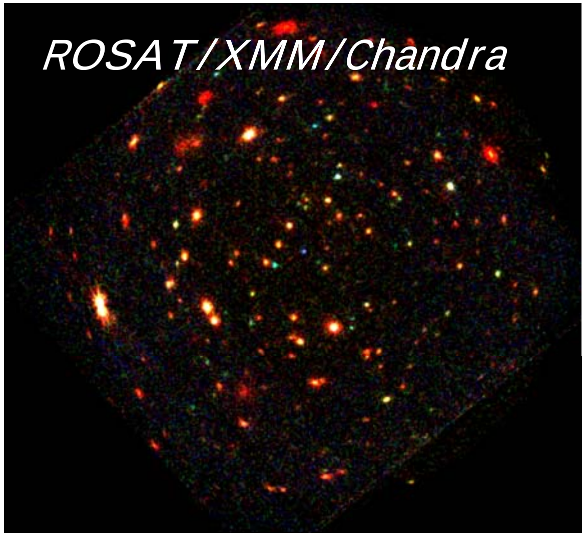


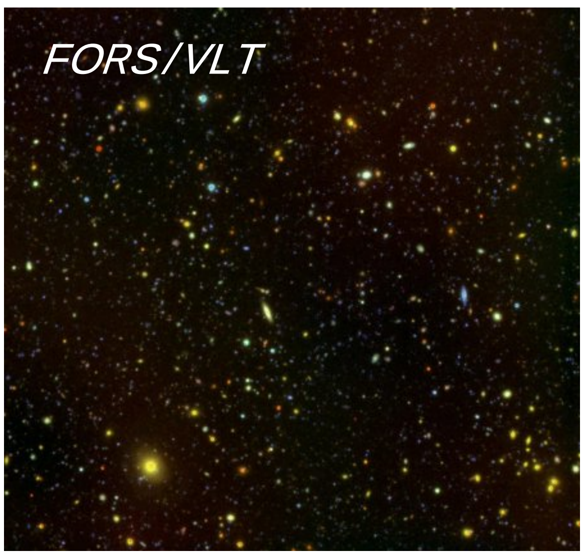


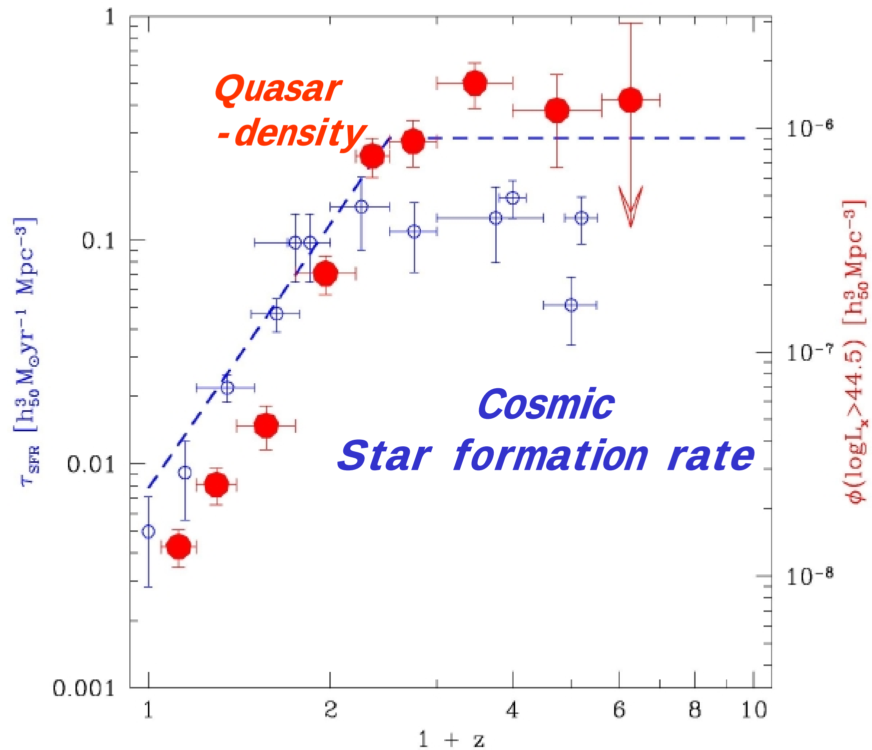



*Hasinger et al. 1999, 2002, Steidel et al. 1999,*
*Bender und FORS Team 2002, Osmer 2003, Fan et al. 2002*

# Black Holes and Galaxy Formation




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

# *Nearby Black Holes as Ashes of the QSO Era*

$$\rho_{QSO} = \left(\int_0^\infty dz \int_0^\infty \left(dL \frac{dn(L,z)}{dL} L\right) \frac{dt}{dz}\right) / (\varepsilon c^2) \approx \frac{10^4}{\varepsilon}\ \mathrm{M}_\odot\ \ \mathrm{Mpc}^{-3}$$

$$\rho_{bulge,early} = 2x10^8\ \mathrm{M}_\odot\ \ \mathrm{Mpc}^{-3}$$

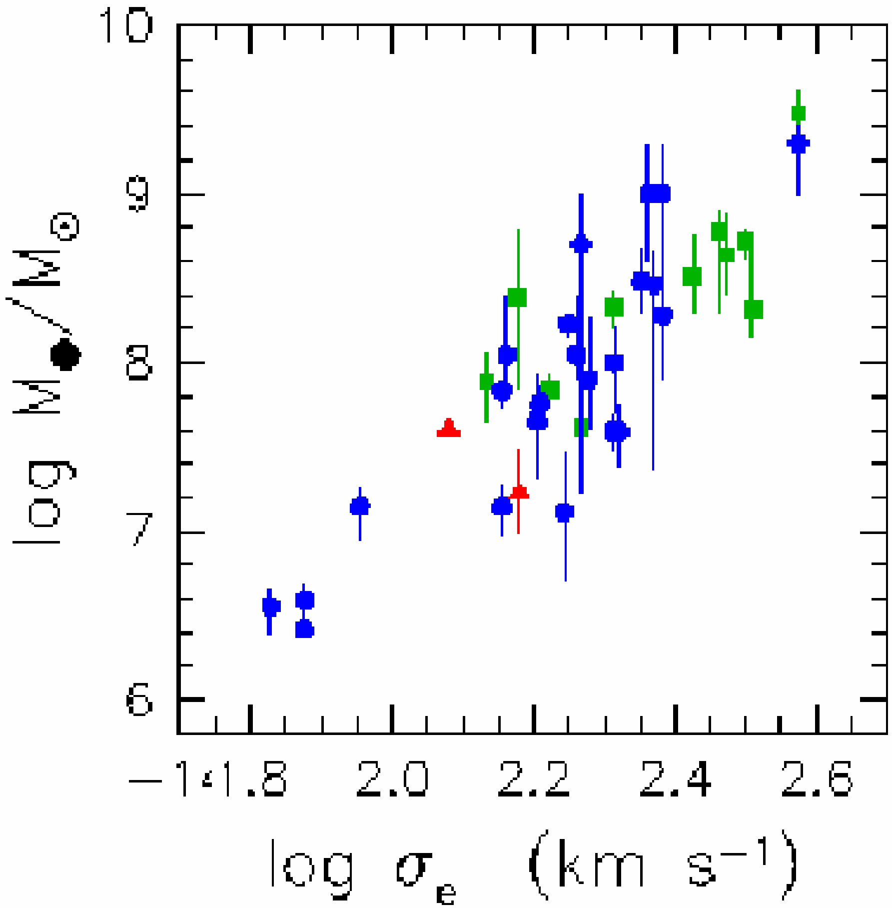
$$< \varepsilon_{accretion} > = 5x10^{-5} \frac{\rho_{bulge}}{\rho_\bullet} \approx 5x10^{-5}\, x\ 600 \approx 3x10^{-2}$$

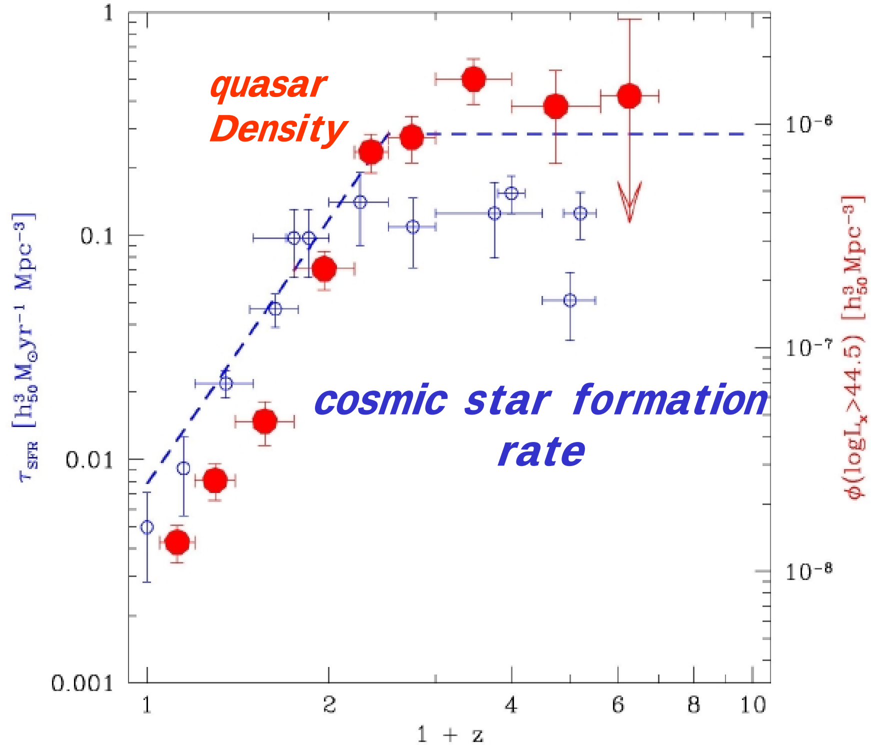
$$\varepsilon_{\bullet,theoretical} \approx 0.1$$

*Gebhardt et al. 2000*

*e.g. Soltan et al. 1982, Yu & Tremaine 2002*

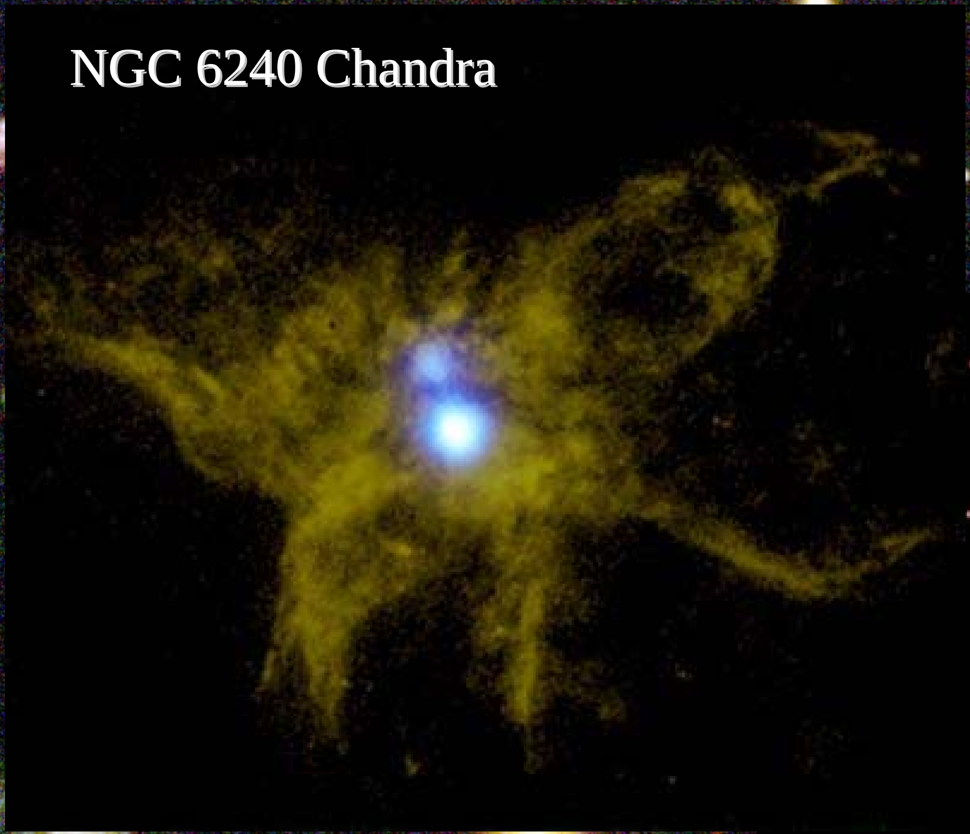
# Black Holes and Galaxy formation

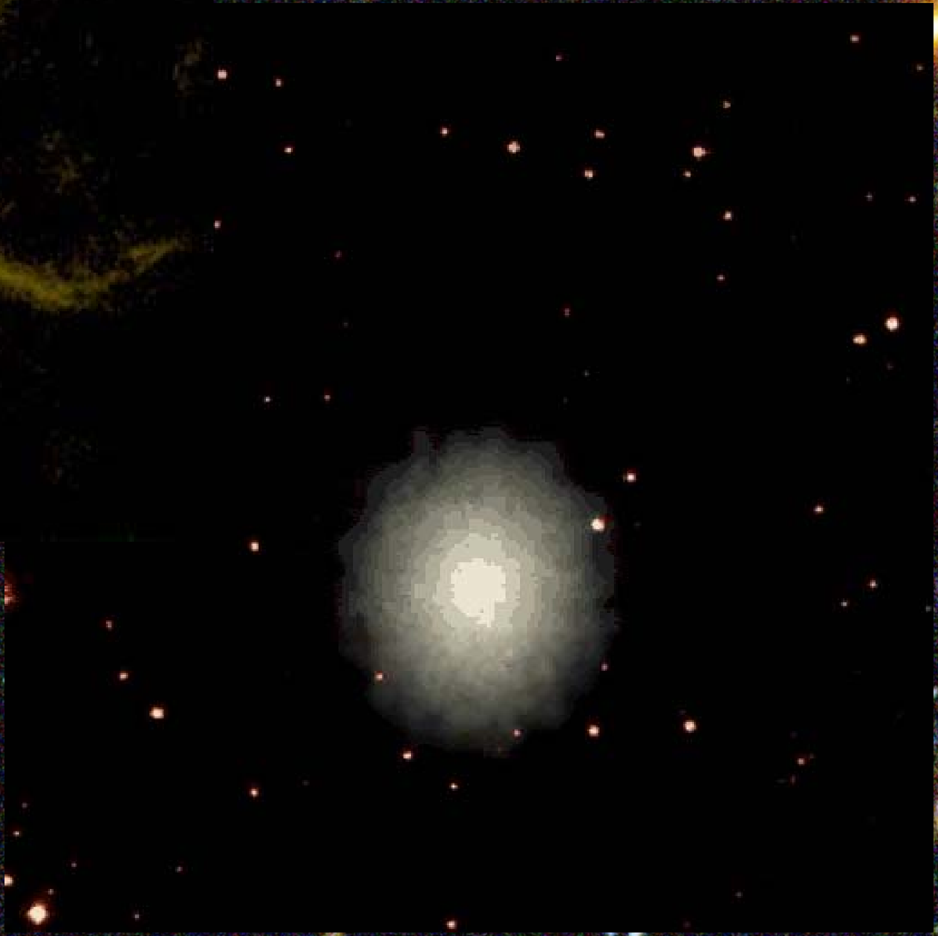



*Magorrian et al. 1998, Kormendy and Ho 2000, Gebhardt et al. 2000, Merritt and Ferrarese 2000, Hasinger et al. 1999, Steidel et al. 1999*

# Formation of Quasars



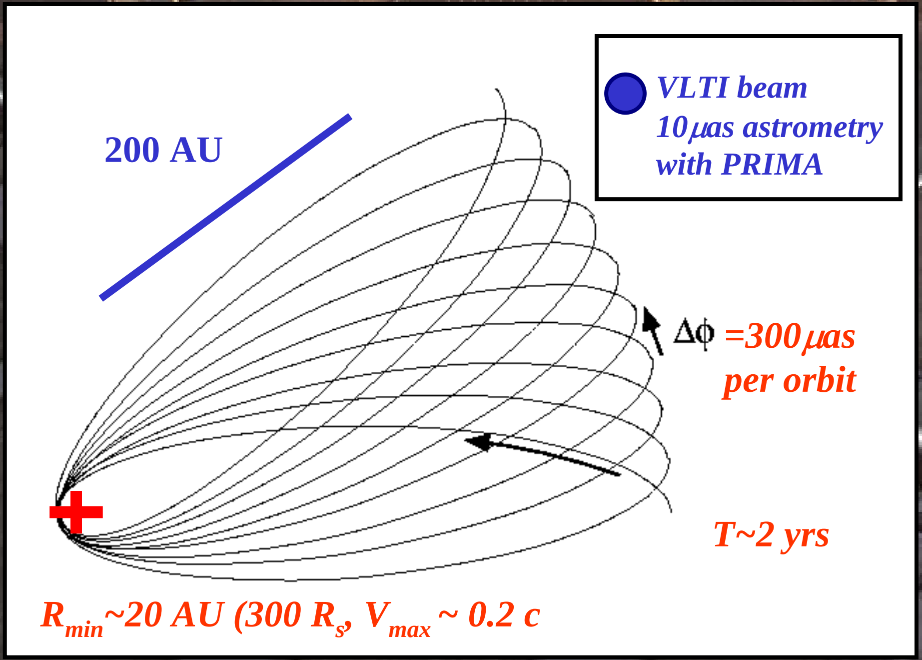



*Springel 2001*
*Binary black hole: Komossa & Hasinger 2003*

# *The future*


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

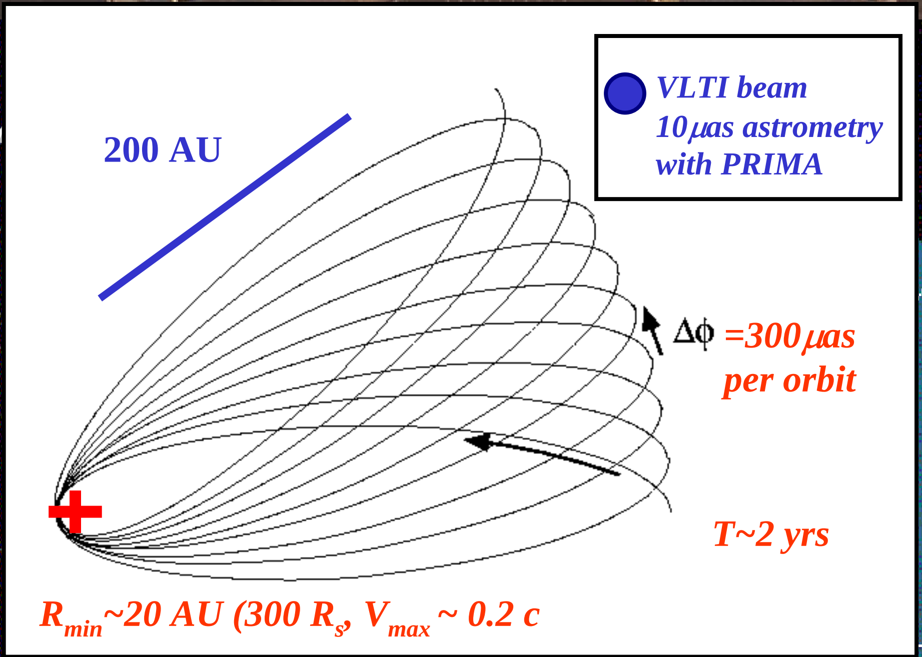
# *the future*


ESO-VLT(I)

# *the future*

‘shadow’ of the Black Hole


*ESO-VLT(I)*

# *Galactic center summary*

- ***SgrA* is a ~3 million solar mass black hole, beyond any reasonable doubt***
- ***mm/IR/X-ray emission from BH accretion zone: probably synchrotron/self-Compton emission***
- ***QPOs of flares: a≥0.5 ?***
- ***detection of power-law stellar cusp around BH***
- ***two disks of young massive stars formed ~5Myrs ago: cloud infall and star formation in accretion disk?***
- ***cusp stars at < 22 light days : paradox of youth***