

The Paradoxes of Massive Black Holes: A Case Study in the Milky Way

SINFONI in the Galactic Center: young stars and IR flares in the central light month

ApJ, scheduled for 20 July 2005, v628

F.Eisenhauer, R.Genzel, T.Alexander, R.Abuter,
T.Paumard, T.Ott, S.Gillessen, S.Trippe, A.Eckart,
R.Schödel, S.Zucker et al.

Max-Planck-Institut für extraterrestrische Physik

Weizmann Institute of Science

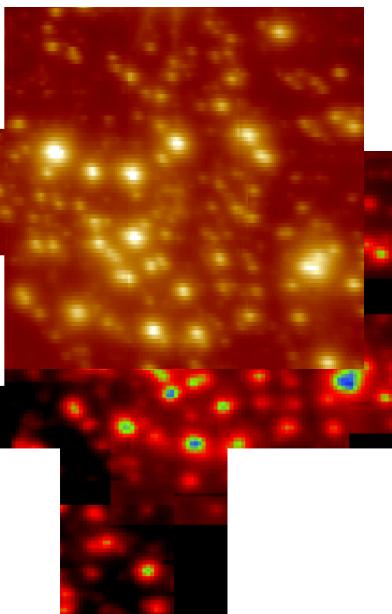
Universität Köln

University of California Berkeley

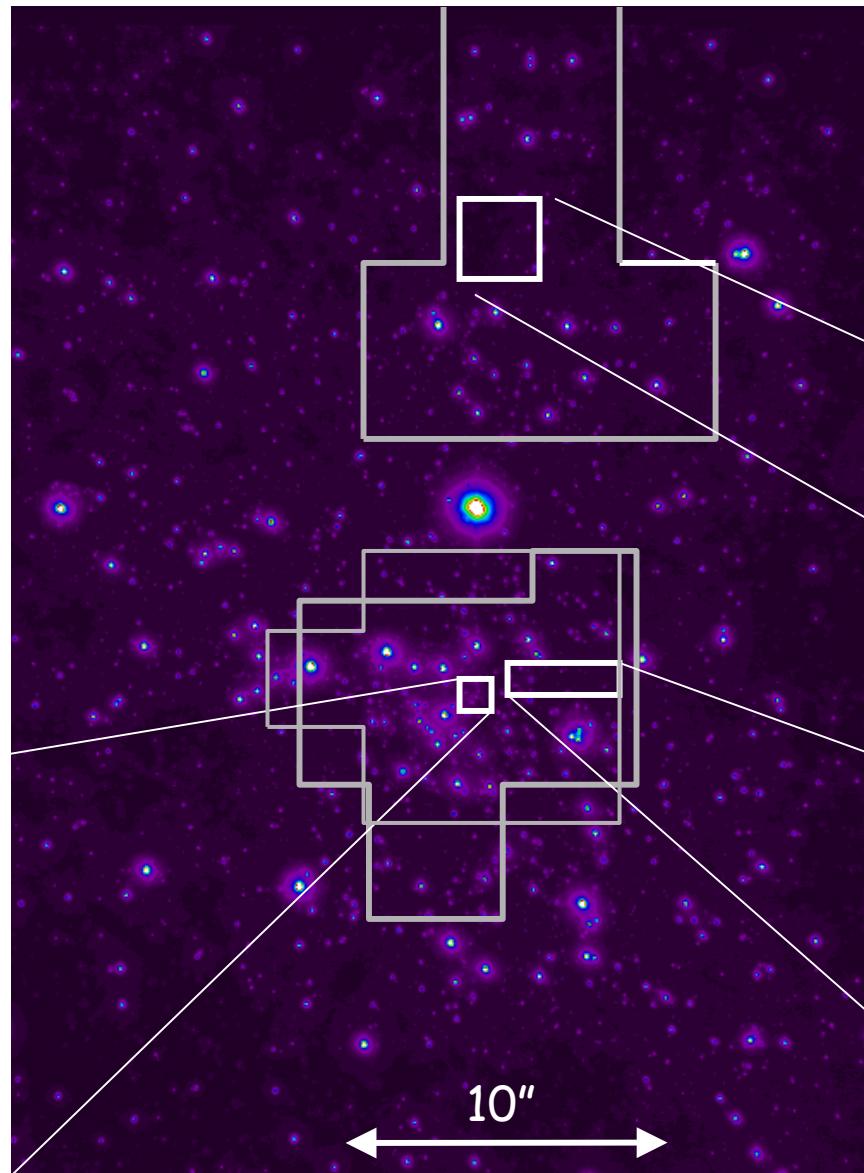
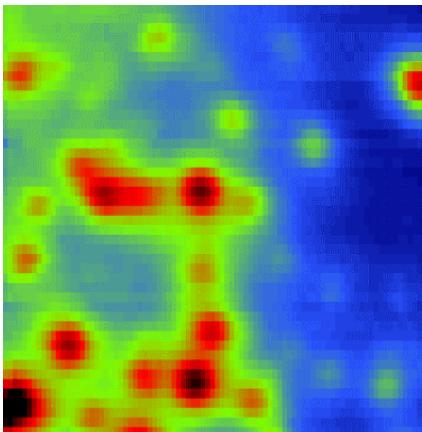
Kavli Institute for Theoretical Physics, UCSB, 14 April 2005

SINFONI in the Galactic Center

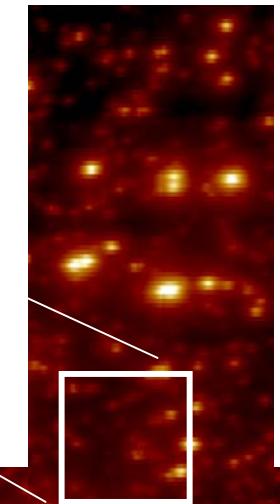
Central Field



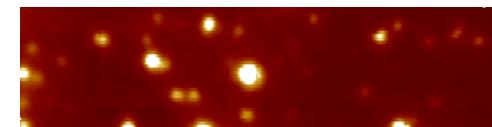
S Stars



Northern Field



Western Strip



SINFONI

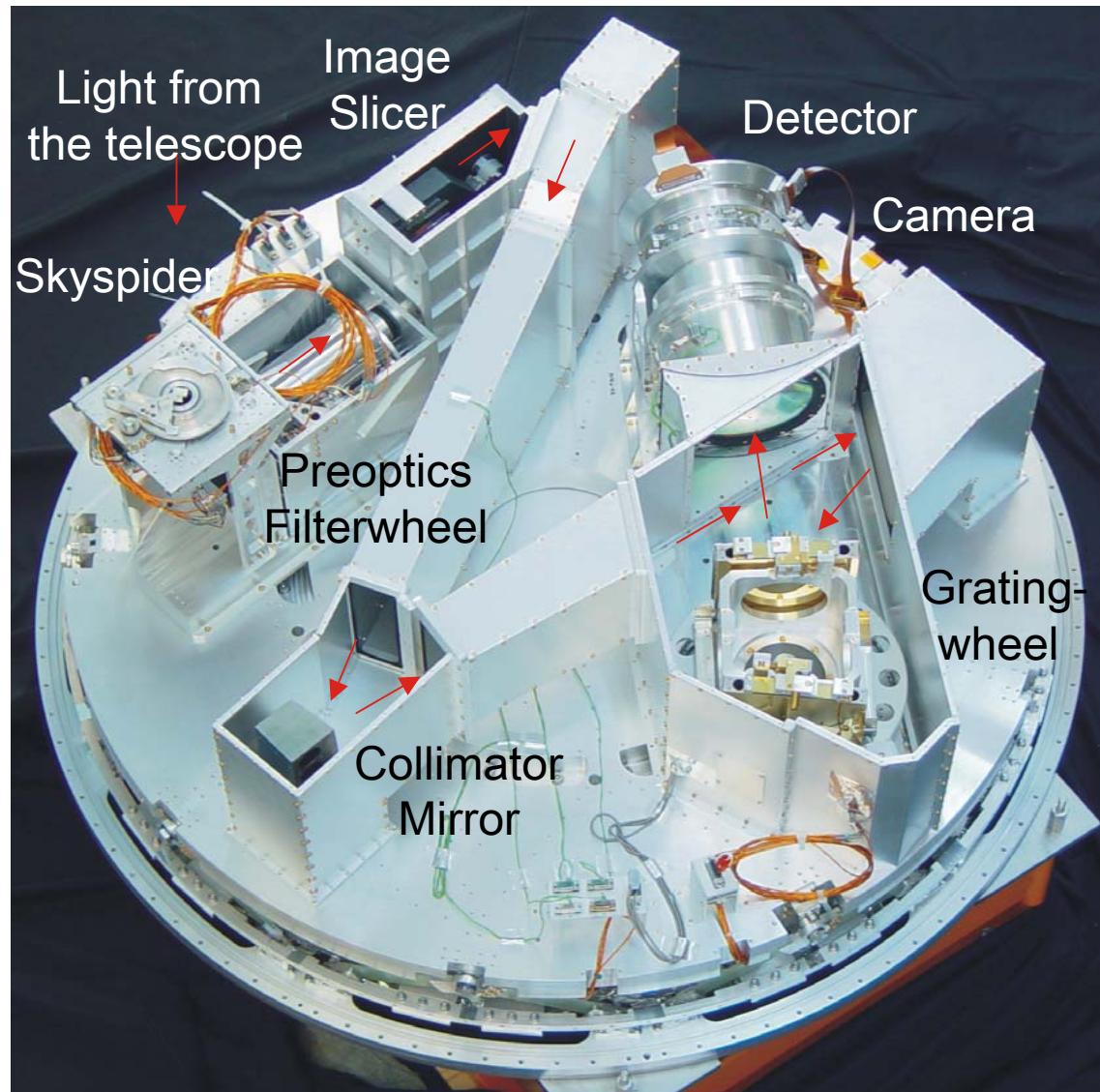
- Integral field spectrometer SPIFFI (MPE in collaboration with ESO, NOVA)
- Adaptive optics MACAO (ESO)



Eisenhauer et al. 2003
Bonnet et al. 2004

SPIFFI

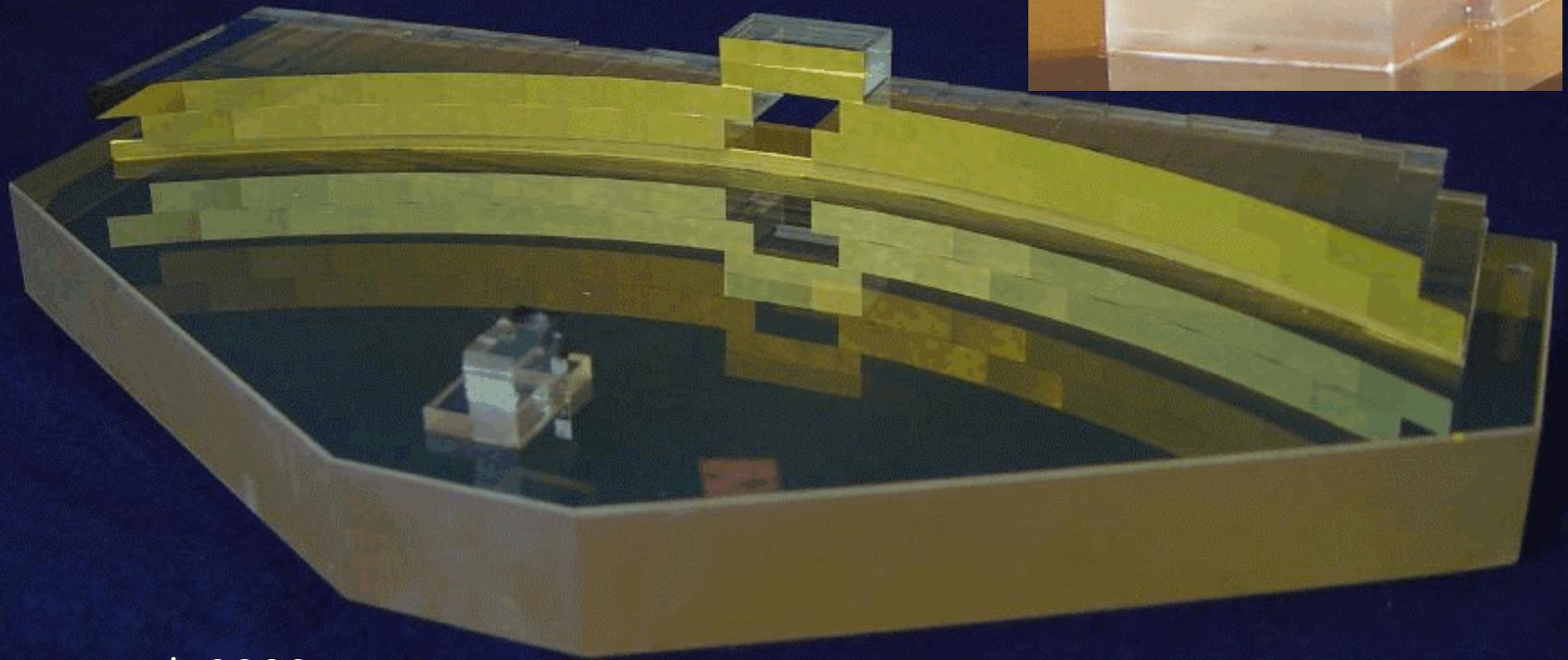
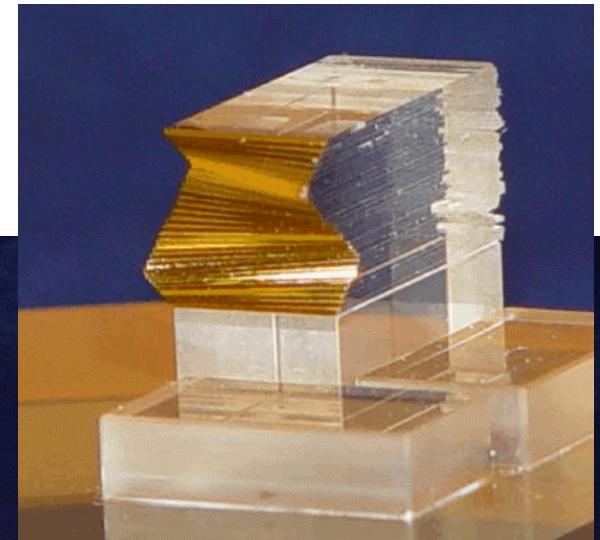
- $1 - 2.5 \mu\text{m}$
- 64×32 spatial pixels
- 2048 spectral channels
- $\lambda/\delta\lambda \sim 4000$



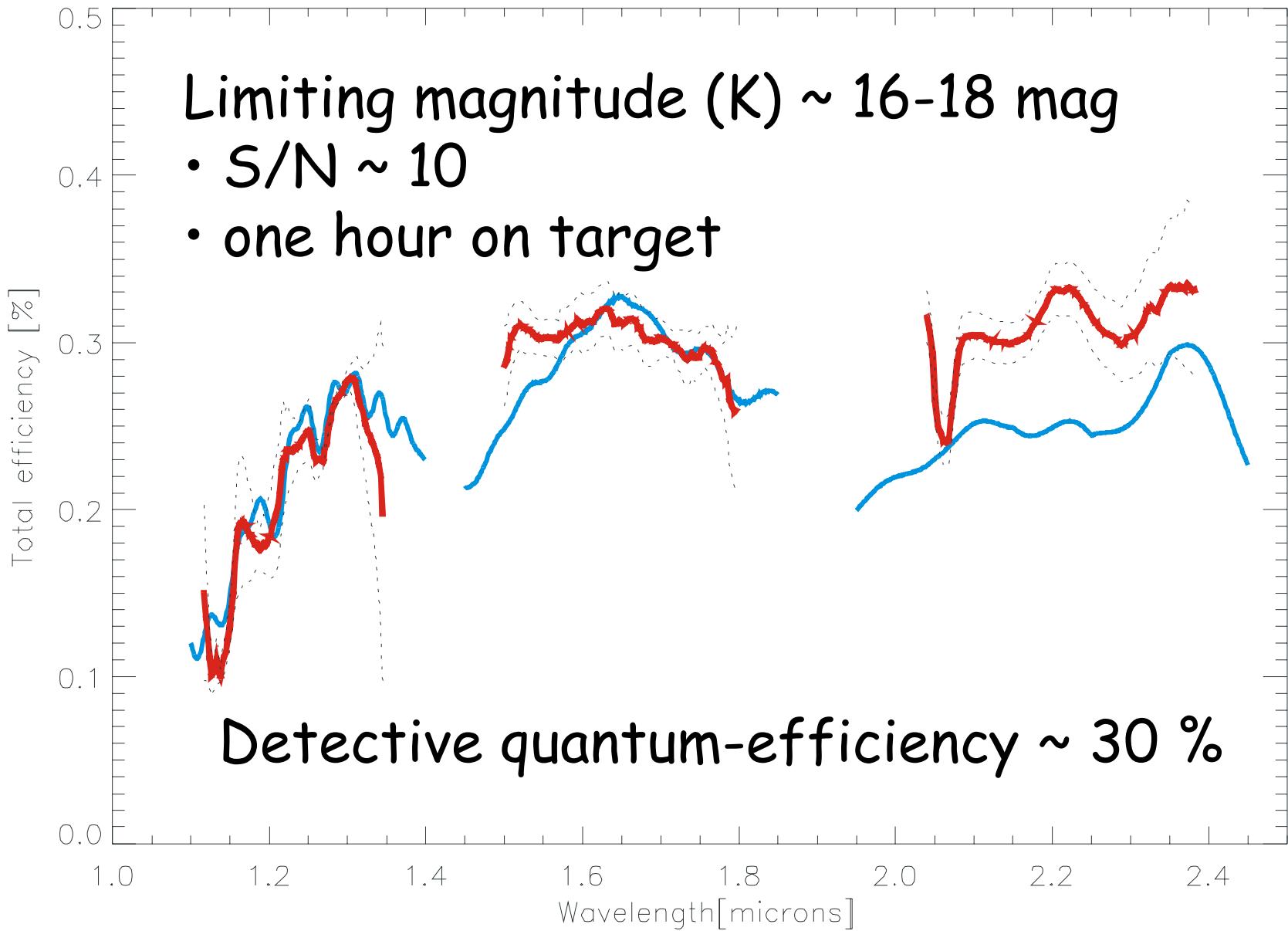
Eisenhauer et al. 2003

Image Slicer

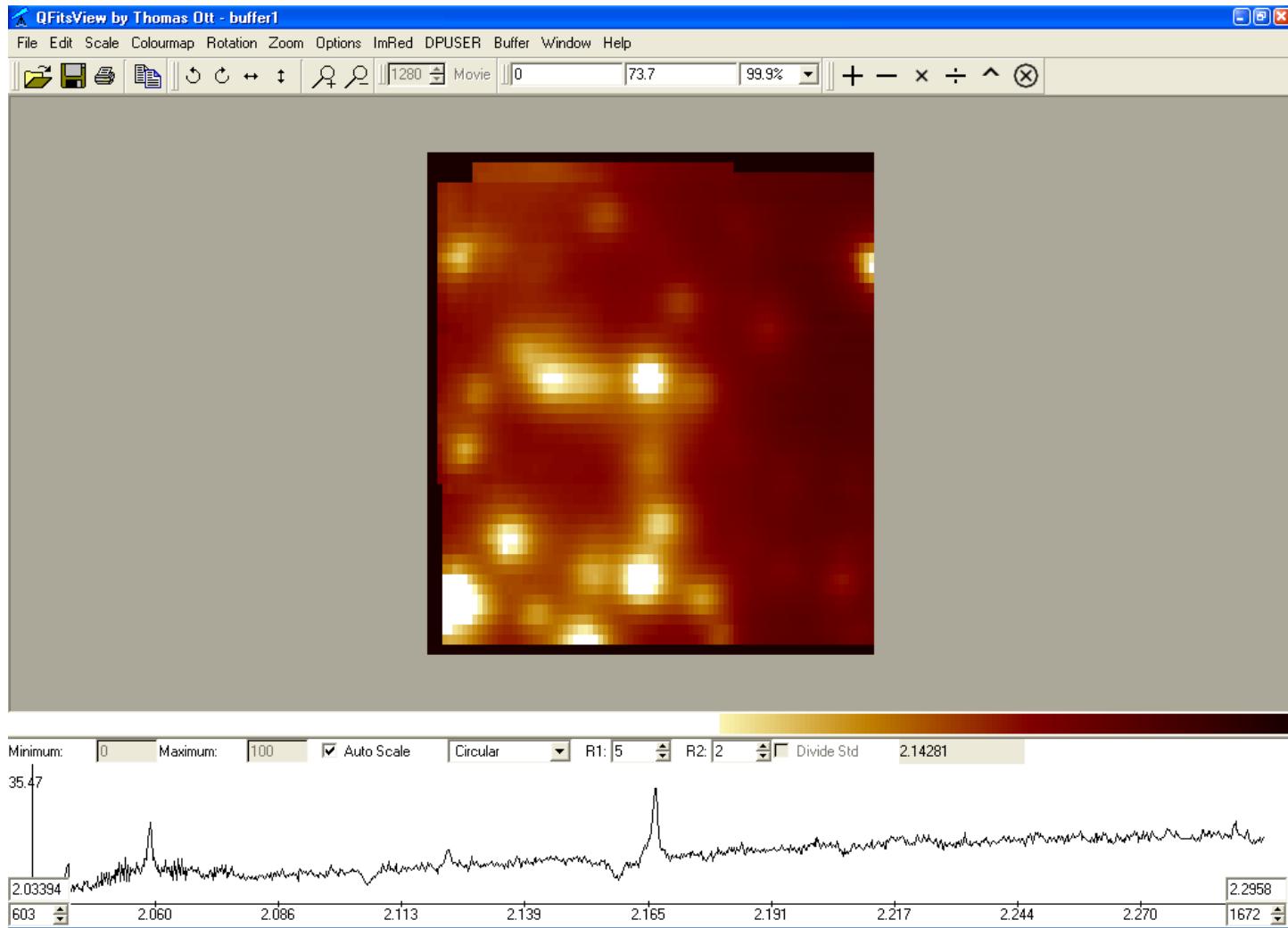
Fully monolithic design



Efficiency

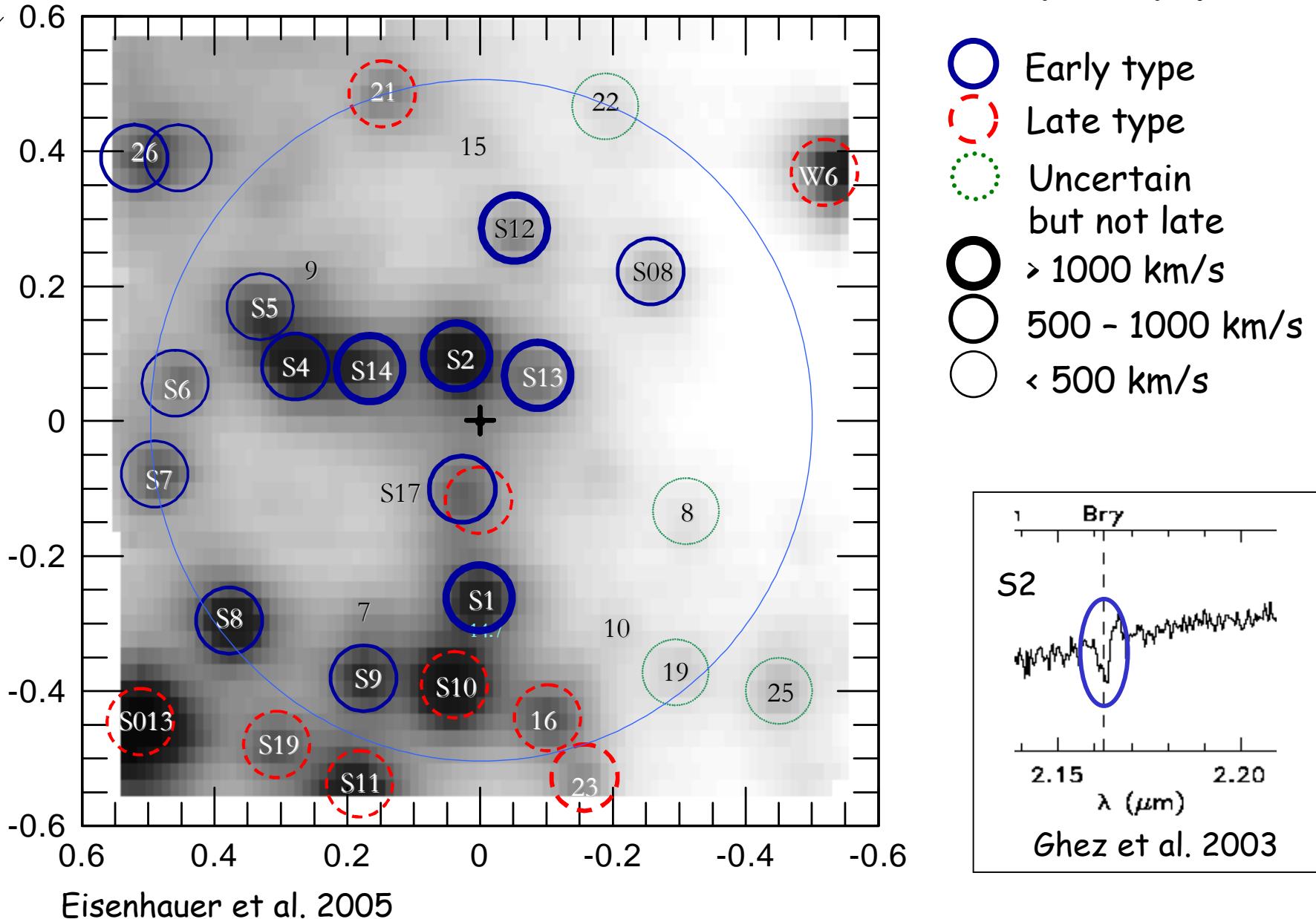


SINFONI Data Cubes



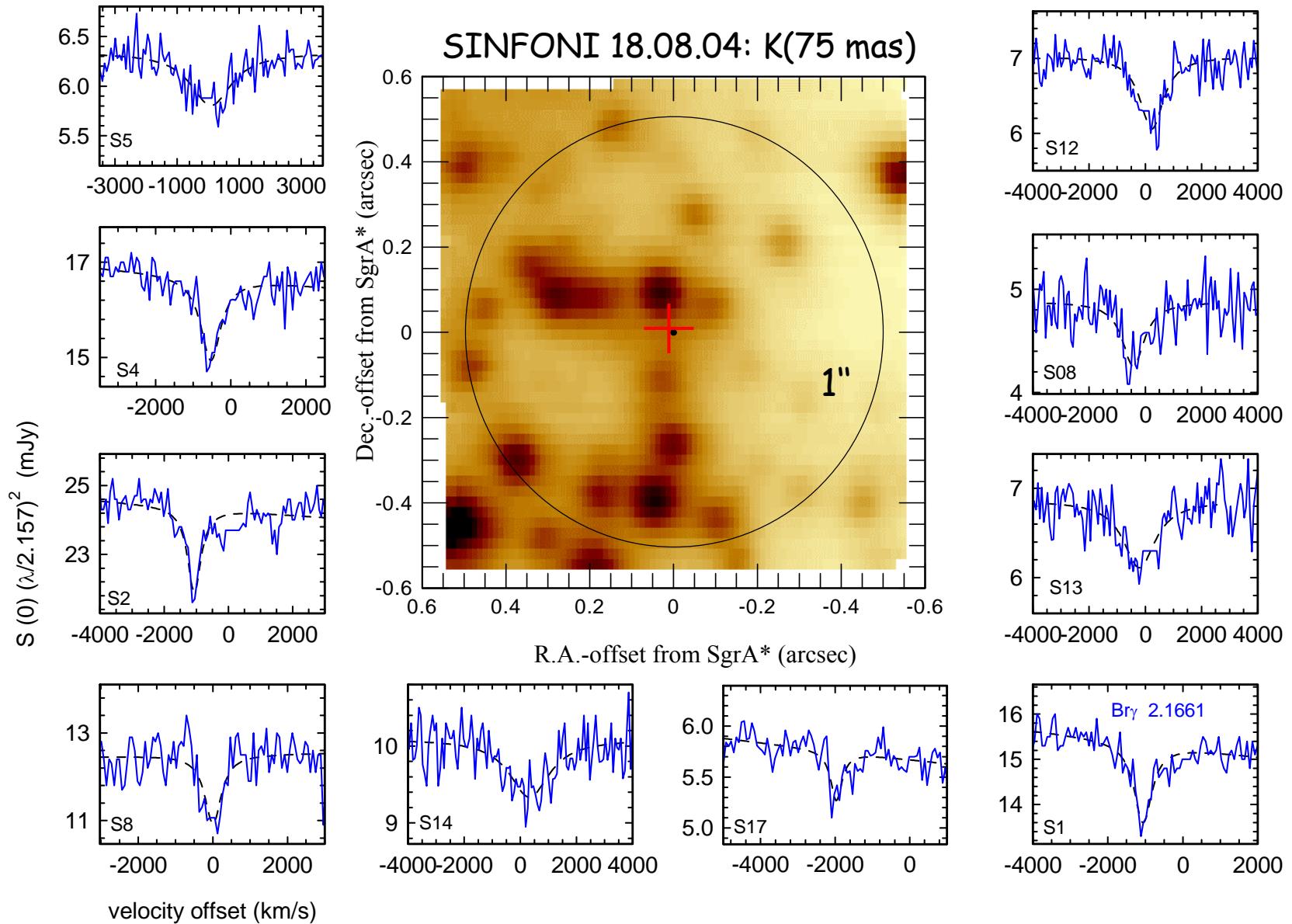
QFitsView: Thomas Ott

90% of S stars are early type



Ghez et al. 2003

Brg easily detected for K<16



Two basic scenarios

- In situ formation
 - From molecular clouds
 - Formation in massive disc
 - Collision of less massive stars

General problem: Tidal field

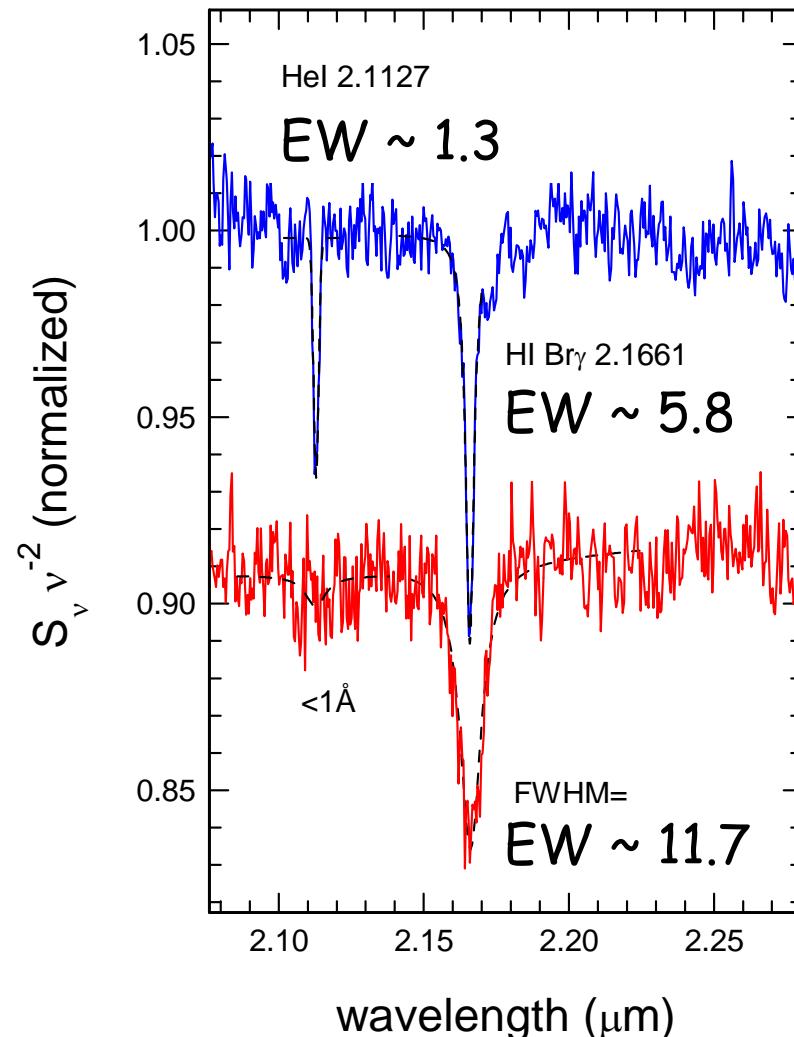
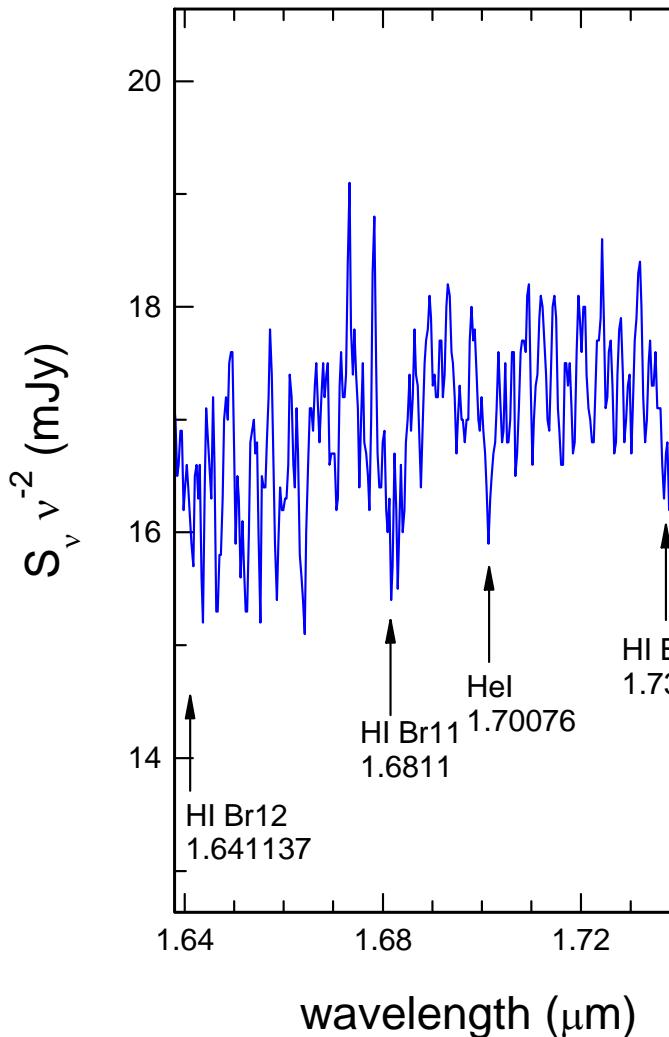
- Outside star formation
 - Mass segregation
 - Spiral in of a star cluster
 - Scattering

General problem: Timescale and efficiency

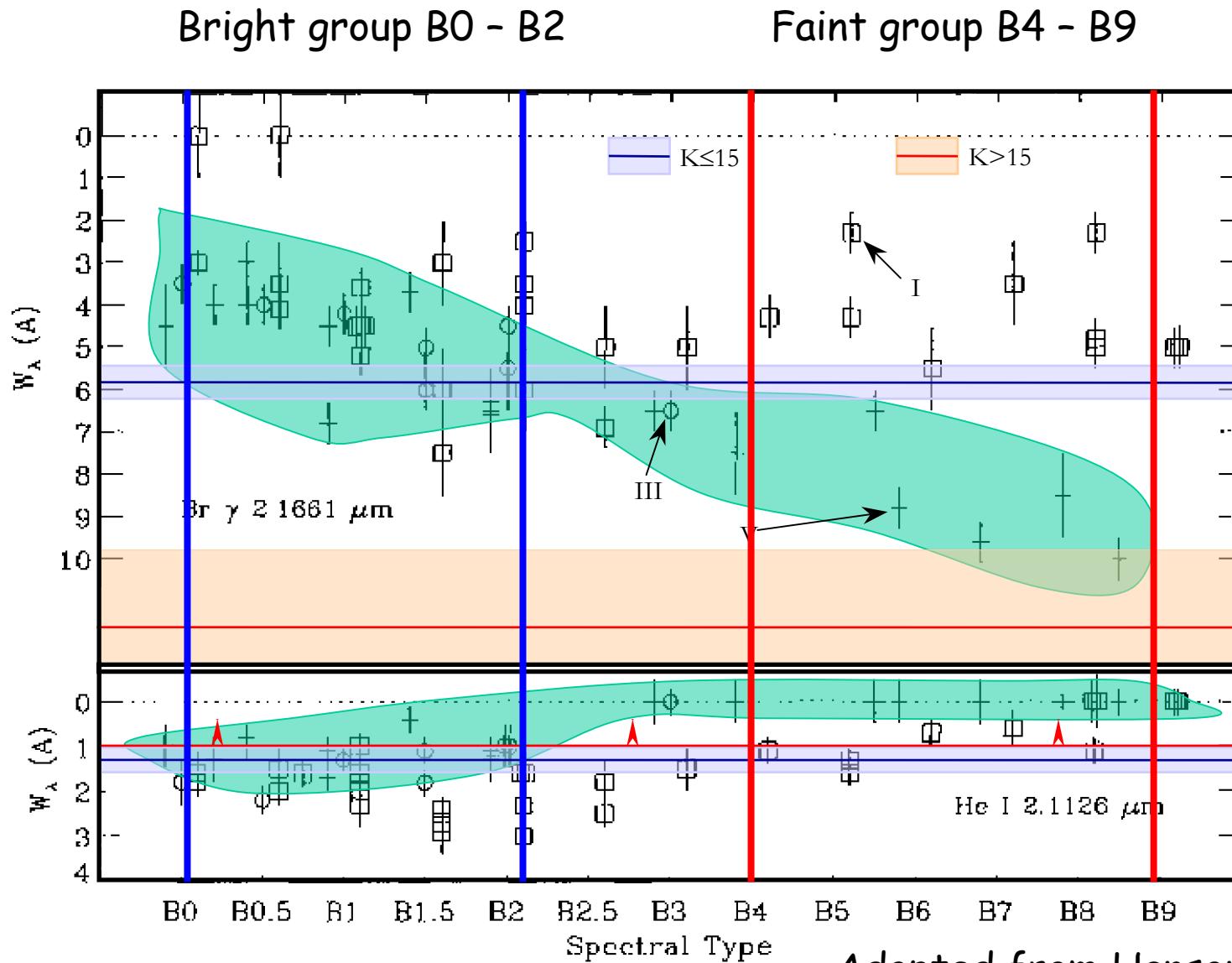
Morris 1993, Genzel, Hollenbach & Townes 1994, Lee 1994, Sanders 1998, Gerhard 2001,
Portegies Zwart et al. 2002, Levin & Beloborodov 2003, Nayakshin et al. 2003, 2004, Gould &
Quillen 2003, Genzel et al. 2003, Hansen & Milosavlevic 2003, Kim & Morris 2003, Alexander
2003, Milosavlevic & Loeb 2004

Ordinary B-stars

— K=15.1-16: S5,6, 08, 12, 13, 14 July+Aug
— K≤15: S1,2,4,8,9 July+Aug



S-stars are ordinary B dwarfs



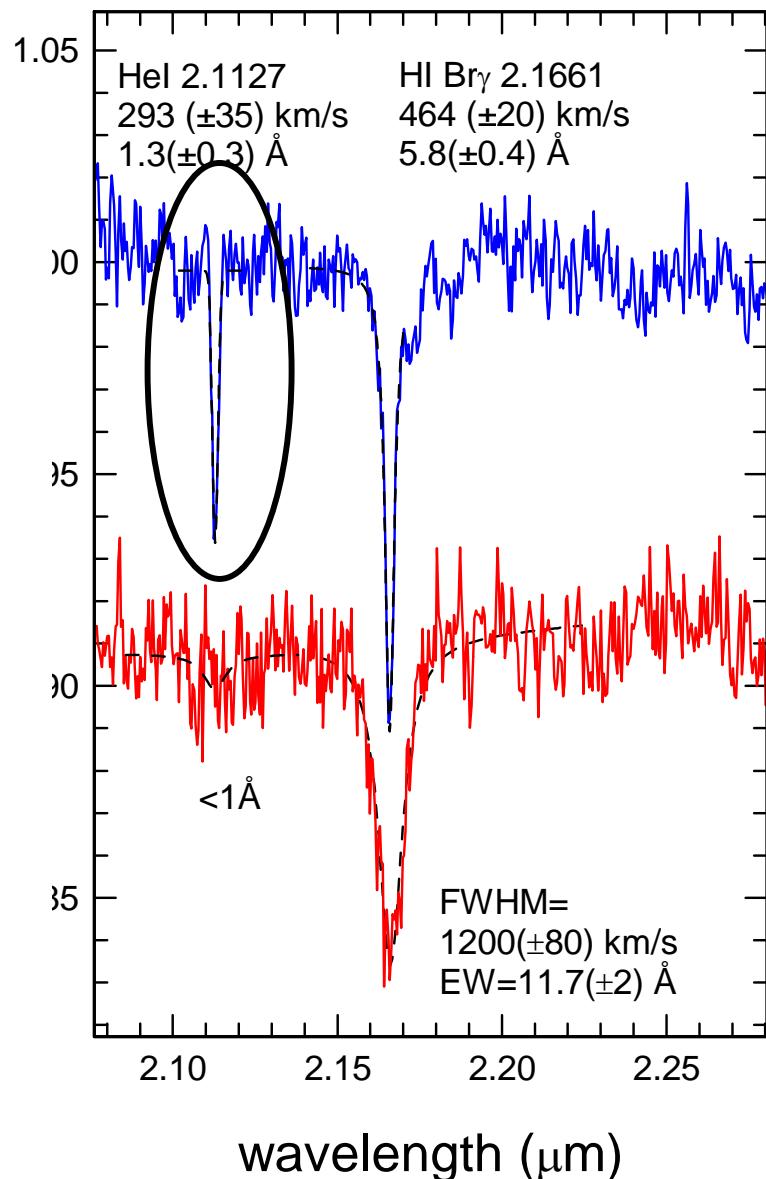
Adopted from Hanson et al. 1996

B-stars have normal rotation

HeI: FWHM 280 km/s
rotational velocity:

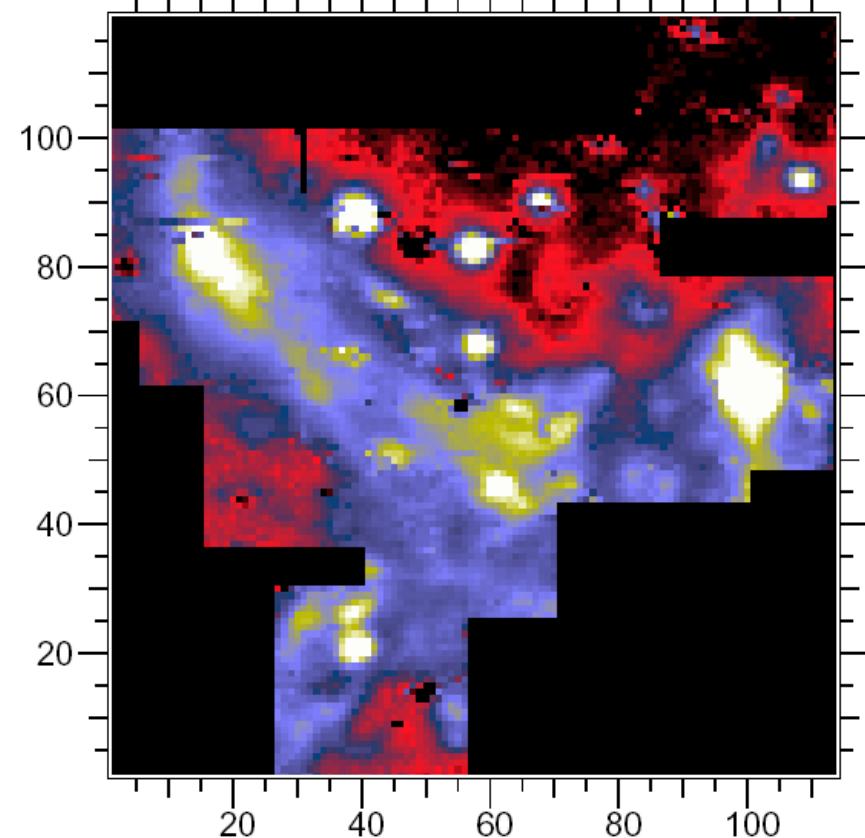
$v_{\text{rot}} \sin(i) \sim 0.55 \text{ FWHM} = 154(\pm 19)$
km/s.

Good agreement with rotation
velocity of nearby early B stars
 $\langle v_{\text{rot}} \sin i \rangle \sim 130 \text{ km/s}$
(Gathier, Lamers & Snow 1981)



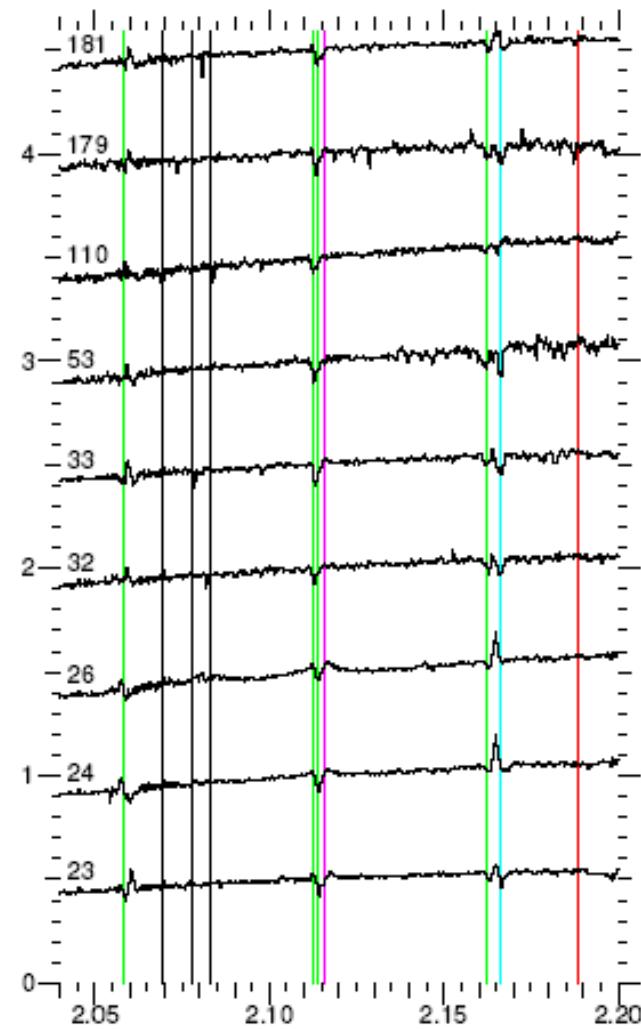
Missing O-type Stars found

Removing the mini-spiral



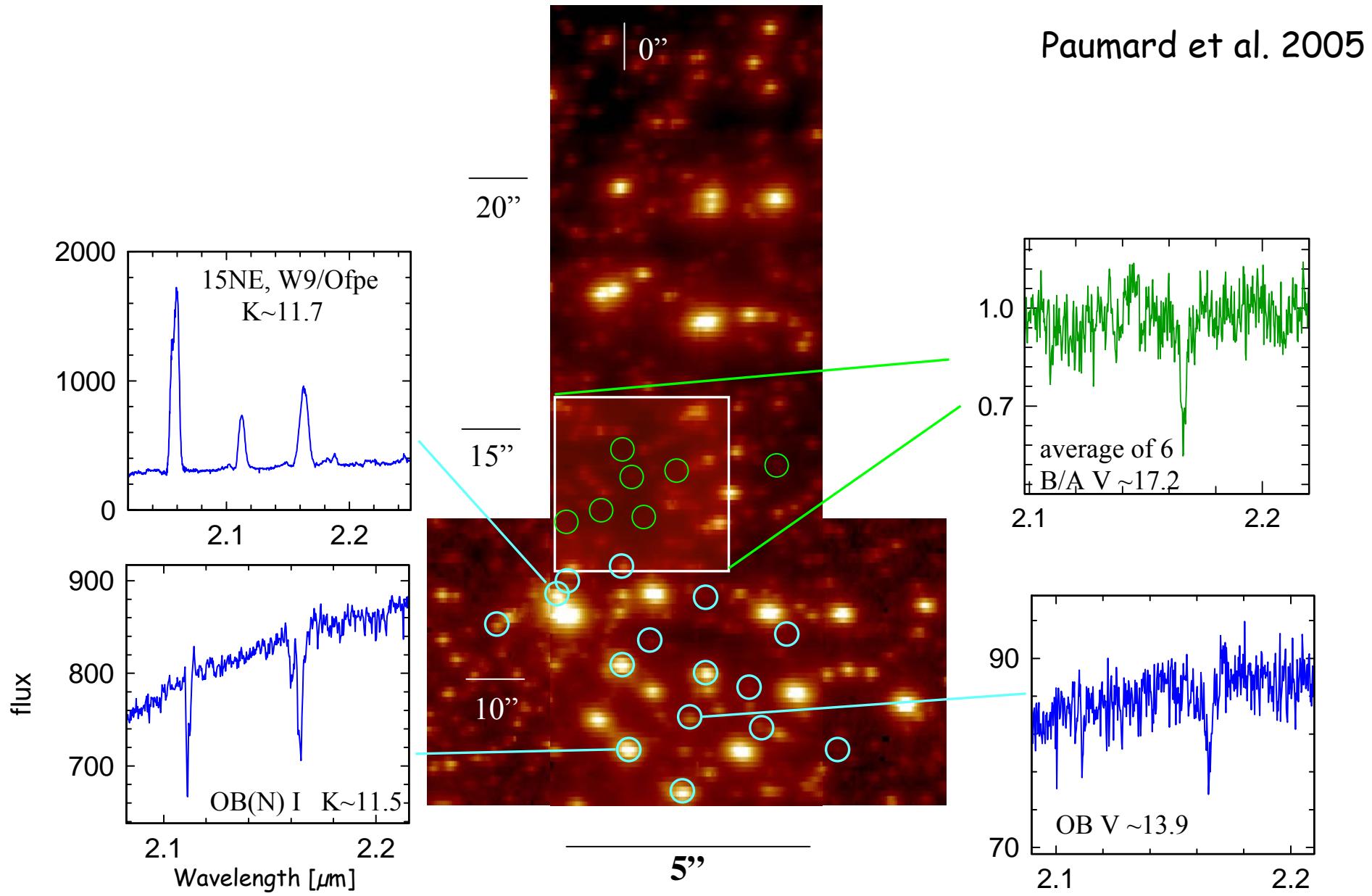
WR / O $\sim \cancel{20}$ 1

Paumard et al. 2004



N and He rich O-stars
(OBN stars)

Number of OB stars drops at 15"

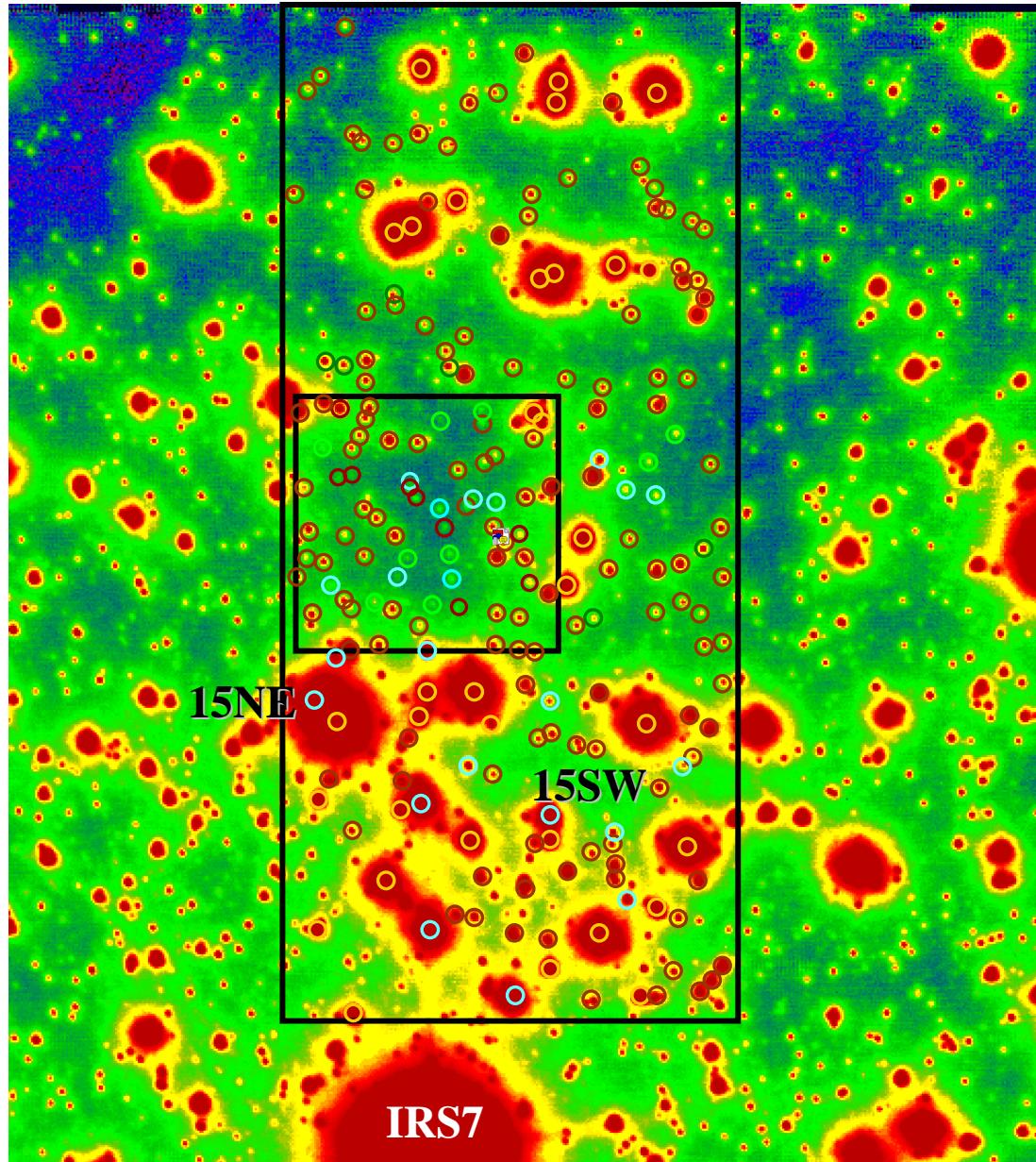


Most K~16 stars are late type

deep field:
 $t=70$ min,
 $K_{\text{limit}} \sim 18$

→
14" N of SgrA*

large field:
 $t=10$ min,
 $K_{\text{limit}} \sim 15$

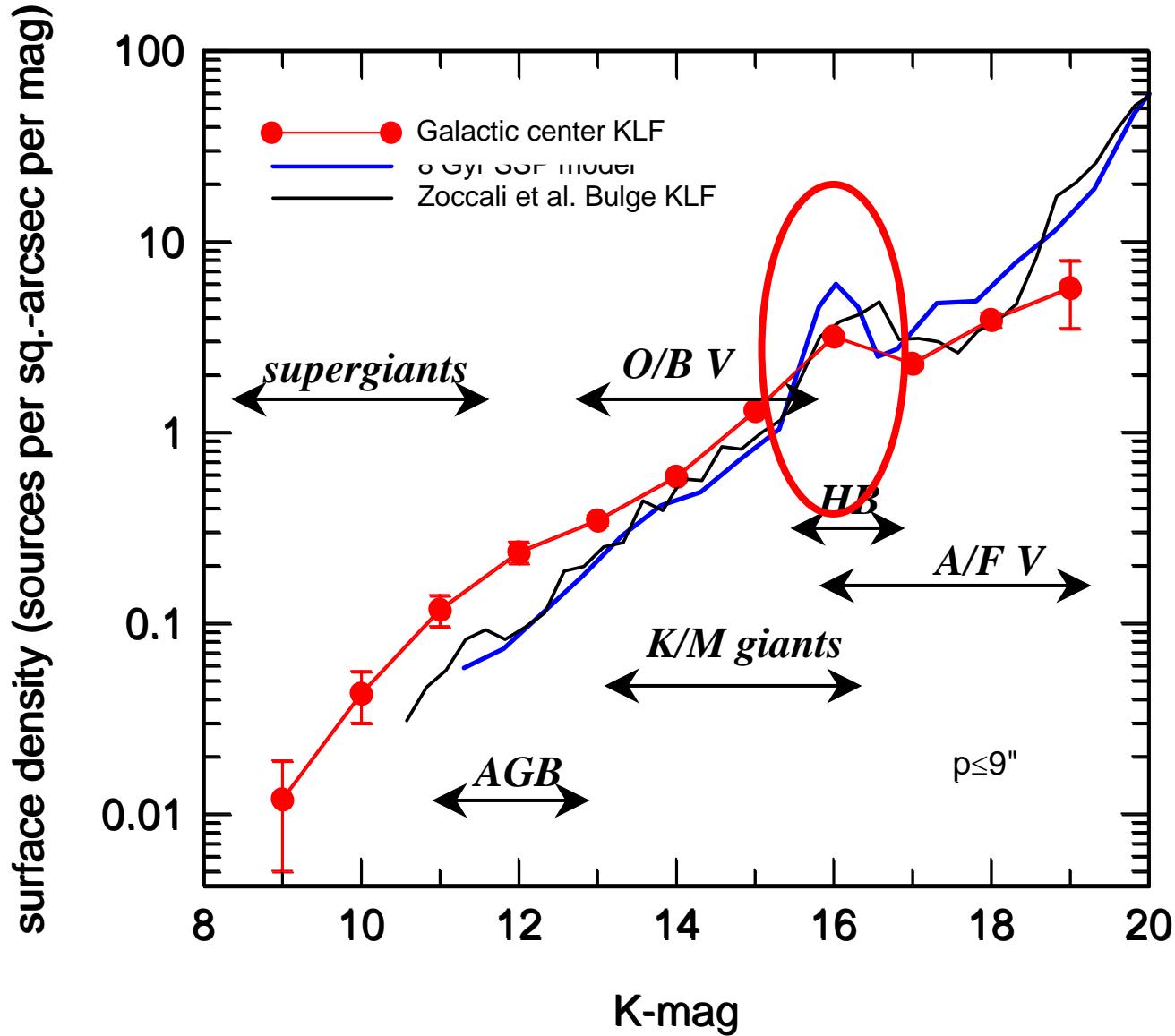


Paumard et al. 2005

○ late type
○ early type
○ not late

Colors:
red: $K=11-13$
just red: $K \sim 14$
yellow: $K \sim 15.5$
faint green: $K \sim 16.7$

Bump in LF is from late-type stars



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

Comparably few B-stars at 15"

Paumard et al. 2005

Deep fields

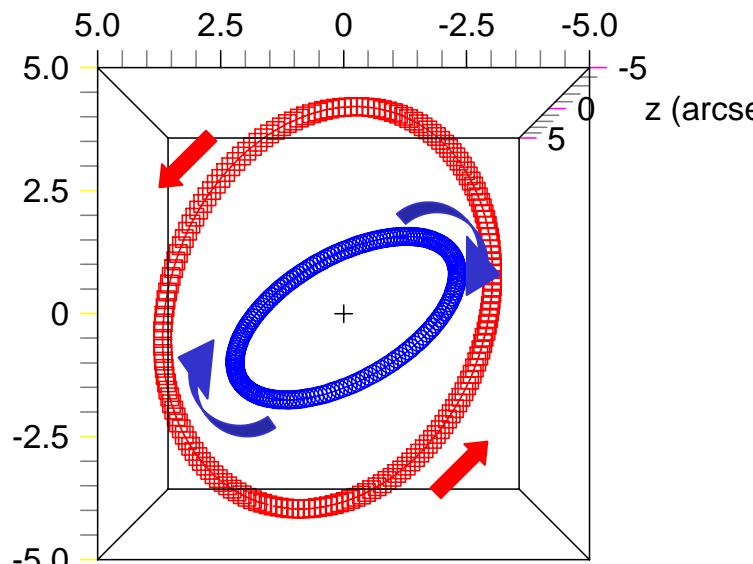
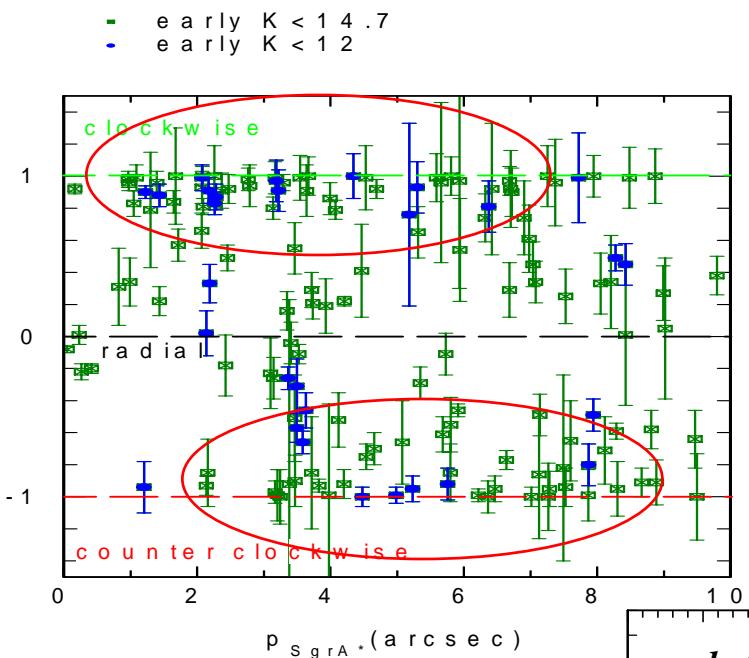
- Limiting magnitude K~18
- About 100 stars in 20 square arcsec
- 1 B star \rightarrow 0.05 Stars / square arcsec
- 7 A stars \rightarrow 0.2 Stars / square arcsec

Exchange capture with stellar black holes
scenario may need modification

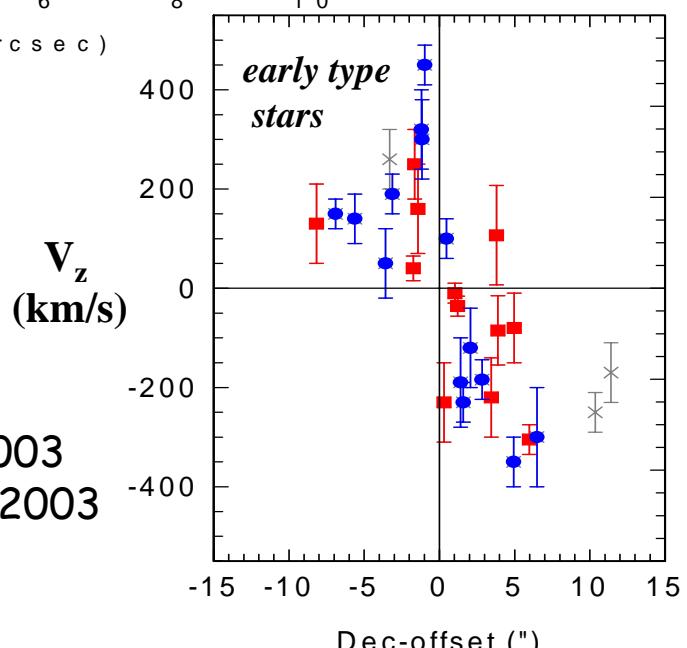
Alexander & Livio 2004

Two counter rotating discs

x(arcsec)

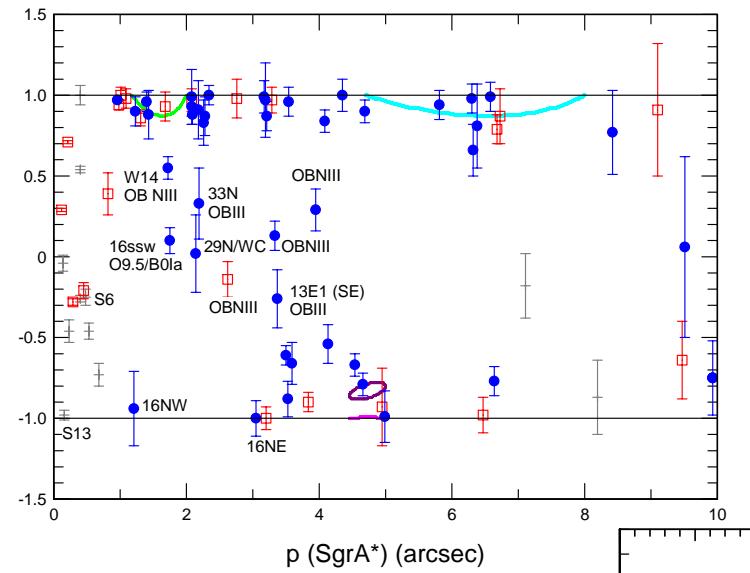


2003: 26 stars

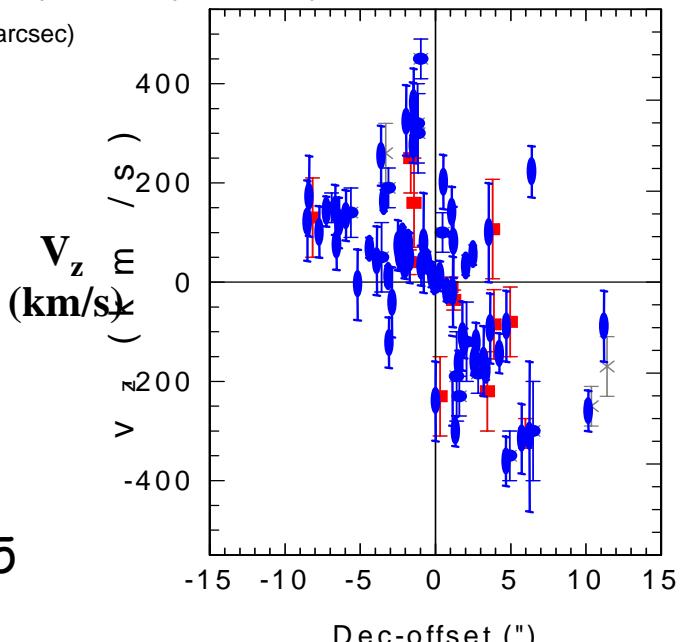


Genzel et al. 2000, 2003
Levin & Beloborodov, 2003
Paumard et al. 2001

Enlarging the sample 26 \rightarrow 65



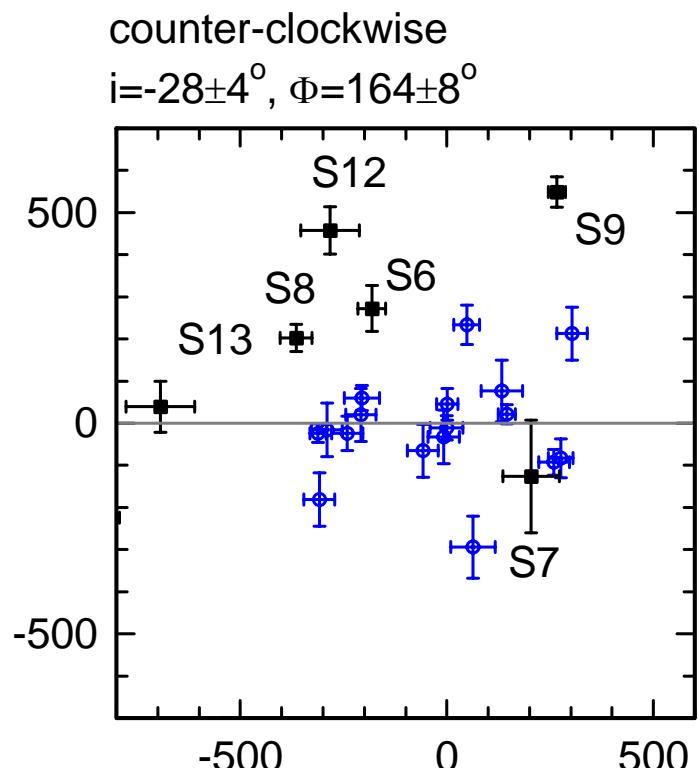
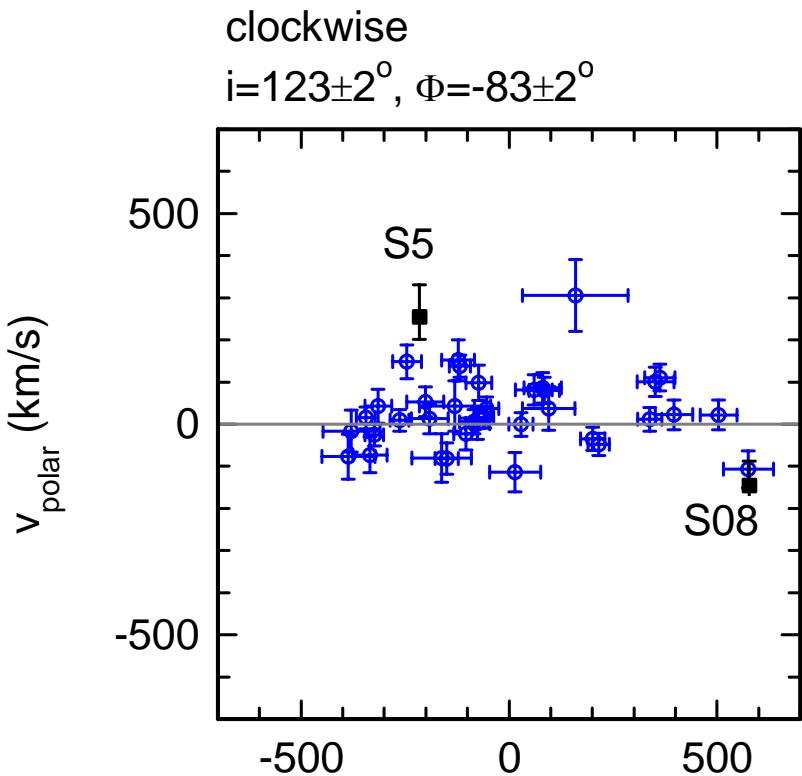
2003: 65 stars



Paumard et al. 2005

- Total 65 stars with spectroscopic classification and radial velocities
 - 43 move clockwise
 - 22 move counterclockwise
- Membership
 - Outside S-star cluster
 - 54 of 65 (83%) belong to one of the discs
 - 5 stars outside the discs with large eccentricities
 - 6 stars with large error bars
 - $P < 0.8''$
 - Only 5 of 13 (38%) have $|J_z/J_{z\max}| > 0.5$

Both discs are somewhat thick



From the ratio of velocities perpendicular to the disks to those within the disks: $h_z/R \sim 0.2-0.3$ or half opening angle ~ 15 degrees

[Beloborodov & Levin](#) for Orbital Roulette analysis

Discs are coeval

Percentages of different early type stars

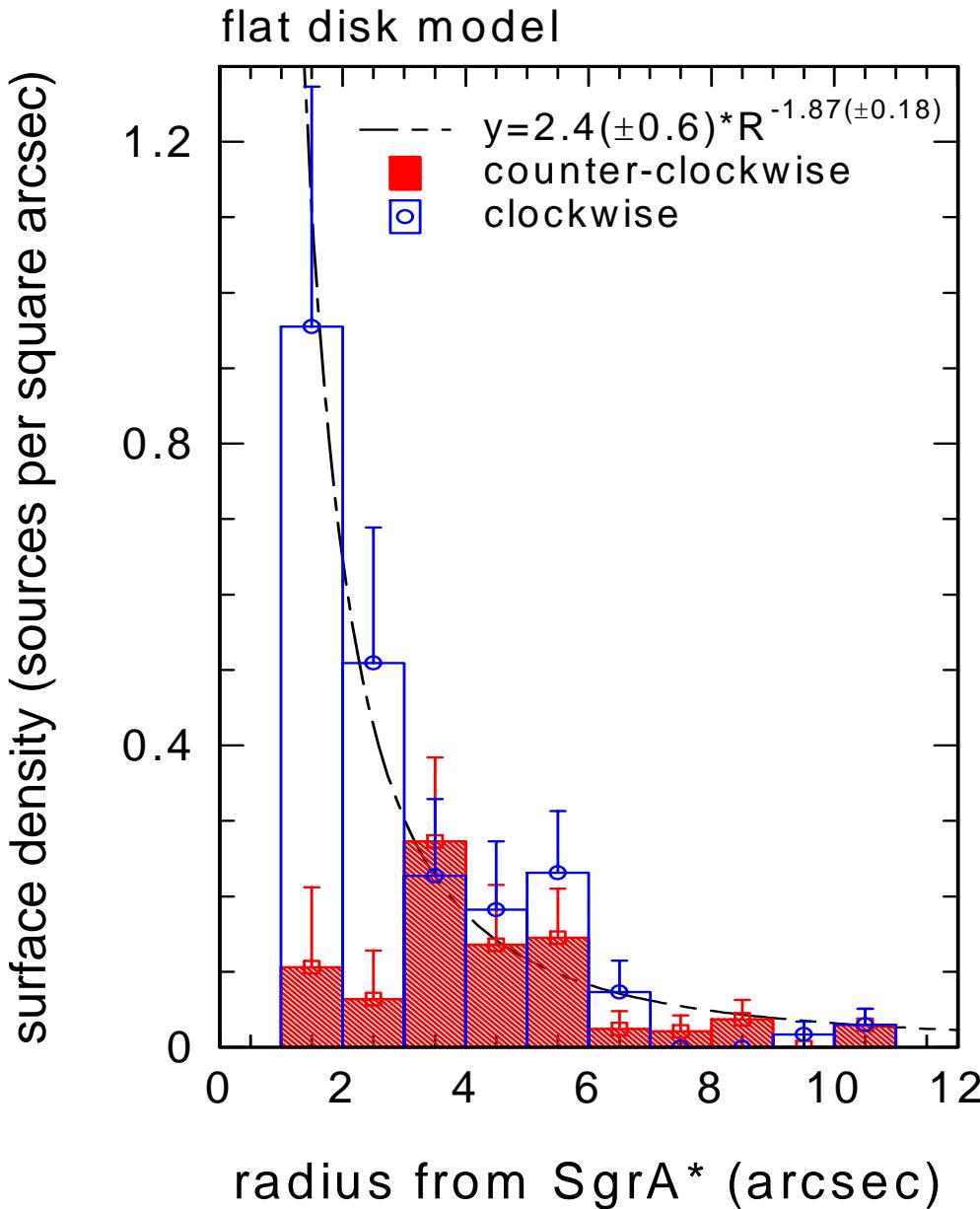
	clockwise	counter-clockwise
OB (I,III)	> 63	> 55
WNL+LBV	20	22
WNE	2.4	2.5
WC	15	20

→ $t=4 \pm 1$ Myrs for both disks
(Meynet 1995)

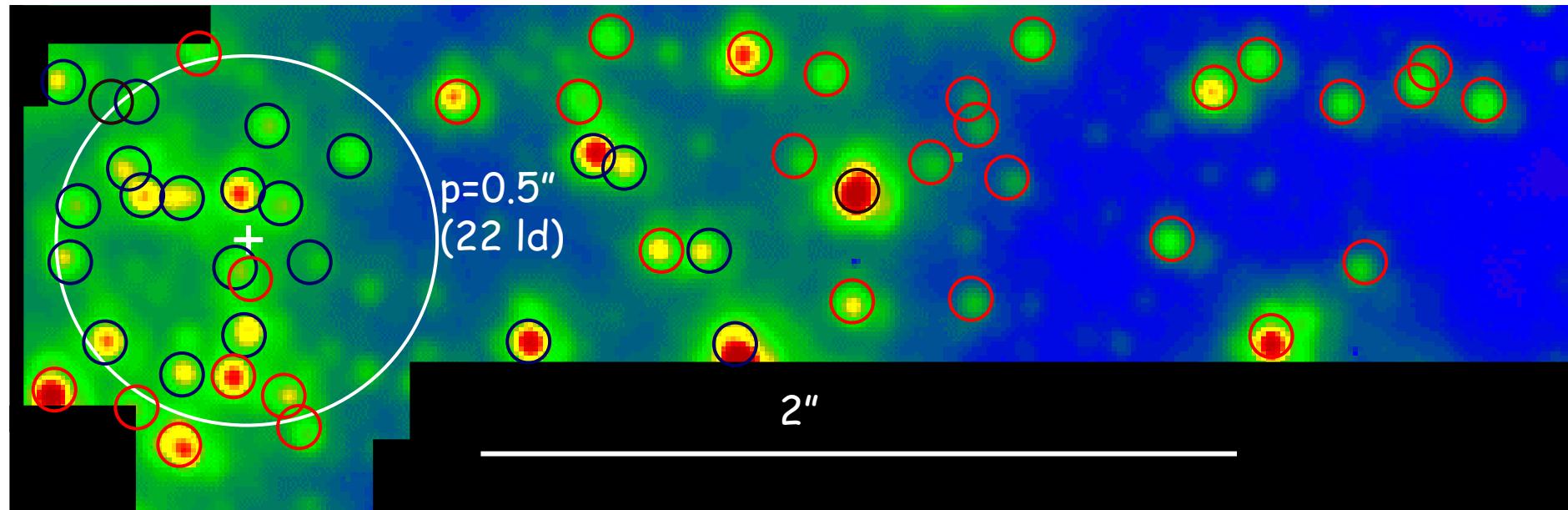
McGinn et al. 1989, Sellgren et al. 1990,
Krabbe et al. 1995, Haller et al. 1996,
Genzel et al. 2000, 2003, Paumard et al.
2001, 2005, Figer et al. 2003

Discs have different structure

- **Clockwise:**
 - most numerous at 1"-3"
 - Power law distribution
- **Counterclockwise:**
 - ringlike 3"-5"



No discs at small distance



- late type stars
- early type stars

Getting to the 3D structure

Simple "Toy" models for getting z assuming

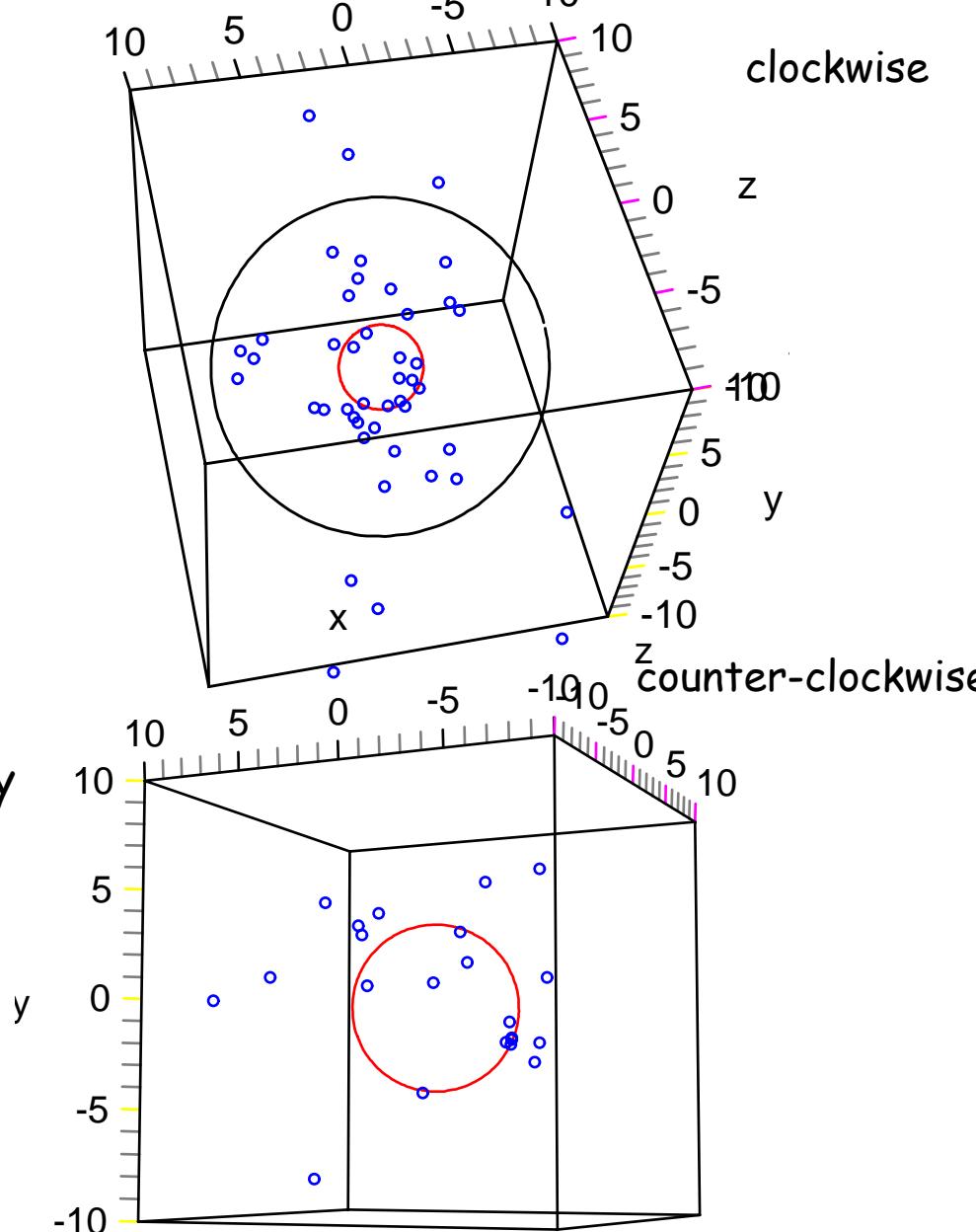
- Circular orbits:
 - Energy $V^2 = GM/R$
 - Scalar product $\vec{r} \cdot \vec{v} = 0$
- Thin disc
 - Cross product: $\vec{r} \times \vec{n} = 0$

Clockwise:

- Smooth
- azimuthally symmetric
- Power law radial surface density distribution
- Sharp inner edge $\sim 2''$

Counterclockwise:

- Peak at 4"-5" (IRS 13)
- Smaller statistics

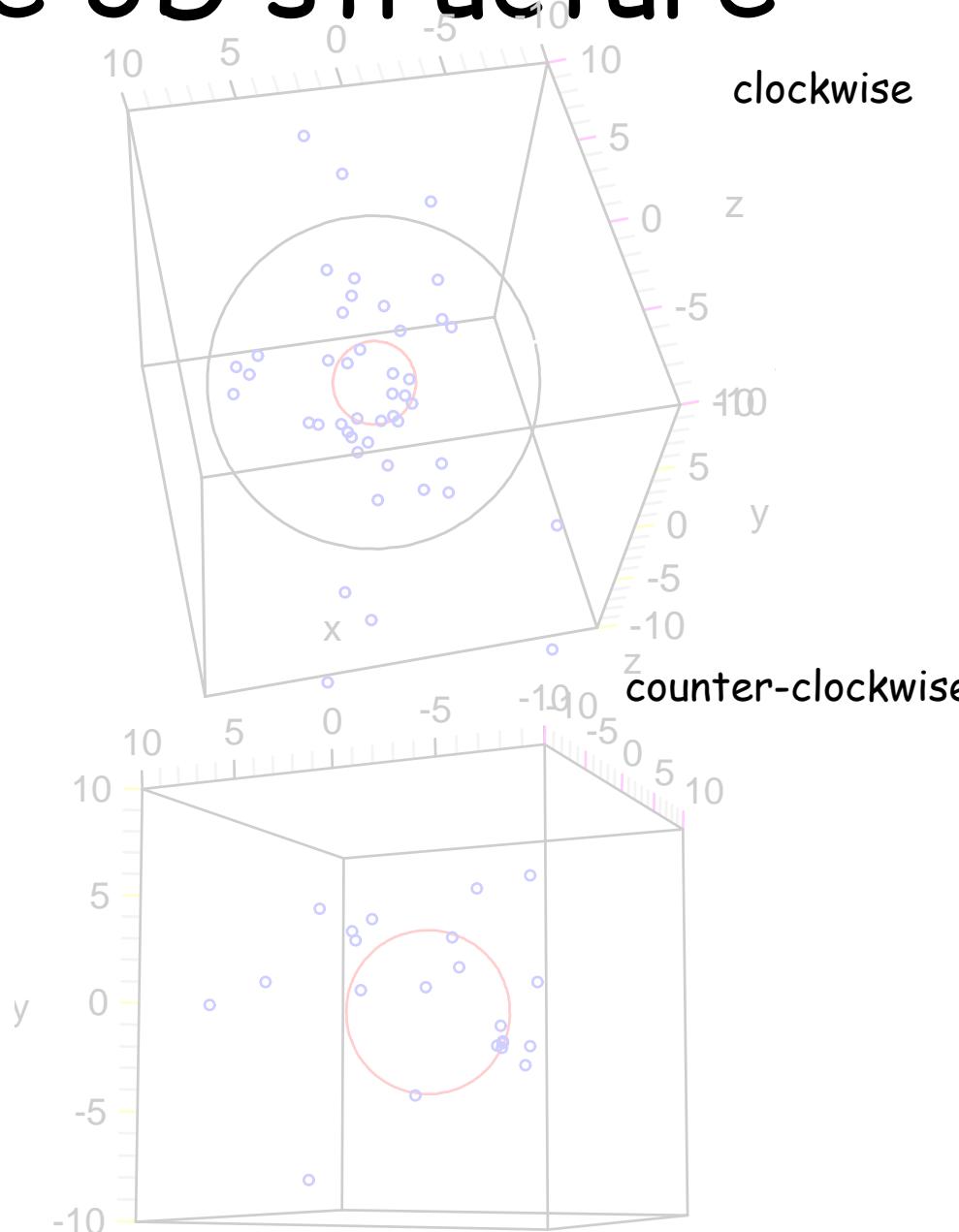


Getting to the 3D structure

Dynamical Modeling

- Some early insights
 - Inner radius of 1-2":
 $M_{\text{disk}} \geq 10^4 M_{\text{sun}}$
 - $\Delta z/R \sim 0.2 - 0.4$:
 $M_{\text{disk}} \leq 10^4 M_{\text{sun}}$
- Consistent with current stellar content
 - >a few $10^3 M_{\text{sun}}$
 - flat IMF

Nayakshin & Cuadra

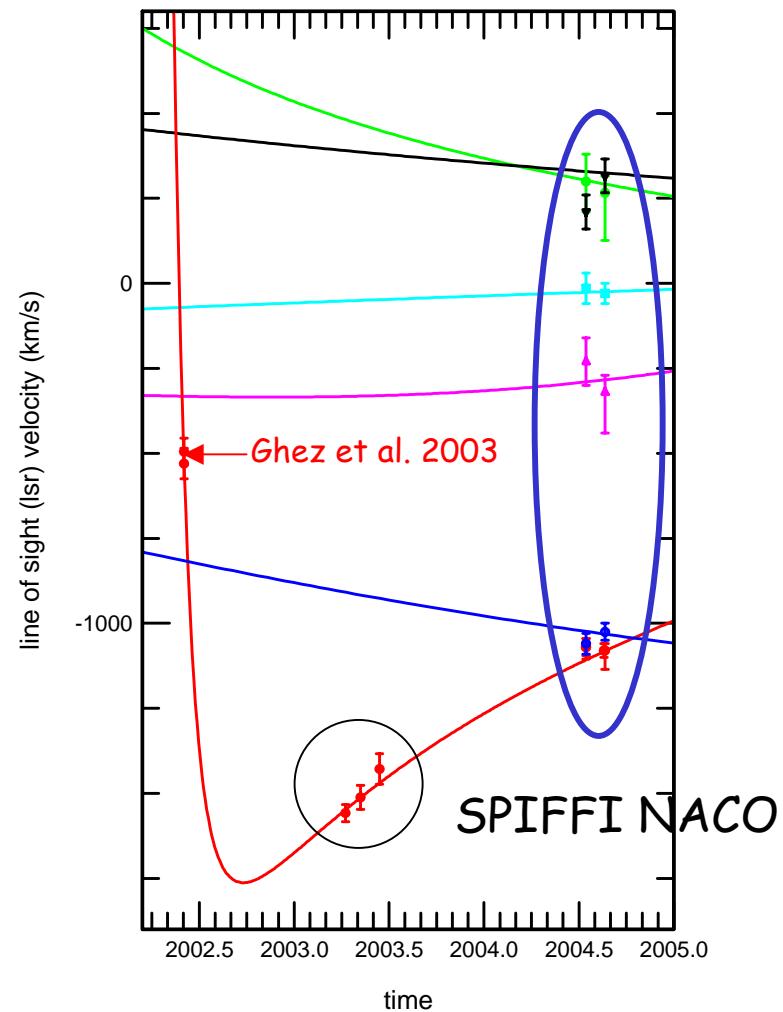
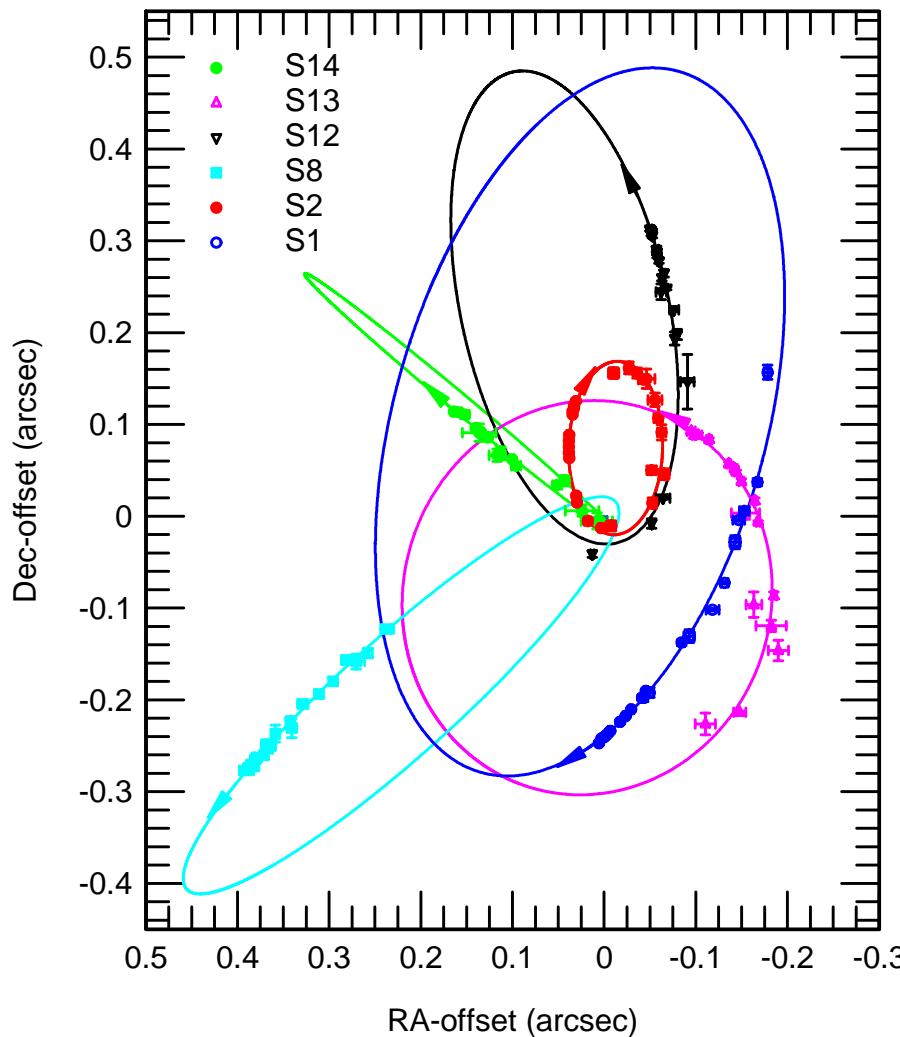


Schödel et al. 2003

Ghez et al. 2003

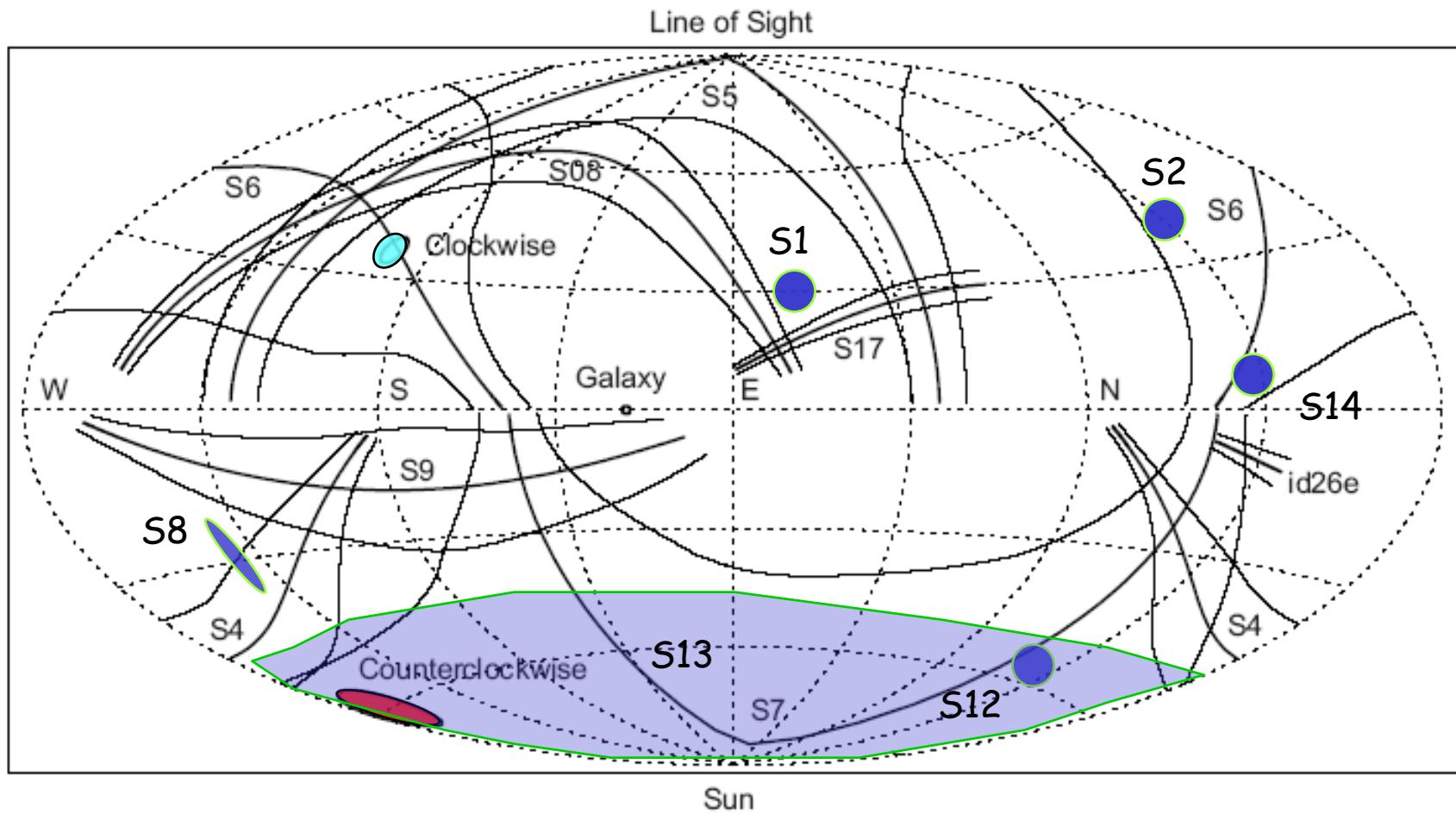
Eisenhauer et al. 2005

3D Orbits



First relativistic corrections within reach of measurements:
Zucker, Alexander et al., Gillessen et al.

Orientation of orbital spin is random

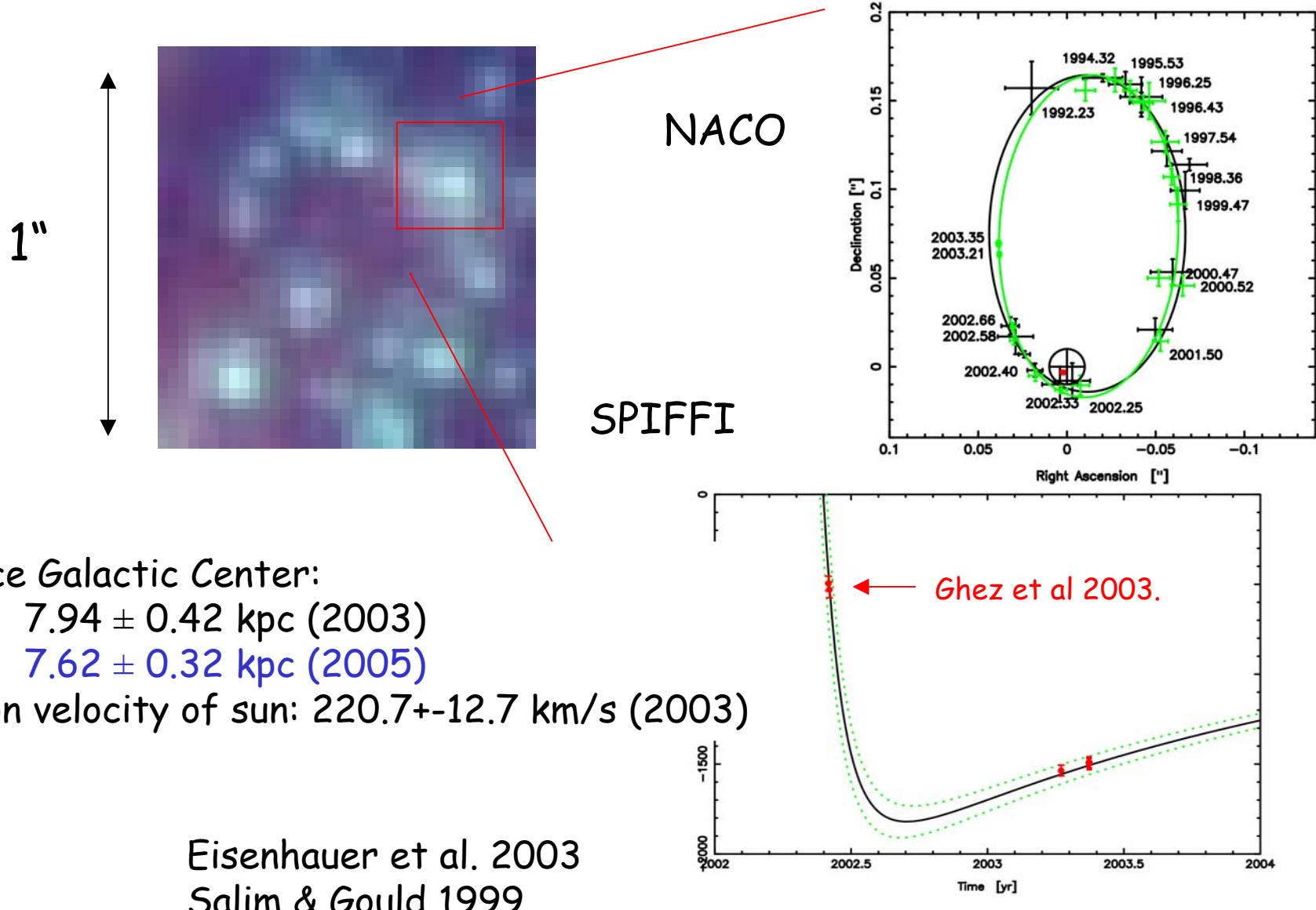


No relation of orbits from central stars with counter-rotating discs:

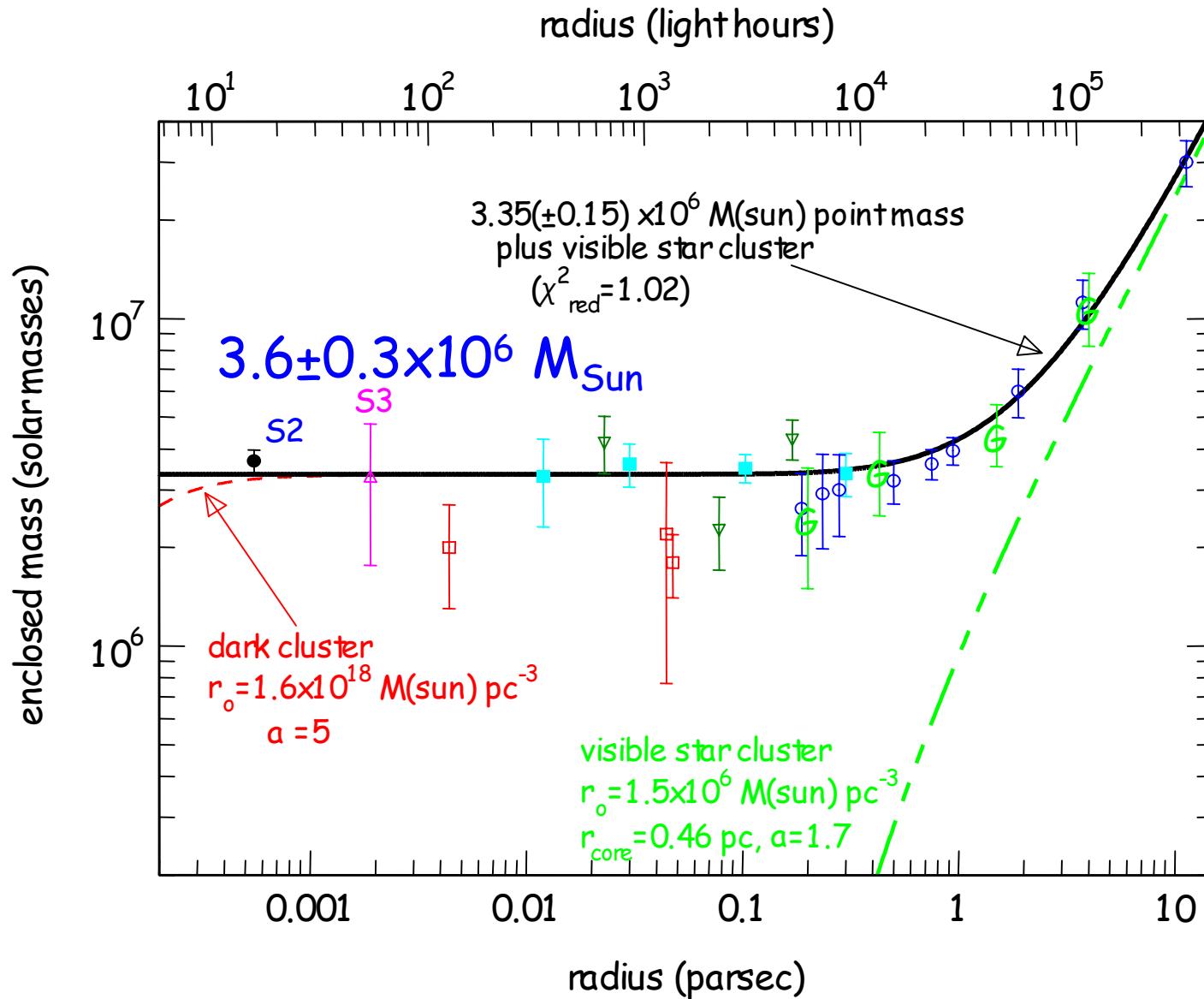
For comparison

- Lense-Thirring precession: $S_{2,14,17} \sim 10 \text{ Myr}$, $S_{1,8,12,13} > 10^8 \text{ yr}$
- Lifetime: $\sim 10 \text{ Myr}$

Distance to Galactic Center



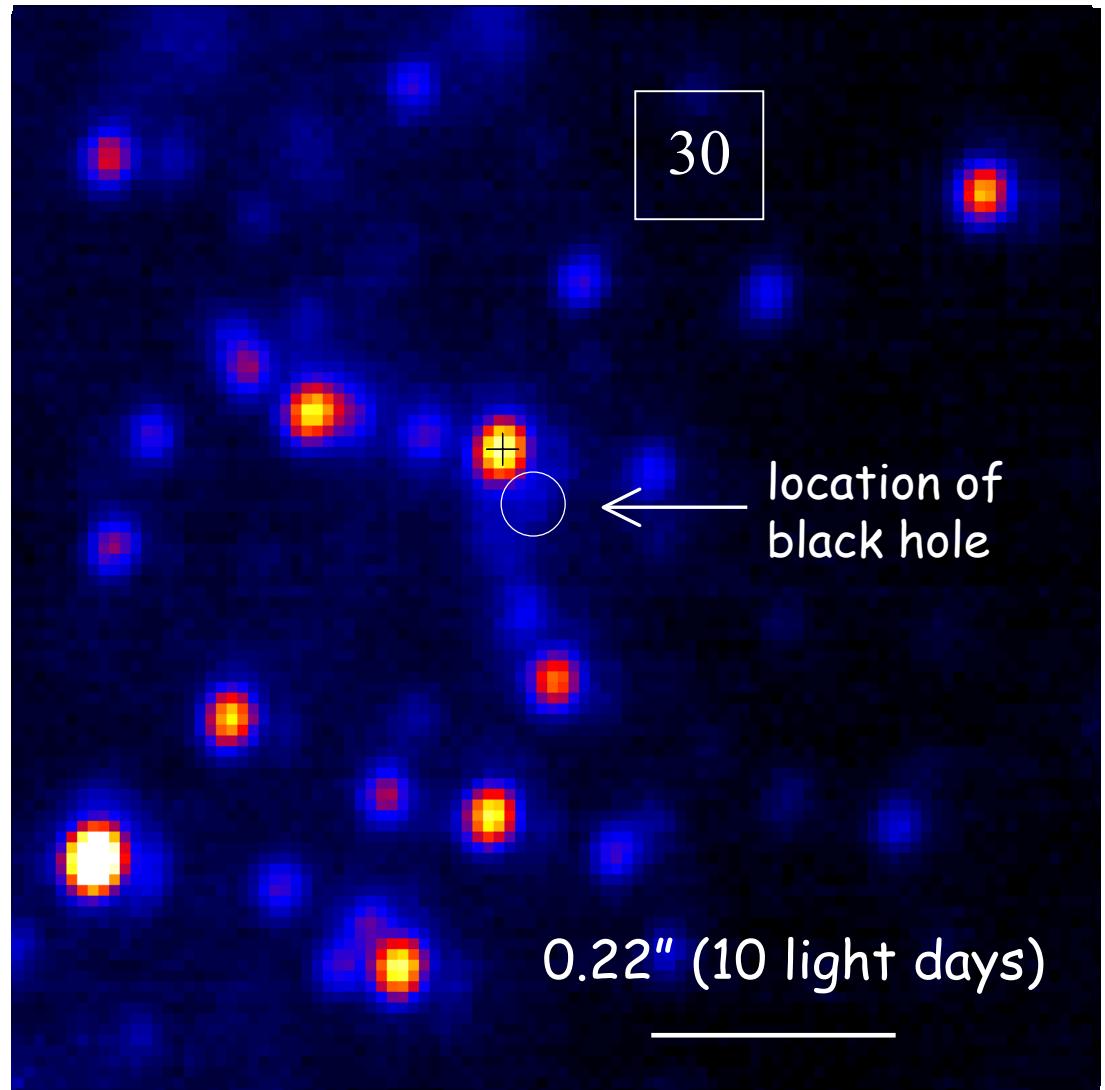
Mass of the Black Hole



Schödel et al. 2002, 2003, Ghez et al. 2003, Eisenhauer et al. 2003, 2005

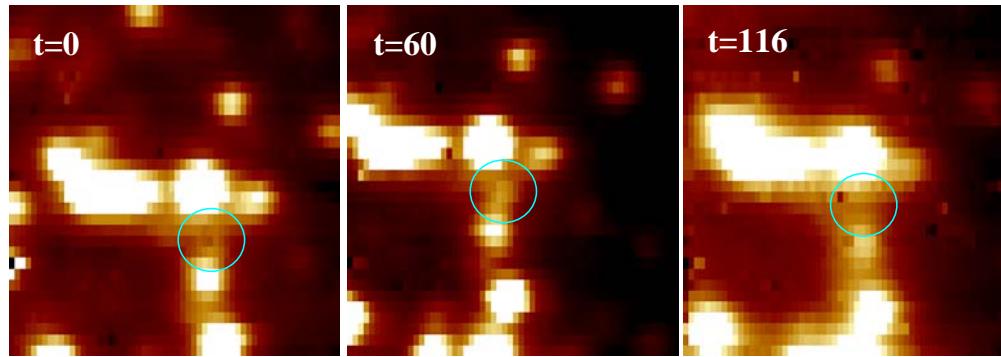
Infrared Flares of SgrA*

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



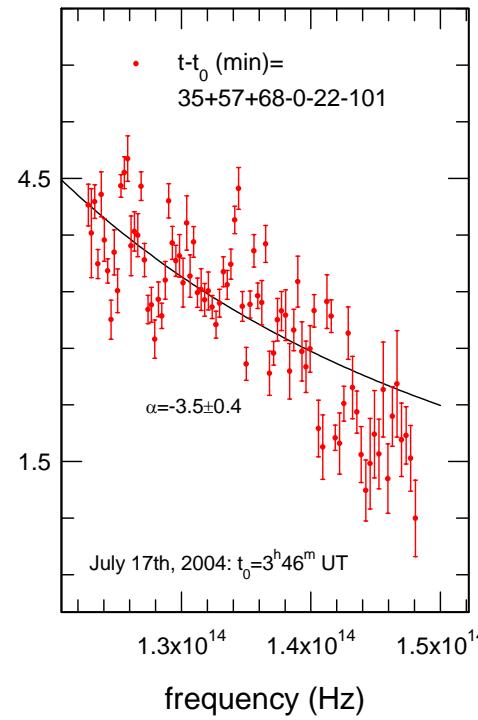
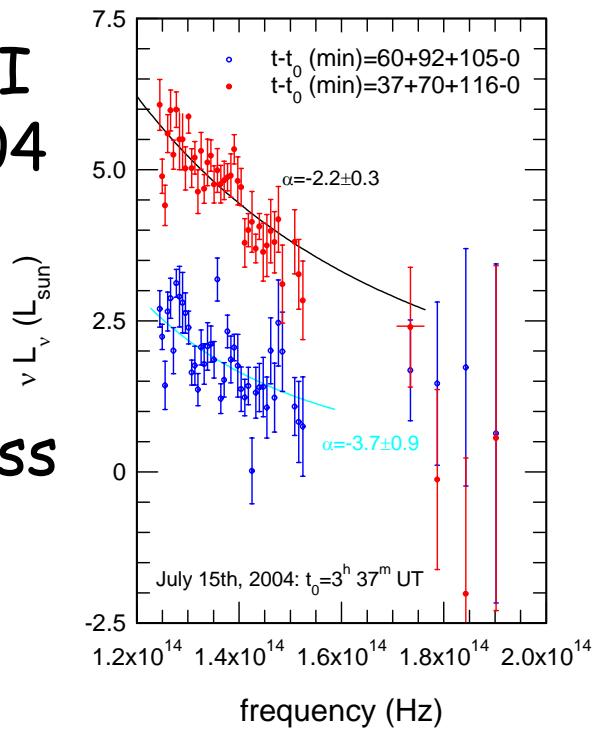
Genzel et al. 2003
Nature 425, 934

Infrared Spectrum of Flare



SINFONI
15 July '04

Red and
featureless

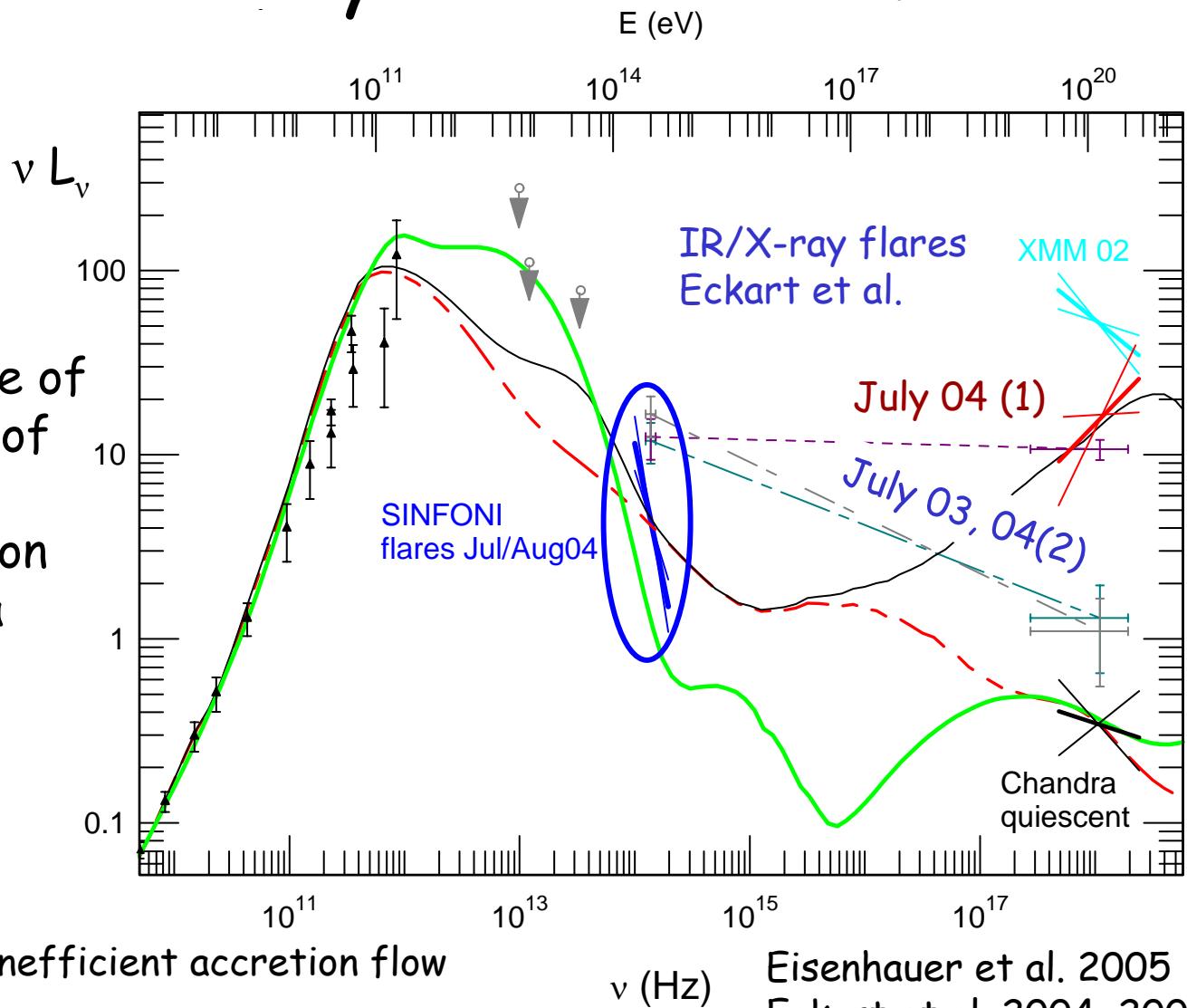


SINFONI
17 July '04

$$vL_v \sim v^{-3 \pm 1}$$

Infrared Flare is Synchrotron Emission

Infrared emission is caused by an increase of the non-thermal tail of highly relativistic electrons (synchrotron models) due to extra heating/acceleration



Jet-Disc vs. Radiatively inefficient accretion flow

Eisenhauer et al. 2005

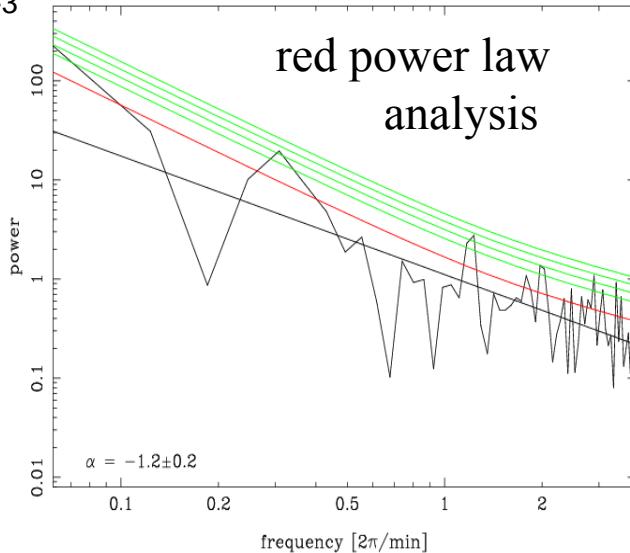
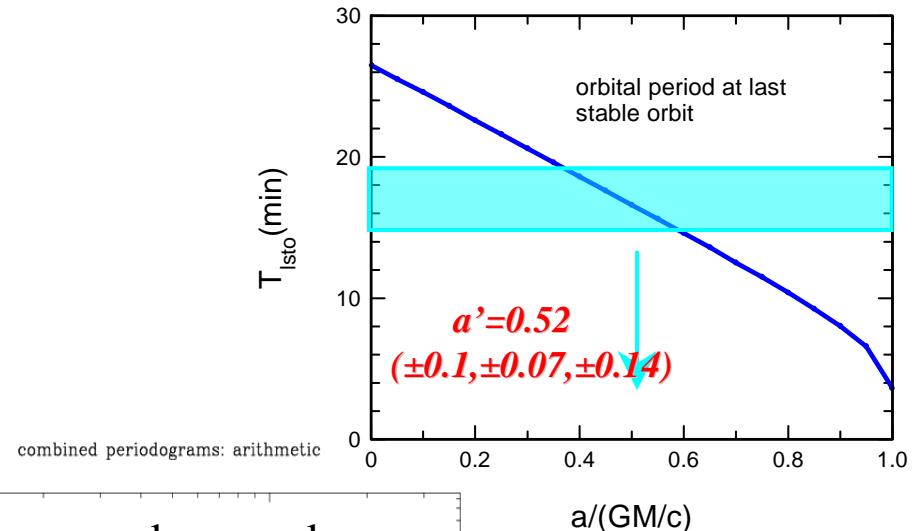
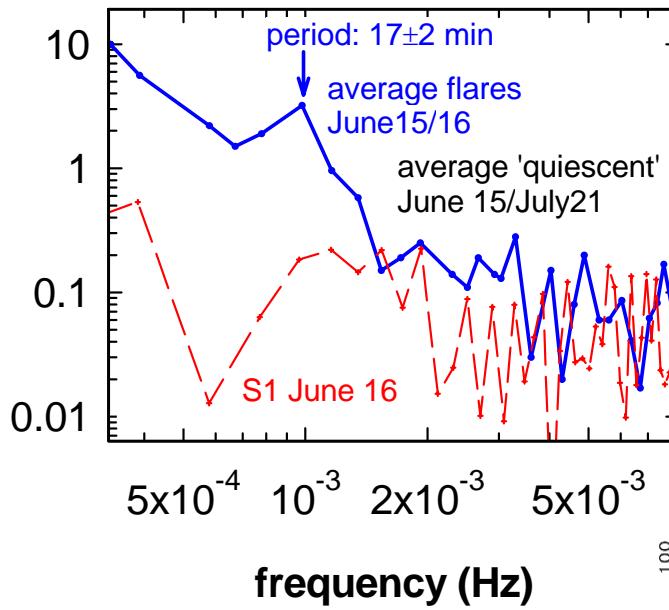
Eckart et al. 2004, 2005

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

SgrA* flare variability and evidence for significant BH spin

Normalized power spectrum



Genzel et al. 2004, Aschenbach et al. 2004, Benlloch et al. 2001, Vaughan et al. 2004, Trippe, Gillessen et al. 2005

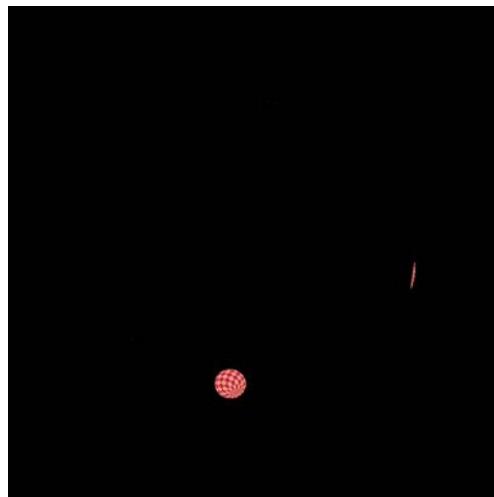
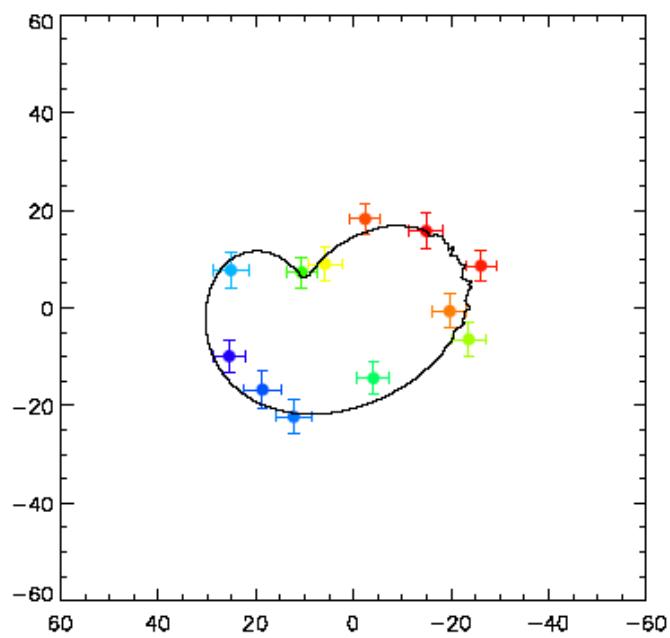
The next steps

Obvious and secret

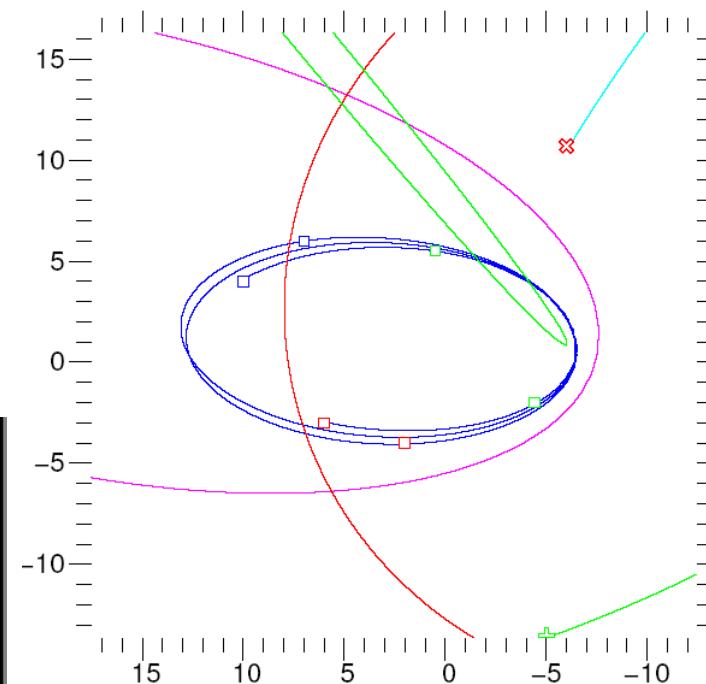
And beyond

GRAVITY: Probing Space Time

Proposal for 2nd generation
VLTI instruments by MPE,
Paris observatory, Cologne
University



3 Schwarzschild Radii



Paumard et al. 2005
Eisenhauer et al. 2005