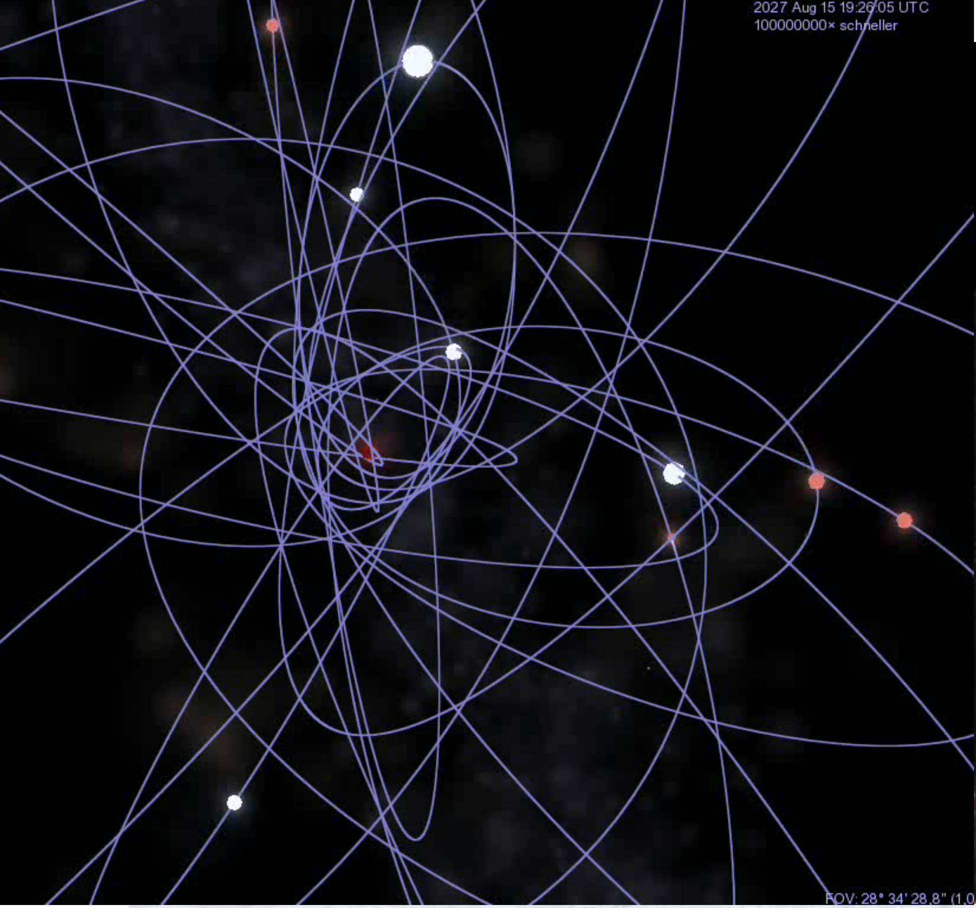
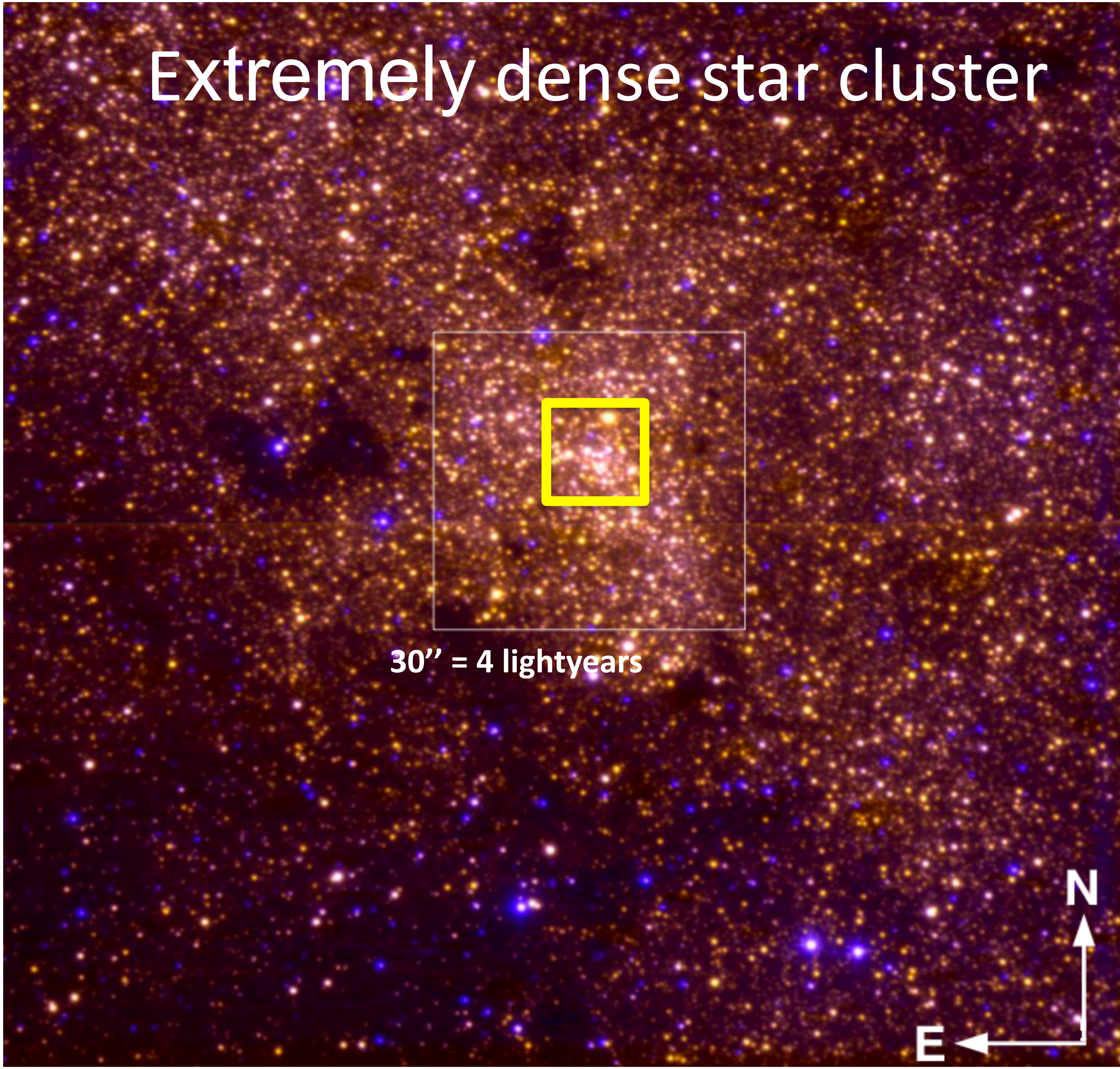


A unique laboratory: The Massive Black Hole in the Galactic Center

Stefan Gillessen, Reinhard Genzel, Frank Eisenhauer, Thomas Ott,
Hendrik Bartko, Katie Dodds-Eden, Oliver Pfuhl, Tobias Fritz

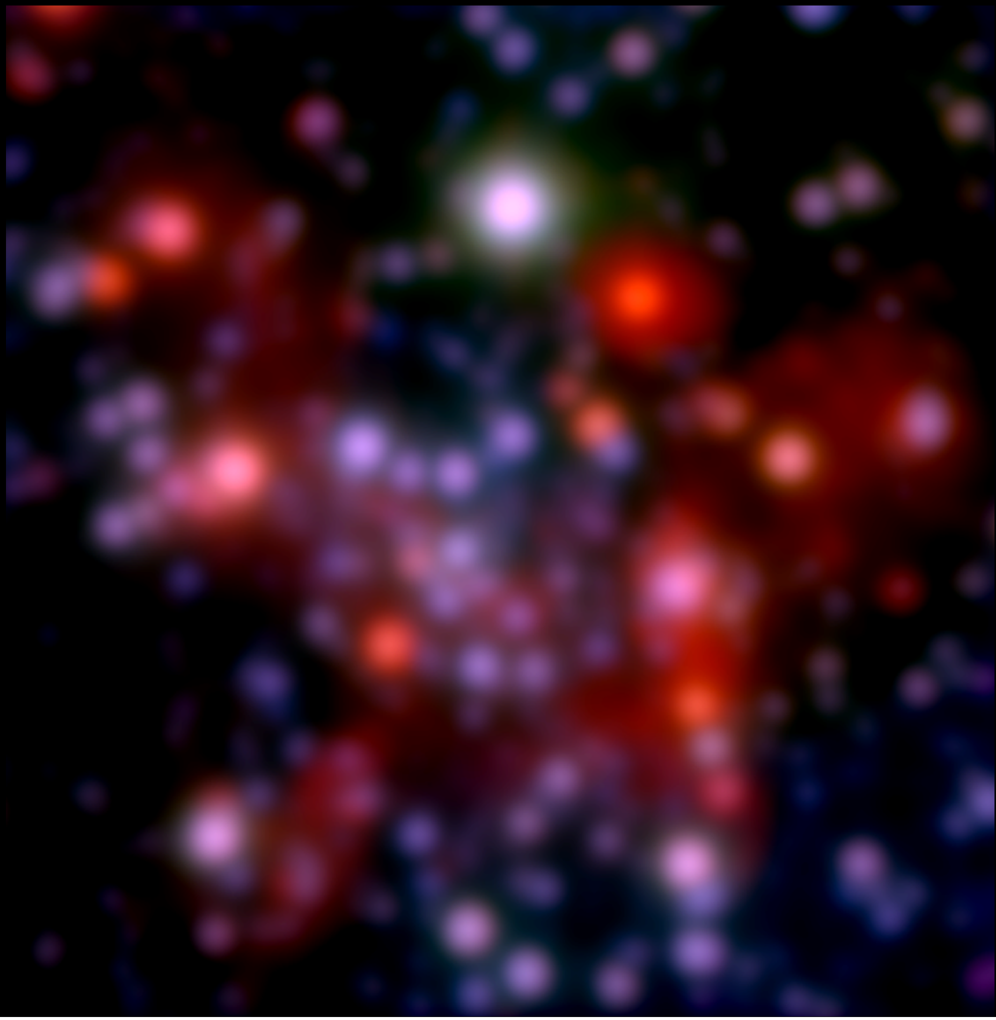
MPE

Extremely dense star cluster

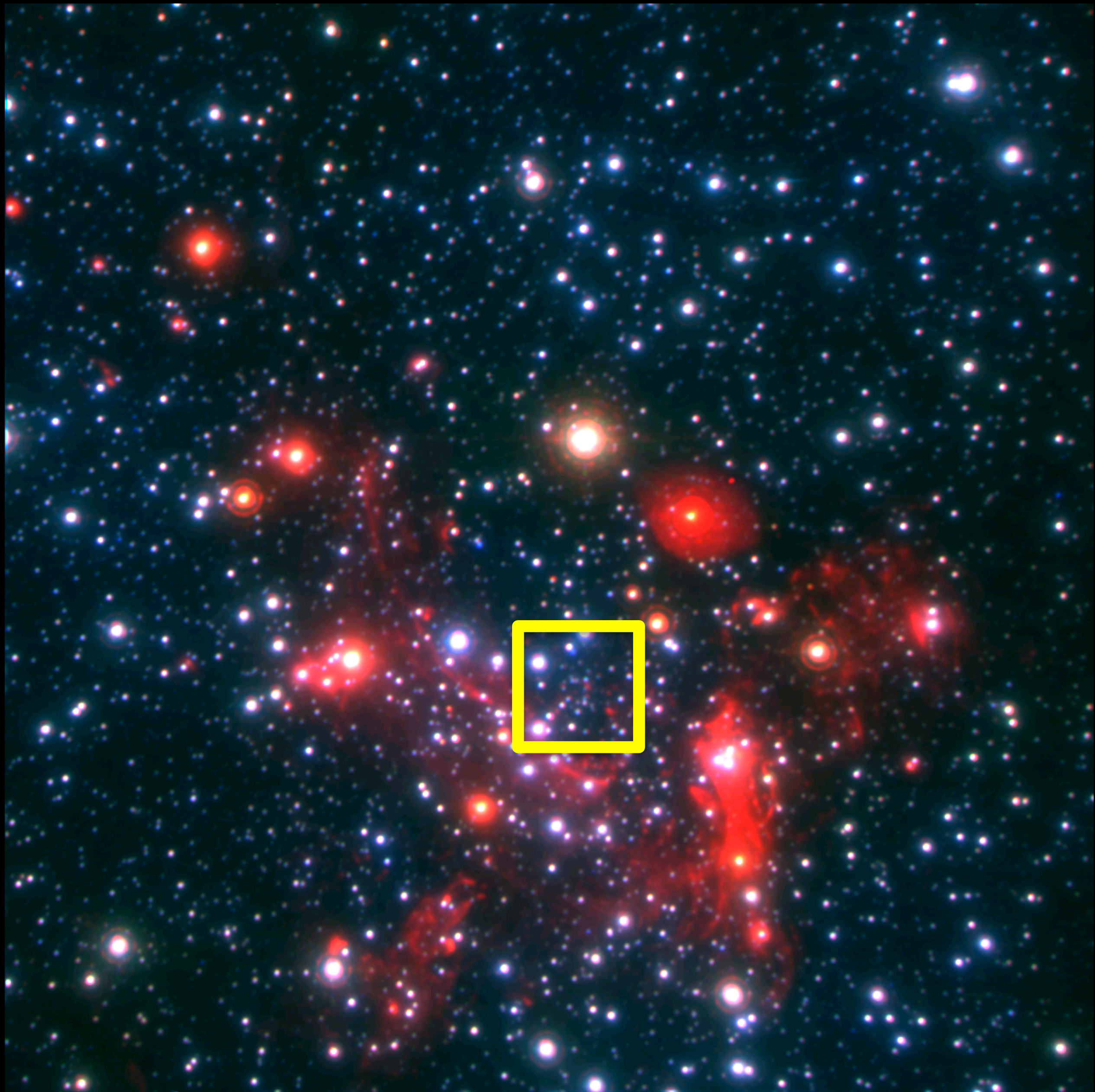


Schödel+ 2006
(ISAAC, VLT)

The central 20’’: Seeing limited

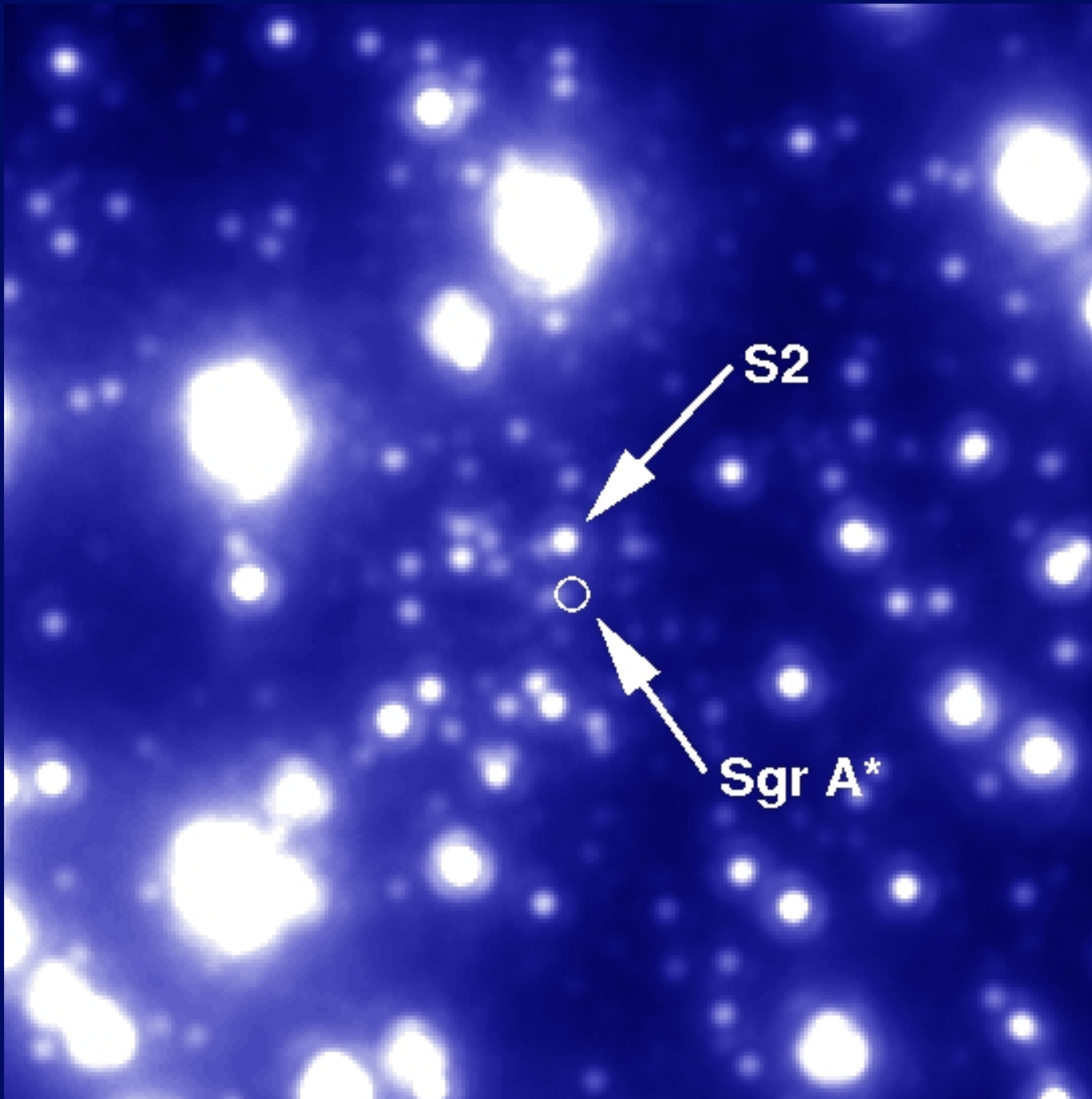


Adaptive Optics

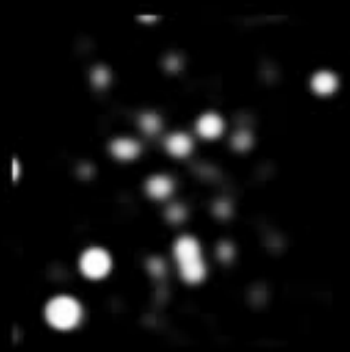


NACO,
HKL color composite

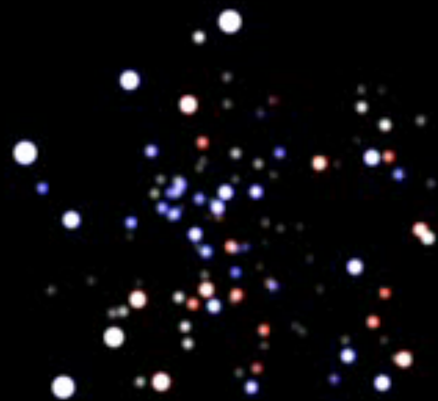
Diffraction-limited images



Stars move on Keplerian orbits

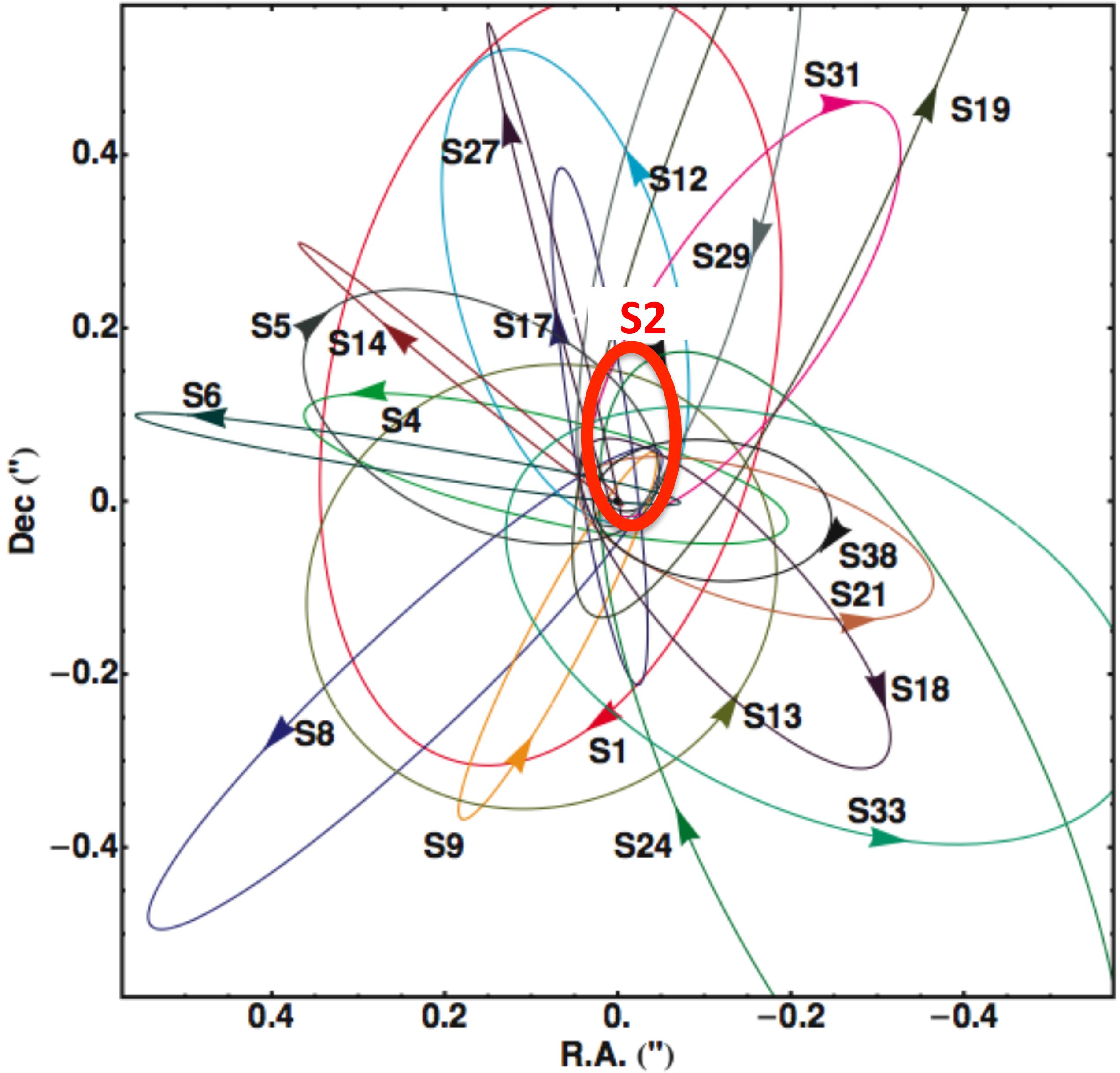


Real Data (!)

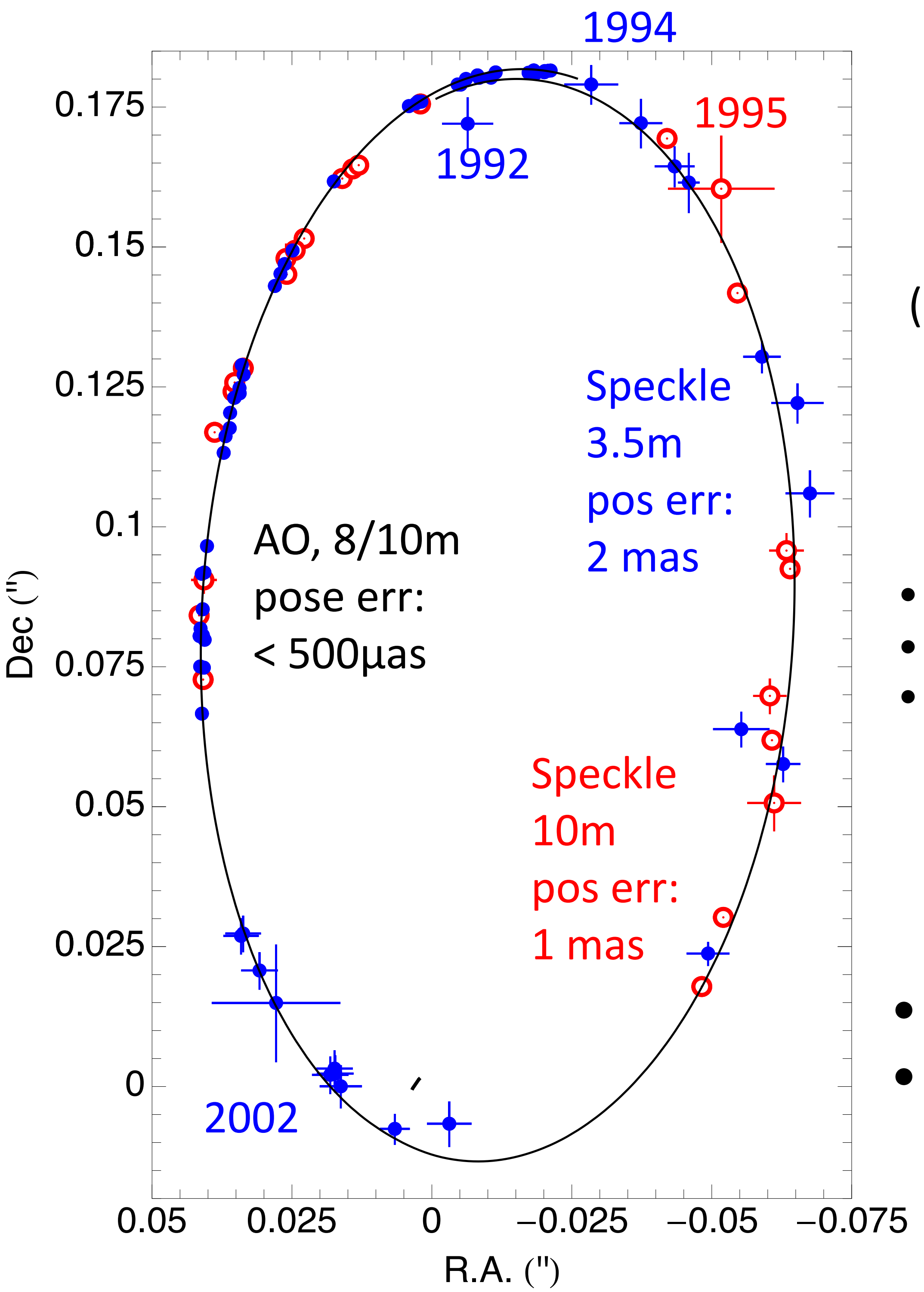


Model

Currently: 30 orbits known



20 stars shown,
Gillessen+ 2009



VLT & Keck data suitably combined

(Gillessen et al. 2009, ApJL, 707, 114)

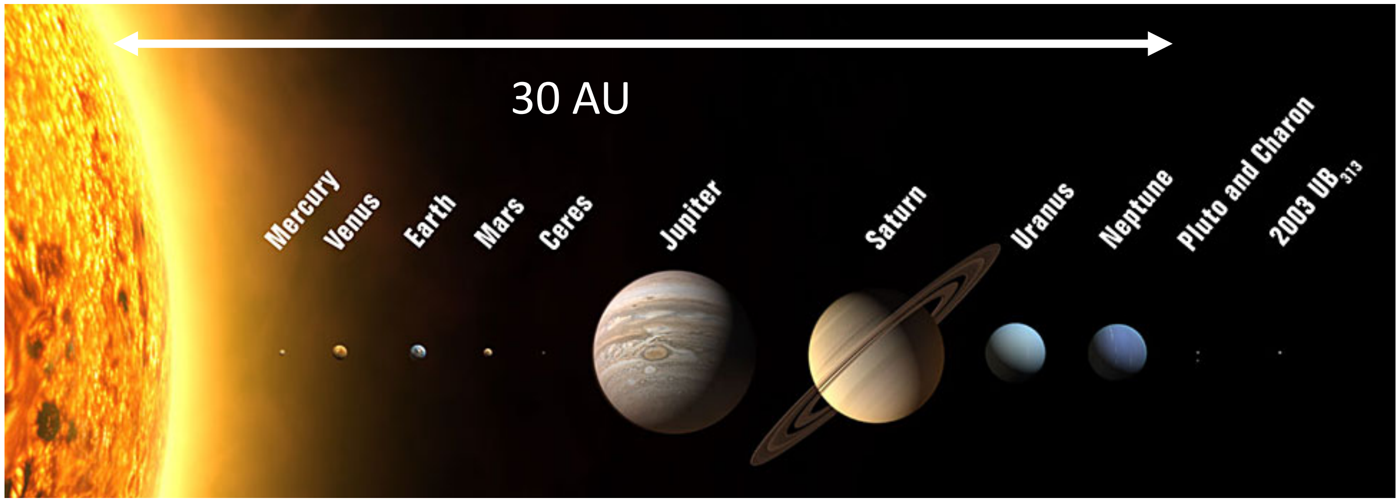
- period: 15.9 years
- semi major axis: 125 mas
- eccentricity 0.88

- $M = 4.30 \pm 0.06 \pm 0.35 \times 10^6\ M_\odot$
- $R_0 = 8.28 \pm 0.15 \pm 0.30$ kpc

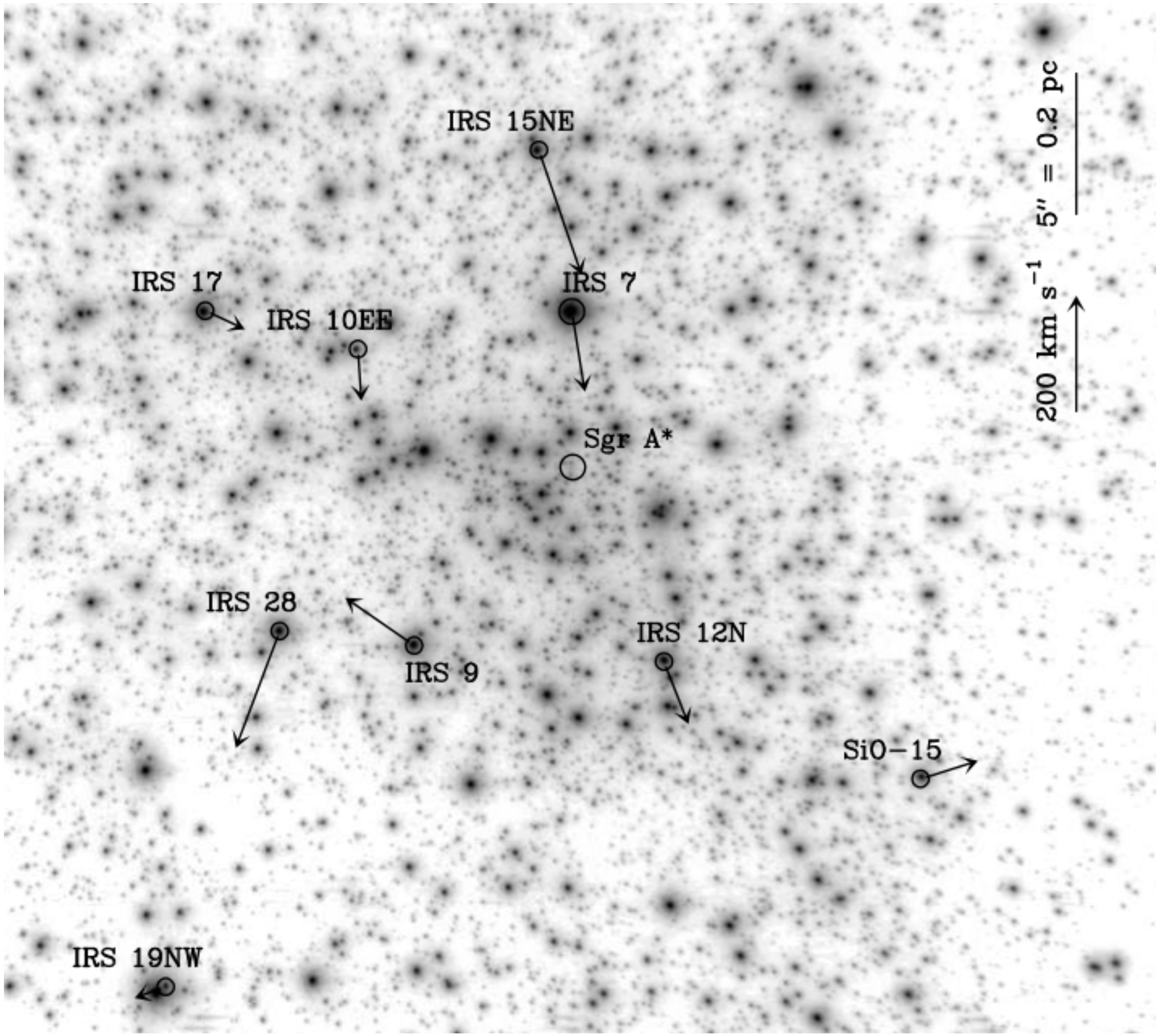
$M = 4 \times 10^6\ M_\odot$ in 100 AU

$$
\begin{aligned}
M &= 4\pi^2 \frac{a^3}{GT^2} \\
&= 4\pi^2 \frac{(0.12'' \times 8\,\mathrm{kpc})^3}{6.67 \times 10^{-11}\,\mathrm{m^3 kg^{-1} s^{-2}} \times 15.2\,\mathrm{yr}^2} \\
&= 4 \times 10^6 M_\odot
\end{aligned}
$$

$$
\begin{aligned}
p &= a(1-e) \\
&= 0.12'' \times 8\,\mathrm{kpc} \times (1 - 0.9) \\
&= 100\,\mathrm{AU}
\end{aligned}
$$



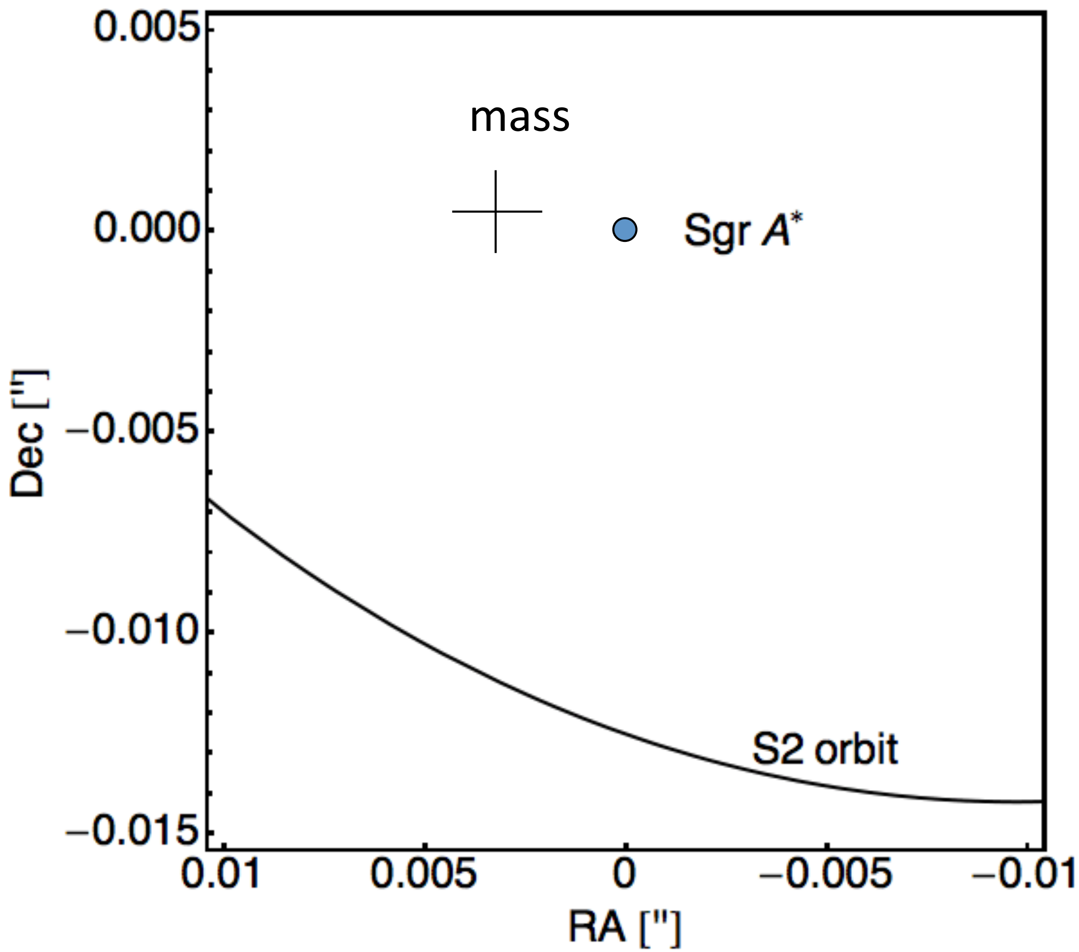
IR coordinate system is tied to ICRF with 9 radio SiO masers



Reid+ 2007

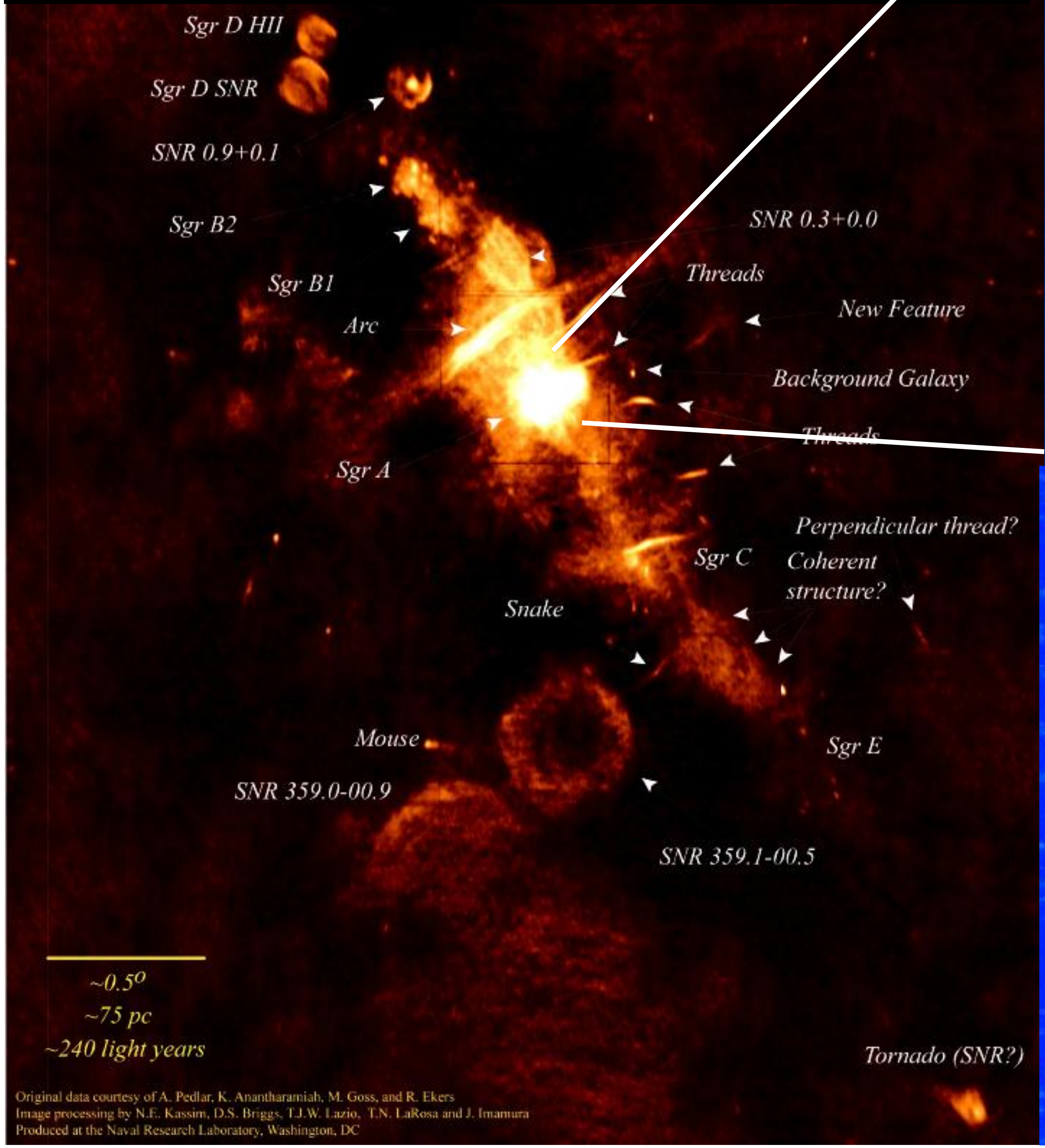
Sgr A* and mass coincide to ~ 3 mas

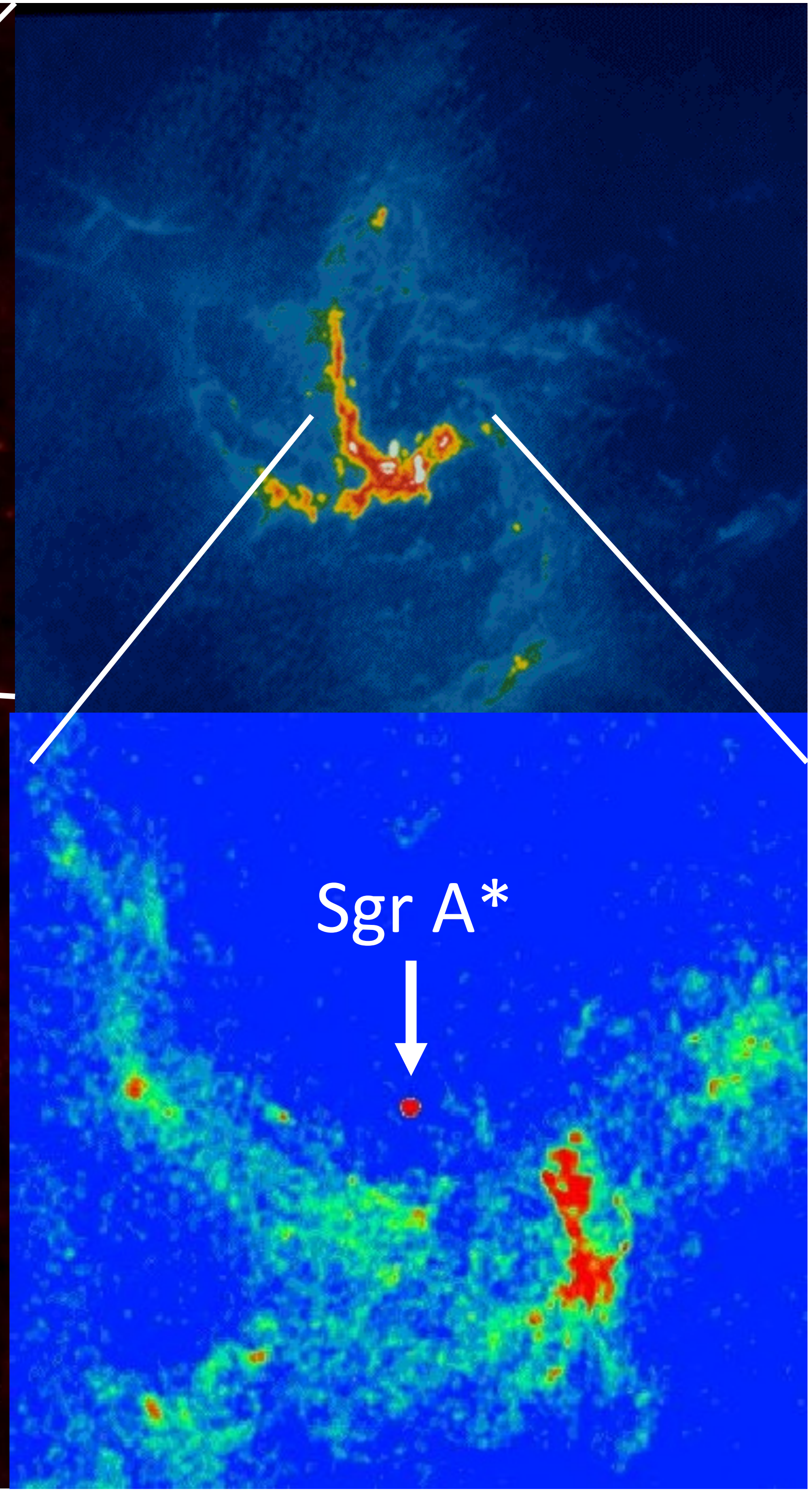
$$\alpha_{\mathrm{MBH}} = 2.9 \pm 0.5|_{\mathrm{stat}} \pm 1.2|_{\mathrm{sys}}\,\mathrm{mas}$$
$$\delta_{\mathrm{MBH}} = 0.4 \pm 0.8|_{\mathrm{stat}} \pm 1.2|_{\mathrm{sys}}\,\mathrm{mas}$$

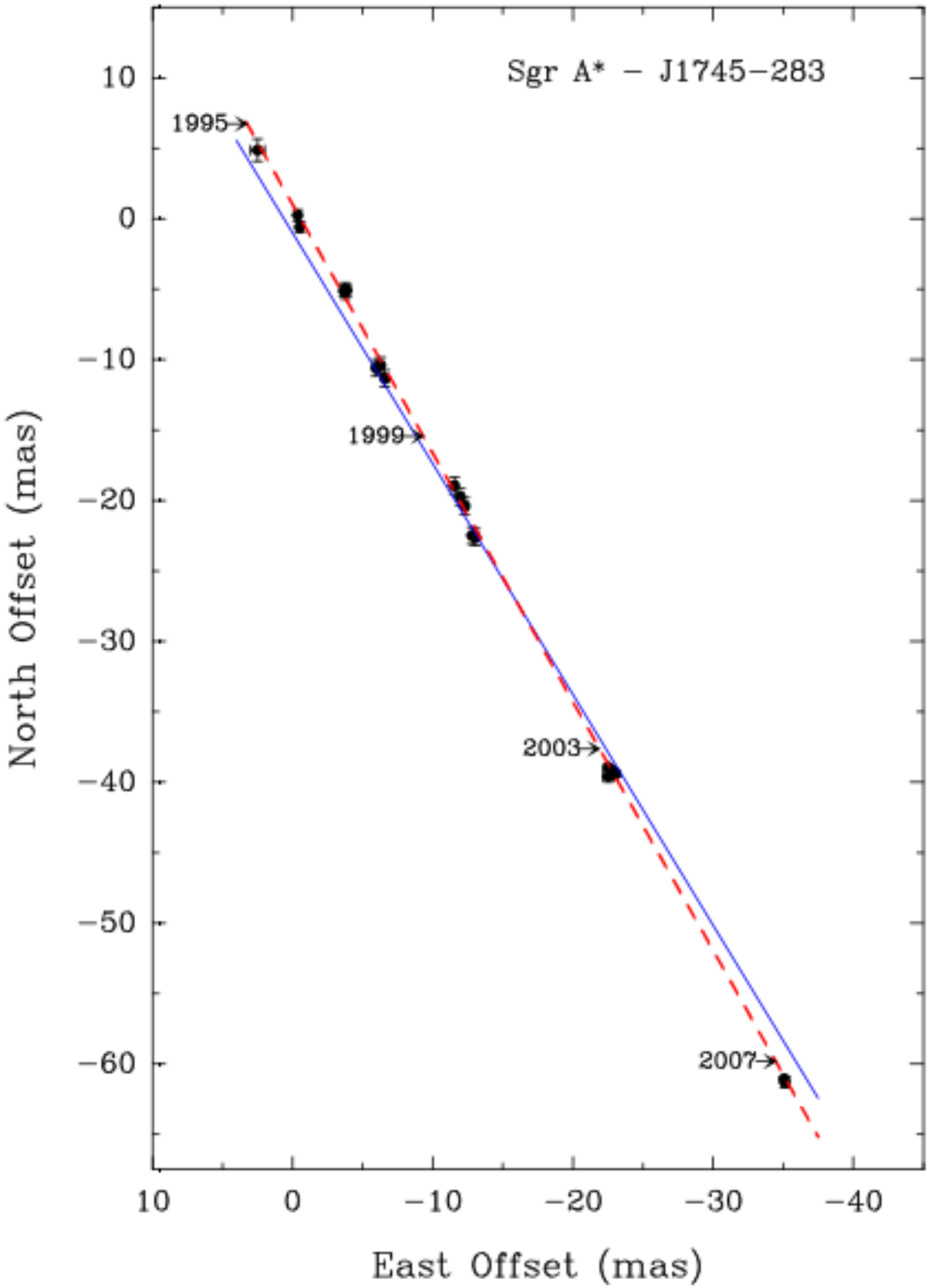


deviation < 3σ

The radio view







Sgr A* must be very heavy

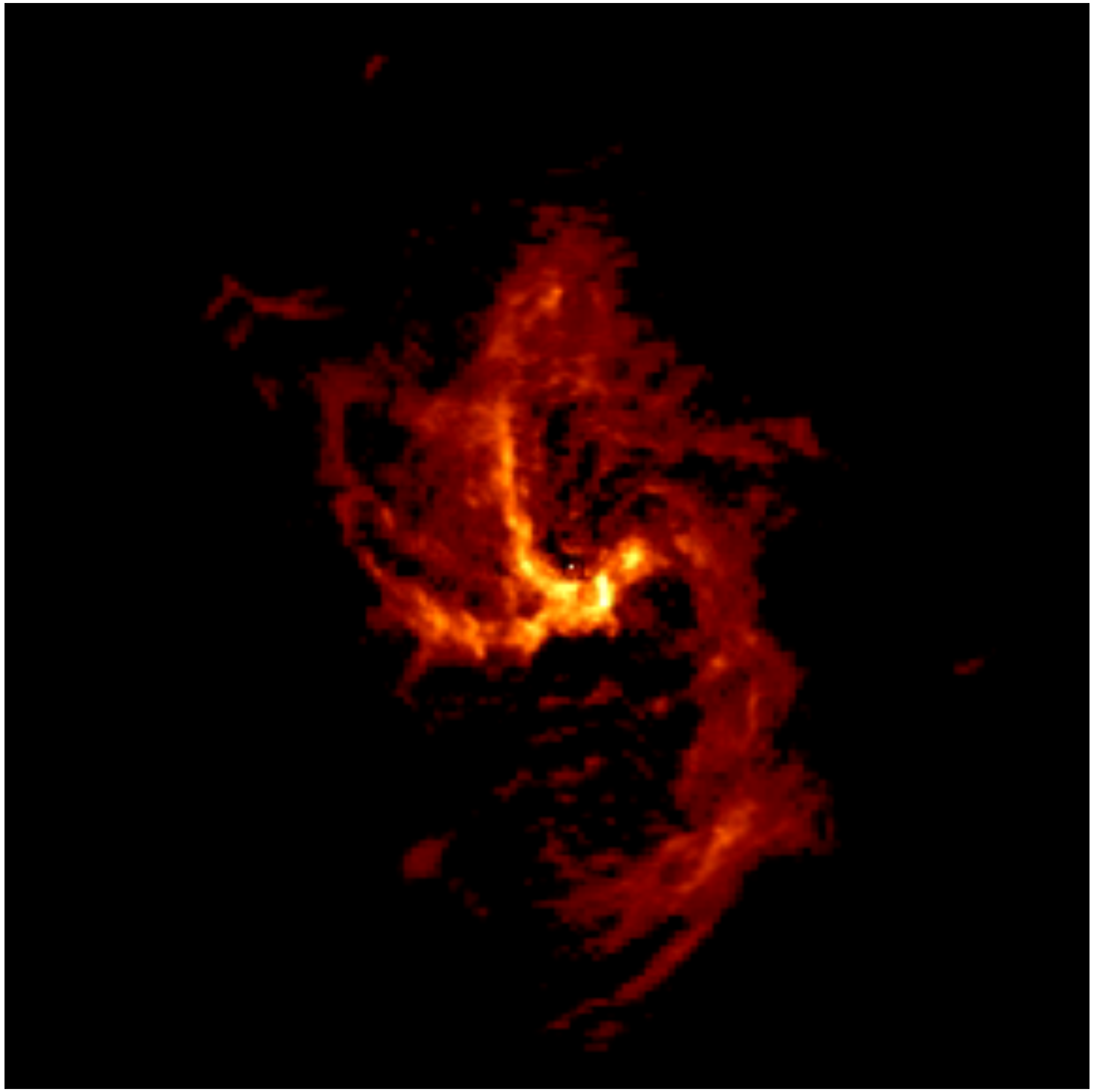
- perfectly linear motion
  - reflex motion of Sun (~200 km/s)

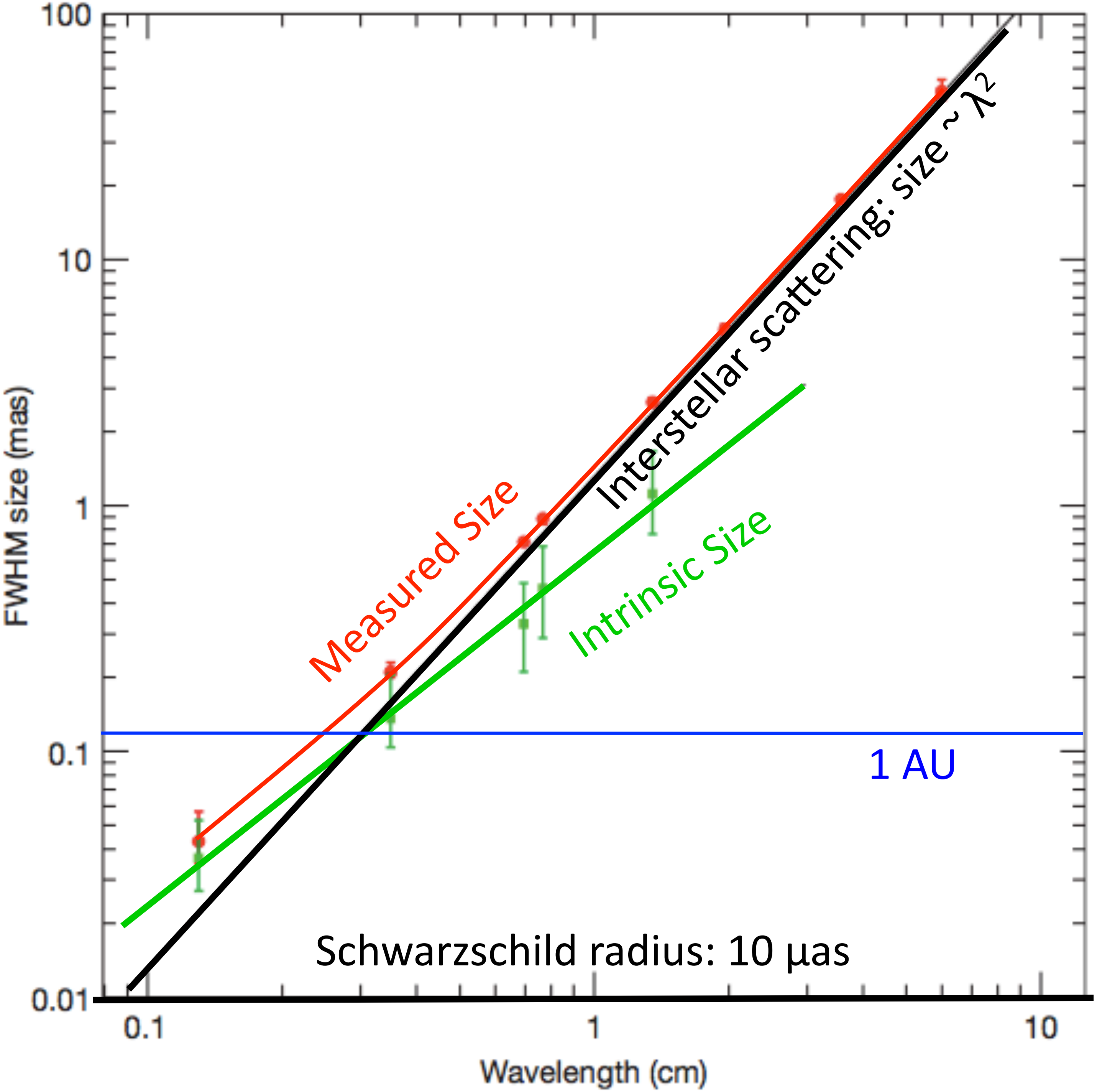
- intrinsic motion
  - gal. l : -7.2 ± 8.5 km/s
  - gal. b: -0.4 ± 0.9 km/s

- Sgr A* is much heavier than surrounding stars
  - > $4 \times 10^5\ M_\odot$

Reid 2007, 2009

Sgr A* is extremely small

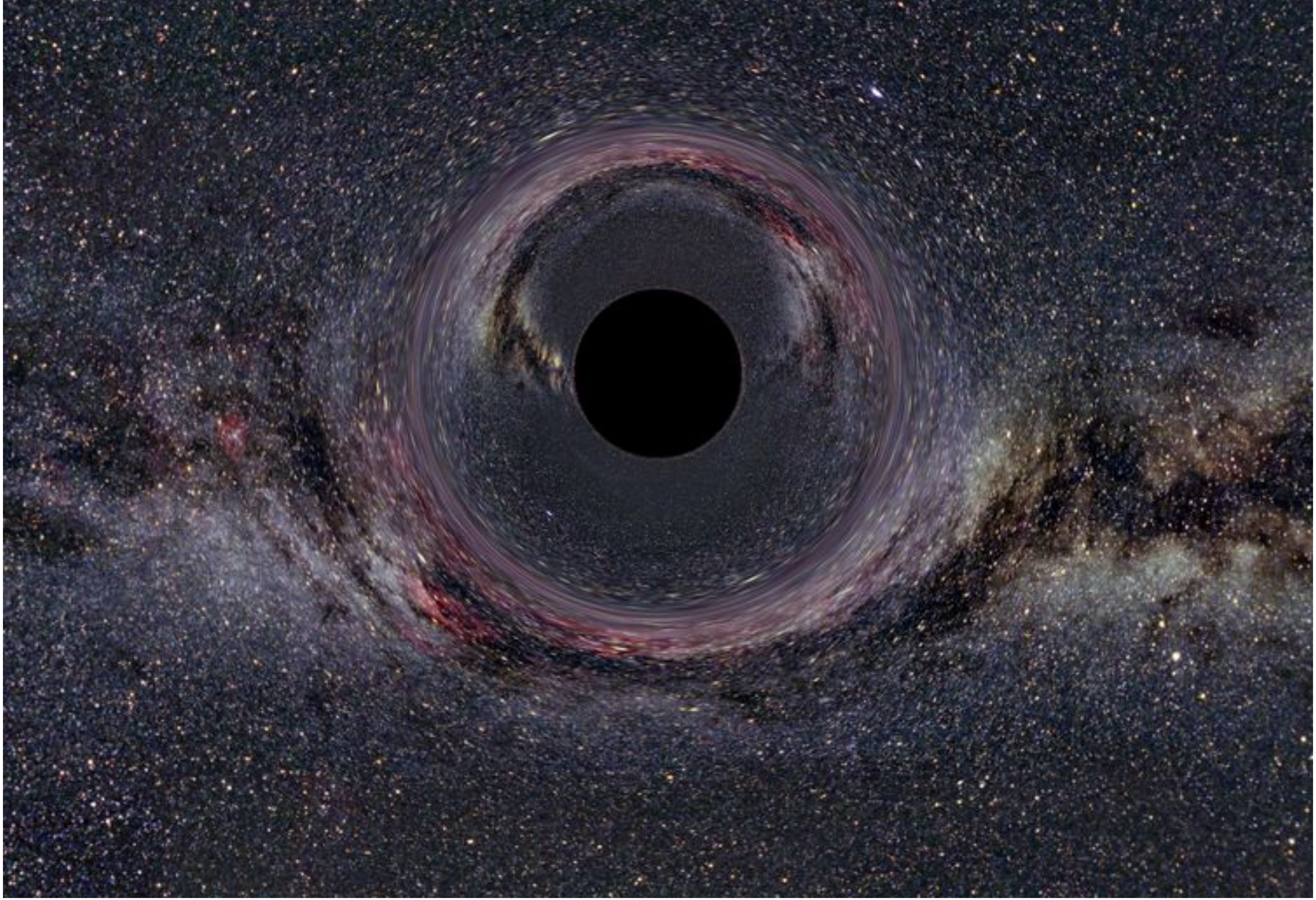




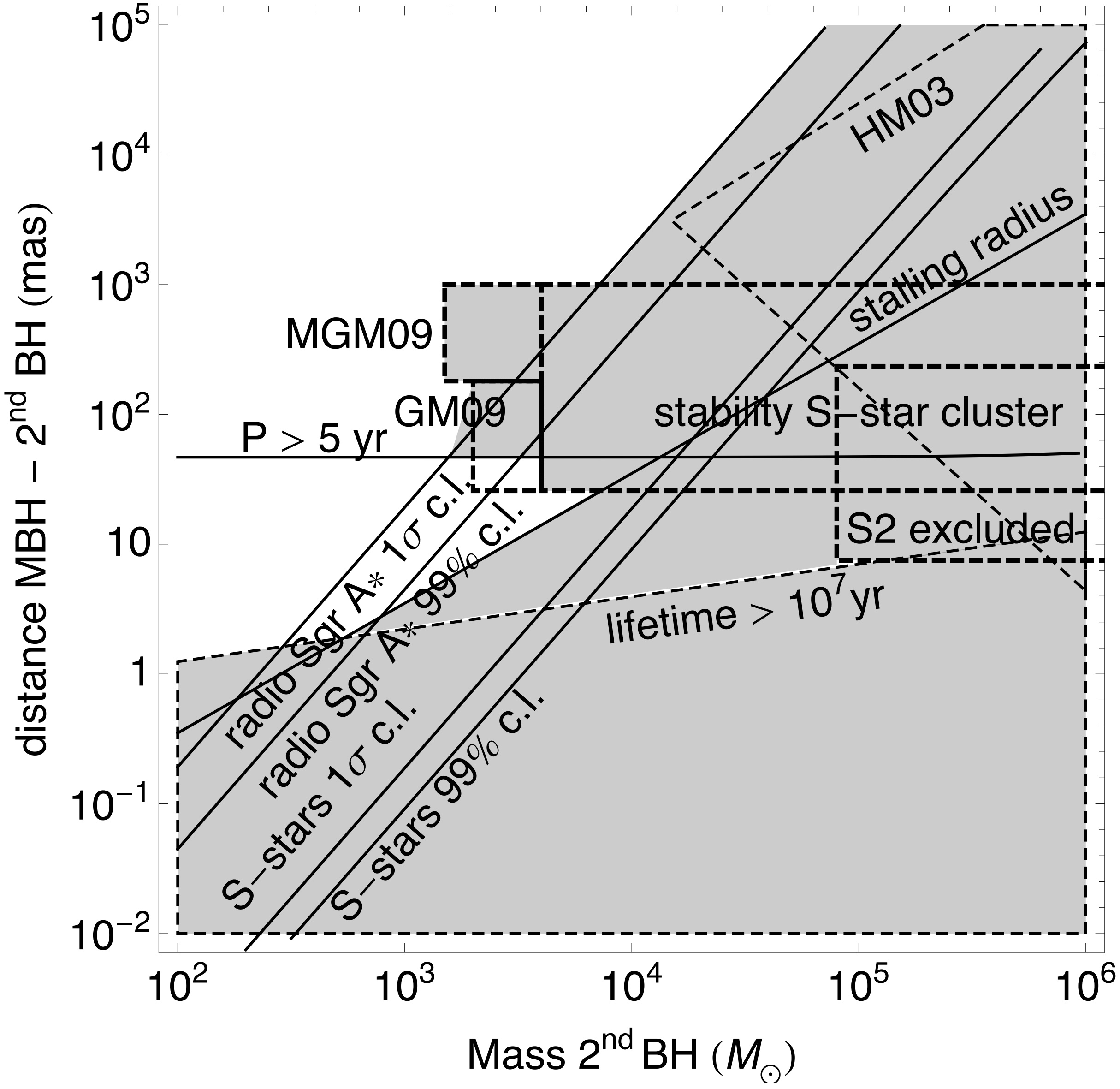
r < 1AU

Shen et al. 2005
Bower et al. 2006
Doeleman et al. 2008
(VLBI)

A rock solid case: Sgr A* is the MBH



A potential second BH in the GC would need to be light & distant



Hansen & Milosavljevic 2003,
Gualandris & Merritt 2007, 2009
Merritt, Gualandris, Mikkola 2009
Reid & Brunthaler 2004
Gillessen+ 2009

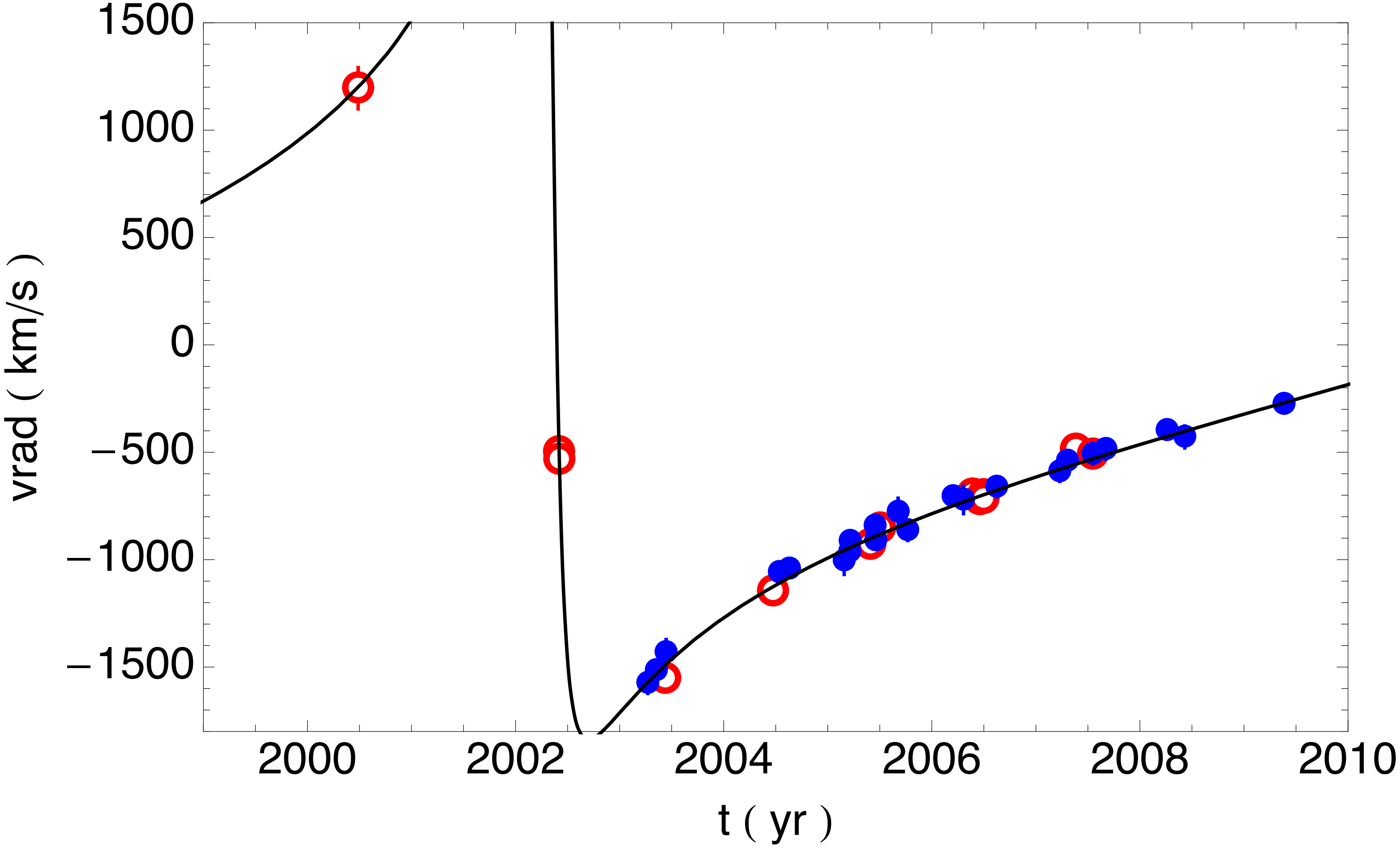
How well do we know that mass is point-like?

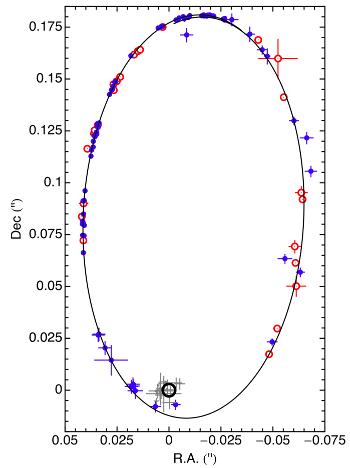
$$\eta\, M_{\rm MBH} = 4\pi \int_{\rm peri}^{\rm apo} dr\, r^2 \int dm\, n(r,m)$$

estimate	η (for $M_\star$ = 10 $M_\odot$)
extrapolating stellar number counts	3.7×10^{-4}
Drain Limit	$\leq 11 \times 10^{-4}$
Dynamical modeling	$1 - 5 \times 10^{-4}$
Number of XRB	1.5×10^{-4}
Dark Matter	$10^{-9} – 10^{-10}$

Measured: $\eta_{\rm S2} = 0.021 \pm 0.019|_{\rm stat} \pm 0.006|_{\rm model}$

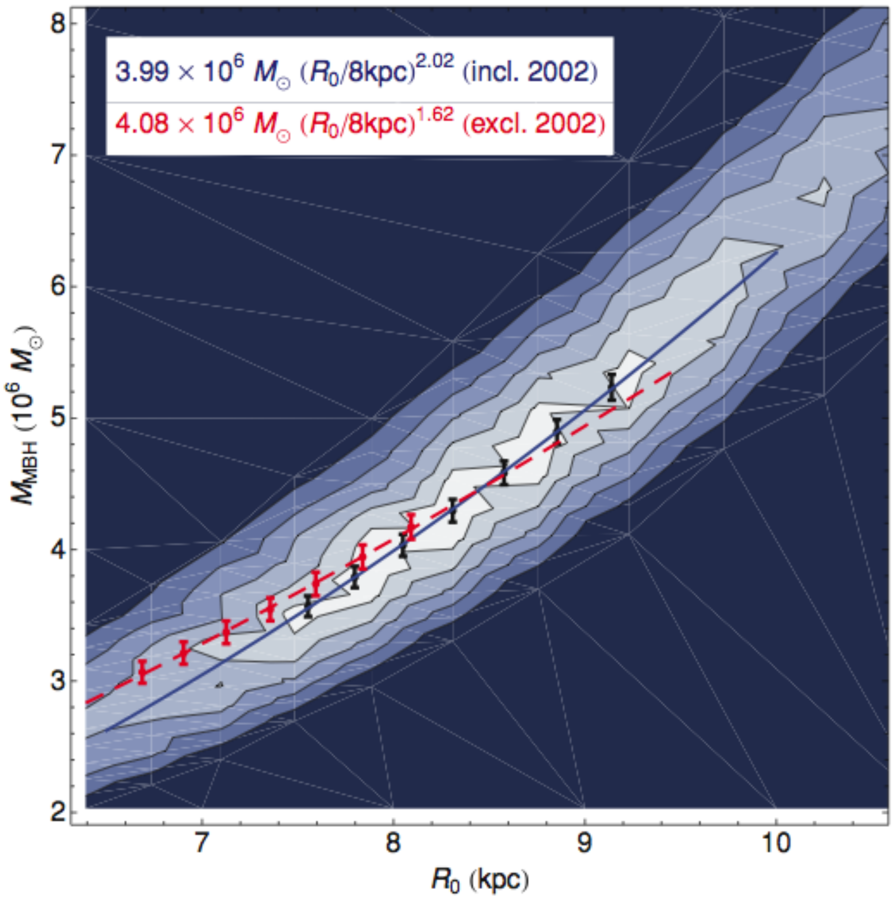
Radial velocity data & fit



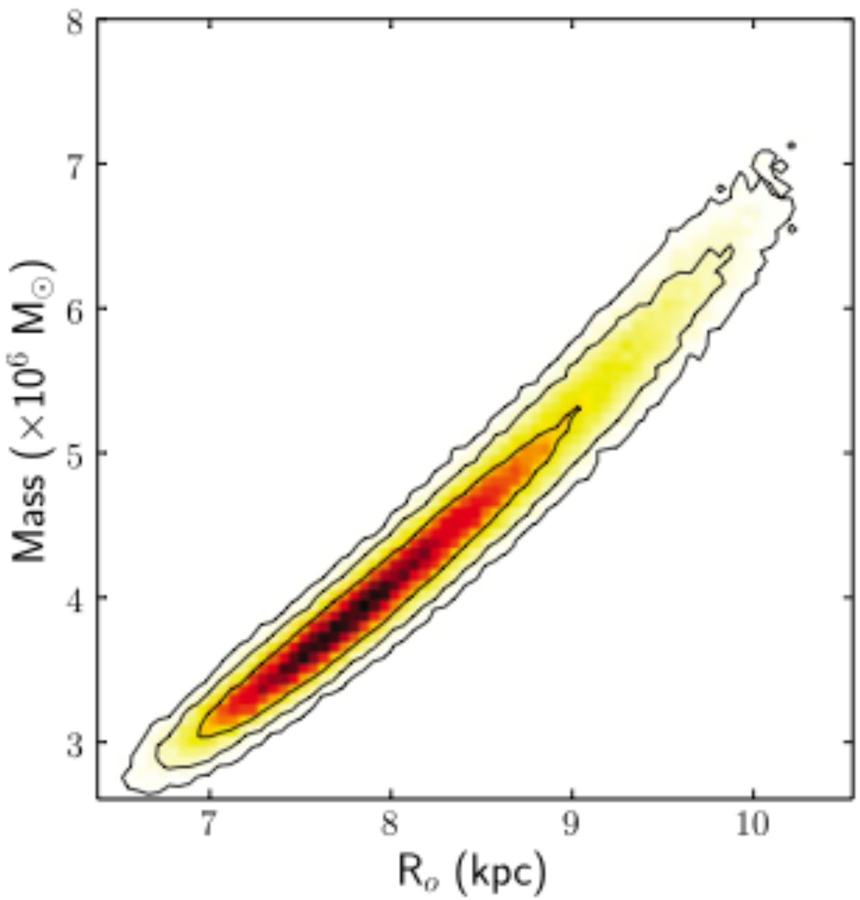


Point mass and Distance are measured & correlated

VLT (Gillessen+ 2009)



Keck (Ghez+ 2008)



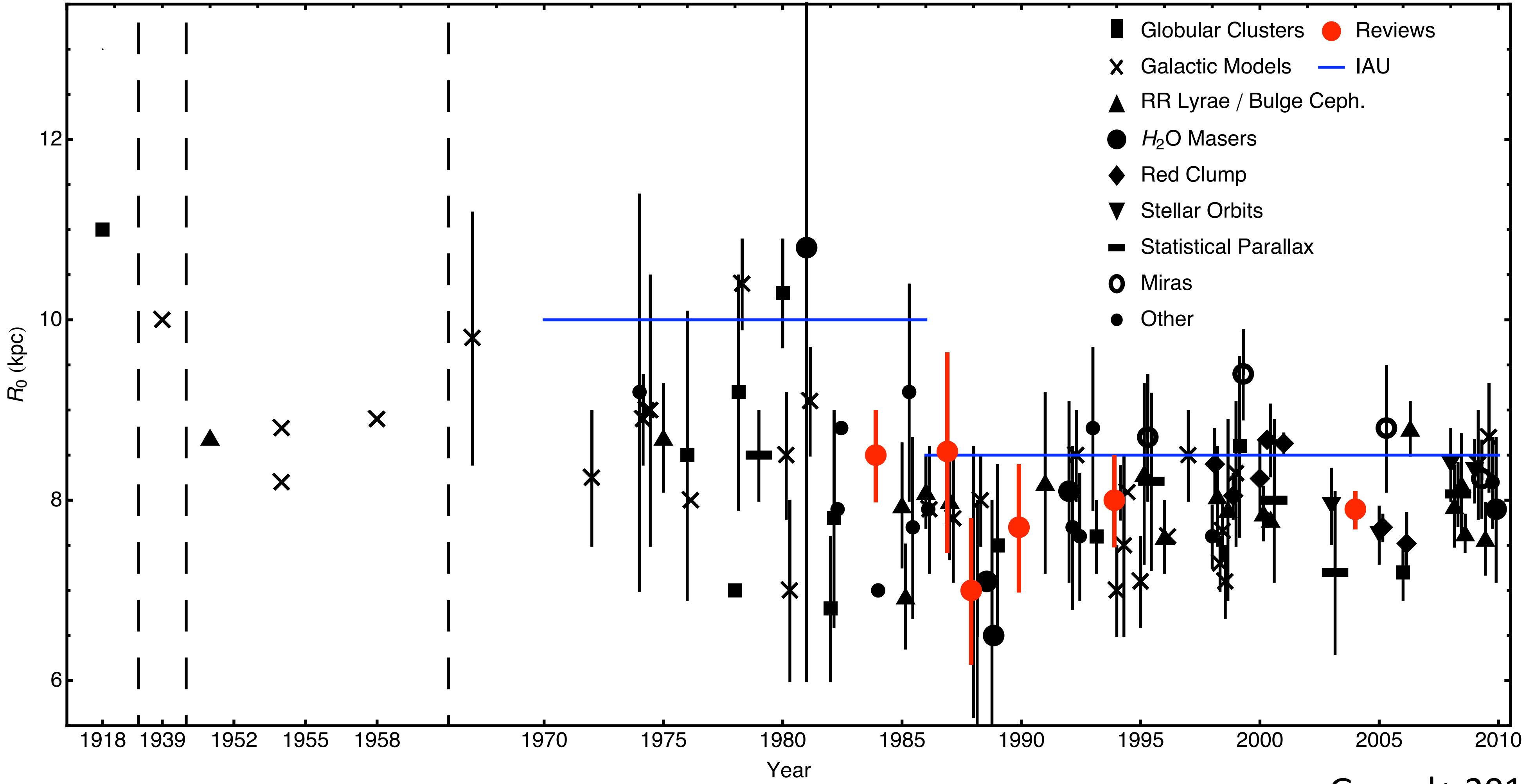
$R_0 = 8.33 \pm 0.17|_{stat} \pm 0.31|_{sys}$ kpc

$M = 4.31 \pm 0.06|_{stat} \pm 0.36|_{R0} \times 10^6 M_\odot$

$R_0 = 8.4 \pm 0.4$ kpc

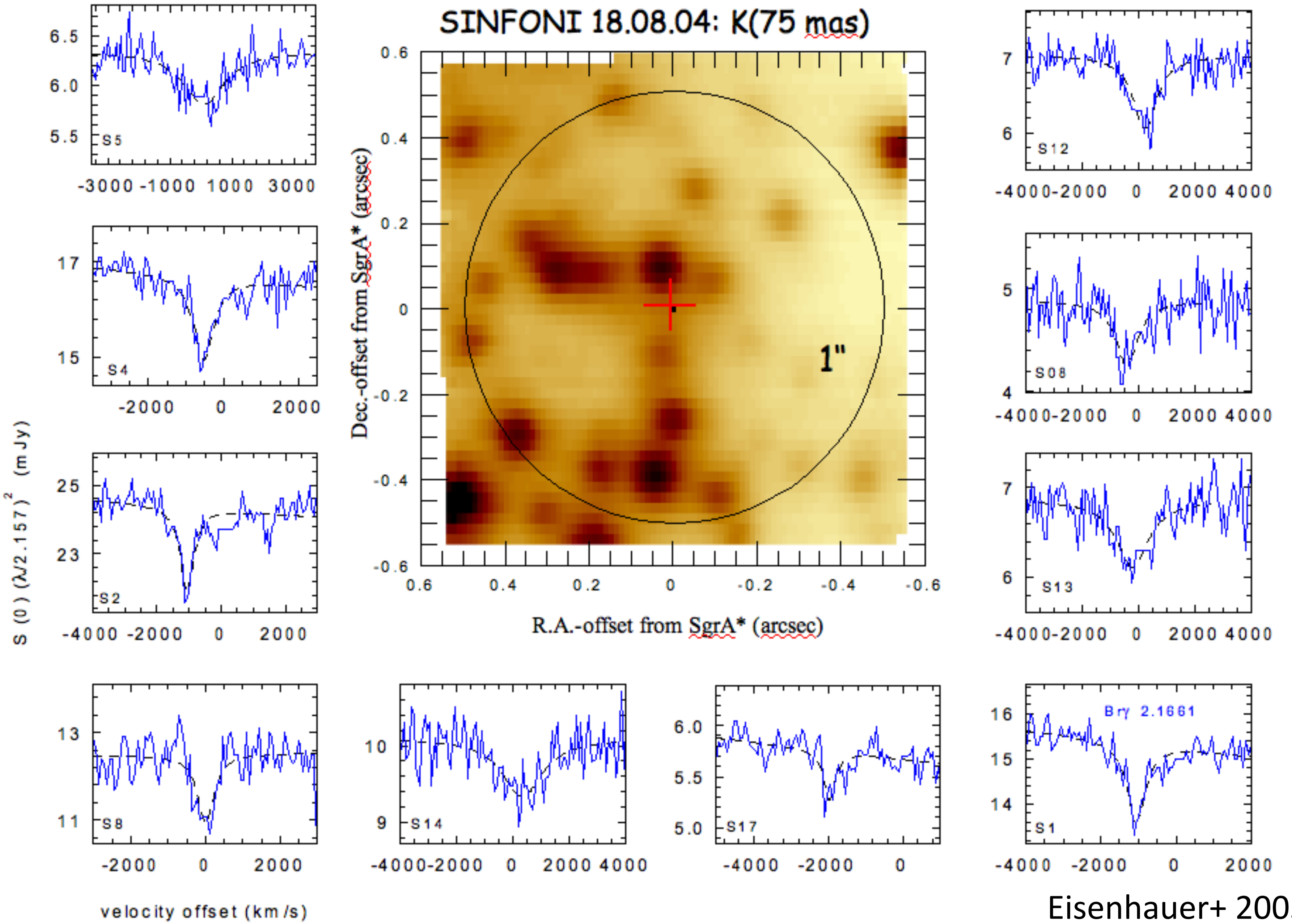
$M = 4.5 \pm 0.4 \times 10^6 M_\odot$

A short history of R_0



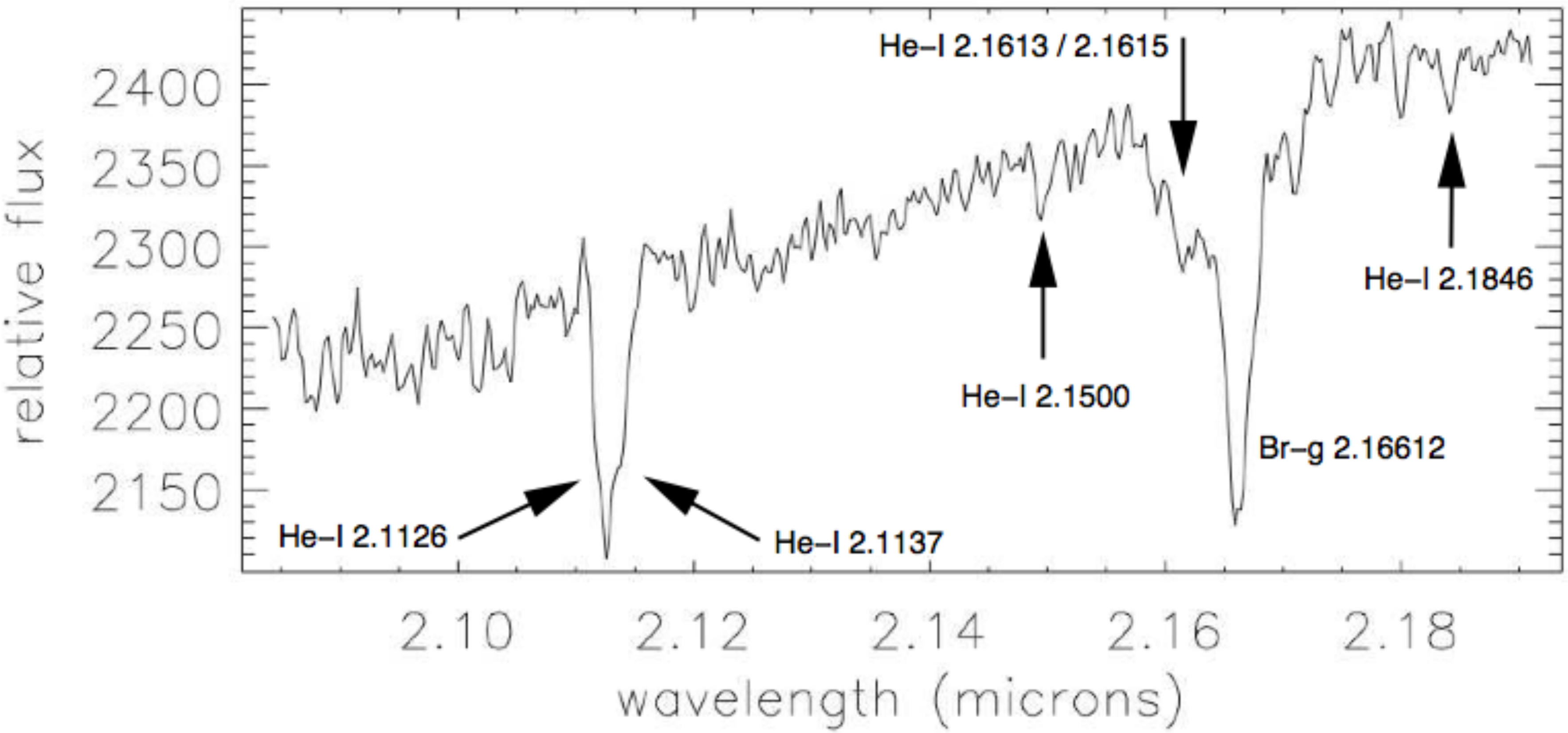
Genzel+ 2010

Surprisingly, the S-stars are young



Eisenhauer+ 2005

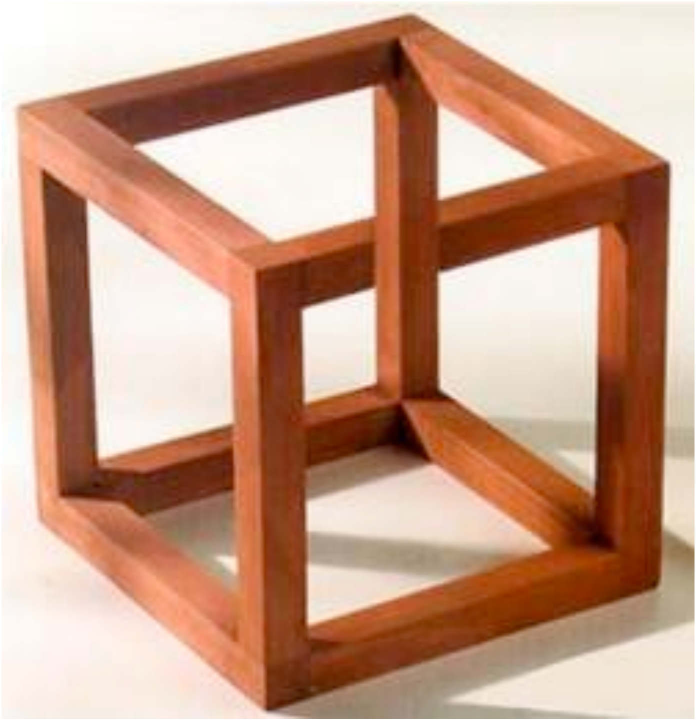
The spectrum of S2 really is that of an ordinary main sequence B2 star



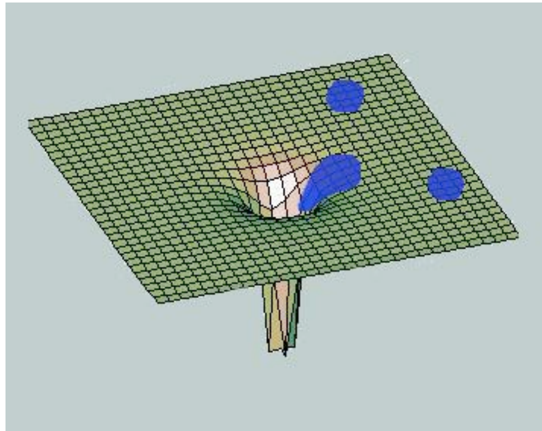
Martins+ 2008

S-stars: A Paradox of Youth

Ghez+ 2003



✧ Star formation so close the MBH impossible



✧ Stars are too young to have migrated from further out

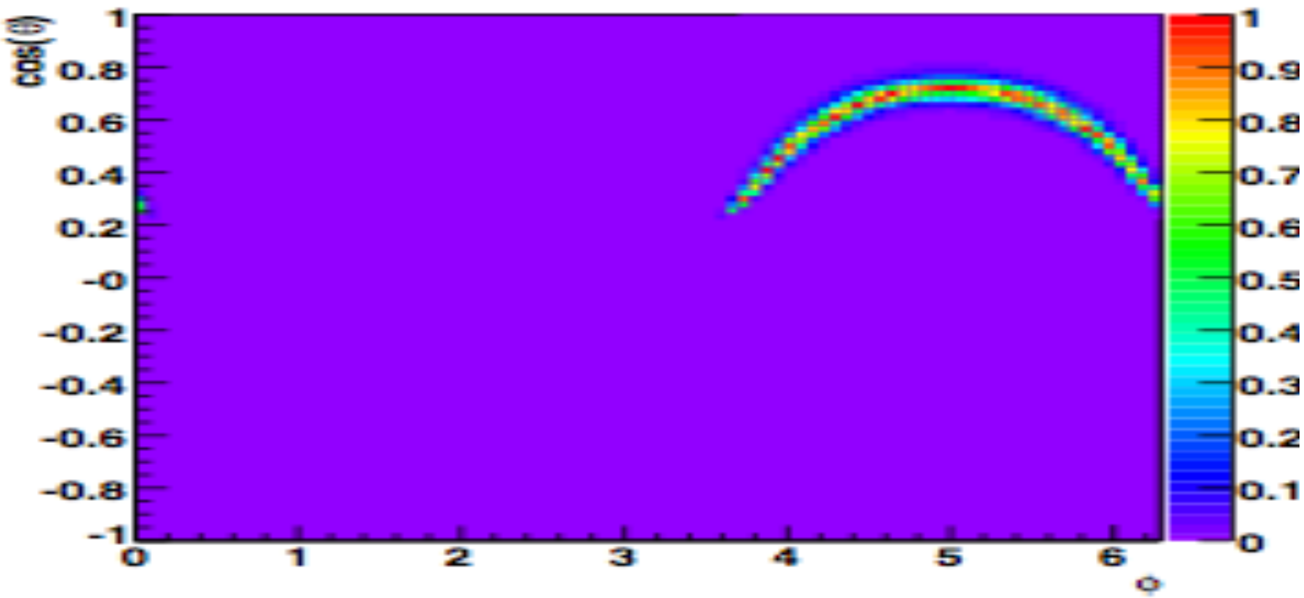
$$t_{\rm 2BR} \approx 3\,{\rm Gyr}$$

$$\gg$$

$$t_{\rm MS} \approx 0.1\,{\rm Gyr}$$

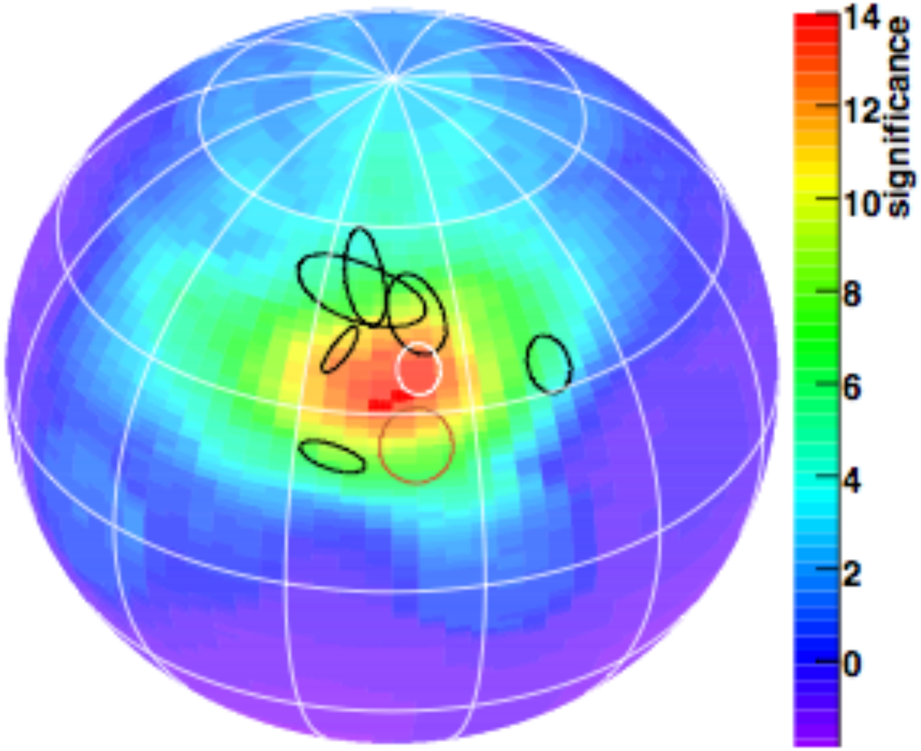
For r > 1’’: Hard to measure accelerations

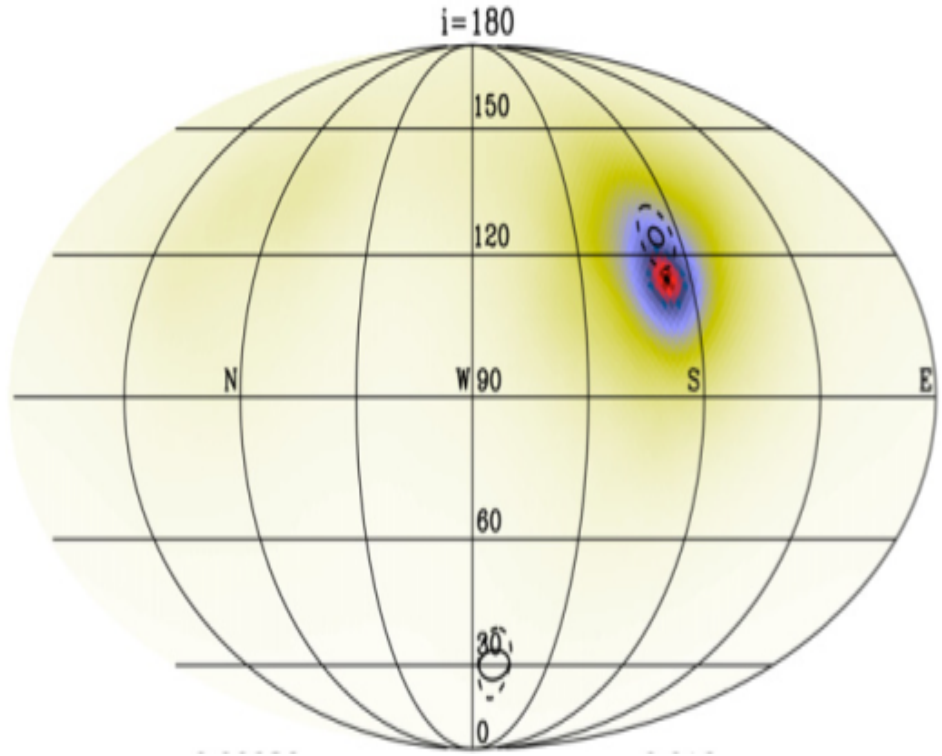
	r < 1’’	r > 1’’
x	✔	✔
y	✔	✔
vx	✔	✔
vy	✔	✔
vz	✔	✔
a_{2D}	✔	✖



(a, e, i, ω, Ω, t)

The traces for the young, clockwise moving stars intersect in one point



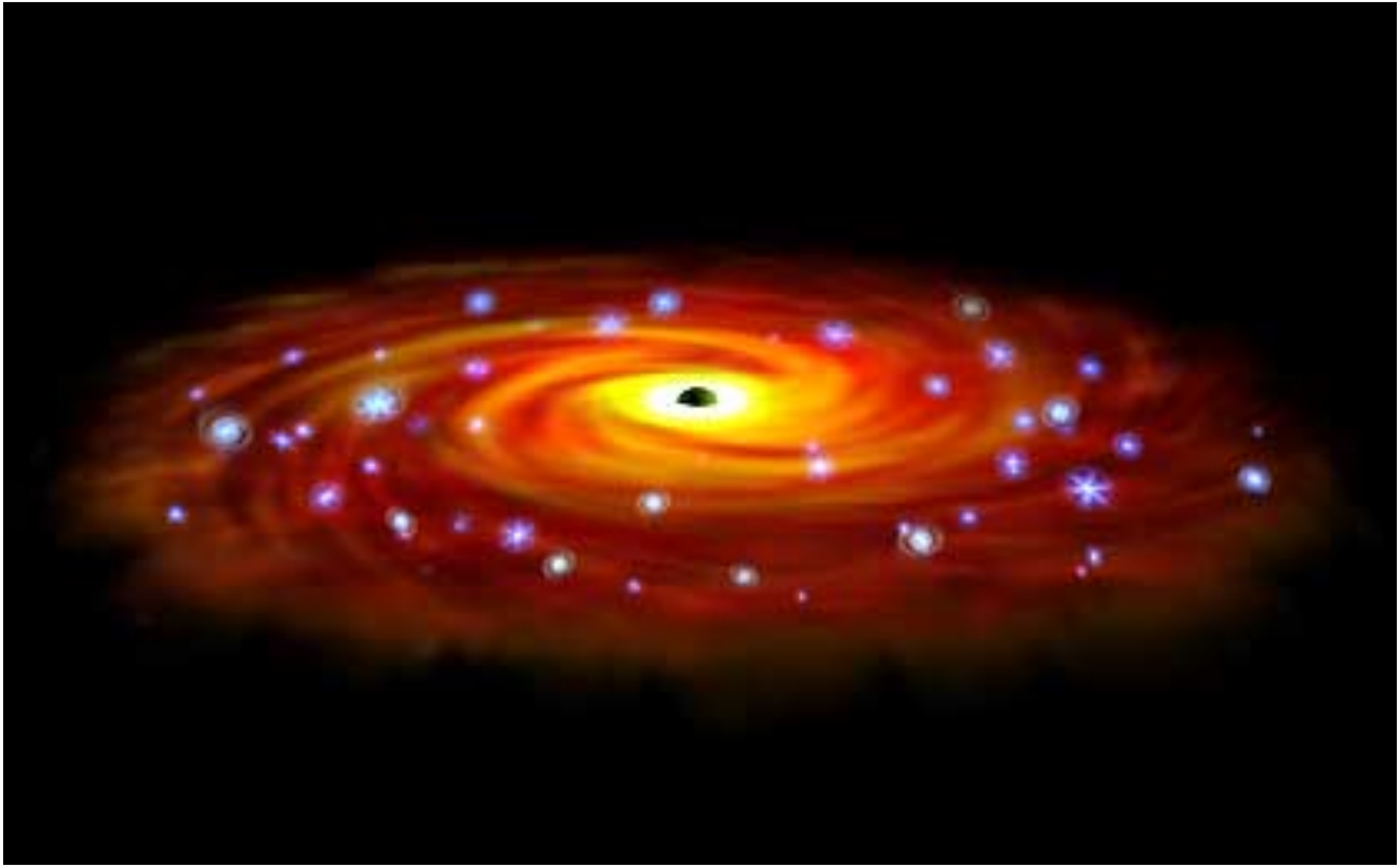


orientation of orbital angular momentum

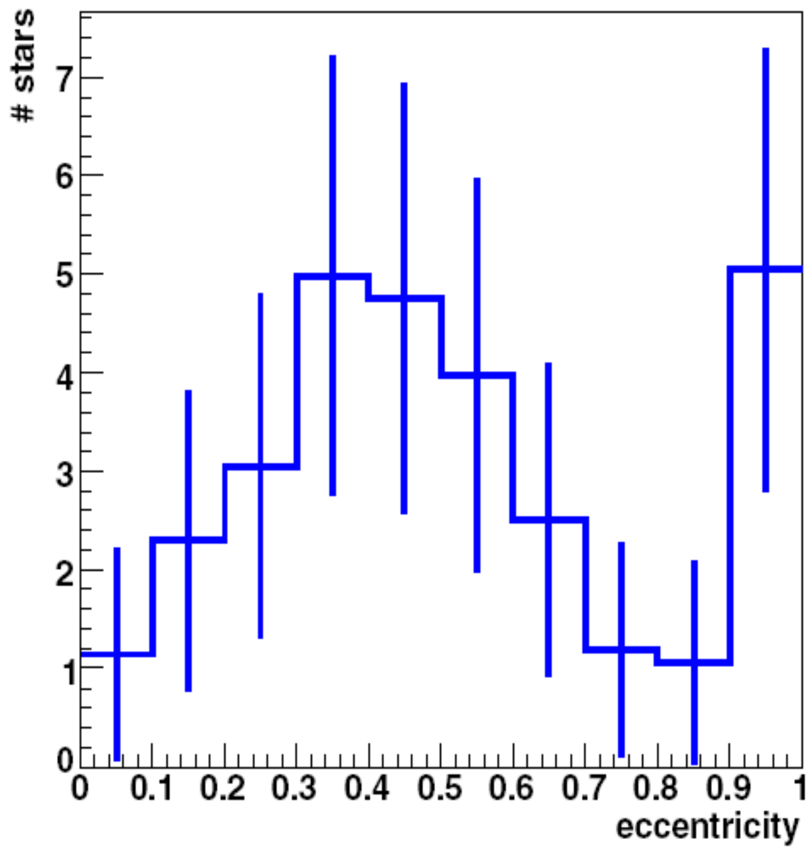
Bartko+ 2009

Lu+ 2009

(Most of) the CW moving O/WR-stars revolve in a disk



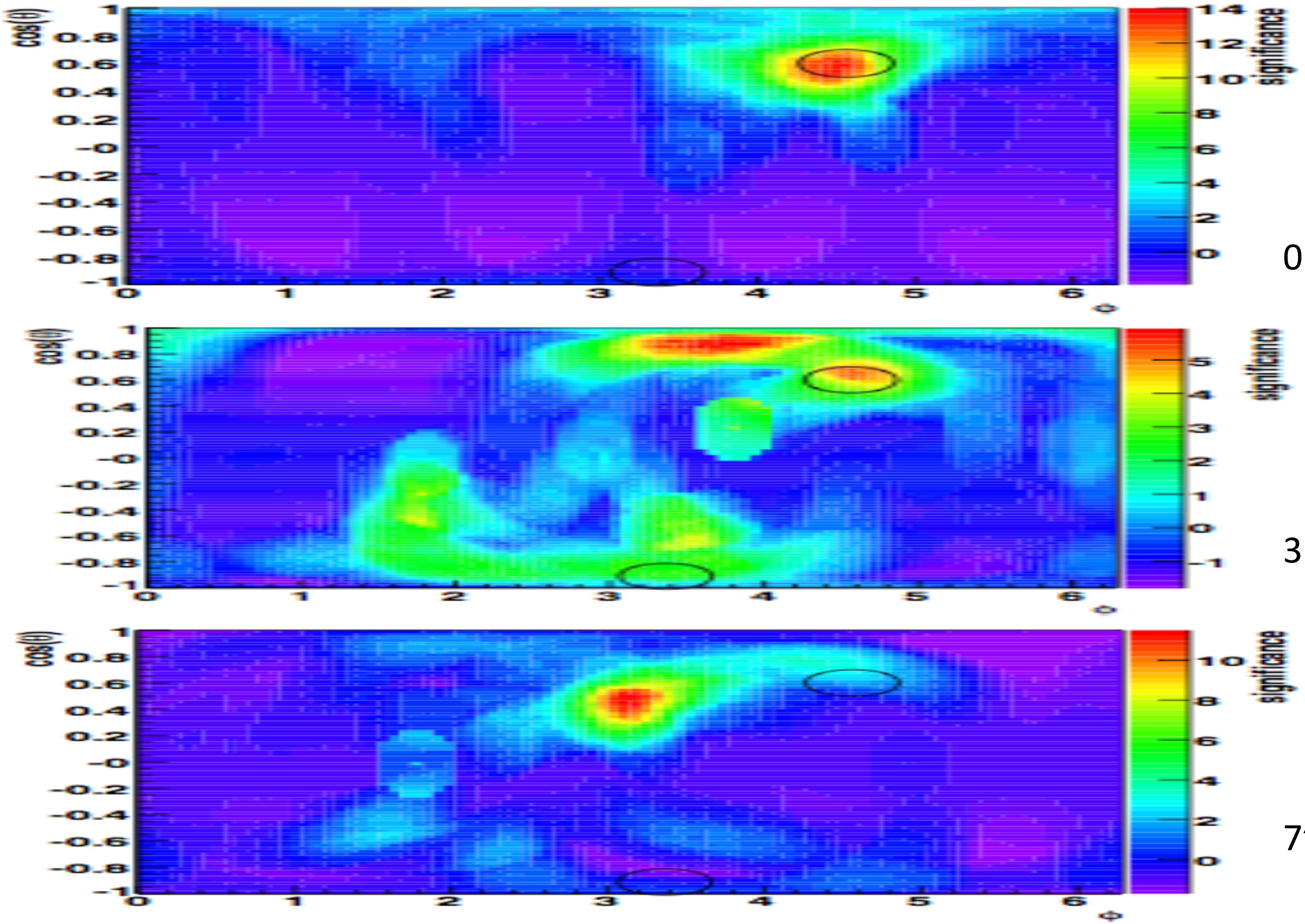
Disk orbits have <e> ≈ 0.4



Bartko+ 2009

The disk is warped & counter-CW feature at r ≈ 5''

Bartko+ 2009

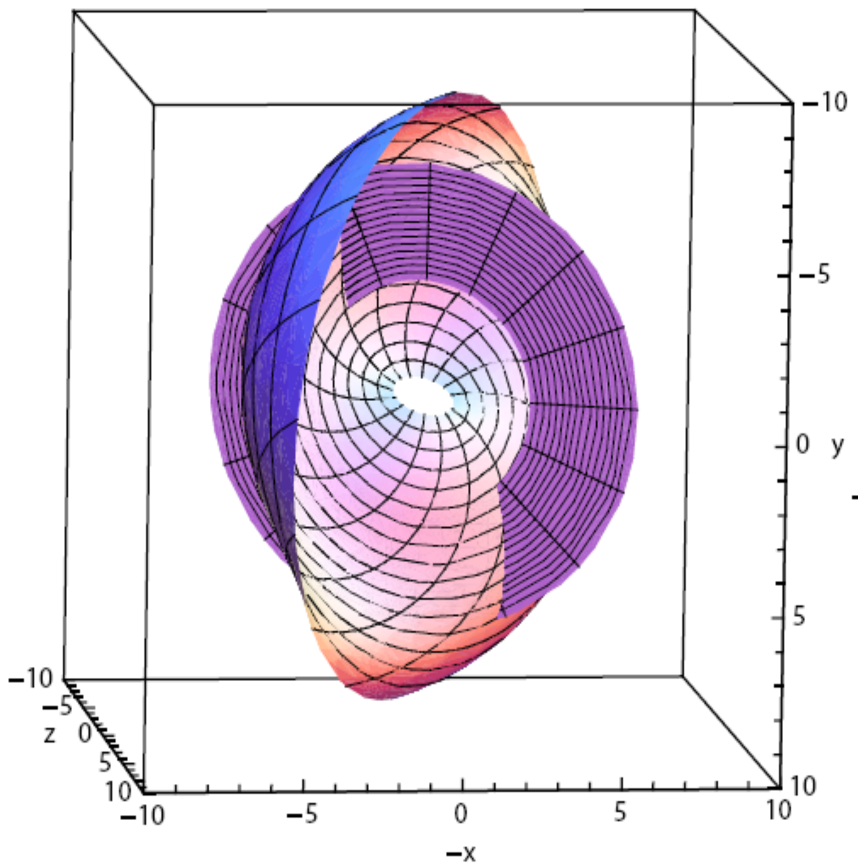


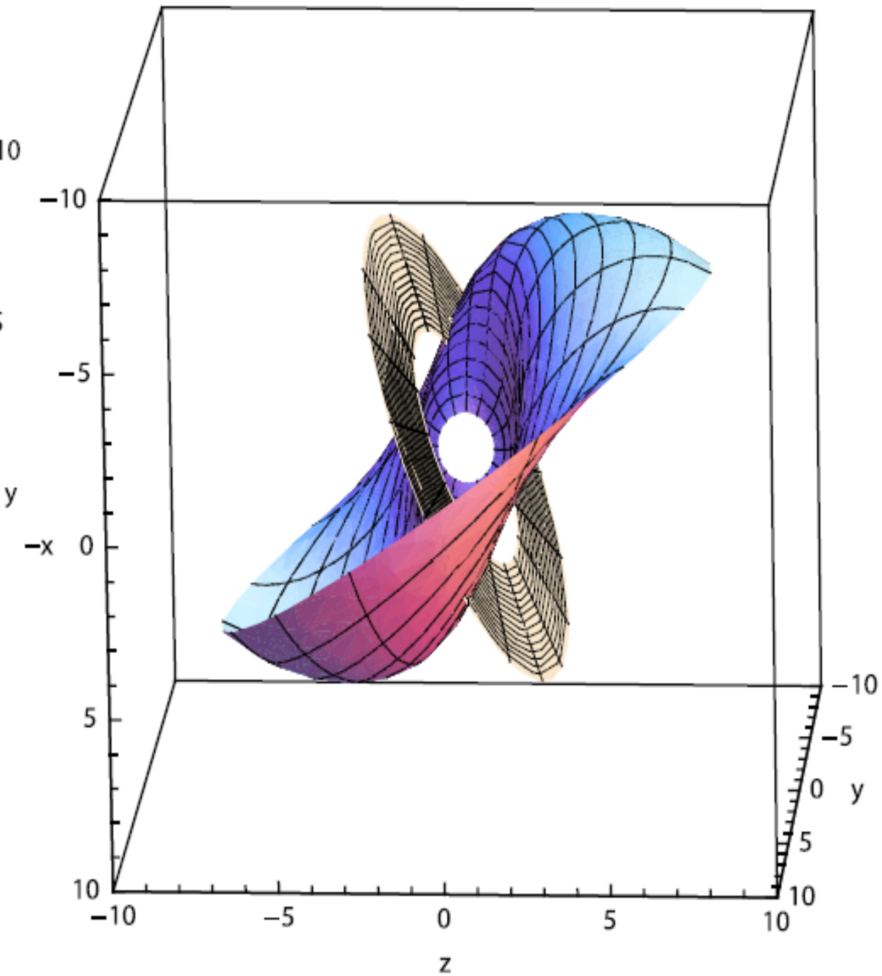
0.8'' < r < 3.5''

3.5'' < r < 7''

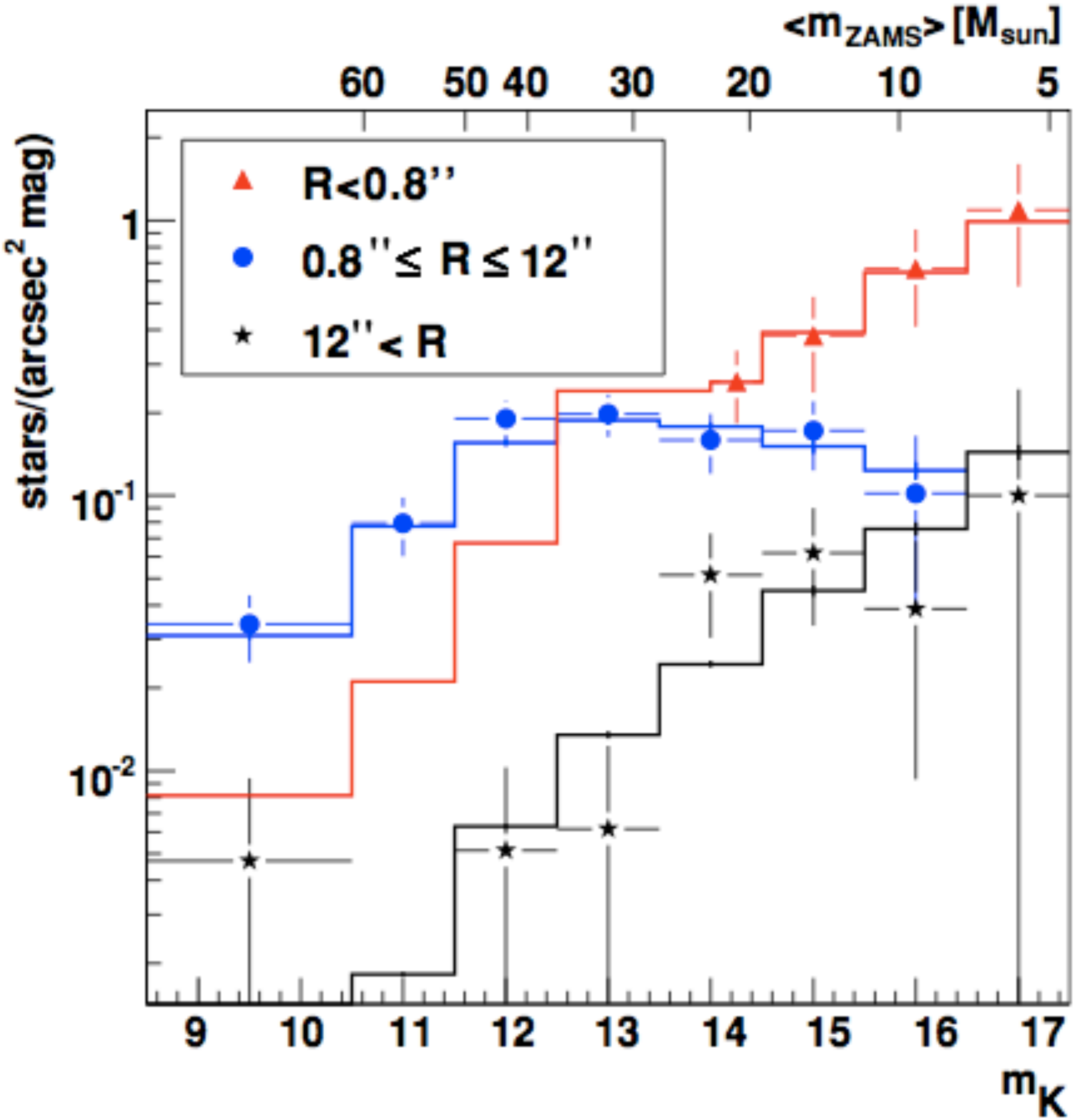
7'' < r < 12''

The disk is warped & counter-CW feature at r ≈ 5”





Disk-IMF is top-heavy

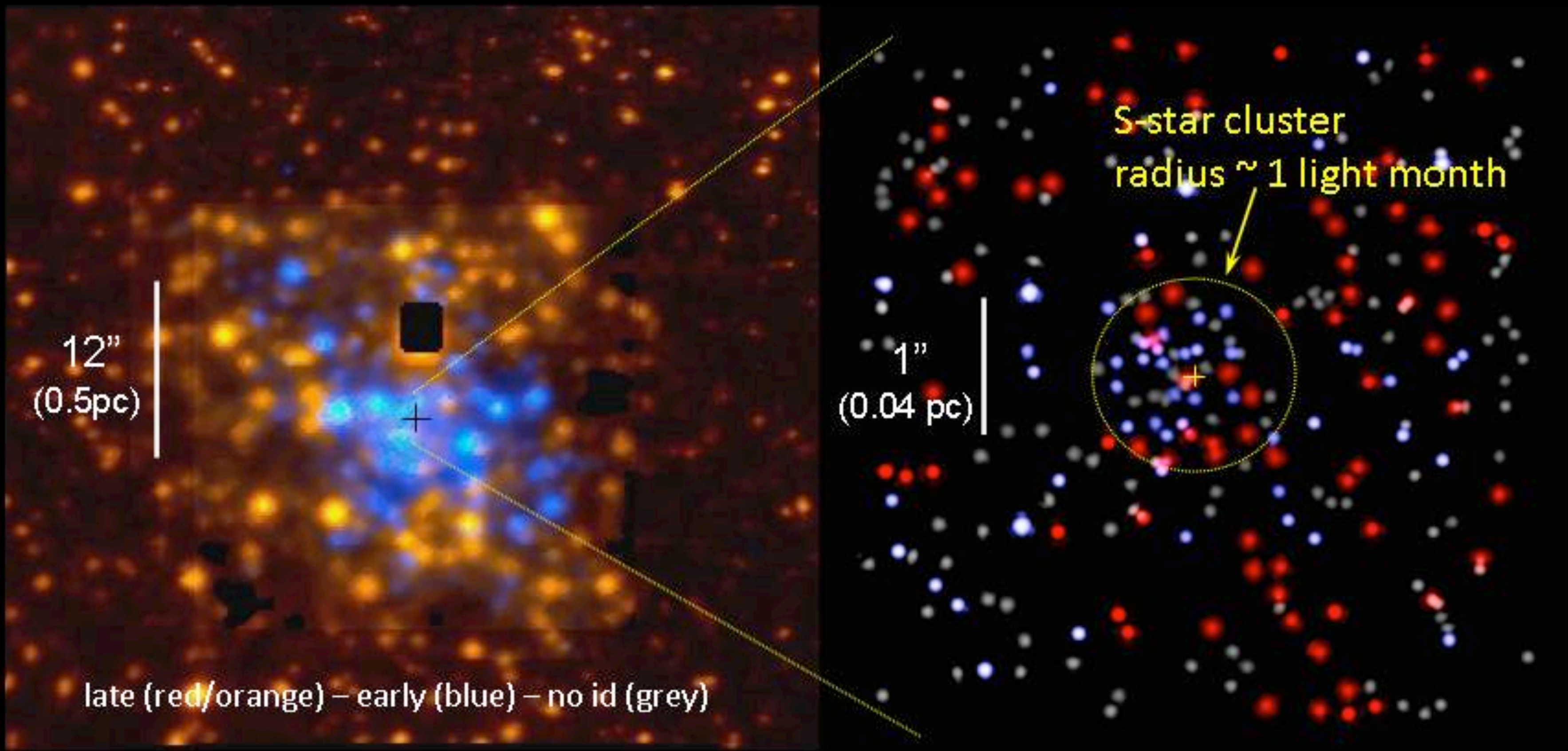


Bartko+ 2010

Two paradoxes of Youth

O/WR stars

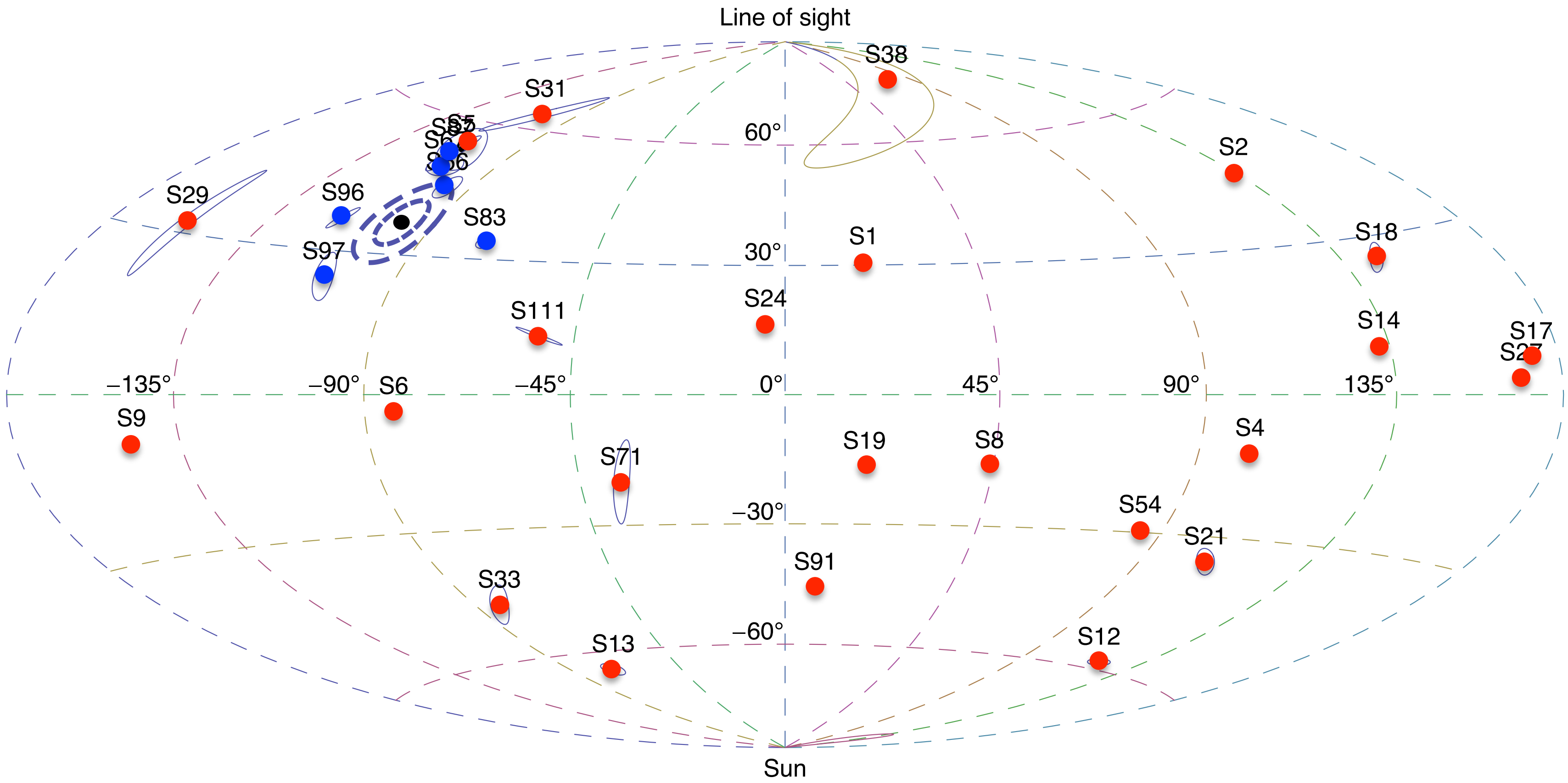
B stars



1" < R < 10"
age ≈ 6 Myr

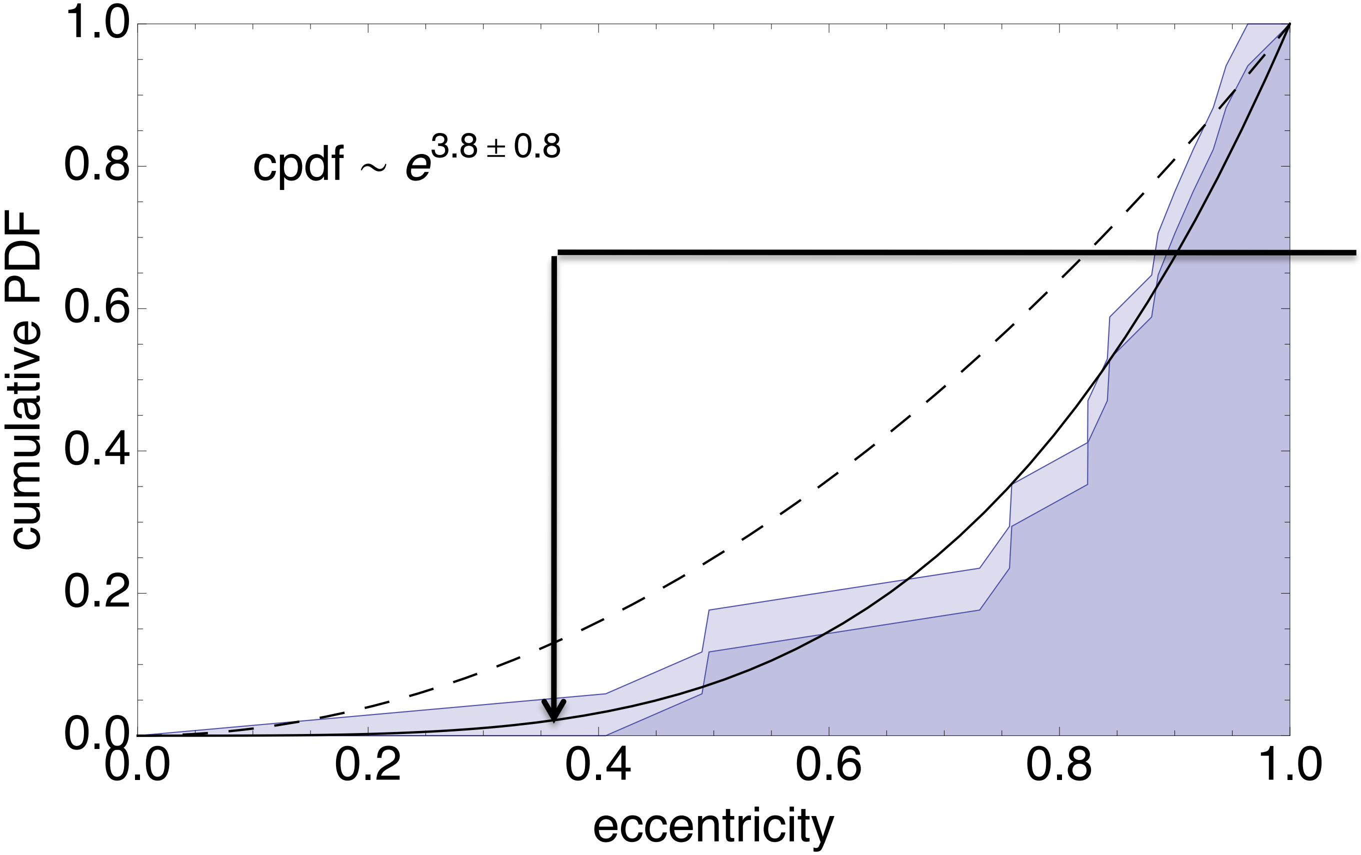
R< 1"
age ≈ 10^8 yr

Orbital planes: S-stars ≠ disk stars



Eccentricities: S-stars ≠ Disk stars

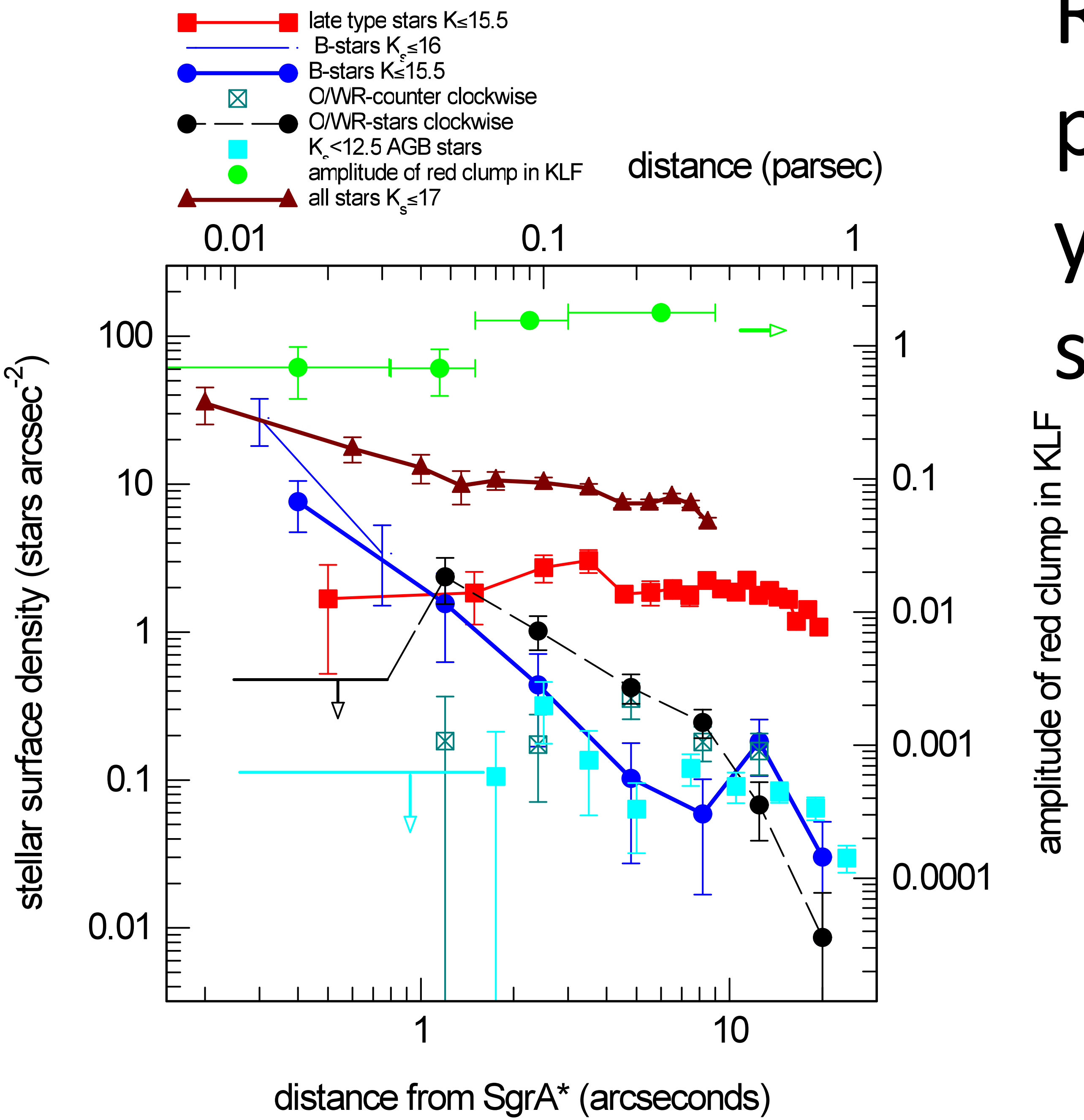
17 early-type S-stars:



6 disk stars:

e = 0.34 ± 0.18

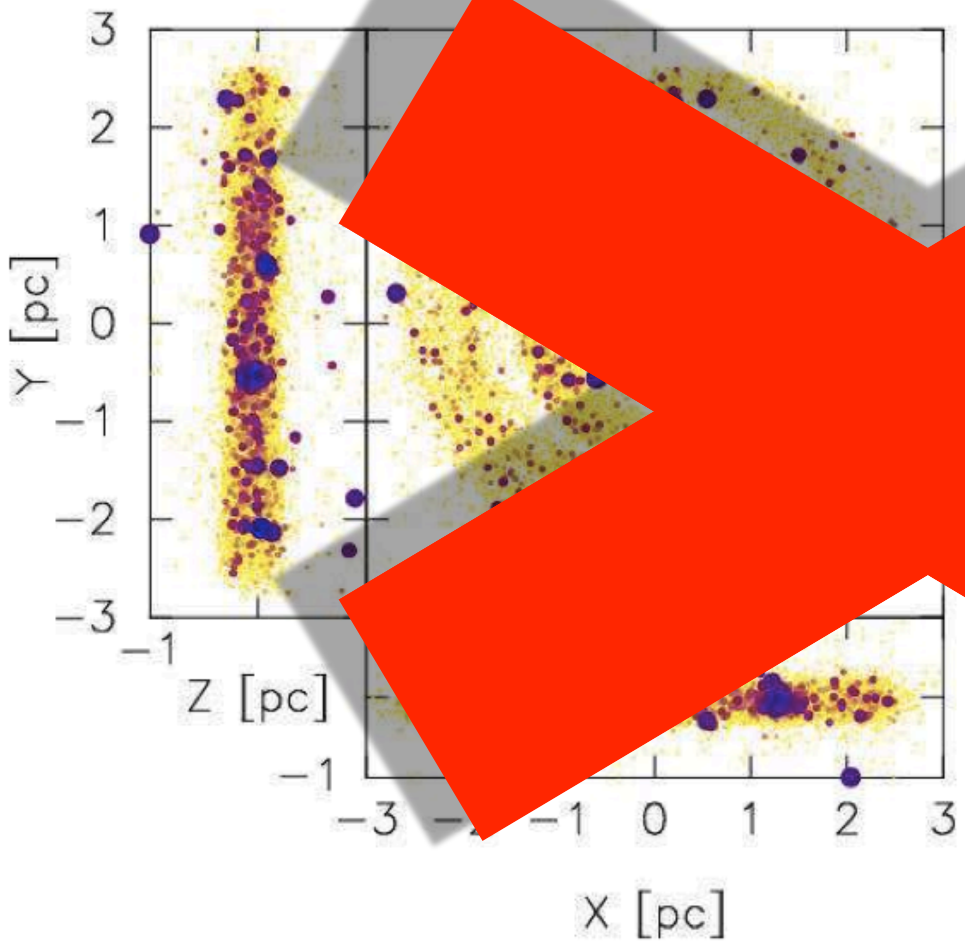
Radial density profile of young stars is steep



Buchholz+ 2009, Do+ 2009, Bartko+ 2010

Idea I: Cluster in-spiral

Gerhard 2001



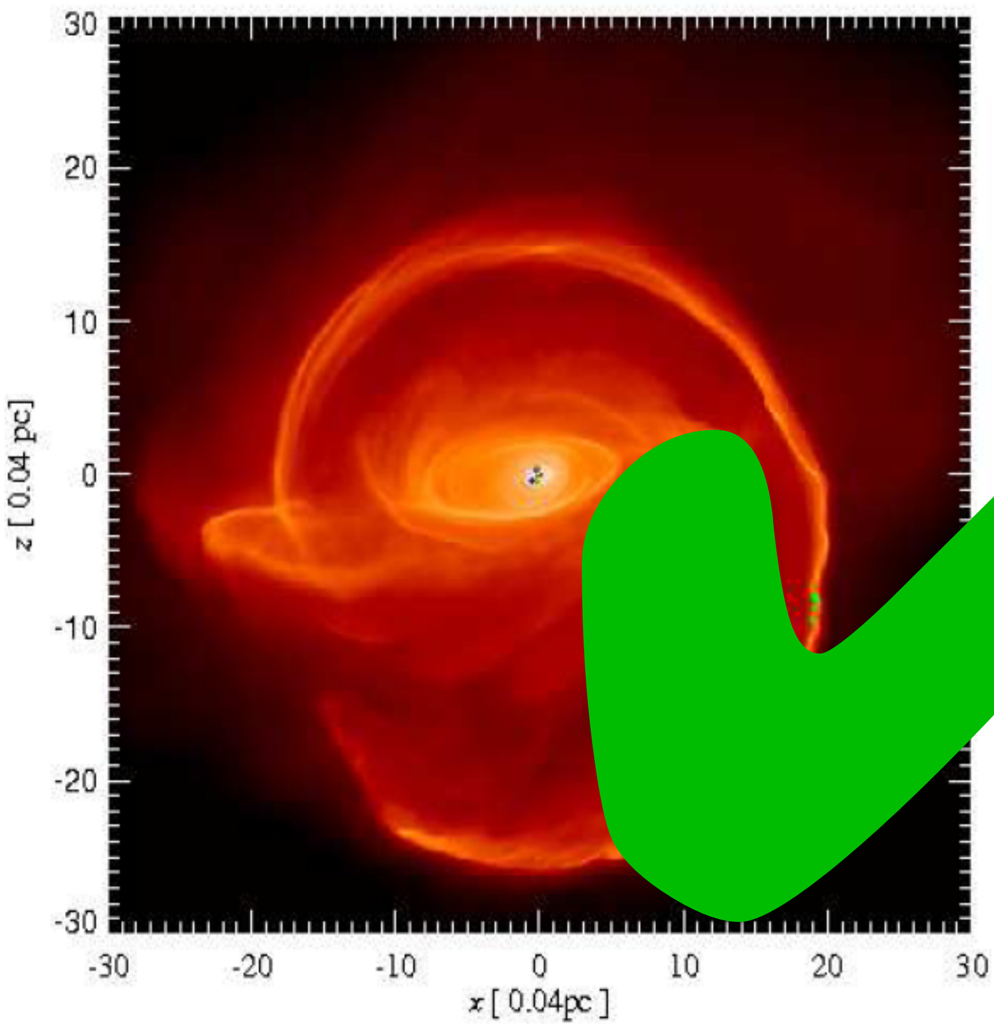
Probler

…in 6 Myr,
…ss would exceed
… mass seen by far
…BH would be required
…ity profile of disk is

• Wh… …e B-stars ?

Portegies-Zwart+ 2005

Idea II: In-situ formation in infalling gas cloud



More promising:

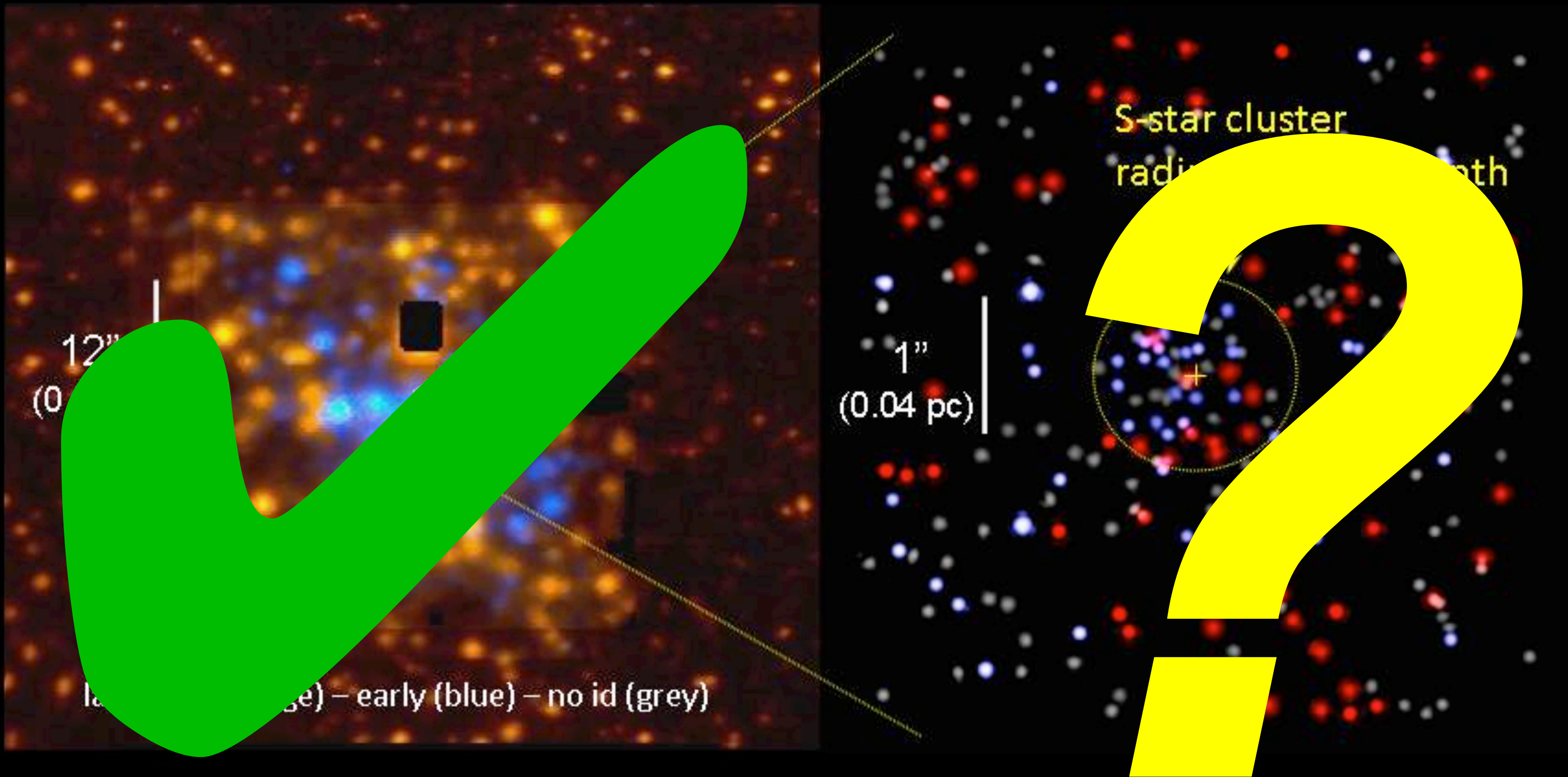
- cri[illegible] density for star [illegible]tion is reached easily
- [illegible]derate eccentricities
- [illegible]MF gets top-heavy
- warps possible

Bonnel & Rice 2008, Hobbs & Nayakshin 2008

Two paradoxes of Youth

O/WR stars

B stars



1” < R < 10”
age ≈ 6 Myr

R< 1”
age ≈ 10^8 yr

The S-stars puzzle is much harder

In-situ formation

- Critical density
  $\sim M/R^3$
  $\approx 2 \times 10^{-11}\ \mathrm{g/cm^3}$
  (for R = 0.5")
- Core of clump in molecular cloud
  $\approx 10^6/\mathrm{cm}^3$
  $\approx 2 \times 10^{-18}\ \mathrm{g/cm^3}$

Fast transport

- cosmic pool game
- fast relaxation processes
- Migration from O/WR star disks

?

Rejuvination

- Stars are actually old but look young
- "stripping" of giants, S-stars are the hot cores
- Spectrum of S2

The Hill's mechanism is the key for fast transport

Massive Perturbers

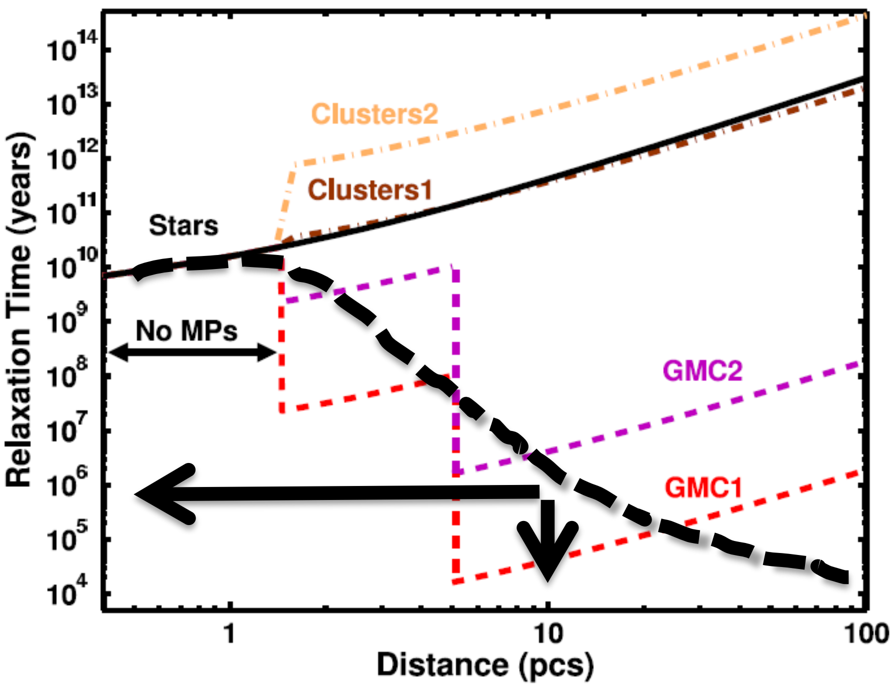
- Scattering of field binaries into near loss cone orbits due to "Massive Perturbers"
- Tidal break-up of binaries at pericenter passage Hills 1988
- Fast Relaxation of orbit to match observed properties
  - Resonant?

Migration

- Formation of B-stars in (former) disks
- Interactions to increase <e> 2nd disk, stellar cusp, **IMBH**, e-instability, ...
- Fast Relaxation
  - **IMBH?**

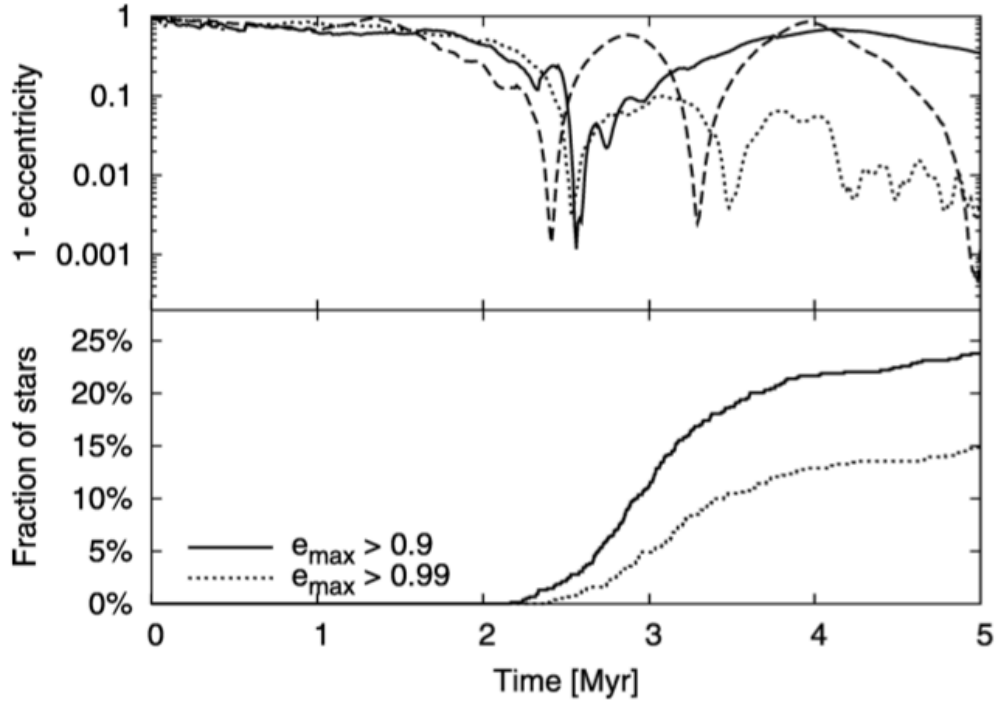
Both scenarios direct stars to large <e> orbits within few Myr

Massive Perturbers

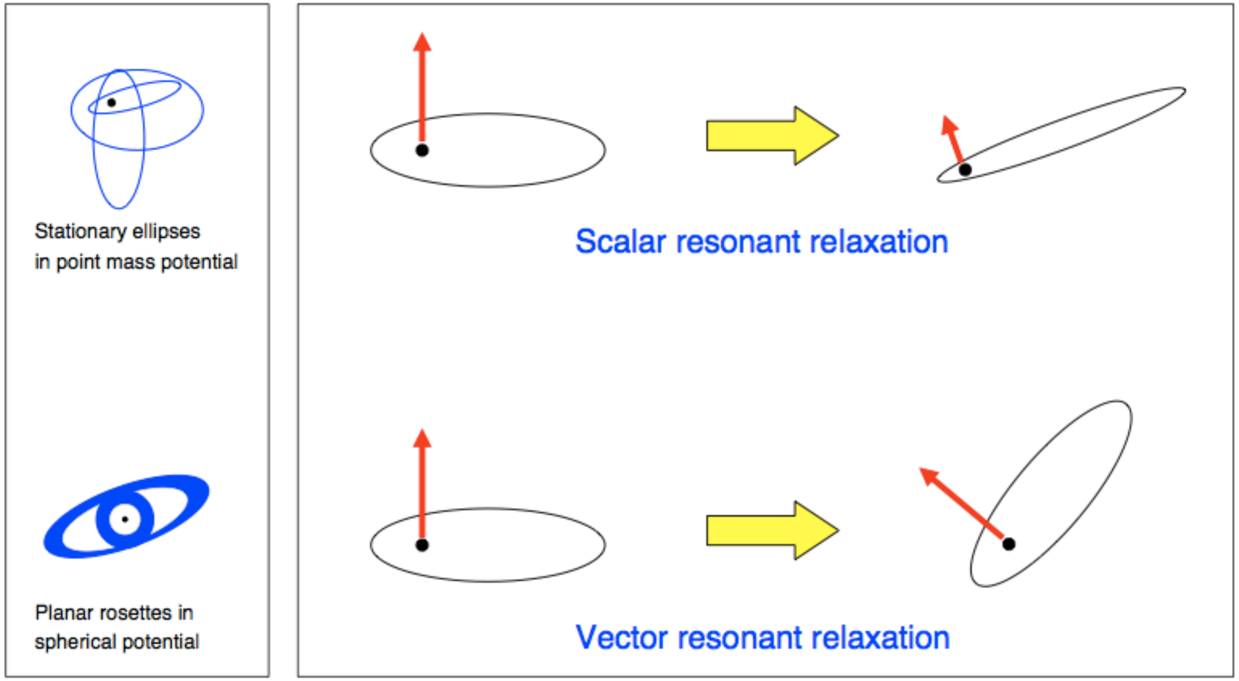


Perets, Hopman & Alexander 2007

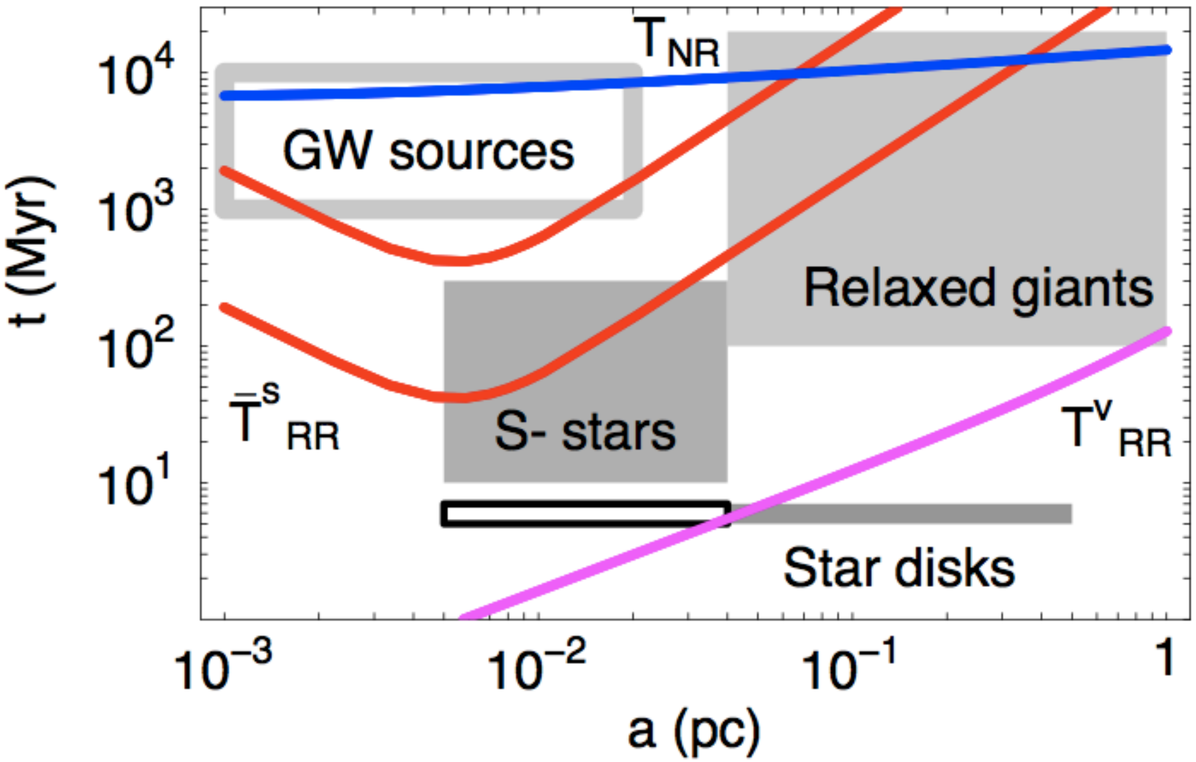
Migration



Löckmann, Baumgardt & Kroupa (2008)

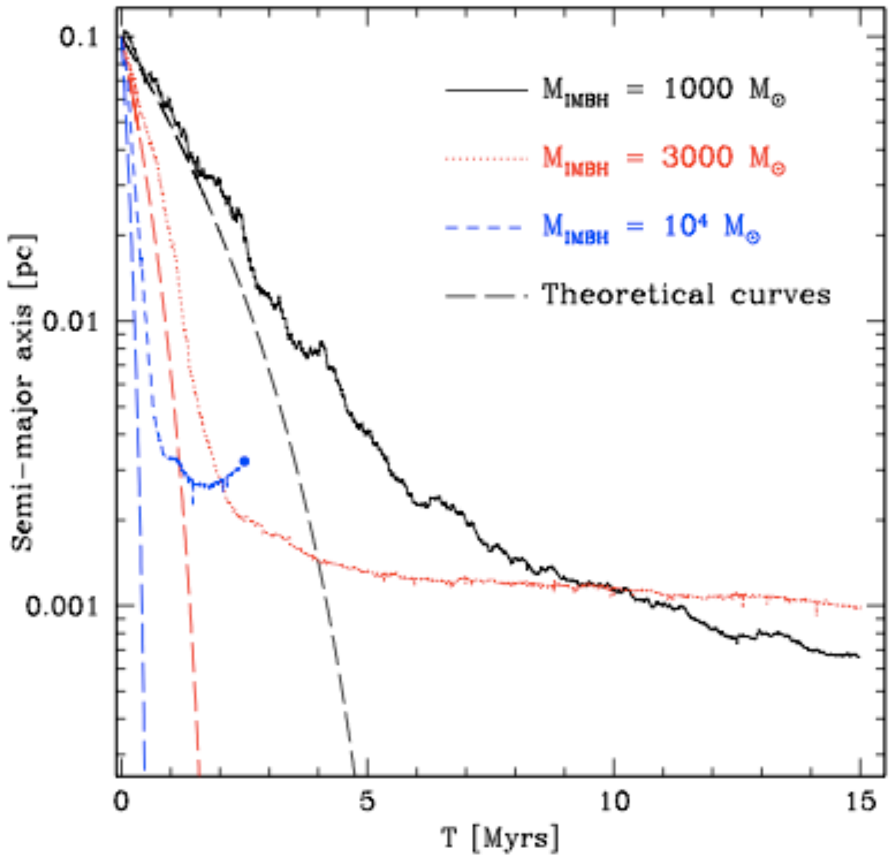


Resonant relaxation is just fast enough

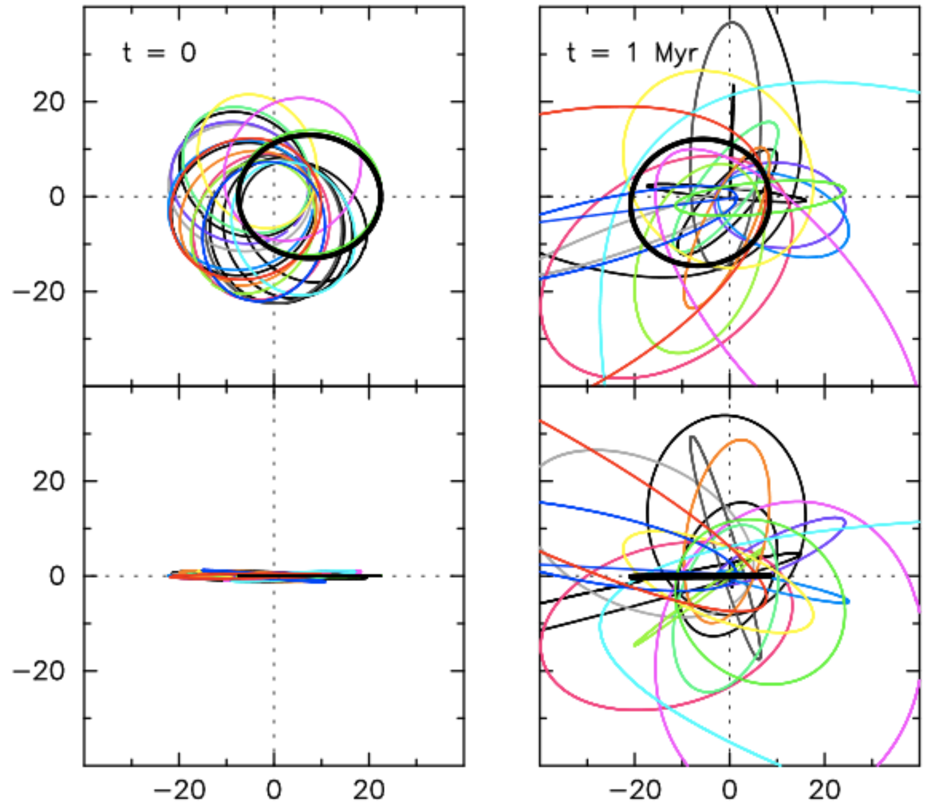


Alexander 2008

IMBH: Would stall at interesting radius and randomize orbits fast enough

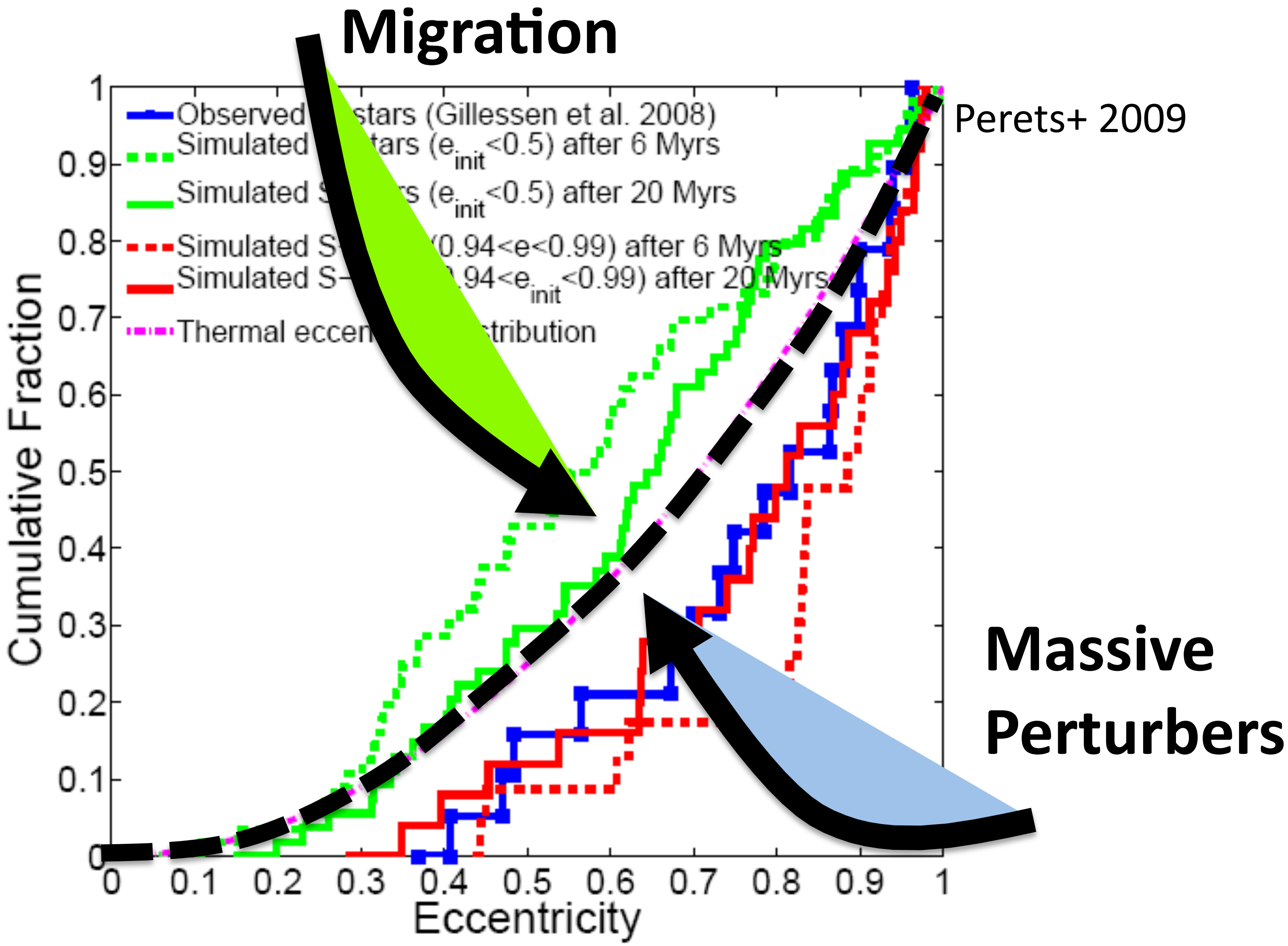


Baumgardt, Gualandris, Portegies Zwart 2006

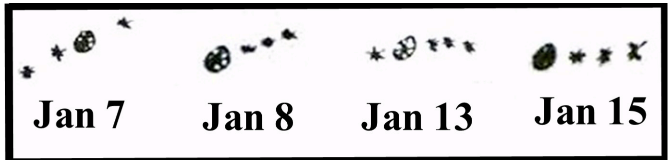


Merritt, Gualandris, Mikkola 2009

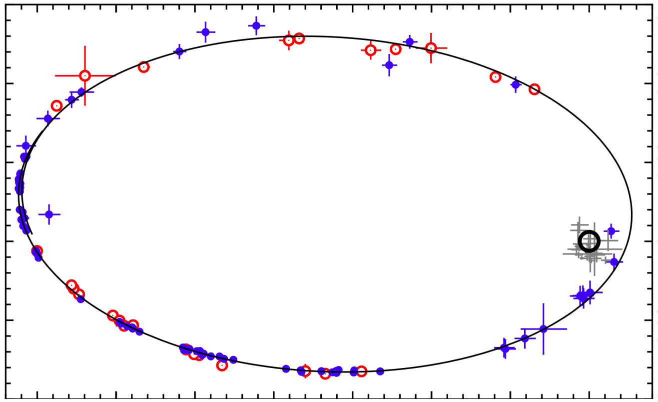
The eccentricity distribution might be the clue



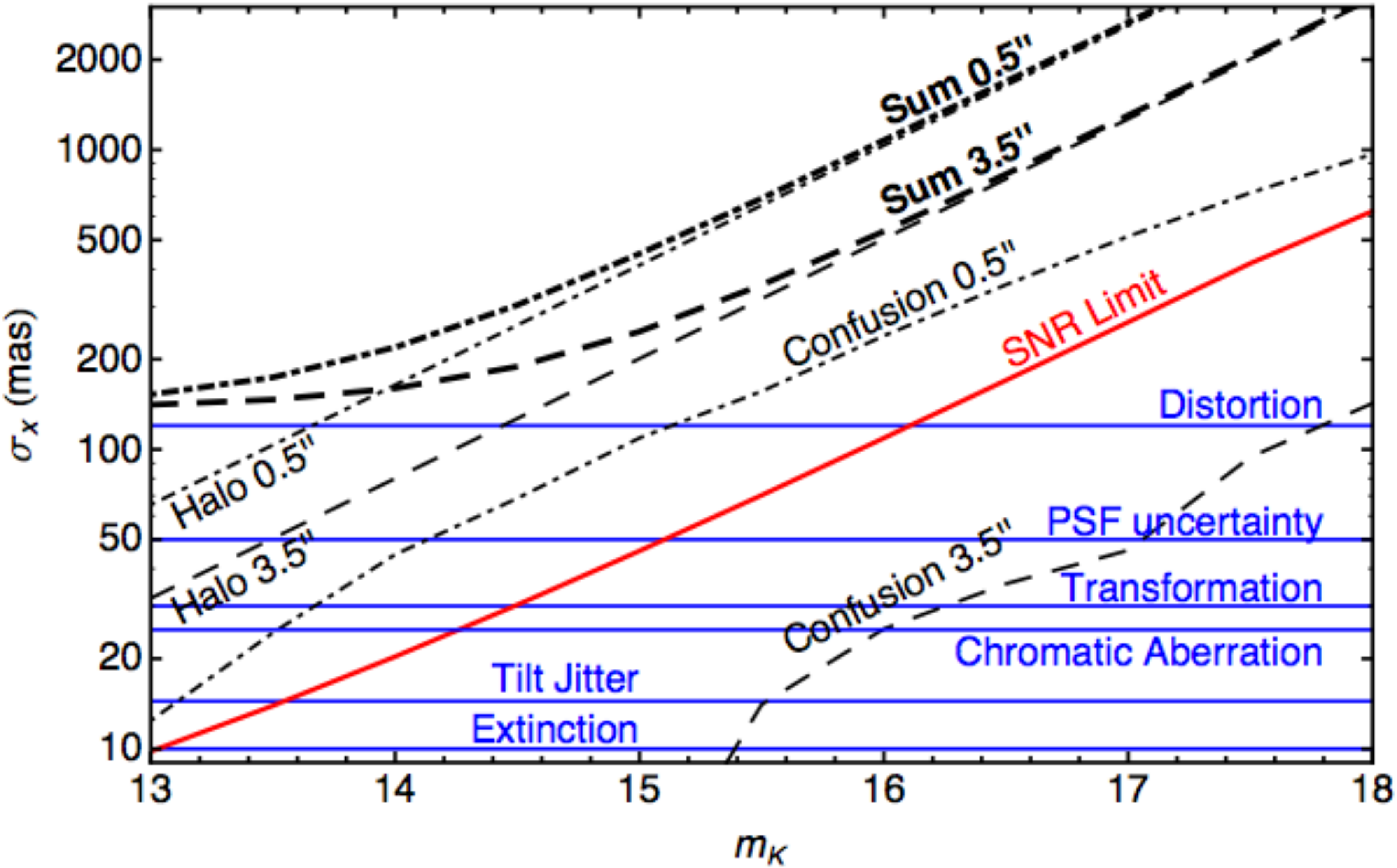
What is limiting astrometry today?



Jupiter and its moons as seen and sketched by Galileo in 1610.



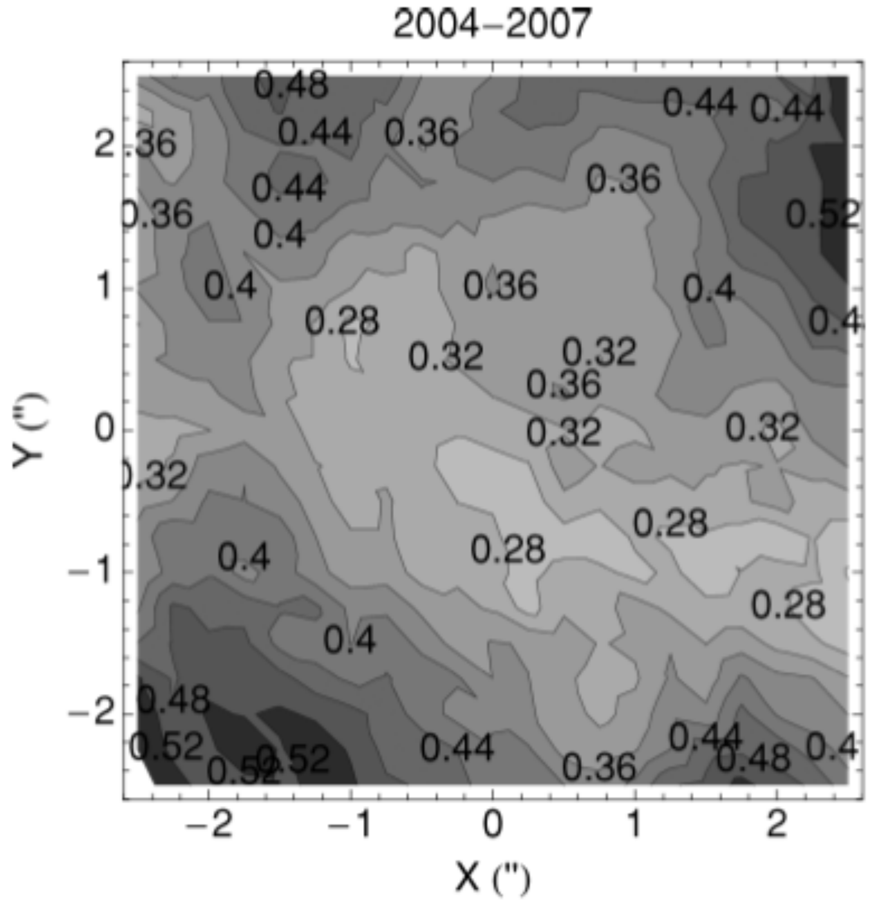
S2–like stars: Distortions
Fainter stars: Halo noise



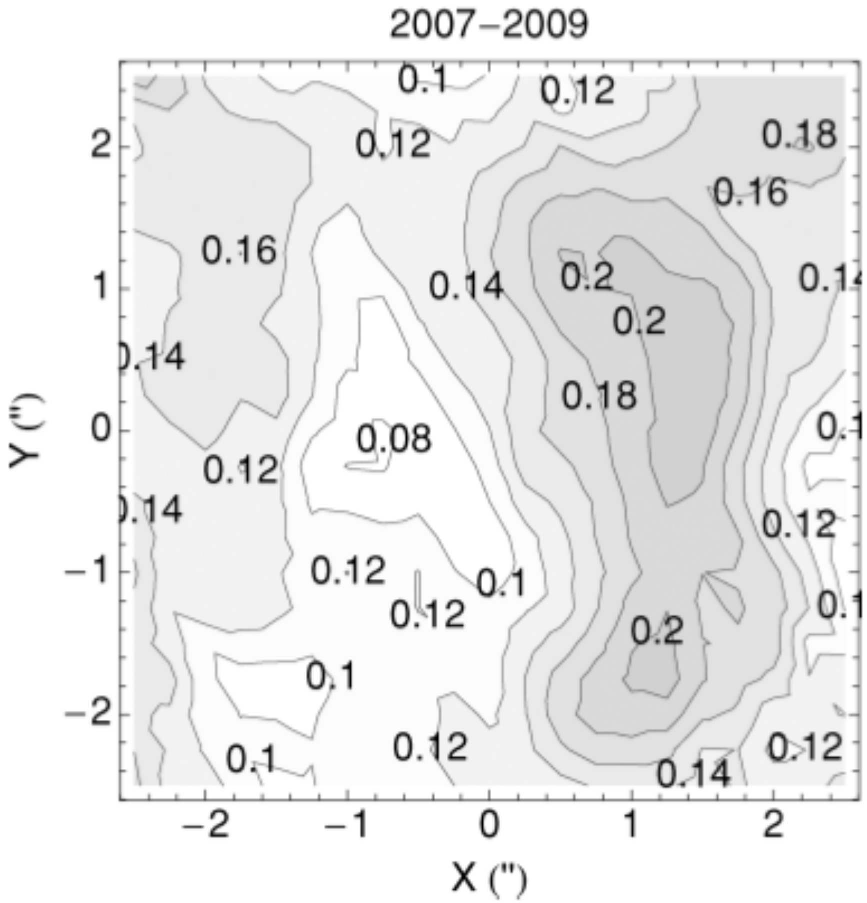
Fritz+ 2009

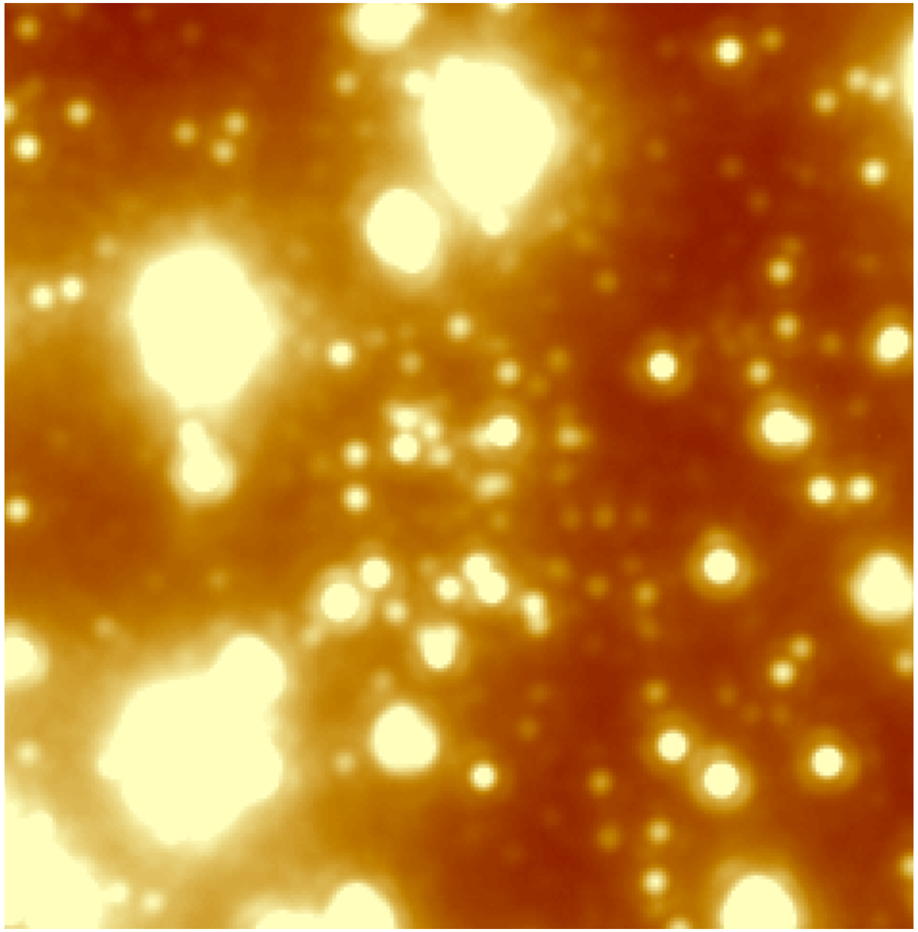
A positional noise floor: Residual Image Distortions

300 μas



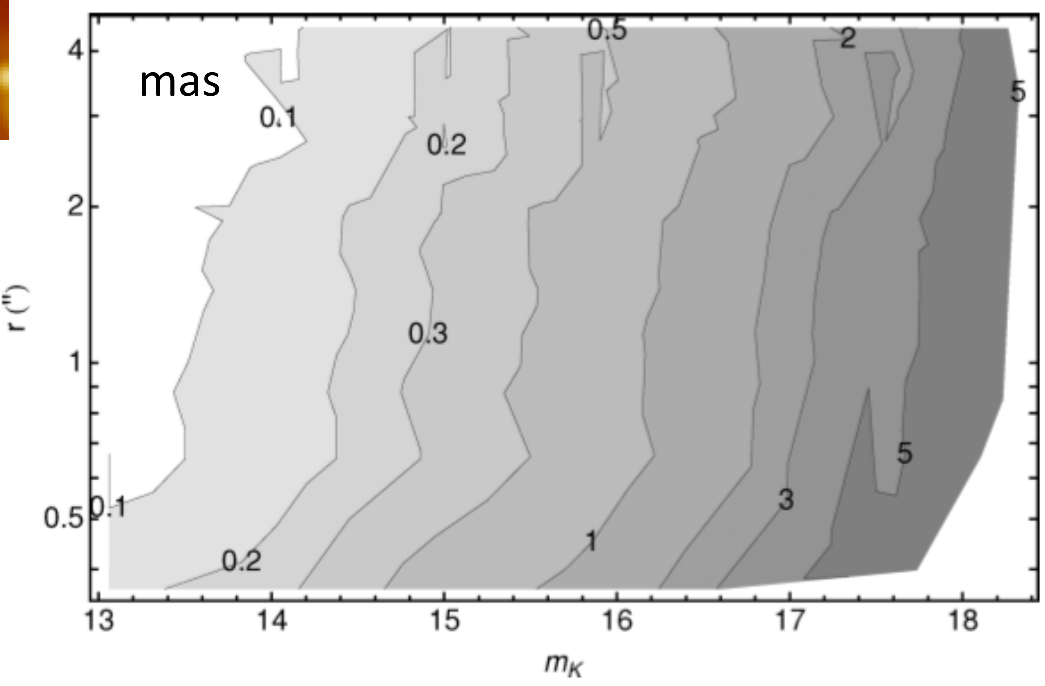
150 μas





“Halo noise”

Seeing halo extends beyond radii
at which the PSF can be determined



- Resolution would help (ELTs)
- High Strehl helps

- room for improvements for PSF determination ?

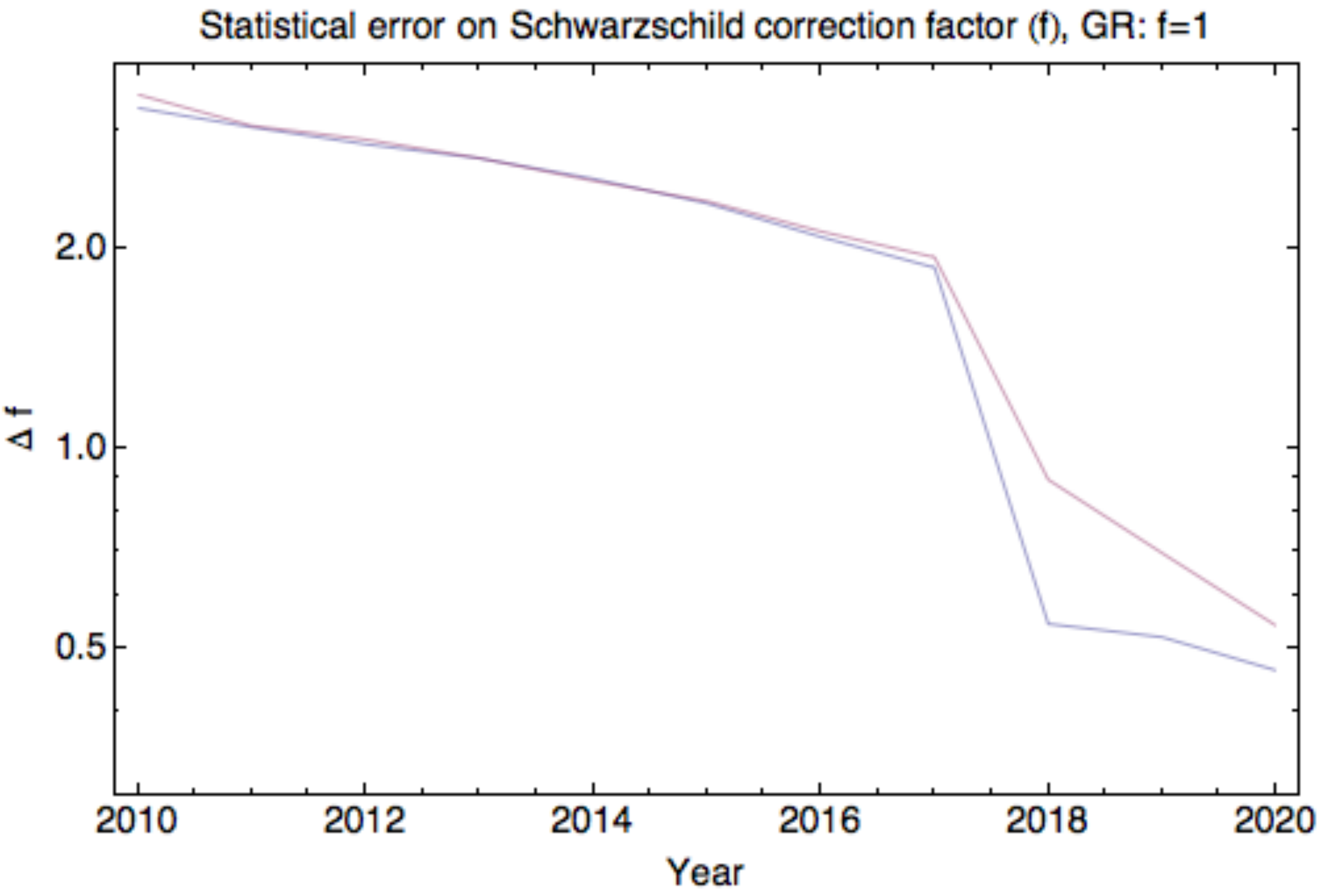
Assume, we continue what we are doing. How well do we do then?

NACO:
Astrometry with 300 μas

SINFONI:
Spectroscopy with 15 km/s

2020: 3σ detection of GR precession possible

$$\Phi = -\frac{G\,M}{r} + f\,\frac{G\,M\,l^2}{c^2\,r^3}$$



A unique laboratory: The Massive Black Hole in the Galactic Center

- ~ 30 S-star orbits (r < 1”)
- MBH most conservative explanation of data
- Astronishing S2 orbit
  - $R_0 = 8.3 \pm 0.4$ kpc
  - $M = 4.3 \pm 0.06|_{stat} \pm 0.35|_{R0} \times 10^6 M_\odot$
  - non−pointlike mass: $\eta < 3\%$
- Warped disk of O/WR stars (1” < r < 10”)
  - Different population of stars
  - in-situr formation from gaseous disk
- S-stars form a harder puzzle
  - Massive Perturbers + Hills mechanism + Resonant relaxation seem more probable than
  - IMBH-assisted migration
- Positional accuracy ~ 200 µas
  - For S2 distortion limited
  - limit for fainter stars: confusion / resolution
  - GR precession in S2 detected after next pericenter passage (2018)

lactic Center
ernung: 0,042280 Lj
zentrum des Sternsystems
1992 Aug 19 02:28:24 UTC
Zeit angehalten
chwindigkeit: 0,00000 m/s
FOV: 28° 34' 28,8" (1,0