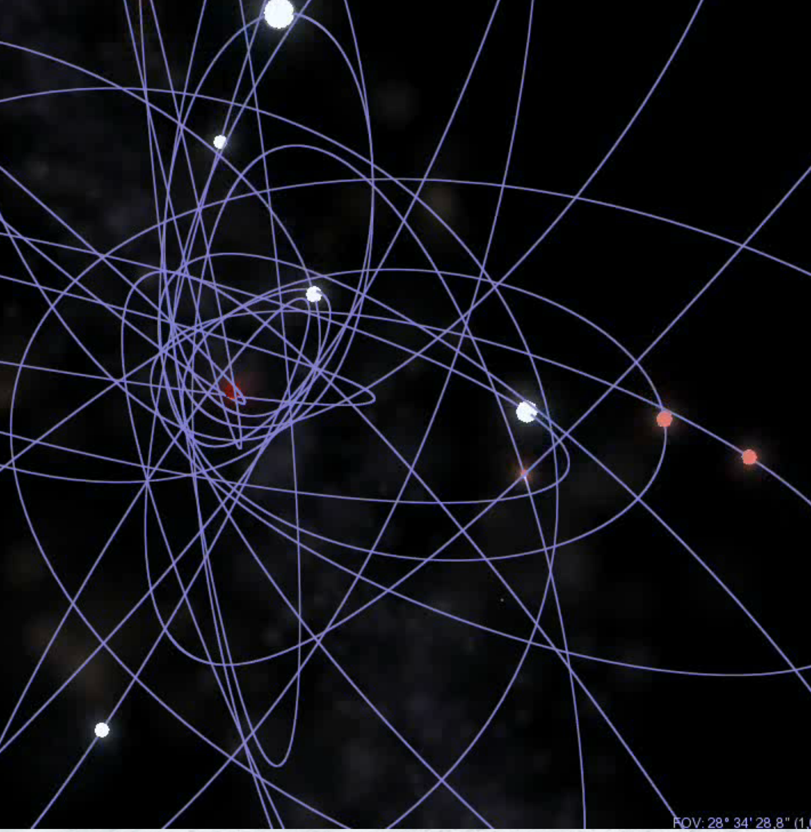
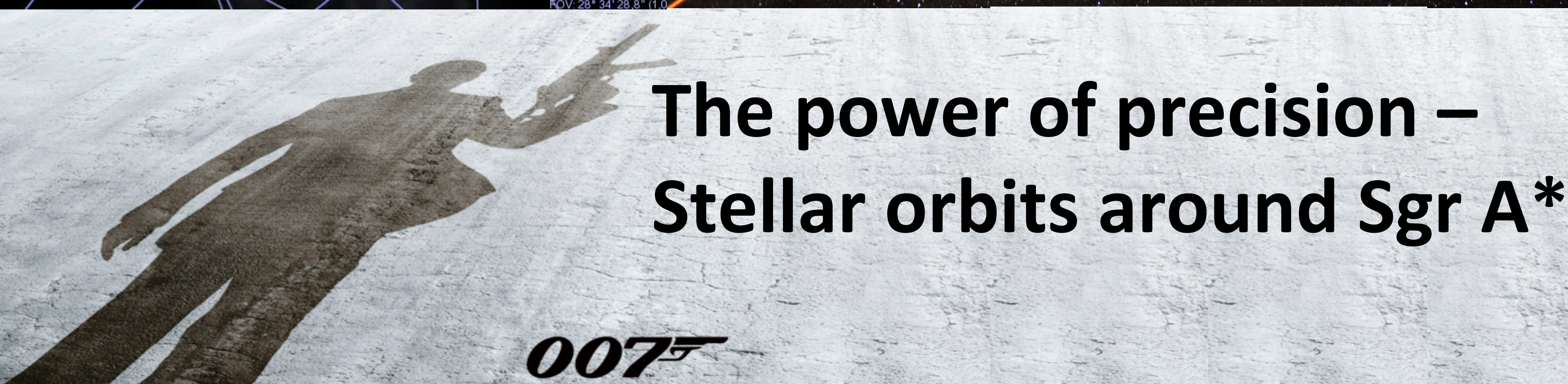


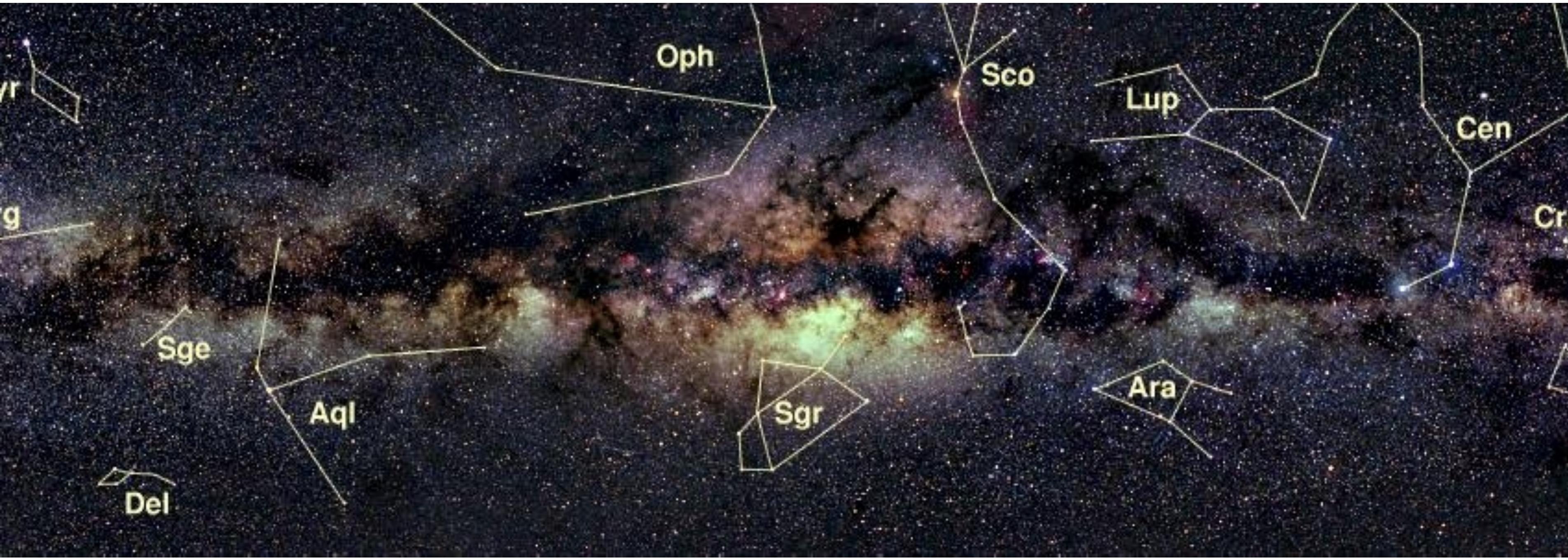


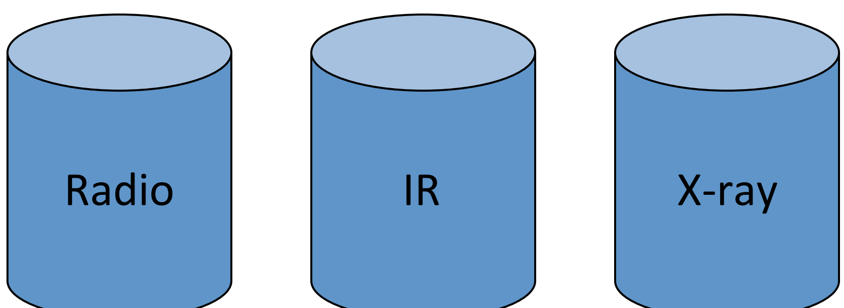
The power of precision – Stellar orbits around Sgr A*

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

MPE

The GC is highly obscured





All 3 wavebands are important

Radio:

✔ Excellent resolution (VLBI: sub-mas)

✖ traces only gas (non-gravitational forces)

IR:

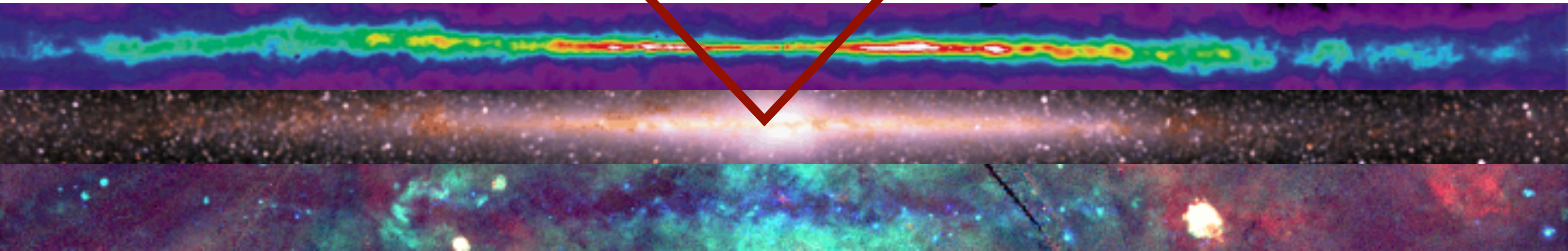
✔ Good resolution (VLT/Keck: 50mas)

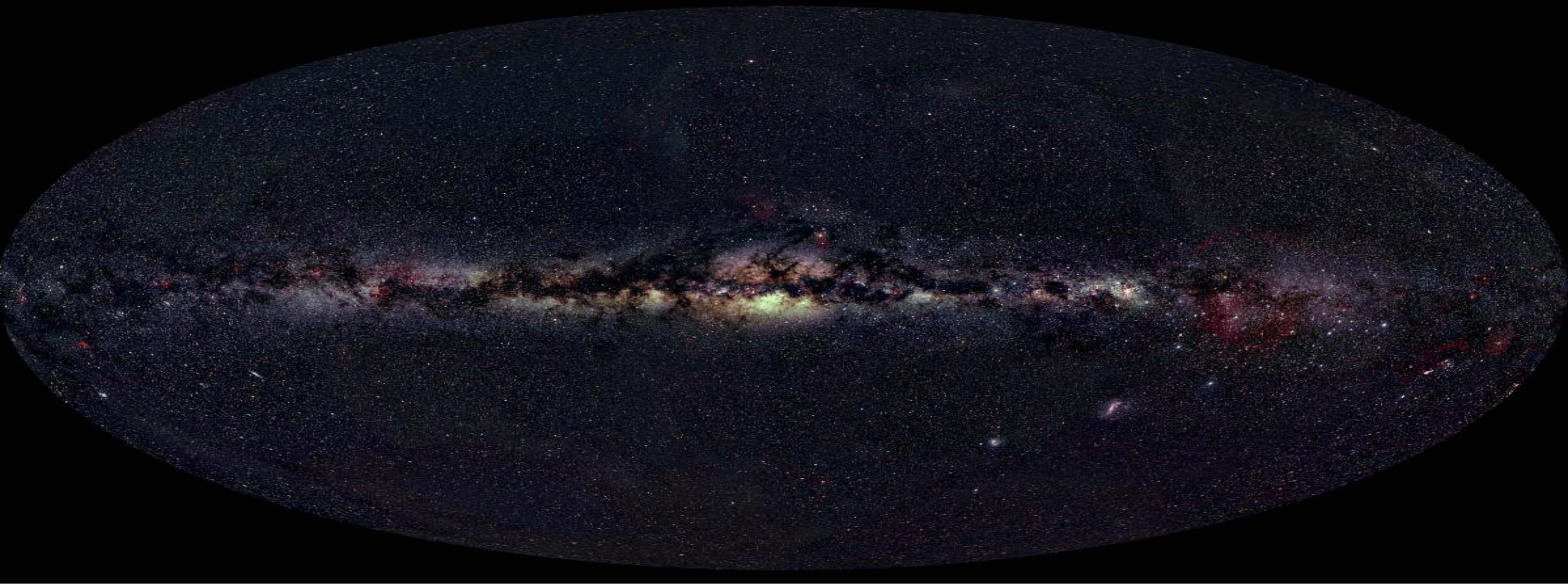
✔ traces stars (only gravitational forces)

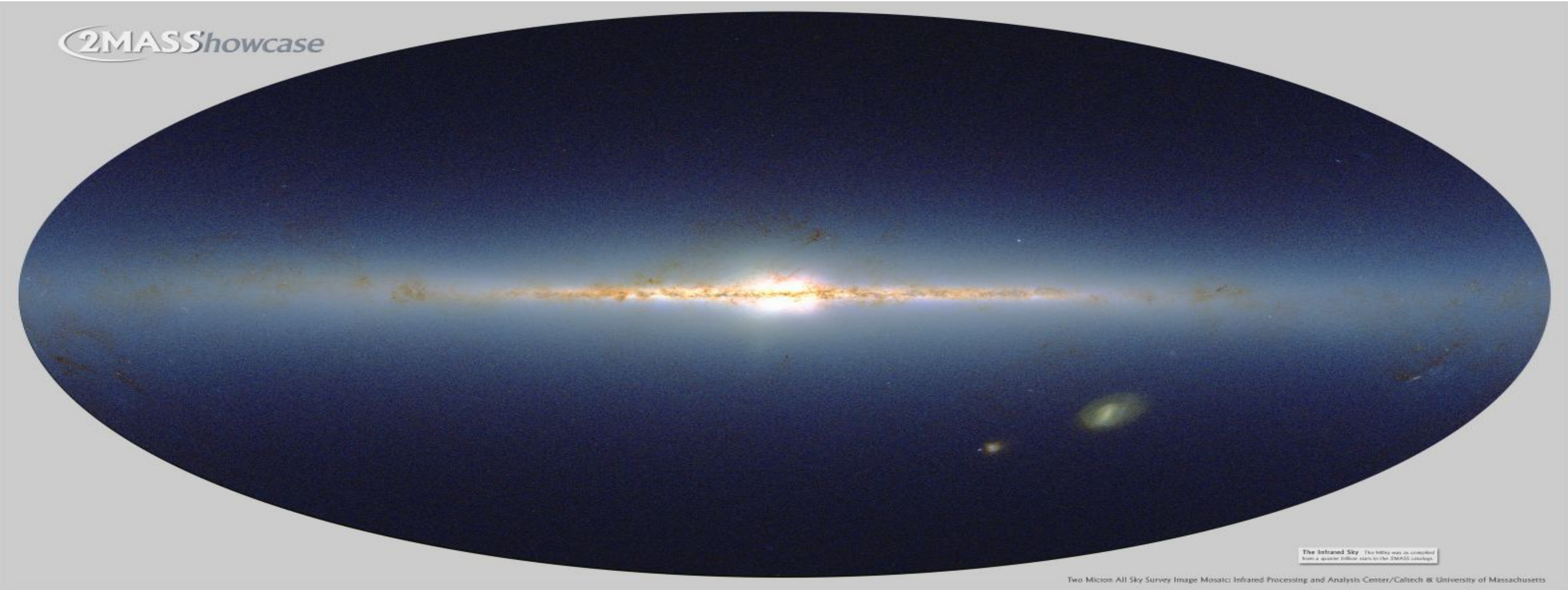
X-ray:

✖ Poor resolution (XMM/Chandra: 1000mas)

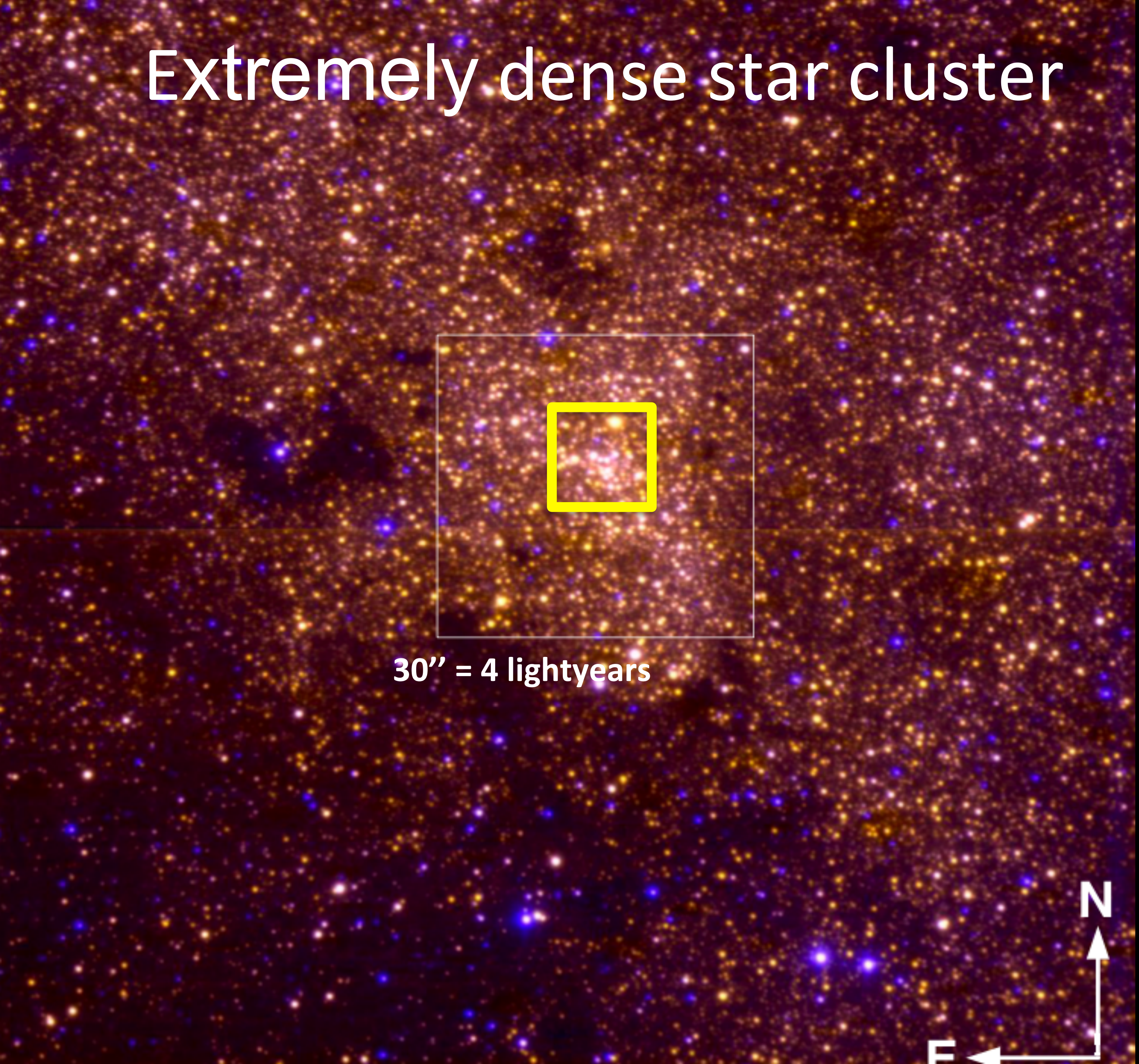
✔ traces high energetic processes





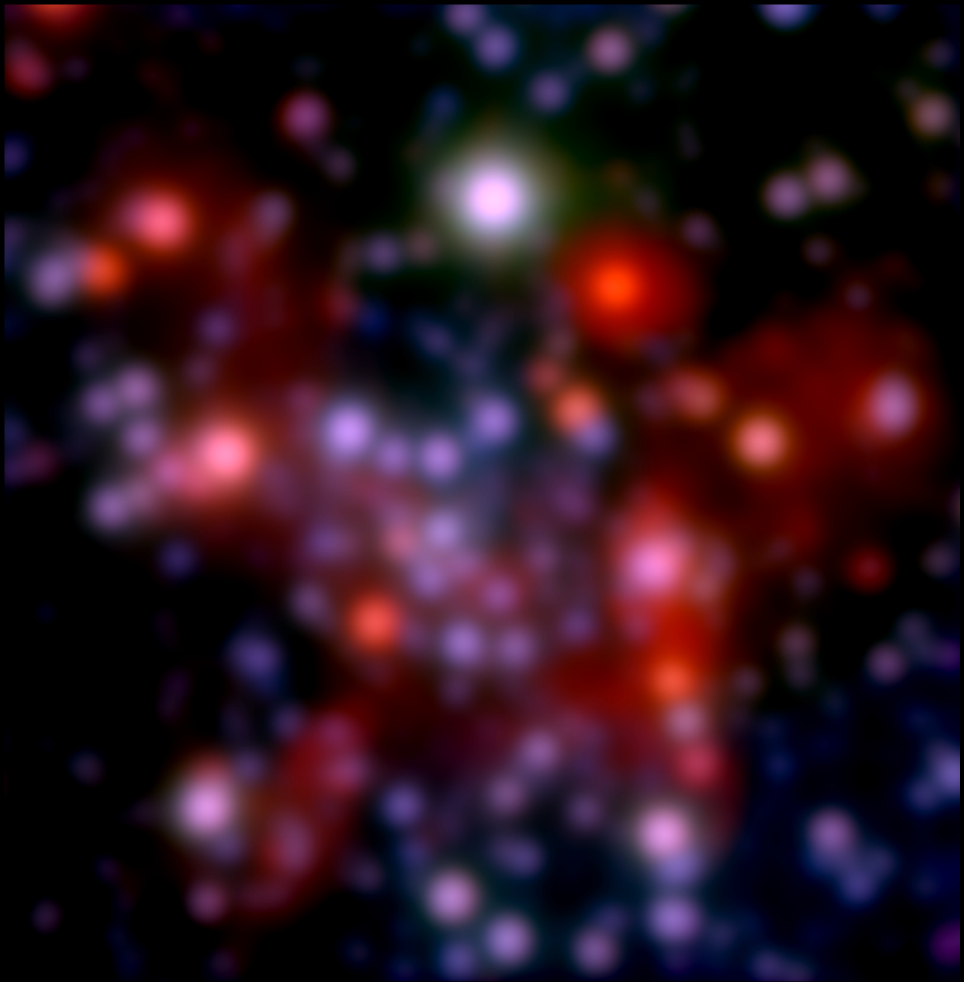

2MASSshowcase
The Infrared Sky
Two Micron All Sky Survey Image Mosaic: Infrared Processing and Analysis Center/Caltech & University of Massachusetts

Extremely dense star cluster

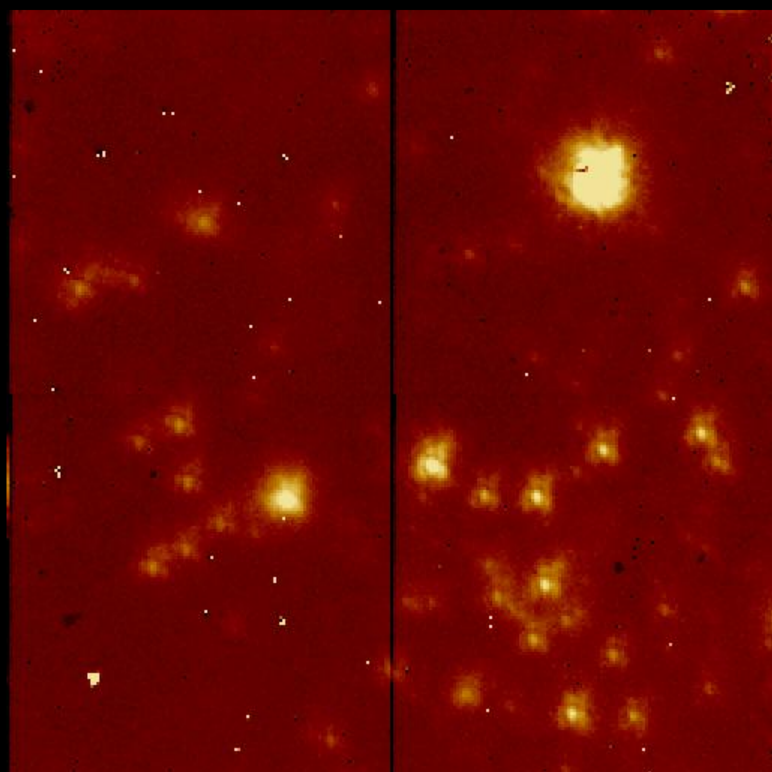


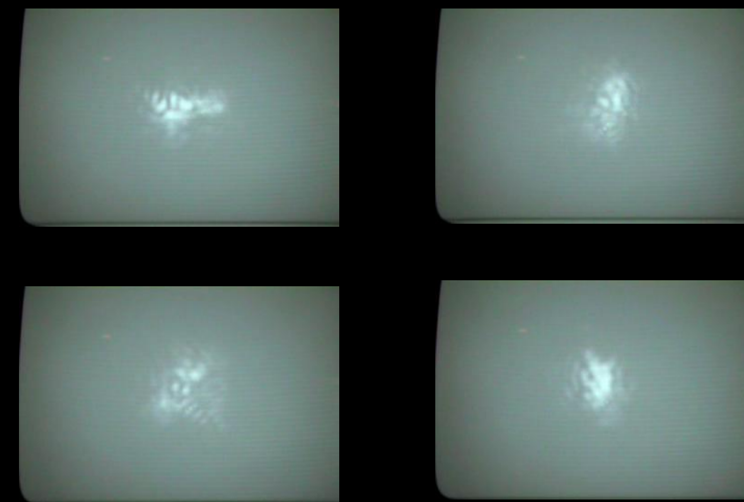
Schödel+ 2006
(ISAAC, VLT)

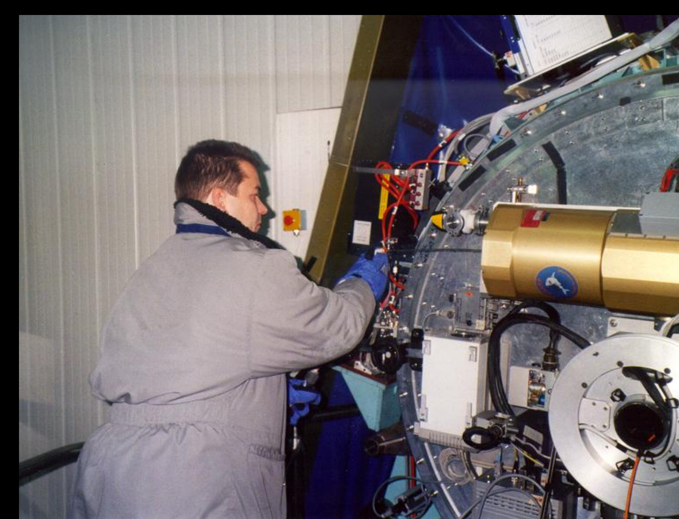
The central 20’’: Seeing limited



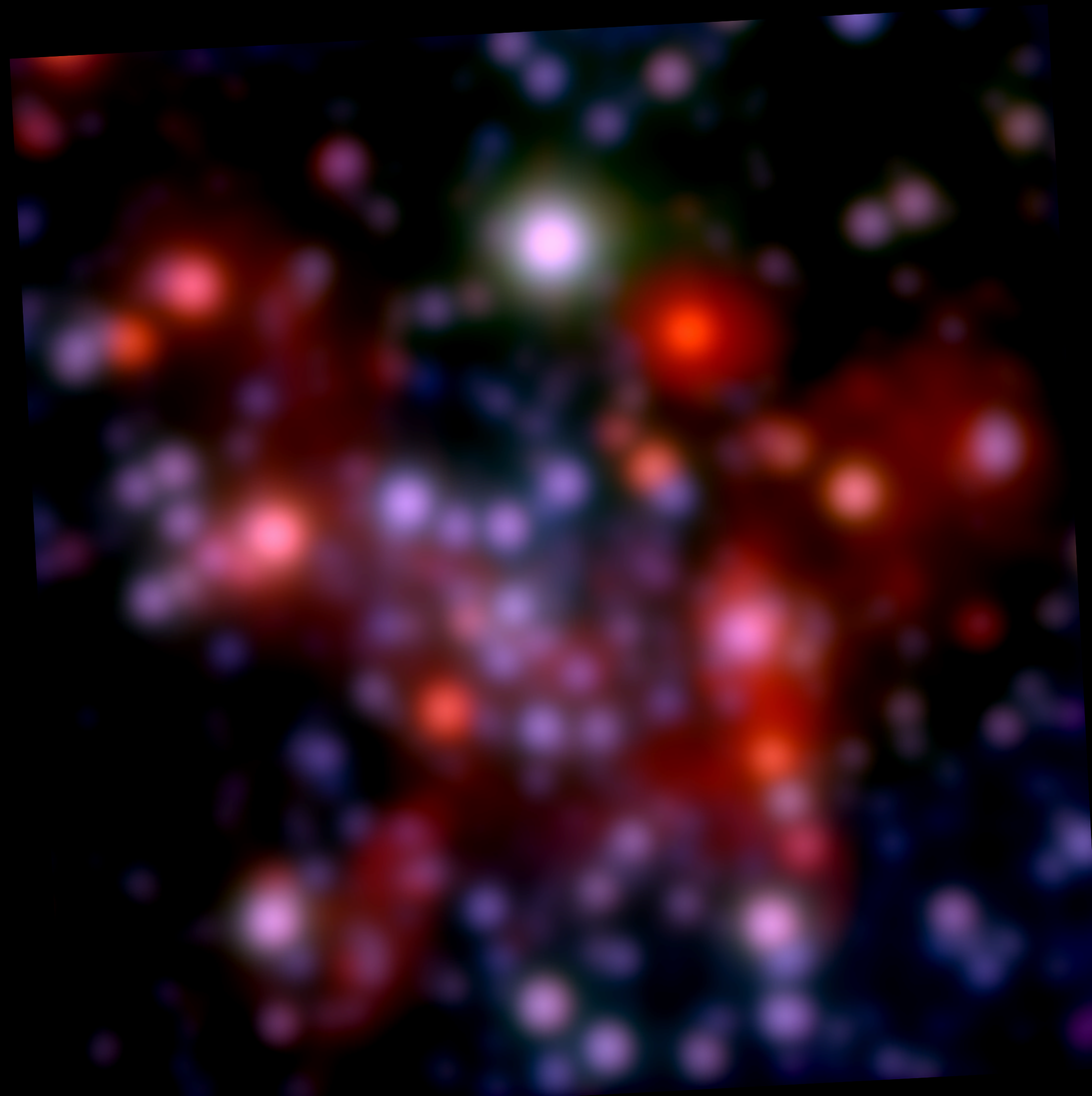
1992 - 2001: “Speckle”-Imaging



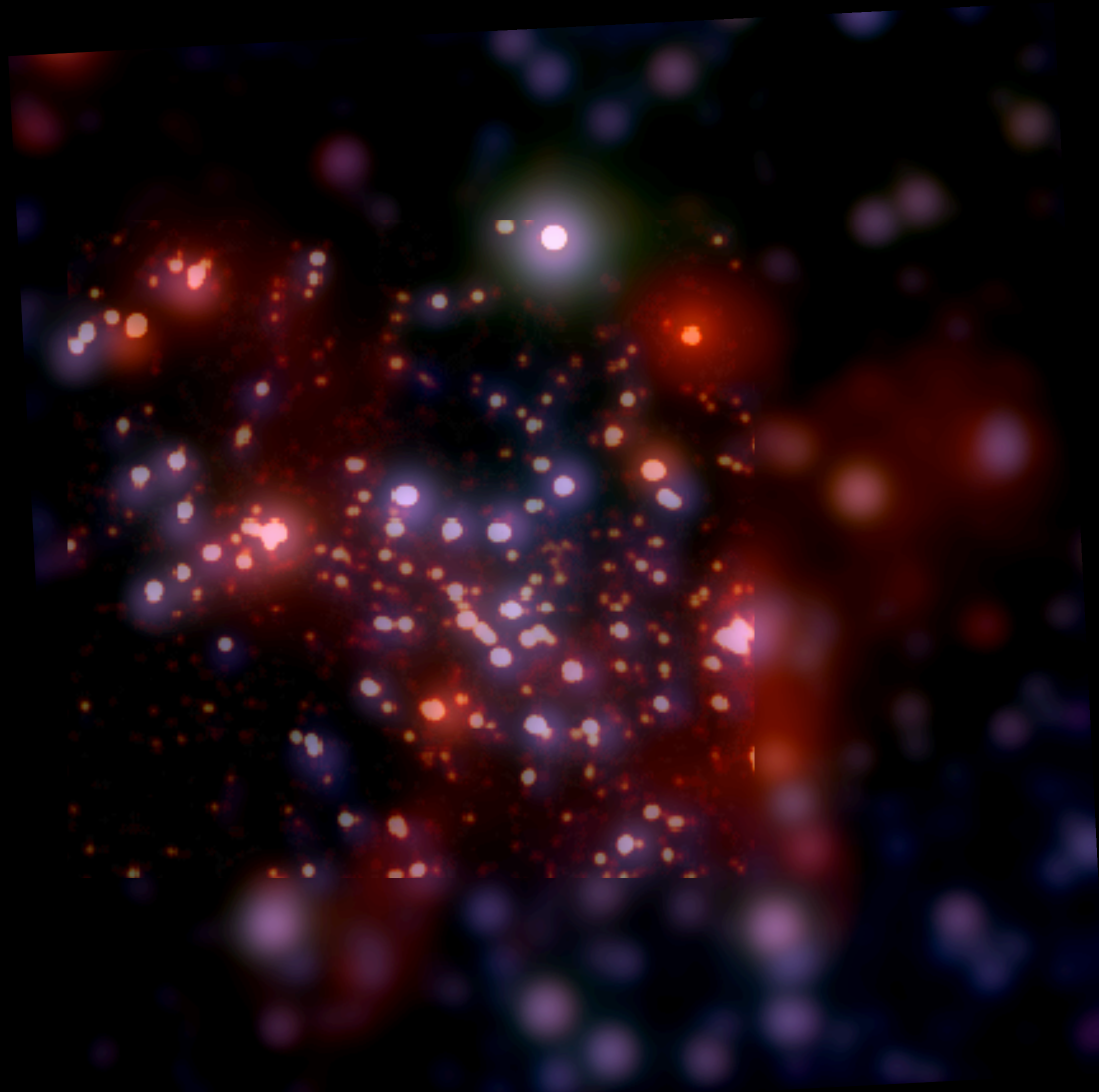




You go from seeing-limited ..

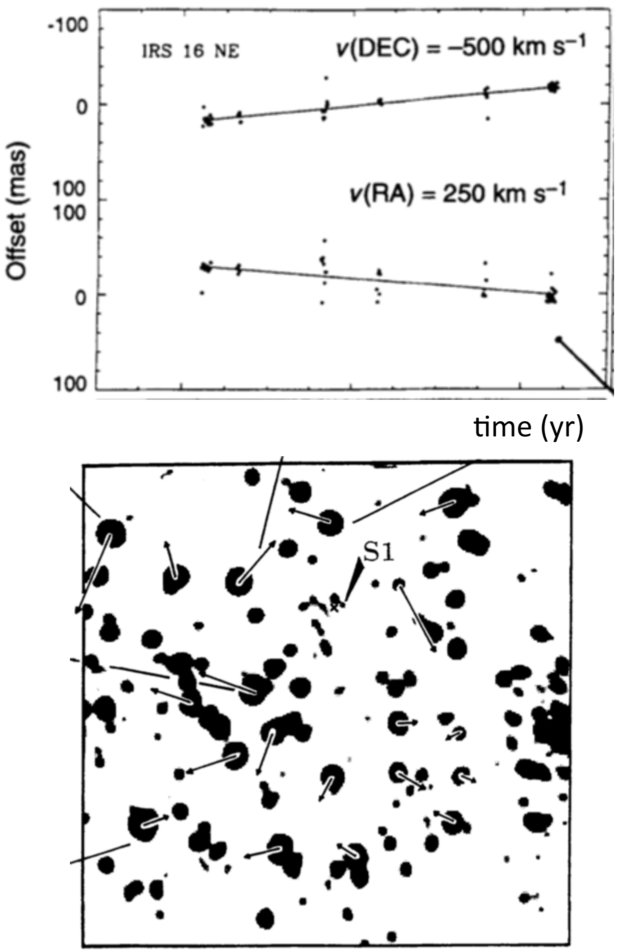


.. to diffraction-limited



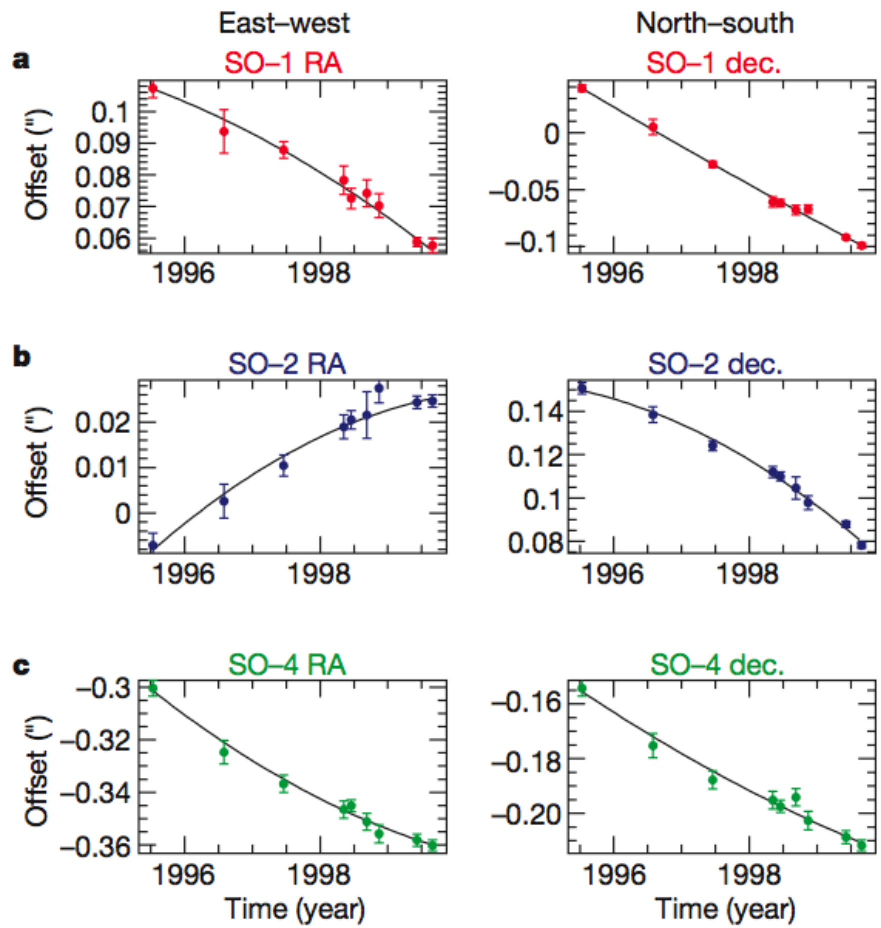
Progress due to high resolution

High proper motions



Eckart+ 1996

Accelerations

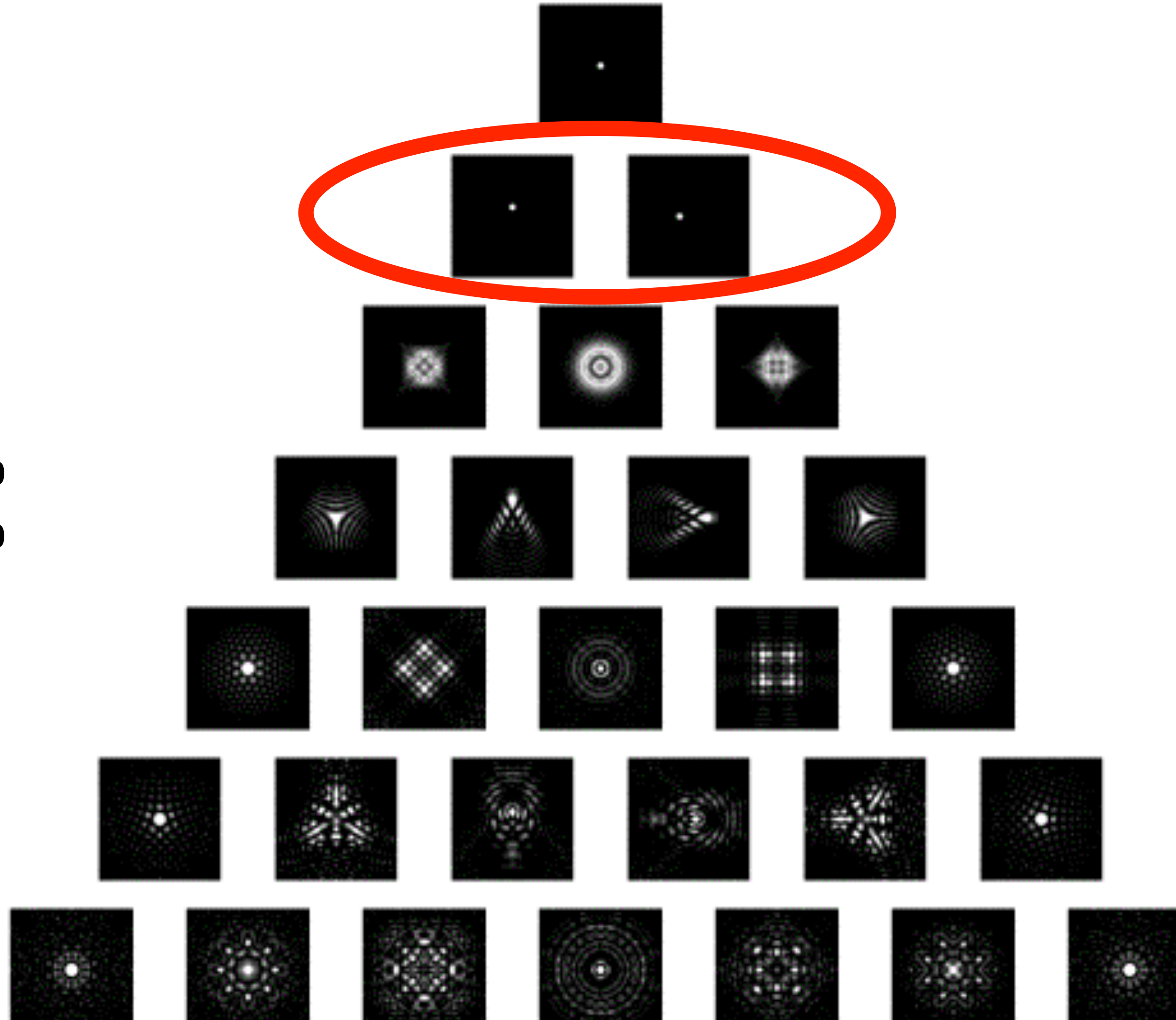


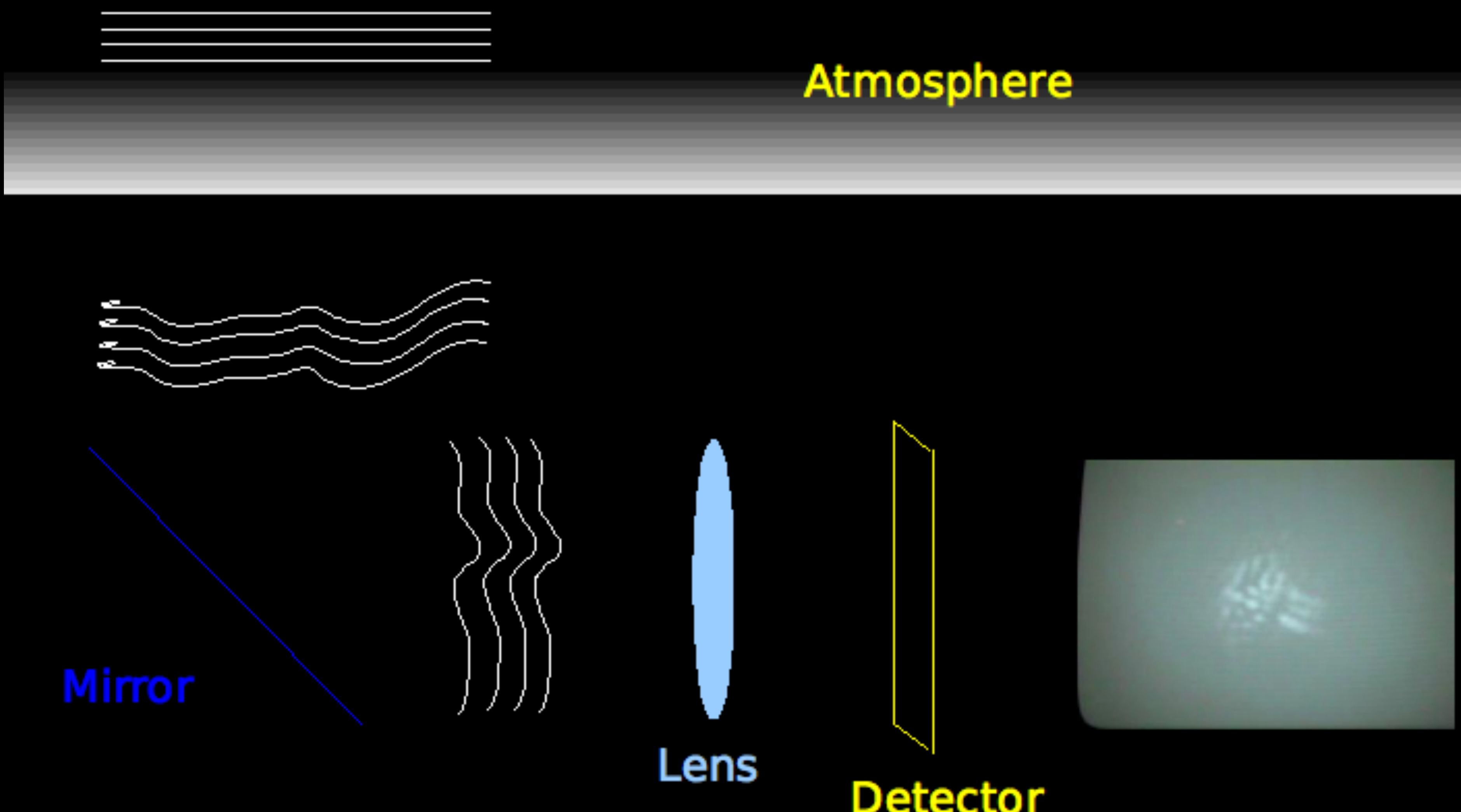
Ghez+ 2000

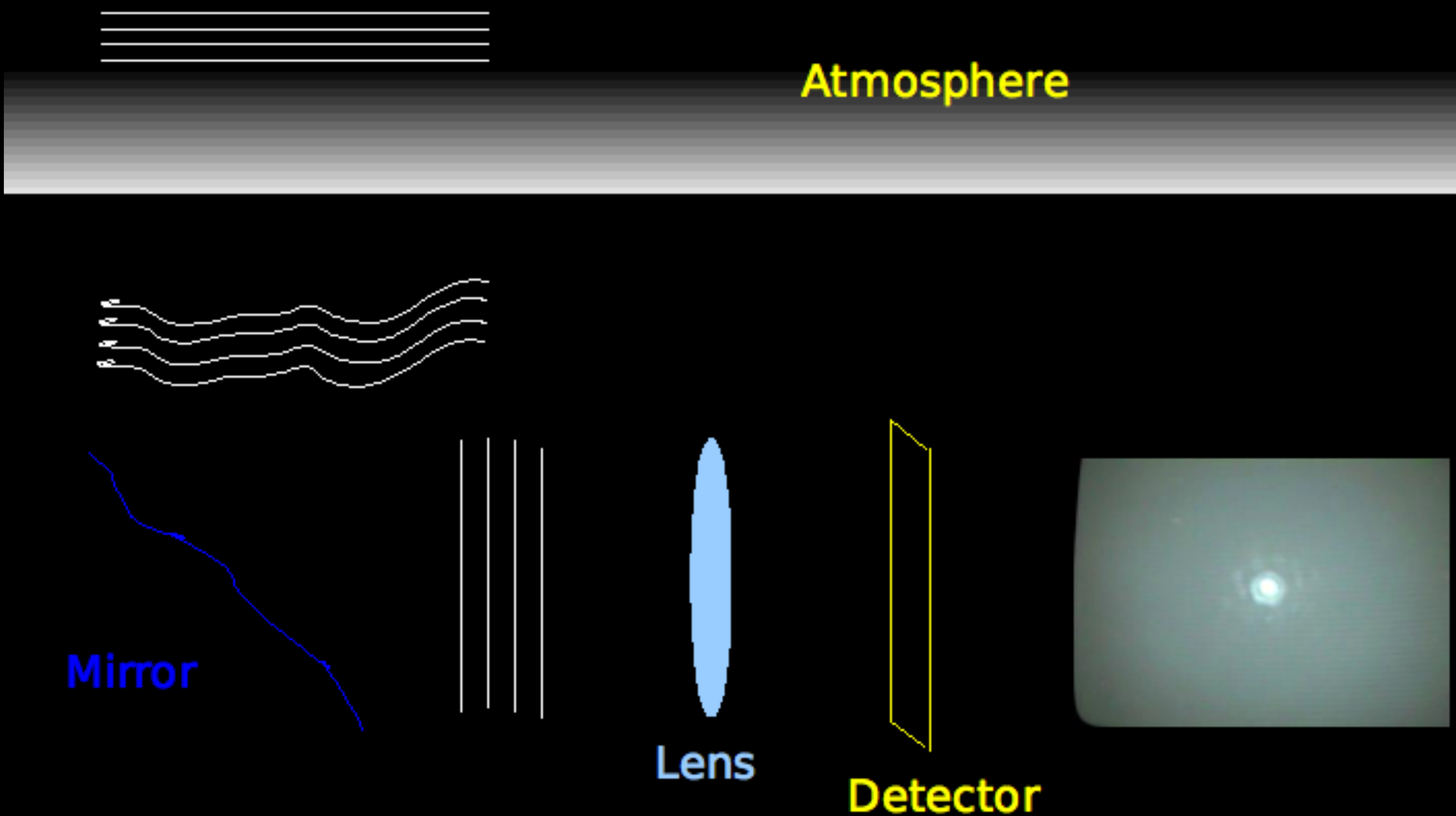
Simple-Shift & Add:
corrects two terms of wavefront aberrations
suppresses higher orders

6

=

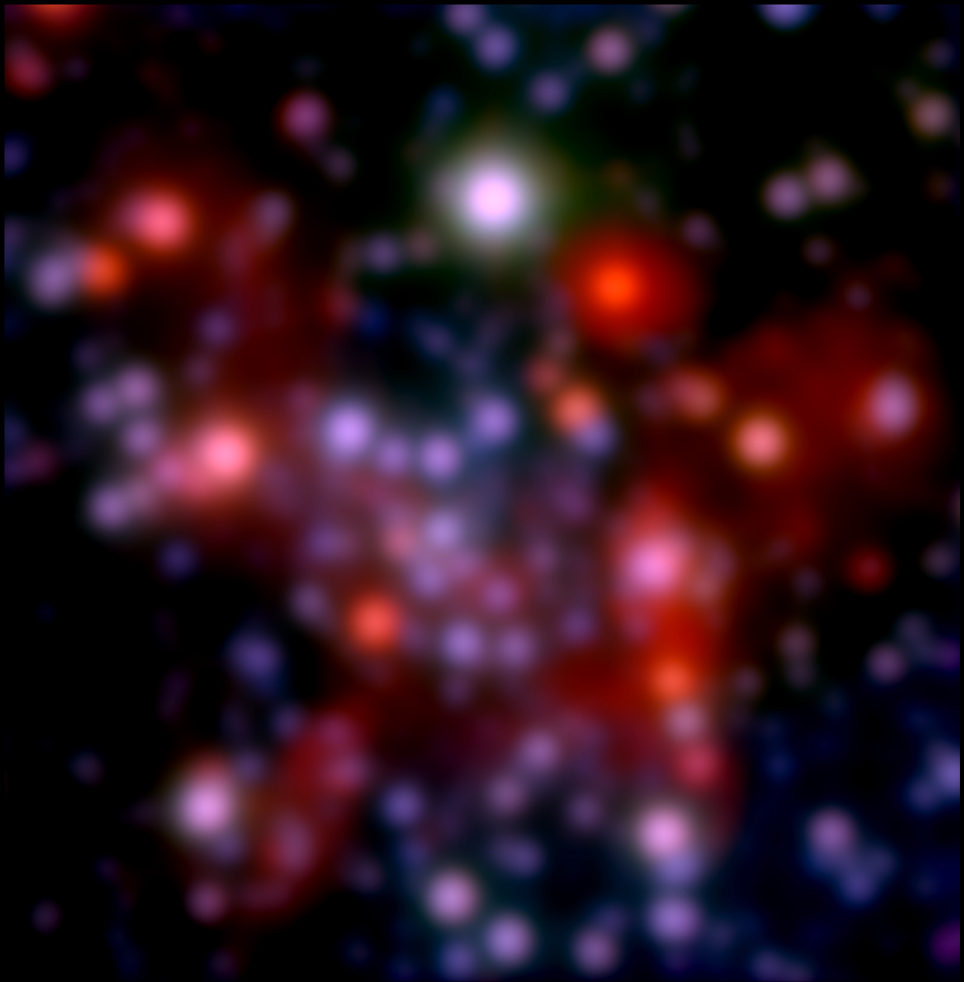


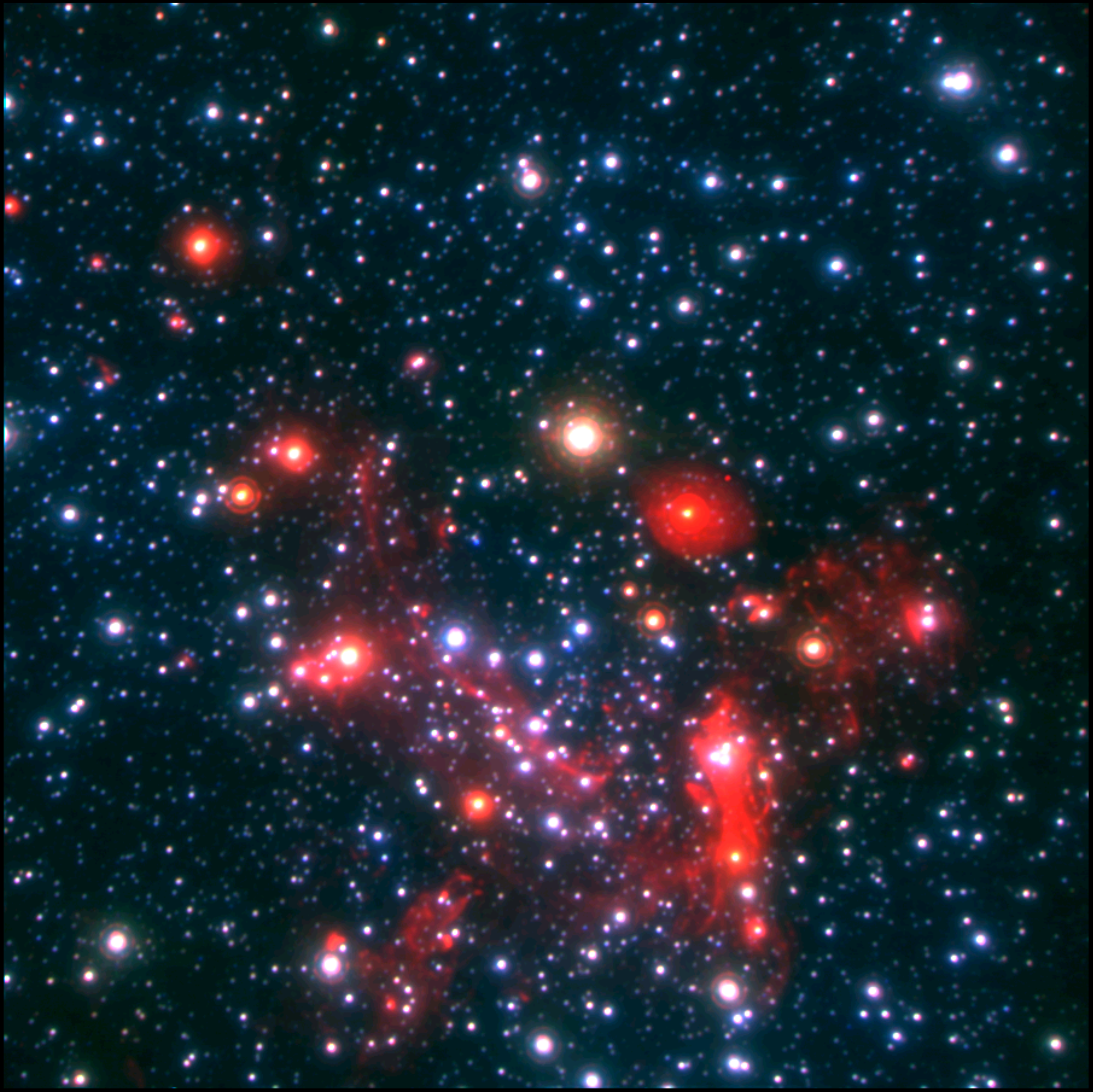

Atmosphere
Mirror
Lens
Detector



Atmosphere
Mirror
Lens
Detector

Really a big step forward: AO

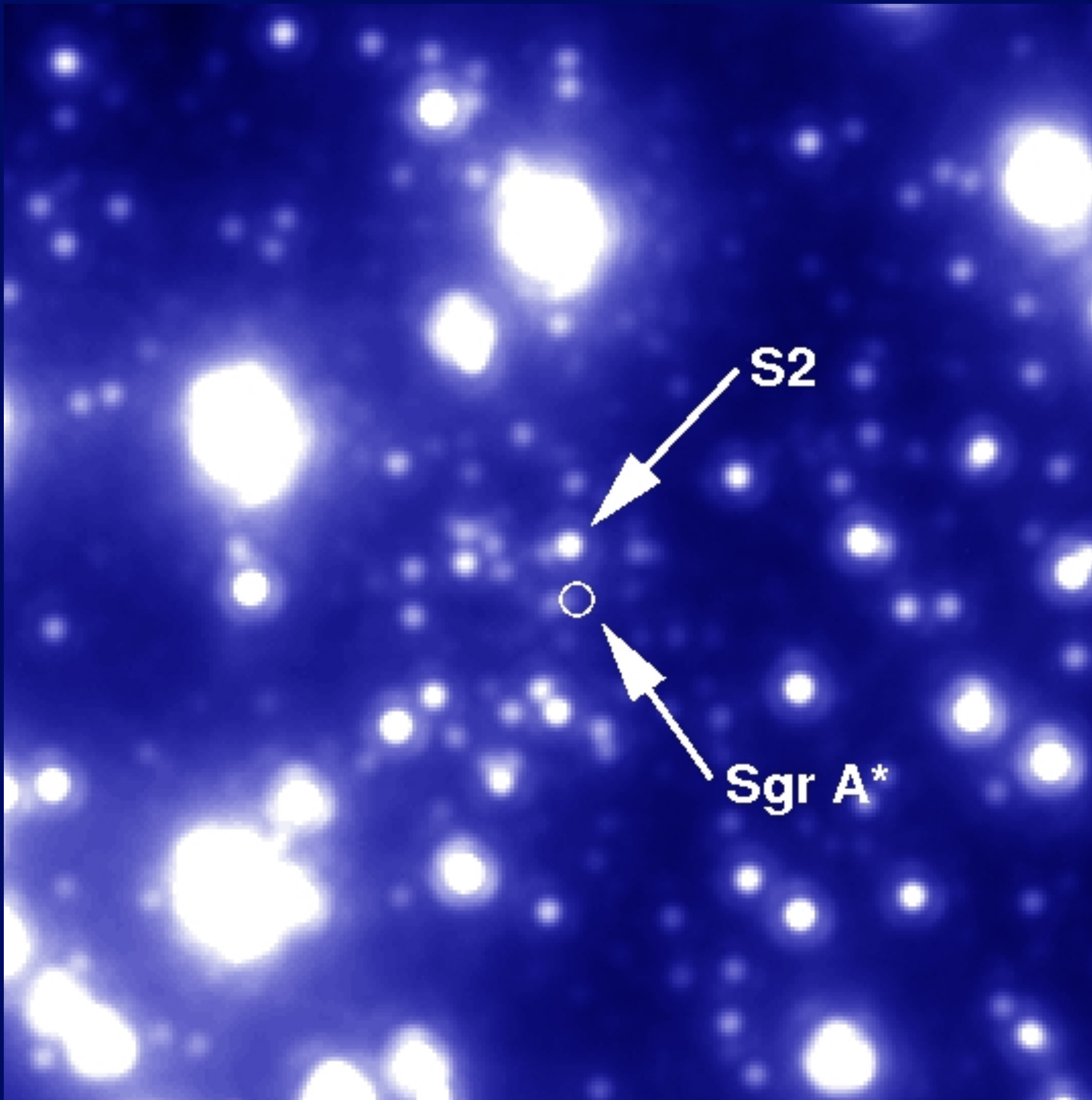




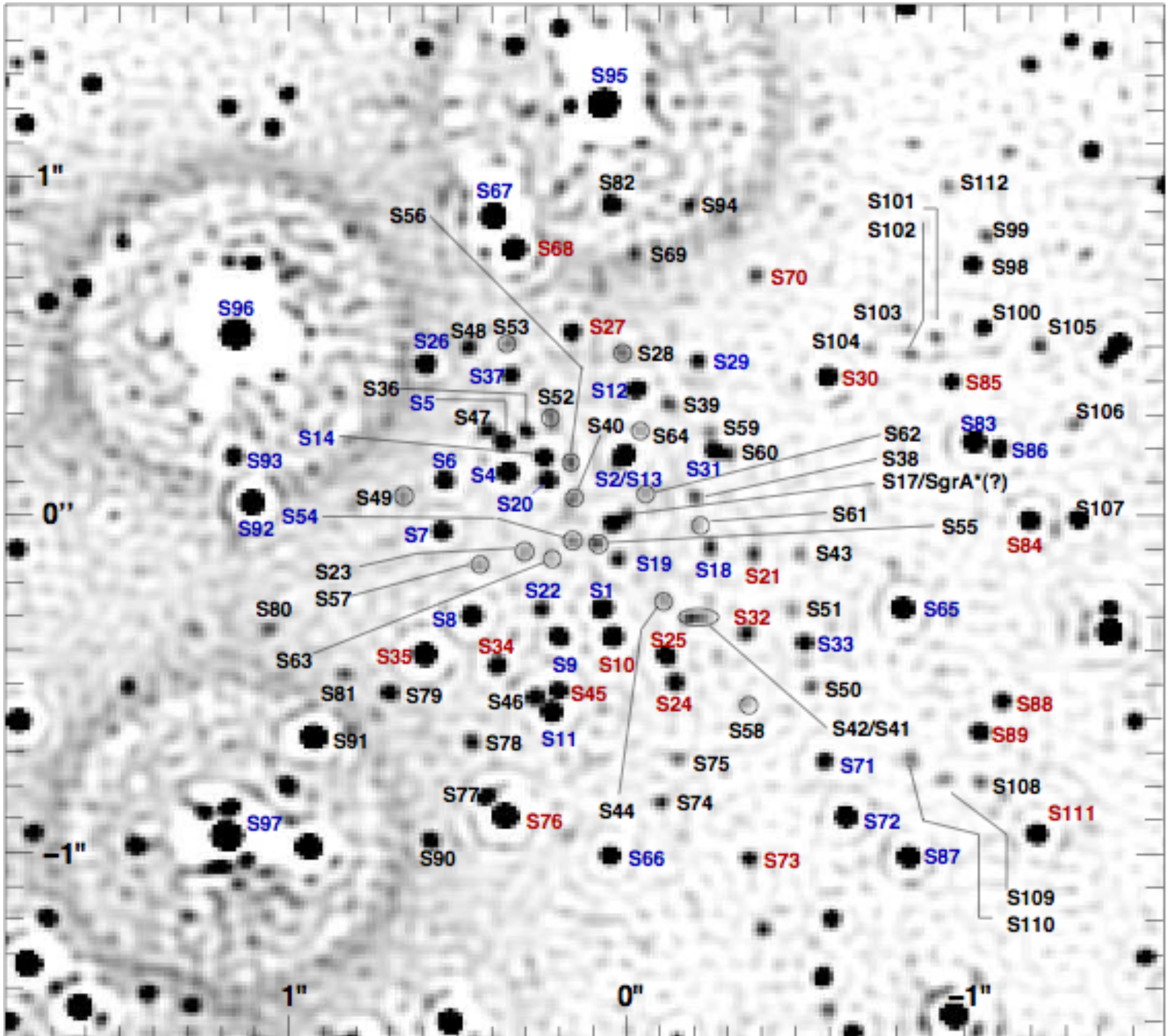
Strehl ratio 40%

NACO,
HKL color composite

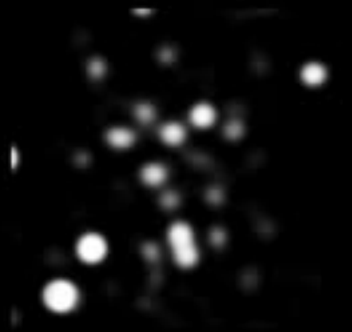
Diffraction-limited images



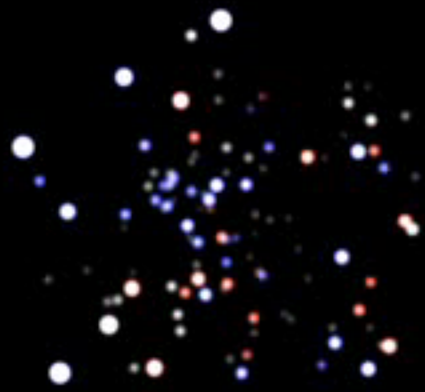
Around 100 stars with r < 1''



Stars move on Keplerian orbits

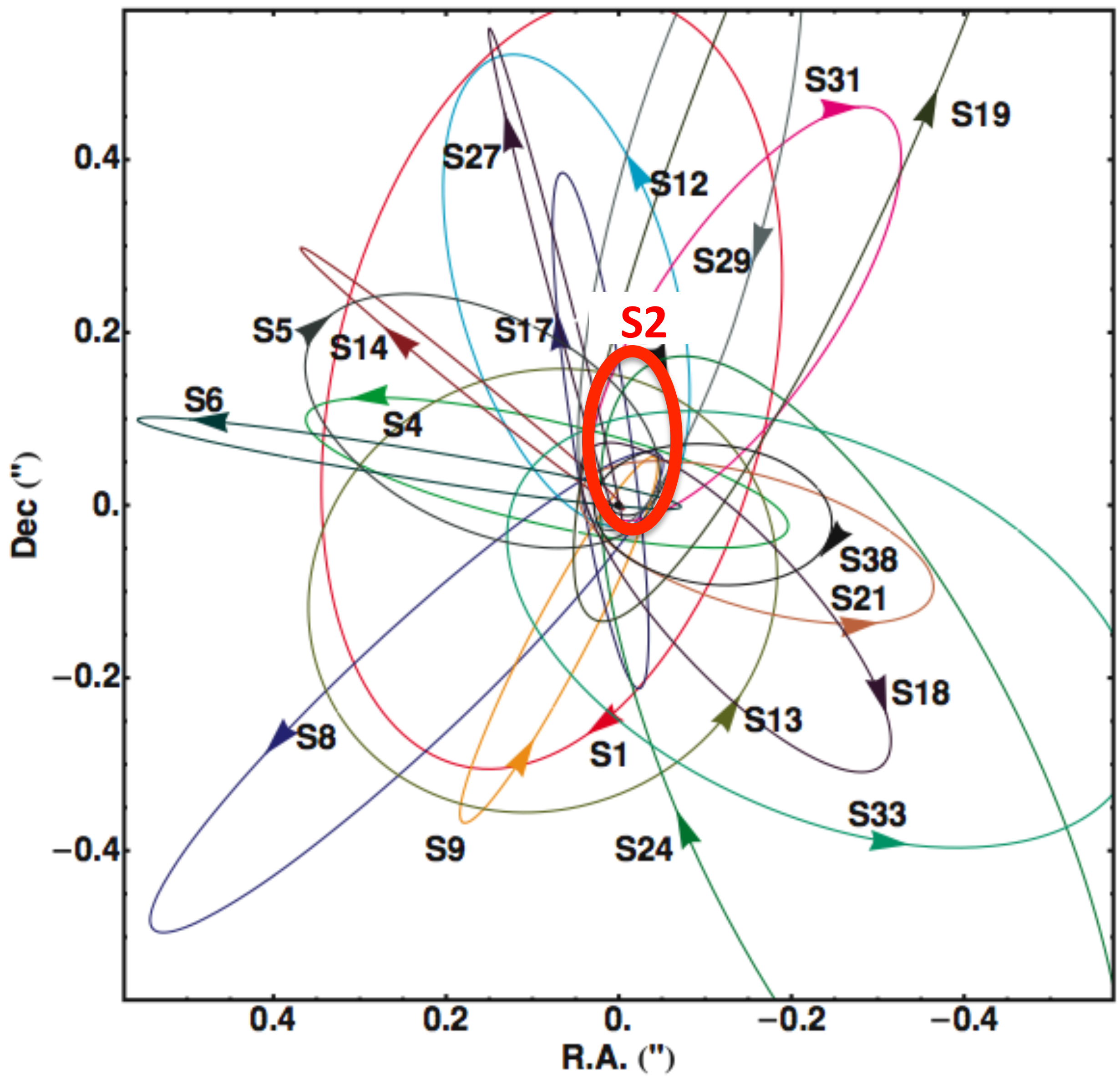


Real Data (!)



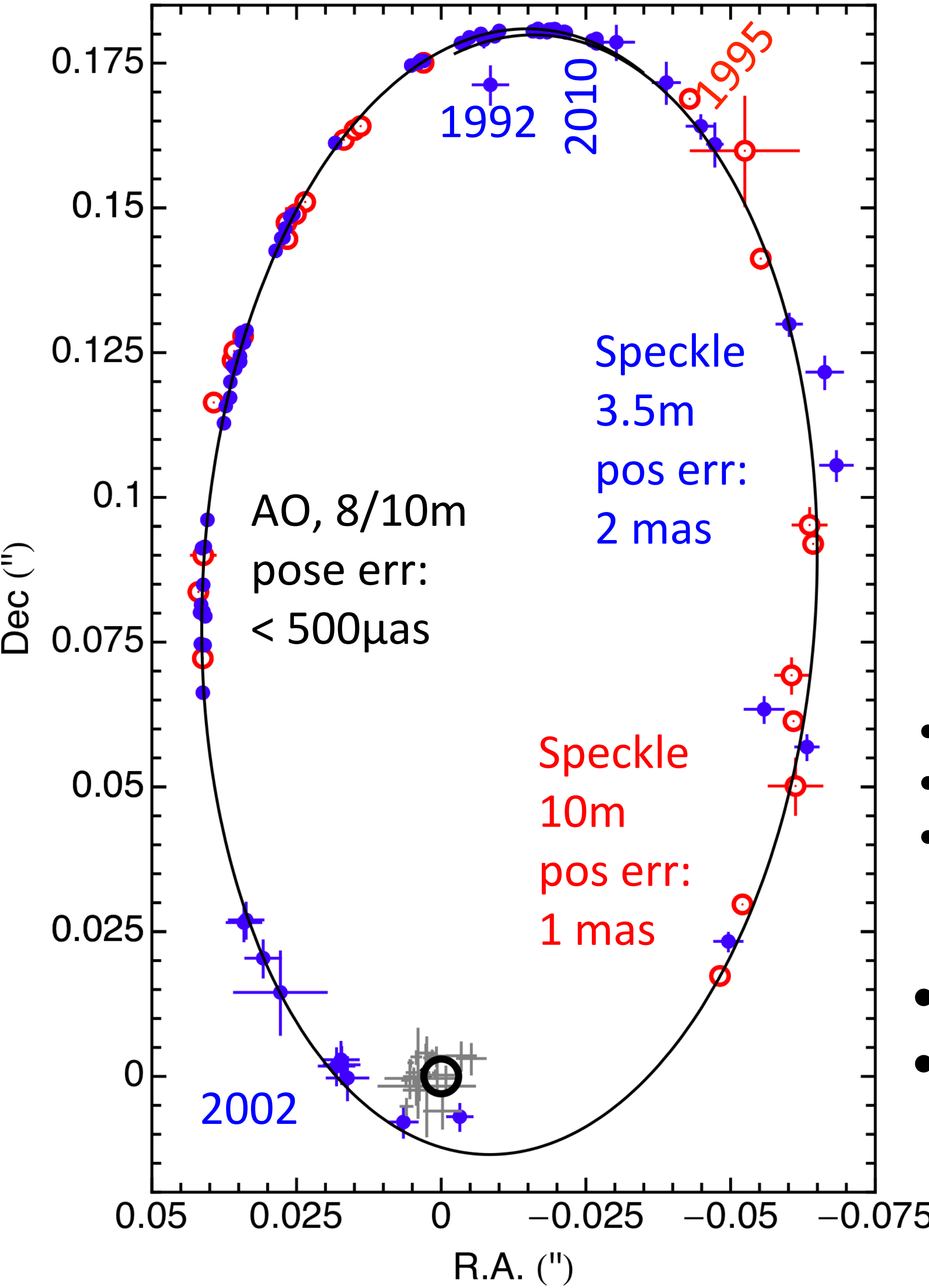
Model

Currently: > 30 orbits known



20 stars shown,
Gillessen+ 2009

S2: the showcase star



VLT & Keck data suitably combined

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

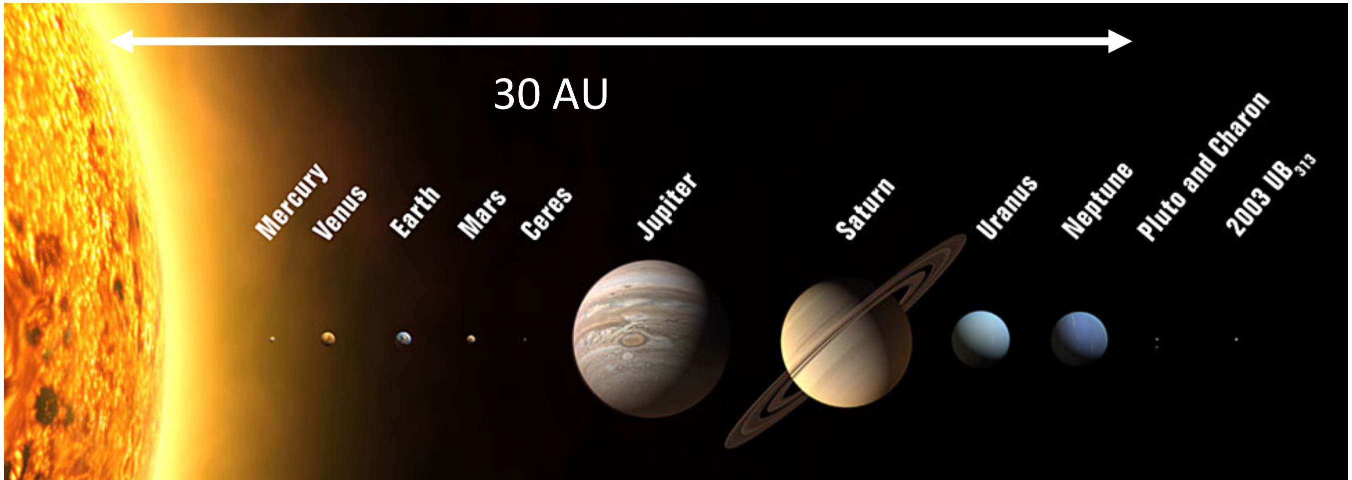
- period: 15.9 years
- semi major axis: 125 mas
- eccentricity 0.88

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

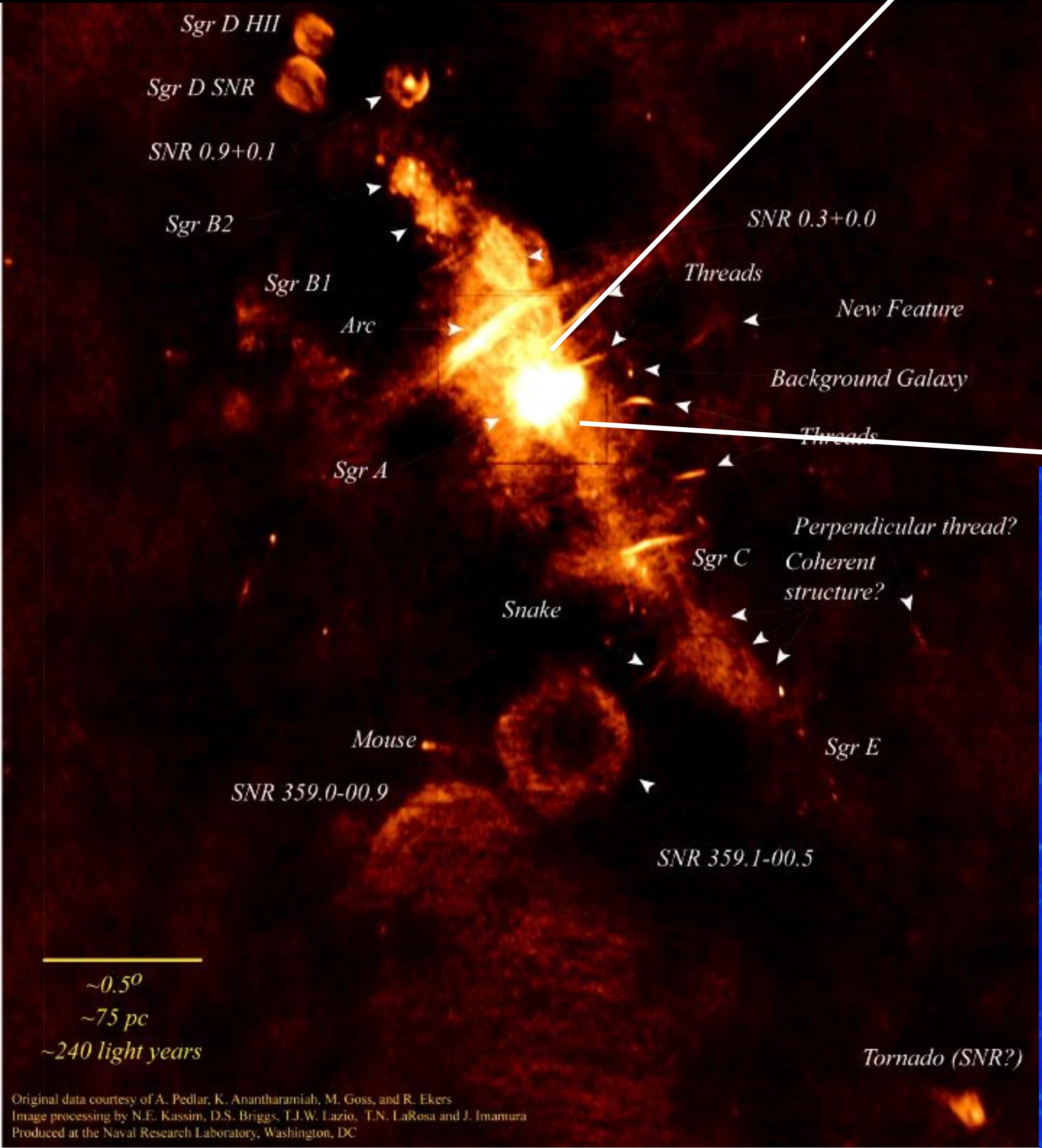
$M = 4 \times 10^6\, M_\odot$ in 100 AU

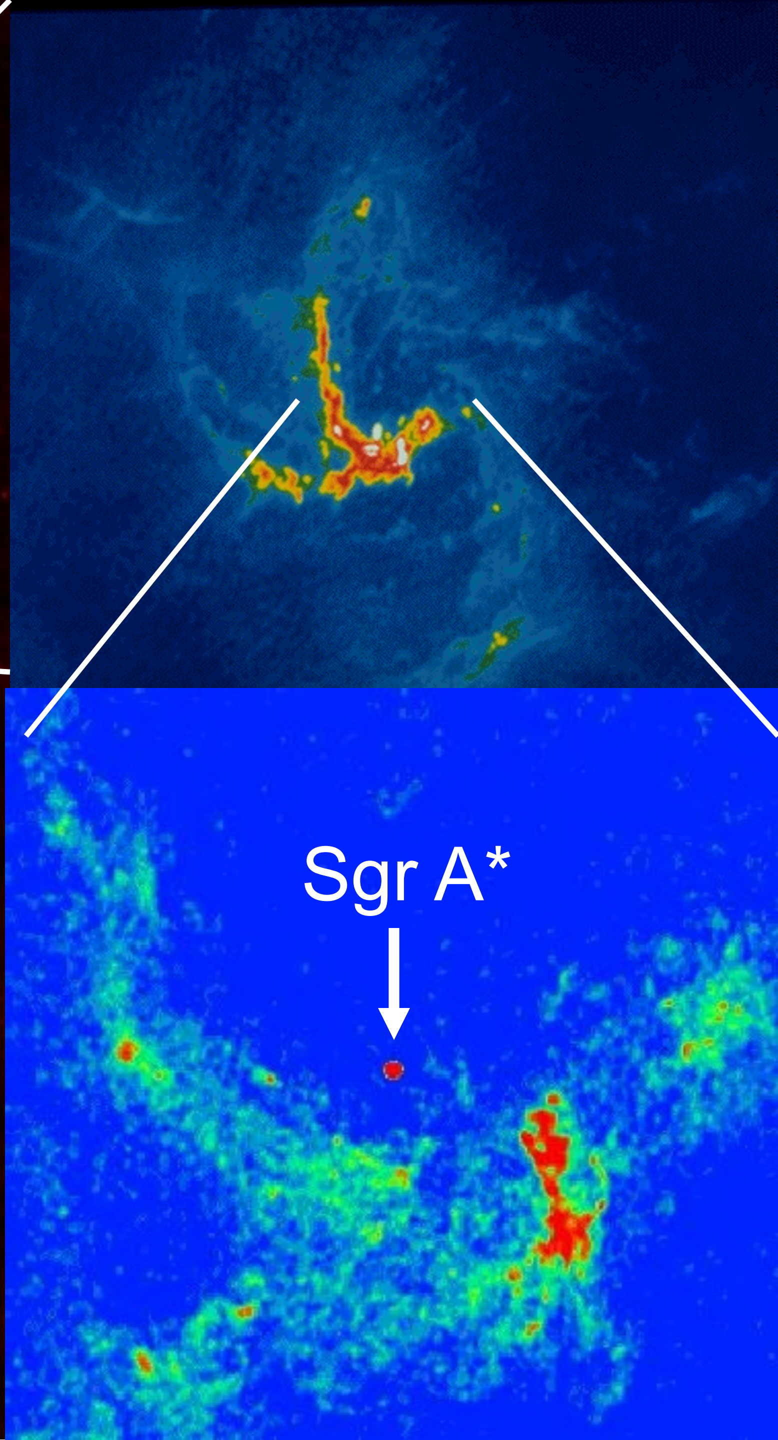
$$
\begin{aligned}
M &= 4\pi^2 \frac{a^3}{GT^2} \\
&= 4\pi^2 \frac{(0.12'' \times 8\,\mathrm{kpc})^3}{6.67 \times 10^{-11}\,\mathrm{m^3 kg^{-1} s^{-2}} \times 15.2\,\mathrm{yr}^2} \\
&= 4 \times 10^6 M_\odot
\end{aligned}
$$

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

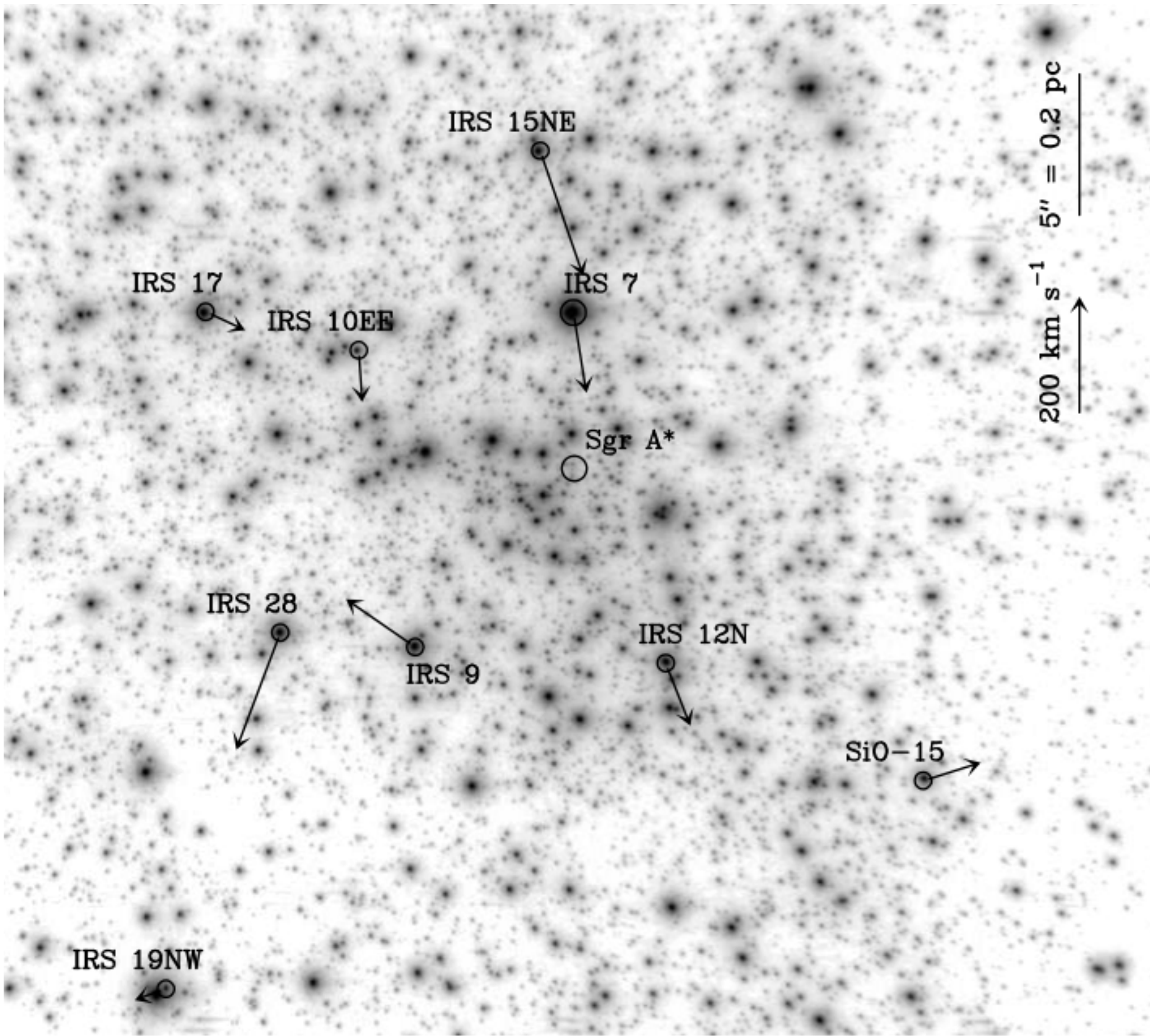


The radio view

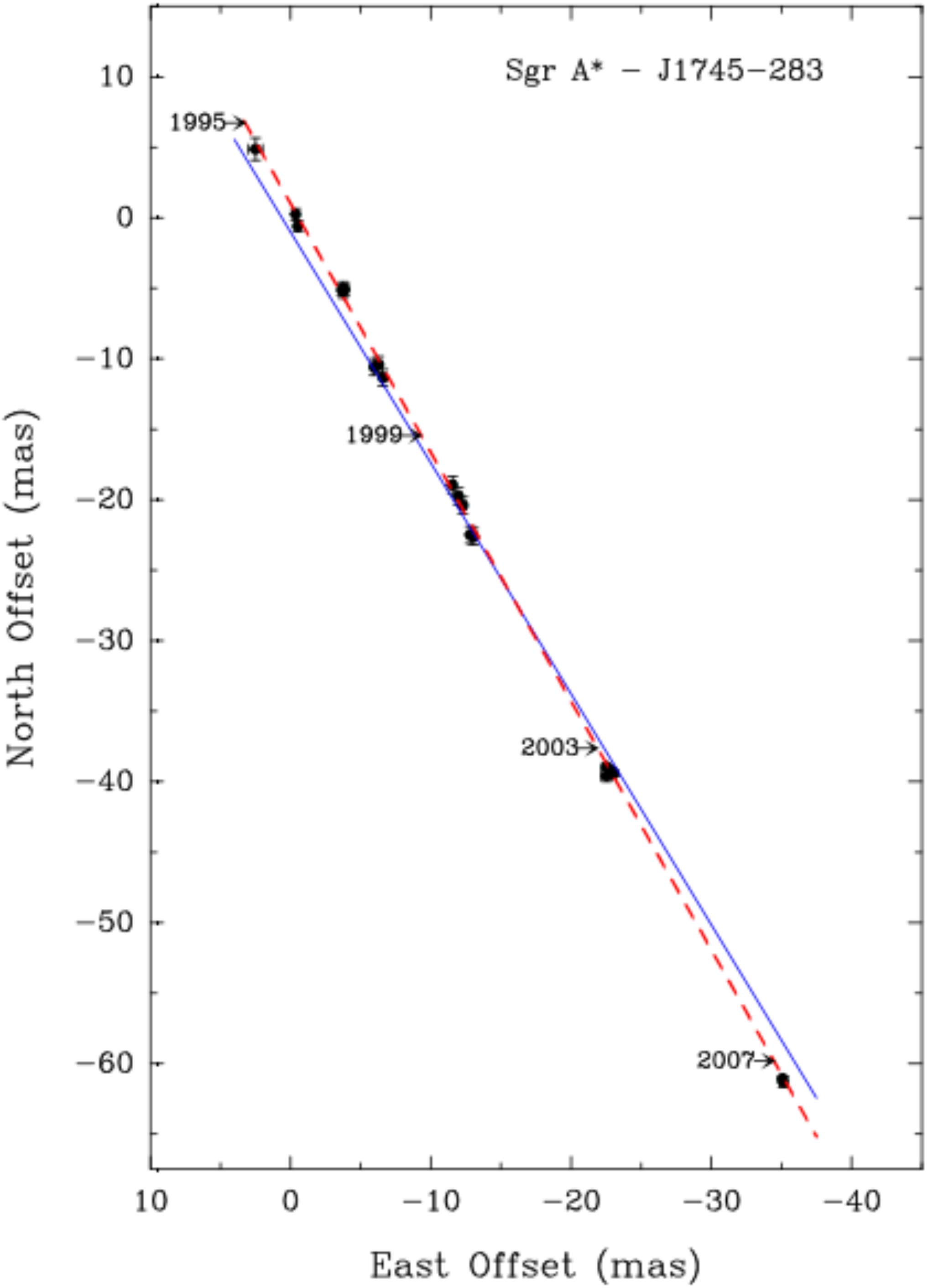




Sgr A* and mass coincide to within 2mas



Reid+ 2007

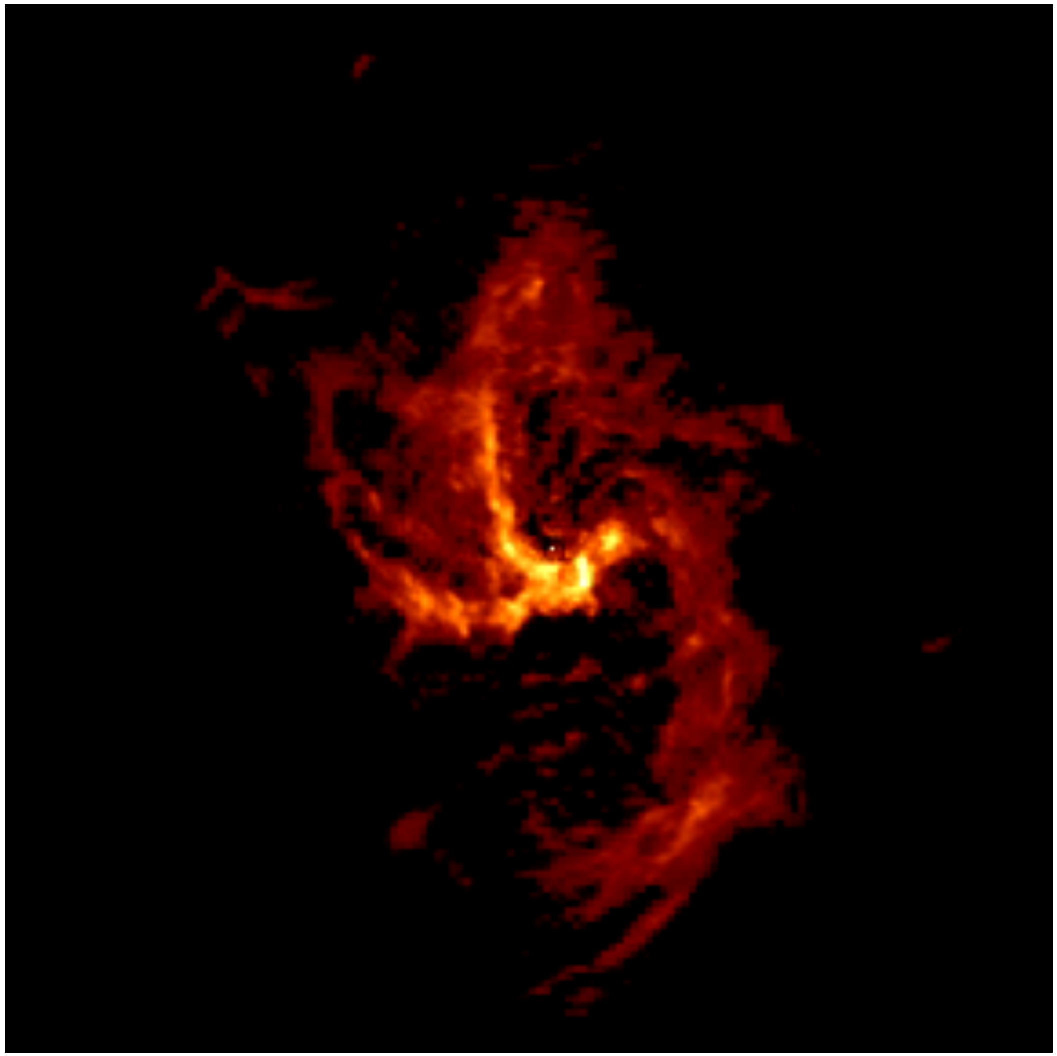


Sgr A* must be very heavy

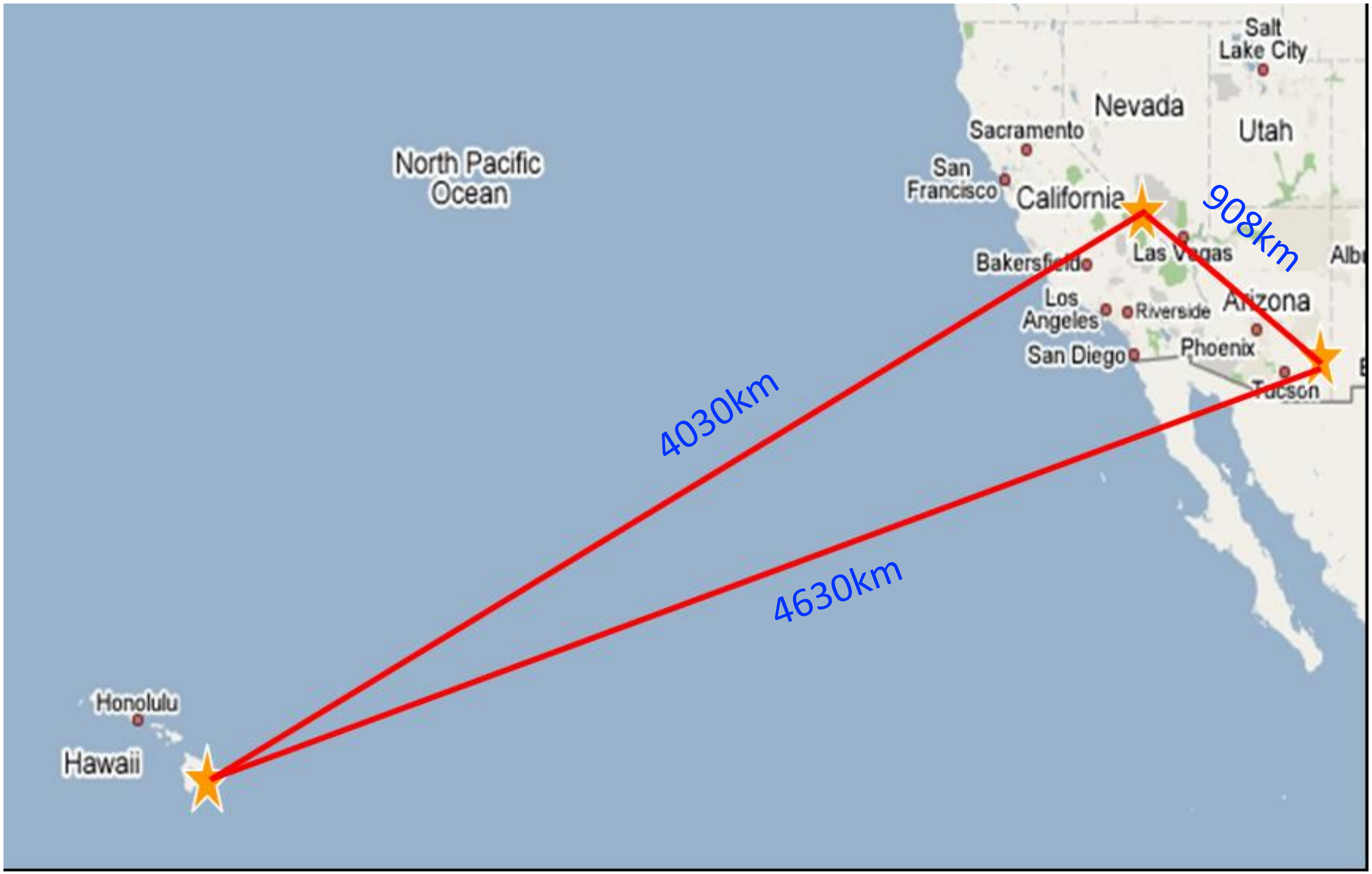
- perfectly linear motion
  - reflex motion of Sun (~200 km/s)
- intrinsic motion
  - gal. l : -7.2 ± 8.5 km/s
  - gal. b: -0.4 ± 0.9 km/s
- Sgr A* is much heavier than surrounding stars
  - > 4 x 10^5 $M_\odot$

Reid 2007, 2009

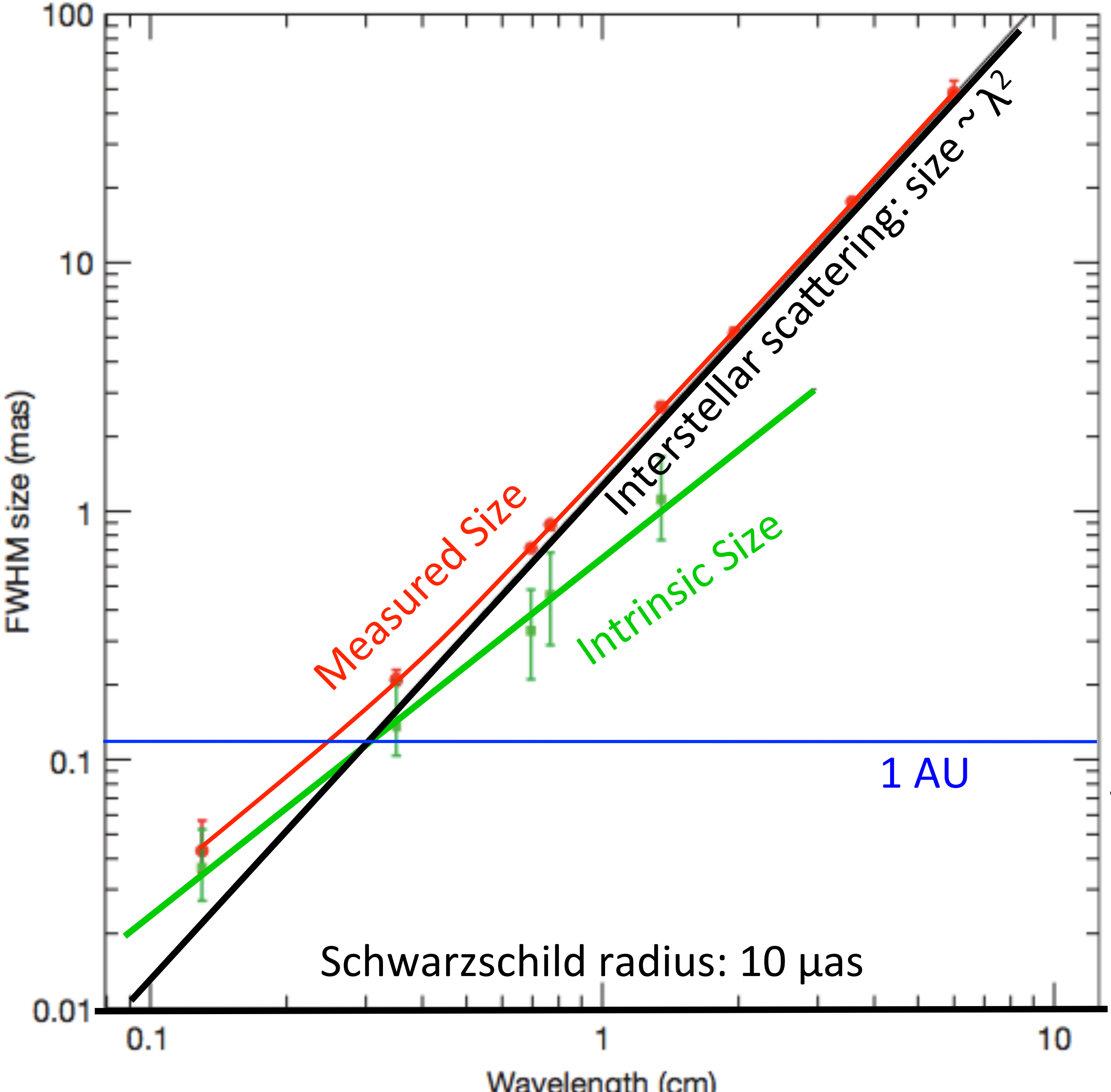
Sgr A* is a bright & extremely small radio source



1.3mm VLBI



Salt Lake City
Nevada
Utah
Sacramento
North Pacific Ocean
San Francisco
California
908km
Bakersfield
Las Vegas
Los Angeles
Riverside
Arizona
Phoenix
San Diego
Tucson
4030km
4630km
Honolulu
Hawaii

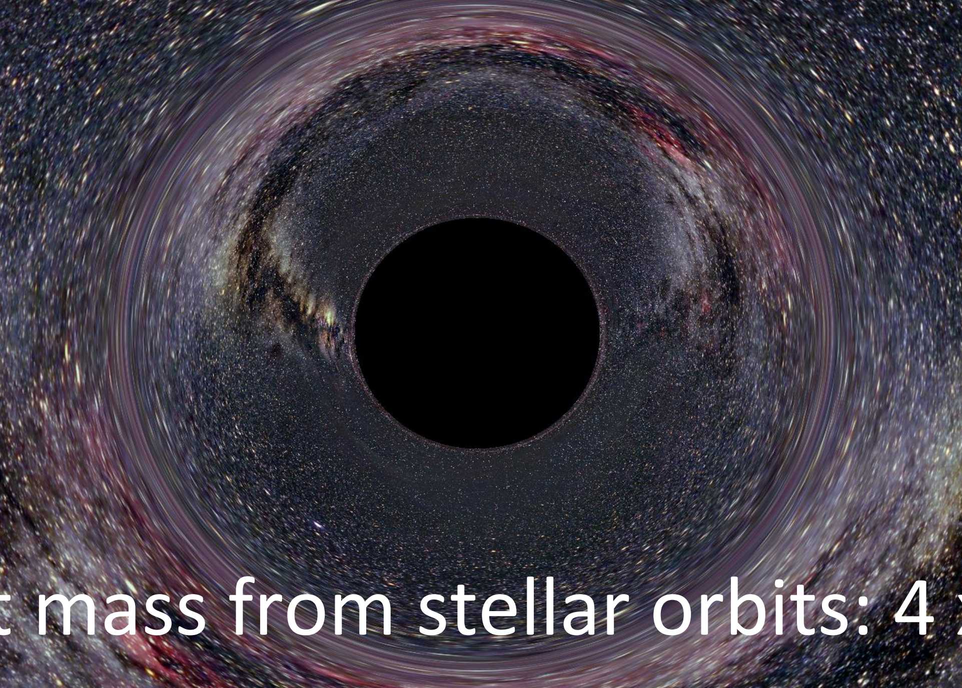


r < 1AU

r = 3.7 R_S

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

Sgr A* is a MBH

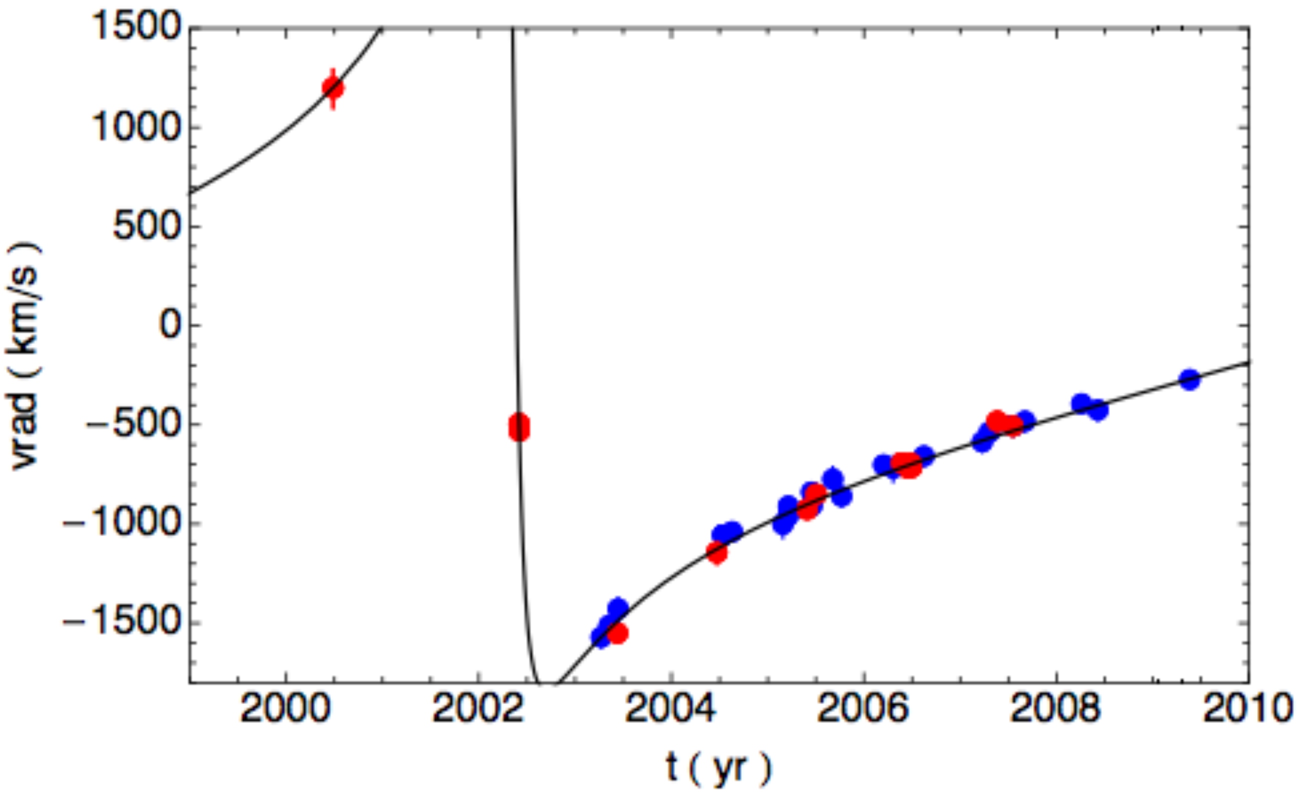


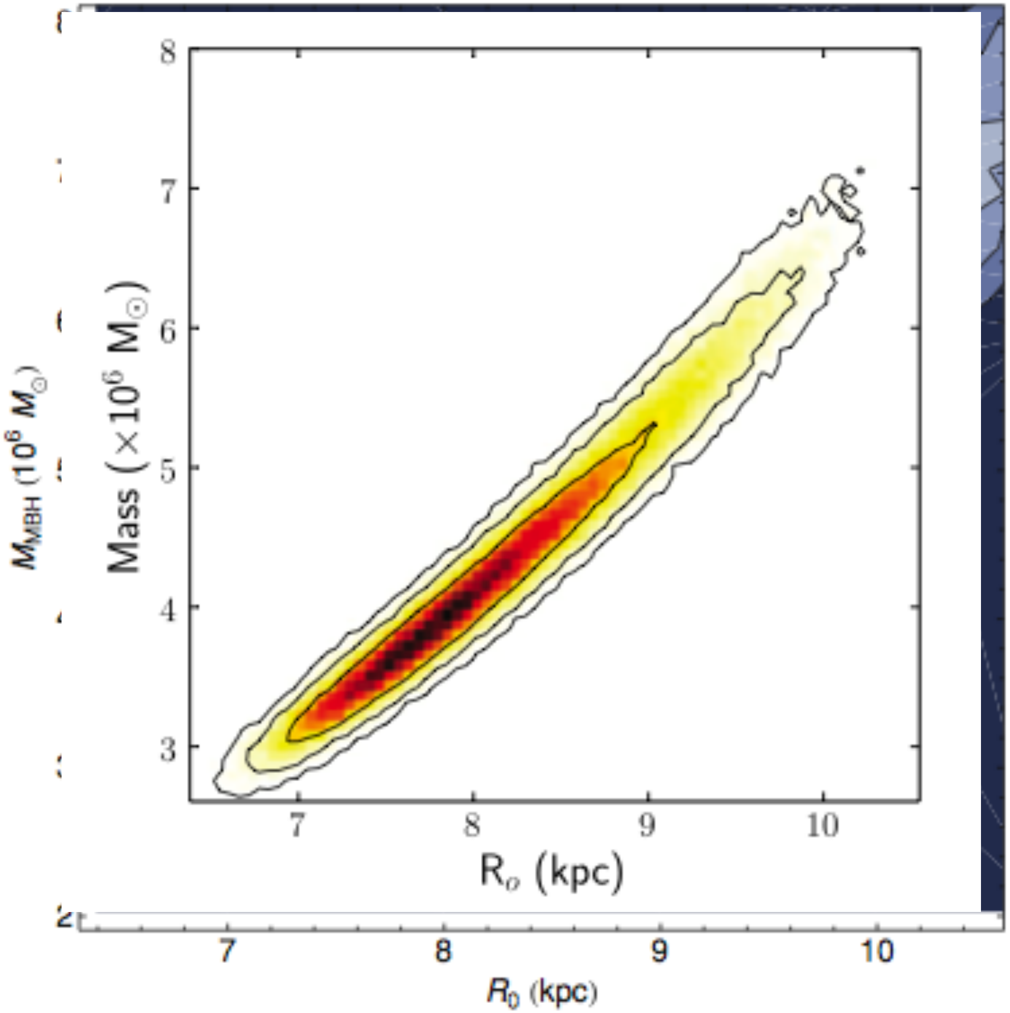
- Compact mass from stellar orbits: $4 \times 10^6 M_\odot$
- Radio Sgr A* coincied with the mass
- Radio Sgr A* moves in a straight line
- Radio Sgr A* is < 1 AU

The power of monitoring stellar orbits

- Measure the mass of the central MBH
- Geometric Distance to the GC, R_0
- Test for an extended mass distribution around SgrA*
- Potential to check Schwarzschild metric
- Measure special relativistic effects
- Formation of the enigmatic stars:
  - distribution of orbital planes
  - eccentricity distribution
- Test for the existence of an IMBH in the central arcsecond
- TeV astronomy might profit

The radial velocity information allows for the geometric distance estimate





Mass and R_0 are highly correlated

pure astrometry:
M ~ R^3

astrometry + radial velocities:
M ~ $R^{2.0}$

only radial velocities:
M ~ R^0

How well do we know that potential is that of a point mass ?

Measured fraction of mass inside of S2 orbit that is not pointlike

$$\eta = 0.018 \pm 0.014|_{\rm stat} \pm 0.005|_{\rm model}$$

Only 2 tests:

- If S-stars formed 6 Myrs ago in disk &
- if they reached current orbits via 2-body-relaxation:

$\eta = 0.033$

- If diffuse X-ray emission is due to neutron stars:

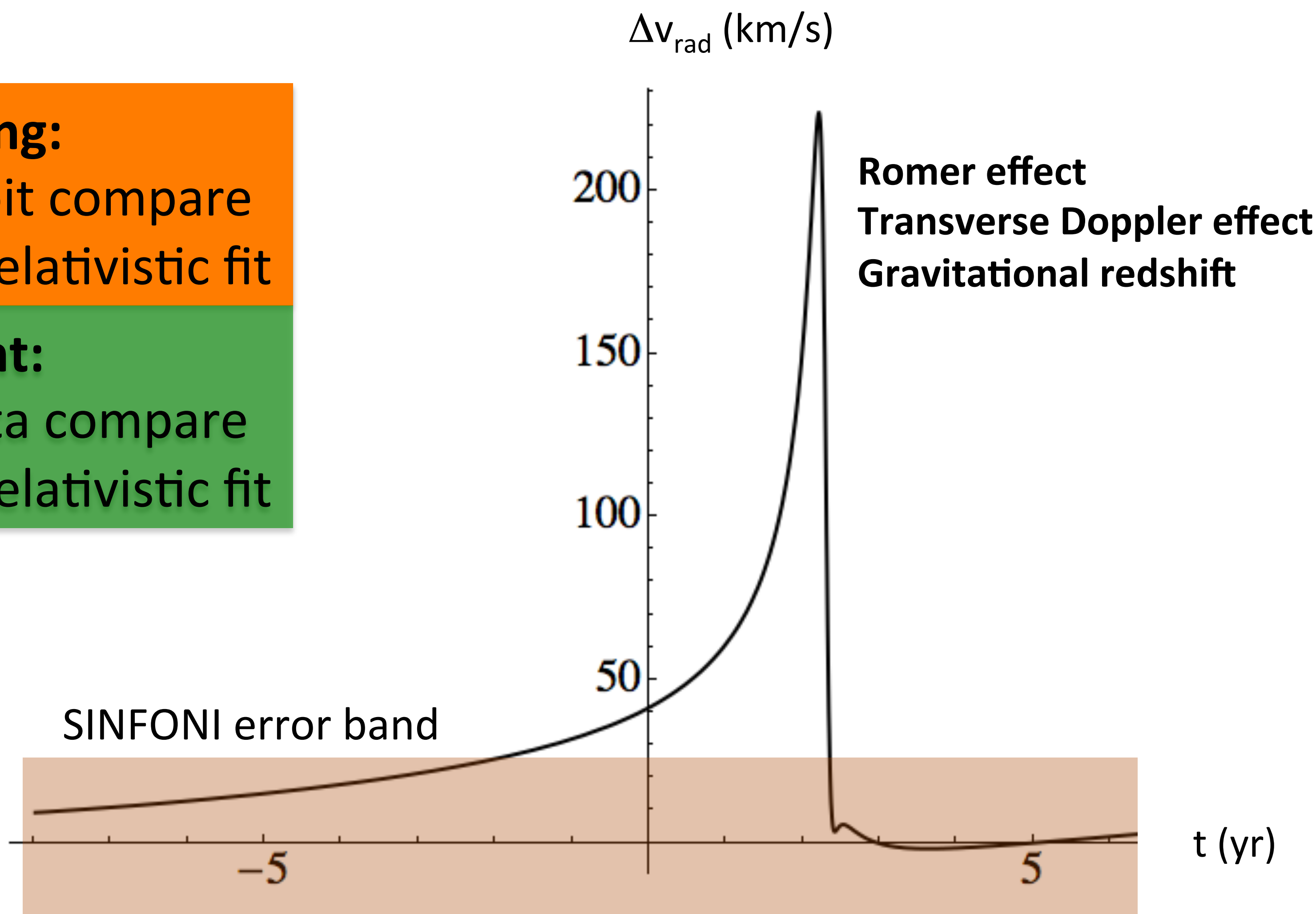
$\eta = 0.07$

Special relativistic effects during close peri-passage observable with today's technique

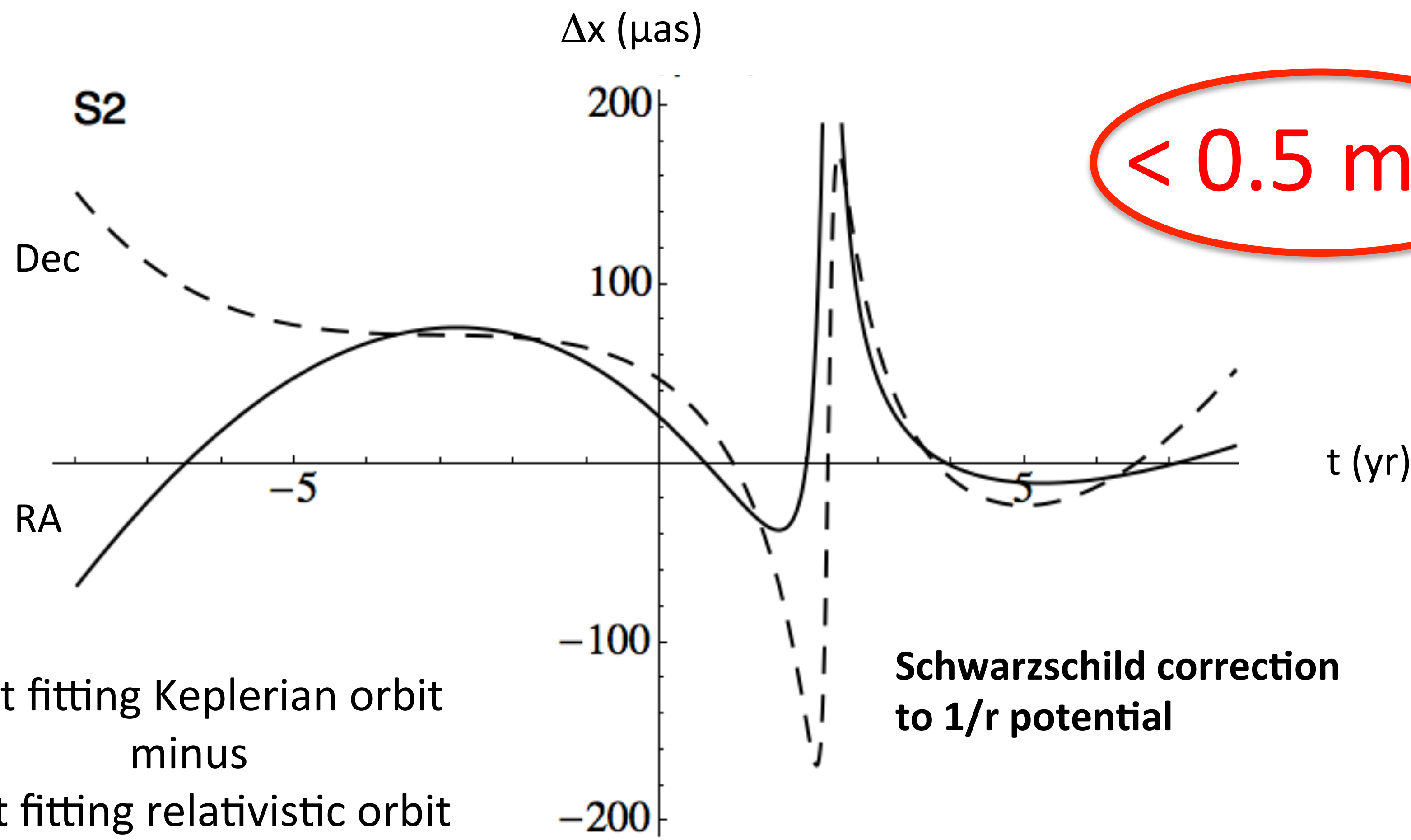
Zucker+ 2005

Wrong:
For given orbit compare
Keplerian & Relativistic fit

Right:
For given data compare
Keplerian & Relativistic fit



Astrometric deviations are much harder to detect

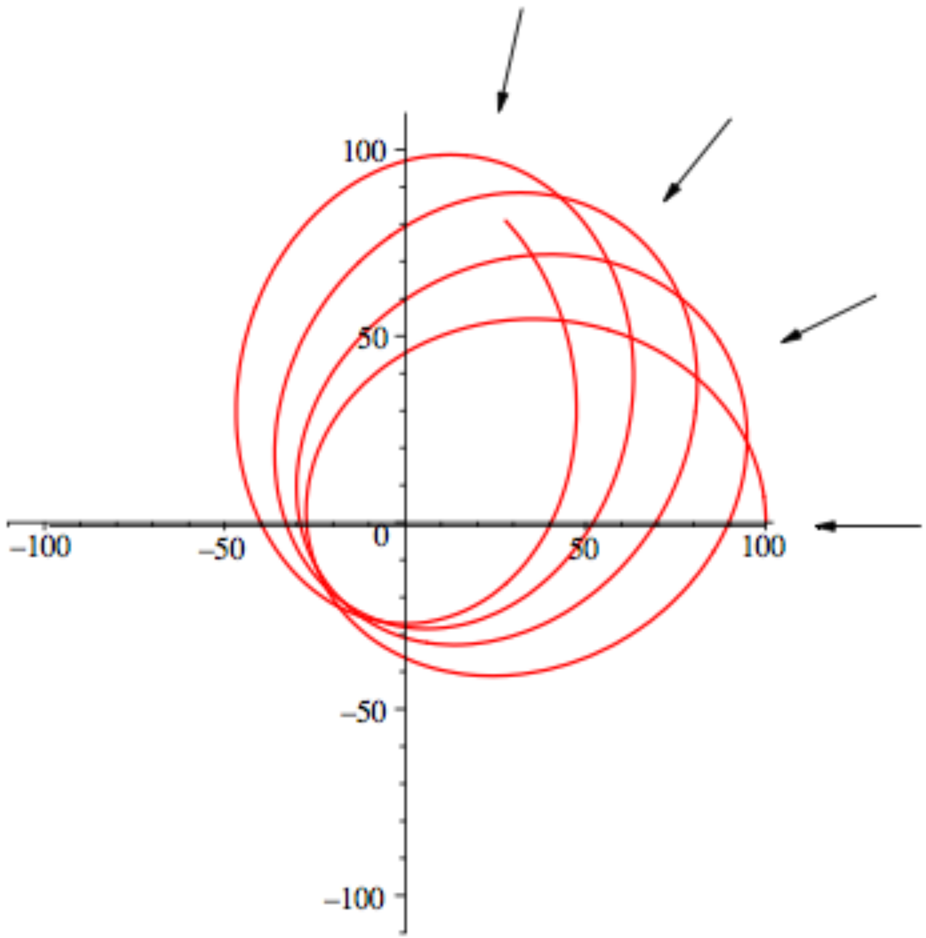


< 0.5 mas

Schwarzschild correction to 1/r potential

best fitting Keplerian orbit
minus
best fitting relativistic orbit

Another way to look at it: Measure pericenter shift explicitely

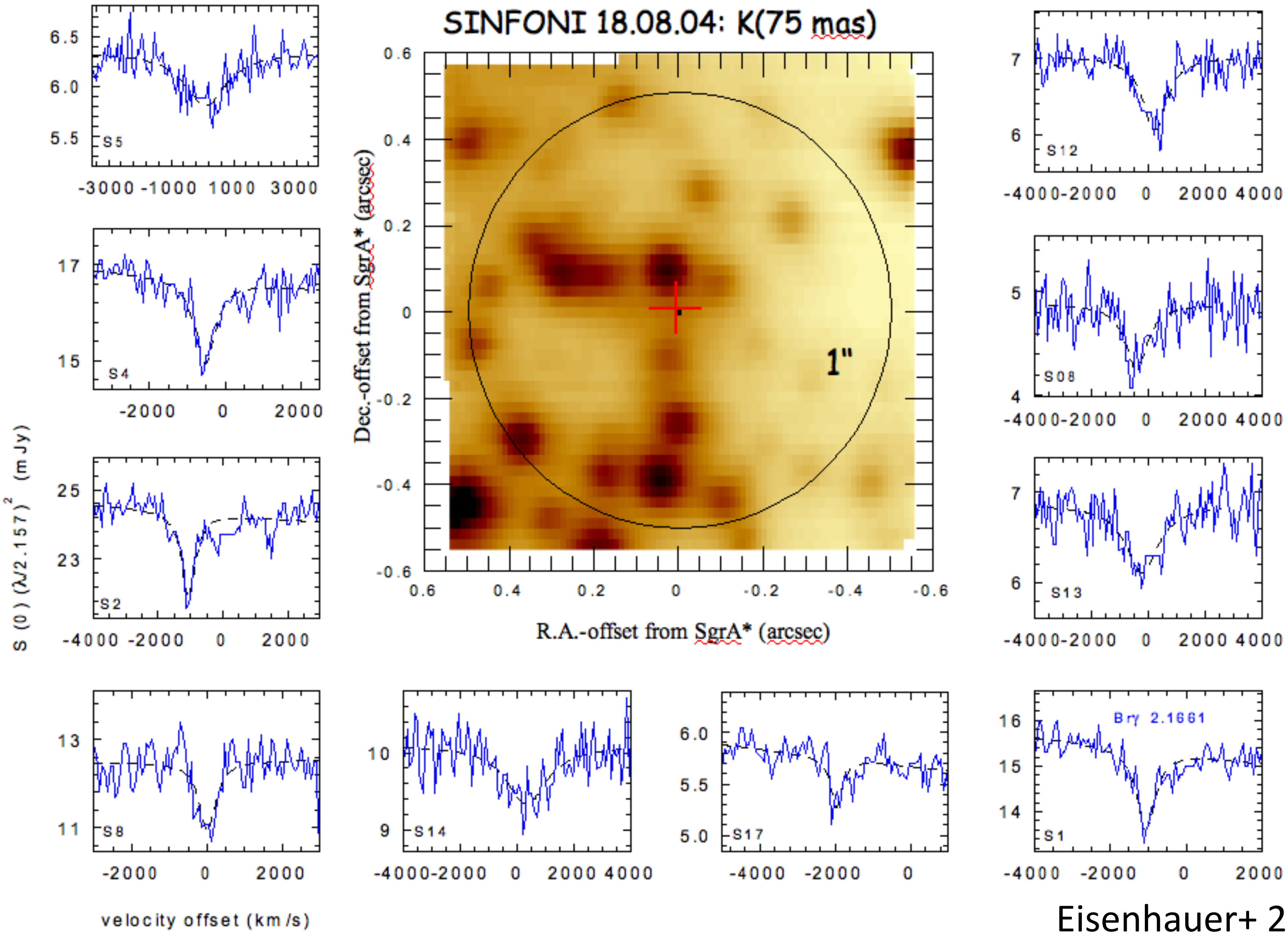


expected:
$\Delta\omega = 0.22°$ per revolution
(16 years)

measured:
$\Delta\omega = 0.84°$ in 18 years

Rubilar & Eckart (2001)

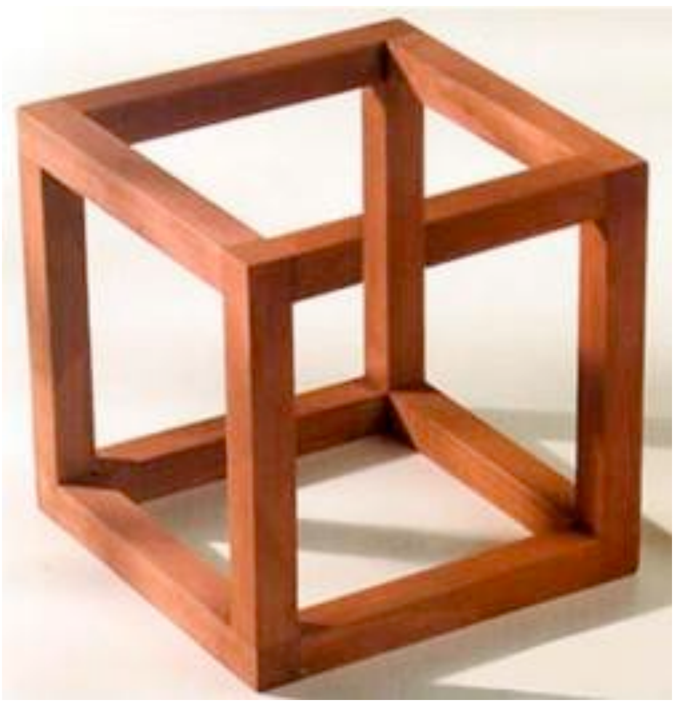
Surprisingly, the S-stars are young



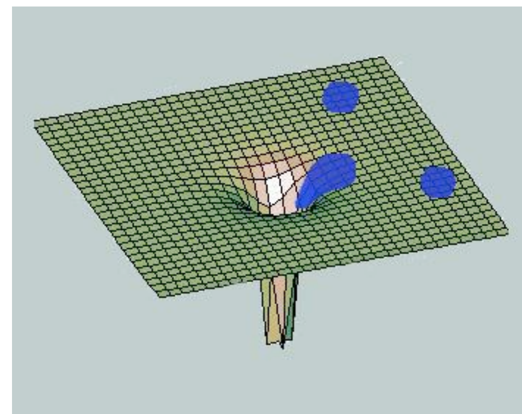
Eisenhauer+ 2005

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

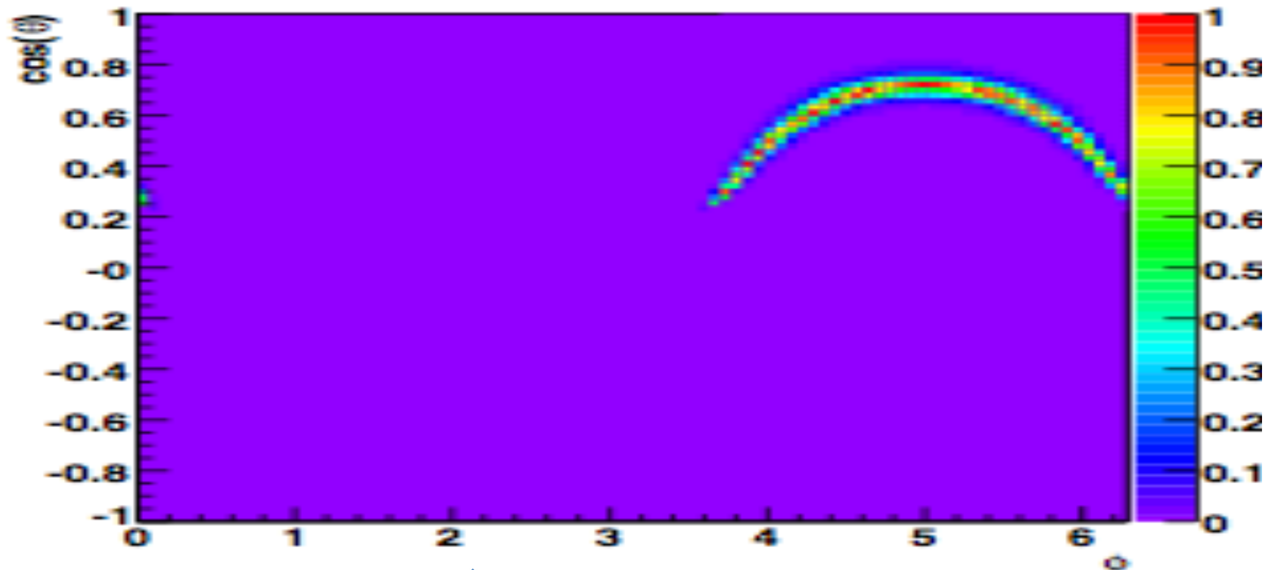
$$t_{2\mathrm{BR}} \approx 3\,\mathrm{Gyr}$$

$$\gg$$

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

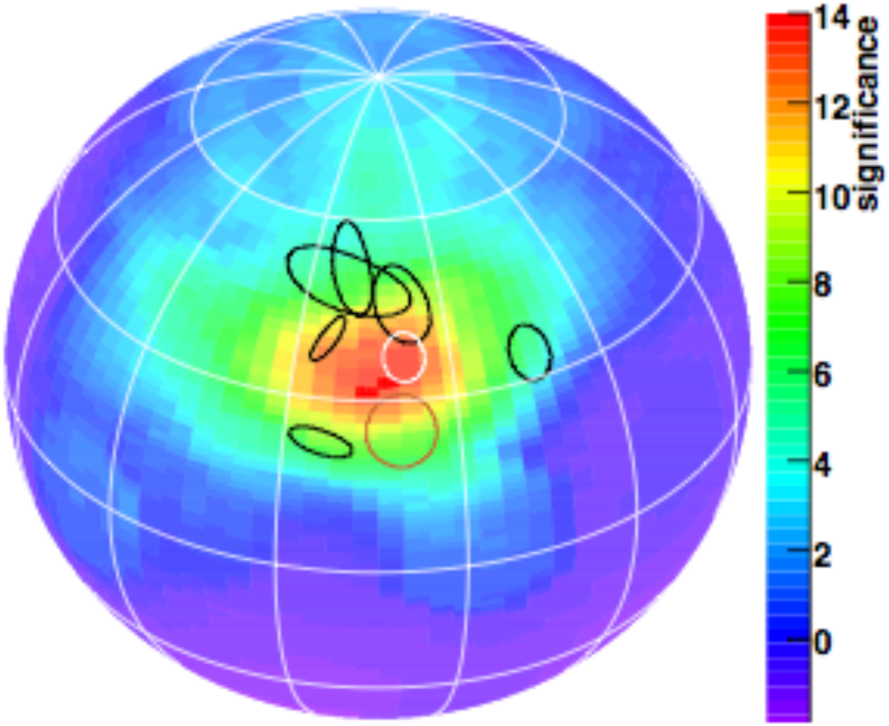
For r > 1'':
Hard to measure accelerations

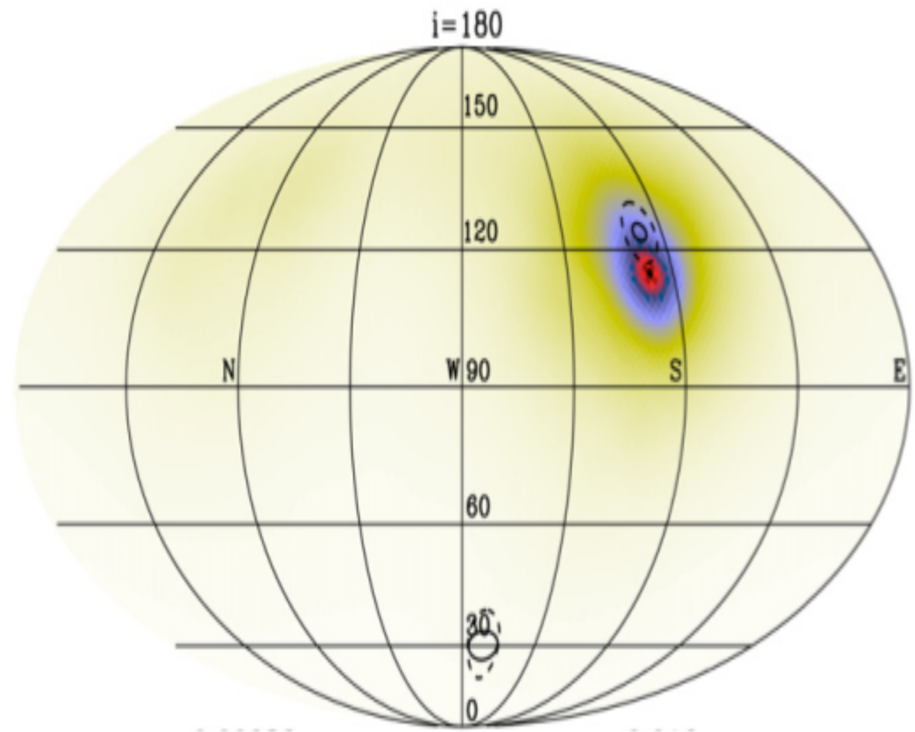
	r < 1''	r > 1''
x	✔	✔
y	✔	✔
vx	✔	✔
vy	✔	✔
vz	✔	✔
a_{2D}	✔	✖



(a, e, i, ω, Ω, t)

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



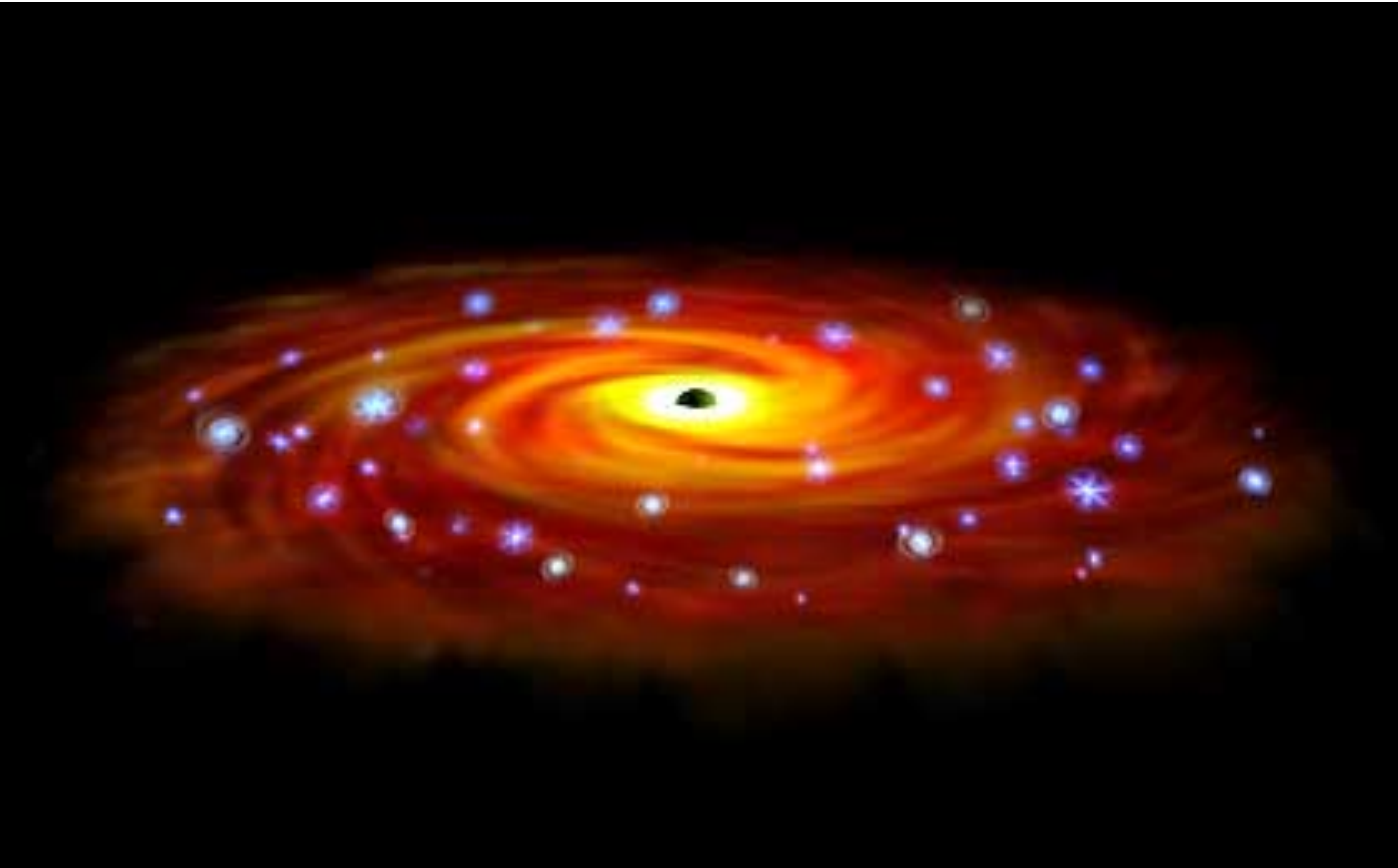


orientation of orbital angular momentum

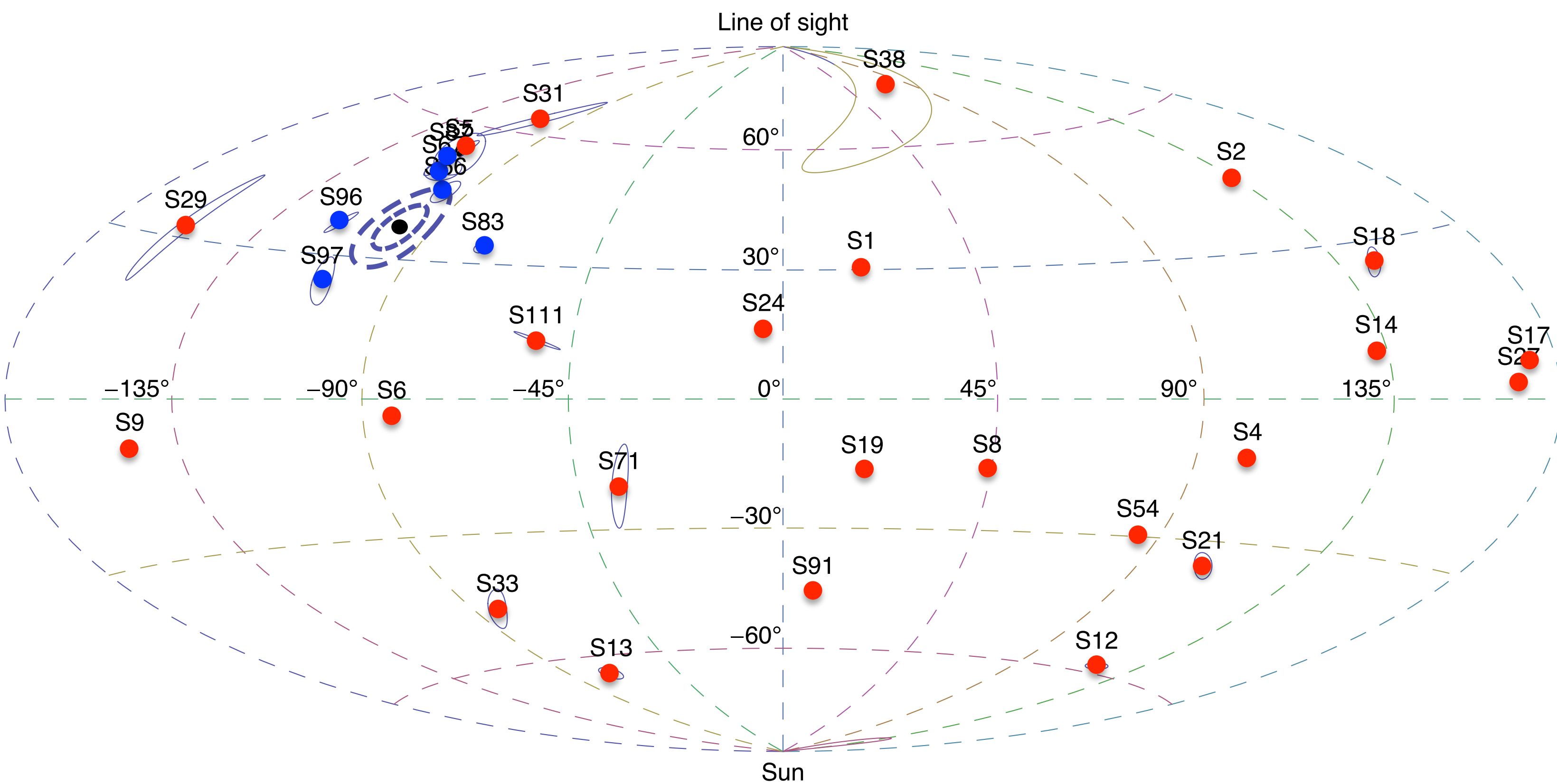
Bartko+ 2009

Lu+ 2009

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

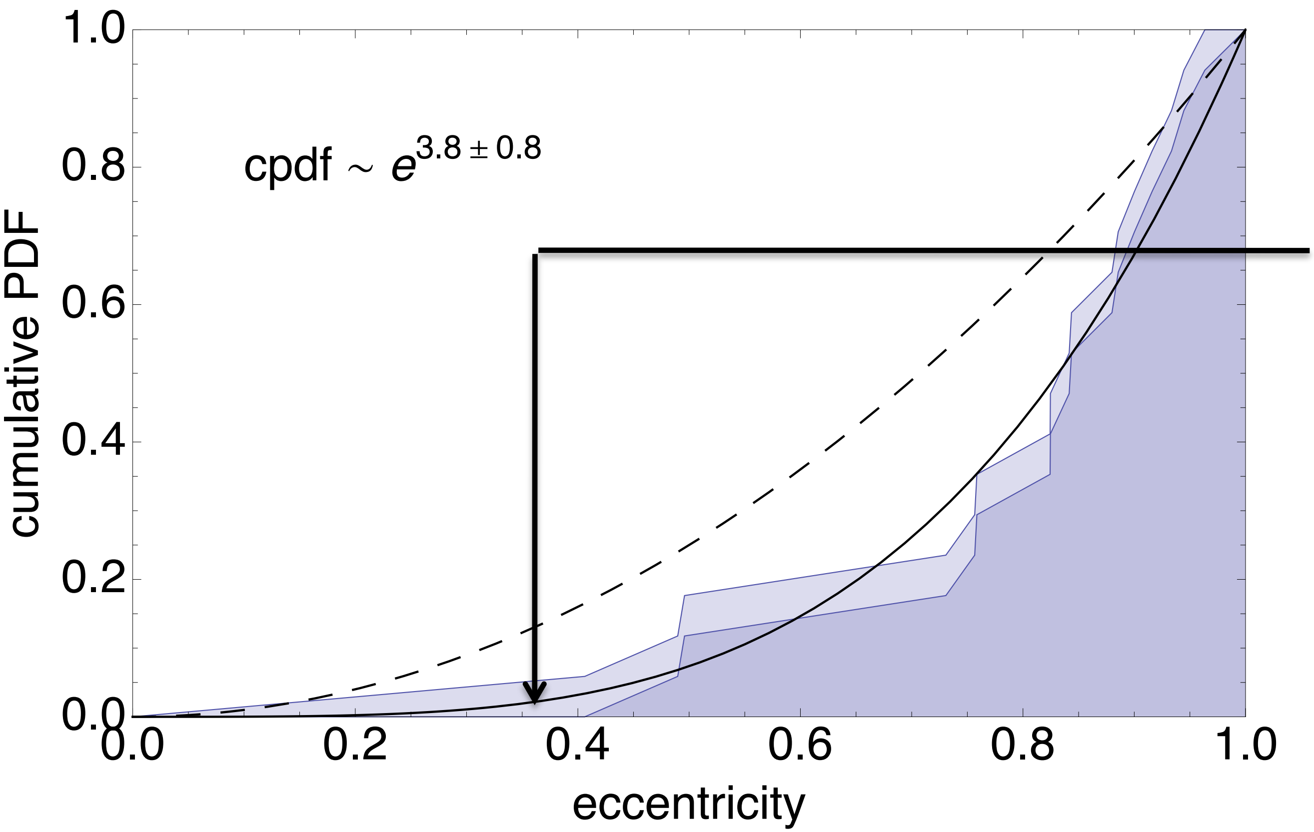


Orbital planes: S-stars ≠ disk stars



Eccentricities: S-stars ≠ Disk stars

17 early-type S-stars:



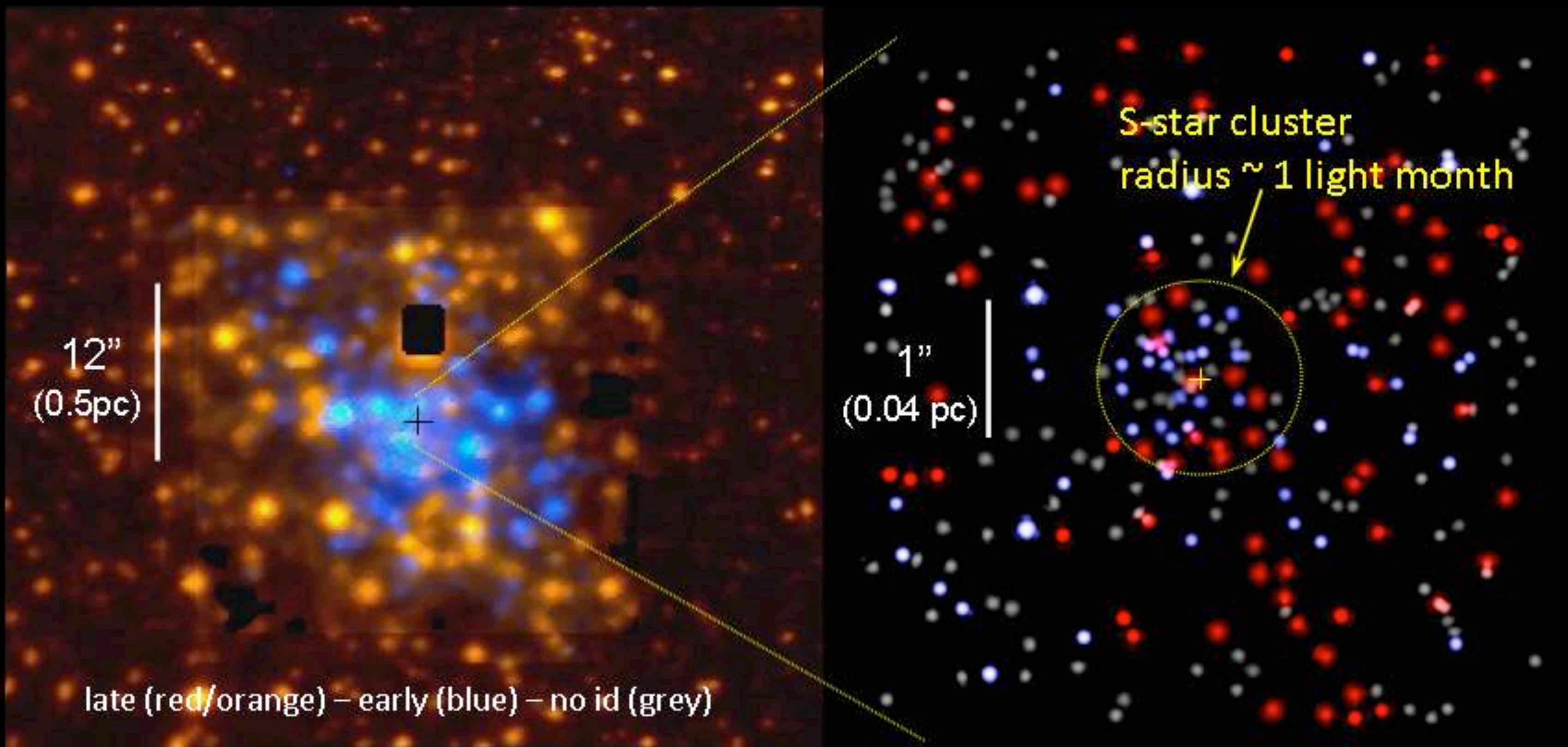
6 disk stars:

e = 0.34 ± 0.18

Two paradoxes of Youth

O/WR stars

B stars

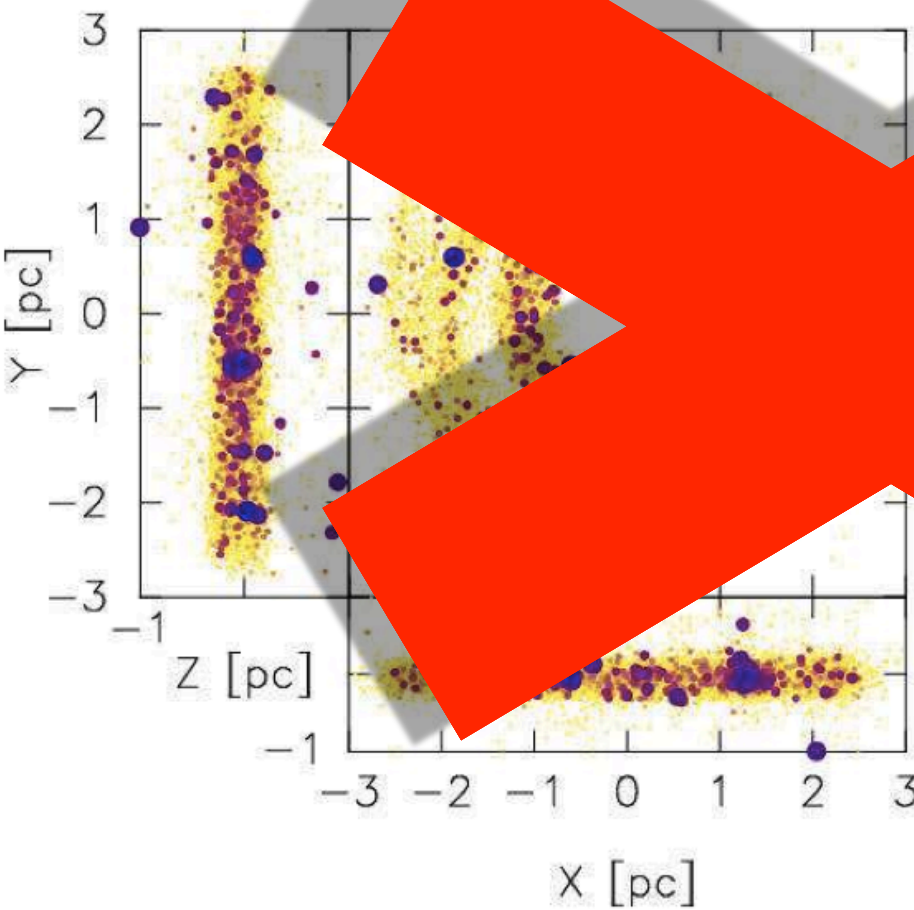


1" < R < 10"
age ≈ 6 Myr

R< 1"
age ≈ 10^8 yr

Idea I: Cluster in-spiral

Gerhard 2001



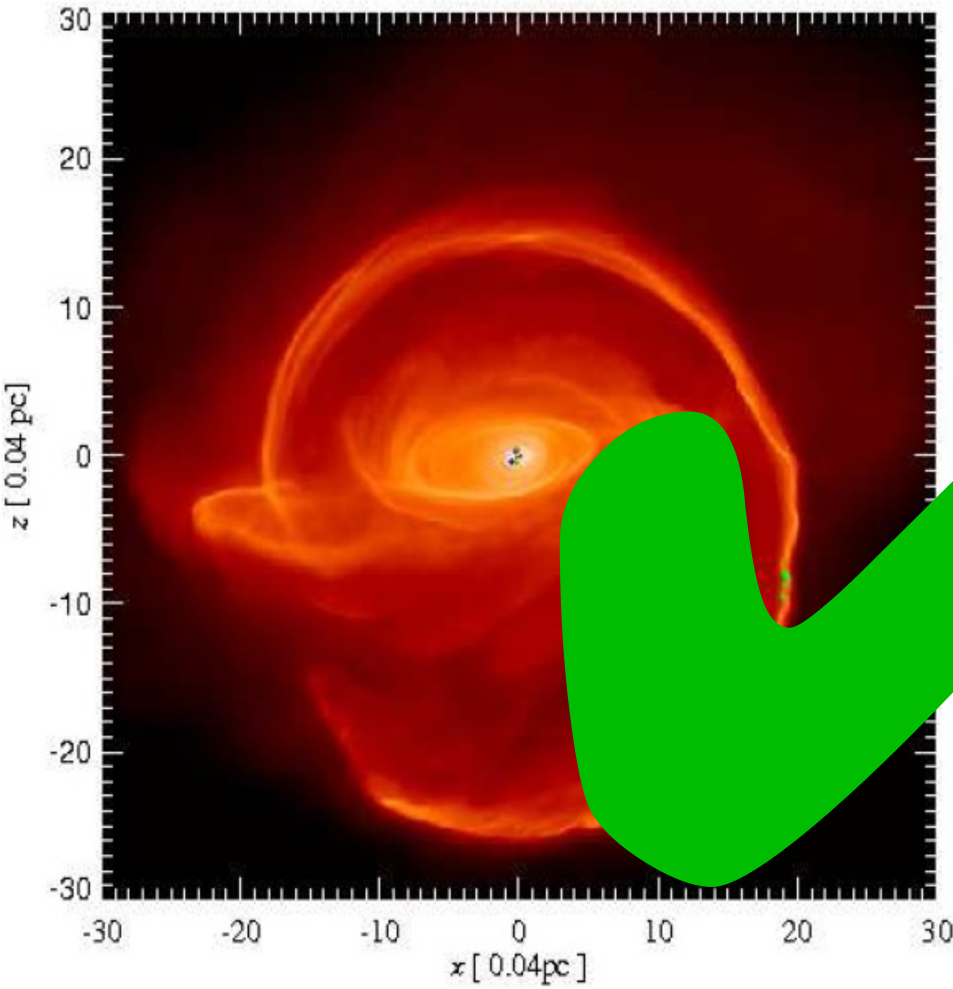
Pr

within 6 Myr,
mass would exceed
ass seen by far
would be

- su y profile of
  disk is to eep
- Where are the B-stars ?

Portegies-Zwart+ 2005

Idea II: In-situ formation in infalling gas cloud



More promising:

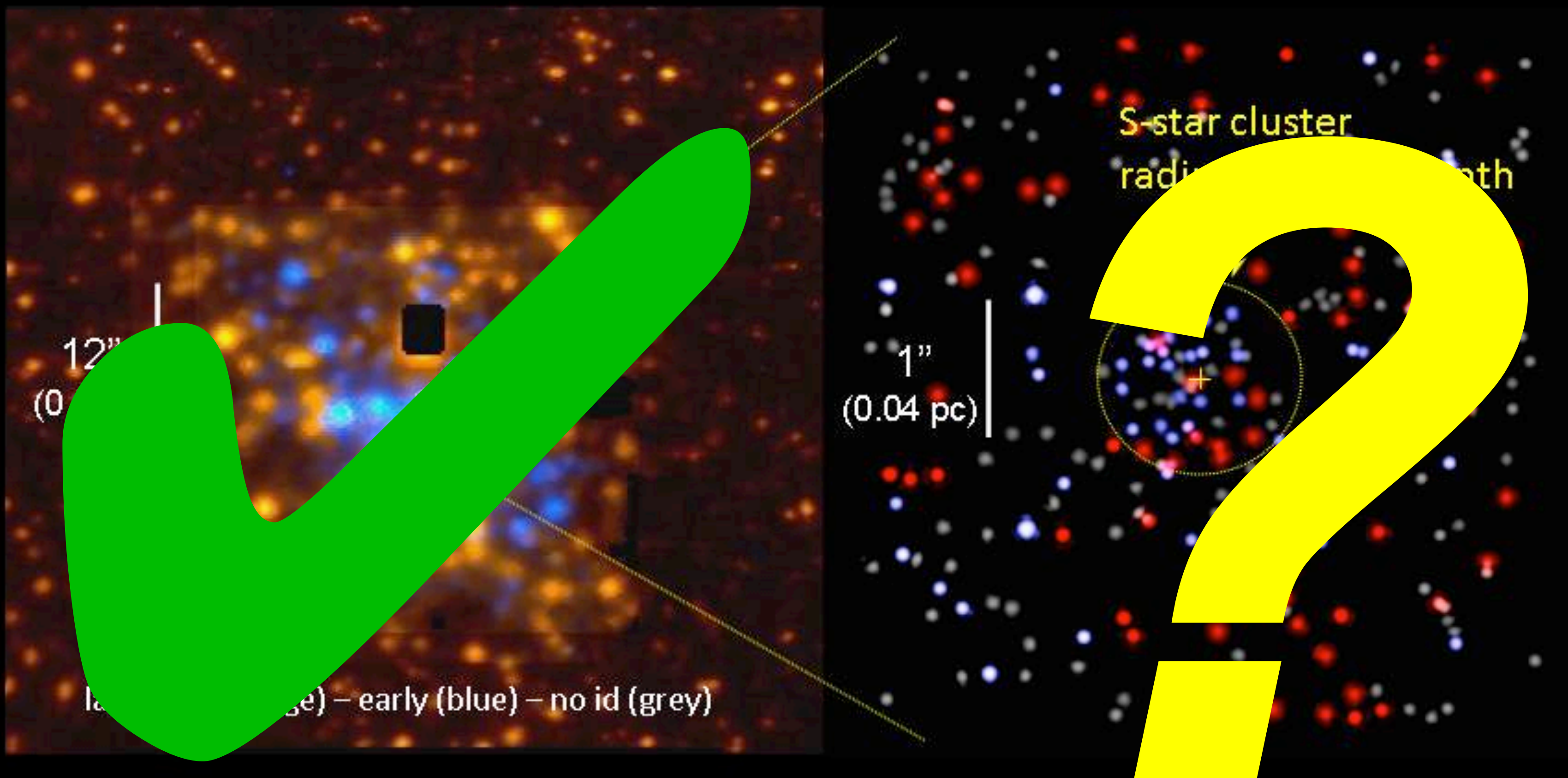
- cri density for star
 tion is reached easily
- derate eccentricities
- MF gets top-heavy
- warps possible

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 hard

In-situ formation

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

Currently a Hills-like mechanism seems to be preferred

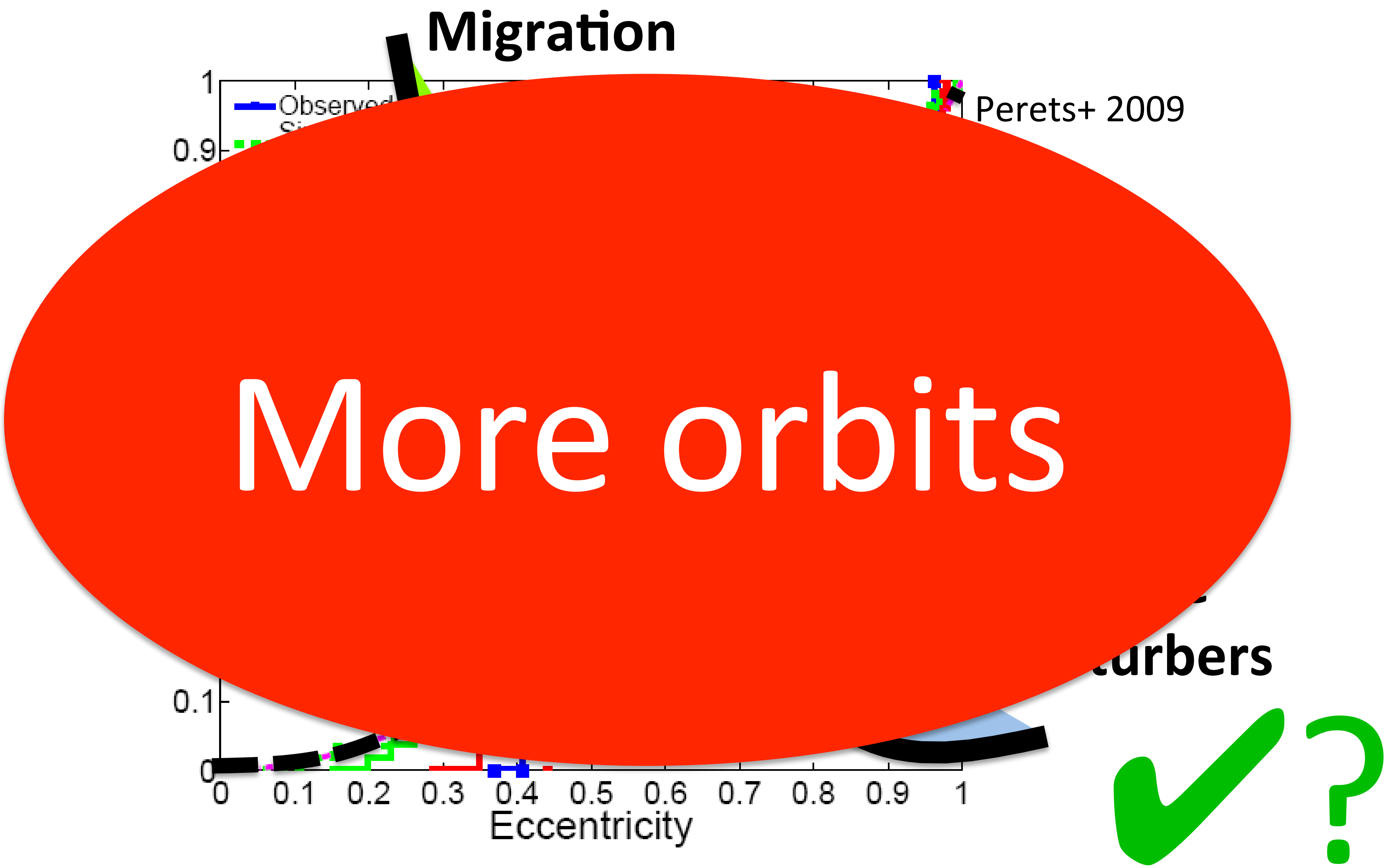
Massive Perturbers

- 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
  - Resonan

Migration

- Formation of B-stars in (former) disks
- Interactions to increase <e> 2^{nd} disk, stellar cusp, **IMBH**
- Interactions to lower <a> planetary migration
- Fast Relaxation
  - **IMBH?**

The eccentricity distribution might be the clue

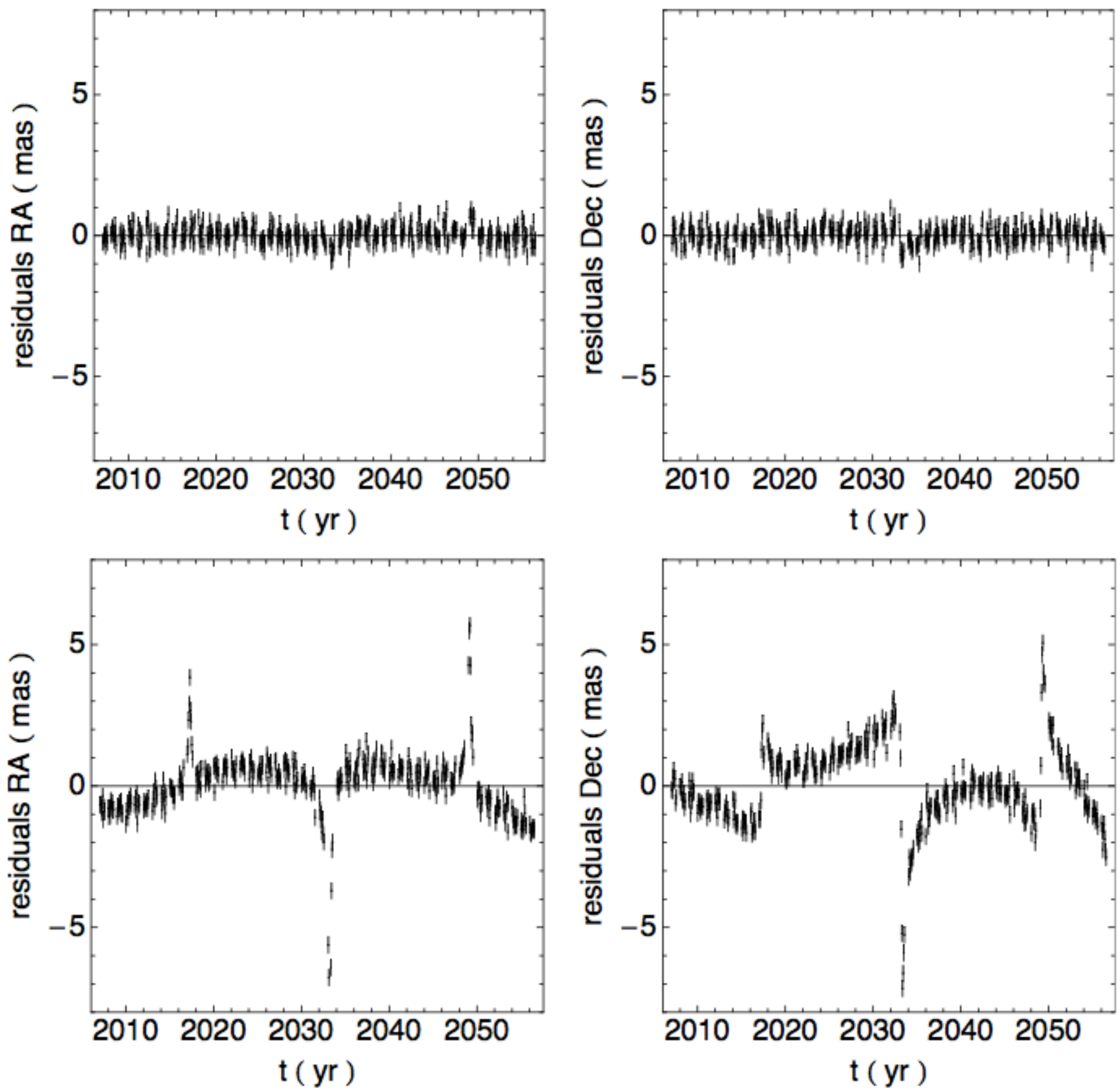


Also an IMBH could be detectable

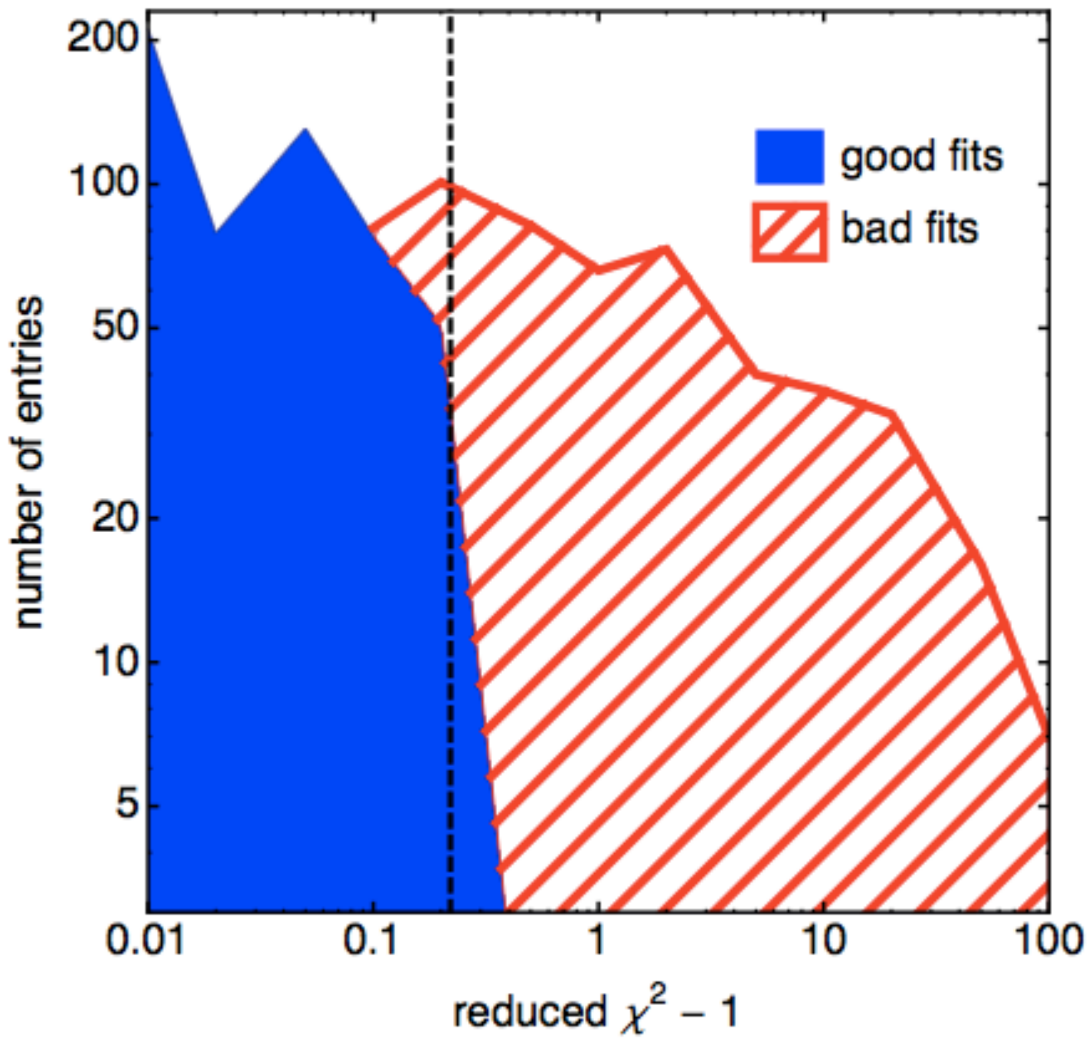
Gualandris, Gillessen & Merritt 2010

- Simulate S-stars, SMBH and IMBH
- Simulations with a grid of parameters:
  - M_{IMBH} = 400, 1000, 4000, 10000 $M_{\odot}$
  - a_{IMBH} = 0.3, 1, 3, 10, 30 mpc
  - e_{IMBH} = 0, 0.5, 0.7, 0.9
  - 12 orientations
- Check whether IMBH is detectable from S2 data

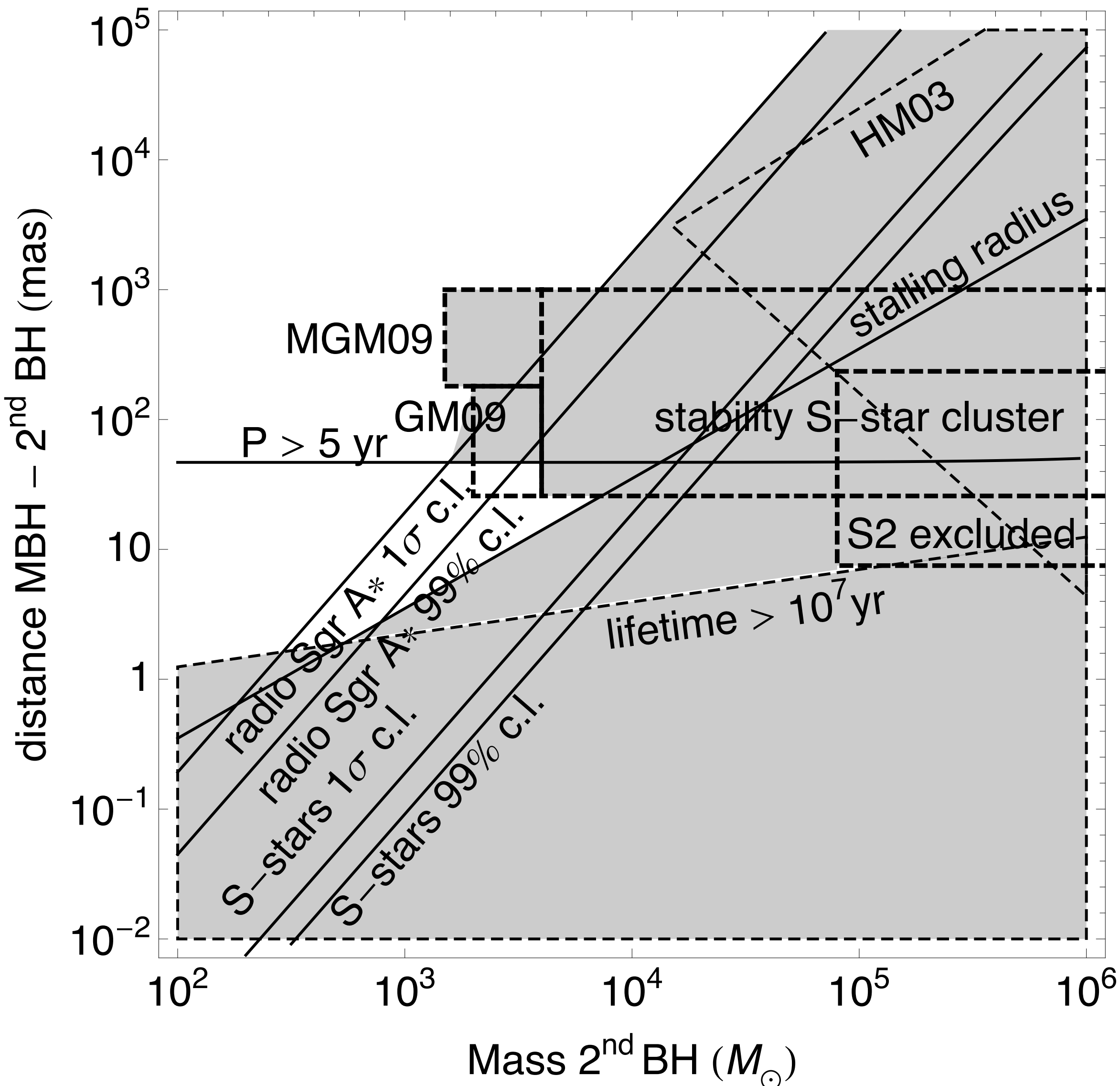
Fit residuals of mock S2 data: Sometimes IMBH is detectable



In roughly 50% of the cases the IMBH would have been detected.

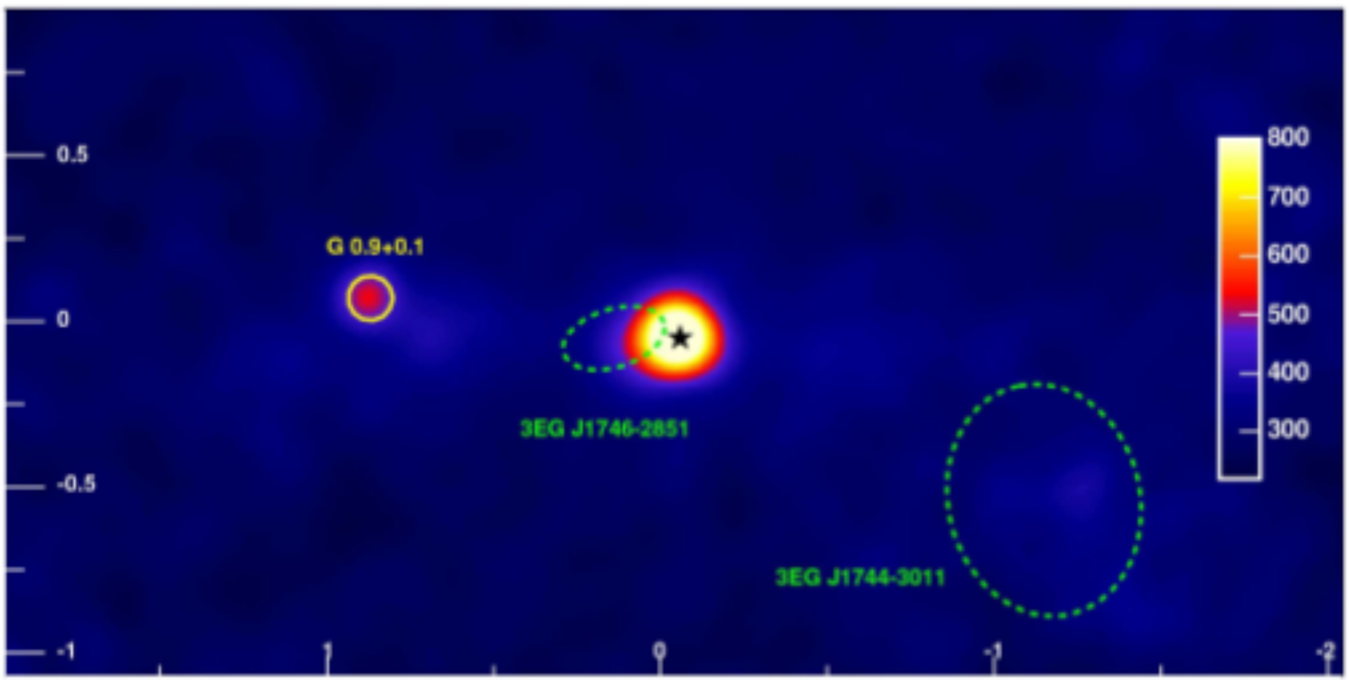


A potential second BH in the GC would need to be light & distant

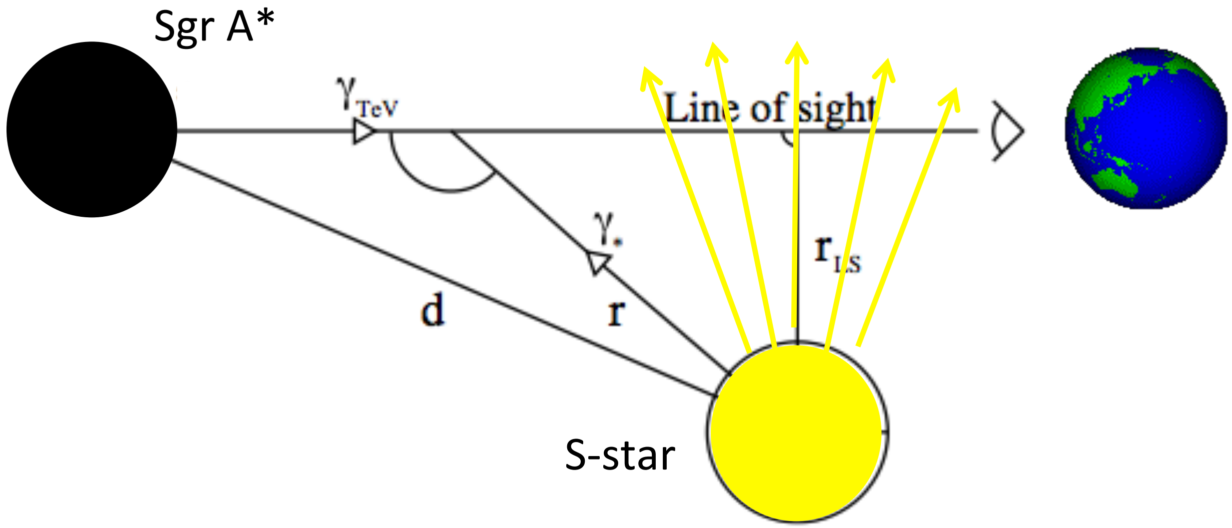


Hansen & Milosavljevic 2003,
Gualandris & Merritt 2007, 2009
Merritt, Gualandirs, Mikkola 2009
Reid & Brunthaler 2004
Gillessen+ 2009

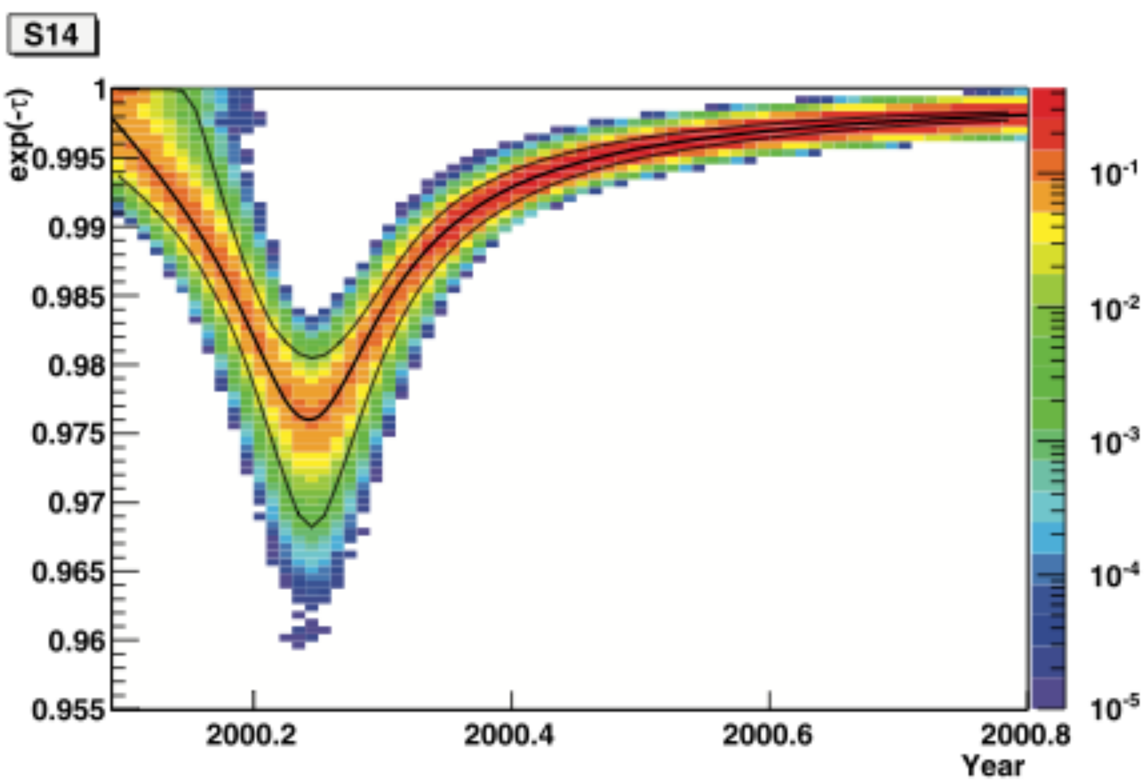
The nature of the TeV source at the GC is unknown



Aharonian+ 2006, The H.E.S.S. collaboration



S-stars could "eclipse" Sgr A*

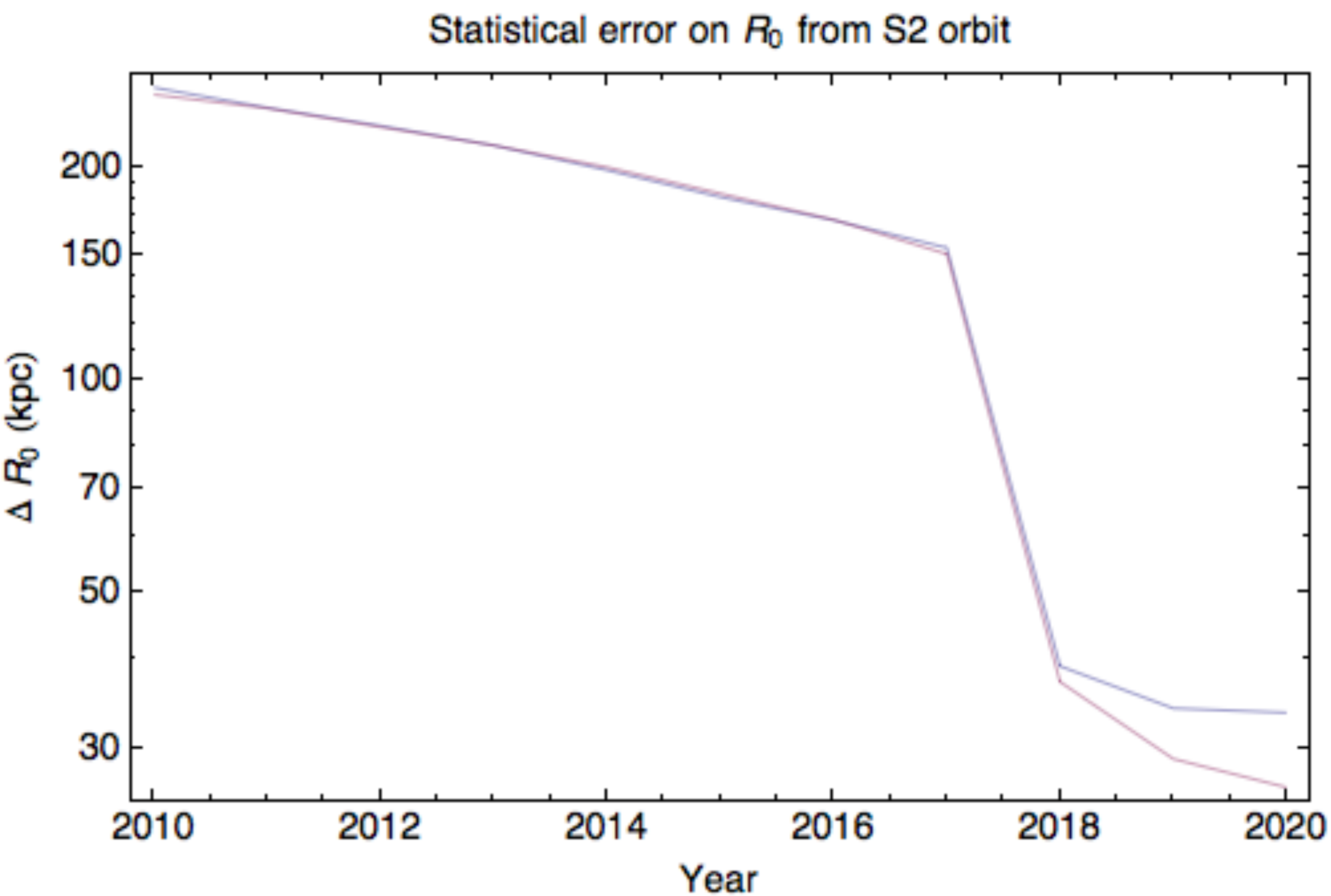


Assume, we continue what we are doing. How well do we do then?

NACO:
Astrometry with 300 μas

SINFONI:
Spectroscopy with 15 km/s

2020: R_0 measured to 30 pc



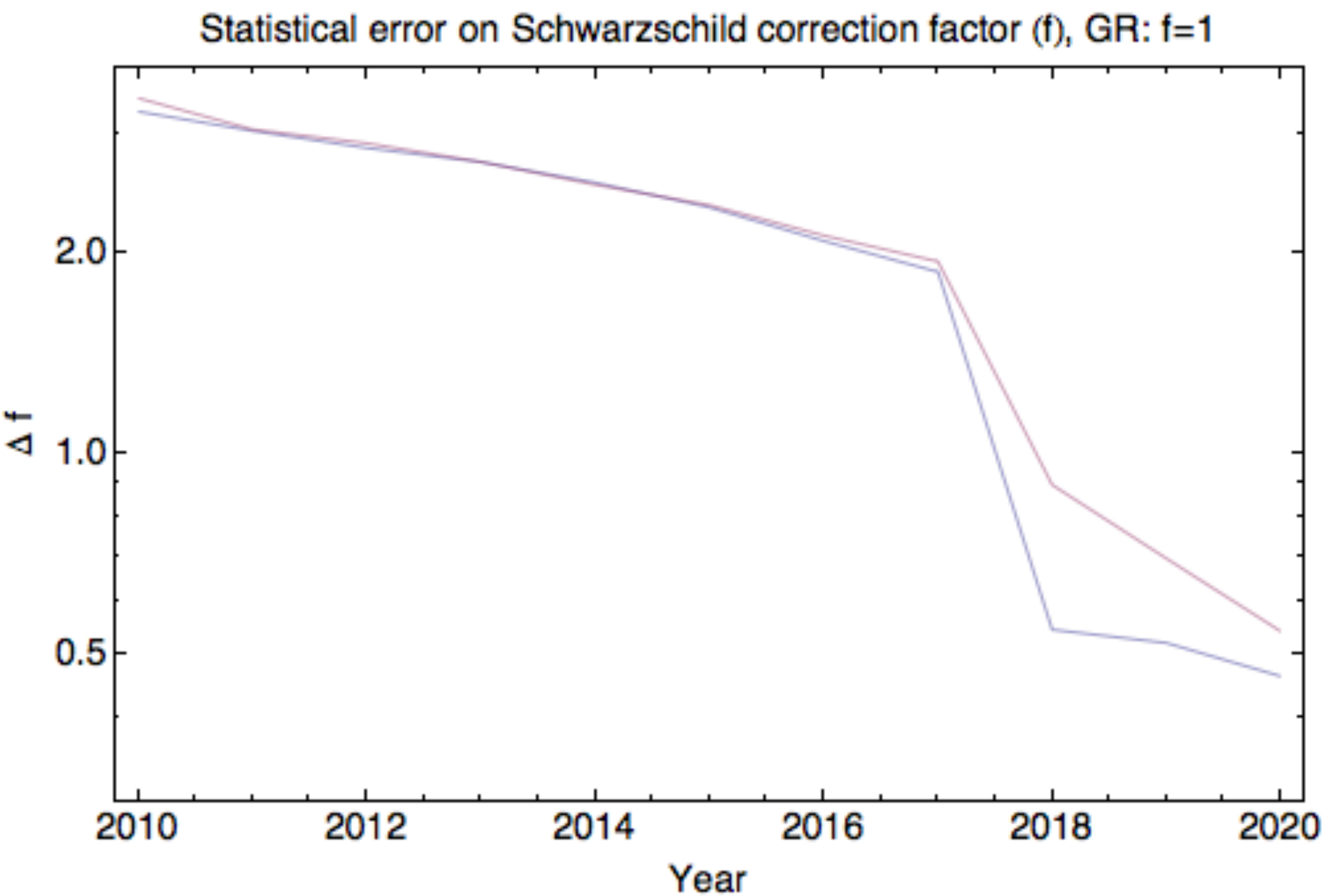
S2 only
6 positions per year

2 radial velocities per year,
6 per year in 2017 & 2018

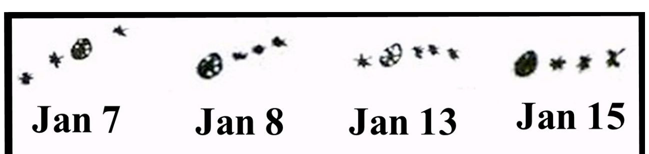
2 radial velocities per year

2020: 3σ detection of GR precession possible

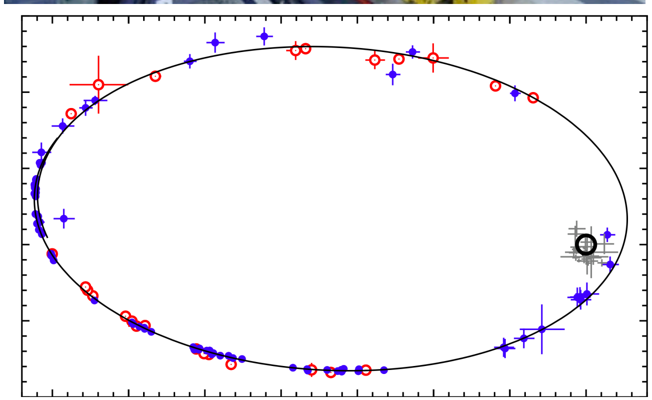
$$\Phi = -\frac{G\,M}{r} + f\,\frac{G\,M\,l^2}{c^2\,r^3}$$



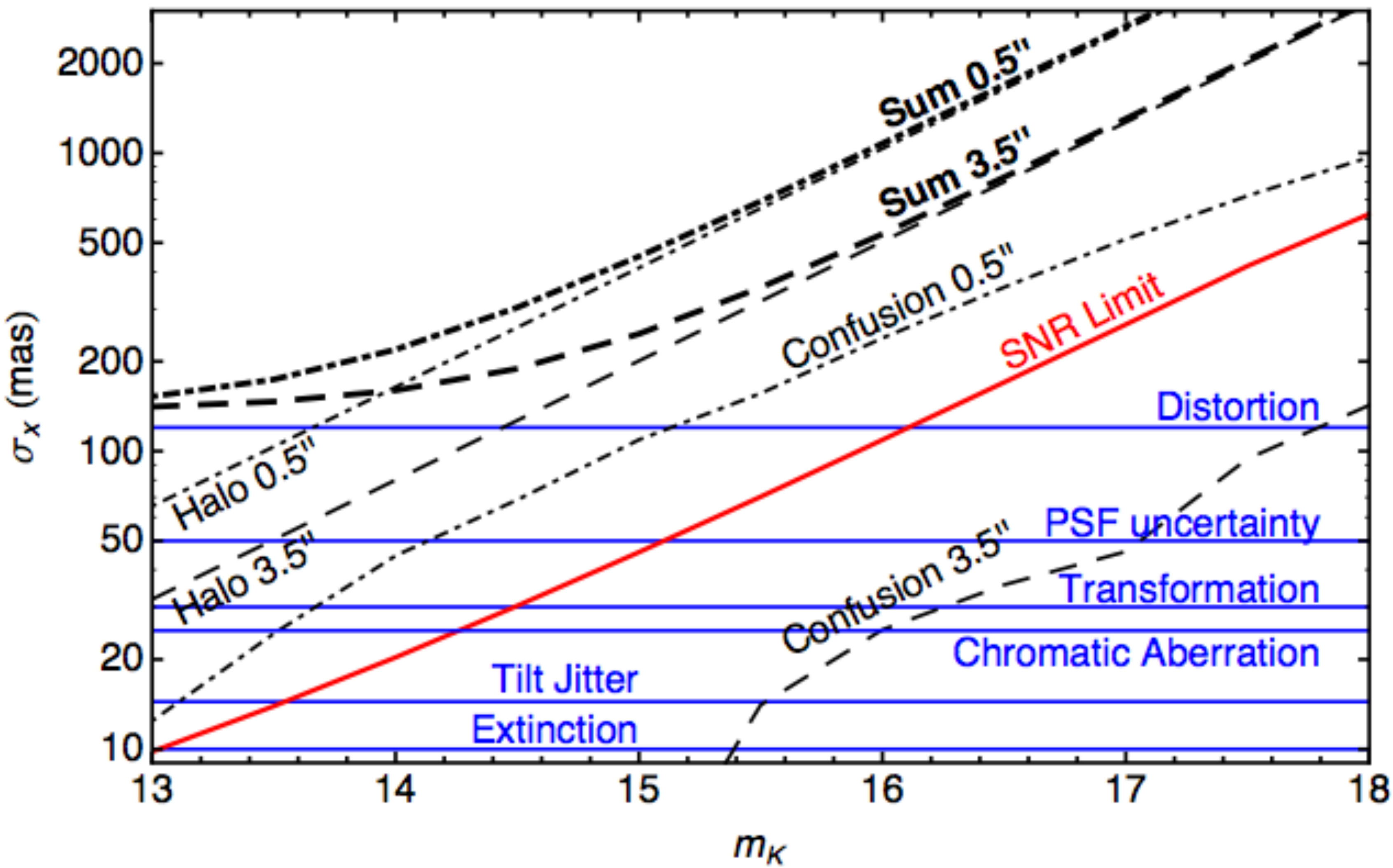
What is limiting astrometry today?



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



Bright stars: Image distortions
Faint stars: Stray light



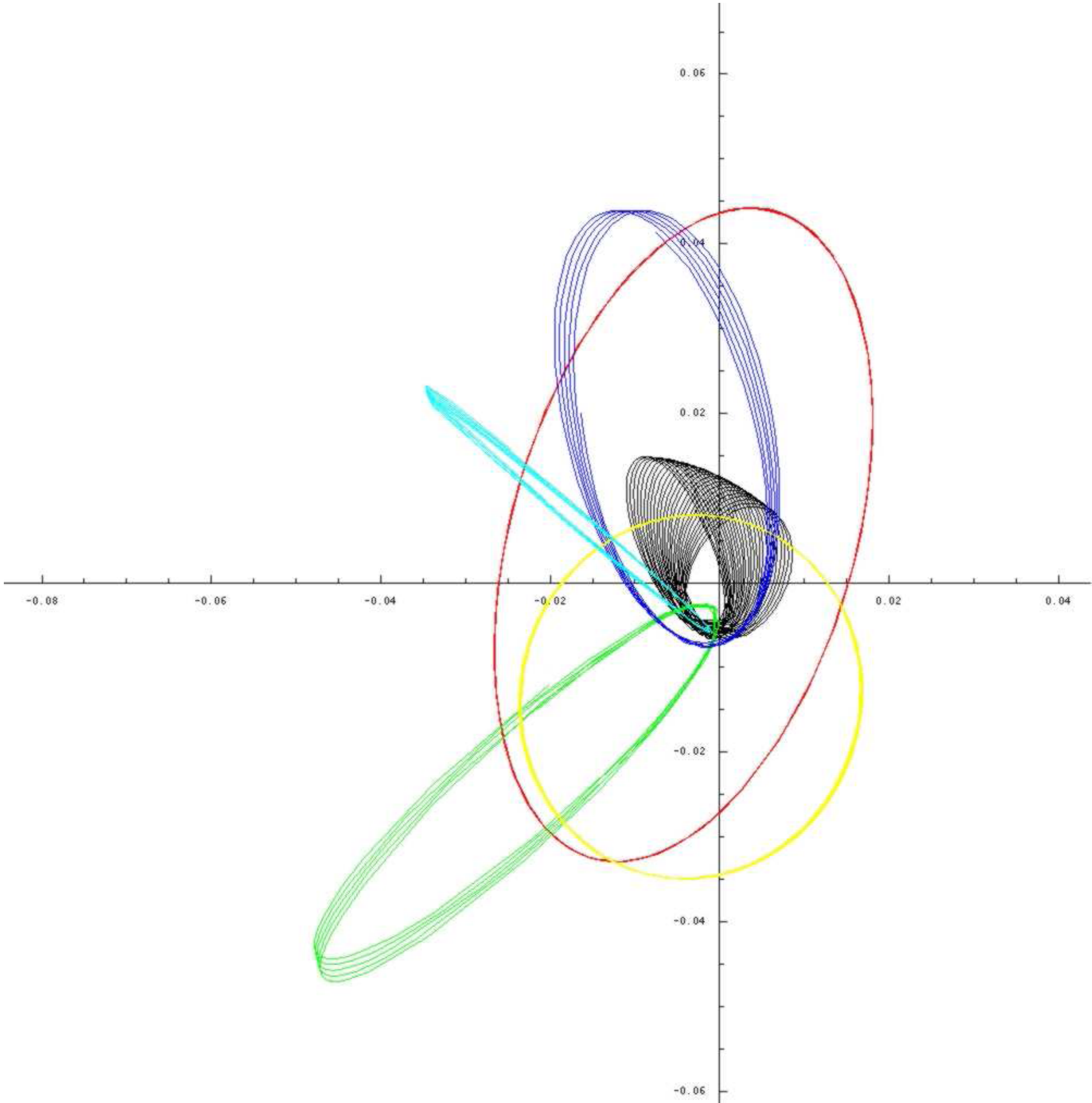
Fritz+ 2009

Imagine you could zoom in further

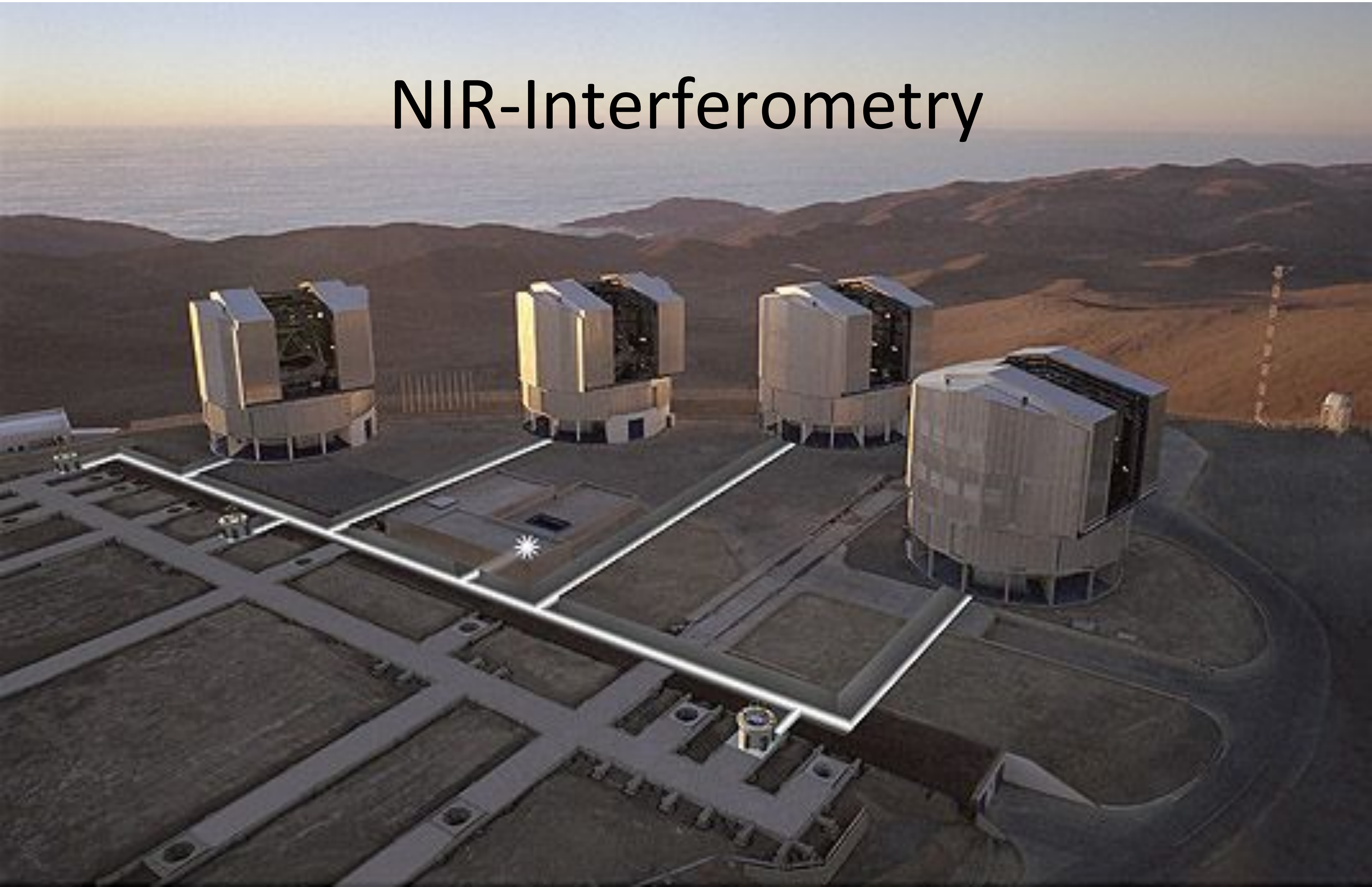
Expected in central
100 mas:
-- ~5 stars
-- K = 17..19 mag

Orbital Period:
1 year

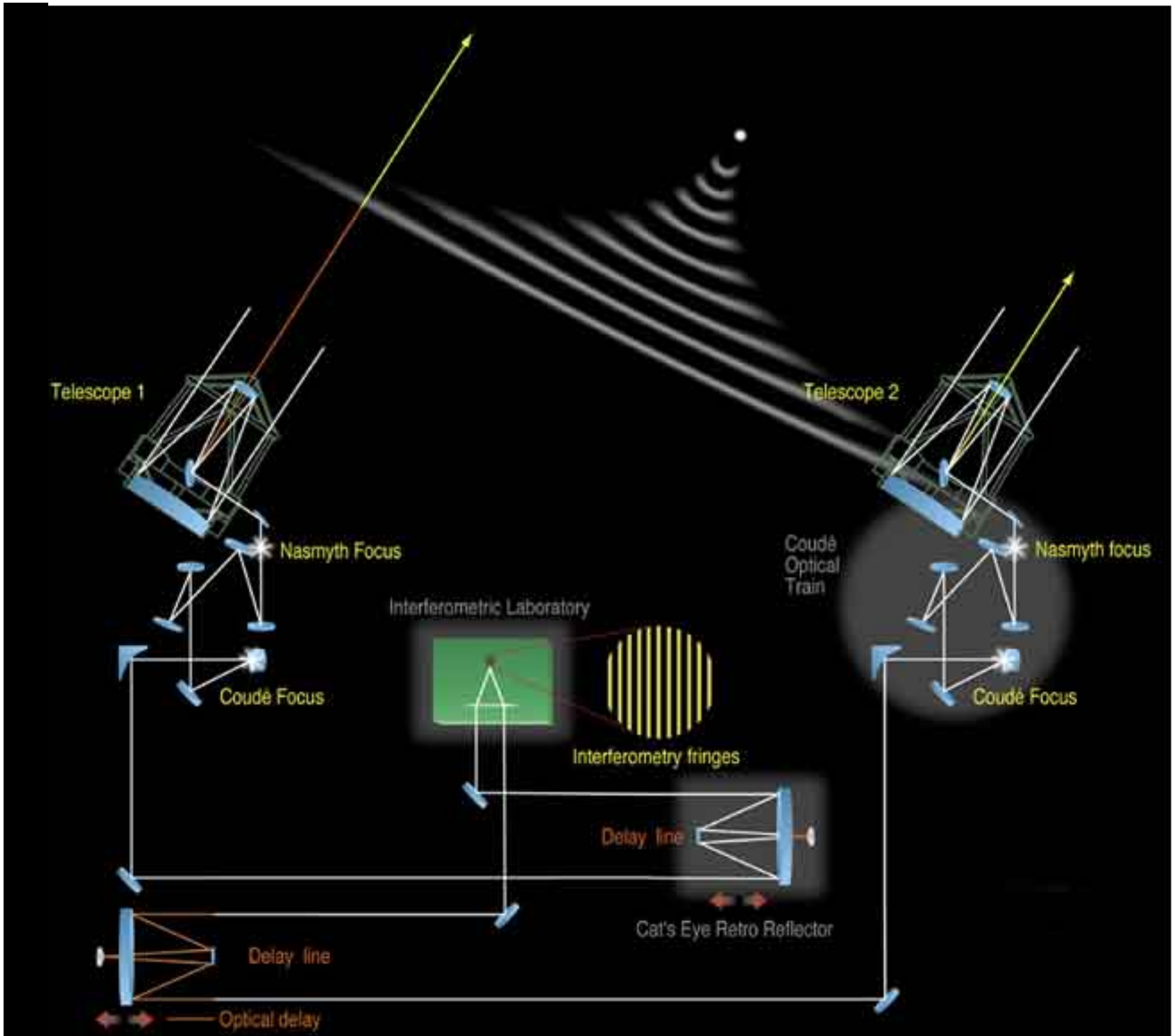
Precession:
~ few ° per year



The next step in angular resolution:

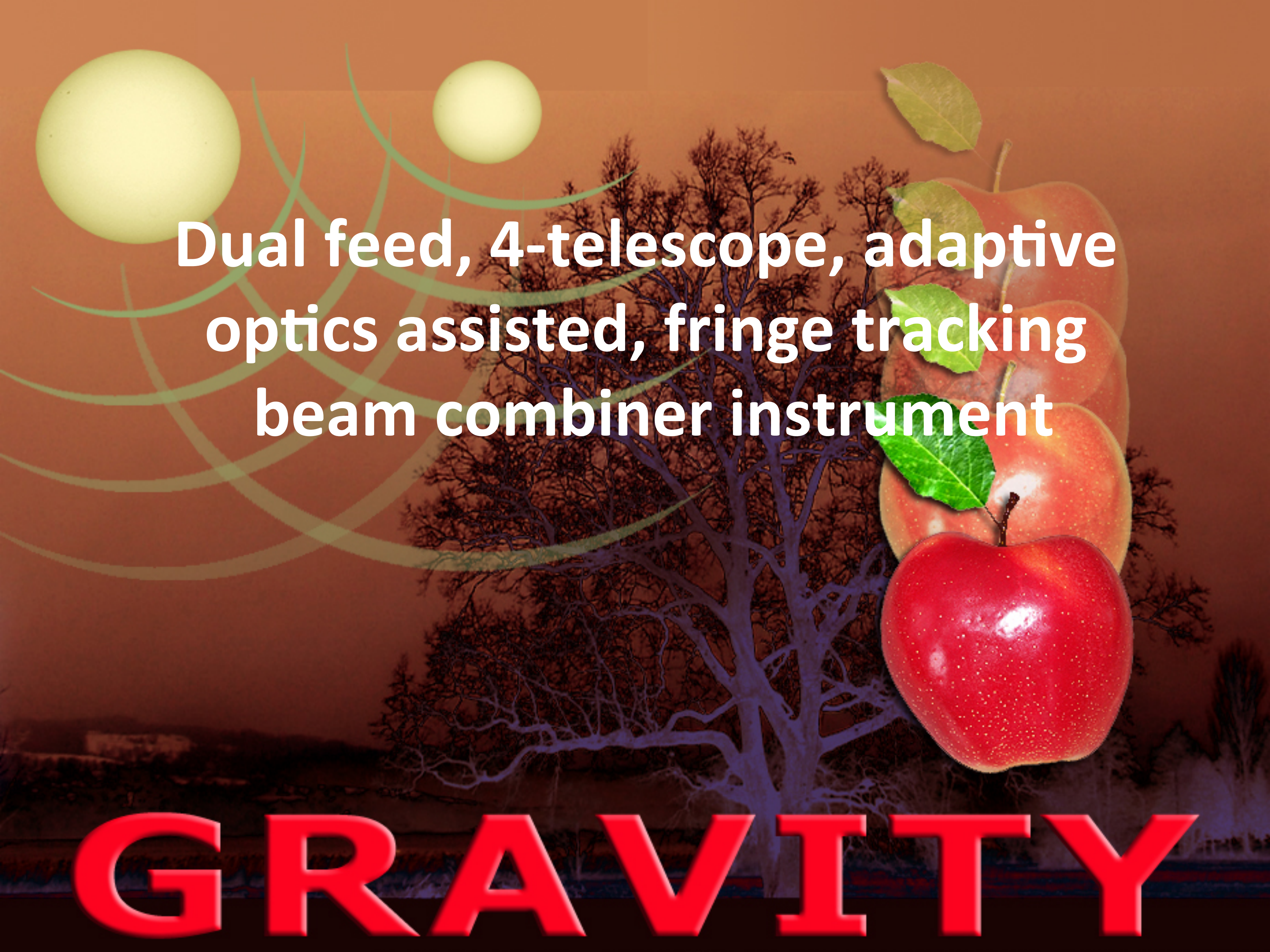


A factor 15 more powerful than the VLT

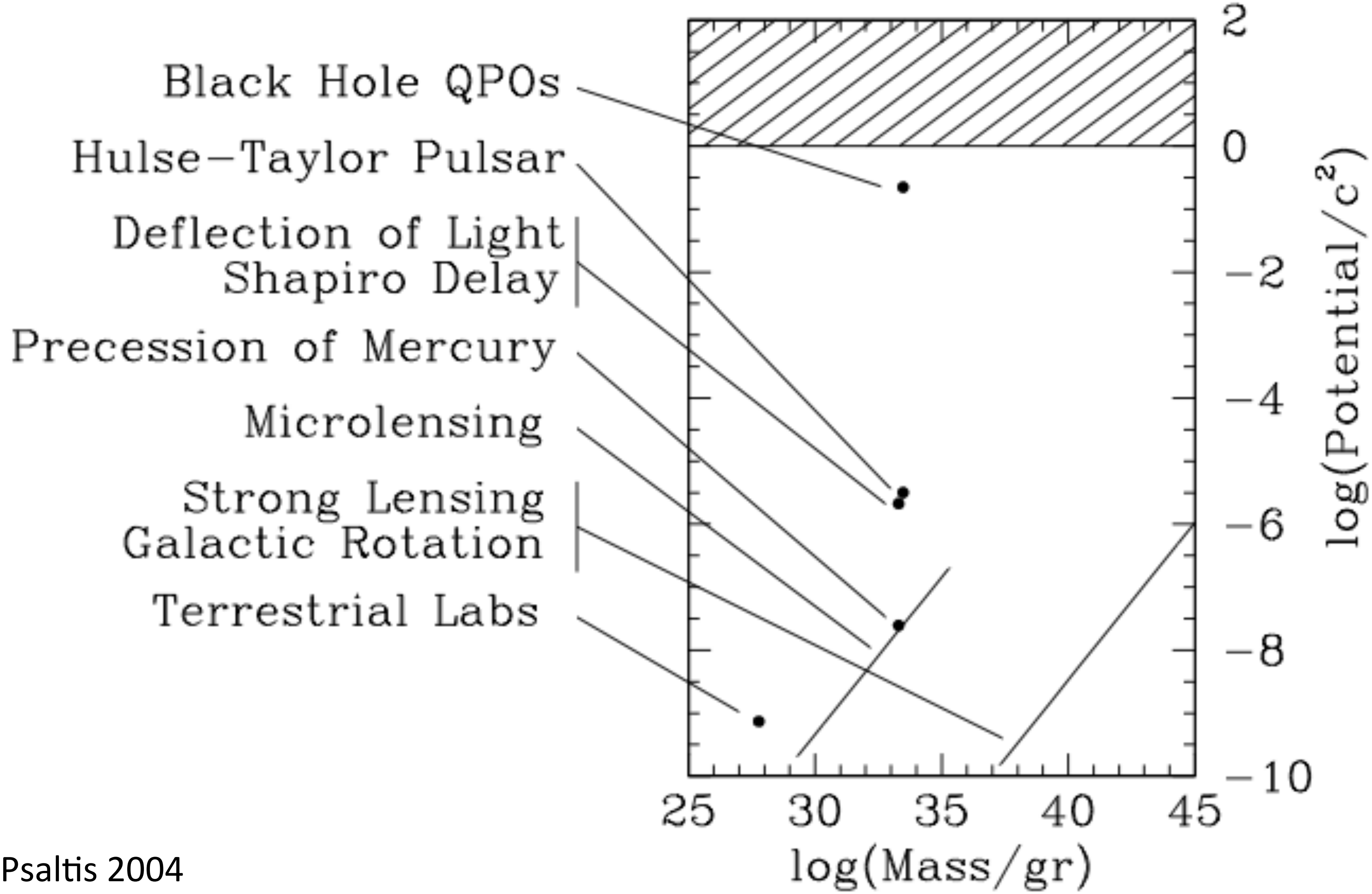


VLT (8m):
R = 50 mas
Δx = 150 μas

VLTI (120m):
R = 3 mas
Δx = 10 μas

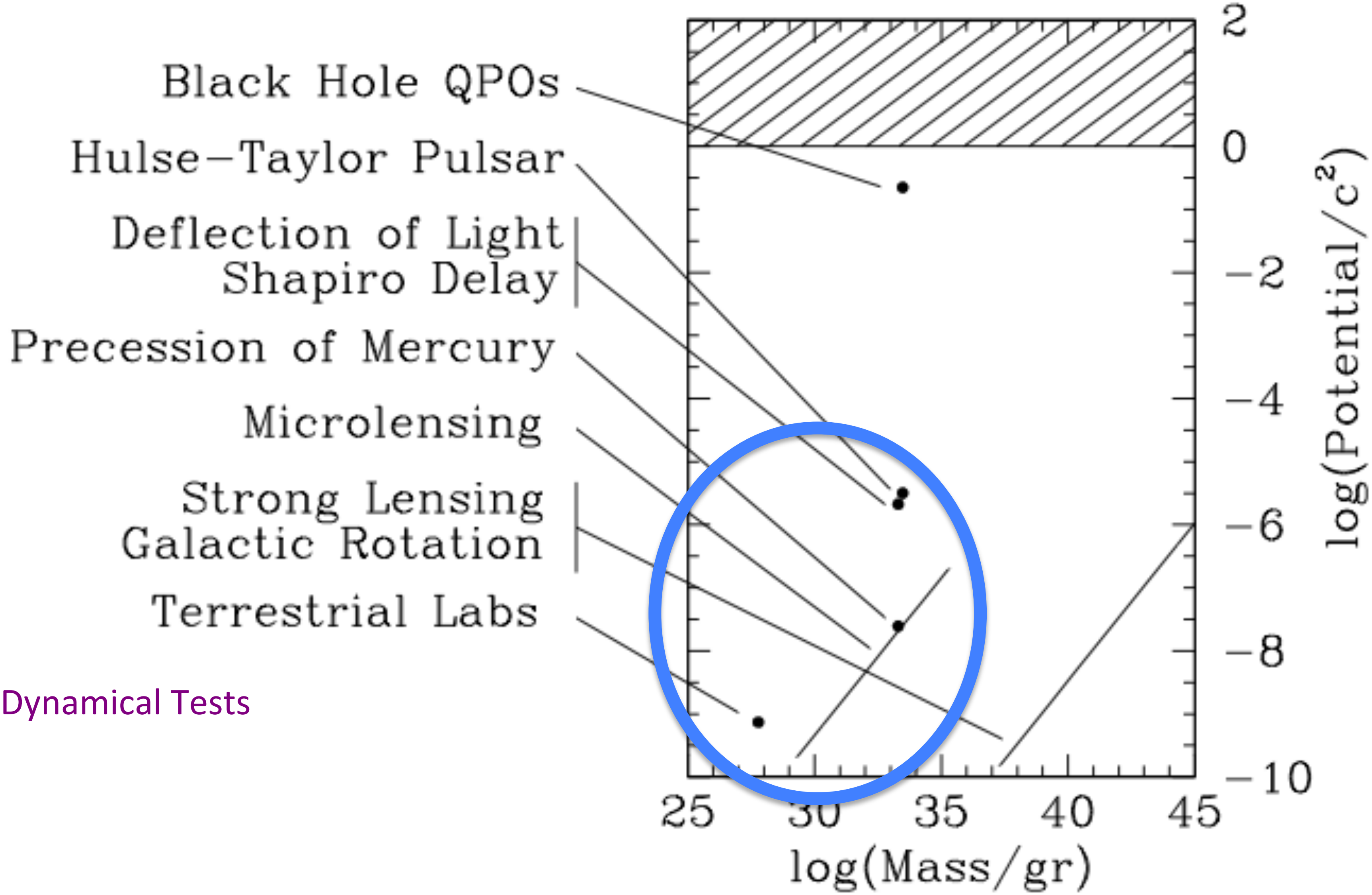

Dual feed, 4-telescope, adaptive optics assisted, fringe tracking beam combiner instrument
GRAVITY

The physics perspective: Tests of GR



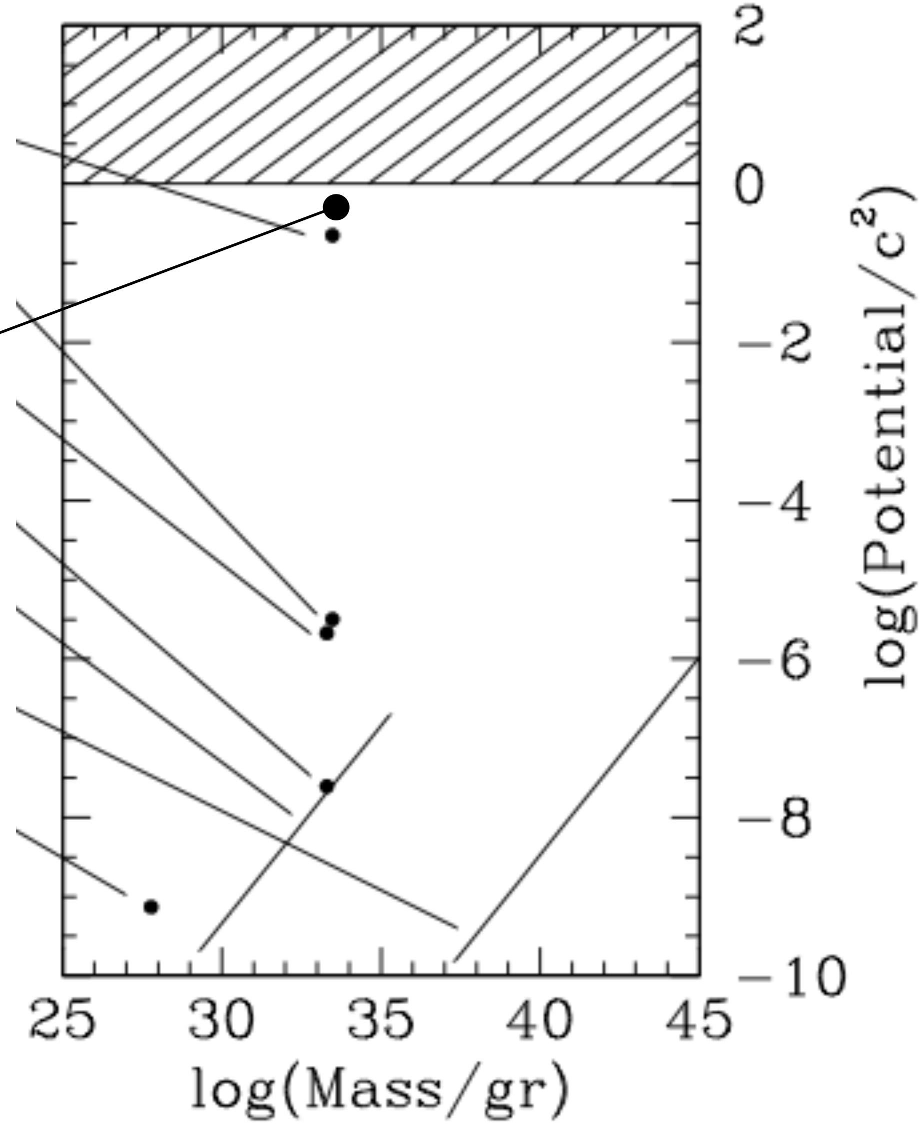
Psaltis 2004

Dynamical tests: Low curvature, low mass

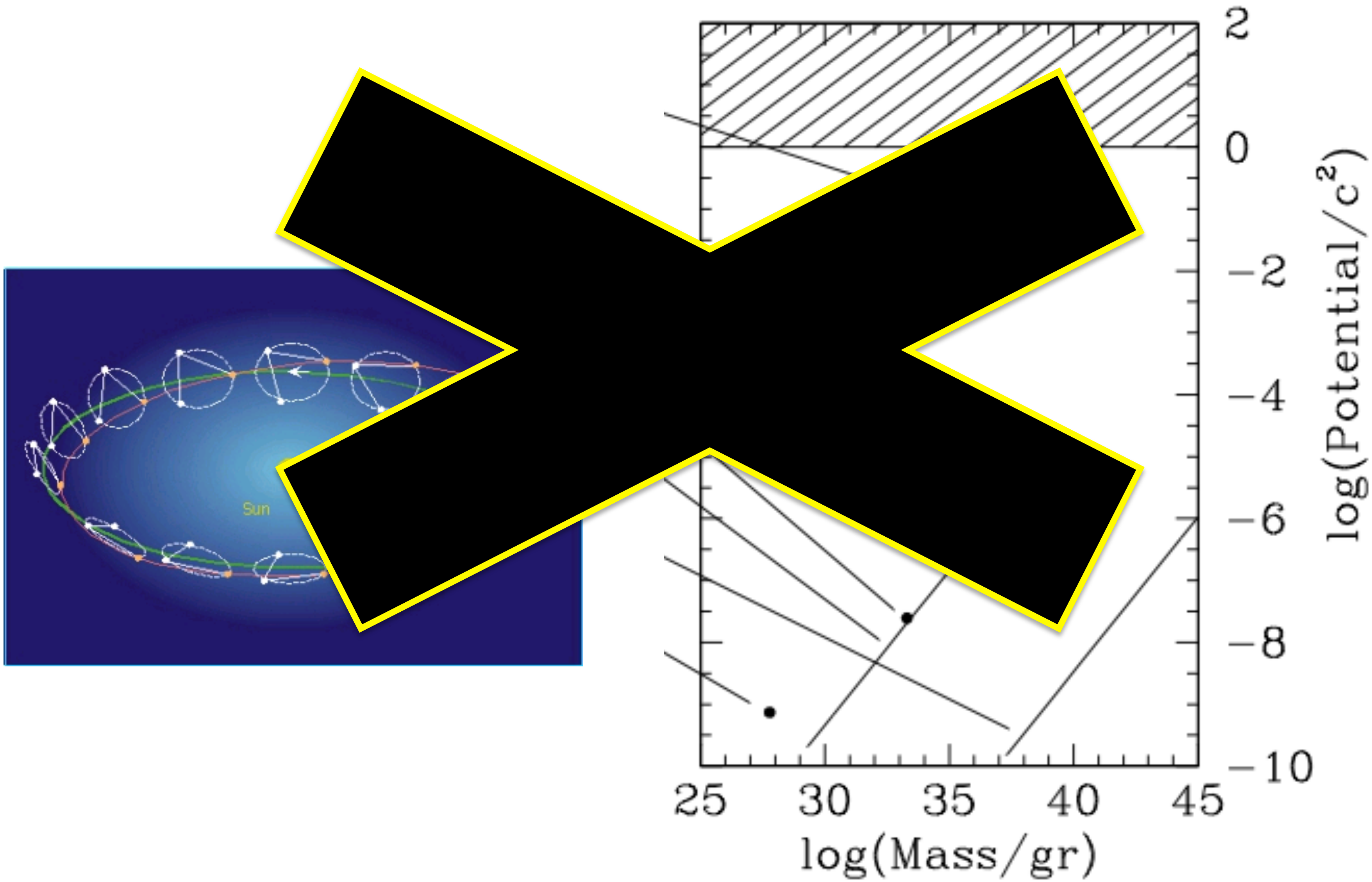


Dynamical Tests

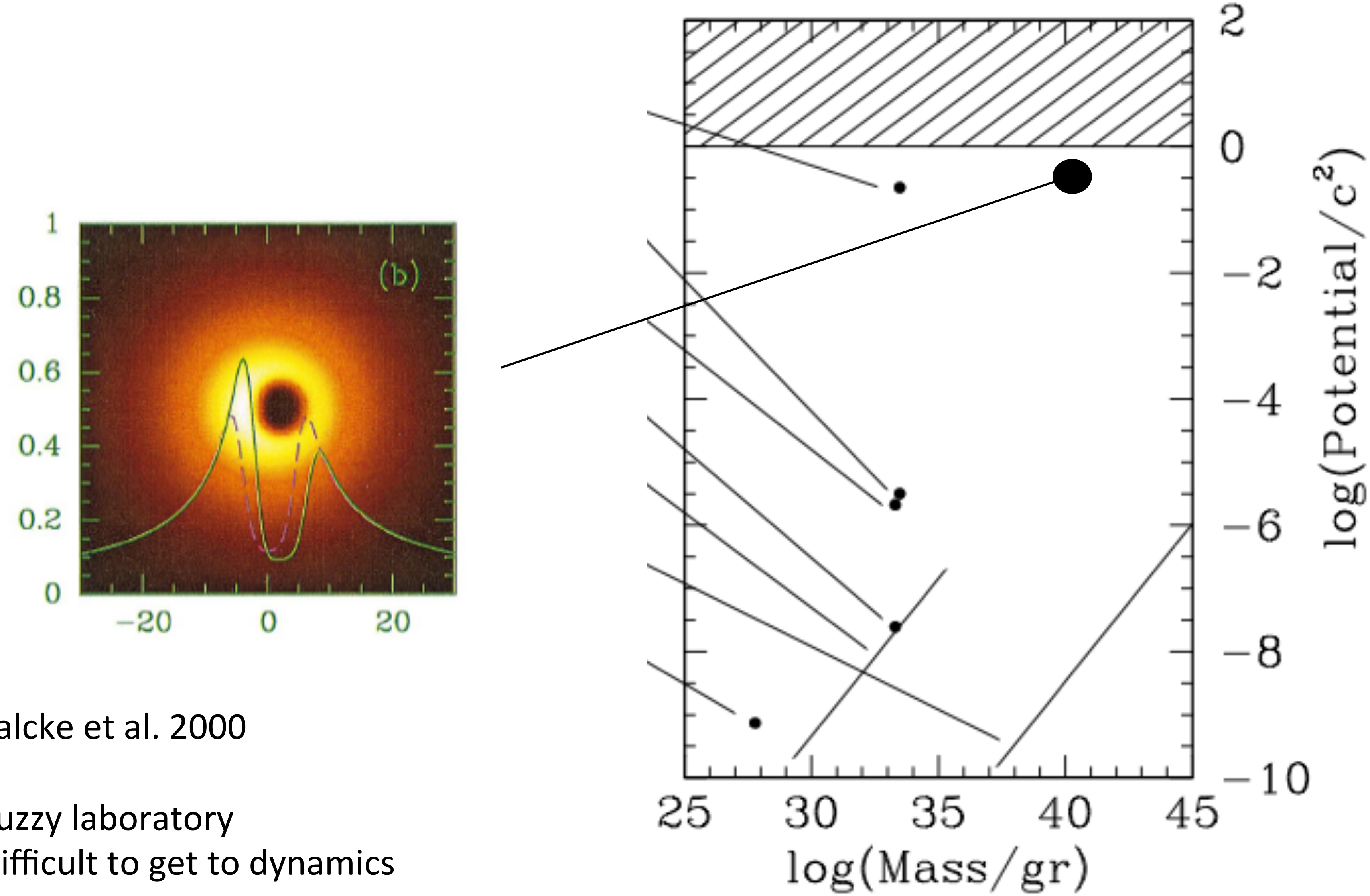
LIGO: Supernovae & gravitational waves



LISA: SMBH mergers & gravitational waves



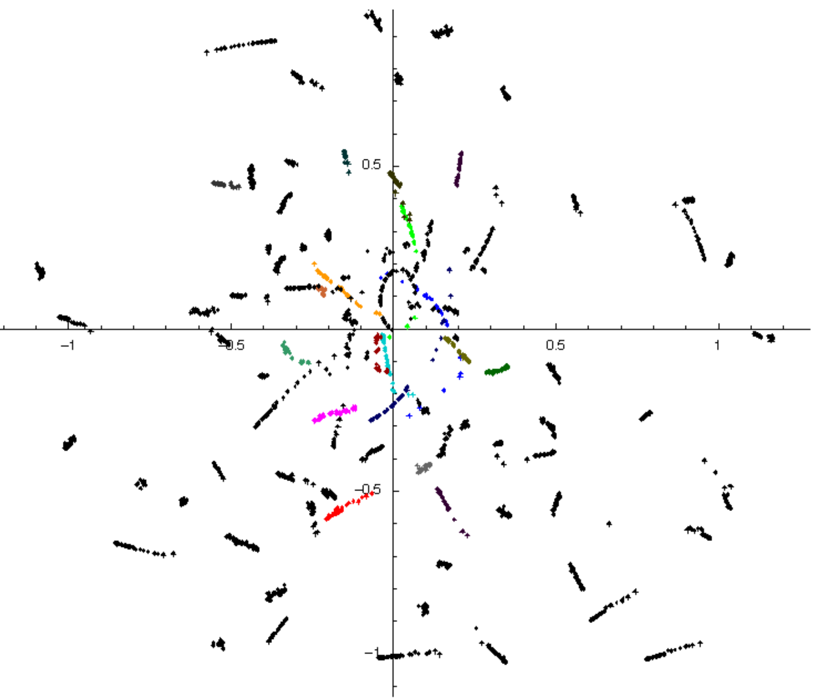
submm-shadow of MBH in GC



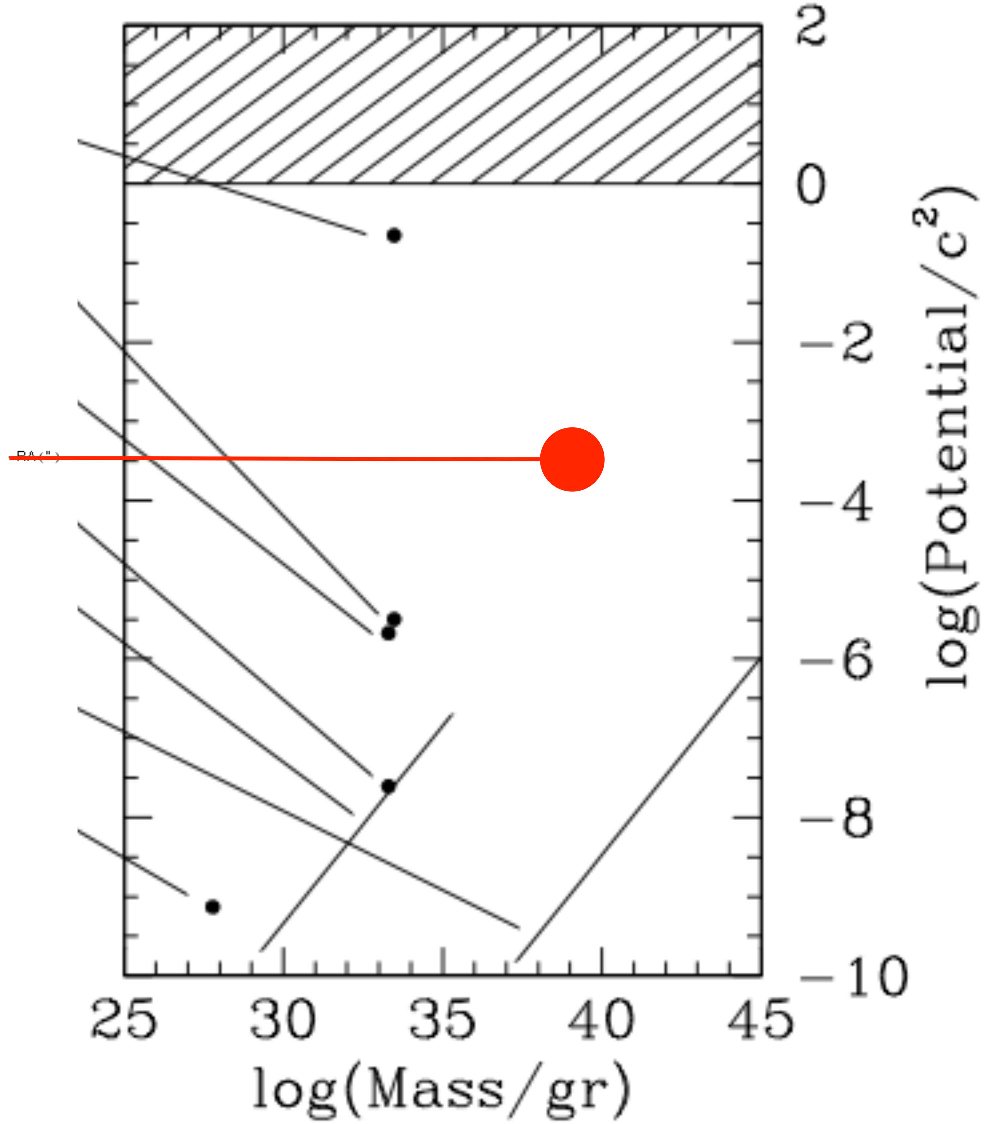
Falcke et al. 2000

Fuzzy laboratory
Difficult to get to dynamics

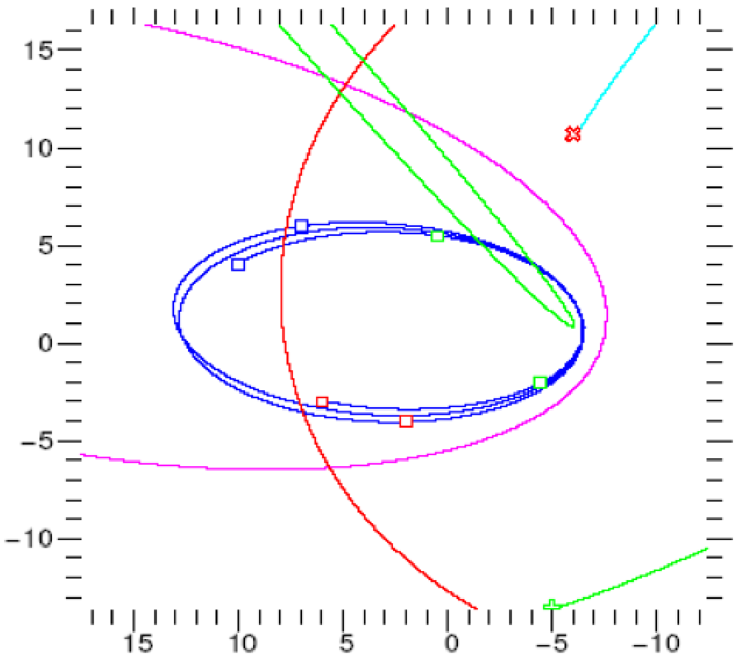
VLTI in GC: GRAVITY



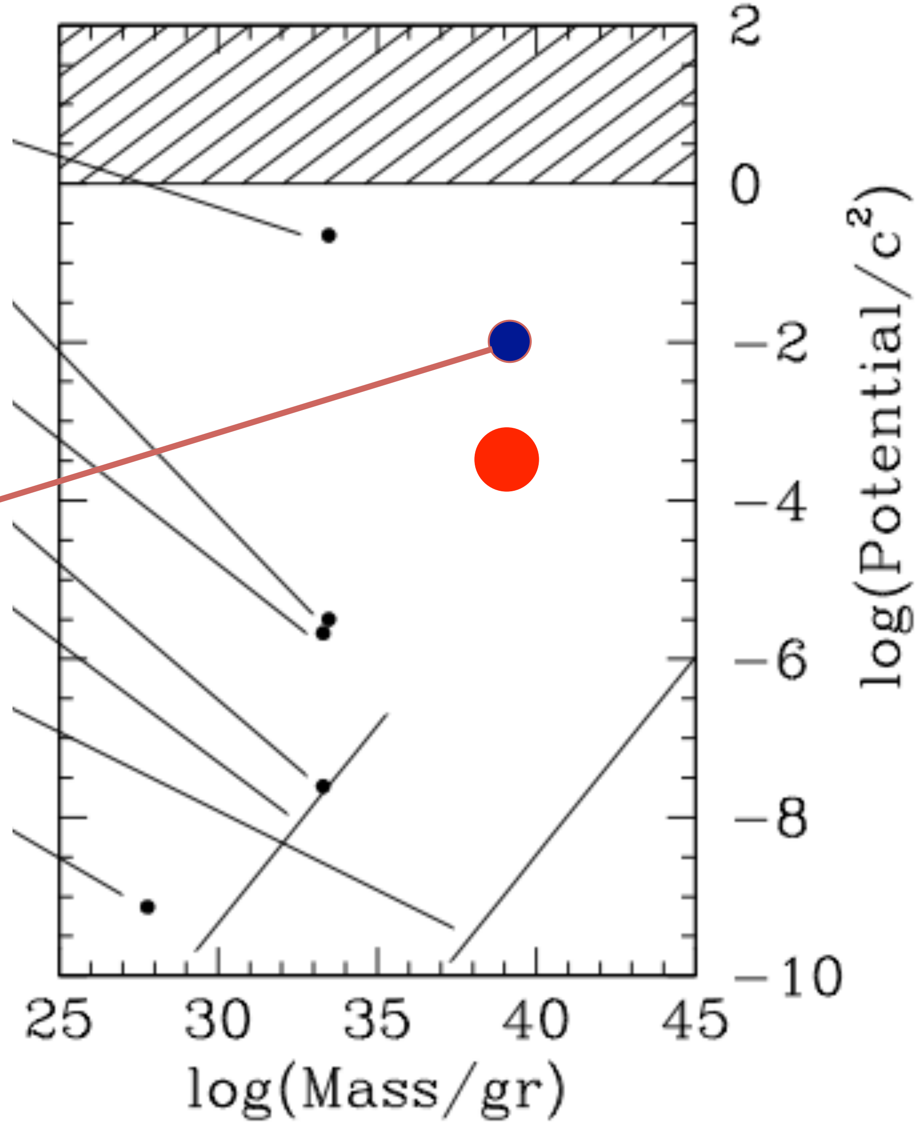
β^2 effects in stellar orbits



VLTI in GC: GRAVITY

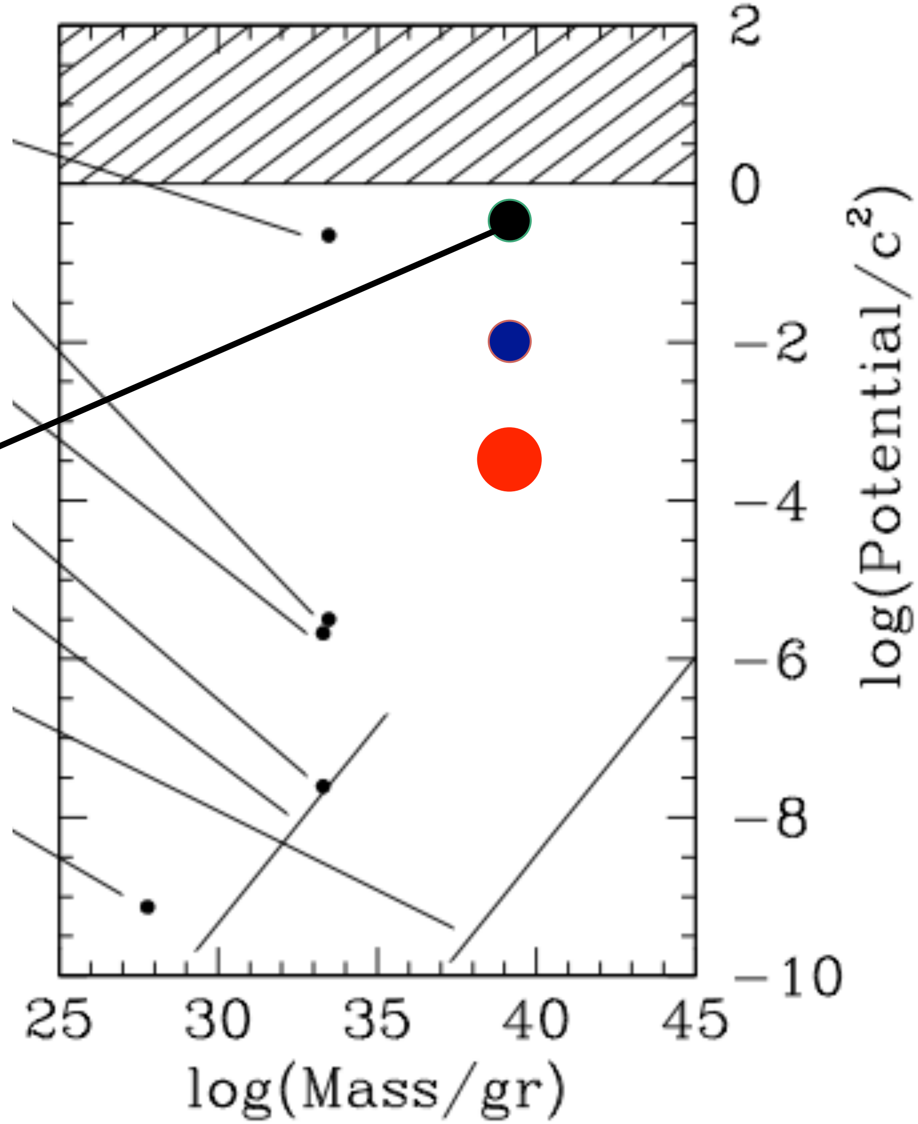


Lense-Thirring precession
of central cusp stars



VLTI in GC: GRAVITY

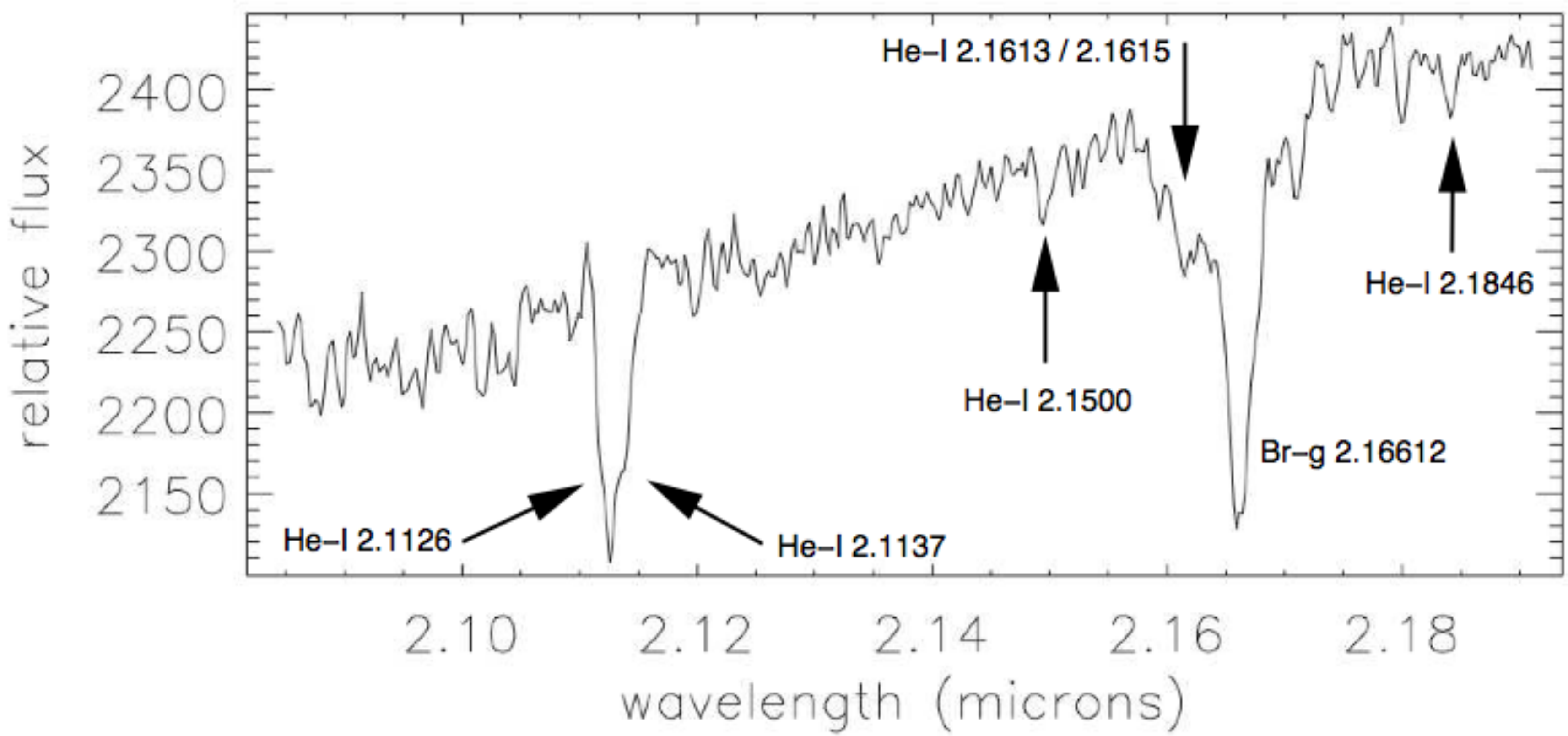
Flares at last stable orbit



Summary

- The Galactic Center harbors a MBH
- Stellar orbits are an extremely useful tool for the astrophysics close to the MBH
- Stellar orbits are an extremely clean tool
- We keep on discovering things
  - as we speak
  - stay tuned

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



Martins+ 2008