The black hole in the Galactic Center

MPE Team

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

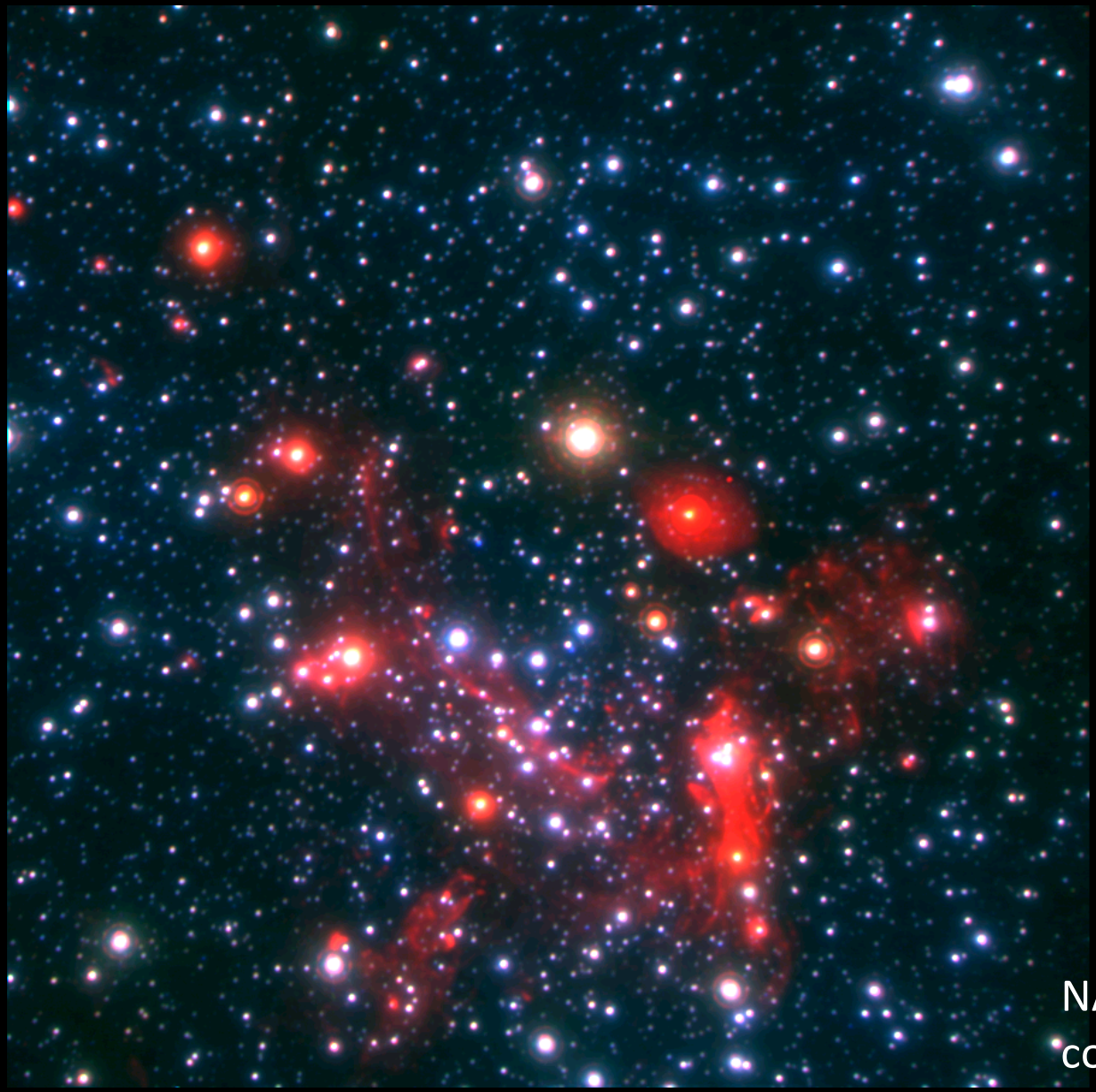
Why should you care about the Galactic Center?

- Template for a galactic nucleus – EMRI rates
  - Black hole mass function
  - In-spiral rate at a given mass
- EMRBs might be observable
- Key advantage: Stellar population is resolved
  - Chance to understand stellar system around a MBH in detail
  - Surprisingly complex dynamical state

Summary

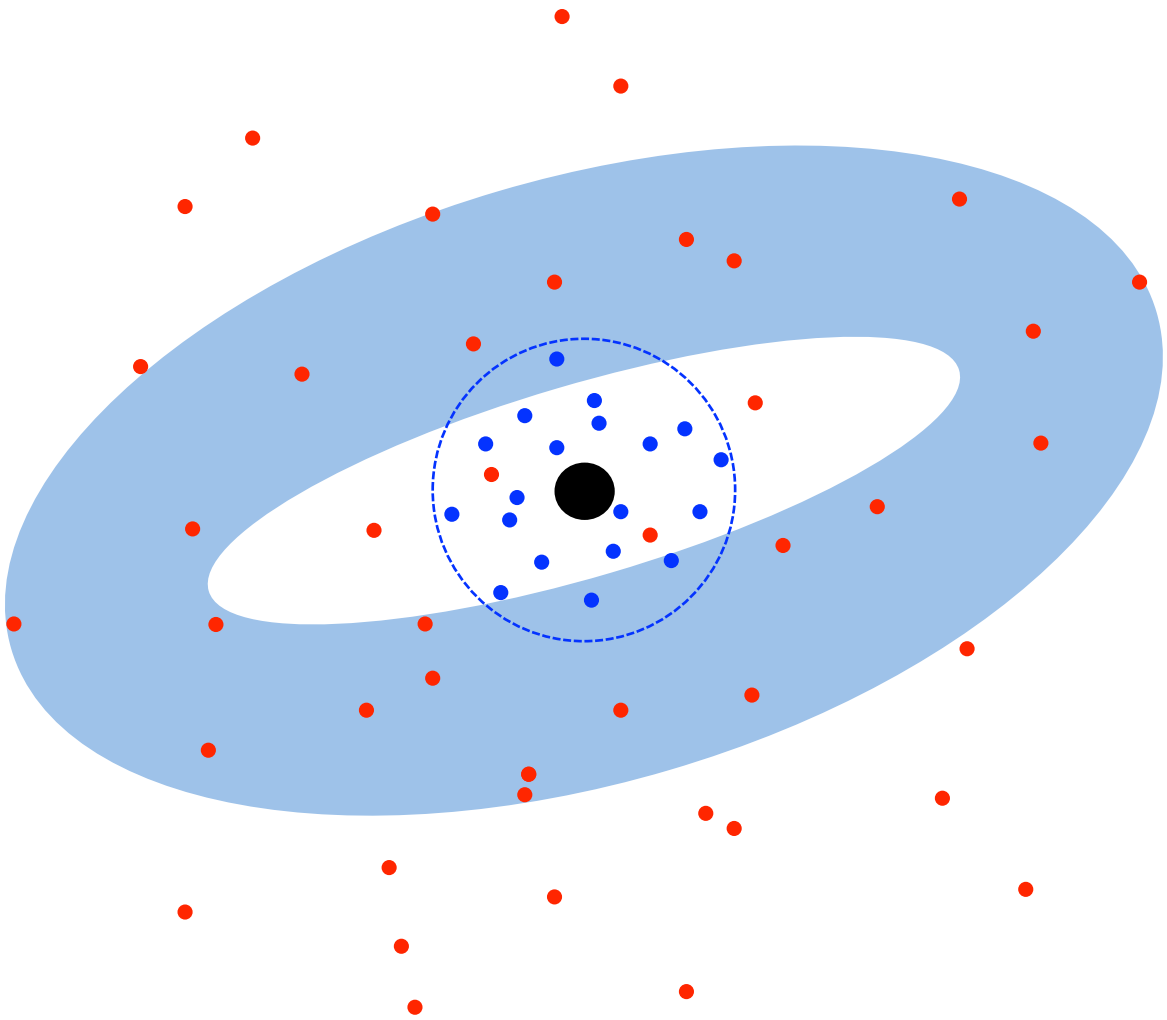
- GC is a unique laboratory for observing a stellar system around a MBH
- At least 3 distinct stellar populations
  - S-stars: orbits
  - Disk stars
  - Old stars
- Future:
  - Gradual improvements
  - A huge step forward due to NIR interferometry
- Exciting astrophysics: Infalling gas cloud

A dense stellar system



NACO, HKL
color composite

Cartoon version of the stellar system



- S-stars
  - young, 10^8 yr
  - $r < 0.05$ pc
  - orbits
- Stellar disk
  - younger, 10^7 yr
  - $0.05\ \text{pc} < r < 0.5\ \text{pc}$
- Old stars
  - everywhere
- and more:
  - stellar black holes
  - neutron stars
  - white dwarfs
  - fainter MS stars

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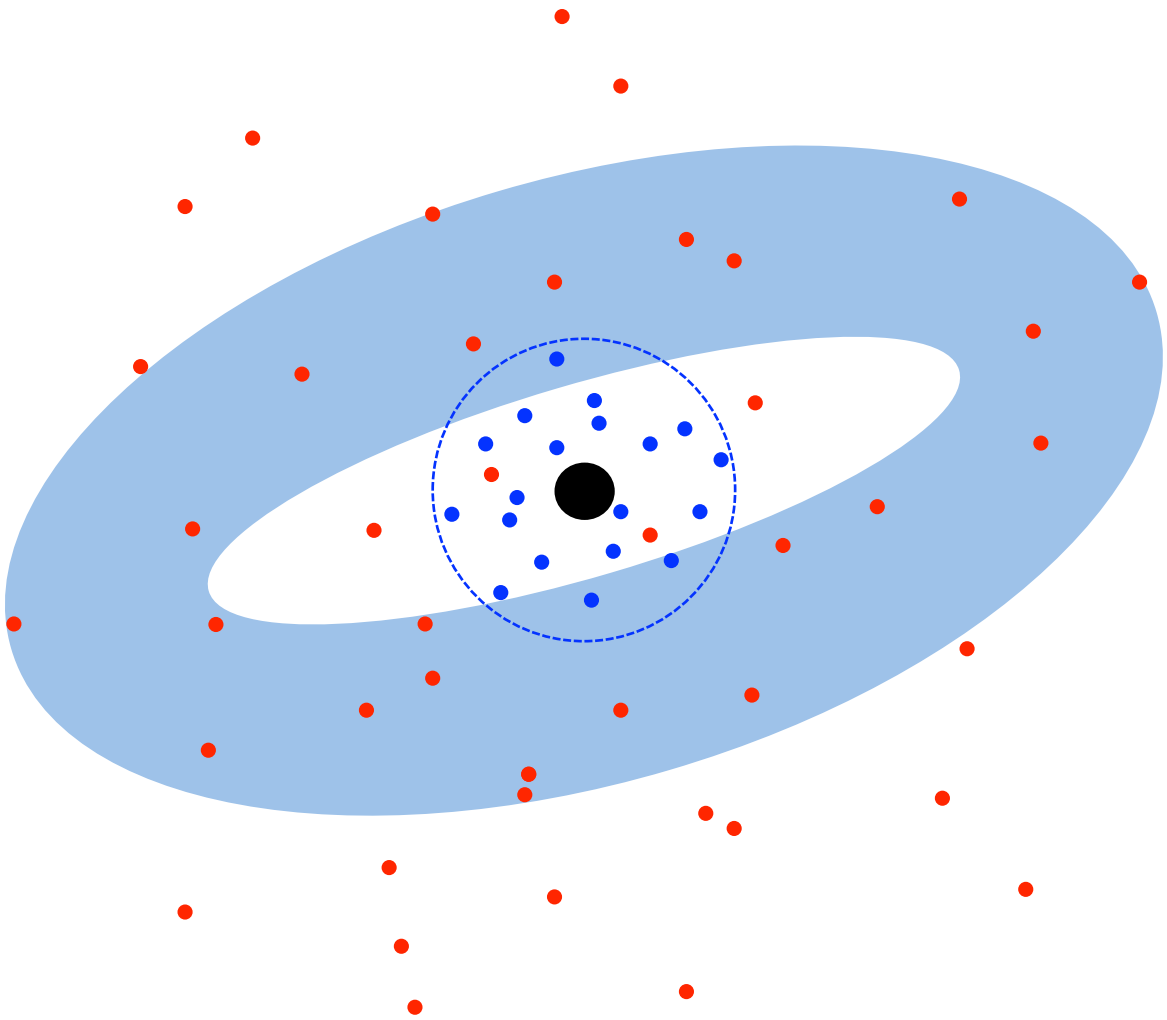

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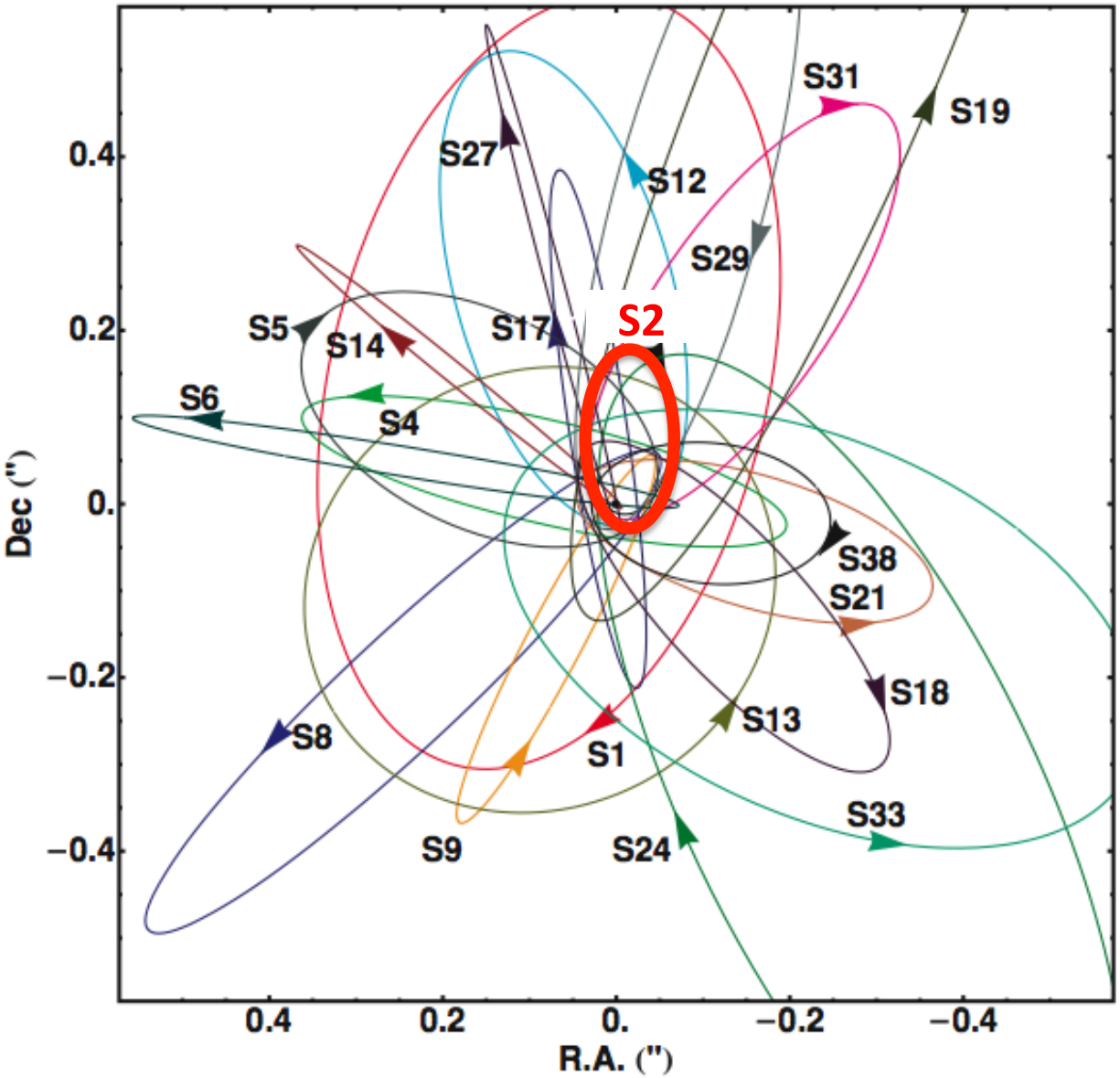
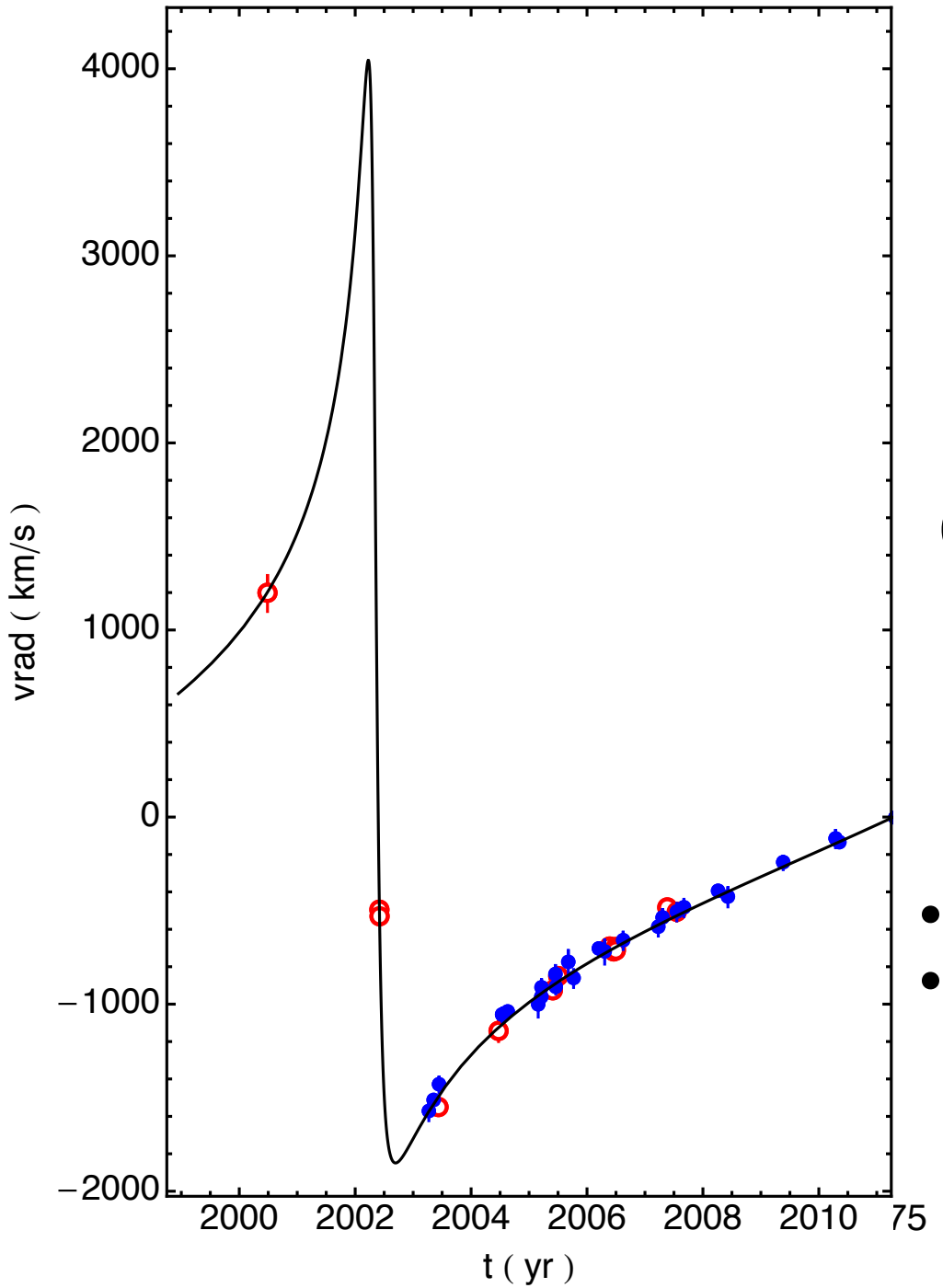
Currently: ≈ 30 orbits known



20 stars shown,
Gillessen+ 2009



S2: the showcase star

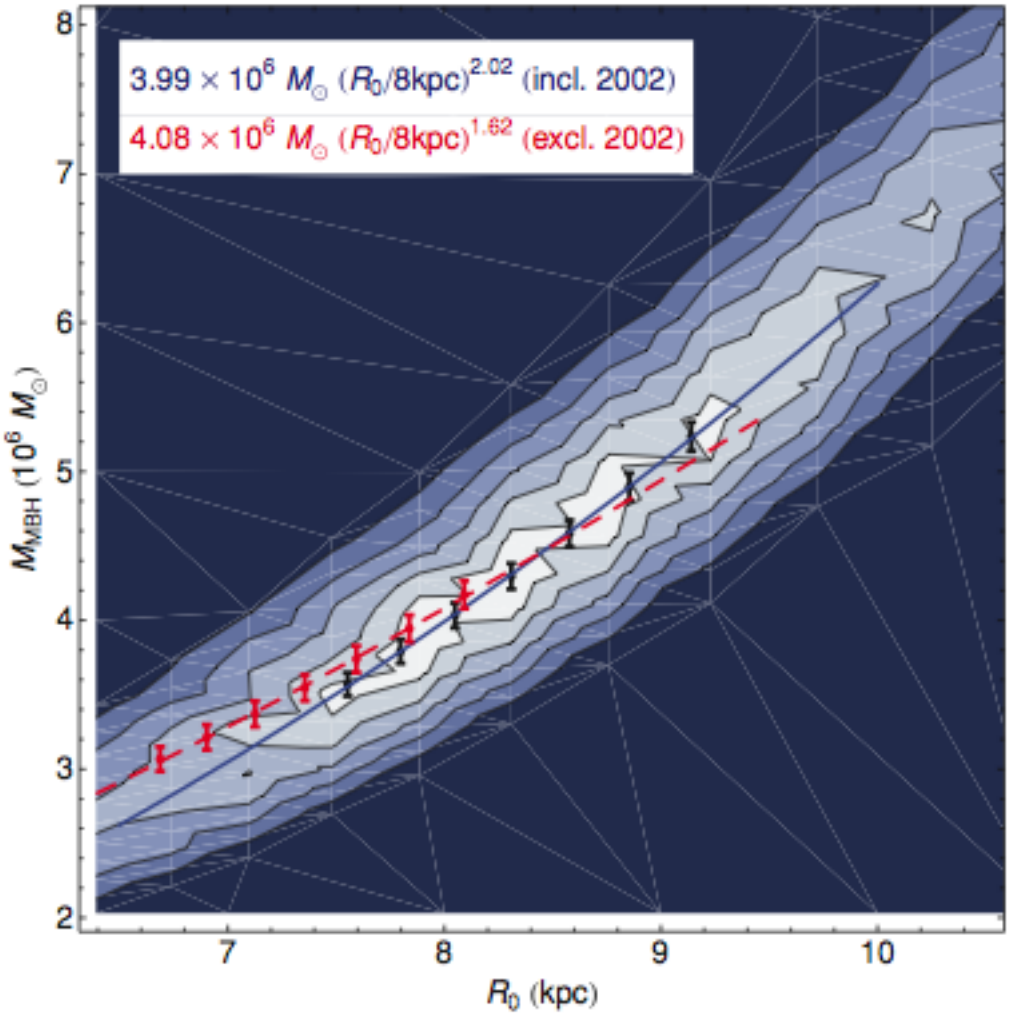
VLT & Keck data suitably combined

(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

Mass and R_0 are highly correlated

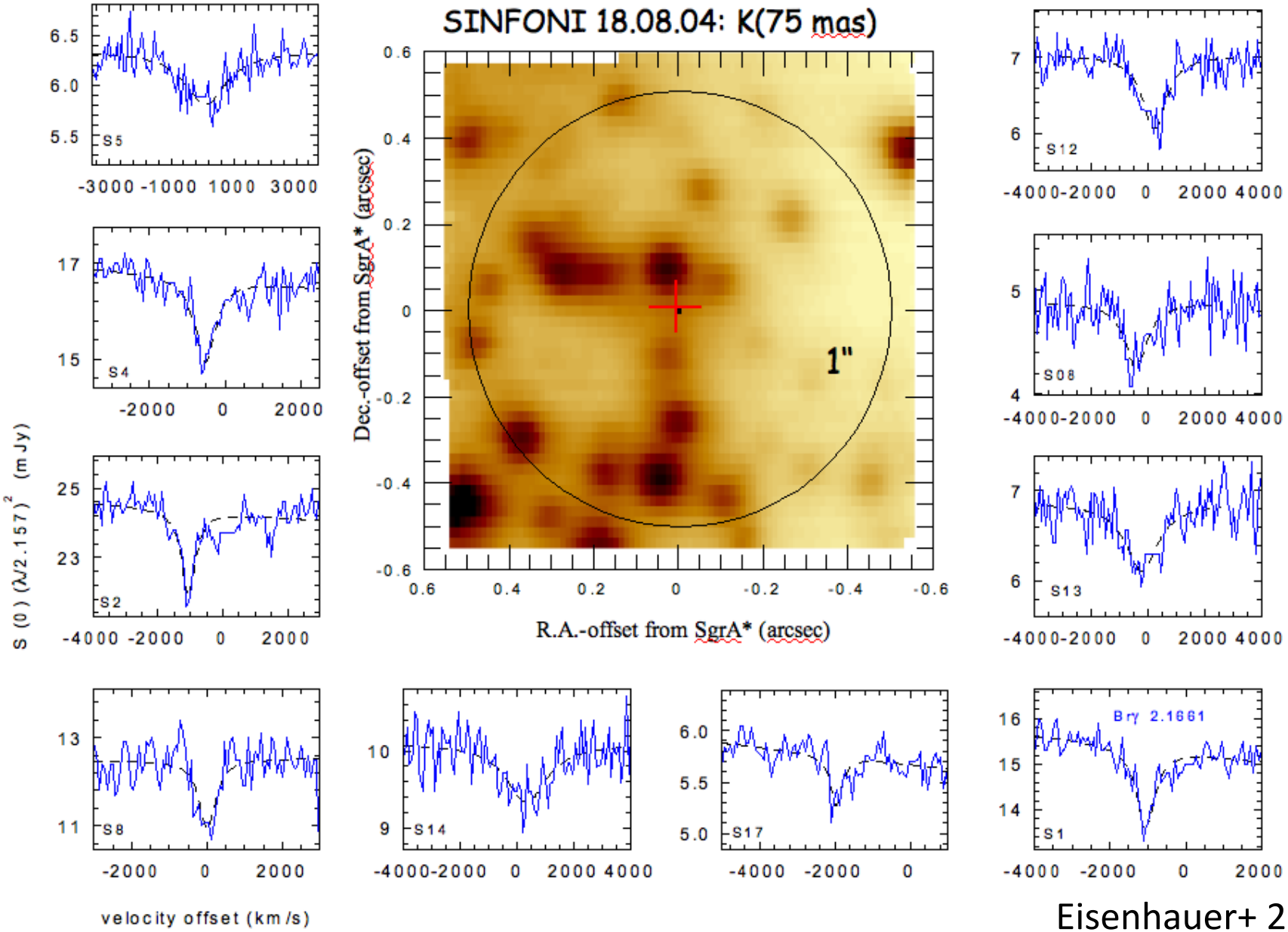


pure astrometry:
$M \sim R^3$

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

only radial velocities:
$M \sim R^0$

Surprisingly, the S-stars are young

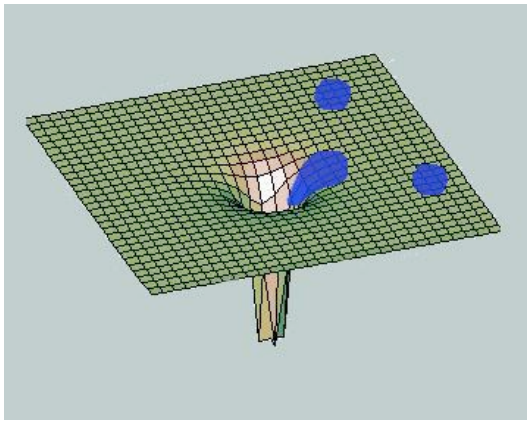


Eisenhauer+ 2005

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

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

$$\gg$$

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

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

al. 2009

98% of
4 million suns in
100 AU

much less

The drain limit

"Require steady state for SBHs"

Rate of SBHs lost

<

Number of SBHs present / t_{Hubble}

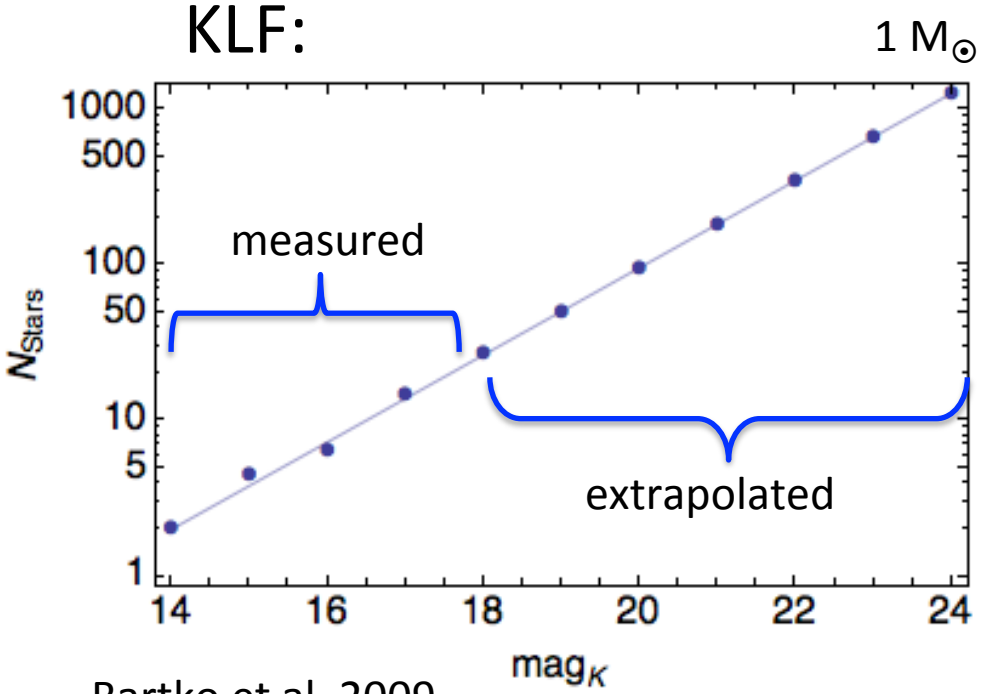
$$\max N_\bullet(<r_\bullet) \sim \frac{2\log(2\sqrt{r_\bullet/r_S})}{3\log(0.4\max N_\bullet)}\left(\frac{m}{M_\bullet}\right)^2 \frac{P(r_\bullet)}{t_H}$$

(Alexander & Livio 2004)

$$\eta \lesssim 0.0011 \times \left(\frac{m_\star}{10}\right)^{-0.7}$$

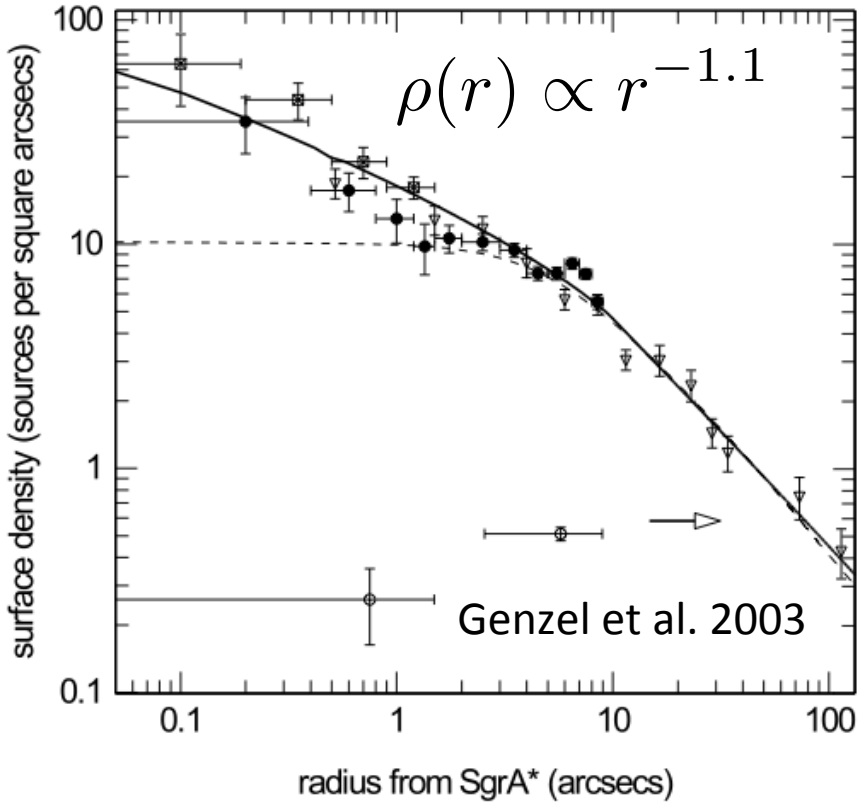
Stellar mass from extrapolation

KLF:



Bartko et al. 2009

Density profile:

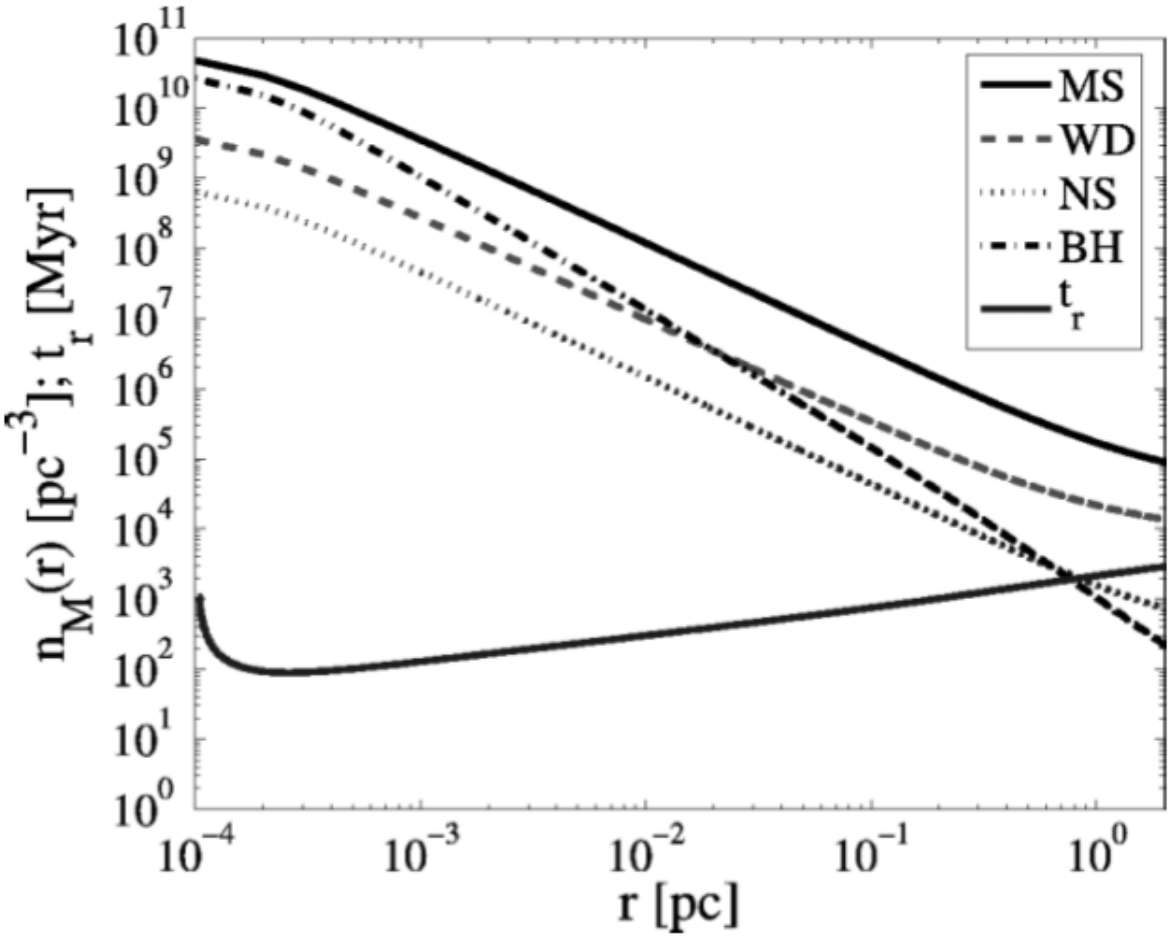


$$\eta \approx 10^{-4}$$

BUT:

- stellar black holes
- mass segregation

Dynamical modelling

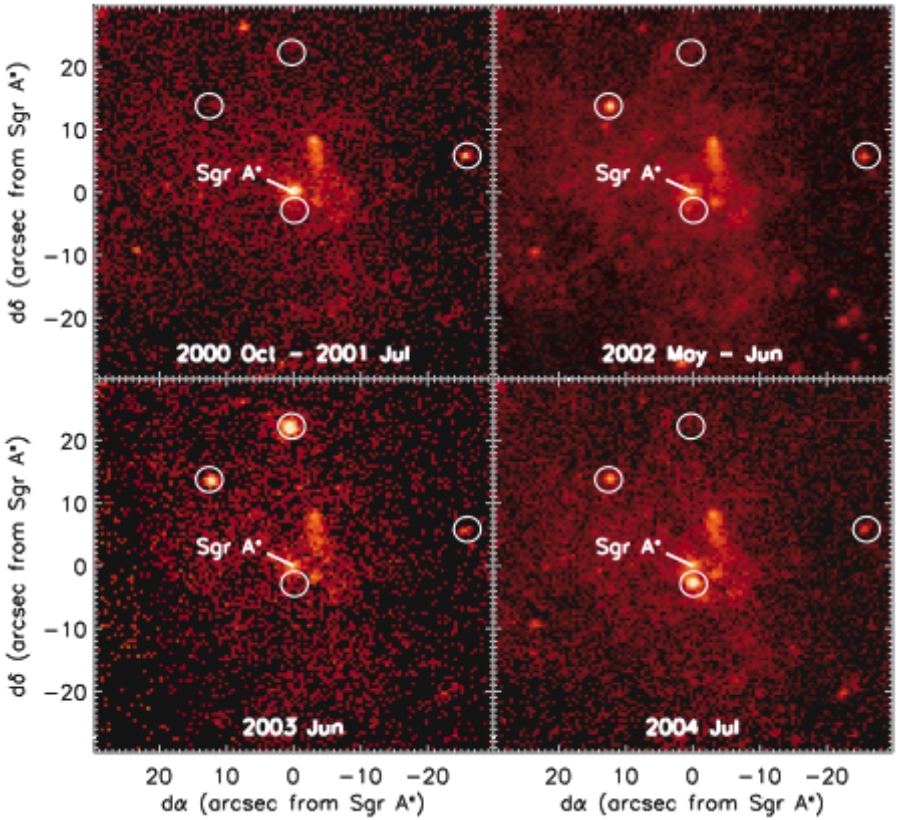


(Hopman & Alexander 2006)

$$\eta \approx 5 \times 10^{-4}$$

Freitag et al. (2006):

$$\eta \approx 10^{-4}$$



Number of X-ray binaries

Muno et al. 2005:
4 X-ray transients in central pc

"Chemical" equilibrium:

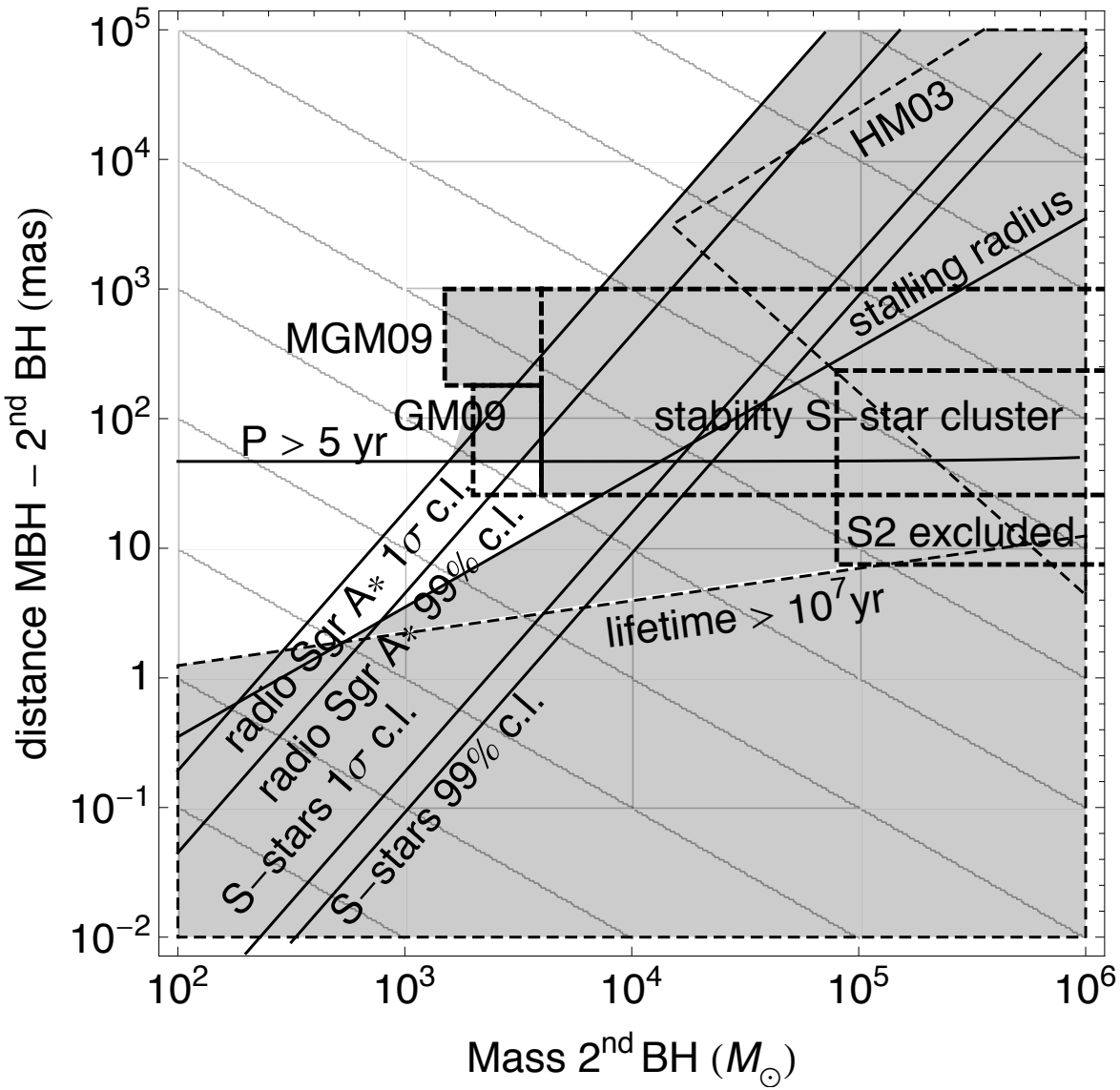
$\mathrm{Binary} + \mathrm{SBH} \rightarrow \mathrm{XRB} + \mathrm{Star}$	$\mathrm{XRB} + \mathrm{Star} \rightarrow \mathrm{Binary} + \mathrm{SBH}$ life time of τ
$\gamma_+ = n_\star n_\mathrm{b} \Sigma \sigma_1$ =	$\gamma_- = \frac{1}{2} n\, n_\mathrm{XRB} \Sigma \sigma_1 + \frac{n_\mathrm{XRB}}{\tau}$

$$\eta \approx 3.8 \times 10^{-7} \frac{N_{\mathrm{X},<1\,\mathrm{pc}}}{f_\mathrm{X}}$$

$$\approx 1.5 \times 10^{-4}$$

Similar:
Deegan & Nayakshin 2007:
$\eta \approx 2.1 \times 10^{-4}$

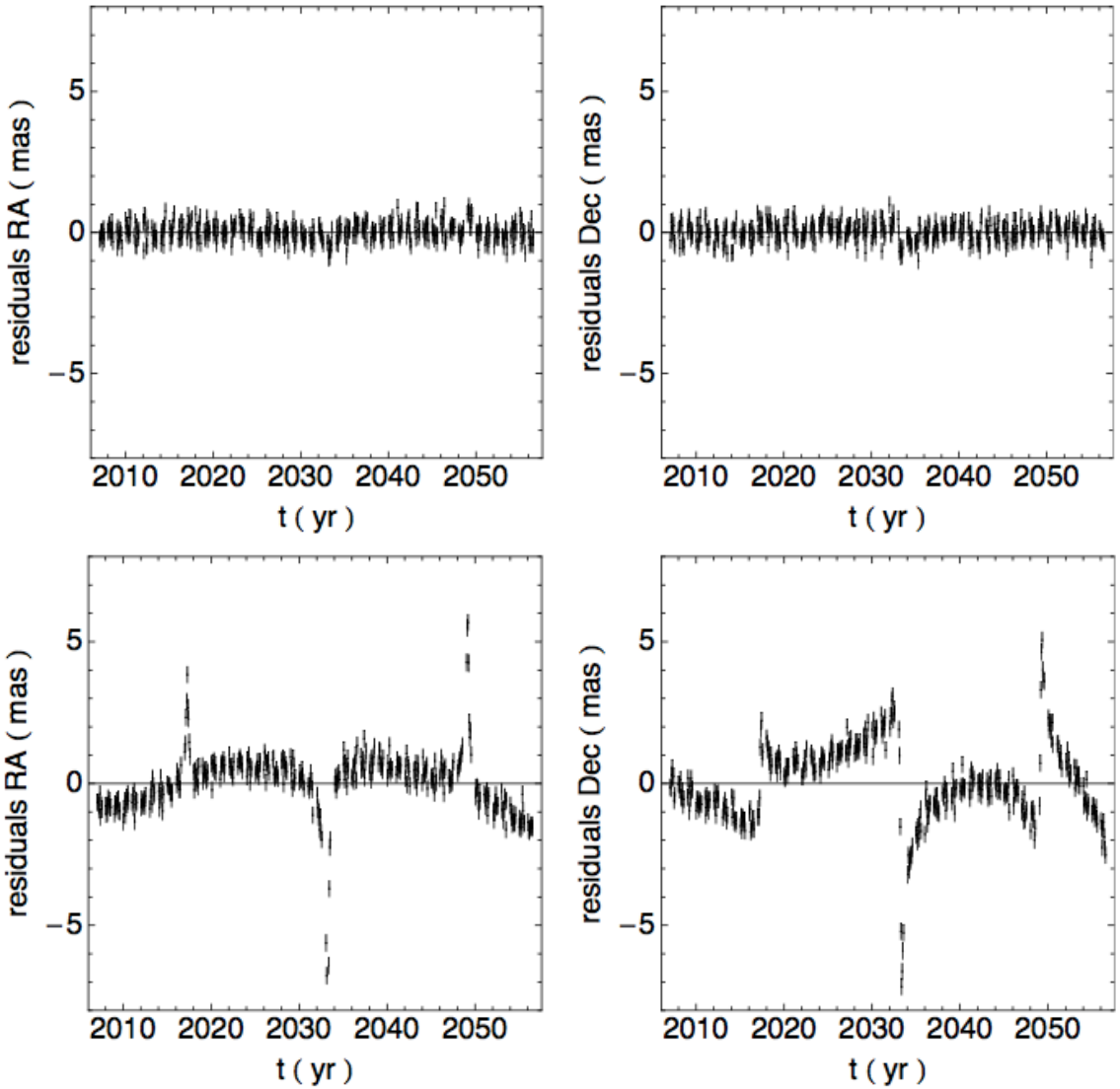
A potential second BH in the GC would need to be light & distant

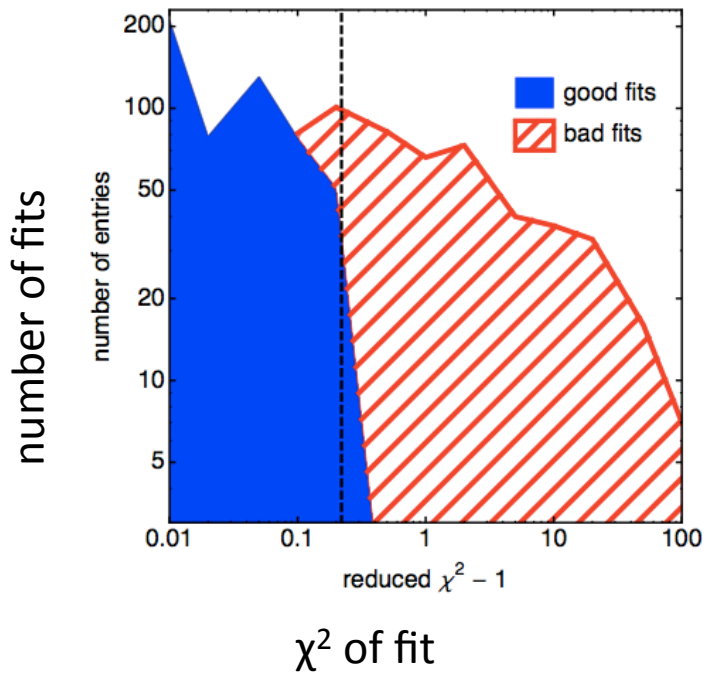


Hansen & Milosavljevic 2003,
Gualandris & Merritt 2007, 2009
Merritt, Gualandirs, Mikkola 2009
Reid & Brunthaler 2004
Gillessen+ 2009

An IMBH could be detectable directly

Gualandris, Gillessen & Merritt 2010





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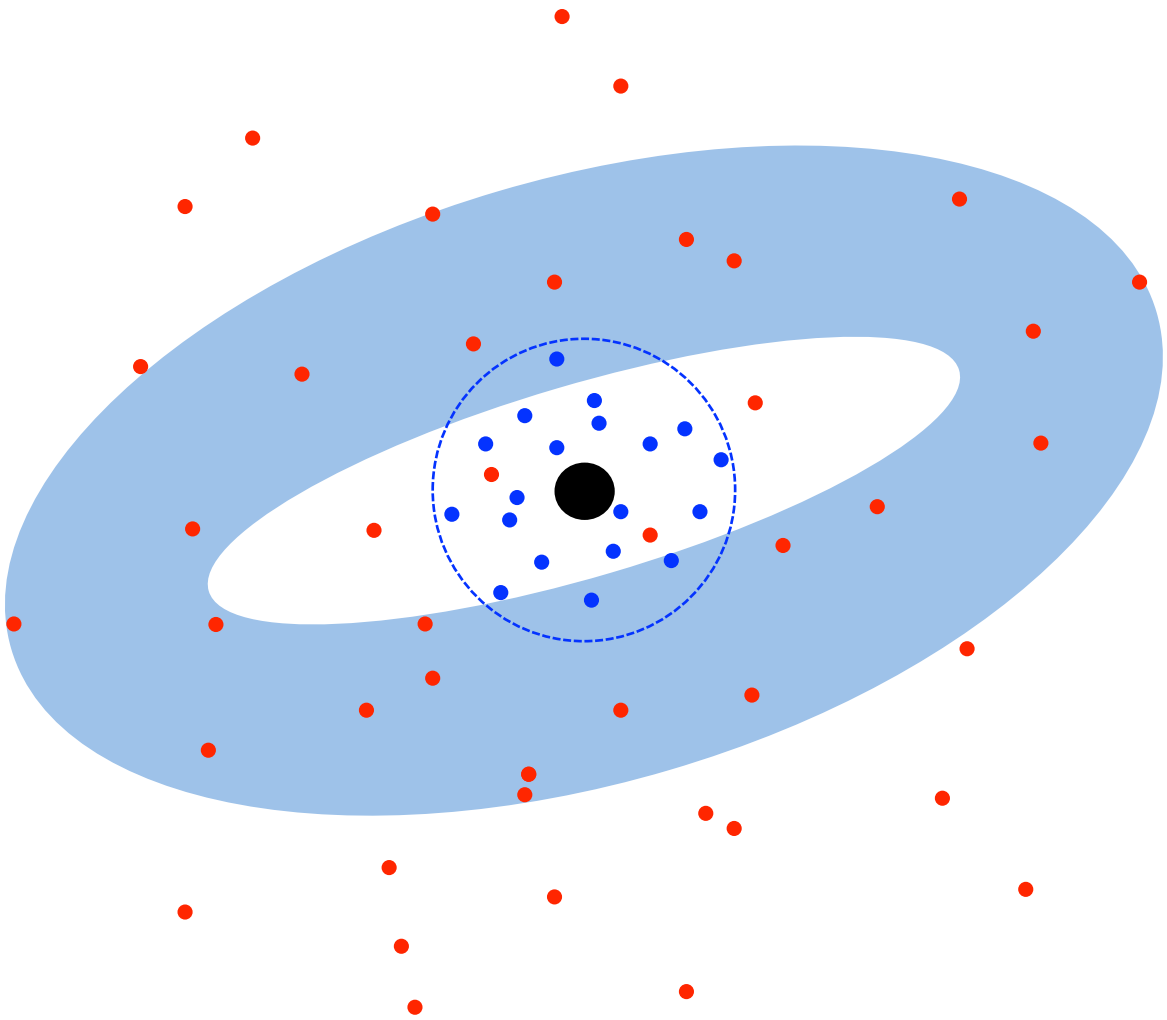

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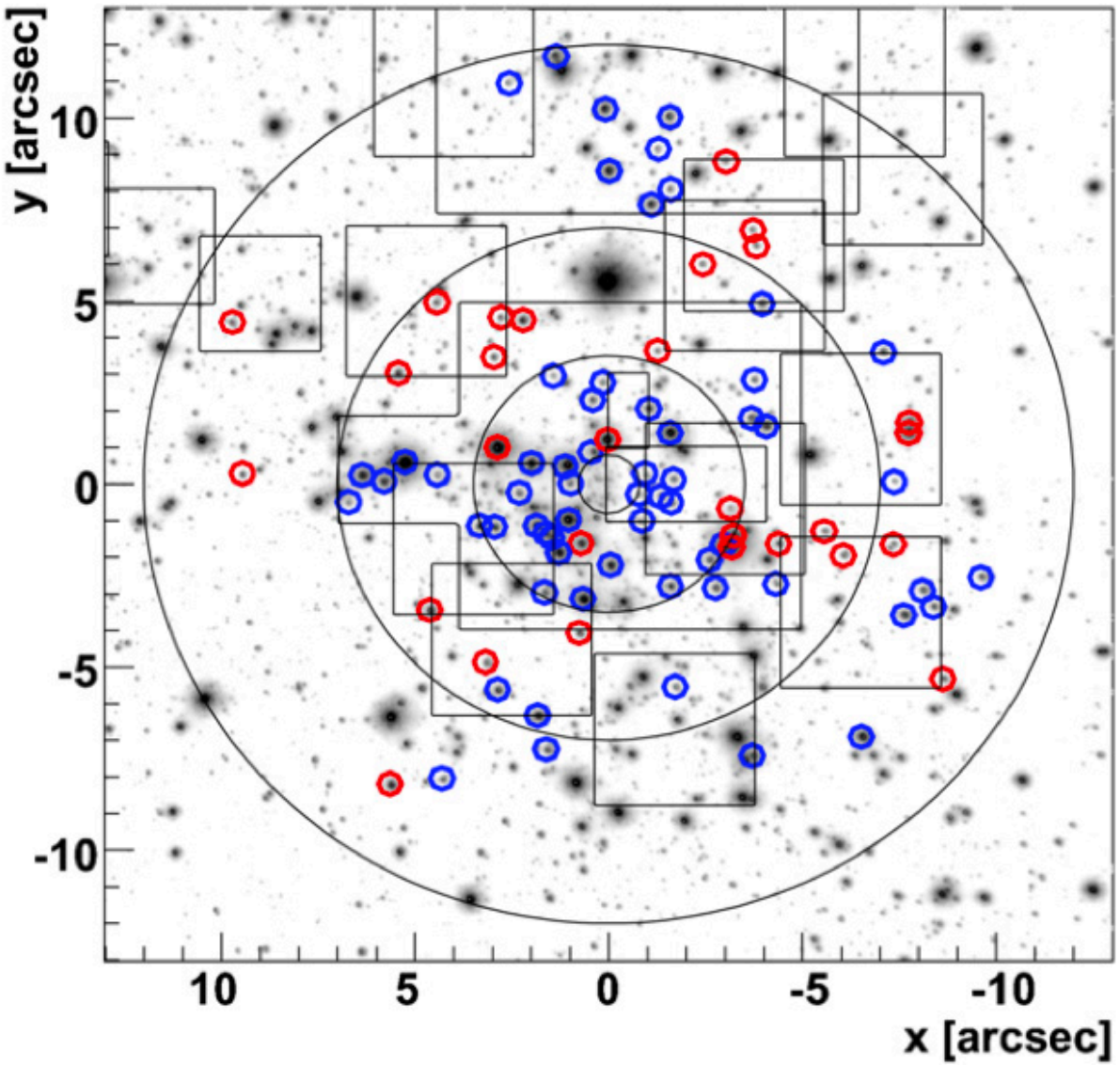
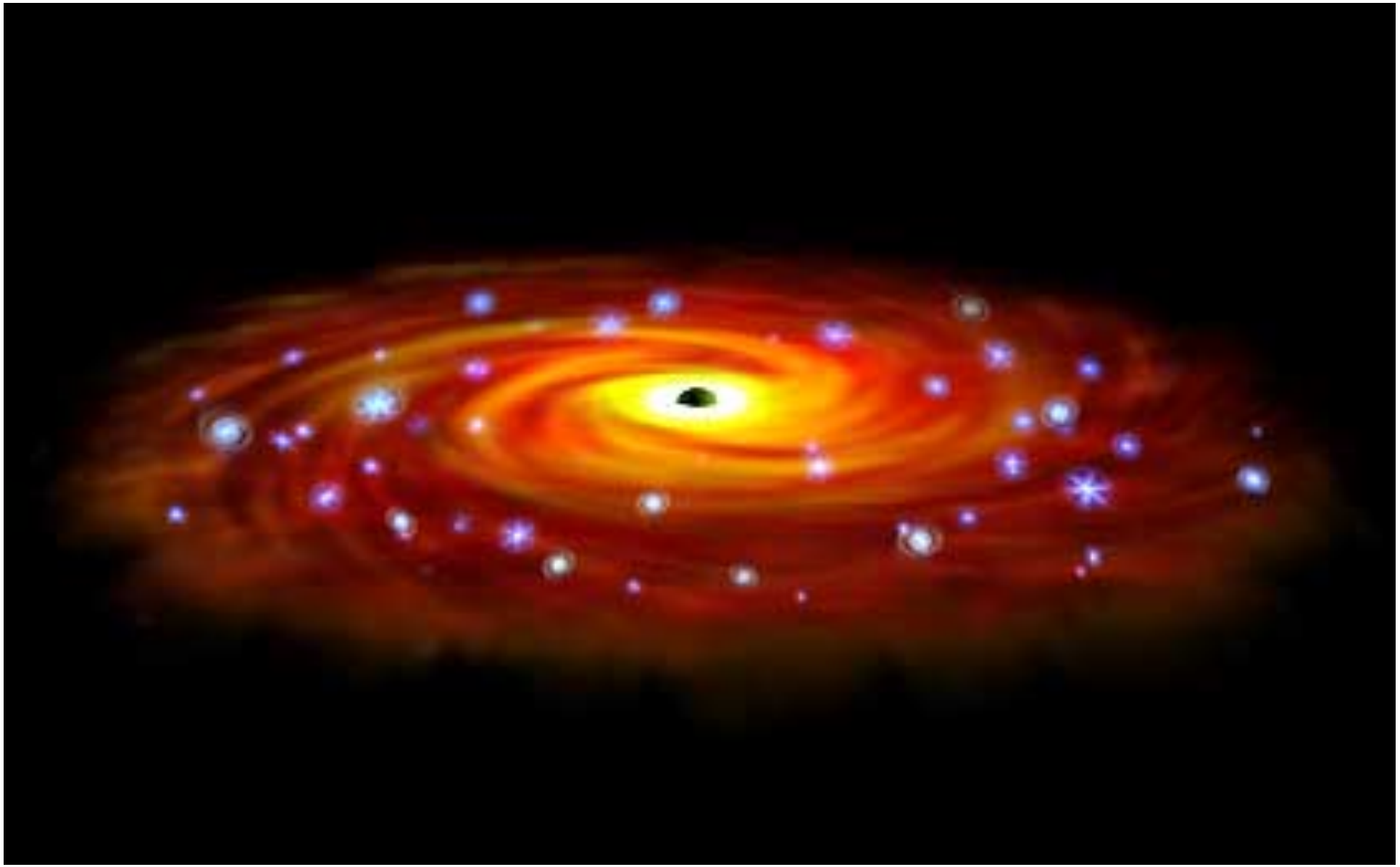
A large concentration of young O/WR-stars between 1'' and 10''



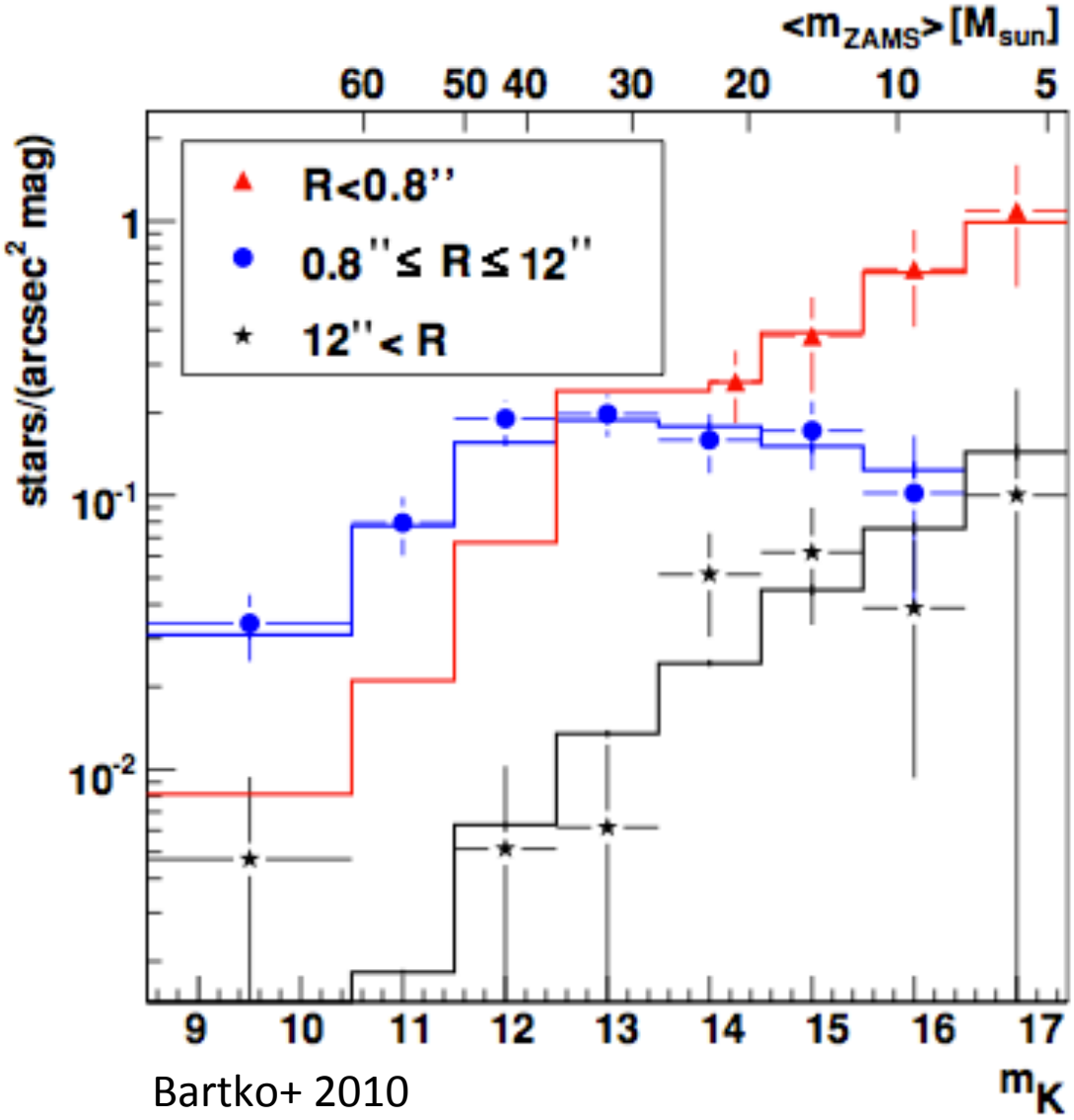
clockwise
counter-clockwise

Bartko+ 2009

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

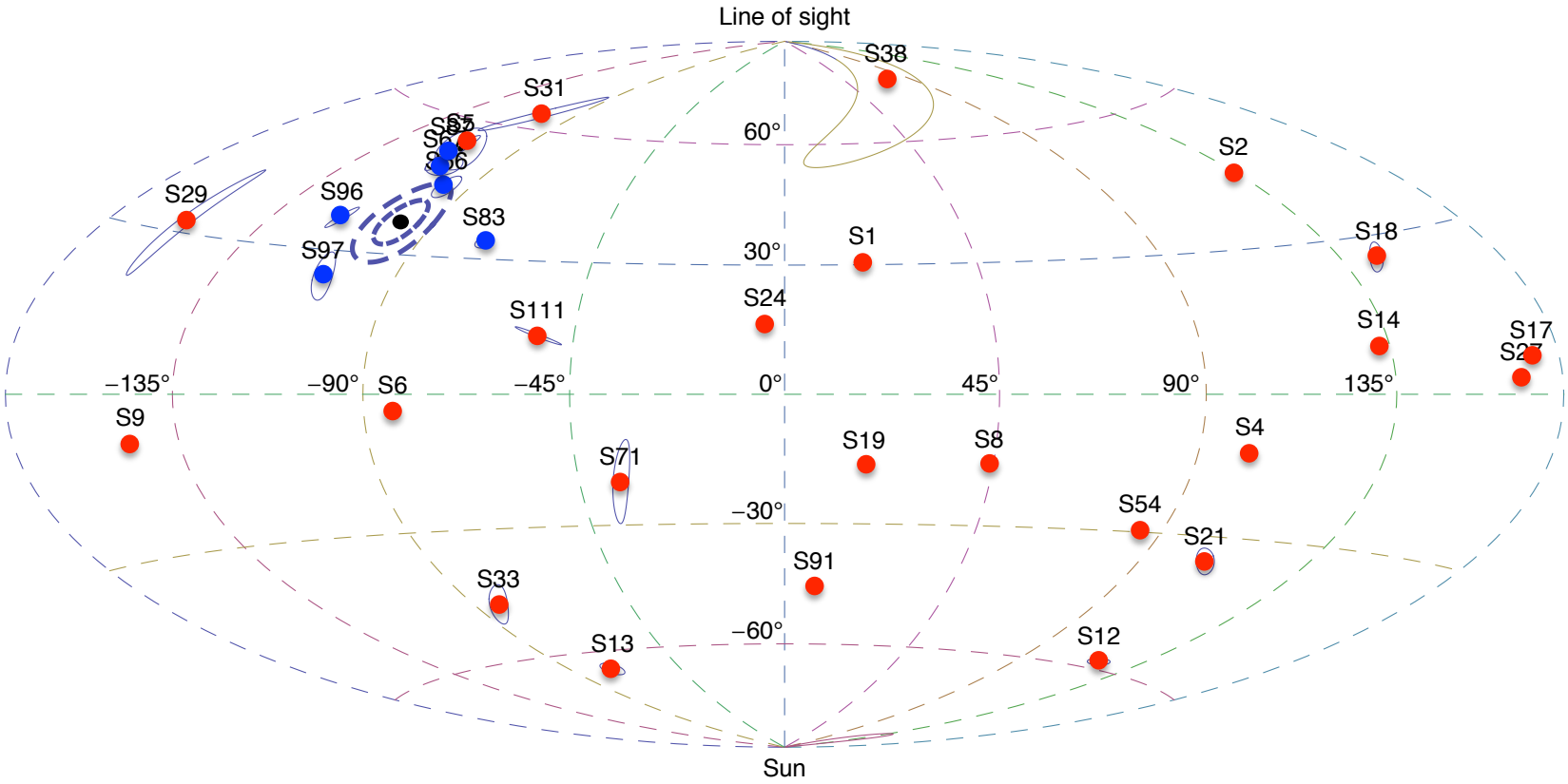


The disk has a top-heavy IMF



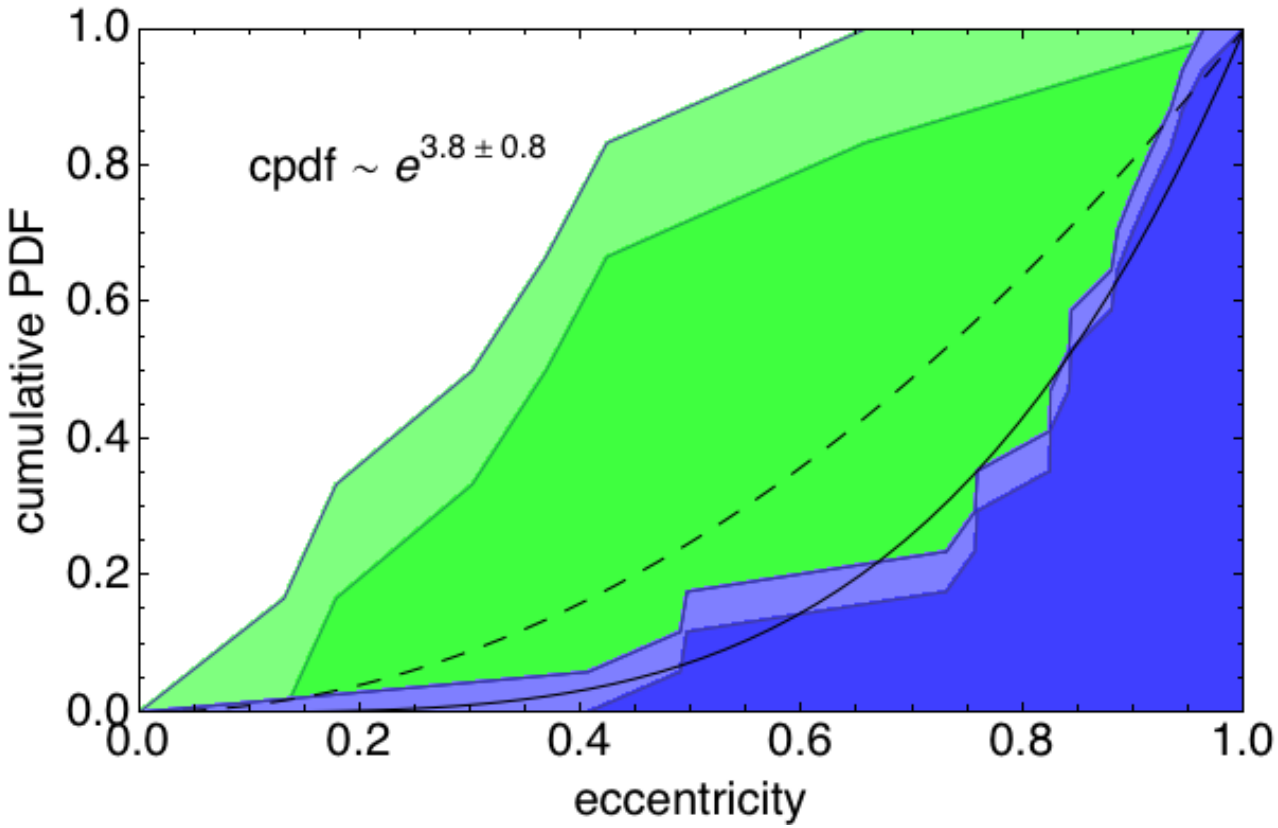
Bartko+ 2010

Orbital planes: S-stars ≠ disk stars



Eccentricities: S-stars ≠ Disk stars

6 disk stars: <e> = 0.34 ± 0.18

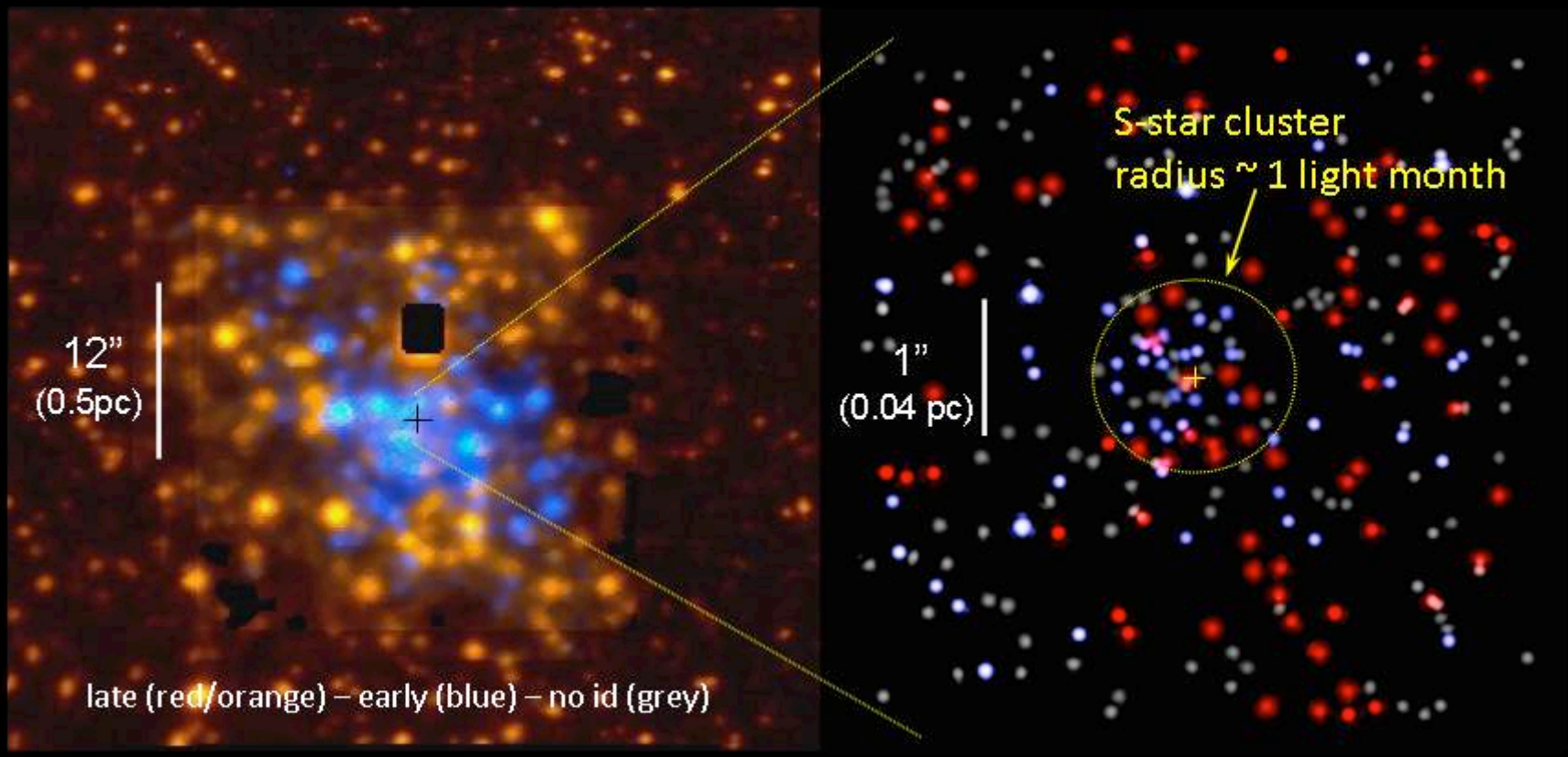


17 early-type S-stars: large <e>

Two paradoxes of Youth

O/WR stars

B stars

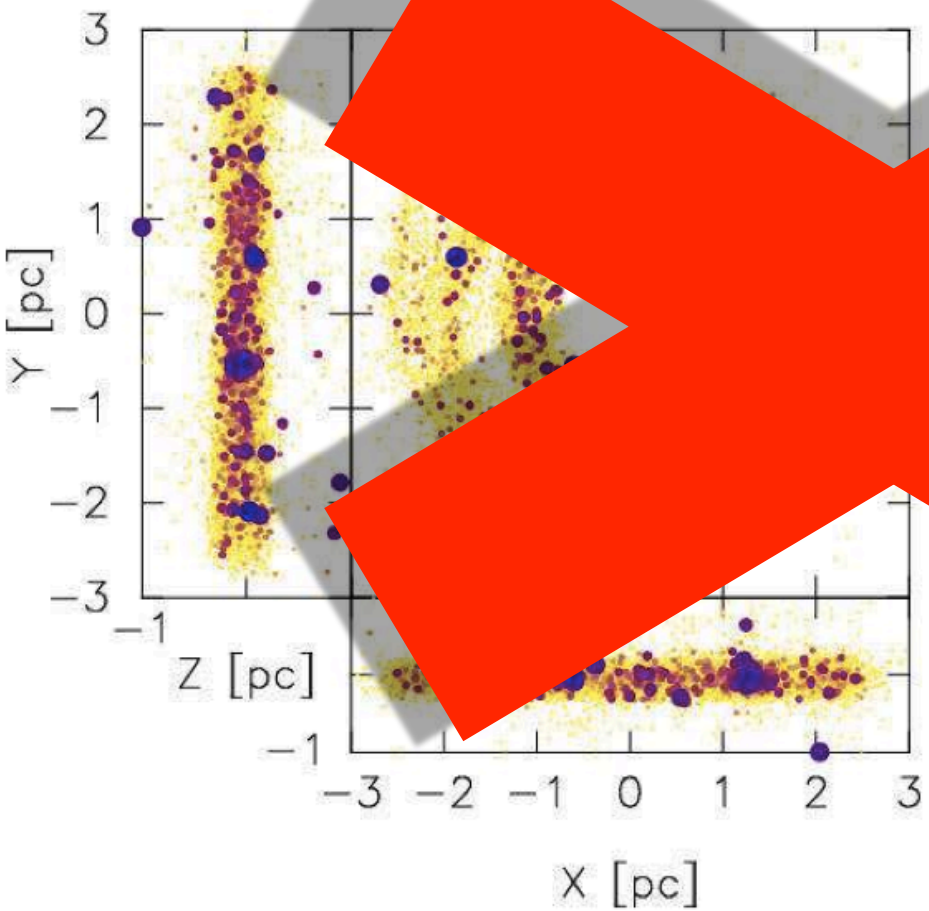


1" < R < 10"
age ≈ 6 Myr

R< 1"
age ≈ 10^8 yr

Idea I: Cluster in-spiral

Gerhard 2001



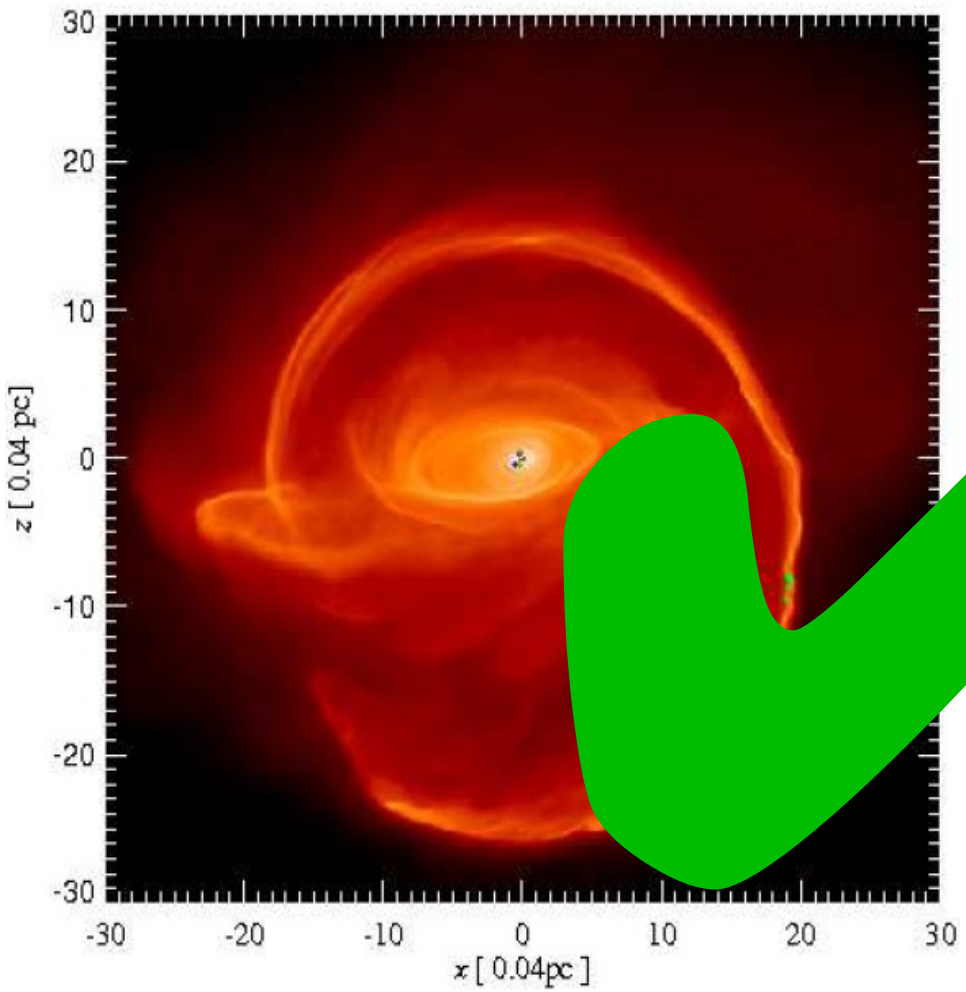
Pr

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

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

Portegies-Zwart+ 2005

Idea II: In-situ formation in infalling gas cloud



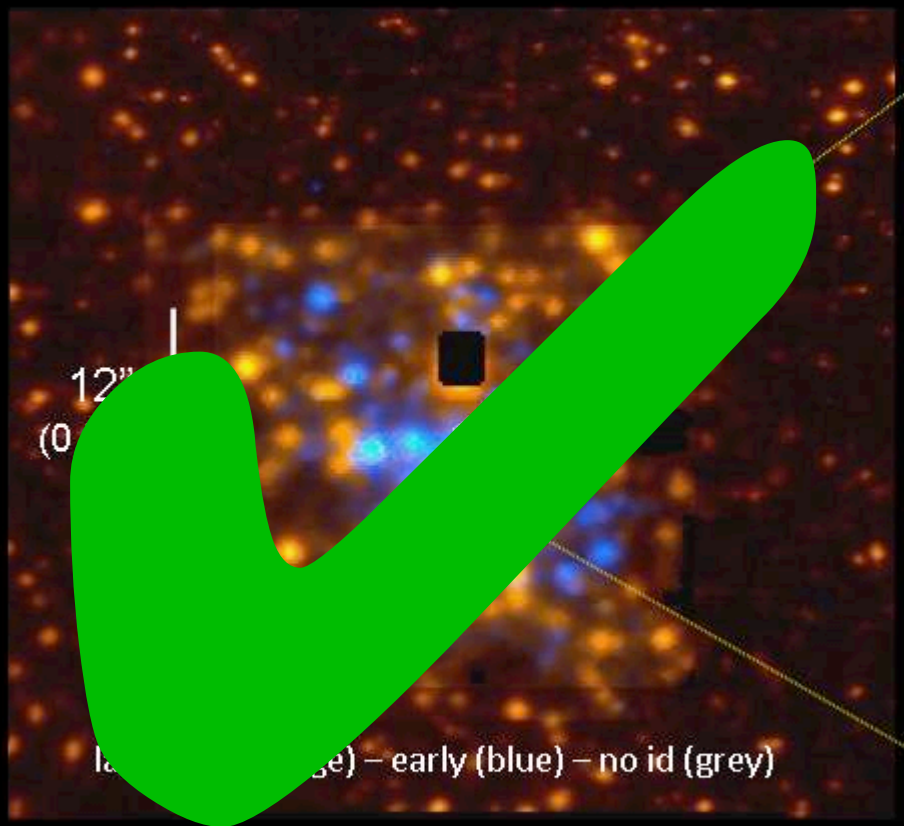
More promising:

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

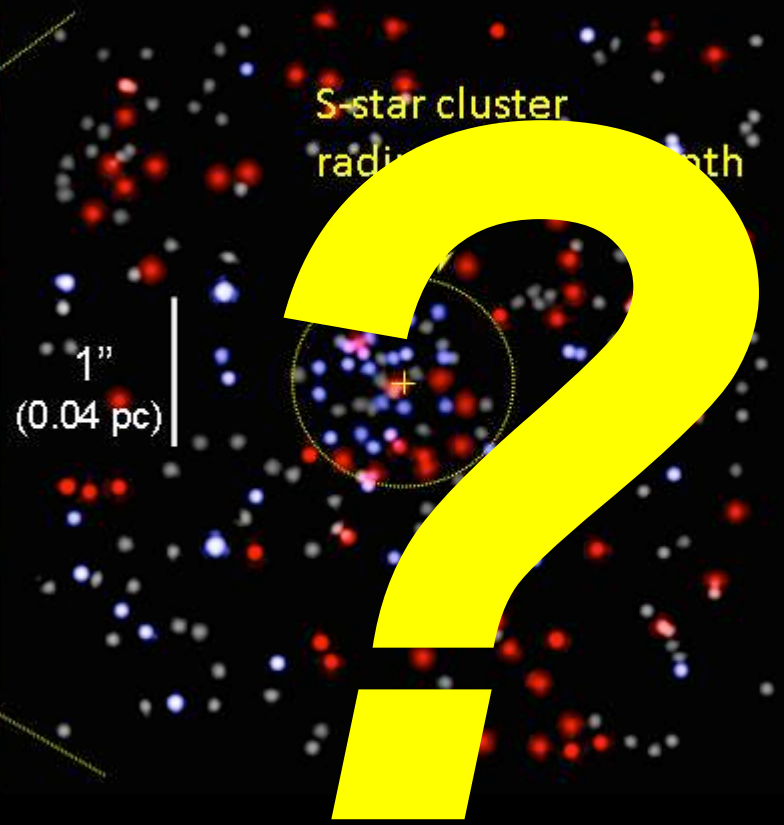
Bonnel & Rice 2008, Hobbs & Nayakshin 2008

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 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

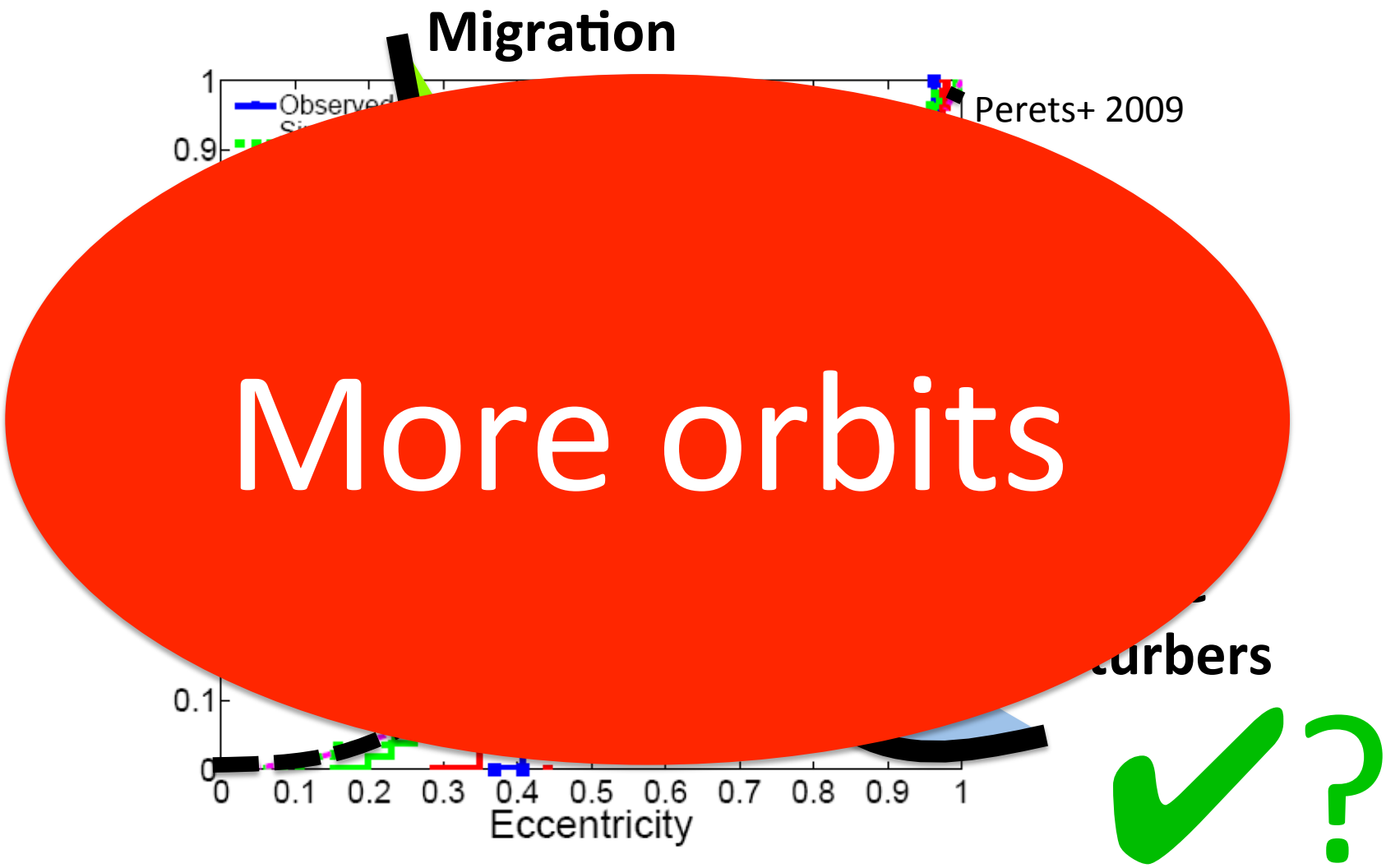
Massive Perturbers

- 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
  - Resonances

Migration

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

The eccentricity distribution might be the clue



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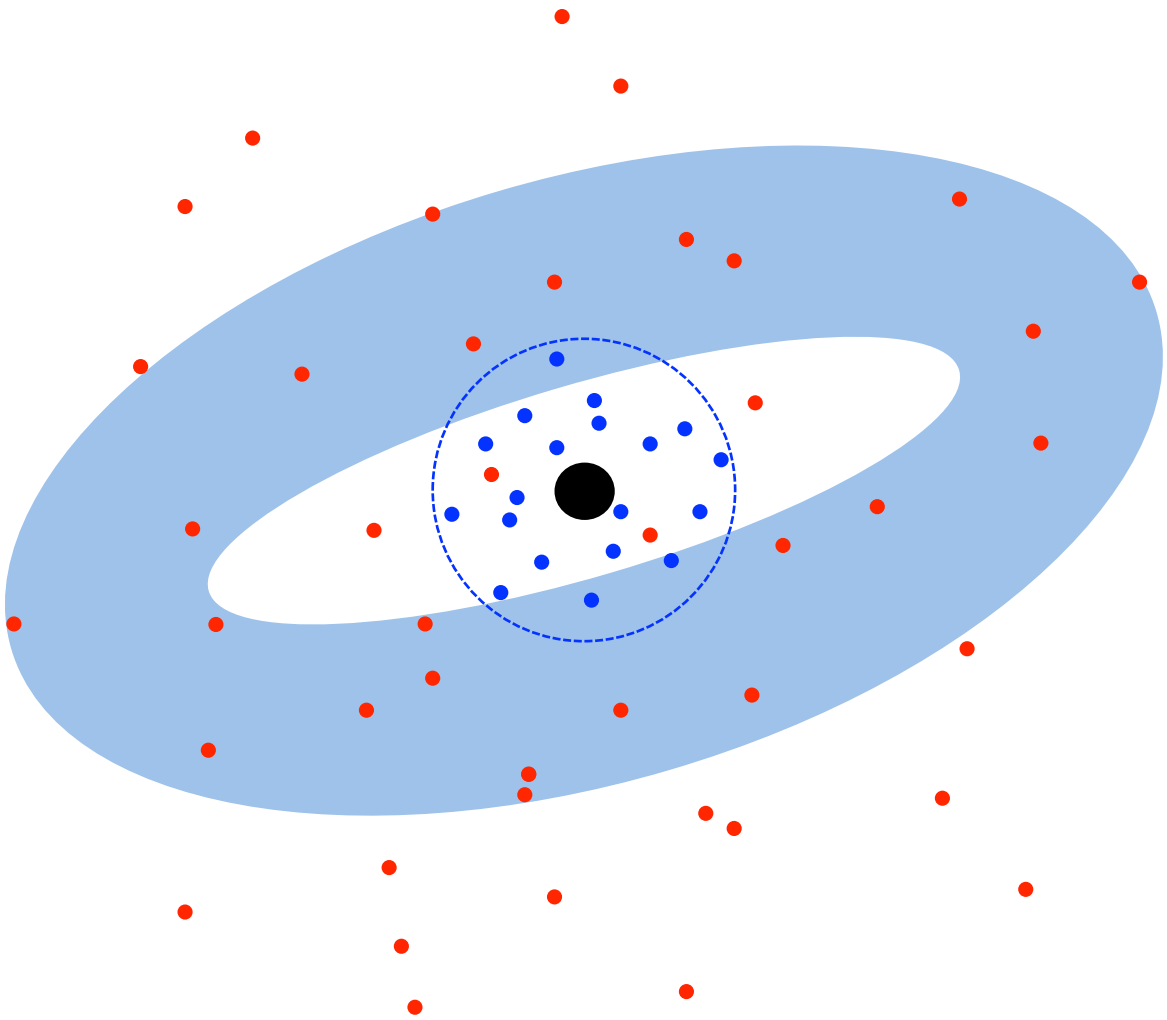

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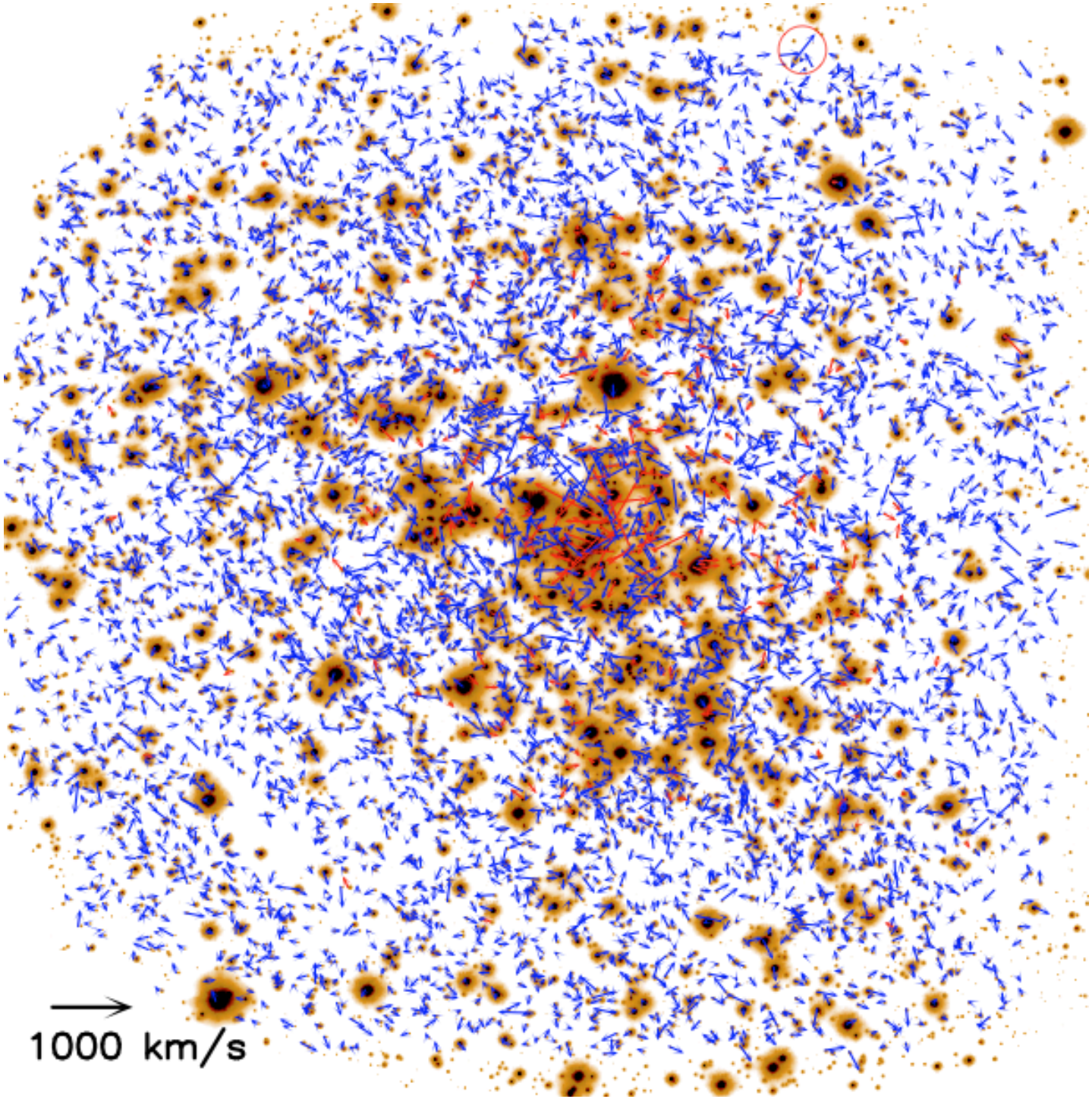
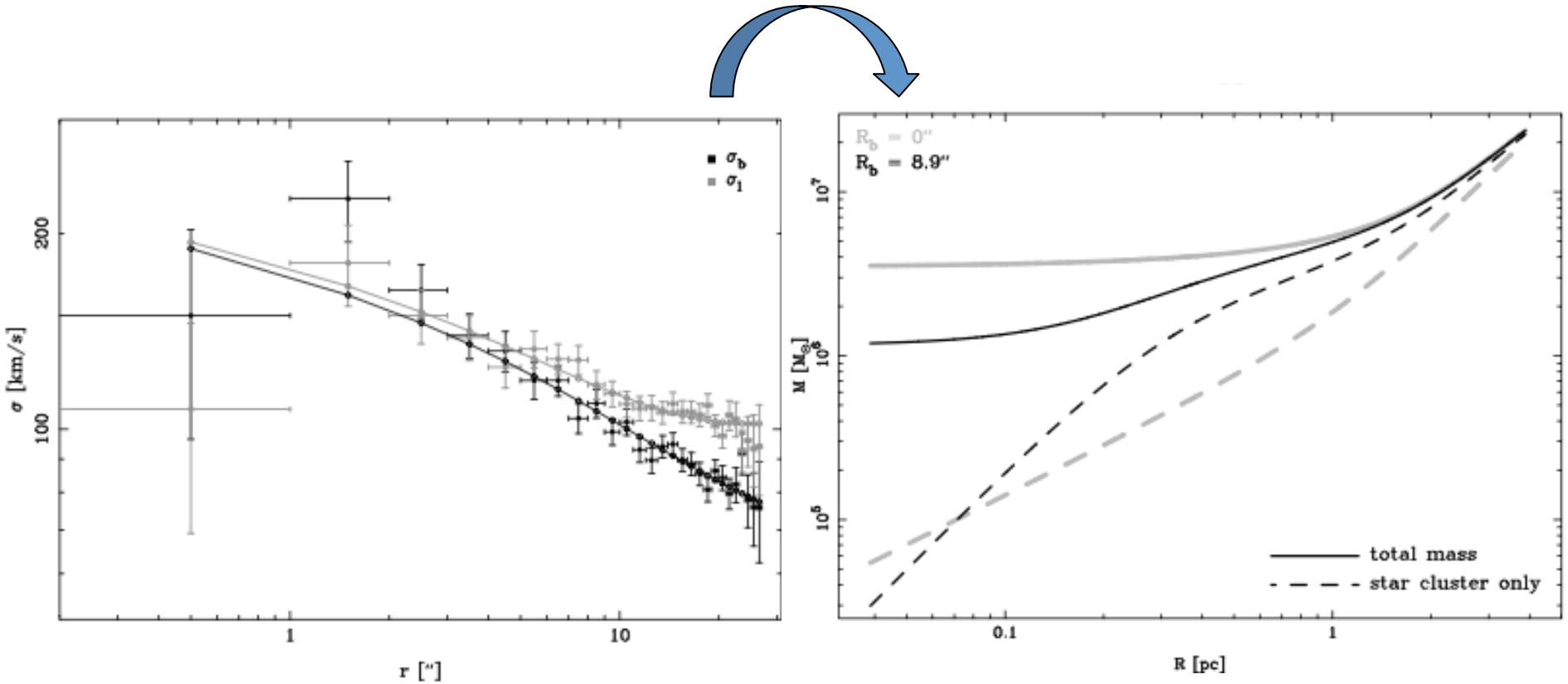


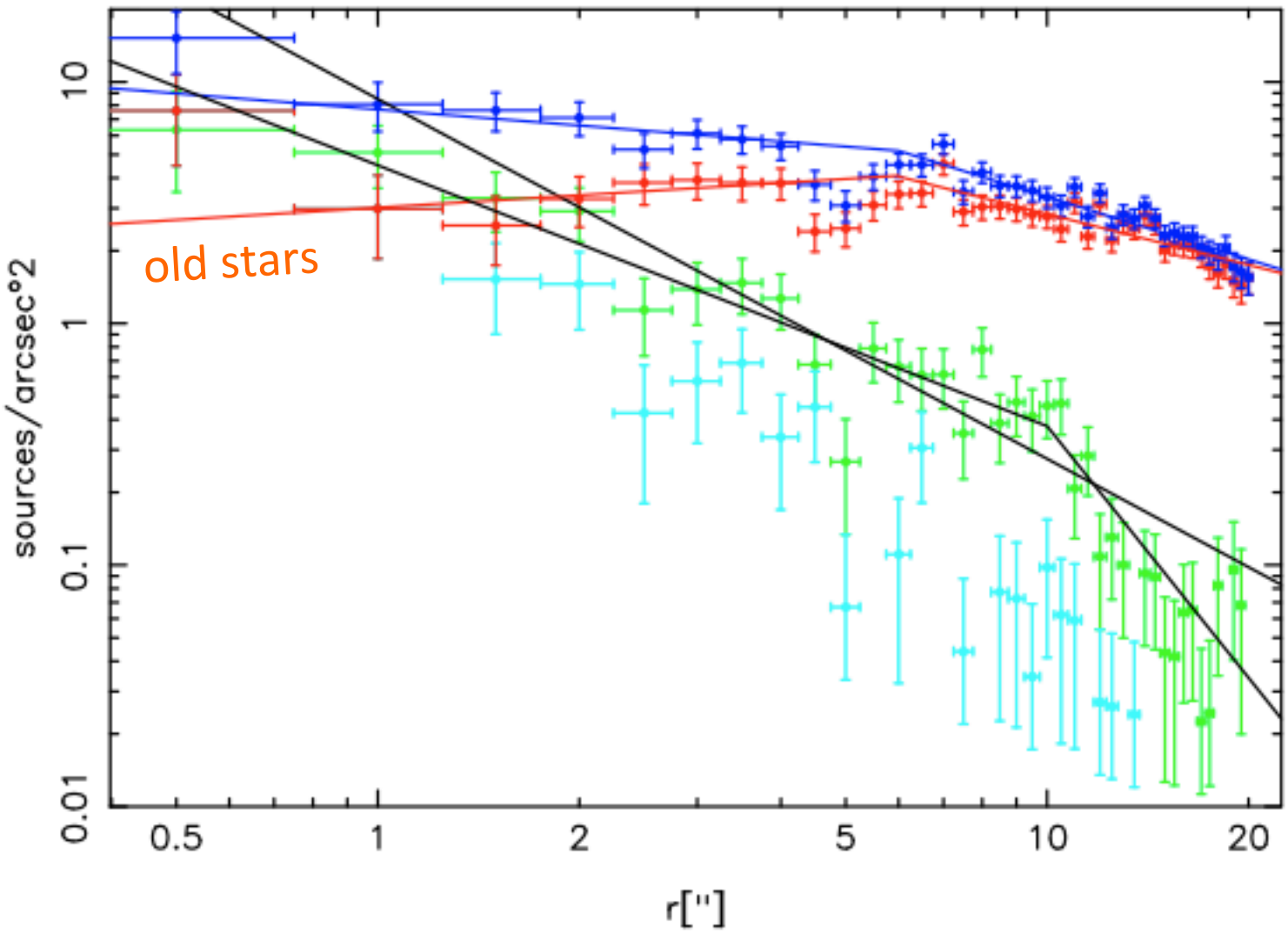
Dynamics of the star cluster

Schödel+ 2009

“Standard game”: σ ➔mass



The old stars: missing towards the center?



Buchholz+ 2009, Do+ 2009, Bartko+ 2010

If confirmed, that has consequences for the EMRI rates

- Challenges basic stellar dynamics: Bahcall-Wolf cusp:
  - $\rho \approx r^{-7/4}$ for single species;
  - ρ between $r^{-7/4}$ and $r^{-3/2}$ for multiple species

- Proposed solutions:
  - Relaxation time of GC system > Hubble time — Merritt 2010
  - Giants are destroyed by stellar collisions — Davies+ 2011

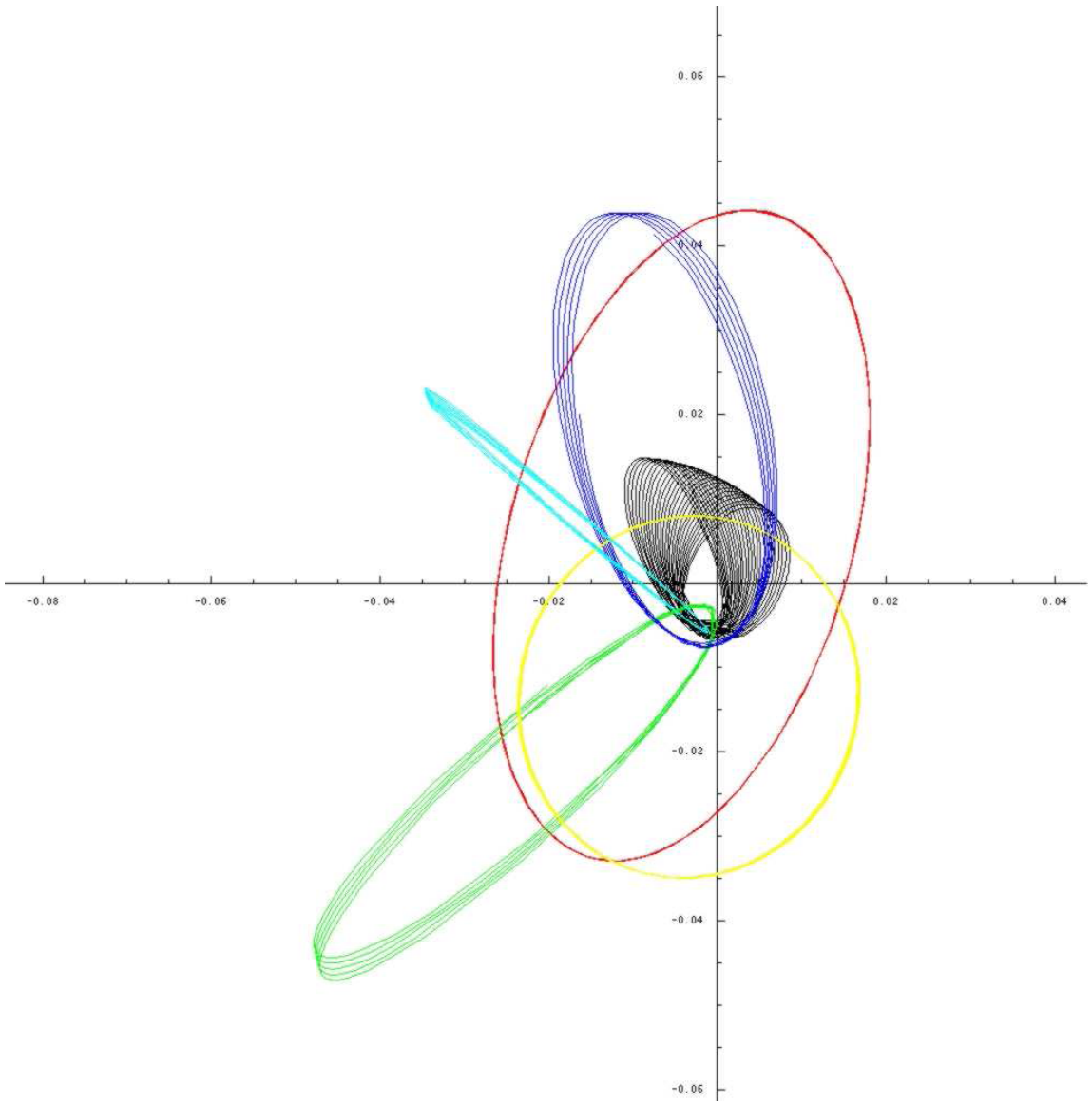
- Does the same hold for the sea of stellar black holes, neutron stars, white dwarfs?

Imagine we could zoom in further

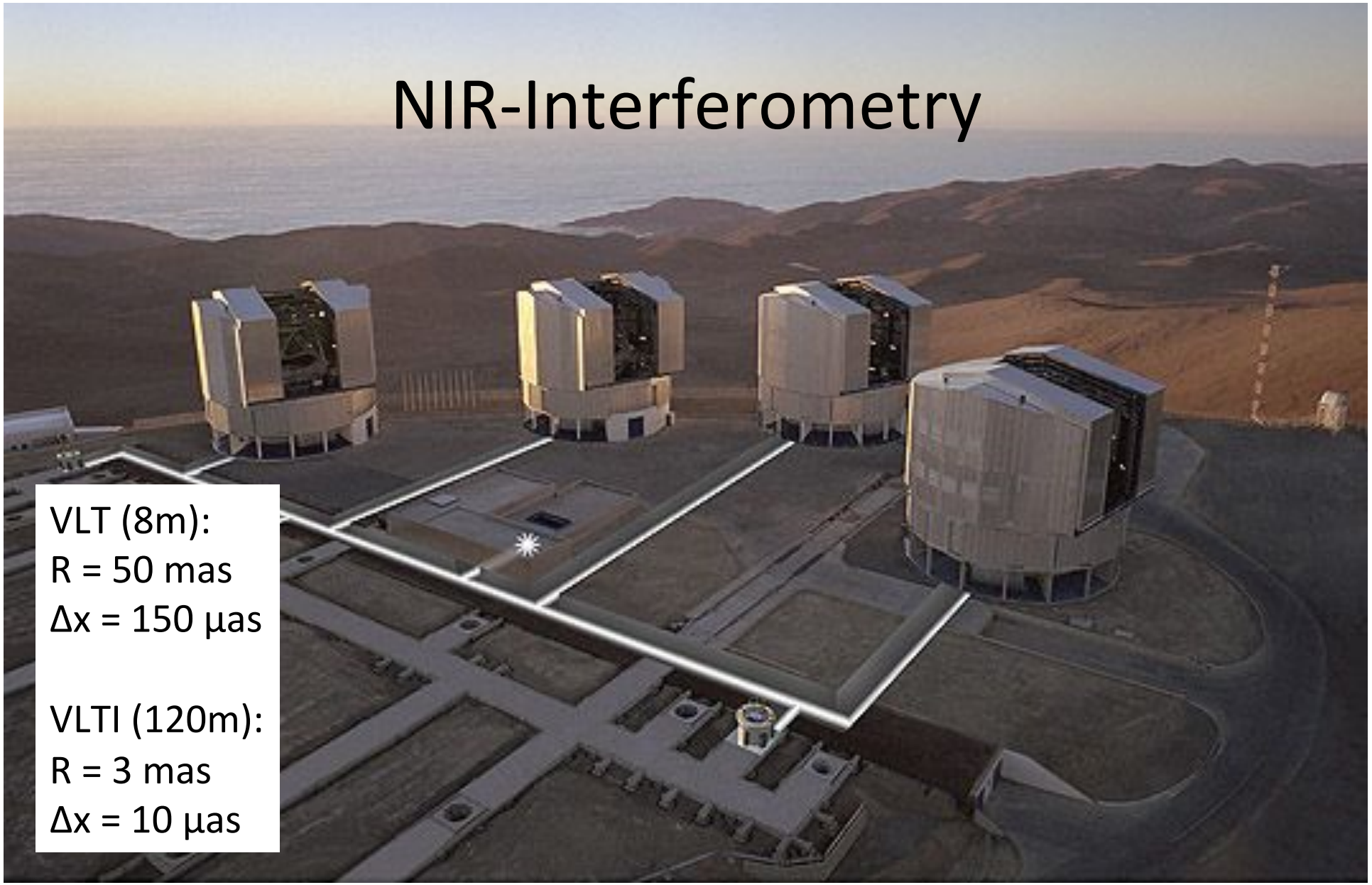
Expected in central
100 mas:
-- ~5 stars
-- K = 17..19 mag

Orbital Period:
1 year

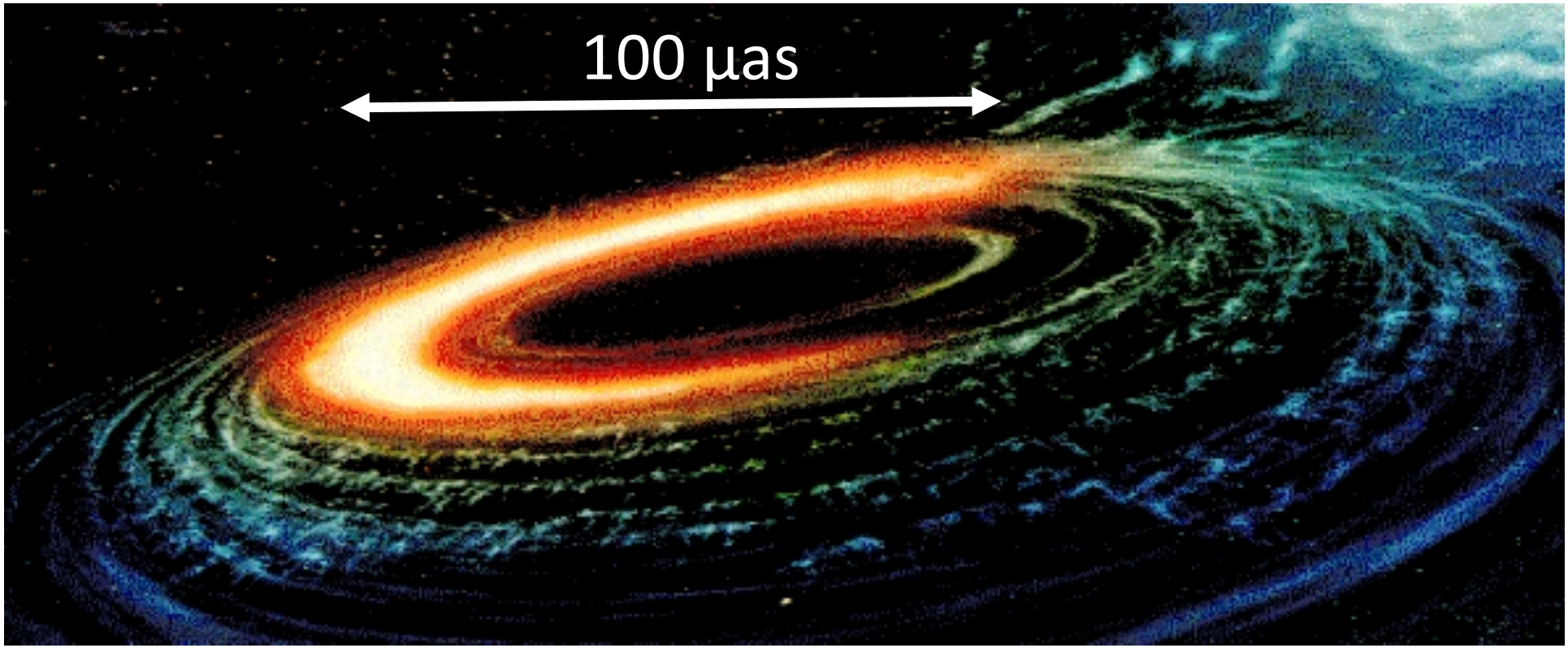
Precession:
~ few ° per year



The next step in angular resolution:

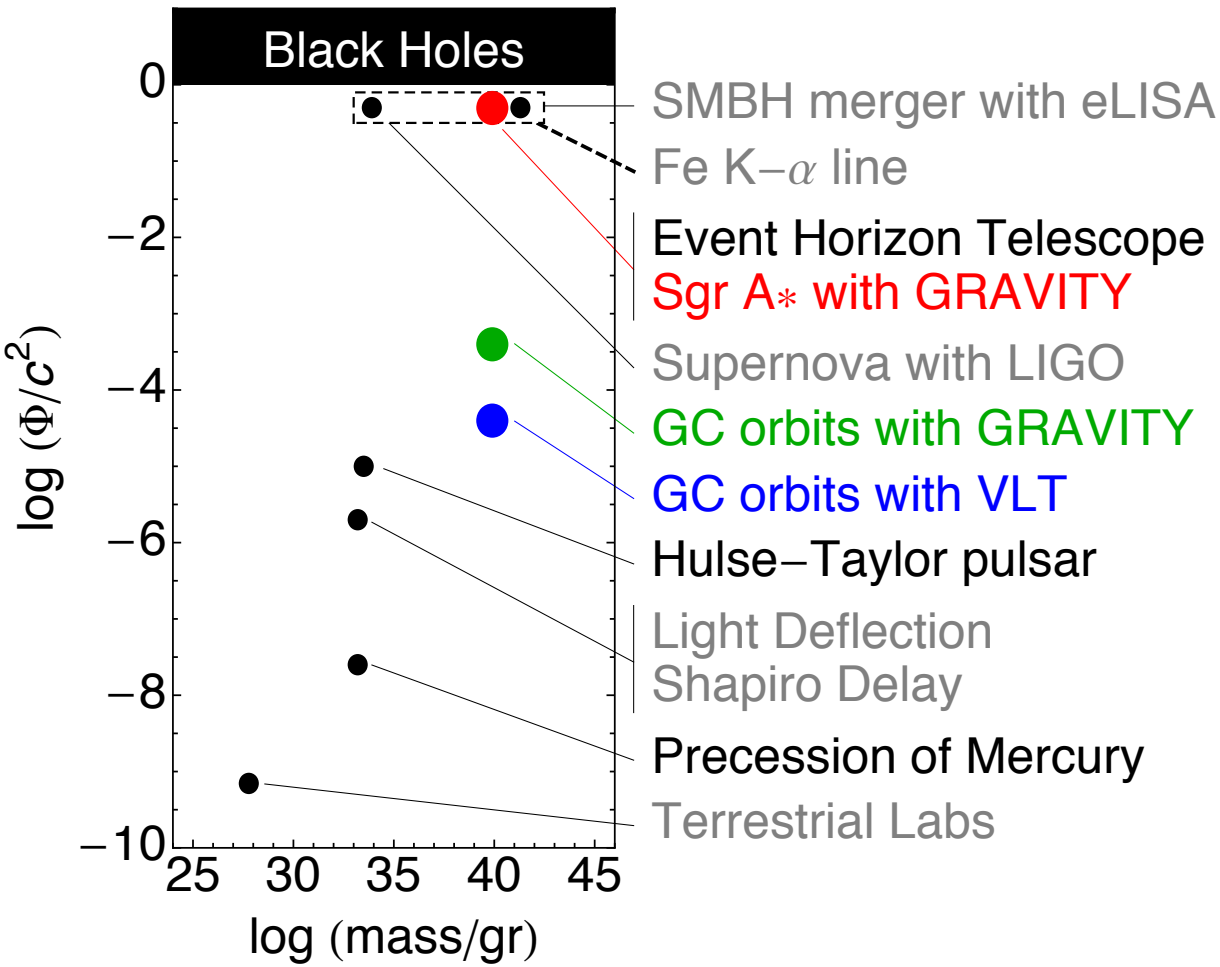


The accretion disk has a diameter 10 x larger than the 10μas accuracy




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

GRAVITY in context:
Astrophysical tests of general relativity



adapted from Psaltis 2004

nature

THE INTERNATIONAL WEEKLY JOURNAL OF SCIENCE

FEELING THE FORCE

The giant gas cloud heading for the MilkyWay's black hole PAGES XX & 51

EXPERIMENTS

RISING TO THE CHALLENGE

Five of the hardest tasks left in science

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ETHICS

HOW TO STOP PLAGIARISM

We ask the experts for their prescriptions

PAGE 21

PHYSICS

LOST IN TIME

A 'time cloak' shaped by optical manupulation

PAGES XX & 62

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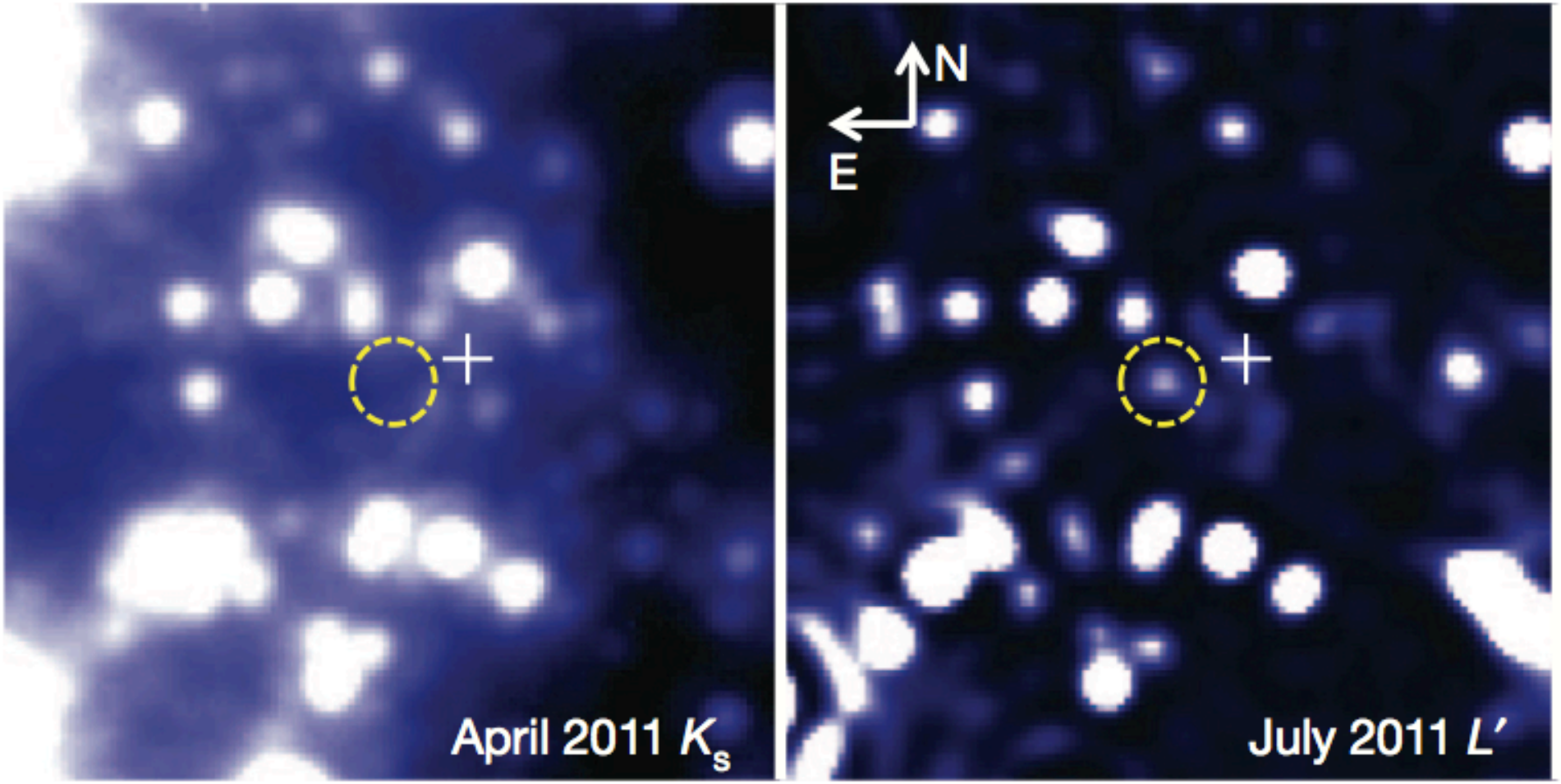
A ‘cool’ object: T ≈ 600K

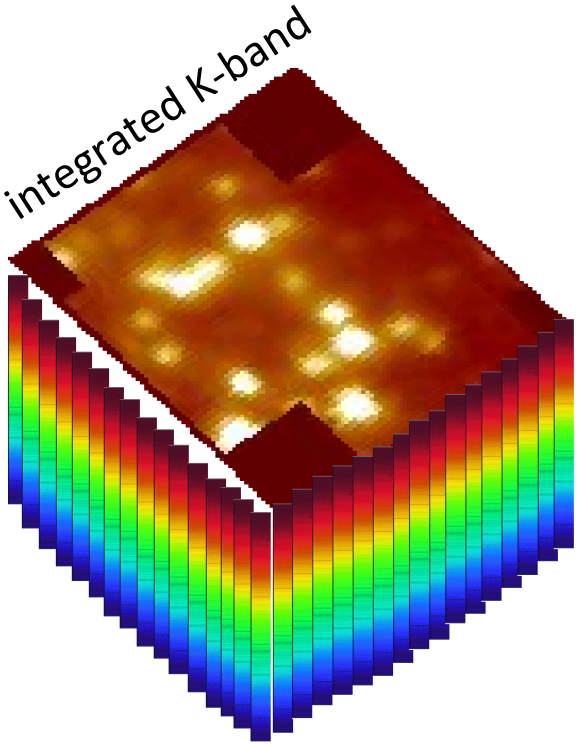


2.15 µm

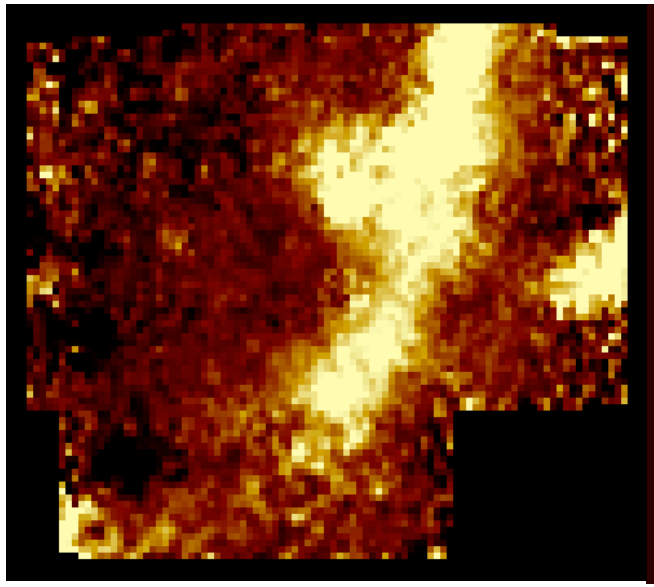
3.8 µm

The object is a dusty, ionized gas cloud of 3 Earth masses

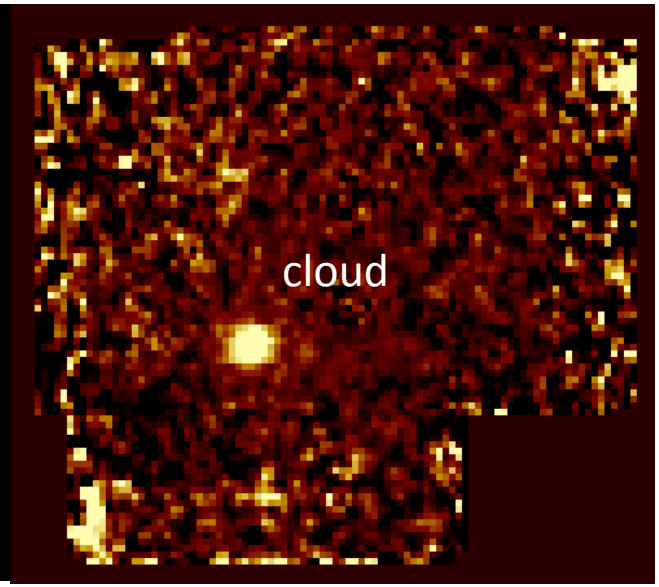
Integral-field spectroscopy: SINFONI



full data cube

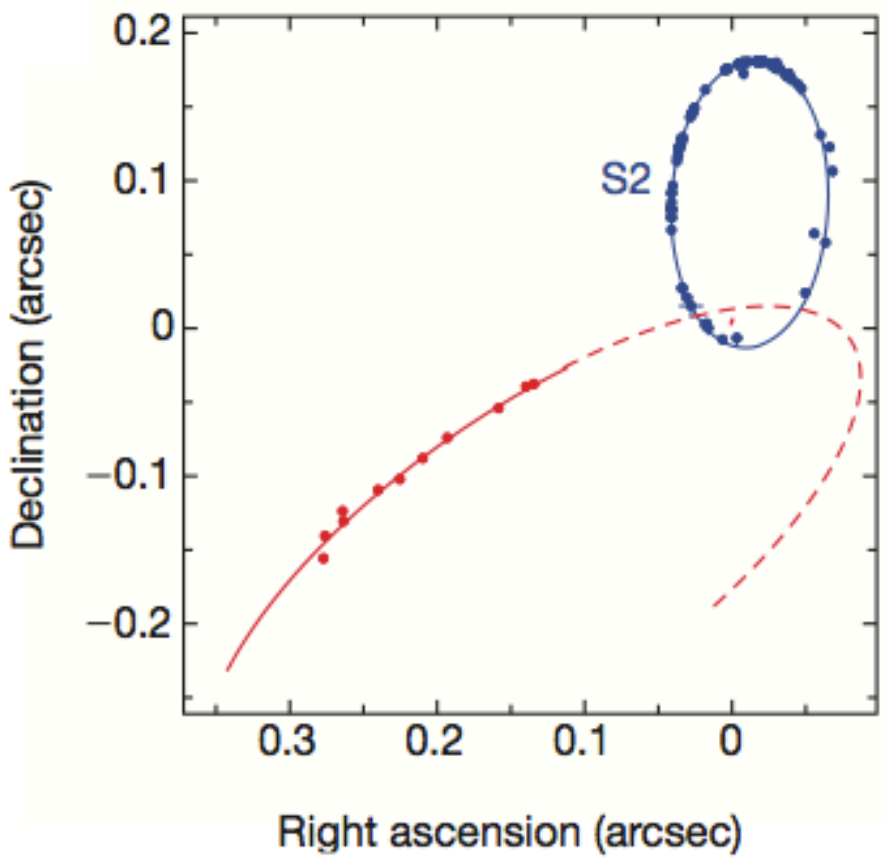


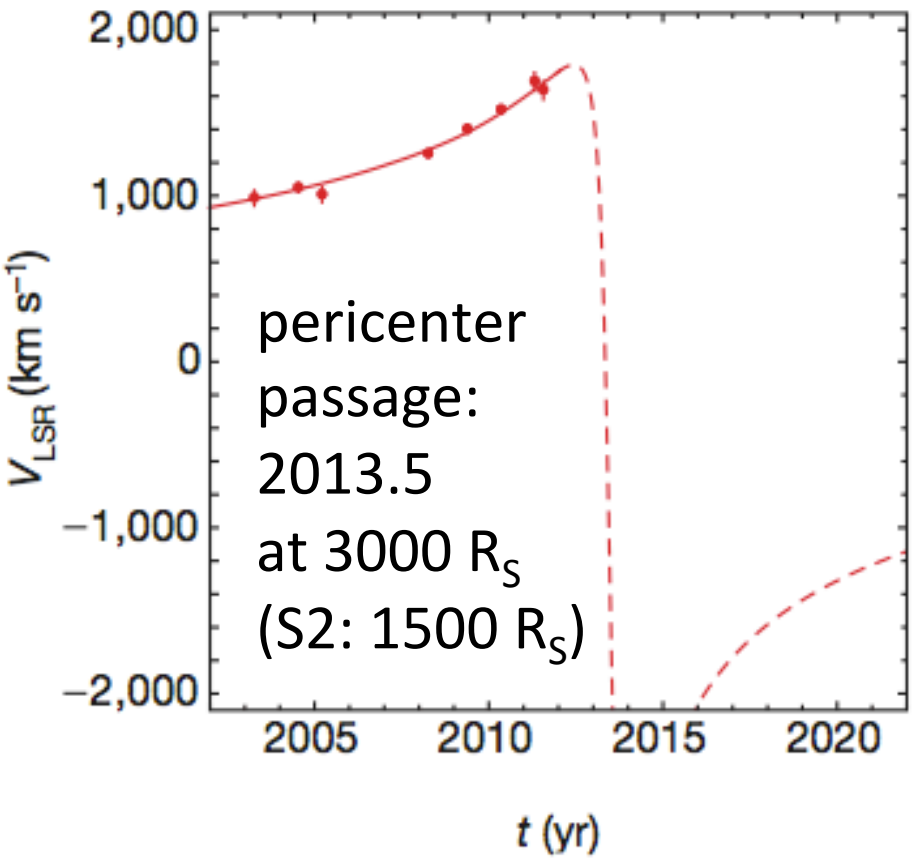
channel map at
Br-γ
(2.166 μm)



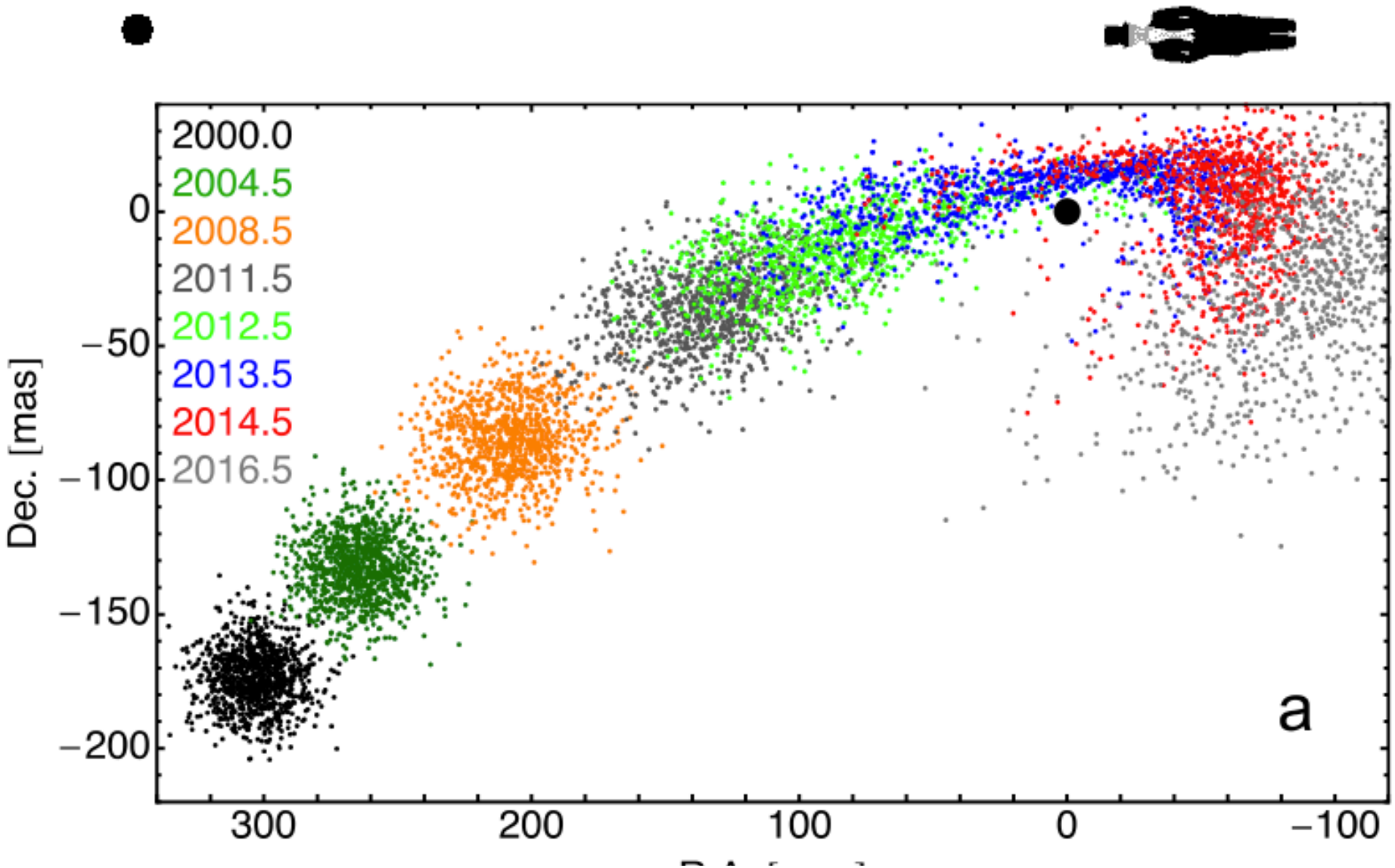
channel map at
Br-γ + 1300 km/s
(2.175 μm)

The cloud's orbit is well-constrained

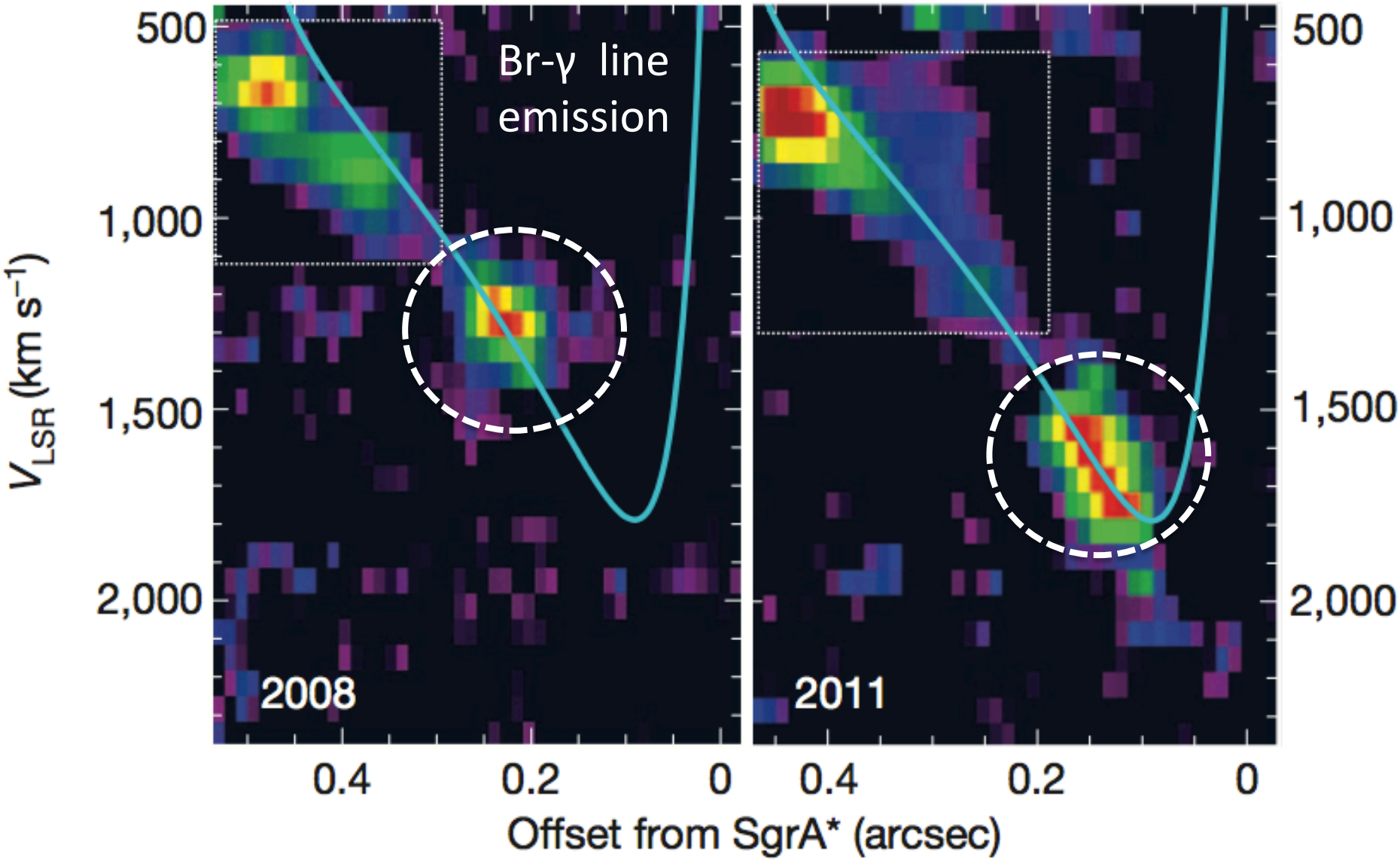




A non-gravitating gas cloud cannot survive that



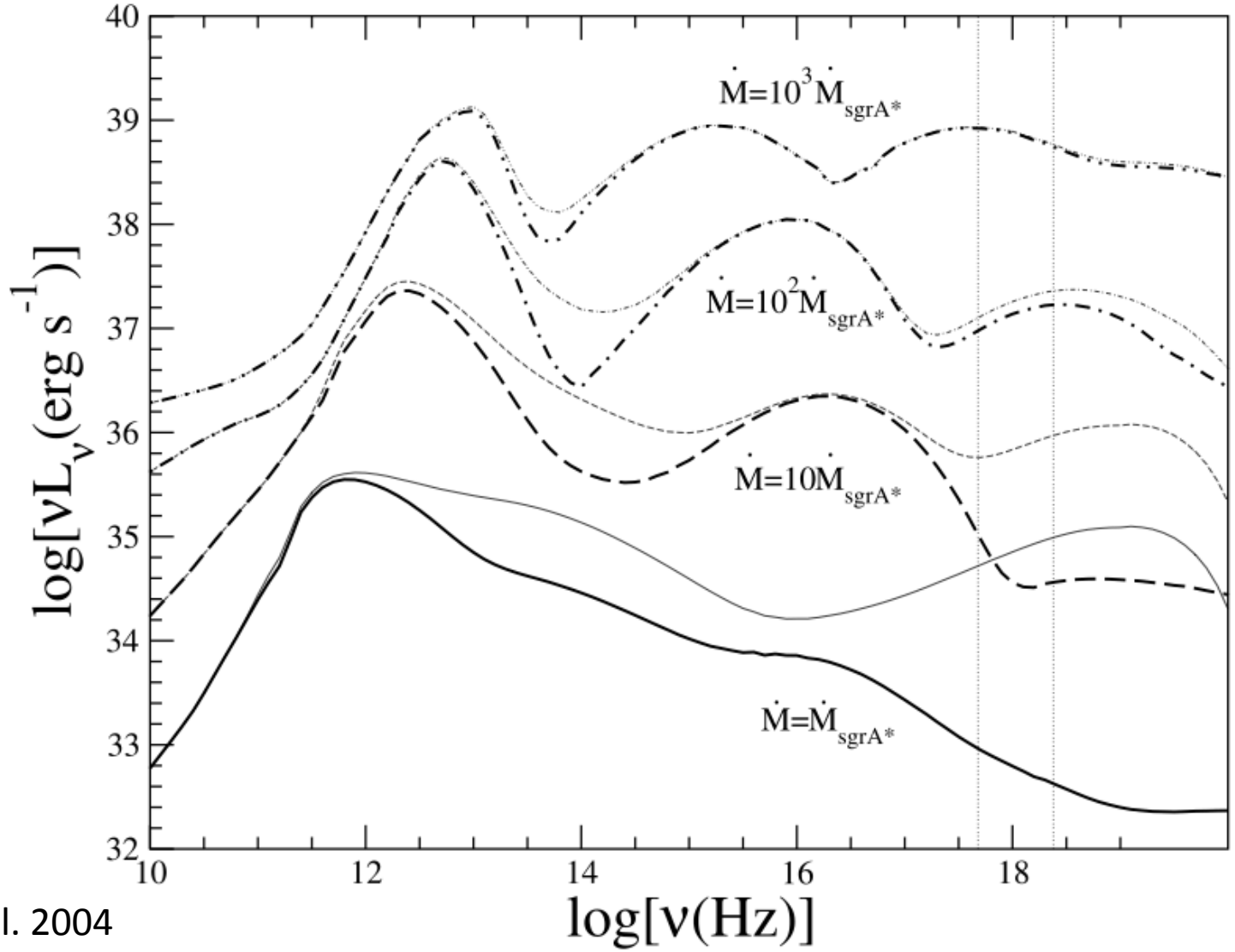
We see the tidal shear develop between 2008 and 2011



Missing: Interaction with accretion flow

Accretion rate might increase for years

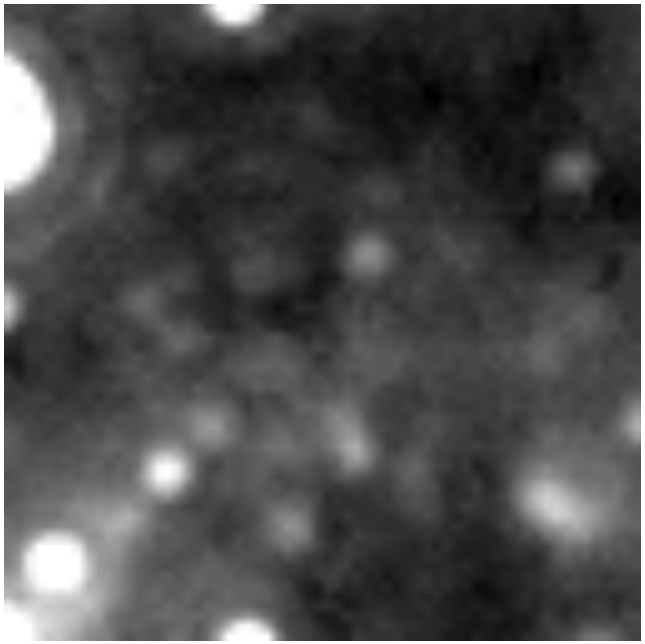
Flux will vary because of changed accretion rate



RIAF

Yuan et al. 2004

This is different from the flares of Sgr A*

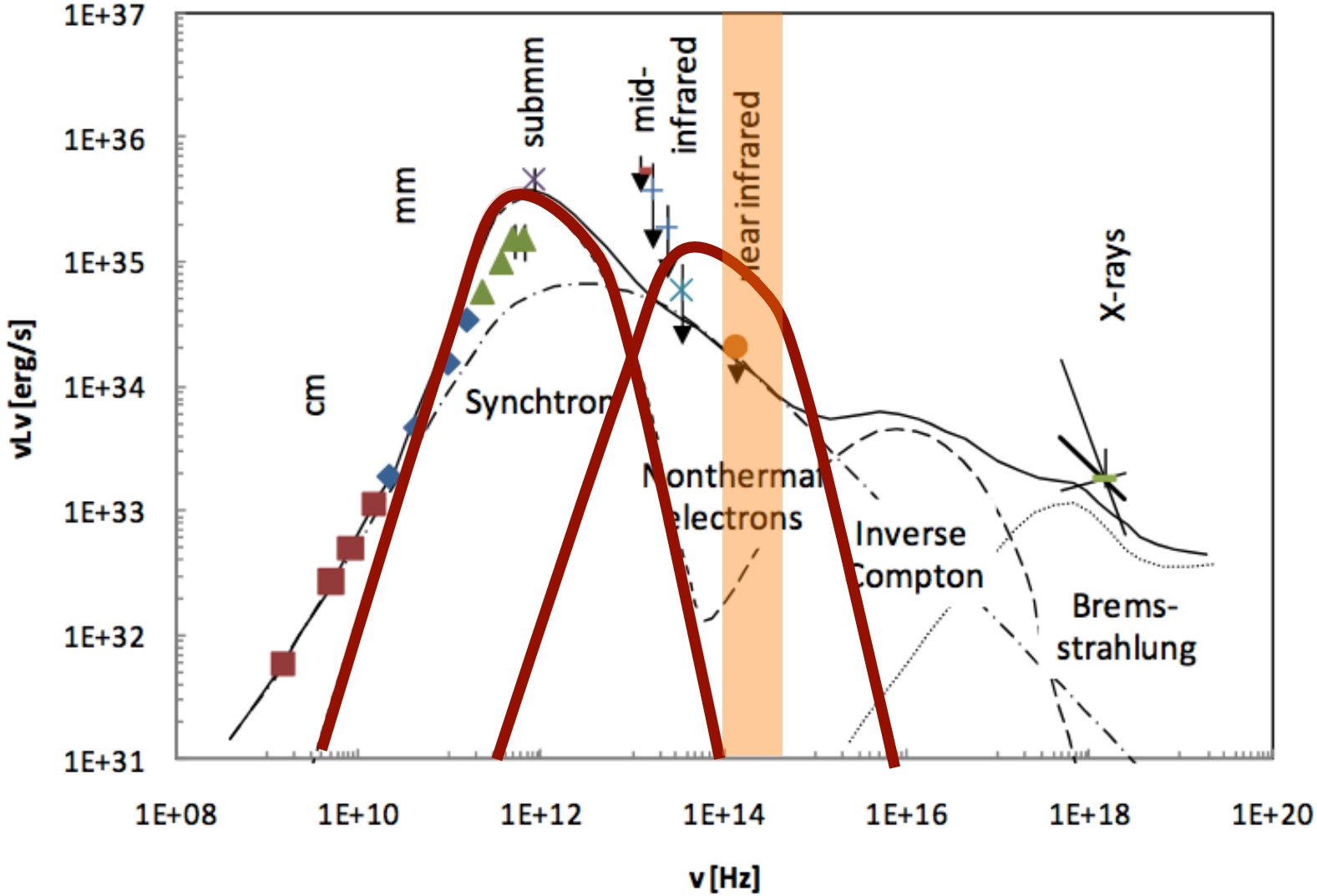


- Typically one flare per night
- Lasts ~ 90 min
- Much redder than the stars

Genzel et al. 2003,
Eisenhauer et al. 2005
Gillessen et al. 2006,
Hornstein et al. 2007
Dodds-Eden et al. 2009

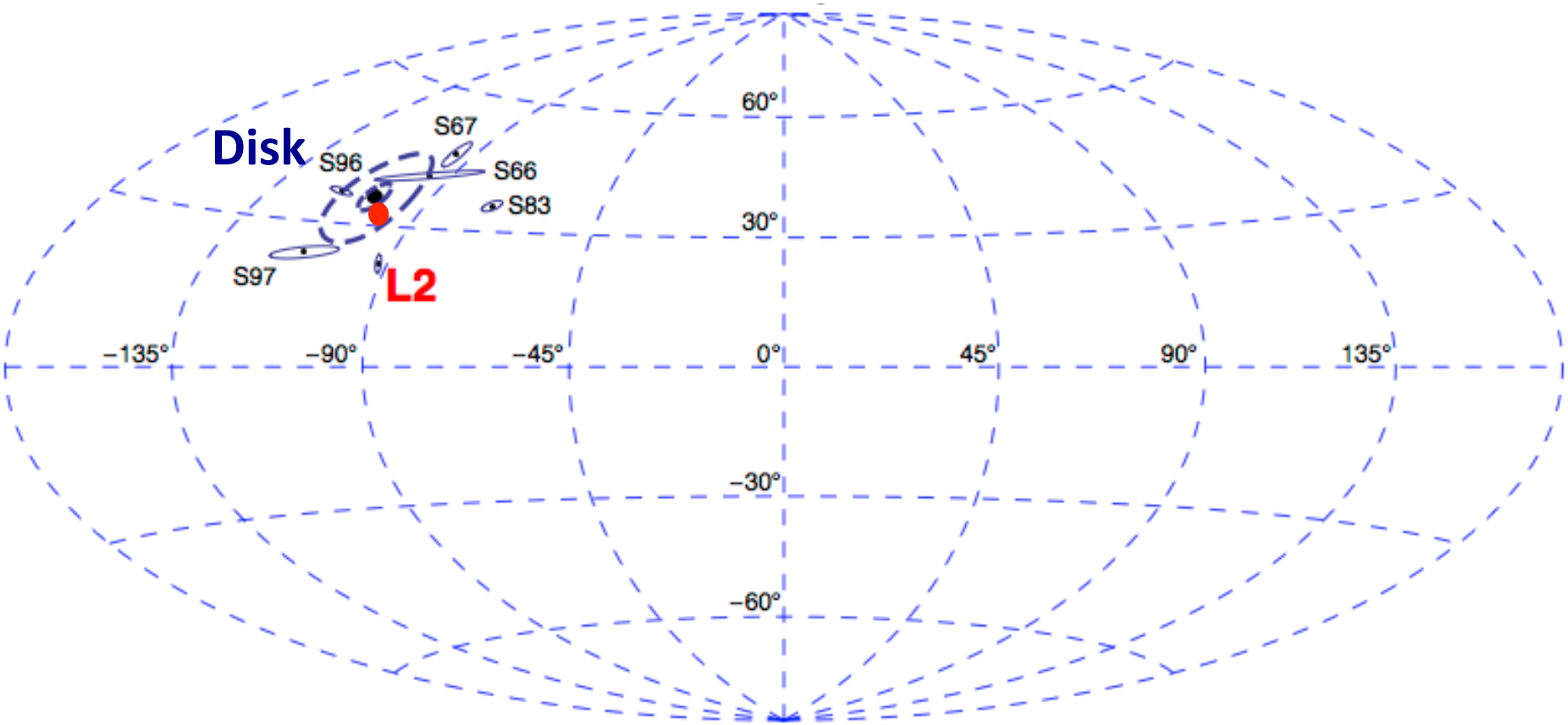
Flares are ‘ignition events’

Flares are synchrotron emission of transiently heated electrons



What is the origin of the cloud?

- Orbital plane coincides with disk of young stars
- Apocenter of the orbit coincides with the inner edge of the disk



Two scenarios proposed

Clumplet from stellar winds / wind collisions

- Stellar winds of massive, young stars of disk
- wind speeds ≈ orbital speeds
- Creation of fragment with low angular momentum
- Ballistic infall
- First time event (but frequent events)
- tidal shear leads to a decreasing surface brightness

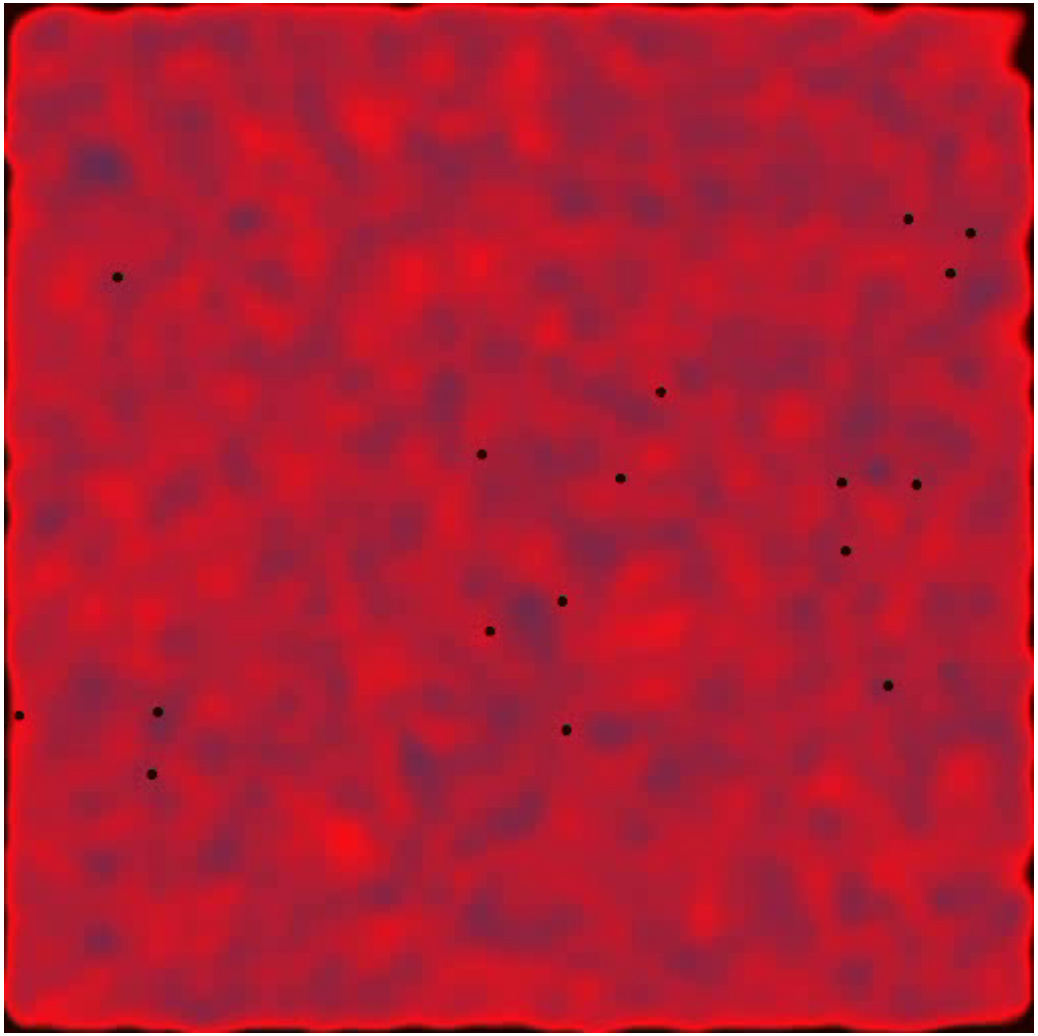
- Burkert et al. 2012

Evaporating disk around protostar

- Young stellar object from disk of massive, young stars
- Scattered to low-angular momentum orbit
- Disk around the star glows in UV light of hot stars
- Object on similar orbit for many orbits
- "tidal comet" – surface brightness will increase

- Murray-Clay & Loeb 2012

Simulations of the winds show a very clumpy structure



Cuadra et al. 2006

Problems for the two scenarios

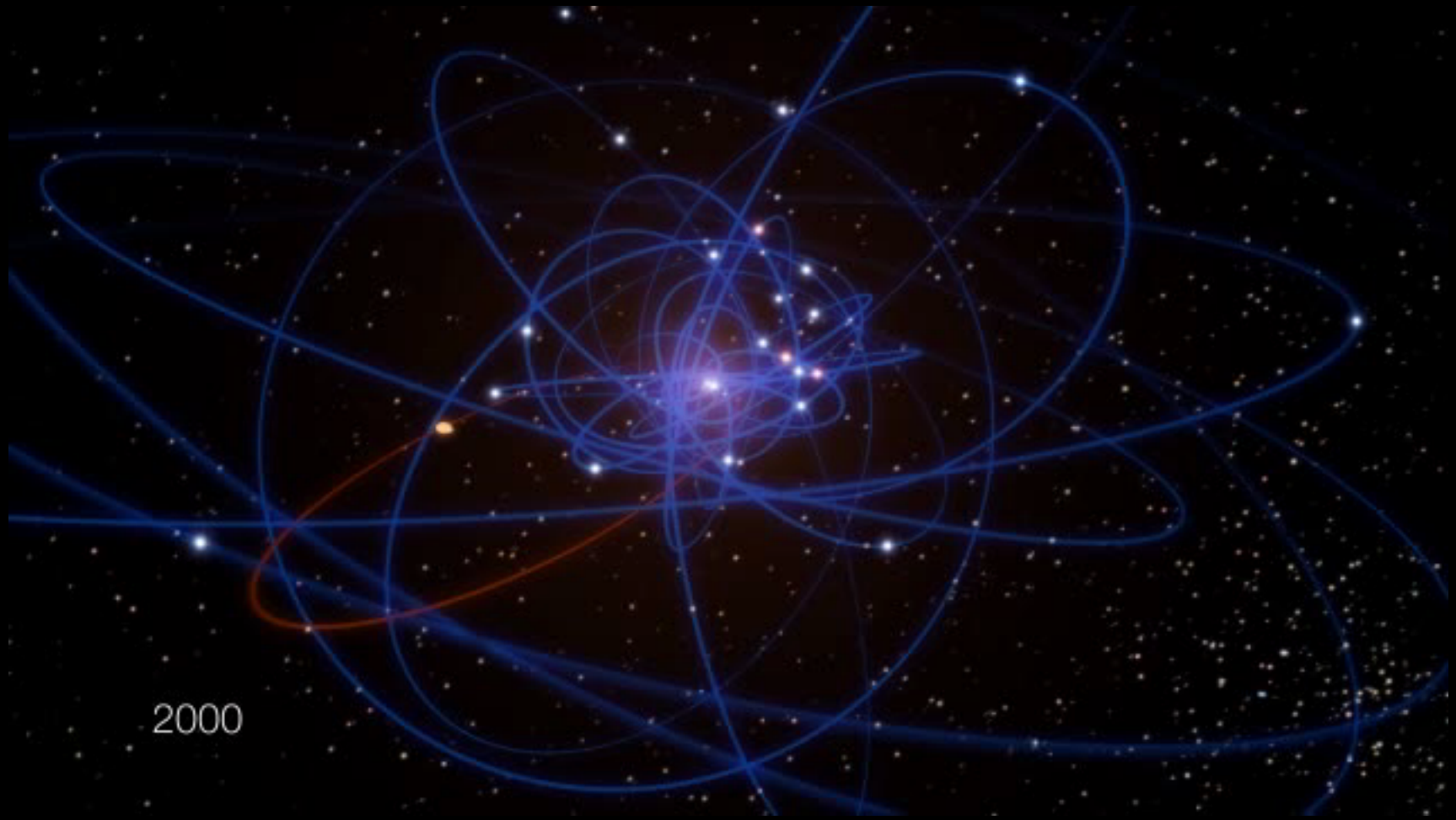
- expect formation at apocenter – but then cloud should be stretched much more than observed

- Disk around protostar cannot survive scattering to current orbits
- Event rate estimate over-estimated
- Stripped material would be slower than Keplerian orbit, not faster

Summary

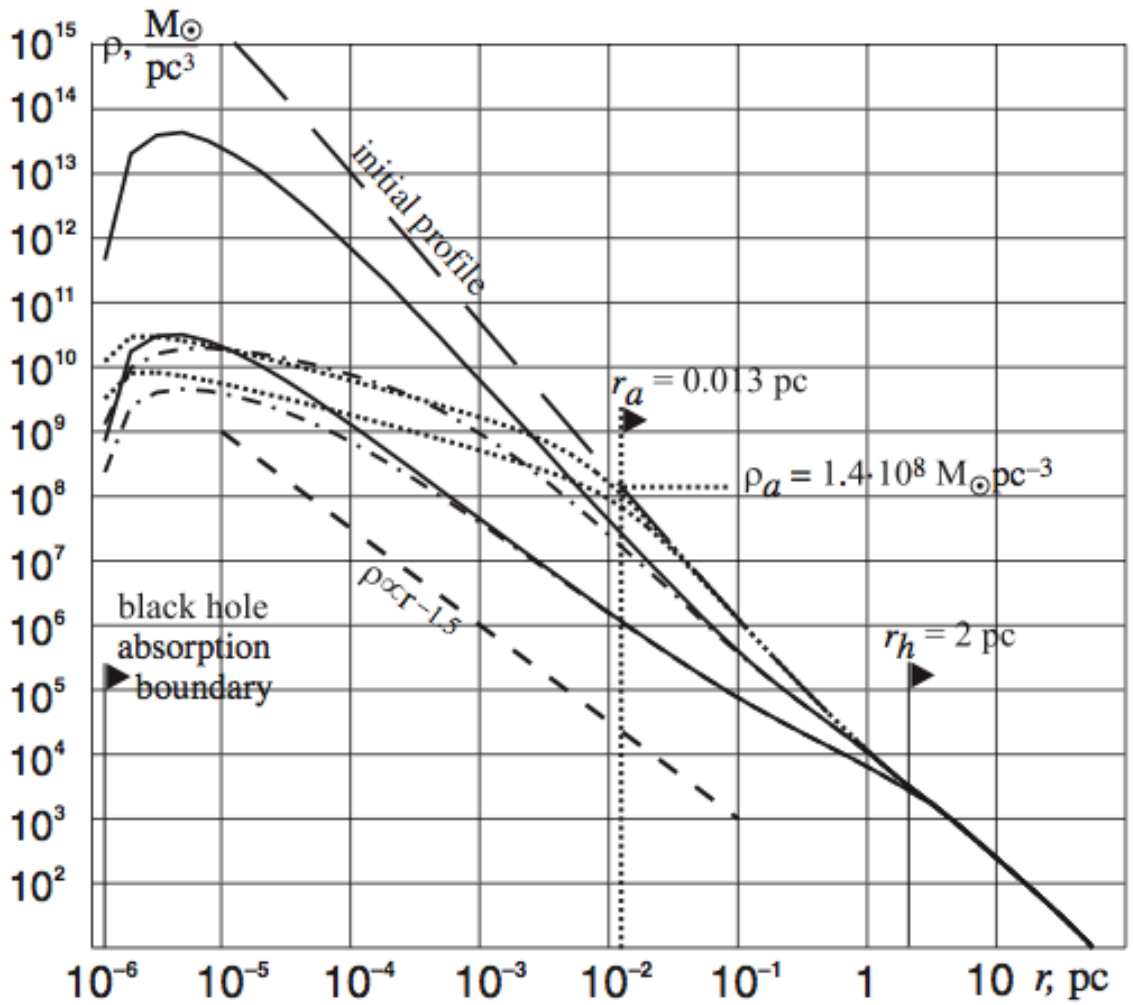
- GC is a unique laboratory for observing a stellar system around a MBH
- At least 3 distinct stellar populations
  - S-stars: orbits, constrain the extended mass around Sgr A*, paradox of youth, eccentricity distribution
  - Disk stars: formed 6 Myr during gas infall
  - Old stars: Deficit in the central 0.2pc, “bad” news?
- Future:
  - Gradual improvements
  - A huge step forward due to NIR interferometry
- Exciting astrophysics: Infalling gas cloud

Thanks for your attention!



Backup

Cosmolgical Dark Matter



Vasiliev & Zelnikov 2008

$$\eta_{\rm DM} < 10^{-2}\,\eta_*$$

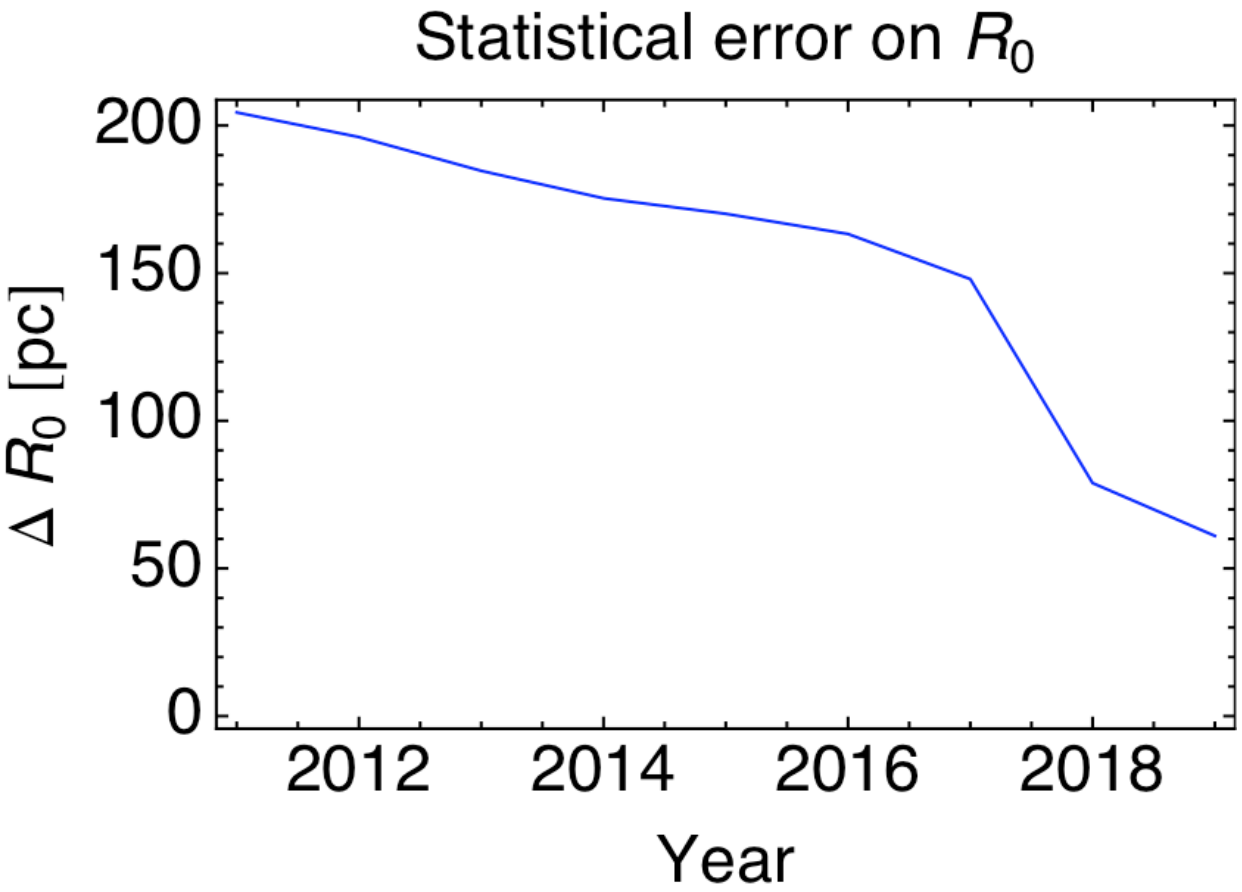
(Dark Matter will not be detected from stellar orbits)

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

NACO:
Astrometry with 300 µas

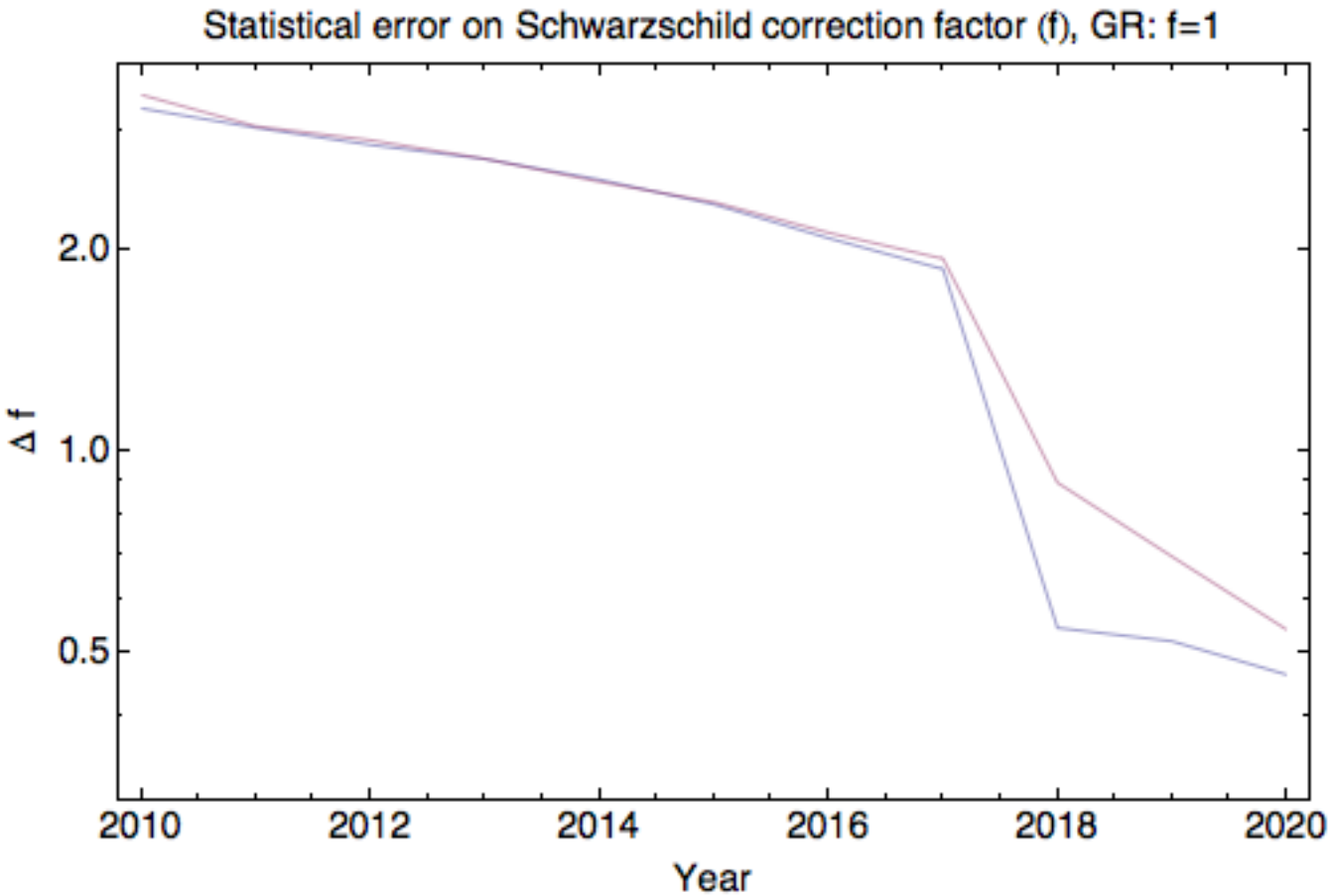
SINFONI:
Spectroscopy with 15 km/s

The distance to the GC will be determined to a precision of 1%



2020: 3σ detection of GR precession possible

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



GRAVITY Key Figures

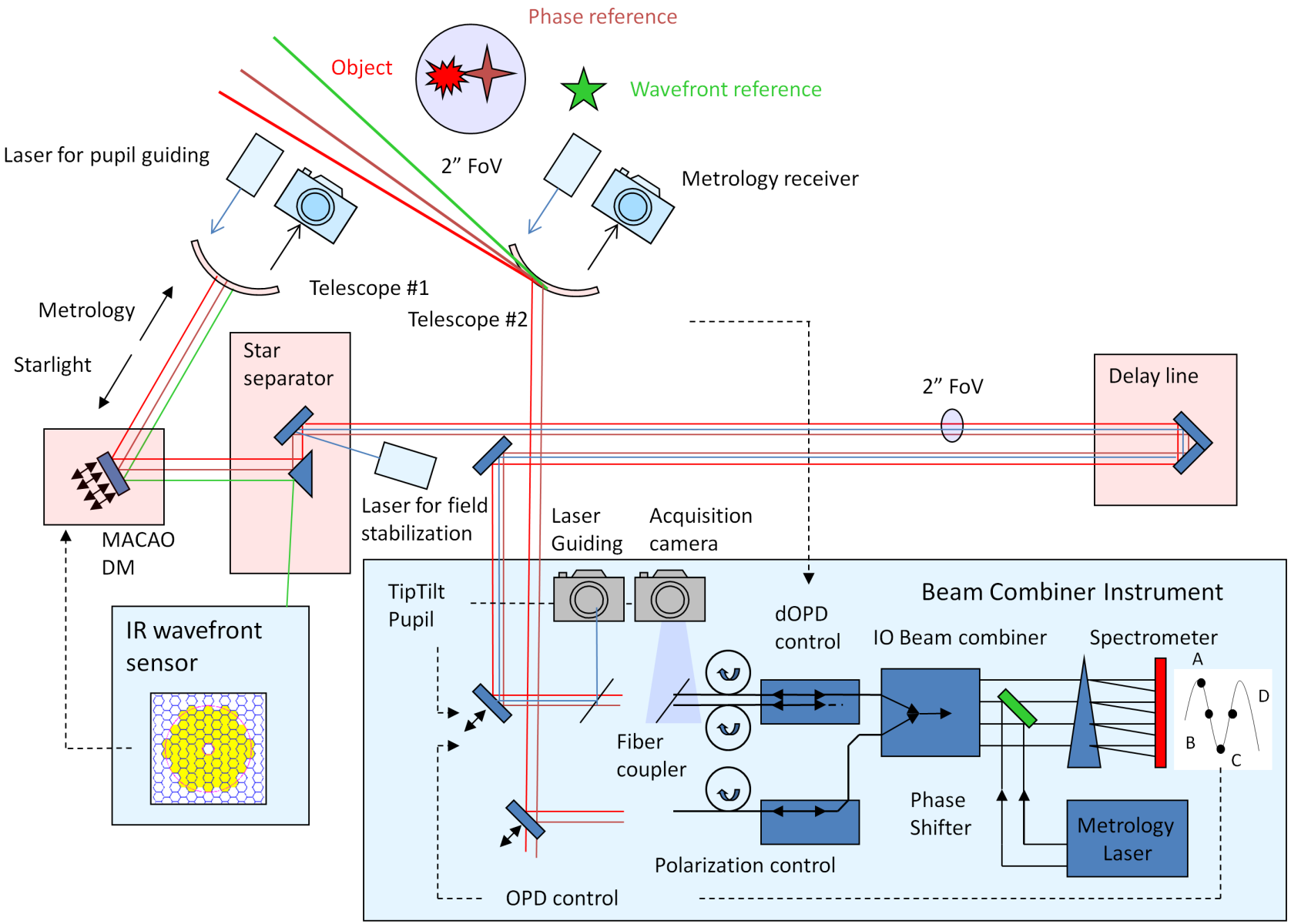
Milestones:
- Final design in 2011/12
- Installation at the telescope in 2014

Fringe Tracking:
- UTs: K≈10 mag
- ATs: K≈7 mag

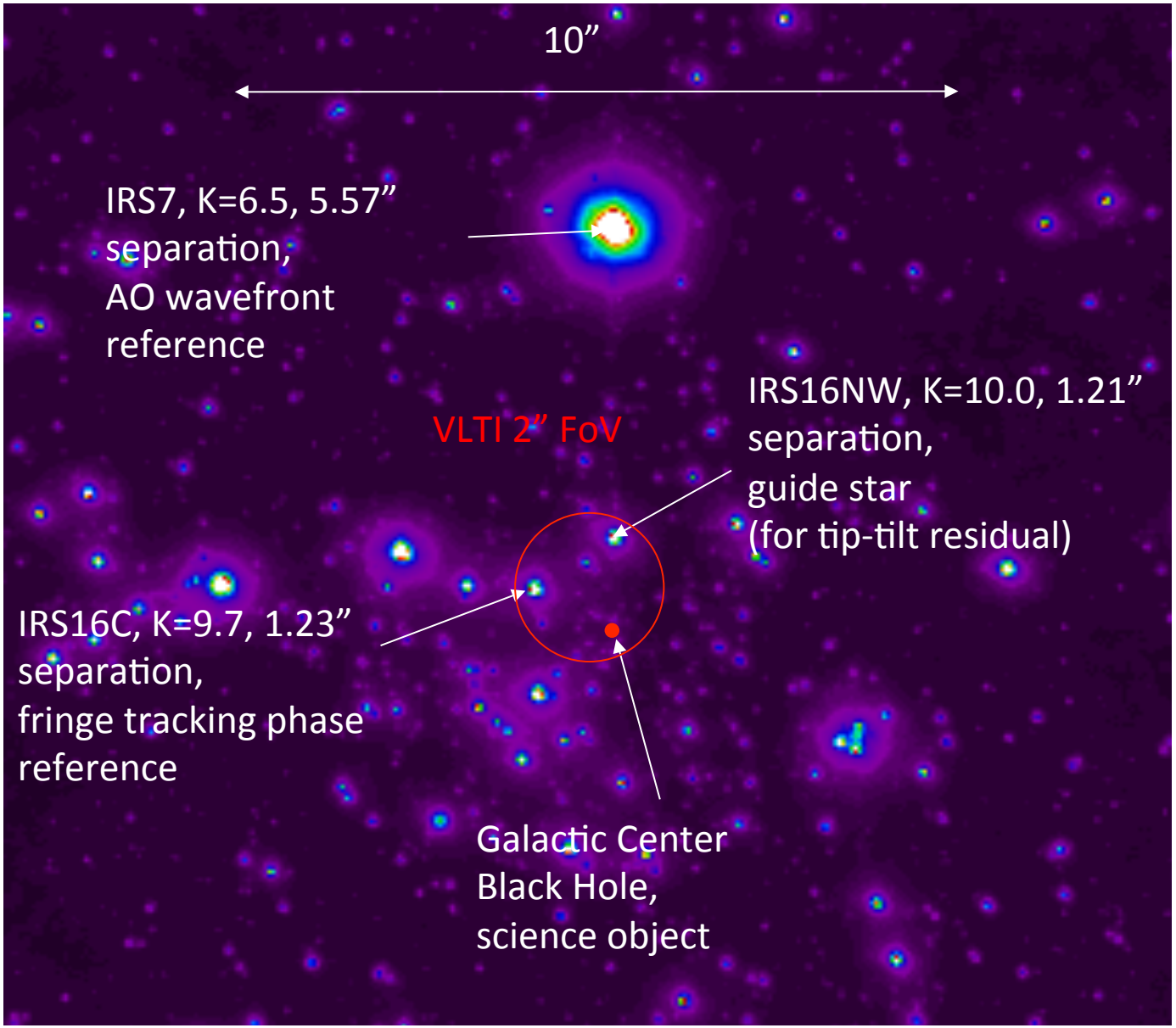
Astrometry:
- few 10 µas in 5 minutes

Interferometric Imaging:
- UTs: K≈16, ATs: K≈13 in 100s
- K≈18 doable
- SNR(V) = 10 for visibility
- $\sigma(\phi)$ = 0.1 rad for referenced phase

GRAVITY: Working principle

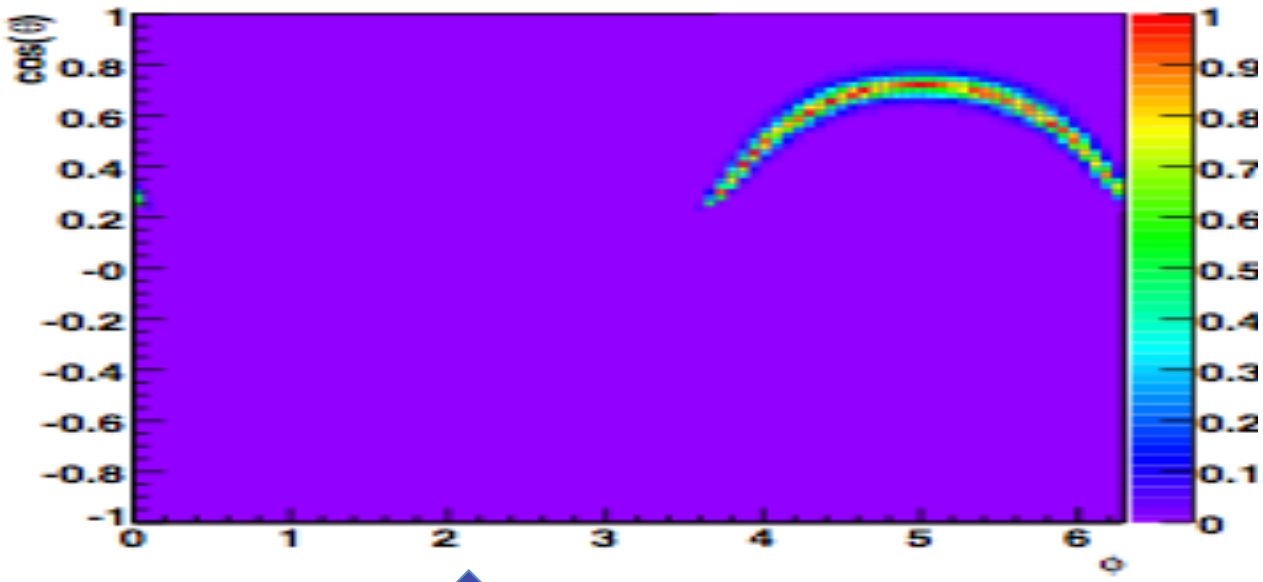


The GC offers all GRAVITY needs



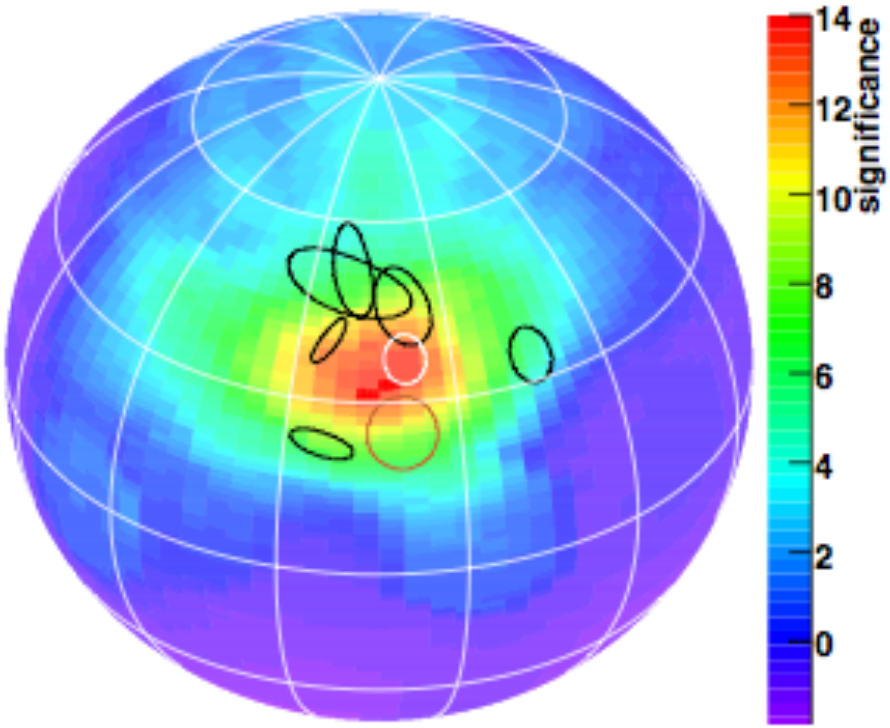
For r > 1'':
Hard to measure accelerations

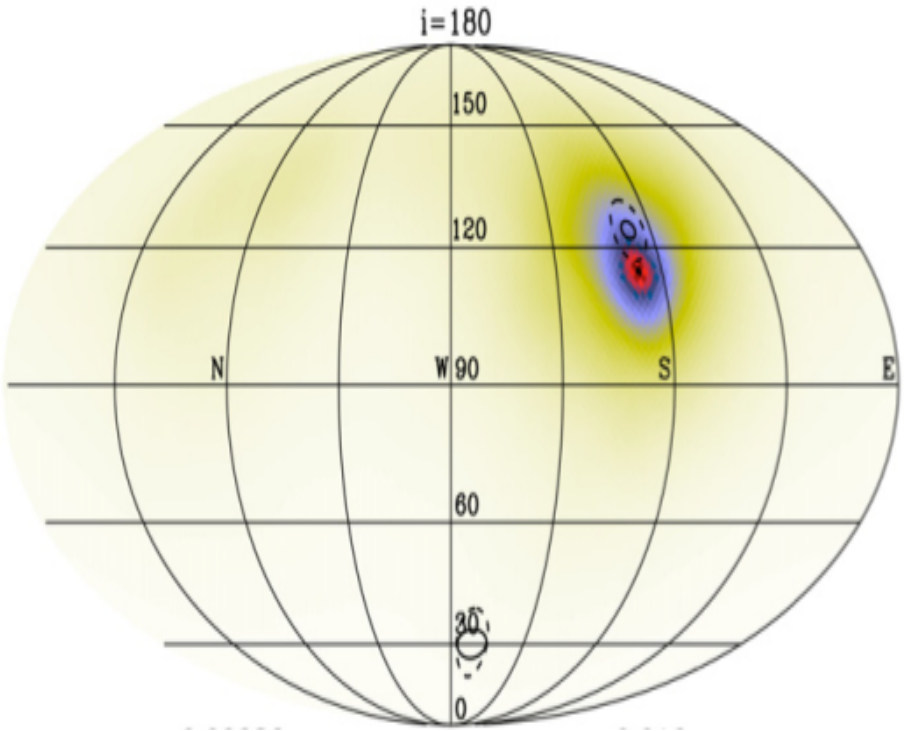
	r < 1''	r > 1''
x	✔	✔
y	✔	✔
vx	✔	✔
vy	✔	✔
vz	✔	✔
a_{2D}	✔	✖



(a, e, i, ω, Ω, t)

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



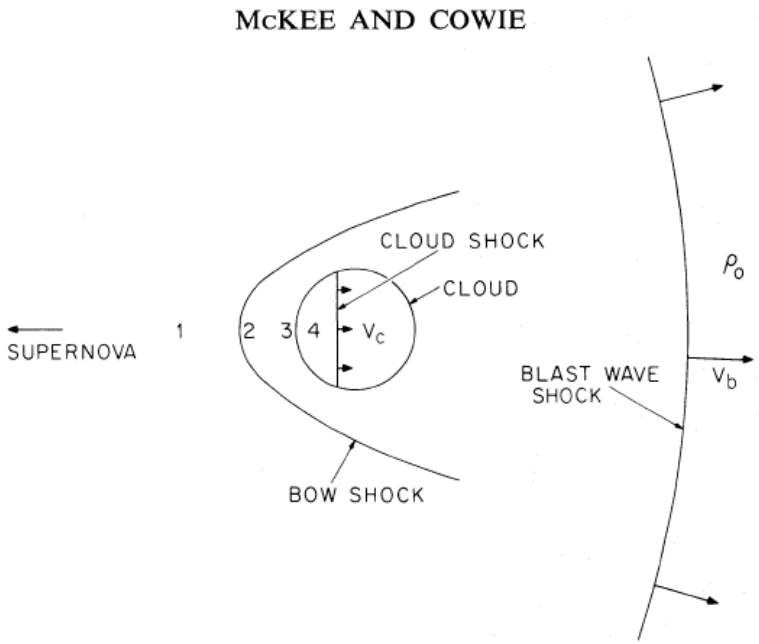


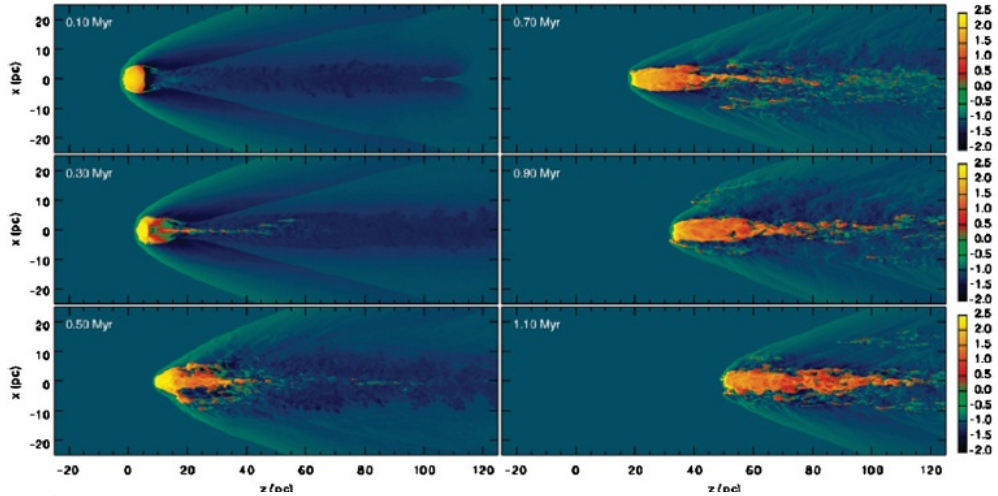
orientation of orbital angular momentum

Bartko+ 2009

Lu+ 2009

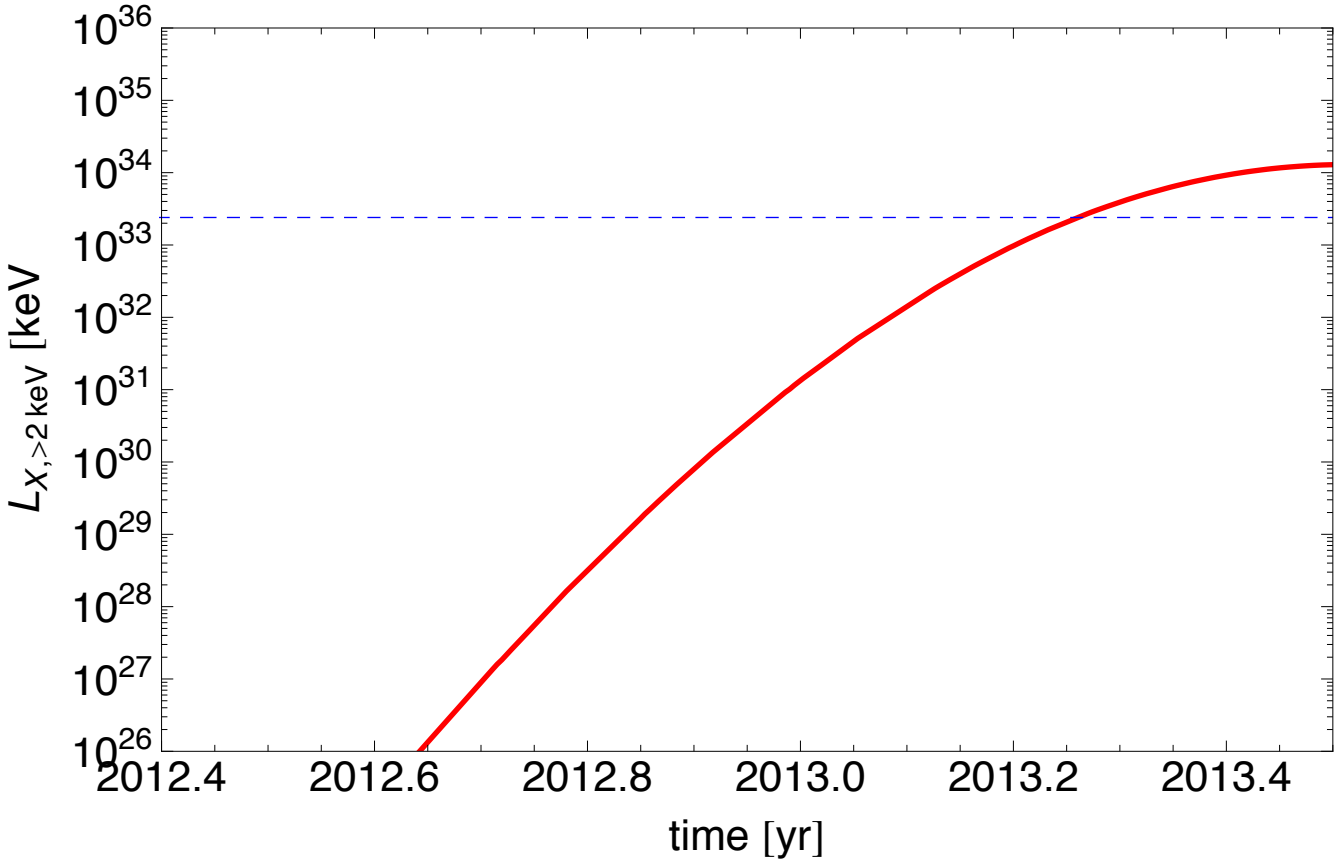
Famous astrophysics problem





McKee & Cowie 1975, Klein & McKee 1994, Vieser et al. 2000, Cooper et al. 2009

X-ray luminosity of “Sgr A*” should increase in 2013

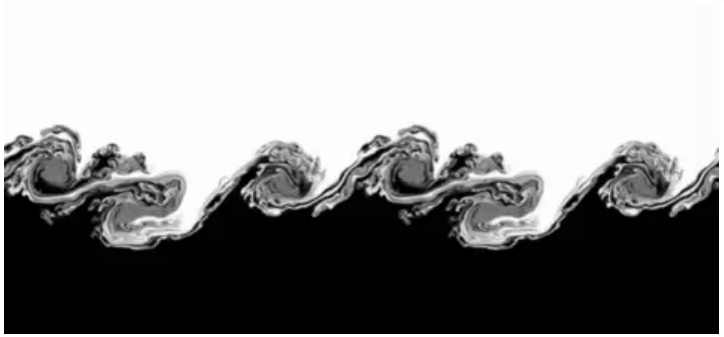


But expect complex interactions

- Orbital period: 137 yr (but highly eccentric orbit)
- Compression ti
- Sound
- Insta
  - Kel
  - Rayleig

All time scales similar

complex hydrodynamics



KH

RT