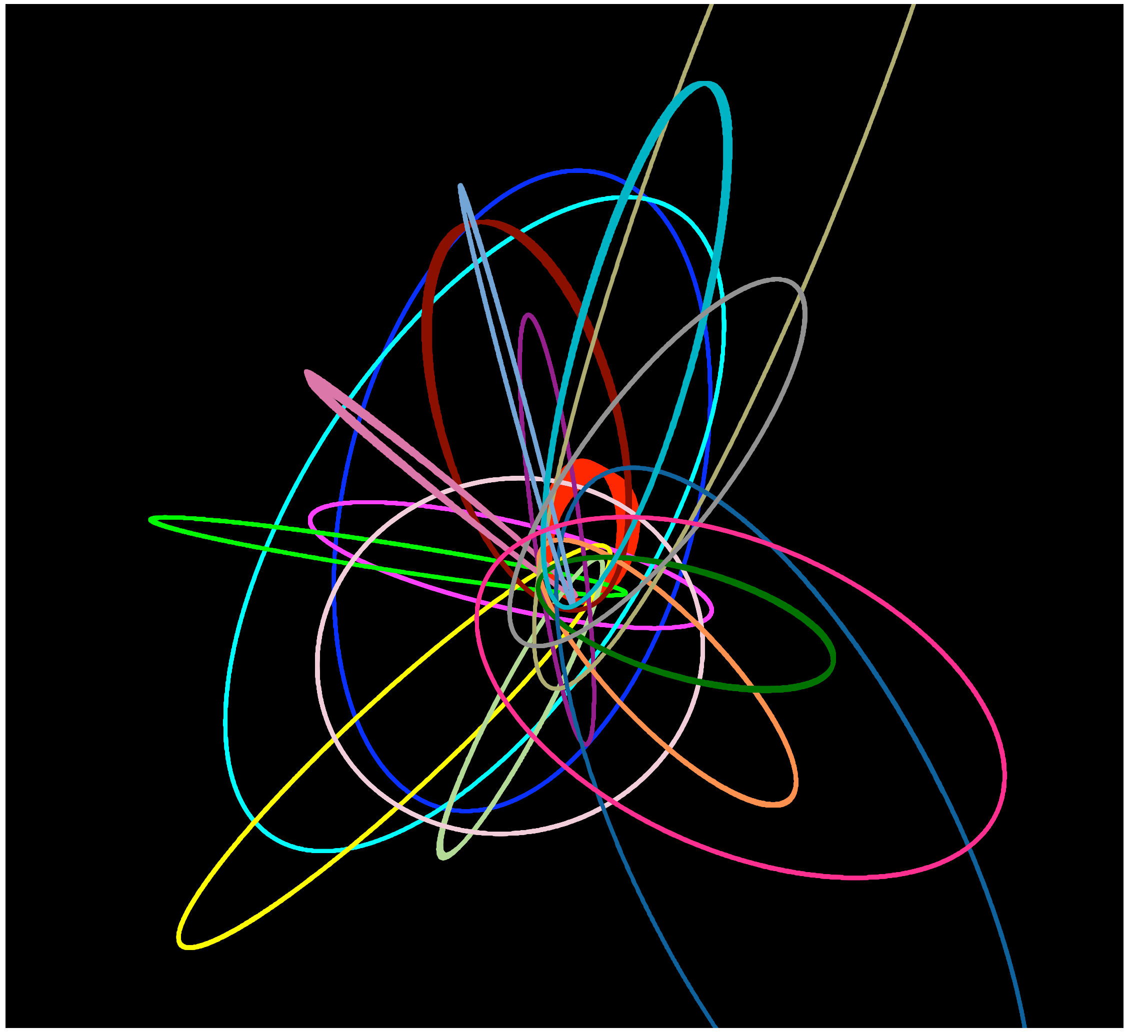
The young stars in the Galactic center

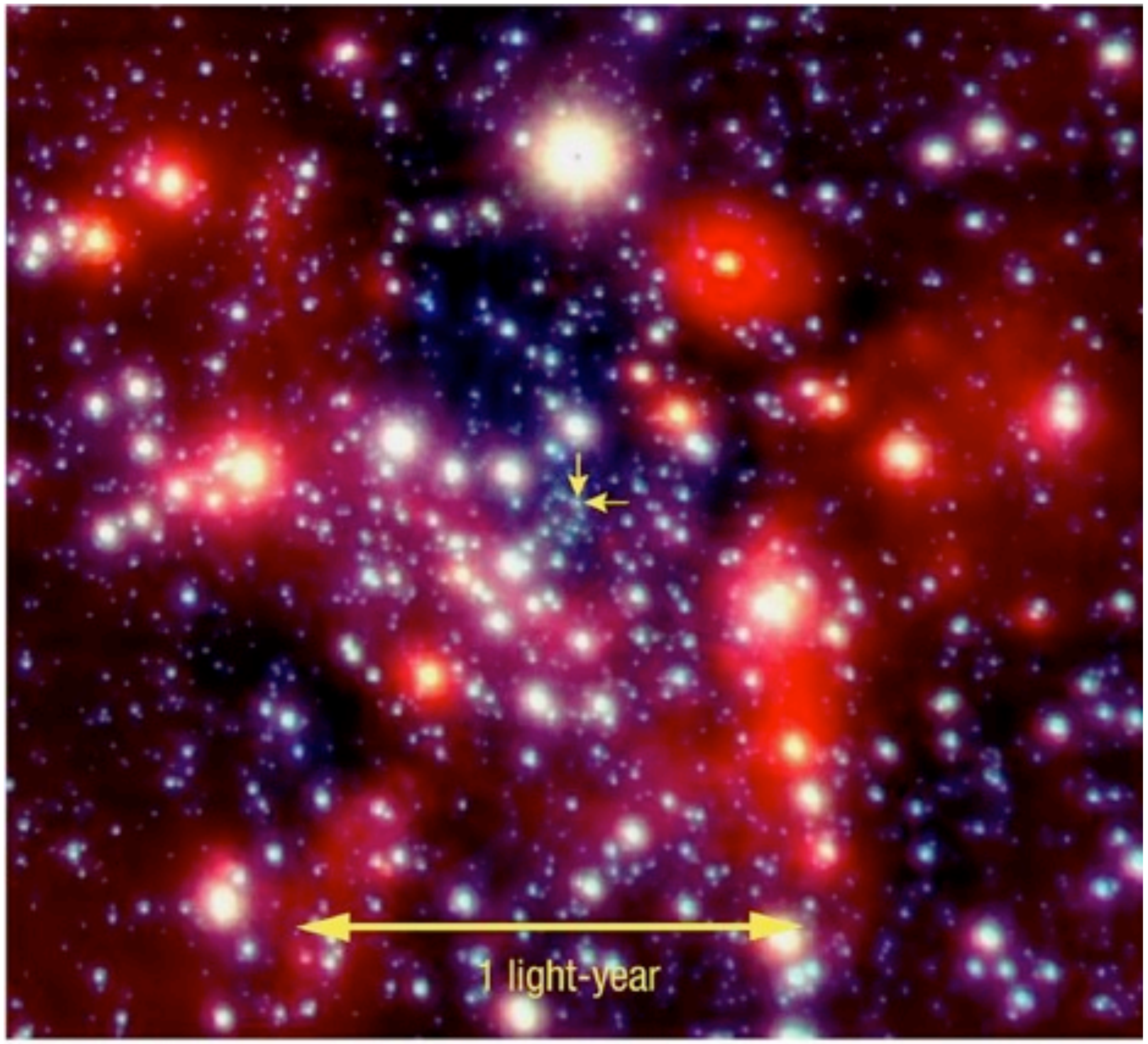


Alessia Gualandris

Max-Planck Institut für Astrophysik, Garching

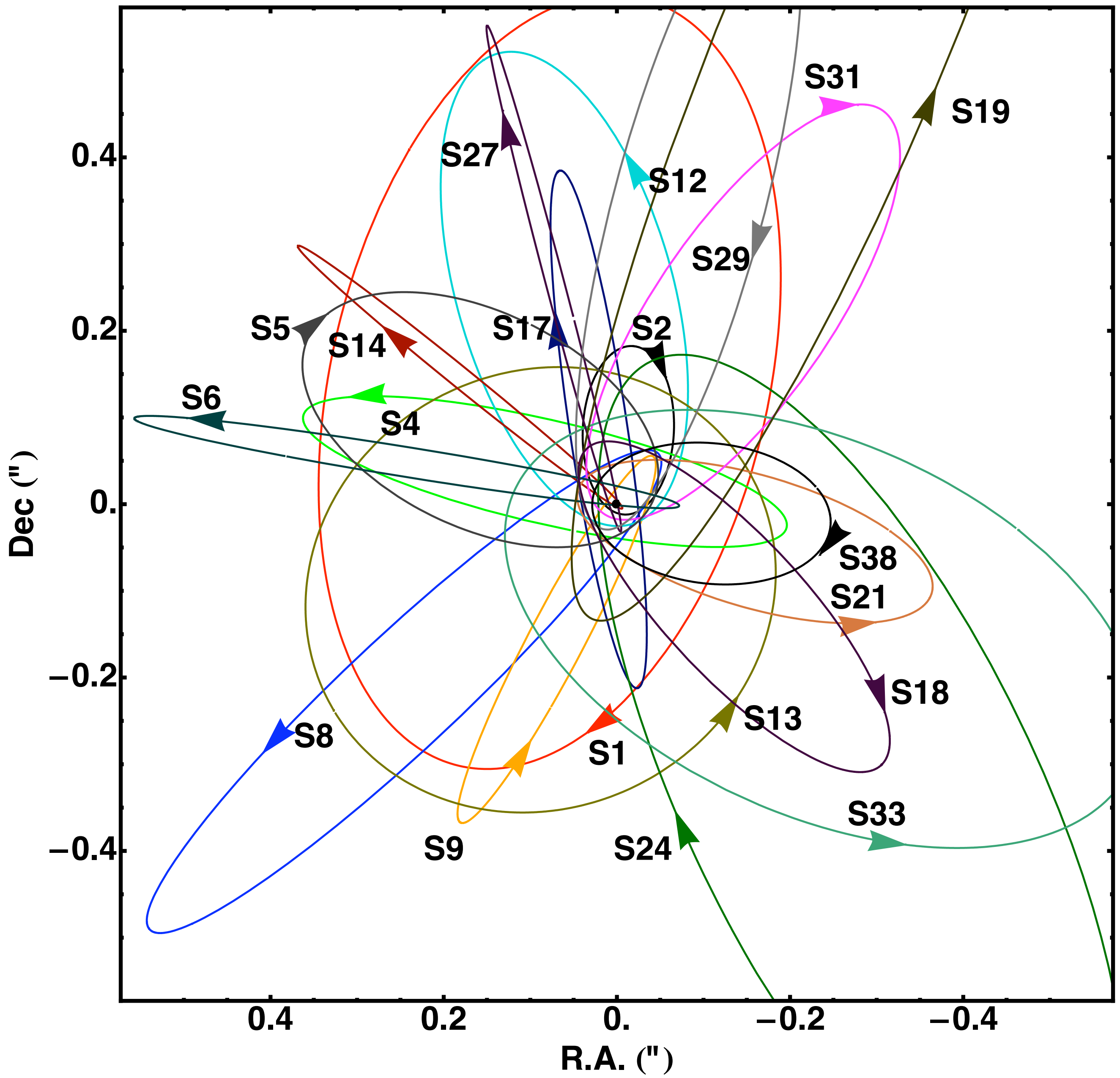
The Galactic Center

- SMBH M = $4 \times 10^6 M_\odot$
- Stellar cusp d ≲ 3 pc
- CW stellar disk
  scale 0.04 - 0.4 pc
  mass $\sim 10^4\ M_\odot$
  age ~ 6 Myr
- S-cluster N ~ 20
  B-type stars
  a = 5-50 mpc
  random orientations



The Centre of the Milky Way
(VLT YEPUN + NACO)
ESO PR Photo 23a/02 (9 October 2002)

The S-star cluster



2008

N = 20 stars

15 early-type stars

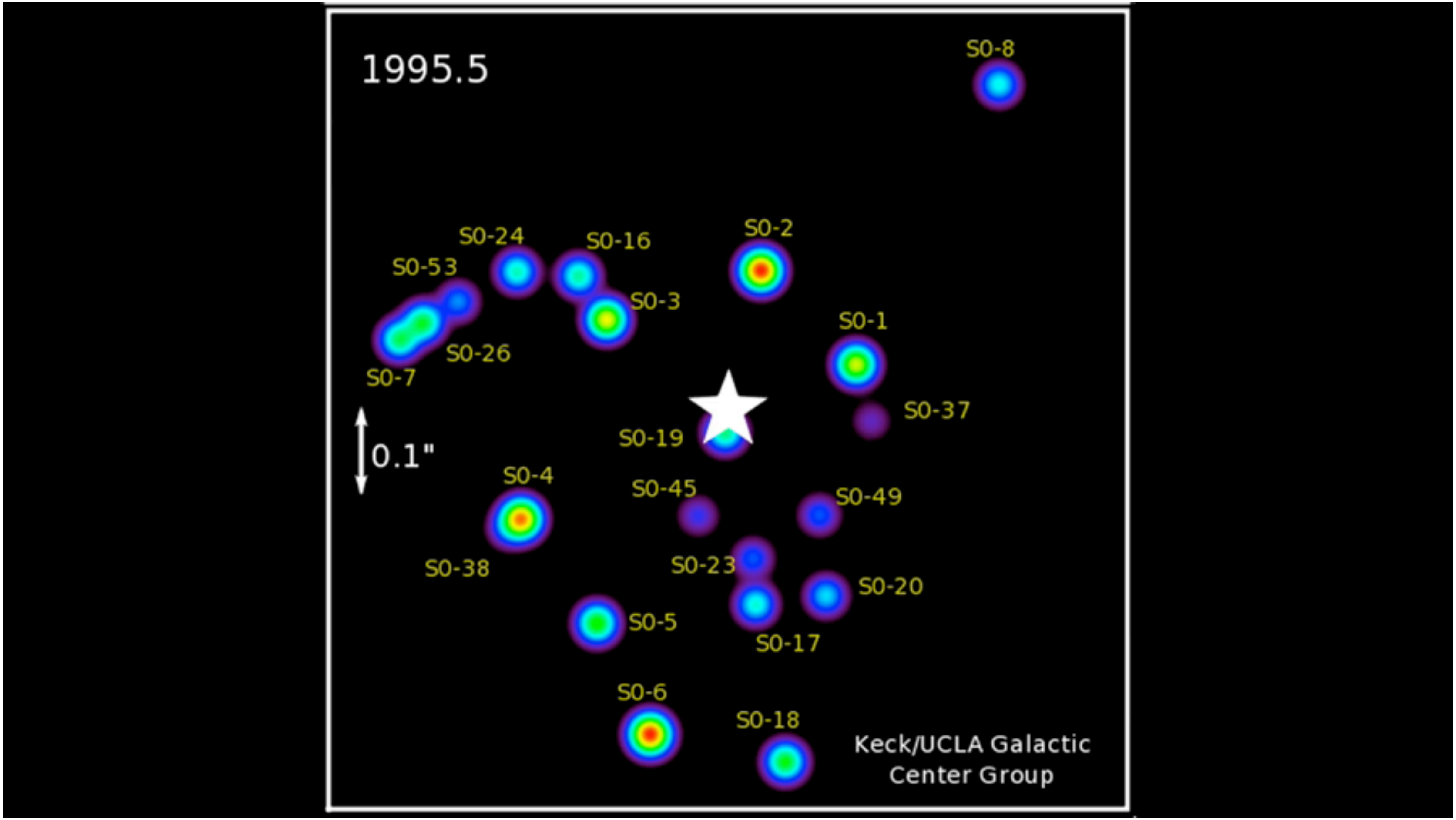
5 late-type stars

m ~ 10-15 $M_\odot$

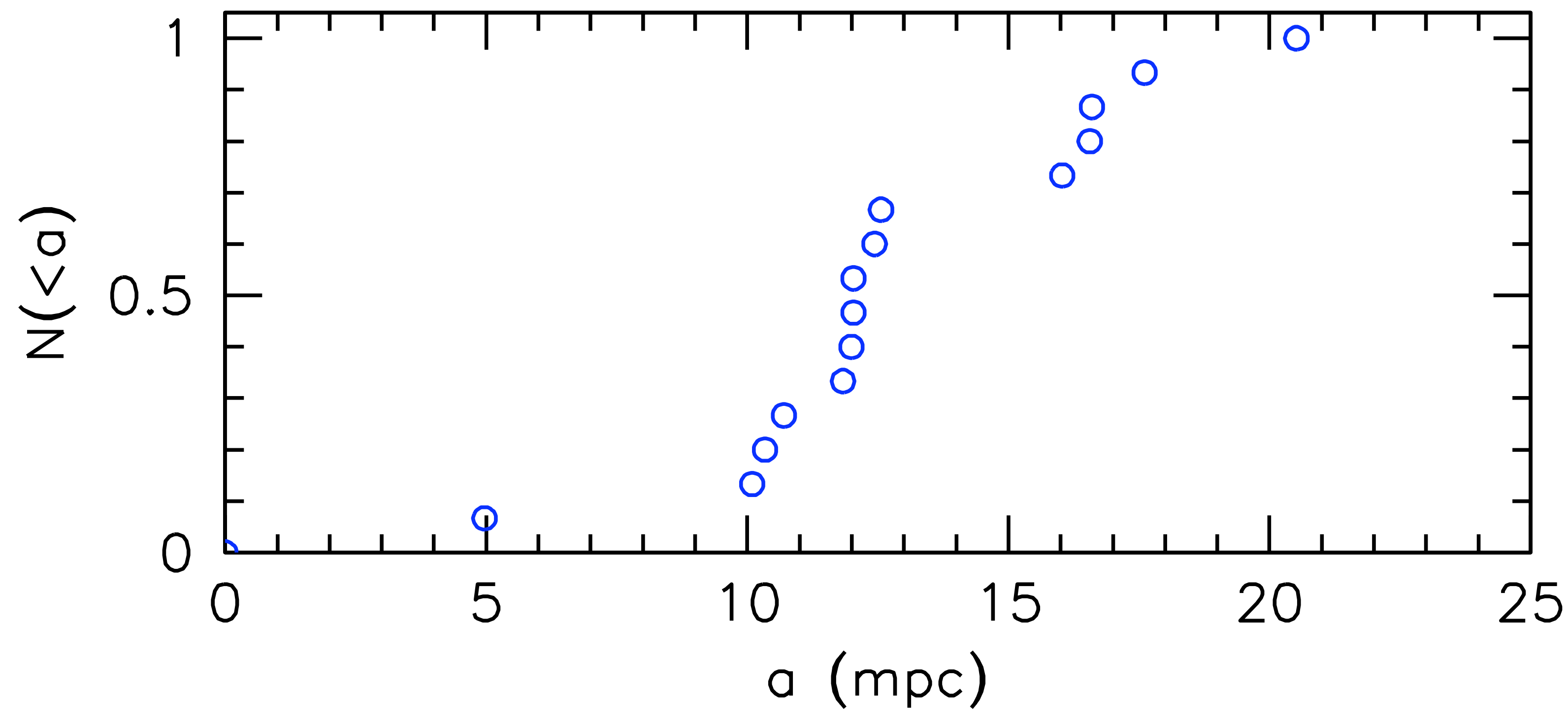
T ~ 10 Myr

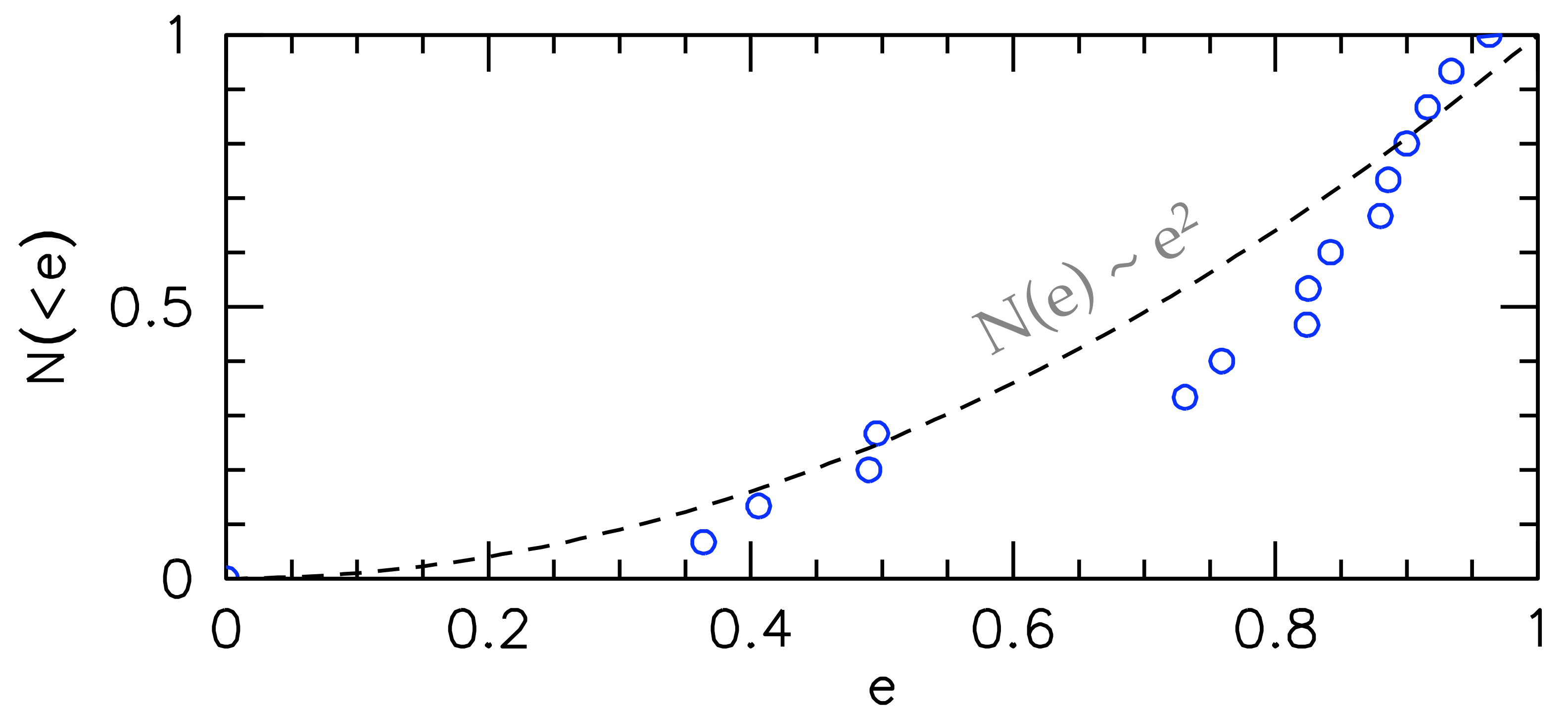
Gillessen et al. (2009)

The S-star cluster



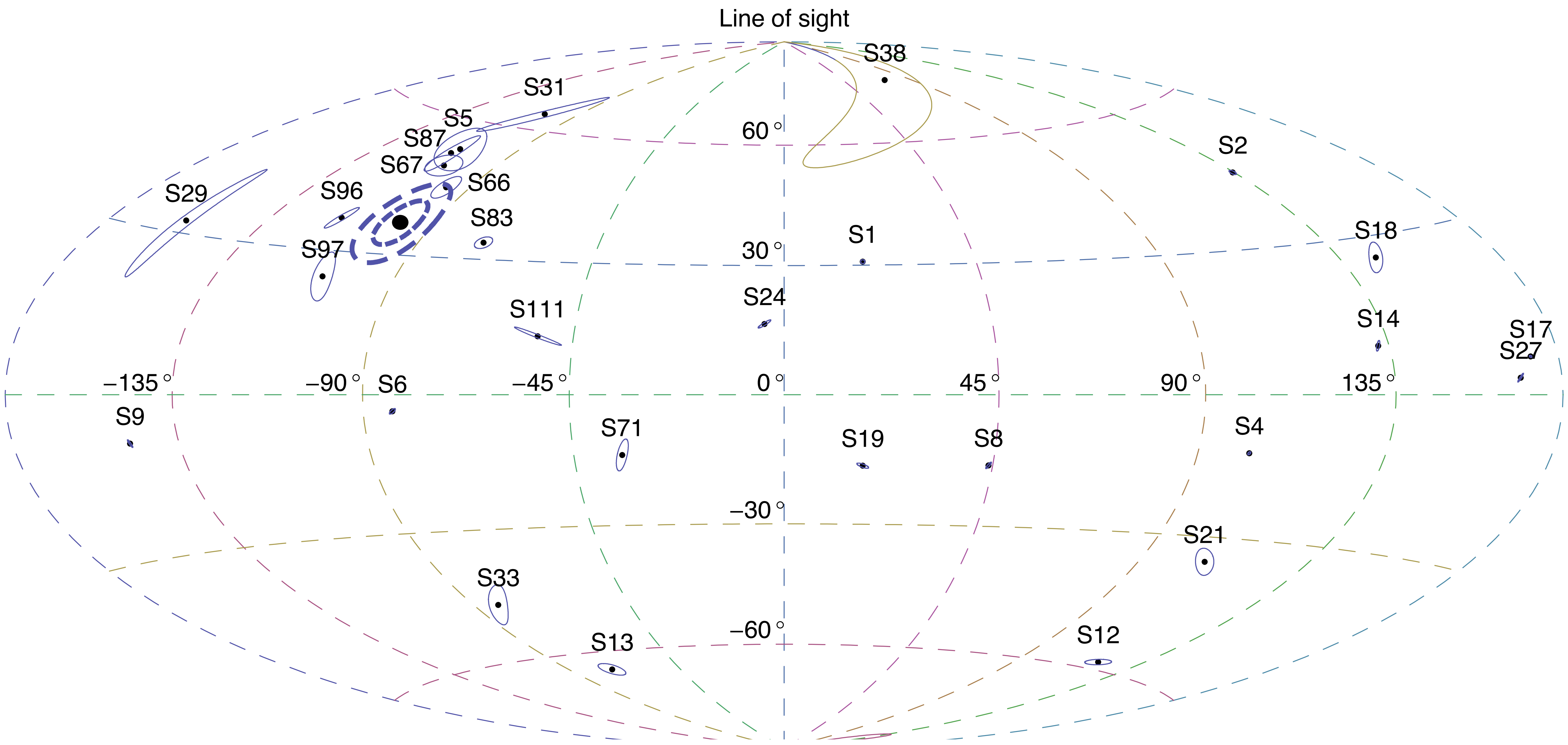
The S-star cluster





Alessia Gualandris, Weizmann Institute, 13/12/09

The S-star cluster



Gillessen et al. (2009)

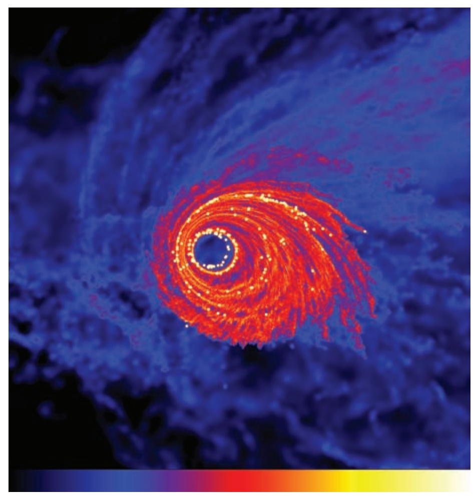
Alessia Gualandris, Weizmann Institute, 13/12/09

Origin of the S-star cluster

Proposed models:

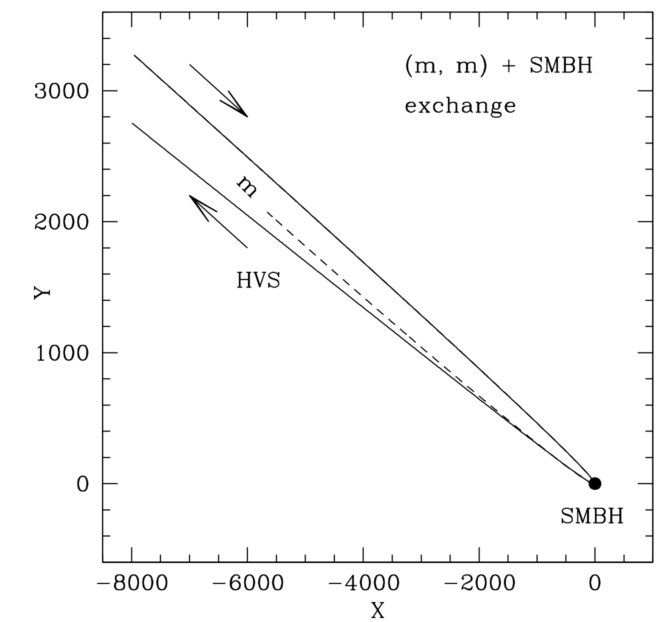
in-situ
formation

Bonnell & Rice (2008)



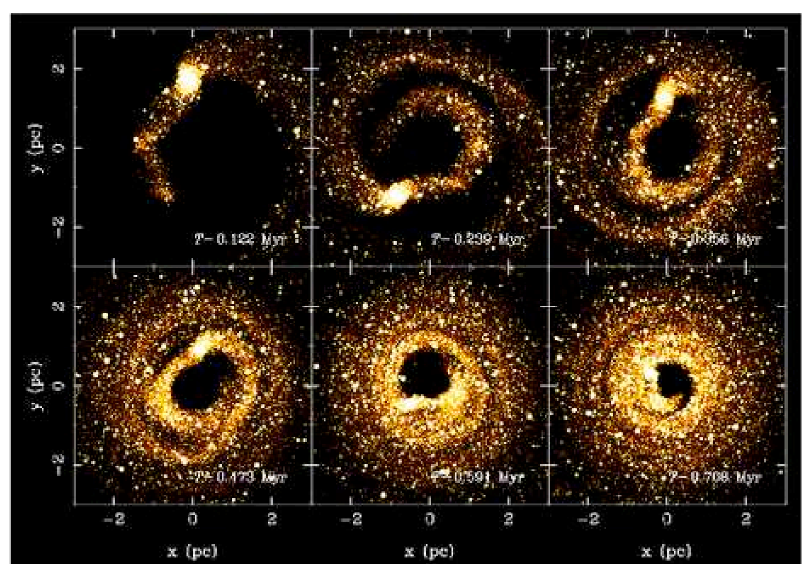
binary
capture

Gualandris, Portegies Zwart,
Sipior (2005)



cluster
infall

Fujii et al. (2008)



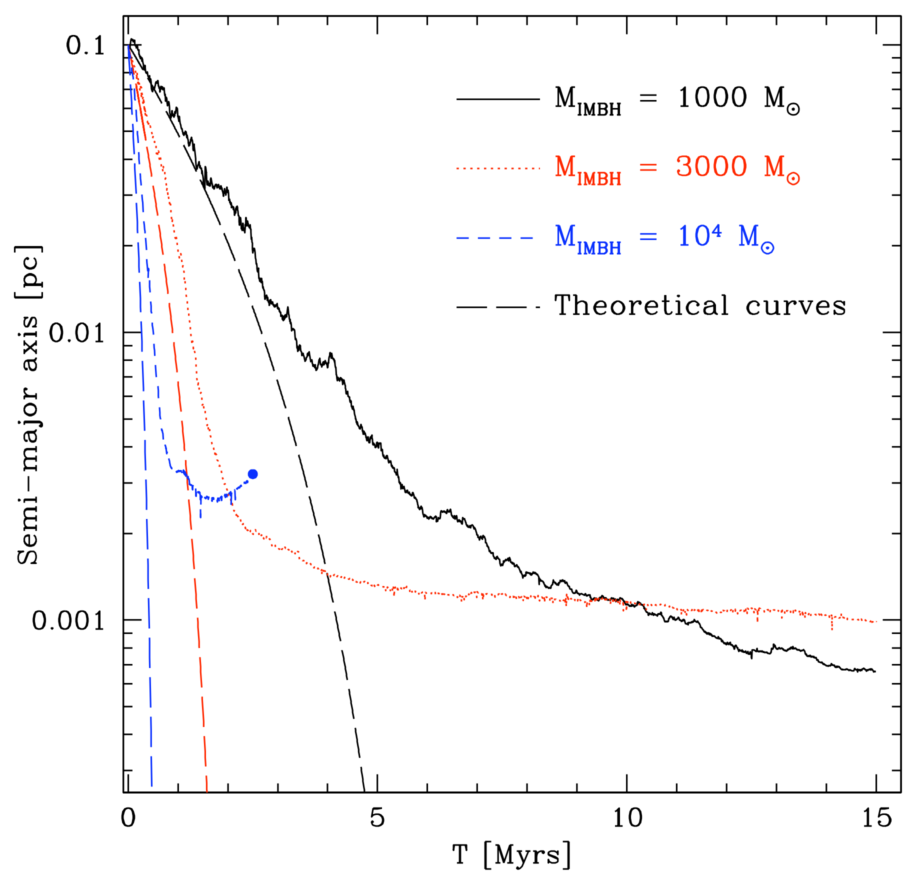
Cluster infall model

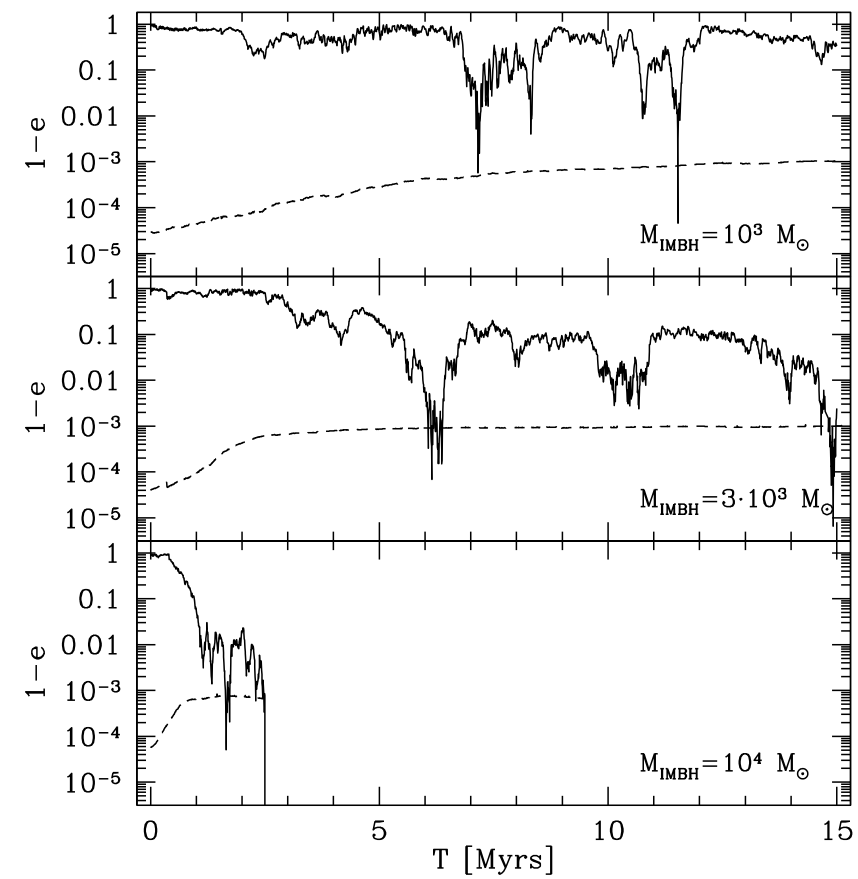
Properties of IMBH infall:

- stalling
- eccentric orbit

$$a_{\rm stall} \sim 0.2 \frac{q}{1+q} r_h$$

Merritt (2006)





Baumgardt, Gualandris, Portegies Zwart (2006)

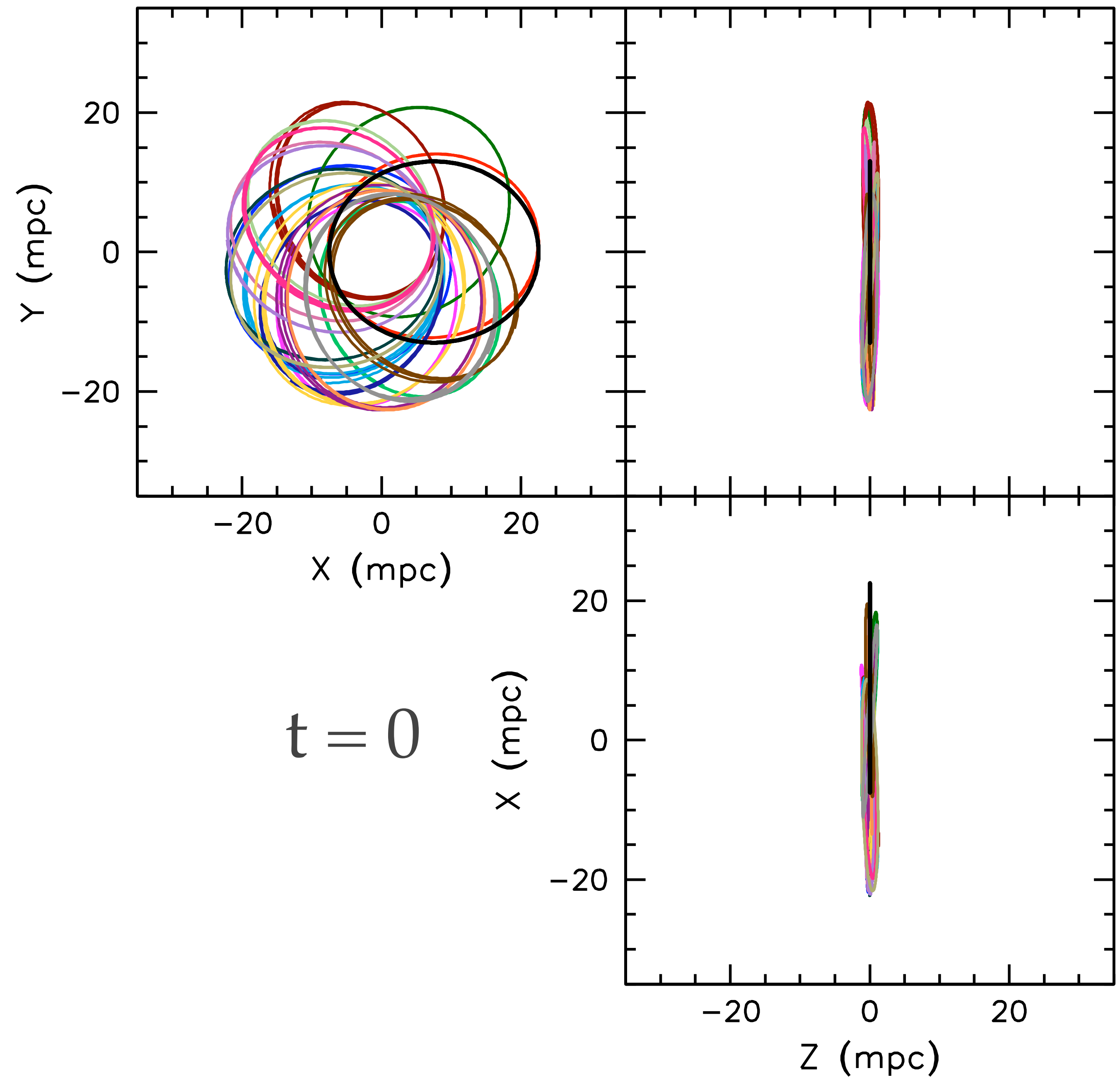
Alessia Gualandris, Weizmann Institute, 13/12/09

N-body simulations

BBH initial conditions:

- $M_{SMBH} = 4.5 \times 10^6\ M_\odot$
- IMBH $q = 10^{-4} - 10^{-3}$
- $a = 10 - 80$ mpc
- $e = 0.2 - 0.5$

Stars initial conditions: orbits similar to those of tidally stripped stars, with a small thickness



Alessia Gualandris, Weizmann Institute, 13/12/09

Simulating the Galactic Center

- φGRAPE: parallel direct summation N-body code, 4th order Hermite integrator, predictor-corrector scheme, GRAPE support

  Harfst, Gualandris, Merritt, Portegies Zwart, Berczik (2007)

- AR-CHAIN: algorithmic regularization code with PN terms up to order 2.5

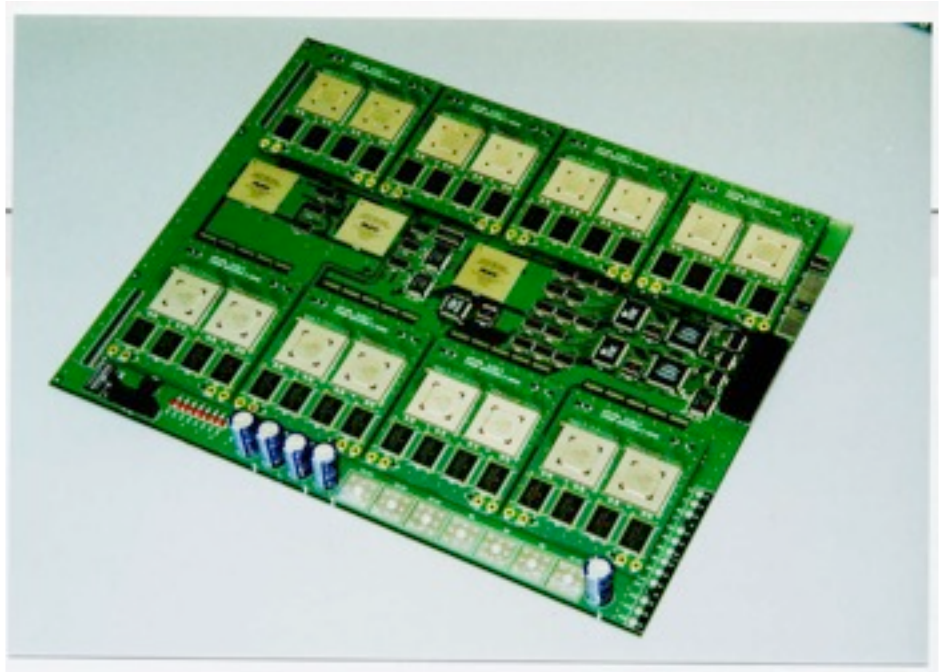
  Mikkola & Merritt (2008)

- φGRAPEch: hybrid N-body φGRAPE + chain regularization

  Harfst, Gualandris, Merritt, Mikkola (2008)

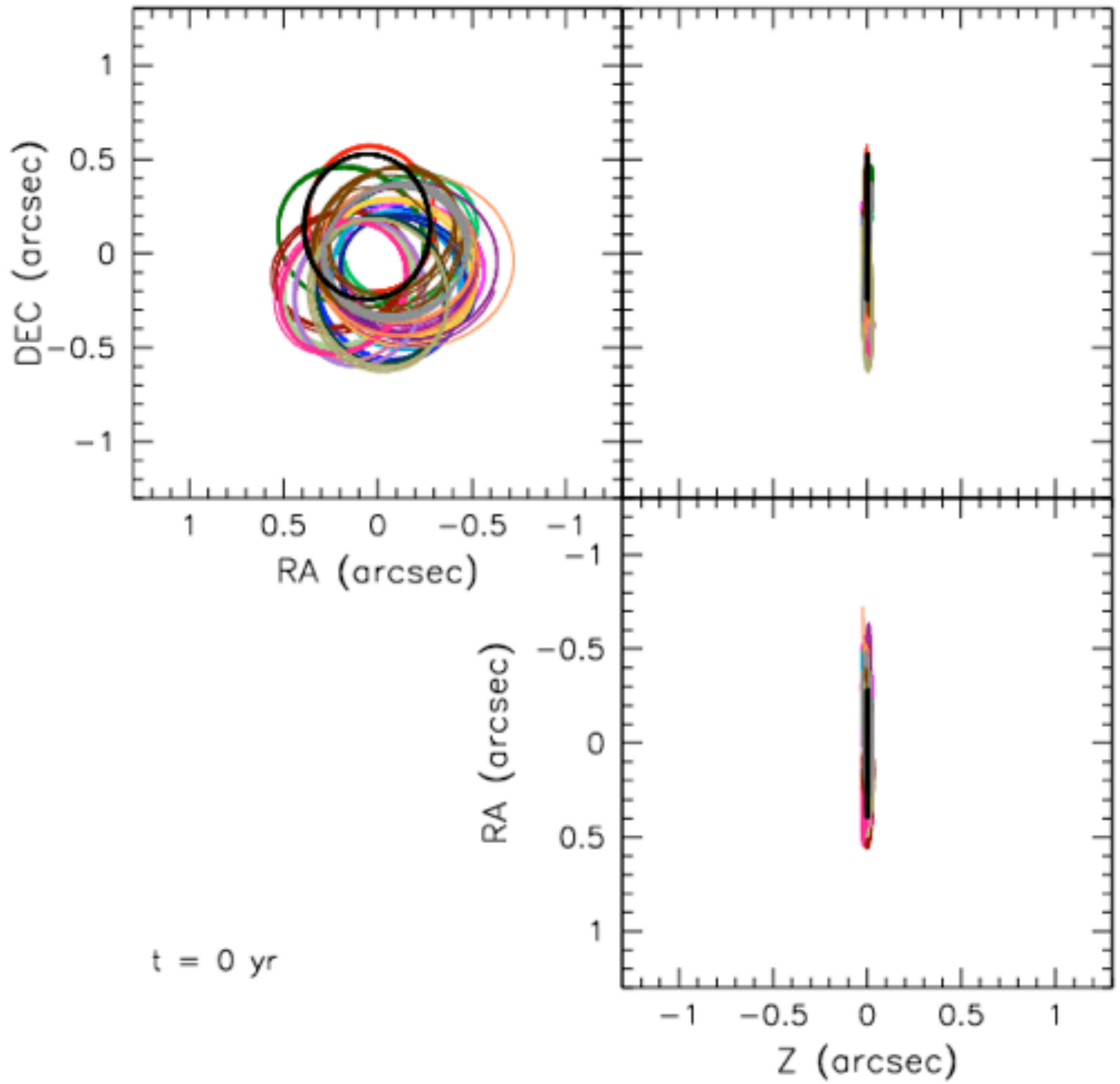
Simulating the Galactic Center

Gravity Simulator @ RIT



Alessia Gualandris, Northwestern University, 12/01/09

N-body simulations



stars N=20

BBH
q = 0.001
a = 15 mpc
e = 0.5

AR-CHAIN
algorithmic
regularization code

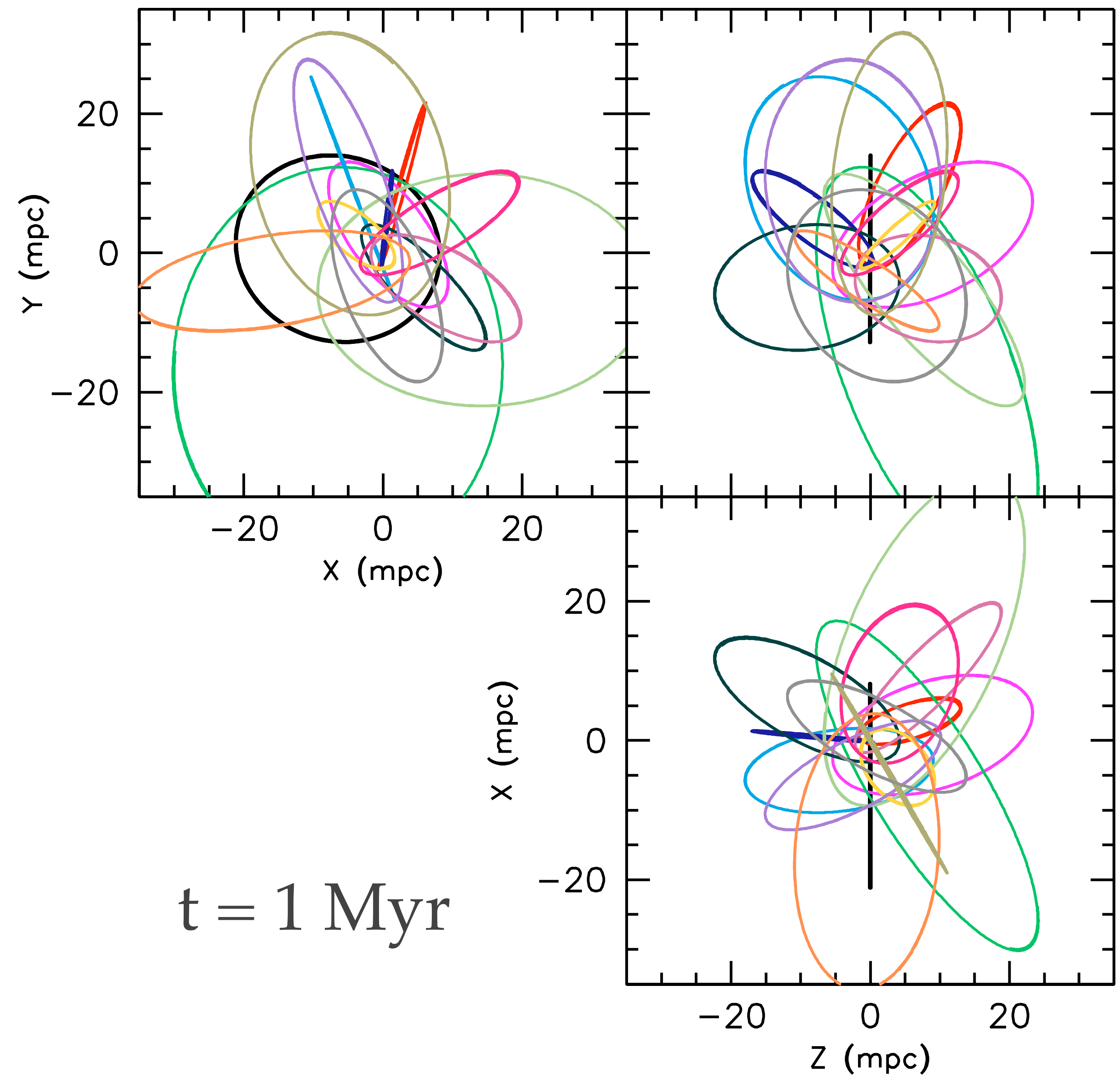
Merritt, Gualandris, Mikkola (2009)

Alessia Gualandris, Weizmann Institute, 13/12/09

N-body simulations

stars
N=20

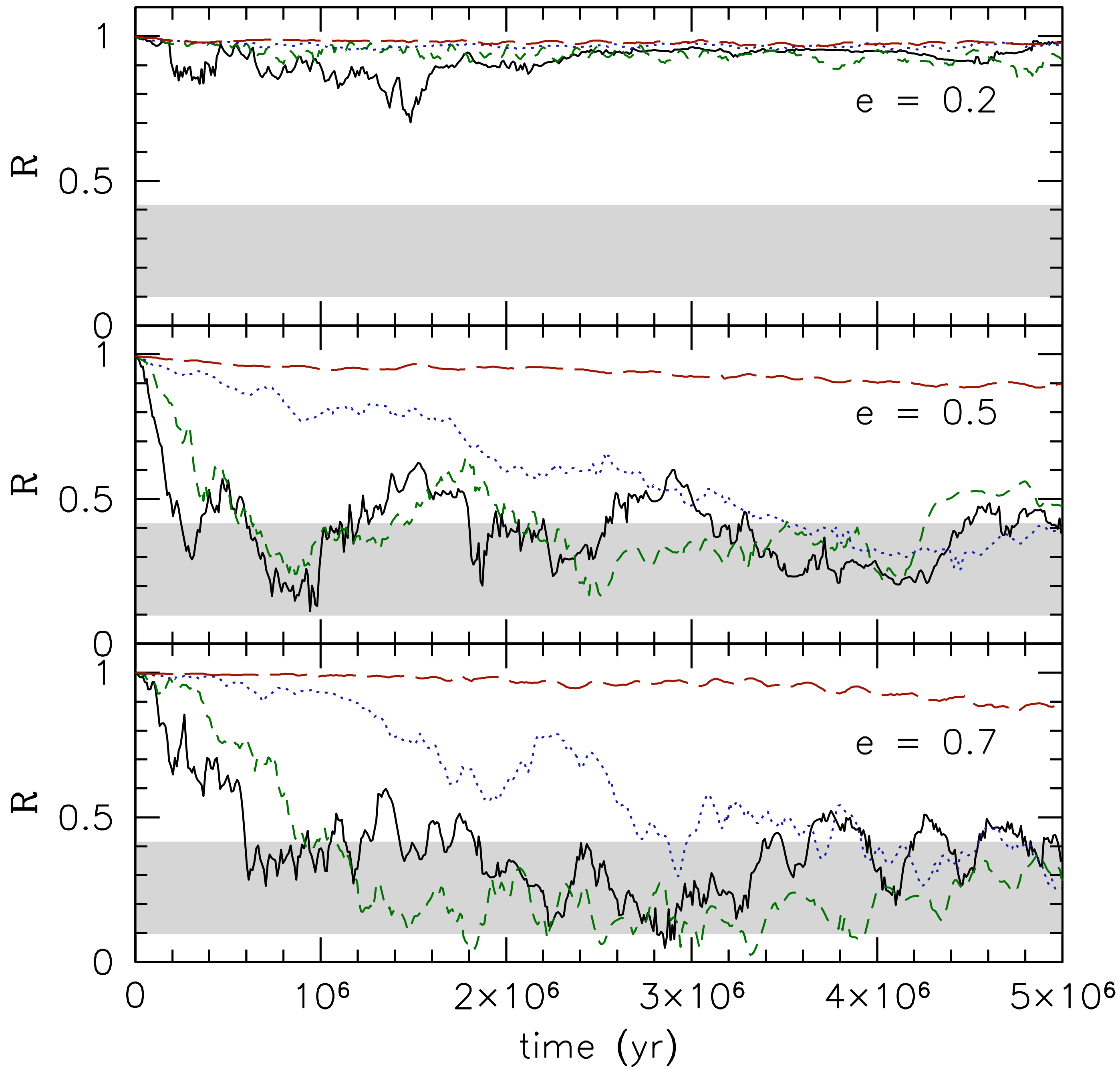
BBH
$q = 0.001$
$a = 15$ mpc
$e = 0.5$



$t = 1$ Myr

Alessia Gualandris, Weizmann Institute, 13/12/09

Orbital inclinations



Rayleigh parameter

$$R = \frac{1}{N}\left|\sum_{i}^{N} \mathbf{r_i}\right|$$

$a_{IMBH} = 30$ mpc

$q = 1.0\text{x}10^{-3}$

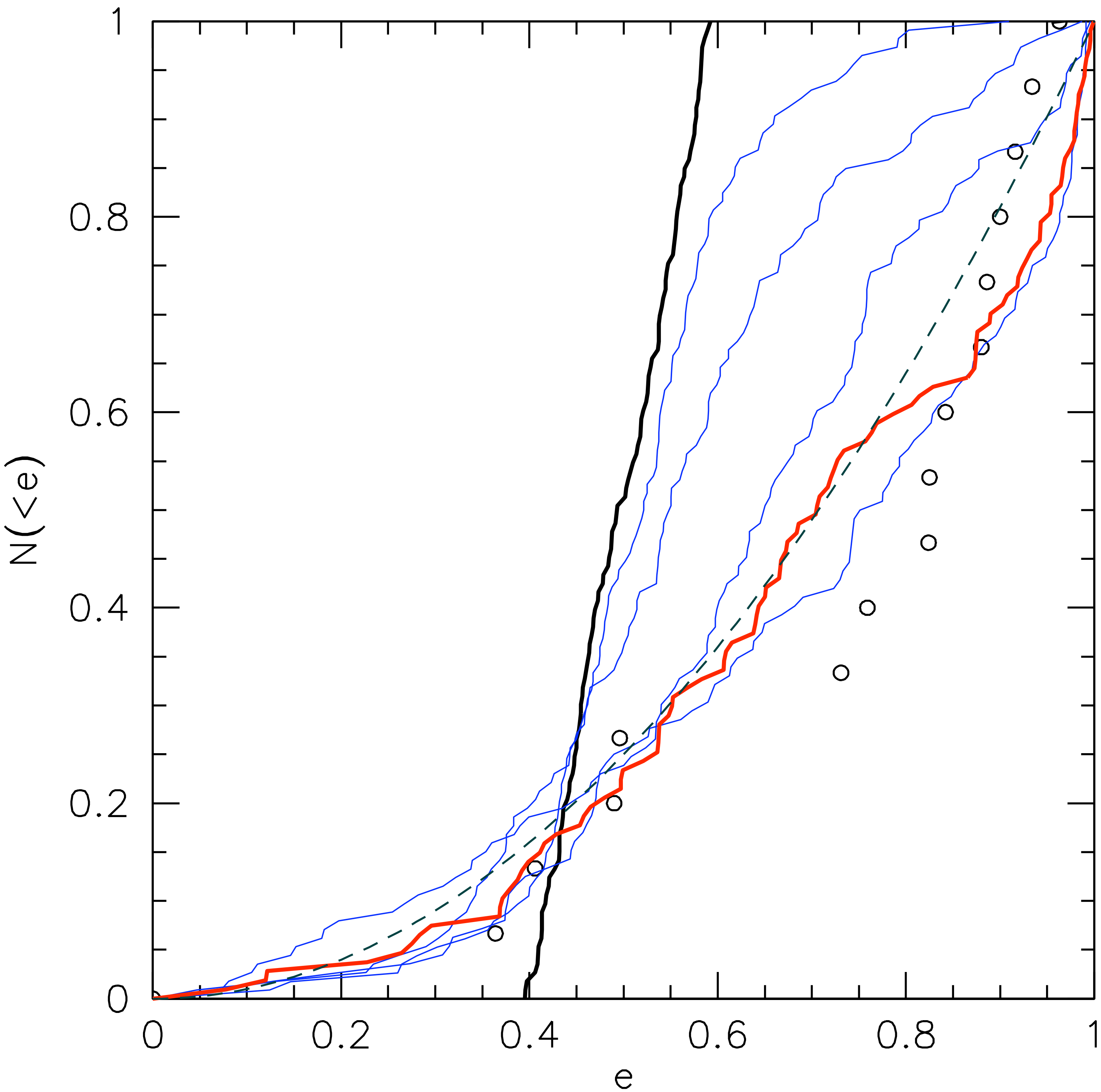
$q = 5.0\text{x}10^{-4}$

$q = 2.5\text{x}10^{-4}$

$q = 1.0\text{x}10^{-4}$

Merritt, Gualandris, Mikkola (2009)

Eccentricities



$M_{IMBH} = 4000\ M_\odot$

$a = 15$ mpc

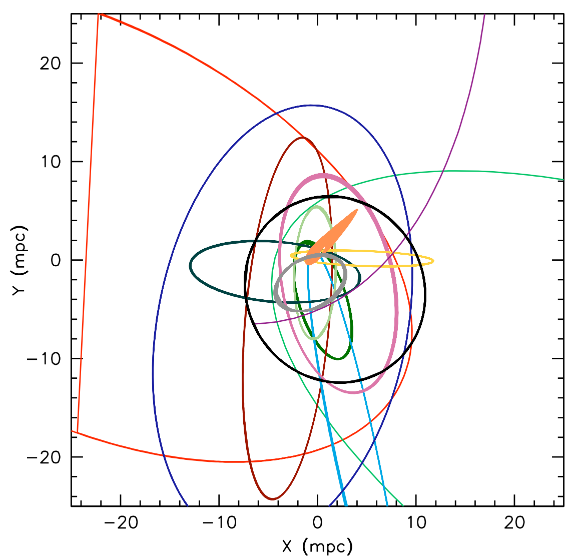
$e = 0.5$

efficient thermalization of eccentricities

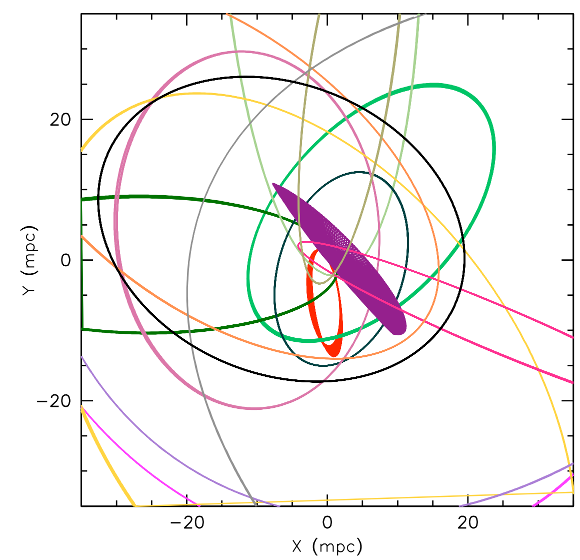
Merritt, Gualandris, Mikkola (2009)

Alessia Gualandris, Weizmann Institute, 13/12/09

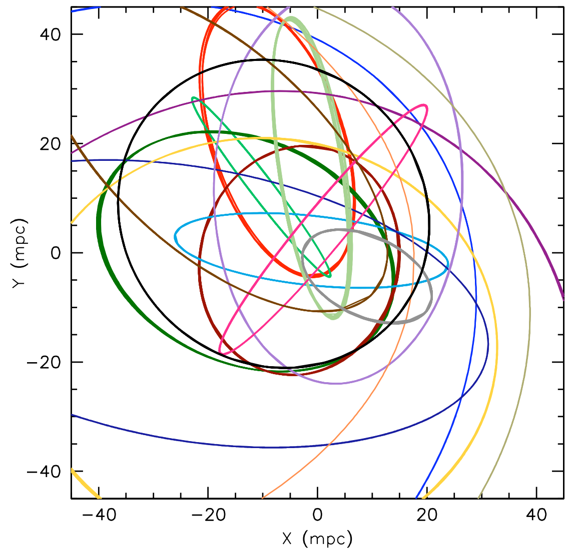
Semi-major axes



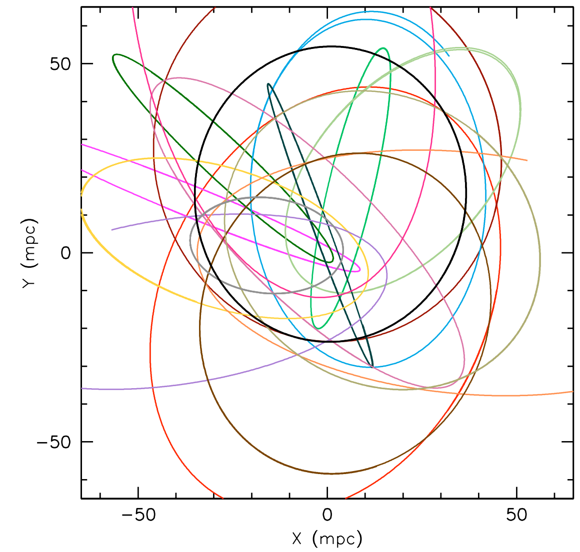
a = 15 mpc



a = 20 mpc



a = 30 mpc



a = 40 mpc

$M_{IMBH} = 2250\ M_\odot$

$e = 0.5$

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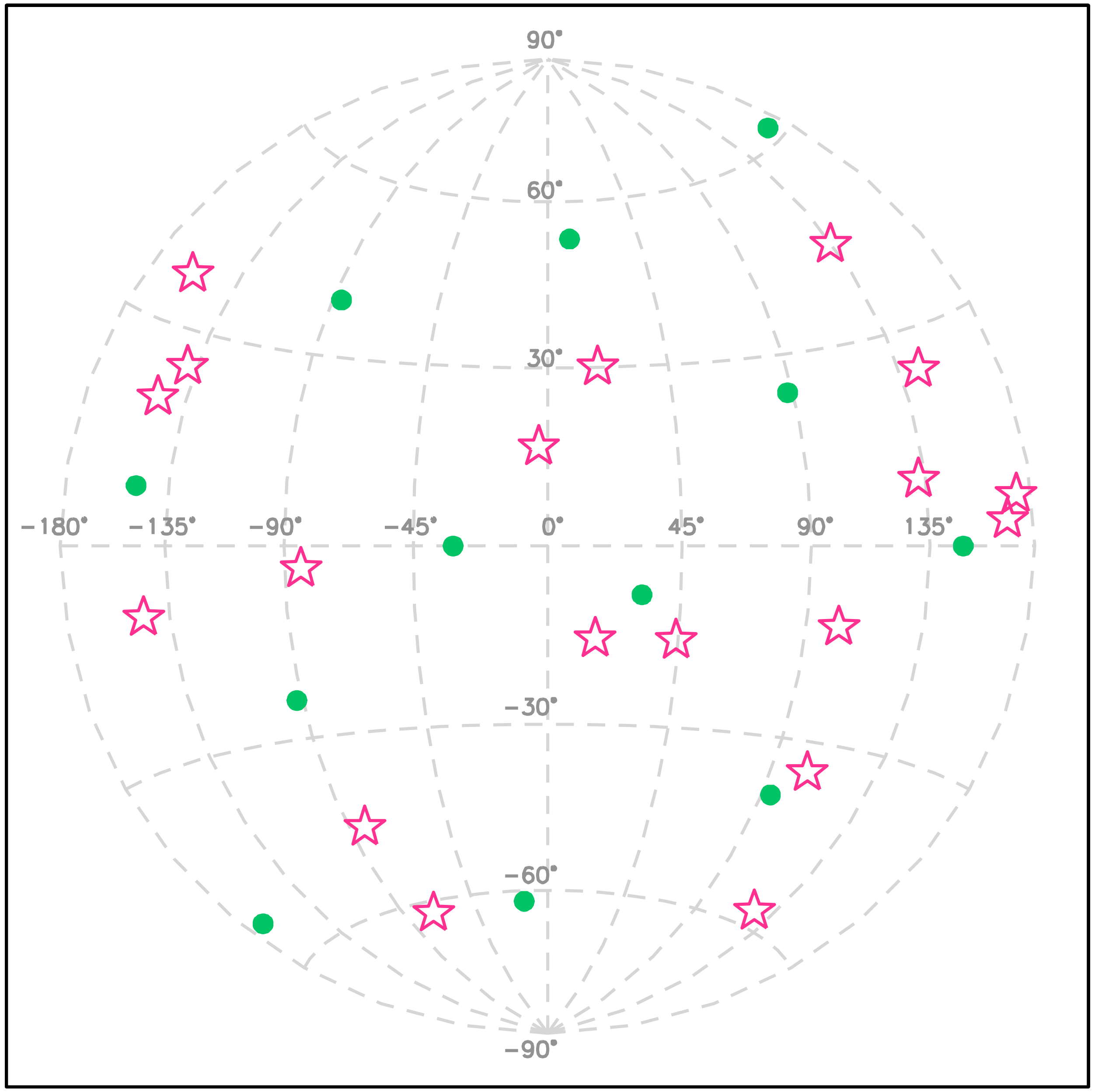
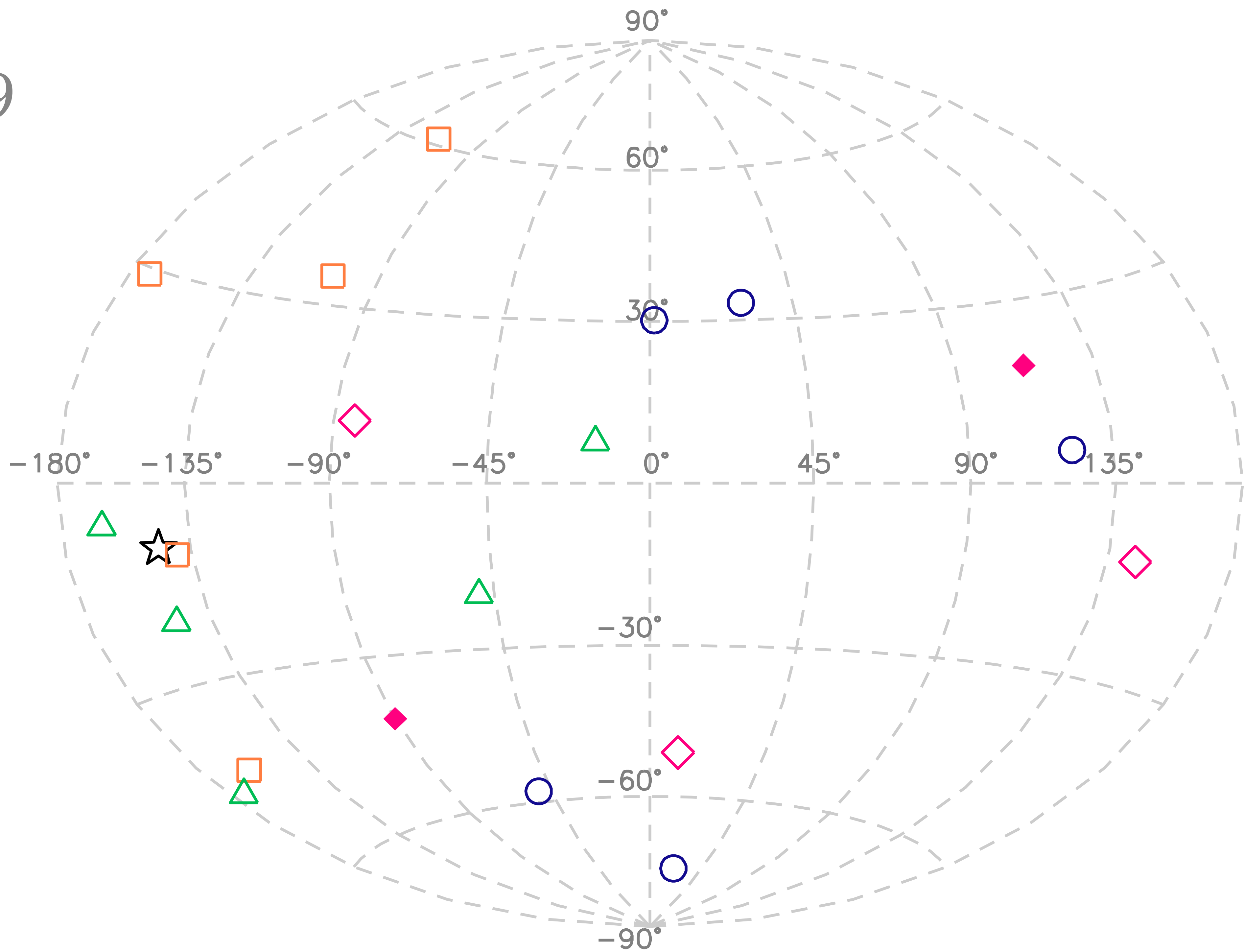
Evolution of S-stars + IMBH



- SMBH $M_{SMBH} = 4x10^6 M_\odot$
- 19 S-stars $m = 10M_\odot$
- IMBH $M_{IMBH} = 400, 1000, 2000, 4000 M_\odot$
- $a = 0.3, 1, 3, 10, 30$ mpc
- 12 positions on the sky
- $e_{IMBH} = 0, 0.7$

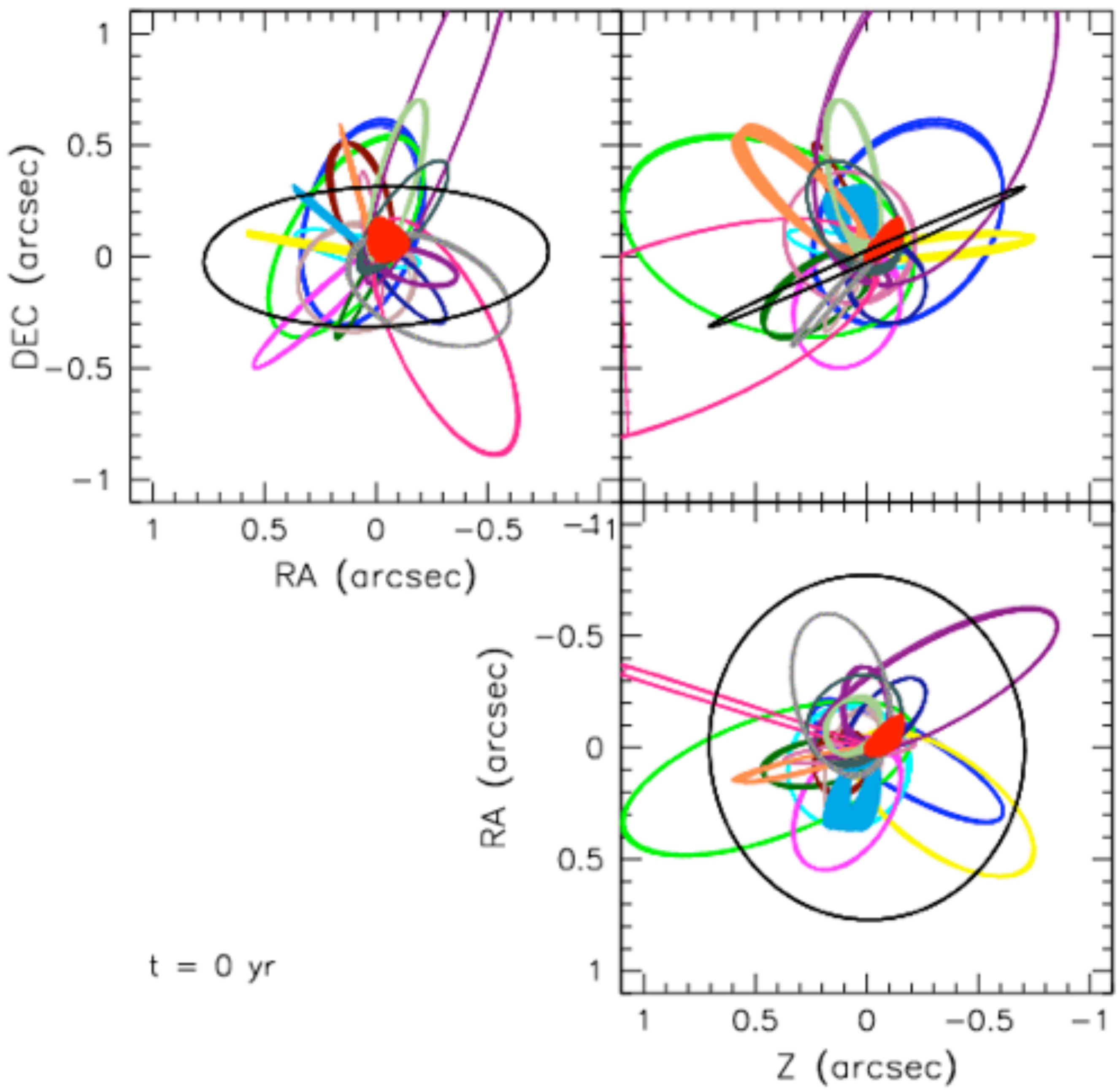
Randomization of inclinations

star S9



Gualandris & Merritt (2009)

Long-term perturbations on the S-stars



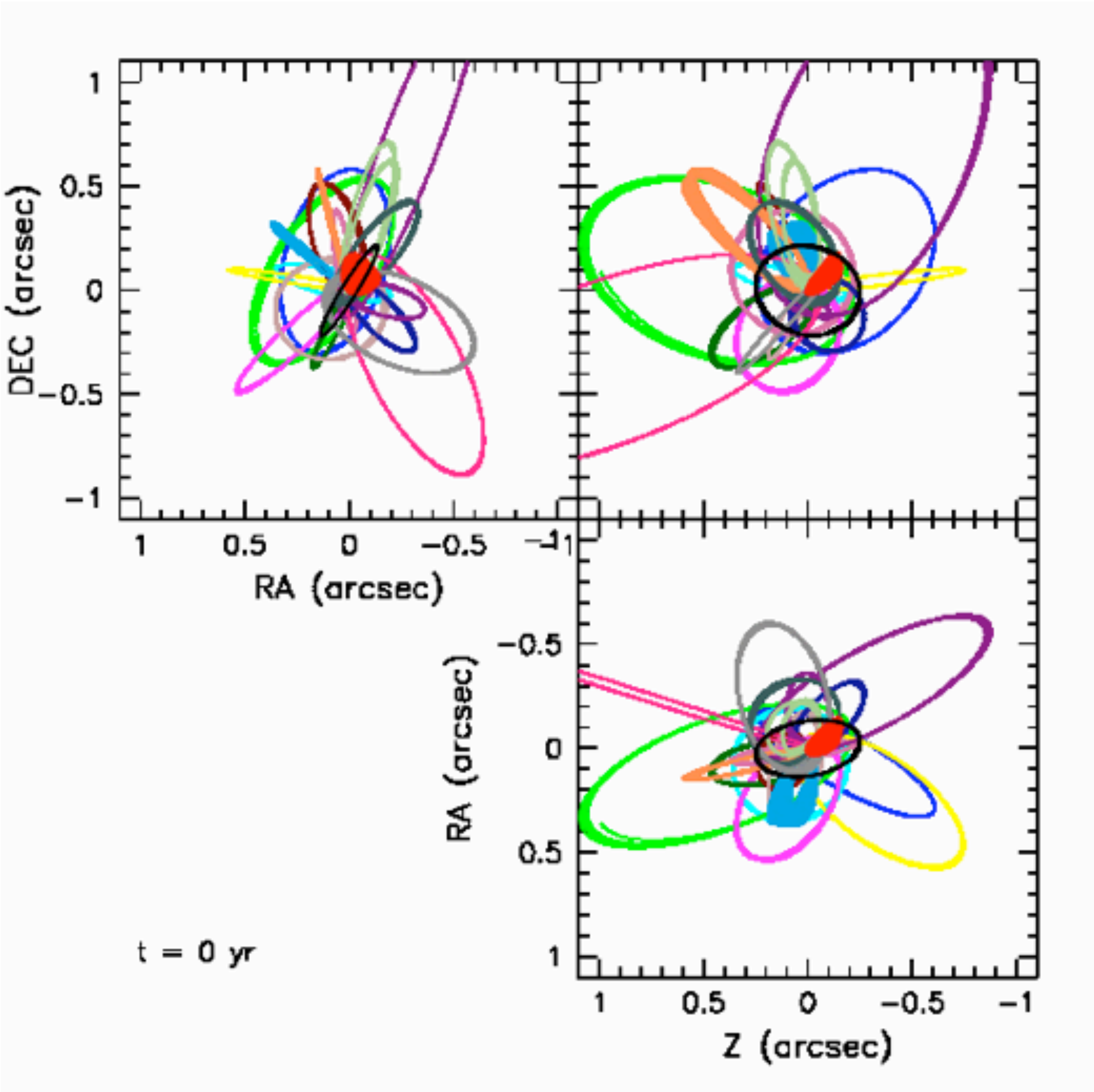
$M_{IMBH} = 4000 M_{\odot}$

$a = 30$ mpc

perturbations

Gualandris & Merritt (2009)

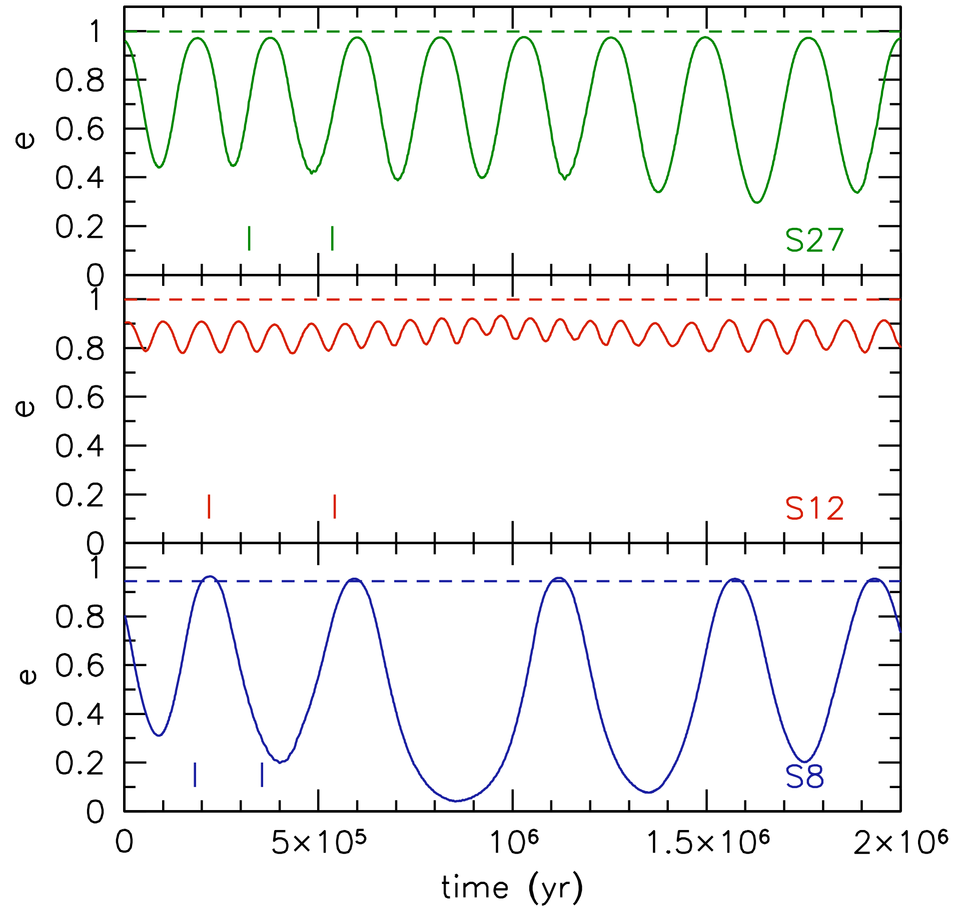
Long-term perturbations on the S-stars

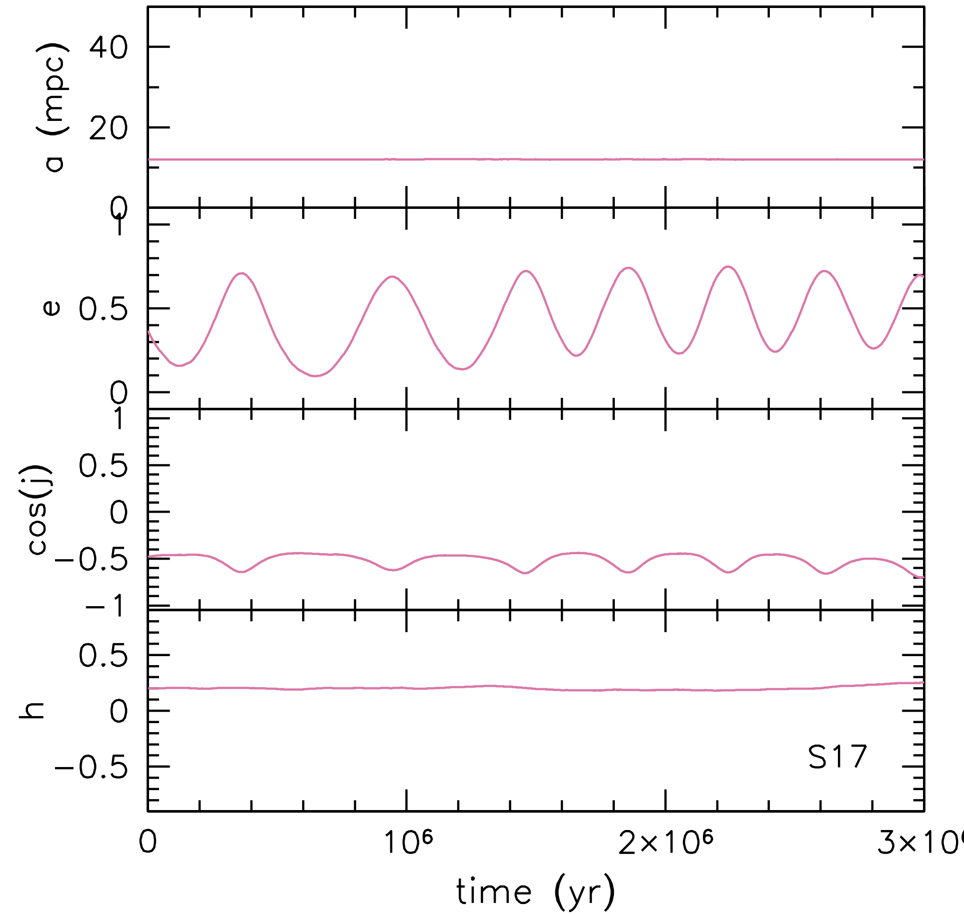


$M_{IMBH} = 2000 M_\odot$
$a = 10$ mpc
ejection

Gualandris & Merritt (2009)

Kozai oscillations





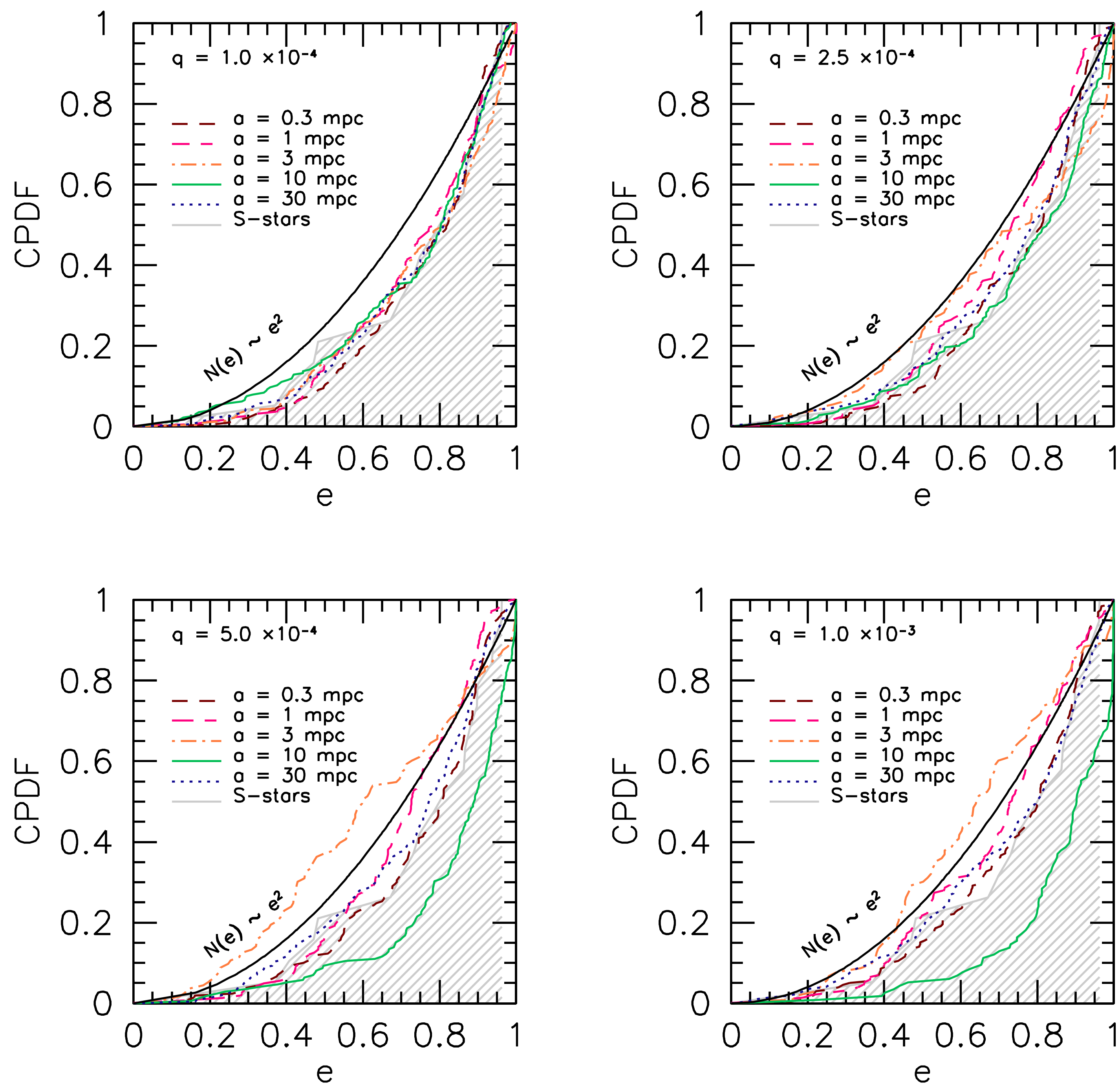
$$T_K = \kappa \frac{P_{\rm out}^2}{P_{\rm in}} \frac{M_{\rm BH} + m}{M_p} \left(1 - e_{\rm out}^2\right)^{3/2}$$

$$\kappa = \kappa\left(j, e_{\rm inn}, \omega\right)$$

$$e_{\rm max} = e_{\rm max}\left(j, e_{\rm inn}, \omega\right)$$

$$h = \left(1 - e^2\right) cos^2(j)$$

Eccentricity distribution



Gualandris & Merritt (2009)

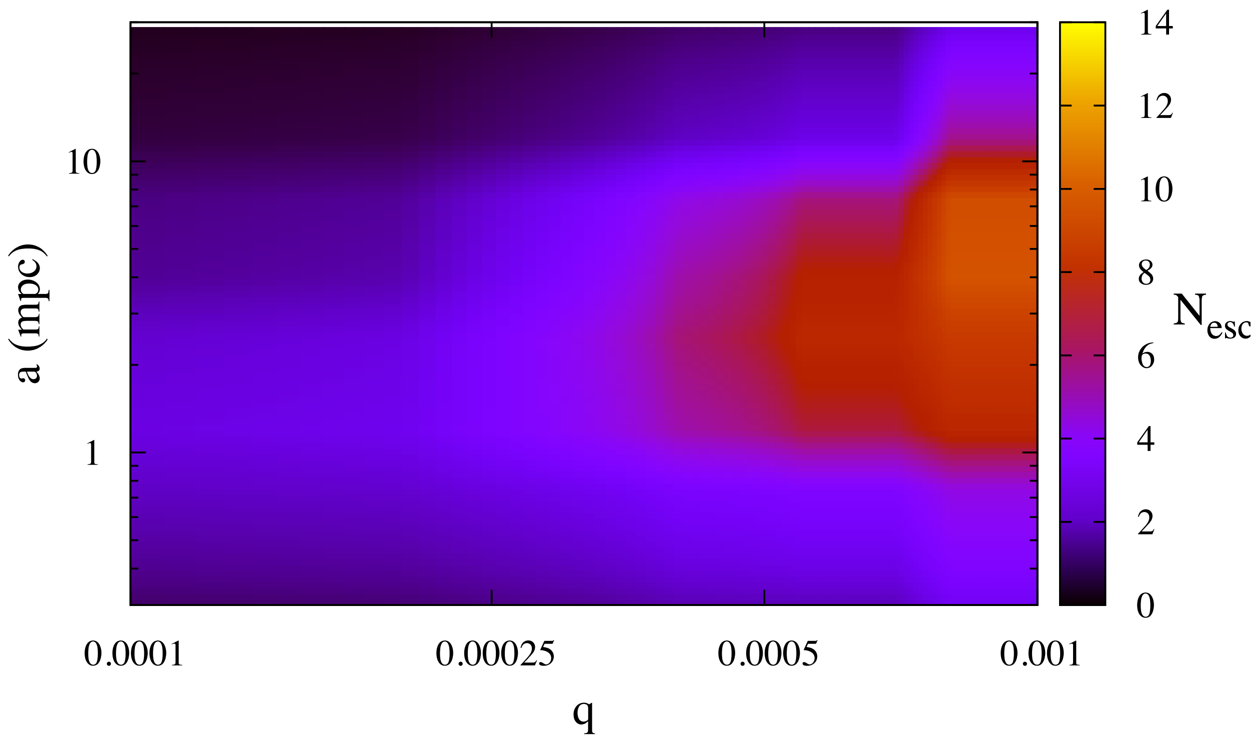
circular binary

Effects on eccentricity distribution and number of escapers

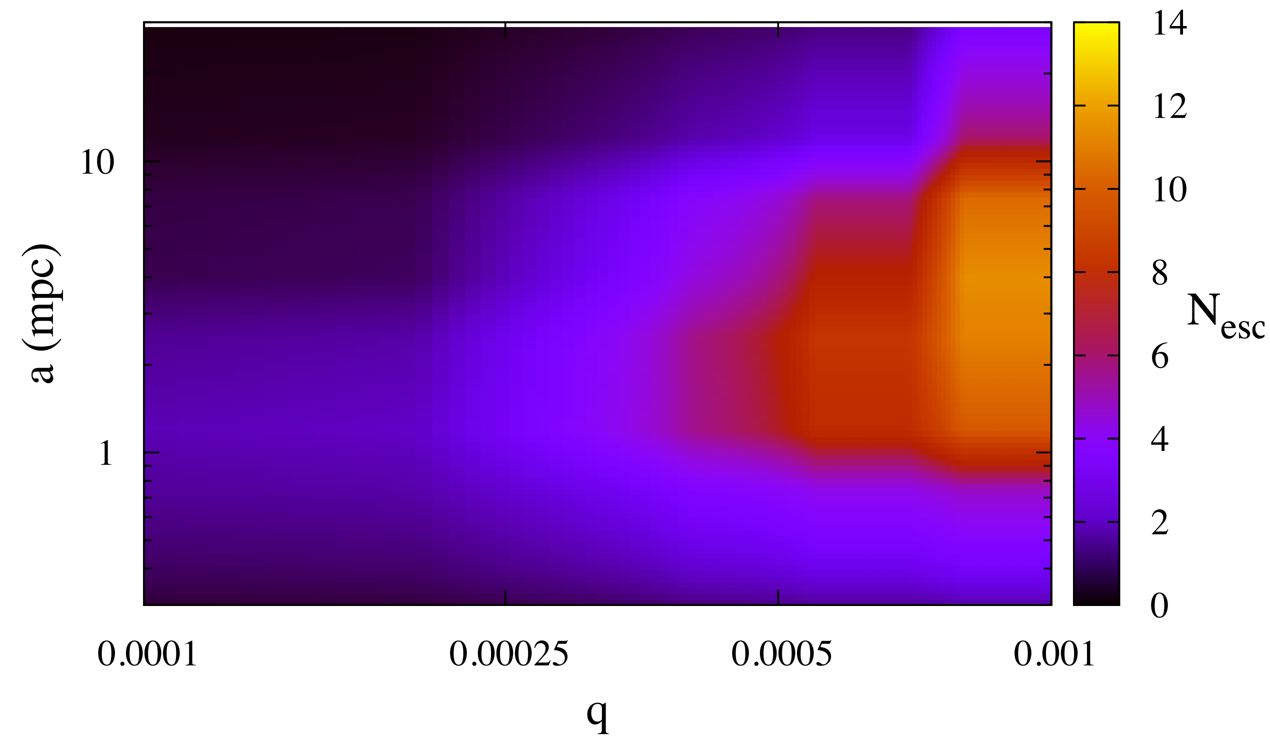
⇓

Exclude parameters:
a = 3-10 mpc
M_{BH} = 2000-4000$M_\odot$

Ejections



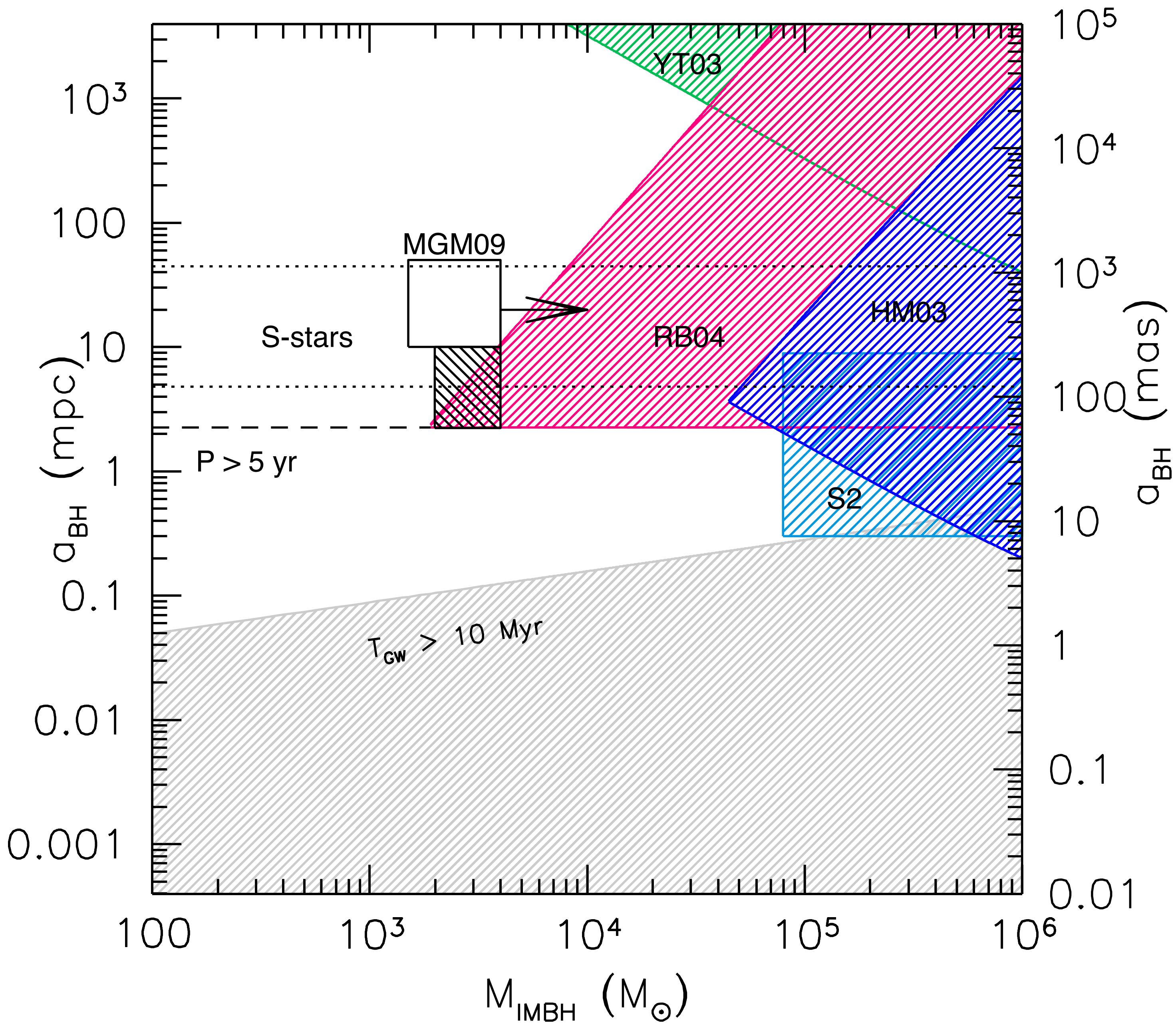
circular binary



eccentric binary

Gualandris & Merritt (2009)

Constraints on IMBH parameters

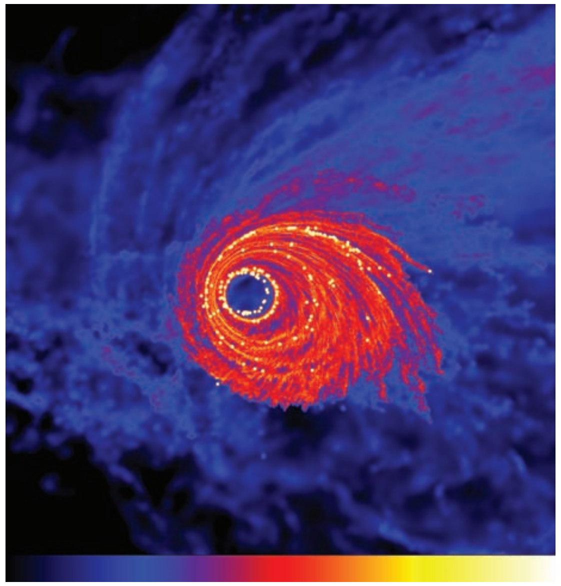


Gualandris & Merritt (2009)

- BBH com ~ peak stellar distribution within uncertainties (YT03)
- lifetime $T_{GW} > 10^7$ yr
- mass enclosed within orbit of S2 < 0.02 M_{BH}
- motion of SgrA* (HM03, RB04)
- stability of S-cluster

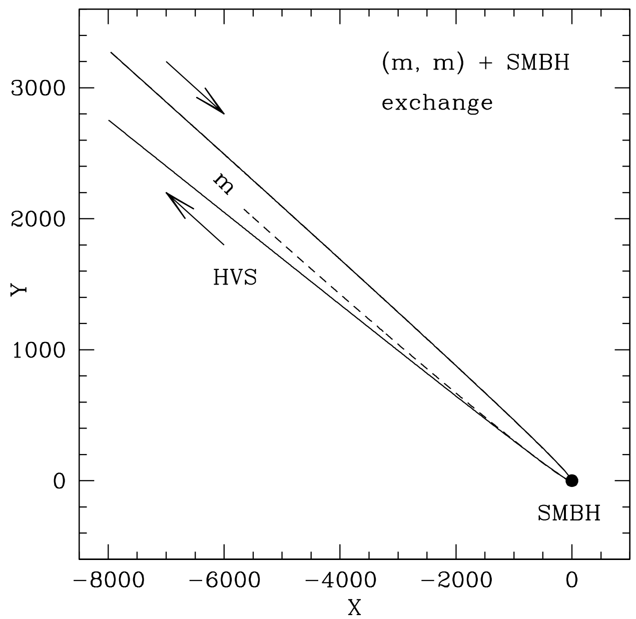
Origin of the S-star cluster

In-situ formation



formation in a gas disk (either current CW disk or older disk)
+ migration
↪ low eccentricities

Binary capture



formation in a binary
+ scattering off massive perturbers
+ tidal disruption
+ resonant relaxation
↪ high eccentricities

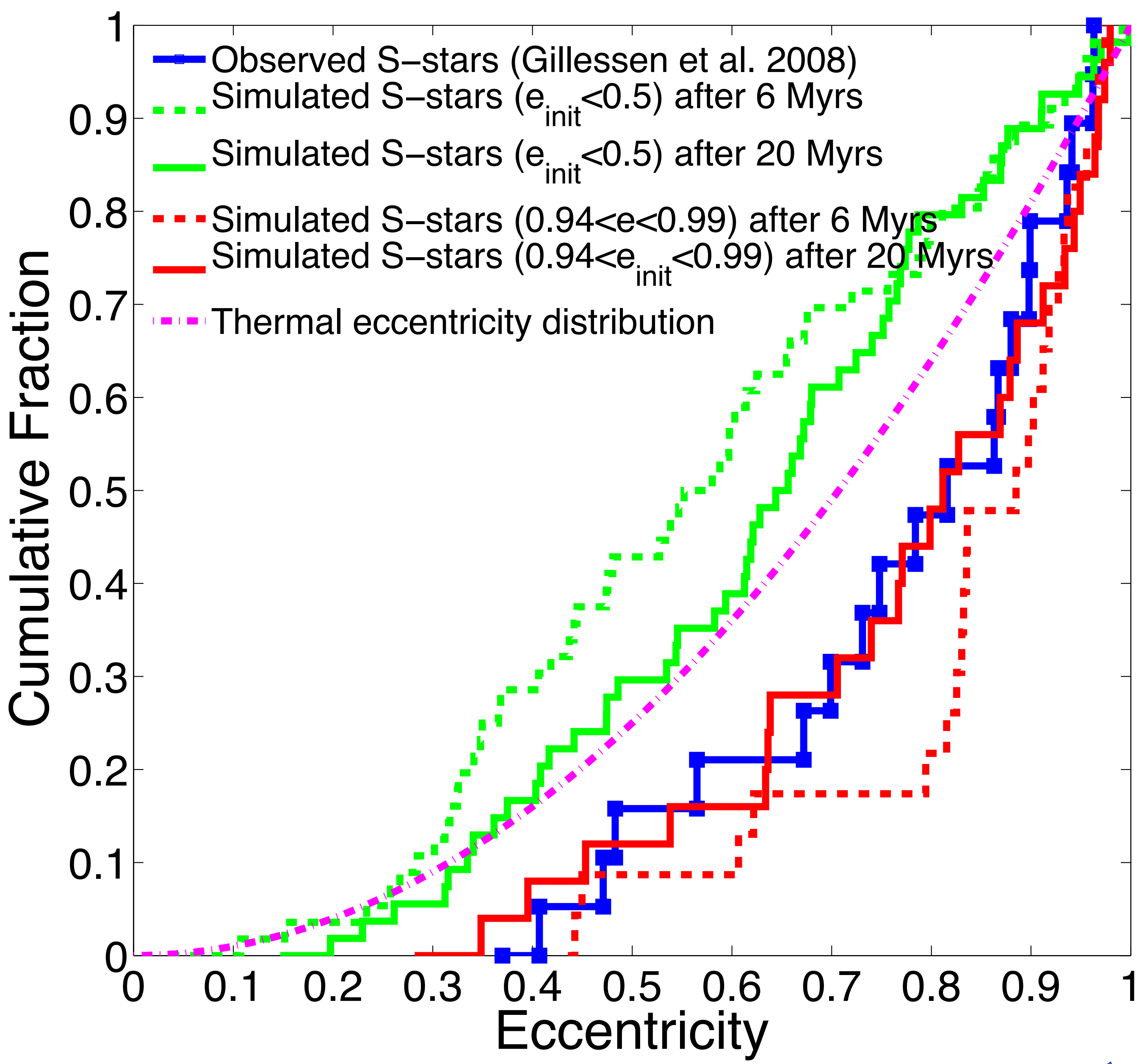
Origin of the S-star cluster

- Isotropic cusp $N = 1200$ $r < 0.3$ pc
- $N_1 = 200$ $N_2 = 1000$
- $m_1 = 3\ M_\odot$ S-stars, $m_2 = 10\ M_\odot$ bhs
- $M_{BH} = 3.6 \times 10^6\ M_\odot$
- Power-law distribution $r^{-\alpha}$, $0.001 < r < 0.05$ pc
  $\alpha = 2$ for bhs, $\alpha = 1.5$ for S-stars

Alessia Gualandris, Weizmann Institute, 13/12/09

Origin of the S-star cluster

Eccentricity distribution



high initial eccentricities (e>0.96) binary disruption

low initial eccentricities (e<0.5) disk origin

Binary disruption t = 20 Myr

is the favored model

Perets, Gualandris, Merritt, Alexander (2009)

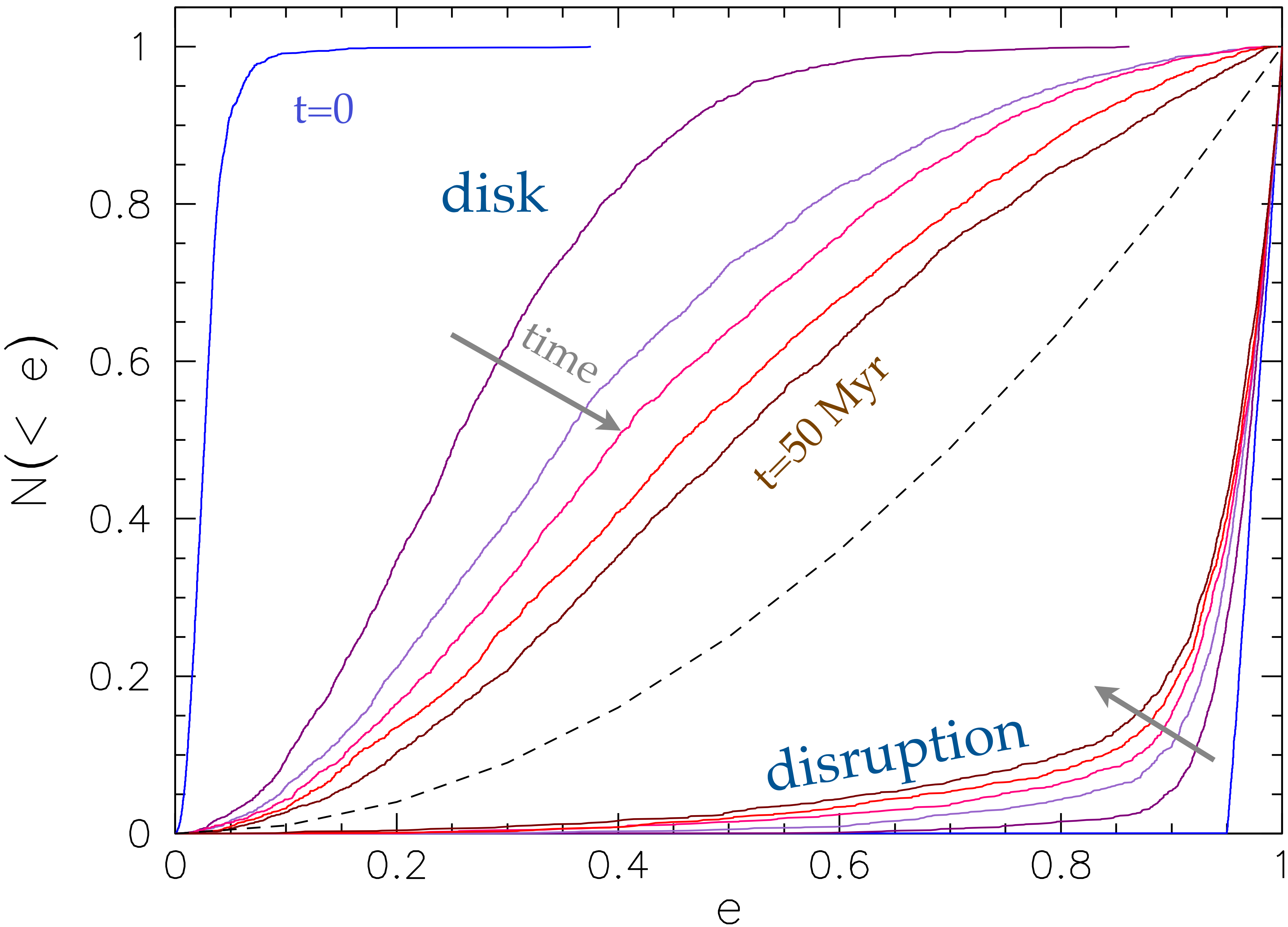
Origin of early-type stars beyond 0.5 pc

New identification of 35 early-type stars beyond 0.5 pc (~13 as) isotropically distributed

Bucholz et al. (2009)

- Isotropic cusp of stellar black holes: N_1=16000, $m_1 = 10\ M_\odot$
- Power-law distribution r^{-2}, $0.03\ pc < r < 0.8\ pc$
- Stellar disk with Salpeter MF: N_2=2500
- $M_{BH} = 3.6 \times 10^6\ M_\odot$

Origin of early-type stars beyond 0.5 pc



Perets et al. (in prep)

Conclusions

Models for origin of S-stars in the Galactic center:

* In-situ formation can be excluded
* Binary disruption scenario explains all the properties but requires chain of events
* Cluster infall scenario with IMBH naturally explains all properties and time-scales
* Long-term perturbations from an IMBH allow to constrain orbital parameters