Dynamical Friction on Star Clusters near the Galactic Center

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The Central Parsec of the Galaxy

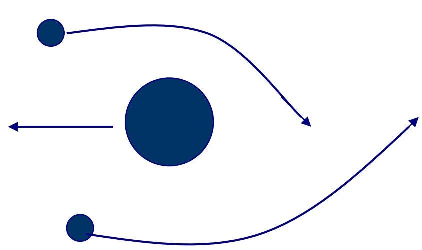
- Contains a cluster of very young stars, including ~20 very luminous He I emission line stars as well as many O and B stars.
- The He I stars appear to be very massive (>50 $M_\odot$) stars at the luminous blue variable phase or Wolf-Rayet stage, with stellar ages of ~5 Myr.

Star Formation in the Central Parsec?

- However, in situ formation of these stars is highly problematic owing to strong tidal forces in the central parsec region.
  - Maximum gas density observed $\approx$ a few 10^6 cm^{-3}
  - Minimum density to remain bound $\approx 6\times10^7$ cm^{-3}
- Similar stars have also been found in two clusters outside the central parsec: The Arches and Quintuplet clusters, ~30 pc away from the center, contain ~10^4 $M_\odot$ of 2–4 Myr old stars.
- **Then, would it be possible to form a star cluster outside the central parsec and bring it to the center within a few Myr?**

Dynamical Friction

- Dynamical friction might be able to do the job (Gerhard 2000, among others).
- If a star cluster is massive enough, it will feel a dragging force in the direction opposite to its motion due to the “wake” behind it, and such dynamical friction will eventually bring the cluster to the Galactic center.



The Chandrasekhar Formula

- Numerical simulations of dynamical friction for globular clusters and satellite galaxies in the halo have shown that the Chandrasekhar formula (Chandrasekhar 1943) provides an accurate description for the orbital motion of a body experiencing dynamical friction:

$$\mathrm{Drag} = -5.4\, G^2 \ln \Lambda \frac{\rho_{\mathrm{gal}} M_{\mathrm{cl}}^2}{v_{\mathrm{cl}}^2}$$

- However, the Chandrasekhar formula describes the orbiting cluster as a single, rigid particle, while the final capture of the cluster by the central compact object will be determined by the detailed structure of the disrupting cluster at the final moment, which can be obtained only through numerical simulations.

Observational Constraints

- Move the cluster in ~5 Myr.
- Leave a few tens of massive stars (>50 $M_\odot$).
- Put almost all massive stars inside the central 0.5 pc.

Numerical Considerations

- Dynamical Friction on the Cluster
- Internal Dynamics of the Cluster
- Growth of the IMBH in the Cluster
- The Galactic Potential

Related Works

- (Semi-) Analytical Studies
  - Kim, Morris & Lee (1999)
    – Dynamical friction on the Arches & Quintuplet clusters
  - Gerhard (2001)
    – Dynamical friction as a mechanism to bring young stars to the central parsec
  - McMillan & Portegies Zwart (2003)
    – Survey of dynamical friction timescales
  - Hansen & Milosavljević (2003)
    – Dynamical friction of star clusters with an IMBH

Related Works (cont.)

- Numerical Studies
  - Kim & Morris (2000, 2003)
    - Central parsec cluster (collisionless n-body, Gadget)
  - Portegies Zwart, McMillan & Gerhard (2003)
    - IRS 16 (collisional n-body, Starlab)
  - Kim, Figer & Morris (2004)
    - Central parsec cluster (collisionless n-body with IMBH, Gadget)
  - Gürkan & Rasio (2004)
    - Central parsec cluster (collisional n-body with IMBH, Monte Carlo)
  - Kim et al. (2005, in prep.)
    - Central parsec cluster (collisional n-body with IMBH, Aarseth Nbody6)

Simulation Set 1 :
Star Clusters without an IMBH

- Goals
  - Find the initial cluster conditions that result in the observed distribution of massive stars in the central parsec.
  - Accurately calculate the dynamical friction.
  - Ignore the internal dynamics.

Star Clusters without an IMBH

Simulation

- Code: Parallelized tree n-body code, GADGET (Springel, Yoshida, & White 2000)
- No. of particles: 2×10^6 for the Galaxy
  10^5 for the cluster (representing stars and remnant gas)
  1 for the black hole
- Initial density models: Truncated, softened power-law for the Galaxy

$$\frac{4\times10^6}{1+(r/0.17\mathrm{pc})^{1.8}}\exp(-(r/80\mathrm{pc})^6) \quad M_\odot\ \mathrm{pc}^{-3}$$

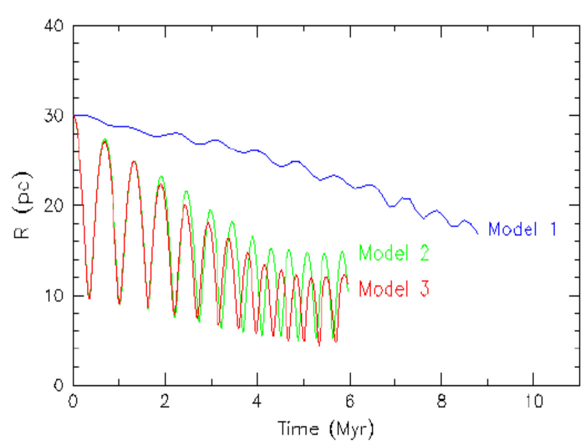
Plummer sphere for the cluster

$$\frac{3M_{\mathrm{cl}}}{4\pi r_{\mathrm{cl}}^3}\left(1+\frac{r^2}{r_{\mathrm{cl}}^2}\right)^{-5/2}$$

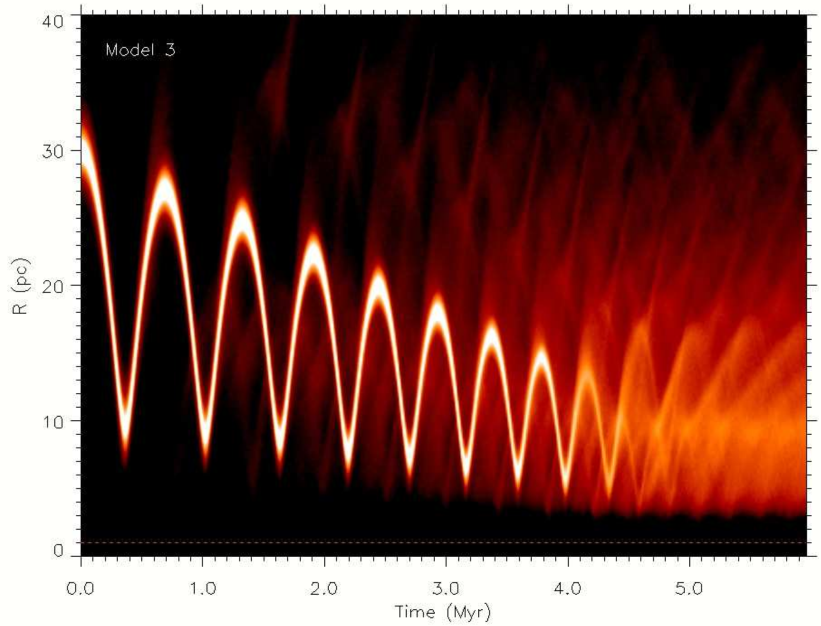
Star Clusters without an IMBH:

Massive Version of Arches & Quintuplet

- R = 30 pc
- $M_{cl} = 10^6 M_\odot$
- Moderate Concentration
  $r_{tidal} / r_{core} = 6$
  $\rightarrow \rho_{core} = 1.3\times10^5 M_\odot\ pc^{-3}$
- Model 1 : Circular Orbit
- Model 2 : Eccentric Orbit
- Model 3 : Eccentric Orbit & Rotating Galaxy



Star Clusters without an IMBH:
Massive Version of Arches & Quintuplet (cont.)

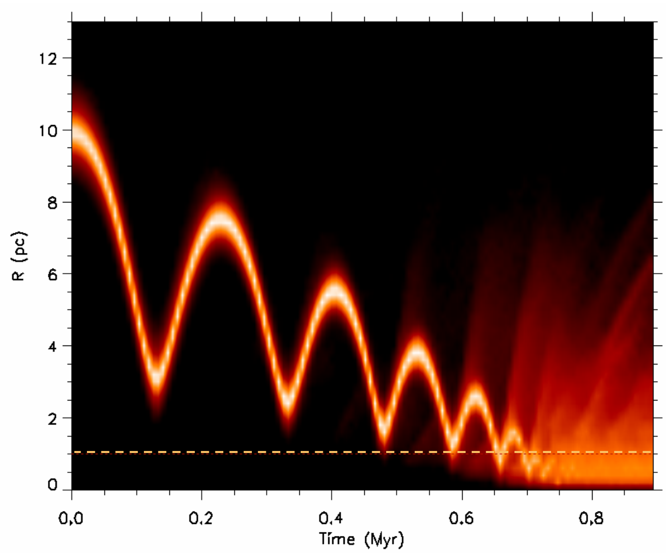


Star Clusters without an IMBH:
10^6 $M_{\odot}$ Cluster at 10 pc

- R = 10 pc
- M_{cl} = 10^6 $M_{\odot}$
- Moderate Concentration

  r_{tidal} / r_{core} = 9.3

  $\rightarrow \rho_{core} = 3.8\times10^6\ M_{\odot}\ pc^{-3}$
- Eccentric Orbit

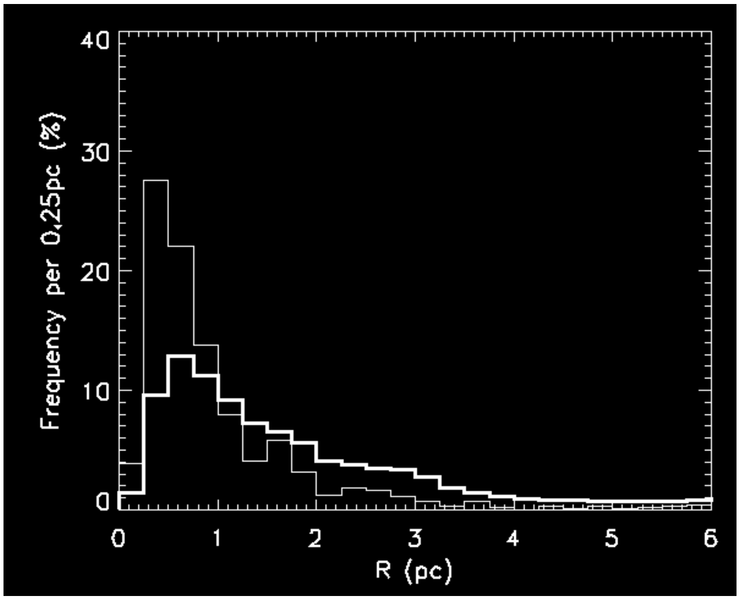


Star Clusters without an IMBH:

10^6 M☉ Cluster at 10 pc (cont.)

Thick line : whole cluster

Thin line : cluster core



Star Clusters without an IMBH:

10^6 M☉ Cluster at 10 pc (cont.)

- 90% of the core 1% stars are found within the central parsec of the projected sky at the final stage.
- This gives a probability of 19% for all He I stars to be found within the central parsec.
- For a Salpeter IMF, # of He I stars would be ~500.

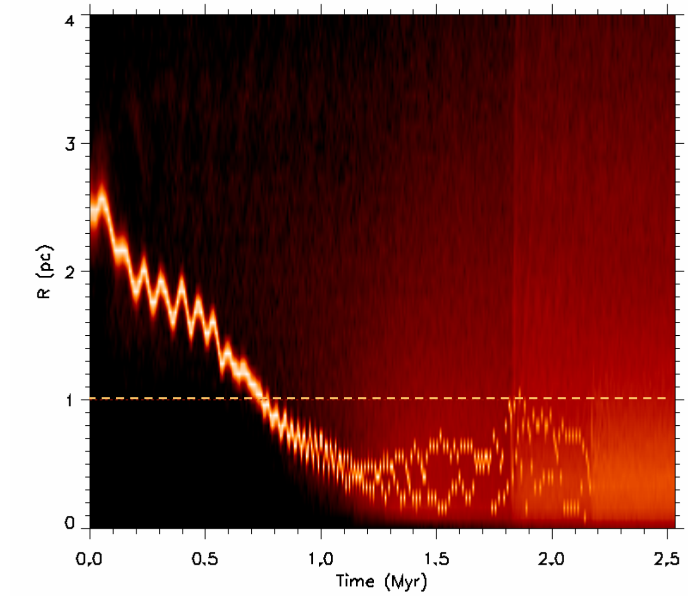
Star Clusters without an IMBH:

$10^5\ M_\odot$ Cluster at 2.5 pc

- R = 2.5 pc
- $M_{cl} = 10^5\ M_\odot$
- Large Concentration

  $r_{tidal} / r_{core} = 12$

  $\rightarrow \rho_{core} = 1.3\times10^8\ M_\odot\ pc^{-3}$
- Circular Orbit

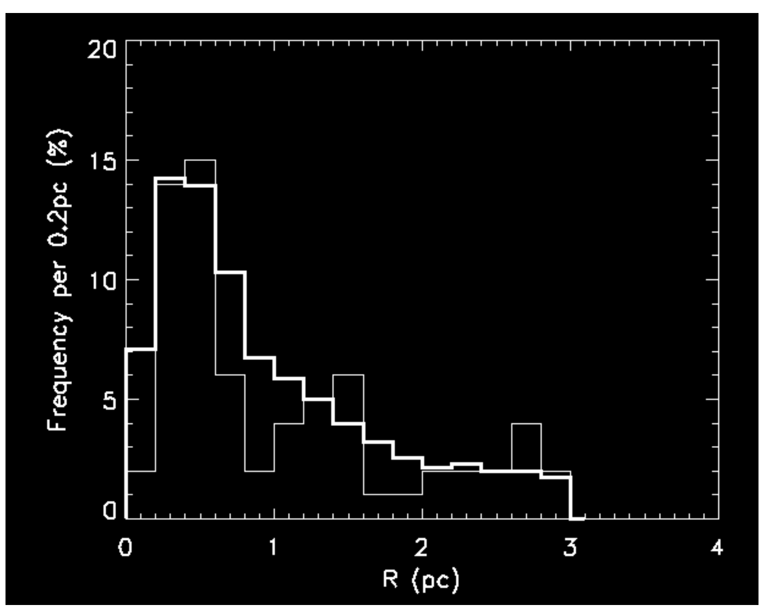


Star Clusters without an IMBH:

$10^5\ M_\odot$ Cluster at 2.5 pc (cont.)

Thick line : whole cluster

Thin line : cluster core



Star Clusters without an IMBH:
$10^5\ M_\odot$ Cluster at 2.5 pc (cont.)

- 90% of the cluster stars are found within the central parsec of the projected sky at the final stage.
  → ~20% chance for all He I stars to be found within the central parsec.

Star Clusters without an IMBH:
Conclusion

- Dynamical friction *CAN* bring a cluster down to the central parsec within the lifetime of He I stars.
- $10^6\ M_\odot$ Clusters :
  - need to start at $R \leq 10$ pc
  - need to initially have He I stars in the cluster core
- $10^5\ M_\odot$ Clusters :
  - need to start at $R \leq 5$ pc
  - need to initially have very high central density

Simulation Set 2 :
Star Clusters with an IMBH

- Hansen & Milosavljević (2003) suggested that an IMBH in the cluster core can stabilize the core against disruption and more easily bring young stars down to the central parsec.
- Goals
  - Redo the previous simulations with IMBHs.
  - Accurately calculate the dynamical friction and ignore the internal dynamics.

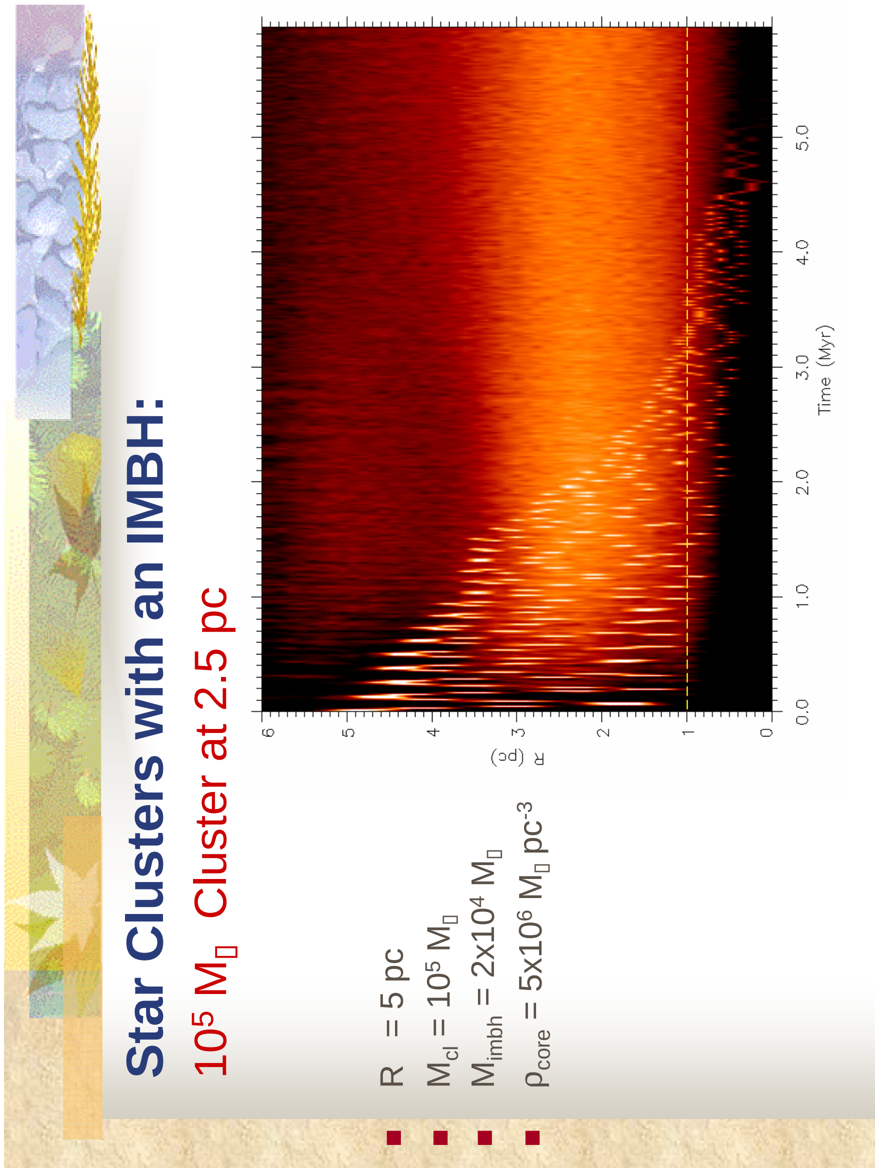
Star Clusters with an IMBH:
Simulation

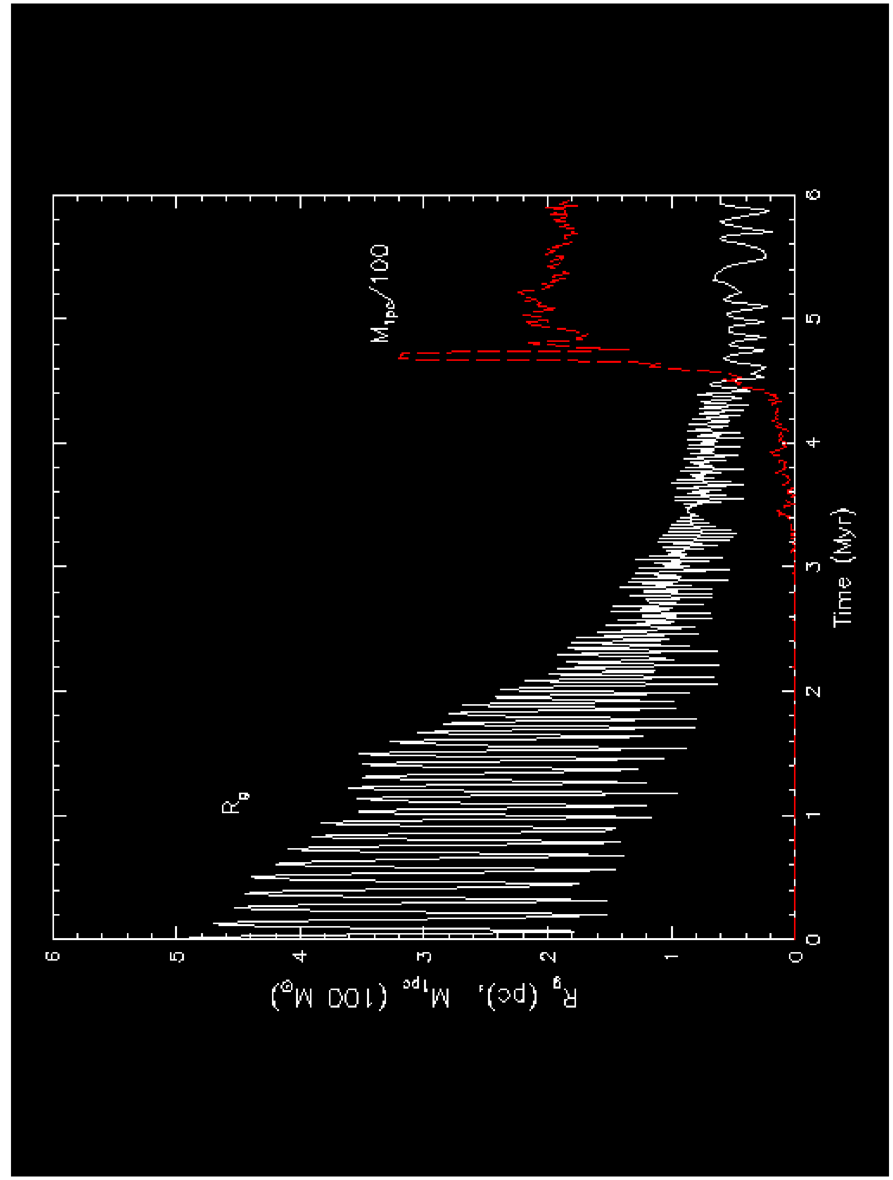
- Code: Parallelized tree n-body code, GADGET (Springel, Yoshida, & White 2000)
- No. of particles:
  - 2.8×10^5 for the Galaxy
  - 10^4 for the cluster
  - 1 for the SMBH
  - 1 for the IMBH
- Initial density models: Truncated, softened power-law for the Galaxy

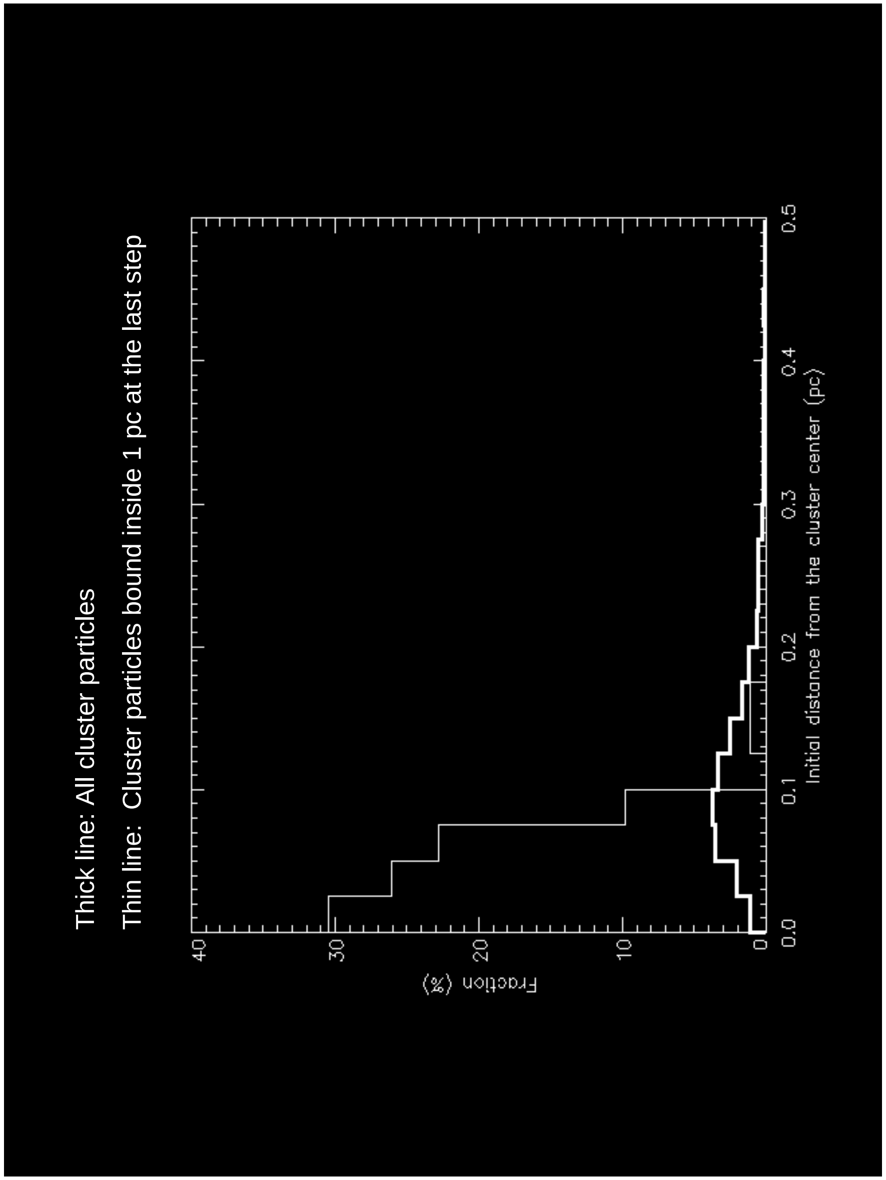
$$\frac{4\times10^6}{1+(r/0.17\mathrm{pc})^{1.8}}\exp(-(r/80\mathrm{pc})^6)\ \mathrm{M}_\odot\ \mathrm{pc}^{-3}$$

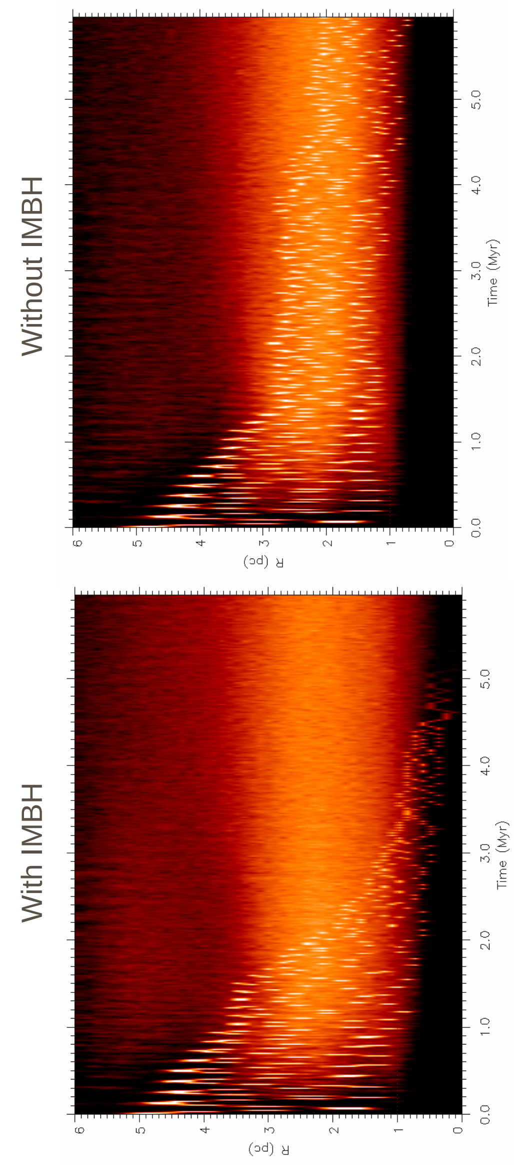
Plummer sphere for the cluster

$$\frac{3M_{\mathrm{cl}}}{4\pi\, r_{\mathrm{cl}}^3}\left(1+\frac{r^2}{r_{\mathrm{cl}}^2}\right)^{-5/2}$$


Star Clusters with an IMBH:
10^5 M☉ Cluster at 2.5 pc
R = 5 pc
$M_{cl} = 10^5$ M☉
$M_{imbh} = 2\times10^4$ M☉
$\rho_{core} = 5\times10^6$ M☉ pc^{-3}
R (pc)
Time (Myr)


R_g
$M_{1pc}/100$
R_g (pc), M_{1pc} (100 M☉)
Time (Myr)


Thick line: All cluster particles
Thin line: Cluster particles bound inside 1 pc at the last step
Fraction (%)
Initial distance from the cluster center (pc)
0.0
0.1
0.2
0.3
0.4
0.5
0
10
20
30
40


With IMBH
Without IMBH
Time (Myr)
R (pc)

Star Clusters with an IMBH:

Conclusion

- IMBHs *do* help bringing a star cluster to the central parsec with less extreme initial conditions (cluster mass and central density).
- For 10^5 $M_\odot$ clusters initially at 5 pc, the IMBH mass should be larger than 10 % of the cluster mass.
- This mass fraction is much larger than that estimated by Portegies Zwart & McMillan with numerical simulations of IMBH formation by successive merging of stars, 0.1~0.2 %.

Simulation Set 3 :

Star Clusters with an IMBH & Internal Dynamics

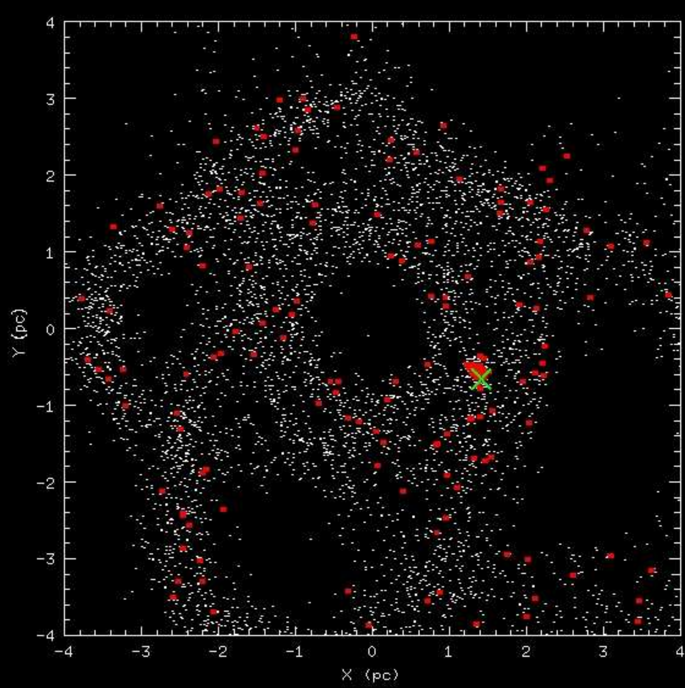
- Compact clusters suffer two-body relaxation between cluster stars, which may cause core collapse, mass segregation, and formation of an IMBH by runaway collisions.
- Goals
  - Accurately calculate the internal dynamics.
  - For dynamical friction, use the Chandrasekhar formula calibrated to the previous simulations.

Star Clusters with an IMBH & Internal Dynamics:

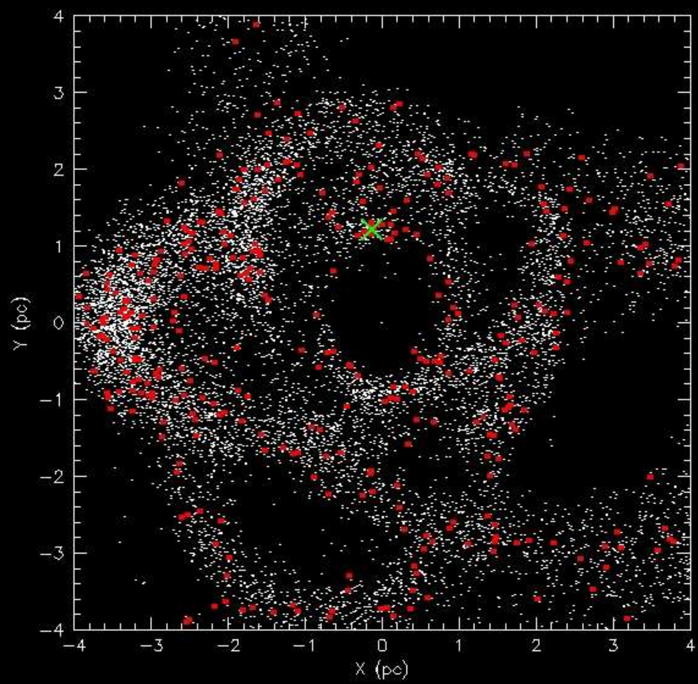
Simulation

- Code: Aarseth's Nbody6
- 13024 stars
- Mass function : α=1.75, $m_L = 1\ M_\odot$, $m_U = 150\ M_\odot$
- Density profile: King models with W_0=4 or 10
- Galactic potential: Softened power-law density models

- R = 5 pc
- $M_{cl} = 10^5\ M_\odot$
- $W_0 = 10$



- R = 5 pc
- $M_{cl} = 10^5 M_{\odot}$
- $W_0 = 4$
- $M_{imbh} = 10^3 M_{\odot}$



Summary

- Transportation of young stars into the central parsec in few Myr via dynamical friction is possible.
- However, the observed distribution of massive stars in the central parsec is not easily obtained with the dynamical friction scenario.
- The observed number of massive stars in the central parsec is another challenging constraint to the scenario.
- Formation of an IMBH in the cluster core does not significantly alleviate the above problems.