Fully self-consistent *N*-body simulation of star clusters near the Galactic center

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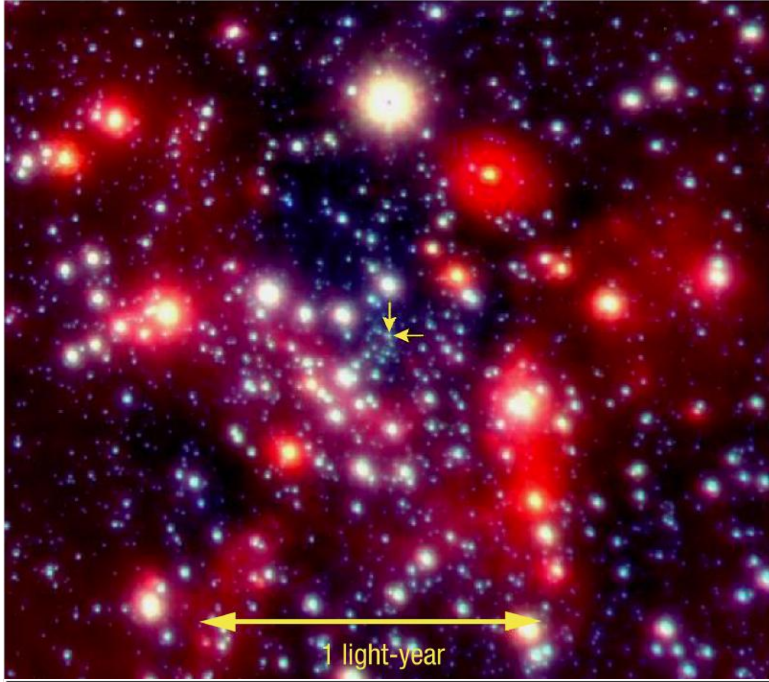
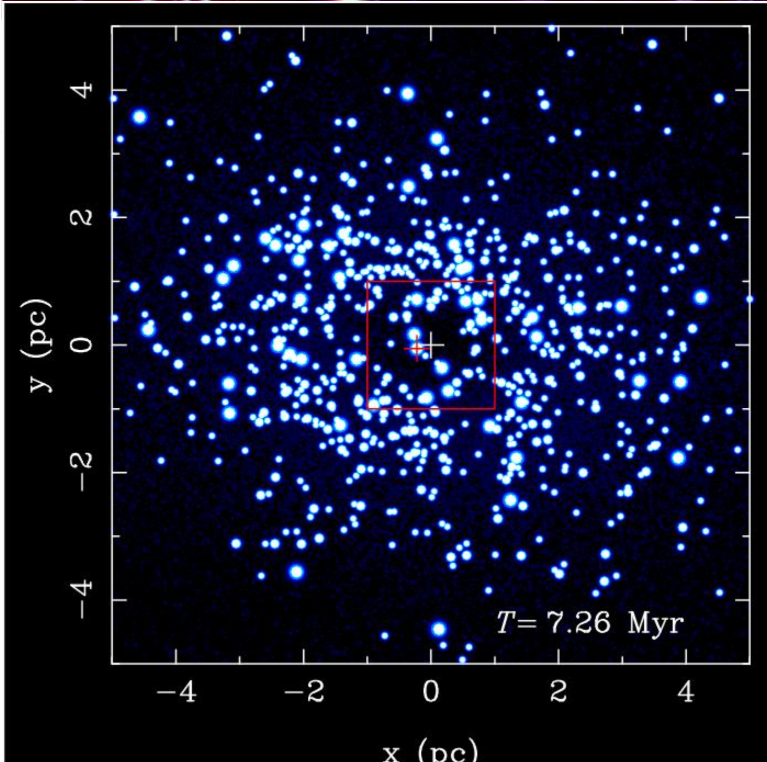
Abstract

- Young massive stars near the Galactic center (GC)
  - Were they carried by clusters?
- Fully self-consistent *N*-body simulation of star clusters and their parent galaxy systems
  - Both clusters and the host galaxy are modeled as *N*-body systems
  - Stellar collisions → formation of an IMBH
  - We developed a new scheme.
- If an IMBH formed in a cluster, young stars are carried by the 1:1 mean motion resonance.





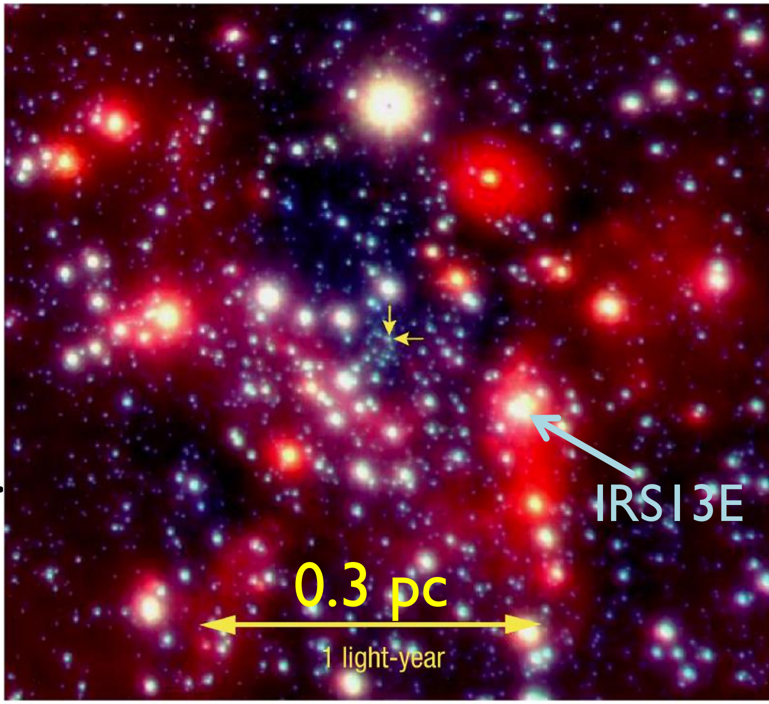
Outline

- Introduction
  - Young massive stars near the Galactic center
  - In-situ formation / star cluster
  - Previous works
- *N*-body simulation
  - BRIDGE: a direct-tree hybrid code
  - With runaway collisions and mass loss
- Results
  - New mechanism to carry young stars
- Summary

Introduction: Observations

- Young massive stars (OB stars) in the Galactic center
  - R <~ 1 pc from the GC
  - Several Myrs old
  - Eccentric orbits (Paumard et al. 2006; Lu et al. 2006)
  - Located on one/two disks
  - IRS13E (Maillard et al. 2004)
    - It might have an IMBH.
    - A remnant of a cluster core?
  - S-stars (Genzel et al. 2003; Ghez et al. 2005)
    - Very close to the SMBH (R<0.01pc).
- In-situ star formation is difficult.
  - Because of the strong tidal field of the SMBH.

➢ How were they formed?

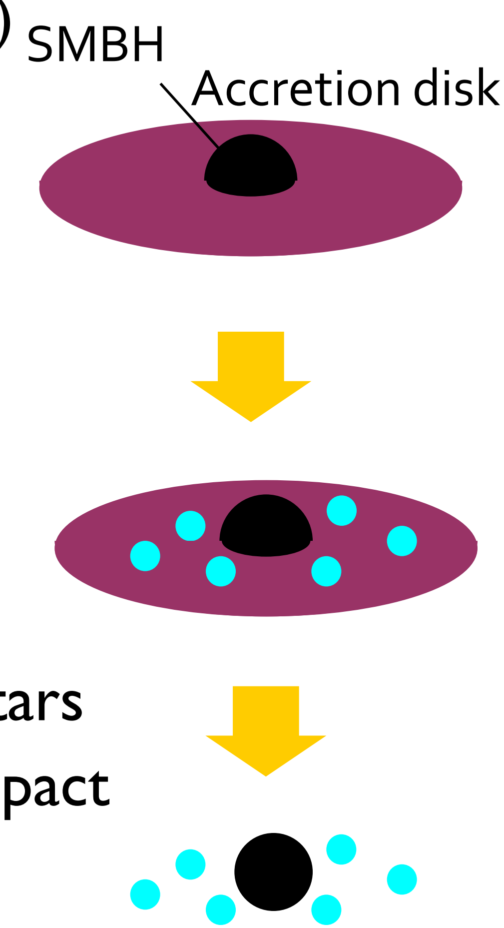


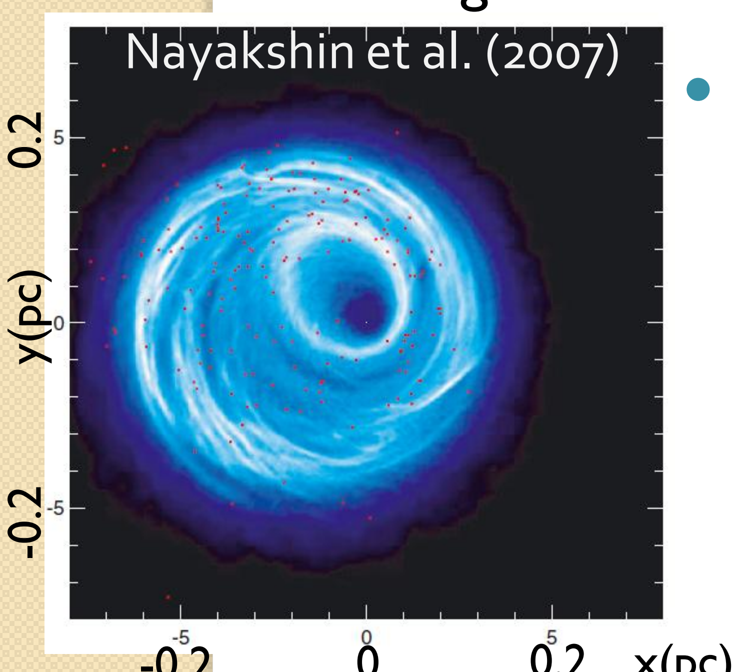
The Centre of the Milky Way
(VLT YEPUN + NACO)

ESO PR Photo 23a/02 (9 October 2002)

I. In-situ formation scenario

- In-situ formation (Levin & Beloborodov 2003)
  - A massive gaseous disk formed around the central SMBH.
  - Disk became gravitationally unstable, fragmentation occurred in it.
  - The fragments collapsed to stars

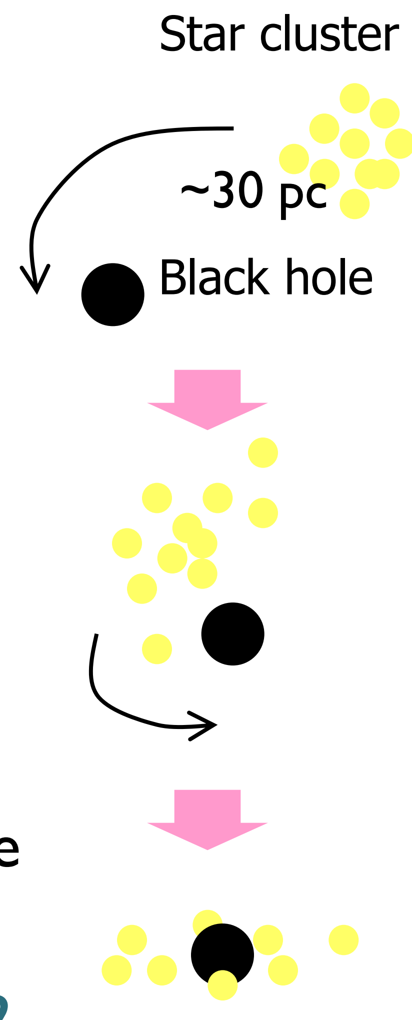




- Some problems
  - Two disks?
  - High eccentricities of stars
  - Difficult to make a compact system like IRS 13E.
  - S-stars?

2. Star cluster inspiral scenario

- Cluster inspiral scenario (Gerhard 2001)
  - A star cluster formed (like Arches cluster).
  - It migrated through the dynamical friction.
  - (An IMBH formed.)
  - Disrupted by the tidal field of the SMBH.
  - Within several Myrs.
- Comparison with observation
  - An eccentric orbit of a cluster can produce stars with eccentric orbit.
  - IRS 13E might be a remnant of a cluster core with an IMBH.
- How fast/deep can a cluster carry stars?

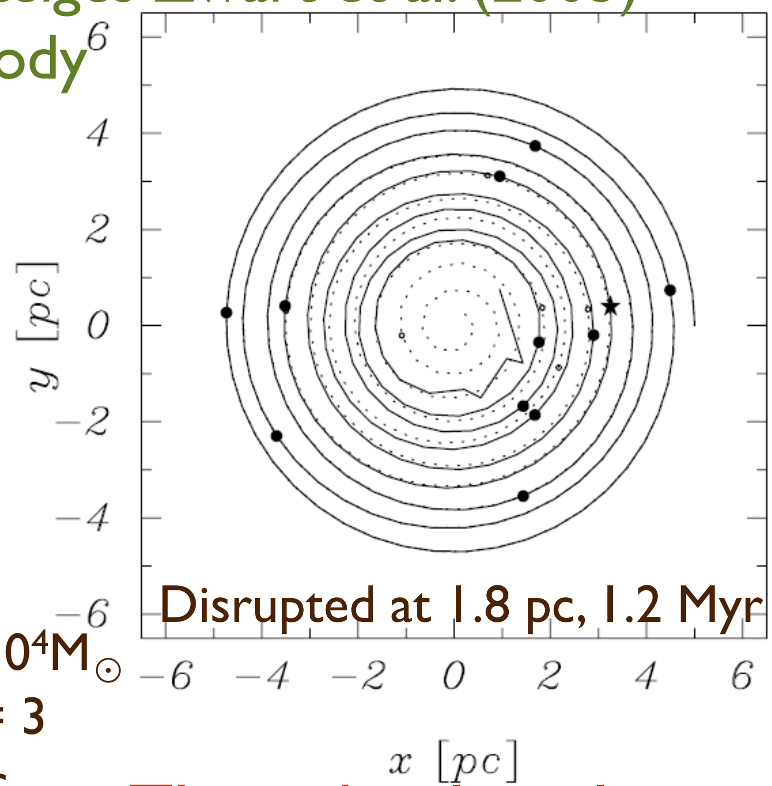


Previous simulations 1

- They calculated internal evolution of star clusters properly.
- Their orbital evolutions were calculated semi-analytically.
- Very massive/dense clusters are needed.

Porteiges Zwart et al. (2003)

N-body



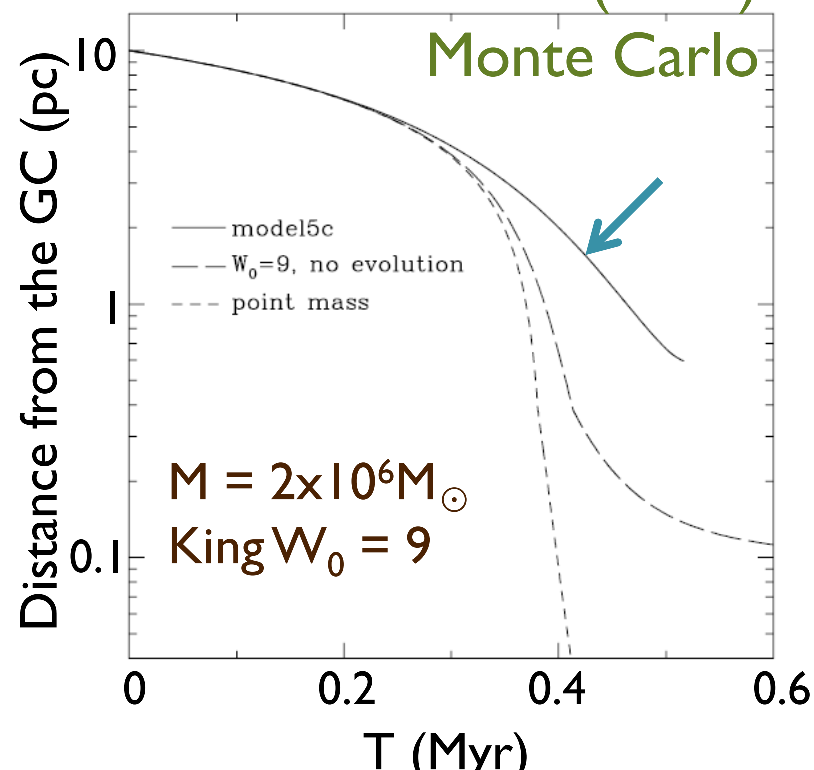
$M = 6.4 \times 10^4 M_\odot$

King $W_0 = 3$

$r_c = 0.2$ pc

Gürkan & Rasio (2005)

Monte Carlo



$M = 2 \times 10^6 M_\odot$

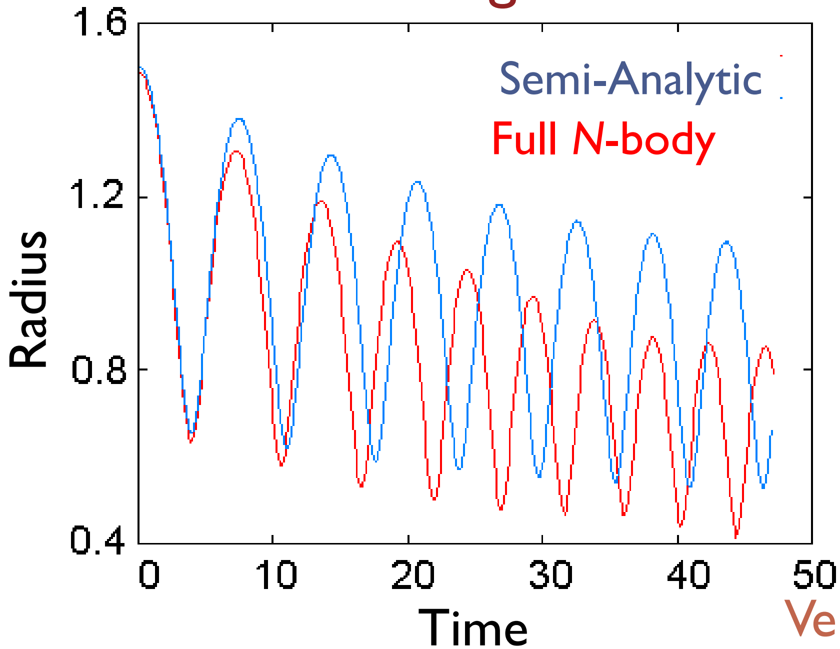
King $W_0 = 9$

The orbital evolution might be incorrect!

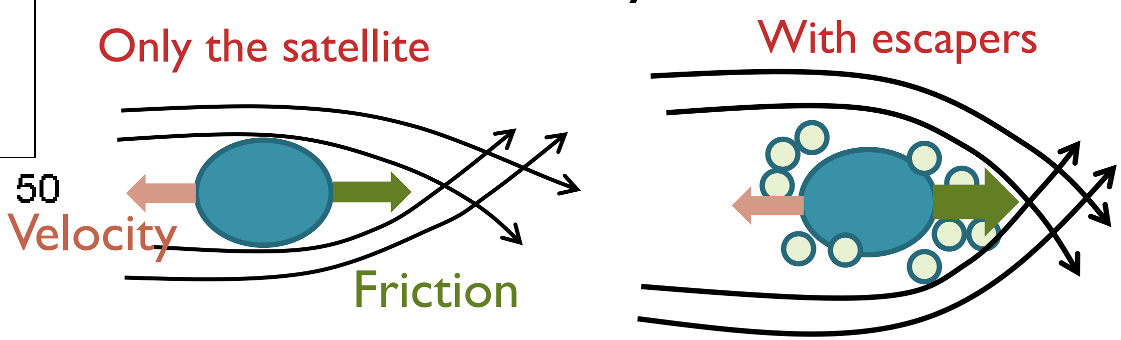
Dynamical friction on subsystems

(Fujii et al. 2006)

Orbital evolution of satellite galaxies



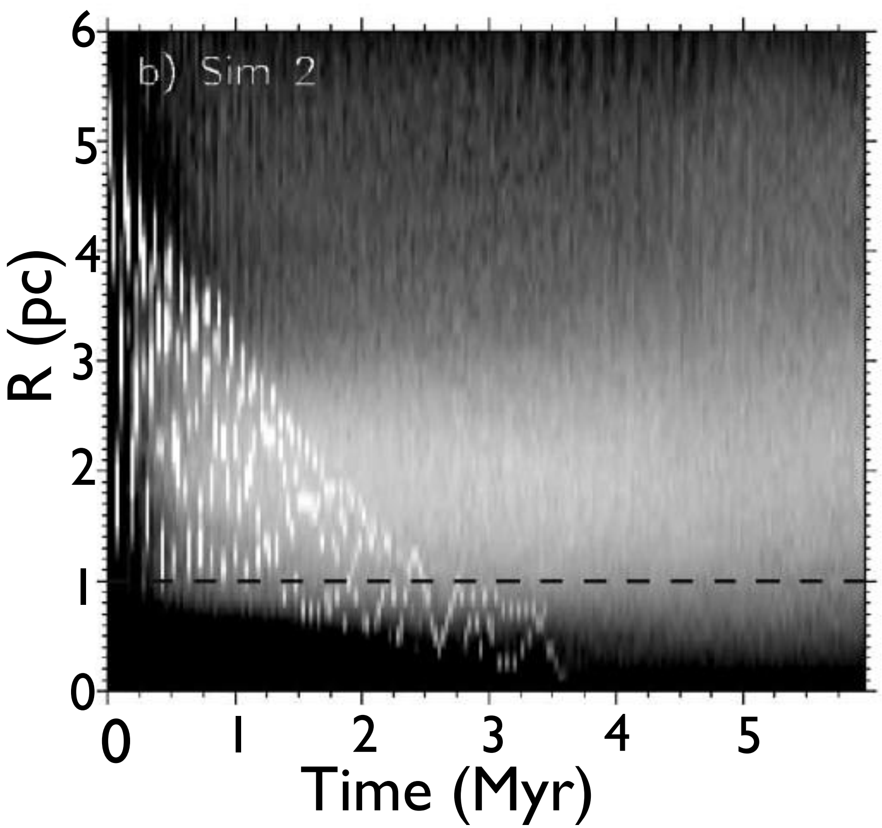
- Stars escaping from the satellite enhance the friction
  - Escaping stars
  1. Act as a direct drag force
  2. Remain close to the satellite and enhance the dynamical friction



- Full *N*-body simulation is needed to obtain correct orbital evolutions.

Previous simulations 2

- Kim et al. (2004)
  - Self-consistent *N*-body simulation
  - Initially contain an IMBH (It makes a cluster survive longer.)

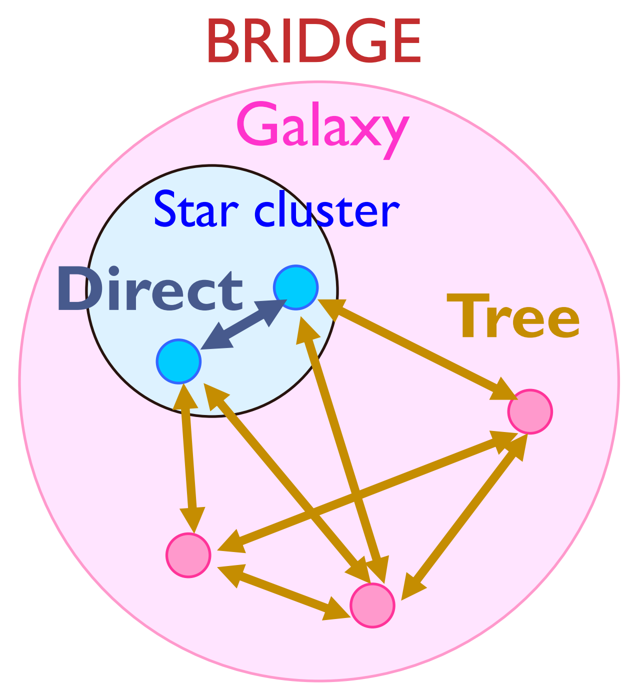


Initial conditions of this cluster
M = $1\times10^5 M_\odot$, equal mass
$M_{IMBH} = 2\times10^4 M_\odot$
Plummer model
r_c = 0.13 pc

They could not treat the internal evolution of clusters, because they used a tree code.

Fully self-consistent *N*-body simulation

- No simulation could treat the internal and orbital evolution of clusters at the same time.
- It was difficult to treat both galaxies and clusters as *N*-body models.
  - Star cluster
    - Small-*N*, need high accuracy
    - Direct + Hermite integrator
      - The cost is $O(N^2)$
  - Galaxy
    - Large-*N*, need fast scheme
    - Tree + leapfrog integrator
      - Low accuracy



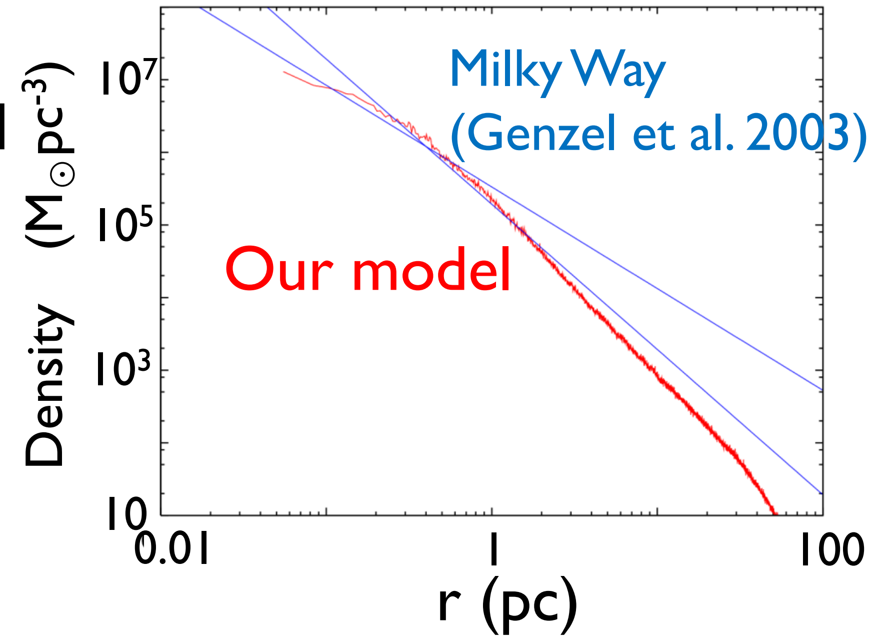
- **BRIDGE**: Direct-tree hybrid code
  - It can treat large-*N* systems with small scale systems fully self-consistently and fast.

(Fujii et al. 2007)

Model

- Stellar collisions (IMBH formation)
- Mass loss due to the stellar wind

- Galaxy
  - King model $W_0 = 10$ + SMBH
    - $M_{BH} = 3.6 \times 10^6 M_\odot$
  - $N = 2 \times 10^6$
  - $M_{Galaxy} = 5.8 \times 10^7 M_\odot$
  - Softening = 4.9×10^{-2} pc



- Star cluster
  - King model $W_0 = 6$, $r_{core} = 0.06$pc
  - $N = 65536$
  - $M_{cluster} = 2.1 \times 10^5 M_\odot$
  - IMF: Salpeter 1 - 100 $M_\odot$
  - Softening = 0.0

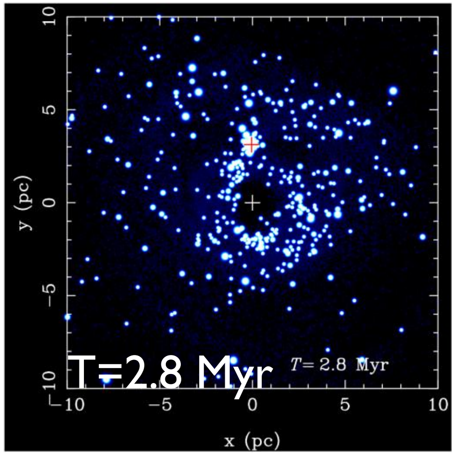
Tried some parameters

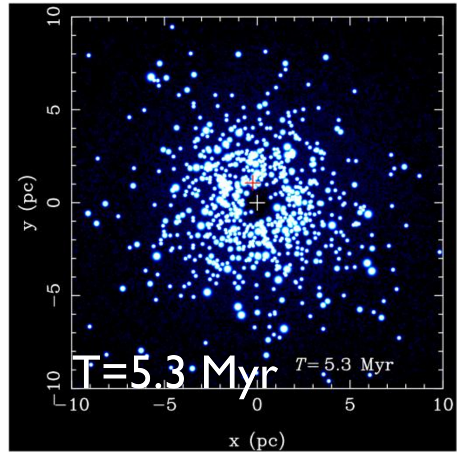
- Mass loss (Castor et al. 1975)
  - $L_* \propto M_*$ (assumption)
  - $dM/dt = c \times M_*$
  - For $m > 300 M_\odot$
- Collision: sticky sphere
- Radius (Herley et al. 2000)

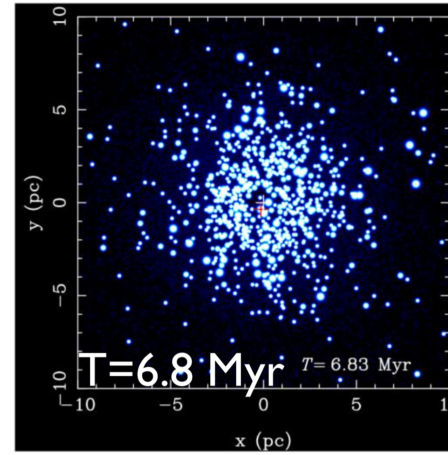
MOVIE

- Only the star cluster is show.
- + show the position of the most massive star in the cluster.
- Calculated using GRAPE6 (~10 days)

Results1: Snapshots and observations

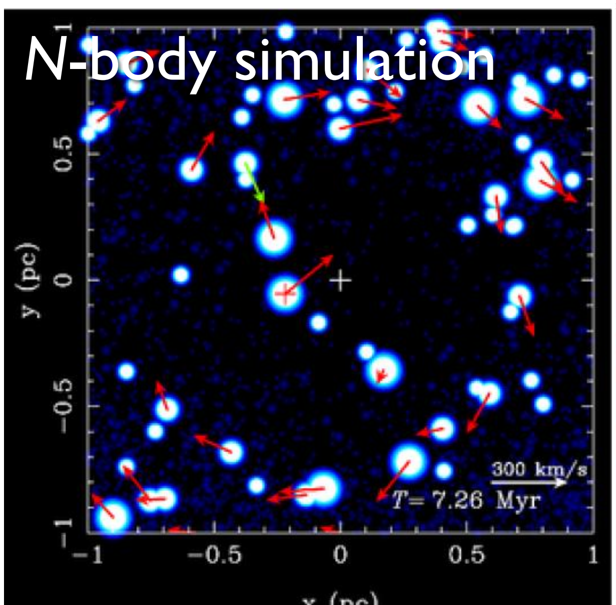


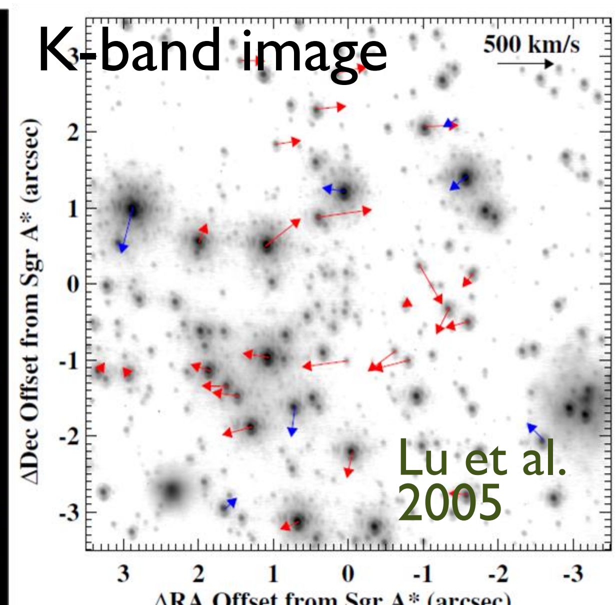




Stars were gradually carried to the GC.

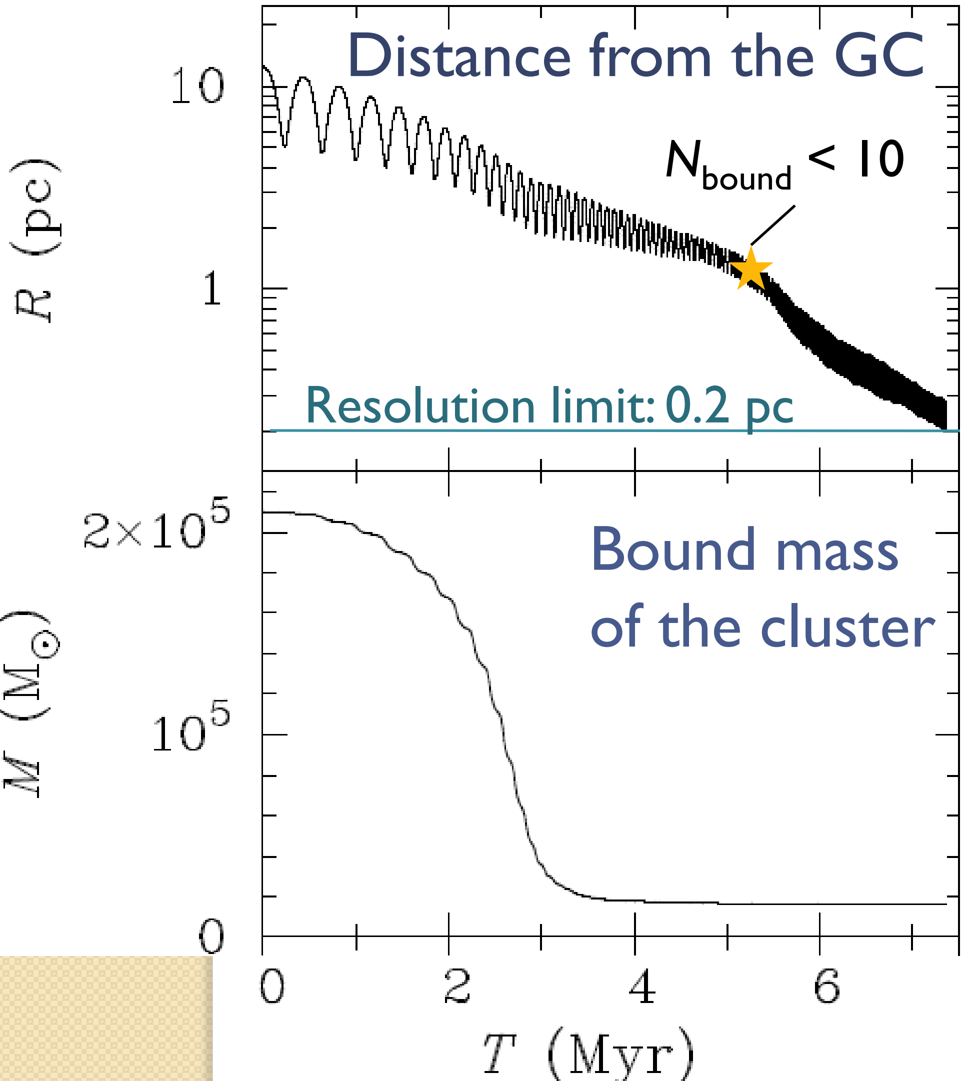
Projection on the same angle as the observed disk

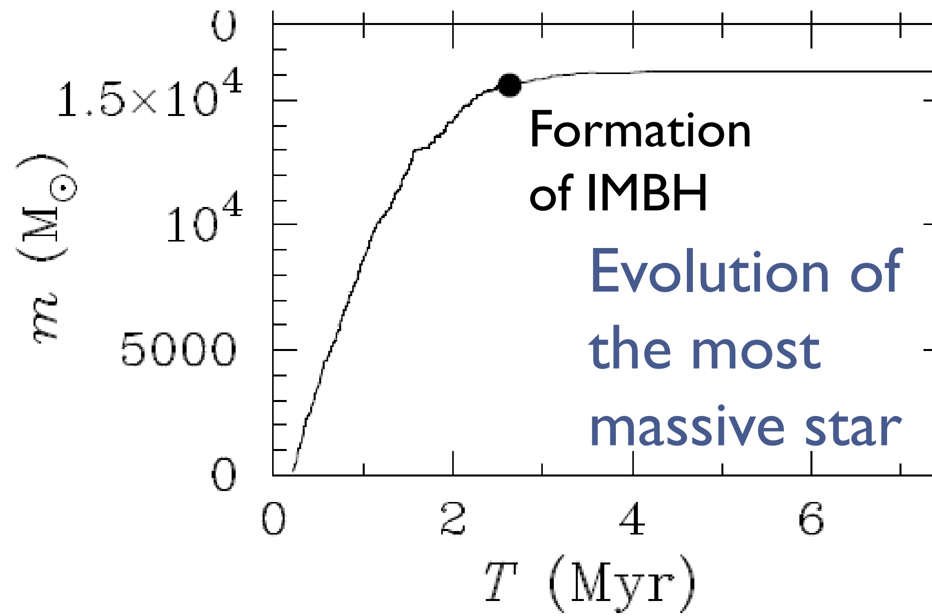




- Our results look like the observed image of the GC.

Results 2: Evolution of the star cluster



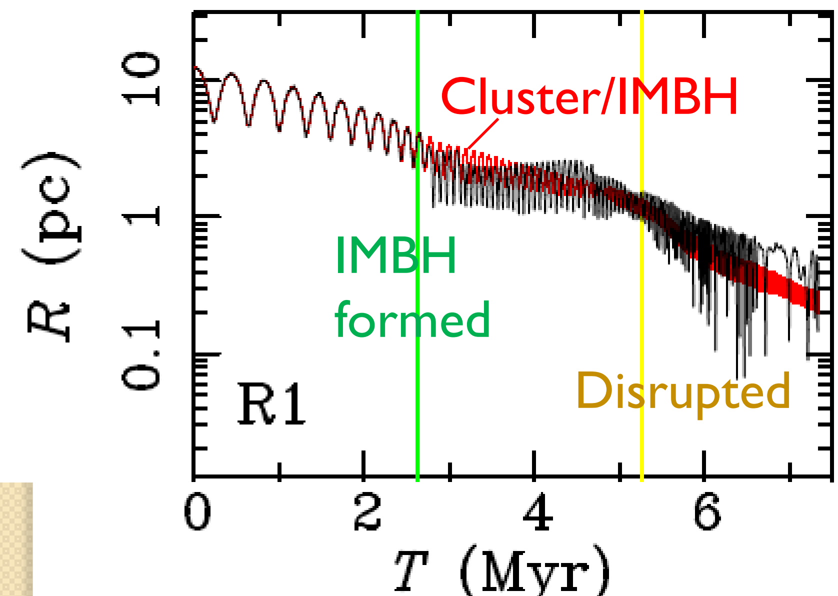


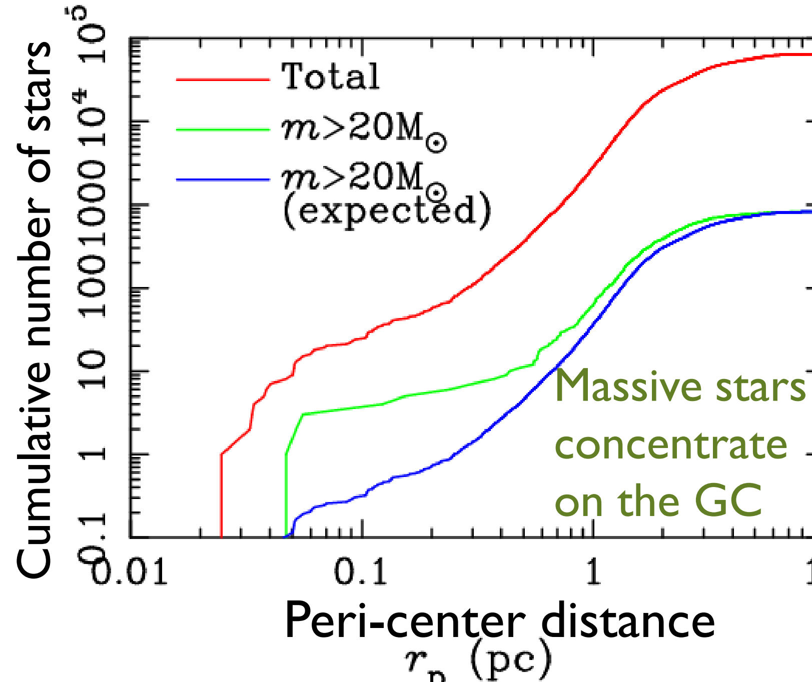
- An IMBH formed in the cluster.
  - After MS-lifetime, without mass loss
- Almost all stars escaped at ~1pc.
- But, many stars were carried to the inner 1pc!

New Scenario: Resonant stars

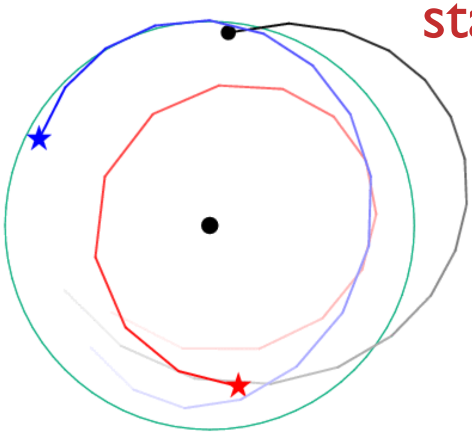
(Fujii et al. 2009, ApJ in press)

Orbital evolution of a star

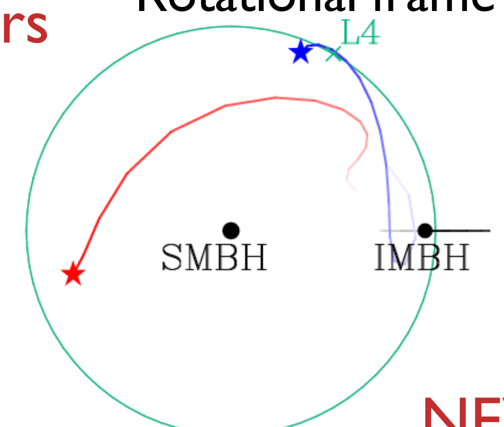




Resonant stars



Rotational frame



Once an IMBH formed in the cluster, the 1:1 mean motion resonance with the SMBH and IMBH carries stars to the GC. (like Trojan stars)

NEW Channel to carry young stars !

Summary

- We performed fully self-consistent *N*-body simulations of star clusters near the Galactic center.
  - We have developed a new direct-tree hybrid code, BRIDGE.
- Once an IMBH formed in the cluster, the 1:1 mean motion resonance carries stars to the Galactic center.
- Star cluster scenario may explain the observation of the Galactic center.