Can globular clusters bring millisecond pulsars in the Galactic center?: Tidal disruption of star clusters in the Galactic center

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Outline

γ-ray excess in the Galactic center

Evolution of globular clusters in the Galactic halo

Formation of the nuclear star cluster

Formation of the Milky Way and globular clusters

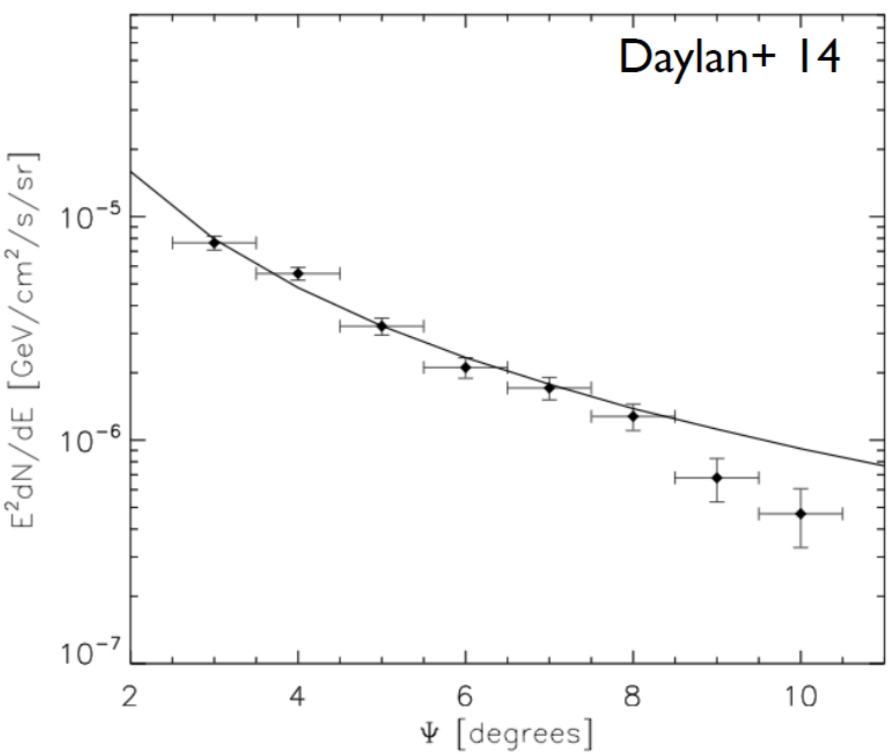
Summary

γ-ray excess in the Galactic center

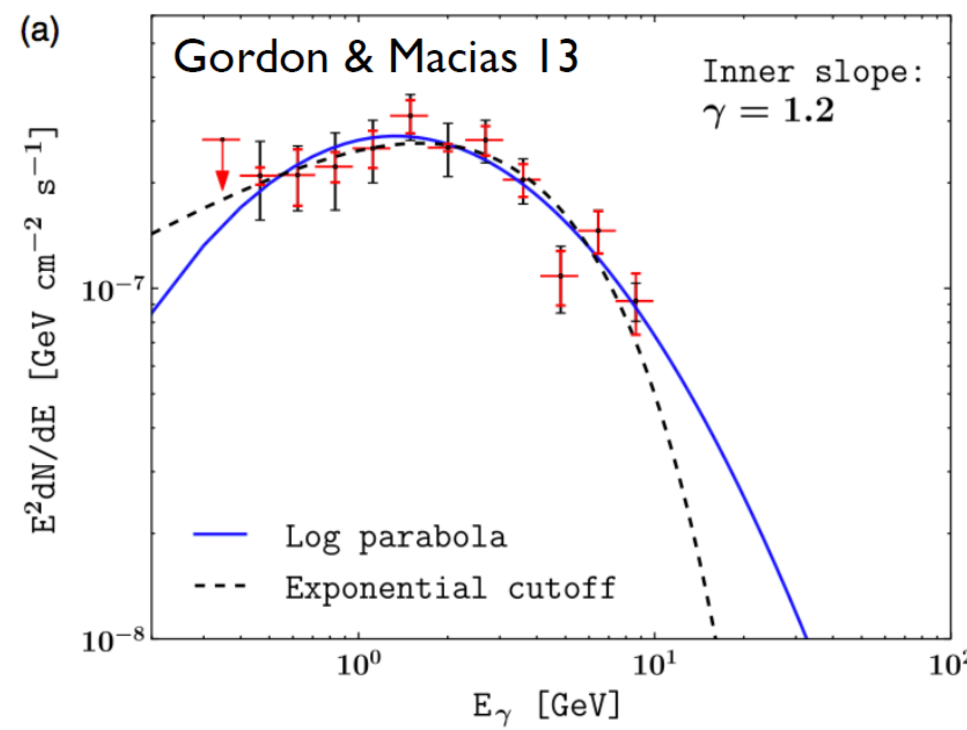
γ-ray excess in the Galactic center

The Fermi satellite detected GeV γ-ray excess from the Galactic center
(Goodenough & Hooper 2009, etc.)

Extend to 1.5-3 kpc from Sgr A*

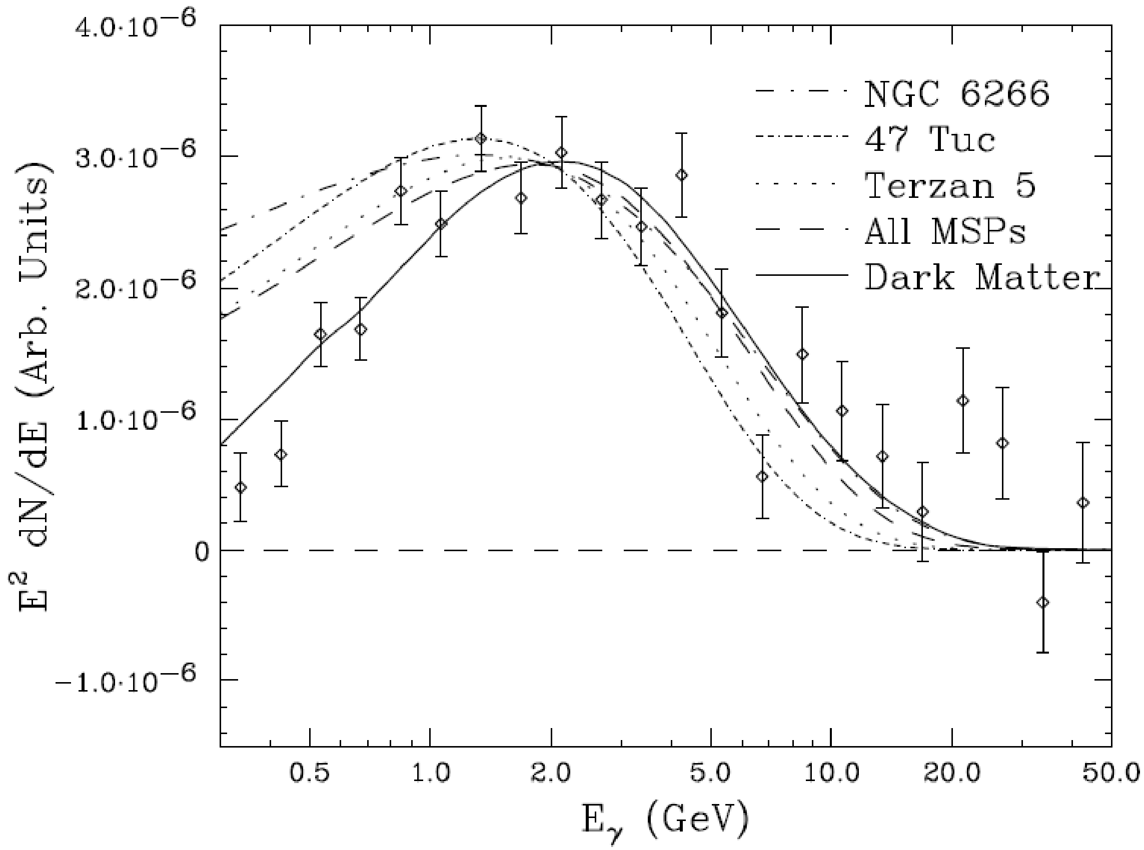


Peak at ~2 GeV



From Ioka-san's slides "Testing MSP Scenario of Gev Excess with VHE gamma-rays"

Millisecond pulsar or dark matter annihilation?



These are famous globular clusters

Daylan et al. (2014)

Millisecond pulsars show a similar spectrum (Bednarek & Sobczak 2013)

Millisecond pulsars (MSPs)

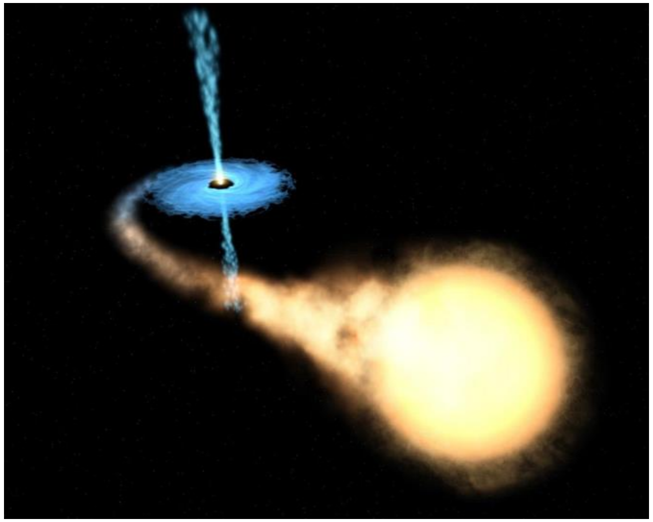
MSP: old, rapidly rotating neutron stars

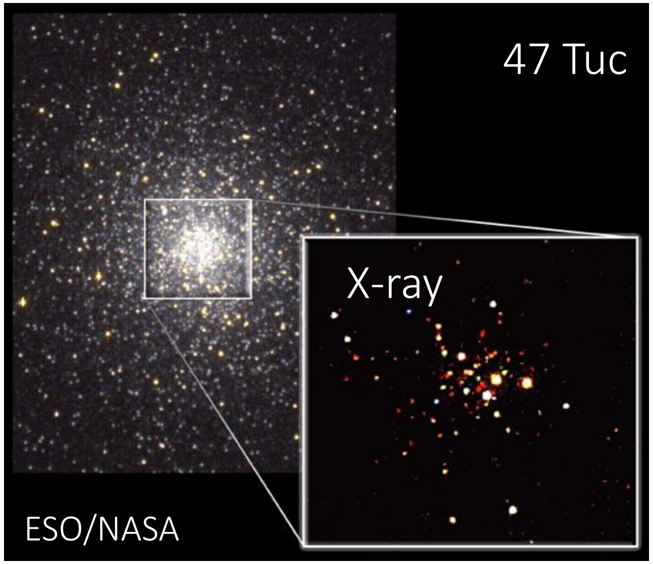
Formed via spin up (or "recycled“) through accretion from a companion star in a close binary system

- Evolved from low-mass X-ray binary

Dense environment of star clusters causes three-body encounters and form very close binaries

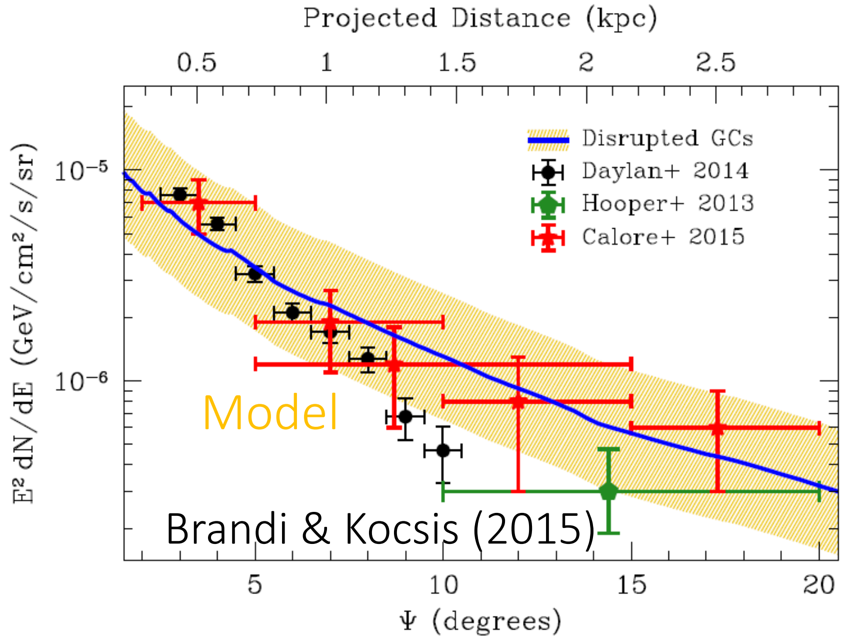
MSPs were observed in globular clusters: Ter 5, 47 Tuc, M15, M28, M62, etc.
(Abdo+ 2010)

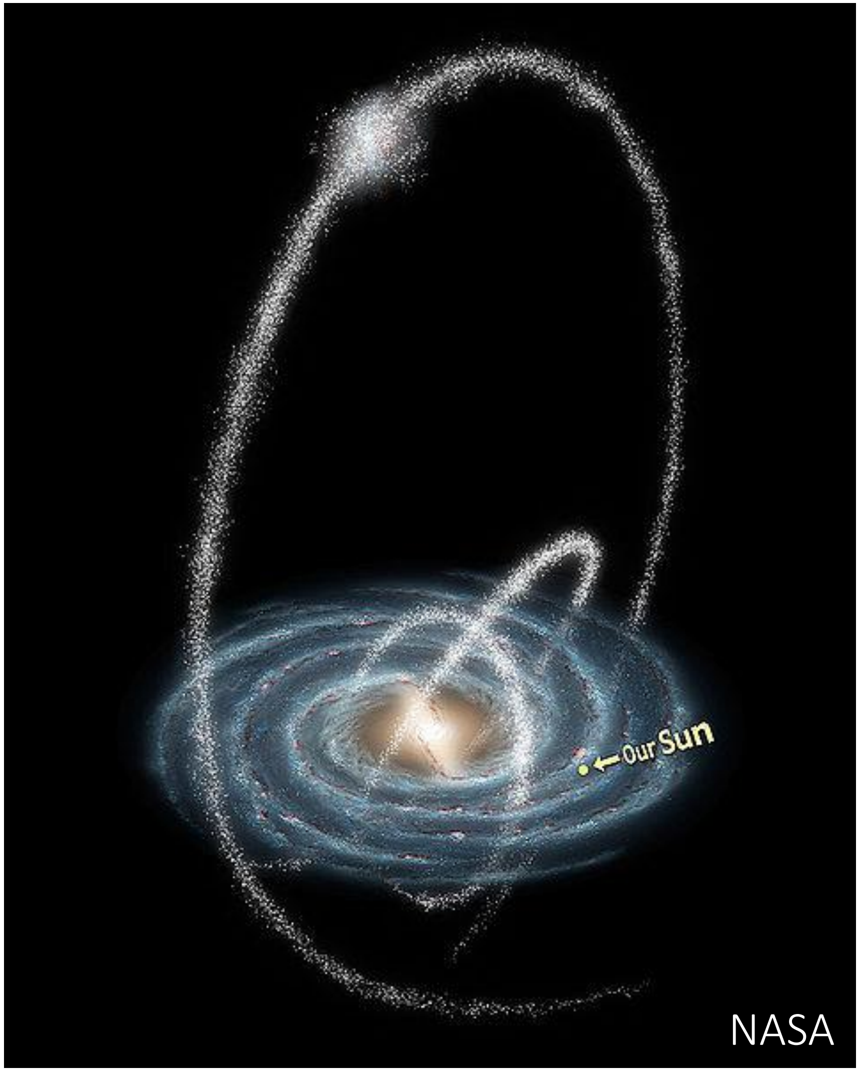




Accretion of globular clusters to the Galactic center

If globular clusters accrete to the Galactic center, MSPs formed in clusters can explain the GeV excess (Bednarek & Sobczak 2013, Brandi & Kocsis 2015)





Evolution of globular clusters in the Galactic halo

Globular clusters in the Milky Way

Age ~ 10 Gyr

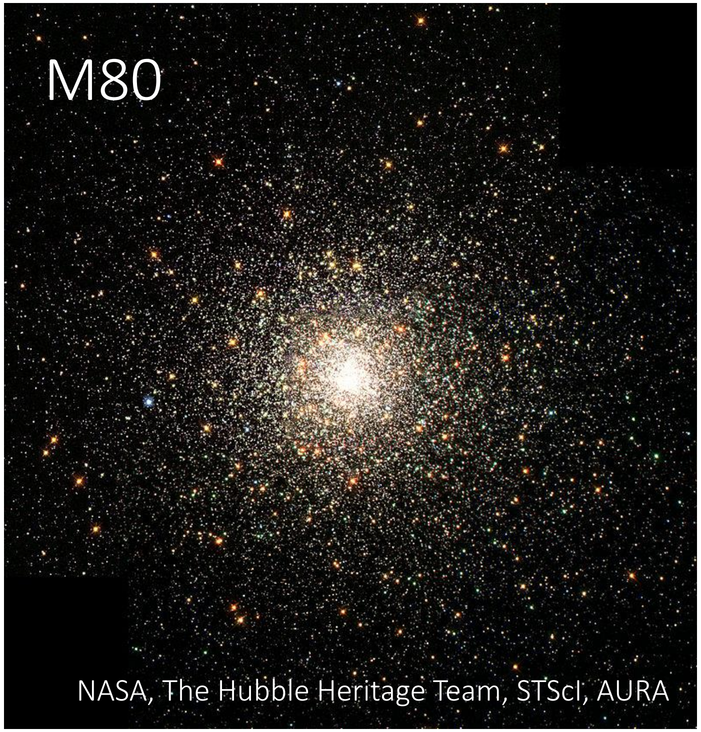
Mass ~ $10^{5\text{-}6}$Msun

Size ~ 10 pc

Located in the Galactic halo

Old, massive, and dense star clusters

The densest environment in the MW except for the Galactic center



The formation process is still unclear

Core of dwarf galaxy? (Omega Cen)

Accreted with dwarf galaxies?

Internal dynamical evolution of clusters

Core collapse: The core shrinks on the relaxation timescale

Mass segregation: Massive stars concentrates on the cluster core due to the energy equipartition

Binary formation: Three-body encounters form hard binaries

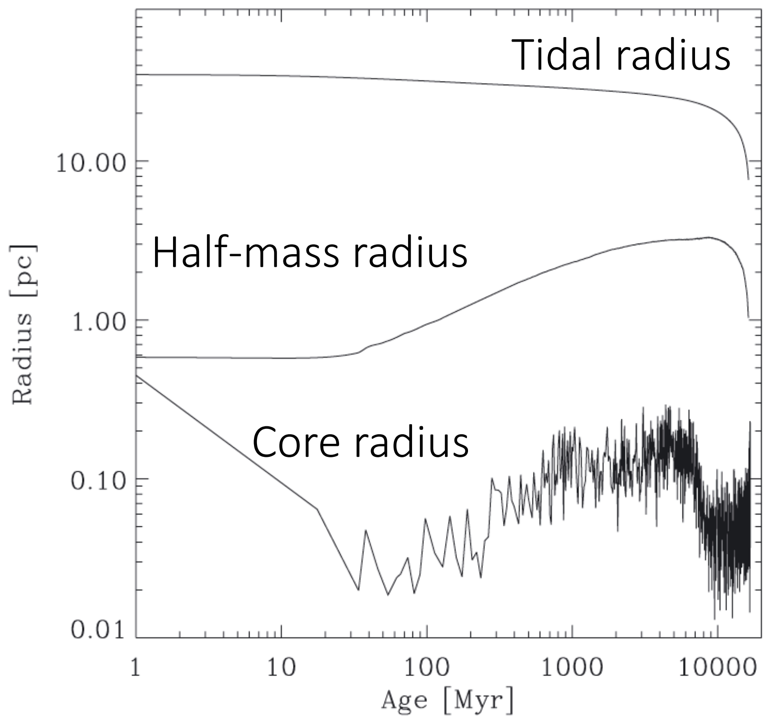
Post-collapse evolution (expansion):
Cluster expands after the core-collapse due to the energy flux from hard binaries

Globular clusters host hard binaries of massive objects such as black holes and neutron stars.

These proceed on the relaxation timescale

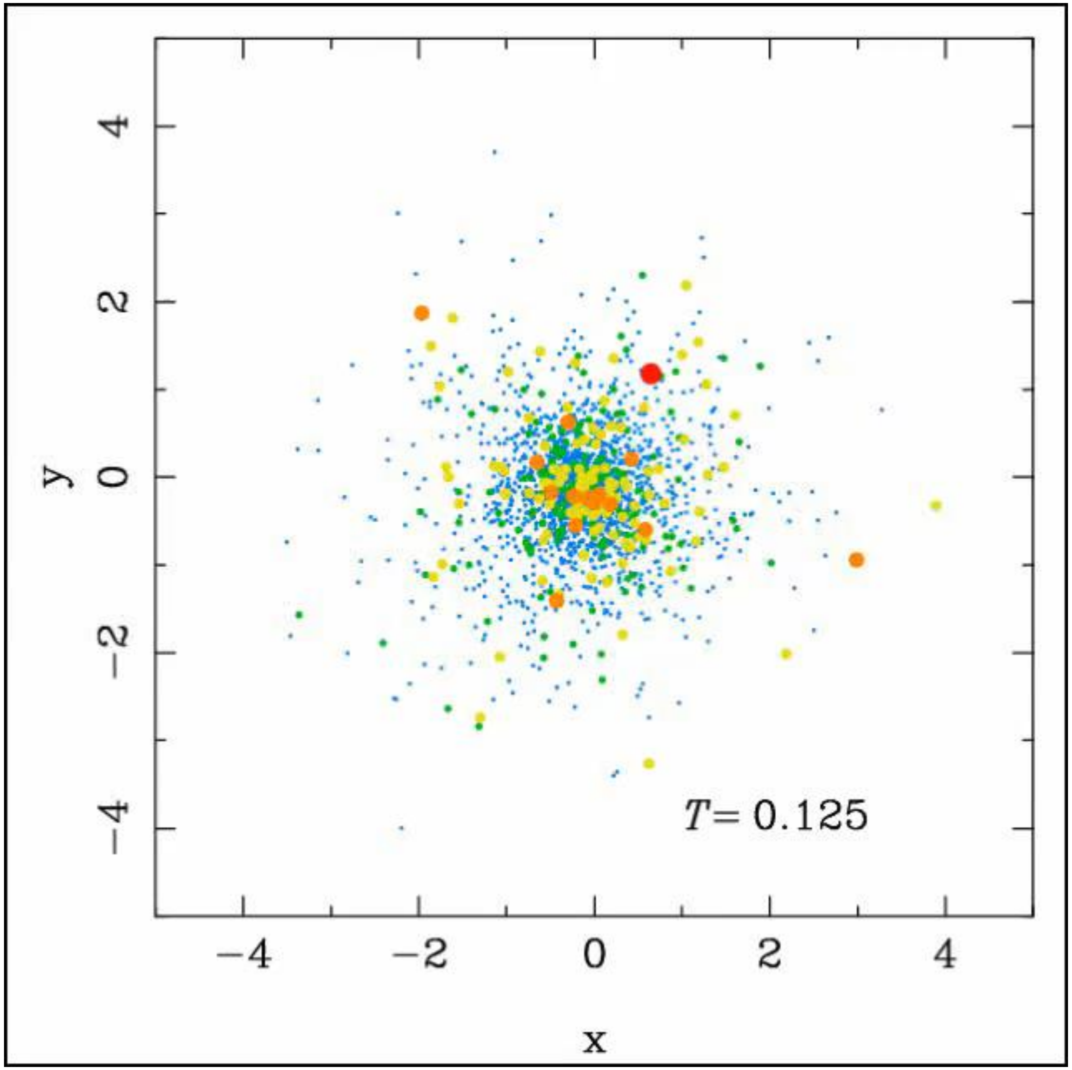
$$t_{\rm rh} \sim 2 \times 10^8\,{\rm year} \left(\frac{M}{10^6\,{\rm M}_\odot}\right)^{1/2} \left(\frac{r_{\rm vir}}{1{\rm pc}}\right)^{3/2} \left(\frac{\langle m \rangle}{{\rm M}_\odot}\right)^{-1}$$

Stellar evolution (incl. evolution of binaries)



Simulation of M4-like globular cluster
Including tidal effect (Giersz & Heggie 2008)
Figure from Gieles et al. (2011)

N-body simulation of star clusters

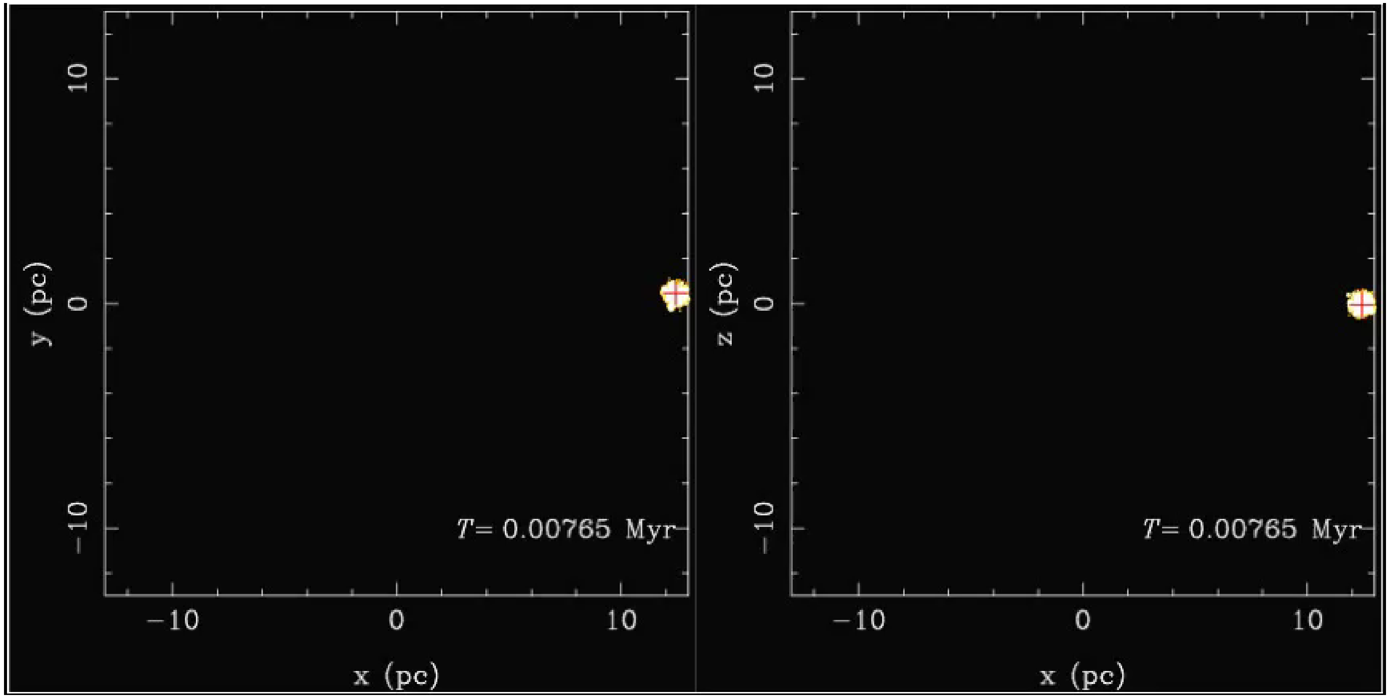


Full N-body simulations ($N \sim 10^6$) for 10 Gyr including binaries are still not easy.

External dynamical evolution of clusters

Tidal disruption: Clusters are tidally stripped due to the tidal field of galaxies and finally disrupted

Dynamical friction: Clusters accrete to the galactic center giving its orbital energy to the halo



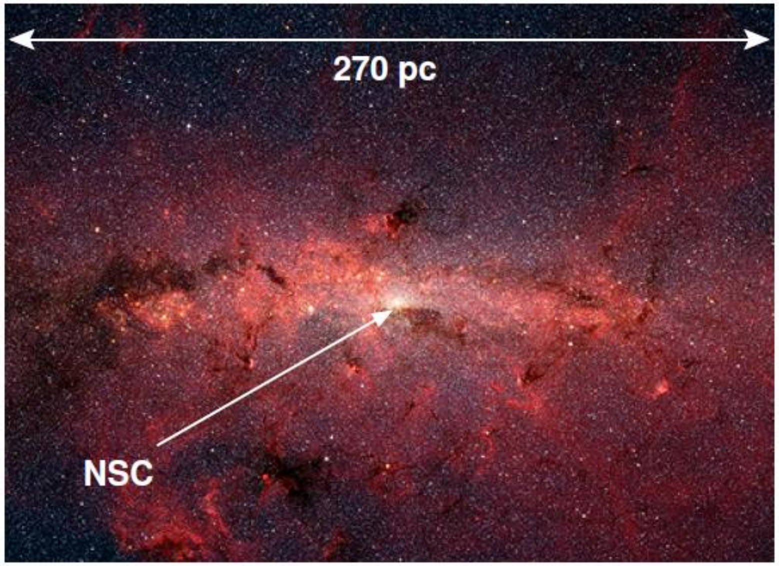
Simulation from Fujii et al. (2009)

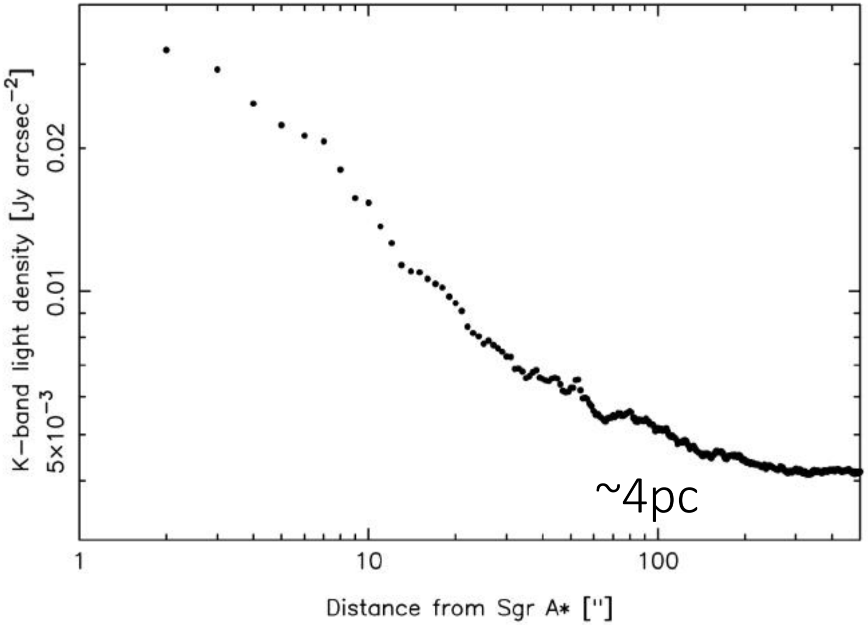
Formation of
the nuclear star cluster

Nuclear star cluster in the Galactic center

Nuclear star cluster (NSC) in the MW (~$10^7 M_{sun}$, ~5pc) may have formed via mergers of globular clusters (Tremaine+1975, Capuzzo-Dorcetta 1993, Antonini+ 2012, Gnedin 2014)

K-band Surface density





Schoedel et al. (2008)

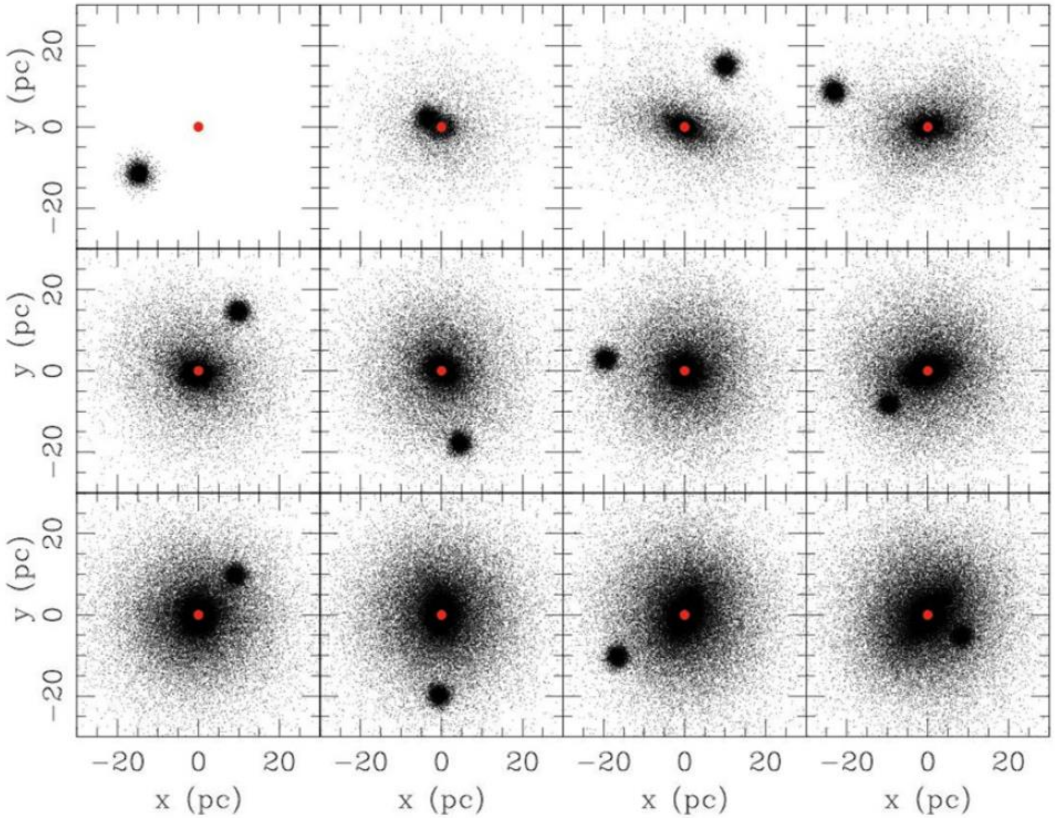
Distance from the SgrA*

Direct N-body simulations

N-body simulations can investigate the NSC structure, but they are computationally expensive
(Bekki+2004, Capuzzo-Dolcetta & Miocchi 2008, Antonini+ 2012)

The maximum number of particles we can use for a cluster is $\sim 10^{5\text{-}6}$

The initial positions of clusters are a few tens pc



Antonini et al. (2012)

Analytic models

Modeling internal and external evolution of star clusters

1. *Accretion of clusters due to the dynamical friction*

$$t_{\rm df} = 0.45\,{\rm Gyr} \left(\frac{r}{\rm kpc}\right)^2 \left(\frac{V_c(r)}{\rm km\,s^{-1}}\right) \left(\frac{M(t)}{10^5\,M_\odot}\right)^{-1} f_\epsilon$$

2. *Disruption of clusters due to the tidal disruption*

$$t_{\rm tid}(r, M) \approx 10\,{\rm Gyr} \left[\frac{M(t)}{2\times 10^5\,M_\odot}\right]^\alpha P(r), \qquad P(r) \equiv 41.4 \left(\frac{r}{\rm kpc}\right) \left(\frac{V_c(r)}{\rm km\,s^{-1}}\right)^{-1}$$

3. *Evaporation of clusters due to the internal evolution of clusters*

$$t_{\rm iso}(M) = \frac{t_{\rm rh}}{2.5\,\xi_e} \approx 17\,{\rm Gyr} \left[\frac{M(t)}{2\times 10^5\,M_\odot}\right]$$

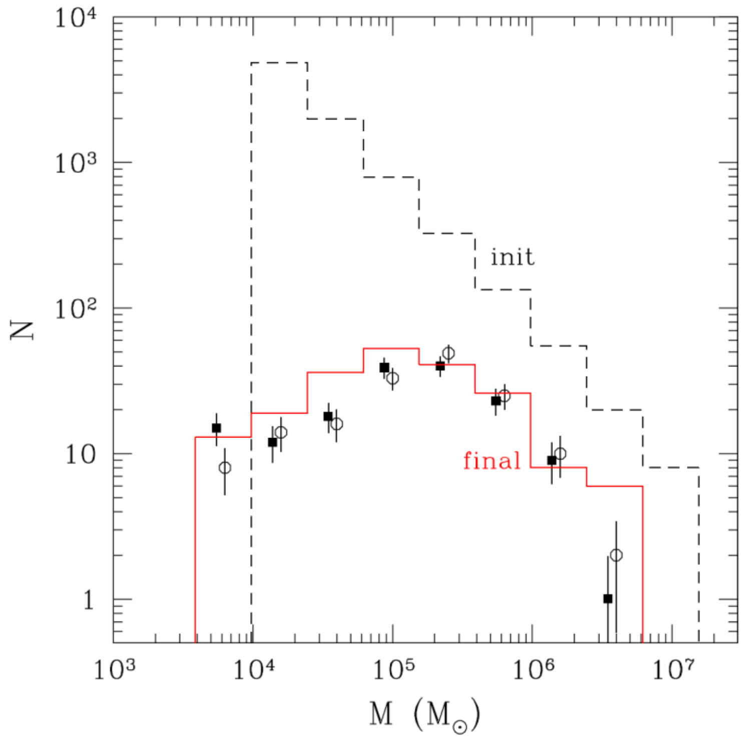
Assuming the initial distribution of globular clusters and the galactic potential, we can investigate the final distribution of globular clusters and their debris

Gnedin et al. (2014), see also Gieles et al. (2011)

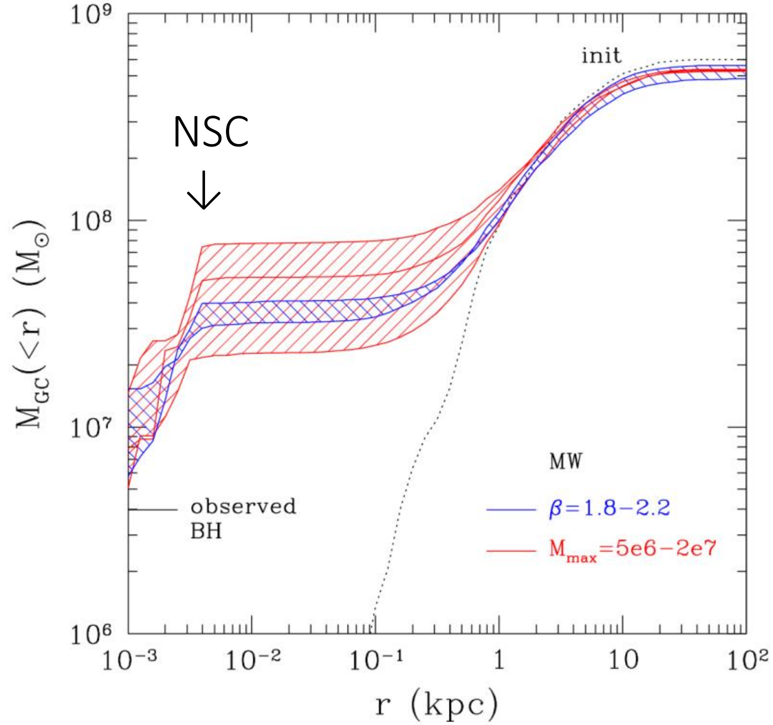
Formation of NSC: Gnedin et al. (2014)

Assuming the initial distribution of globular clusters, Gnedin et al. (2014) investigated the final distribution of globular clusters and their debris

Initial and final cluster mass function



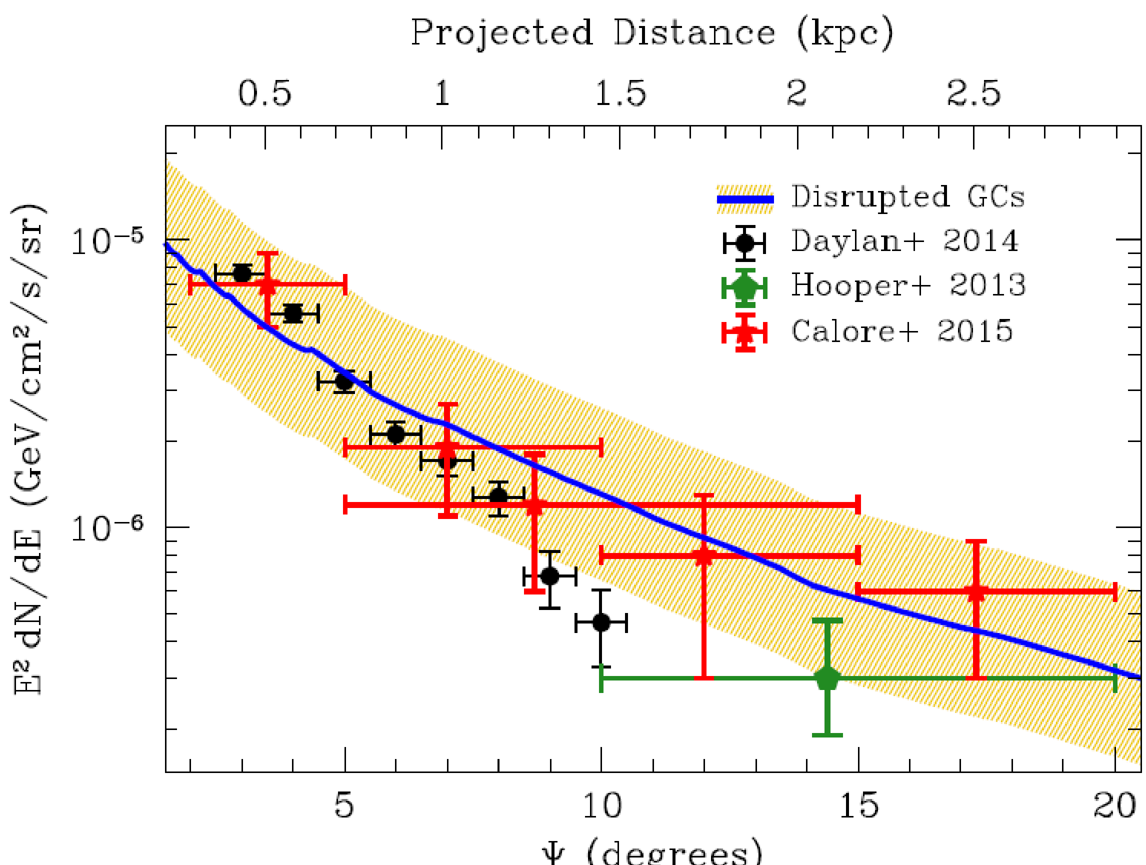
Initial and final mass distribution originated from clusters



Estimated emission from NSC and debris

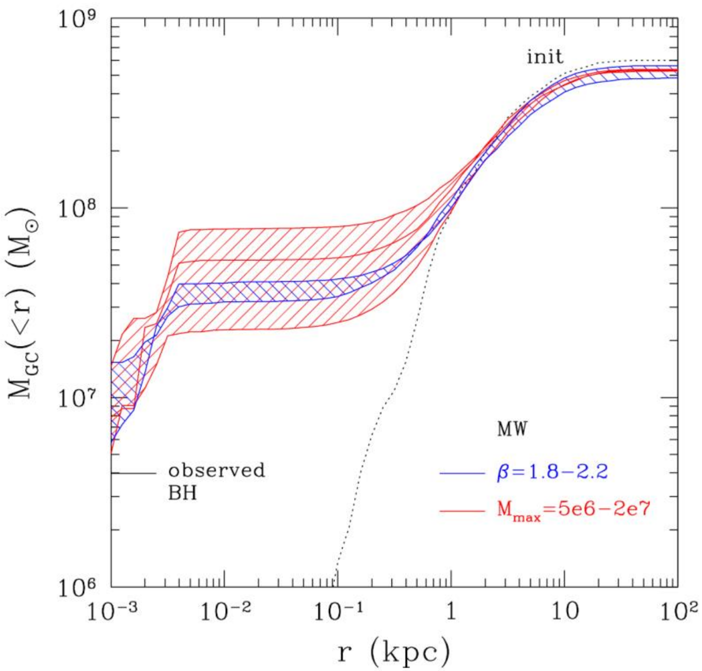
Brandt & Kocsic (2015) estimated emission from NSC and cluster debris using the result of Gnedin et al. (2014)

The TeV emission in the Galactic center (< 1 few pc) can be explained by accelerated leptons in the shock formed by pulsar wind (Bednarek & Sobczak 2013)



Where were the accreted clusters born?

Clusters initially within ~1kpc contribute to the NSC



Accretion (dynamical friction) timescale

$$t_{\rm df} = 0.45\,{\rm Gyr}\left(\frac{r}{\rm kpc}\right)^2\left(\frac{V_c(r)}{\rm km\,s^{-1}}\right)\left(\frac{M(t)}{10^5\,M_\odot}\right)^{-1} f_\epsilon$$

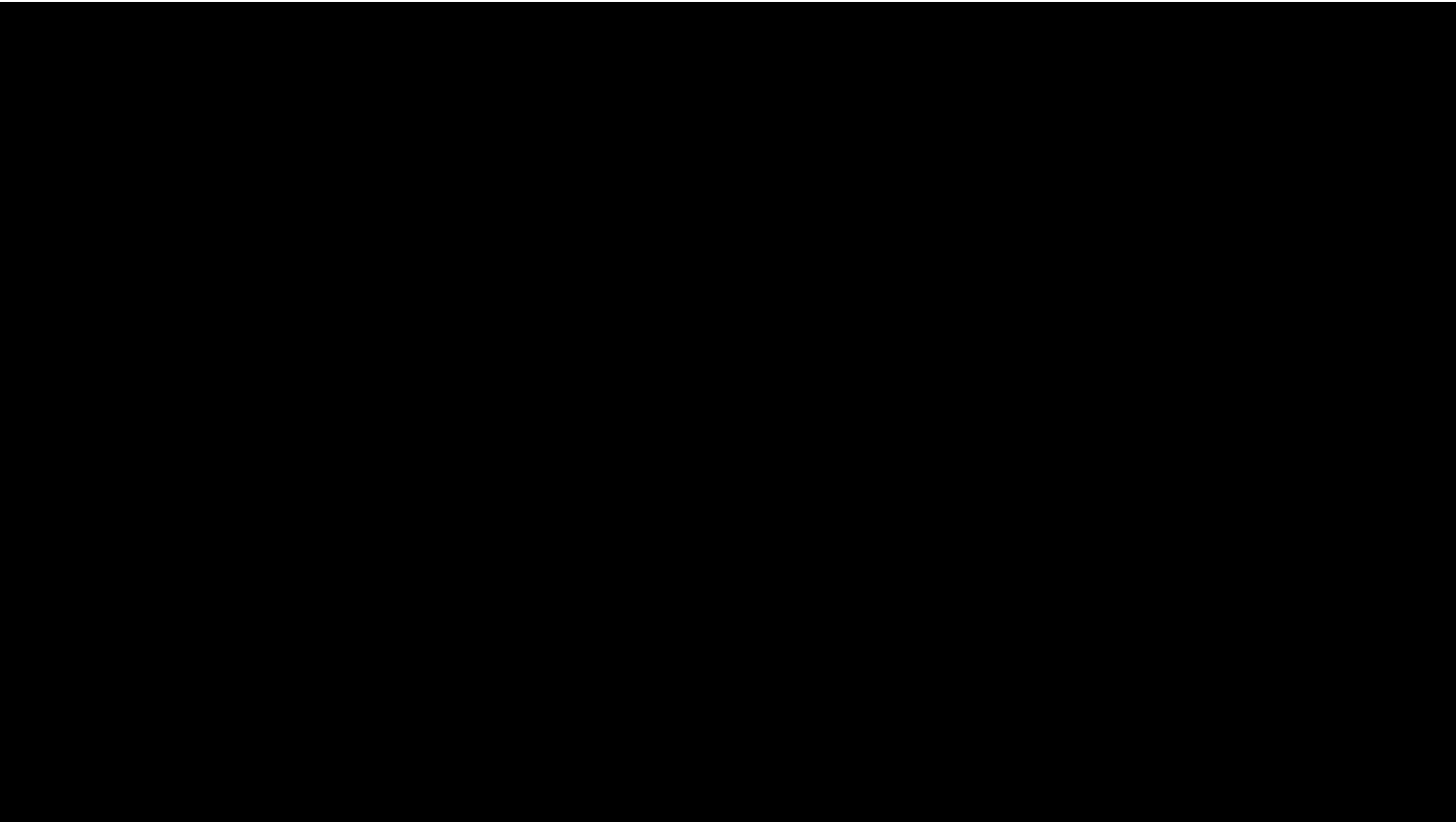
For example, t_{df} ~ 5Gyr
for r=1kpc, Vc=100 km/s, M=10^6Msun
Clusters at >>1kpc cannot accrete in Hubble time

These are also unclear:
- The initial distribution of globular clusters
- The formation process of globular clusters
- The formation history of the Milky Way (analytic model is spherical)

Formation of the Milky Way and globular clusters

Movie from 4d2u, NAOJ

Simulation performed by **Takayuki Saitoh**



Star clusters in galaxy-formation simulations

We cannot resolve the evolution of star clusters in the simulations of galaxy formation

Cosmological simulations of MW-size galaxies

Typical mass resolution is >1000 Msun. N is 10^{6-7} for stars and gas

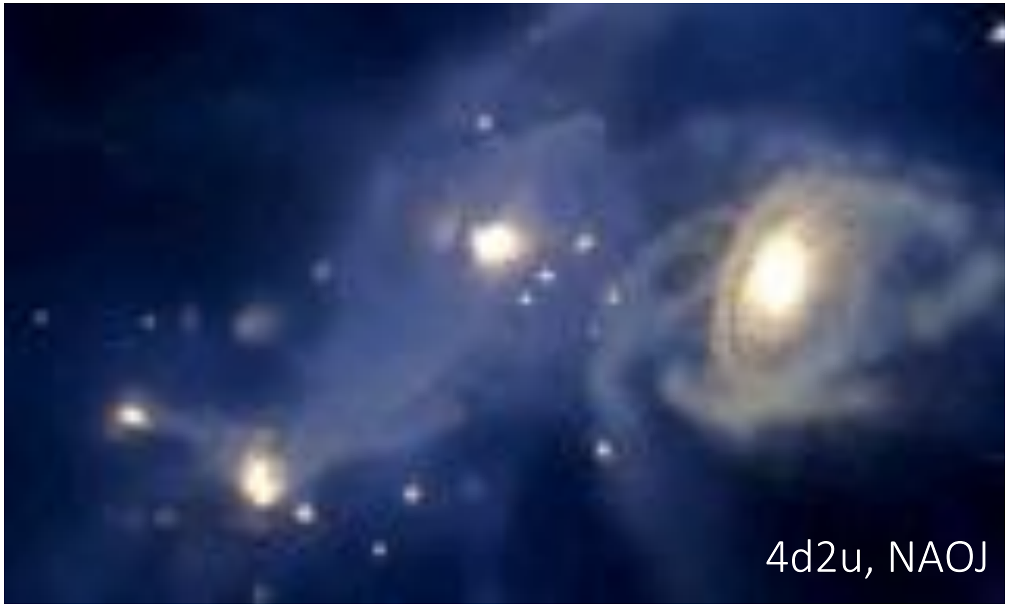
~100 particles per cluster

Such systems are disrupted much faster than real clusters

They are collisional system i.e., the number of particles change the dynamical evolution timescale (relaxation time)

The largest simulation:

N ~ 10^{10} for stars and gas



Difficulty of N-body simulations

It is still very difficult to perform a star-by-star ($N \sim 10^6$) simulation of star clusters for 10 Gyr.

Because of hard binaries and high stellar densities in the core

The simulations are not efficiently parallelized

The largest runs ($N \sim 10^{5-6}$) take several month

The first million-body run has been performed in the last year (Wang et al. in MODEST15-S in Dec 2015)

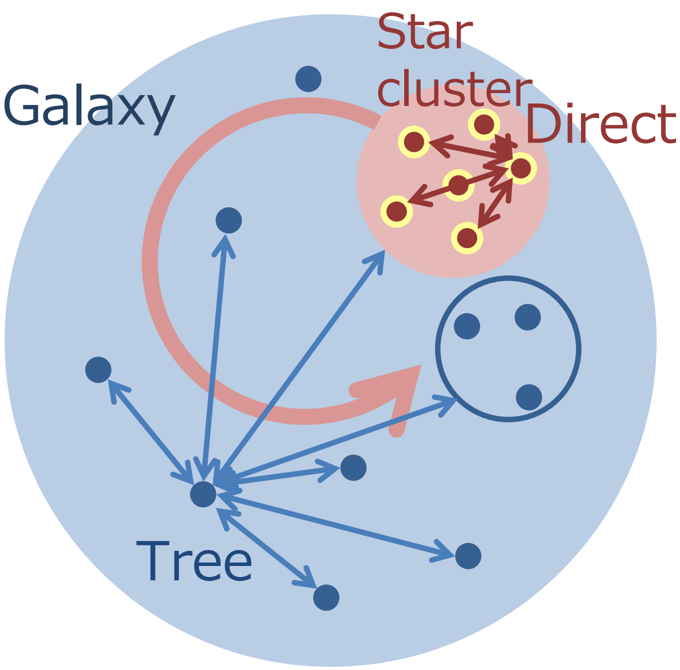
Star clusters require a higher accuracy than galaxies due to their high density

We need to treat internal evolution of star clusters in galaxy simulation

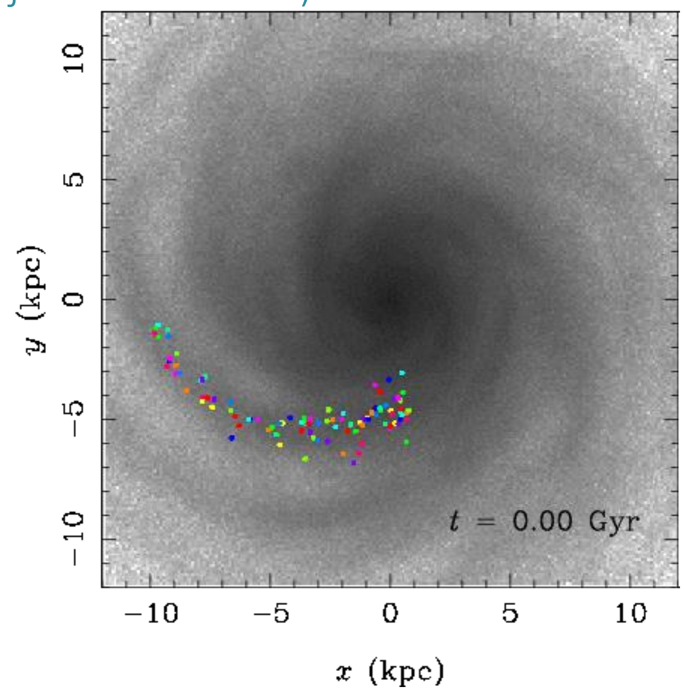
A hybrid N-body method

BRIDGE (Fujii et al. 2007)

Bridging two methods: Direct scheme for star clusters and tree code for galaxies



Evolution of star clusters in live spiral arms (Fujii & Baba 2011)



This type of methods may enable us to treat evolution of star clusters in cosmological simulations

Summary

Cluster accretion scenario can explain the formation of the nuclear star cluster and GeV excess in the Galactic center

However, we do not know the initial distribution of globular clusters nor the formation history of the Milky Way

Where were globular clusters born?

How did they accrete?

Cosmological simulations resolving clusters have still some difficulties

We will need a hybrid approach