Dynamical Evolution of Globular Cluster Systems: The Milky Way & M87

Sungsoo S. Kim[1]
Jihye Shin[1]
Myung Gyoon Lee[2]
Narae Hwang[2]
Koji Takahashi[3]

[1] Kyung Hee Univ. (Korea)
[2] Seoul Natl. Univ. (Korea)
[3] Saitama Inst. of Tech. (Japan)

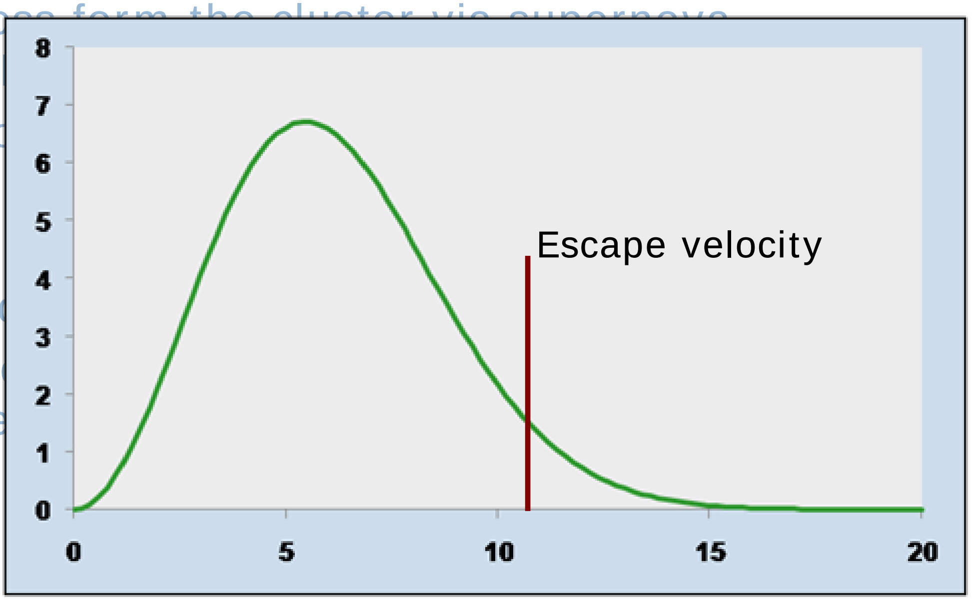
Mostly based on Shin, Kim & Takahashi (2008, MNRAS, 386, L67)

Dynamical Evolution of Individual Globular Clusters

- Dynamical evolution of a GC is driven by various mechanisms and factors:
  - **Two-body relaxation**: Heat exchange between two stars keeps filling the high velocity end of the Maxwell-Boltzmann distribution where stars can escape from the cluster. Thus all GCs are destined to completely evaporate eventually.
  - **Stellar evolution**: Mass loss form the cluster via supernova explosion acts as "indirect heating" and causes the GC to expand.
  - **Binary heating**: Interaction between a binary and a third star heats the GC.
  - **Galactic tidal field**: Lowers the escape velocity from the GC
  - **Disk / bulge shocks**: Rapid change in external potential heats GCs.
  - **Dynamical friction**: Causes GCs to spiral into the inner region of the galaxy where GCs experience deeper external potentials.
  - **Eccentric cluster orbits**: Causes GCs to experience deep and shallow external potentials alternatively.

Dynamical Evolution of Individual Globular Clusters

- Dynamical evolution of a GC is driven by various mechanisms and factors:
  - **Two-body relaxation**: Heat exchange between two stars keeps filling the high velocity end of the Maxwell-Boltzmann distribution where stars can escape from the cluster. Thus all GCs are destined to completely evaporate eventually.
  - **Stellar evolution**: Mass loss form the cluster via supernova explosion acts as “indirect
  - **Binary heating**: Interactic heats the GC.
  - **Galactic tidal field**: Lowe
  - **Disk / bulge shocks**: Rapi
  - **Dynamical friction**: Caus the galaxy where GCs expe
  - **Eccentric cluster orbits**: shallow external potentials



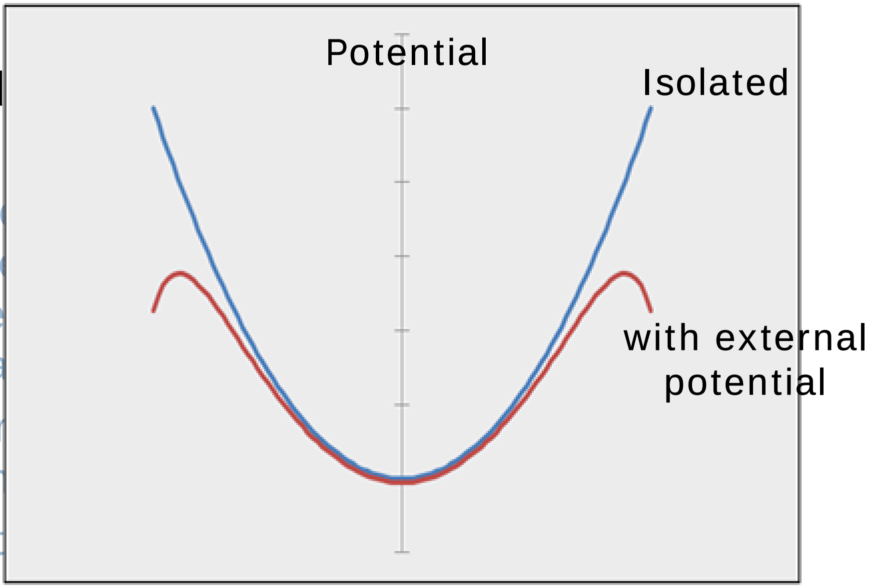
Dynamical Evolution of Individual Globular Clusters

- Dynamical evolution of a GC is driven by various mechanisms and factors:
  - **Two-body relaxation**: Heat exchange between two stars keeps filling the high velocity end of the Maxwell-Boltzmann distribution where stars can escape from the cluster. Thus all GCs are destined to completely evaporate eventually.
  - **Stellar evolution**: Mass loss form the cluster via supernova explosion acts as “indirect heating” and causes the GC to expand.
  - **Binary heating**: Interaction between a binary and a third star heats the GC.
  - **Galactic tidal field**: Lowers the escape velocity from the GC
  - **Disk / bulge shocks**: Rapid change in external potential heats GCs.
  - **Dynamical friction**: Causes GCs to spiral into the inner region of the galaxy where GCs experience deeper external potentials.
  - **Eccentric cluster orbits**: Causes GCs to experience deep and shallow external potentials alternatively.

Dynamical Evolution of Individual Globular Clusters

- Dynamical evolution of a GC is driven by various mechanisms and factors:
  - **Two-body relaxation**: Heat exchange between two stars keeps filling the high velocity end of the Maxwell-Boltzmann distribution where stars can escape from the cluster. Thus all GCs are destined to completely evaporate eventually.
  - **Stellar evolution**: Mass loss form the cluster via supernova explosion acts as "indirect heating" and causes the GC to expand.
  - **Binary heating**: Interaction between a binary and a third star heats the GC.
  - **Galactic tidal field**: Lowers the escape velocity from the GC
  - **Disk / bulge shocks**: Rapid change in external potential heats GCs.
  - **Dynamical friction**: Causes GCs to spiral into the inner region of the galaxy where GCs experience deeper external potentials.
  - **Eccentric cluster orbits**: Causes GCs to experience deep and shallow external potentials alternatively.

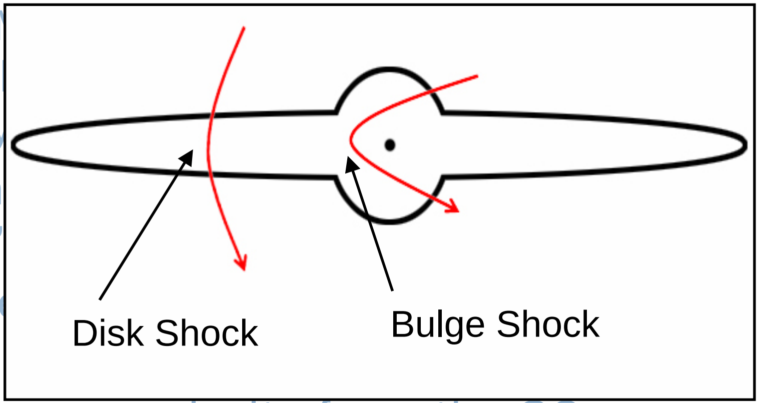
Dynamical Evolution of Individual Globular Clusters



- Dynamical evolution of a GC is d
and factors:
  - **Two-body relaxation**: Heat ex
filling the high velocity end of th
where stars can escape from the
to completely evaporate eventua
  - **Stellar evolution**: Mass loss fo
explosion acts as “indirect heatin
  - **Binary heating**: Interaction bet
heats the GC.
  - **Galactic tidal field**: Lowers the escape velocity from the GC
  - **Disk / bulge shocks**: Rapid change in external potential heats GCs.
  - **Dynamical friction**: Causes GCs to spiral into the inner region of the galaxy where GCs experience deeper external potentials.
  - **Eccentric cluster orbits**: Causes GCs to experience deep and shallow external potentials alternatively.

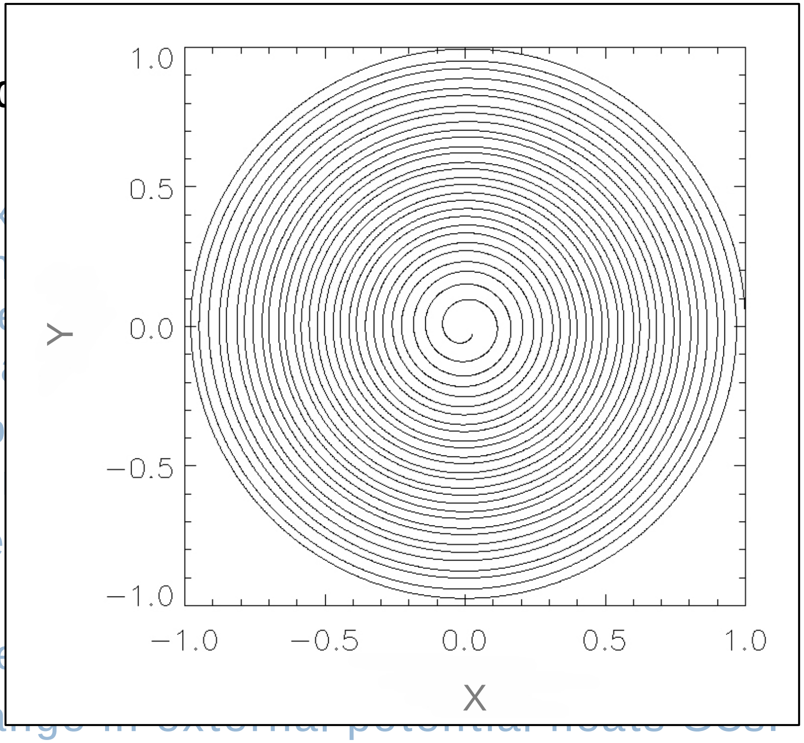
Dynamical Evolution of Individual Globular Clusters

- Dynamical evolution of a GC is driven by various mechanisms and factors:
  - **Two-body relaxation**: Heat exchange between two stars keeps filling the high velocity end of the where stars can escape from the c to completely evaporate eventually
  - **Stellar evolution**: Mass loss form explosion acts as “indirect heating
  - **Binary heating**: Interaction betw heats the GC.
  - **Galactic tidal field**: Lowers the escape velocity from the GC
  - **Disk / bulge shocks**: Rapid change in external potential heats GCs.
  - **Dynamical friction**: Causes GCs to spiral into the inner region of the galaxy where GCs experience deeper external potentials.
  - **Eccentric cluster orbits**: Causes GCs to experience deep and shallow external potentials alternatively.



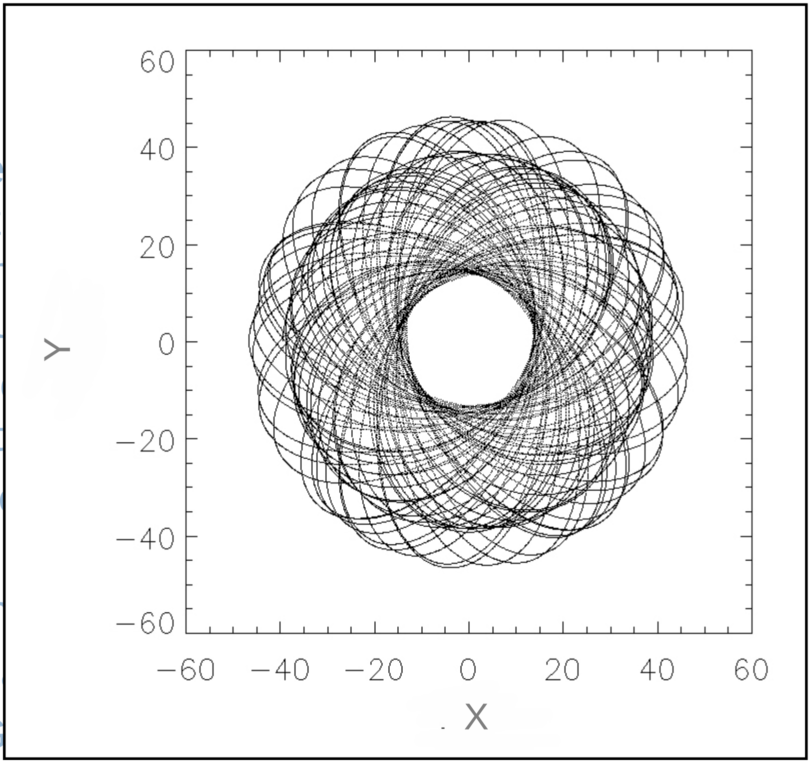
Dynamical Evolution of Individual Globular Clusters

- Dynamical evolution of a GC is d
  and factors:
  - **Two-body relaxation**: Heat ex
    filling the high velocity end of th
    where stars can escape from the
    to completely evaporate eventua
  - **Stellar evolution**: Mass loss fo
    explosion acts as "indirect heati
  - **Binary heating**: Interaction be
    heats the GC.
  - **Galactic tidal field**: Lowers the
  - **Disk / bulge shocks**: Rapid change in external potential heats GCs.
  - **Dynamical friction**: Causes GCs to spiral into the inner region of the galaxy where GCs experience deeper external potentials.
  - **Eccentric cluster orbits**: Causes GCs to experience deep and shallow external potentials alternatively.



Dynamical Evolution of Individual Globular Clusters

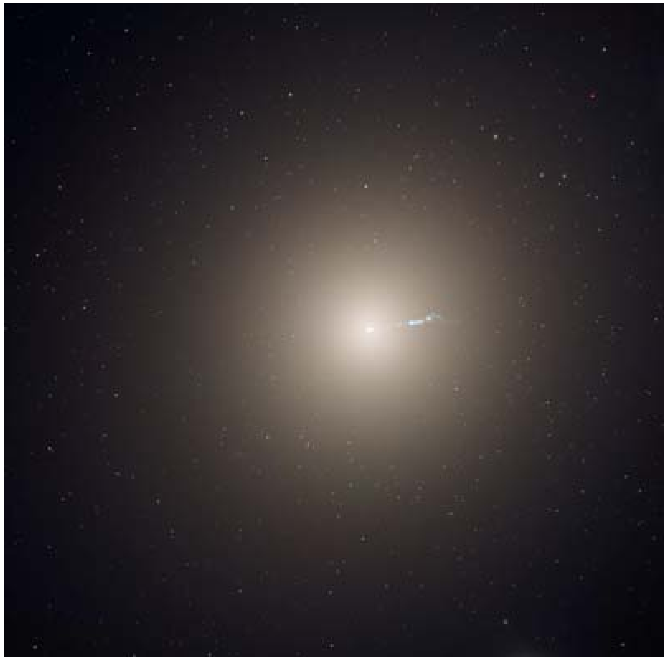
- Dynamical evolution of a GC is
  and factors:
  - **Two-body relaxation**: Heat e
    filling the high velocity end of t
    where stars can escape from th
    to completely evaporate eventu
  - **Stellar evolution**: Mass loss f
    explosion acts as “indirect heat
  - **Binary heating**: Interaction b
    heats the GC.
  - **Galactic tidal field**: Lowers th
  - **Disk / bulge shocks**: Rapid ch
  - **Dynamical friction**: Causes G
    the galaxy where GCs experience deeper external potentials.
  - **Eccentric cluster orbits**: Causes GCs to experience deep and shallow external potentials alternatively.



GC Systems in the Era of High Resolution Survey

- Observations of the GC systems in the local universe
  - require high spatial resolution to distinguish GCs from stars (<1”)
  - need to cover a large area in the sky (several degrees)

- Recent and near future observations will enable us to study the evolution of the external GC systems in greater details.



M87, HST/ACS

NGC 1399, HST

Previous Studies on the Evolution of GC Systems

- Analytical models
  - Aguilar, Hut, Ostriker (1988), Vesperini (1997), Fall & Zhang (2001), Parmentier & Gilmore (2007), ...
  - Relatively simple. Various mass loss rates are linearly added.
- N-body models
  - Vesperini & Heggie (1997), Baumgardt (1998), Vesperini (1998), ...
  - The most realistic. Still CPU-expensive to cover a large parameter space of initial conditions.
- Fokker-Planck models
  - Gnedin & Ostiker (1997), Murali & Weinberg (1997), ...
  - Difficult to consider various disruption factors with. Much faster than N-body.

$$\frac{\partial f}{\partial t} + \frac{\partial f}{\partial \mathbf{x}} \cdot \frac{\mathbf{p}}{m} + \frac{\partial f}{\partial \mathbf{p}} \cdot \mathbf{F} = \left.\frac{\partial f}{\partial t}\right|_{\mathrm{coll}} .$$

Our models

- Most advanced anisotropic (E,J) Fokker-Planck model
  - Modified from Takahashi & Lee (2000) for
    - disk/bulge shocks (recipe by Gnedin, Lee, Ostriker 1999)
    - dynamical friction
    - eccentric cluster orbits
  - Implements an Alternating Direction Implicit (ADI) integration scheme (Shin & Kim 2007, JKAS, 40,91).
  - Agrees well with N-body results (Baumgardt & Makino 2003) for clusters with eccentric orbits and $M>10^4$ M .

Simulations & Analyses

- Hundreds of FP calculations are performed for the evolution of individual clusters.
  - A large parameter space of initial cluster conditions are explored for mass, galactocentric radius, orbit eccentricity & inclination.
  - Massively independent, rather than parallel.

- The FP results are synthesized with appropriate weights to represent a GC system with a given initial MF and RP.

- We find the best initial MF and RP models that simultaneously fit the observed MF and RP the best.
  - We minimize the sum of two chi-squares from MF and RP histograms.
  - Previous studies either fixed the RP or considered MFs in two or three radial bins.

Study I : The Milky Way

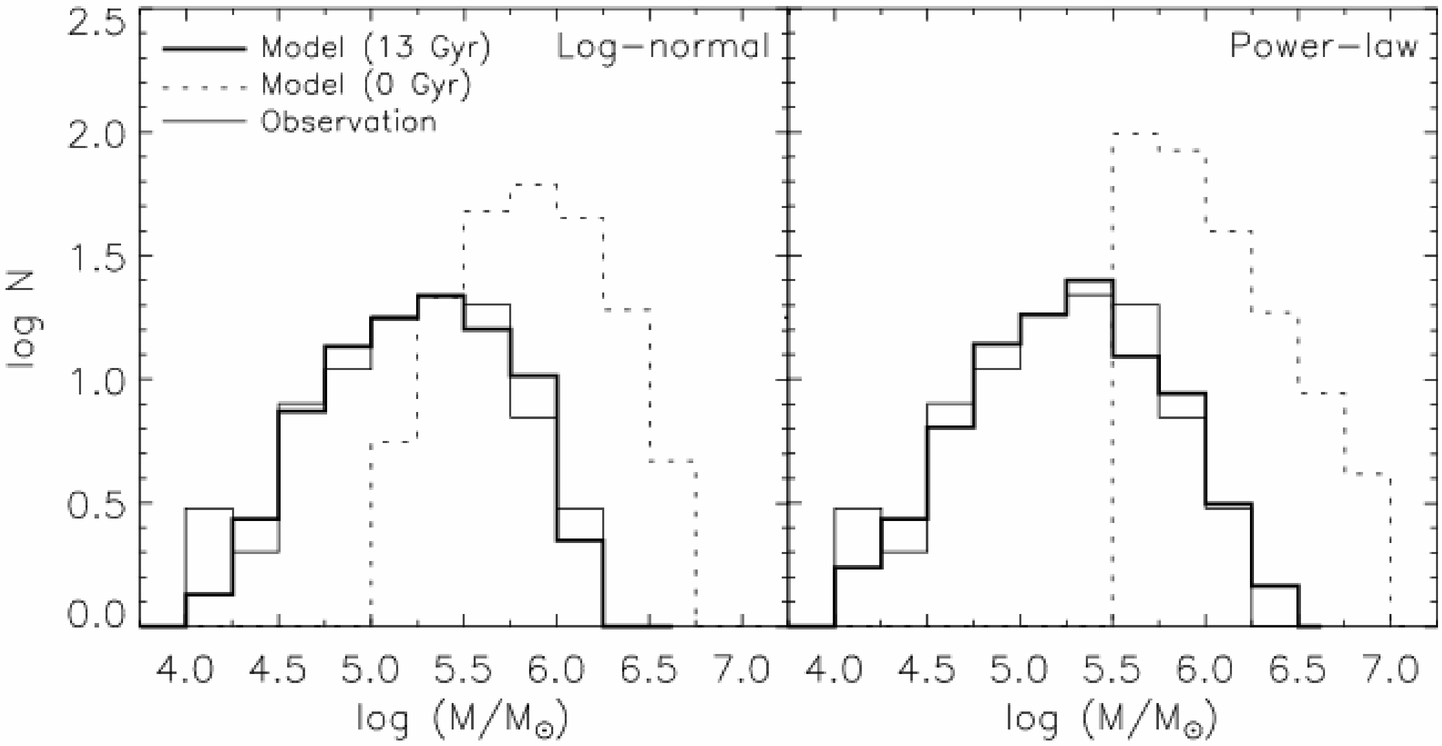
Shin, Kim & Takahashi (2008)

- Initial conditions for individual clusters:
  - mass: $10^{3.5} – 10^{7}$ M (8 values)
  - galactocentric radius : 1–50 kpc (6 values)
  - orbit eccentricity : 0, 0.125, 0.25, 0.5 & 0.75 (5 values)
  - orbit inclination : 15°, 45° & 75° (3 values)

- Initial conditions for the distribution of GC systems:
  - MF: log-normal, truncated power-law
  - RP: softened power-law
  - e : isotropic ($dN \propto 2e\, de$), starting at the pericenter or apocenter
  - i : isotropic ($dN \propto \sin i\, di$)

- When comparing to observations, we consider ‘native’ GCs only (Old Halo & Bulge/Disk GCs; N=95).

Evolution of Mass Functions

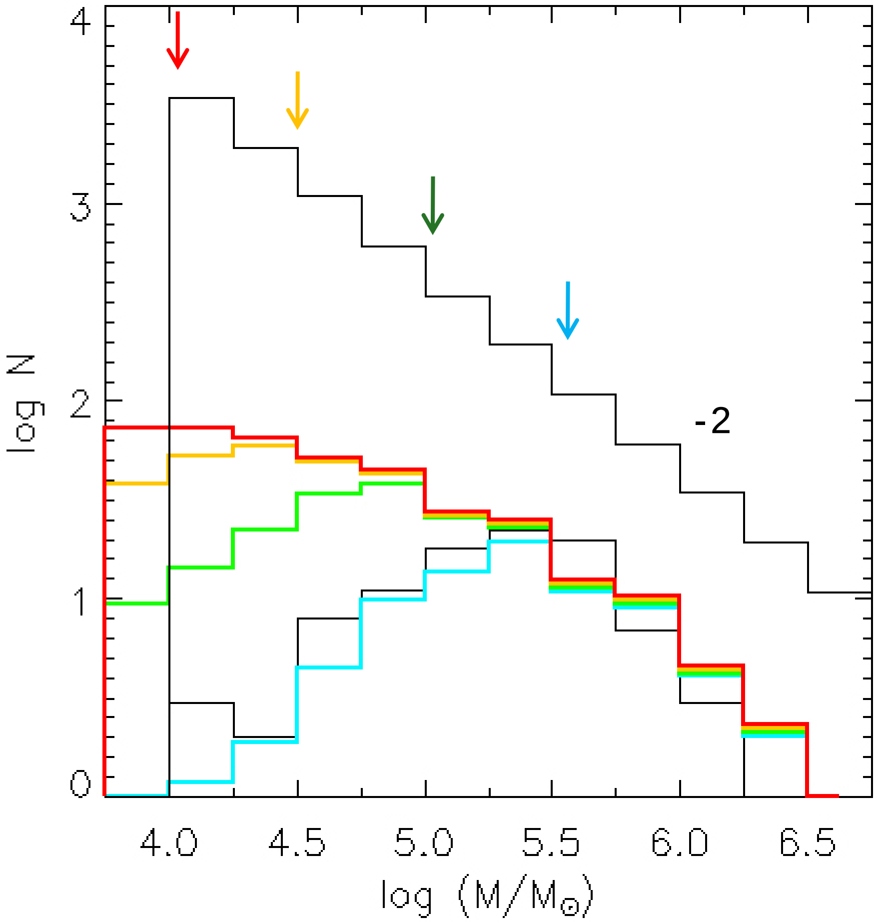


Both log-normal and power-law IGCMF evolves into the PD GCMF.

(Our models do not consider the gas expulsion during the early stage of the cluster.)

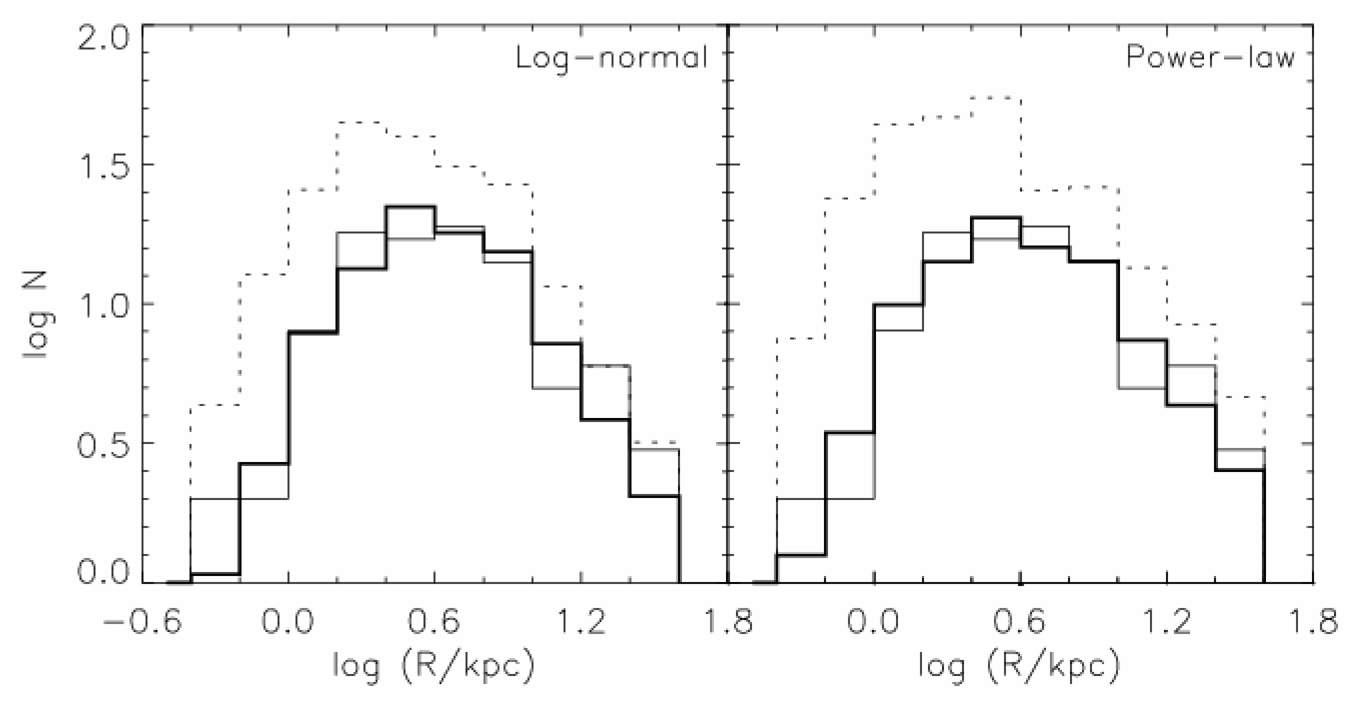
- The best-fit log-normal IGCMF shifts downward by 0.35 dex during 13 Gyr.
  - Larger M_p and smaller $\sigma_{\log M}$ than previous studies (Vesperini 1998, Fall & Zhang 2001)
- The best-fit power-law IGCMF needs to have a cutoff mass of $> 10^5$ M .
  - In agreement with Parmentier & Gilmore (2007)

Effect of Lower Mass Cutoff in Power-law IGCMF



Evolution of GCMFs starting with the same power-law slope, but with different lower mass cutoffs

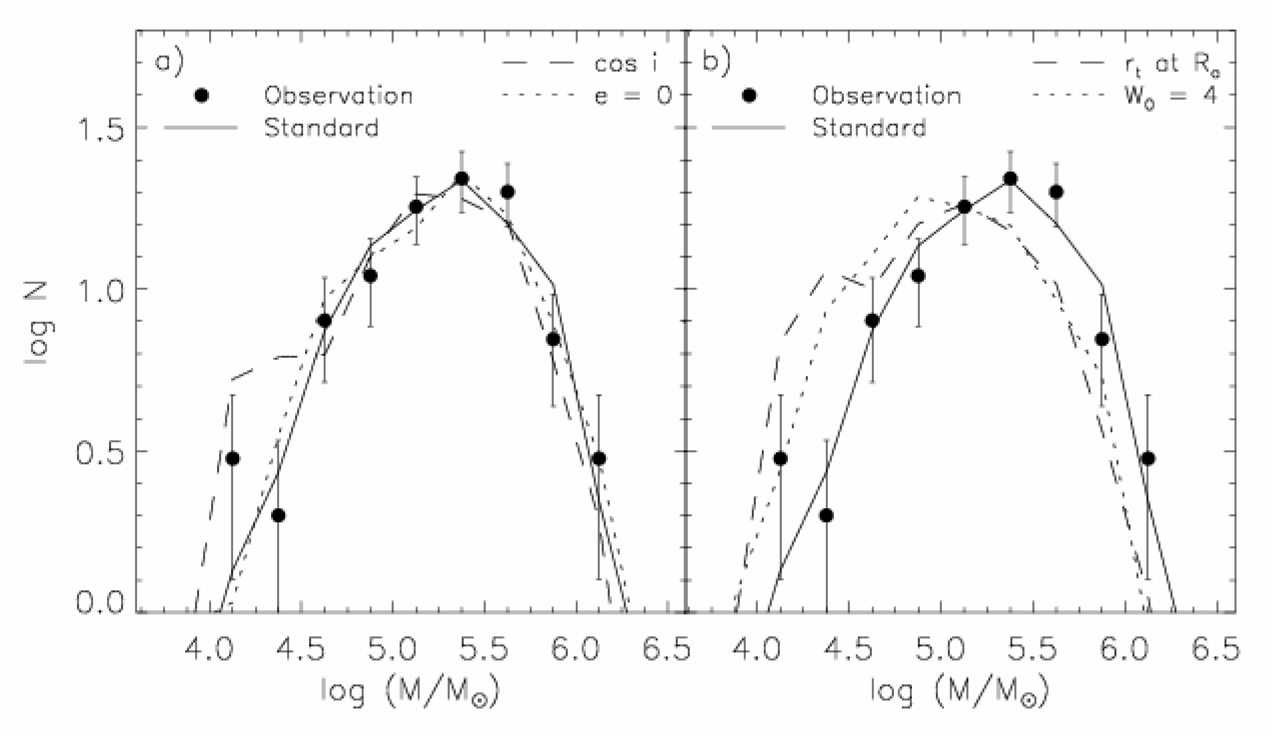
Evolution of Radial Profiles



- The overall shape of the RP does not change significantly during the evolution.
- The best fit initial RP: $$dN \propto \frac{4\pi R^2 dR}{1+(R/2.9\ \mathrm{kpc})^{4.24}}$$

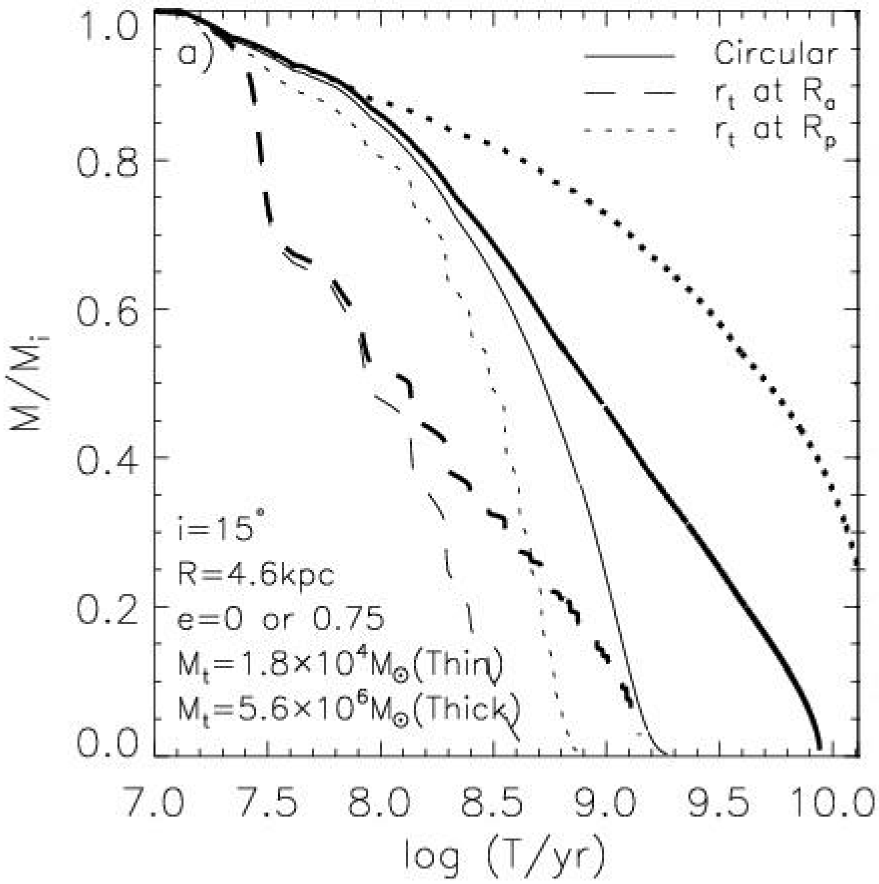
  → Similar to the Hernquist profile with a core radius of the size of the bulge.

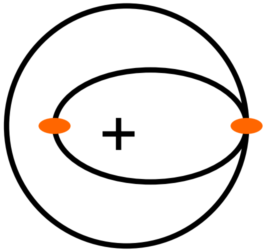
Model Dependences



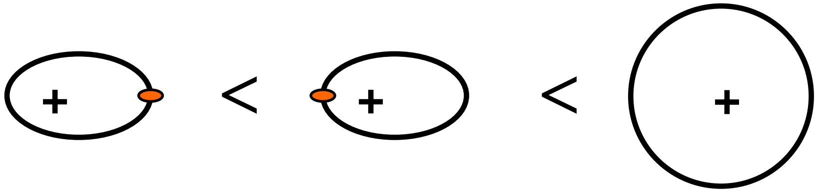
- Our results are quite insensitive to the initial distribution models for orbital inclination and eccentricity.
- But they do sensitively depend on how the initial tidal radii are defined and the initial concentration.

Evolution of Individual GCs: Dependence on Initial Tidal Radius

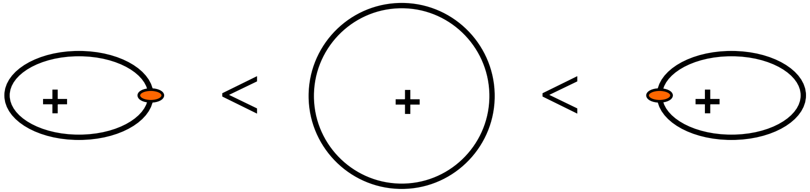




T_{evap} for light clusters:



T_{evap} for massive clusters:



Initial Fraction of Stars in GCs

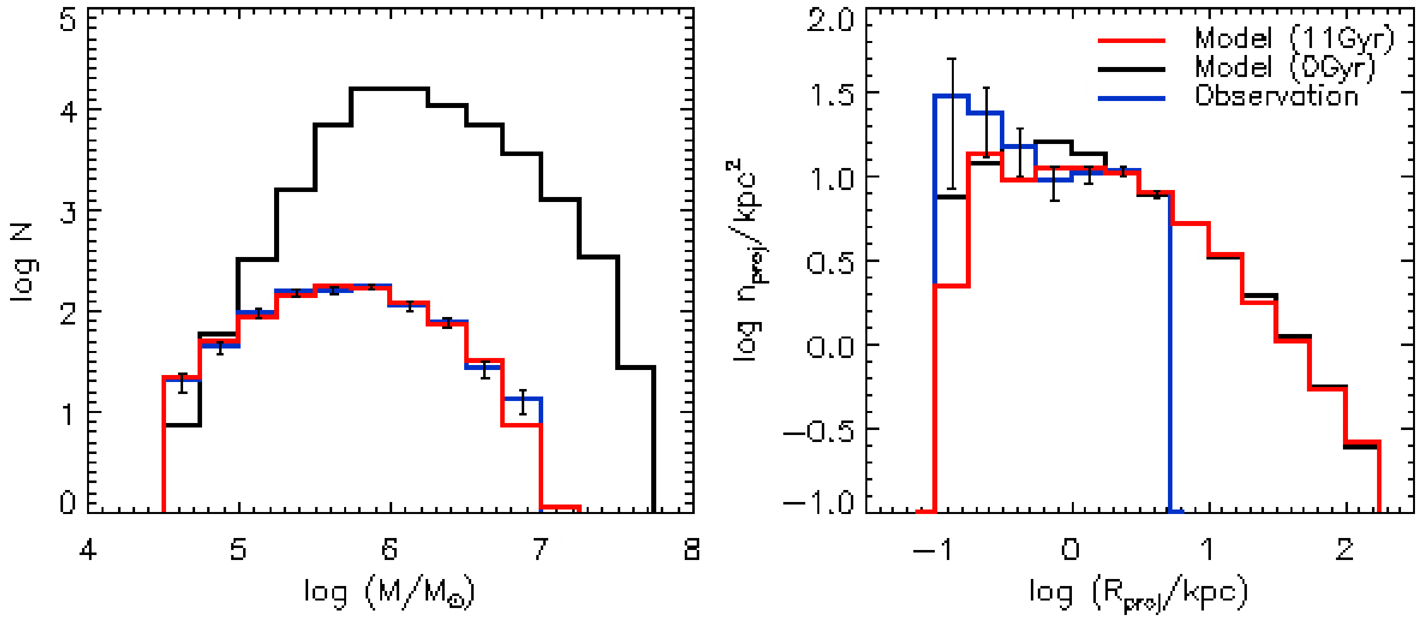
- Current mass in the stellar halo in 4–25 kpc is $9\text{x}10^8$ M .
- The mass that has left from the GCs during 13 Gyrs:
  - $1.2\text{x}10^8$ M for our standard model
  - $6.6\text{x}10^8$ M for the model with $r_t = r_t(R_a)$

- Was not able to find any initial MF and RP distributions that fit the current observations when $W_0=4$.
  - Most of the GCs start with $W_0 \geq 7$?

Study II : M87

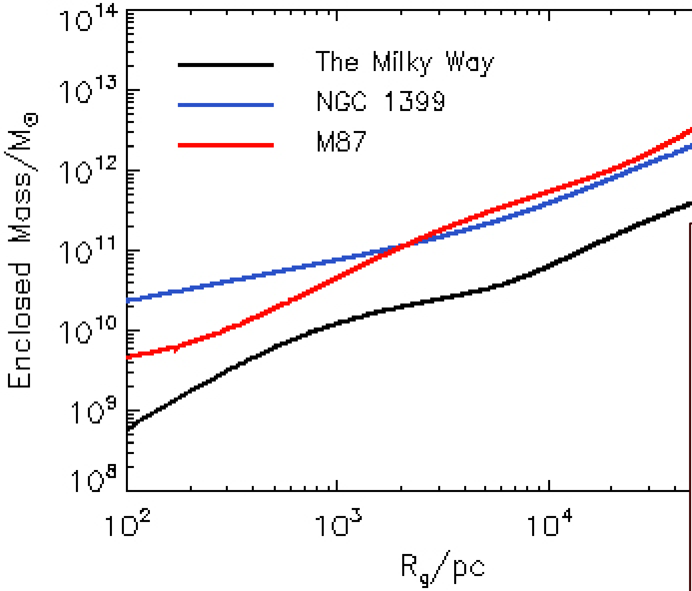
- M87 is a giant elliptical galaxy in Virgo cluster with more than 10,000 GCs.
- We use the same initial distribution models as for the Milky Way, except that we don't need the orbit inclination.
- We use the HST/ACS data by Cote et al. (2008) and adopt the potential model of McLaughlin (1999).
- We assume that major merging events stopped at 2–3 Gyr, and we consider the evolution of the GC system afterwards (last ~11 Gyr).

Evolution of Mass Functions

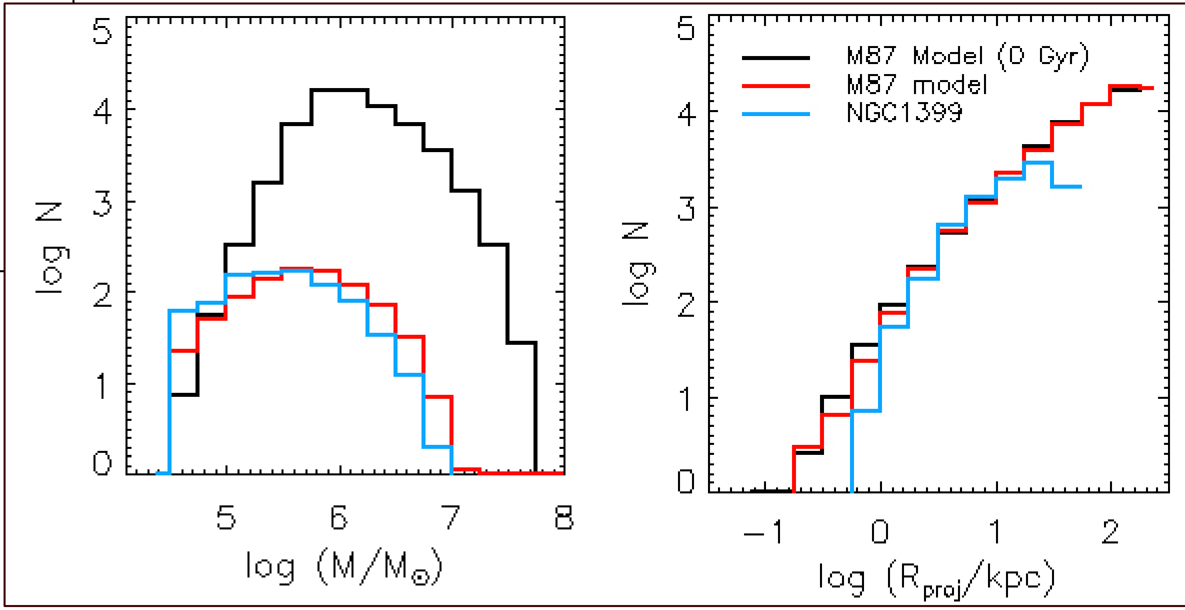


- *Double-log-normal* IGCMF fits the observed MF very well. Reminiscence of major merger?
- Only ~1 % of the initial GC stars stays in the GC system currently.
- We were not able to reproduce the cusp in the RP. A hint of separate population at the center?

Dependence on the Galactic Potential



A set of simulations was done with the potential of NGC 1399 and the best-fit initial conditions for M87



- NGC 1399, which has a larger enclosed mass in the inner region, has a only slightly lower peak in its PD GCMF.
- Many giant elliptical galaxies are likely to have similar enclosed mass distribution, and thus similar peak masses in their GCMF.

Summary

- Milky Way
  - Both log-normal and power-law IGCMF evolves into the PD GCMF.
    - Best-fit log-normal IGCMF shifts downward by 0.35 dex during 13 Gyr.
    - Best-fit power-law IGCMF needs a cutoff mass > $10^5 M$.
  - 15 % of the current halo stellar mass can be attributed to the GCs as their origin. This becomes 75 % if GCs are formed at the apocenter.
  - Best-fit initial RP is similar to the Hernquist profile with a core radius of the size of the bulge.
  - The results are significantly dependent on where the initial tidal radii are defined. If defined at the apocenter, the origin of the most of the halo stars can be attributed to GCs.

- M87
  - Double-log-normal IGCMF fits very well.
  - Only ~1% of the GC stars survived in the GC system.
  - Appears to have a separate bulge GC population.
  - Evolution of GC system sensitively depends on the galactic potential.