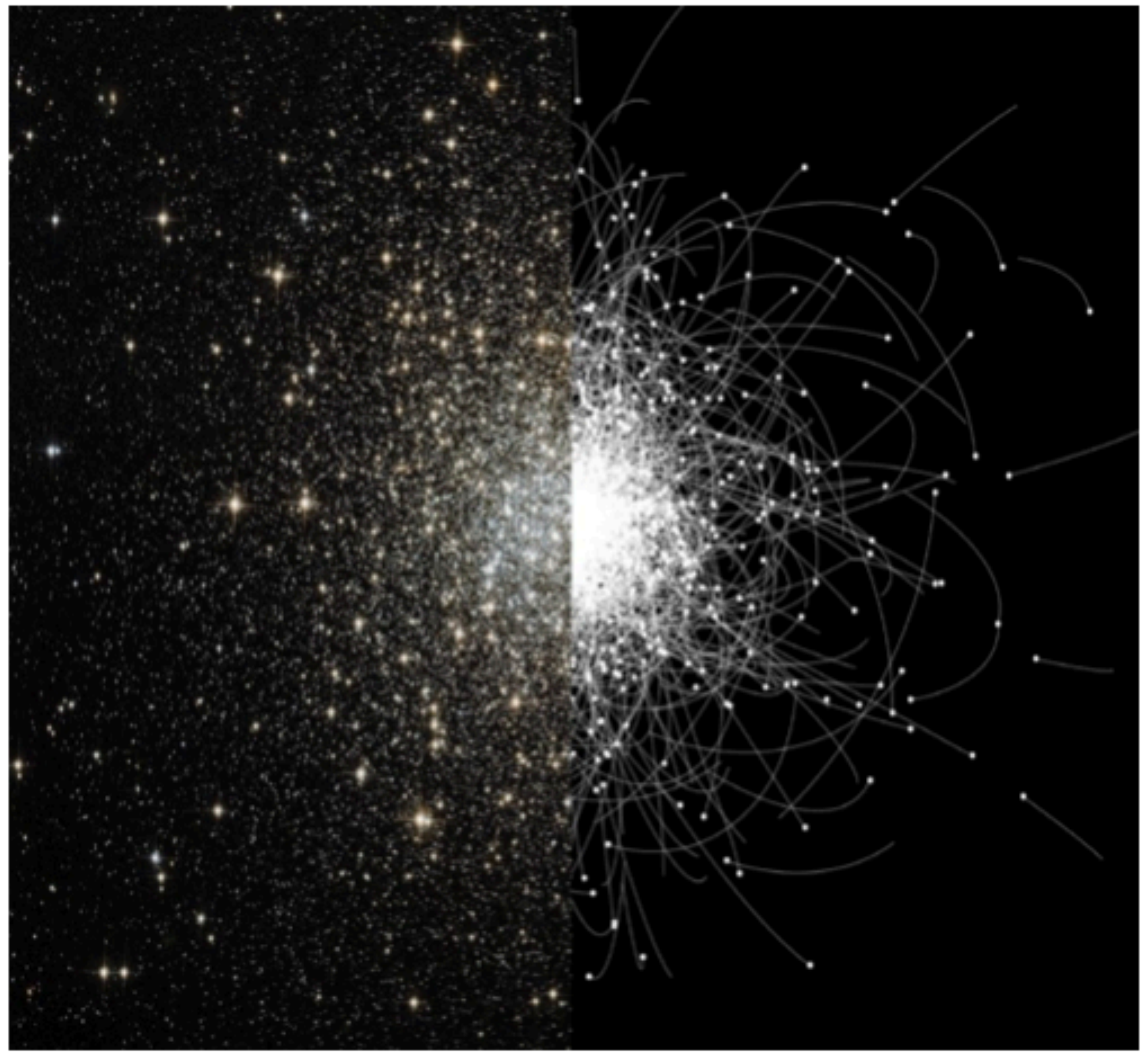
# Star Cluster Dynamics and Evolution



**Geoplanet Doctoral School Lecture Course (Spring 2024)**

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CAMK PAN

NATIONAL SCIENCE CENTRE POLAND

MOCCA

BH GROWTH
Growing Black Holes in Star Clusters

# Course outline

- Lecture 1: Introduction to star clusters and stellar dynamics
- Lectures 2 - 4: Collisionless and collisional stellar dynamics
- Lecture 4-5 : Direct *N*-body and Monte Carlo method for evolving star clusters
- Lecture 6: Thermodynamics of stars clusters and simple star cluster models
- Lecture 7: Internal physical processes in star cluster evolution
- Lecture 8: External physical processes in star cluster evolution
- Lectures 9: Observations and astrophysical importance of star clusters
- Lecture 10-11: Black holes in star clusters and formation of gravitational wave sources
- Lecture 12: Summary lecture with key takeaways + instructions on assignment

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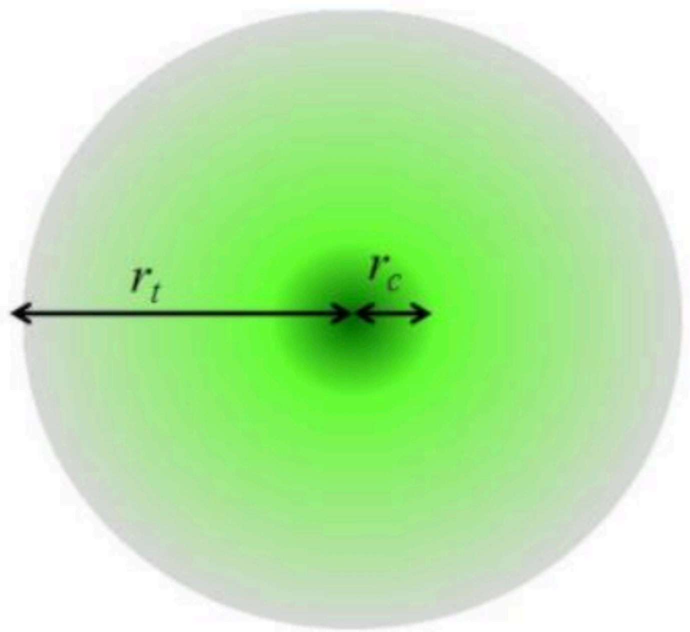
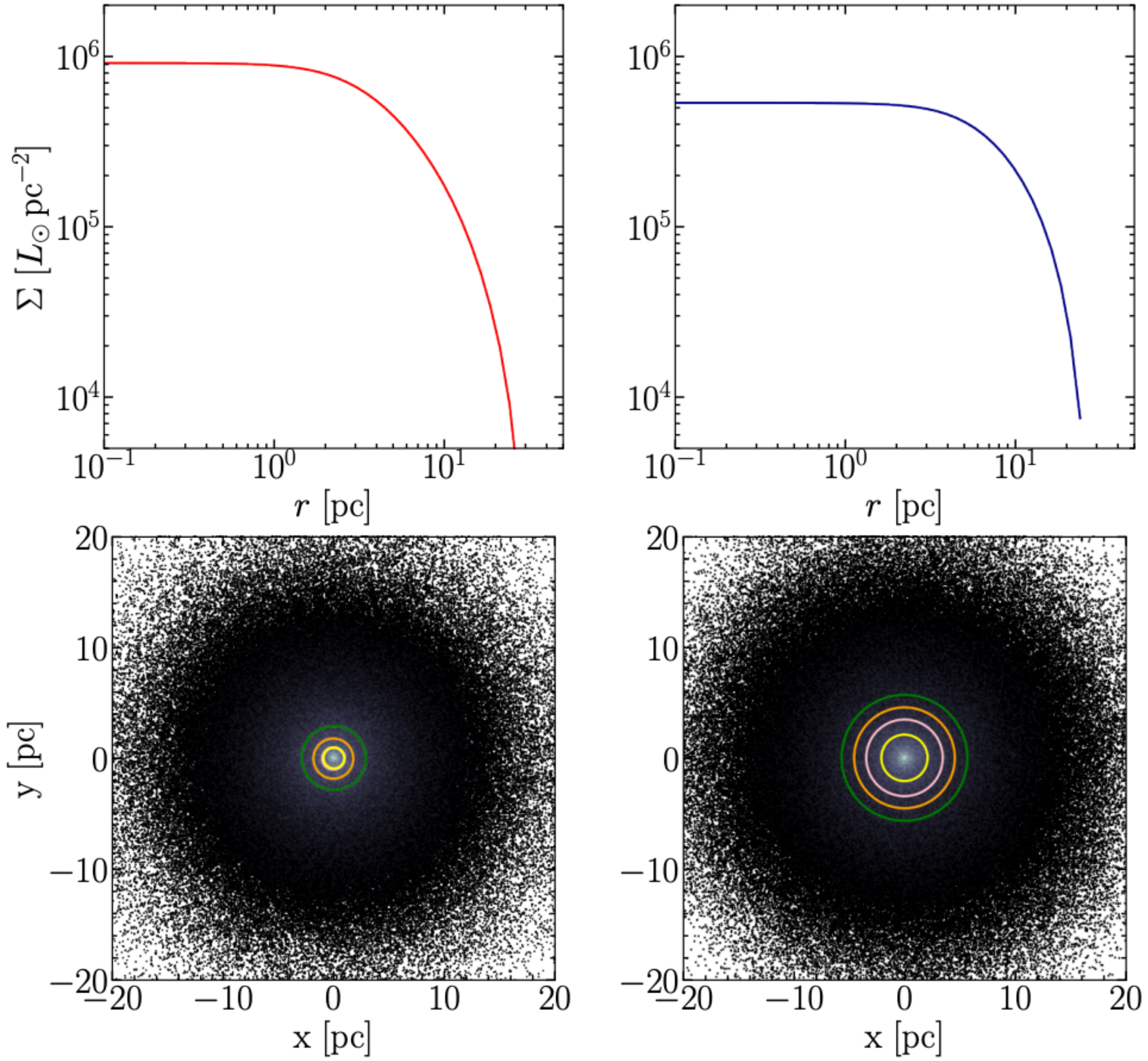
# Observations and astrophysical importance of star clusters

- Overview of observed star clusters in the Milky Way
- Observations of stellar exotica in globular clusters
- Multiple sellar populations in globular clusters

# Characteristic radii of star clusters

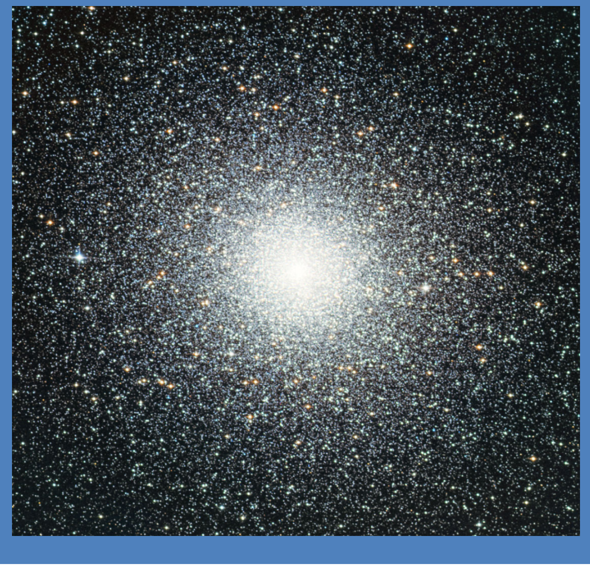
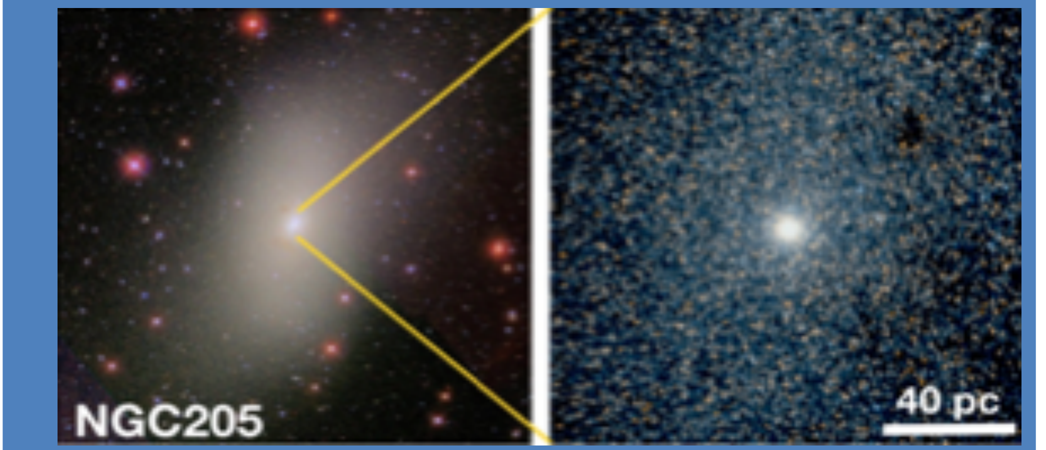
- Half-mass or half-light radius:
  - $r_{\mathrm{hm}}$ Radius containing half the mass of the cluster
  - $r_{\mathrm{hl}}$ Radius within which half of the total cluster luminosity is contained
- Core radius
  - $r_{\mathrm{c}}$ Radius where the central velocity dispersion is half of the central value.
  - $r_{\mathrm{c,\,obs}}$ Radius at which the surface brightness is equal to half the central value
- Tidal radius
  - $r_{\mathrm{t}}$ Radius where the host Galaxy's gravitational field dominates the cluster's field



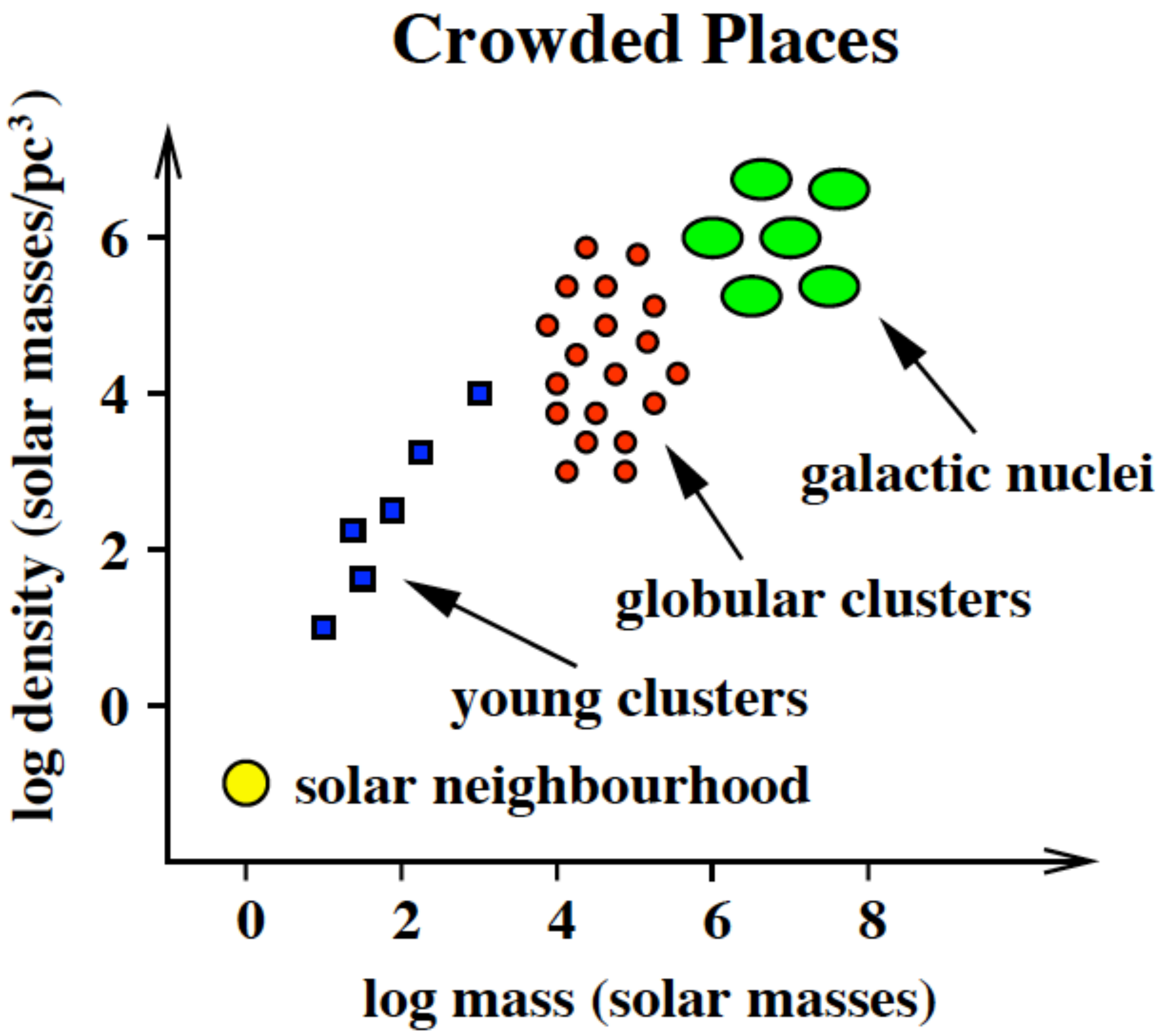


12 Gyr snapshots of simulated MOCCA star cluster models
Half-light radius - green, observational core radius in pink

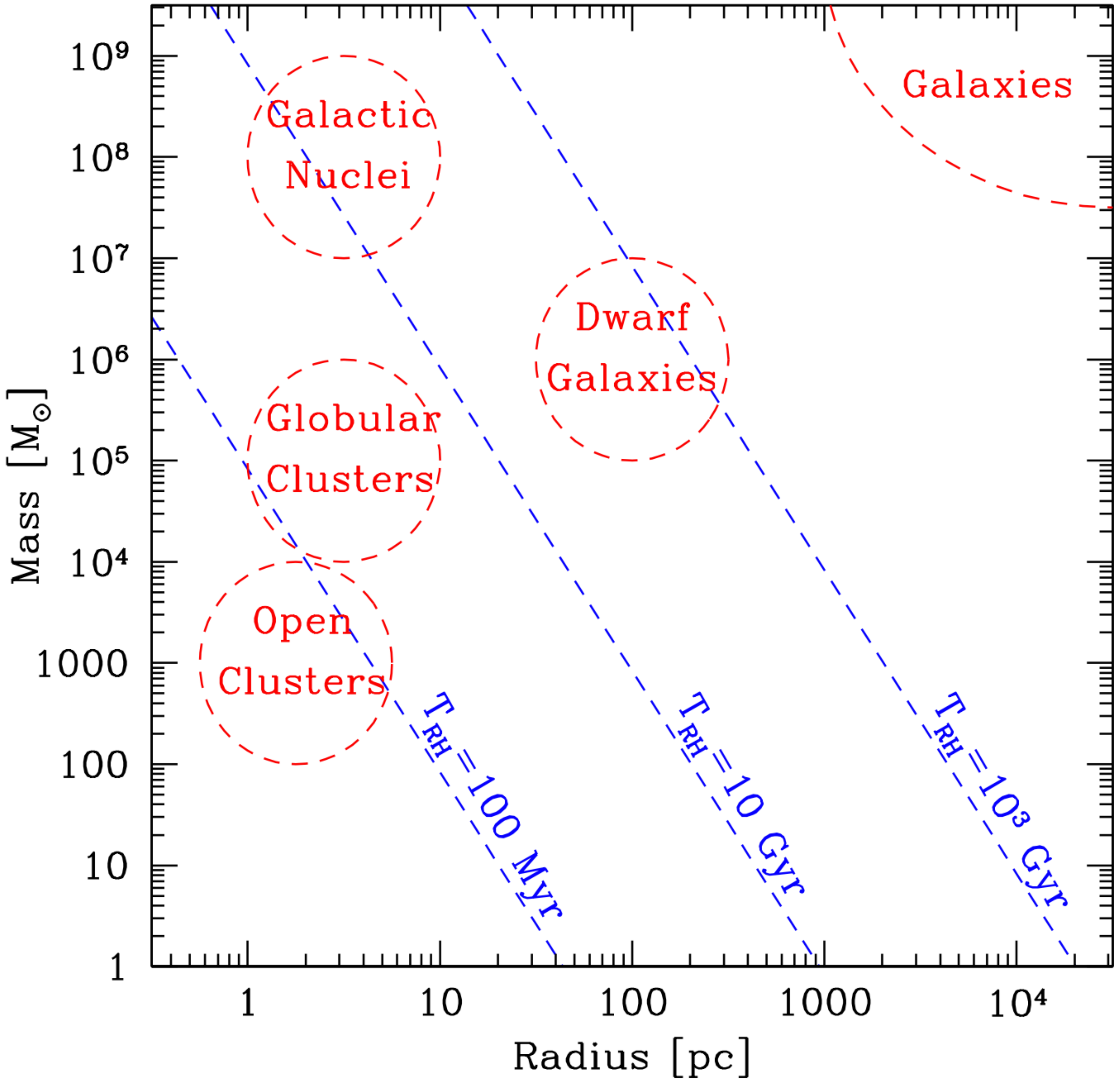
# Different types of stellar clusters

| | Open Clusters & Young Massive Clusters | | Globular Clusters | Nuclear Star Clusters |
|---|---|---|---|---|
| |  |  |  |  |
| **Mass** | $100 - \lesssim 10^4\ \mathrm{M}_\odot$ | $10^4 - 10^5\ \mathrm{M}_\odot$ | $10^4 - 10^6\ \mathrm{M}_\odot$ | $10^5 - 10^8\ \mathrm{M}_\odot$ |
| **Radius** | $\sim 1 -$ few pc | $\sim 1 - 10$ pc | $\sim 10 - 30$ pc | $\sim 1 - 5$ pc |
| **Central Density** | $\lesssim 10^3\ \mathrm{M}_\odot\ \mathrm{pc}^{-3}$ | $\gtrsim 10^3\ \mathrm{M}_\odot\ \mathrm{pc}^{-3}$ | $\gtrsim 10^4 - 10^5\ \mathrm{M}_\odot\ \mathrm{pc}^{-3}$ | $10^5 - 10^7\ \mathrm{M}_\odot\ \mathrm{pc}^{-3}$ |
| **Ages** | $\sim 1$ Myr to few Gyr | a few to $\lesssim 100$ Myr | $\gtrsim 8 - 13$ Gyr | Age Spread |

# Typical cluster masses, densities and relaxation times



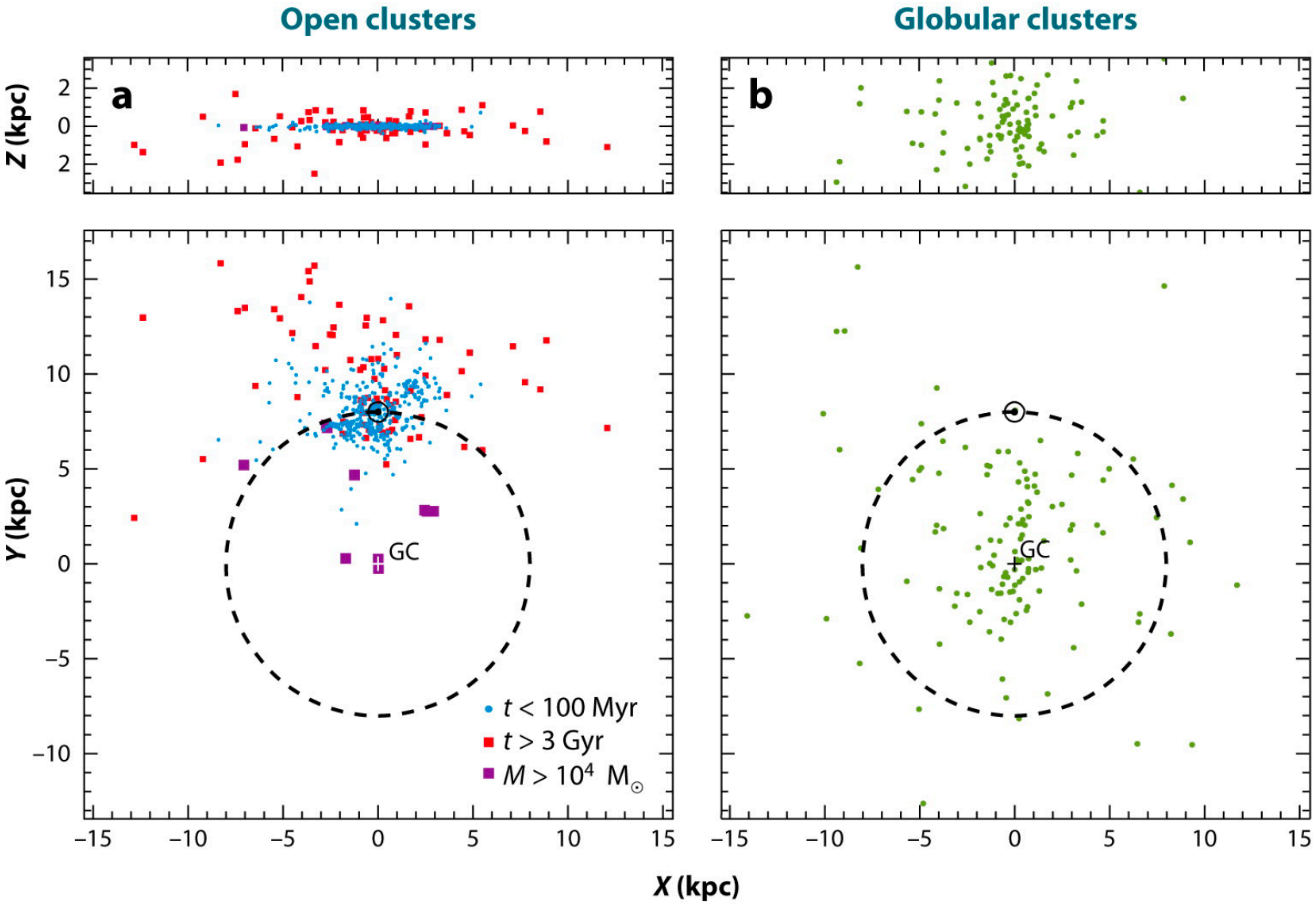
Credit: Melvyn Davies



$$T_{rh} \sim 15\ \mathrm{Myr} \left(\frac{M_{\mathrm{TOT}}}{10^4\ M_\odot}\right)^{1/2} \left(\frac{R_h}{1\mathrm{pc}}\right)^{3/2} \left(\frac{1M_\odot}{m}\right)$$

Credit: Holger Baumgardt

# Distribution of star clusters within the Milky Way



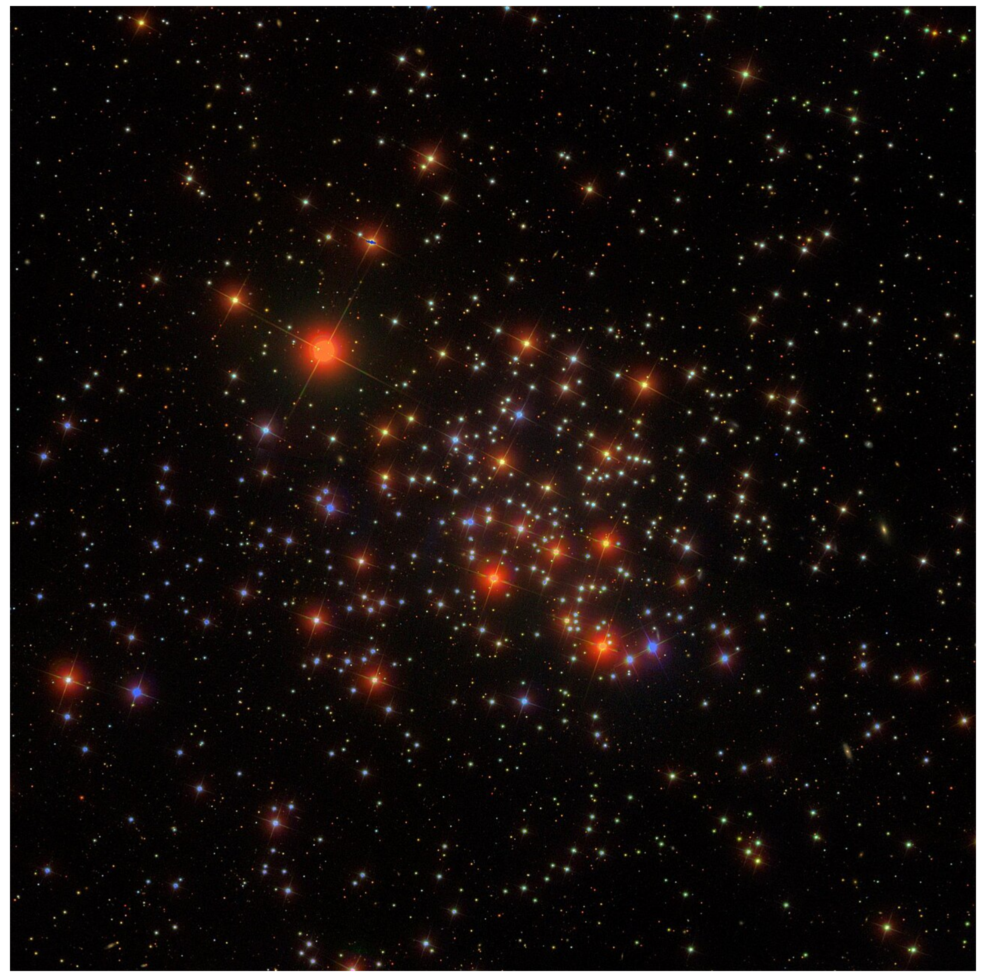
Portegies Zwart, McMillan & Gieles (2010)

- Open Clusters: Located mostly in the Galactic disc
- Globular Clusters: ~150: mostly located in the halo
- Nuclear stellar cluster: Located in the Galactic center

# Open Clusters

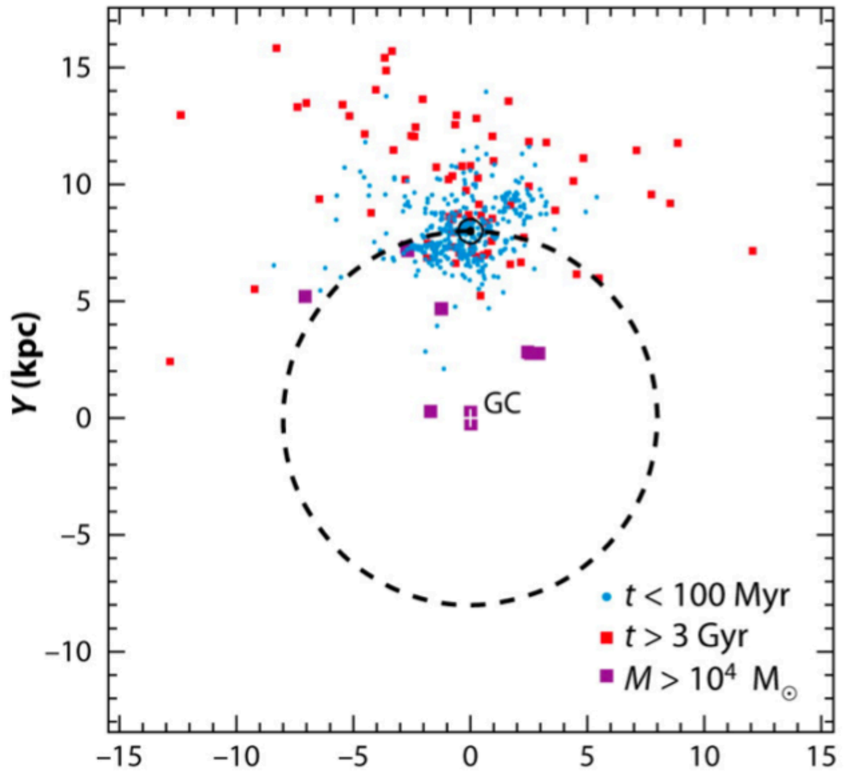
- Radii $\sim 1 - \text{few pc}$
- Mass: $100 - \lesssim 10^4\ \mathrm{M_\odot}$
- Age: a few Myr to a few Gyr
- No gas left
- Gravitationally bound
- Typical density: $\lesssim 10^3\ \mathrm{M_\odot\ pc^{-3}}$

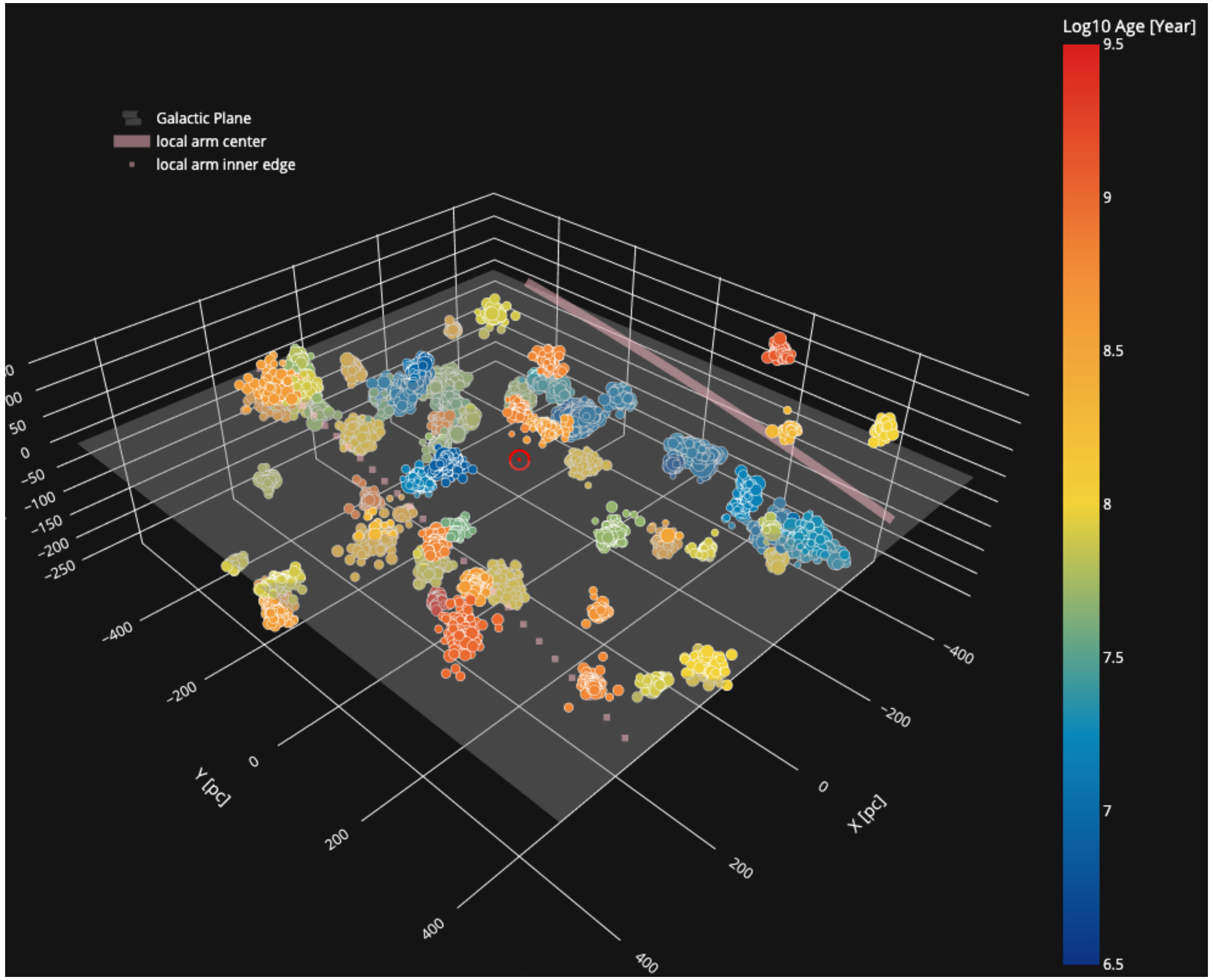
M67: Old Open Cluster (~3 Gyr)



# Open clusters in the solar neighbourhood

- Few thousand (~4000) identified open clusters in our Galaxy.
- More than 100,000 could possibly exist in the galaxy
  - Difficult to observe due to extinction

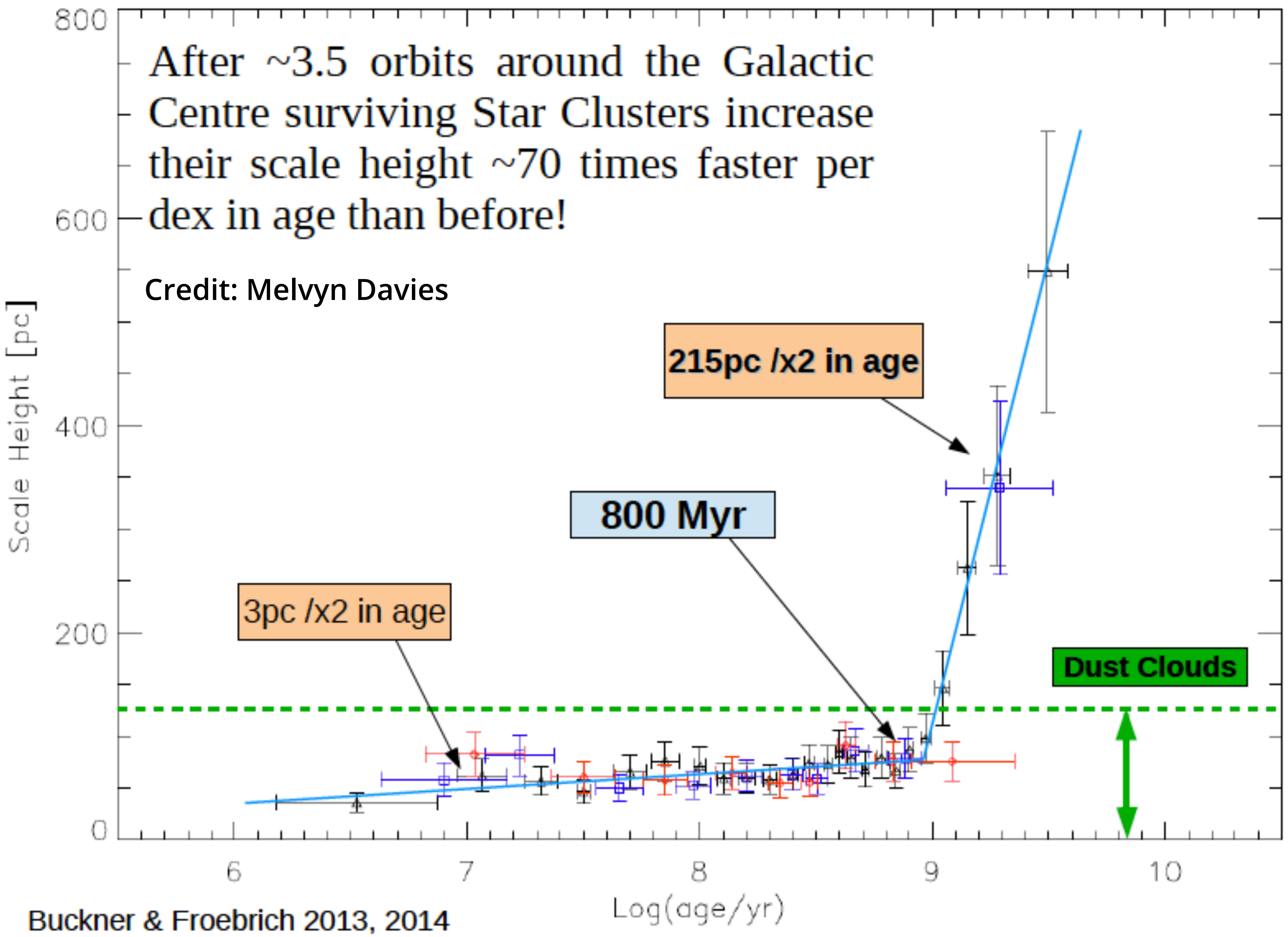




- 3D morphology of open clusters in the solar neighbourhood
  - Made possible with Gaia
- 85 open clusters only in the solar neighbourhood (650 pc)

**Pang et al. 2022: https://arxiv.org/abs/2204.06000**
**http://3doc-morphology.lowell.edu/**

# Scale height and age of open clusters



After ~3.5 orbits around the Galactic Centre surviving Star Clusters increase their scale height ~70 times faster per dex in age than before!

Credit: Melvyn Davies

Buckner & Froebrich 2013, 2014

- Old (> 1 Gyr) open clusters have systematically higher scale height in our Galaxy
- Interactions with giant molecular clouds could:
  1) scatter cluster from disk to higher scale heights (Gustafsson et al. 2016)
  2) lead to their destruction

# Globular Clusters

- Spherical collection of stars that orbits a galactic core as a satellite.
- Comprise 100,000 to millions of stars.
- Globular clusters in the Milky Way are estimated to be at least 10 billion years old.
- Stars are clumped closely together, especially near the centre of the cluster (high central densities)
- Half-light radii range from 1-10 pc
- Large range in core radius (depends on dynamical evolution)
- Typical velocity dispersion of stars ~ 10 km/s (cf surface escape speed of Sun $\sim 600 \text{ km/s}$)

NGC 104 aka 47 Tucanae

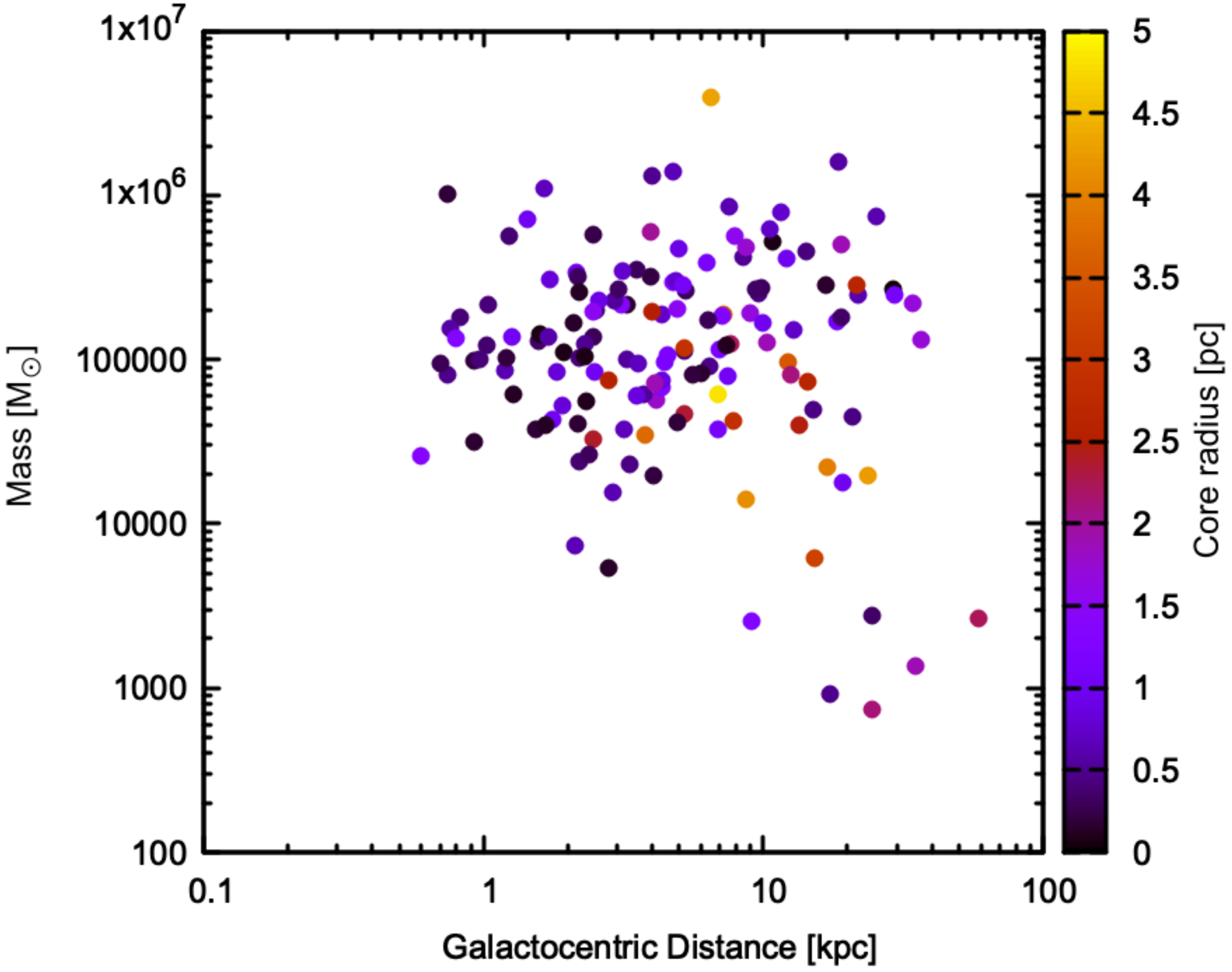
Radius $\sim$ 23 pc (75 lyrs)

$\text{Mass} \sim 7 \times 10^5 \text{M}_\odot$

Age ~ 13 Gyr

# Properties of Milky Way globular clusters

William Harris' (1996, updated 2010) Catalogue of Milky Way globular clusters
https://physics.mcmaster.ca/~harris/mwgc.dat



Holger Baumgardt et al. (2020) properties of Milky Way (and also few extragalactic) globular clusters:
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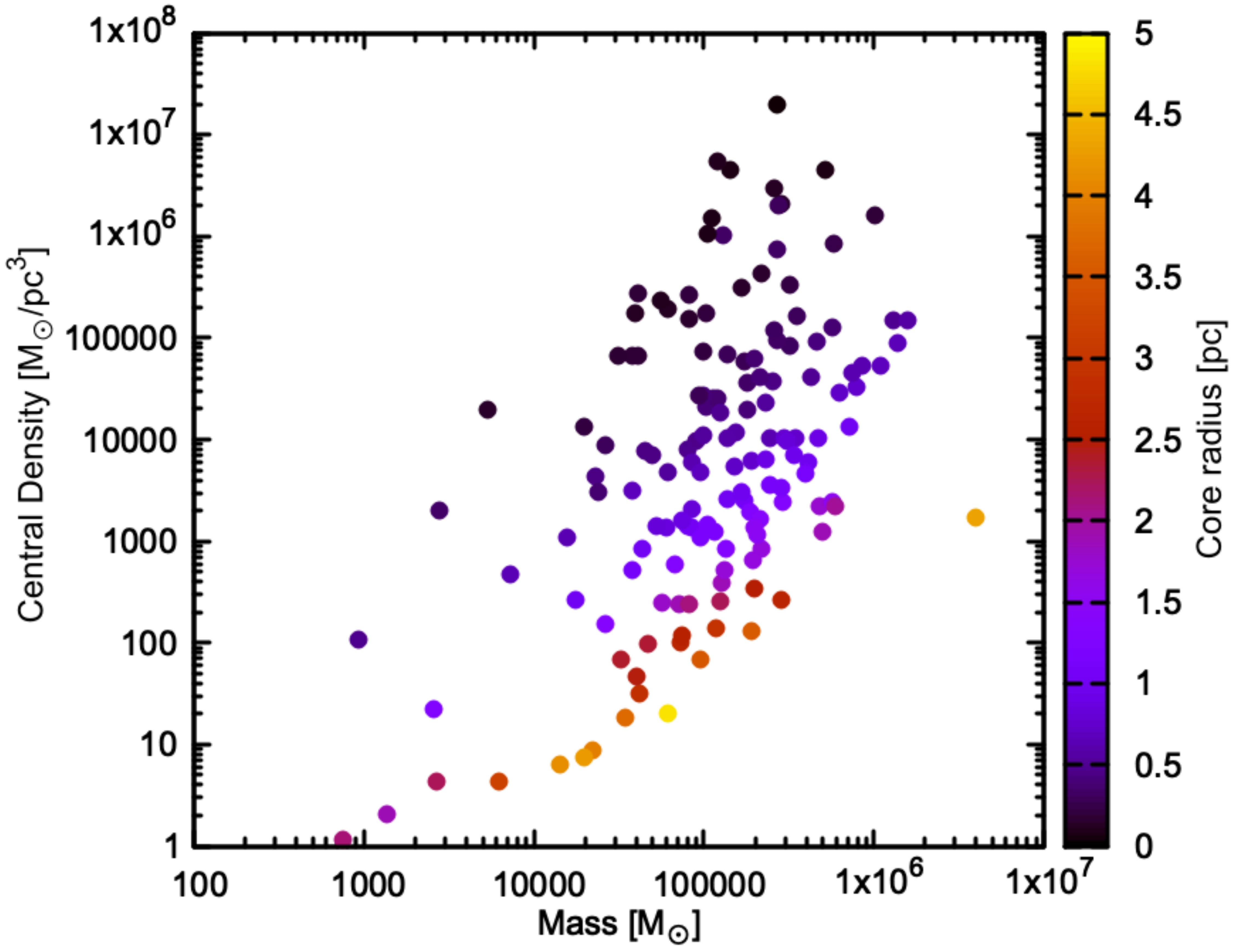

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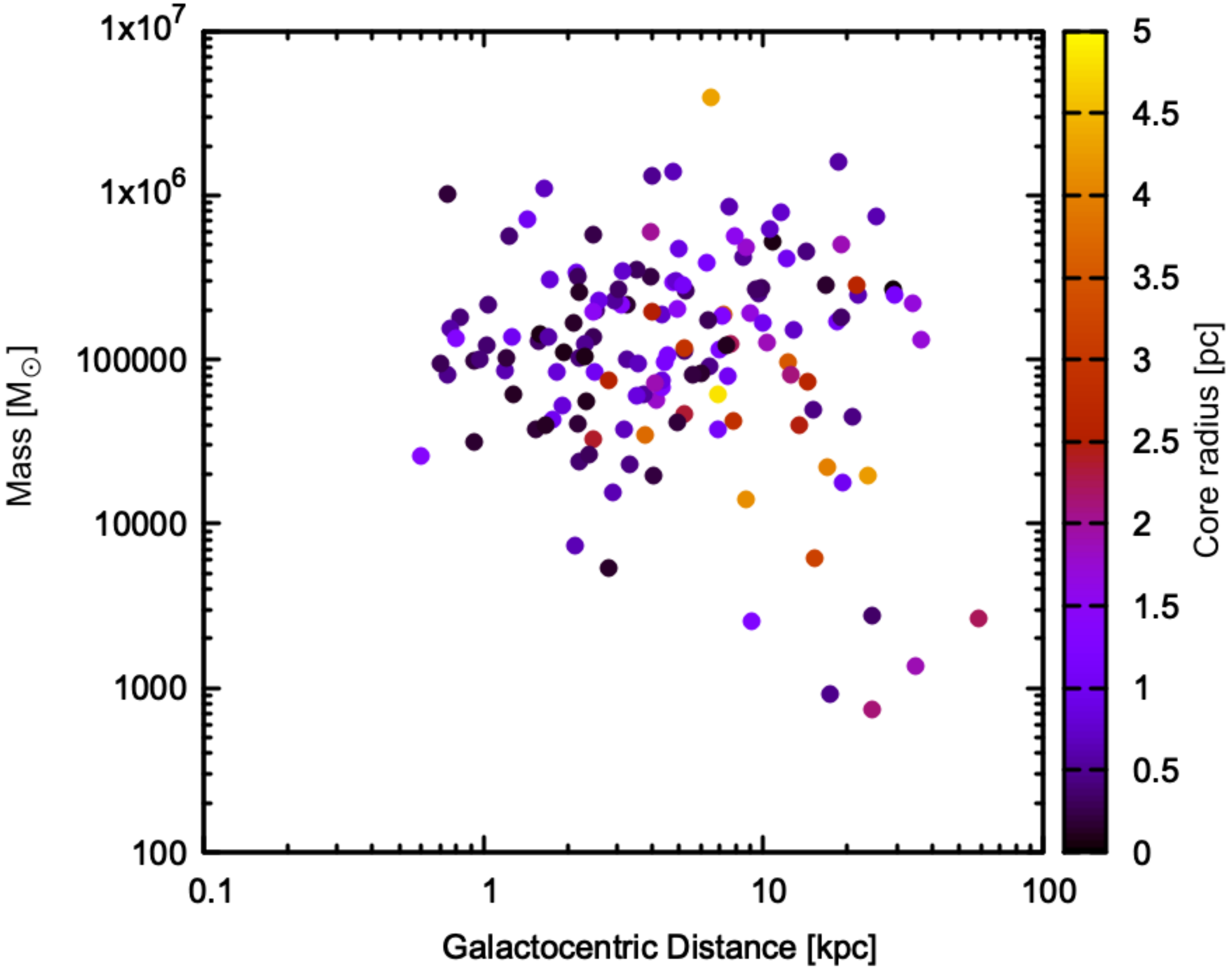

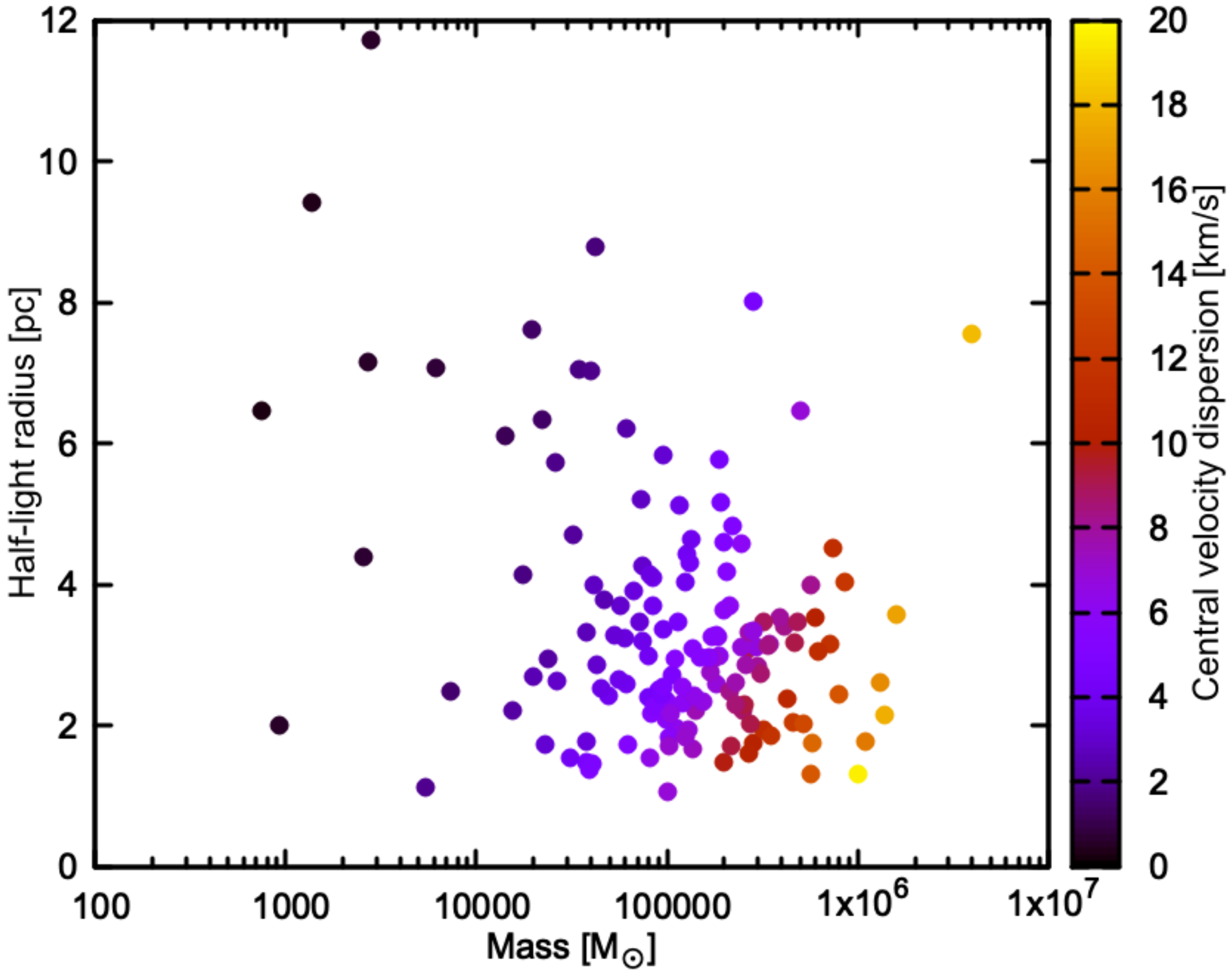

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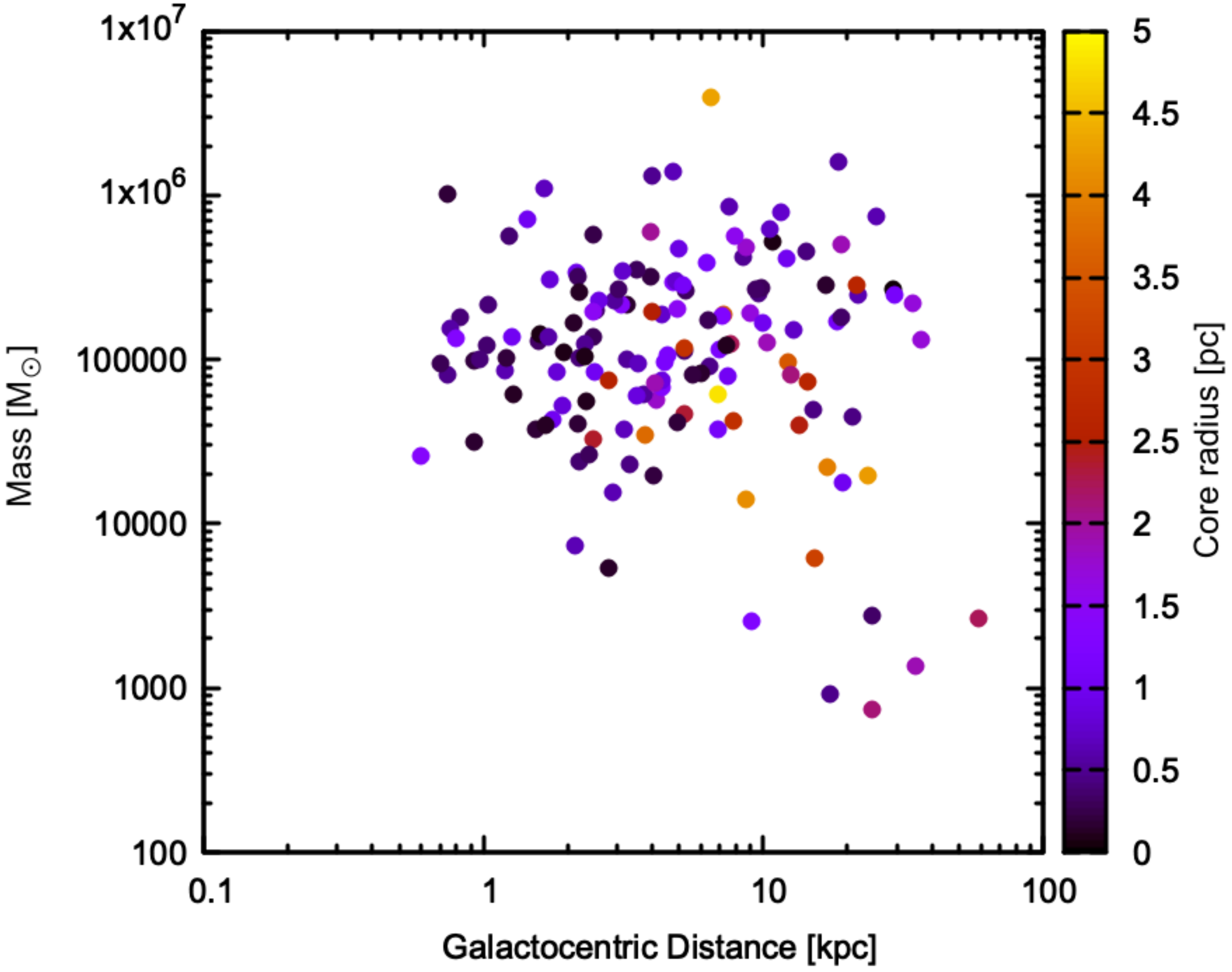

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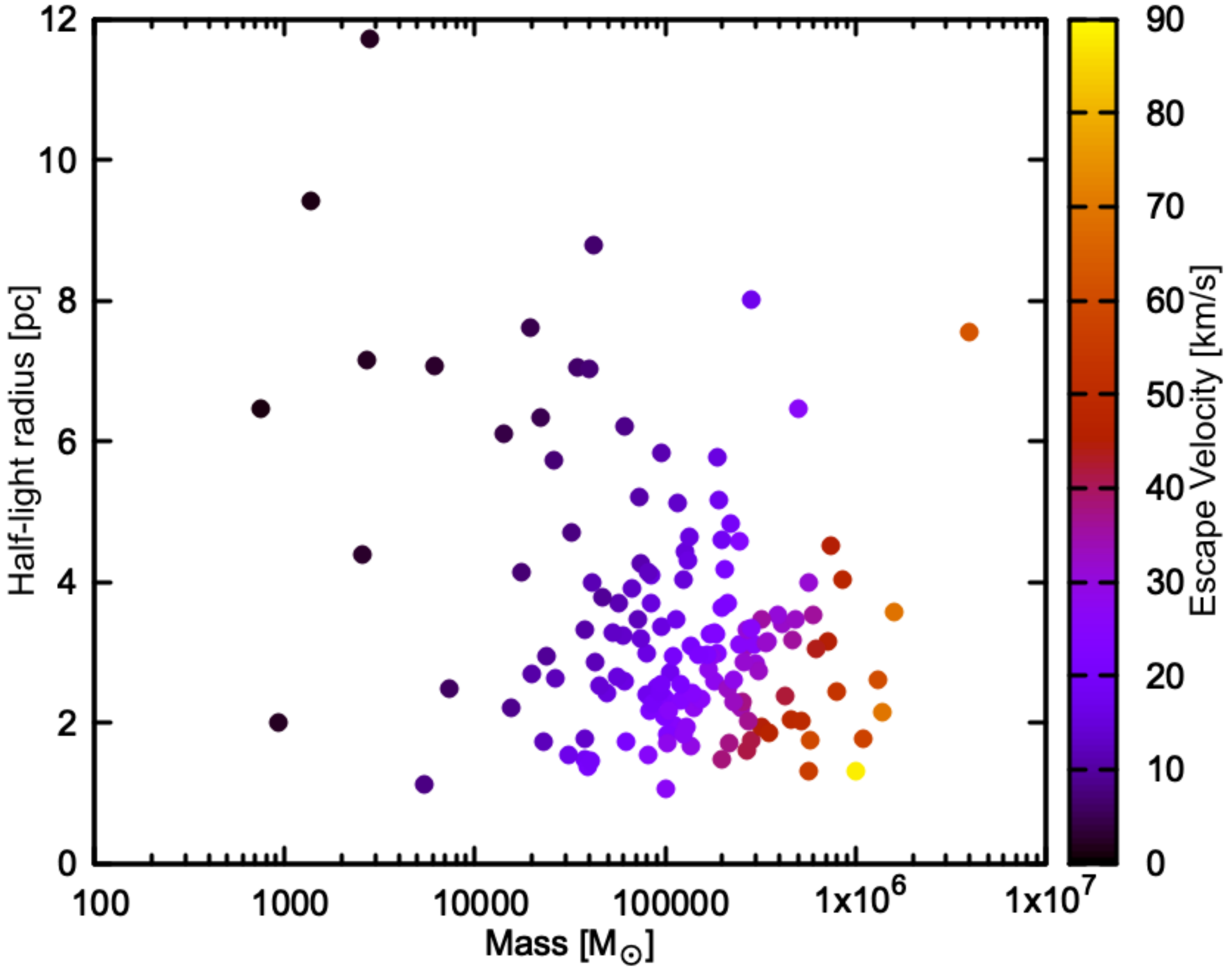


# Importance of globular clusters

## Witnesses of the early Galactic evolution

- First to form
- Mostly metal poor/Chemically uncontaminated

## Stellar Evolution Laboratories

- ‘Simple’ stellar populations
- Test of the ‘stellar clock’

## Distance  and Age Indicators

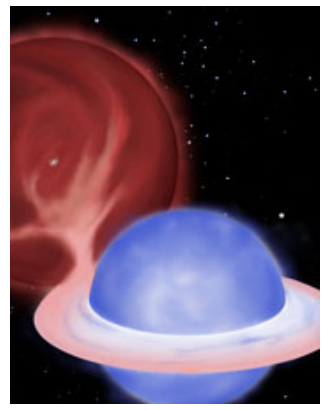
- Standard candles: the RR Lyrae stars
- GC system integrated luminosity function
- The turn-off luminosity = ‘the clock’

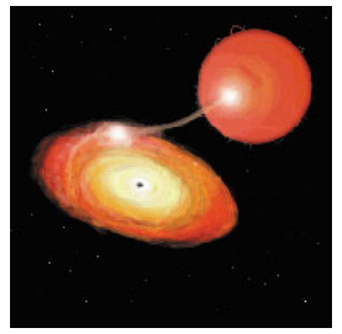
## Stellar/Galactic Dynamics

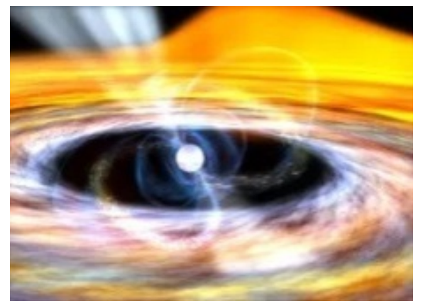
- **Dense environments (laboratories for stellar dynamics):**
- evaporation, mass segregation, core collapse, strong interactions, collisions, mergers
- Test particle of the galactic gravitational field

## Populations of Peculiar Objects/ Stellar Exotica

- X-ray Sources (strong–weak–diffuse)/LMXBs
- Blue Stragglers
- Eclipsing  Binaries
- White Dwarfs, Planetary Nebulae
- Cataclysmic Variables
- Millisecond Pulsars and Neutron Stars
- Stellar Mass Black Holes
- Binary black holes
- Intermediate Mass Black Hole?







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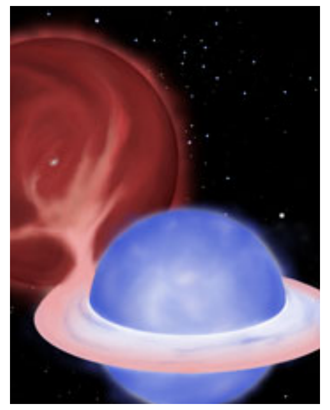
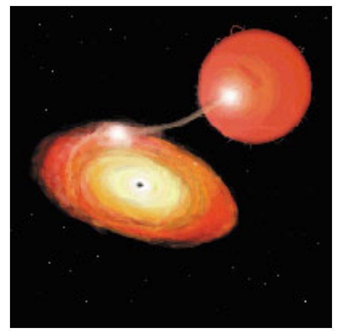
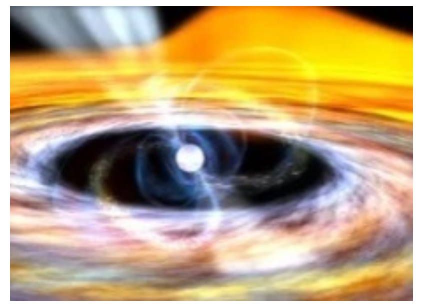






# Stellar encounter timescales

- The cross section for two stars ($M_1$ and $M_2$), having a relative velocity at infinity of $V_\infty$, to pass within a distance $R_{\rm min}$ is given by:

$$\Sigma = \pi R_{\rm min}^2 \left( 1 + \frac{2G\left(M_1 + M_2\right)}{R_{\rm min} V_\infty^2} \right)$$

$$V^2 = \frac{2G\left(M_1 + M_2\right)}{R_{\rm min}}$$

**where V is the relative velocity of the two stars at closest approach in a parabolic encounter**

$$\Sigma = \pi R_{\rm min}^2 \left( 1 + \frac{V^2}{V_\infty^2} \right)$$

**If $V \ll V_\infty$ (e.g., galactic nuclei with extremely high velocity dispersions), we recover the result $\Sigma \propto R_{\rm min}^2$. However, if $V \gg V_\infty$ as will be the case in systems with low velocity dispersions, such as globular clusters,** $\Sigma \propto R_{\rm min}$

Recall gravitational focussing from lecture 7

# Stellar encounter timescales

- We can estimate the timescale for a given star to undergo an encounter with another star, $\tau_{\rm enc} = 1/n\Sigma V$. For clusters with low velocity dispersions:

$$\tau_{enc} \sim 10^{11} yr \left( \frac{10^5/pc^3}{n} \right) \cdot \left( \frac{M_\odot}{M} \right) \cdot \left( \frac{R_\odot}{R_{\rm min}} \right) \cdot \left( \frac{V_\infty}{10 \text{ km/s}} \right)$$

where $n$ is the number density of single stars of mass $M$

- For an encounter between two single stars to be hydrodynamically interesting, we typically require $R_{\rm min} \sim 3R_\star$ (e.g, Davies, Benz & Hills 1991; McMillan et al. 1987).
- For typical globular clusters, where $n \sim 10^5$, up to $\sim 10 - 20\,\%$ of the stars in the cluster cores will have undergone close encounters some point during the lifetime of the cluster.
- Recall from lecture 7: **Binary systems will have an even shorter encounter rate since binary semi-major axis $a \gg R_\star$**

# Stellar collisions during close 2-body, 3-body and 4-body encounters

- Outcomes of collisions:
  - MS-MS collisions -> some mass loss (1-10%)

  - In globular clusters, typical $\Delta V$ is of the order $\sim$100 km/s
    reminder: (cf surface escape speed of Sun $\sim 600\ \mathrm{km/s}$)
    - Collisions are likely to lead to mergers
    - In high velocity dispersion environments (e.g., galactic center), collisions could lead to complete disruption of the star

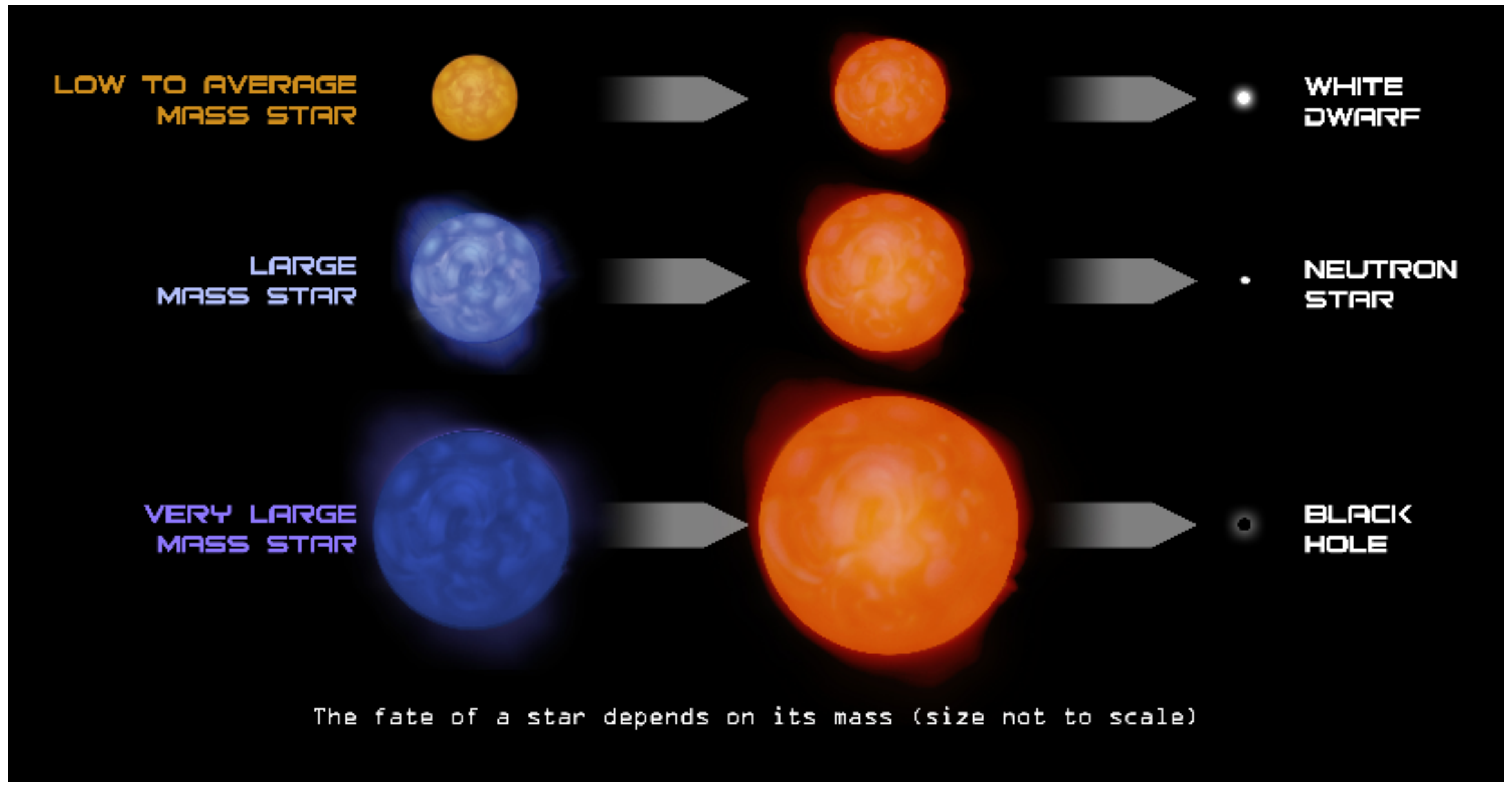
  - Collisions between stars and compact objects: tidal disruption event and/or mergers
  - Close encounters could lead to tidal captures (as dicussed in the context of binary formation in Lecture 7: Fabian, Pringle & Rees 1975)
- Collisions and close encounters between stars in cluster cores can produce exotic objects.

# Quick recap of stellar evolution

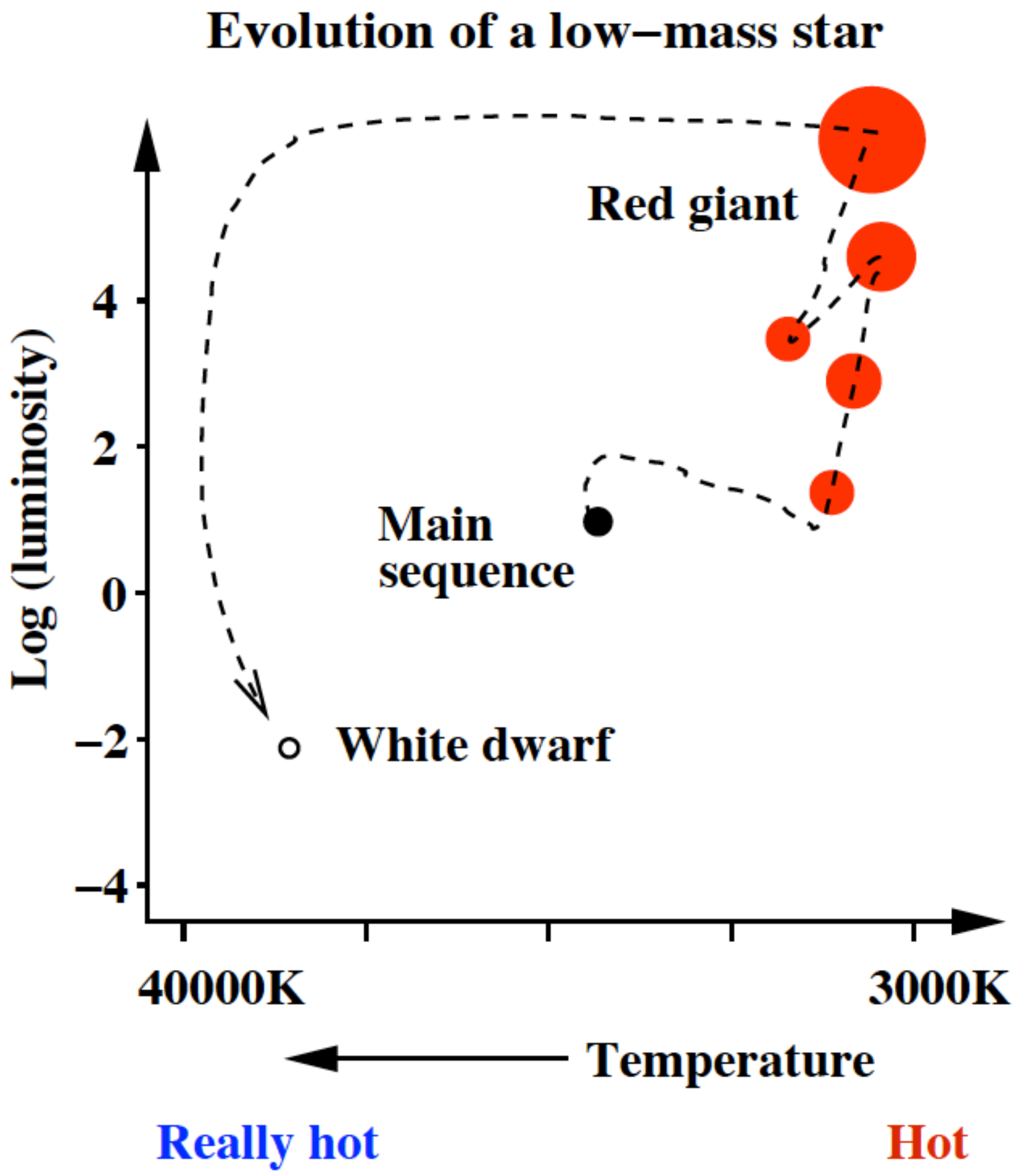
$M_{\mathrm{ZAMS}} \lesssim 8\ M_{\odot}$

$8\ M_{\odot} \lesssim M_{\mathrm{ZAMS}} \lesssim 20\ M_{\odot}$

$M_{\mathrm{ZAMS}} \gtrsim 20 M_{\odot}$

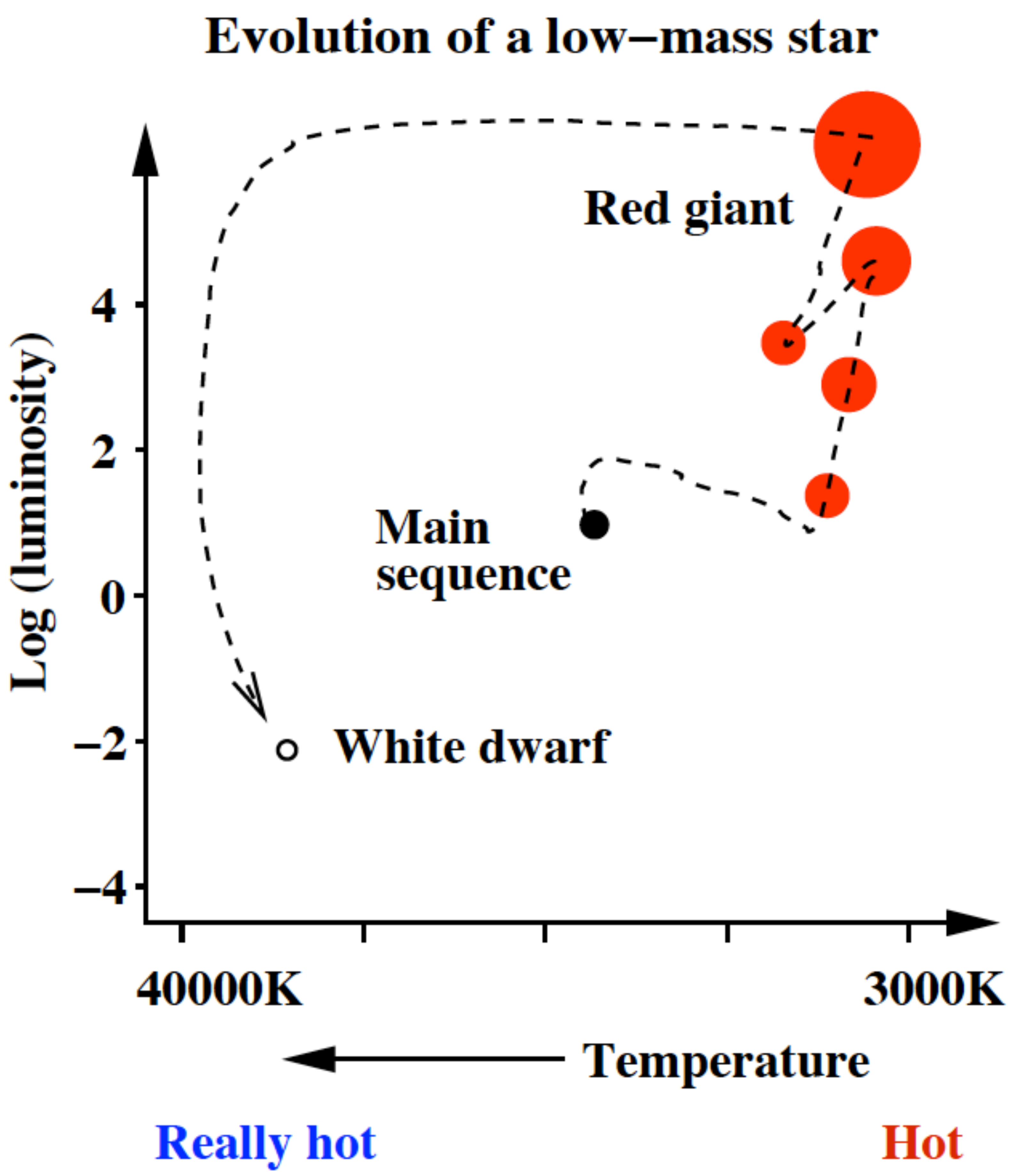


- Depends on initial mass of the star and its metallicity
- Stars go through various phases of evolution between the MS and compact object
  - Radius of a star changes in these evolutionary stages
  - Timescales of these evolutionary stages can be short



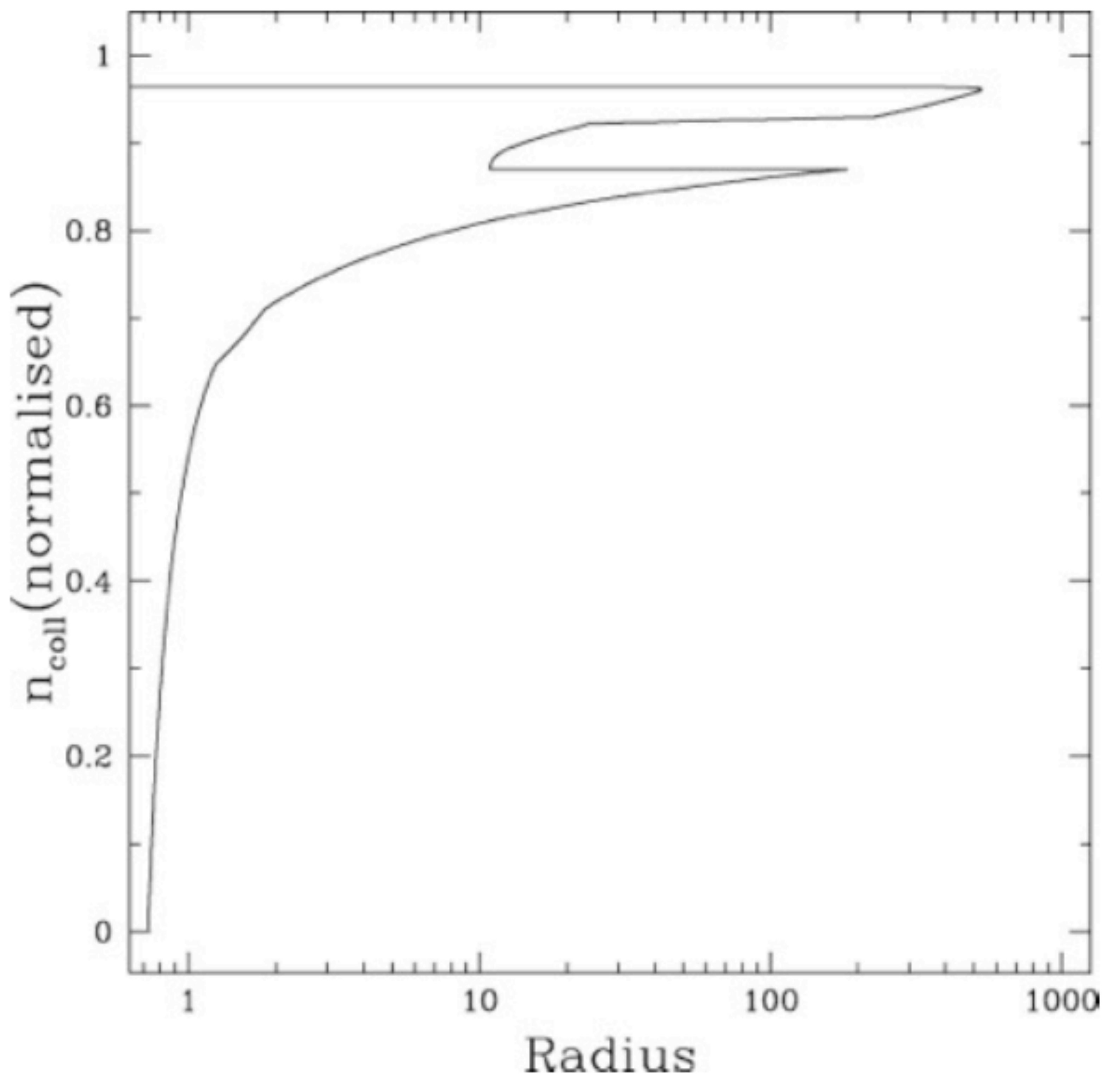
Credit: Melvyn Davies

# Stellar evolution and collisions



Credit: Melvyn Davies

Stellar radius vs cumulative number of collisions



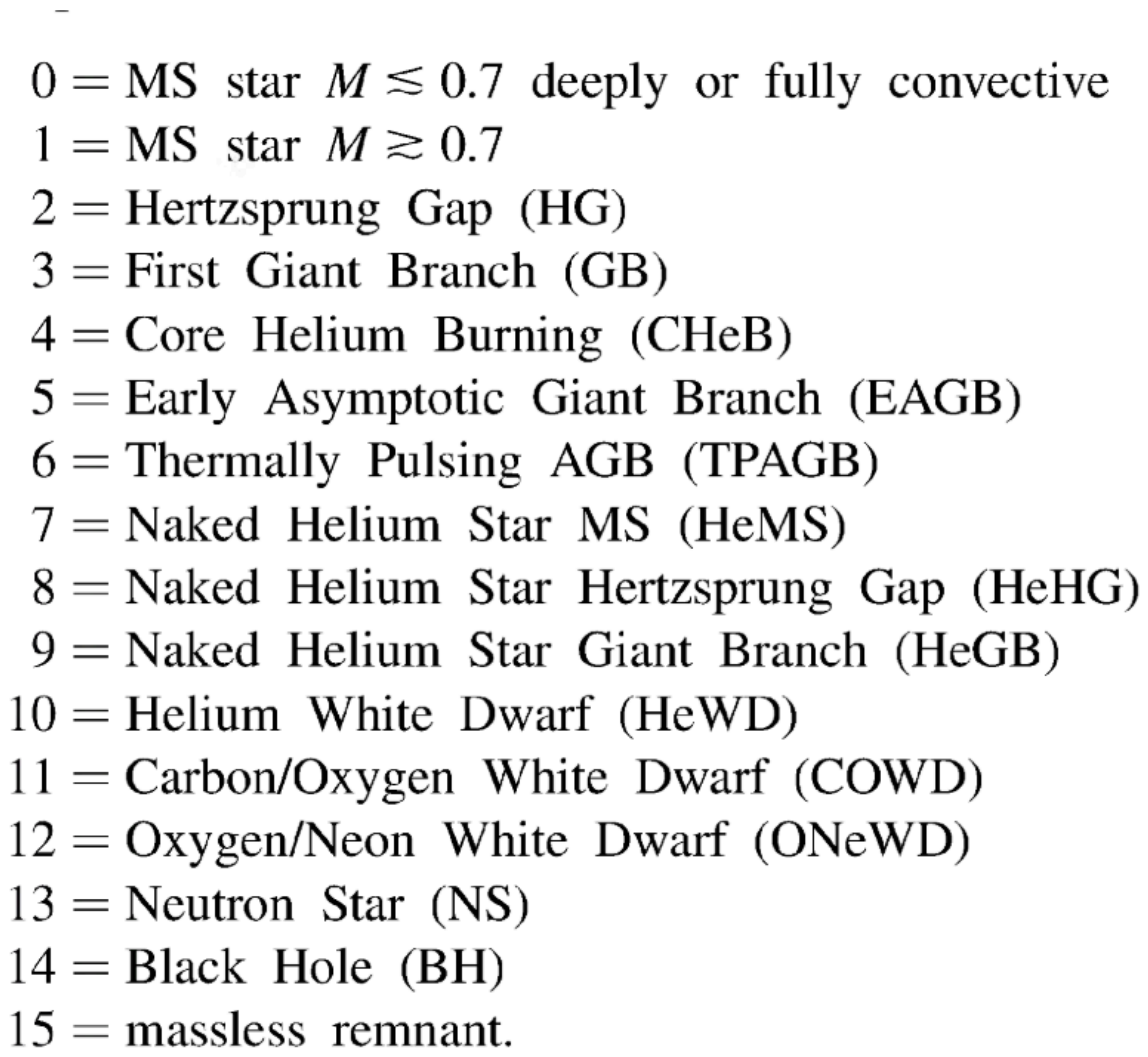
low-mass star in a globular cluster

Sills et al. 2005

# Outcome of stellar collisions

| | Main Sequence Star | Giant Star | White Dwarf | Neutron Star | Black Hole |
|---|---|---|---|---|---|
| Main Sequence Star | Blue Straggler Stars | Common envelope/ interacting binary | Giant star | Neutron Star | Black Hole |
| Giant Star | Common envelope/ interacting binary | Common envelope/ interacting binary | Interacting binary | Interacting binary | Interacting binary |
| White Dwarf | Giant star | Interacting binary (WD-WD) | Type Ia supernova or ONeMg or evolved star | Neutron Star | Black Hole |
| Neutron Star | Neutron Star | Interacting binary (NS-WD) | Neutron Star | Neutron Star or Black Hole | Black Hole |
| Black Hole | Black Hole | Interacting binary (BH-WD) | Black hole | Black Hole | Black Hole |

# Outcome of stellar collisions


0 = MS star $M \lesssim 0.7$ deeply or fully convective
1 = MS star $M \gtrsim 0.7$
2 = Hertzsprung Gap (HG)
3 = First Giant Branch (GB)
4 = Core Helium Burning (CHeB)
5 = Early Asymptotic Giant Branch (EAGB)
6 = Thermally Pulsing AGB (TPAGB)
7 = Naked Helium Star MS (HeMS)
8 = Naked Helium Star Hertzsprung Gap (HeHG)
9 = Naked Helium Star Giant Branch (HeGB)
10 = Helium White Dwarf (HeWD)
11 = Carbon/Oxygen White Dwarf (COWD)
12 = Oxygen/Neon White Dwarf (ONeWD)
13 = Neutron Star (NS)
14 = Black Hole (BH)
15 = massless remnant.

## Collision Matrix from BSE population synthesis code

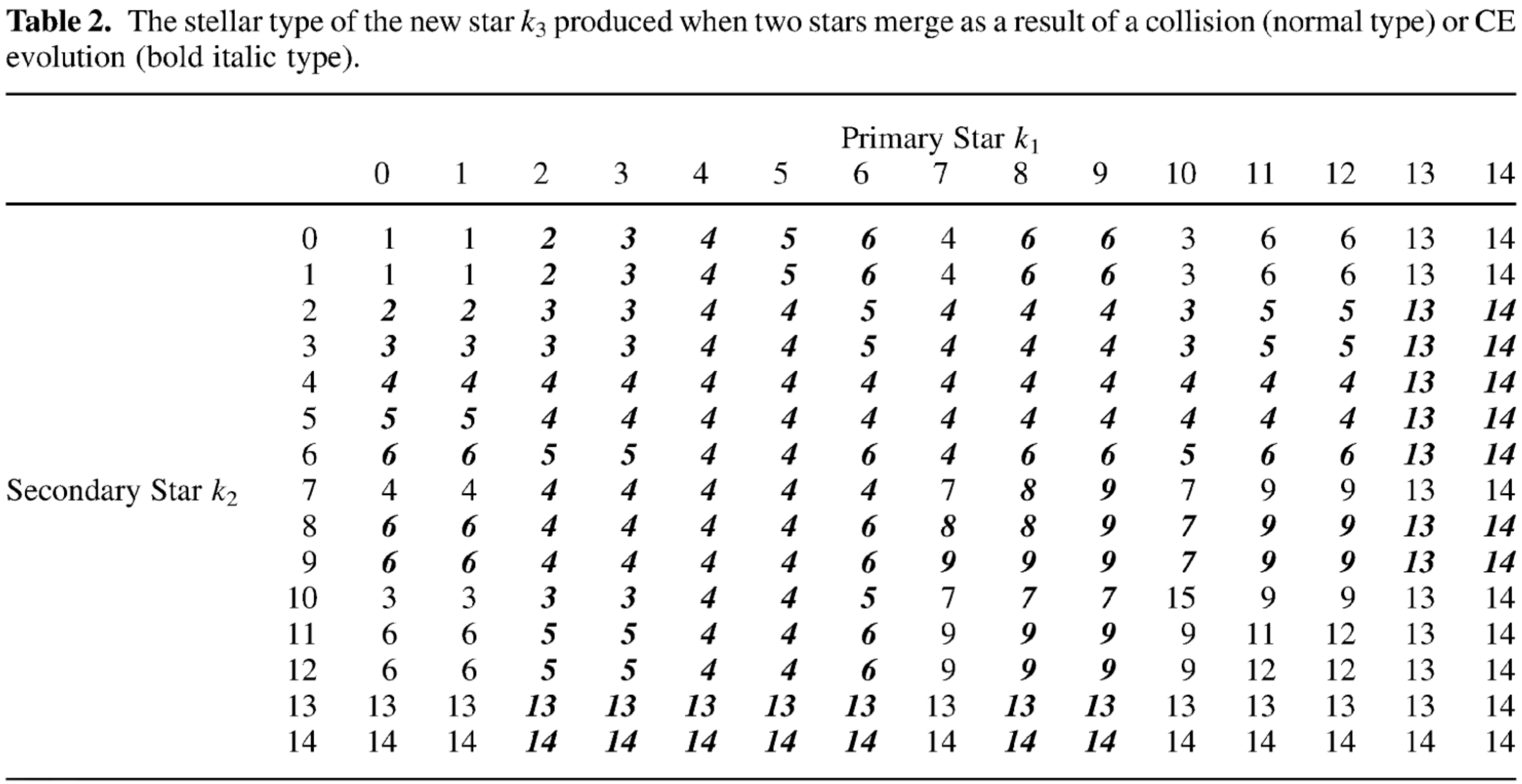


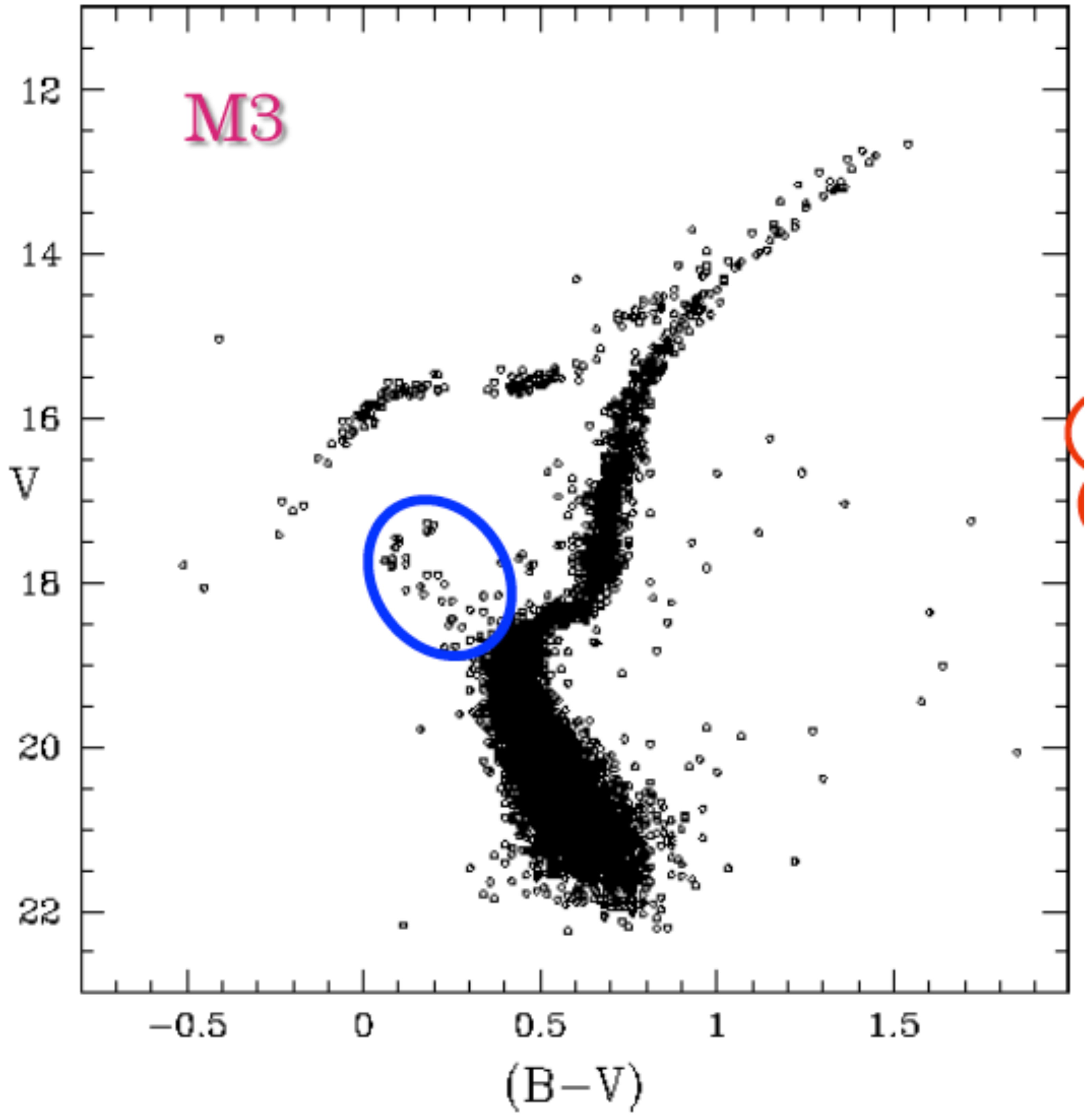
**Table 2.** The stellar type of the new star $k_3$ produced when two stars merge as a result of a collision (normal type) or CE evolution (bold italic type).

| | | Primary Star $k_1$ | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
| Secondary Star $k_2$ | 0 | 1 | 1 | ***2*** | ***3*** | ***4*** | ***5*** | ***6*** | 4 | ***6*** | ***6*** | 3 | 6 | 6 | 13 | 14 |
| | 1 | 1 | 1 | ***2*** | ***3*** | ***4*** | ***5*** | ***6*** | 4 | ***6*** | ***6*** | 3 | 6 | 6 | 13 | 14 |
| | 2 | ***2*** | ***2*** | ***3*** | ***3*** | ***4*** | ***4*** | ***5*** | ***4*** | ***4*** | ***4*** | ***3*** | ***5*** | ***5*** | ***13*** | ***14*** |
| | 3 | ***3*** | ***3*** | ***3*** | ***3*** | ***4*** | ***4*** | ***5*** | ***4*** | ***4*** | ***4*** | ***3*** | ***5*** | ***5*** | ***13*** | ***14*** |
| | 4 | ***4*** | ***4*** | ***4*** | ***4*** | ***4*** | ***4*** | ***4*** | ***4*** | ***4*** | ***4*** | ***4*** | ***4*** | ***4*** | ***13*** | ***14*** |
| | 5 | ***5*** | ***5*** | ***4*** | ***4*** | ***4*** | ***4*** | ***4*** | ***4*** | ***4*** | ***4*** | ***4*** | ***4*** | ***4*** | ***13*** | ***14*** |
| | 6 | ***6*** | ***6*** | ***5*** | ***5*** | ***4*** | ***4*** | ***6*** | ***4*** | ***6*** | ***6*** | ***5*** | ***6*** | ***6*** | ***13*** | ***14*** |
| | 7 | 4 | 4 | ***4*** | ***4*** | ***4*** | ***4*** | ***4*** | 7 | ***8*** | ***9*** | 7 | 9 | 9 | 13 | 14 |
| | 8 | ***6*** | ***6*** | ***4*** | ***4*** | ***4*** | ***4*** | ***6*** | ***8*** | ***8*** | ***9*** | ***7*** | ***9*** | ***9*** | ***13*** | ***14*** |
| | 9 | ***6*** | ***6*** | ***4*** | ***4*** | ***4*** | ***4*** | ***6*** | ***9*** | ***9*** | ***9*** | ***7*** | ***9*** | ***9*** | ***13*** | ***14*** |
| | 10 | 3 | 3 | ***3*** | ***3*** | ***4*** | ***4*** | ***5*** | 7 | ***7*** | ***7*** | 15 | 9 | 9 | 13 | 14 |
| | 11 | 6 | 6 | ***5*** | ***5*** | ***4*** | ***4*** | ***6*** | 9 | ***9*** | ***9*** | 9 | 11 | 12 | 13 | 14 |
| | 12 | 6 | 6 | ***5*** | ***5*** | ***4*** | ***4*** | ***6*** | 9 | ***9*** | ***9*** | 9 | 12 | 12 | 13 | 14 |
| | 13 | 13 | 13 | ***13*** | ***13*** | ***13*** | ***13*** | ***13*** | 13 | ***13*** | ***13*** | 13 | 13 | 13 | 13 | 14 |
| | 14 | 14 | 14 | ***14*** | ***14*** | ***14*** | ***14*** | ***14*** | 14 | ***14*** | ***14*** | 14 | 14 | 14 | 14 | 14 |

Hurley, Tout & Pols (2002)

# Blue Straggler Stars (BSS)

- Stars brighter and bluer (hotter) than the cluster main sequence turn-off, along an extension of the main sequence (appear younger than the rest of the cluster population)

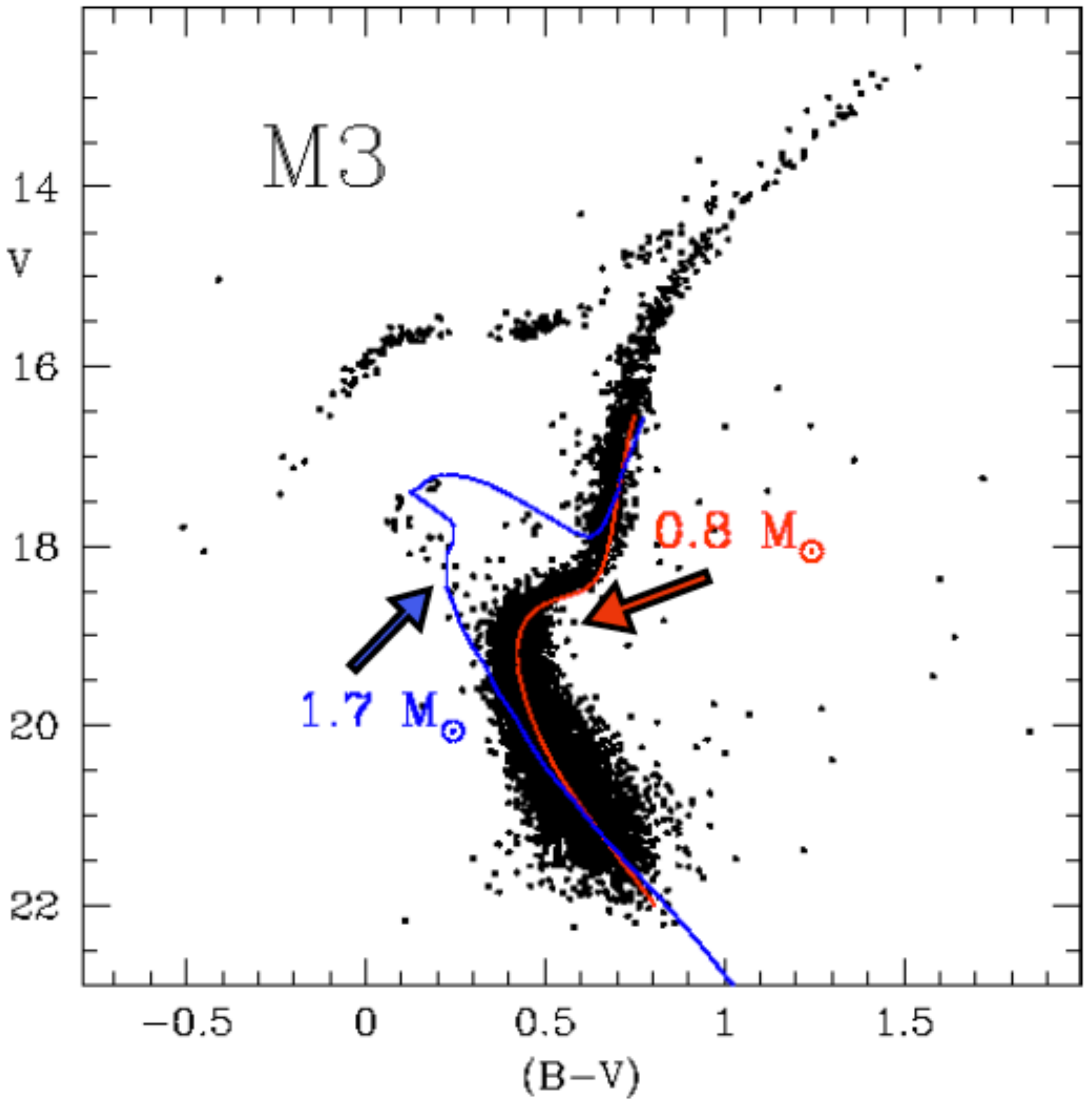


First detected by Sandage (1953) in Galactic globular cluster M3

**Credit: Adam Block/Mount Lemmon SkyCenter/University of Arizona**

# Blue Straggler Stars (BSS)

- Young and brighter than main sequence (MS) stars: if cluster members this implies they are more massive than the main sequence turn off

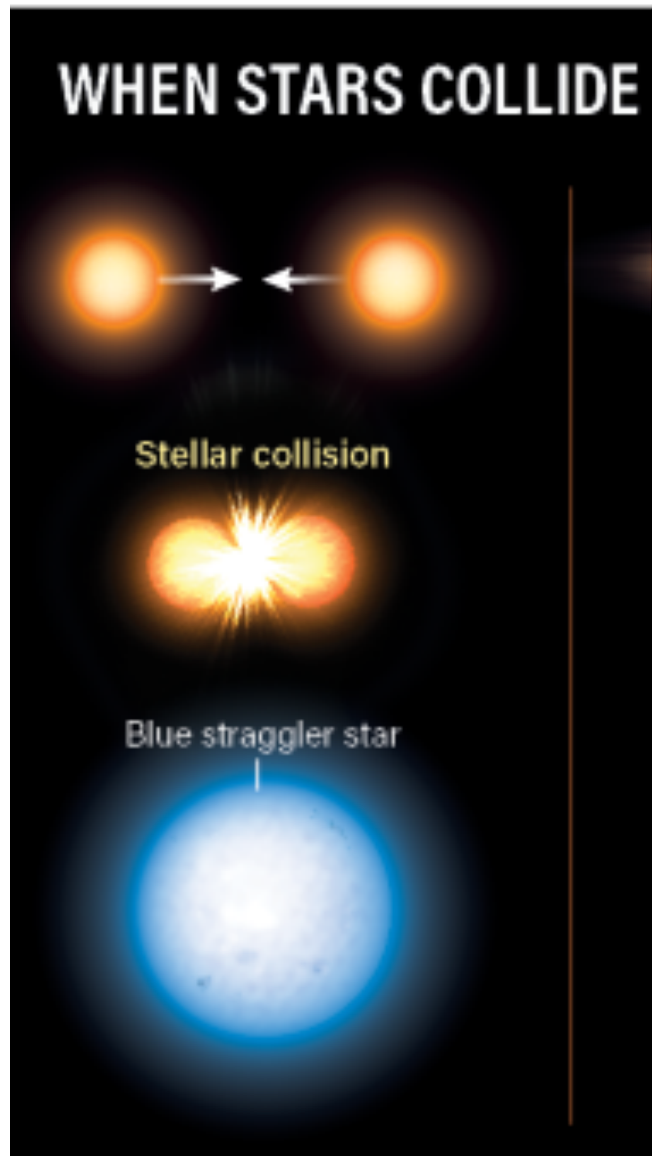


Credit: Francesco Ferraro

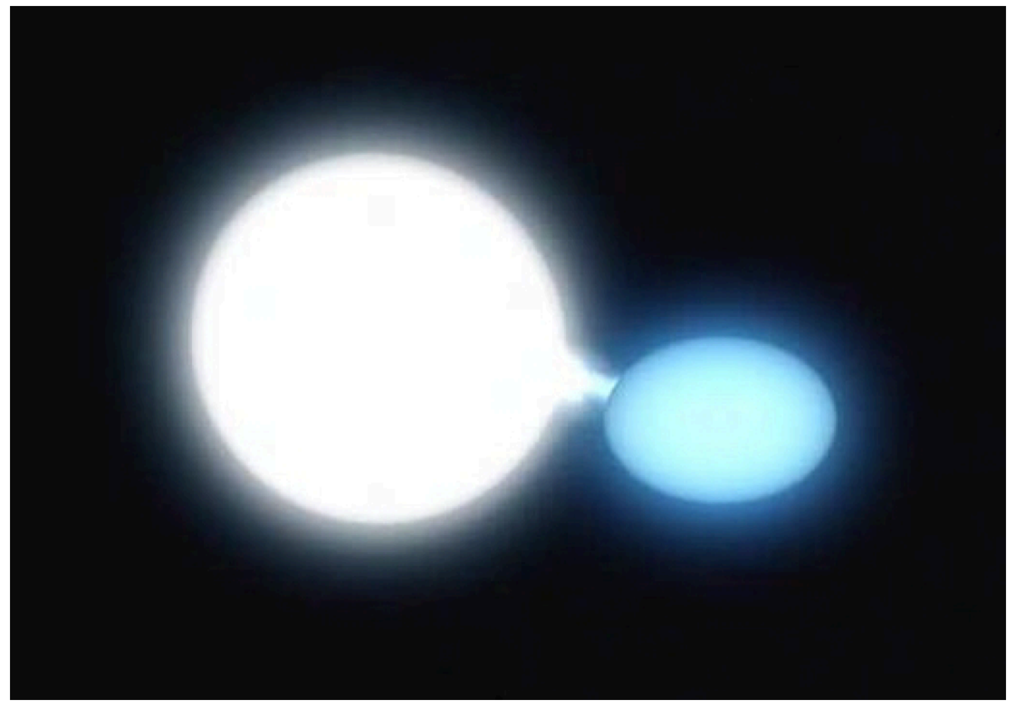
- Direct mass measurements of BSS confirmed that they are more massive than normal stars (Shara et al. 1997)
- Likely to have formed from the merger of 2 low-mass MS stars

# Different ways to form BSS

- Direct collisions between two main sequence stars during 2-body encounters, binary-single or binary binary encounters
  - Probe the dynamical state of the cluster
  - **Can you think of a phase in cluster evolution when BSS production could increase?**



Credit: *Astronomy*: Roen Kelly



# Different ways to form BSS

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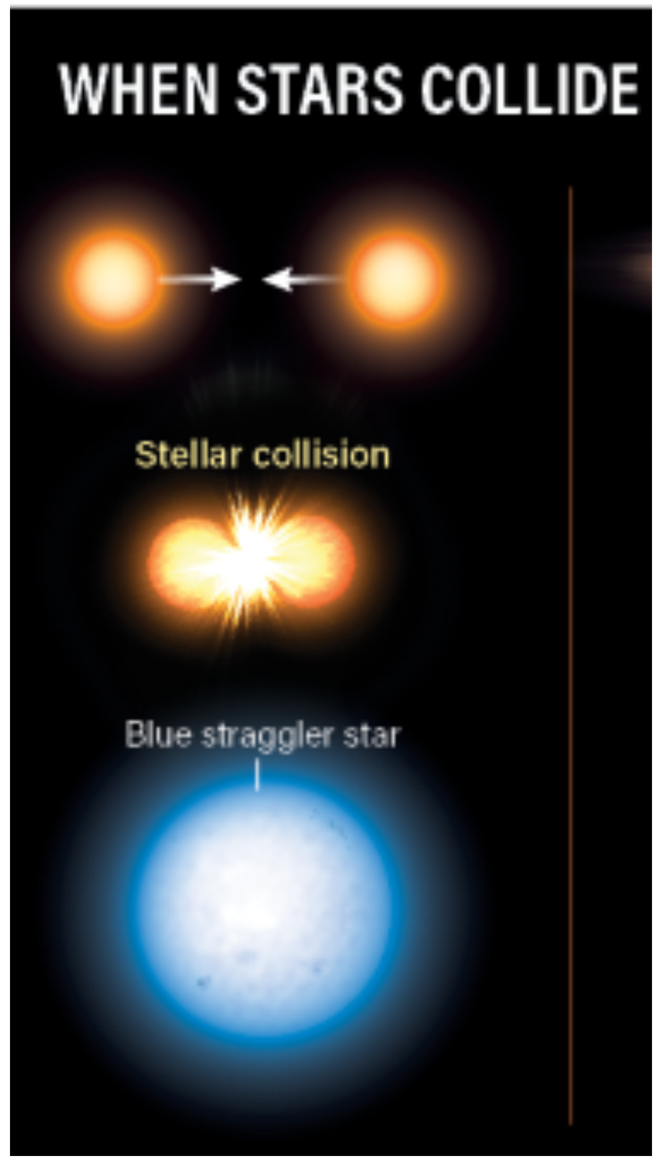

Credit: *Astronomy*: Roen Kelly

# Things we learned from binary-single encounters

- Hard binary: $\frac{Gm_1m_2}{2a} > \frac{1}{2}\langle m\rangle\sigma^2$ binding energy higher than the average kinetic energy of a star in the cluster
- Soft binary: $\frac{Gm_1m_2}{2a} < \frac{1}{2}\langle m\rangle\sigma^2$ binding energy lower than the average kinetic energy of a star in the cluster
- All types of interactions can occur, but on average, hard binaries (those bound more tightly than the average binding energy in the cluster) give away more energy than they absorb, and become ever more tightly bound (binary hardening/shrinking)
- Soft binaries more likely to absorb energy and become more loosely bound or unbound (binary disruption/ionization)

**Heggie/Hill's (1975) Law: In 3-body encounters hard binaries become harder (increase $E_b$ ) and soft binaries tend to become softer (decrease $E_b$)**

- Exchanges can occur: lowest-mass star likely to be ejected
- Stellar collisions can occur during binary-single encounters

# Different ways to form BSS

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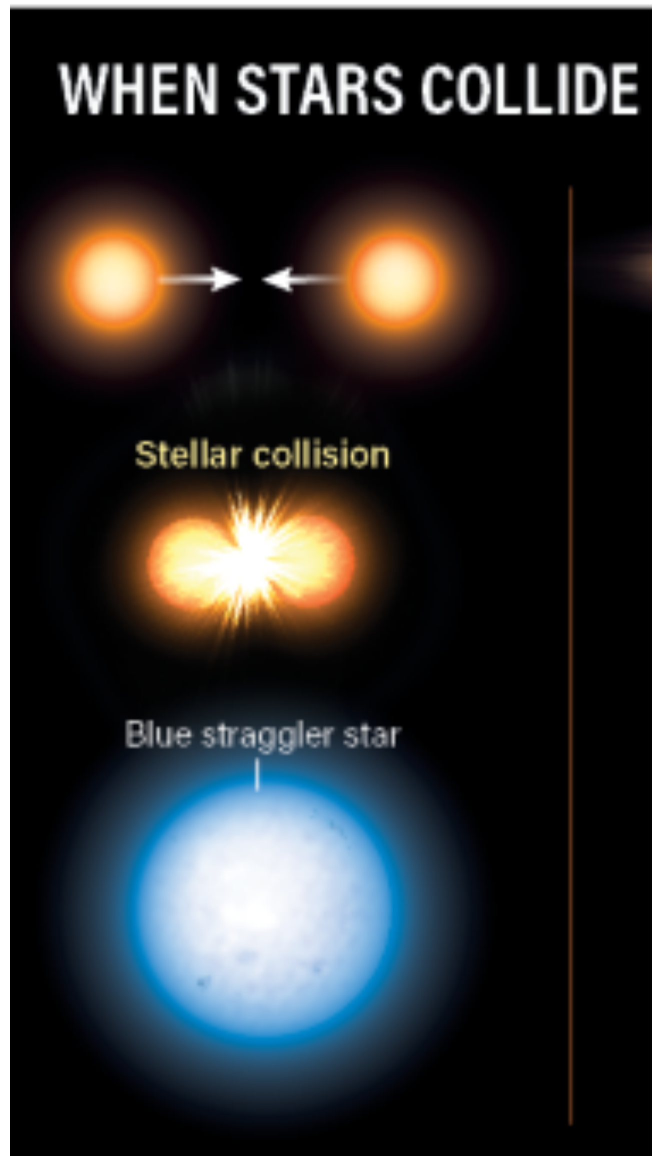
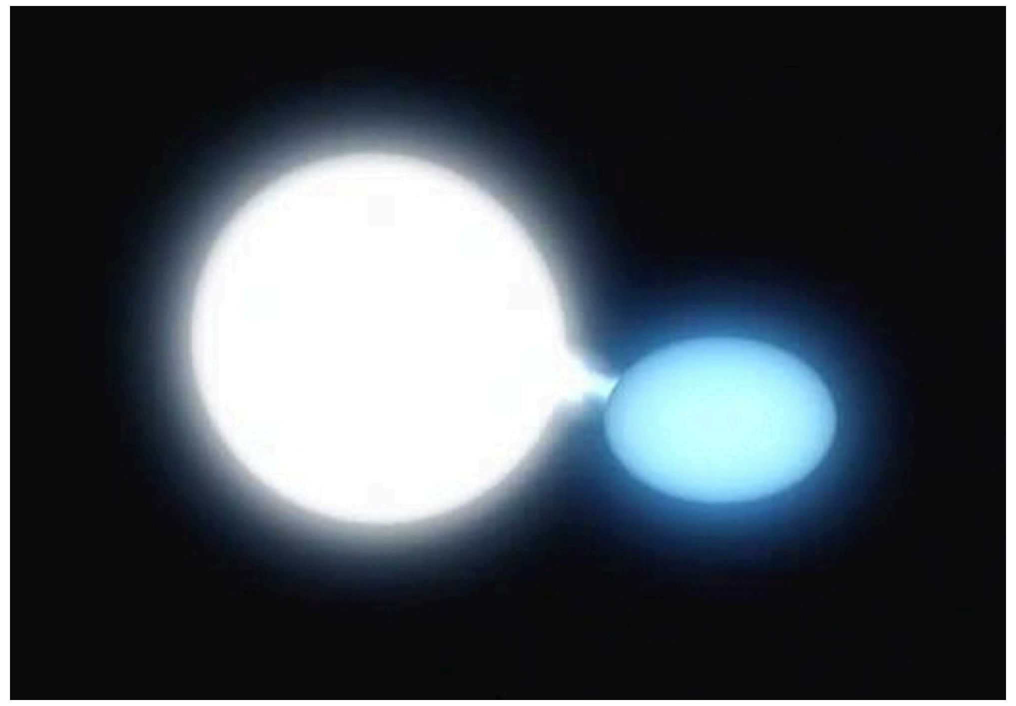
  - **Core Collapse → when stellar density in the core increases and encounters become more frequent**
- Mass transfer during binary evolution
  - e.g., a primordial binary in which we have an evolved star transferring mass onto a main-sequence star
  - Dynamical interactions could also induce mass transfer in binaries
    - Exchange encounters
    - Hardening and eccentricity changes due to binary-single encounters
  - Channel could depend on primordial binary fraction
- Can also form in mergers or mass transfer in triple systems



Credit: *Astronomy*: Roen Kelly



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    - Exchange encounters
    - Hardening and eccentricity changes due to binary-single encounters: binary burning
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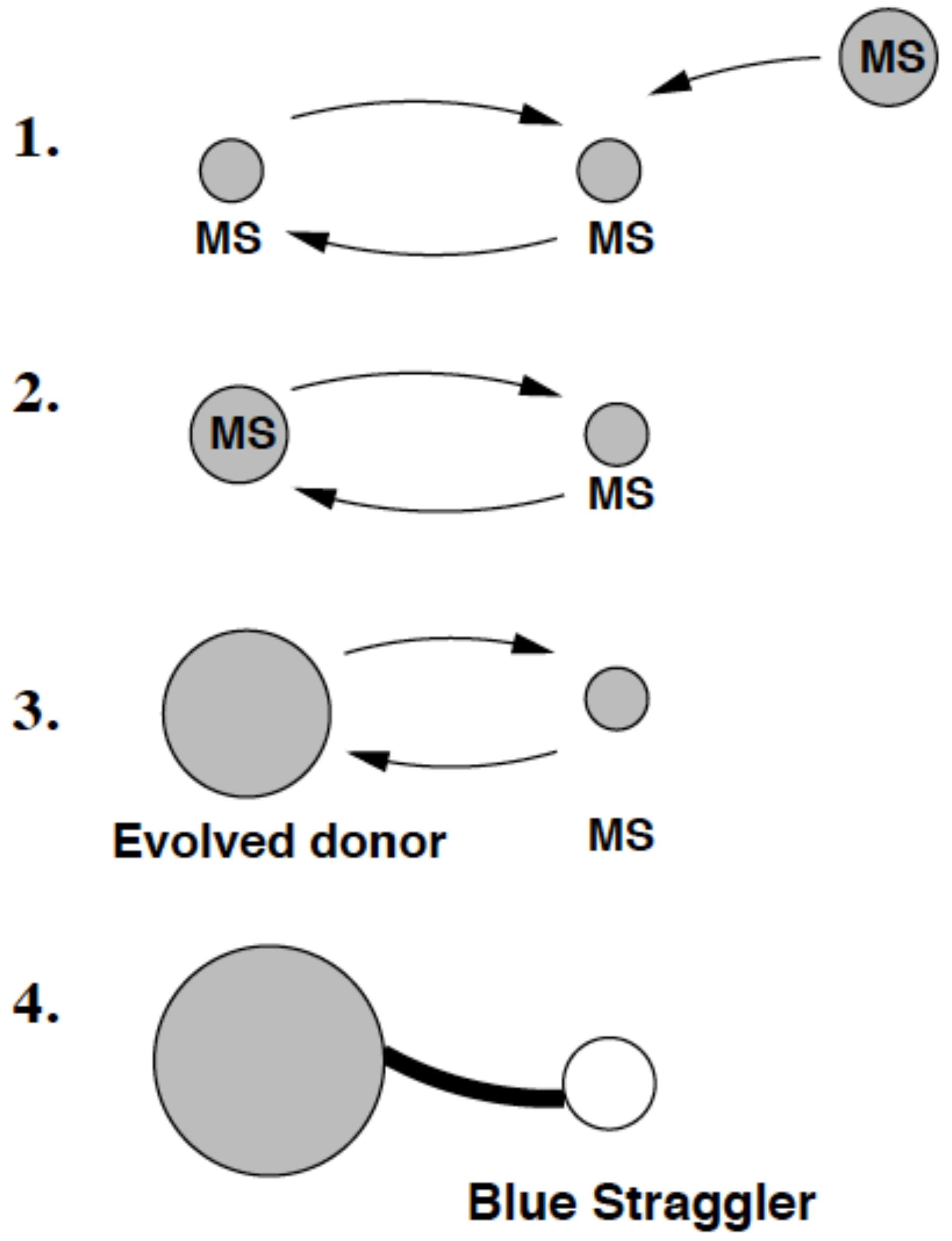
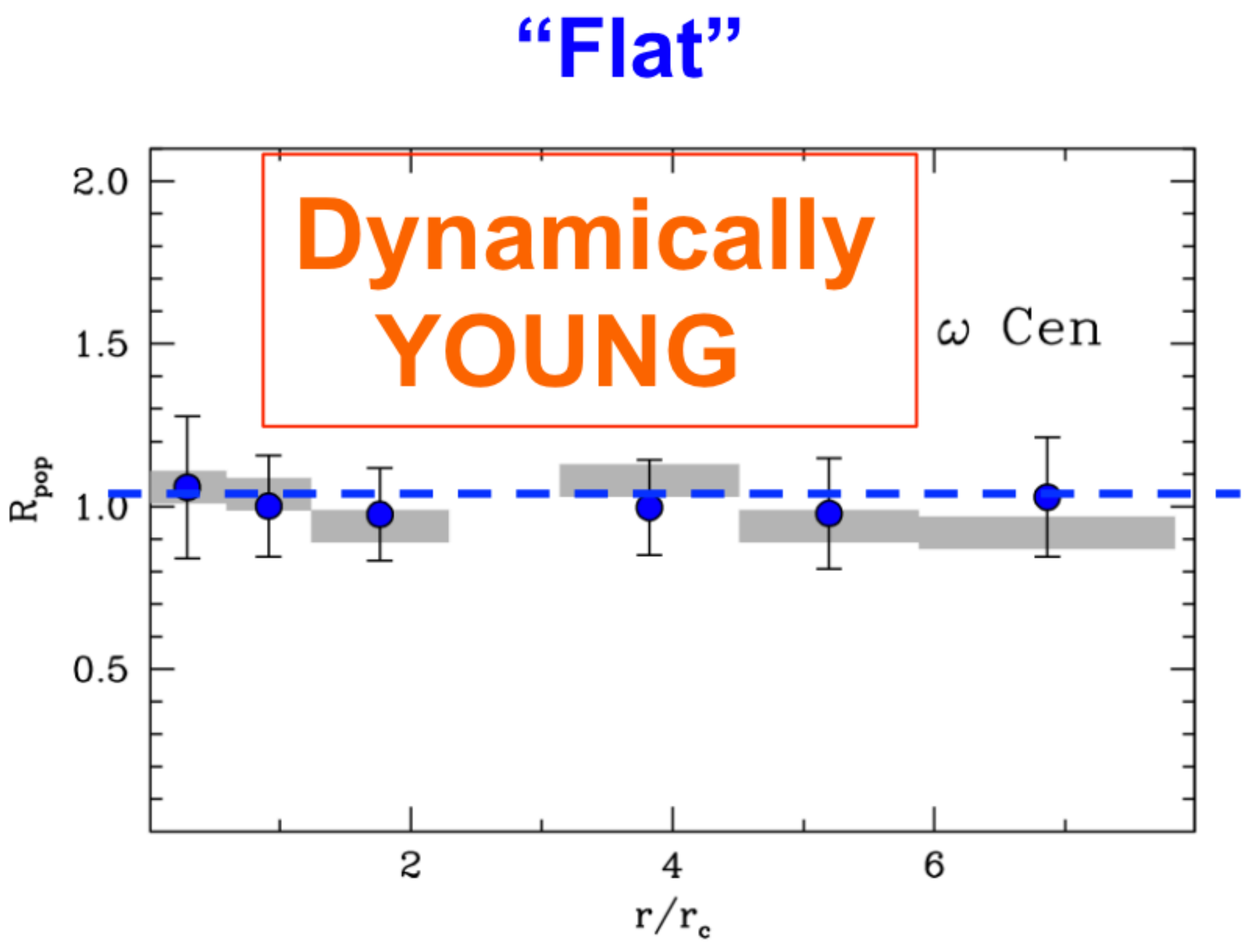
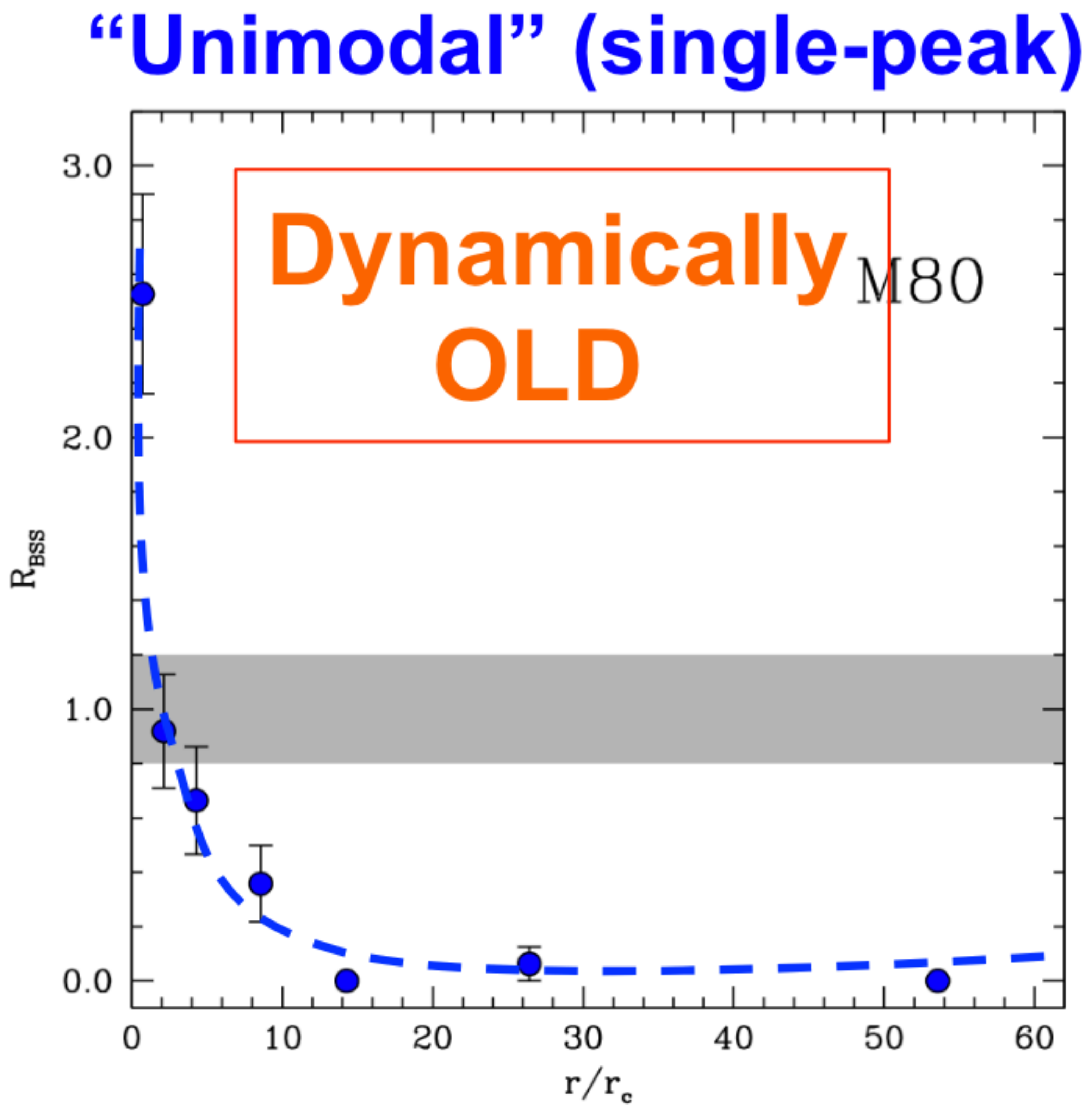


(Davies, Piotto, and De Angeli 2004)

# BSS as probes of dynamical age

- The BSS radial distribution is shaped by dynamical friction, which progressively segregates BSS at larger and larger radii

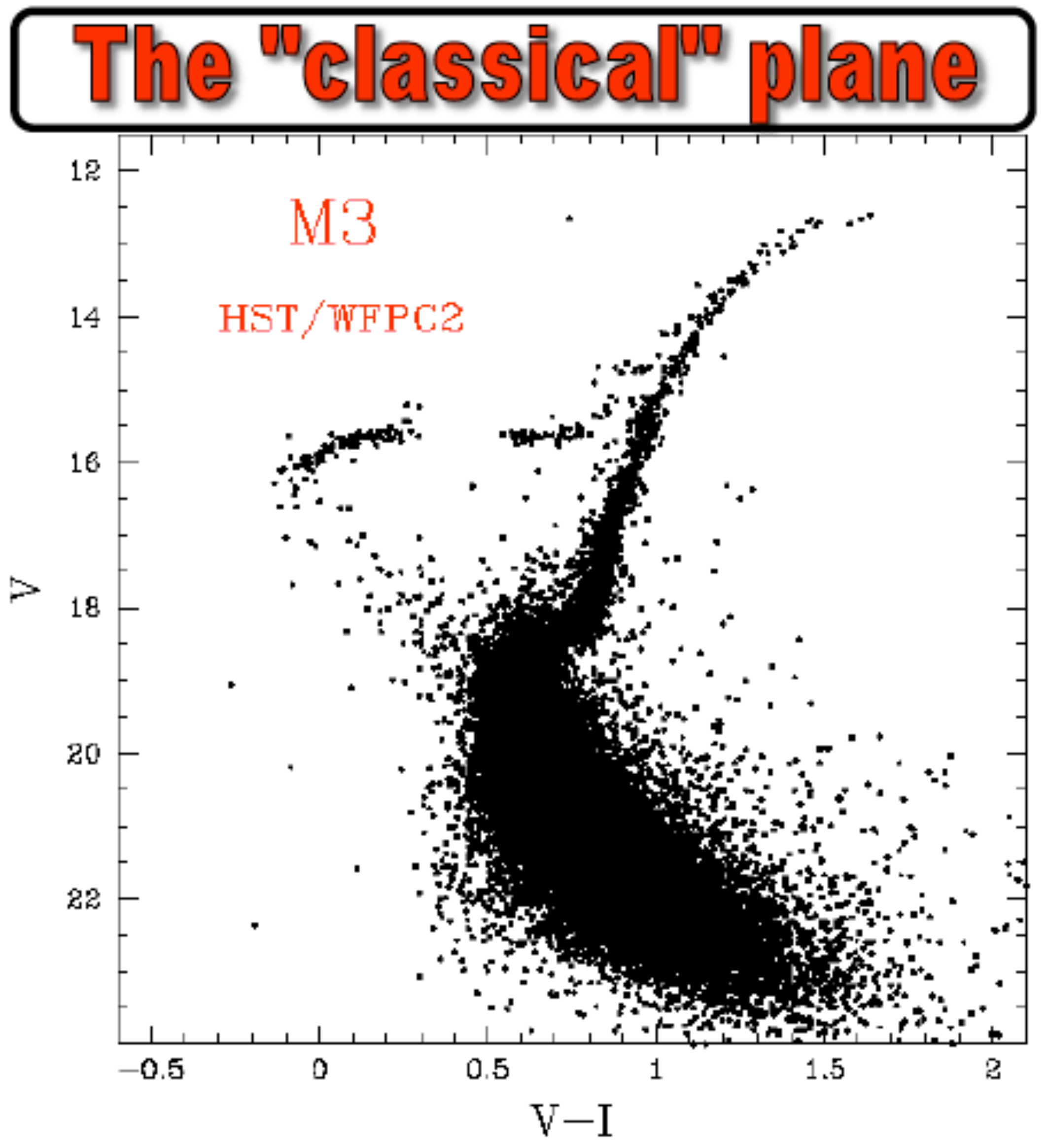


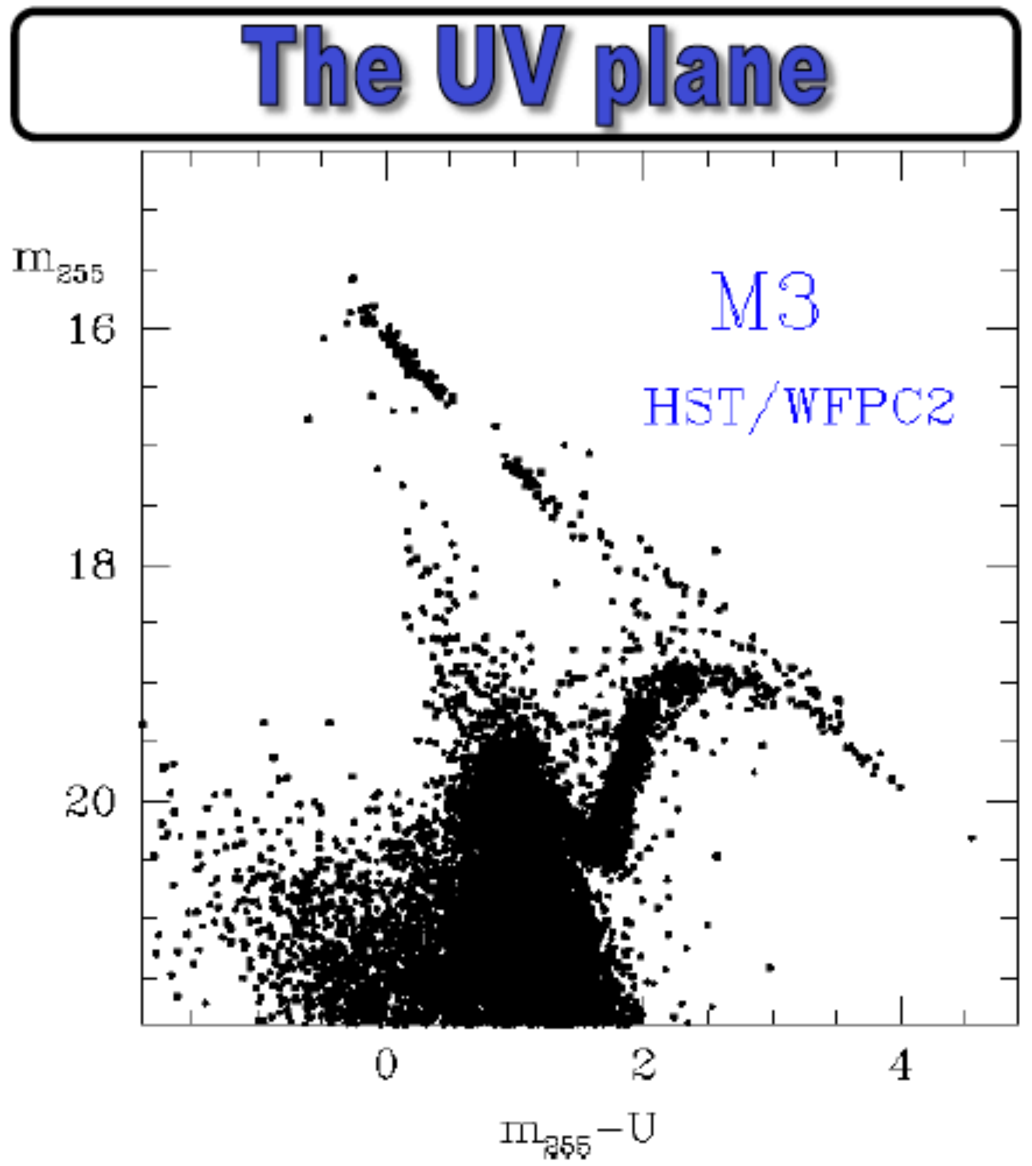


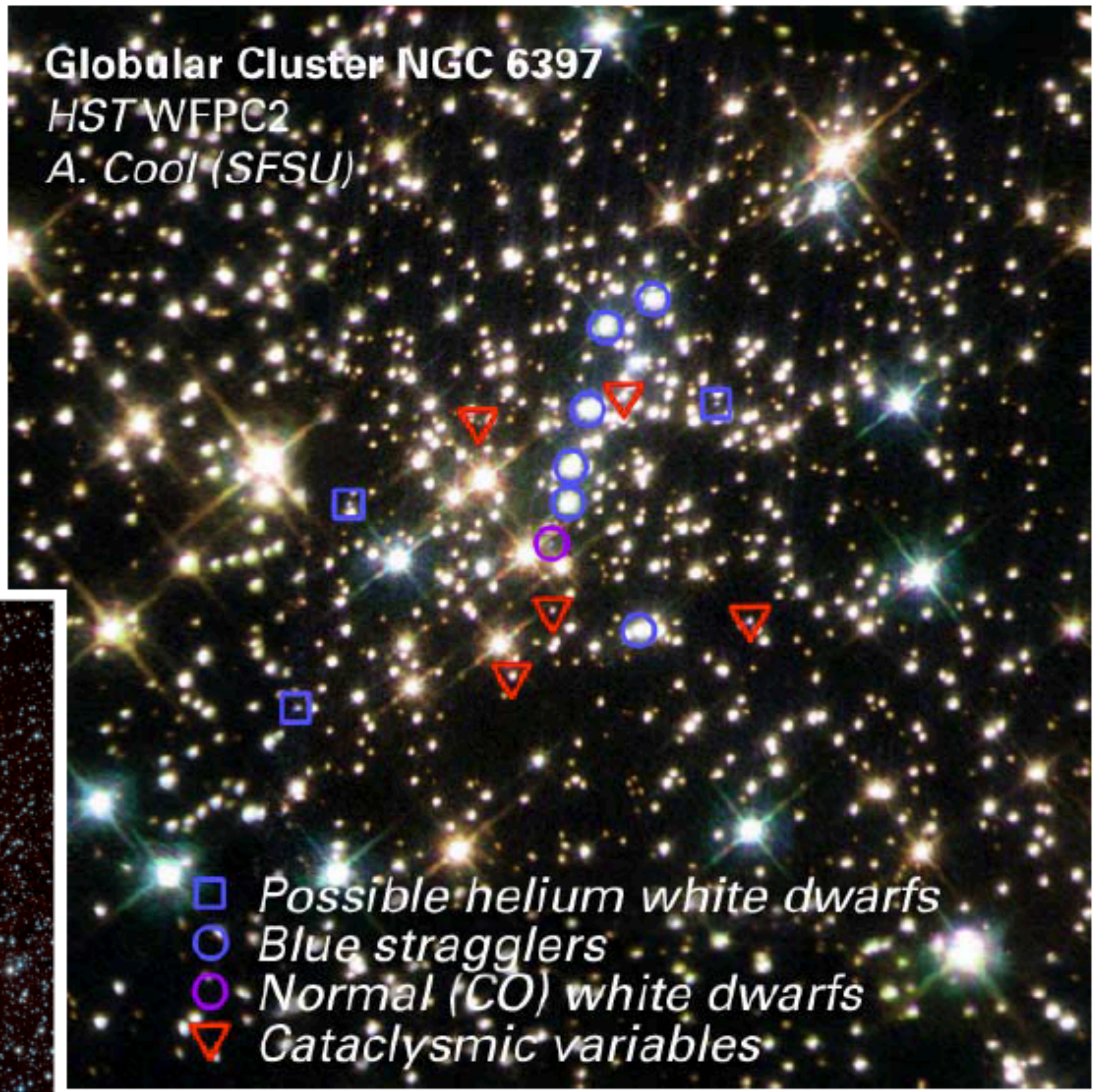
**Credit: Francesco Ferraro**

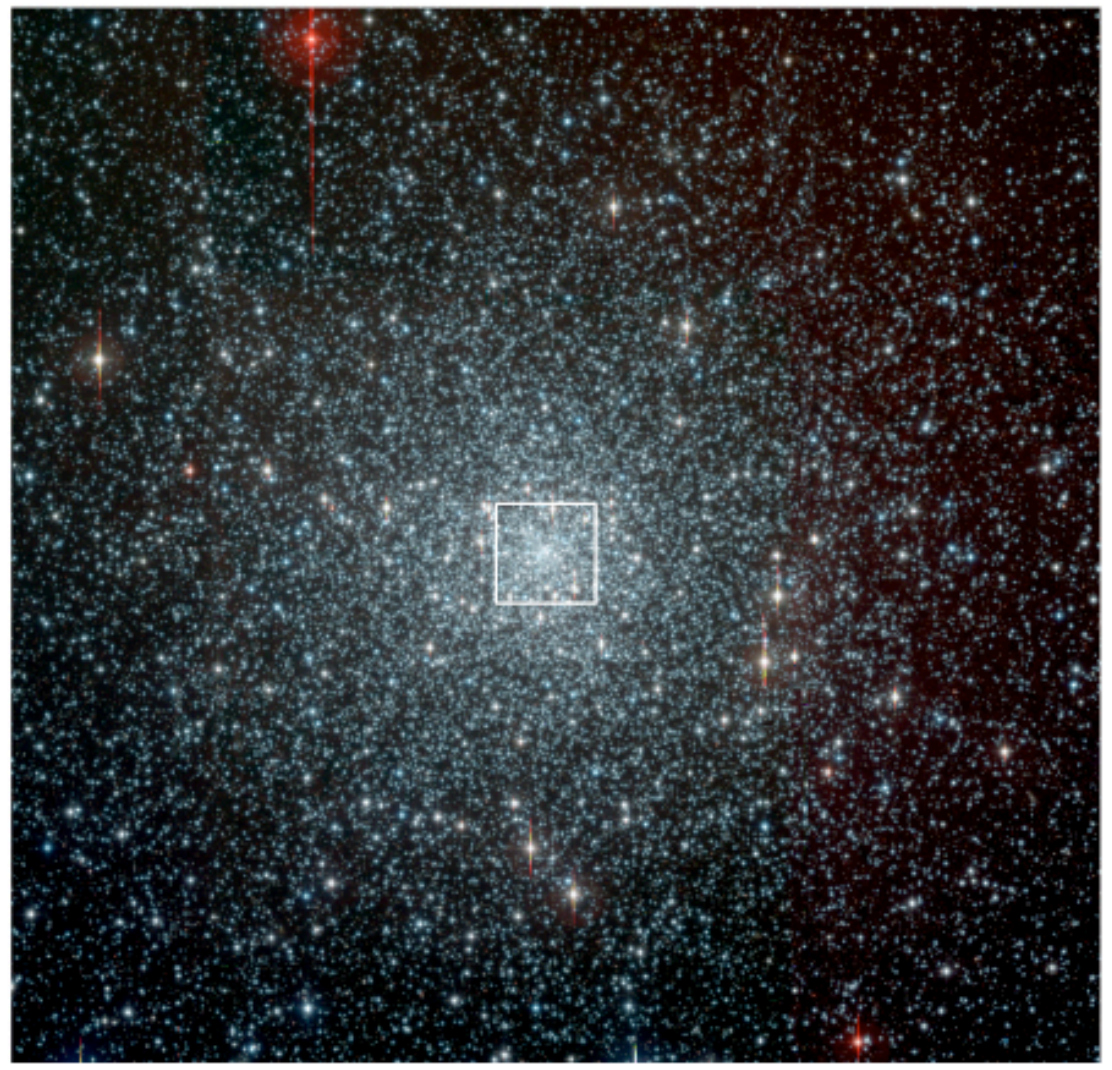
# Observing blue stragglers

- Difficult to observe in optical bands because giant stars are much brighter than BSS
- Much easier to obsessive in UV









Globular clusters images in UV are not dominated by the red giant light, and therefore are significantly less crowded.

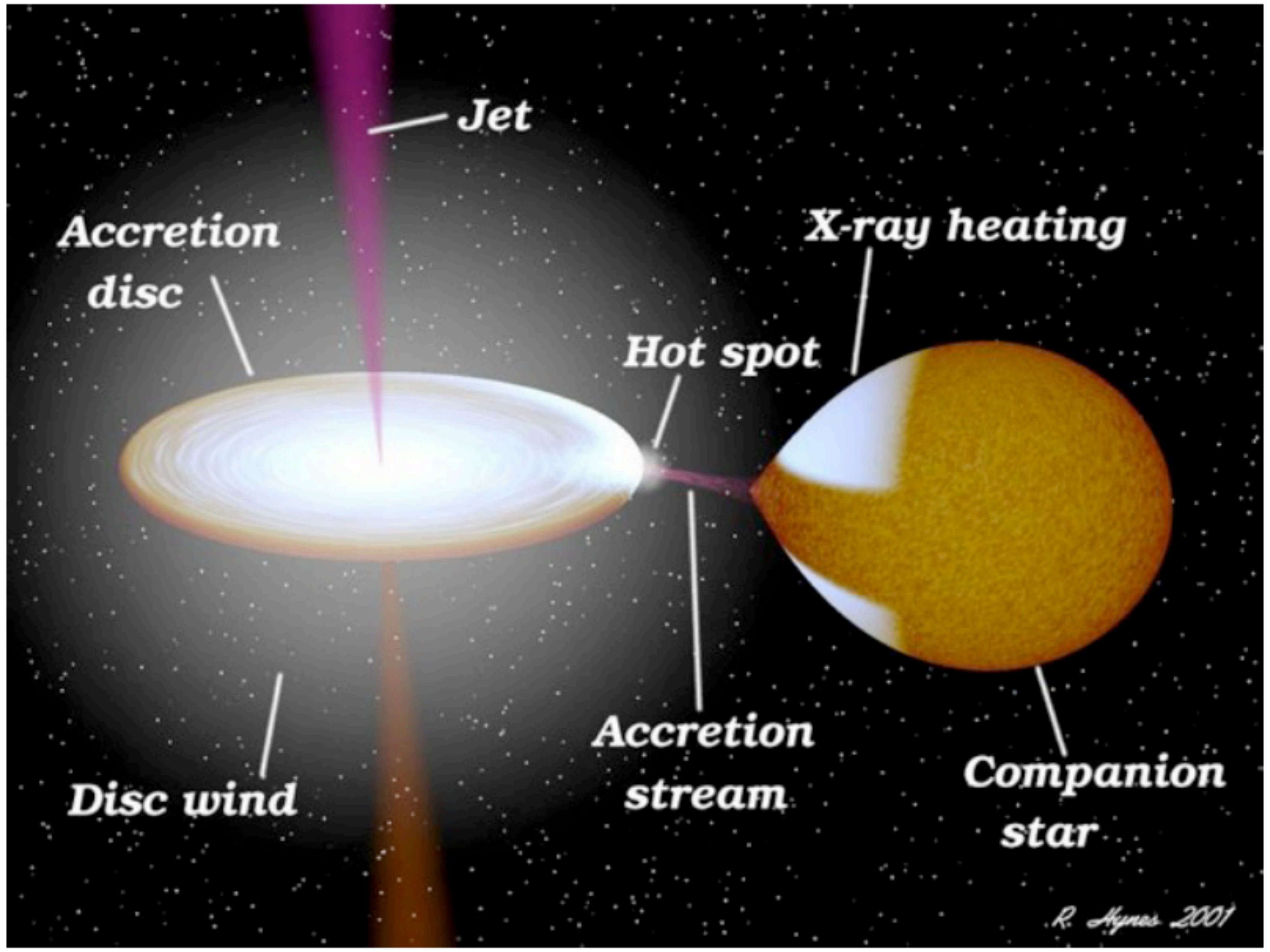
**Credit: Francesco Ferraro**

# Outcome of stellar collisions

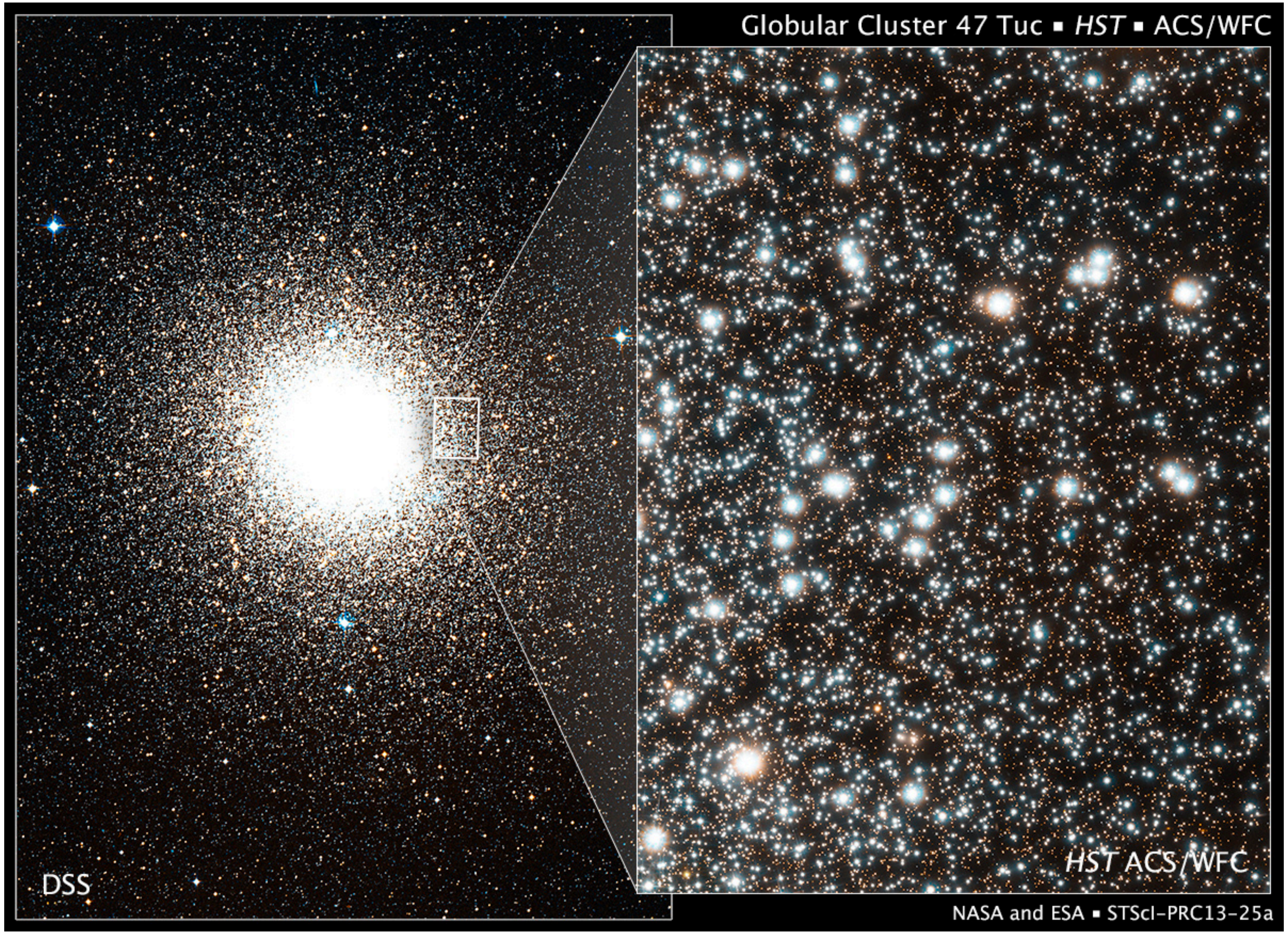
| | Main Sequence Star | Giant Star | White Dwarf | Neutron Star | Black Hole |
|---|---|---|---|---|---|
| Main Sequence Star | Blue Straggler Stars | Common envelope/ interacting binary | Giant star | Neutron Star | Black Hole |
| Giant Star | Common envelope/ interacting binary | Common envelope/ interacting binary | Interacting binary | Interacting binary | Interacting binary |
| White Dwarf | Giant star | Interacting binary (WD-WD) | Type Ia supernova or ONeMg or evolved star | Neutron Star | Black Hole |
| Neutron Star | Neutron Star | Interacting binary (NS-WD) | Neutron Star | Neutron Star or Black Hole | Black Hole |
| Black Hole | Black Hole | Interacting binary (BH-WD) | Black hole | Black Hole | Black Hole |

# Interacting compact object binaries in star clusters

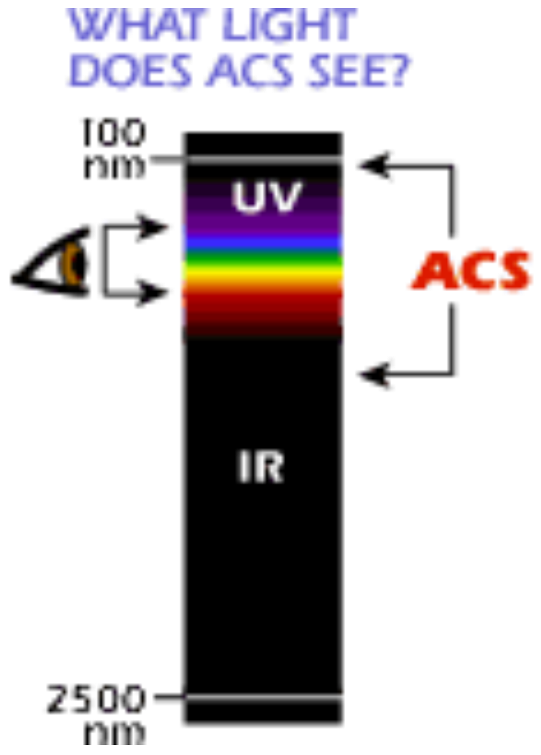
- Close binary systems comprising a compact object and a star
  - Cataclysmic variables (CVs) → accreting white dwarfs → novae outbursts
  - Low-mass X-ray binaries (LMXBs) → neutron star or black hole accretors with low-mass donor stars
  - intermediate-mass X-ray binaries (IMXBs) → neutron star or black hole accretors with intermediate-mass companions
  - Millisecond pulsars (MSPs)→ neutron star spun up due to accretion
  - Ultraluminous X-ray sources (ULXs) → neutron star or BH accretors with high X-ray luminosities
  - Ultracompact X-ray binaries (UCXBs) → Black hole + white dwarf binary system
- Accretion in these binaries results in the emission of X-rays → important sources of high energy astrophysics



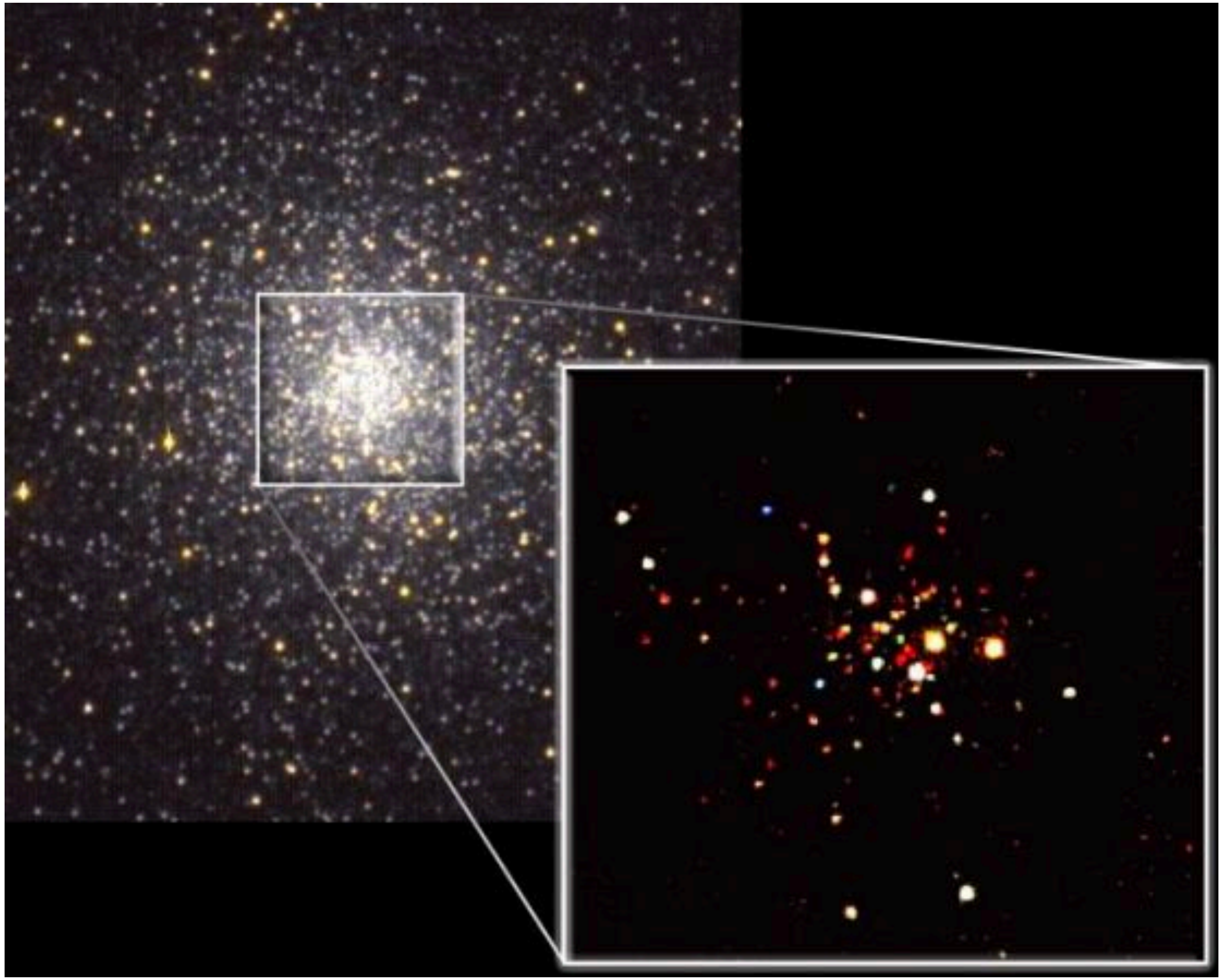
# 47 Tuc and population of stellar exotica



NASA and ESA ▪ STScI-PRC13-25a



# X-ray sources in the globular cluster 47 Tuc



Credit:
Credit: X-Ray: J, Grindlay (CfA) et al., CXO, NASA Optical: W. Keel (U. Alabama Tuscaloosa) et al. 1.5m Telescope, CTIO

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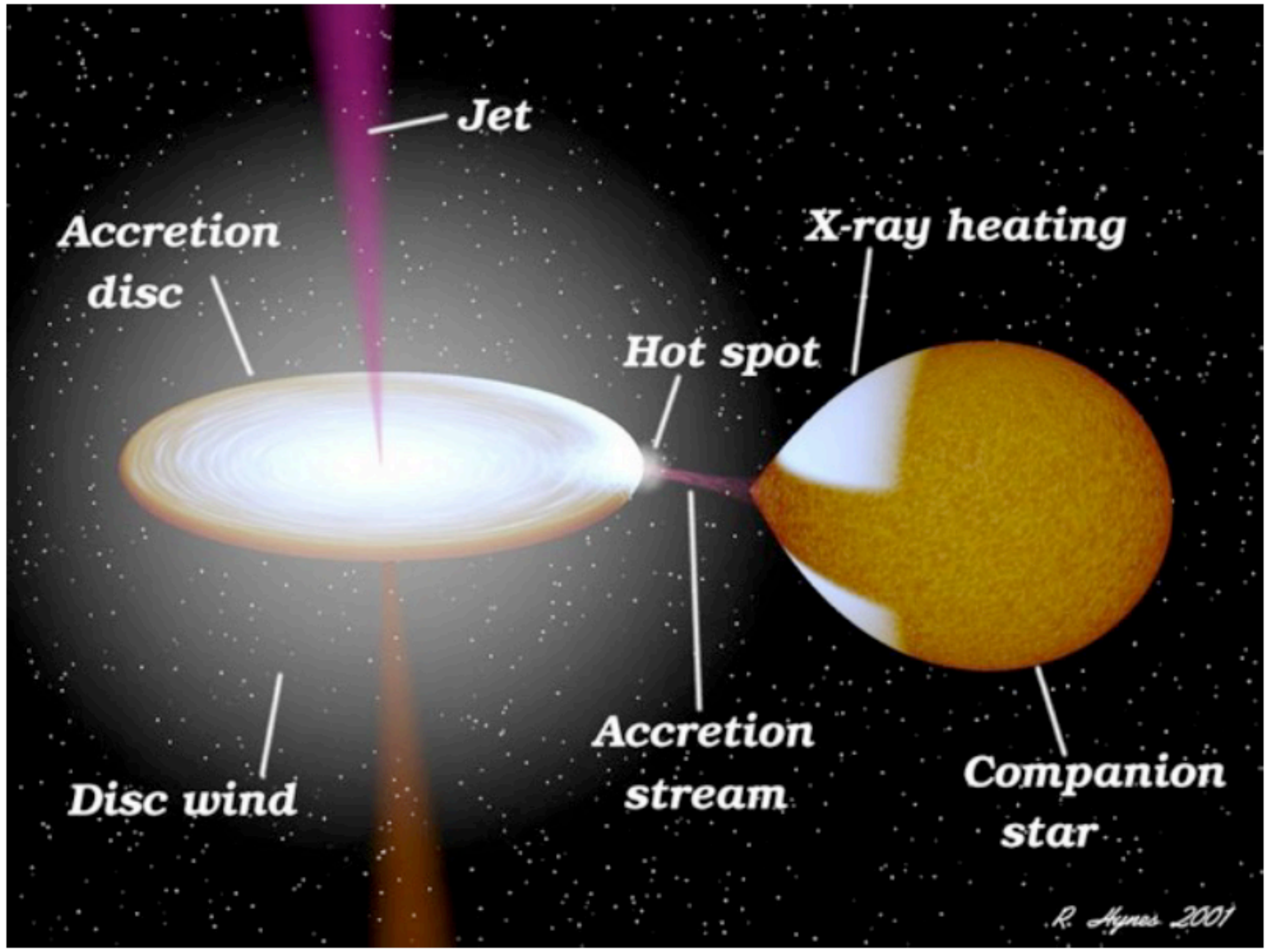
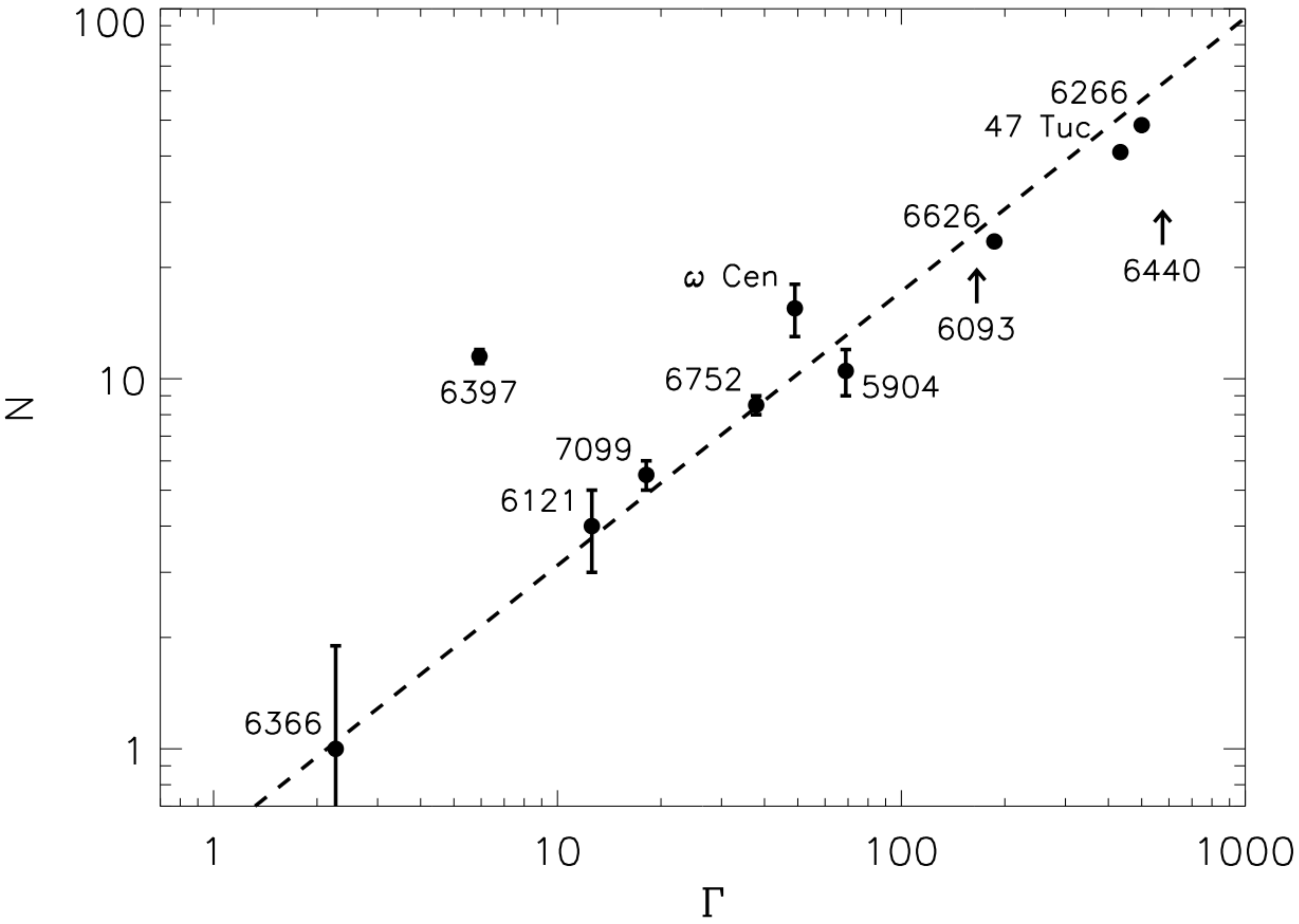
  - Millisecond pulsars (MSPs)→ neutron star spun up due to accretion
  - **Ultraluminous X-ray sources (ULXs) → neutron star or BH accretors: Few observed in extragalactic globular clusters (Dage et al. 2024)**
  - **Ultracompact X-ray binaries (UCXBs) → Black hole + white dwarf binary system: 47 Tuc X9 (Bahramian et al. 2017)**
  - **More details about them in lecture on ULXs and UCXBs in lecture on black holes in star clusters**



- Accretion in these binaries results in the emission of X-rays → important sources of high energy astrophysics

# Evidence that X-ray binaries are made dynamically in star clusters

- Number of X-ray sources with $L_X \gtrsim 4 \times 10^{30}\ \mathrm{erg\,s^{-1}}$ in Galactic globular clusters correlate with ~ encounter rate ($\Gamma \propto \rho_o^{1.5} r_c^{2}$)
- Higher fraction of X-ray binaries found in globular clusters (Verbunt & Hut 1987)
  - Number of LMXBs per unit mass is several factors higher in clusters than in the field



From Pooley et al. (2003)

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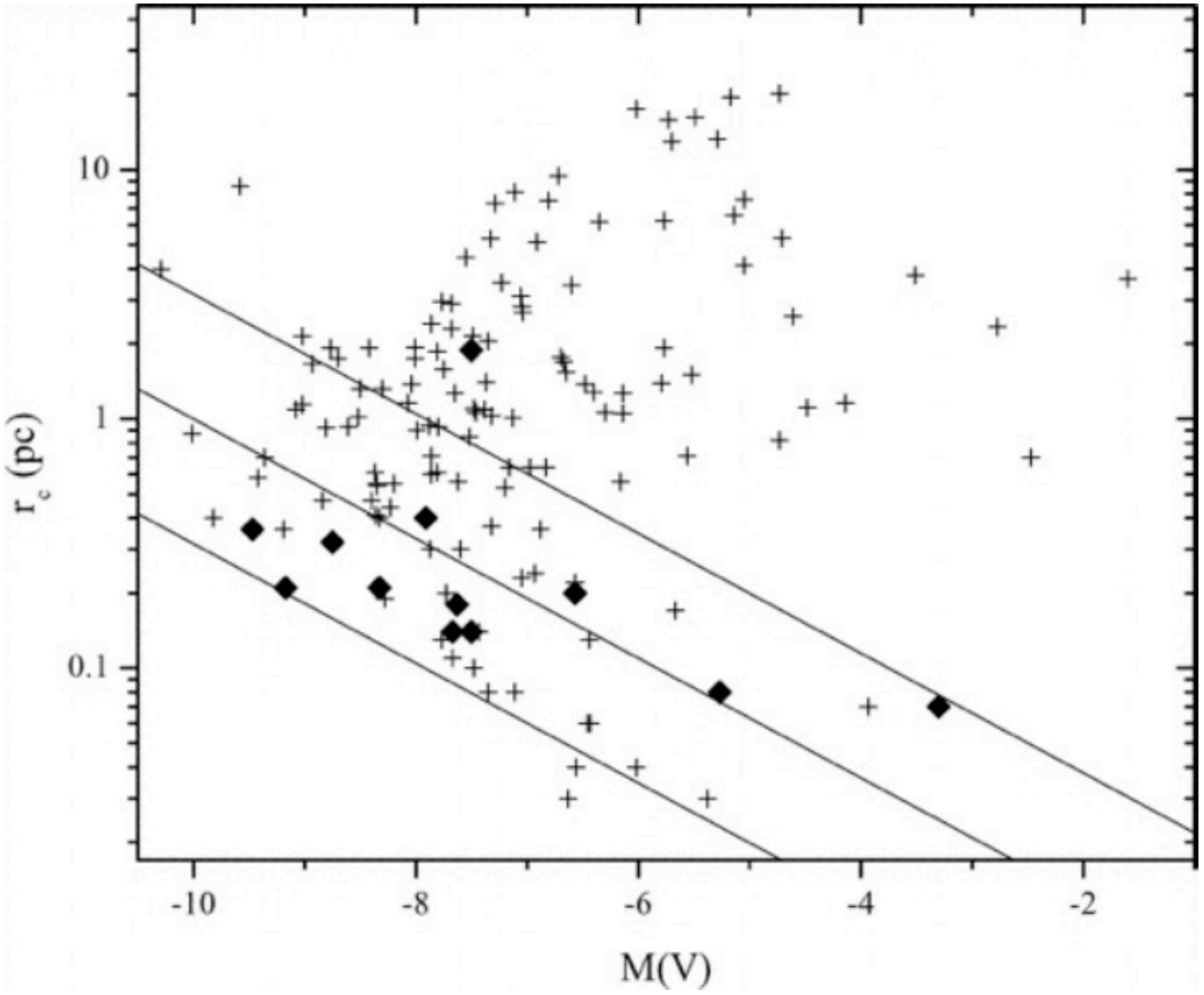
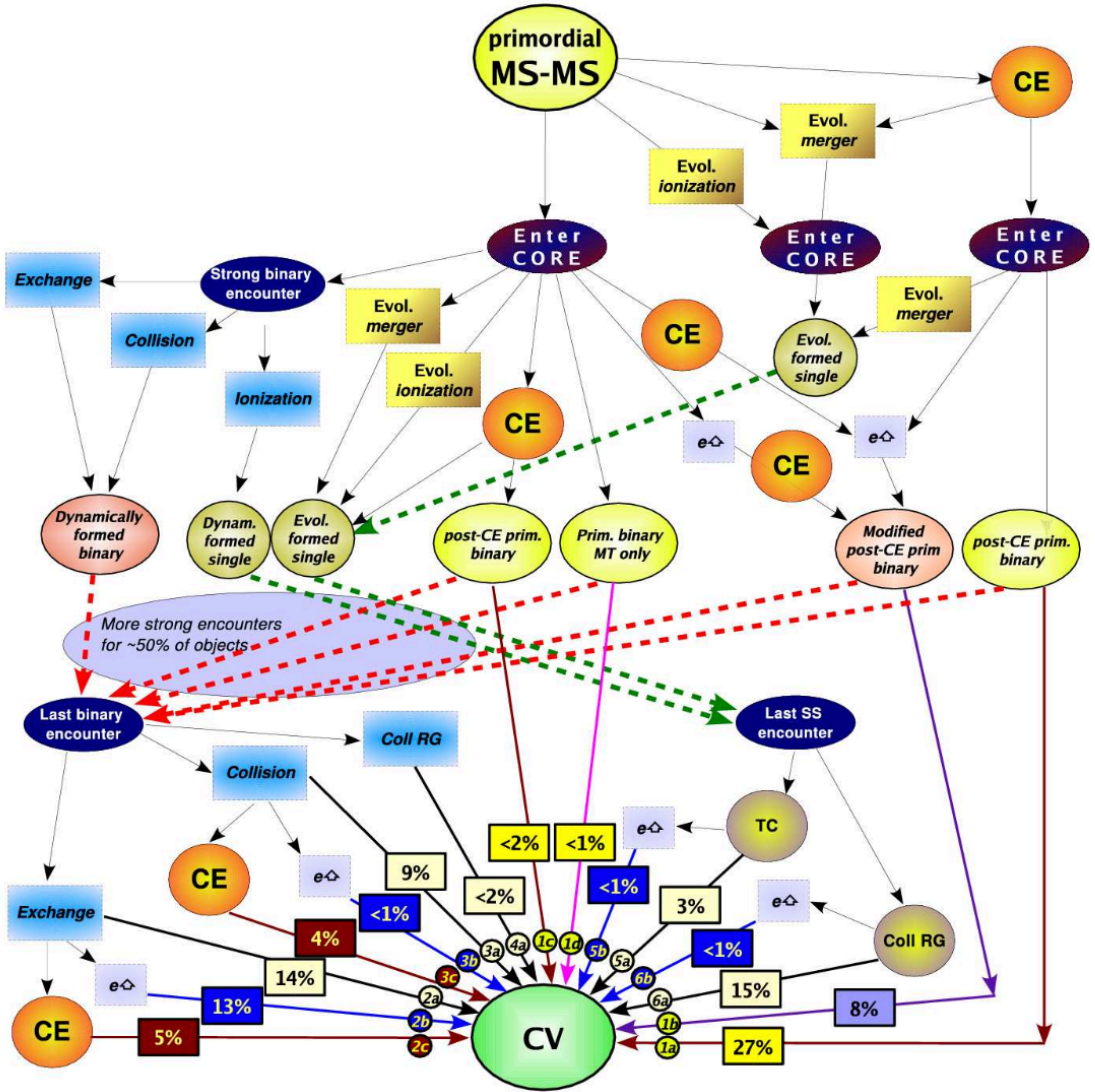
  - Number of LMXBs per unit mass is several factors higher in clusters than in the field
- Clusters that harbour LMXBs have denser cores



From Bregman et al. (2003)

# Formation (and destruction) channels of cataclysmic variables (CVs)



From Ivanova et al. 2006

## Are CVs primordial or made dynamically?

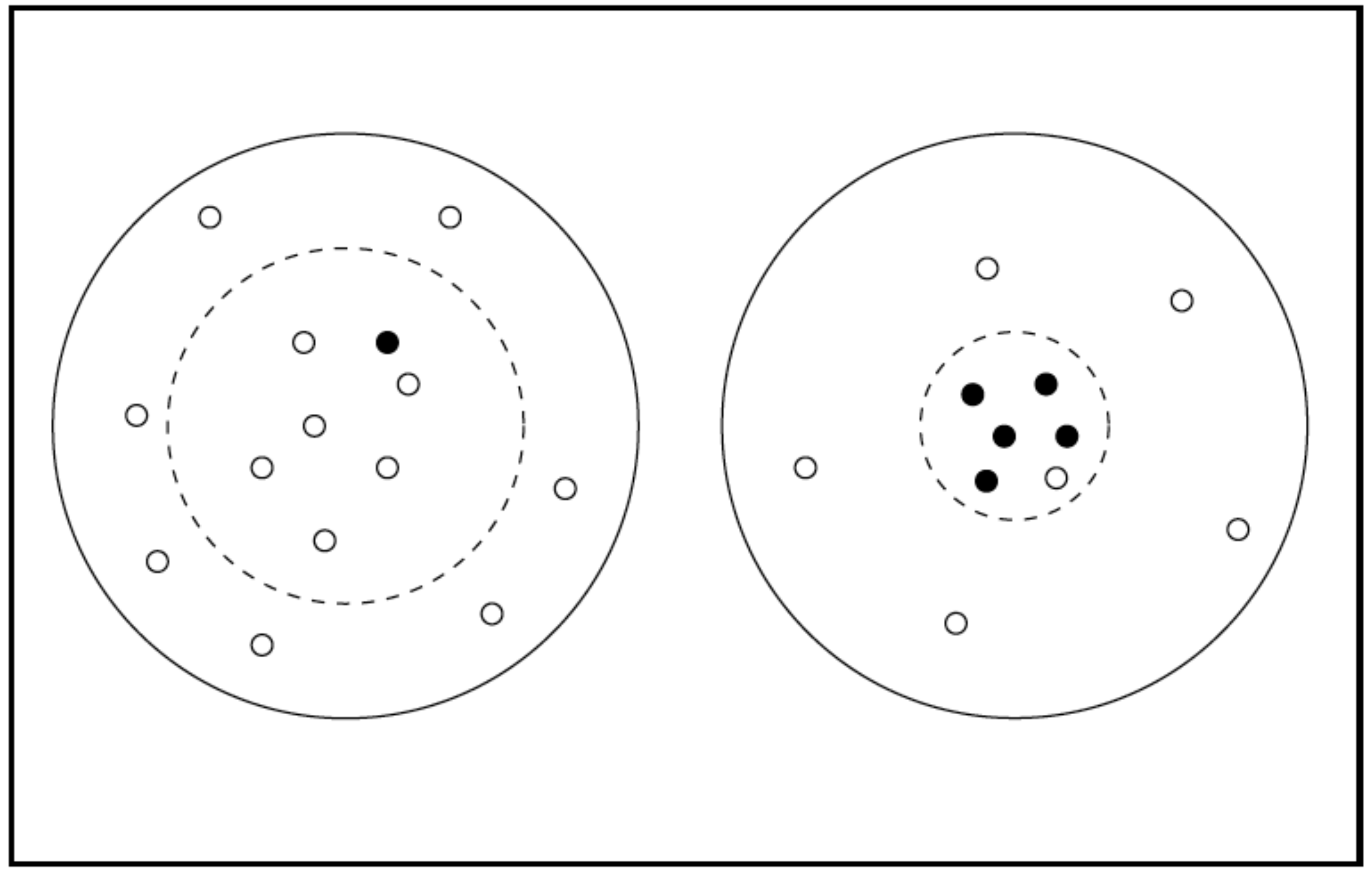
- Primordial binaries that are potential progenitors of CVs (PCVs) are typically soft binaries in globular clusters → can be dynamically destroyed
  - Binary softening or disruption
- CVs can also form through exchanges in binary-single binary-binary encounters

**See Belloni et al. (2016; 2017 and 2019)**

**Figure 7.** Main formation channels of all CVs that are present in a “standard” cluster at the age of 10 Gyr. Notations: numbers in squares represent contributions from different channels, small circles contain the labels for each channel. “CE” - common envelope, “Evol. merger” - evolutionary merger, “Evol. ionization” - destruction of the binary via SN explosion, “e⇑” – increase of the eccentricity during fly-by encounters, “Strong binary encounter” – three- or four-body encounter with an outcome as exchange, binary destruction (“ionization”) or physical collision (“Collision”); “TC” – tidal capture, “Coll RG” – physical collision with a RG.

# Formation (and destruction) channels of cataclysmic variables (CVs)

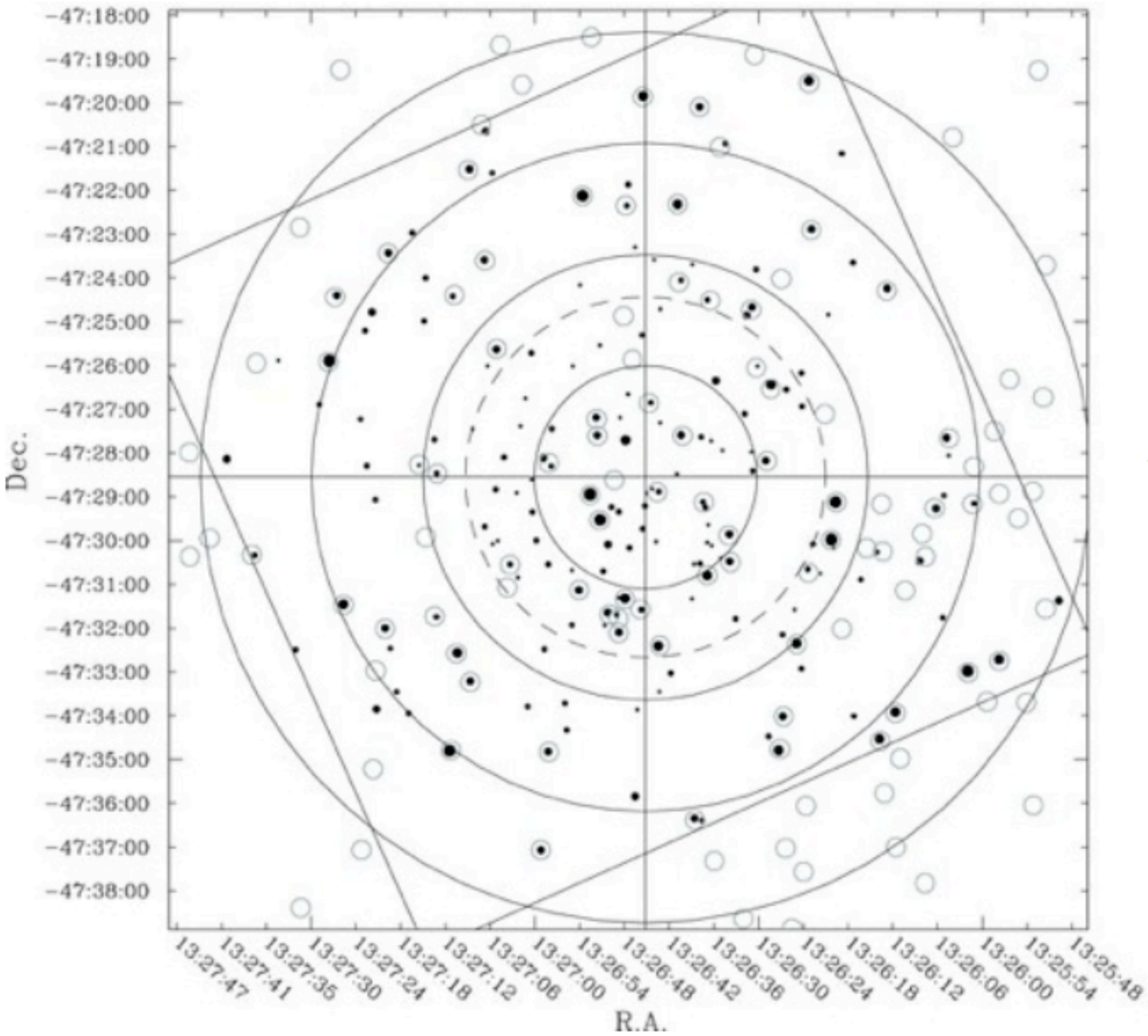
Possible distribution of CVs in globular clusters



white dots are primordial CVs, black dots are made dynamically

Credit: Melvyn Davies

Chandra study of Omega Centauri



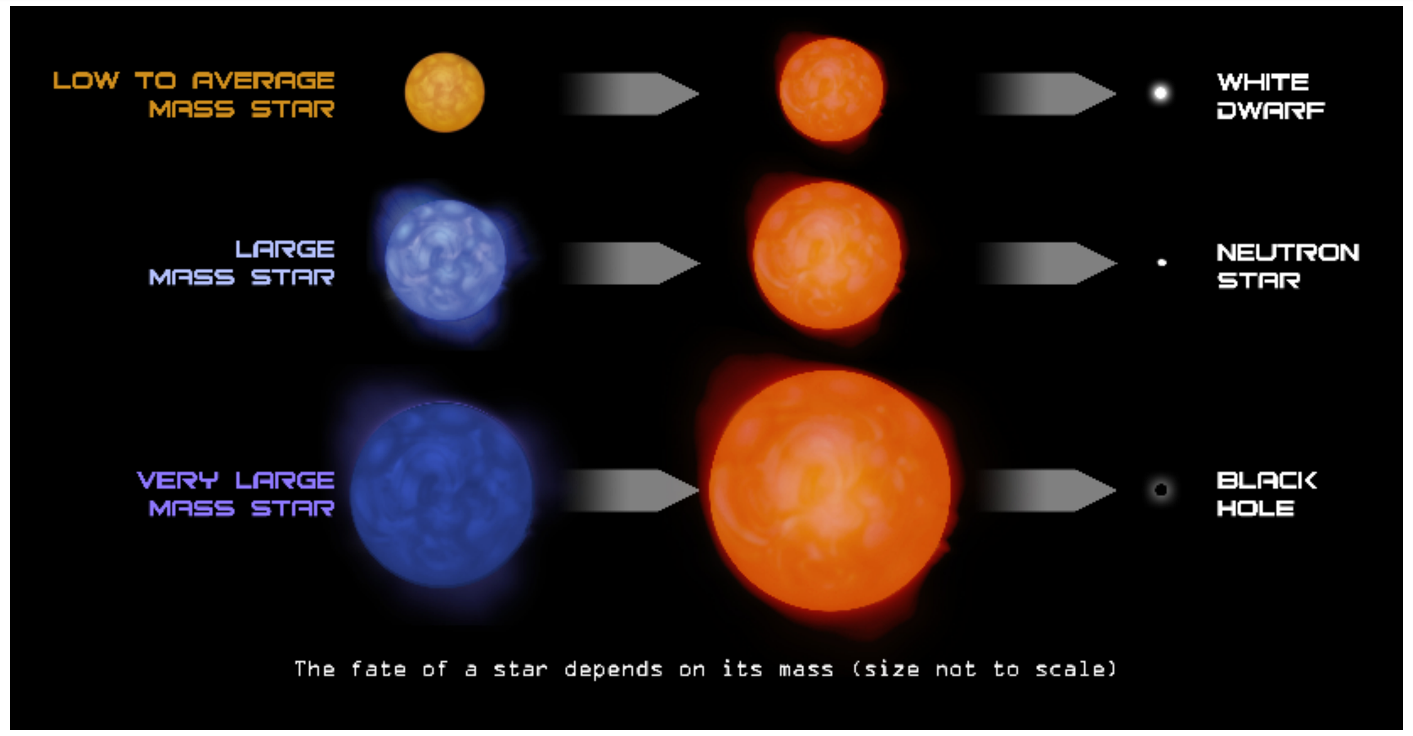
Number of CVs per unit mass is 2-3 times lower than in the field indicating that PCVs are being destroyed.

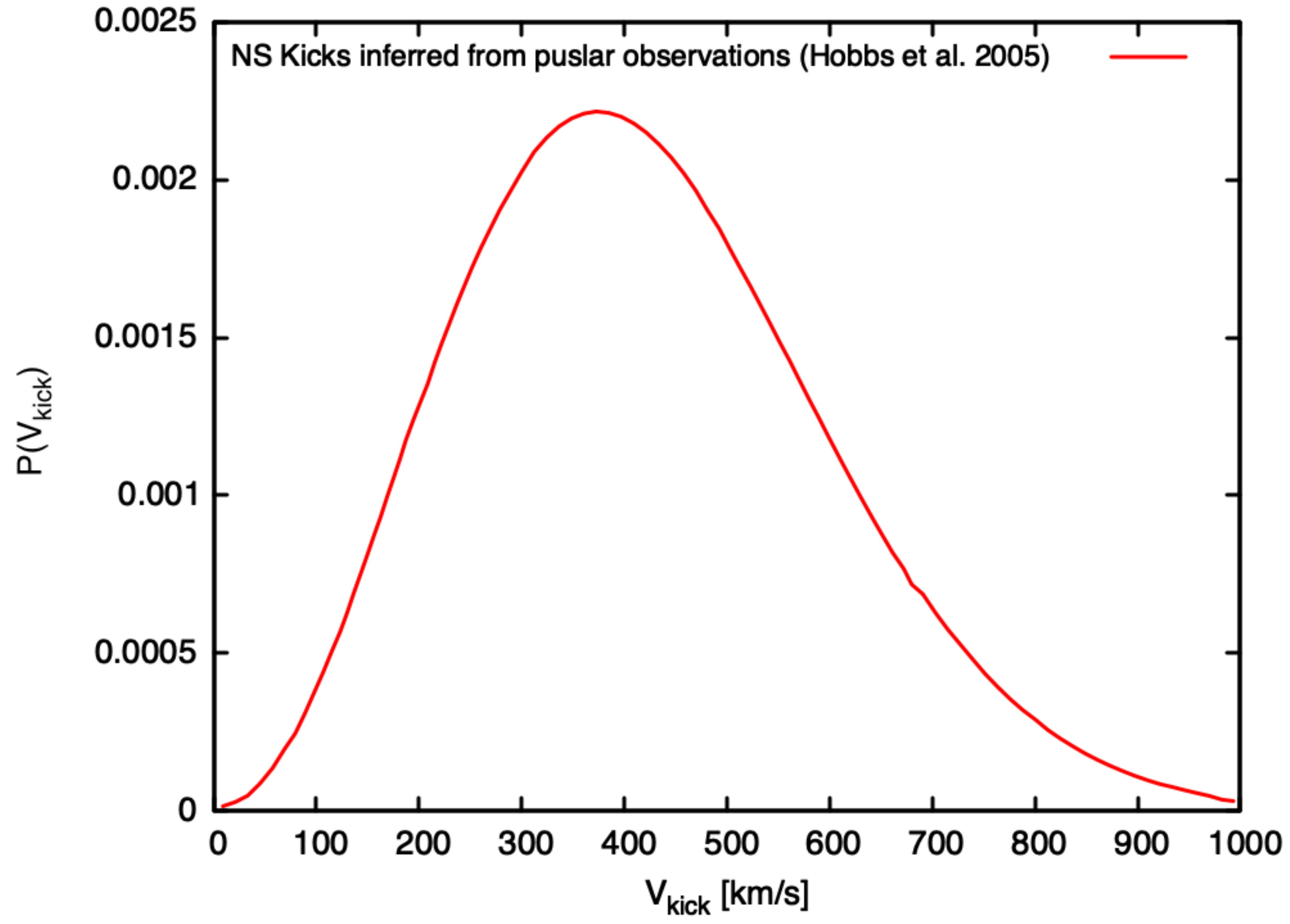
Haggard, Cool, and Davies (2009) and Belloni et al. (2019)

# Neutron star and pulsar formation

- Most neutron stars form from core collapse supernovae (Type II)
- Proper motion of Galactic pulsars indicate that they larger natal kicks (also known as supernova kicks) → Hobbs et al. 2005 inferred a Maxwellian distribution of neutron star natal kicks (with $\sigma = 265\ \mathrm{km/s}$)
  - Larger than the escape of globular clusters ~50 km/s (could be larger earlier in their evolution)
- Forming neutron stars with low natal kicks:
  - Electron-capture supernova (natal kicks few km/s)
  - Accretion induced collapse of a white dwarf

$$8\ \mathrm{M}_\odot \lesssim \mathrm{M}_{\mathrm{ZAMS}} \lesssim 20\ \mathrm{M}_\odot$$





Taken from Fig. 3 in Abbott et al. 2017

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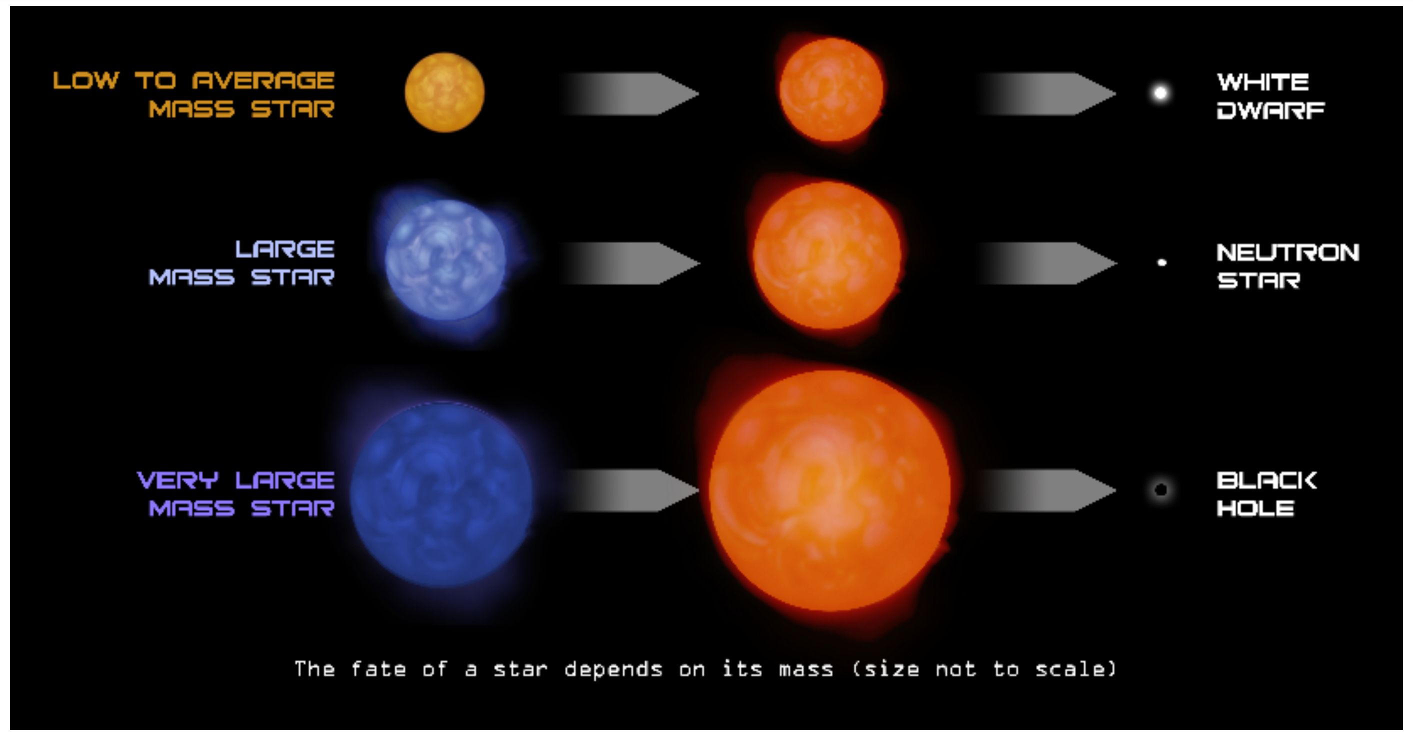
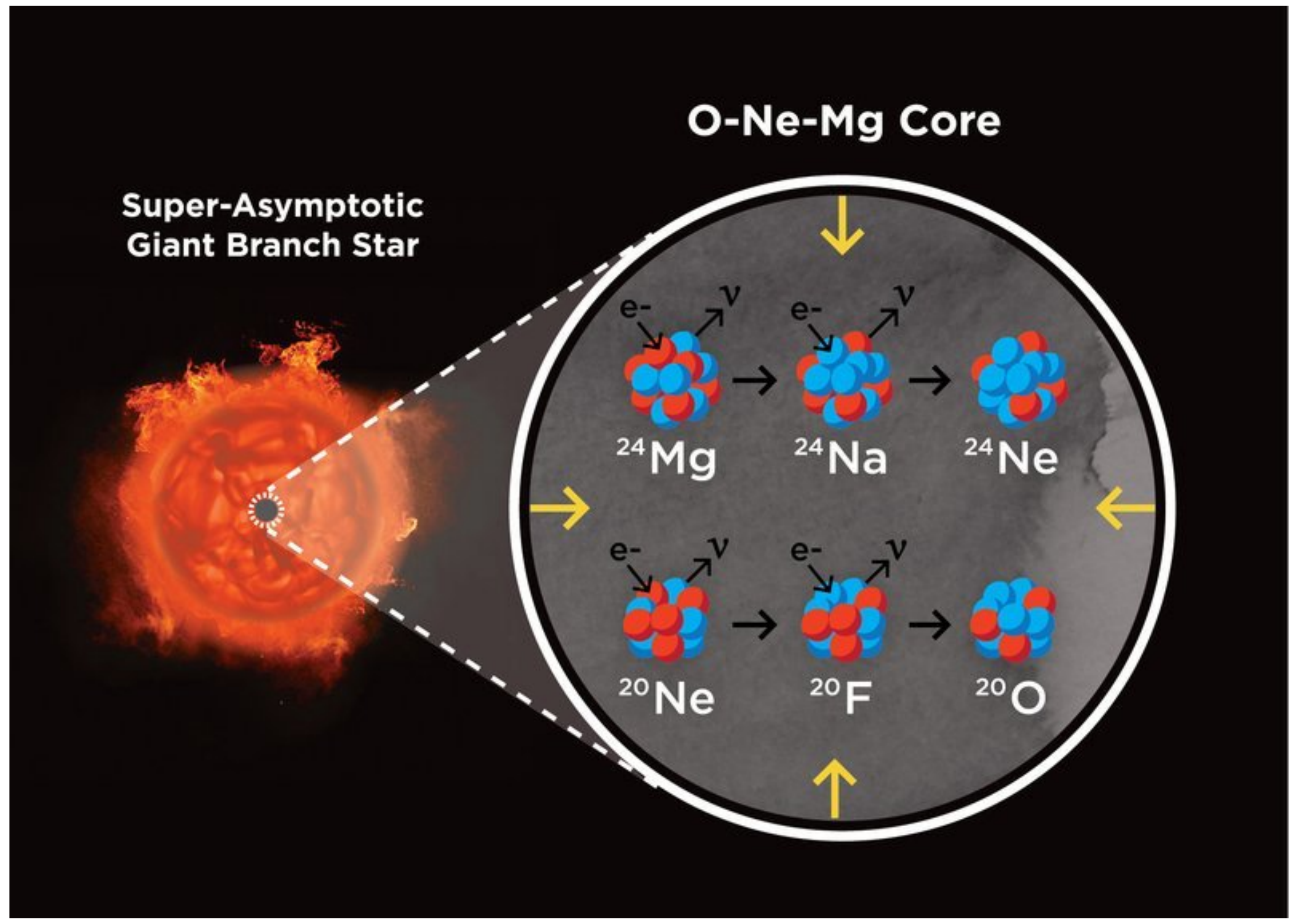


$6\ \mathrm{M}_\odot \lesssim \mathrm{M}_{\mathrm{ZAMS}} \lesssim 8\ \mathrm{M}_\odot$



When the AGB core gets too dense (WDs, the neon and magnesium atoms start absorbing their electrons

Credit: S. Wilkinson/ Las Cumbres Observatory.

# Pulsars and millisecond pulsars in globular clusters

- More than 322 pulsars have been observed in Galactic globular clusters
- Many of these are millisecond pulsars

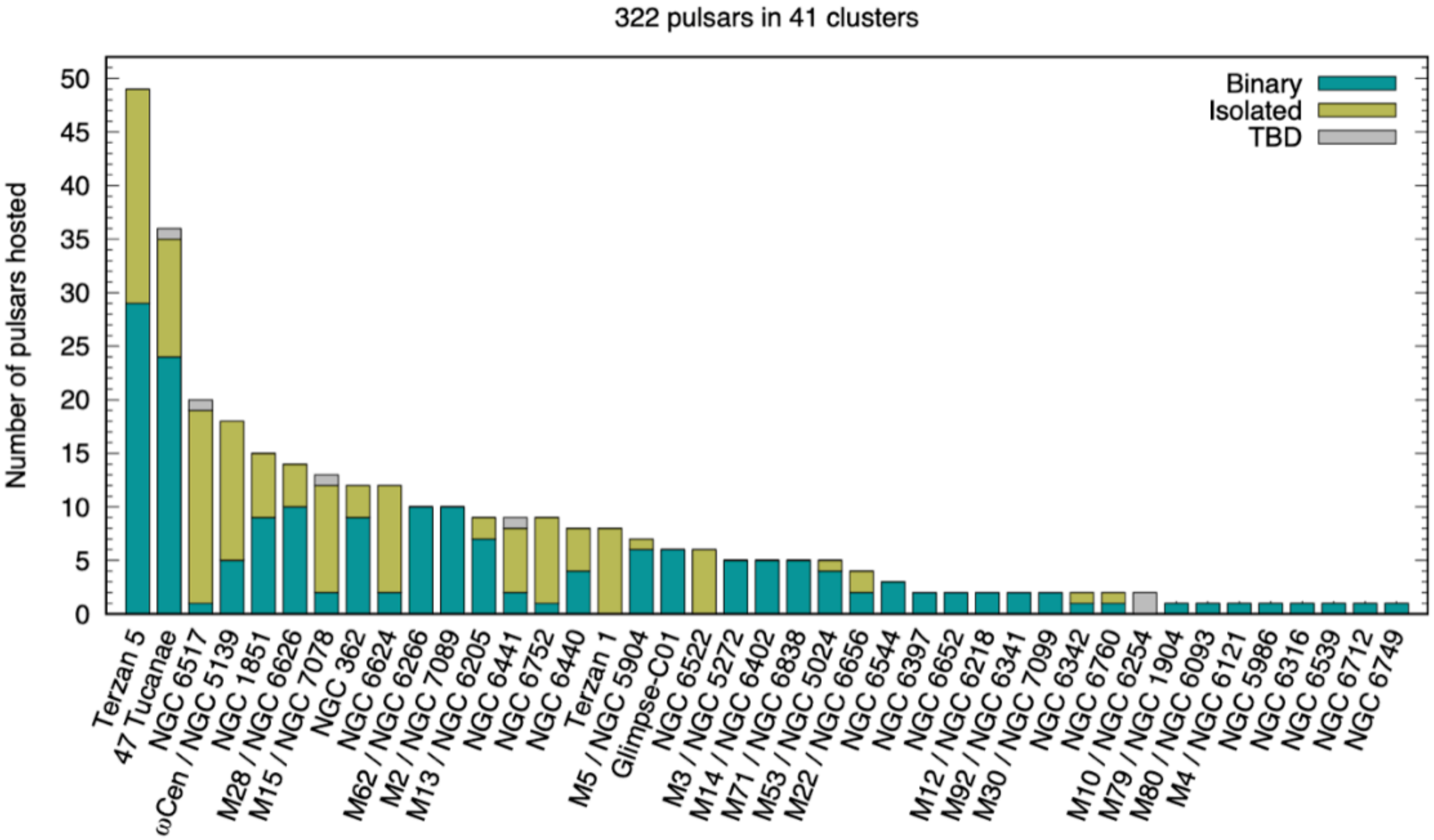


Fig. 1: Histogram of globular cluster pulsars per cluster.

Credit: Alessandro Ridolfi.

**From Paolo Freiere's catalogue of pulsars in globular clusters:**
**https://www3.mpifr-bonn.mpg.de/staff/pfreire/GCpsr.html**

# Pulsars and millisecond pulsars in globular clusters

- More than 322 pulsars have been observed in Galactic globular clusters
- Many of these are millisecond pulsars
- Millisecond pulsars are produced in LMXBs
- Due to dynamical interactions in star clusters an old pulsar can find a companion to spin up to form a recycled millisecond pulsar.

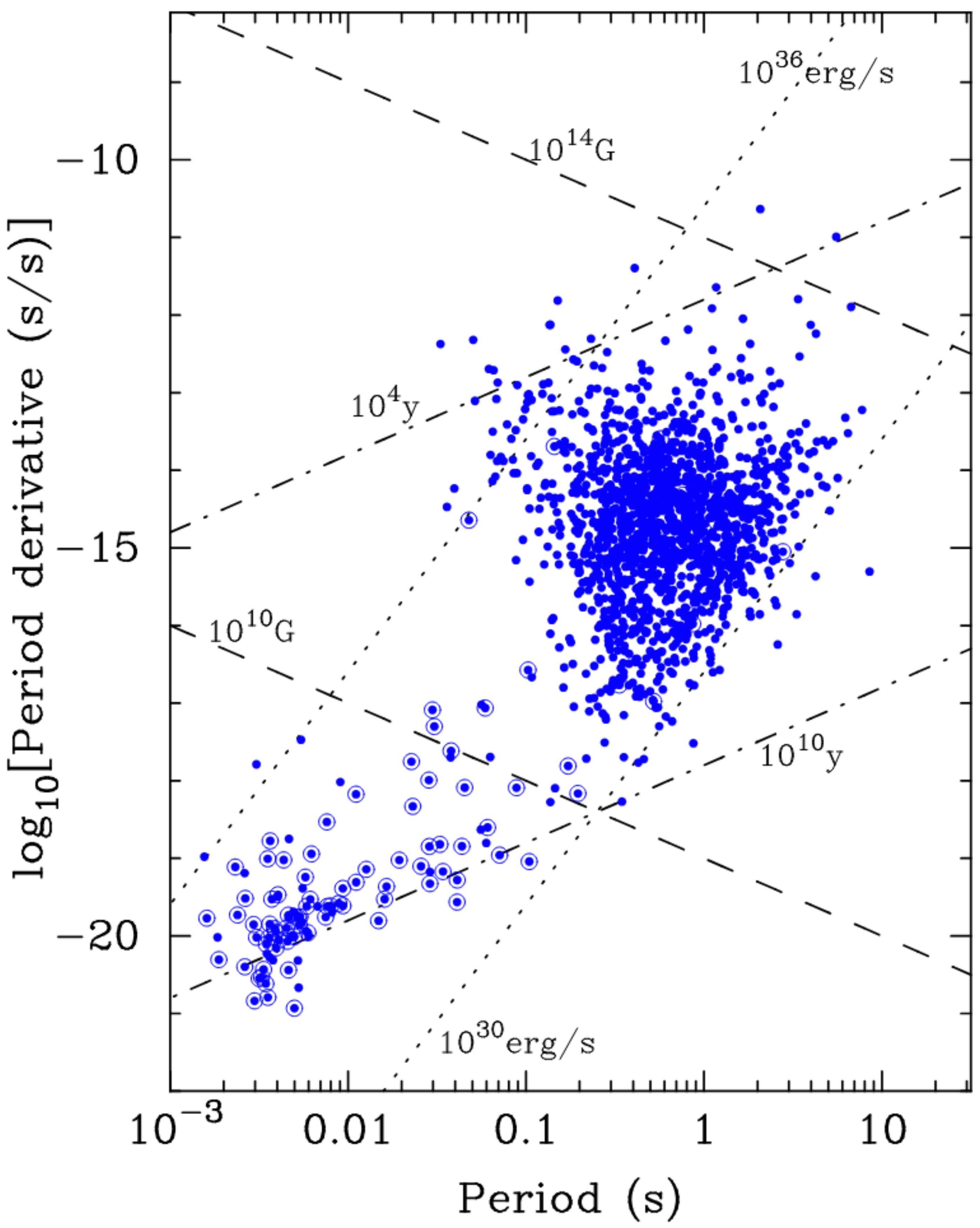


Figure 3: The $P$–$\dot{P}$ diagram showing the current sample of radio pulsars. Binary pulsars are highlighted by open circles. Lines of constant magnetic field (dashed), characteristic age (dash-dotted) and spin-down energy loss rate (dotted) are also shown.

**Lorimer (2008)**

$$\tau \propto P/\dot{P}$$

By timing pulsars individually, one can measure the variation in period with time.

$$P(t) = P\left(t_0\right) + \left.\frac{\mathrm{d}P}{\mathrm{d}t}\right|_{t_0}\left(t - t_0\right) + \left.\frac{\mathrm{d}^2P}{\mathrm{d}t^2}\right|_{t_0}\frac{\left(t - t_0\right)^2}{2!} + \dots$$

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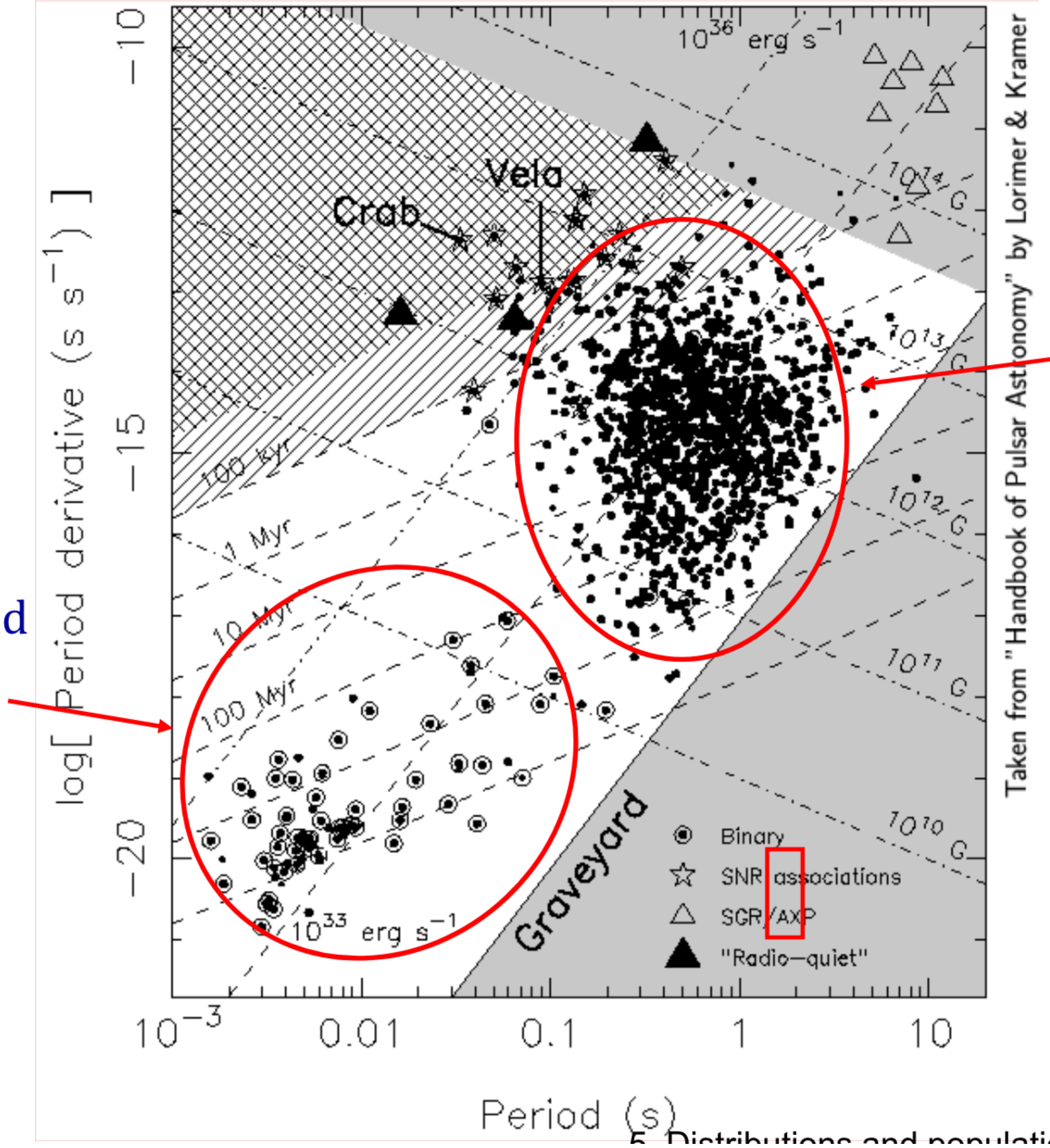


millisecond pulsars

"normal" pulsars

By timing pulsars individually, one can measure the variation in period with time.

**Lorimer (2008)**

$$P(t) = P\left(t_0\right) + \left.\frac{\mathrm{d}P}{\mathrm{d}t}\right|_{t_0} \left(t - t_0\right) + \left.\frac{\mathrm{d}^2P}{\mathrm{d}t^2}\right|_{t_0} \frac{\left(t - t_0\right)^2}{2!} + \ldots$$

# Formation pathway for interacting binaries with neutron stars

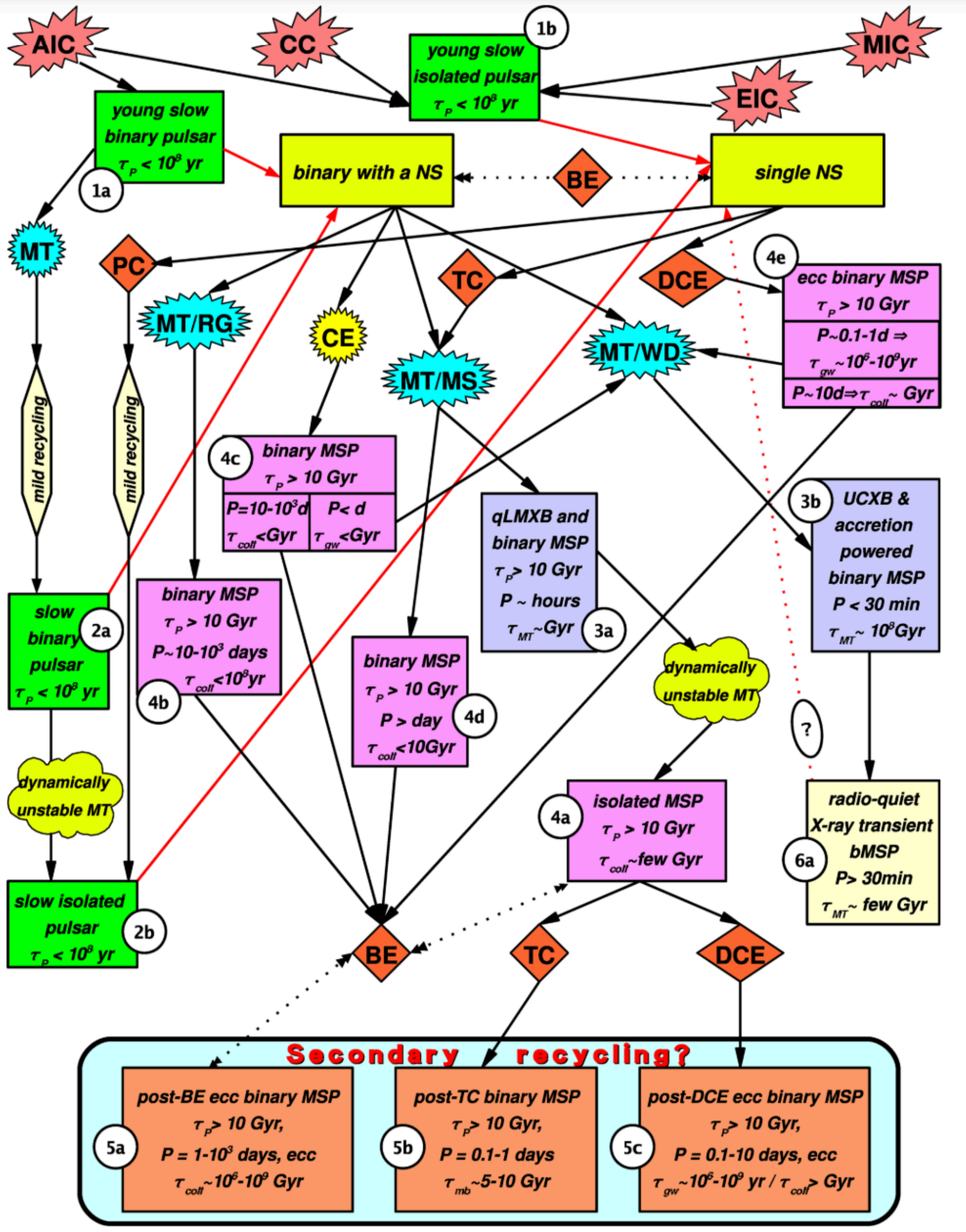


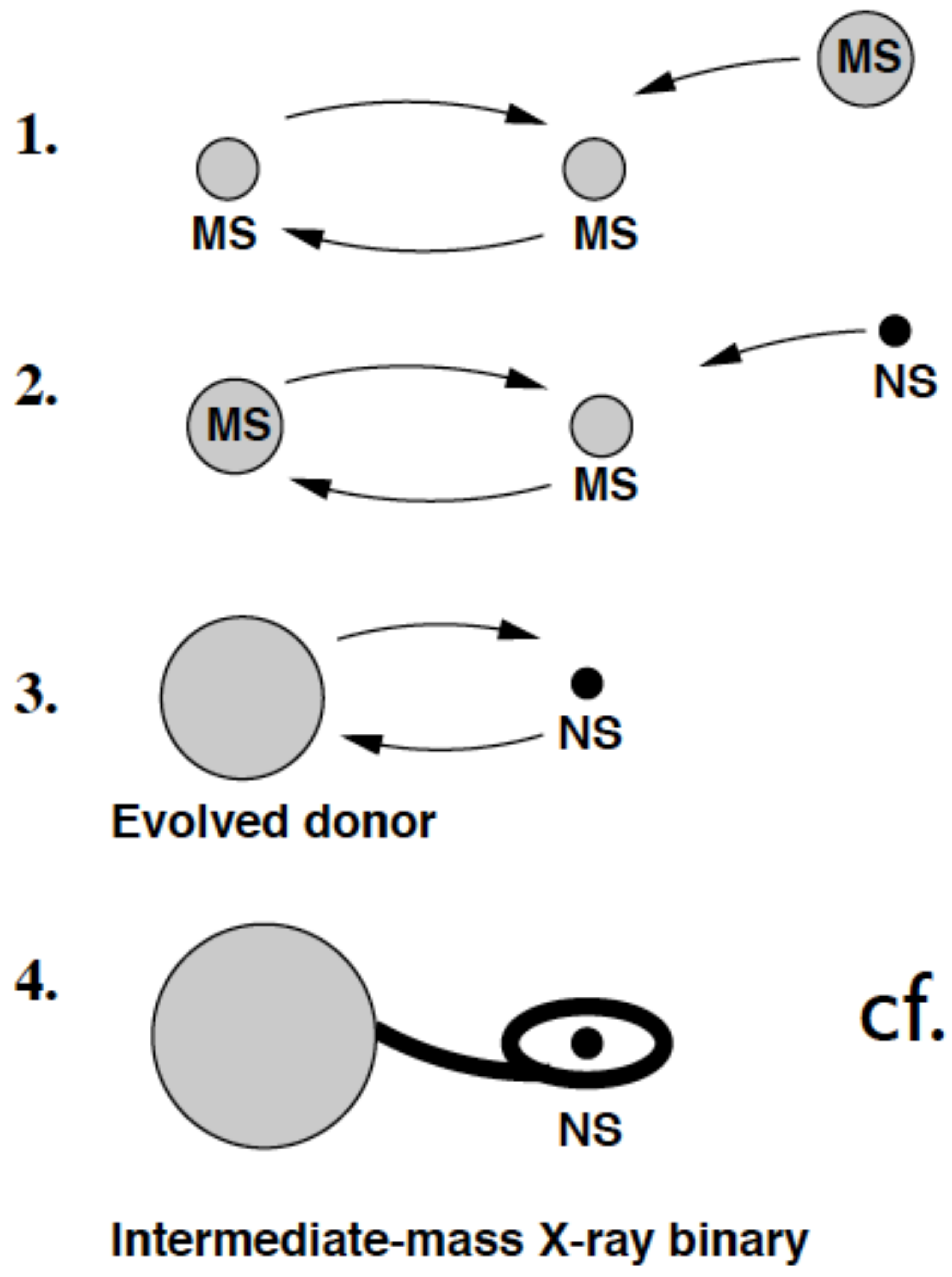
**Figure 1.** The scenario for the formation and evolution of MSPs in GCs. $\tau_P$ is the lifetime of a radio pulsar after formation. $\tau_{MT}$, $\tau_{mb}$, $\tau_{gw}$ and $\tau_{coll}$ indicate which time-scale determines the lifetime of the indicated binary: $\tau_{MT}$ – while MT lasts, $\tau_{mb}$ and $\tau_{gw}$ – until magnetic braking or gravitational radiation merges the binary, $\tau_{coll}$ – before the next dynamical encounter. The final fate of radio-quiet X-ray transient bMSPs (‘6a’) is not determined.

From Ivanova et al. 2008

- Large natal kicks of neutron stars (following supernova explosions) can eject them from host star clusters (Hobbs et al. 2005; Janka 2013)
- Most likely that neutron stars in globular clusters formed via electron-capture supernova (Ivanova et al. 2008)

- Globular clusters contain many more millisecond pulsars than LMXBs

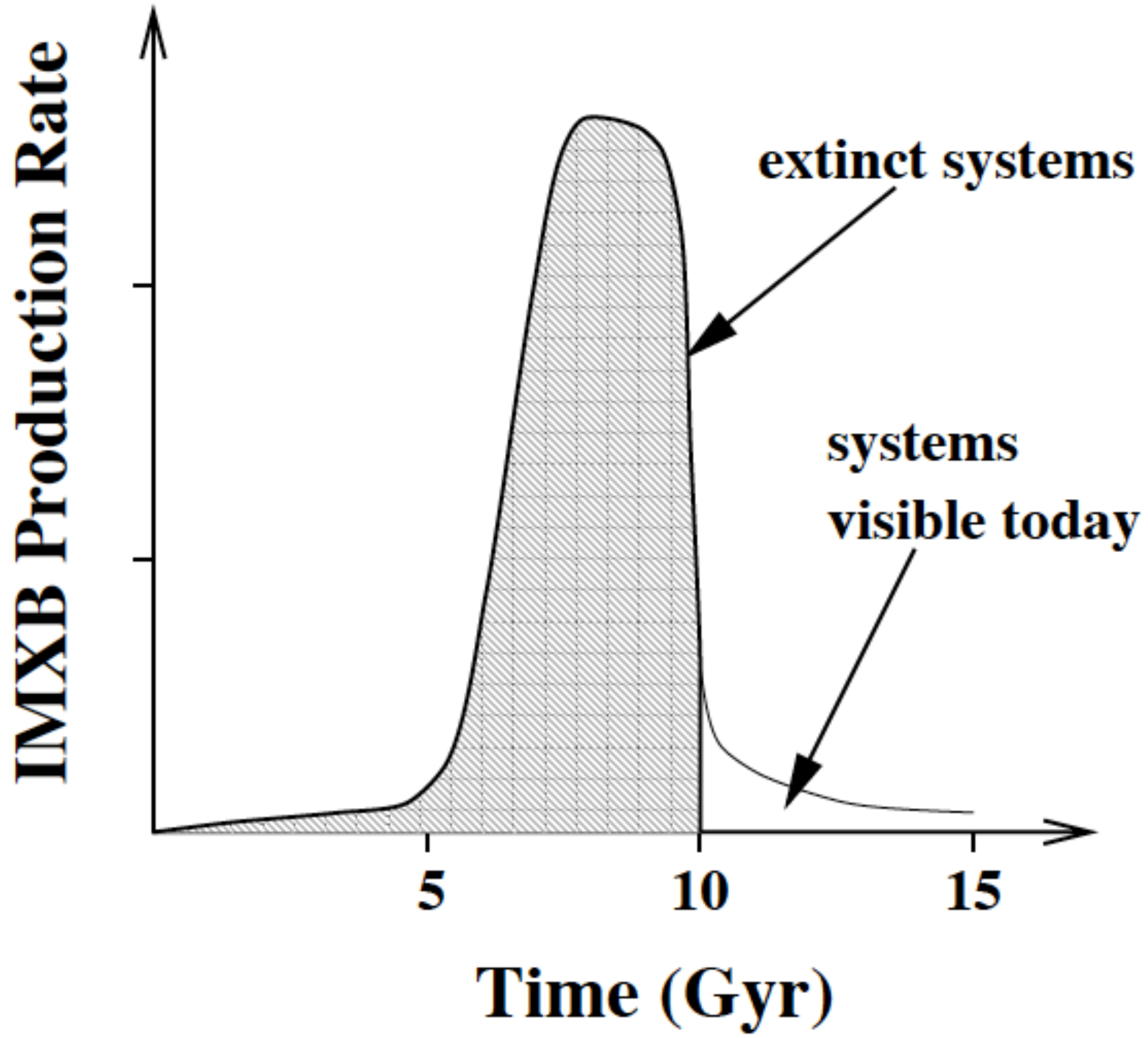
# Making millisecond pulsars in intermediate-mass X-ray binaries



cf. Cygnus X-2

Davies & Hansen 1998

IMXBs make MSPs in the past



Davies (2002)

# Key takeaways

- The interplay between gravitational dynamics and stellar/binary evolution can lead to the formation of stellar exotica
- Blue straggler stars form when 2 stars merge or when the mass of a star is increased due to mass transfer
  - Can be used to infer the dynamical age of the cluster
- Stellar mergers/and collisions can also lead to formation of interacting binary systems
  - Particularly those with compact objects
  - A high fraction of X-ray sources are observed in globular clusters compared to the field (higher efficiency of production per unit mass) →. Due to dynamics
  - Dynamics can also destroy progenitors of interacting binary systems: Like cataclysmic variables
  - Neutron stars retained in globular clusters are likely to have formed with low natal kicks