

# Second Generation Star Formation in Globular Clusters of Different Masses

(Submitted to MNRAS)

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**INAF**  
ISTITUTO NAZIONALE  
DI ASTRONOMIA E FISICA



# Globular Clusters

As a Simple stellar population (SSP)

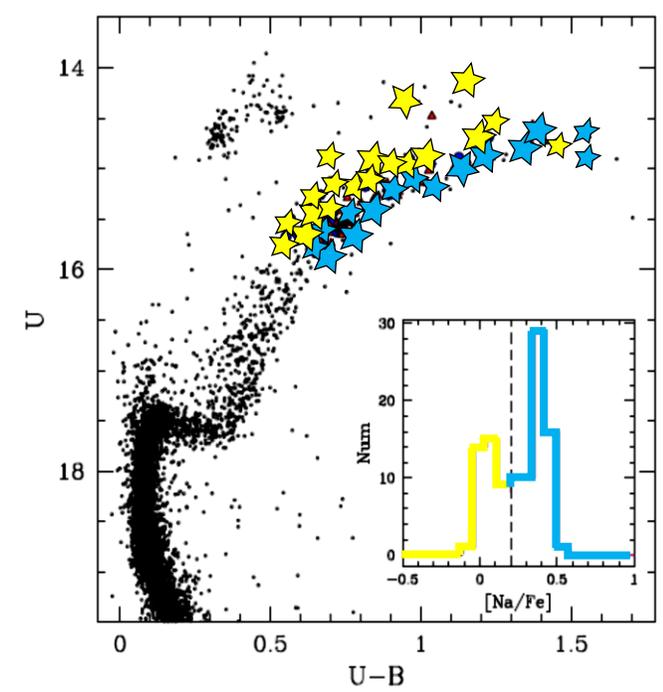
A set of stars with:

- The same age
- The same chemical compositions
- different masses
- Only a single isochrone on the CMD



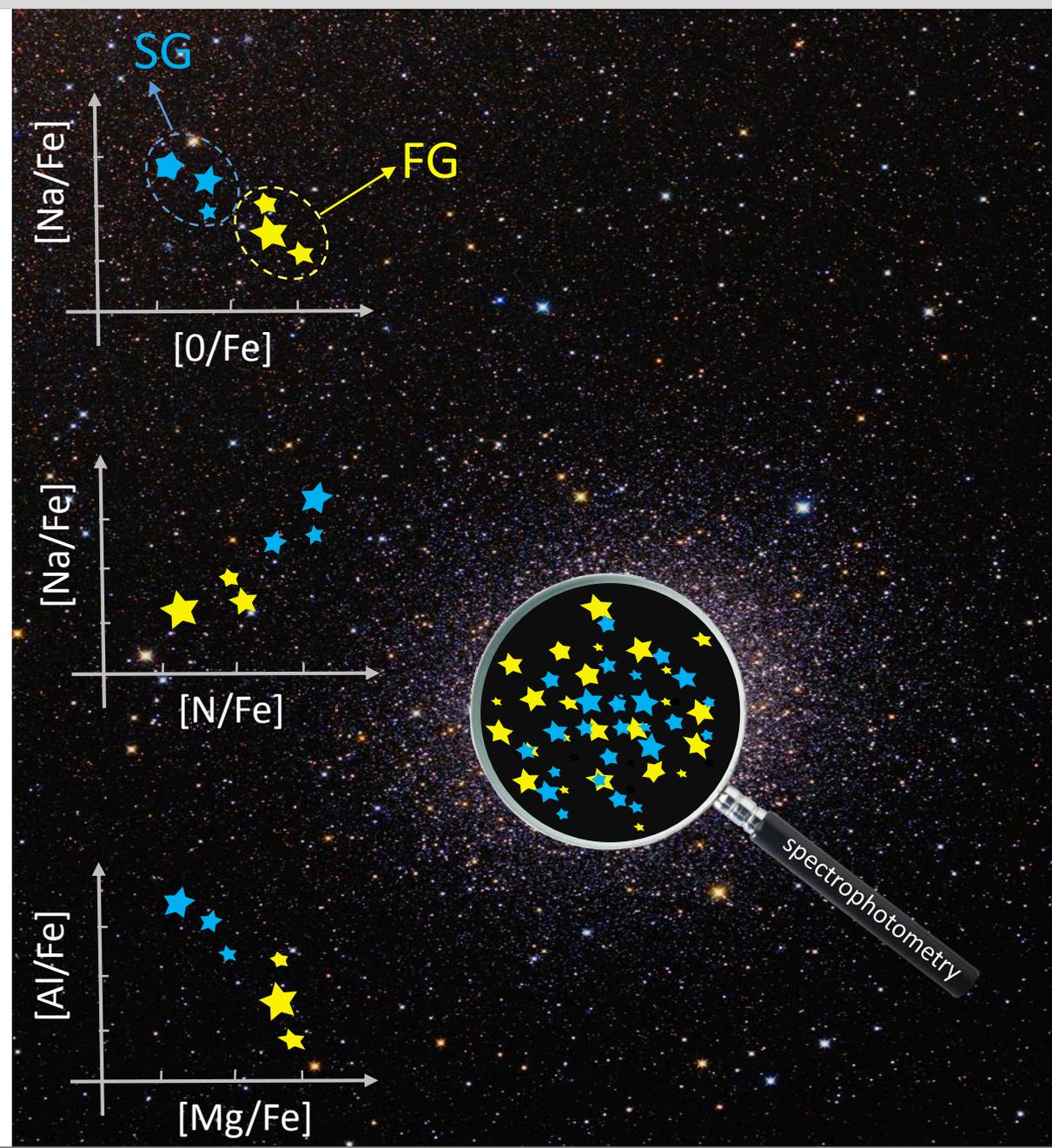
# Globular Clusters

New observations:



**NGC 6124 (M4)**  
(Marino et al (2008))

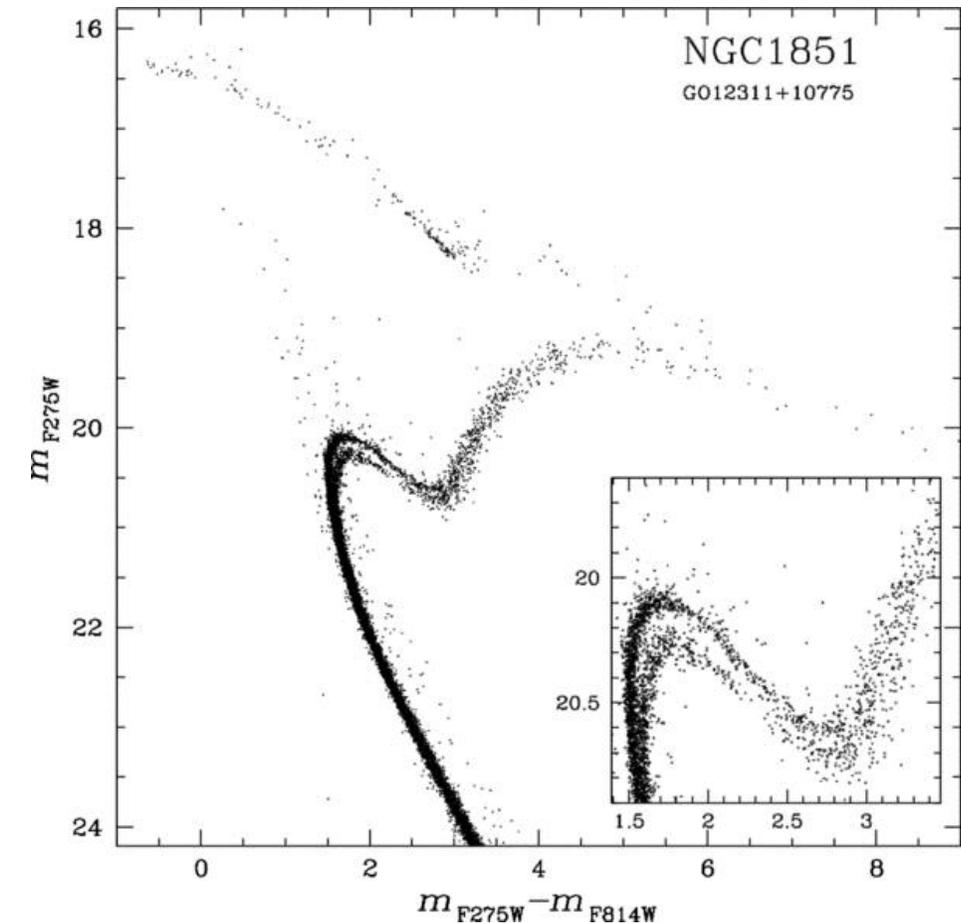
- Star-to-star variations in the light element abundances, but no spread in the iron abundance for the majority of GCs.



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- **Splitting the CMD into some sequences in some GCs.**

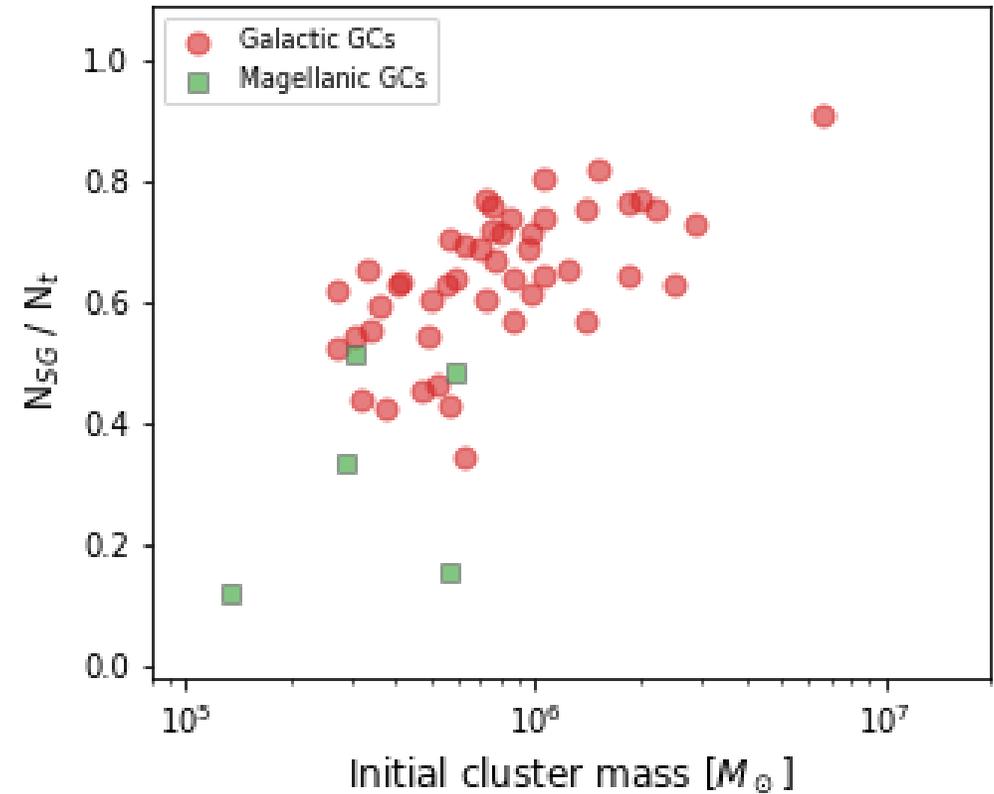


D'Antona et al. 2013

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- Splitting the CMD into some sequences in some GCs.
- **A strong correlation between the number ratio of SG to FG and the present-day cluster mass.**

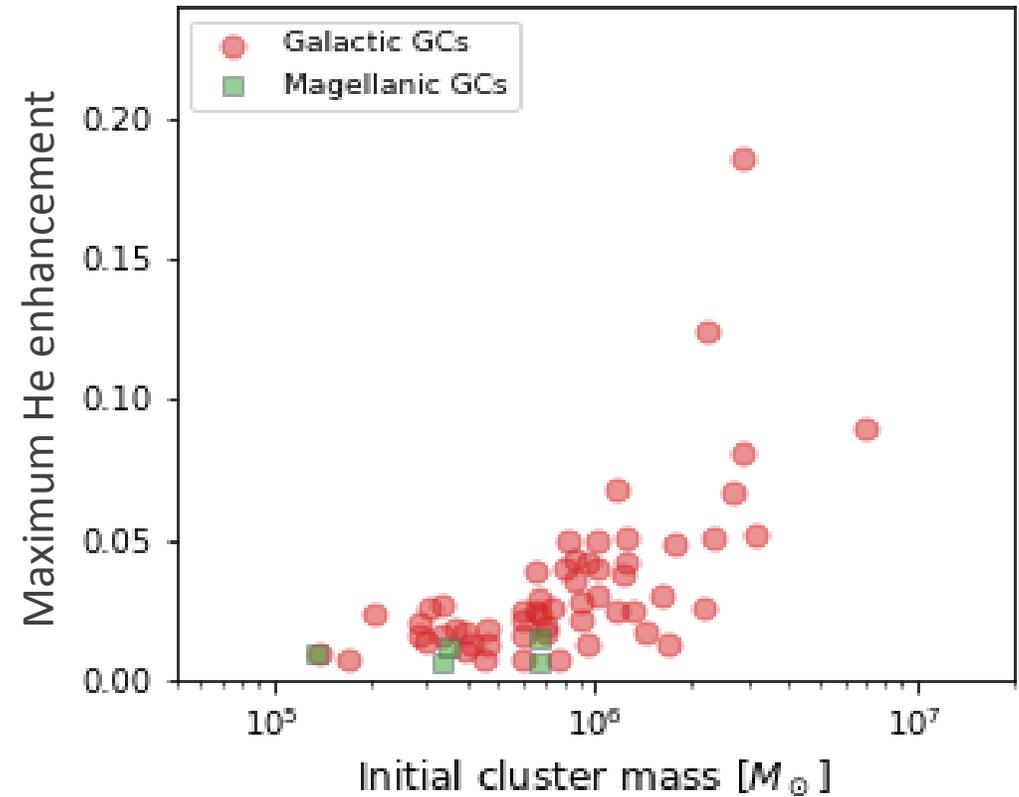


Data from Milone et. al 2020

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- **Another correlation between the observed the He enhancement and the cluster mass.**

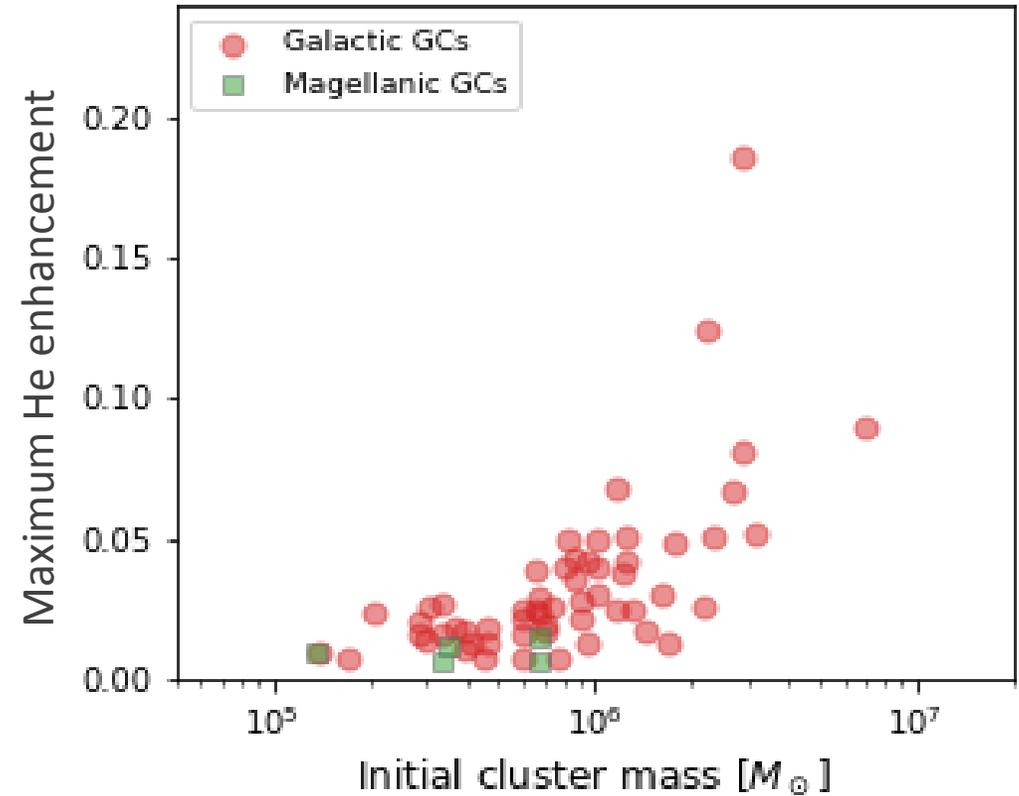


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- Splitting the CMD into some sequences in some GCs.
- A strong correlation between the number ratio of SG to FG and the present-day cluster mass.
- Another correlation between the observed He enhancement and cluster mass.
- **Observing these anomalous abundances in all Galactic GCs and some in nearby galaxies**



- Multiple stellar populations in globular clusters
- **How are such populations formed in GCs?**
- Our results; second generation star formation in globular clusters (GCs) of different masses



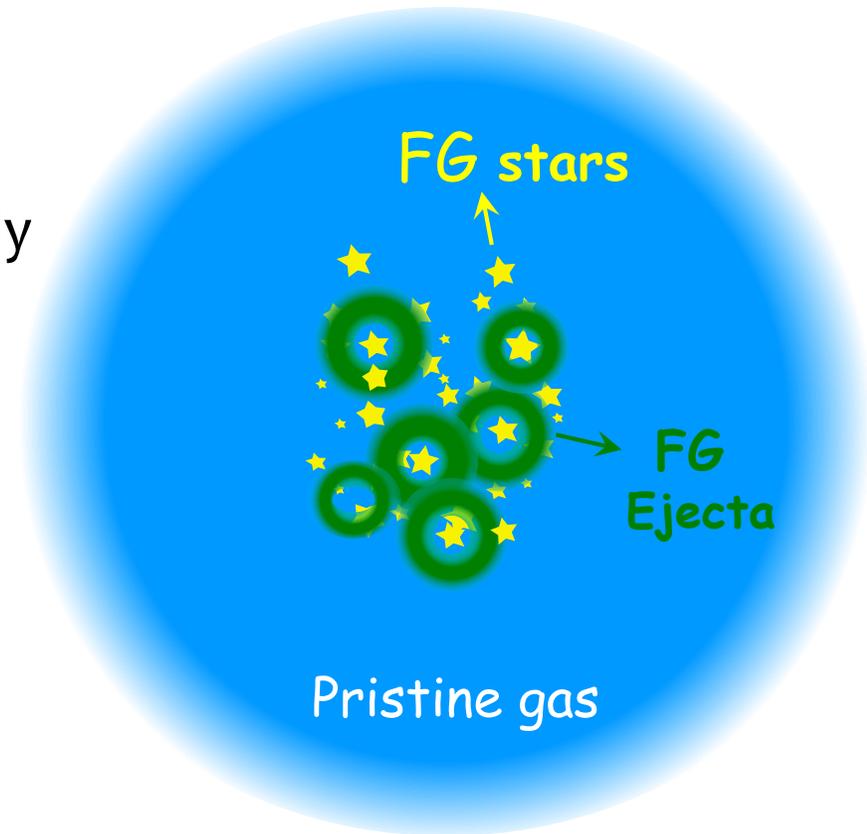
## How are such populations formed in GCs?

### Some scenarios for the SG formation:

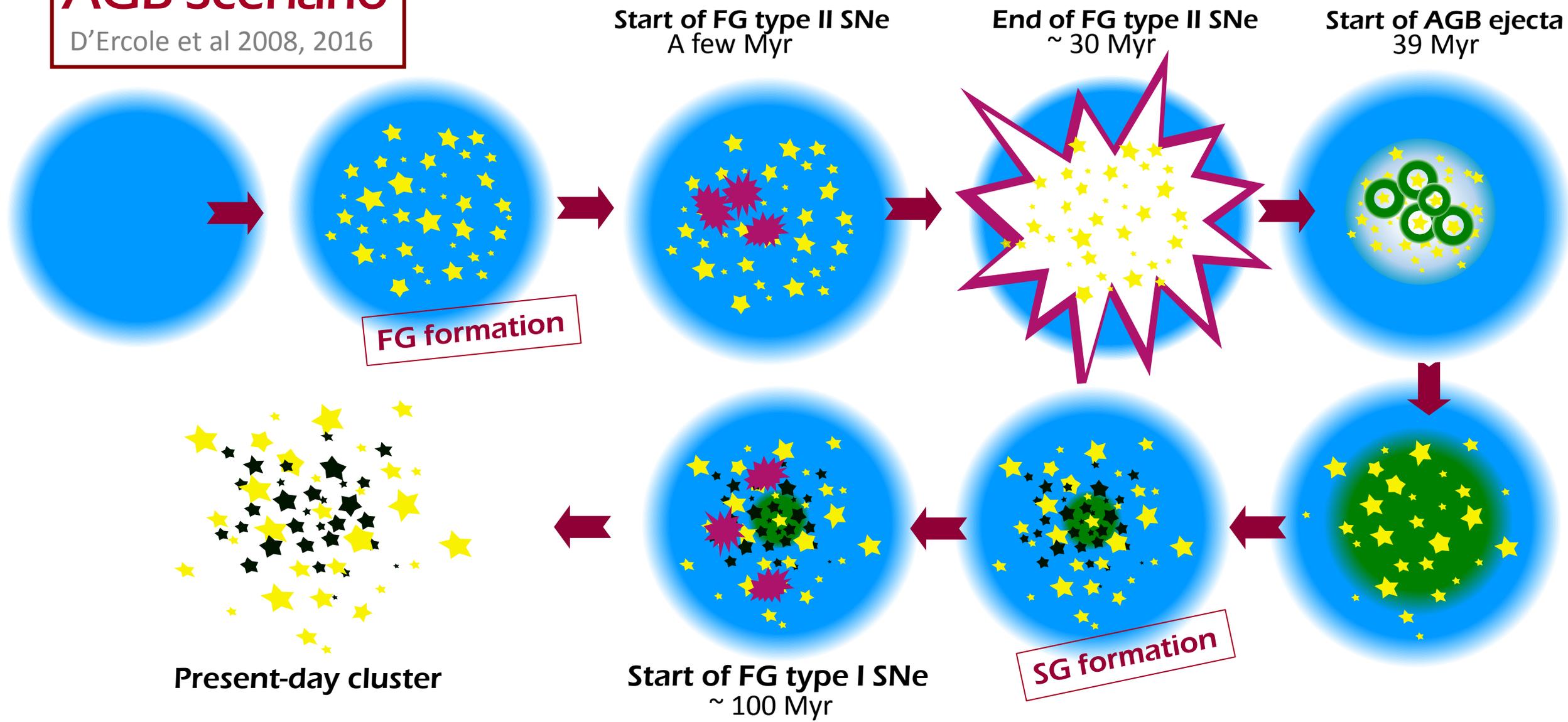
AGB Scenario , Fast Rotating Massive Stars (FRMS), Interacting Binaries (IBs) , Very Massive Stars (VMS), Early Disc Accretion Scenario, ...

In most of the scenarios, a mix of the gas enriched by the ejecta of FG stars and the pristine gas forms the SG stars.

Renzini et al. 2015



**AGB Scenario**  
 D'Ercole et al 2008, 2016



# AGB Scenario

D'Ercole et al 2008, 2016

Some Challenges :

A very massive FG is required to form a massive SG.

Also a large amount of pristine gas is necessary to dilute the AGB ejecta in order to reproduce the observed properties of SGs.

(D'Ercole et al 2008)

$$\sigma^2 \propto \frac{GM}{r_P}$$

The cluster can accrete the ISM gas if:

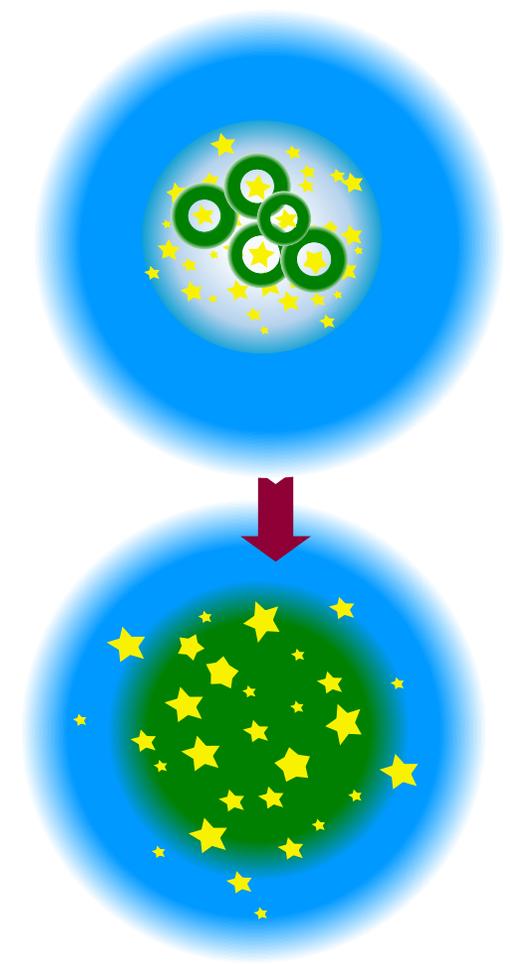
Lin & Murray 2007

$$\sigma^2 \gg v_{GC}^2 + c_s^2$$

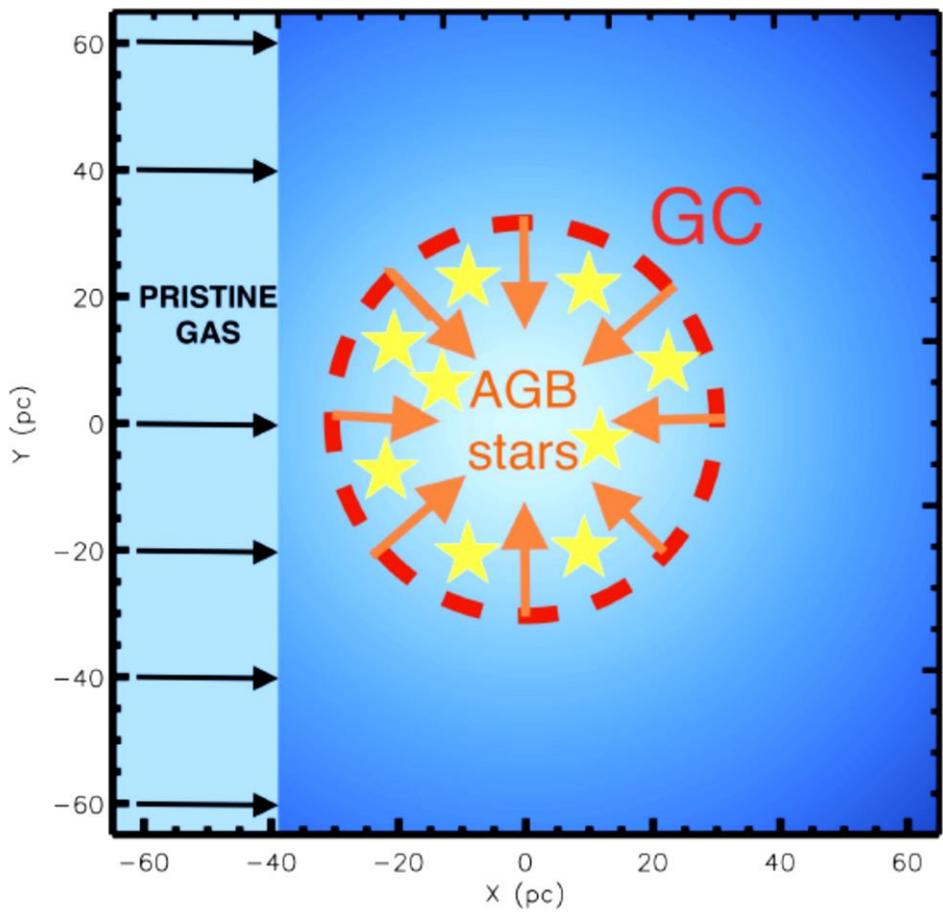
The cluster can retain its AGB ejecta if:

Naiman et al 2018

$$\sigma \gg v_{wind}$$



# Second generation star formation based on the AGB scenario

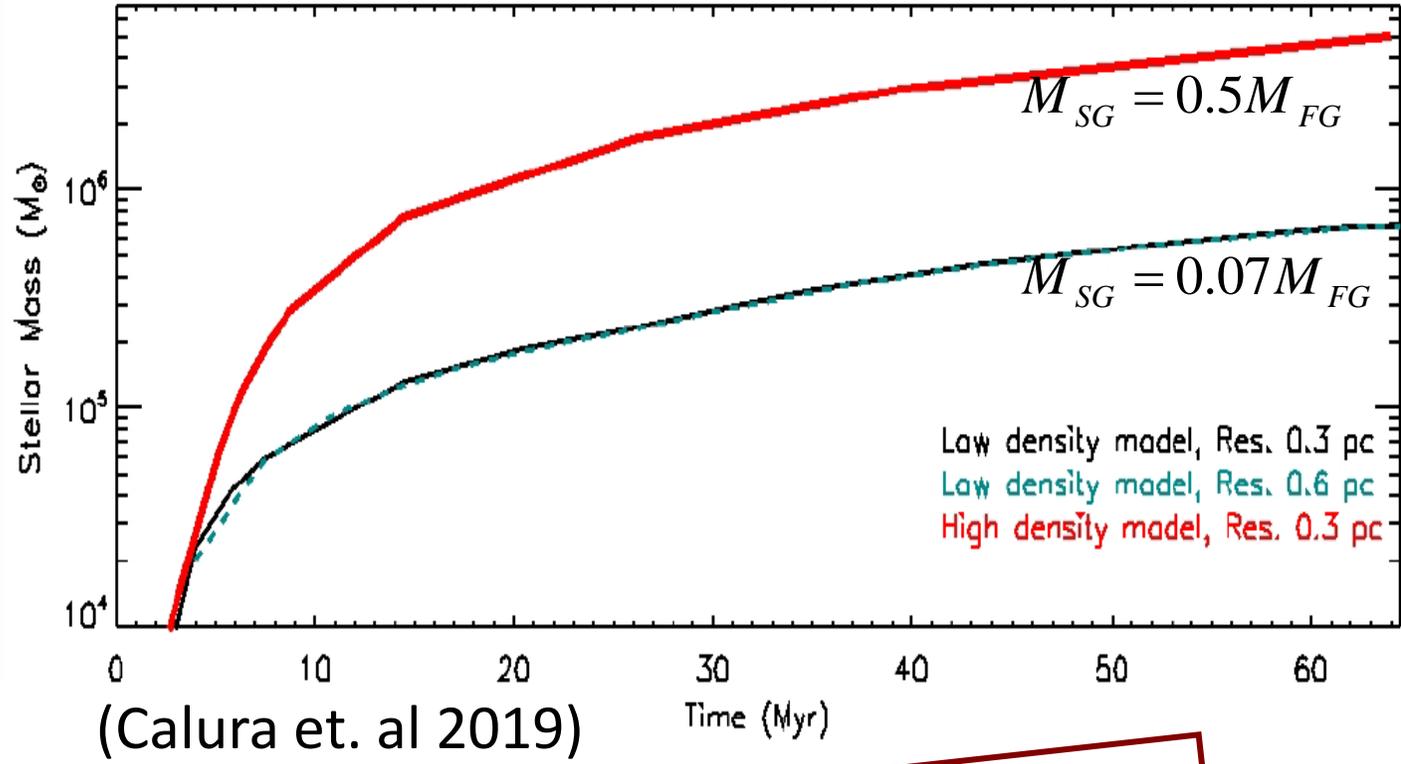
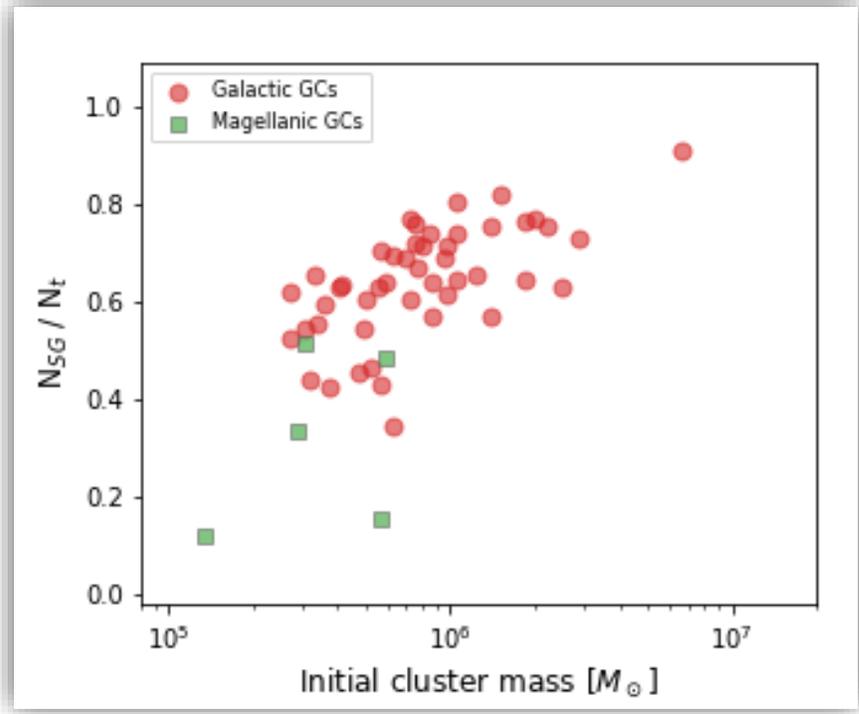


| Parameter   | Description                               | Adopted values                      |
|-------------|---|-------------------------------------|
| $\rho_{pg}$ | density of pristine gas                   | $10^{-23}; 10^{-24} \text{ g cm}^3$ |
| $v_{pg,6}$  | pristine gas velocity                     | $20 \text{ km/s}$                   |
| $T_{pg}$    | temperature of the pristine gas           | $10^4 \text{ K}$                    |
| $T_{floor}$ | Minimum temperature of the simulations    | $10^3 \text{ K}$                    |
| $t_*$       | Star formation timescale                  | $0.1 \text{ Cyr}$                   |
| $M_{FG}$    | Mass of first generation stars            | $10^7 M_{\odot}$                    |
| $r_{Plum}$  | Plummer radius of FG stellar distribution | $23 \text{ pc}$                     |
| $t_{end}$   | Duration of SG star formation             | $65 \text{ Myr}$                    |

(Calura et. al 2019)

**RAMSES CODE**  
 (R.Teyssier, A&A, 385, 2002)

# Second generation star formation based on the AGB scenario



(Calura et. al 2019)

**RAMSES CODE**  
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- How are such populations formed in GCs?
- **Our results: second generation star formation in globular clusters (GCs) of different masses**



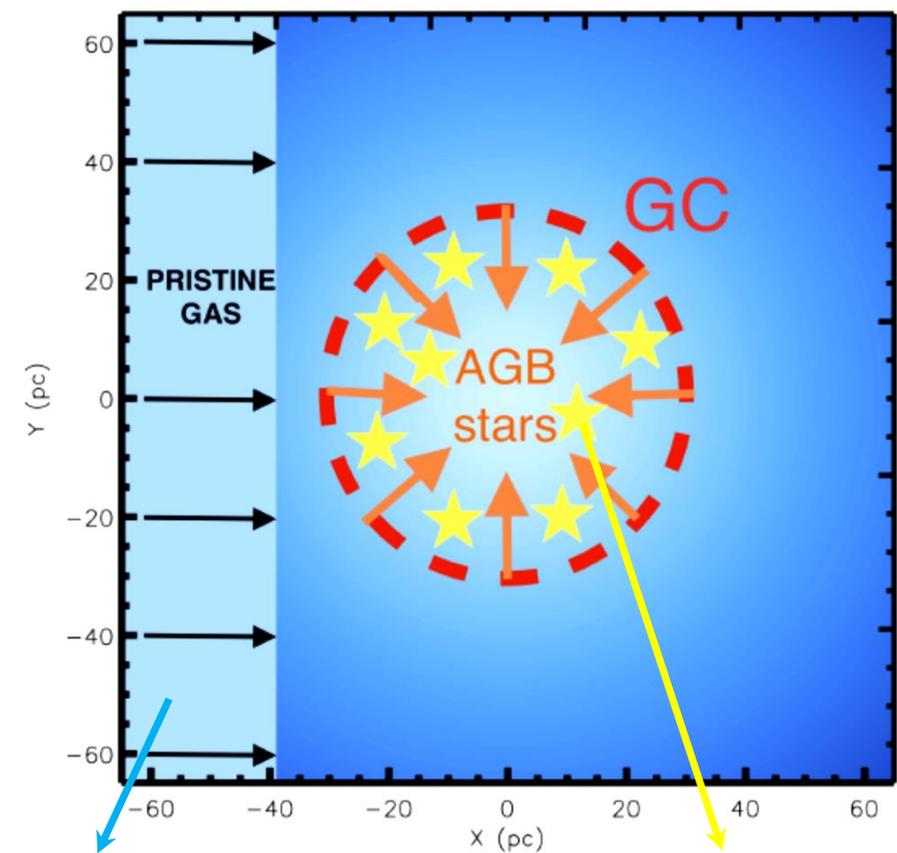
# The setup of our simulation:

| Model       | $M_{FG} [M_{\odot}]$ | $\sigma [10^6 \text{ cm s}^{-1}]$ | $\rho_{pg} [g \text{ cm}^{-3}]$ |
|-------------|----------------------|-----------------------------------|---------------------------------|
| M6-Infall24 | $10^6$               | 2.68                              | $10^{-24}$                      |
| M5-Infall24 | $10^5$               | 0.85                              | $10^{-24}$                      |
| M6-Infall23 | $10^6$               | 2.68                              | $10^{-23}$                      |
| M5-Infall23 | $10^5$               | 0.85                              | $10^{-23}$                      |

$$v_{clus} = 2.3 \times 10^6 \text{ cm/s}$$

$$v_{wind} = 2 \times 10^6 \text{ cm/s}$$

$$c_s = 1.6 \times 10^6 \text{ cm/s}$$



$Y = 0.26$

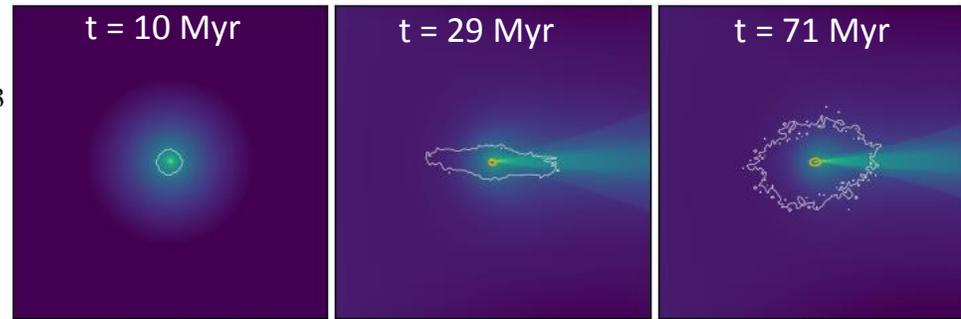
$0.36 > Y > 0.32$

# Results:

## Gas and particle evolutions

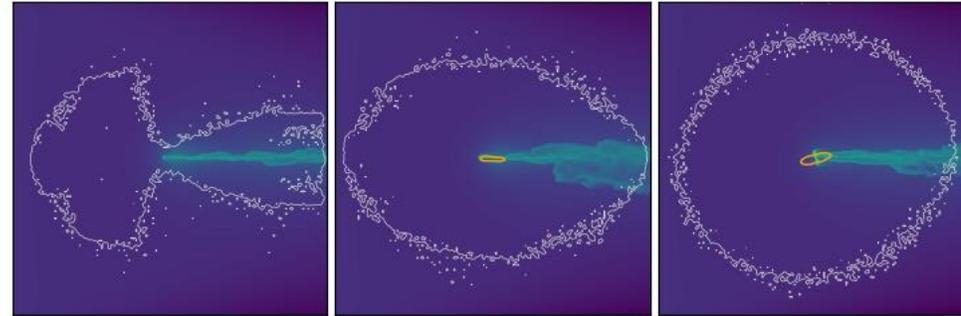
$$\rho_{pg} = 10^{-24} \text{ gcm}^{-3}$$

$$M_{FG} = 10^6 M_{\odot}$$



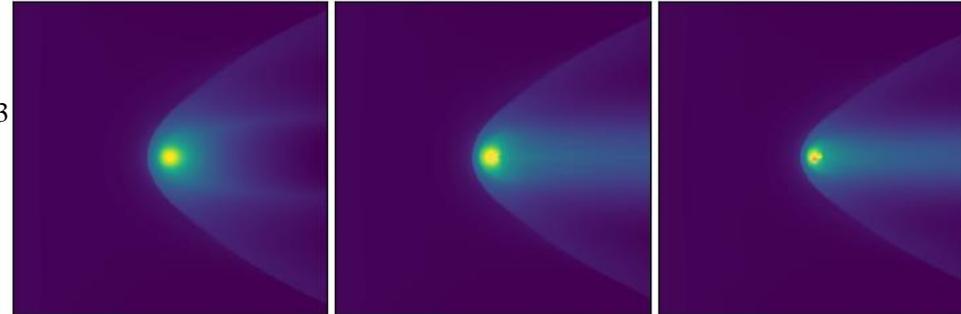
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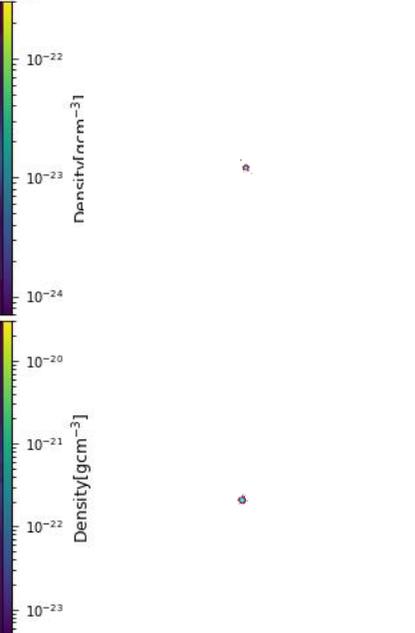
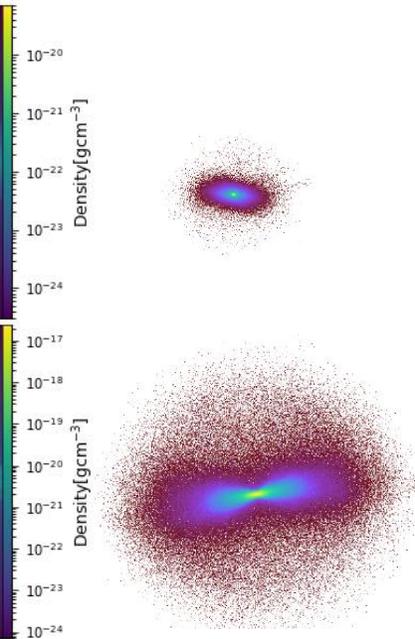
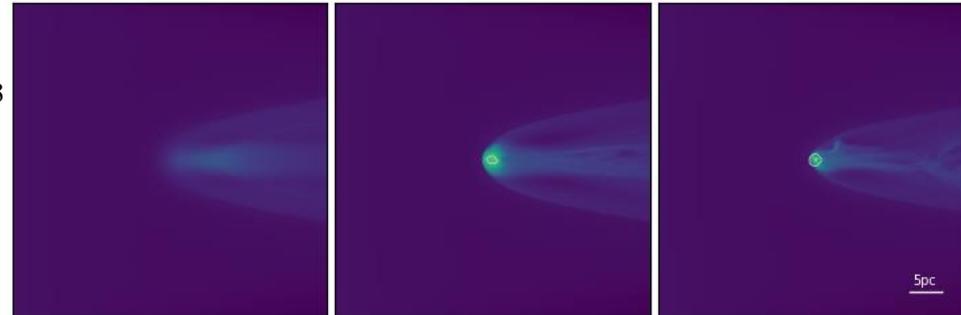
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# Results:

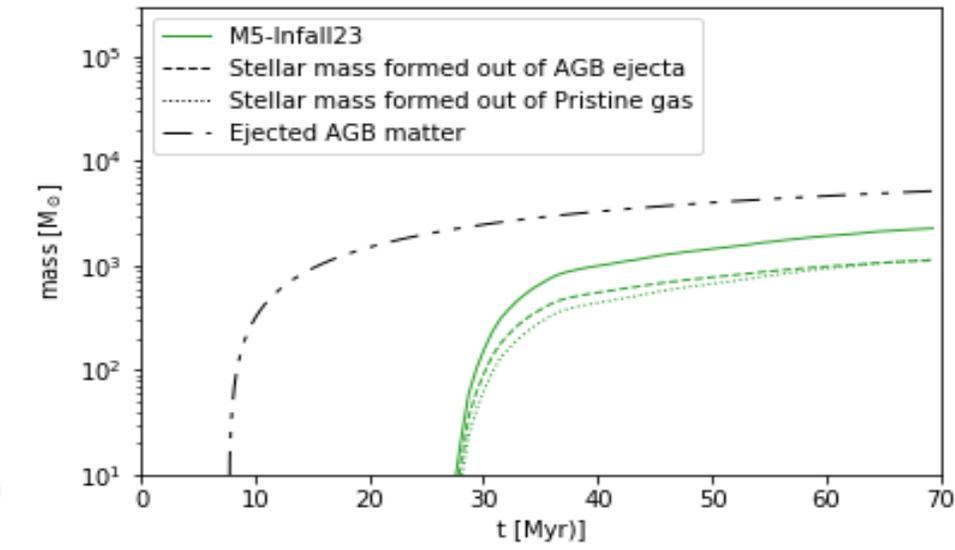
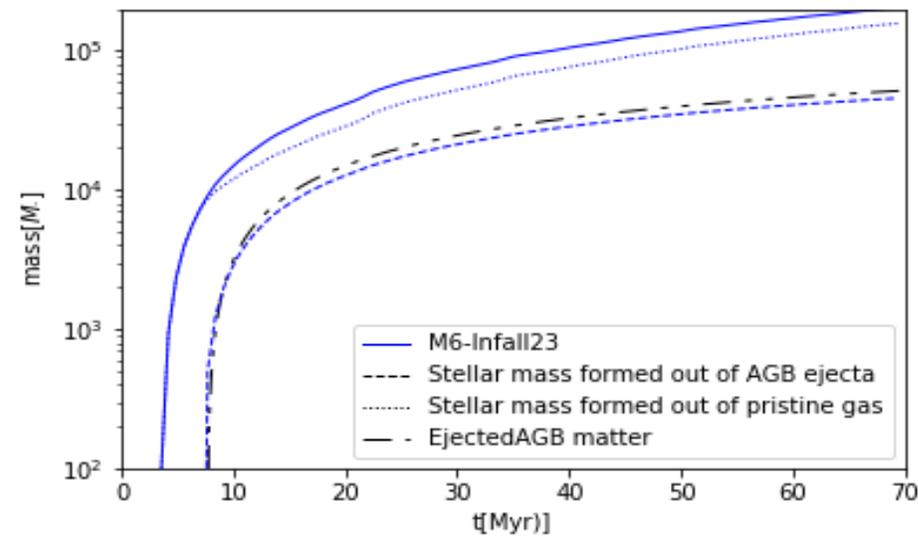
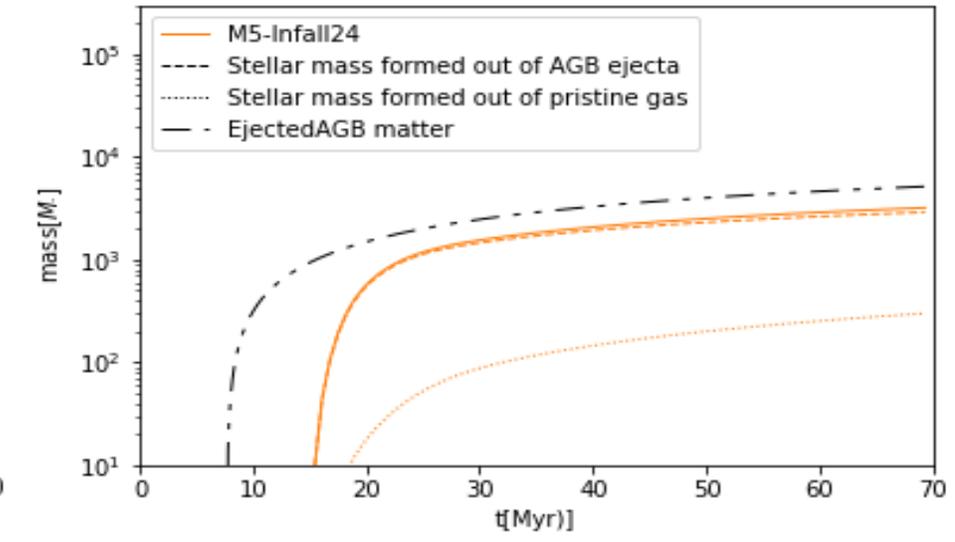
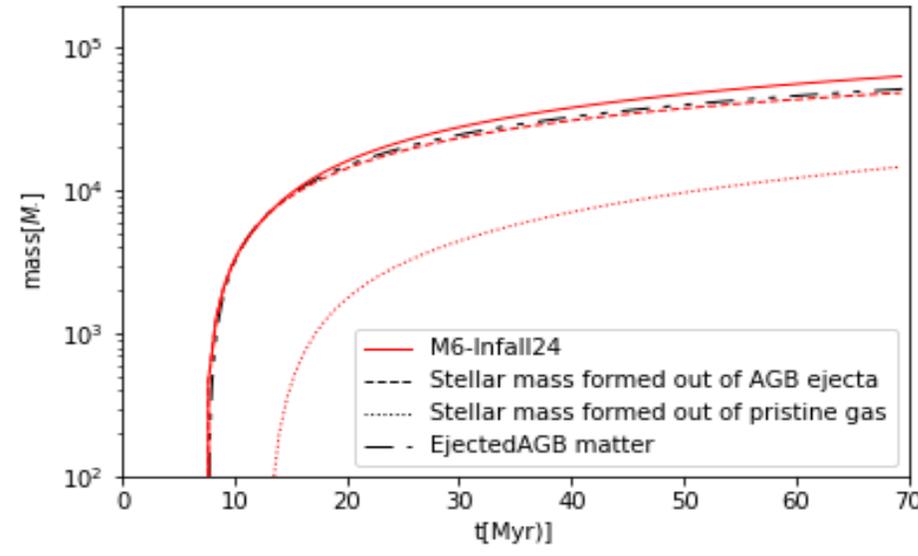
## Dilution of AGB ejecta

$$\rho_{pg} = 10^{-24} \text{ g cm}^{-3}$$

$$\rho_{pg} = 10^{-23} \text{ g cm}^{-3}$$

$$M_{FG} = 10^6 M_{\odot}$$

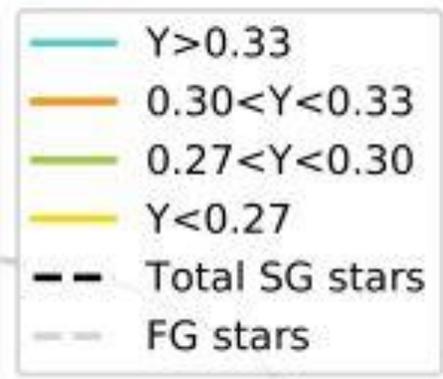
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# Results:

## SG & FG density profiles

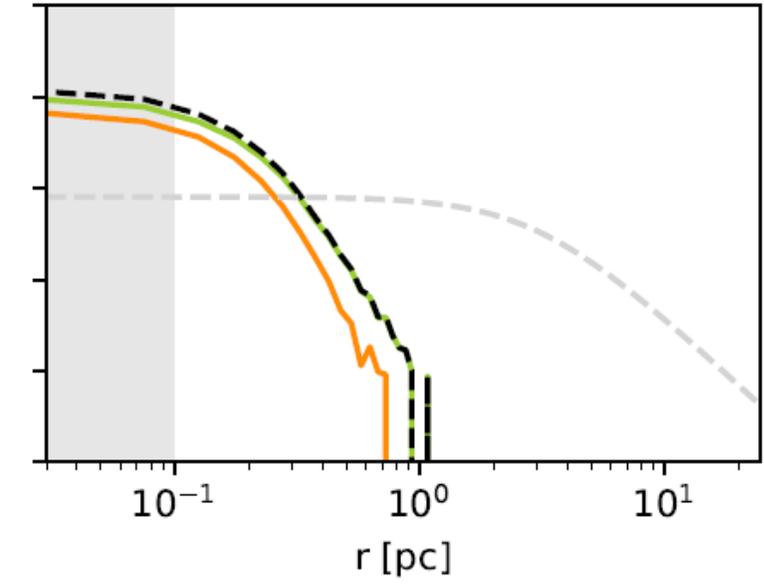
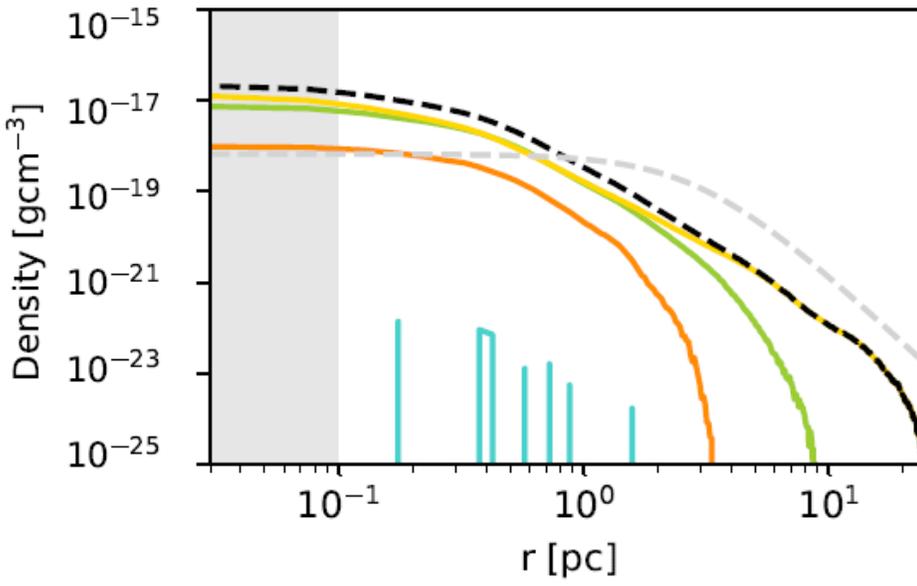
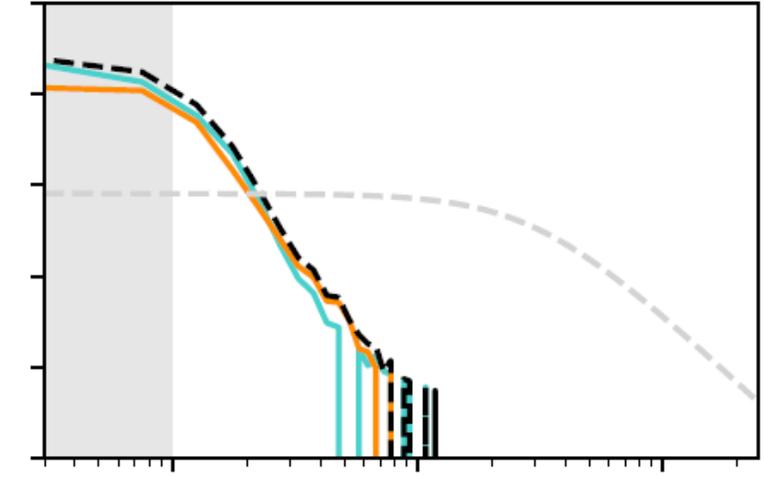
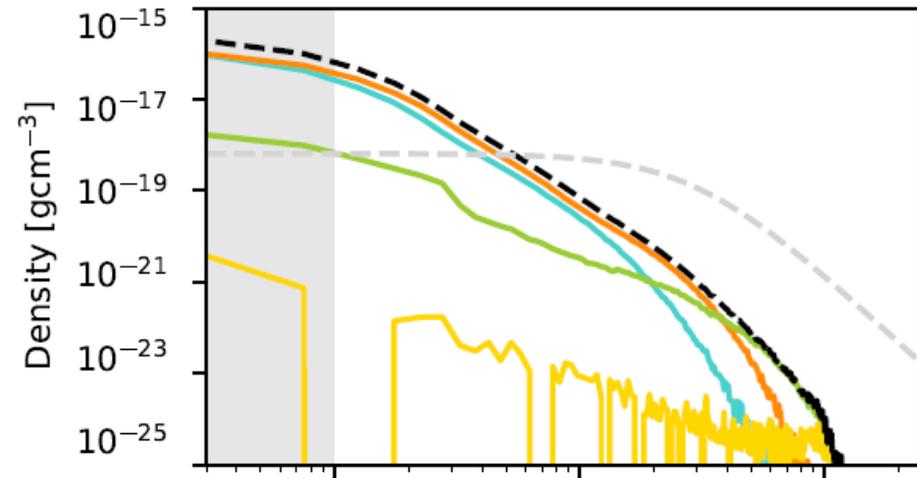
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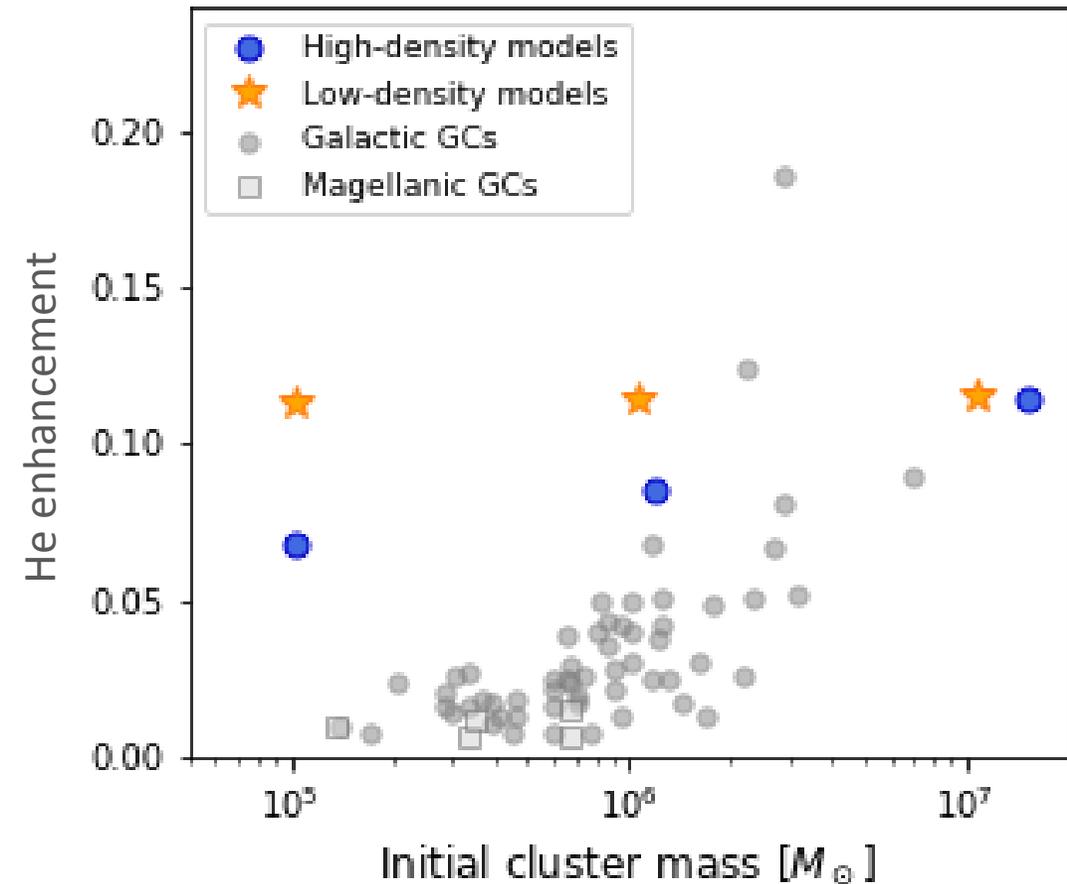
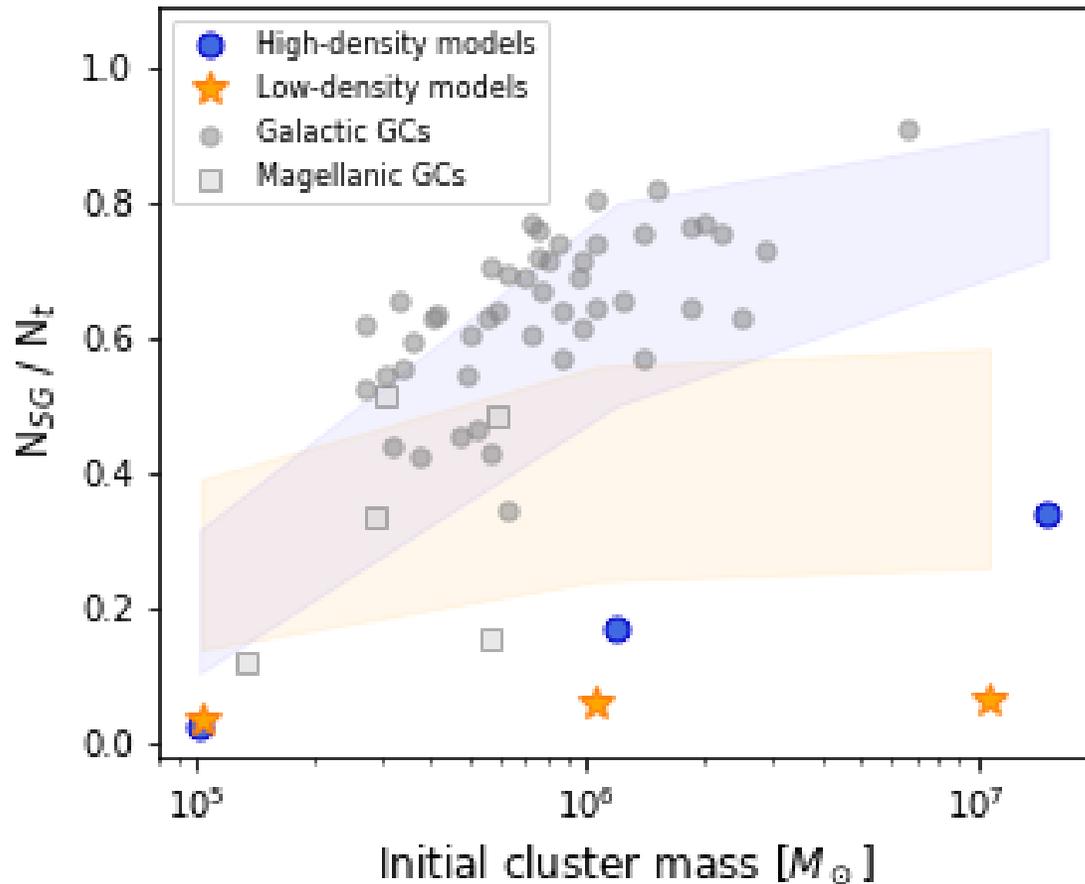
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# Results:

## SG fraction and He enrichment as a function of the initial mass



## Conclusions:

- The SGs formed in our simulations are more concentrated than the FGs and also SG sub-components with higher He abundances are more concentrated toward the center, in agreement with observations.
- In the low-density cases, weakly perturbed by the external ram pressure, a compact central He-rich SG stellar component is formed.
- In the  $M_{FG} = 10^6 M_{\odot}$  cluster the gravitational potential can overcome the ram pressure and a more extended and less He-enhanced SG can be formed.
- In agreement with existing observations, we find positive correlations between the SG-to-total mass ratio and maximum He fraction in SG stars as a function of the initial cluster mass.