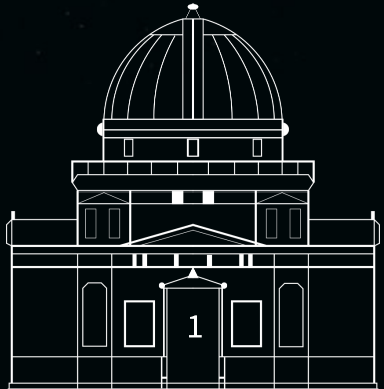
Supervised by **Paolo Bianchini**

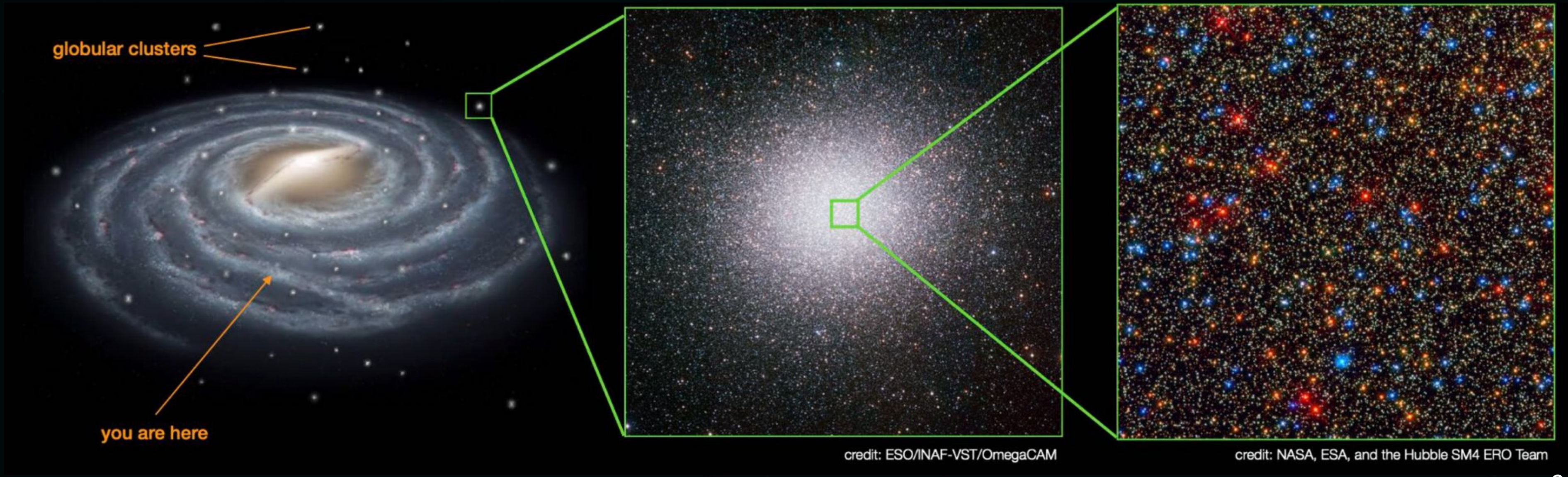
N-body simulations of globular clusters for deep-learning applications.



Hugo Spitz
Gabriel Bounias

What is a globular cluster ?

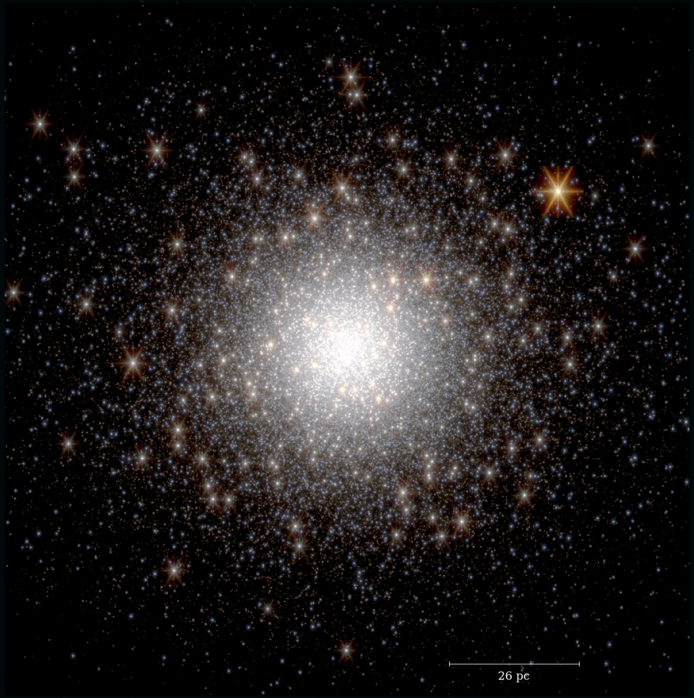
- Really high star **density**
- Quite **old** and stable structure



Intuitive characteristics :

- Number of stars : 100 000 to 1 million
- Diameter : 20 to 50 pc
- Distance to galaxy center : 40 to 100 kpc
- Age : ~11 Gyr

↳ Simulation



Objectives

- Extract the **mass distribution** and fundamental **characteristics** of globular clusters from a simulation

- Transform data of the simulation as if it was observed by the **JWST** to feed a **deep learning project**

- Create a **visualisation** of the simulated globular cluster and its **evolution**

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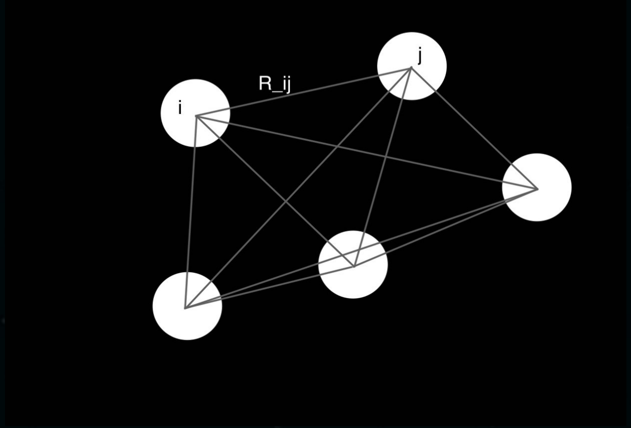
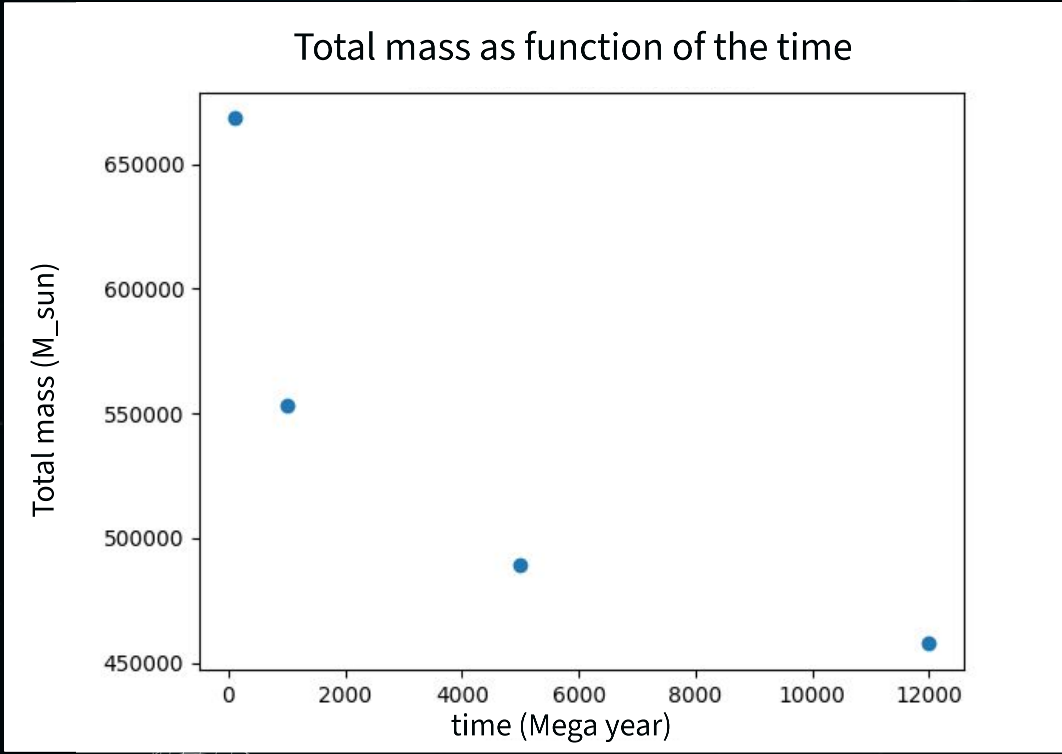
Simulation and data extraction

Upstream work



- **N-body simulation** : a lot of interactions → **HPC**, the greatest simulation of globular clusters (400 days)
- Code : Nbody6++GPU (*ref : Wang, 2016, Renaud and Gieles, 2015*) → combine **gravitational interactions** and **stellar evolution** of 1 million stars
- To begin we took 4 among 5000 snapshots to study the globular cluster

Mass of stars in the globular cluster



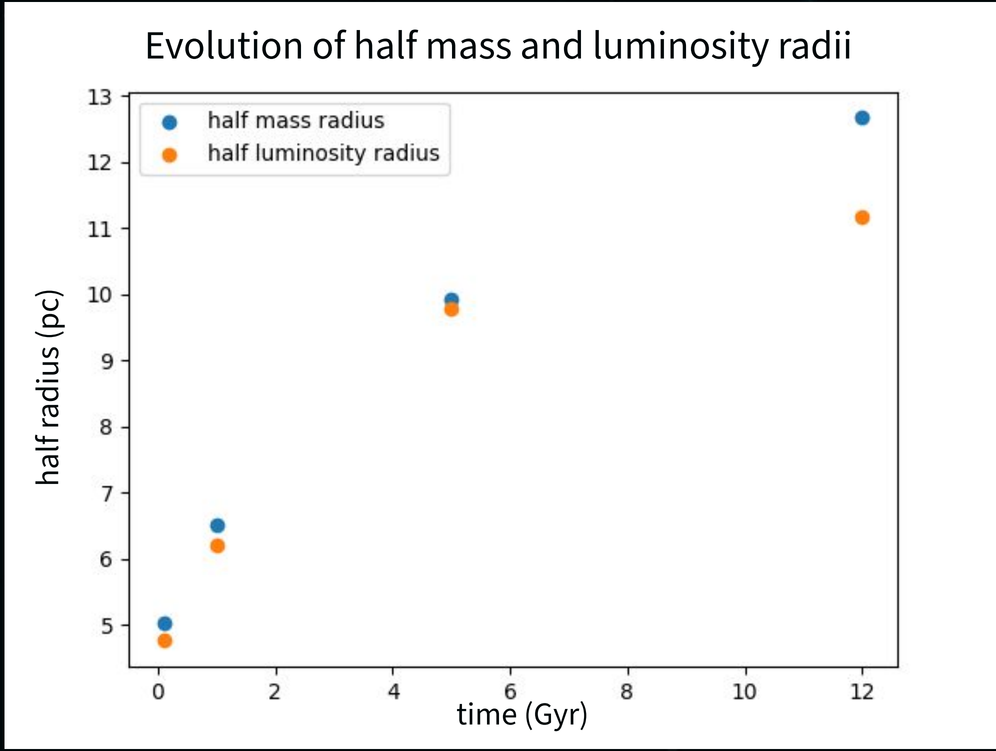
- Stars **escape** the globular cluster towards the galaxy

- Stars are **losing mass** because of **stellar evolution**

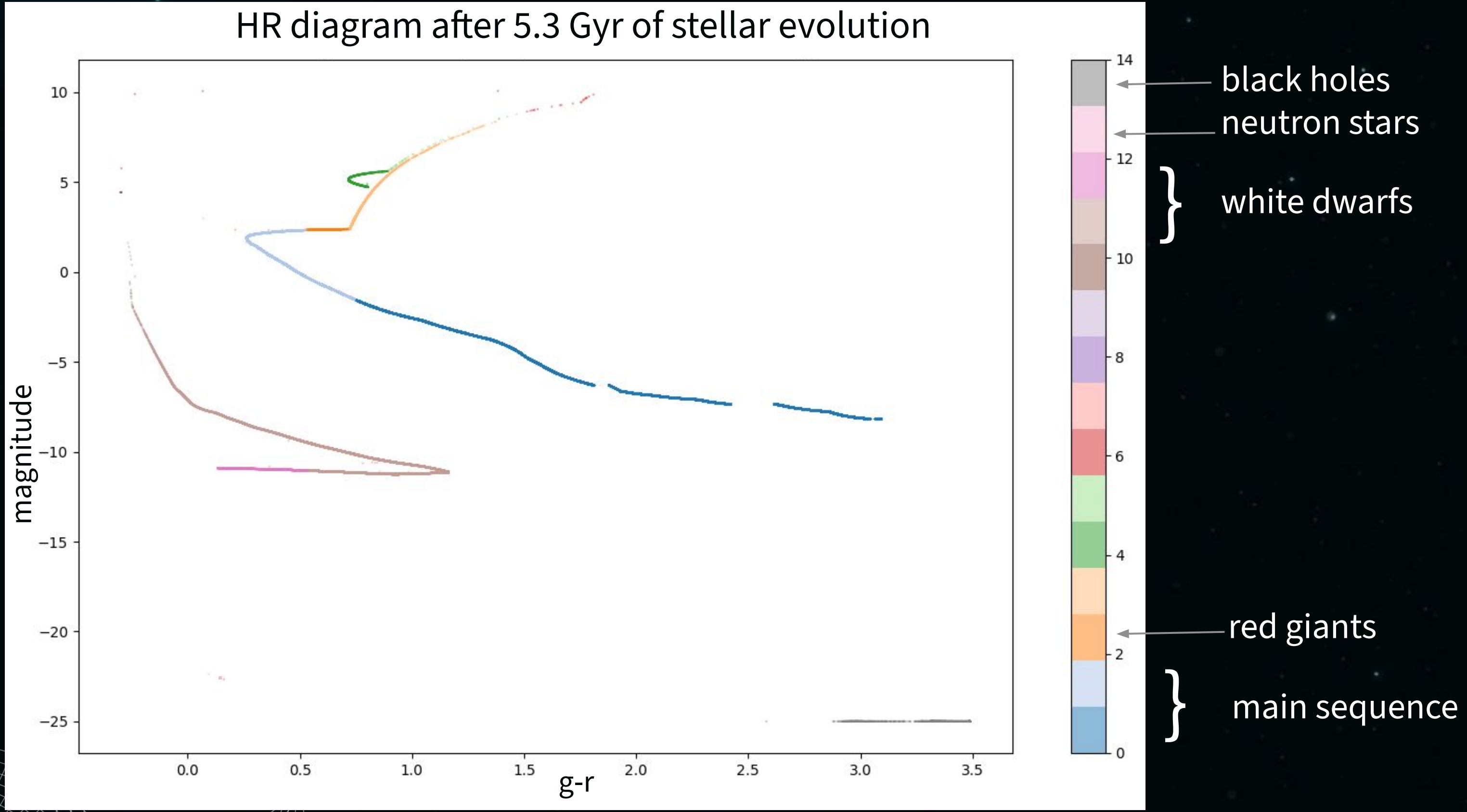
Half mass and half luminosity radii

- The **size** of the globular cluster **increases** induced by virial theorem

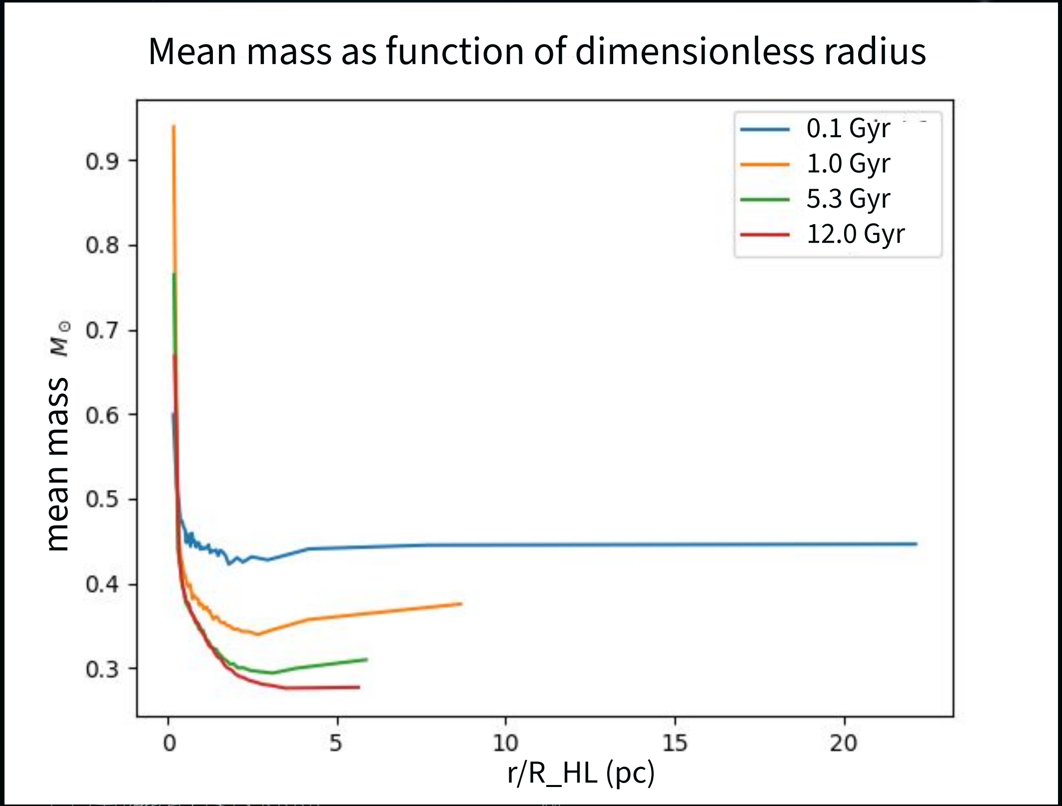
- Small **difference** due to stellar evolution and dark remnant



HR diagram


HR diagram after 5.3 Gyr of stellar evolution
magnitude
g-r
10
5
0
−5
−10
−15
−20
−25
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
14
12
10
8
6
4
2
0
black holes
neutron stars
white dwarfs
red giants
main sequence

Mass segregation

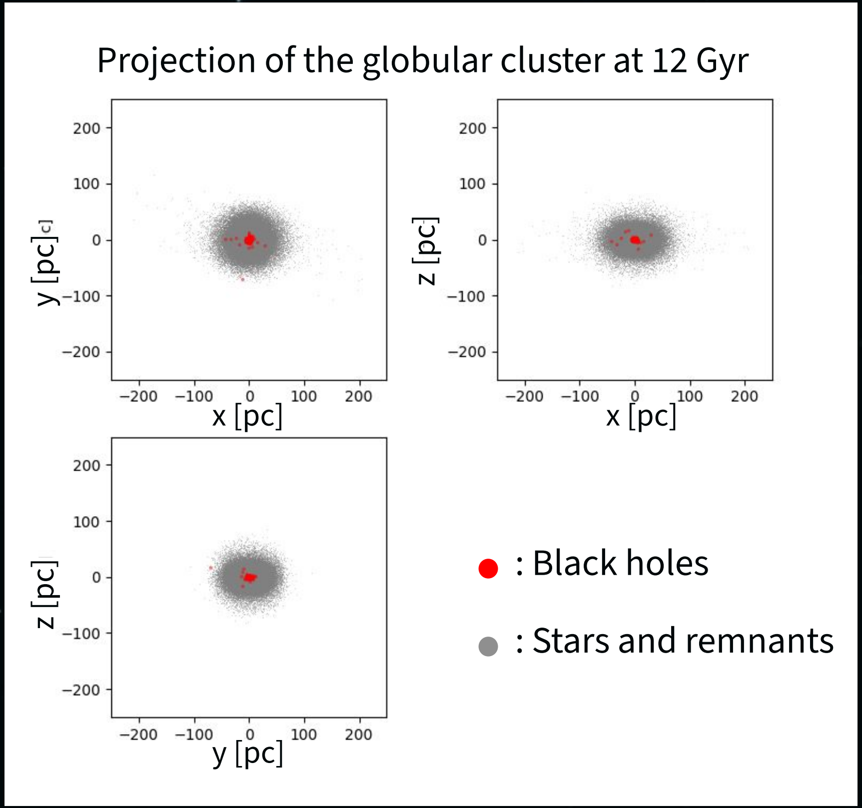


- Most **massive** stars go to the **center** of the globular cluster : **mass segregation**
- It is due to loss of **kinetic energy** for high mass stars in **interaction** with smaller ones

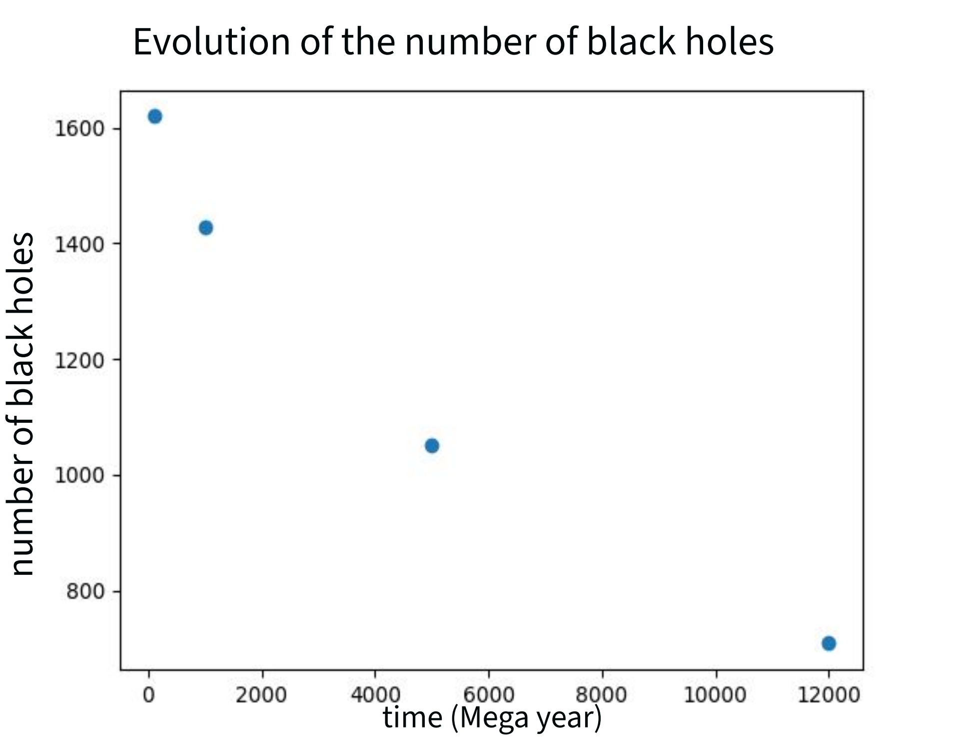
Black holes segregation

- We clearly see the **segregation effect** :
  ⇒ black holes go to the **center** of the globular cluster with time

- The globular cluster is not spherical but **elliptical** on the x-z/y-z plane (rotation along z-axis)



Number of black holes

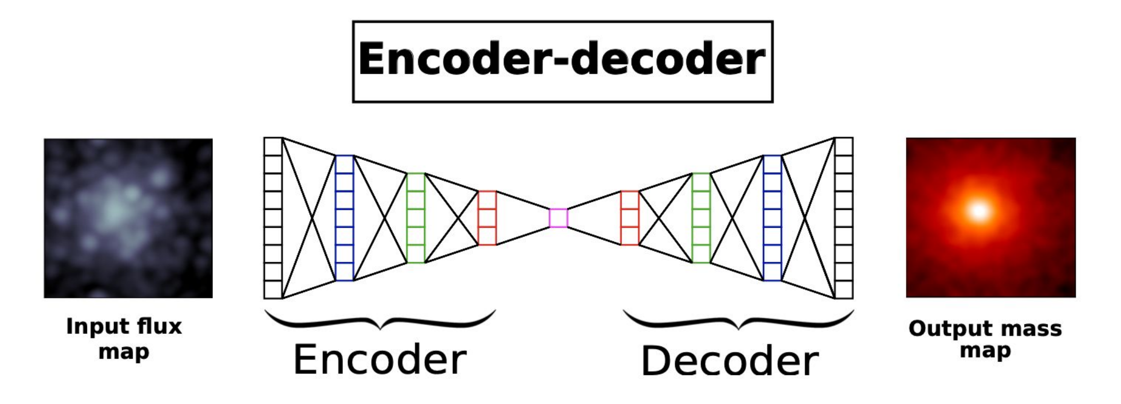


- As stellar evolution creates black holes only **early** in time, we expect **constant** number of black holes in the cluster

- **Decrease** of the number of black holes : huge **central density** leads to high energetic interactions **kicking** them

Artificial Intelligence necessity

- Difficult to predict the **mass** of a globular cluster and its **distribution** because multi-dimensional system with complex **dynamical properties** in constant **evolution**
- Hard to **fit** each observation of globular clusters with precise simulations
  → need **deep-learning** to generalise the process.



π-doc process that transform an observed flux map into a mass distribution

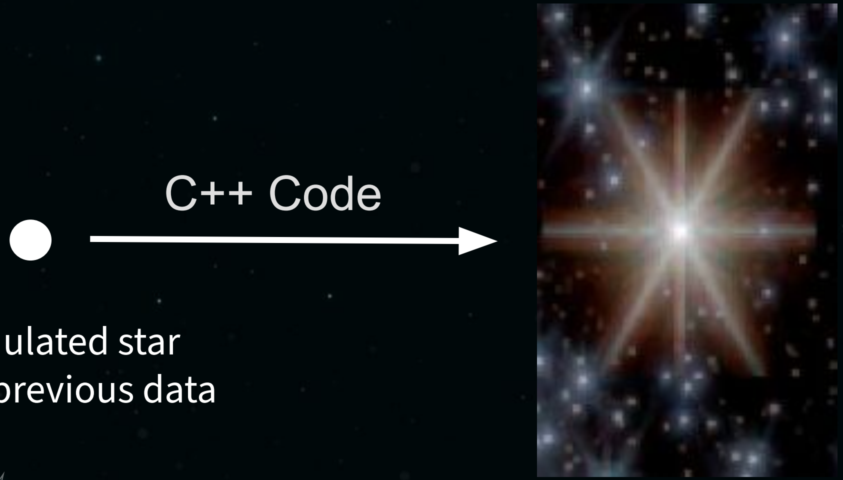
Paolo Bianchini & Pietro Cardini (2021)

02

From simulation to images

How to create realistic images ?

- Images as seen by **JWST** using **C++ code** made in collaboration with **P. Bianchini**
- **Code** : from positions, velocities, masses, luminosities… → “realistic” **images** (color, optical distortion…)

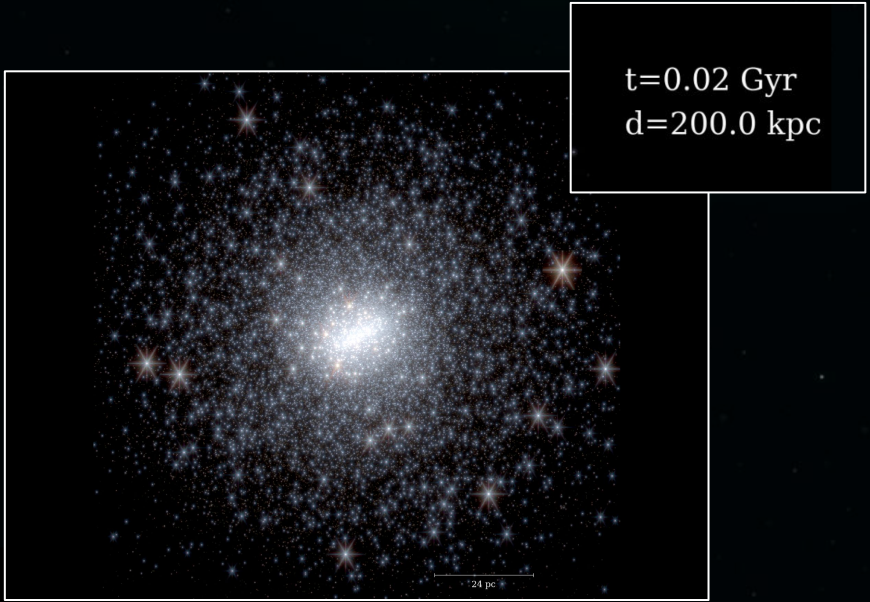


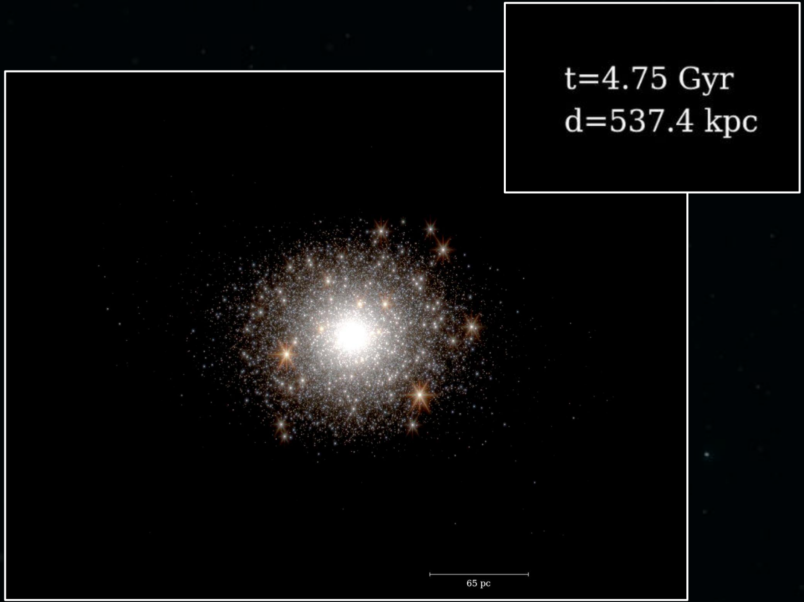
Simulated star
from previous data

JWST simulation

First images of the globular cluster

- Images combine observations in **3 filters** of JWST on 3 different wavelengths domains
- We can adjust parameters such as **distance**, **angle** or **age**

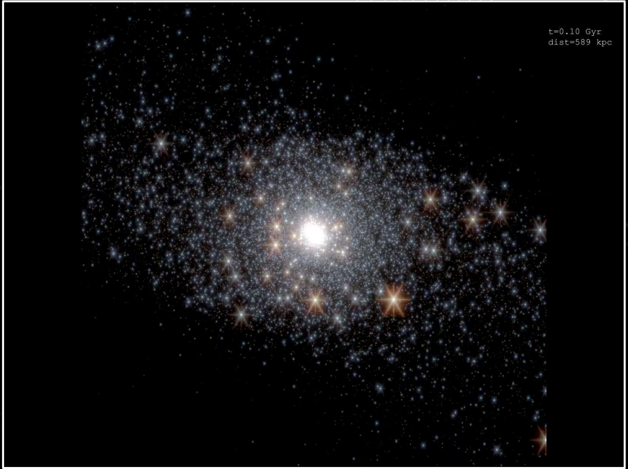




Toward a video

- Necessity to understand how to make the video **fluid** and **esthetic** (distance step, time step..)

- Understand wich **phenomena** we want to **highlight** with our videos



Challenges

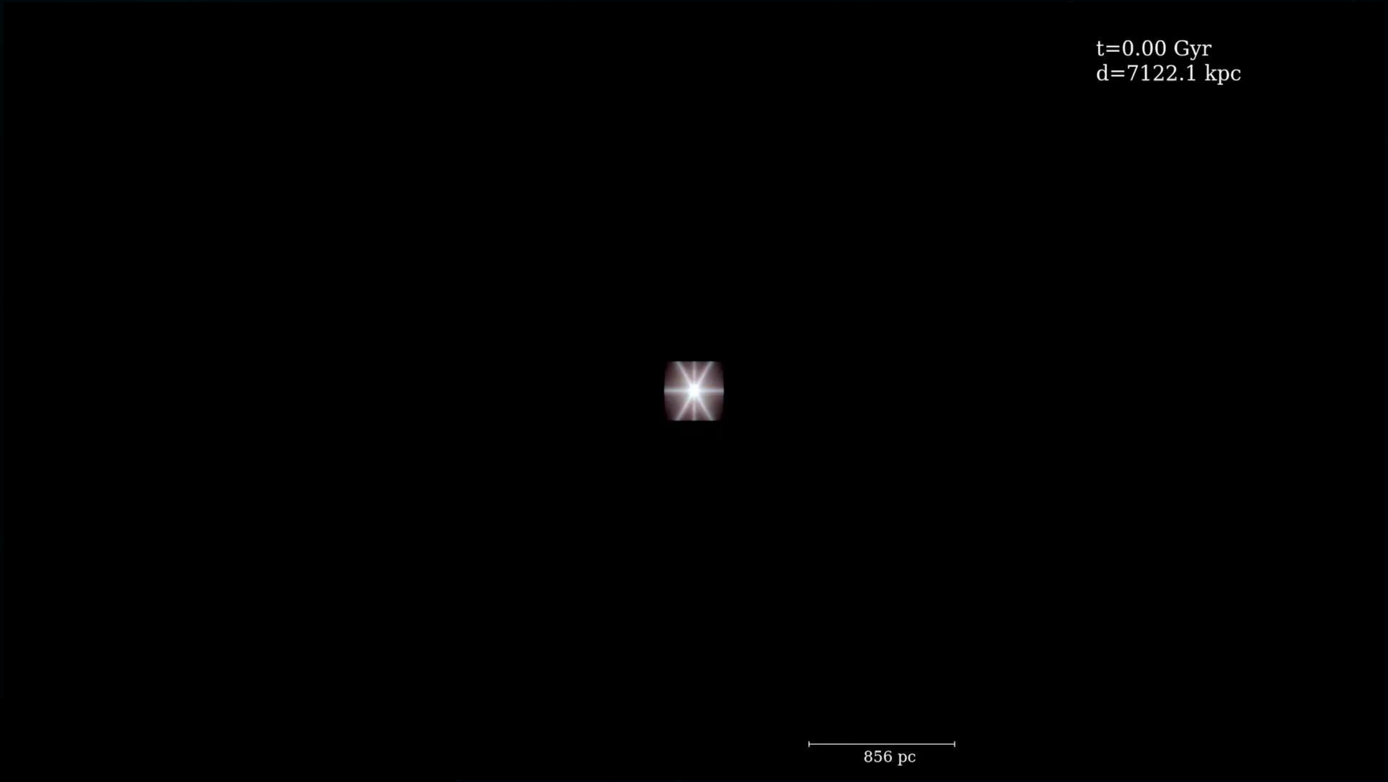
- Deal with **2 terabytes** of data (the **greatest** globular cluster simulation)
- The huge **runtime** of our C++ code to give us a **single** image
  ↳ **10 minutes** per image and **18 images per second** of video
    ↳ 5000 images → **34 days** of running code !
- How can we manage this problem ?

Answers

- Use the **HPC** to deal with big data and can run 24h/24

- Make the code **parallel** (simultaneous task on several CPUs)
    ↳ **40** CPUs → **1 day** of running code

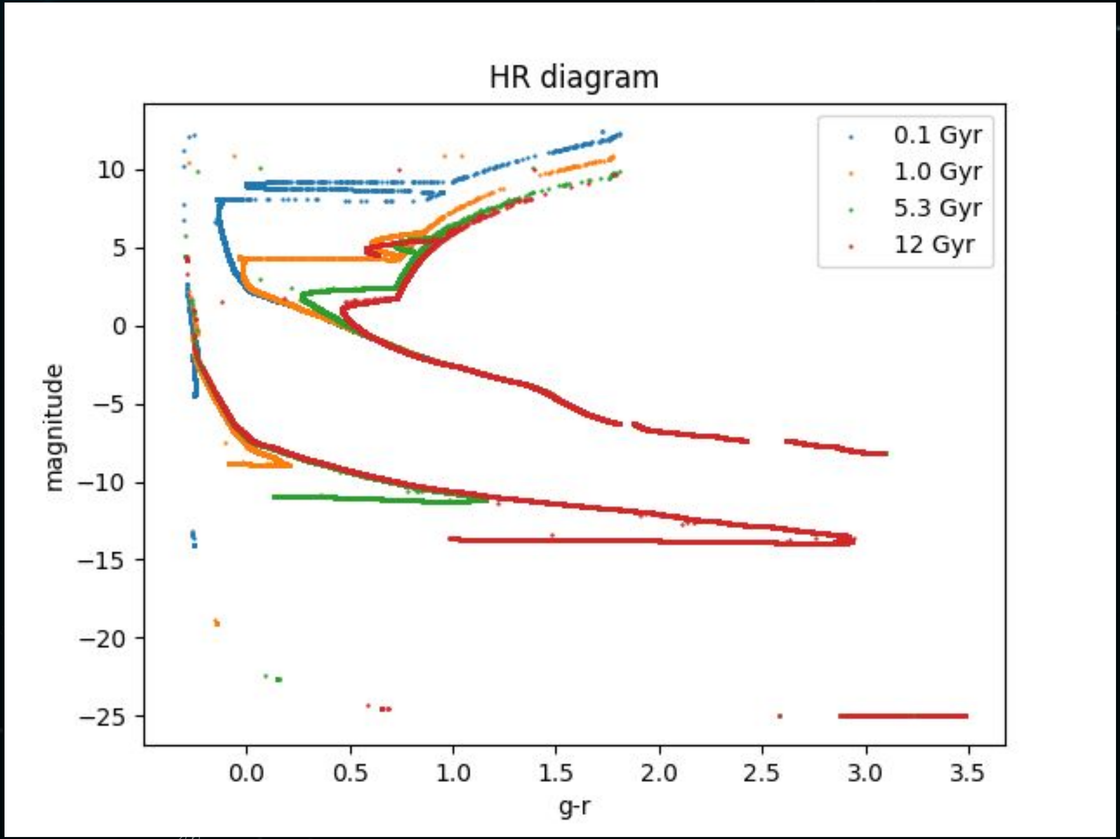
The final video



Conclusion

- Globular clusters are **complex** dynamical systems and need **new tools** to be understood
- We worked on visualisation and “**realization**” processes
- Our images **contribute** to the beginning of a **machine learning** project

Annex : Stars evolution in a HR diagram



Annex : Virial theorem

$$2K + W = 0$$

Kinetic energy

Gravitational potential

If $W \searrow$ due to escaping stars $\Rightarrow$ $K \nearrow$ to respect virial theorem

$\Rightarrow$ The cluster size increases

Annex : JWST filters