Towards a comprehensive understanding of the origin of globular clusters and of their multiple stellar populations

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(multiple populations)
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(cosmological context)
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Raffaele Pascale (INAF-OAS, Italy)
Joki Rosdahl (CRAL, Lyon, France)
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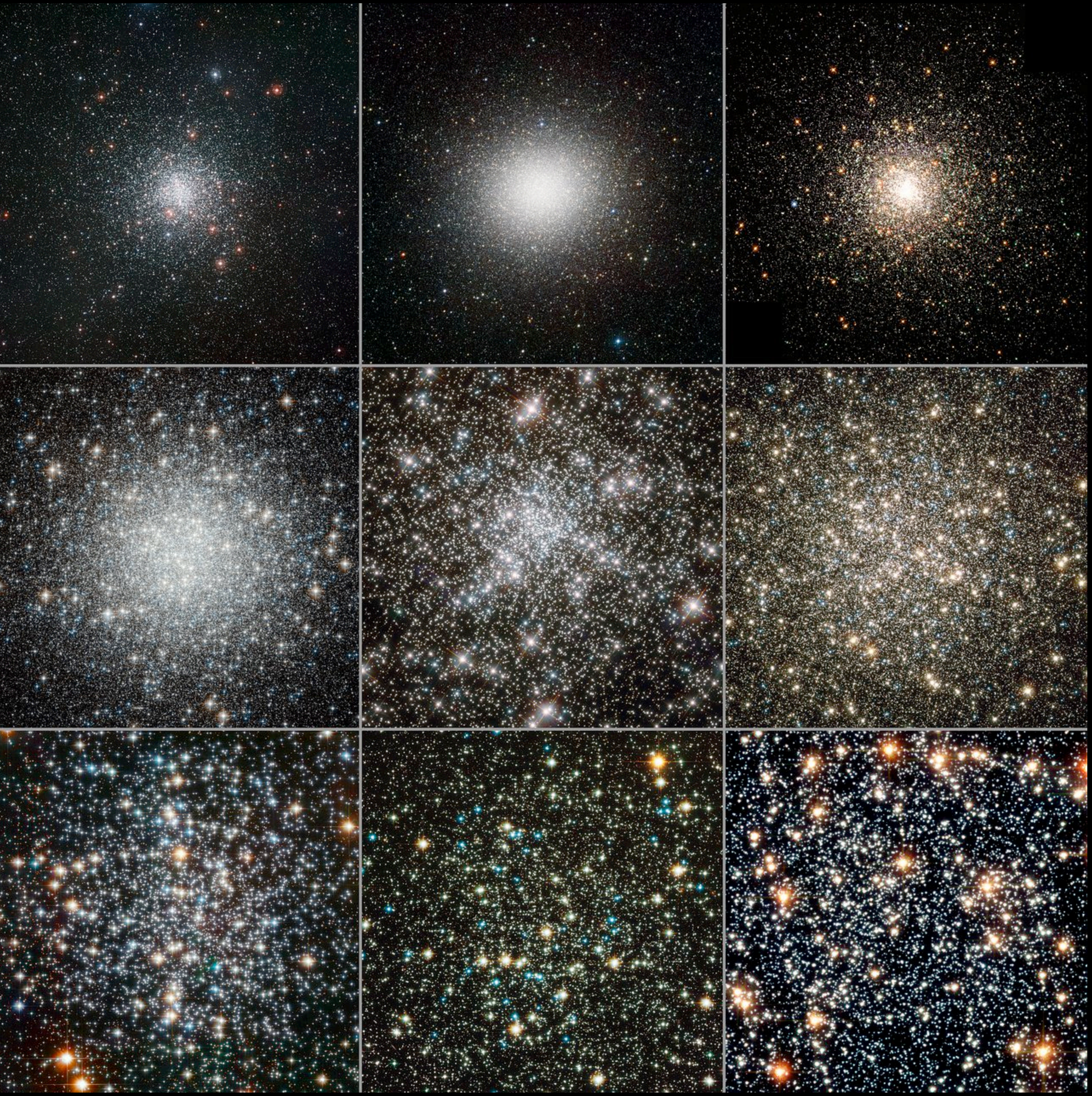
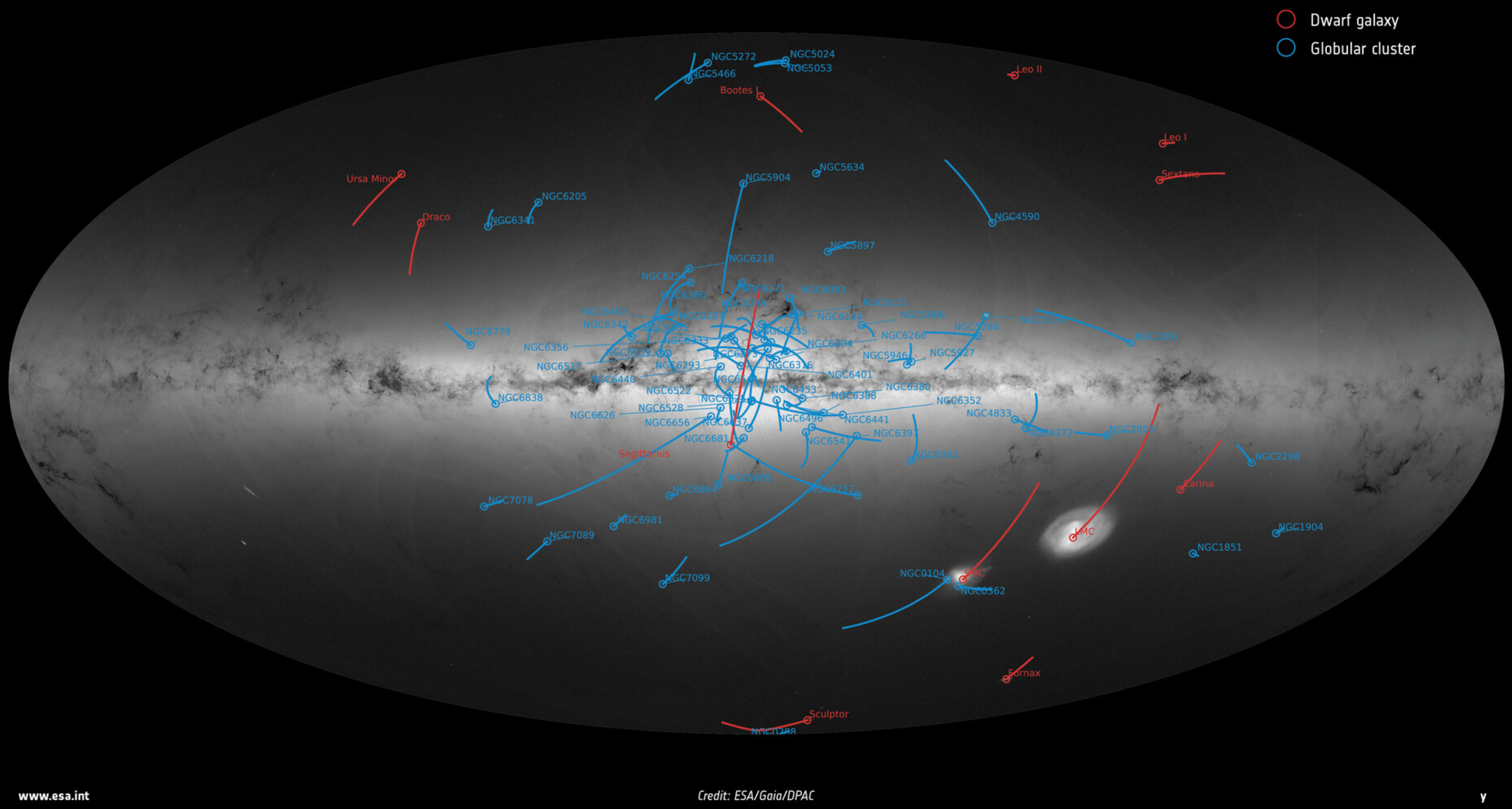
Massimo Meneghetti (INAF-OAS, Italy)

IFPU Focus Week - Galactic Archaeology: reconstructing the history of galaxies

Globular clusters

Top row: Messier 4 (ESO), Omega Centauri (ESO), Messier 80 (Hubble)
Middle row: Messier 53 (Hubble), NGC 6752 (Hubble), Messier 13 (Hubble)
Bottom row: Messier 4 (Hubble), NGC 288 (Hubble), 47 Tucanae (Hubble)

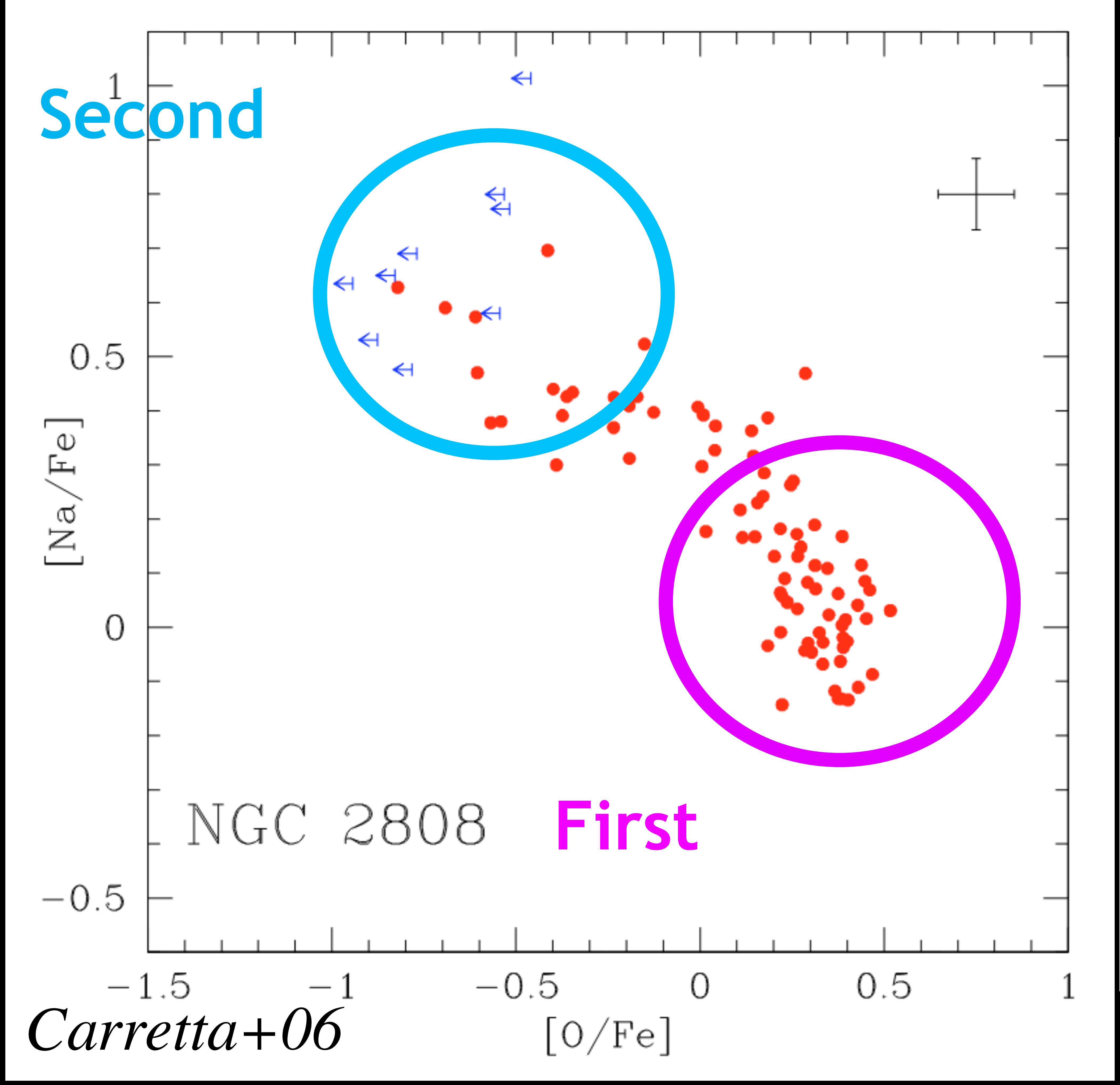




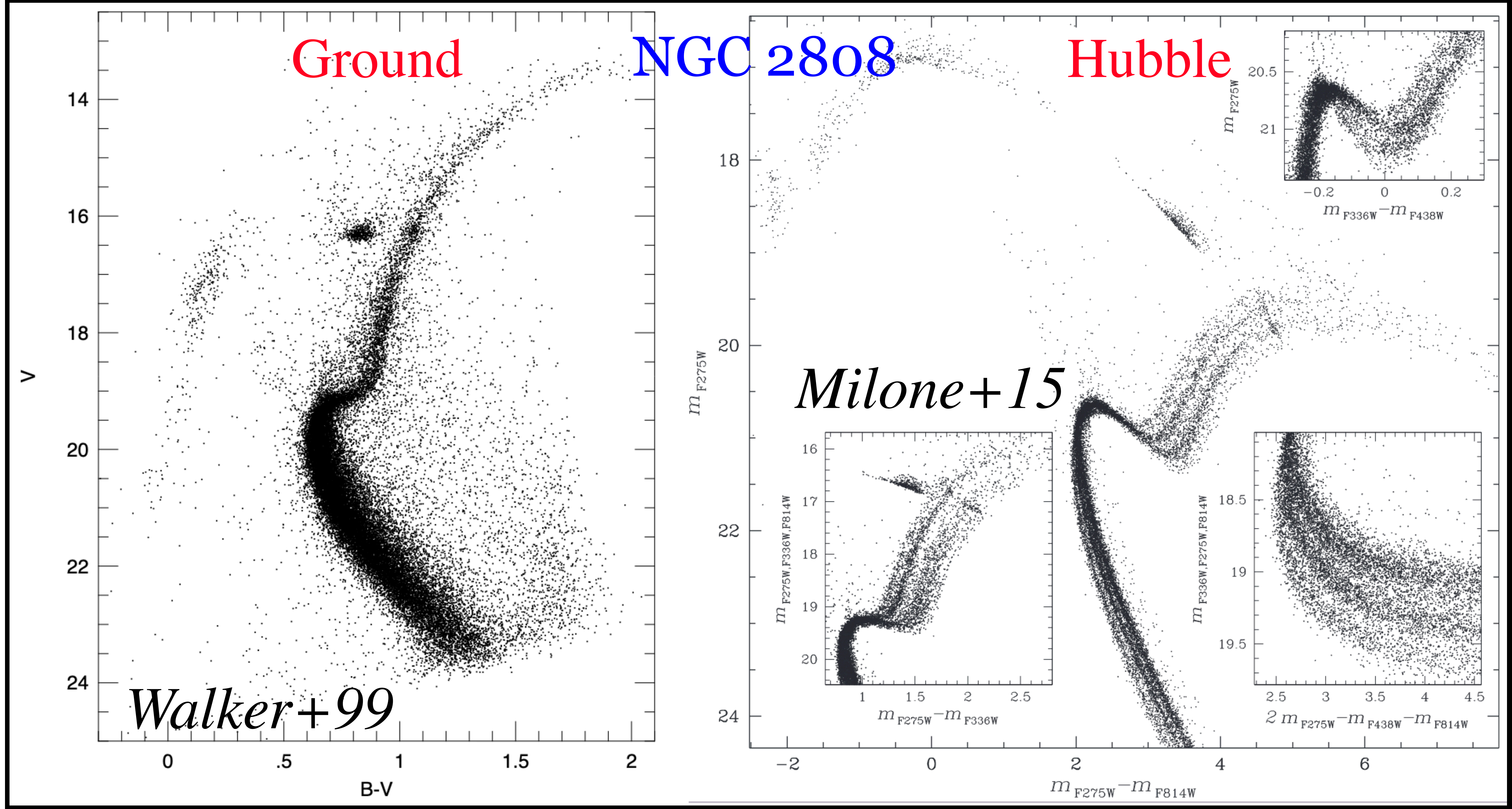
- ★ old: GGC age of ~10-12 Gyr
- ★ compact: $R_h \sim$ a few pc
- ★ typical mass $\sim 2 \times 10^5 M_\odot$
- ★ almost mono-metallic $\sigma_{[Fe/H]} < 0.05$ dex
- ★ show **anti-correlations among light elements** abundances (C, N, O, Na, Al, Mg)

Multiple stellar populations

From spectroscopy…



…and photometry.



Globular clusters Abundance pattern

"Anomalous"
2nd gen pop.

~60-70 %

"Normal"
1st gen pop.

~30-40%

Carretta et al.
(2010)

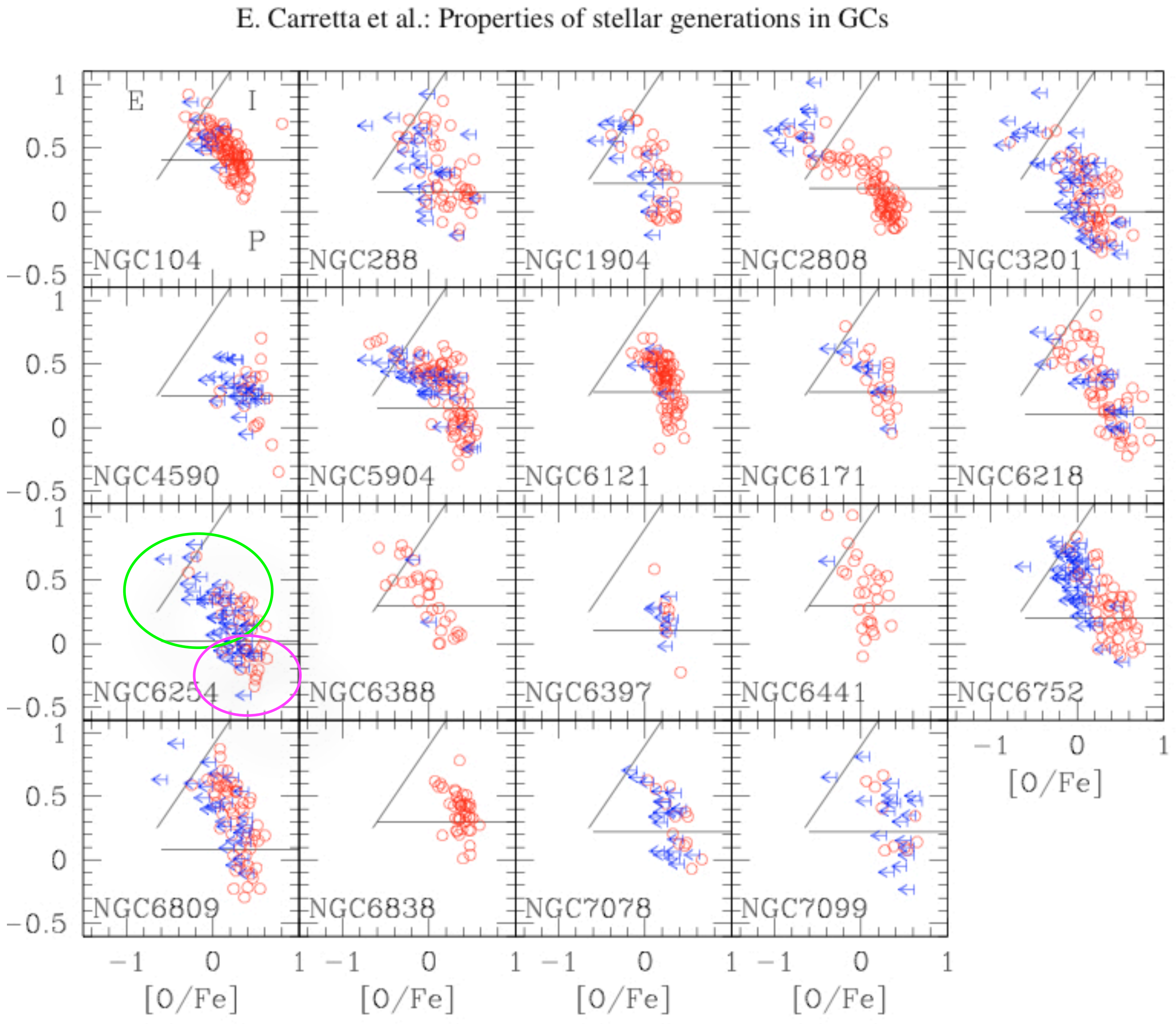


Fig. 1. Summary of the Na-O anticorrelation observed in the 19 GCs of our sample. Arrows indicate upper limits in O abundances. The two lines in each panel separate the primordial component (located in the Na-poor/O-rich region), the Na-rich/O-poor extreme component, and the intermediate component in-between (called P, E, and I, respectively as indicated only in the first panel). See Sect. 2 for details.

Globular clusters Abundance pattern

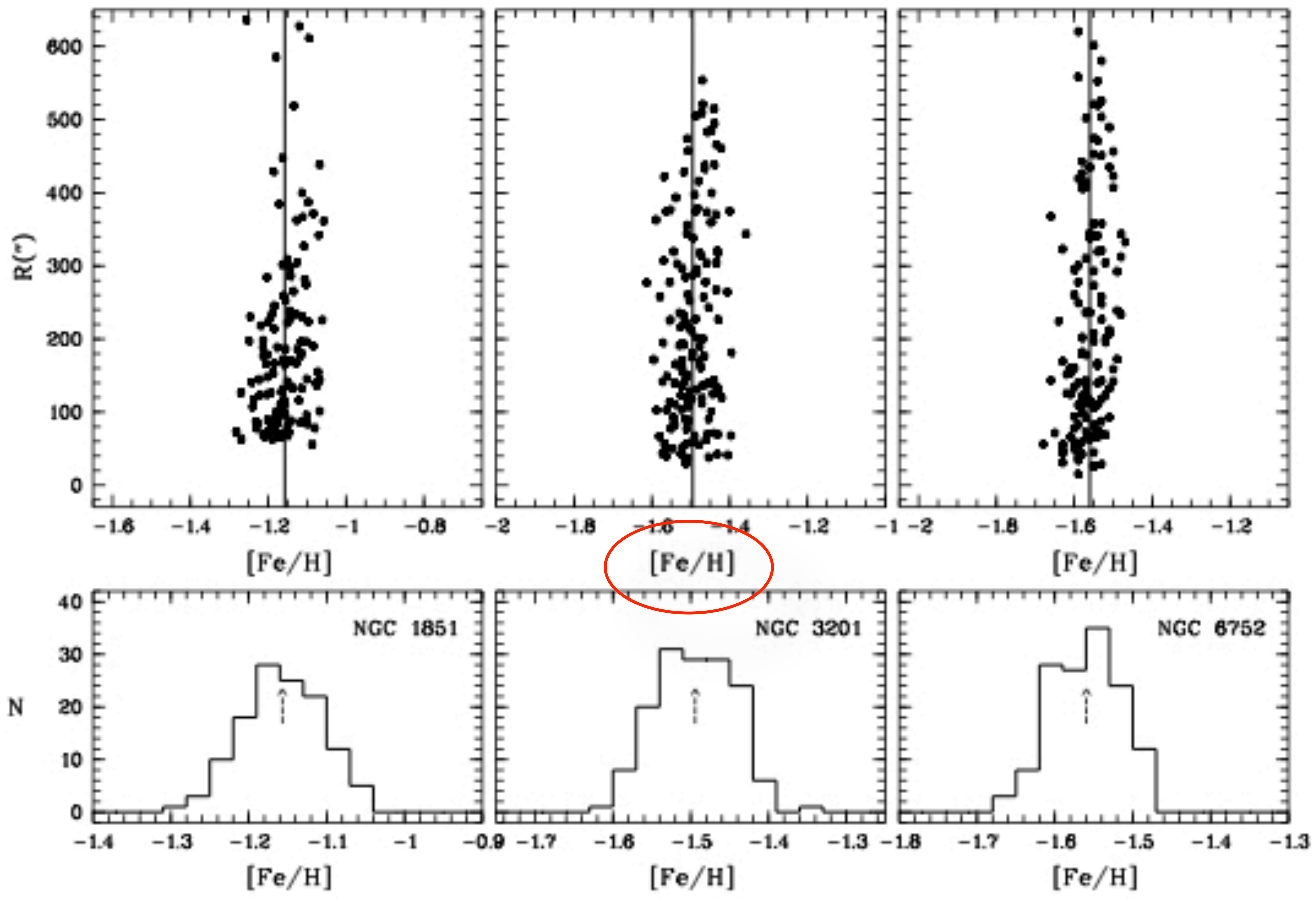
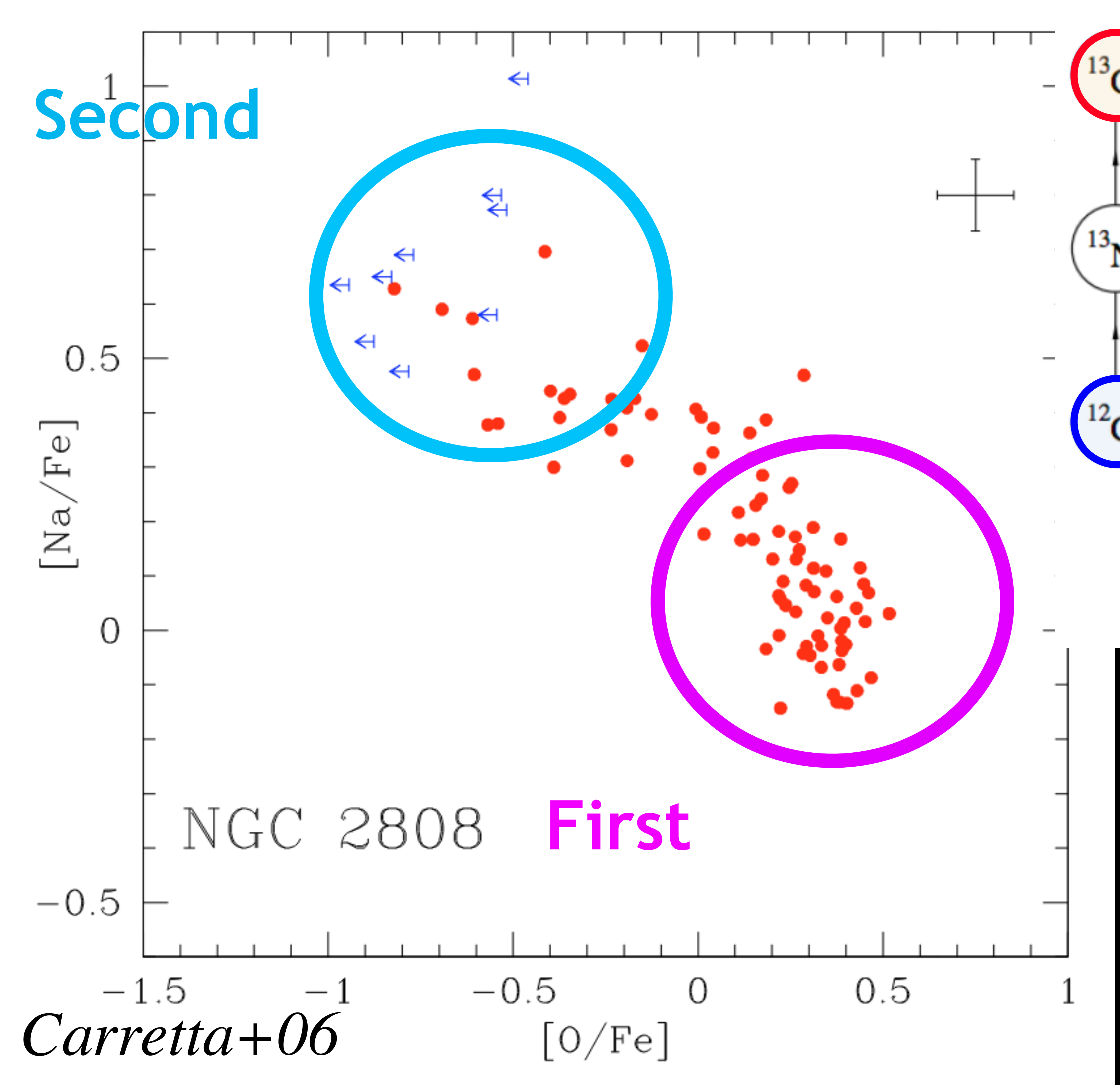


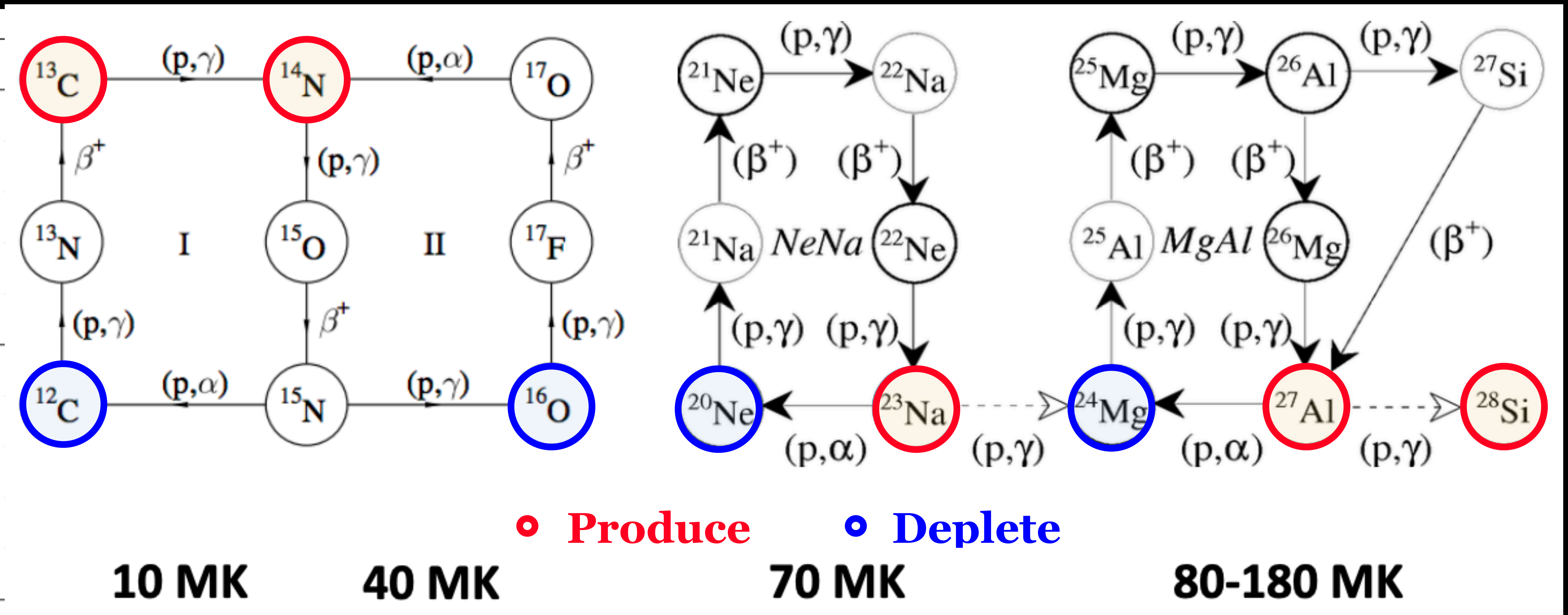
Fig. 1. Upper panels show $[Fe/H]_I$ - PRAD diagrams and lower panels are metallicity distribution histograms in NGC 1851, NGC 3201, and NGC 6752. The continuous lines and arrows mark the mean values of $[Fe/H]_I$ in the upper and lower panels, respectively.

Kravtsov (2013)

Multiple stellar populations

H-burning happening at high temperature





First generation → Second generation

Globular cluster formation

- Main formation scenarios proposed to explain chemical anomalies in MPs:

  -AGB (e.g. D'Ercole+2008)

  -Fast rotating Massive stars (Decressin+2010)

  -Massive interacting binaries (de Mink+09)

  -Very supermassive stars (Denissenkov & Hartwick 2014)

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AGB scenario

Second generation (SG) stars form from the AGB ejecta of the first generation (FG)

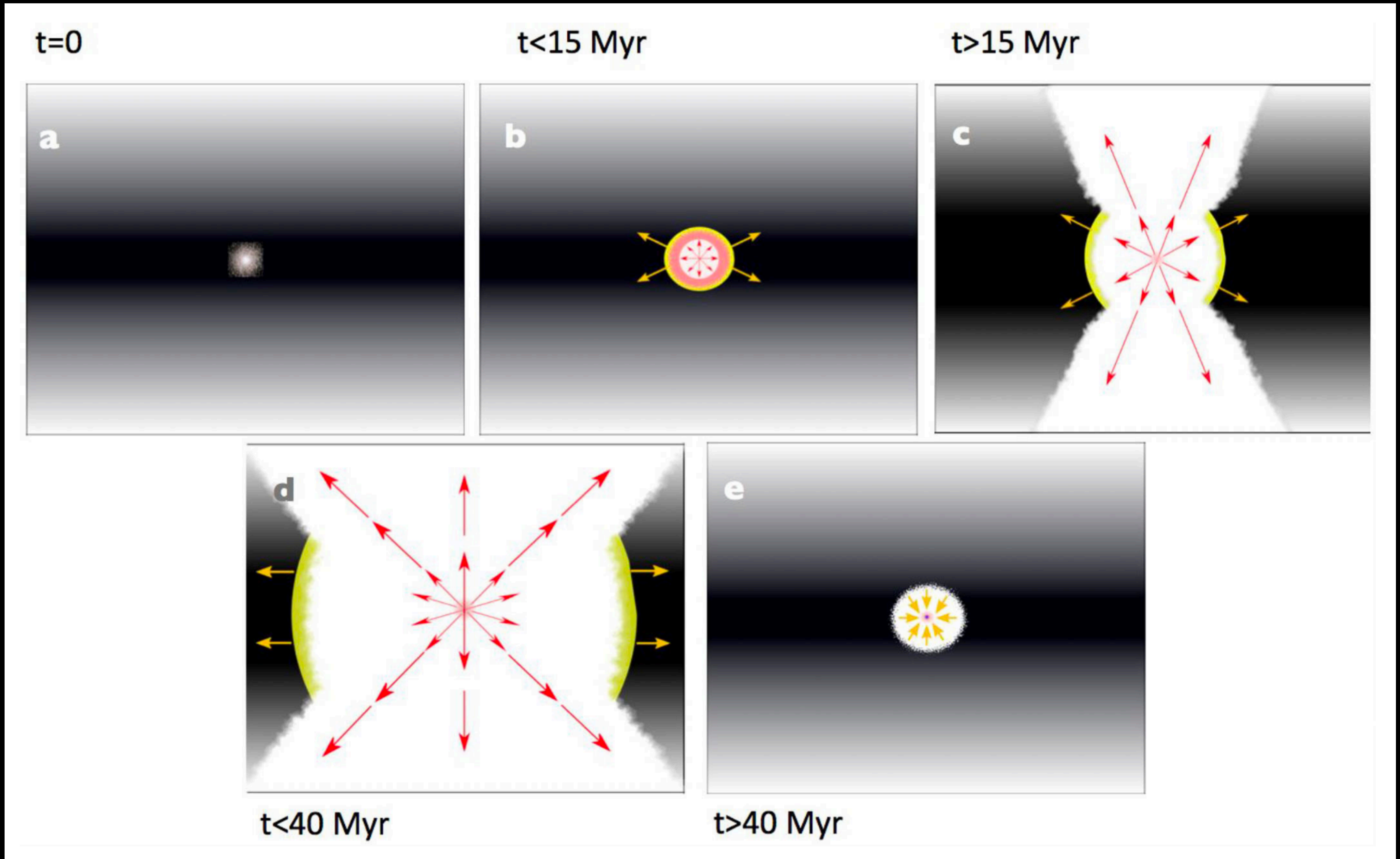
BUT

With AGB ejecta only, SG abundance patterns are not reproduced

↓

dilution with pristine gas

SG stars abundances ranges from those of FG ones to pure AGB yields



D'Ercole+16

AGB scenario

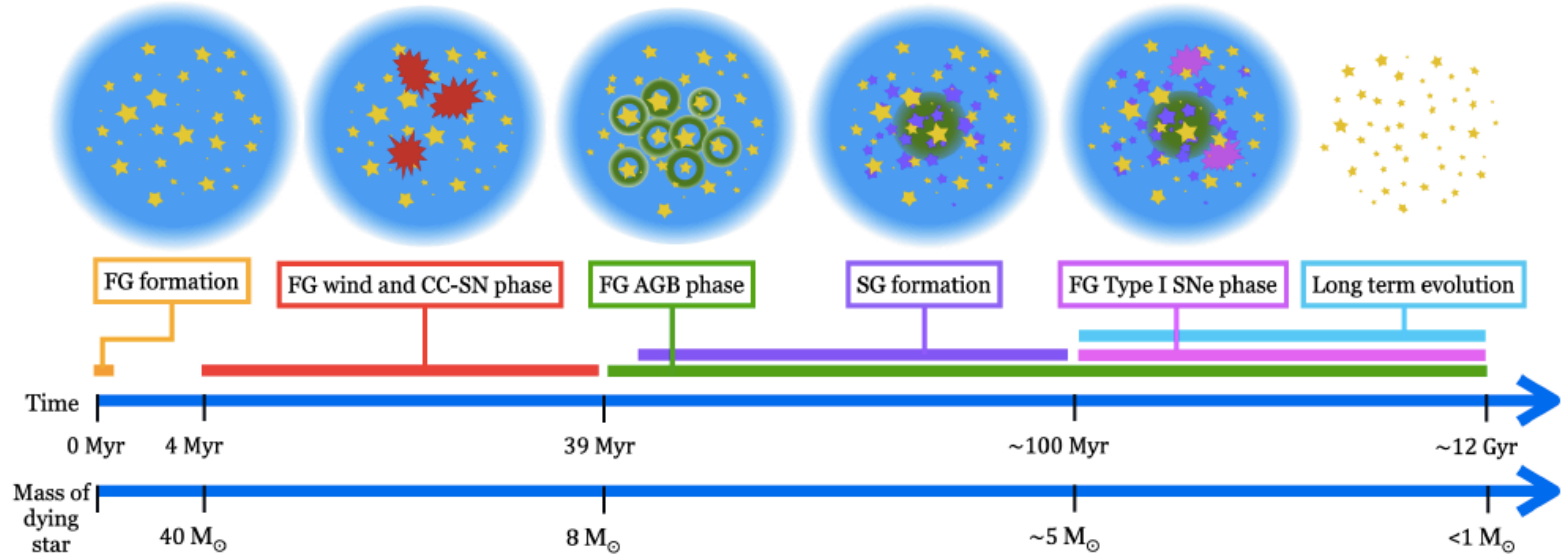


Figure 3.3: *Schematic visualization of the different phases of the formation of MPs in a GC in the AGB scenario, highlighting the main feedback sources in action as a function of time.*

E. Lacchin, 2023, PhD Thesis

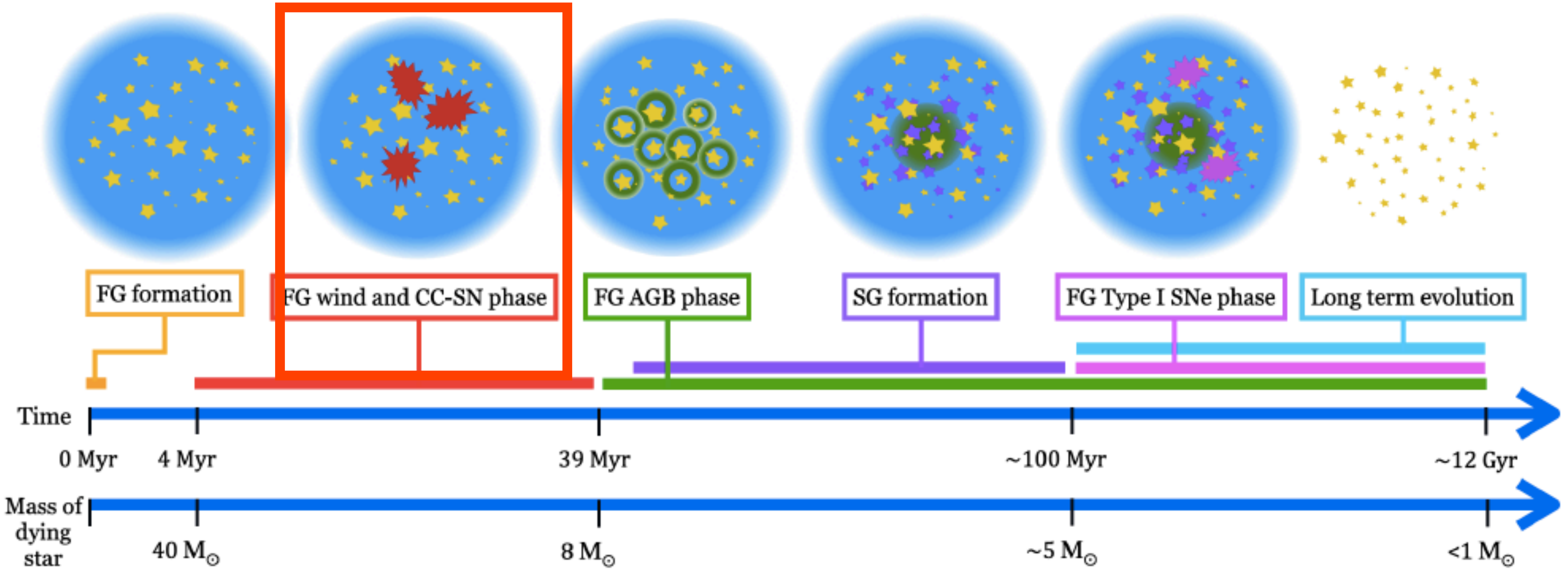
SIMULATING THE AGB SCENARIO

I. Feedback of wind-driven bubbles in star clusters

- We run 3D Adaptive Mesh Refinement (AMR) simulations to study the feedback from Massive stars in a proto-GC of mass ~ 10^7 Msun
- Code used: RAMSES (Teyssier 2002)

FC.; Few, C. G.; Romano, D.; D'Ercole, A., 2015, ApJ, 814, L14

AGB scenario



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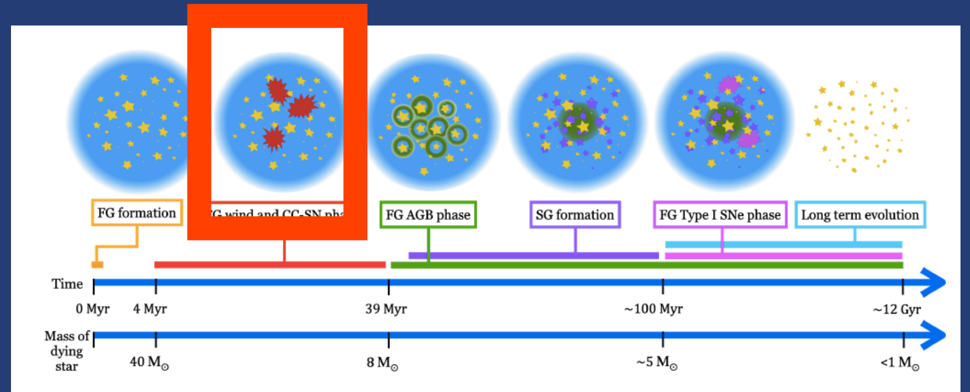
FG -Winds and SNe



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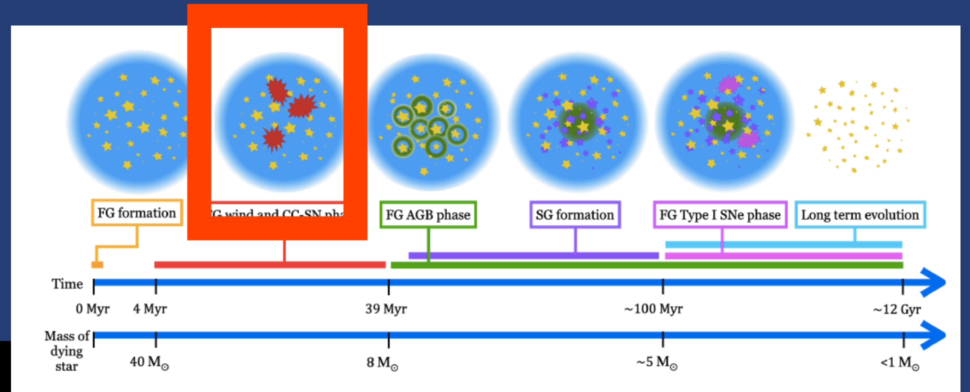

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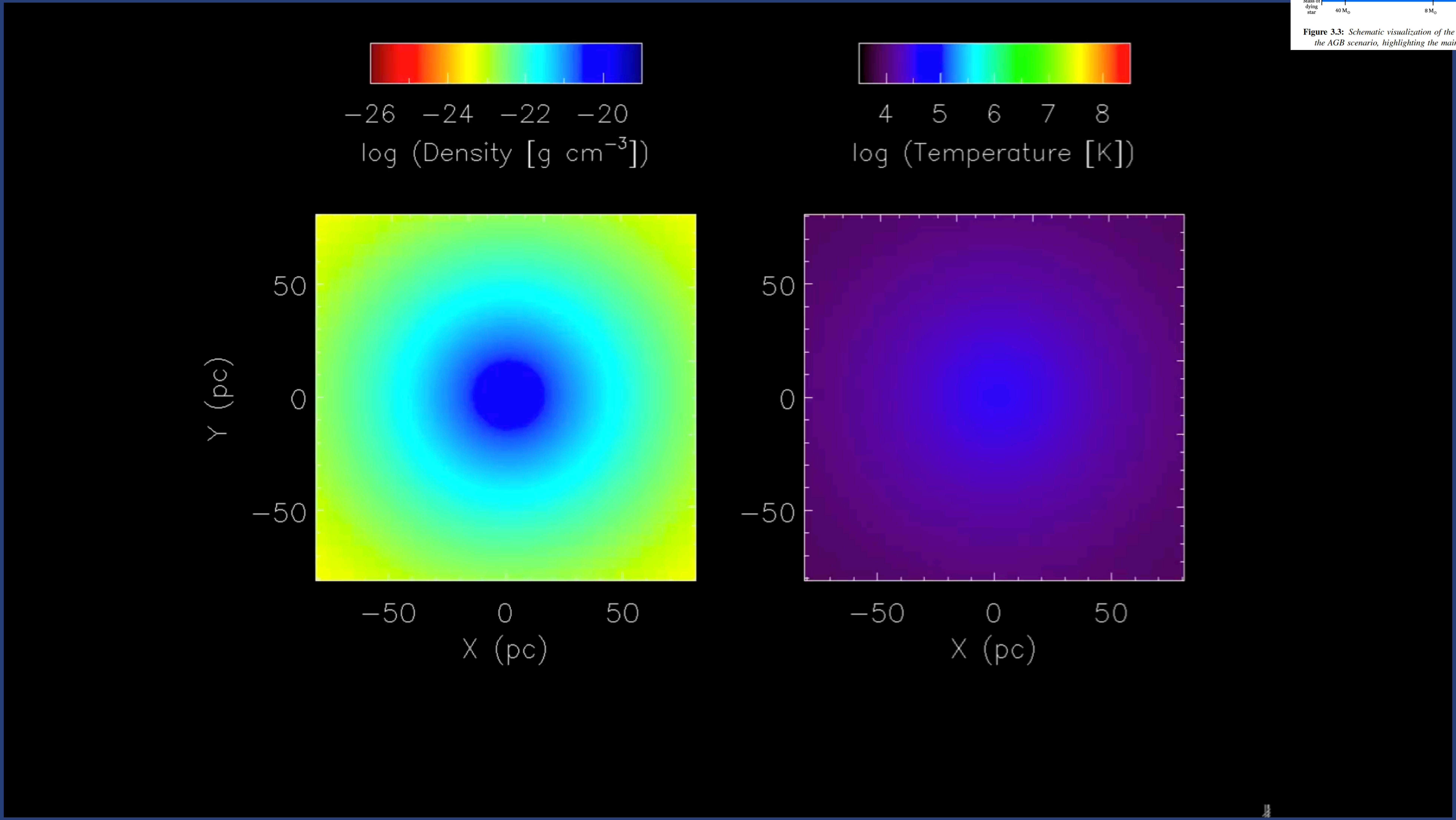

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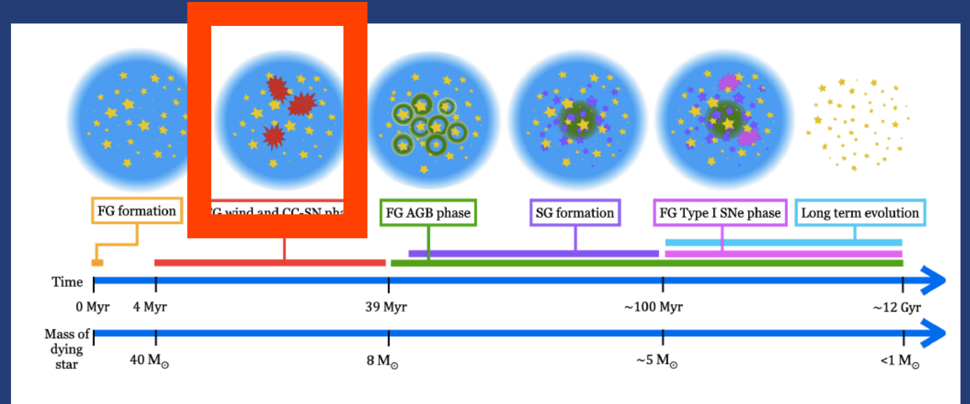
Different feedback schemes



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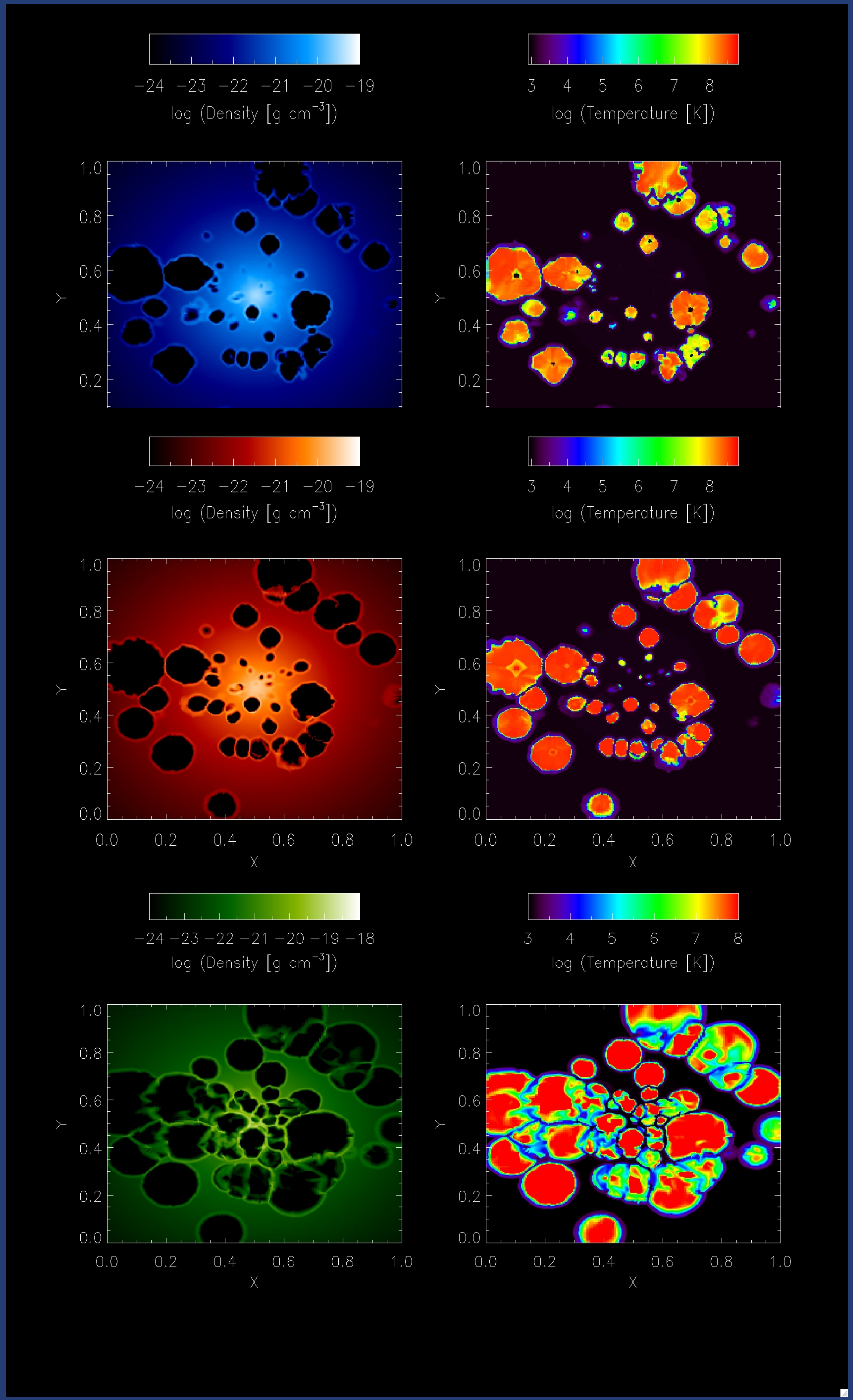


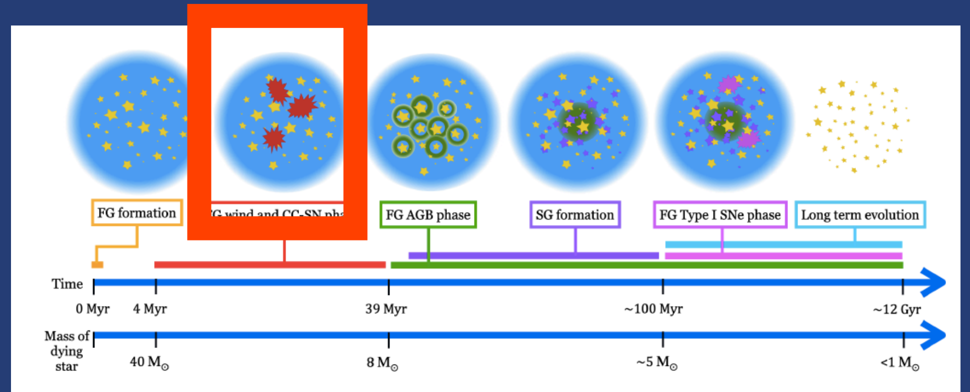
Momentum

Energy

Energy + switch off cooling for σ_{turb}>50 km/s

FC, 2020

Different feedback schemes



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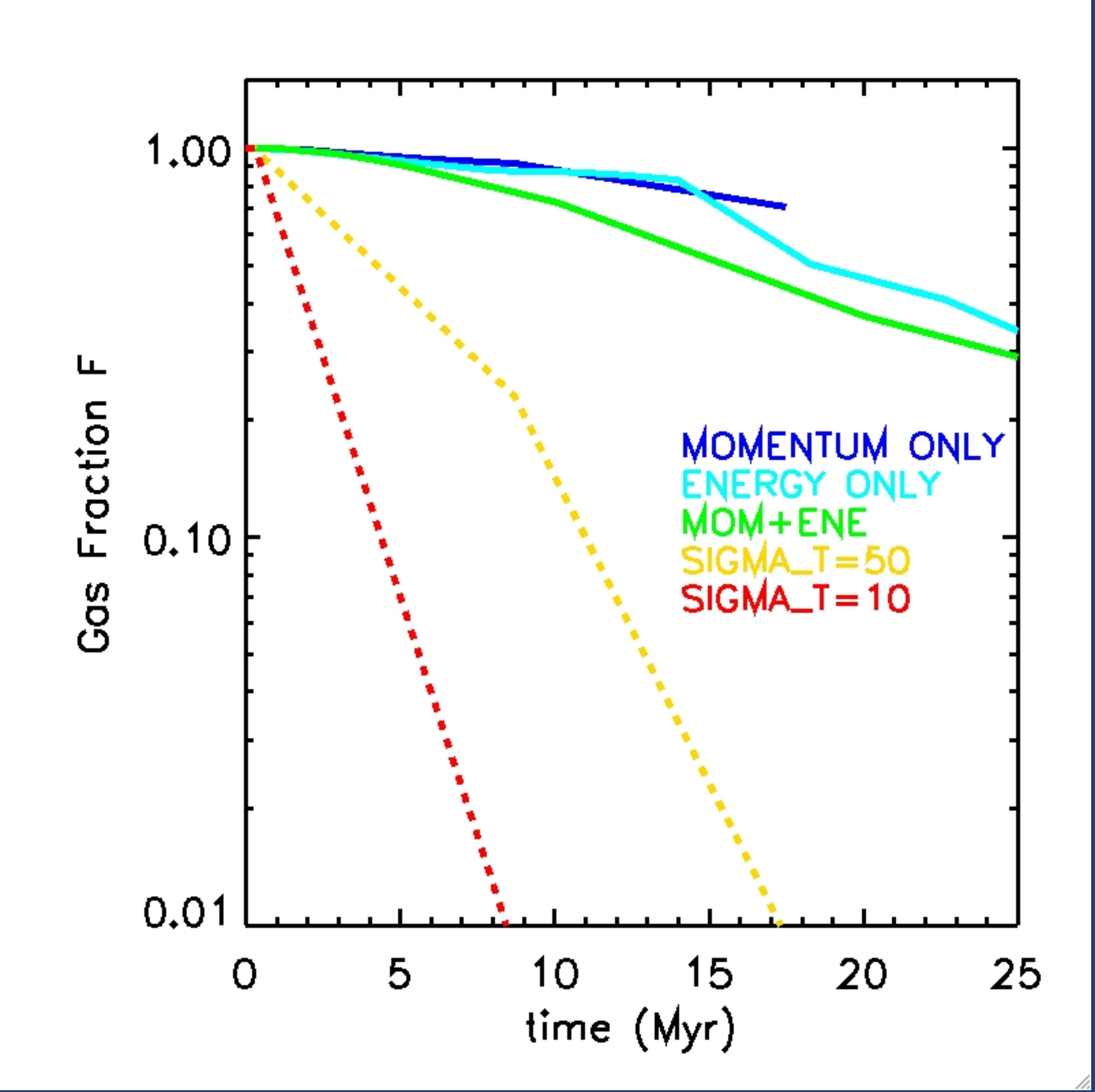
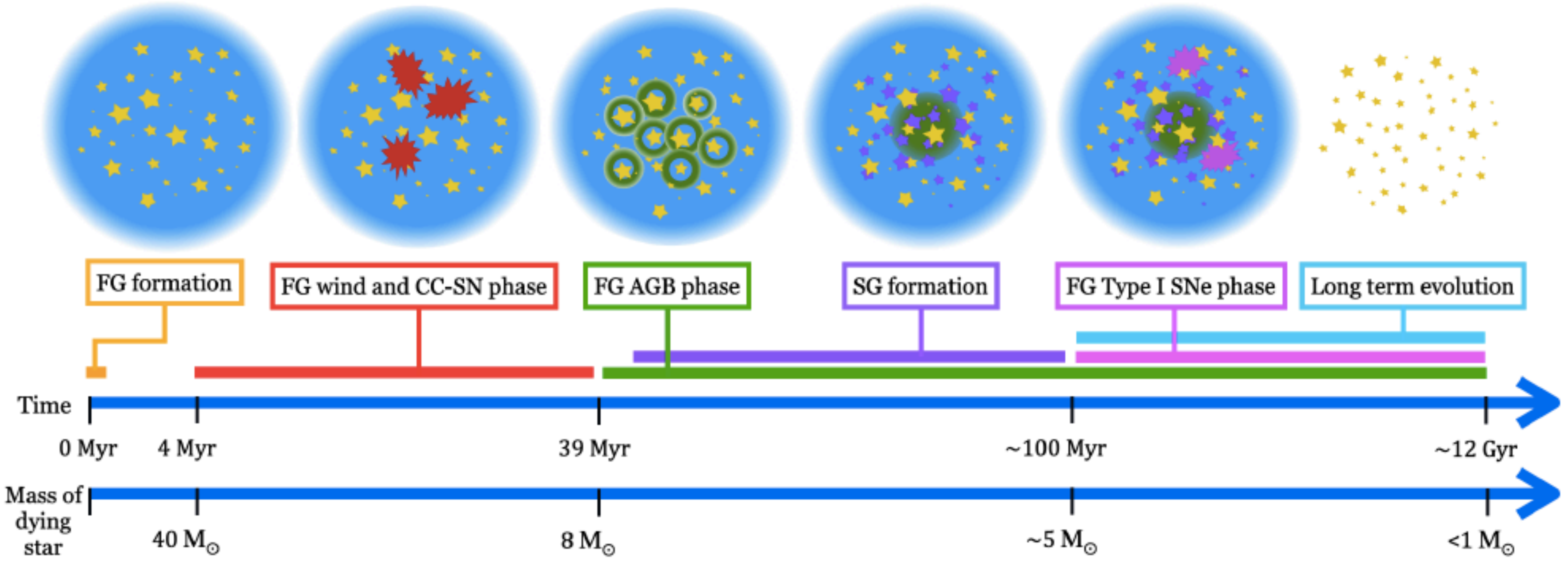


FC et al., 2015, ApJ, 814, L14
FC, 2020

AGB scenario



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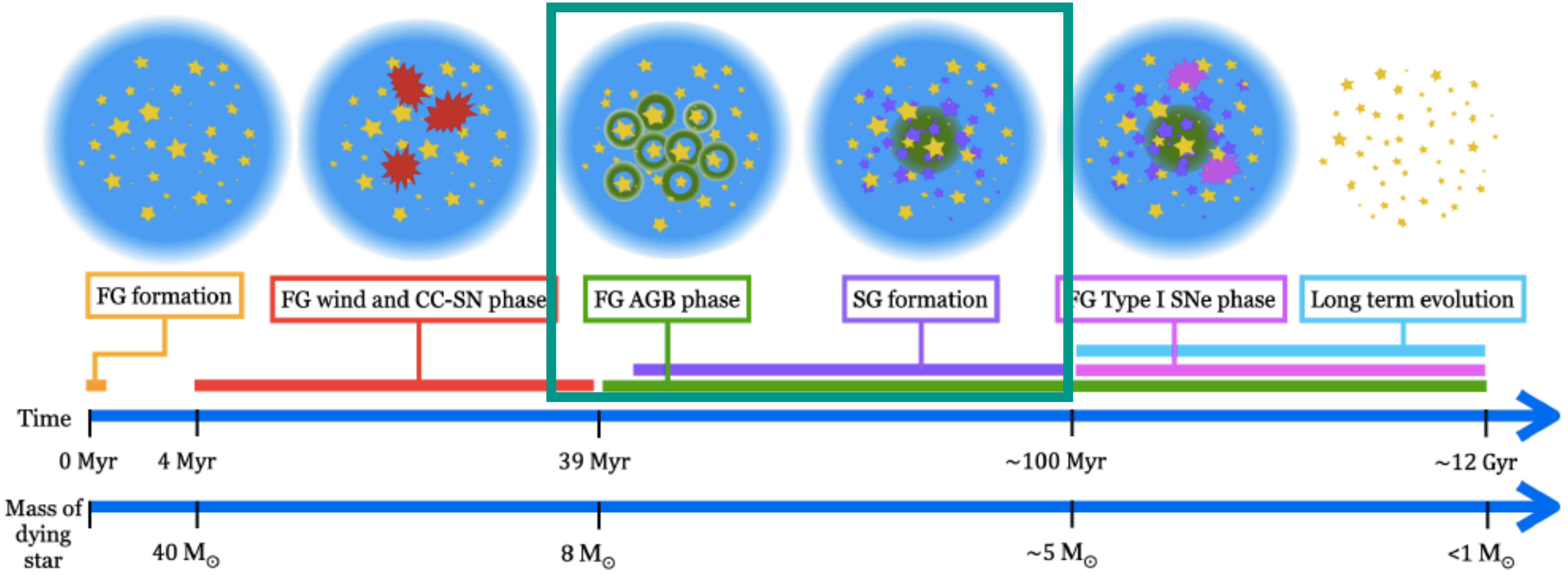

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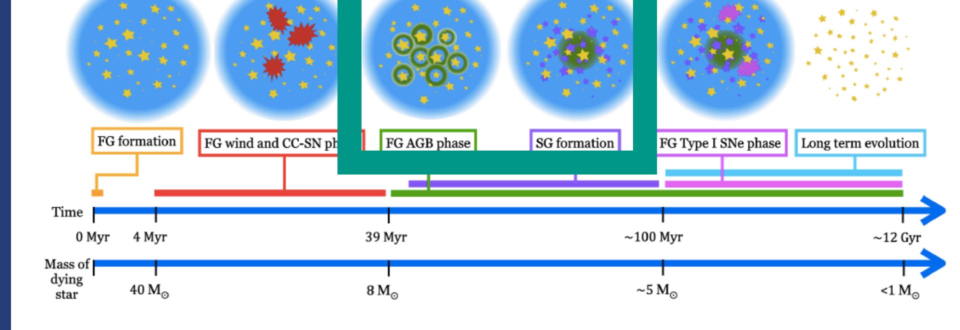
Schematic setup



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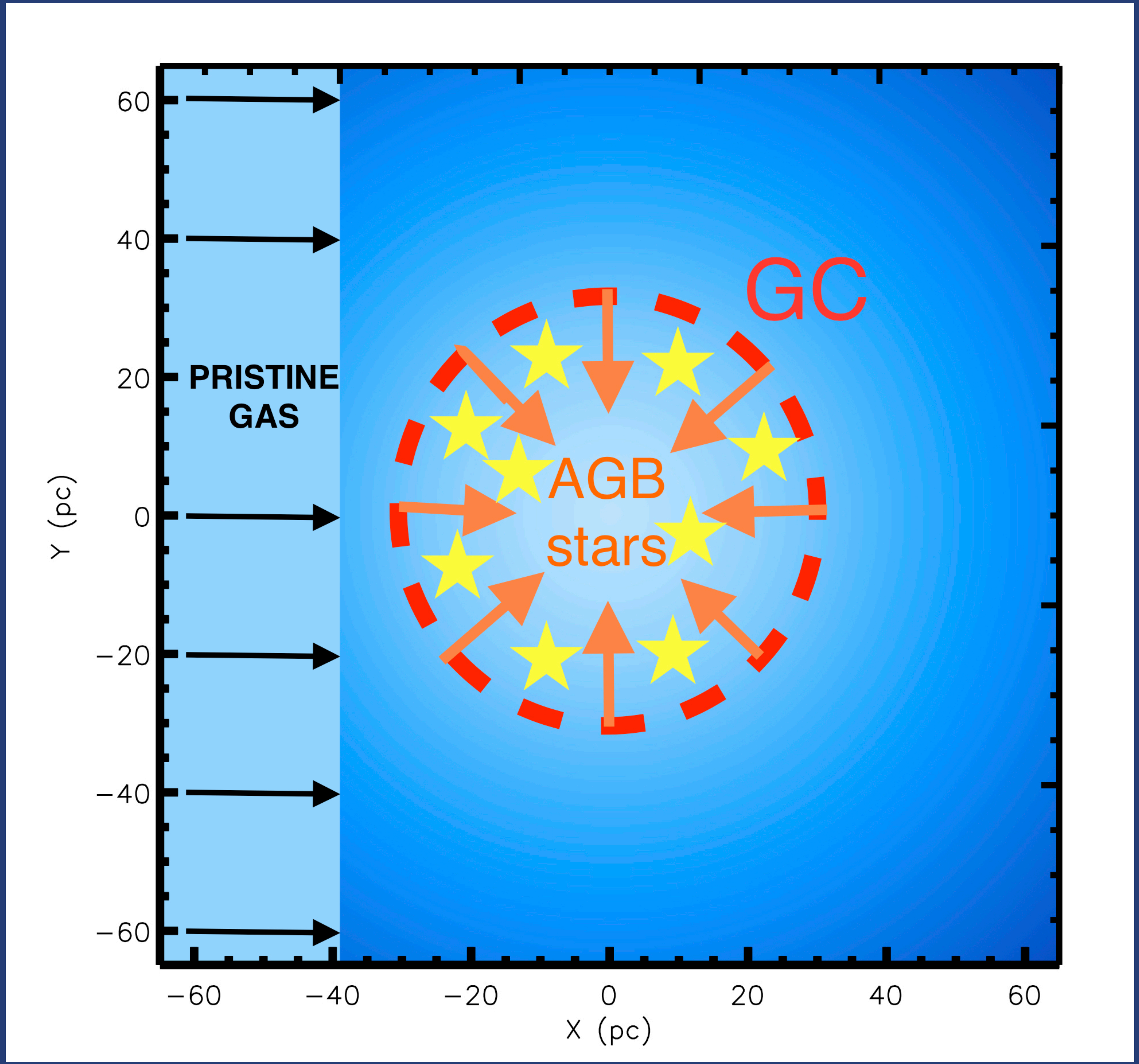
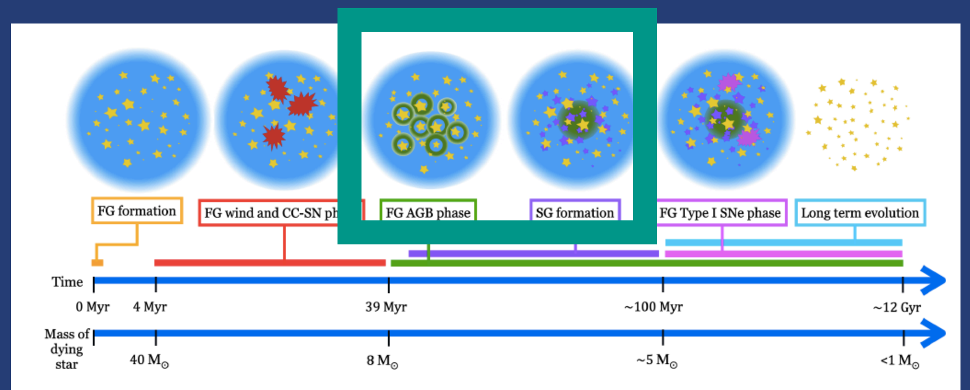


F. Calura et al., 2019

Ingredients



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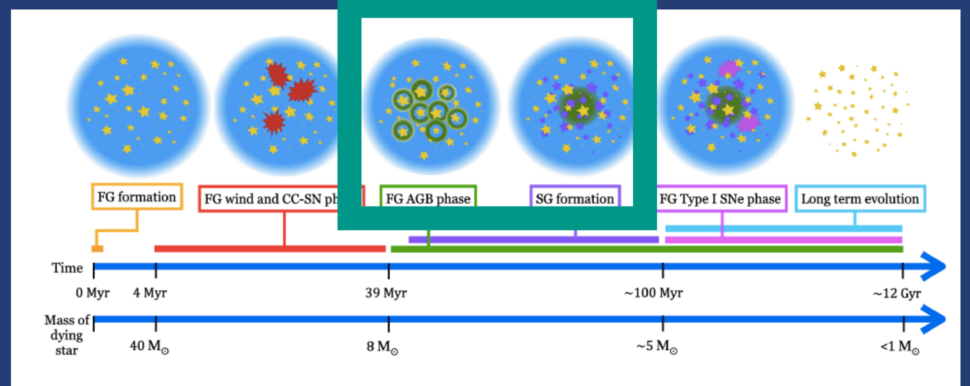
- Gravity of ~ 10^7 M_{sun} FG (static potential)
- SG Star formation
- SG stars dynamics (N-body)
- Infall
- Self-gravity of the gas and SG stars
- Radiative cooling
- Chemical evolution (He, Z)

F. Calura et al., 2019

Results



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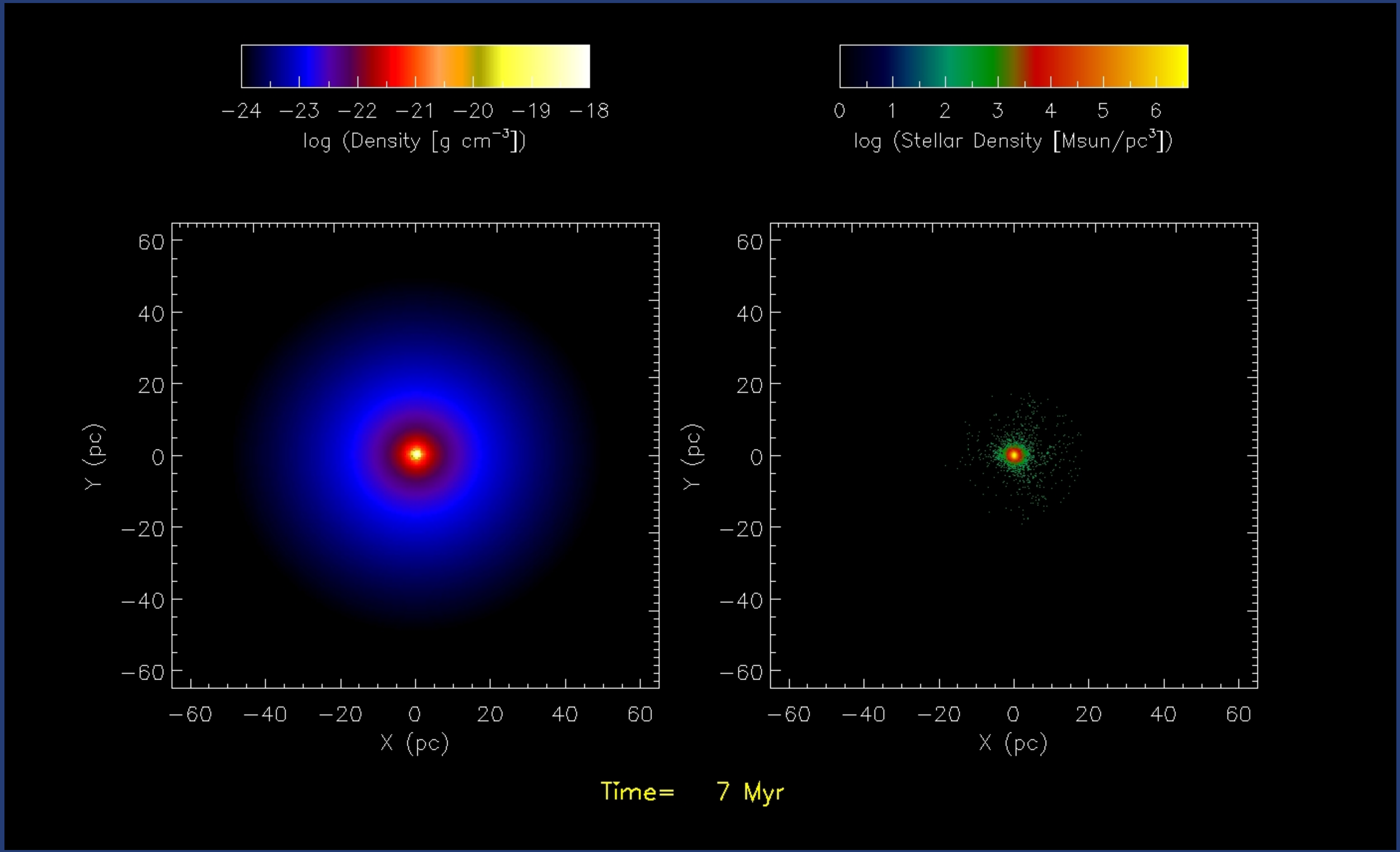
Gas

SG Stars



Infall density: ~1 cm^{-3}

F. Calura et al., 2019

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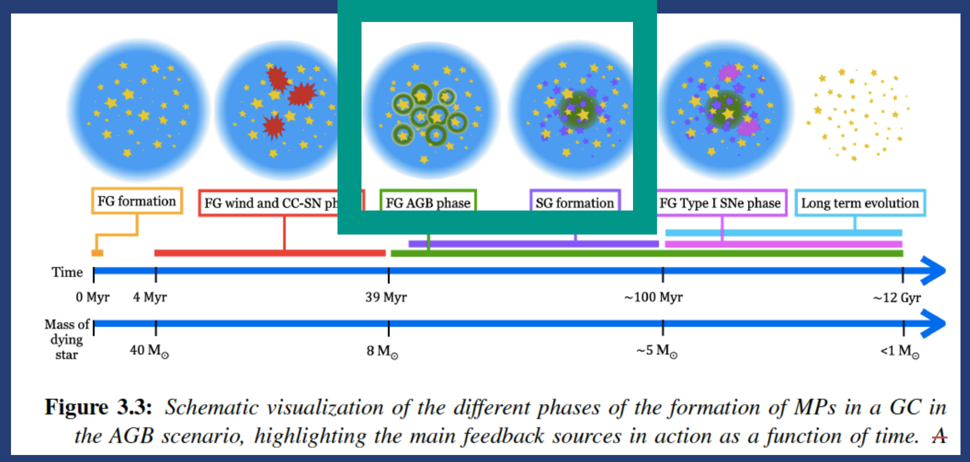

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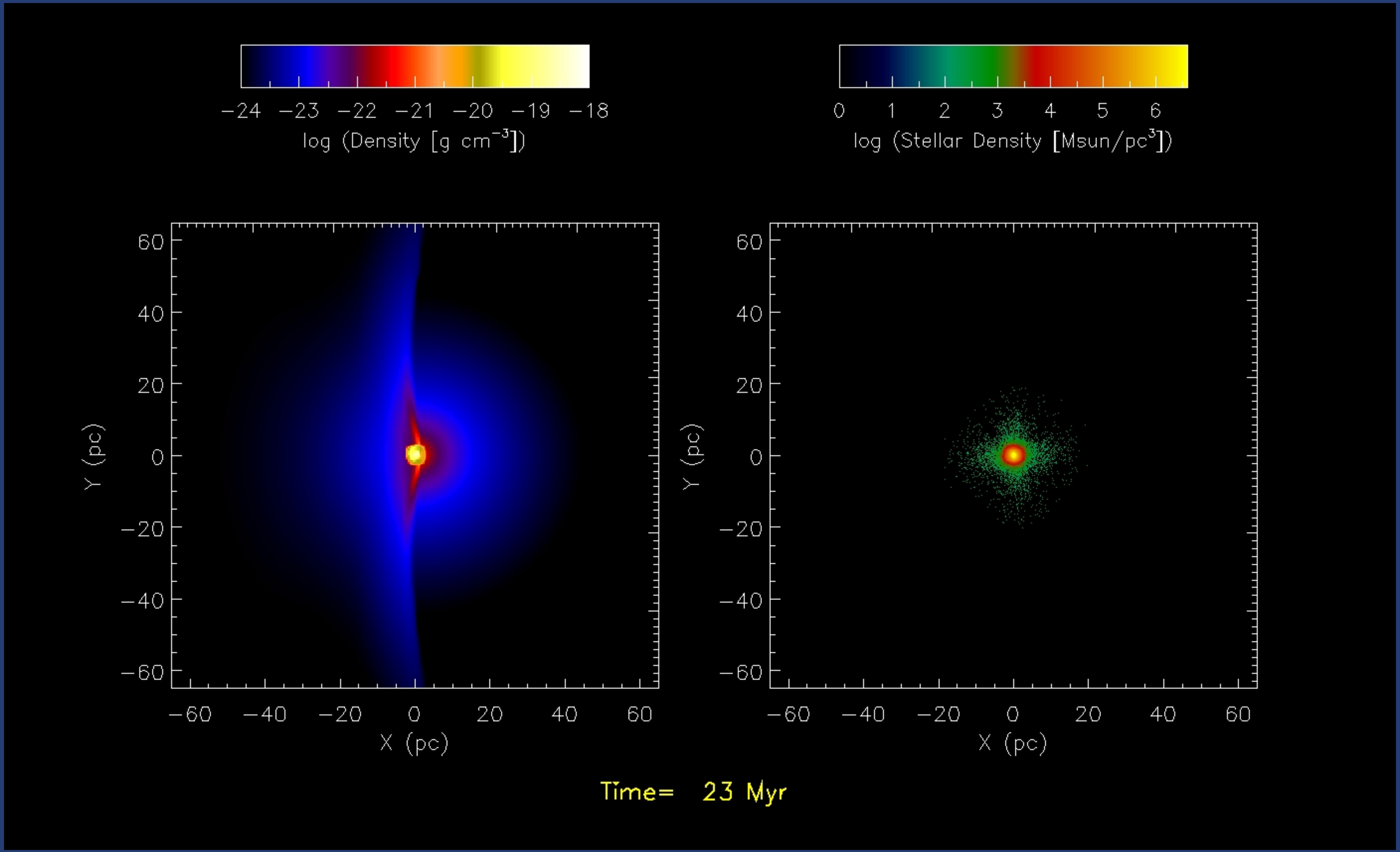

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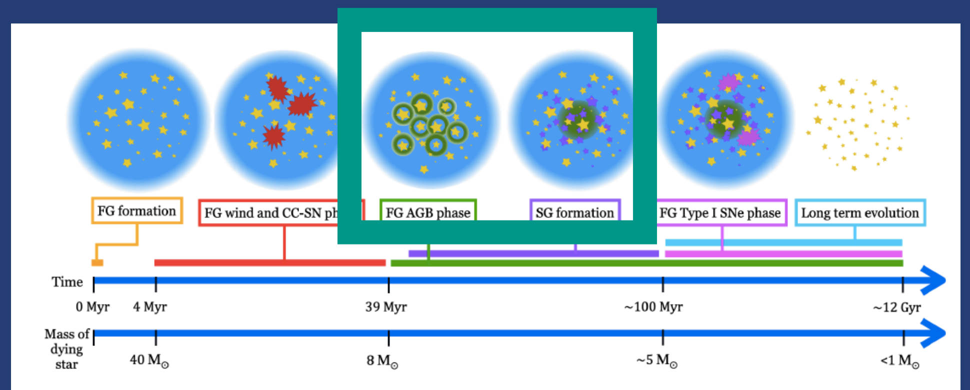

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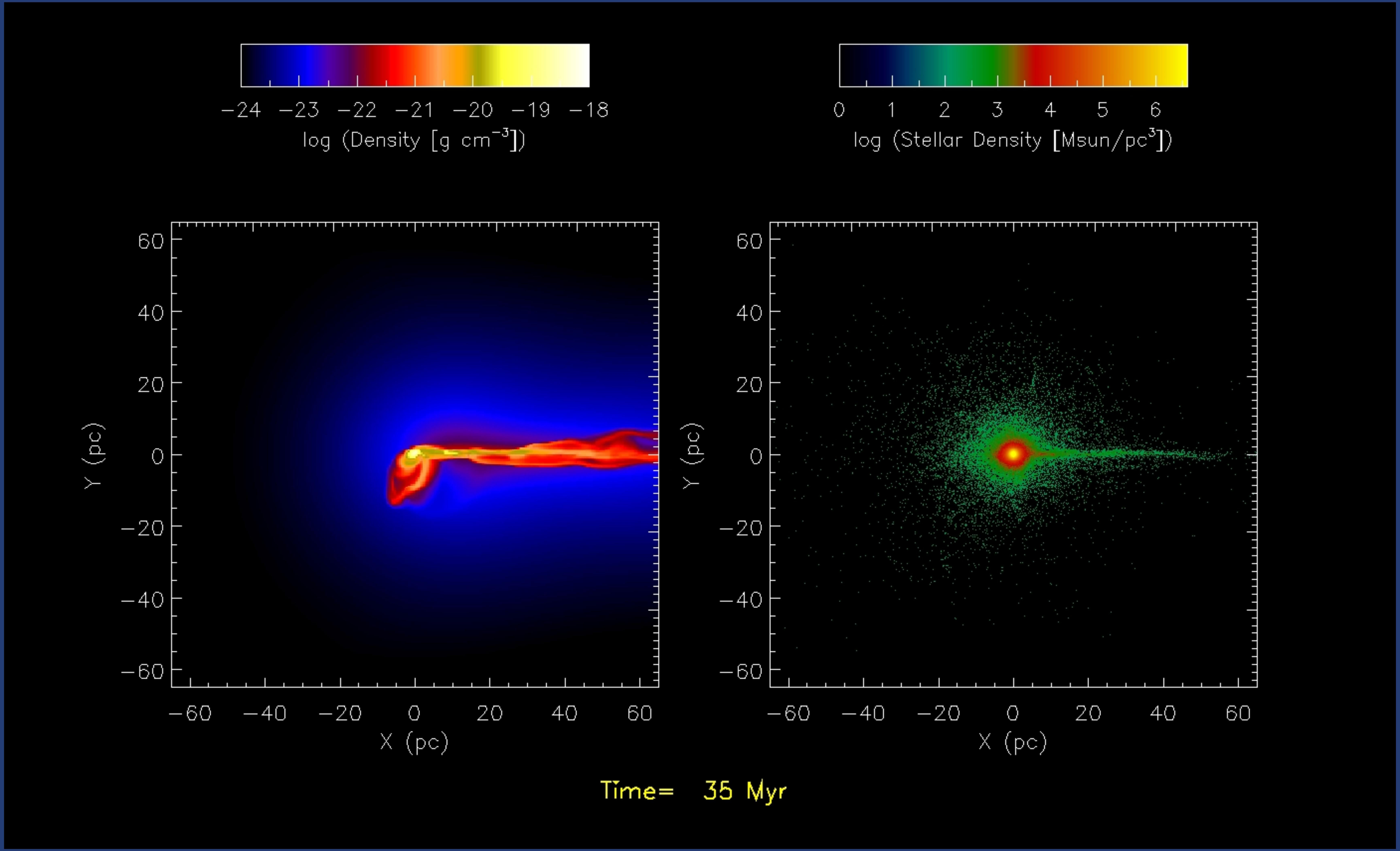
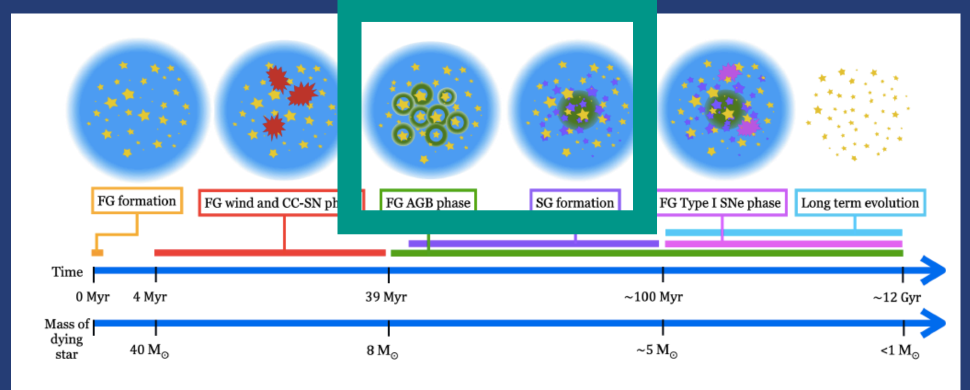


Infall density: ~1 cm^{-3}

F. Calura et al., 2019

He abundances



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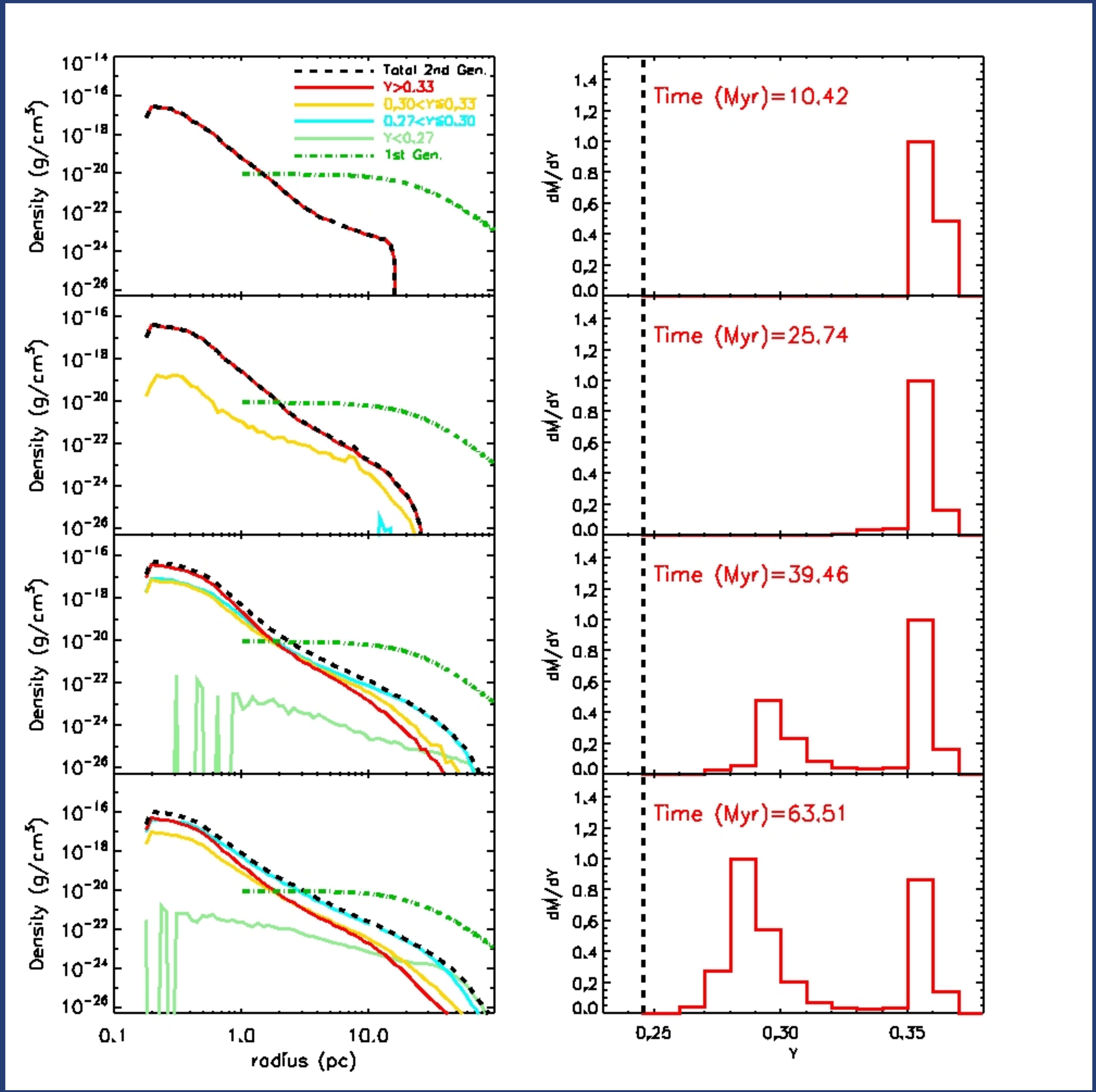
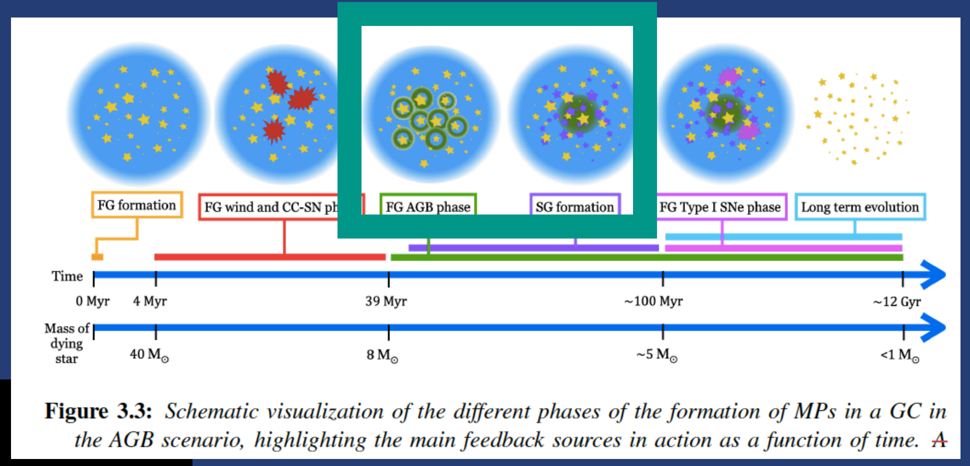


F. Calura et al., 2019

Denser gas infall



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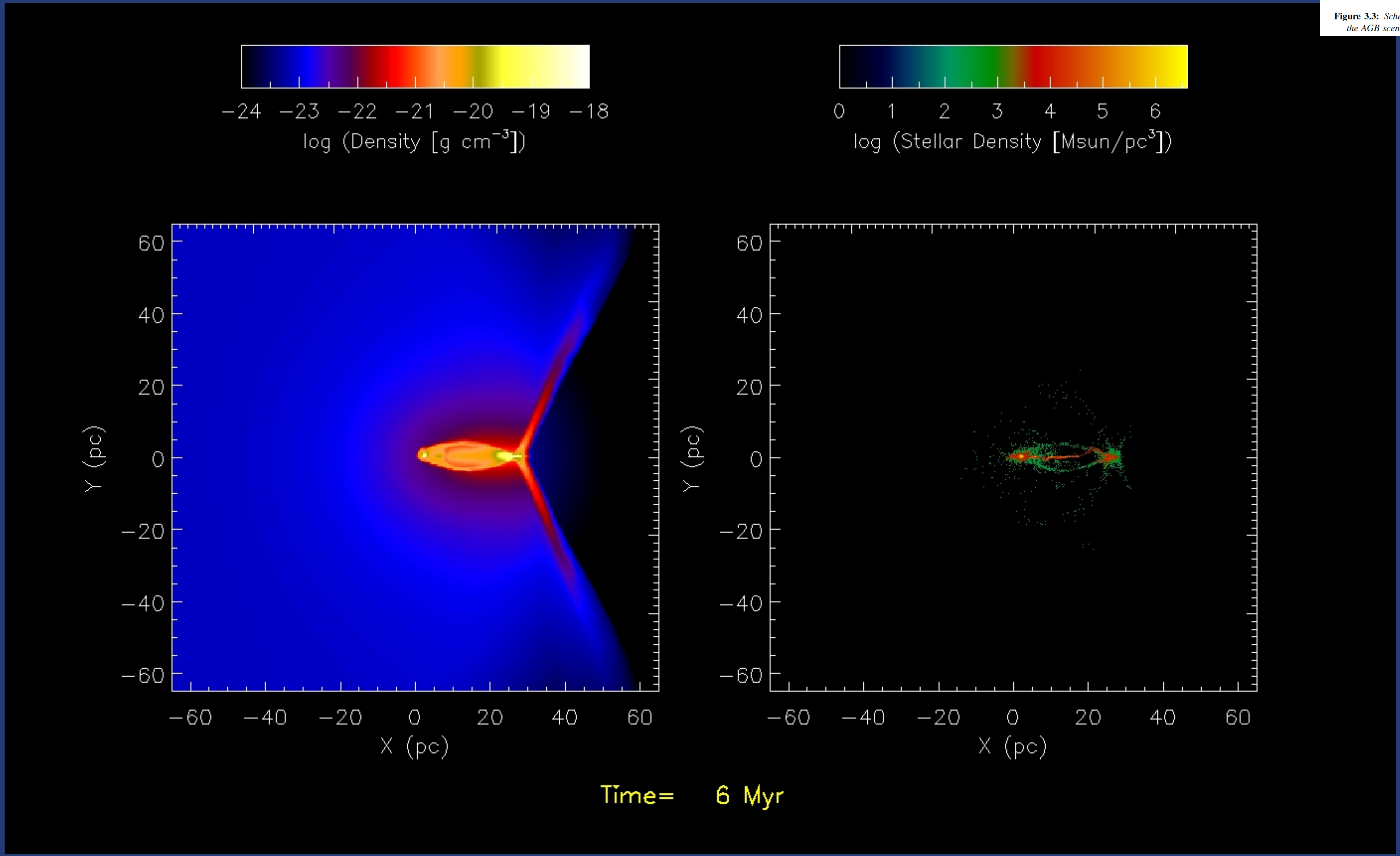
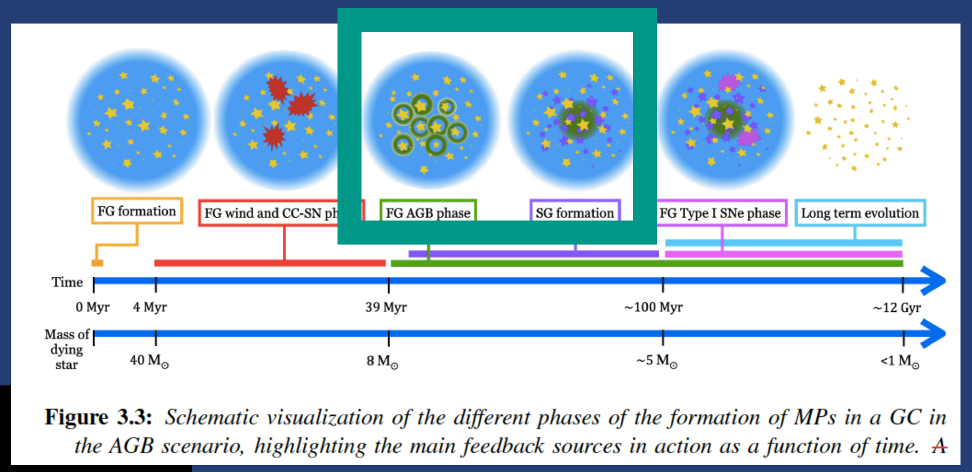


Infall density: ~10 cm^{-3}

F. Calura et al., 2019

Denser gas infall



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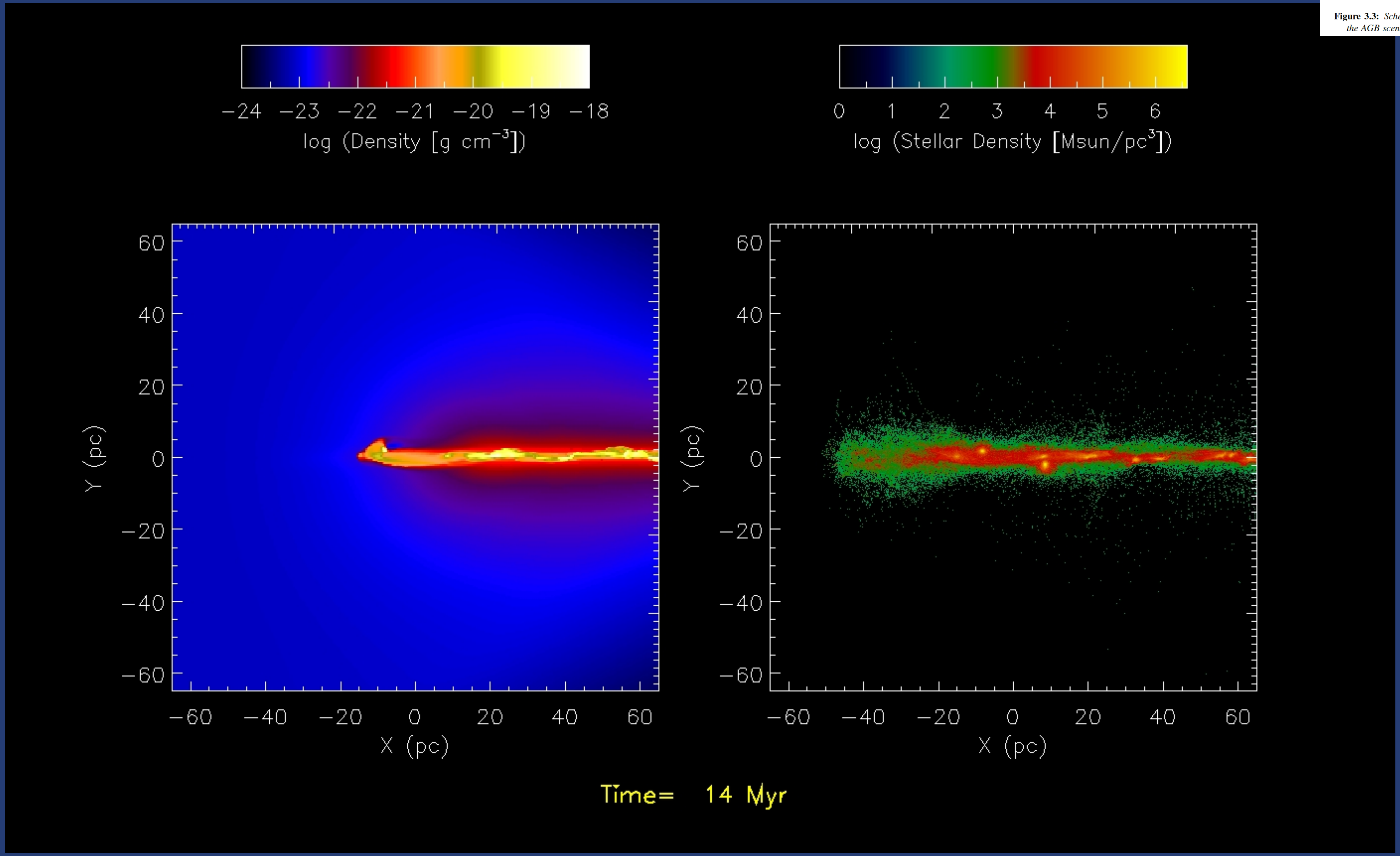

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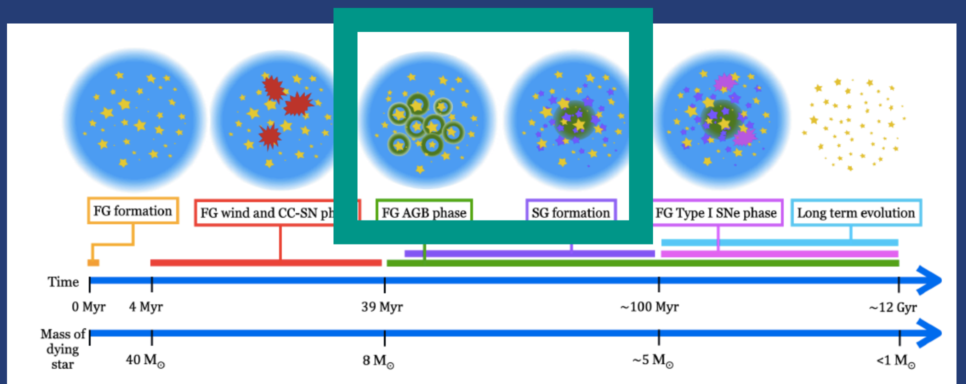

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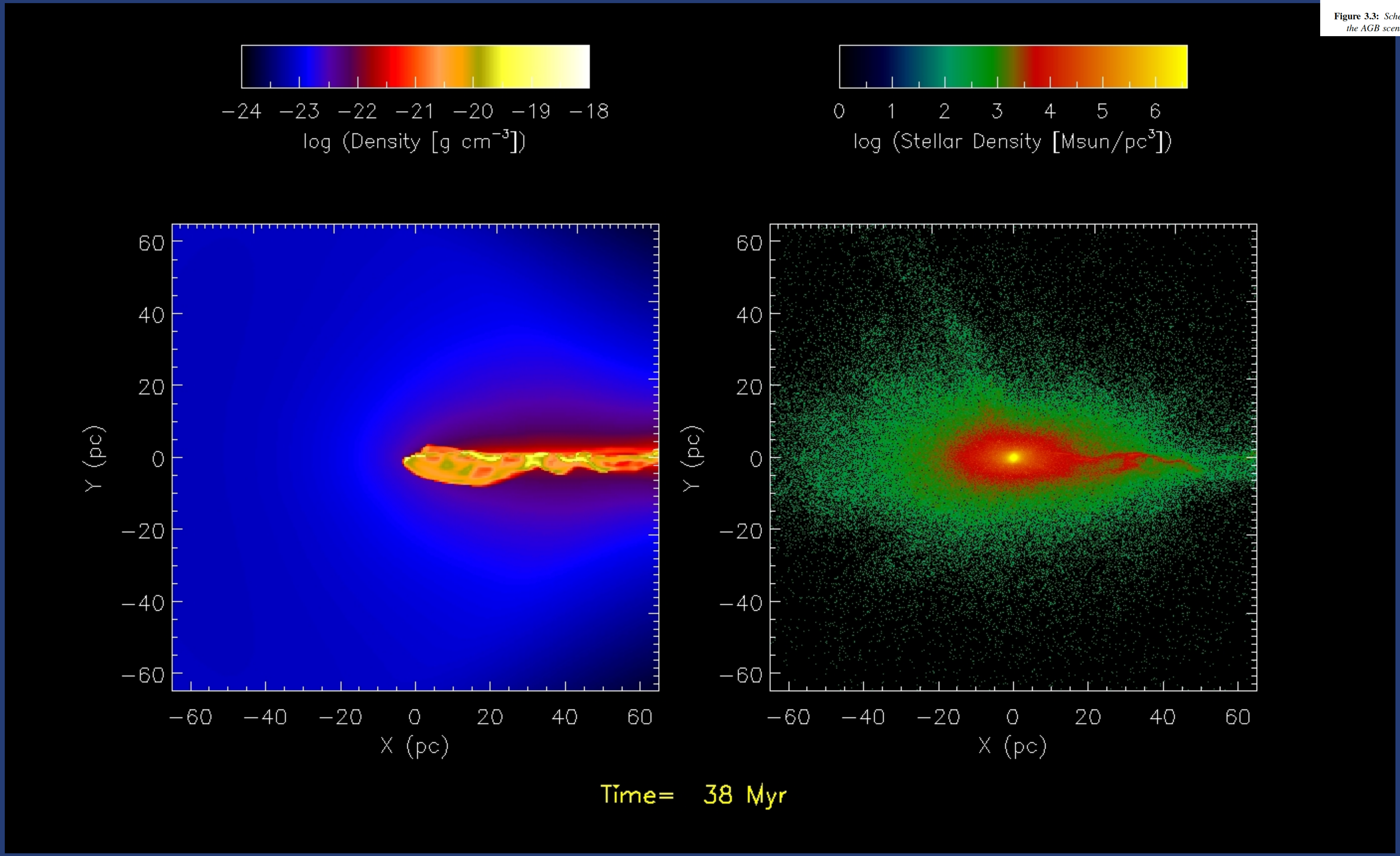

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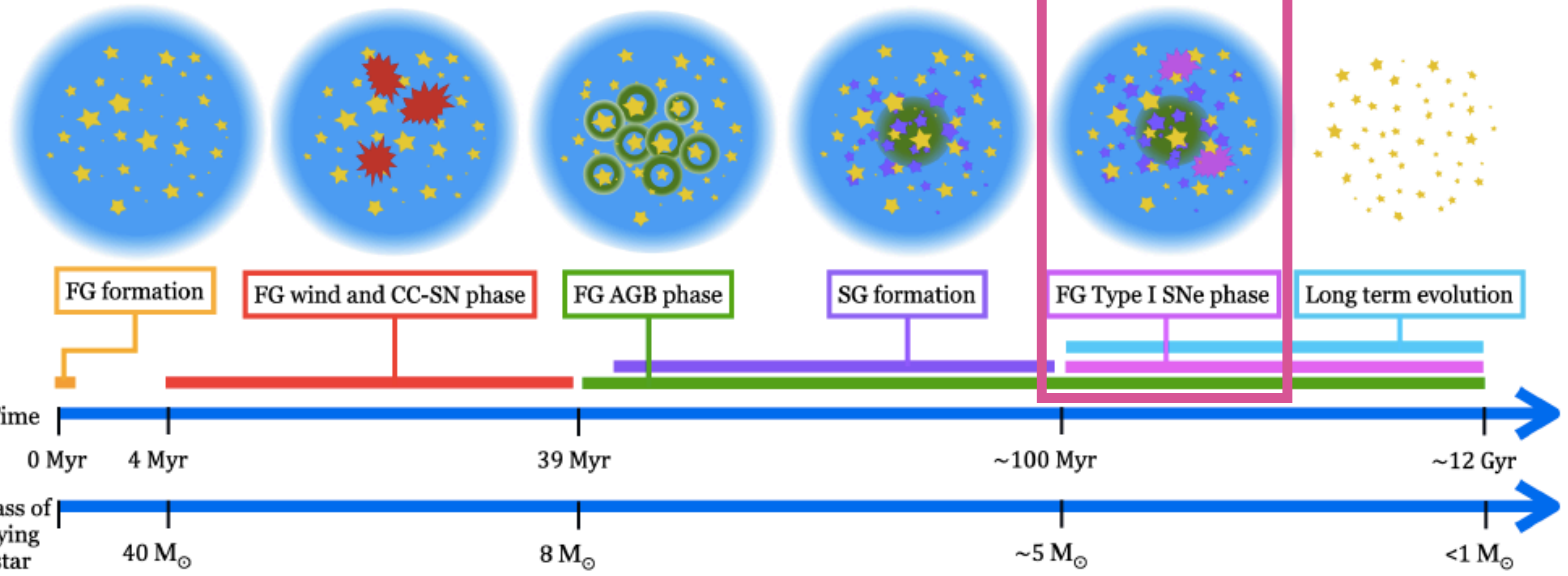
AGB scenario



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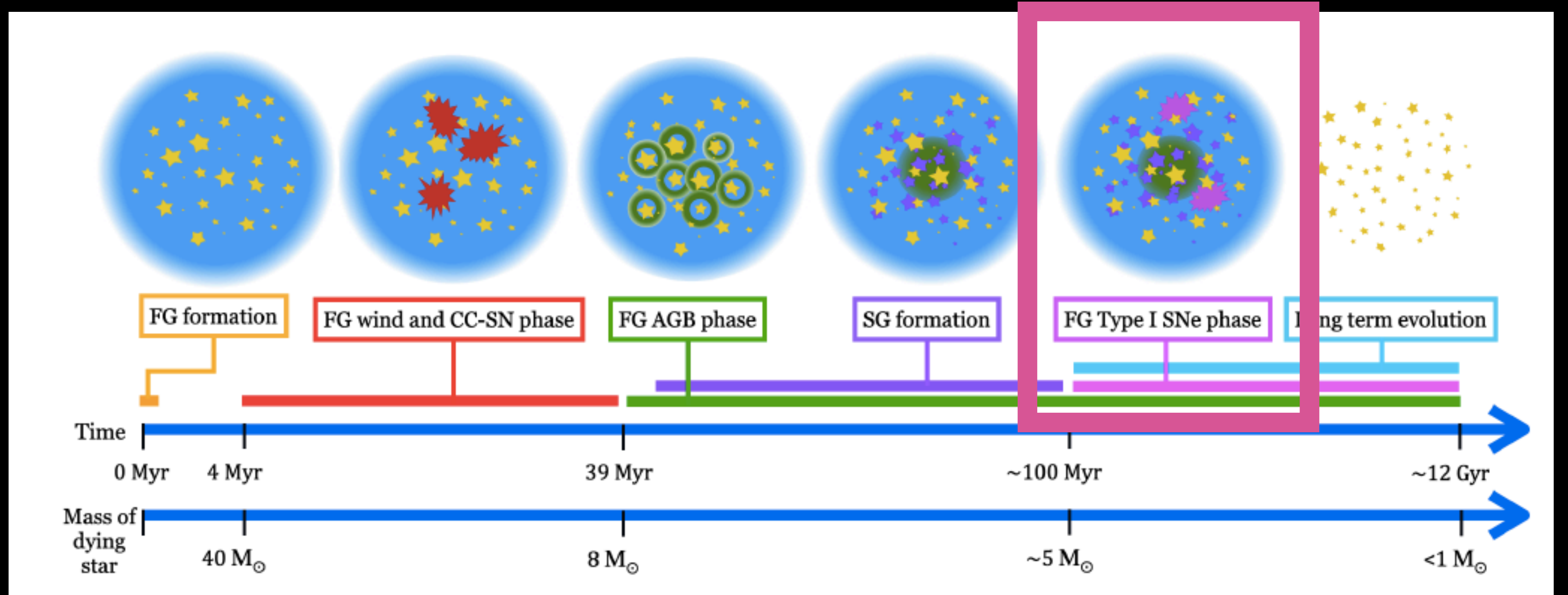

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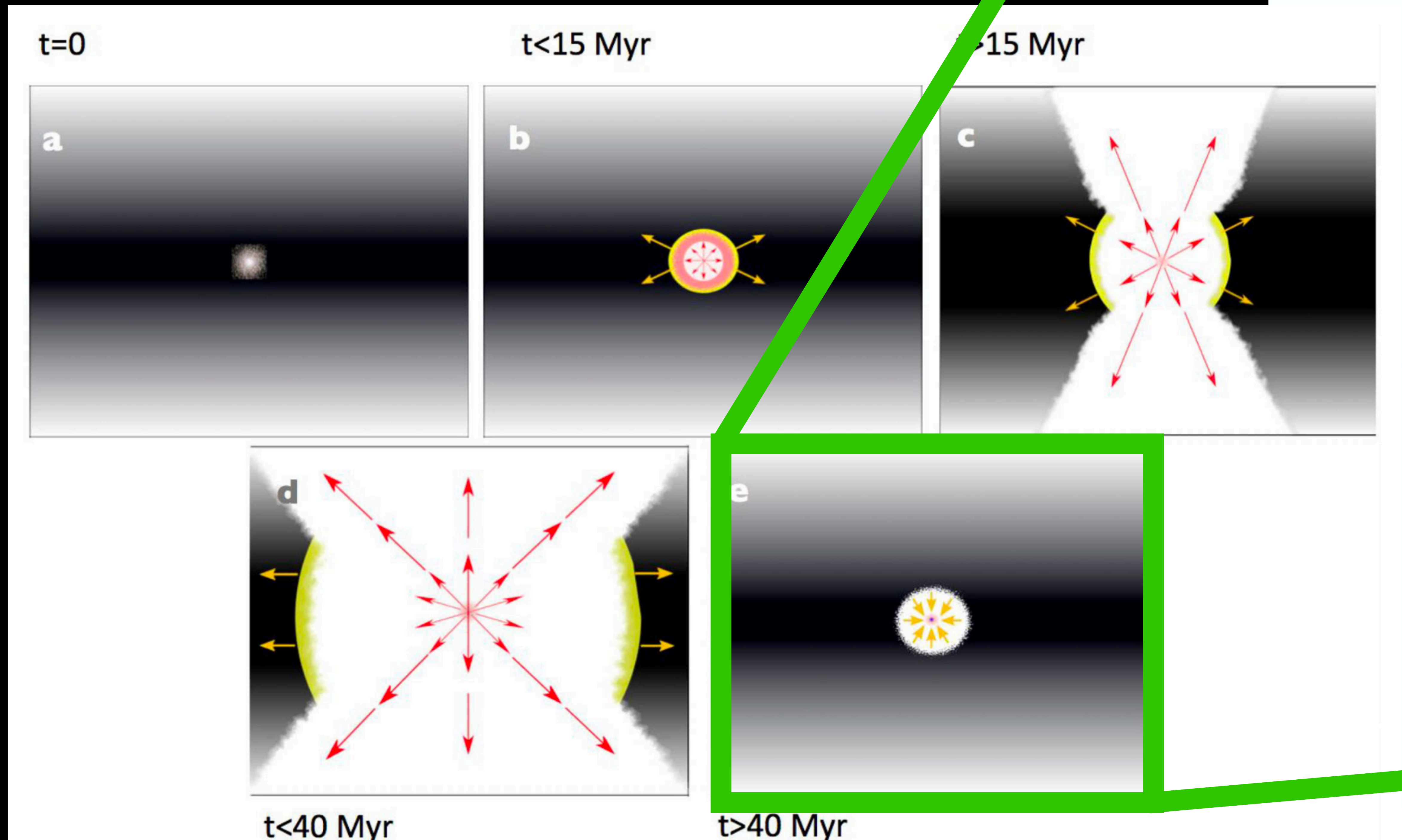
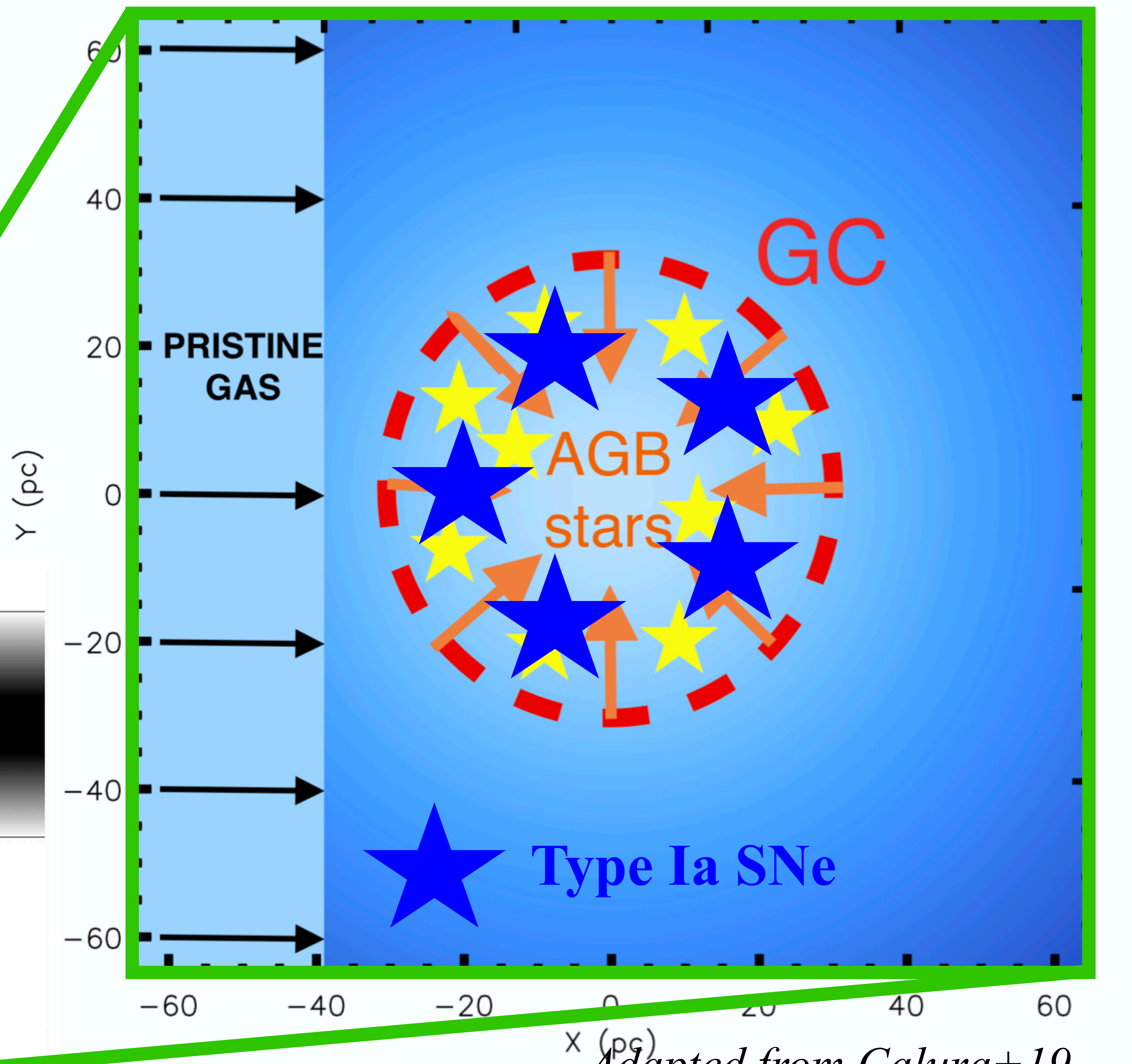
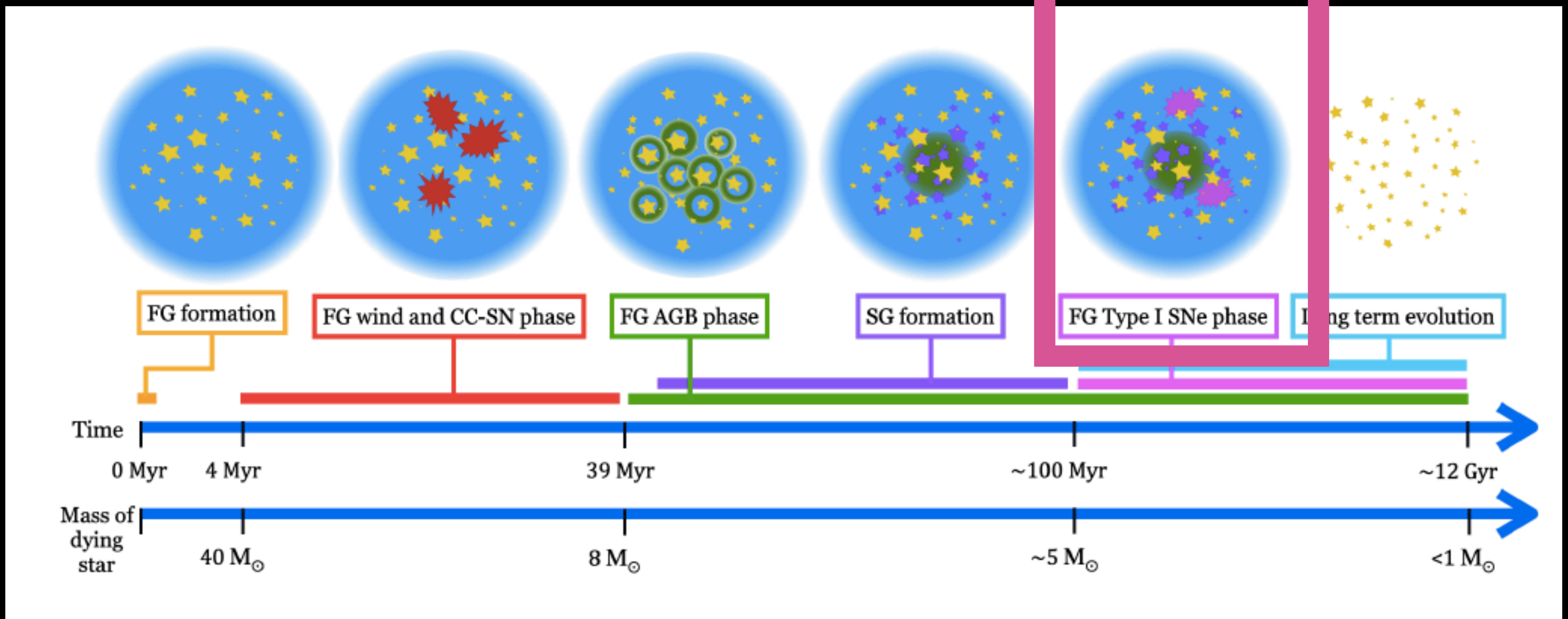
D'Ercole+16





Adapted from Calura+19

What is halting the SG formation?



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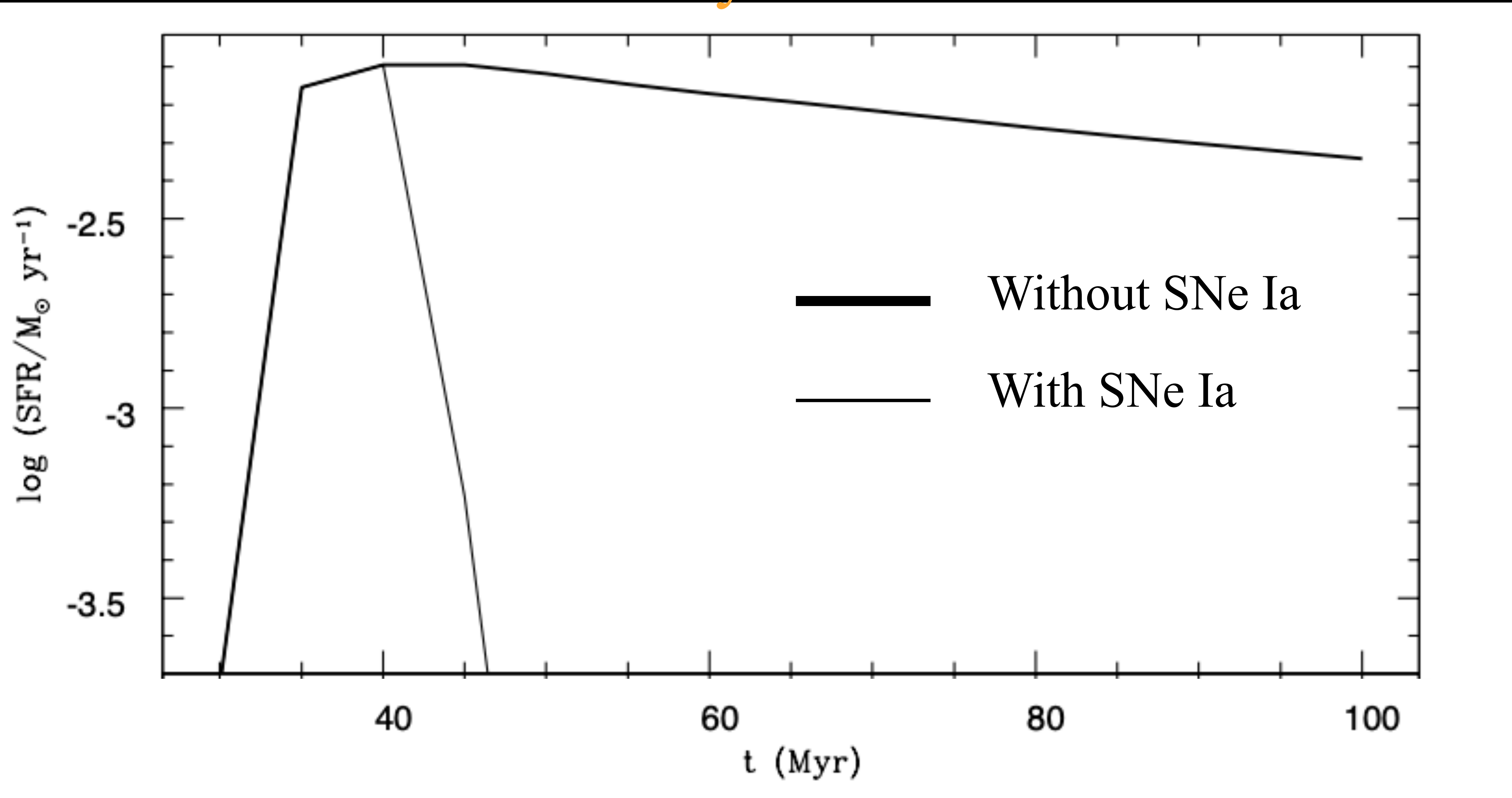
In the AGB scenario, it is assumed that **Type Ia SNe** halt the SG formation after some hundreds Myr

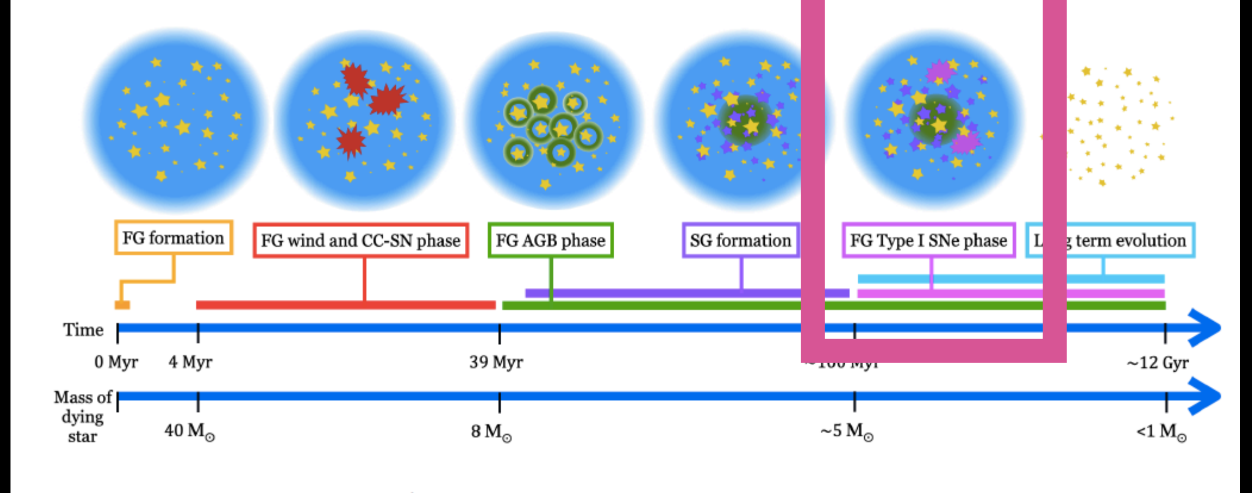
SFR evolution in **1D** hydro simulations



D'Ercole+08

Is it really so in 3D?

Type Ia SNe - feedback



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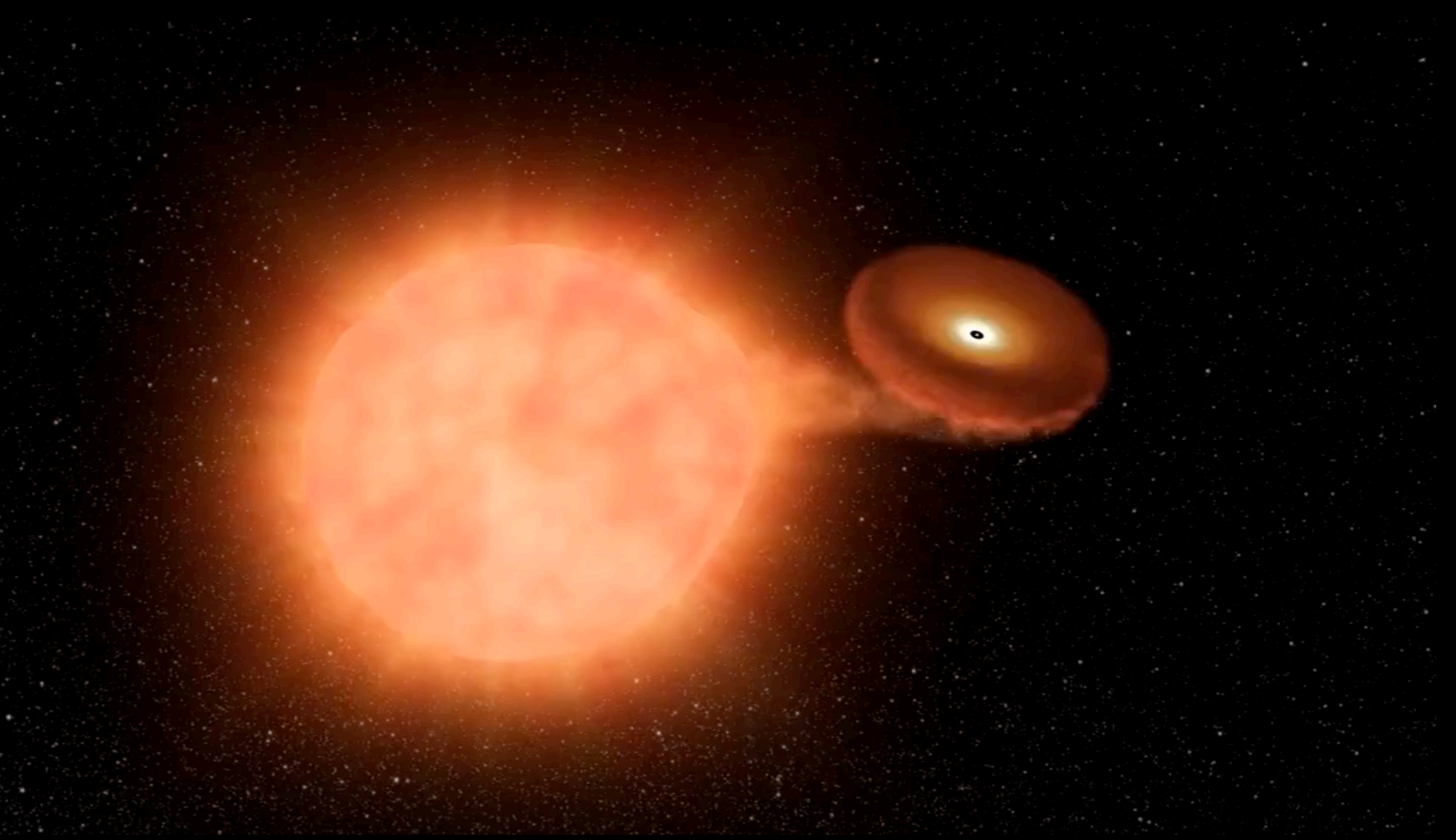
Each SN injects:

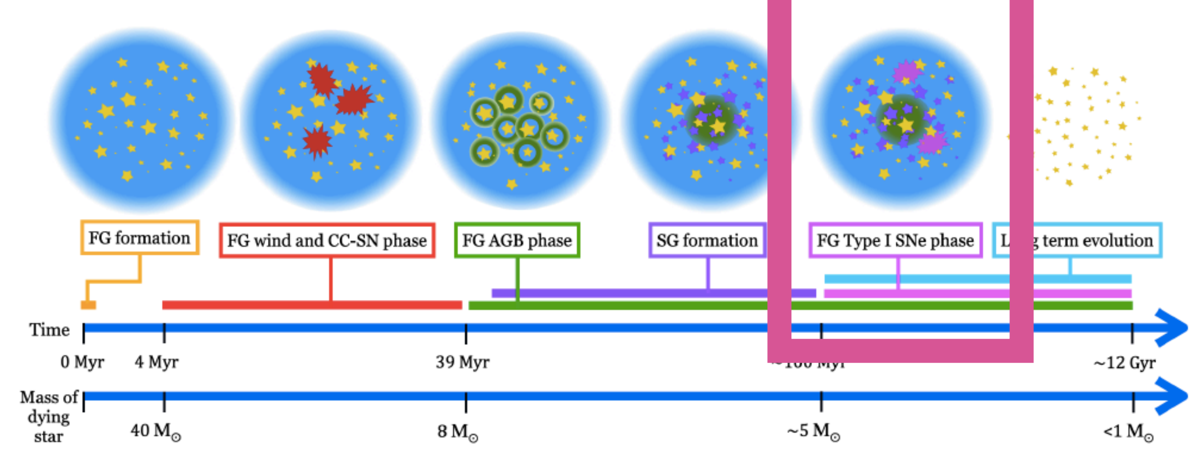
- ★ 1.44 $M_\odot$ of ejecta, all metal
- ★ 0.5 $M_\odot$ of Fe *Scalzo+14*
- ★ 10^{51} erg of thermal energy



Credit: NASA/JPL-Caltech

SNR 0509-67.5

Image: NASA, ESA, CXC, SAO, the Hubble Heritage Team



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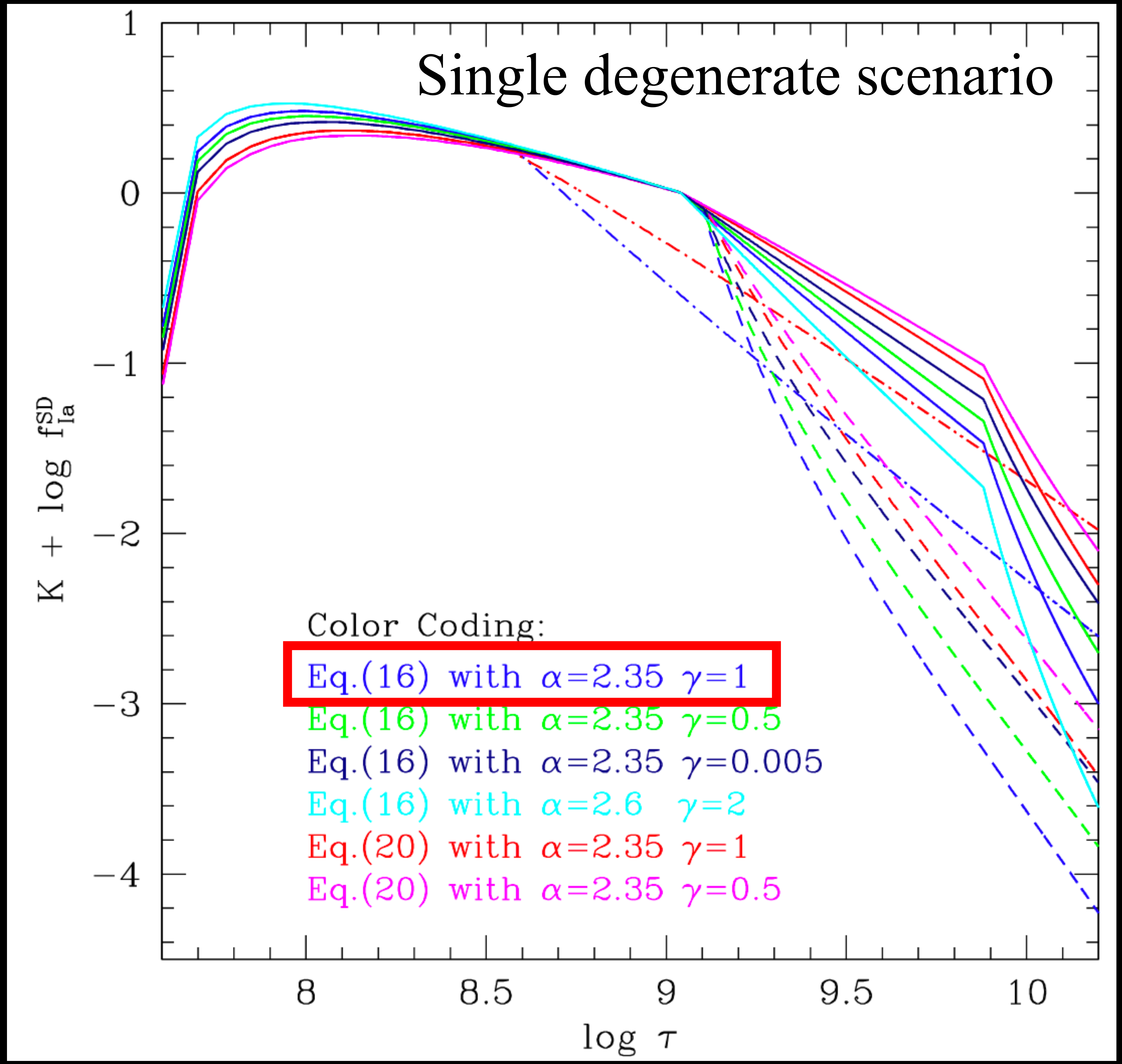
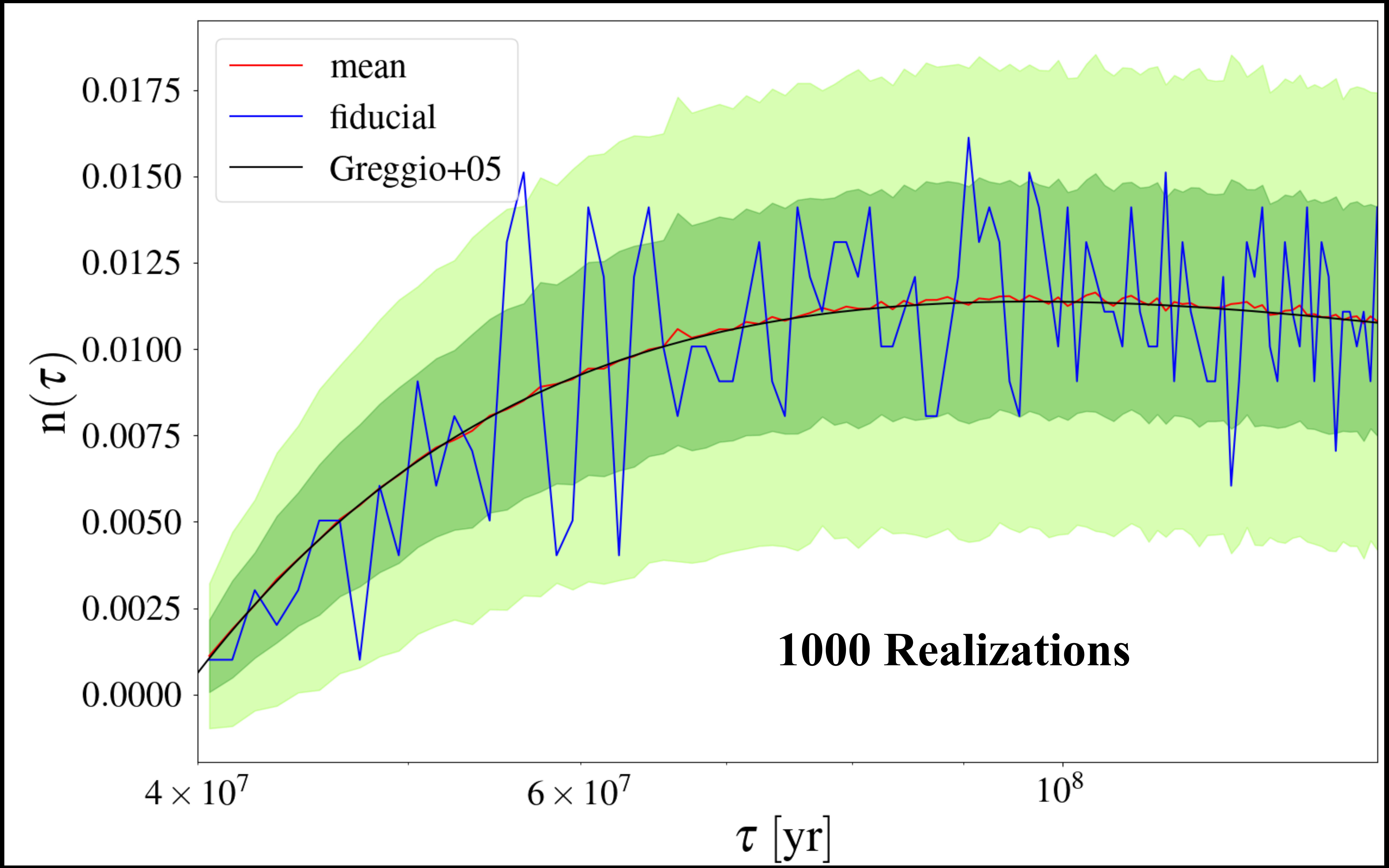
Type Ia SNe - Delay time distribution

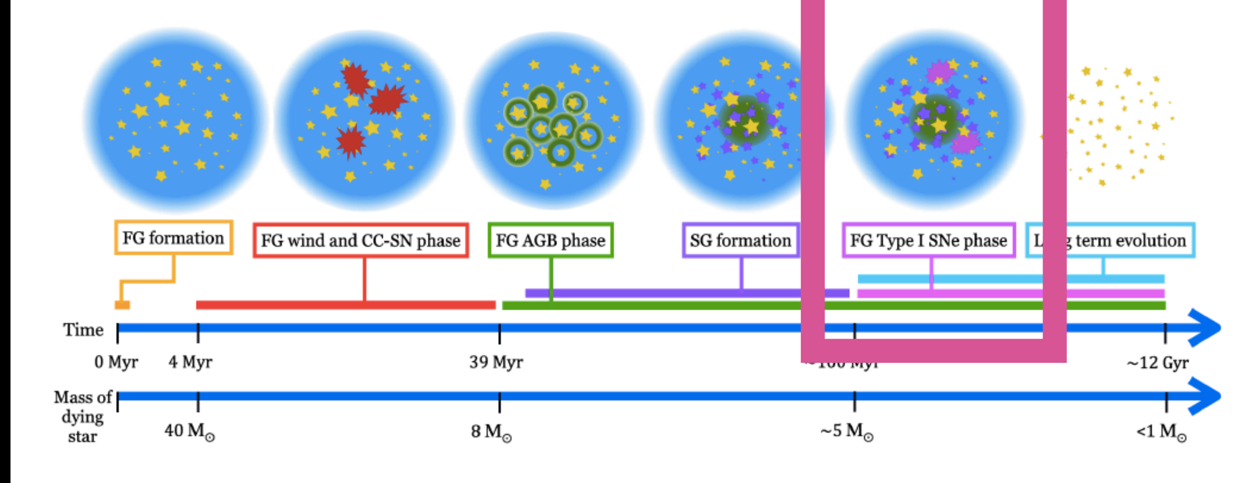


Greggio+05



Lacchin+21

Delay time distributions - models vs. observations



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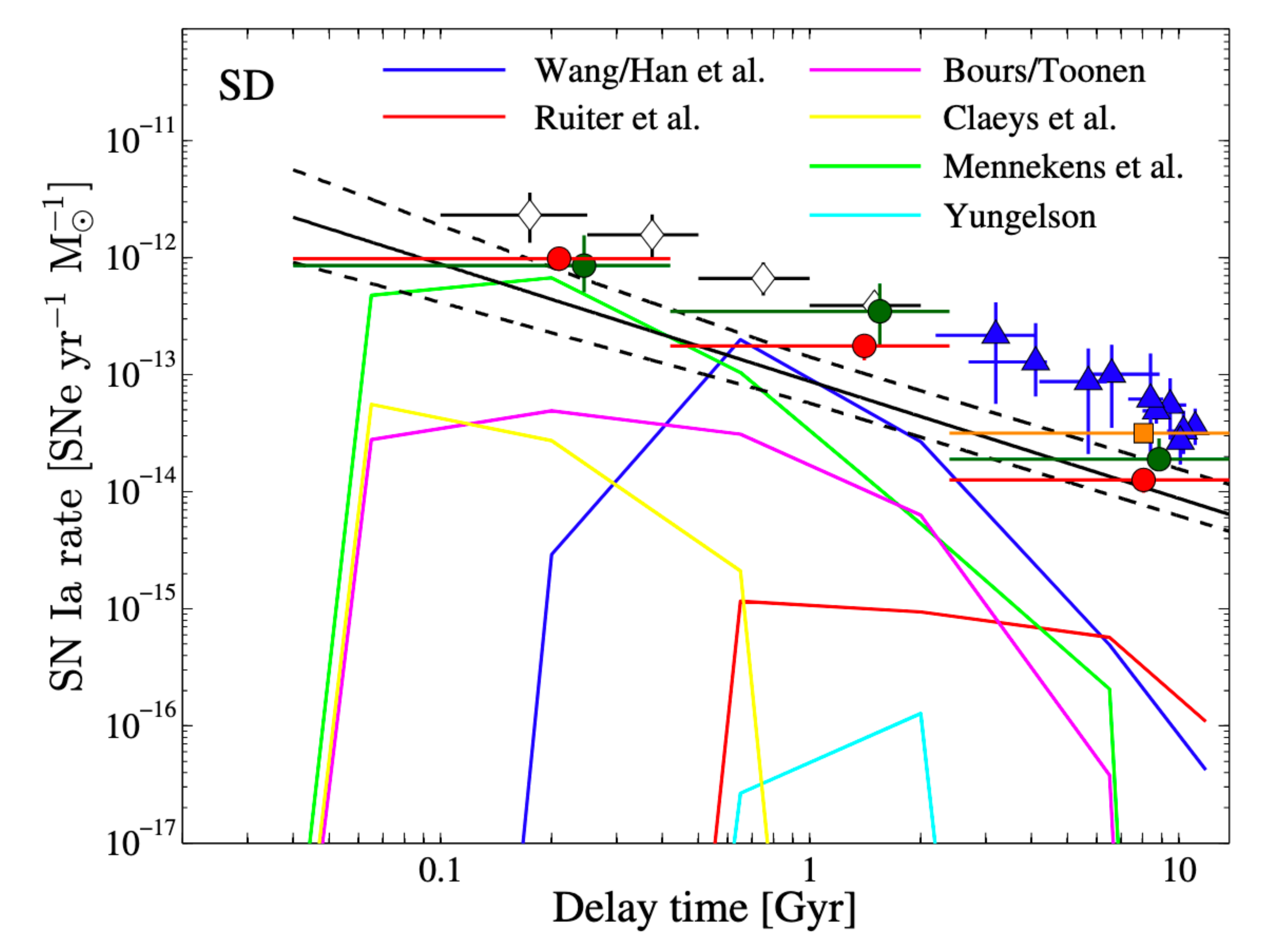
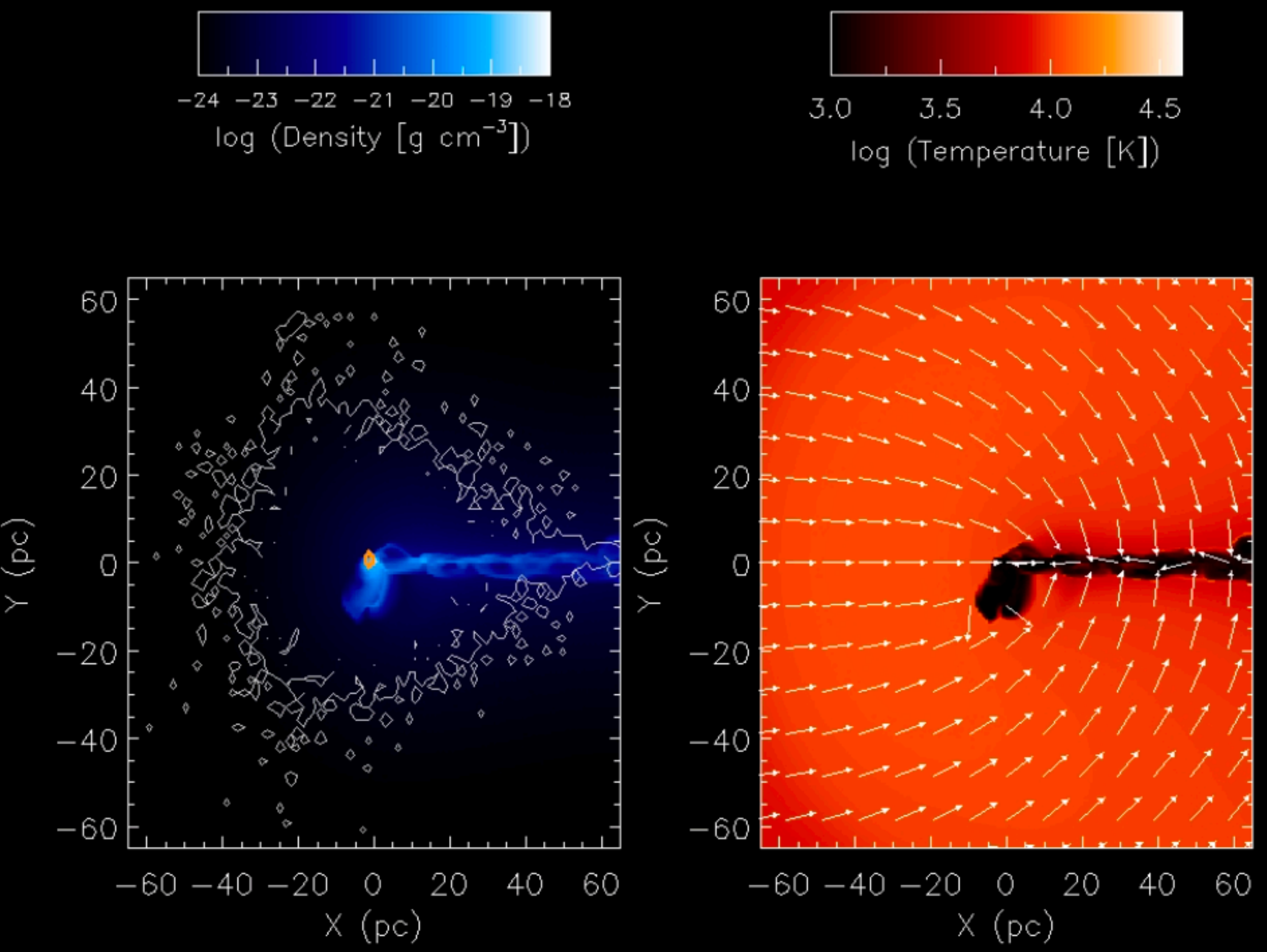


Tested a case in which Type Ia SN are delayed of ~25 Myr

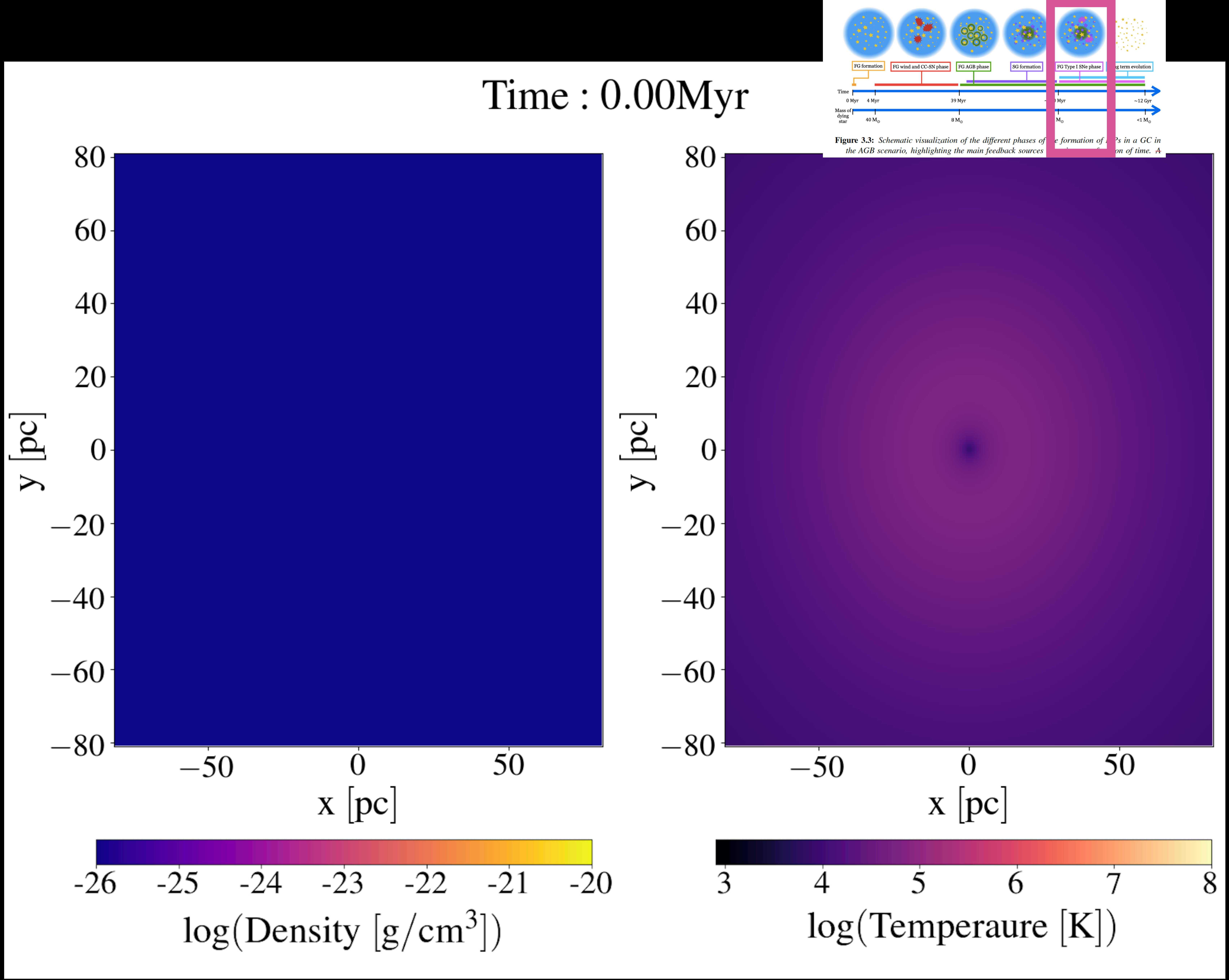
Maoz+14

Low density

$$\rho_{\rm pg} = 10^{-24}{\rm g/cm^3}\ \ -\ \ t_{\rm inf} = 21{\rm Myr}$$



Calura+19

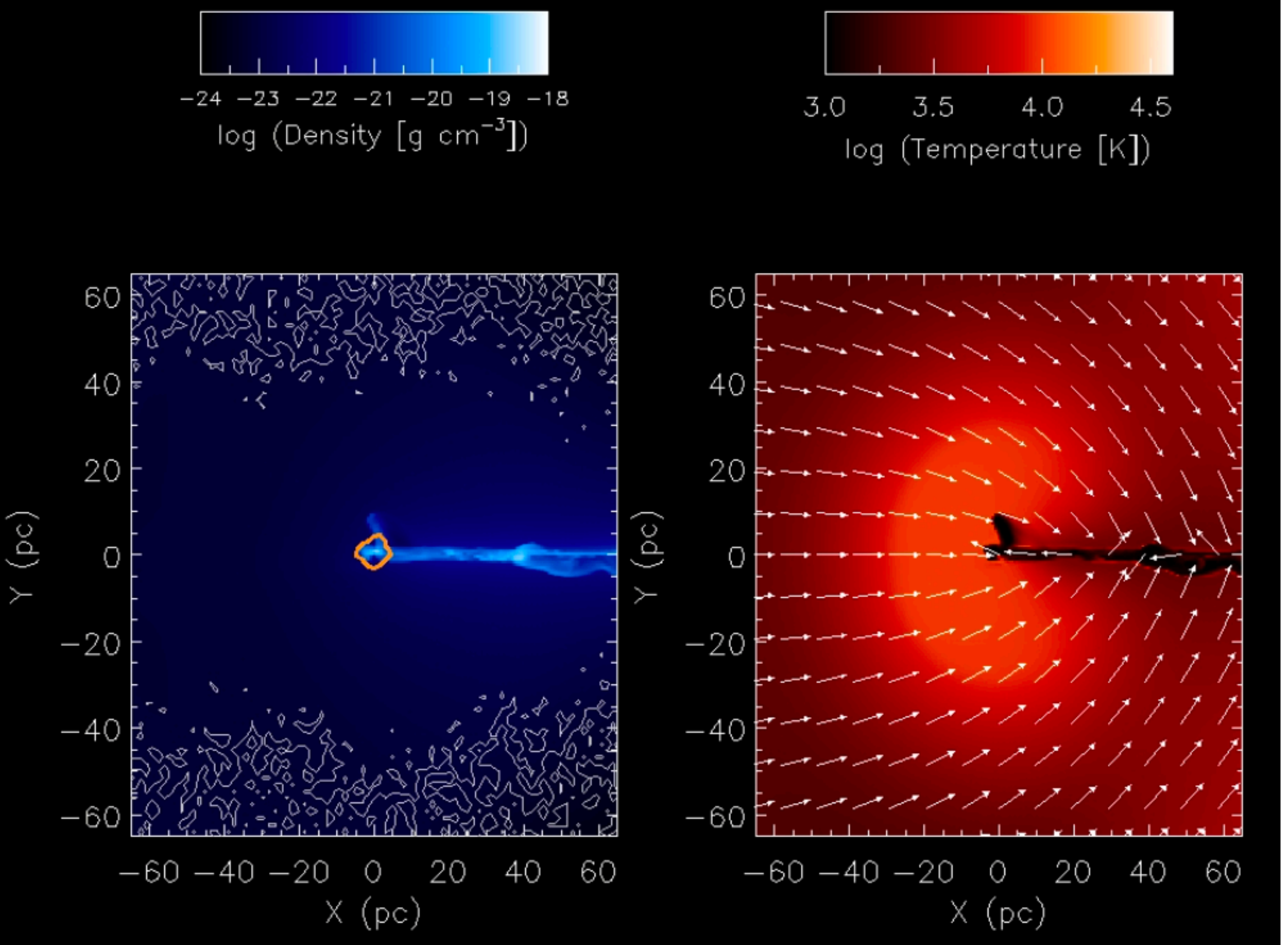


Lacchin+21

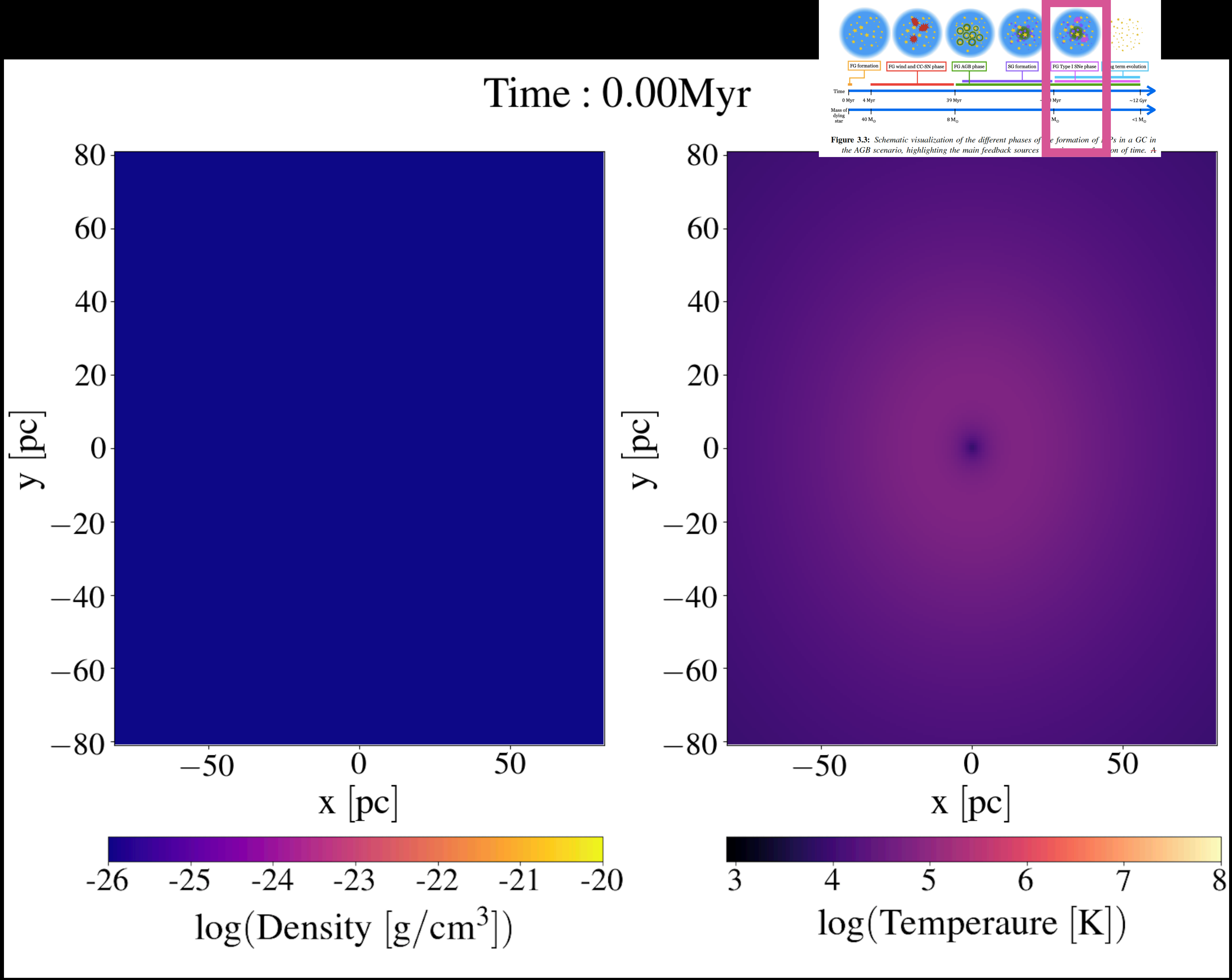
High density

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

$t_{inf} = 1\mathrm{Myr}$

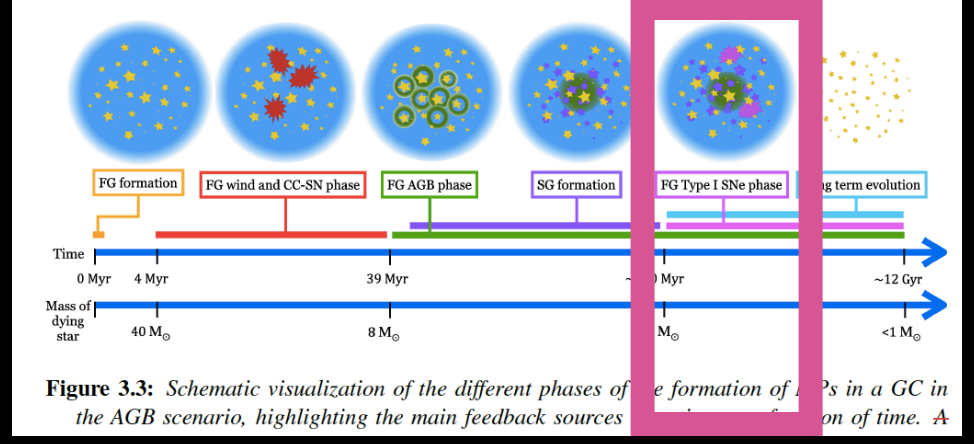


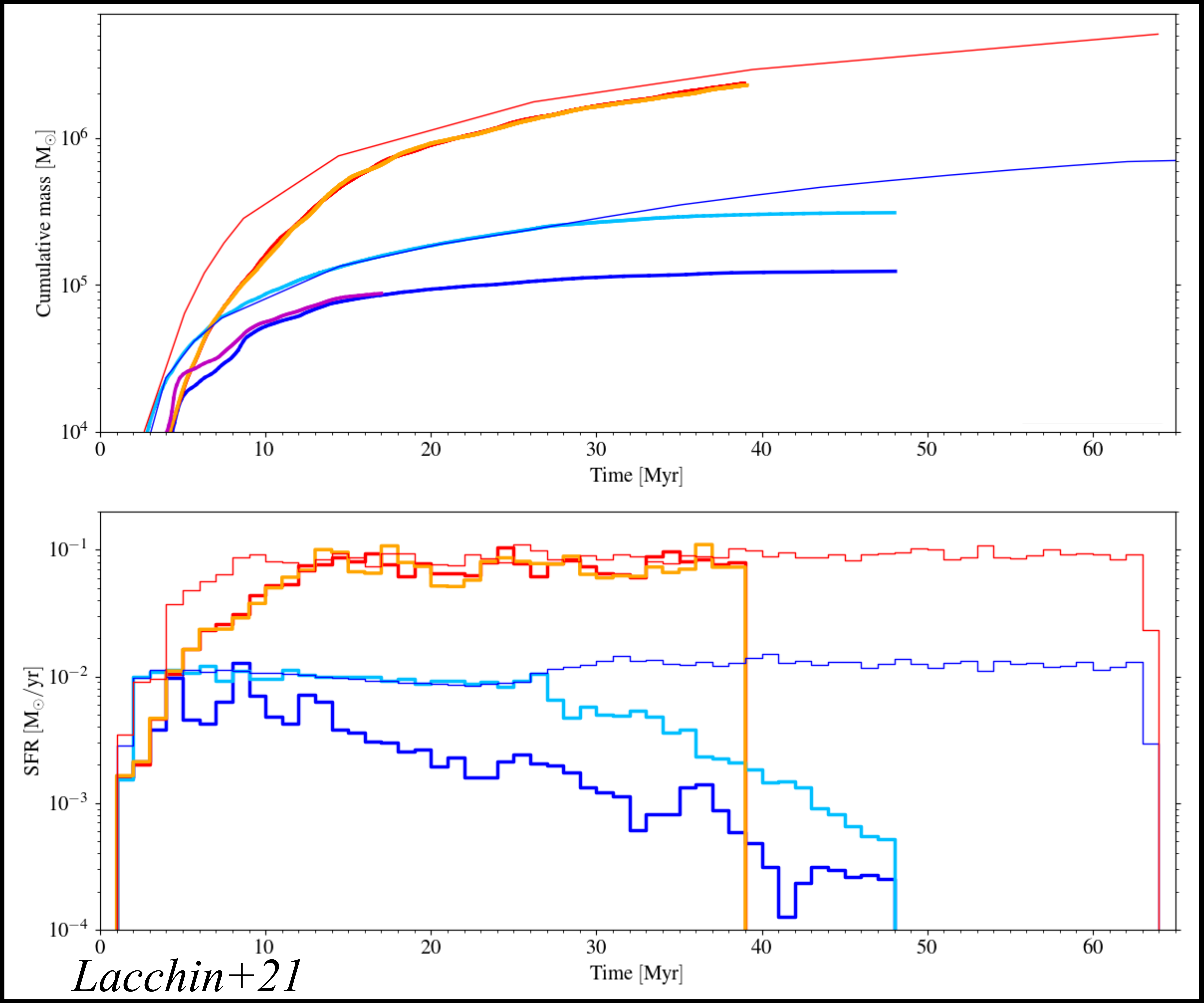
Calura+19



Lacchin+21

SFR vs time & $M_\star$ vs time





Without SNe Ia

With SNe Ia

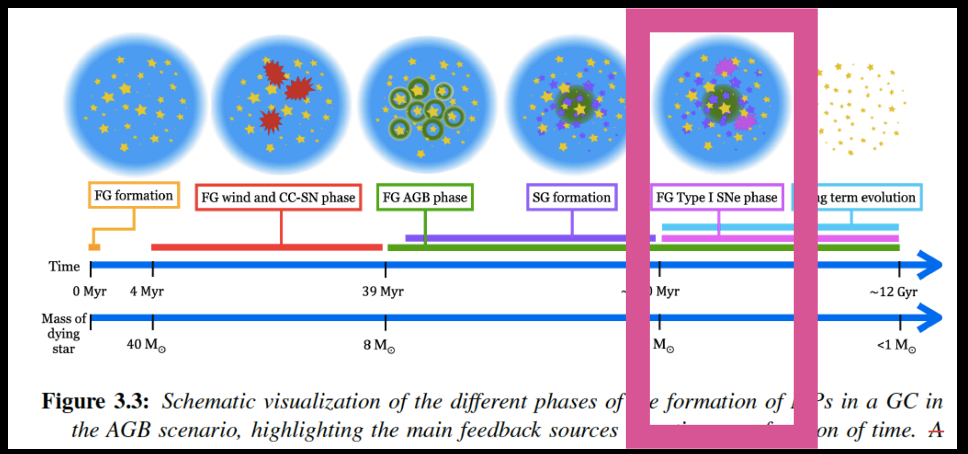
High density

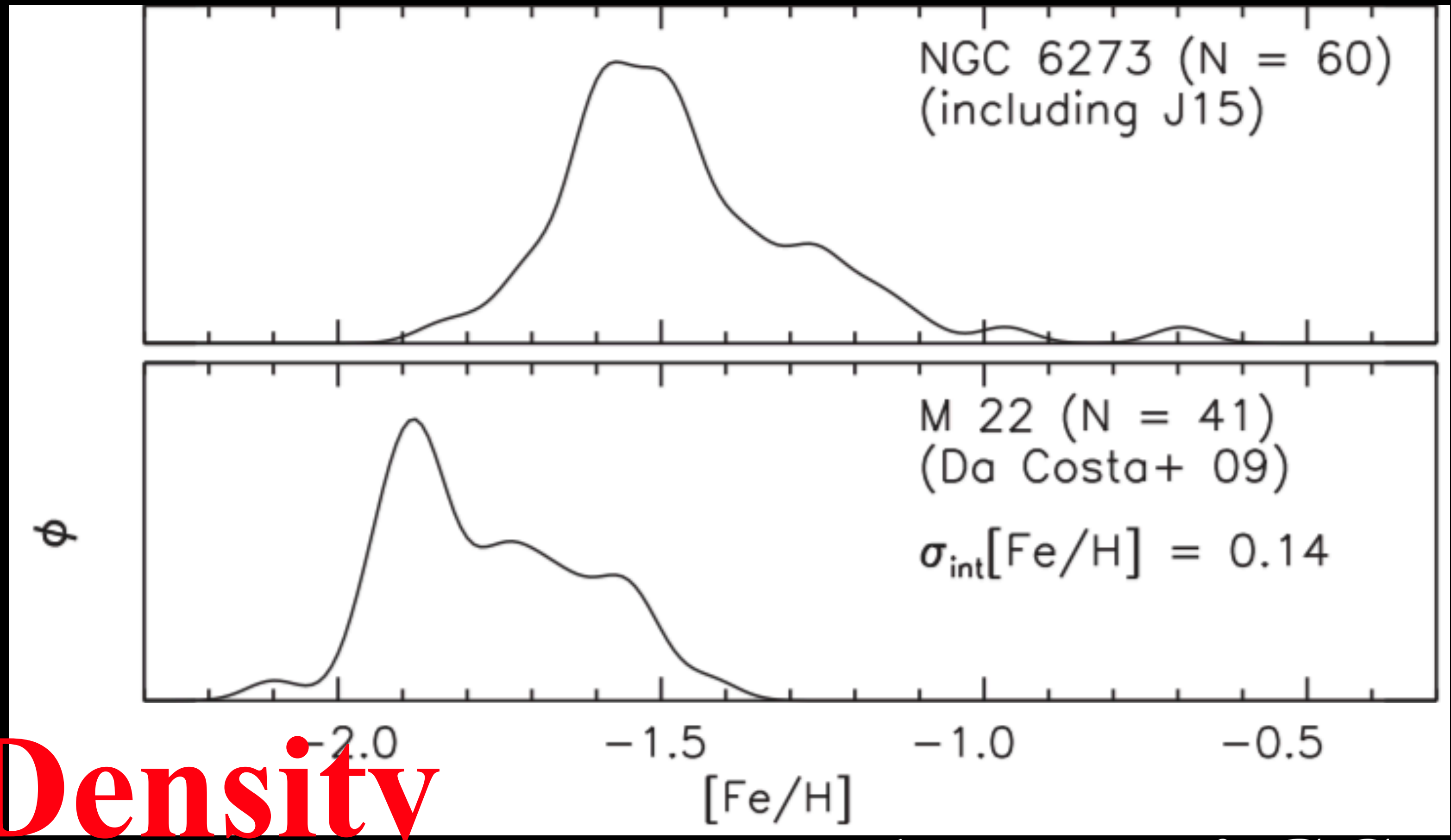
Low density

Low density:
- SF is not completely stopped
- $M_\star^{final}$ reduced by 80%

High density:
- little effects on SFR
- $M_\star^{final}$ reduced by 20%

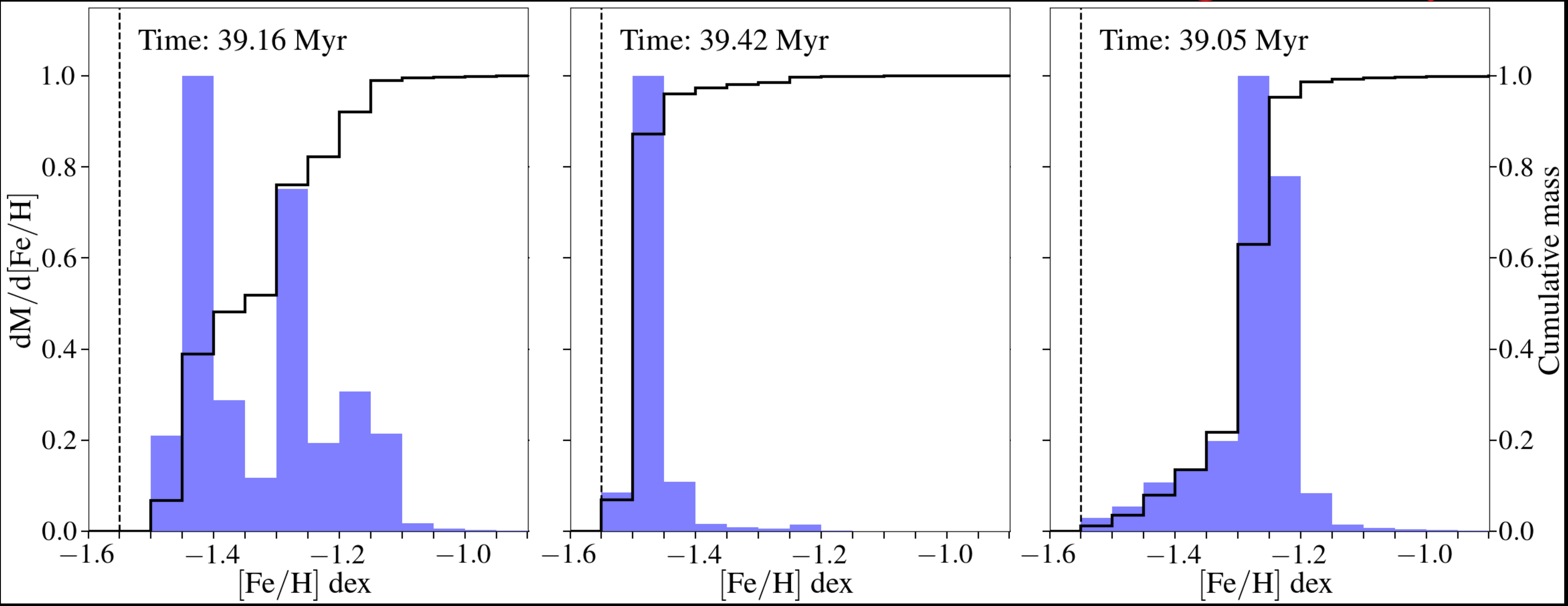
Iron distribution





'Type II' GCs
Yong+16

Low Density **Low Density + delayed SNe** **High Density**



Lacchin+21

$\sigma_{[Fe/H]} = 0.14$ dex $\sigma_{[Fe/H]} = 0.07$ dex $\sigma_{[Fe/H]} = 0.14$ dex

AGB scenario

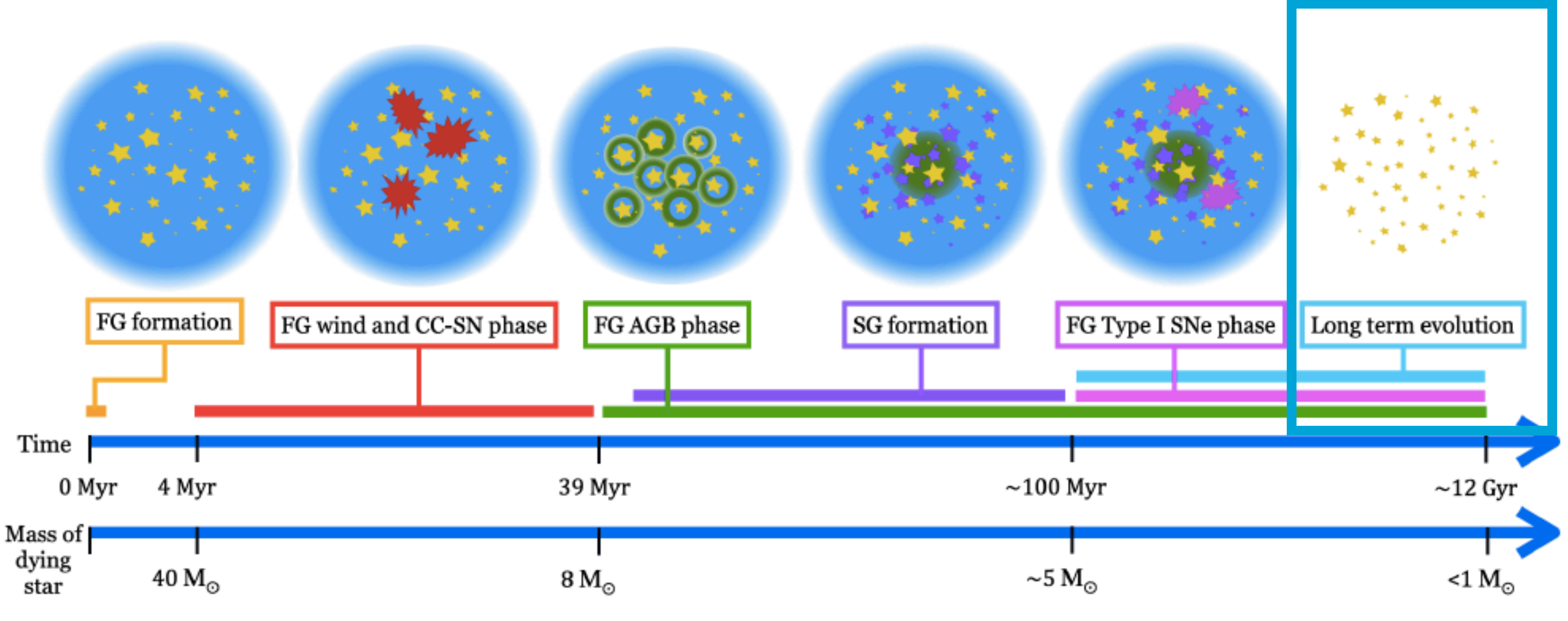


Figure 3.3: *Schematic visualization of the different phases of the formation of MPs in a GC in the AGB scenario, highlighting the main feedback sources in action as a function of time.*

E. Lacchin, 2023, PhD Thesis

Can we recover present-day GCs?

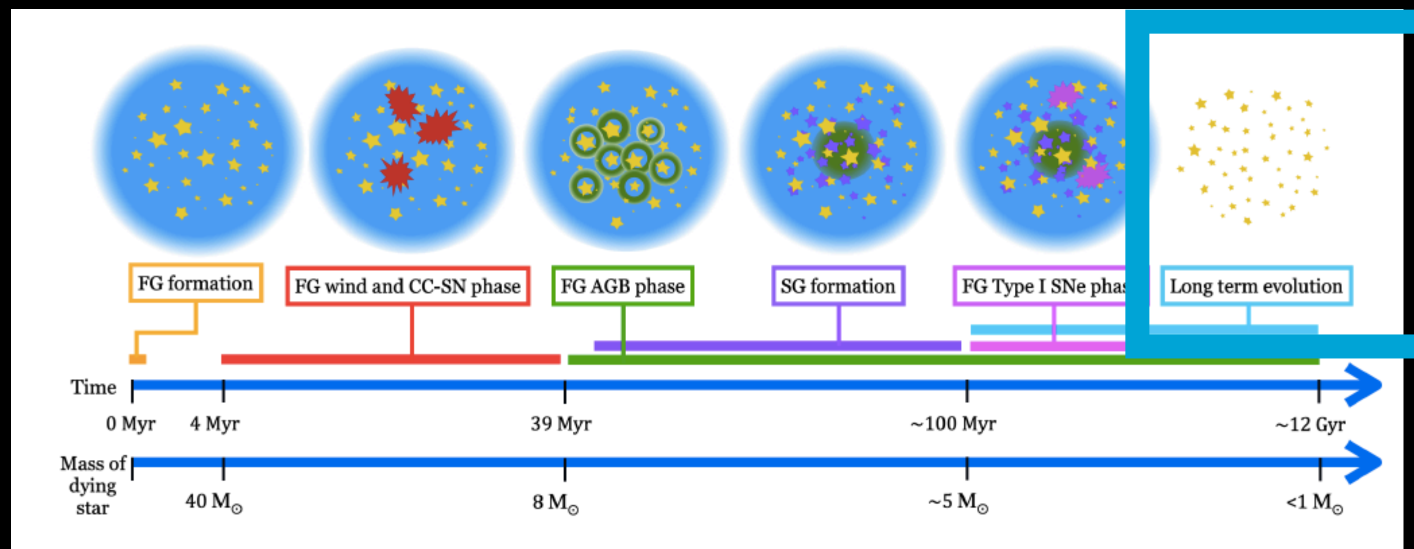
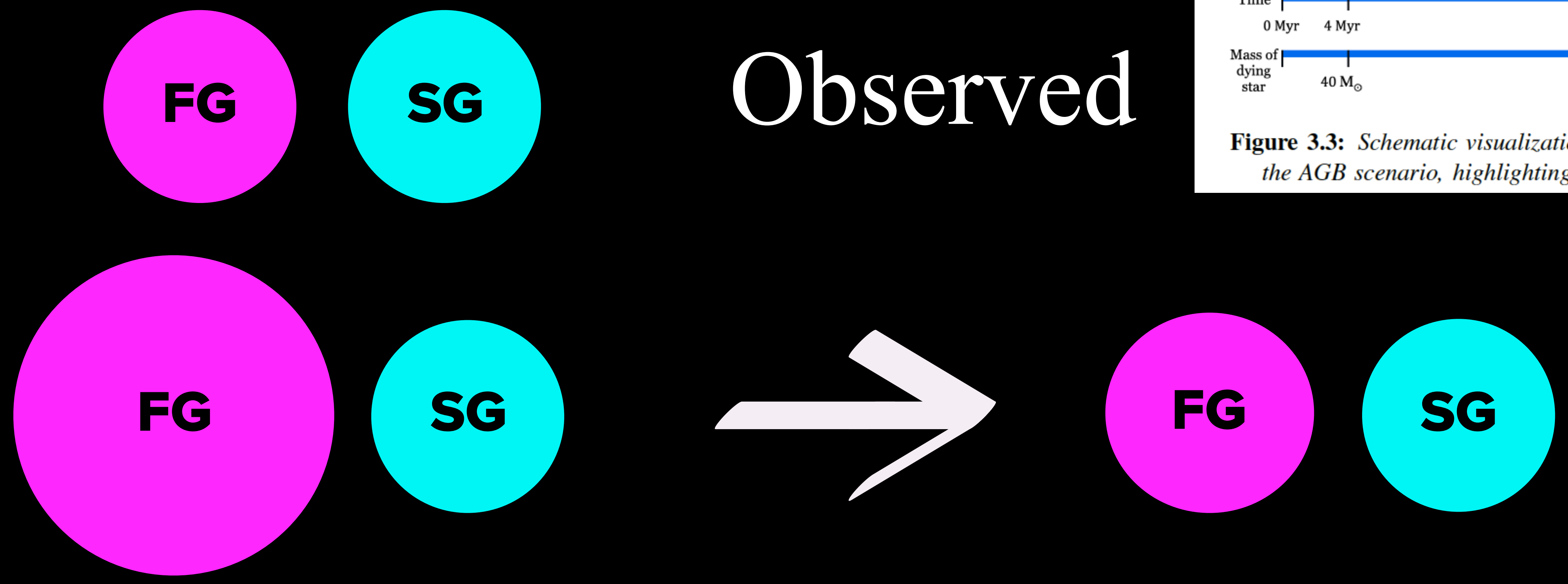


Figure 3.3: *Schematic visualization of the different phases of the formation of MPs in a GC in the AGB scenario, highlighting the main feedback sources in action as a function of time.*

Mass budget problem



Initial FG mass ~ 5 - 20 times more massive than present day

Most of FG stars must be lost during the evolution

Feasible?

D'Ercole+08, Vesperini+21, Sollima22 for positive answers

Larsen+14, Bastian & Lardo 2015, Reina-Campos+18 for negative answers

Can we recover present-day GCs?

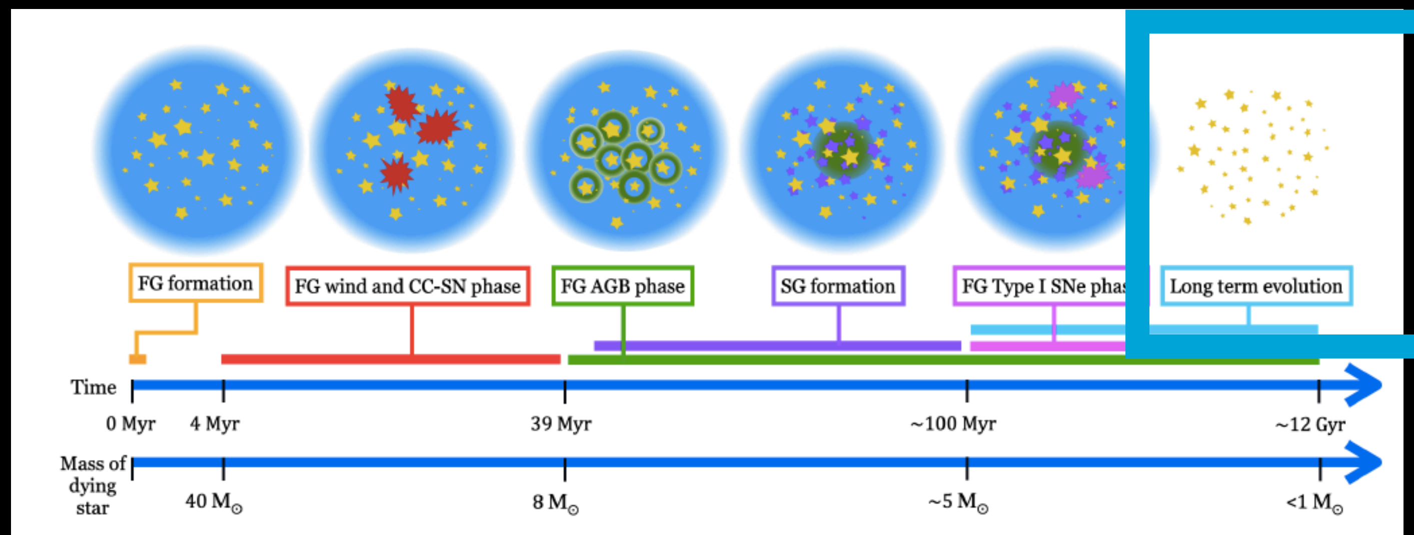
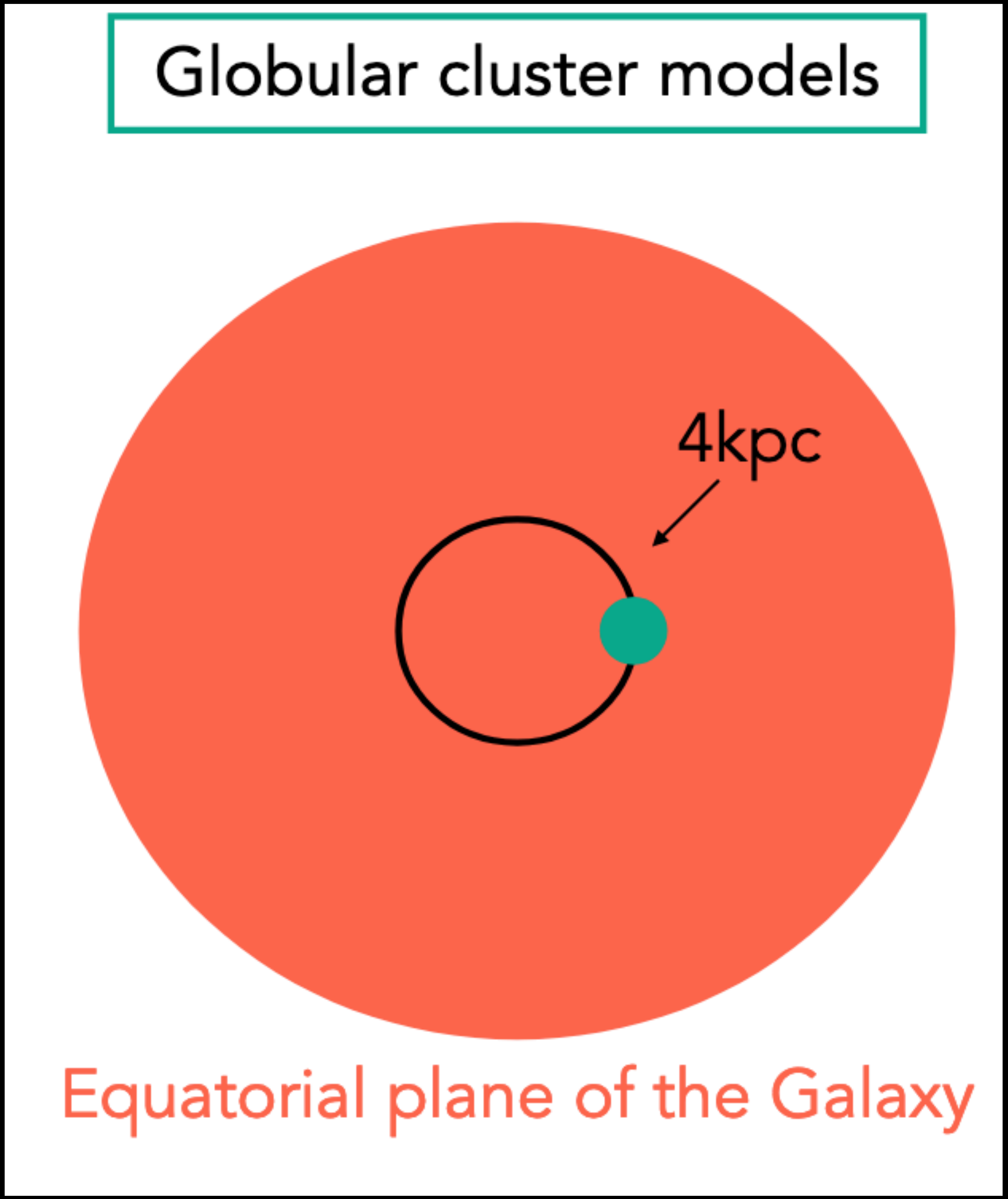


Figure 3.3: *Schematic visualization of the different phases of the formation of MPs in a GC in the AGB scenario, highlighting the main feedback sources in action as a function of time.* A

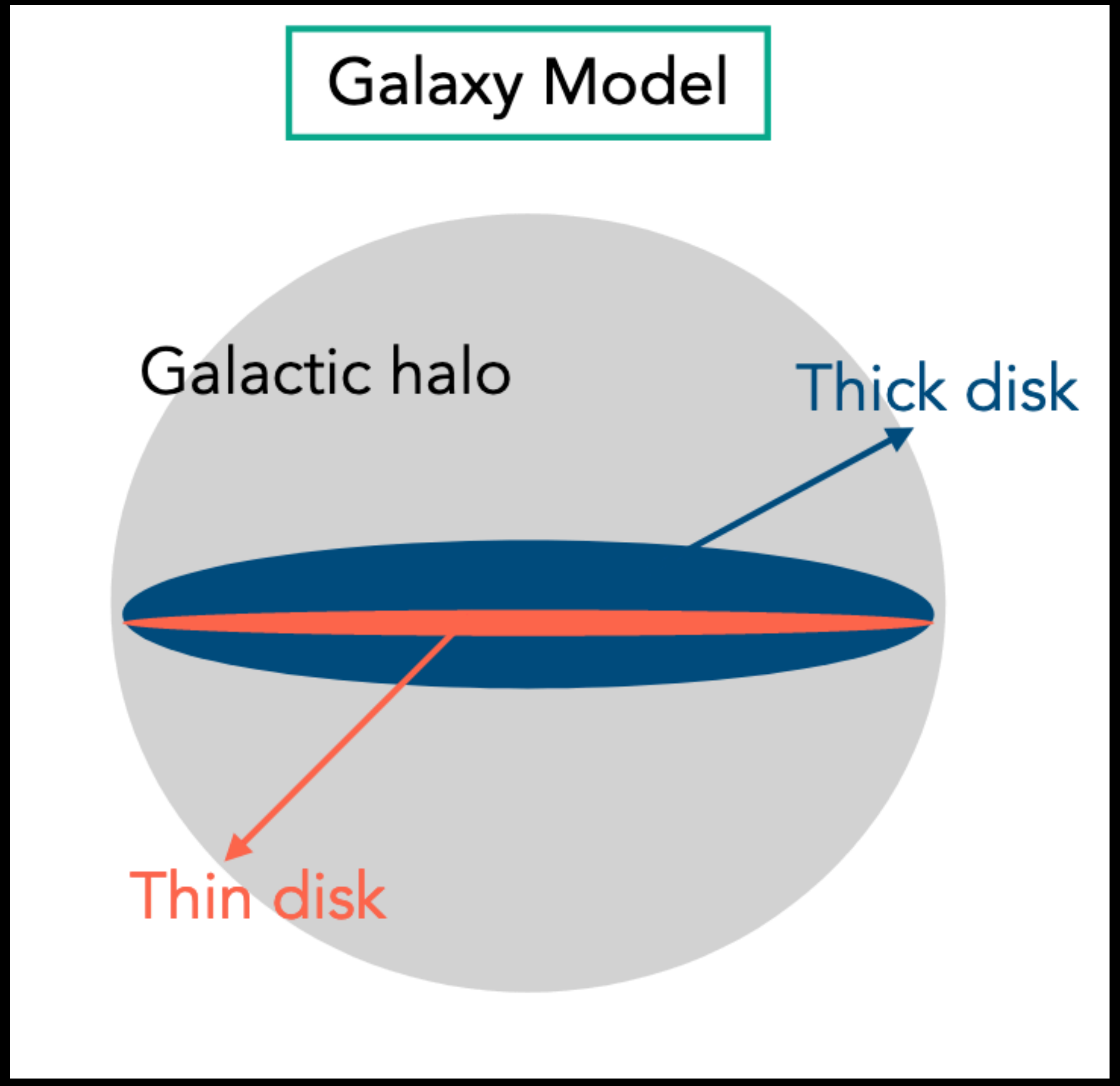


N-Body simulations

NBSymple

Capuzzo-Dolcetta+11

- ★ $M = 10^7 M_\odot$
- ★ 2 component represented by a King model
- ★ Evolved for 12 Gyr



Long term evolution

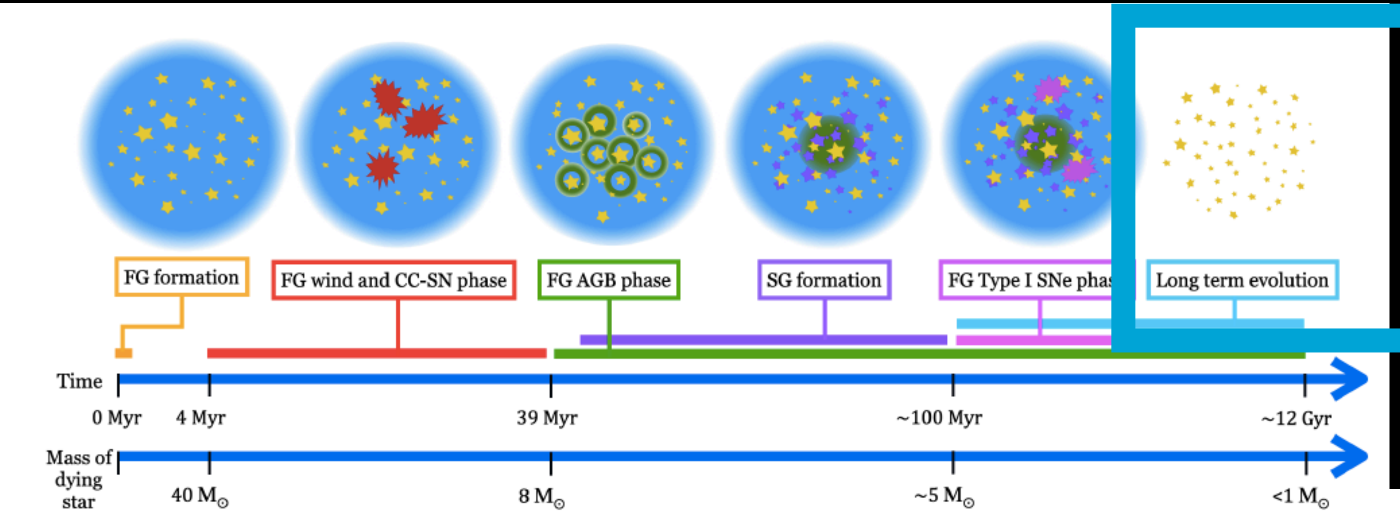


Figure 3.3: *Schematic visualization of the different phases of the formation of MPs in a GC in the AGB scenario, highlighting the main feedback sources in action as a function of time.* A

Long term evolution

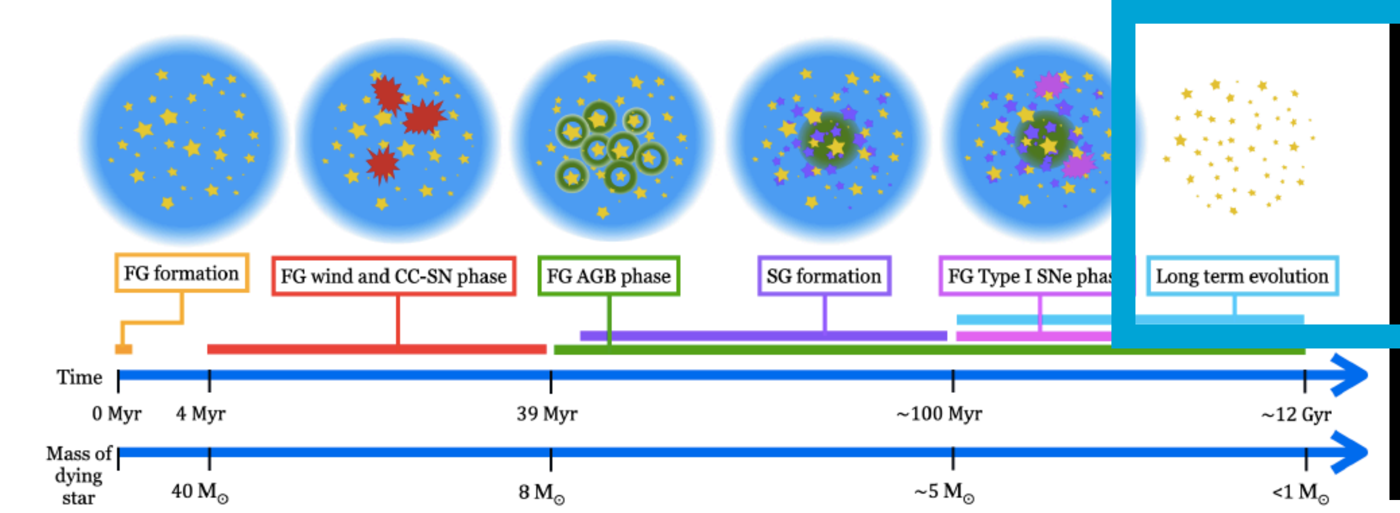


Figure 3.3: *Schematic visualization of the different phases of the formation of MPs in a GC in the AGB scenario, highlighting the main feedback sources in action as a function of time.* ~~*A*~~

Mass loss

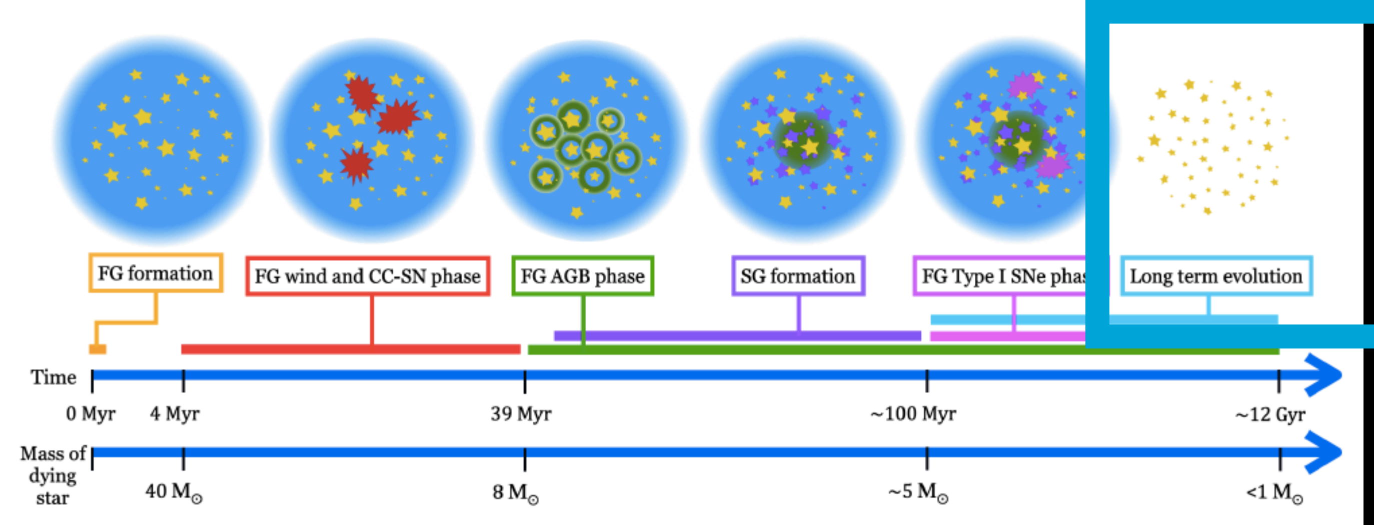
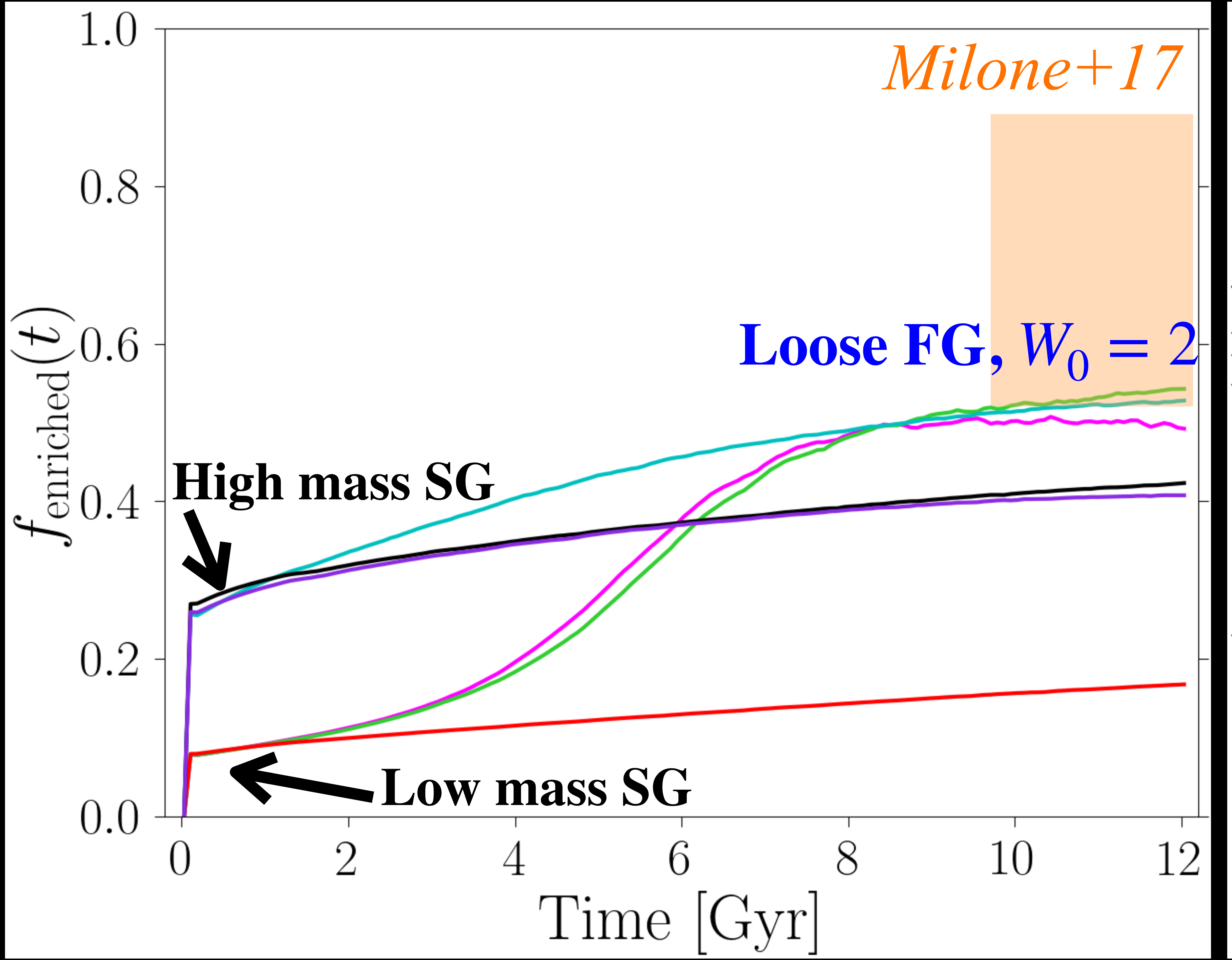
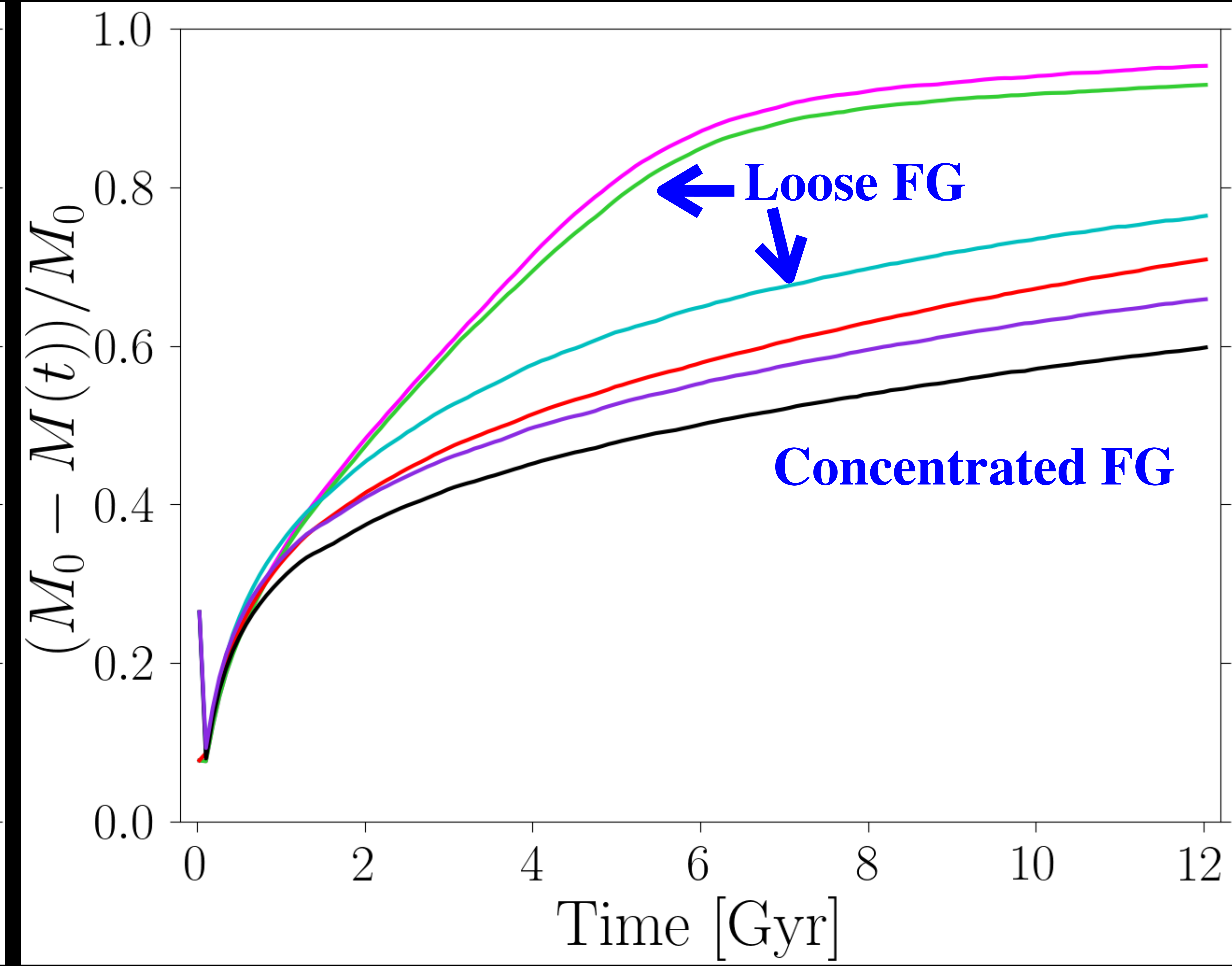


Figure 3.3: *Schematic visualization of the different phases of the formation of MPs in a GC in the AGB scenario, highlighting the main feedback sources in action as a function of time.* A

Only clusters with a compact and low mass SG inside a low-concentrated and massive FG can lead to what is observed





Take home messages & future prospects

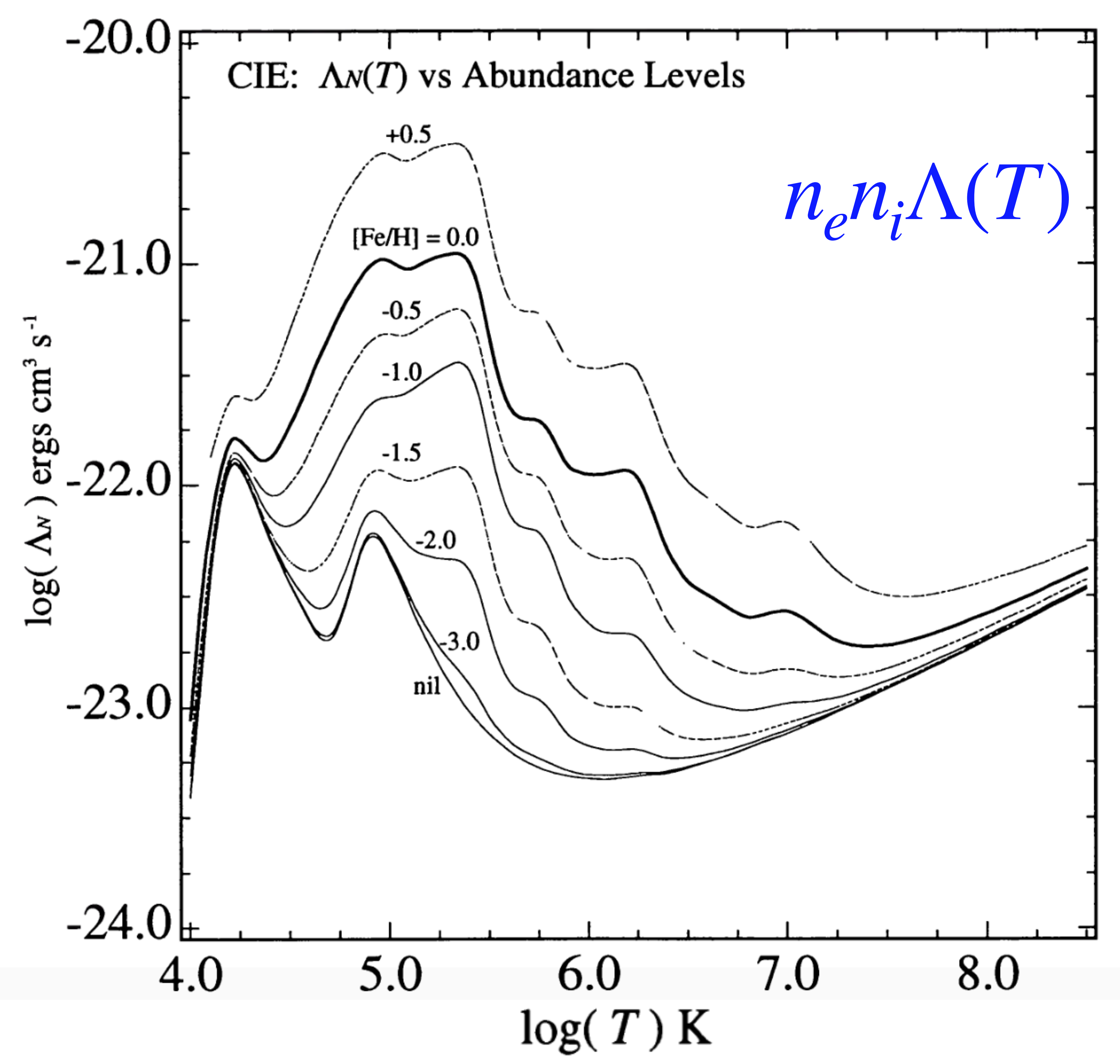
- ⋆ AGB scenario for multi-pop.s seems reasonable, but several issues still to clarify (e. g. role of massive stars)
- ⋆ SNe Ia are not able to halt the SF in very massive GCs. They significantly affect the chemical composition of SG stars
- ⋆ Significant mass loss can take place in clusters with loose FG and low mass SG reaching $f_{enriched}$ values comparable to the observed ones.
- ⋆ Studying the interplay between different physical processes together is fundamental to reach a deeper knowledge of MPs formation

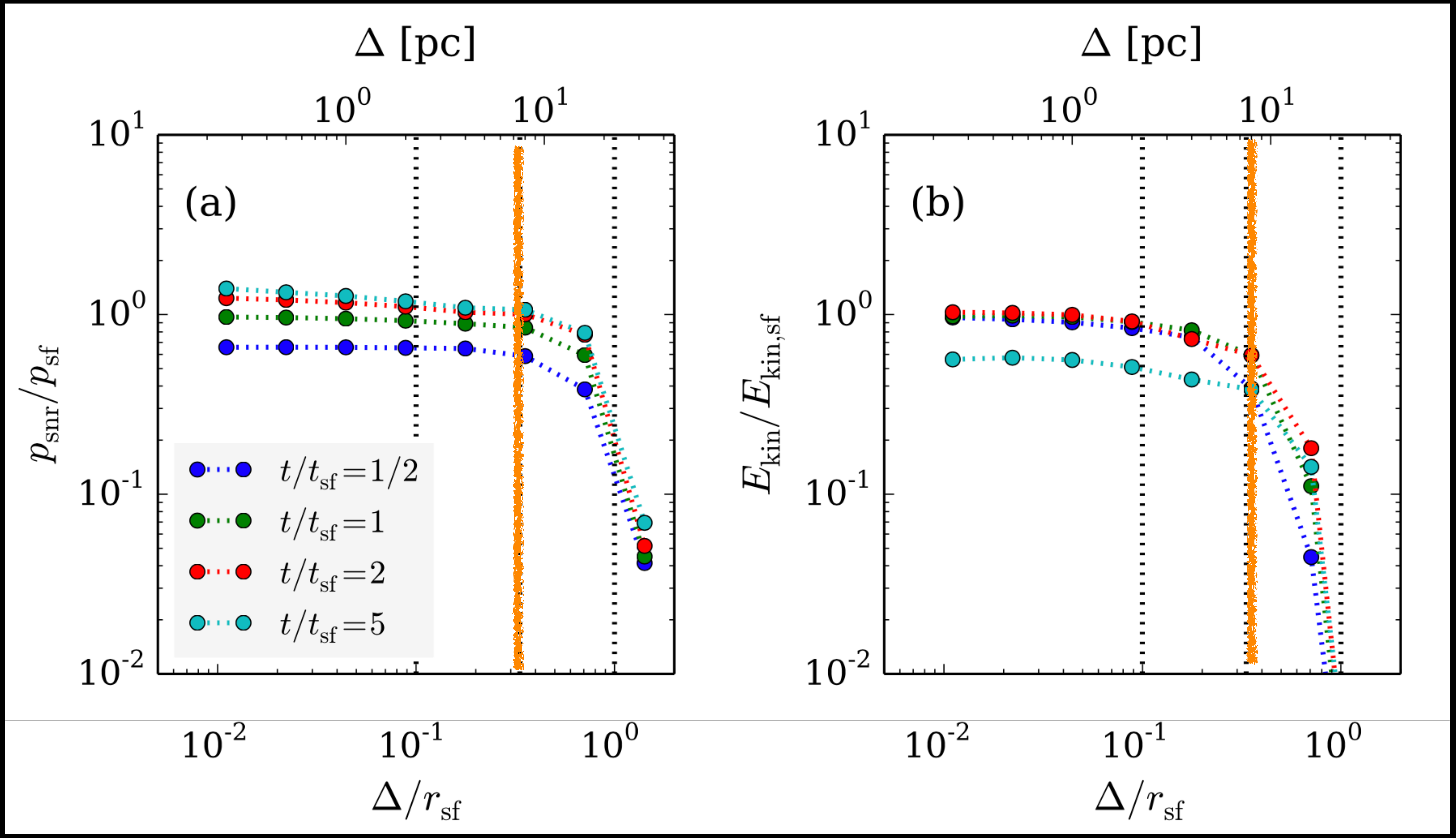
Backup slides

Sutherland & Dopita+93

Overcooling problem

insufficient numerical resolution artificially suppresses the dynamical impact of SN feedback to the surrounding medium





$$\Delta x < r_{sf}/3$$

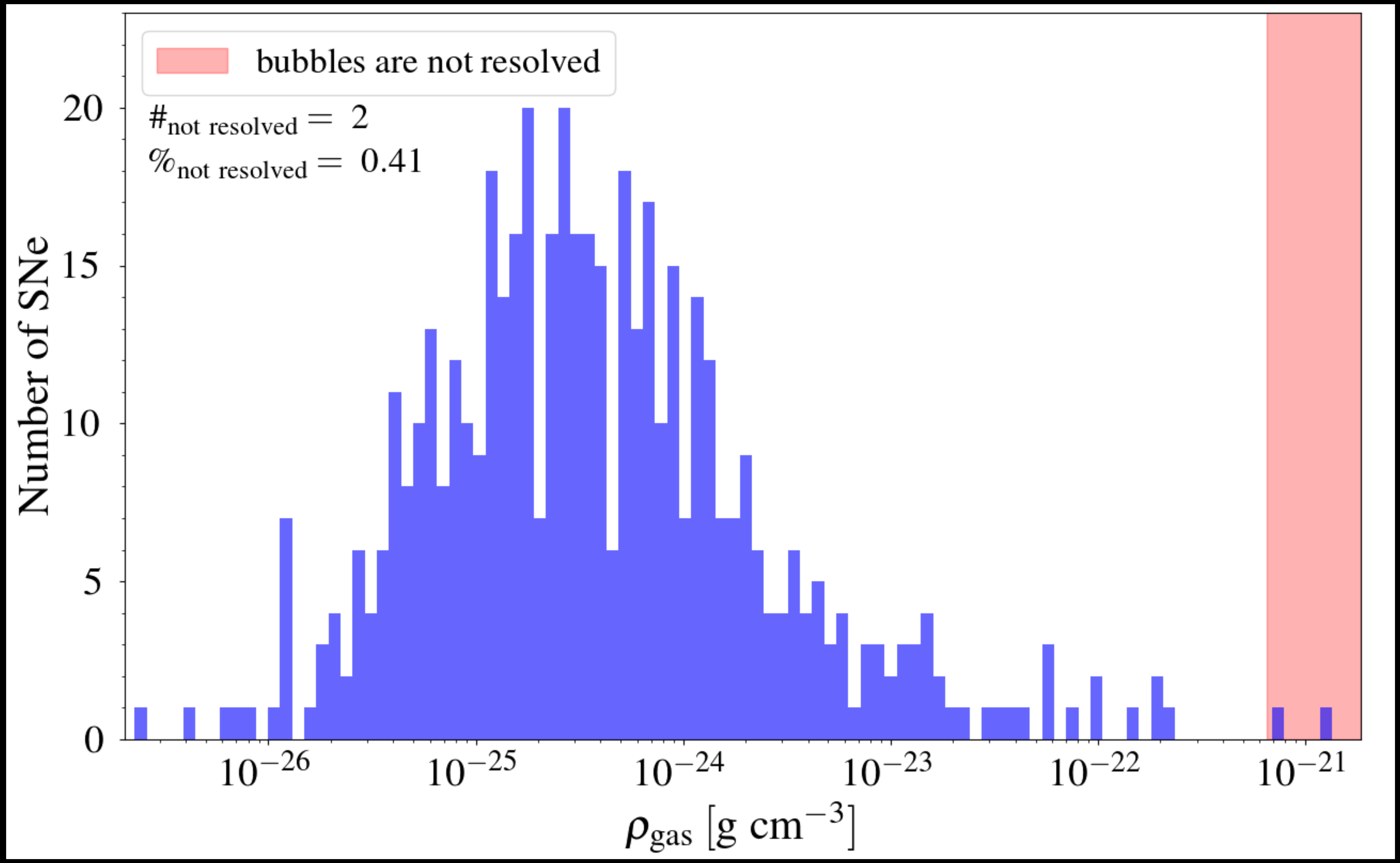
For a uniform medium:

$$r_{sf} = 22.1 \text{ pc } n_0^{-0.43}$$

Kim & Ostriker+15

Are the bubbles resolved?

Low density infall



High density infall