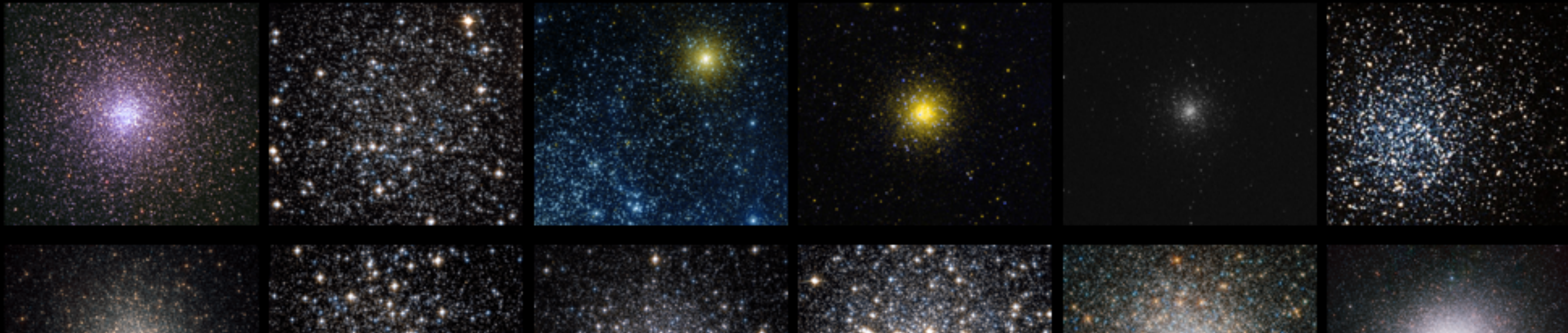

# Globular cluster ISM: how to get rid of it?


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# Galactic Globular clusters

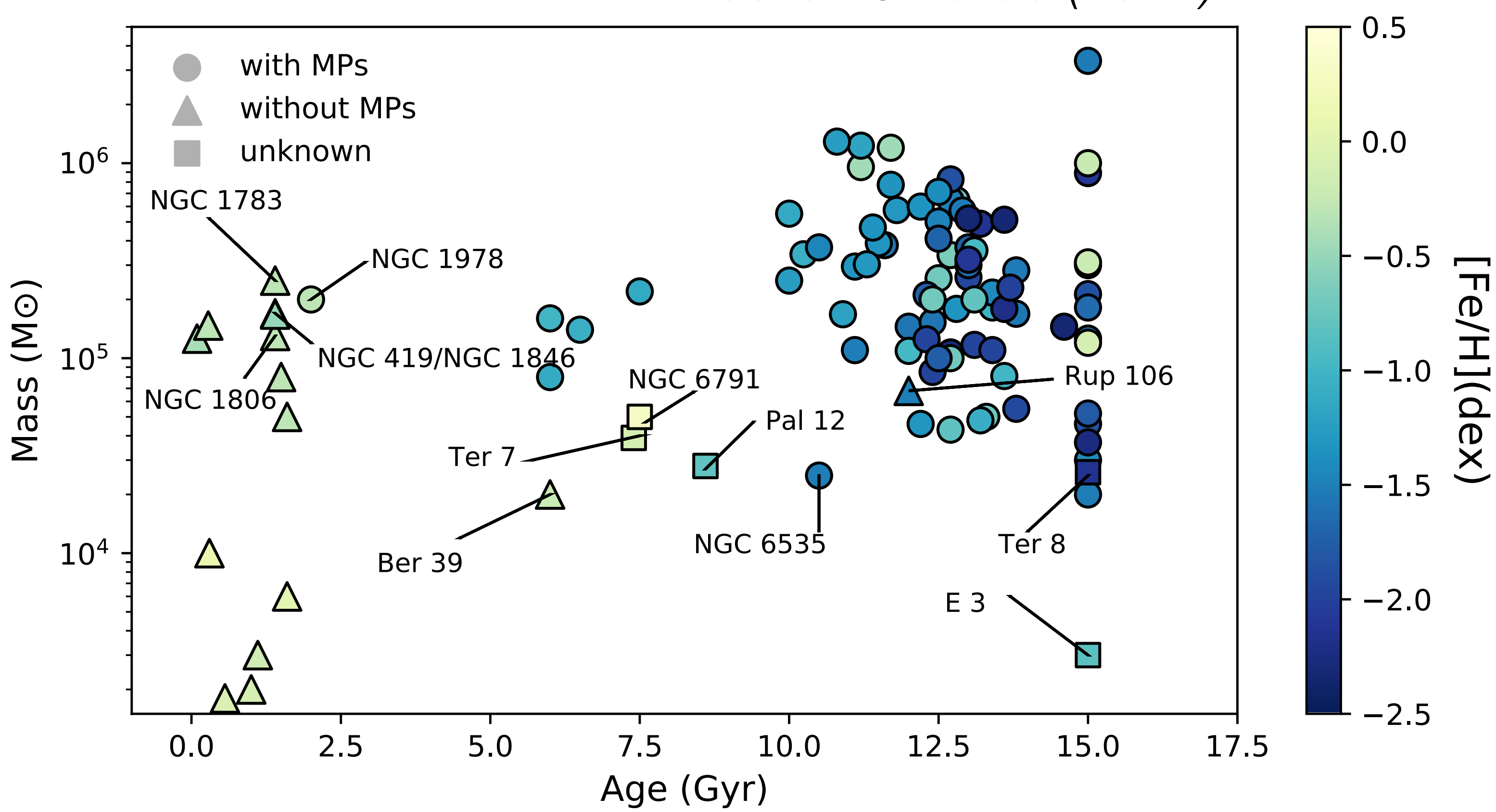
**Help to constrain:**

- **Star formation/assembly histories of the host galaxy**
- **Early chemical evolution of galaxies**
- **Distribution of dark-matter in present-day galaxies**
- **Stellar evolution models**

## The single stellar population paradigm is no more valid!

- **~150 globular clusters in the Galaxy**
- **Mass up to a few ~$10^6$ $M_\odot$**
- **-0.5 < [Fe/H] < -2.5**
- **9-13 Gyr**
- **$r_h$ ~ 5 pc; $r_t$ ~ 50 pc**
- **Up to $10^6$ stars /$pc^3$ in the center**

*Bastian & Lardo (2017)*



# Galactic Globular clusters

**NGC 104 (47 Tuc)**

**~12.5 Gyr**

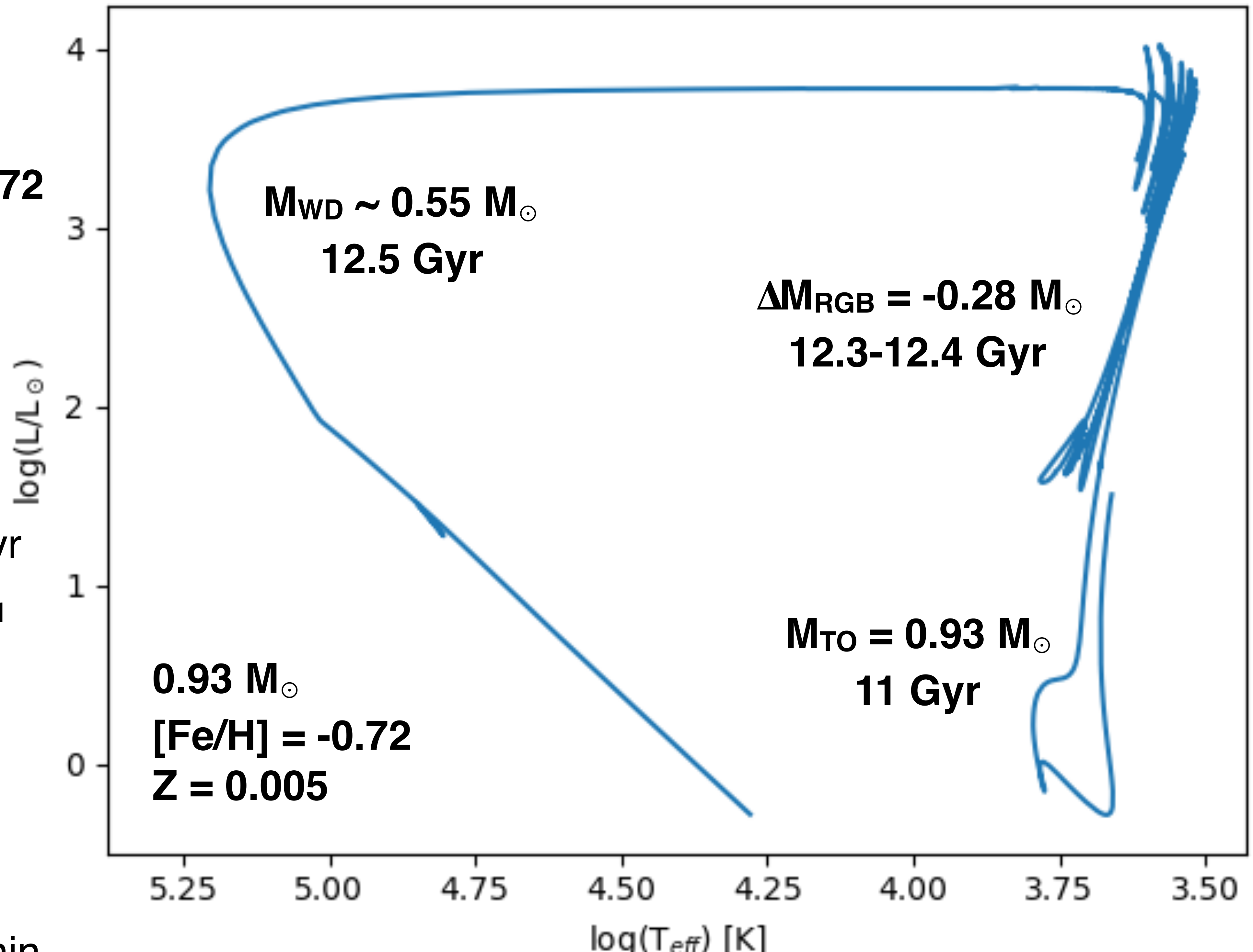
**7.8 x $10^5$ $M_\odot$, [Fe/H] = -0.72**

**Prediction**

- ~ 930 HB stars
- ~ 50-100 AGB stars
- $M_{lost}$ = ~260 $M_\odot$/100 Myr
- RGB $v_{wind}$ ~ 5-30 km.$s^{-1}$
- 47 Tuc $v_{esc}$ ~ 50 km.$s^{-1}$
- Accumulation of gas in the stellar cluster

**Observation**

- ~ 0.1 $M_\odot$ of plasma within the central 2.5 pc *(Freire et al., 2001)*



# Galactic Globular clusters ICM observations

**Observations in a large number of globular clusters**

***Dust***

- ~ 5 x $10^{-4}$ $M_\odot$ of dust in the core of M15/NGC7078 *(Evans et al., 2003)*
- ~ 9 x $10^{-4}$ $M_\odot$ of dust in the core of M15 *(Boyer et al., 2006)*

***Neutral gas***

- ~ 0.3 $M_\odot$ of neutral hydrogen in the core of M15 *(van Loon et al., 2006)*

***Ionised gas***

- ~ 0.1 $M_\odot$ of plasma within 2.5 pc of 47 Tuc *(Freire et al., 2001)*
- ~ 0.023 $M_\odot$ of plasma within 1 pc of 47 Tuc *(Abbate et al., 2018)*

- **Ram pressure stripping by the Galactic disc crossing.** ***Only every $10^8$-$10^9$ yr.***
- Flare stars mass loss heating the intracluster gas *(Coleman & Worden,1977). Flaring properties, numbers and distribution of M-dwarfs within GCs are highly uncertain.*
- Hot horizontal branch stars *(Vandenberg and Faulkner, 1977). 1D hydrodynamical simulations, however these stars are not present in all GCs.*
- Classical novae explosions *(Scott and Durisen, 1978; Moore and Bildsten, 2011)*. Novae much less common than previously thought, axisymmetric outflows, thus less efficient at removing gas from the cluster potential, especially in the most massive ones.
- Pulsar winds *(Spergel,1991). Model briefly investigating the energy requirement for lifting gas from a GC potential well (e.g. no study on the transmission of the energy to the ICM).*
- X-ray bursters *(Yokoo & Fukue,1992). Model briefly investigating the energy requirement for lifting gas from a GC potential well.*
- Stellar wind heating the intracluster gas *(Smith,1999; Naiman et al. 2018). 1D hydrodynamical simulations including only mass and energy input from stellar winds.*
- Accretion onto stars *(Thoul et al., 2002).*
- Stellar collisions *(Umbreit et al., 2008). Collisions too infrequent to clear ICM in time-scales of the order of ~Myr (required for some GCs).*
- Fast winds *(Smith et al., 2004: Dupree et al., 2009). Only 40% of the outflows have sufficient speed as to allow escape of material from the globular cluster.*
- Ram pressure stripping by Galactic halo medium *(Frank & Gisler, 1976: Priestley et al., 2011). Cannot effectively strip material from the most massive clusters.*
- Accretion onto compact stellar remnant *(Leigh et al., 2013).*
- UV radiation from WDs *(McDonald & Ziljstra, 2015).*

# GCs motion through the Halo

***(Priestley et al. 2011)***

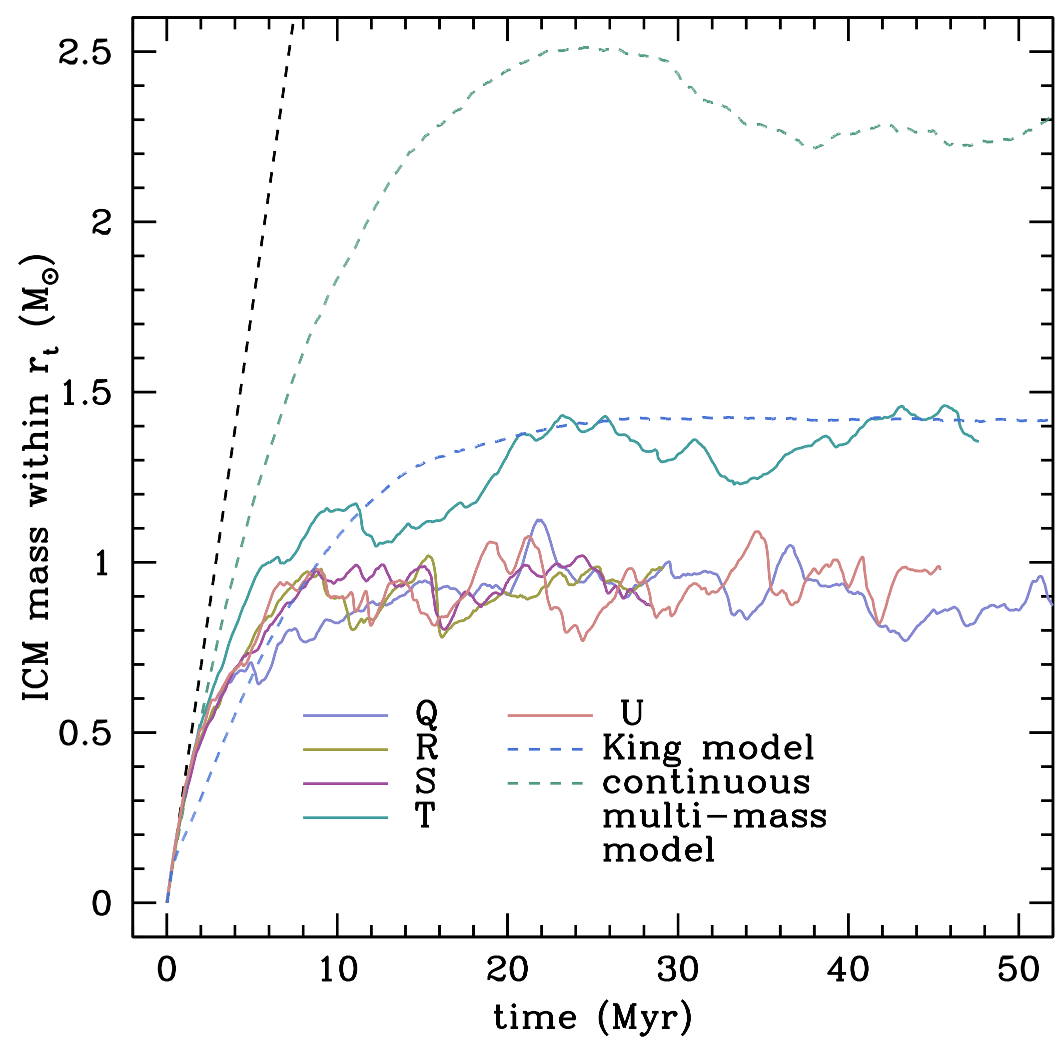
**3D hydrodynamical simulations: discrete multi-mass stellar population**

- Neglect N-body calculations
- $v_{GC}$ = 200 km $s^{-1}$, $\rho_H = 10^{-27}$ g.cm$^{-3}$, $T_H = 10^{5.5}$ K, $\alpha = 1 \times 10^{-19} s^{-1}$

- Can strip the ICM of a $10^5$ $M_\odot$ GC
- Predict a detectable medium for a $10^6$ $M_\odot$ GC

**Discrete multi-mass stellar population mandatory**

**Needs an additional mechanism to strip the ICM of massive GCs**



# Ionisation by post-AGB stars and WDs

***(McDonald et al. 2015)***

**Analytical study of the ionising flux produced by post-AGB stars and WDs in 47 Tuc:**

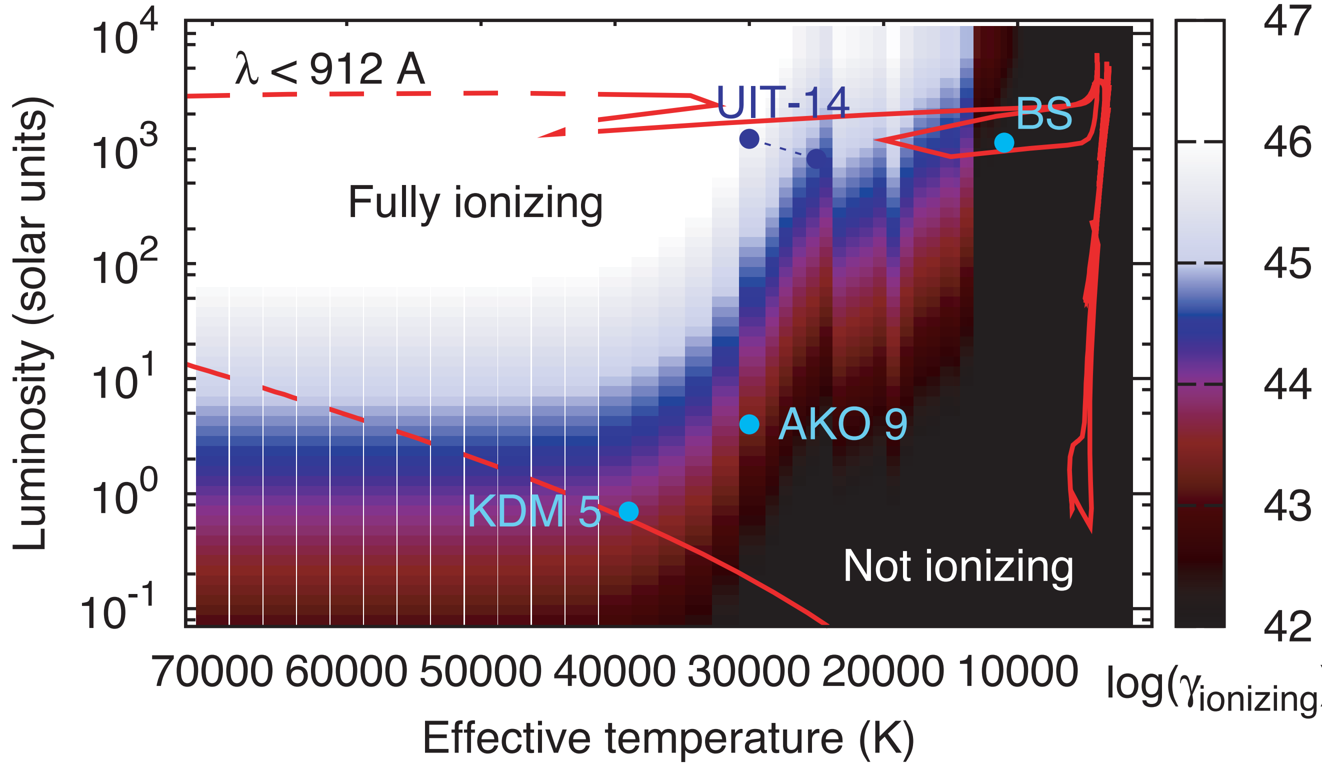
- Recombination rate of hydrogen in the cluster + $M_{loss}$ by the GC
- 1.6 x $10^{44}$ ionising photons $s^{-1}$ for ionisation of the ICM

**High energy sources**

- γ-ray pulsars: ~9 x $10^{31}$ ionising photons $s^{-1}$
- Brightest X-ray sources: ~9 x $10^{31}$ ionising photons $s^{-1}$

**UV sources**

- ***B8***, bright post-AGB star: 4 × $10^{41}$ ionising photons.$s^{-1}$
- ***UIT-14***: 1 × $10^{44}$ - 5 × $10^{45}$ ionising photons.$s^{-1}$
- ***AKO9***, WD: 3 × $10^{44}$ ionising photons.$s^{-1}$
- ***KDM5***, WD: 8 × $10^{43}$ ionising photons.$s^{-1}$



# Ionisation by post-AGB stars and WDs

***(McDonald et al. 2015)***

**Summary:**

- Each WD can ionise all the material injected into the cluster by stellar winds for ~3 Myr
- ~40 such WDs exist at any point
- WDs can continually ionise the observed ICM of 47 Tuc **(between $2 \times 10^{46}$ and $8 \times 10^{47}$ ionising photons.$s^{-1}$)**
- Pressure-supported ICM -> expansion over the cluster's tidal radius

**Observations:**

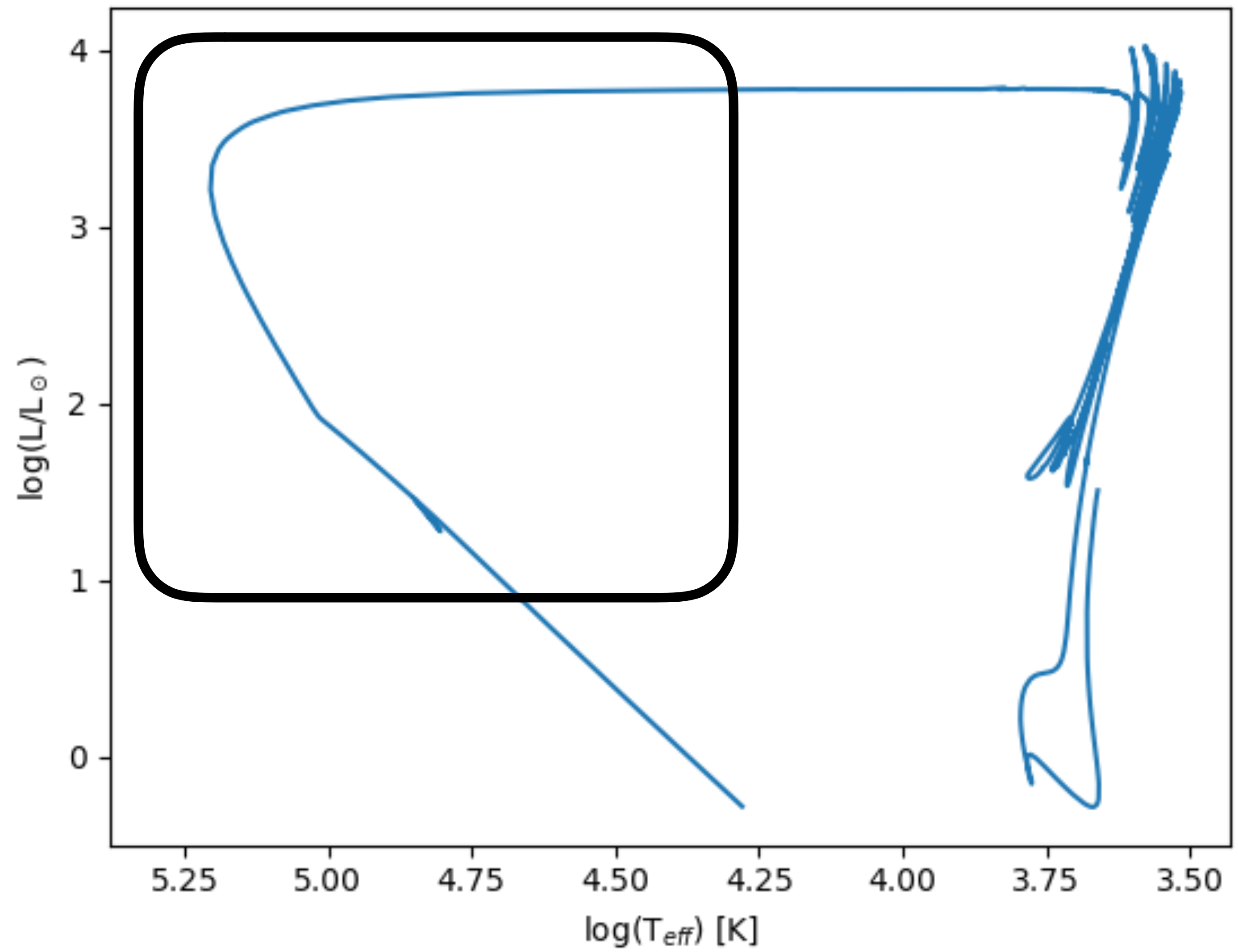
- ~ $9 \times 10^{-4}$ $M_\odot$ of dust in the core of M15/NGC7078 *(Boyer et al., 2006)*
- ~ 0.3 $M_\odot$ of neutral hydrogen in the core of M15 *(van Loon et al., 2006)*
- Neutral cloud in M15? Temporary overdensity?
- -> Uncertainties on the recombination rate of hydrogen in the cluster
- -> Evolutionary rates of post-AGB stars and early WDs

# Ionisation by post-AGB stars and WDs

***Project in collaboration with Pawel Biernacki***

**SED**

- 0.93 $M_\odot$ (12.5 Gyr)
- [Fe/H] = -0.72 / Z = 0.005
- L ~ 3700 $L_\odot$
- $T_{eff}$ ~ 95000 K
- Black-body approximation




**Parameters for the RAMSES simulation:**

- SED from post-AGB stars / WDs
- $10^6$ $M_\odot$ cluster with Chabrier IMF from 0.08 to ~0.9 $M_\odot$
- Ambient density of $1\times10^{-3}$ H.cm$^{-3}$, T/mu = $1\times10^6$ K and Z = 0.005
- $v_{wind}$ = 20 km.s$^{-1}$, $\alpha = 2.55 \times 10^{-12}$ $M_\odot$ .yr$^{-1}$ $M_\odot^{-1}$
- 120 pc box, resolution of ~0.12 pc
- -> $1.44 \times 10^{47}$ ionising photon.s$^{-1}$

# Ionisation by post-AGB stars and WDs

*Project in collaboration with Pawel Biernacki*

**Early results:**

- ICM ionised in less than 0.1 Myr
- Slight diffusion of the ICM after a few Myrs

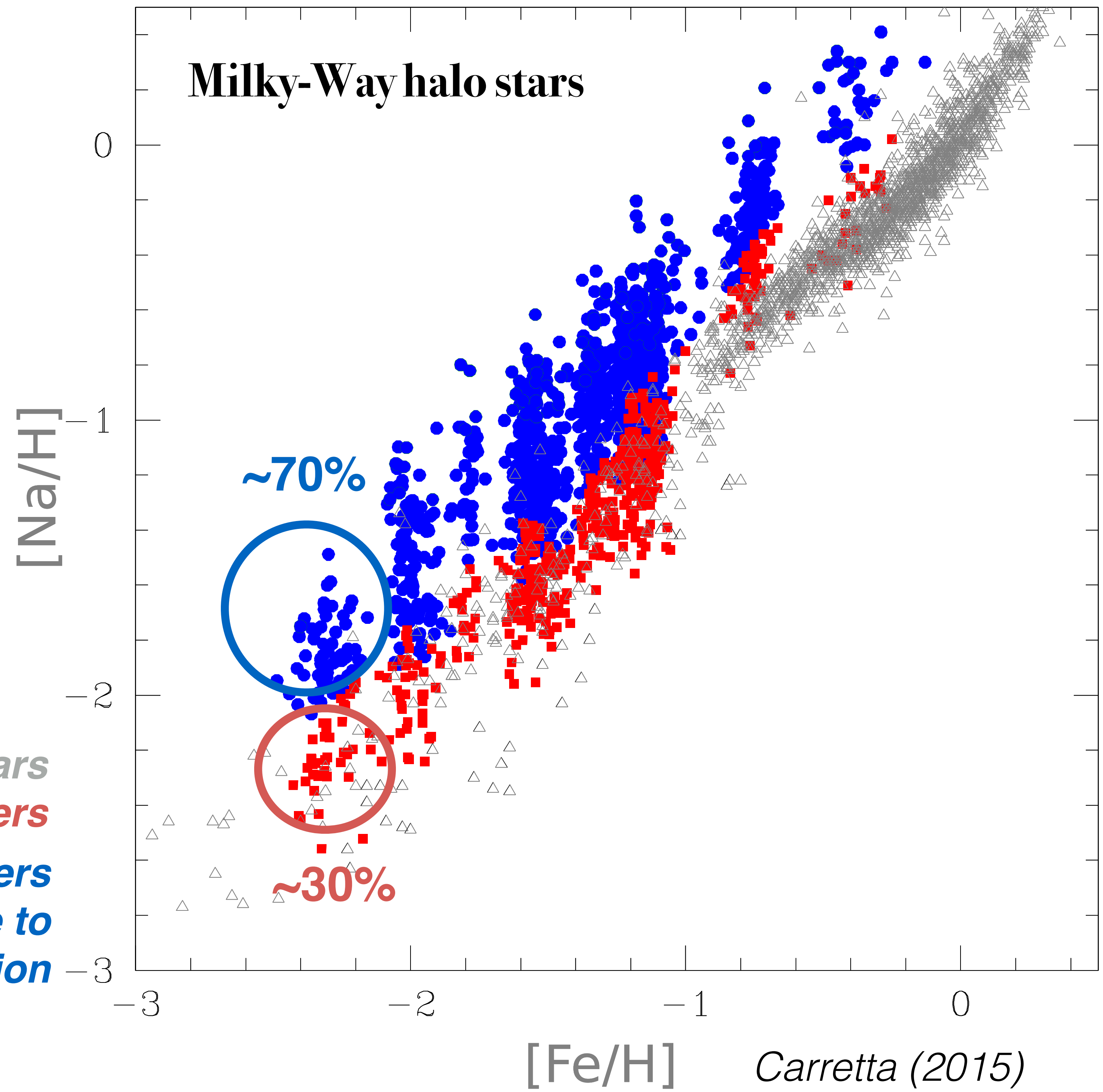
**Next steps:**

- More appropriate discret multi-mass stellar population for globular clusters as initial conditions *(LIMEPY, Gieles & Zocchi 2015 )*
- SED from atmosphere models
- Changing SED as a function of time and stars
- Motion of the cluster through the Galactic halo *(Priestley et al. 2011)*

# The multiple stellar populations paradigm

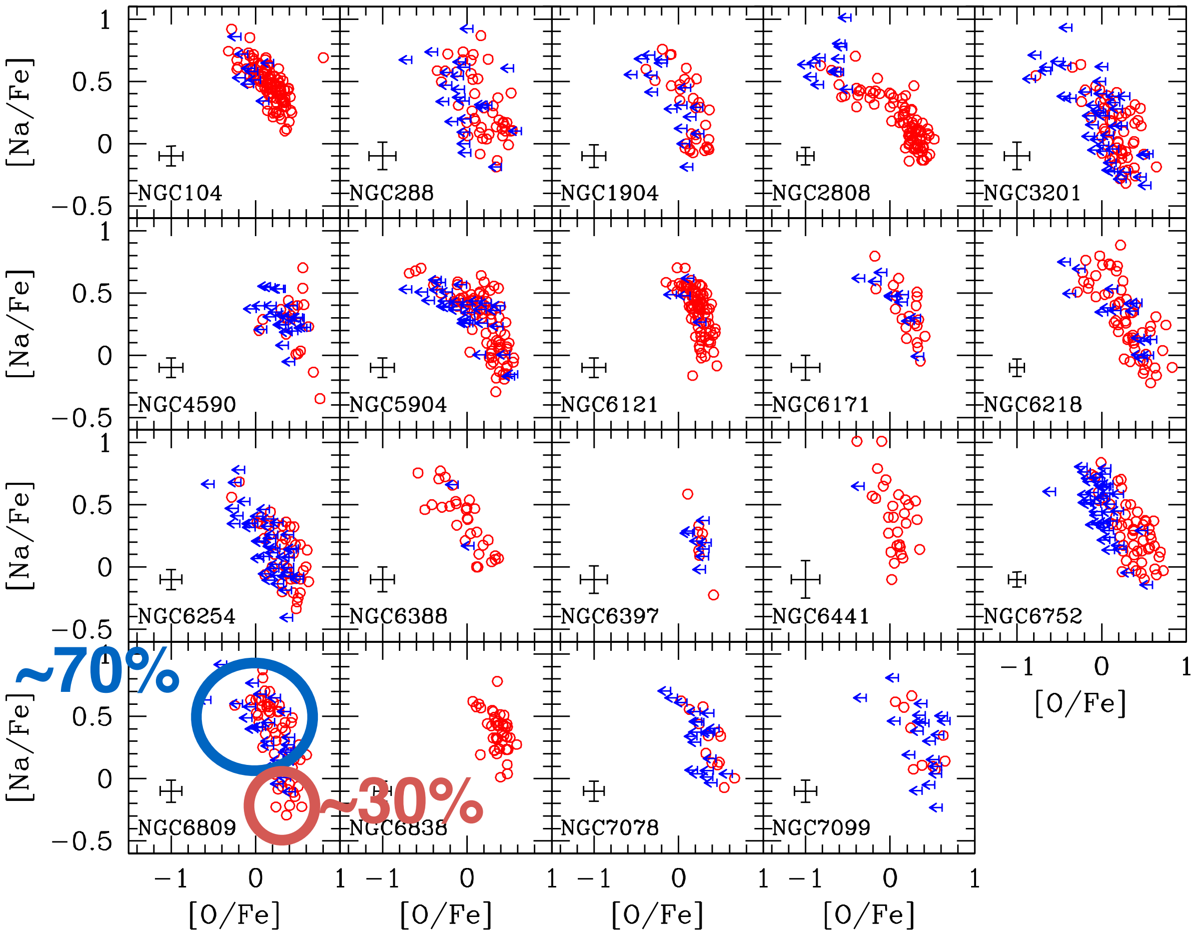
# The multiple stellar populations paradigm

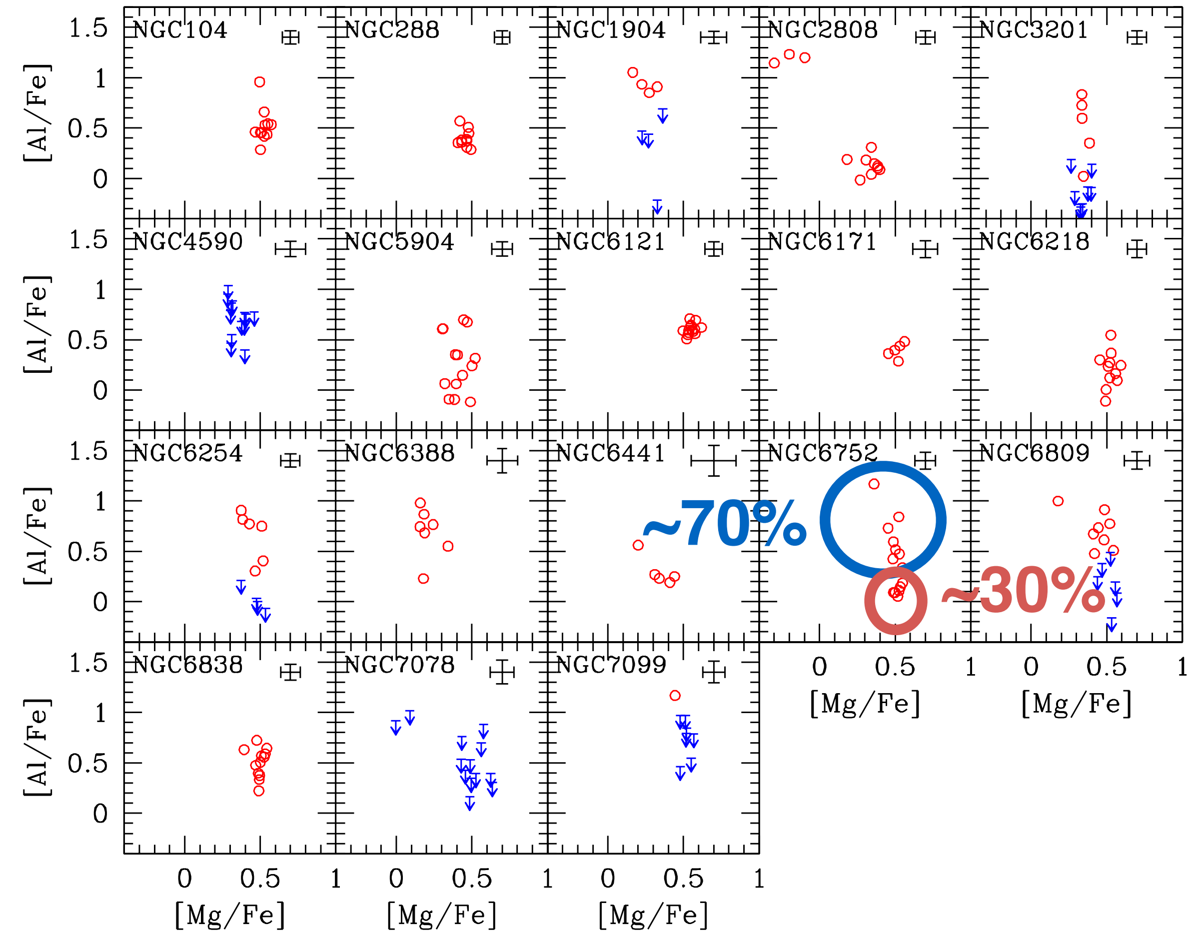
## Non standard chemical evolution in globular clusters compared to the Galactic chemical evolution




*Field stars*
*Stars of globular clusters*
*Stars of globular clusters with sodium variations not due to Galactic chemical evolution*

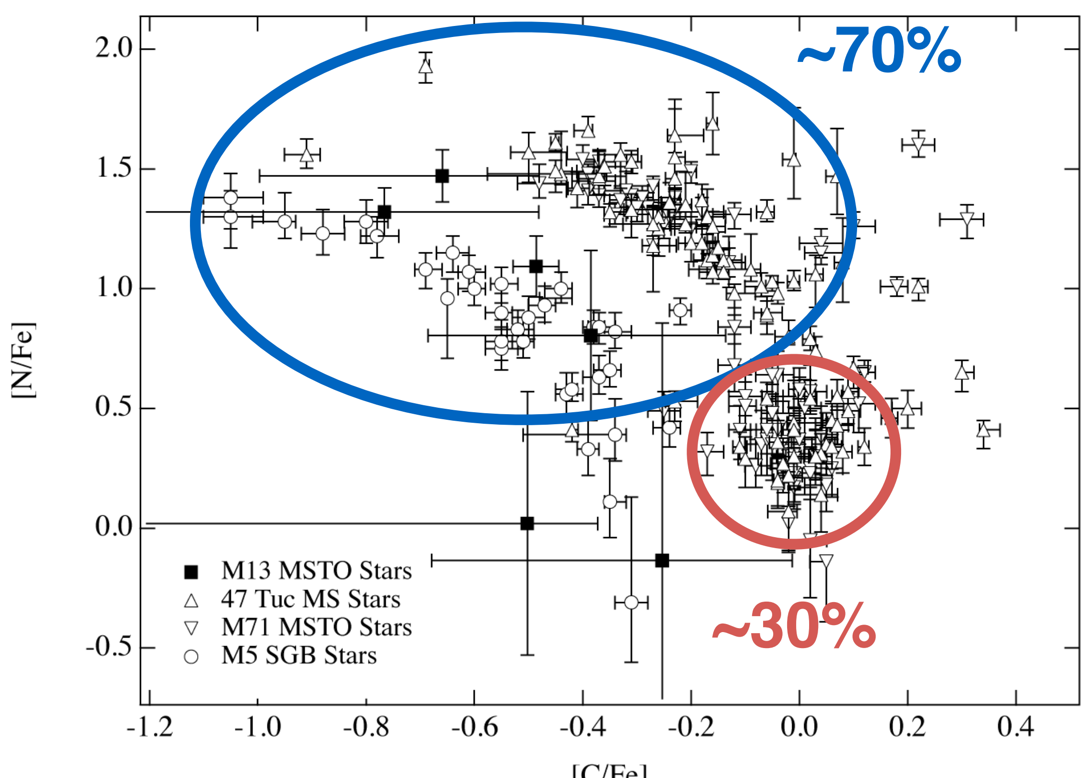
# The multiple stellar populations paradigm




**RGB stars, UVES and GIRAFFE (VLT)**

*Carretta et al. (2009)*




**MS stars, compilation from literature** Figure 6

*Briley et al. (2004)*

# The multiple stellar populations paradigm

**General abundance patterns are the result of hydrogen burning at high temperature**

**CNO cycle**

CN cycle above ~15 MK

NO cycle above ~20 MK

C+N+O mass fraction constant

**H, $^{16}$O,$^{12}$C,$^{12}$C/$^{13}$C**

**$^{4}$He,$^{13}$C,$^{14}$N**

**NeNa and MgAl chains**

NeNa chain above ~25 MK

**$^{23}$Na**

**$^{20}$Ne**

MgAl chain above ~50 MK

**$^{27}$Al**

**$^{24}$Mg**

**Multiple stellar populations needed, main hypothetical sources:**

**Intermediate-mass asymptotic giant branch stars (6.5-8 $M_{\odot}$)**

*D'Antona et al. (1983); Ventura et al. (2001); Ventura et al. (2013)*

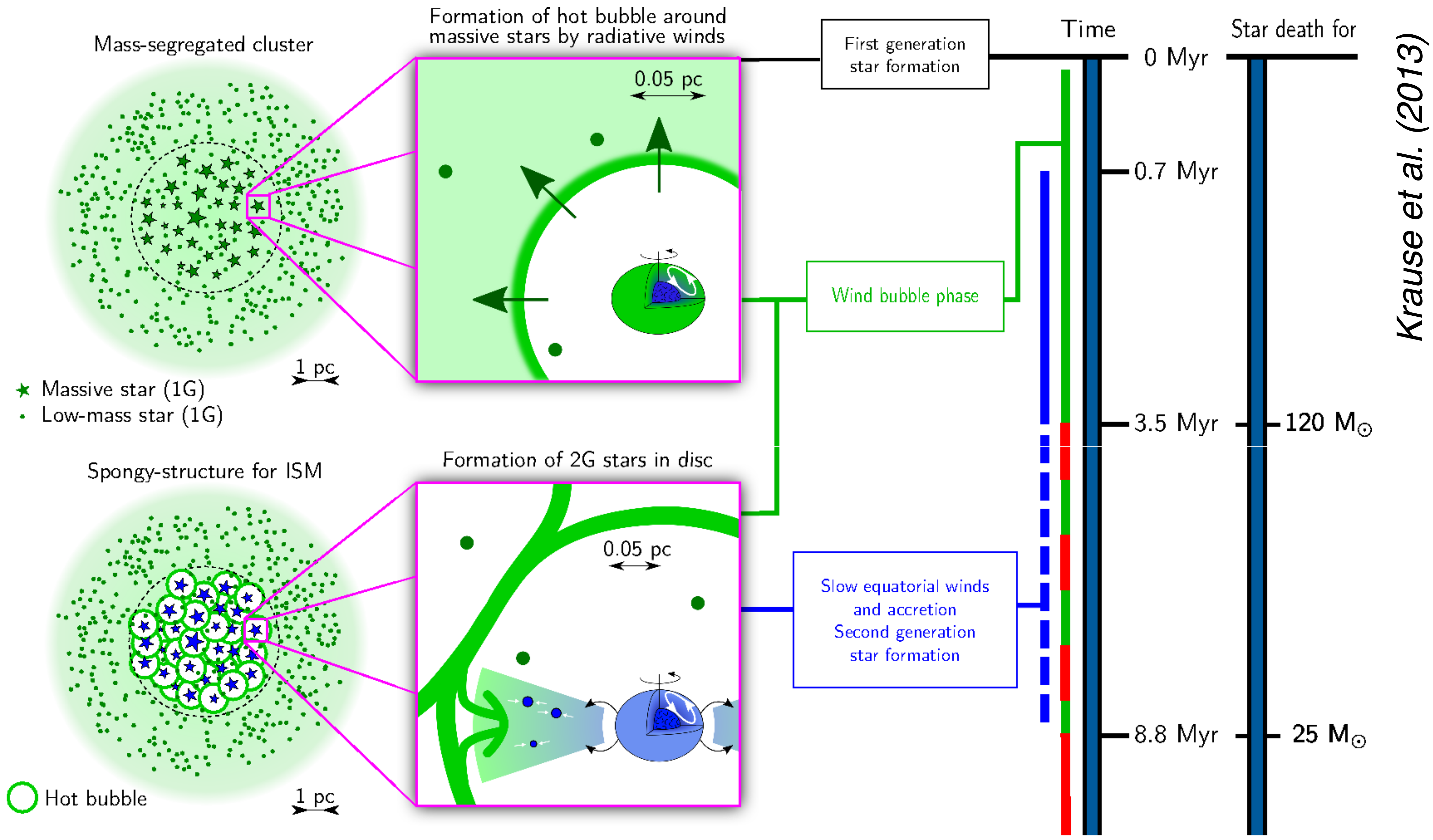
**Super-massive stars ($M > 10000\ M_{\odot}$)**

*Denissenkov and Hartwick (2014); Denissenkov et al. (2015); Gieles et al. (2018)*

**Fast rotating massive stars ($25\ M_{\odot} < M < 120\ M_{\odot}$)**

*Maeder and Meynet (2006), Prantzos and Charbonnel (2006), Decressin et al. (2007a,b)*

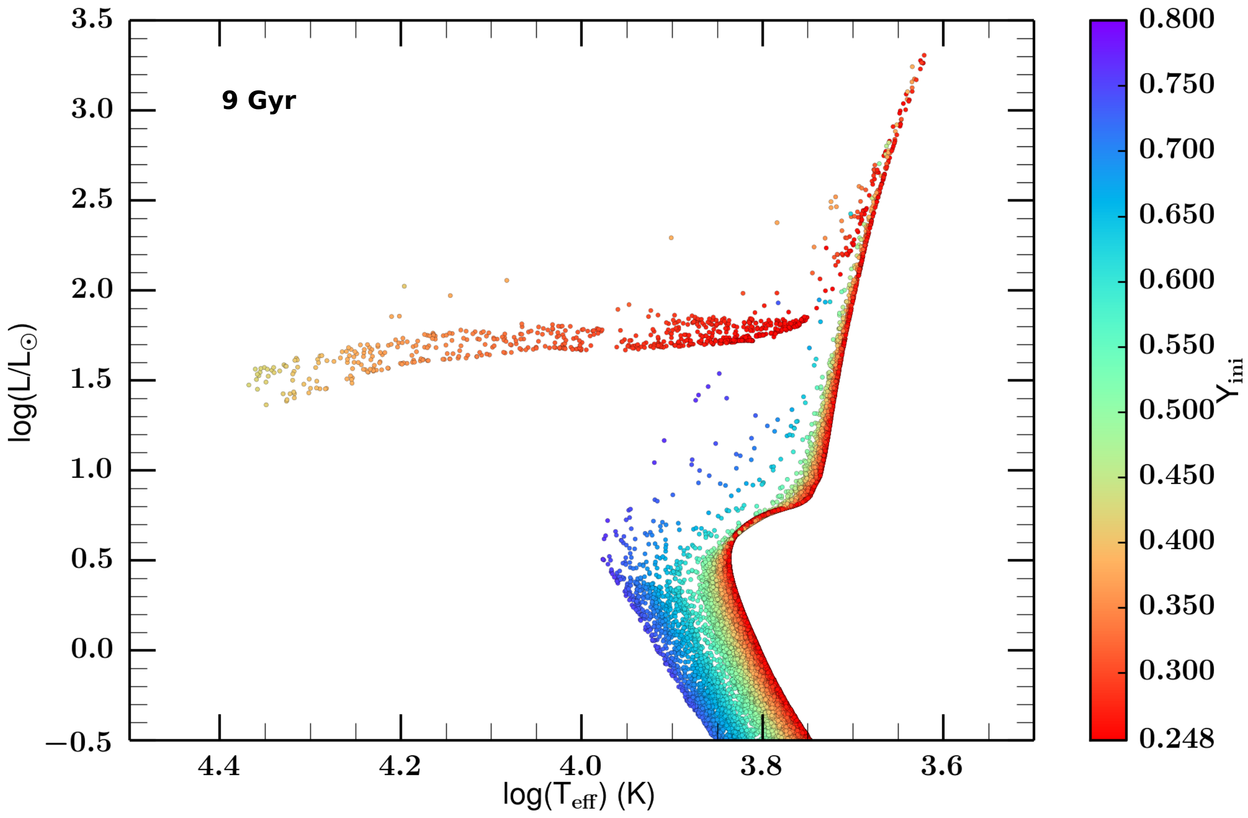
# The fast rotating massive stars scenario




Matter ejected via slow mechanical/equatorial wind and mixed with ICM to form a disc/ bubble around the star wherein the second population of low-mass stars will form

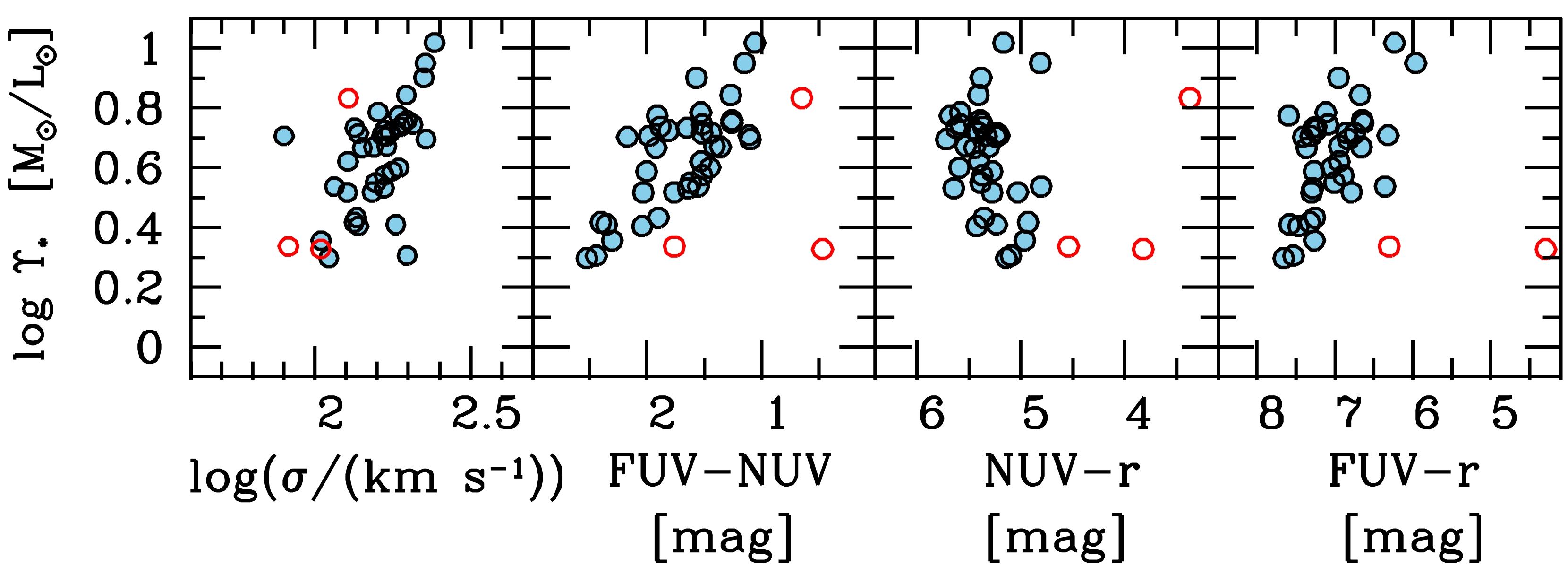
# The multiple populations paradigm

*Chantereau et al. (2016)*



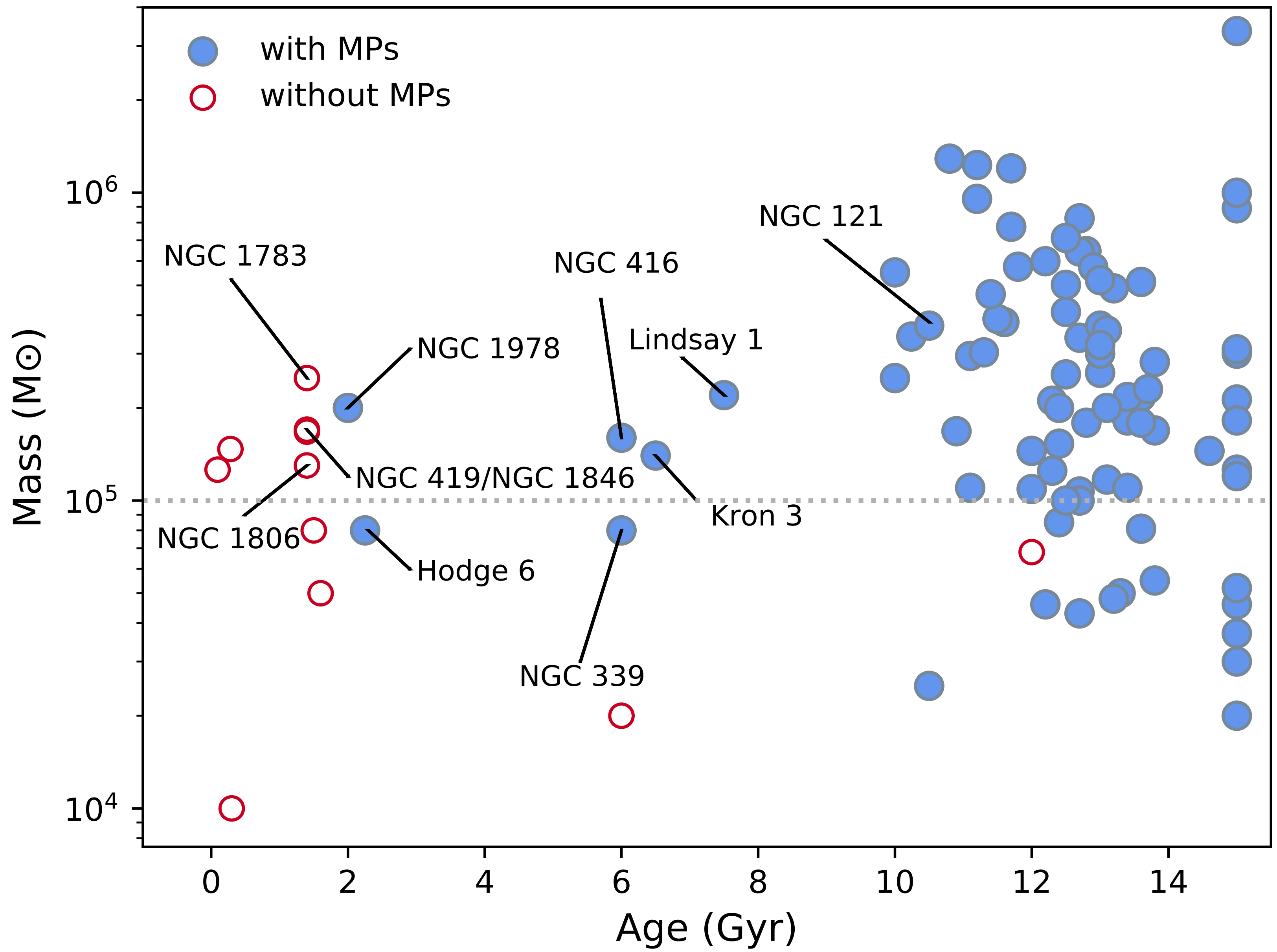

Multiple stellar populations are hotter and brighter

*Zaritsky et al. (2015)*




Very high far UV-luminosities, 'UV-upturn' phenomenon present in ETGs

# The multiple populations paradigm




*Hollyhead et al. (submitted)*

Present in all most clusters regardless of the environment, questioning the formation of stellar populations in stellar clusters

**A dozen of proto-GC in action associated with a few high-z galaxies can produce ~ 20% of the total Lyα luminosity observed** ***(Vanzella et al. 2017, 2018)***

- **GCs’ ICM ionised and diffused by extreme UV sources + ram pressure Halo stripping to get rid of the ICM**
- **Need to investigate overdensities in GCs**

- **Hydrodynamical simulations mandatory to understand the multiple populations paradigm and the formation of stellar populations in stellar clusters**