Multiple stellar populations in globular clusters

Constraints from nuclear physics and the formation scenarios

Corinne Charbonnel

Main collaborators in the field
N.Prantzos, M.Krause, M.Gieles, D.Schaerer
N.Bastian, F.Primas, K.Lind
T.Decressin, W.Chantereau, Y.Wang, T.Dumont

Multiple stellar populations in globular clusters

Why do we care?

Aggregates of ~ $10^5 - 10^7$ stars packed into a small volume ~ (10 pc - 30 pc)^3

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GCs – Tools for cosmology

Milky Way GCs range among the oldest objects of the Universe (11 to 13.5 Gyr for the oldest ones)

→ Independent probe (vs CMB) of the **age of the Universe**

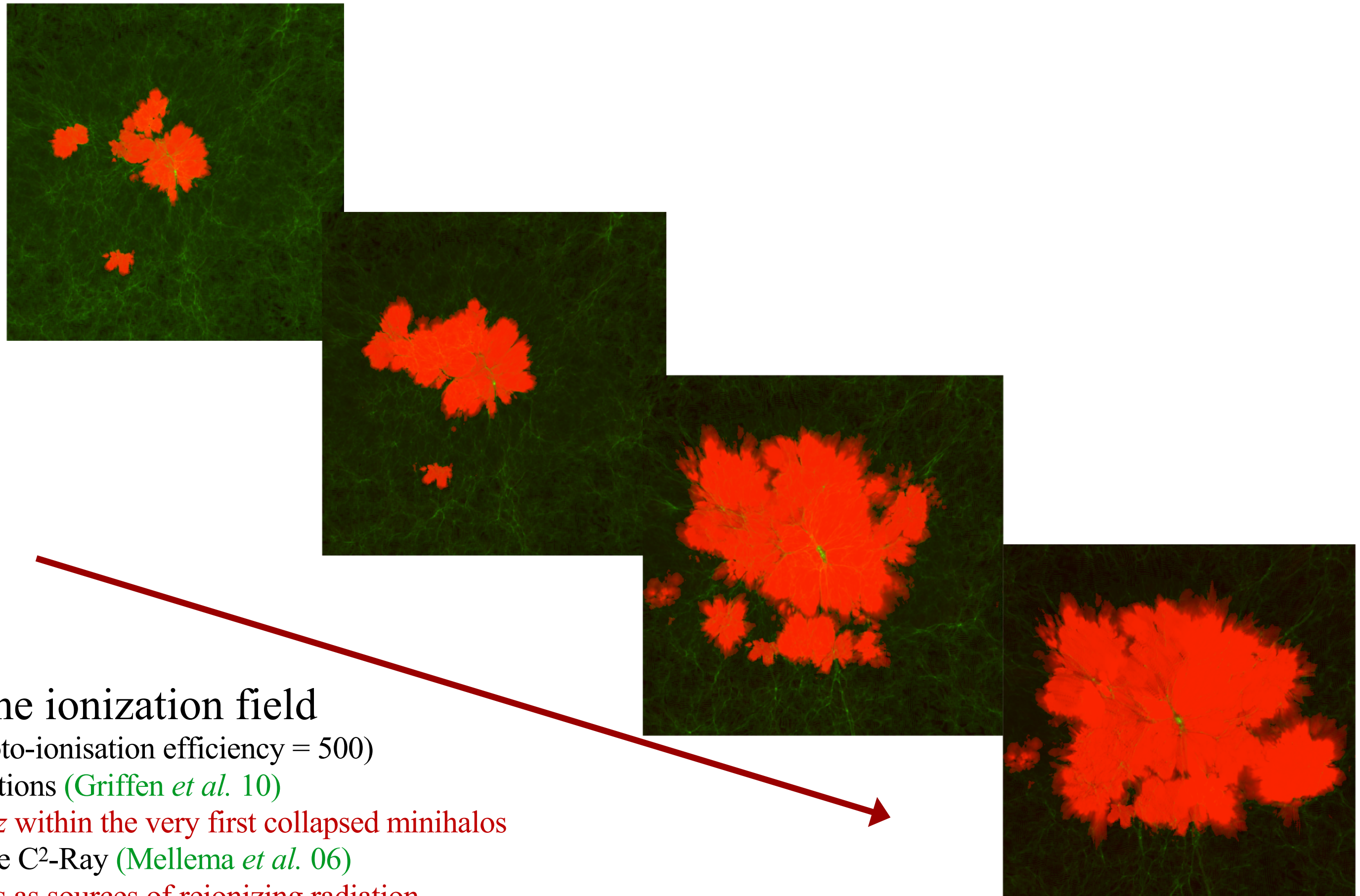
GCs – Tools for cosmology

\# Milky Way GCs range among the oldest objects of the Universe (11 to 13.5 Gyr for the oldest ones)

→ Independent probe (vs CMB) of the **age of the Universe**

\# GCs are potential important contributors to the **reionization** process at high-*z*

e.g. Ricotti (02) Schaerer & Charbonnel (11)



Time evolution of the ionization field

(Spatial size 460 h^{-1} kpc; photo-ionisation efficiency = 500)

Aquarius dark-matter simulations (Griffen *et al.* 10)

→ GC formation at high-*z* within the very first collapsed minihalos

\+ 3D, non-eq. chemistry code C^2-Ray (Mellema *et al.* 06)

→ Model metal-poor GCs as sources of reionizing radiation

GCs – Guides to galaxies

Intrinsically bright objects that can be observed at large distances in MW and external galaxies

Found in **galaxies of all Hubble types**

Very similar ∀ the parent galaxy

→ **Common path** in the early phases of galaxy evolution

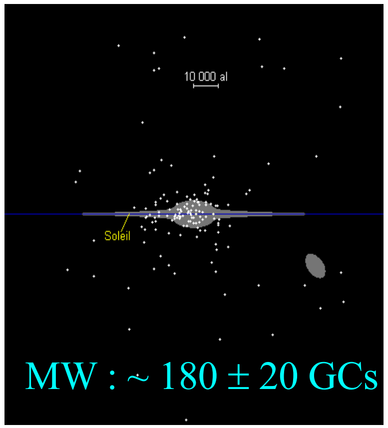
Specific frequency (the number of GCs in a galaxy divided by the galaxy's luminosity,) depends on galaxy morphology (higher in ellipticals than in spirals)

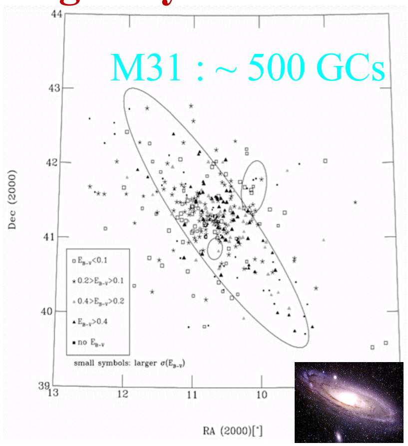
Observed correlation between the number of GCs and the virial mass of their host dark matter halos (∀ galaxy morphology) → Suited for high-precision **determination of M_{VIR}**

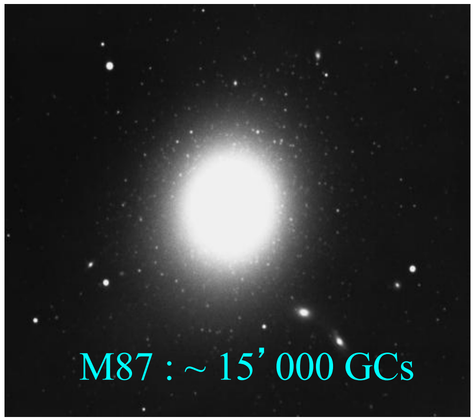
→ Dynamical tracers of the luminous and dark matter distribution at large (kpc) scales

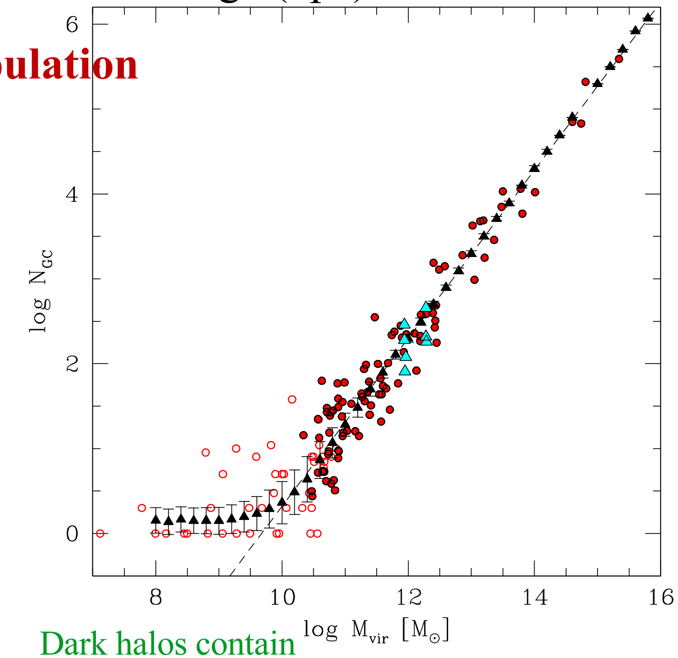
#Probe **hierarchical cosmological merging of a high-z halo seed population** that hosted a number of GCs per dark matter mass

→ Clues on **galaxy formation and halo growth**









Harris (99)

Barmby *et al.* (00)

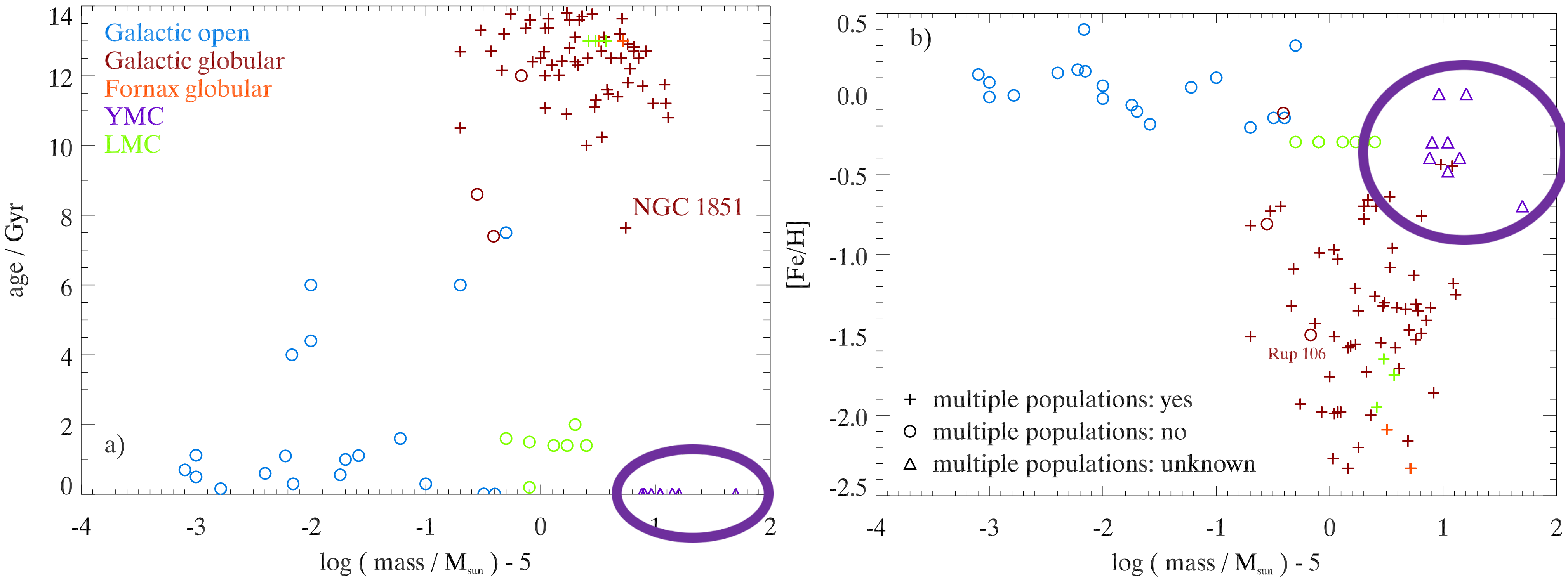
Dark halos contain 5×10^9 $M_\odot$ of dark matter per GC

Burkert & Forbes (2019)

GCs – Guides to cluster formation

Milky Way GCs :
Old, age spread ~ 25 %

GCs are not all uniformly old
LMC, SMC, M31 and M33 contain intermediate-age and young GCs – **YMSC**



Krause, Charbonnel *et al.* (16)

GCs – Guides to cluster formation

Milky Way GCs :
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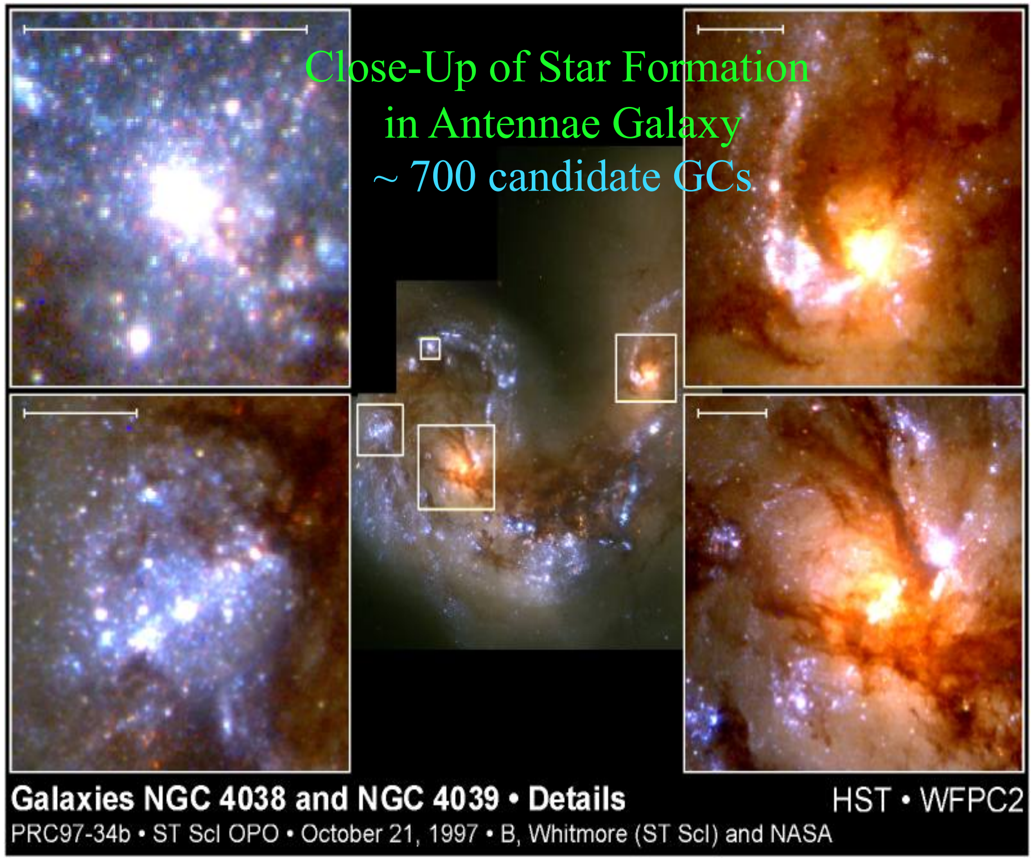
LMC, SMC, M31 and M33 contain intermediate-age and young GCs – **YMSC**

Evidence for continued formation of very massive clusters in Local Group galaxies, and in ongoing mergers and starburst galaxies
→ Clues on **star formation** in various environments and at different redshifts

→ Are such forming and YMSC the modern counterparts of the **proto-GCs**?

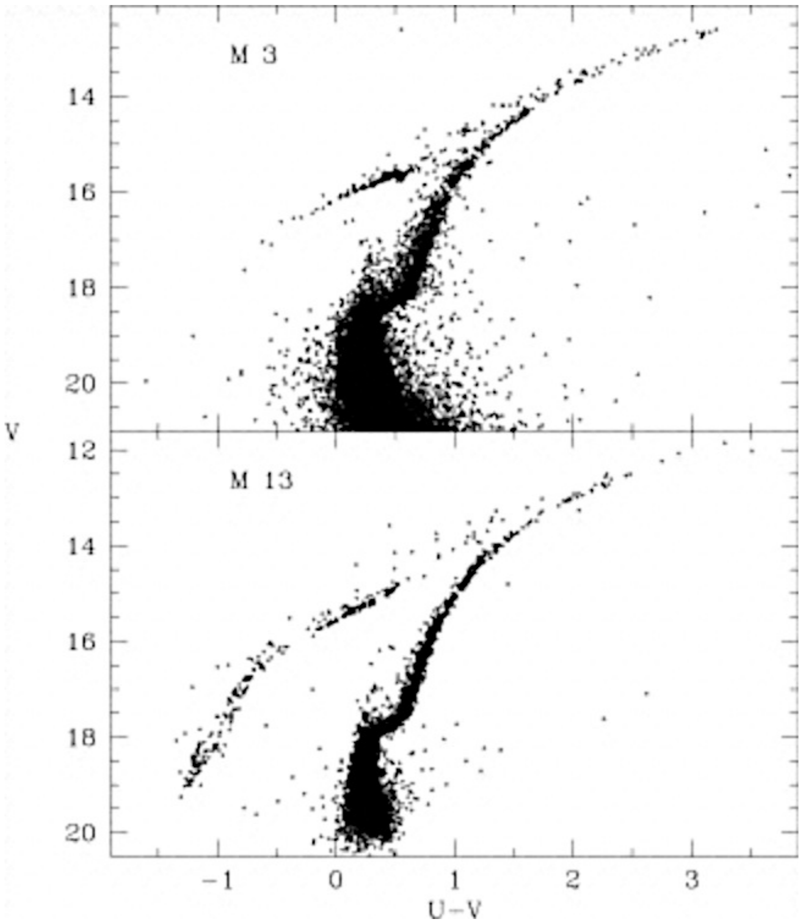


GCs – Guides to stars

Contain ~ 10^5 – 10^7 stars packed into a small volume ~ (10 pc - 30 pc)^3,
with the same [Fe/H] abundance (except Ω Cen and a few (rare) others);
broad [Fe/H] range (~ -2.3 to ~ -0.3) from cluster to cluster

Host a wide variety of interesting and unusual objects (millisecond pulsars, blue stragglers, low-mass X-ray binaries, …)

→ Natural laboratories to study **stellar evolution (and formation!)**



Nuclear physics laboratories

GCs – Formation

GC studies bring insight on
- cosmology,
- galaxy formation and evolution,
- stellar dynamics,
- stellar evolution.

But their formation mechanism and evolution are still poorly understood

Multiple stellar populations in globular clusters

Spectroscopy and photometry
Towards a new paradigm

GC = single, coeval stellar population
born with homogeneous chemical composition

Classical paradigm

Most GGCs are mono-metallic

No internal scatter in
alpha-elements (Si, Ca)
neutron-capture elements (Ba, La, Eu)
iron-peak elements (Bi, Cu, Mn)

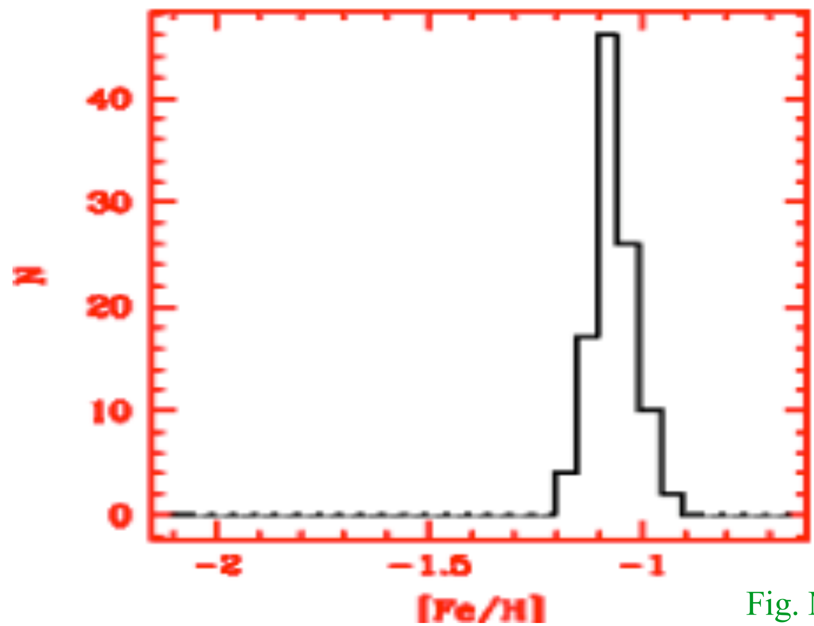


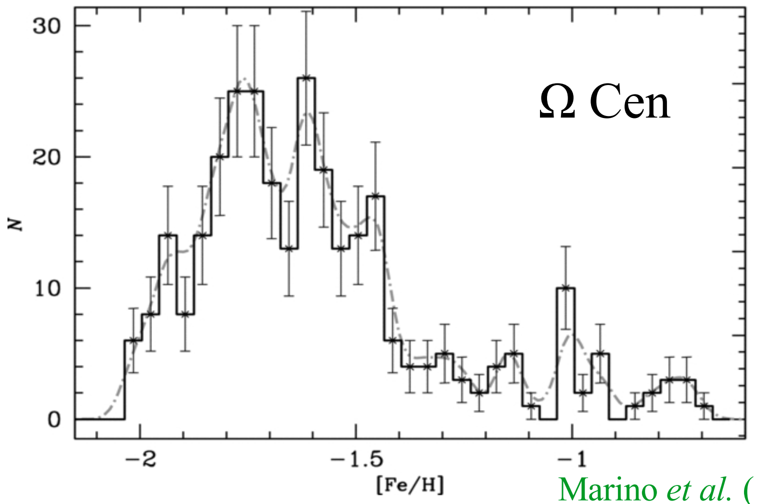
Fig. Marino

→ No self-enrichment by
SNe products and r/s processes

GC = single, coeval stellar population
born with homogeneous chemical composition

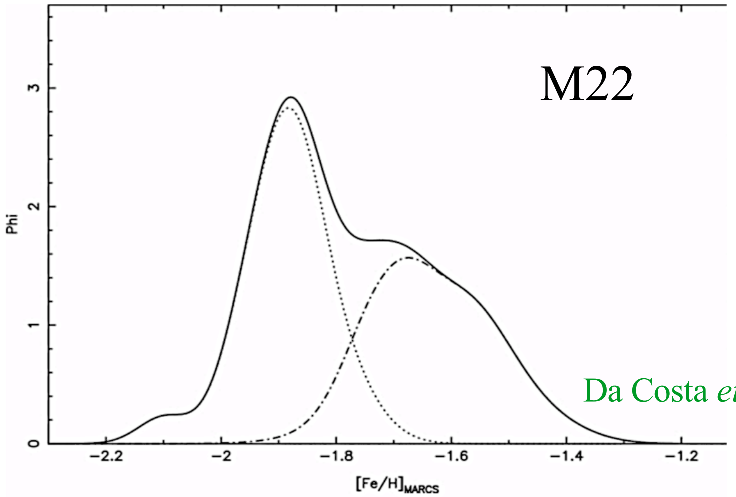
Classical paradigm

Rare exceptions:
The most massive GGCs
ΩCen, M54, M22, NGC 3201, NGC 1851



Marino *et al.* (11)

Remnant of a dwarf galaxy? Gaia Ibata *et al.* (19)



Da Costa *et al.* (09)

Most GGCs are mono-metallic

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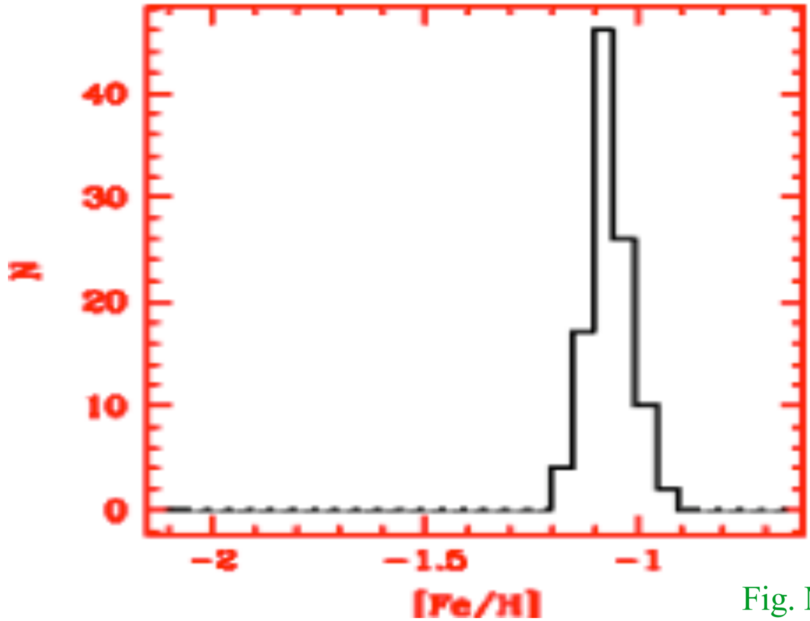

Fig. Marino

→ No self-enrichment by
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GC = single, coeval stellar population
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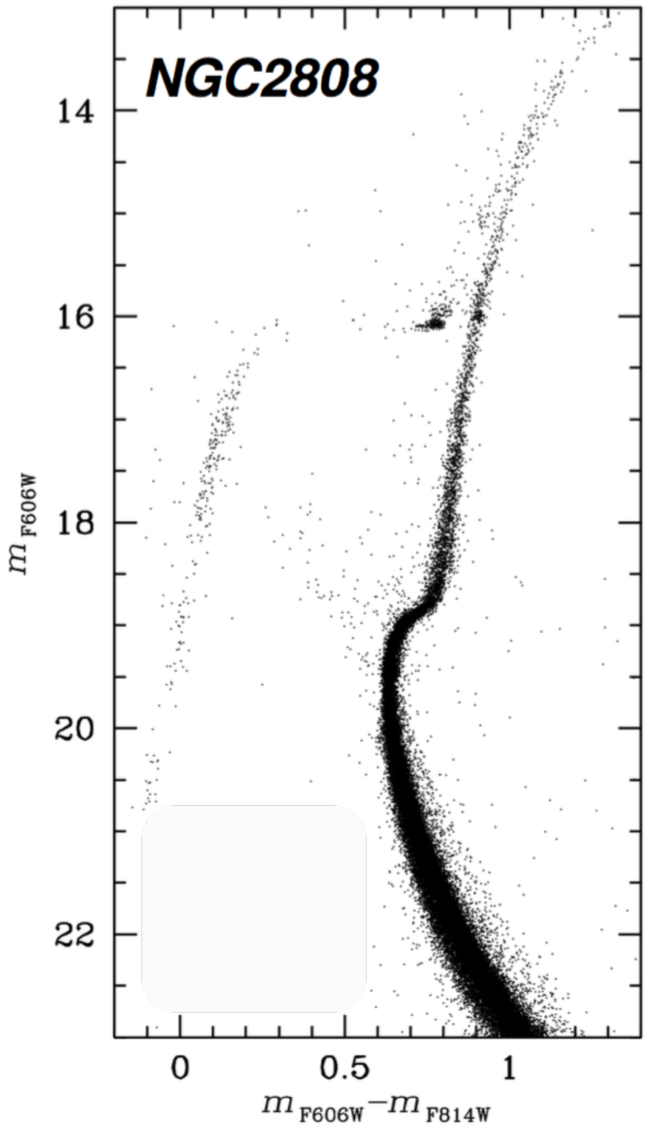
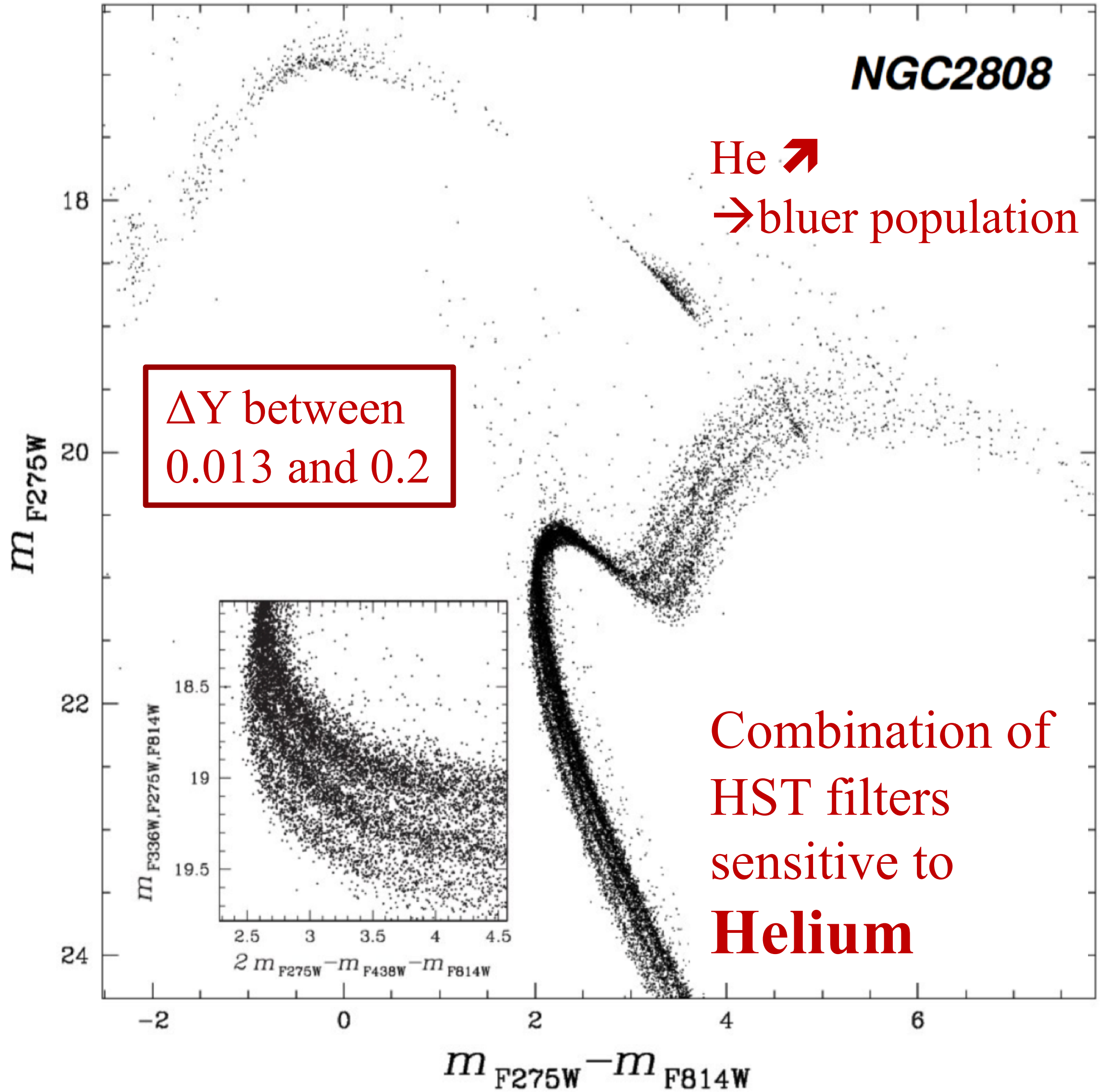
MSPs – Photometric evidence



Anderson *et al.* (08)



Milone *et al.* (13, 15)

Piotto *et al.* (15)
HST UV Legacy Survey
of 57 Galactic Globular Clusters

MSPs – Spectroscopic clues

- ✓ Large star-to-star abundance variations
  of light elements C, N, O, Na, Mg, Al, Li, F (Si)
  Lick-Texas group, Carretta *et al.* (09, 10, +), Lind *et al.* (09, 11), Gratton *et al.* (12 ARAA), Marino ++, many others

  - ✓ C-N, O-Na, Mg-Al(Si) anticorrelations
  - ✓ Li-Na, F-Na anticorrelations

!! From the turnoff to the RGB (and AGB)

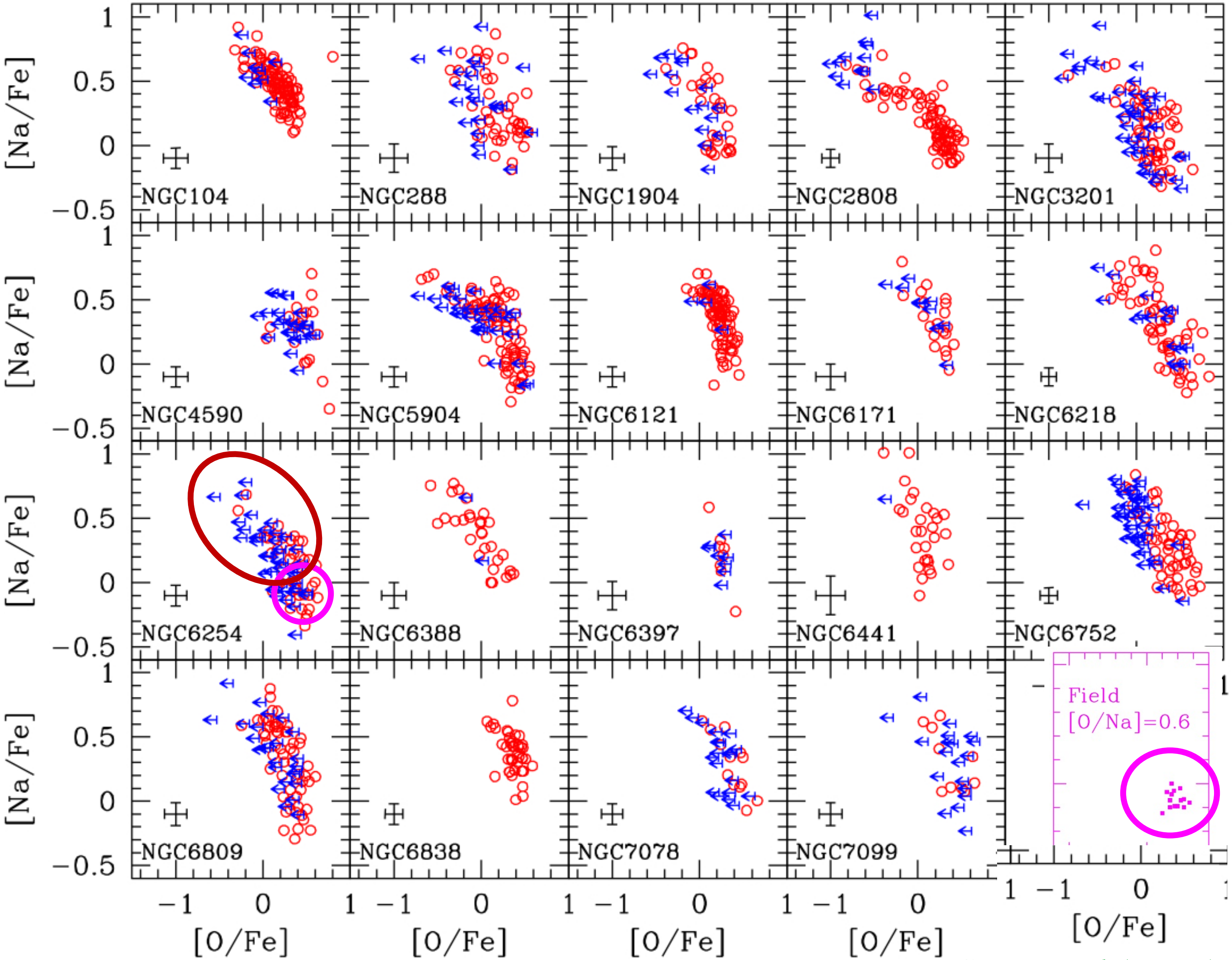
O-Na anticorrelation

Shape and extension vary – **Stochasticity**?

Bastian *et al.* (15)

O-depleted
Na-enriched
2[d] population

"Field" O and Na:
Formed out of
original GC material
1[st] population



Carretta *et al.* (10, VII)

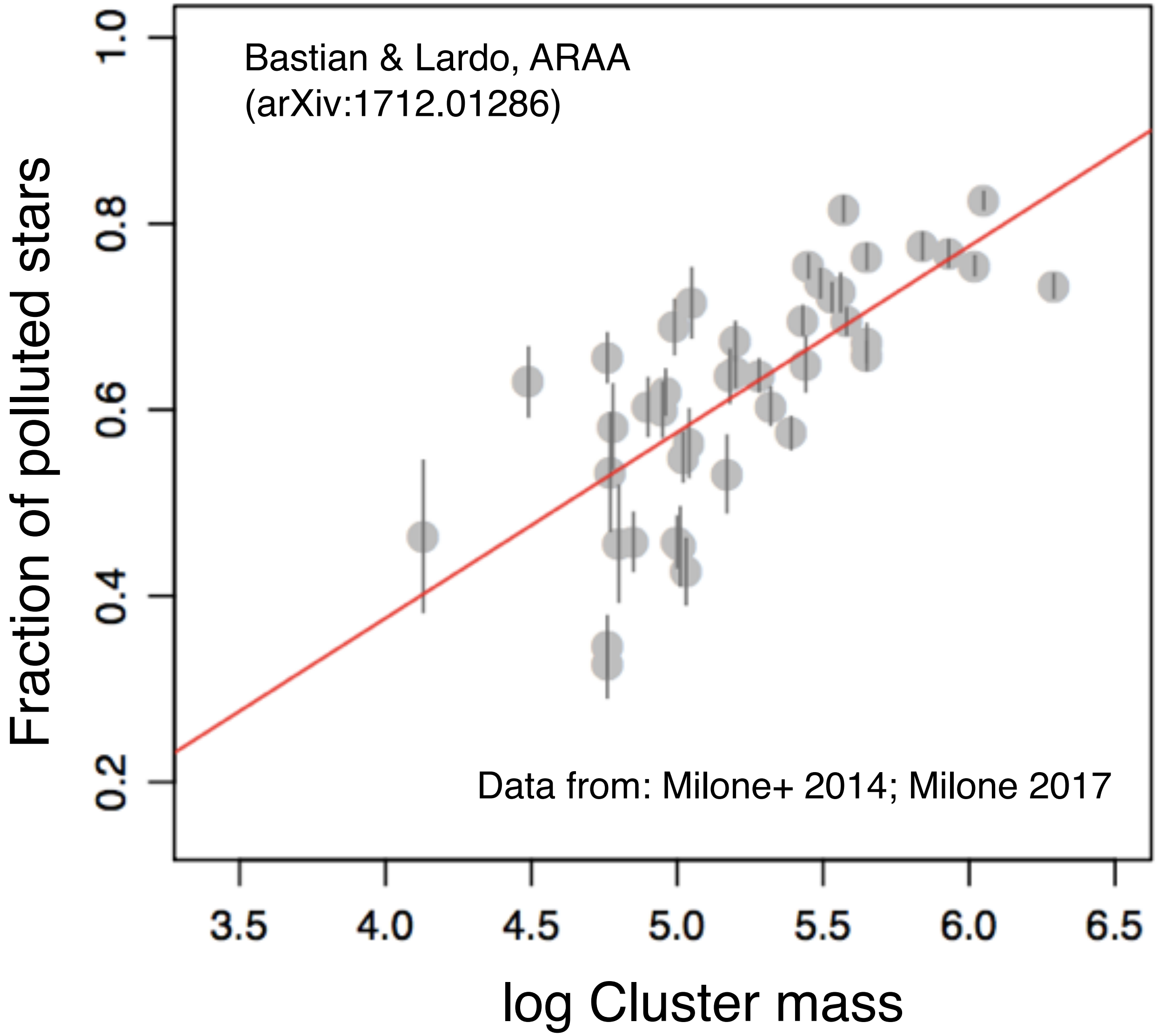
MW GCs with
- -2.16 ≤ [Fe/H] ≤+0.07
- a large range of physical properties (≠ total M, concentration, density, HB morphology)
- disk and halo population

An ubiquitous property above a mass threshold

O-Na anticorrelation

Fraction of 2P stars (~ 30 to ~ 80 % !)
increases with M(GC)

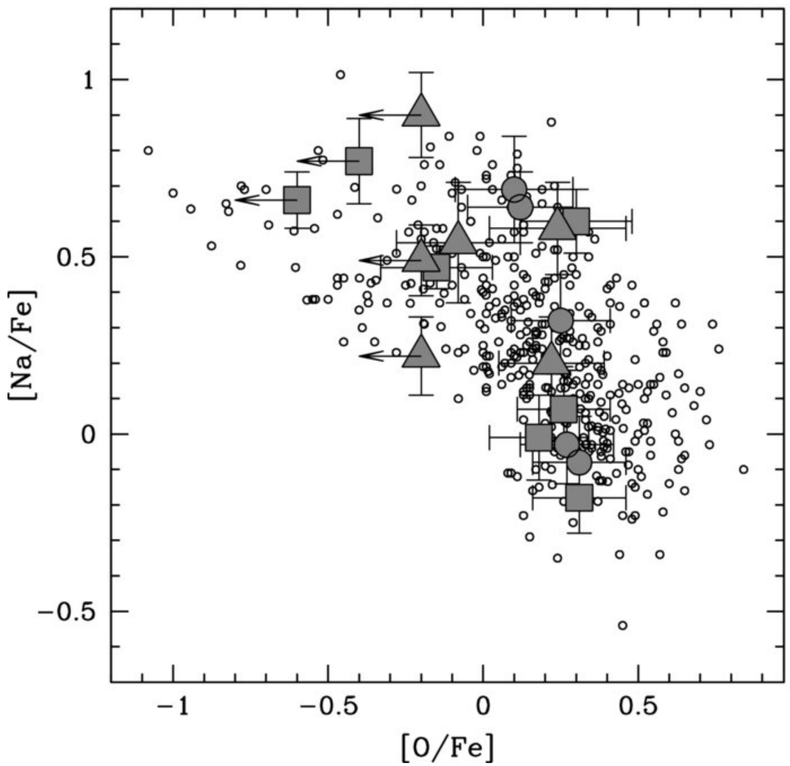
Minimum
present-day mass
for a star cluster to
exhibit the O-Na anticorrelation
~ 2 x 10^4 $M_\odot$

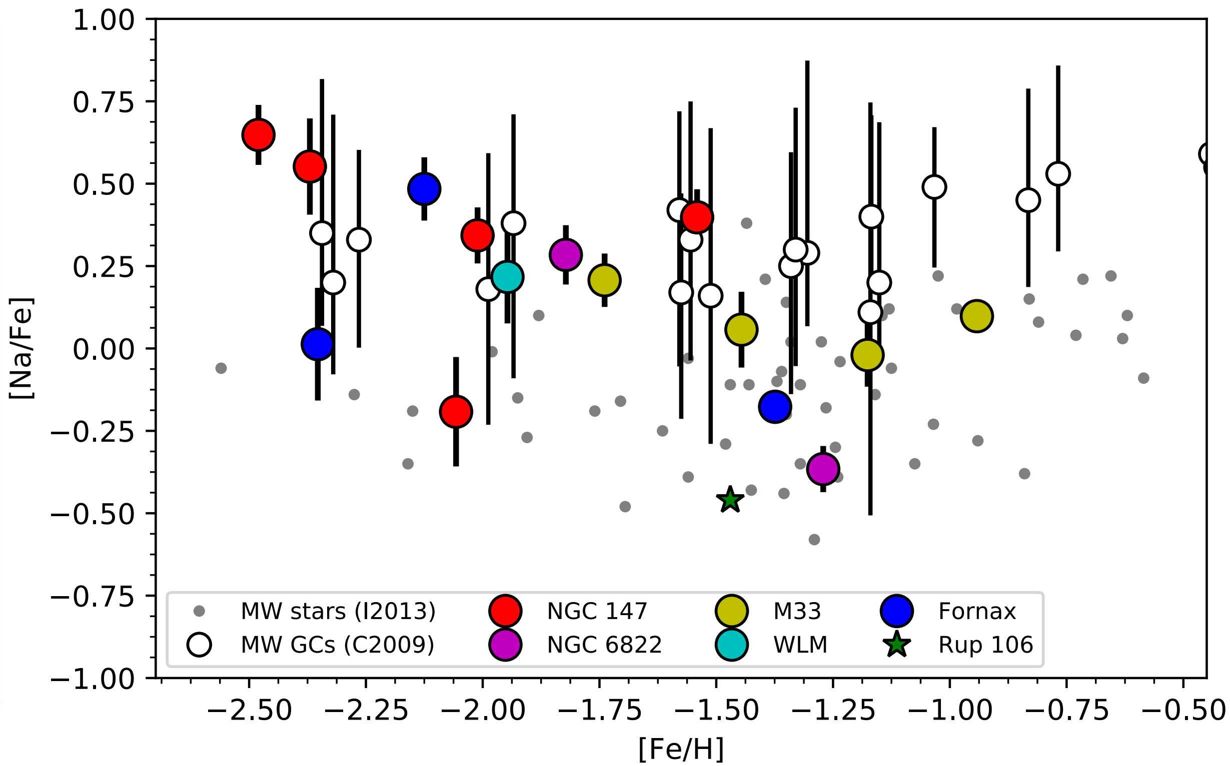


An ubiquitous property above a mass threshold

O-Na anticorrelation

Local Group



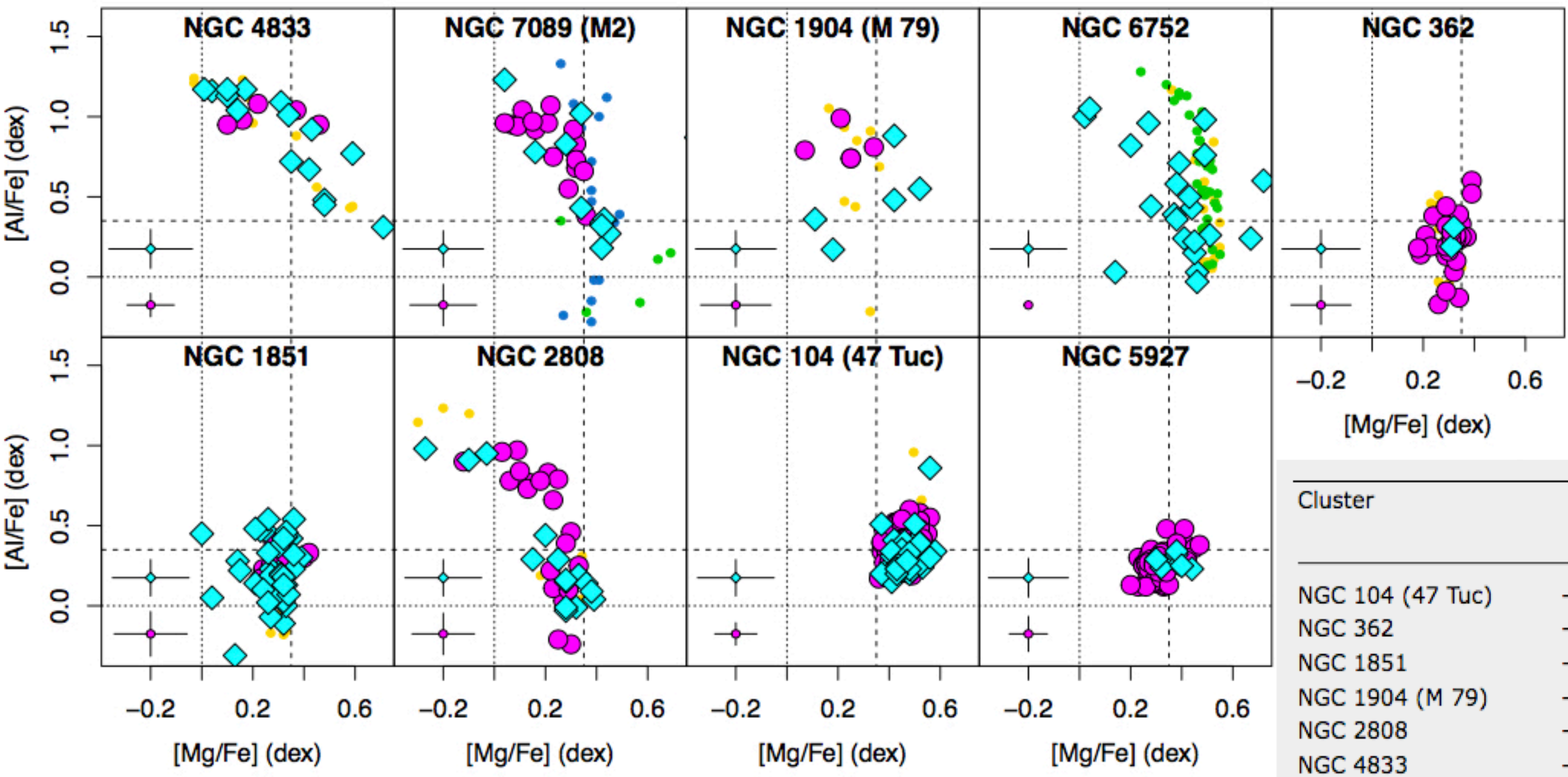


3 old and metal-poor LMC clusters:
NGC 1786, 2210, 2257
Individual star spectroscopy
FLAMES@VLT
Mucciarelli *et al.* (09)

GCs in LG galaxies
Integrated-light spectra
HIRES@Keck – UVES@VLT
Larsen *et al.* (18)

ELTs: A unique tool to look at abundance properties of resolved stellar populations in GCs of the Local Group

Mg-Al anticorrelation



Cluster	[Fe/H]$_{GES}$ (dex)	log ($M/M_\odot$) (dex)
NGC 104 (47 Tuc)	−0.71±0.02	6.05±0.04[a]
NGC 362	−1.12±0.03	5.53±0.04[a]
NGC 1851	−1.07±0.04	5.49±0.04[a]
NGC 1904 (M 79)	−1.51±0.03	5.20±0.04[a]
NGC 2808	−1.03±0.03	5.93±0.05[a]
NGC 4833	−1.92±0.03	5.20±0.21[b]
NGC 5927	−0.39±0.04	5.32±0.21[b]
NGC 6752	−1.48±0.04	5.16±0.21[b]
NGC 7089 (M 2)	−1.47±0.03	5.84±0.05[a]

Pancino *et al.* (17)
***Gaia*-ESO Survey**
Mg-Al anti-correlation in iDR4 globular clusters
UVES – GIRAFFE – UVES literature
Increasing metallicity *from left to right* and *from top to bottom*

Mg-Al anticorrelation

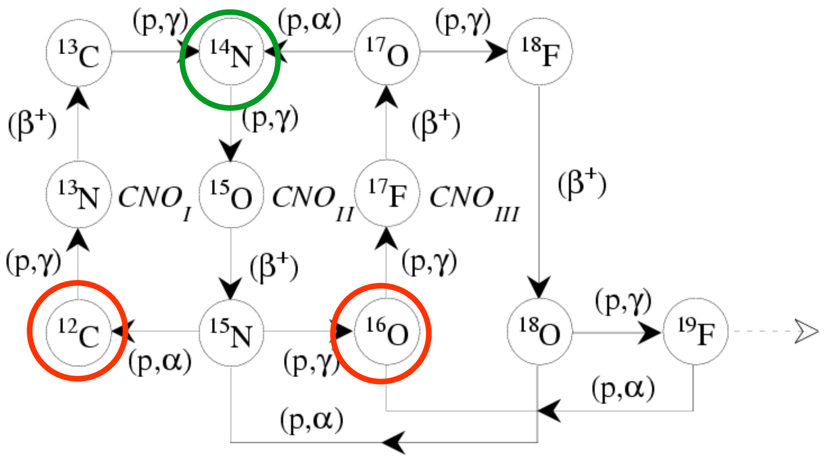
- not seen in all GCs
- more extended in the more massive and/or more metal-poor GCs

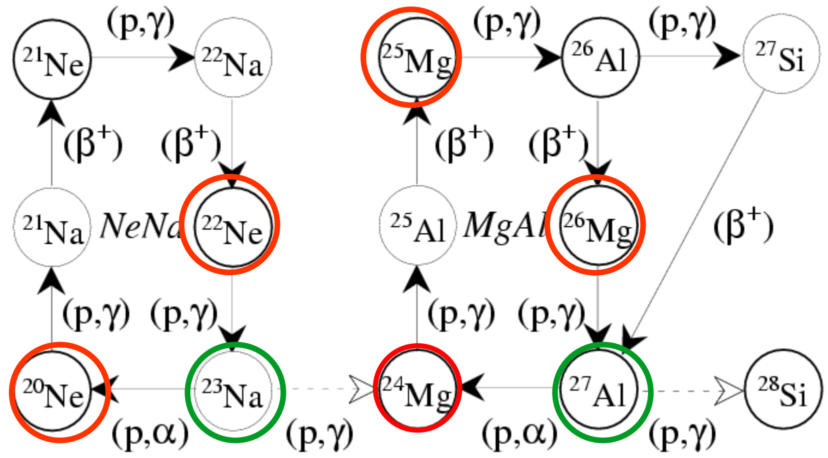
Multiple stellar populations in globular clusters

Nucleosynthesis
and early chemical evolution

H-burning through CNO, NeNa, MgAl (AlSi)

C-N, O-Na, Mg-Al (Si) anticorrelations





Denissenkov & Denissenkova (90)
Langer, Hoffman & Sneden (93)
Arnould, Goriely & Jorissen (99)
Prantzos, Charbonnel & Iliadis (07, 17)

$T \geq 15 \times 10^6$ K : CN

$T \geq 25 \times 10^6$ K : CNO, $^{22}Ne \rightarrow {}^{23}Na$

$T \geq 40 \times 10^6$ K : CNO, $^{20}Ne \rightarrow {}^{23}Na$

$^{25,26}Mg \rightarrow {}^{26}Al, {}^{27}Al$

T ~ 72 to 78 MK →

$T \geq 70 \times 10^6$ K : ^{24}Mg (and $^{25,26}Mg$) $\rightarrow {}^{26}Al, {}^{27}Al$

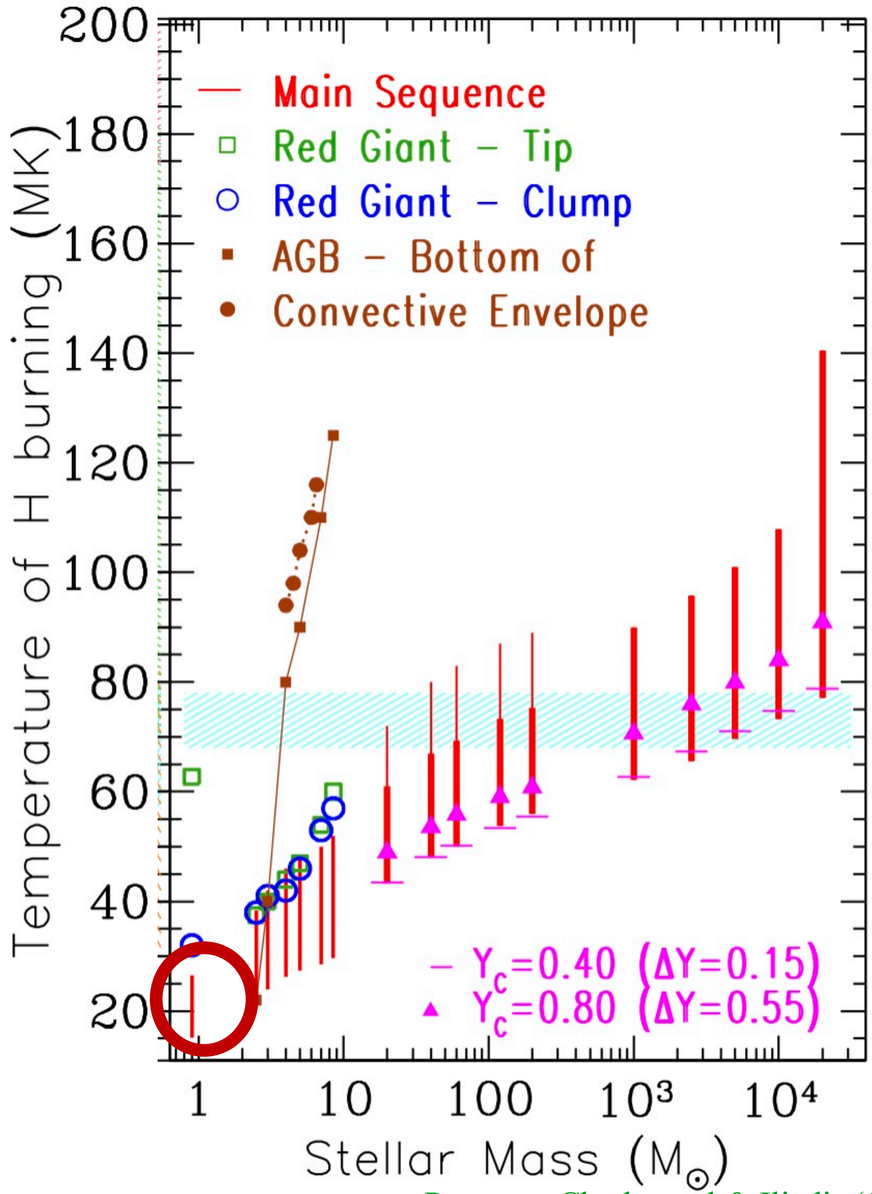
$T \geq 80 - 90 \times 10^6$ K : $^{27}Al \rightarrow {}^{28}Si$

^{23}Na

H-burning temperature in stars

→ 2P stars born out of material polluted by hot H-burning ashes of
more massive, short-lived 1P stars
("polluters")

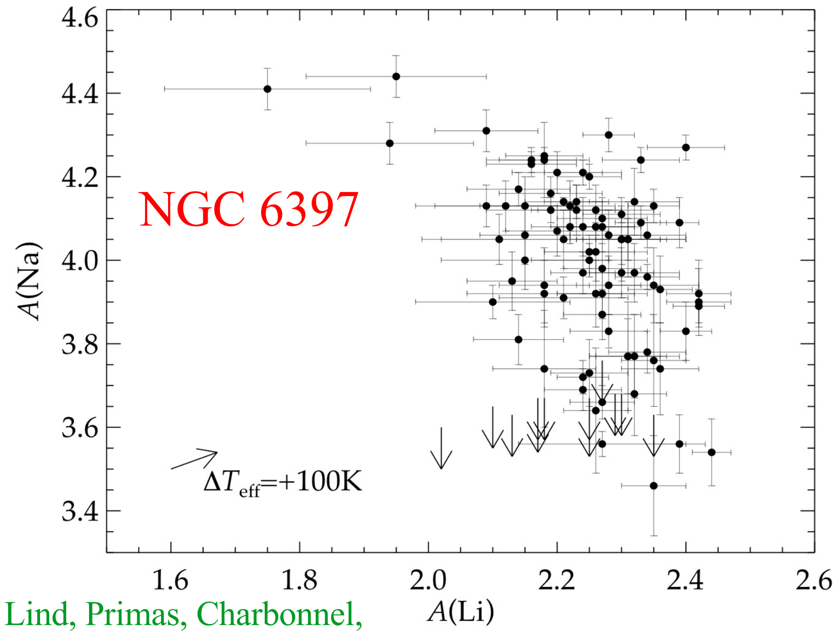
Low-mass GCs we observe today:
M(turnoff) ~ 0.8 $M_{\odot}$
H-burning T ≤ 25 MK



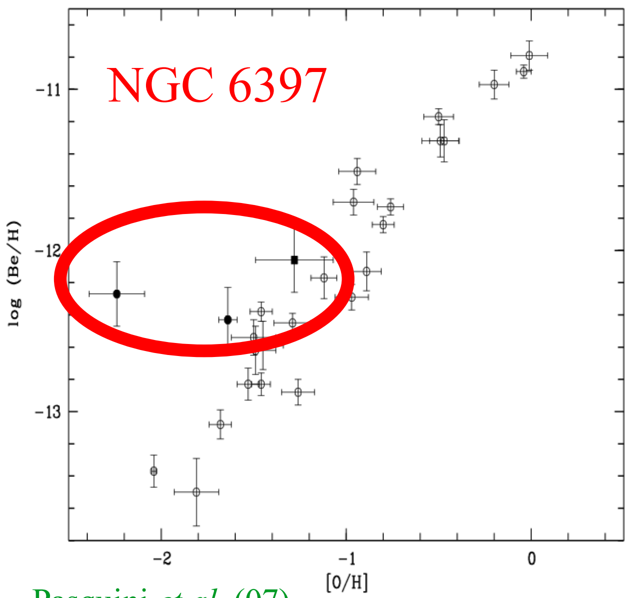
Prantzos, Charbonnel & Iliadis (17)

Second population stars

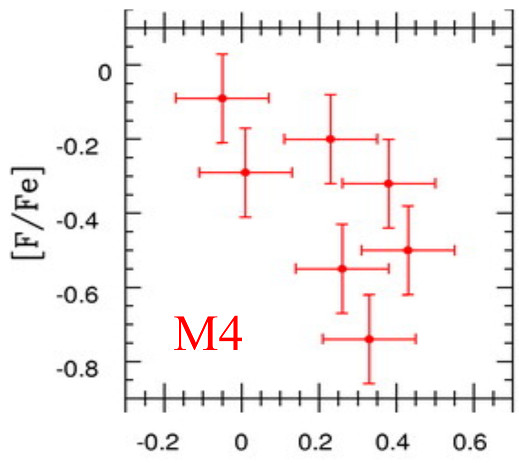
- ✓ C-N, O-Na, Mg-Al(Si) anticorrelations
  H-burning via CNO, NeNa, MgAl @ ~ **75MK**
  in first population short-lived and massive stars (**polluters**)
- ✓ LiBeBF
  H-burning ashes diluted with pristine gas



Lind, Primas, Charbonnel, Grundahl & Asplund (09)

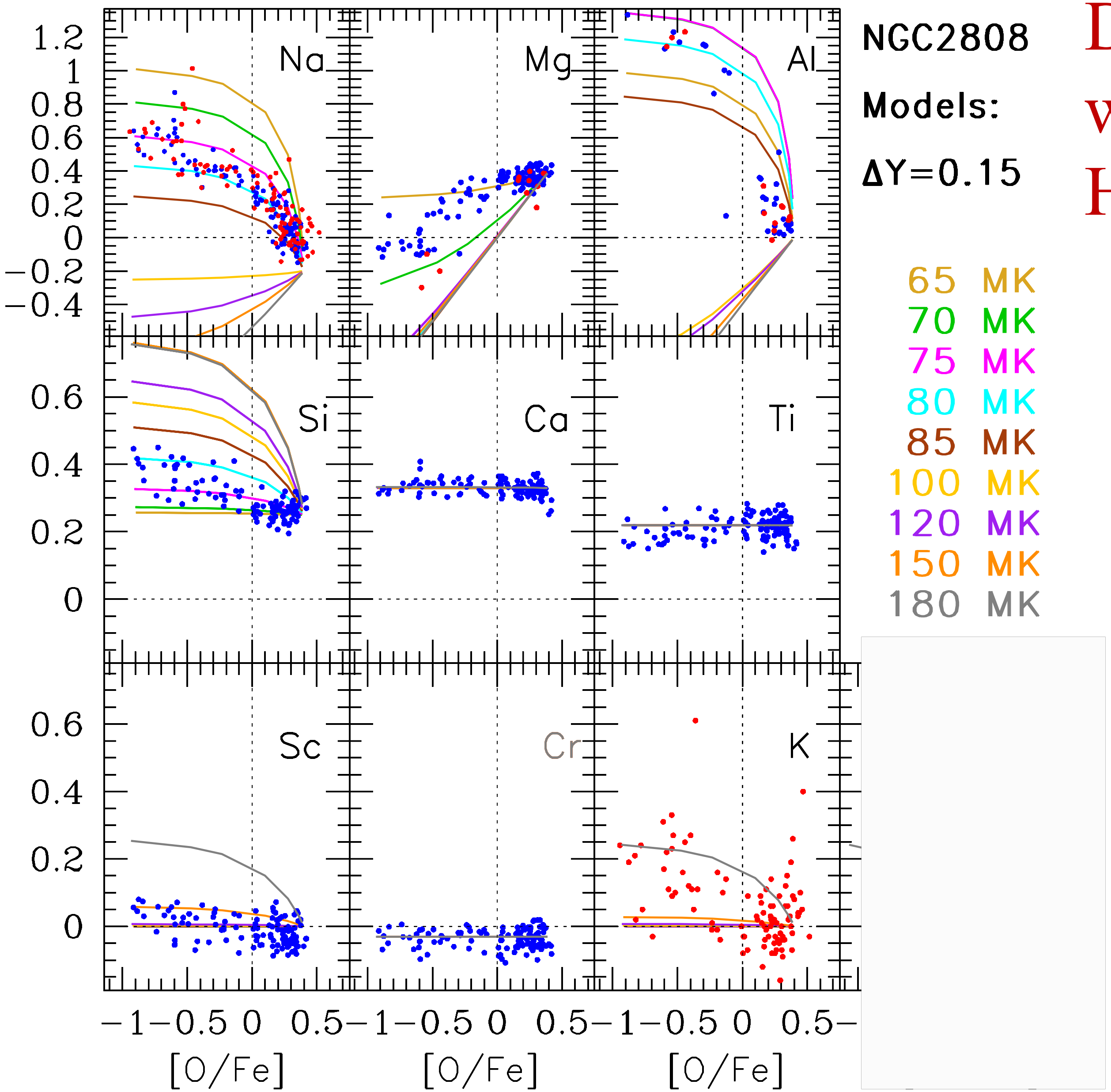


Pasquini *et al.* (07)



Smith *et al.* (05)

The case of NGC 2808



Dilution curves with hot H-burning yields

~ 50 % of original gas (LiBeBF-rich)
& 50 % of H-burning ashes (LiBeBF-free)

Prantzos, Charbonnel & Iliadis (17)
Data from Carretta (14,15) & Mucciarelli *et al.* (15)

C-N, O-Na, Mg-Al anticorrelations
He enrichment (CMD)
Li-Na (F-Na) anticorrelations

H-burning via CNO, NeNa, MgAl @ ~ 75MK
Modest He enrichment
H-burning ashes mixed with pristine gas

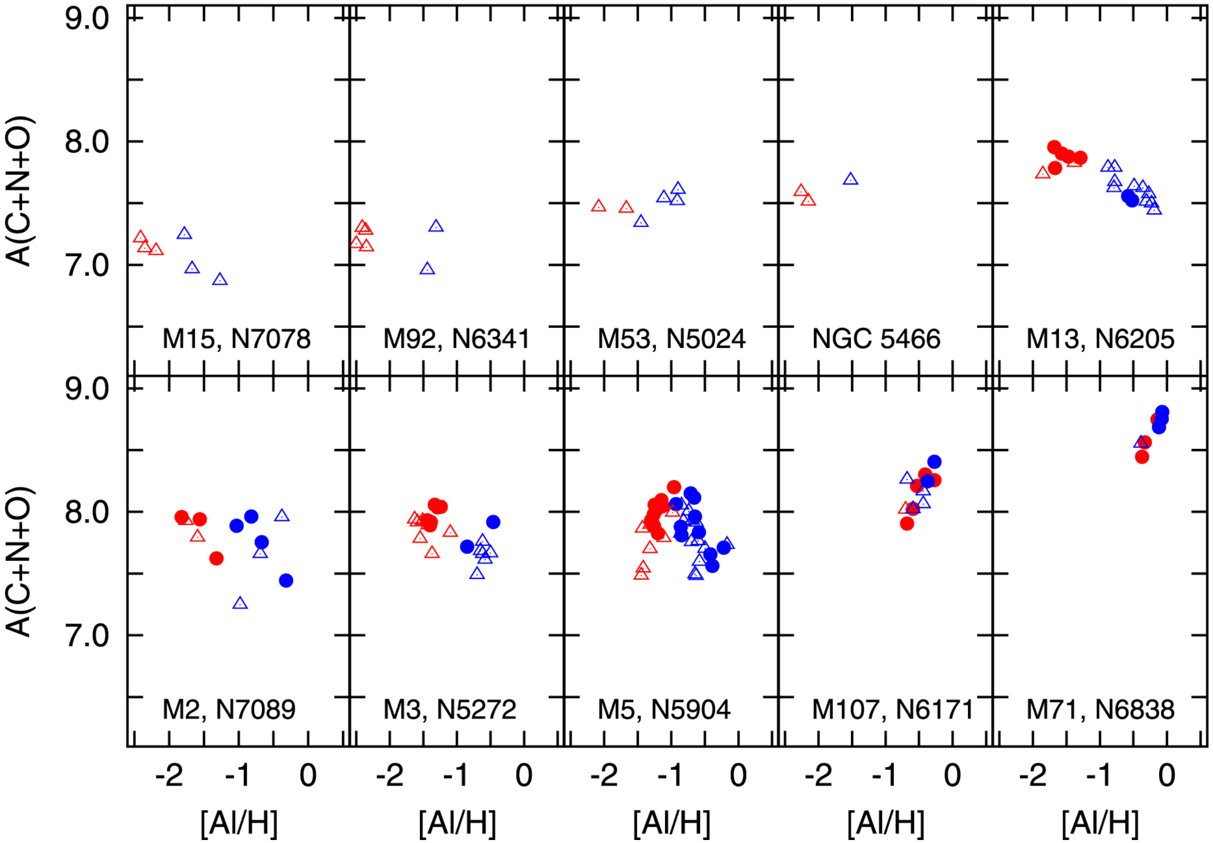
→2d population

C-N, O-Na, Mg-Al anticorrelations

He enrichment (CMD)

Li-Na (F-Na) anticorrelations

[(C+N+O)] ~ constant



1P – 2P

No recycling of He-burning products

C+N+O vs Al
Mészáros et al. (2015)
Northern GCs observed by Apogee

C-N, O-Na, Mg-Al anticorrelations
He enrichment (CMD)
Li-Na (F-Na) anticorrelations
[(C+N+O)] ~ constant
[Fe/H] ~ constant

H-burning via CNO, NeNa, MgAl @ ~ 75MK
Modest He enrichment
H-burning ashes mixed with pristine gas

} → 2d population

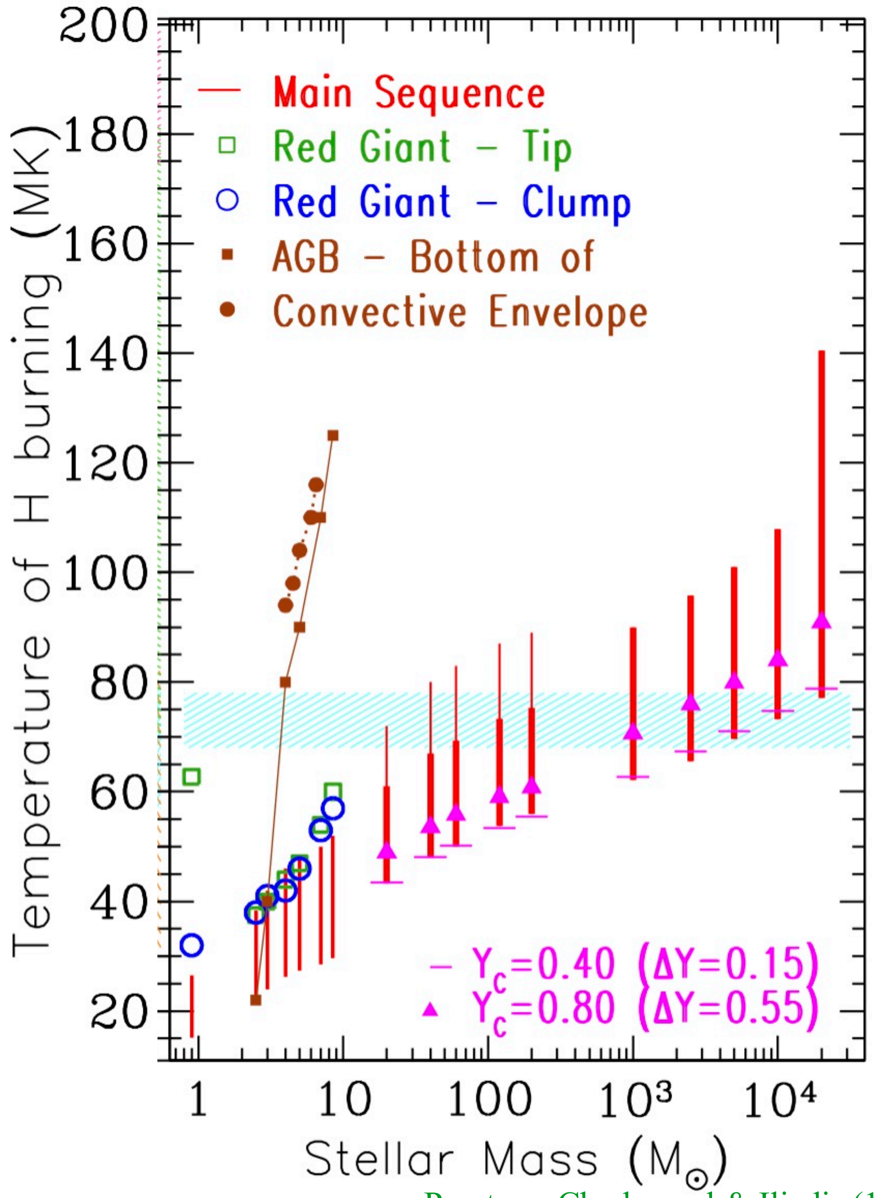
No recycling of He-burning products

No recycling of supernovae ejecta,
except in some rare (most massive) cases (e.g., Ω Cen or M22)

Multiple stellar populations in globular clusters

Possible polluters

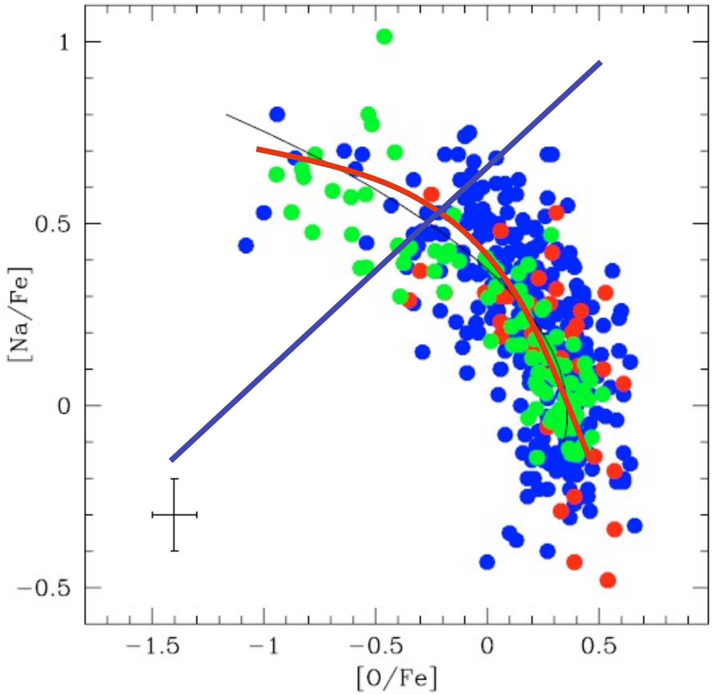
H-burning temperature in stars

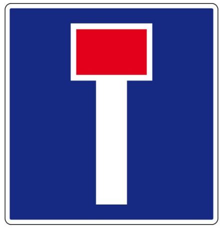


Prantzos, Charbonnel & Iliadis (17)

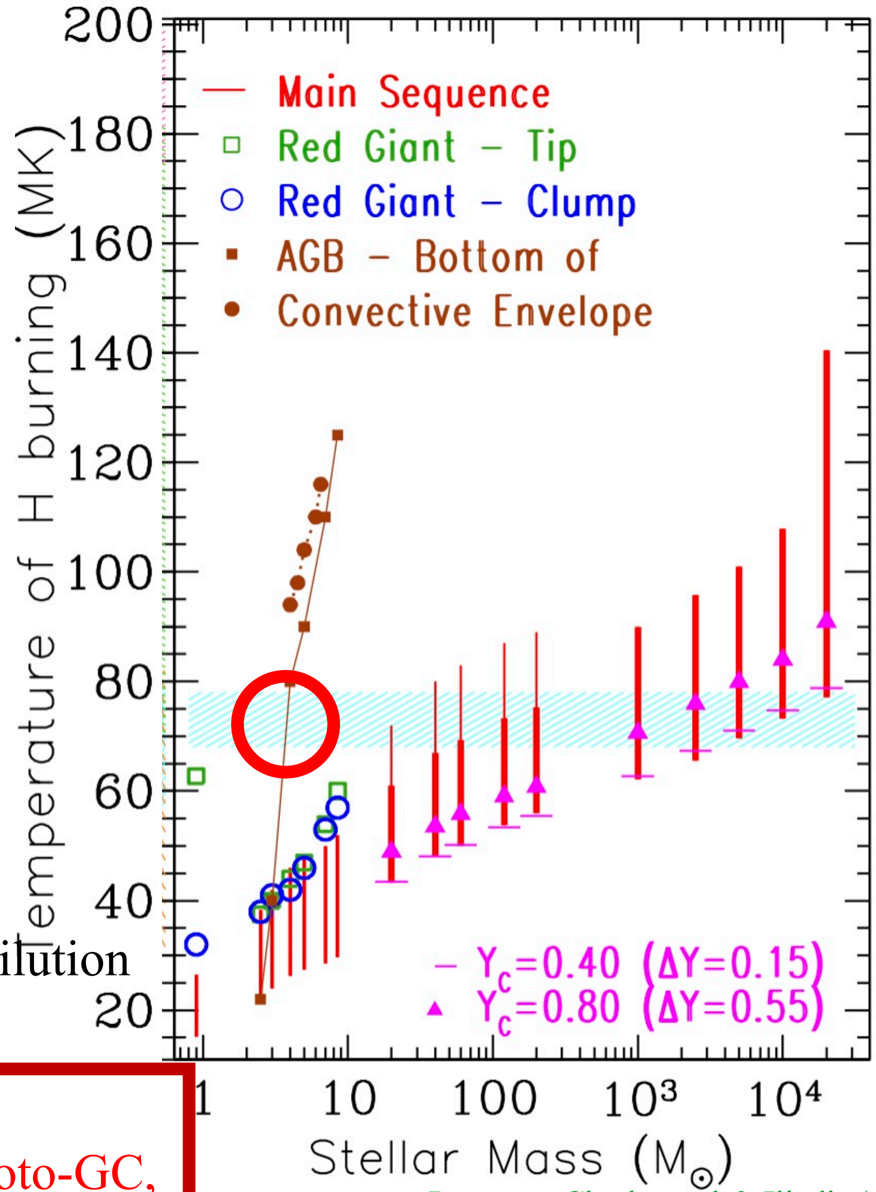
~ 5 – 6 $M_\odot$

Ventura *et al.* (01, 11, 13)
D'Ercole *et al.* (11)





Candidate polluters – AGBs



Prantzos, Charbonnel & Iliadis (17)

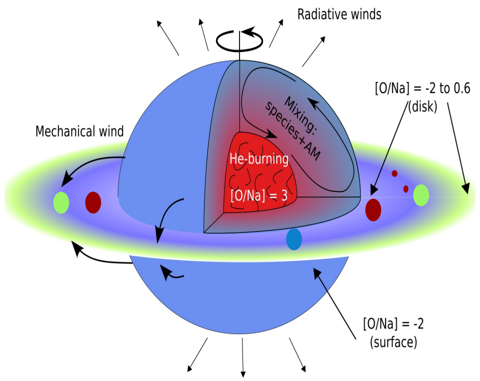
AGB yields → O-Na correlation

→ He-burning products: C+N+O ↑
in glaring conflict with observations

Lifetime ~ 40 – 80 Myr : SNe ejecta ?
→ Expel protocluster gas, and re-accrete later for dilution

How do all the GCs manage to re-accrete gas
with exactly the same [Fe/H] than the one of the proto-GC,
after having travelled around for ~ 40 – 80 Myrs?

Candidate polluters – FRMS



Fast Rotating Massive Stars (FRMS) $\geq 25\ M_{\odot}$

Prantzos & Charbonnel (06)
Decressin, CC *et al.* (07a,b), Krause, CC *et al.* (12,13)

MS ejecta, O-Na and Mg-Al obtained directly, and no He-burning products

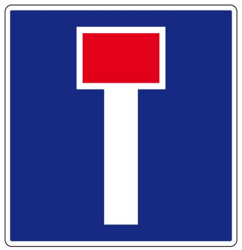
Lifetime ~ 2 – 5 Myr

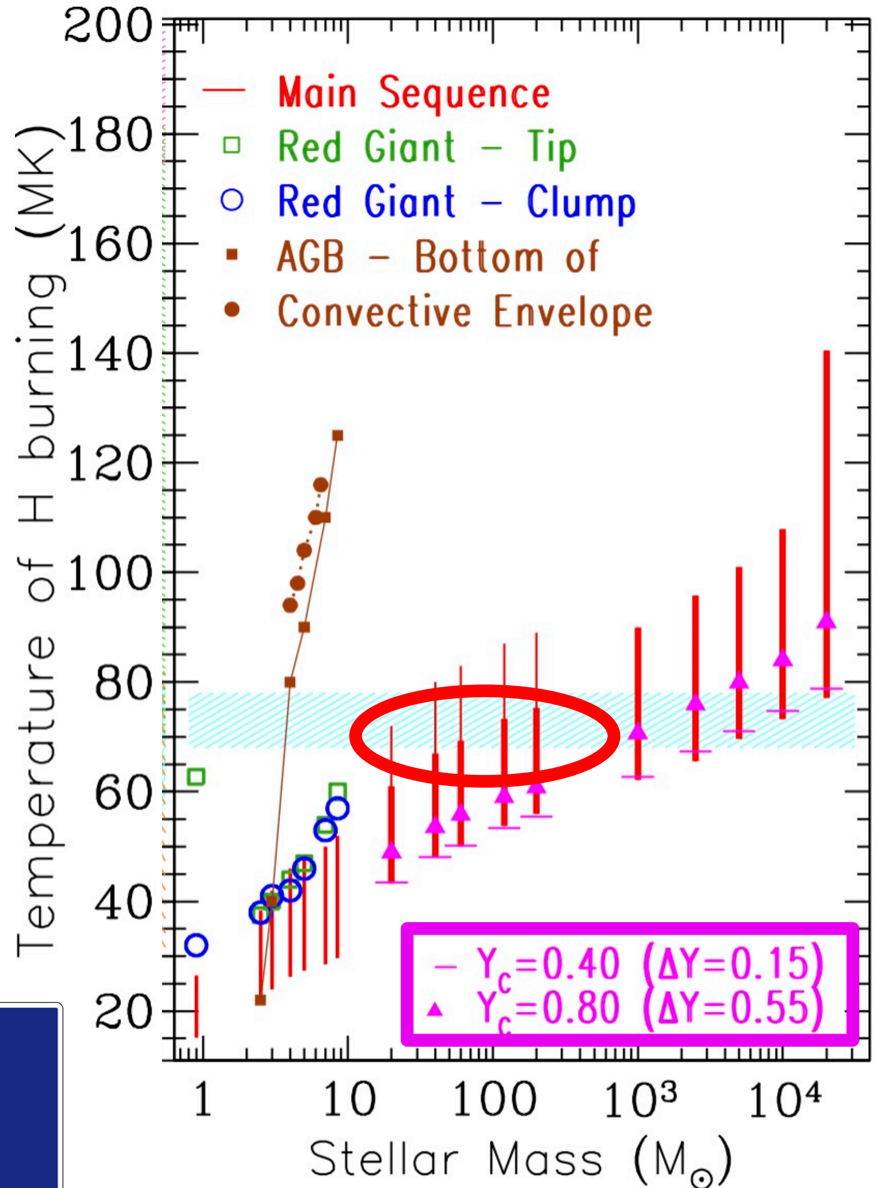
→ Before SNe explosion
→ Pristine gaz is still present
→ **Formation of 2P stars in the immediate surroundings of the polluter (decretion disk)**

Reach Mg-burning temperature
for substantial He-enrichment only

In tension with the photometric determination of He enrichment (ΔY between 0.013 and 0.2)

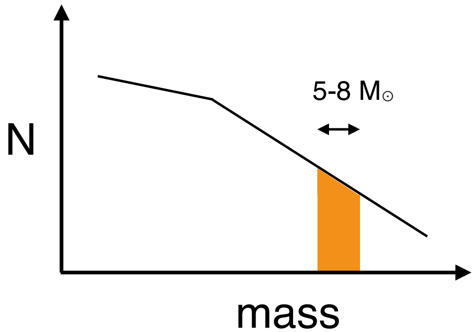
Piotto *et al.* (15)
Chantereau, CC, Meynet (15,16,17)

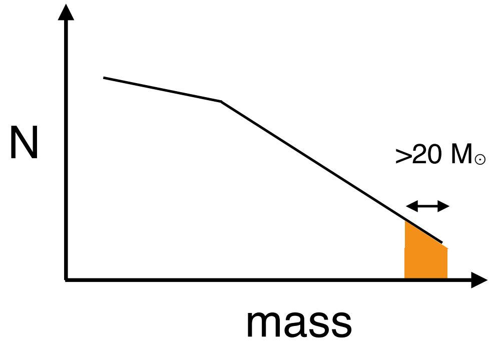


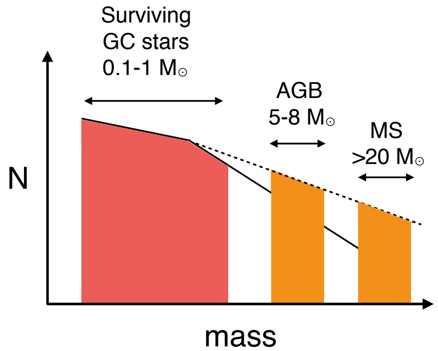


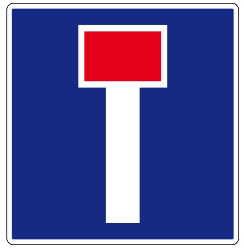
Prantzos, Charbonnel & Iliadis (17)

Mass budget issues









For normal IMF → Only 10% GC stars should present abundance anomalies (2P)
Obs: 30 to 80 % Prantzos & CC (06) , Decressin, CC *et al.* (07) , Schaerer & CC (11) Carretta *et al.* (10 +), Milone (17)

Loss of ~ 95% 1P stars ? Simultaneous expulsion of gas and 1P stars? Prantzos & Charbonnel (06), Decressin *et al.* (07) D'Ercole *et al.* (08, 10), Vesperini *et al.* (10) Schaerer & Charbonnel (11), Conroy (12)

Impossible to achieve with SNe Krause, CC *et al.* (12, 13)

Gas accretion on dark remnants? Could work after last SN explosion @ ~ 50Myr

Young Massive Star Clusters (no gas @ ~ 5 Myr) Bastian *et al.* (14)

→ Hypernovae? Krause, CC *et al.* (16)
→ Extreme (≥80%) SFE?

GCs were 10 – 25 more massive at birth ? Schaerer & Charbonnel (11)
Constraints from field stars Martell & Grebel (10), Carretta+(10)
In tension with halo/GC populations in dwarf galaxies Larsen *et al.* (12,14)

Non-standard IMF? Prantzos & CC (06)

Candidate polluters – SMSs

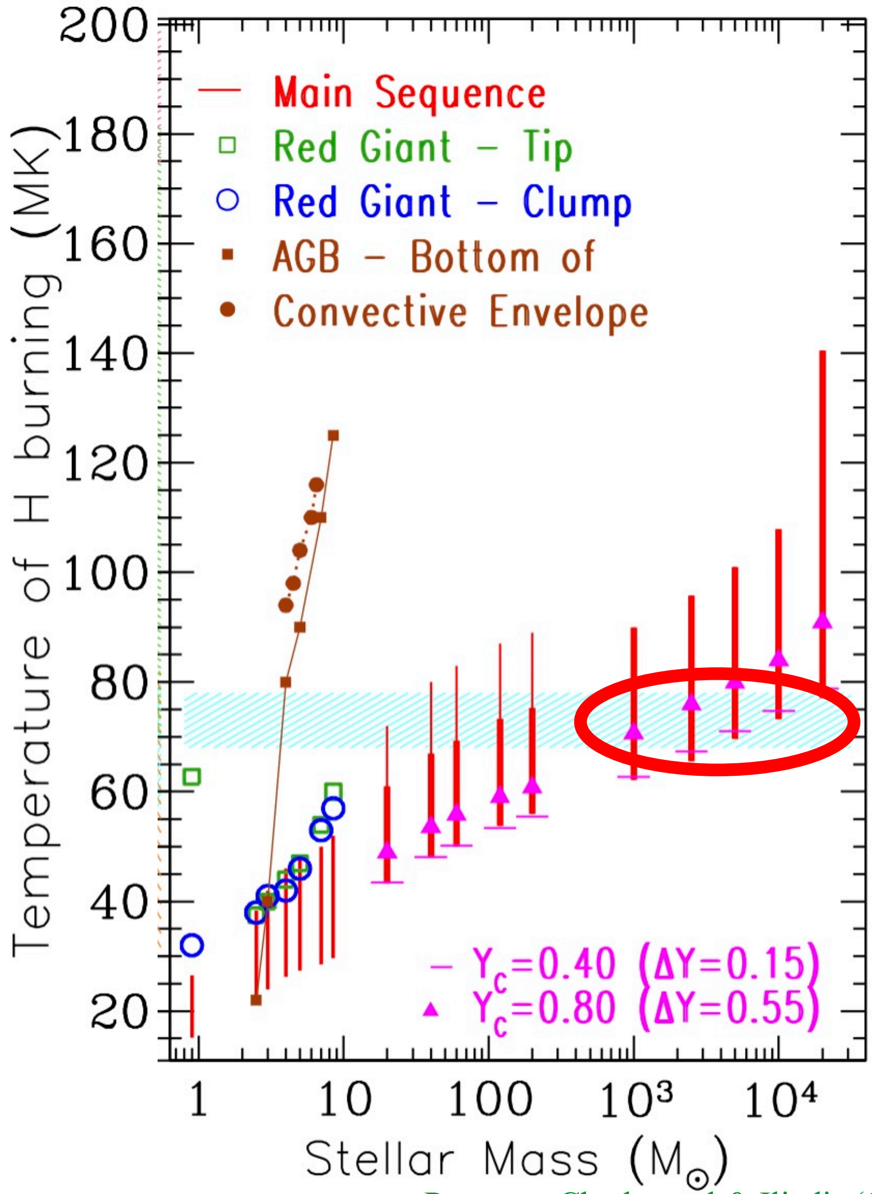
Supermassive stars

~ 2 x 10^3 – 2 x 10^4 $M_\odot$

Denissenkov & Hartwick (14)
Denissenkov *et al.* (15)
Gieles, Charbonnel *et al.* (18)

High Tc reached at the beginning of the MS
→ Modest He enrichment

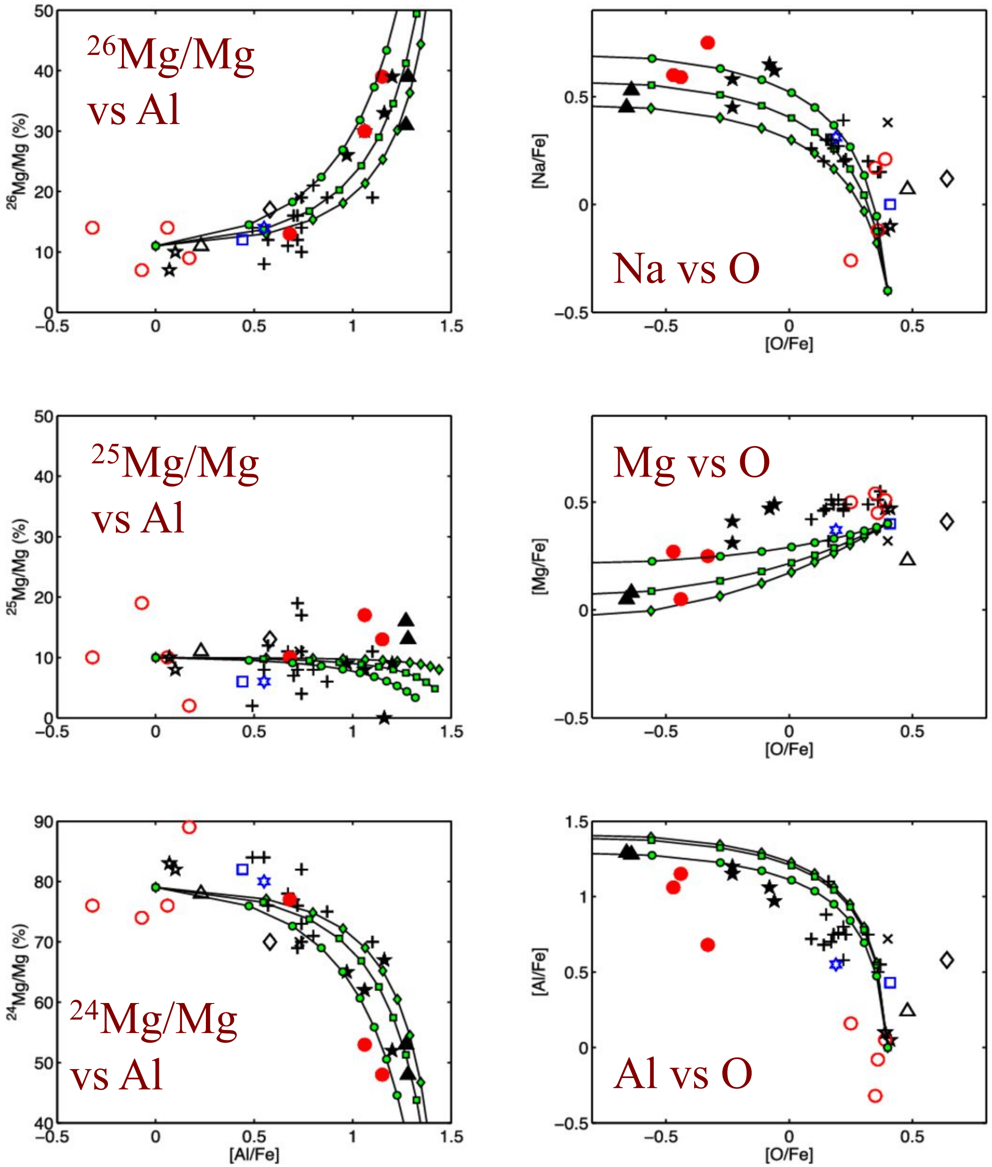
CMD →ΔY between 0.013 and 0.2
→SMS best candidate vs He



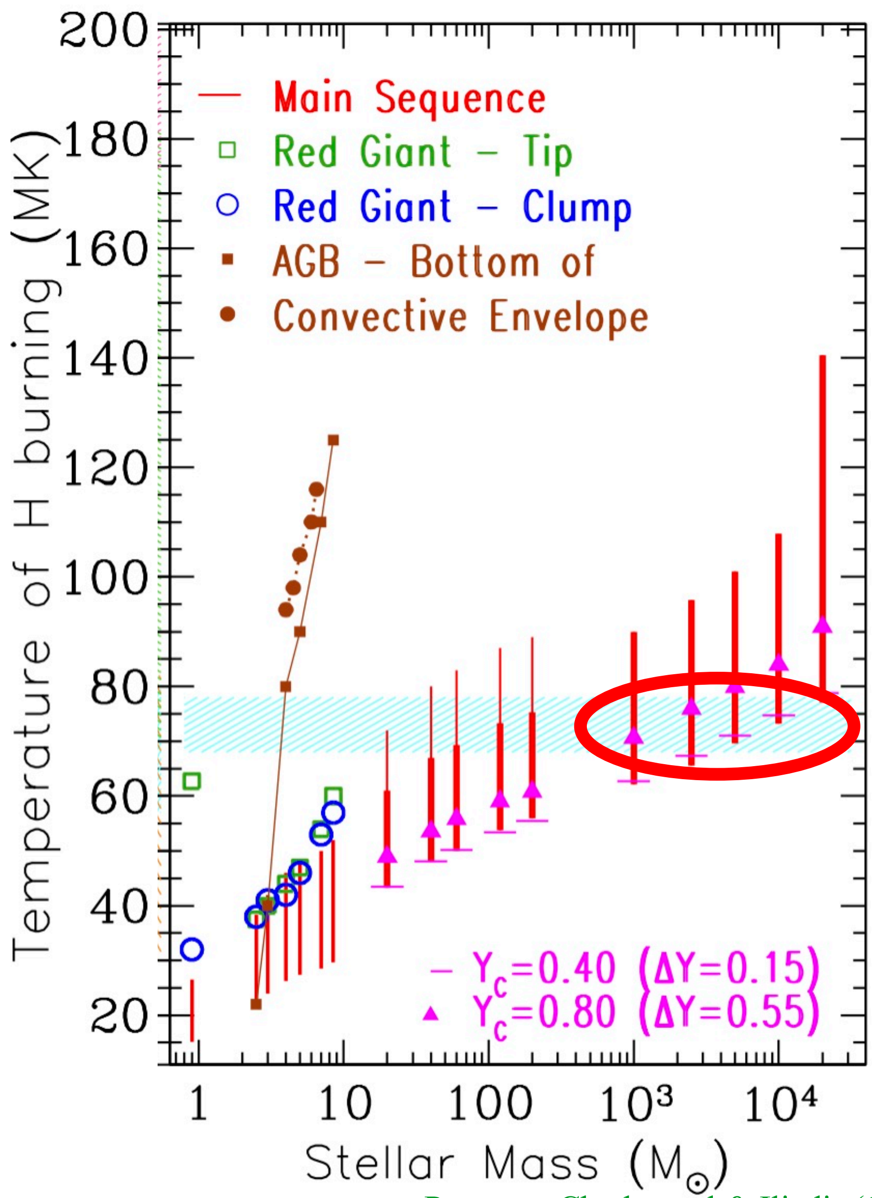
Prantzos, Charbonnel & Iliadis (17)

Candidate polluters – SMSs

Dilution curves using yields of ~ (2 – 3 – 4) x 10^4 $M_\odot$



Denissenkov & Hartwick (14)



Prantzos, Charbonnel & Iliadis (17)

Multiple stellar populations in globular clusters

A new scenario :
Concurrent formation of supermassive stars
and GCs / massive star clusters

Concurrent formation of supermassive stars and globular clusters: implications for early self-enrichment

Mark Gieles[1★], Corinne Charbonnel[2,3], Martin G.H. Krause[4], Vincent Hénault-Brunet[5,6], Oscar Agertz[7], Henny J.G.L.M. Lamers[8], Nathan Bastian[9], Alessia Gualandris[1], Alice Zocchi[10,11], James A. Petts[1]

(2018 MNRAS 478, 2461)

SMS – Formation

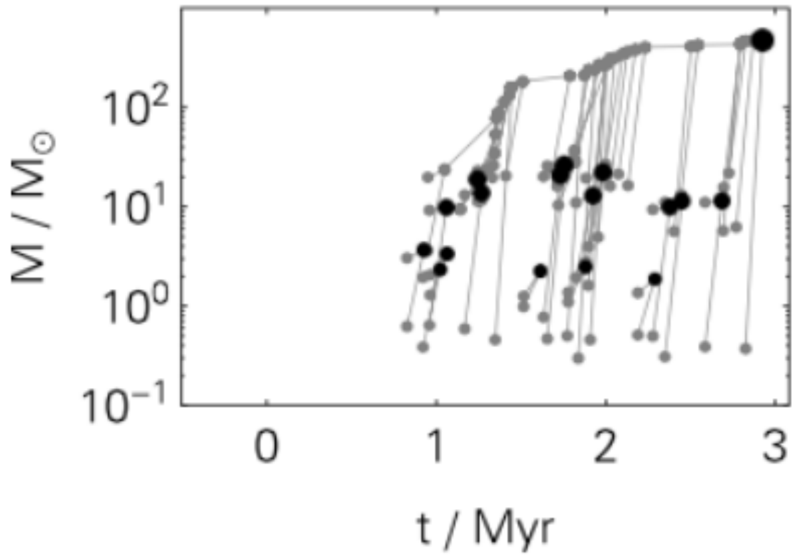
(Pop III) Direct monolithic collapse of no/low-Z gas clouds
Abell *et al.* (02), Regan & Haehnelt (09)

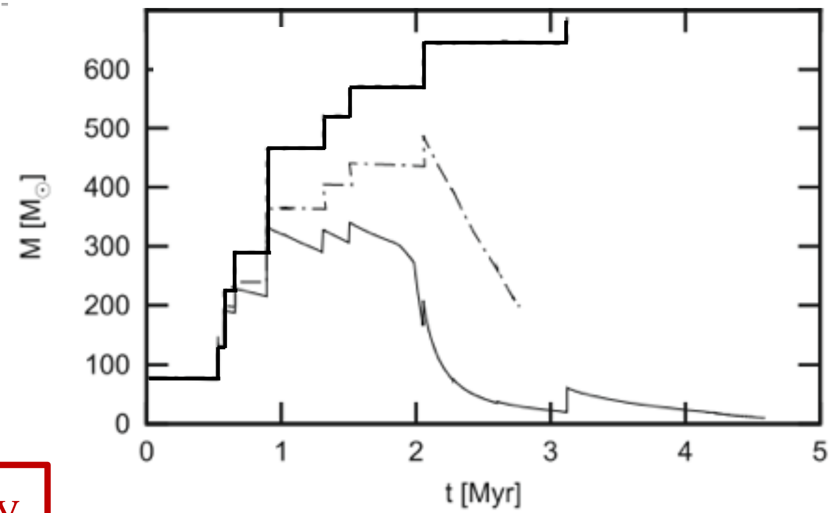
Needs to work at all Z !

Collisions of massive stars in the core of very dense young star clusters

Mass segregation → Massive stars form at / sink to the center of the cluster and eventually collide (path to form IMBH)

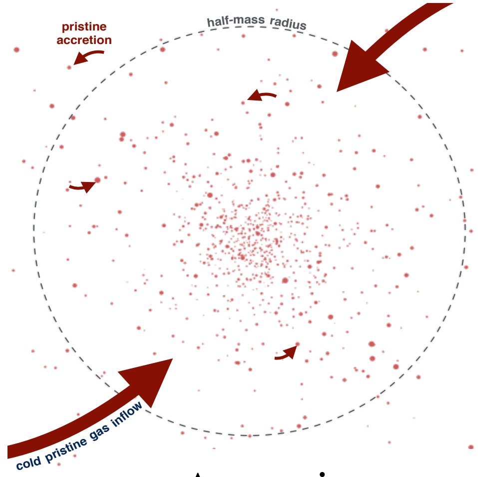
Portegies Zwart *et al.* (99, 04), Freitag *et al.* (06), Bonnel *et al.* (98); Giersz *et al.* (05) Krumholtz *et al.* (09), Mapelli (16), Li *et al.* (17)





Previous studies:
For relatively low density environments
→ Maximum mass << 10^4 $M_\odot$
due competition between growth/collision rate and (very uncertain) mass loss rate

Need to reach higher density
→ Gas inflow and accretion
→ Runaway collisions



SMS – Formation through runaway collisions

Accreting proto-GC:
N(accreting proto-stars)
Gas inflow $\dot{M} = 10^5\ M_\odot$/ Myr

@ time 0 :
Proto-stellar mass function (Kroupa-like) with a peak mass $m_0 = 0.1M_\odot$

After t_0 $\quad \dot{m}_{acc,*} \propto m_{0,*}$

@ 5Myr : Mass spectrum (Kroupa-like) with a peak mass $m = 0.6M_\odot$

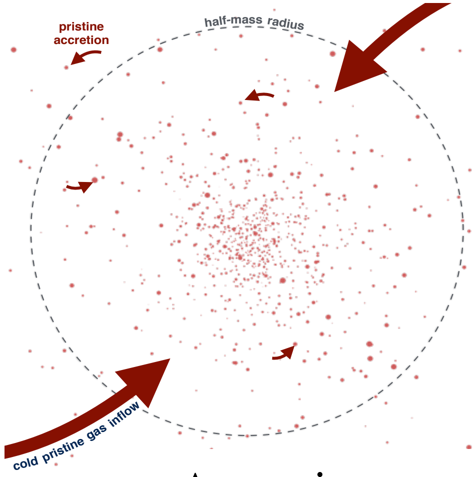
$< \dot{m}_{acc} > = 0.1\ M_\odot$ / Myr Hartmann+16; De Marchi+17; Offner & Chaban 17

$\dot{M}_{acc} = < \dot{m}_{acc} >$ N ($M_\odot$ / Myr)

> 5Myr : Accretion halted by stellar feedback

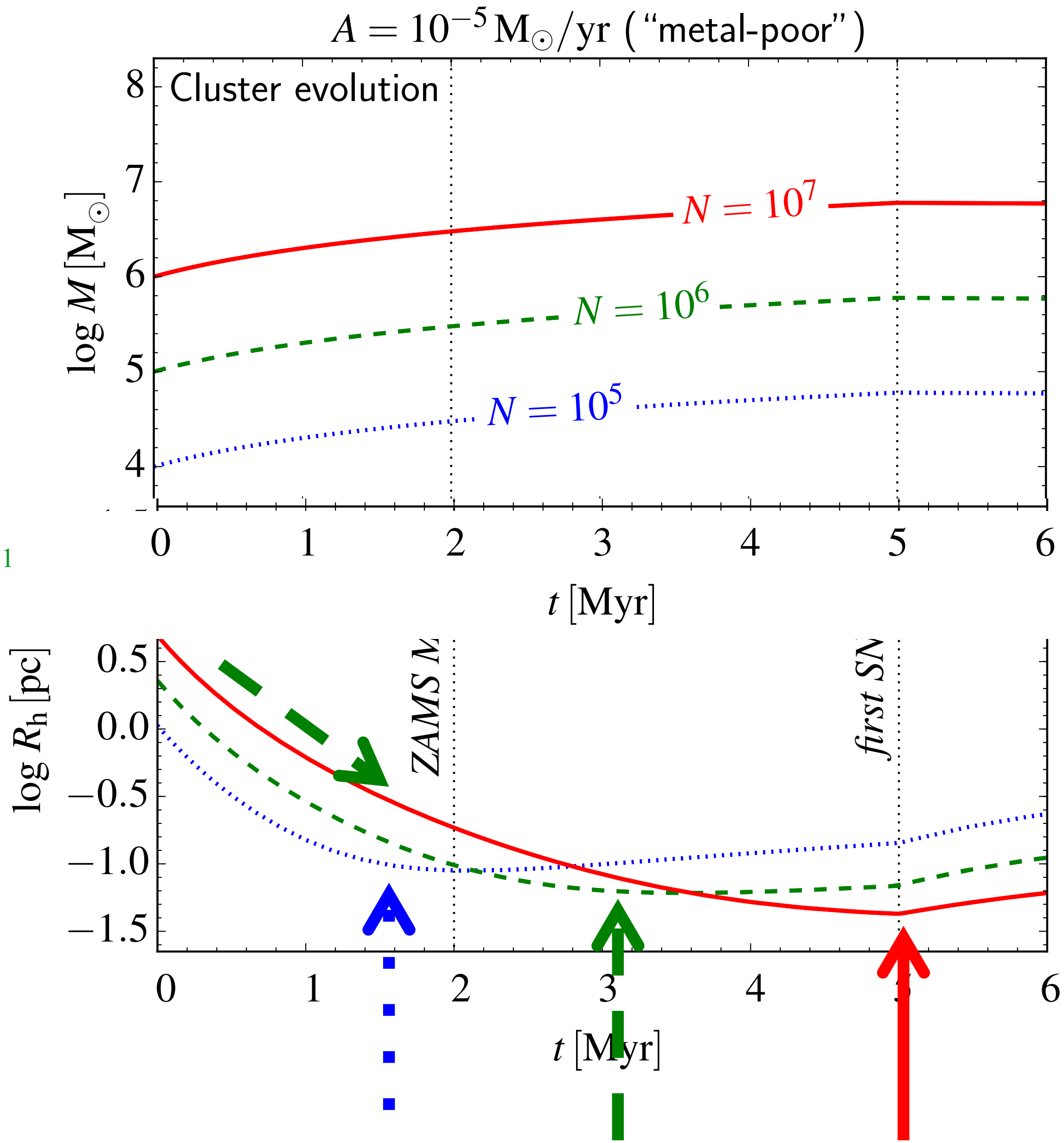
(Gieles *et al.* 18)

SMS – Formation through runaway collisions



Accreting proto-GC:
N(accreting proto-stars)
Gas inflow $\dot{M} = 10^5\ M_\odot$/ Myr

$N = 10^6$ stars
$M_{0,cluster} = N \times m_0 = 10^6 \times 0.1 = 10^5\ M_\odot$
$\dot{M}_{acc} = \langle \dot{m}_{acc} \rangle N = 0.1 \times 10^6 = 10^5\ M_\odot.\ Myr^{-1}$
$M_{cluster}(5Myr) = 6.10^5\ M_\odot$



Accretion-driven contraction
Angular momentum conservation
→ Cluster contracts as $R_h \propto M^{-3}$ (Bonnell+98)

Relaxation-driven expansion
Binaries dynamically heat the cluster
→ Maximum coalescence rate set by two-body relaxation

(Gieles *et al.* 18)

Properties of the super massive star

Mass-radius relation

$$r_{\rm SMS} = 30\,{\rm R}_\odot \left(\frac{m_{\rm SMS}}{100\,{\rm M}_\odot}\right)^{\delta}$$

$0 < \delta \lesssim 1$ for $m_{\rm SMS} > 100\,{\rm M}_\odot$

$\delta = 0.5$ for $m_{\rm SMS} < 100\,{\rm M}_\odot$

Highly uncertain
(obs of massive stars, and SPH models of stellar collisions)
→ varying δ

Mass loss (wind)

$$\dot{m}_{\rm wind} = A \left(\frac{m_{\rm SMS}}{100\,{\rm M}_\odot}\right)^{\eta}$$

$A = 10^{-4}$ and 10^{-5} $M_\odot\,yr^{-1}$ (metallicity effect)

$\eta = 0.75$ and 1.5

Ok with observations of very massive stars (Crowther+10)
SPH models of stellar collisions (Lombardi+03; Suzuki+07)
SMS models (Denissenkov+15)

Collision rate experienced by the SMS

$$\dot{N}_{\rm coll} = 2\sqrt{2\pi}\left(\frac{m_{\rm SMS}+m}{m_{\rm SMS}}\right)^{1/2} n V_{\rm rms} d^2 \left(1 + \frac{G m_{\rm SMS}}{d V_{\rm rms}^2}\right) \propto N^{4/3}$$

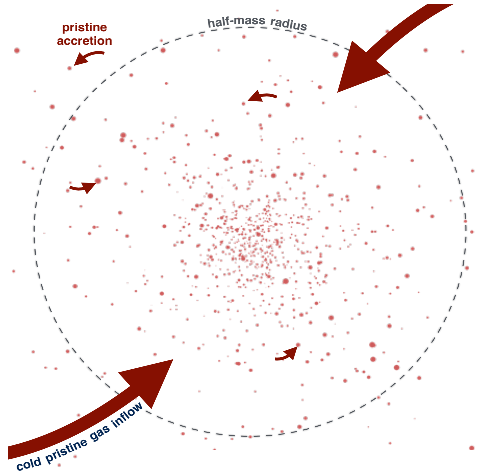
n : stellar density, $V_{\rm rms}$: velocity dispersion of the system $V_{\rm rms} \simeq \sqrt{GM/(6R_{\rm h})}$ (Hills & Day 76; Binney & Tremaine 08)

m, r : mass, radius of other stars

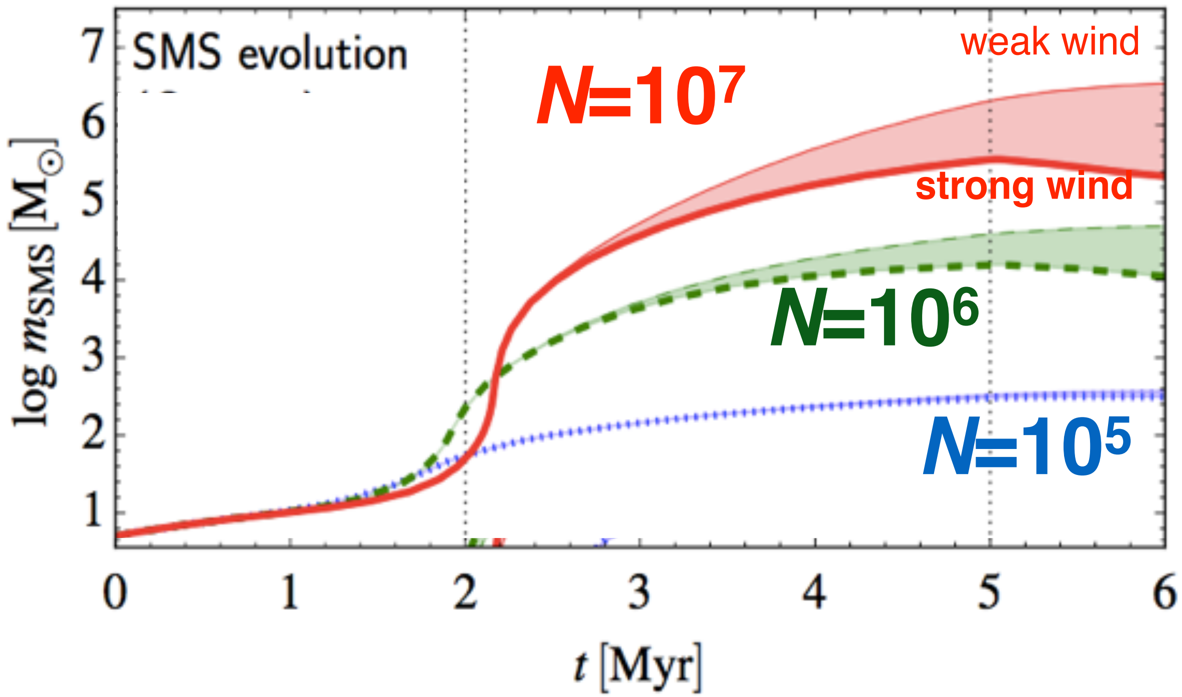
d : distance at which a collision occurs $d = r + r_{\rm SMS}$

(Gieles *et al.* 18)

SMS – Formation through runaway collisions



Accreting proto-GC:
N(proto-stars) $\geq 5 \times 10^5$
Gas inflow $\dot{M} \geq 10^5\ M_\odot$/ Myr
Stellar collisions ↑ → SMS formation

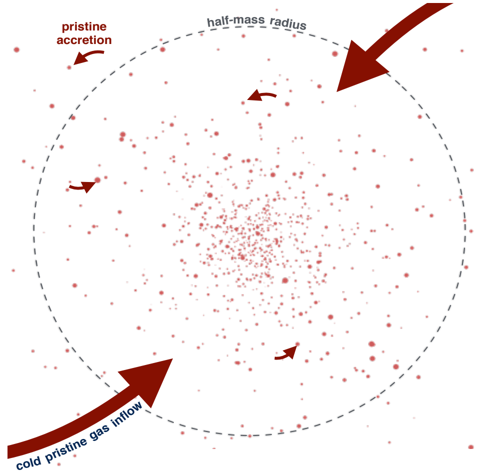


→ SMS form
only in the most massive clusters
✓ Abundance anomalies seen only in GCs

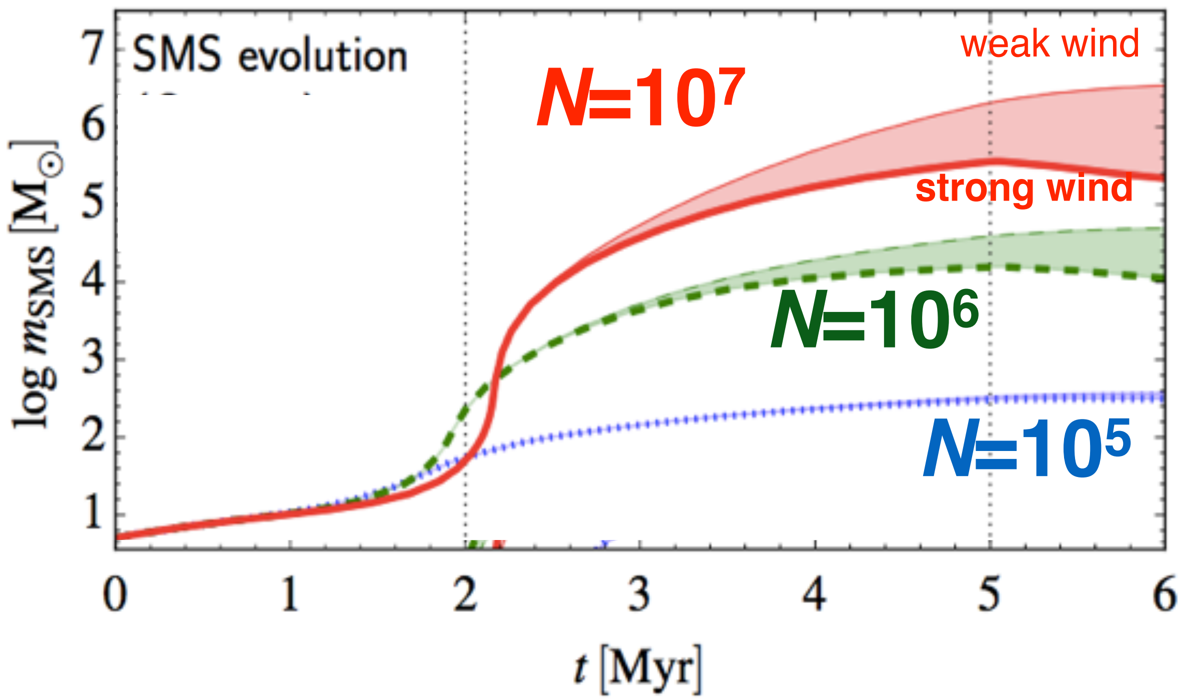
Maximum SMS mass depends on
✓ N
✓ the very uncertain mass loss by super-Eddington radiation continuum-driven wind

Super-linear scaling between
the mass of the SMS
and the mass of the GC

(Gieles *et al.* 18)



SMS – Formation through runaway collisions



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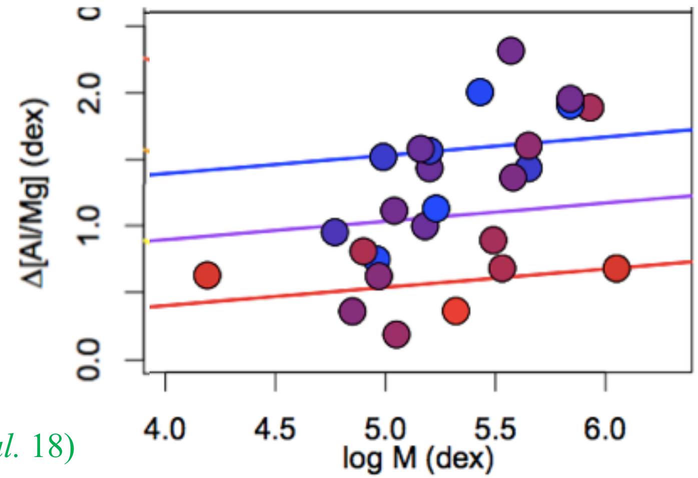


(Gieles *et al.* 18)

Super-linear scaling between
the mass of the SMS
and the mass of the GC

✓ Extent of the Mg-Al anticorrelation increases with $M_{cluster}$

SMS evolution and wind

Conveyor belt

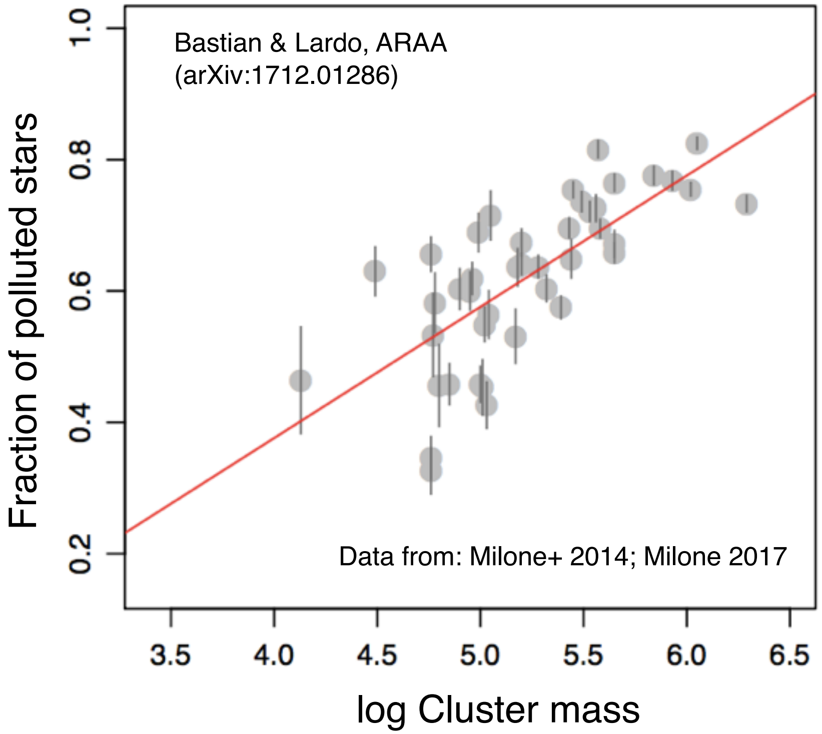
Material processed through SMS (super nuclear reactor)

→ Continuous SMS rejunevation

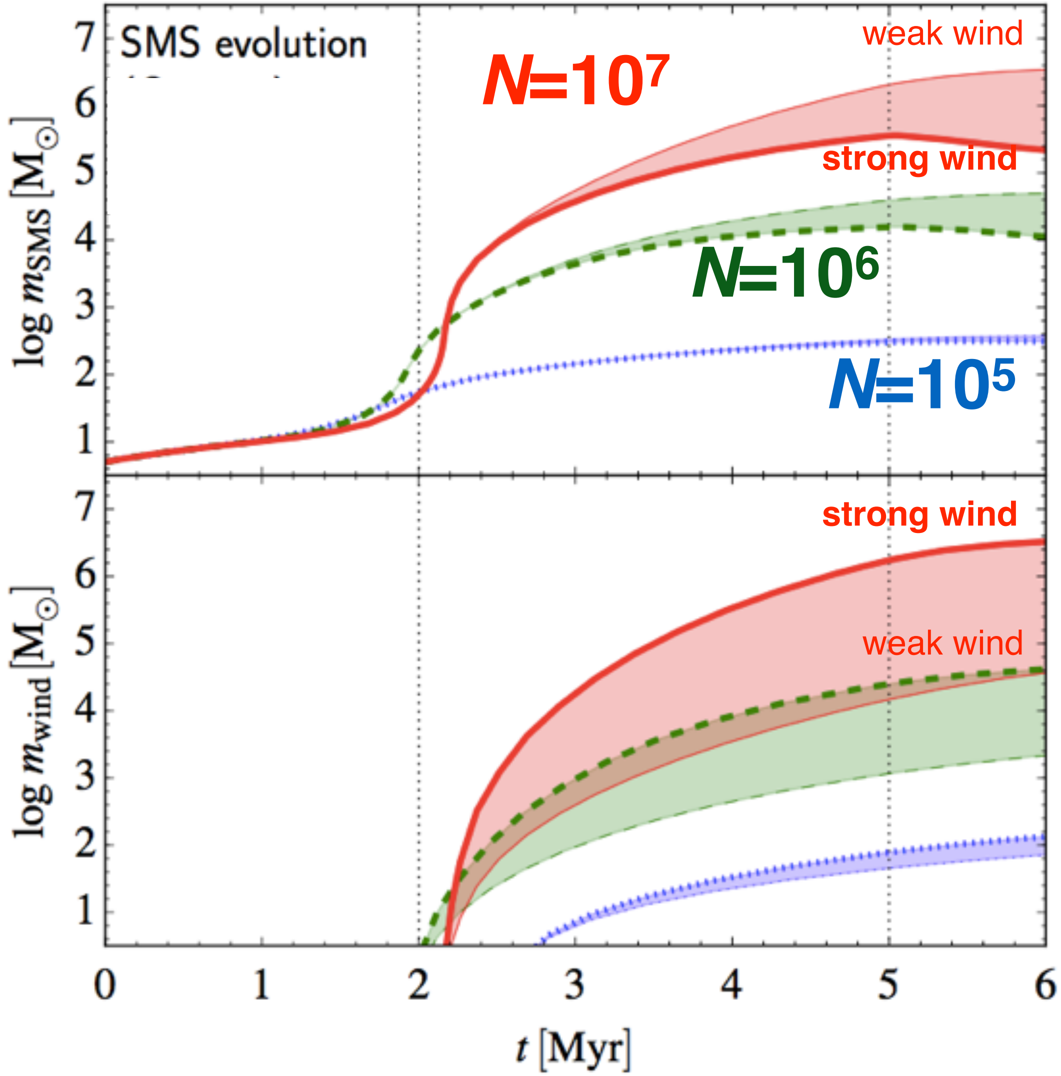
→ $M_{wind} >> M_{SMS}$

✓ Overcomes the mass budget problem

→ No need to lose 1P stars to account for the 1P/2P ratios



(Gieles *et al.* 18)



Super-linear scaling between m_{SMS} (and $\dot{m}_{wind}$) and $M_{cluster}$

✓ Fraction of 2P stars increases with $M_{cluster}$

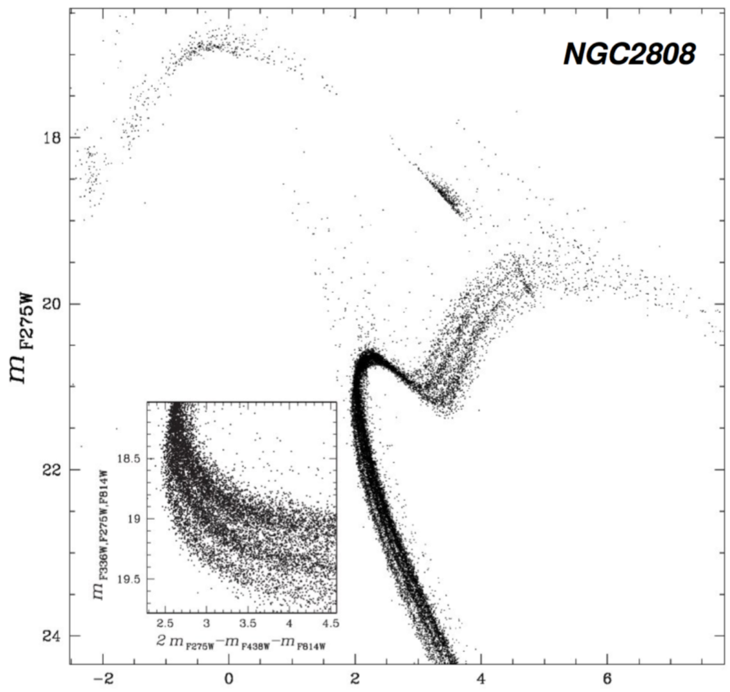
SMS evolution and wind

Conveyor belt

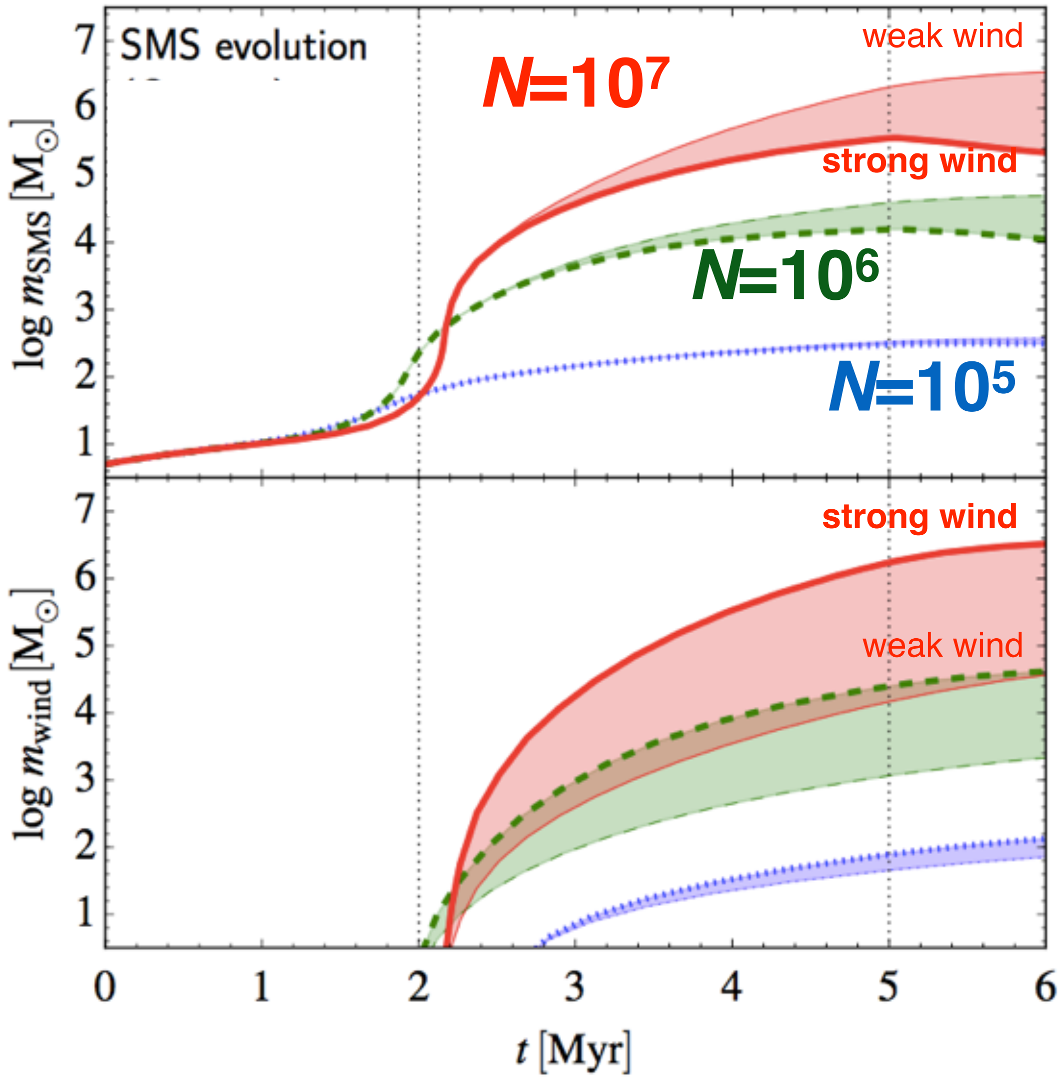
Material processed through SMS
(super nuclear reactor)

→ Continuous SMS rejunevation

→ $M_{wind} >> M_{SMS}$



ilone et al. 2015, ApJ, 808, 51



✓ Ok with He enhancement from HST photometry

(Gieles *et al.* 18)

Cluster enrichment by SMSs

Accreting cluster with gas inflow

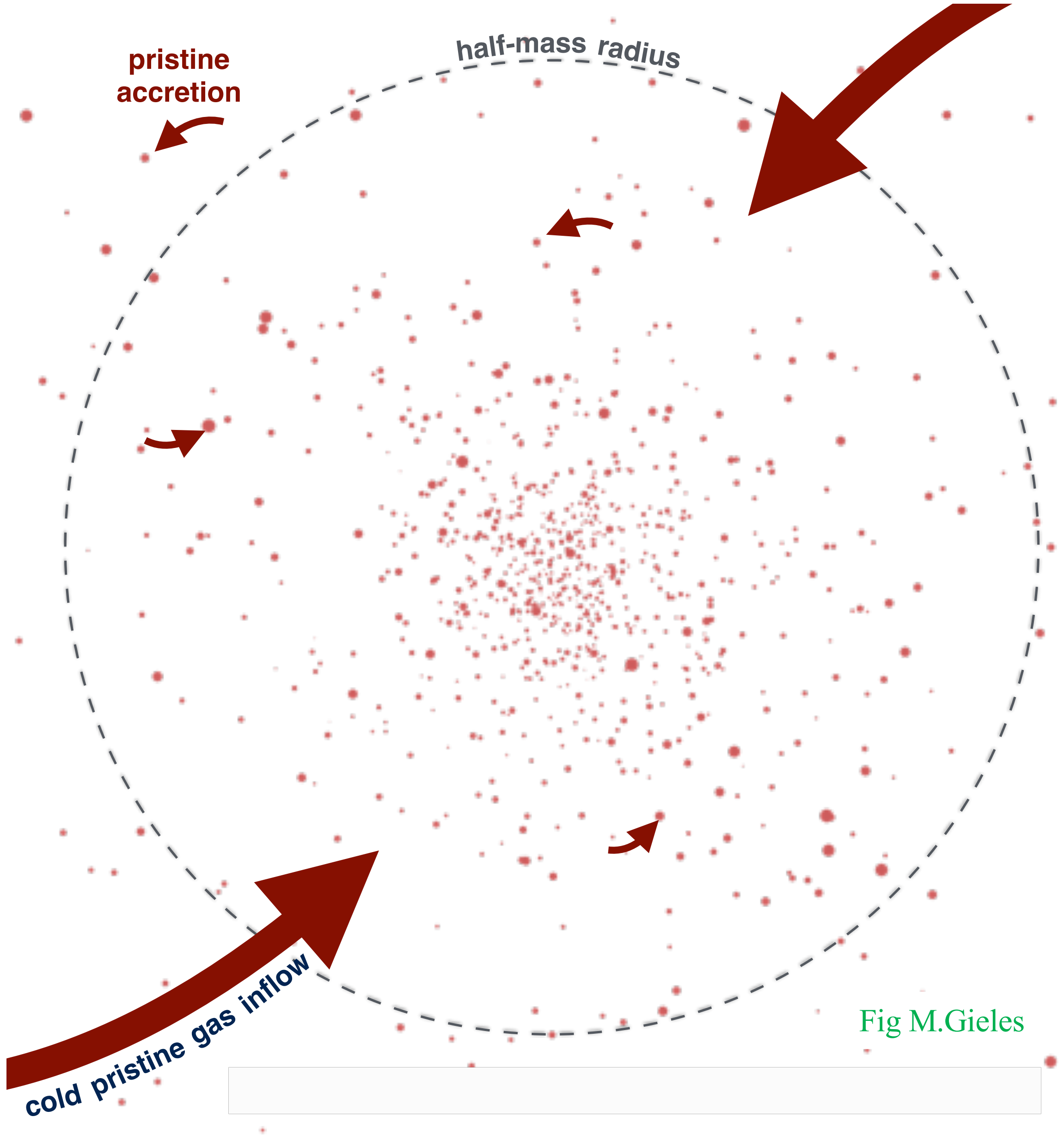


Fig M.Gieles

(Gieles *et al.* 18)

Cluster enrichment by SMSs

Accreting cluster with gas inflow

Strong SMS wind
rich in hot H-burning yields
pollutes the intracluster medium
→ C-N, O-Na, Mg-Al
with low He enrichment

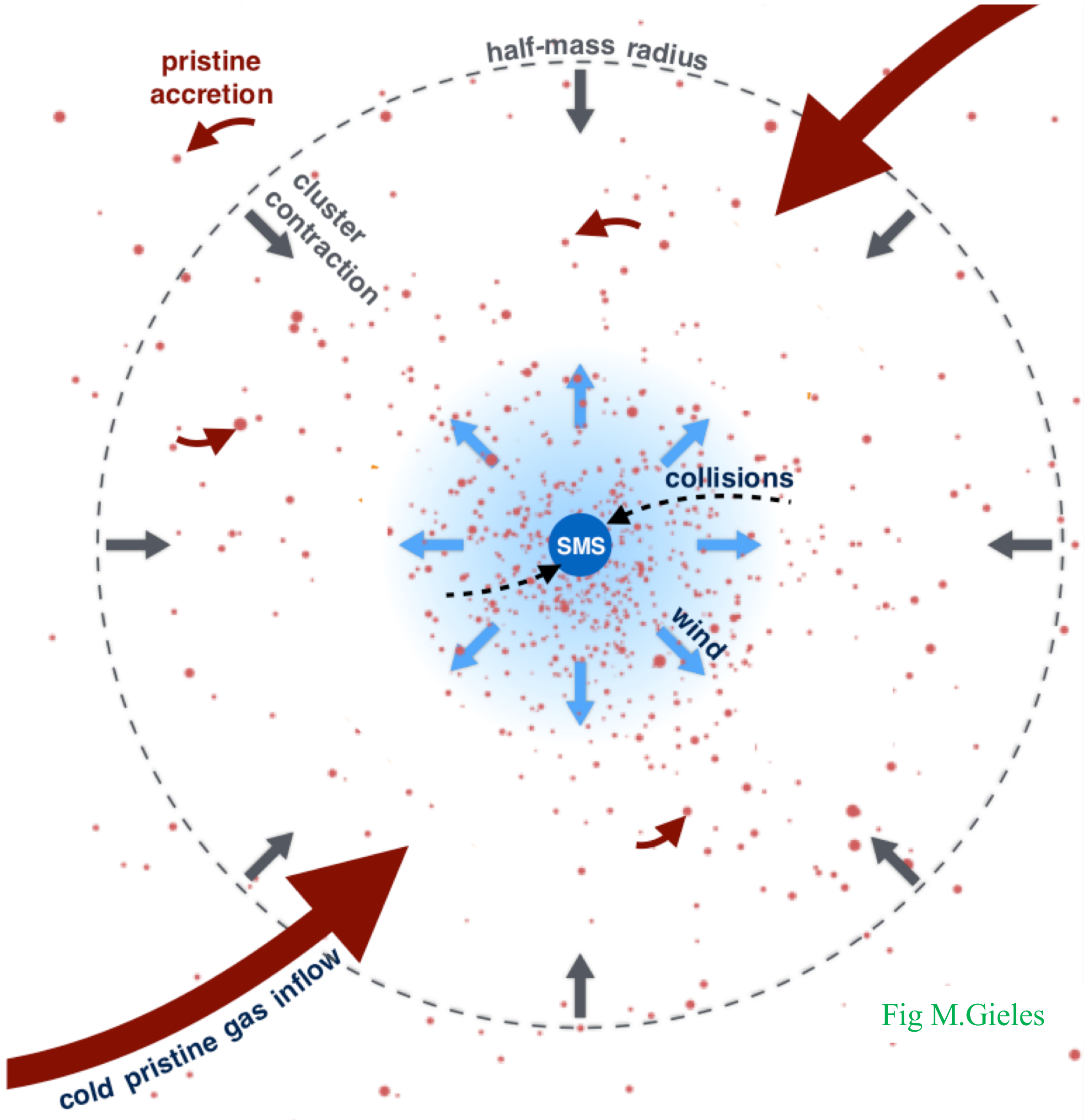


Fig M.Gieles

(Gieles *et al.* 18)

Cluster enrichment by SMSs

Accreting cluster with gas inflow

Strong SMS wind
rich in hot H-burning yields
pollutes the intracluster medium
→ C-N, O-Na, Mg-Al
with low He enrichment

Wind interacts with inflowing gas,
cools and accretes on protostars

Dilution with pristine gas → Li

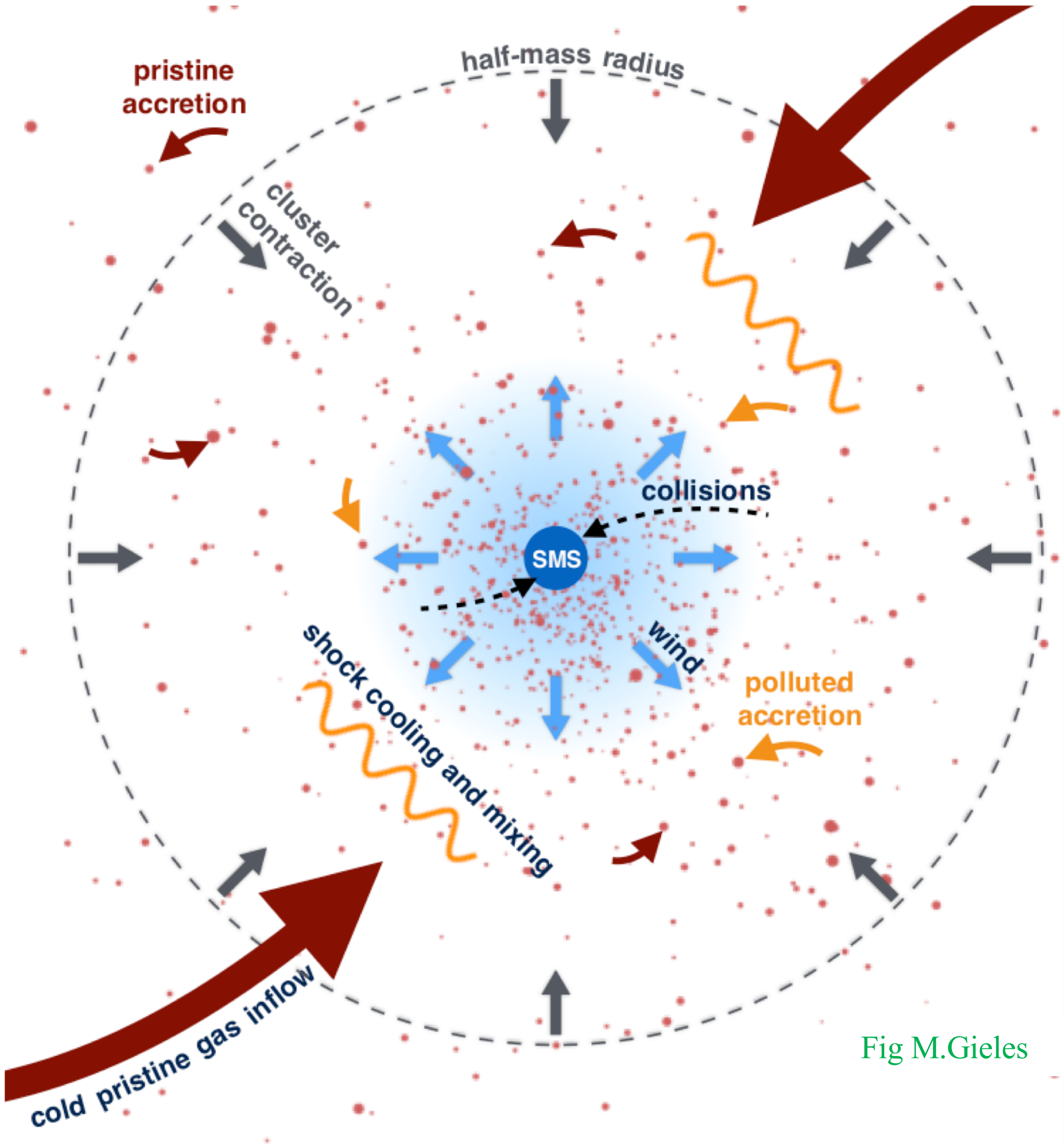
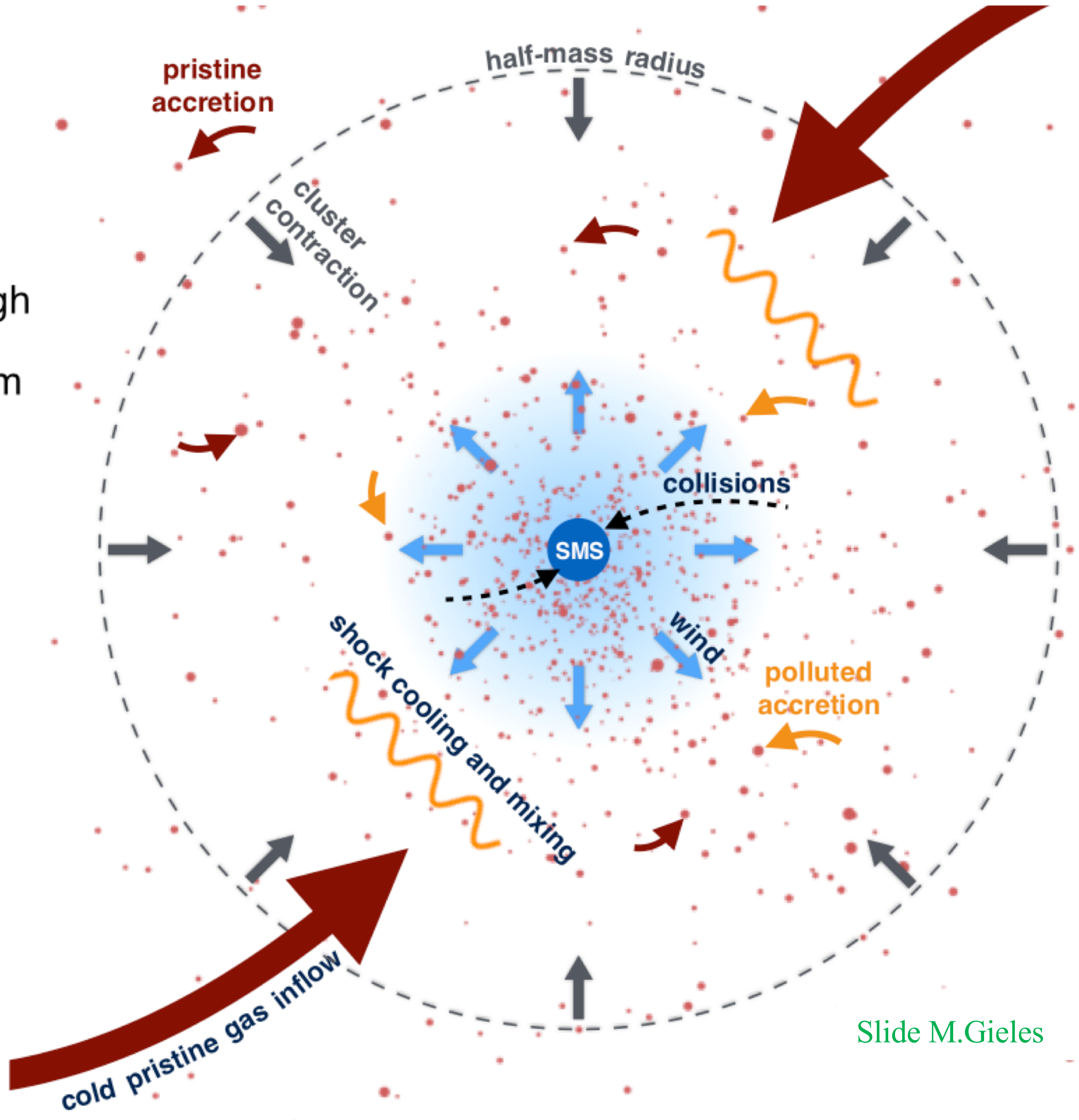


Fig M.Gieles

(Gieles *et al.* 18)

Cluster enrichment by SMSs

- ✔ 1. Anti-correlations: C-N, Na-O, Mg-Al
- ✔ 2. Both ΔY and f_{poll} correlate with M_{GC}
- ✔ 3. ΔY typically small, ΔNa typically high
- ✔ 4. Overcome the mass budget problem
- ✔ 5. No [Fe/H] spread within GC
- ✔ 6. Dilution with pristine gas (for Li)
- ✔ 7. Ubiquitous, at all [Fe/H]
- ✔ 8. Discreteness
- ✔ 9. Cluster-to-cluster variation
- ✔ 10. Make testable predictions!



Slide M.Gieles

(Gieles *et al.* 18)

Gieles, CC + 18

MSP in GC – What's next?

Modelling and testing

SMS models : Formation and stability

Merger process, including shock heating, hydrodynamic mixing and mass loss
Gravitational, pulsational, and general relativistic instabilities

Formation and evolution of the low-mass stars

GC models : Accretion, feedback, N-body

SMS theoretical spectra –> High-z observations

Massive star clusters with high inflow rates 10^{4-5} $M_\odot$ Myr^{-1} (ALMA)

GC – YMSC connection

Field stars with MSP properties

MSPs with abundance variations (He) → Interpretation of HST photometry

→ Age of the GCs