The origin of the Multiple Populations within Stellar Clusters

an alternative explanation

Nate Bastian
(LJMU)

arXiv:1309.3566

Henny Lamers (Amsterdam),
Selma de Mink (Carnegie),
Steve Longmore (LJMU),
Simon Goodwin (Sheffield),
Mark Gieles (Surrey)

23/09/13

Padova 23 sept 2013

Old Paradigm

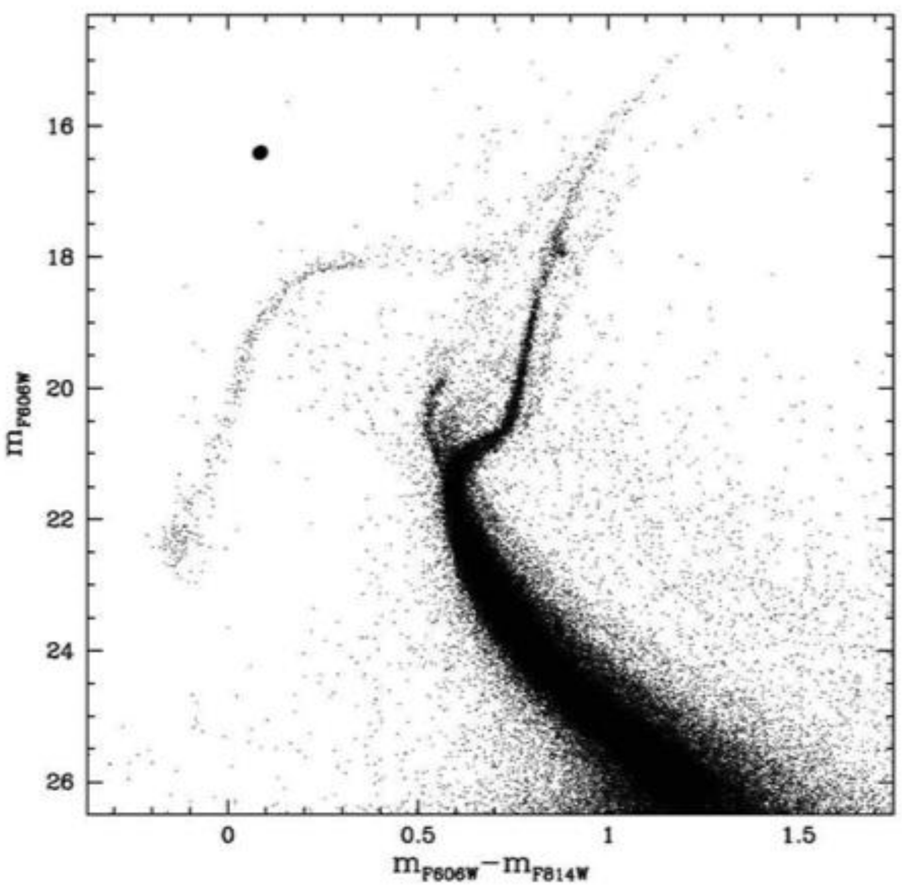
Globular Clusters are
“ simple stellar populations “

1. 1. Formed from one IS cloud
2. 2. Stars have same initial composition
3. 3. Stars are about equally old

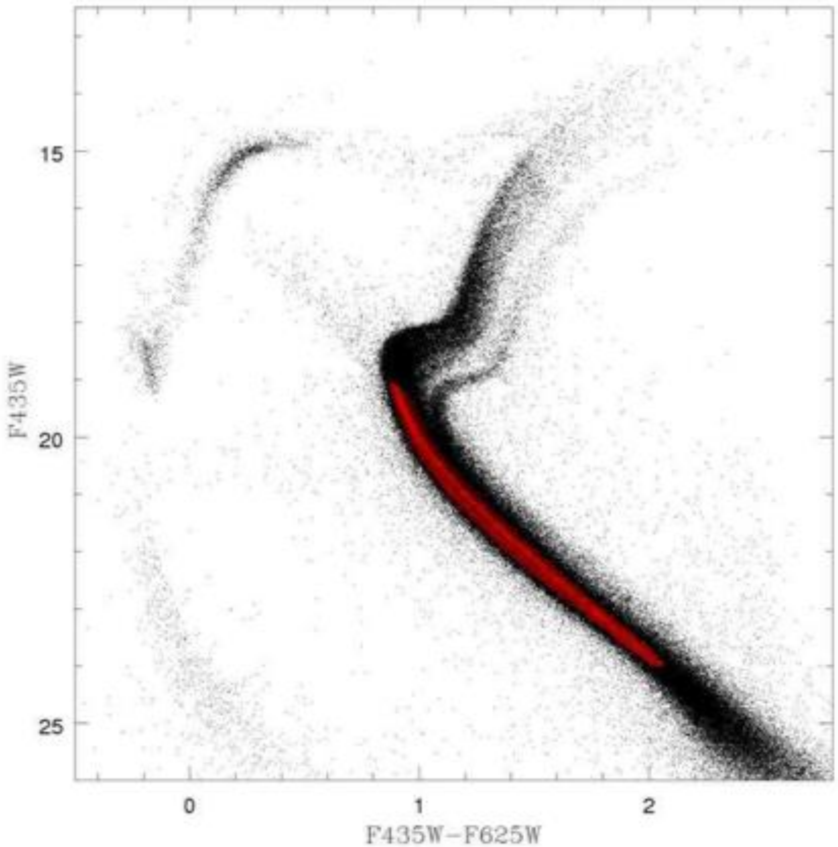
Their HR-diagrams are simple :
isochrones

Ancient globular clusters are not simple stellar populations

M54

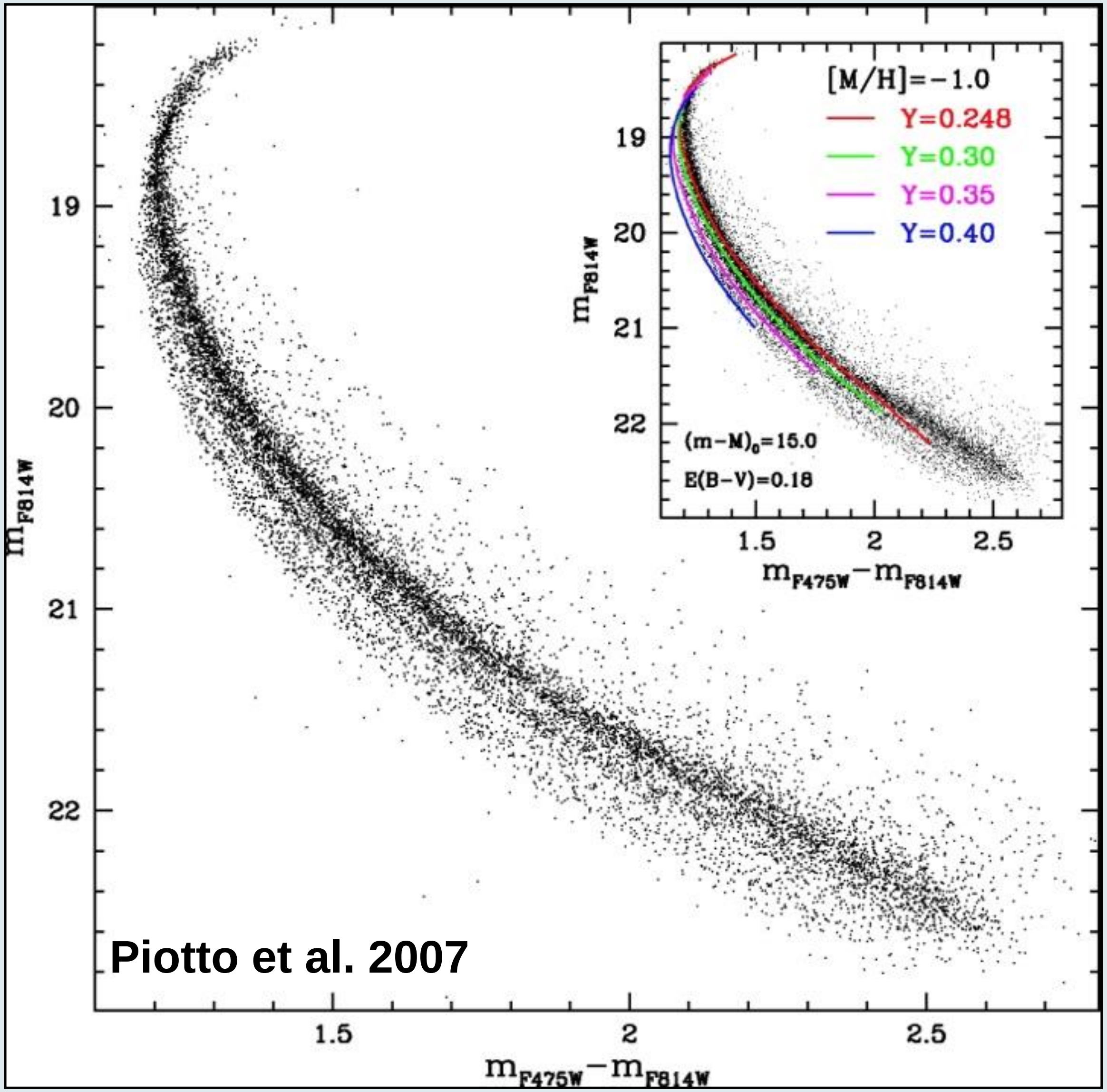


omega cen



Piotto 2008

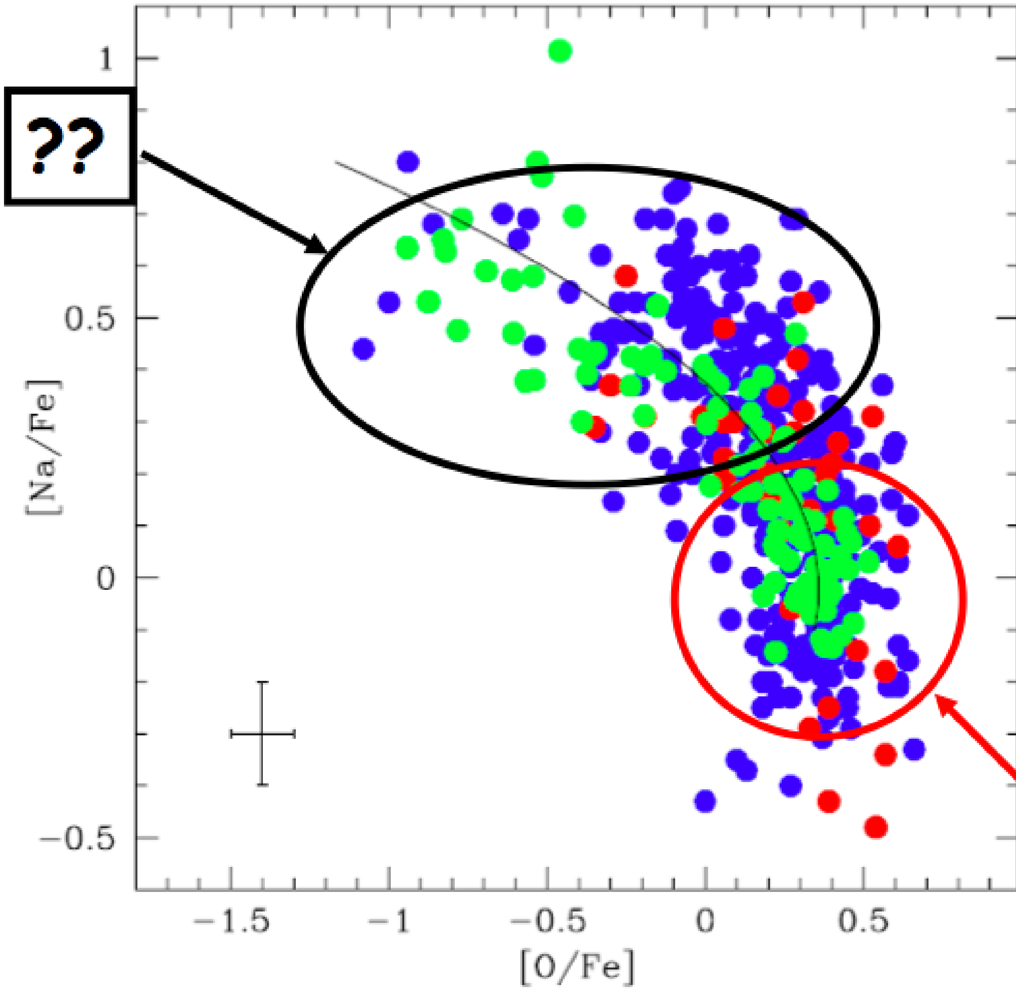
NGC 2808 - photometric anomalies



~60% of stars on nominal main sequence
("first generation")

~30% of stars are He enriched
("second generation")

Not just He: chemical anomalies



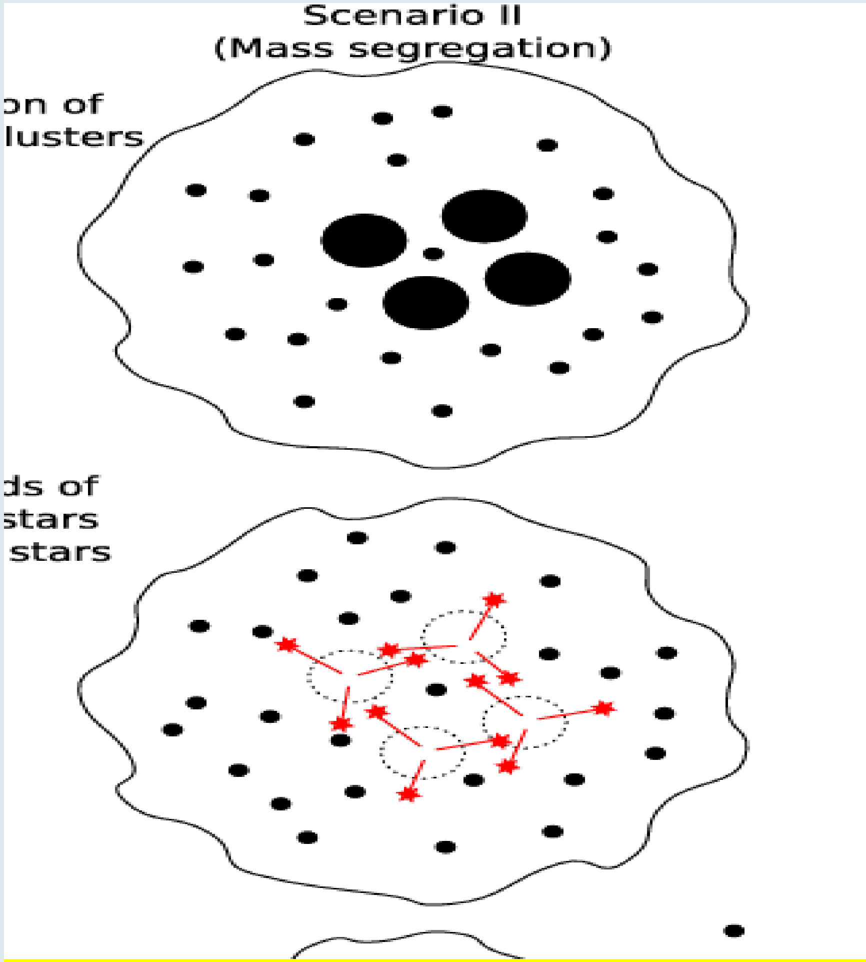
Carretta et al. 2006 A&A 450, 523

Na-O anticorrelation

collection of stars in about 20 globular clusters. Blue points are RGB stars from literature studies; red points are **scarcely evolved stars (turnoff or subgiant stars)** from Gratton et al. (2001) and Carretta et al. (2004); green points are RGB stars in NGC 2808 from the present study.

this is the range of abundances in low metallicity field stars

D'Antona 2012 (Vatican Observatory Lectures)



Evolutionary model for second generation stars

1. **Very massive cluster**
2. **Massive stars or AGB eject polluted winds**
3. **Polluted gas stays in cluster**
4. **Accumulate enough gas for second starburst in**

If clusters consist now ½ first generation and ½ second generation stars: the original cluster mass must have been much higher than now ! (10 – 100 x) Mass budget problem!

What are the polluters ?

1. AGB stars   (d'Antona: Rome-Padua group)
   + slow winds (~10 km/s) remain in cluster
   - only small mass range 4 – 10 Msun
     does not produce enough enriched gas

2. Rapidly rotating massive stars (spin stars)
   (Decressin: Geneva group)
   + enough material if MF is top-heavy
   - winds too fast? (~50 km/s), SN blow-out?

What are the polluters ?

1. AGB stars (d'Antona: Rome-Padua group)
   + slow winds (~10 km/s) remain in cluster
   - only small mass range 4 – 10 Msun does not produce enough enriched gas (IMF)

2. Rapidly rotating massive stars (spin stars) (Decressin: Geneva group)
   + enough material if MF is top-heavy
   - winds too fast?, (~50 km/s)

3. Winds from interacting massive binaries (de Mink: Utrecht-Bonn group)
   + enough material with normal IMF !
   - very slow winds, blown-out by SN?

Problems for models of multiple populations in GCs

1) non-standard IMF

2) that the clusters can retain ejecta gas for long periods

3) that GCs were 10-100 times more massive than presently seen
(mass budget problem)**,**

Larsen 2012 showed that in Fornax galaxy the low metalicity populaton, [Fe/H]<-2, is about 25 to 50% in clusters and 50-75% in field stars

Omega Cen - ESO

few million Msun

~12 Gyr

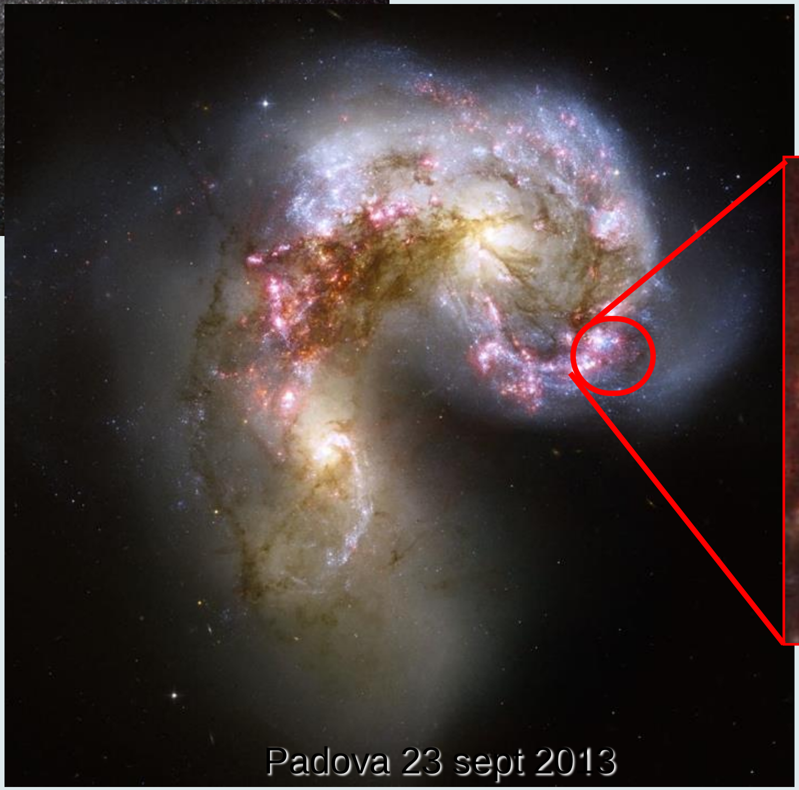
R_{eff} ~ 10 pc

Massive strars are still forming today!!

few million Msun

~7 Myr

R_{eff} ~ 4 pc



“Knot S”
Antennae colliding galaxies - HST

Do clusters retain (polluted) gas for long time?

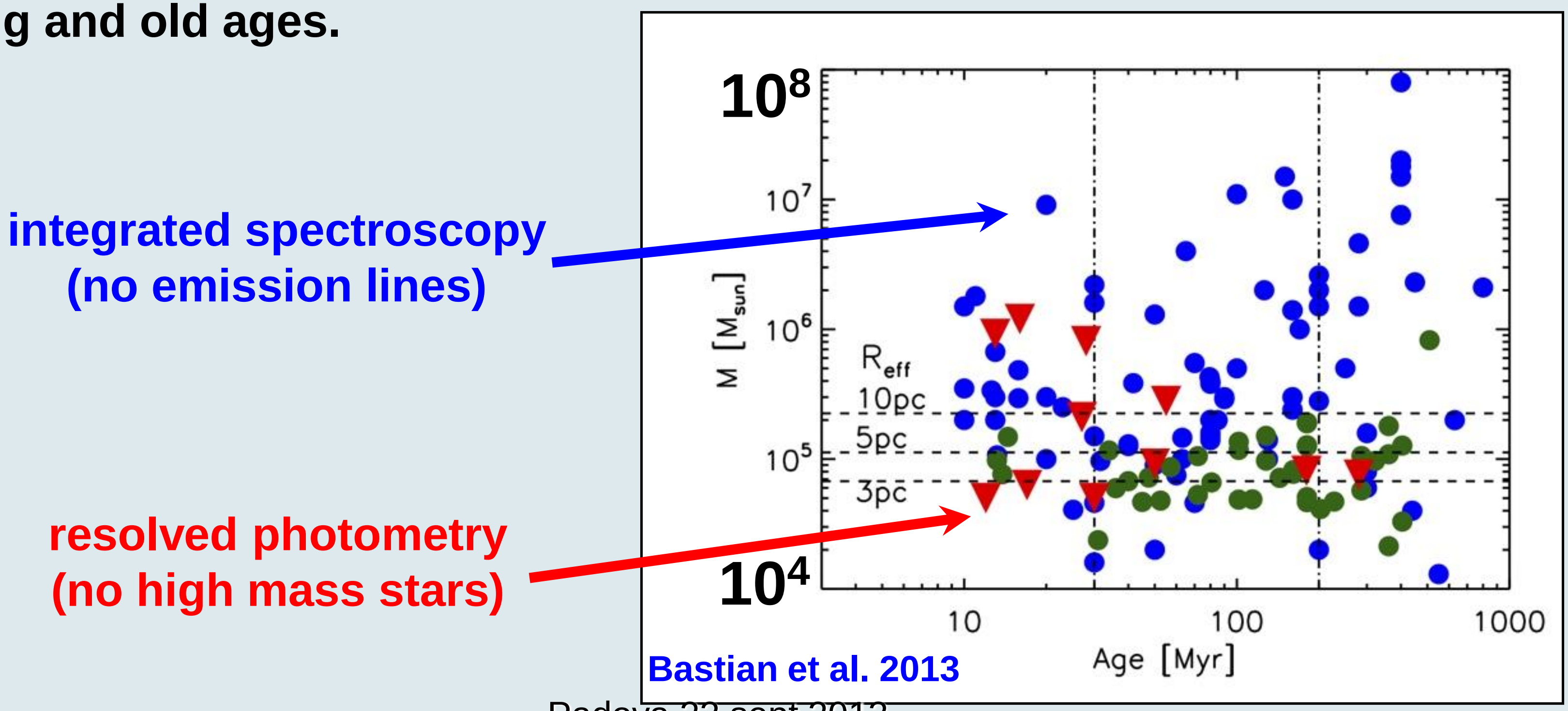
- No evidence for ongoing star-formation within any YMCs observed to date (130 with 10^4 < Mass/Msun < 10^8 and 10 < age/Myr < 1000)

  Bastian et al. 2013

- From integrated spectroscopy - no evidence for extended or discrete multiple star formation episodes (for clusters >10^7 Msun, ages few hundred Myr)

  Cabrera-Ziri et al. in prep.

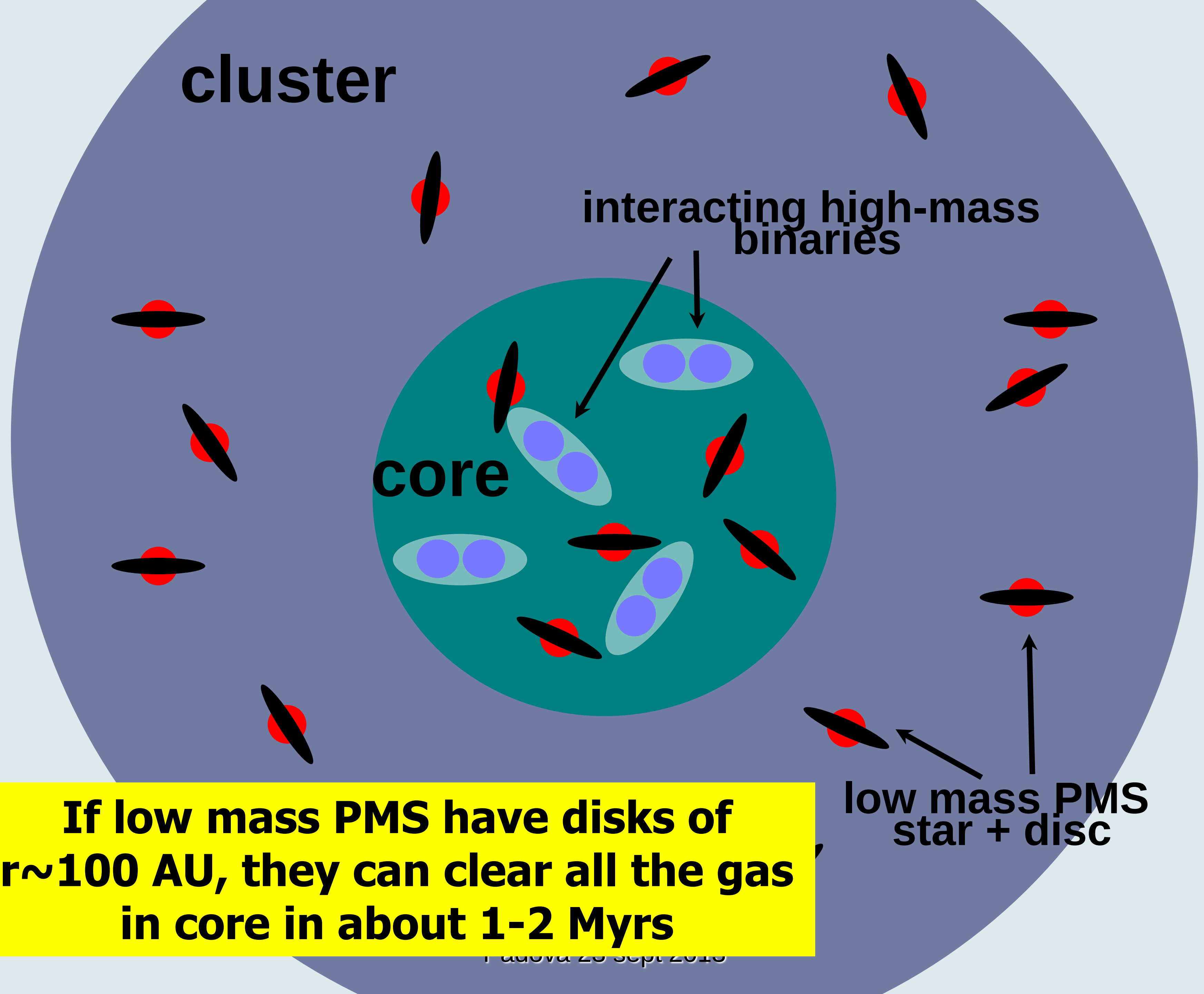
- Clusters appear to be incapable of retaining gas lost from stellar evolution at young and old ages.



New model

Bastian et al. 2013, MNRAS (in press)

- **One burst of star formation (i.e. an SSP) - as observed in young clusters**
- **High mass stars (binaries) in center : mass segregated**
- **interacting binaries and spin-stars eject (low velocity) material into the cluster - this material has been processed by the high mass stars (70% of high mass stars are in binaries that will interact - Sana et al. 2012)**
- **low mass stars keep their discs for 5-15 Myr (e.g., Bell et al. 2013), which can entrain material as they move in the cluster**
- **the material eventually accretes onto the young star**
- **this will only happen to low-mass stars (<2 Msun), as they stay in the pre-main sequence phase for >6 Myr.**
- **Known as “tail end accretion” - Throop & Bally 2008**

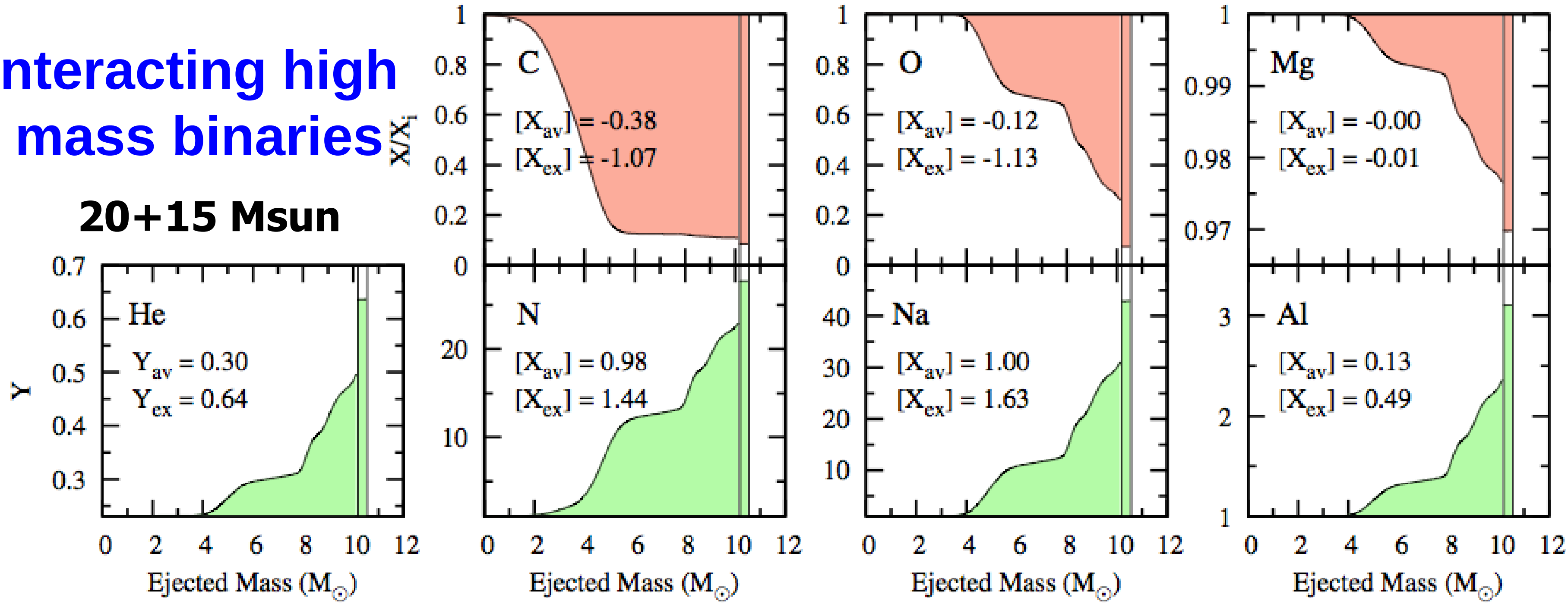


If low mass PMS have disks of r~100 AU, they can clear all the gas in core in about 1-2 Myrs

1) Source of the enriched material

Interacting high mass binaries

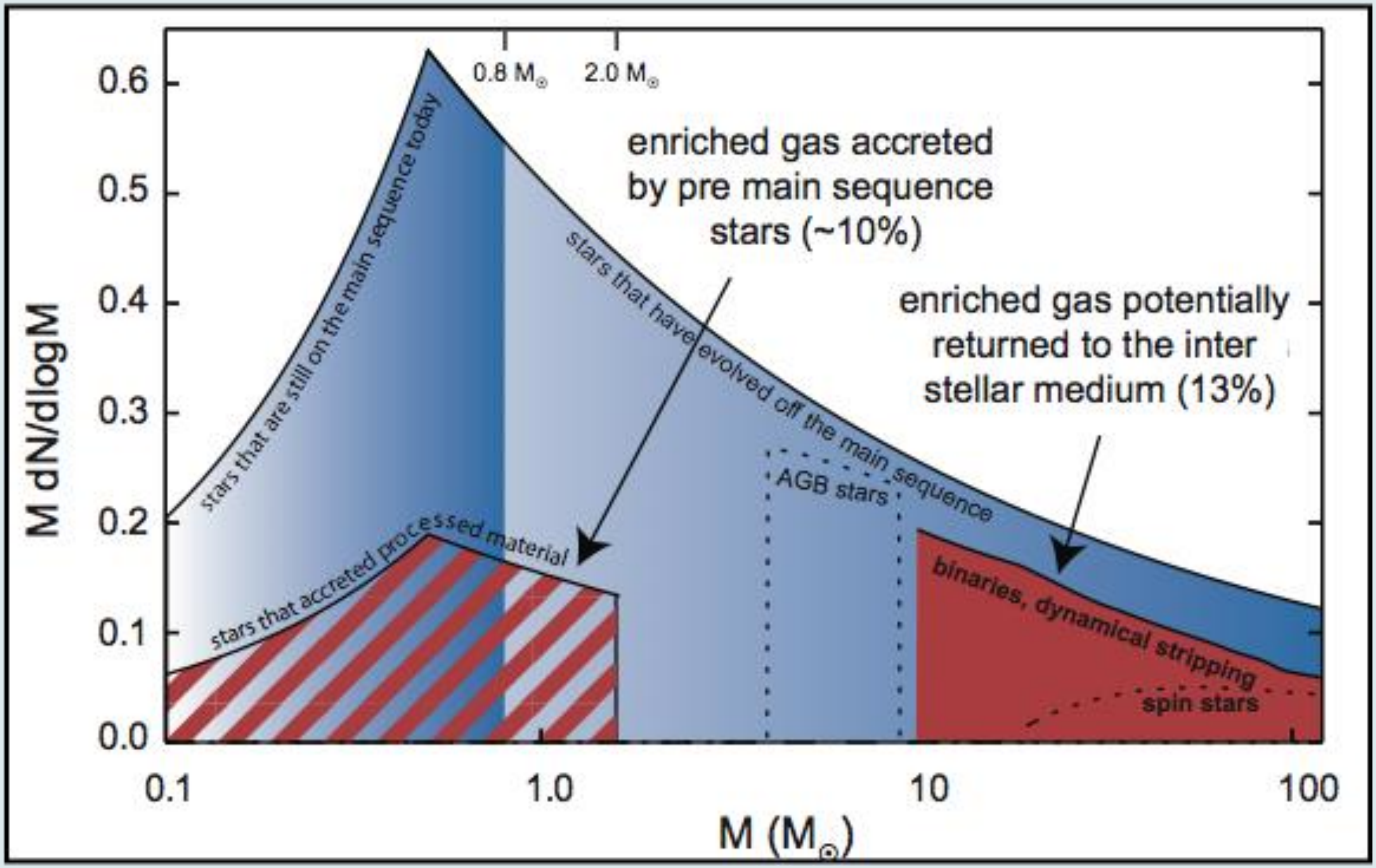
20+15 Msun



de Mink et al. 2009

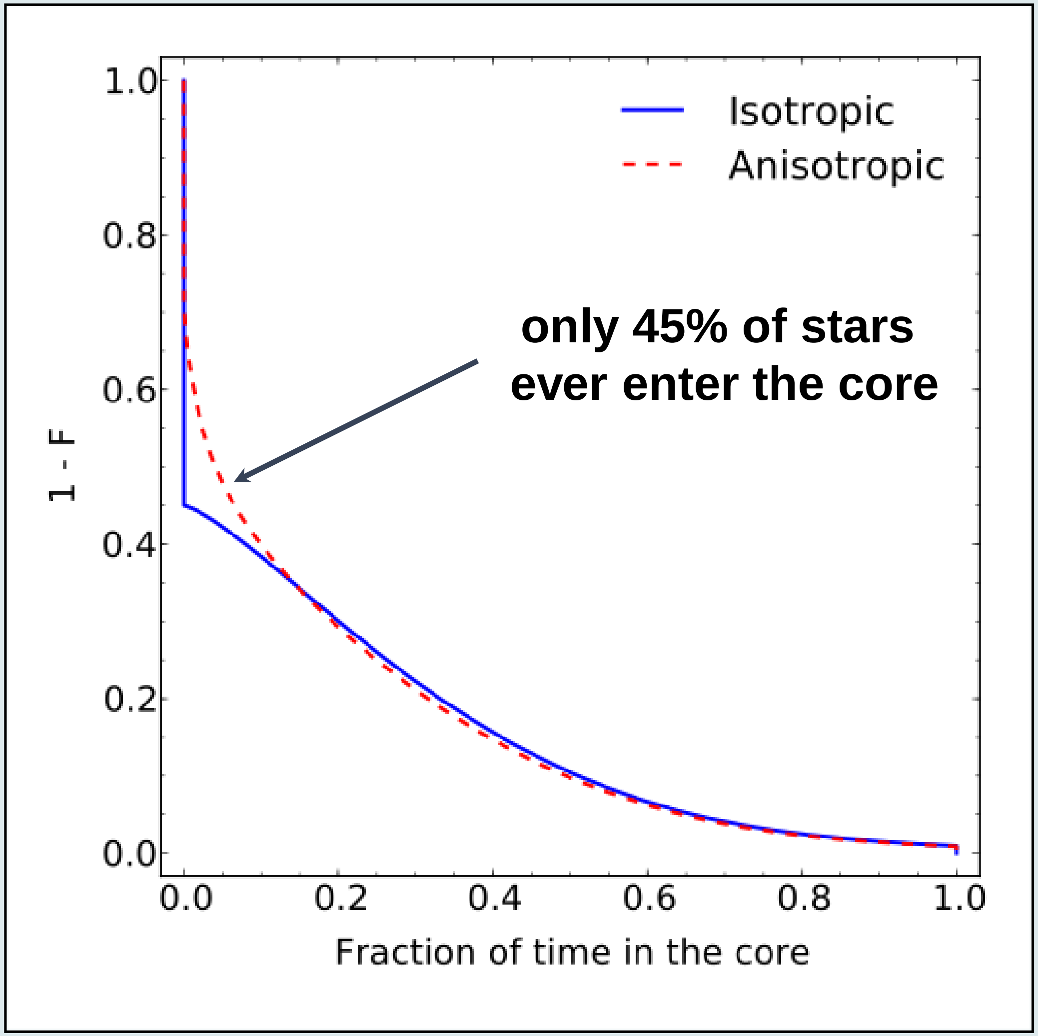
- The ejected envelope is very He rich
- All abundance trends reproduced
- Ejected at low velocities (<20-30 km/s)

2) Mass budget problem?



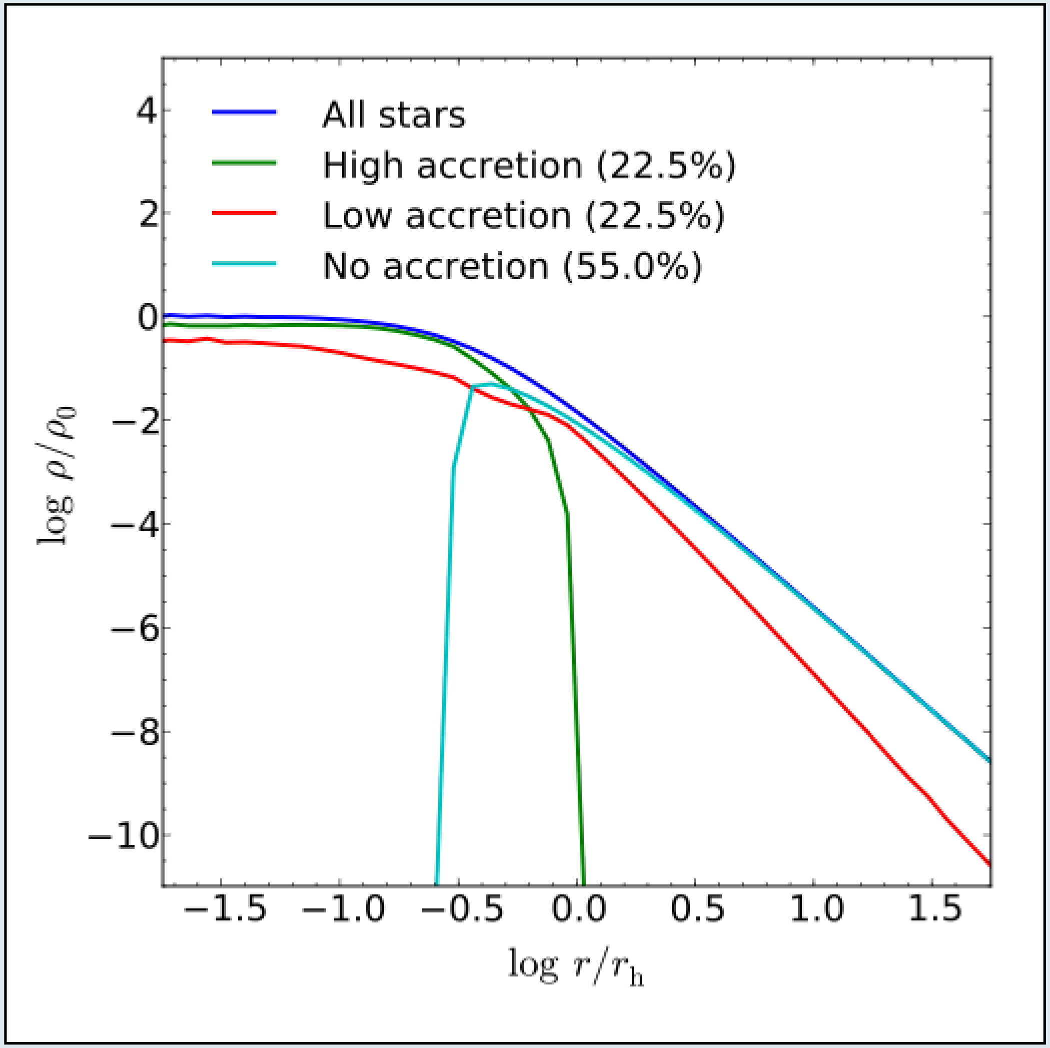
Since a star is already in place to accrete the material, we can make the extreme approximation that a star accretes ~50% (in reality it will be much less). In that case only <10% of the initial cluster mass needs to be accreted.

3) Quantization of He and other elements?



Dynamics: stars passing through the core

4) Predicted distribution of the stars in a young massive cluster



Padova 23 sept 2013

Mark Gieles

Summary of the model (1)

- Low mass stars with discs sweep up (and eventually accrete) material processed by and ejected from high mass binary and/or "spin stars"
- The entire volume core is swept out every ~1-2 Myr
- Without invoking multiple episodes of SF, the model
  1) accounts for the enrichment patterns observed,
  2) Quantised abundances (and fractions),
  3) doesn't have a "mass budget problem"
  (other models miss the mass budget by 10-100)
- Explains why young massive clusters are observed to be gas free from young ages (~1-2 Myr) and don't show evidence for extended SF

Summary of the model (2)

- Prediction: Same effects should be visible in resolved young massive clusters, although more difficult to see due to higher metllicity
- Uncertainty: Can the PMS disks survive long enough (7 Myr?)
- Caveat: The model requires a low coupling between SNe and dense cool matter in the discs of young stars and in the ejecta material from binaries..
  ..supported by radiation-hydrodynamical models - e.g., Rogers & Pittard (2013)

For more details: Bastian et al. 2013 MNRAS arXiv 1309.3566

the end

Problems for models of multiple populations in GCs

- **Extremely ad-hoc, many adjustable parameters, mix of theory and 'fixes' to fit observations**

- **Generally assume that a cluster can hold on to gas expelled from stars (and accrete new gas at the precise right time) for 10s to 100s of Myr**

- **Mass budget? Larsen 2012 showed that in Fornax galaxy the low metalicity populaton [Fe/H]<-2 is about 25 to 50% in clusters and 50-75% in field stars.**

- **All require**
  1) non-standard stellar IMFs,
  2) *that GCs were 10-100 times more massive than presently seen (mass budget problem)*,
  3) that the clusters can retain ejecta gas for long periods

Directly in contradiction with observations !

Observables

- **Na-O anti-correlation**
- **Large Al spread, small (or no) Mg spread. Some spread in other light elements (e.g C, N). No spread in Fe.**
- **Discrete main sequences/turn-offs, sub-giant branches, presumably due to discrete He abundances (although multiple main sequences in the UV are tracing different CN abundances)**
- **YMCs should also show evidence for ongoing star-formation or multiple bursts in their star-formation histories (SFHs)**

Sources of the enriched material

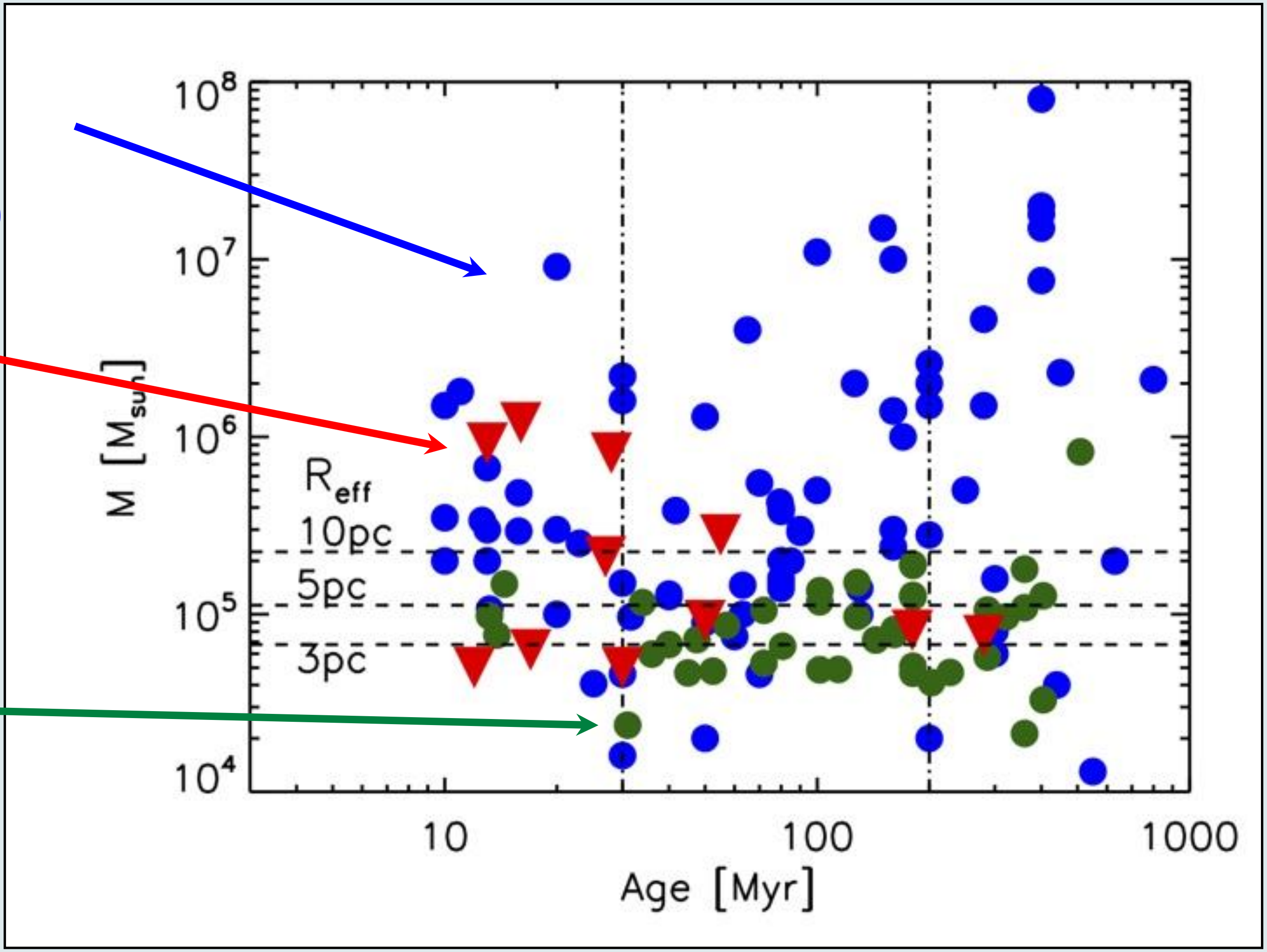
- **Only certain stars produce the right abudances. SNe can't do it.**
- **AGB stars (although wrong Na-O correlation), spin-stars (rapidly rotating O-stars), interacting massive binaries, stellar collisions (high mass stars)**

No clusters older than 10 Myr show any signs of ongoing star formation

integrated spectroscopy (from literature)

resolved photometry

integrated spectroscopy (newly presented)



Bastian et al. 2013, submitted

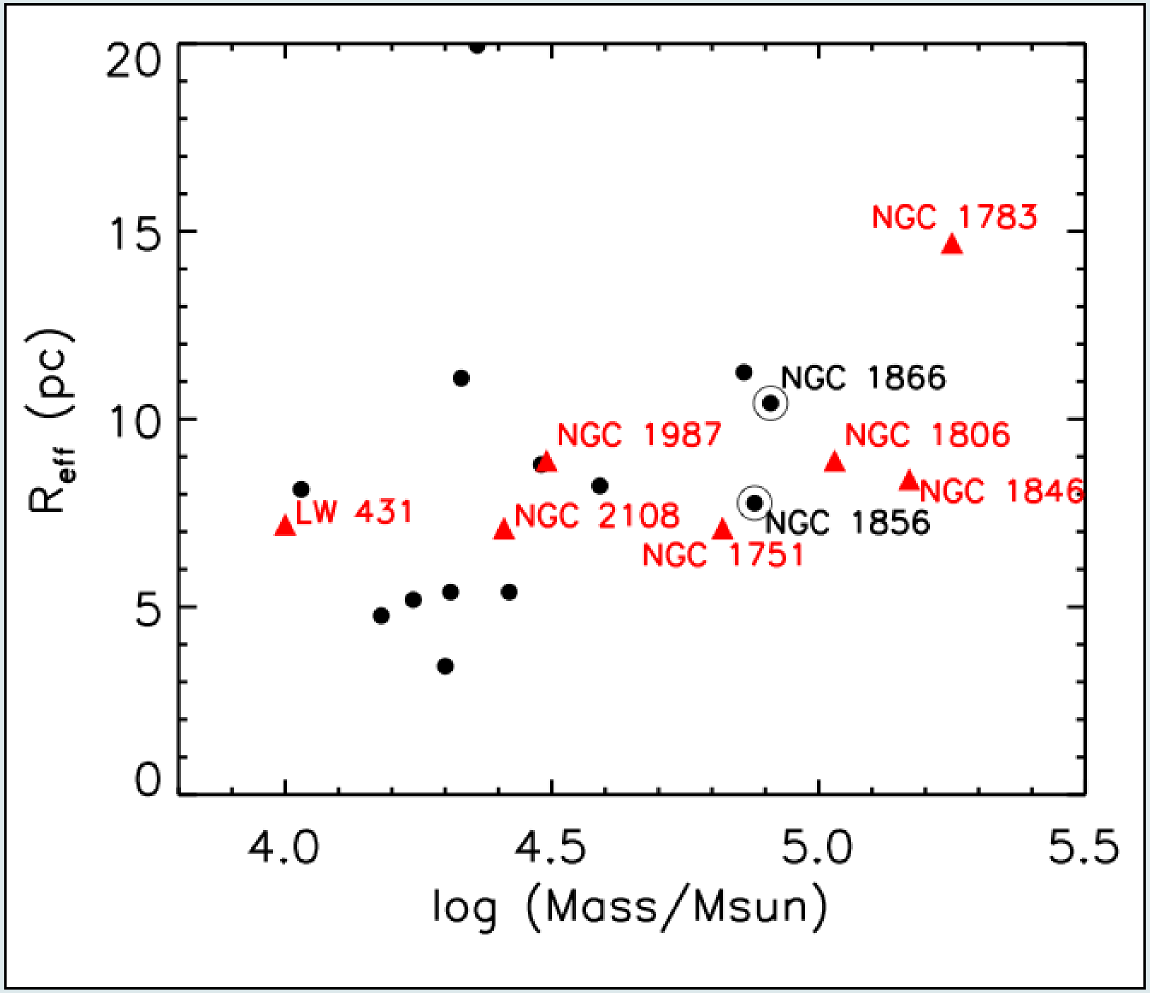
Summary of young clusters

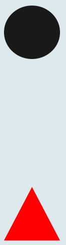
- Appear to be gas free at young ages (<2 Myr)
- No evidence for extended star formation histories in resolved massive clusters
- No evidence for ongoing star formation in *any* young massive cluster studied to date
- What is causing the MSTO spread in intermediate age clusters? ***Possibly stellar rotation - Bastian & de Mink (2009), Yang et al. (2013)***
- So what is going on in Globular Clusters?

Extended main sequence turn-offs in LMC/SMC clusters

- Often interpretted as an age spread of 100-500 Myr
- If true, clusters with similar masses/radii, but younger ages should also show it (and be much more easily detectable, due to the rapid CMD changes of young stars)
- Not seen in resolved photometry of NGC 1856 and NGC 1866 (10^5 Msun)
- Also ruled out in much more massive clusters, as half of the sample should show evidence for ongoing star-formation, but none do.

If an age spread, and a common feature of clusters, this should be seen in younger clusters with similar properties





Bastian & Silva-Villa 2013

NGC 1856

Age ~ 280 Myr

mass ~ 10^5 msun

A_V ~ 0.8 mag

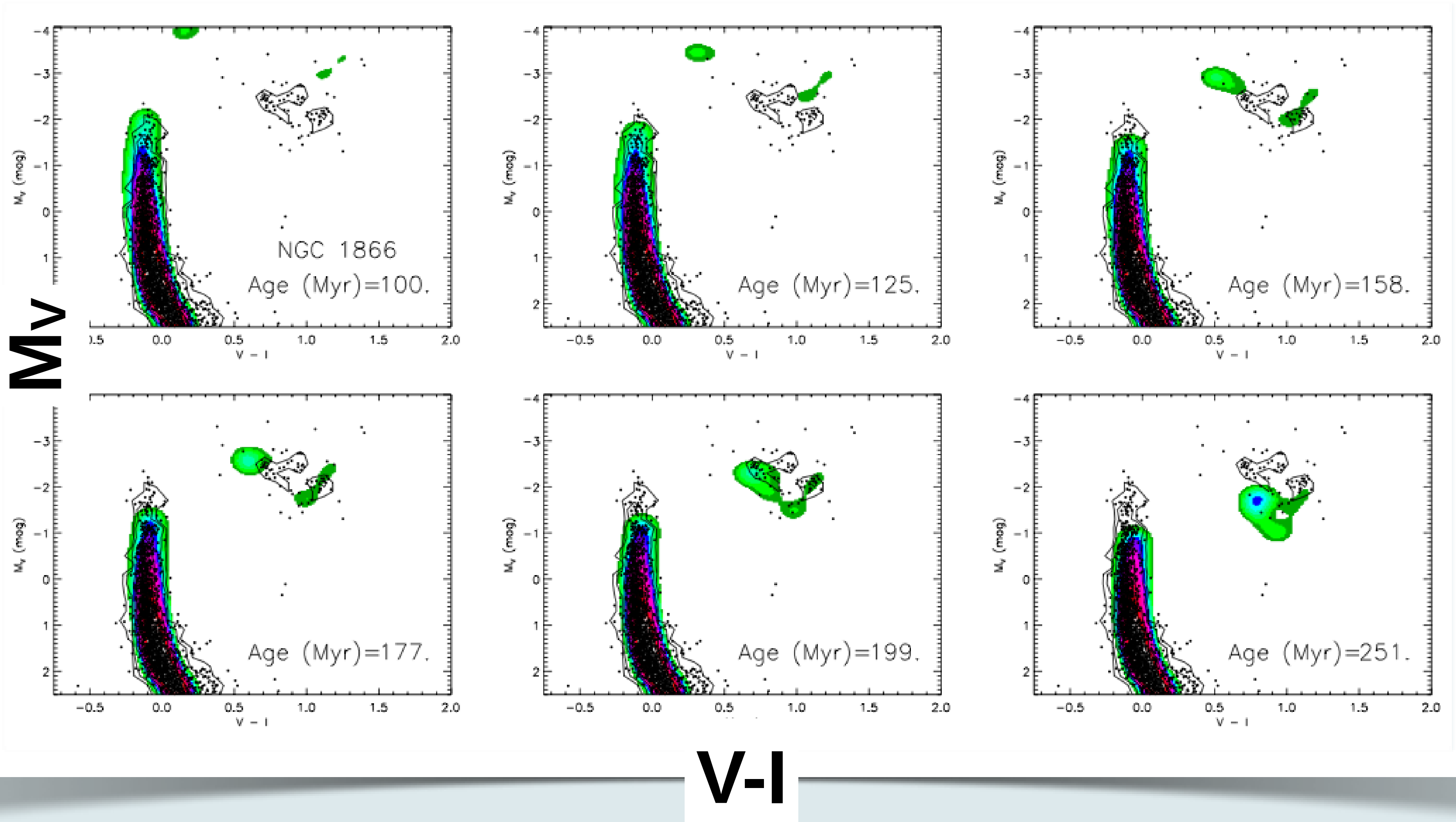
NGC 1866

Age ~ 180 Myr

mass ~ 10^5 msun

A_V ~ 0.15 mag

published HST photometry in Brocatto et al. 2001 and 2003



To avoid background contaminations, only inner 4.8pc were used in both clusters

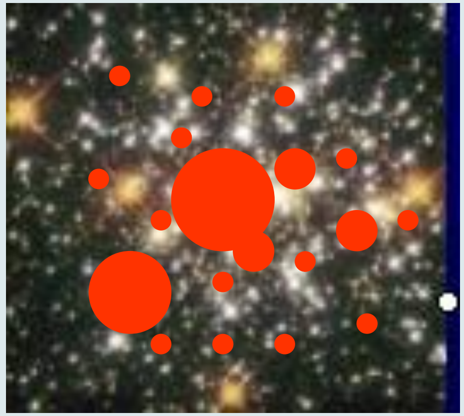
Clusters historically viewed as simple stellar populations

- All stars have the same age (very small spread, < 1-2 Myr - based on open clusters and YMCs)
- All stars have the same abundances
- Range of stellar massses (and potentially rotation rates)

But....

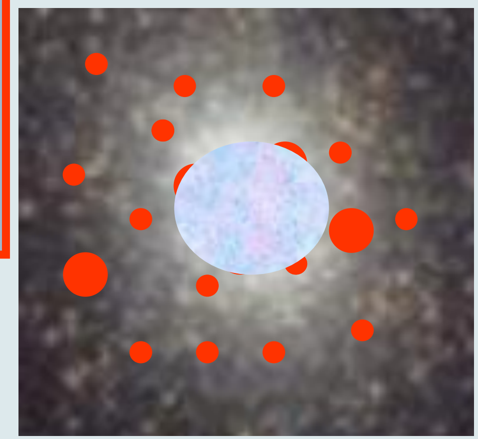
4. massive AGBs lose their envelopes in LOW VELOCITY WINDS

$t > 40 \times 10^6$ yr

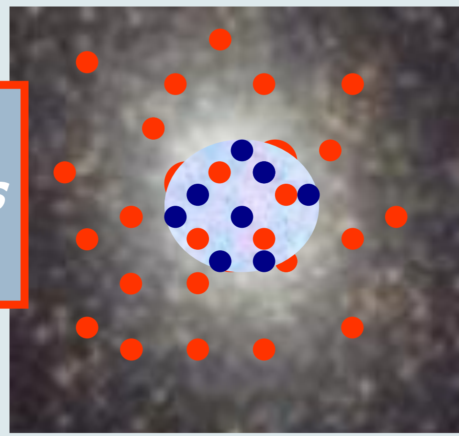


$t > 40 \times 10^6$ yr

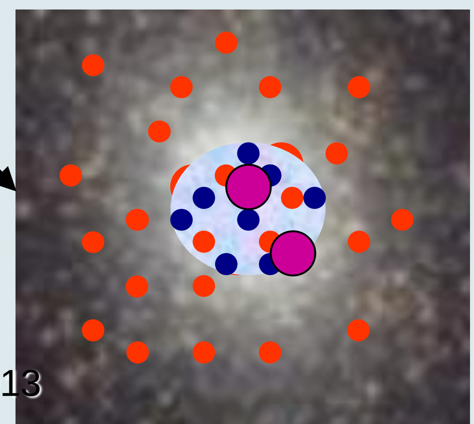
4. gas collects at center of the cluster



5. 2nd generation stars are born



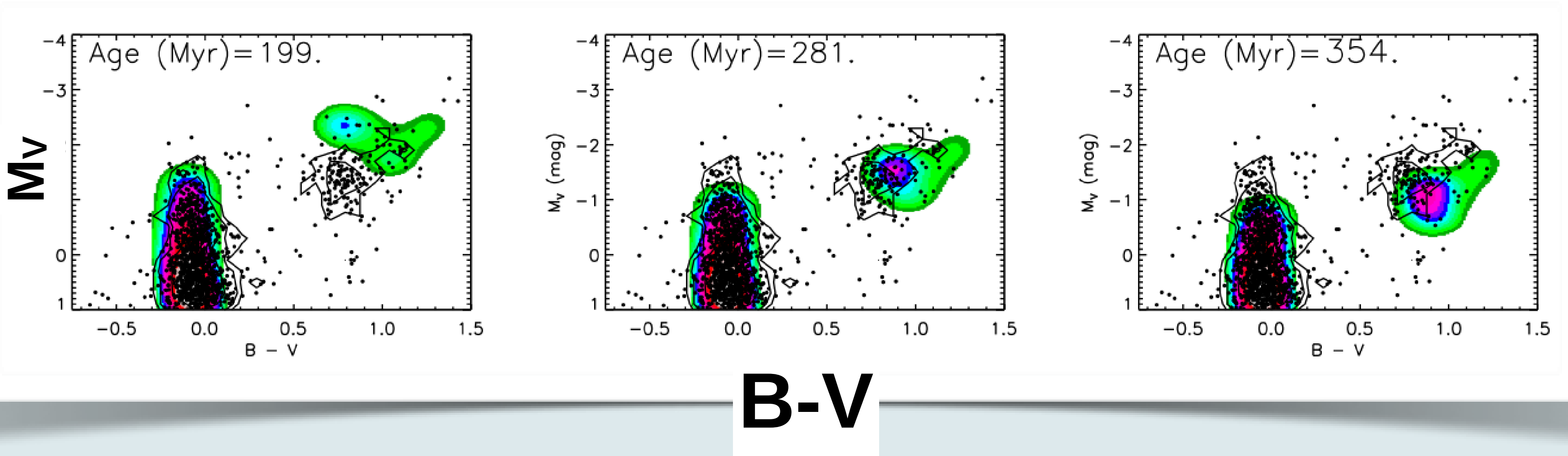
6. 2nd star formation phase ends



$t <\sim$ 100Myr

Courtesy: Franca d'Antona

NGC 1856

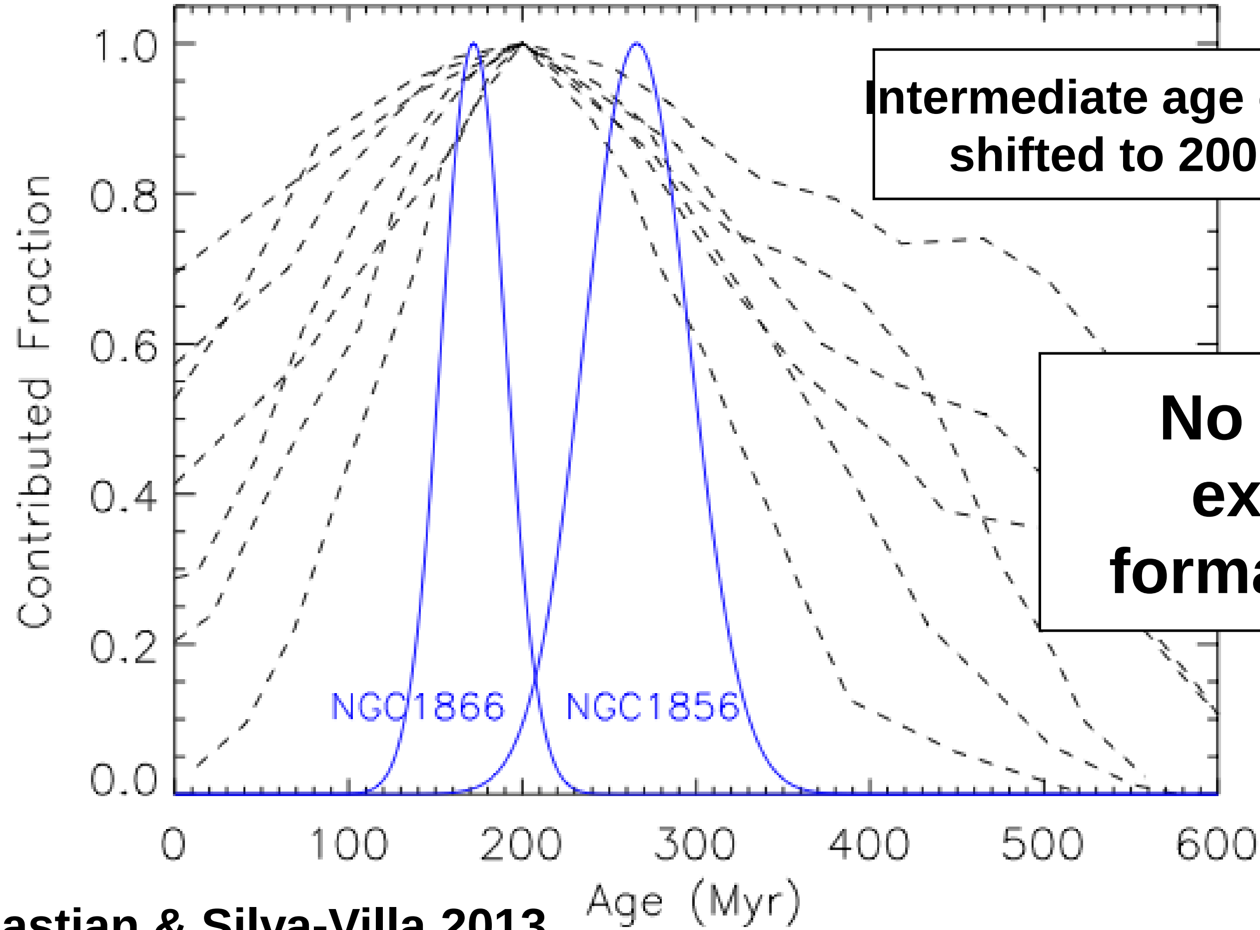


Quantitative results: use the FITSFH (Silva-Villa & Larsen 2010) code to derive the SFH of the clusters

-Takes into account photometric errors
-Adopts Salpeter IMF (above 1 Msun)
-Uses Padova isochrones (Bressan et al. 2012) at z=0.008

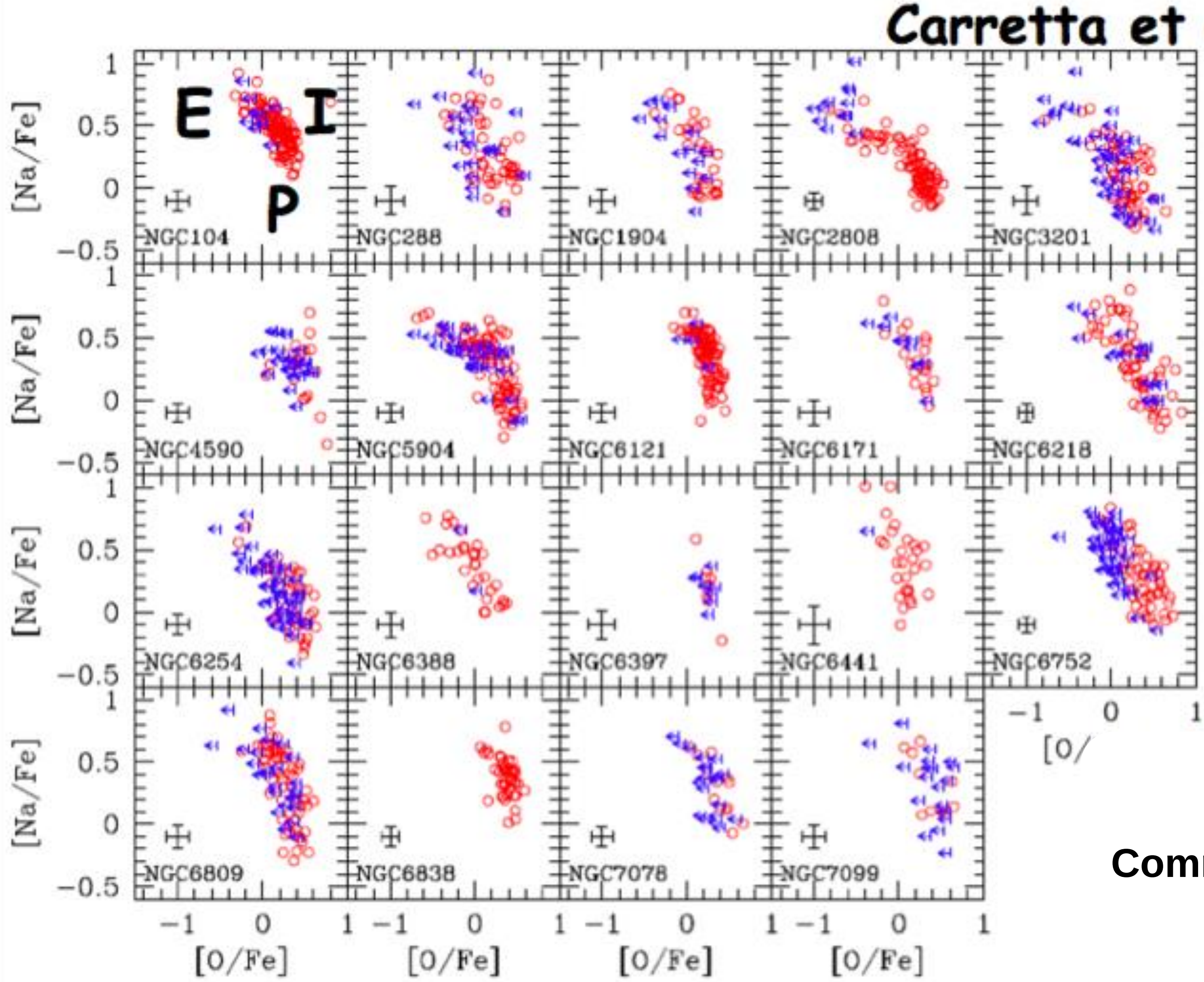
upper limits on the width

Intermediate age clusters shifted to 200 Myr



No evidence for extended star formation histories

Bastian & Silva-Villa 2013



more than 1200 red giant stars in 19 GCs

Common feature

D'Antona 2012 (Vatican Observatory Lectures)

Globular Clusters

M80

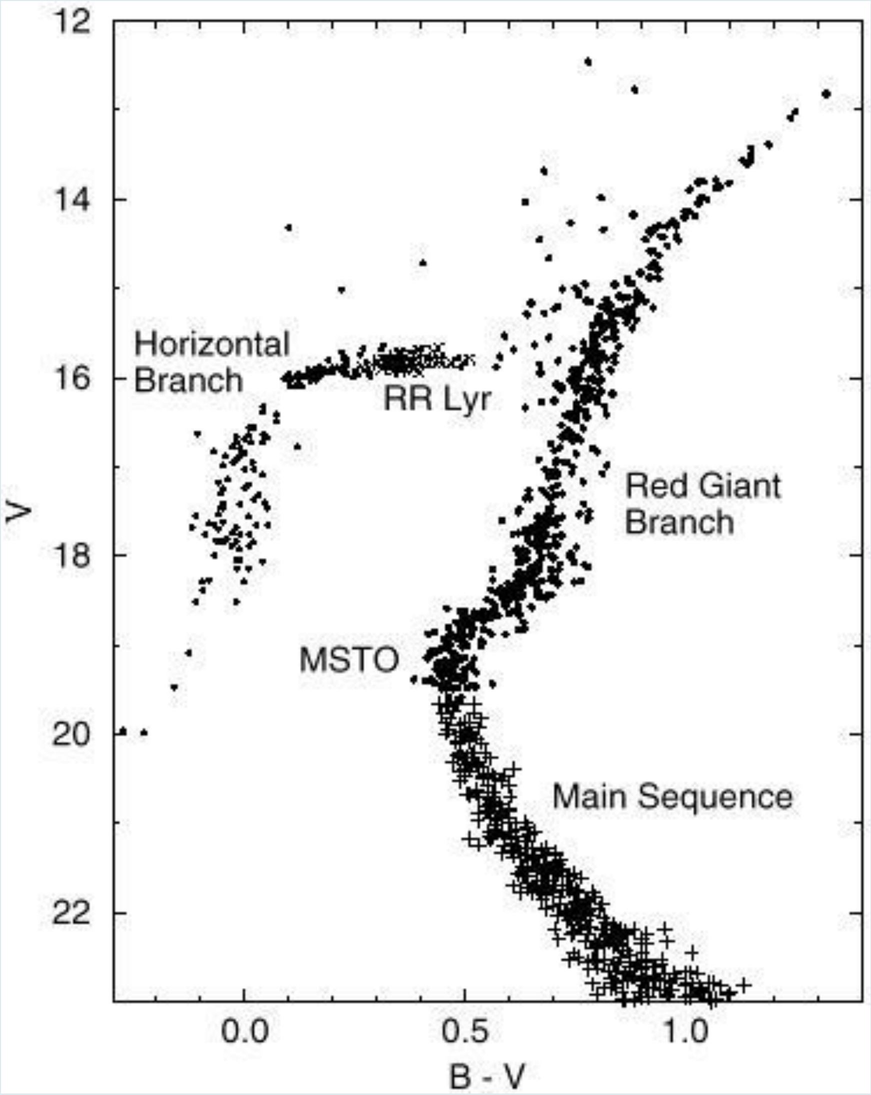
- 10^4 - 10^6 Msun
- 10 - 13 Gyr
- low metallicity
- bulge/halo of the Galaxy

Clusters historically viewed as simple stellar populations

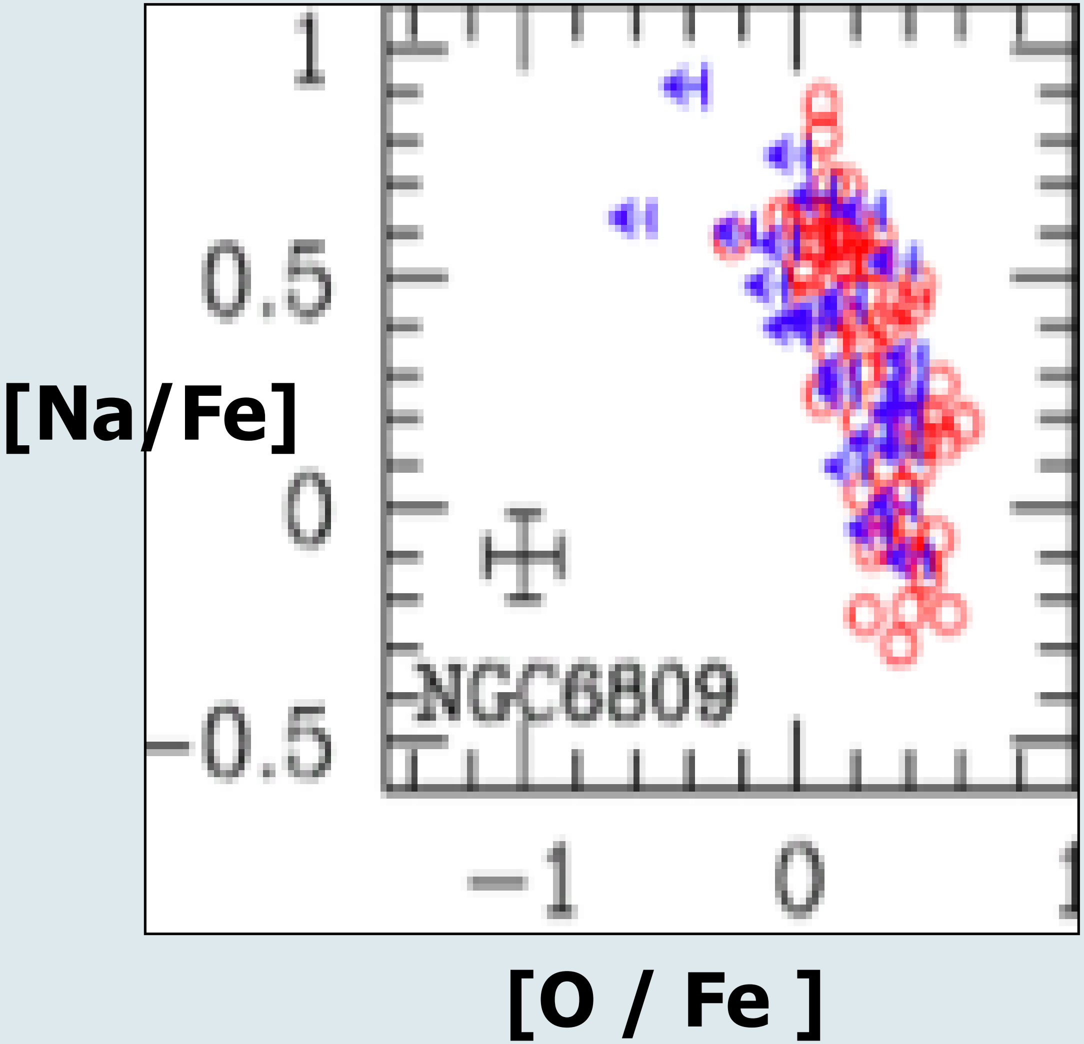
- All stars have the same age (very small spread, < 1-2 Myr - based on open clusters and YMCs)
- All stars have the same abundances
- Range of stellar massses (and potentially rotation rates)

But....

HRD of a globular clusters



Peculiar abundances: not only He/H!



Red= turn-off stars

Blue = Red Giant Branch

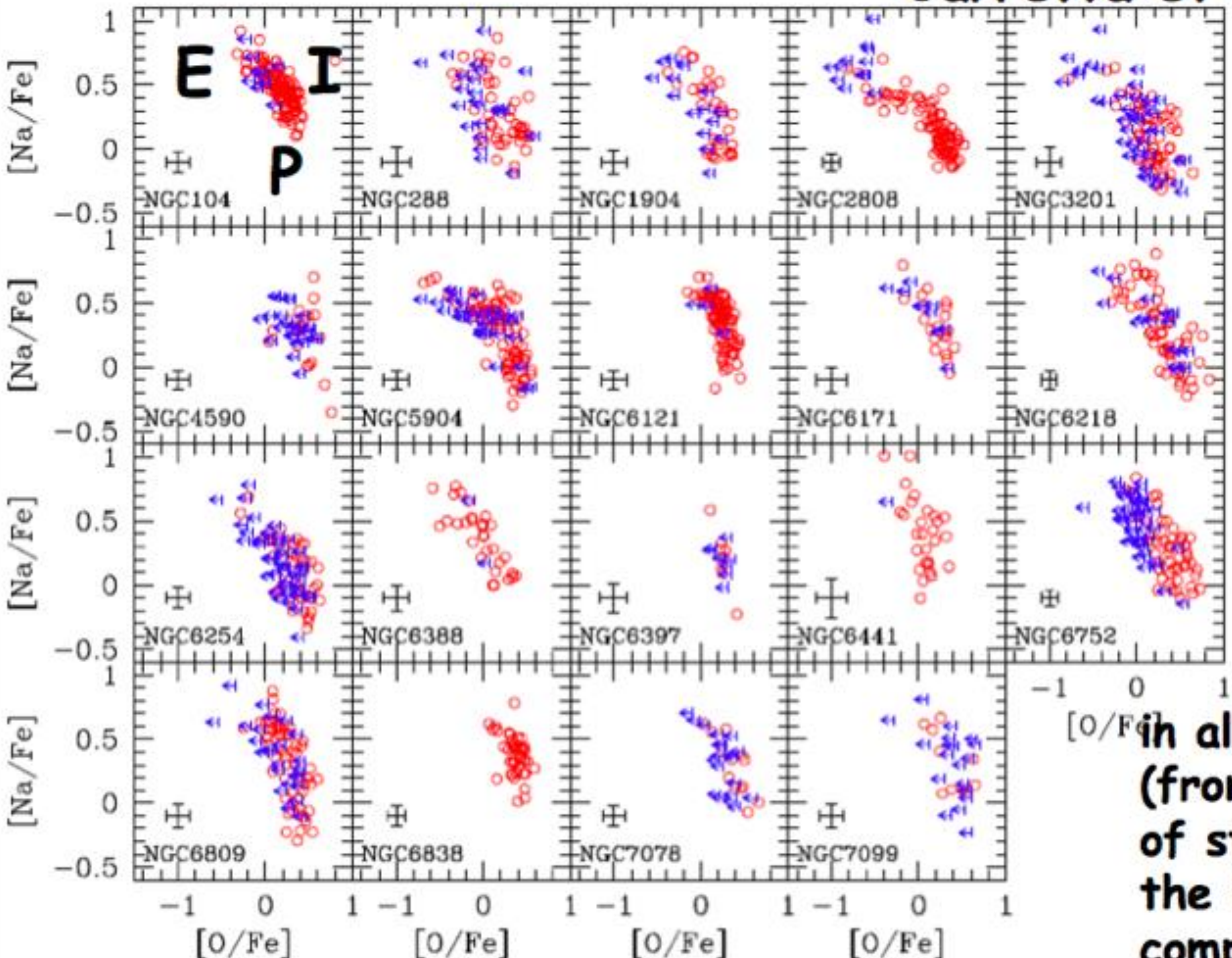
The Na/O anti-correlation within each cluster

Also Mg/Al anticorrelation

Carretta et al. 2006

In every massive GC : a range of abundances

Carretta et al. 2009a

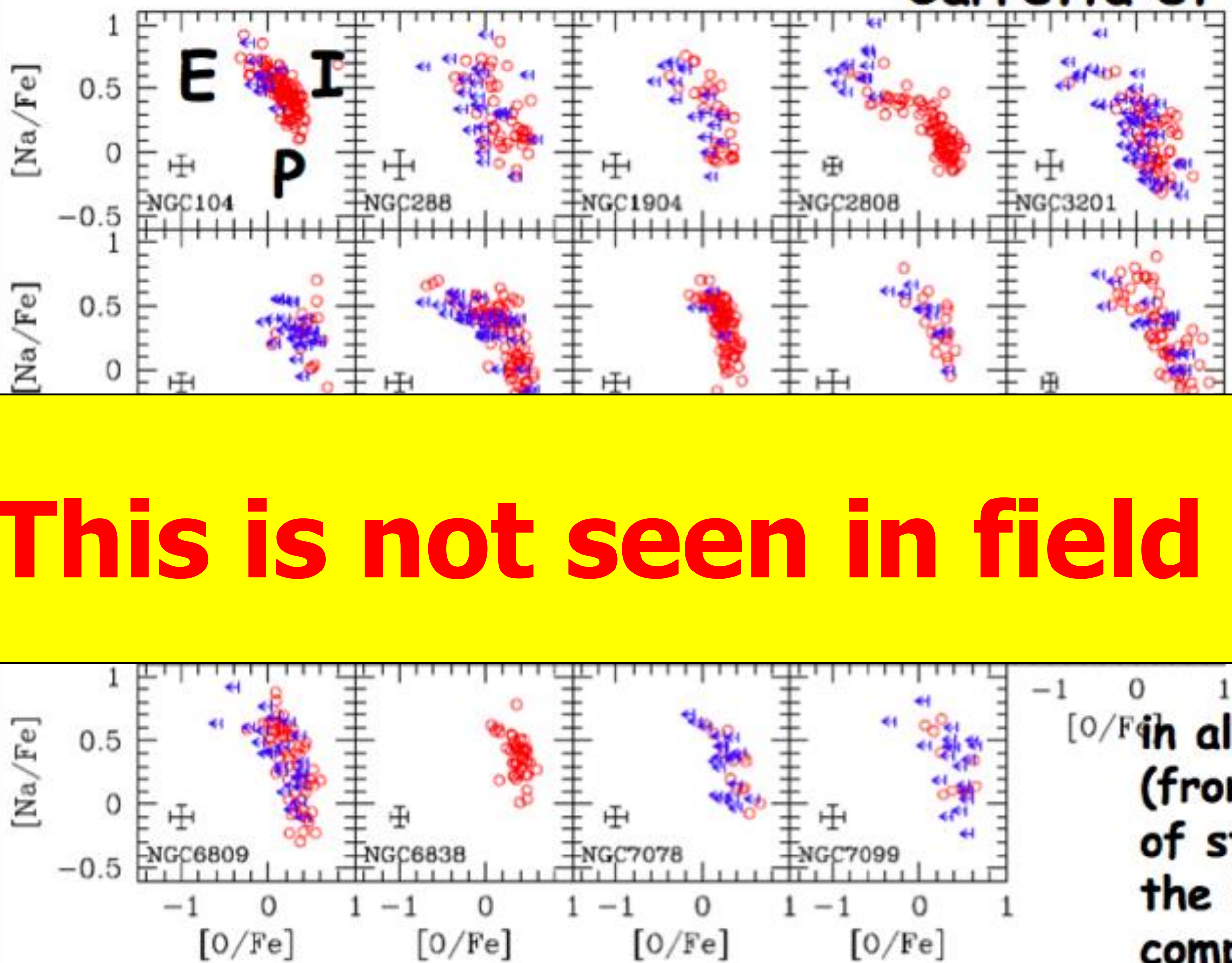


more than 1200 red giant stars in 19 GCs

in all GCs the bulk (from 50 to 80%) of stars belong to the intermediate component.

In every massive GC : a range of abundances

Carretta et al. 2009a



more than 1200 red giant stars in 19 GCs

This is not seen in field stars

In all GCs the bulk (from 50 to 80%) of stars belong to the intermediate component.

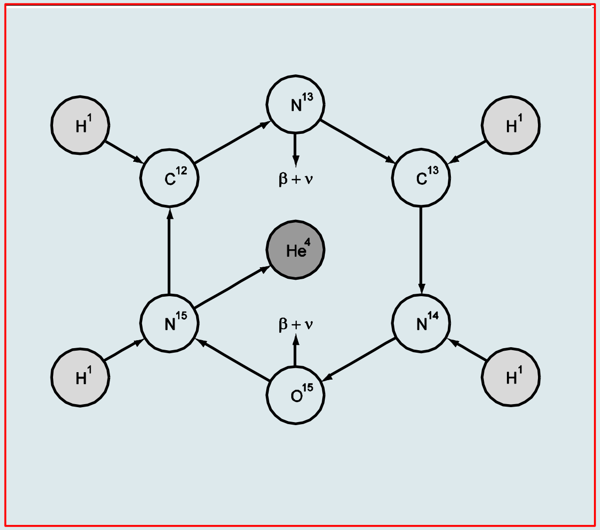
Abundance anomalies within GCs

1. High He/H ratios
2. Na/O anticorrelations
3. Mg/Al anticorrelations
4. But total C+N+O = constant
5. Fe abundance is constant

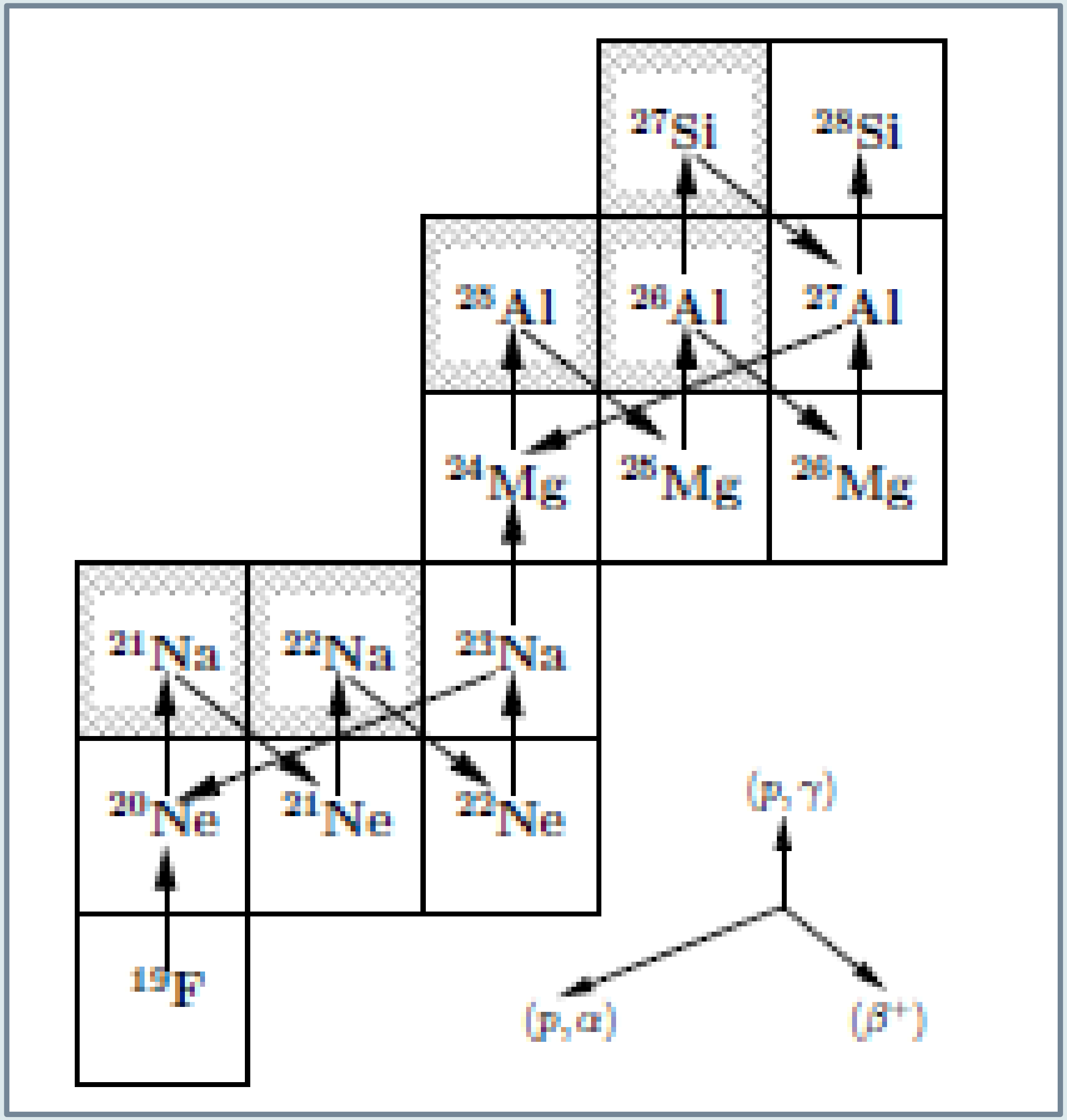
Abundance anomalies within GCs

1. High He/H ratios
2. Na/O anticorrelations
3. Mg/Al anticorrelations
4. But total C+N+O = constant
5. Fe abundance is constant

Polluted by products of H-He fusion by hot CNO cycle (~70 MK)



Nuclear networks for Na, Ne, Al, Mg



Branches of high-T CNO-cycle

Decressin 2007

Abundance anomalies within GCs

1. High He/H ratios
2. Na/O anticorrelations
3. Mg/Al anticorrelations
4. But total C+N+O = constant
5. Fe abundance is constant

Polluted by products of H-He fusion by hot CNO cycle (~70 MK)

Second generation starformation within the cluster : from gas enriched by the first generation !! (not SN)

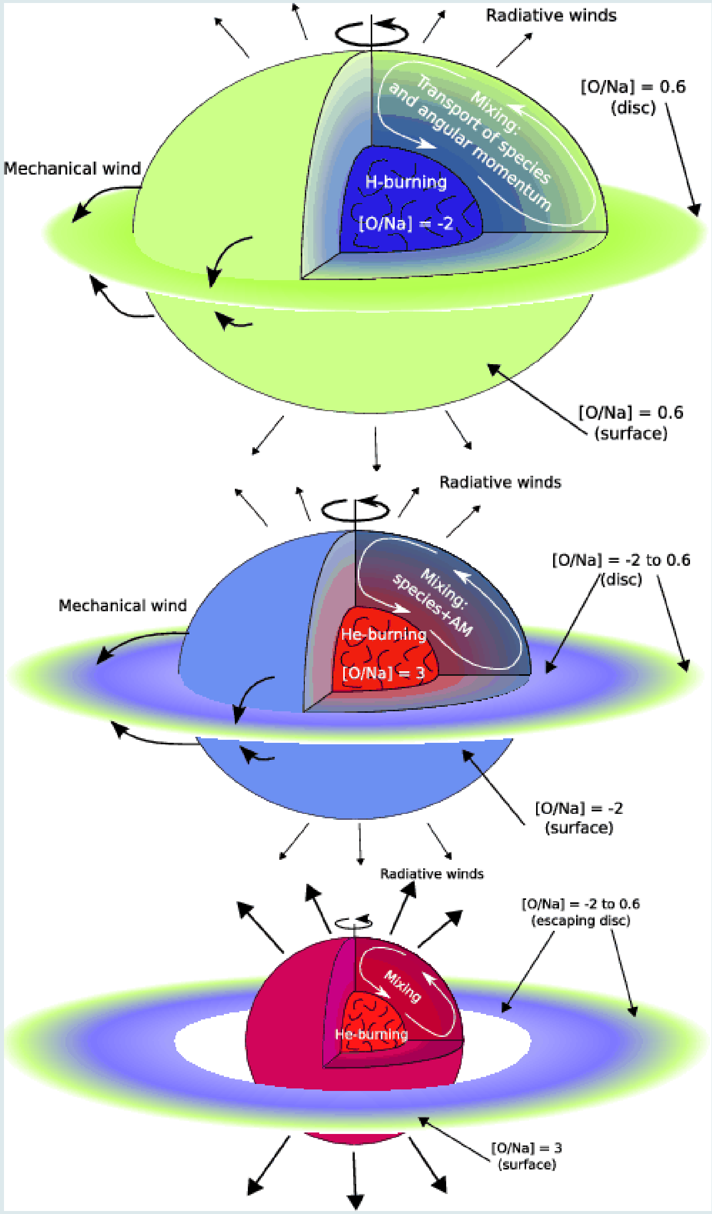
Abundance anomalies within GCs

1. High He/H ratios
2. Na/O anticorrelations
3. Mg/Al anticorrelations
4. But, total C+N+O ... constant

Paradigm 2
GCs had multiple starforming periods .

Second generation starformation within the cluster : from gas enriched by the first generation !! (not SN)

Spin-star model

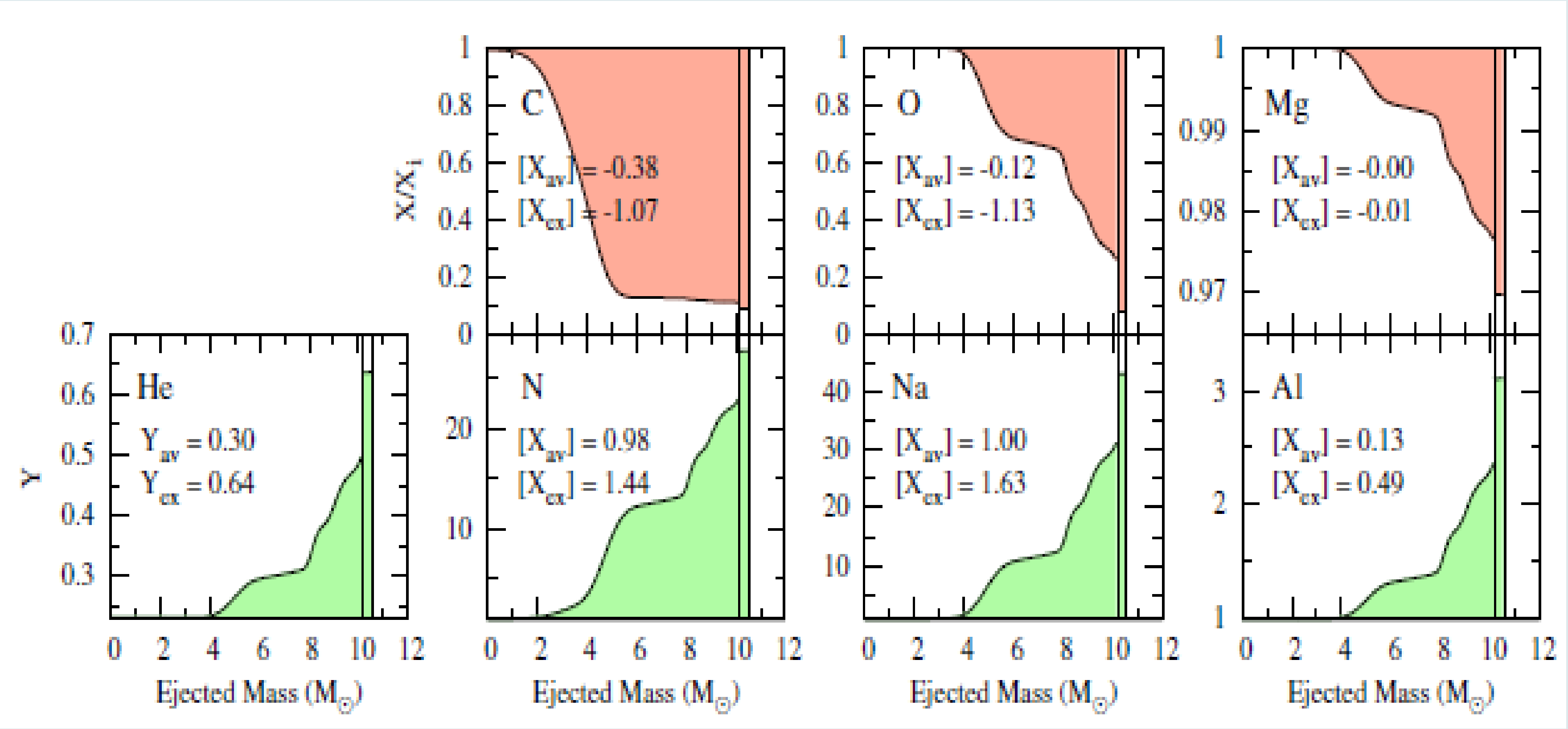


very rapidly
rotating
massive star

Decressin et al . 2007
A&A 464, 1029

Enriched ejected gas

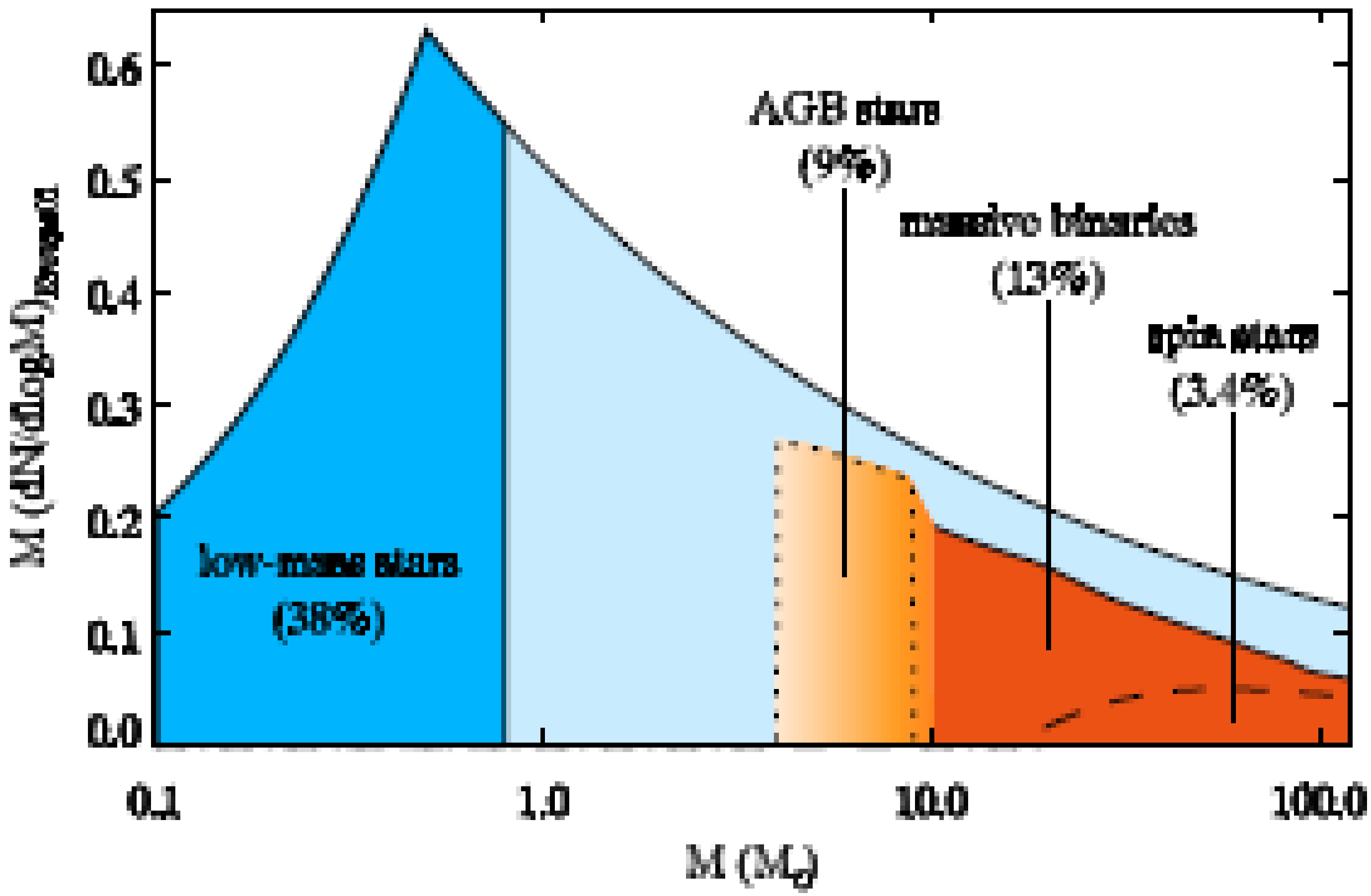
Close binary of 20 + 15 Msun binary



Red = decreased abundance
Green = increase abundance

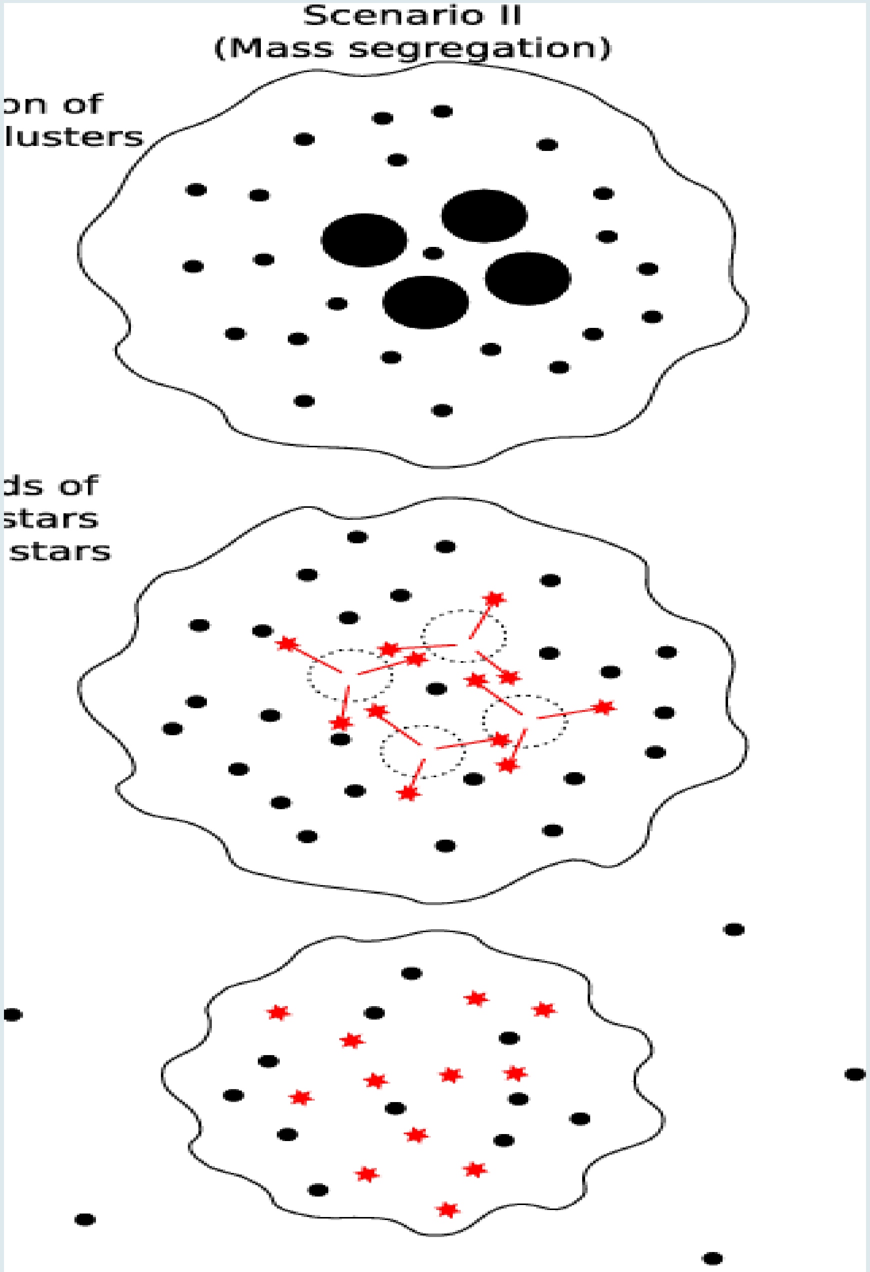
de Mink et al. 2009 A&A 507 L1

Fraction of polluted mass ~1/4



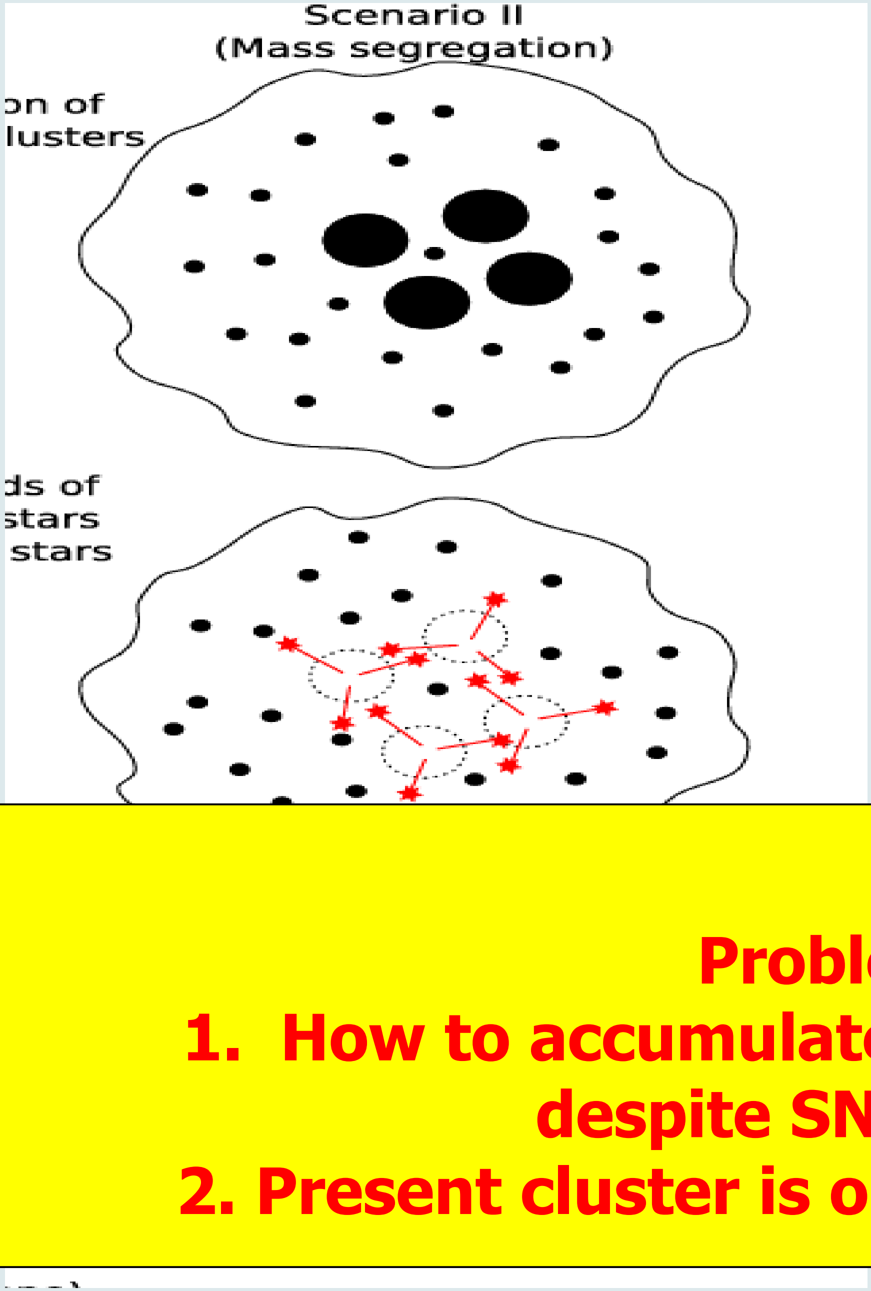
This is for a Kroupa IMF (bend at 0.5 Msun)

de Mink et al 2009



Evolutionary model for second generation stars

1. Very massive cluster
2. Massive stars in center eject polluted winds
3. Polluted gas stays in cluster
4. Accumulate enough gas for second starburst in center
5. Remove most of first generation stars



Evolutionary model for second generation stars

1. **Very massive cluster**
2. **Massive stars in center eject polluted winds**
3. **Polluted gas stays in**

Problems !!

1. **How to accumulate enough polluted gas, despite SN blow-outs**
2. **Present cluster is only fraction of original**

Our Suggestion

Pollution by massive stars

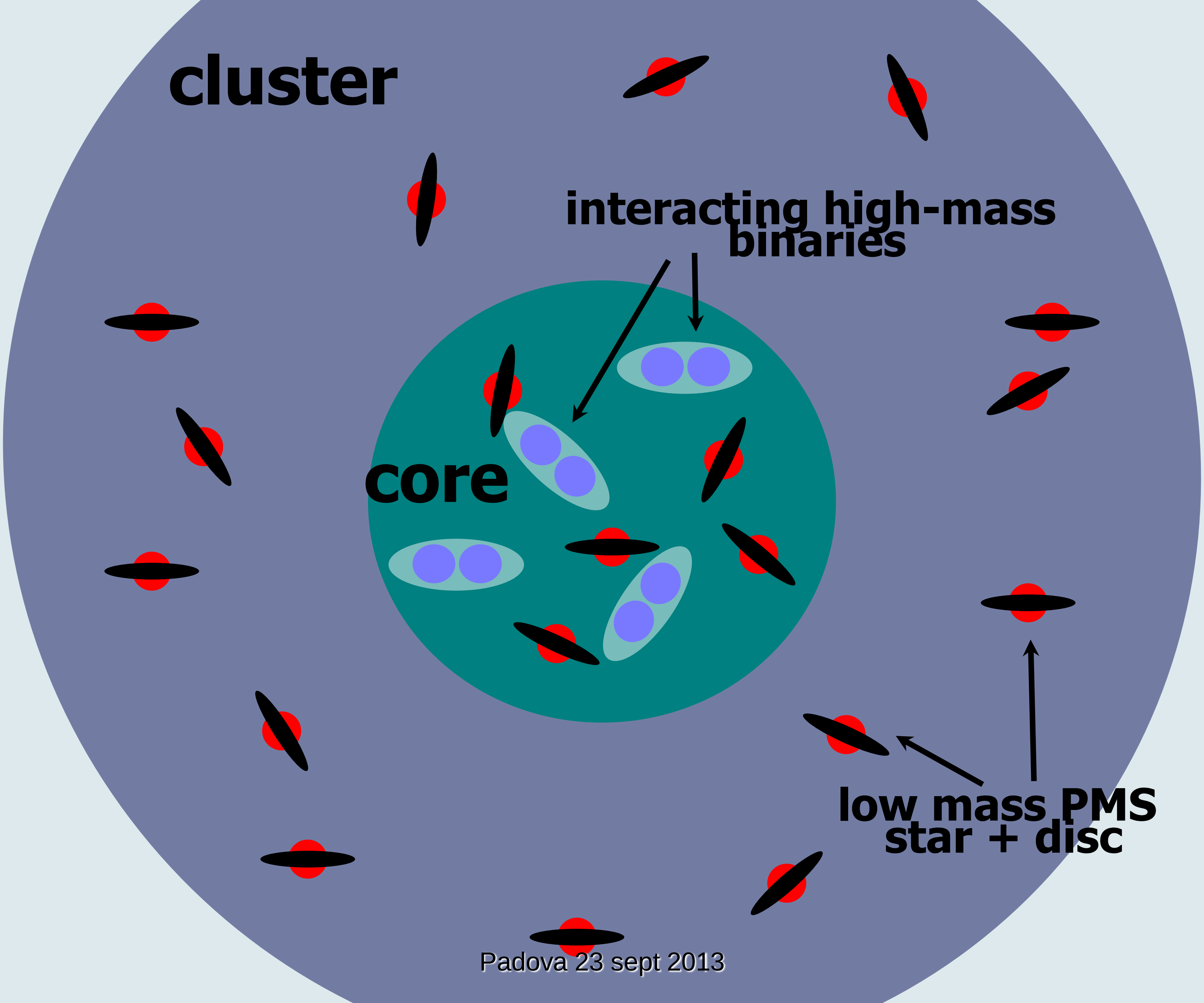
during about 10-15 Myr

while the low mass stars are being formed

during about 15-20 Myr

This requires capture of polluted gas by the circumstellar disks of low mass stars

Bastian et al, 2013, Nature (submitted)


cluster
interacting high-mass binaries
core
low mass PMS star + disc

Simple estimates

1. Cluster 10^6 Msun, radius = 2 pc,
   core density = 3. 10^4 stars/pc^3

2. Mean velocity of stars 20 km/s

3 PMS-disc radius ~ 100 AU

4 All gas in core is swept-up in 0.4 Myr

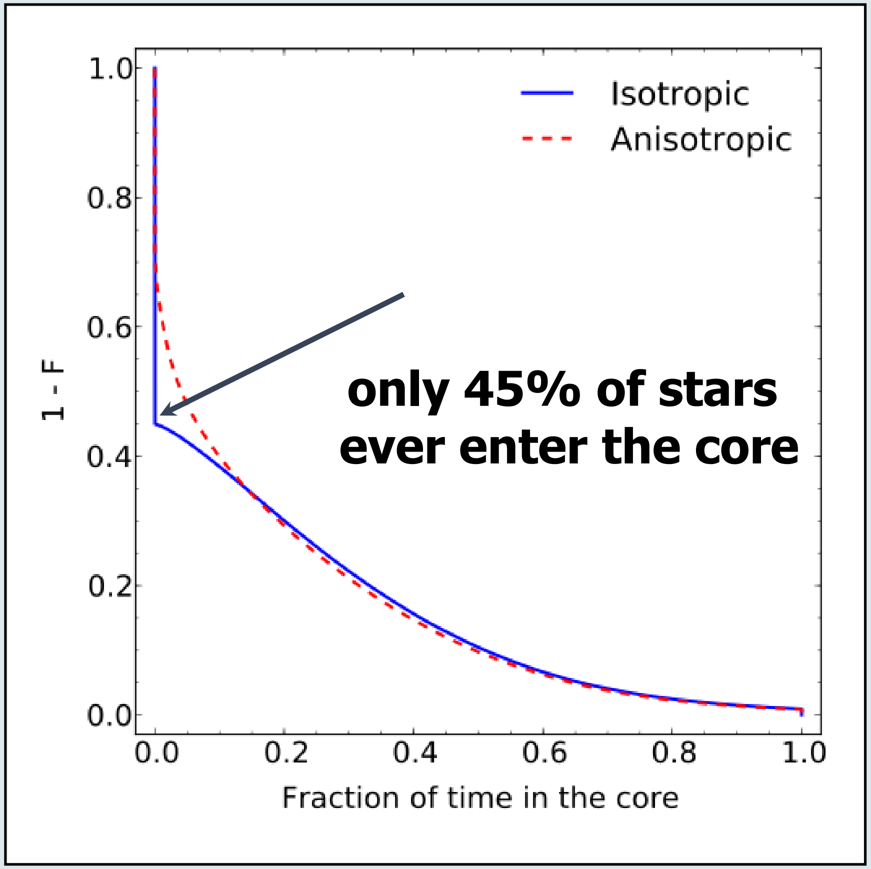
What is needed ?

1. **Early pollution : within about 10 Myr**
   Massive spin stars and binaries ok

2. **Slow PMS evolution of accreting stars:**
   only low mass stars accrete ok

3. **Extended lifetime of CS disks:**
   up to ~15-20 Myr:
   possible in high density environment ?

Only PMS stars that enter the core can accrete polluted gas



Result from dynamical simution

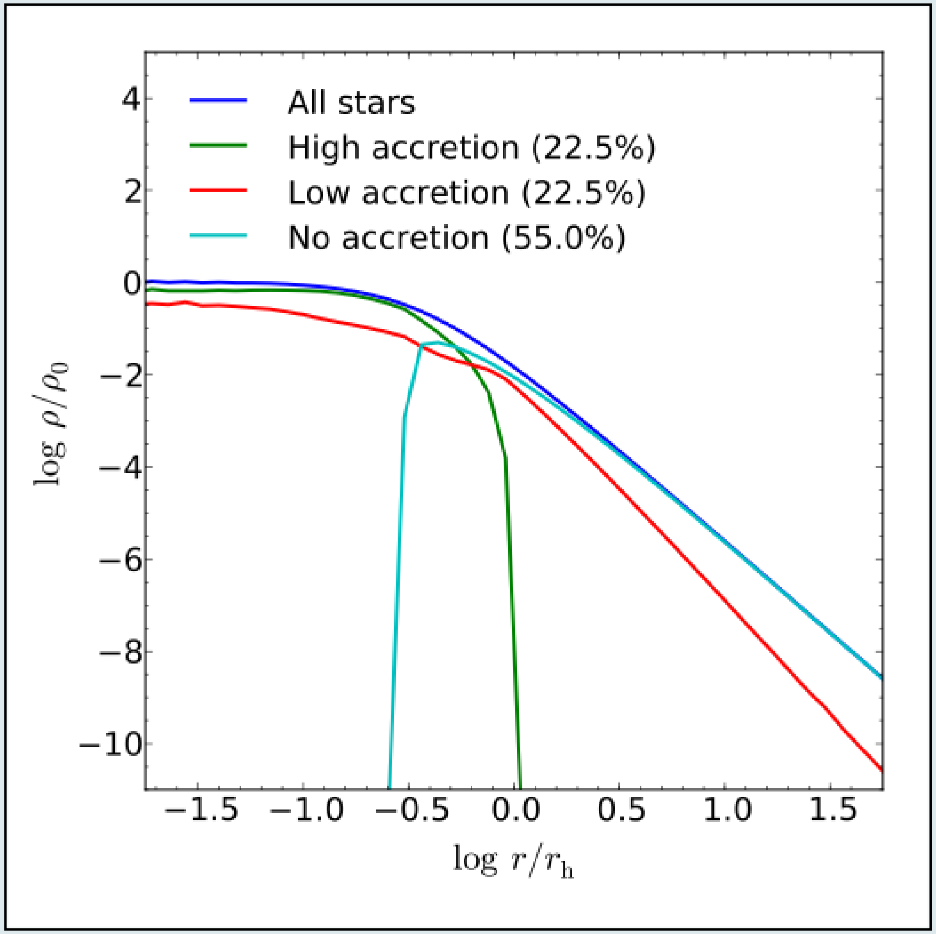
This explains why not all the stars are polluted

different He-abundances
+
range of Na/O

Padova 23 sept 2013

Mark Gieles

Distribution of the stars in the cluster

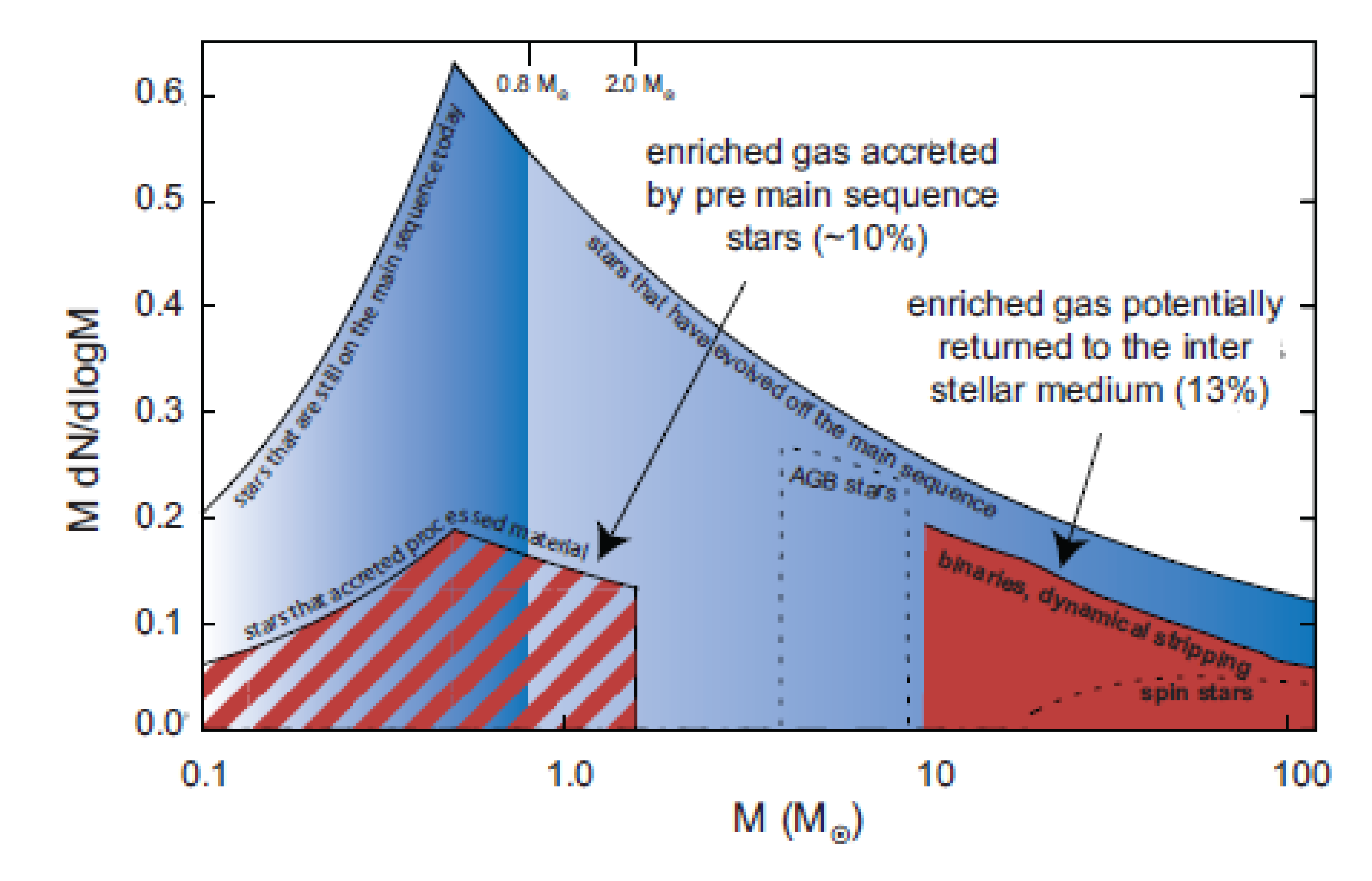


22.5 % of stars are in high density center = high accretion

55 % of stars stay in outskirts = no accretion

Mass-weighted mass function

equal mass in equal surface



Bastian et al. 2013

Mass budget

1. About 1/3 to 1/4 of low mass PMS will be severely polluted =
   ~50% initial gas,
   ~50% polluted gas
2. Unpolluted low mass stars will be in outskirts of the clusters,
   where they are easily lost by evaporation and tidal stripping.
3. This results in about ~50% polluted and ~50% unpolluted stars

Conclusions and uncertainties

1. Models of two/multiple starformation in GCs have severe problems (accumulation vs SN blowout)
2. Pollution of low mass stars during their PMS disk-phase does not have this problem.
3. Natural explanation of range in abundances

Main uncertainty

Can low mass PMS stars keep their disks long enough to accumulate sufficient gas (up to 50%)

Critical tests of our model

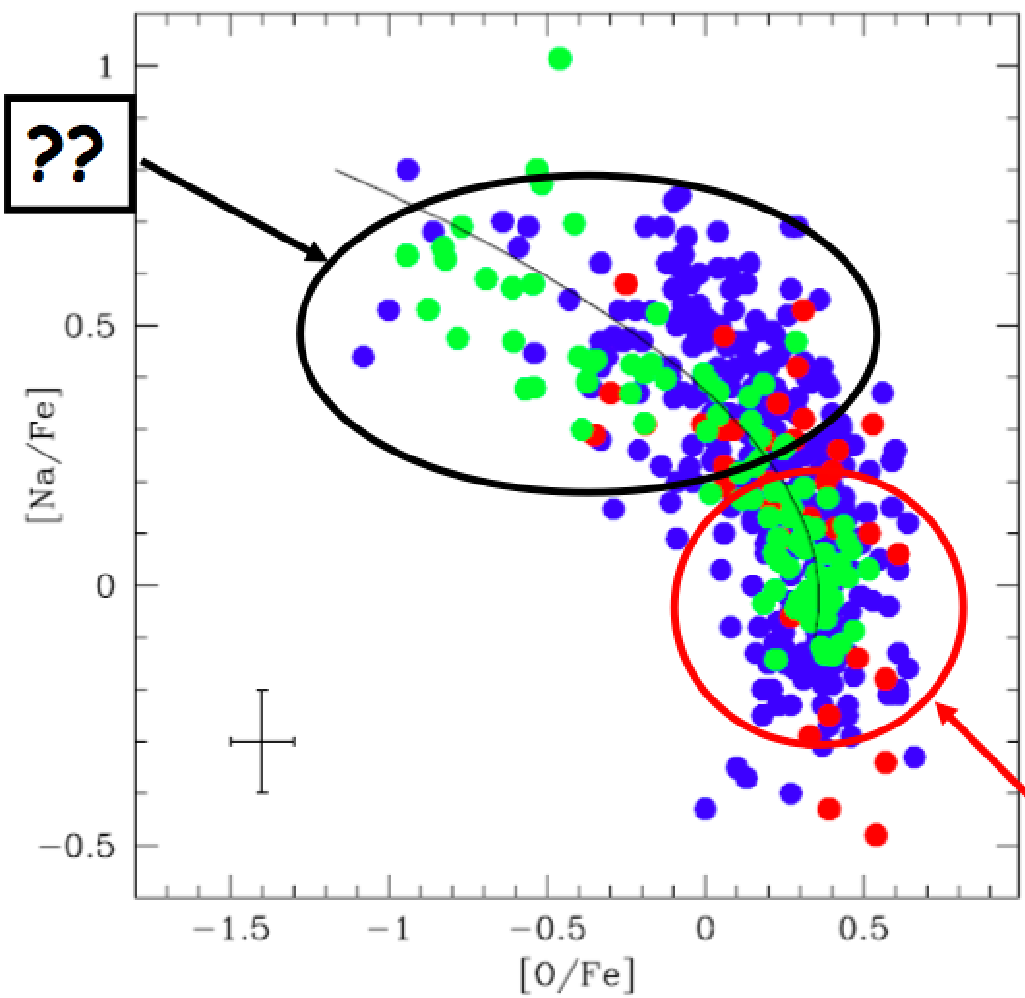
1. Stars in outskirts are on average less polluted
2. Pollution is strongest in massive clusters
3. Catch massive cluster in first 10 Myr (abundance of low M)

That's all folks !

Henny Lamers
h.j.g.l.m.lamers@uu.nl

Spare slides

A range in abundances !



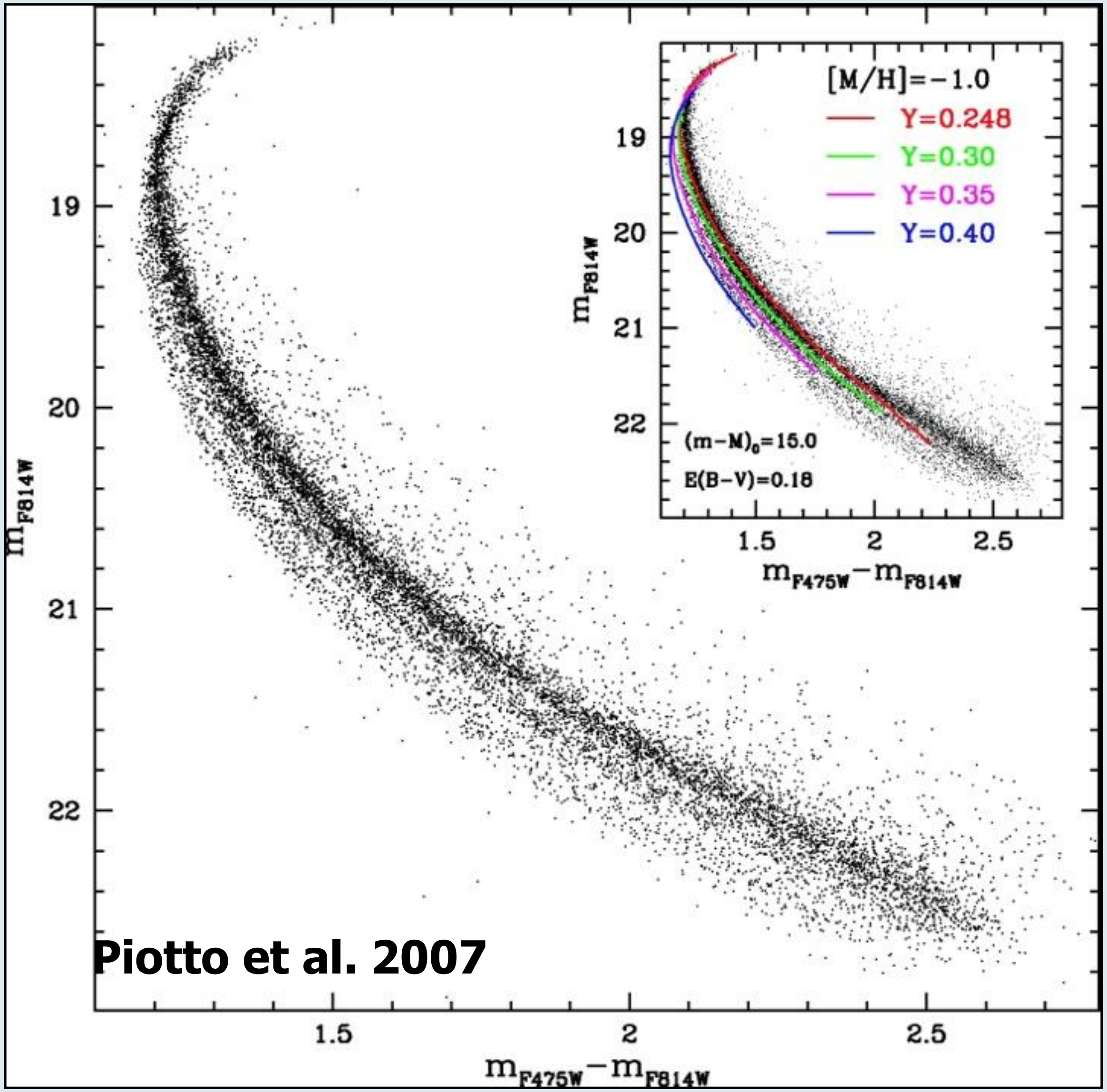
Carretta et al. 2006 A&A 450, 523

Na/O anticorrelation in ~20 clusters
Blue + green: RGB stars
Red : unevolved stars

this is the range of abundances in low metallicity field stars

D'Antona 2012 (Vatican Observatory Lectures)

NGC 2808 : multiple main sequences!

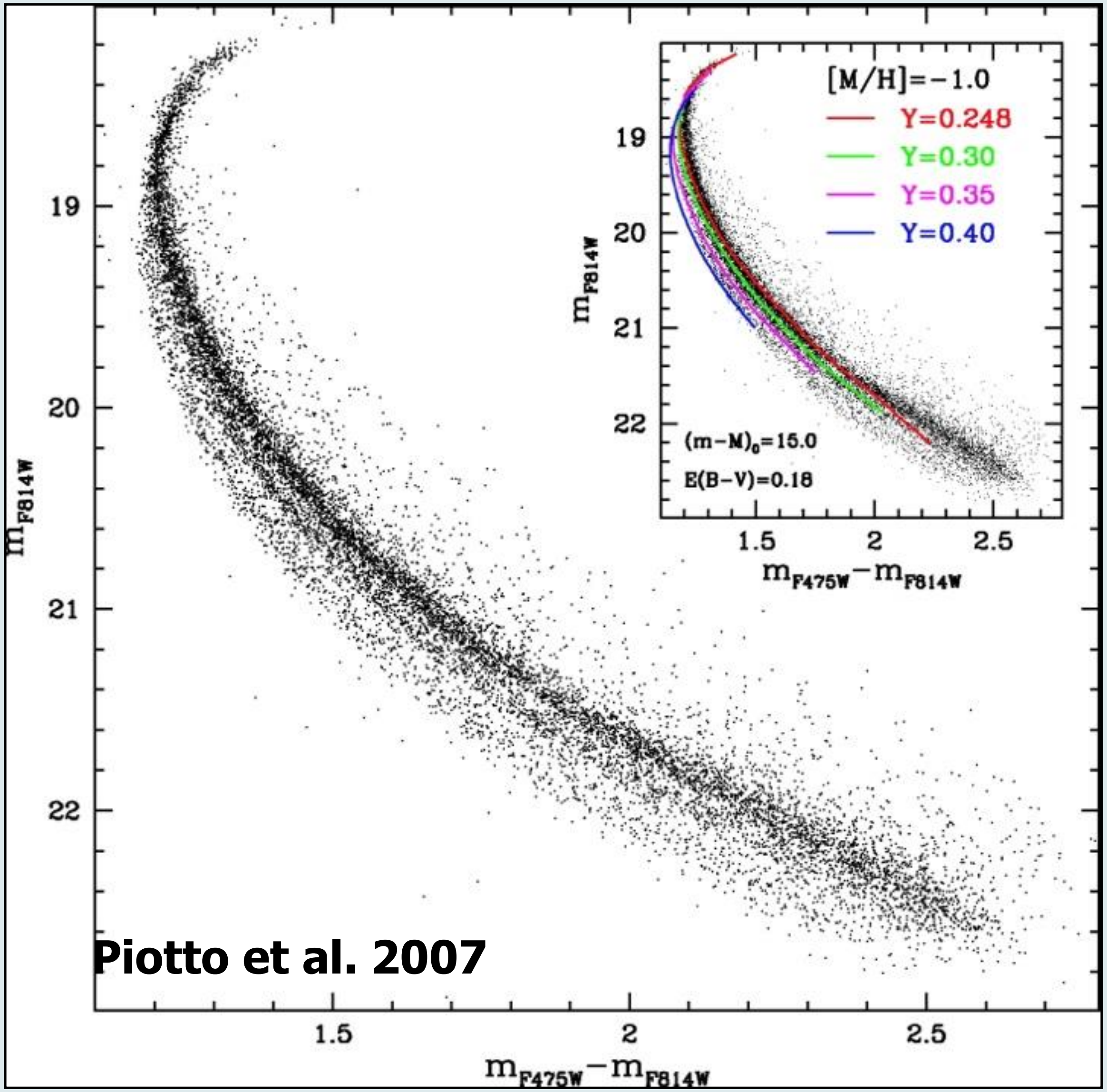


Multiple He abundances !

~60% of stars on nominal main sequence "first generation"

~30% of stars are He enriched "second generation"

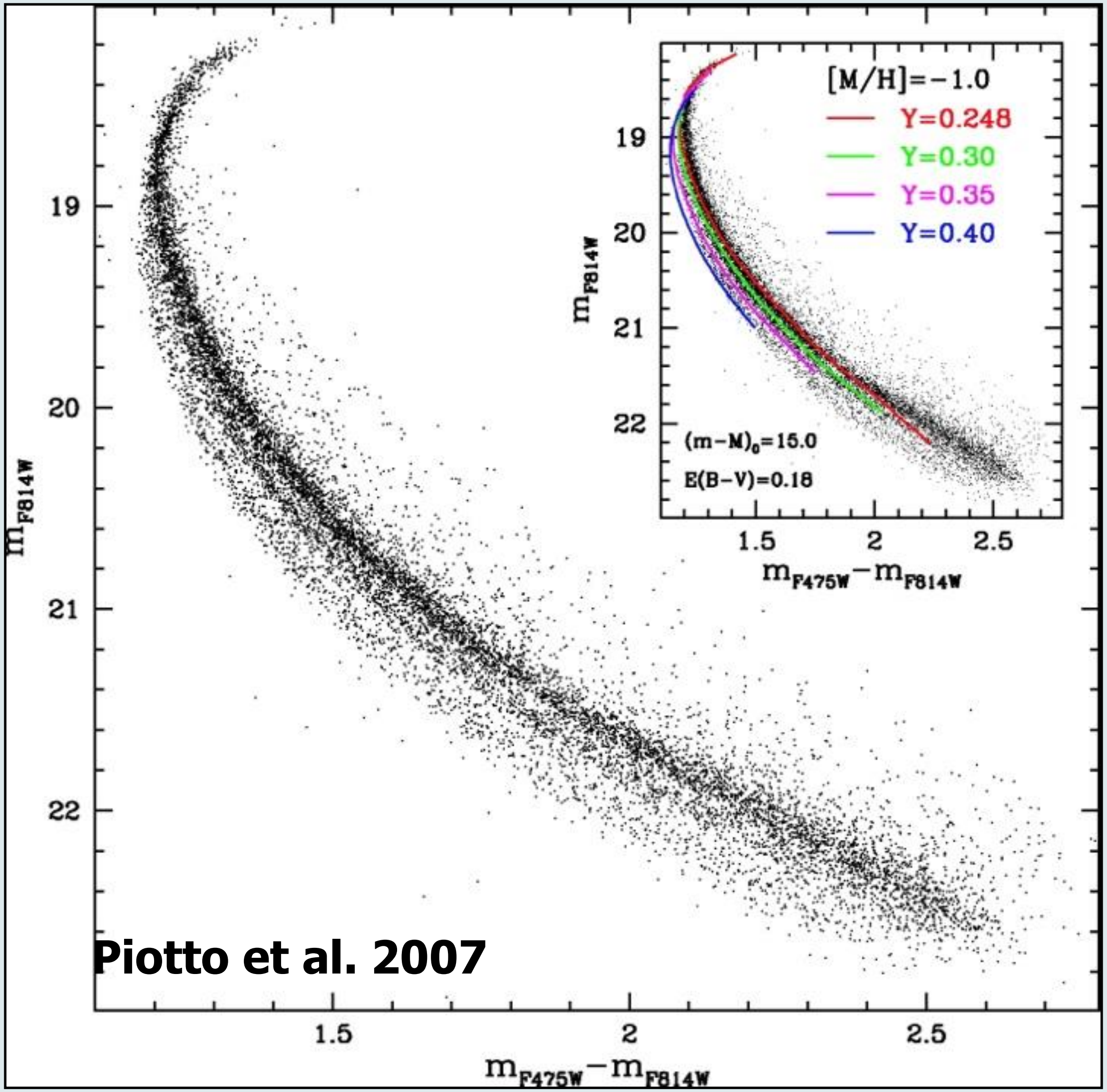
NGC 2808 : multiple main sequences!



HST

Piotto et al. 2007

NGC 2808 : multiple main sequences!



Multiple He abundances !

~60% of stars on nominal main sequence

~30% of stars are He enriched

3) Quantisation of He and other elements?