Na-O Anticorrelation and the distribution of stars along the HB

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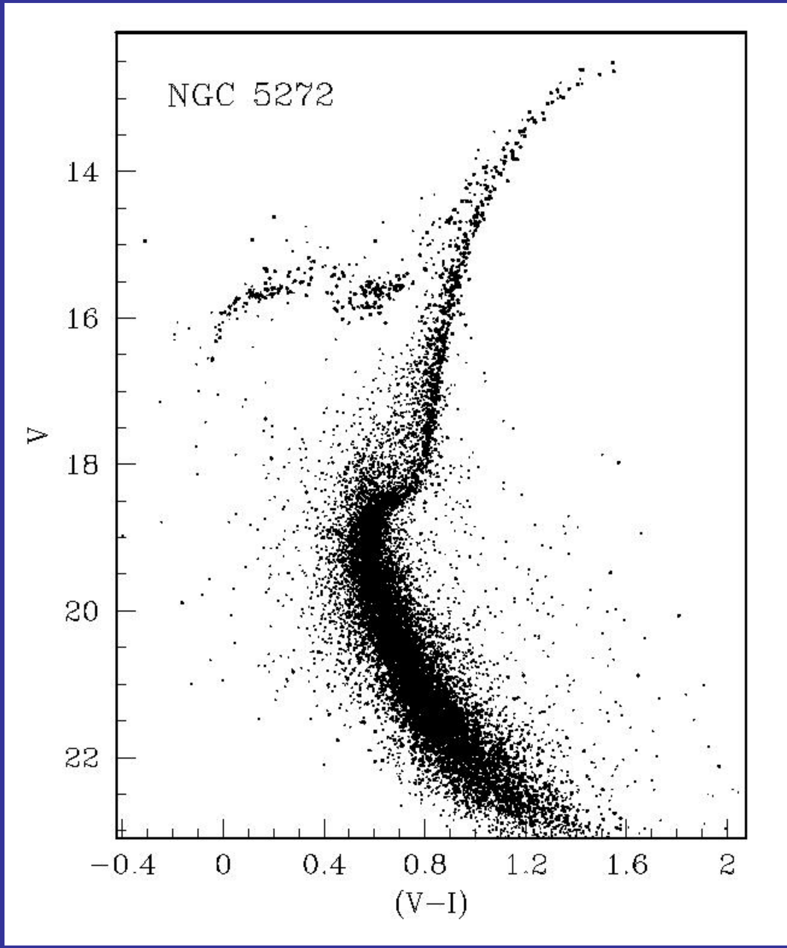
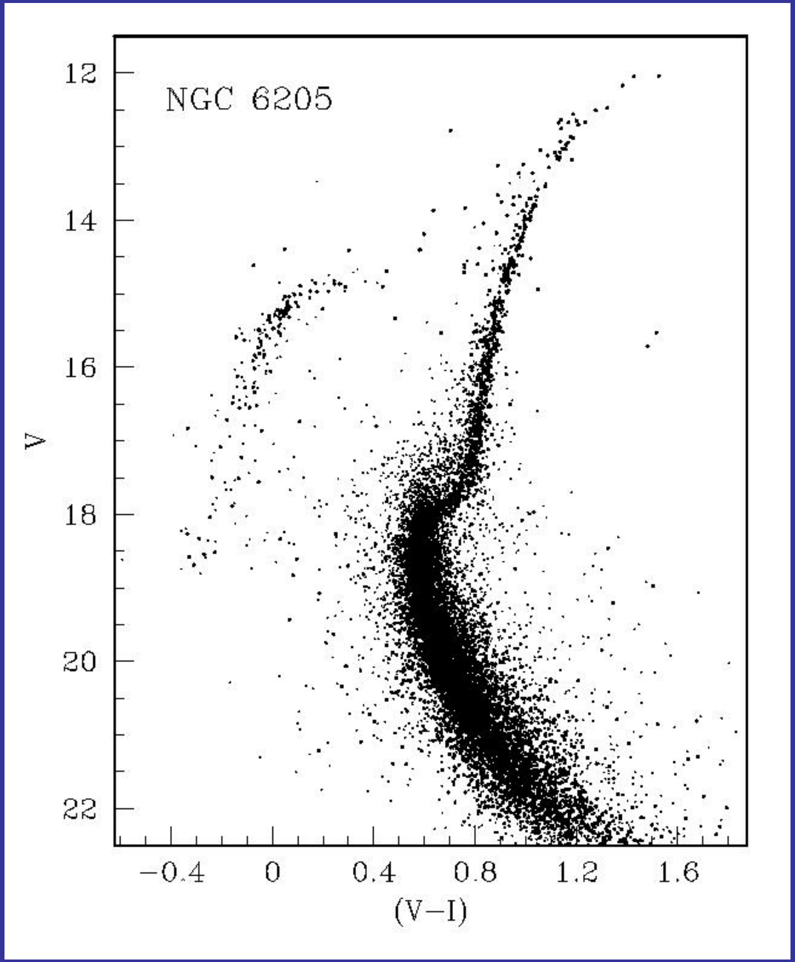
and all the Naaah collaboration

Faulkner (1966): metallicity drive colours of HBs for GCs
Second parameter effect (discovered by Sandage & Wildey 1967; and Van den Bergh 1967)
(M3-M13: data from Rosenberg): The two clusters have nearly the same metallicity ([Fe/H]~-1.4) and very different HB

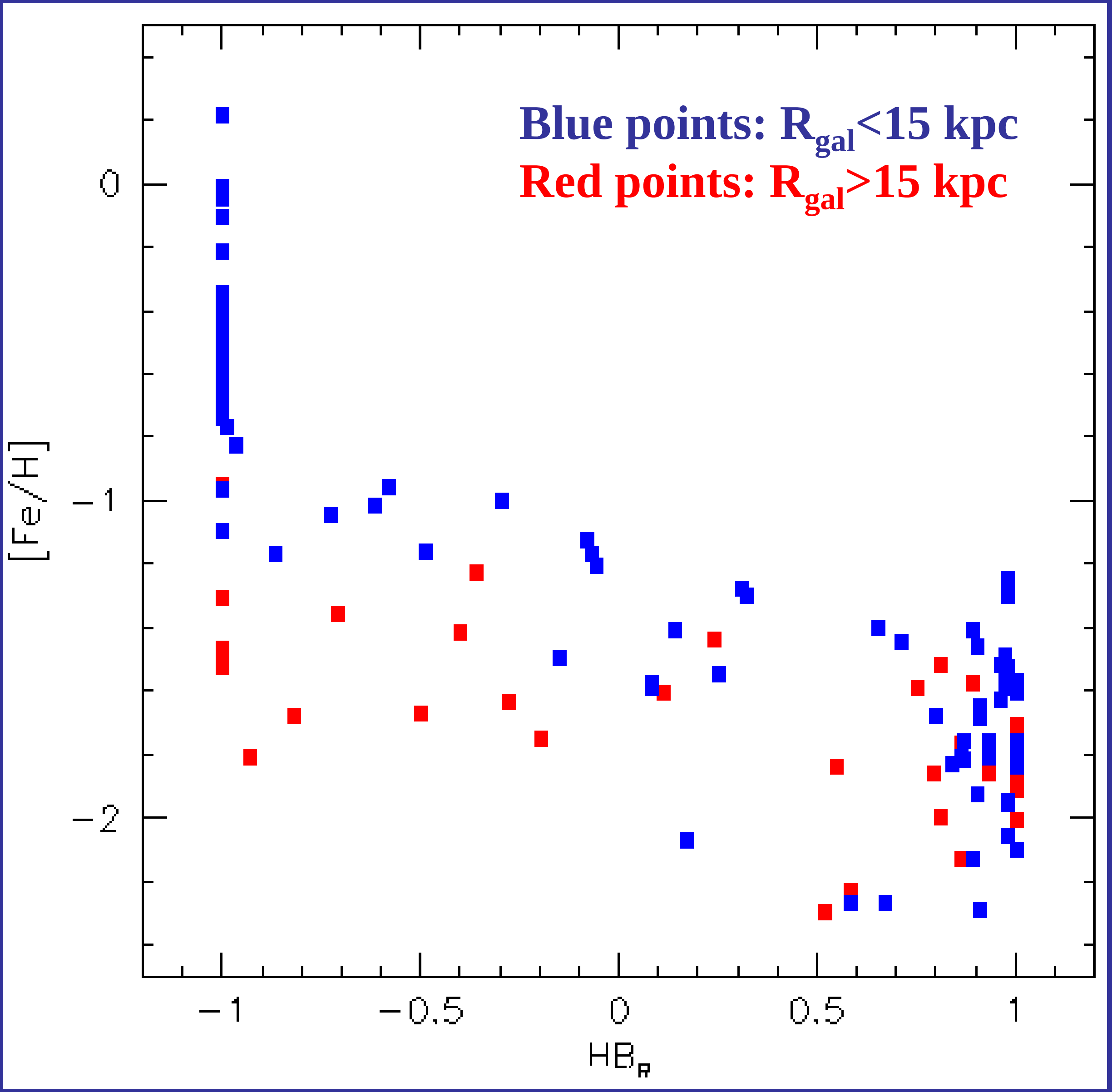




Second parameter effect

Zinn (1978) noticed that the galactocentric distance r_{gal} is a second parameter.

This might be related to age differences of about 2 Gyrs between inner and outer halo GCs

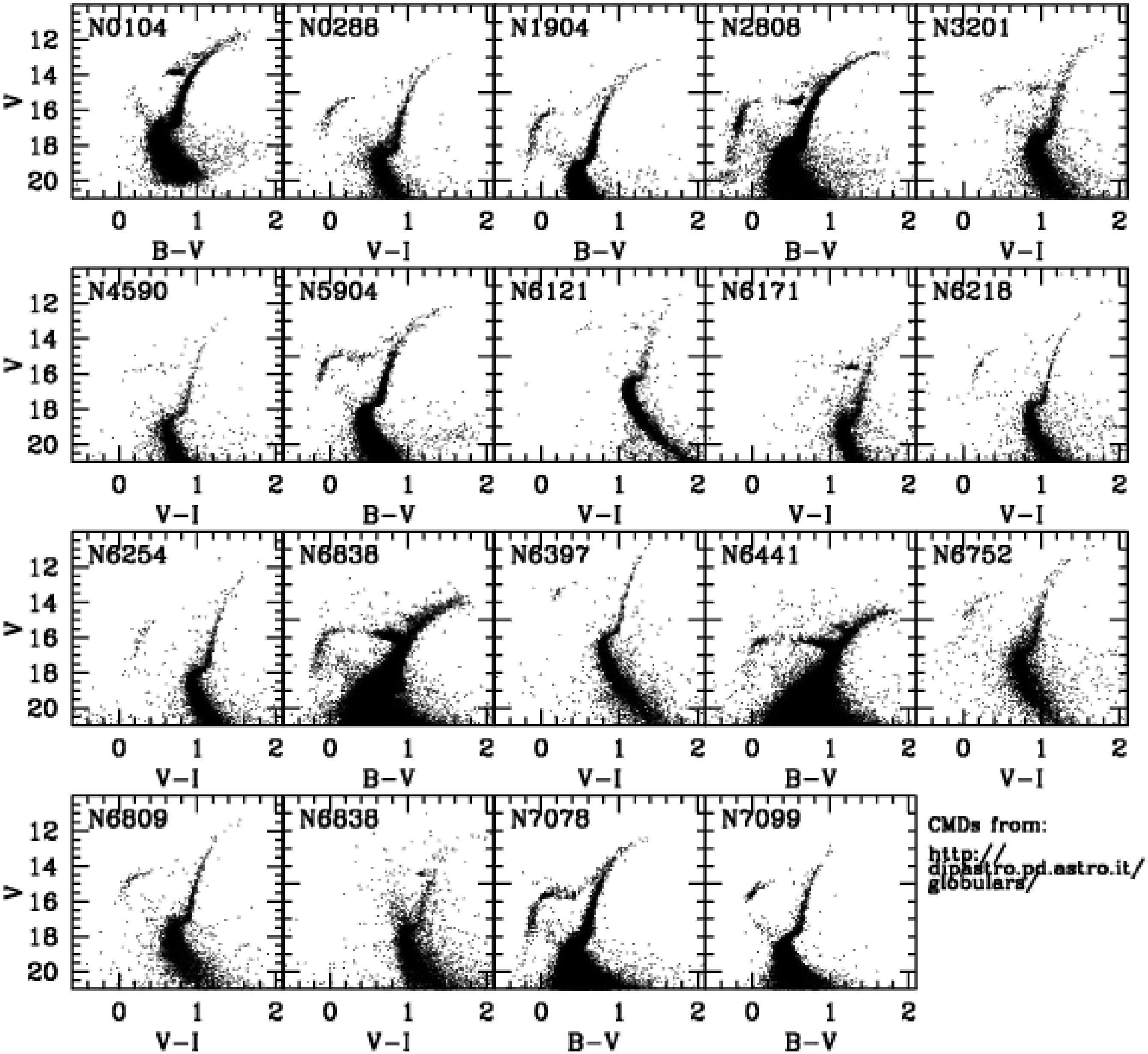


The second parameter

- However there is more than one second parameter
- Many indications that the second parameter is related to the O-Na anticorrelation (D'Antona & Caloi, etc.)
- A way to discuss the second parameter is quantifying mass loss between the TO and the HB

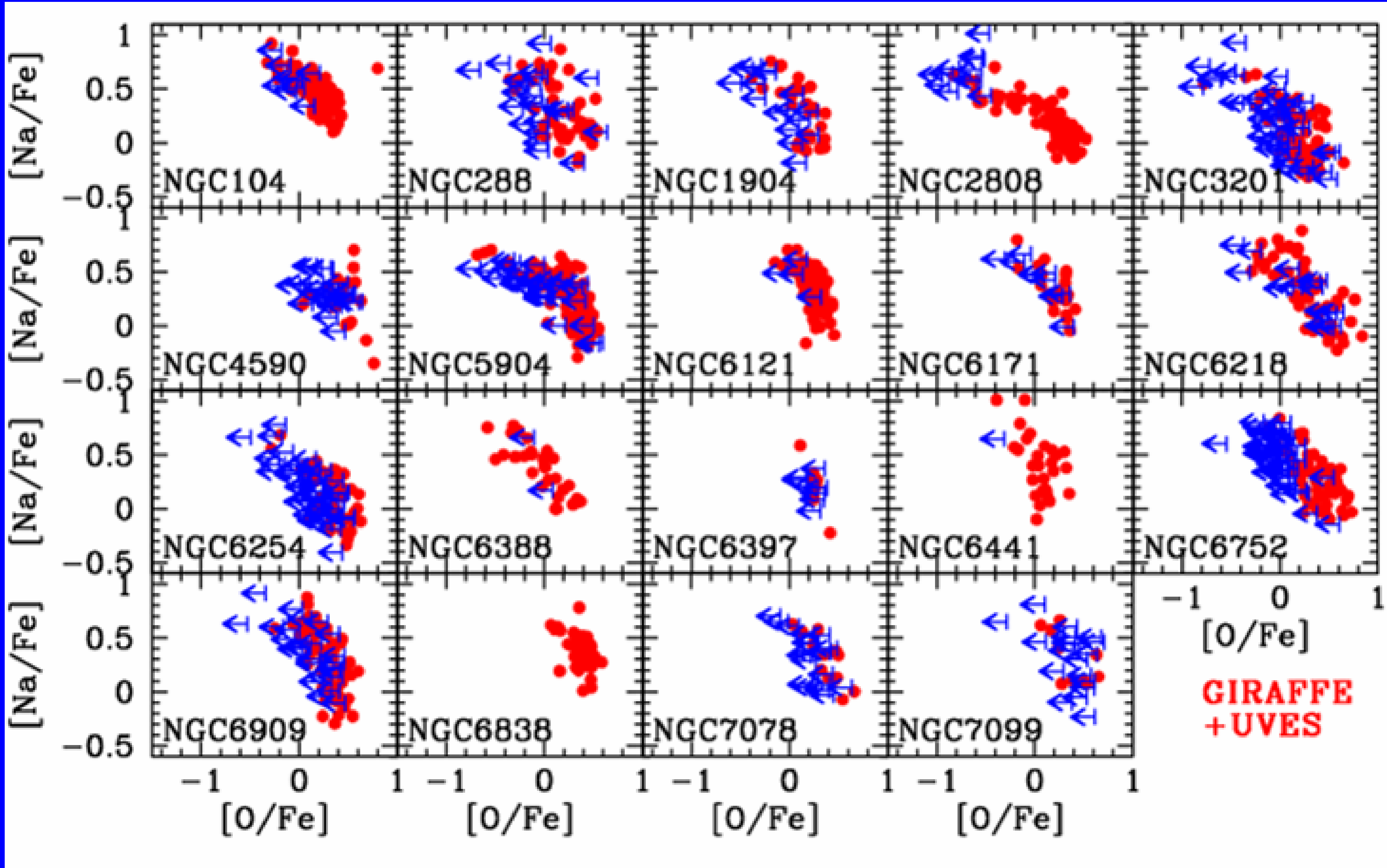
New data available

- Homogeneous set of c-m diagrams
- Accurate relative age determinations (Rosenberg et al., De Angeli et al.): error ~5-7% (even best from ACS data, but not yet published)
- Our new determinations of the chemical composition



From Piotto’s database

(Padova)



Homogeneous analysis, Giraffe spectra for large statistics in Na and O, UVES spectra for a lot of elements + Some literature data (NGC 362, M3, M13, M92)

Mass Loss determination

- Masses of stars at Turn-off:

  from the following relation fitting isochrones:

  $$M_{TO} = 0.834\ 10^{-0.259 \log Age} \left(1.0 + 0.297 \times 10^{[Fe/H] + 0.7 [\alpha/Fe]}\right) M_{o}$$

  Age term

  Metal abundance term

  [α/Fe] term

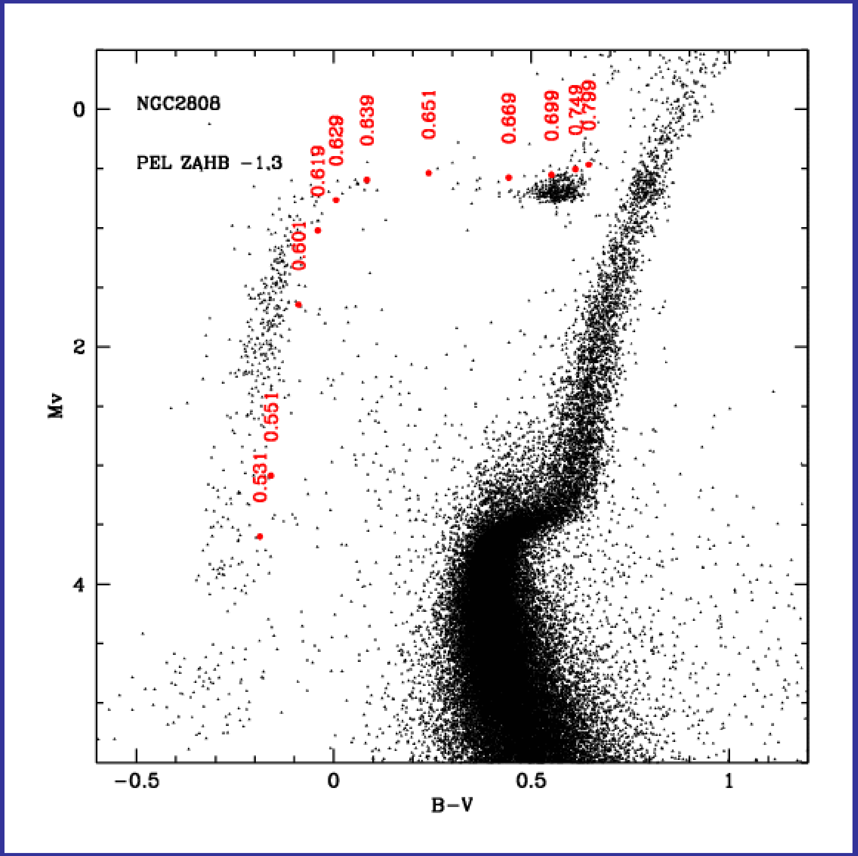
  Age is the age parameter from De Angelis et al., or where missing from Rosenberg et al.

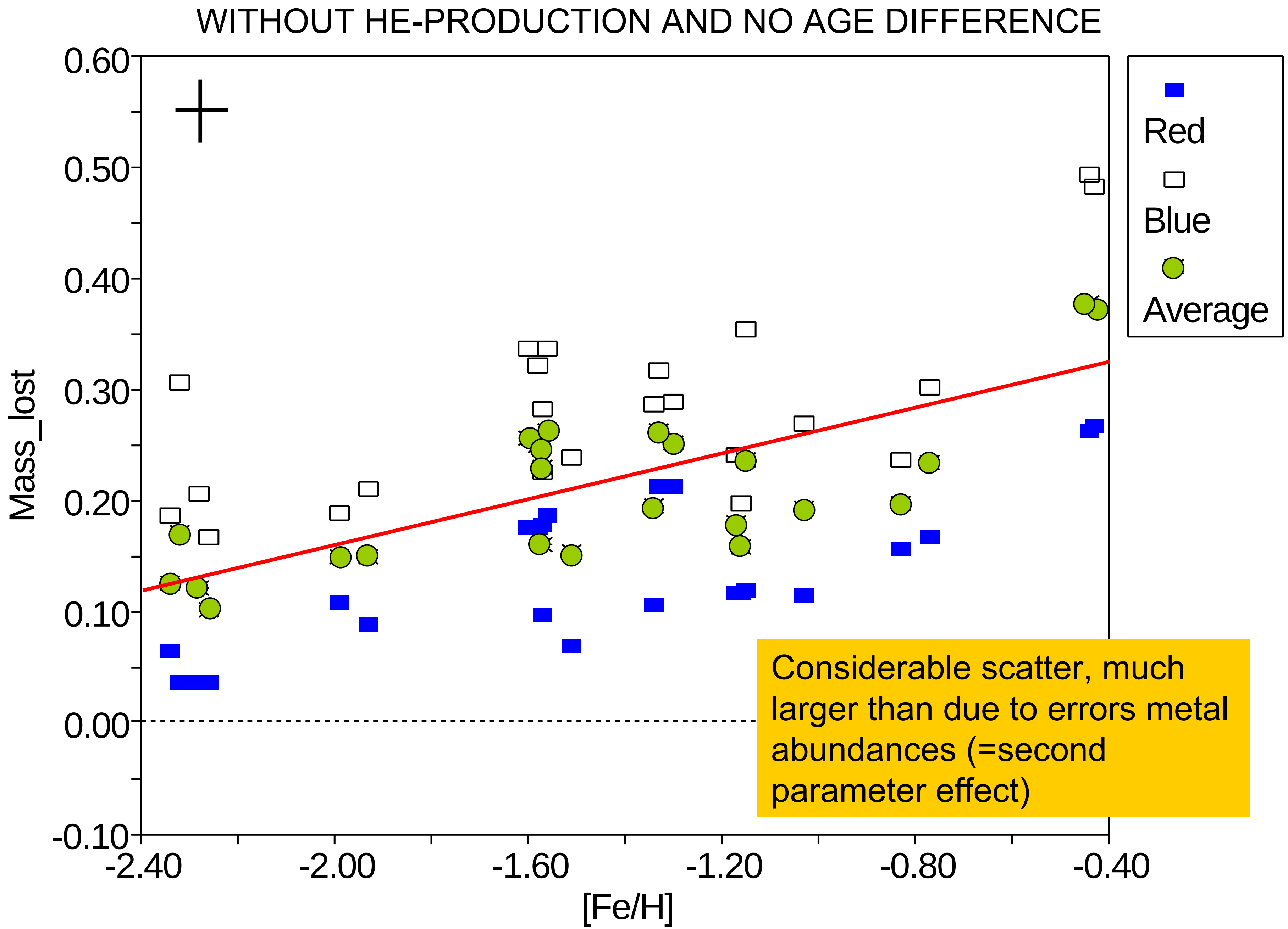
  [Fe/H] and from our determinations

  We assumed a similar overabundance of α-elements in all stars ([α/Fe]=0.4)

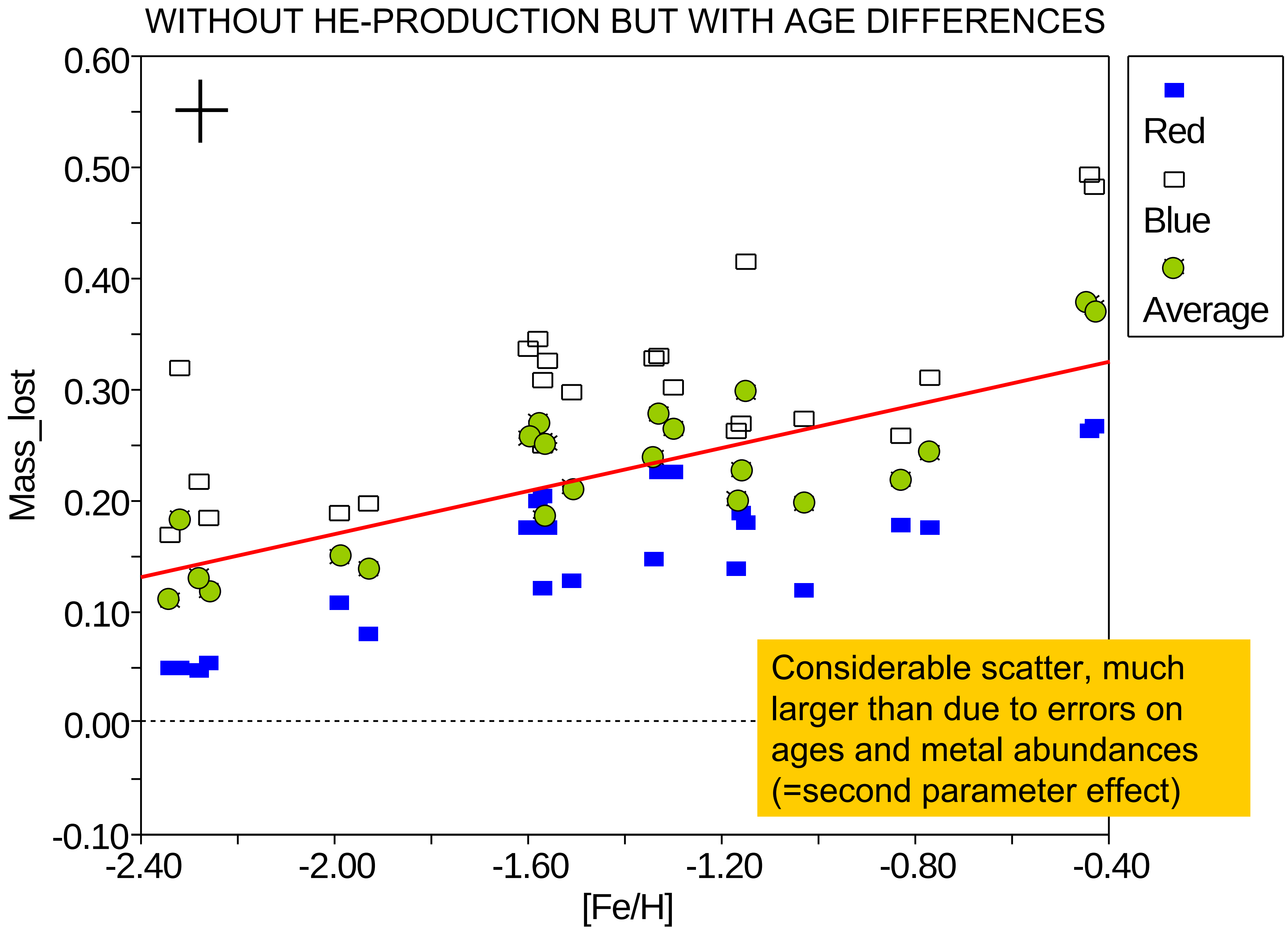
Masses of stars on HB

- Masses of stars on the HB from eye comparison between observed c-m diagrams and HB models by the Pisa Evolutionary Library
- Interpolations in a grid of ZAHB models of different metallicity
- The red edge (=larger mass) is uncertain in metal-rich clusters due to saturation





WITHOUT HE-PRODUCTION AND NO AGE DIFFERENCE
0.60
0.50
0.40
0.30
0.20
0.10
0.00
-0.10
Mass_lost
-2.40
-2.00
-1.60
-1.20
-0.80
-0.40
[Fe/H]
Red
Blue
Average
Considerable scatter, much larger than due to errors metal abundances (=second parameter effect)


WITHOUT HE-PRODUCTION BUT WITH AGE DIFFERENCES
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Mass_lost
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[Fe/H]
Red
Blue
Average
Considerable scatter, much larger than due to errors on ages and metal abundances (=second parameter effect)

He abundance as a second parameter

- Let us assume that the He abundance is a second parameter
- He abundance has two effects:
  - A different (generally smaller) mass for stars at TO
  - A different color and luminosity of stars on the HB. Due to these effects, a different mass is obtained for stars on the HB
- How to obtain the He abundances: from the distribution of the O-Na anticorrelation
- However, we lack of reliable nucleosynthesis predictions
- For this reason we will adopt a model (based on dilution) with at least one free parameter, that will be obtained by fitting data.

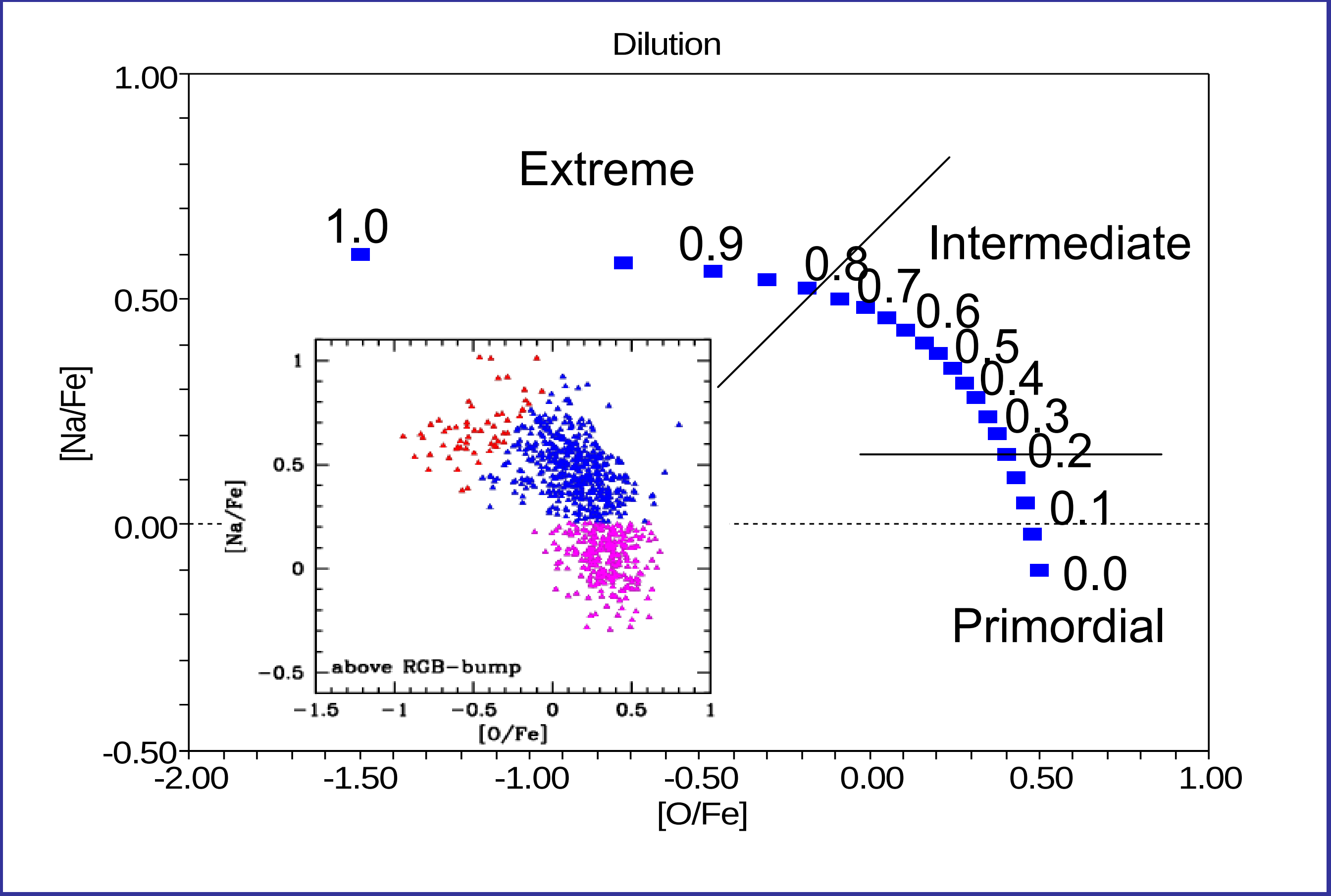
Dilution Model

- A model where polluted Na-rich, O-poor material is diluted into pristine Na-poor, O-rich material reproduces very well the expected O-Na anticorrelation (see Prantzos & Charbonnel 2006)
- It also reproduces Li abundances (Li is not null in the O-poor stars of NGC6752!)
- It is very interesting to use such a simple model in order to predict the distribution of stars on the HB starting from the observed distribution of stars along the Na-O anticorrelation
- In this model the logarithmic abundance of an element [X] for a given dilution factor dil is given by:

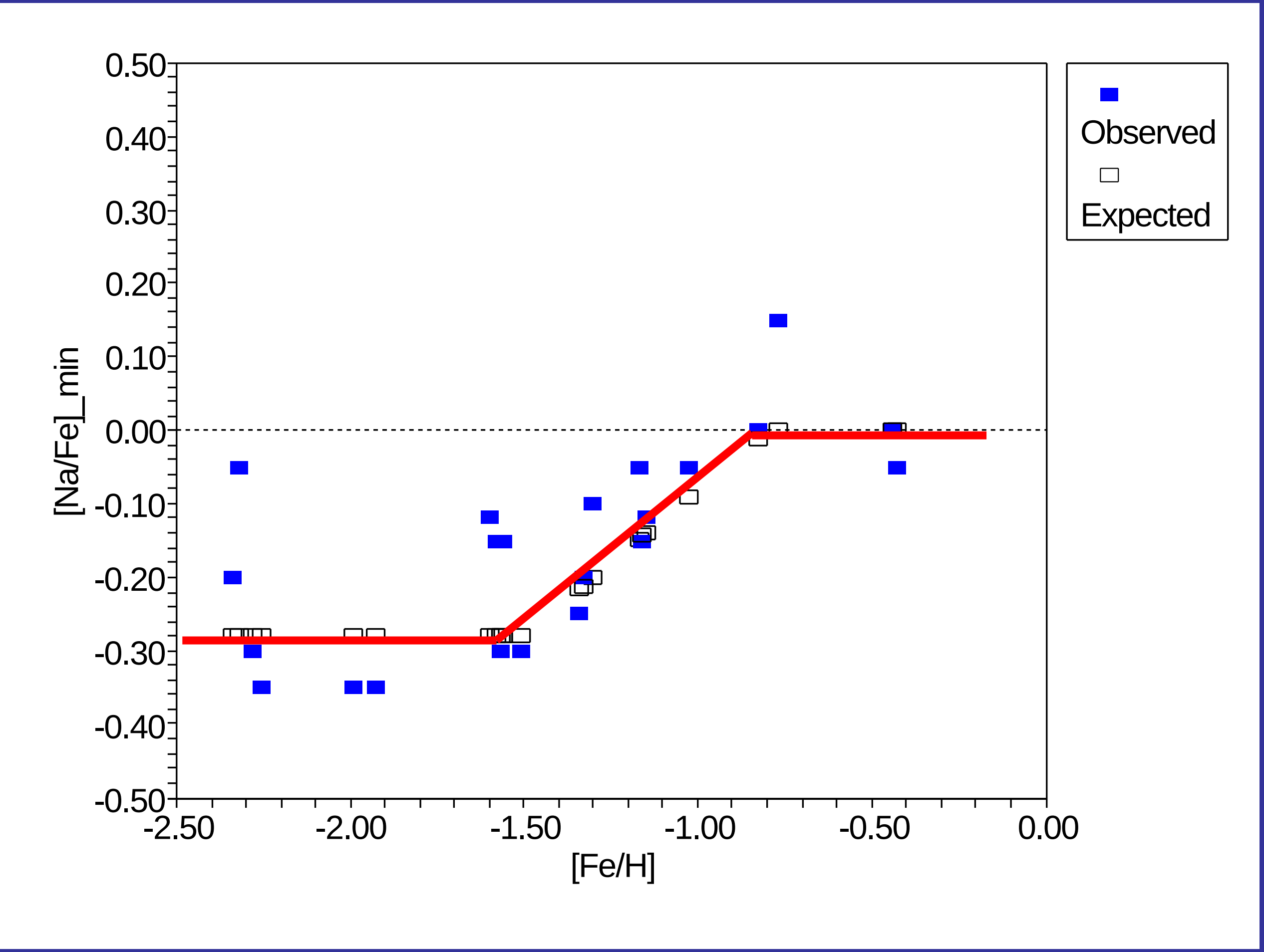
  $[X] = \log\{(1-dil)\, 10^{[Xo]} + dil\, 10^{[Xp]}\}$,

  where [Xo] and [Xp] are the logarithmic abundance of the element in the original and polluted material

	[Na/Fe]	[O/Fe]
$[X_o]$	Na expected	0.5
$[X_p]$	0.6	-1.5

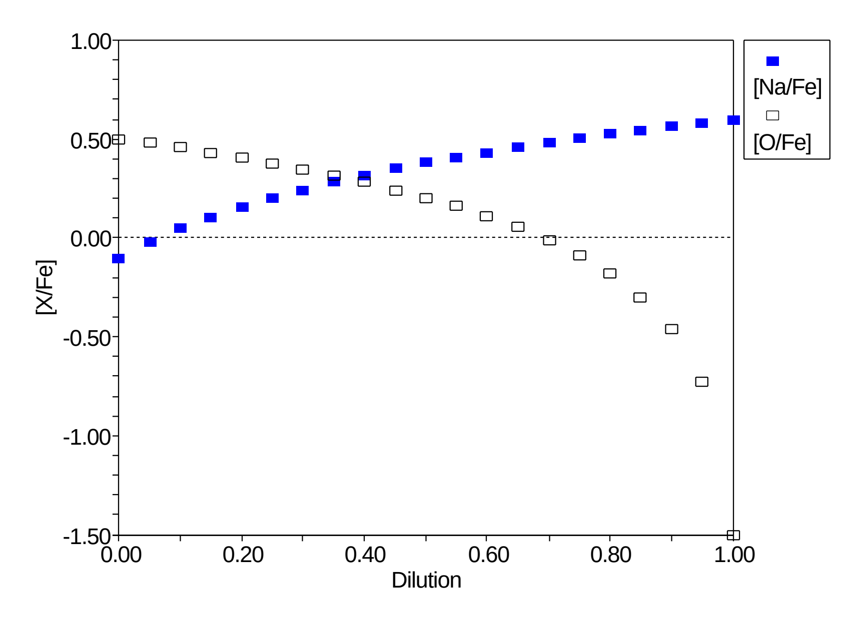


Expected original Na abundance



Estimate of minimum and maximum dilution

- In principle, minimum and maximum dilution can be derived from both O and Na abundances
- However, Na abundances is much better suited for minimum dilution and O for maximum dilution because of saturation



He and dilution

- Once the minimum and maximum dilution are determined, the minimum and maximum He content can be derived:

$$Y_{min} = Y_{BB} + x\ Dil_{min}$$
$$Y_{max} = Y_{BB} + x\ Dil_{max}$$

- In this model x is a free parameter, which represents the (average) He enrichment of the polluting material

TO mass in stars of different He

- The minimum and maximum mass of TO stars are then derived using the relation:
  - $M_{max}(TO) = M_{ref} - 1.3\ dil_{min}\ x$
  - $M_{min}(TO) = M_{ref} - 1.3\ dil_{max}\ x$
- The value of x is adjusted in order to have on average the same mass loss for stars at the blue and red edge of the HB

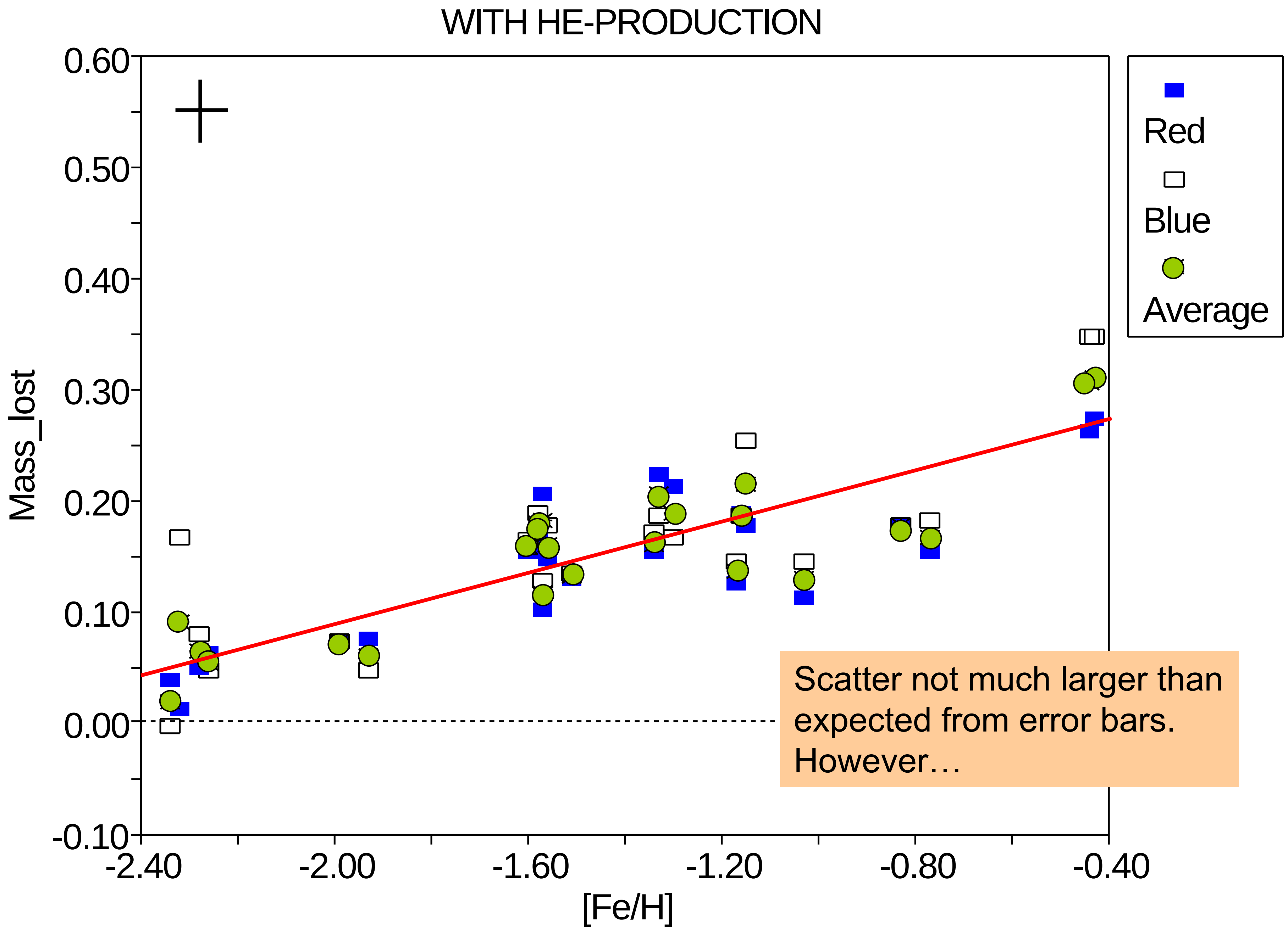
HB mass in stars of different He

- Before making this comparison, we should note that the masses derived for stars on the HB depend on the assumed He abundance
- The effect is important only for the minimum mass (i.e. stars at the blue edge)
- We corrected the mass previously derived (where Y=0.25) using the formula:

  $M_{min}(HB) = M_{min}(HB)_{Y=0.25} + \Delta M$

  Where:

  $\Delta M = \max\{0, [-0.27 ([Fe/H]+1.5) +0.12] [Y_{max}-0.25] \}$
- Of course, this procedure should be solved iteratively, because the value of Y_{max} depends on x, which on turn is determined by assuming a given value for $M_{min}(HB)$
- The best value for x is x=0.12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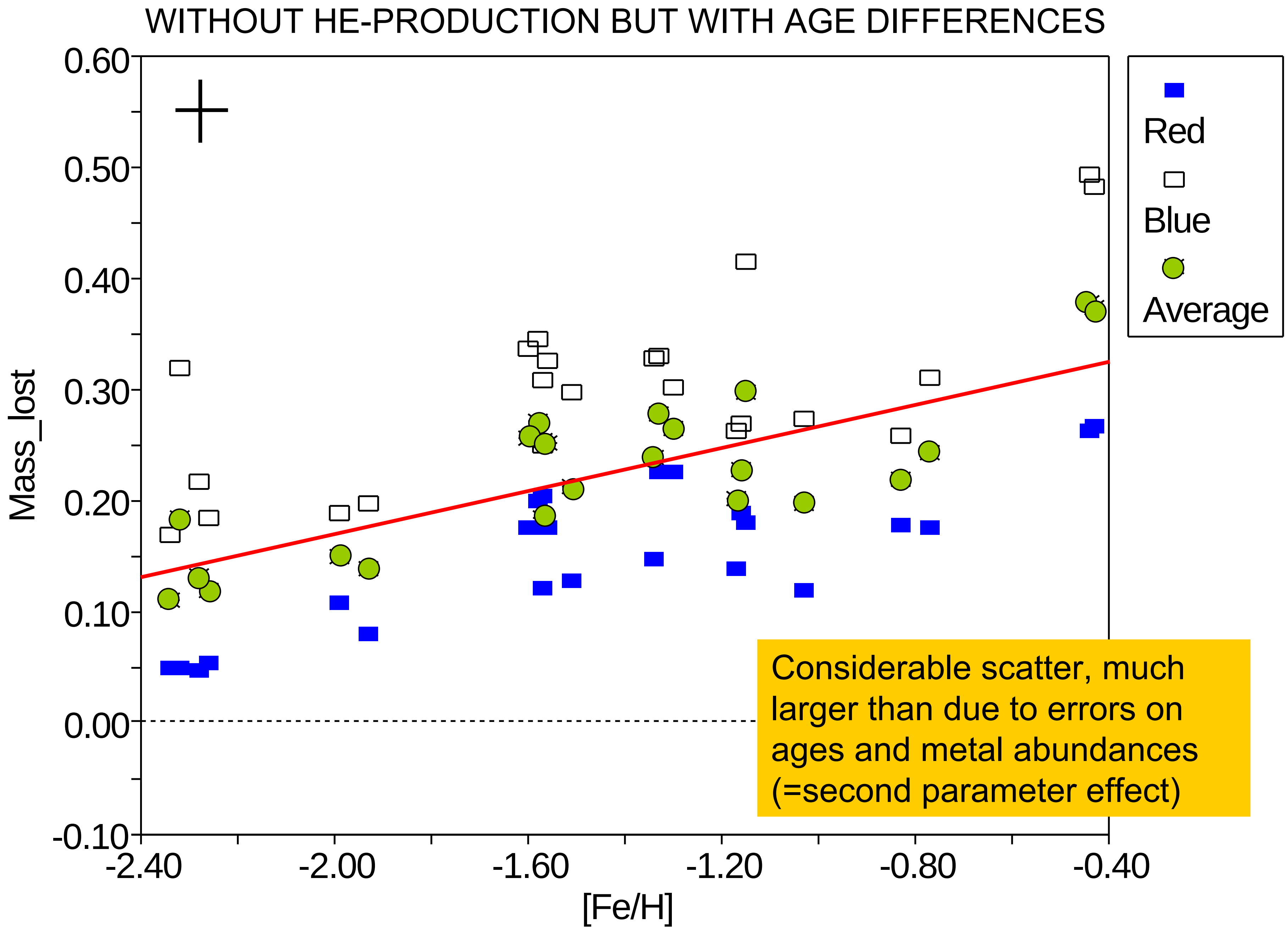
Scatter not much larger than
expected from error bars.
However…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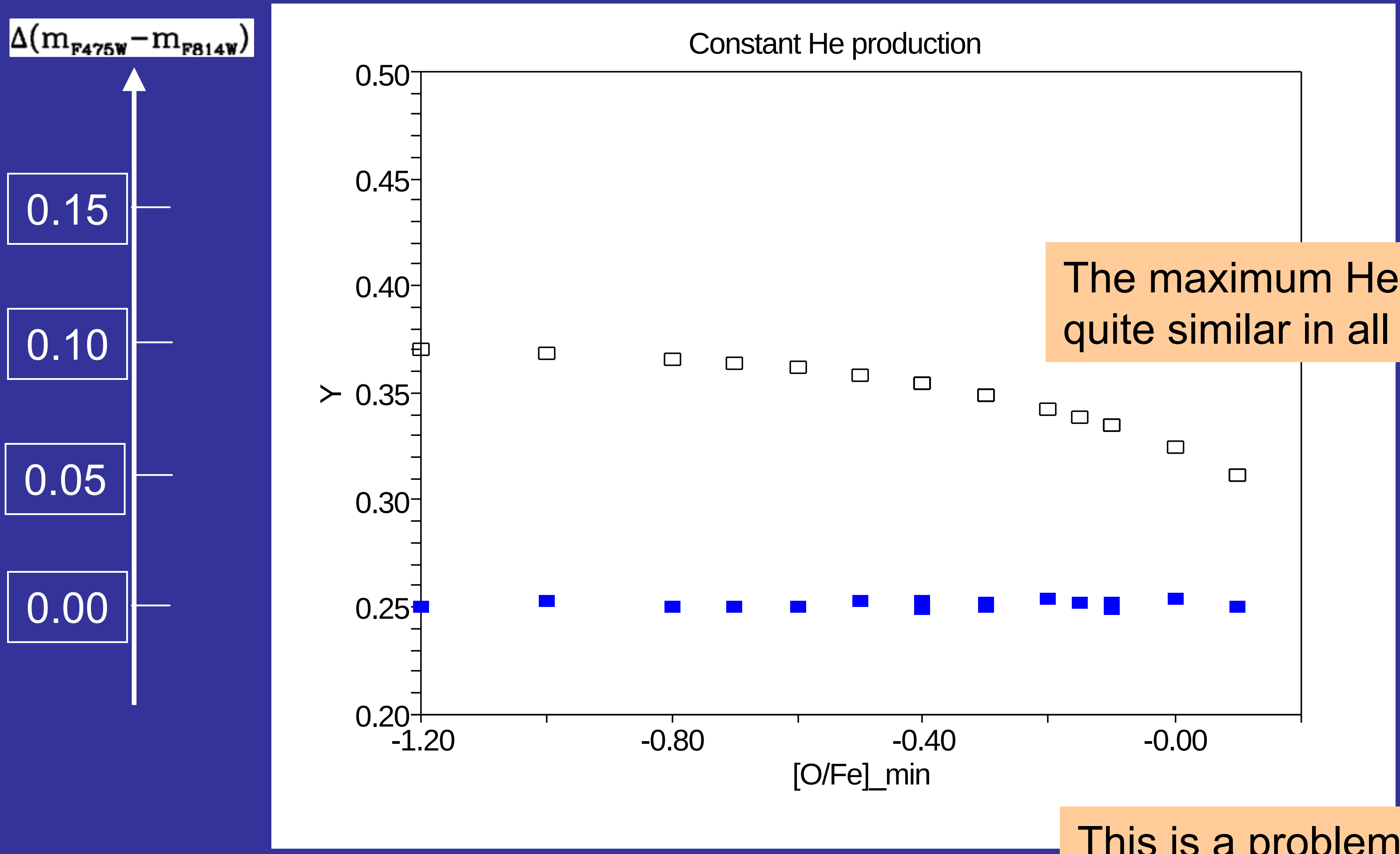
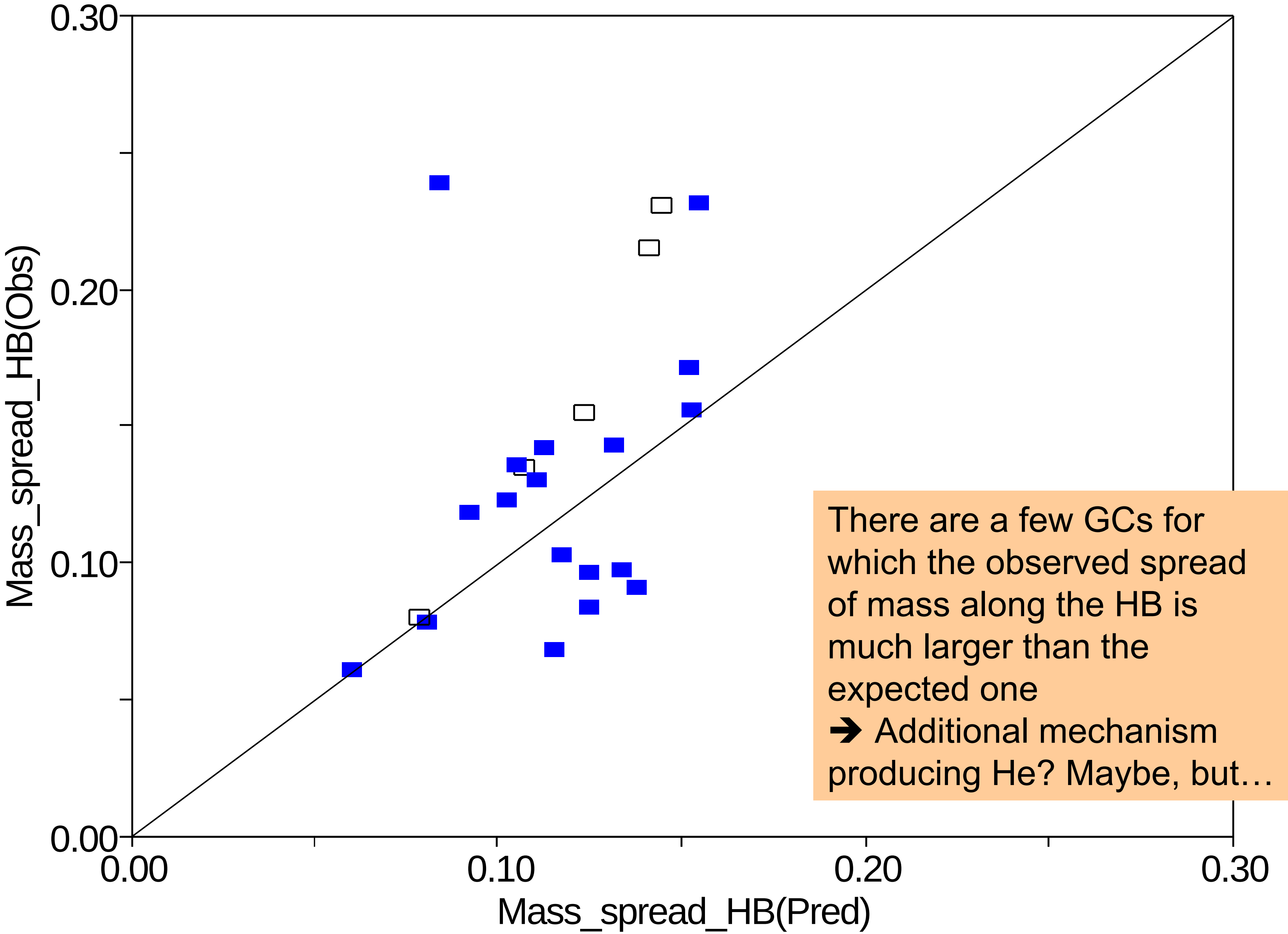
How much He is needed?



The maximum He value is quite similar in all clusters

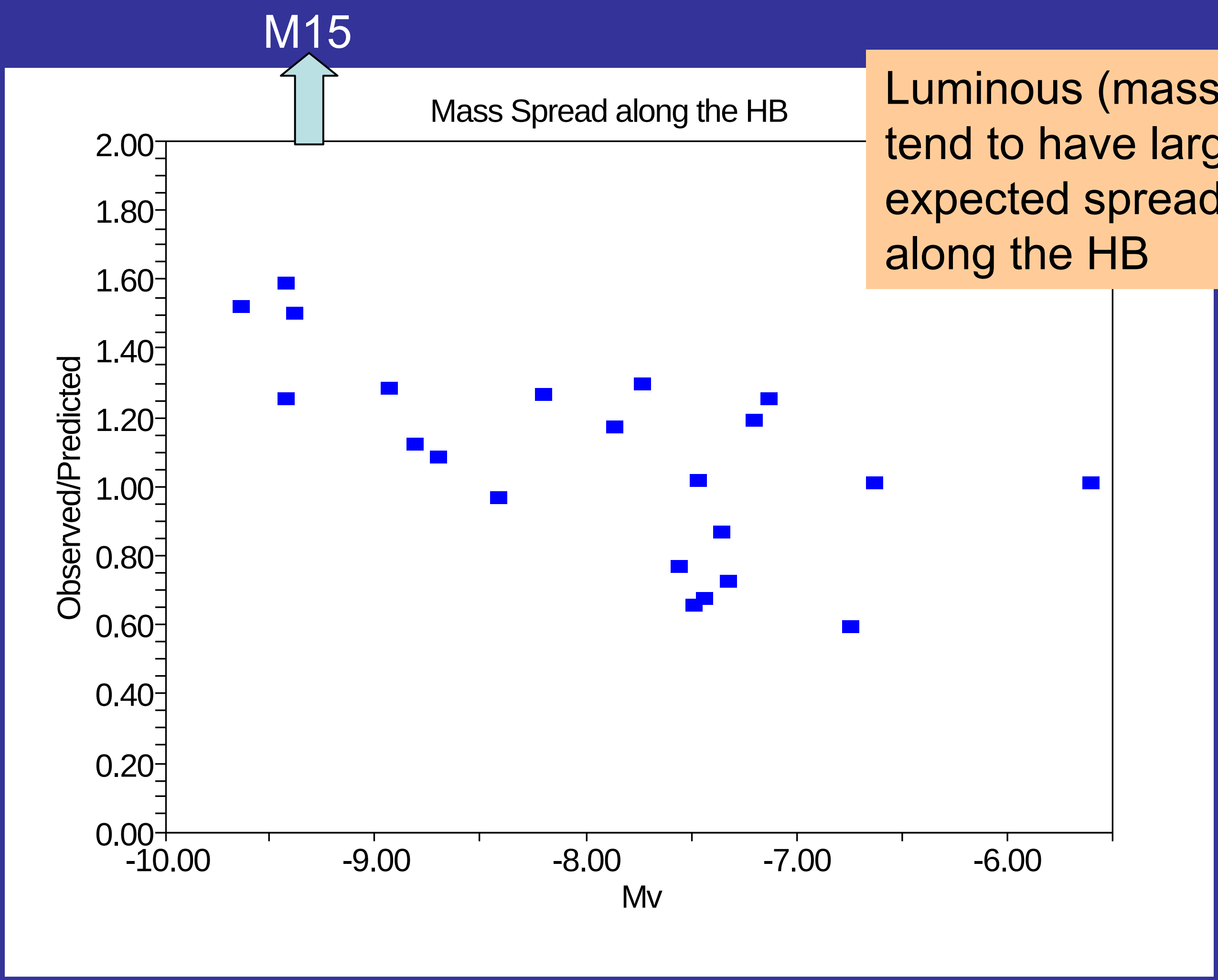
This is a problem, because multiple MS's are rare



There are a few GCs for which the observed spread of mass along the HB is much larger than the expected one

➔ Additional mechanism producing He? Maybe, but…

Correlation with M_V



Luminous (massive) GCs tend to have larger than expected spread of mass along the HB

He production f(Mv)

Let us assume that the He production is not constant, but rather depends on M_V:

$x = -0.034 - 0.14\ M_V$

Or:

$\Delta Y = (-0.034 - 0.14\ M_V)\ Dil$

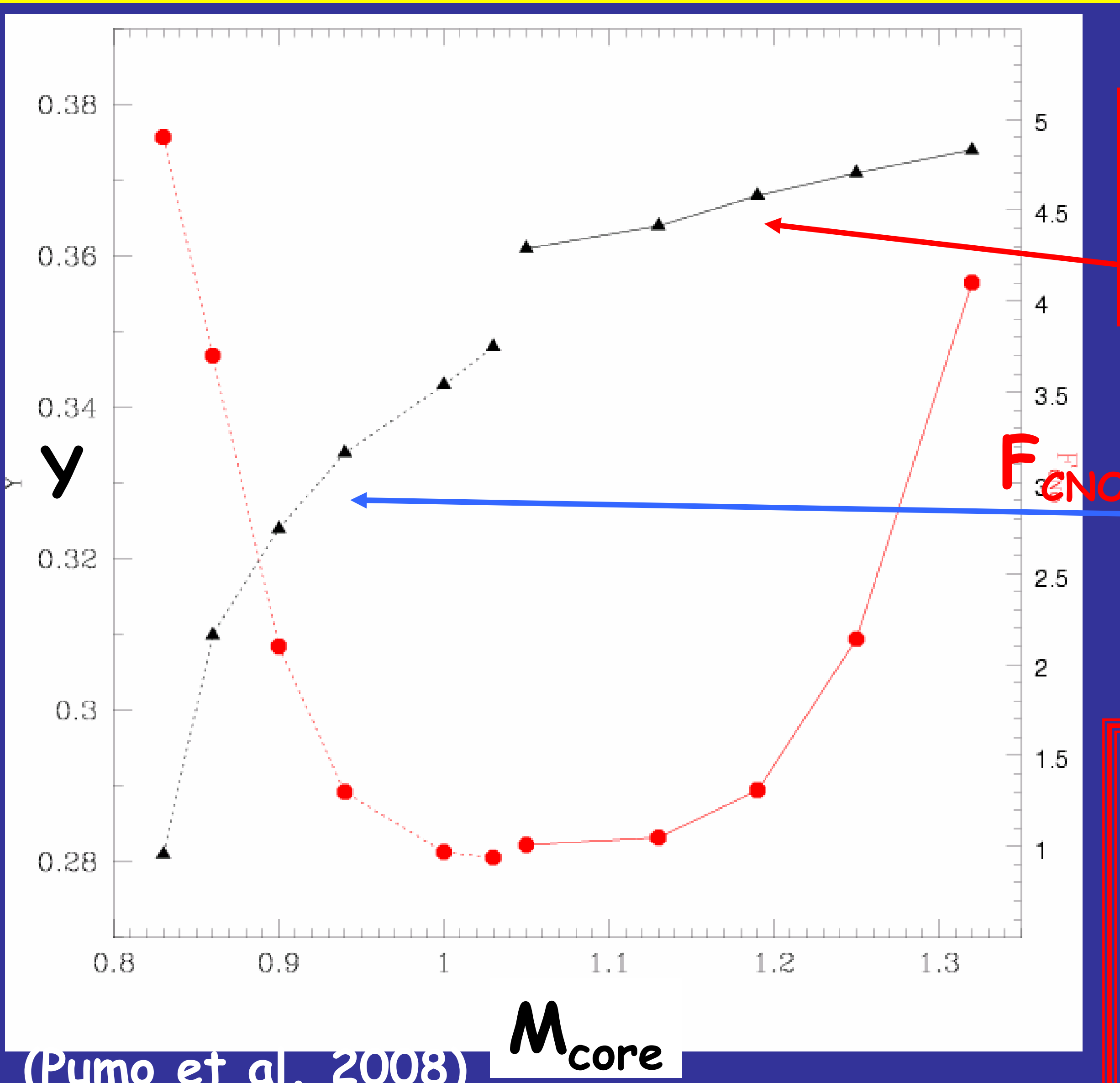
Does a variable Y at a given dilution have a reasonable explanation?

- Maximum depletion of O corresponds to the CNO burning equilibrium abundances
- Maximum production of Na corresponds to complete transformations of ^{22}Ne into ^{23}Na
- These are saturation values!
- Hence different polluters may produce different He while producing the same Na and destroying the same O

Does a variable Y at a given dilution have a reasonable explanation?

- Let us then assume that the amount of He produced is a function of the mass of the polluters
- For instance, suppose that more massive stars produce more He (super-massive AGB stars: see Pumo et al. 2008; Renzini 2008)

Helium yields from super-AGBs can!



(Pumo et al. 2008)

superAGB models (Siess 2007) at 2nd dredge up

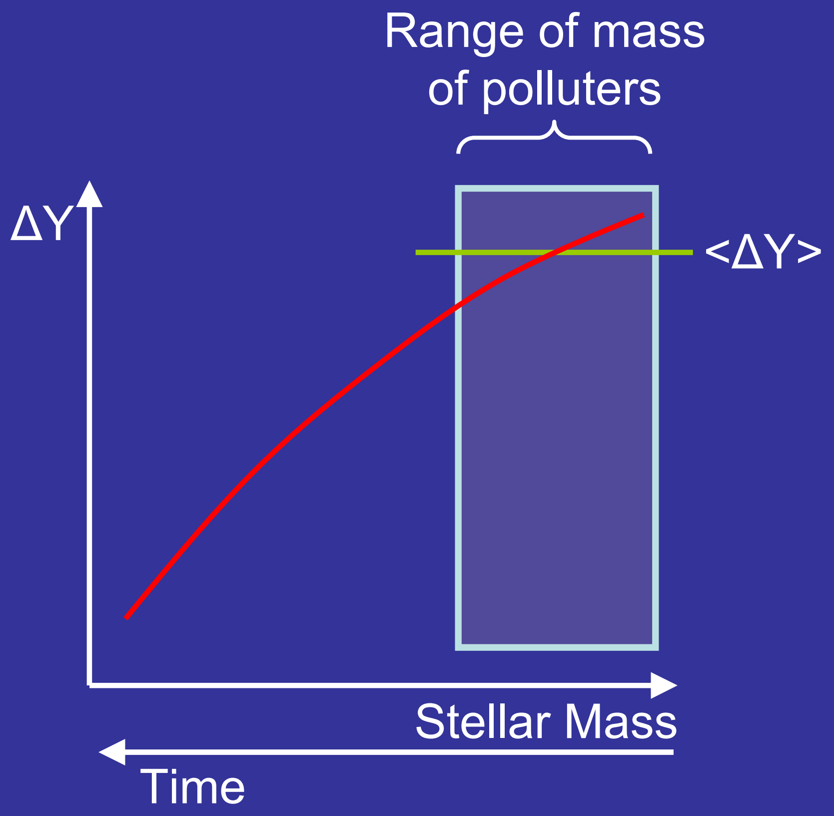
AGB M<6.3Msun (VD 2007)

superAGBs reach the Y values needed to fit the blue MS in ωCen and NGC 2808

- In this case the first polluting stars produce a lot of He (see also Renzini 2008)
- Let us also assume that the material lost by these stars does not form 2nd generation stars immediately, but rather goes into a pool from which 2nd generation stars form
- This is needed in order to have individual populations with different He (e.g. the case of NGC2808 and ω Cen; see Renzini 2008 and D'Ercole et al. 2008)

With time, the average Y of the pool decreases

- This pool will be initially very He-rich, but later its He content decreases, because the weight of the most massive stars progressively decreases



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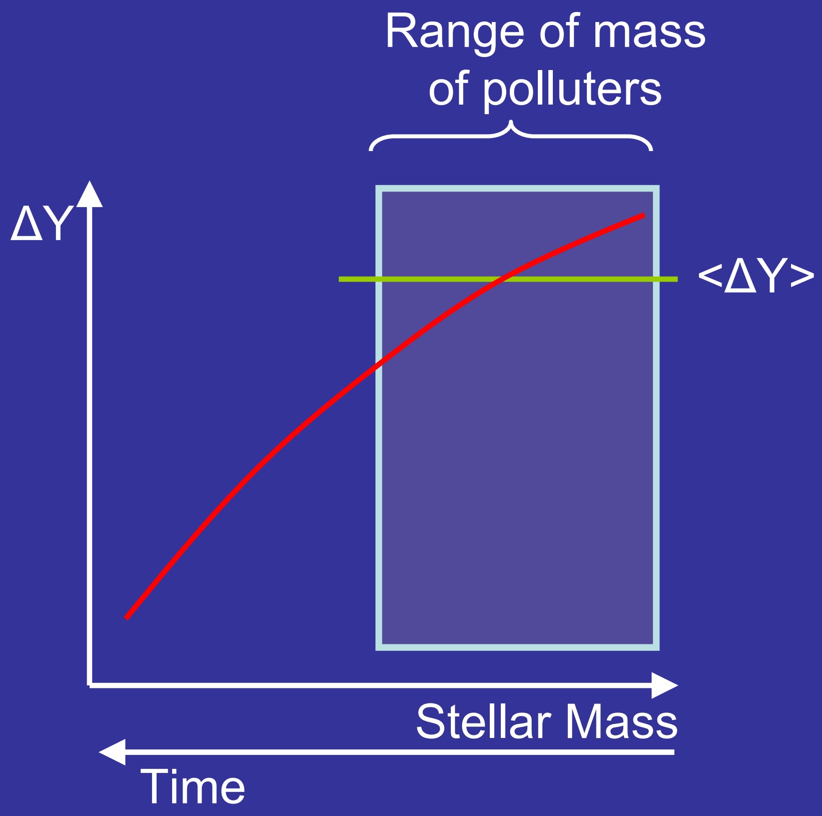

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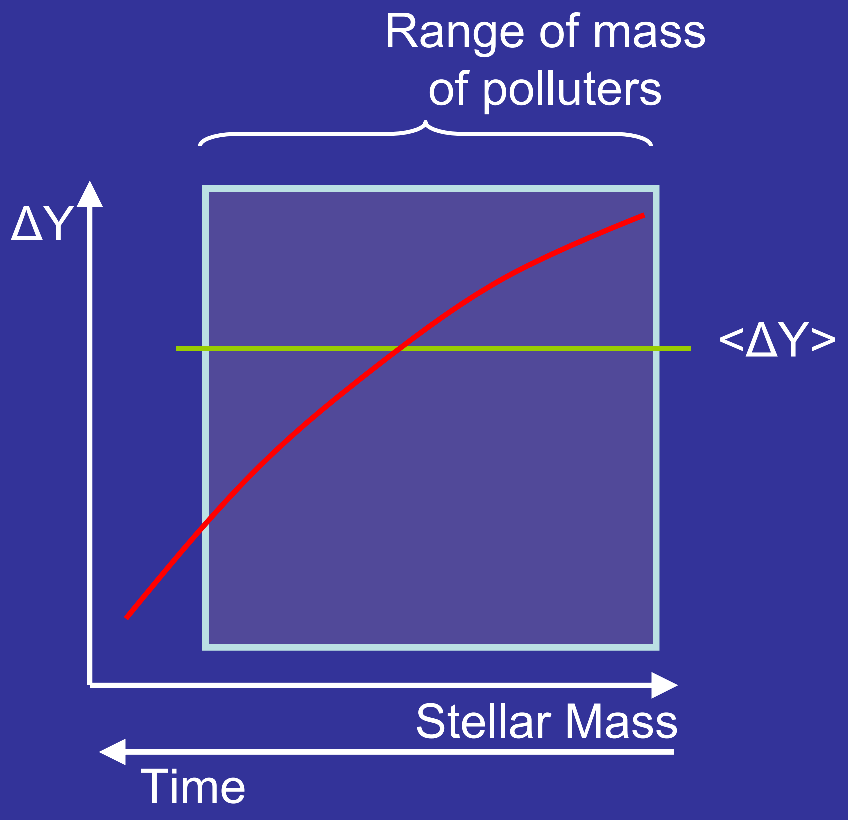
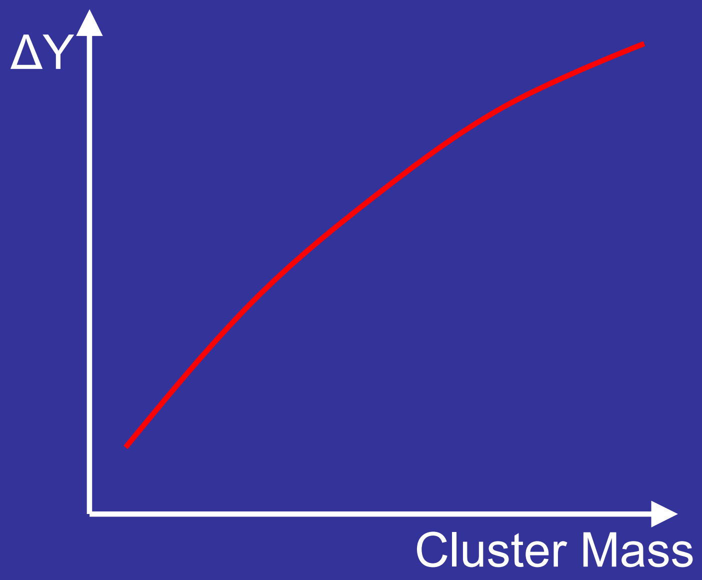


Dependence of He production on cluster mass

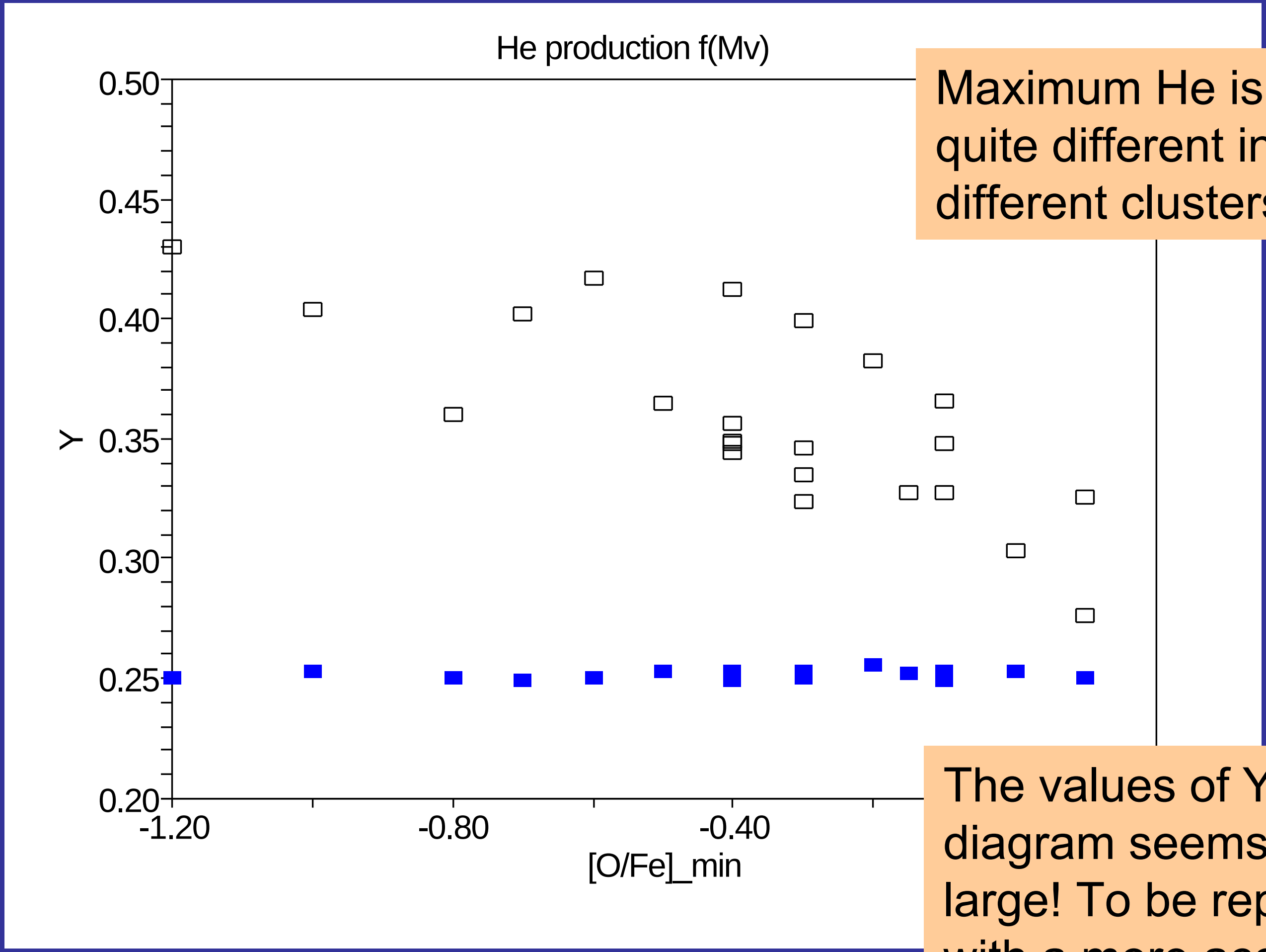
- It is reasonable to expect that formation of 2nd gen. stars only starts when a threshold mass is reached, and stops when first 2nd gen. SNe explode (see Renzini 2008)
- The whole process is then expected to be faster in more massive GCs

➔ In these clusters only the most massive stars contribute, while in less massive GCs less massive stars also participate

- In this way we may generate a dependence of x on cluster mass

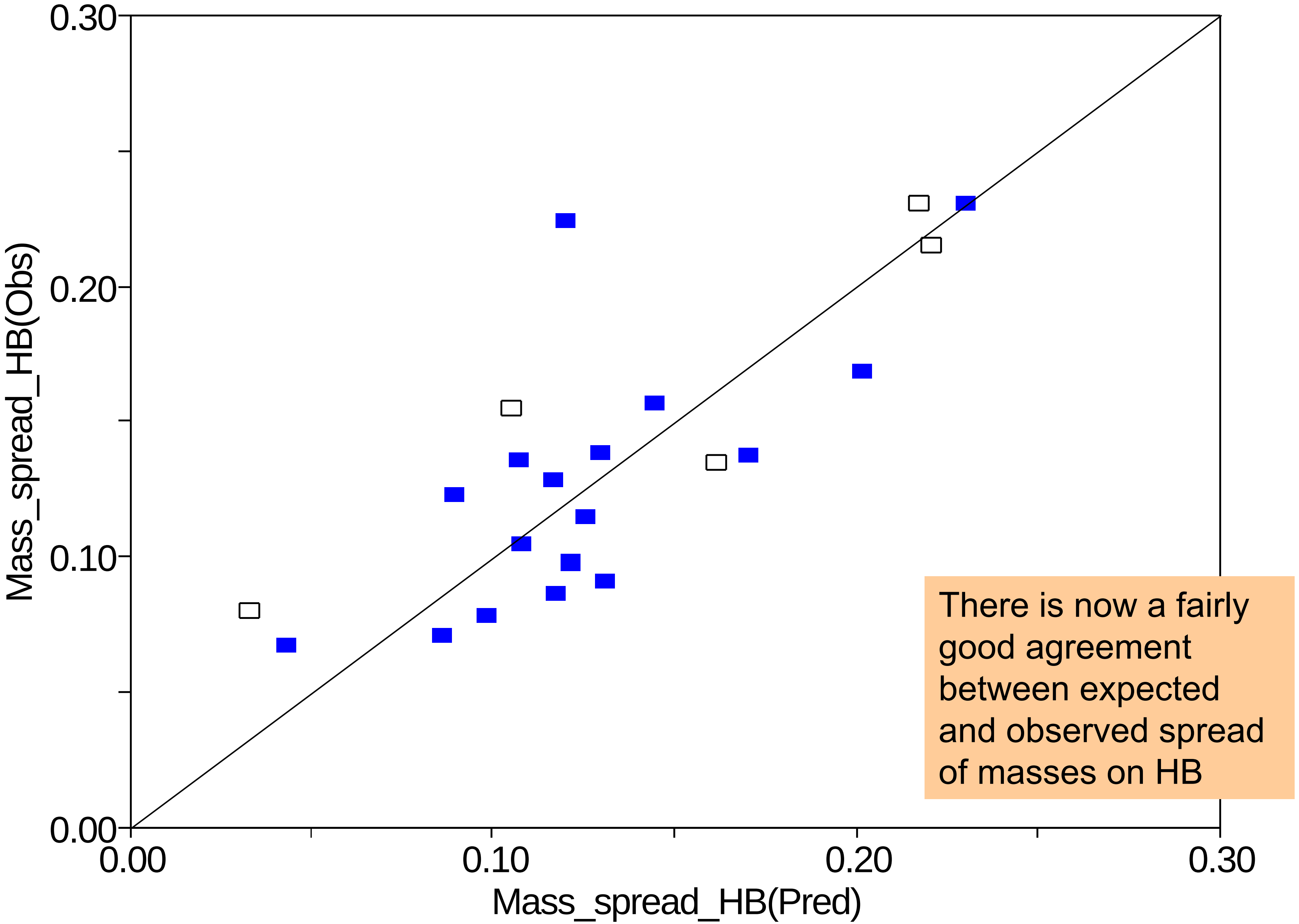


He production $f(M_V)$

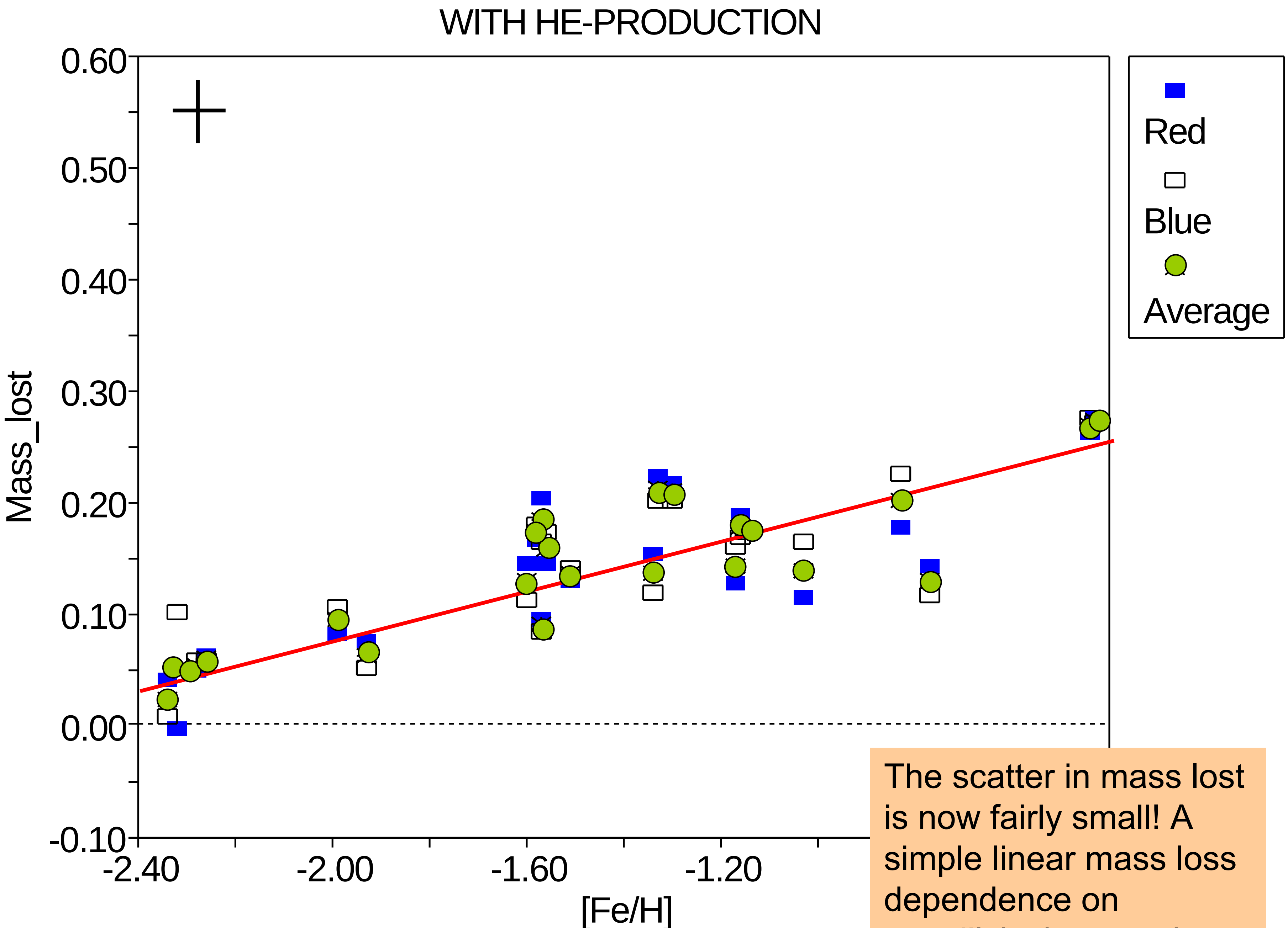


Maximum He is now quite different in different clusters

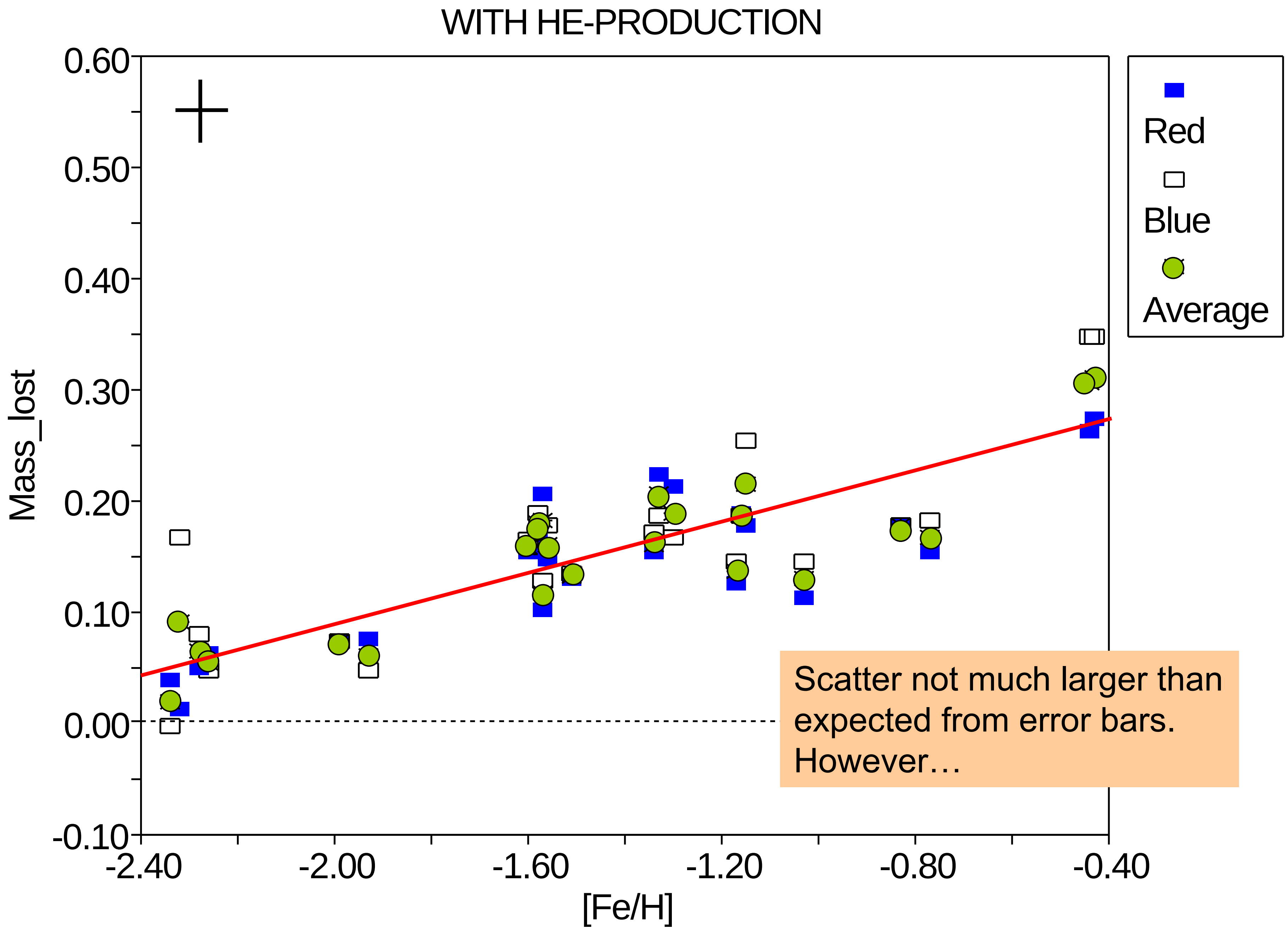
The values of Y in this diagram seems too large! To be repeated with a more accurate approach



0.30
0.20
0.10
0.00
0.00
0.10
0.20
0.30
Mass_spread_HB(Obs)
Mass_spread_HB(Pred)
There is now a fairly good agreement between expected and observed spread of masses on HB



The scatter in mass lost is now fairly small! A simple linear mass loss dependence on metallicity is enough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[Fe/H]
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Average
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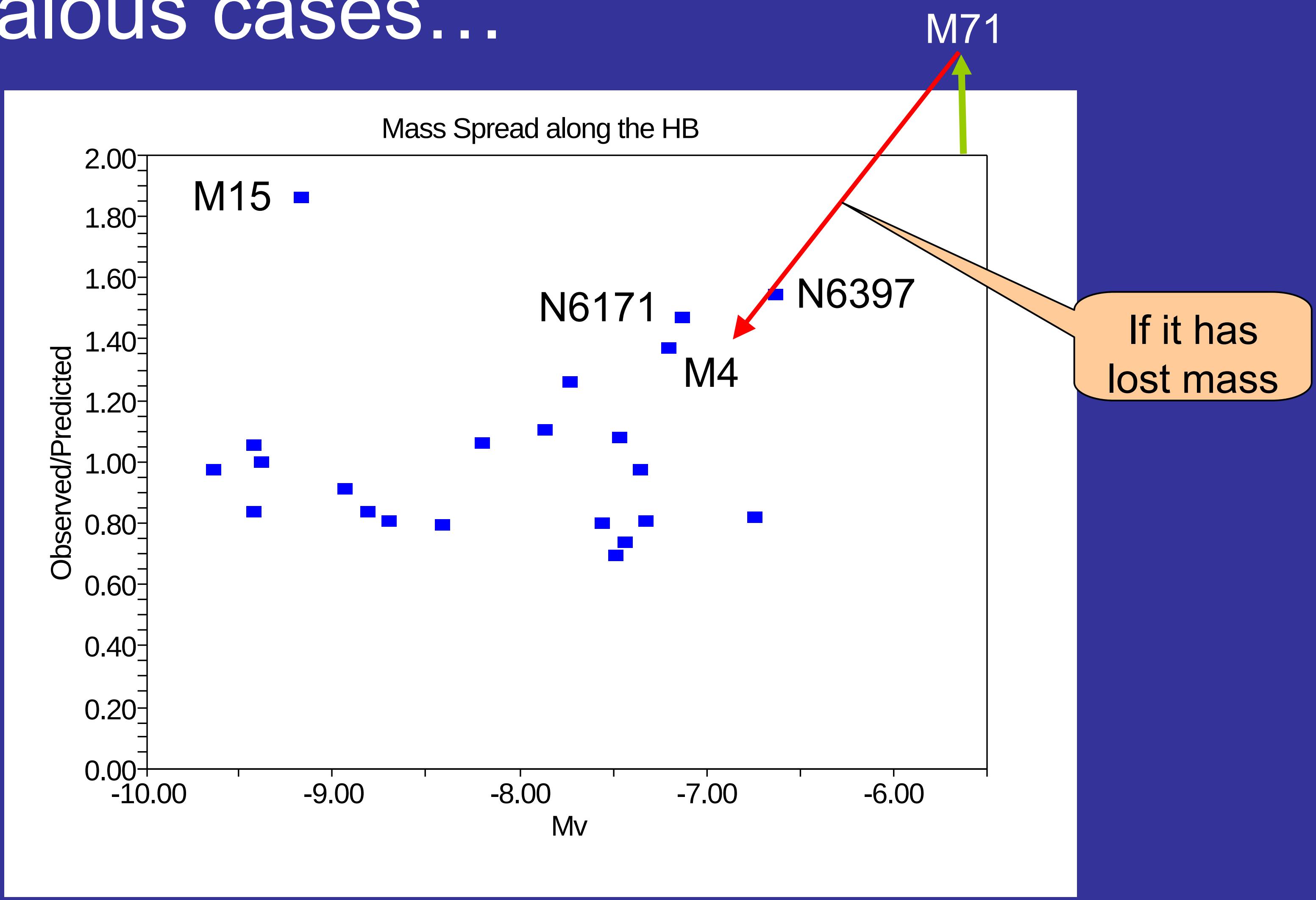
Anomalous cases…



… might have an explanation

Conclusions

- Age is a second parameter, but it is not enough to justify HB morphologies
- Self pollution in globular clusters is most likely responsible for a large variety of the second parameter features
- Self pollution may be in part described using the O-Na anticorrelation, but modulation according to cluster luminosity is required

Many points remain to be done

- First and most important, what are the polluters?
  - **Progresses in modeling AGB stars**
  - **Observations of young objects**
    - **Very young clusters (RSGC1 and RSGC2)**
    - **Intermediate age clusters in the LMC**
  - **Abundances of other elements**
- **A number of confirmation of this scenario are required**
  - **Direct determinations of He, Na and O in HB stars**
    - **The case of NGC 6752**
    - **New observations in both NGC6752 and M4**
  - **Do variables properties agree with expectations?**
  - **Are multiple sequences observed where they are expected?**
  - **Are anticorrelations found where expected (M54 and NGC1851)?**
- **Scenario refinements**
  - **Analytic dependences adopted throughout this discussion should be reviewed; updated age determinations should be used**
  - **Comparison of integrated mass lost along the RGB with mass loss laws (e.g. Reimers)**
  - **What is the lower mass limit for this scenario (NGC6791)**
- **Hydro-dynamical models**