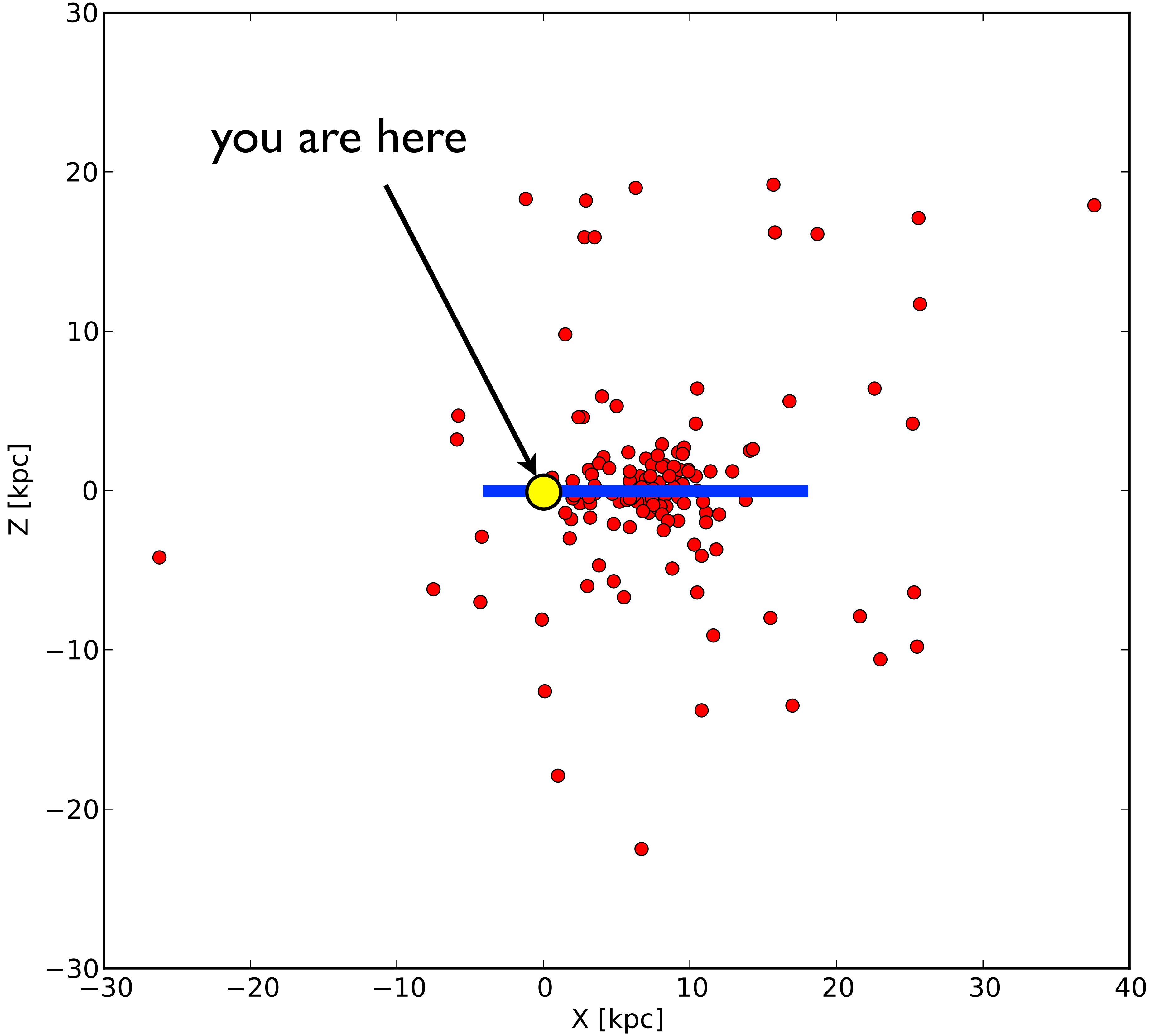
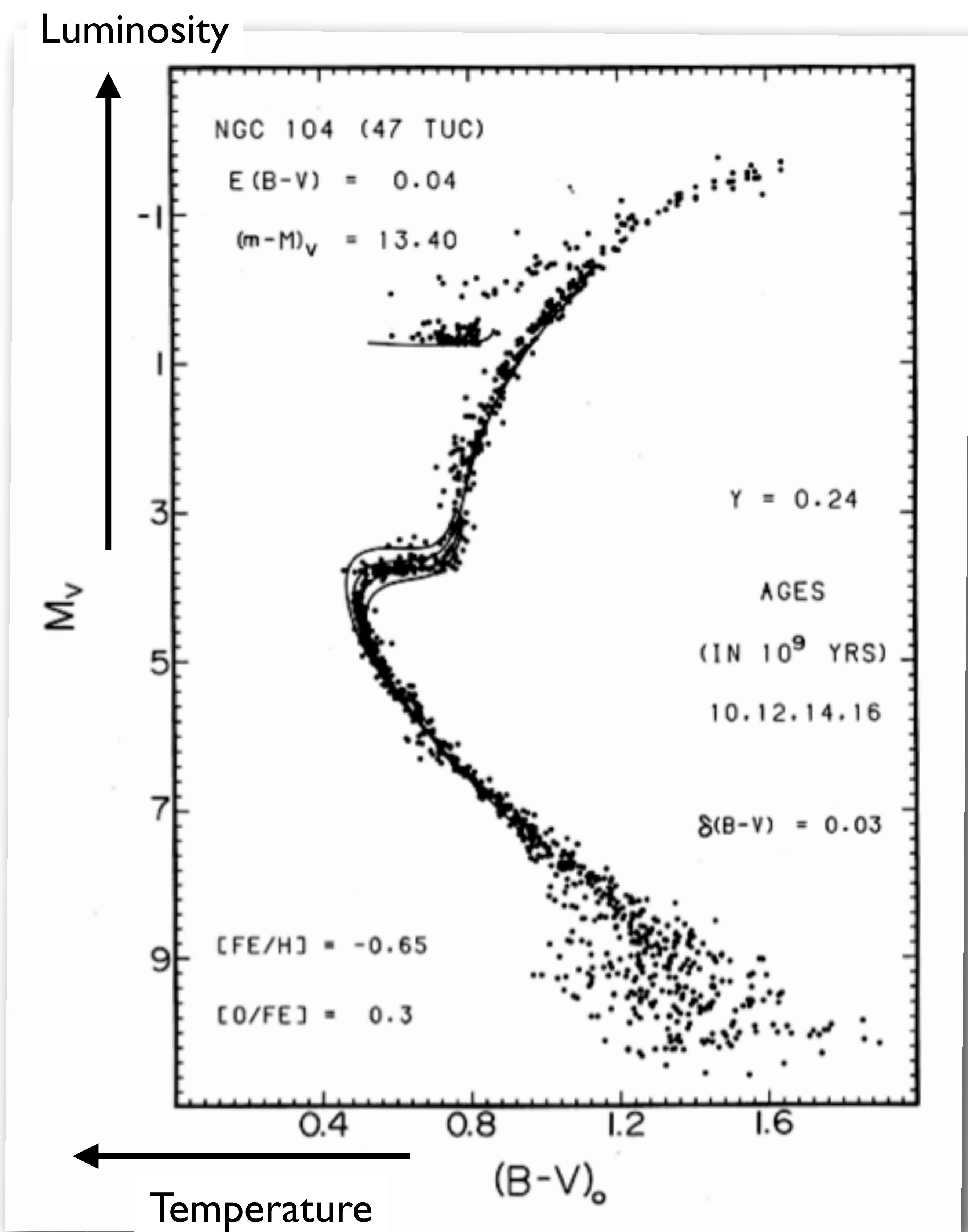
Globular Clusters

Globular clusters in the Milky Way



1 kpc = 3×10^{19} m

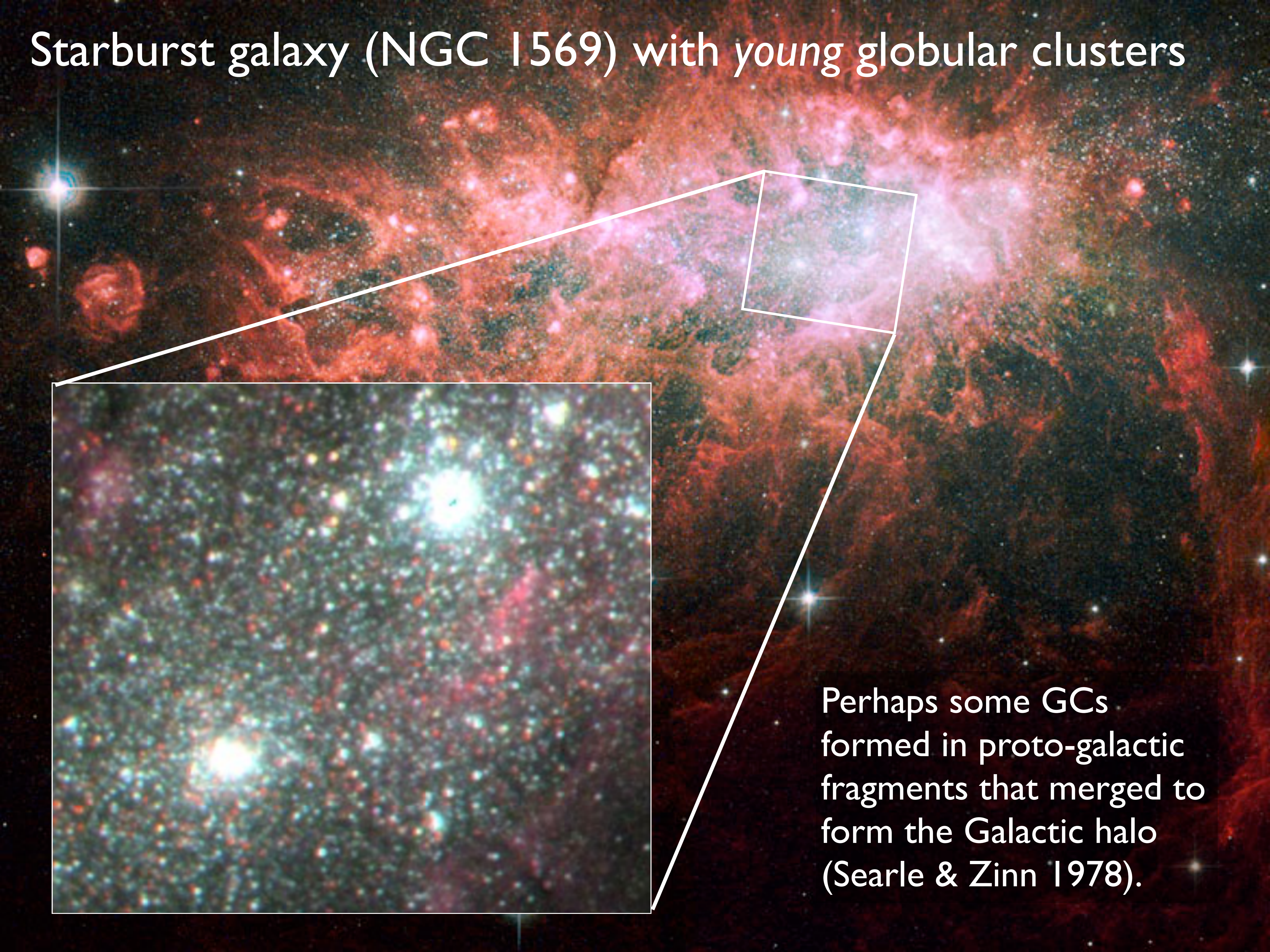
Globular clusters: "Cosmic Fossils"



Comparison with stellar models shows that most GCs (in the Milky Way) are *old* (>10^{10} years).

Colour-magnitude diagrams generally well matched by a *single* stellar isochrone.

Hesser et al. 1987, PASP 99, 739

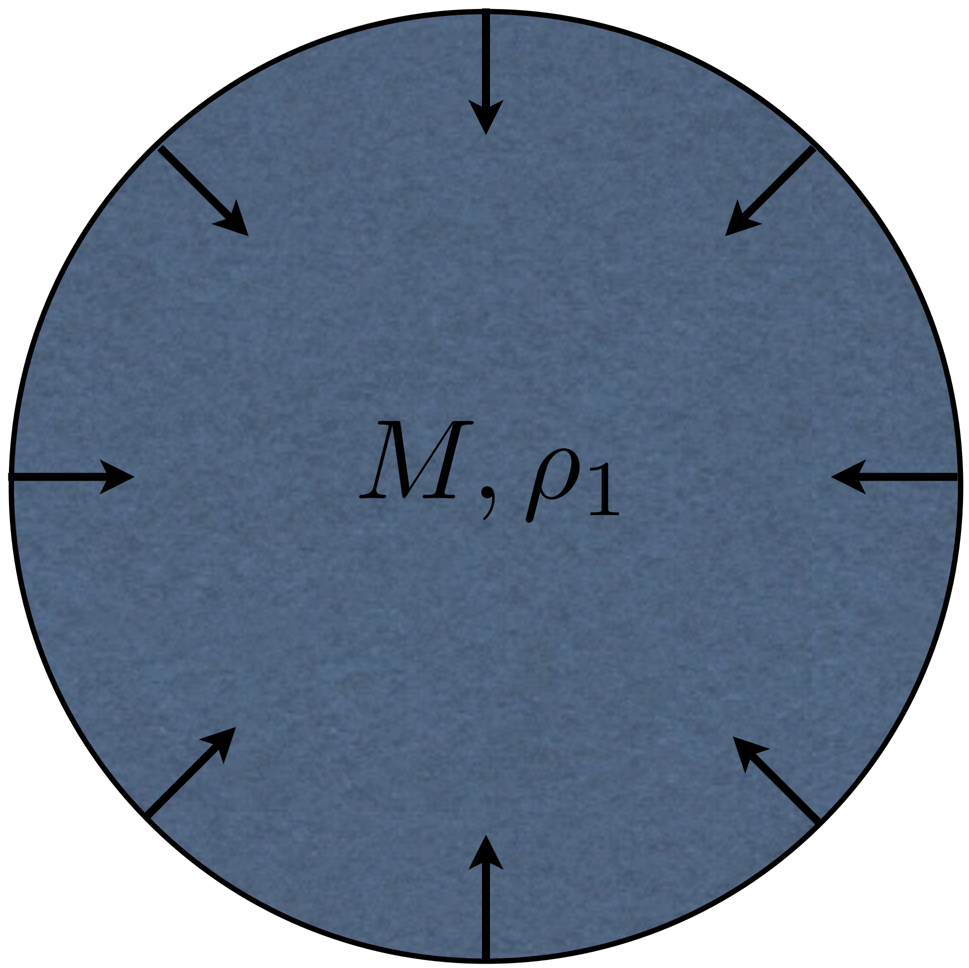

Starburst galaxy (NGC 1569) with *young* globular clusters
Perhaps some GCs formed in proto-galactic fragments that merged to form the Galactic halo (Searle & Zinn 1978).

Globular star clusters: Some numbers

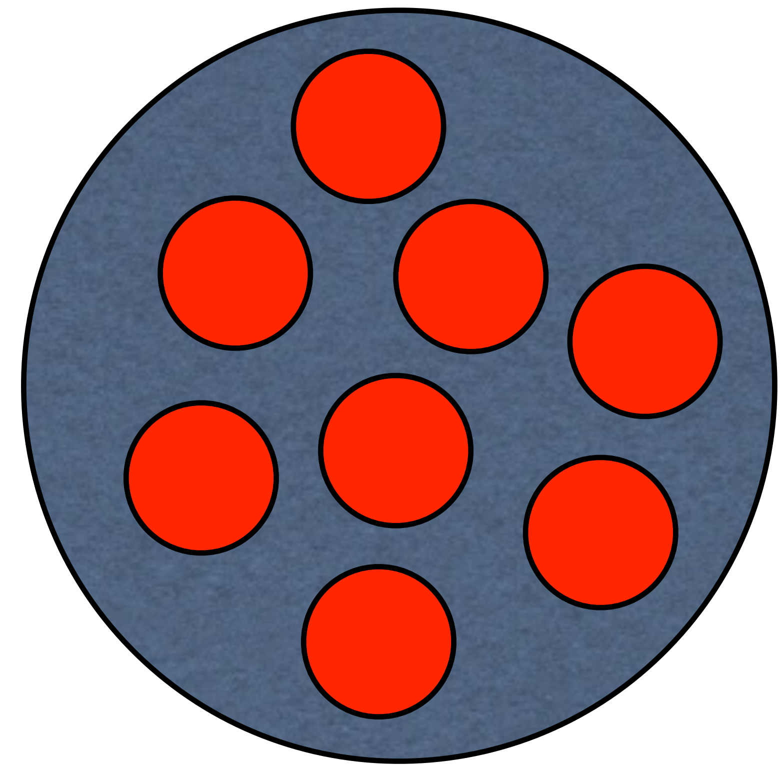
- Masses 10^5 - $10^6\ M_\odot$ ($1\ M_\odot = 2\times10^{30}$ kg)
  (Half-mass) radii $\approx$ 3 pc (1 pc = 3×10^{16} m)
- Present-day stellar
  - half-mass densities:
    $\approx 10^3\ M_\odot\ \mathrm{pc}^{-3}$ ($n_H \approx 10^5\ \mathrm{cm}^{-3}$)
  - central surface/column densities:
    $\approx 10^5\ M_\odot\ \mathrm{pc}^{-2}$ ($\approx$ 10 g cm^{-2})
- Initial gas densities probably much higher

Cartoon picture of star (cluster) formation

Giant Molecular Cloud



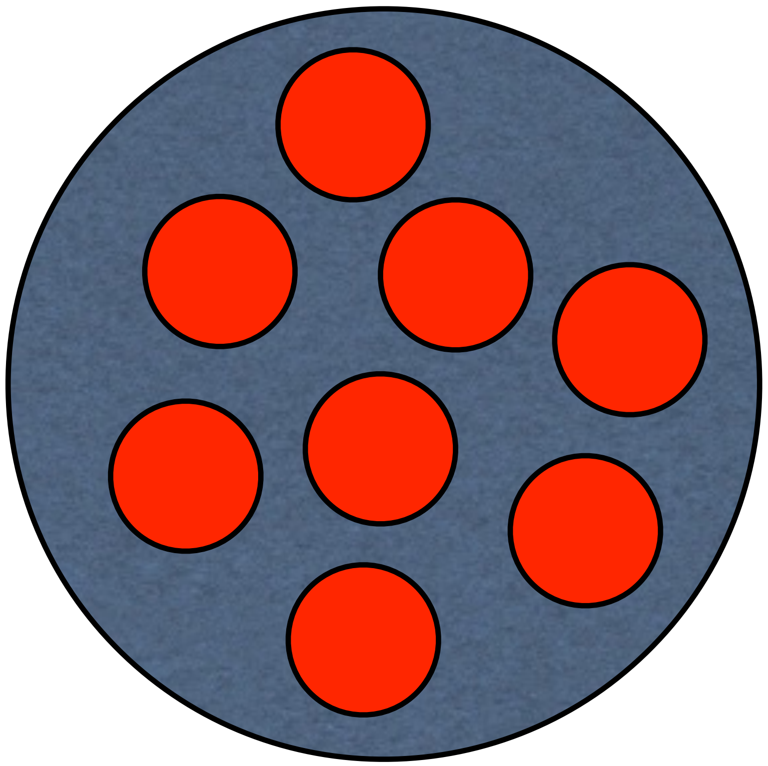
Fragmentation

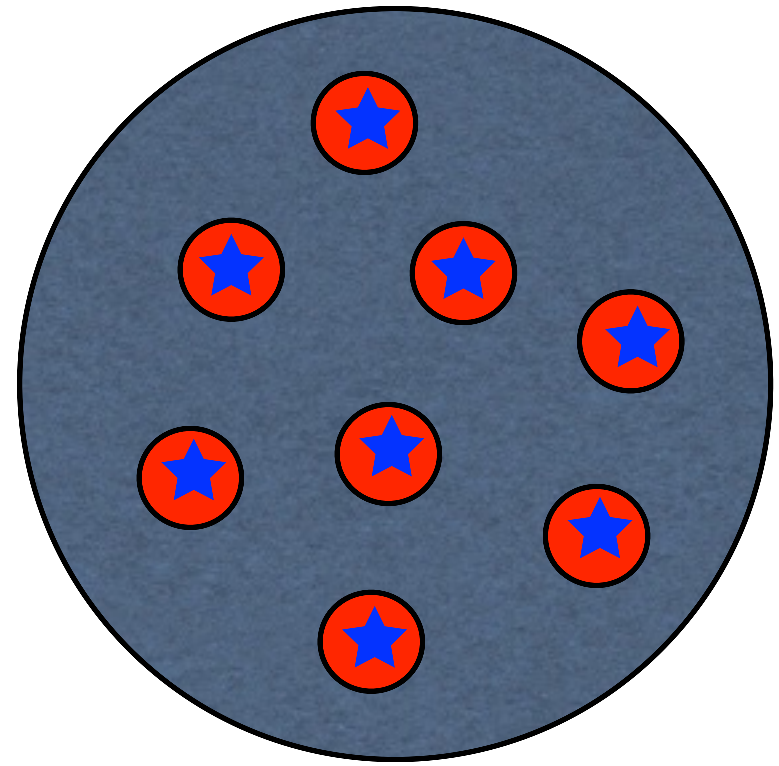


1: Collapse (if free fall) on time scale $t_{\rm coll} = \left(\frac{3\pi}{32G\rho}\right)^{1/2}$

Overdense regions collapse first $\rightarrow$ *fragmentation*

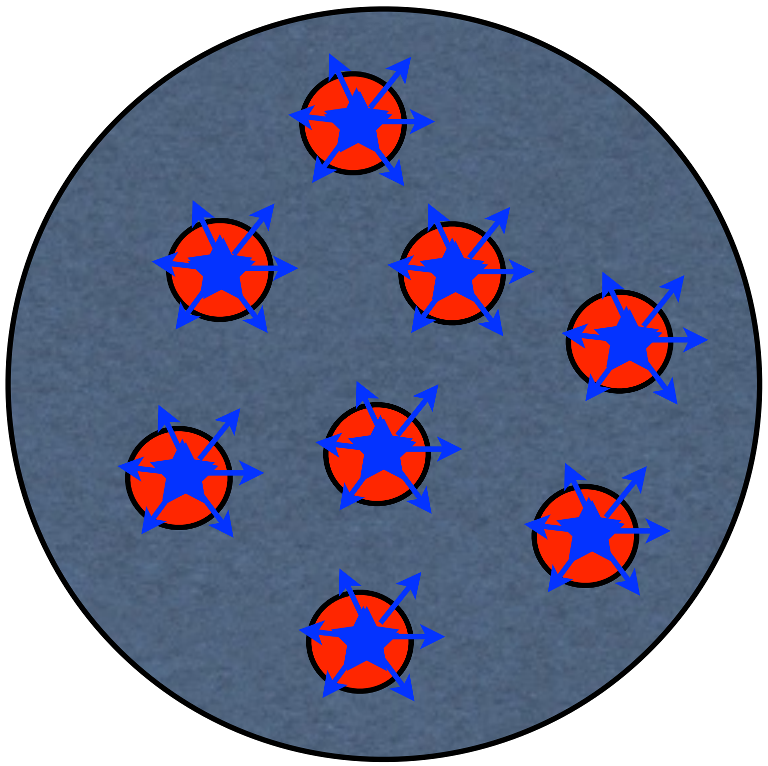
Cartoon picture of star (cluster) formation



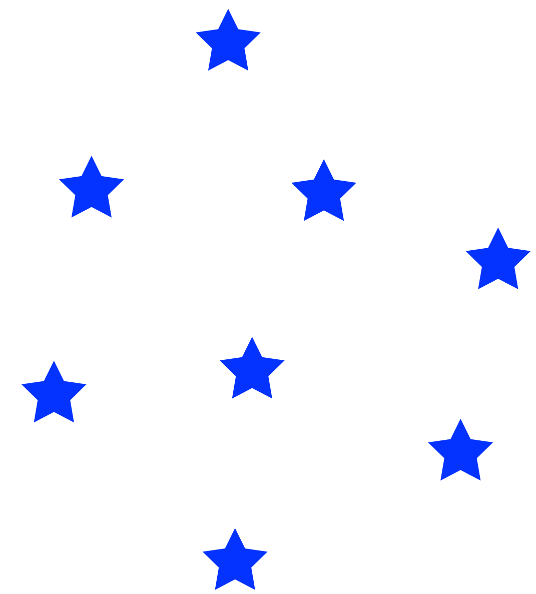


2: Stars form in the densest regions of GMC

Cartoon picture of star (cluster) formation

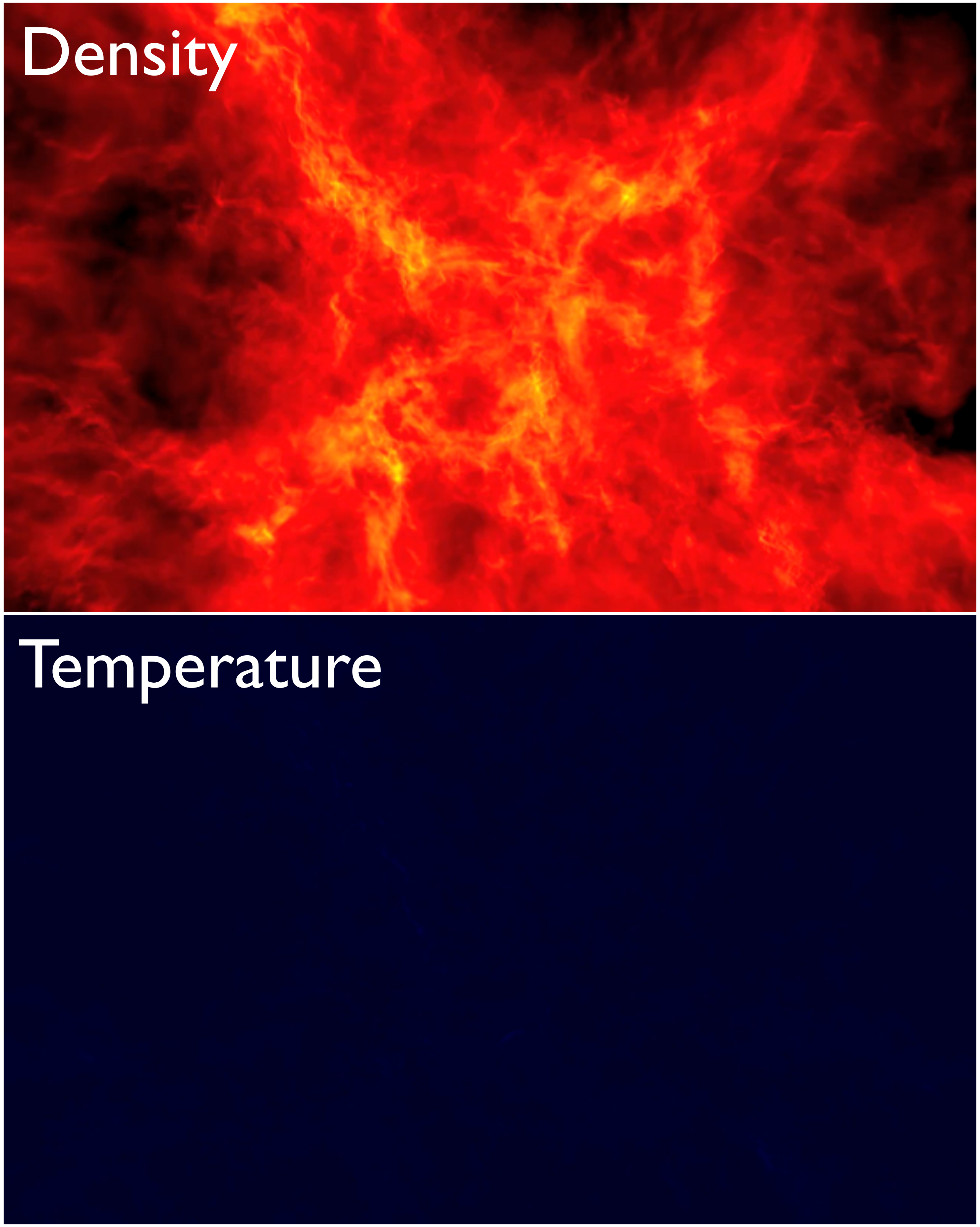


Feedback from newly-formed stars expels residual gas



After a few 10^6 years, a star cluster is born!

Hydrodynamic simulation of cluster formation

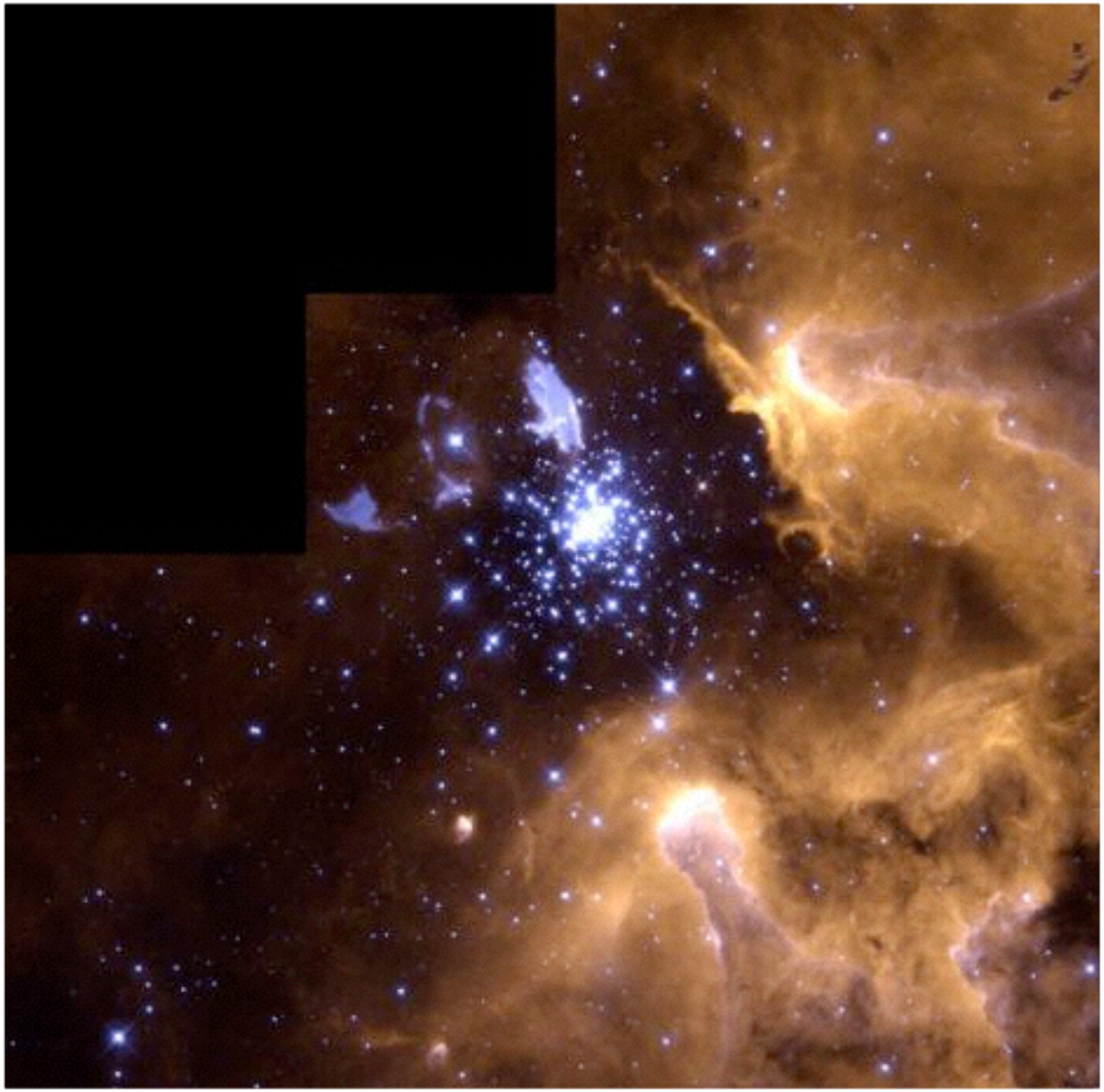


- 500 solar mass cloud (35×10^6 particles).
- T(simulation) = 285000 years.
- T(free-fall) = 190000 years.
- Radiative feedback included.

Note: this is a very small cluster!

Courtesy Matthew Bate, Exeter University

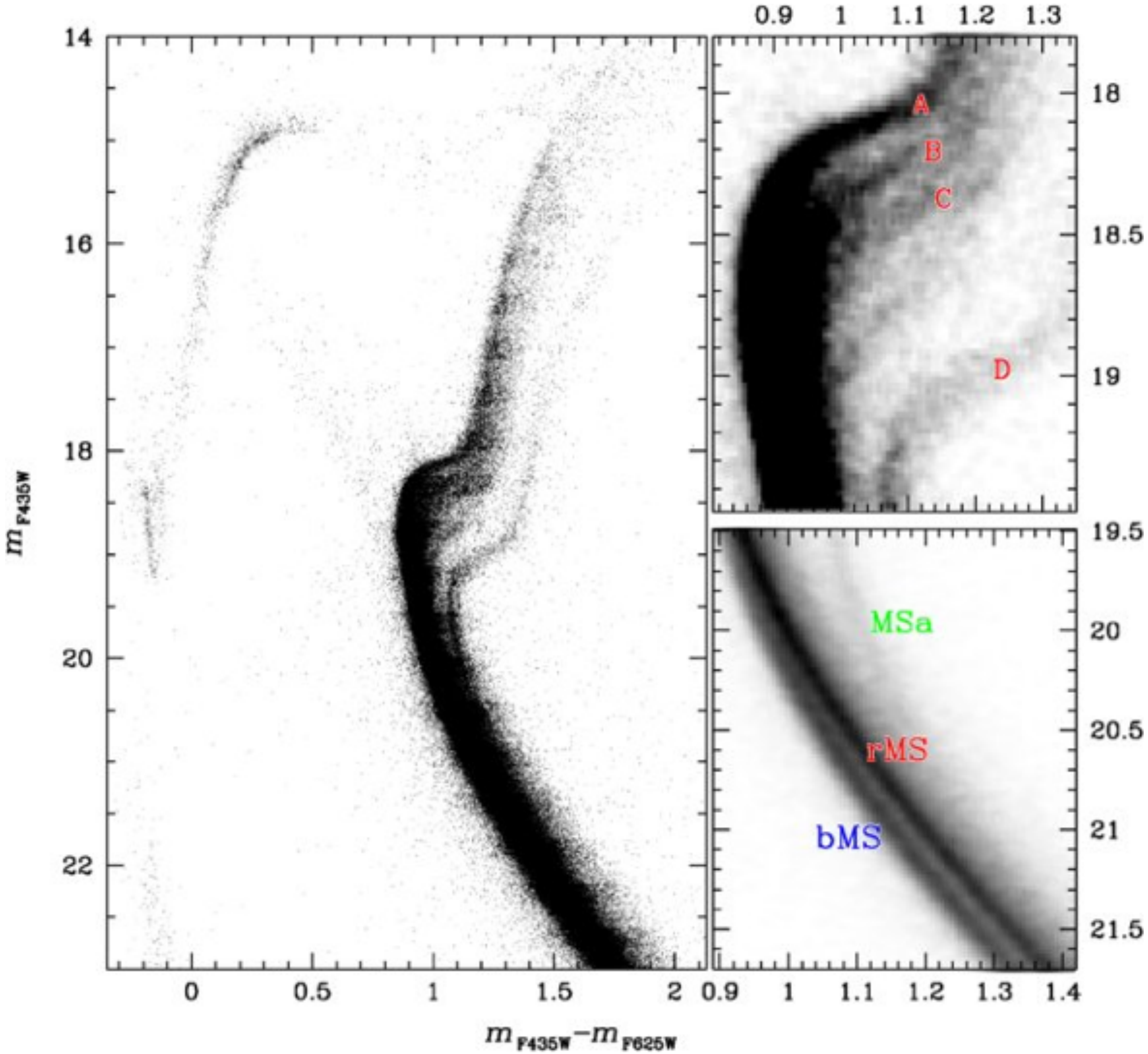
Young cluster in the Milky Way



Age ~ 2×10^6 years
Spread < 10^5 years

NGC 3603
(Kudryavtseva et al. 2012)

Globular Clusters are not that simple: Omega Cen

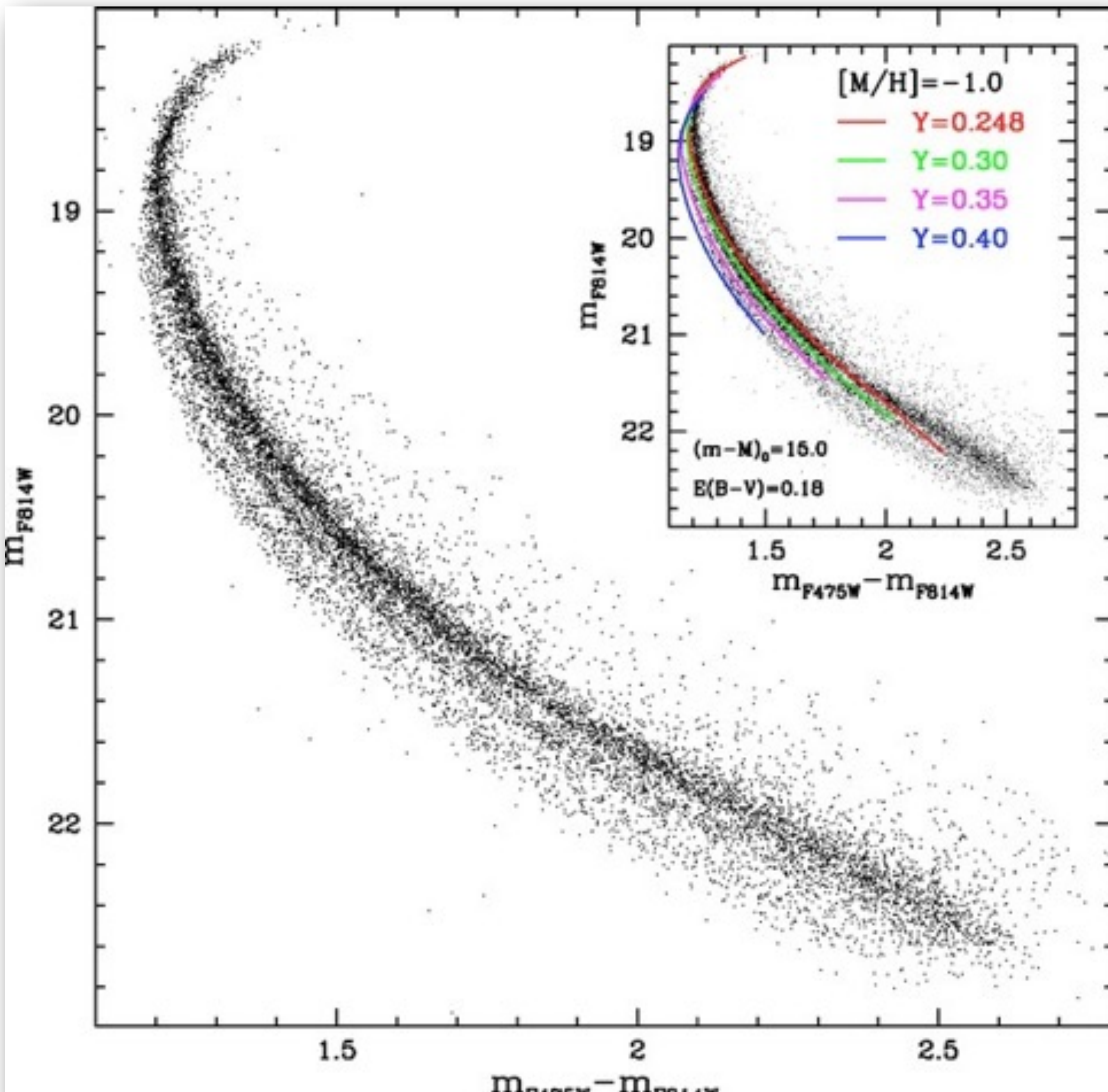


Complex colour-magnitude diagram.

Multiple episodes/mechanisms of star formation!

Bellini et al. (2011)

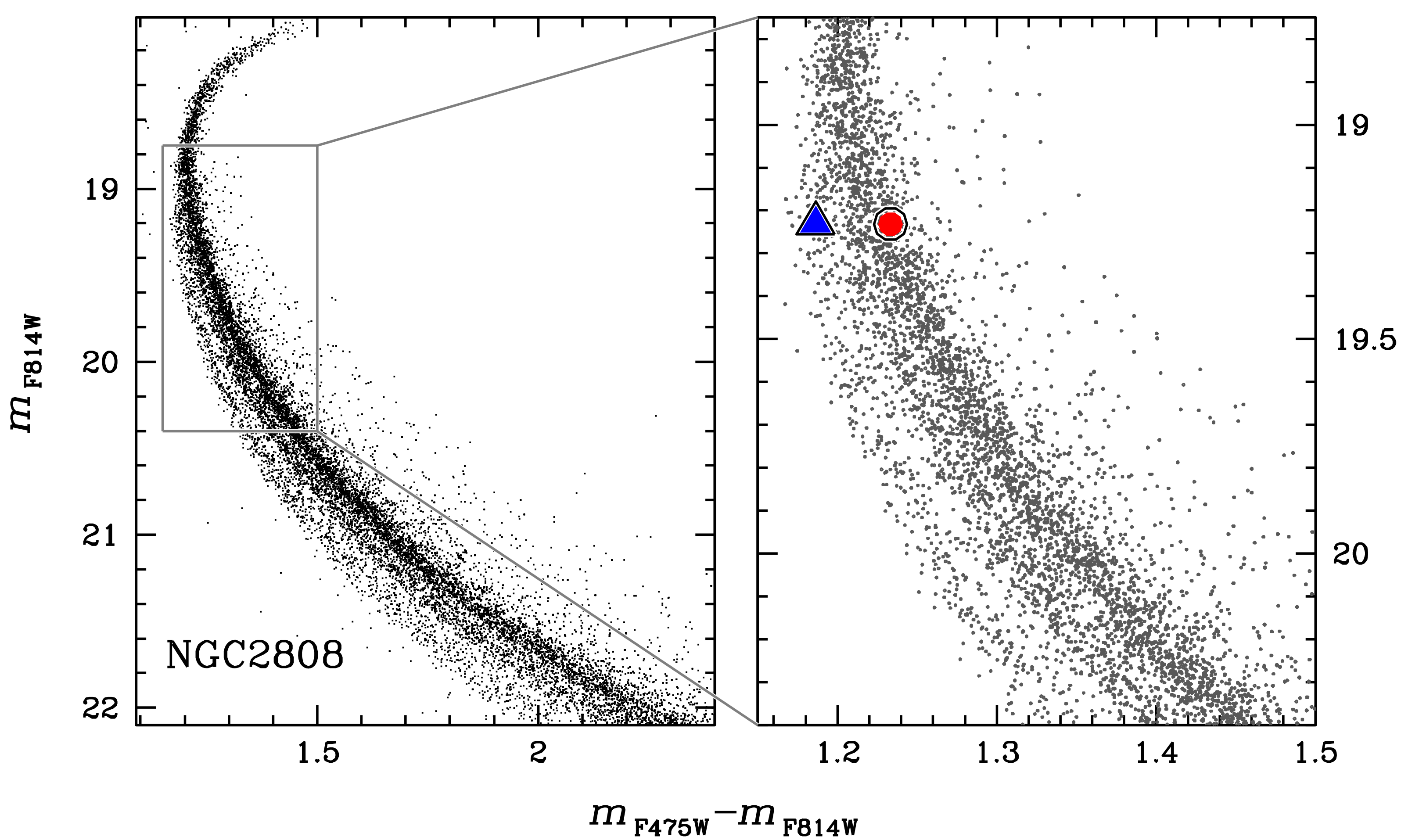
Three main sequences in NGC 2808



Piotto et al. (2007)

NGC 2808

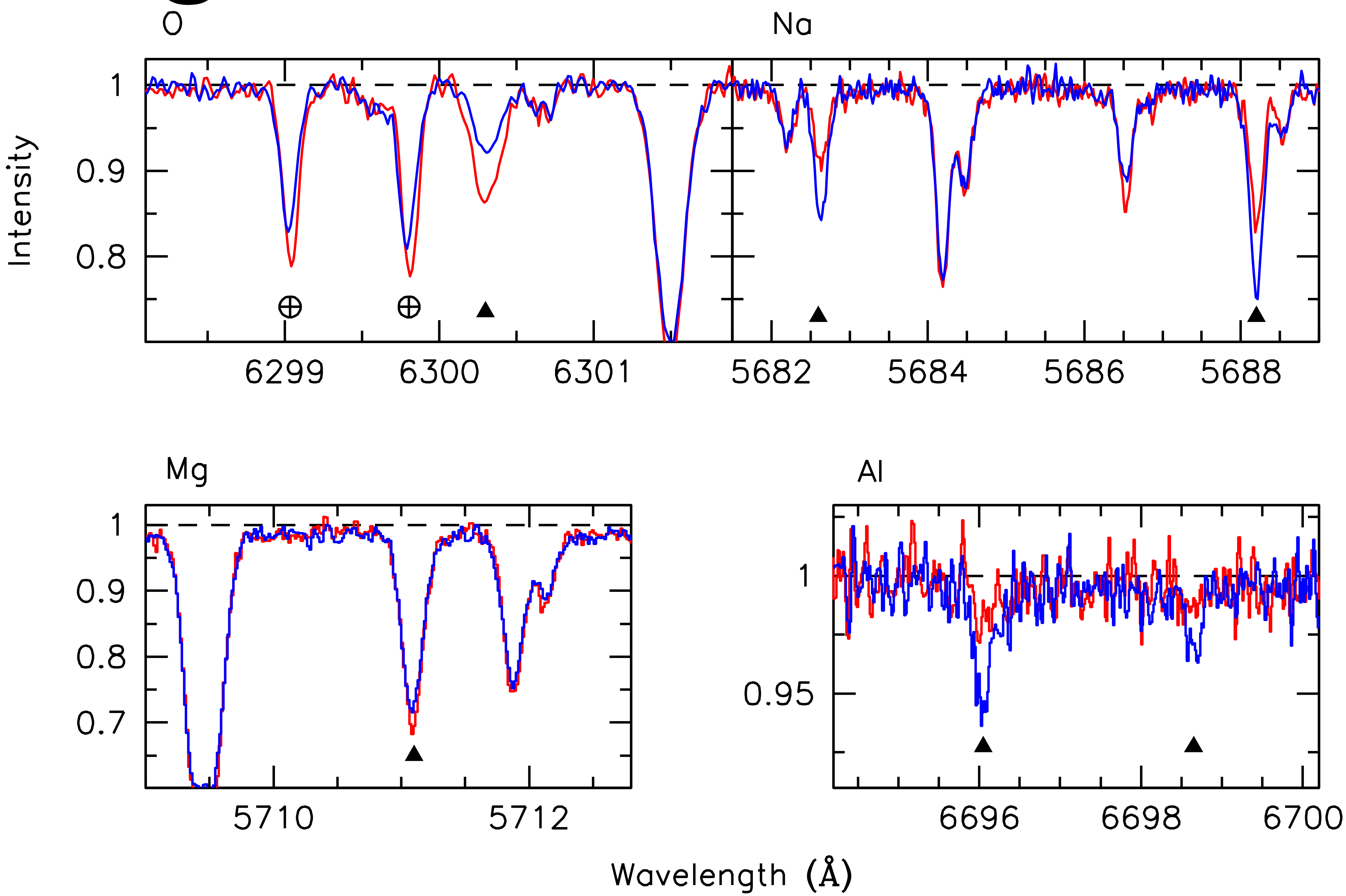
Globular clusters contain large numbers of stars (typically ≳50%) with anomalous chemical composition (not seen outside GCs).



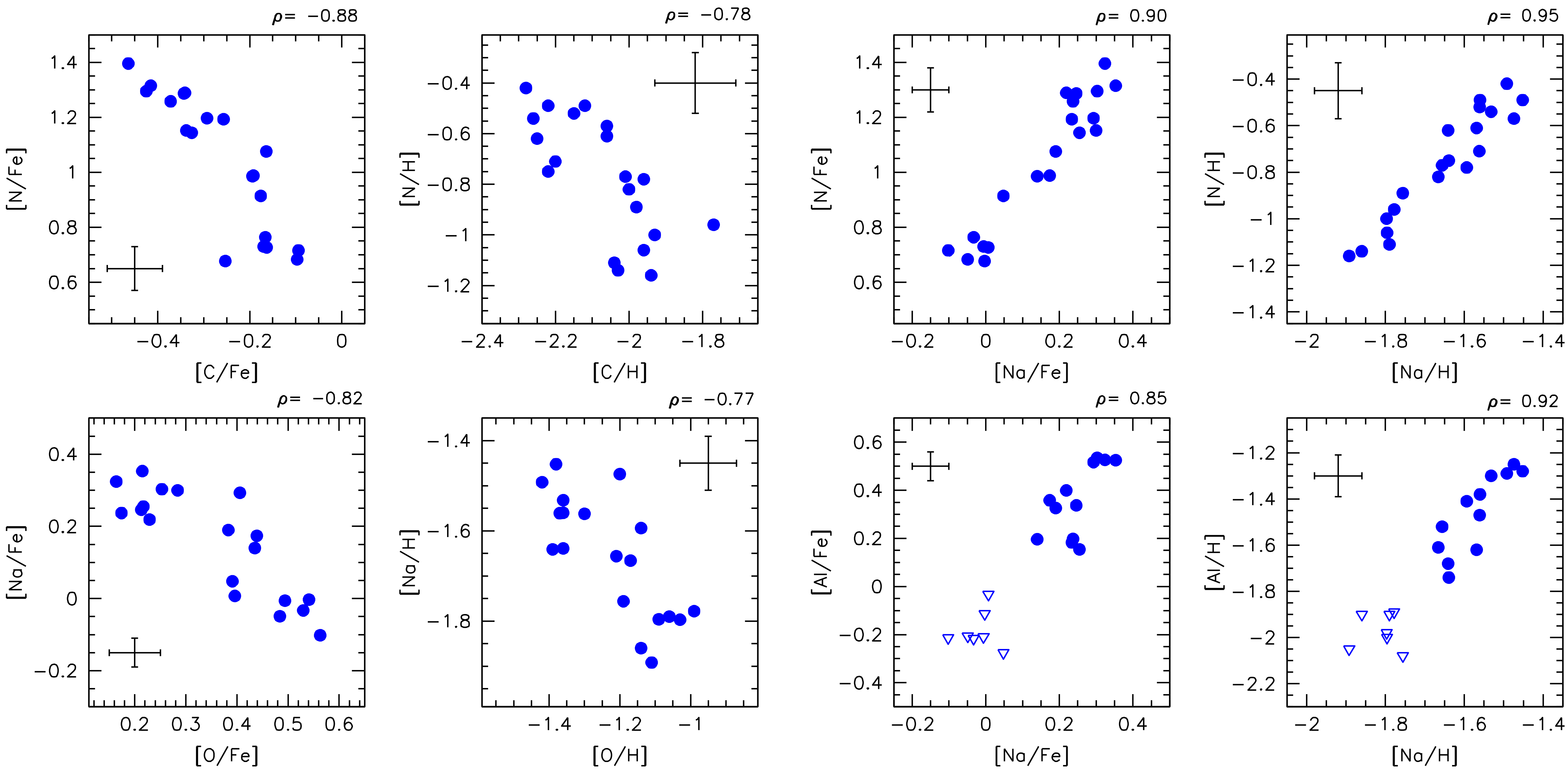
- Red MS: normal chemical composition.
- Blue MS: enhanced Al, Na, N, depleted C and Mg.
- Blue + Red: Same Fe, Ca abundance

(Bragaglia et al. 2010)

Light elements in GCs



NGC 6752: Lapenna et al. (2016)



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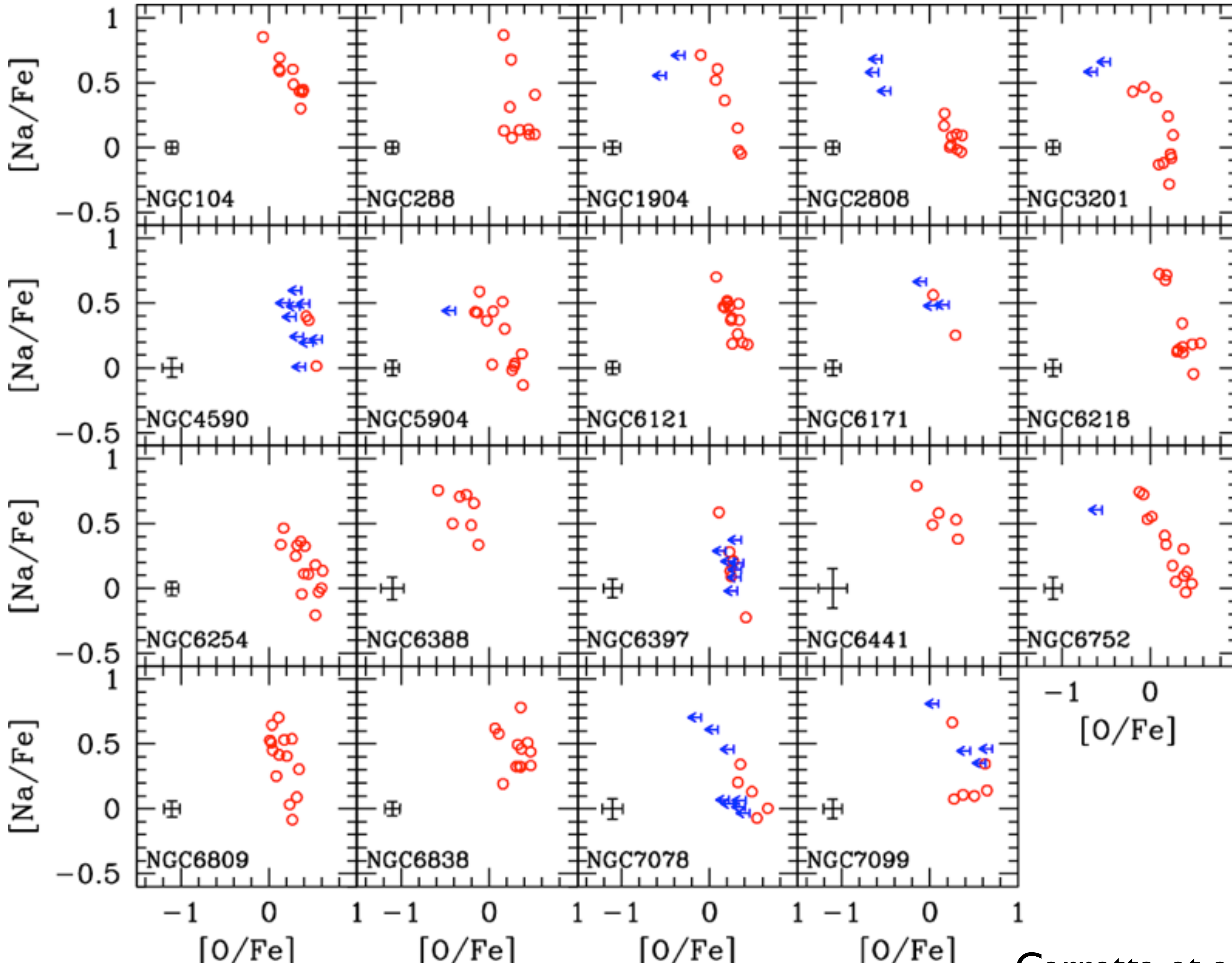
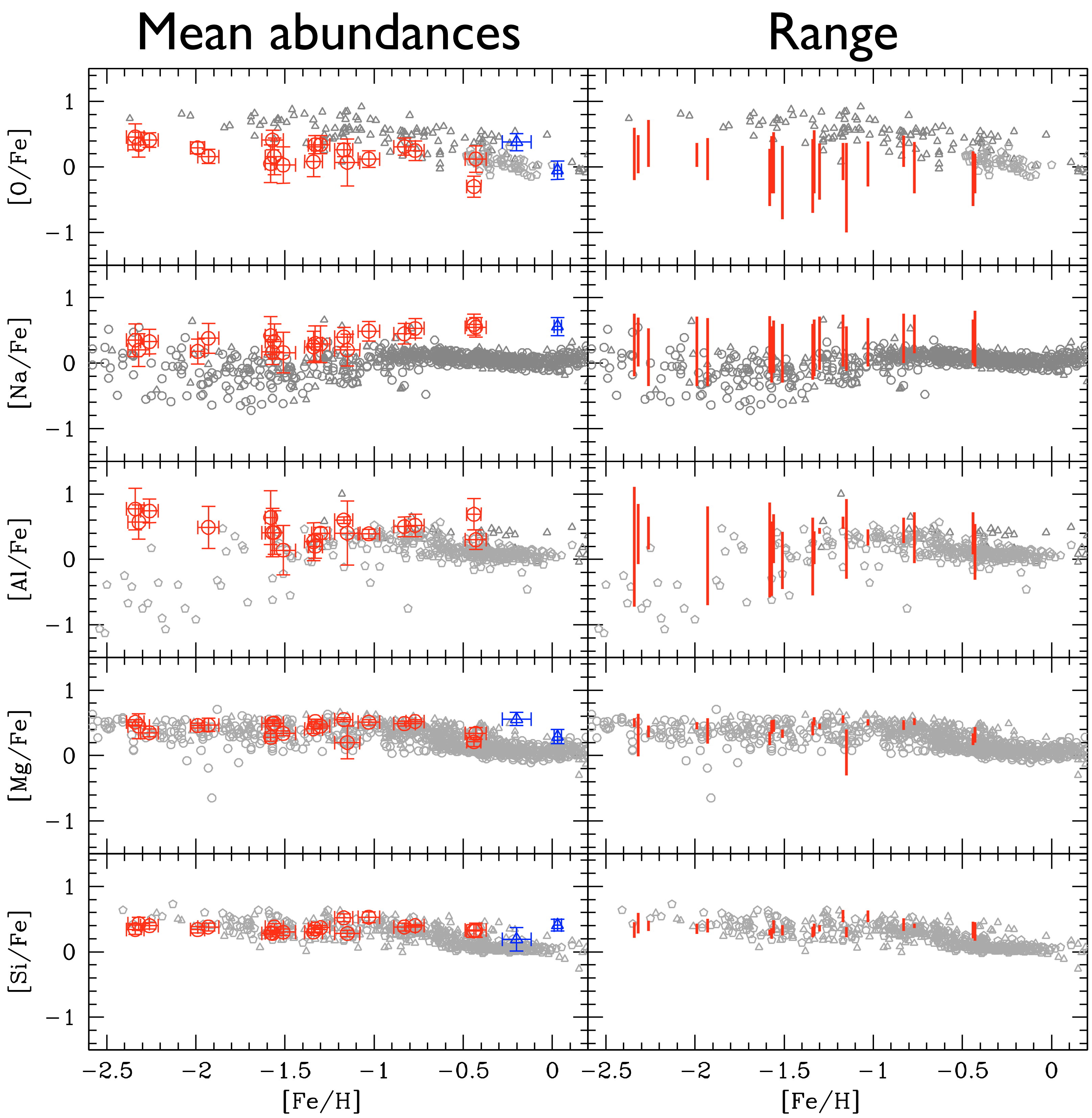


Carretta et al. 2009

Abundances in GCs and field

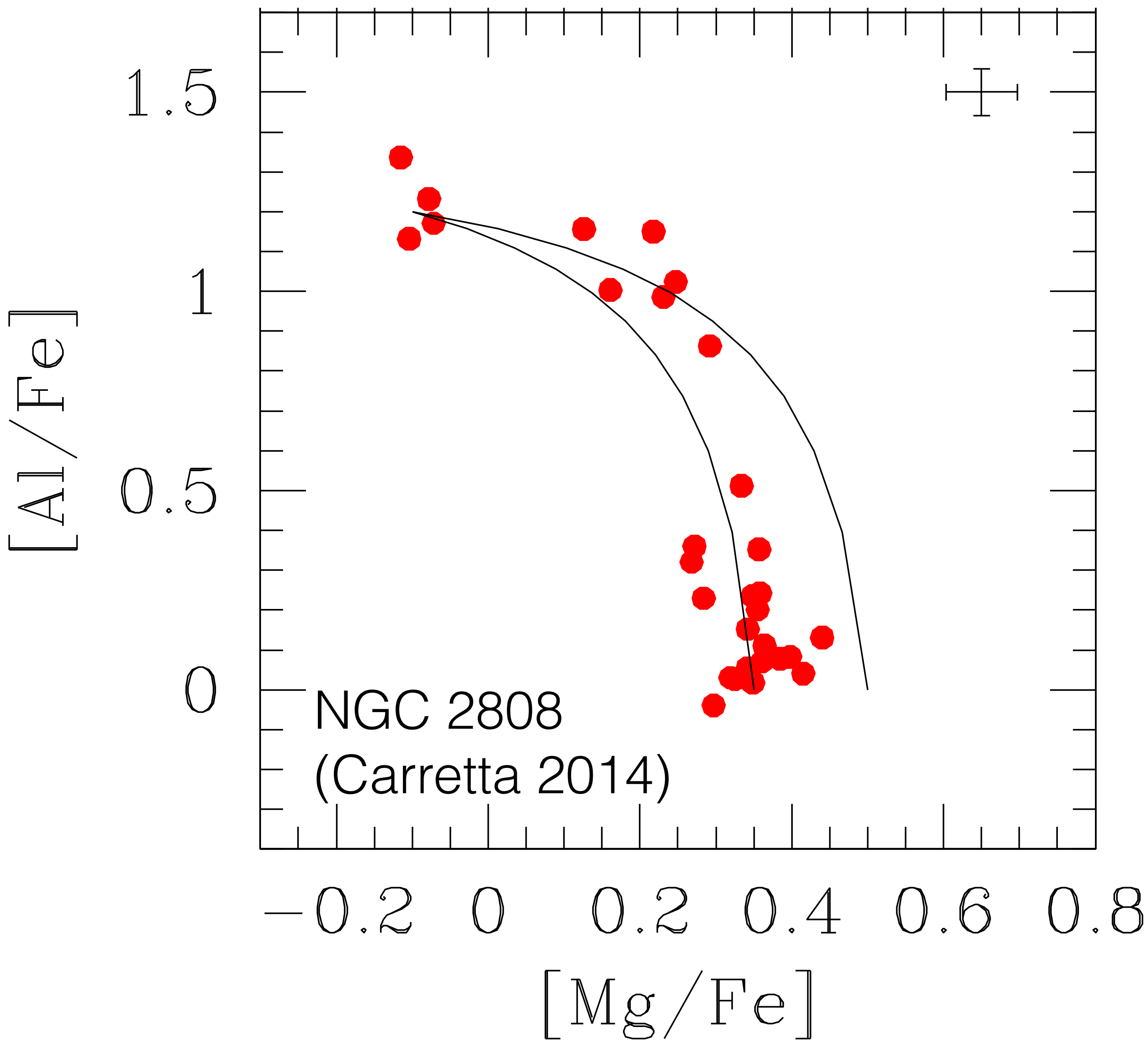


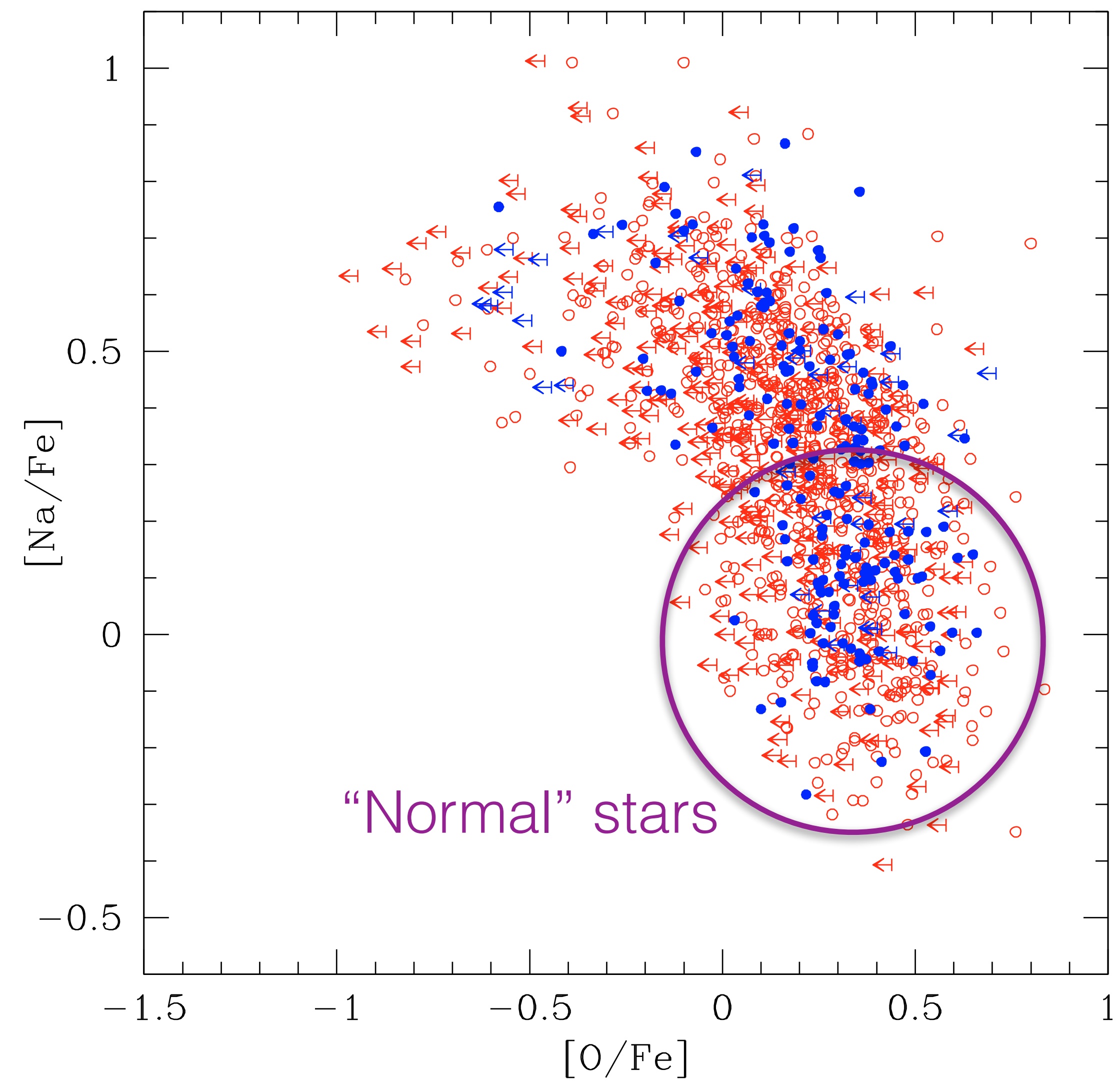
Grey: field stars
Red/blue: GC stars

~50% of GC stars show
enhanced Na, Al, Si
(He, N)
depleted O, Mg, (C)

Carretta et al. (2009)

Abundance anti-correlations in GCs





19 GCs (Carretta et al. 2009)

Origin of abundance anomalies in GCs

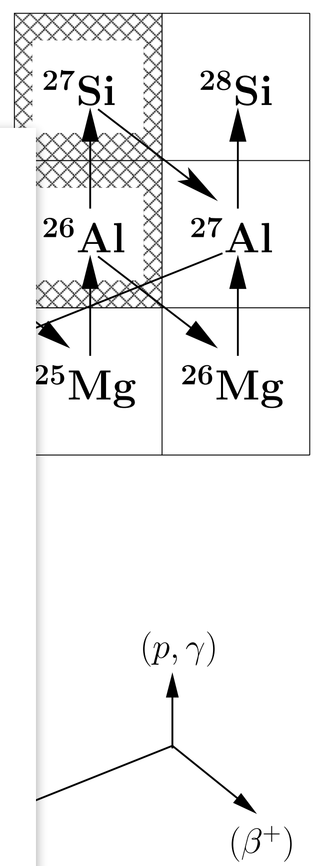
p-capture nucleosynthesis:

^{22}Ne(p,γ)^{23}Na
^{16}O(p,γ)^{17}F
^{25}Mg(p,γ)^{26}Al
^{26}Mg(p,γ)^{27}Al
etc..

Requires high temp., $T > 2\times10^{7}$ K

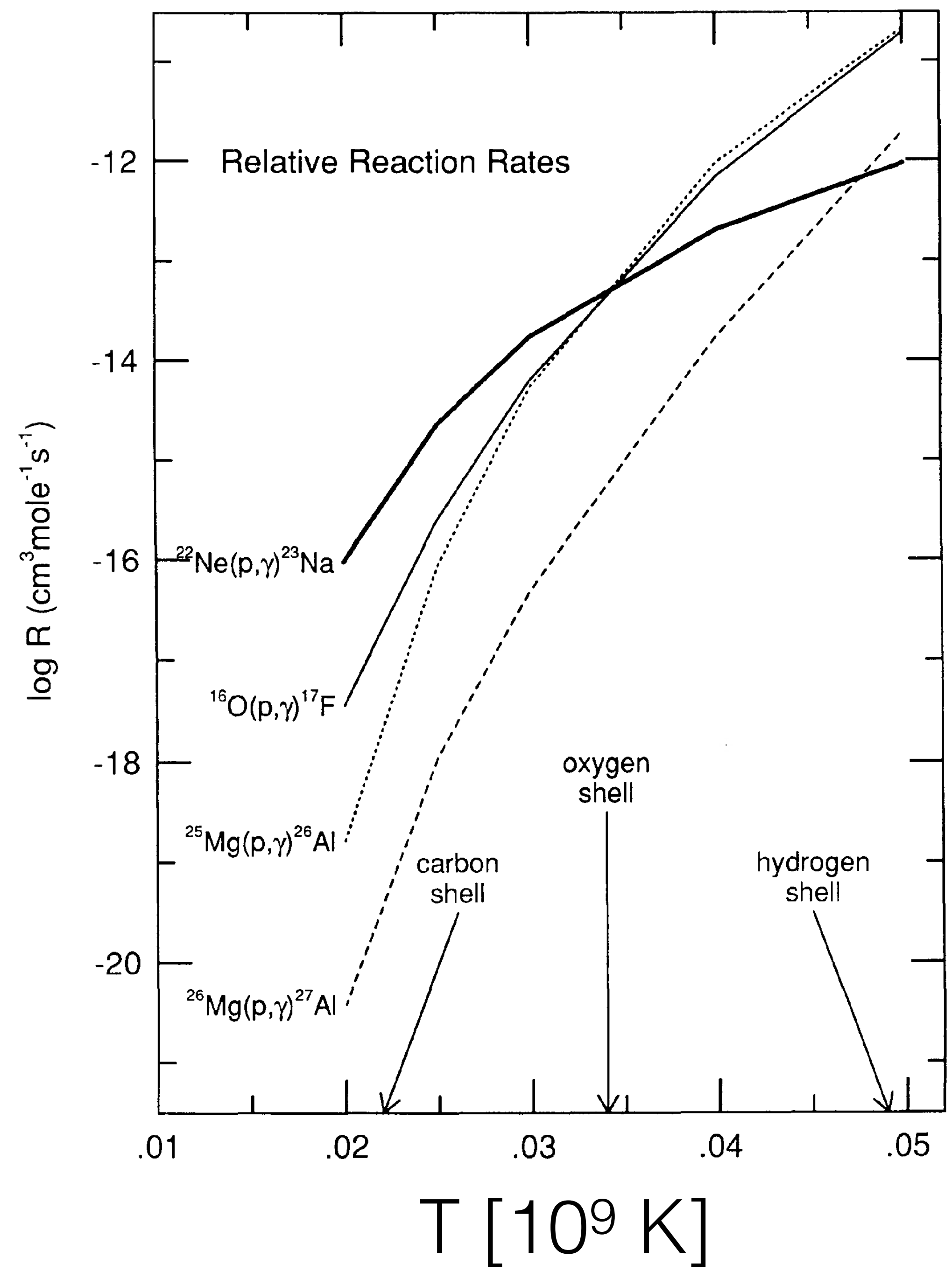
Not reached in low-mass main-sequence stars
(T~15 MK at centre of the Sun)

GC stars must have been polluted already at birth.

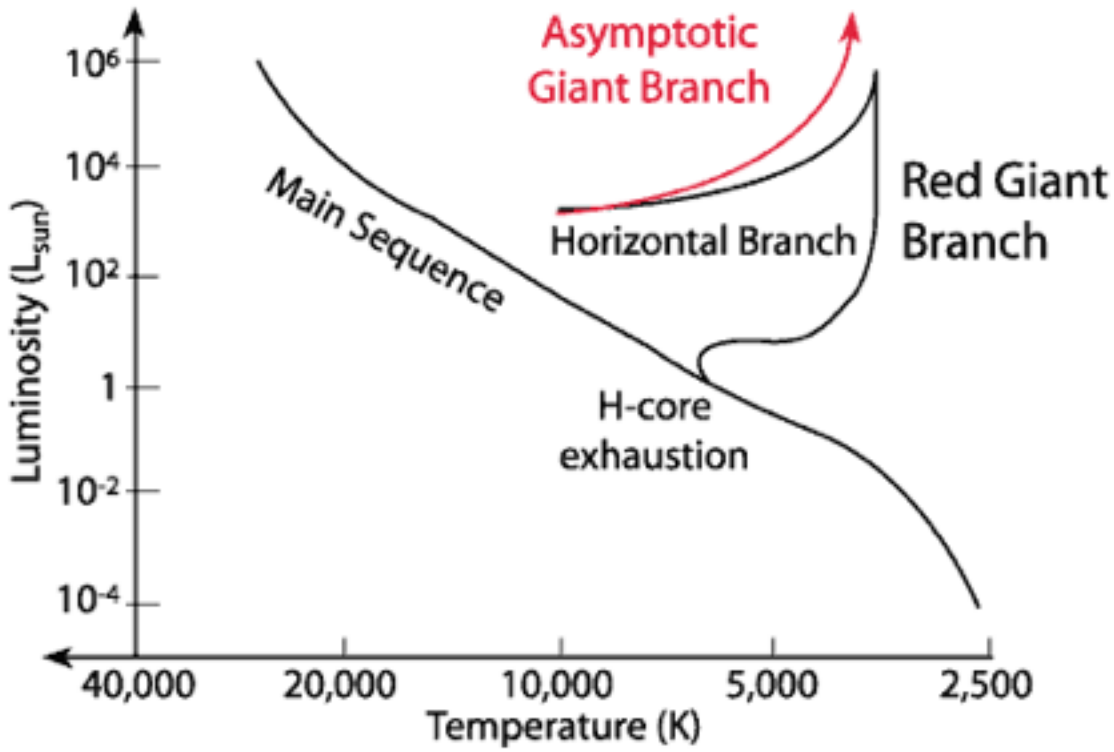


Decressin et al. 2007

Langer et al. 1993

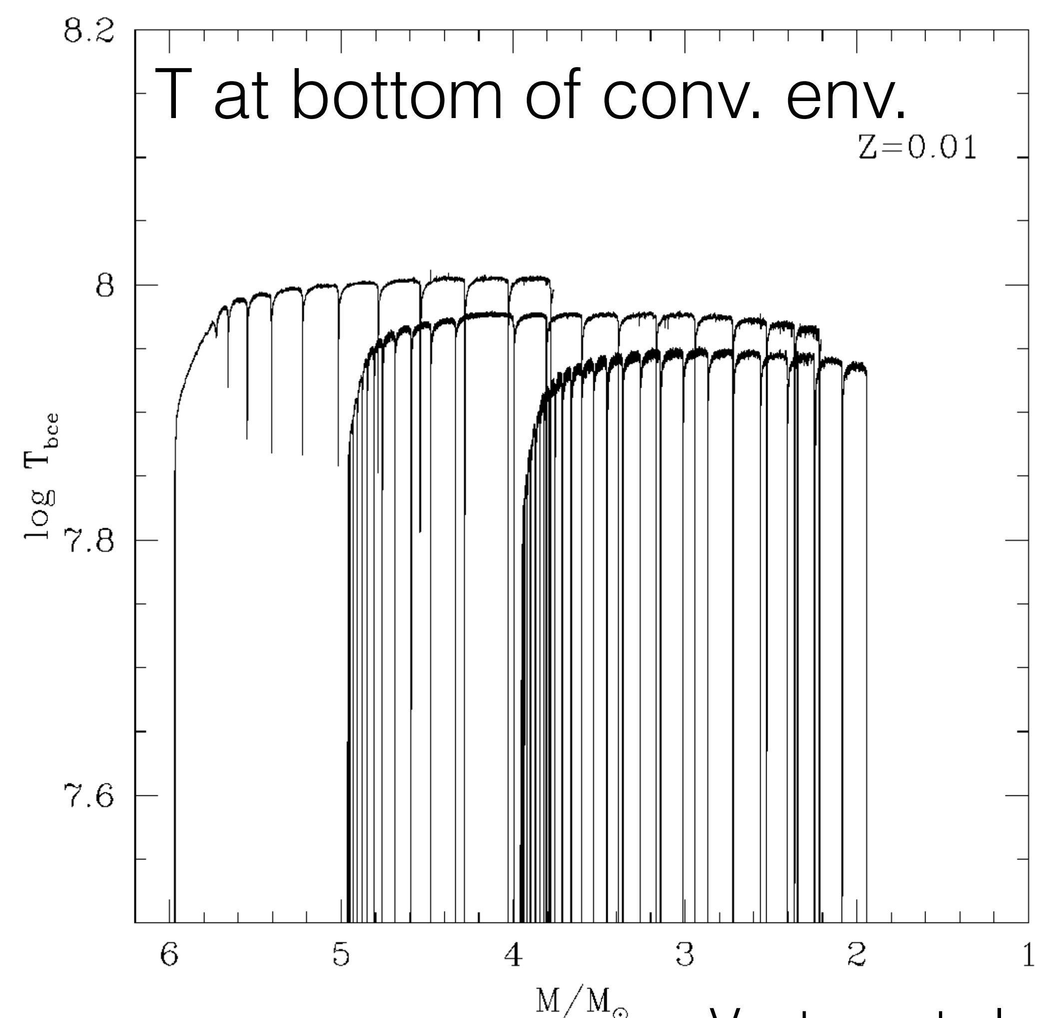


Possible polluters - I.



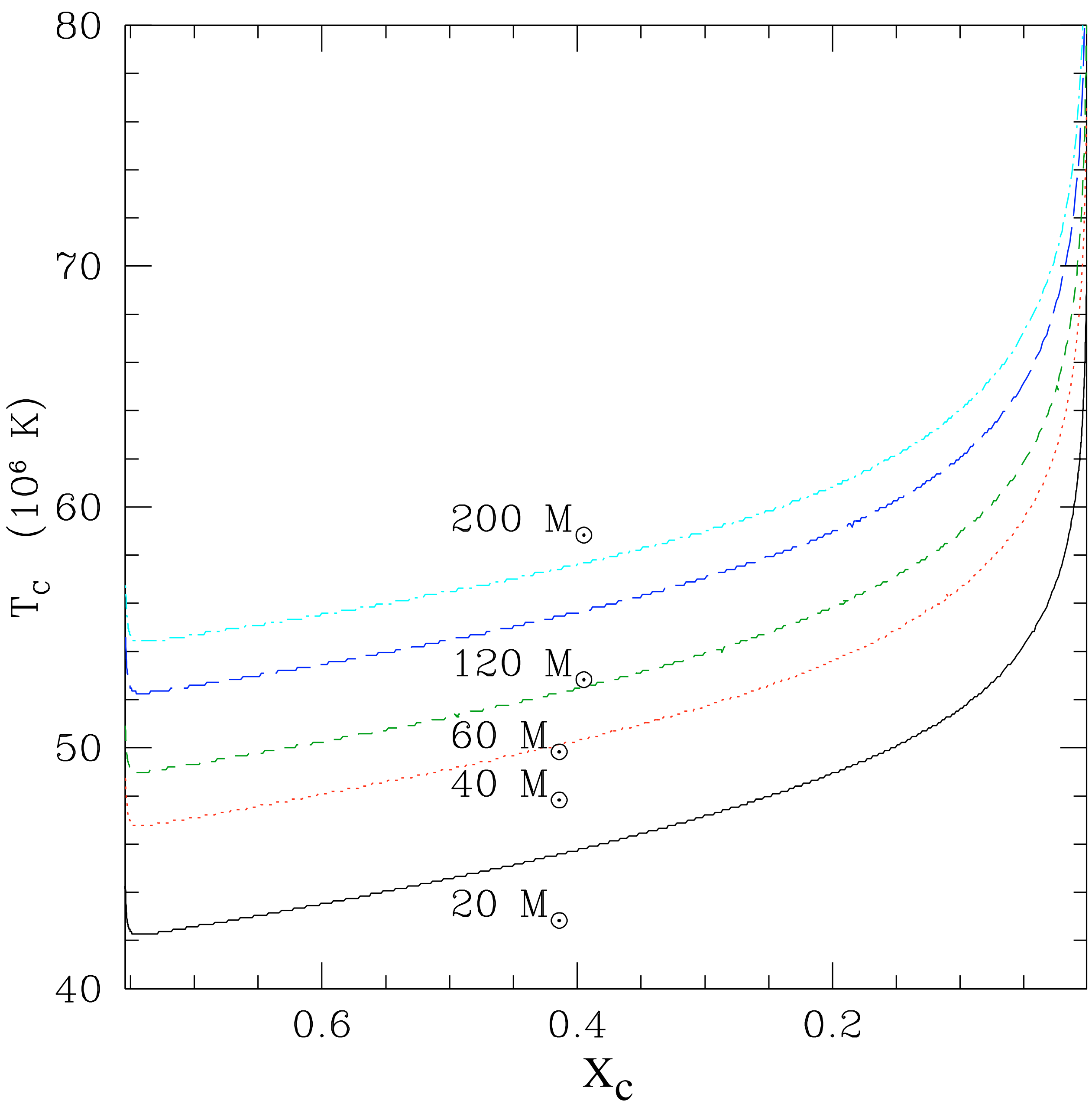
Massive *Asymptotic Giant Branch* (AGB) stars:

Can reach high T at bottom of convective envelopes. Mass lost in a slow *stellar wind*.



Ventura et al. (2001)

Possible polluters - II.



Decressin et al. (2007)

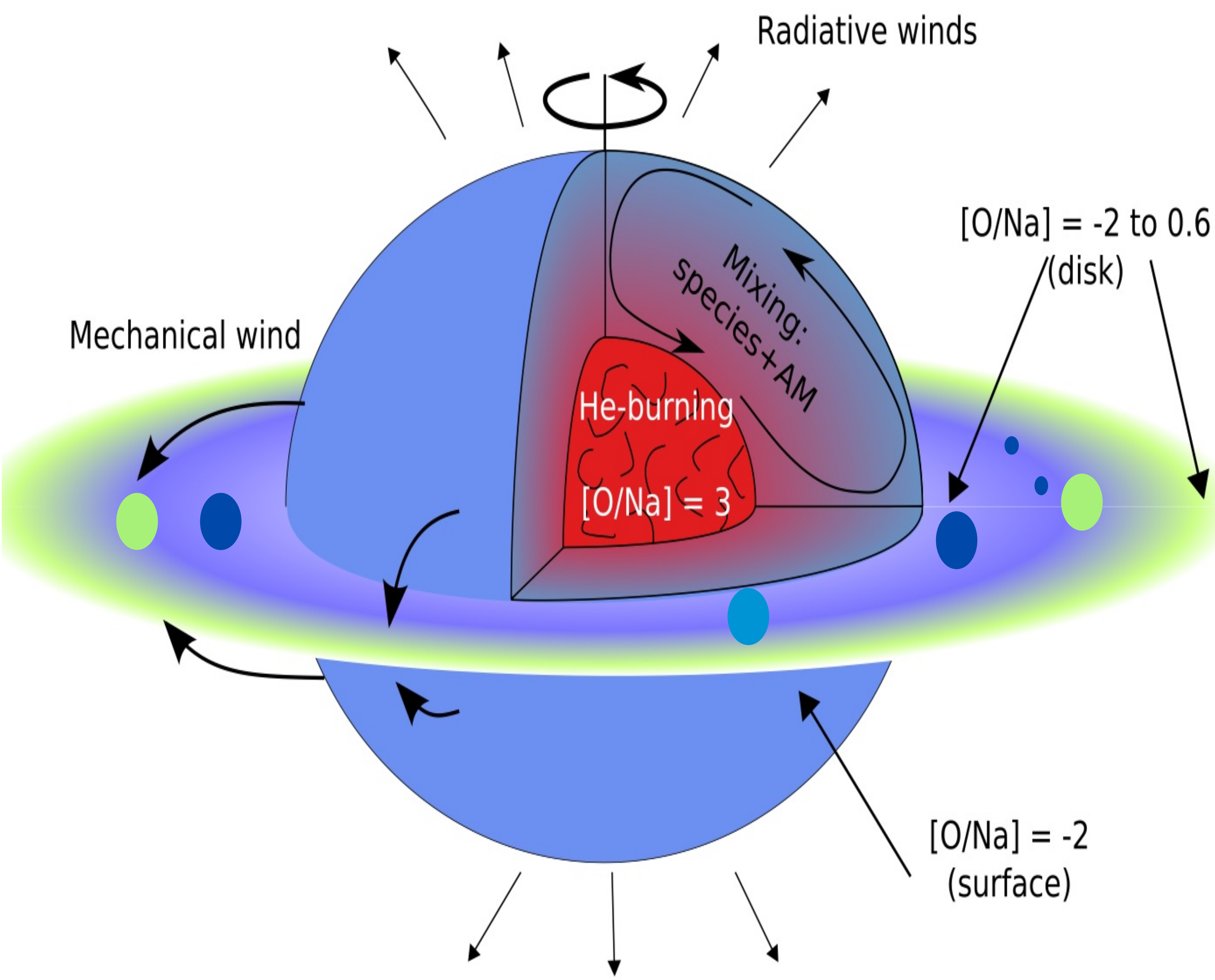
Massive main sequence stars.

Cores can reach required high T.

Processed material brought to the surface by **rotational mixing** and lost via "mechanical wind"
(Prantzos & Charbonnel 2006)
or
binary interactions
(de Mink et al. 2009)

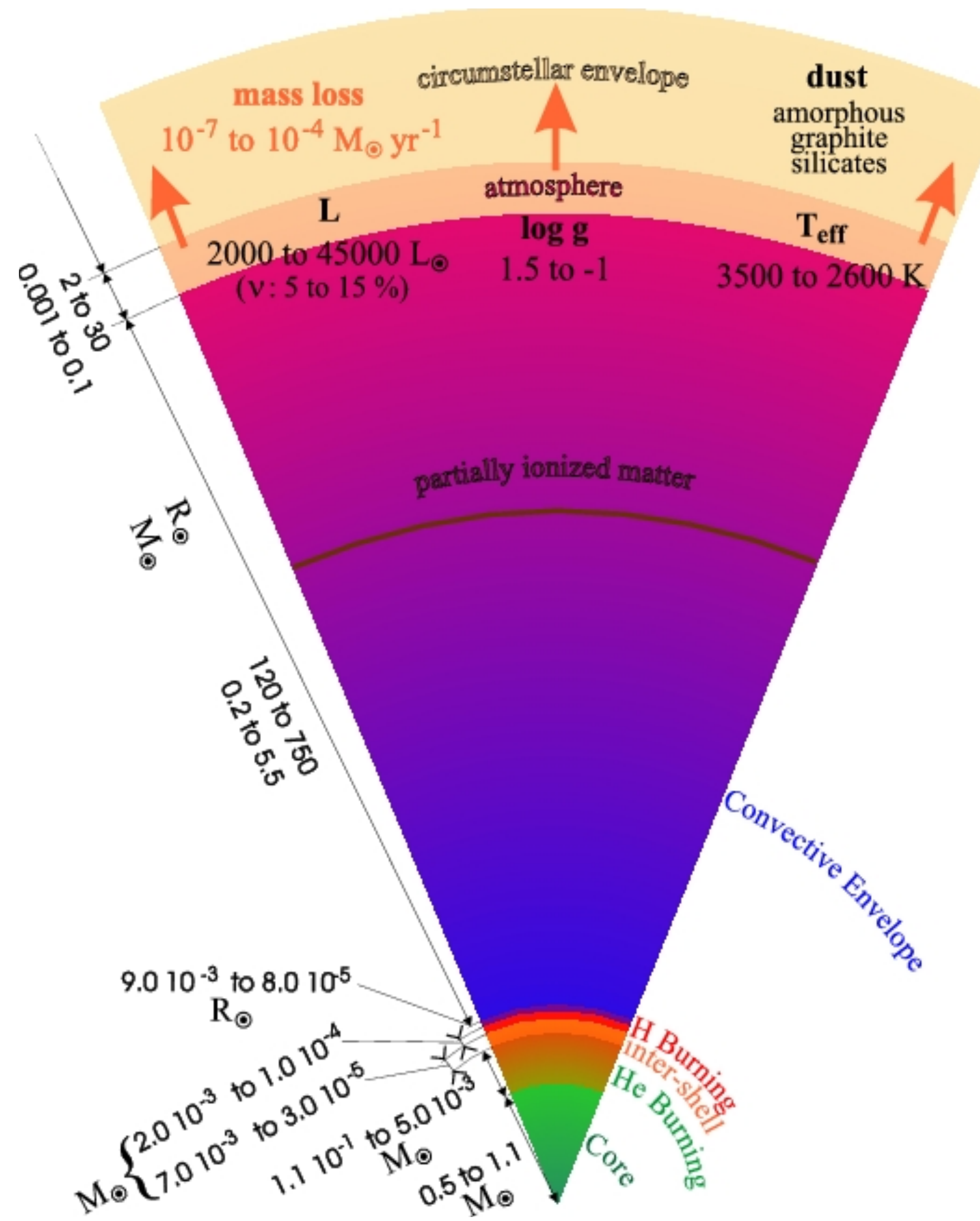
Possible polluters

Fast rotating massive (>25 M⊙) main sequence stars



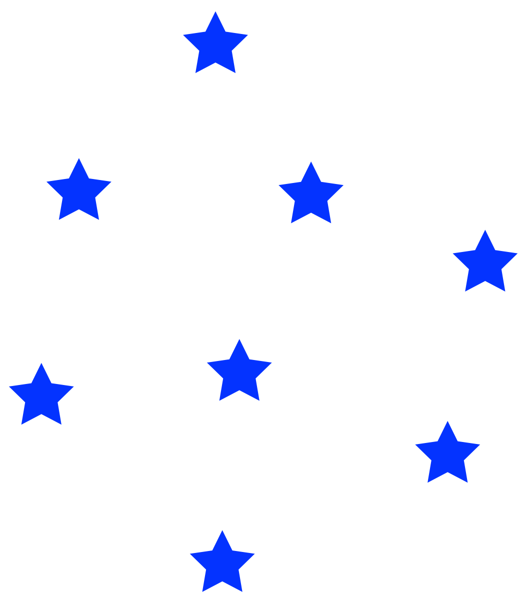
Prantzos & Charbonnel 2006; Decressin et al. 2007; Krause et al. 2012,2013

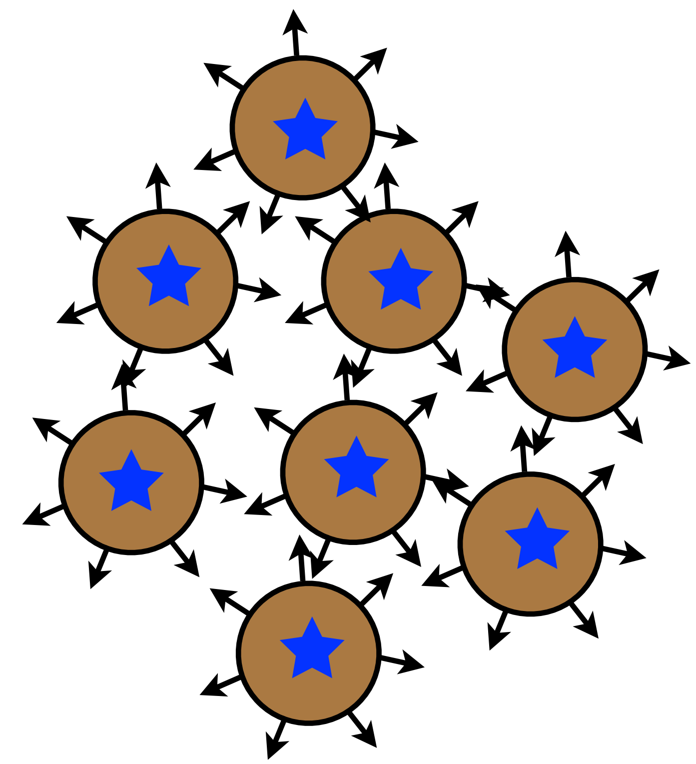
Asymptotic giant branch stars (M ~ 5-6 M⊙)



Ventura et al. 2001, 2011
D'Ercole et al. 2008

Revised cartoon picture of GC formation

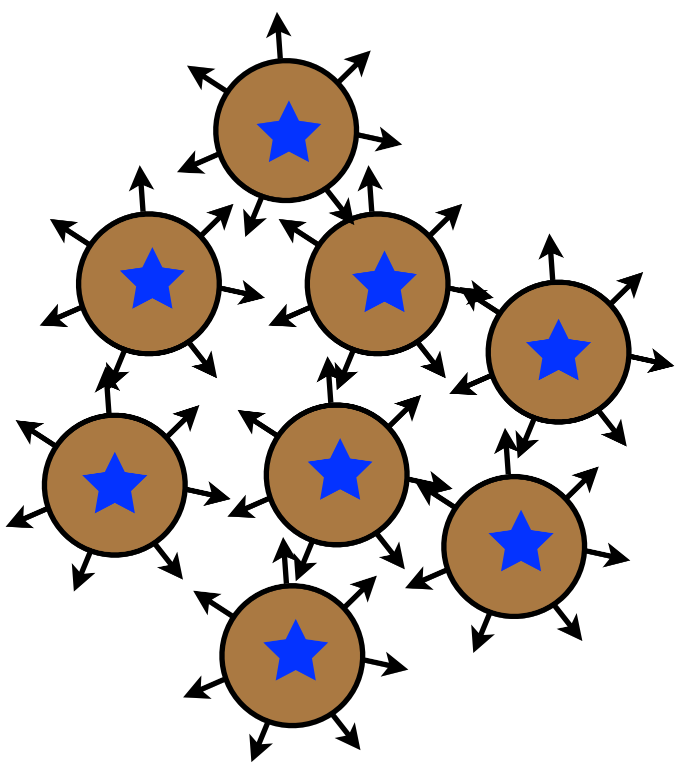




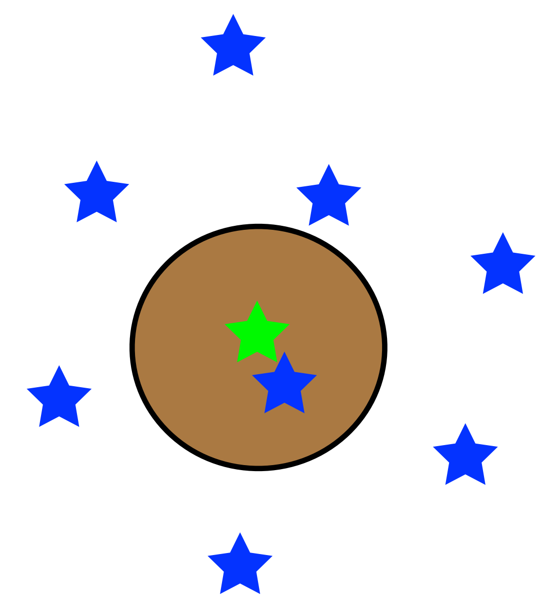
After a few 10^6 years, a star cluster is born!

1st generation stars lose "polluted" gas

Revised cartoon picture of GC formation



1st generation stars lose
“polluted” gas.



Polluted gas accumulates at
the centre of cluster.
2nd generation of stars form

Problem: the mass budget

Is it really possible to form the observed numbers of enriched stars out of ejecta from AGB (or massive) stars?

Total mass of a stellar population:

$$M = \eta \int_{m_{\rm min}}^{m_{\rm max}} m\phi(m)\,{\rm d}m$$

η is a normalisation constant

For a Salpeter IMF:

$$M = \eta \int_{m_{\rm min}}^{m_{\rm max}} m^{-1.35}\,{\rm d}m$$

$$= \frac{\eta}{0.35}\left(m_{\rm min}^{-0.35} - m_{\rm max}^{-0.35}\right)$$

Problem: the mass budget

AGB scenario: only stars with $4 < m/M_\odot < 8$ produce the "right" abundances (lower masses: 3rd dredge-up modifies CNO sum).

If *all* mass in such stars is used:

$$\frac{M(\mathrm{AGB})}{M(\mathrm{tot})} = \frac{(4M/M_\odot)^{-0.35} - (8M/M_\odot)^{-0.35}}{(0.15M/M_\odot)^{-0.35} - (100M/M_\odot)^{-0.35}} \approx 7\%$$

For massive stars:

$$\frac{(10M/M_\odot)^{-0.35} - (50M/M_\odot)^{-0.35}}{(0.15M/M_\odot)^{-0.35} - (100M/M_\odot)^{-0.35}} \approx 11\%$$

The mass budget - I

Formation of the polluted stars:

Initial mass = M_{ini}, *all "first generation"*

Polluted gas returned = $\beta\ M_{ini}$, $\beta \approx 0.05$ (AGB scenario)

If 2nd gen is formed with 100% efficiency: $M_{2G} = \beta\ M_{ini}$

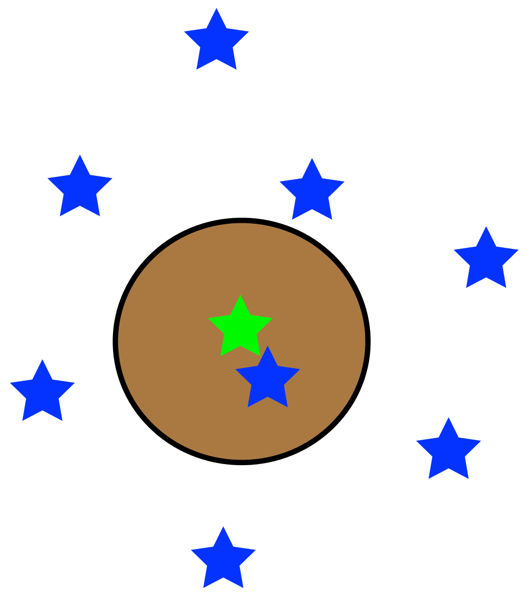
After ~12 Gyr:

If 2nd gen consists only of stars with $M < 0.8\ M_\odot$: $M_{2G} \sim 0.05\ M_{ini}$.

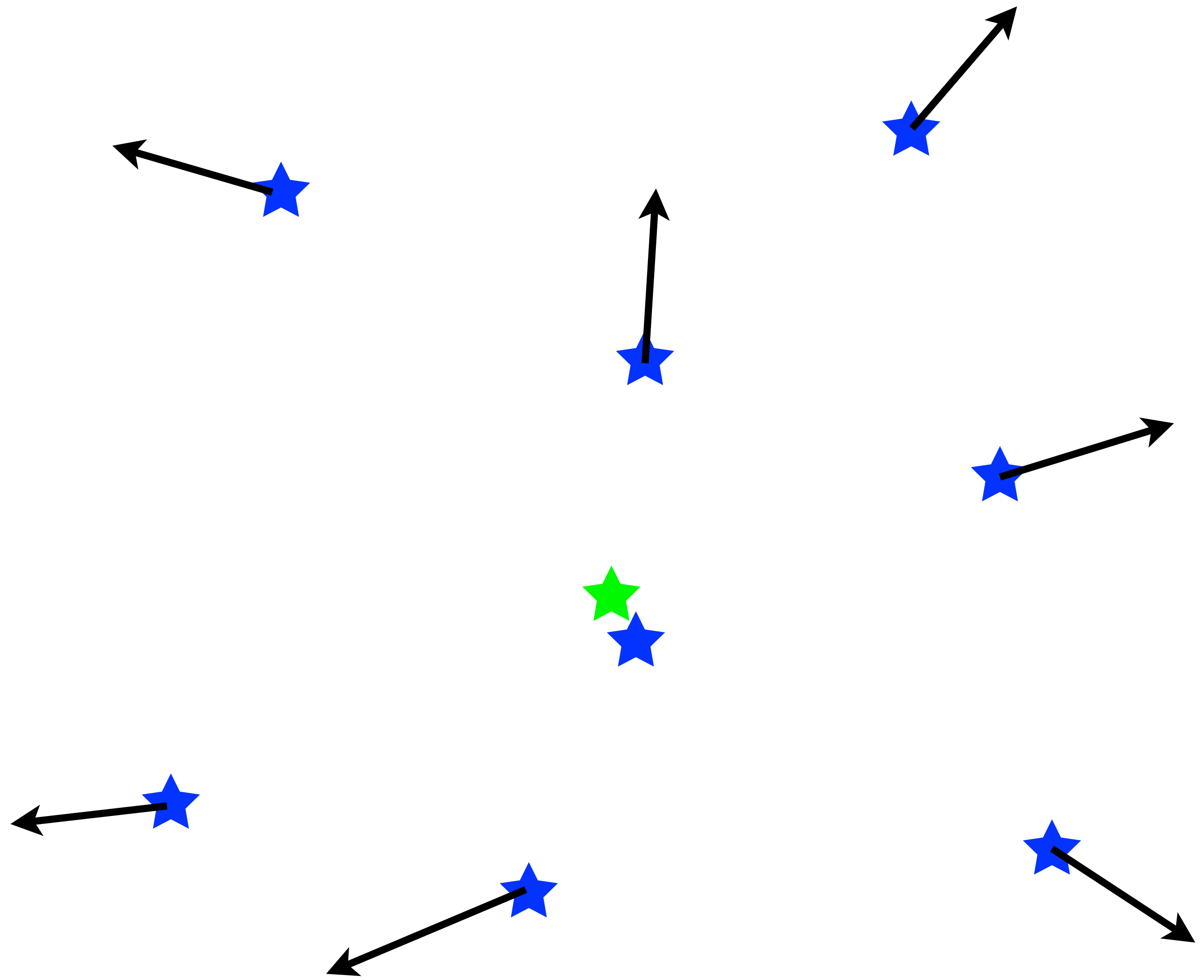
Mass of first gen: $M_{1G} \sim \dfrac{\int_{0.1M_\odot}^{0.8M_\odot} \Phi(m)\, m\, \mathrm{d}m}{\int_{0.1M_\odot}^{100M_\odot} \Phi(m)\, m\, \mathrm{d}m} M_{\rm ini}$ $\sim 0.5\ M_{ini}$

Result: $M_{1G} / M_{2G} \sim 10:1$, not ~1:1 as observed

Revised cartoon picture of GC formation



Material accumulates in centre of cluster.
2nd generation of stars form



Most (90% or more) of the 1st gen stars become unbound.
End result is ~50% 1st gen and ~50% 2nd gen stars

Mass budget: MW halo

- Present-day mass of GCs ~ 2.8×10^7 $M_\odot$
  (e.g. Kruijssen & Portegies Zwart 2009).
  If 1/2 GC stars are 2nd gen → ~1.3×10^8 $M_\odot$ "lost" 1st gen. stars

- Present-day mass of halo field stars ~ 10^9 $M_\odot$
  (e.g. Suntzeff et al. 1991)

- ~2-3% halo stars with anomalous abundances, possibly from disrupted GCs (Carretta et al. 2010; Martell & Grebel 2010)

- 20%-50% of the halo may consist of dissolved GCs
  (Martell et al. 2011; Gratton et al. 2012) - *based on chemistry alone*

Modelling the integrated light of star clusters

Adding EWs

How do we calculate the strength (EW) of lines in composite spectra (i.e. the sum of spectra of individual stars)?

Recall def. of EW:

$$W = \int \left(1 - \frac{F_\lambda}{F_C}\right) \mathrm{d}\lambda$$

Sum of two spectra:

$$W = \int \left(1 - \frac{F_{\lambda,1} + F_{\lambda,2}}{F_{C,1} + F_{C,2}}\right) \mathrm{d}\lambda$$

Over a small range in wavelength, $F_{C,2} \approx k F_{C,1}$ where *k* is a constant.

A bit of algebra then leads to

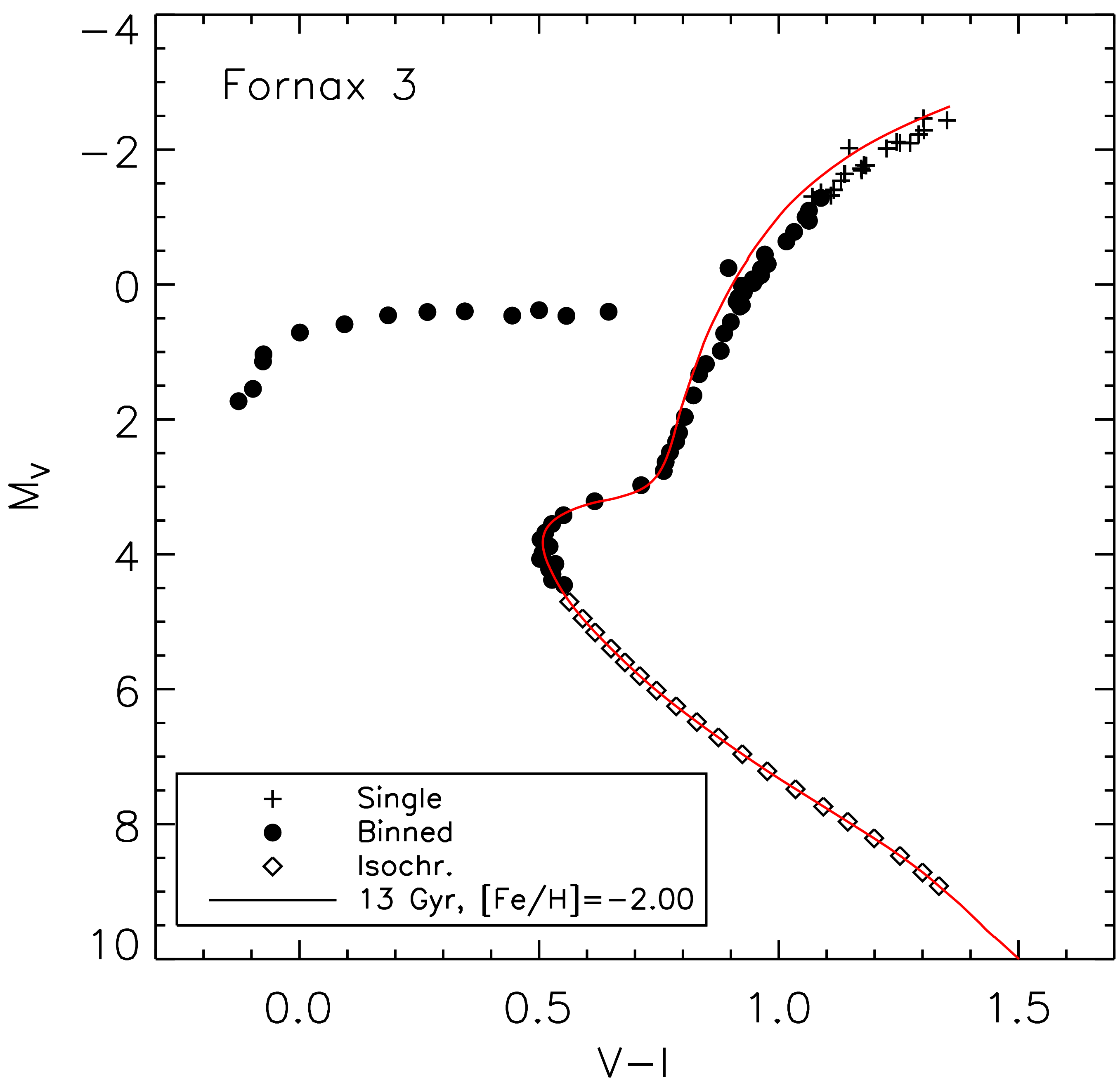
$$\begin{aligned} W &= \frac{1}{1+k} \left[\int \left(1 - \frac{F_{\lambda,1}}{F_{C,1}}\right) \mathrm{d}\lambda + k \int \left(1 - \frac{F_{\lambda,2}}{F_{C,2}}\right) \mathrm{d}\lambda \right] \\ &= \frac{1}{1+k} \left(W_1 + k W_2\right) \end{aligned}$$

Adding EWs

$$W = \frac{1}{1+k}\left(W_1 + kW_2\right)$$

The EW of a line in a composite spectrum is the continuum-flux weighted average of the EWs of the line in the individual spectra.

Stellar parameters

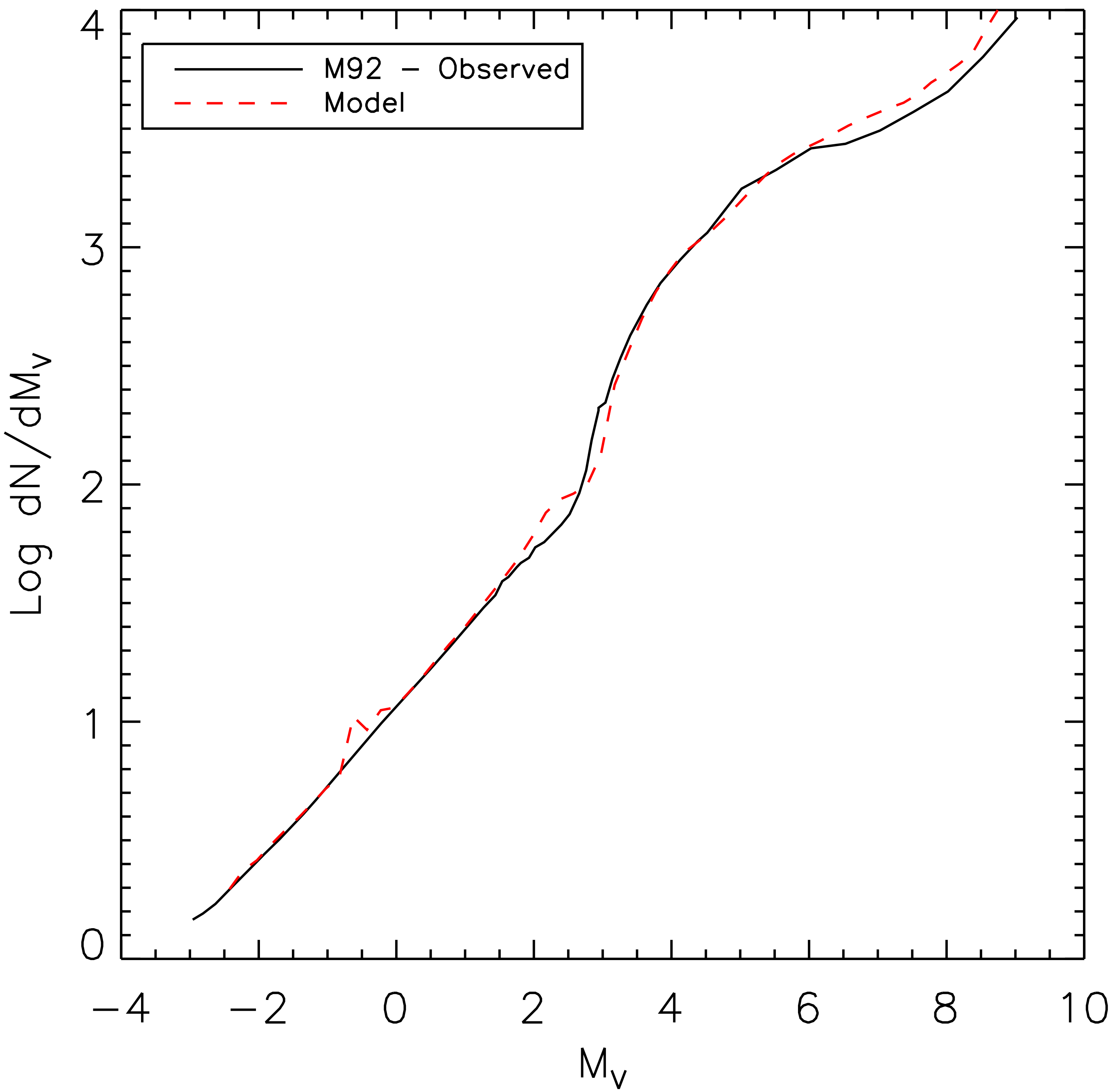


Properties of stars may be determined in different ways:

1) *Empirically* (e.g. from the colour-magnitude diagram of a cluster)
2) *Theoretically* (e.g. from model isochrones)

Sometimes, a mix of the two approaches is used.

Luminosity functions



Number of stars per luminosity bin.

Again, can be determined *empirically* (just "counting the stars") or *theoretically* (from the IMF)

Physical parameters of stars - I

From theory:

A model spectrum will give us *F*. Then, if *R* is known we can get *L*:

$$L_\lambda = 4\pi R^2 F_\lambda$$

Stellar models usually tabulate the surface gravity as a function of *M*; then we can find *R*:

$$mg = G\frac{Mm}{R^2}$$

$$g = \frac{GM}{R^2}$$

Physical parameters of stars - II

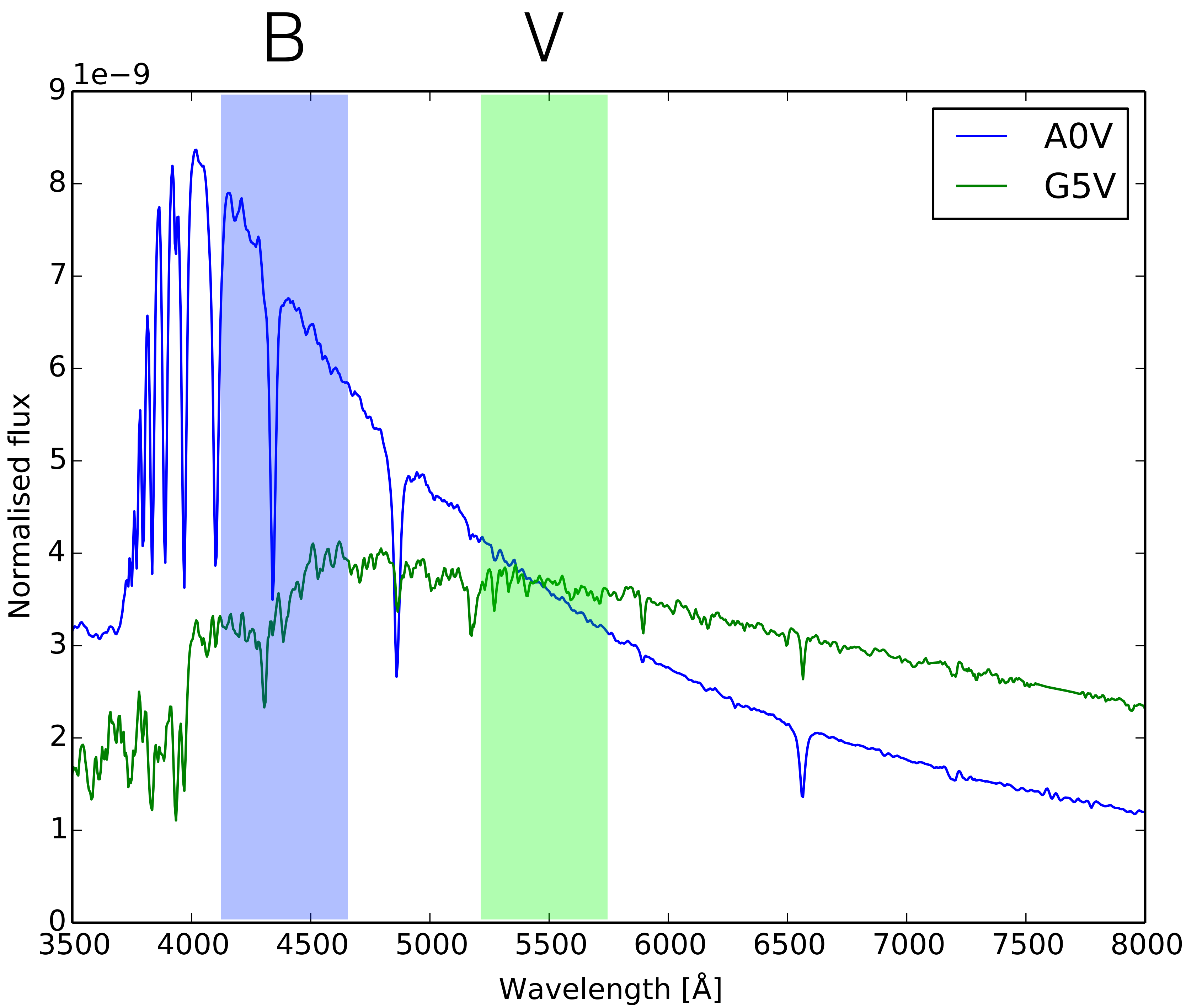
From observations:

Observables:

- Flux integrated over some wavelength range, $\int_{\lambda_1}^{\lambda_2} F_\lambda \mathrm{d}\lambda$

- Ratio of fluxes at different wavelengths: $F_{\lambda 1}/F_{\lambda 2}$

Desired: R, $T_{\rm eff}$, log g.



Temperature:

Increasing F_B/F_V → increasing $T_{\rm eff}$.

Luminosity:

Bolometric correction:

$$\frac{\int_{\mathrm{all}\lambda} F_\lambda \mathrm{d}\lambda}{\int_V F_\lambda \mathrm{d}\lambda}$$

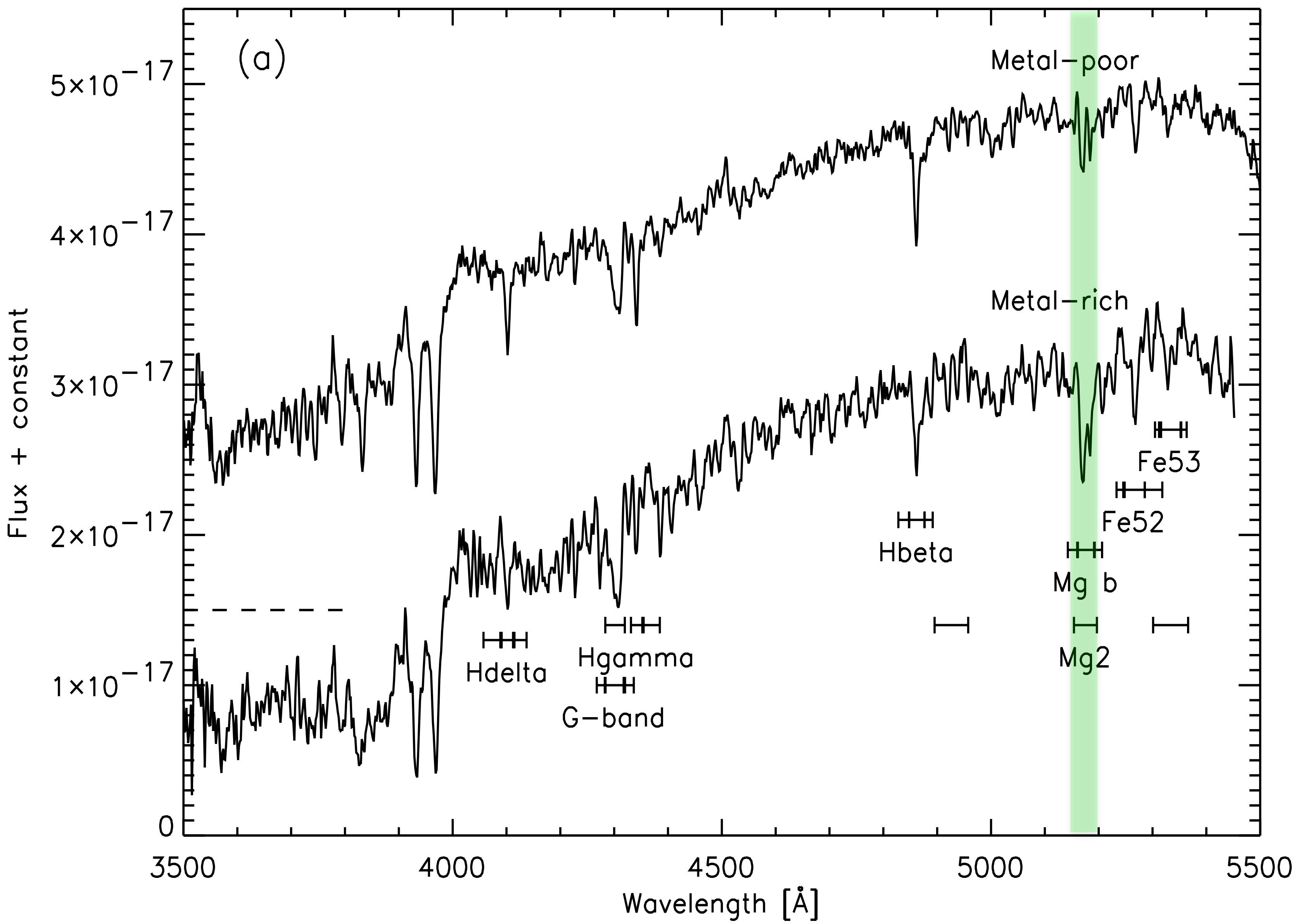
Function of $T_{\rm eff}$.

We can then find the total F. If the distance is known, L follows

Radius:

$$L = 4\pi R^2 \sigma T_{\rm eff}^4$$

Spectroscopy of GCs



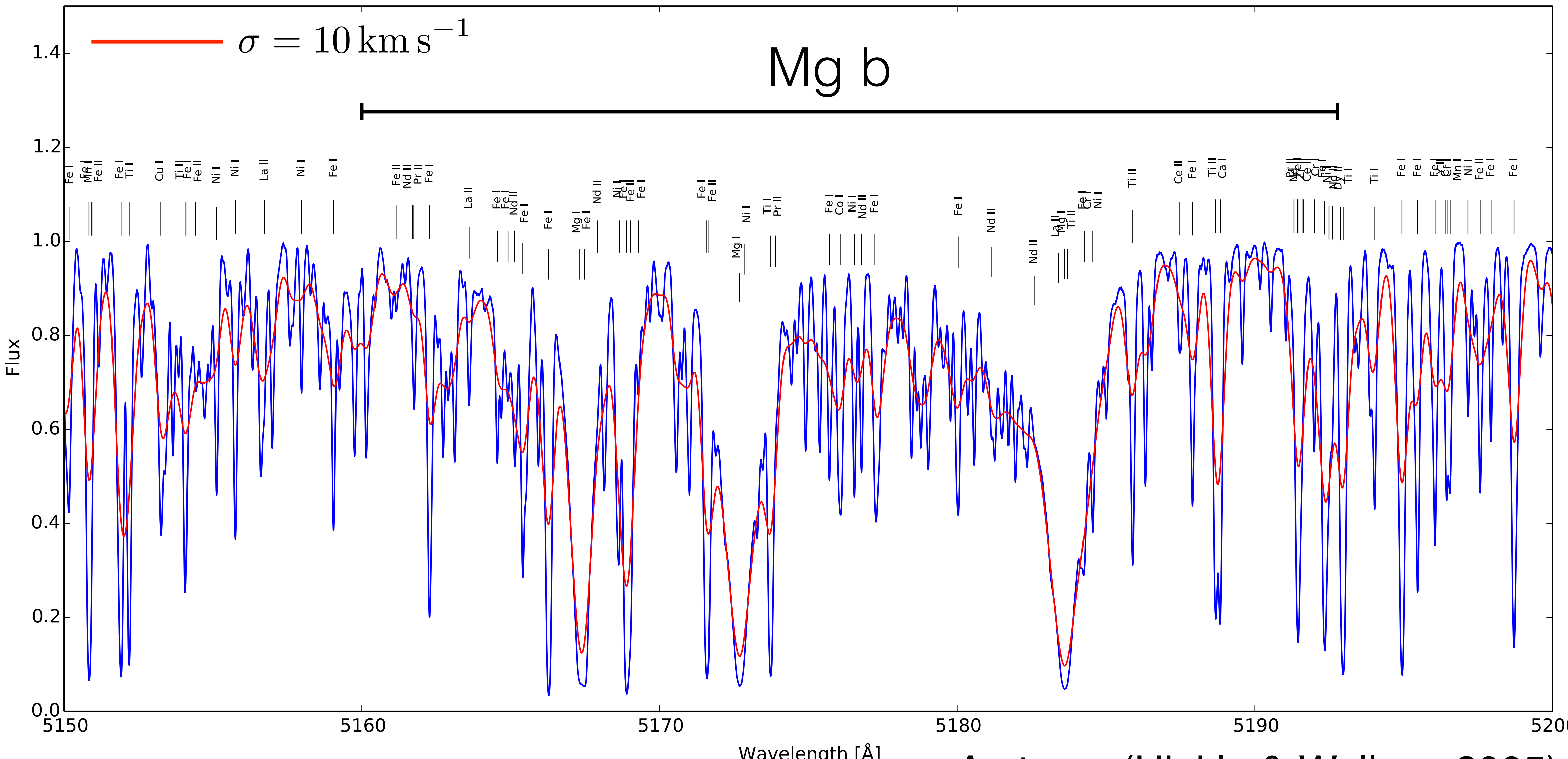
Low-dispersion spectroscopy - strong features (Lick/IDS system)

- ages,
- metallicities,
- some constraints on detailed chemistry (e.g. [α/Fe])

Larsen et al. (2002) - GCs in Sombrero galaxy

Integrated-light spectroscopy at high resolution

Cluster spectra far superior to Lick/IDS resolution, but blending still significant for many lines → Spectral synthesis / full spectral fitting

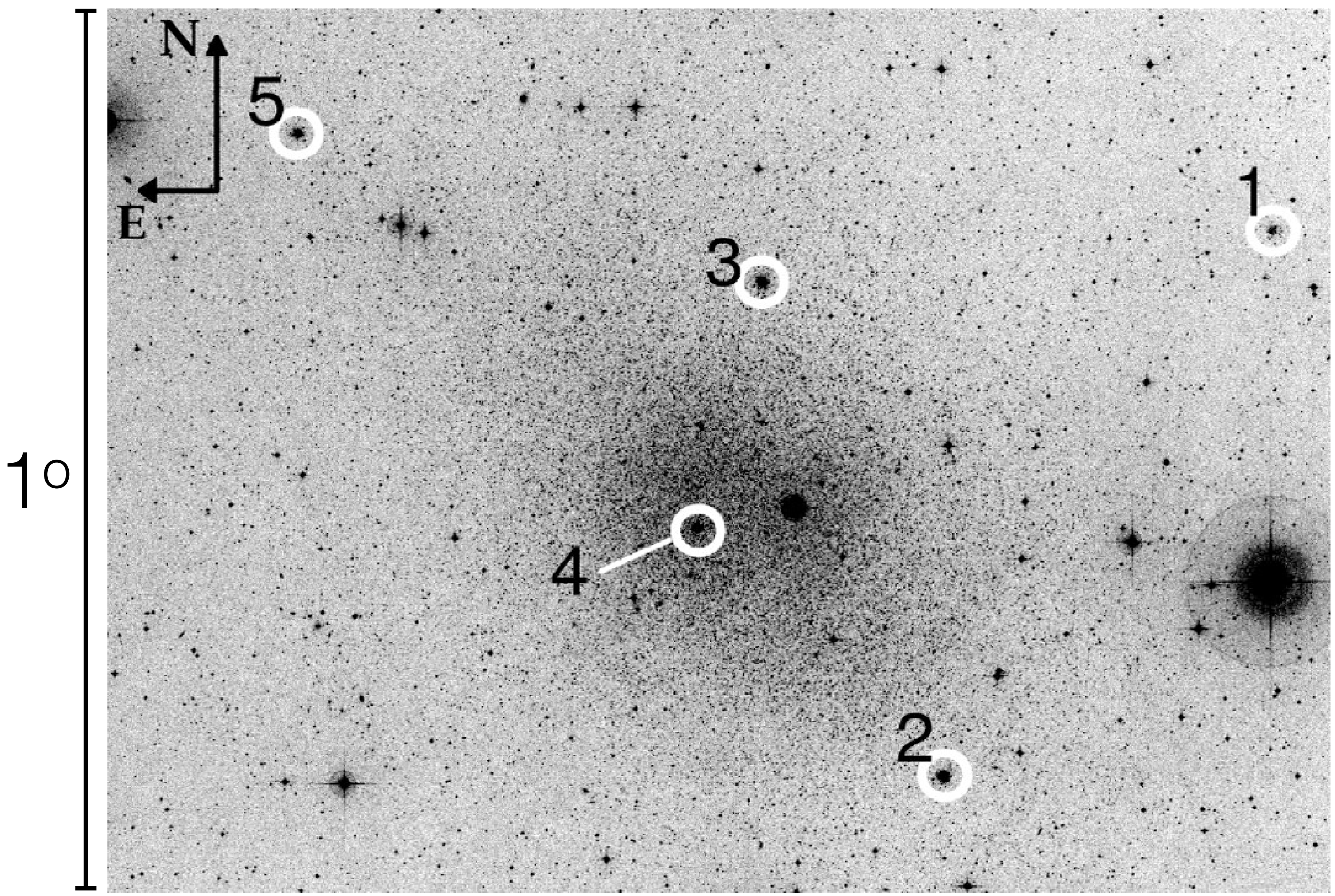


Arcturus (Hinkle & Wallace 2005)

Abundance analysis from integrated light

- Photometry for individual stars → stellar parameters (T_{eff}, logg, L)
- Assume chemical composition:
  - Compute model atmospheres (ATLAS9 - 1D, LTE, plane parallel, static, etc.)
  - Compute synthetic spectra (SYNTHE)
  - Degrade to instrumental resolution
- Co-add spectra, tune abundances until the model fits the data

The Fornax dSph



5 GCs, $M_V \sim -13.1$
(Hodge 1961; Mateo 1998)

Total stellar mass *formed*
$M^* \sim 6\times10^7\ M_\odot$
(Coleman & de Jong 2008).

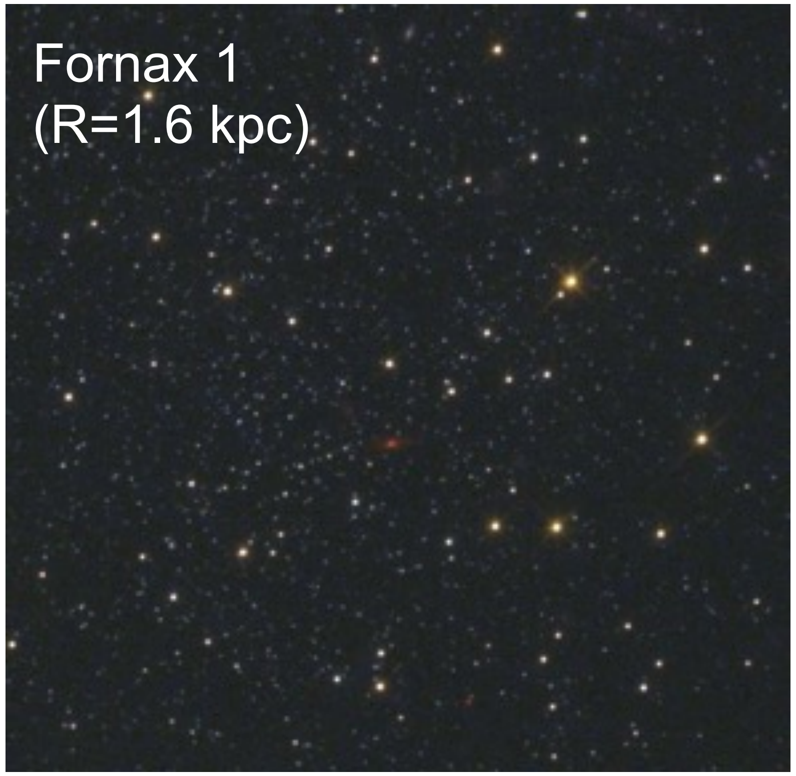
Mass of GCs $\sim 10^6\ M_\odot$
(~1.7% of M*)

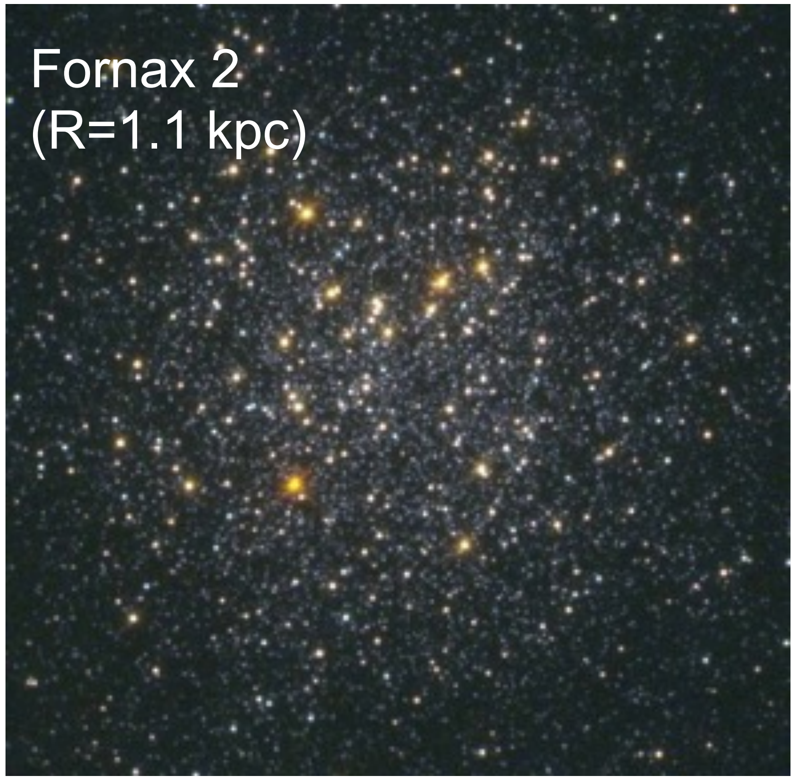
(image from Letarte et al. 2006)

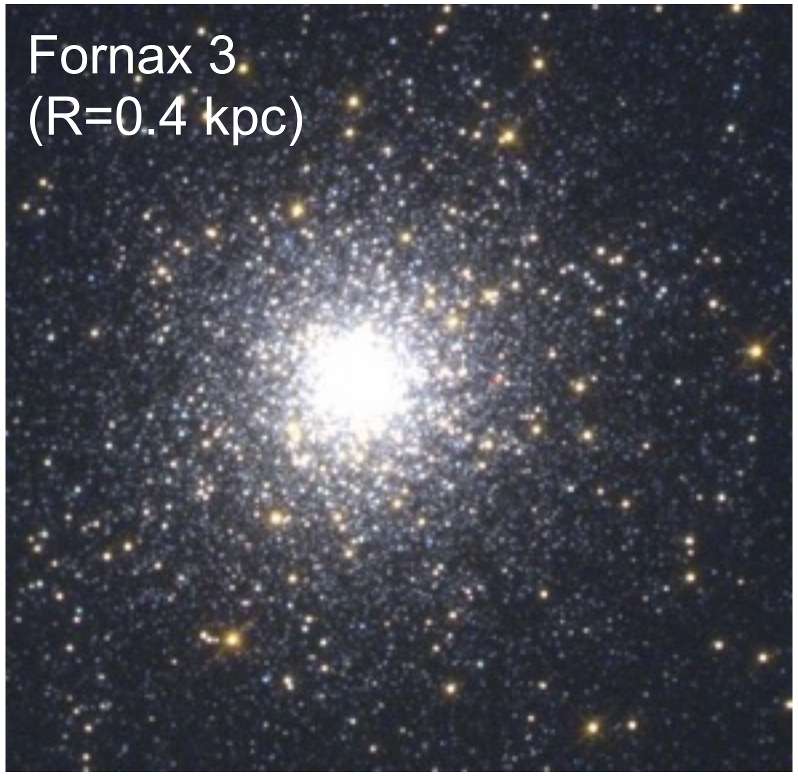
The Fornax GCs

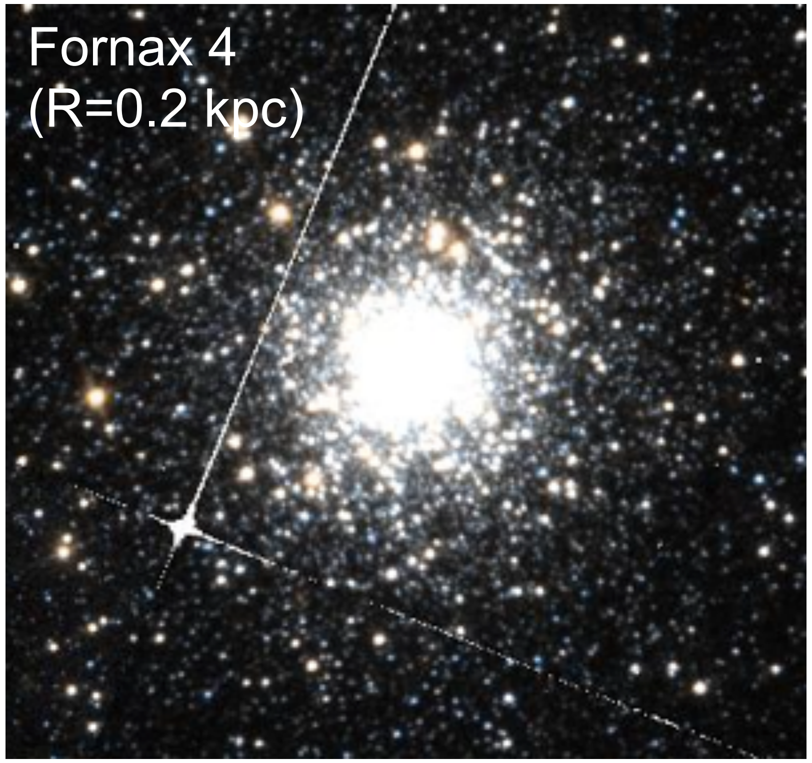
HST WFPC2+WFC3
F343N/F555W/F814W

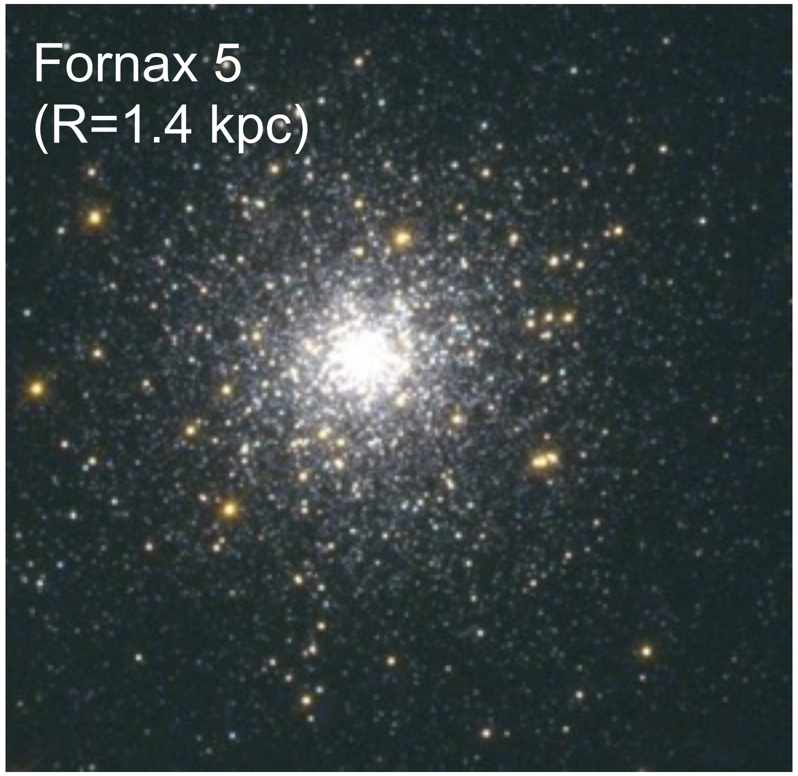
~24 pc



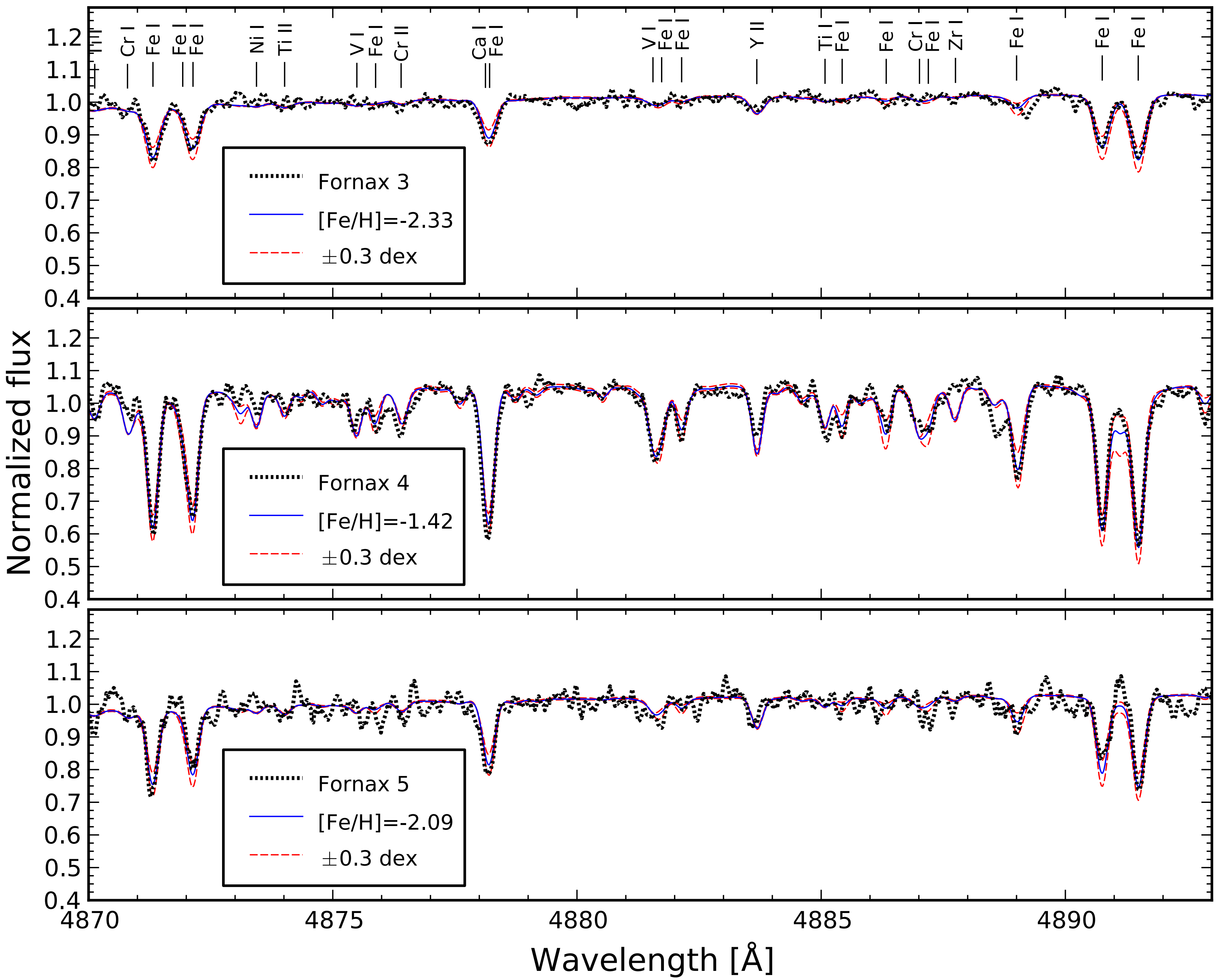








Metallicities of Fornax GCs



VLT/UVES integrated-light drift-scan spectra

Black dotted curves:
Observed spectra

Blue curves:
Best-fitting integrated-light model spectra based on:
- Observed CMDs
- ATLAS9+SYNTHE model atmospheres +synthetic spectra

Larsen et al. (2012)

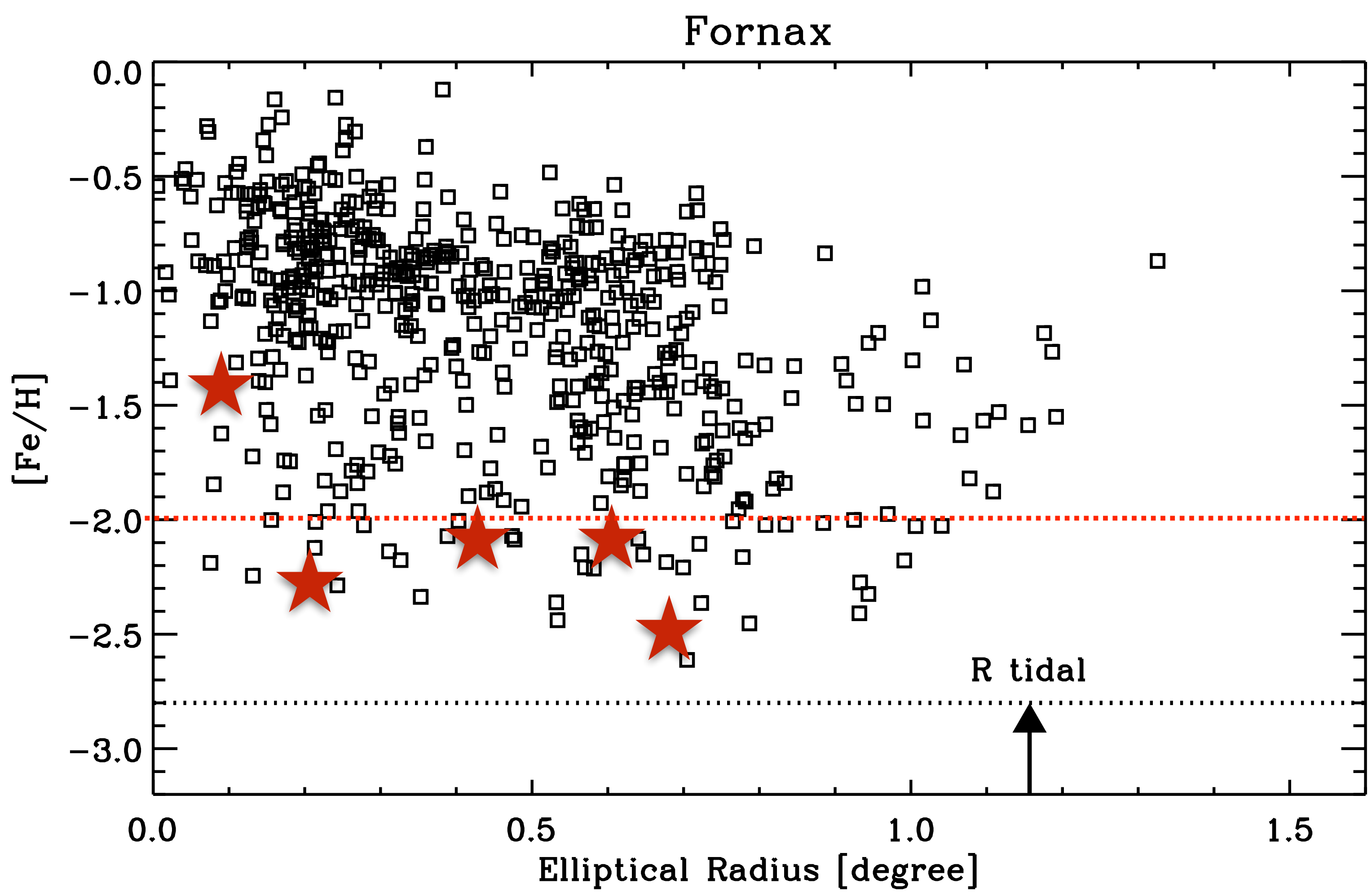
Metallicities from high-dispersion spectroscopy

	[Fe/H]	[Ca/Fe]	v_r (km s^{-1})	Source	
Fornax 1	−2.5 ± 0.1	+0.15 ± 0.04	59 ± 1	Letarte et al. 2006	Indiv. stars
Fornax 2	−2.1 ± 0.1	+0.20 ± 0.03	64 ± 1	Letarte et al. 2006	Indiv. stars
Fornax 3	−2.3 ± 0.1	+0.25 ± 0.08	60.4 ± 0.2	This work	Integr. light
Fornax 4	−1.4 ± 0.1	+0.13 ± 0.07	47.2 ± 0.1	This work	Integr. light
Fornax 5	−2.1 ± 0.1	+0.27 ± 0.09	60.6 ± 0.2	This work	Integr. light

- Fornax 1, 2, 3, 5 all have [Fe/H] < -2
- Field star metallicities peak near [Fe/H] = -1
  (Battaglia et al. 2006; Kirby et al. 2011).

Larsen et al. (2012)

GCs and field stars in Fornax

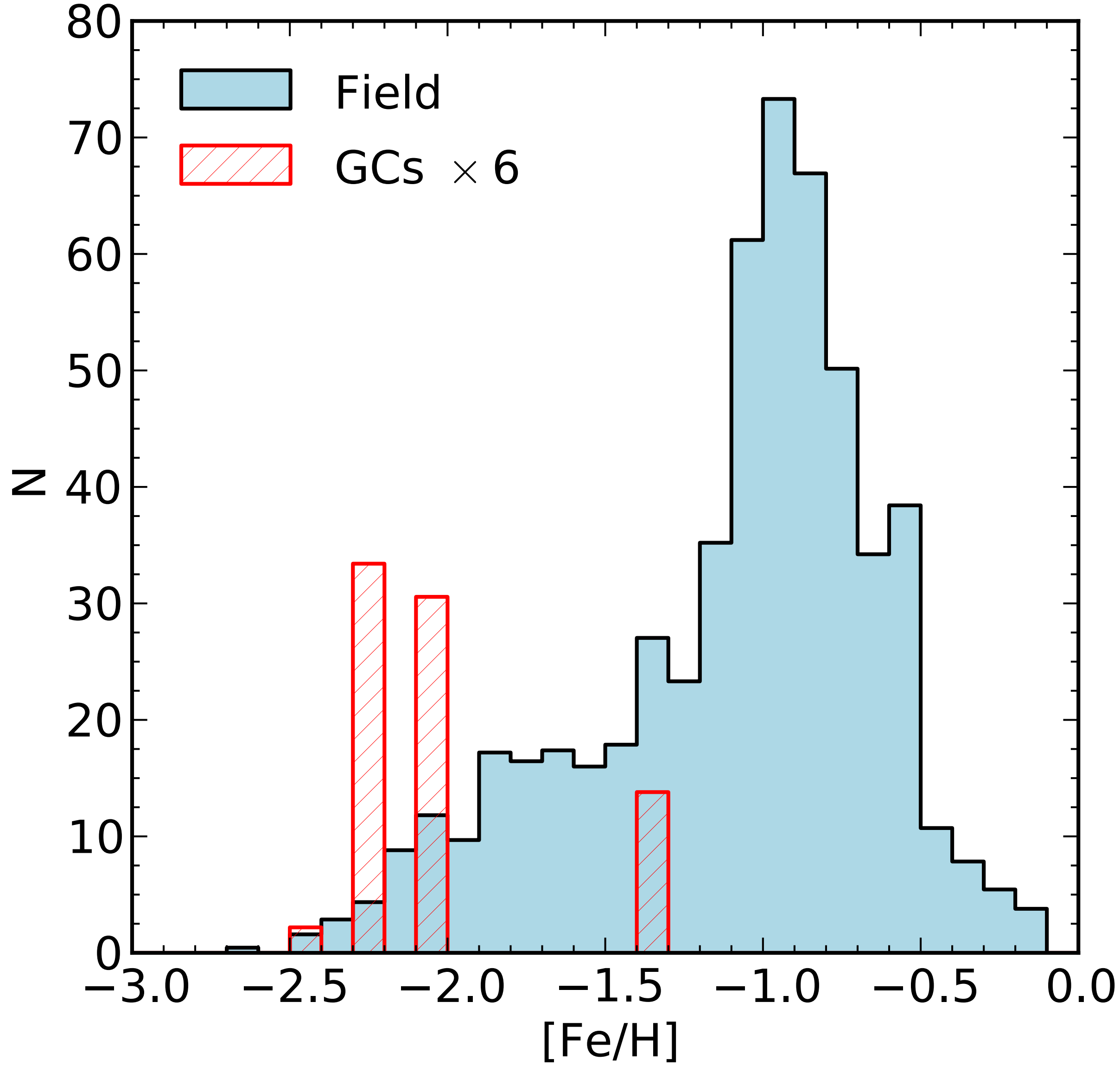


GCs much more metal-poor than most field stars.

Few field stars at [Fe/H]<-2

Field stars: Battaglia et al. (2006), Ca II triplet spectroscopy.
GCs: Letarte et al. (2006); Larsen et al. (2012)

Field stars and GCs in Fornax: Metallicity distributions



Larsen et al. (2012, A&A 544, L14)
Field stars: Battaglia et al. (2006), corrected for spatial coverage.
GCs: Letarte et al. (2006), Larsen et al. (2012)

For [Fe/H] < -2: Mass in
- Field stars: ~ 3×10^6 $M_\odot$
- GCs ~ 1×10^6 $M_\odot$

About 1/5-1/4 of all metal-poor stars in Fornax dSph *currently* belong to F1+F2+F3+F5.

(Milky Way halo: about 2-3%)

Difficult to accommodate large amount of cluster mass loss/ dissolution in Fornax dSph.

The mass budget - II

Need to lose 9 out of 10 1G stars to get $M_{1G,GC}$ / M_{2G} ~ 1:1

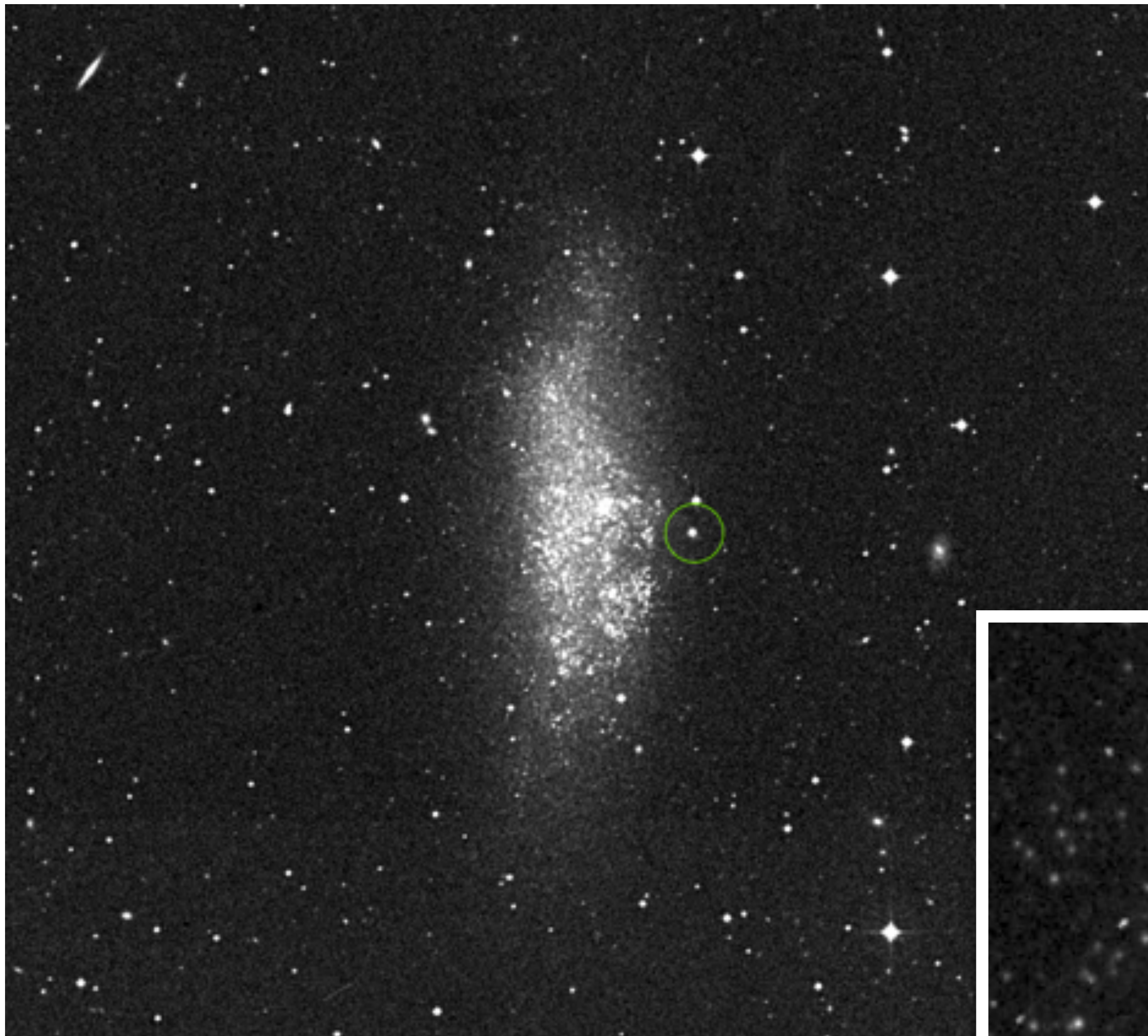
Fraction of stars still in GC is then:

$$(M_{1G,GC}+M_{2G})/(M_{1G}+M_{2G}) = 2/11 \sim 18\%$$

We have assumed:

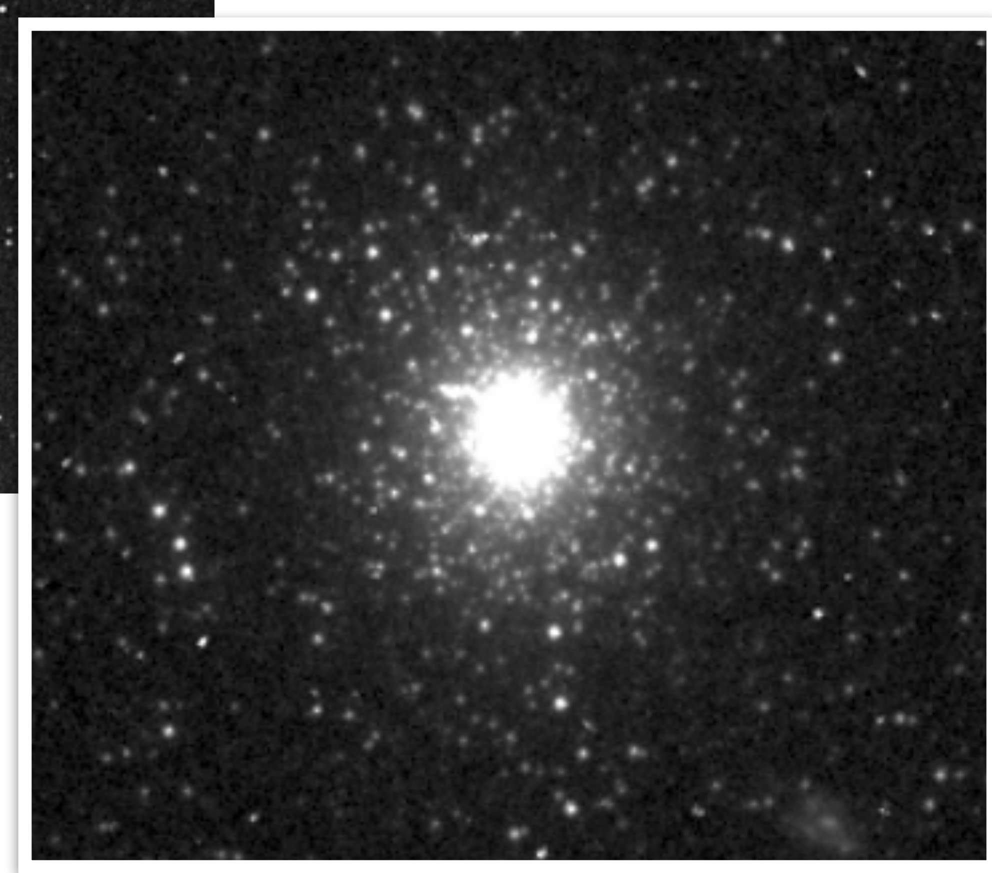
- Extreme SFE: 100% of AGB ejecta form new stars
- Highly unusual IMF: no 2G stars with $m > 0.8\ M_{\odot}$.
- *No* 2G stars lost from cluster (but 90% of 1G)
- No other field stars or disrupted GCs

Other cases: The WLM dIrr



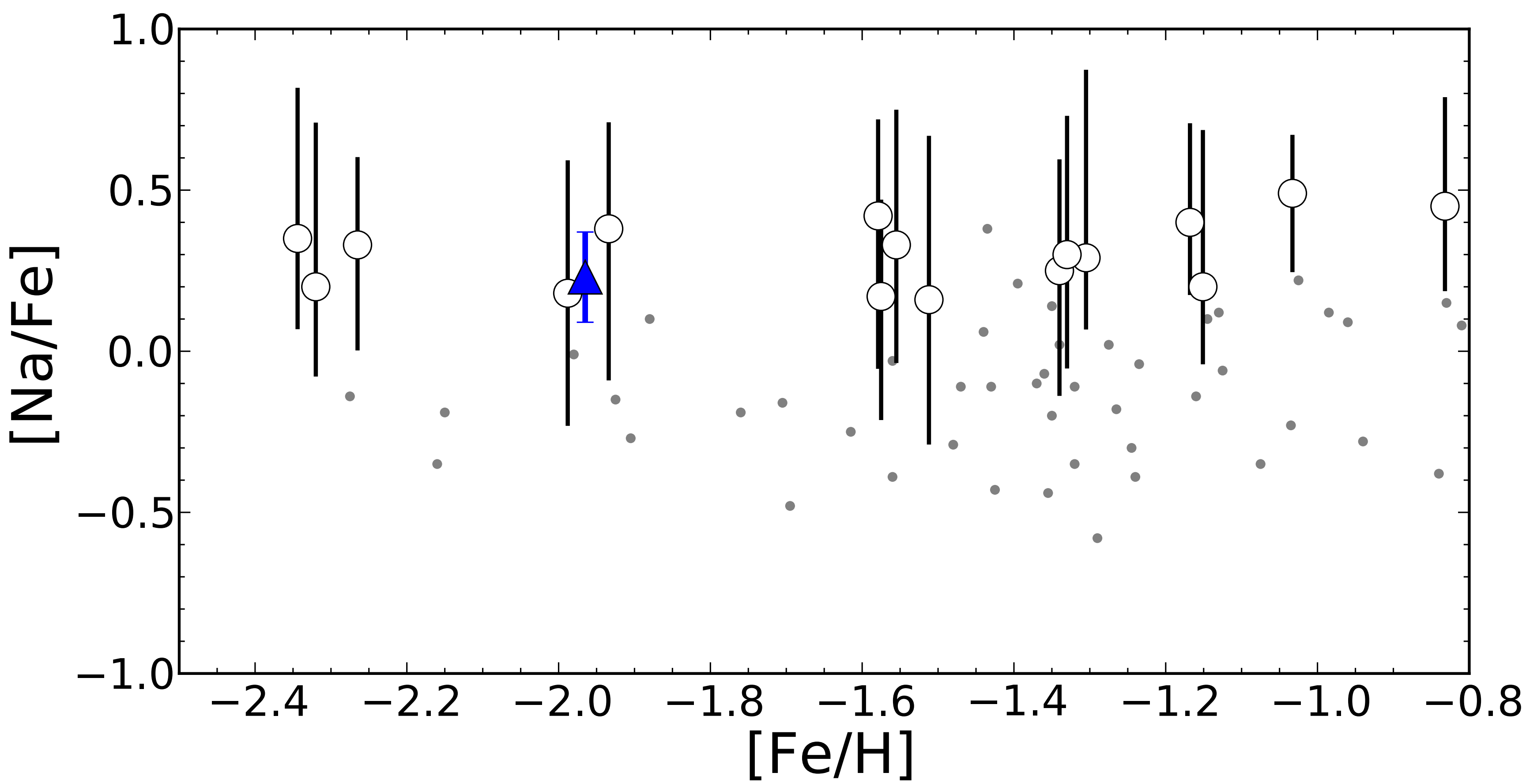
D(WLM-Milky Way)~925 kpc
D(WLM-M31) ~ 950 kpc
Near edge of Local Group
M_V ~ -14.5

1 old GC: M_V=-9.0, M~6×10^5 $M_\odot$
(Humason et al. 1956; Ables & Ables 1977; Sandage & Carlson 1985; Larsen et al. 2014a)



Na in WLM GC

Integrated-light [Na/Fe] in WLM GC is similar to average [Na/Fe] for Milky Way GCs; enhanced compared to field

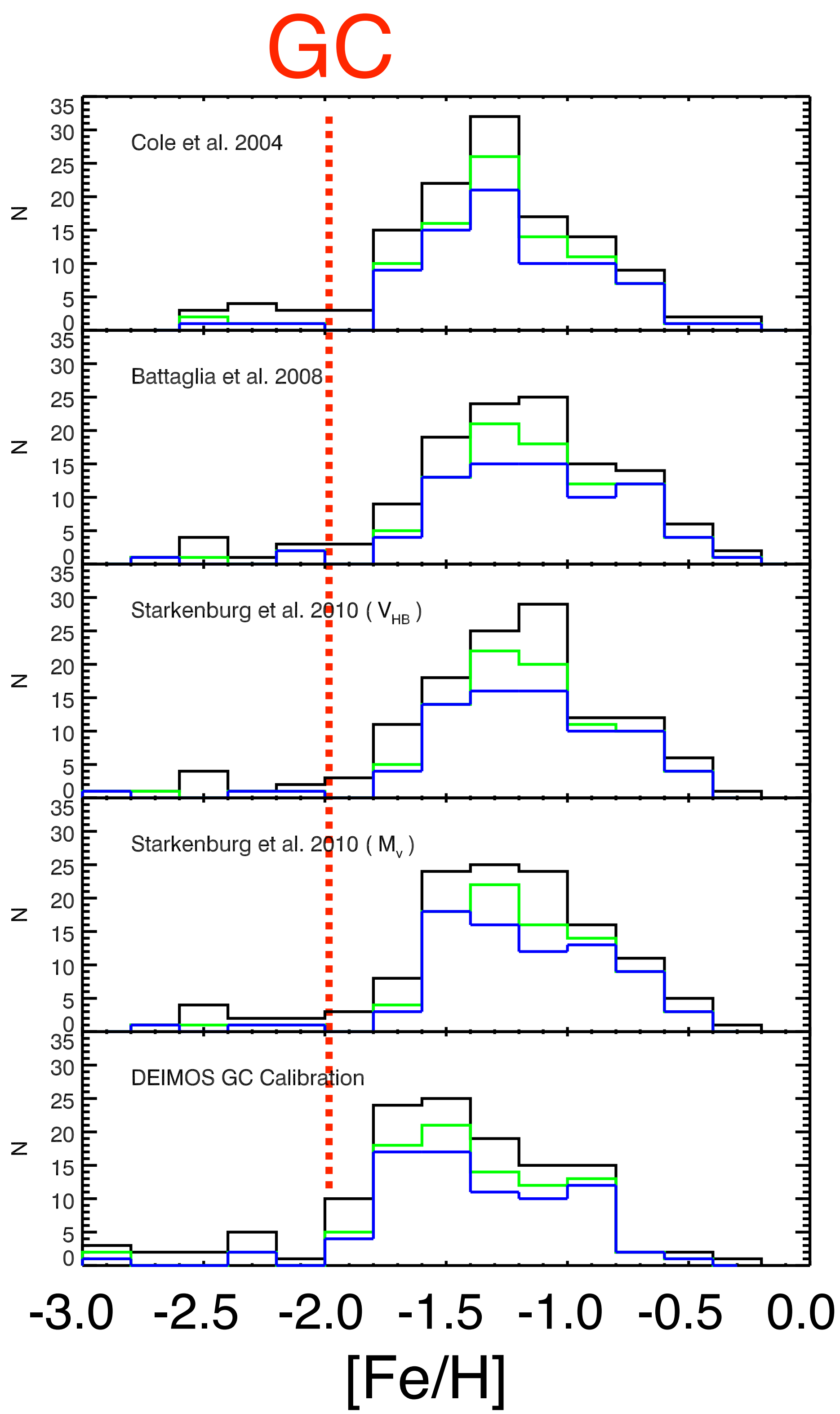


Dots: MW field stars (Ishigaki et al. 2013)

Circles: MW GCs (Carretta et al. 2009)

Triangle: WLM GC (Larsen et al. 2014)

WLM: field stars vs GC



Leaman et al. (2013)

Field stars:

Stellar mass $M^* \sim 1.6\times10^7\ M_\odot$

(Zhang et al. 2012)

<[Fe/H]> = -1.28

8% of RGB stars have [Fe/H]<-2

(Leaman et al. 2013, Ca II IR triplet spectroscopy of RGB stars)

Globular cluster:

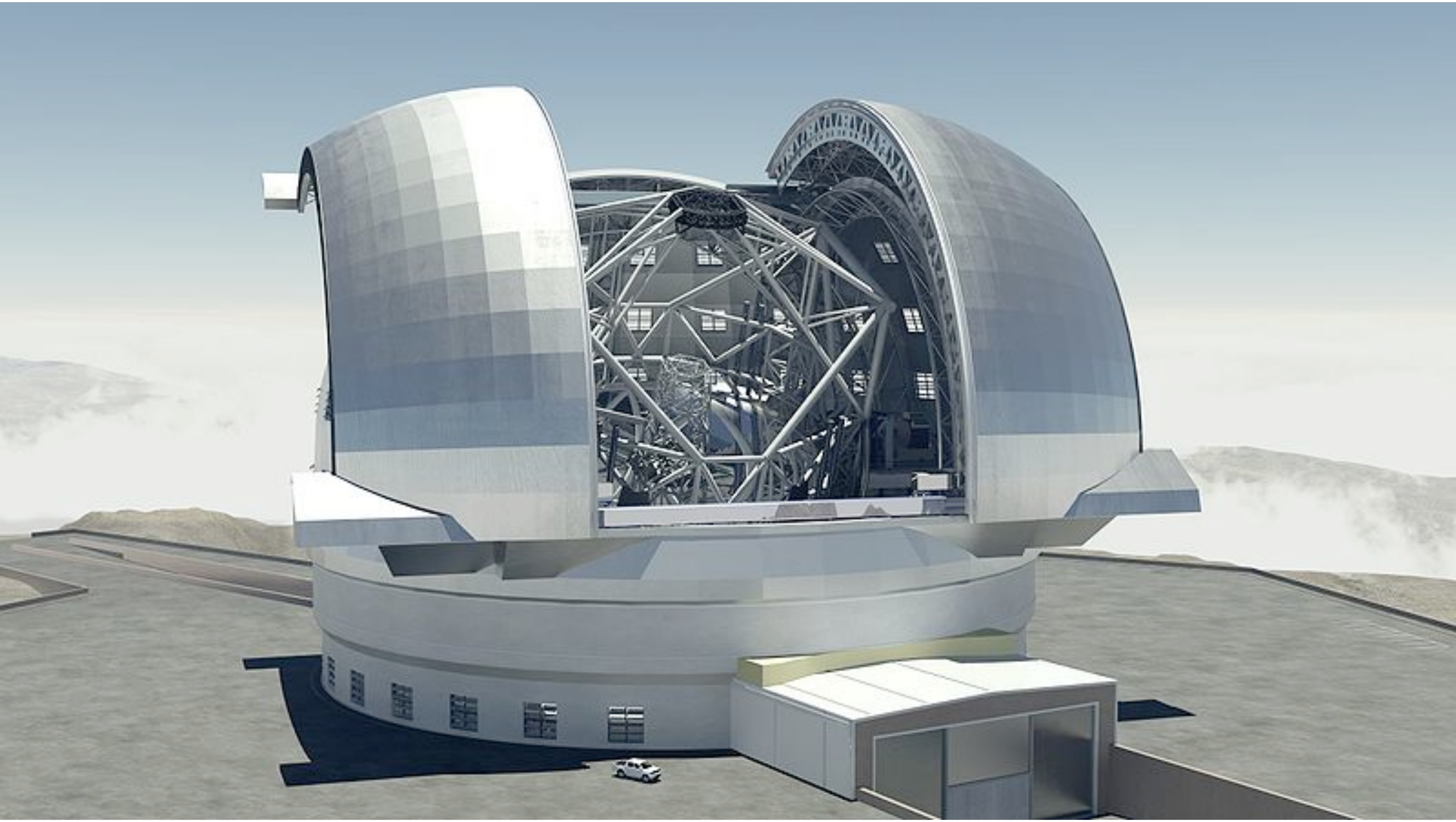
$M_{GC} \sim 6\times10^5\ M_\odot$

Metal-poor ([Fe/H]~-2.0)

GC accounts for 17%-31% of metal-poor stars

(Larsen et al. 2014a)

Globular Clusters with the E-ELT

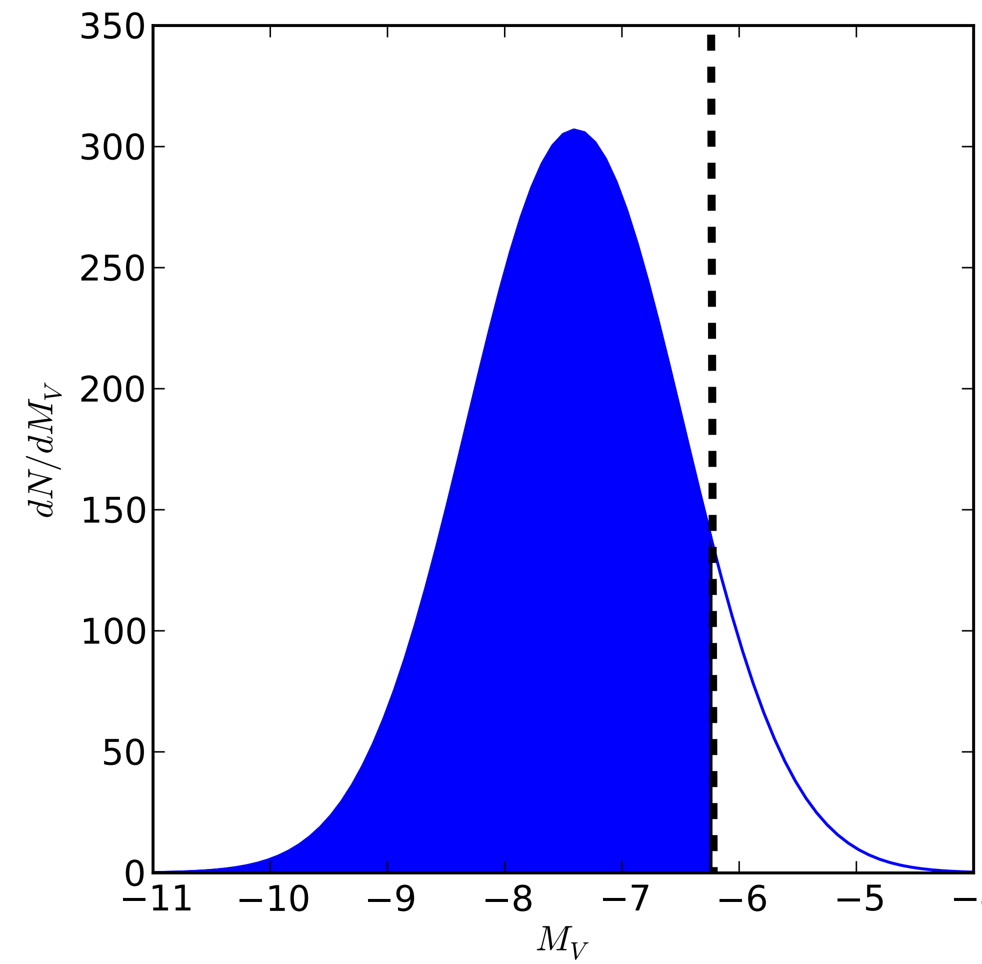


Cen A - the nearest giant elliptical

Estimated total of ~1000-2000 globular clusters (e.g. Harris et al. 2004)

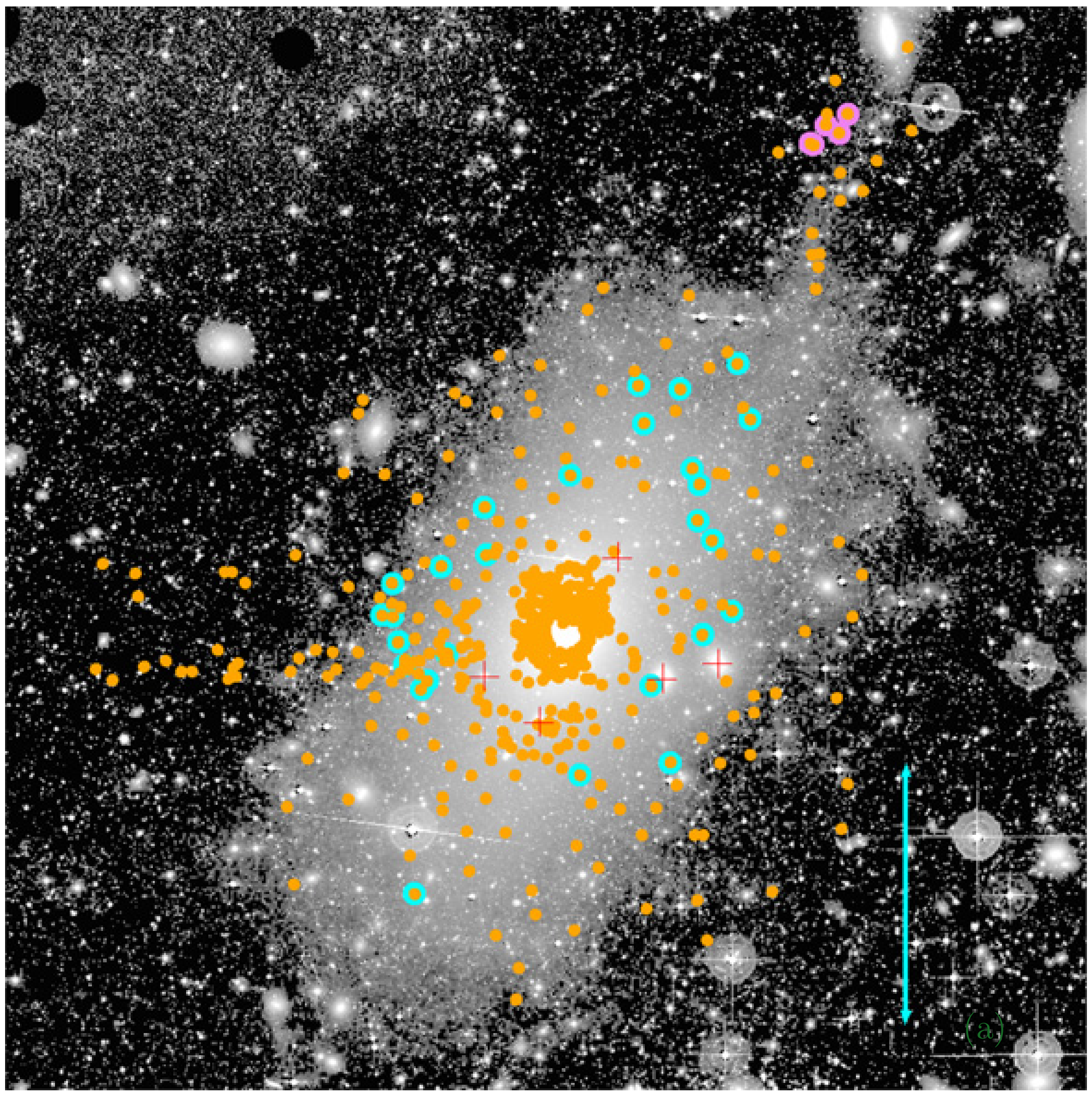
The majority are within reach of MOSAIC (about half with V < 20.5)

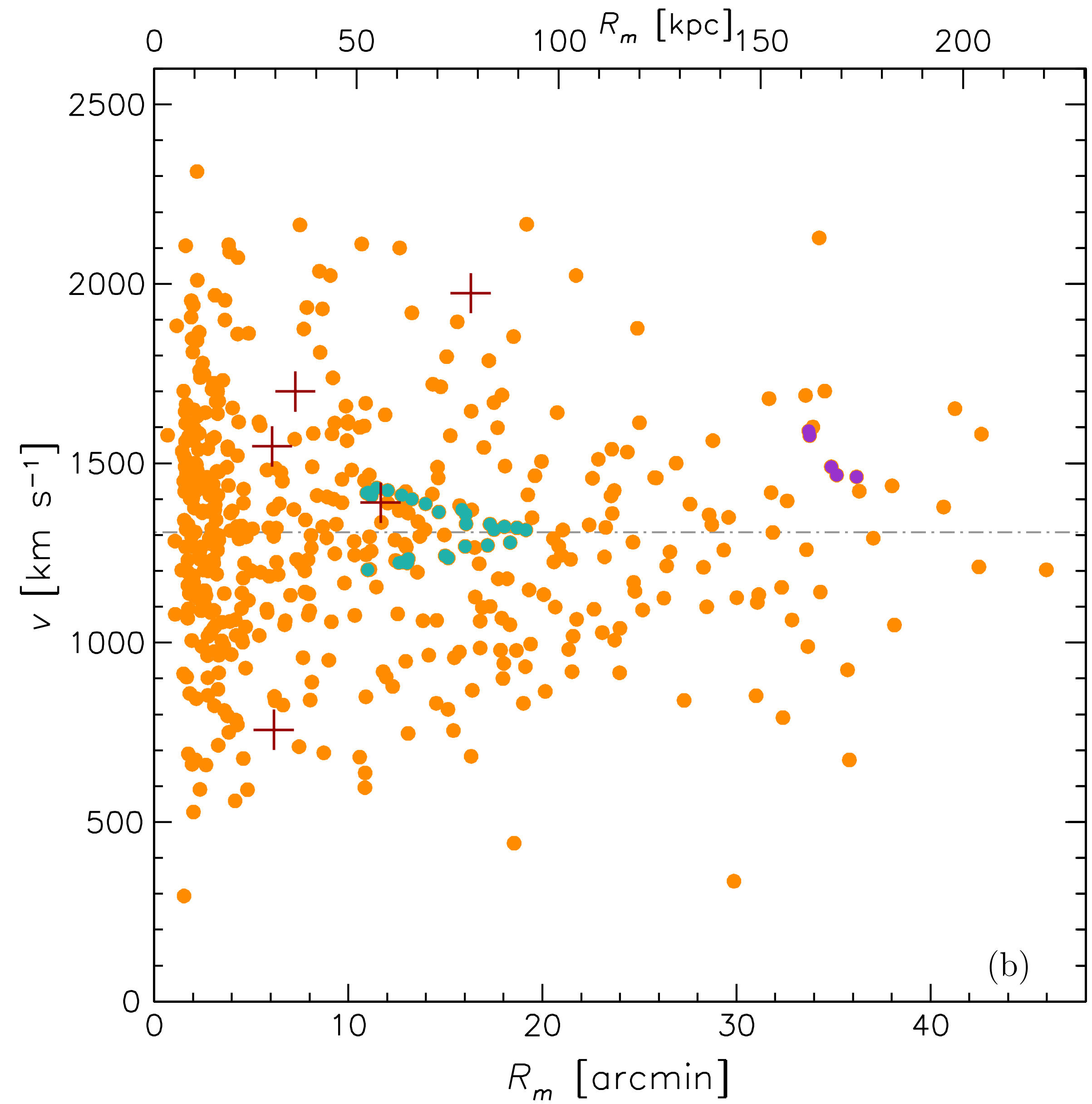
V=22



Assembly of halos and GC systems

Kinematic substructure related to chemical composition?





Romanowsky et al. (2012): Keck/DEIMOS kinematics for 488 GCs in M87

“The Local Volume”

MOSAIC

Meaningful comparison with theory requires *statistical* samples of galaxies along (and off) the Hubble sequence

- Distances < 15-20 Mpc (Virgo, Fornax)
- Most individual stars still too faint for detailed spectroscopy (RGB tip at V~28)
- Individual stars can be imaged with ELTs → reconstruction of star formation histories
- *Star clusters:* Discrete sampling points in space and time; also for “minority populations” (e.g., halos).
- Potentially access to *entire* star formation histories