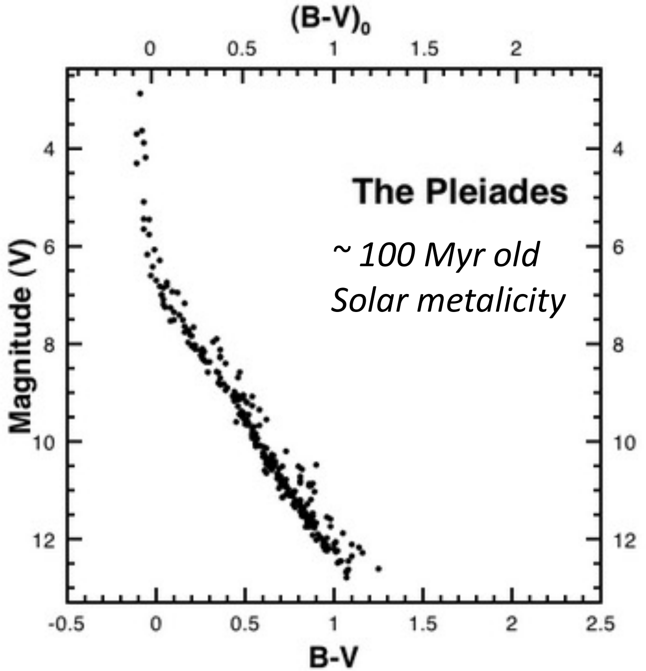
Open Clusters

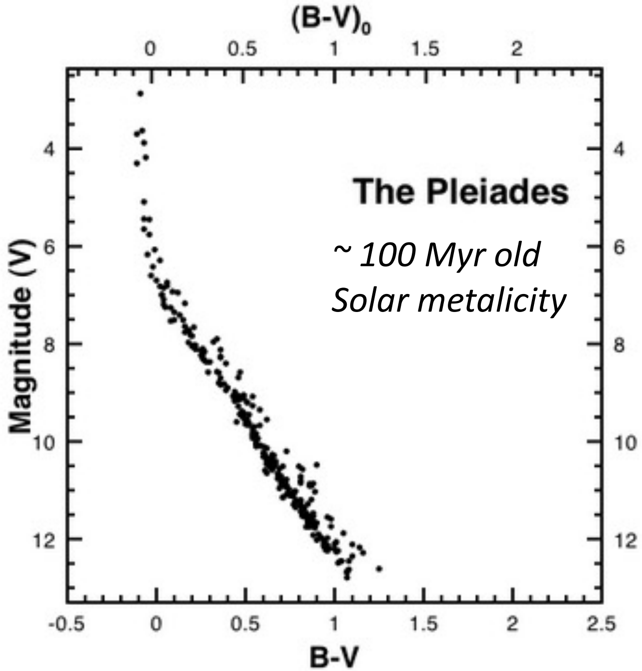


Star Clusters:
- single age
- single metallicty

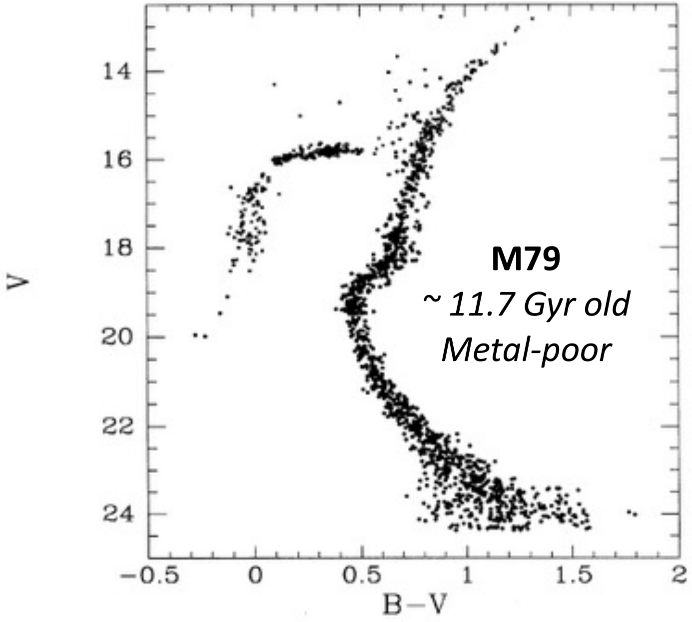
Open Clusters

Young, main sequence fully(?) populated

Open Clusters



Globular Clusters



Star Clusters:
- single age
- single metallicty

Open Clusters

Young, main sequence fully(?) populated

Globular Clusters

Old, upper main sequence missing.

Red giant branch and horizontal branch stars present.

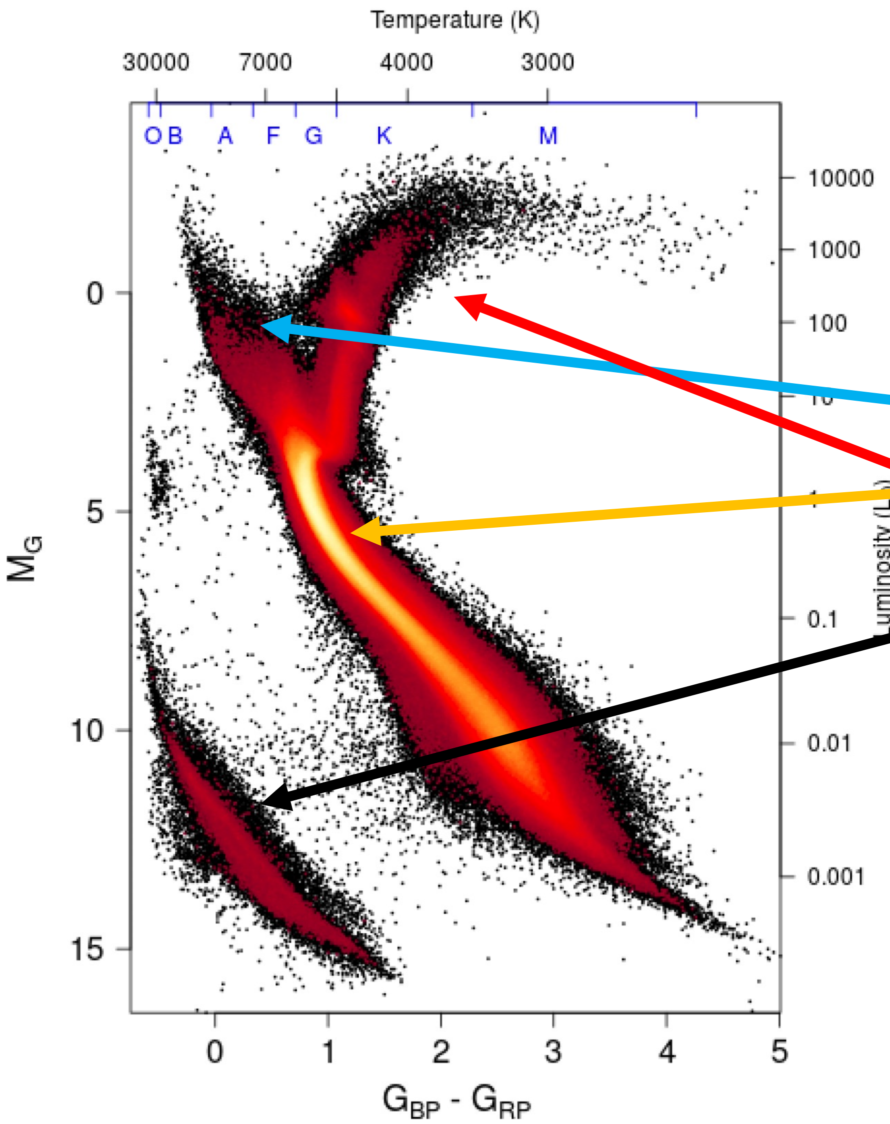


Fig. 5. *Gaia* HRD of sources with low extinction ($E(B–V) < 0.015$ mag) satisfying the filters described in Sect. 2.1 (4 276 690 stars). The colour scale represents the square root of the density of stars. Approximate temperature and luminosity equivalents for main-sequence stars are provided at the top and right axis, respectively, to guide the eye.

CMD for the nearby Galactic disk

Continuous star formation over time, so we see a range of ages from young to old.

We see

- upper main sequence (massive, young)
- lower main sequence (low mass, all ages)
- red giant branch (old stars)
- white dwarfs (dead stars)

Gaia 2018 (A&A 616 A10)

Main Sequence Lifetime

Main Sequence: stars fusing H to He in their core

Luminosity is much higher for more massive stars:

$$L \sim M^{3.5}$$

Luminosity comes from ”burning” hydrogen into helium.

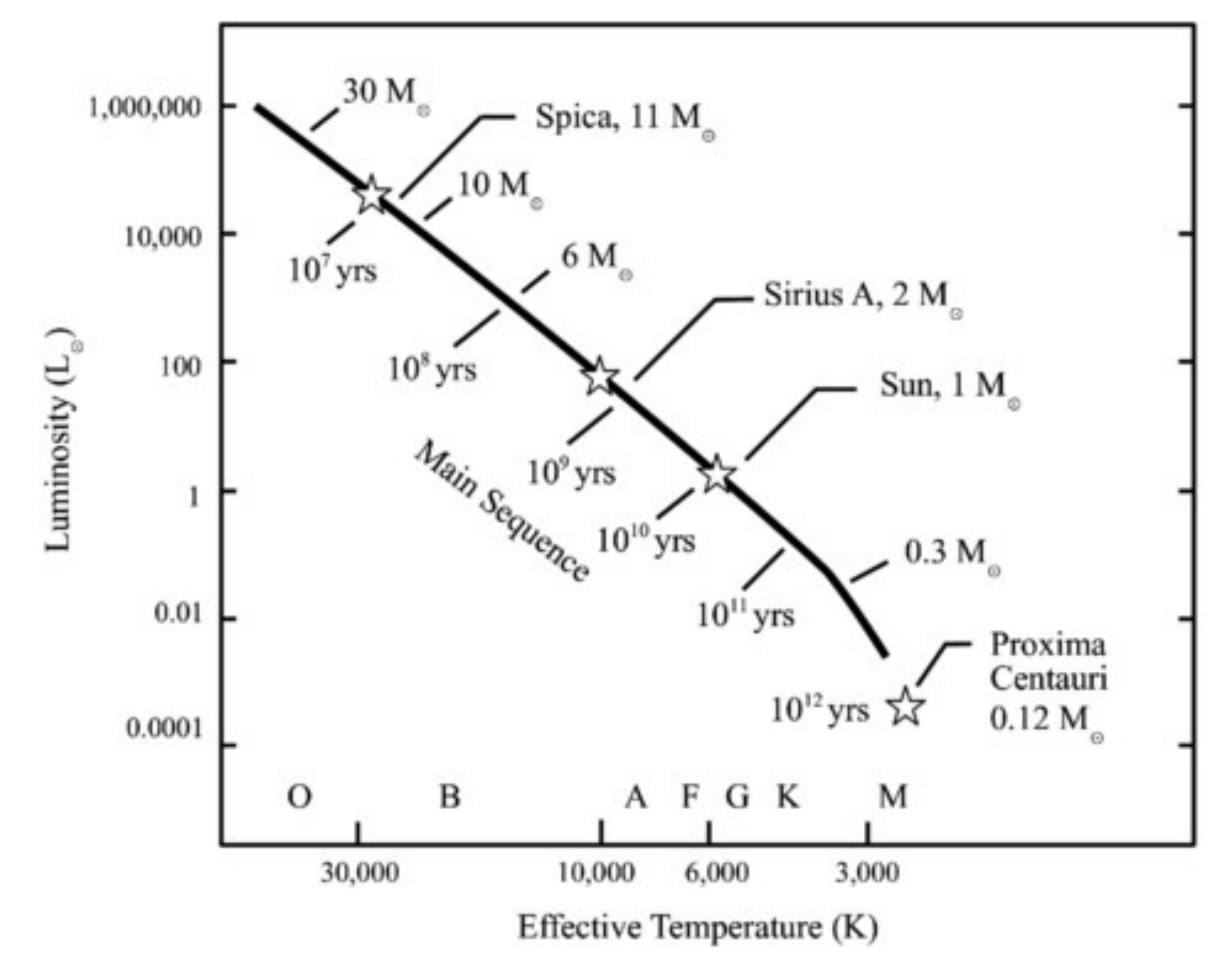
“Fuel tank” argument:

Fuel = Mass

Luminosity = Mass burn rate = dM/dt

Timescale = M/L

Fuel is depleted faster for more massive stars, so they have much shorter MS lifetimes.



Courtesy Kenneth Lang, Tufts Univ

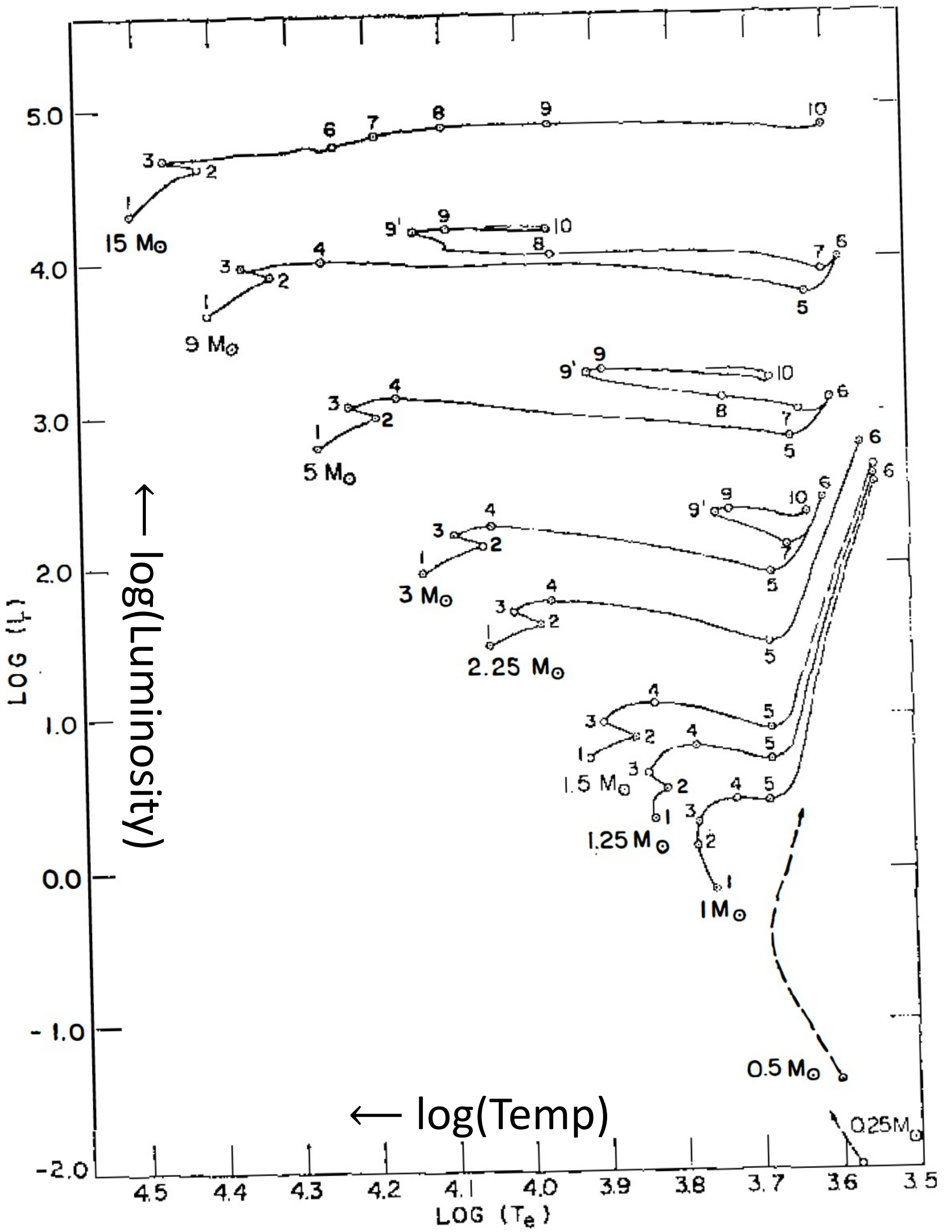


FIG. 3. Paths in the H-R diagram for metal-rich stars of mass $(M/M_\odot) = 15$, 9, 5, 3, 2.25, 1.5, 1.25, 1, 0.5, 0.25. Units of luminosity and surface temperature are the same as in Figure 1. Traversal times between labeled points are given in Tables III and IV. Dashed portions of evolutionary paths are estimates.

TABLE III

STELLAR LIFETIMES (yr)[a]

Mass ($M_\odot$) \ Interval ($i-j$)	(1–2)	(2–3)	(3–4)	(4–5)	(5–6)
15	1.010 (7)	2.270 (5)		7.55 (4)	
9	2.144 (7)	6.053 (5)	9.113 (4)	1.477 (5)	6.552 (4)
5	6.547 (7)	2.173 (6)	1.372 (6)	7.532 (5)	4.857 (5)
3	2.212 (8)	1.042 (7)	1.033 (7)	4.505 (6)	4.238 (6)
2.25	4.802 (8)	1.647 (7)	3.696 (7)	1.310 (7)	3.829 (7)
1.5	1.553 (9)	8.10 (7)	3.490 (8)	1.049 (8)	≥2 (8)
1.25	2.803 (9)	1.824 (8)	1.045 (9)	1.463 (8)	≥4 (8)
1.0	7 (9)	2 (9)	1.20 (9)	1.57 (8)	≥1 (9)

[a] Numbers in parentheses beside each entry give the power of ten to which that entry is to be raised.

TABLE IV

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Mass ($M_\odot$) \ Interval ($i-j$)	(6–7)	(7–8)	(8–9)	(9–10)
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9	4.90 (5)	9.50 (4)	3.28 (6)	1.55 (5)
5	6.05 (6)	1.02 (6)	9.00 (6)	9.30 (5)
3	2.51 (7)	4.08 (7)		6.00 (6)

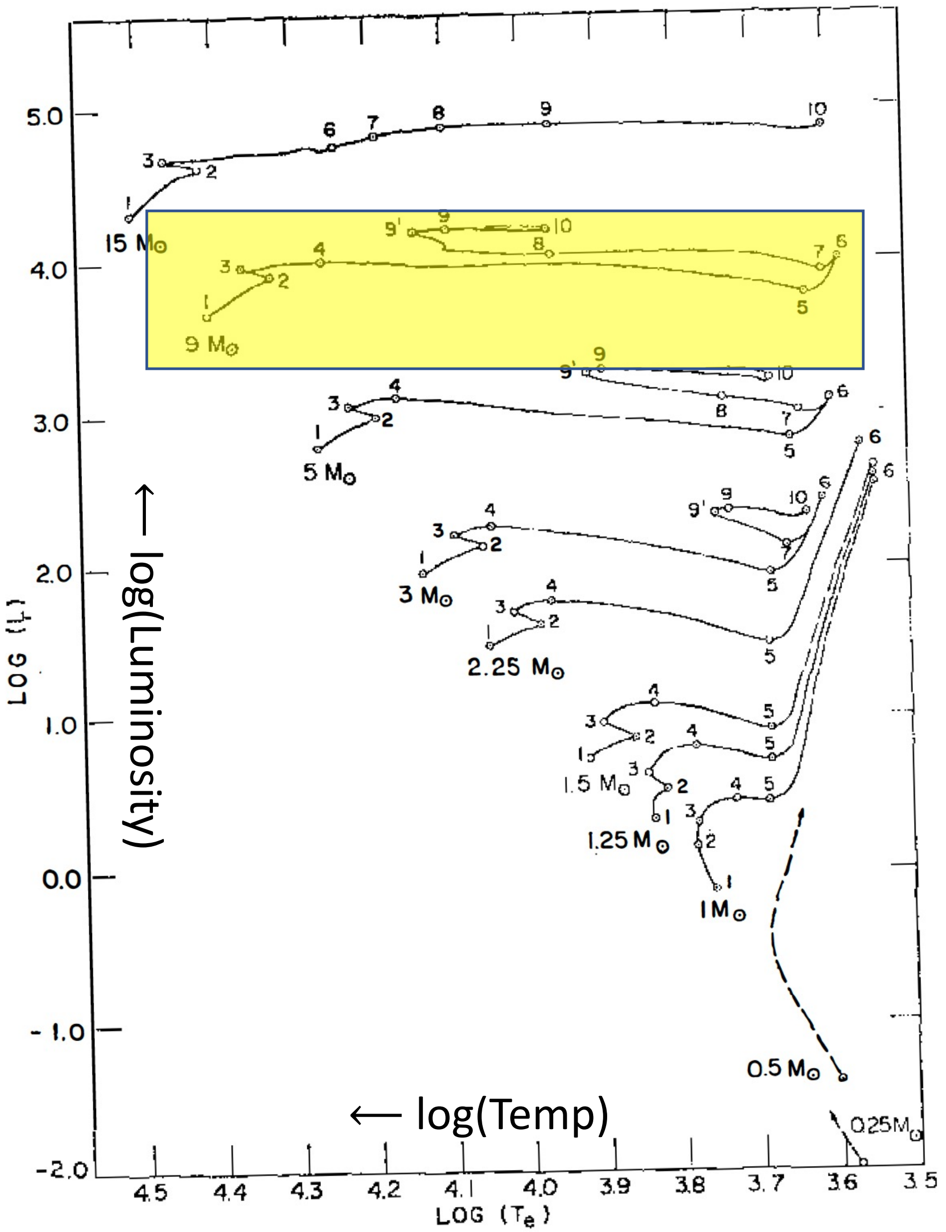
[a] Numbers in parentheses beside each entry give the power of ten to which that entry is to be raised.

Stellar evolution

Theoretical evolutionary tracks.

Tick marks on plot show ages in table where the notation "A.AAA (B)" means $A.AAA \times 10^B$ yrs

Stellar Evolutionary Tracks
Iben ARAA 1968



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[a] Numbers in parentheses beside each entry give the power of ten to which that entry is to be raised.

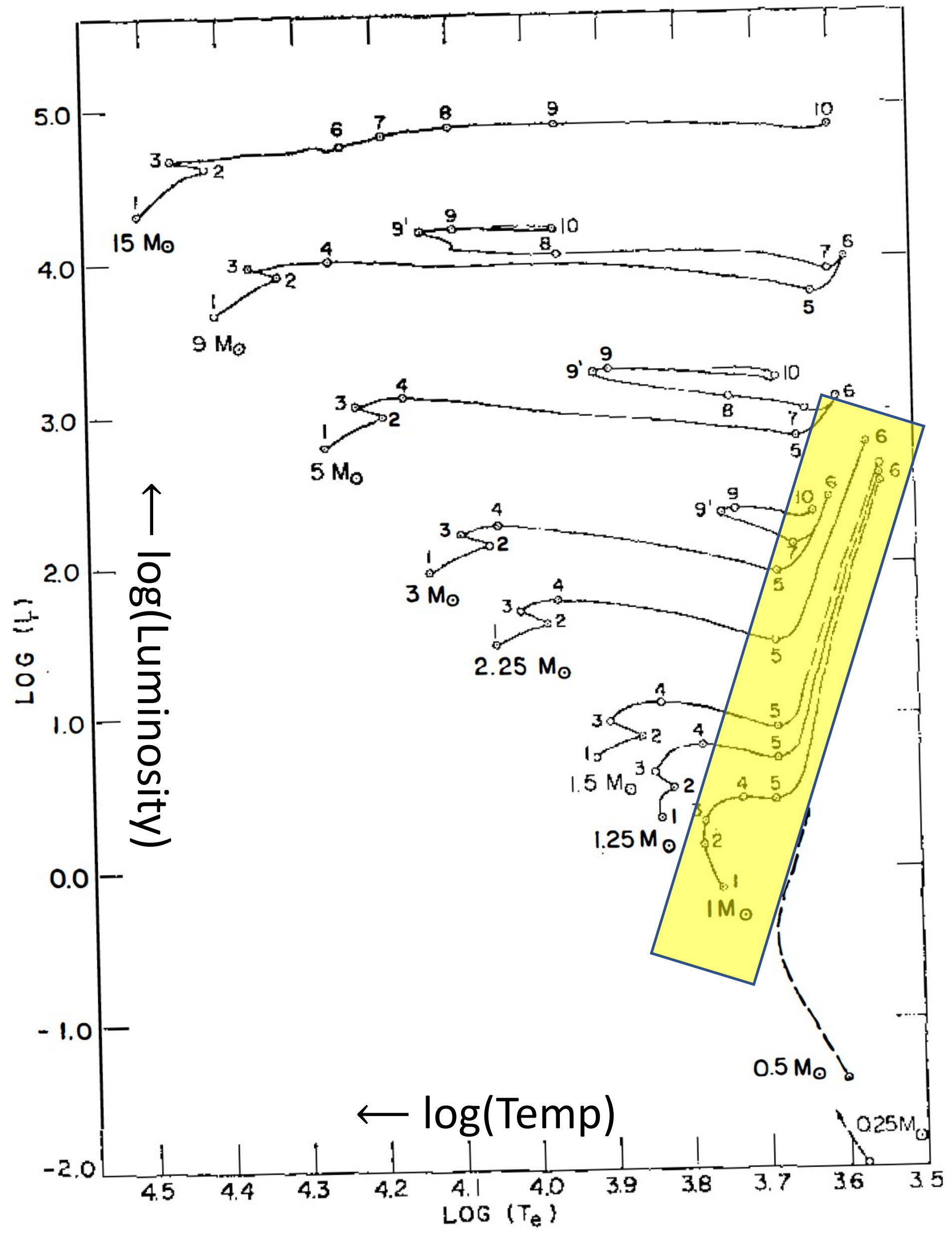
Stellar evolution

9 $M_\odot$ star evolves off of MS in ~ 20 Myr.

Evolves back and forth on the CMD: "blue loop stars"

Goes supernova only a few Myr after it evolves off MS.

Stellar Evolutionary Tracks
Iben ARAA 1968



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[a] Numbers in parentheses beside each entry give the power of ten to which that entry is to be raised.

Stellar Evolutionary Tracks
Iben ARAA 1968

Stellar evolution

1 $M_\odot$ star evolves off of MS in ~ 7 Gyr.

Evolves up on the CMD: “red giant stars”

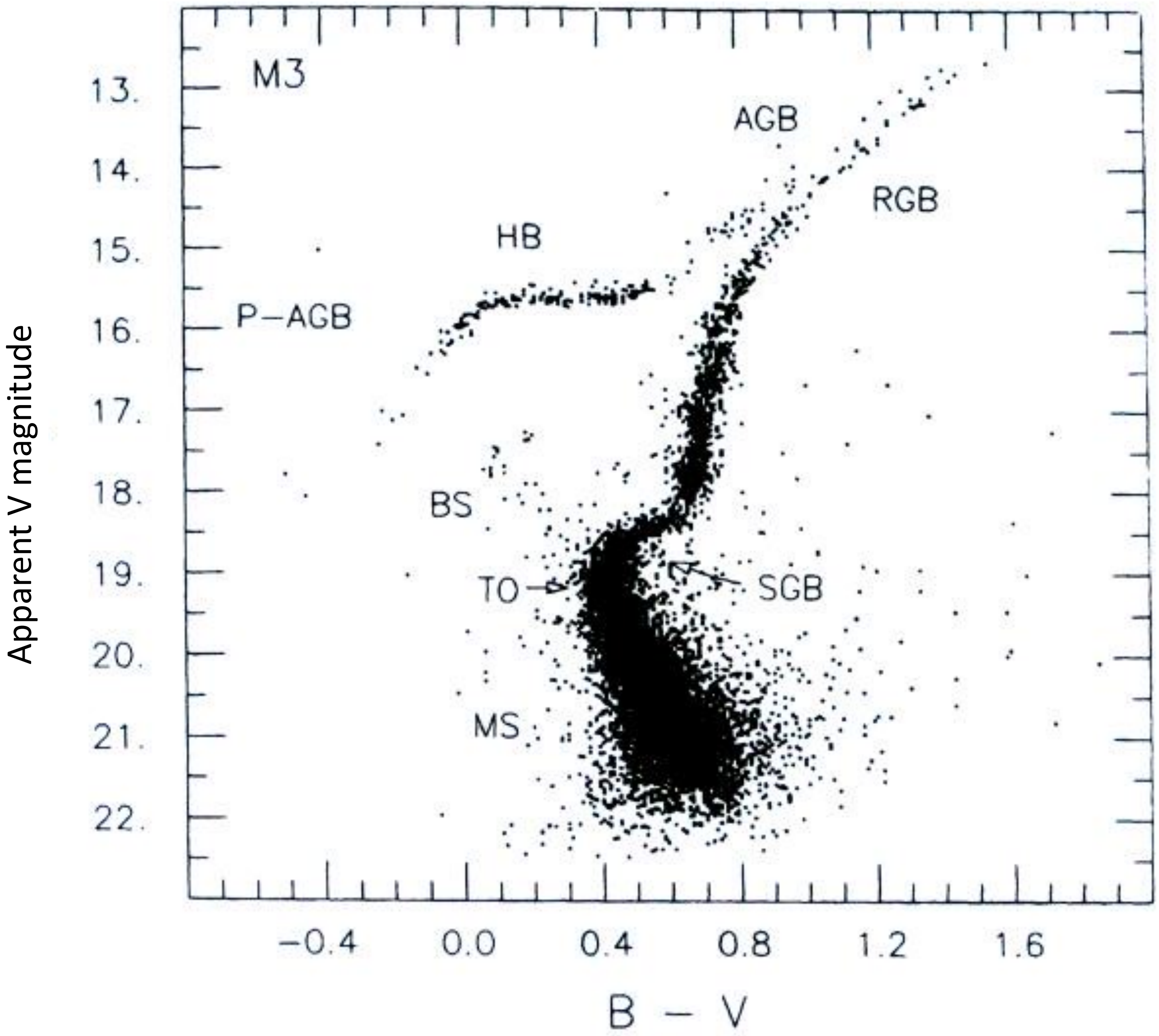
Lives as a red giant for another Gyr or so.

After that, evolves to horizontal branch and back up the giant branch before evolving into a white dwarf.

Old Populations:
Globular Cluster M3

In an old stellar population, massive stars have died out, so we see the phases of evolution corresponding to low mass stars.

MS: (lower) Main Sequence
TO: Turn Off
SGB: Subgiant Branch
BS: Blue Stragglers
RGB: Red Giant Branch
HB: Horizontal Branch
AGB: Asymptotic Giant Branch
P-AGB: Post AGB



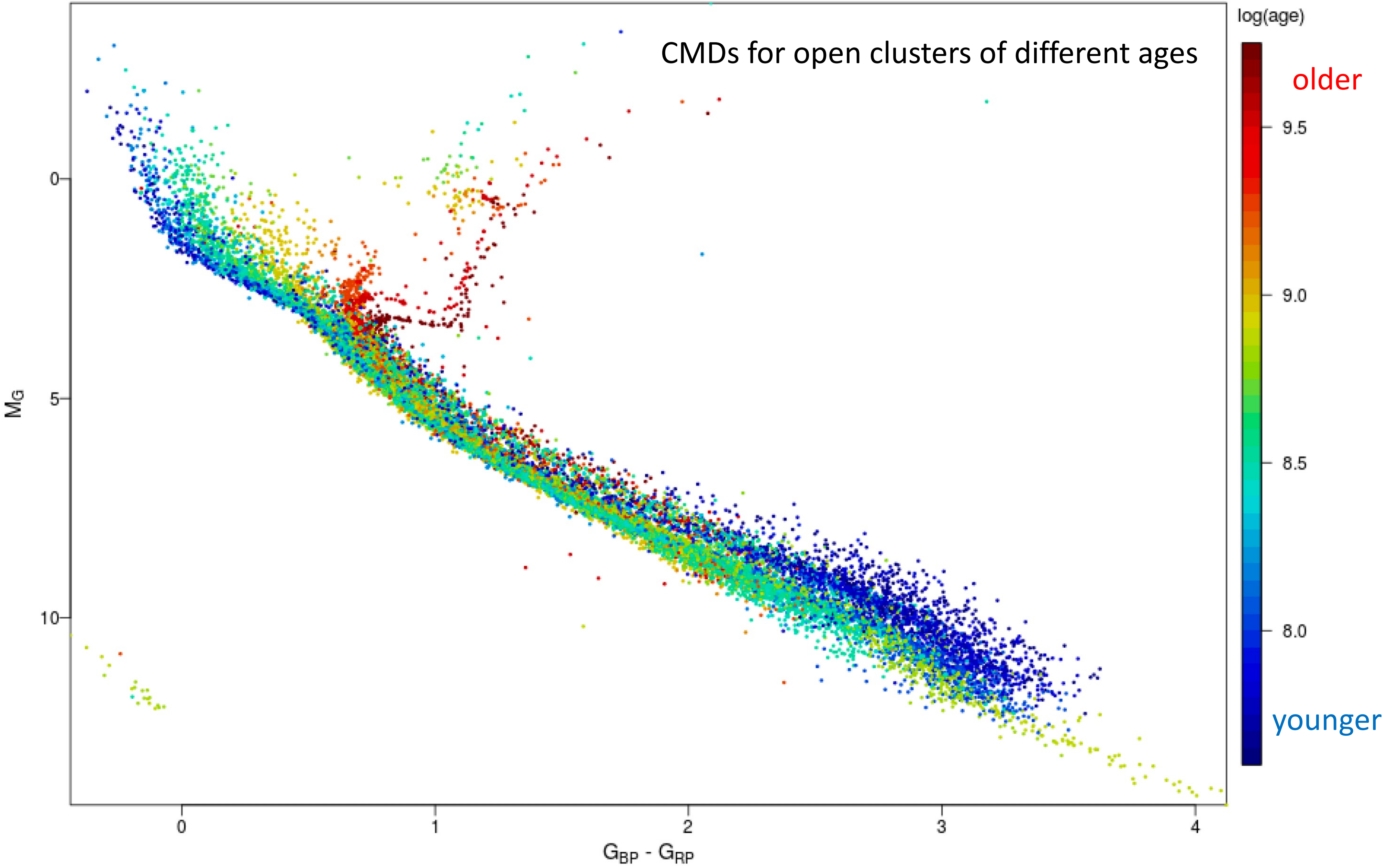


Fig. 2. Composite HRD for 32 open clusters, coloured according to log(age), using the extinction and distance moduli as determined from the *Gaia* data (Table 2).

Gaia 2018 (A&A 616 A10)

Young + Old Populations:
Dwarf Galaxy NGC 4068

In a mixed stellar population, we see massive stars forming/evolving as well as the older populations:

MS: Main Sequence
BHeB: Blue Helium Burning stars
RHeB: Red Helium Burning stars
TRGB: Tip of the Red Giant Branch
AGB: Asymptotic Giant Branch

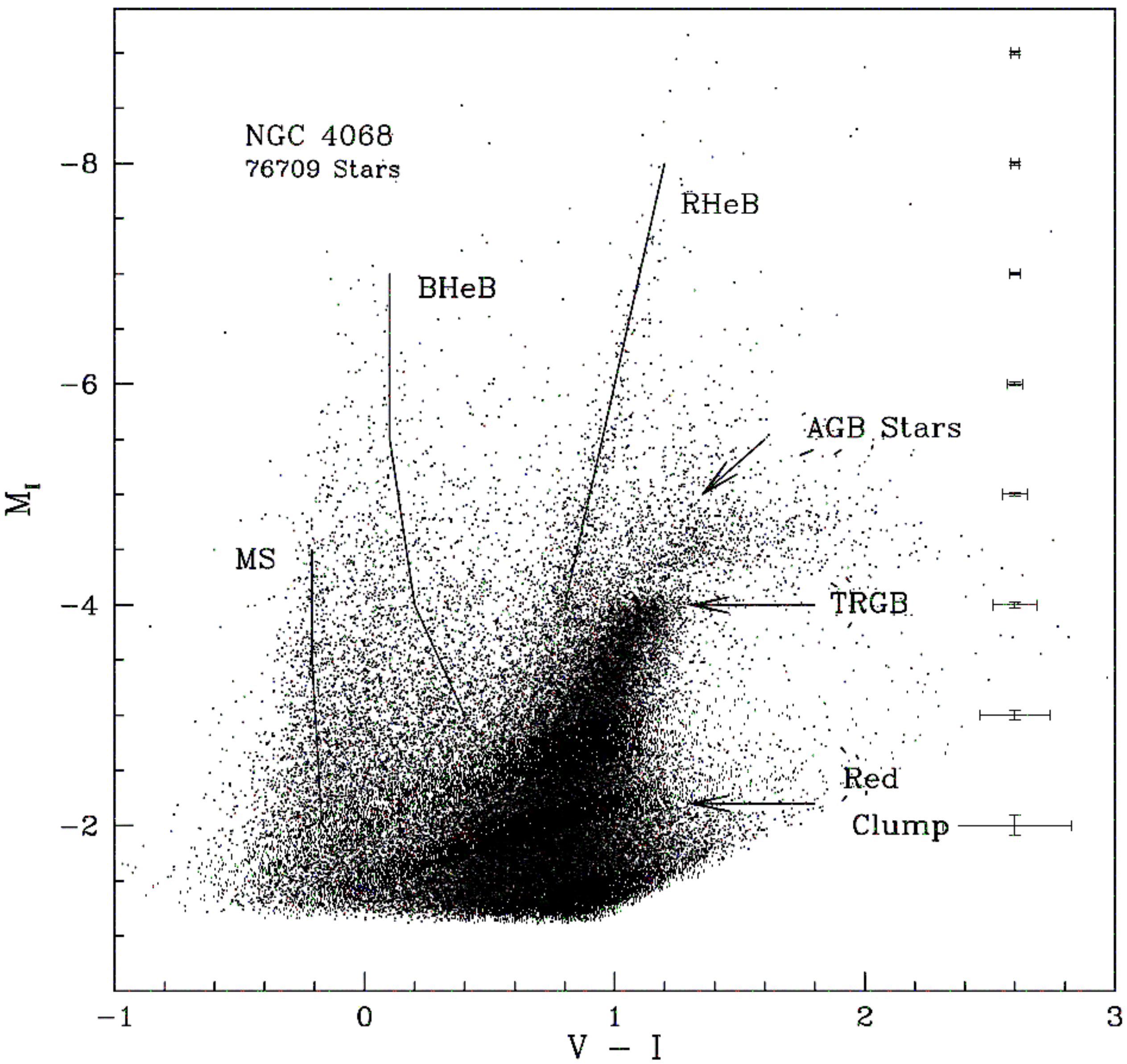


Figure 4. CMD of NGC 4068 with the evolutionary stages of the stellar populations labeled. The MS, BHeB, RHeB, RGB, AGB, and red clump evolutionary stages are all easily identified in the stellar populations.

The effect of metallicity

First, remember different ways of expressing metallicity (chemical composition)

Bracket Notation: logarithmic, relative to solar:

$$[X/H] = \log_{10}\{n(X)/n(H)\} - \log_{10}\{n(X)/n(H)\}_{\odot}$$

- $n(X)$ refers to the number density of atoms of element X
- $[X/H] = 0.0$ means solar abundance.
- $[Fe/H] = -1.0$ means that the abundance of iron is 1/10 that of the Sun.
- Often see $[M/H]$, which refers to the abundance of metals in general.

X, Y, Z Notation: mass fraction of hydrogen(X), helium(Y), and everything else (Z, or "metals")

- $X + Y + Z = 1.0$
- Solar: $X \approx 0.7,\ Y \approx 0.28,\ Z \approx 0.02$
- $Z = 0.002$ would be $1/10^{th}$ of solar.

Remember: when we measure the metallicity of a star, we are measuring the metallicity in its outer layers, not the overall metallicity.

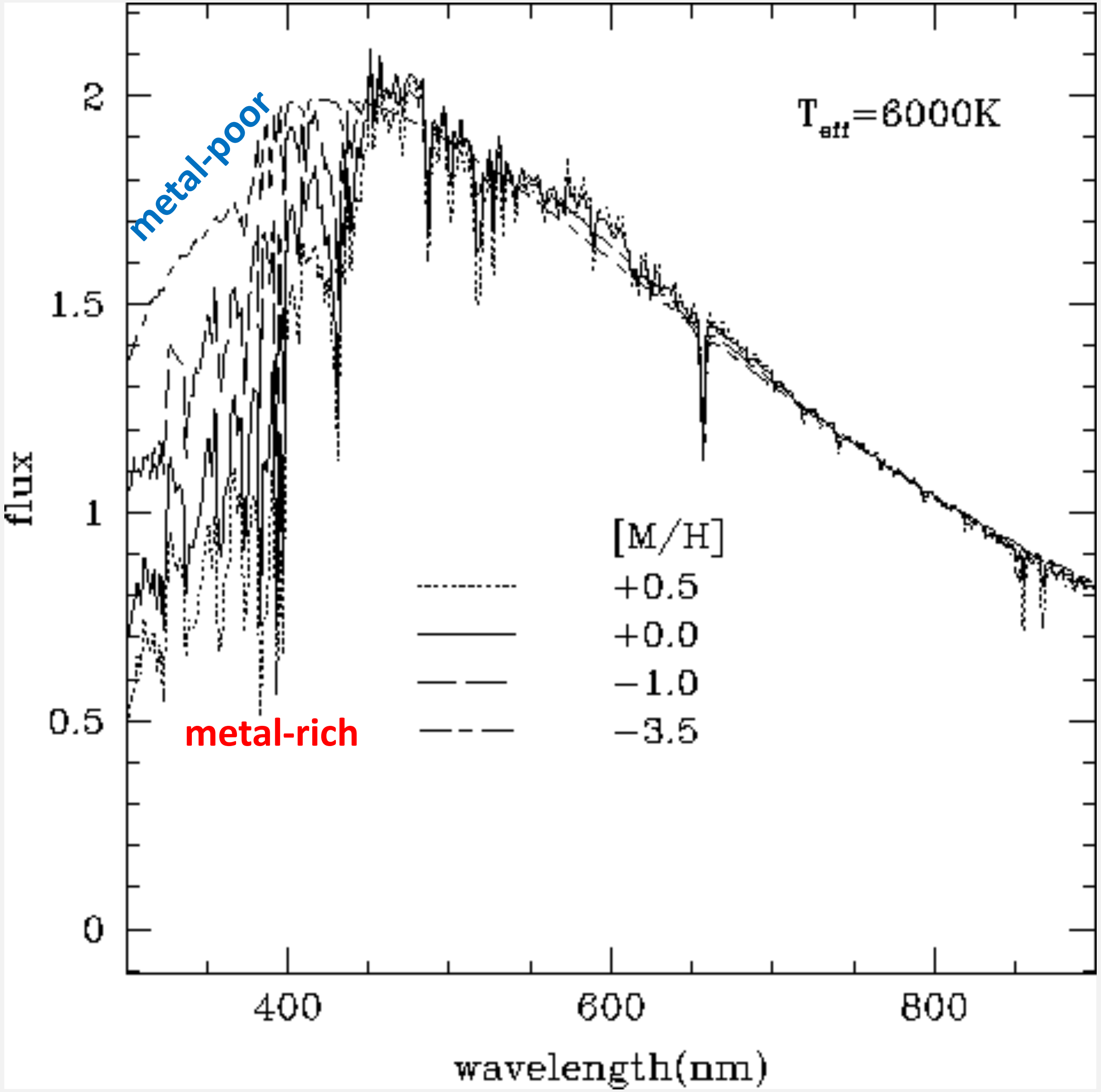
Abundances change in the interior due to nuclear reactions, but the metallicity of the outer layers does not change with time.

Metallicity of a star is determined largely by the gas it formed from.

Stellar populations evolve in metallicity over time, but individual stars do not.

The effect of metallicity

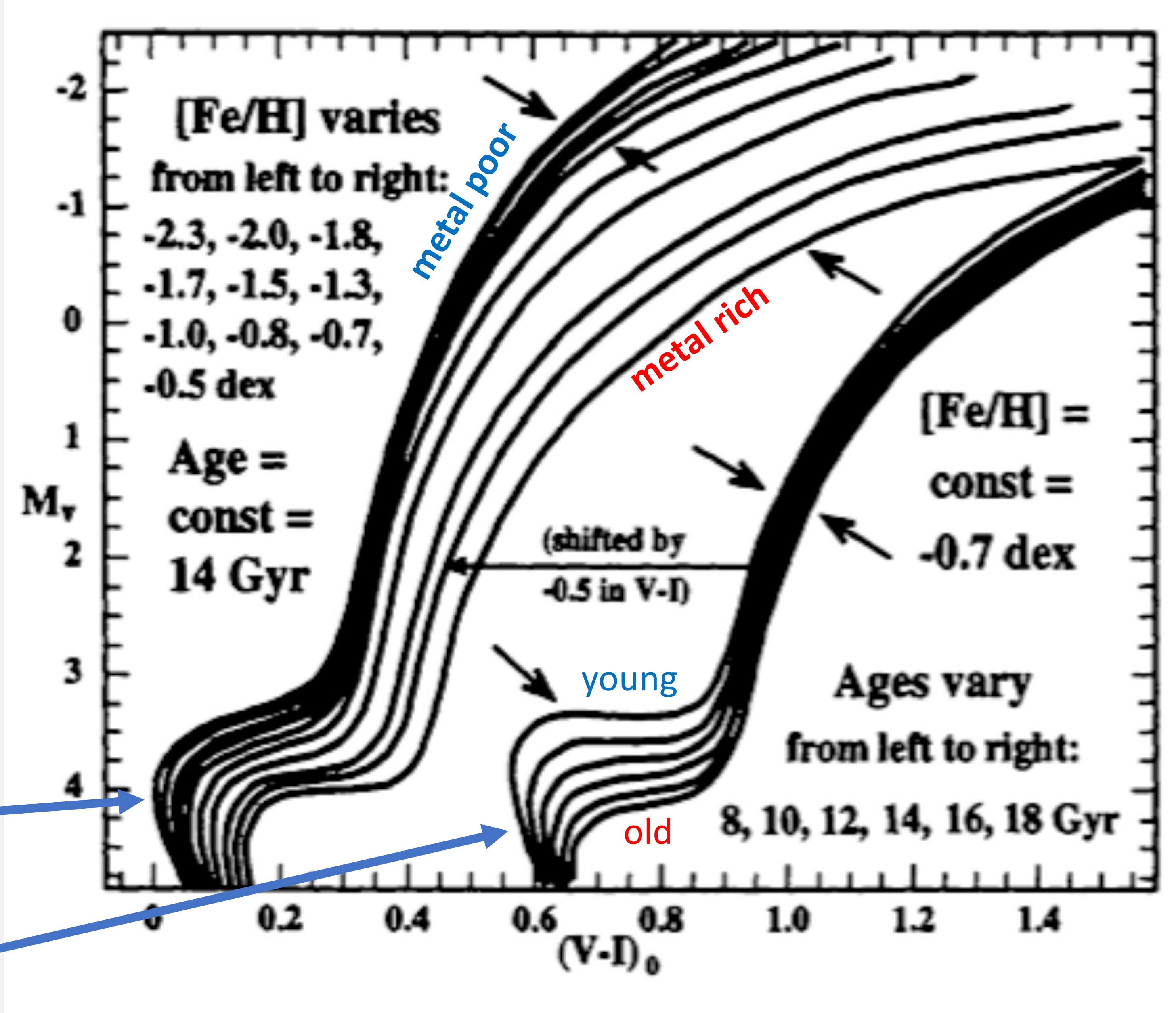
Line blanketing: Metals (particularly iron) absorb strongly in the blue part of the spectrum. So, metal rich stars appear redder.



The effect of metallicity

Line blanketing: Metals (particularly iron) absorb strongly in the blue part of the spectrum. So, metal rich stars appear redder.

Opacity: more metals mean greater absorption in the stellar envelopes. This bottles up the energy trying to get out, which makes the star swell up. Metal-rich red giants expand more, which makes them cooler and redder.



All these tracks
have been offset to the left for clarity, otherwise they would sit on top of these tracks

The effect of metallicity

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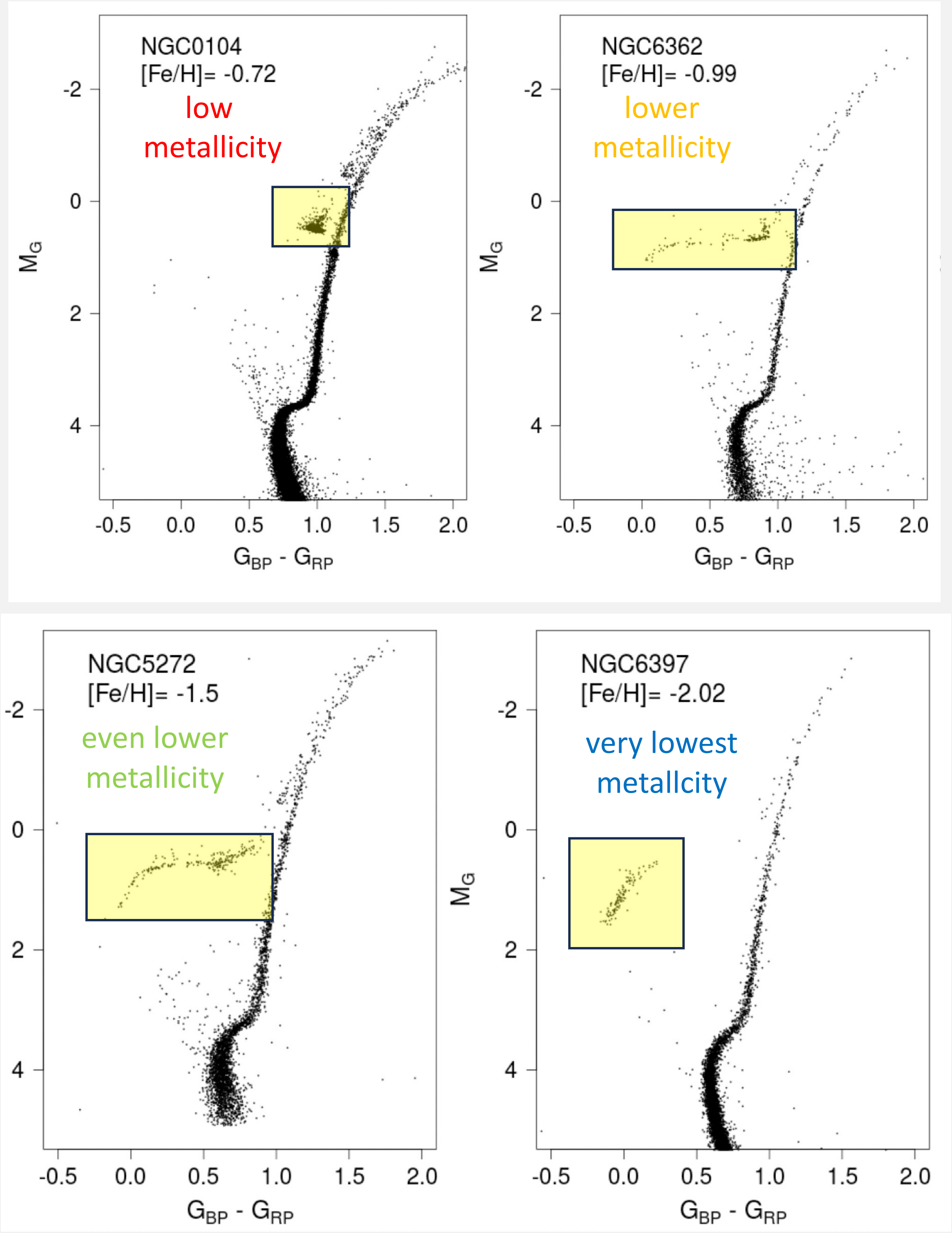
Horizontal Branch morphology: some combination of stellar evolution and atmosphere effects means that HB stars are, generally, bluer in metal poor pops.



Gaia 2018 (A&A 616 A10)

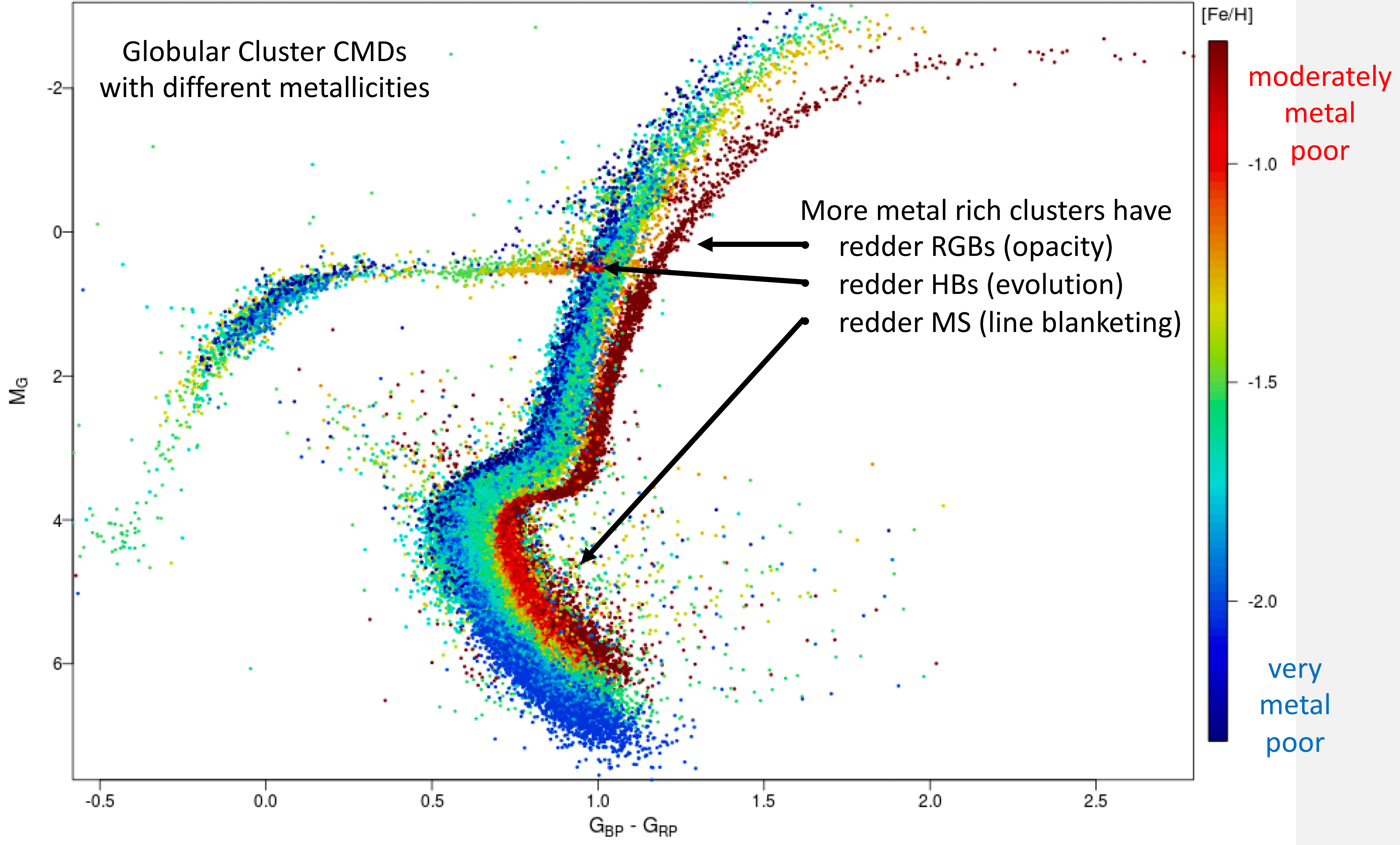


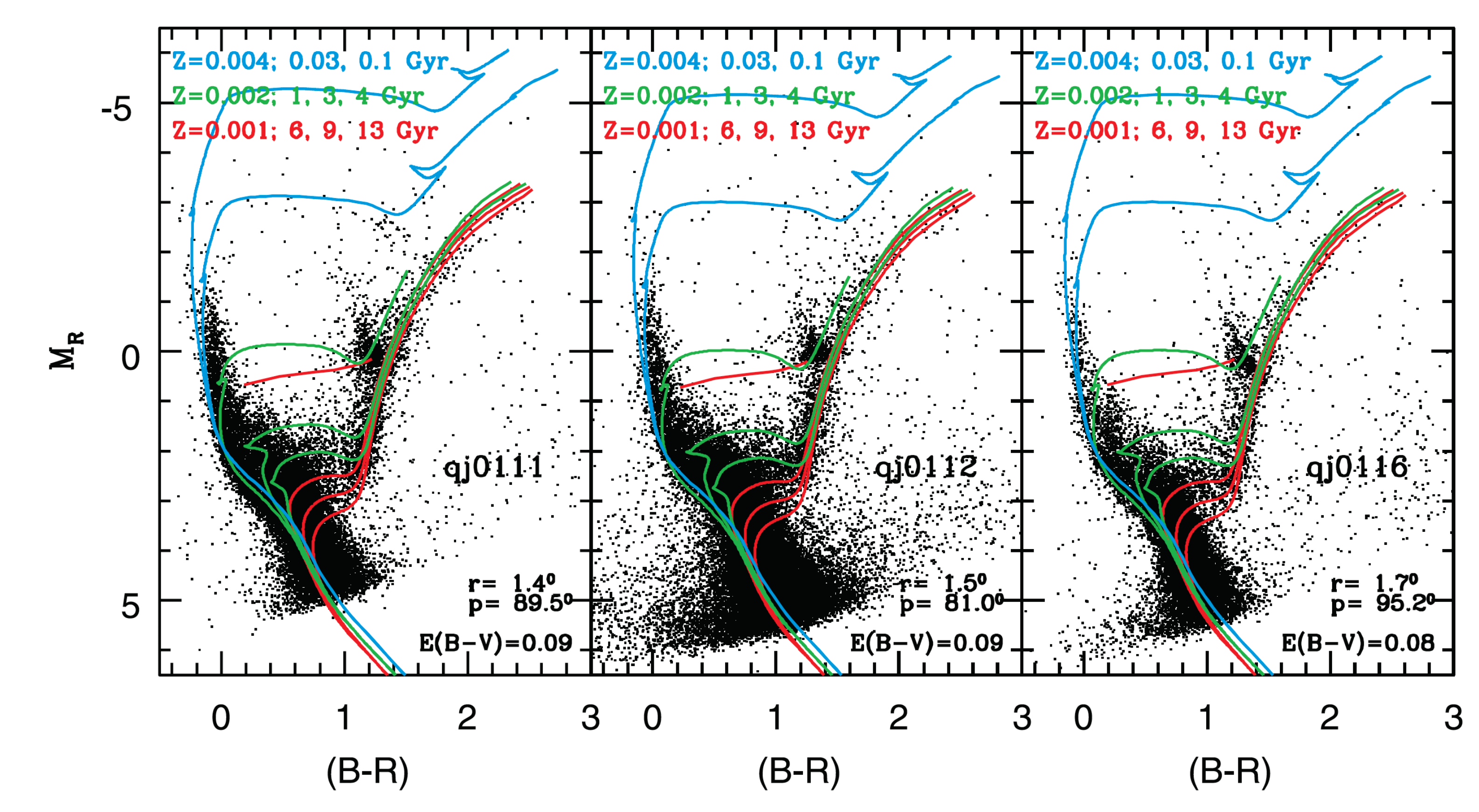
Fig. 3. Composite HRD for 14 globular clusters, coloured according to metallicity (Table 3).

Gaia 2018 (A&A 616 A10)

Studying Stellar Populations in Other Galaxies

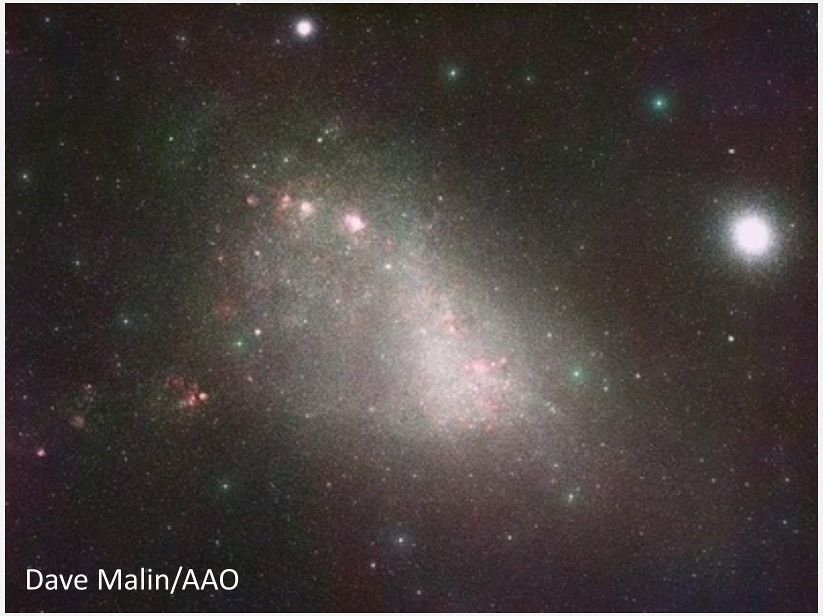
In the Milky Way, we see stars down to very low mass (at least locally). Can construct precise CMDs.

In other galaxies, this becomes difficult. For MW satellites, we can generally resolve stars down to the main sequence turnoff.



Noel+07:

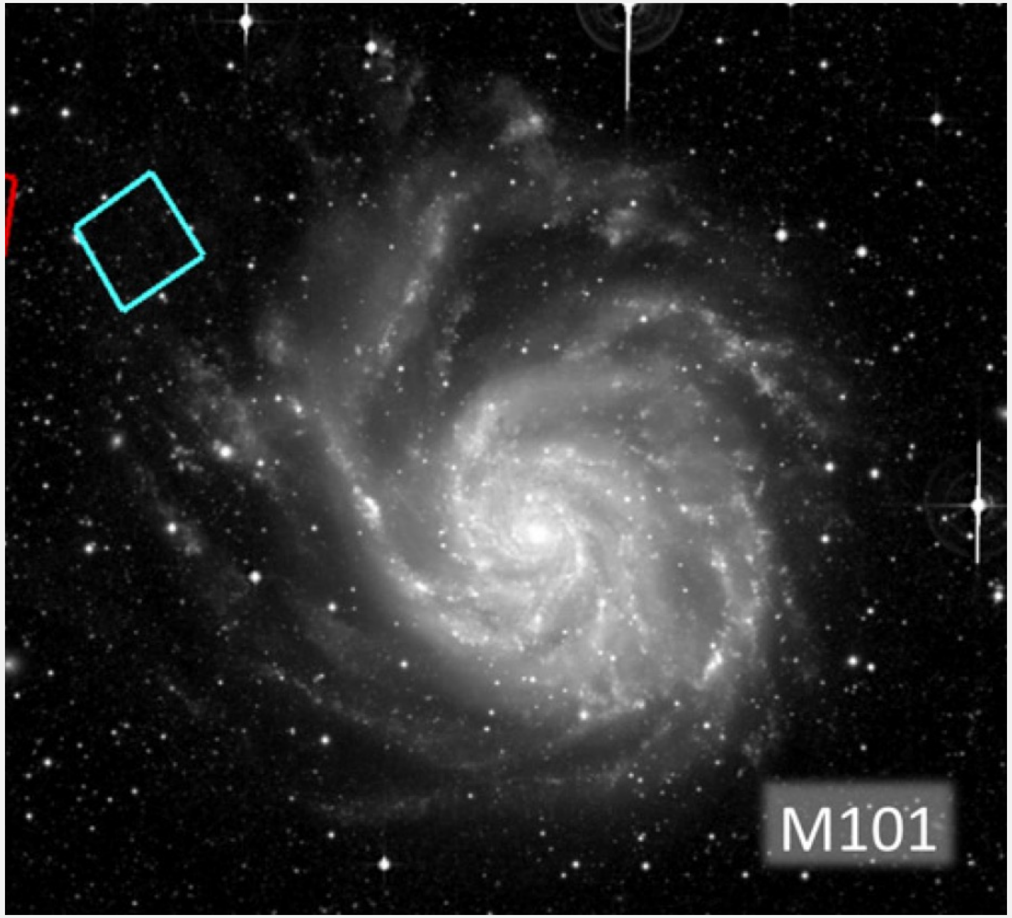
CMDs for fields in the Small Magellanic Cloud (D ≈ 60 kpc)

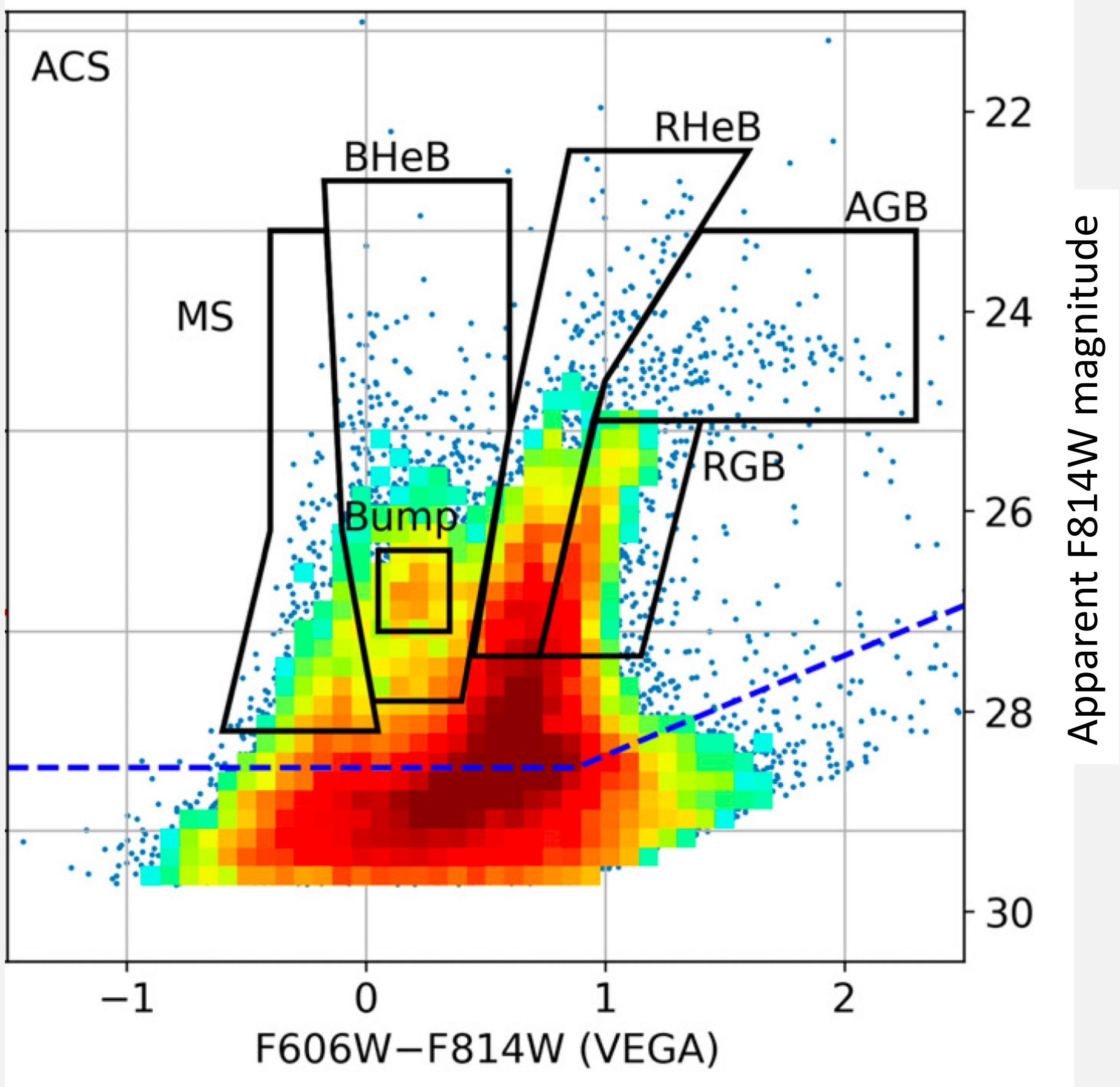


Studying Stellar Populations in Other Galaxies

For galaxies within the Local Volume (D<10 Mpc), we can see only down to the brightest MS turnoffs of a few hundred Myr:

M101 outer disk stars, D=7 Mpc
Mihos+18





Solar type stars are waaay down there, too faint to see.

Studying Stellar Populations in Other Galaxies

And out to the distance of the Virgo Cluster of Galaxies (D=16.5 Mpc), painstaking work only gets us the RGB/AGB.

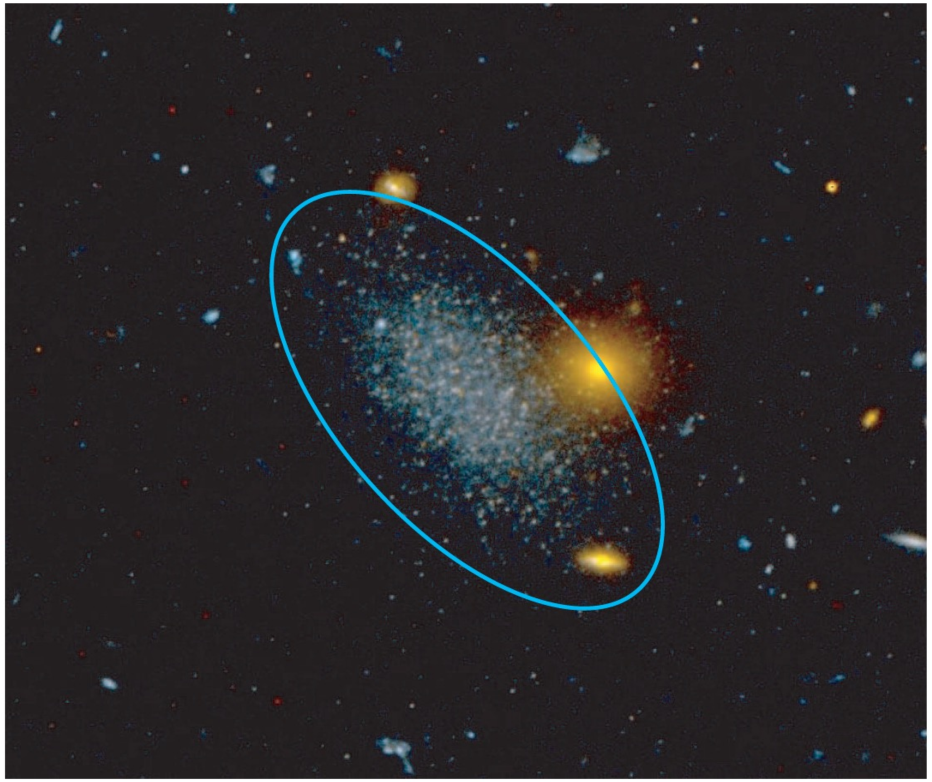


FIG. 1.—Color image of a 28″ × 24″ section of our image, centered on the dSph galaxy. In the image, blue represents 2(F606W − F814W), green represents F606W, and red represents F814W. The ellipse denotes the boundary used to defined a subsample of stars that minimizes contamination (see text). North is to the top, and east is to the left.

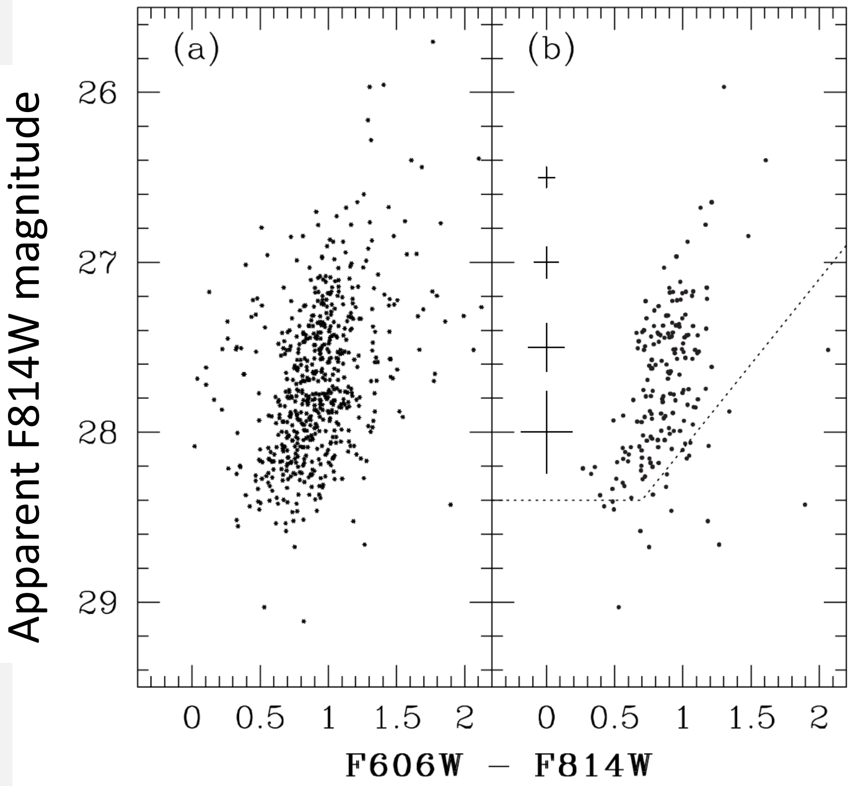


FIG. 4.—(*a*) Color-magnitude diagram (in the Vegamag system) for the 611 stellar objects located in a 66″ × 48″ region centered on the dSph galaxy. (*b*) The "dwarf-only" CMD, formed from a subset of 181 stars located within the inner elliptical region shown in Fig. 1. The dotted lines denote the 50% completeness levels, while the error bars represent the typical photometric uncertainties. Note the discontinuity at F814W ∼ 27.1; this is the tip of the red giant branch.

RGB stars in a Virgo Cluster dwarf galaxy.

Durrell+07

Studying Stellar Populations in Other Galaxies

*For galaxies far away, we only have **integrated light**: the summed light of all the stars put together. Need to think about how this light behaves.*

Coma Cluster

Studying Stellar Populations in Other Galaxies

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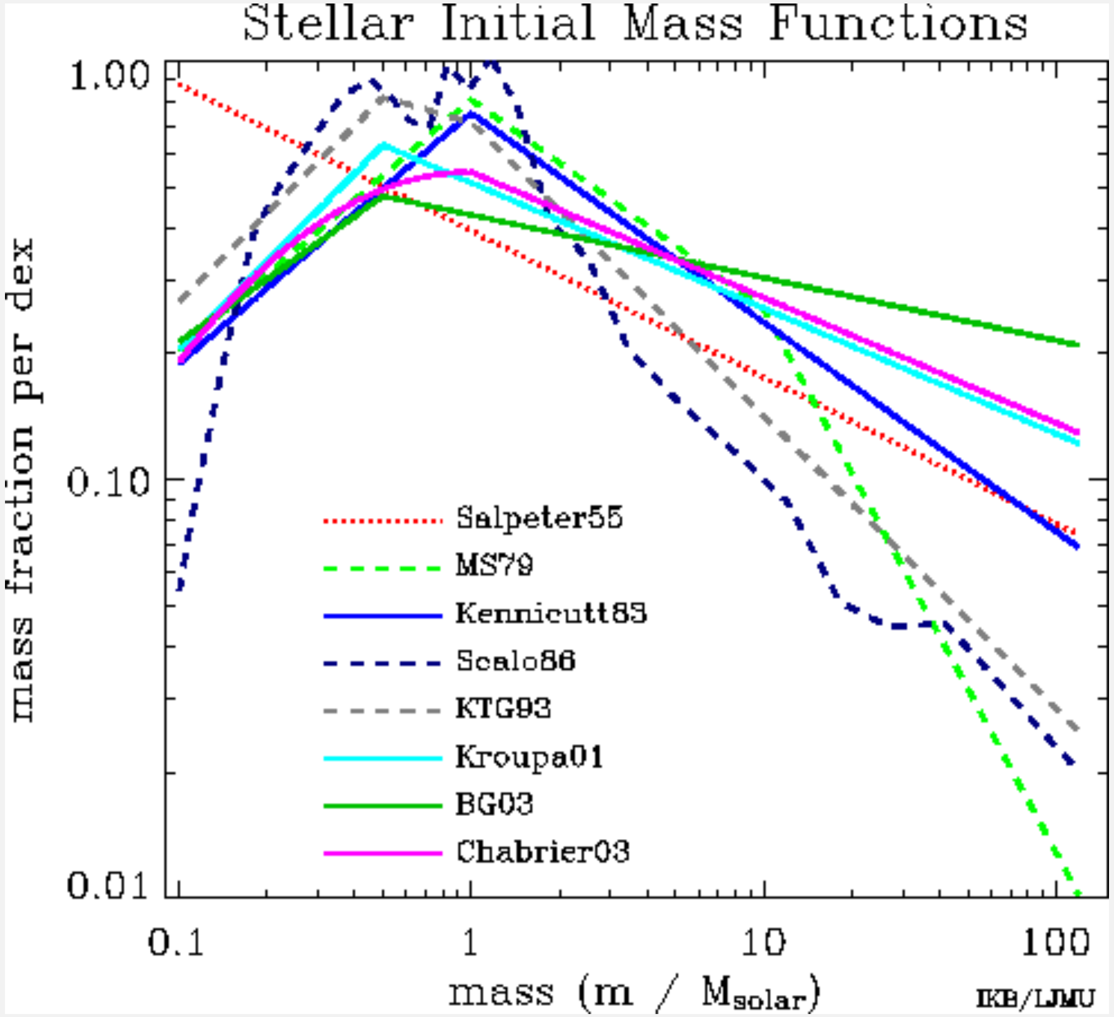
Population Synthesis Concepts

I: We need to know how stars are formed:

- Star formation rate: SFR(t)
- Initial mass function (IMF): N(M)

Easy analytic (but not really correct) IMF is the Salpeter IMF:

$$N(M)dM = CM^{-2.35}dM$$



Courtesy Ivan Baldry

Studying Stellar Populations in Other Galaxies

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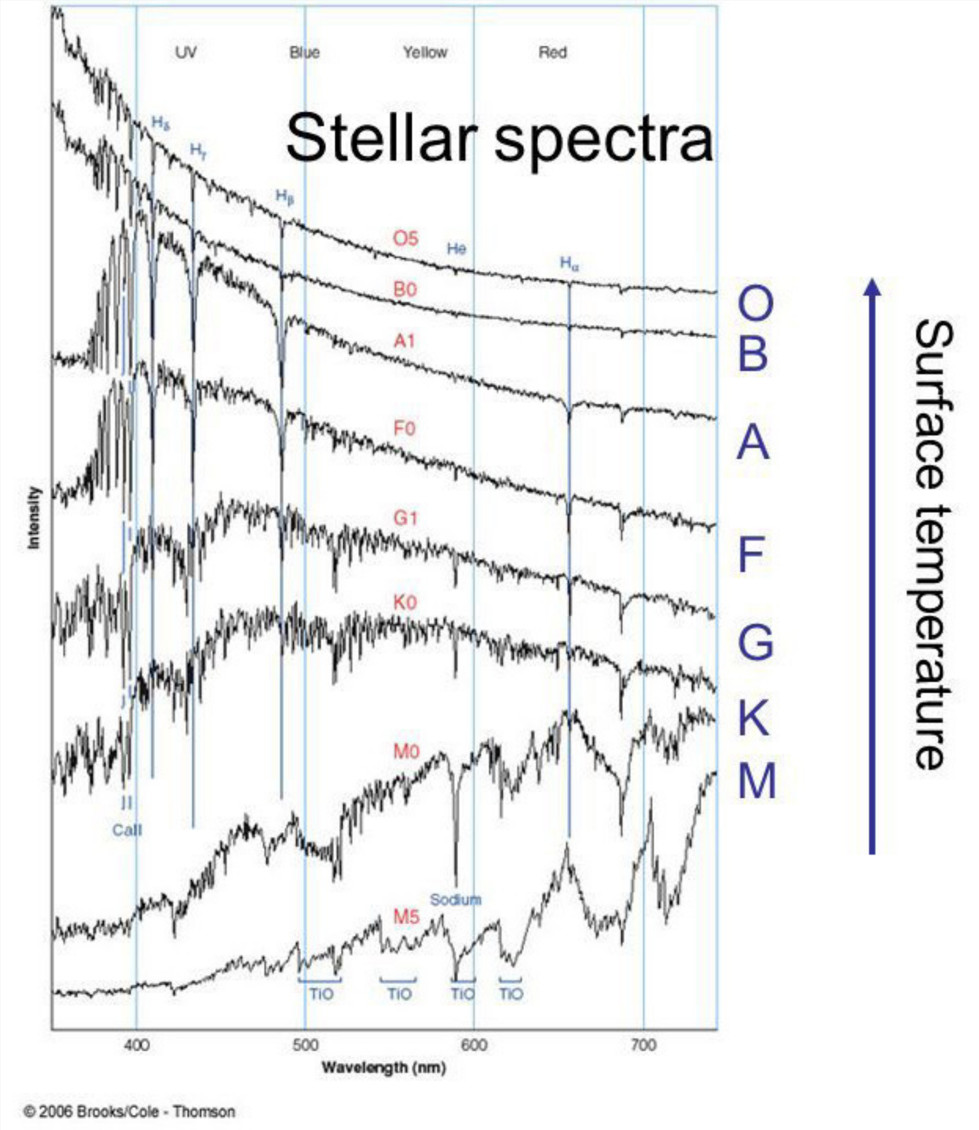
II: We need to know the light output of stars:

- Stellar interiors and energy production
- Stellar atmospheres, spectra, and colors



Studying Stellar Populations in Other Galaxies

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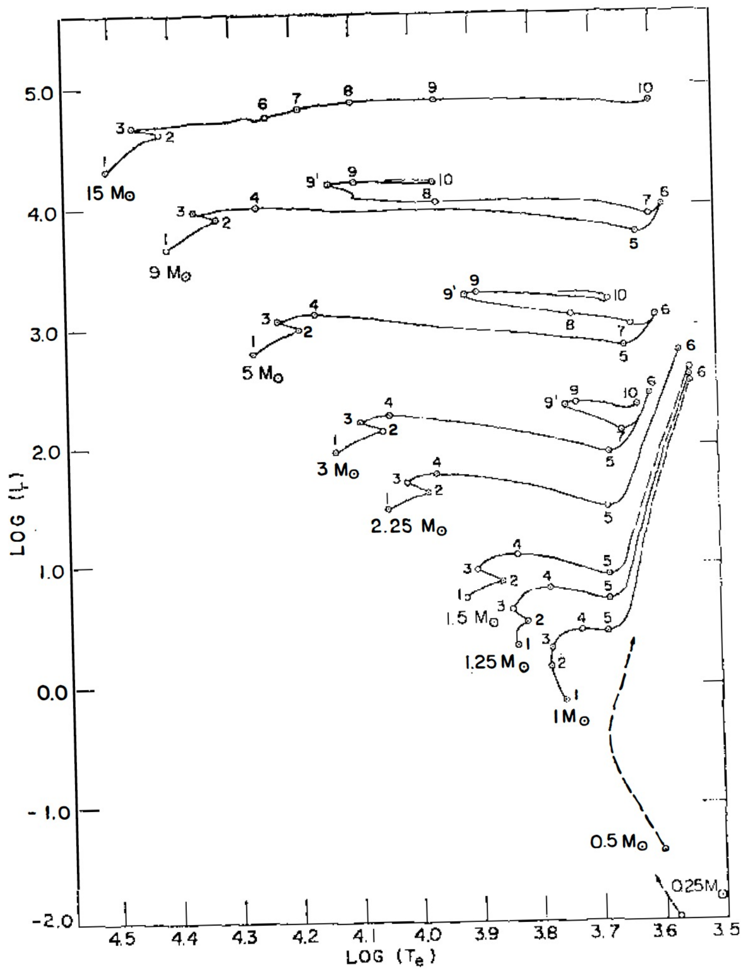
- Star formation rate: SFR(t)
- Initial mass function (IMF): N(M)

II: We need to know the light output of stars:
- Stellar interiors and energy production
- Stellar atmospheres, spectra, and colors

III: We need to know how stars evolve with time:
- As a function of mass
- As a function of metallicity

Integrated light is the integral of all these messy things!



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