Integrated Stellar Populations

What is a stellar population?

Simple cases: star clusters

Single age, single metallicity

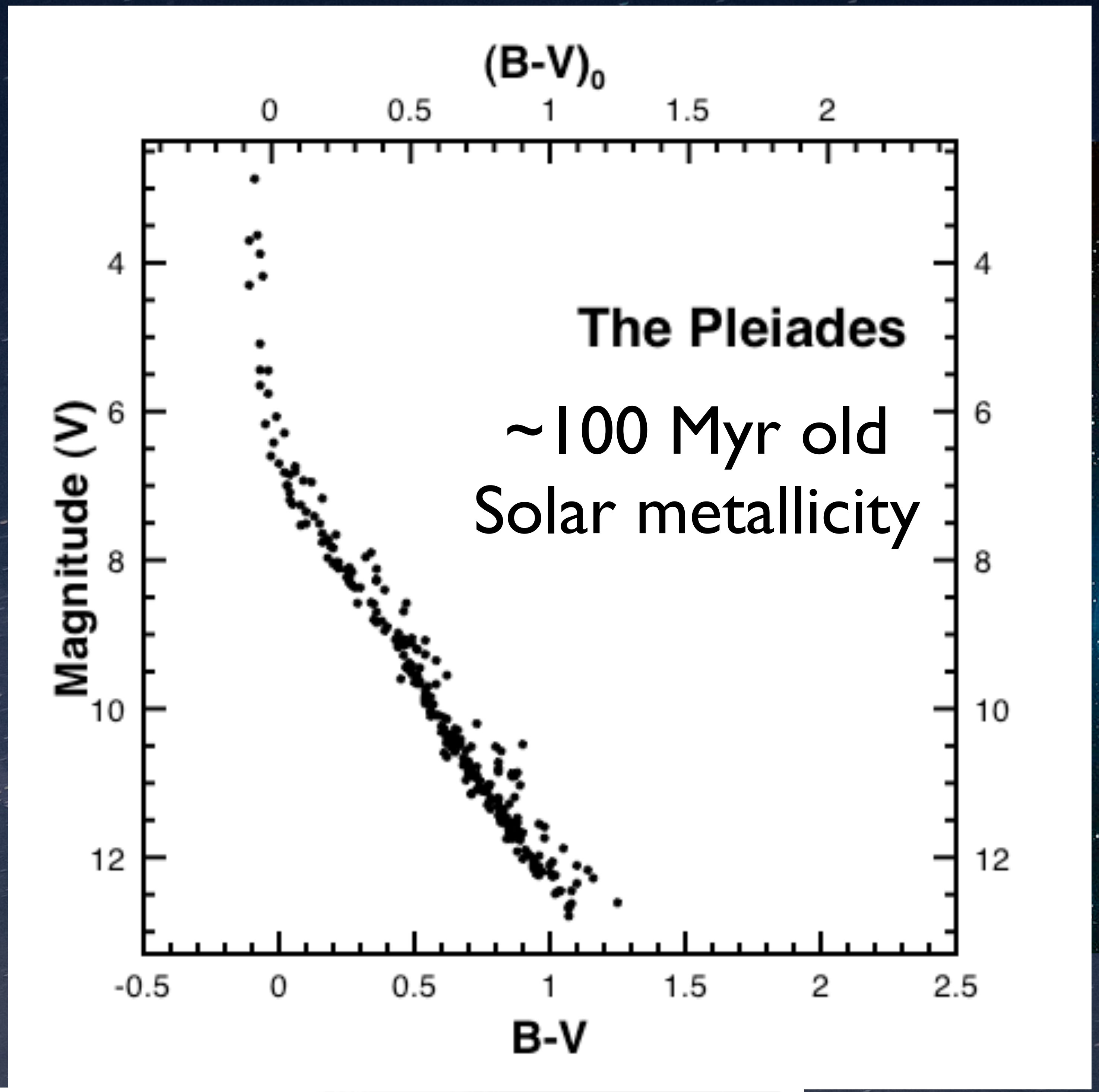
Open Clusters

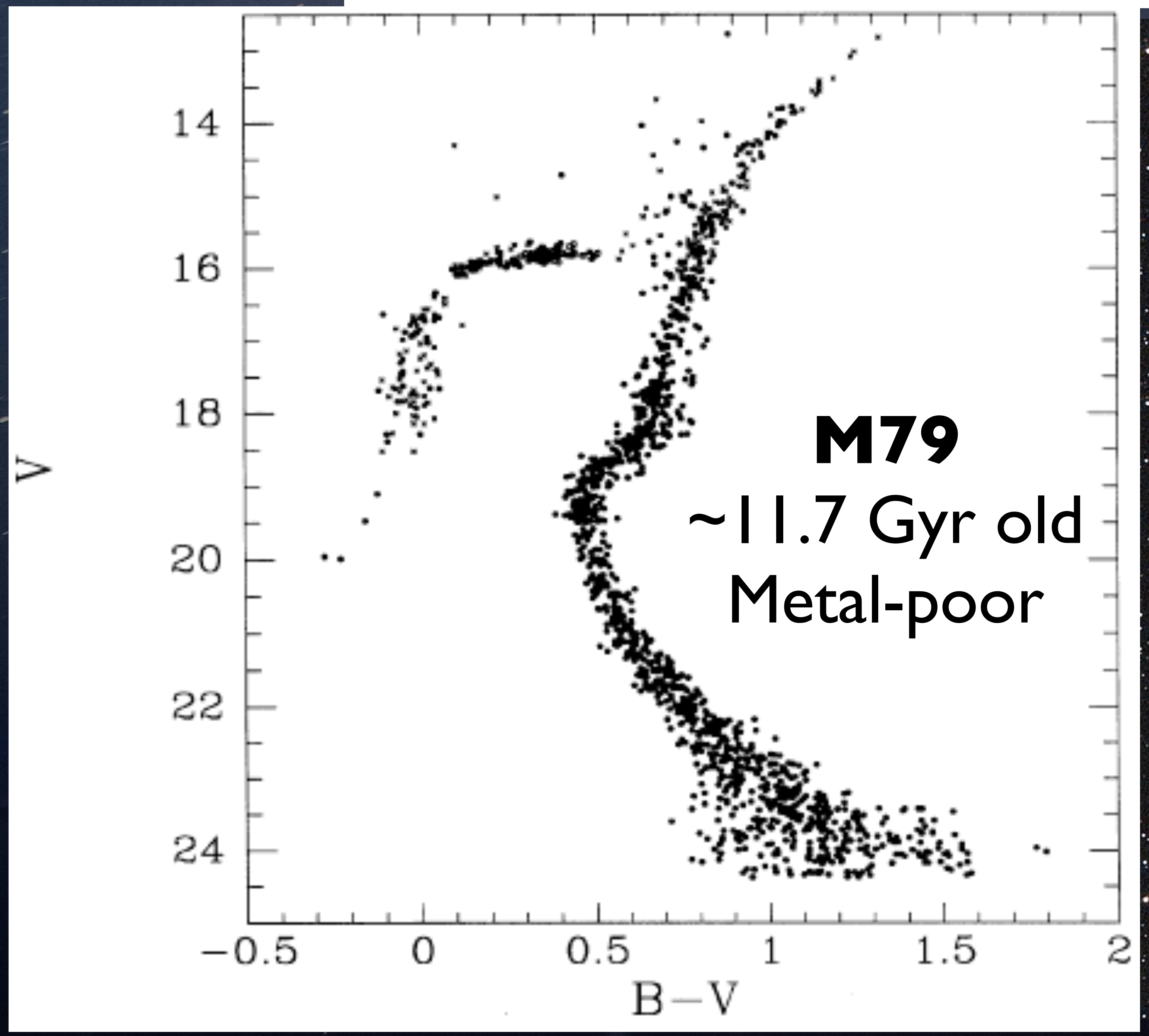
Young, main sequence fully populated

Globular Clusters

Old, upper main sequence missing

Red giant branch and horizontal branch stars present



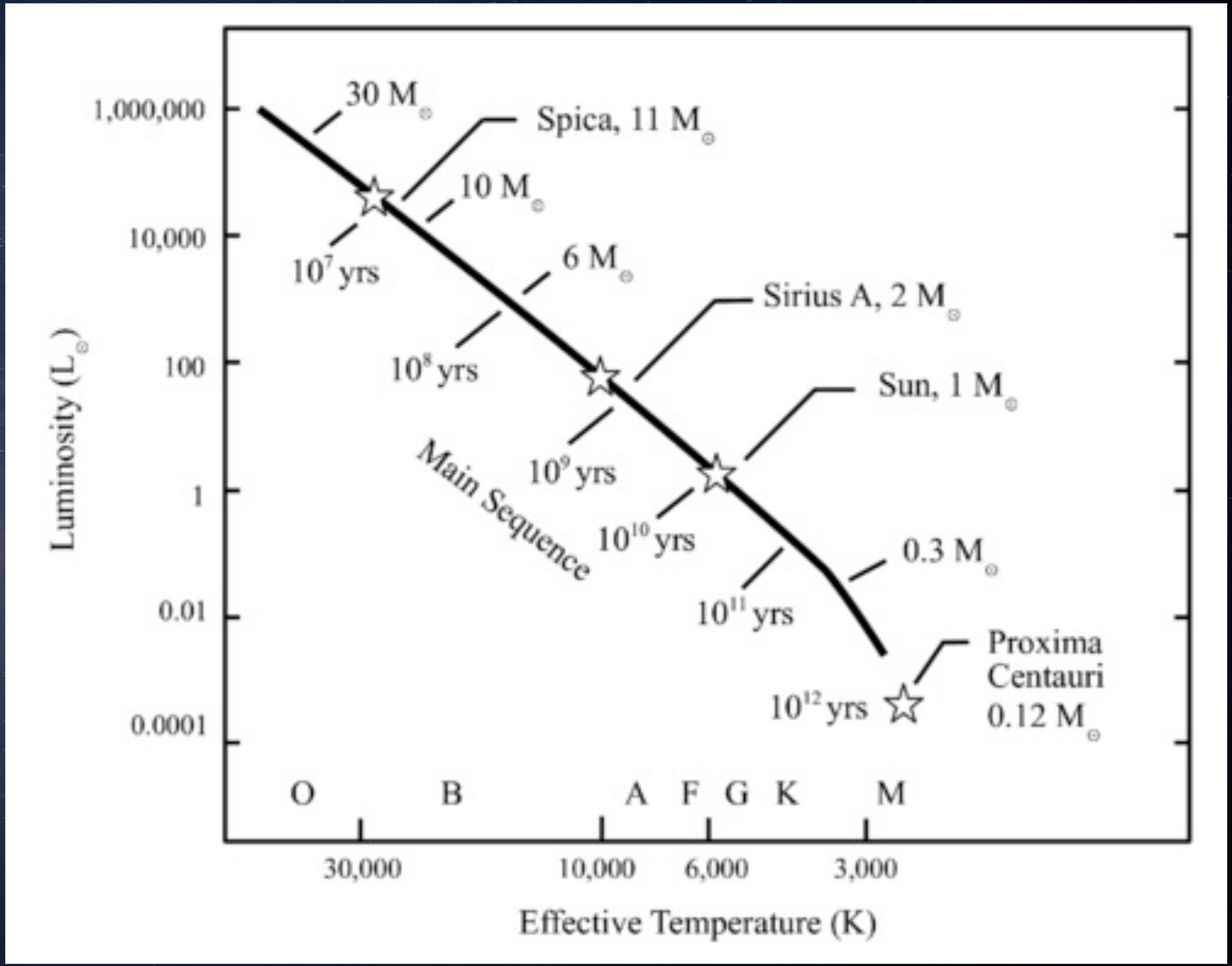


Stellar Evolution Review:
Main-Sequence Lifetime

Stars are burning H ➔ He in their core

Fusion rate is higher for more massive stars:

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



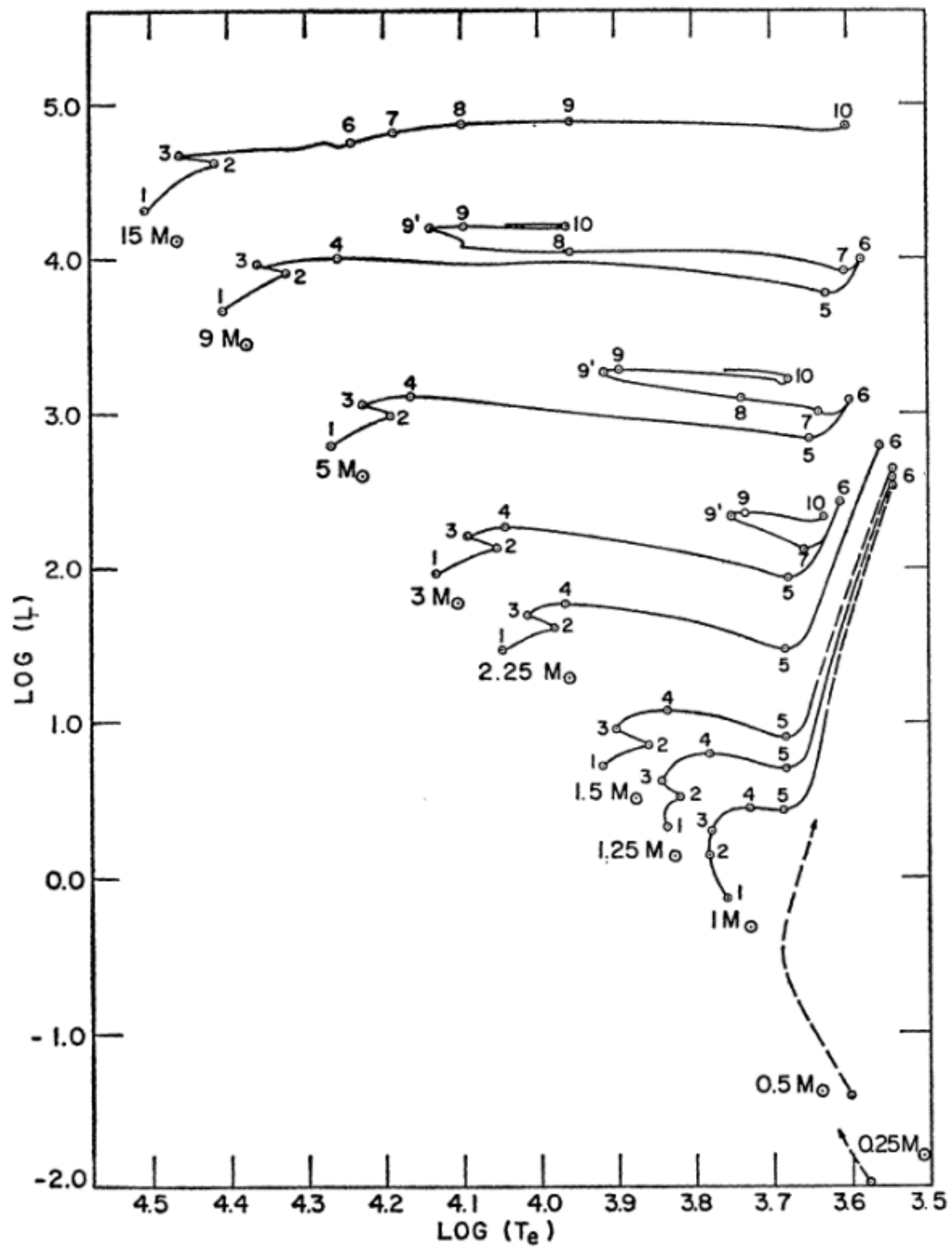


FIG. 3. Paths in the H-R diagram for metal-rich stars of mass $(M/M_\odot) = 15$, 9, 5, 3, 2.25, 1.5, 1.25, 1, 0.5, 0.25. Units of luminosity and surface temperature are the same as in Figure 1. Traversal times between labeled points are given in Tables III and IV. Dashed portions of evolutionary paths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

STELLAR LIFETIMES (yr)[a]

Mass ($M_\odot$) \ Interval ($i-j$)	(6–7)	(7–8)	(8–9)	(9–10)
15	7.17 (5)	6.20 (5)	1.9 (5)	3.5 (4)
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 Review:

Stellar Evolution

Theoretical evolutionary tracks

Tick marks on plot show ages in table

Iben 1968

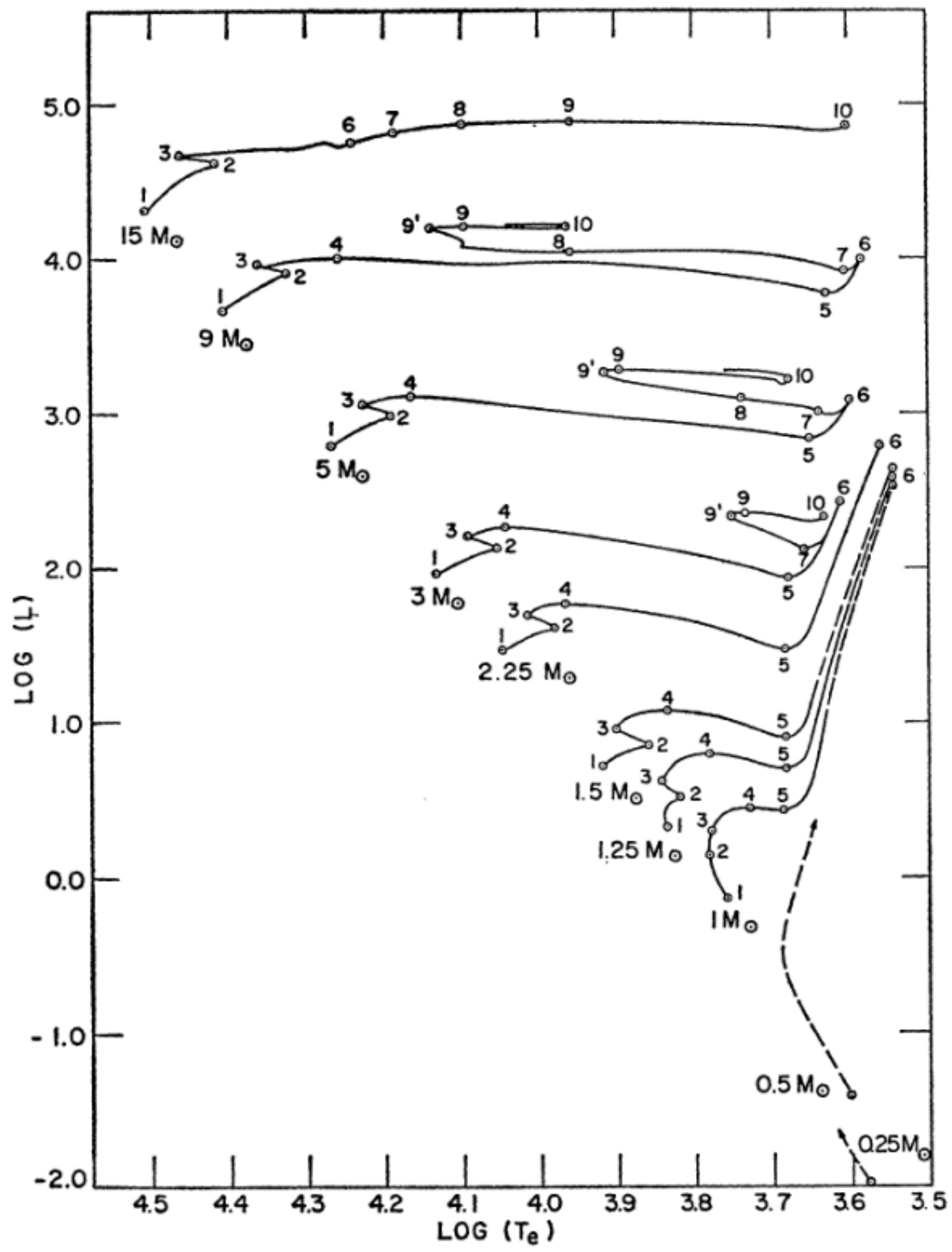


FIG. 3. Paths in the H-R diagram for metal-rich stars of mass $(M/M_{\odot}) = 15$, 9, 5, 3, 2.25, 1.5, 1.25, 1, 0.5, 0.25. Units of luminosity and surface temperature are the same as in Figure 1. Traversal times between labeled points are given in Tables III and IV. Dashed portions of evolutionary paths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

STELLAR LIFETIMES (yr)[a]

Mass ($M_{\odot}$) \ Interval ($i-j$)	(6–7)	(7–8)	(8–9)	(9–10)
15	7.17 (5)	6.20 (5)	1.9 (5)	3.5 (4)
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 Review:

Stellar Evolution

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

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

Dies only a few Myr after it evolves off MS

Iben 1968

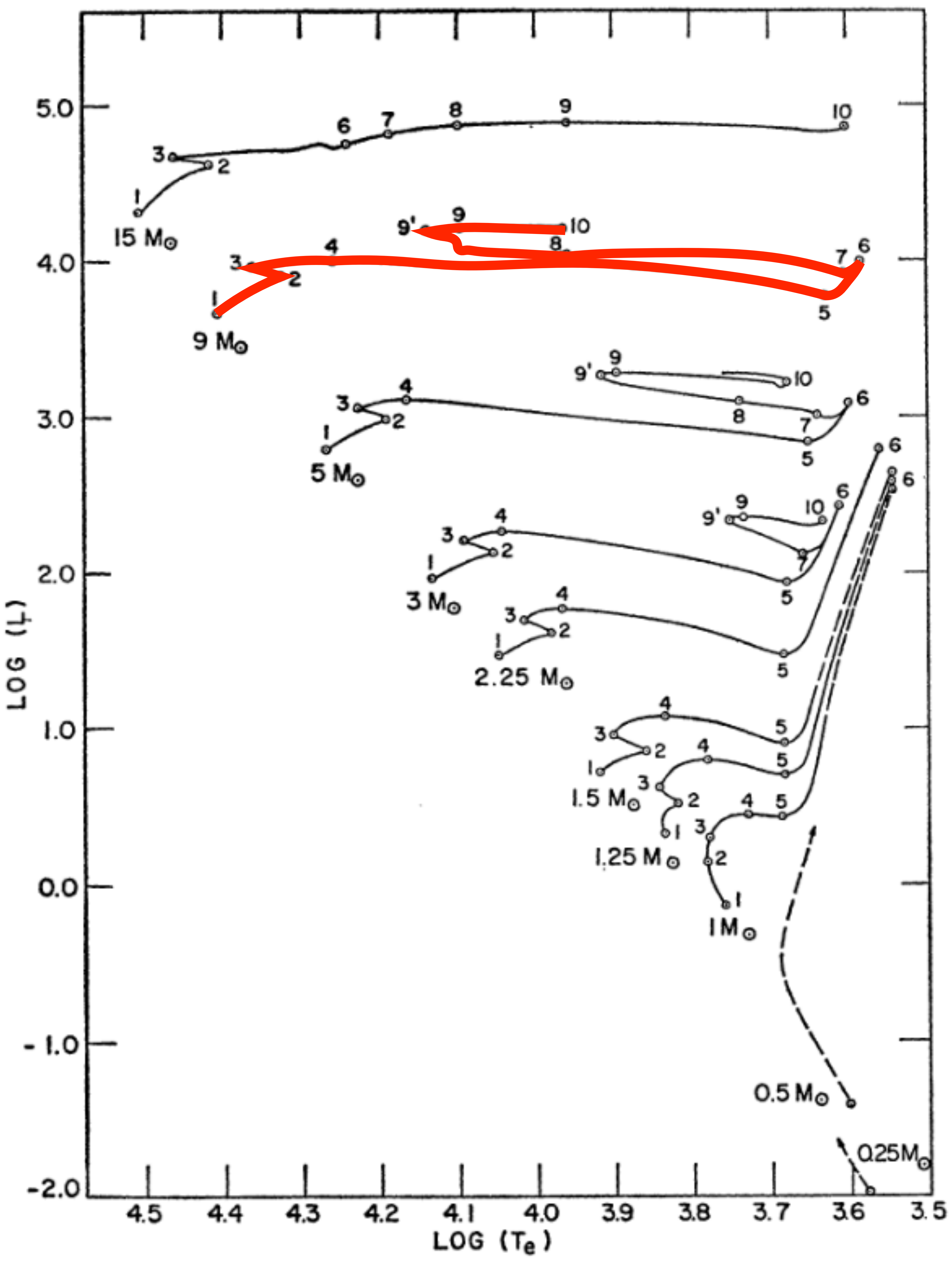


FIG. 3. Paths in the H-R diagram for metal-rich stars of mass $(M/M_\odot)$ = 15, 9, 5, 3, 2.25, 1.5, 1.25, 1, 0.5, 0.25. Units of luminosity and surface temperature are the same as in Figure 1. Traversal times between labeled points are given in Tables III and IV. Dashed portions of evolutionary paths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

STELLAR LIFETIMES (yr)[a]

Mass ($M_\odot$) \ Interval ($i-j$)	(6–7)	(7–8)	(8–9)	(9–10)
15	7.17 (5)	6.20 (5)	1.9 (5)	3.5 (4)
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 Review:

Stellar Evolution

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

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

Dies only a few Myr after it evolves off MS

Iben 1968

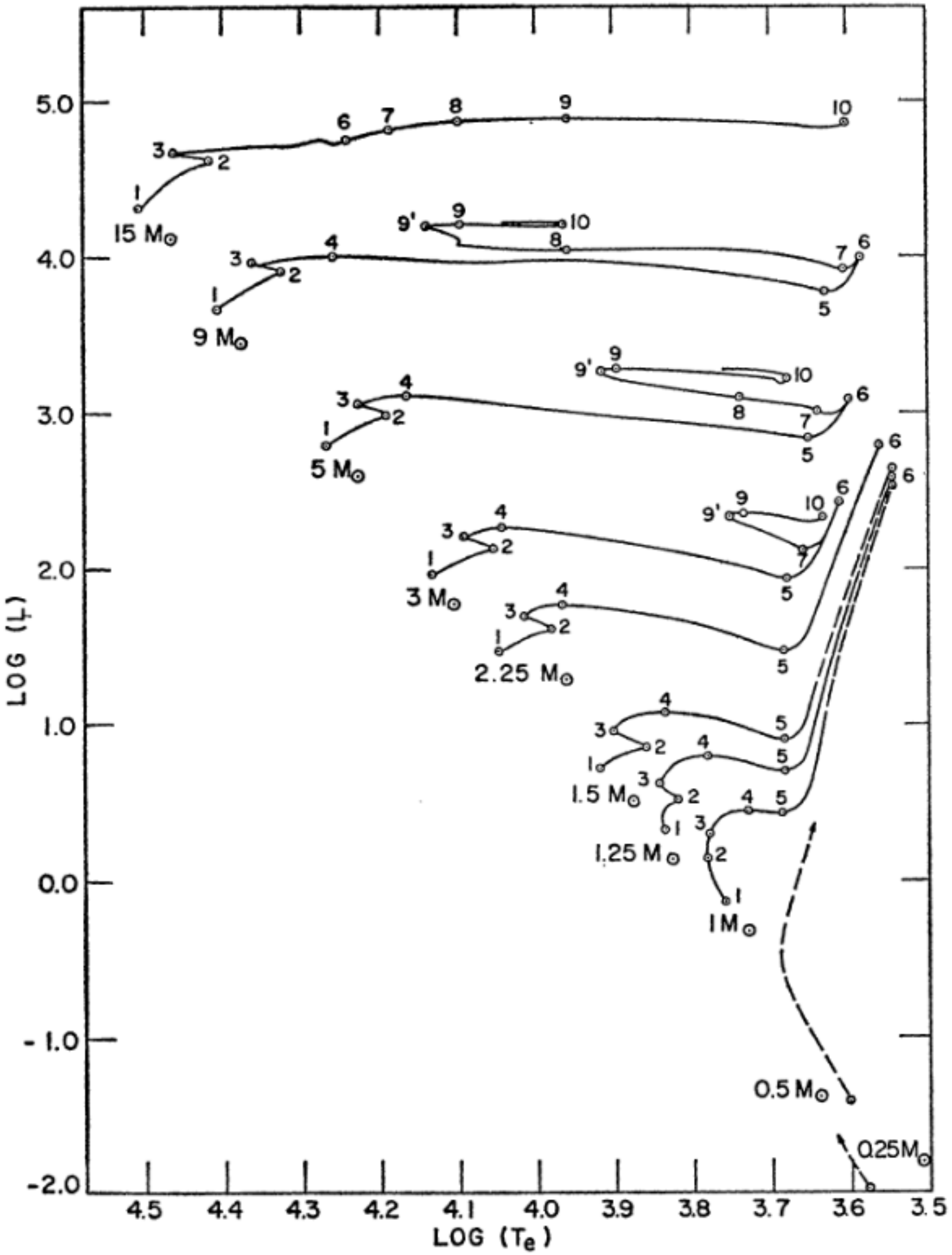


FIG. 3. Paths in the H-R diagram for metal-rich stars of mass $(M/M_\odot) = 15$, 9, 5, 3, 2.25, 1.5, 1.25, 1, 0.5, 0.25. Units of luminosity and surface temperature are the same as in Figure 1. Traversal times between labeled points are given in Tables III and IV. Dashed portions of evolutionary paths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

STELLAR LIFETIMES (yr)[a]

Mass ($M_\odot$) \ Interval ($i-j$)	(6–7)	(7–8)	(8–9)	(9–10)
15	7.17 (5)	6.20 (5)	1.9 (5)	3.5 (4)
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.

Iben 1968

Stellar Evolution Review:

Stellar Evolution

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

Evolves up on the CMD: "red giant stars"

Lives as a red giant for another Gyr or so

Evolves to horizontal branch and back up the giant branch: "asymptotic giant"

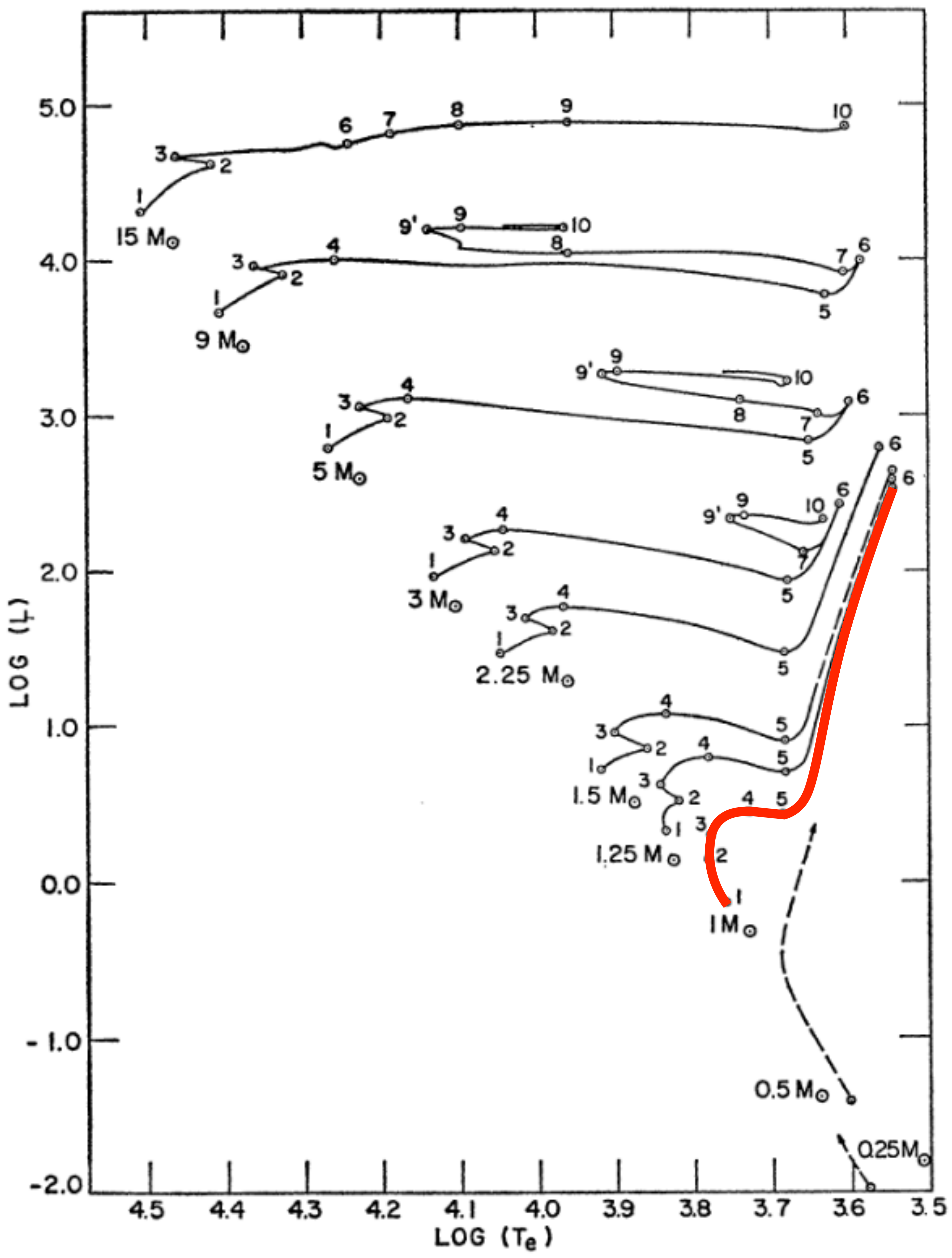


FIG. 3. Paths in the H-R diagram for metal-rich stars of mass $(M/M_\odot)=15$, 9, 5, 3, 2.25, 1.5, 1.25, 1, 0.5, 0.25. Units of luminosity and surface temperature are the same as in Figure 1. Traversal times between labeled points are given in Tables III and IV. Dashed portions of evolutionary paths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

STELLAR LIFETIMES (yr)[a]

Mass ($M_\odot$) \ Interval ($i-j$)	(6–7)	(7–8)	(8–9)	(9–10)
15	7.17 (5)	6.20 (5)	1.9 (5)	3.5 (4)
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.

Iben 1968

Stellar Evolution Review:

Stellar Evolution

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

Evolves up on the CMD: "red giant stars"

Lives as a red giant for another Gyr or so

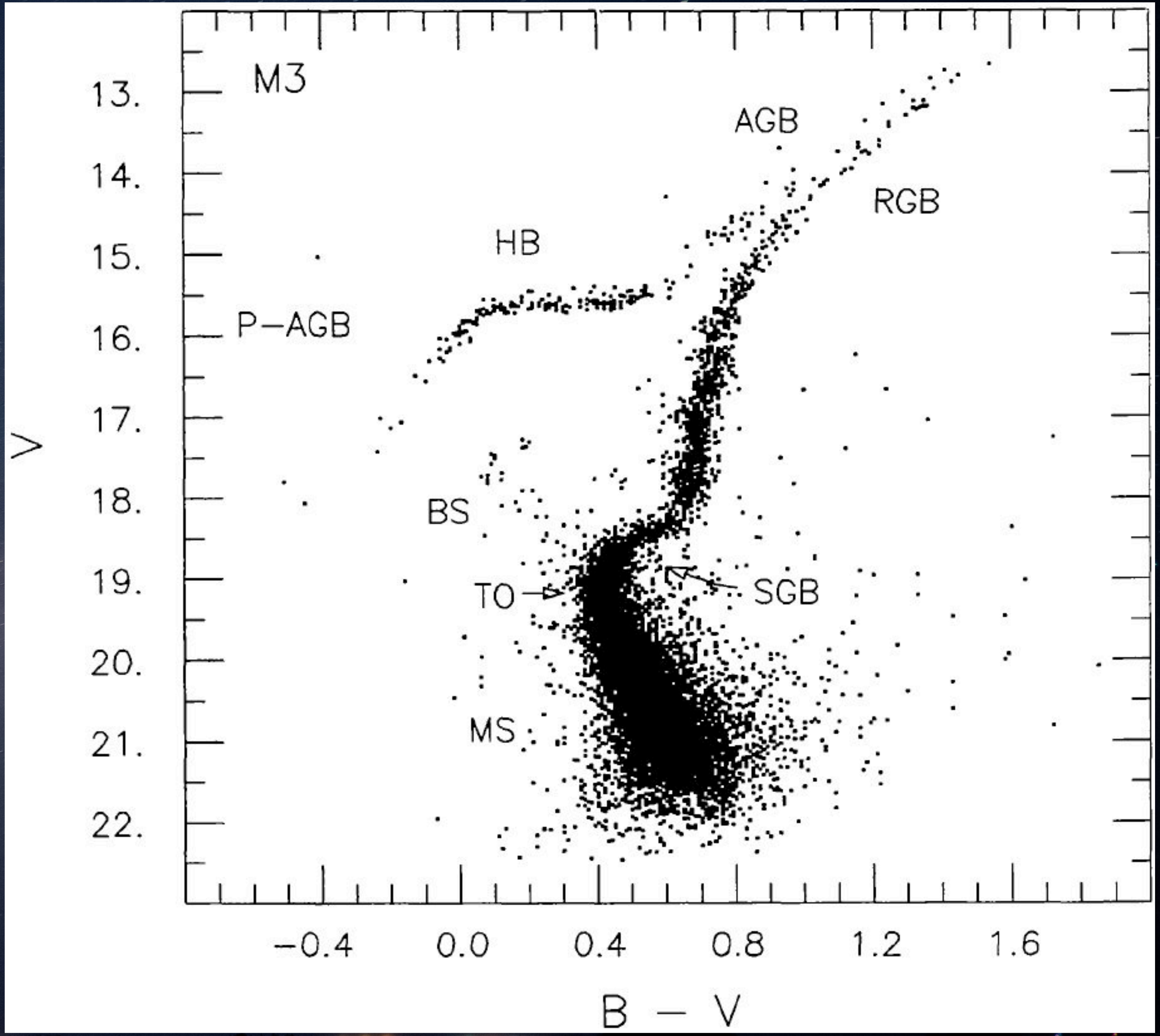
Evolves to horizontal branch and back up the giant branch: "asymptotic giant"

Globular Cluster M3

In old stellar populations, we see all these phases of evolution

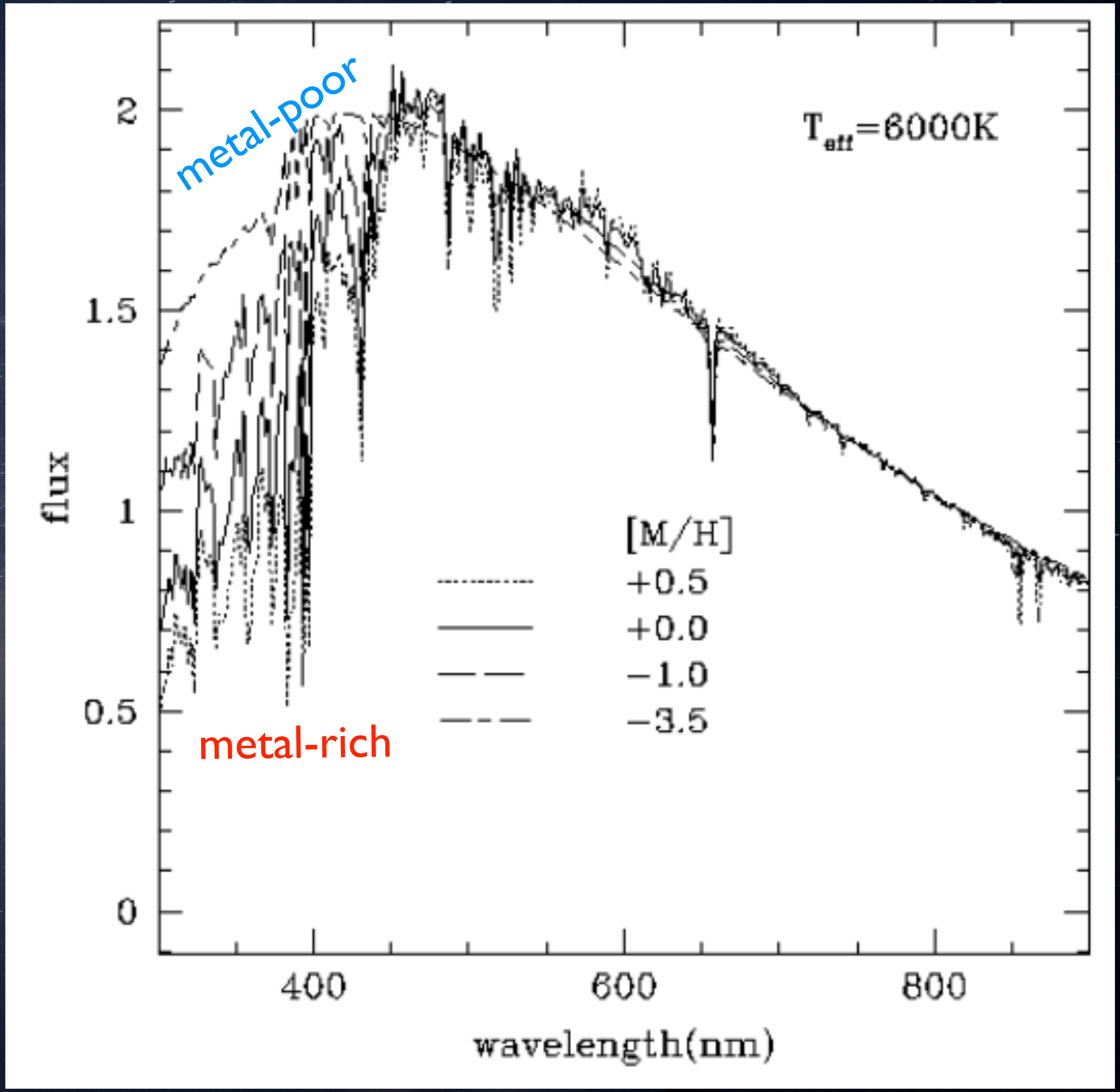
Age affects color: old stars are red and young stars are blue

But that's not the only thing!



The Effects of Metallicity

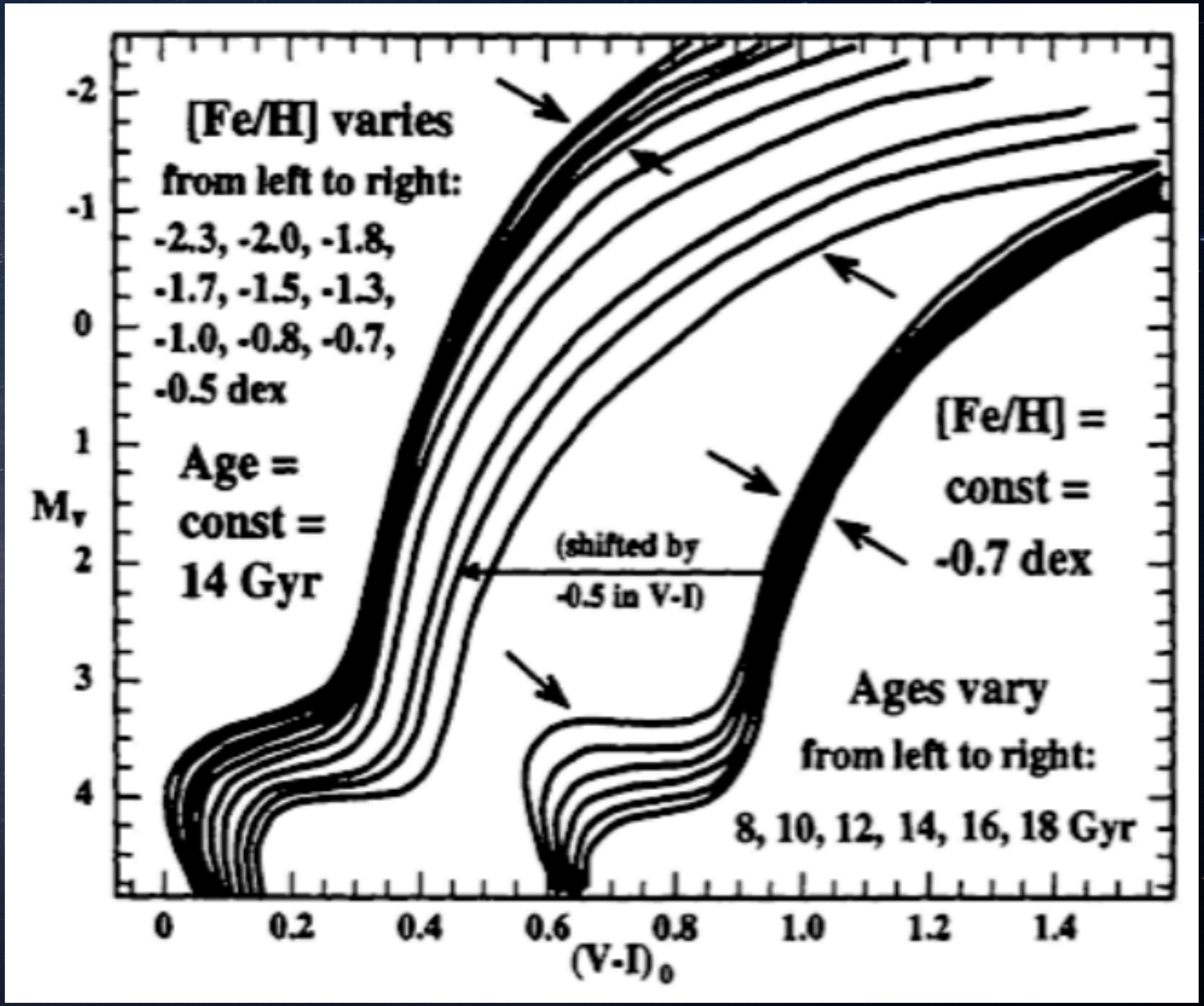
Line blanketing: Metals absorb strongly in the blue spectrum ➔ metal-rich stars appear redder



The Effects of Metallicity

Line blanketing: Metals absorb strongly in the blue spectrum ➔ metal-rich stars appear redder

Opacity: More metals ➔ greater absorption in stellar atmospheres ➔ red giants expand more ➔ cooler & redder

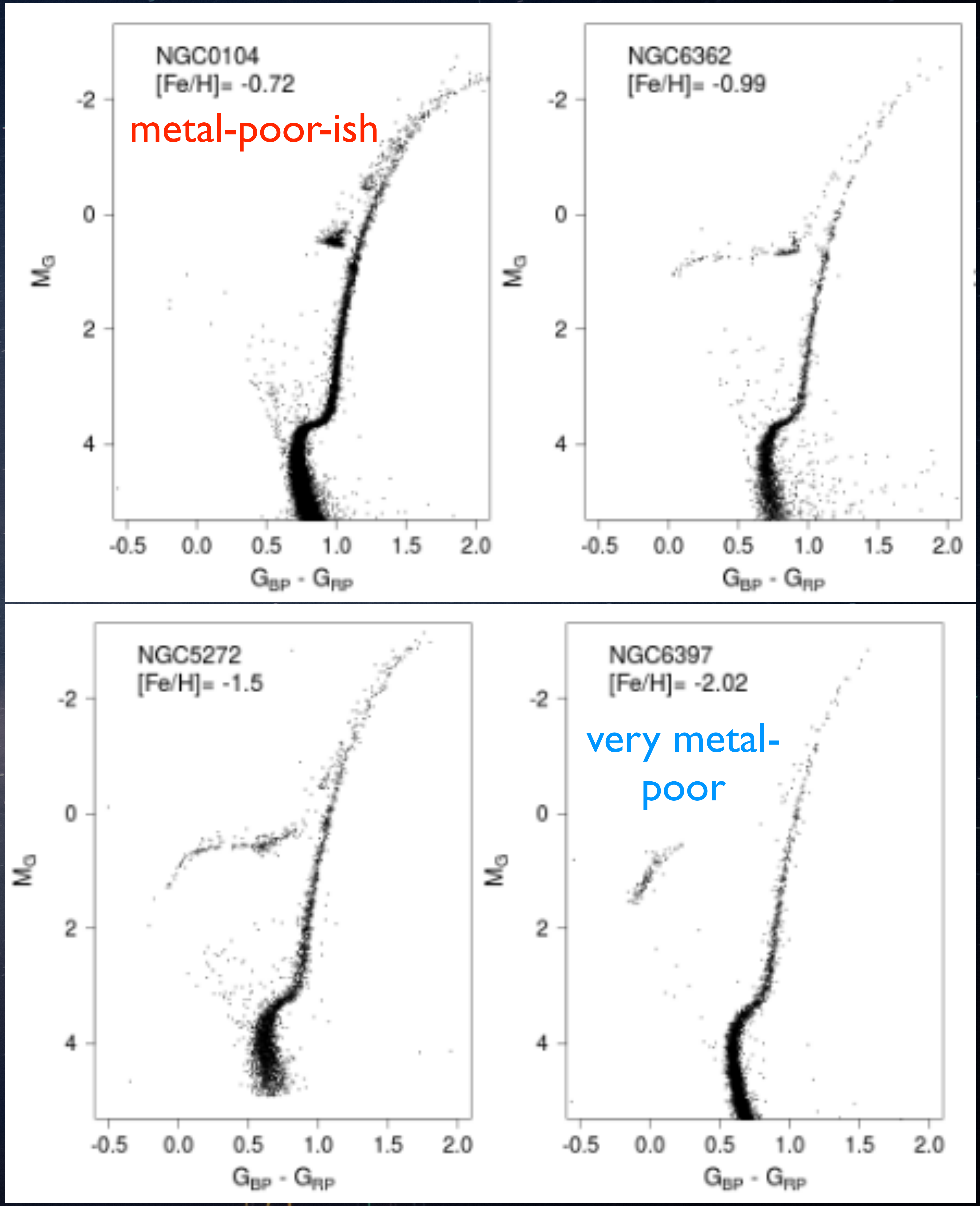


The Effects of Metallicity

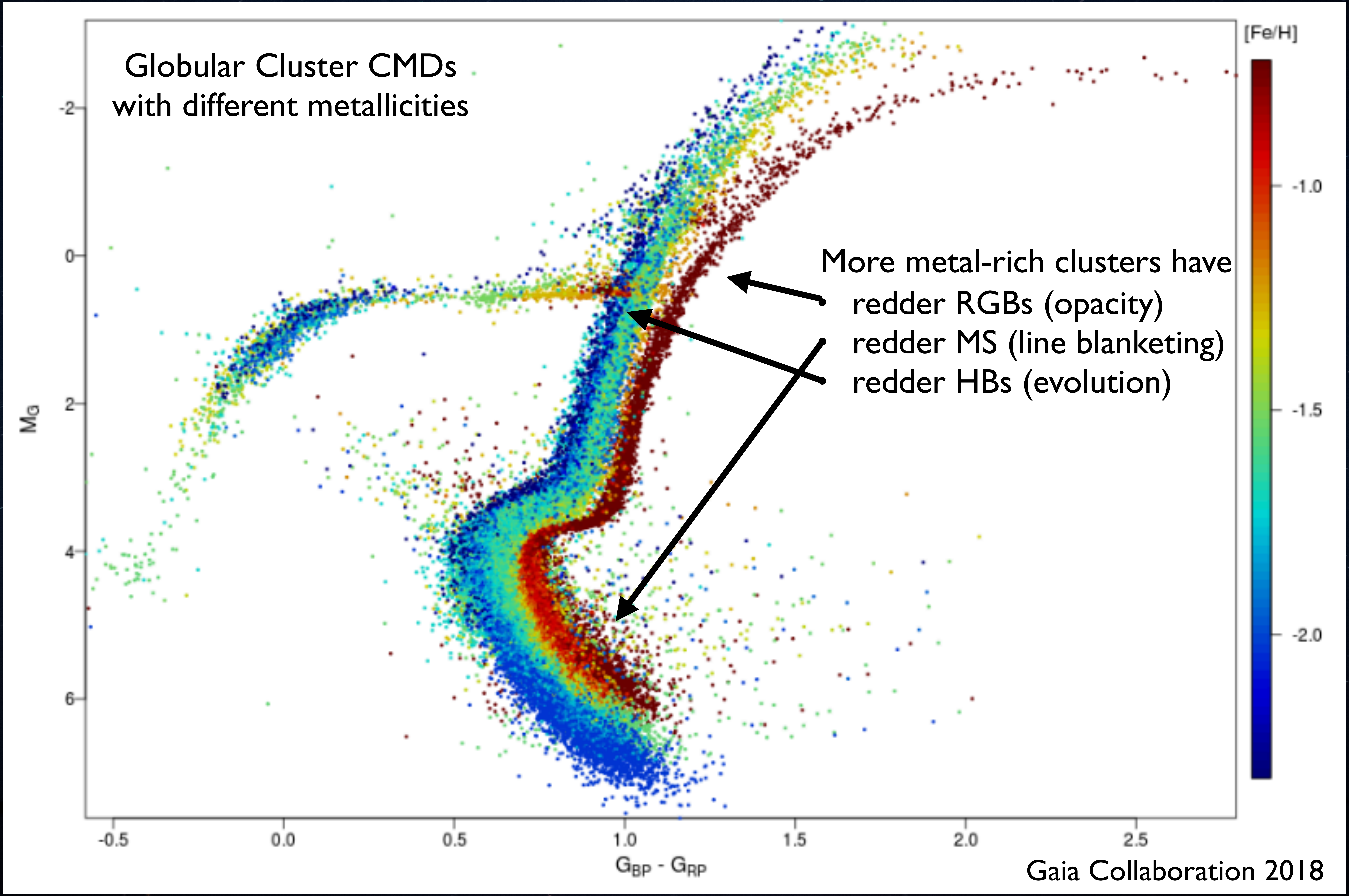
Line blanketing: Metals absorb strongly in the blue spectrum ➔ metal-rich stars appear redder

Opacity: More metals ➔ greater absorption in stellar atmospheres ➔ red giants expand more ➔ cooler & redder

Horizontal Branch morphology: stellar evolution & atmosphere effects combine to make HB stars bluer in metal-poor populations

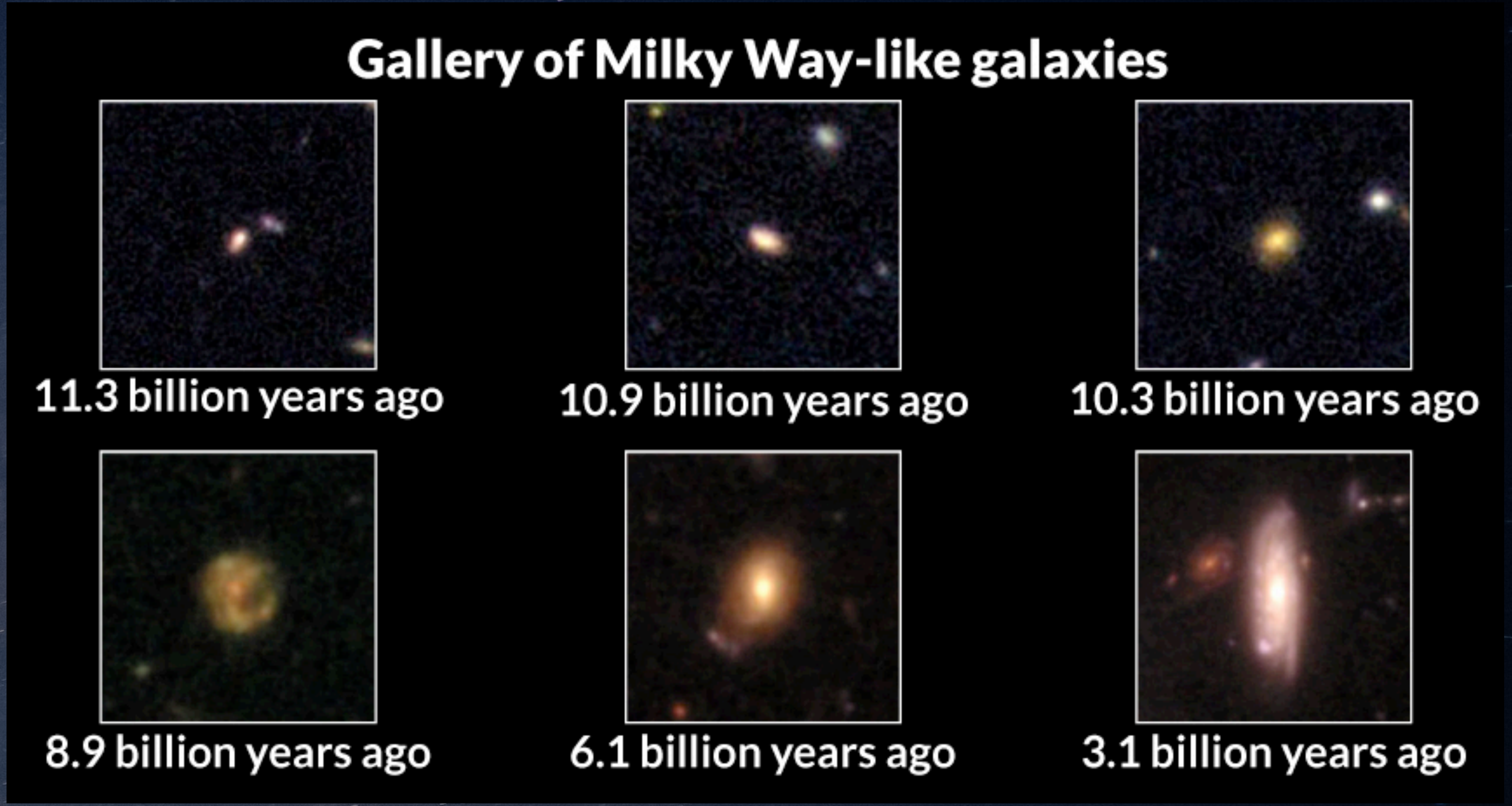


Gaia Collaboration 2018


Globular Cluster CMDs
with different metallicities
More metal-rich clusters have
redder RGBs (opacity)
redder MS (line blanketing)
redder HBs (evolution)
[Fe/H]
-1.0
-1.5
-2.0
M_G
-2
0
2
4
6
-0.5
0.0
0.5
1.0
1.5
2.0
2.5
$G_{BP} - G_{RP}$
Gaia Collaboration 2018

Why are we talking about stars?

Galaxies **<u>are</u>** stars!!!



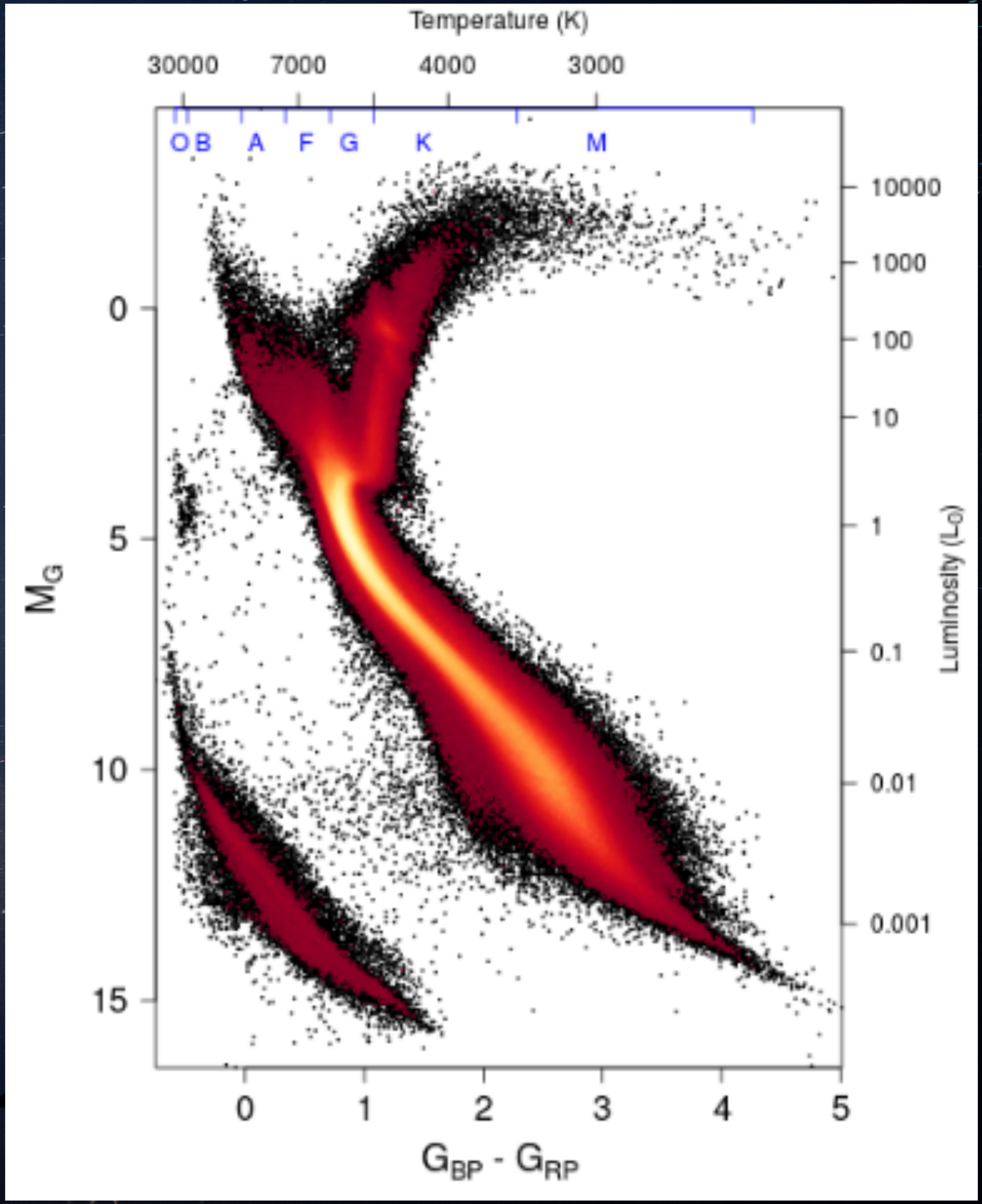
Two primary ways of studying galaxies:

- Lookback studies, observing progenitors at high redshifts when the Universe was young
- Studying present-day properties, such as <u>stellar populations</u>, structure, and kinematics

Studying Stellar Populations in Other Galaxies

In the Milky Way, we can see stars down to very low mass. Can construct precise CMDs

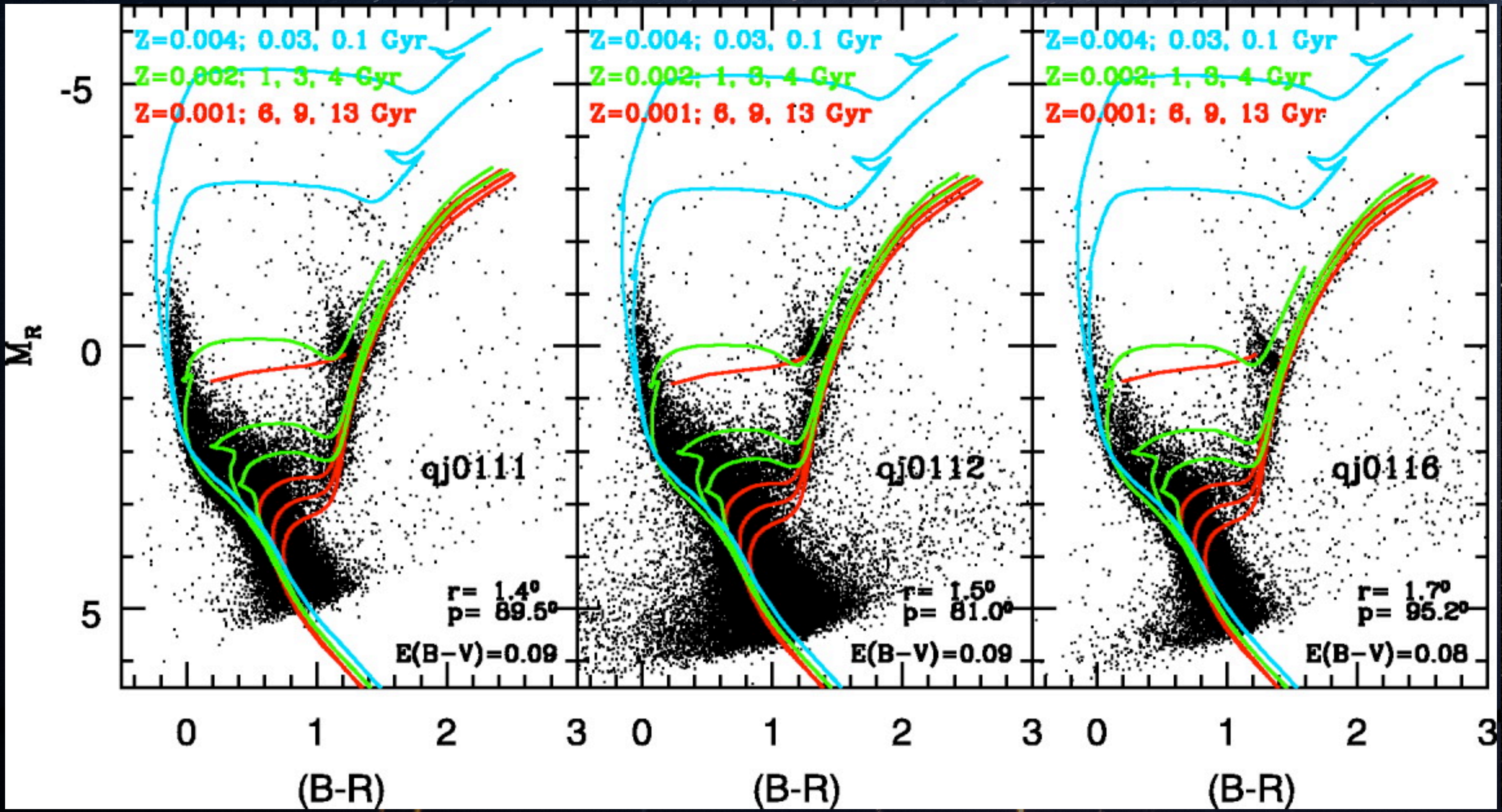
Gaia Collaboration 2018



Studying Stellar Populations in Other Galaxies

In the Milky Way, we can see stars down to very low mass. Can construct precise CMDs

In other galaxies, this is difficult. For MW satellites, we can resolve stars down to the MS turnoff



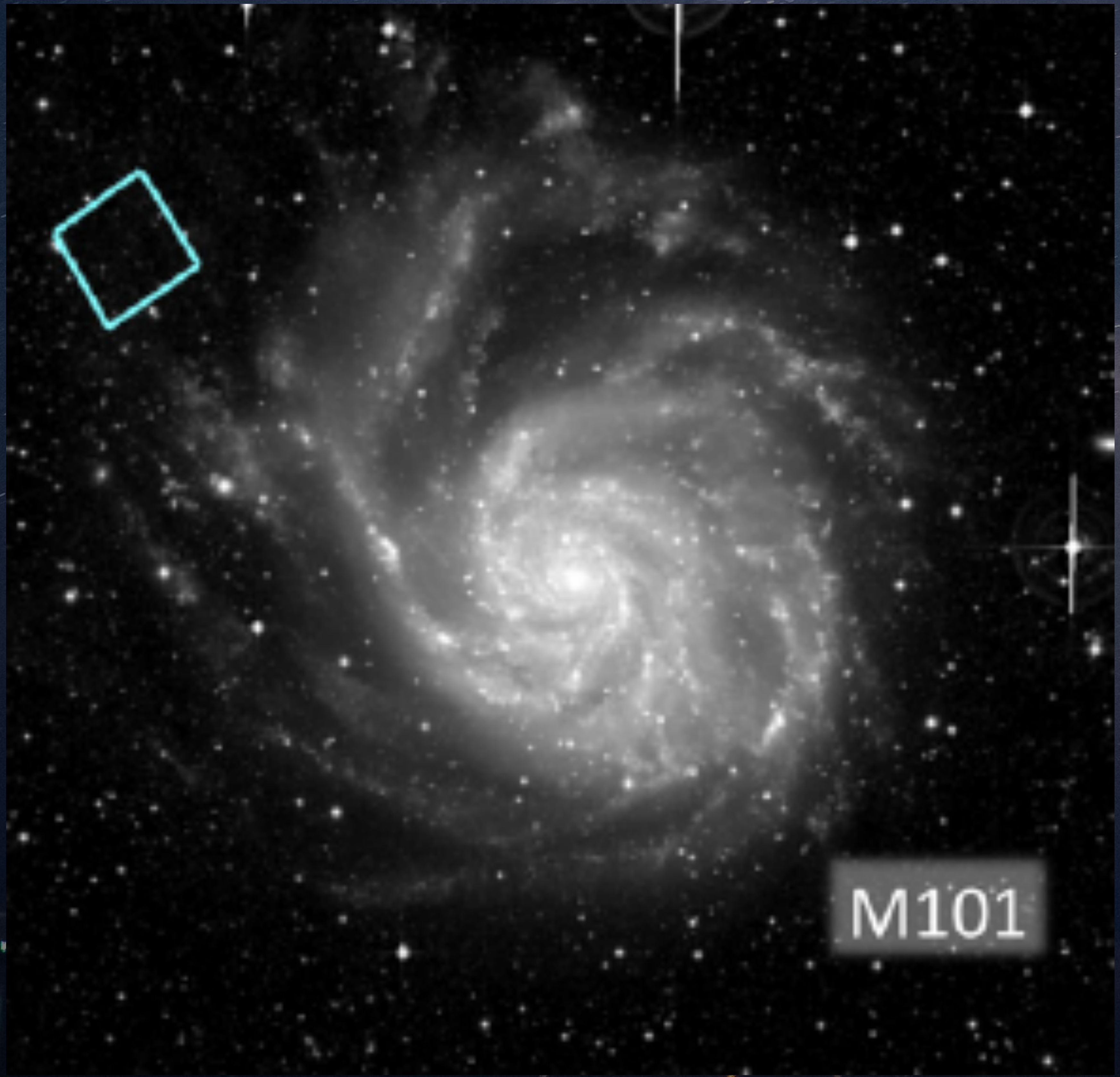
Noël+07

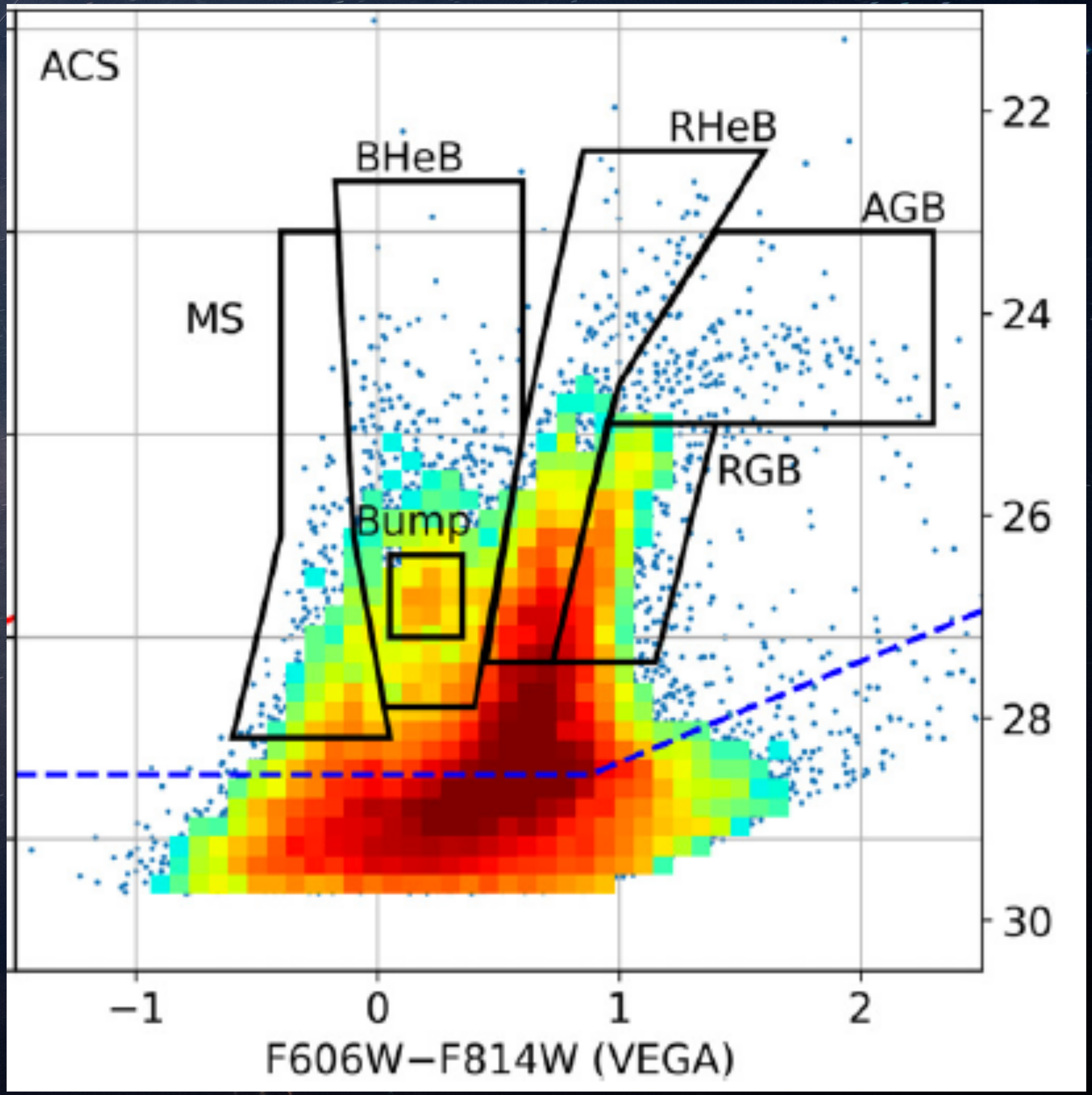
Small Magellanic Cloud
ESO/VISTA VMC

Studying Stellar Populations in Other Galaxies

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

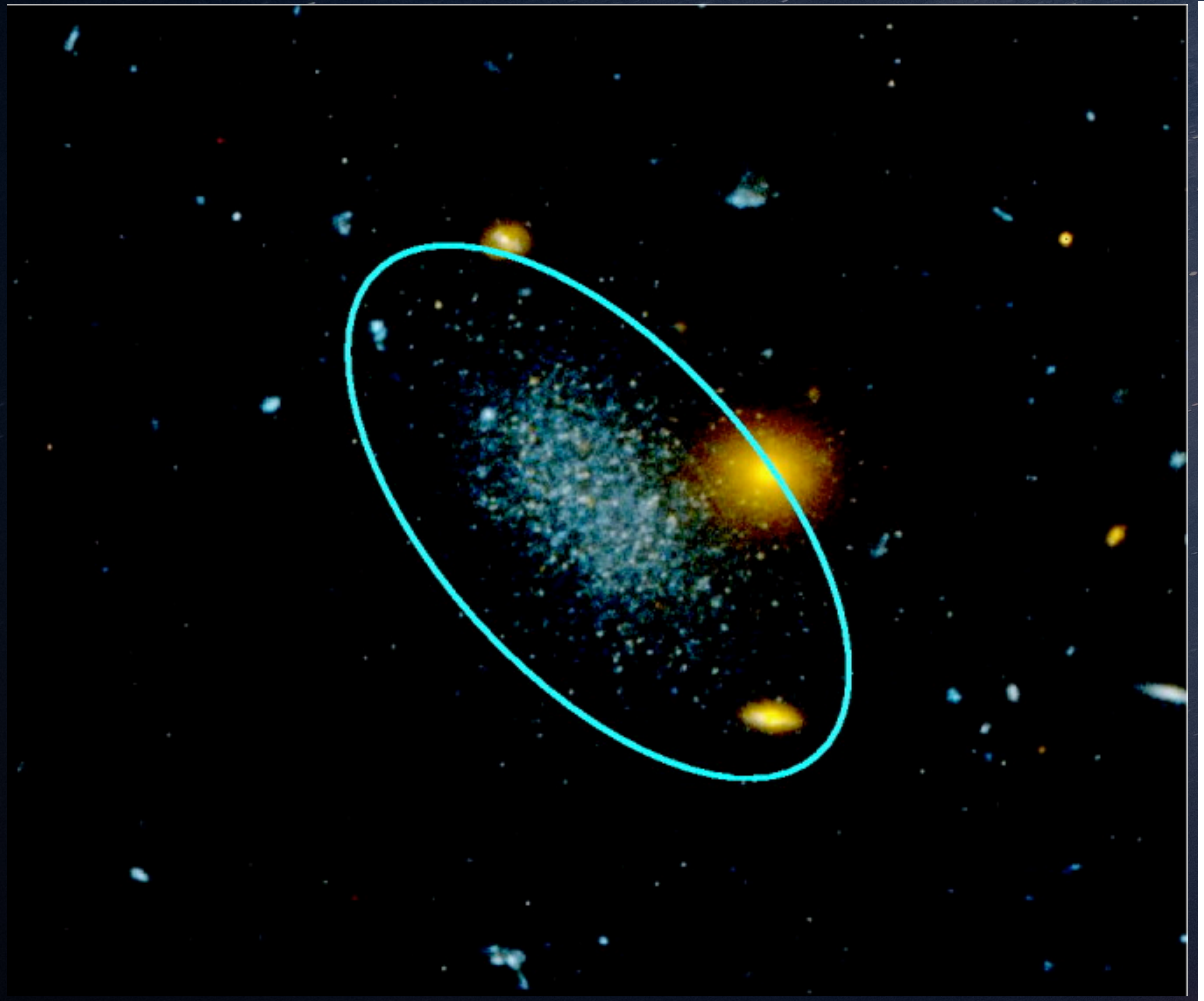
M101 outer disk stars, D = 6.9 Mpc
Mihos+18

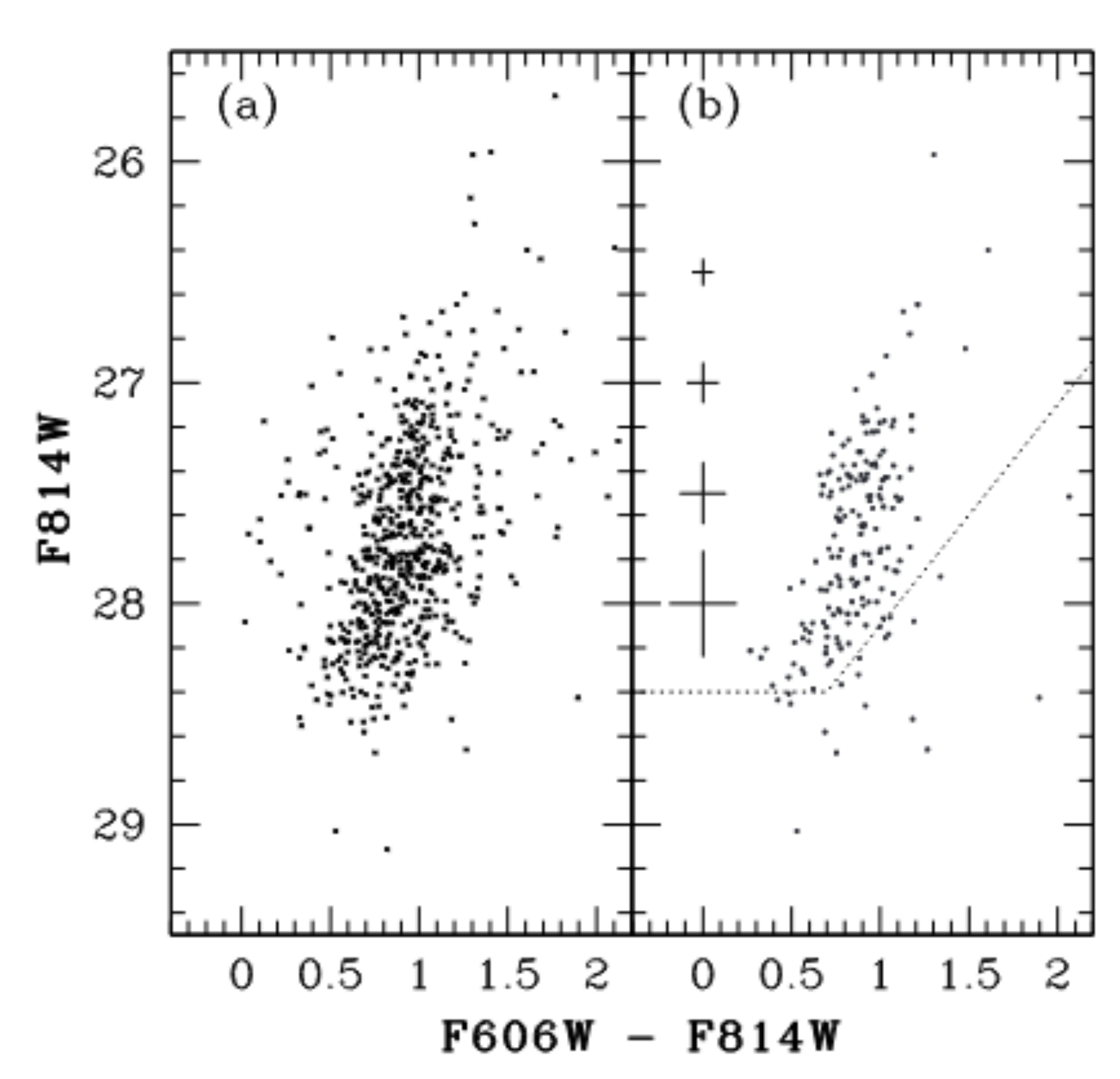




Studying Stellar Populations in Other Galaxies

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





Durrell+07

What about galaxies far away?

For galaxies far away, we only have integrated light:
the summed light of all the stars put together!

This depends on:

I. How stars are formed

II. What kind of light is output by stars

III. How stars evolve with time

What about galaxies far away?

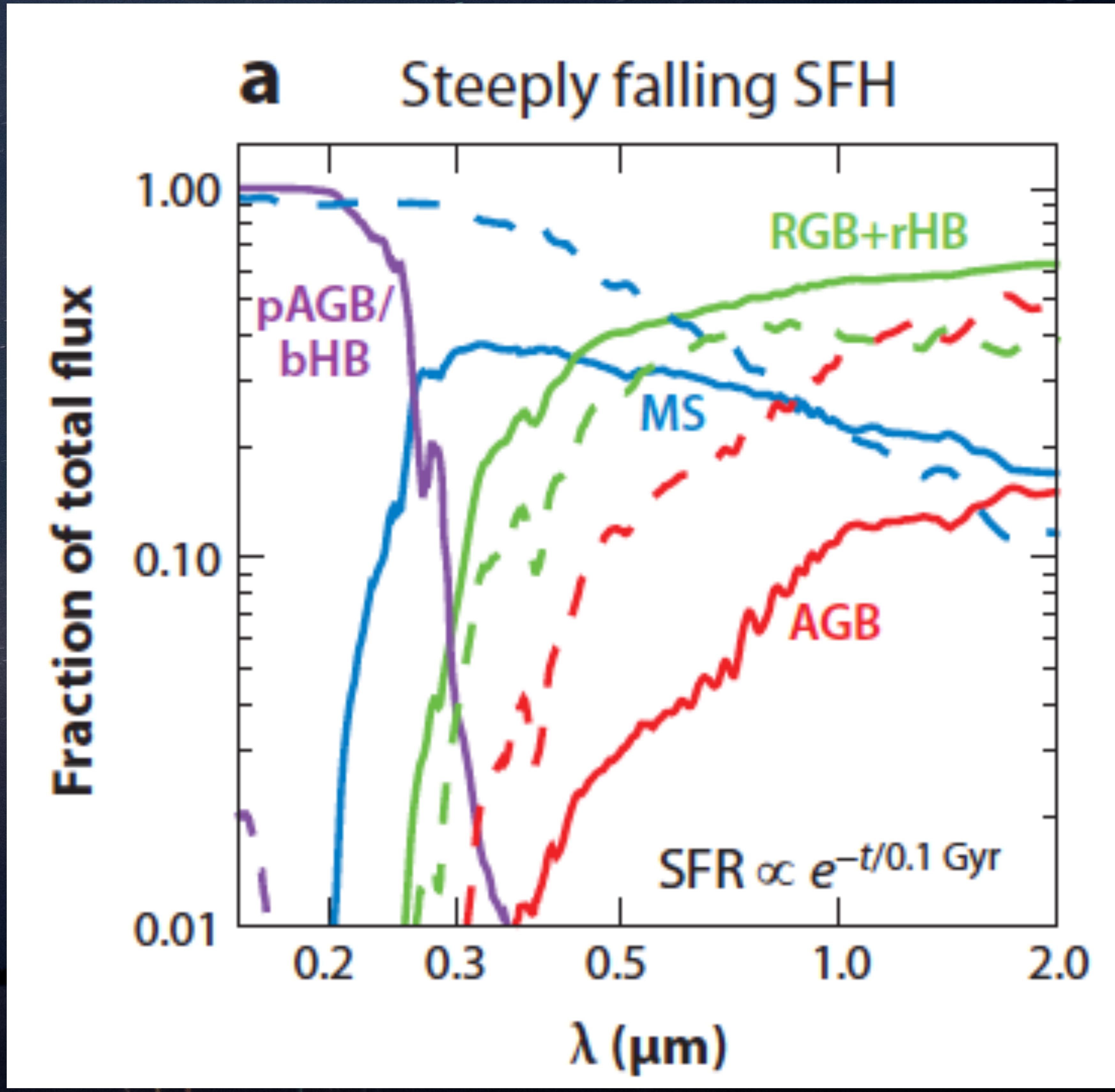
For galaxies far away, we only have integrated light:
the summed light of all the stars put together!

This depends on:

I. How stars are formed

II. What kind of light is output by stars

III. How stars evolve with time



What about galaxies far away?

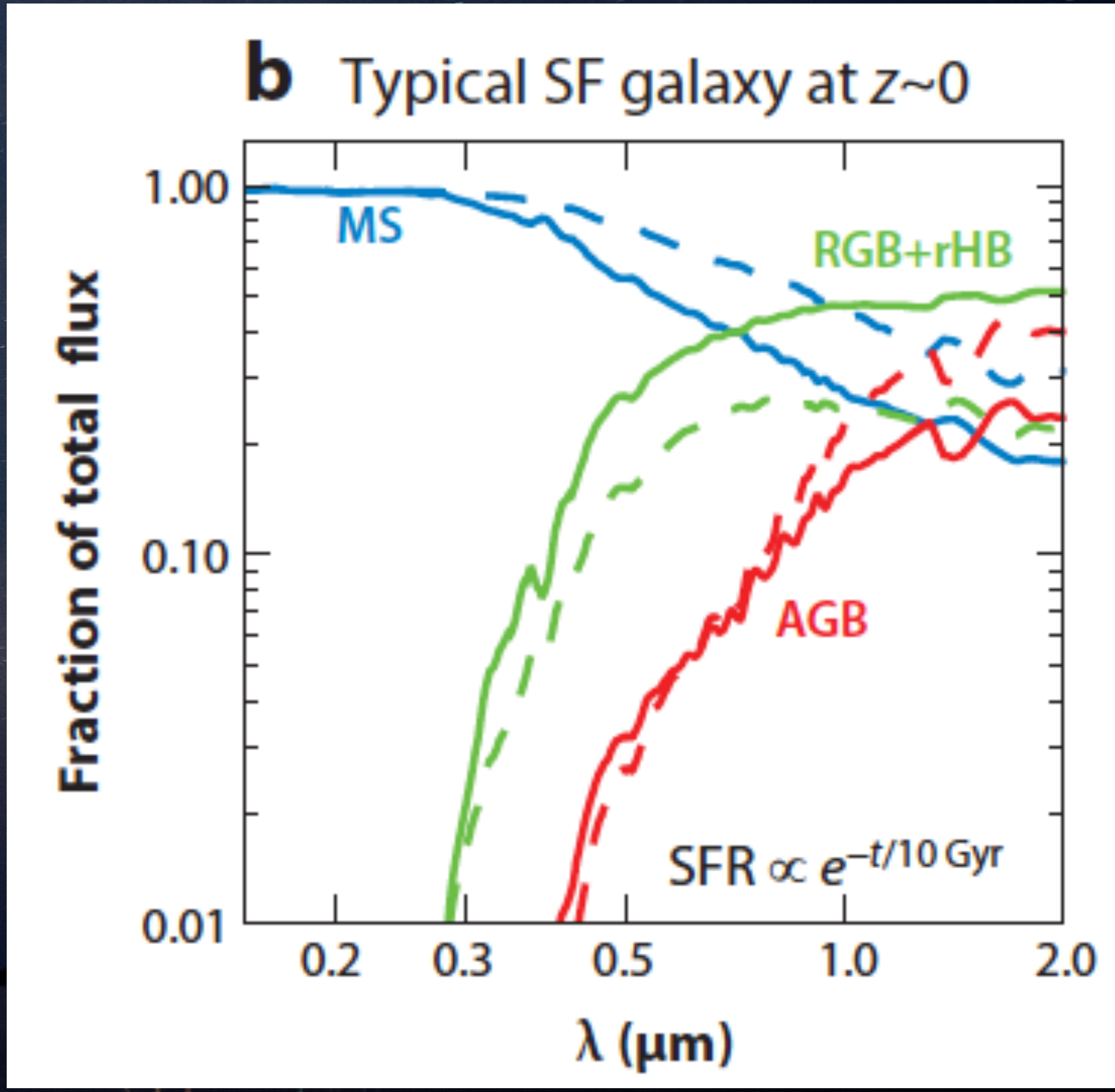
For galaxies far away, we only have <u>integrated light</u>:
the summed light of all the stars put together!

This depends on:

I. How stars are formed

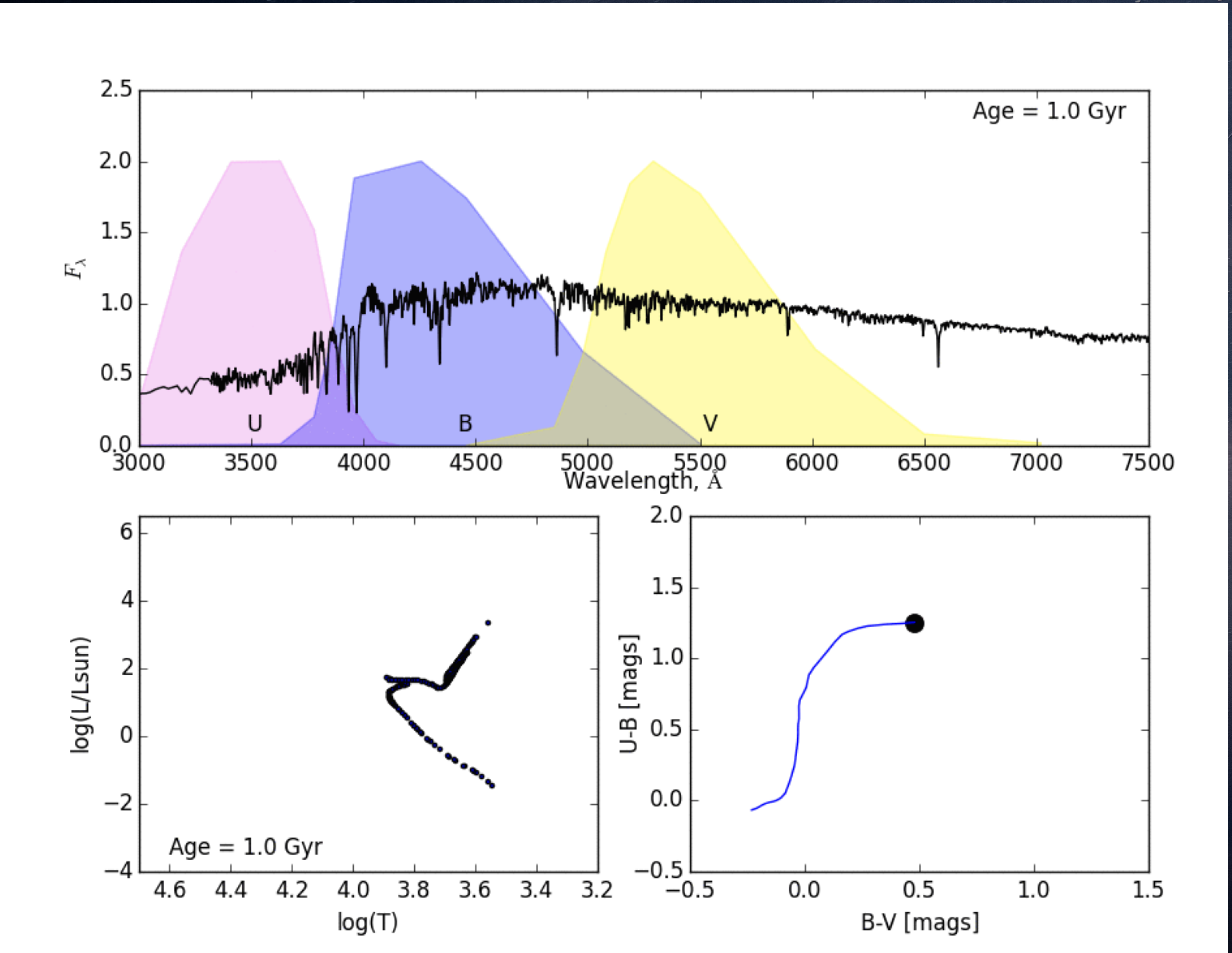
II. What kind of light is output by stars

III. How stars evolve with time



Observables: Colors

Imaging and photometry is "quick and easy"

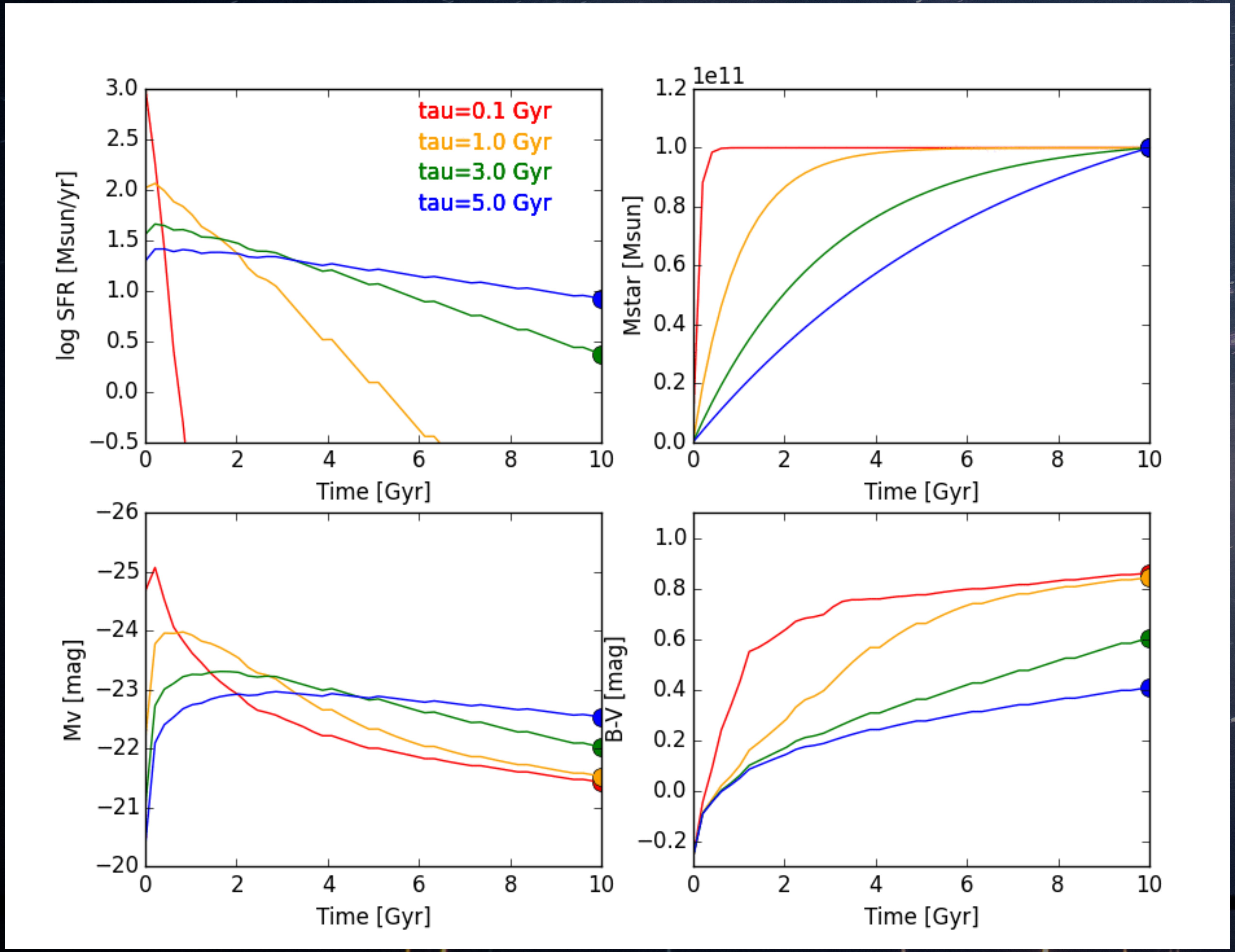


Evolution of a single burst population

Top: Integrated light spectrum
Bottom left: evolving CMD
Bottom right: evolving integrated colors

Observables: Colors

Imaging and photometry is "quick and easy"



Evolution of different star-formation histories

$$\mathrm{SFR}(t) = Ce^{-t/\tau}$$

Small tau: fast burst
Large tau: slowly declining SFR

Fast burst: As massive stars quickly die out, they fade rapidly and turn red

Slow decline: Constantly replenishing stars of all types, fade slowly or not at all, don't get as red

Contributions from Different Evolutionary Stages

Integrated light is always dominated by the brightest stars, even though they are not always the most common stars

Colors and spectra of galaxies, measuring the integrated light, are "*luminosity-weighted sums*"

When we study dynamics, we do "*mass-weighted sums*"

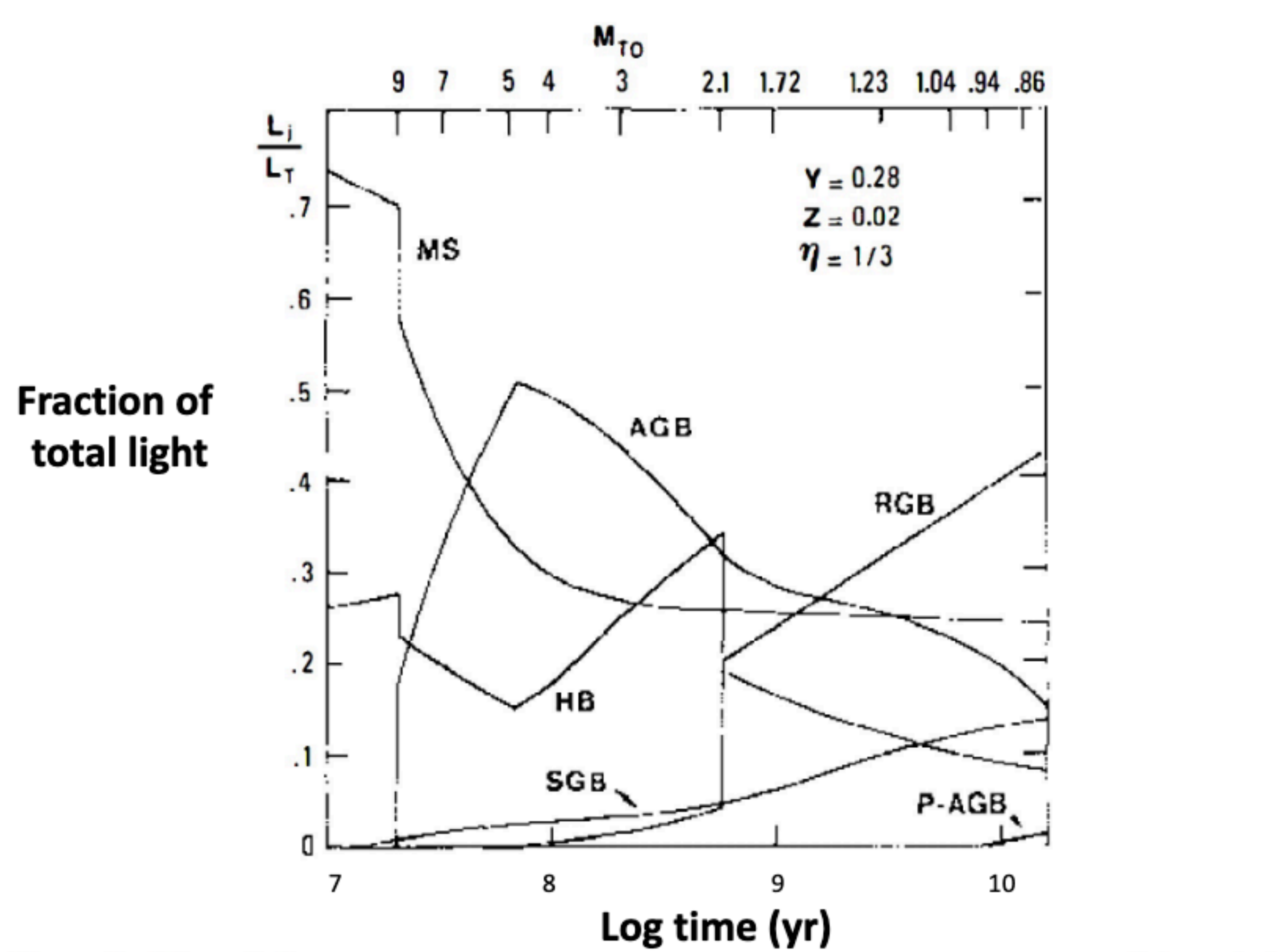


Figure 2 The relative contributions of the various evolutionary stages to the integrated light of a stellar population as a function of age (Renzini & Buzzoni 1986), for the indicated composition and mass-loss parameter η (cf. Section 4.1.3). The age t is in years.

Mass-to-Light Ratios

If we can understand the stellar pops we are observing, we can use their total luminosity to infer their stellar mass by invoking the mass-to-light ratio, $(M/L)_*$

Star	Spec. Type	Mass	Luminosity	$(M/L)_*$
Sun	G2V	1 $M_\odot$	1 $L_\odot$	1 $M_\odot/L_\odot$
Polaris	F7Ib	5.4 $M_\odot$	1260 $L_\odot$	0.004 $M_\odot/L_\odot$
Betelgeuse	M1Ia	17 $M_\odot$	126000 $L_\odot$	0.0001 $M_\odot/L_\odot$
Proxima Centauri	M5.5V	0.1 $M_\odot$	0.002 $L_\odot$	50 $M_\odot/L_\odot$
Sirius B	wd	1 $M_\odot$	0.06 $L_\odot$	17 $M_\odot/L_\odot$

Mass-to-Light Ratios

To get the ratio for a population of stars, sum up the light to get the luminosity, sum up the mass to get total mass, and divide!

But we usually don't resolve stars, so we have to infer the population by modeling the integrated colors of the galaxy

Galaxy	Mass	Luminosity	$(M/L)_*$
Spirals	$10^9 - 10^{12}\ M_\odot$	$10^8 - 10^{11}\ L_\odot$	$2 - 10\ M_\odot/L_\odot$
Ellipticals	$10^5 - 10^{13}\ M_\odot$	$10^6 - 10^{11}\ L_\odot$	$10 - 20\ M_\odot/L_\odot$
Irregulars	$10^8 - 10^{11}\ M_\odot$	$10^7 - 2 \times 10^9\ L_\odot$	$1 - 10\ M_\odot/L_\odot$