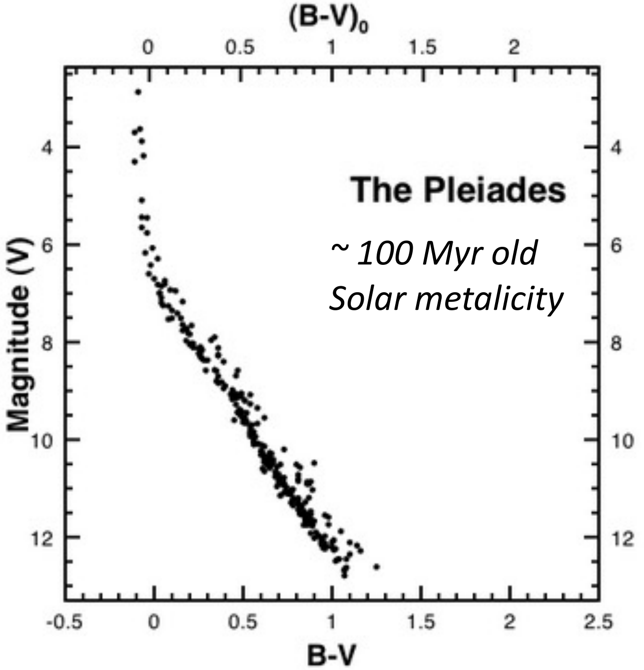
Open Clusters



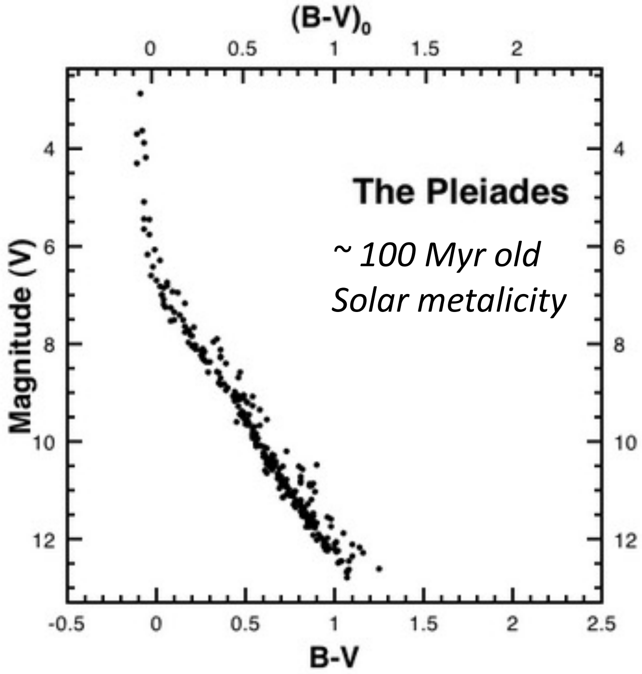
Star Clusters:

- single age
- single metallicty

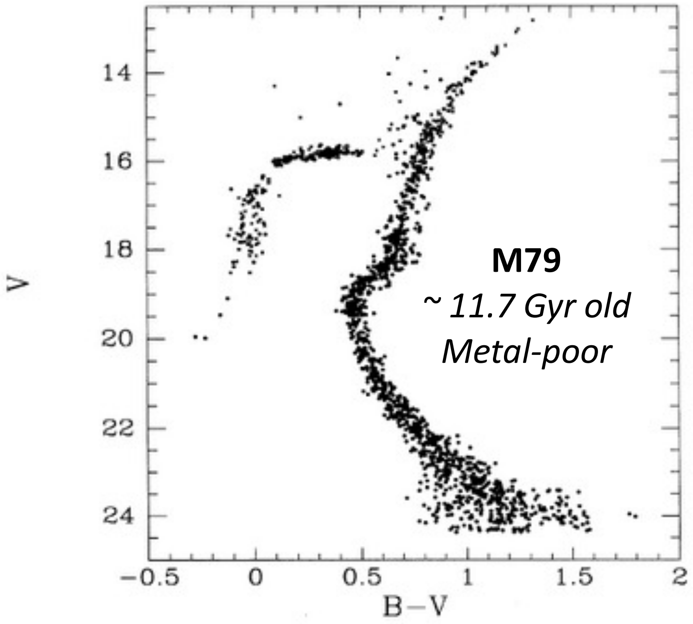
Open Clusters

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.

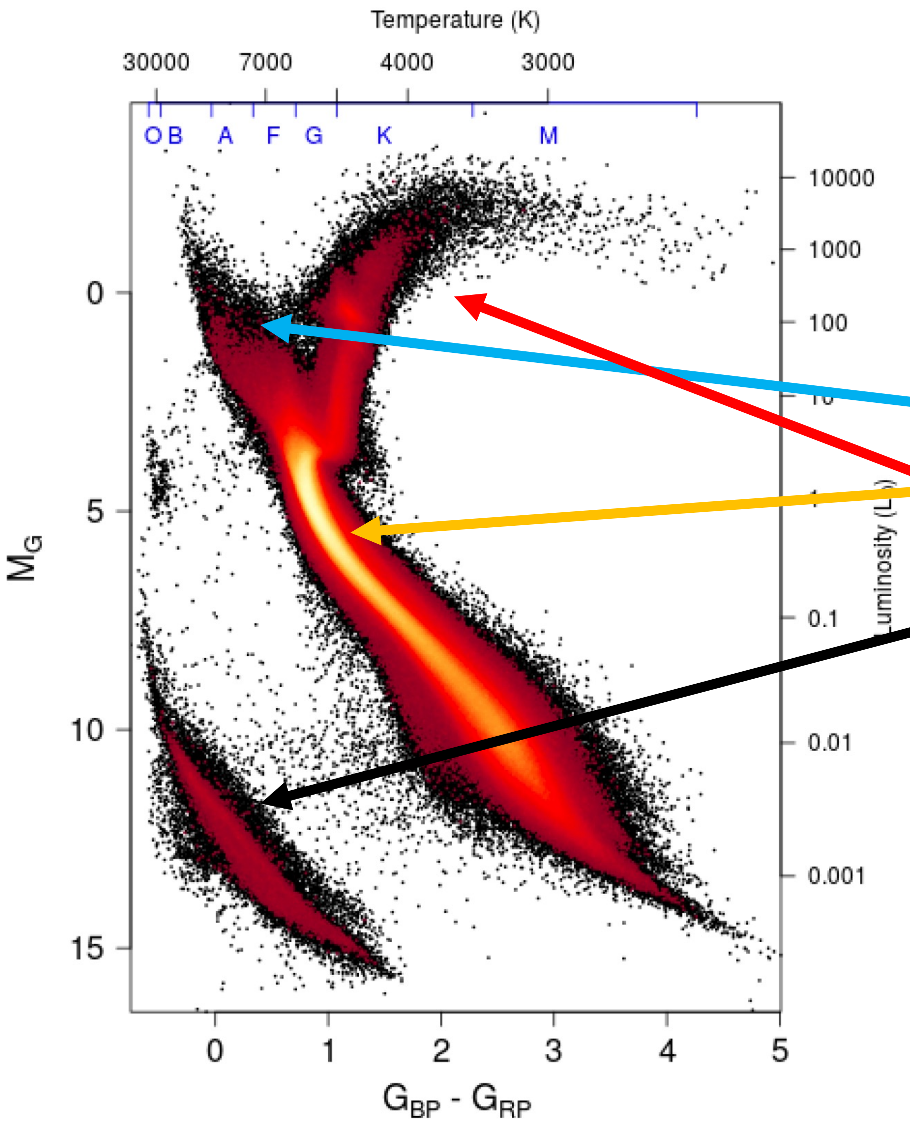


Fig. 5. *Gaia* HRD of sources with low extinction ($E(B–V) < 0.015$ mag) satisfying the filters described in Sect. 2.1 (4 276 690 stars). The colour scale represents the square root of the density of stars. Approximate temperature and luminosity equivalents for main-sequence stars are provided at the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

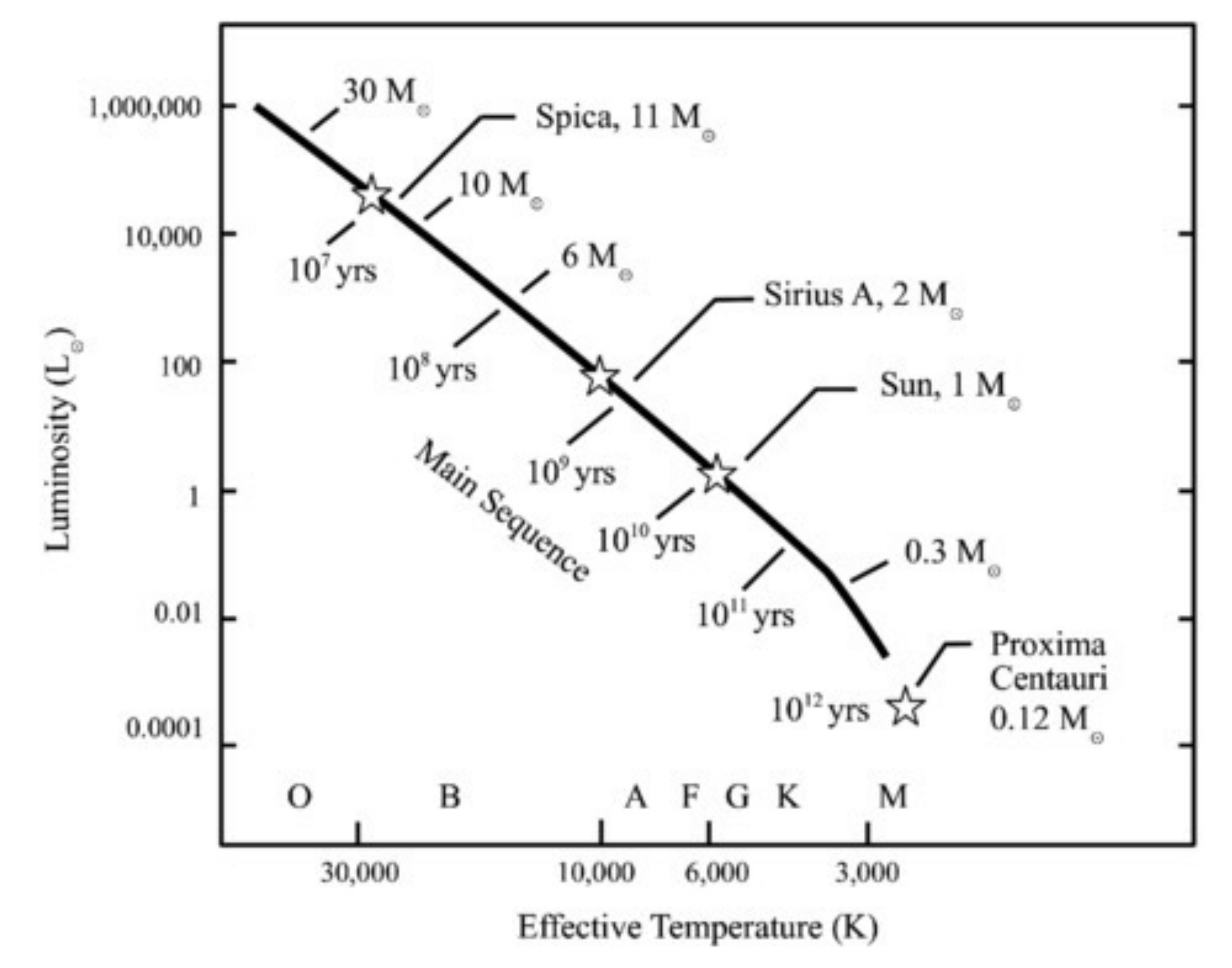
“Fuel tank” argument:

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

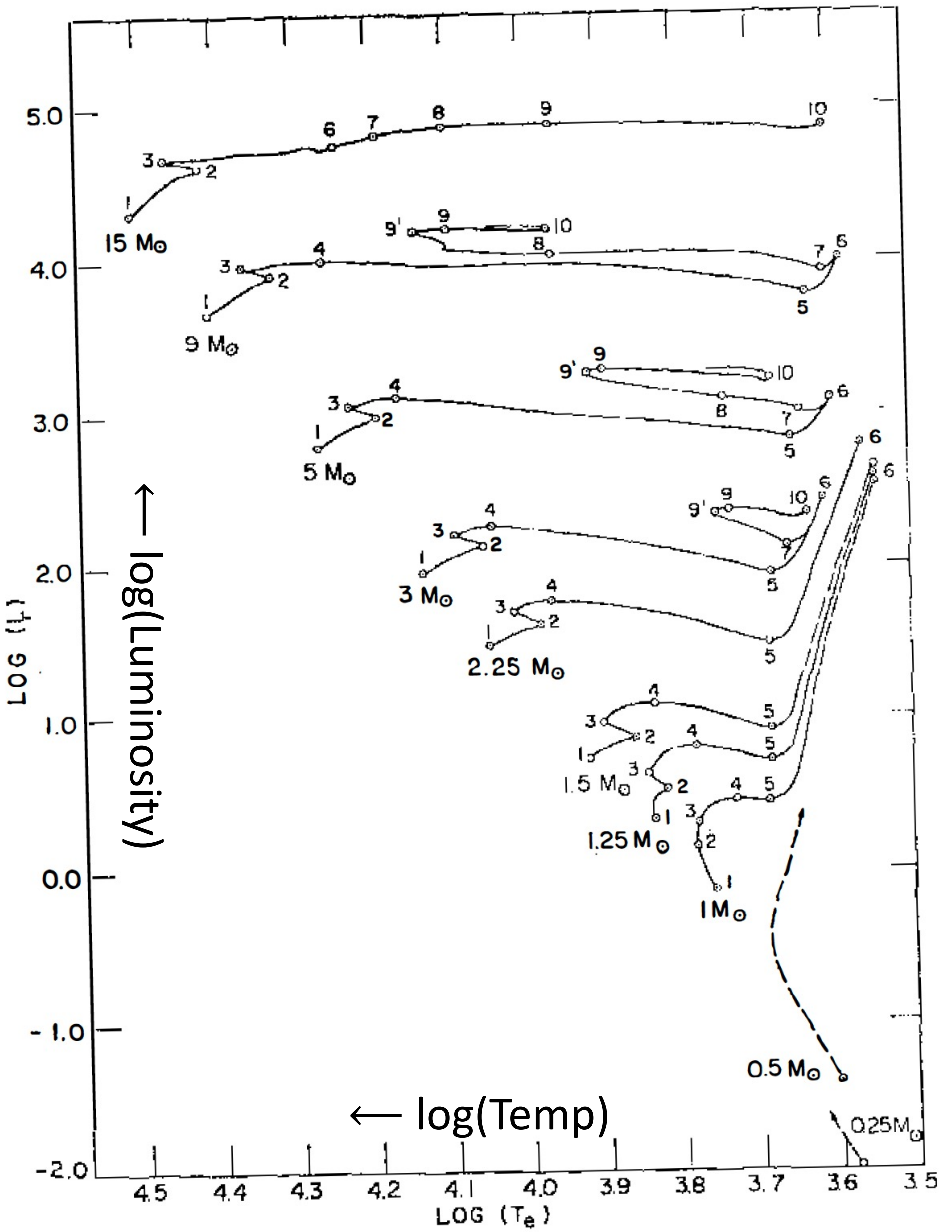


FIG. 3. Paths in the H-R diagram for metal-rich stars of mass $(M/M_\odot)=15$, 9, 5, 3, 2.25, 1.5, 1.25, 1, 0.5, 0.25. Units of luminosity and surface temperature are the same as in Figure 1. Traversal times between labeled points are given in Tables III and IV. Dashed portions of evolutionary paths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

STELLAR LIFETIMES (yr)[a]

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

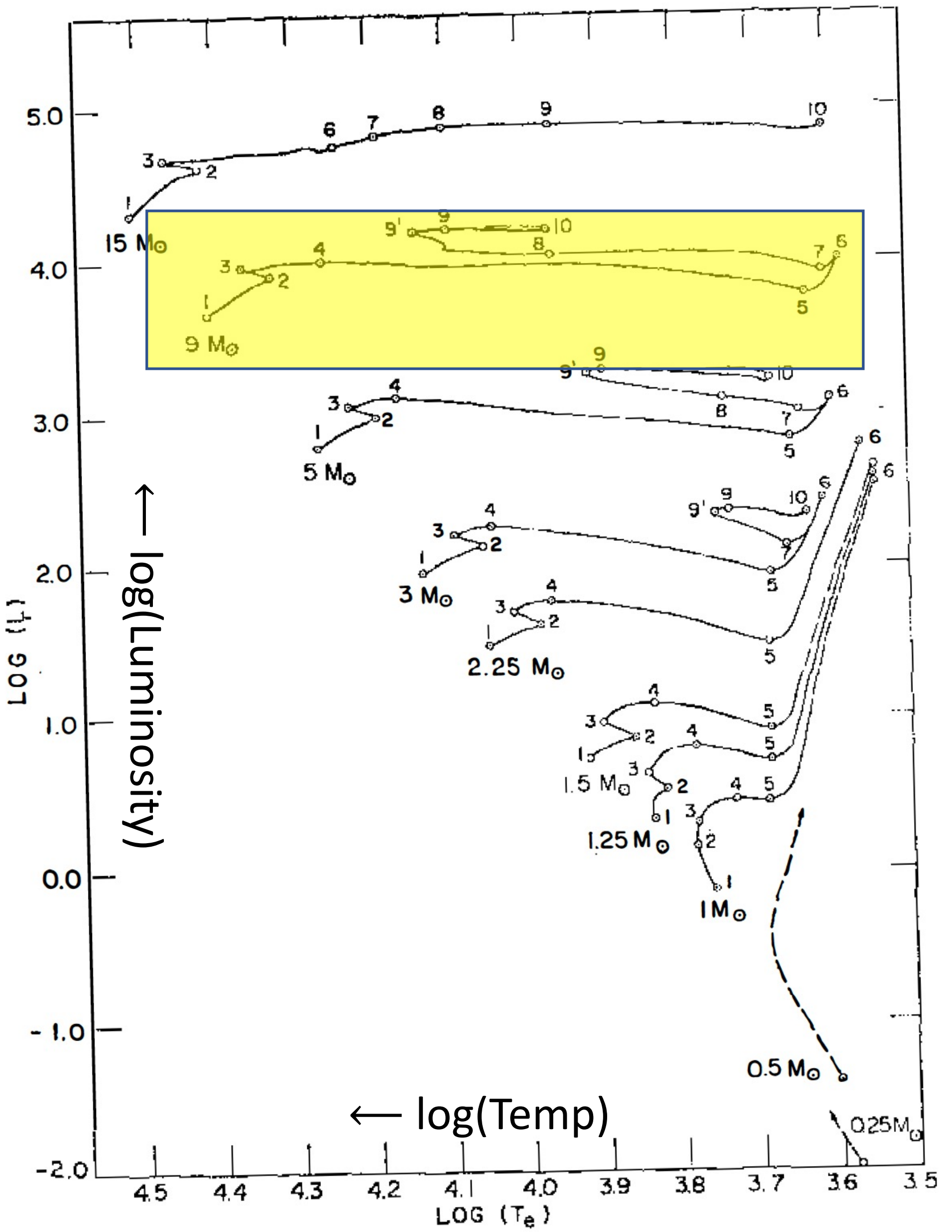

FIG. 3. Paths in the H-R diagram for metal-rich stars of mass $(M/M_{\odot}) = 15$, 9, 5, 3, 2.25, 1.5, 1.25, 1, 0.5, 0.25. Units of luminosity and surface temperature are the same as in Figure 1. Traversal times between labeled points are given in Tables III and IV. Dashed portions of evolutionary paths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

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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

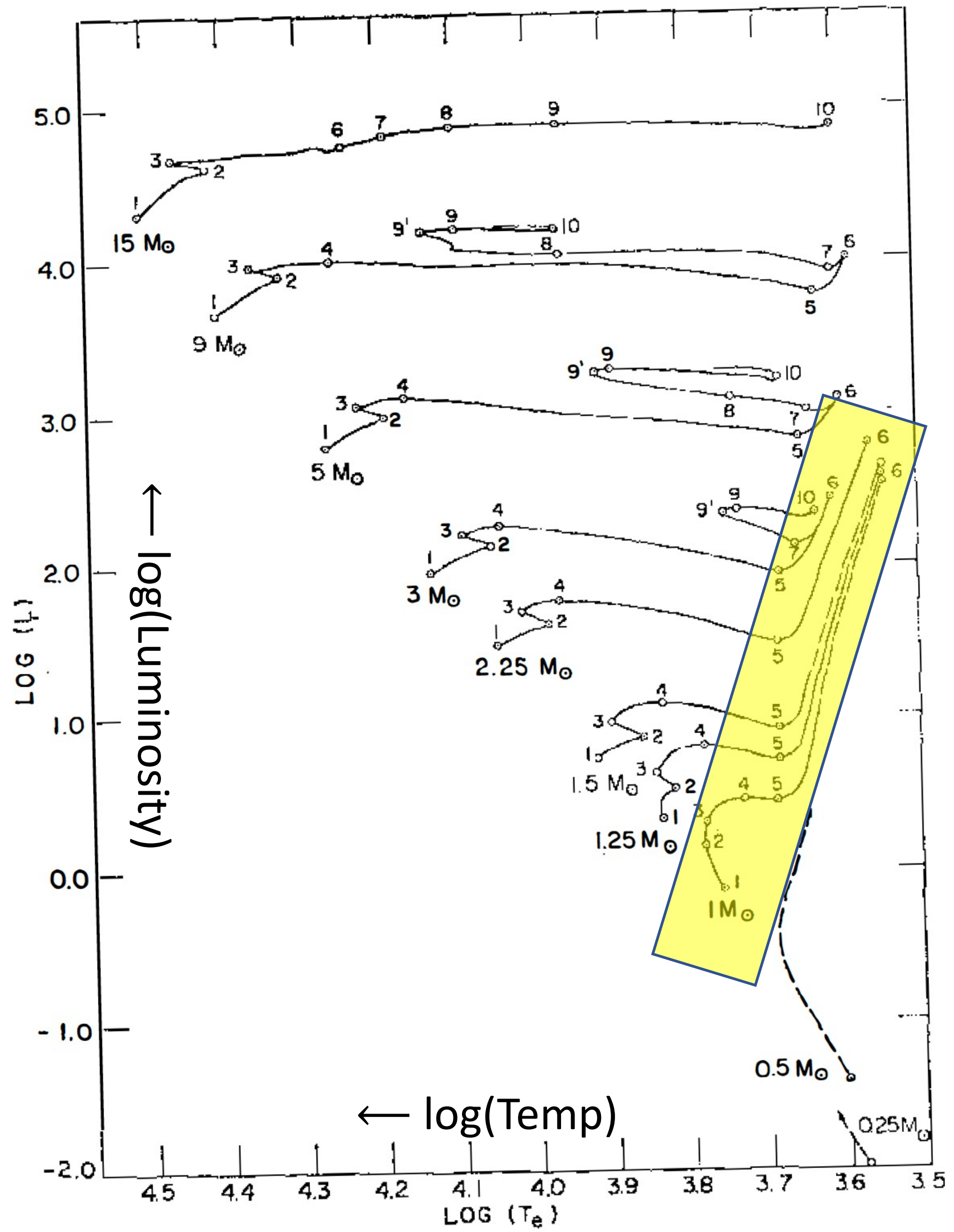

FIG. 3. Paths in the H-R diagram for metal-rich stars of mass $(M/M_\odot)=15$, 9, 5, 3, 2.25, 1.5, 1.25, 1, 0.5, 0.25. Units of luminosity and surface temperature are the same as in Figure 1. Traversal times between labeled points are given in Tables III and IV. Dashed portions of evolutionary paths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

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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”

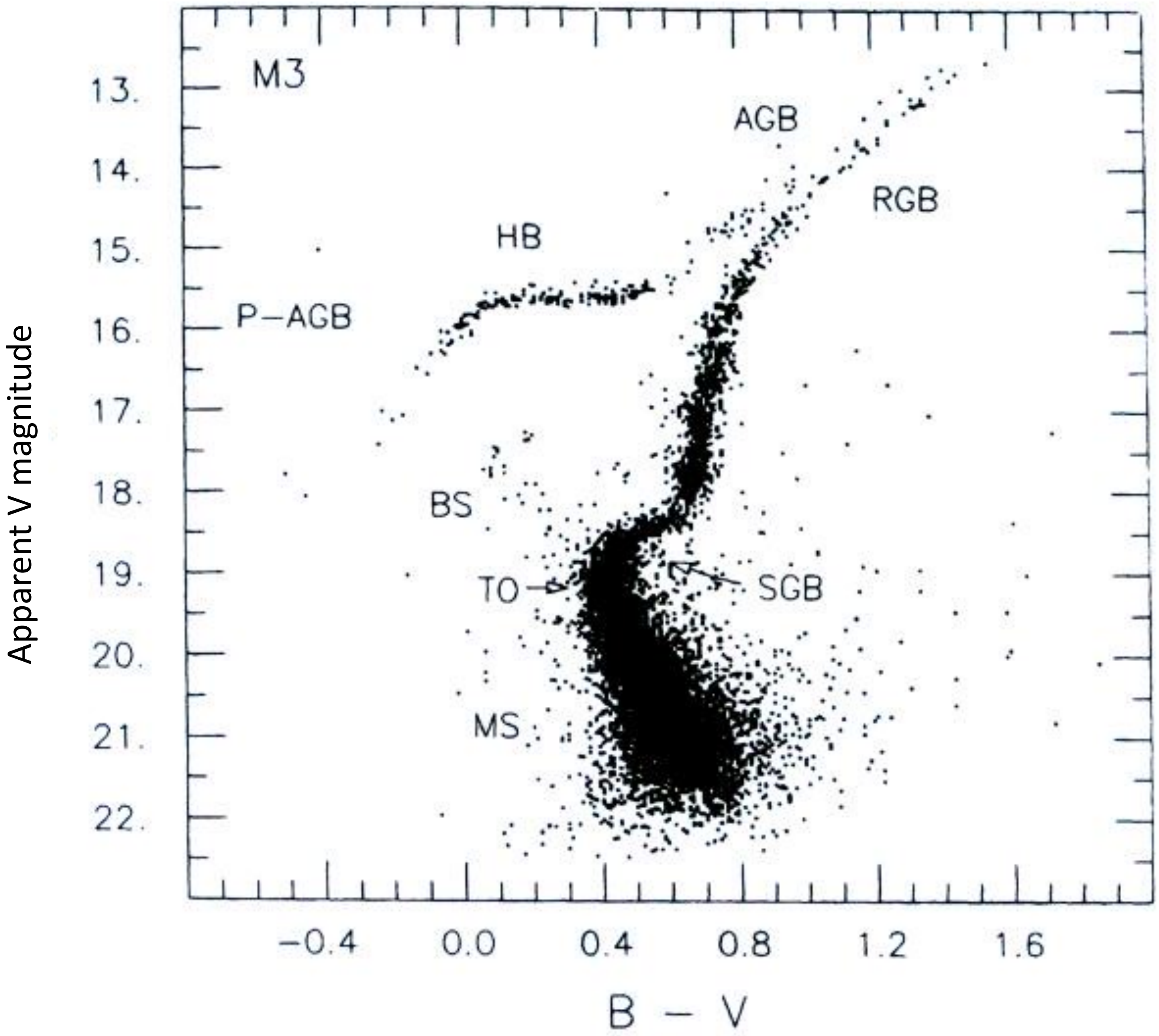
Lives as a red giant for another Gyr or so.

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



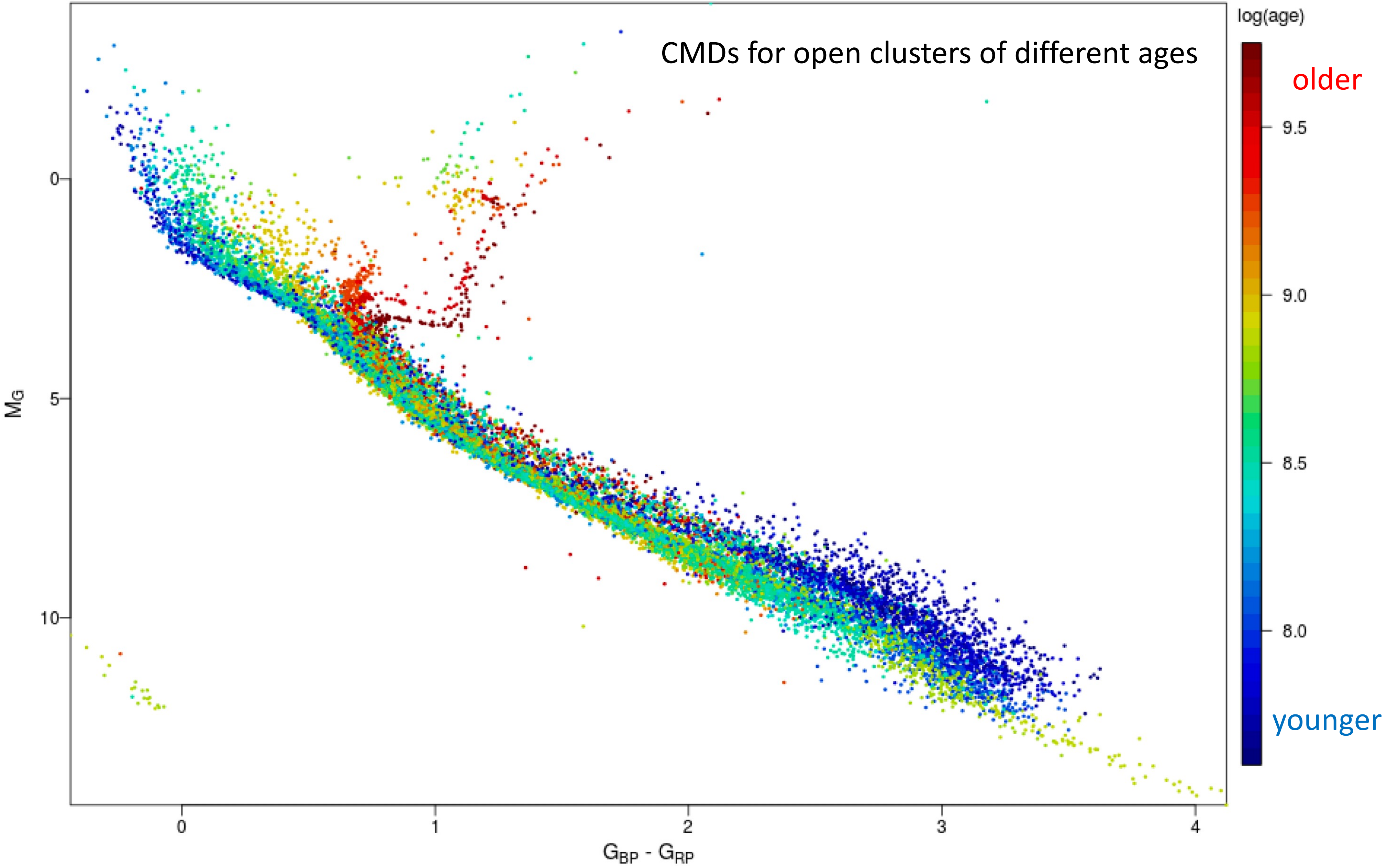


Fig. 2. Composite HRD for 32 open clusters, coloured according to log(age), using the extinction and distance moduli as determined from the *Gaia* data (Table 2).

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

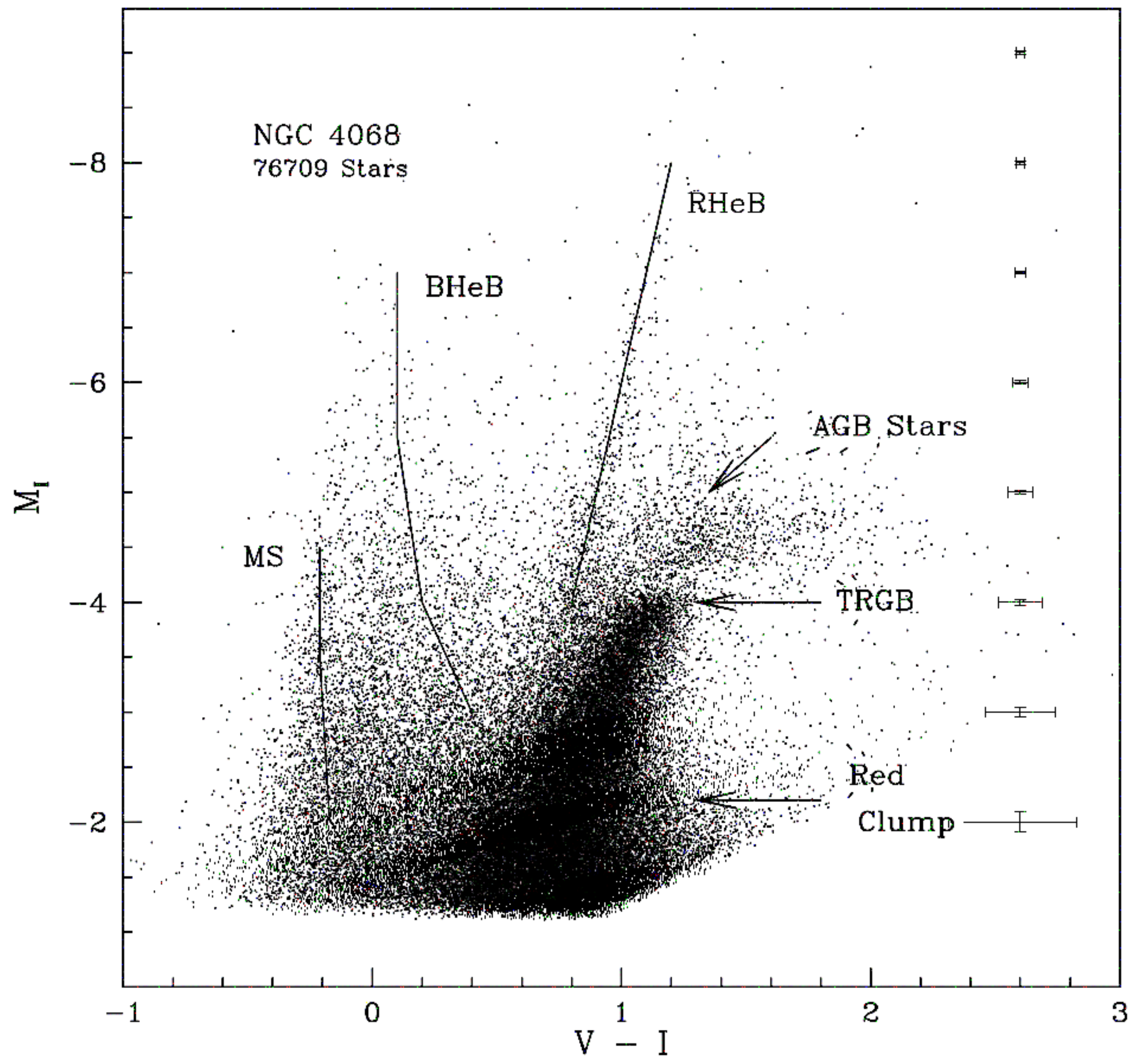


Figure 4. CMD of NGC 4068 with the evolutionary stages of the stellar populations labeled. The MS, BHeB, RHeB, RGB, AGB, and red clump evolutionary stages are all easily identified in the stellar populations.

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 1/10th of solar.

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

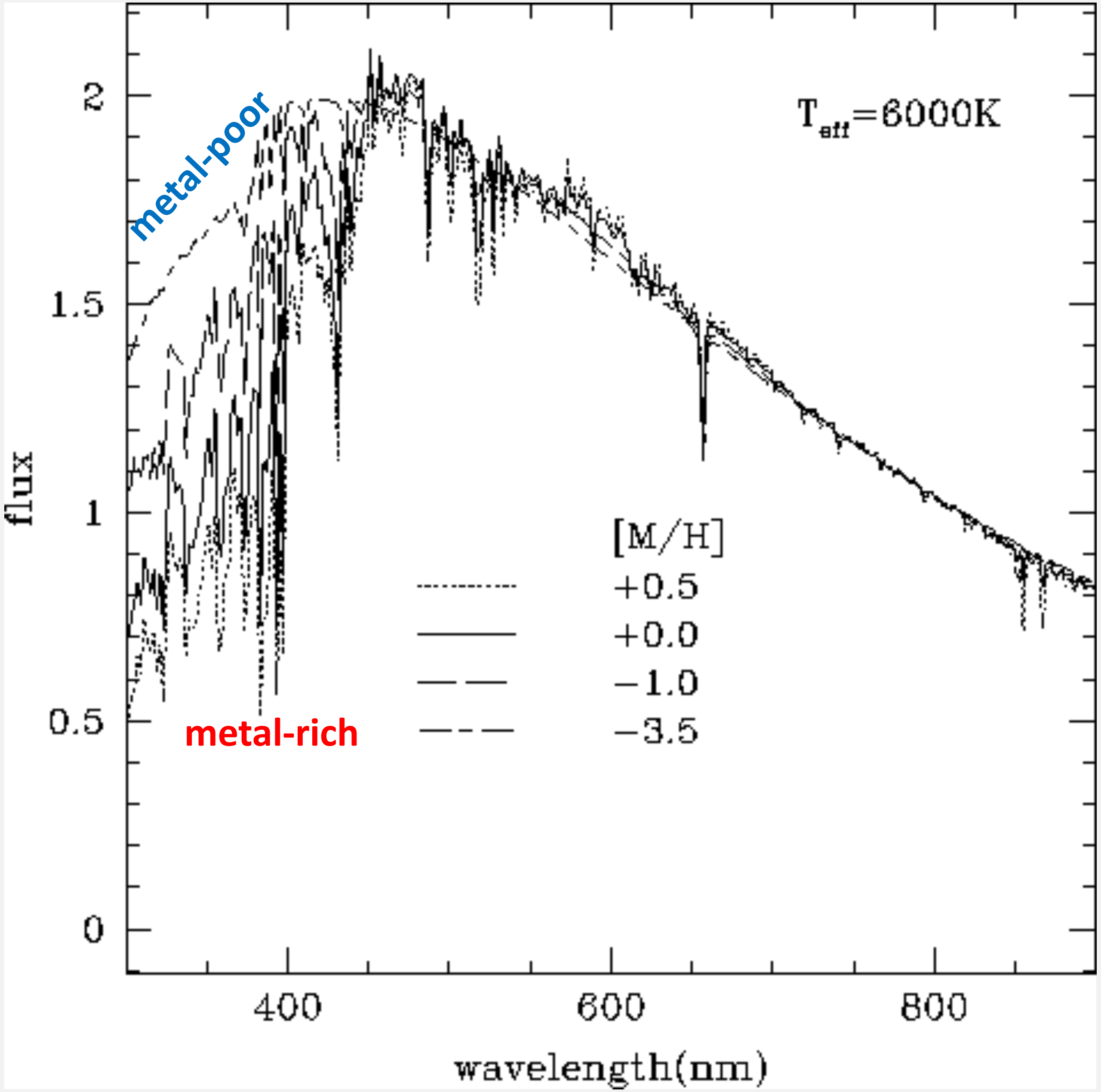
Abundances change in the interior due to nuclear reactions, but the metallicity of the outer layers does not change with time.

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

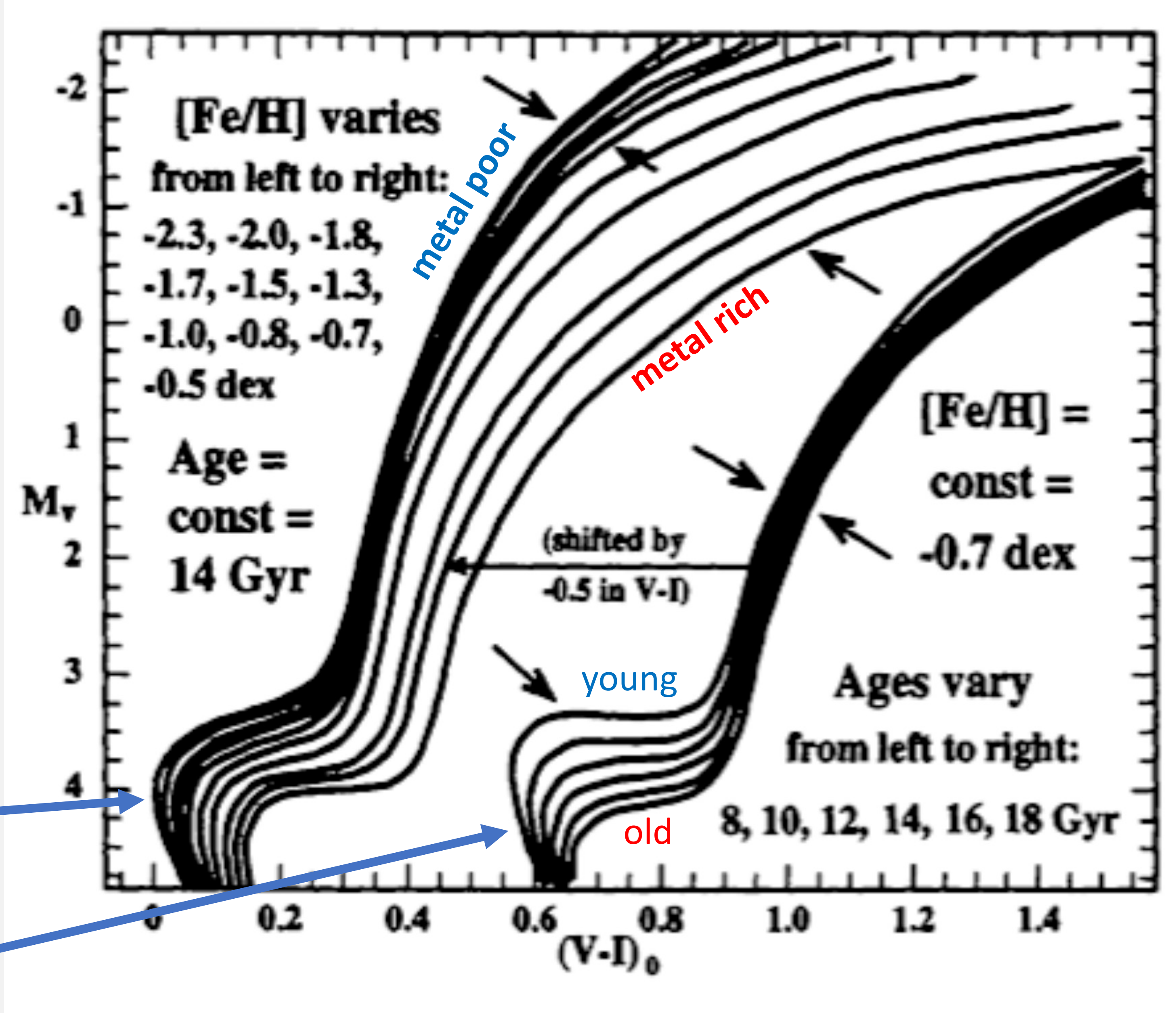
Line blanketing: Metals (particularly iron) absorb strongly in the blue part of the spectrum. So, metal rich stars appear redder.



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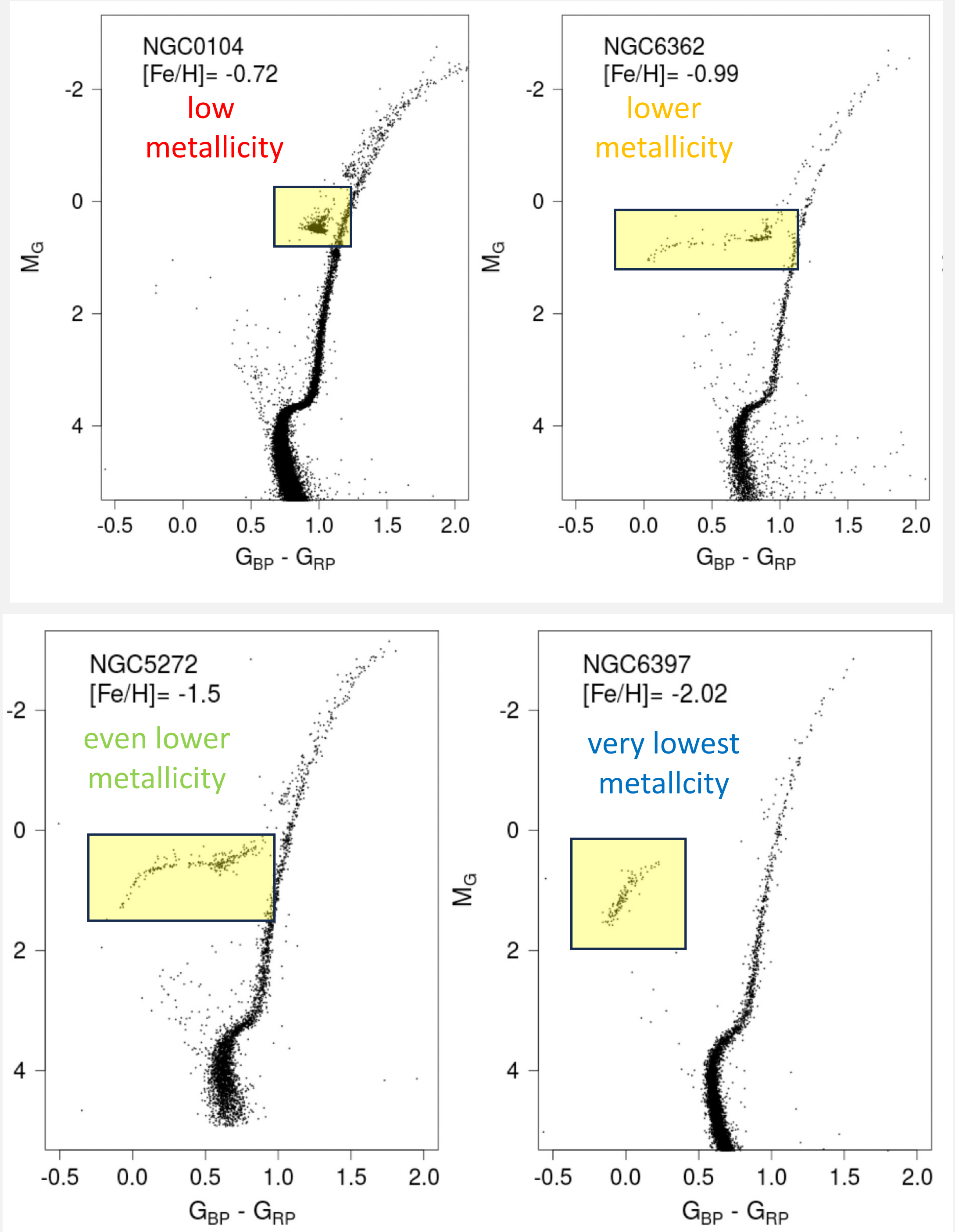
Horizontal Branch morphology: some combination of stellar evolution and atmosphere effects means that HB stars are, generally, bluer in metal poor pops.



Gaia 2018 (A&A 616 A10)

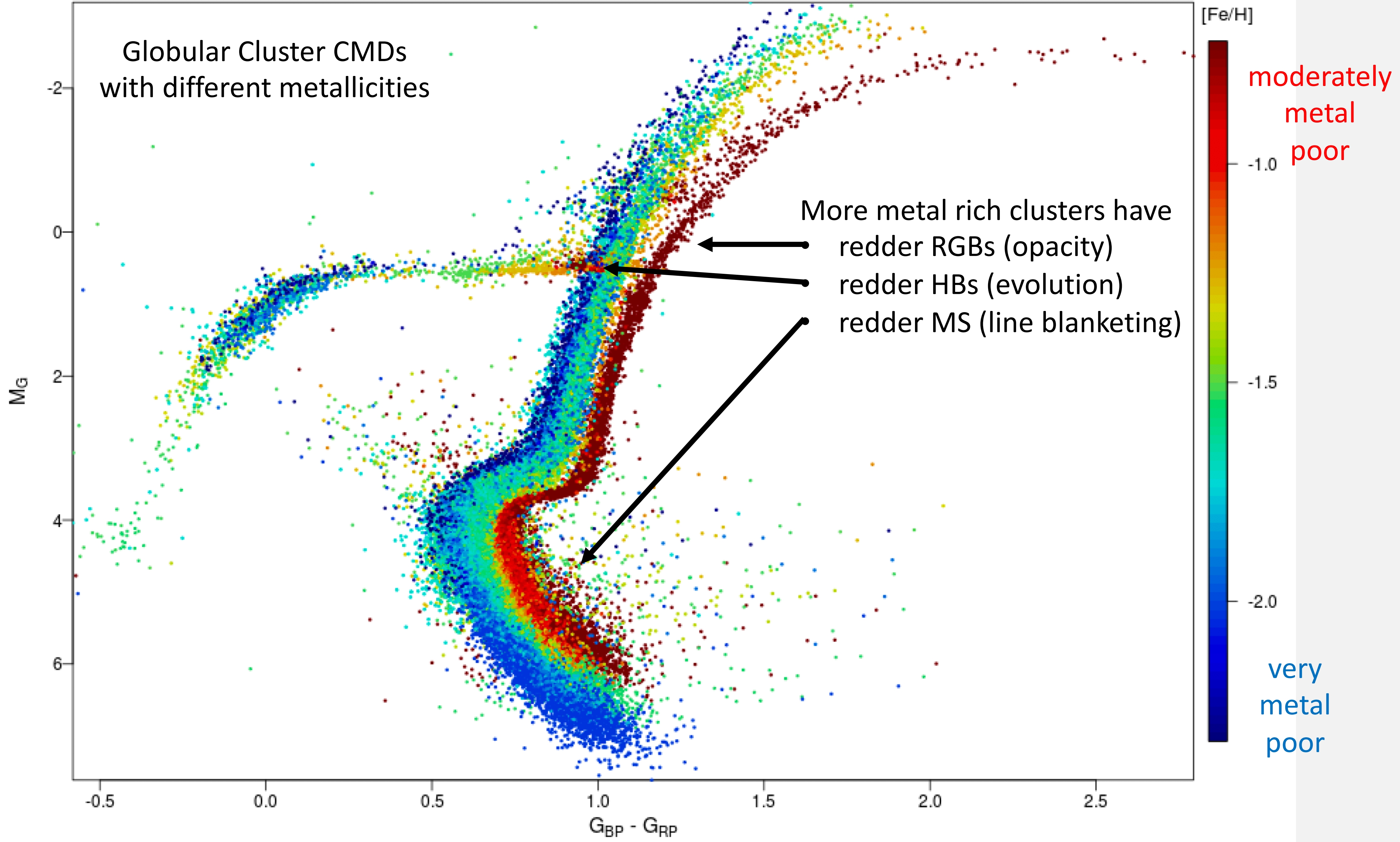


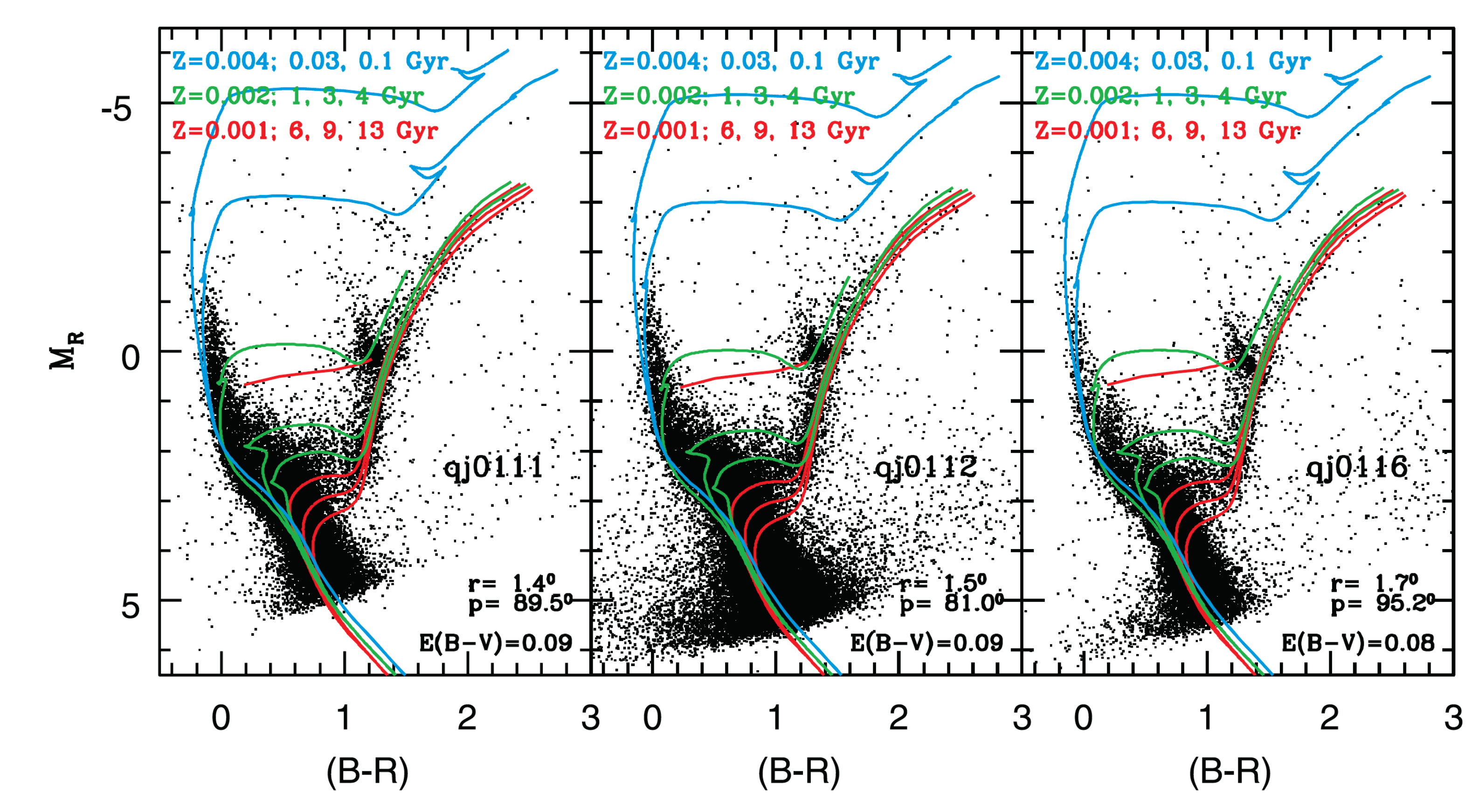
Fig. 3. Composite HRD for 14 globular clusters, coloured according to metallicity (Table 3).

Gaia 2018 (A&A 616 A10)

Studying Stellar Populations in Other Galaxies

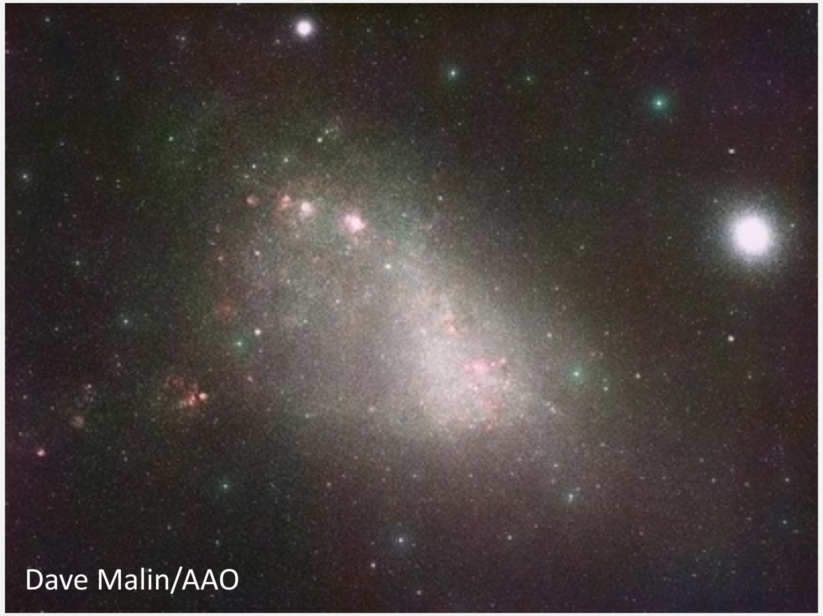
In the Milky Way, we see stars down to very low mass (at least locally). Can construct precise CMDs.

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



Noel+07:

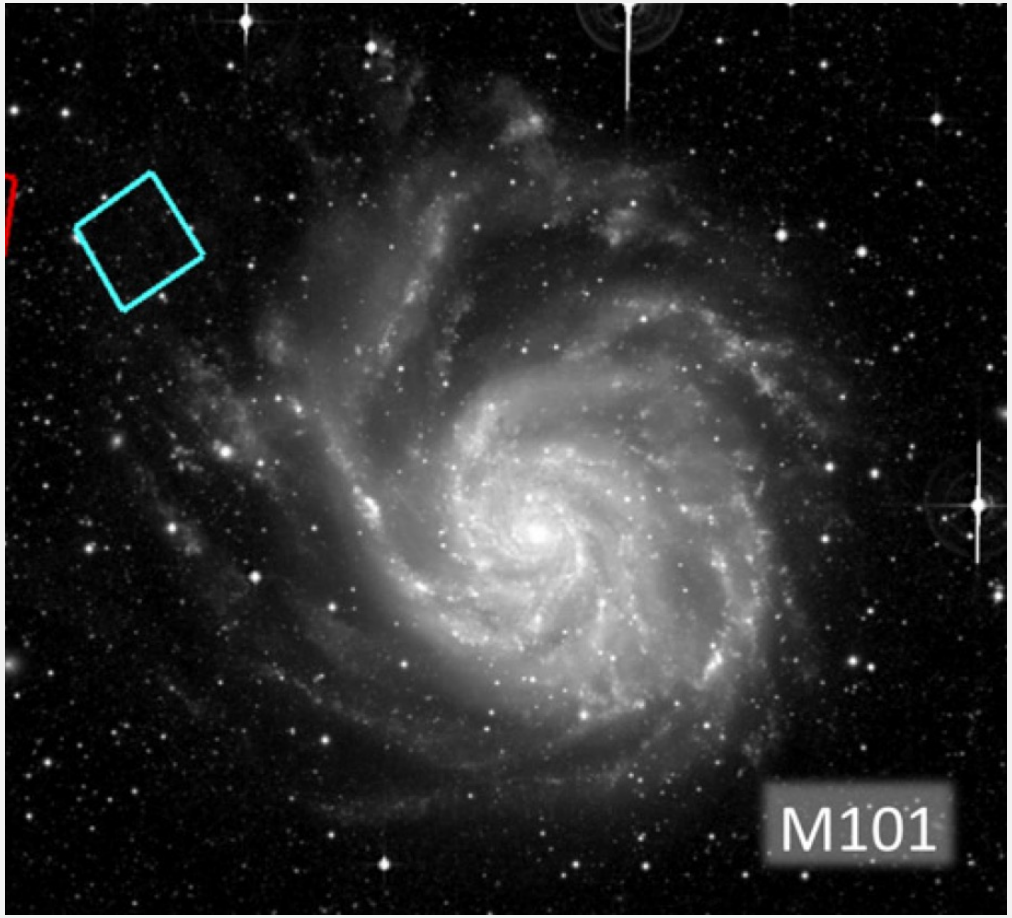
CMDs for fields in the Small Magellanic Cloud (D ≈ 60 kpc)

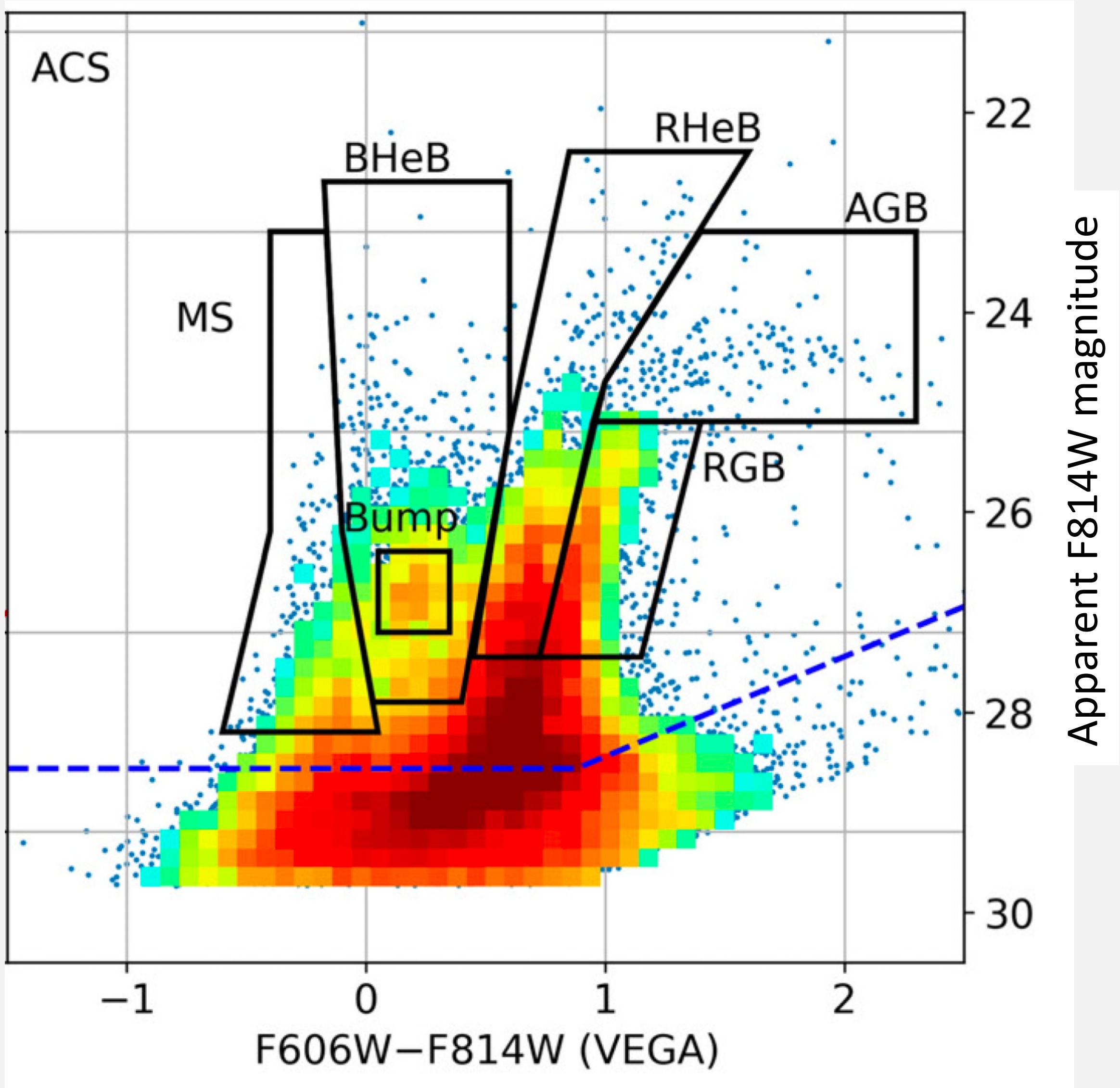


Studying Stellar Populations in Other Galaxies

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.

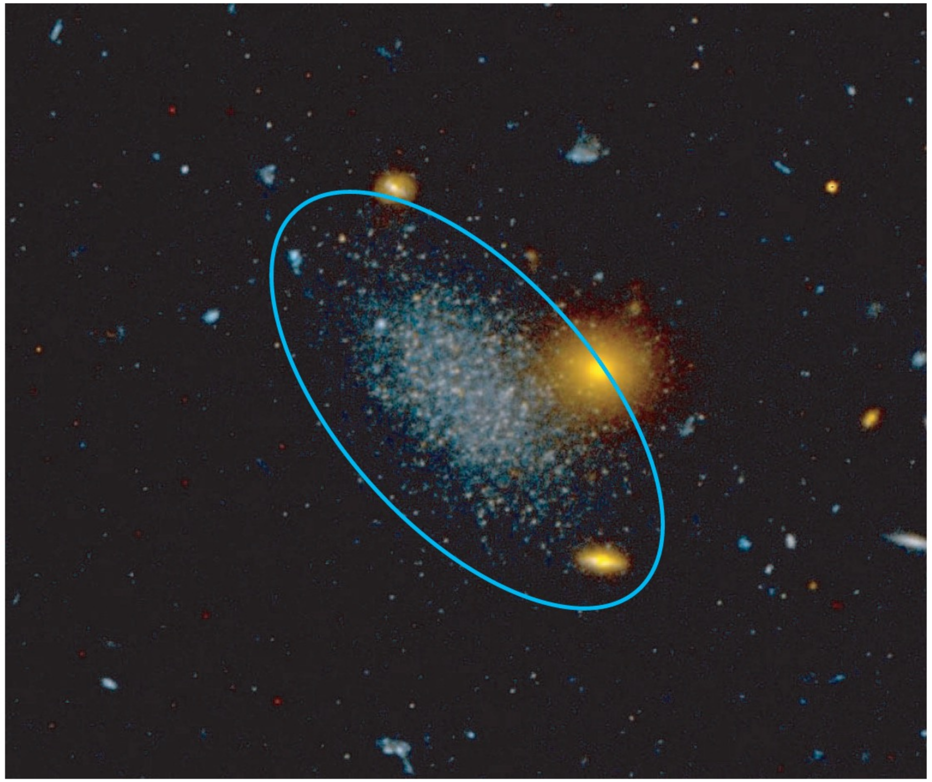


FIG. 1.—Color image of a 28″ × 24″ section of our image, centered on the dSph galaxy. In the image, blue represents 2(F606W − F814W), green represents F606W, and red represents F814W. The ellipse denotes the boundary used to defined a subsample of stars that minimizes contamination (see text). North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

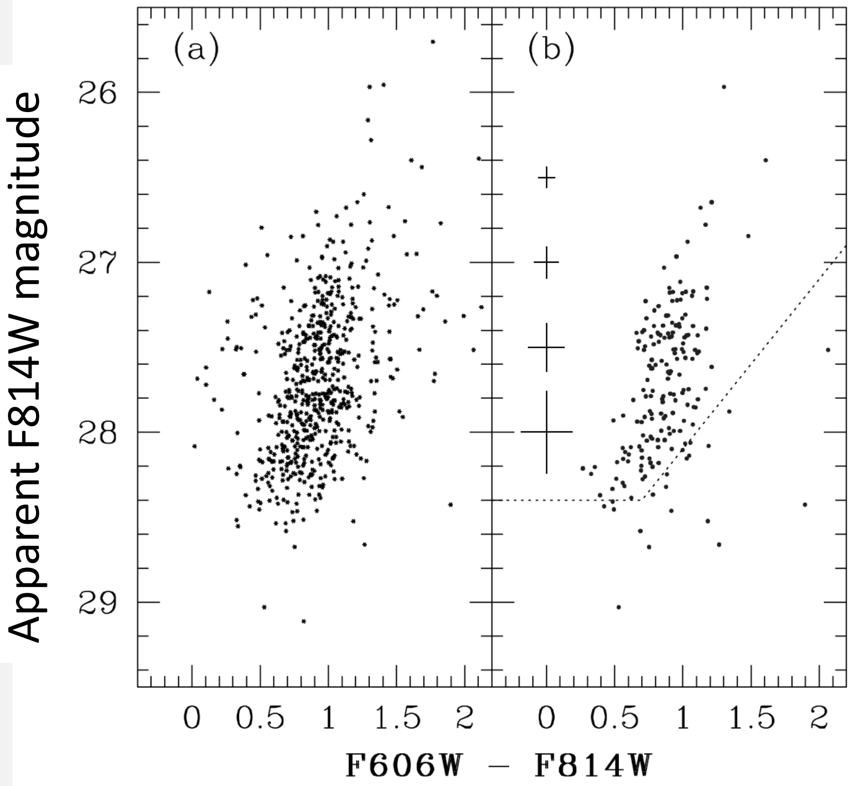


FIG. 4.—(*a*) Color-magnitude diagram (in the Vegamag system) for the 611 stellar objects located in a 66″ × 48″ region centered on the dSph galaxy. (*b*) The "dwarf-only" CMD, formed from a subset of 181 stars located within the inner elliptical region shown in Fig. 1. The dotted lines denote the 50% 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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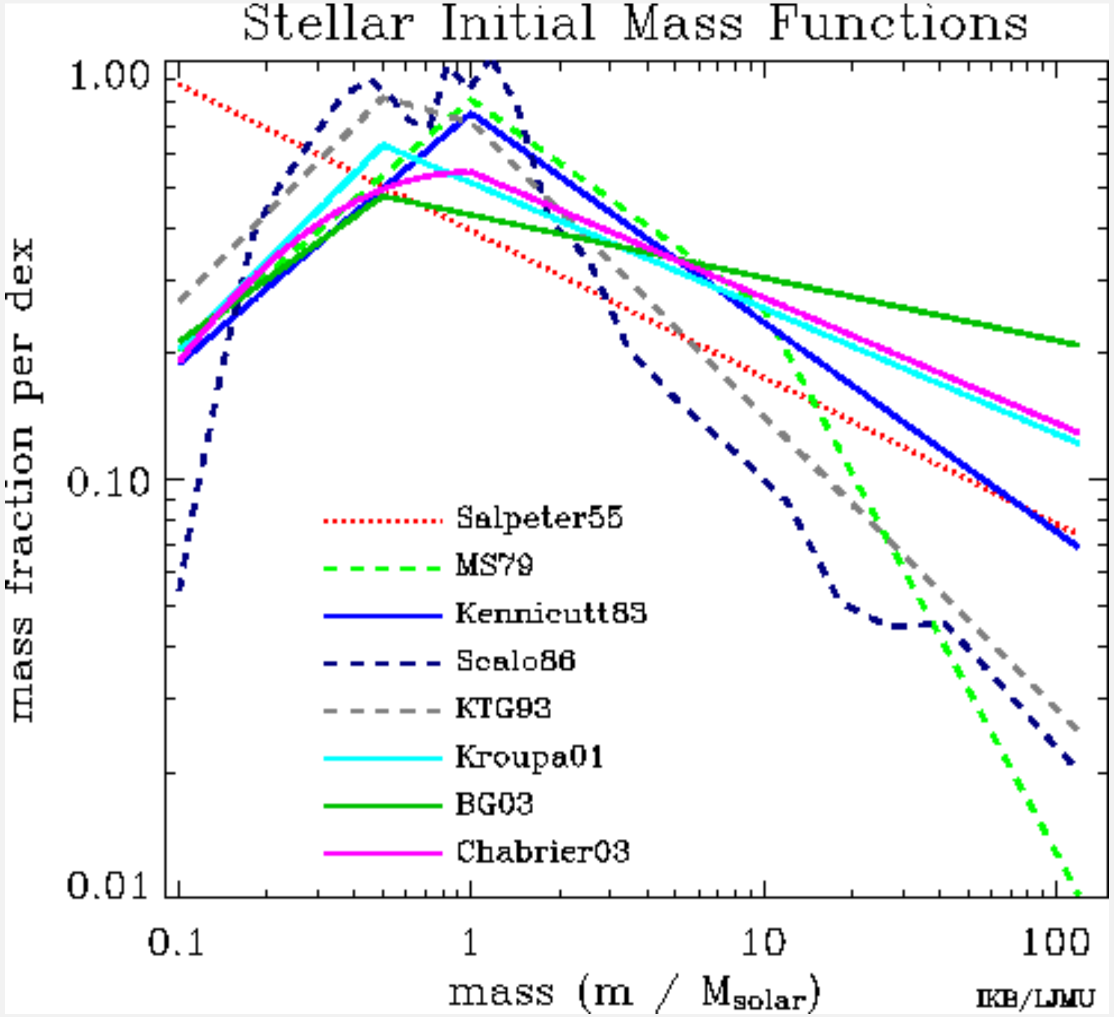
Population Synthesis Concepts

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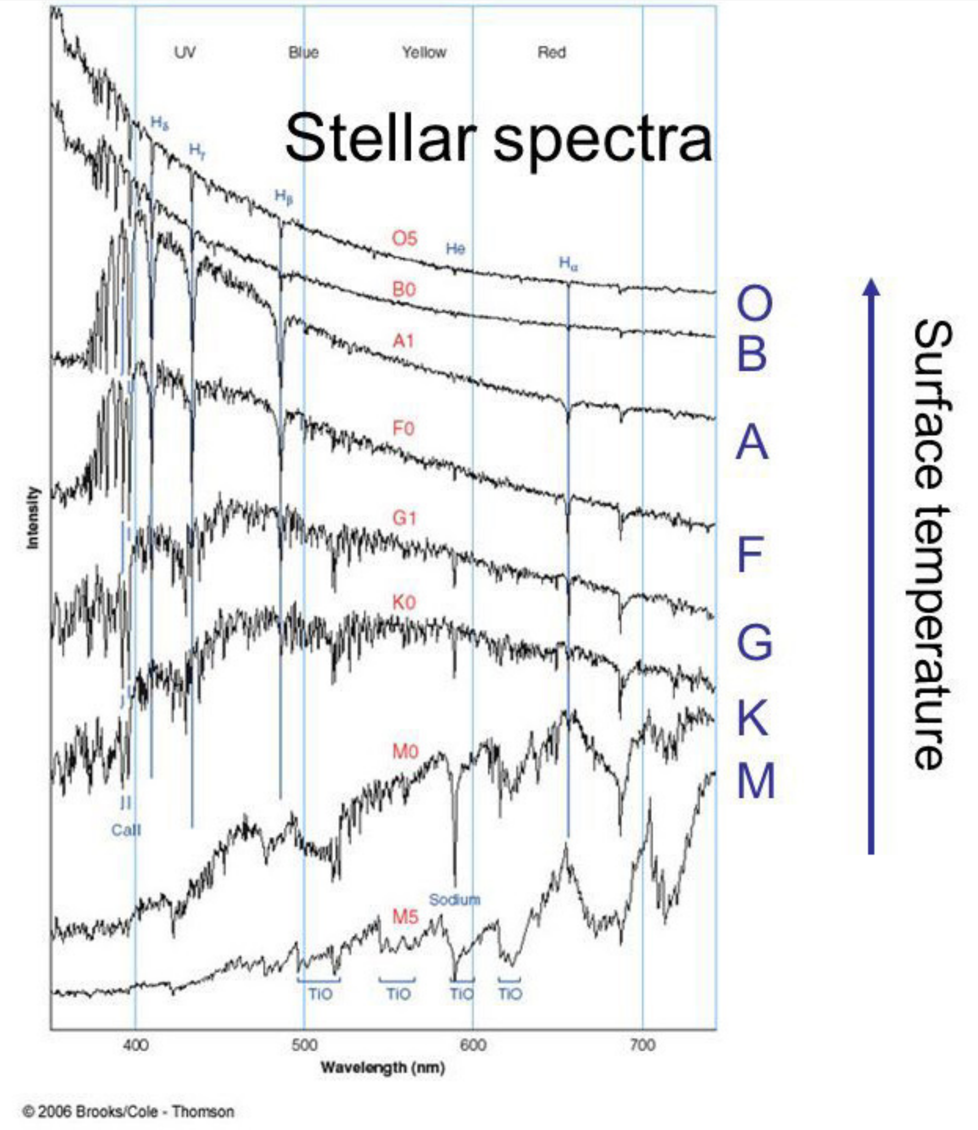
II: We need to know the light output of stars:

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



Studying Stellar Populations in Other Galaxies

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- 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!

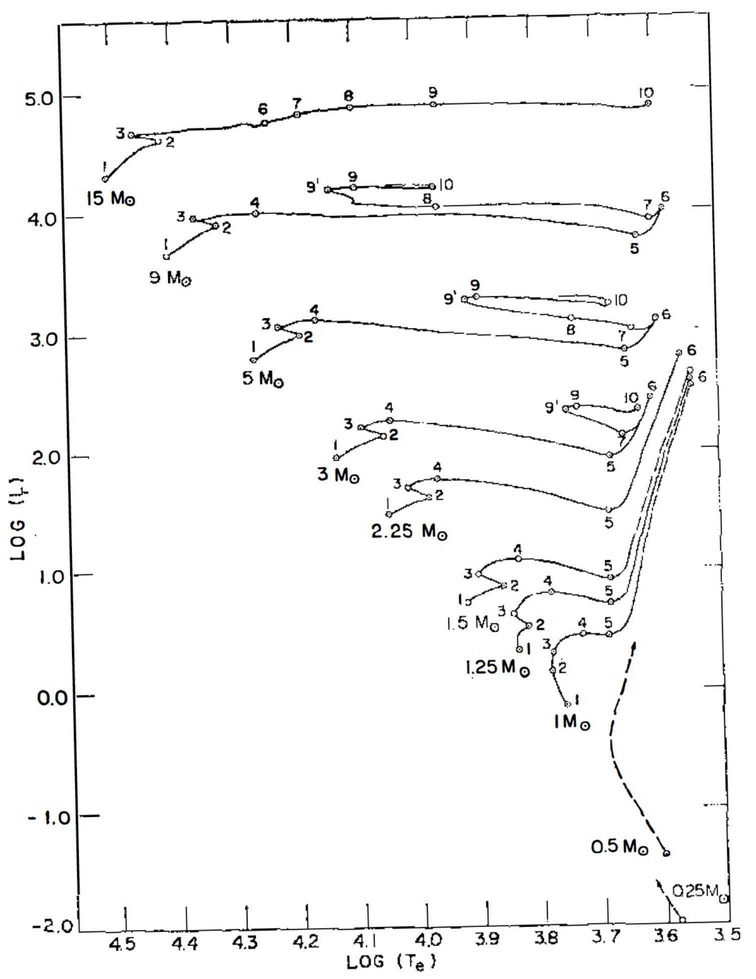
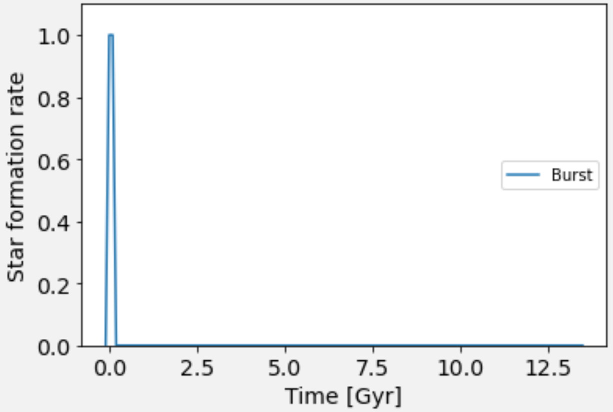


FIG. 3. Paths in the H-R diagram for metal-rich stars of mass $(M/M_\odot) = 15$, 9, 5, 3, 2.25, 1.5, 1.25, 1, 0.5, 0.25. Units of luminosity and surface temperature are the same as in Figure 1. Traversal times between labeled points are given in Tables III and IV. Dashed portions of evolutionary paths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

Spectral Evolution of different stellar populations

SFR(t): single burst at t=0



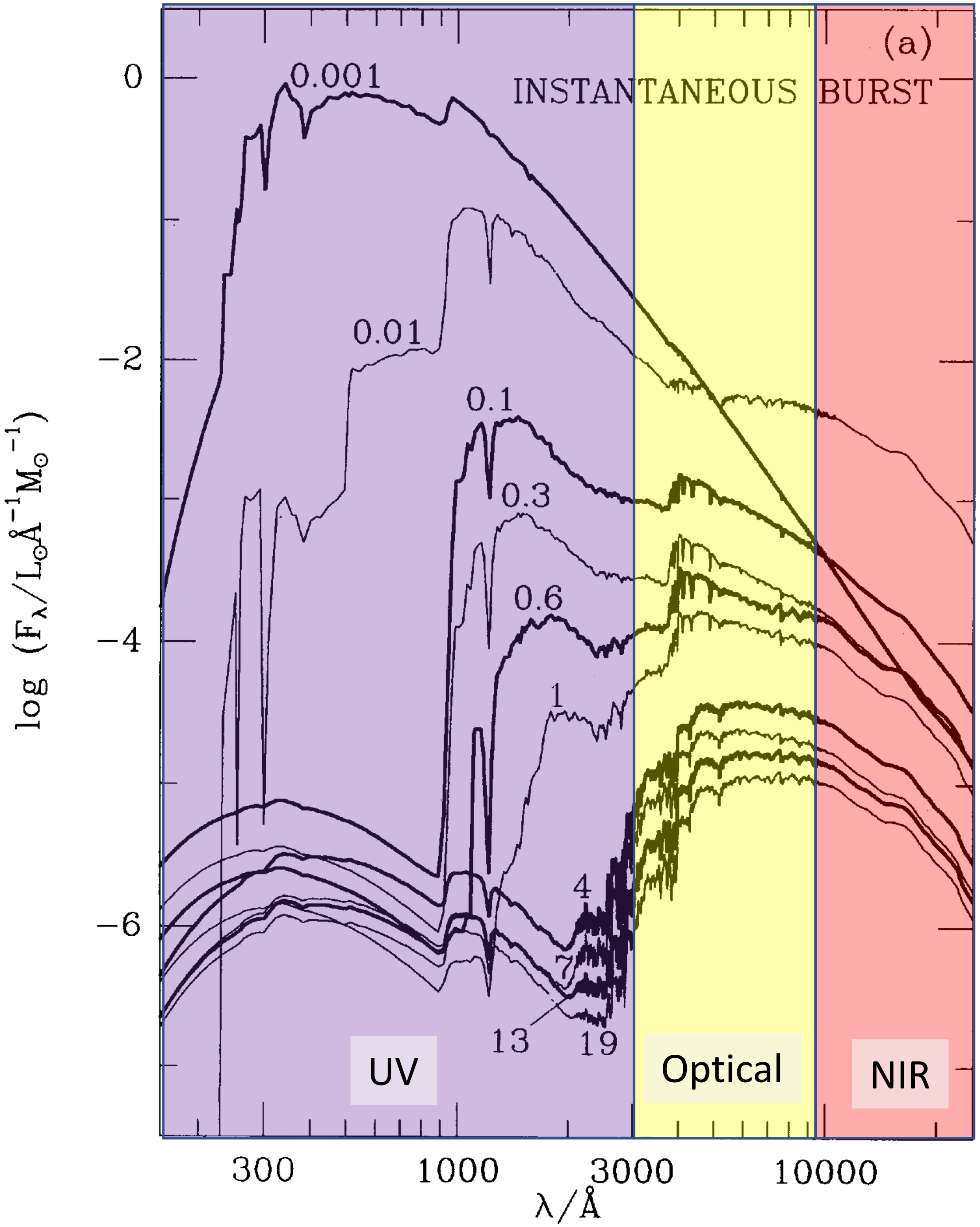
Ages marked in Gyr

UV light decreases very fast, since all the massive young blue O and B stars that provide that light are dying out quickly.

At later times, the (weak) UV light comes from evolved horizontal branch stars.

Optical and NIR light drop more slowly as lower mass stars begin to die out over longer time scales.

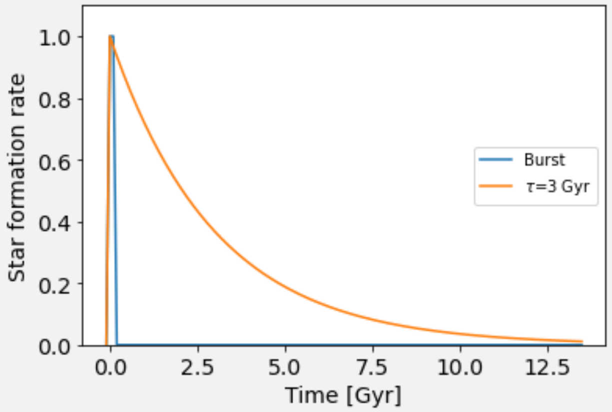
Bruzual & Charlot 1993



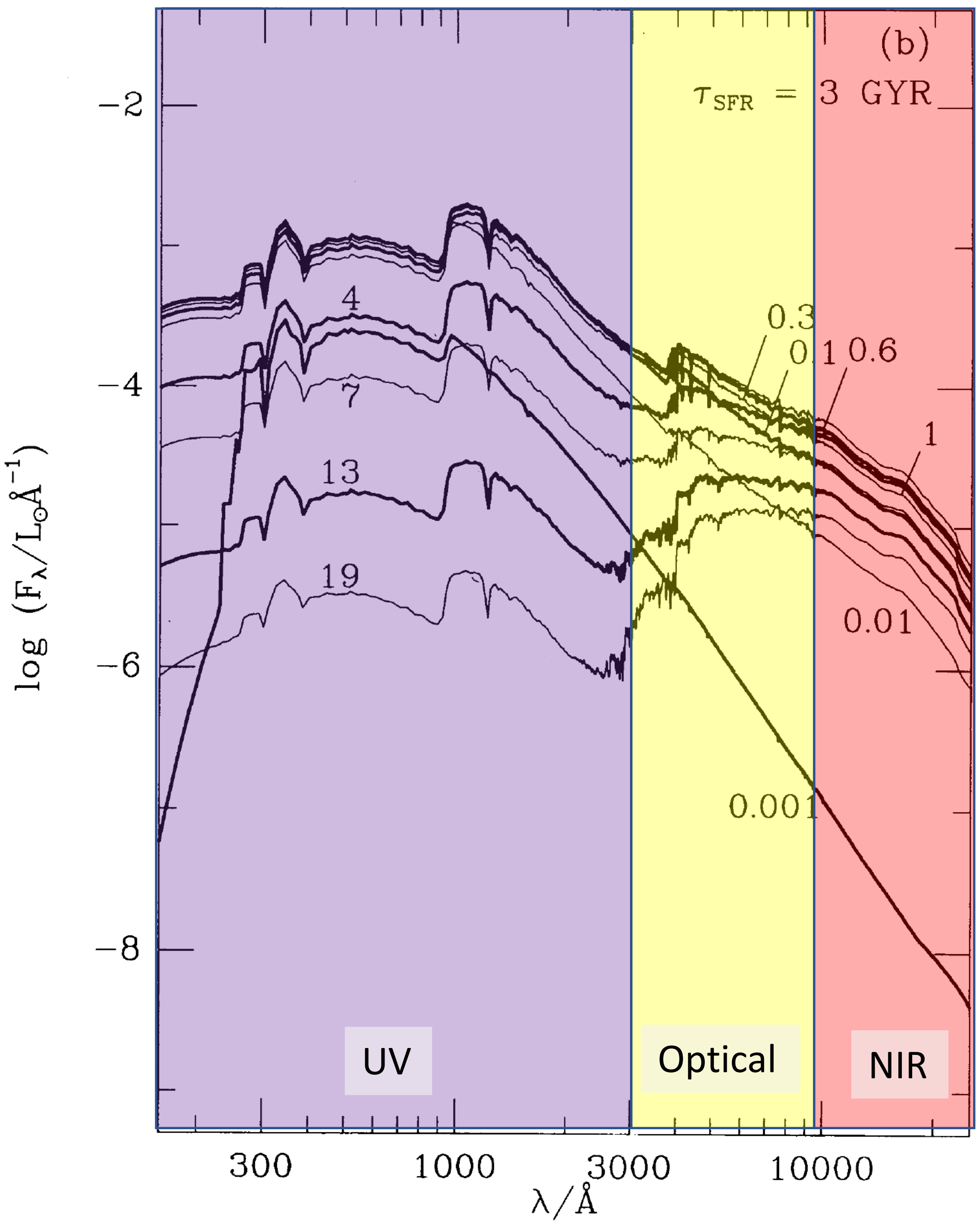
Spectral Evolution of different stellar populations

SFR(t): $e^{-t/\tau}$, τ=3 Gyr

Ages marked in Gyr



UV light does not drop so quickly because you continue to make stars (although at a slower rate), including O and B stars that can produce UV light.

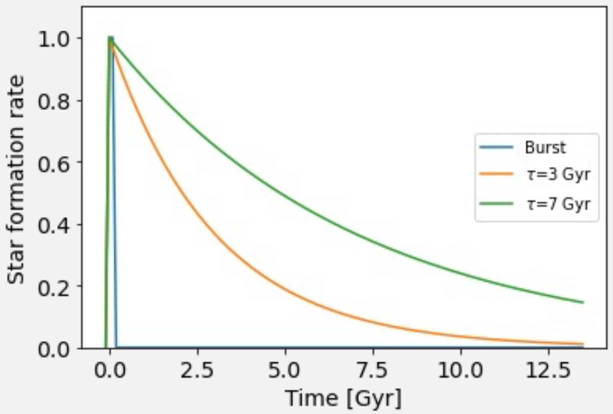


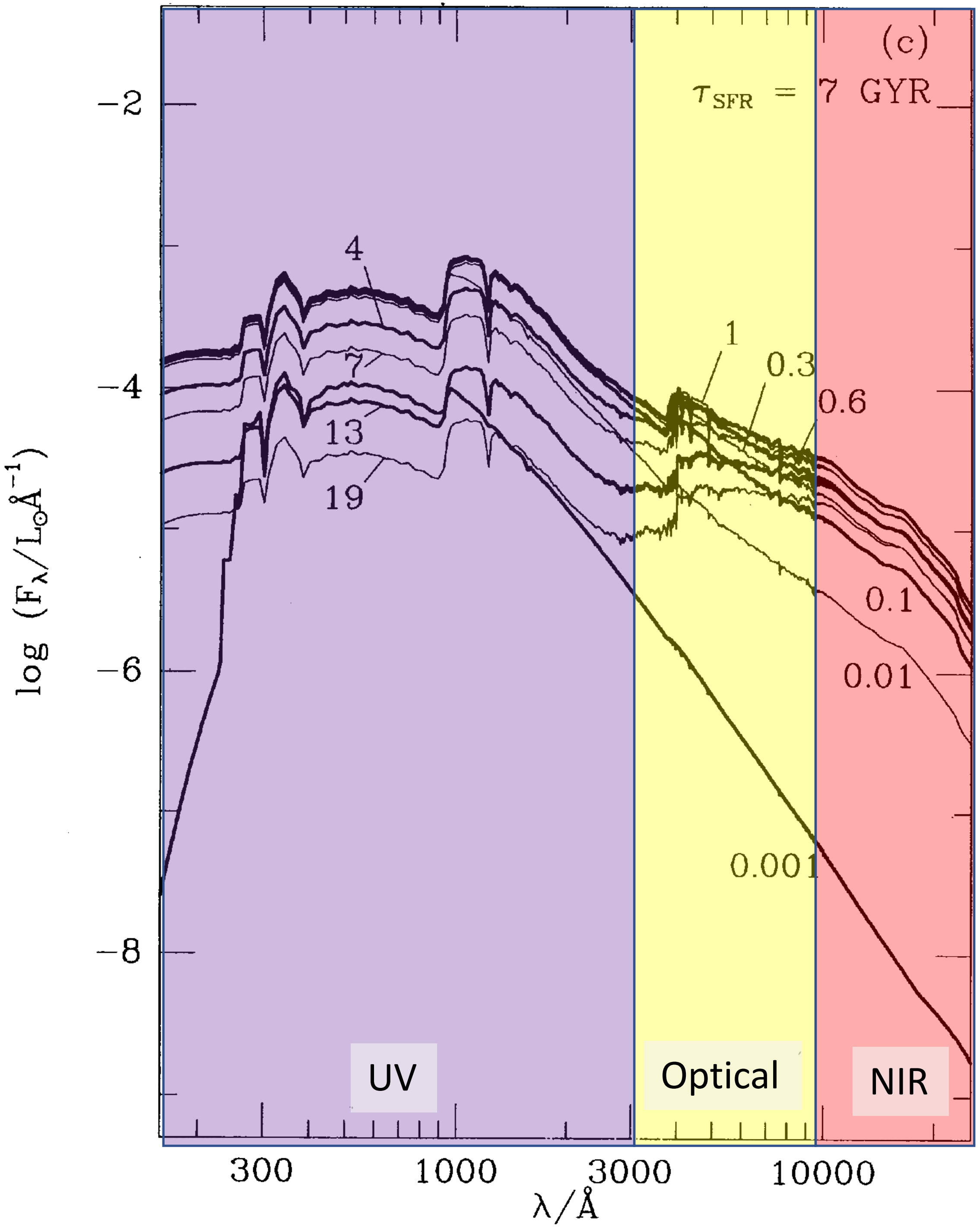
Bruzual & Charlot 1993

Spectral Evolution of different stellar populations

SFR(t): $e^{-t/\tau}$, τ=7 Gyr

Ages marked in Gyr



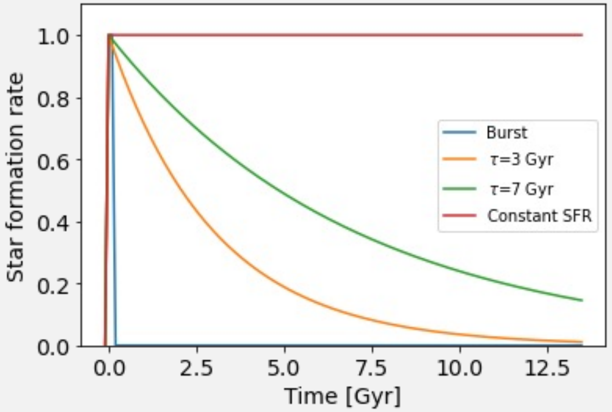


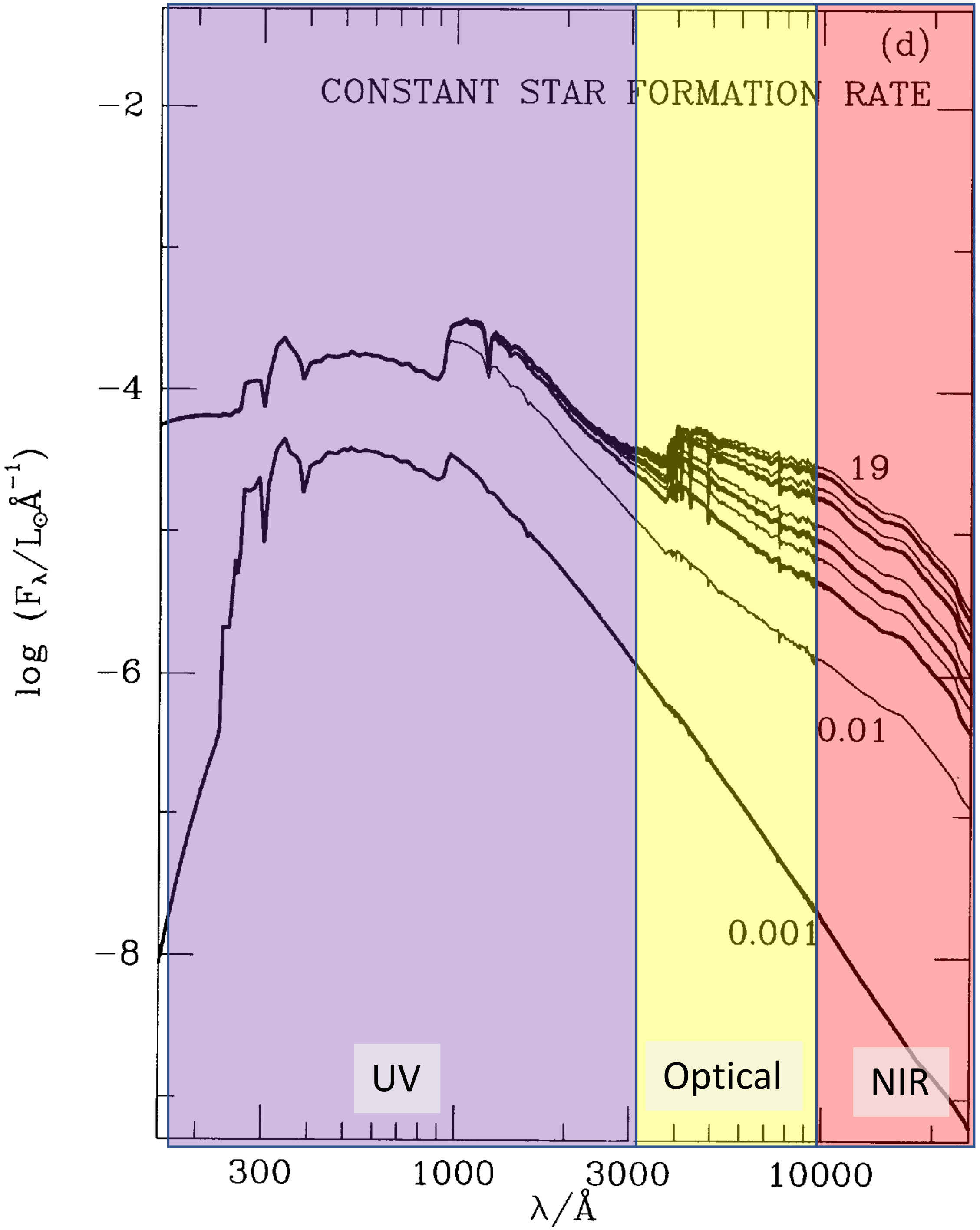
Bruzual & Charlot 1993

Spectral Evolution of different stellar populations

SFR(t): constant over time

Ages marked in Gyr





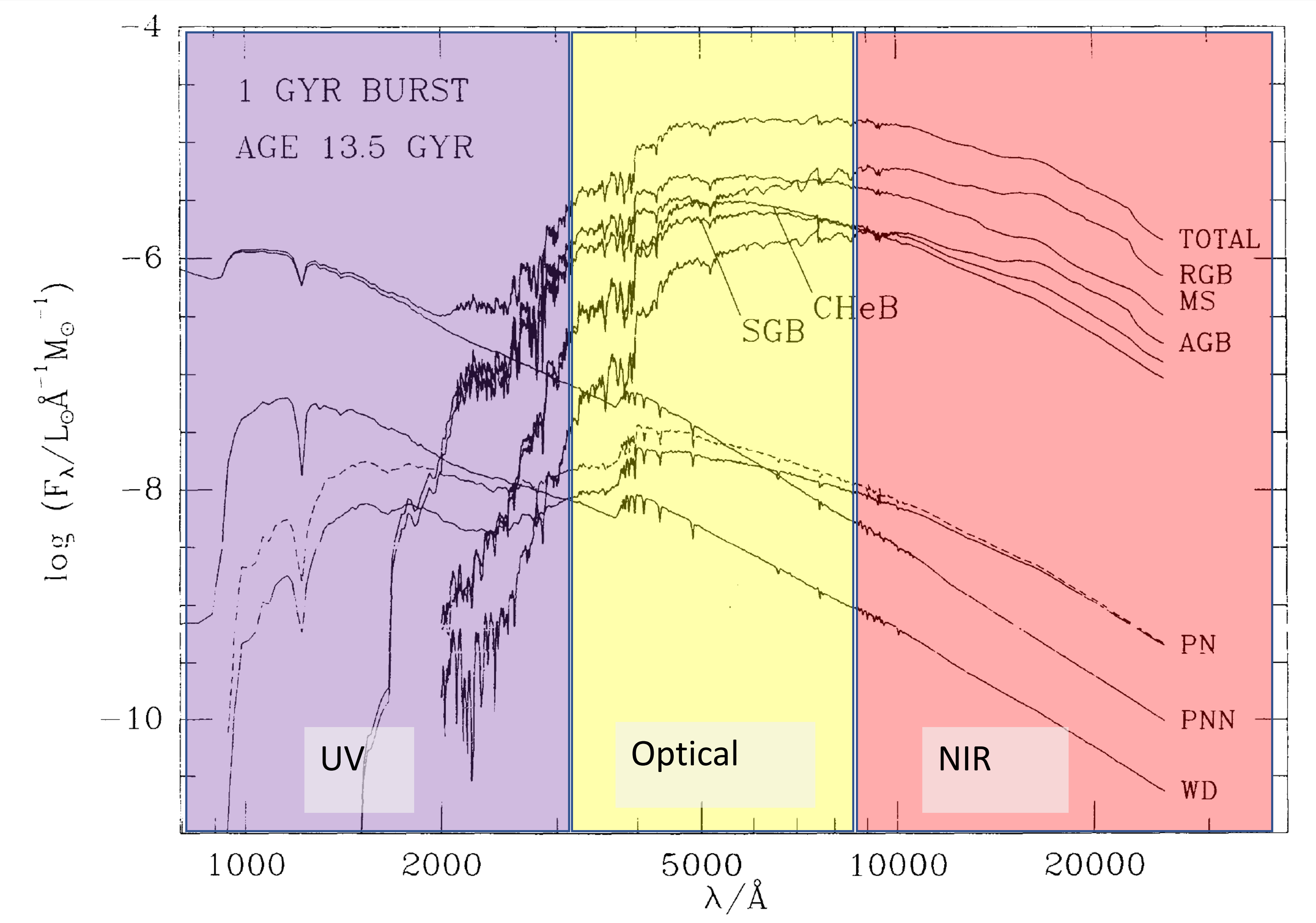
Bruzual & Charlot 1993

Contribution from different evolutionary stages

Old, single burst population

In optical and infrared, light is dominated by RGB stars, MS stars, and horizontal branch stars (CHeB).

In UV, much less light, and it is dominated by horizontal branch stars (CHeB) and planetary nebula nuclei (PNN).



Bruzual & Charlot 1993

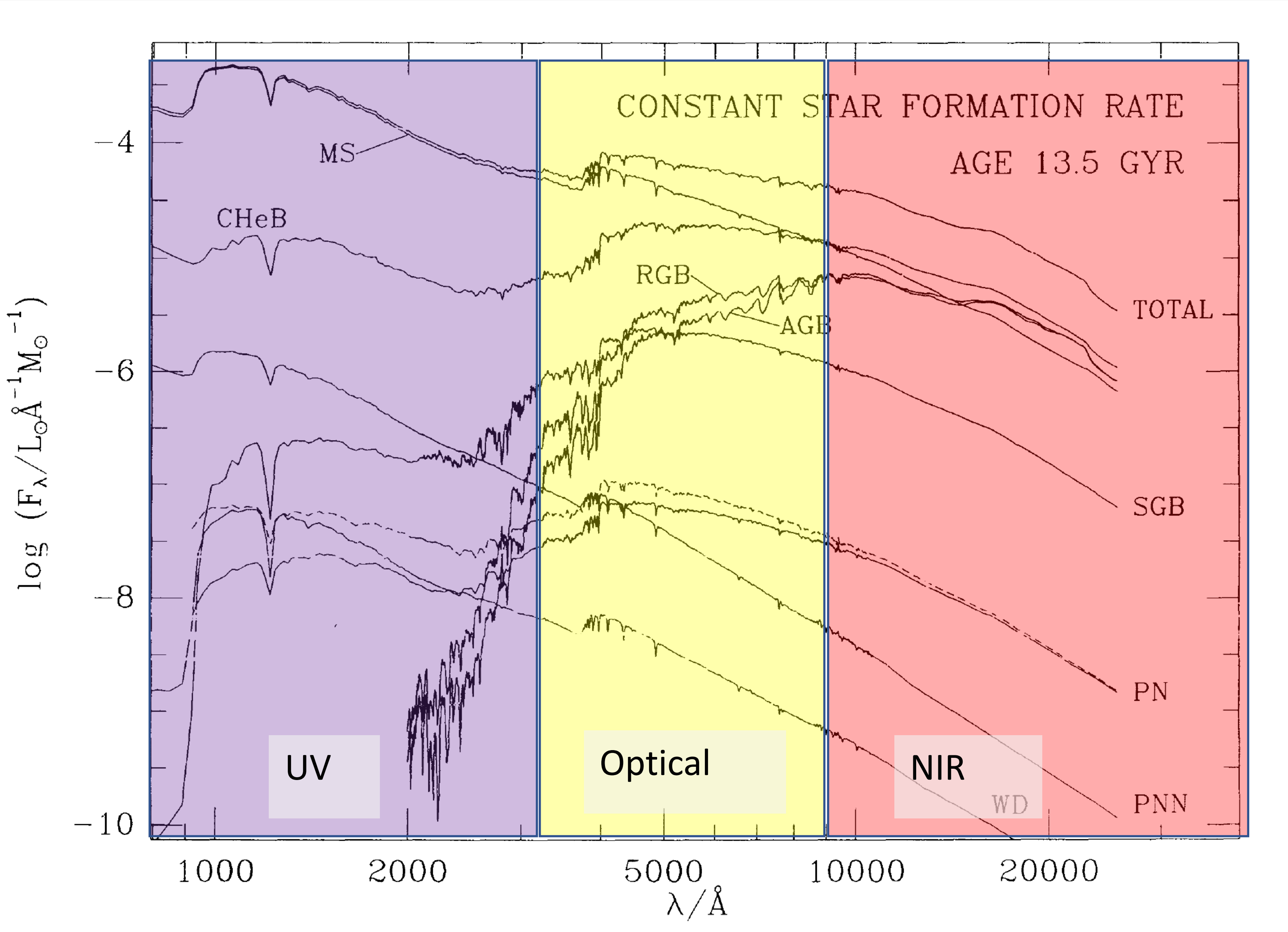
Contribution from different evolutionary stages

Constant star-forming population

In optical, light is dominated by MS stars, except at the reddest colors.

In the IR, evolved stars contribute much of the light.

Very bright in the UV, from massive young stars on the upper main sequence.



Bruzual & Charlot 1993

Contribution from different evolutionary stages

The integrated light is always dominated by the brightest stars, even though they may not be the most common stars.

The dominant population changes as the population evolves ⇒

Colors and spectra of galaxies (i.e., measured of the integrated light) are "luminosity weighted sums".

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

These things are very different!

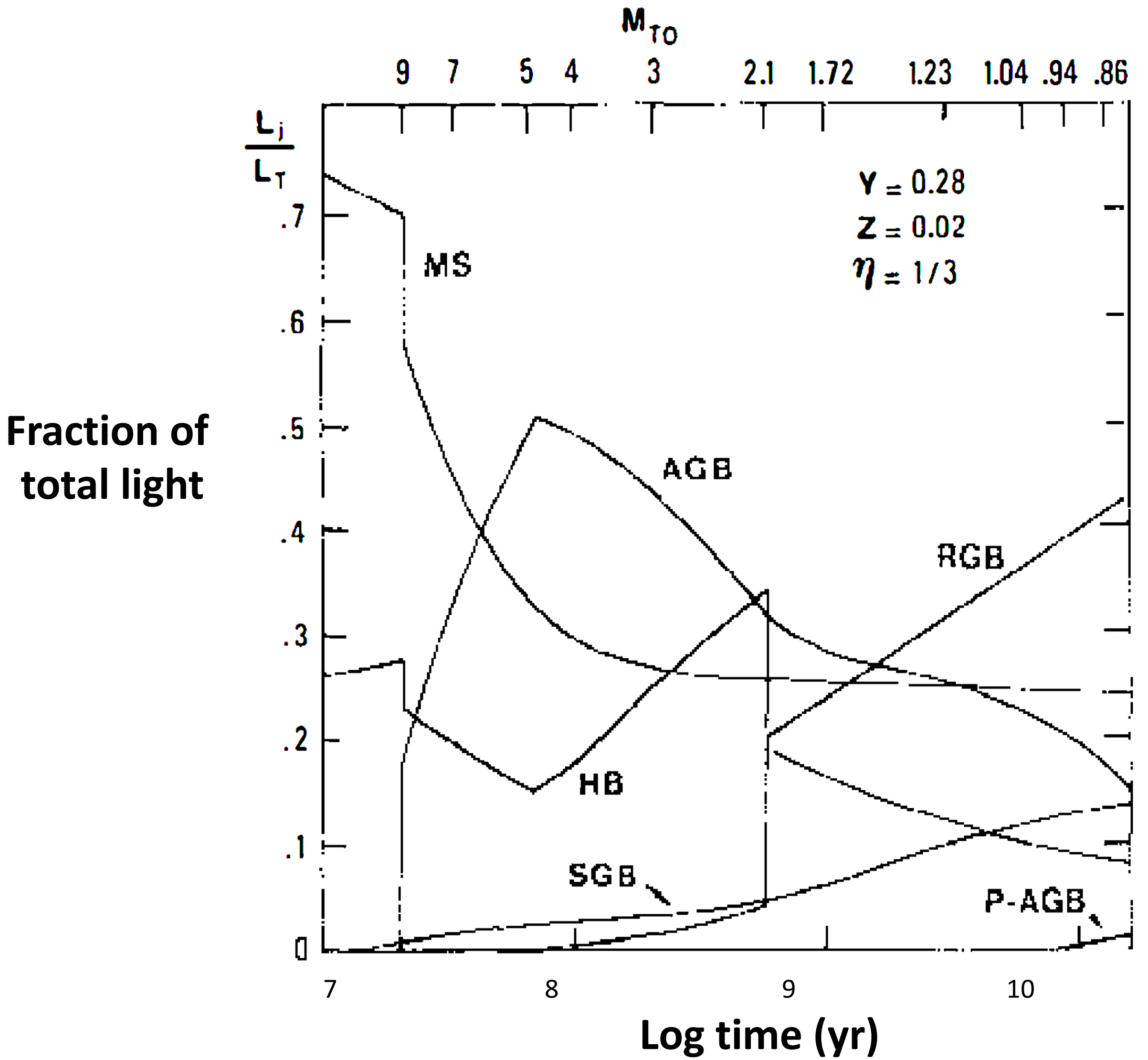
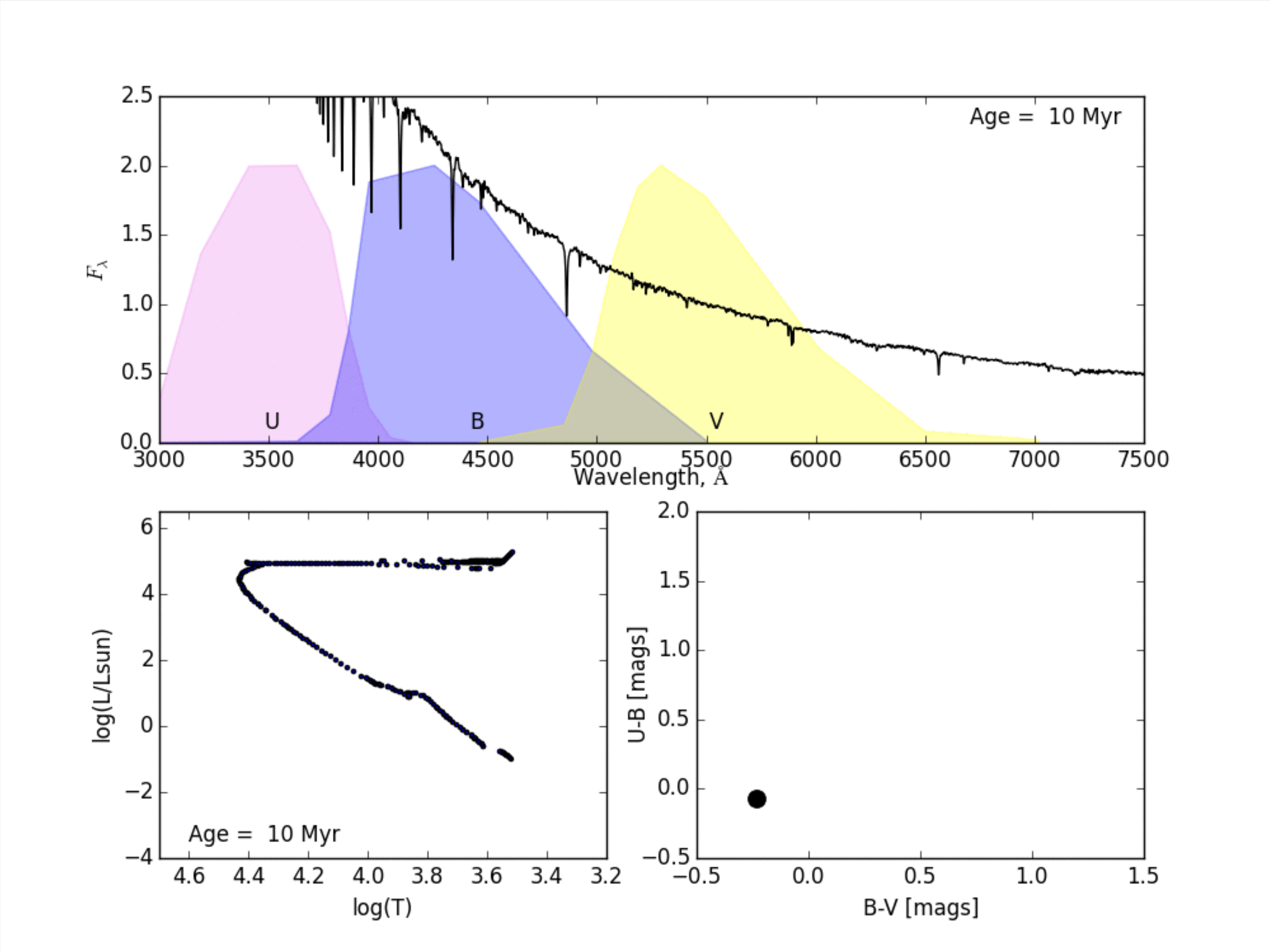


Figure 2 The relative contributions of the various evolutionary stages to the integrated light of a stellar population as a function of age (Renzini & Buzzoni 1986), for the indicated composition and mass-loss parameter η (cf. Section 4.1.3). The age t is in years.

Observables: Colors

Imaging and photometry is "quick and easy": Can study the colors, color gradients, etc of galaxies.



Evolution of a single burst population

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

Remember: when looking at colors, smaller or more negative numbers means bluer colors.

Observables: Colors

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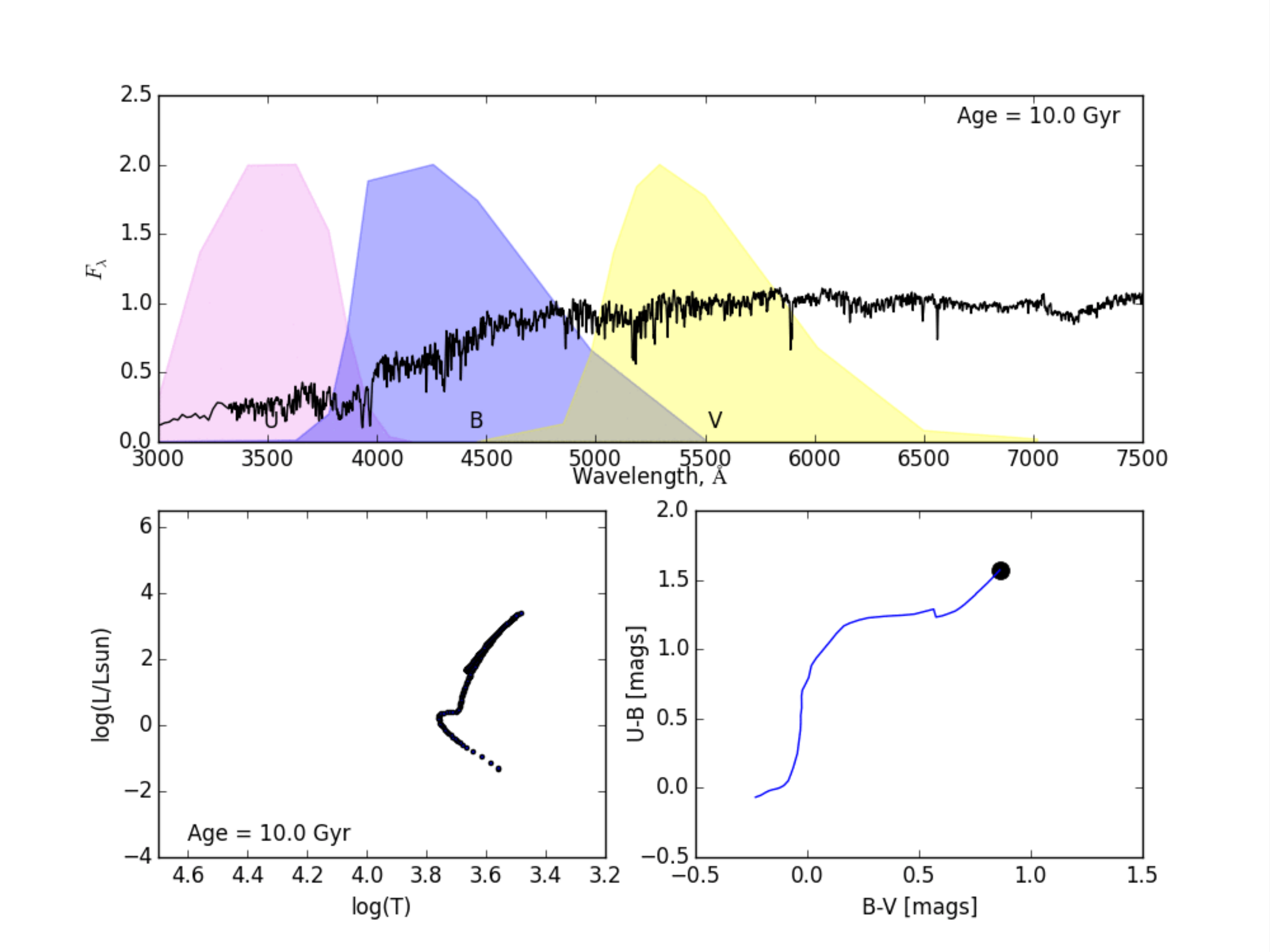

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(see the course website for a link to the animated figure…)

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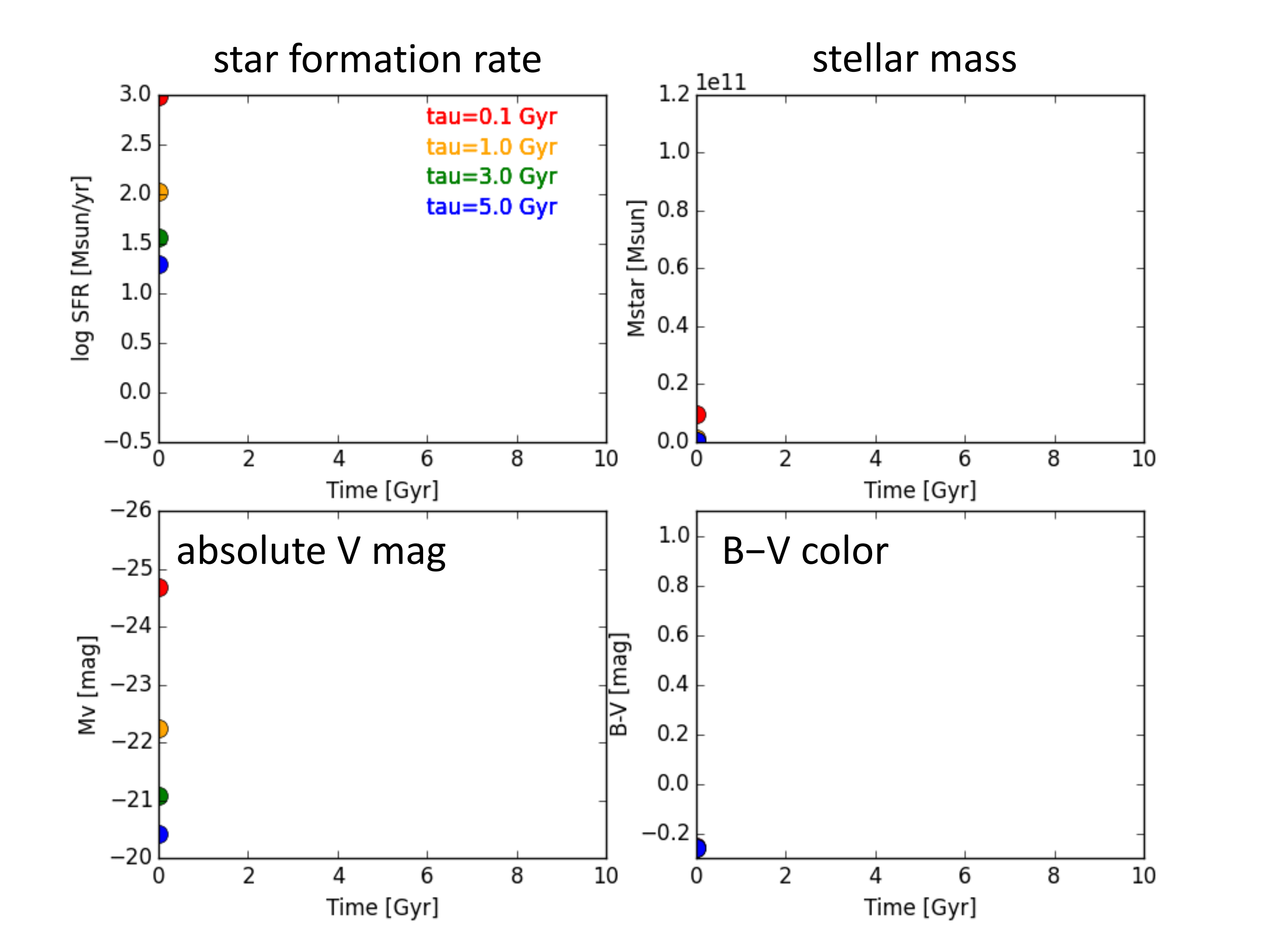


Evolution of a different star forming histories

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

Small tau: fast burst
Large tau: slowly declining SFR

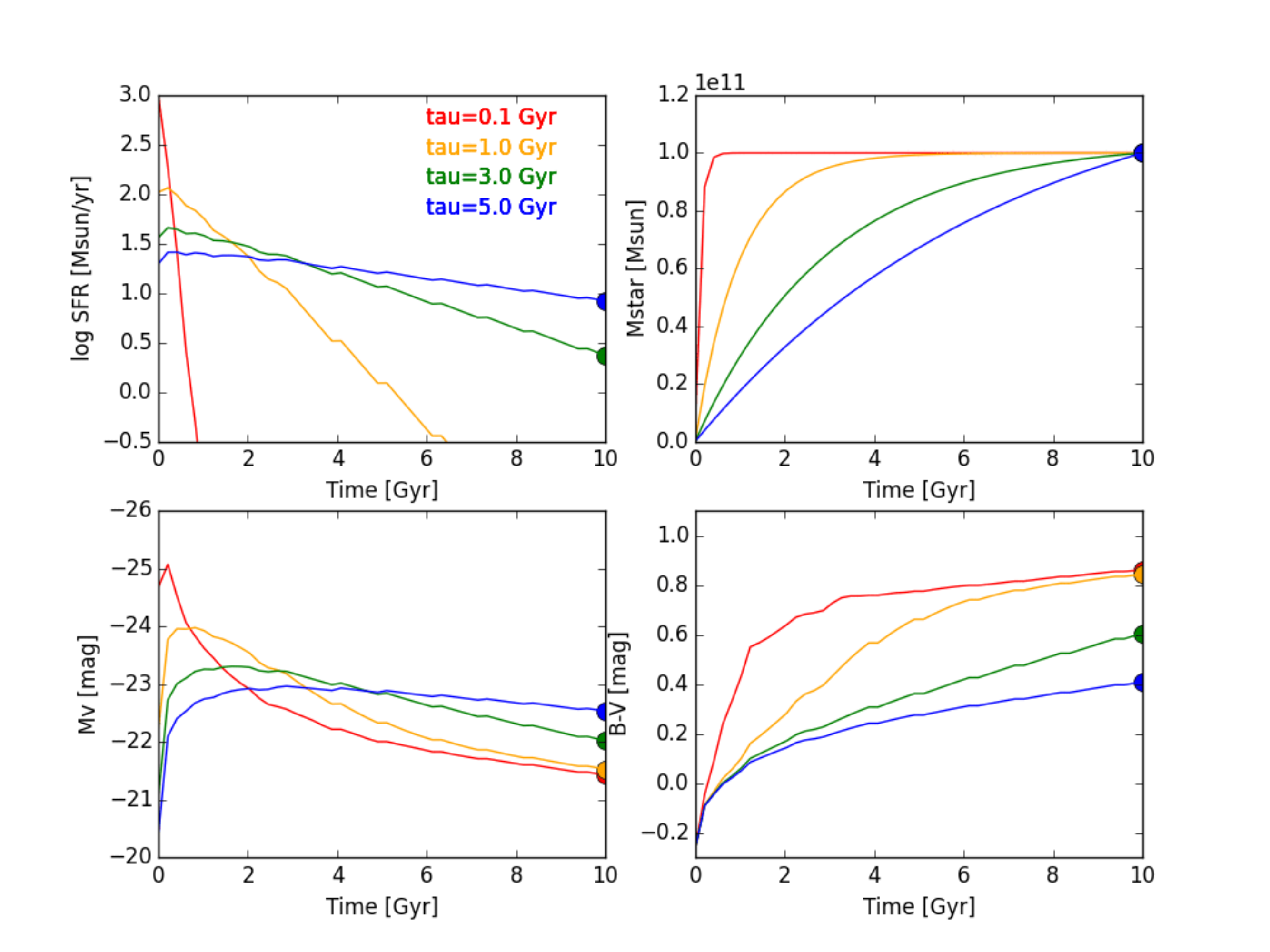
Fast bursts: As massive stars quickly die out, they fade rapidly and turn red.

Slowly changing SFR: Constantly replenishing stars of all types through new star formation. Fade slowly or not at all, don’t get as red.

Remember: when looking at colors, smaller or more negative numbers means bluer colors.

Observables: Colors

Imaging and photometry is "quick and easy": Can study the colors, color gradients, etc of galaxies.



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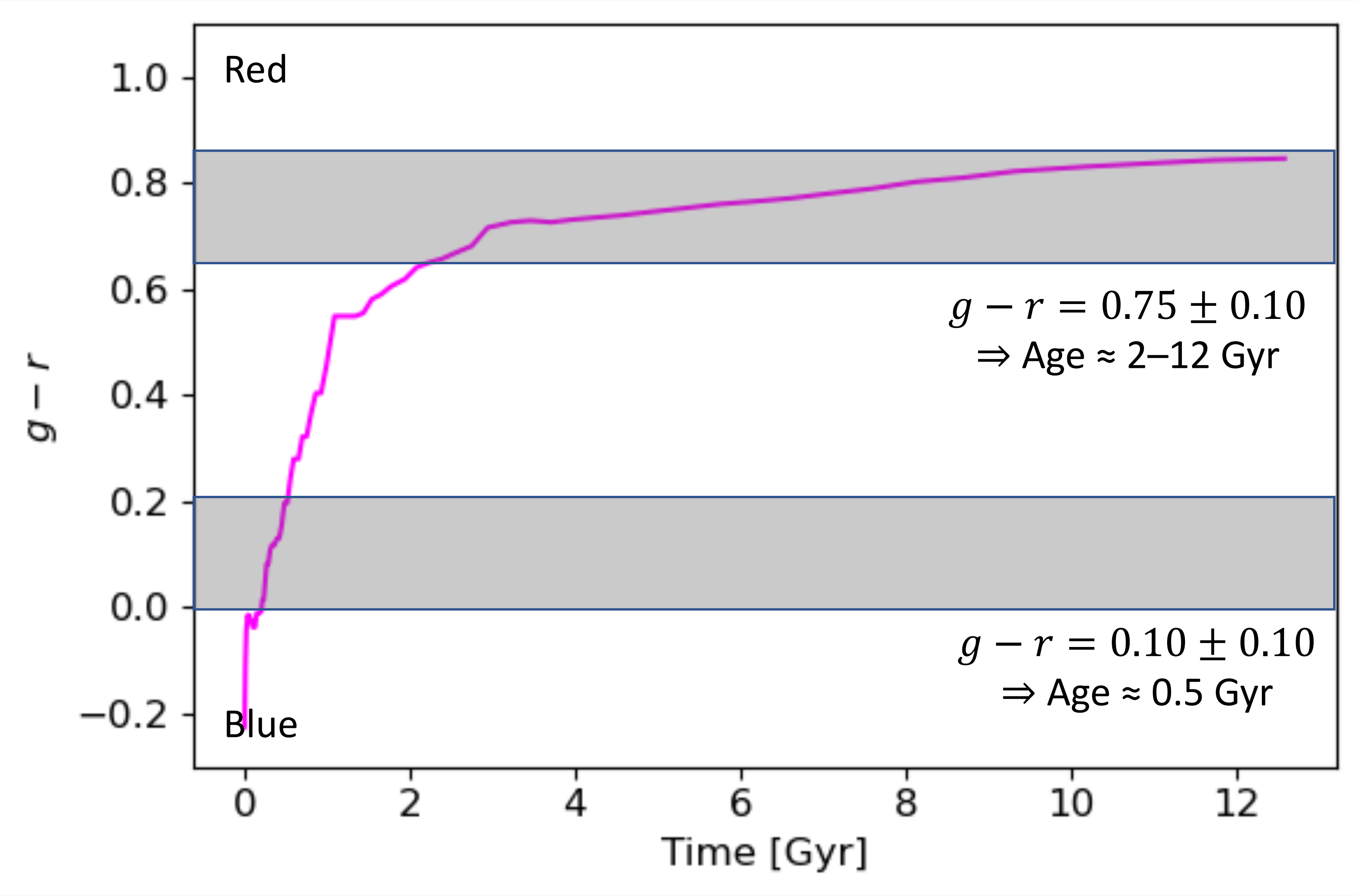
Colors, ages, and metallicity

Colors evolve rapidly for young populations (<2 Gyr), but then the color evolution is much weaker. This means constraining ages gets much more difficult for old populations.

Uncertainty in color can lead to a big uncertainty in age.

Color evolution for a single burst stellar population with solar metallicity.



Banana analogy
courtesy of Mia de los Reyes (Caltech)

Colors, ages, and metallicity

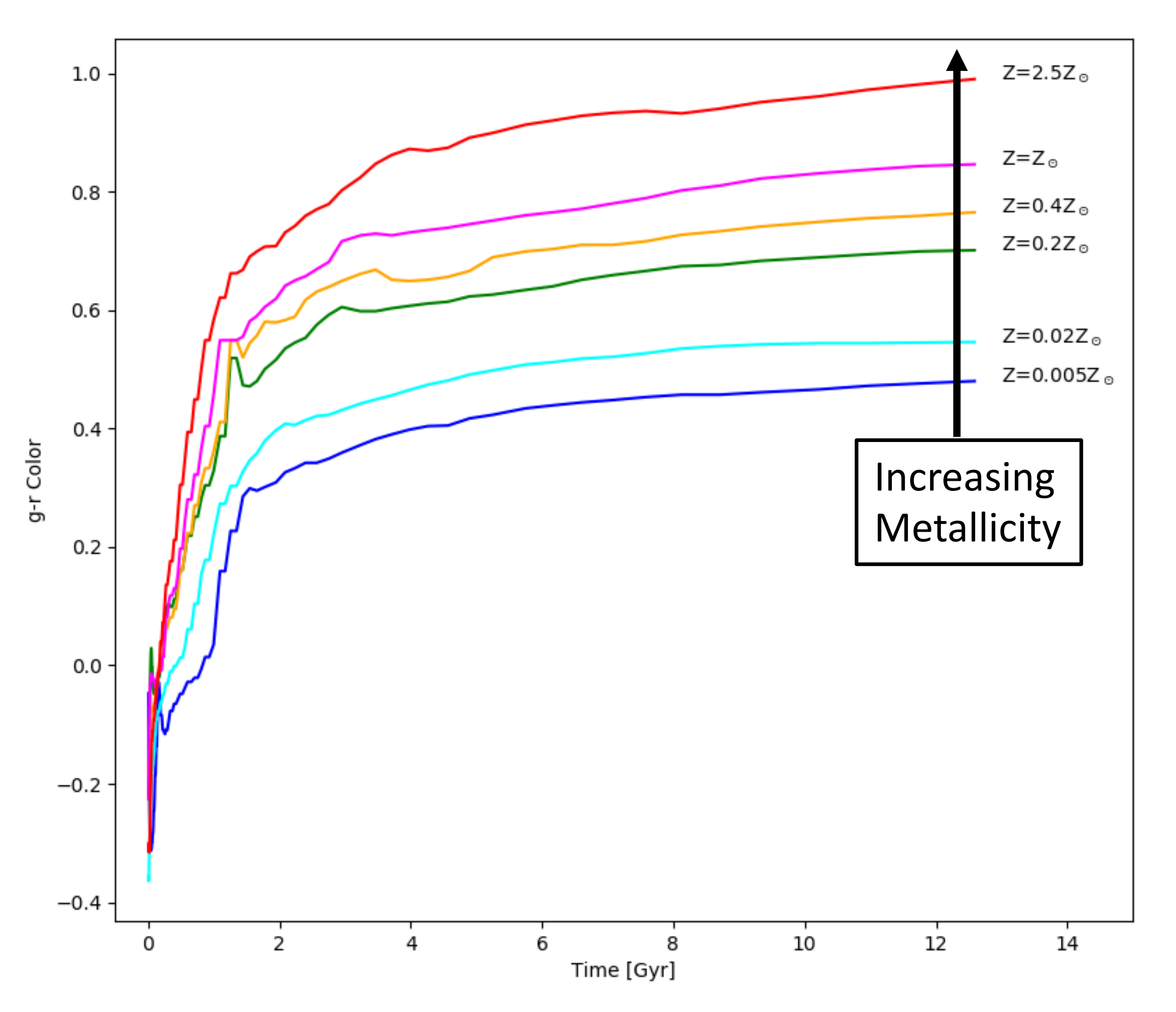
Colors evolve rapidly for young populations (<2 Gyr), but then the color evolution is much weaker. This means constraining ages gets much more difficult for old populations.

Uncertainty in color can lead to a big uncertainty in age.

They also suffer from the notorious “**age-metallicity degeneracy**”. Since higher metallicity makes stars redder, if you see a blue population is it young, or is it metal poor?

Multiple colors (imaging in many filters) helps break this degeneracy since the evolution is different at different wavelengths.

….but we haven’t even mentioned dust!



Observables: Spectra

Spectroscopy is “expensive”: need big telescopes, multiobject spectrographs, etc. But delivers lots of information:

Overall shape (“continuum”) tells you color.

Absorption lines gives you specific information about stellar ages and metallicities.

Emission lines (gas ionized by young stars) tells you information about the star formation rate and metallicity.

Kong+03

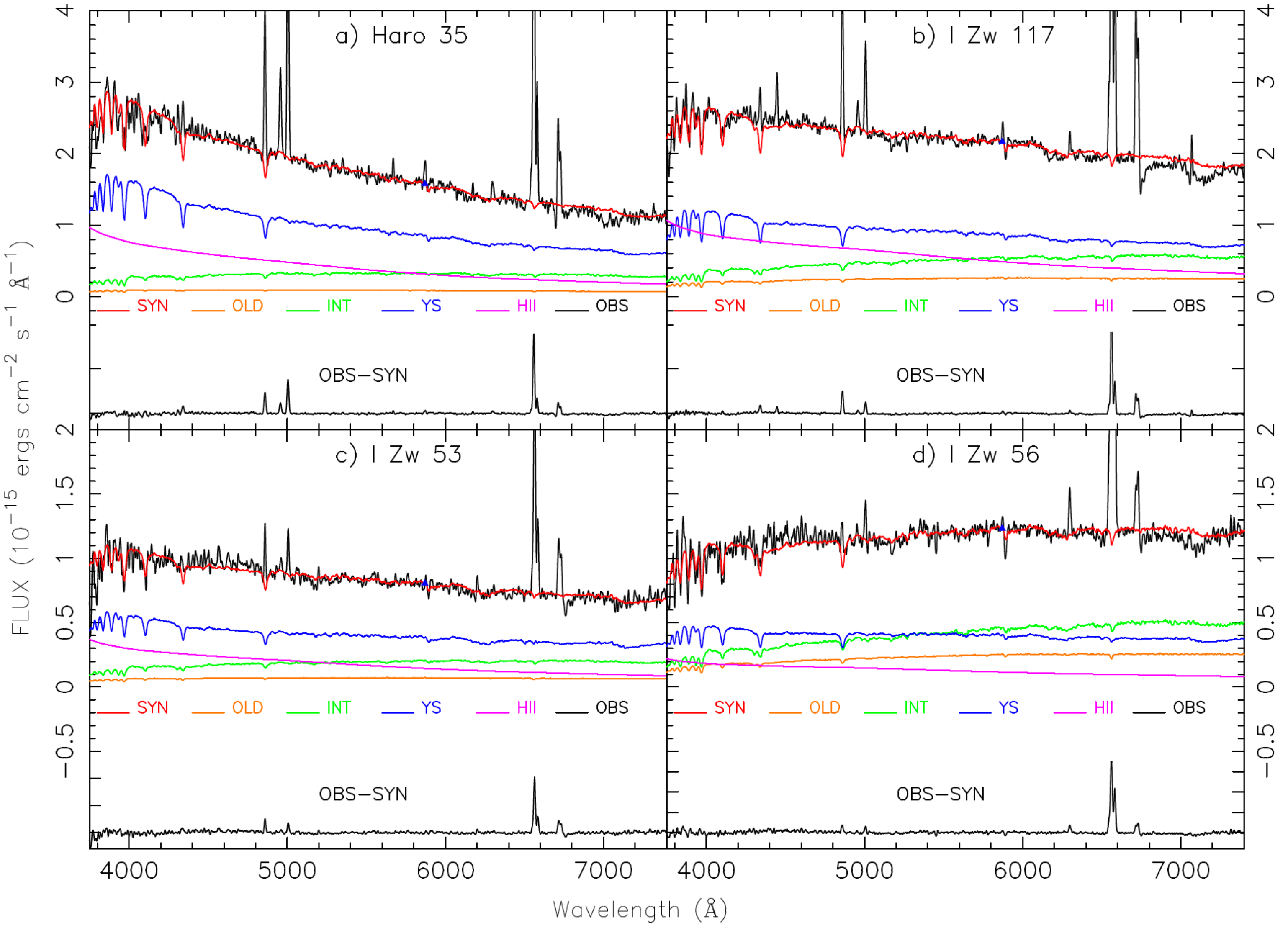
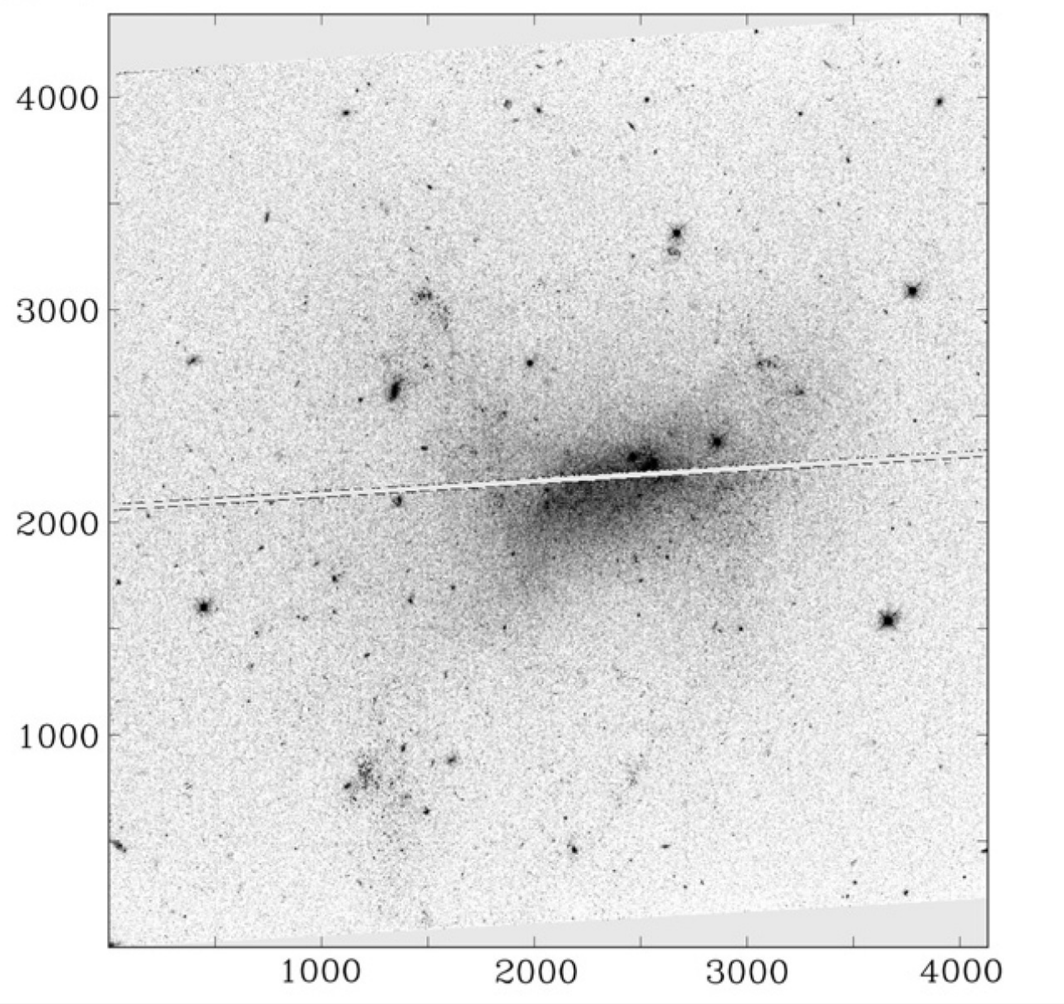


Fig. 3.— Comparison of synthetic spectra (red-solid lines) to the observed spectra of four BCGs (corrected for Galactic reddening; black-solid lines): Haro 35, I Zw 117, I Zw 53, and I Zw 56. The contributions to the synthetic spectra by old stars (OLD, 10^{10}yr), intermediate-age stars (INT, 10^9, 5×10^9yr), young stars (YS, $10^7 - 5 \times 10^9$yr), and newly-born stars (H II) are also shown. The emission line spectrum appears in the OBS–SYN difference, at the bottom of each panel.

Observables: Color Magnitude Diagrams

For nearby galaxies where we resolve individual stars, we can actually synthesize CMDs as well.



Observed CMD

Modeled CMD
(stars color-coded by age)

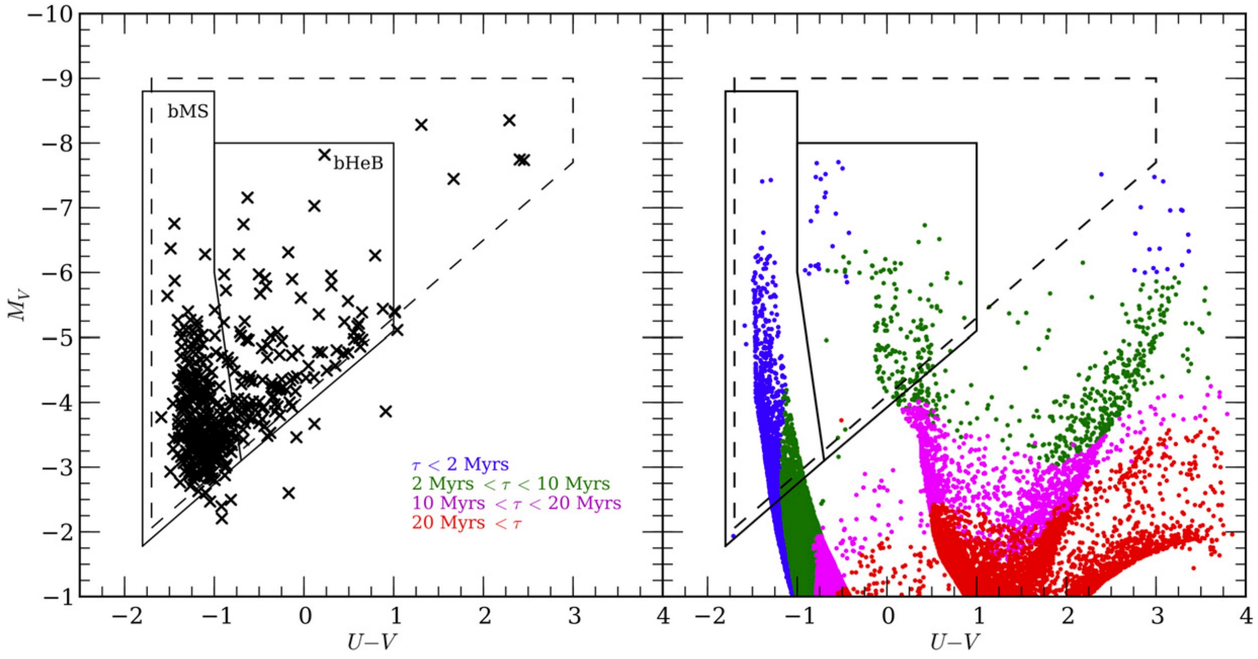


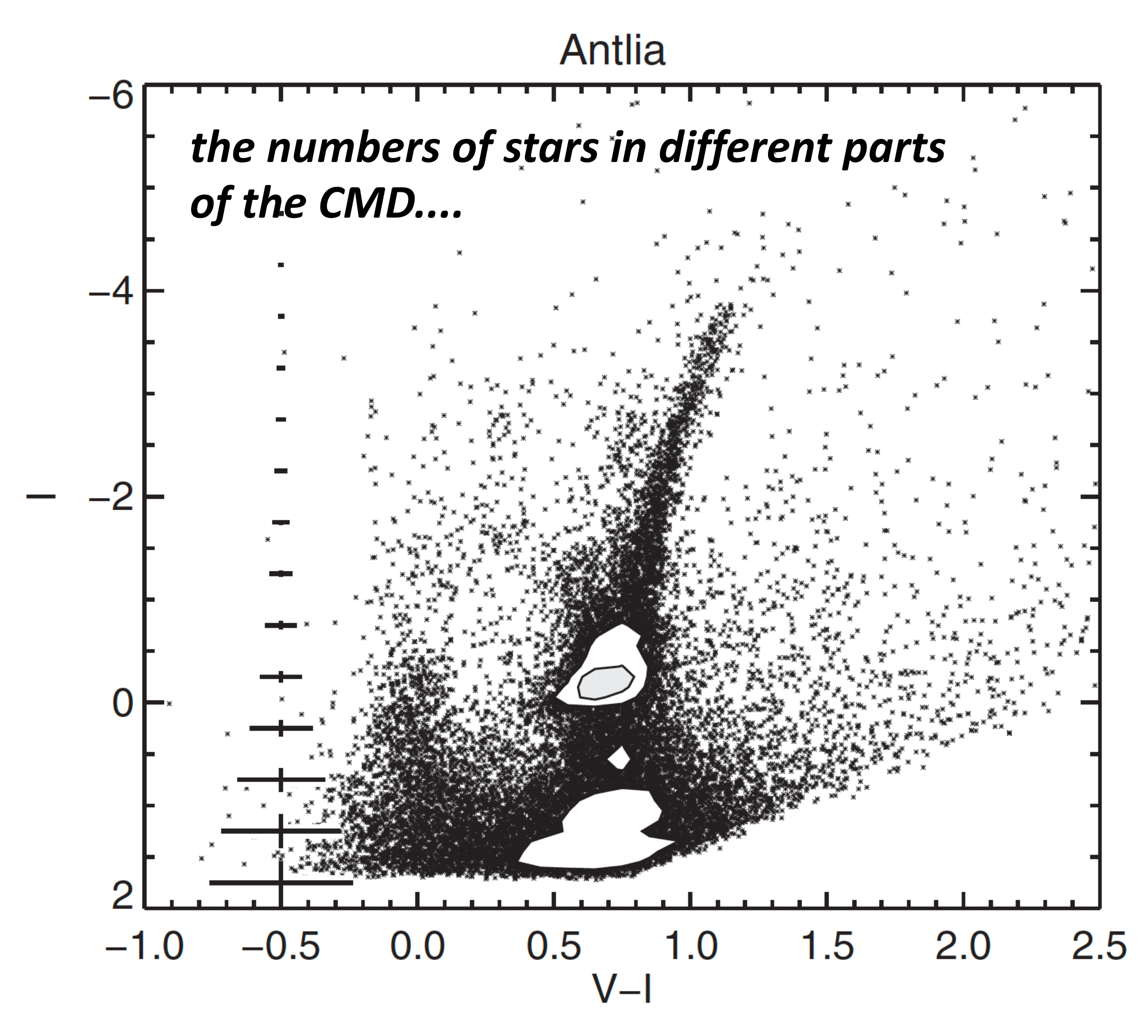
Figure 21. $U-V$ CMD for F415-3 compared with an IAC-STAR simulation of enhanced recent star formation ([Fe/H] = −0.4). The completeness, bMS, and bHeB regions are marked. The bMS and bHeB branches (measuring 2 and 10 Myr stars, respectively) are clearer in the $U-V$ plane than $V-I$, and the ratio of the bMS and bHeB stars will measure recent star formation on timescales of 2–10 Myr.

Schombert & McGaugh 2015

Observables: Color Magnitude Diagrams

For nearby galaxies where we resolve individual stars, we can actually synthesize CMDs as well.

Antlia Dwarf Galaxy
McQuinn+10



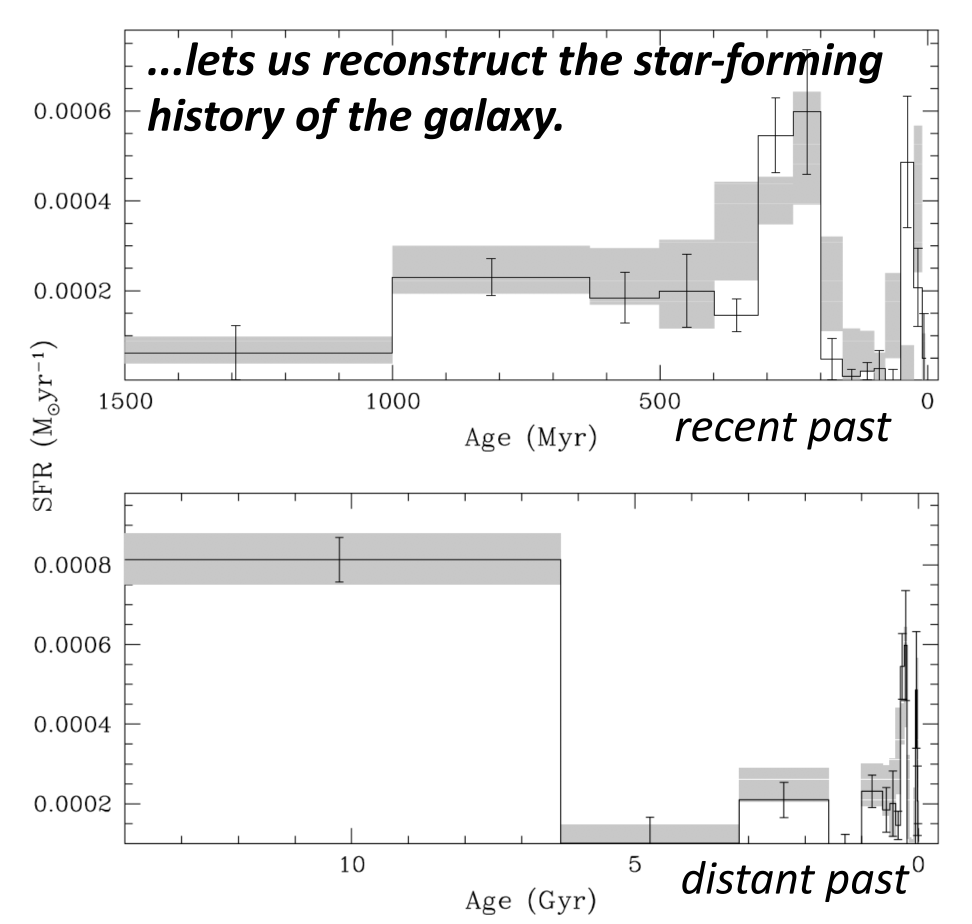


Figure 5. Best SFH fit with metallicity constrained to increase in time for the Antlia dwarf galaxy is plotted as a solid line with the best SFH fit with unconstrained metallicity evolution overplotted in shaded gray. The solutions are in excellent agreement in both the ancient and recent time bins.