Stellar Populations

The mix of stars for a given star formation history and metallicity distribution.

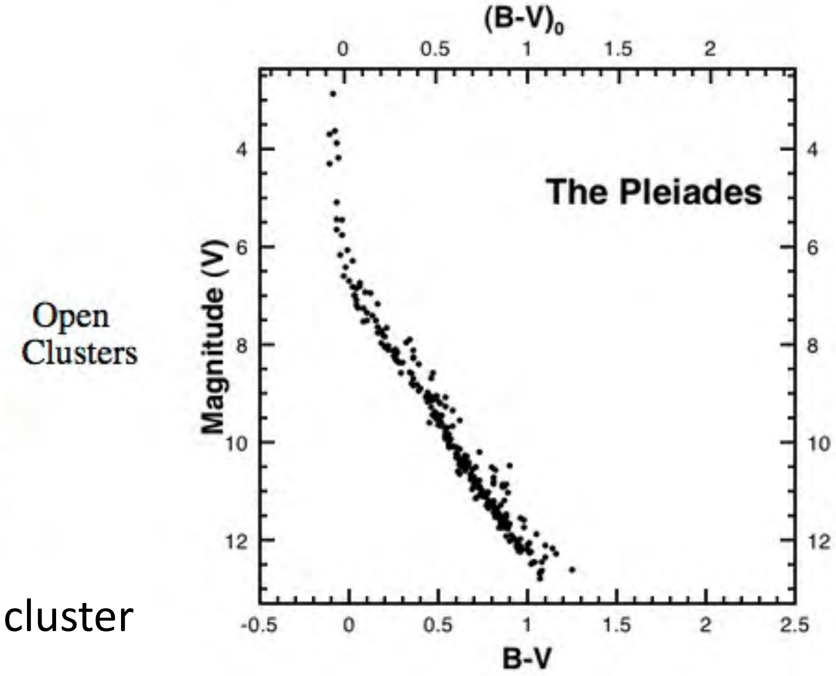
Think of the color-magnitude diagram (CMD) for different types of star clusters.

CMD reveals information about age and metallicity of the stellar populations.

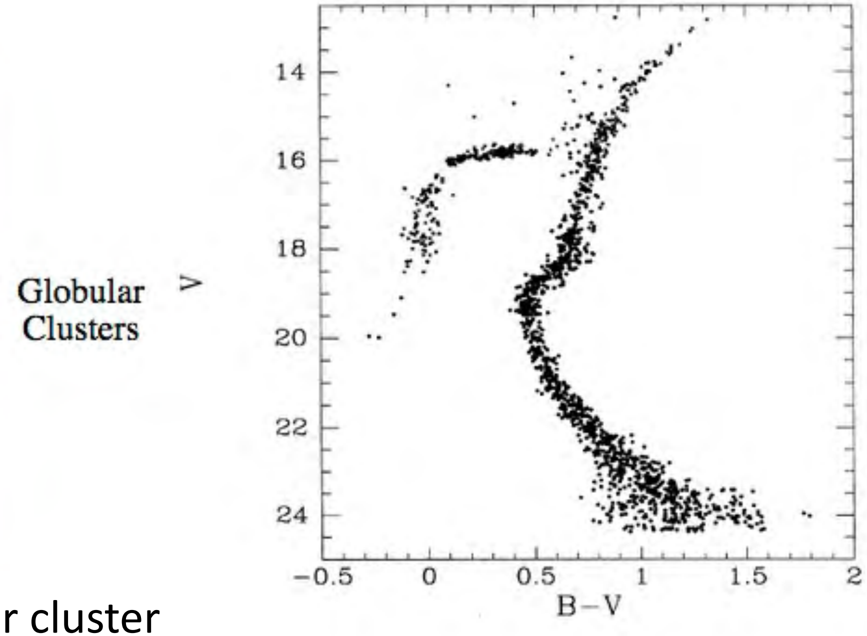
These are “simple stellar populations”, meaning all the stars have the same age and metallicity.

Galaxies form stars over time, and the metallicity of each generation of stars can increase with time.

So a galaxy CMD is a mix of stars with different ages and metallicities.



young, metal-rich open cluster



old, metal-poor globular cluster

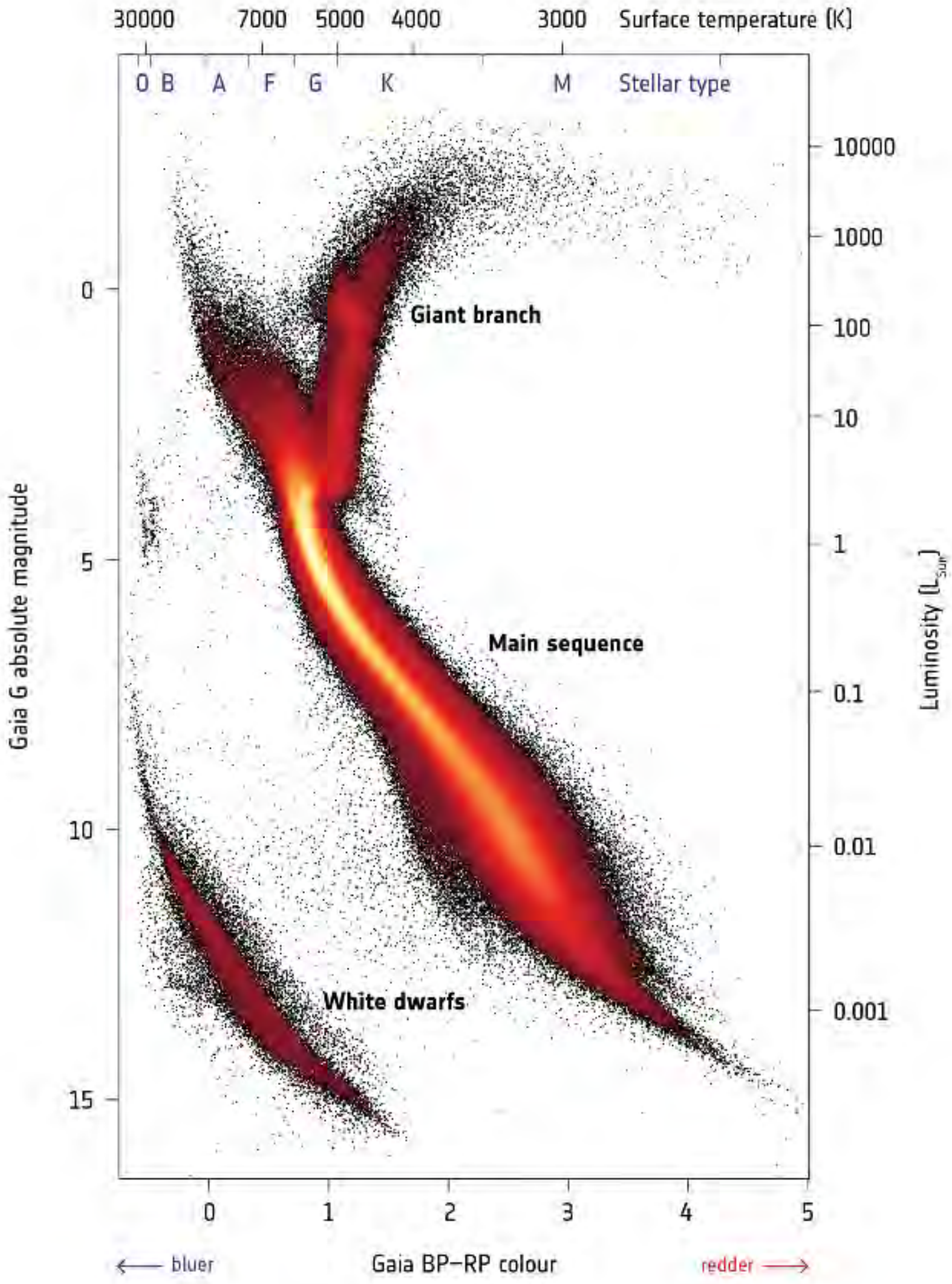
The color-magnitude diagram for the Milky Way's disk

Age information:

- The upper main sequence: young massive stars
- The lower main sequence: stars of a wide range of ages
- The giant branch and white dwarf sequence: old evolved stars

Metallicity information (see also notes from Jan 23):

- Main sequence: higher metallicity results in more metal absorption lines in the blue part of a star's spectrum ("line blanketing"), so metal-rich stars are slightly redder than low metallicity stars.
- Red giants: higher metallicity means more absorption by the stellar envelope, which makes it swell up more and become cooler. Metal-rich red giants are redder than metal-poor ones.

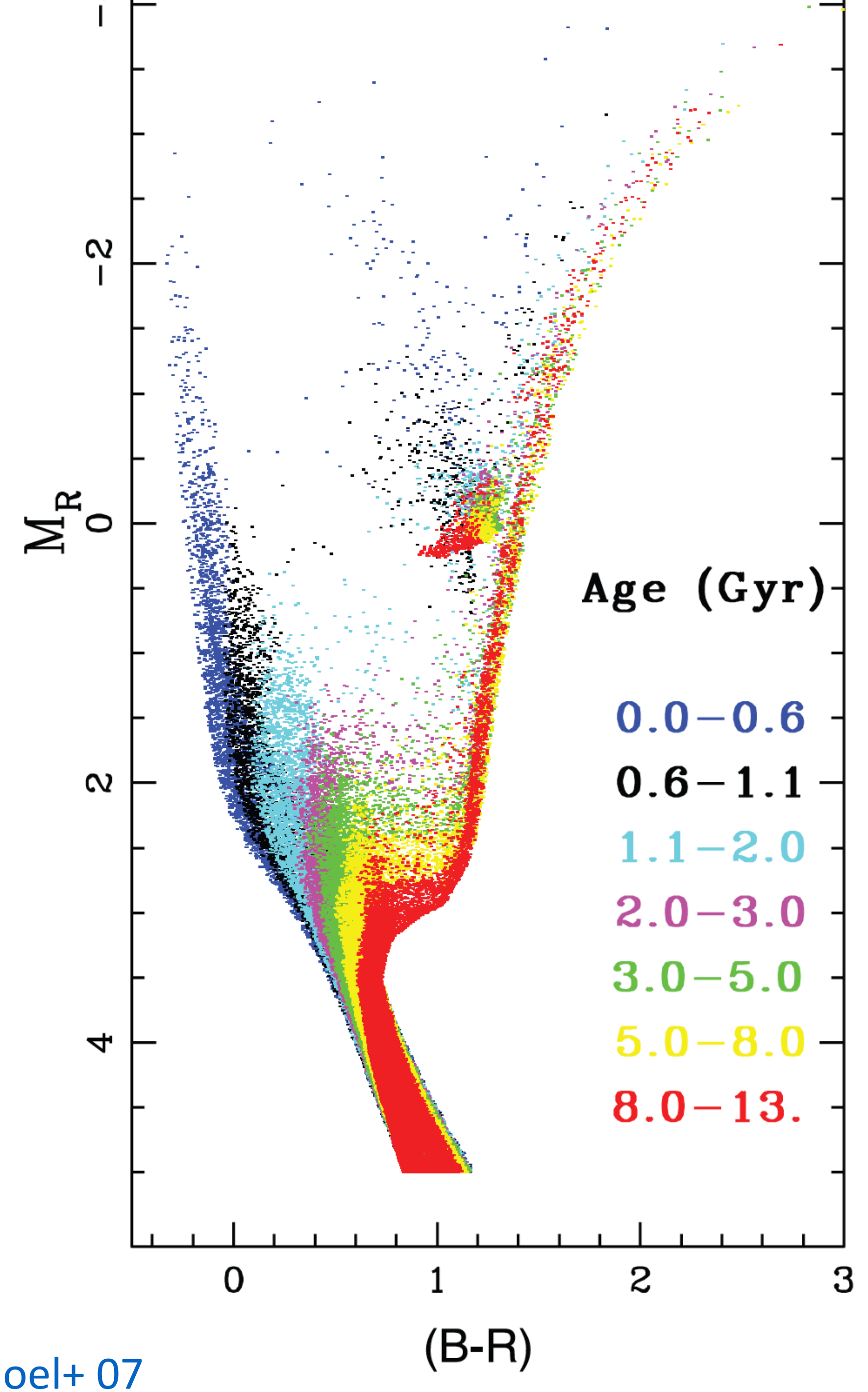


A synthetic color magnitude diagram

Using computer models you can simulate the CMD for any star formation history and metallicity distribution.

CMD from a constant star formation rate for 13 billion years (13 Gyr) ⇒

Milky Way satellite galaxies are close enough that we see this full CMD, including the faint main sequence turn off stars. Very good information on the age and metallicity distribution of stars in these galaxies.



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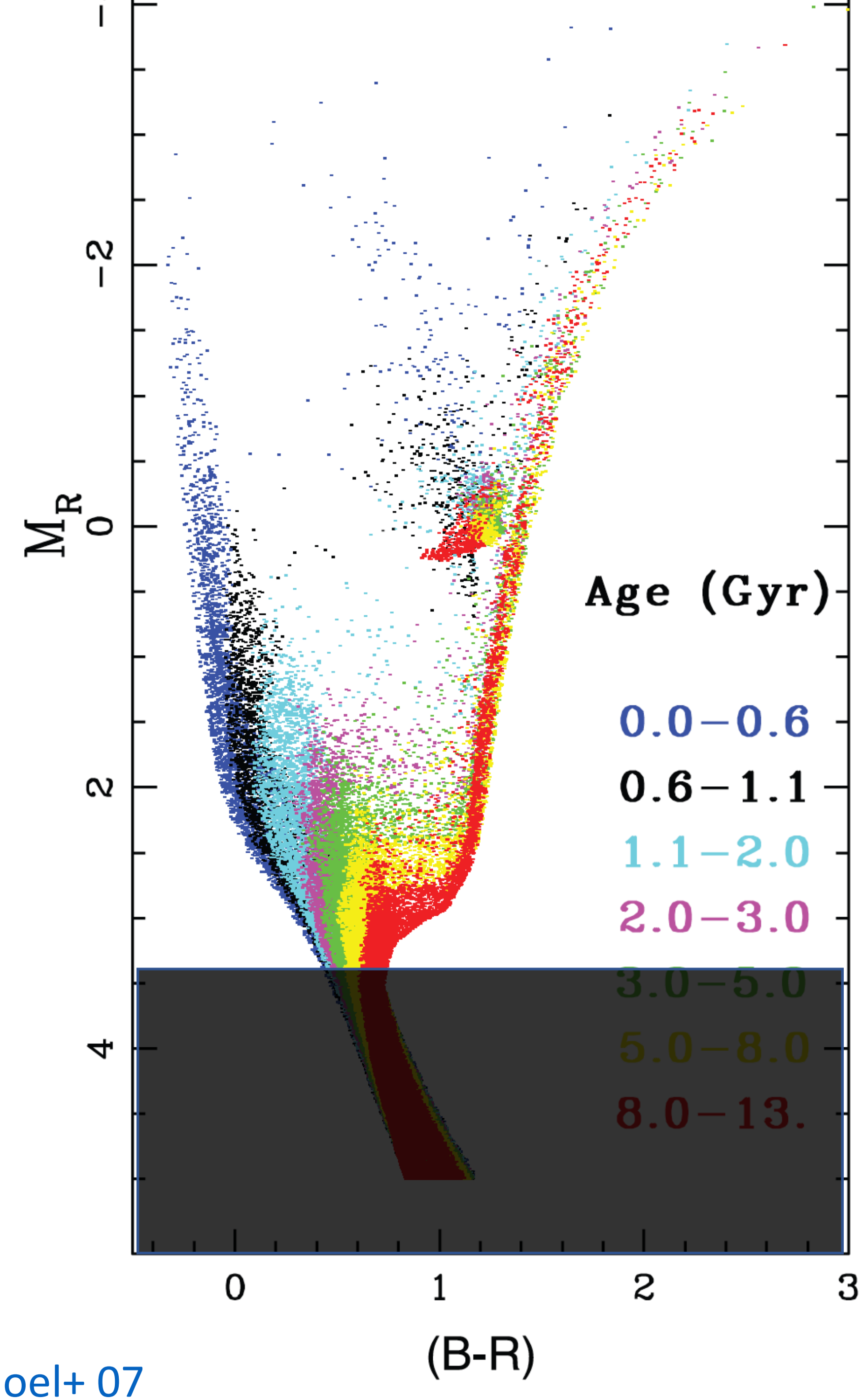
Using computer models you can simulate the CMD for any star formation history and metallicity distribution.

CMD from a constant star formation rate for 13 billion years (13 Gyr) ⇒

For Andromeda (750 kpc away), we can only see down just past the main sequence turnoff. Fainter stars are not seen individually, but contribute to the overall brightness of the galaxy.



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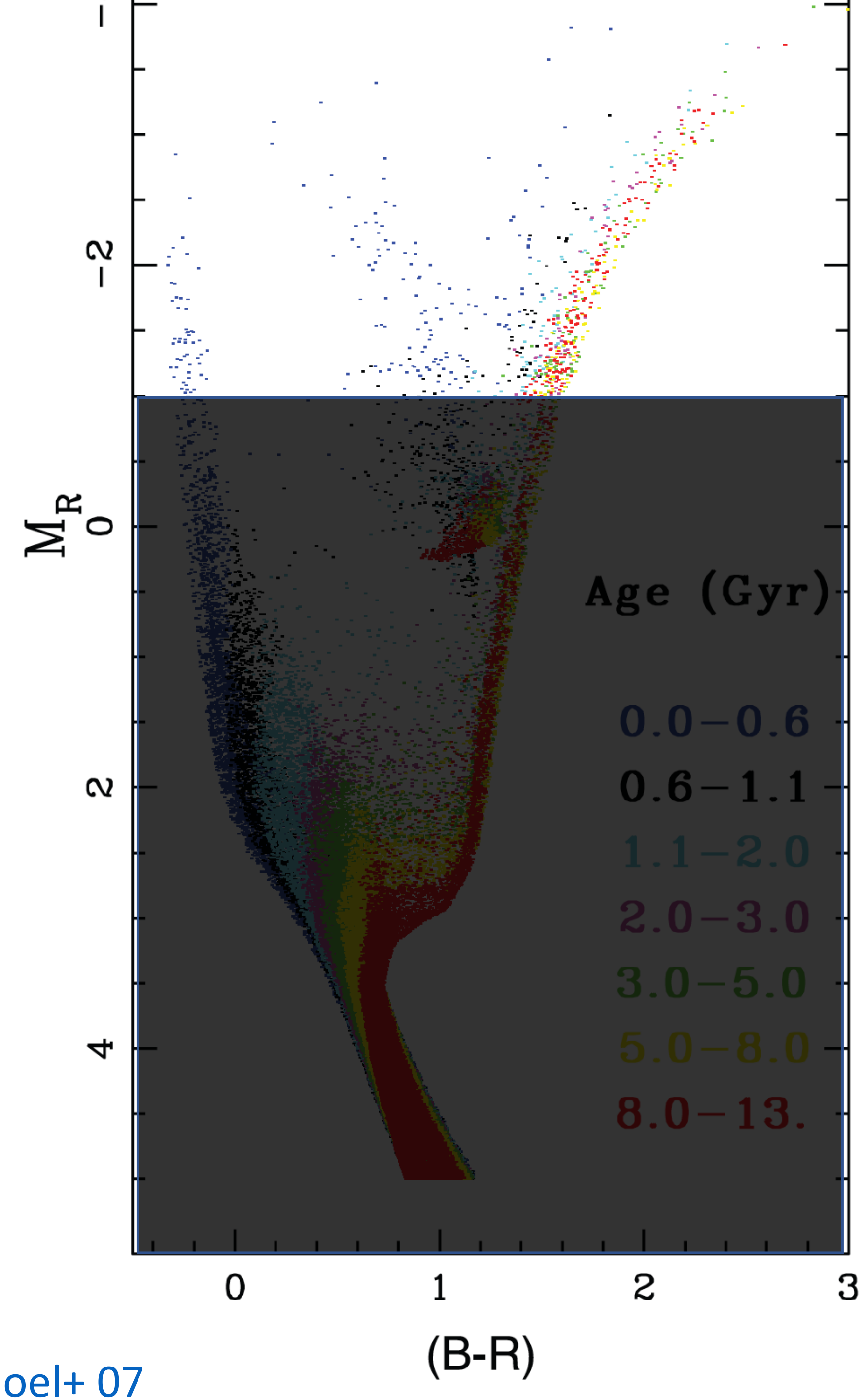
CMD from a constant star formation rate for 13 billion years (13 Gyr) ⇒

For galaxies further away, we start to lose all but the very brightest (youngest) stars on the main sequence, and old stars on the red giant and asymptotic giant branches. (M101, 7 Mpc away)



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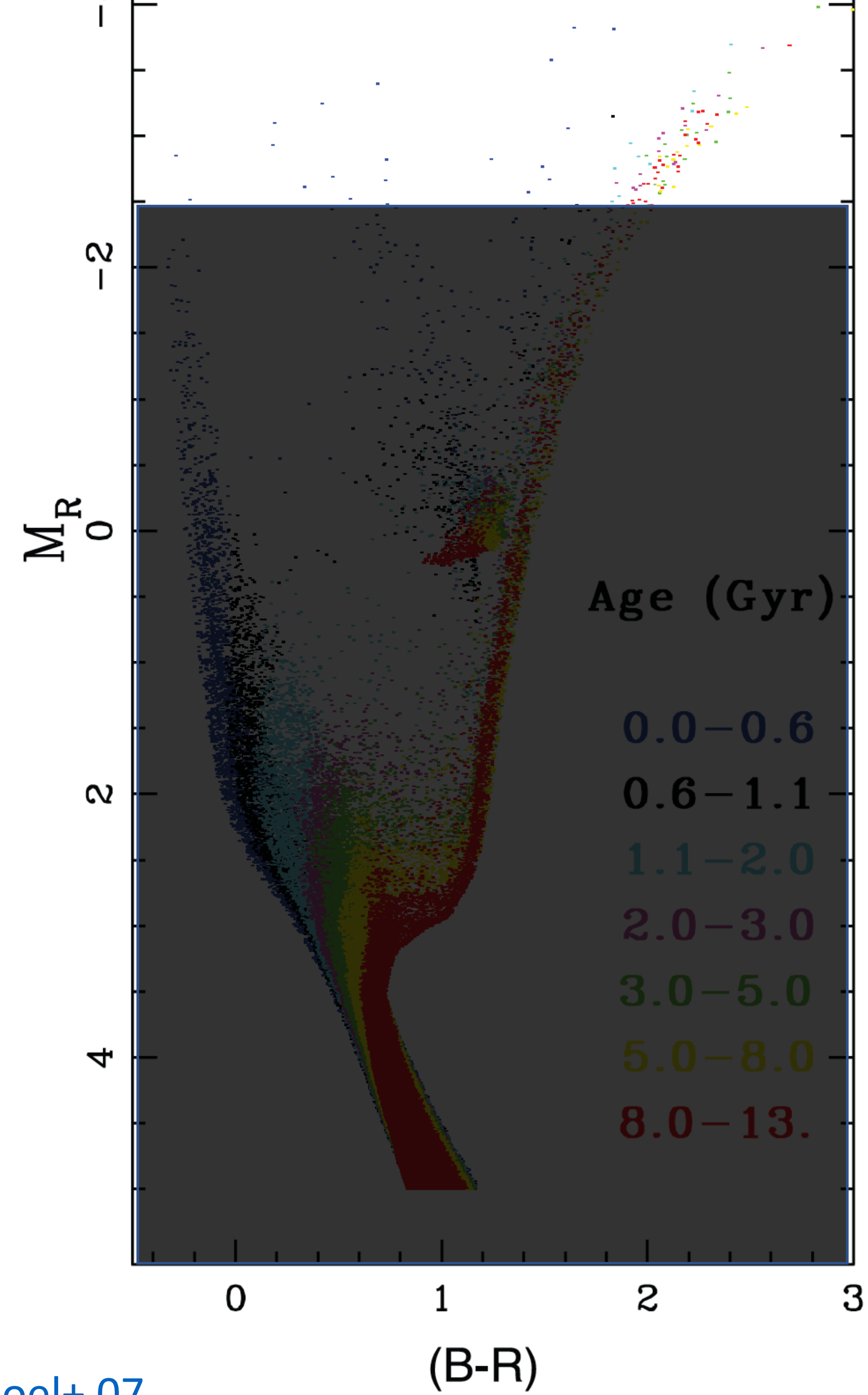
CMD from a constant star formation rate for 13 billion years (13 Gyr) ⇒

At the distance of the Virgo cluster (16 Mpc), it's difficult to get anything but the very brightest stars. And beyond that, information about individual stars is pretty much lost completely.



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Integrated Light and Surface Brightness

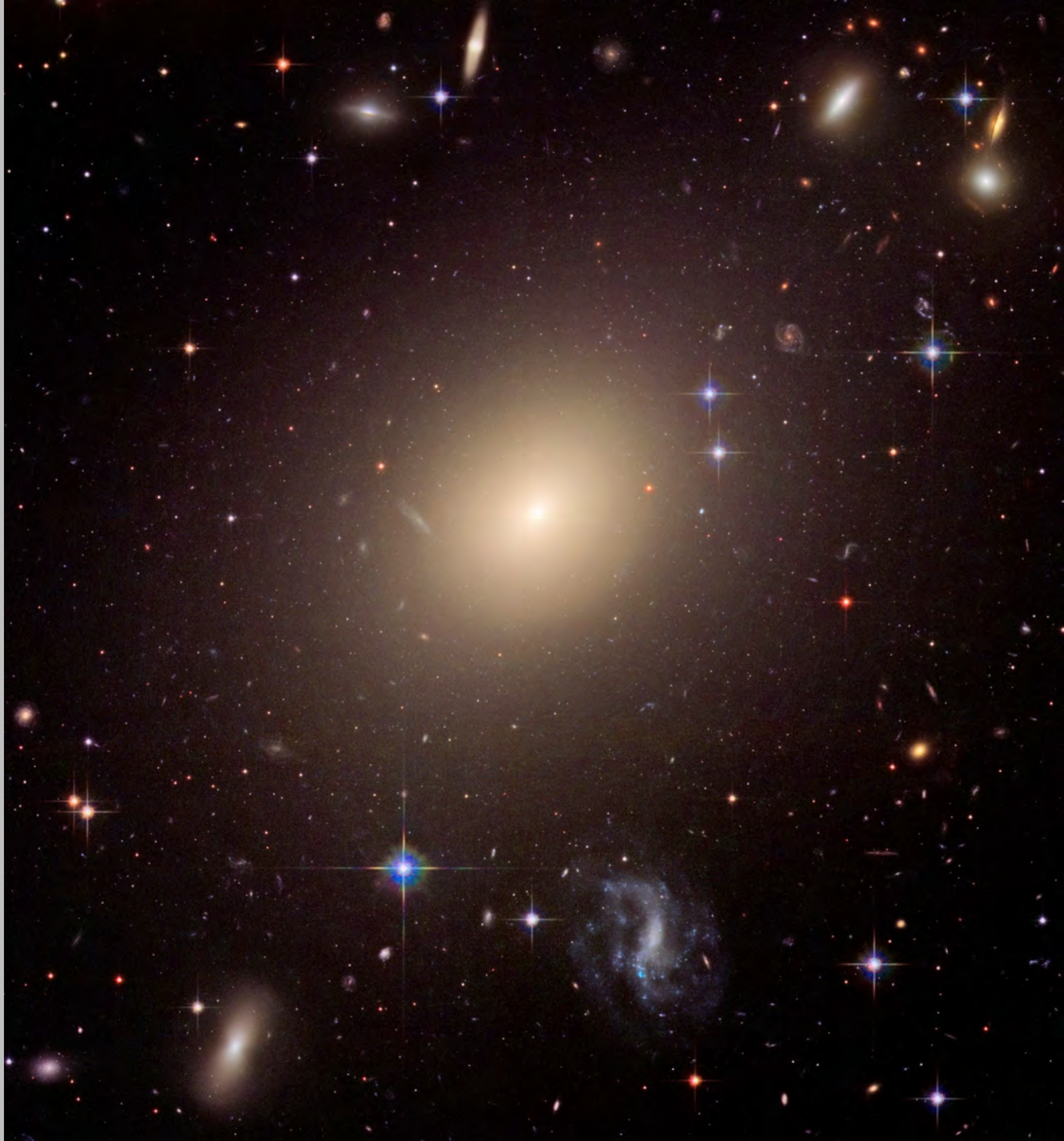
Most galaxies are too distant to see their individual stars. Stars are too faint, and they are also crowded too closely together. Instead, we see the "integrated light" of all those stars mixed together.

When the flux from all the stars is spread over a galaxy, we talk about galaxy's flux per area (f/A), or surface brightness (μ).

Surface brightness is a logarithmic measure of flux per area, just like magnitudes are a logarithmic measure of flux.

$$\begin{aligned}\mu &= -2.5\log(f/A) + C \\ &= -2.5\log f + 2.5\log A + C \\ &= m + 2.5\log A\end{aligned}$$

The units are typically given as "magnitudes per square arcsecond", but **be careful**: $\mu \neq m/A$



Integrated Light and Surface Brightness

Example surface brightness calculation.

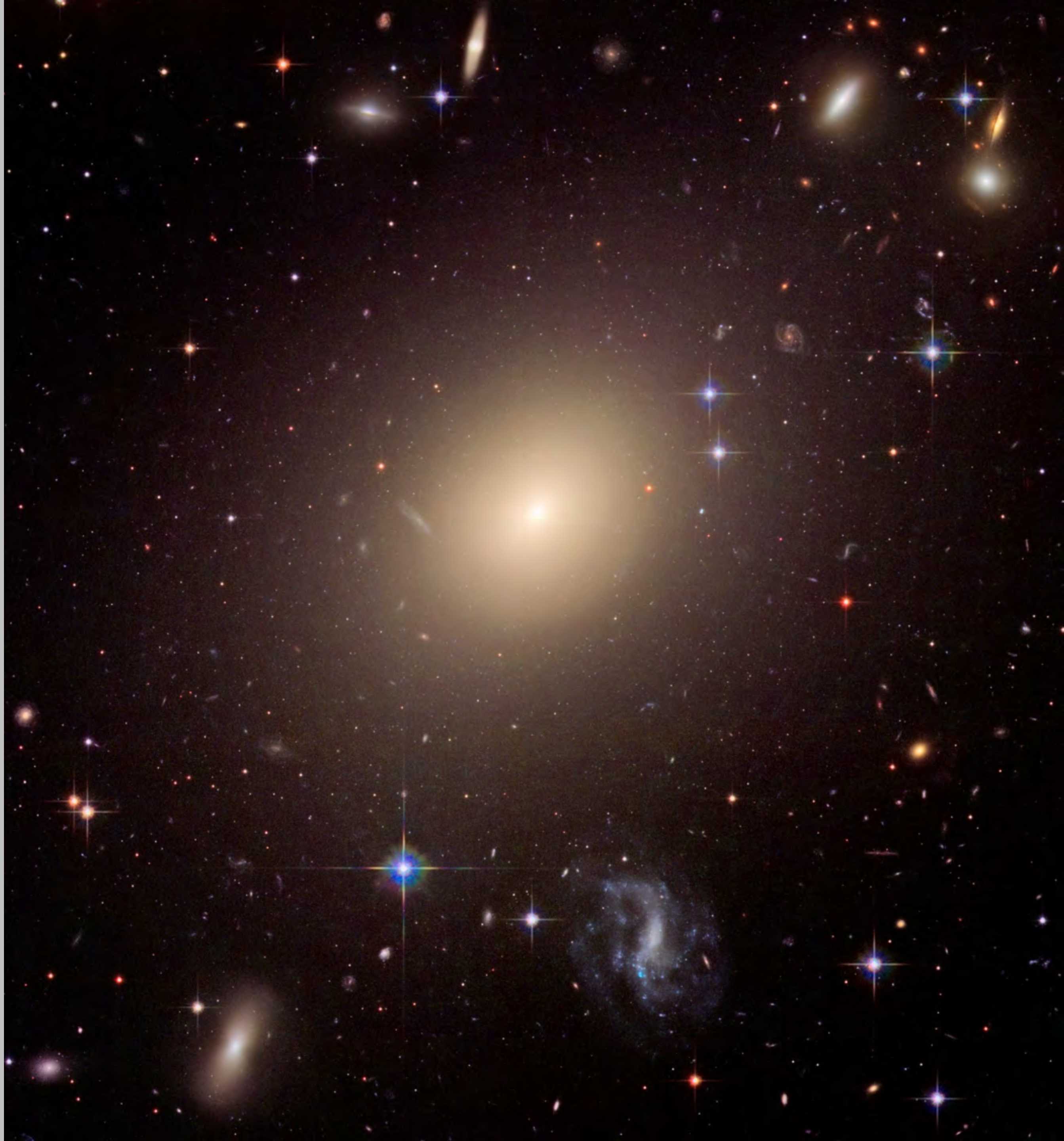
An elliptical galaxy has an integrated, total apparent magnitude (all its stars put together) of $m_{V,tot} = 12.0$ and a half-light radius of $r_e = 30$ arcseconds. What is its average surface brightness inside the effective radius?

$$\begin{aligned} m_{V,1/2} - m_{V,tot} &= -2.5\log\left(L_{1/2}/L_{tot}\right) \\ &= -2.5\log(1/2) \\ &= 0.75 \end{aligned}$$

So $m_{V,1/2} = m_{V,tot} + 0.75 = 12.75$

Then the galaxy's average surface brightness inside that radius is:

$$\begin{aligned} \langle\mu\rangle &= m_{V,1/2} + 2.5\log(\pi r_e^2) \\ &= 12.75 + 2.5\log(\pi 30^2) \\ &= 21.38\ \text{mag/arcsec}^2 \end{aligned}$$



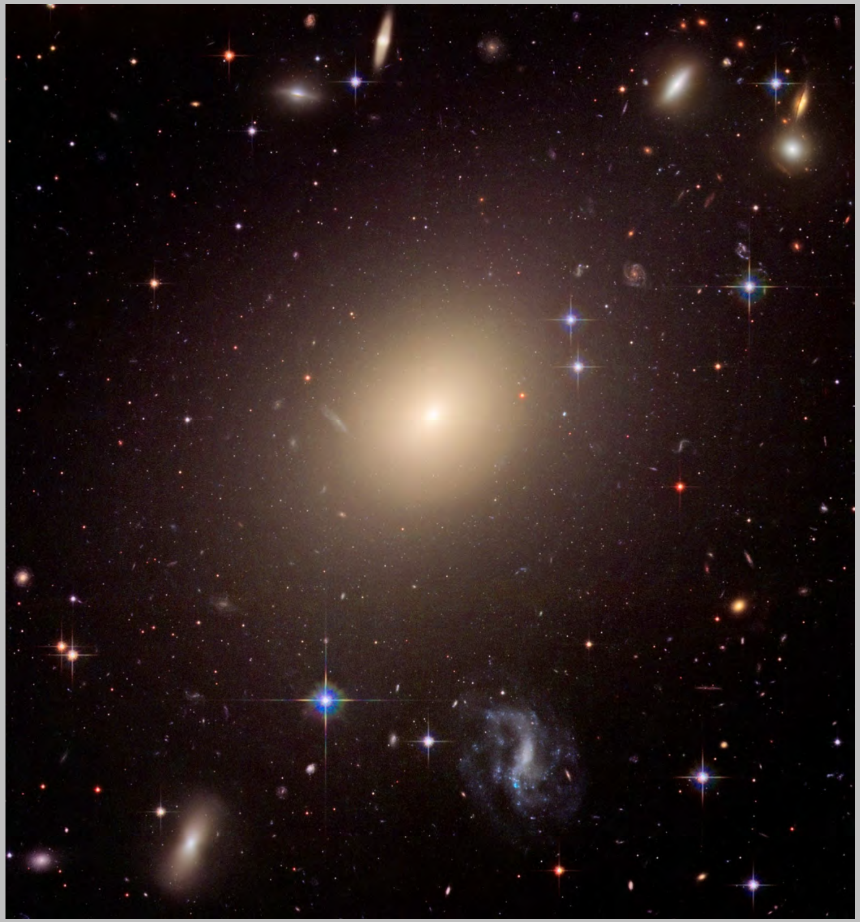
Surface Brightness and Luminosity Density

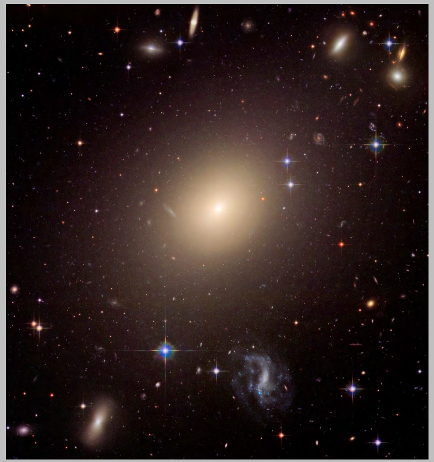
Think about flux per area will change if you move a galaxy to twice its distance.

Flux drops by $1/r^2 = 1/4$
Size drops by $1/r$, so area drops by $1/r^2 = 1/4$

So flux per area stays constant.

The observed surface brightness of a galaxy does not depend on distance! It is an ***intrinsic property*** of the galaxy.





The surface brightness can be converted to a luminosity surface density of the galaxy.

Surface brightness: flux/area (logarithmic mag/arcsec^2)
Luminosity density: luminosity/physical area ($L_\odot/pc^2$)

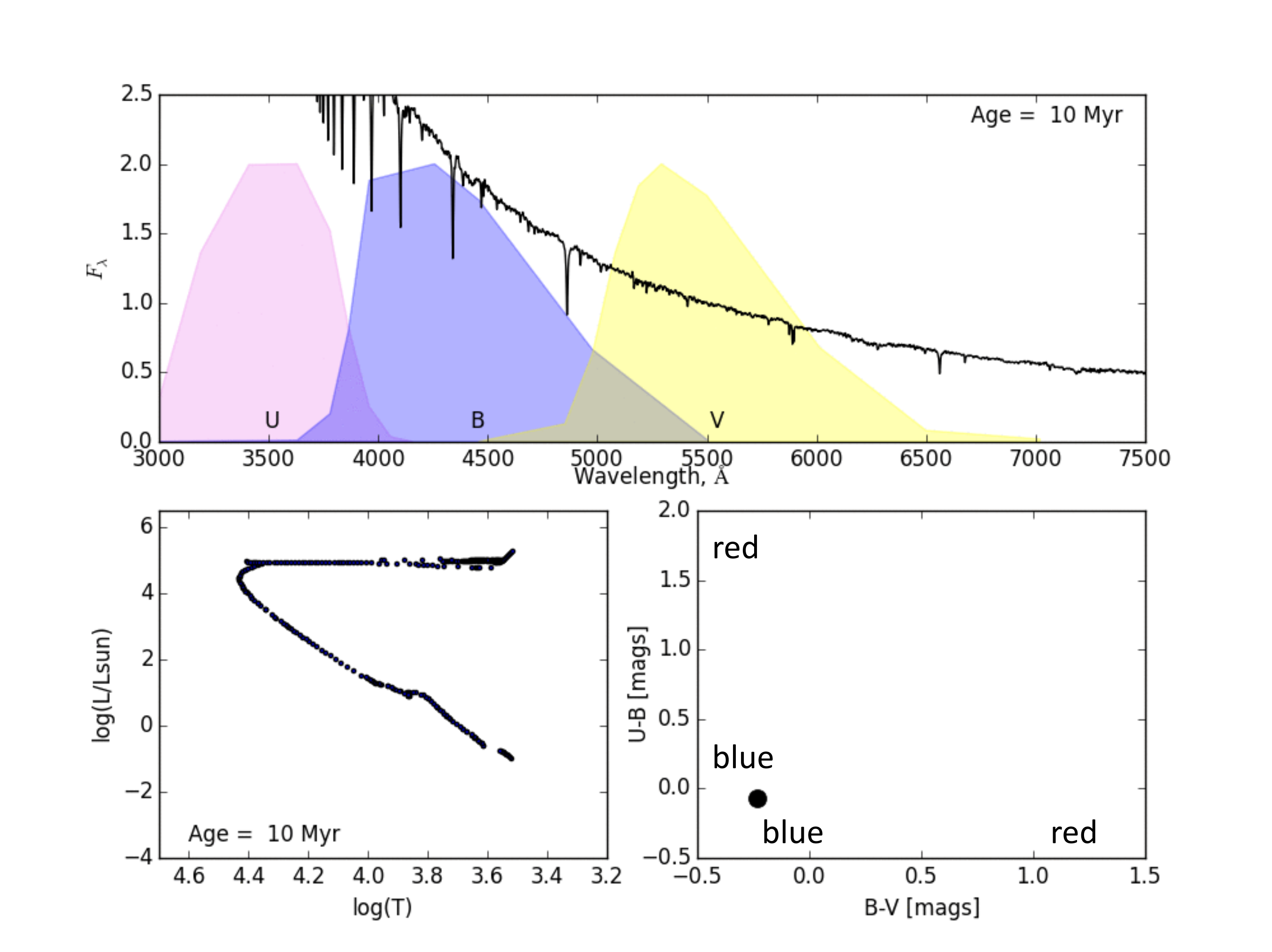
Back to Stellar Populations

We can measure the colors of galaxies and take spectra of galaxies, but when we do that we are measuring the integrated light of all its populations put together. A galaxy spectrum (or color) is different from a star spectrum (or color).

Look at a simple stellar population (SSP):
A single burst of star formation, whose stars then just evolve and die over time.

Look at how the spectrum changes.
Look at how the CMD changes
Look at how the U-B and B-V colors change.

Time evolution of an evolving SSP ⇒



Stellar Populations with different star formation histories

The properties of the integrated light depend on the mix of stellar populations, which depends on the star formation history of a galaxy.

Imagine a star formation rate that follows an exponential decline with time:

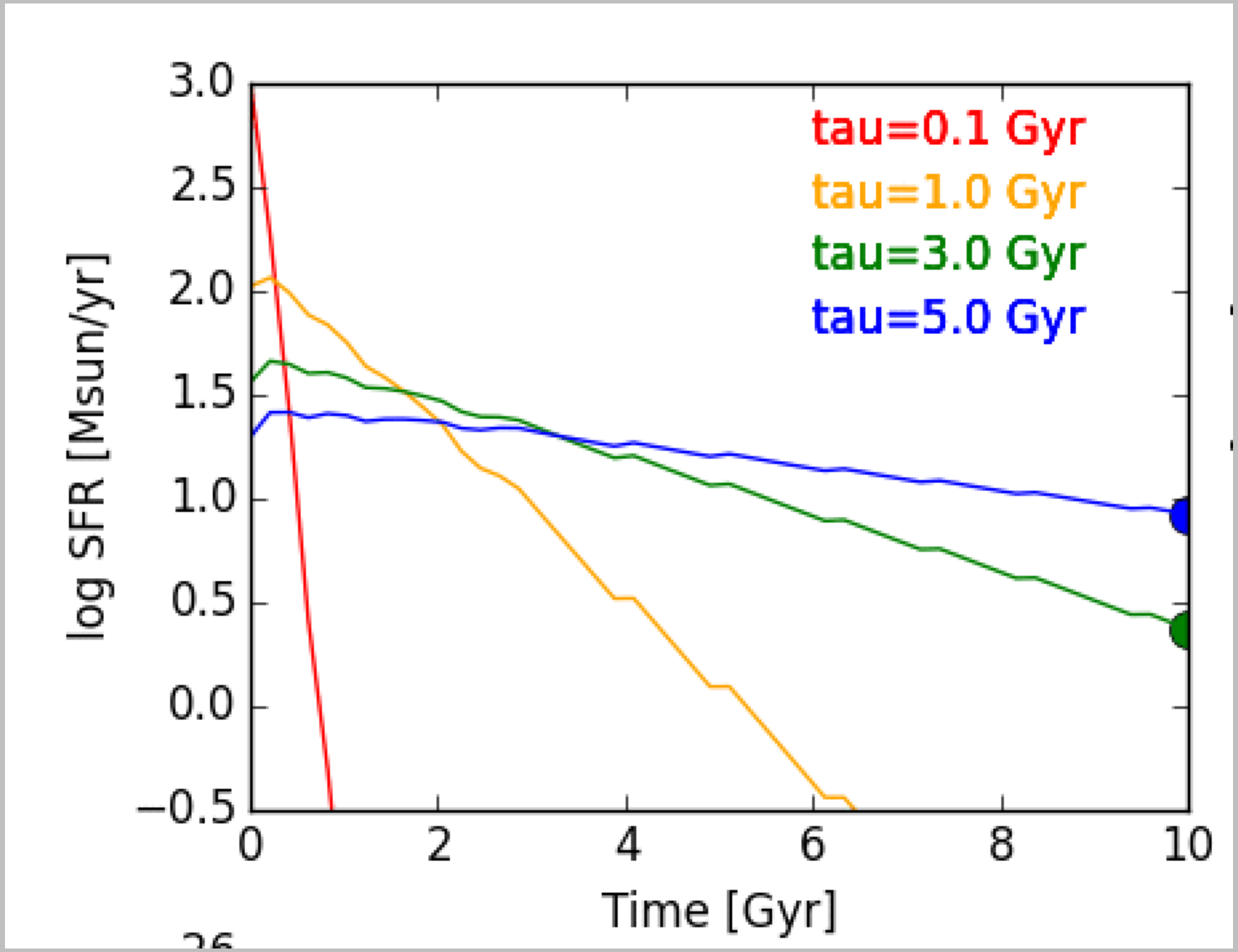
$$SFR(t) = Ce^{-t/\tau}$$

where τ is a characteristic time scale.

$\tau = 0.1$ Gyr: rapid burst, quickly dies out
$\tau = 5.0$ Gyr: very gradual decline in SFR

Look at four different τ models, each of which has made a total amount of 10^{11} $M_\odot$ worth of stars after 10 Gyr.

How does the color change with time?



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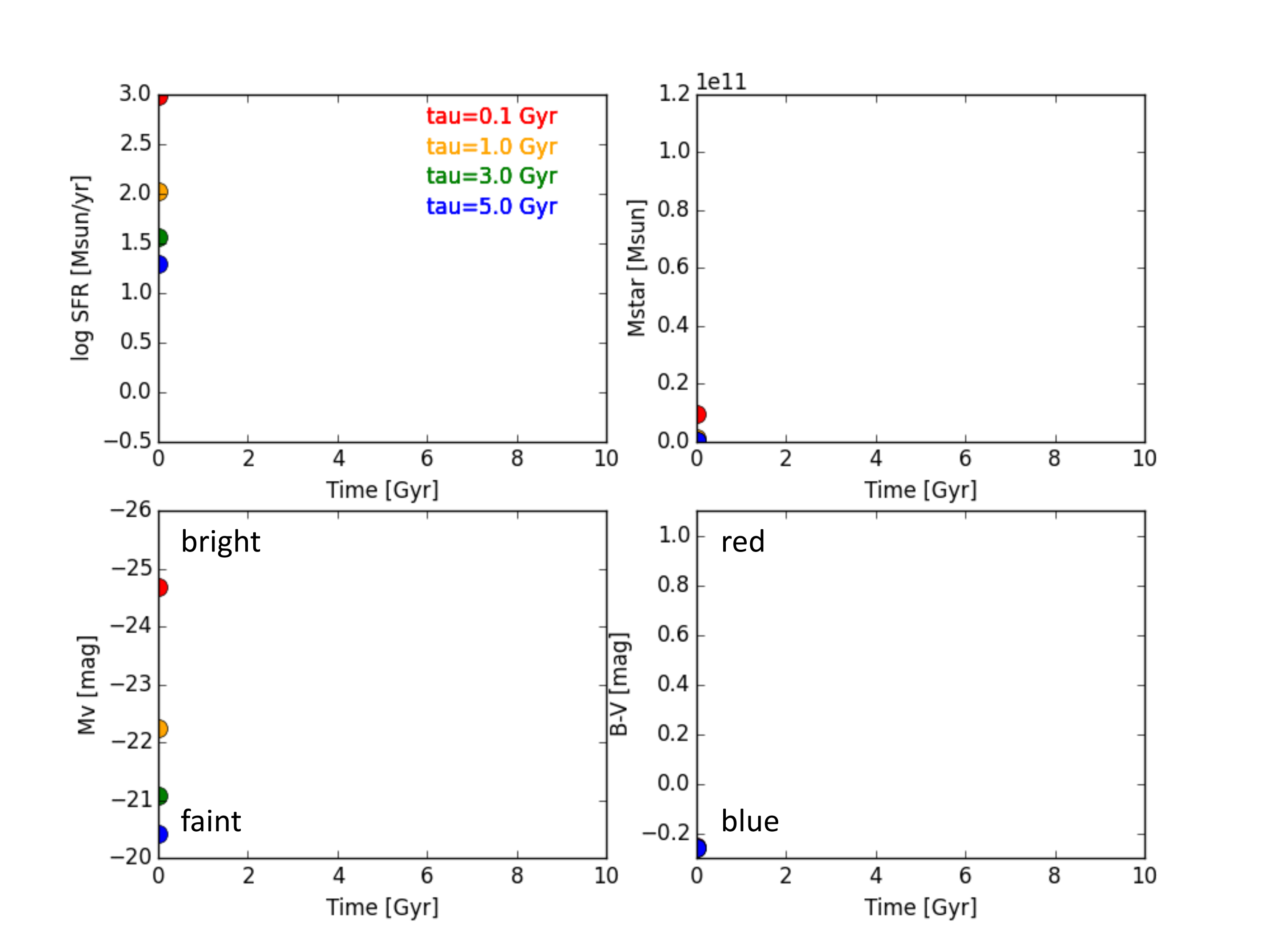
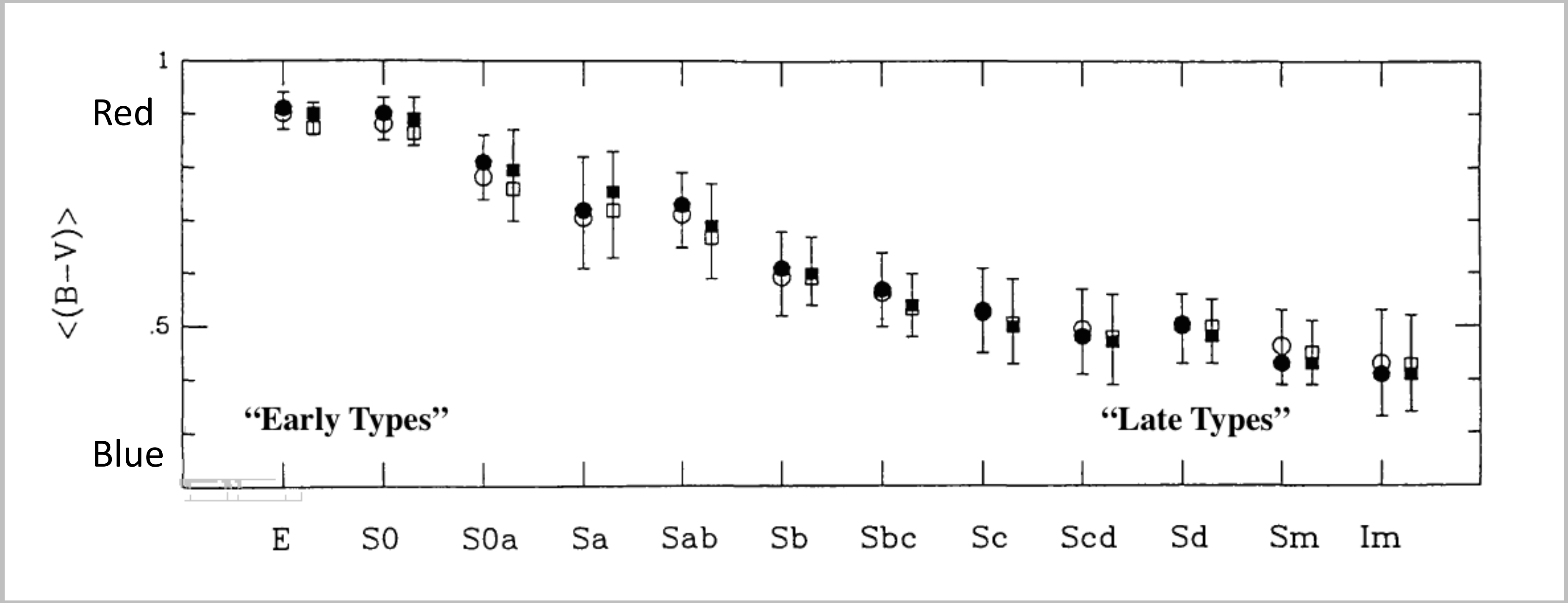


Integrated colors of galaxies

Look at how the average B−V color of galaxies changes across different galaxy types.



Early type galaxies (E/S0) have redder colors than late type galaxies (Sc/Sm/Im). This is largely a difference in stellar population age. Stars in early type galaxies are, on average, older than those in late type galaxies.

But even late type galaxies have lots of old stars.

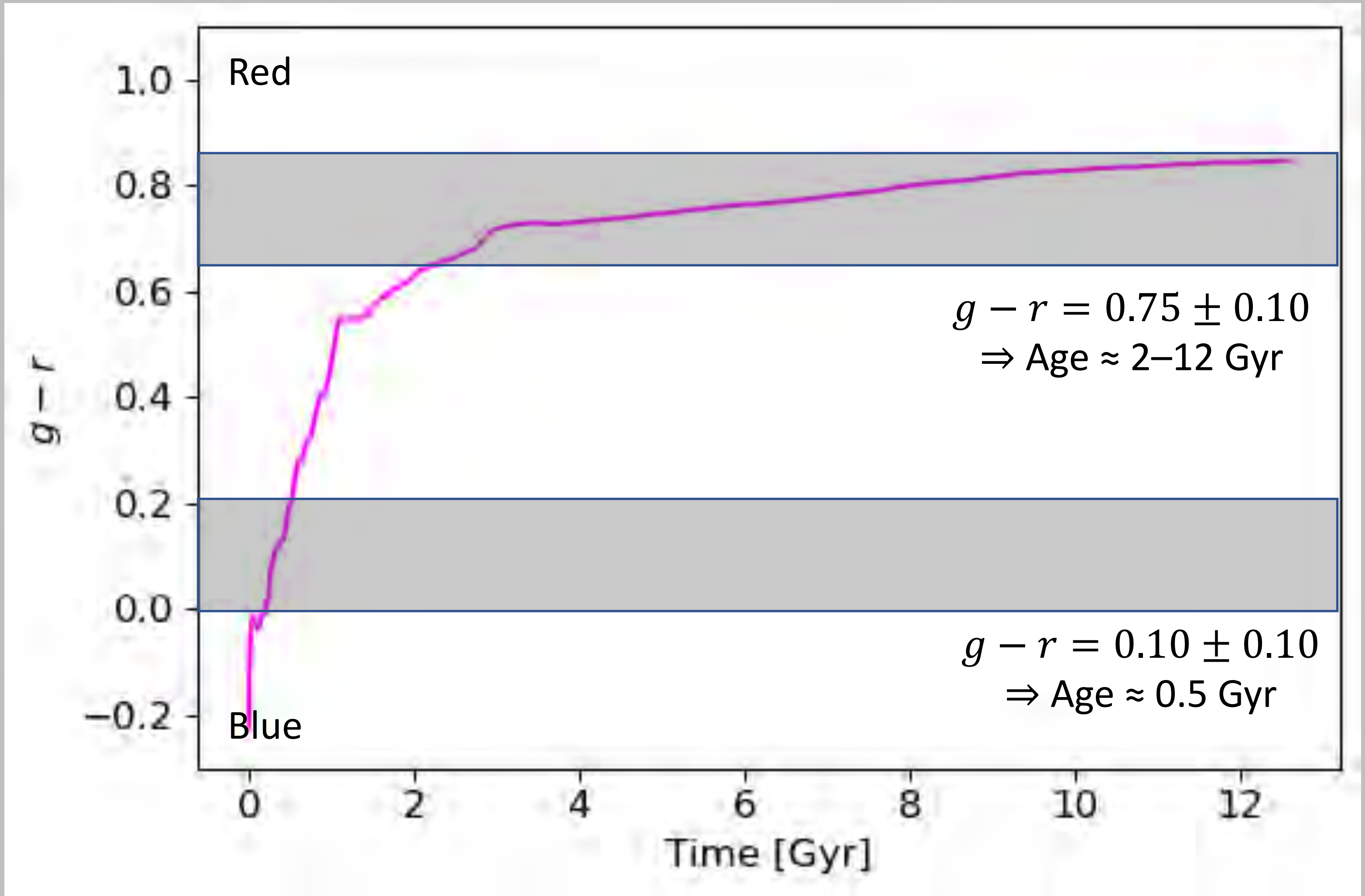
And even a small amount of new star formation can turn a galaxy blue, due to the brightness of massive young stars.

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.



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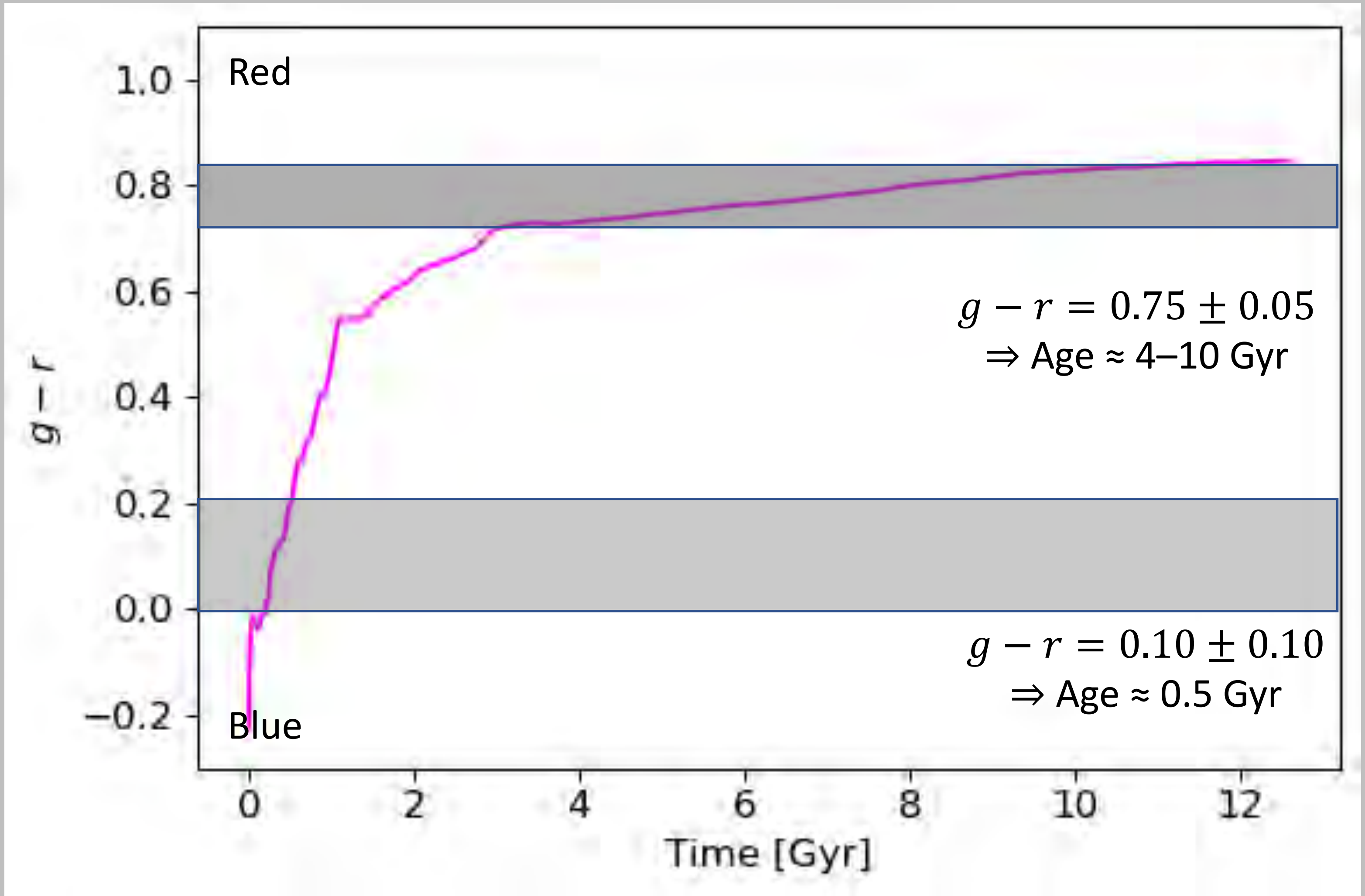

Banana analogy
courtesy of Mia de los Reyes (Caltech)

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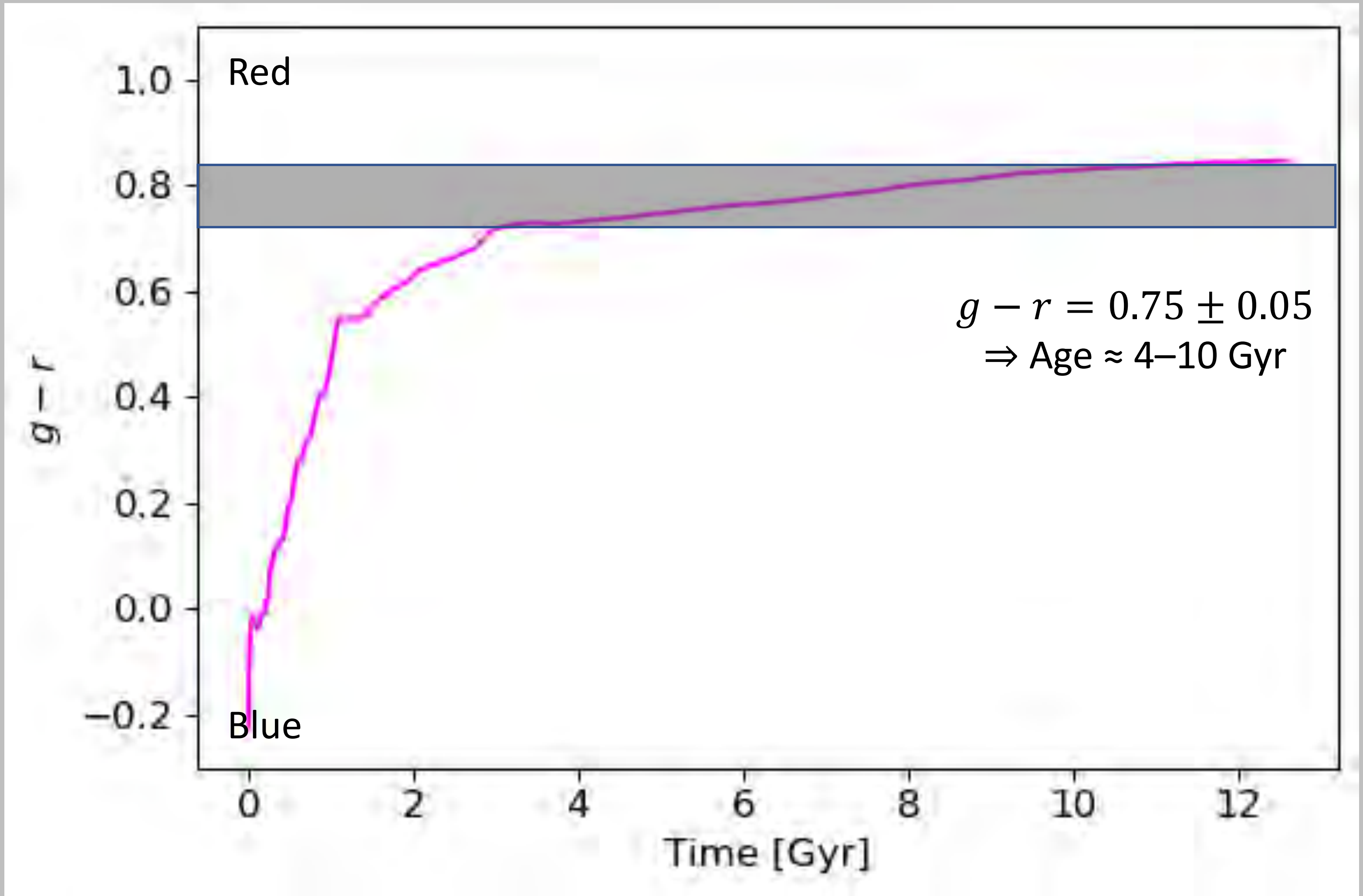

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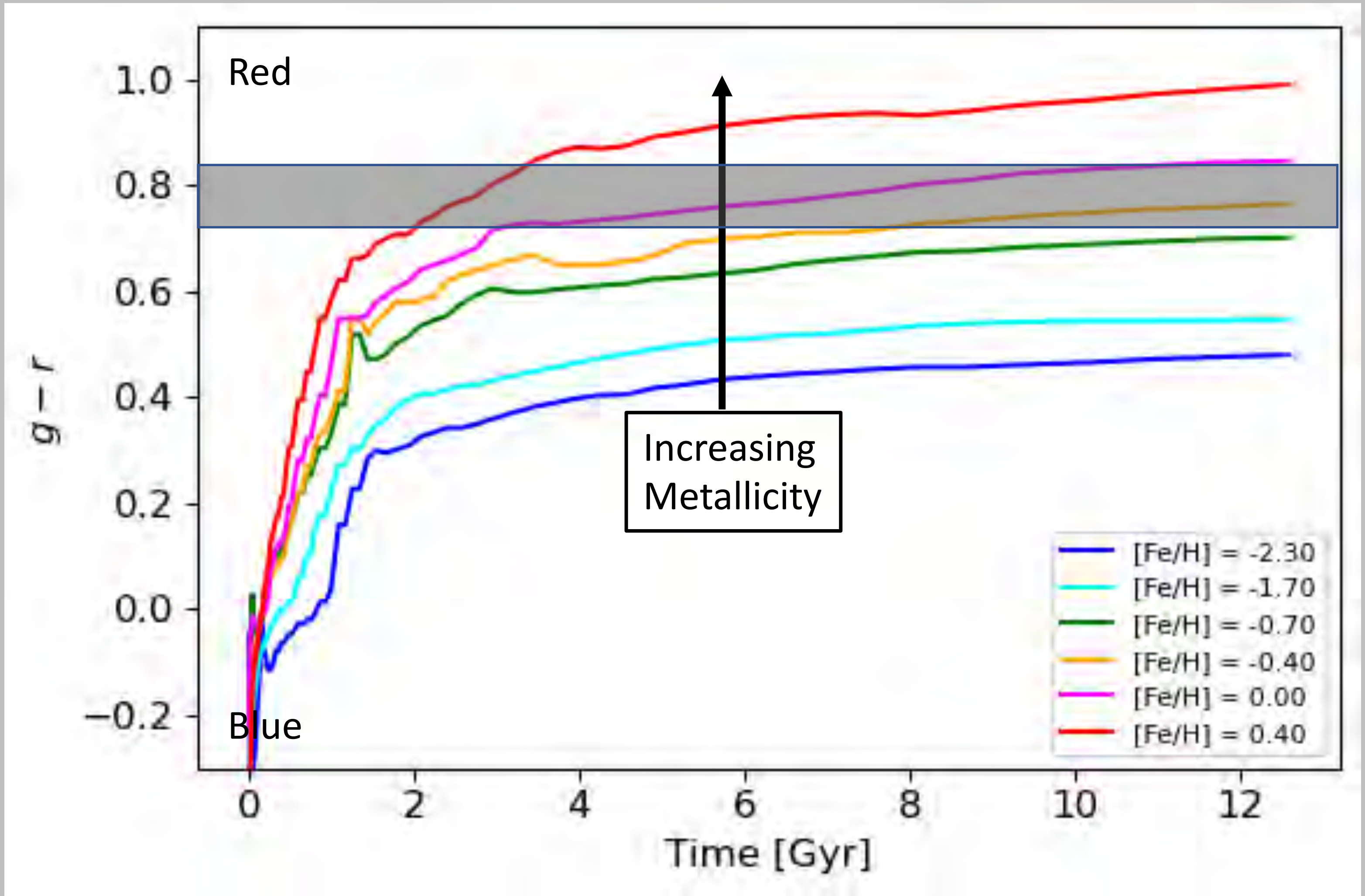
Age-metallicity degeneracy: Metallicity effects makes this even harder: red populations can be younger and metal-rich, or older and metal-poor.

Dust and different star formation histories further complicate things!

Solutions (both time-consuming):

- Many different filters / wavelengths.
- Spectroscopy.

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



Stellar mass-to-light ratio: $(M/L)_*$

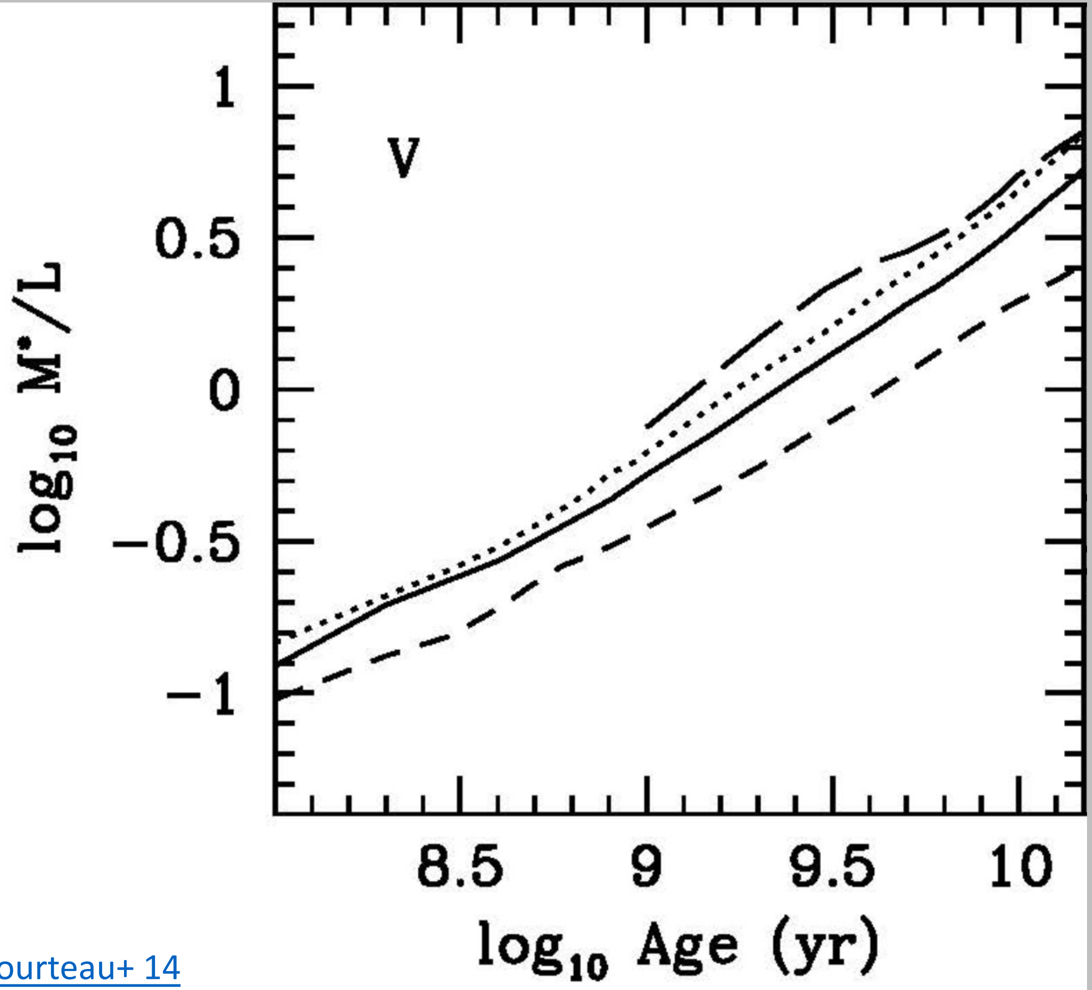
We measure a galaxy's integrated light, but we would like to convert that to a stellar mass. How much stellar mass does it take to get a given amount of light? What is the ratio of mass to light **for stars**?

Star	Mass ($M_\odot$)	Luminosity ($L_{\odot,V}$)	$(M/L)_{*,V}$ (solar units)
Sun	1	1	1.000
O star	20	6000	0.003
M dwarf	0.4	0.006	67
Red Giant	1	25	0.04

For a galaxy, it depends on the mix of stars in the galaxy. In general, $(M/L)_*$ increases as age increases. ⇒

It is also very sensitive to which wavelength you are observing. $(M/L)_*$ changes quickly with age at blue wavelengths, much less at red/infrared wavelengths.

Generally $(M/L)_*$ must be inferred by modeling the population.



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