Exploring the Galaxy with Gaia

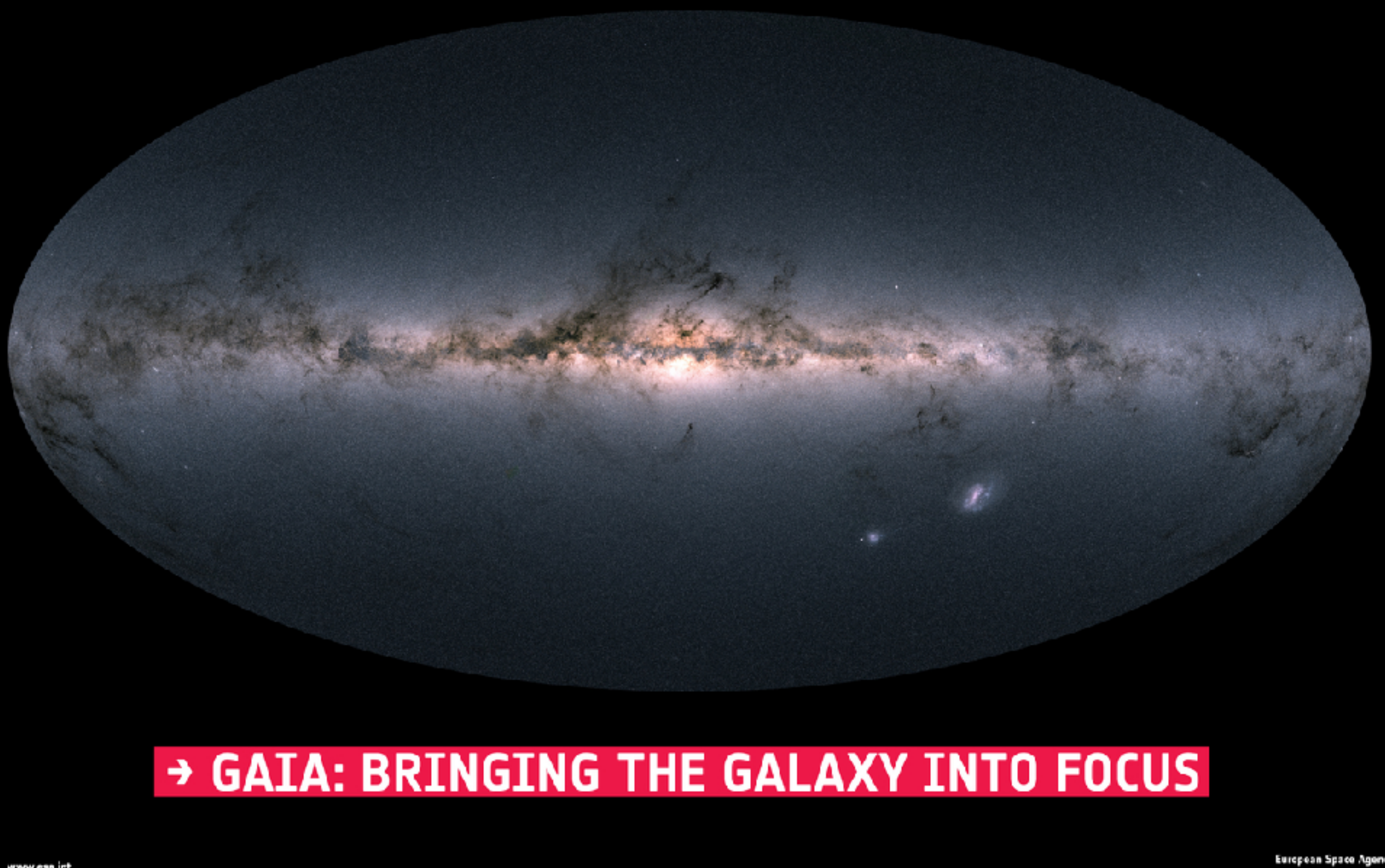
ASTRO 322

Erik Rosolowsky

Gaia - Global Astrometric Interferometer for Astrophysics
ESA Mission launched in Dec. 2013
Objective: locations and motions of 1 billion stars

Image credit: ESA

Gaia DR2 from 2018



Gaia Measurements

For >10^9 objects, Gaia precisely measures:

- Positions (Right Ascension / Declination)
- Brightnesses in three “colours”
- Stellar *parallax*
- *Proper motions*
- Radial velocities

Coordinates

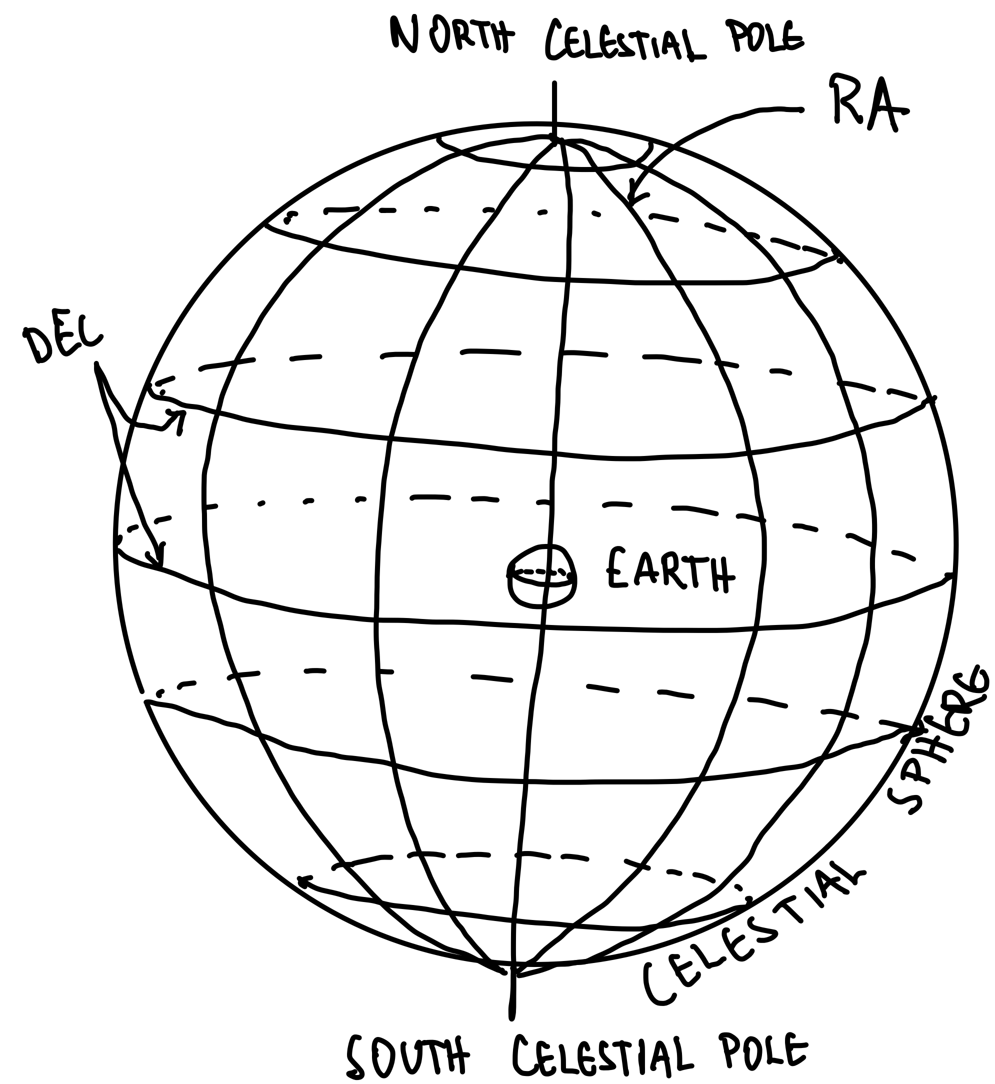
Measured on the *celestial sphere* in coordinates of:

Right Ascension ("RA"; longitude-like)

Declination ("Dec"; latitude-like)

Declination is measured in degrees

RA can be measured in degrees or units of time (??)



Galactic Coordinates

- ℓ = Galactic longitude
- b = Galactic latitude
- Usually measured in degrees.

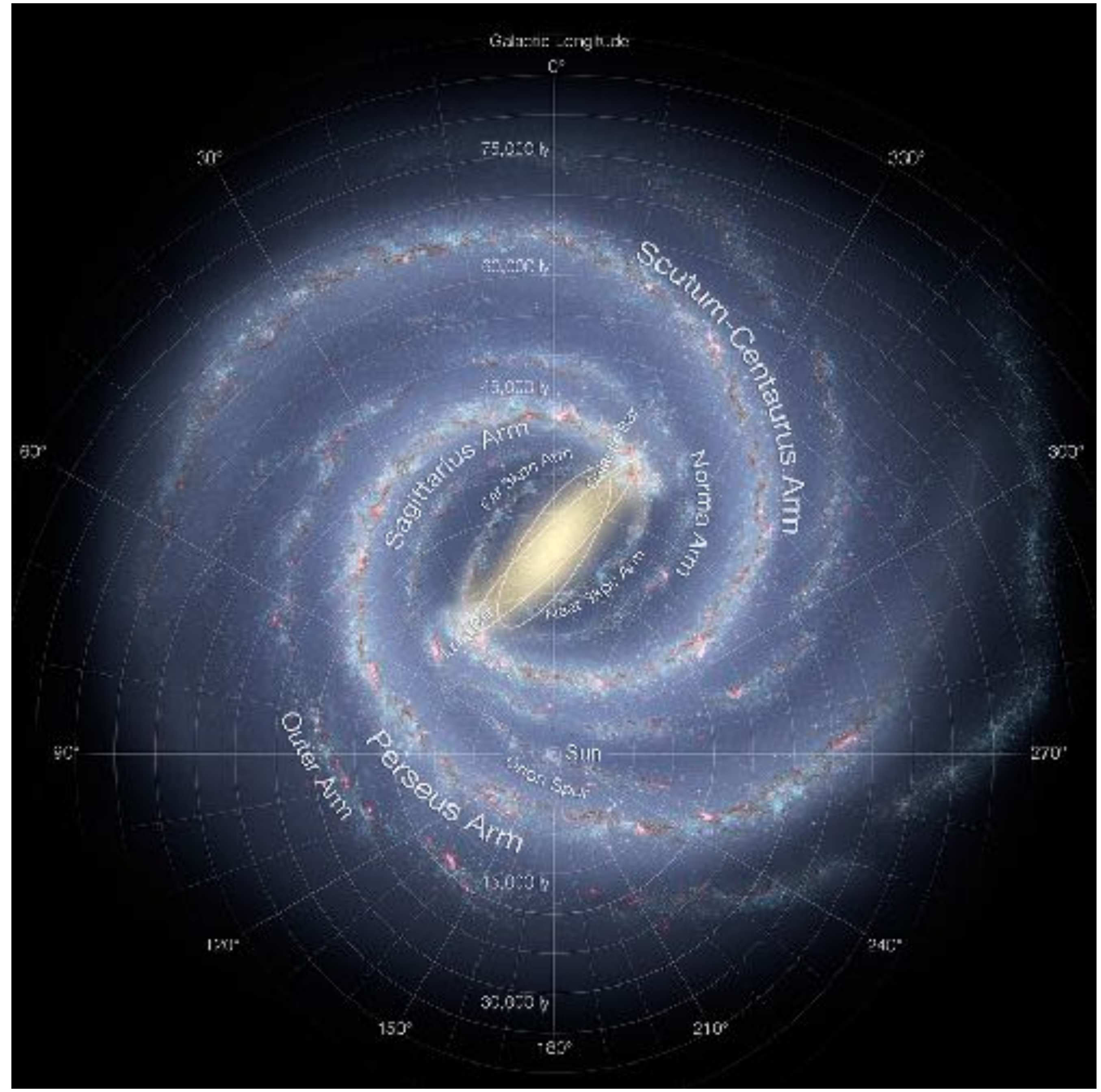
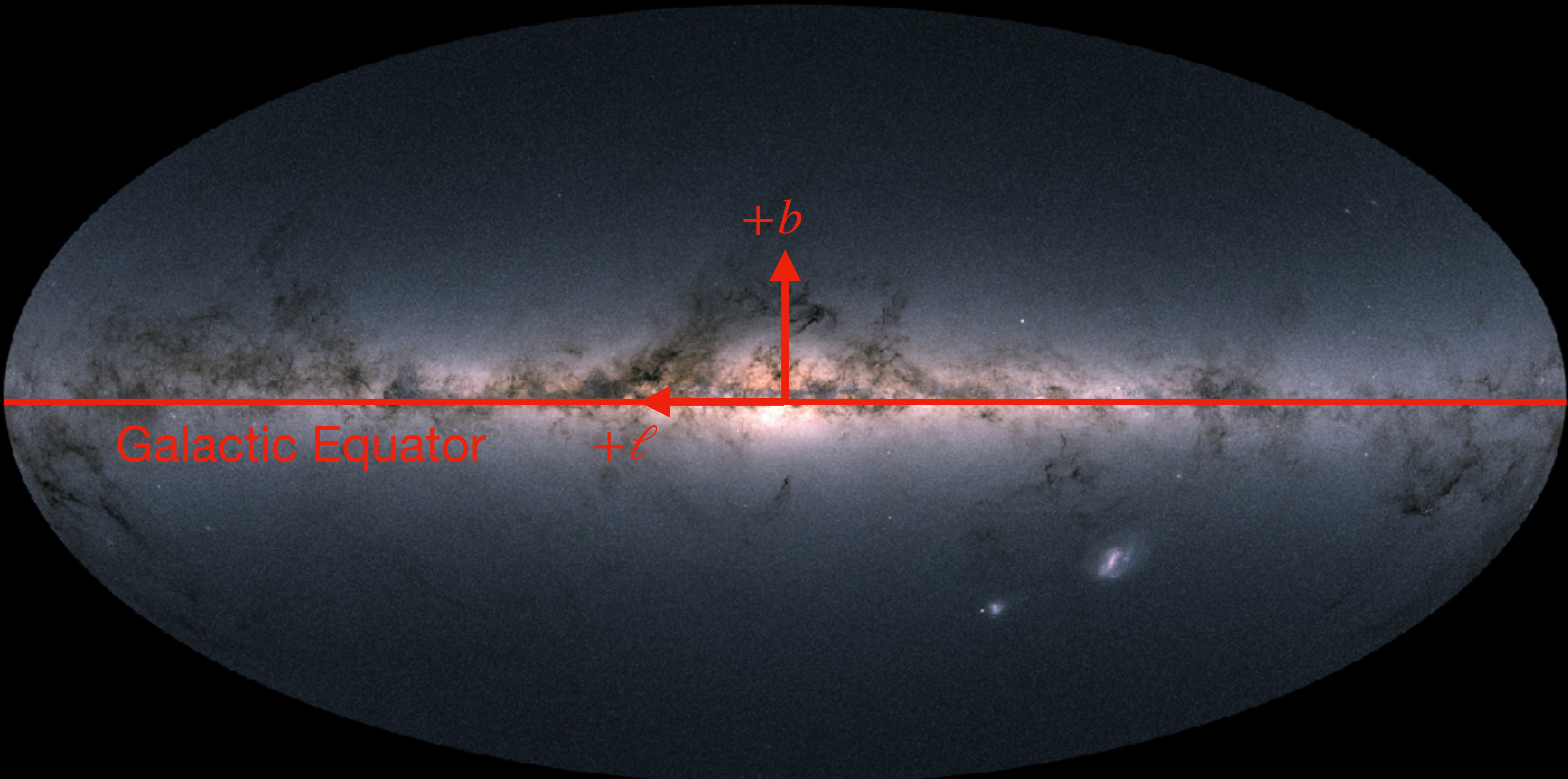


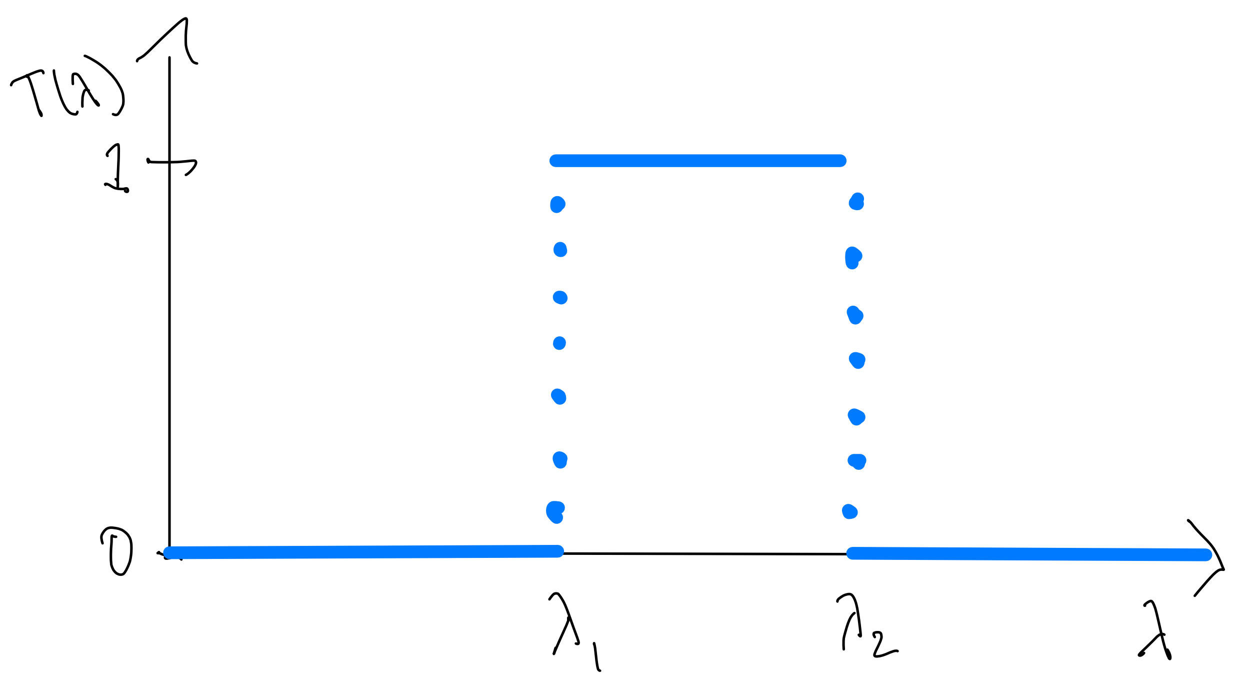
Image Credit: R Hurt (JPL/NASA)



→ GAIA: BRINGING THE GALAXY INTO FOCUS

Quantifying Light
Filters and Colours

- CCD cameras are only sensitive to number of photons not their colour.
- Use filters to limit the range of wavelengths.



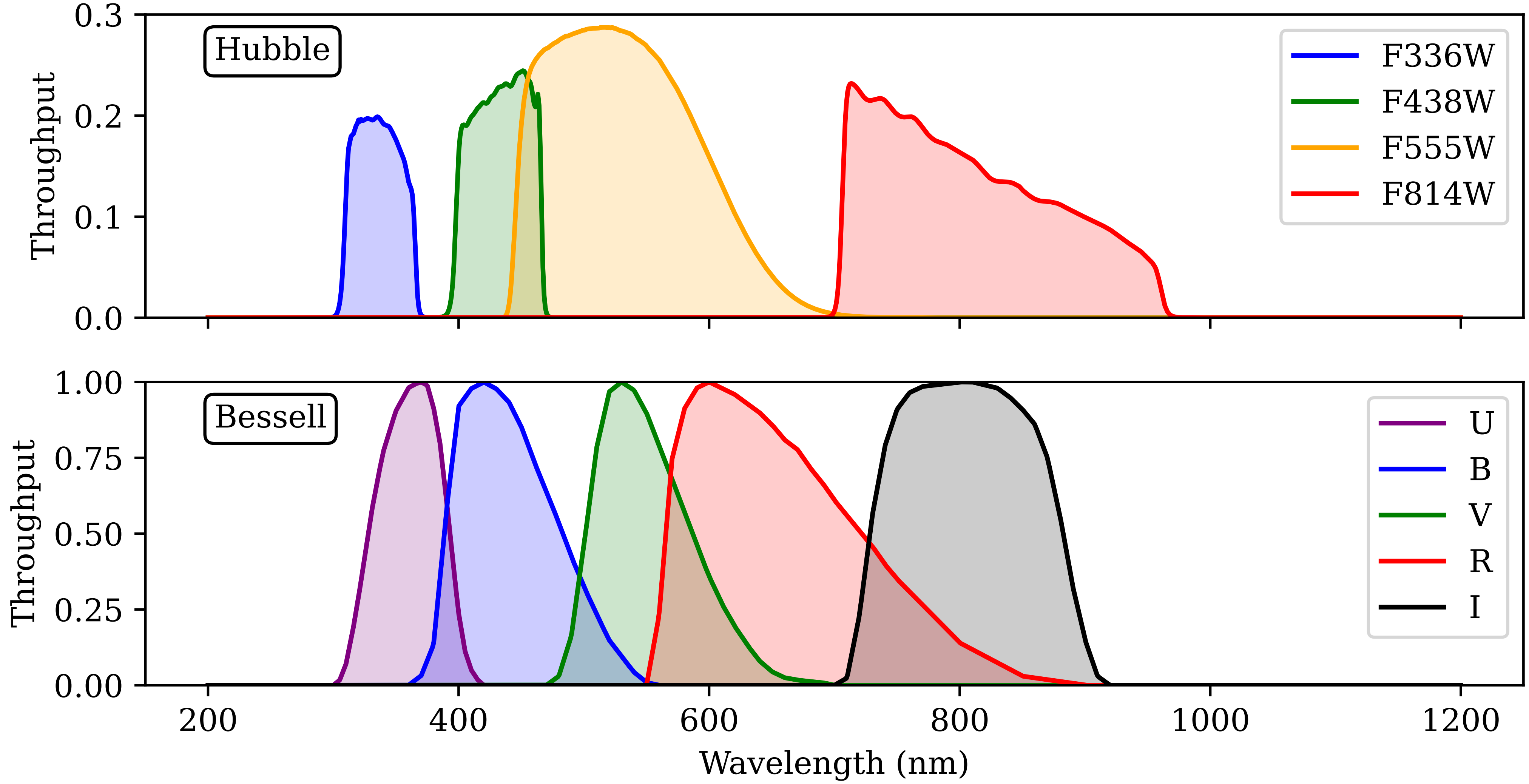
$$f_{\text{obs}} = \int_0^\infty T(\lambda) f_\lambda(\lambda)\, d\lambda$$

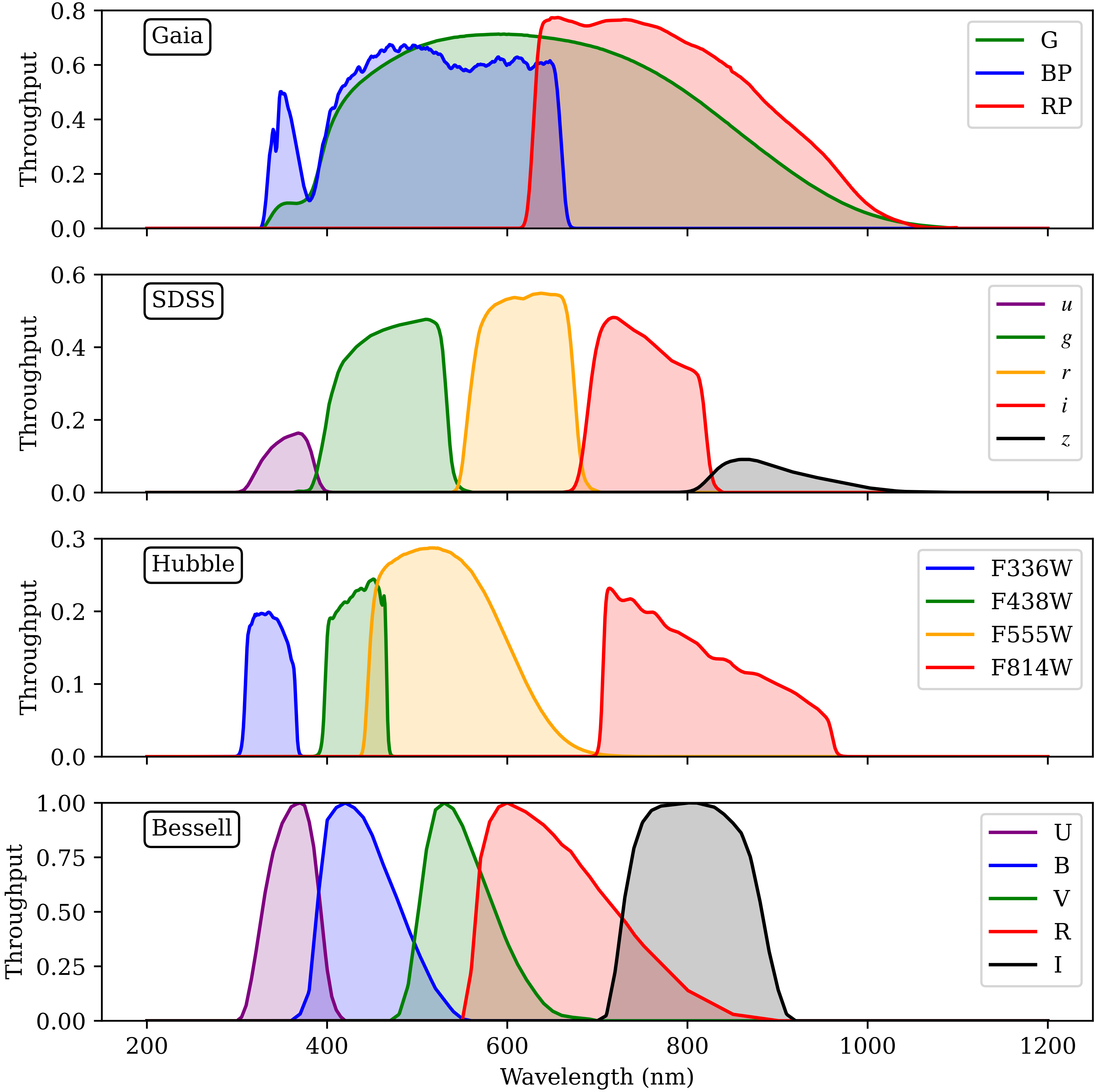
$$f_{\text{obs}} = \int_{\lambda_1}^{\lambda_2} T(\lambda) f_\lambda(\lambda)\, d\lambda$$

$$= \int_{\lambda_1}^{\lambda_2} f_\lambda(\lambda)\, d\lambda\,.$$

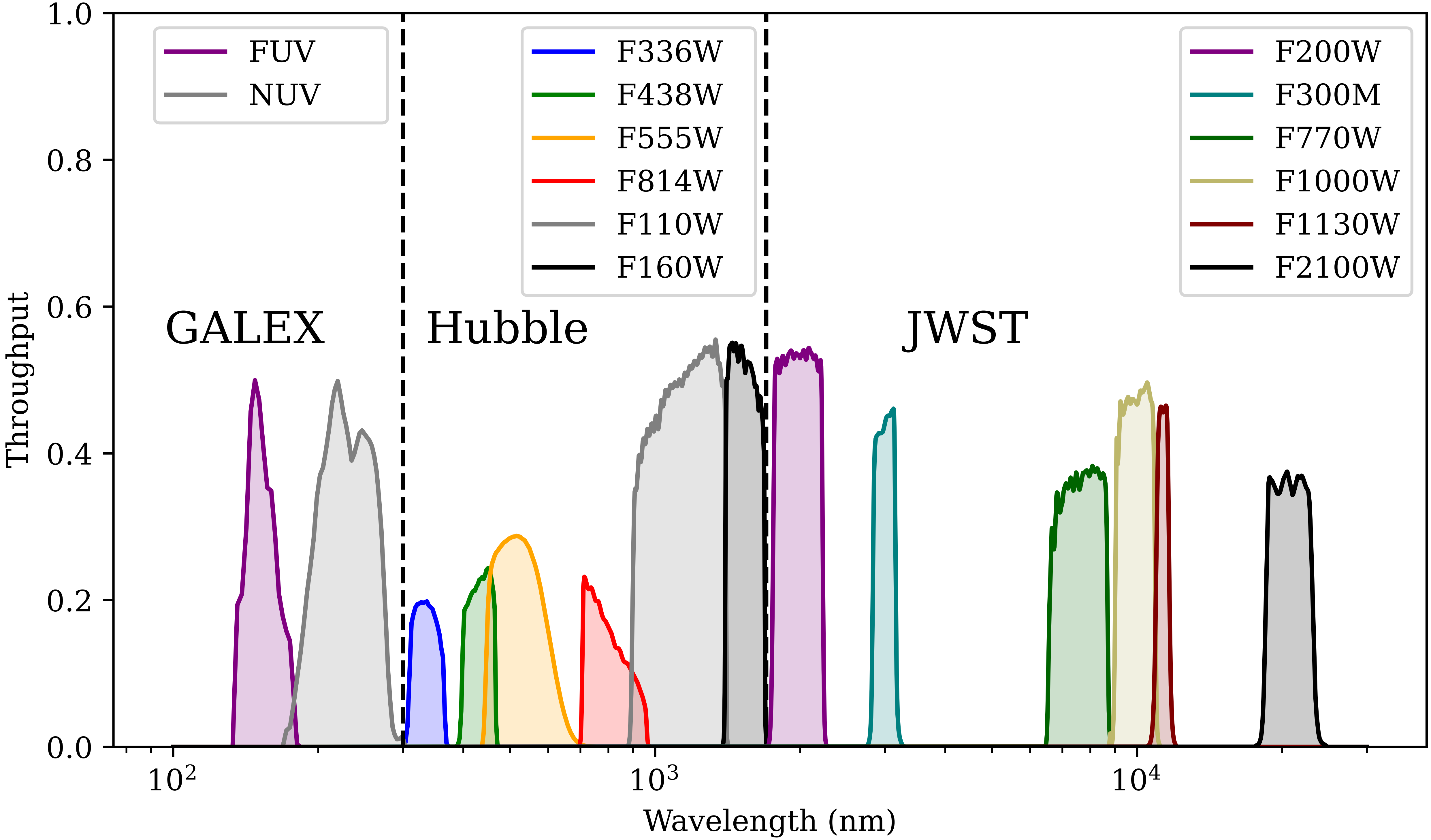
Quantifying Light
Filters and Colours

- Actual filters are more complicated
- Filters have standard names





Gaia
G
BP
RP
SDSS
u
g
r
i
z
Hubble
F336W
F438W
F555W
F814W
Bessell
U
B
V
R
I
Throughput
Wavelength (nm)

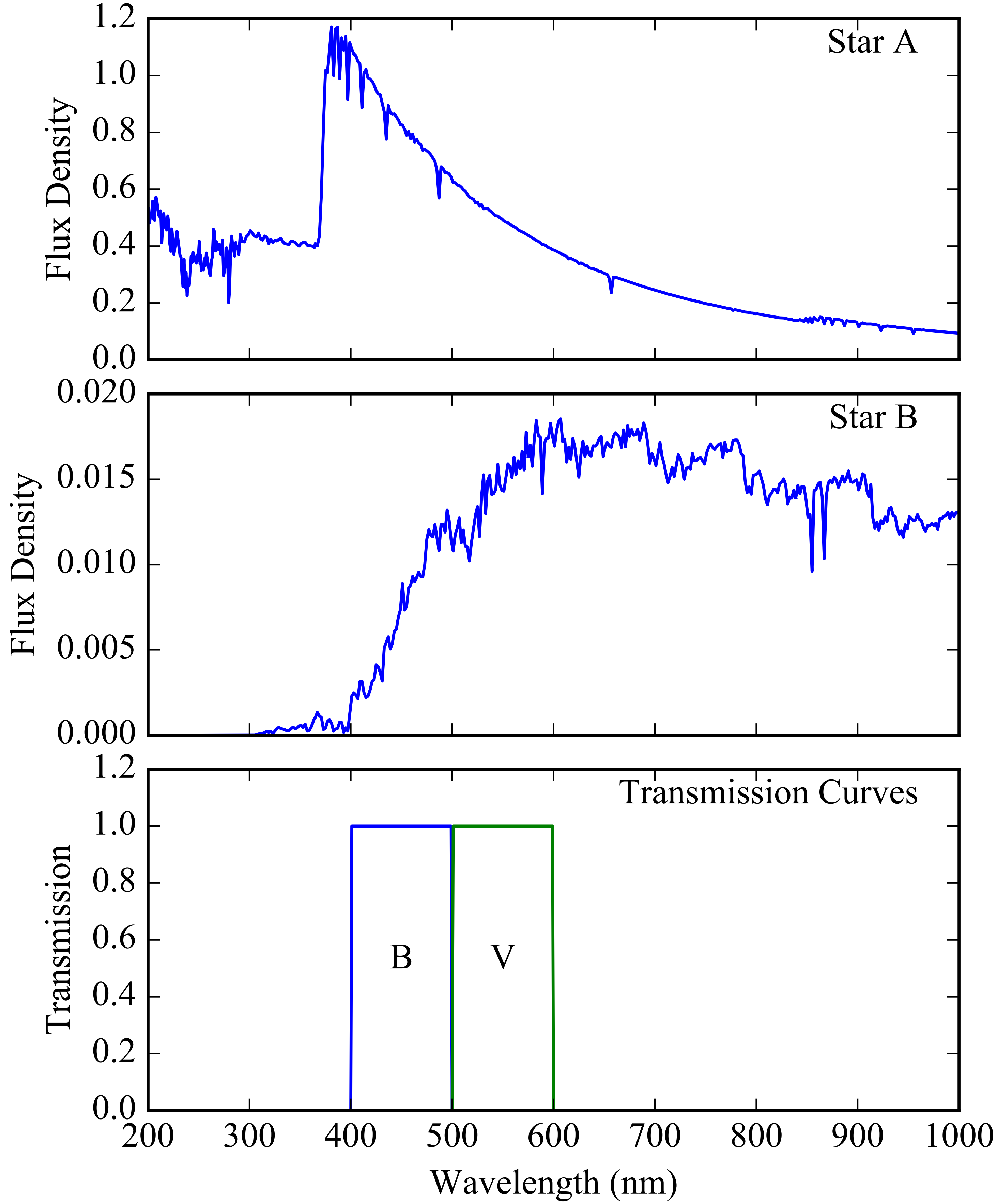

FUV
NUV
F336W
F438W
F555W
F814W
F110W
F160W
F200W
F300M
F770W
F1000W
F1130W
F2100W
GALEX
Hubble
JWST
Throughput
1.0
0.8
0.6
0.4
0.2
0.0
10^2
10^3
10^4
Wavelength (nm)

Quantifying Light
Filters and Colours

- A *colour* or *colour index* is the difference between the fluxes measured in two filters

$$g' - r' = -2.5\log_{10}\left(\frac{f_{\mathrm{obs},g'}}{f_{\mathrm{obs},r'}}\right) = -2.5\log_{10}\left(\frac{\int_0^\infty T_{g'}(\lambda) f_\lambda(\lambda)\, d\lambda}{\int_0^\infty T_{r'}(\lambda) f_\lambda(\lambda)\, d\lambda}\right)$$

Example: estimate the *B-V* colour index of Star A.

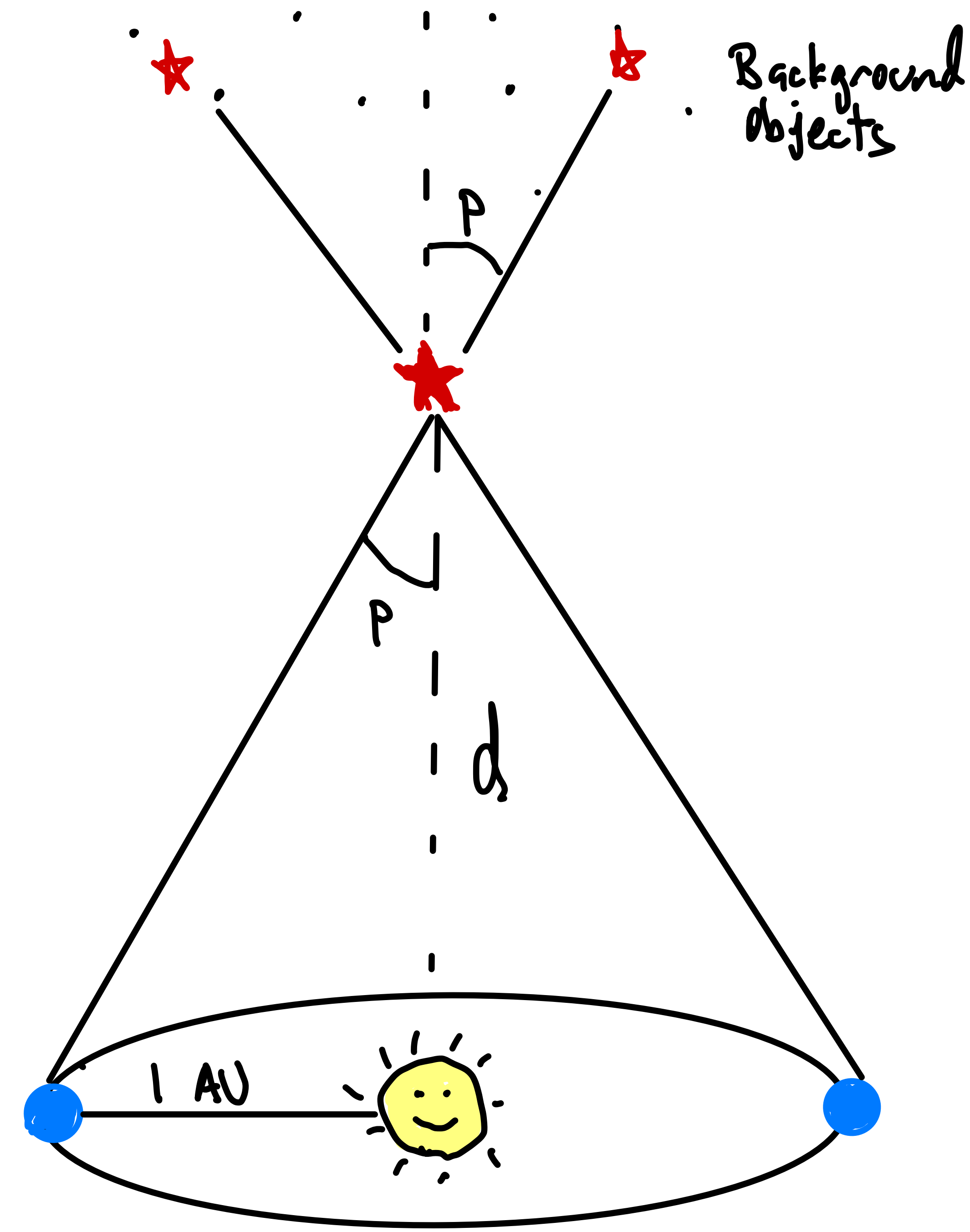


Parallax

Apparent motion of a nearby object with respect to a background objects.

Parallax tells us the **distance** to objects

$$d = \frac{1\ \text{AU}}{\tan p} \approx \frac{1\ \text{AU}}{p}$$



Proper Motion

Motion of a star with respect to more distant background stars

Caused by stars actually moving through space

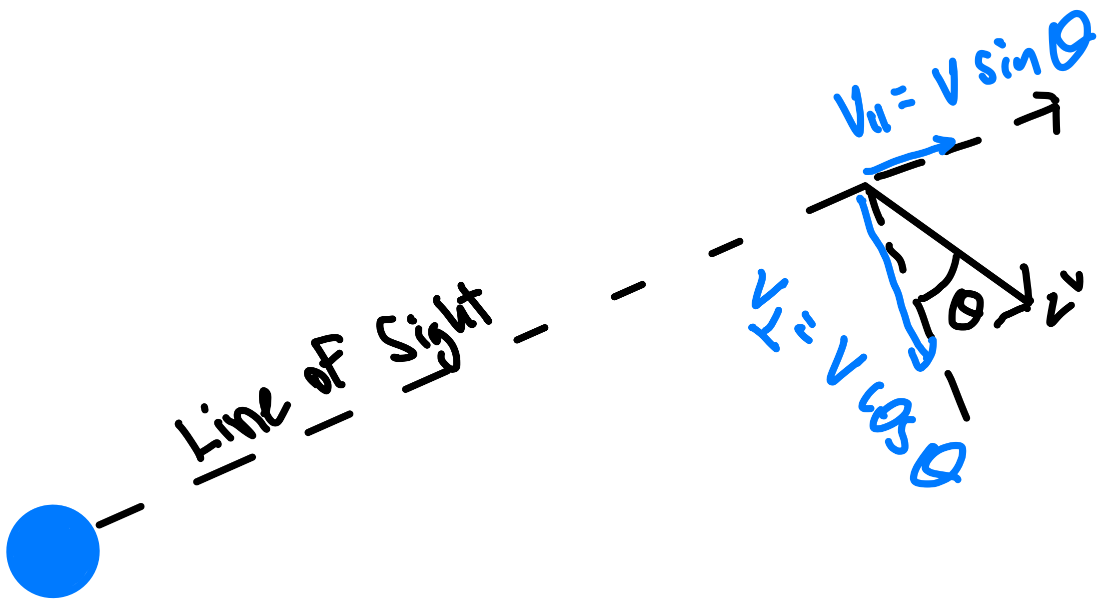
Barnard's Star
Image from S. Quirk; Public Domain

Proper motion

Proper motion is in contrast with parallax motion.

Actual change in coordinates because of motion of stars.

Measured in angular speed.



$$\boldsymbol{\mu} = (\mu_\alpha \cos\delta, \mu_\delta)$$

cos(dec) because of longitude line convergence

$$\left(\frac{v_\perp}{\mathrm{km\ s^{-1}}}\right) = 4.74 \left(\frac{d}{1\ \mathrm{pc}}\right) \left(\frac{|\boldsymbol{\mu}|}{1\ ''/\mathrm{yr}}\right).$$

Radial velocities

Measure the "radial" velocity of sources from lines in a stellar spectrum:

$$\frac{v_r}{c} = \frac{\lambda_{\rm obs} - \lambda_{\rm rest}}{\lambda_{\rm rest}}$$

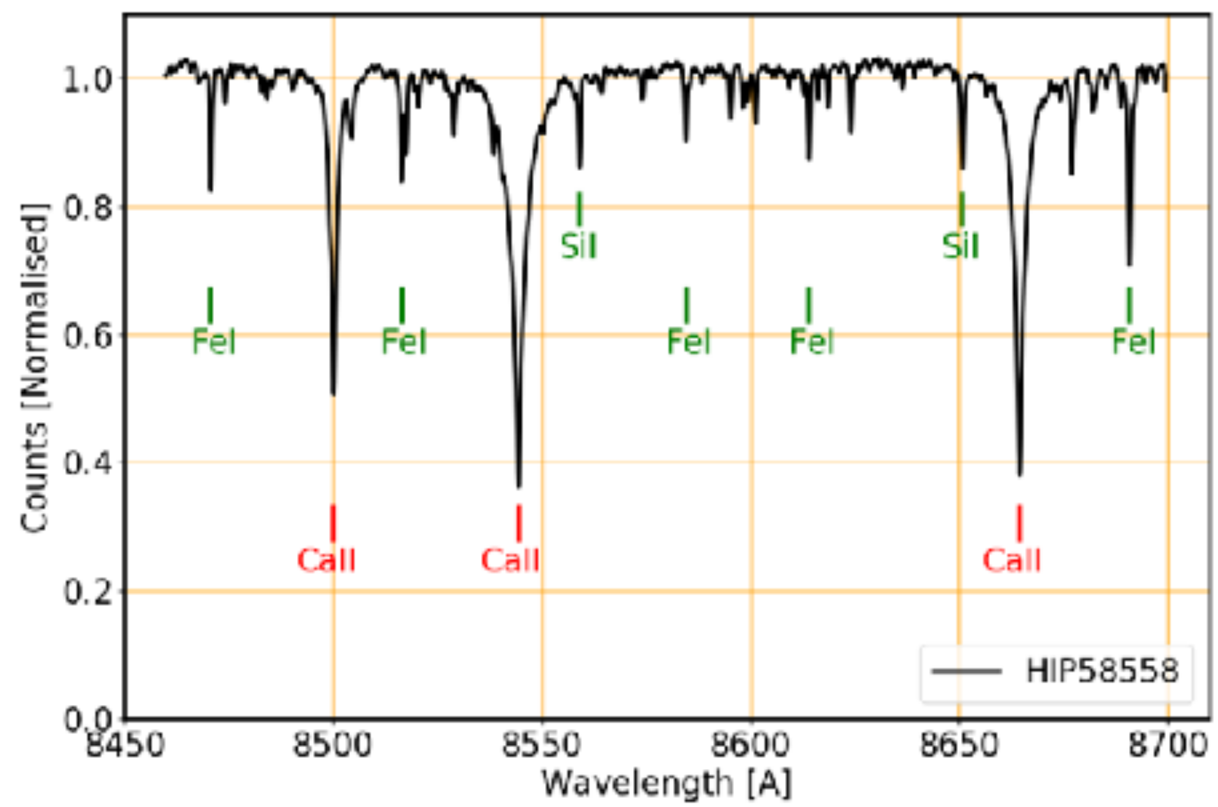


Fig. 1: RVS spectrum of the star HIP 58558.

From Gaia Data Release 2 by Katz et al. (2018)

Gaia Measurements

For $>10^9$ objects, Gaia precisely measures:

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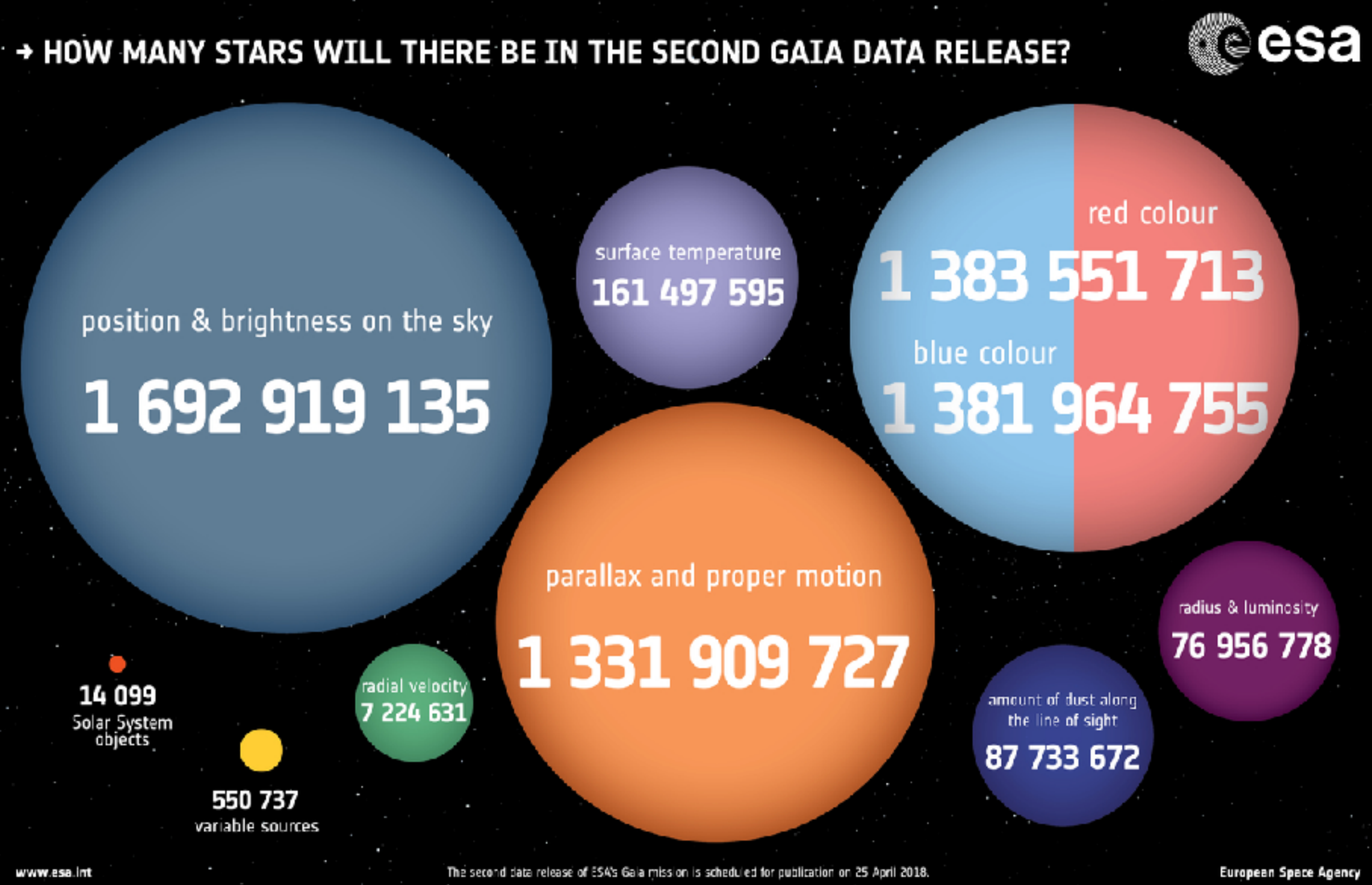
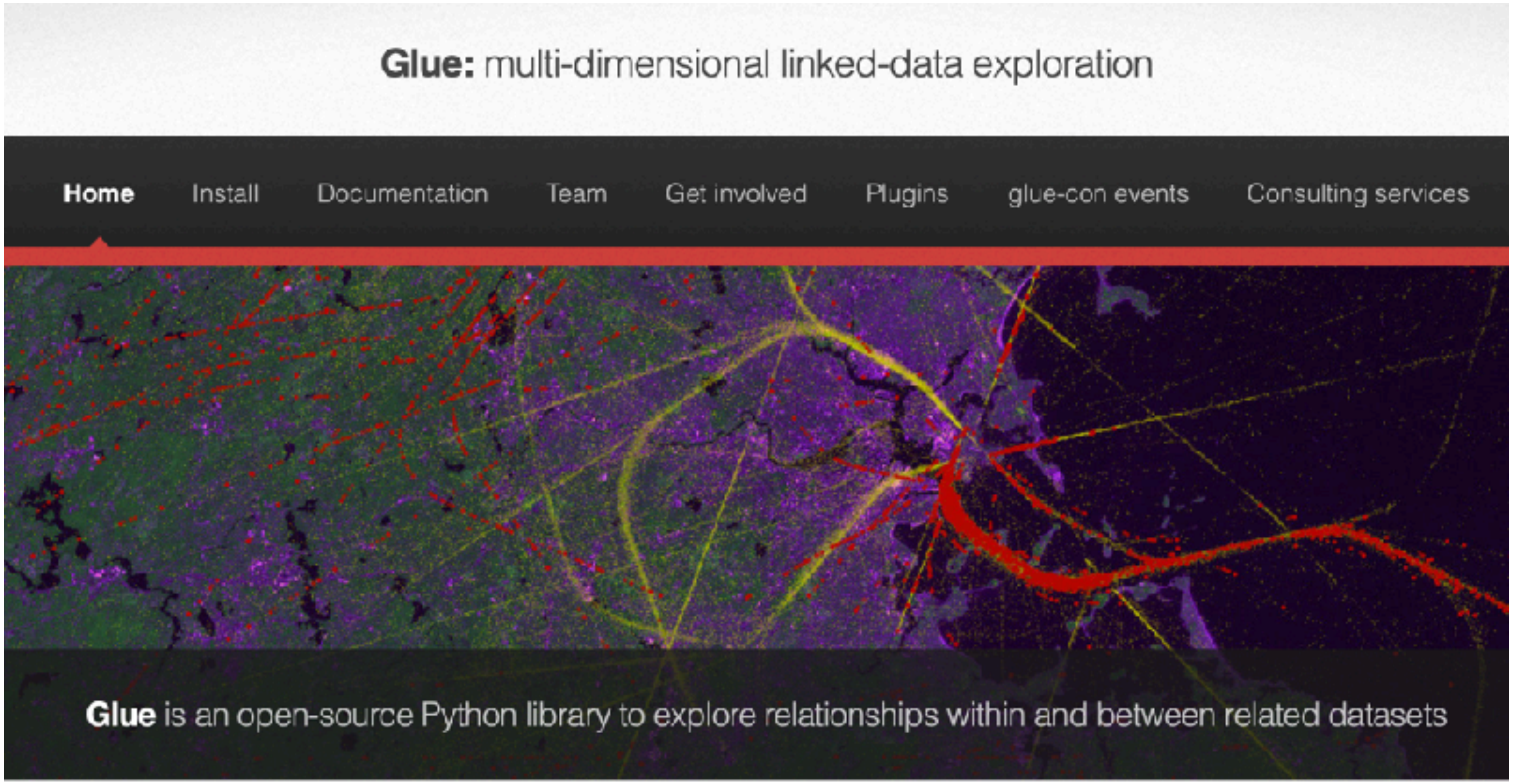
- Brightnesses in three "colours"
- Stellar *parallax*
- *Proper motions*
- Radial velocities

→ **Measurements in 6D:**
3D in space
3D in velocity

All measurements not available for all objects!


→ HOW MANY STARS WILL THERE BE IN THE SECOND GAIA DATA RELEASE?
esa
position & brightness on the sky
1 692 919 135
surface temperature
161 497 595
red colour
1 383 551 713
blue colour
1 381 964 755
parallax and proper motion
1 331 909 727
radius & luminosity
76 956 778
amount of dust along the line of sight
87 733 672
radial velocity
7 224 631
14 099
Solar System objects
550 737
variable sources
www.esa.int
The second data release of ESA's Gaia mission is scheduled for publication on 25 April 2018.
European Space Agency

https://glueviz.org



Linked Visualizations

Flexible linking across data

Full scripting capability

Data on Google Drive

https://drive.google.com/drive/folders/1x9bWCXdzw1Aq8eB_y5o2ft2XsK0Geyw1?usp=share_link

Image credit: NASA, ESA, AURA/Caltech, Palomar Observatory

Astronomy Data types

Catalogues - Spreadsheet-like data showing objects with measured properties

Images - Astronomical images plus “metadata” which describes what’s in the image

Formats:

- FITS - Flexible Image Transport System
- csv - Comma separated values

Glue Use

Follow along at home!!

‘source_id' — Gaia source identifier
‘mg’ — Absolute magnitude in the Gaia G band
‘phot_g_mean_mag' — Apparent magnitude in the Gaia G band
‘bp_rp' — Gaia Blue-Red colour
‘parallax' — Parallax angle in milliarcseconds
‘parallax_error' — Uncertainty in the parallax
‘ra’ — Right Ascension
‘dec' — Declination
‘pmra' — Proper motion in the RA direction
‘pmdec' — Proper motion in the Dec direction
‘pmra_error' — Uncertainty in pmra
‘pmdec_error' — Uncertainty in pmdec
‘radial_velocity' — Radial velocity of star in km/s
‘radial_velocity_error' — Uncertainty in radial velocity
‘e_bp_min_rp_val' — line-of-sight reddening E(BP-RP), a measure of dust
‘a_g_val' — Dust extinction in the G band
‘l' — Galactic longitude
‘b' — Galactic latitude
‘ecl_lat’ — Ecliptic latitude
‘ecl_lon' — Ecliptic longitude

Gaia Data

Exercise 1

Use the Glue software program to identify the Pleaides star cluster using the Gaia satellite data and proper motion selection. Make a histogram of the parallax of stars in this proper motion selected sample.

Calculate the distance to the Pleaides given the peak in the histogram.

Stars

A “black box” set of physics

- Basic stellar structure and physical processes
- Observed stellar properties
- The HR Diagram
- Stellar winds and supernovae
- Evolutionary tracks

Key properties of stars

1. Initial mass (range from $0.08 < M/M_{\odot} \lesssim 300$)
2. Chemical composition

   Described by mass fractions of:

   X - Hydrogen. Typically 0.72-0.75

   Y - Helium. Typically 0.25-0.26

   Z - “Metals” everything else. Typically 0-0.02
3. Binary / multiple stellar system
4. Initial angular momentum

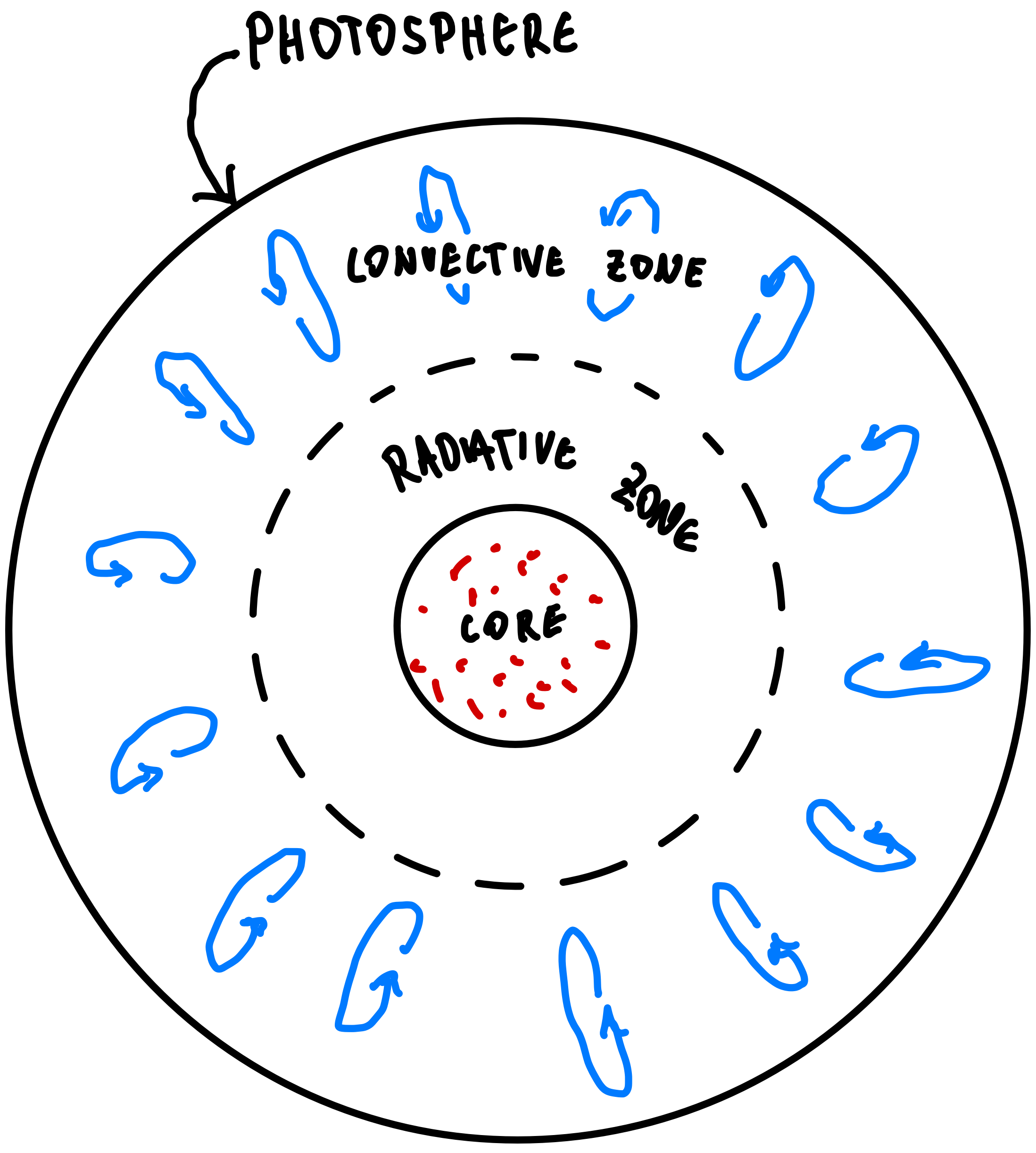
Stellar anatomy

Stars - nearly spherical gas structures, generates energy through nuclear fusion.

Core - central fusion engine

Envelope - Outer layers

Photosphere - “surface” of star where light flows out



Essential Stellar Physics

Hydrostatic equilibrium

Force balance between *pressure gradient* and *self-gravity* is dominant physics in star

Required central pressure to support against gravity:

$$P \sim \frac{GM^2}{R^4}$$

Pressure provided by:

1. Gas pressure
2. Radiation pressure
3. Degeneracy pressure

Essential Stellar Physics

Equations of state

Gas pressure (perfect gas law)

$$P_{\rm gas} = nkT \ (k = 1.38 \times 10^{-23} \ {\rm J/K})$$

Radiation pressure

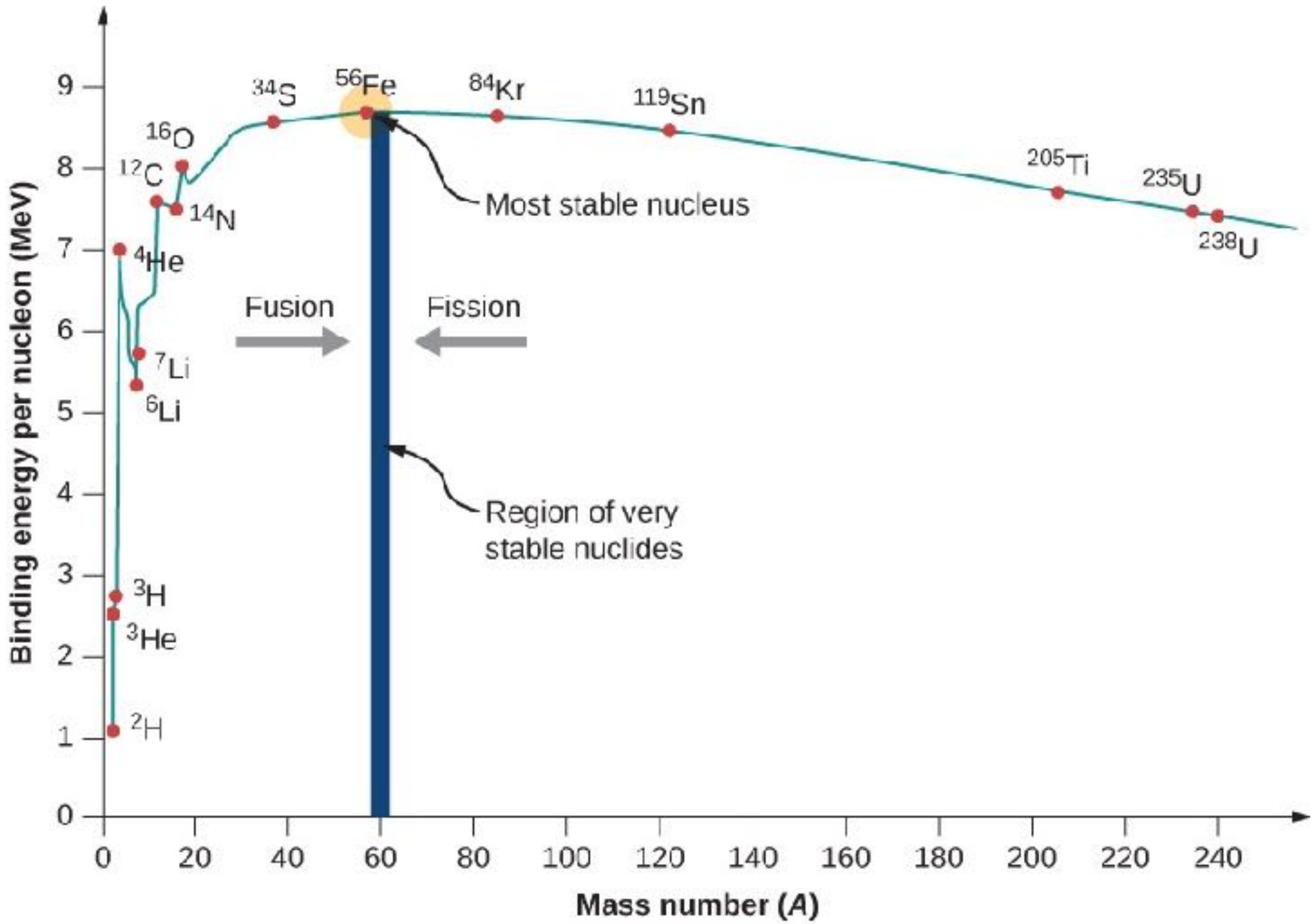
$$P_{\rm rad} = \frac{4}{3}\frac{\sigma_{\rm SB}T^4}{c} \ (\sigma_{\rm SB} = 5.67 \times 10^{-8} \ {\rm W/m^2/K^4})$$

Degeneracy Pressure

$$P_{\rm deg} = K_1 \left(\frac{\rho}{\rm kg \ m^{-3}}\right)^{5/3}$$ where ρ is the mass density

Essential Stellar Physics

Nuclear Fusion

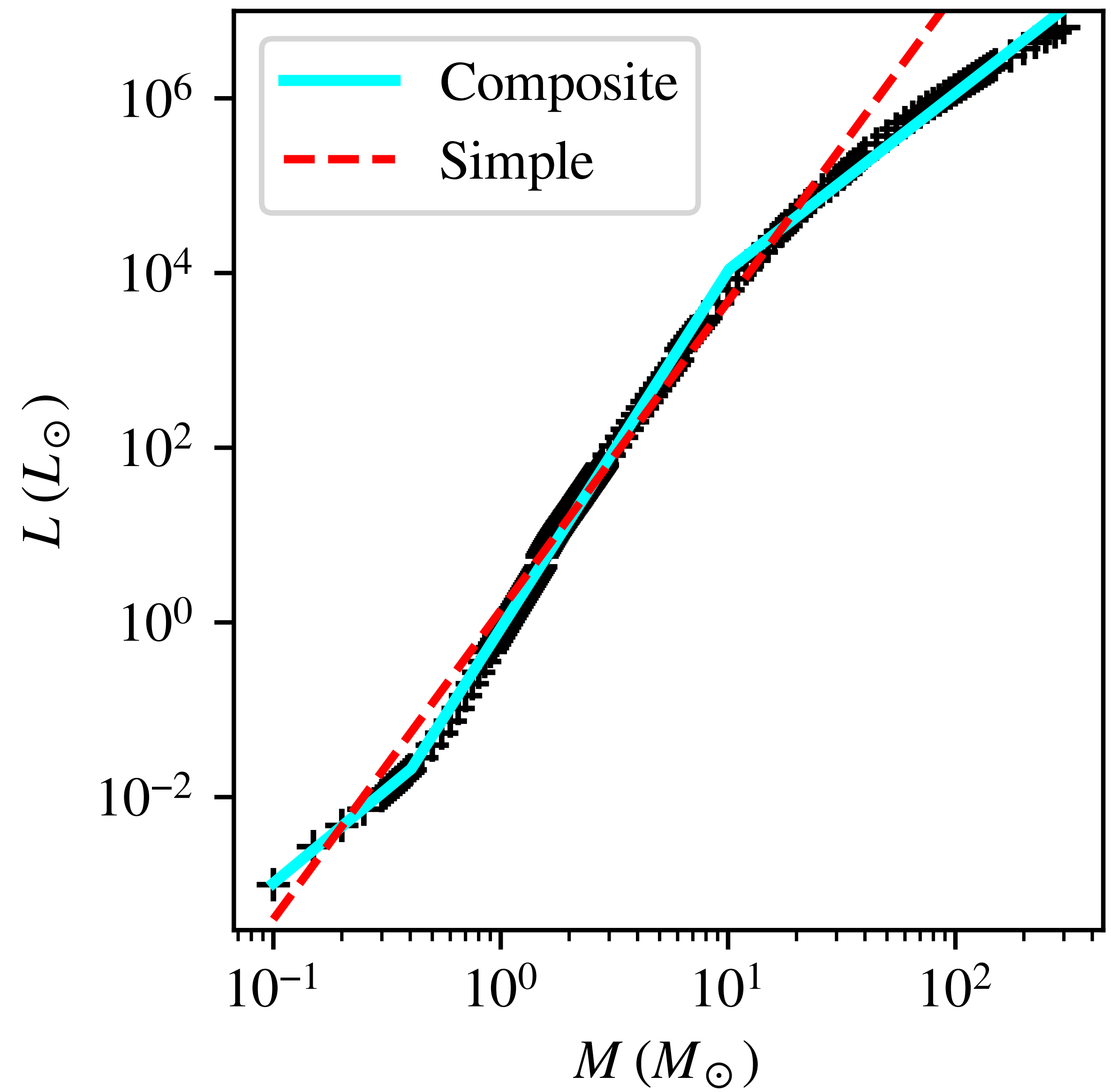


Observed Stellar Properties

Mass-Luminosity relationship

Main sequence stars (hydrogen fusion in core) follow approximately:

$$L = 1\ L_\odot \left(\frac{M}{M_\odot}\right)^{3.5}$$

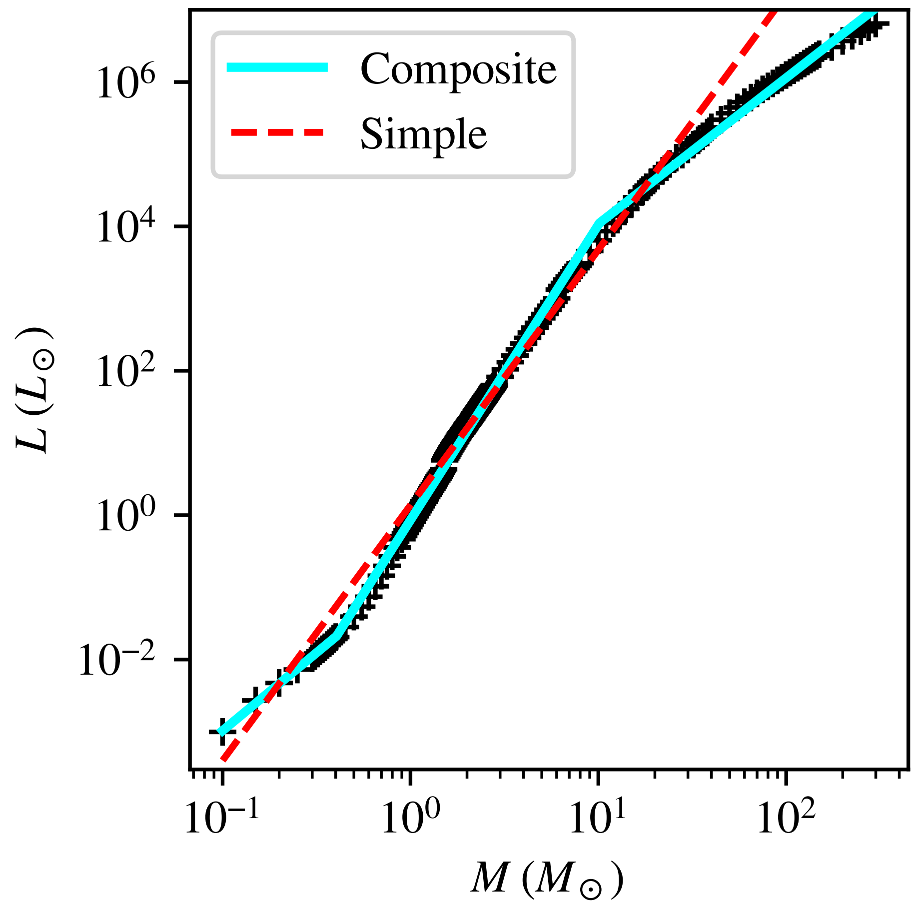


Observed Stellar Properties

Mass-Luminosity relationship

Fancier “composite” version

$$\frac{L}{L_\odot} = \begin{cases} 0.16(M/M_\odot)^{2.1} & ; \quad M/M_\odot < 0.4 \\ 1.00(M/M_\odot)^{4.1} & ; \quad 0.4 < M/M_\odot < 10 \\ 126.(M/M_\odot)^{2.0} & ; \quad 10 < M/M_\odot \end{cases}$$



Observed Stellar Properties

Implied stellar lifetimes

Mass-luminosity relationship implies main sequence lifetime of stars

$$\tau_{\rm MS} = \tau_{\rm MS,\odot} \left(\frac{M}{M_\odot}\right)\left(\frac{L}{L_\odot}\right)^{-1} = 10^{10}\ {\rm yr} \left(\frac{M}{M_\odot}\right)^{-2.5}$$

High mass stars have short lifetimes.

- Shortest lifetime is ~3 Myr.
- All stars with $M < 0.9\ M_\odot$ have not evolved off the main sequence in the age of the Universe (14 Gyr)

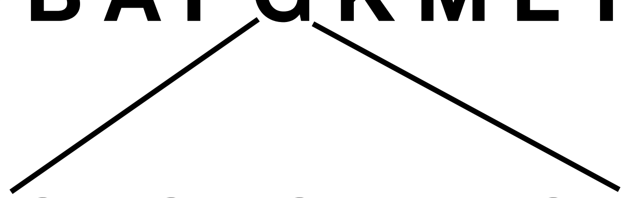
Observed Stellar Properties

Stellar spectra

Classified by the lines in the spectrum.

Stellar spectral types

O B A F G K M L T Y



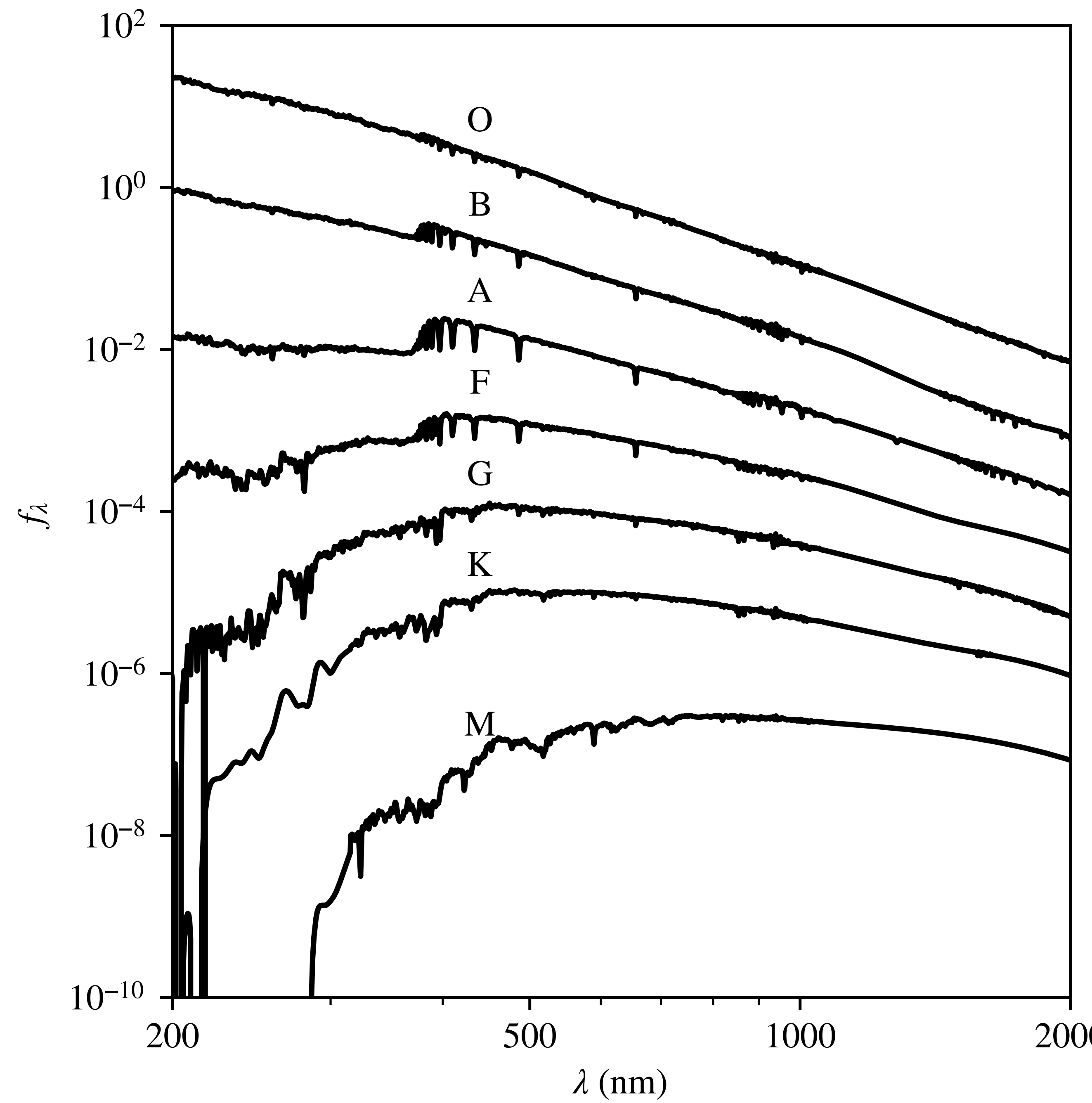
F9 G0 G1 G2 …. G9 K0

T_{eff} order:

O = hottest <u>star</u>

M = coolest <u>star</u>

L, T, Y = brown dwarfs



Observed Stellar Properties

Stellar spectra

Stellar luminosity classes

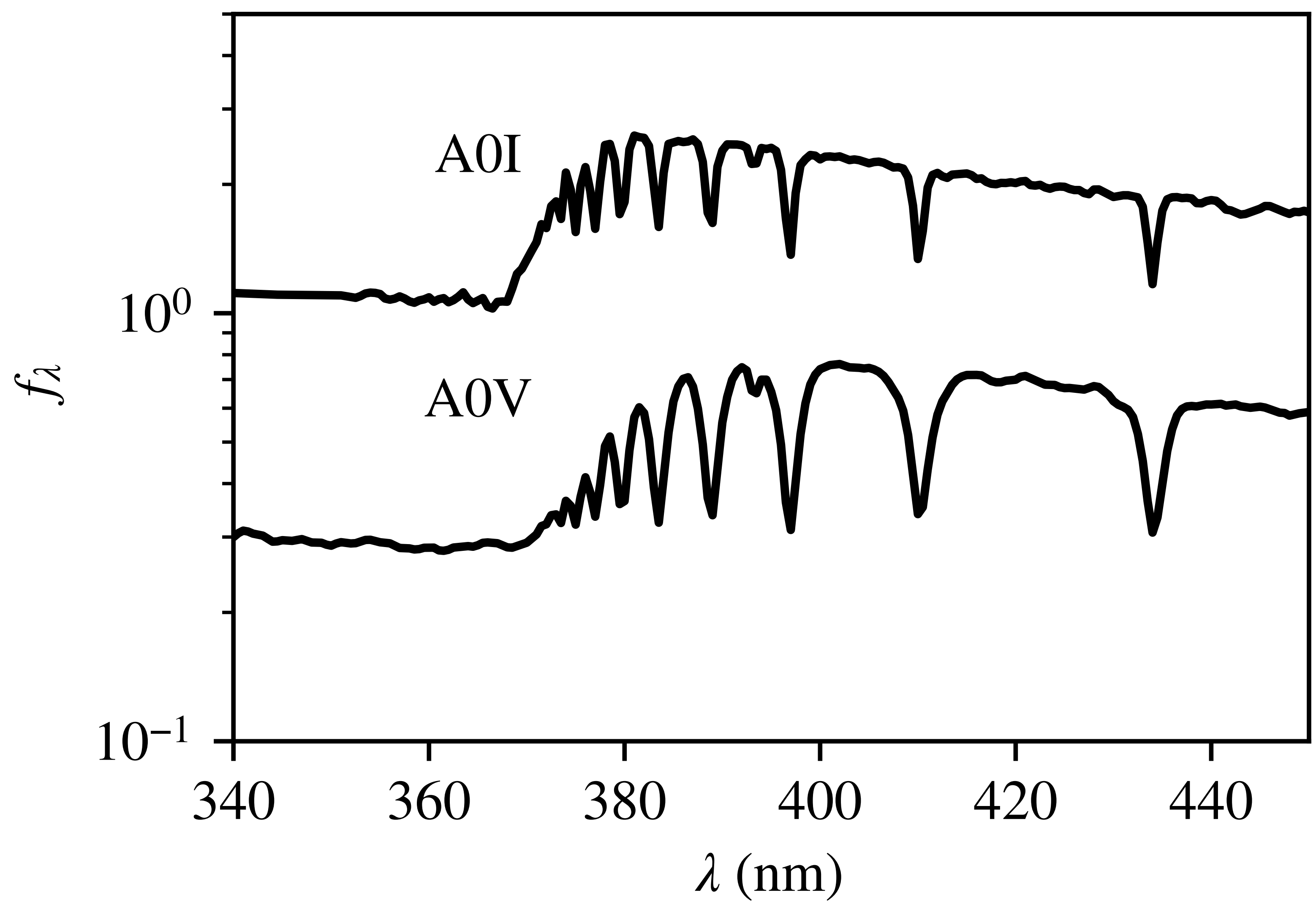
I - Supergiants

II, III - Giants

IV - Subgiants

V - Dwarfs

VI - Subdwarfs



Observed Stellar Properties

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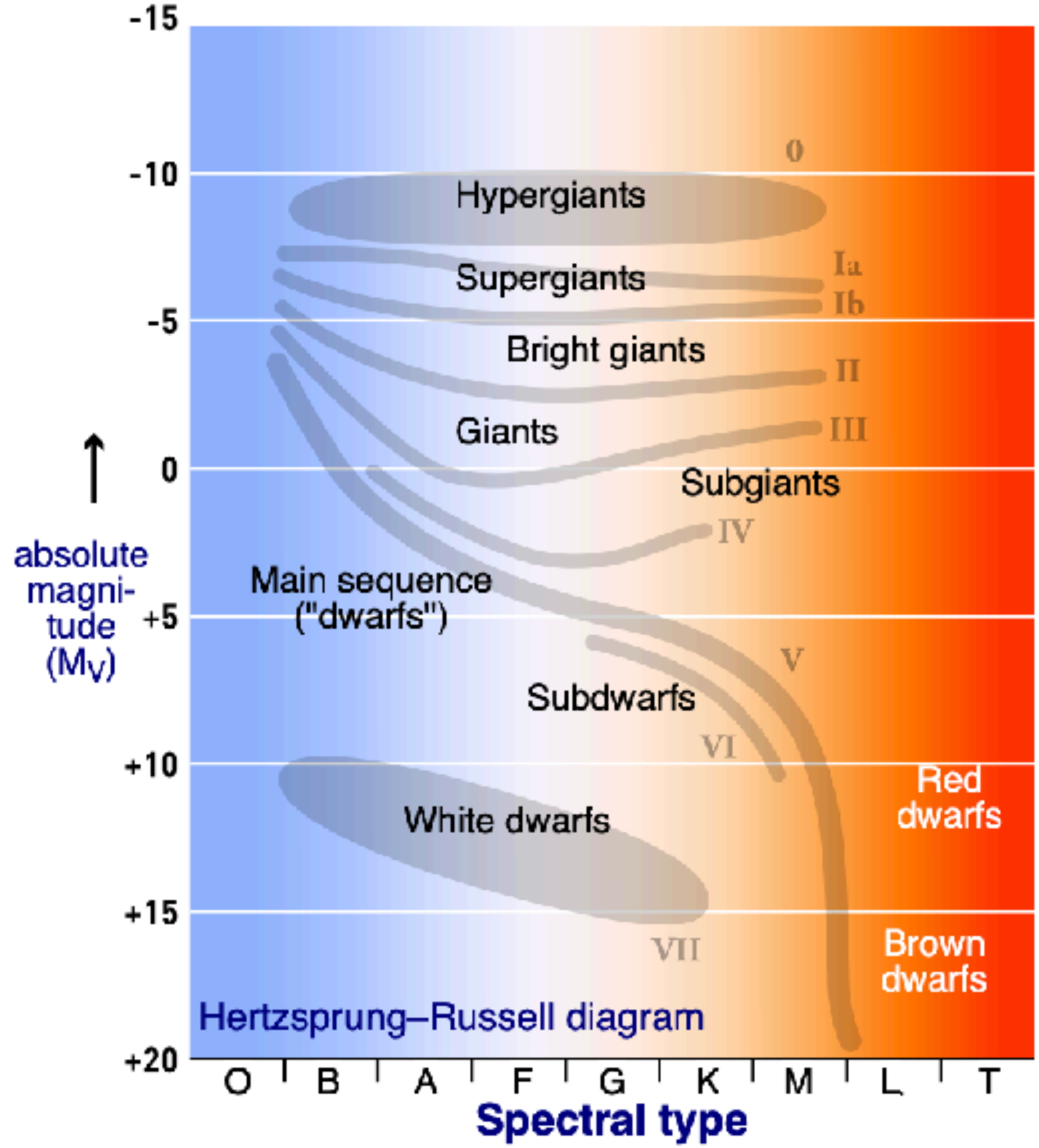


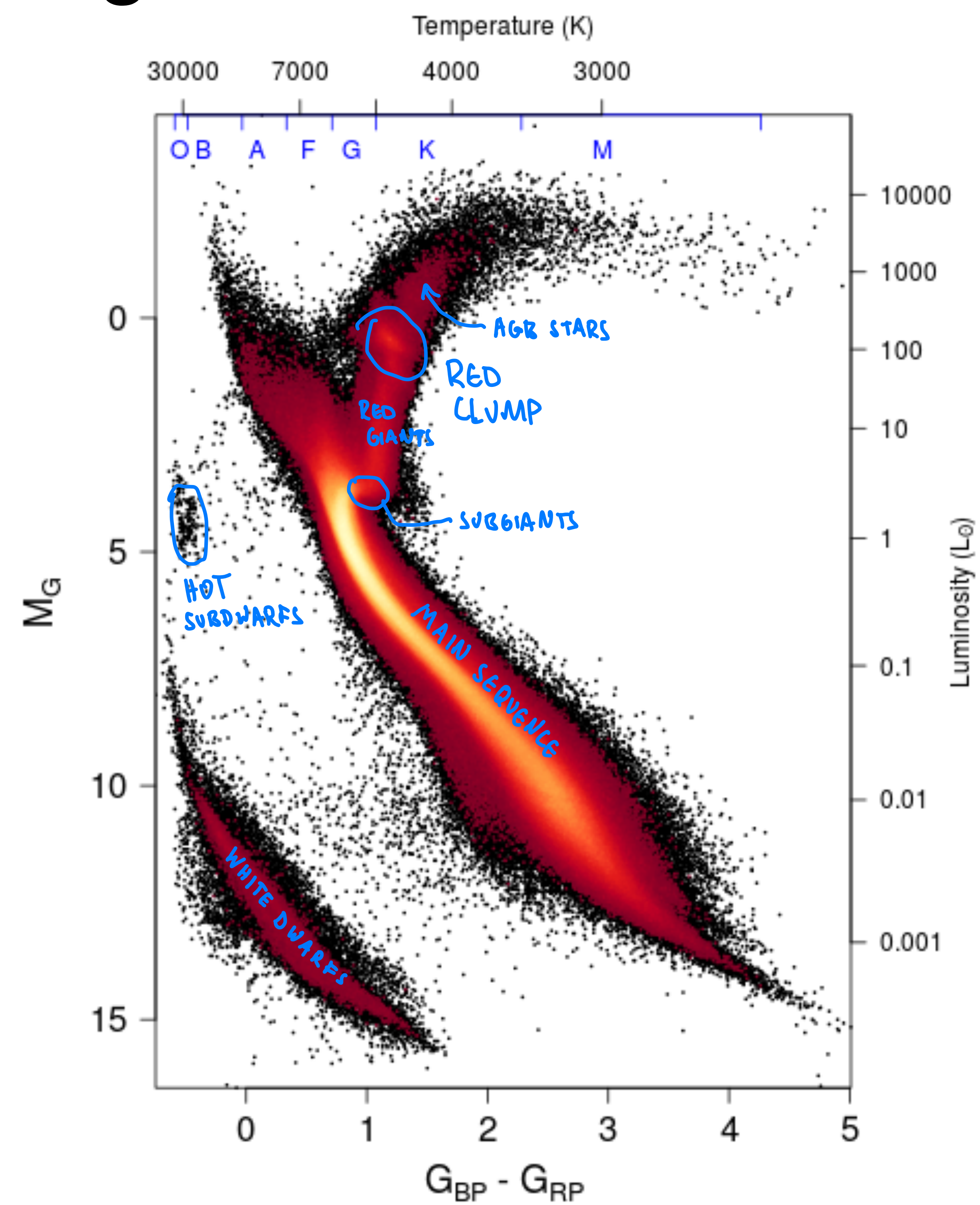
Observed Stellar Properties

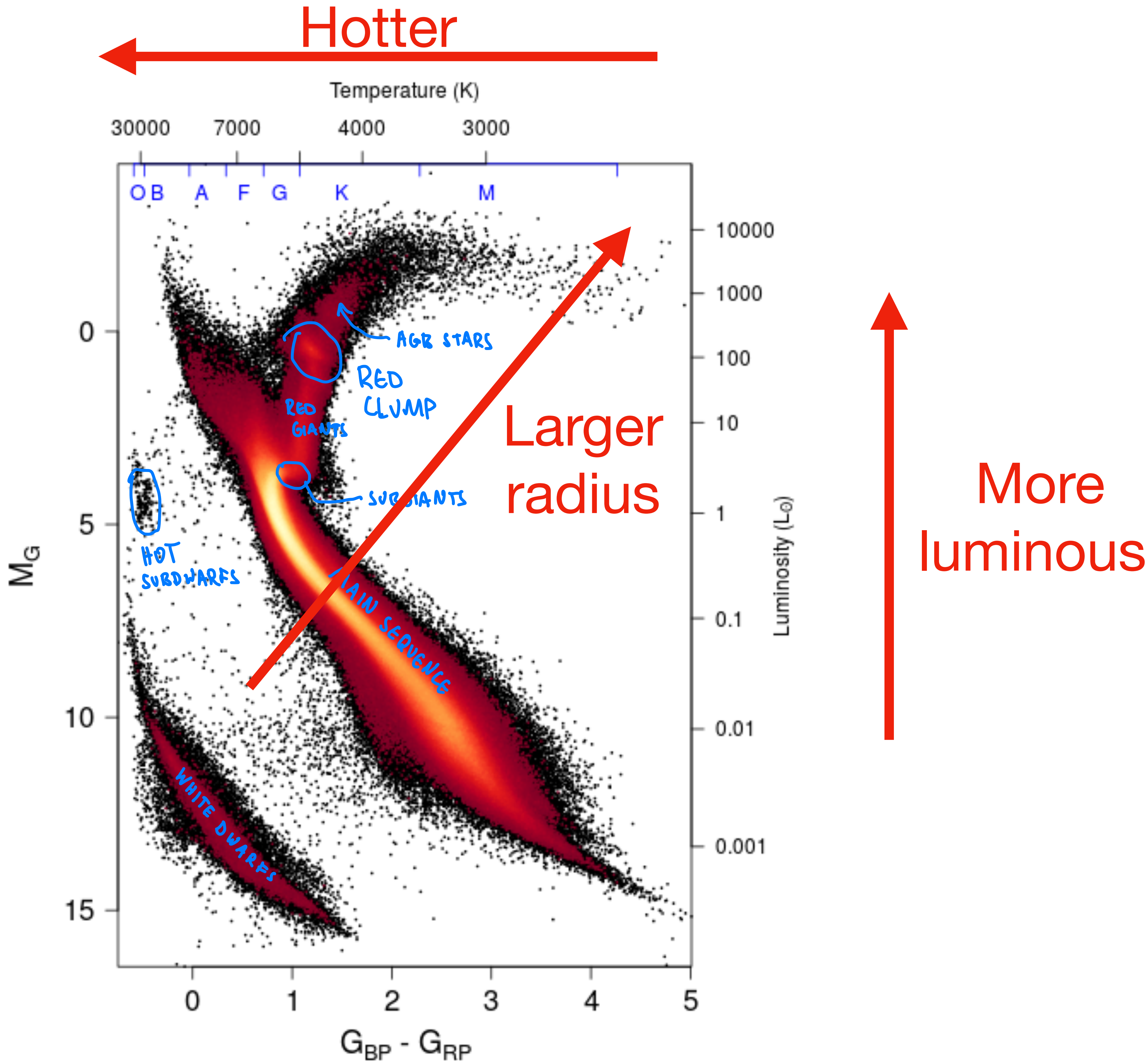
The Hertzsprung-Russell Diagram

Plot of Luminosity / absolute magnitude vs colour index / temperature

Identify groups of stars and classify them

HR magic - groups of stars share common physical properties.





Hotter
Temperature (K)
30000
7000
4000
3000
O B A F G K M
10000
1000
100
10
1
0.1
0.01
0.001
Luminosity ($L_\odot$)
0
5
10
15
M_G
0 1 2 3 4 5
G_{BP} - G_{RP}
AGB STARS
RED CLUMP
RED GIANTS
SUBGIANTS
HOT SUBDWARFS
MAIN SEQUENCE
WHITE DWARFS
Larger radius
More luminous

Gaia Data

Exercise 2

Select a cluster from the open cluster Gaia data.

Calculate the average distance to this cluster using the data in the Gaia file.

Make an observational HR diagram of the cluster using Glue.

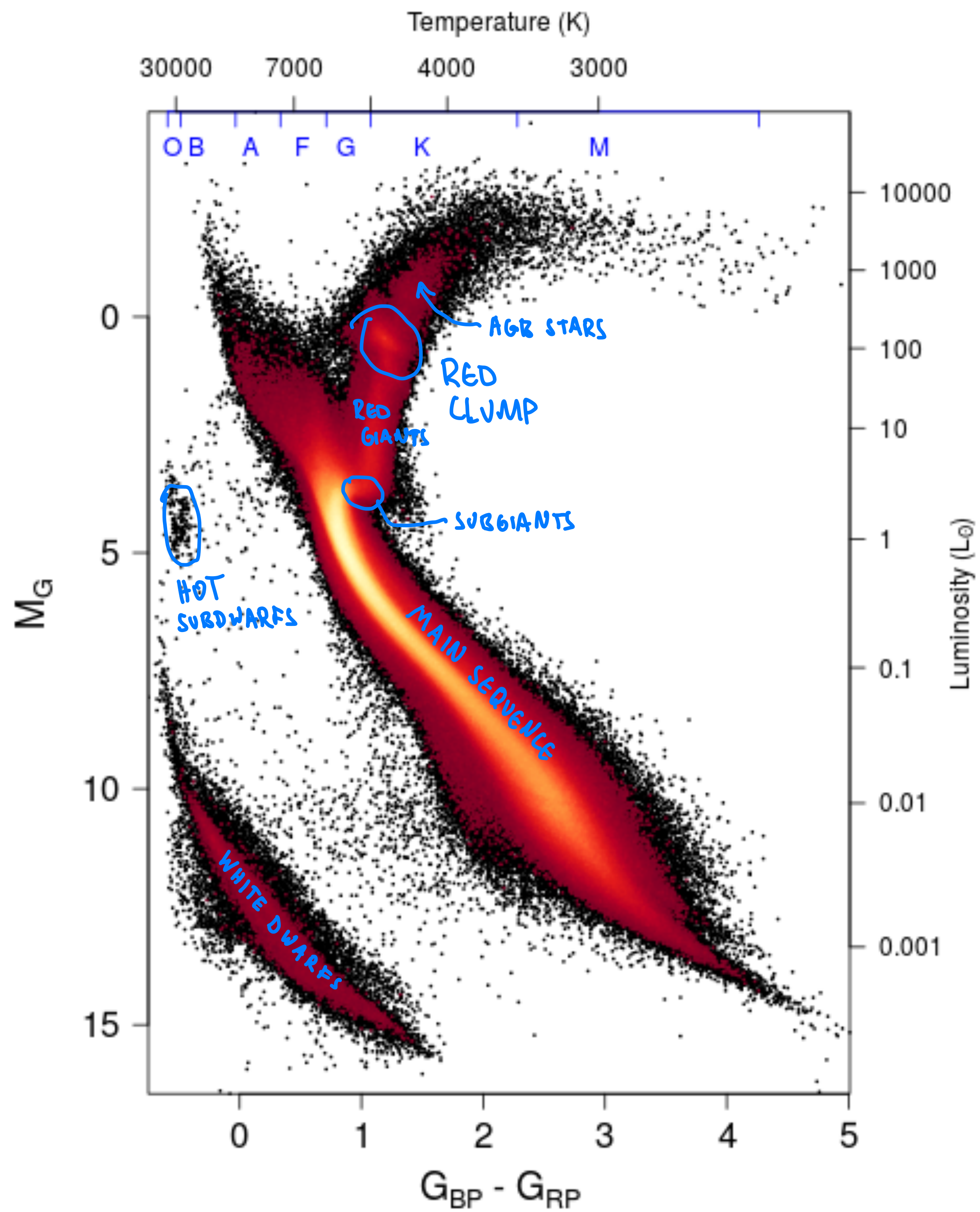
Identify:

- Main sequence stars
- The main sequence turnoff
- A binary star system
- Red giants
- White dwarfs

Stellar populations

The Goal

"Resolved"



Stellar Populations

The ingredients

- **Initial mass function** - the PDF of stellar masses from the star formation process
- **Metallicity of formed stars** - The enrichment process
- **Companion frequency** - Fraction of stars in binary / multiple systems with other stars or brown dwarfs
- **Star formation history** - Mass of stars formed over time (next time)

The Initial Mass Function

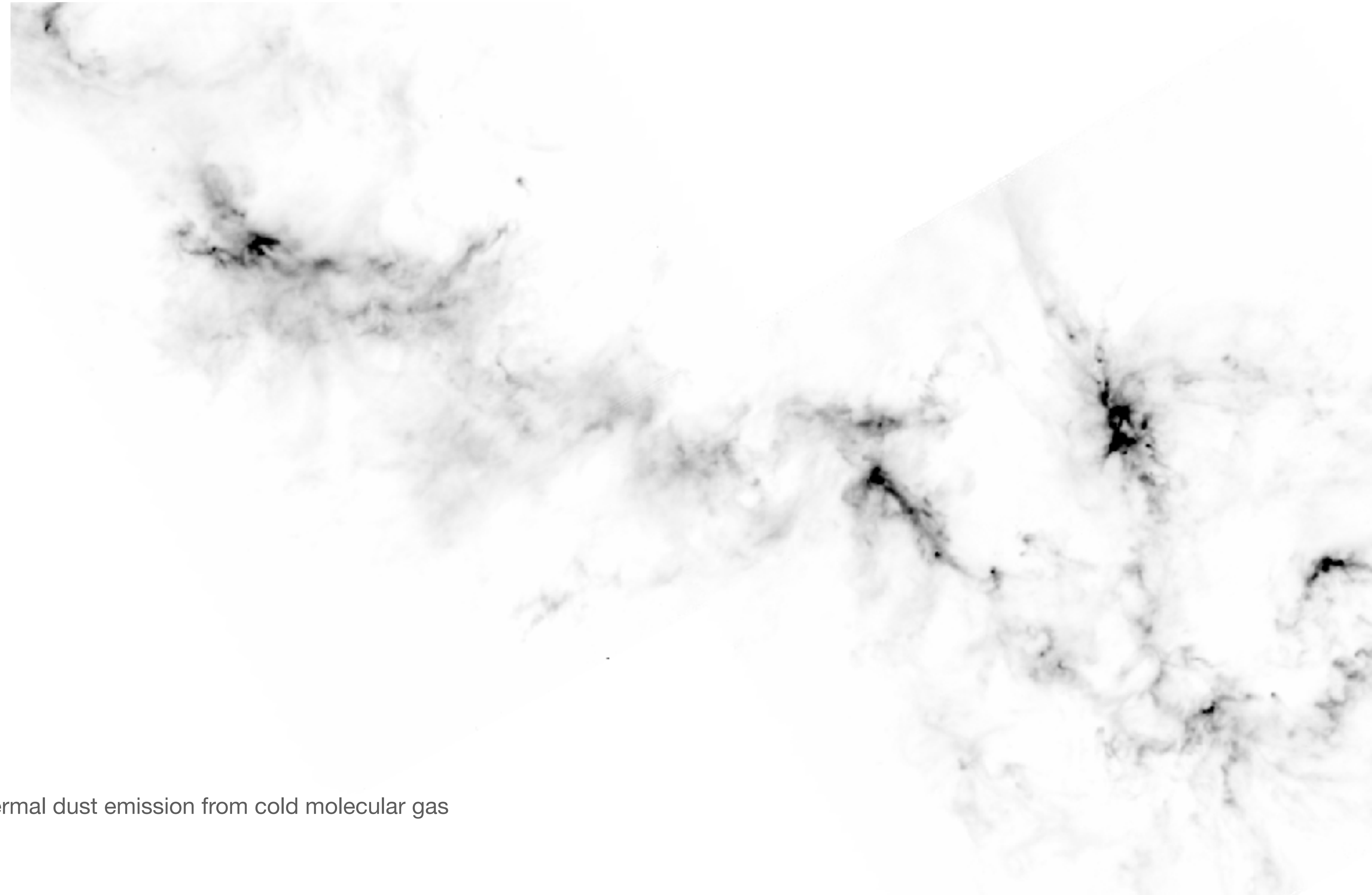
Star Formation

What is the characteristic mass of stars that form?

…Where do stars form?

Image credit: Adam Block and Tim Puckett

Protostars found in gas with $n_{H_2} \sim 10^8\ \mathrm{m}^{-3}$ and $T = 10\ \mathrm{K}$



Thermal dust emission from cold molecular gas

The Initial Mass Function

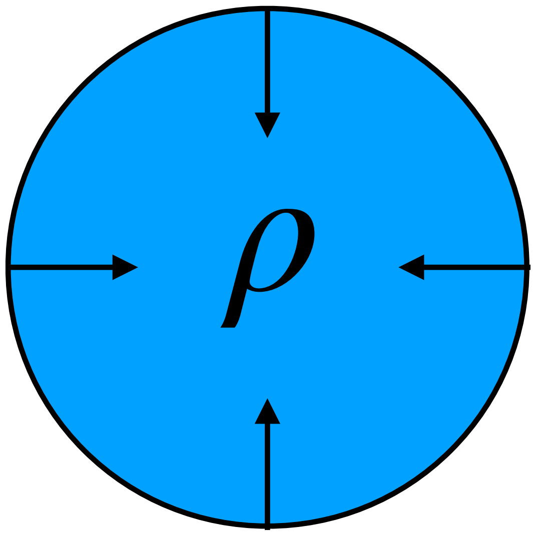
Star Formation

What is the characteristic mass of stars that form?

Dominant forces: pressure tries to resist gravitational collapse.

Set $t_{\rm ff} = t_{\rm cross}$, i.e. a free-fall time compared to crossing time. Free fall time for uniform cloud of mass density ρ is

$$t_{\rm ff} = \sqrt{\frac{3\pi}{32 G\rho}}$$



The Initial Mass Function

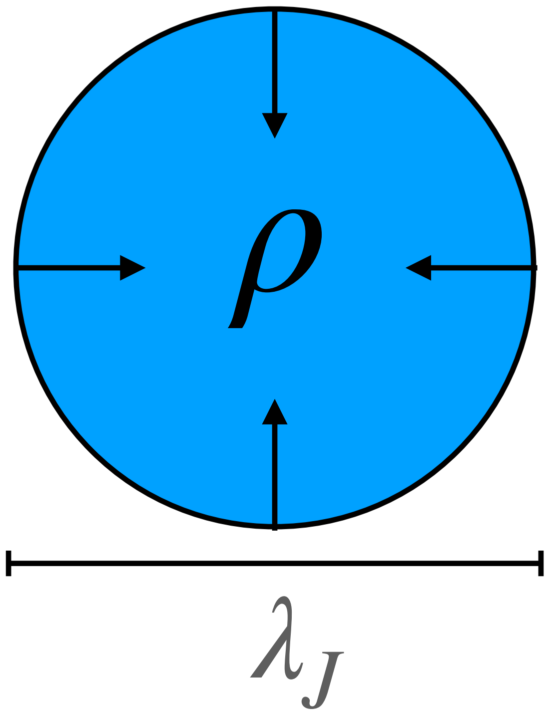
Star Formation

Set $t_{\mathrm{ff}} = t_{\mathrm{cross}}$, i.e. a free-fall time compared to crossing time.

$$t_{\mathrm{ff}} = \sqrt{\frac{3\pi}{32G\rho}}$$

Sound crossing time for a pressure wave is

$$t_{\mathrm{cross}} = \frac{\ell_J}{c_s}; \qquad c_s = \sqrt{\frac{kT}{m}}$$



The Initial Mass Function

Star Formation

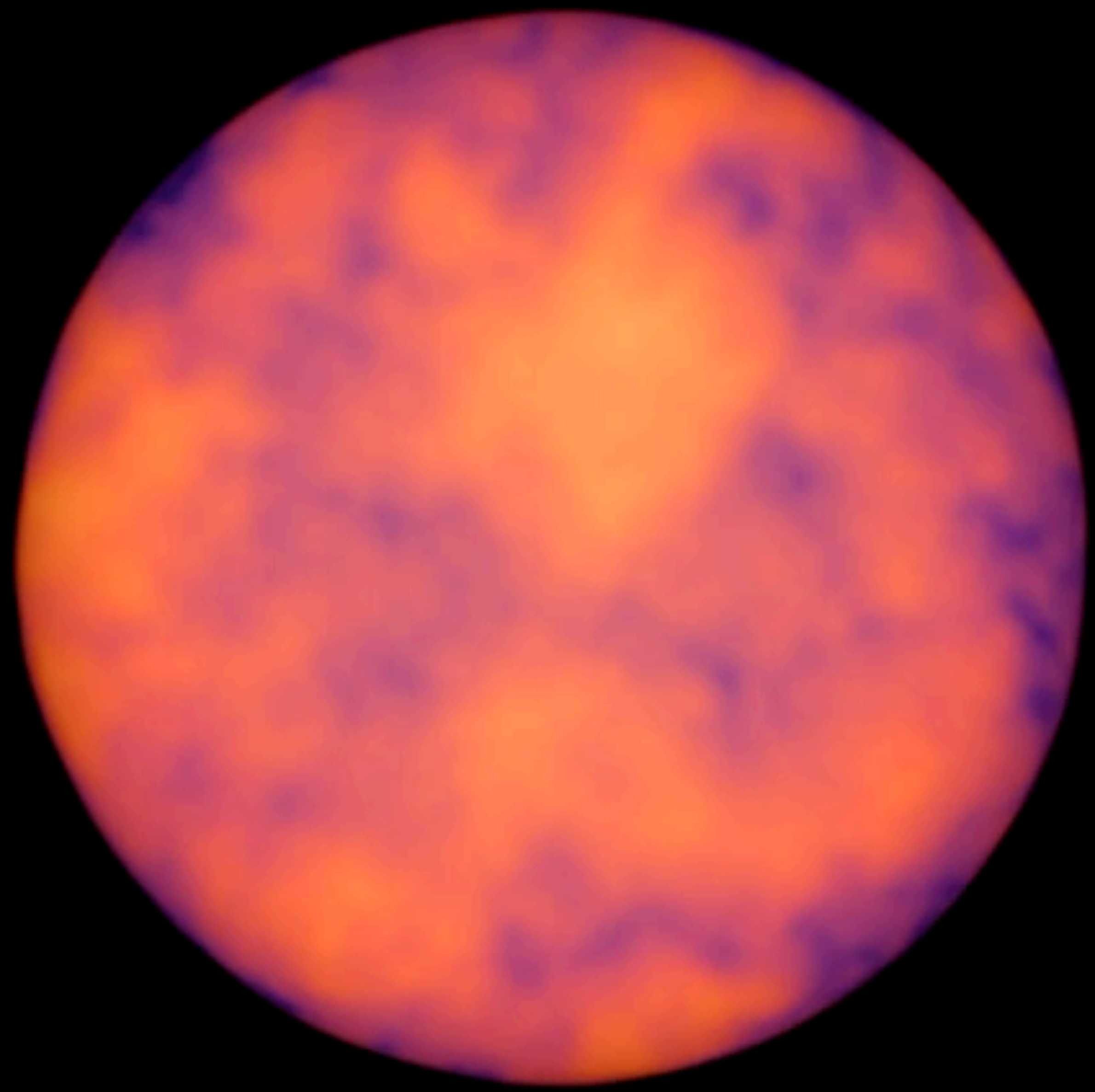
Solve to get λ_J:

$$\ell_J = \left(\frac{3\pi kT}{32Gm\rho}\right)^{1/2}$$

Set $M_J \sim \rho \ell_J^3$ to get the **Jeans mass**:

$$M_J = \frac{\pi^{3/2}}{8}\frac{c_s^3}{G^{3/2}\rho^{1/2}}$$

$$M_J = 6.9\ M_\odot \left(\frac{T}{10\ \mathrm{K}}\right)^{3/2}\left(\frac{n_{\mathrm{H}_2}}{10^8\ \mathrm{m}^{-3}}\right)^{-1/2}$$



Starforge collaboration: Grudic, Guszejnov et al.
https://starforge.space

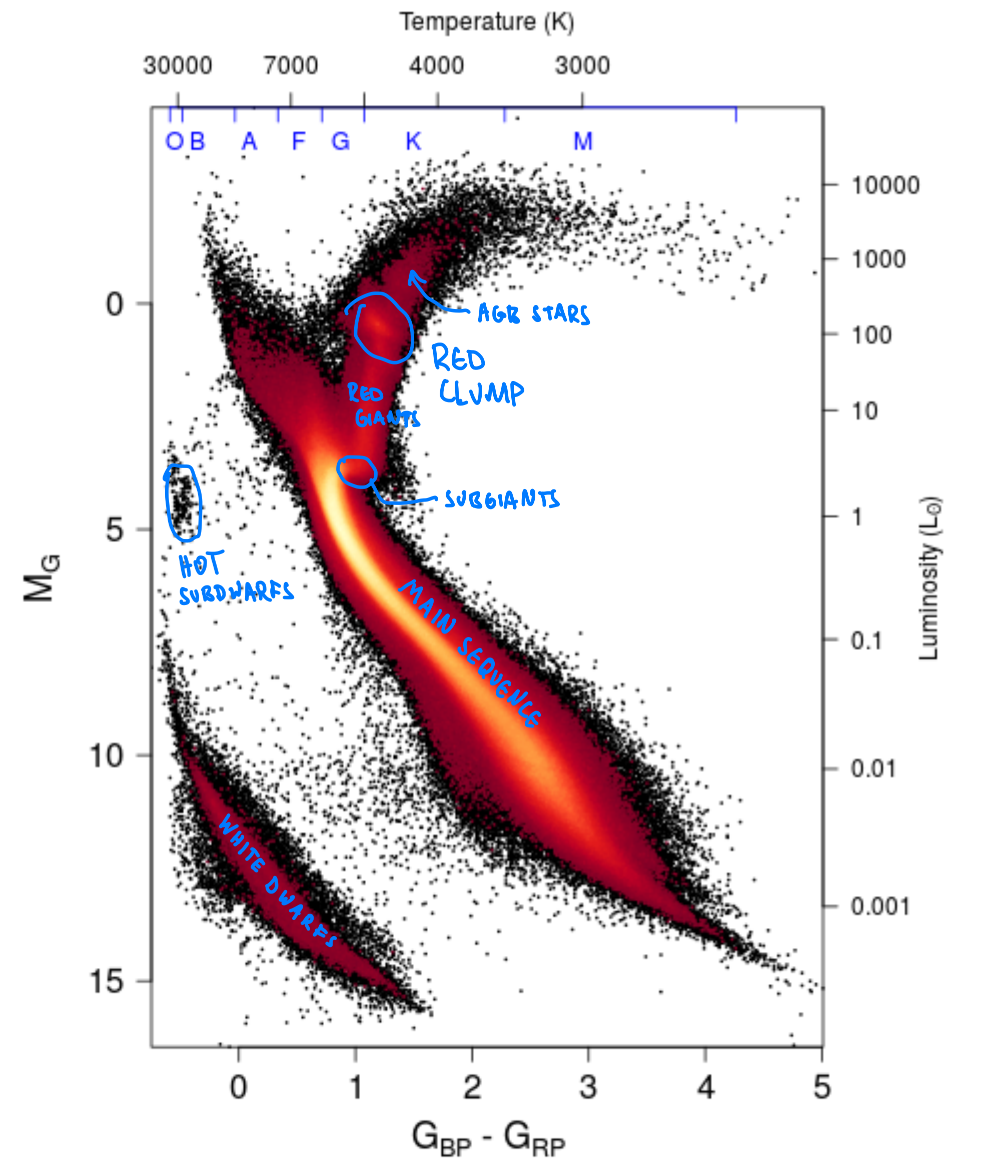
The Initial Mass Function

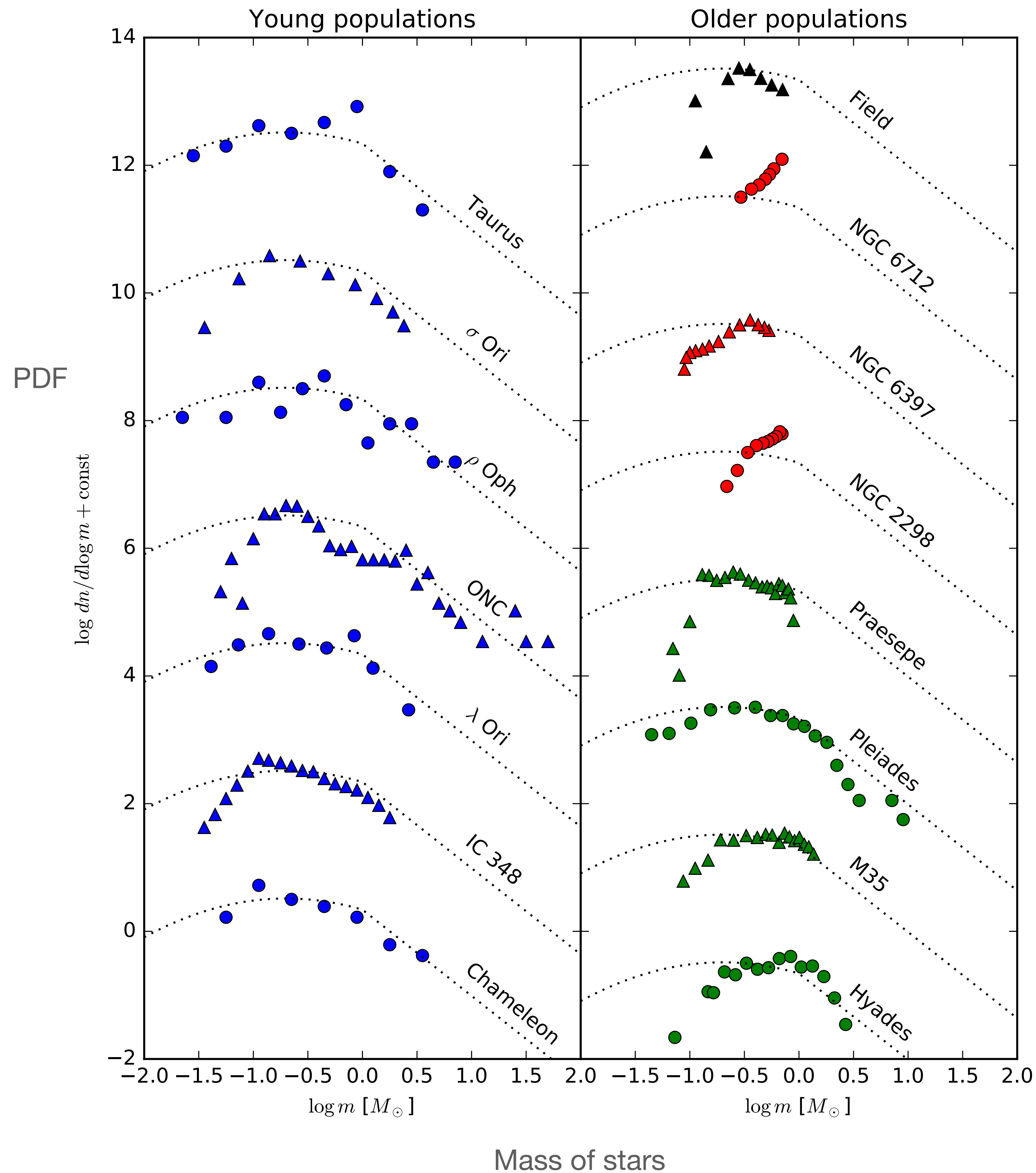
Functional forms of the IMF

"Field" stars affected by evolution

- High mass stars have died, low mass stars still here

Examine masses of stars in regions of star formation, all stars similar age!





Local initial mass functions are all similar (?!)

Bastian et al. (2010)

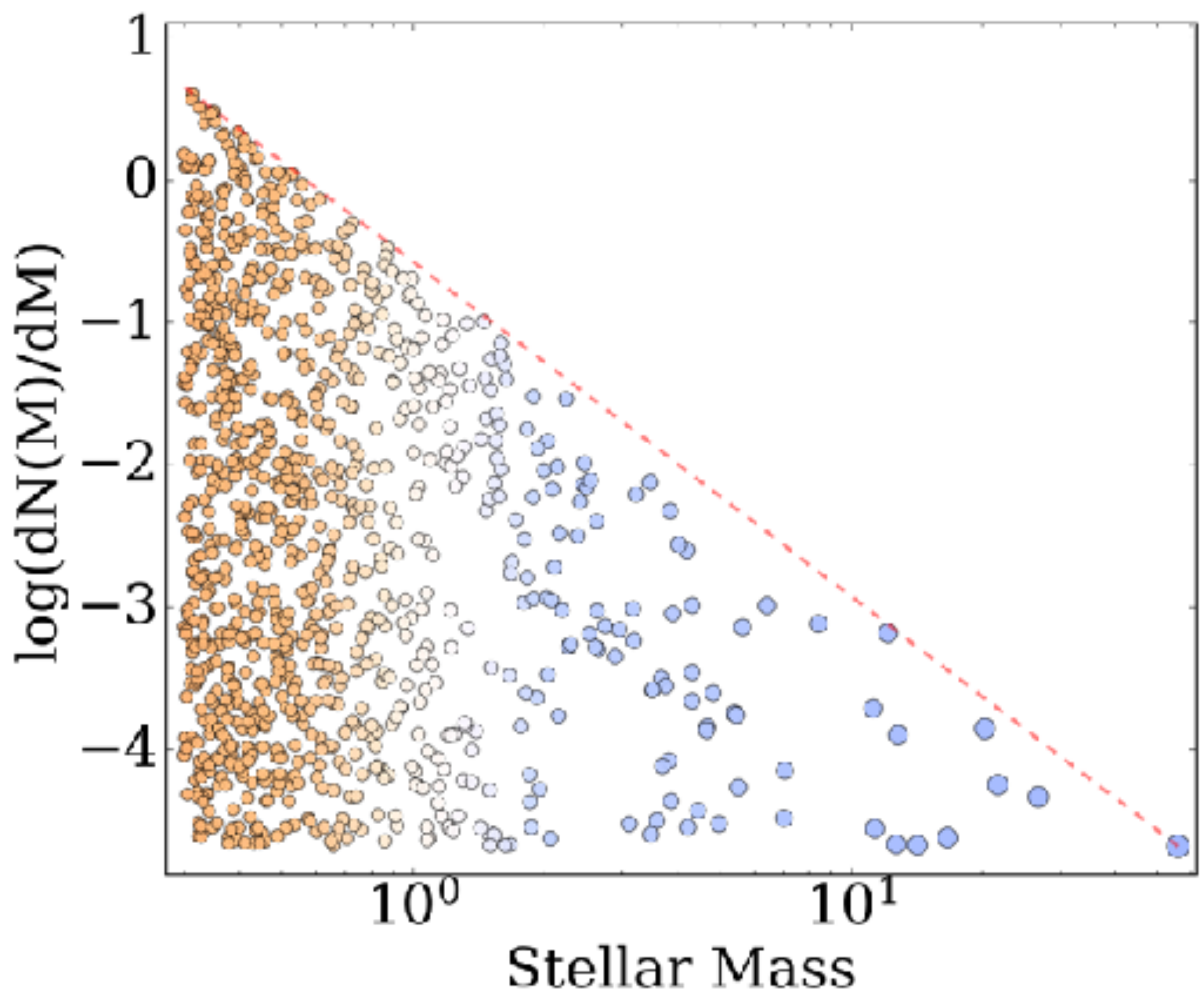
The Initial Mass Function

Functional forms of the IMF

Describe IMF with different functional forms. Simplest is **Salpeter** IMF:

$$\frac{dN}{d\mathscr{M}} = c_\star \mathscr{M}^{-2.35}$$

where $c_\star$ is a constant set by individual stellar formation event.

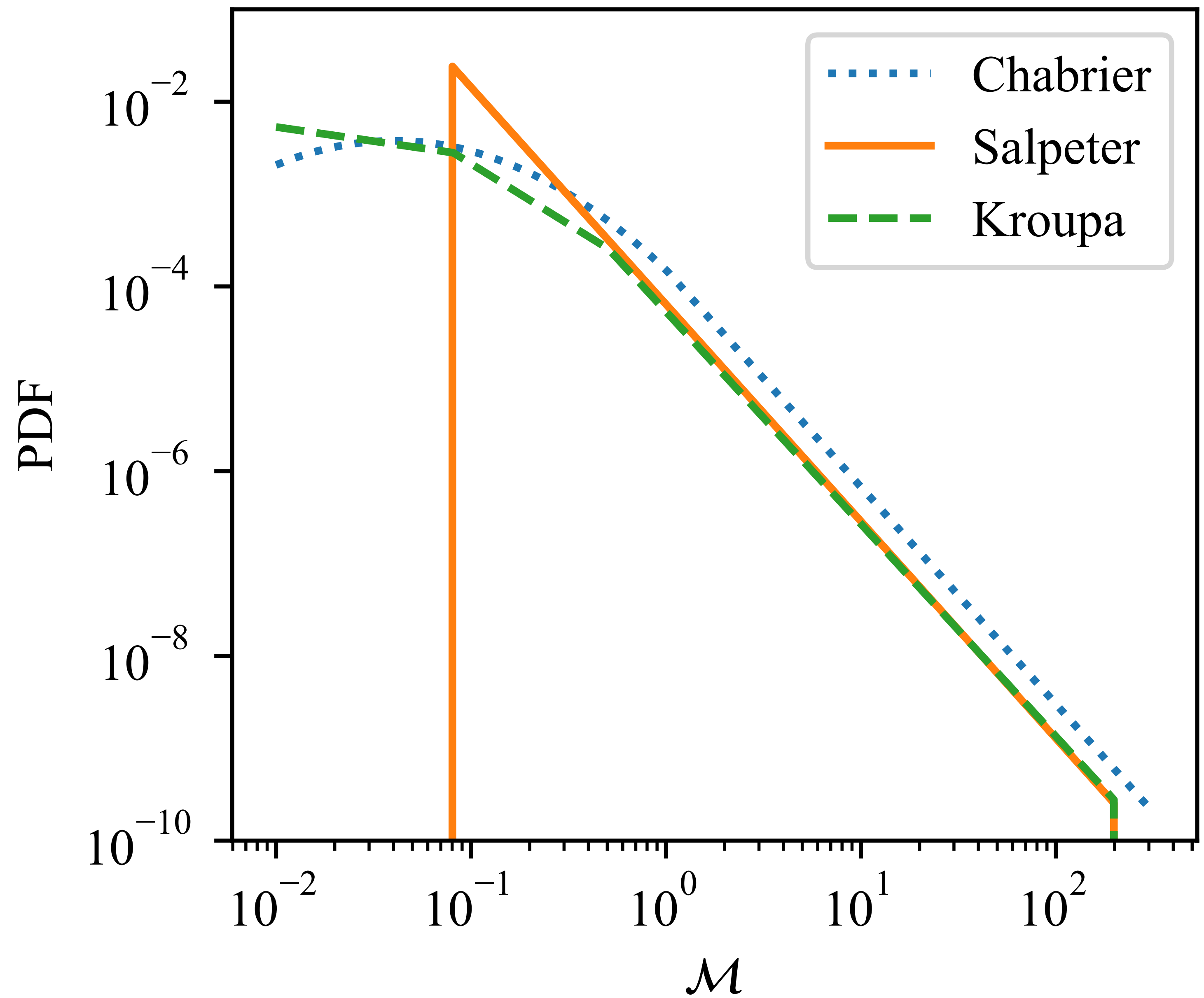


The Initial Mass Function

Functional forms of the IMF

Chabrier and Kroupa forms capture a turnover at low mass.

Open question: lowest mass objects made by SF?



Simple Stellar Populations

SSPs are a population of stars that

(1) formed at the same time from gas with

(2) the same metallicity.

Stars in SSPs have different masses.

Clusters are the classic example of SSPs.

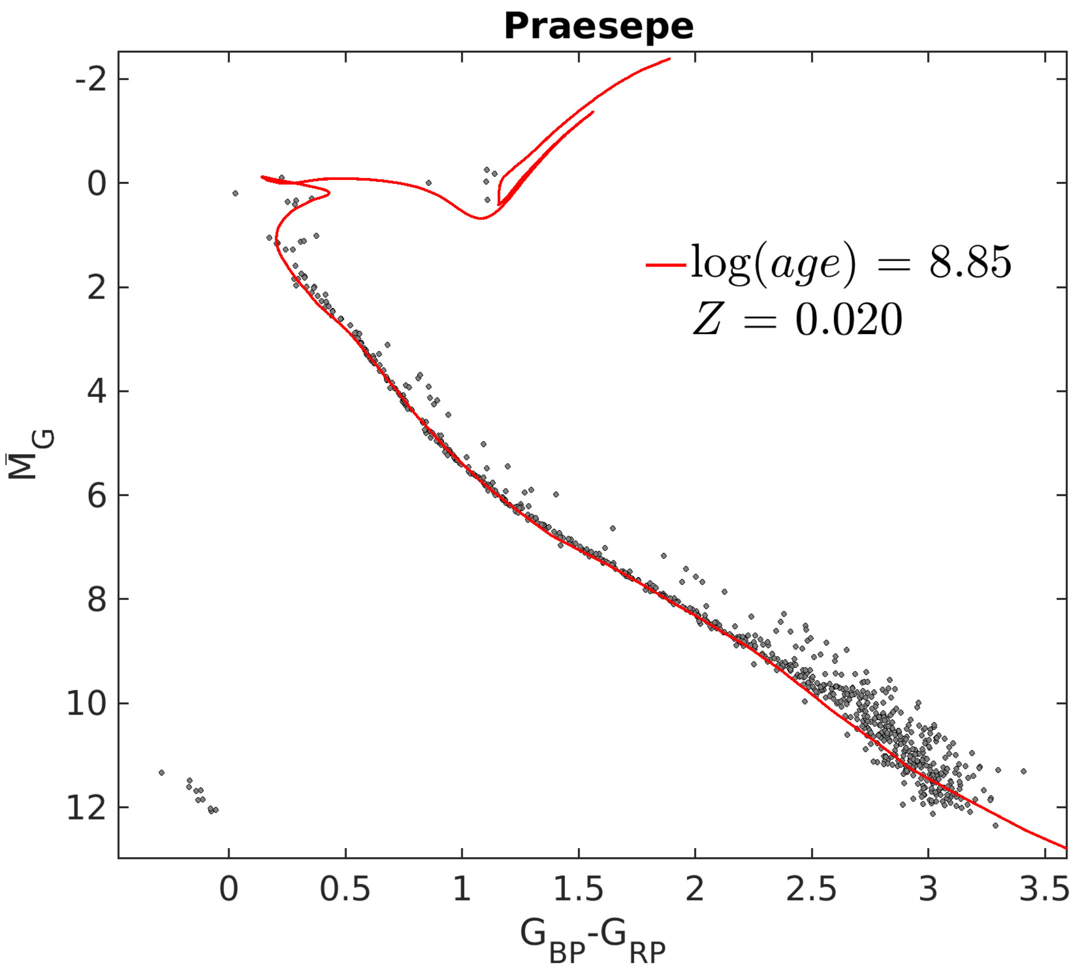
Praesepe (Beehive cluster)

Simple Stellar Populations

Isochrones

Stars evolve at different rates based on their mass.

Stars in SSPs fall along *isochrones* - locus of stars with different masses but **same age**



Gaia Collaboration et al. (2018)

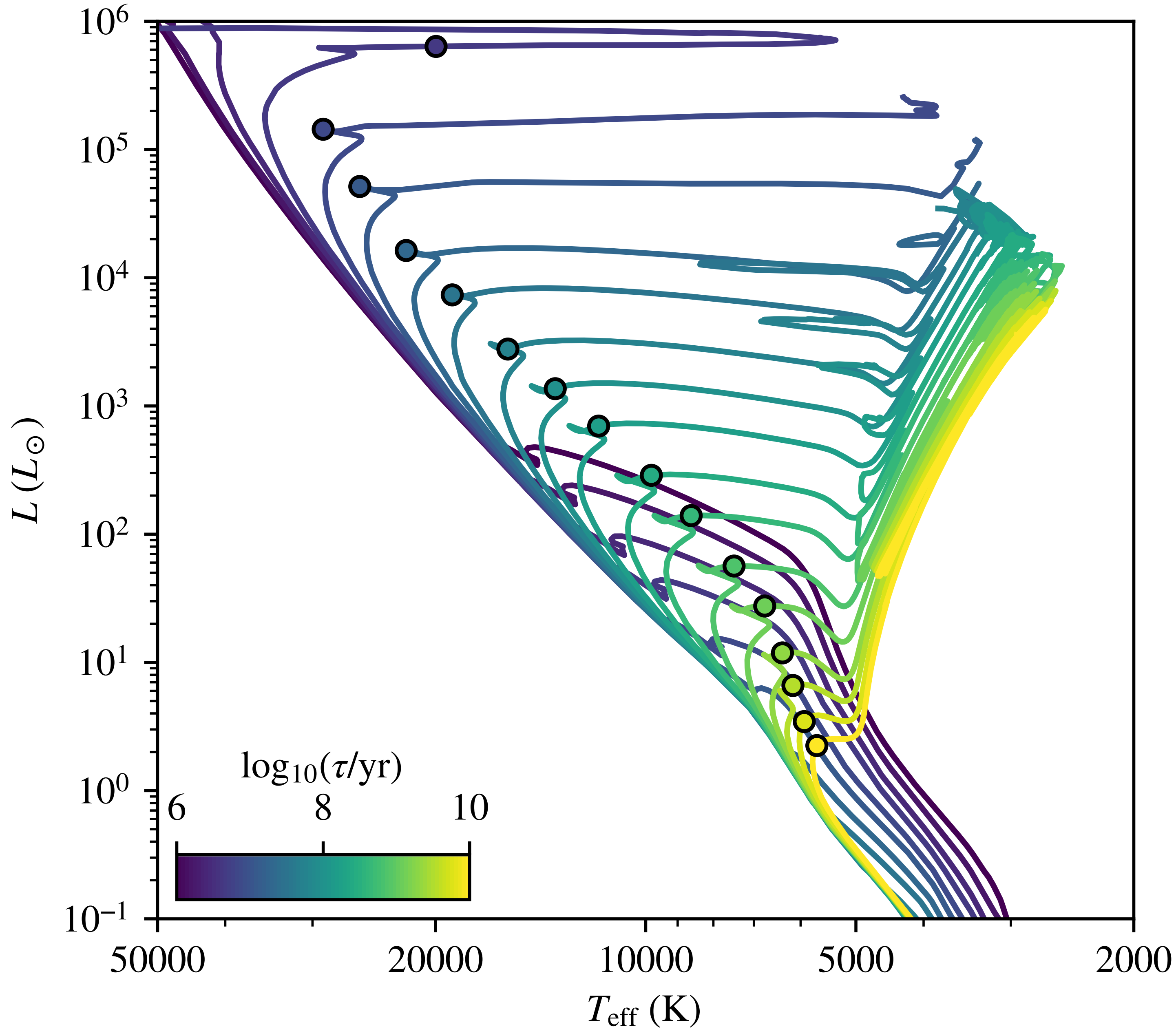
Simple Stellar Populations

Isochrones

Solar metallicity isochrones

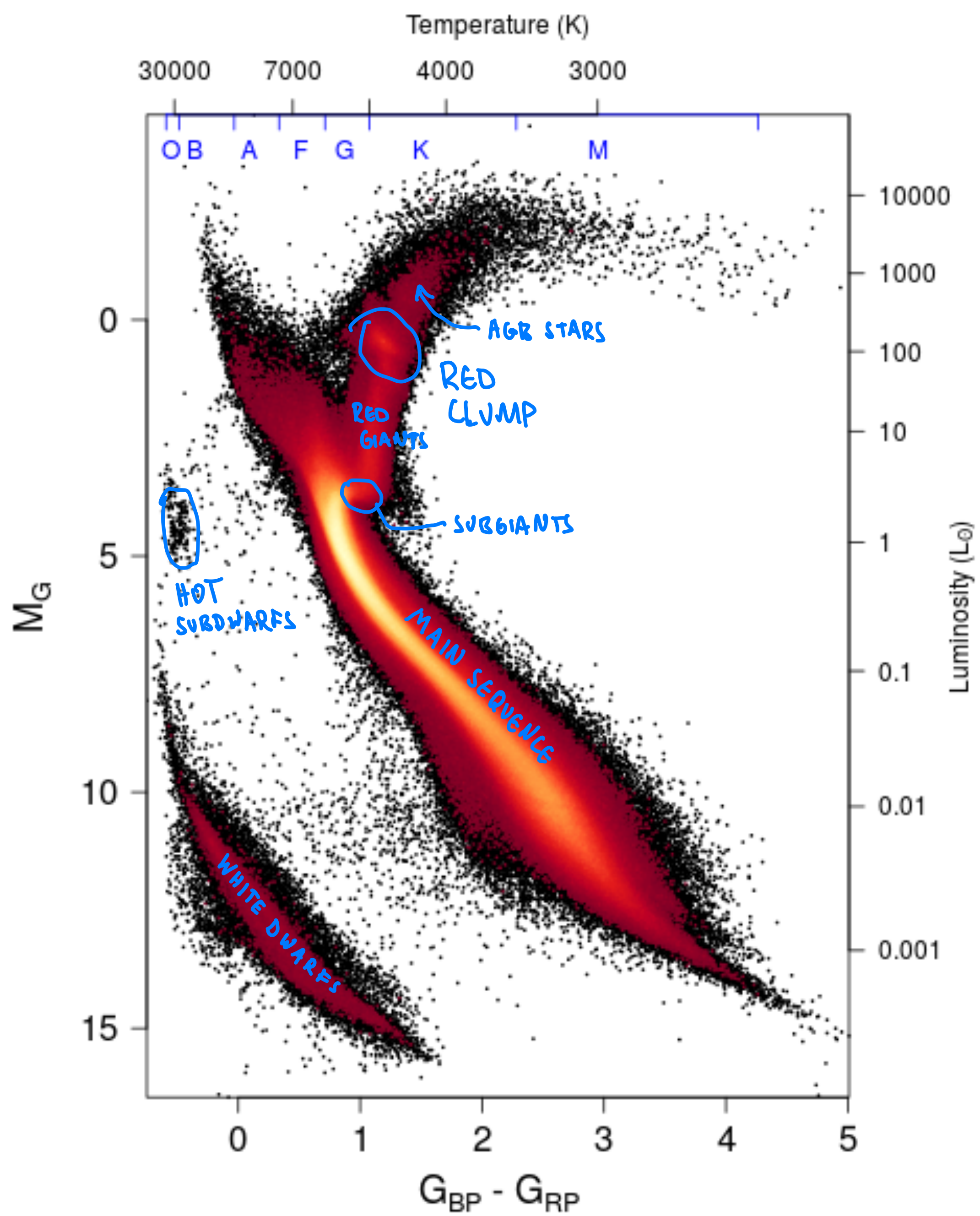
High mass stars evolve onto the MS faster than low mass.

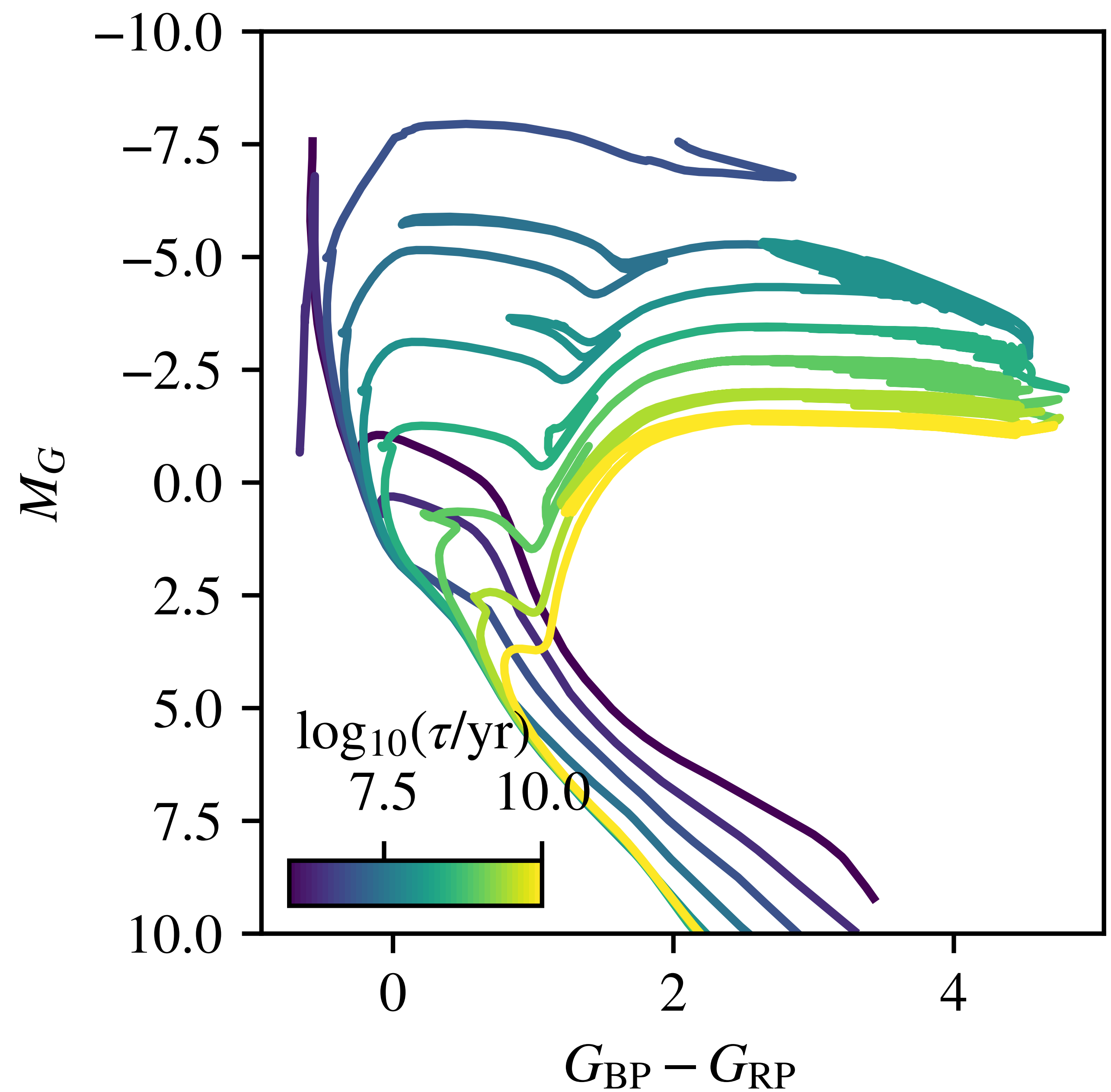
Main sequence turn off (MSTO) marked with •



Simple Stellar Populations

Isochrones

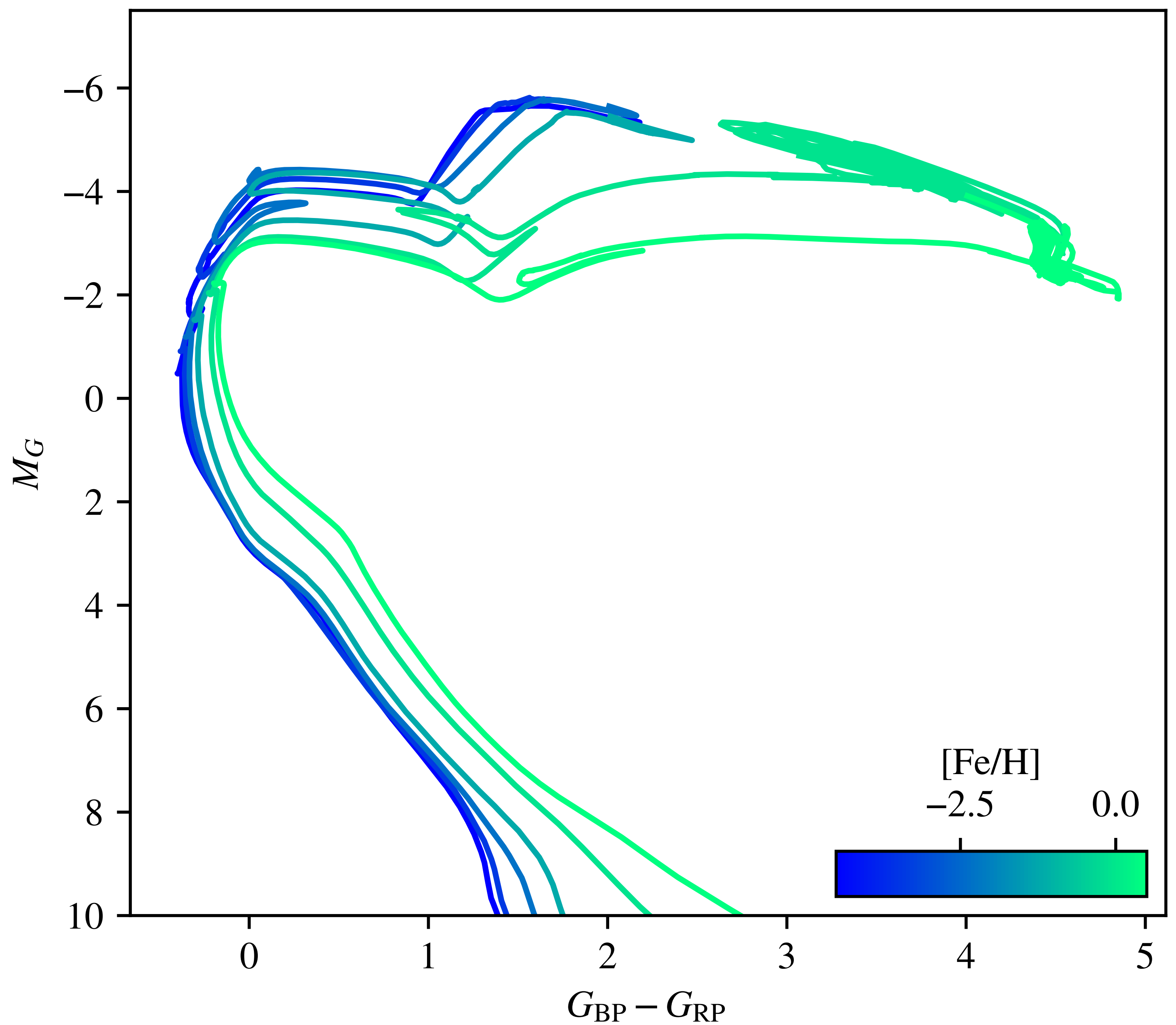




Match into isochrones into Gaia passbands

Simple Stellar Populations

Metallicity variation



Lower metallicity systems shifted in HR diagram

Gaia Data

Exercise 3

Select a cluster from the open cluster Gaia data.

Find an isochrone that's the best fitting representation of the cluster.

Simple Stellar Populations

Binary Stars

- Companion frequency:

$$\mathrm{CF} = \frac{N_{\star\ \mathrm{in\ multiples}}}{N_{\mathrm{systems}}}$$

e.g., Polaris is a “triple”

- Low mass ($M < 1\ M_\odot$) stars tend to be single.
- High-mass stars ($M > 10\ M_\odot$) tend to be twins. Otherwise, random draw from IMF.
- Nearly all multiples are coeval (formed together)

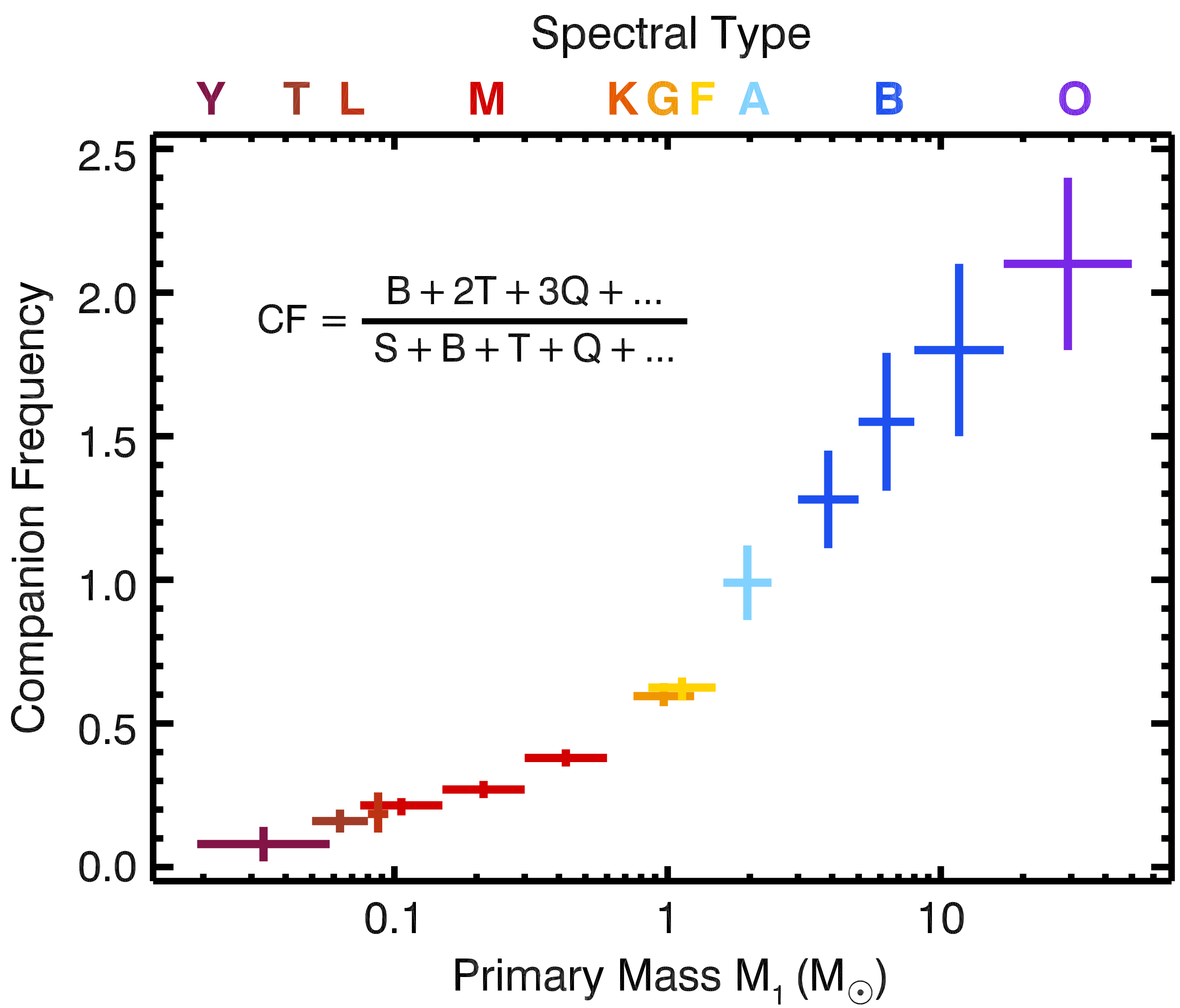


Figure from Offner et al. (2022)

Real Stellar Populations

Multiple stellar populations

Observational effects

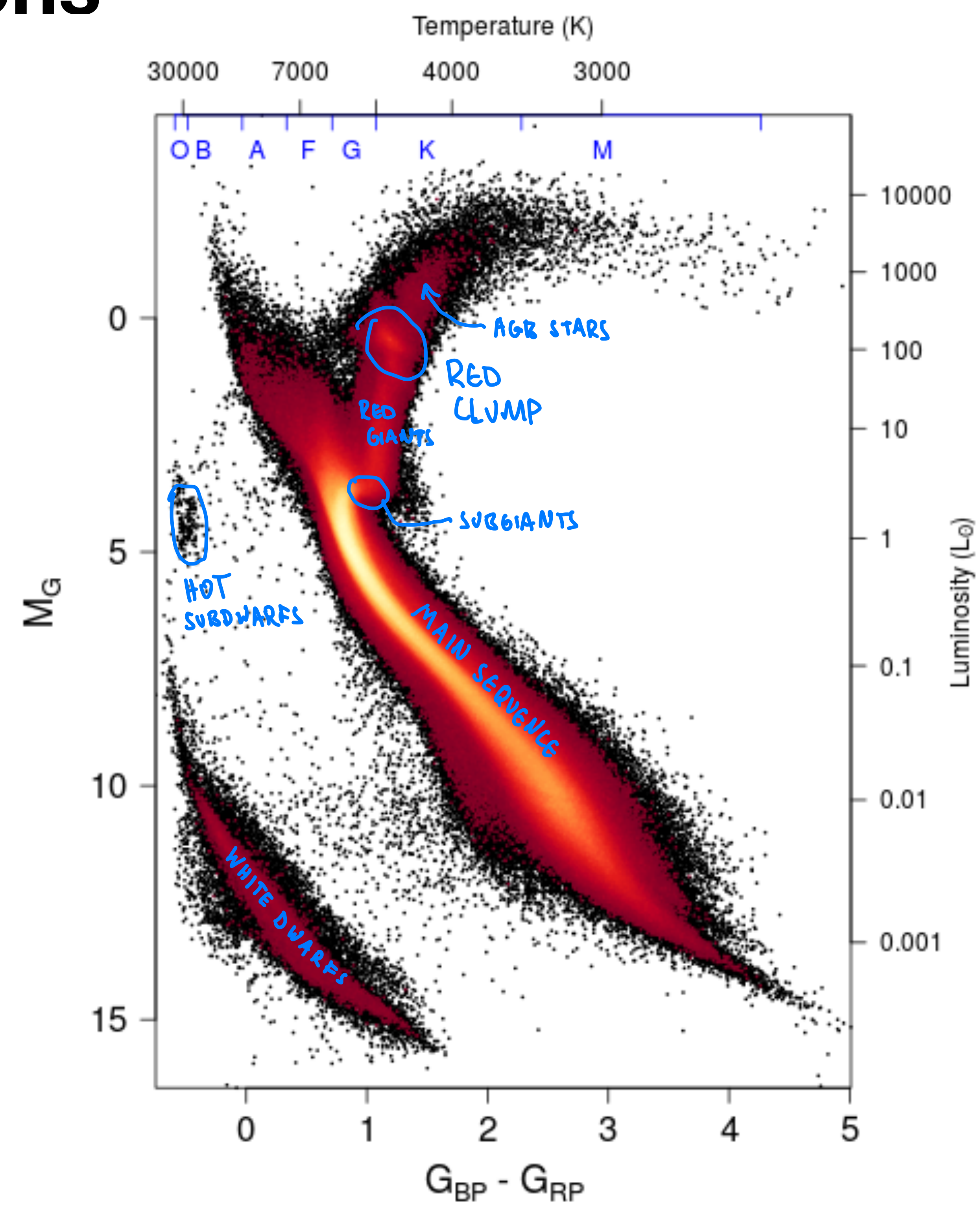
- Biases, numbers of stars

Dust

- Causes extinction and reddening

Non-simple populations

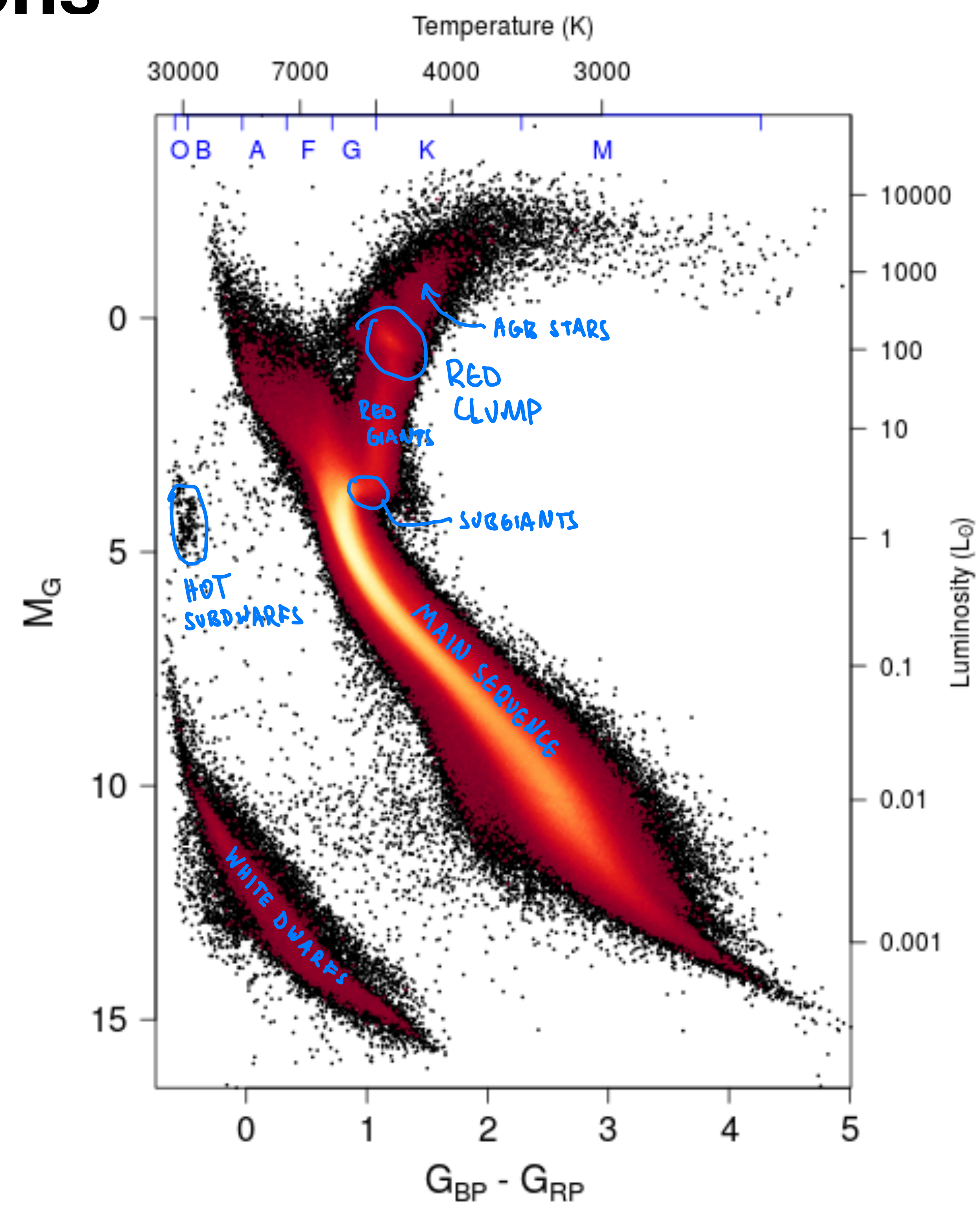
- Star formation history
- Metallicity varies with time and space



Real Stellar Populations

Multiple stellar populations

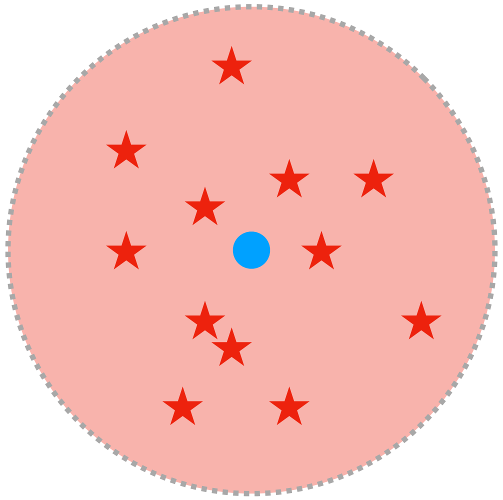
Why is the most common star in the Gaia sample of the HR diagram a sun-like star?



Real Stellar Populations

Multiple stellar populations

Luminosity bias - we can see more luminous objects over a larger volume than we can see faint objects.

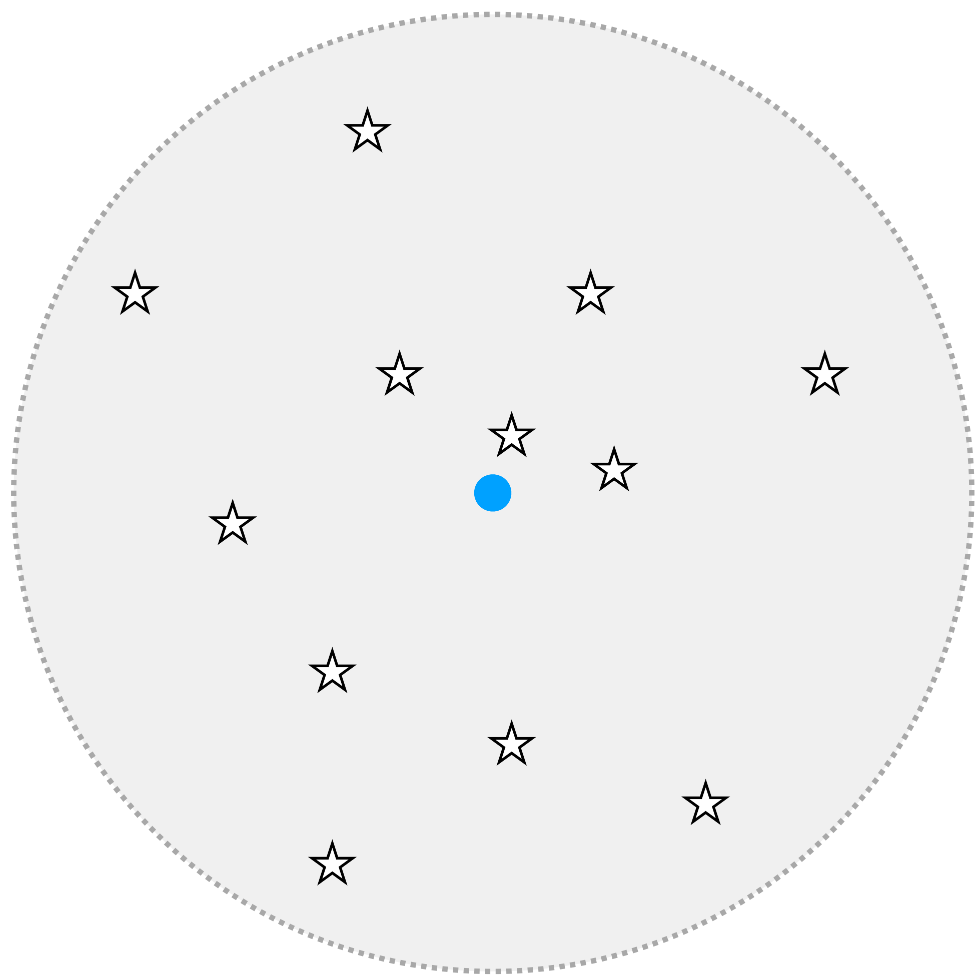


M0V stars

Real Stellar Populations

Multiple stellar populations

Luminosity bias - we can see more luminous objects over a larger volume than we can see faint objects.



V_{complete}

Volume over which a survey is *complete,* meaning we see all objects of that type.

A0V stars

Real Stellar Populations

Multiple stellar populations

The observed ratio of stars reflect three main factors:

$$\left(\frac{N_{\rm high}}{N_{\rm low}}\right)_{\rm observed} = \left(\frac{N_{\rm high}}{N_{\rm low}}\right)_{\rm formed} \left(\frac{\tau_{\rm high}}{\tau_{\rm low}}\right)\left(\frac{V_{\rm high}}{V_{\rm low}}\right)$$

1. The relative number of stars that are formed (IMF)
2. How long those stars live (stellar evolution)
3. How far away we can see those stars (observational effects)

Real Stellar Populations

Multiple stellar populations

For this example, the V_{complete} for the bright stars is $10^{12}\times$ larger than for the faint stars.

Overcomes rarity of high mass stars from IMF.

Short lifetimes of high mass stars will reduce their relative frequency.

Density of stars in HRD is a product of (1) observational selection (2) star formation history, and (3) lifetimes of stars at that stage.

Real Stellar Populations

Dust

Interstellar dust is mixed throughout the neutral gas in the Galaxy. The effect of dust:

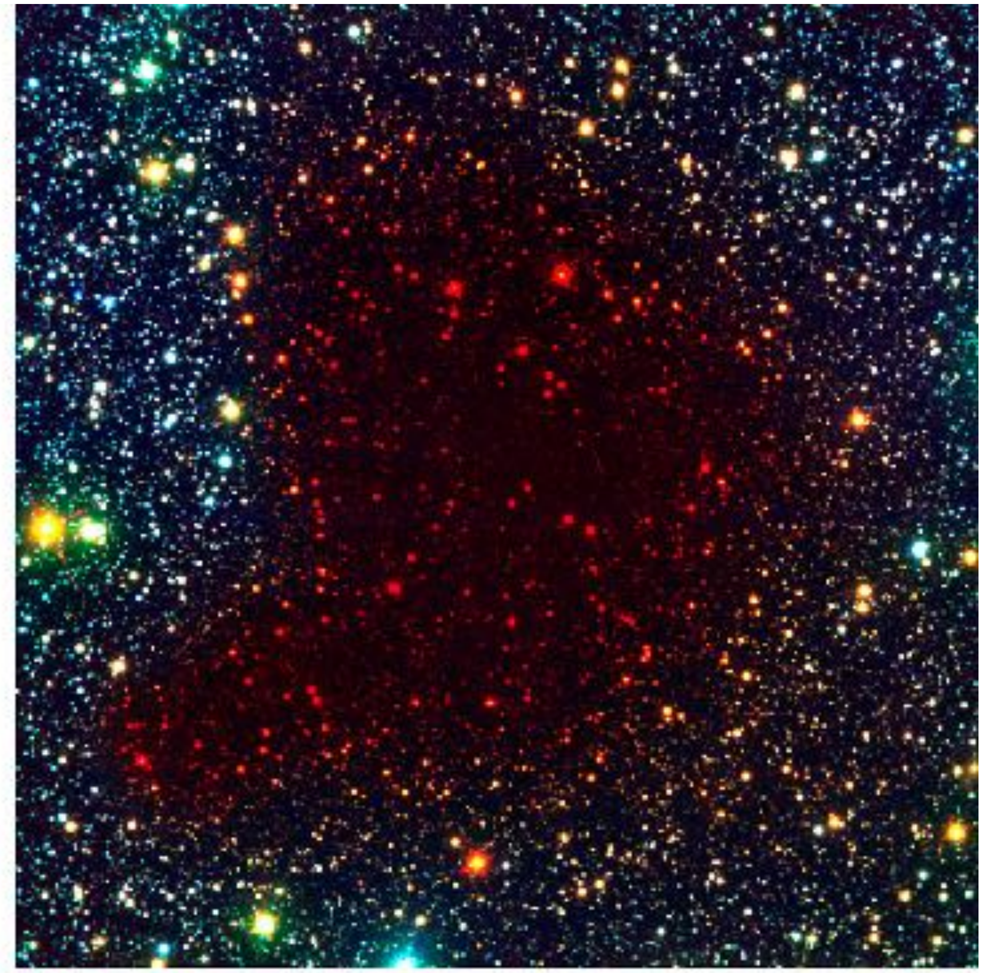
(1) blocks optical light

(2) blocks bluer light more than red light

(3) reradiates absorbed light in the infrared

B, V, I

Optical-only image



Optical + Infrared (in red) band

B, I, K

Long wavelength observations can “see through” the dust to embedded or background sources.

Image credit: ESO

Real Stellar Populations

Dust

$\tau_\lambda \equiv n\sigma\ell$ is the *optical depth*

We usually represent the extinction in the magnitude system using the variable *A*.

$$A_\lambda = 1.086\tau_\lambda$$

Real Stellar Populations

Cross sections

Cross section is a general concept:

$$\sigma = \frac{N_{\rm coll}/N_{\rm targets}}{N_{\rm incident}/A}$$

where $N_{\rm coll}$ is the number of collisions per number of targets $N_{\rm targets}$, and $N_{\rm incident}$ is the number of particles passing through a total area A.

When $\sigma = \pi r^2$, this is the geometric cross section.

Example: Imagine a long hallway with 70 watermelons suspended from the ceiling at different heights and random positions. The hallway has a cross sectional area of 10 m^2. You stand at one end a fire 100 bullets down the hall with your trusty physics lab issued AK-47. Because of excessive recoil and perhaps some liquor before you headed down to do physics, your shots are essentially randomly shot down the hallway. You count a total of 35 exploded watermelons after the storm of bullets. What is the cross section of a watermelon?

Real Stellar Populations

Reddening

Reddening occurs because $A_{\lambda_1} > A_{\lambda_2}$ if $\lambda_1 < \lambda_2$ (dust blocks blue light better than red light).

Specifically, dust blocks like with $\sigma_\lambda \propto \lambda^{-1}$ and scatters light with $\sigma_\lambda \propto \lambda^{-4}$.

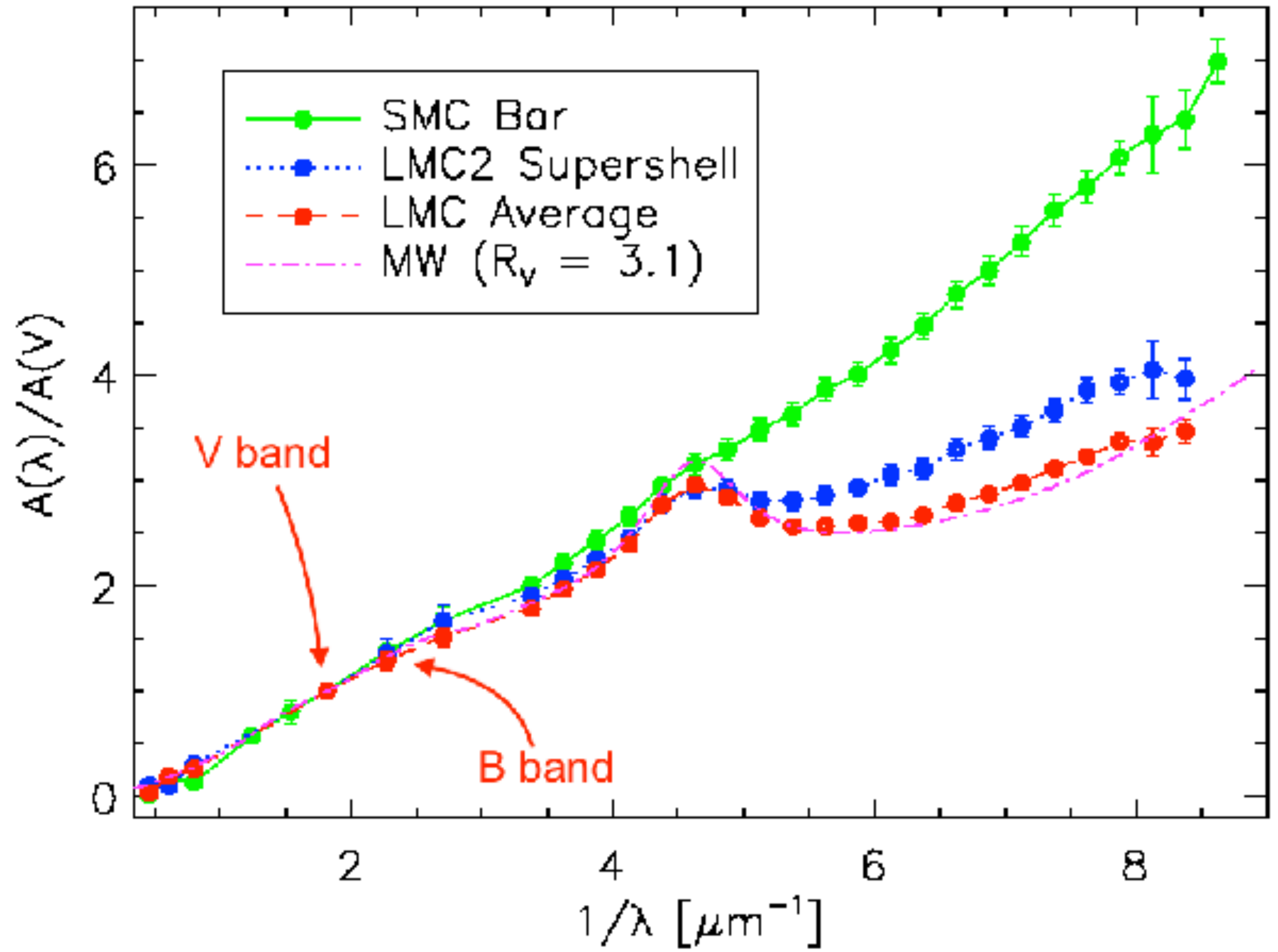
Real Stellar Populations

Reddening Curve

Compare extinction to a reference waveband. Usually the *V* band at $\lambda = 550\ \mathrm{nm}$

The *reddening* value is usually given as

$$R_V = \frac{A_V}{A_B - A_V} \approx 3.1$$



K. Gordon based on Gordon et al. (2003)

Real Stellar Populations

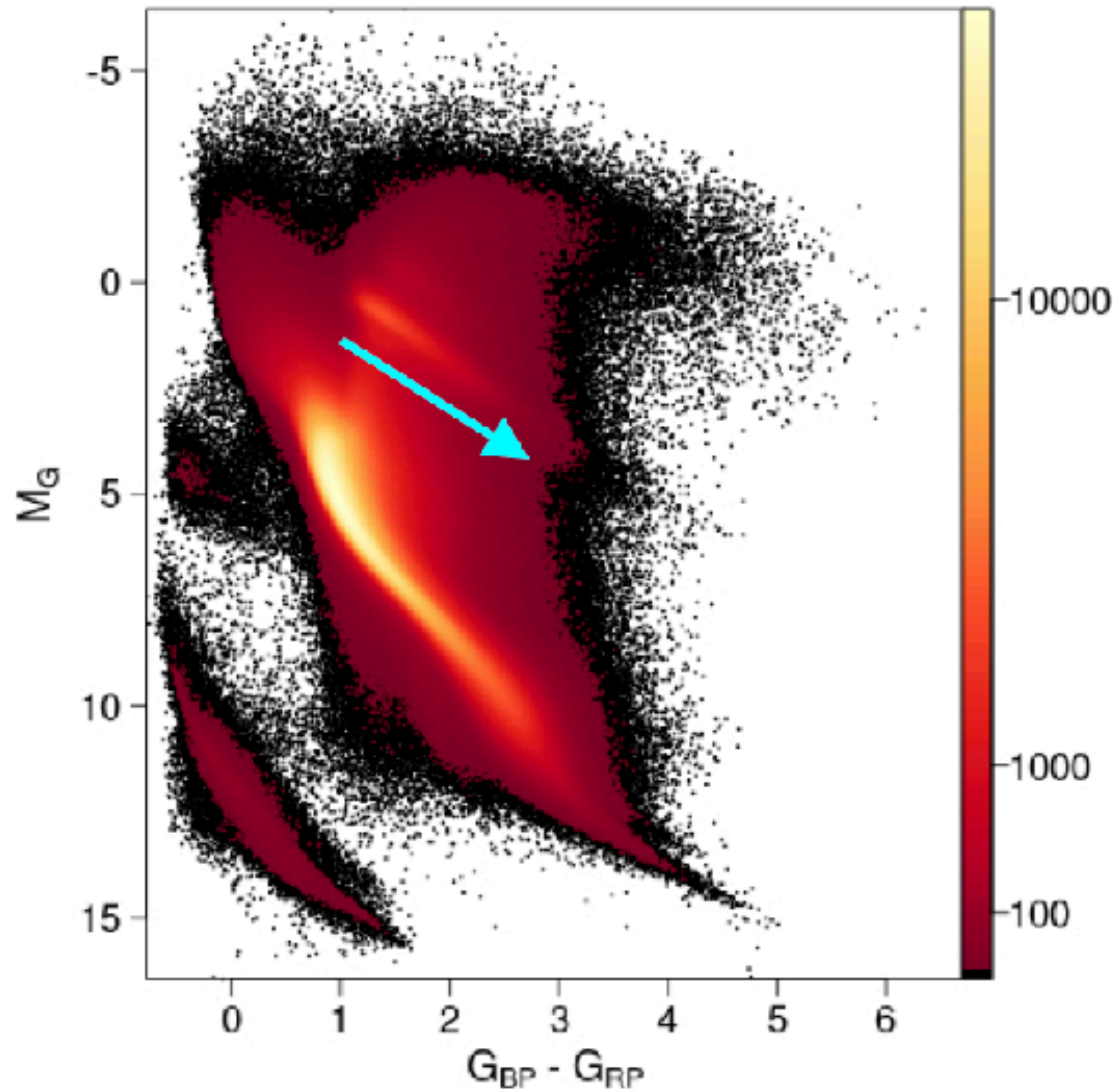
Reddening Vector

The slope of reddening relative to extinction shows up in the HR Diagram.

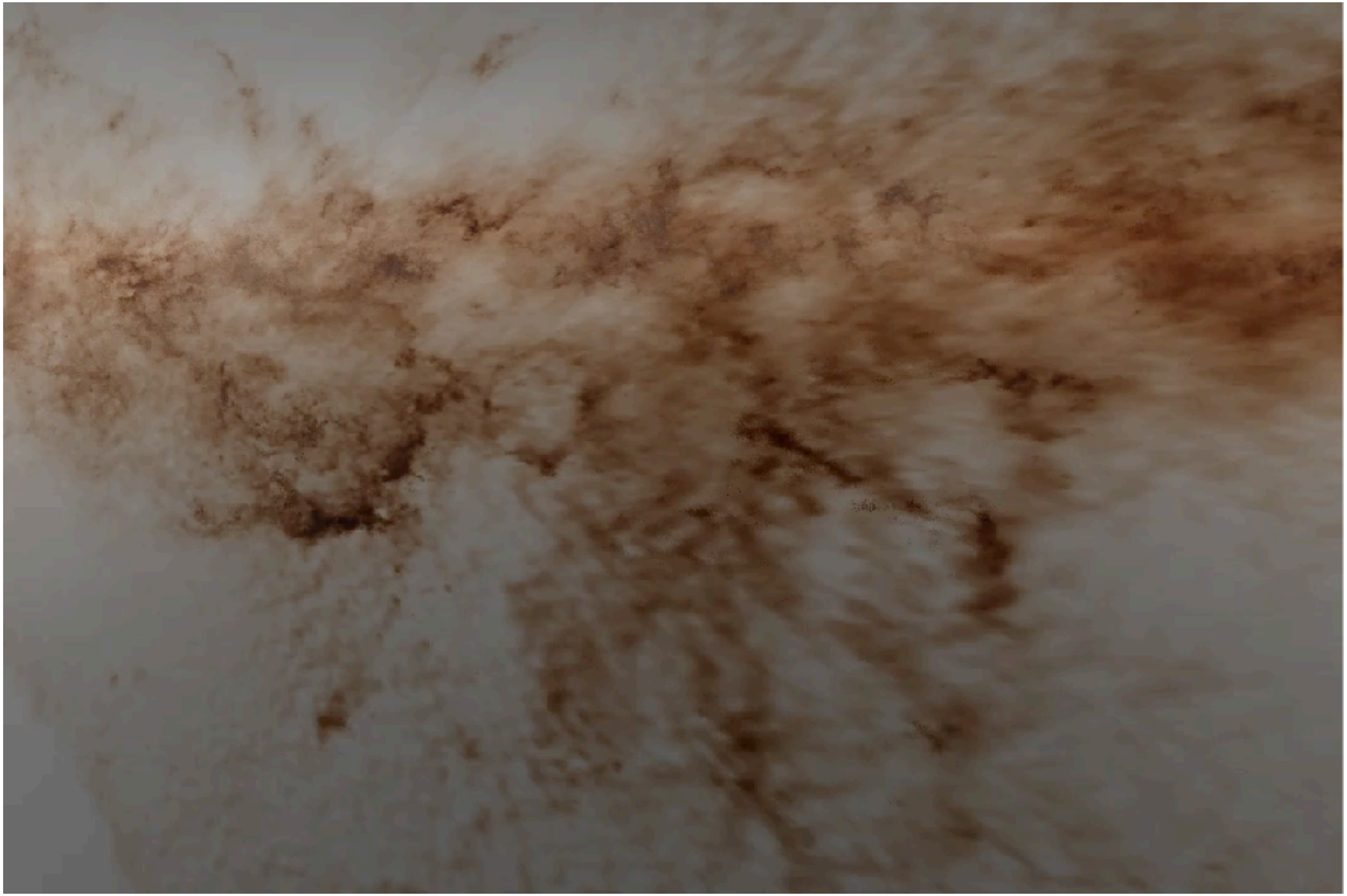
For Gaia:

$$R_G \approx \frac{A_G}{A_{\mathrm{BP}} - A_{\mathrm{RP}}} \approx 1.8$$

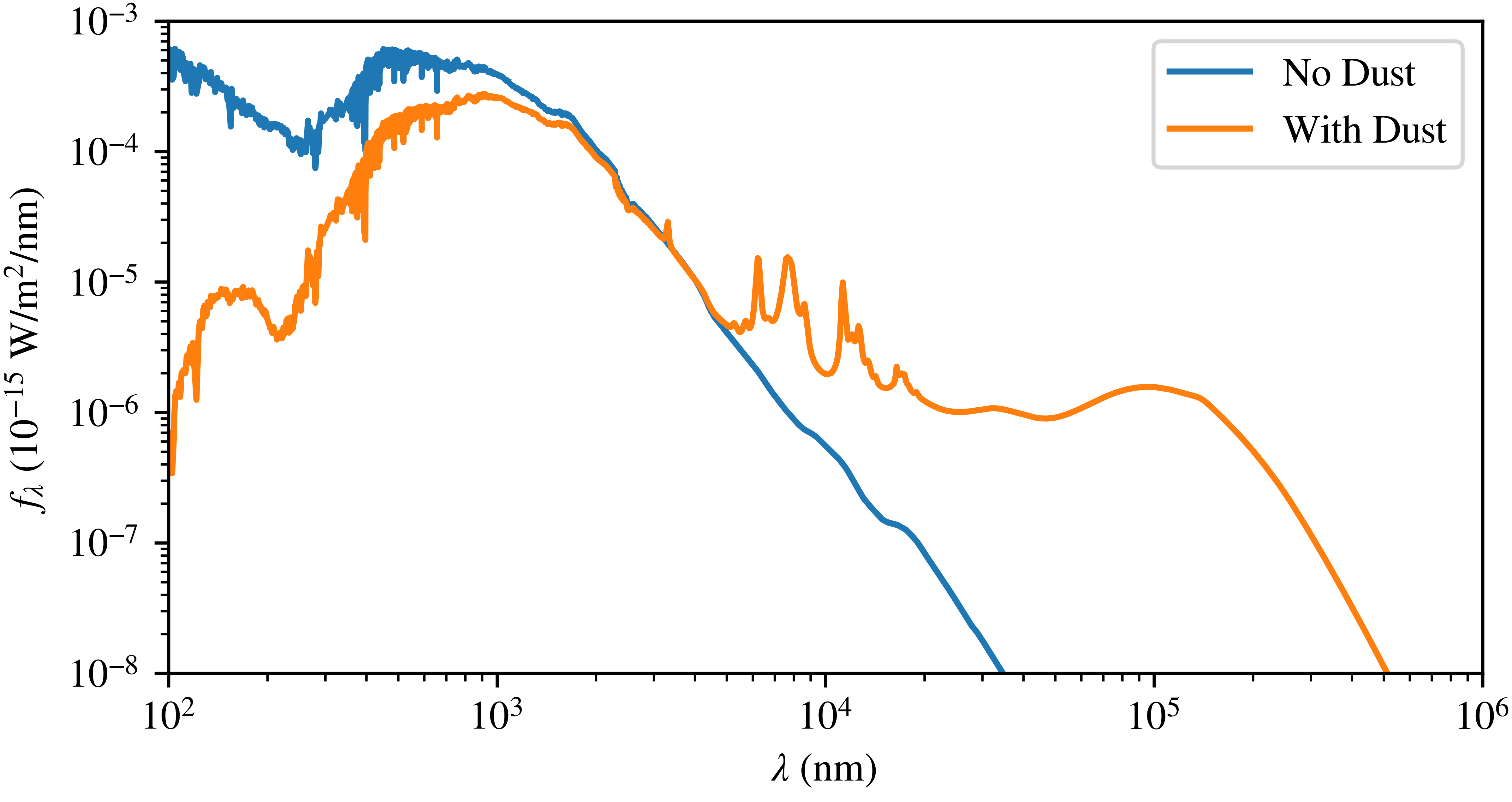
Note how red clump is "smeared" out. Bigger displacement = Bigger reddening.



Gaia Collaboration (2018)



Green et al. Dust mapping with PanSTARRS
http://argonaut.skymaps.info/



No Dust
With Dust
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
f_λ (10^{-15} W/m^2/nm)
10^2
10^3
10^4
10^5
10^6
λ (nm)

Real Stellar Populations

Star Formation Histories

Predict the density of stars in the HR Diagram

Set by the $\dot{M}_\star(t)$, also known as star formation rate, SFR.

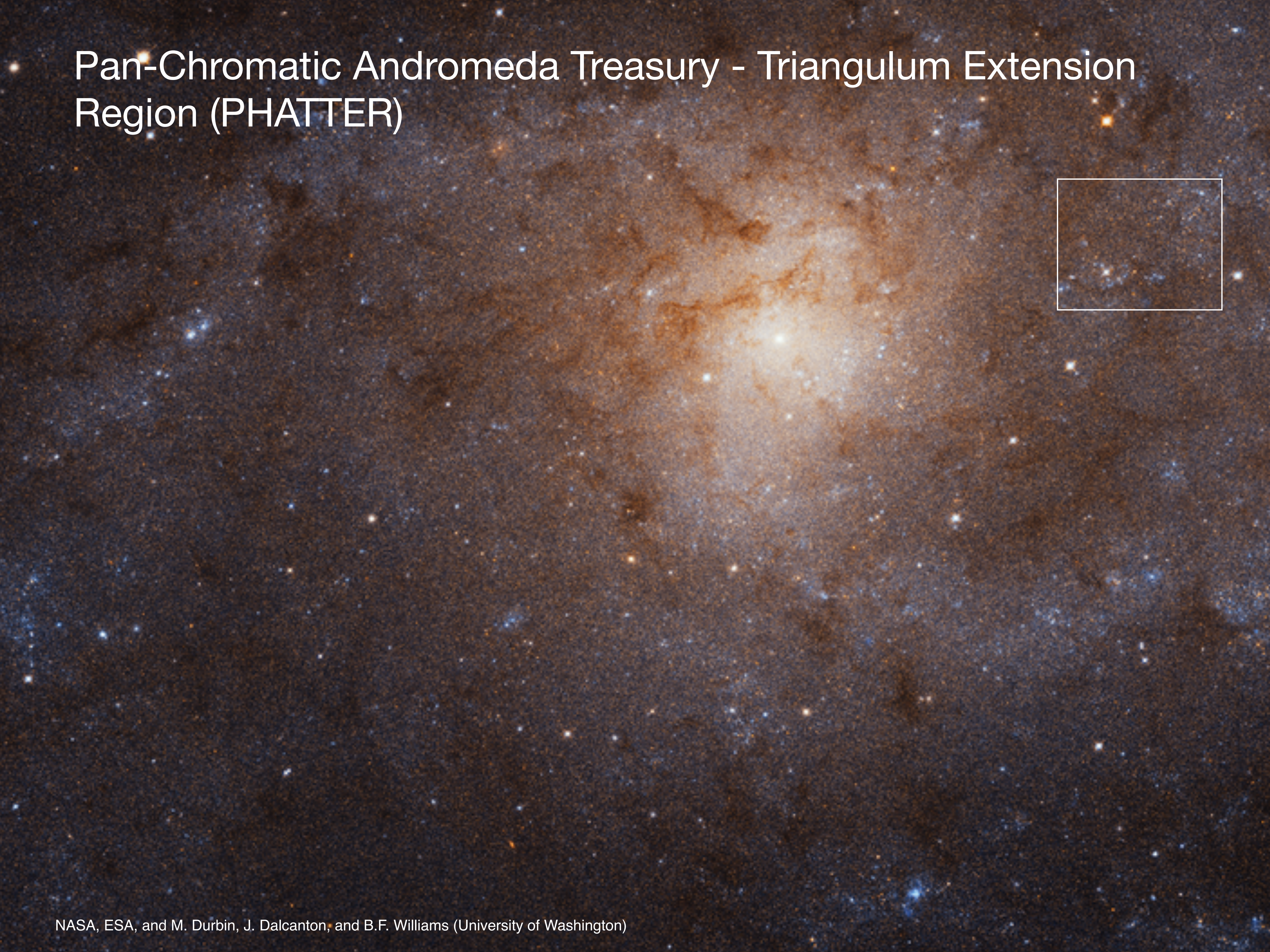
Number of stars on MS at mass *M* is

$$N_{\star,M} = f_M \int_0^{t_{\rm stop}} \dot{N}_\star dt = f_M \int_0^{t_{\rm stop}} \frac{\dot{M}_\star}{\langle M \rangle} dt$$

Where $t_{\rm stop}$ is smaller of MS lifetime or age of Universe

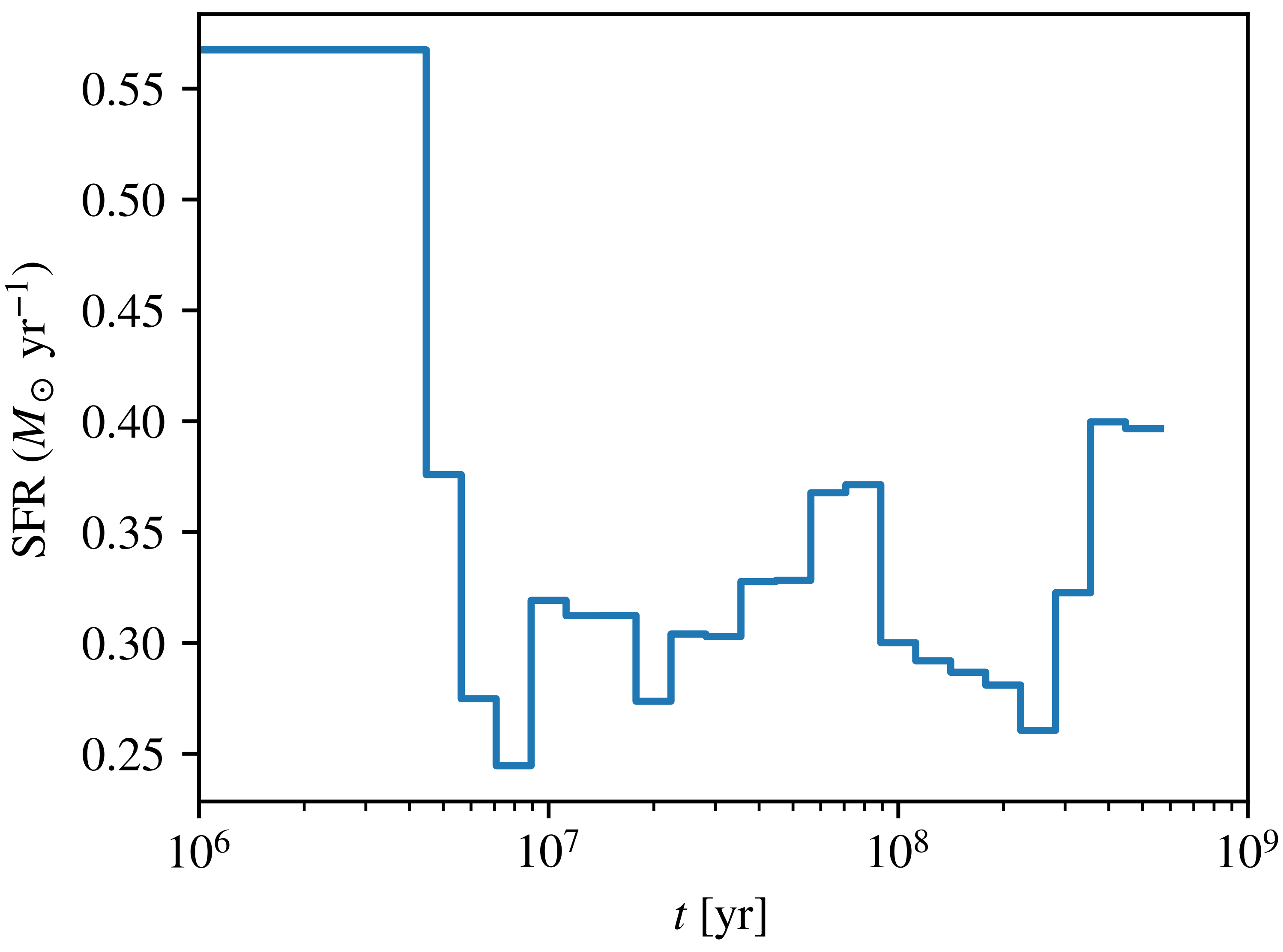
Able to Infer SFR vs time

Pan-Chromatic Andromeda Treasury - Triangulum Extension Region (PHATTER)

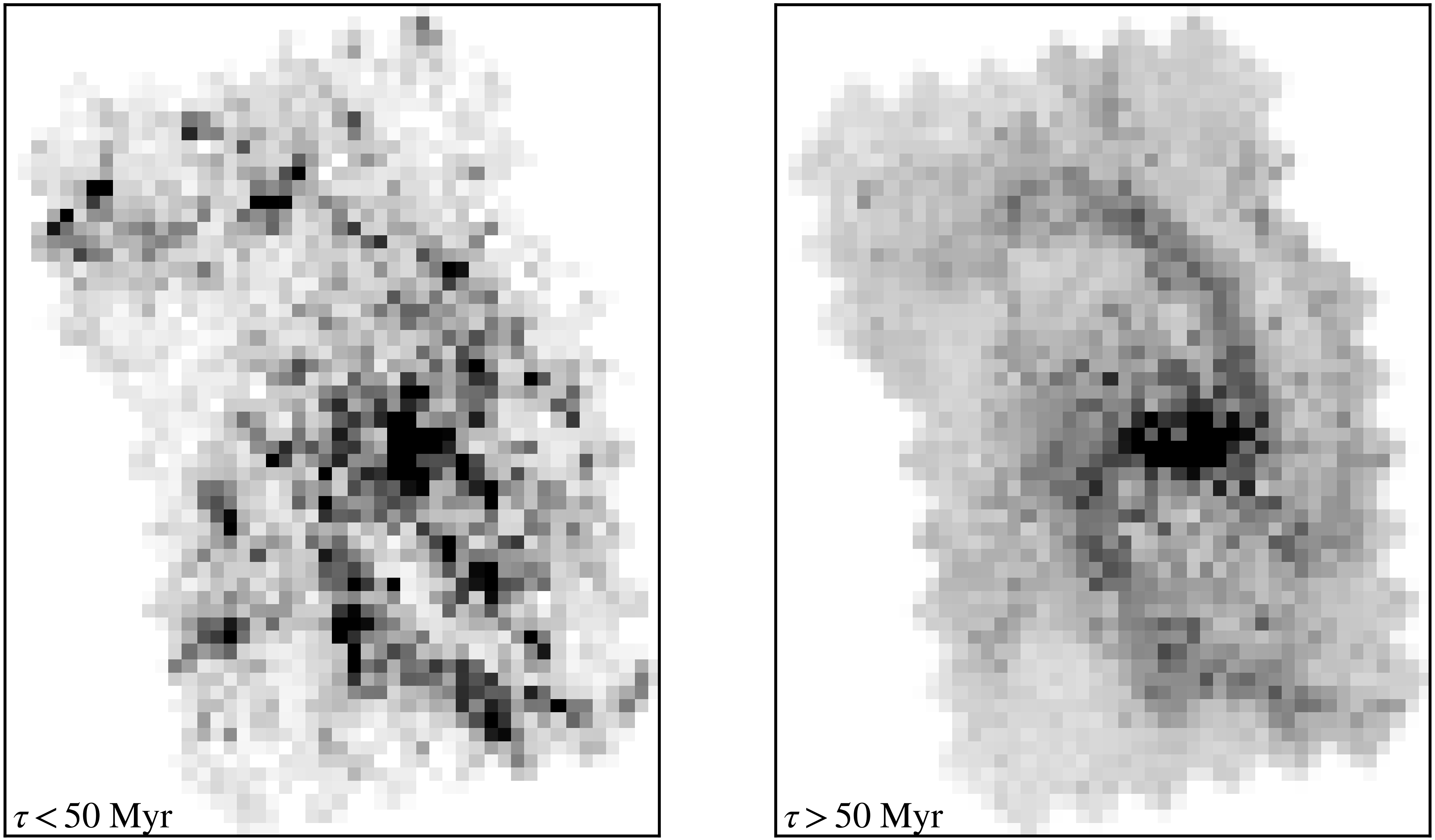


NASA, ESA, and M. Durbin, J. Dalcanton, and B.F. Williams (University of Washington)

Star density on HR diagram gives us ability to reconstruct SFH of a galaxy.



SFH of M33
Lazzarini et al. (2022)



SFH of M33
Lazzarini et al. (2022)

Gaia Data

Exercise 4

Use the gaia_field_stars.csv file from eClass and Glue to make a plot of the HR diagram of stars. Your HR diagram should colour each star by its extinction value AG

Use the values of A_{G} and $E(BP - RP)$ in the data file (ag_gspphot and ebpminrp_gspphot respectively) to make a new HR diagram with each star's position corrected for extinction and reddening.

Make a plot of *E(BP–RP)* as a function of galactic latitude *b*.Explain the feature you see in this plot.

Gaia Data

Exercise 4

Plot an extinction-and-reddening-corrected HR diagram, and calculate the mean distance from the midplane of the Galactic coordinate systems for red clump stars $\langle z_{\rm gal} \rangle$.

Using the same HR diagram, plot a histogram of the differences in heights of the red clump stars from this average value $z_{\rm gal} - \langle z_{\rm gal} \rangle$.

Estimate the scale height *H* of the red clump stars by calculating the standard deviation of $z_{\rm gal}$ for that subset of stars.

Using a similar approach as in the previous problem, calculate the scale height for massive main sequence stars with $BP - RP < 0.5$. Compare your result to the previous problem and explain why these answers should be different.