

## Feedback: the effect of massive stars

**Stellar winds:** radiation pressure from O and B stars drives energetic outflows of gas from the stars.

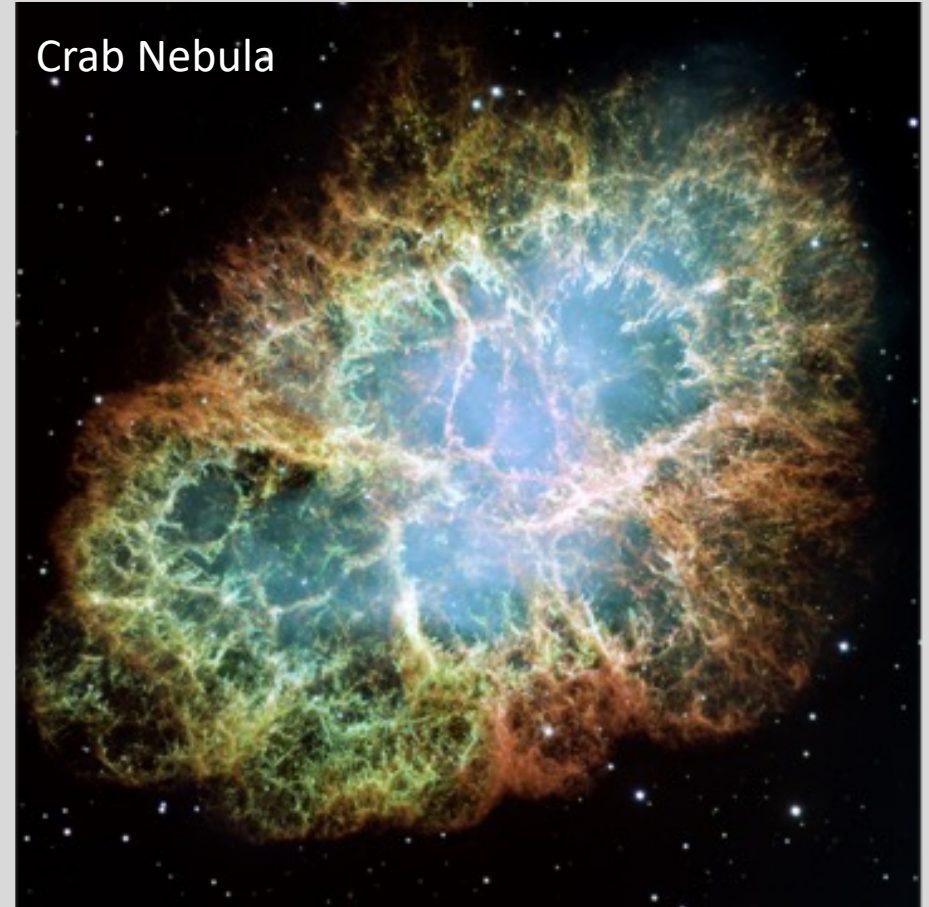
**Supernovae:** stars  $\gtrsim 9M_{\odot}$  go supernovae.

Together, these dump  $\approx 10^{53.5}$  erg *per star* into the surrounding ISM, heating the gas and driving shocks and outflows.

LL Orionis



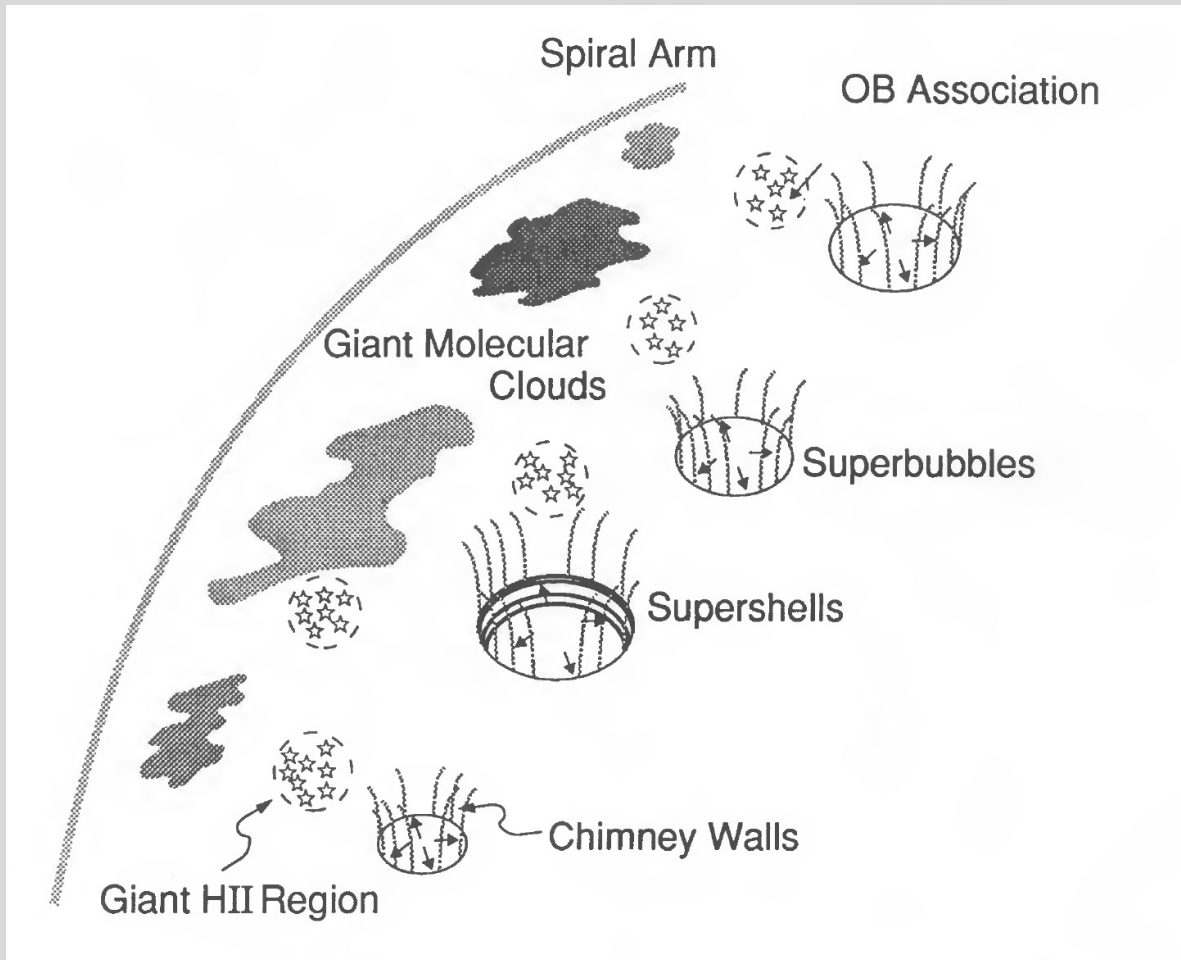
Crab Nebula



# Feedback: the effect of massive stars

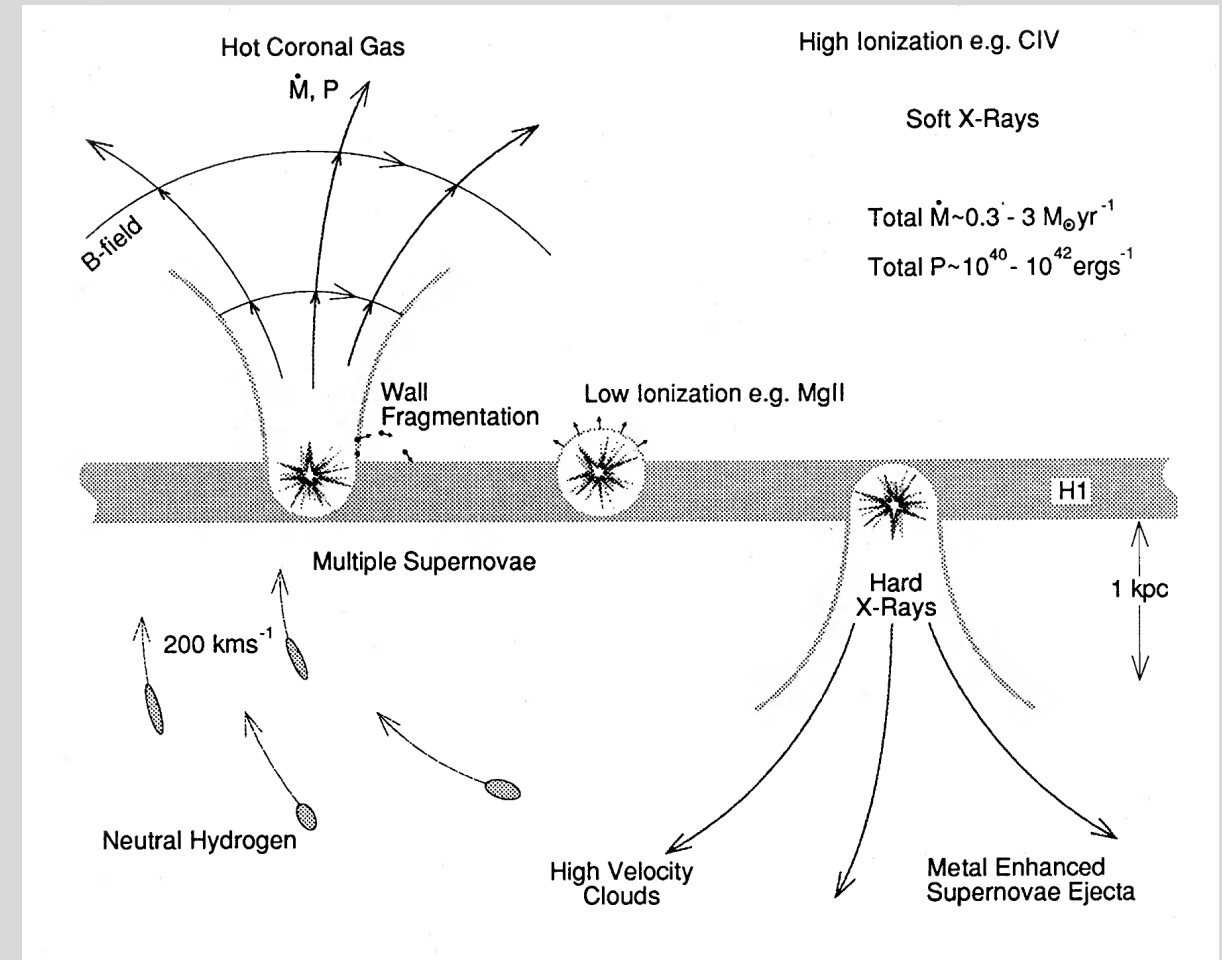
Star formation: when HI density gets high, gas clouds start to contract and get denser. Form molecular clouds. Form stars.

Feedback: Young stars (and supernovae) heat and ionize the gas. Energy dumped into clouds, disperses them.



galaxy disk cartoon

Norman & Ikeuchi 89

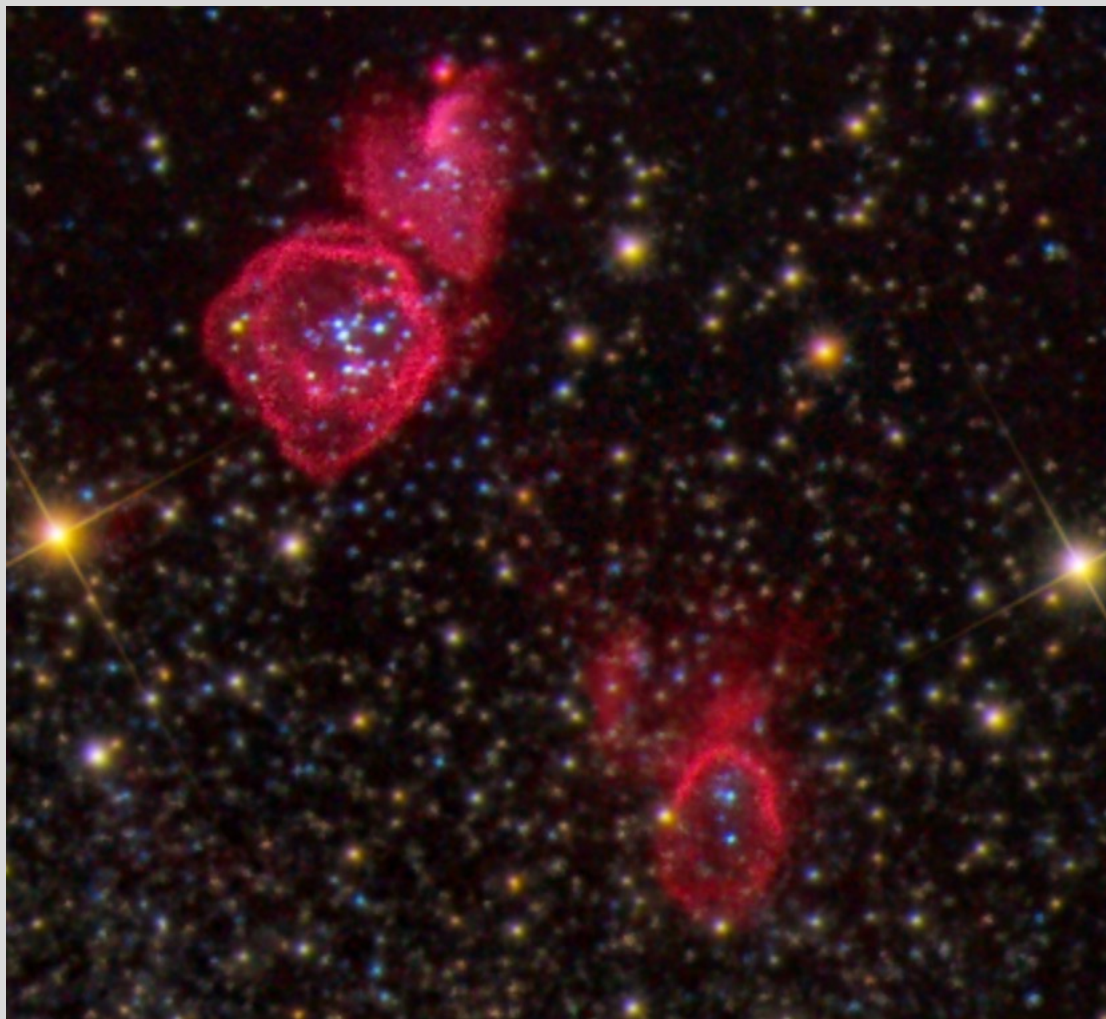


edge-on view of disk



## Feedback: the effect of massive stars

Ionized gas bubbles in NGC 6822 ([Pugh/Hanson](#))



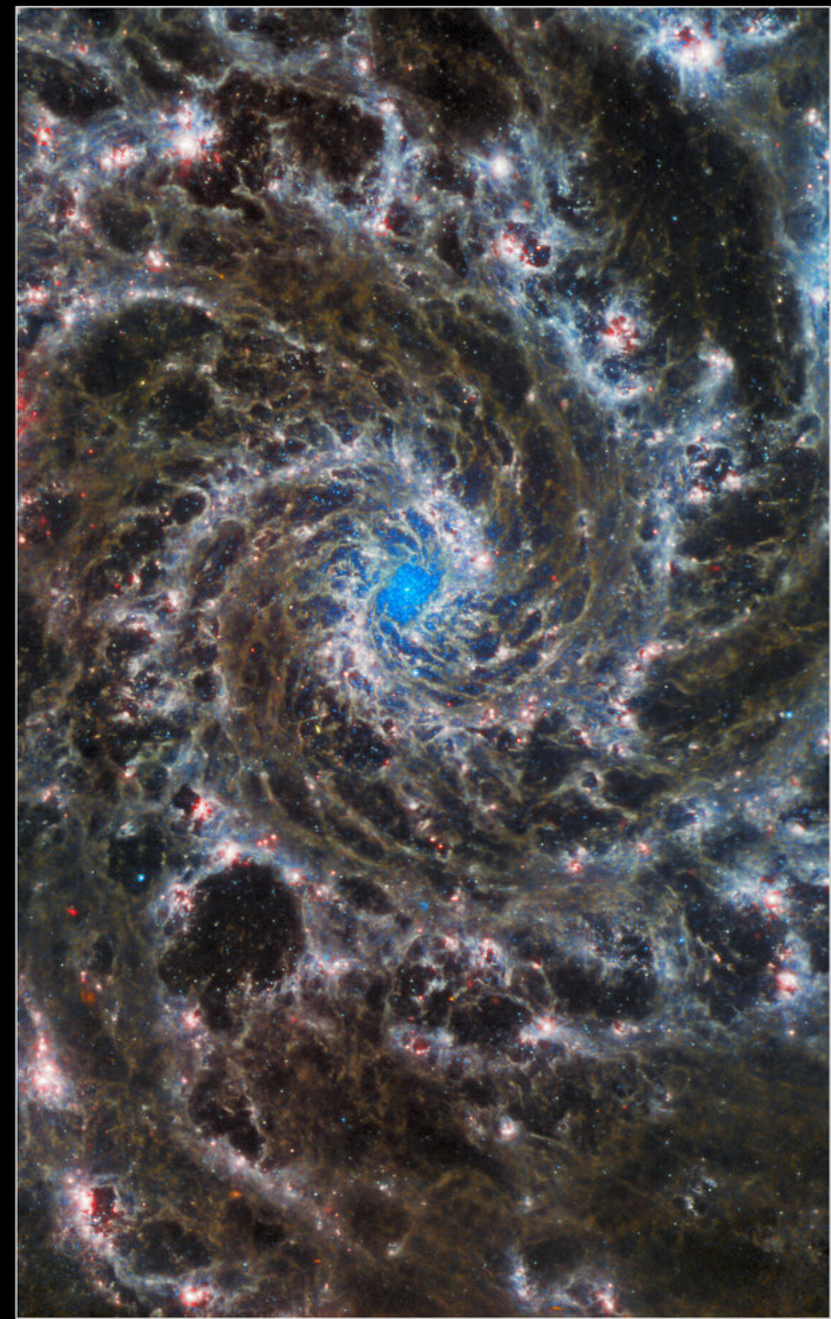




Hubble / Optical



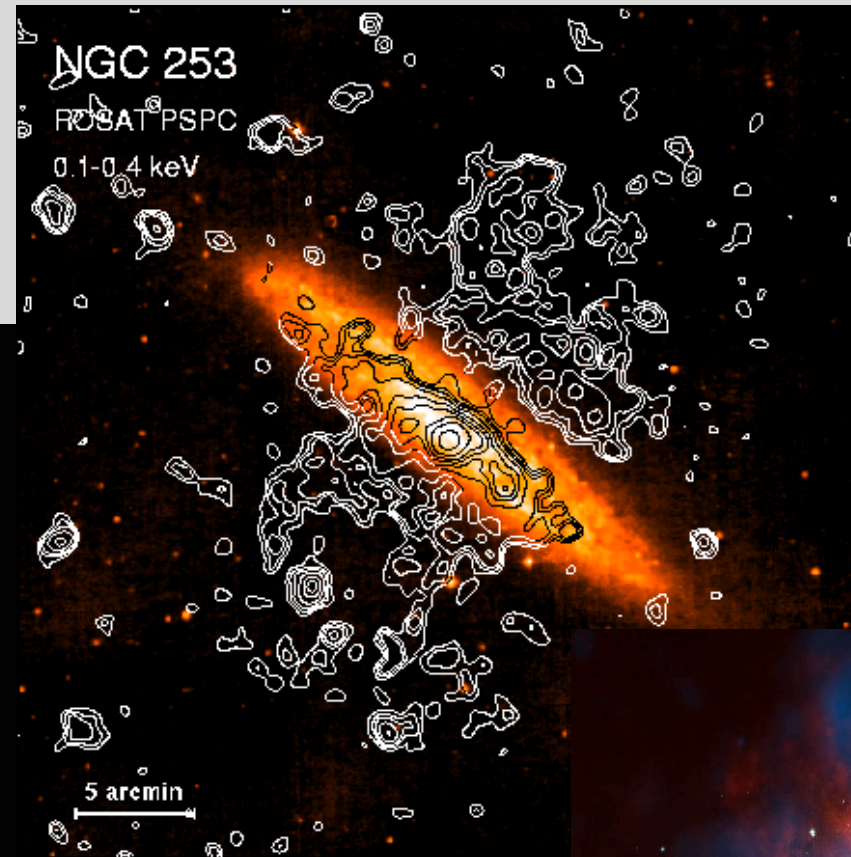
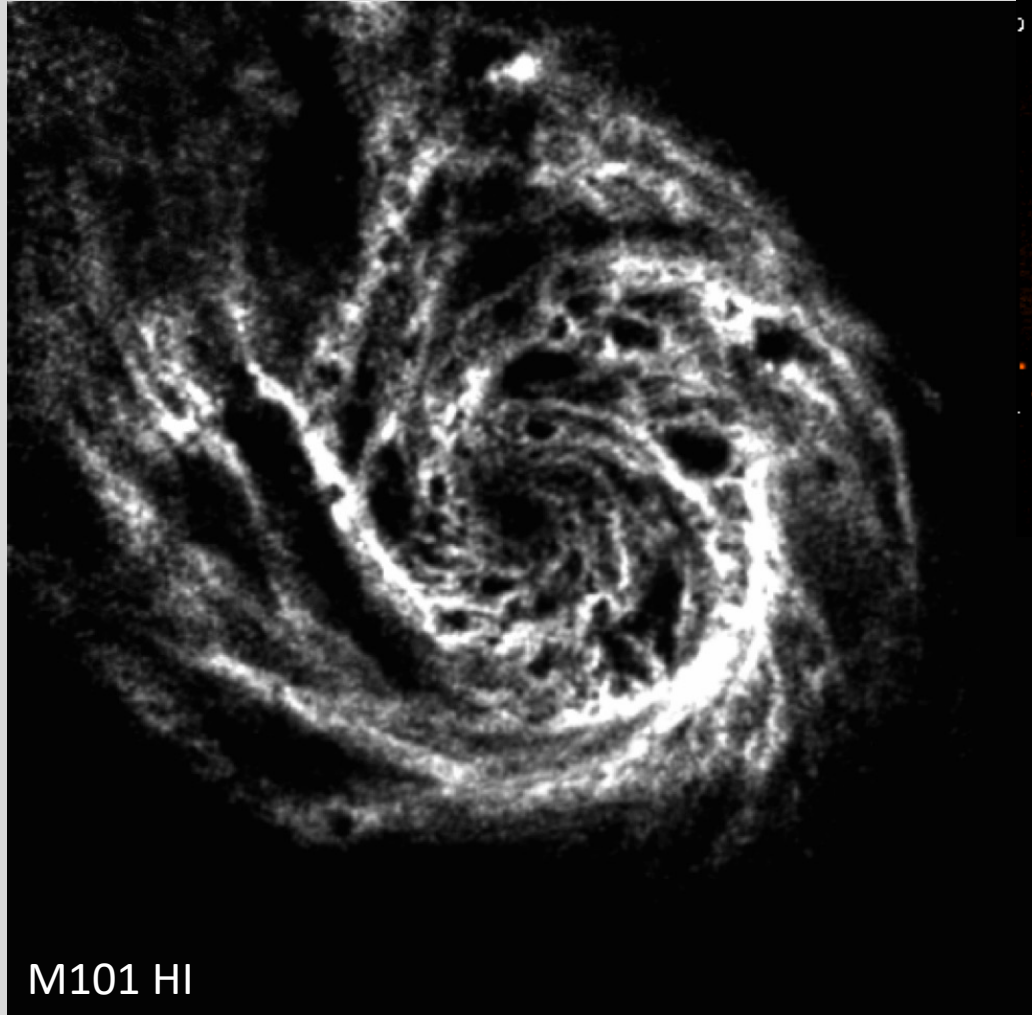
Hubble & Webb



Webb / Infrared



## Feedback: the effect of massive stars



NGC 253:  
orange = optical  
contours = X-ray

M82  
blue = optical  
red = H $\alpha$   
blue = X-ray





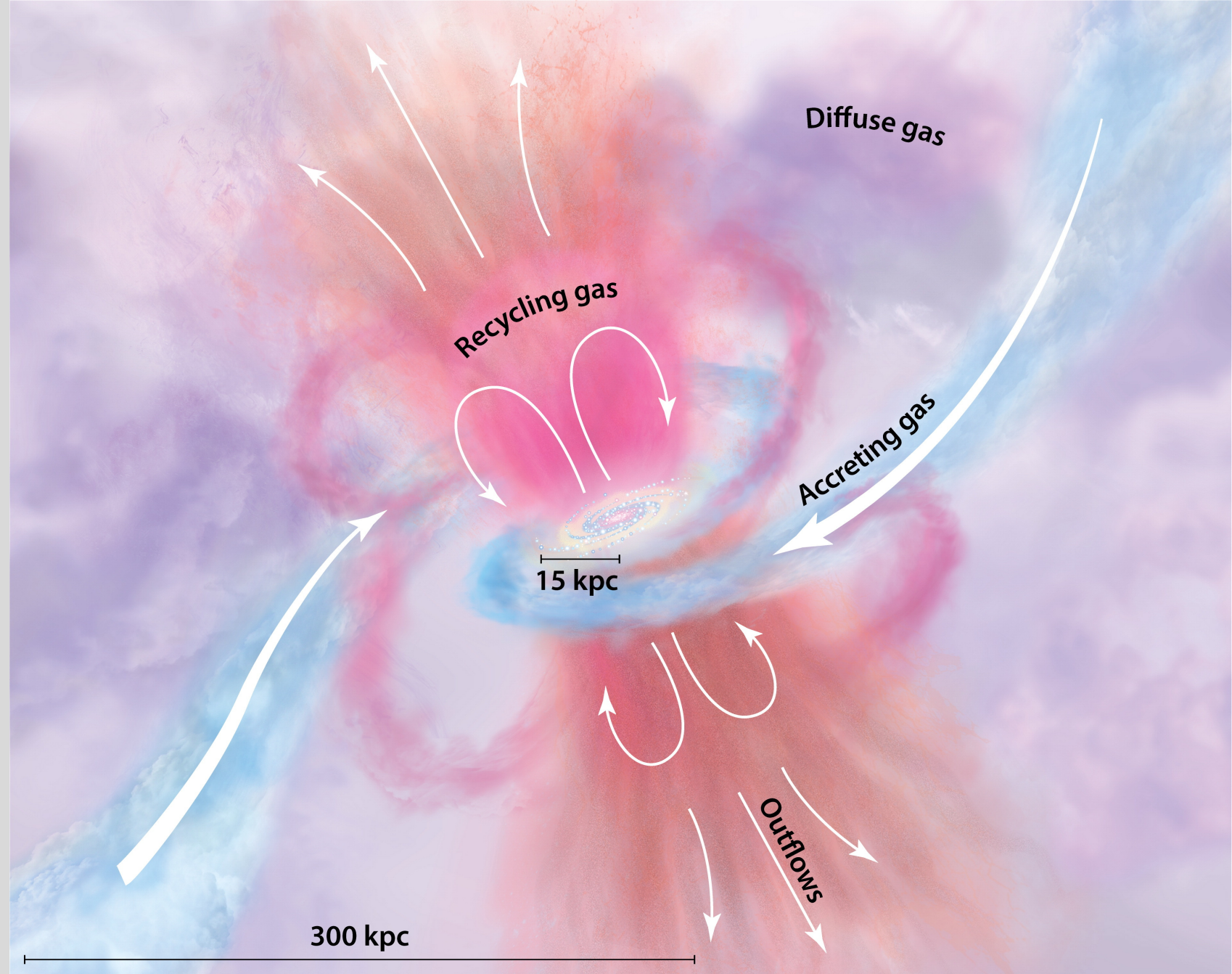
# The Baryon Cycle in Galaxies

**Inflows of gas** from circumgalactic environment, generally metal-poor (primordial?).

- Can fuel additional star formation.
- Hot phase? Cool phase? Unclear...

**Outflows of gas** from supernovae and stellar winds. Metal-enriched.

- Some expelled completely
- Some falls back to the galaxy (“recycled gas”)
- Maybe also ejecta from active nucleus?





# Chemical Evolution

Initially, gas has primordial composition from the Big Bang: hydrogen, helium, no heavy metals.

Over time, successive generations of stars produce heavy elements and eject them into space, increase the metallicity of the galaxy's interstellar medium.

As new stars form from this metal-enriched gas, subsequent generations of stars will be more metal rich. Metallicity patterns in a galaxy's stellar populations can be used to unravel the galaxy's star formation history and timescales.

## Important things to remember:

- **Enrichment can happen quickly.** Old populations can also be metal-rich populations. Examples: Milky Way bulge, or massive ellipticals. Metallicity does not map to absolute age in any simple fashion.
- **Individual stars do not evolve in metallicity.** Nuclear fusion happens in the core, but we measure the metallicity of the star's outer layers. A star's metallicity reflects the metallicity of the gas it was born from, not what's happening inside the star.

Abundance patterns can help us work things out. *Time to review stellar evolution!*

<p><i>Remember</i></p> $[X/H] \equiv \log(X/H) - \log(X/H)_{\odot}$
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## Nucleosynthesis in **Low Mass Stars** ( $\lesssim 8 M_{\odot}$ )

Main Sequence: fusing  $H \Rightarrow He$

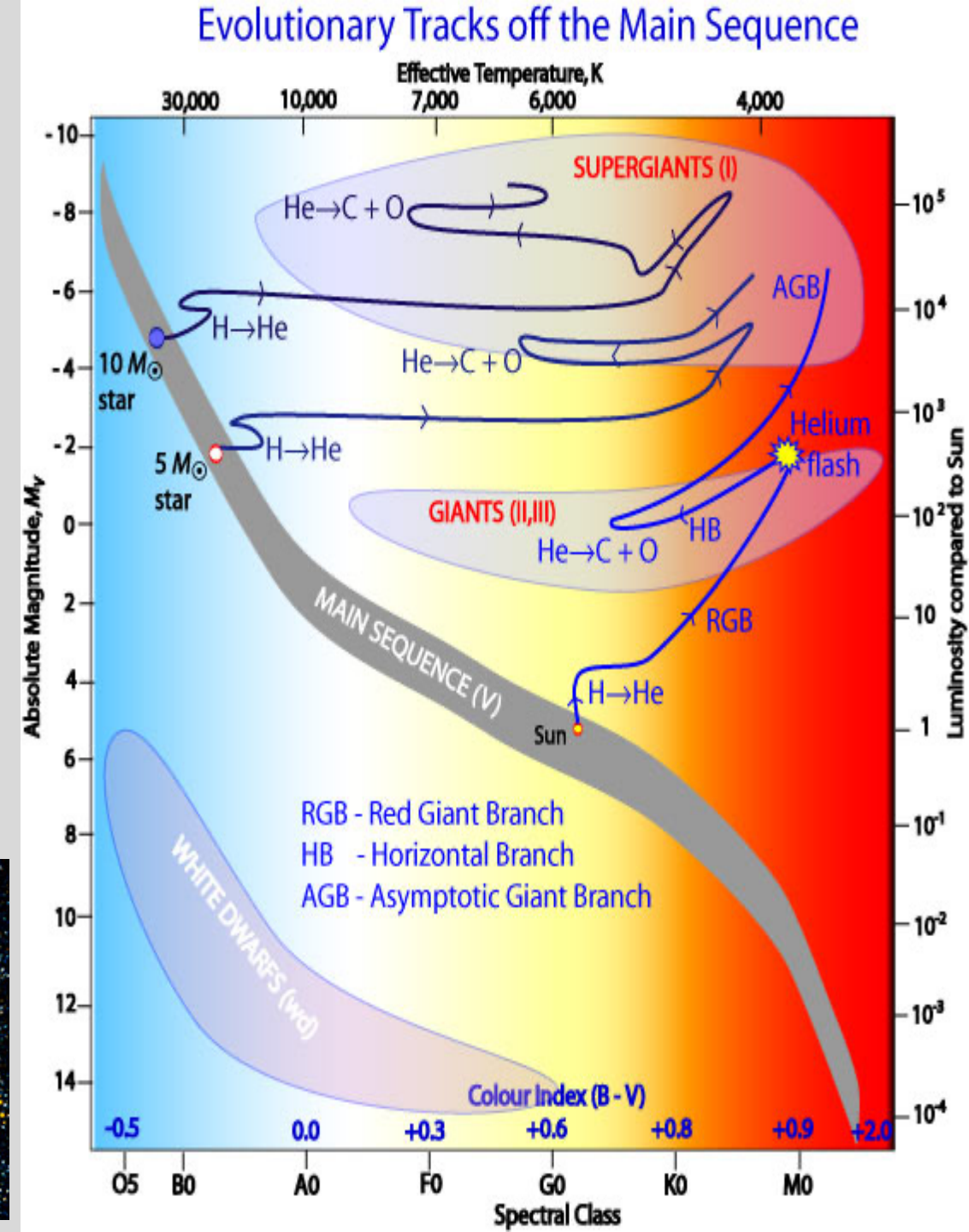
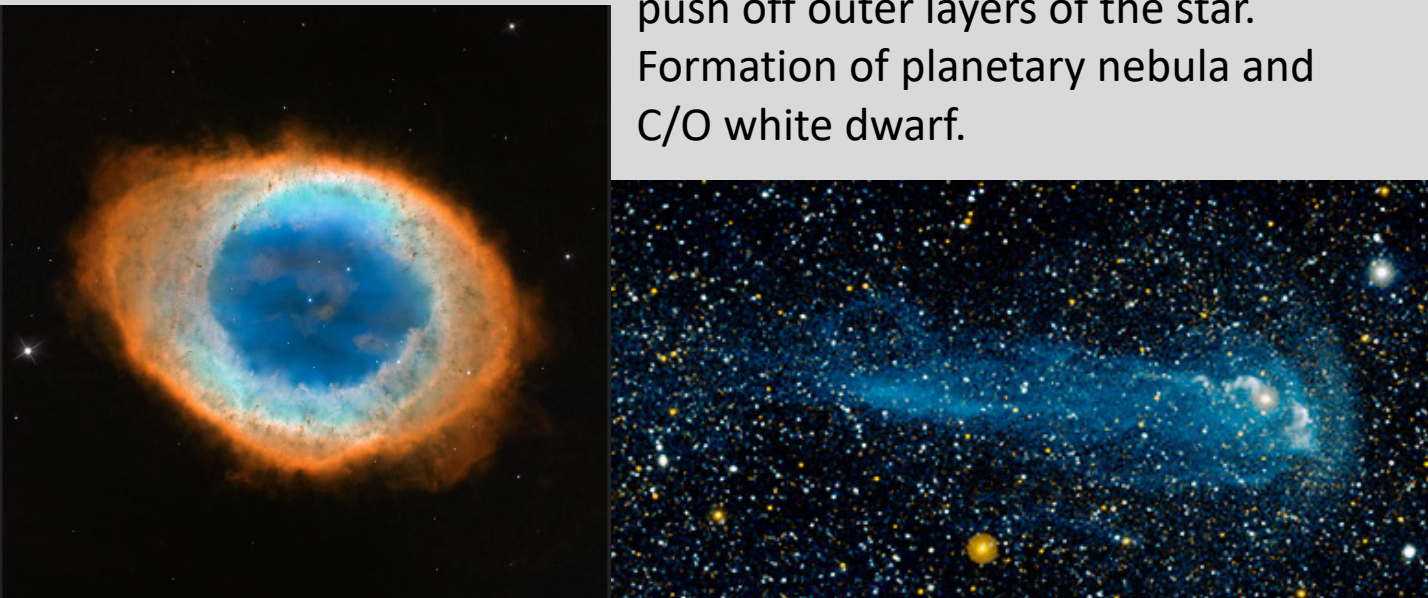
Red Giant Branch: running out of H, until He flash

Horizontal Branch:  $\text{He} + \text{He} \Rightarrow \text{C}$ ,  $\text{C} + \text{He} \Rightarrow \text{O}$

## Asymptotic Giant Branch: running out of He

**s-process elements:** slow capture of neutrons by nuclei deep inside the star, “dredged up” during AGB phase. Elements like Strontium (Sr), Barium (Ba), Zirconium (Zr), etc.

Unstable pulsations along the AGB  
push off outer layers of the star.  
Formation of planetary nebula and  
C/O white dwarf.





# Nucleosynthesis in Massive Stars ( $\gtrsim 10 M_{\odot}$ )

Main Sequence: fusing  $H \Rightarrow He$

Later stages of evolution:

- $^{12}C + He \Rightarrow ^{16}O$
- $^{16}O + He \Rightarrow ^{20}Ne$
- $^{20}Ne + He \Rightarrow ^{24}Mg$
- $^{24}Mg + He \Rightarrow ^{28}Si$
- $^{16}O + ^{16}O \Rightarrow ^{32}S$

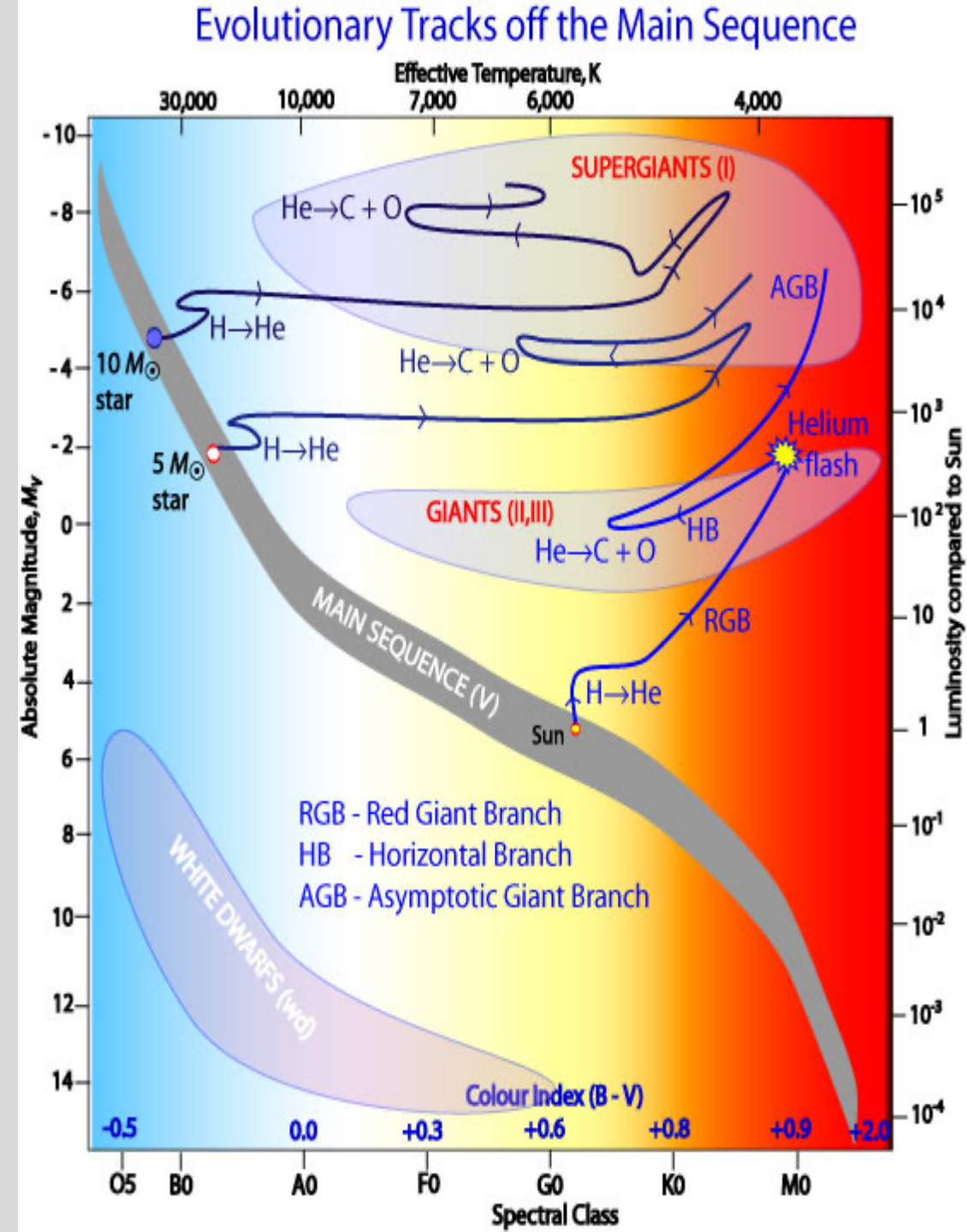
Helium nuclei are also known as “ $\alpha$  particles”, so these elements made by adding  $\alpha$  particles to nuclei are known as “ $\alpha$  elements”

and on up to Iron ( $^{56}Fe$ ).

**Type II supernovae:** core collapse of a massive star.

**r-process elements:** during SN, rapid neutron flux irradiates nuclei, producing elements like Europium (Eu), Platinum (Pt), etc.

Most of the iron gets swallowed up in the formation of the neutron star or black hole. *Relatively little iron ejected!*





# Type Ia Supernovae

Binary system: CO white dwarf + companion

Mass transfer from companion onto WD increases the WD mass beyond the Chandresakhar mass of  $1.4 M_{\odot}$ .

Explosive nucleosynthesis, producing Mg, Si, Ni, and Fe and the whole WD explodes.

***Most of the Fe in the universe is made this way.***





# Chemical Evolution

Recapping:

- Massive stars quickly make  $\alpha$  elements (O, Ne, Mg, etc) and promptly eject them out into space. They swallow up most of the Iron (Fe) that they make, but some is ejected to enrich the surrounding gas.
- Low mass stars eventually make C/O, which gets locked up in their core. After a while, these stars become white dwarfs, then Type Ia supernovae turn the C/O into Fe and eject it into space.

*Happens fast!*

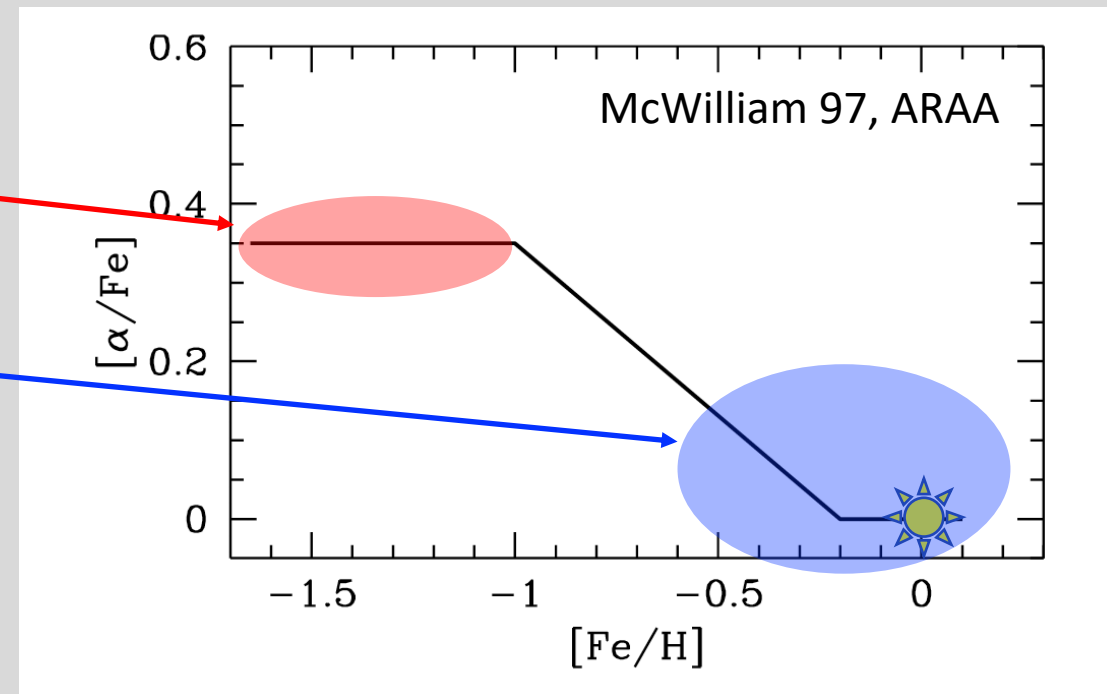
*Takes a while!*

## Alpha abundances $[\alpha/\text{Fe}]$ vs Iron Abundances $[\text{Fe}/\text{H}]$

Early, fast star formation will produce stellar populations with enhanced alpha abundances.

As time goes by, Type Ia start to explode and add Iron to the ISM.  $[\text{Fe}/\text{H}]$  increases and  $[\alpha/\text{Fe}]$  drops.

Where the transition happens depends on details of how fast new stars are made, how efficient metal ejection is, etc....





# Chemical Evolution

Fulbright+07

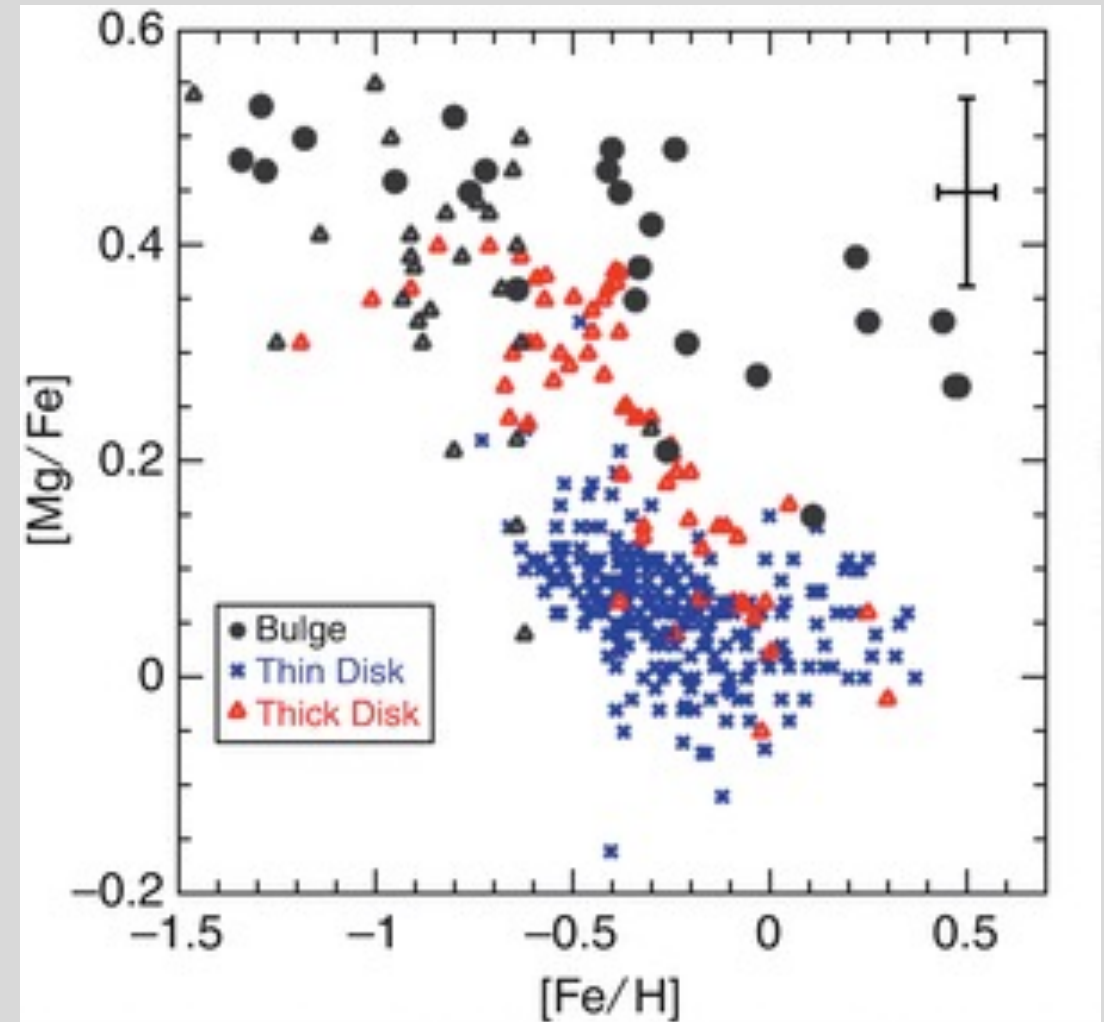
## Example: Abundances in the Milky Way

Magnesium is an  $\alpha$  element, look at  $[\text{Mg}/\text{Fe}]$  vs  $[\text{Fe}/\text{H}]$ .

**Bulge:** high  $[\text{Mg}/\text{Fe}]$  over a wide range of metallicity. Population formed in a fast early burst of star formation.

**Thin disk:** solar  $[\text{Mg}/\text{Fe}]$ , star formation occurred more slowly over time. Population built up over time.

**Thick disk:** somewhere in between...





# Studying the Milky Way means understanding stars

From a perspective of understanding galaxies, for the Milky Way we'd like to know:

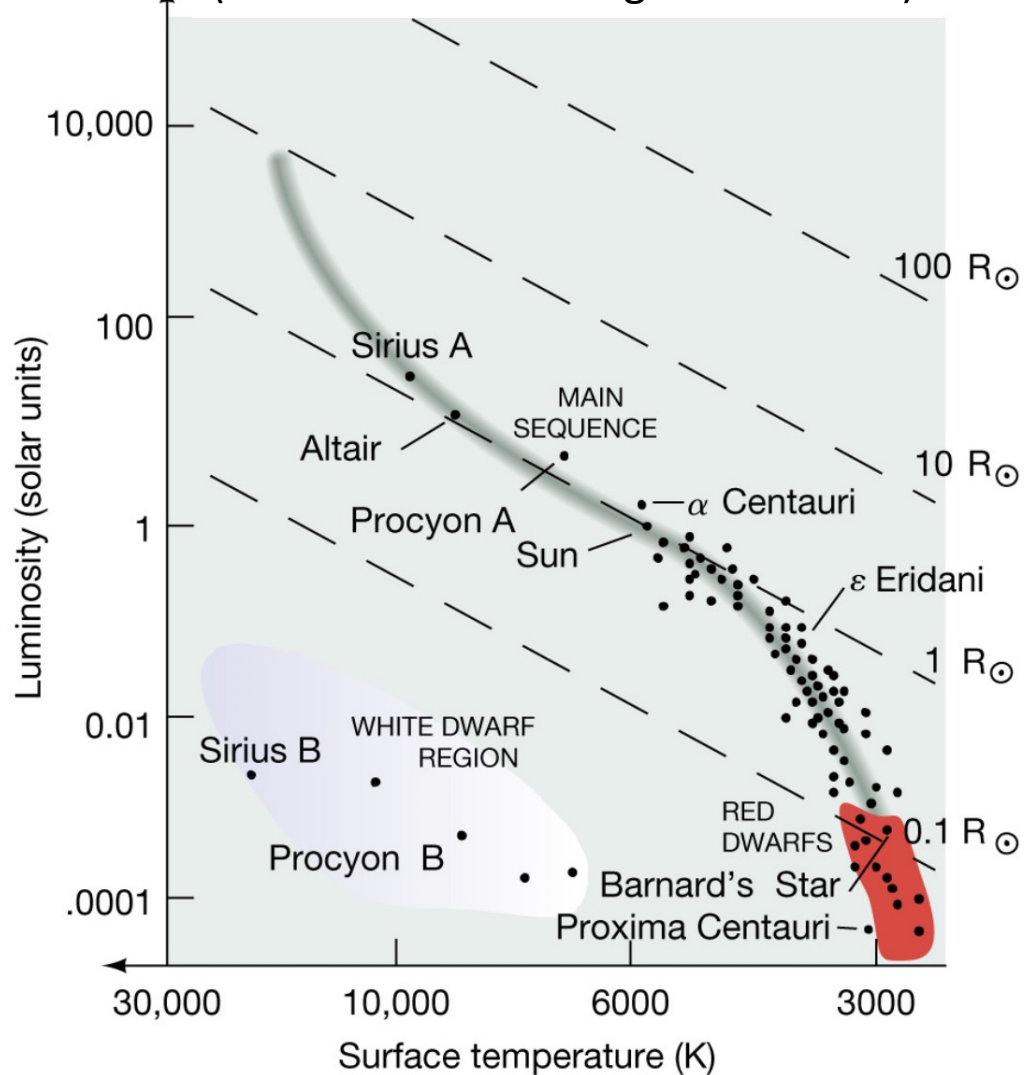
- Its 3-dimensional structure and physical components (disk, halo, bulge, bar...)
- Its kinematics (rotation, random motions, kinematic subgroups....)
- Its evolutionary history (star formation rate, accretion history, dynamical evolution....)

We use stars as our primary tracers of the Galaxy, so we need to know distances, ages, metallicities, velocities. Some of these are harder to measure than others (and none are easy!)



## Volume-limited

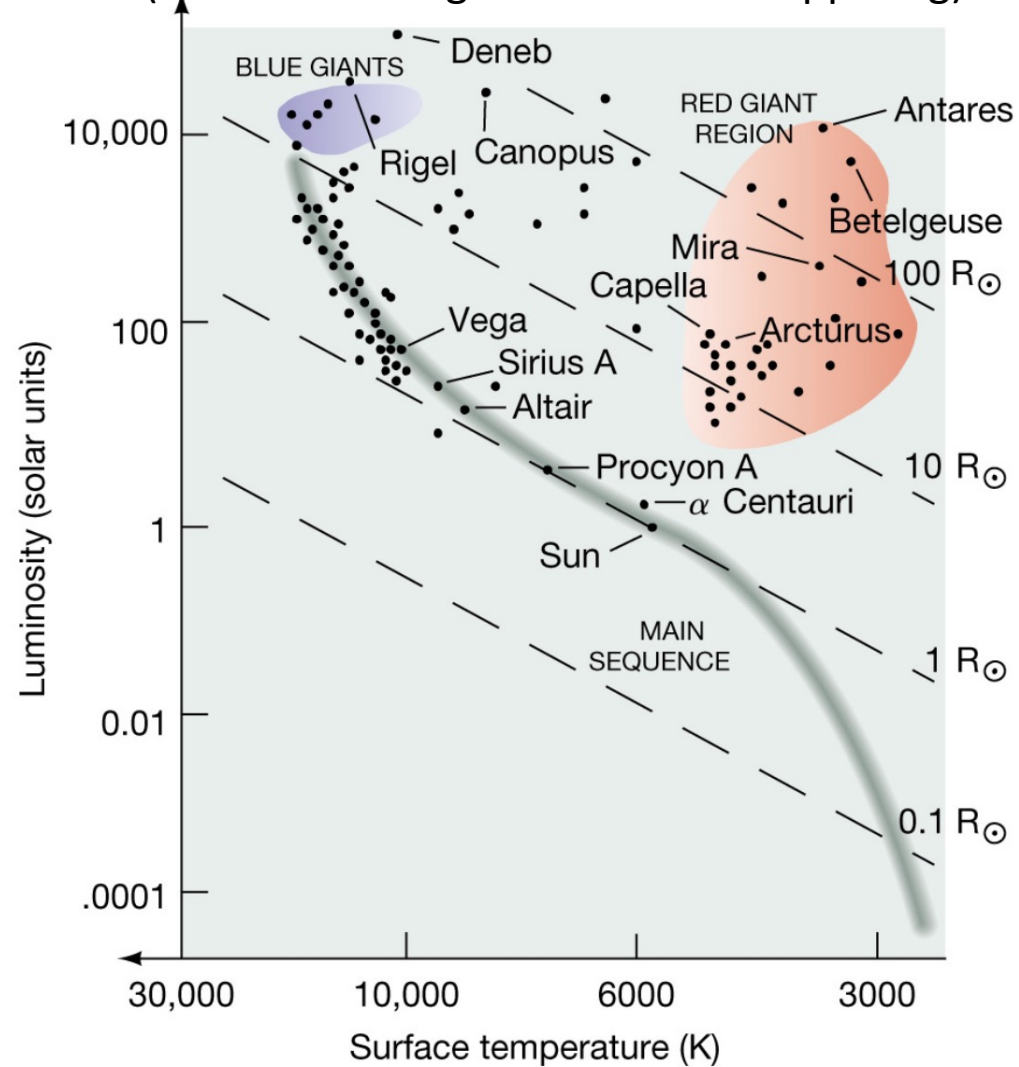
(all the stars out to a given distance)



Spectral classification

## Brightness-limited

(all the stars brighter than some app-mag)



Spectral classification

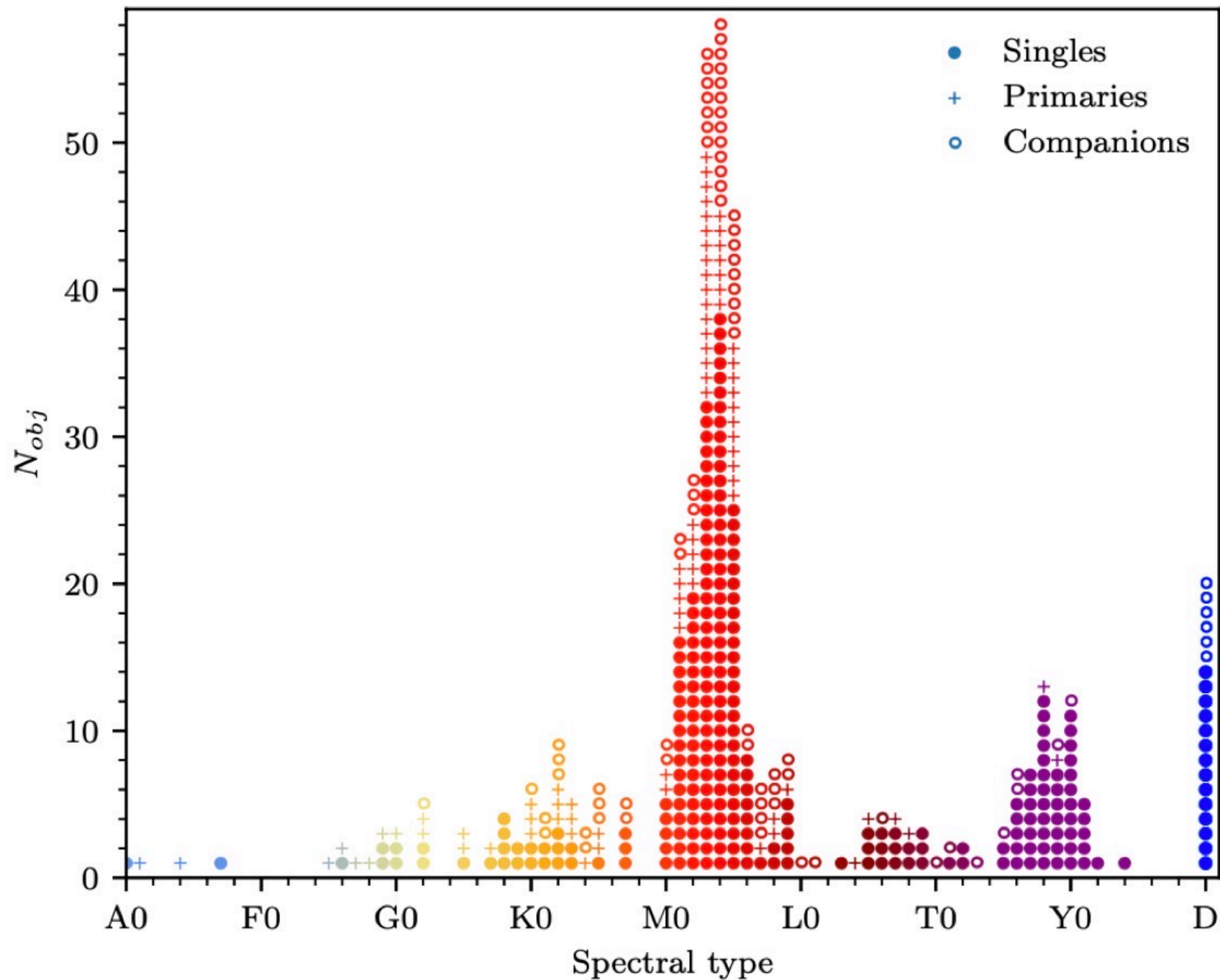


## The 10pc Local Volume

[Reyle+21](#)

3D maps

<https://gruze.org/10pc/resources/>



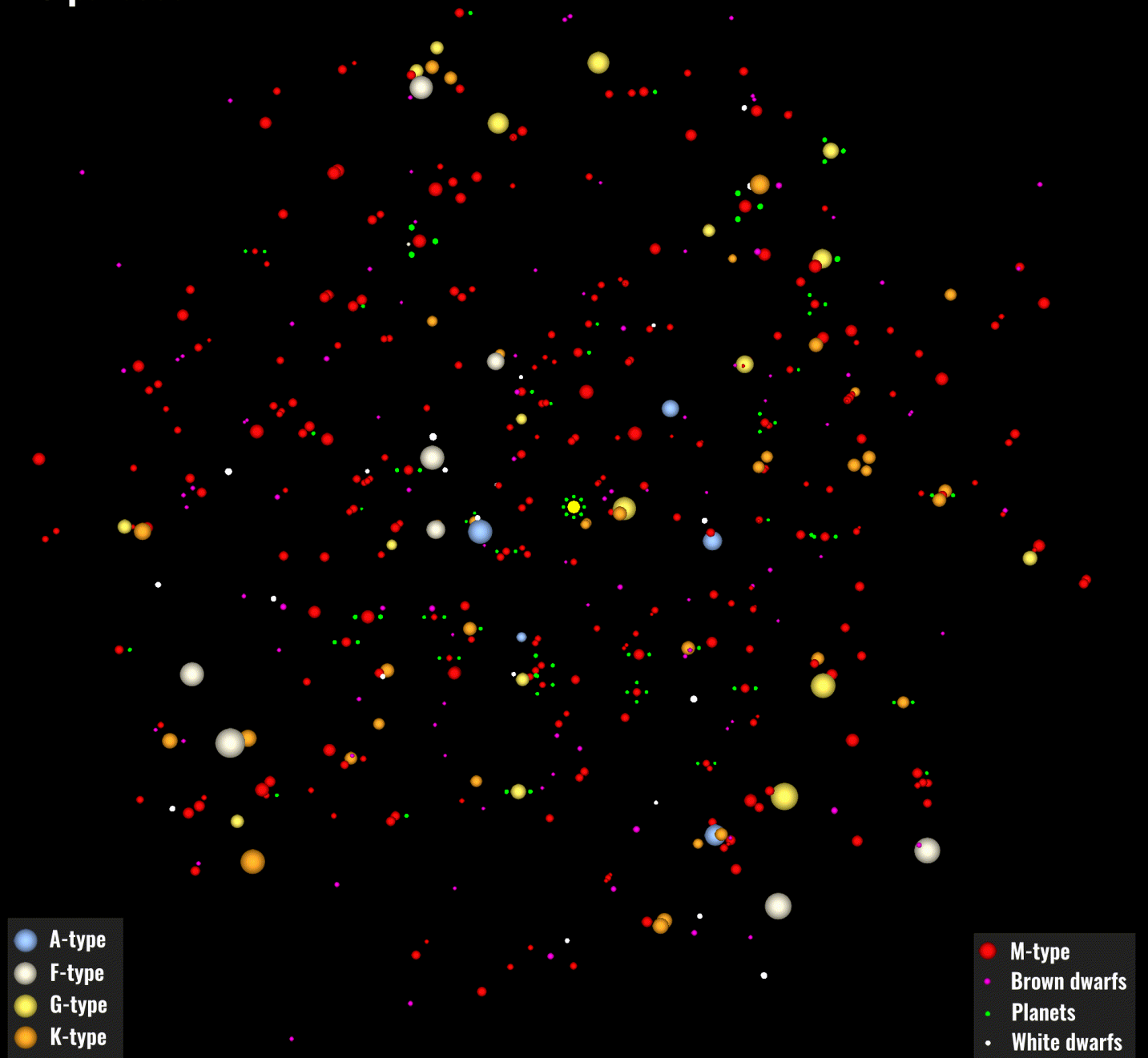
# The 10pc Local Volume

[Reyle+21](#)

3D maps

<https://gruze.org/10pc/resources/>

10 parsecs





# Fundamental Data for Stars

## *What we can measure*

**Photometry:** apparent magnitudes and colors, variability

“Easy” to get: wide-field multiband imaging

**Spectroscopy:** spectral classification, absorption line strengths, radial velocities

Much harder to get and expensive in terms of telescope resources

**Stellar Motions:** proper motion, parallax

Need accurate measures over a long time baseline; hard to get from ground. But now Gaia.....

## *What we want to know*

**Distances**

**Luminosities**

**Temperatures**

**Metallicities**

**Space Velocities**

**Masses**

**Ages**

## Distances to Stars: Parallax

$$\frac{1 \text{ AU}}{d} = \tan p \approx p \quad (\text{if } p \text{ is in radians})$$

Define distance unit “**parsecs**” to be the distance at which a star has a parallax of 1”, then we have simply:

$$d(\text{pc}) = \frac{1}{p(\text{arcsec})}$$

Sounds easy? Why is this hard to do?

- Parallaxes are small (typically  $\ll 1''$ )
- Stars move!

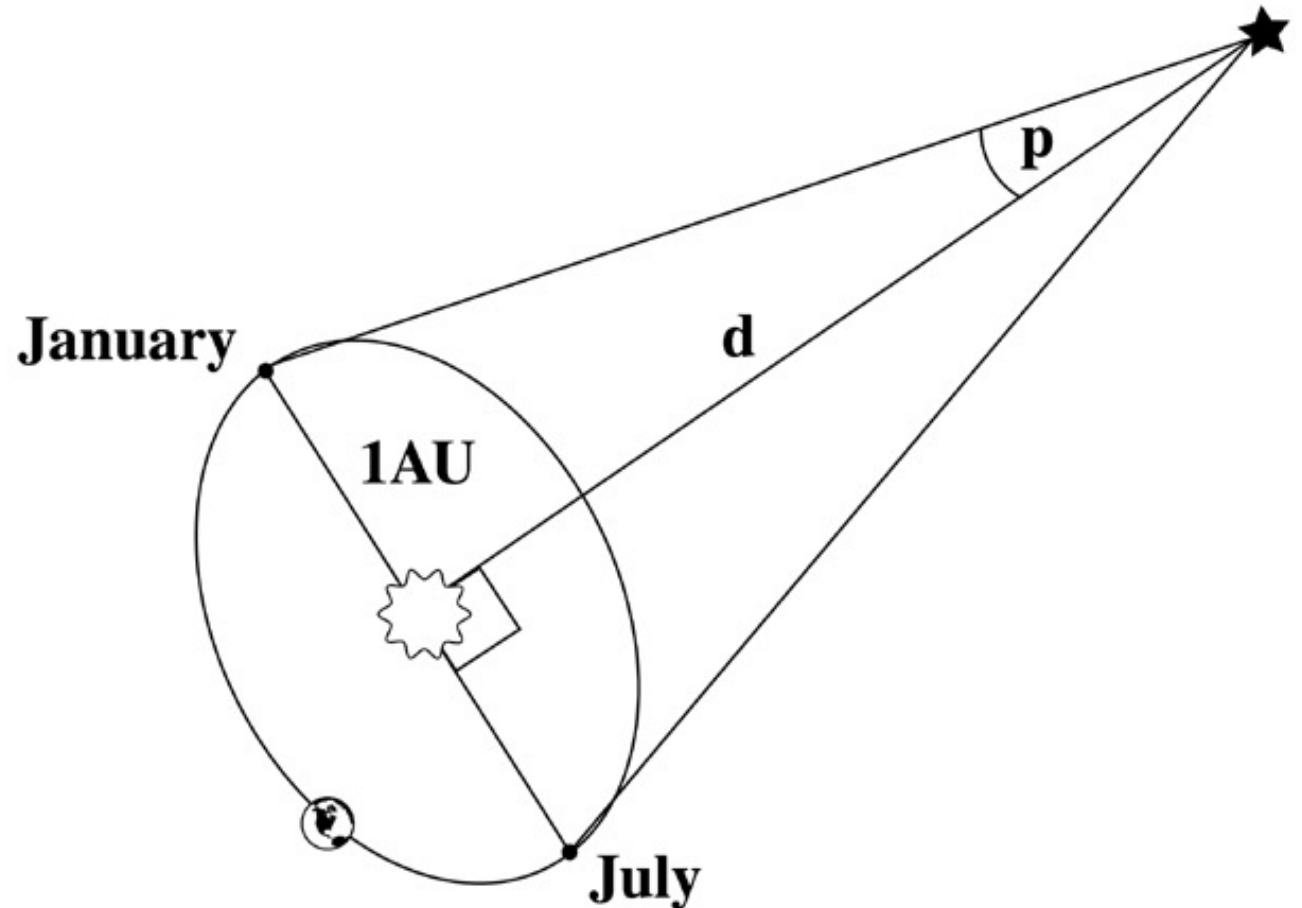


Fig 2.1 'Galaxies in the Universe' Sparke/Gallagher CUP 2007



# Distances to Stars: Parallax

	Ground	Hipparcos	Gaia
Dates		1989-1993	2014-
Limiting Magnitude		~ 12	~ 20
Parallax precision	0.01 arcsec (modern)	~ milli-arcsec	20 micro-arcsec (@15 <sup>th</sup> mag) 200 micro-arcsec (@20 <sup>th</sup> mag)
Distance limits	< 100 pc	< 1 kpc	10 kpc
Number of stars	~ 1000	~ 10 <sup>5</sup>	~ 2x10 <sup>7</sup> (1% error) ~ 2x10 <sup>8</sup> (10% error)

Hipparcos CMD

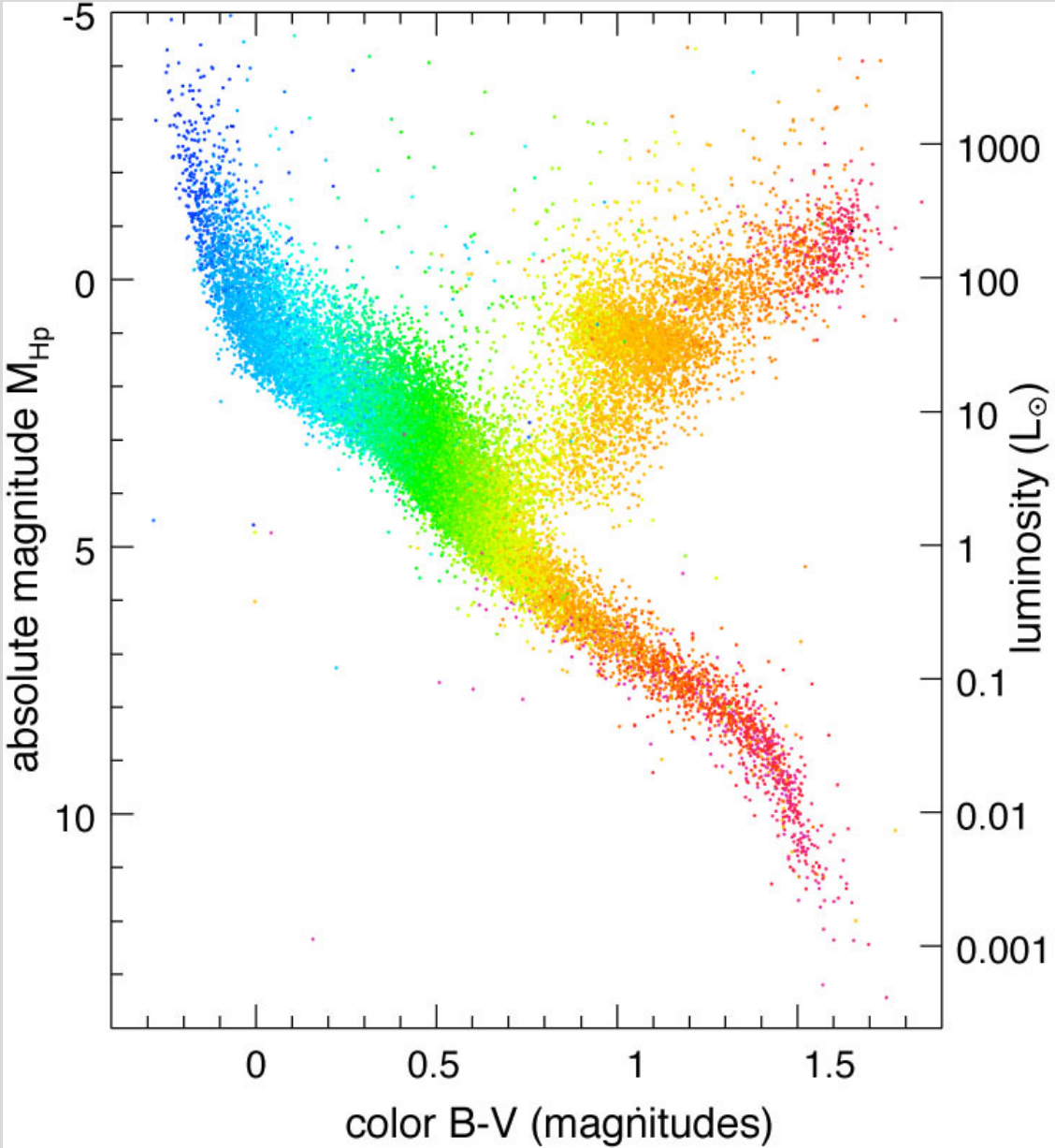
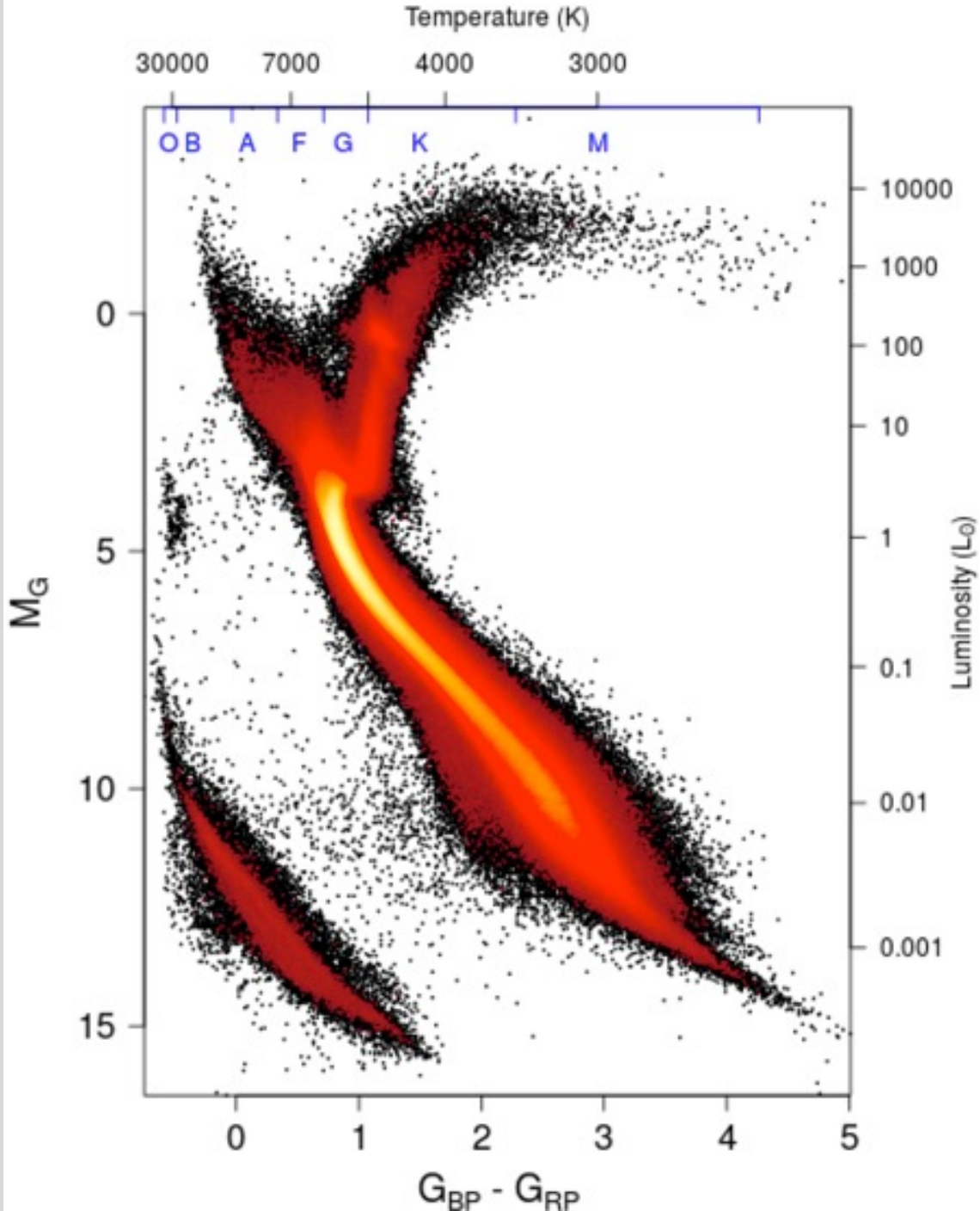


Fig 2.2 (F. van Leeuwen) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

# Distances to Stars: Parallax

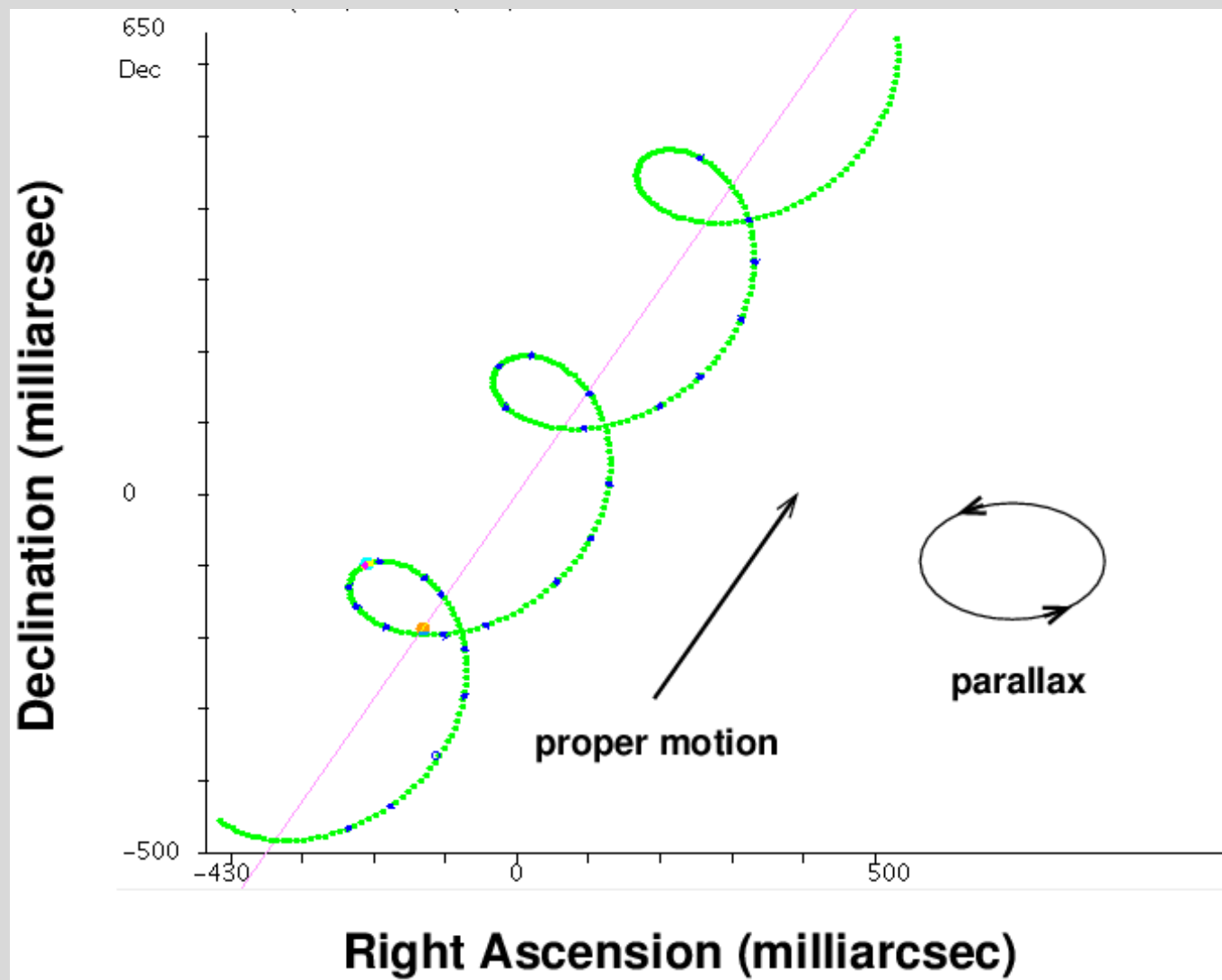
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Gaia CMD





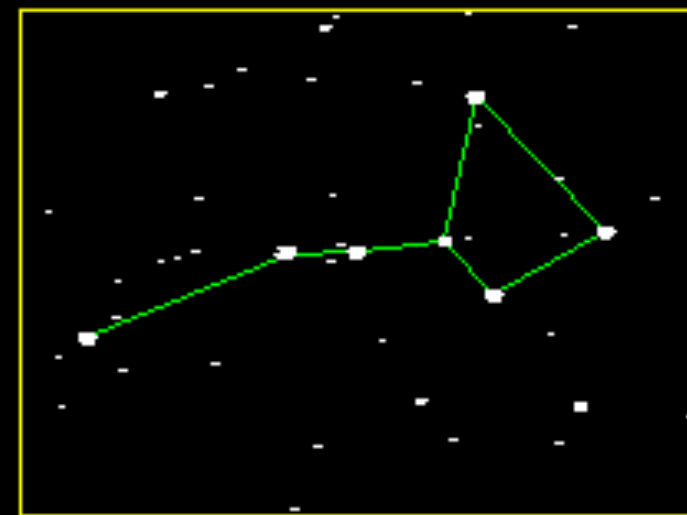
# Proper Motions



courtesy Michael Richmond, RIT



100000 BC



courtesy Rick Pogge, OSU

# Proper Motions

Two components to stellar motions:

**Radial (line of sight) velocity:  $v_r$**

Measured spectroscopically via doppler shift.

**Transverse velocity (2 dimensions):  $v_t$**

Need to measure both a proper motion and a distance. If:

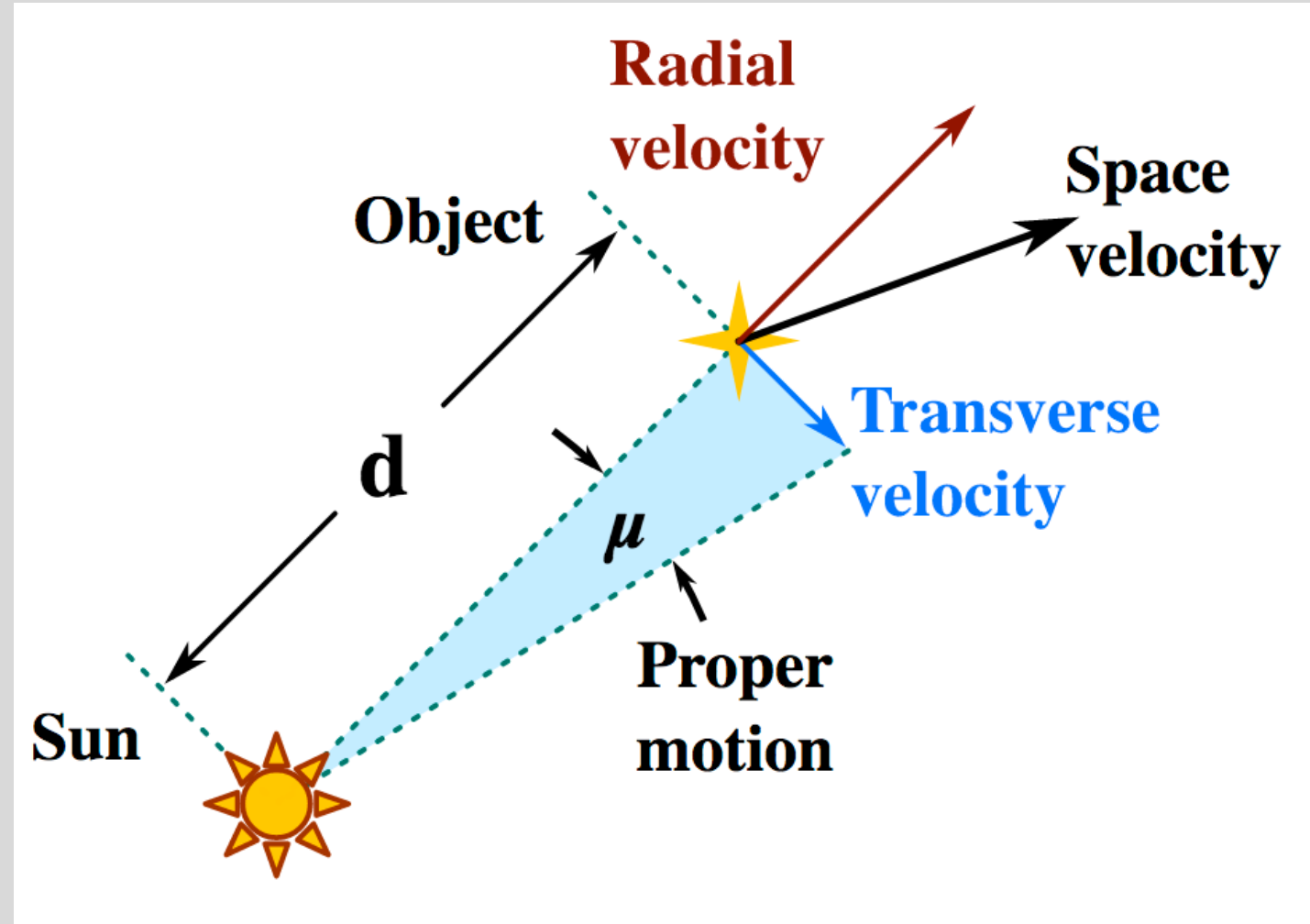
$\mu$  = proper motion (arcsec/yr)

$d$  = distance (pc)

then:

$$v_t(\text{km/s}) = 4.74\mu d$$

Break it down into  $v_\alpha$  and  $v_\delta$ , the components in RA and Dec. But better to transform into Galactic coordinates.



Space velocity:  $(v_r, v_\alpha, v_\delta)$

Speed is the quadrature sum:  $v^2 = v_r^2 + v_\alpha^2 + v_\delta^2$



## Stars in the Local Solar Neighborhood: Observed Luminosity functions

Observed populations consist of stars formed over the Milky Way's history that are still alive today.

Black: Number of stars per magnitude bin.

Red: total mass in stars per magnitude bin.

Blue: total light in stars per magnitude bin. Dotted line shows contribution from main sequence stars only.

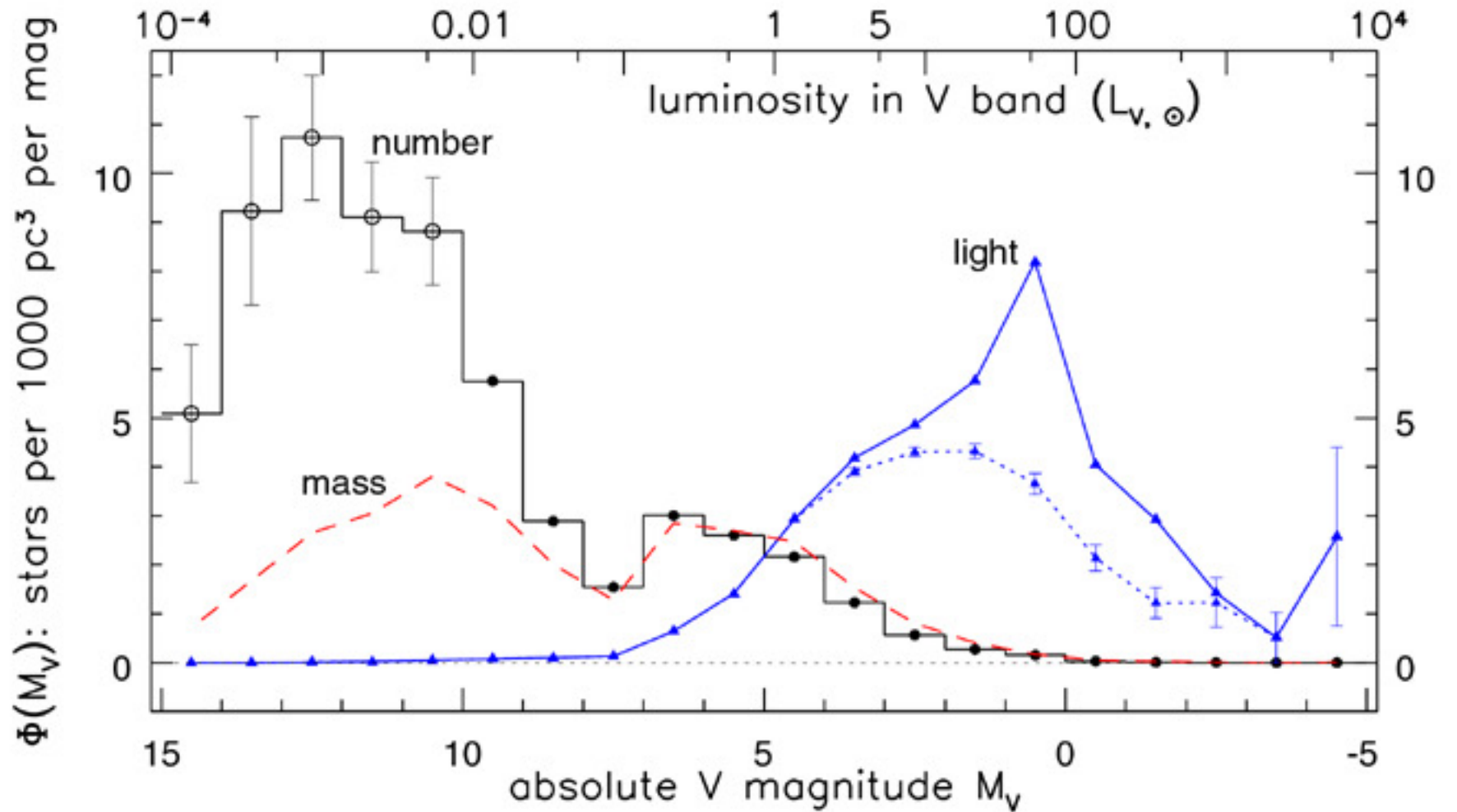


Fig 2.3 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

## Stars in the Local Solar Neighborhood: Observed Luminosity functions $\Rightarrow$ Initial Mass Function

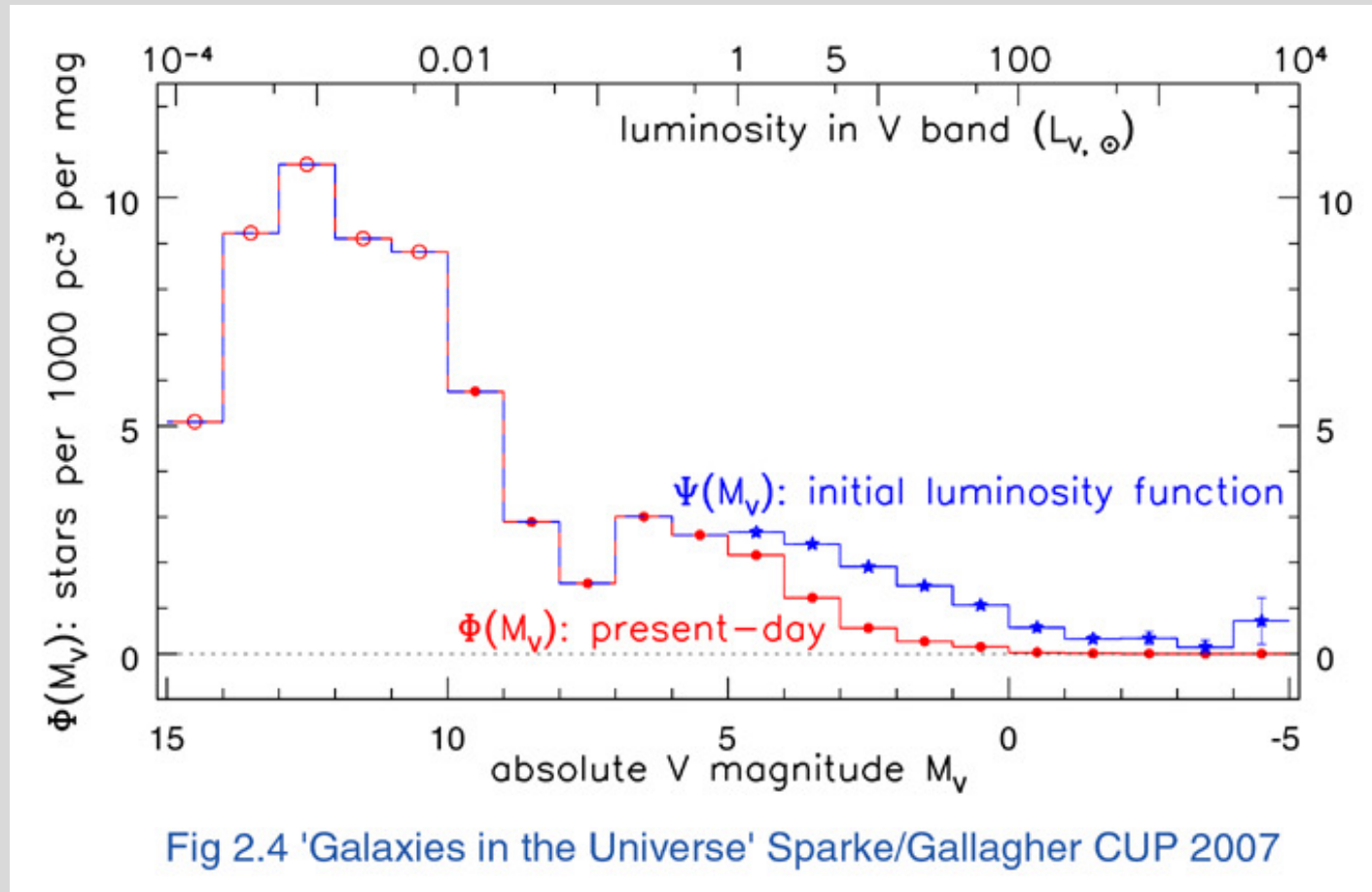
But remember, the observed present-day luminosity function is not the same as the luminosity distribution that stars originally form at: “the initial luminosity function”.

Look at stars only on the main sequence:

- Present-day (observed) LF:  $\phi_{MS}(M_V)$
- Initial LF:  $\psi_{MS}(M_V)$

Need to correct for lifetime of stars, and star formation history of galaxy. Simplest approach: constant star formation over a lifetime  $\tau_{gal}$ :

$$\begin{aligned}\psi_{MS}(M_V) &= \phi_{MS}(M_V) && \text{for } \tau_{MS} \geq \tau_{gal} \\ \psi_{MS}(M_V) &= \phi_{MS}(M_V) \times \frac{\tau_{gal}}{\tau_{MS}(M_V)} && \text{for } \tau_{MS} \leq \tau_{gal}\end{aligned}$$



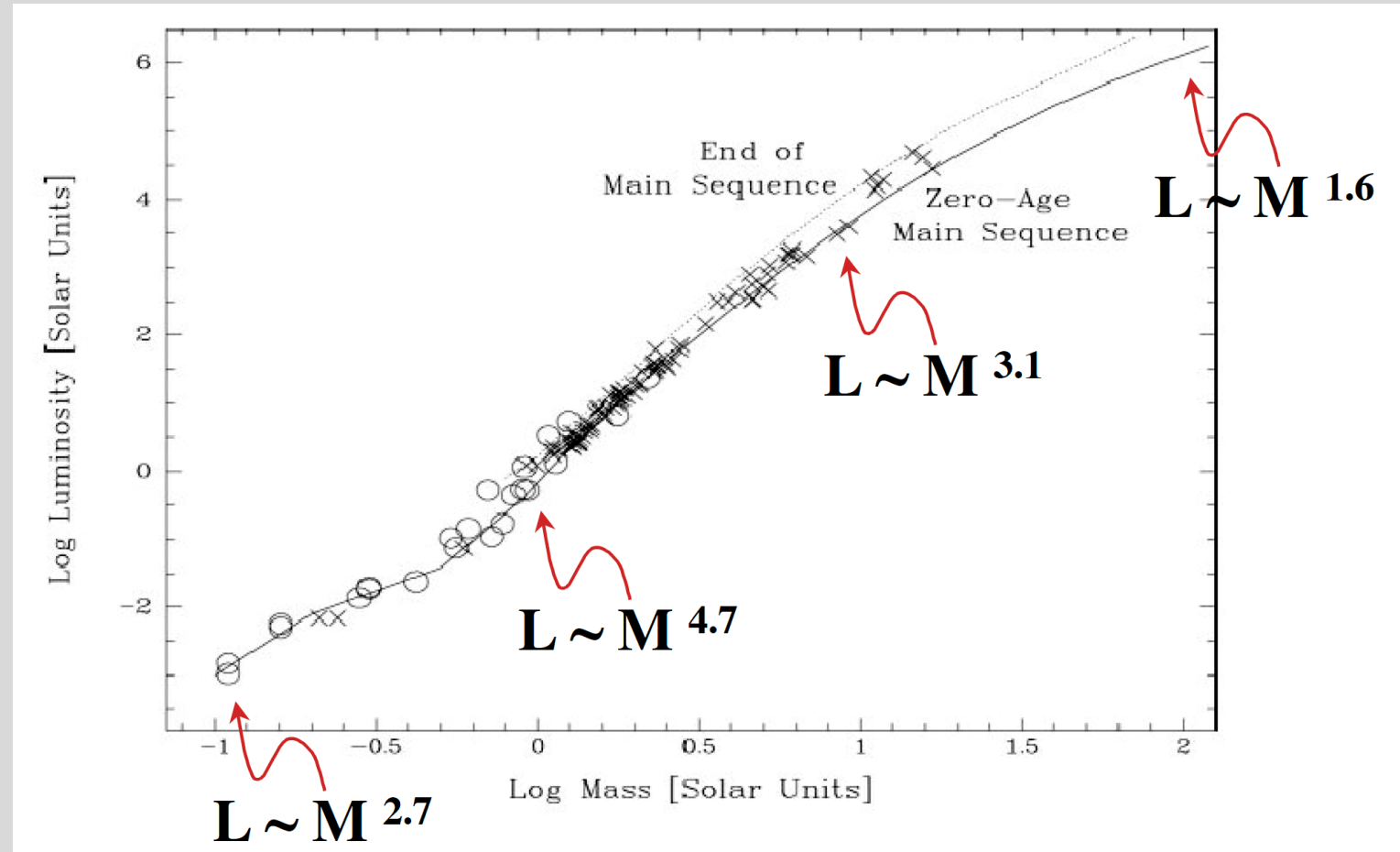


## Stars in the Local Solar Neighborhood: Observed Luminosity functions $\Rightarrow$ Initial Mass Function

That gives us the initial luminosity function.

To go from that to the initial mass function, we need to know how luminosity scales with mass along the main sequence.

Simple parameterization is  $L \sim M^{3.5}$ , but details are more complicated than this.



from Djorgovski lecture notes

## Stars in the Local Solar Neighborhood: Observed Luminosity functions $\Rightarrow$ Initial Mass Function

Scalo (1986) Initial Mass Function:

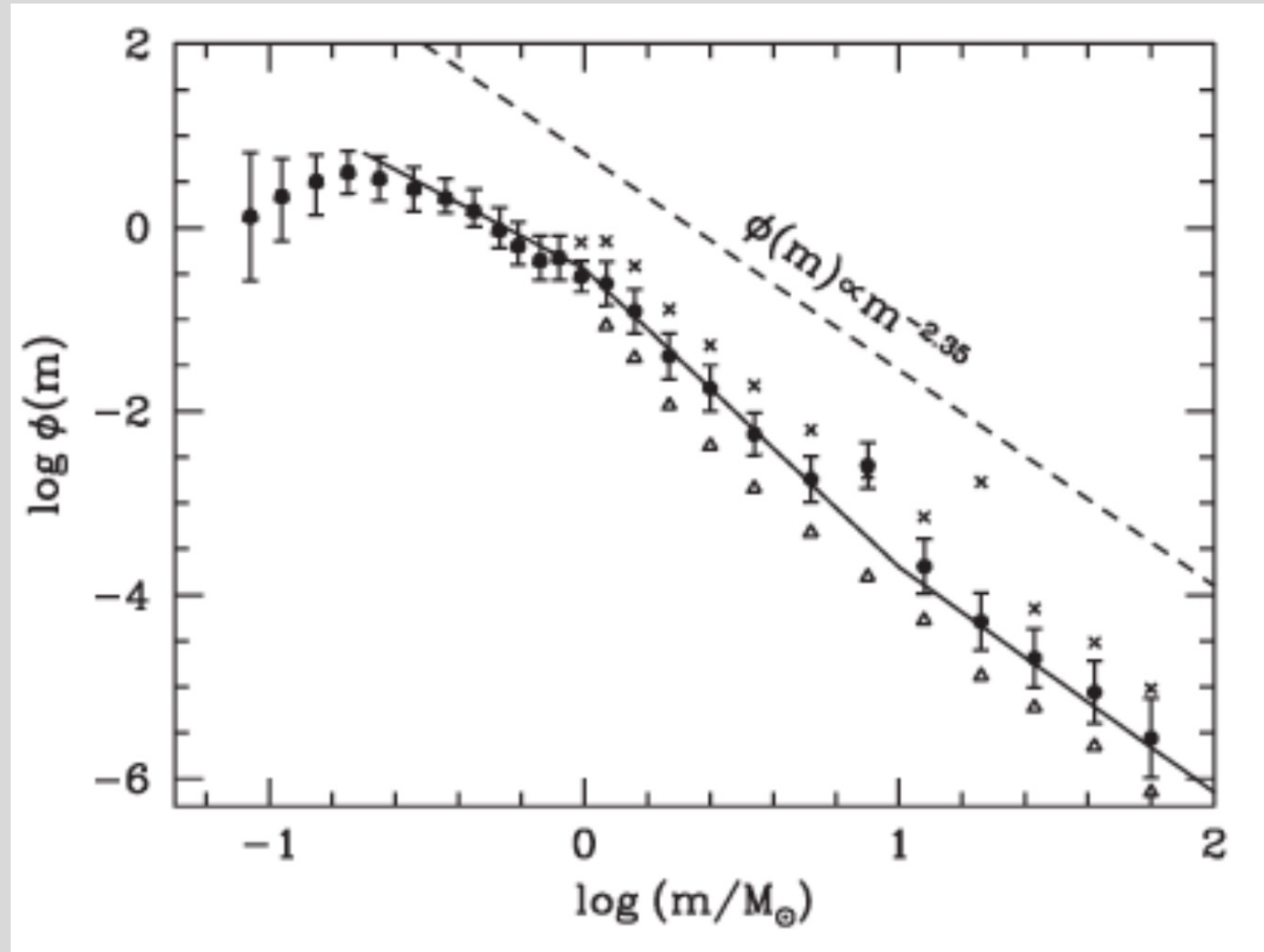
$$\begin{aligned}\xi(M) &\sim M^{-2.45} && \text{for } M > 10 M_{\odot} \\ \xi(M) &\sim M^{-3.27} && \text{for } 1 M_{\odot} < M < 10 M_{\odot} \\ \xi(M) &\sim M^{-1.83} && \text{for } M < 0.2 M_{\odot}\end{aligned}$$

But there are many different parameterizations!

Salpeter:  $\xi(M) \sim M^{-2.35}$

Kroupa (2001), Chabrier (2003) all somewhat different in (important) details: high mass slope, low mass cutoff, etc.

**Many arguments** about whether or not the IMF varies with environment: SFR, metallicity, etc.





## Stars in the Local Solar Neighborhood: Observed Luminosity functions $\Rightarrow$ Initial Mass Function

Alternative approach: measure it in young star clusters. For example, the Pleiades.

Problem: not many stars, so uncertainties are large....

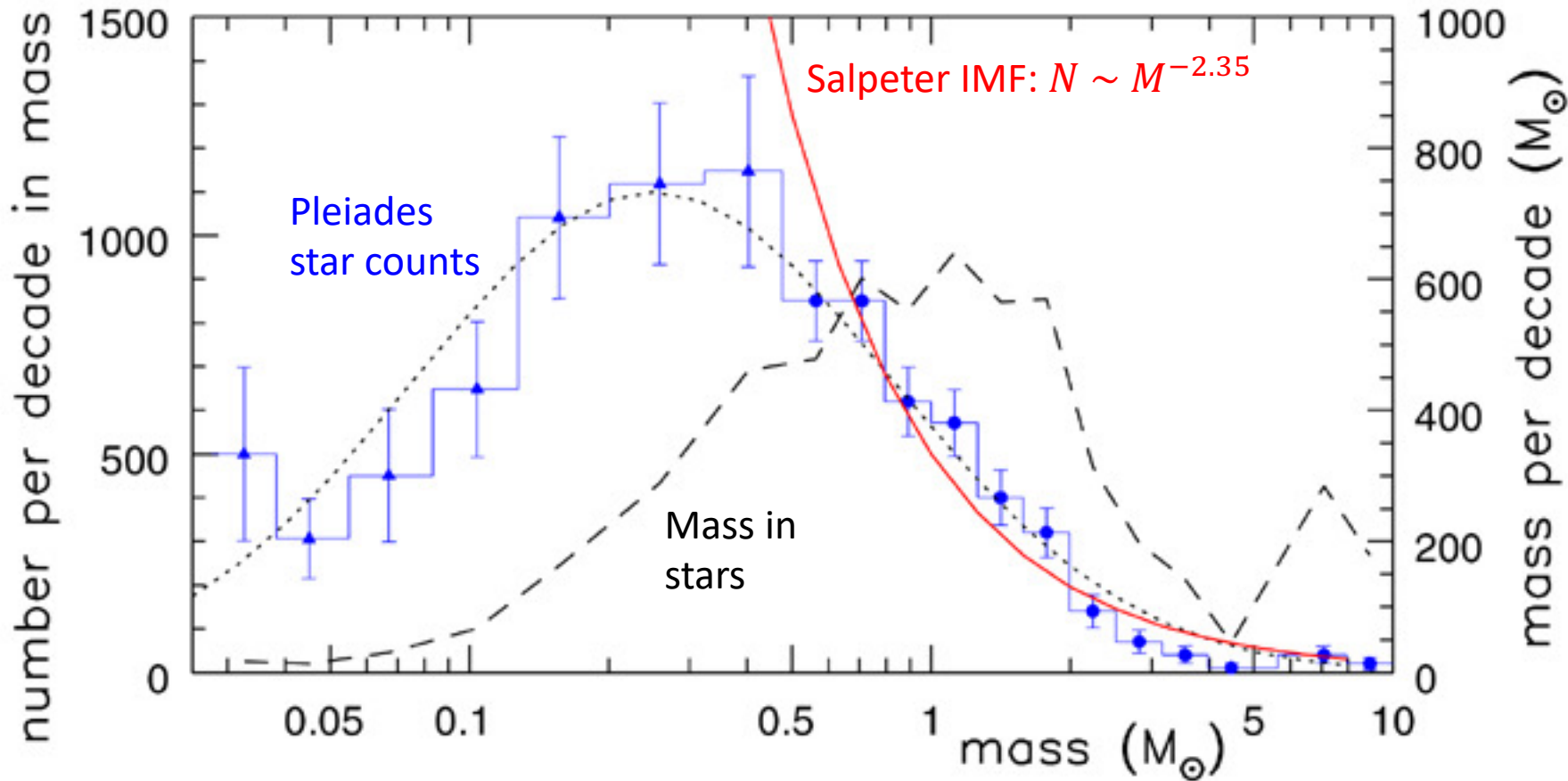


Fig 2.5 (E. Moreau) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007



dist  $\sim$  130 pc