

# PROPERTIES OF STARS

Lezione III- Fisica delle Galassie

Capitolo 3 di Binney & Merrifield (1998)

Lezione 4 di M. Pettini (<https://www.ast.cam.ac.uk/~pettini/STARS/>).

Cap. 'Binary Systems and Stellar Parameters'

Carrol & Ostlie

Laura Magrini

# Aim of this lecture

- Derive the main physical properties of stars from observations:
  - *Mass*
  - *Radius*
  - *Age*
  - *Chemical composition (in the next lectures)*
  
- Many physical relations involves these quantities
- They are often only theoretically determined

**→ Need strong observational constraints**

# The masses of stars

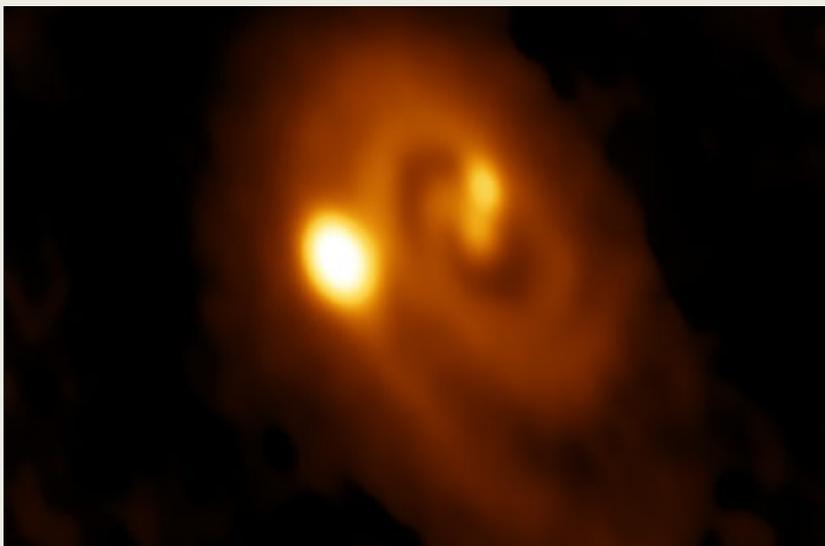
The most important property of a star is its **mass**.

- It determines the lifetime in the main sequence
- It determines the final evolution
- It can be measured ONLY studying the **gravitational interaction** with other objects
- It can be measured in Binary (or Multiple) Systems

We consider here only **binary systems**, dividing them in:

- Visual binaries
- Eclipsing binaries
- Spectroscopic binaries

# How many binary stars?

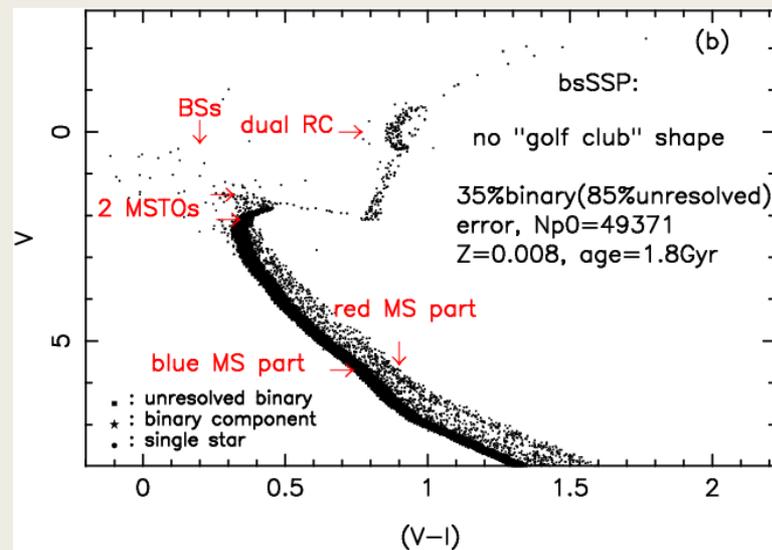


A radio image of a triple star system forming within a dusty disk in the Perseus molecular cloud obtained by ALMA in Chile.

(Image: Bill Saxton, ALMA (ESO/NAOJ/NRAO), NRAO/AUI/NSF)

- More binaries in the youngest systems
- Following the model of Stahler & Sadavoy (2017) all stars were born at least in binary system
- Even the Sun had a companion, named Nemesis

- Their presence has an effect on the Colour-Magnitude diagram
- Separate sequence for binary and single stars

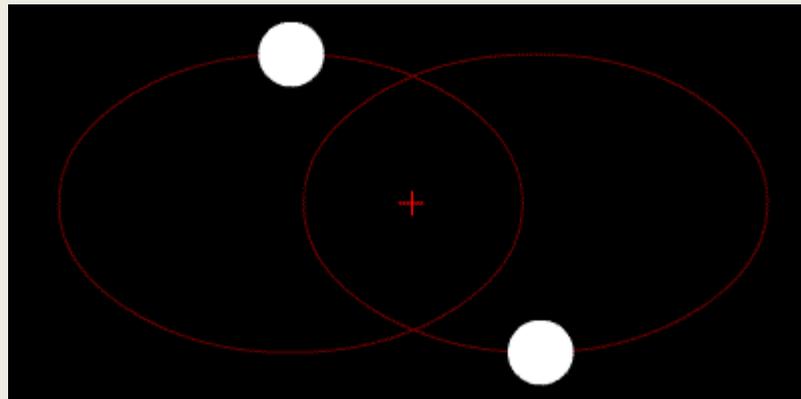


# Binary systems: Visual binaries

Stellar masses can be measured only in binary systems where we can estimate the effect of gravitational forces.

There are about **1000 close-binary systems**, in which both components are visible.

- Detached  $\rightarrow$  no interactions (material flowing from a star to the other)
- Strong bias towards the more common stars: **low-mass stars**
- Short or medium periods: **observational bias again!**

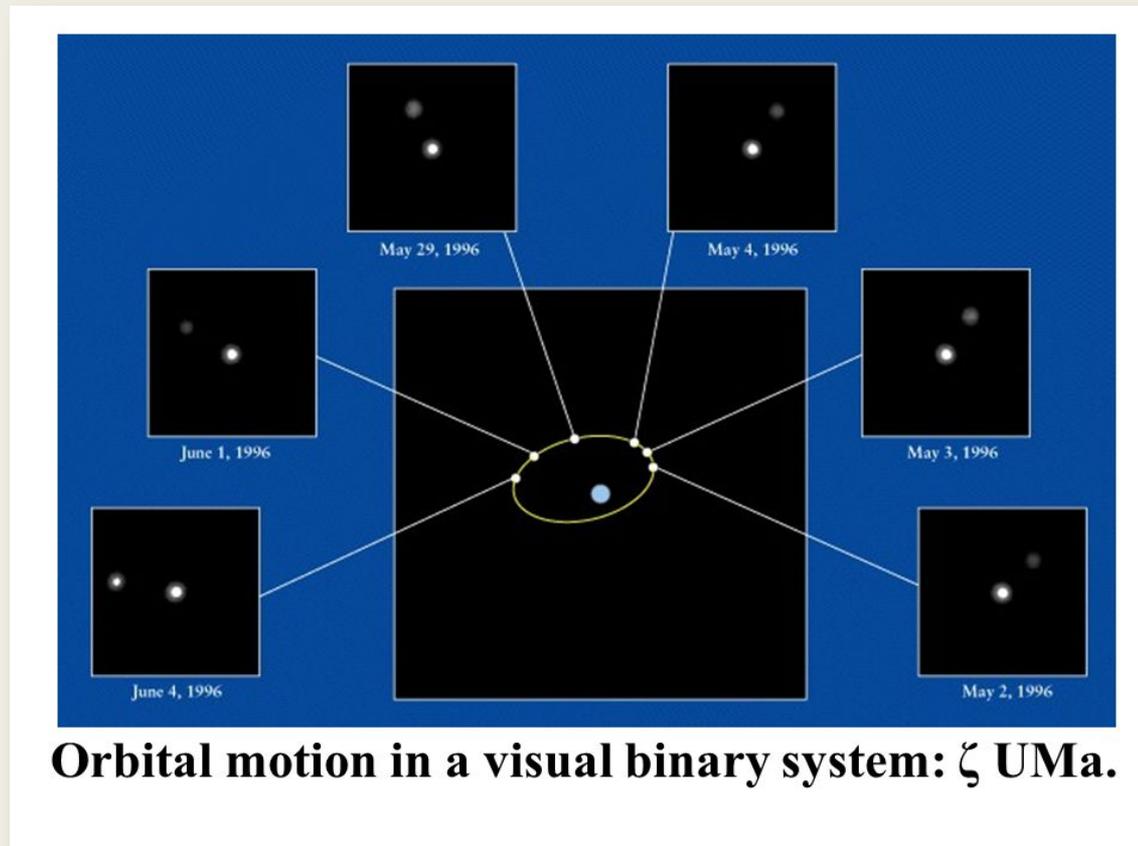


# Binary systems: Visual binaries

1. Both stars are visible: systems relatively close to us so that the individual stars can be resolved

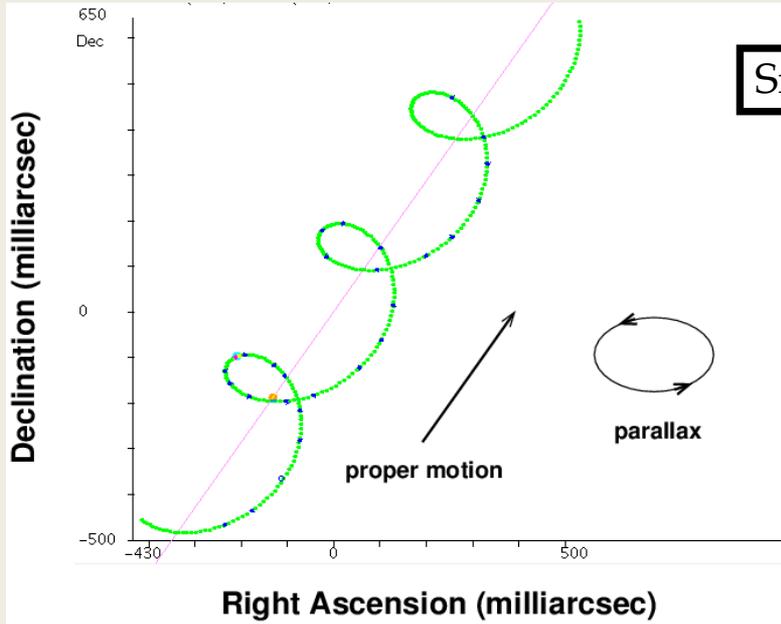
*Visual Binary*: their orbits can be studied → by monitoring them over the years

- Observations repeated in time to derive **orbital parameters**
- To **separate parallax, proper motion and orbit effects**

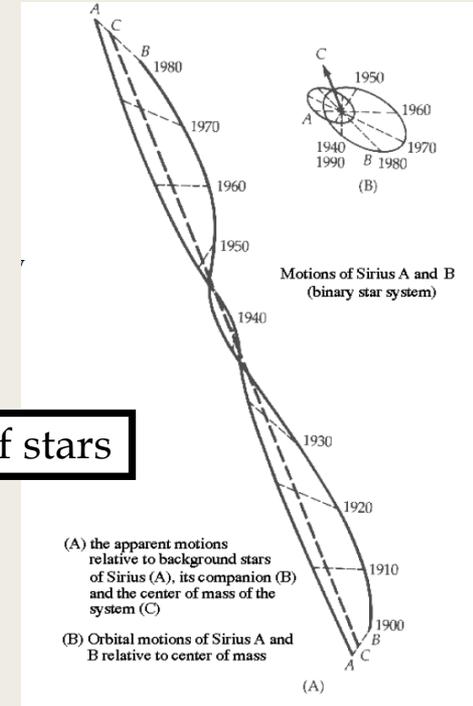


# Binary systems: Visual binaries

- **Separate parallax, proper motion and orbit effects**

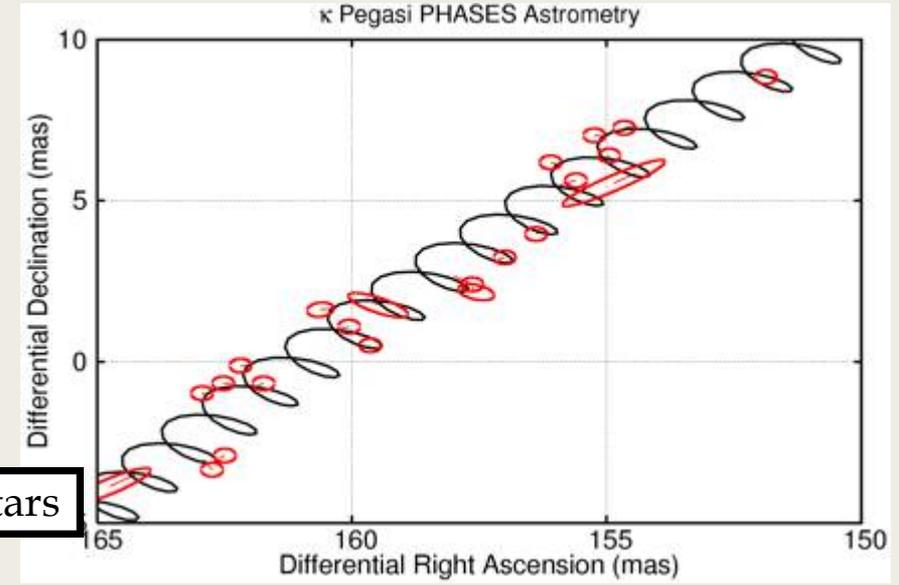


Single star



Binary system of stars

Triple system of stars



# Binary systems: Visual binaries

Face-on systems:

The distance from the **centre of mass** is inversely proportional to the mass of the stars:

$$m_1 r_1 = m_2 r_2$$

We can measure the angular distances from the centre of mass:

$$\vartheta_1 = r_1/d$$

$$\vartheta_2 = r_2/d$$

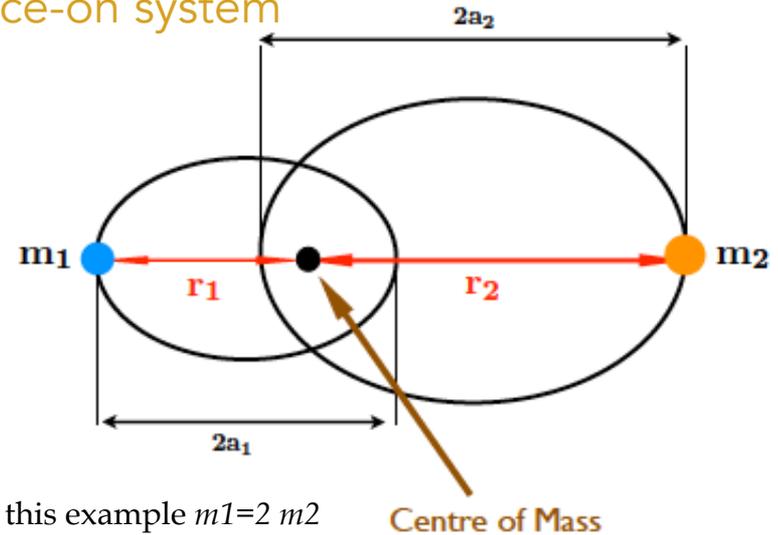
Where **d** is the linear distance to the system.

Thus the ratio between the angular distances of the two stars is

$$m_1/m_2 = \vartheta_2/\vartheta_1$$

proportional to the **mass ratio**.

Face-on system



In this example  $m_1 = 2 m_2$

Centre of Mass

From the general 3<sup>rd</sup> Kepler law we can derive also the total mass (where  $\vartheta = \vartheta_1 + \vartheta_2$ ):

$$m_1 + m_2 = \frac{4\pi^2}{G} \frac{(\theta d)^3}{P^2} :$$

And **having the mass ratio, we can have the masses of the two components**

**→ We must also know the distance d to the binary system**

# Binary systems: Visual binaries



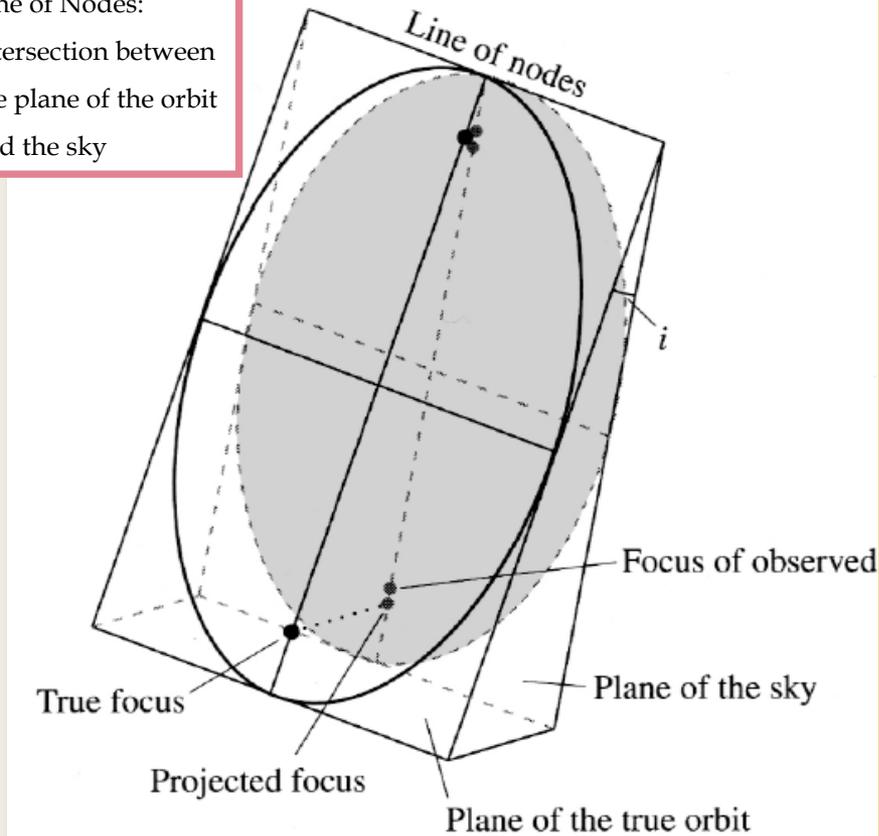
From the ideal face-on case, to real observations....

To derive the masses from the angular distance measurements  $\vartheta_1$  and  $\vartheta_2$ , we need:

- i) Measure the **parallax of the system** → they are usually close systems, thus their parallax can be measured → we need to observe the system for more than one year
- ii) Measure the **proper motion of the centre of mass** → find the point of the system that move at constant velocity
- iii) Derive the **inclination of the plane** of the orbit relative to the plane of the sky → it isn't easy!

# Binary systems: Visual binaries

Line of Nodes:  
intersection between  
the plane of the orbit  
and the sky



Consider the special case where the orbital plane is inclined at angle  $i$  to the plane of the sky.

Reality is more complex, and orbits are often inclined along both the major and minor axes!

If the system is inclined (angle  $i$ ), the mass ratio does not change

$$\vartheta_1' = \vartheta_1 \cos i$$

$$\vartheta_2' = \vartheta_2 \cos i$$

Thus the ratio between the angular distances of the two stars is:

$$m_1/m_2 = \vartheta_2'/\vartheta_1'$$

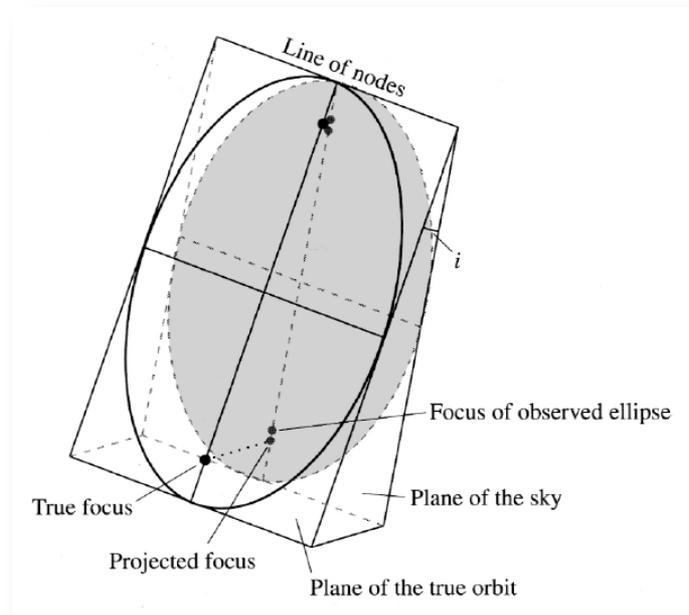
$$m_1 + m_2 = \frac{4\pi^2}{G} \frac{(\theta d)^3}{P^2} = \frac{4\pi^2}{G} \left( \frac{d}{\cos i} \right)^3 \frac{\theta^3}{P^2}$$

but **it affects the estimation of the total mass**, in which the uncertainty on the **determination of the cosine remains**.

# Binary systems: Visual binaries

To evaluate the sum of the masses properly → **measure the inclination angle  $i$**

- Estimate the differences in the location of the **focus of the observed ellipse** and the centre of mass (located at the position of the **projection of the 'true' focus on the plane of the sky**)

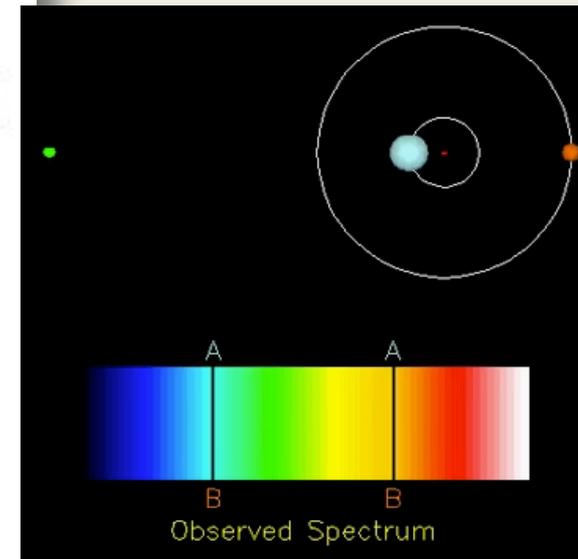
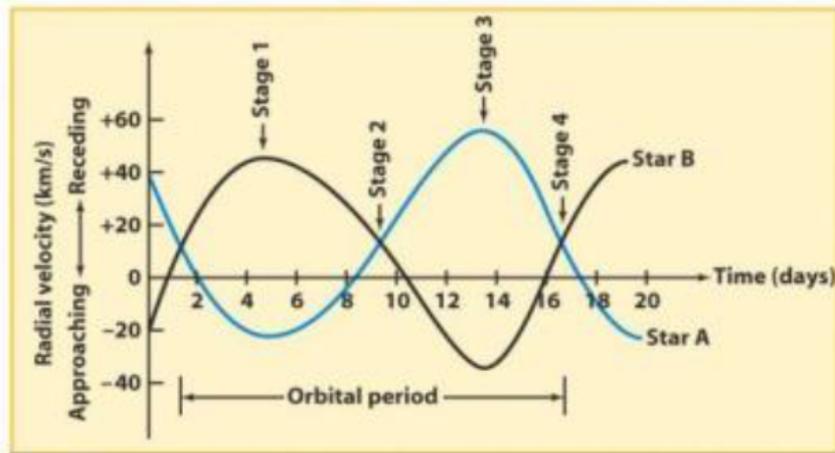
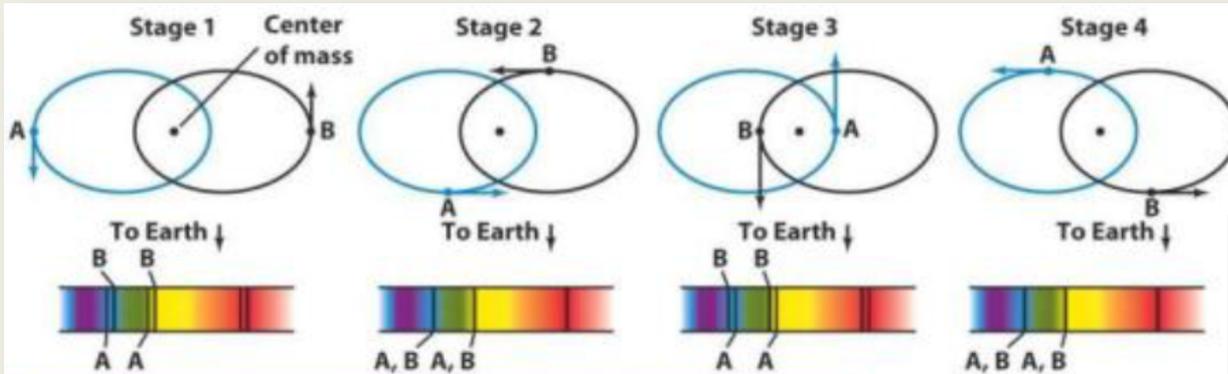


- The real situation is even more complicated because in general the orbital plane is inclined along the minor and major axes!

# Binary systems: Spectroscopic binaries

2. The stars cannot be separated (more distant objects or more close orbits)

- the spectrum of the system is seen as the superposition of two set of spectral features (different if stars have different spectral type) → **double-lined spectroscopic binaries**
- their orbital motions are seen as Doppler shifts in their spectra.

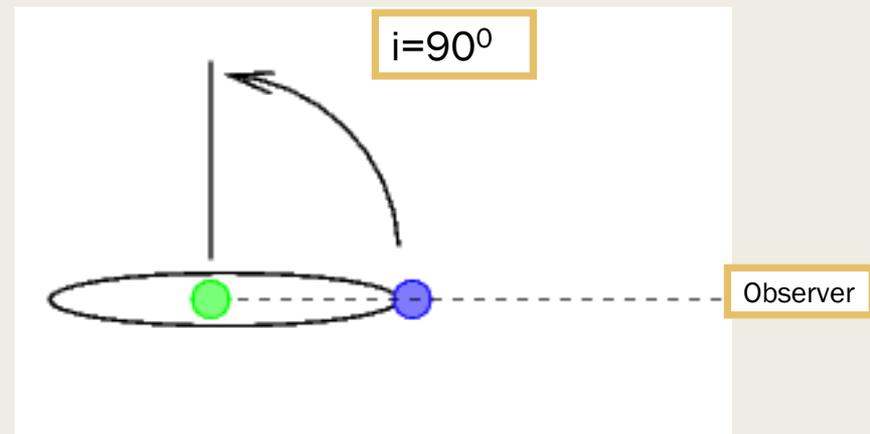
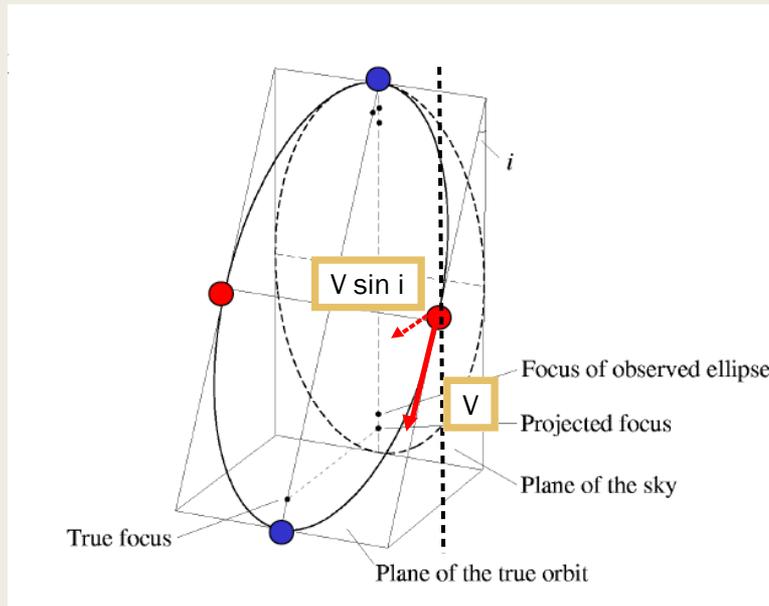


# Binary systems: Spectroscopic binaries

- The radial velocity component (to Earth) modify periodically the composite spectra of the system
- Need repeated observations

The maximum blueshift and redshift we measure within an orbit are lower limits to the true velocities because of the unknown inclination  $i$  of the orbital plane to the line of sight:

$$v_{1 \text{ rmax}} = v_1 \sin i \text{ and } v_{2 \text{ rmax}} = v_2 \sin i.$$



# Binary systems: Spectroscopic binaries

Considering that spectroscopic binary are close systems, they tend to have circular orbits (tidal forces) and their velocities can be expressed as:

- $v_1 = 2\pi a_1/P$  and  $v_2 = 2\pi a_2/P \rightarrow$  at small eccentricities  $e \ll 1$  the orbital velocity is constant

Thus  $m_1/m_2 = a_2/a_1 = v_2/v_1$  and expressed with the observed quantities

$$m_1 / m_2 = v_{2r} / v_{1r}$$

(independent of the inclination angle)

However, the sum of the masses does require the knowledge of  $\sin i$ .

$$m_1 + m_2 = \frac{P}{2\pi G} \frac{(v_{1r} + v_{2r})^3}{\sin^3 i}.$$

**$\sin i$  cannot be measured**, and thus we assume that the orbits are **randomly inclined** relative to our line of sight and use the integral average of  $\sin^3 i$  between  $0^\circ$  and  $90^\circ$  to give a statistical estimate,  $\langle \sin^3 i \rangle \sim 0.589$

# The units of stellar mass

## Stellar masses are measured in units of Solar mass

- Considering that the mass of the Sun is much larger than the Earth mass, we have:

$$G M_{\odot} P_{\oplus}^2 = 4 \pi^2 a_{\oplus}^3$$

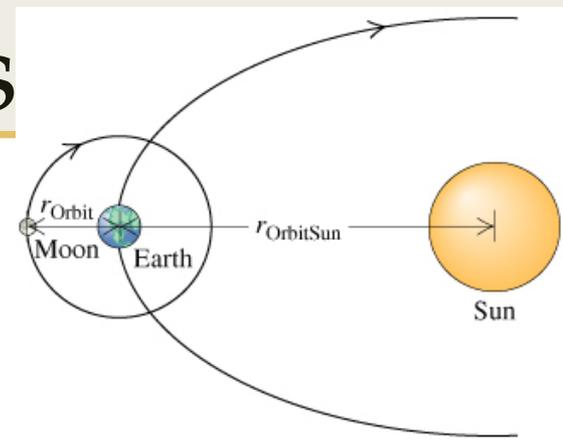
where  $P_{\oplus}$  is the period of revolution (1 year),  $a$  is the mean distance Earth-Sun (1 AU).

- Taking the ratio between the general equation and that for the Earth-Sun system

$$(m_1 + m_2) P^2 = a^3$$

So, if periods are expressed in years and distances in AU, star masses will be in Solar masses → we usually derive the total mass of the system

$M_{\odot} = 1.99 \times 10^{33}$  kg [the mass of the Sun is computed in the same way, considering the system Earth/Moon]



# Binary systems: Eclipsing binaries

## 2. The stars cannot be separated

- *Eclipsing Binary*: the total brightness drops when they periodically eclipse each other.
- There is no ambiguity about the orientation of the orbit (the orbit on the same plane, edge-on,  $i=90^\circ$  or close to it)  $\rightarrow$  note that for  $i > 75^\circ$ ,  $\sin(i) > 0.9$ , so the error in the masses, assuming  $i=90^\circ$  is only 10%!

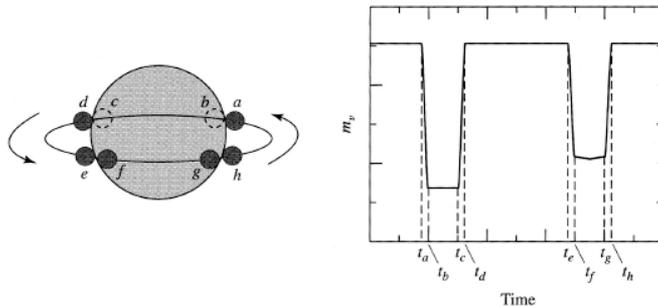
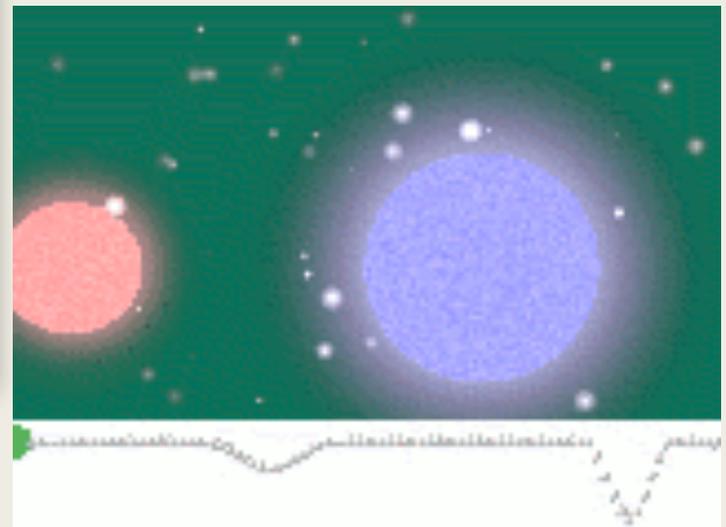


Figure 4.6: Schematic diagram of an eclipsing binary. The smaller star is assumed to be hotter than the larger one. (Reproduced from Carroll & Ostlie's *Modern Astrophysics*).



# Binary systems: Stellar radii

We can both measure the mass of the system, and, moreover, the **radii of the two stars**.

When the **eclipse is total**, we can deduce the radii of both stars from **accurate timing of the phases of the eclipse**.

With the assumption the the secondary stars is moving perpendicularly to our line-of-sight during the eclipse, the radius can be derived:

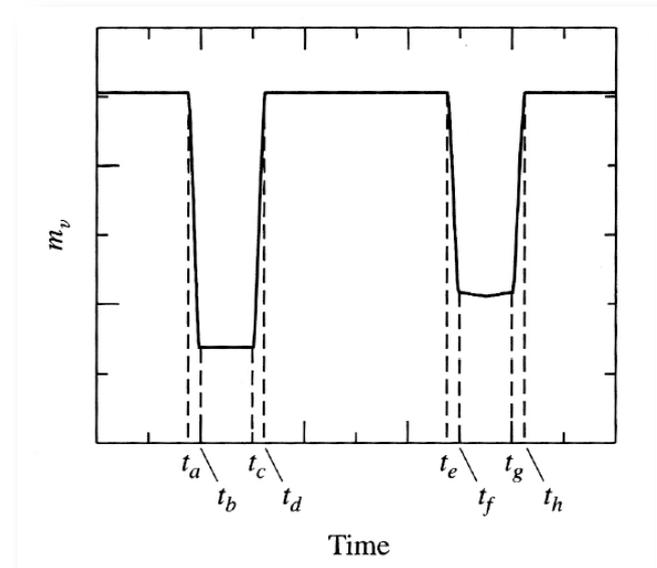
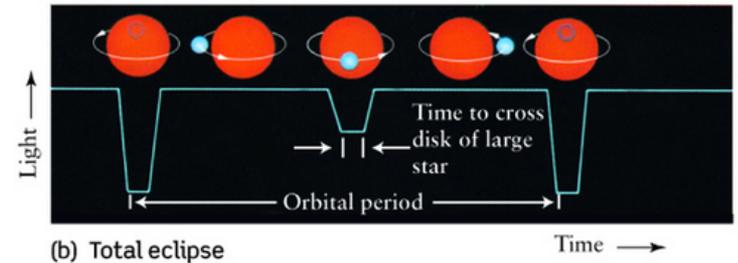
Secondary star

$$r_s = \frac{v}{2} (t_b - t_a)$$

Primary star

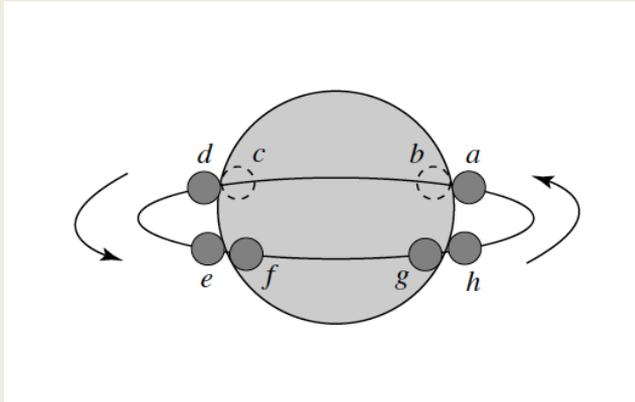
$$r_l = \frac{v}{2} (t_c - t_a)$$

Where  $t_a$  and  $t_b$  are the times of the **first contact** and **minimum light**, respectively, and  $v=v_a+v_b$  is the relative velocity of the two stars



# Binary systems: effective temperatures

The ratio of the effective temperatures of two stars in an eclipsing system can be estimated assuming that they are Black Bodies, and measuring the amount of light received during the eclipse.



$F_r = \sigma T^4 \rightarrow$  radiative surface flux

When both stars are visible:

$$B_0 = k (\pi r_\ell^2 F_{r\ell} + \pi r_s^2 F_{rs})$$

$F_{r\ell}$  and  $F_{rs}$  are the radiative flux of the primary and secondary stars.

**Primary minimum:** when the hotter star (in this case the smallest one) pass behind the primary companion.

$$B_p = k \pi r_\ell^2 F_{r\ell}$$

**Secondary minimum:** when the hotter star (in this case the smallest one) pass behind the primary companion.

$$B_s = k (\pi r_\ell^2 - \pi r_s^2) F_{r\ell} + k \pi r_s^2 F_{rs}$$

# Binary systems: effective temperatures

$$\frac{B_0 - B_p}{B_0 - B_s} = \frac{F_{rs}}{F_{r\ell}}$$

$$\frac{B_0 - B_p}{B_0 - B_s} = \left( \frac{T_s}{T_\ell} \right)^4 .$$

What we usually measure are magnitudes, so for instance, if the maximum magnitude (both stars visible) is  $m_0=6.3$ , and  $m_{\text{prim\_min}}=9.6$ , and  $m_{\text{sec\_min}}=6.6$ , we can derive:

$$\frac{B_p}{B_0} = 100^{(m_{\text{bol},0} - m_{\text{bol},p})/5} = 0.048.$$

( $m=2.5 \log L \rightarrow L=10^{(2m/5)}=100^{m/5}$ .....)

$$\frac{B_s}{B_0} = 100^{(m_{\text{bol},0} - m_{\text{bol},s})/5} = 0.76.$$

And thus, we can find the ratios between the radiative fluxes and the temperatures.

$$\frac{F_{rs}}{F_{r\ell}} = \frac{1 - B_p/B_0}{1 - B_s/B_0} = 3.97. \quad \longrightarrow \quad \frac{T_s}{T_\ell} = \left( \frac{F_{rs}}{F_{r\ell}} \right)^{1/4} = 1.41.$$

# Interferometry: Stellar radii

- INTERFEROMETRY for nearby stars

Long baseline interferometers now measure the angular diameters of nearby stars with sub-percent accuracy.

The finite angular size of a star (in Figure  $\alpha$ -Cen A with an angular diameter of 8.5 mas) causes a **reduction of the contrast of the fringes**, that can be measured with great accuracy.

There is a direct relation between the **visibility of the fringes and the angular size of the star** (Zernike-Van Cittert theorem), that allows to **retrieve the angular size of the star**.

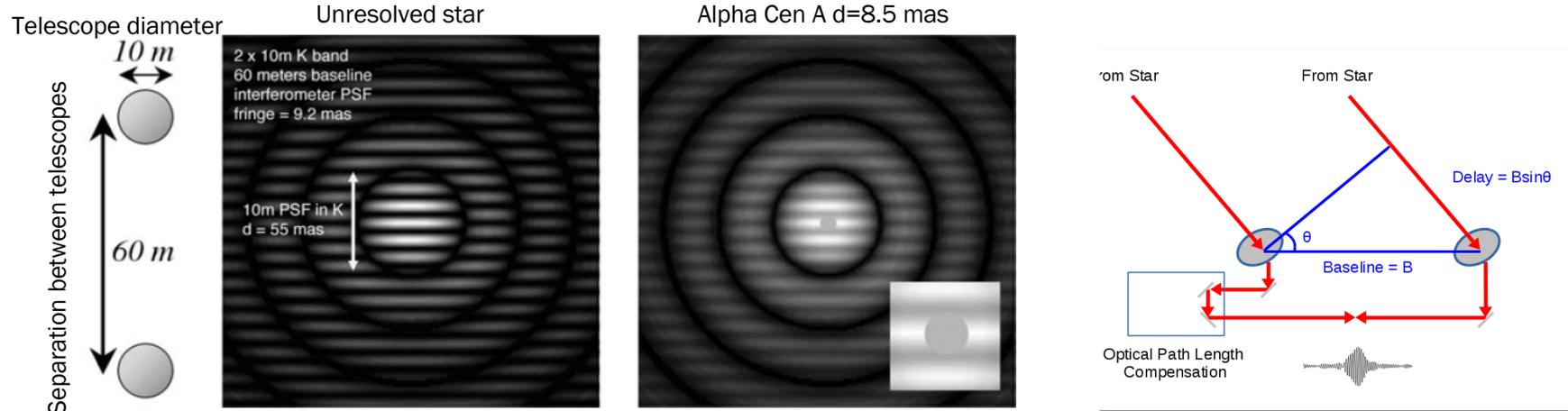


Figure 1. *Left:* Pupil of an interferometer of two 10 m telescopes separated by 60 m. *Middle:* Point Spread Function of this interferometer, when operated in the K band. The fringe spacing is 9.2 mas. *Right:* Image of  $\alpha$  Cen A ( $\theta \approx 8.5$  mas) formed by this interferometer, with the superimposed stellar disk. The fringes have a lower contrast than on the left, as the star is partially resolved. As shown in the insert on the right, the light from the stellar disk "leaks" in the dark fringes.

# Lunar occultation: Stellar radii

- LUNAR OCCULTATIONS

The angular velocity of the Moon is  $0''.52/s$ .  
A star similar to the Sun, at 10 pc, has  $d= 0.00038''$ .

$$t=0.00038'' / 0.52'' s^{-1} = 0.0007 \text{ s}$$

→ We need to measure **very short time intervals!**

The occultation pattern varies:

- for dwarf is diffraction limited
- giant stars has a smooth profile

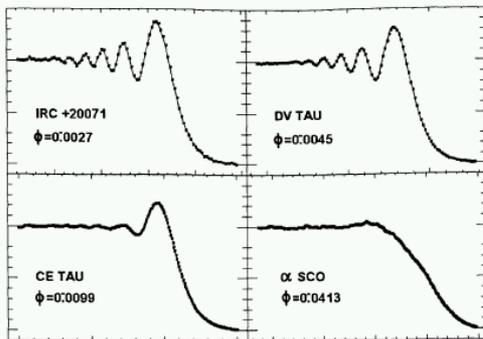
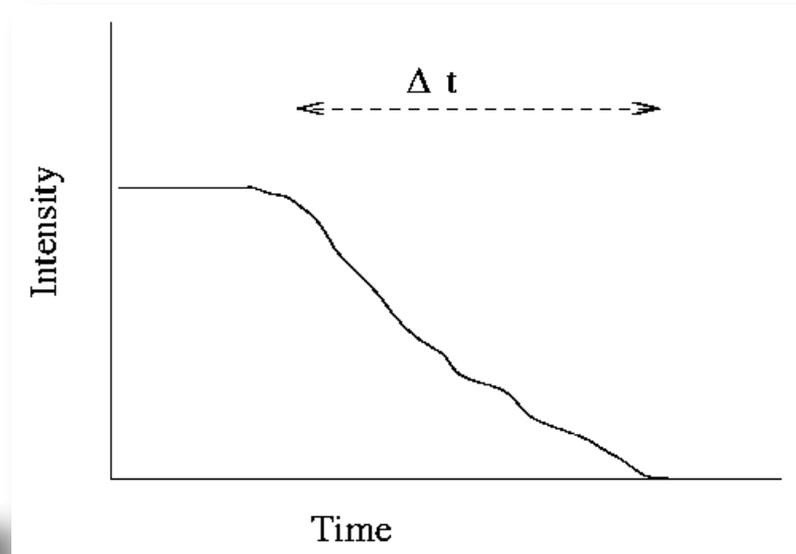


Figure 1. Occultation data (dots) and corresponding fits (solid lines) for four late-type stars with increasing angular diameter (data of the Arcetri LO group). The axes have been rescaled for each data set, bringing the time of occultation and the rate of the event to a common value and renormalizing the intensity values, in order to provide a more direct illustration of the phenomenon of fringe smoothing as a function of the angular

# From the Stefan-Boltzmann law: Stellar radii

Stefan-Boltzmann Law gives us the **energy radiated** per **sec** per **unit area** on the surface of a blackbody

$$E = \sigma T^4$$

where  $\sigma$  is a constant,  $\sigma = 5.67 \cdot 10^{-5} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ K}^{-4}$

The total amount of energy radiated per second by a star (the luminosity) can be found by multiplying  $E$  in the equation above by the **total surface area of the star**.

For a sphere, the area is  $4\pi R^2$ , where  $R$  is the radius of the star.

$$L = (4 \pi R^2) \sigma T^4$$

We can also find the temperature using Wien's law or from spectroscopy.

Therefore, we can then find the radius using

$$R = \sqrt{L/4 \pi \sigma T^4}$$

\* Here we assume that the star is Black Body

# From the Stefan-Boltzmann law: an example

## Stellar radii are usually given in Solar units:

From the S-B law, we have

$$L/L_{\odot} = (4\pi\sigma R^2 T^4)/(4\pi\sigma R_{\odot}^2 T_{\odot}^4) = (R/R_{\odot})^2 (T/T_{\odot})^4$$

$$R/R_{\odot} = (T_{\odot}/T)^2 (L/L_{\odot})^{1/2}$$

To find the ratio  $L/L_{\odot}$ , we use the absolute magnitudes of the stars.

The magnitude scale is a logarithmic scale. For every decrease in brightness of 1 magnitude, the star is 2.51 times as bright. Therefore,  $L/L_{\odot}$  can be found from the equation

$$L/L_{\odot} = 2.51^{\Delta m}$$

where  $\Delta m = m_{\odot} - m$

**Sirius** has a visual magnitude of -1.44 and a parallax of  $p=379.21$  mas. From the parallax, we estimate distance:

$$d = 1/p = 1/0''.37921 = 2.63 \text{ pc}$$

The absolute magnitude is:

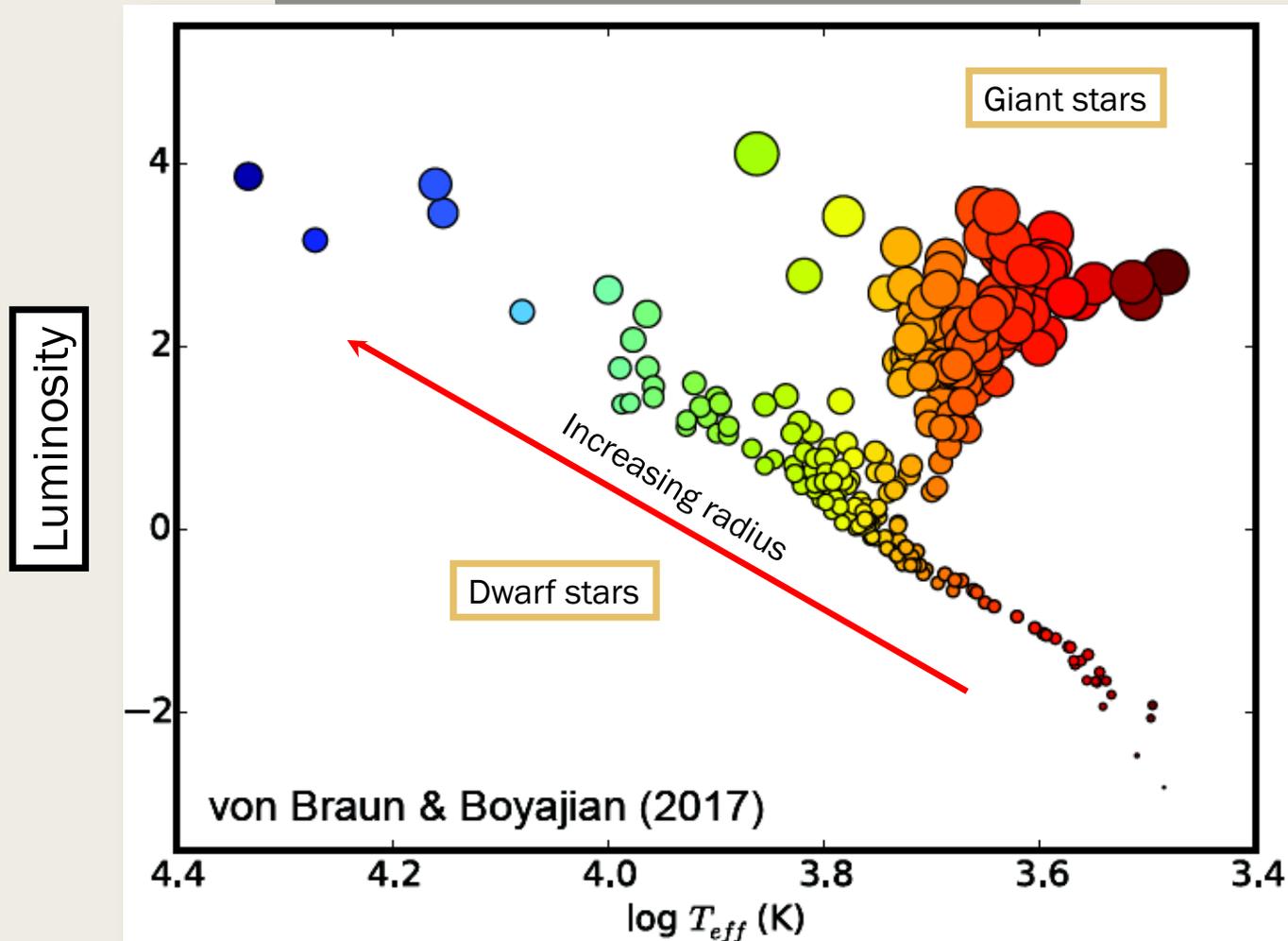
$$M = m - 5 \log d + 5 = -1.44 - 5 \log (2.63) + 5 = 1.46$$

The Sun has an absolute magnitude of 4.83, a temperature  $\sim 5800\text{K}$  and the temperature of Sirius is  $\sim 9500\text{K}$ .

$$R/R_{\odot} = (5800/9500)^2 (2.51^{3.37})^{1/2} = 1.76$$

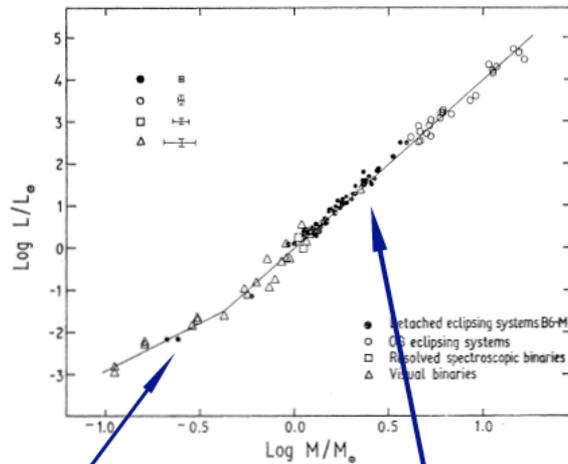
# Comparing observations with theory: stellar radii in and out the main sequence

Empirical stellar radii in the HR diagram



# Comparing observations with theory: The mass-luminosity relationship

When we bring together the best determinations of stellar masses from different types of binary stars, we find a well defined mass-luminosity relation for hydrogen burning dwarf stars:

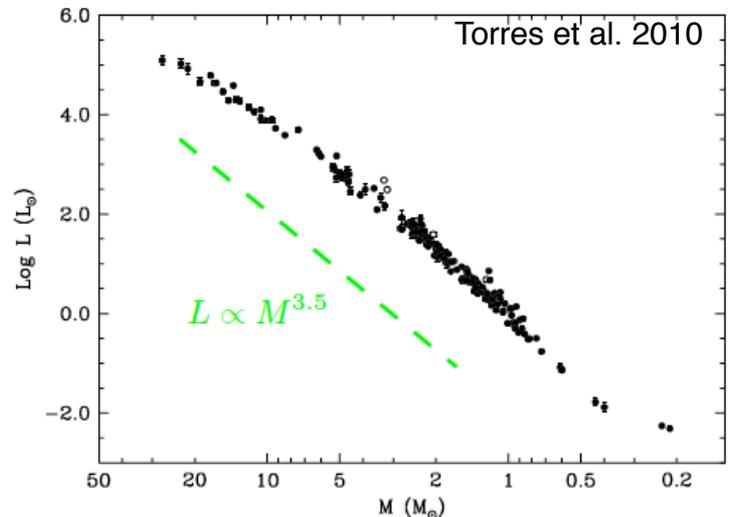


R C Smith 1983

$$\frac{L}{L_{\odot}} \propto \left(\frac{M}{M_{\odot}}\right)^{2.3}$$

$$\frac{L}{L_{\odot}} \propto \left(\frac{M}{M_{\odot}}\right)^4$$

- Theories of stellar evolution must be able to reproduce such a relationship
- The location in the plane is determined only by the mass
- **Stars do not evolve along the main sequence, they evolve off the main sequence.**



Torres et al. 2010

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

- If  $L \propto dM/dT$  then  $T \propto M/L = M^{-2.5}$

the steep slope of the stellar mass luminosity relation implies a very strong dependence of the **stellar lifetimes** on their **mass**

# The spectral classification of stars

We have seen how the main parameters (**mass and radius**) can be measured, now we want to **infer other quantities from the spectral appearance of stars**:

- Stars are classified via their spectra
- The classical classification schema:

O B A F G M [R N S]

Based on the observed variation of **ratios of line strengths** of successive ionization stages of chemical elements has then been recognized to be primarily a temperature sequence.

Class	$T_{\text{eff}}$ (K)
O	$\geq 33\,000$
B	10 000 – 33 000
A	7500 – 10 000
F	6000 – 7500
G	5200 – 6000
K	3700 – 5200
M	$\leq 3700$

# The spectral classification of stars

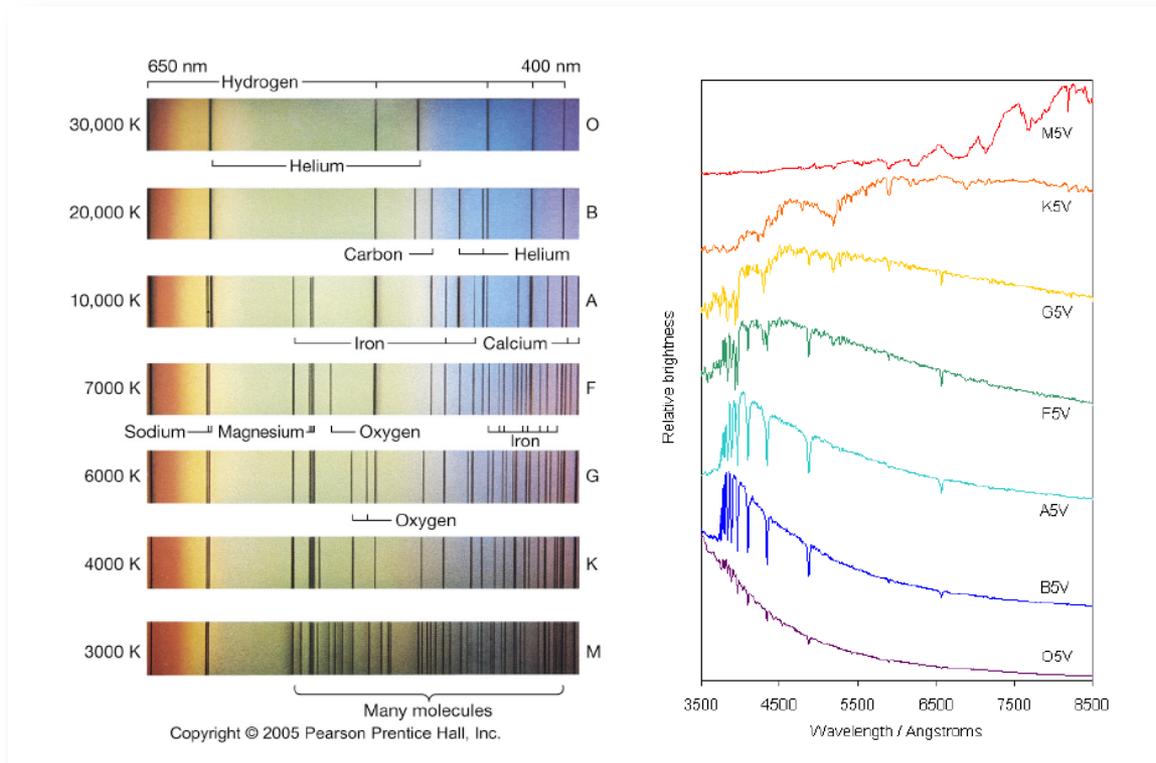
TABLE 1 Harvard Spectral Classification.

Spectral Type	Characteristics
O	Hottest blue-white stars with few lines Strong He II absorption (sometimes emission) lines. He I absorption lines becoming stronger.
B	Hot blue-white He I absorption lines strongest at B2. H I (Balmer) absorption lines becoming stronger.
A	White Balmer absorption lines strongest at A0, becoming weaker later. Ca II absorption lines becoming stronger.
F	Yellow-white Ca II lines continue to strengthen as Balmer lines continue to weaken. Neutral metal absorption lines (Fe I, Cr I).
G	Yellow Solar-type spectra. Ca II lines continue becoming stronger. Fe I, other neutral metal lines becoming stronger.
K	Cool orange Ca II H and K lines strongest at K0, becoming weaker later. Spectra dominated by metal absorption lines.
M	Cool red Spectra dominated by molecular absorption bands, especially titanium oxide (TiO) and vanadium oxide (VO). Neutral metal absorption lines remain strong.
L	Very cool, dark red Stronger in infrared than visible. Strong molecular absorption bands of metal hydrides (CrH, FeH), water (H <sub>2</sub> O), carbon monoxide (CO), and alkali metals (Na, K, Rb, Cs). TiO and VO are weakening.
T	Coollest, Infrared Strong methane (CH <sub>4</sub> ) bands but weakening CO bands.

Need mechanical statistics  
to understand them!

# The spectral classification of stars

Each class is subdivided into 10 sub-classes, with  $T_{\text{eff}}$  decreasing from sub-class 0 to 9. Thus we have spectral classes O9 and B0, the former being just hotter than the latter.



O and B → 'early-type'  
K and M → 'late-type'.

# The spectral classification of stars

## The meaning of the spectral sub-classes (luminosity classes):

Antonia Maury noticed difference between stars with the same temperature but with different luminosity, call c-characteristic.

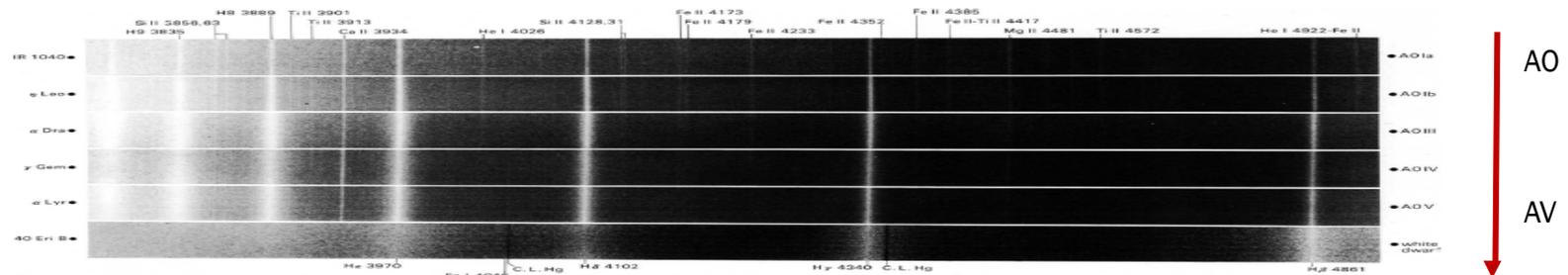
If we consider stars of the same  $T_{\text{eff}}$  but different luminosity, we have, from the Stefan-Boltzmann law, that the star should have a different radius.

$$L=4\pi\sigma R^2T_{\text{eff}}^4$$

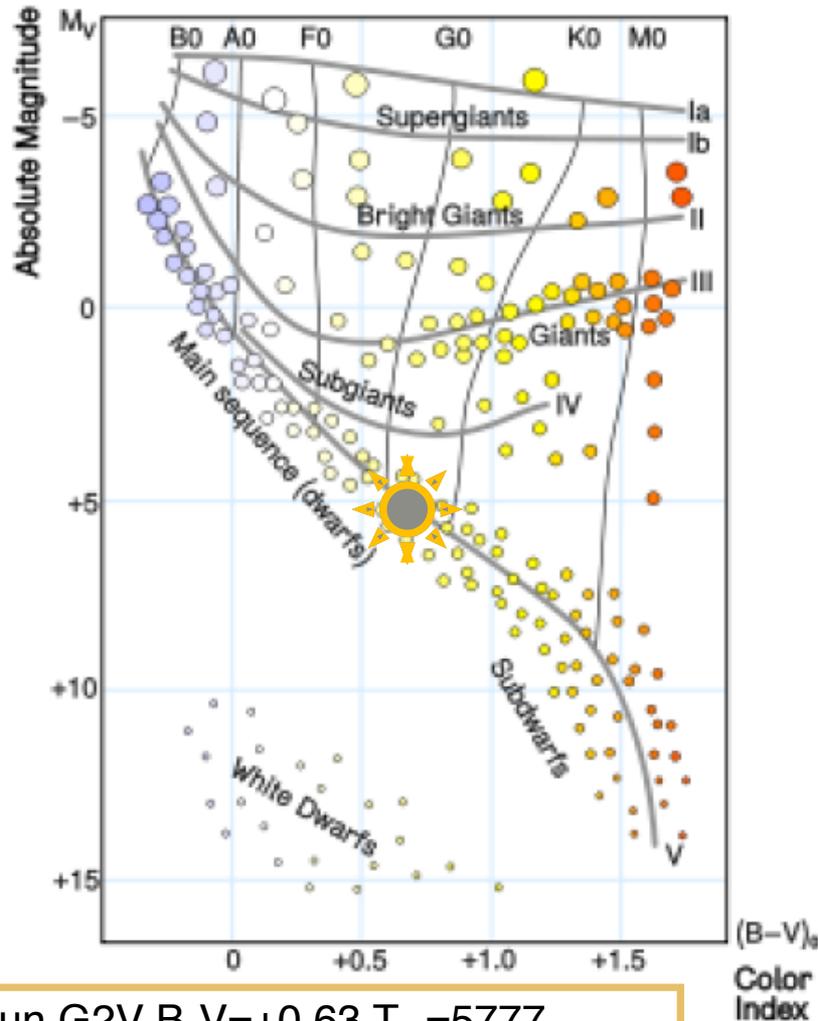
For instance, the surface density and gravity are lower in stars of larger radii.

As a consequence, stars with different luminosities (at a given  $T_{\text{eff}}$ ) will have different conditions in their photospheres and their spectra will contain different absorption lines.

**Thus, the absorption line widths provide a measure of the 'Luminosity Class'.**



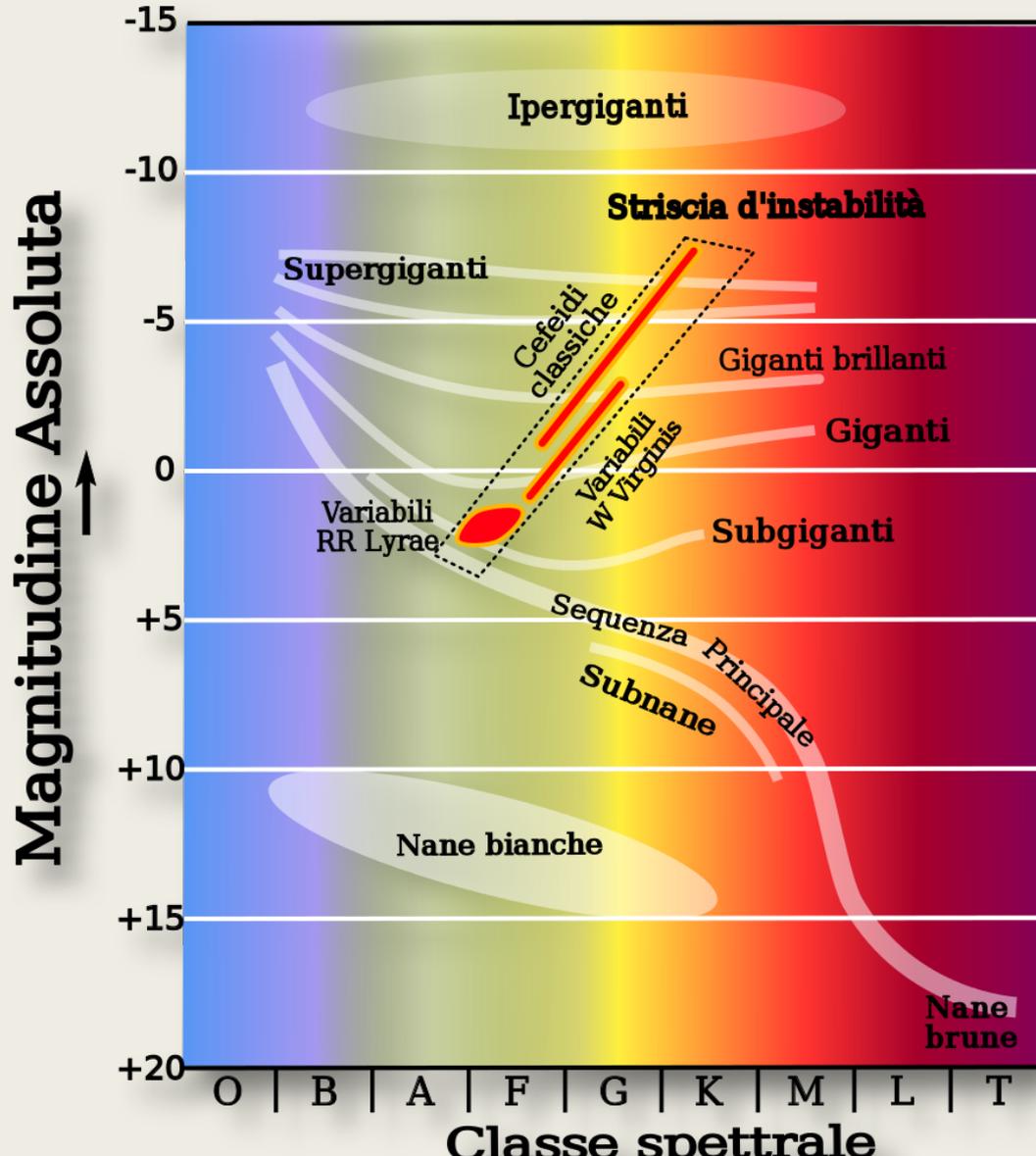
# The spectral classification of stars



Luminosity classes are indicated by roman numerals, from I to V in order of decreasing luminosity.

- Class I: supergiants
- Class II: bright giants
- Class III: giants
- Class IV: subgiants
- Class V: main sequence, sometimes referred as 'dwarfs'.

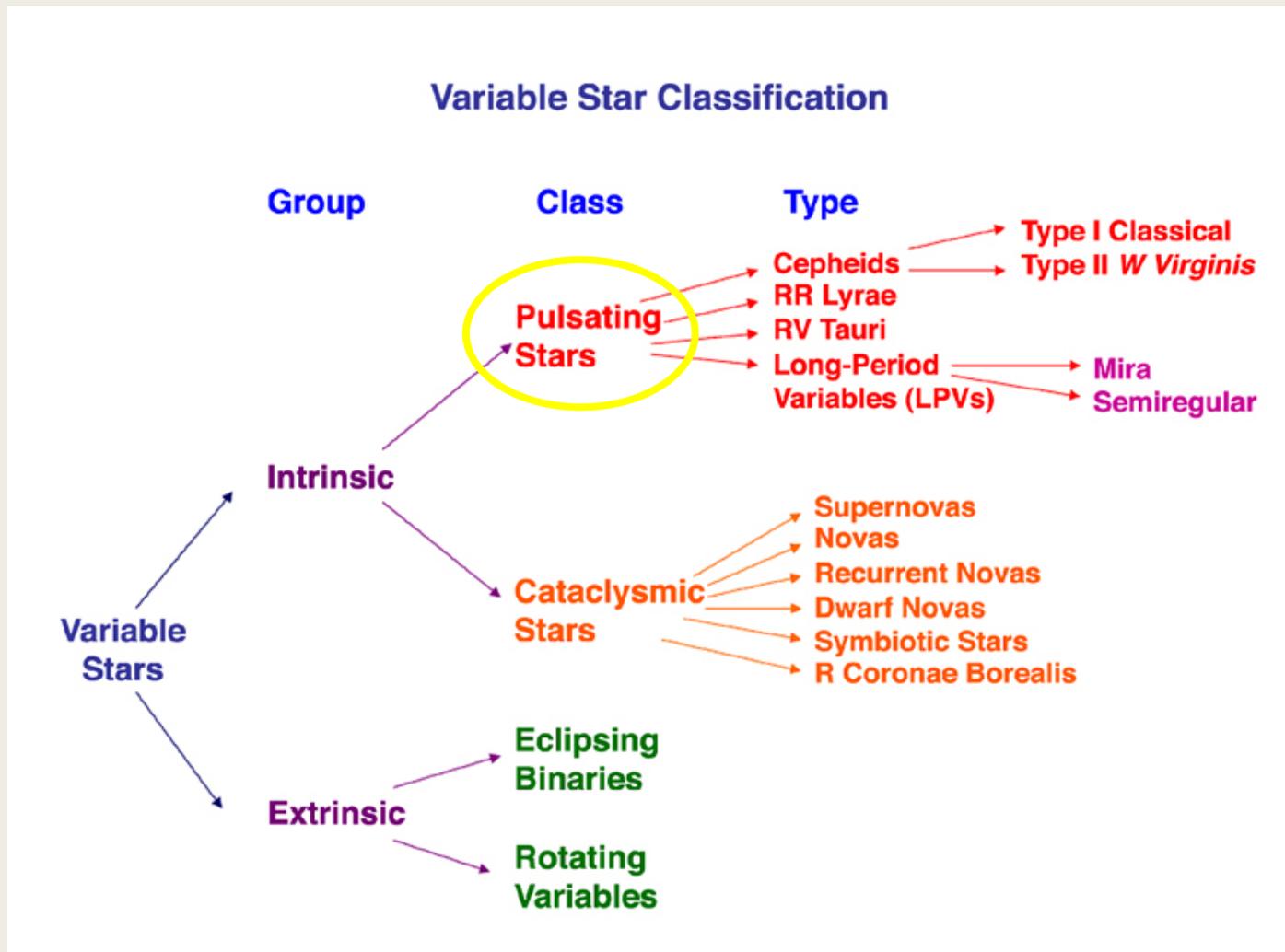
# The classification of stars: variability



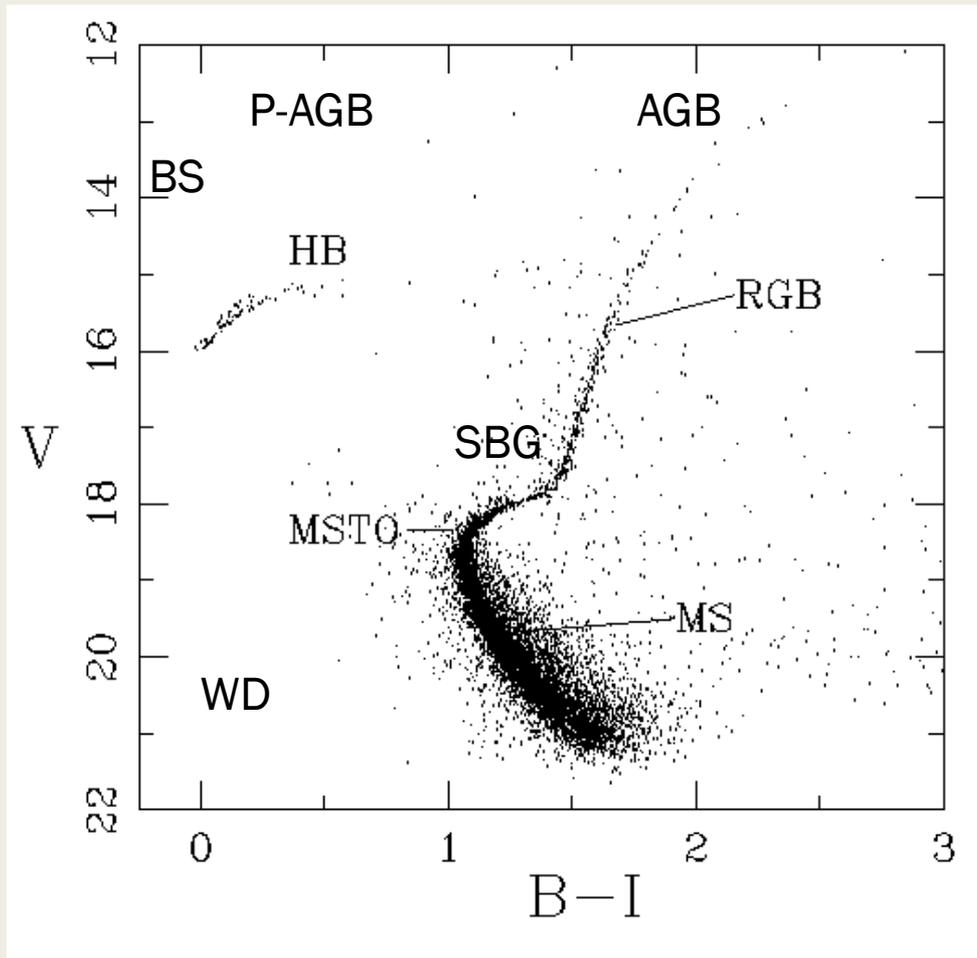
Stars outside the standard classification system:

- Cepheids
- RR Lyrae
- Variable stars

# The classification of stars: variability

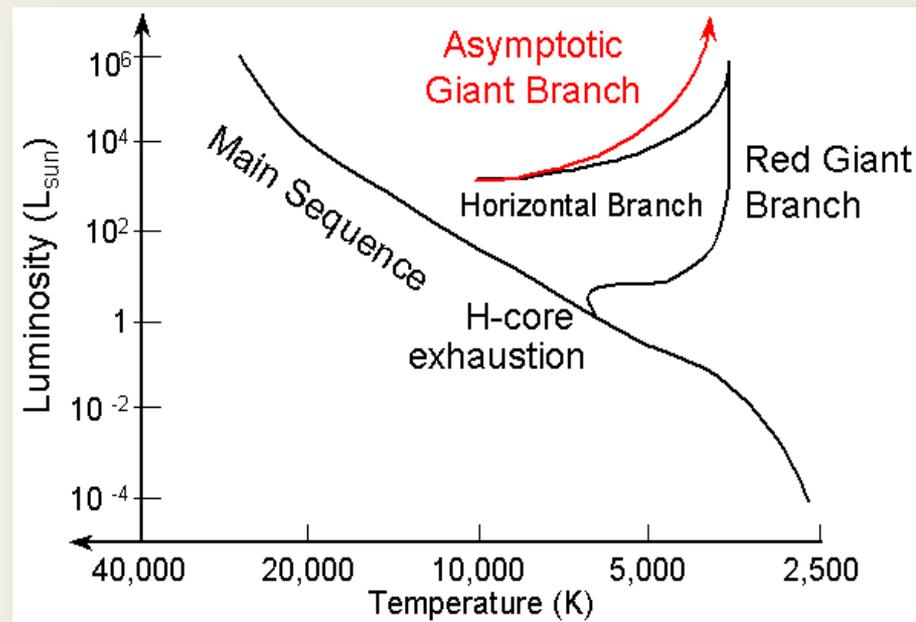


# The HR diagram: classification based on the evolutionary phase



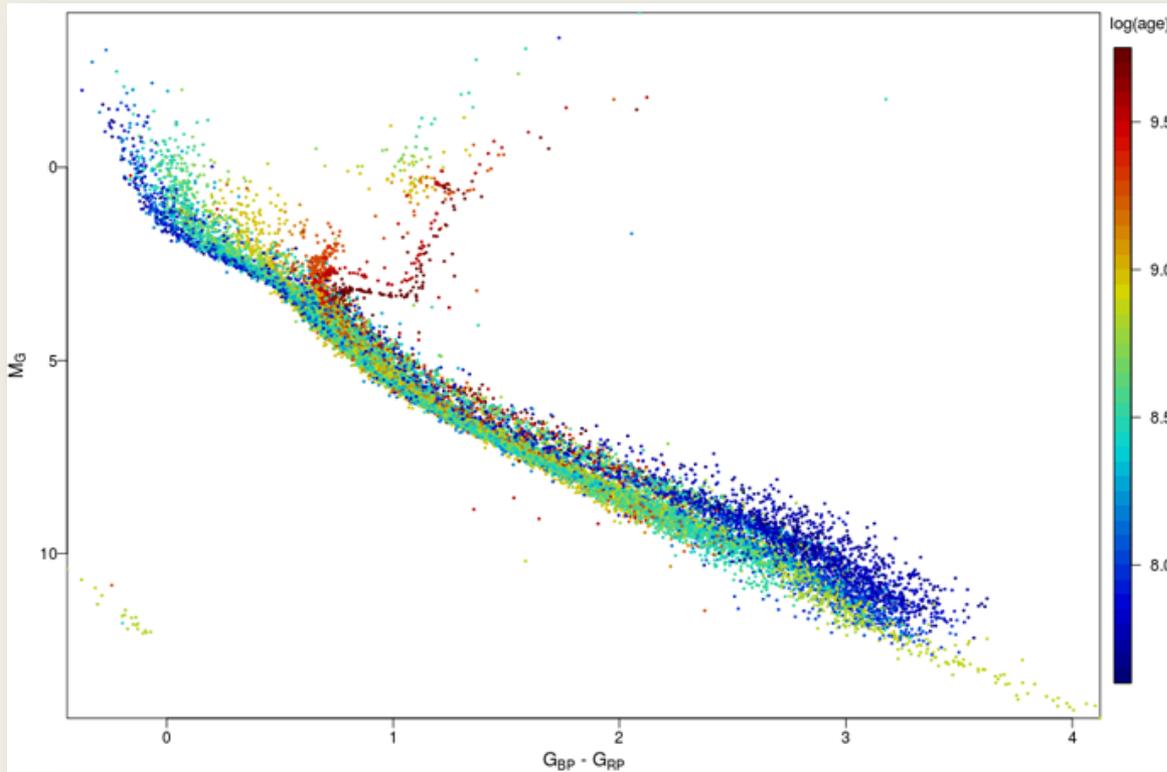
- MS: phase of burning hydrogen in cores
- MSTO (turn-off): end of the MS phase.
- SGB (sub-giant branch): H burning in shell, with increasing brightness
- RGB (red giant branch): the star burns He, and loses mass and eventually becomes a horizontal branch (HB) star.
- AGB (asymptotic giant branch): after the He fusion in its core, energy comes from He fusion in a shell around the inert carbon-oxygen core
- P-AGB (Post-AGB): towards the WD phase
- Blue stragglers (BS) affected by close encounters in the dense cluster region
- WD (white dwarf): no nuclear reaction

# The HR diagram: classification based on the evolutionary phase



- This classification is related to stellar evolution.
- Here an example of the evolution of a low- and intermediate mass stars in the HR diagram
- In a cluster (group of coeval stars) the presence of stars in some evolutionary stages is indicative of the cluster age.

# From the HR diagram: information on the stellar age



HR diagrams of star clusters (coeval and chemically homogeneous group of stars) allows us to analyze evolutionary effects.

This image shows a combined HRD for 32 open clusters made with the second Gaia data release data.

Colour indicates cluster age: stars that are members of younger clusters are shown in blue, stars belonging to older clusters - in red. **The effects of cluster age can clearly be distinguished ( $T \propto M^{-2.5}$ , older cluster less massive MS-TO stars...)**

# Ages of stars

For stars that do not belong to star clusters, measuring ages is much more difficult.

A stellar population is a mixture of stars with different ages, stars in particular evolutionary phases can give indication of the age of the population.

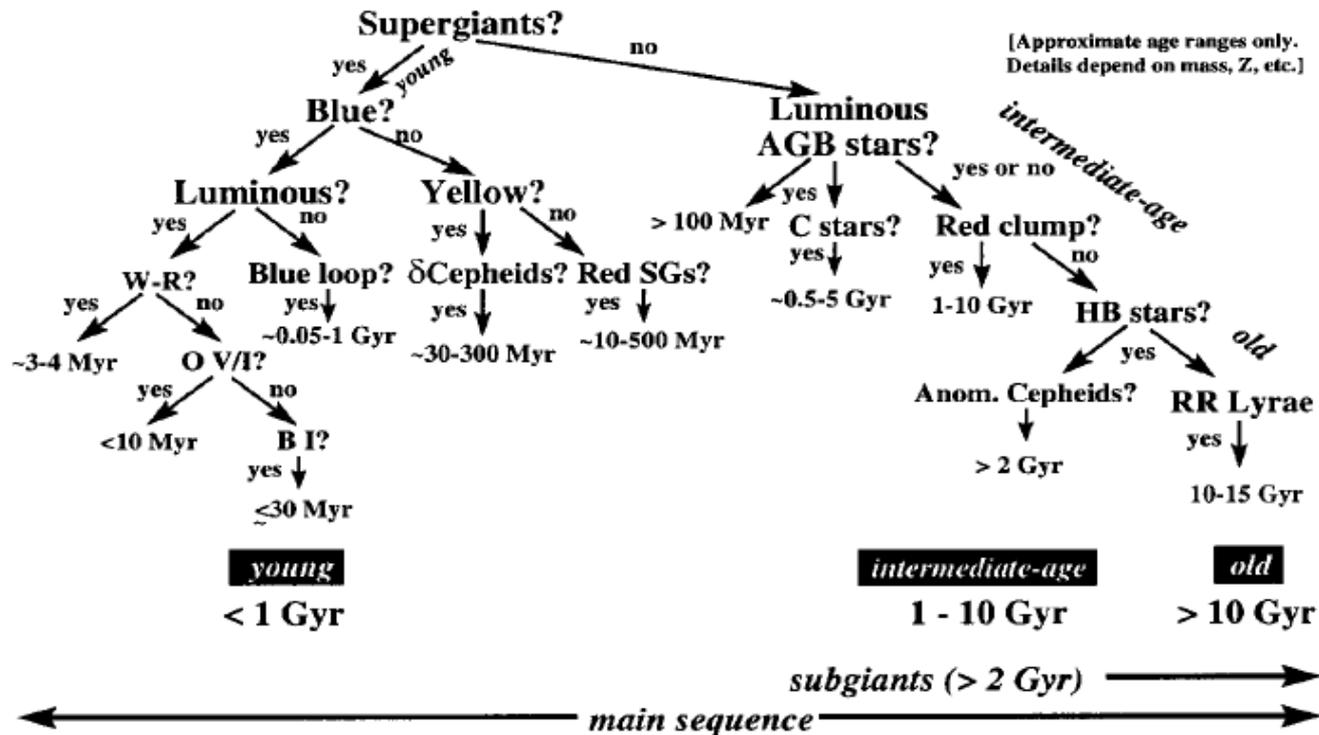


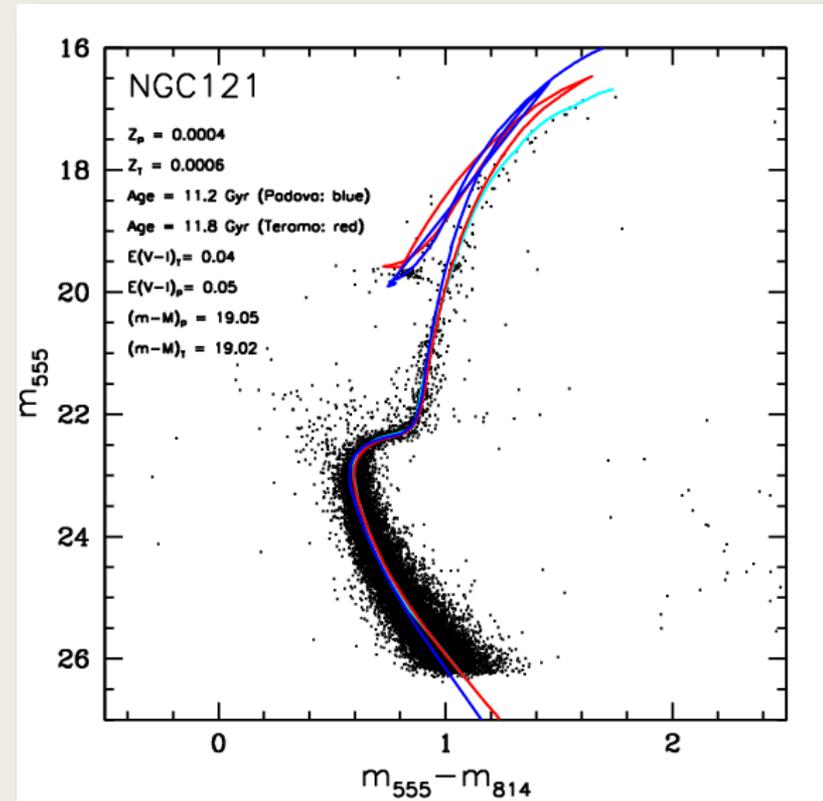
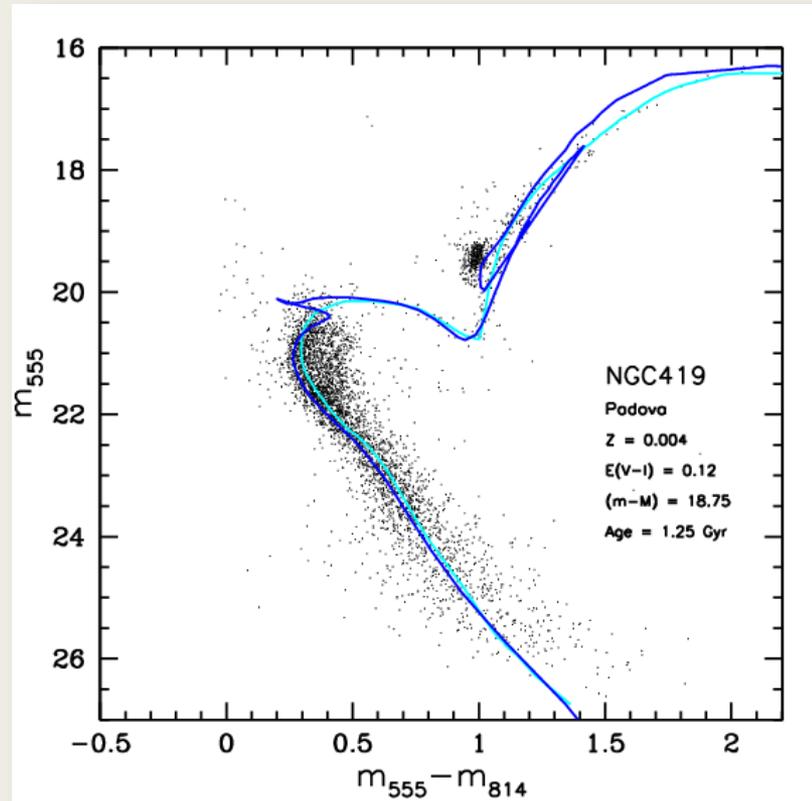
FIGURE 3. Age indicator logic chart for stellar populations. The age resolution is greatest for stellar evolutionary phases corresponding to the more quickly evolving high mass stars. From Grebel (1998).

# Ages of stars: Isochrone fitting

An isochrone is a curve on the CMD (or in the HR diagram) which defines the location of all stars of a given age.

**The isochrone fitting technique allows to estimate the cluster ages**

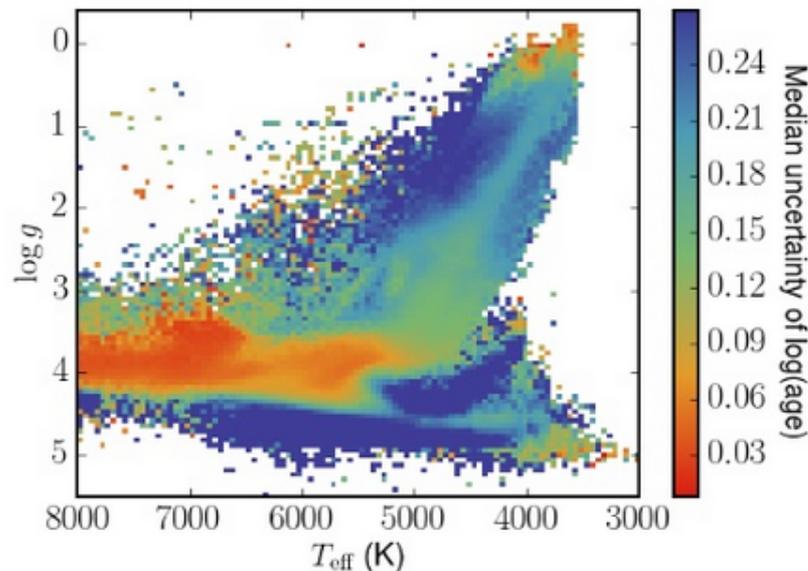
**Limits:** rely on the assumptions of the stellar models, age can varies from isochrones to isochrones, ...



# Ages of stars: Isochrone fitting

- **Isochronal Ages for field stars:**

- Compare a luminosity and color of a star to a grid of theoretical stellar models calibrated against empirical observations of globular and open clusters.
- *Gaia's* precise distances and photometry expands the volume isochronal ages

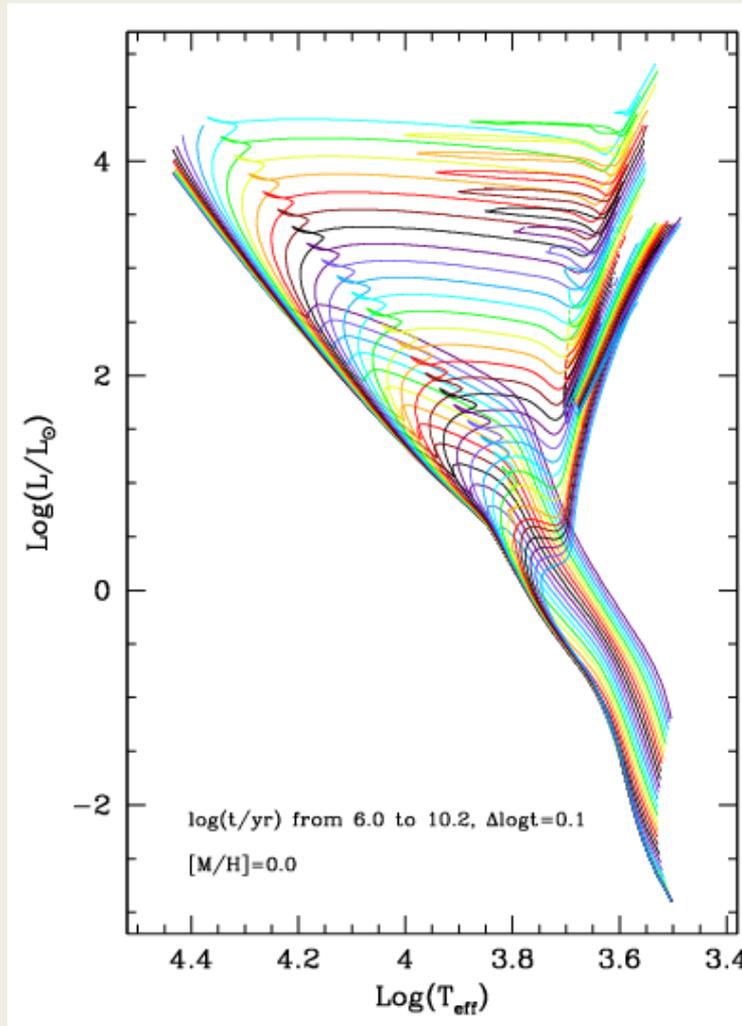


## Limits:

- Reliable results for the turn-off stage and the sub-giant branch
- For other populations there may exist many age-values estimations for the same object due to the overlapping of the different isochrones.
- Need to know metallicity

Errors from Unified tool to estimate Distances, Ages, and Masses (UniDAM) ([Mints and Hekker, 2017](#))

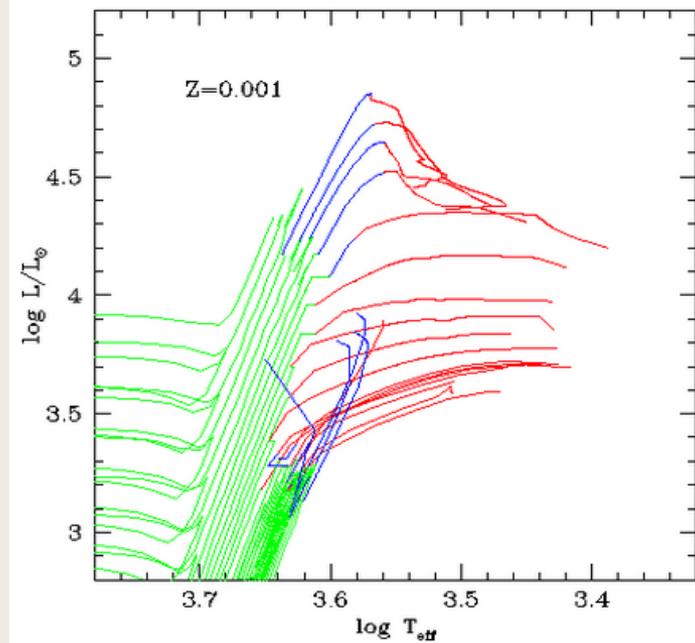
# Ages of stars: Isochrone fitting



Grid of PARSEC isochrones at solar metallicity

## Limits:

- For giant stars: isochrones of different ages are over posed
- In the zoomed plot:  $\text{log}(\text{age})$  from 7.8 to 10.2
- Large errors in the derived ages



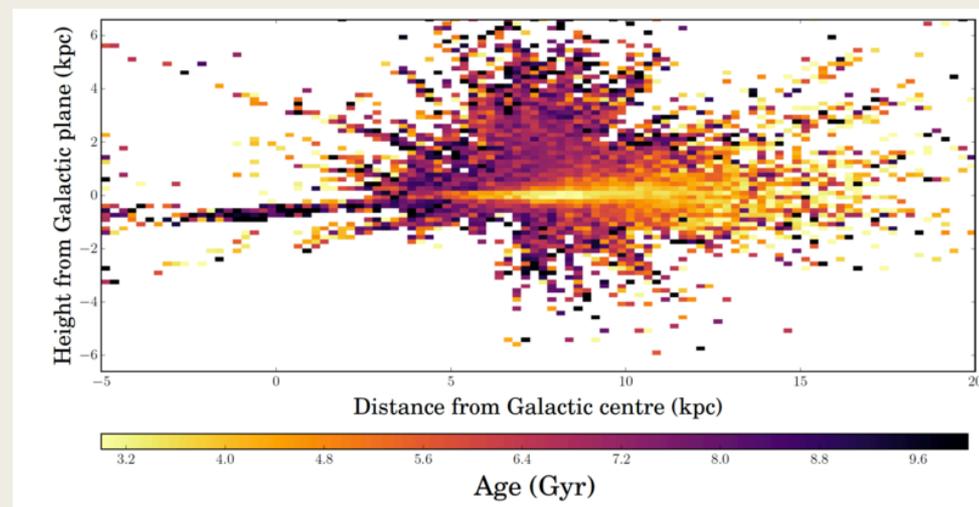
# Ages of stars: stellar properties related to age

Comparison with theoretical models is not always applicable.

We can search for stellar properties related to the age of the star.

These relationships need to be calibrated against ages derived in different ways.

- Magnetic activity
- Stellar structure
- Nuclear cosmochronology
- Chemical composition



# Ages of field stars: relationship with the magnetic field and rotational velocity

Magnetic fields play an important role in stellar evolution. It regulates stellar rotation from the early stages of star formation until the ultimate stages of the life of a star.

'Isolated' stars slowly spin-down as their age increases, as observed by Skumanich (1972).

For G-type stars in the main-sequence (MS), the projected rotational velocity decreases with age

$$v \sin (i) \propto t^{-1/2}$$

The rotational **braking** is believed to be caused by stellar winds, which, outflowing along magnetic field lines, are able to efficiently **remove the angular momentum of the star.**

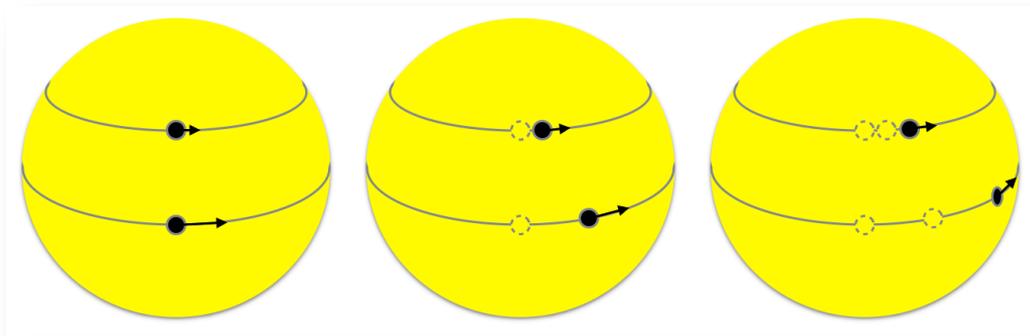
Indicators of magnetic activity:

- **surface spot coverage**
- **emission from the chromosphere, transition region or corona are closely linked to rotation**

# Ages of field stars: relationship with the magnetic field

- **Gyrochronology:**

- Rotation, age, and magnetic field strength are tightly coupled for solar-type stars (fast rotators produce strong magnetic fields, giving rise to stellar winds that carry away angular momentum, reduce the interior rotational shear of the star, and thereby weaken its magnetic field)
- Need to be calibrated with measurements of period of rotation in star clusters
- Periods are measured estimating the variation of the magnitude due to rotation of the starspot.



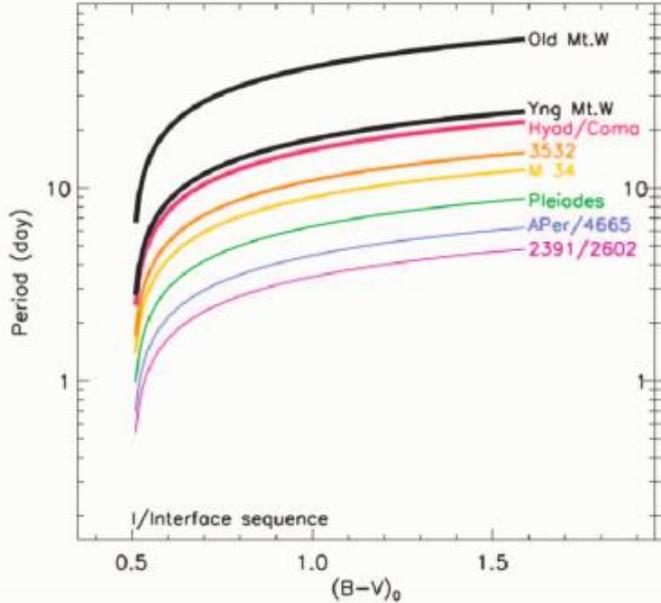
## Limits:

- The relationship saturates for fast rotators
- Time consuming and precision photometry
- LSST (large Synoptic telescope) will improve and enlarge its applicability

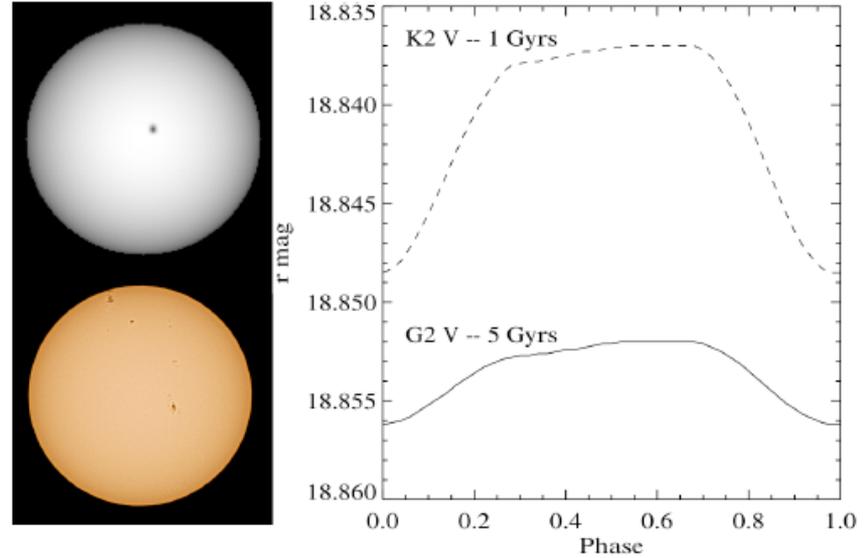
# Ages of field stars: relationship with the magnetic field

The rotational periods are longer for the older populations

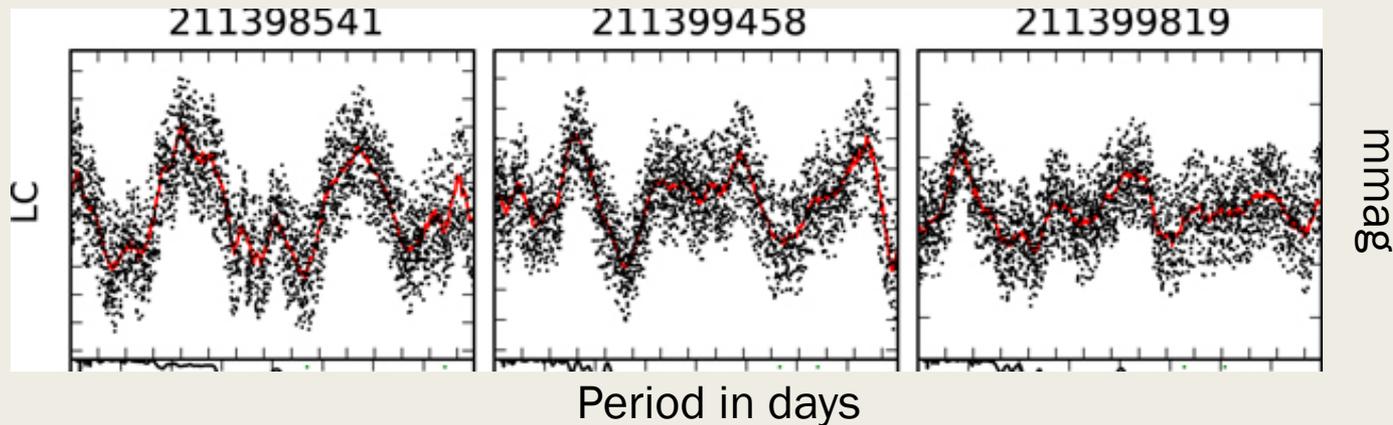
For a given population, they are longer for the cooler (older) stars [on the left side]



## Simulations for the LSST telescope



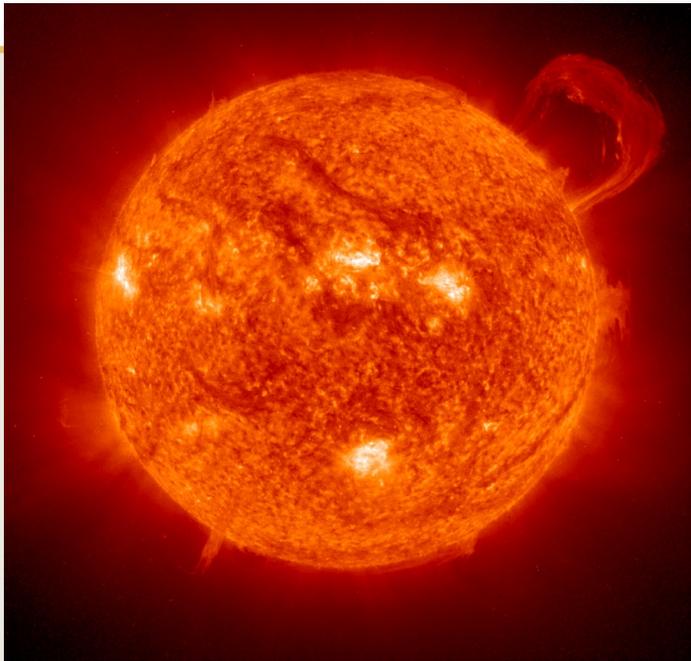
The photometric variation is very small, but still detectable



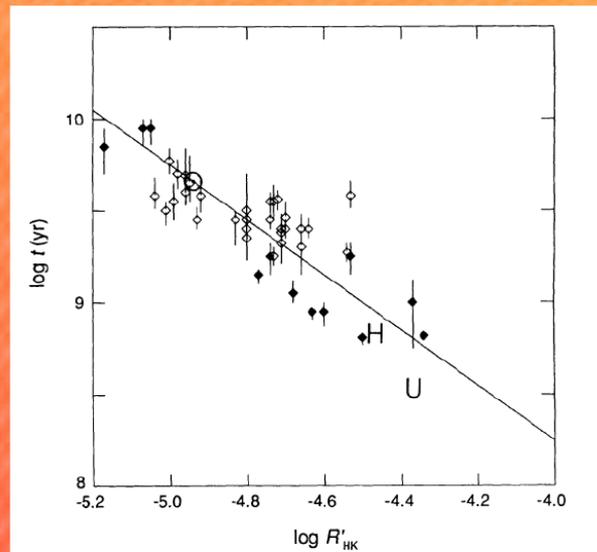
# Ages of field stars: relationship with the magnetic field

## Age-activity relation:

- Stellar flares, which trace the strength of the magnetic field of the star, are another photometric proxy for stellar age → activity decreases with increasing stellar age
- Cluster observations will indicate how the frequency and intensity of stellar flares vary with stellar age and mass.



Soderblom, Duncan & Johnson (1991)



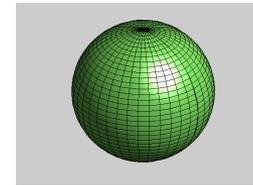
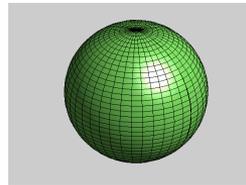
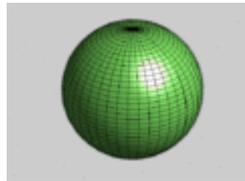
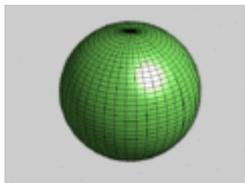
### Limits:

- Can estimate ages for the youngest populations
- Missing calibrations for the oldest populations

# Ages of field stars: from stellar structure

Measuring the vibrational modes of stars, we can study the internal physical conditions and from them to infer stellar chemical composition, rotation profiles and internal physical properties such as temperatures and densities.

## A few examples of stellar vibration modes



**Stellar oscillation can be measured only from the space.**

**There are several space missions aiming at: i) find planets, ii) measure stellar oscillations, as:**

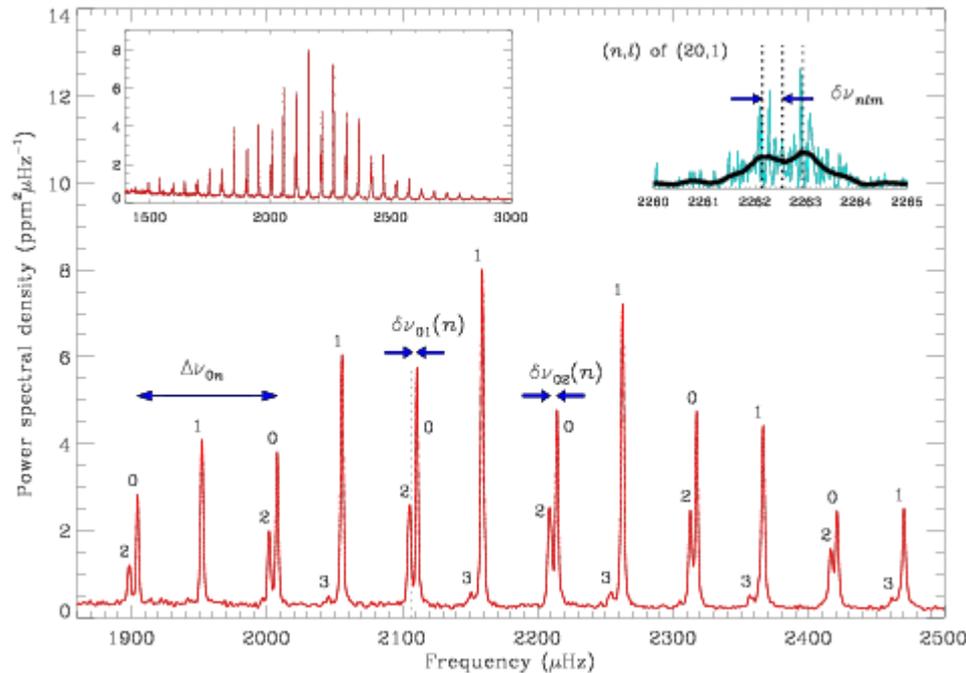
- **CoRoT** was a ESA space observatory mission which operated from 2006 to 2013,
- **Kepler** is a space observatory mission launched by NASA on 2009, which had a 'second life' as Kepler K2
- → They performed asteroseismology by measuring solar-like oscillation in stars.

In the next years: **PLATO and TESS satellites**

# Ages of field stars: from stellar structure

## Asteroseismology

- The oscillation frequencies of a star depend on the properties of stellar interior.
- Since these are tightly linked with the mass and evolutionary status, the mass and age of a star can be estimated from the comparison of its oscillation spectrum with stellar model predictions.



### Limits:

- Only for solar type and giant stars where convection is near to the surface
- uncertainties due to chemical composition → need spectroscopy
- Poor understanding of processes in stellar interiors

# Ages of field stars

- Nuclear cosmochronology
  - High-precision method based on the spectroscopic abundances of **heavy radioactive isotopes**, taking into account the constant rate of radioactive decay, for example  $^{238}\text{U}$  and  $^{232}\text{Th}$ , compared to stable isotope.
  - Based on the knowledge about the half-life time for these elements, the age of the matter from which the star was created, can be estimated.

$^{107}\text{Ag}$ STABLE 51.839%	$^{108}\text{Ag}$ 2.37 M $\beta^-$ : 97.15% $\epsilon$ : 2.85%	$^{109}\text{Ag}$ STABLE 48.161%	$^{110}\text{Ag}$ 24.6 S $\beta^-$ : 99.70% $\epsilon$ : 0.30%
$^{106}\text{Pd}$ STABLE 27.33%	$^{107}\text{Pd}$ 6.5E+6 Y $\beta^-$ : 100.00%	$^{108}\text{Pd}$ STABLE 26.46%	$^{109}\text{Pd}$ 13.7012 H $\beta^-$ : 100.00%
$^{105}\text{Rh}$ 35.36 H $\beta^-$ : 100.00%	$^{106}\text{Rh}$ 29.80 S $\beta^-$ : 100.00%	$^{107}\text{Rh}$ 48.81 H $\beta^-$ : 100.00%	$^{108}\text{Rh}$ 16.8 S $\beta^-$ : 100.00%

## Limits:

- Scarce abundance of uranium and thorium lines in the stellar spectra
- Poor knowledge of the initial isotopic ratios

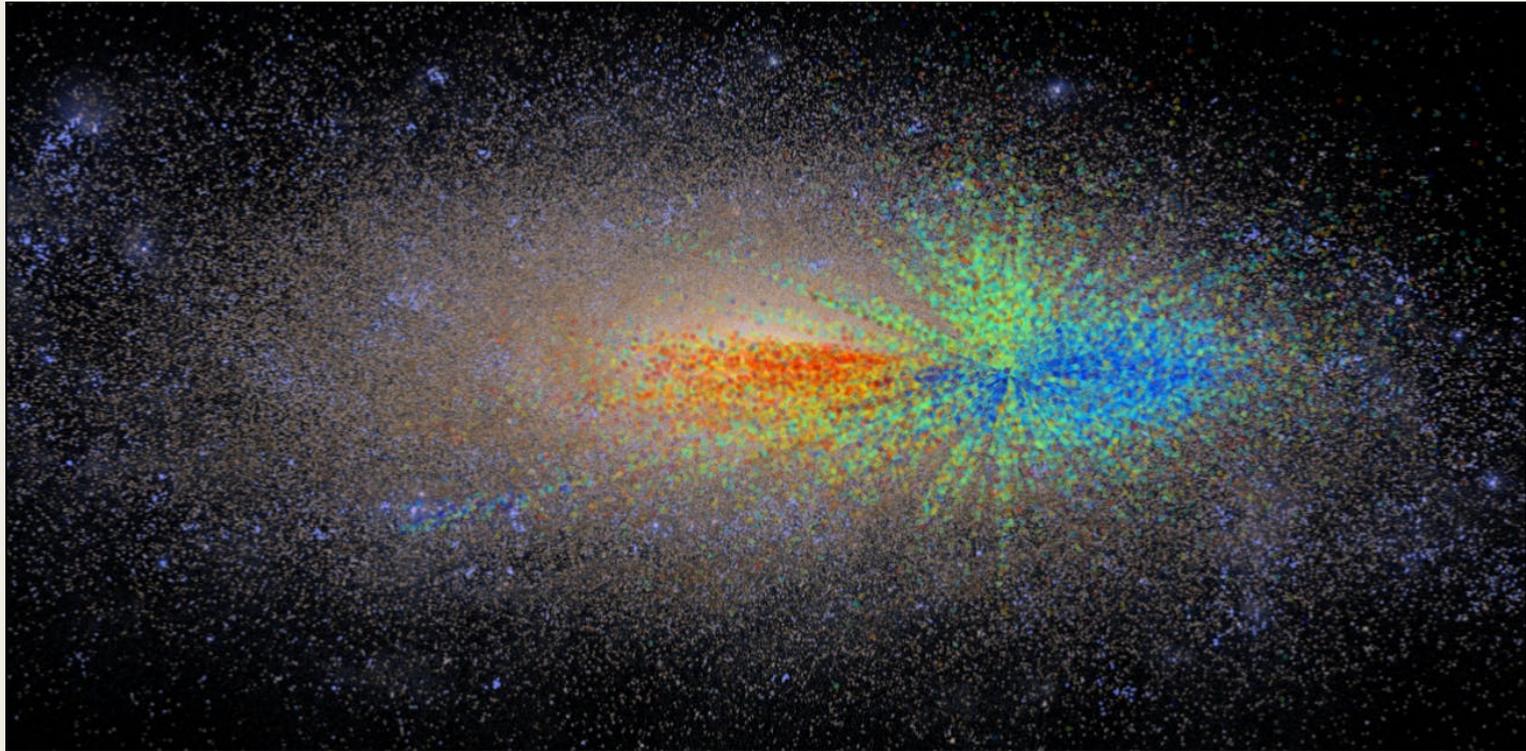
# Ages of field stars

- **Chemical clocks [more details in the next lectures]:**

As the time scales of the various nucleosynthetic processes are different, the chemical abundance ratio of two elements produced by two different channels provides a time estimate.

- [C/N] in giant stars: during the RGB phase the convection dredge-up material in the photosphere, changing the [C/N] abundance ratio. The change depends on the mass of the stars, and thus can trace its age.
- [ $\alpha$ /Fe] :  $\alpha$  elements are synthesized in high-mass, very short-lived stars. Iron is produced by both SN II and type I supernovae (SN Ia), the latter with longer lifetimes  $>0.3$  Gyr. Comparing their relative abundances provides a measure the age.
- [Y/Mg]: Yttrium is produced by intermediate- and low-mass stars, while Mg by massive stars, on different timescales, making of this ratio another good proxy for stellar age dating.

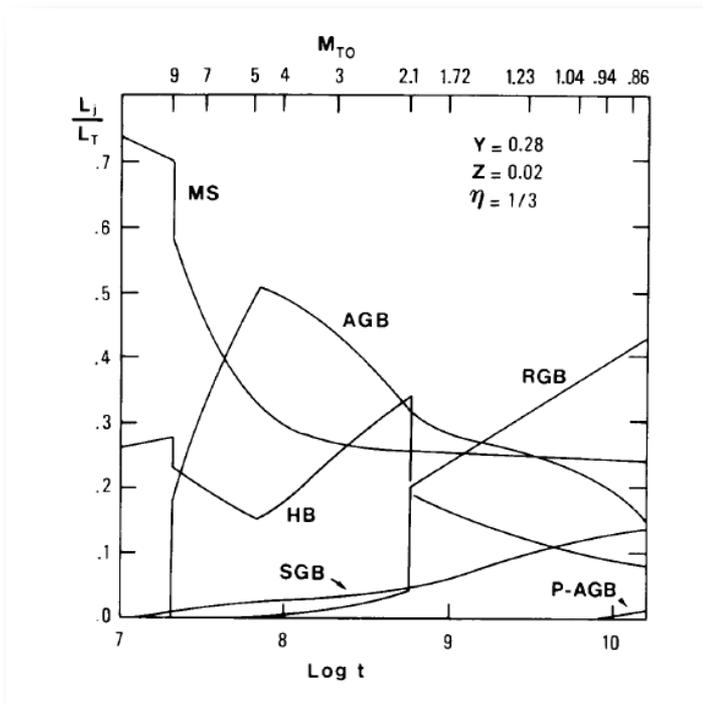
# Map of the ages of the MW disc



Age distribution for a sample of red giant stars ranging from the galactic center to the outskirts of the Milky Way, analyzed by Melissa Ness and colleagues. The sample is embedded in a simulation of a Milky Way-like galaxy.

Age is color coded, with the youngest stars shown in blue, the oldest stars in red, and middle-aged stars in green. The age distribution, including the obvious fact that the oldest stars are concentrated closer to the galactic center, confirms current models of galactic growth that have the Milky Way growing from the inside out.

**How is the Milky Way composed?** Which are the main stellar populations in the different component of the Galaxy?



The luminosity-weighted relative contribution of various evolutionary stages to the integrated bolometric luminosity of a simple stellar population as a function of age (Renzini & Buzzoni 1986) and their TO mass

→ directly linked to the age of the stellar population

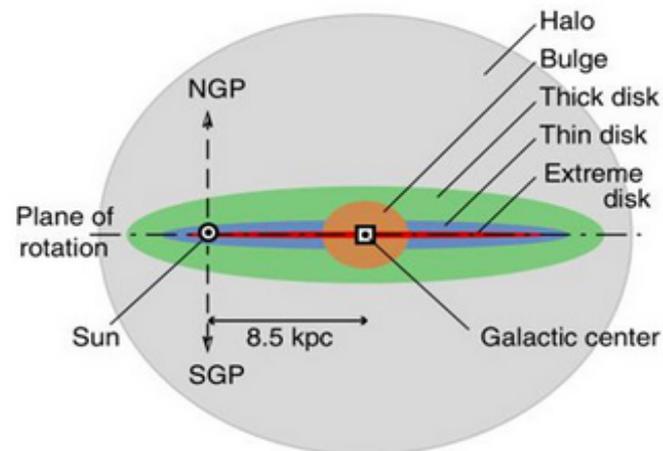
# Stellar population in the Milky Way

**Classically the stellar populations of the Milky Way were divided in:**

- PopI, younger and metal richer stars, located in the thin disc
- PopII, older, metal poorer, located in the thick disk and halo

**A modern classification is shown in the Table:**

<i>Population</i>	<i>typical stars</i>	<i>velocity dispersion</i>	<i>shape of system</i>	<i>metal abundance (respect to H)</i>
<b>Halo pop.</b>	GC, red giants	130	spherical	0.003
<b>Intermediate pop. II</b>	high vel. stars	50	intermediate	0.01
<b>Disc pop.</b>	weak line stars	30	intermediate	0.02
<b>Intermediate pop. I</b>	strong line stars	20	intermediate	0.03
<b>Extreme pop. I</b>	blue supergiants	10	flat	0.04



# Stellar population in the Milky Way

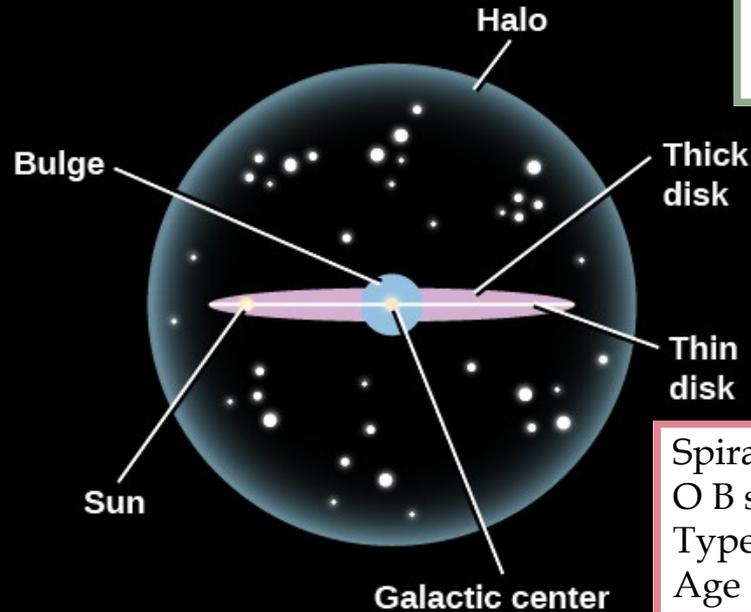
## Characteristics of Pop I and Pop II stars

	<b>Population I</b>	<b>Population II</b>
Age	Young to Old ( $10^6$ - $10^9$ years)	All Old ( $10^{10}$ ) years
Star Temperature	Generally Blue (hot)	Red (cooler)
Location	Disk, concentrated in Spiral Arms	Halo and Bulge
Orbits	Clockwise and circular in Disk	All directions, plunging through Disk
Metals	Lots of Metals (like Sun)	Low Metal Abundance
Supernova	Type II & Type I	Type I ONLY
Examples	OB Clusters, T Tauri stars	Globular Clusters, Metal Poor old stars

Halo:  
Globular clusters  
RR Lyrae  
Type II Cepheids  
 $12 < \text{Age} < 14 \text{ Gyr}$

Thick disk:  
K M stars  
Miras  
RR Lyrae  
 $8 < \text{Age} < 14 \text{ Gyr}$

Bulge:  
K M giants  
RR Lyrae  
A stars  
 $1 < \text{Age} < 14 \text{ Gyr}$

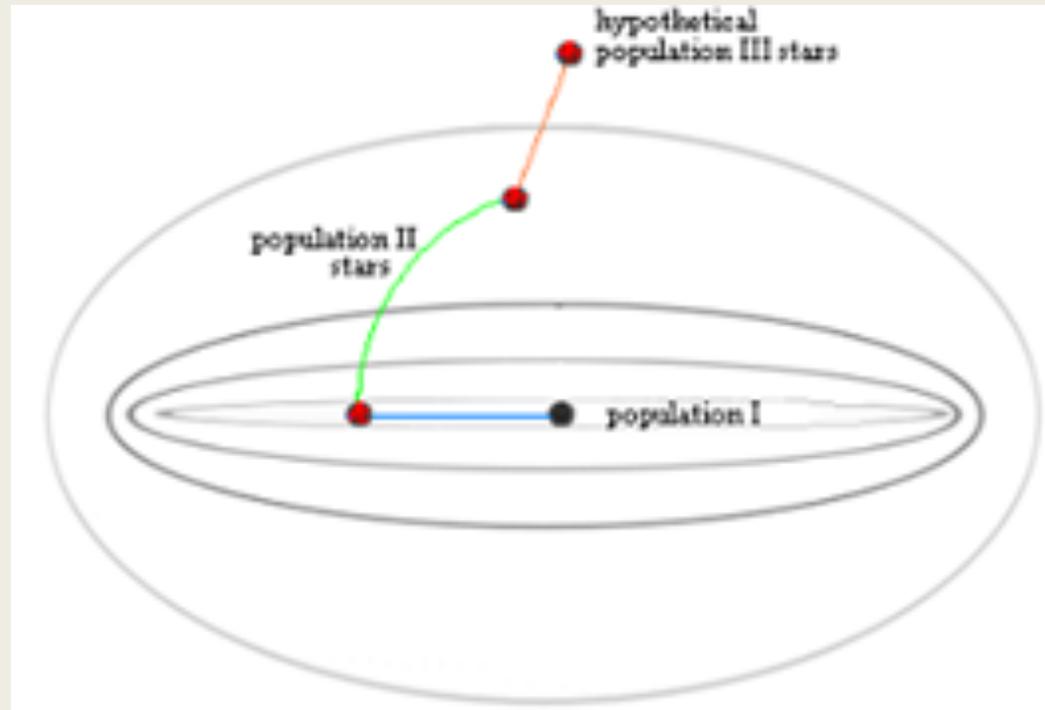


Thin disk:  
A M stars  
Subgiants  
Planetary Nebulae  
 $1 < \text{Age} < 8 \text{ Gyr}$

Spiral arms:  
O B stars (young and massive)  
Type I Cepheids  
 $\text{Age} < 0.1 \text{ Gyr}$

Population I  
Population II  
Bulge Population(s)

# The missing ingredient: population III stars



The first stars are a metal-free (massive) Population III stars formed after the Big Bang

- within a few hundred million years become supernovae and seed the interstellar space with sufficient heavy elements to produce Population II stars.

# 9 stars with $[\text{Fe}/\text{H}] < -4.5$

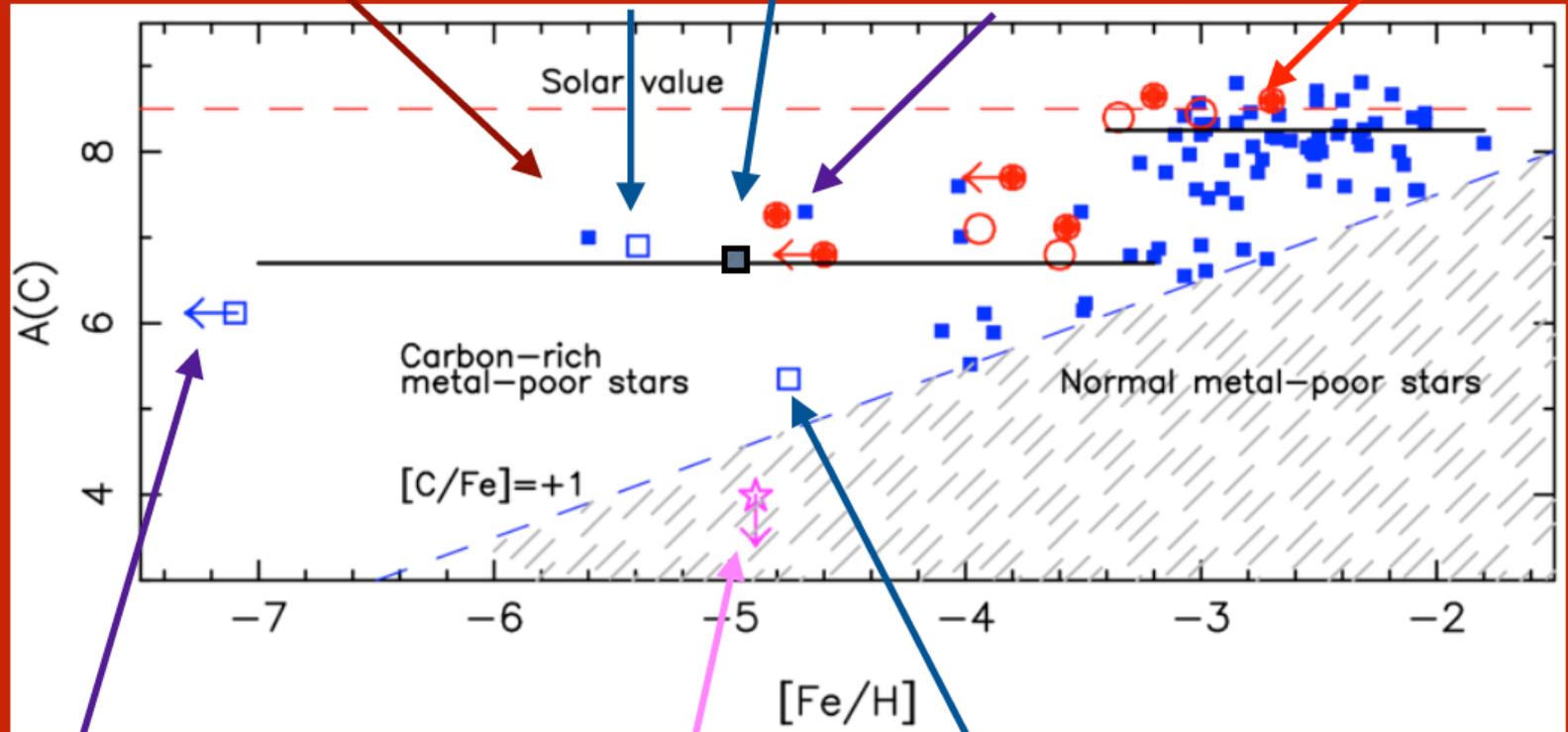
Christlieb (2001)

Allende-Prieto -Frebel 2015

Frebel et al 2005

Norris (2007)

Bonifacio 2015



Keller et al (2014)

Caffau et al 2011

Hansen et al (2014)

# Low mass very metal poor stars open new horizons:

- Metal poor stars (first progenitors of possible PopIII stars) are usually enhanced in other elements, as C
- They have sufficient global metallicity to allow their formation (with normal prescriptions...)
- The Caffau star requires new mechanisms for low mass formation, e.g., dust cooling or fragmentation

# Summary

- To calibrate models (stellar evolution, Galactic evolution, etc.) we need to have 'direct' measurement of basis ingredients:
  - **Stellar masses** → from gravitational forces in binary systems
  - **Stellar radii** → in eclipsing binaries (or interferometry, occultation)
- Stellar evolution models MUST match the empirical relationships found between: mass, radius, luminosity
- **Stellar ages** → from isochrone fitting to chemical clocks, measuring the most difficult quantity in astrophysics
- With all these quantities in hand, we can map the properties of the stellar populations in our Galaxy (and beyond)

→ Missing piece of information: chemical composition and kinematics