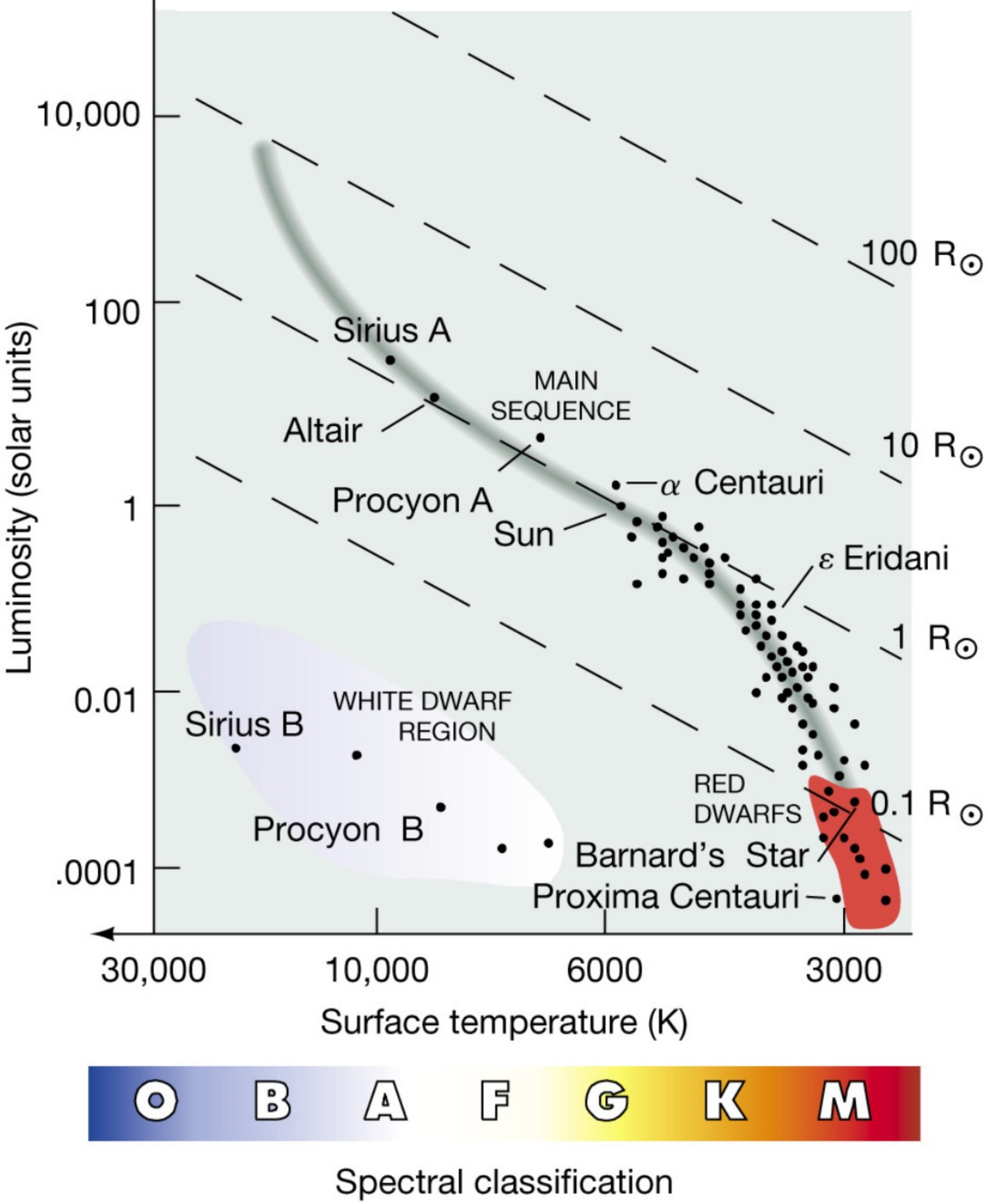
Studying the Milky Way means understanding stars

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

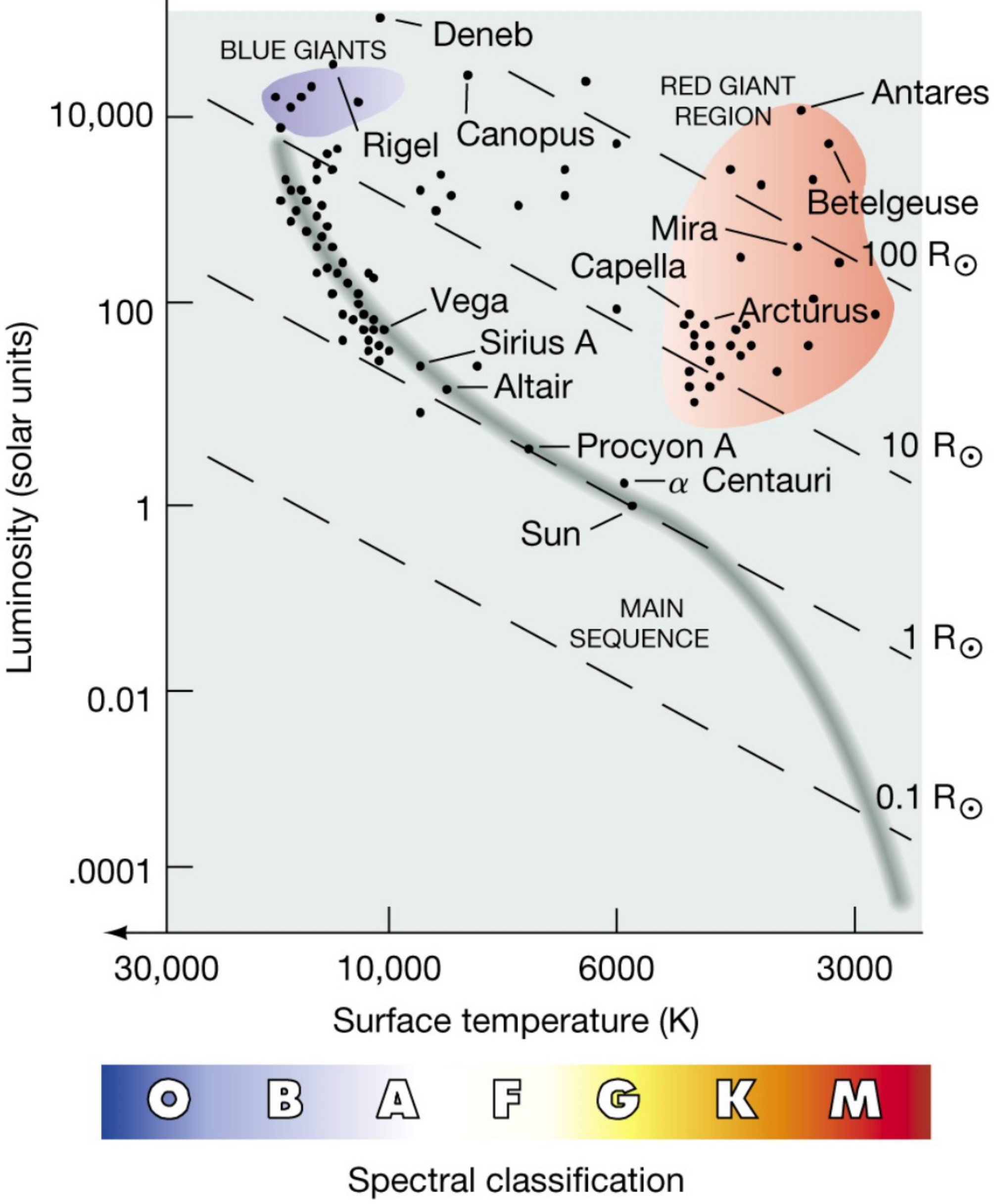
- Its 3-dimensional structure and physical components (disk, halo, bulge, bar…)
- Its kinematics (rotation, random motions, kinematic subgroups….)
- Its evolutionary history (star formation rate, accretion history, dynamical evolution….)

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)



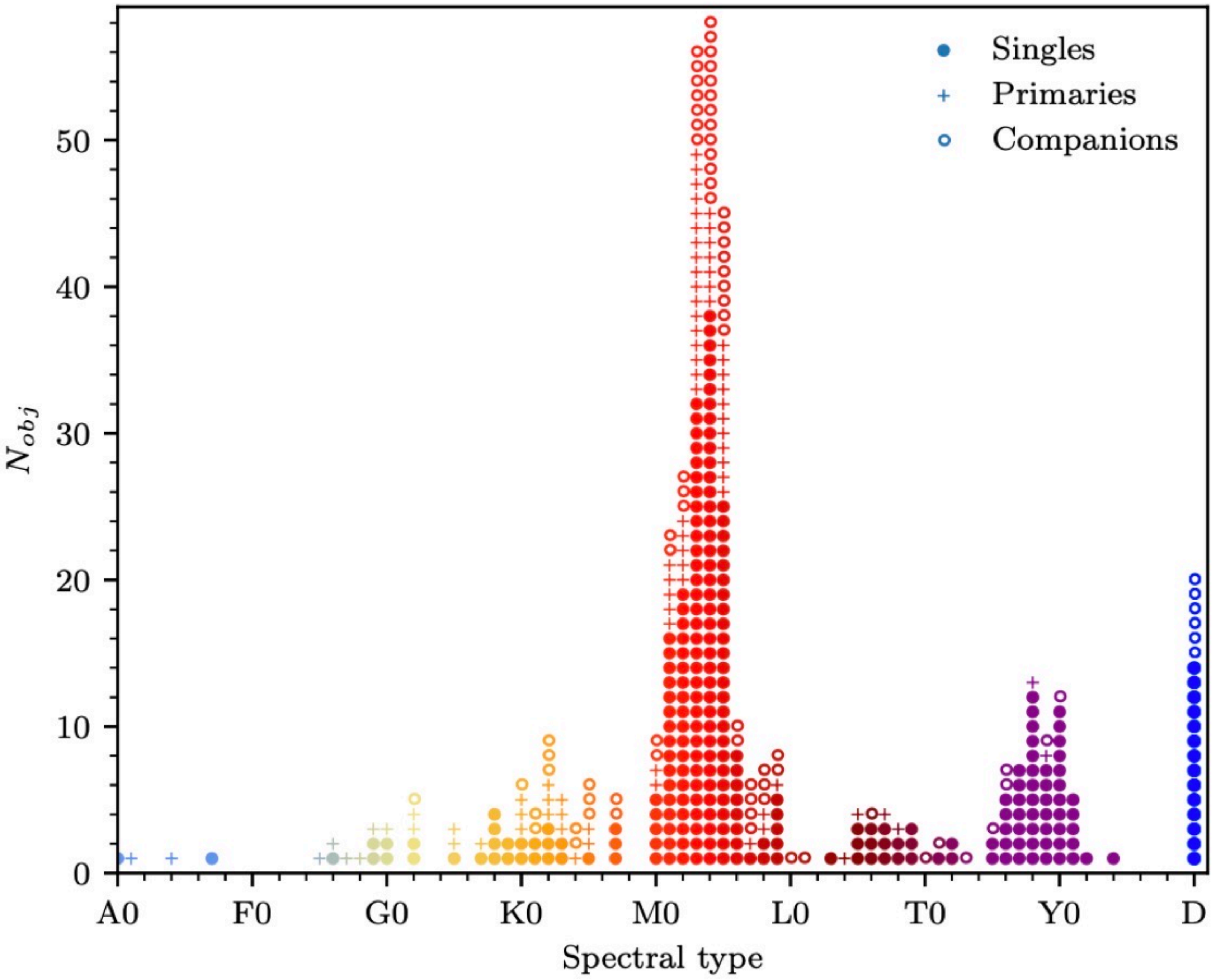
Brightness-limited
(all the stars brighter than some app-mag)



The 10pc Local Volume

[Reyle+21](#)

3D maps
https://gruze.org/10pc/resources/



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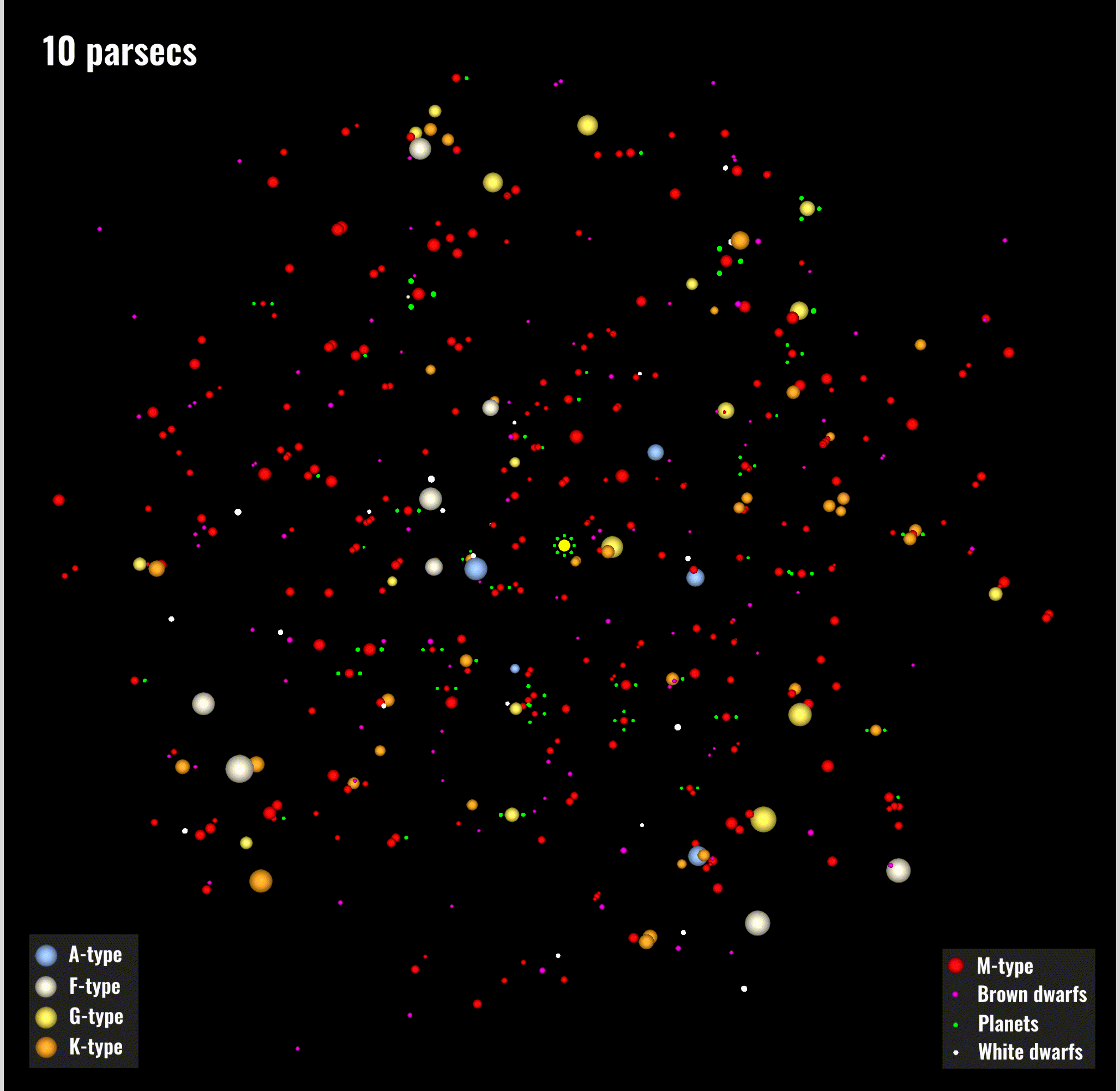

Fundamental Data for Stars

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

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

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

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

Sounds easy? Why is this hard to do?

- Parallaxes are small (typically ≪ 1")
- Stars move!

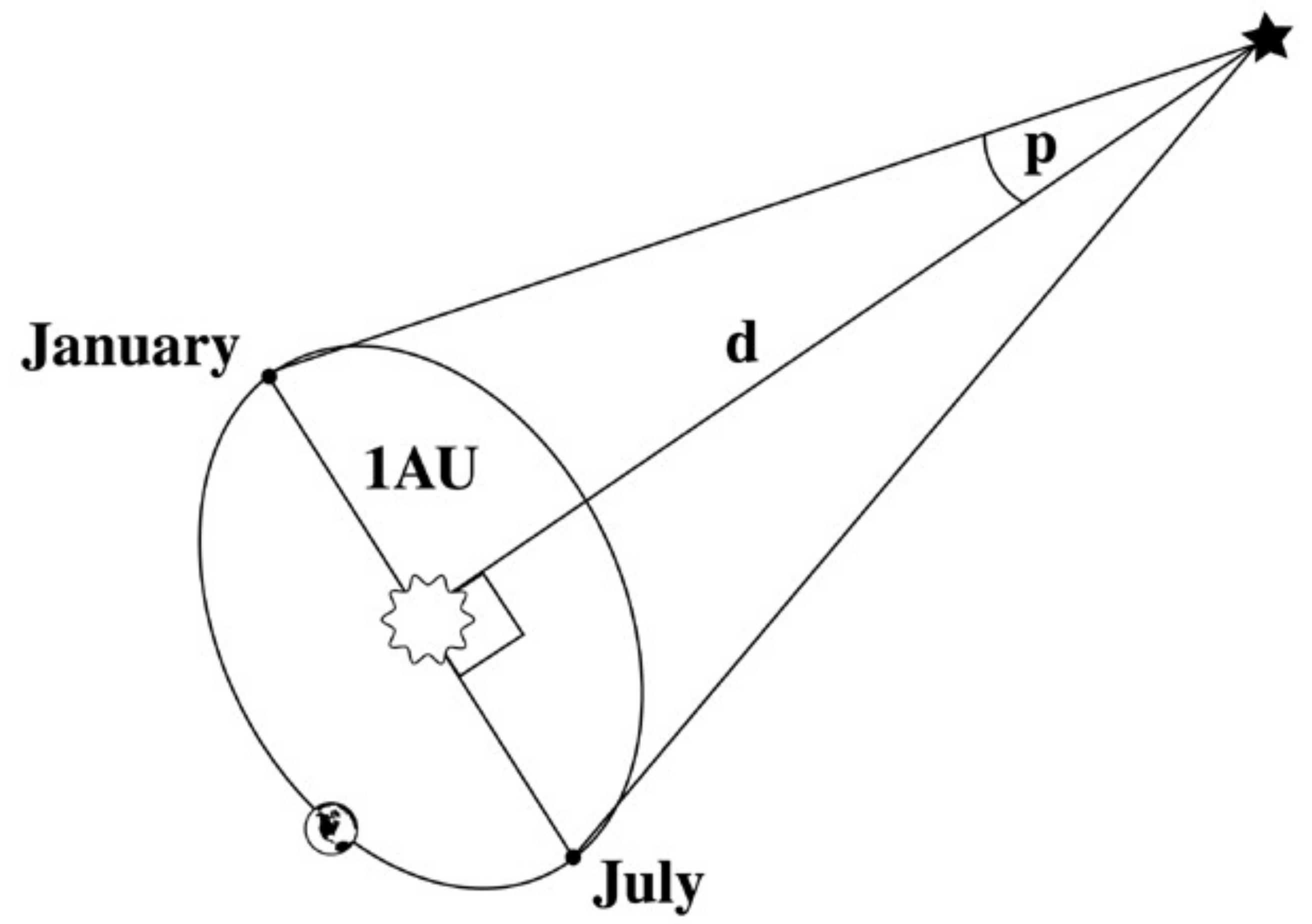

Fig 2.1 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

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 (@15th mag) 200 micro-arcsec (@20th mag)
Distance limits	< 100 pc	< 1 kpc	10 kpc
Number of stars	~ 1000	~ 10^5	~ 2×10^7 (1% error) ~ 2×10^8 (10% error)

Hipparcos CMD

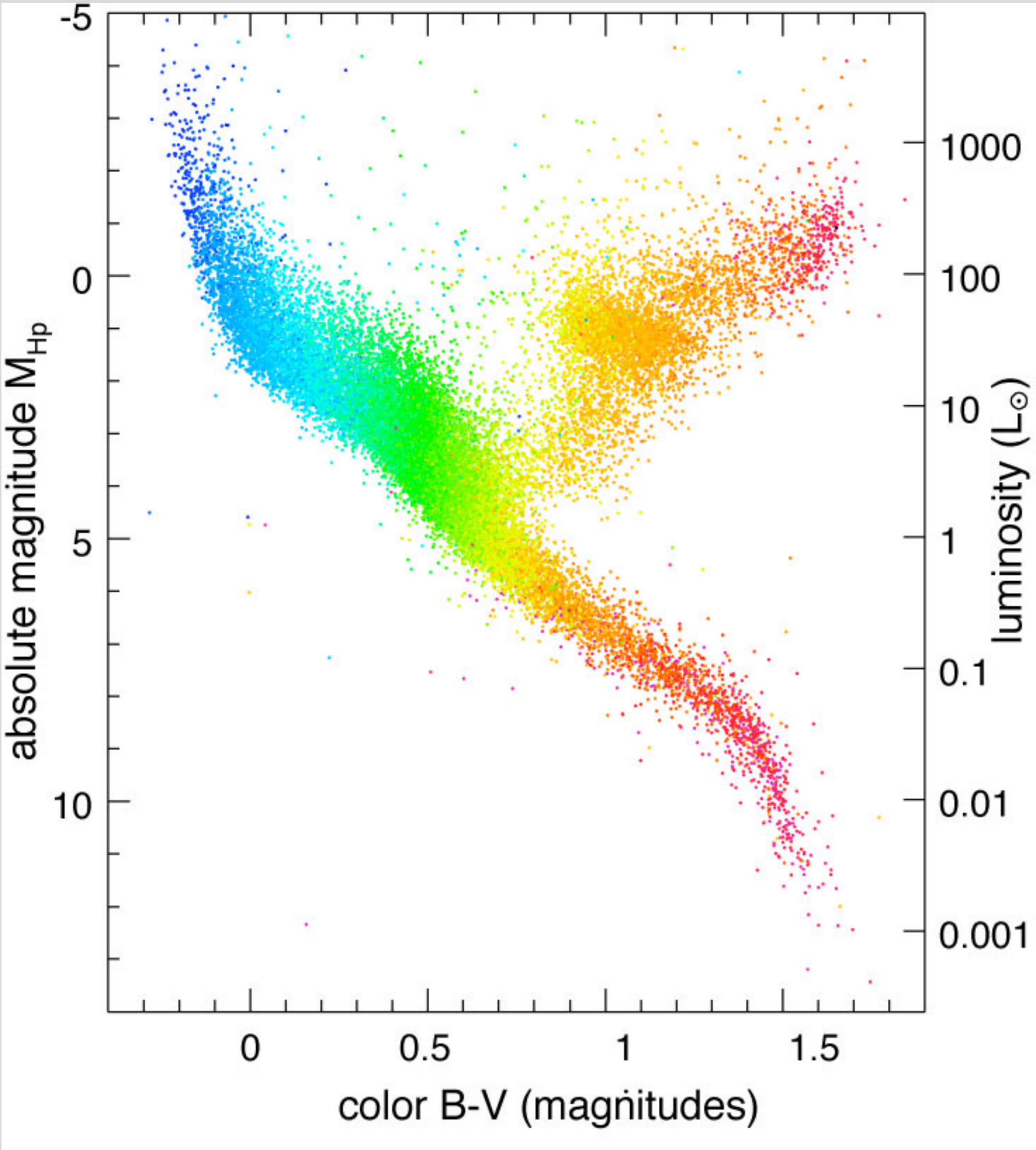

Fig 2.2 (F. van Leeuwen) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Distances to Stars: Parallax

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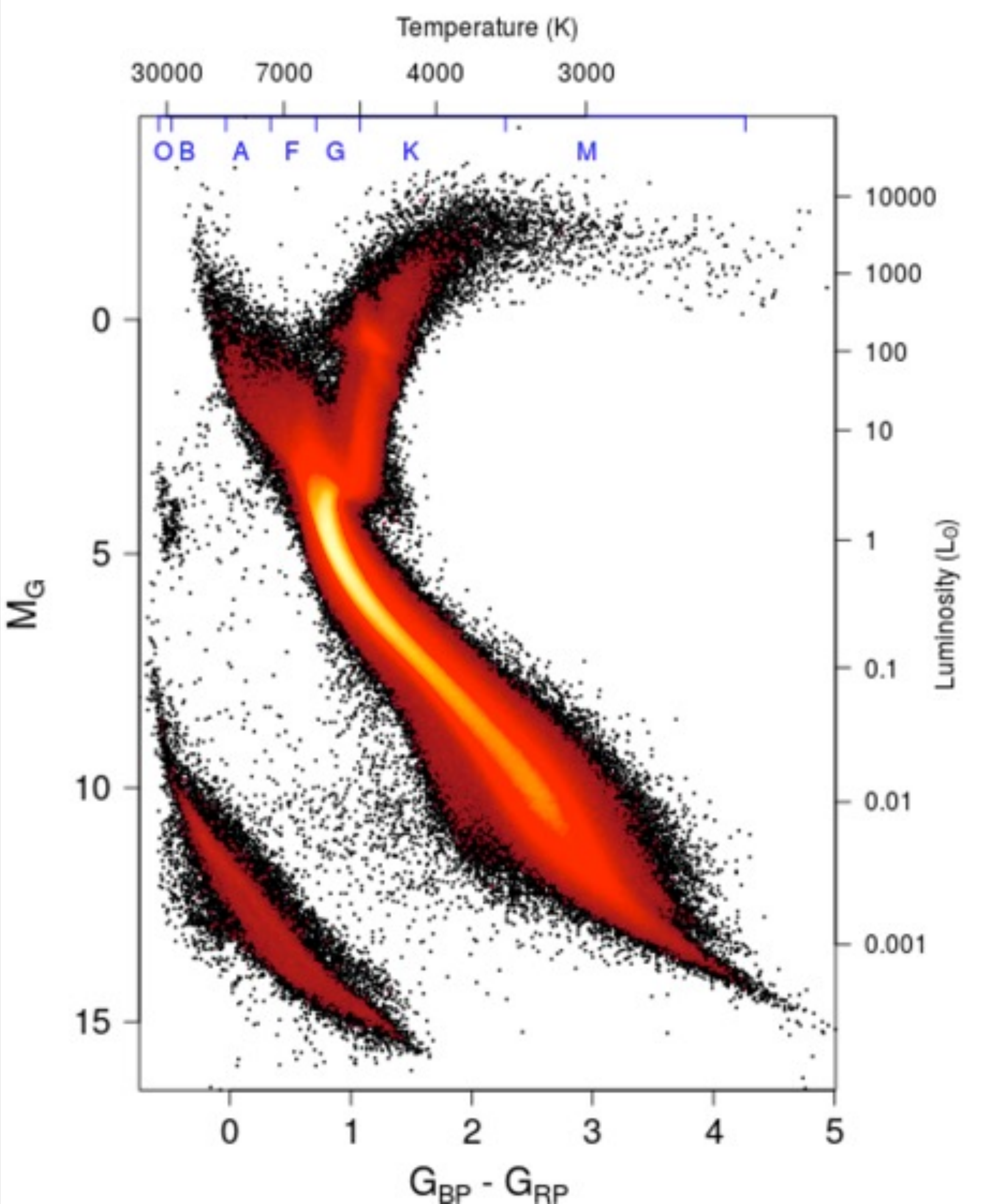
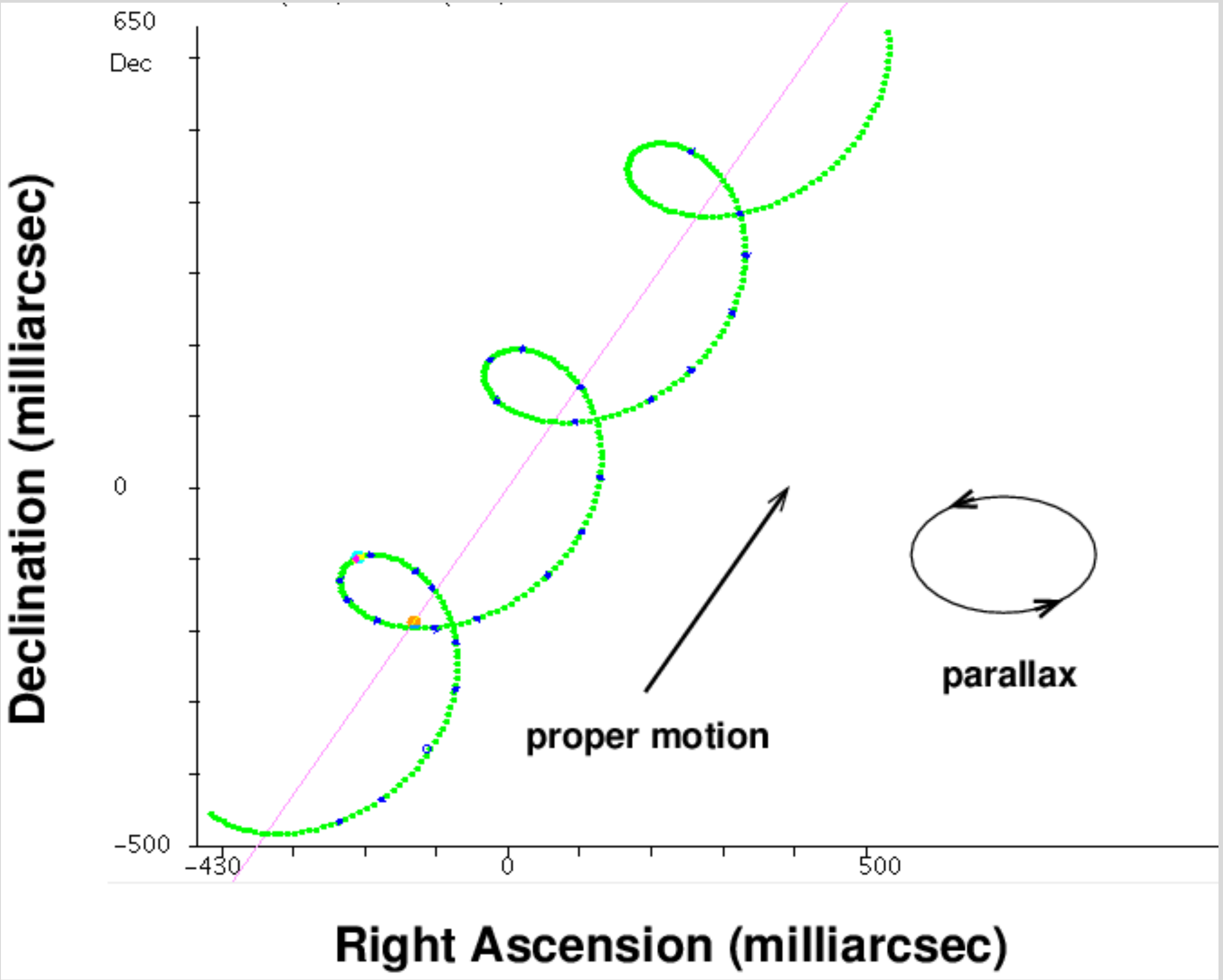
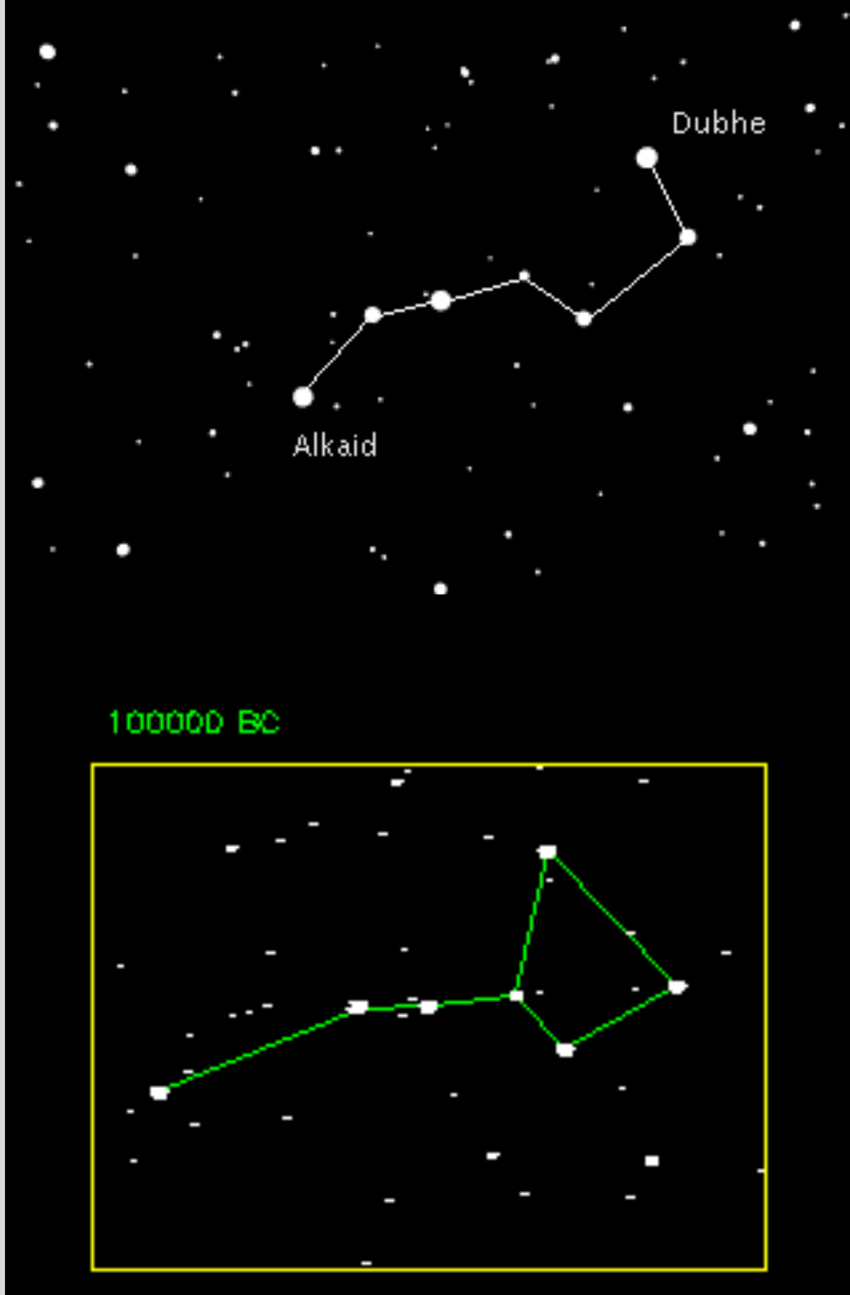
Gaia CMD



Proper Motions



courtesy Michael Richmond, RIT



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

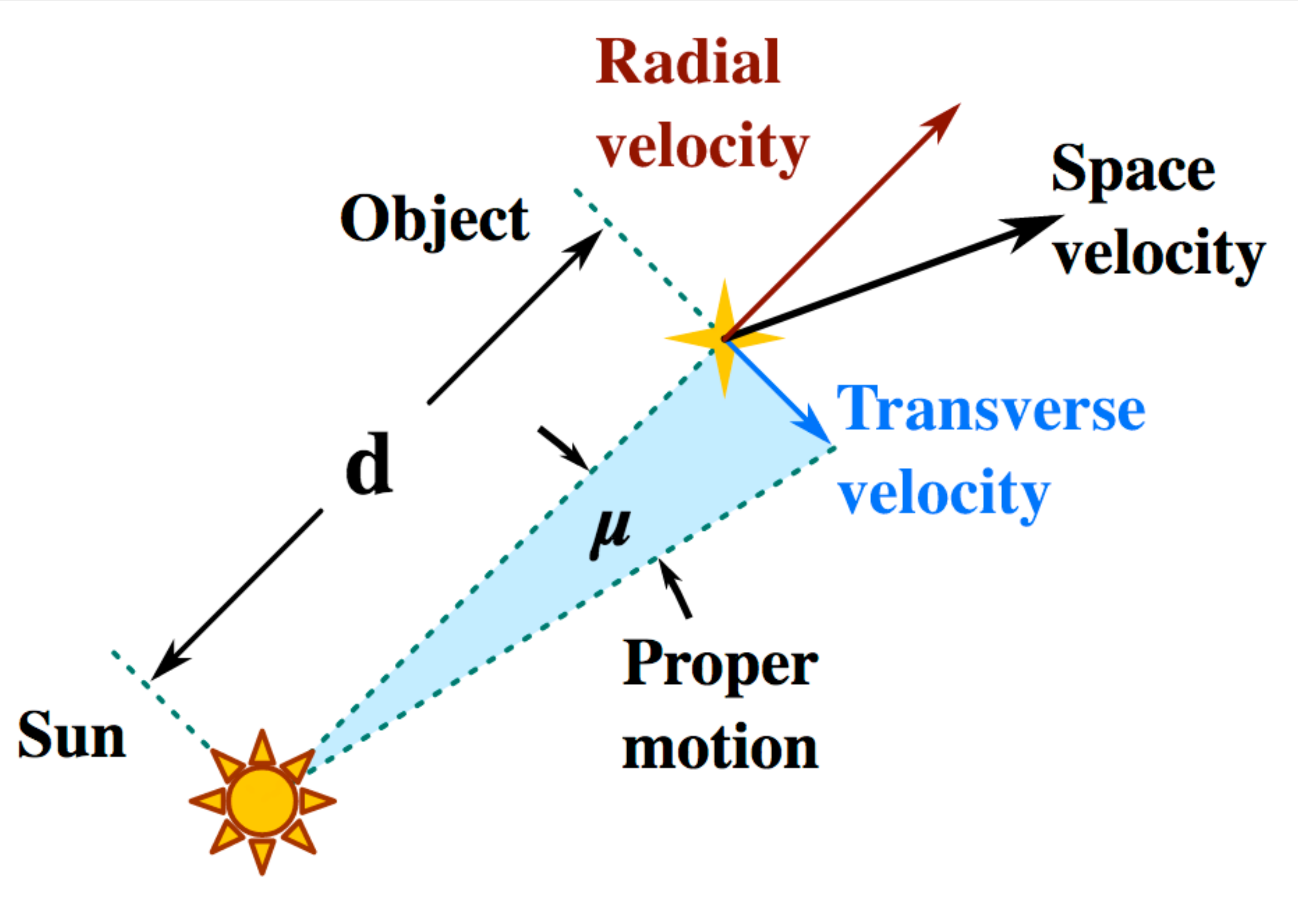
Need to measure both a proper motion and a distance. If:

μ = proper motion (arcsec/yr)
d = distance (pc)

then:

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

Break it down into v_α and v_δ, 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.

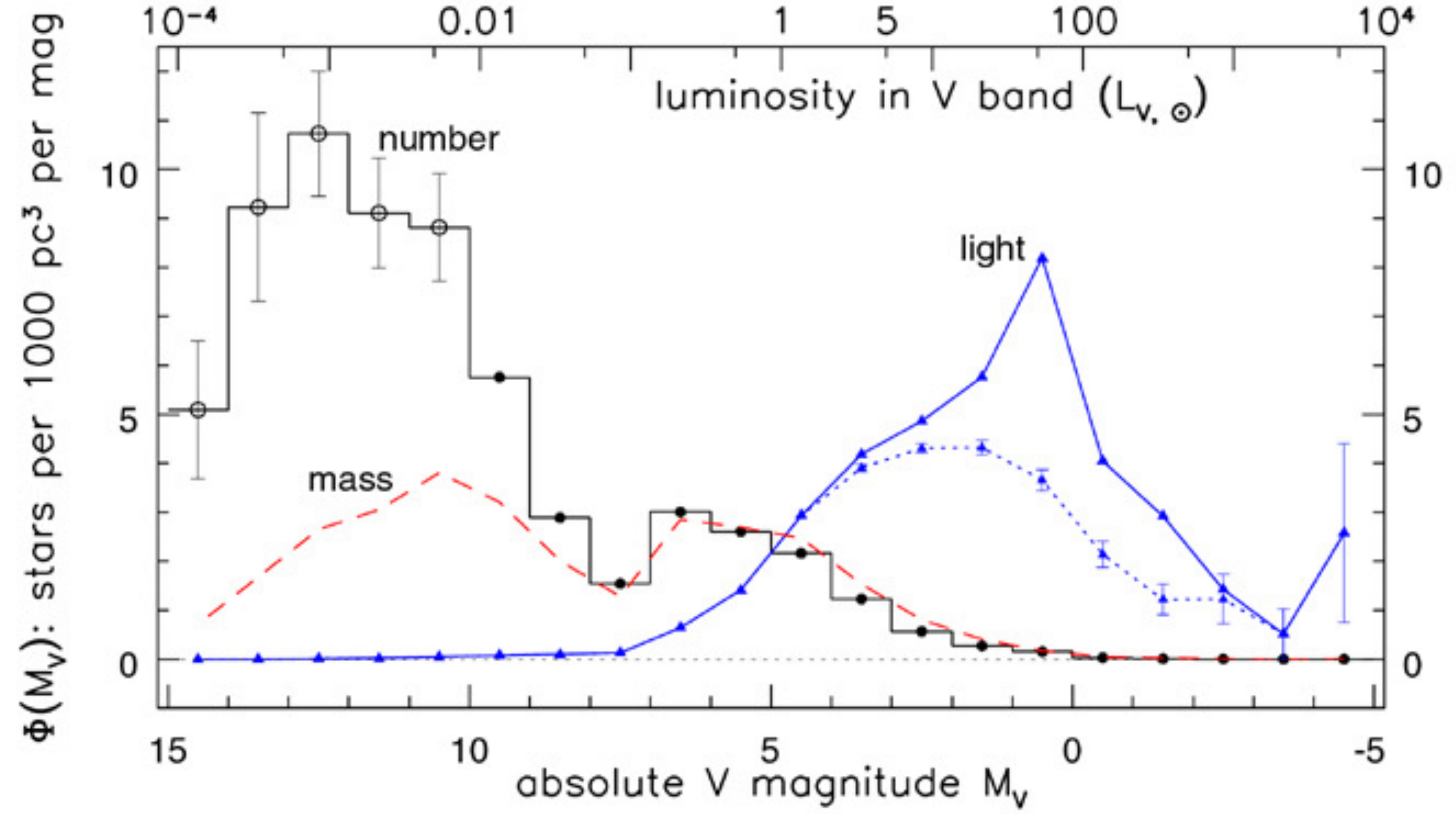


Fig 2.3 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Stars in the Local Solar Neighborhood: Observed Luminosity functions ⇒ Initial Mass Function

But remember, the observed preset-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 τ_{gal}:

$$\psi_{MS}(M_V) = \phi_{MS}(M_V) \quad \text{for } \tau_{MS} \geq \tau_{gal}$$
$$\psi_{MS}(M_V) = \phi_{MS}(M_V) \times \frac{\tau_{gal}}{\tau_{MS}(M_V)} \quad \text{for } \tau_{MS} \leq \tau_{gal}$$

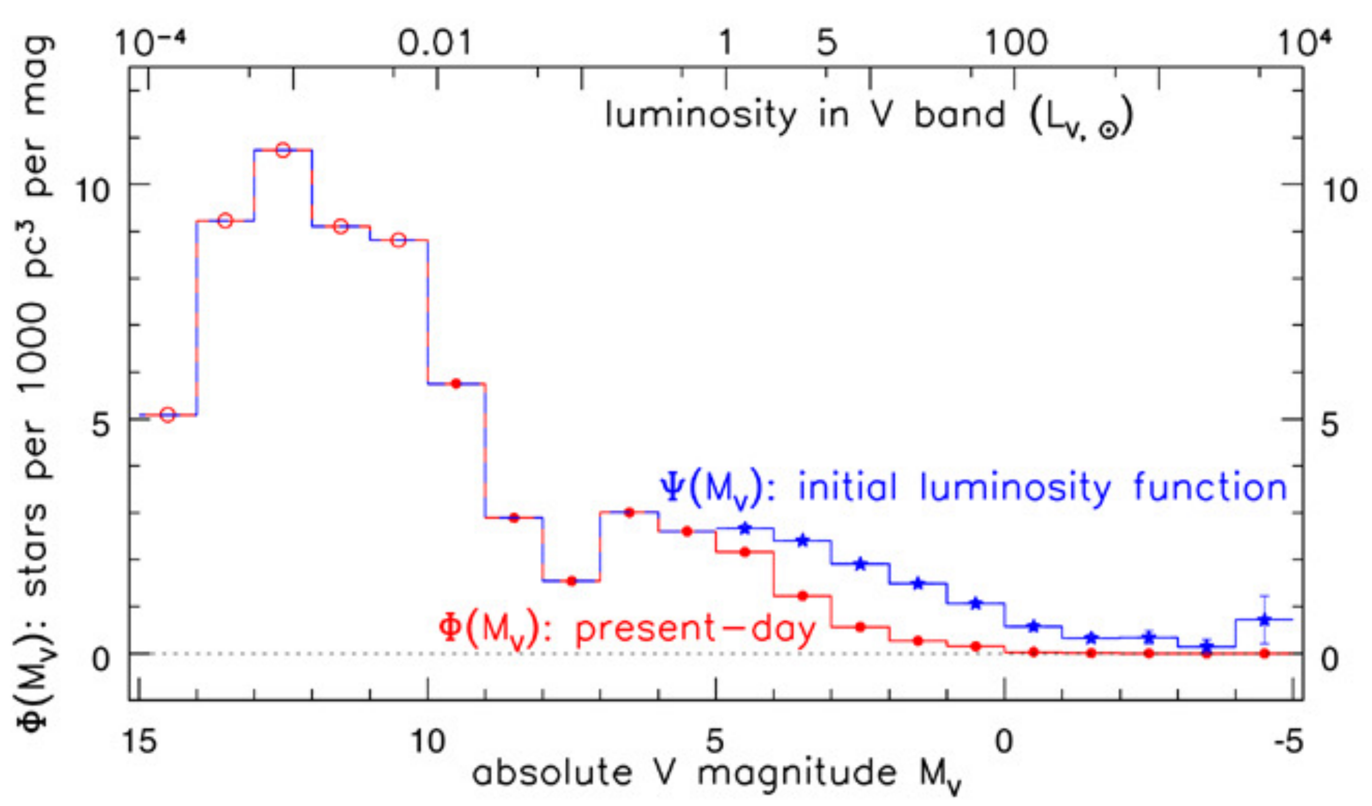


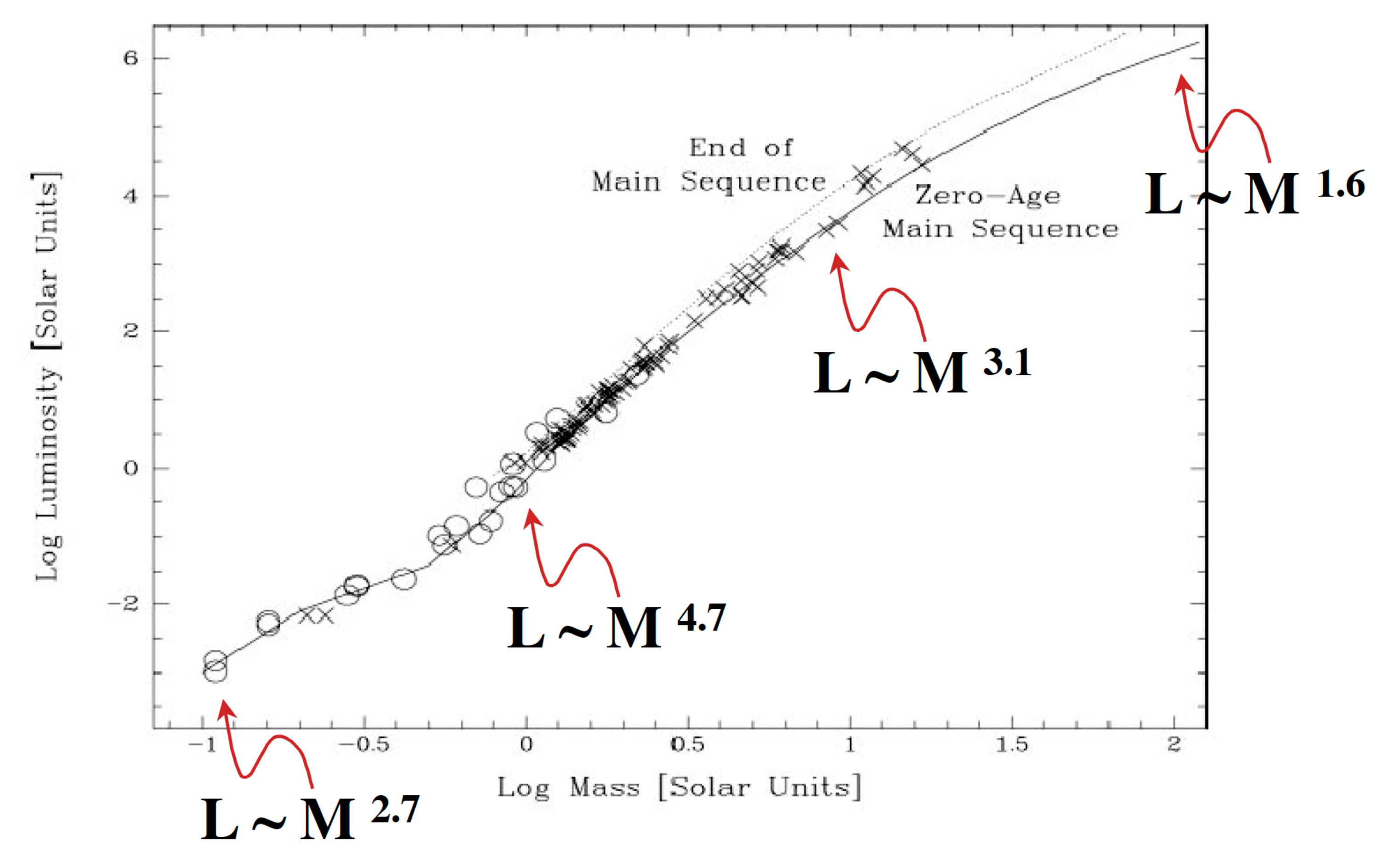
Fig 2.4 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Stars in the Local Solar Neighborhood: Observed Luminosity functions ⇒ 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 ⇒ Initial Mass Function

Scalo (1986) Initial Mass Function:

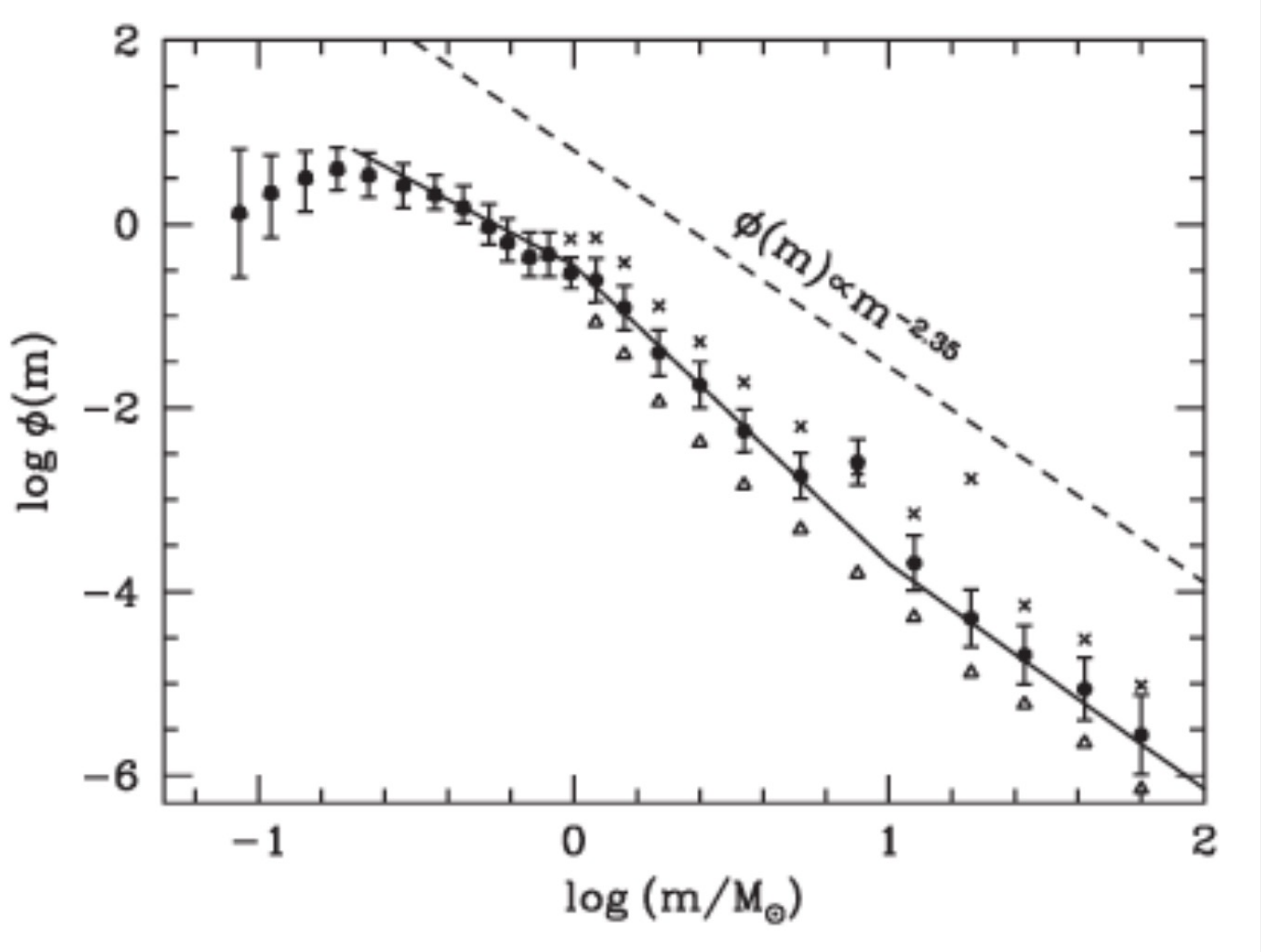
$\xi(M) \sim M^{-2.45}$ for $M > 10M_\odot$
$\xi(M) \sim M^{-3.27}$ for $1M_\odot < M < 10M_\odot$
$\xi(M) \sim M^{-1.83}$ for $M < 0.2\,M_\odot$

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 ⇒ Initial Mass Function

Alternative approach: measure it in young star clusters. For example, the Pleiades.
Problem: not many stars, so uncertainties are large....

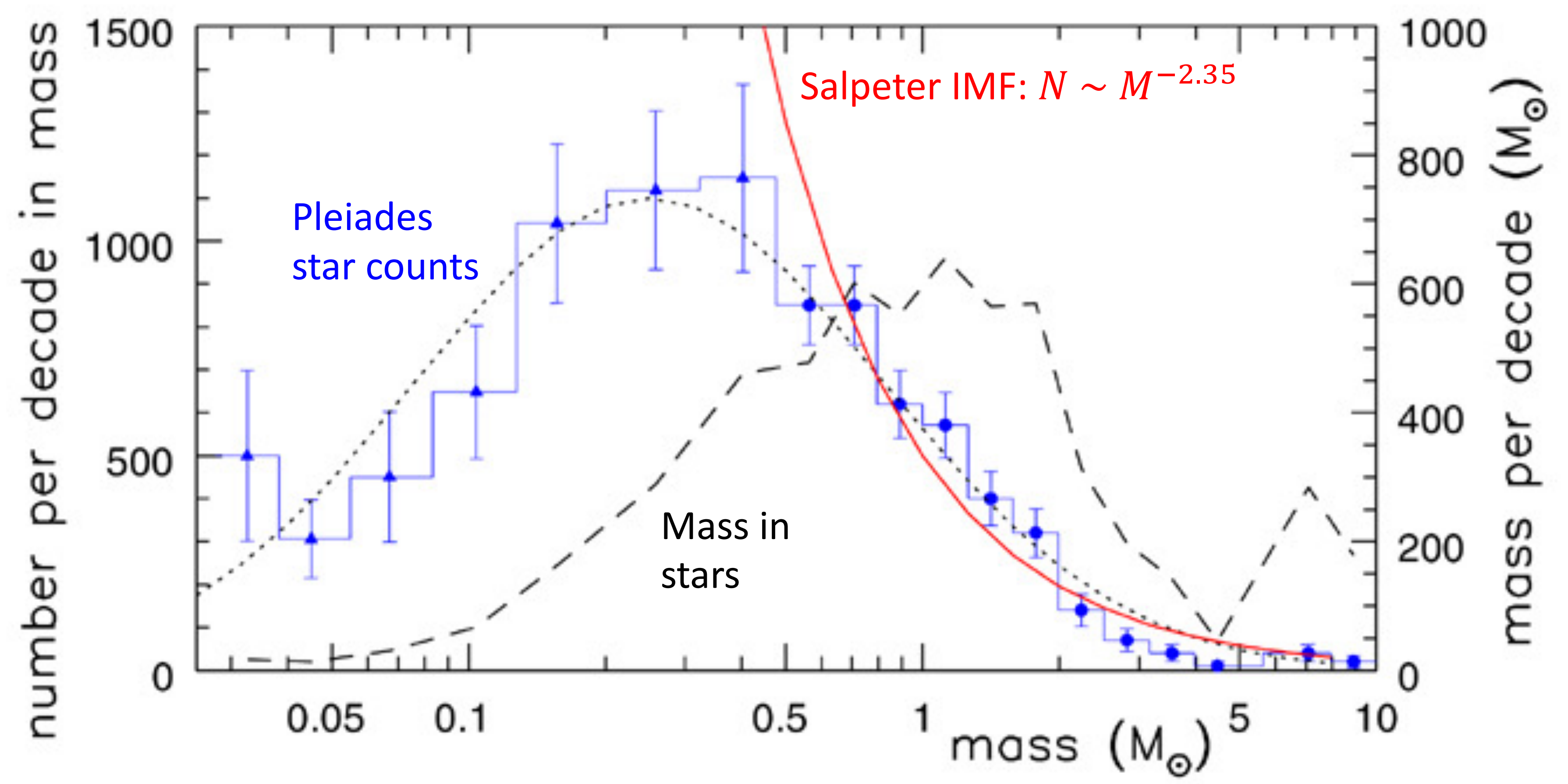
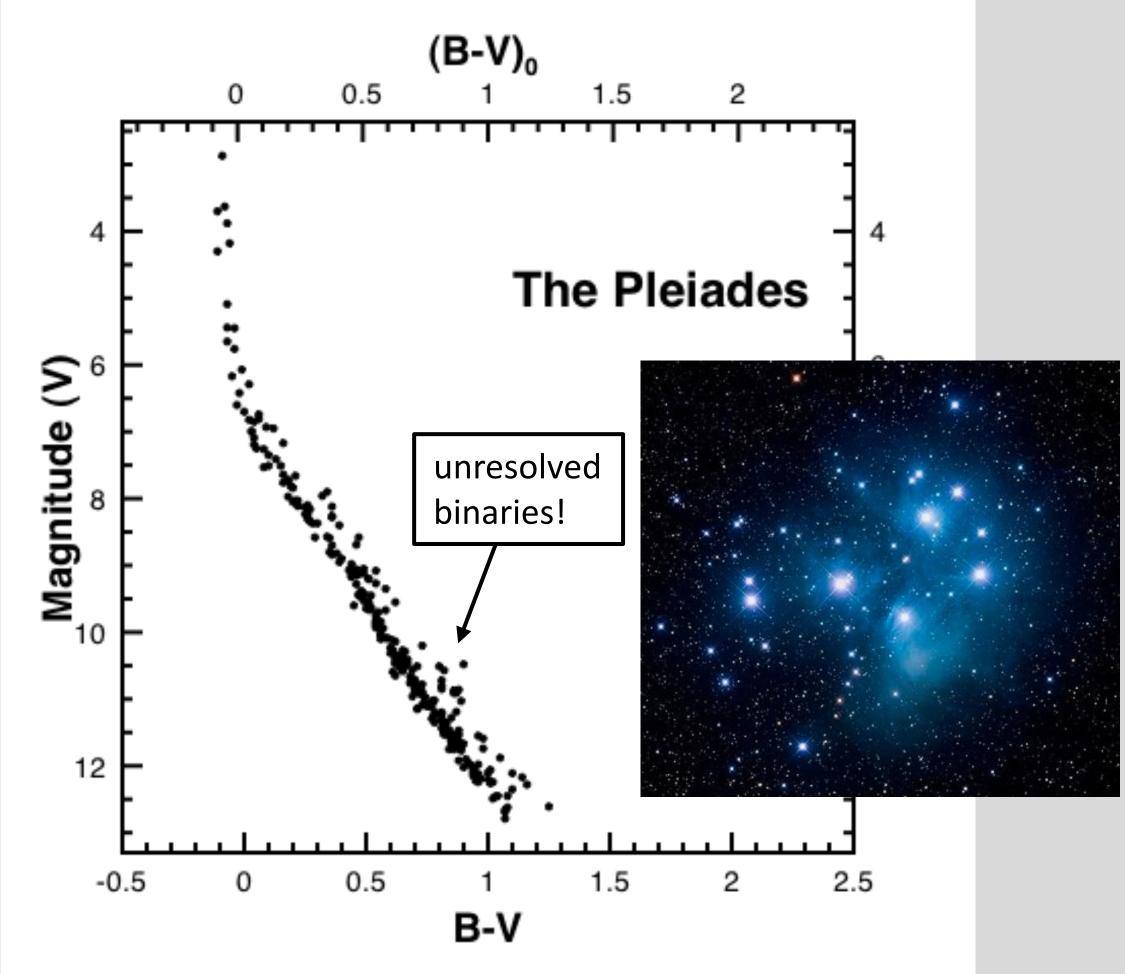


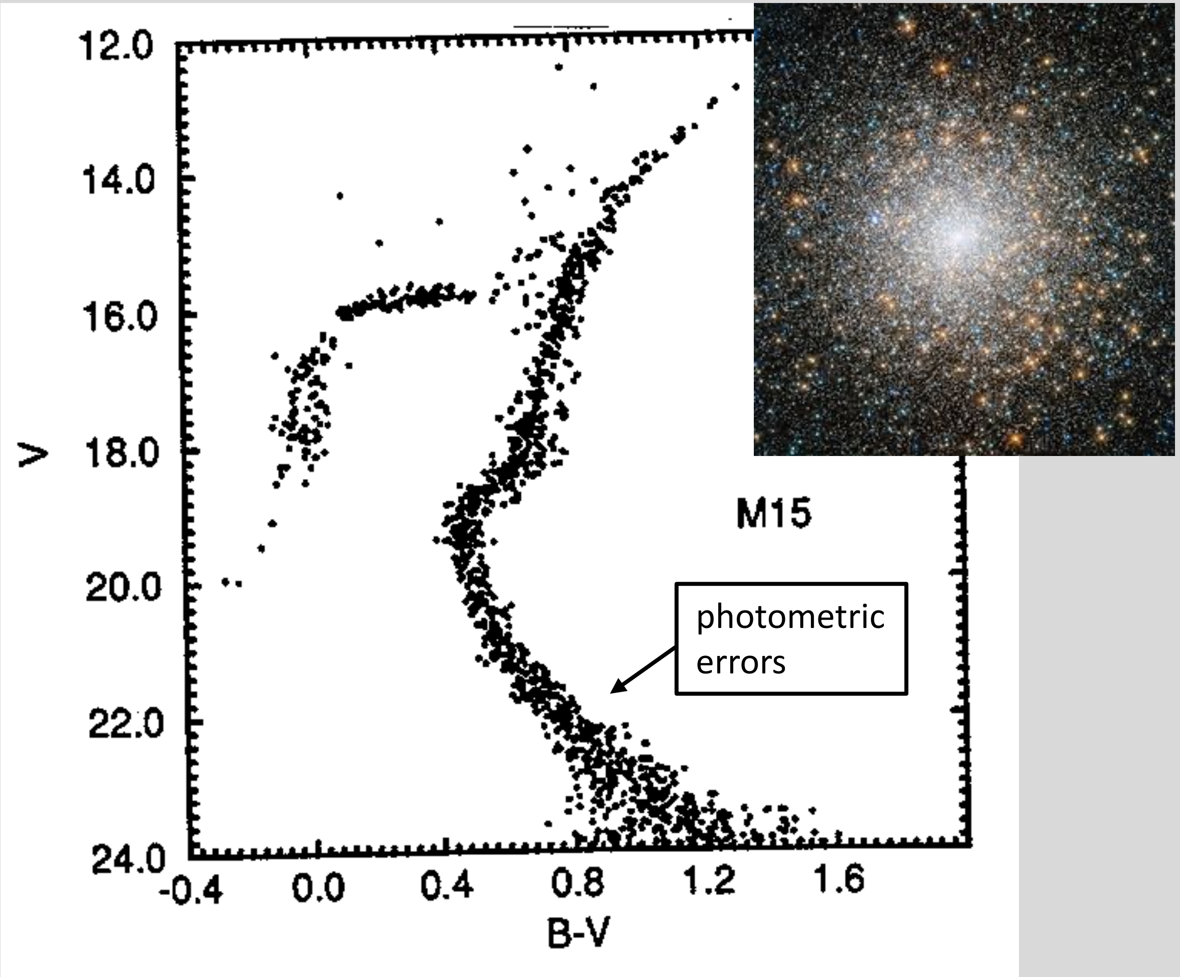
Fig 2.5 (E. Moreau) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

dist ~ 130 pc

Star Clusters: Useful Little Buggers

Star clusters represent a group of stars with common distance, age, and metallicity. Many stars to define an observed color-magnitude diagram, compare to calibrated color-magnitude diagrams to measure distance, age, metallicity, etc.



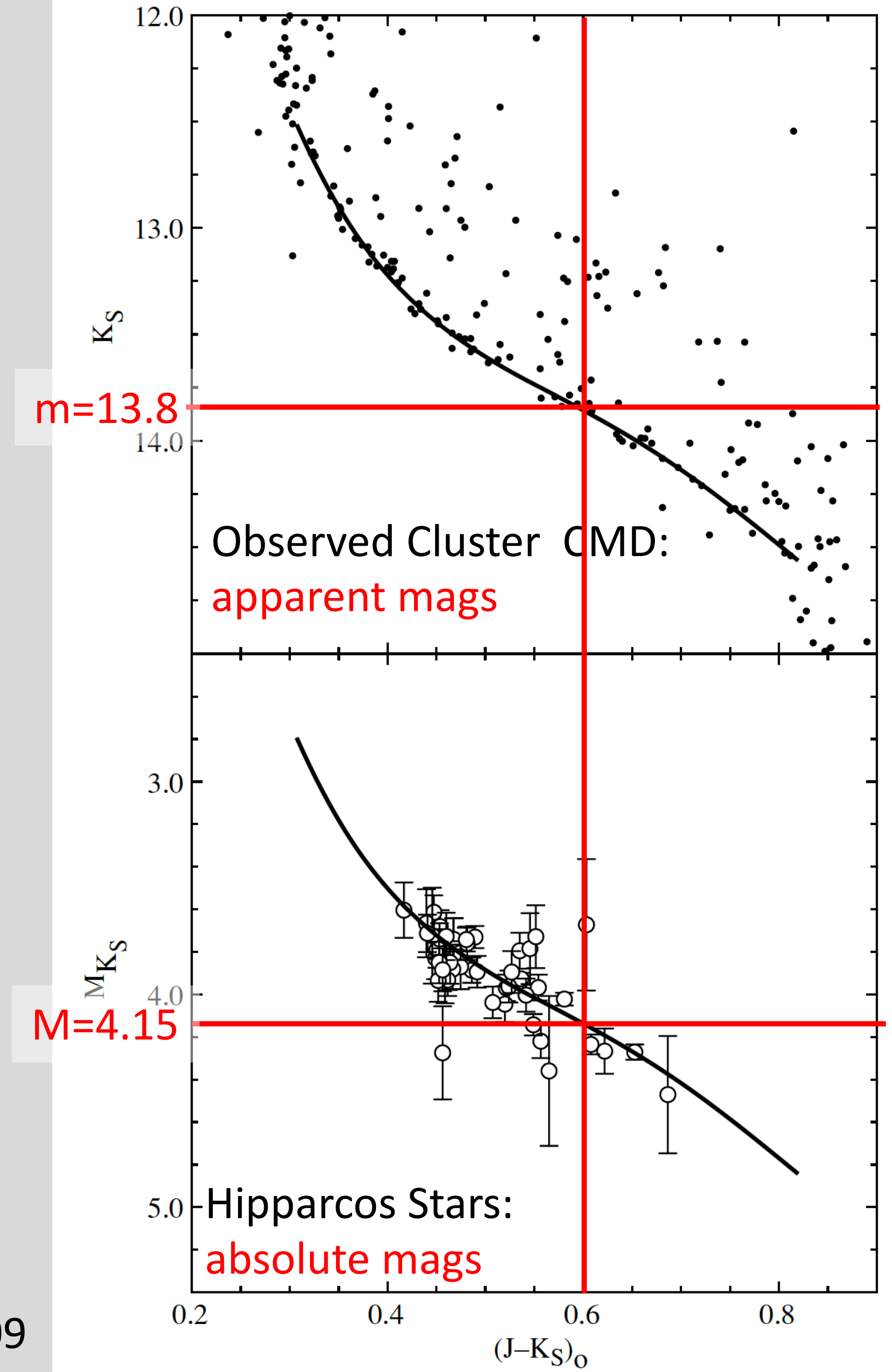


Star Clusters: Useful Little Buggers

Let's figure out the distance to the open cluster M67.

Solving for distance:

$$m - M = 5\log d - 5$$
$$13.8 - 4.15 = 5\log d - 5$$
$$9.65 = 5\log d - 5$$
$$d = 850\ pc$$



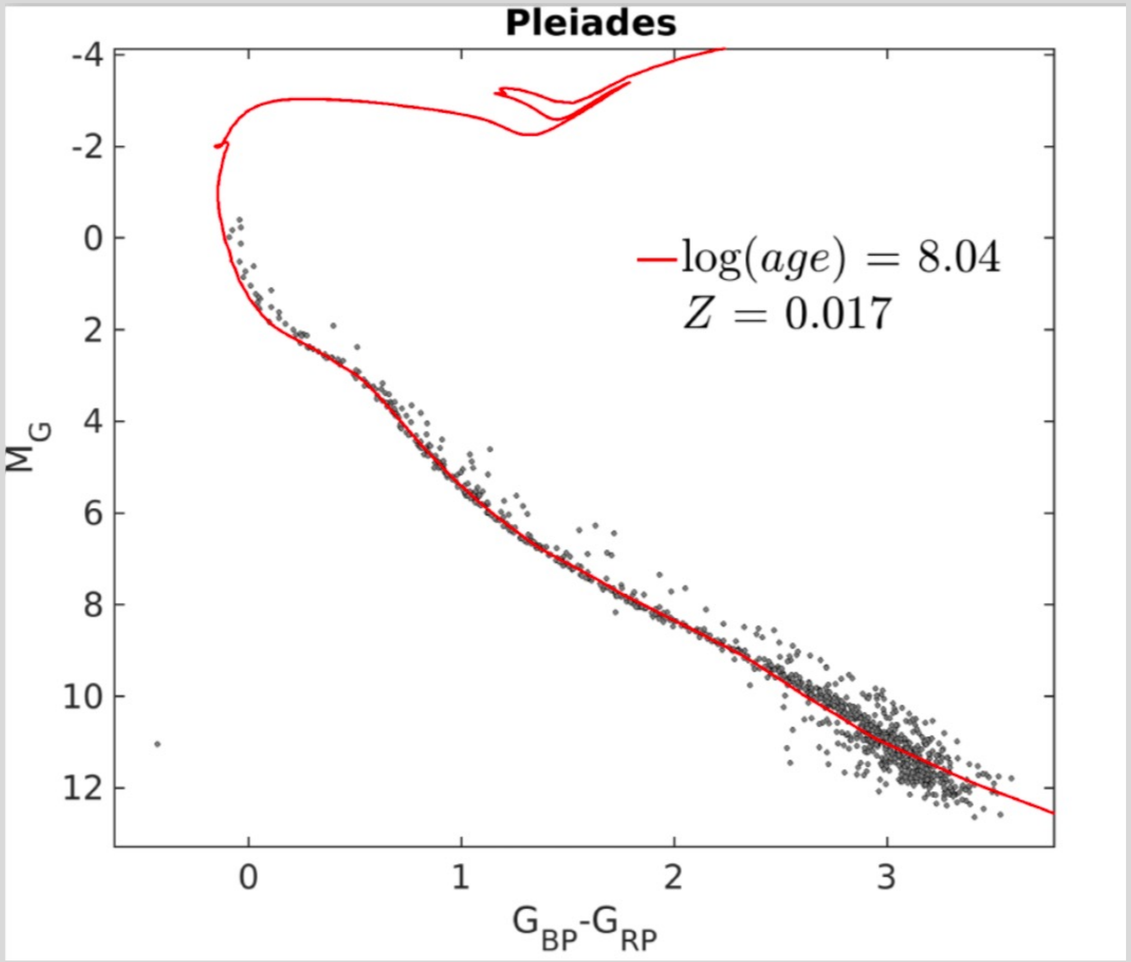
Sarajedini+ 09

Star Clusters: Useful Little Buggers

Compare observed CMDs (using apparent magnitudes) to parallax-calibrated CMDs (which have absolute magnitudes) and stellar models to derive distances, ages, metallicities.

Complications:

- Dust (reddens and dims the apparent magnitudes)
- Metallicity (need calibrated CMDs and stellar models matched in metallicity)
- Contamination (interloper stars not part of the cluster)
- Sparseness of the CMD
- Photometric uncertainty (problematic at faint end of sequences)
- Model uncertainties (not always great at late stages of evolution)



Gaia 2018

Star Clusters: Useful Little Buggers

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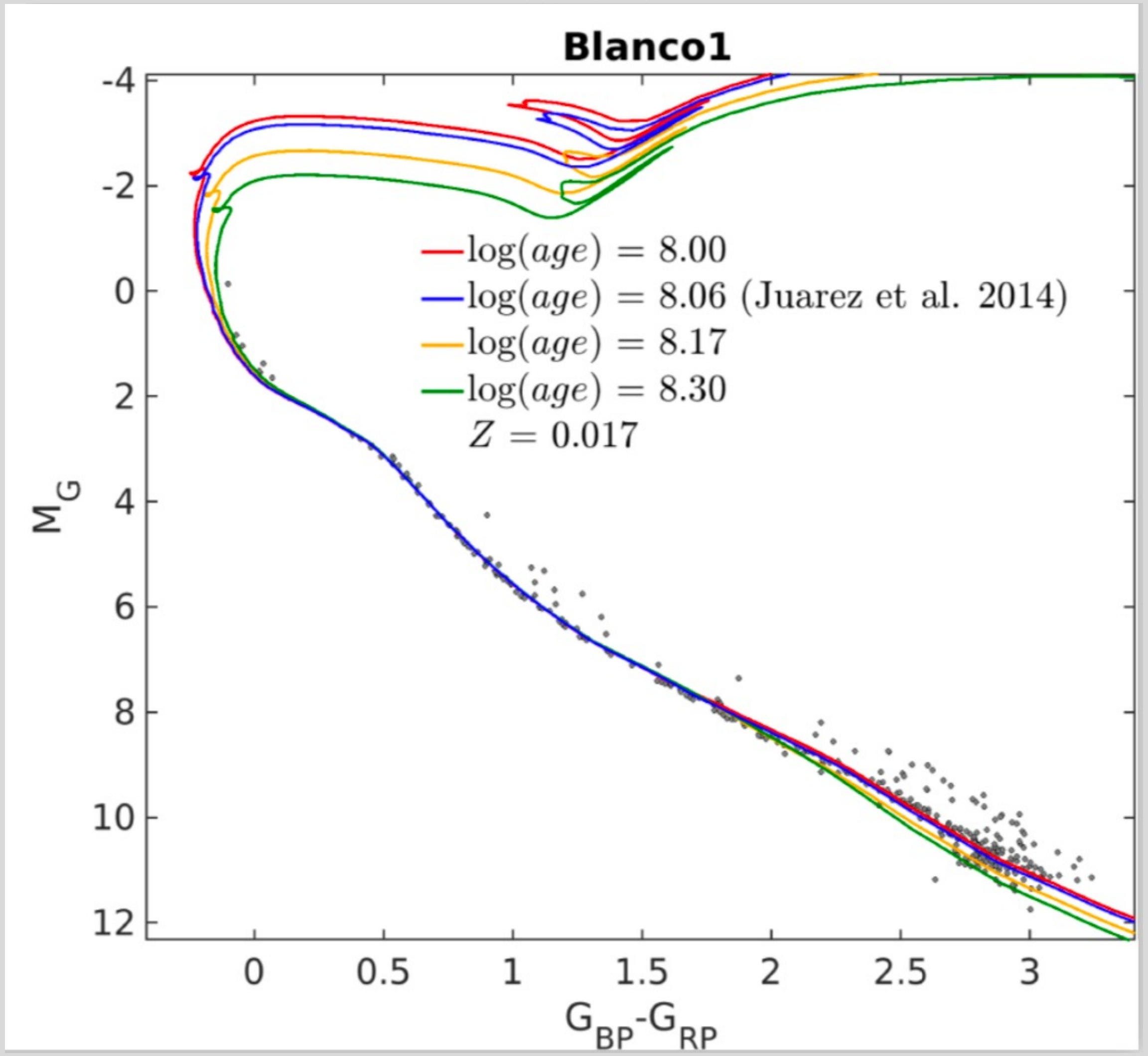
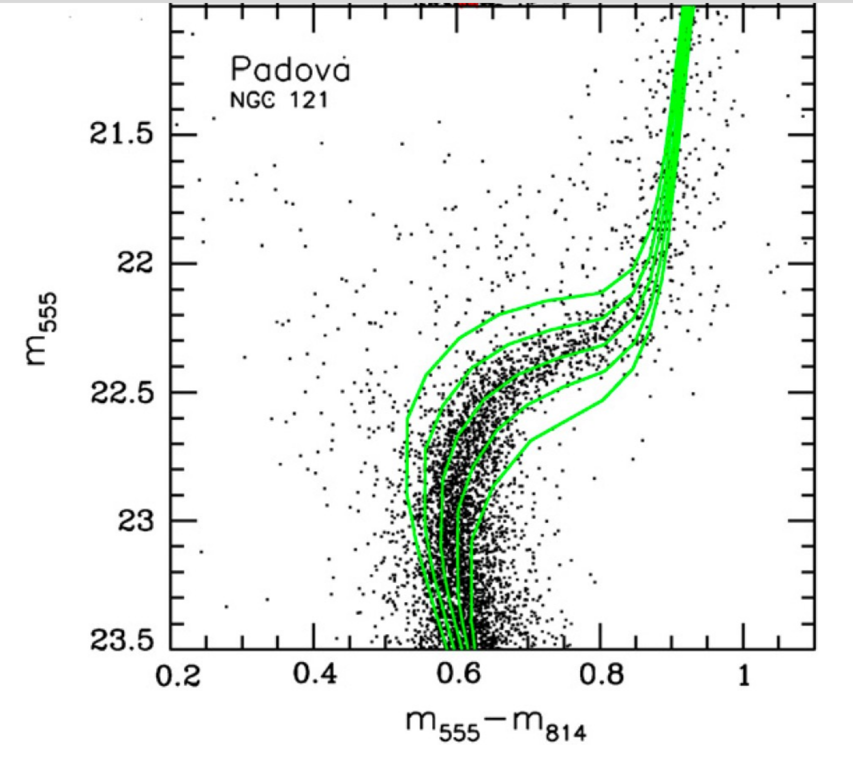
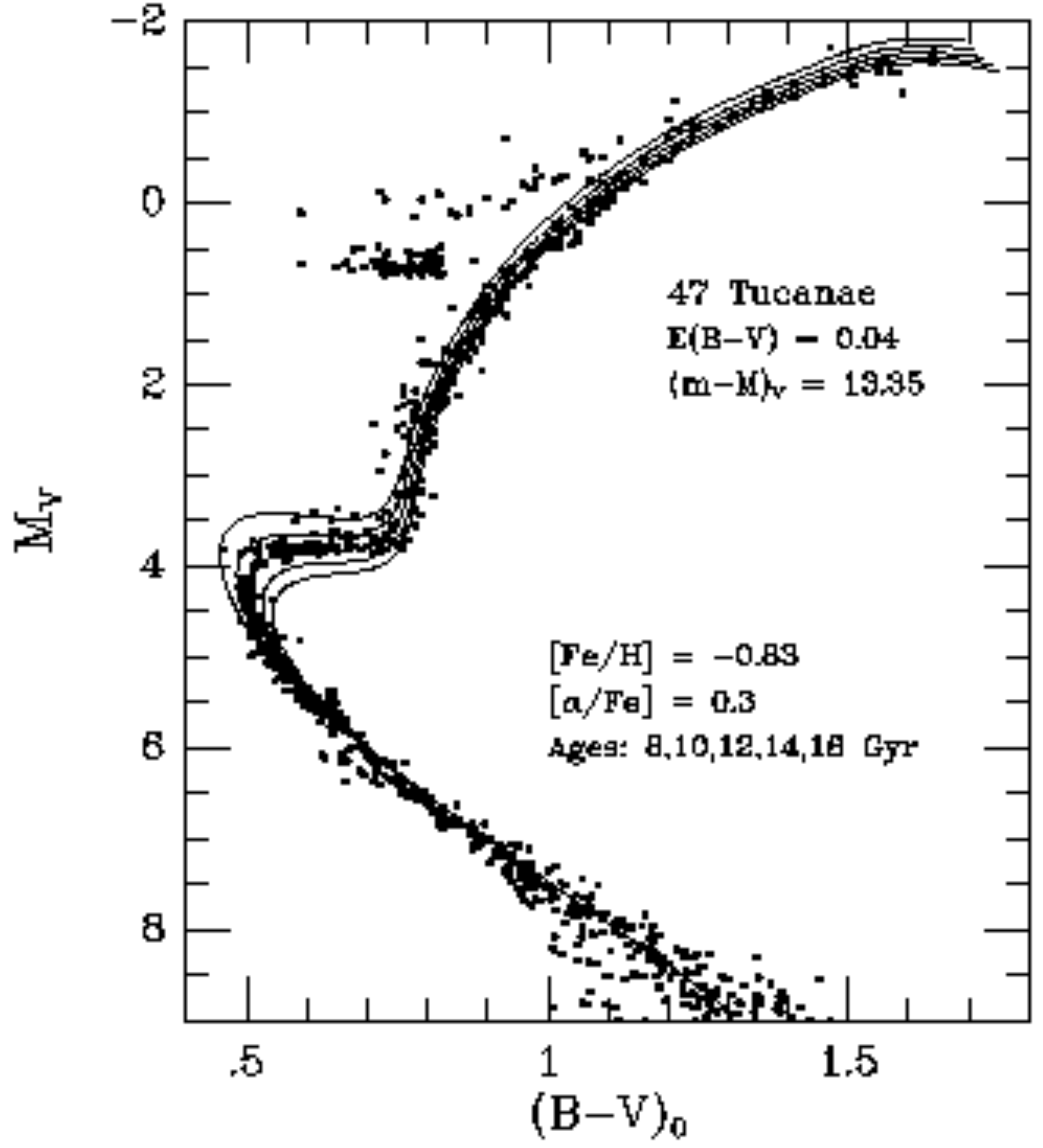


Gaia 2018

Globular Clusters: Old Populations



NGC 121 (Glatt+08)
ages: 10, 10.9, 11.8, 12.6, 13.5 Gyr



Varying Parameters: Old Populations

Isochrones depend on many parameters:

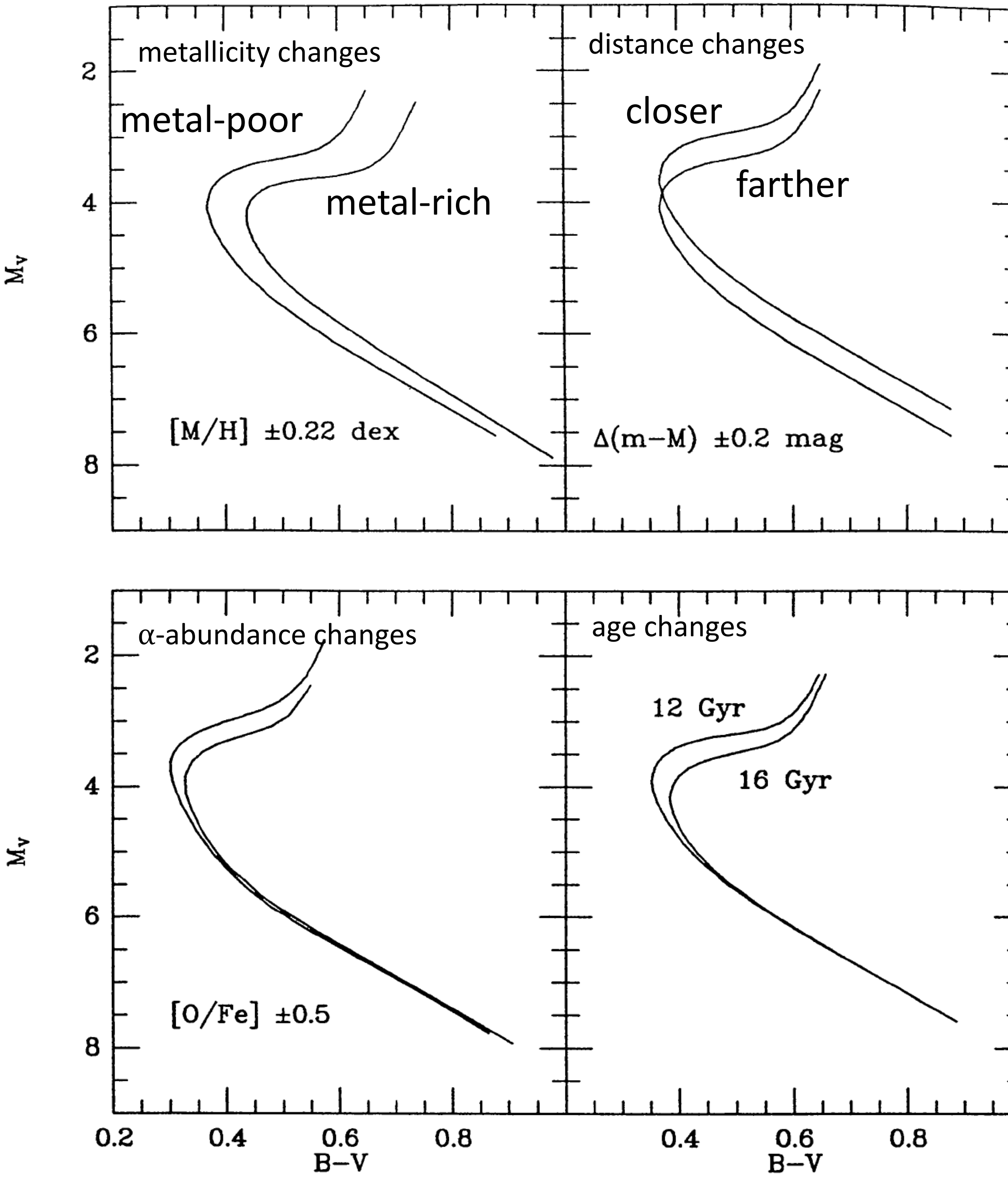
- Age
- Metallicity
- Distance
- α-abundances

All contribute to uncertainties.

Additional data can reduce uncertainties:
- Parallax gives distance
- Spectroscopy can contrain metallicity, α-abundance

How parameter variations change CMD shapes

☞



Bolte 1990

Individual Stars: Much more problematic!

Lets say we have photometry for an individual star:

app mag, color: m_B, B-V

What can we say about its absolute magnitude?

How good is this estimate?

How can we tell if a star is a dwarf or a giant if we don't know the distance? Can we figure out luminosity some other way?

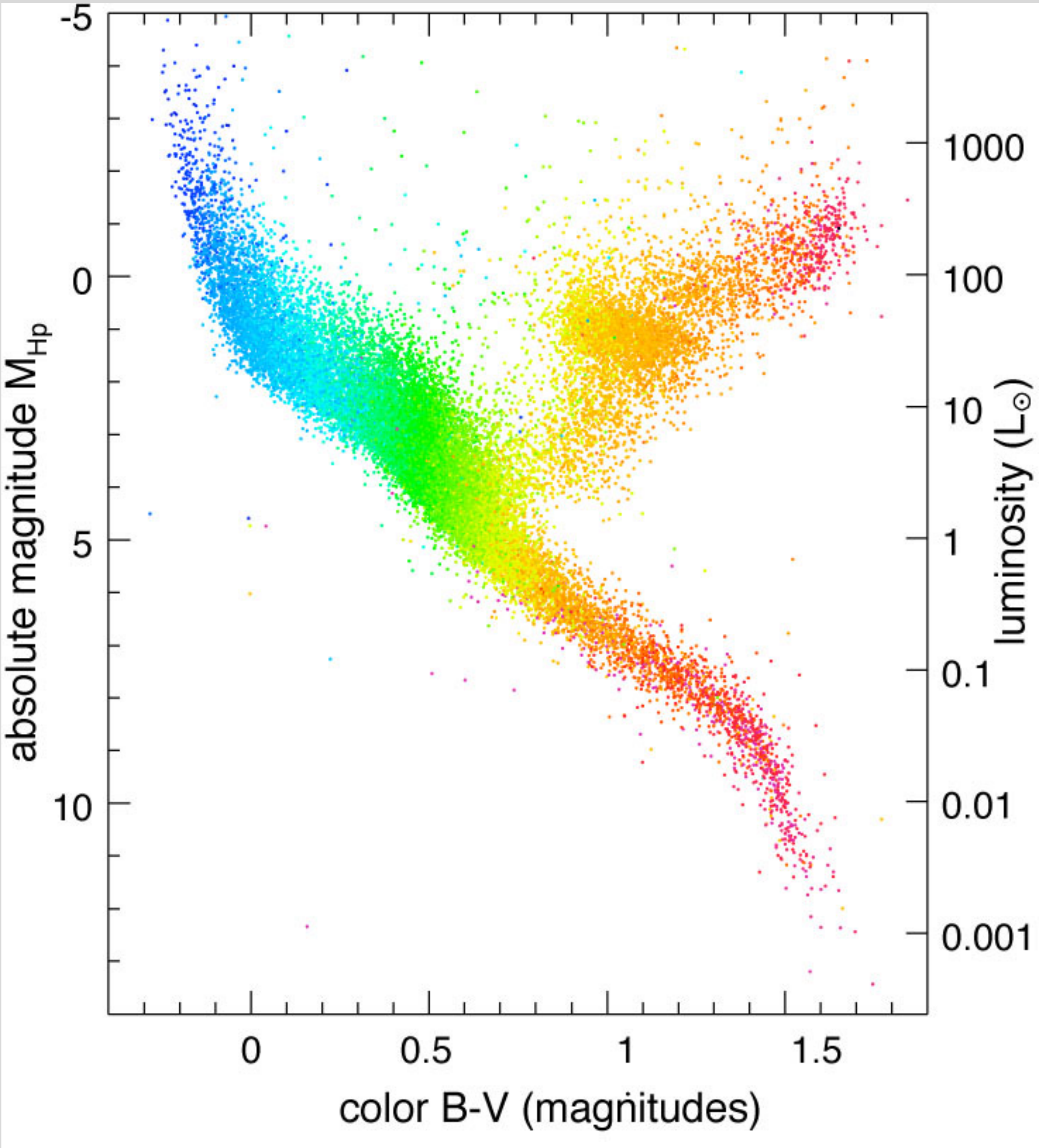


Fig 2.2 (F. van Leeuwen) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Luminosity information: Spectral Signatures

Giants and (*main sequence*) dwarfs have very different “**surface gravities**”

$$g = GM/r^2$$

typically expressed as **log(g)**

Giant stars: very extended, low surface gravity, low density atmospheres

Main sequence dwarfs: smaller, higher g, denser

Pressure broadening:

Collisions blur the energy levels of an atom, broadening the lines. Much stronger at higher densities/pressures, so giants have narrow lines, dwarfs have broader lines.

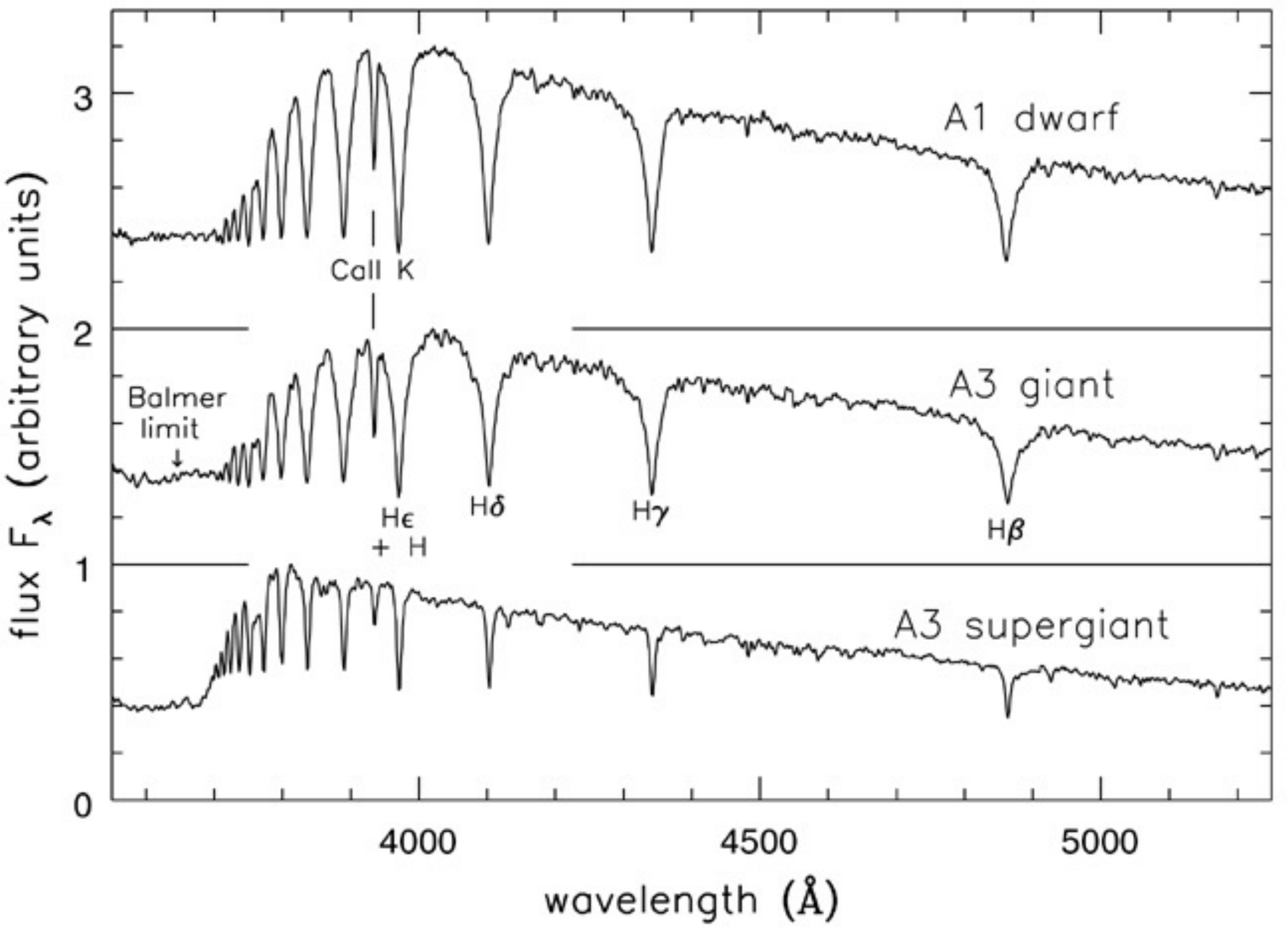


Fig 1.2 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Luminosity information: Spectral Signatures

Molecule formation

Easier to form molecules at higher densities, so *atmospheres of dwarfs have more molecules.*

Molecules are good at creating broad absorption bands, for example magnesium hydride (MgH).

So, MgH absorption is a good discriminator between dwarfs and giants.

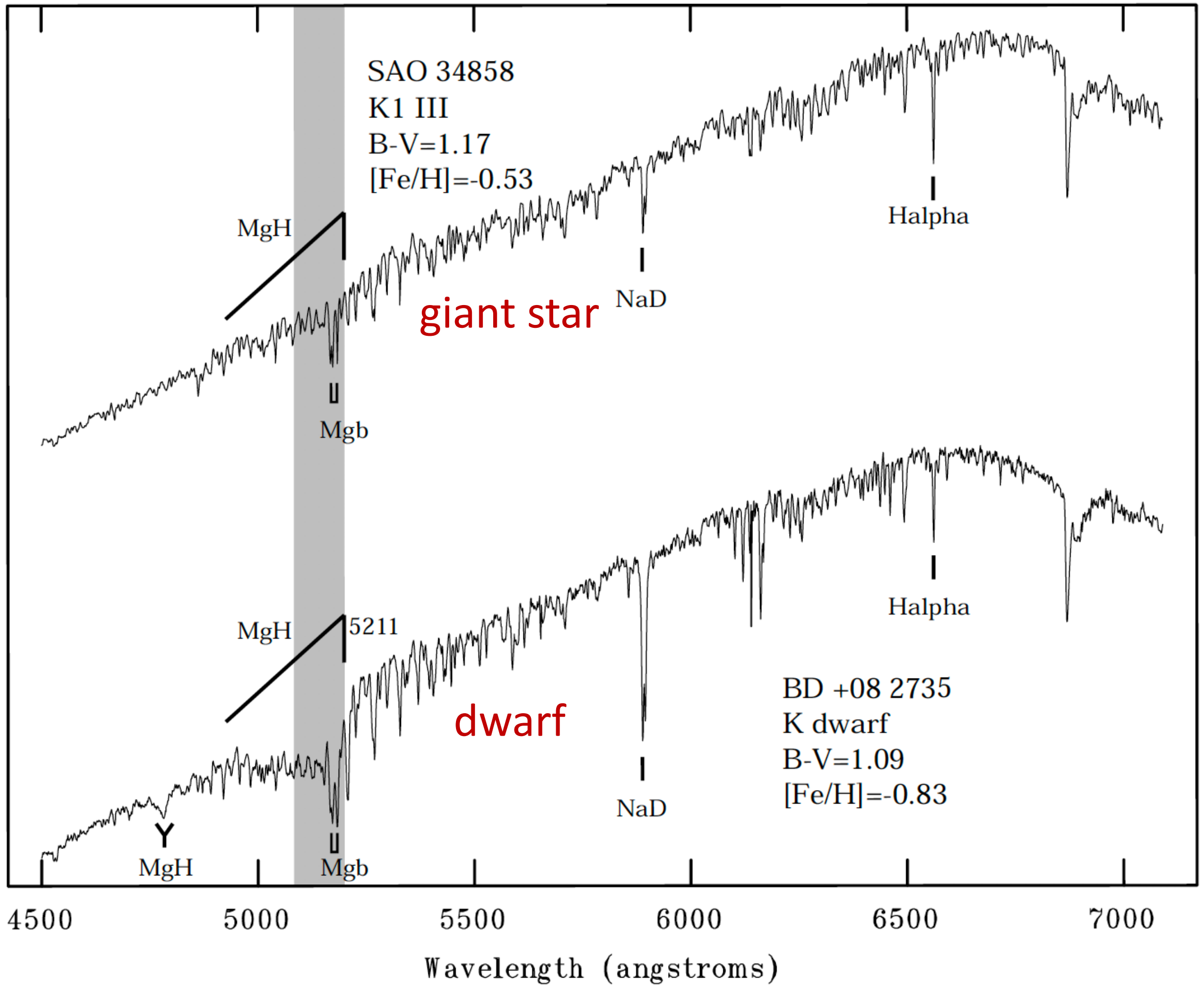


FIG. 1.—Comparison of spectra for K giant and dwarf stars of similar color and abundance, illustrating the dependence of the MgH + Mgb triplet on luminosity class. The location of the DDO51 filter bandpass is indicated by the shaded region. Note also the gravity-sensitivity of both the MgH band near 4850 Å as well as the NaD doublet (Tripicchio et al. 1997).

Majewski+00

Individual Stars: Spectroscopic Parallax

Now we have more information

m_B, B-V, luminosity class, metallicity

Now what can we say about its absolute magnitude?

How good is this estimate?

This technique is called "spectroscopic parallax", but
IT 👏 HAS 👏 NOTHING 👏 TO 👏 DO 👏 WITH 👏 PARALLAX

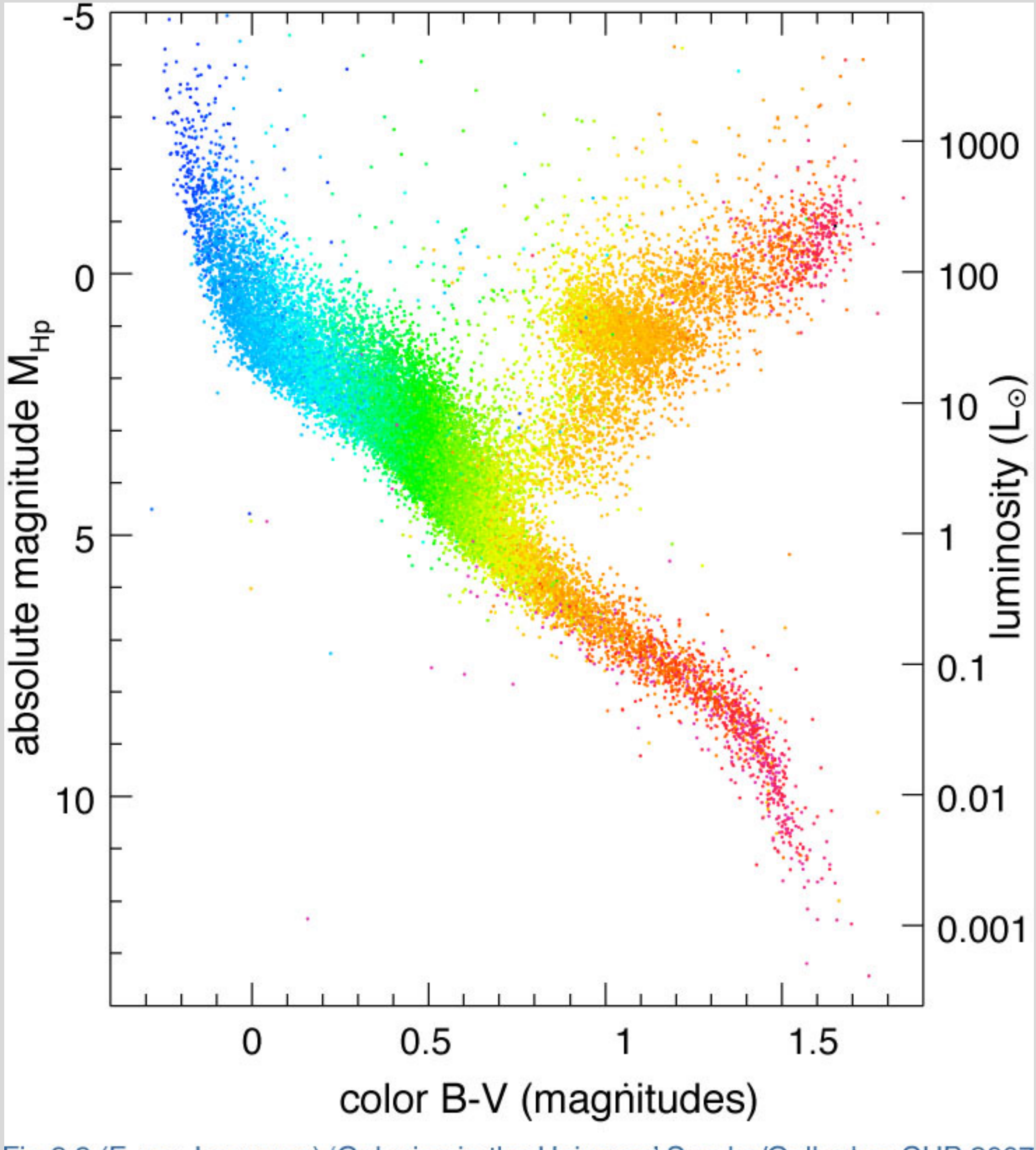


Fig 2.2 (F. van Leeuwen) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Stellar Ages

Ages of *individual* stars are very hard to estimate.

If you have a good estimate of its physical properties, compare to theoretical evolutionary tracks on the CMD.

Need very good data: distance, photometry, metallicity.

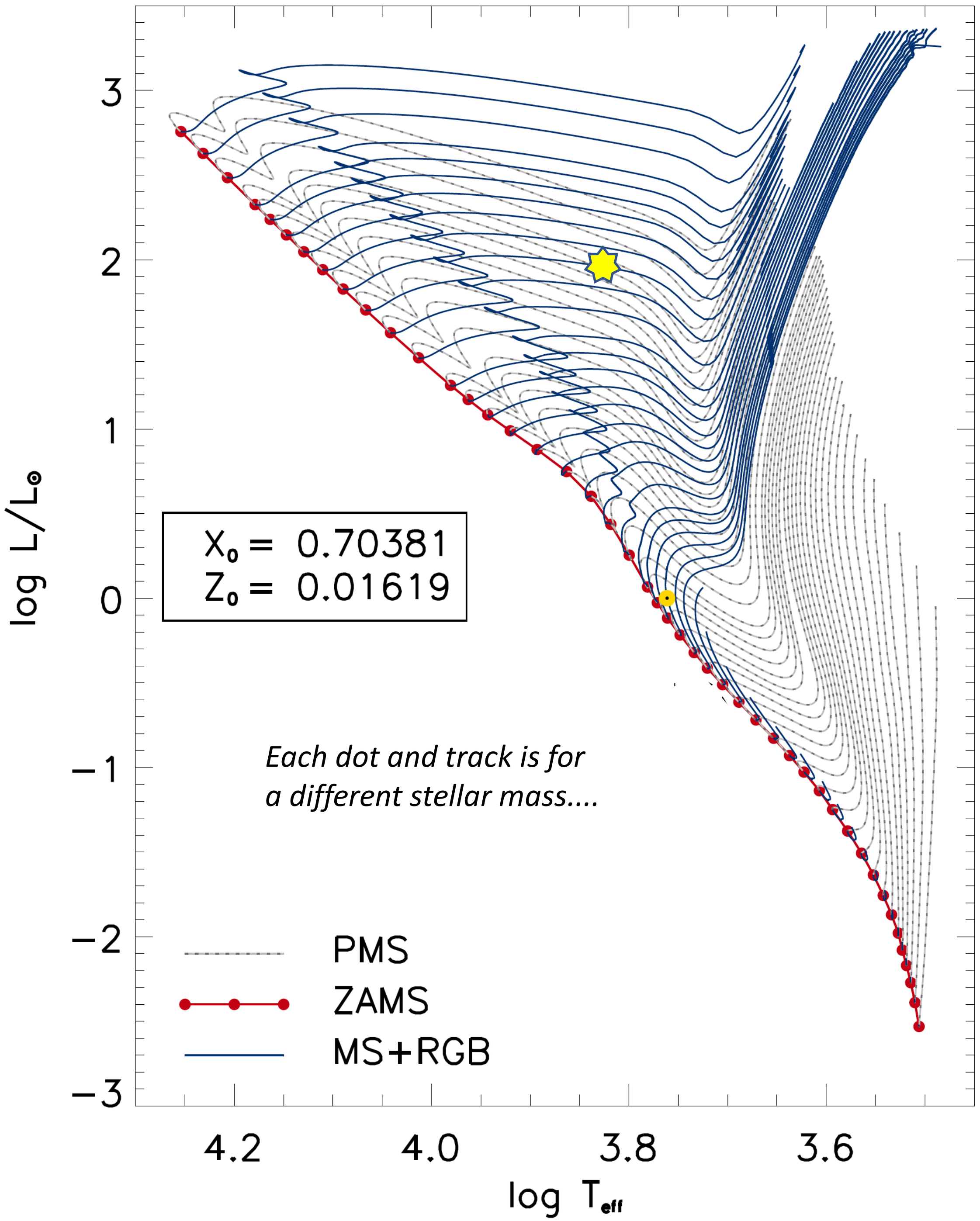
Need very good models that cover all relevant parameters.

Need good transformation between observables and models:

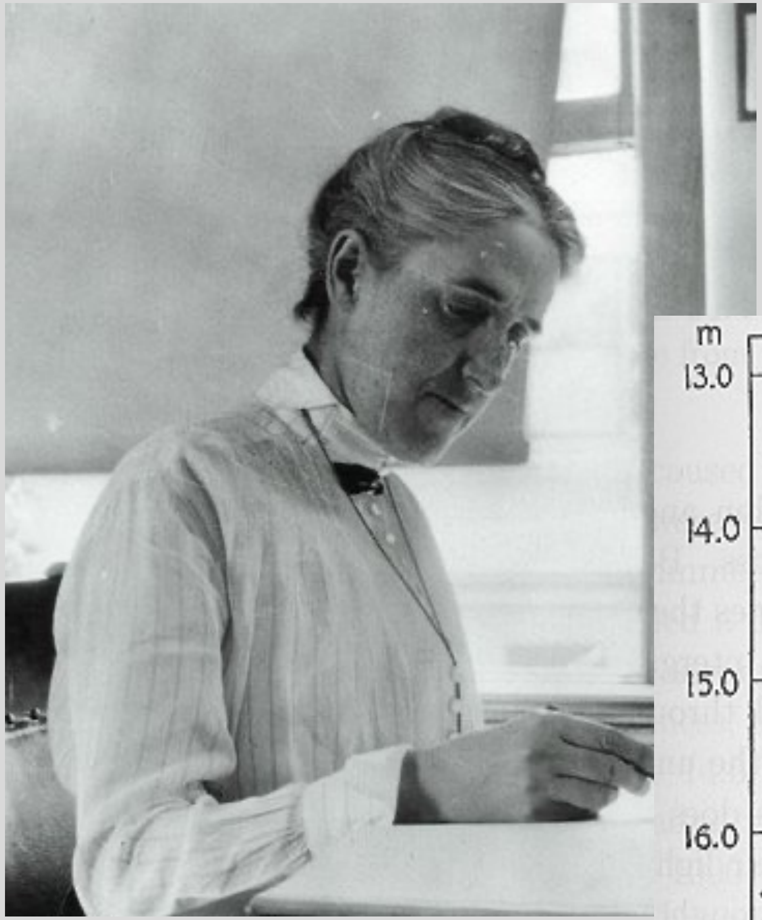
- magnitude and colors ⇔ L_{bol} (bolometric mag = total luminosity)
- colors or spectra ⇔ T_{eff} (surface temperature)
- metallicity, α ⇔ X, Y, Z (chemical composition)

If done carefully, gives you both mass and age.

Yale-Potsdam Isochrones
Mass range: 0.86–5 $M_\odot$
Spada+17

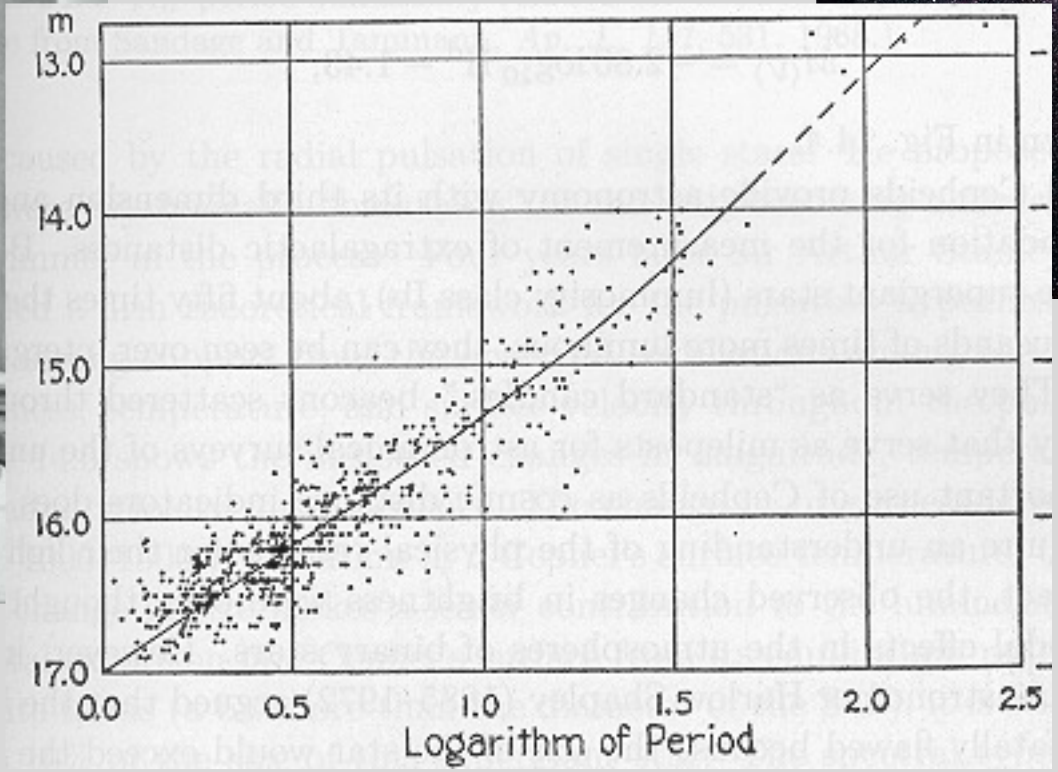


Pulsating Variables: Cepheids and RR Lyraes

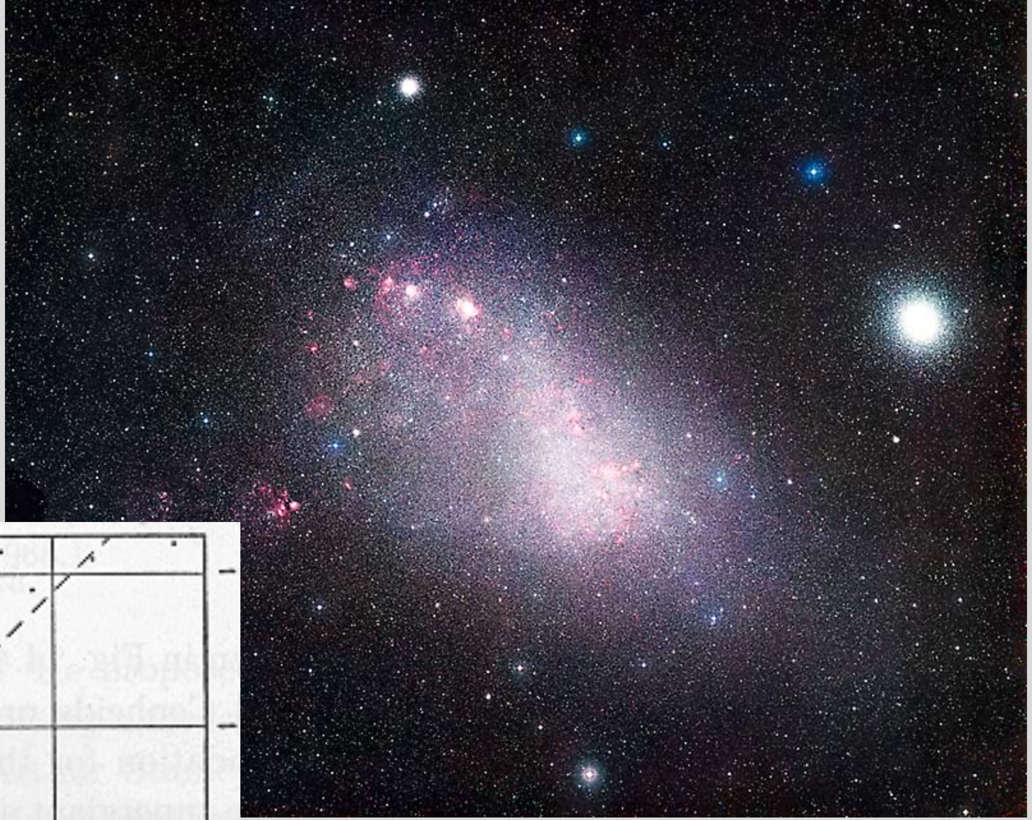


Henrietta Leavitt (1868-1921)

Cepheids in the SMC



apparent mag (m_{pg}) versus log(P)



Small Magellenic Cloud

Since all these stars are at roughly the same distance, this must be a period-luminosity relationship.

If we can calibrate it. We need absolute distances.

Pulsating Stars

As stars evolve off the main sequence, at certain phases their internal structure (temp, pressure, density) makes them unstable to radial oscillations.

This occurs on the instability strip on the HR diagram. (grey shaded regions)

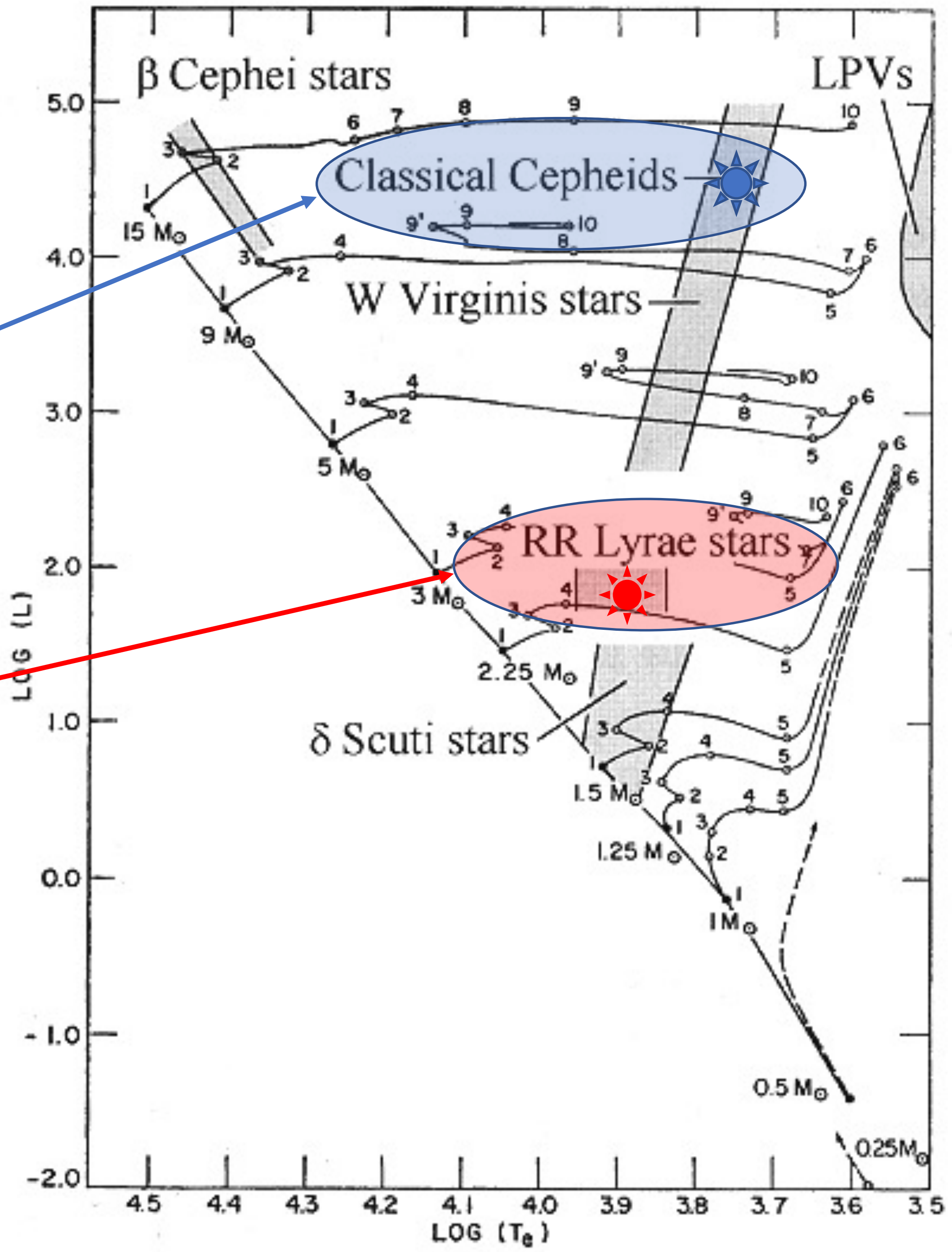
Cepheids: high mass stars ($\gtrsim 8 - 10\ M_\odot$)

Luminous, easy to see. But rare. Traces young populations.

RR Lyraes: low mass stars ($\approx$ few $M_\odot$)

More common, but fainter. Traces old populations.

Very challenging to get direct distances to these kinds of stars. Because they are rare, there aren't many nearby, so hard to get parallaxes to work out distances and absolute mags.



Getting Distances

We see Cepheids and RR Lyraes in large numbers in the LMC and SMC. If we had distances to those galaxies, we could then calibrate the P-L relationship and have a powerful distance estimating tool.

But:

- Metallicity effects (it may actually be a period-luminosity-metallicity relation for these stars)
- Uncertain reddening (particularly for Cepheids which may still be near their original star-forming region)
- Rare objects means none are close enough to get ground-based parallaxes, which makes it hard to calibrate their absolute magnitudes.

Two ways to get direct distances to these stars and do the absolute magnitude calibration!

Small Magellenic Cloud

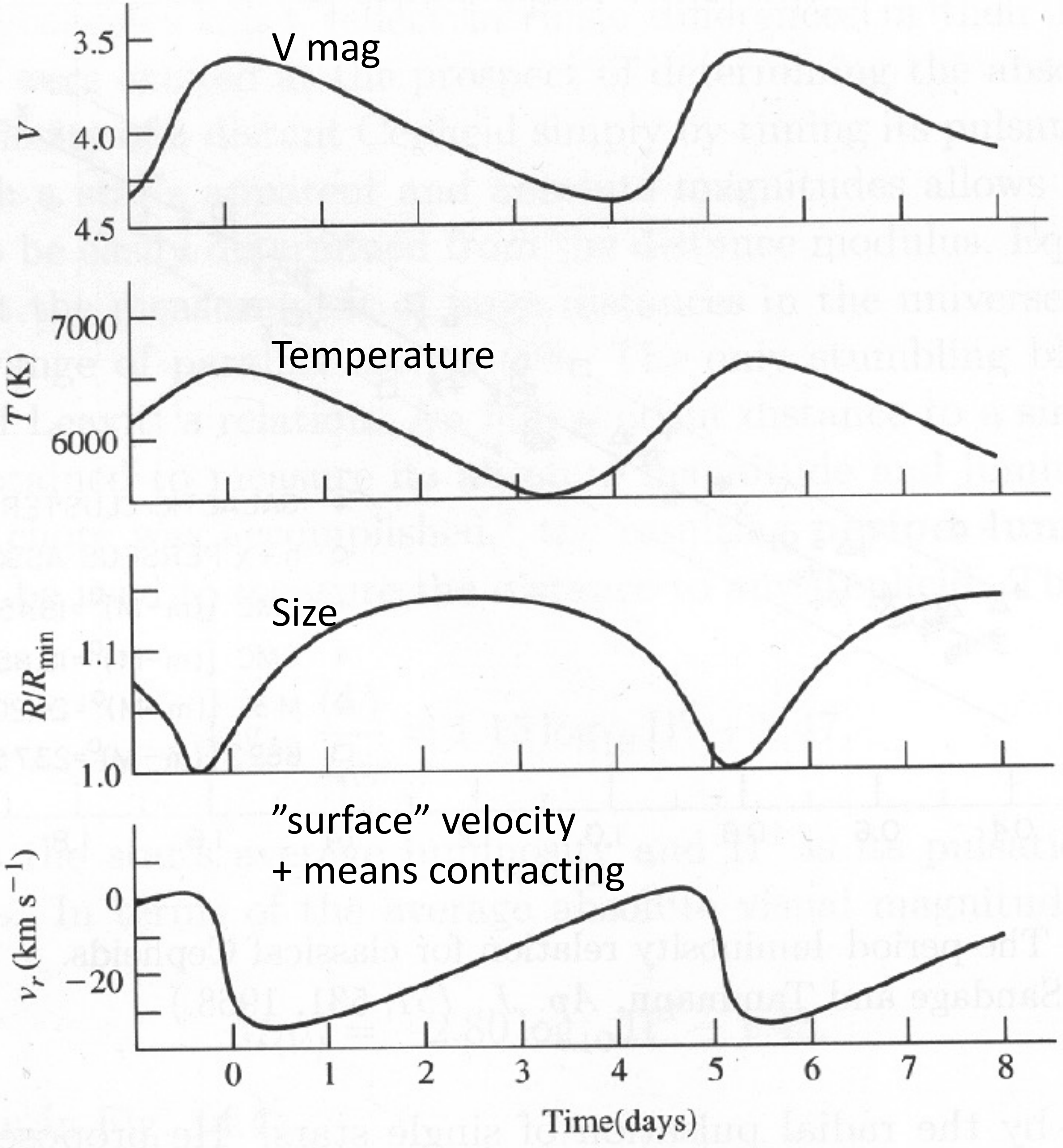
Large Magellenic Cloud

Pulsating Stars

How we know they pulsate: we *see* the velocity of absorption lines in the photosphere changing across the cycle.

When the star is smaller, it is hotter.

Since $L = 4\pi R^2 \sigma T^4$, the temperature increase ($\nearrow T^4$) beats the radius decrease ($\searrow R^2$), and so it is more luminous when it is smaller.



Properties along the pulsation phase

Figure 14.5 Observed pulsation properties of δ Cephei.

Pulsating Stars: Baade-Wesselink Distances

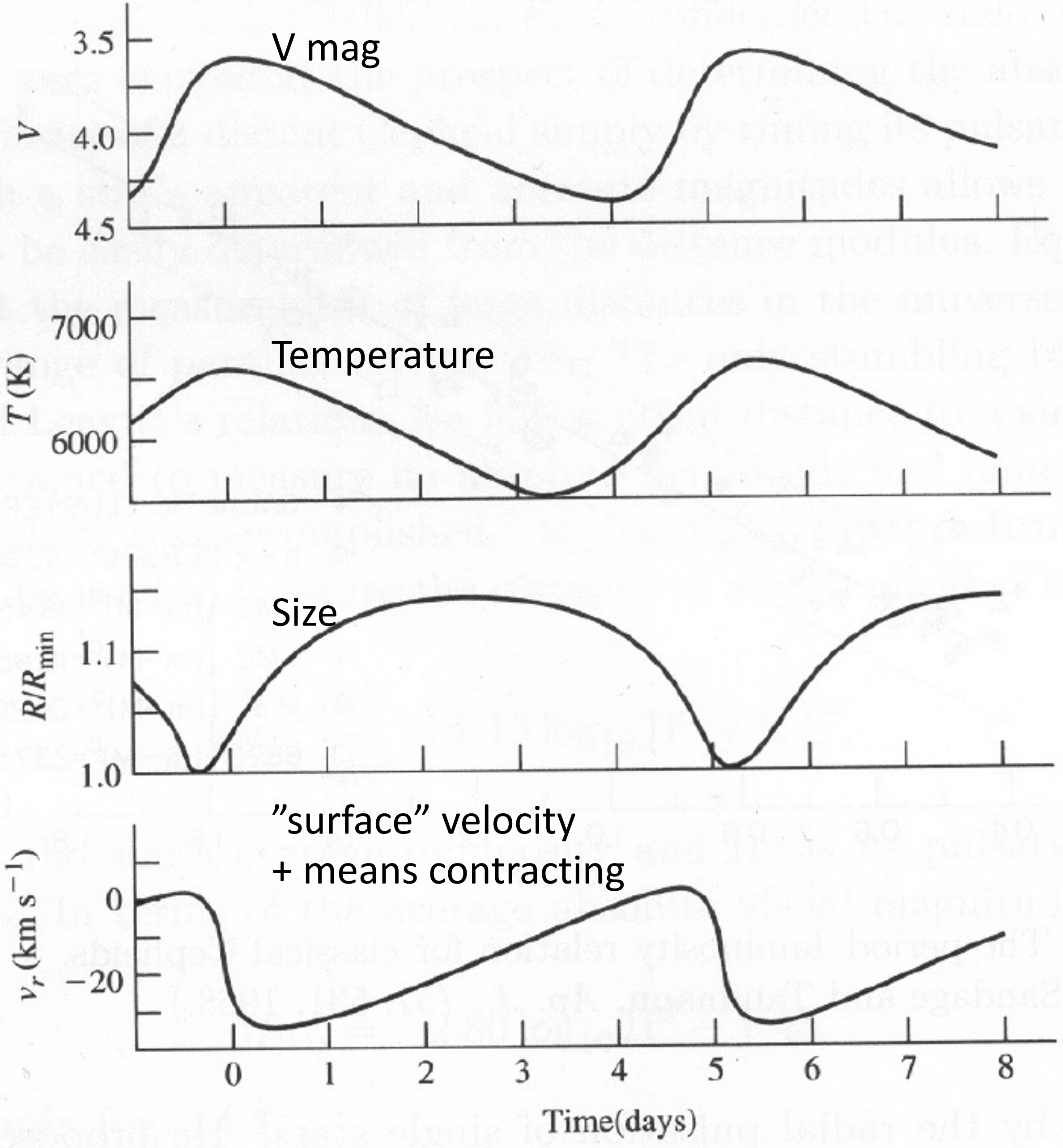
Since $L = 4\pi R^2 \sigma T^4$, the difference in apparent magnitude and temperature along the phase gives us the ratio of radii: R_{max}/R_{min}.

But if we integrate the radial velocity curve over time, we know the difference in size:

$$R_{max} - R_{min} = \int_{t_{min}}^{t_{max}} v_r \, dt$$

Having both R_{max}/R_{min} and $R_{max} - R_{min}$ means we can solve for radius.

Then $L = 4\pi R^2 \sigma T^4$ gives us luminosity, and the combination of luminosity and apparent magnitude gives us distance.



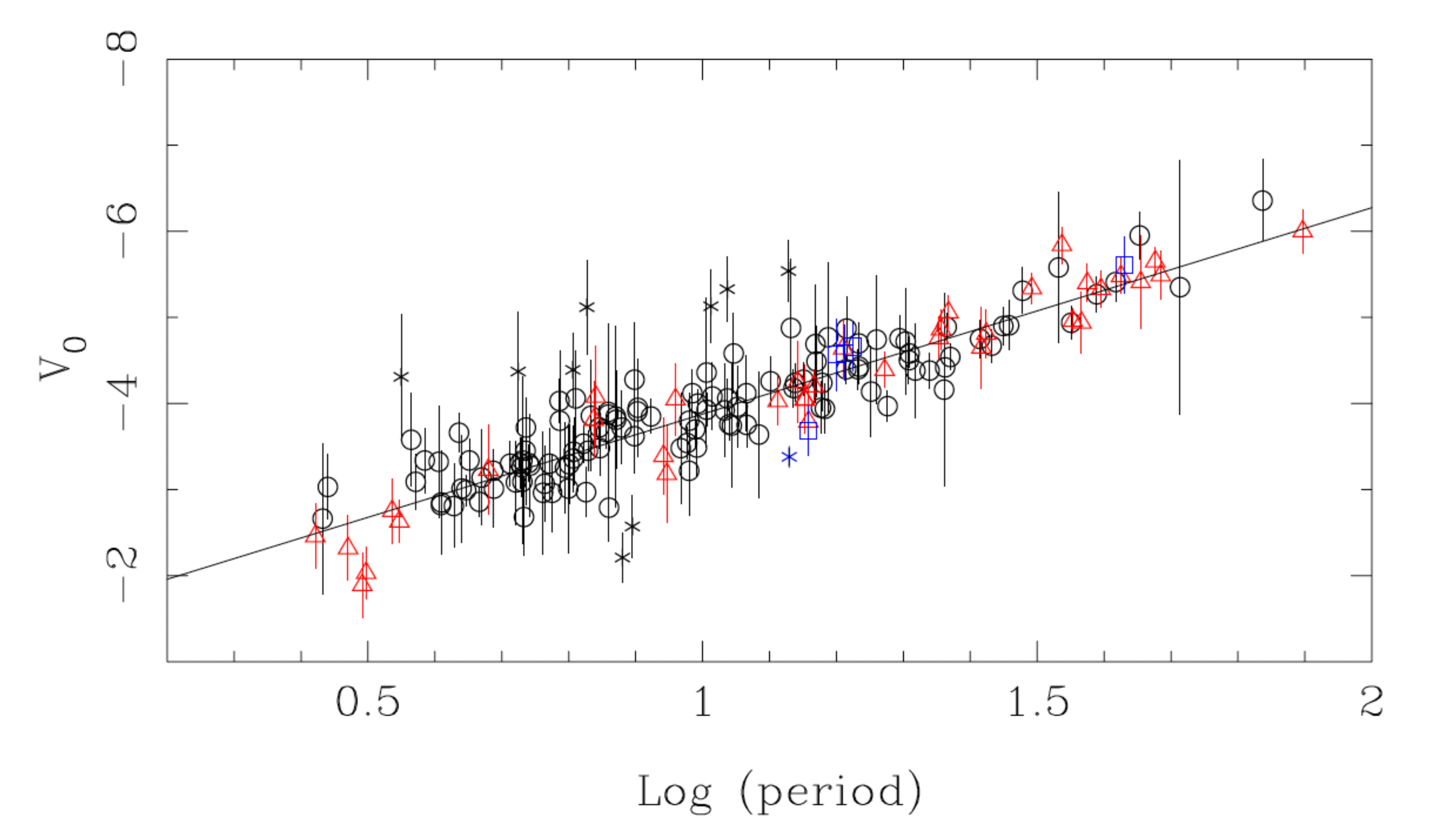
Properties along the pulsation phase

Figure 14.5 Observed pulsation properties of δ Cephei.

Cepheids: Baade-Wesselink PL-relation

Calibrated P-L relationship

Absolute V magnitude! ⇒



Milky Way Cepheids (black)
Large Magellanic Cloud Cepheids (red)
Small Magellanic Cloud Cephedis (blue)

Groenewegen 13

Cepheids: Hubble Parallaxes

Since Cepheids are typically pretty distant, ground based parallax is impossible.

But then the Hubble Space Telescope came along.

Direct calibration of Galactic Cepheids ⇒

Absolute mag vs log(P)

Riess+18

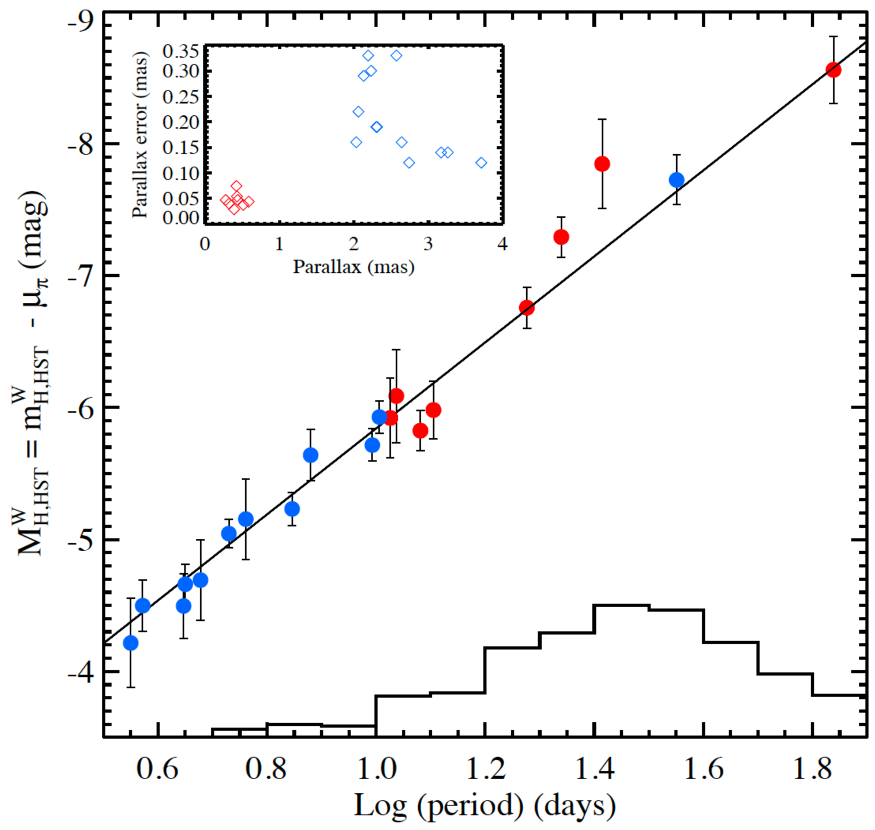
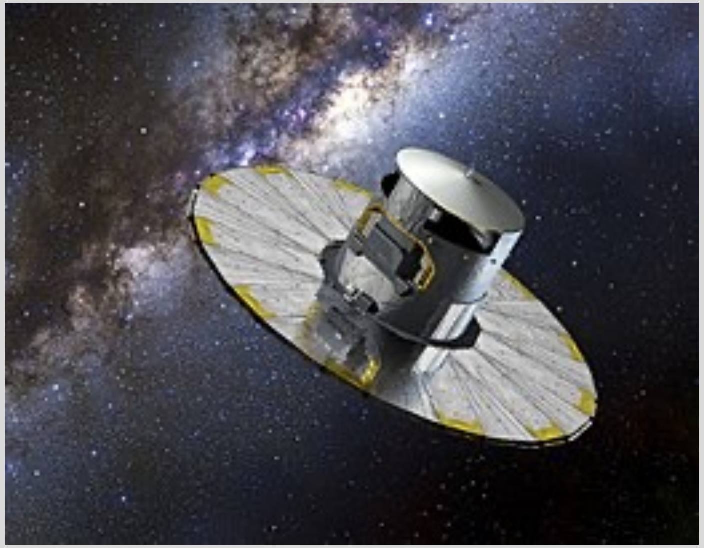


Figure 13. The P–L relation of Milky Way Cepheids based on trigonometric parallax measurements. The points in blue were measured with the *HST* FGS (Benedict et al. 2007) and *Hipparcos* (van Leeuwen et al. 2007) and are all within 0.5 kpc, and the points in red are presented here from spatial scanning of WFC3 and are in the range of $1.7 < D < 3.6$ kpc. The inset shows the uncertainties in the measured parallaxes.

Cepheids: Gaia Parallaxes

And then Gaia came along.

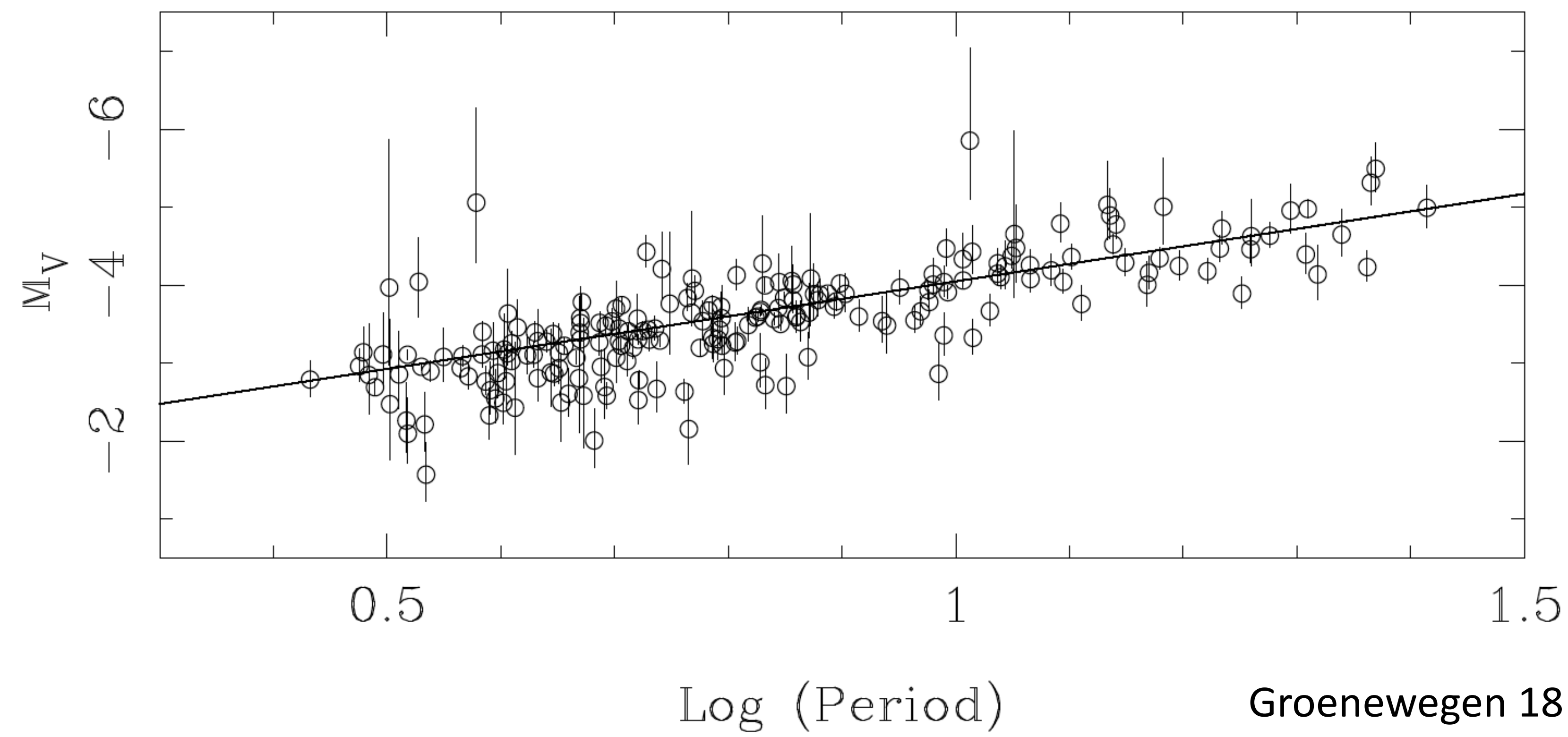


Direct calibration of Galactic Cepheids ⇒

With directly calibrated period-luminosity relationships, our ability to measure distances inside and outside the Galaxy is greatly improved!

Studying pulsating stars in other galaxies

- Need young pops for Cepheids; otherwise RR Lyraes.
- Hubble: Cepheids out to ≈ 15−20 Mpc, RR Lyraes to ≈ 3−5 Mpc or so.
- Even then, these stars are rare.



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