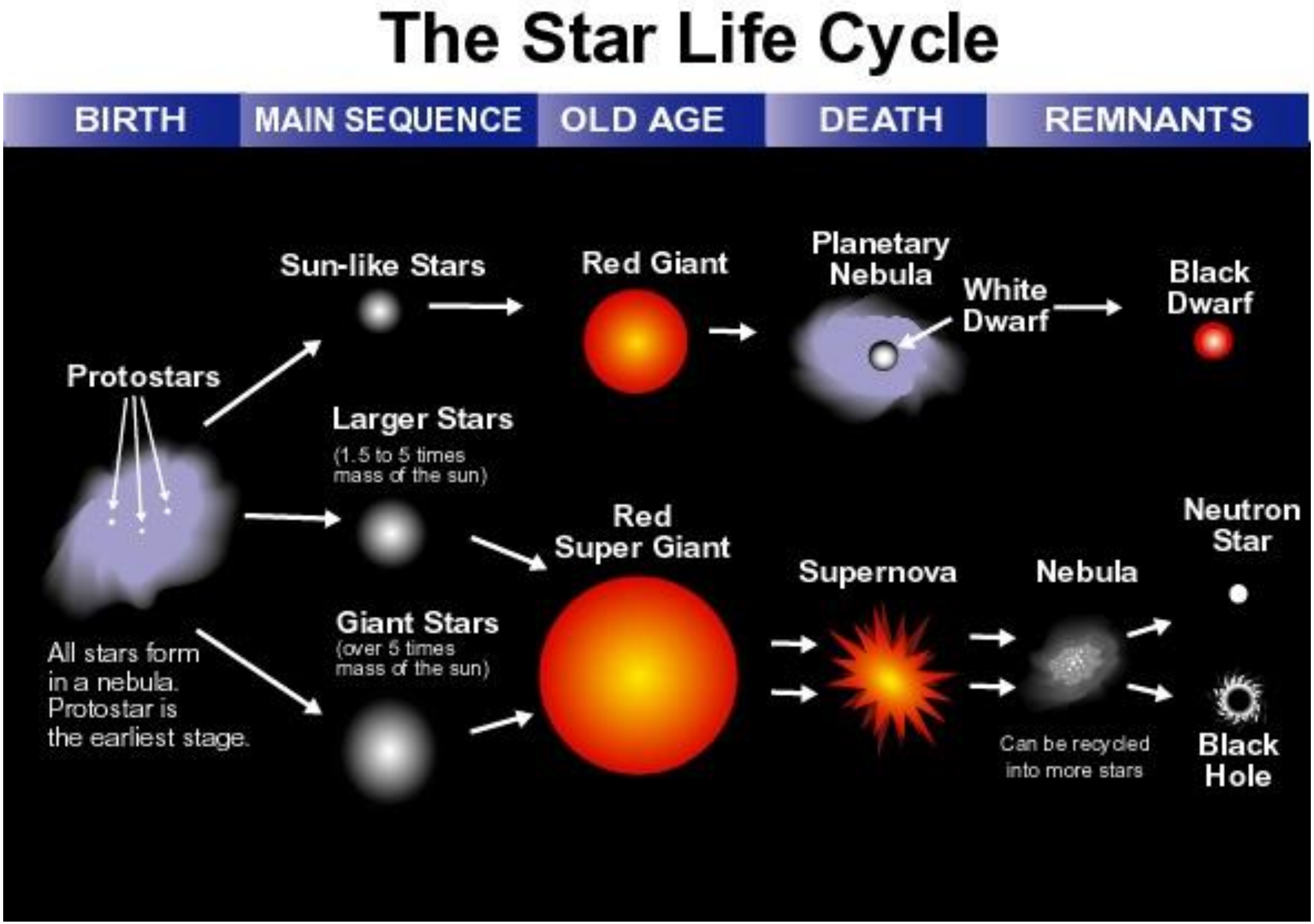
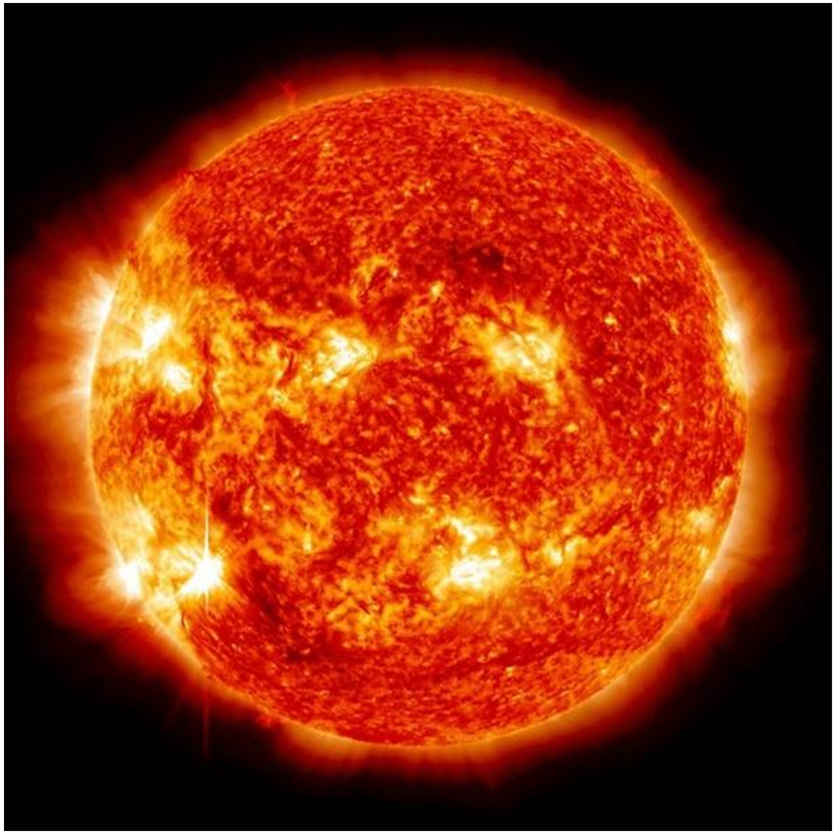
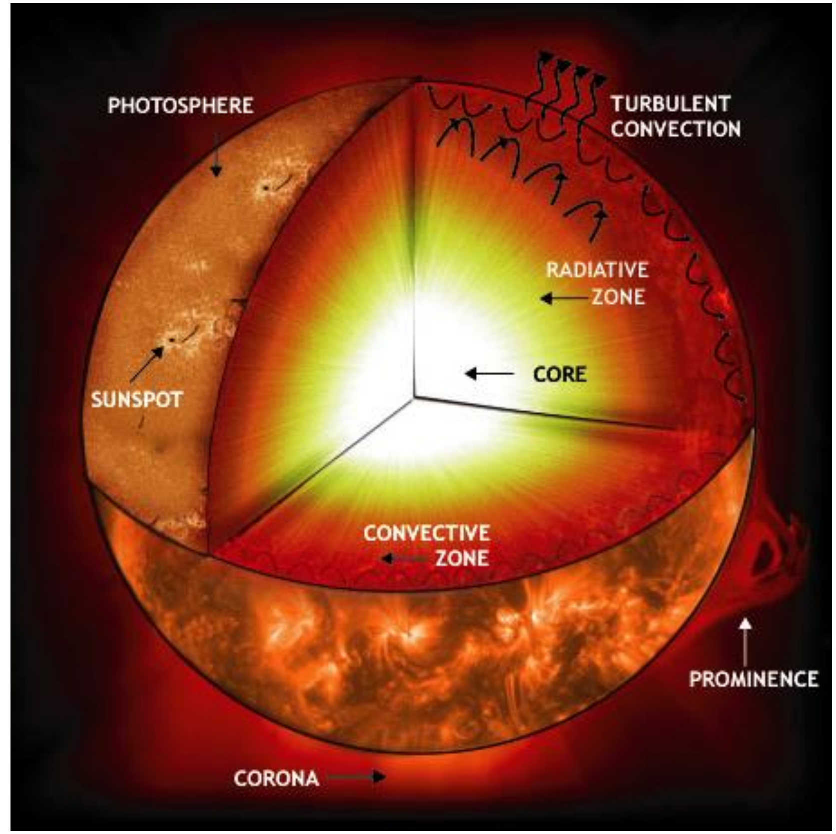
Classical Stellar Evolution



The Sun – best studied example





Stellar interiors not directly observable

Neutrinos emitted at core and detectable

Helioseismology - vibrations of solar surface can be used to probe density structure

Must construct models of stellar interiors – predictions of these models are tested by comparison with observed properties of individual stars

Observable properties of stars

Basic parameters to compare theory and observations:

- Mass (M)
- Luminosity (L)
  - The total energy radiated per second i.e. power (in W)

$$L = \int_0^\infty L_\lambda \, d\lambda$$

- Radius (R)
- Effective temperature (T_{eff})
  - The temperature of a black body of the same radius as the star that would radiate the same amount of energy

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

$\Rightarrow$ 3 independent quantities

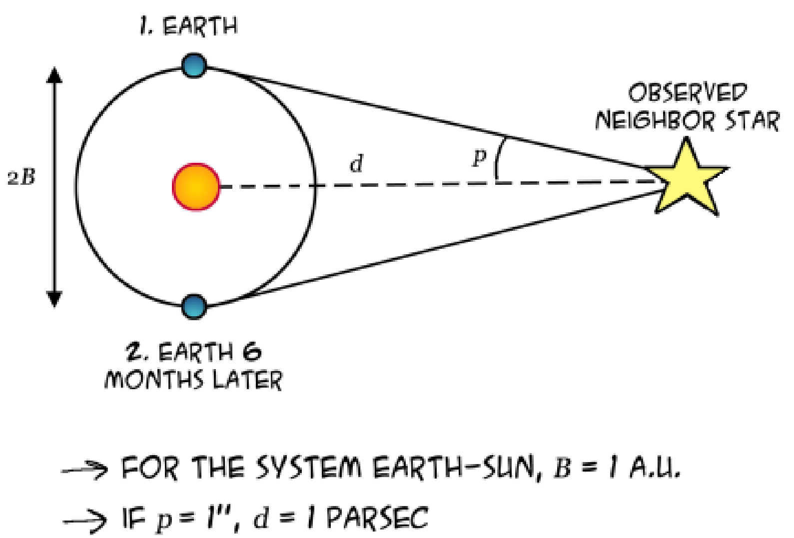
Basic definitions

Measured energy flux depends on distance to star (inverse square law)

$$F = \frac{L}{4\pi d^2}$$

Hence if *d* is known then *L* determined

We can determine distance if we measure *parallax*



Classical astrometric approach

Now: Gaia

Stellar radii

Angular diameter of sun at distance of 10 pc:

$\theta = 2R_{\odot}/10\ \text{pc} = 5\times 10^{-9}$ radians = 10^{-3} arcsec

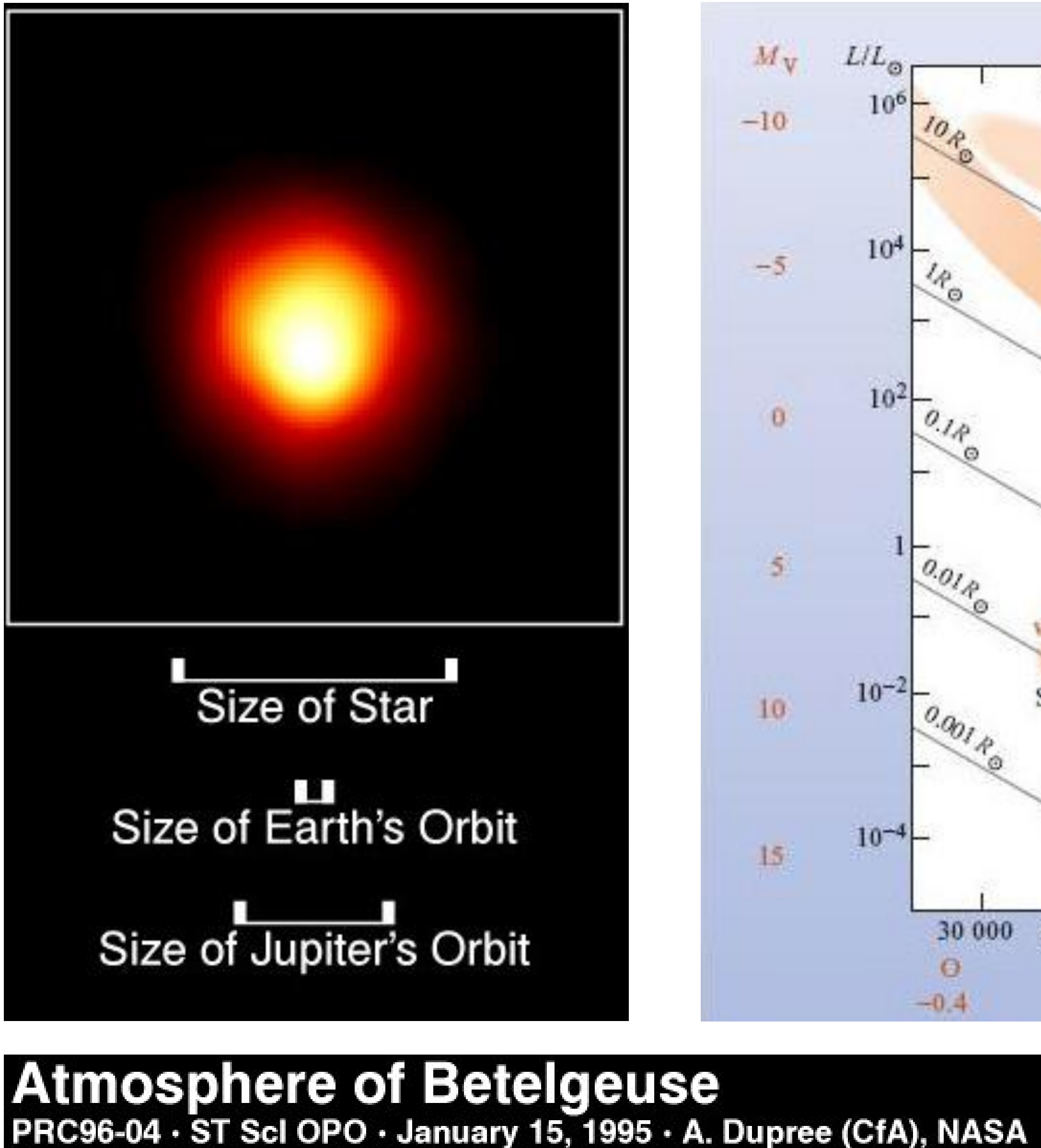
Compare with Hubble resolution of ~0.05 arcsec

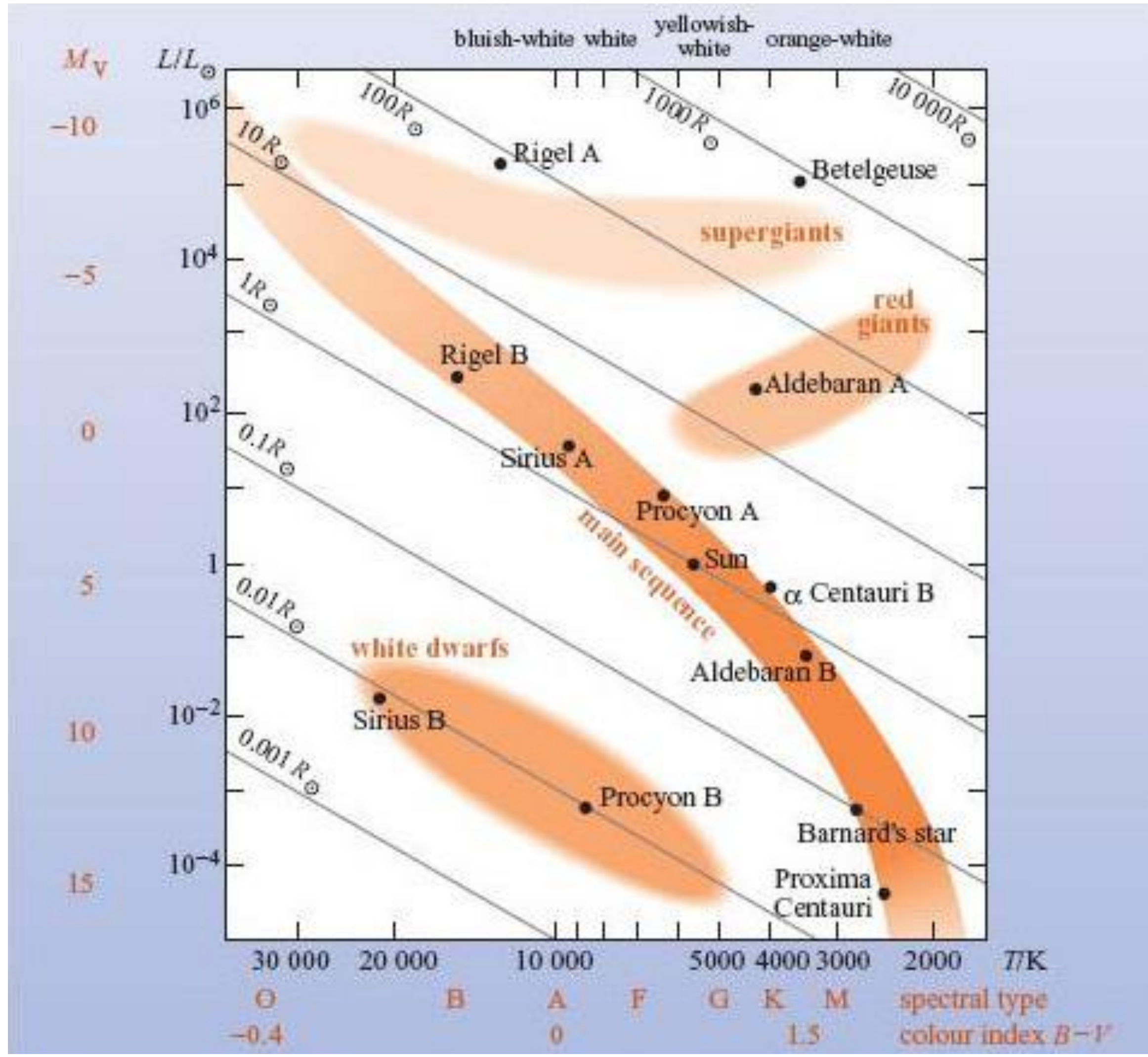
$\Rightarrow$ very difficult to measure R directly

Radii of stars measured with techniques such as interferometry and eclipsing binaries

JMMC Stellar Diameters Catalogue - JSDC. Version 2: about 470 000 stars, median error of the diameters is around 1.5%

Stellar radii





The Hertzsprung - Russell diagram

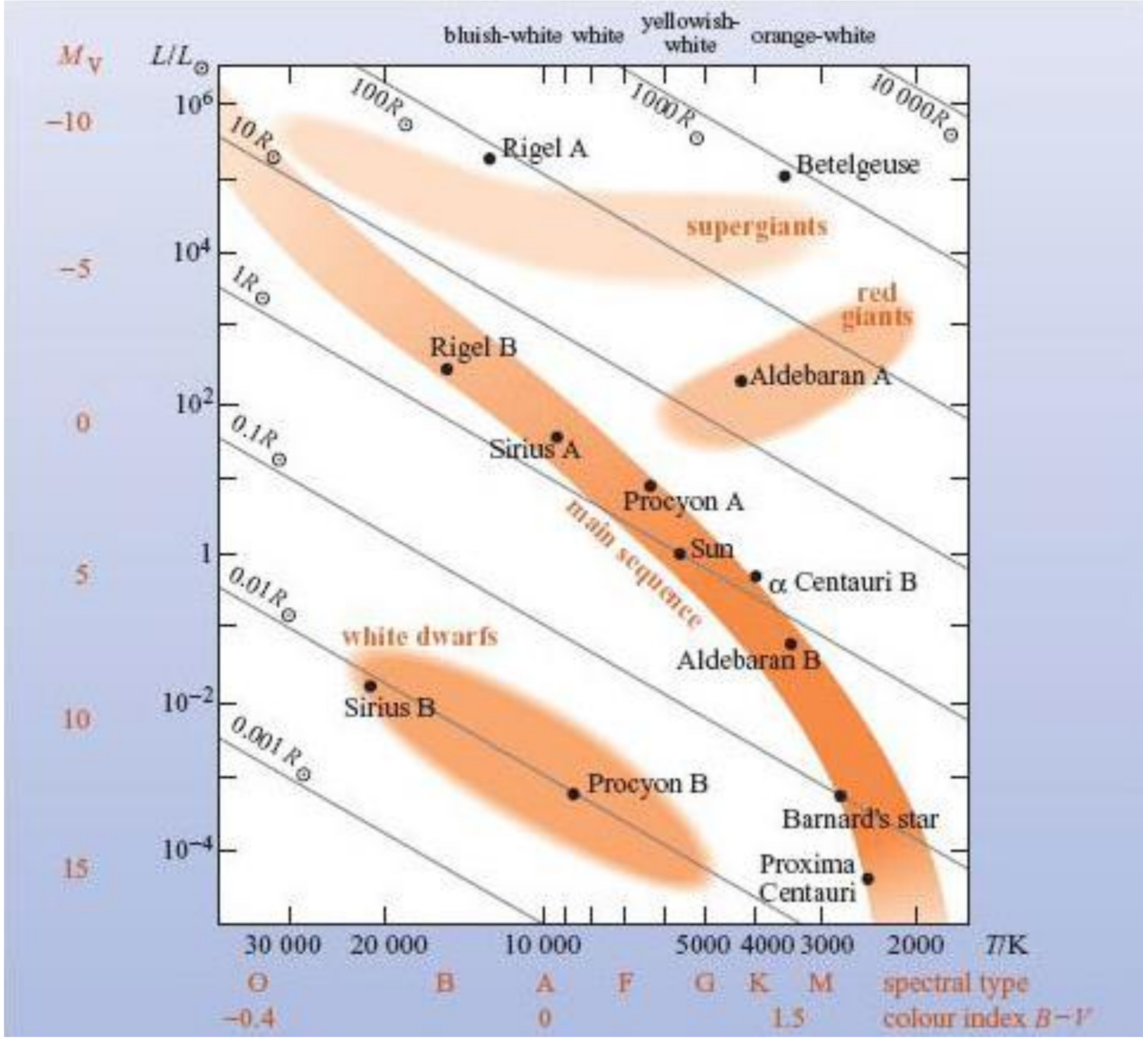
M, R, L and T_{eff} do not vary independently

Two major relationships

– L with T_{eff}

– L with M

The first is known as the *Hertzsprung-Russell* (HR) diagram or the *colour-magnitude* diagram



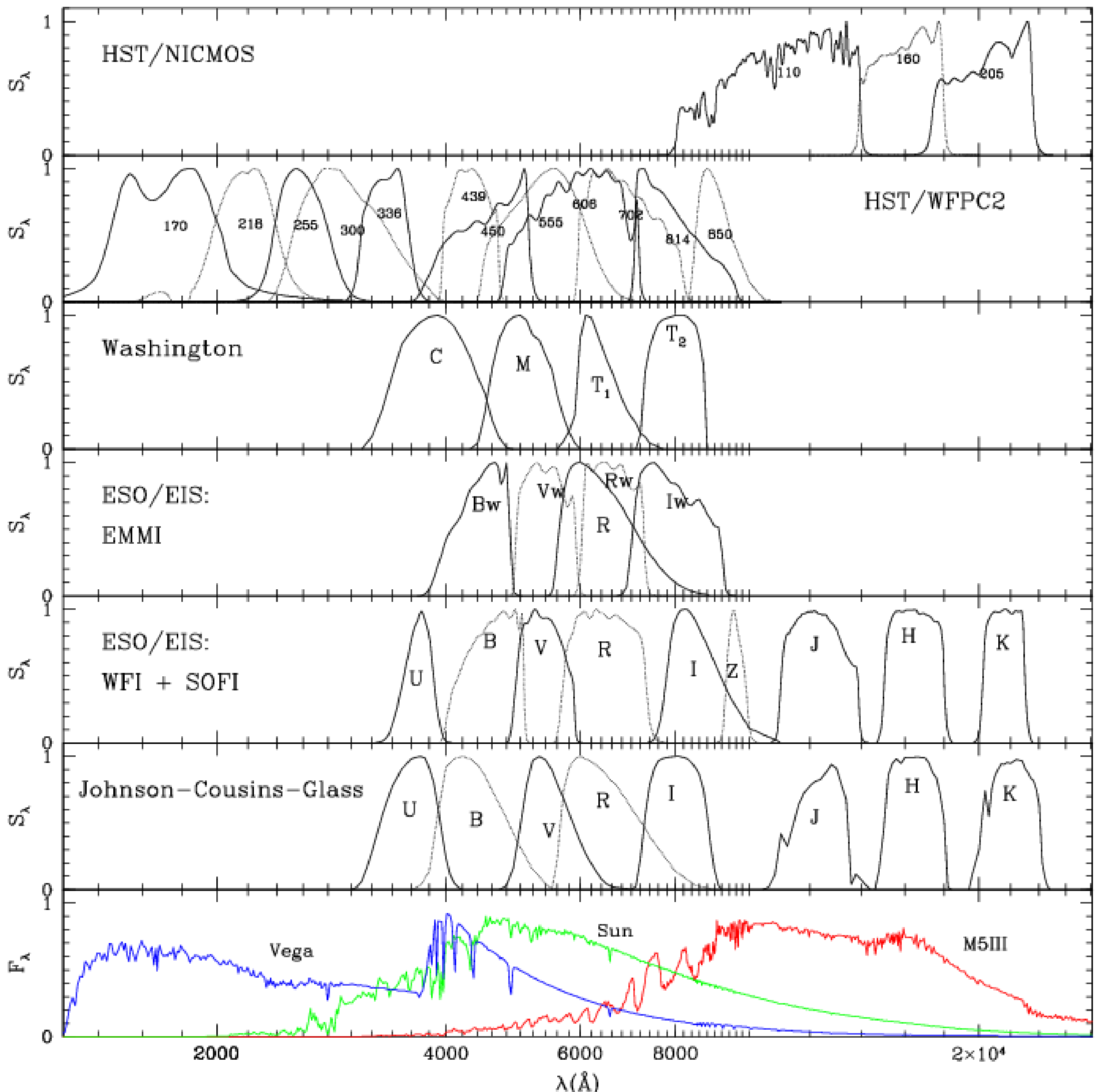
Colour and T_{eff}

- Measuring accurate T_{eff} for stars is an intensive task – spectra needed and model atmospheres

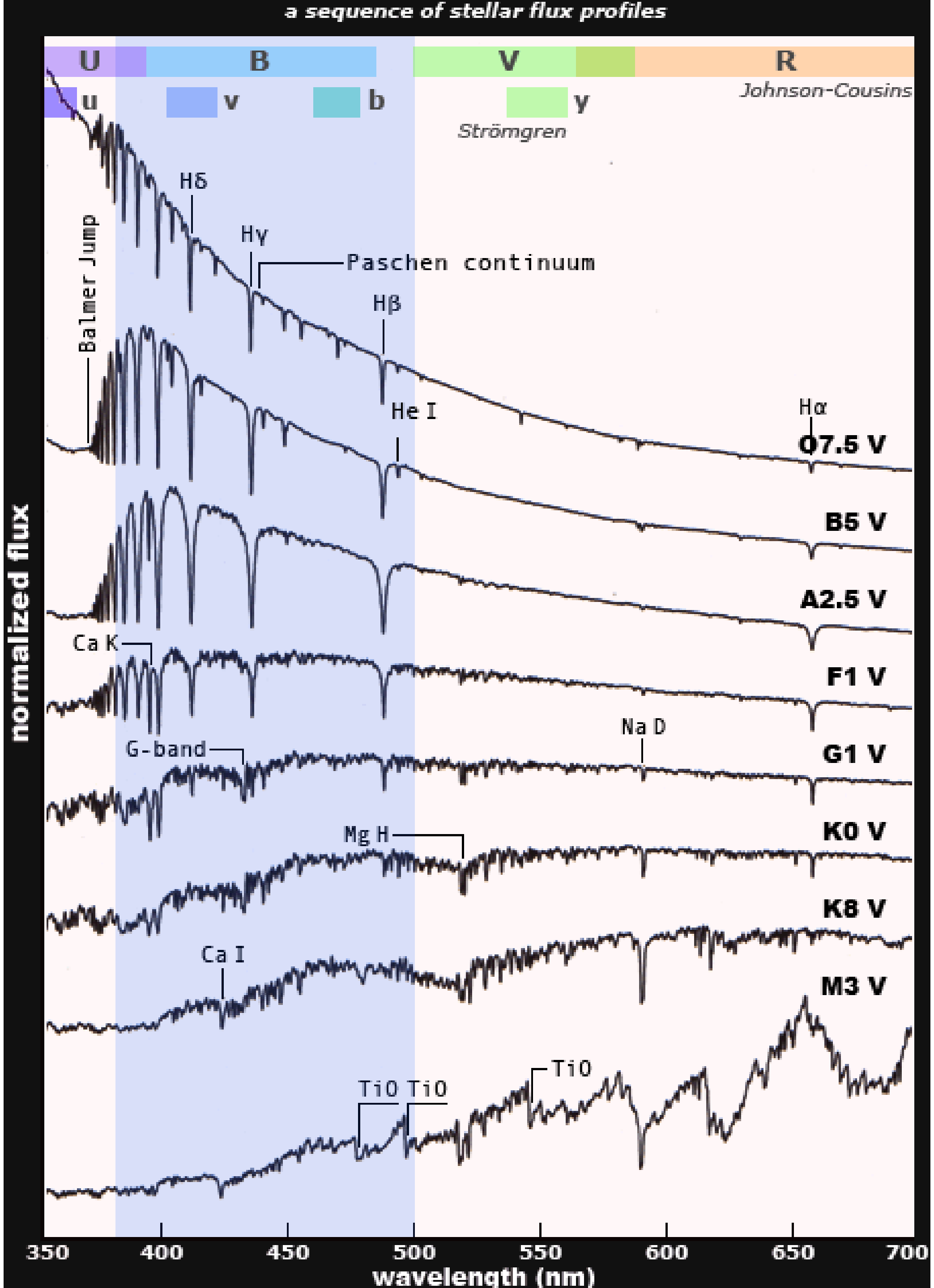
- Magnitudes of stars are measured at different wavelengths

- Colours => Calibration => T_{eff}

- The Asiago Database on Photometric Systems (ADPS) lists about 200 different systems

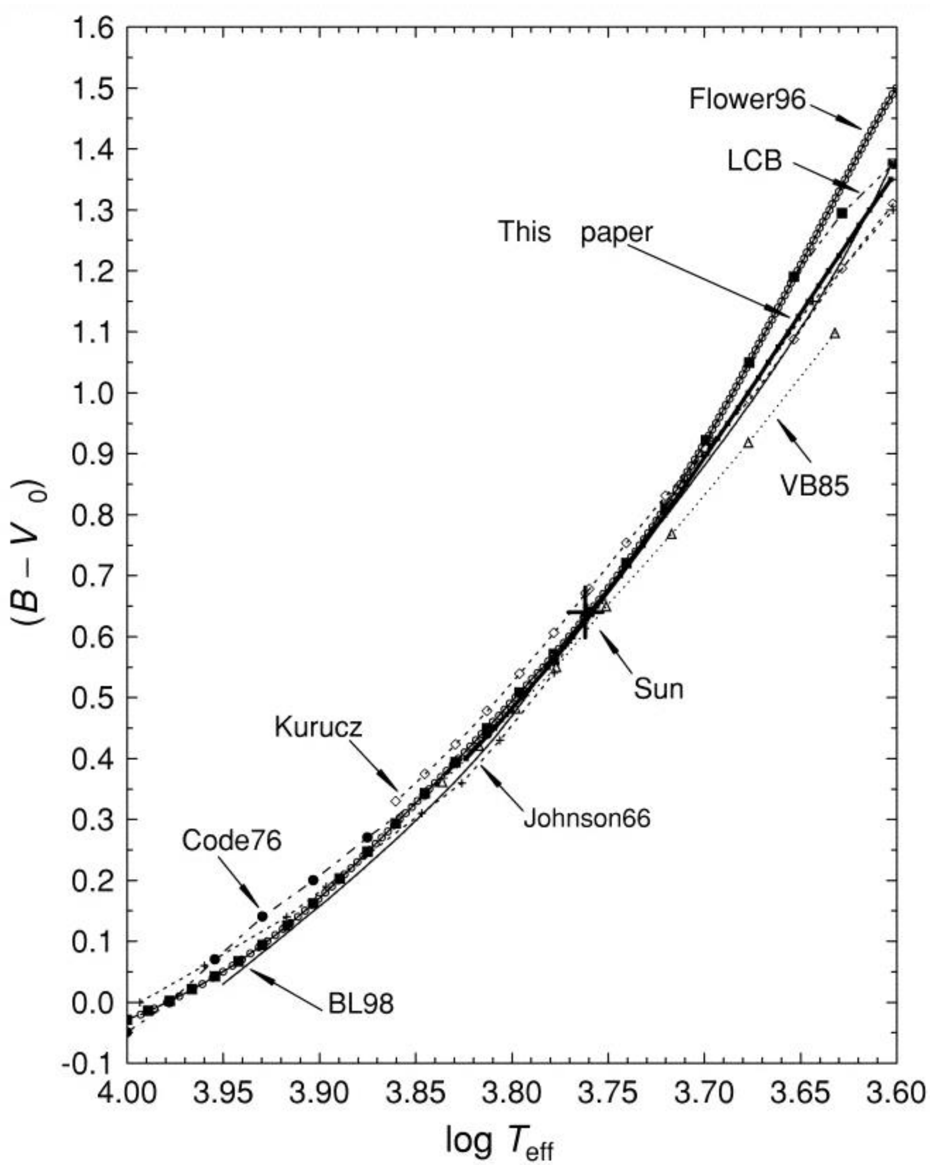


HST/NICMOS
110
160
205
HST/WFPC2
170
218
255
300
336
439
450
555
606
702
814
850
Washington
C
M
T1
T2
ESO/EIS:
EMMI
Bw
Vw
Rw
R
Iw
ESO/EIS:
WFI + SOFI
U
B
V
R
I
Z
J
H
K
Johnson-Cousins-Glass
U
B
V
R
I
J
H
K
Vega
Sun
M5III
Sλ
Fλ
0
1
2000
4000
6000
8000
2×10⁴
λ(Å)



a sequence of stellar flux profiles
U
B
V
R
Johnson-Cousins
u
v
b
y
Strömgren
Hδ
Hγ
Paschen continuum
Hβ
Balmer Jump
He I
Hα
O7.5 V
B5 V
A2.5 V
Ca K
F1 V
Na D
G-band
G1 V
Mg H
K0 V
K8 V
Ca I
M3 V
TiO
TiO TiO
normalized flux
350
400
450
500
550
600
650
700
wavelength (nm)

Colour and T_{eff}



Various calibrations can be used to provide the colour relation:

$(B - V) = f(T_{eff})$

Remember that observed (B - V) must be corrected for interstellar extinction to $(B - V)_0$

Absorption = Extinction = Reddening

- $A_V = k_1 E(B-V) = k_2 E(V-R) = \ldots$

- *General extinction* because of the ISM characteristics between the observer and the object

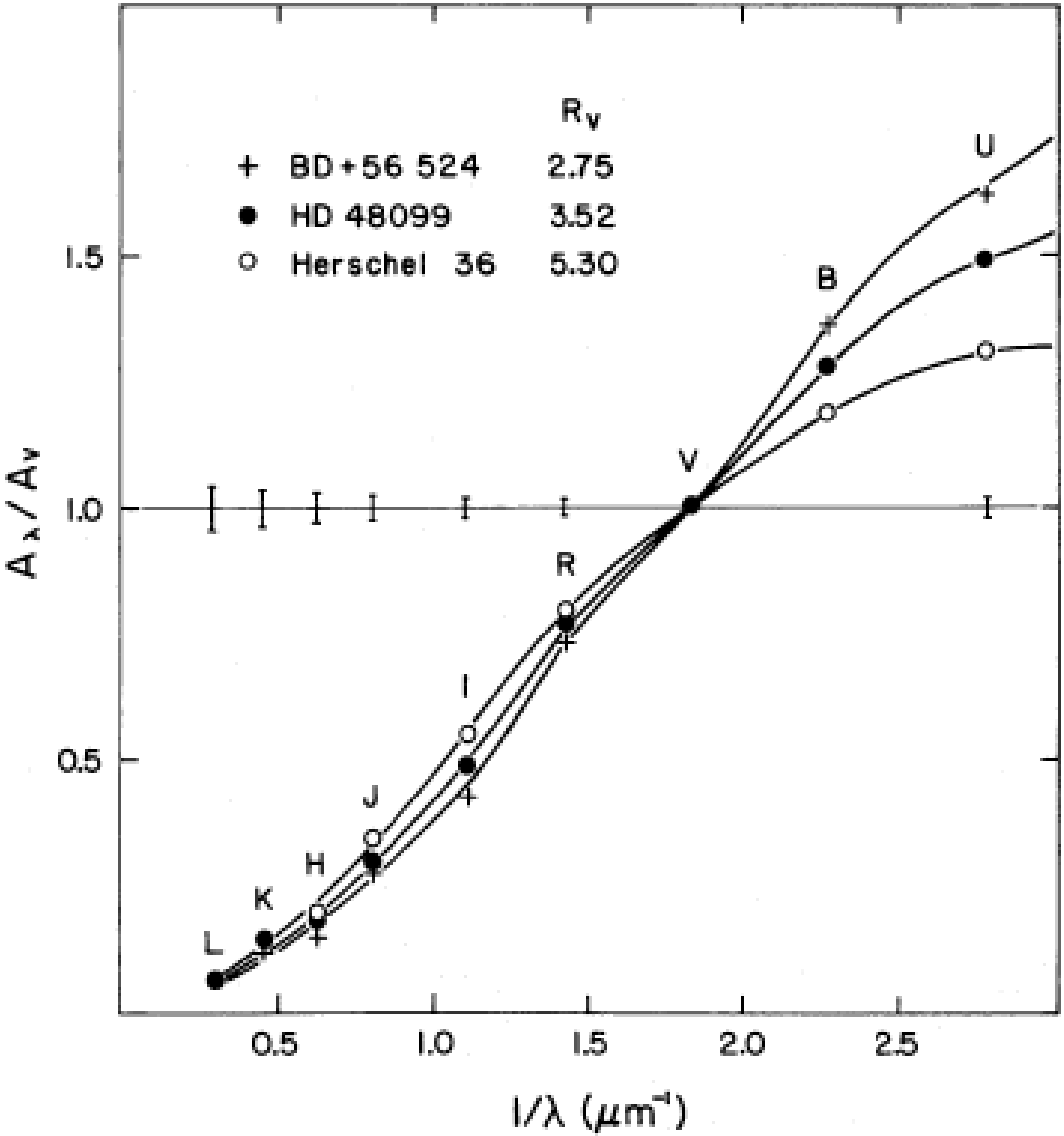
- *Differential extinction* within one star cluster because of local environment

- Both types are, in general *wavelength dependent*

Reasons for the interstellar extinction

- Light scatter at the interstellar dust
- Light absorption => Heating of the ISM
- Depending on the composition and density of the ISM
- Main contribution due to dust
- Simulations and calculations in Cardelli et al. (1989, ApJ, 345, 245)

Cardelli et al., 1989, ApJ, 345, 245



Important parameter:

$R_V = A_V/E(B - V)$

Normalization factor

Standard value used is 3.1

Be careful, different values used!

Depending on the line of sight

Absolute magnitude and bolometric magnitude

- **Absolute Magnitude** *M* defined as apparent magnitude of a star if it were placed at a distance of 10 pc

$$m - M = 5 \log(d/10) - 5$$

where d is in pc

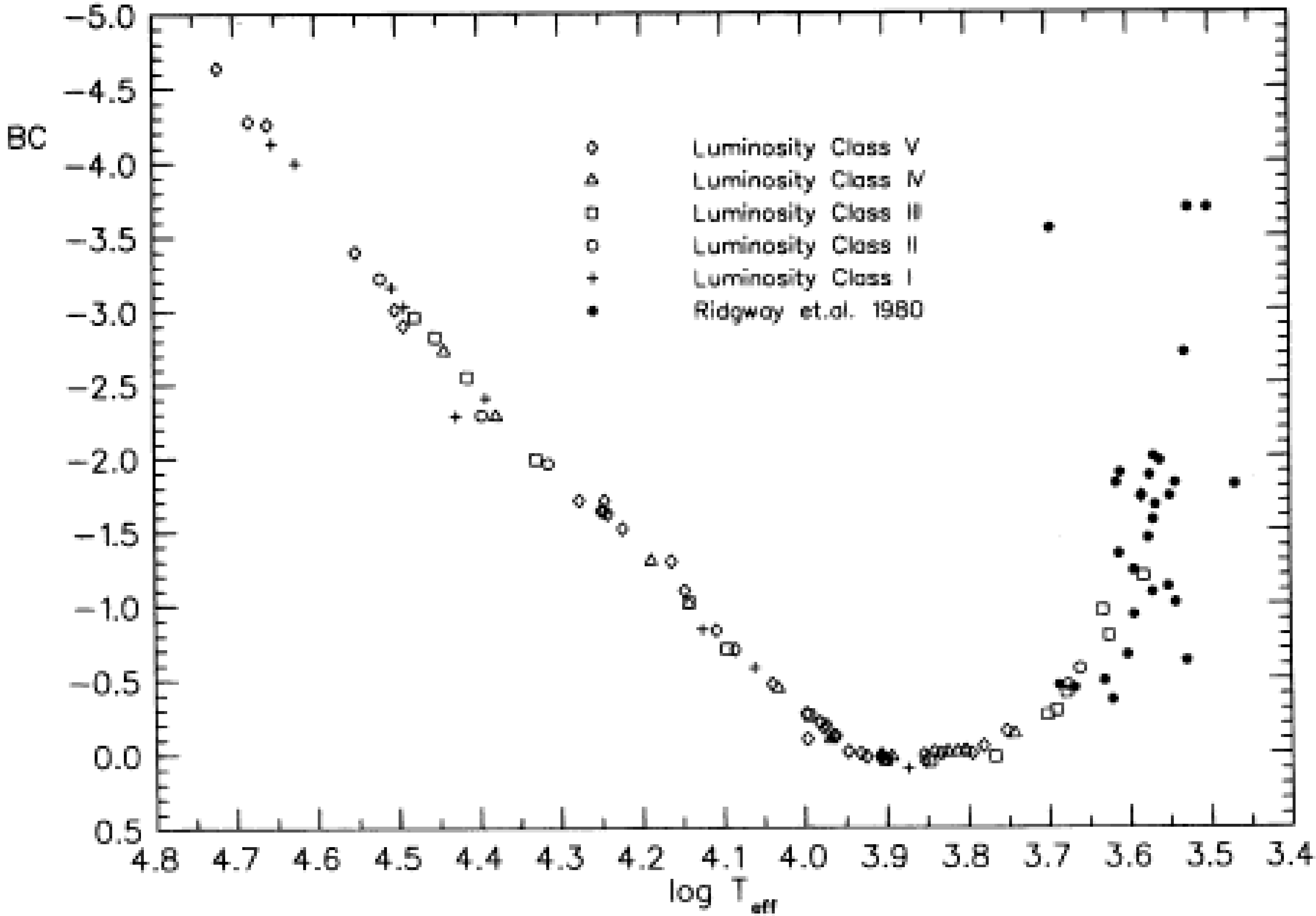
- Magnitudes are measured in some wavelength. To compare with theory it is more useful to determine **bolometric magnitude** $\boldsymbol{M_{bol}}$ – defined as absolute magnitude that would be measured by a bolometer sensitive to all wavelengths. We define the bolometric correction to be

$$BC = M_{bol} - M_V$$

Bolometric luminosity is then

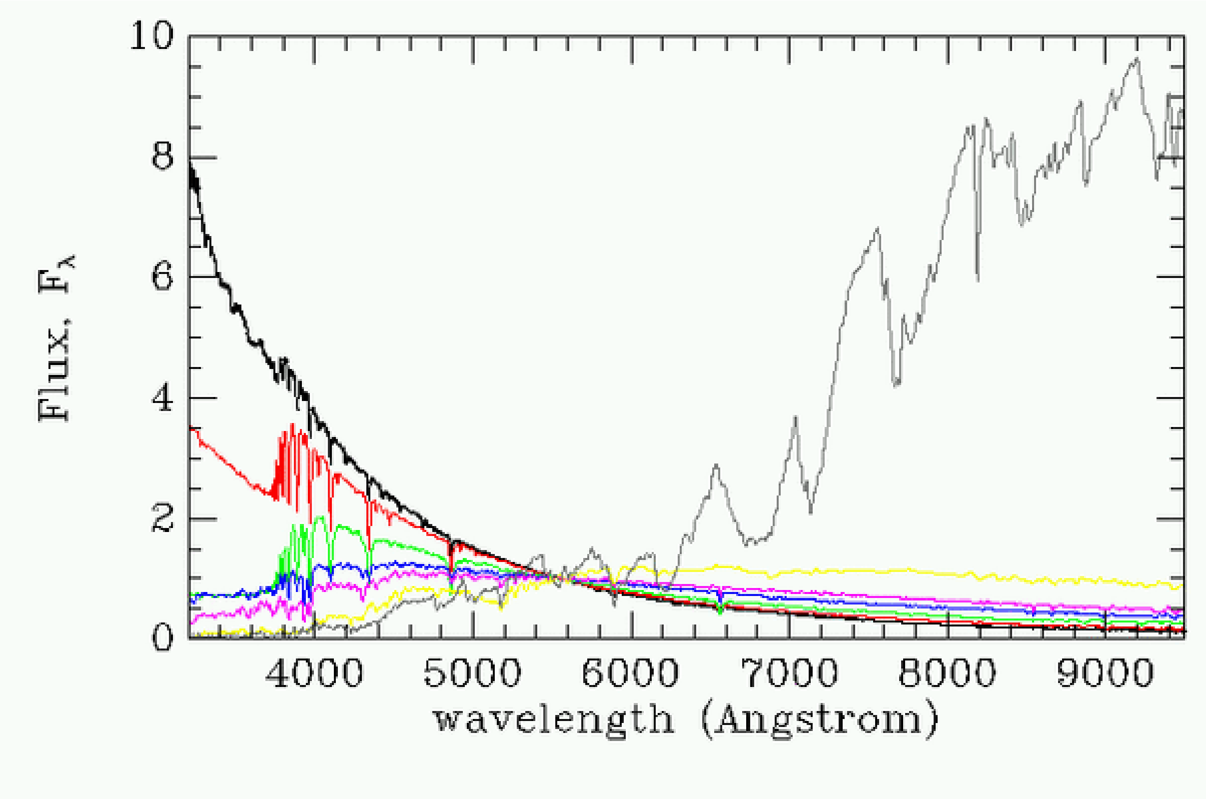
$$M_{bol} - M_{bol,\odot} = -2.5 \log L/L_{\odot}$$

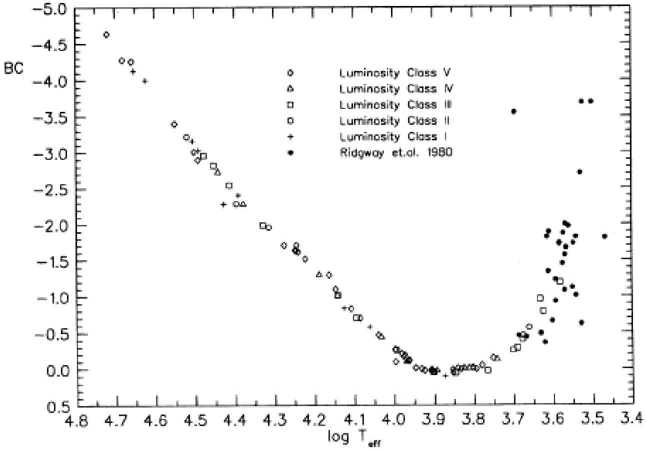
Bolometric Correction



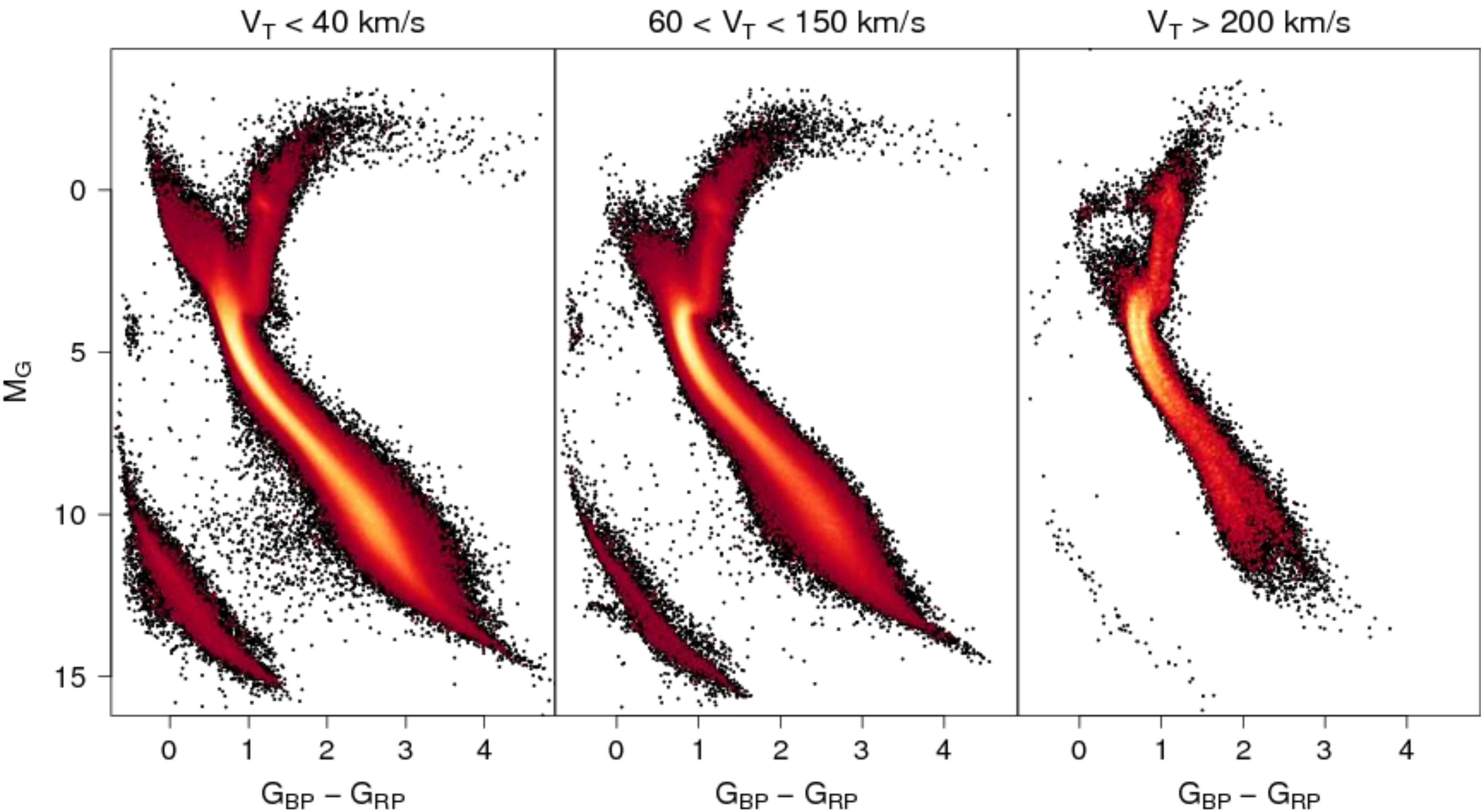
BC from Flower, 1996, ApJ, 469, 355

Bolometric Correction





The Hertzsprung - Russell diagram - Gaia



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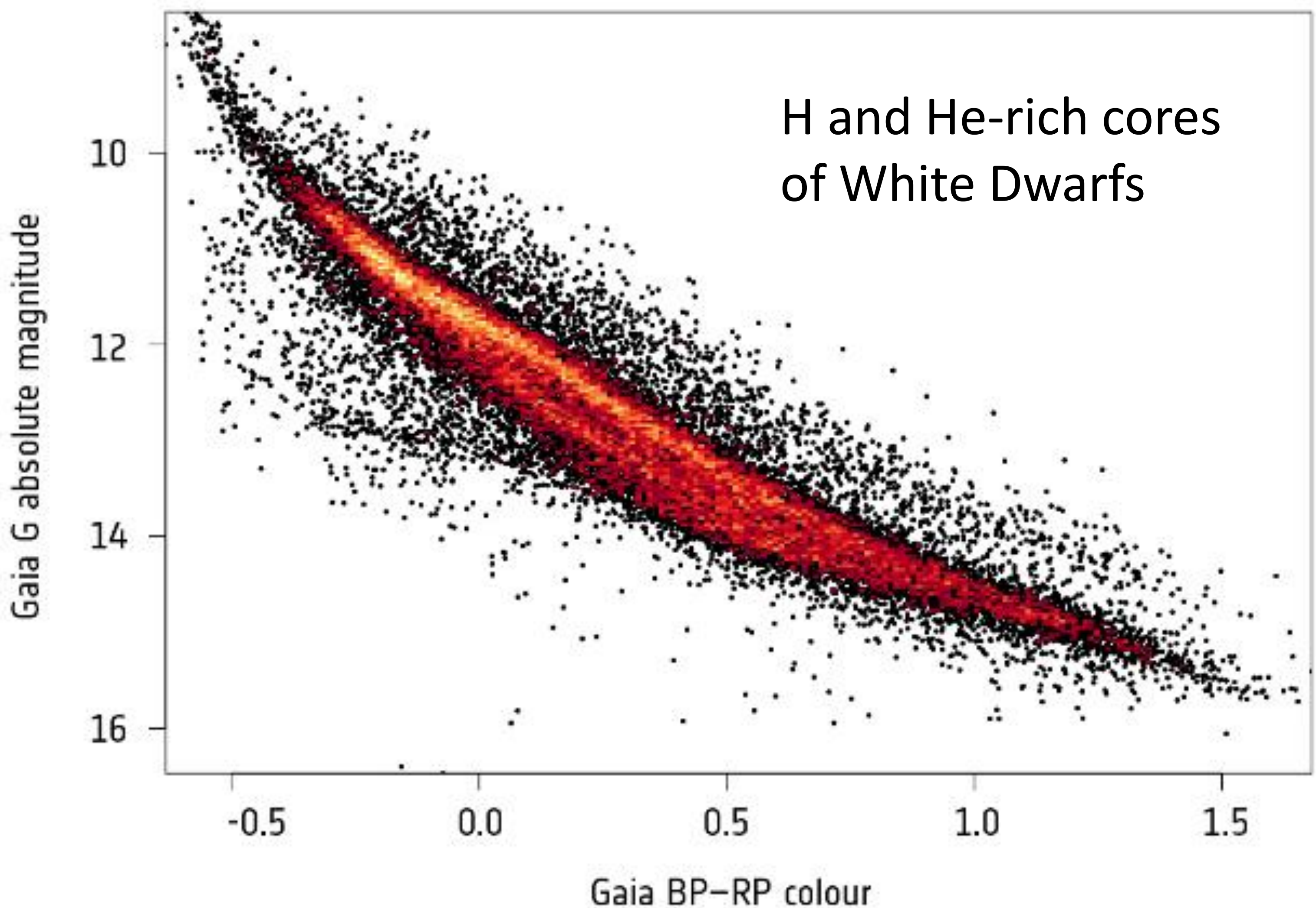

Mass – Luminosity Relation

Masses measured in binary systems

Heuristic mass-luminosity relation

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

Where α = 2 – 5; slope less steep for low and high mass stars

This implies that the main-sequence (MS) on the HRD is a function of mass, i.e. from bottom to top of MS, stars increase in mass

The lifetime on the Main-Sequene