Calculation of Isochrones

The calculation of theoretical isochrone (= lines of equal age) is done with stellar atmospheres

Free parameter : Metallicity [X, Y, Z]

1. Zero Age Main Sequence $[T_{\text{eff}}, L]_0$
2. Chemical and gravitational evolution
3. $[T_{\text{eff}}, L](\mathrm{t})$
4. Adequate stellar atmosphere = **PHYSICS**
5. Absolute fluxes
6. Folding with filter curves
7. Colors, absolute magnitudes and so on

Which astrophysical “parameters” are important?

- Equations of state
- Opacities
- Model of convection
- Rotation
- Mass loss
- Magnetic field
- Core Overshooting
- Abundance of helium
- …

Which astrophysical “parameters” are important?

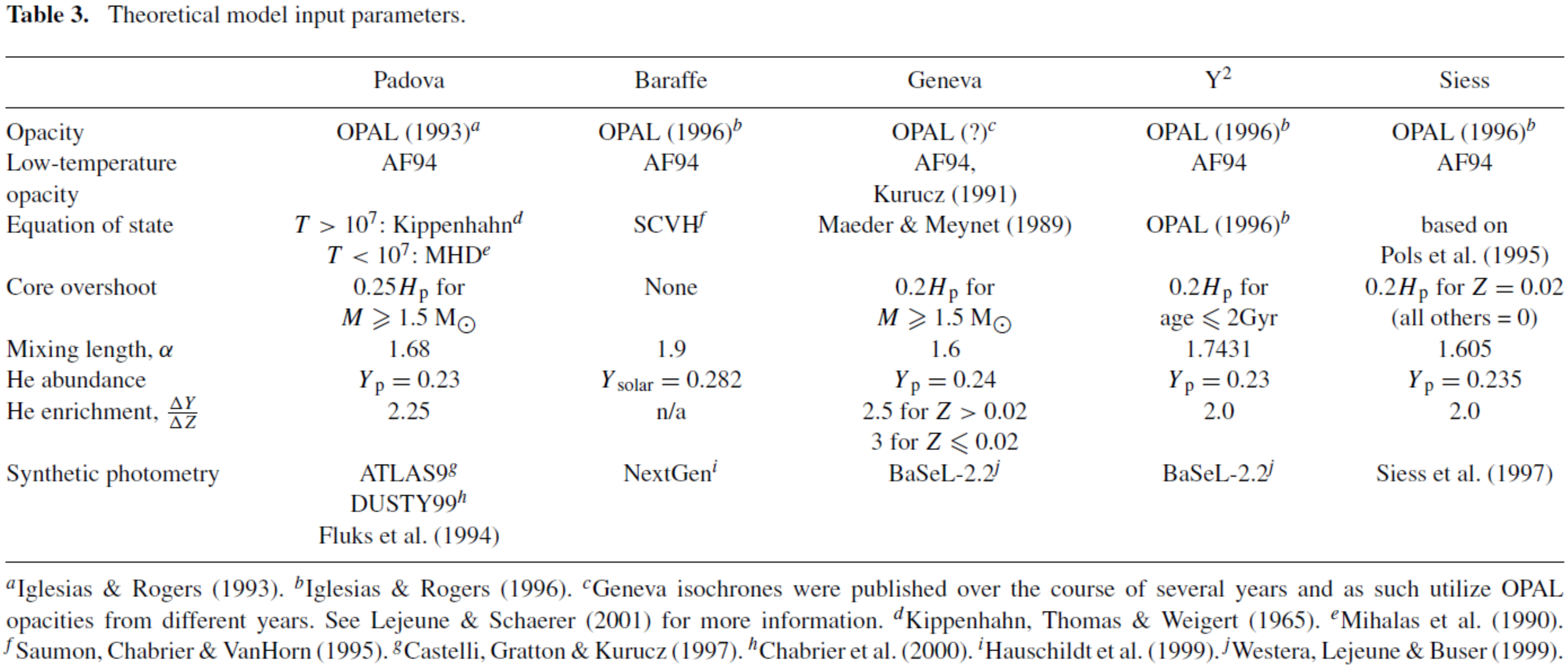


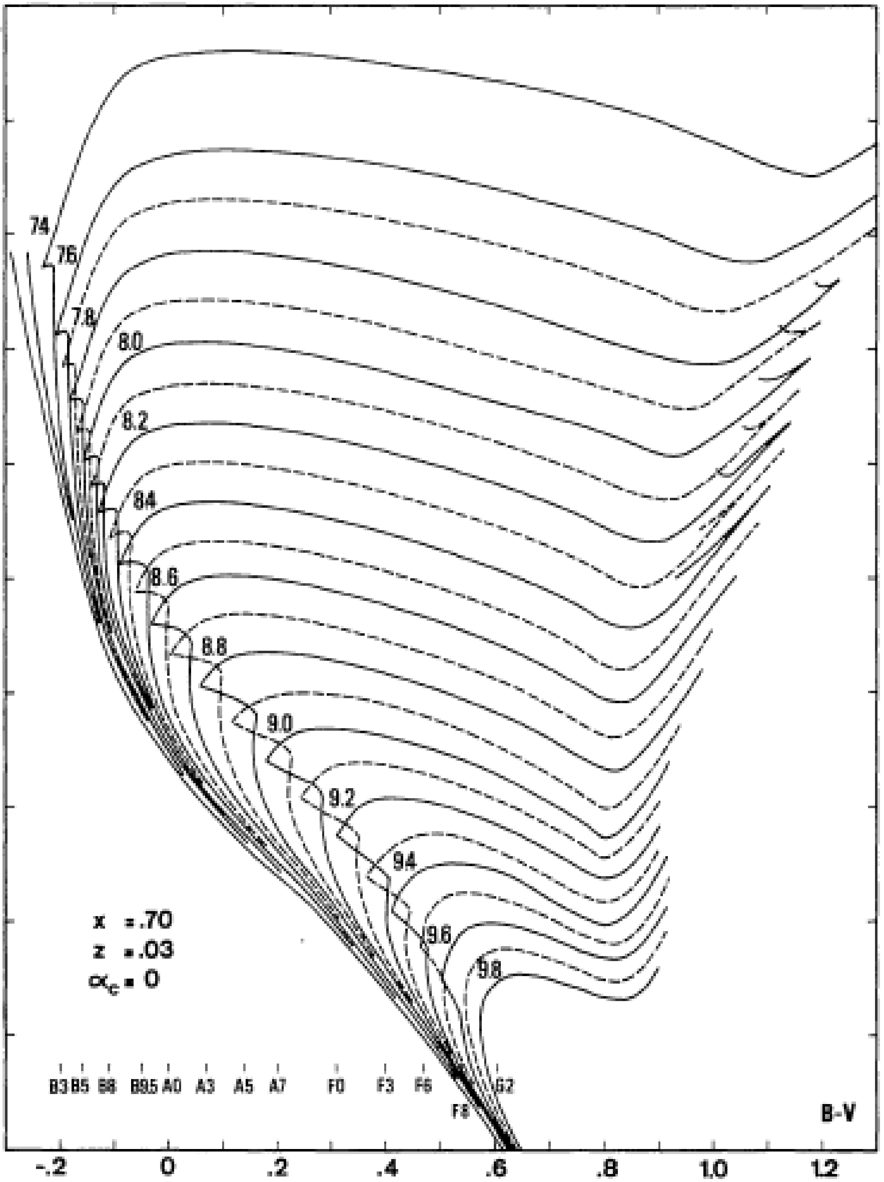
Table 3. Theoretical model input parameters.

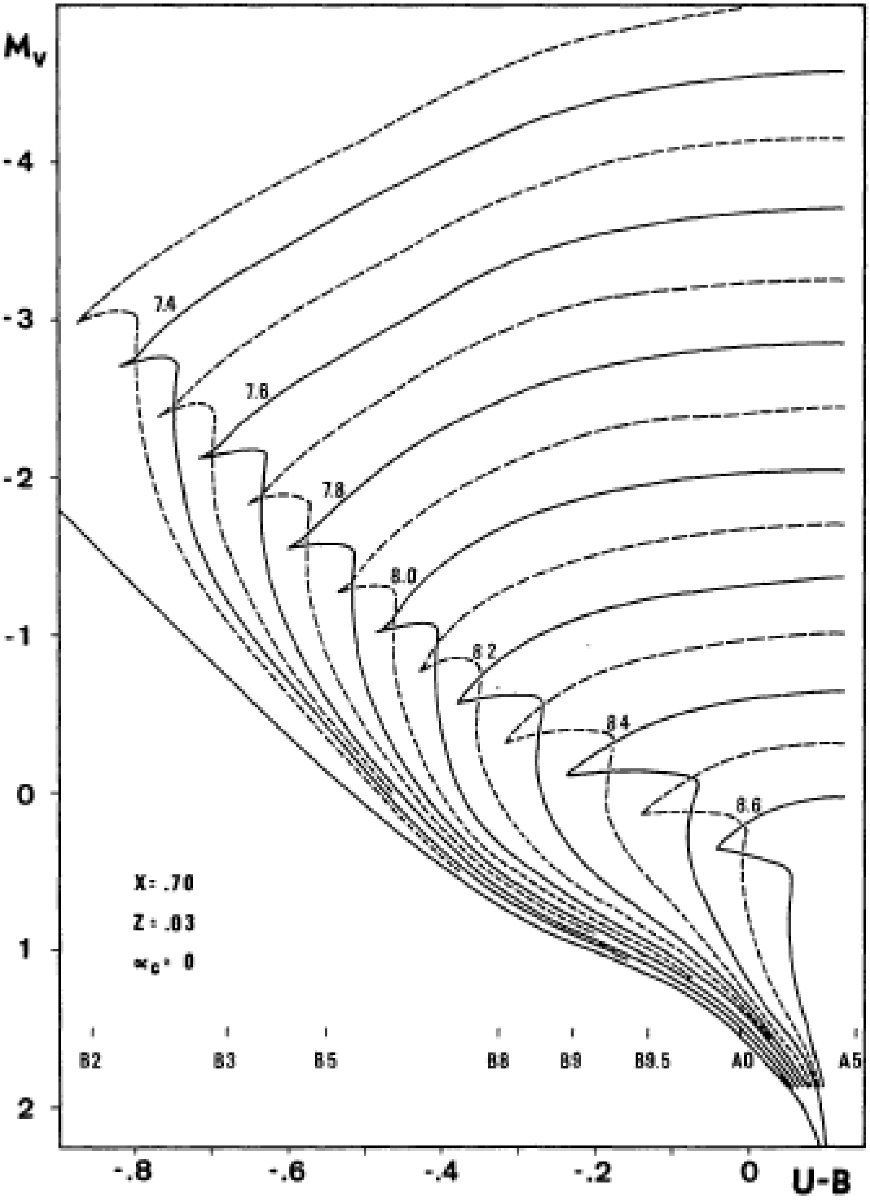
	Padova	Baraffe	Geneva	Y^2	Siess
Opacity	OPAL (1993)[a]	OPAL (1996)[b]	OPAL (?)[c]	OPAL (1996)[b]	OPAL (1996)[b]
Low-temperature opacity	AF94	AF94	AF94, Kurucz (1991)	AF94	AF94
Equation of state	$T > 10^7$: Kippenhahn[d] $T < 10^7$: MHD[e]	SCVH[f]	Maeder & Meynet (1989)	OPAL (1996)[b]	based on Pols et al. (1995)
Core overshoot	$0.25 H_p$ for $M \geqslant 1.5\,M_\odot$	None	$0.2 H_p$ for $M \geqslant 1.5\,M_\odot$	$0.2 H_p$ for age $\leqslant$ 2Gyr	$0.2 H_p$ for $Z = 0.02$ (all others = 0)
Mixing length, α	1.68	1.9	1.6	1.7431	1.605
He abundance	$Y_p = 0.23$	$Y_{solar} = 0.282$	$Y_p = 0.24$	$Y_p = 0.23$	$Y_p = 0.235$
He enrichment, $\frac{\Delta Y}{\Delta Z}$	2.25	n/a	2.5 for $Z > 0.02$ 3 for $Z \leqslant 0.02$	2.0	2.0
Synthetic photometry	ATLAS9[g] DUSTY99[h] Fluks et al. (1994)	NextGen[i]	BaSeL-2.2[j]	BaSeL-2.2[j]	Siess et al. (1997)

[a] Iglesias & Rogers (1993). [b] Iglesias & Rogers (1996). [c] Geneva isochrones were published over the course of several years and as such utilize OPAL opacities from different years. See Lejeune & Schaerer (2001) for more information. [d] Kippenhahn, Thomas & Weigert (1965). [e] Mihalas et al. (1990). [f] Saumon, Chabrier & VanHorn (1995). [g] Castelli, Gratton & Kurucz (1997). [h] Chabrier et al. (2000). [i] Hauschildt et al. (1999). [j] Westera, Lejeune & Buser (1999).

Grocholski & Sarajedini (2003, MNRAS, 345, 1015)

Maeder & Mermilliod, 1981, A&A, 93, 136





ToDo until 26.10.2023

- Search for available isochrones and evolutionary grids
- We need:

1. Parameter space
2. Which photometric systems are available

- Except:

1. Padova: http://stev.oapd.inaf.it/cgi-bin/cmd
2. Geneva: https://www.unige.ch/sciences/astro/evolution/en/database/

Isochrones – evolutionary grids

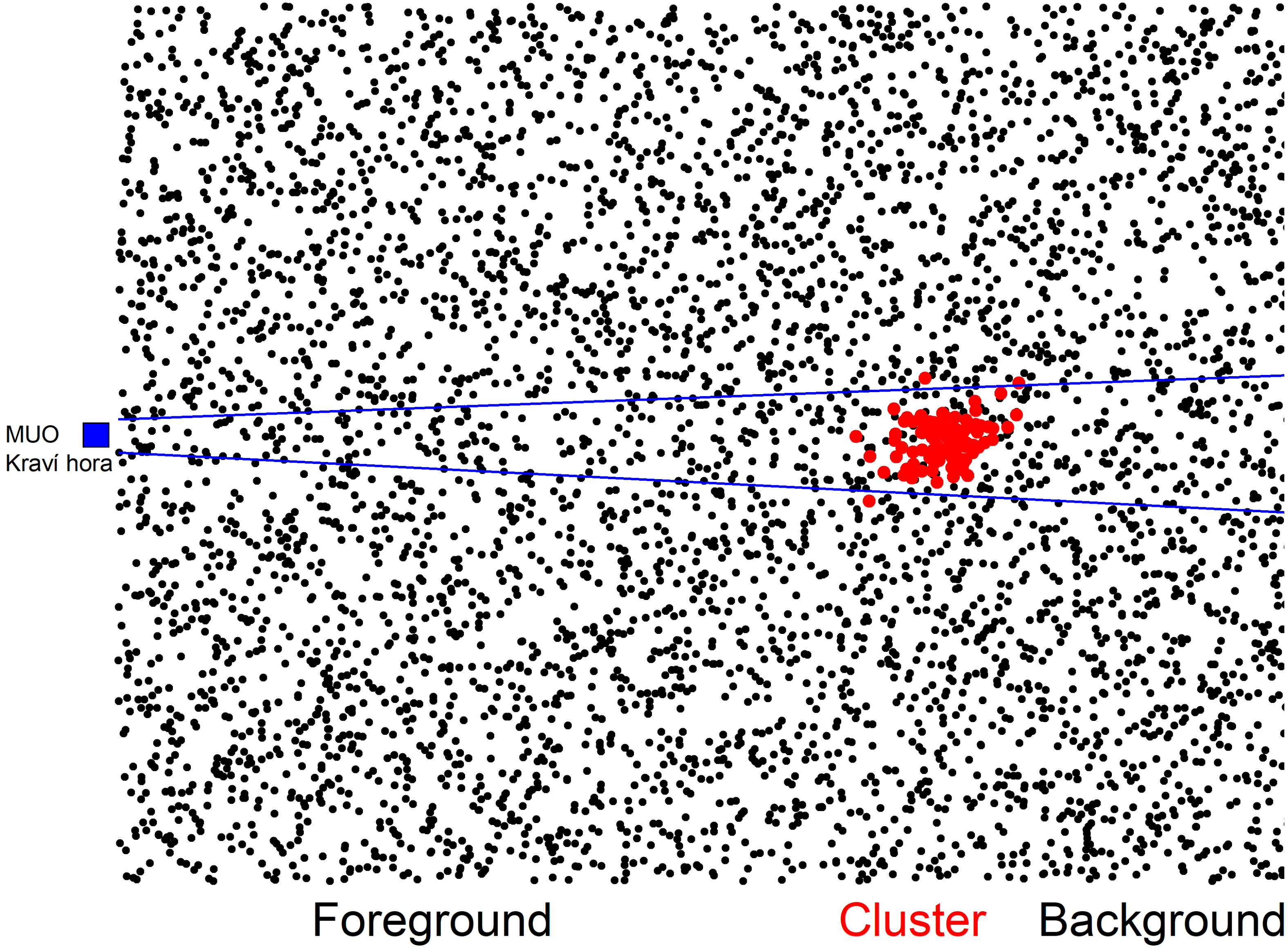
- Isochrones: available for different ages and photometric systems
- Evolutionary grids: available for different masses (and photometric systems)

The cluster parameters

1. Reddening
2. Distance modulus
3. Age
4. Metallicity

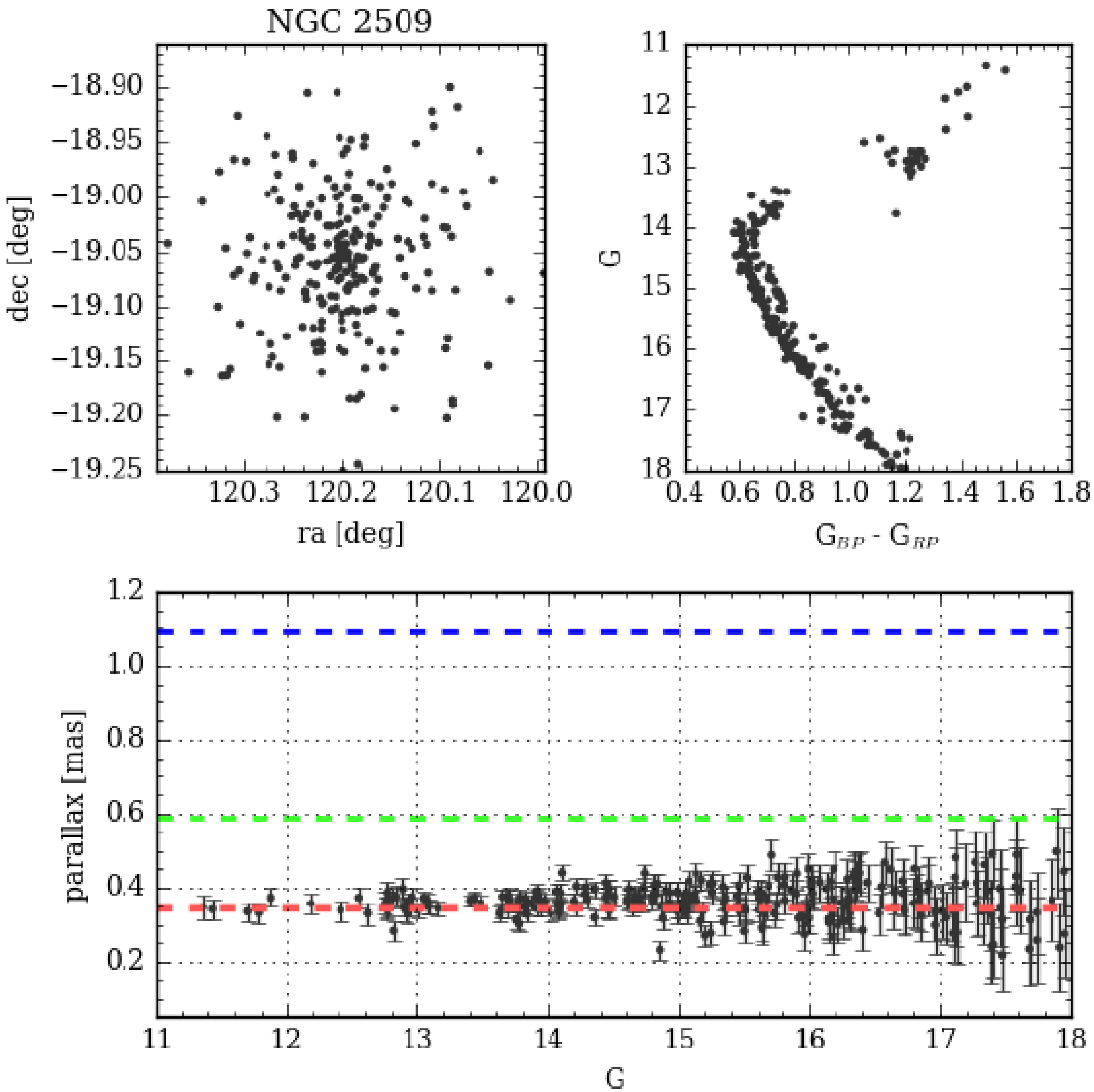
Determination in the order: Reddening, age, distance modulus simultaneously, metallicity with possible iterations

Star Clusters – tricky to analyze



One very well known star cluster

Bossini et al., 2019, A&A, 623, A108

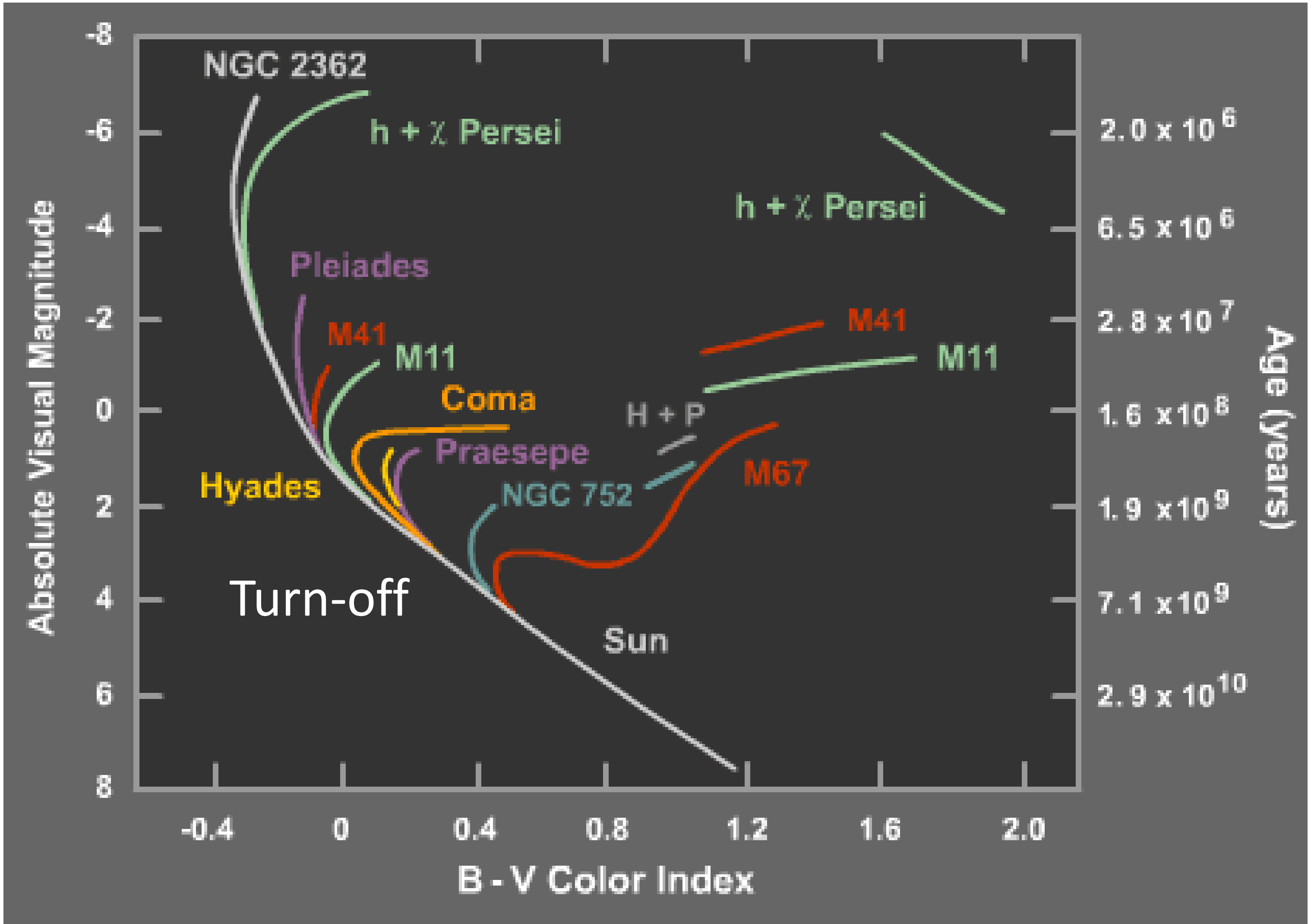


reference 1 (literature)

reference 2 (literature)

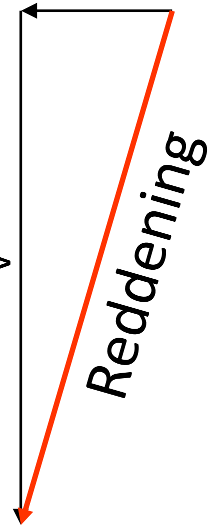
reference 3 (literature)

Distance: $V_0 - M_V$



Turn-off

HR Diagrams for Various Open Clusters



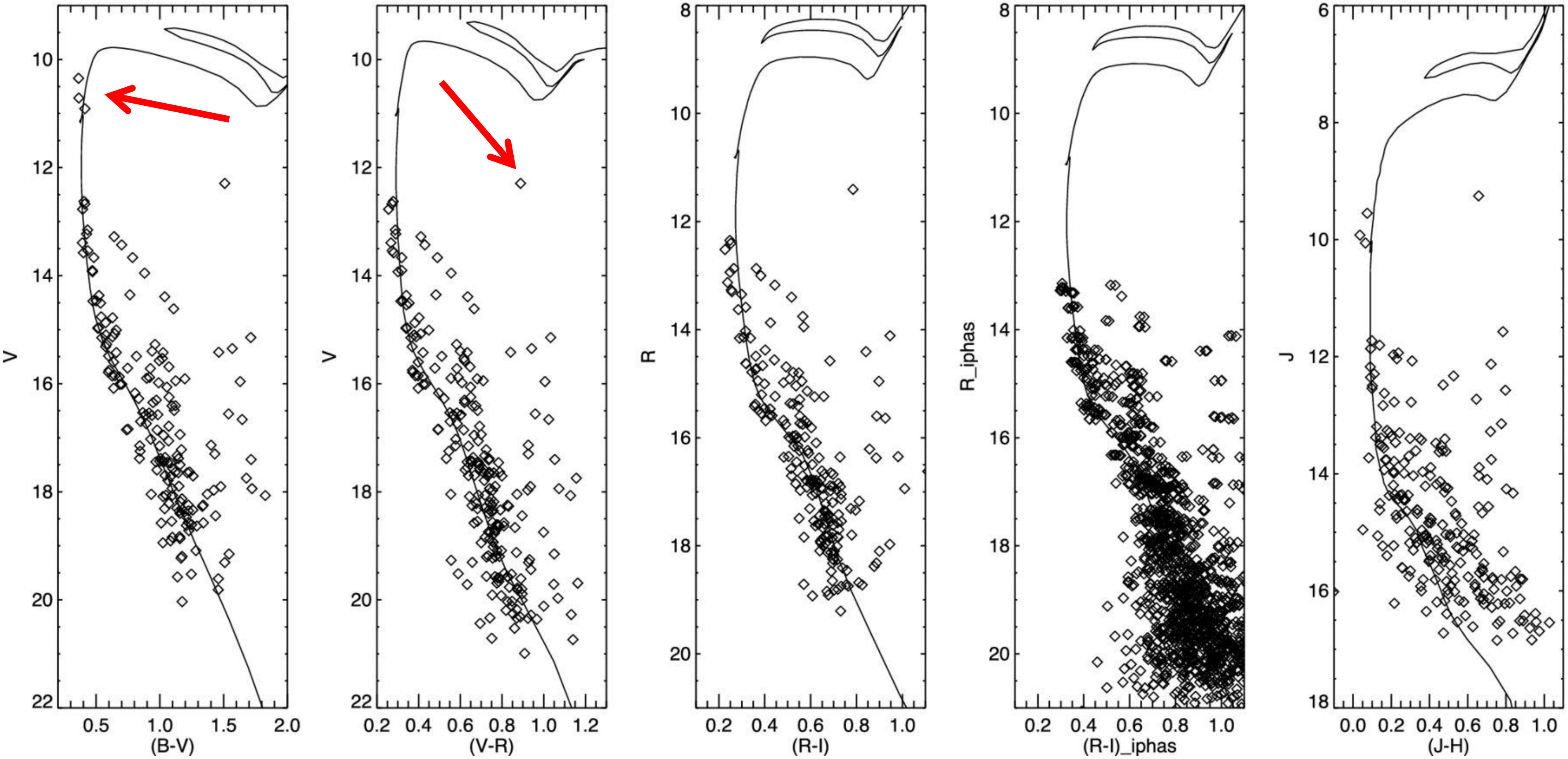
$k \cdot A_V$

A_V

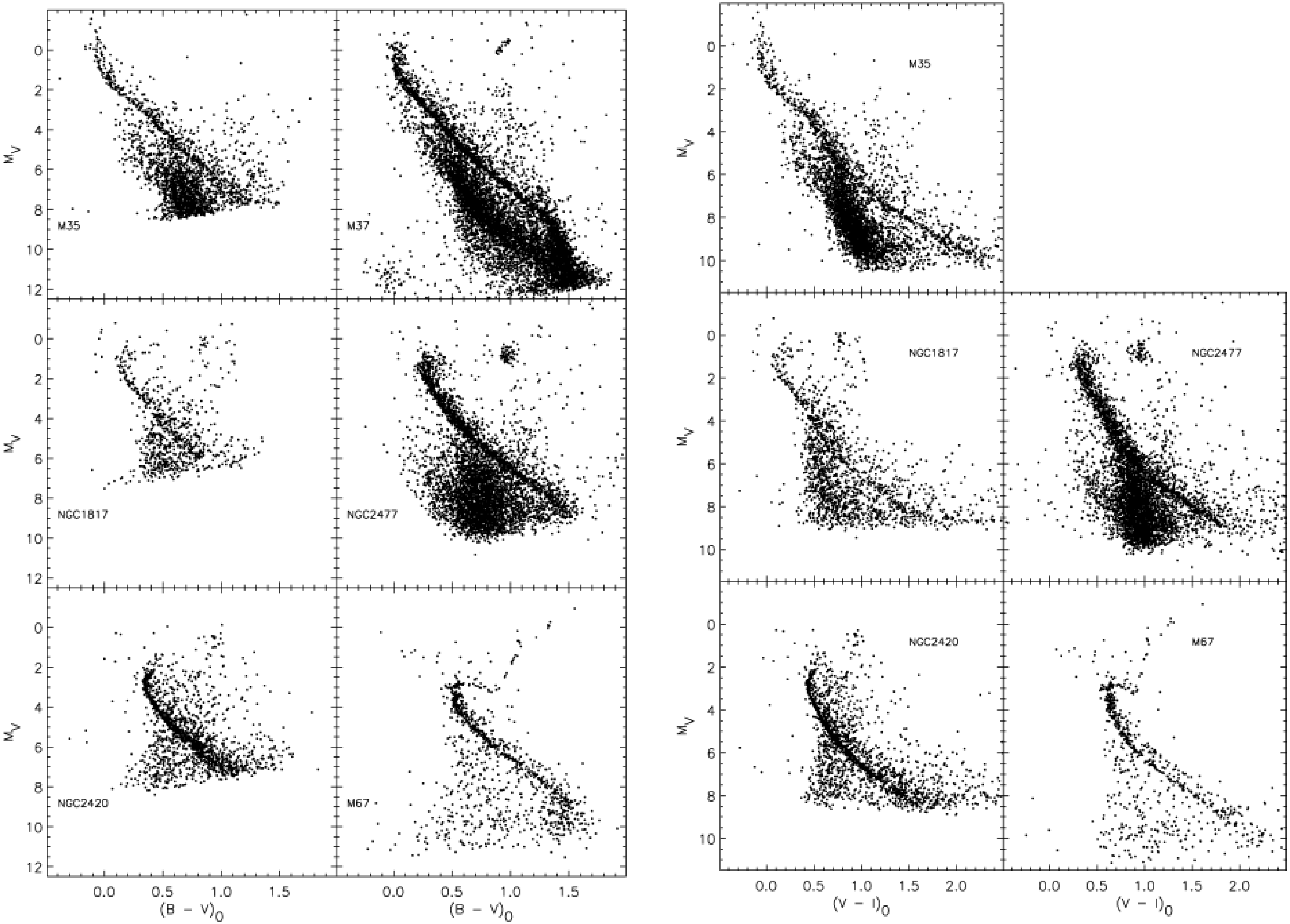
Reddening

Color – Magnitude - Diagram

Different CMDs for one open cluster



Glushkova et al., 2013, MNRAS, 429, 1102



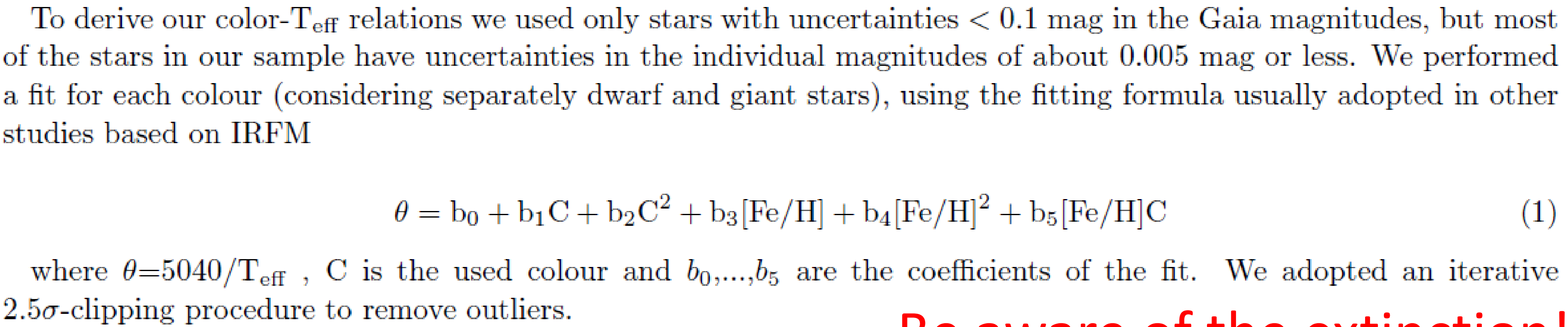
Grocholski & Sarajedini, 2003, MNRAS, 345, 1015

Different photometric indices

Several different indices et al. are available (very much incomplete):

- Sensitive to temperature:
  1. Johnson: B-V, V-I, R-I, V-K, …
  2. Strömgren: b-y, u-b, β
  3. Sloan g-r, r-i, …
  4. Geneva: B2-V1, X, …
  5. Gaia: BP-RP
  6. 2MASS: H-K, J-K and H-J
- „Mixture“:
  1. Johnson: U-B
  2. Strömgren: c_1, m_1, …
  3. Geneva: d, D, m_2, …

Photometric calibrations



To derive our color-T_{eff} relations we used only stars with uncertainties < 0.1 mag in the Gaia magnitudes, but most of the stars in our sample have uncertainties in the individual magnitudes of about 0.005 mag or less. We performed a fit for each colour (considering separately dwarf and giant stars), using the fitting formula usually adopted in other studies based on IRFM

$$\theta = b_0 + b_1C + b_2C^2 + b_3[Fe/H] + b_4[Fe/H]^2 + b_5[Fe/H]C \qquad (1)$$

where θ=5040/T_{eff} , C is the used colour and b_0,...,b_5 are the coefficients of the fit. We adopted an iterative 2.5σ-clipping procedure to remove outliers.

Be aware of the extinction!

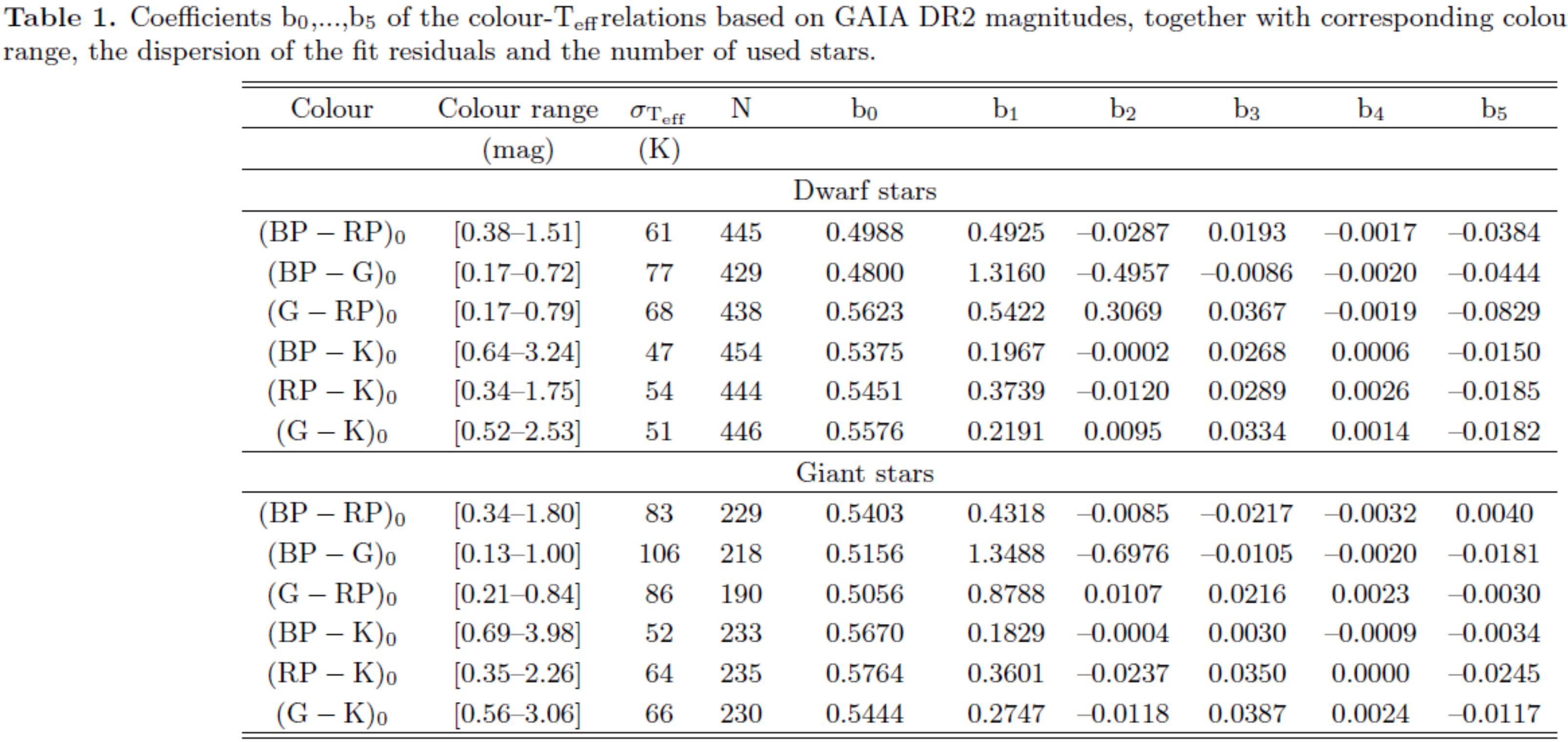


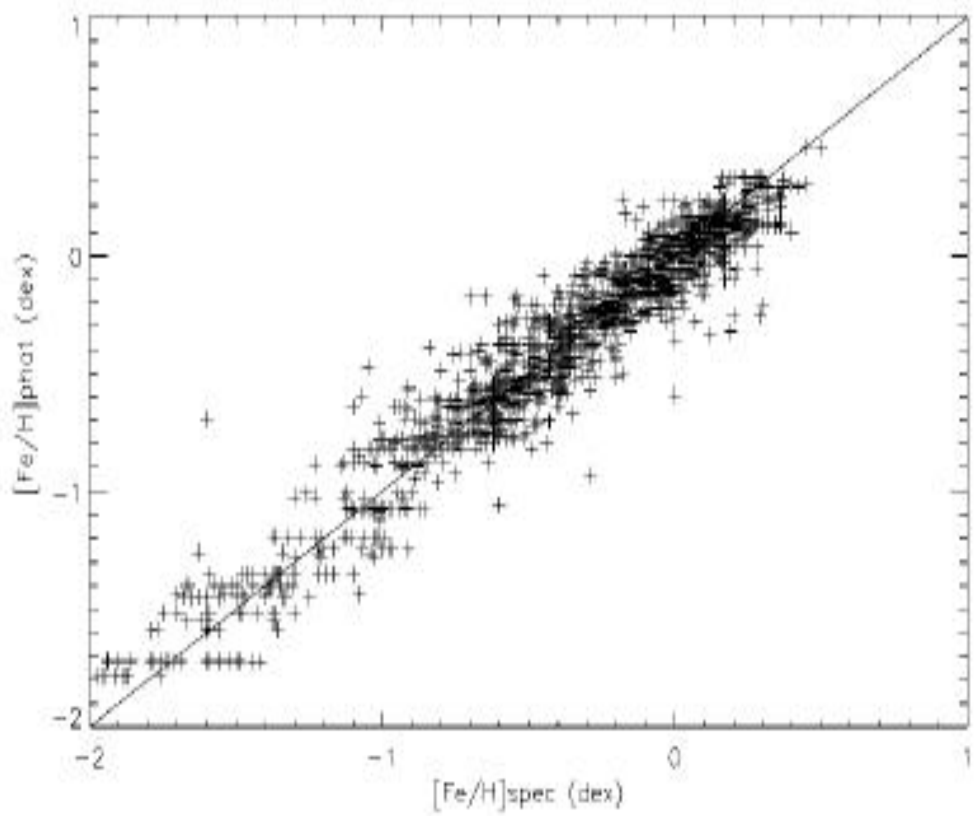
Table 1. Coefficients b_0,...,b_5 of the colour-T_{eff}relations based on GAIA DR2 magnitudes, together with corresponding colour range, the dispersion of the fit residuals and the number of used stars.

Colour	Colour range (mag)	$\sigma_{T_{eff}}$ (K)	N	b_0	b_1	b_2	b_3	b_4	b_5
				Dwarf stars					
$(BP - RP)_0$	[0.38–1.51]	61	445	0.4988	0.4925	–0.0287	0.0193	–0.0017	–0.0384
$(BP - G)_0$	[0.17–0.72]	77	429	0.4800	1.3160	–0.4957	–0.0086	–0.0020	–0.0444
$(G - RP)_0$	[0.17–0.79]	68	438	0.5623	0.5422	0.3069	0.0367	–0.0019	–0.0829
$(BP - K)_0$	[0.64–3.24]	47	454	0.5375	0.1967	–0.0002	0.0268	0.0006	–0.0150
$(RP - K)_0$	[0.34–1.75]	54	444	0.5451	0.3739	–0.0120	0.0289	0.0026	–0.0185
$(G - K)_0$	[0.52–2.53]	51	446	0.5576	0.2191	0.0095	0.0334	0.0014	–0.0182
				Giant stars					
$(BP - RP)_0$	[0.34–1.80]	83	229	0.5403	0.4318	–0.0085	–0.0217	–0.0032	0.0040
$(BP - G)_0$	[0.13–1.00]	106	218	0.5156	1.3488	–0.6976	–0.0105	–0.0020	–0.0181
$(G - RP)_0$	[0.21–0.84]	86	190	0.5056	0.8788	0.0107	0.0216	0.0023	–0.0030
$(BP - K)_0$	[0.69–3.98]	52	233	0.5670	0.1829	–0.0004	0.0030	–0.0009	–0.0034
$(RP - K)_0$	[0.35–2.26]	64	235	0.5764	0.3601	–0.0237	0.0350	0.0000	–0.0245
$(G - K)_0$	[0.56–3.06]	66	230	0.5444	0.2747	–0.0118	0.0387	0.0024	–0.0117

Mucciarelli & Bellazzini, 2020, Research Notes of the AAS, 4, 52

Photometric calibrations

Error: +-0.10 dex



$$
\begin{aligned}
[\mathrm{Fe/H}]_{\mathrm{phot}} = {} & -10.424602 + 31.059003(b-y) \\
& + 42.184476 m_1 + 15.351995 c_1 \\
& - 11.239435(b-y)^2 - 29.218135 m_1^2 \\
& - 11.457610 c_1^2 - 138.92376(b-y) m_1 \\
& - 52.033290(b-y) c_1 + 11.259341 m_1 c_1 \\
& - 46.087731(b-y)^3 + 26.065099 m_1^3 \\
& - 1.1017830 c_1^3 + 138.48588(b-y)^2 m_1 \\
& + 39.012001(b-y)^2 c_1 \\
& + 23.225562 m_1^2(b-y) - 69.146876 m_1^2 c_1 \\
& + 20.456093 c_1^2(b-y) - 3.3302478 c_1^2 m_1 \\
& + 70.168761(b-y) m_1 c_1 .
\end{aligned}
$$

Martell & Laughlin, 2002, ApJ, 577, L45

How to derive cluster parameters?

- Use as much as possible available indices
- Check the literature for published values as least as a starting point
- First try it with a “standard set” of data
- Automatic procedures available, but be careful

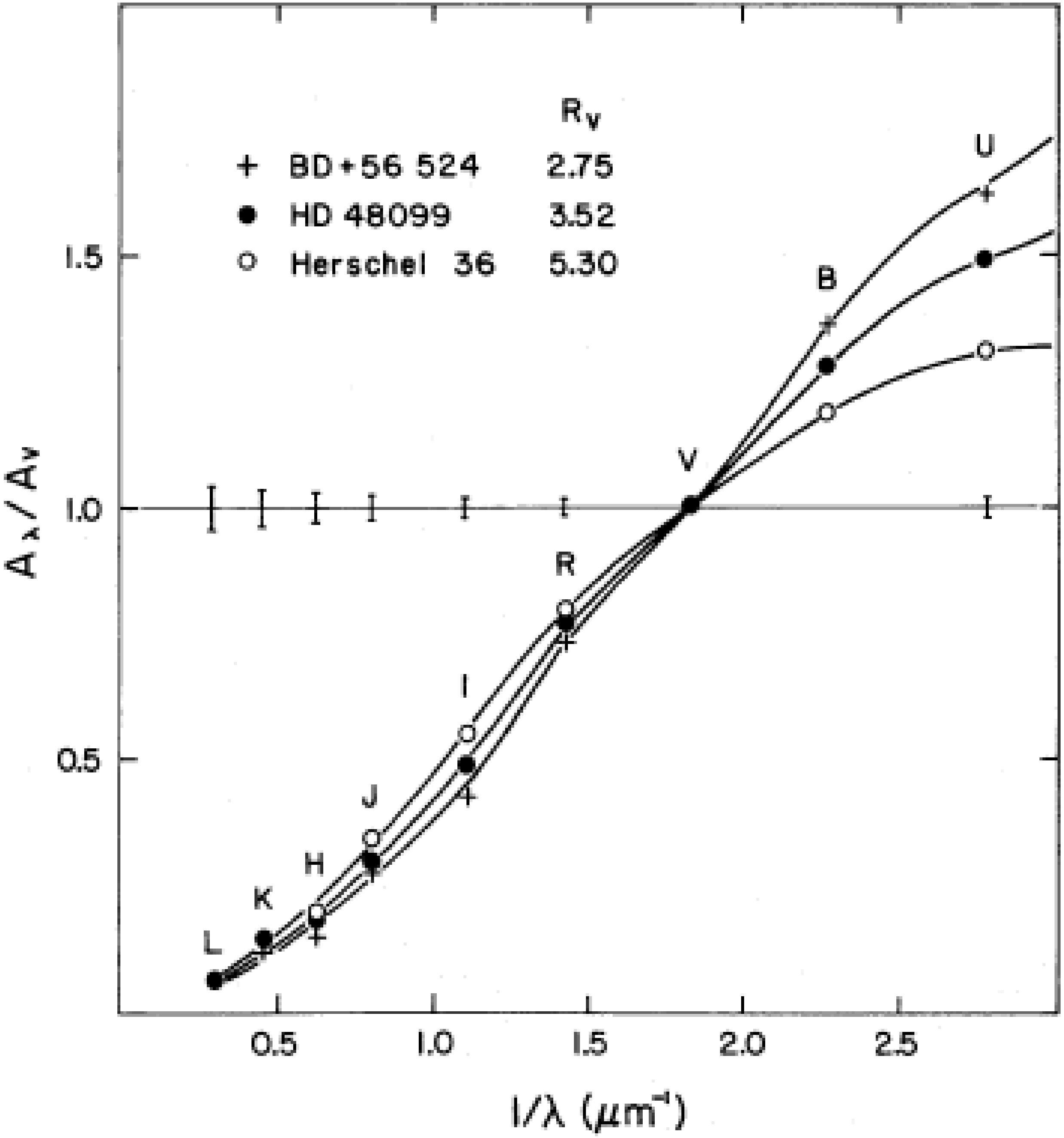
Absorption = Extinction = Reddening

- $A_V = k_1 E(B\text{-}V) = k_2 E(V\text{-}R) = \ldots$
- 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:

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

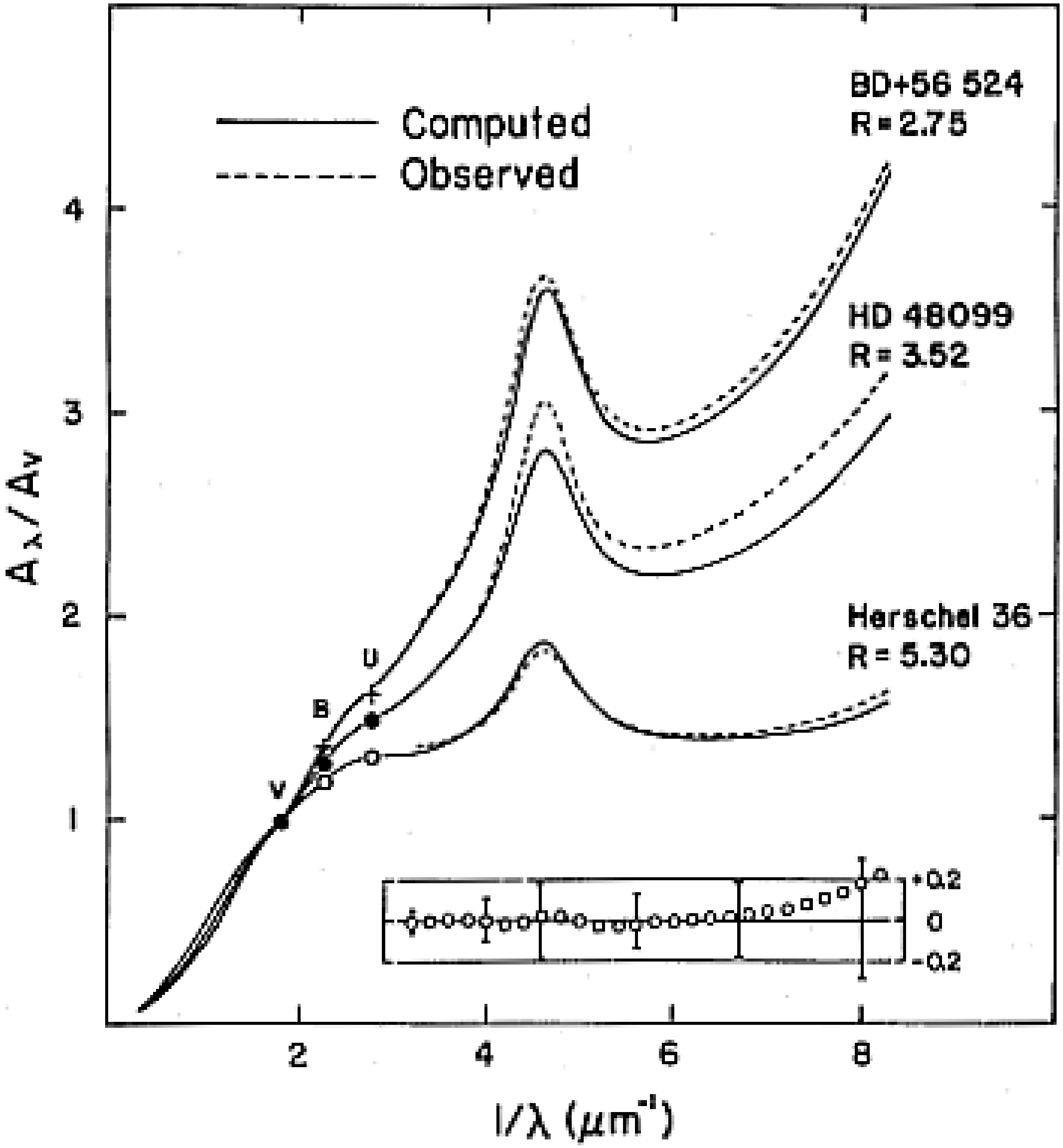
Normalization factor

Standard value used is 3.1

Be careful, different values used!

Depending on the line of sight

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



Dependency of the extinction from R_V

How to derive the reddening?

- Non-Isochrone approach: from photometric and spectroscopic observations

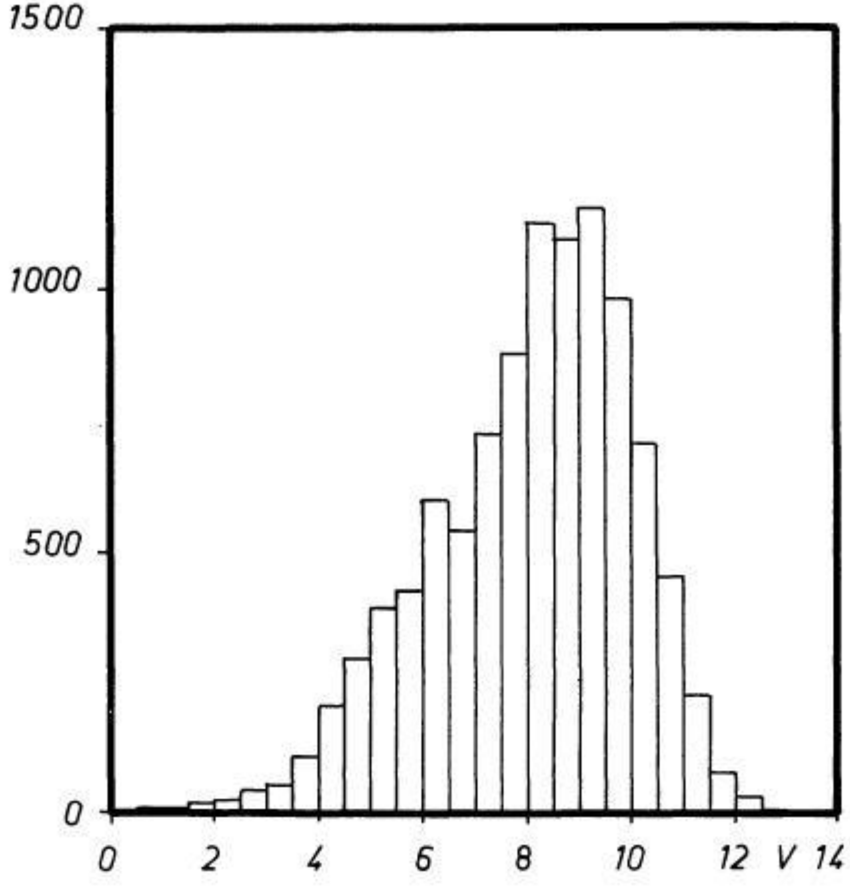


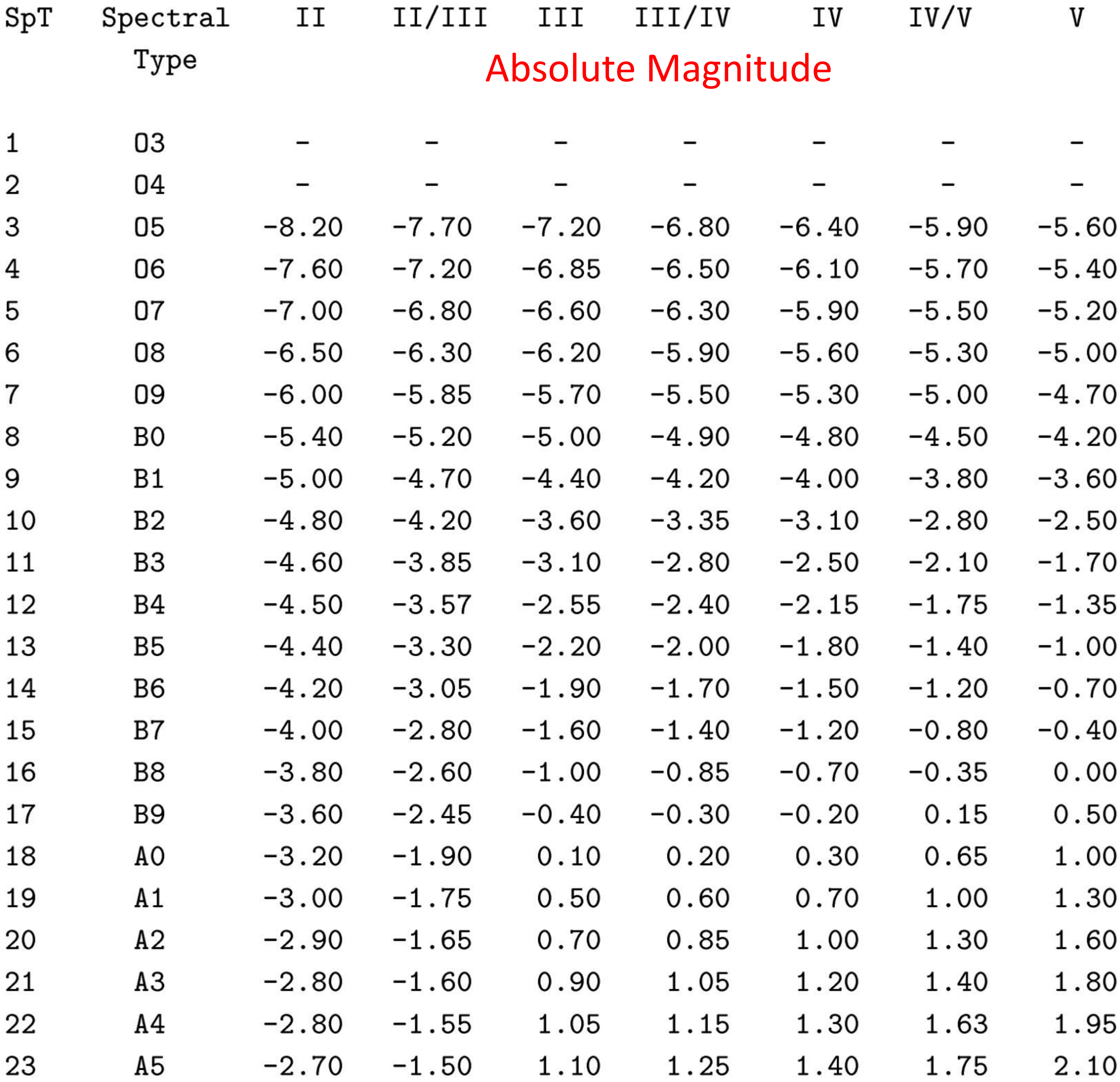
FIGURE 2. — Distribution of the stars *versus* apparent *V*-magnitude.

Classical approach: Neckel & Klare, 1980, A&AS, 42, 251

Take all available UBV and Strömgren β photometry

MK classifications

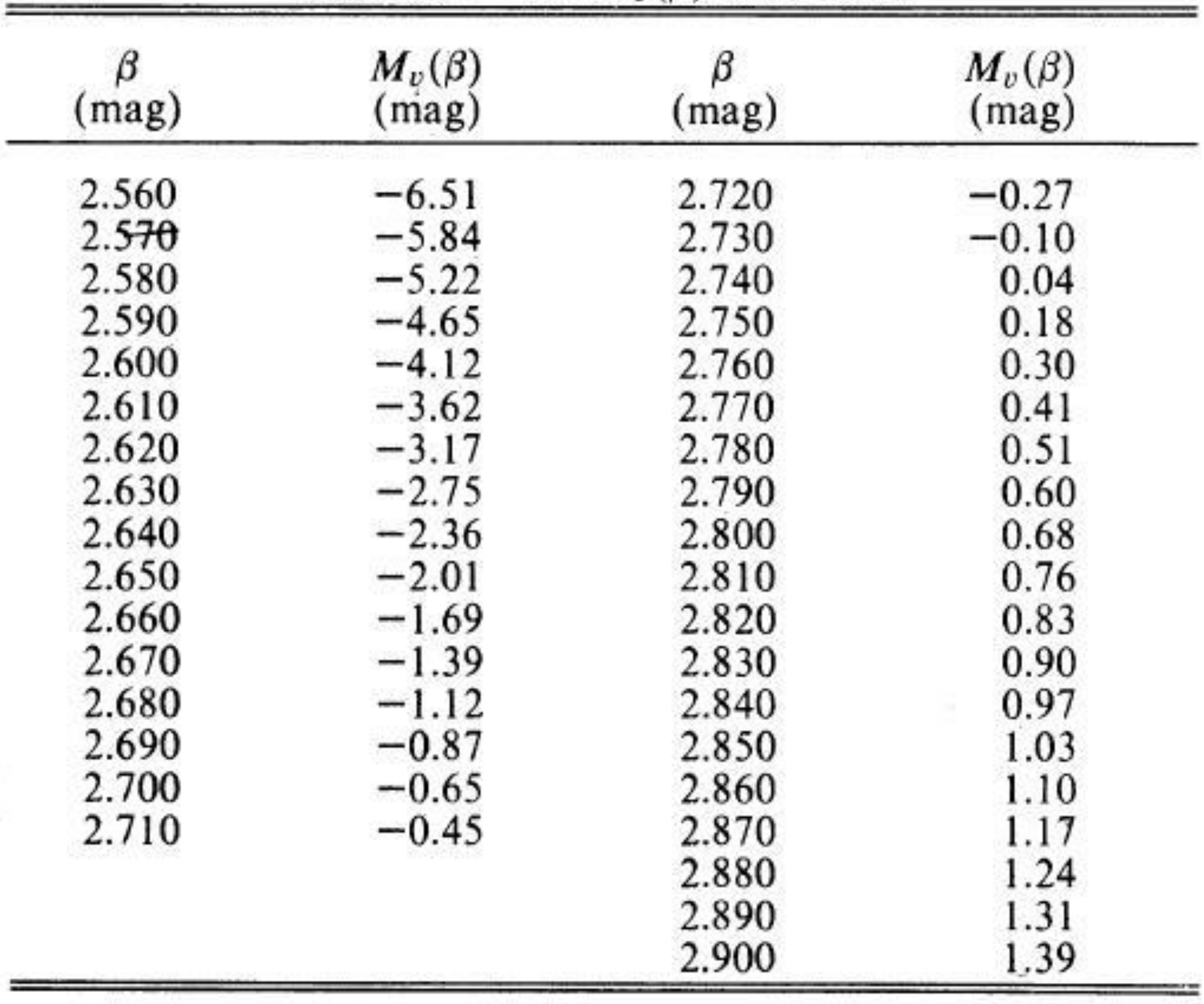
Bailer-Jones,
1996, PhD,
Cambridge
University



Absolute Magnitude

SpT	Spectral Type	II	II/III	III	III/IV	IV	IV/V	V
1	O3	-	-	-	-	-	-	-
2	O4	-	-	-	-	-	-	-
3	O5	-8.20	-7.70	-7.20	-6.80	-6.40	-5.90	-5.60
4	O6	-7.60	-7.20	-6.85	-6.50	-6.10	-5.70	-5.40
5	O7	-7.00	-6.80	-6.60	-6.30	-5.90	-5.50	-5.20
6	O8	-6.50	-6.30	-6.20	-5.90	-5.60	-5.30	-5.00
7	O9	-6.00	-5.85	-5.70	-5.50	-5.30	-5.00	-4.70
8	B0	-5.40	-5.20	-5.00	-4.90	-4.80	-4.50	-4.20
9	B1	-5.00	-4.70	-4.40	-4.20	-4.00	-3.80	-3.60
10	B2	-4.80	-4.20	-3.60	-3.35	-3.10	-2.80	-2.50
11	B3	-4.60	-3.85	-3.10	-2.80	-2.50	-2.10	-1.70
12	B4	-4.50	-3.57	-2.55	-2.40	-2.15	-1.75	-1.35
13	B5	-4.40	-3.30	-2.20	-2.00	-1.80	-1.40	-1.00
14	B6	-4.20	-3.05	-1.90	-1.70	-1.50	-1.20	-0.70
15	B7	-4.00	-2.80	-1.60	-1.40	-1.20	-0.80	-0.40
16	B8	-3.80	-2.60	-1.00	-0.85	-0.70	-0.35	0.00
17	B9	-3.60	-2.45	-0.40	-0.30	-0.20	0.15	0.50
18	A0	-3.20	-1.90	0.10	0.20	0.30	0.65	1.00
19	A1	-3.00	-1.75	0.50	0.60	0.70	1.00	1.30
20	A2	-2.90	-1.65	0.70	0.85	1.00	1.30	1.60
21	A3	-2.80	-1.60	0.90	1.05	1.20	1.40	1.80
22	A4	-2.80	-1.55	1.05	1.15	1.30	1.63	1.95
23	A5	-2.70	-1.50	1.10	1.25	1.40	1.75	2.10

TABLE V. The $M_v(\beta)$ calibration.



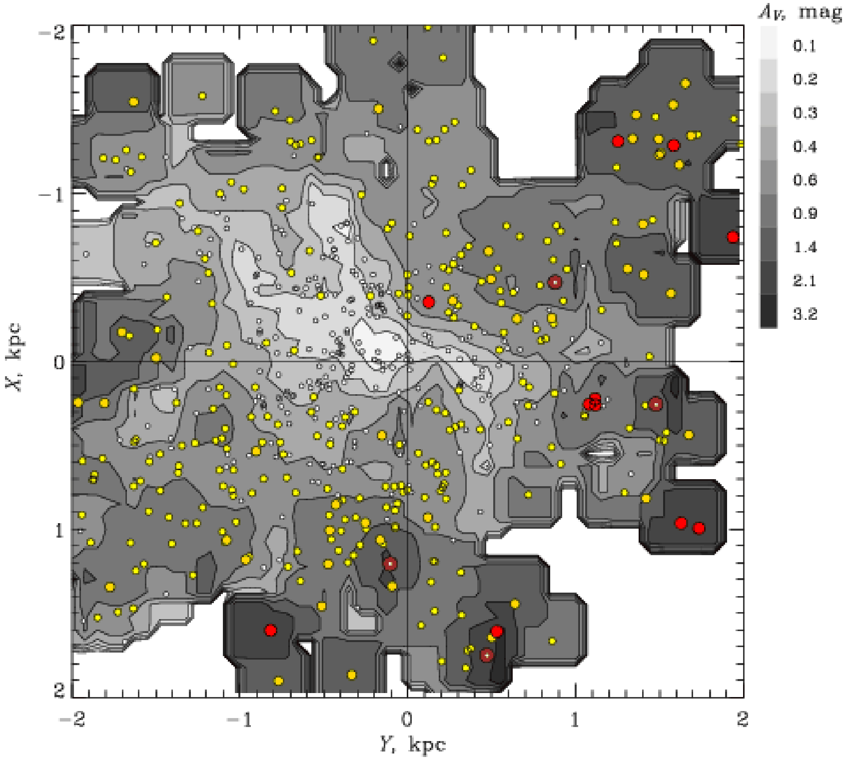
β (mag)	$M_v(\beta)$ (mag)	β (mag)	$M_v(\beta)$ (mag)
2.560	−6.51	2.720	−0.27
2.570	−5.84	2.730	−0.10
2.580	−5.22	2.740	0.04
2.590	−4.65	2.750	0.18
2.600	−4.12	2.760	0.30
2.610	−3.62	2.770	0.41
2.620	−3.17	2.780	0.51
2.630	−2.75	2.790	0.60
2.640	−2.36	2.800	0.68
2.650	−2.01	2.810	0.76
2.660	−1.69	2.820	0.83
2.670	−1.39	2.830	0.90
2.680	−1.12	2.840	0.97
2.690	−0.87	2.850	1.03
2.700	−0.65	2.860	1.10
2.710	−0.45	2.870	1.17
		2.880	1.24
		2.890	1.31
		2.900	1.39

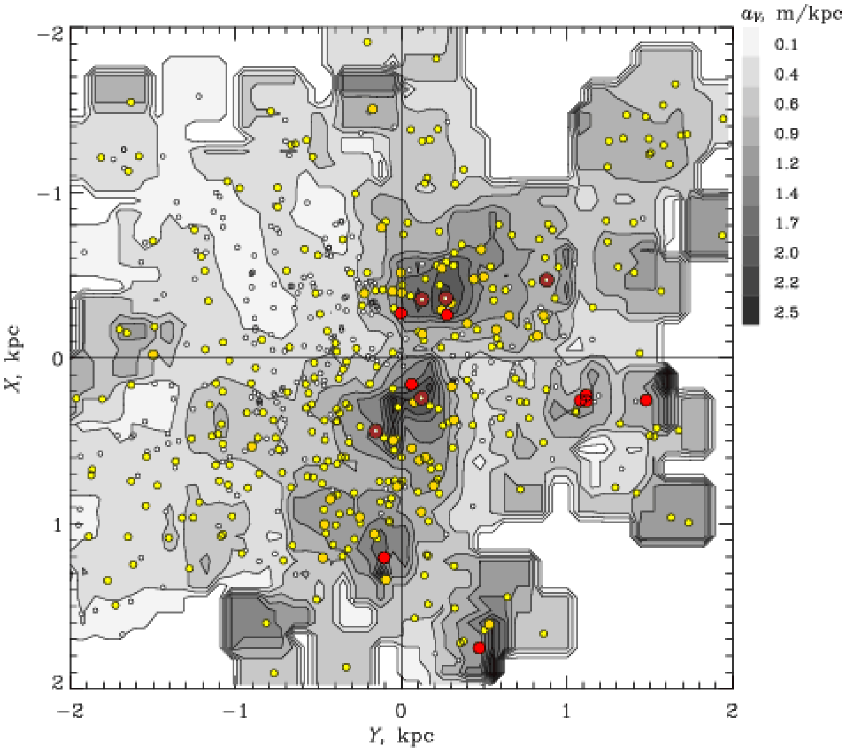
Crawford, 1976, AJ, 83, 48

Example for the β index

Reddening Maps

http://argonaut.skymaps.info/
http://www.univie.ac.at/p2f



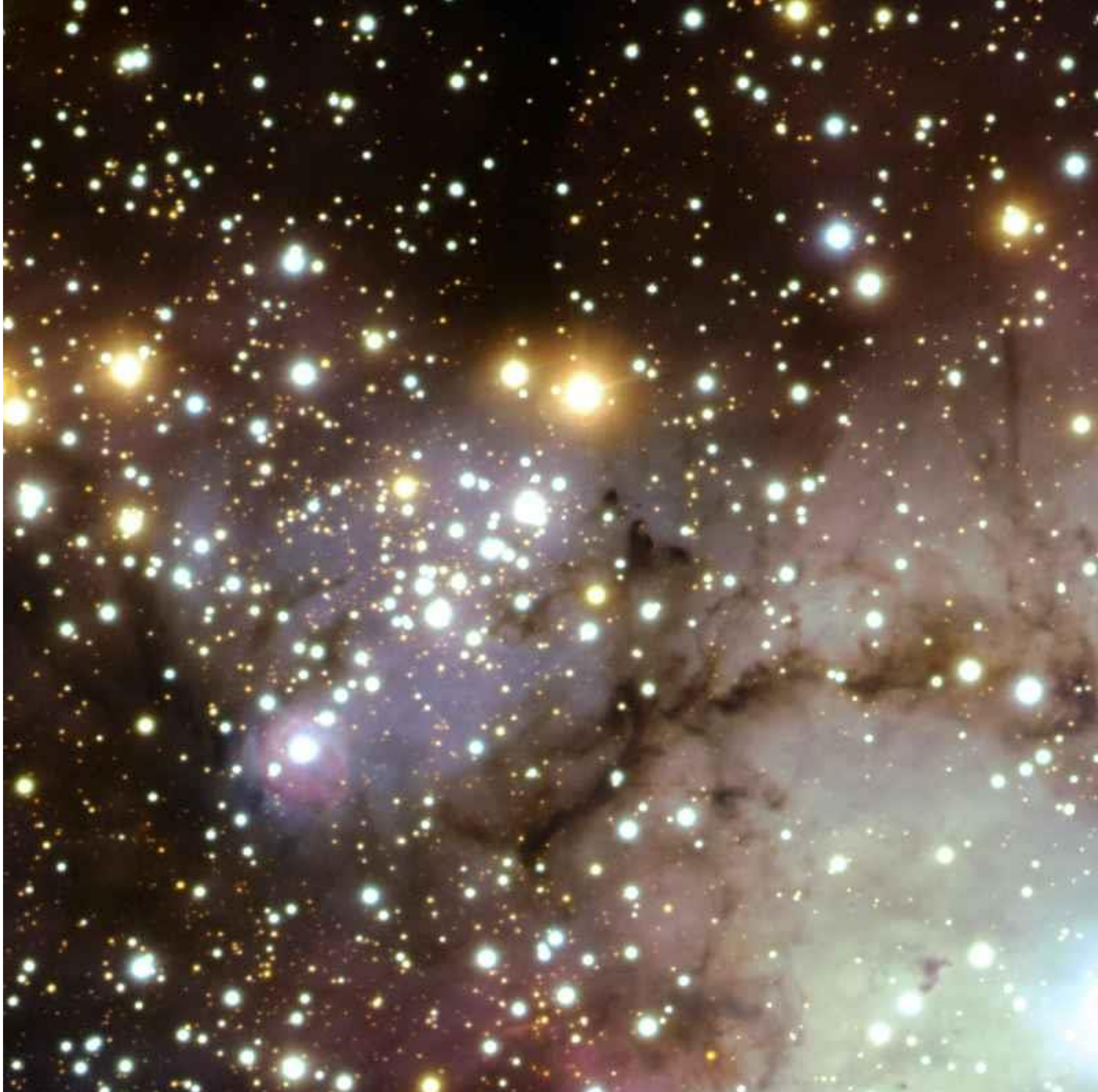


Piskunov et al., 2006, A&A, 445, 545

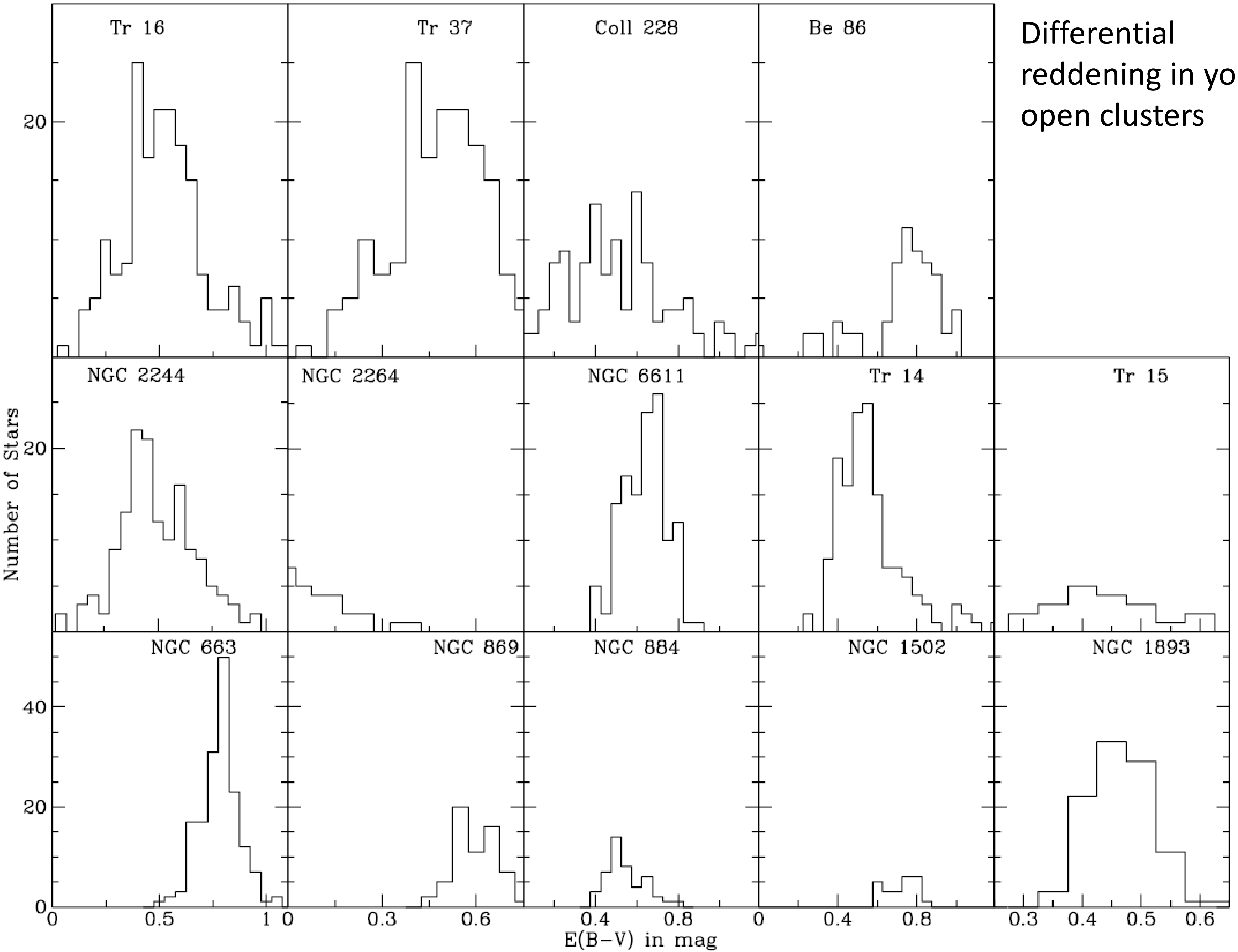
Haffner 18

Age about 8 Myr
d = 6000 pc

differential extinction within the cluster



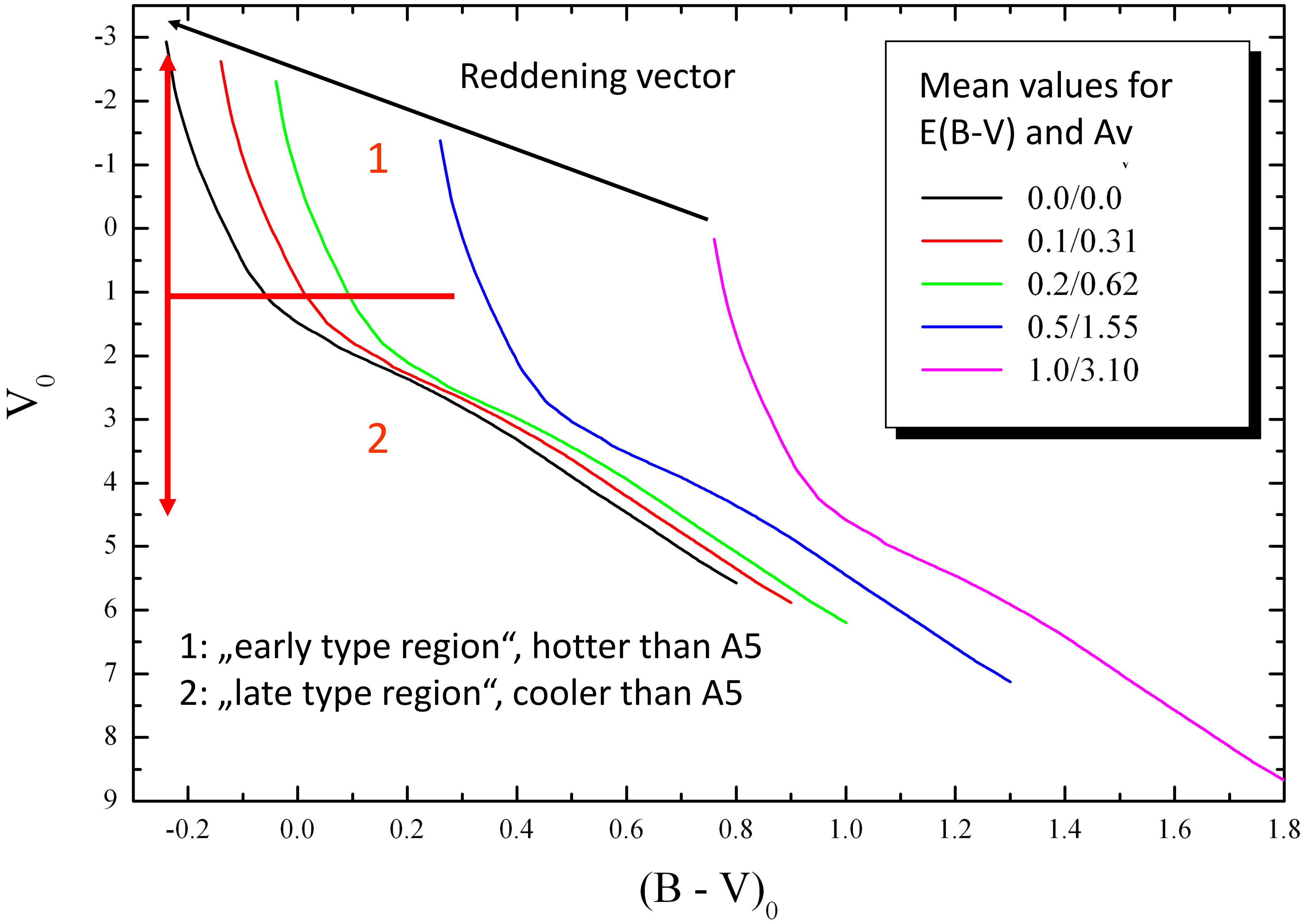
Differential reddening in young open clusters

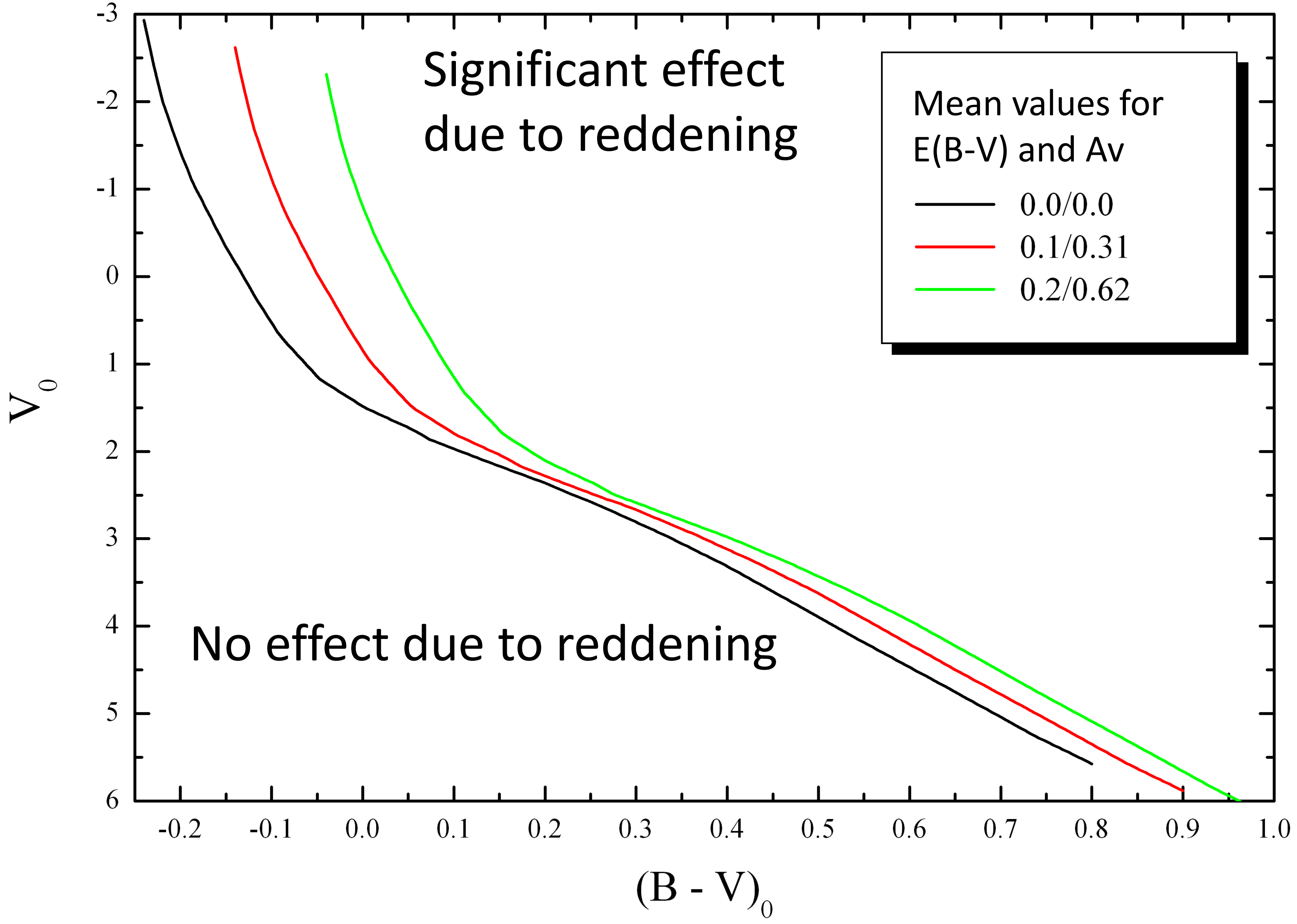


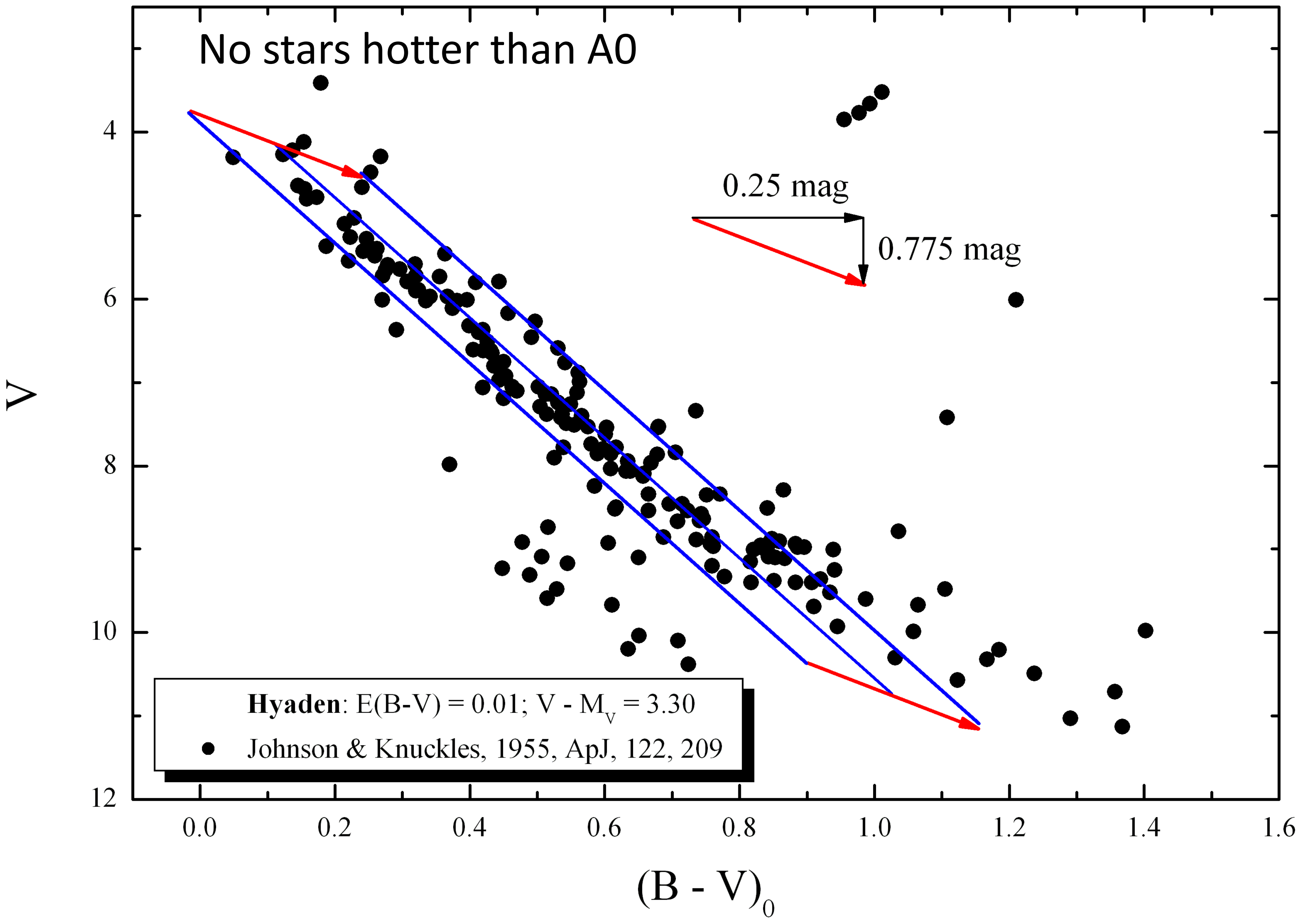
Yadav & Sagar, 2001, MNRAS, 328, 370

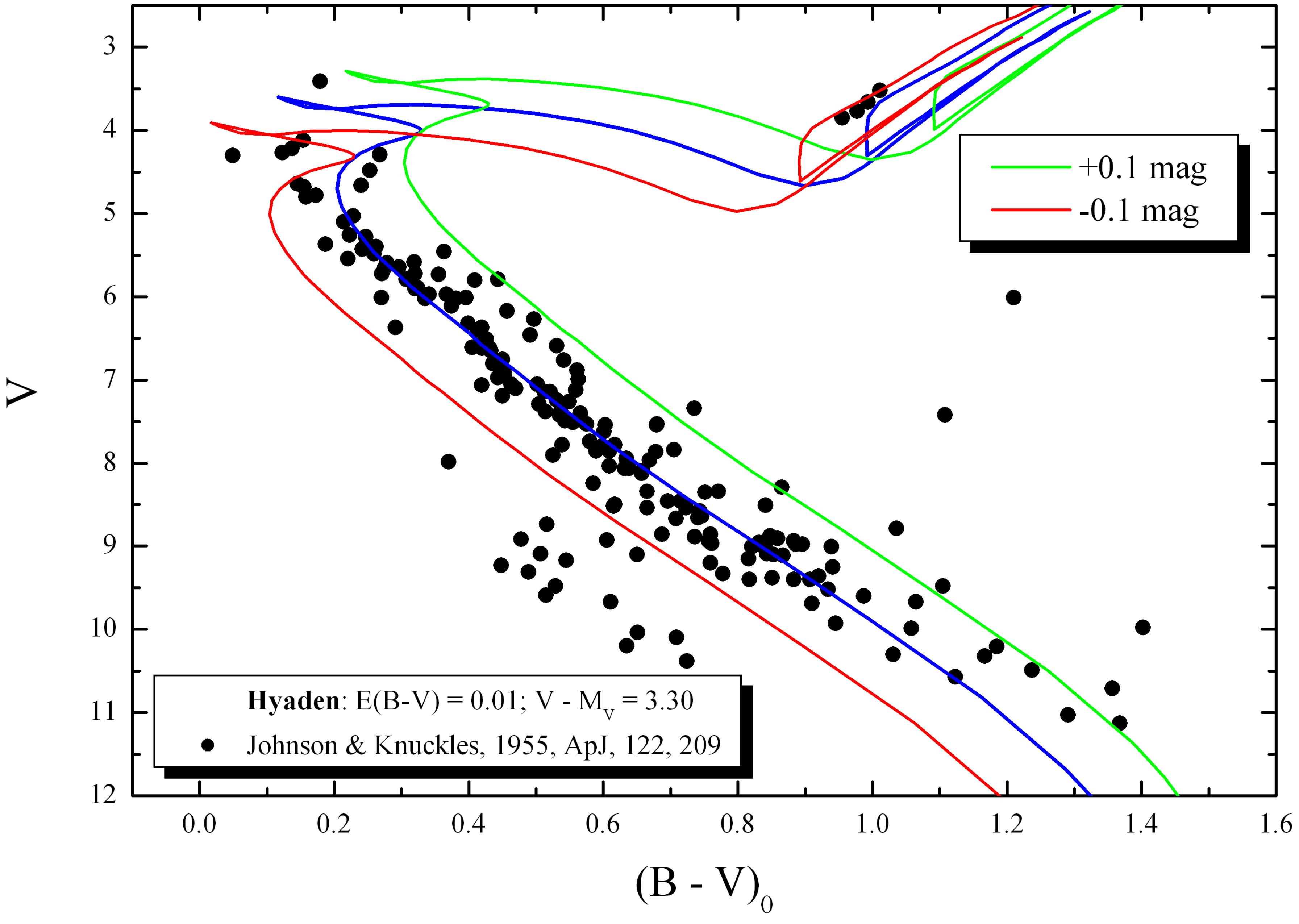
Determination of the reddening - Isochrones

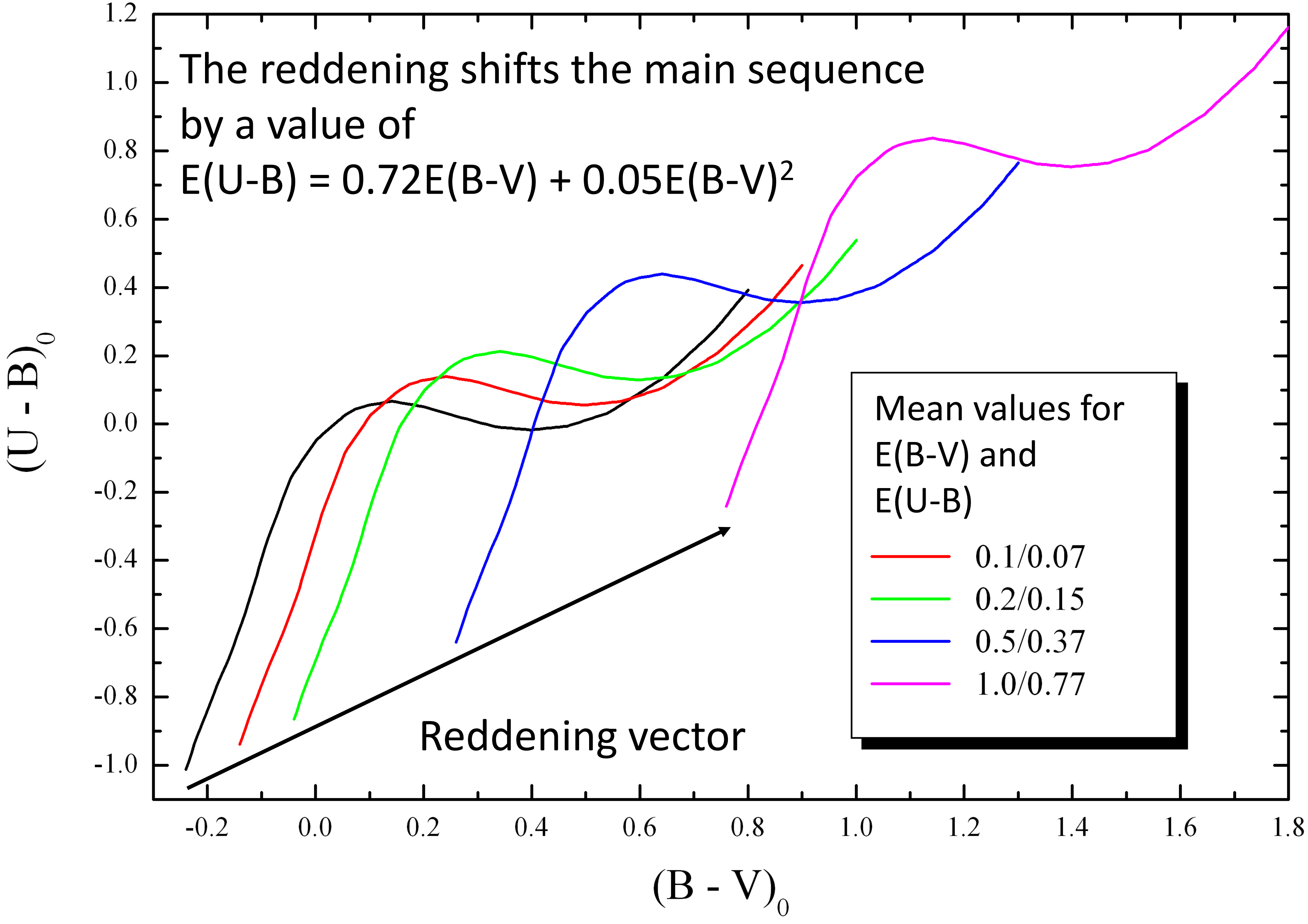
- From two temperature sensitive parameters, the determination of the reddening is not possible
- You need one “other” observational index
- First choices: (U – B), (u – b), [X], β
- Normally, you only have V, J, H, K, and so on


Reddening vector
1
2
Mean values for
E(B-V) and Av
0.0/0.0
0.1/0.31
0.2/0.62
0.5/1.55
1.0/3.10
1: „early type region“, hotter than A5
2: „late type region“, cooler than A5
V_0
-3
-2
-1
0
1
2
3
4
5
6
7
8
9
$(B - V)_0$
-0.2
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8


Significant effect
due to reddening
No effect due to reddening
Mean values for
E(B-V) and Av
0.0/0.0
0.1/0.31
0.2/0.62
V$_0$
(B - V)$_0$
-3
-2
-1
0
1
2
3
4
5
6
-0.2
-0.1
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0


No stars hotter than A0
0.25 mag
0.775 mag
Hyaden: E(B-V) = 0.01; V - M_V = 3.30
● Johnson & Knuckles, 1955, ApJ, 122, 209
V
4
6
8
10
12
(B - V)_0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6

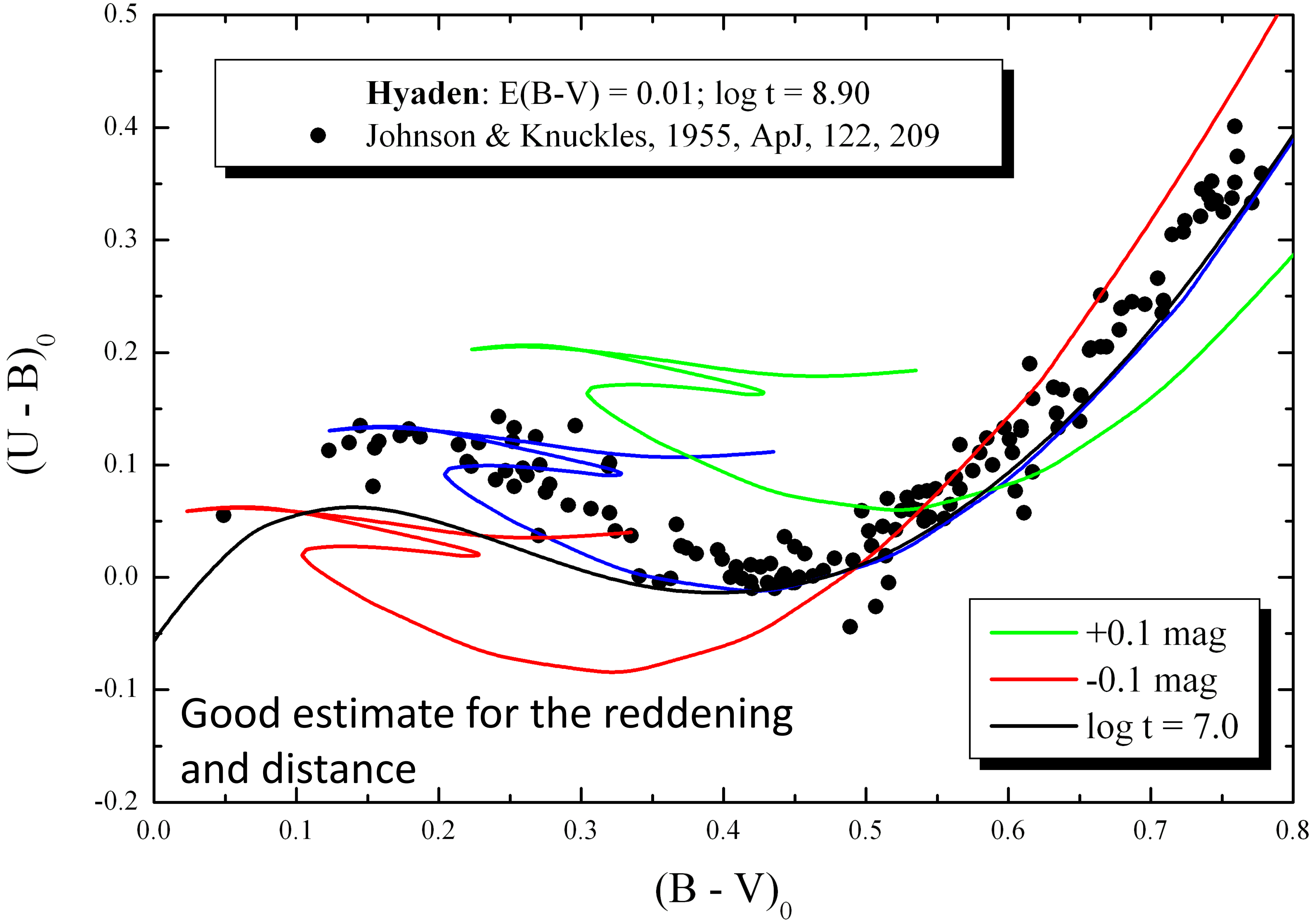

V
(B - V)$_0$
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
3
4
5
6
7
8
9
10
11
12
+0.1 mag
-0.1 mag
Hyaden: E(B-V) = 0.01; V - M$_V$ = 3.30
● Johnson & Knuckles, 1955, ApJ, 122, 209



The reddening shifts the main sequence by a value of

$E(U\text{-}B) = 0.72E(B\text{-}V) + 0.05E(B\text{-}V)^2$

Reddening vector



Good estimate for the reddening and distance

Field stars

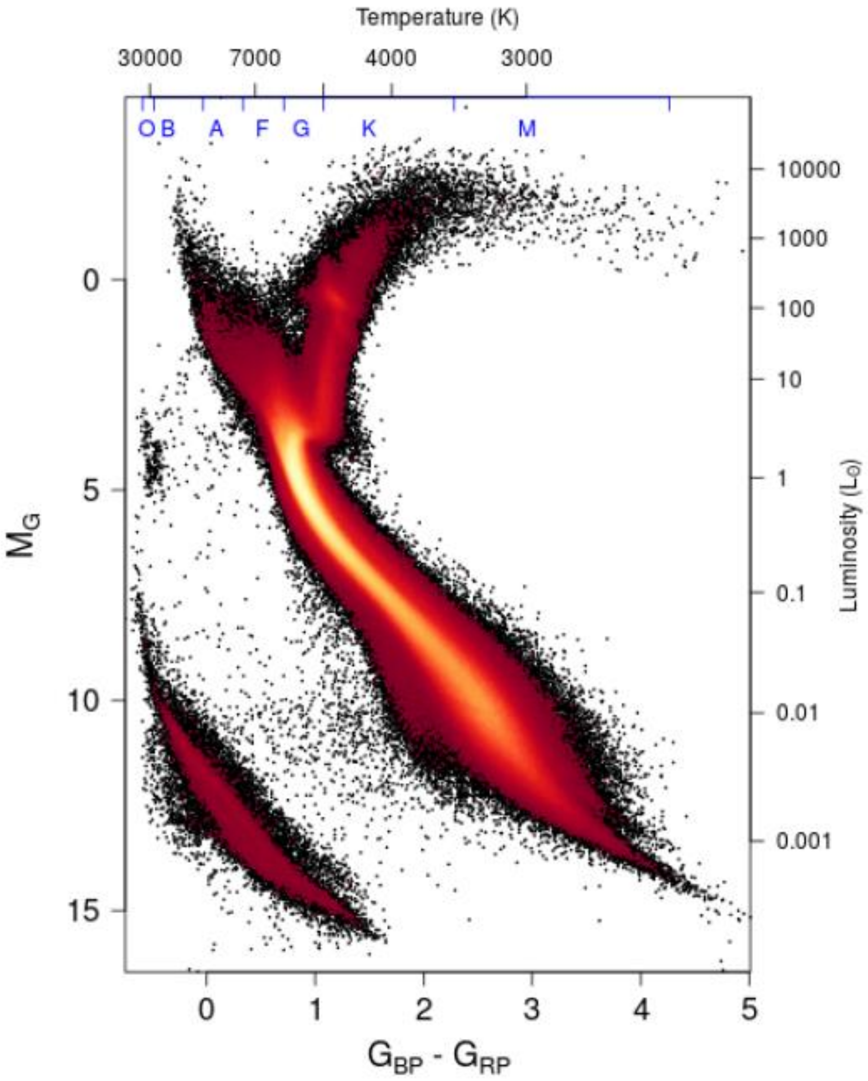


Fig. 5. *Gaia* HRD of sources with low extinction ($E(B–V) < 0.015$ mag)

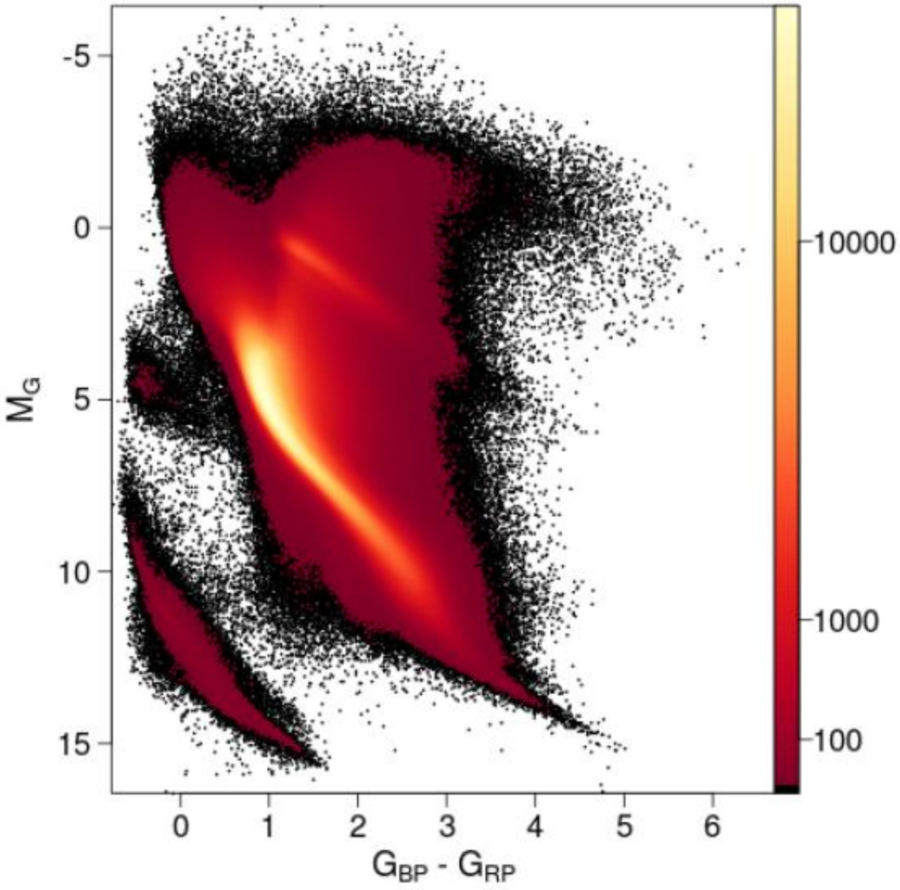


Fig. 1. Full *Gaia* colour-magnitude diagram

Gaia Consortium, 2018, A&A, 616, A10

4. **Extinction values and distances.** — The visual extinction A_v can be derived from

$$A_v = R \{ (B - V) - (B - V)_0 \} . \tag{2}$$

For R we take the value 3.1.

The intrinsic color $(B\text{-}V)_0$ follows directly from the MK calibration, if the MK type is known. In addition, $(B\text{-}V)_0$ can also be derived from the *UBV* and β data. The distance moduli are then given by

$$\boxed{V - M_v} - A_v = 5 \lg r - 5 . \tag{3}$$

If we could derive A_v and r by both methods, we could use the mean values of extinction and distance moduli. This was possible for 1 020 stars. Figure 4 shows the frequency distribution of the differences

$$D = (V - M_v(\mathrm{MK}) - A_v(UBV, \mathrm{MK})) - \\ - (V - M_v(\beta) - A_v(UBV, \beta)) . \tag{4}$$

Distance modulus

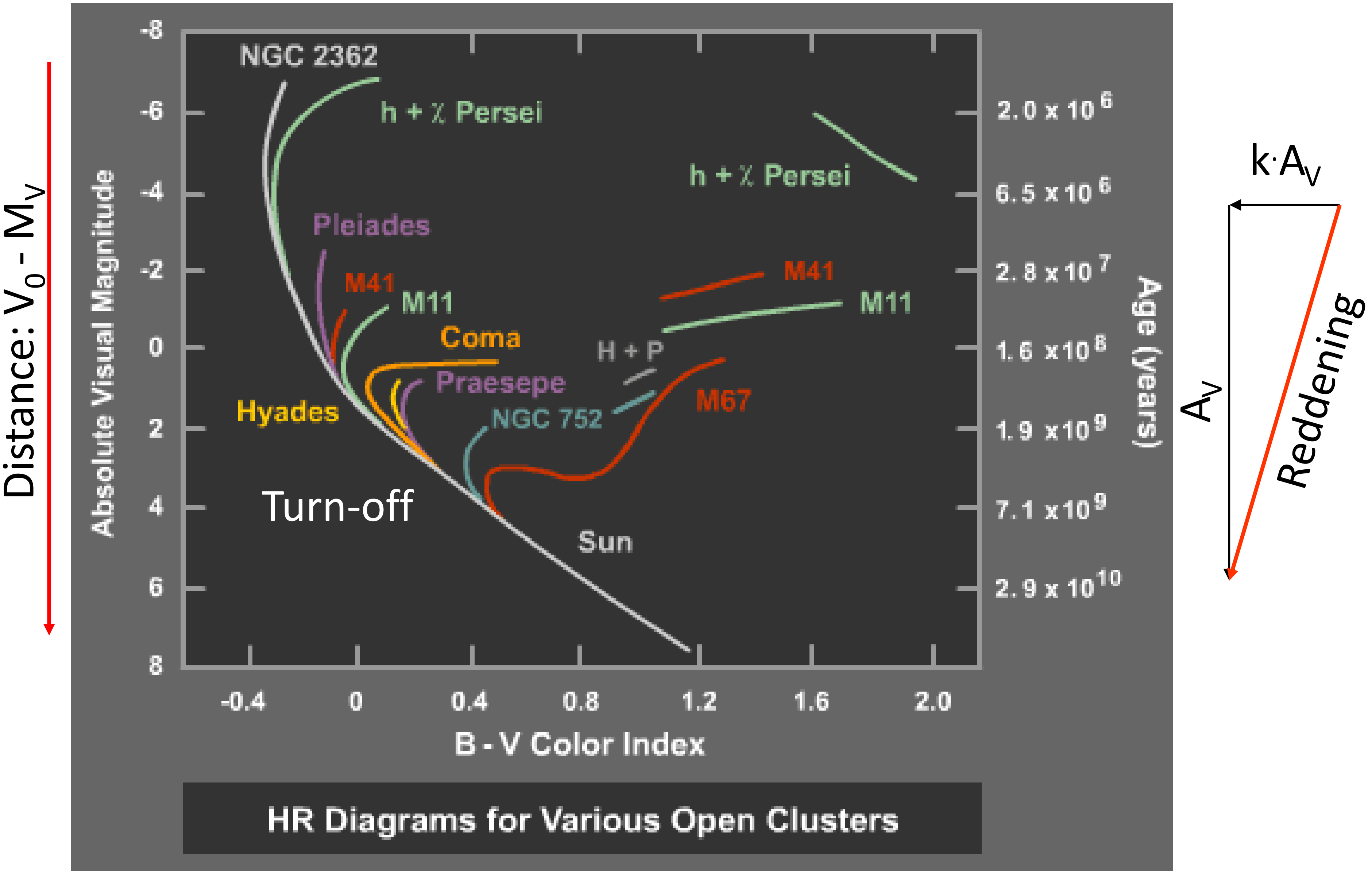
- Apparent DM: $(V - M_V)$ which still includes the reddening
- Absolute DM: $(V - M_V)_0$ or $(V_0 - M_V)$ which not includes the reddening
- Be careful there is always a mixture in the literature!

How to determine the DM?

- Direct isochrone fitting
- Calibrate M_V directly via photometry and spectroscopy with known reddening and V magnitude => distance directly
- Advantage: statistical sample

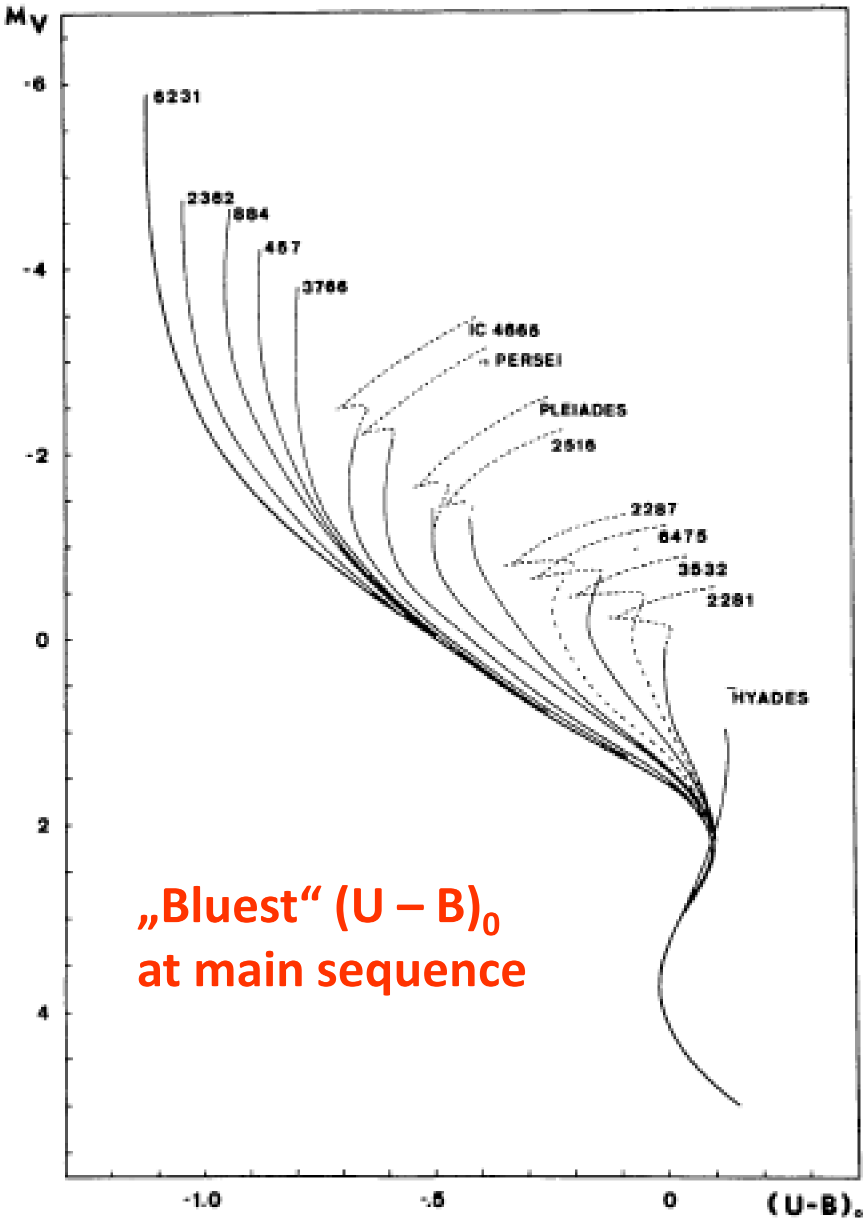
Turn off point

- Where is the turn-off point located?
  - Color/temperature
  - Absolute/apparent magnitude/luminosity
- Direct correlation with the age
- Difficult to define for young star clusters
- First, classical method, just „to look“ at color-magnitude-diagram

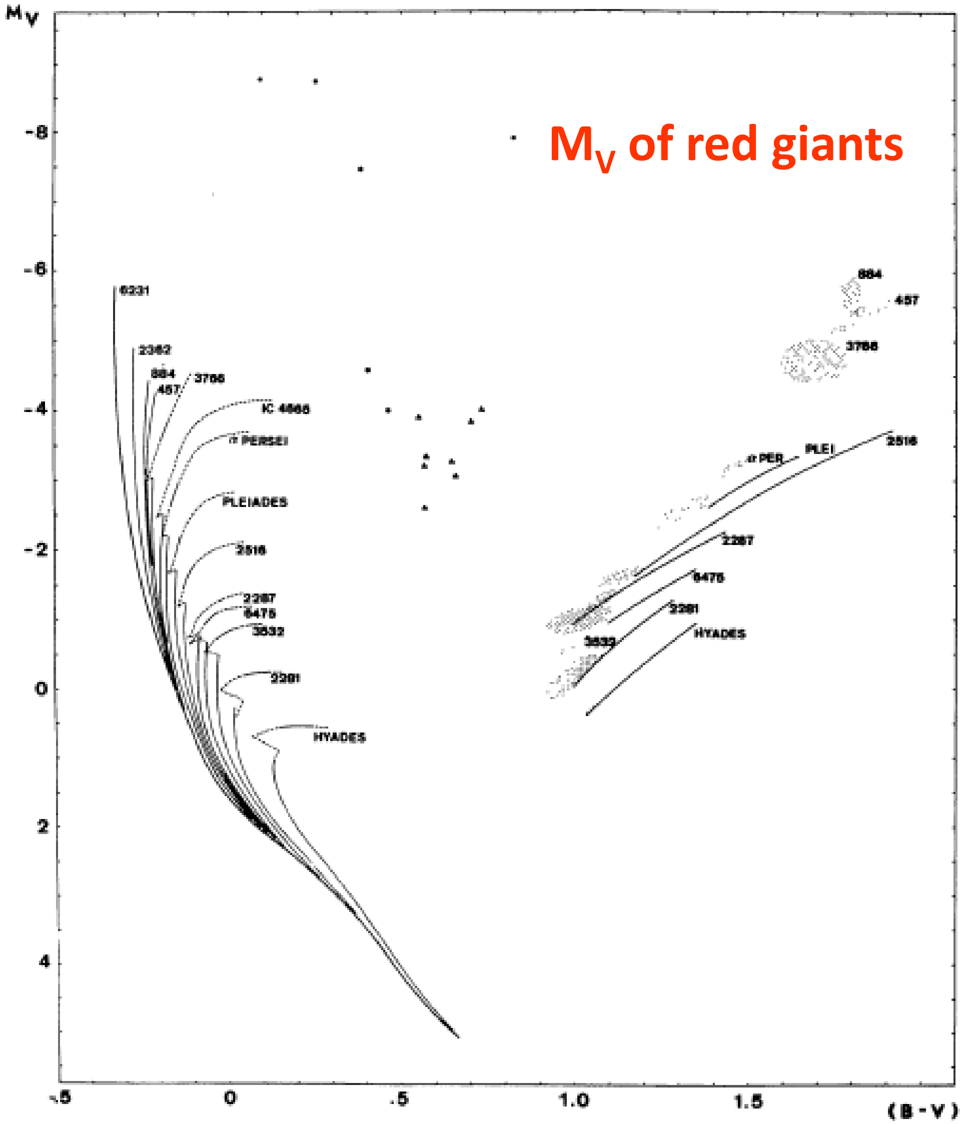


HR Diagrams for Various Open Clusters

Mermilliod, 1981, A&A, 97, 235: no newer paper available!



„Bluest“ $(U-B)_0$ at main sequence



M_V of red giants

Dereddened indices

Mermilliod, 1981, A&A, 97, 235

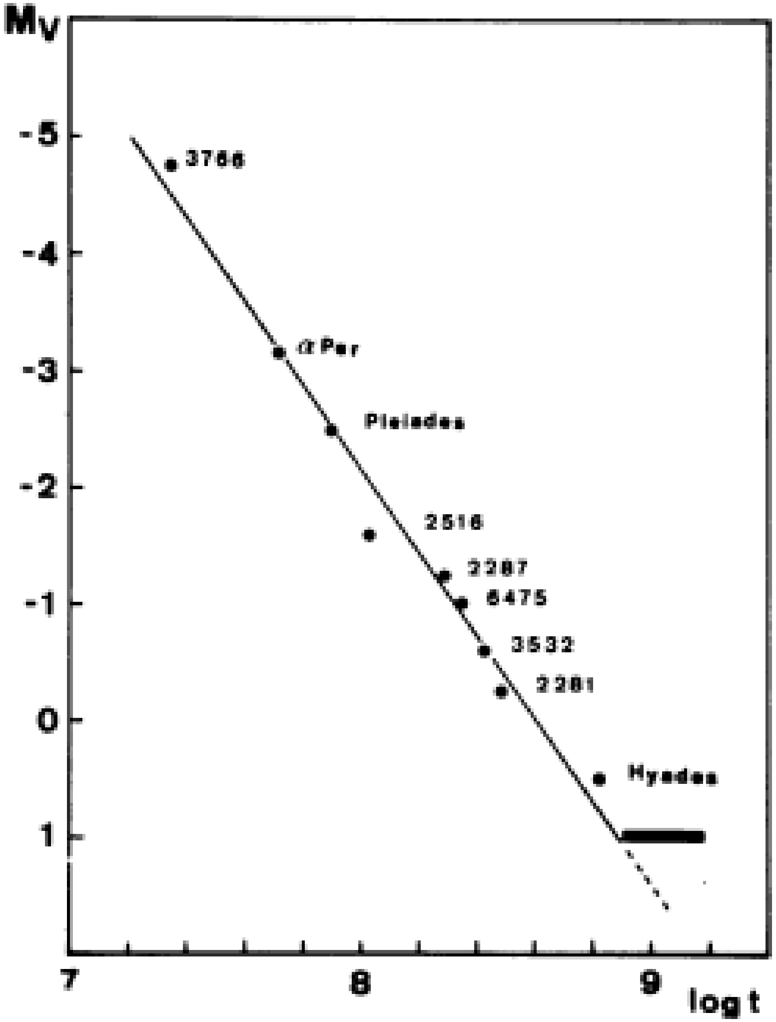


Fig. 7. Relation between the mean absolute magnitude of the red giant concentrations and log *t*. The darkened area at M_V=+1. indicates the position of the clump in old clusters.

A correlation has been established between the mean absolute magnitude of the red giant concentrations and ages (Fig. 7). A straight line has been fitted by eye, which gives the following relation:

$$\log t = 0.280\, M_V + 8.610$$

No direct error estimation possible

Possible to use for star clusters between 20 Myr and 800 Myr

Mermilliod, 1981, A&A, 97, 235

Very precise method

Possible to use between for star clusters between 20 Myr and 300 Myr

$(U-B)_0$ for cooler stars = older ages is almost **constant**

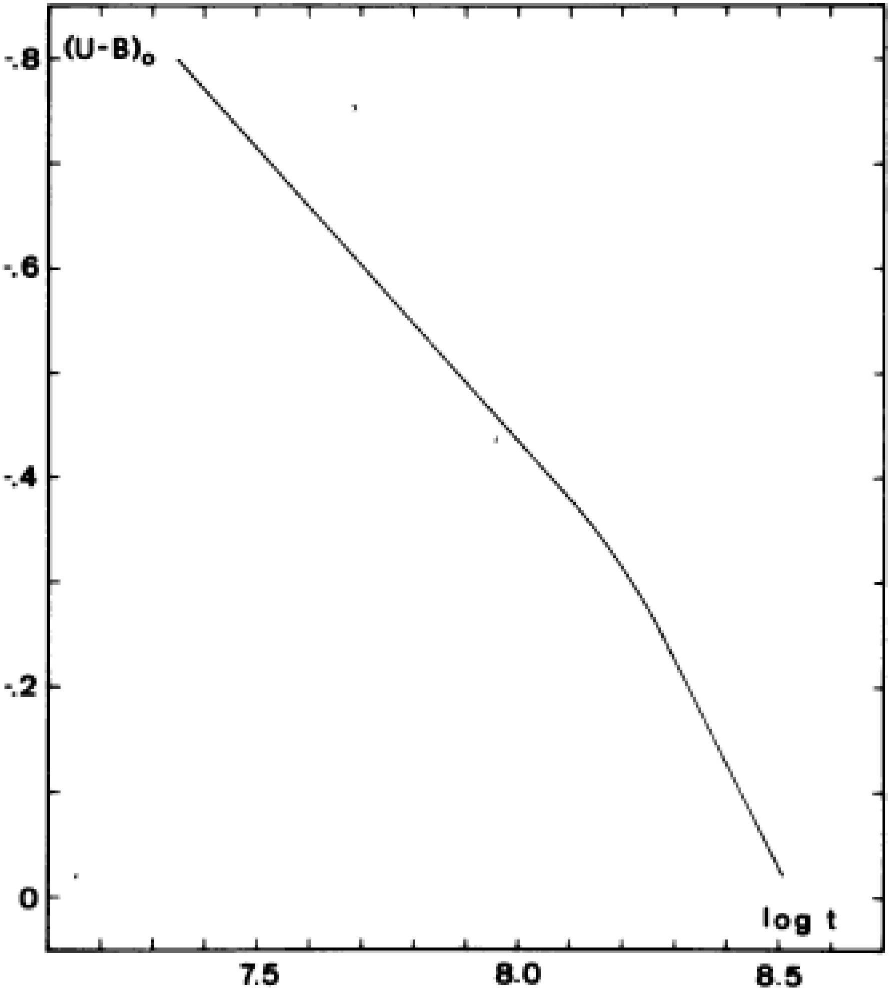
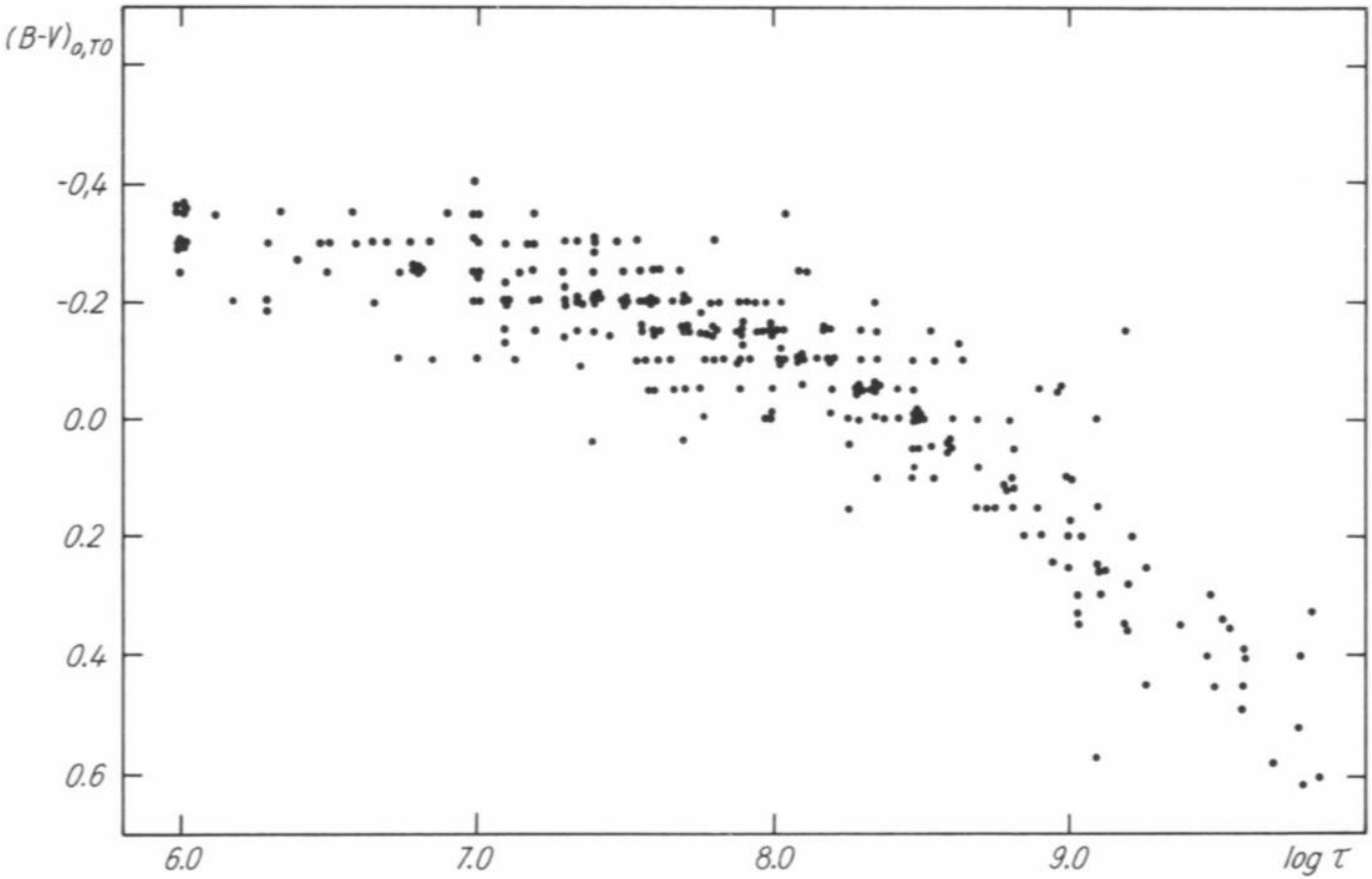


Fig. 6. Calibration of the bluest $(U-B)_0$ on the main sequence in terms of age (log t)

$$-.80 \leq (U-B)_0 < -.35 \quad \log t = 1.795(U-B)_0 + 8.785$$

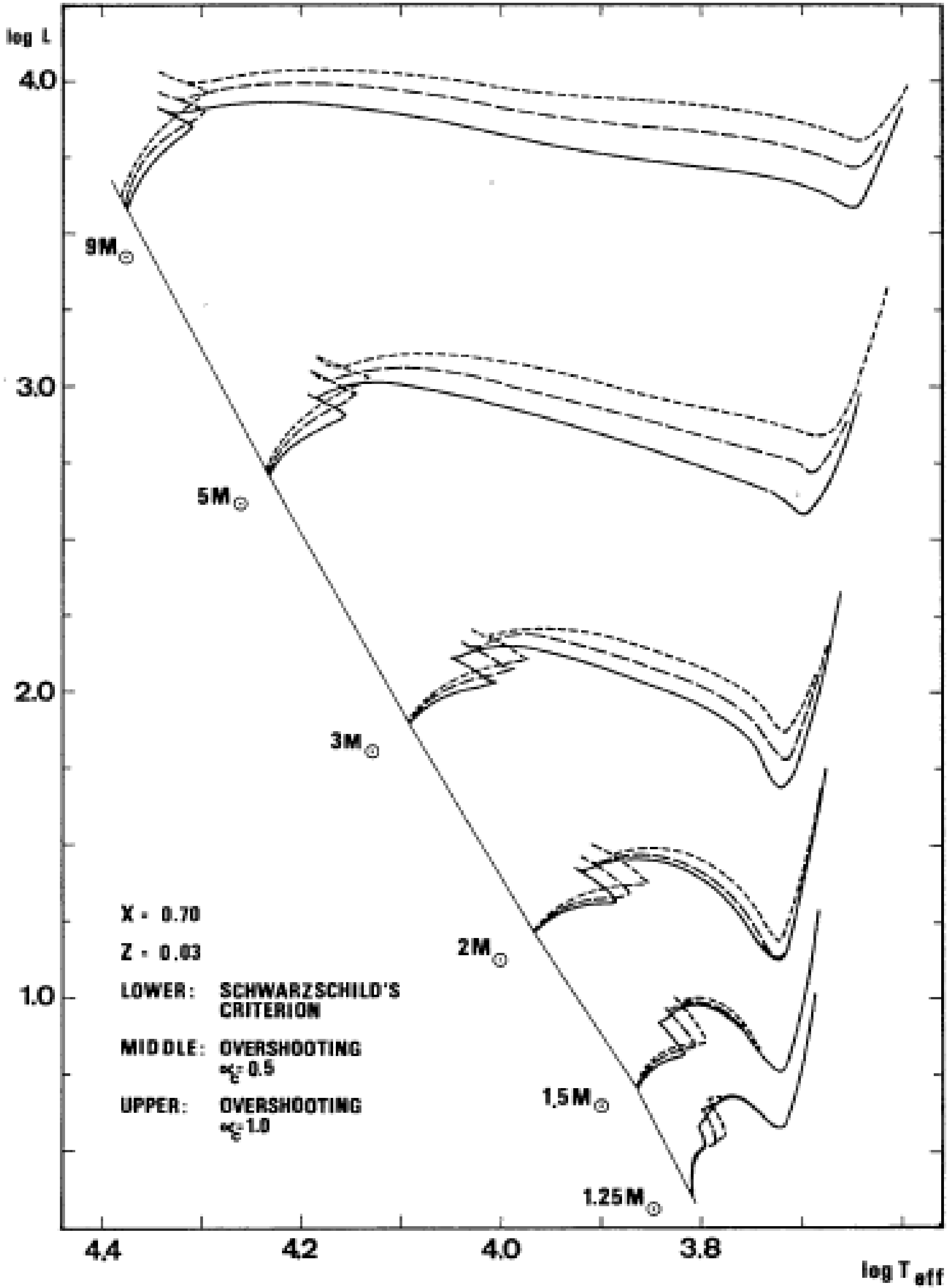
$$-.28 \leq (U-B)_0 < .00 \quad \log t = 0.813(U-B)_0 + 8.487$$



Not very accurate but still useful, never done for 2MASS and NIR

Maeder & Mermilliod, 1981, A&A, 93, 136

Different treatment of convection



Metallicity - Basics

- Metallicity as [X:Y:Z]
- X = Hydrogen
- Y = Helium
- Z = „the rest“

$X \equiv \frac{m_H}{M}$ $Y \equiv \frac{m_{He}}{M}$ $Z = \sum_{i>He} \frac{m_i}{M} = 1 - X - Y$

Metallicity - designations

- In the literature you will find
  - [Z]
  - [Fe/H]
  - [M/H]
  - [Element 1 / Element 2]
- Relations for the transformation are necessary

$$[\mathrm{Fe/H}] = \log_{10}\left(\frac{N_{\mathrm{Fe}}}{N_{\mathrm{H}}}\right)_{\mathrm{star}} - \log_{10}\left(\frac{N_{\mathrm{Fe}}}{N_{\mathrm{H}}}\right)_{\mathrm{sun}}$$

$$[\mathrm{O/Fe}] = \log_{10}\left(\frac{N_{\mathrm{O}}}{N_{\mathrm{Fe}}}\right)_{\mathrm{star}} - \log_{10}\left(\frac{N_{\mathrm{O}}}{N_{\mathrm{Fe}}}\right)_{\mathrm{sun}}$$

$$= \left[\log_{10}\left(\frac{N_{\mathrm{O}}}{N_{\mathrm{H}}}\right)_{\mathrm{star}} - \log_{10}\left(\frac{N_{\mathrm{O}}}{N_{\mathrm{H}}}\right)_{\mathrm{sun}}\right] - \left[\log_{10}\left(\frac{N_{\mathrm{Fe}}}{N_{\mathrm{H}}}\right)_{\mathrm{star}} - \log_{10}\left(\frac{N_{\mathrm{Fe}}}{N_{\mathrm{H}}}\right)_{\mathrm{sun}}\right]$$

Metallicity – designations

$$[\mathrm{M/H}] = \log_{10}\left(\frac{N_{\mathrm{M}}}{N_{\mathrm{H}}}\right)_{\mathrm{star}} - \log_{10}\left(\frac{N_{\mathrm{M}}}{N_{\mathrm{H}}}\right)_{\mathrm{sun}}$$

$$\log_{10}\left(\frac{Z/X}{Z_{\mathrm{sun}}/X_{\mathrm{sun}}}\right) = [\mathrm{M/H}]$$

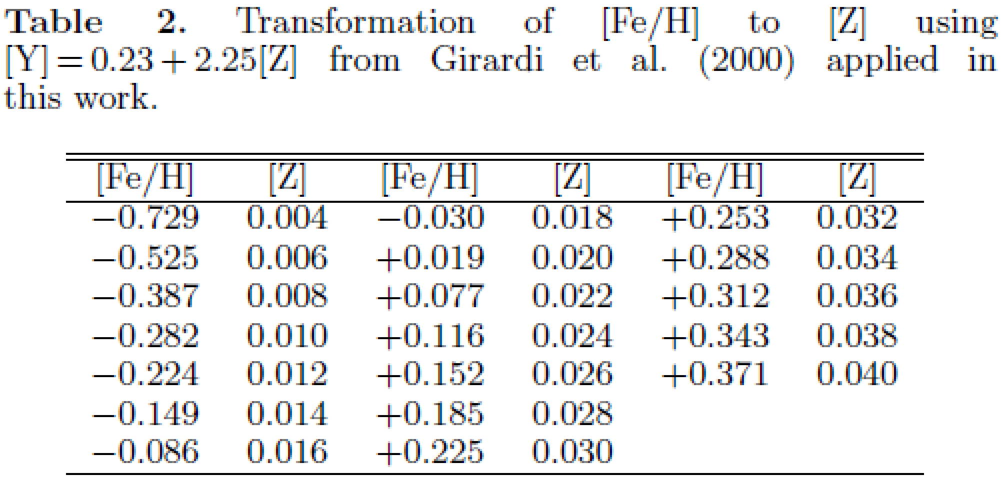


Table 2. Transformation of [Fe/H] to [Z] using $[Y] = 0.23 + 2.25[Z]$ from Girardi et al. (2000) applied in this work.

[Fe/H]	[Z]	[Fe/H]	[Z]	[Fe/H]	[Z]
−0.729	0.004	−0.030	0.018	+0.253	0.032
−0.525	0.006	+0.019	0.020	+0.288	0.034
−0.387	0.008	+0.077	0.022	+0.312	0.036
−0.282	0.010	+0.116	0.024	+0.343	0.038
−0.224	0.012	+0.152	0.026	+0.371	0.040
−0.149	0.014	+0.185	0.028		
−0.086	0.016	+0.225	0.030		

Metallicity - designations

- [dex], e.g. [Fe/H] = -0,5 dex

dex	factor	dex	factor
-2	0,01	0,1	1,26
-1,5	0,03	0,2	1,58
-1	0,10	0,3	2,00
-0,9	0,13	0,4	2,51
-0,8	0,16	0,5	3,16
-0,7	0,20	0,6	3,98
-0,6	0,25	0,7	5,01
-0,5	0,32	0,8	6,31
-0,4	0,40	0,9	7,94
-0,3	0,50	1	10,00
-0,2	0,63	1,5	31,62
-0,1	0,79	2	100,00

The Sun as standard star

- „Our“ standard star for the normalisation of the metallicity is the Sun
- We define:
  - Mass
  - Luminosity = absolute (bolometric) magnitude
  - Temperature = spectral type = color
  - Age
  - Chemical composition
  - Internal structure (rotation, magnetic field, convection, diffusion, pulsation, …)

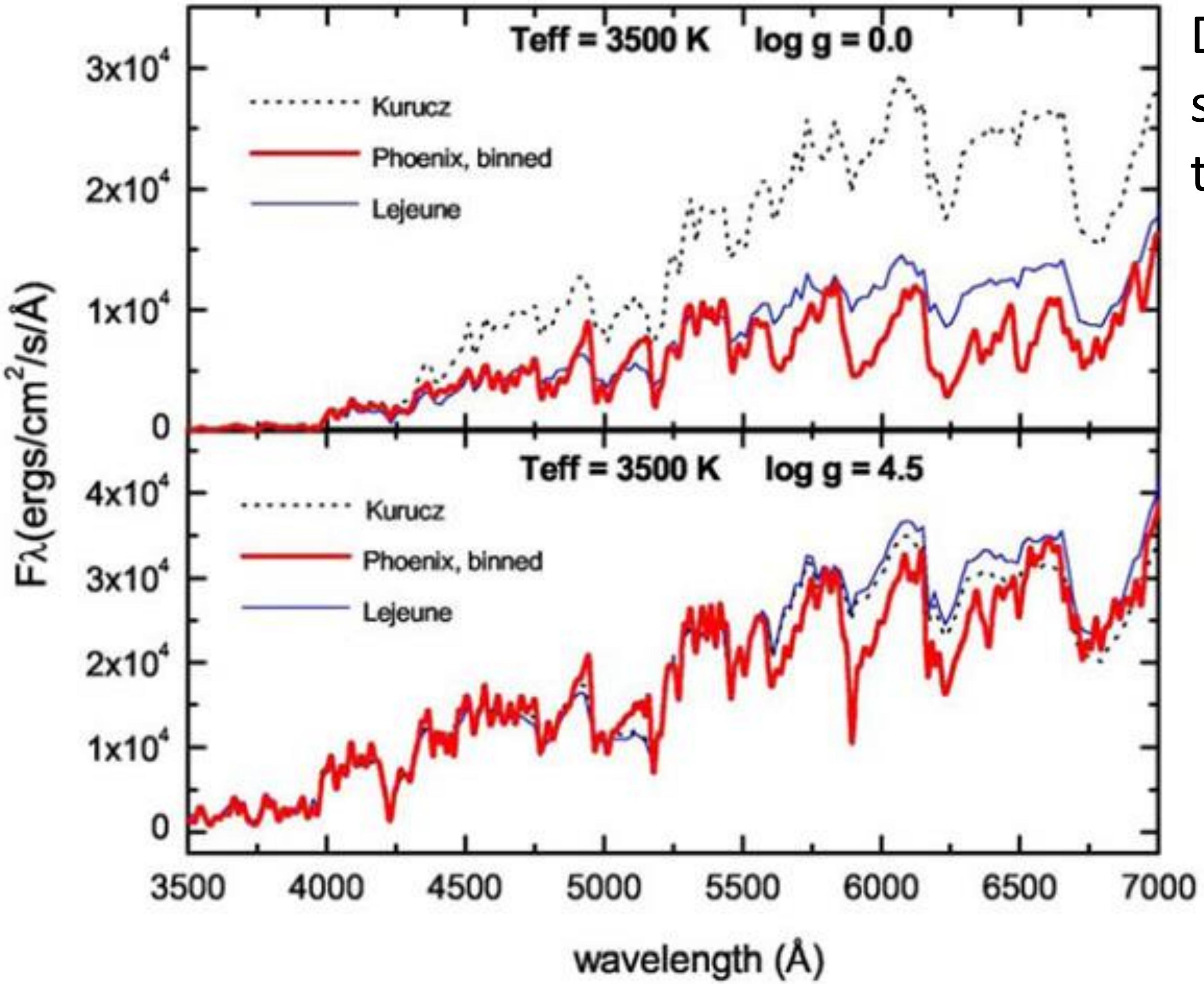
Abundance analysis - Sun

- *Review article:* Asplund et al., 2009, Annual Review of Astronomy & Astrophysics, 47, 481
- Ingredients:
  - Stellar atmosphere
  - Atomic line data
  - High resolution spectra
  - Analysis method
  - Starting parameter
- Gray, 2005, The Observation and Analysis of Stellar Photospheres, Cambridge University Press

Stellar atmospheres

- **ATLAS**, http://atmos.obspm.fr/
- **MARCS**, http://marcs.astro.uu.se/
- **NEMO**, http://www.univie.ac.at/nemo
- **PHOENIX**, http://www.hs.uni-hamburg.de/EN/For/ThA/phoenix/index.html
- **TLUSTY**, http://nova.astro.umd.edu/
- **Stellar Atmospheres Software**, http://www.arm.ac.uk/~csj/software_store/
- **Workshop**: http://astro.physics.muni.cz/events/spec_ws_2017/

Stellar atmospheres



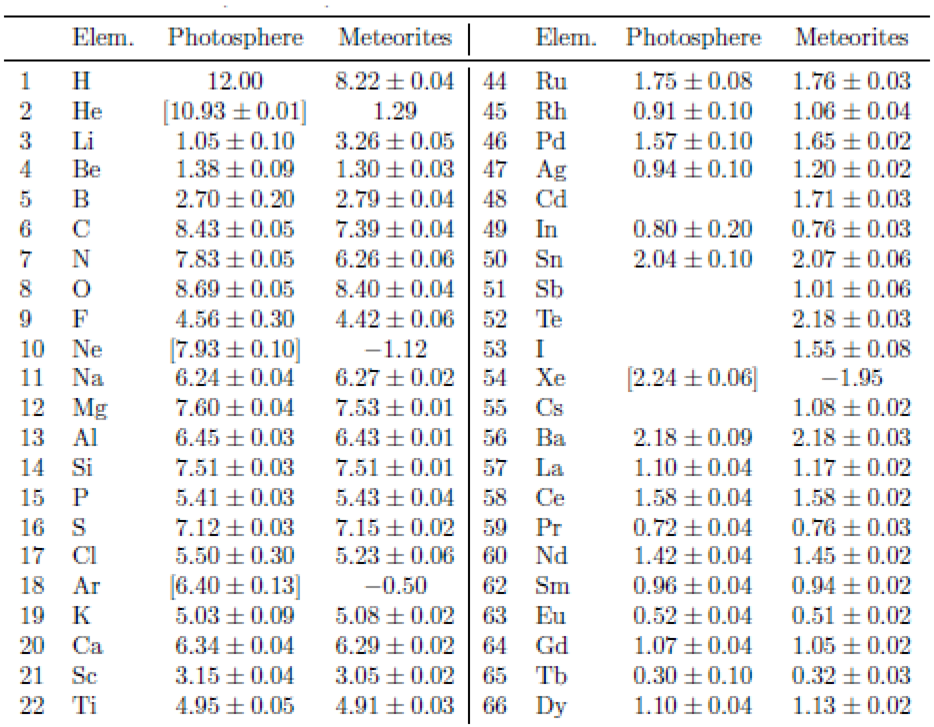
Different synthesized stellar spectra "for the same star"

Abundance - Sun

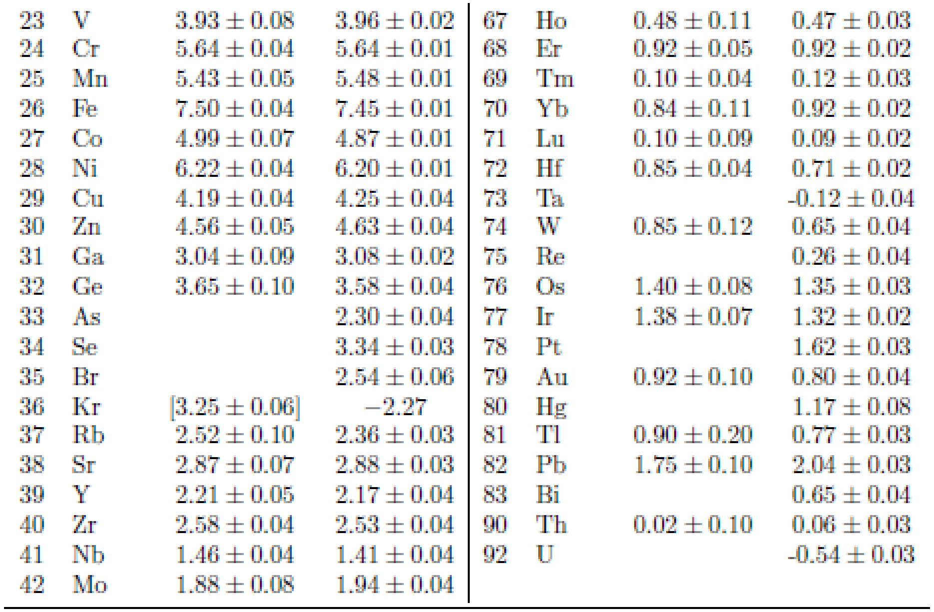
- Problems with
  - Hydrogen
  - Helium
  - Elements with only a few lines
  - Elements with only weak lines
- LTE versus NLTE (Local Thermodynamic Equilibrium)

Abundance - Sun

Asplund et al.

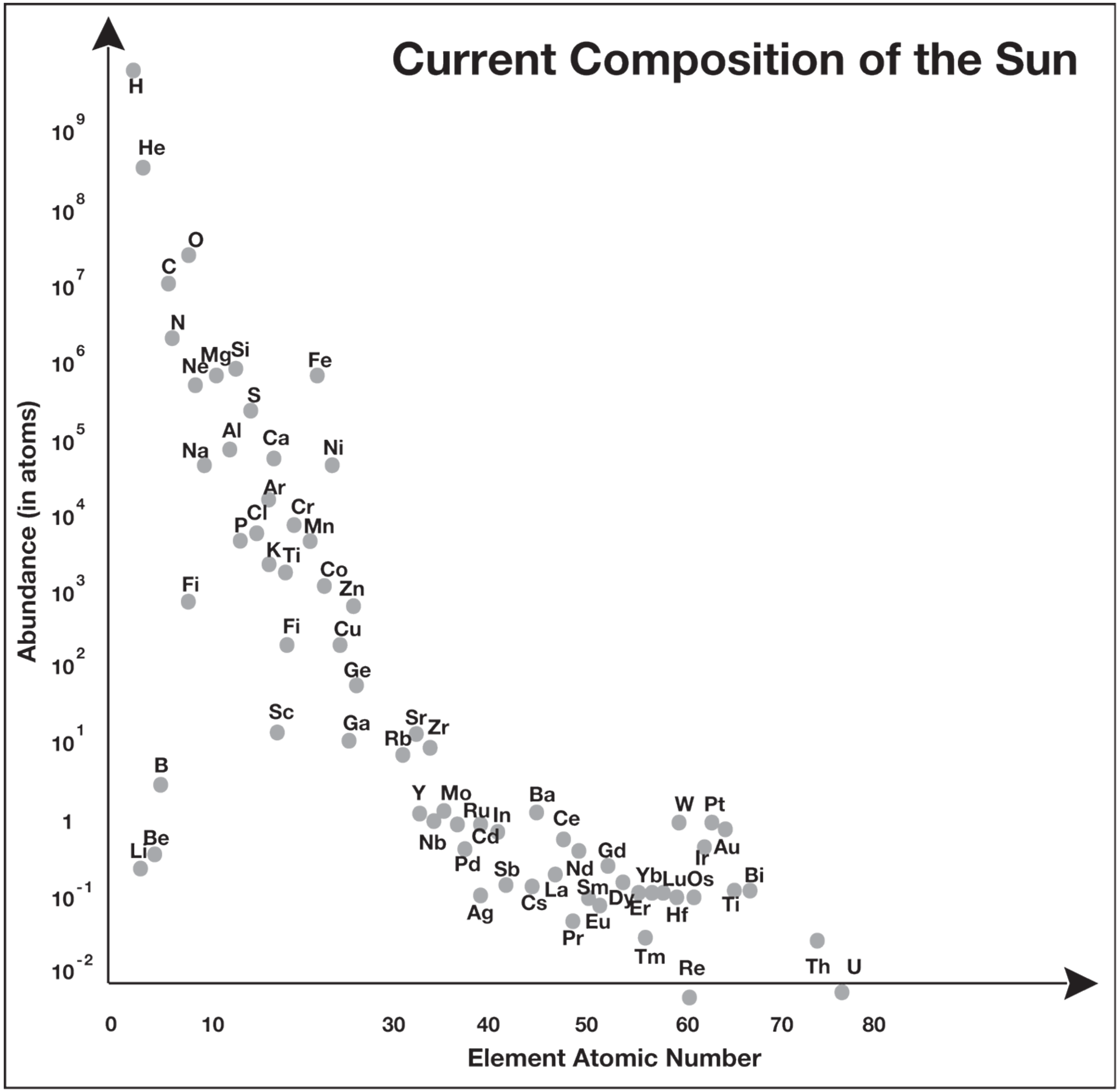


	Elem.	Photosphere	Meteorites		Elem.	Photosphere	Meteorites
1	H	12.00	8.22 ± 0.04	44	Ru	1.75 ± 0.08	1.76 ± 0.03
2	He	[10.93 ± 0.01]	1.29	45	Rh	0.91 ± 0.10	1.06 ± 0.04
3	Li	1.05 ± 0.10	3.26 ± 0.05	46	Pd	1.57 ± 0.10	1.65 ± 0.02
4	Be	1.38 ± 0.09	1.30 ± 0.03	47	Ag	0.94 ± 0.10	1.20 ± 0.02
5	B	2.70 ± 0.20	2.79 ± 0.04	48	Cd		1.71 ± 0.03
6	C	8.43 ± 0.05	7.39 ± 0.04	49	In	0.80 ± 0.20	0.76 ± 0.03
7	N	7.83 ± 0.05	6.26 ± 0.06	50	Sn	2.04 ± 0.10	2.07 ± 0.06
8	O	8.69 ± 0.05	8.40 ± 0.04	51	Sb		1.01 ± 0.06
9	F	4.56 ± 0.30	4.42 ± 0.06	52	Te		2.18 ± 0.03
10	Ne	[7.93 ± 0.10]	−1.12	53	I		1.55 ± 0.08
11	Na	6.24 ± 0.04	6.27 ± 0.02	54	Xe	[2.24 ± 0.06]	−1.95
12	Mg	7.60 ± 0.04	7.53 ± 0.01	55	Cs		1.08 ± 0.02
13	Al	6.45 ± 0.03	6.43 ± 0.01	56	Ba	2.18 ± 0.09	2.18 ± 0.03
14	Si	7.51 ± 0.03	7.51 ± 0.01	57	La	1.10 ± 0.04	1.17 ± 0.02
15	P	5.41 ± 0.03	5.43 ± 0.04	58	Ce	1.58 ± 0.04	1.58 ± 0.02
16	S	7.12 ± 0.03	7.15 ± 0.02	59	Pr	0.72 ± 0.04	0.76 ± 0.03
17	Cl	5.50 ± 0.30	5.23 ± 0.06	60	Nd	1.42 ± 0.04	1.45 ± 0.02
18	Ar	[6.40 ± 0.13]	−0.50	62	Sm	0.96 ± 0.04	0.94 ± 0.02
19	K	5.03 ± 0.09	5.08 ± 0.02	63	Eu	0.52 ± 0.04	0.51 ± 0.02
20	Ca	6.34 ± 0.04	6.29 ± 0.02	64	Gd	1.07 ± 0.04	1.05 ± 0.02
21	Sc	3.15 ± 0.04	3.05 ± 0.02	65	Tb	0.30 ± 0.10	0.32 ± 0.03
22	Ti	4.95 ± 0.05	4.91 ± 0.03	66	Dy	1.10 ± 0.04	1.13 ± 0.02



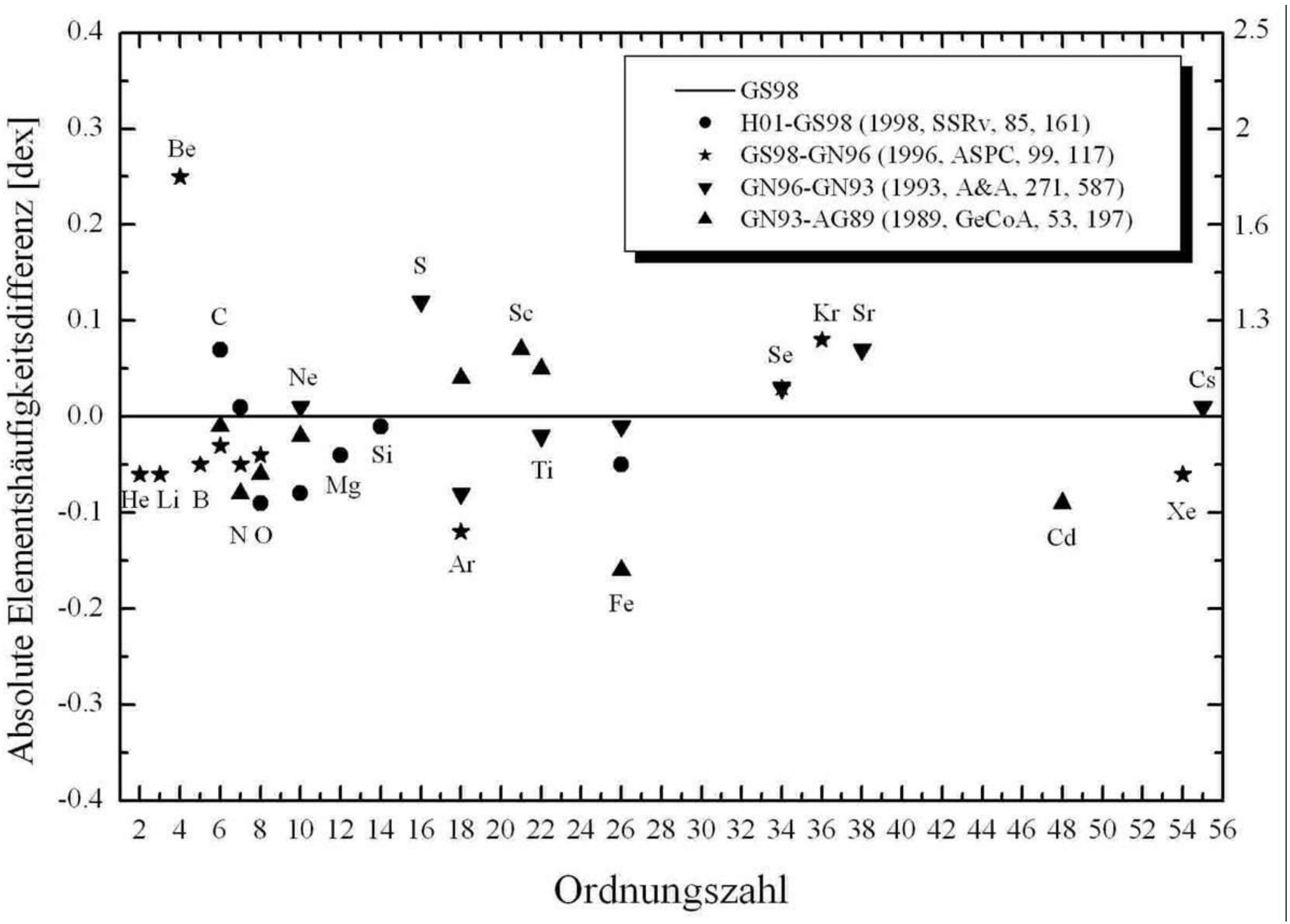
23	V	3.93 ± 0.08	3.96 ± 0.02	67	Ho	0.48 ± 0.11	0.47 ± 0.03
24	Cr	5.64 ± 0.04	5.64 ± 0.01	68	Er	0.92 ± 0.05	0.92 ± 0.02
25	Mn	5.43 ± 0.05	5.48 ± 0.01	69	Tm	0.10 ± 0.04	0.12 ± 0.03
26	Fe	7.50 ± 0.04	7.45 ± 0.01	70	Yb	0.84 ± 0.11	0.92 ± 0.02
27	Co	4.99 ± 0.07	4.87 ± 0.01	71	Lu	0.10 ± 0.09	0.09 ± 0.02
28	Ni	6.22 ± 0.04	6.20 ± 0.01	72	Hf	0.85 ± 0.04	0.71 ± 0.02
29	Cu	4.19 ± 0.04	4.25 ± 0.04	73	Ta		-0.12 ± 0.04
30	Zn	4.56 ± 0.05	4.63 ± 0.04	74	W	0.85 ± 0.12	0.65 ± 0.04
31	Ga	3.04 ± 0.09	3.08 ± 0.02	75	Re		0.26 ± 0.04
32	Ge	3.65 ± 0.10	3.58 ± 0.04	76	Os	1.40 ± 0.08	1.35 ± 0.03
33	As		2.30 ± 0.04	77	Ir	1.38 ± 0.07	1.32 ± 0.02
34	Se		3.34 ± 0.03	78	Pt		1.62 ± 0.03
35	Br		2.54 ± 0.06	79	Au	0.92 ± 0.10	0.80 ± 0.04
36	Kr	[3.25 ± 0.06]	−2.27	80	Hg		1.17 ± 0.08
37	Rb	2.52 ± 0.10	2.36 ± 0.03	81	Tl	0.90 ± 0.20	0.77 ± 0.03
38	Sr	2.87 ± 0.07	2.88 ± 0.03	82	Pb	1.75 ± 0.10	2.04 ± 0.03
39	Y	2.21 ± 0.05	2.17 ± 0.04	83	Bi		0.65 ± 0.04
40	Zr	2.58 ± 0.04	2.53 ± 0.04	90	Th	0.02 ± 0.10	0.06 ± 0.03
41	Nb	1.46 ± 0.04	1.41 ± 0.04	92	U		-0.54 ± 0.03
42	Mo	1.88 ± 0.08	1.94 ± 0.04				

Abundance - Sun



Asplund et al.

Abundance - Sun



PhD thesis – U. Heiter

Abundance - Sun

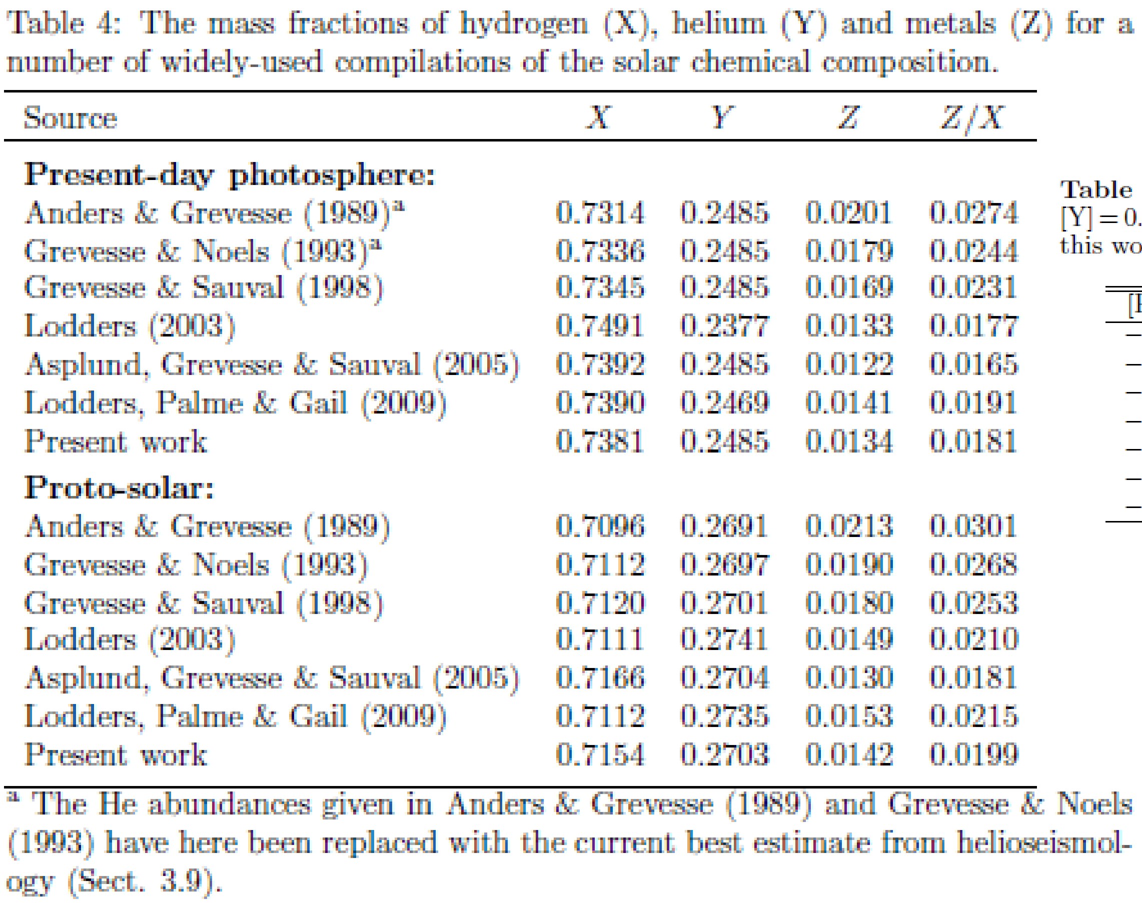
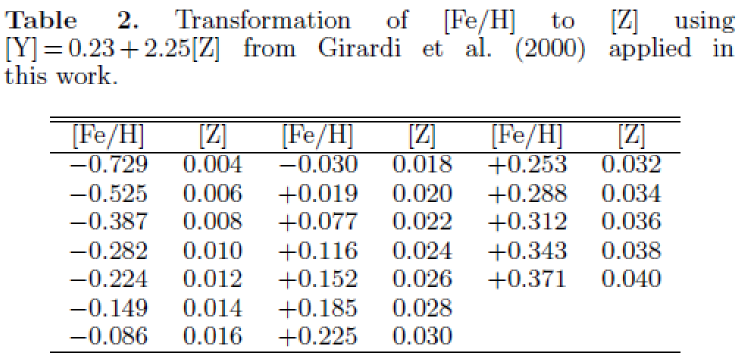


Table 4: The mass fractions of hydrogen (X), helium (Y) and metals (Z) for a number of widely-used compilations of the solar chemical composition.

Source	X	Y	Z	Z/X
Present-day photosphere:				
Anders & Grevesse (1989)[a]	0.7314	0.2485	0.0201	0.0274
Grevesse & Noels (1993)[a]	0.7336	0.2485	0.0179	0.0244
Grevesse & Sauval (1998)	0.7345	0.2485	0.0169	0.0231
Lodders (2003)	0.7491	0.2377	0.0133	0.0177
Asplund, Grevesse & Sauval (2005)	0.7392	0.2485	0.0122	0.0165
Lodders, Palme & Gail (2009)	0.7390	0.2469	0.0141	0.0191
Present work	0.7381	0.2485	0.0134	0.0181
Proto-solar:				
Anders & Grevesse (1989)	0.7096	0.2691	0.0213	0.0301
Grevesse & Noels (1993)	0.7112	0.2697	0.0190	0.0268
Grevesse & Sauval (1998)	0.7120	0.2701	0.0180	0.0253
Lodders (2003)	0.7111	0.2741	0.0149	0.0210
Asplund, Grevesse & Sauval (2005)	0.7166	0.2704	0.0130	0.0181
Lodders, Palme & Gail (2009)	0.7112	0.2735	0.0153	0.0215
Present work	0.7154	0.2703	0.0142	0.0199

[a] The He abundances given in Anders & Grevesse (1989) and Grevesse & Noels (1993) have here been replaced with the current best estimate from helioseismology (Sect. 3.9).



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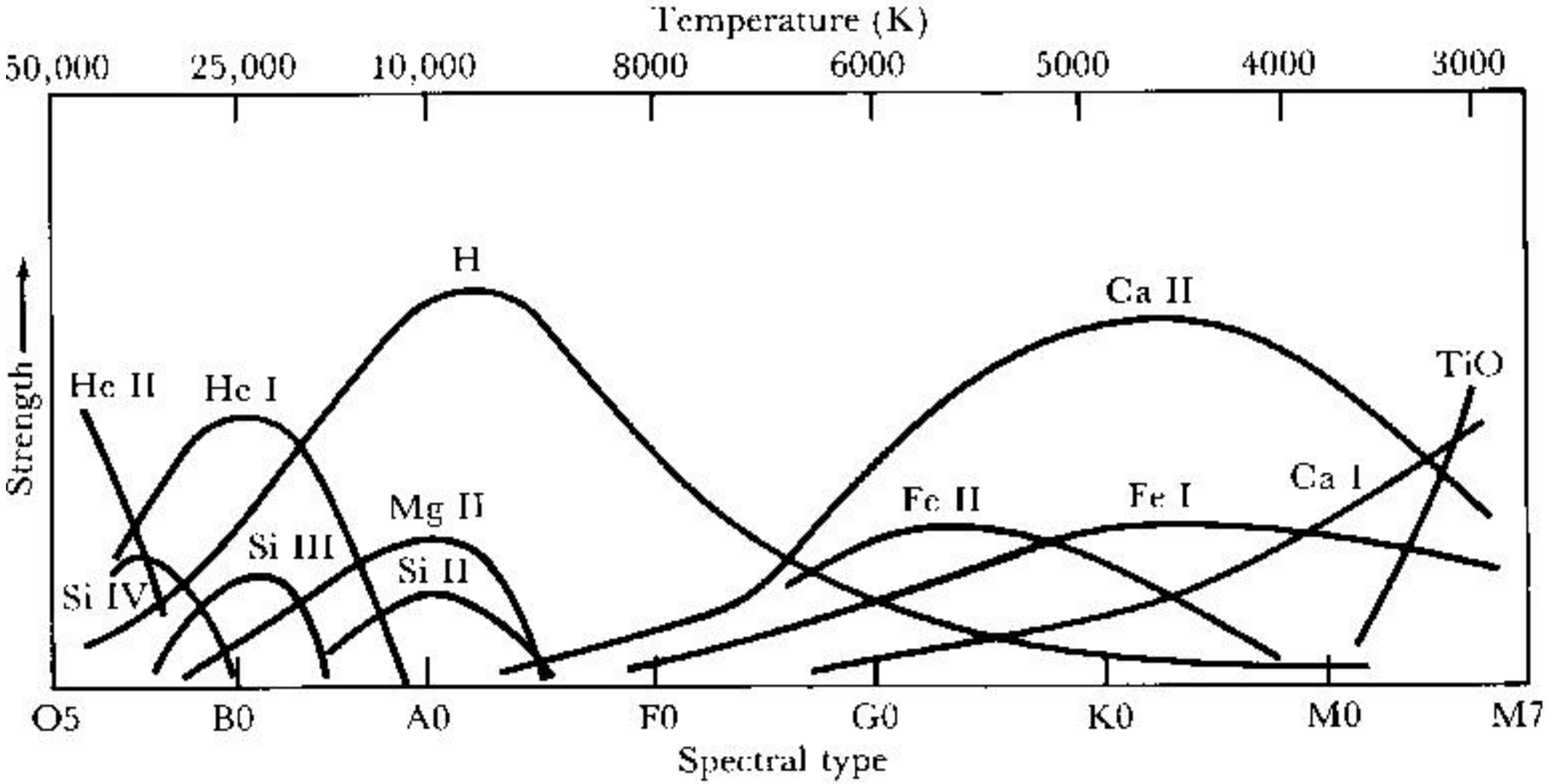
−0.149	0.014	+0.185	0.028		
−0.086	0.016	+0.225	0.030		

Asplund et al.

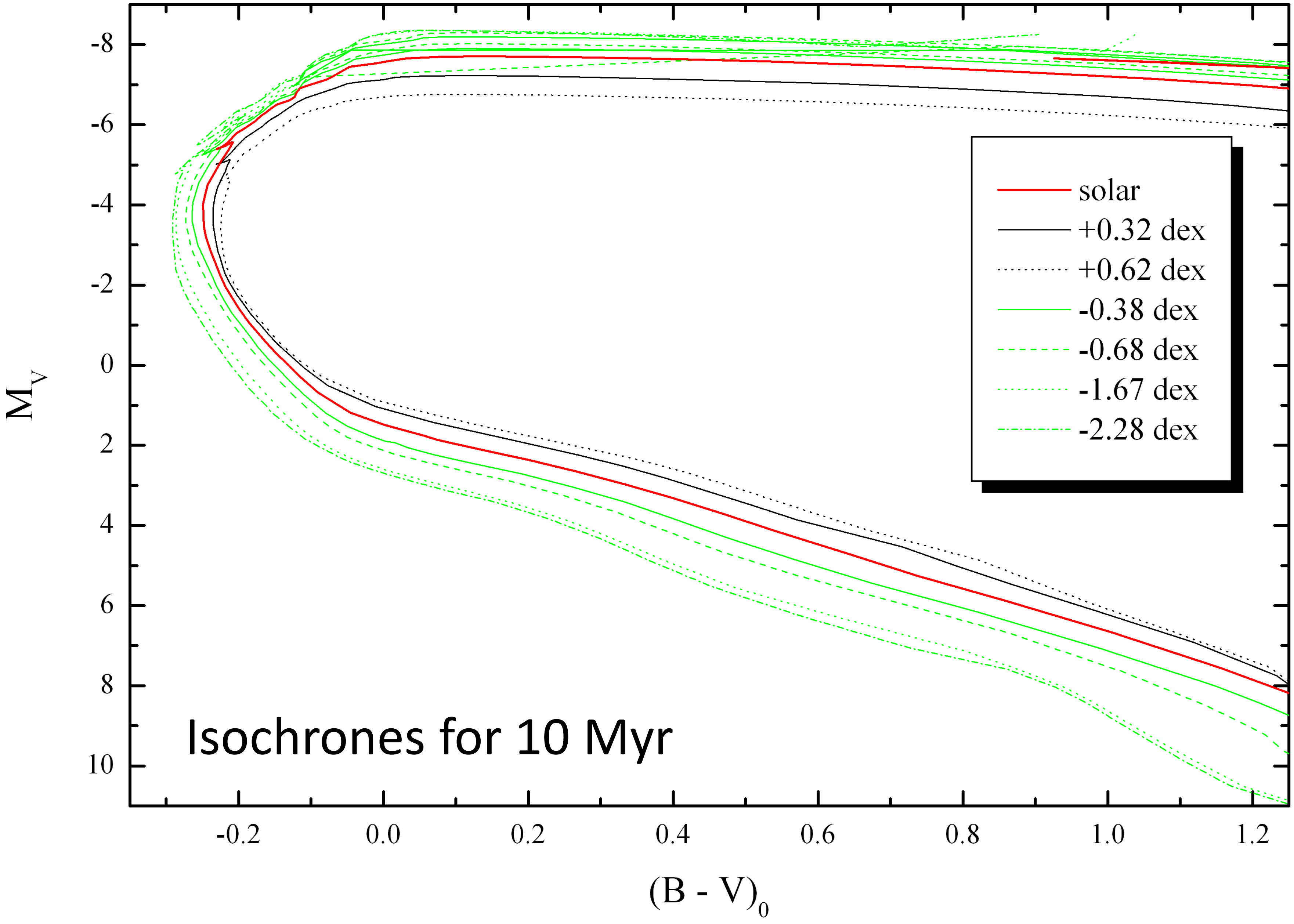
Determination of the metallicity

- The determination of the metallicity can be done in three ways:
    1. Spectroscopic abundance analysis
    2. Fitting of isochrones
    3. Photometric calibrations
- ESO- Gaia survey:
  https://www.gaia-eso.eu/

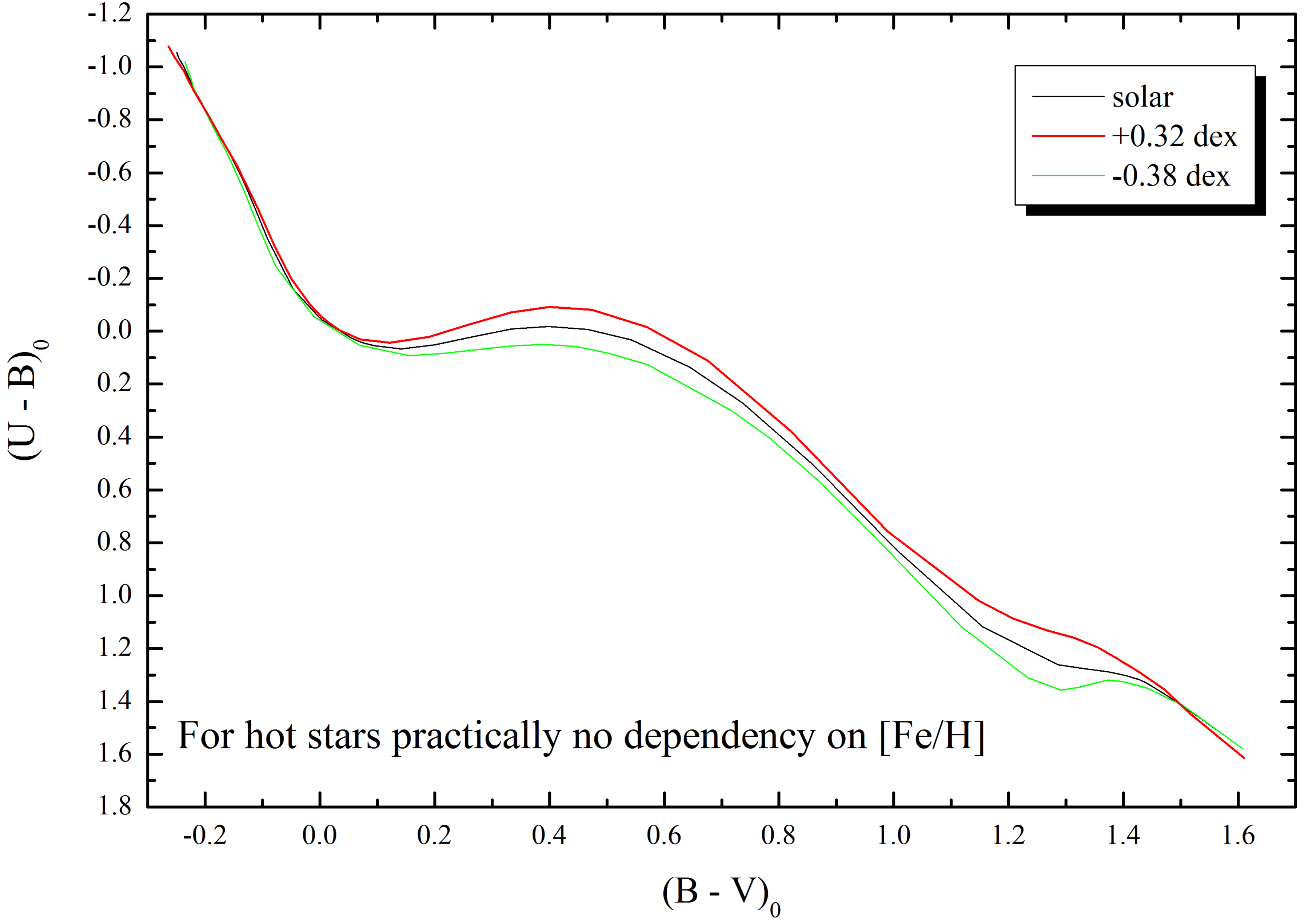
„Metalls“ in stars



Metallicity => different opacity

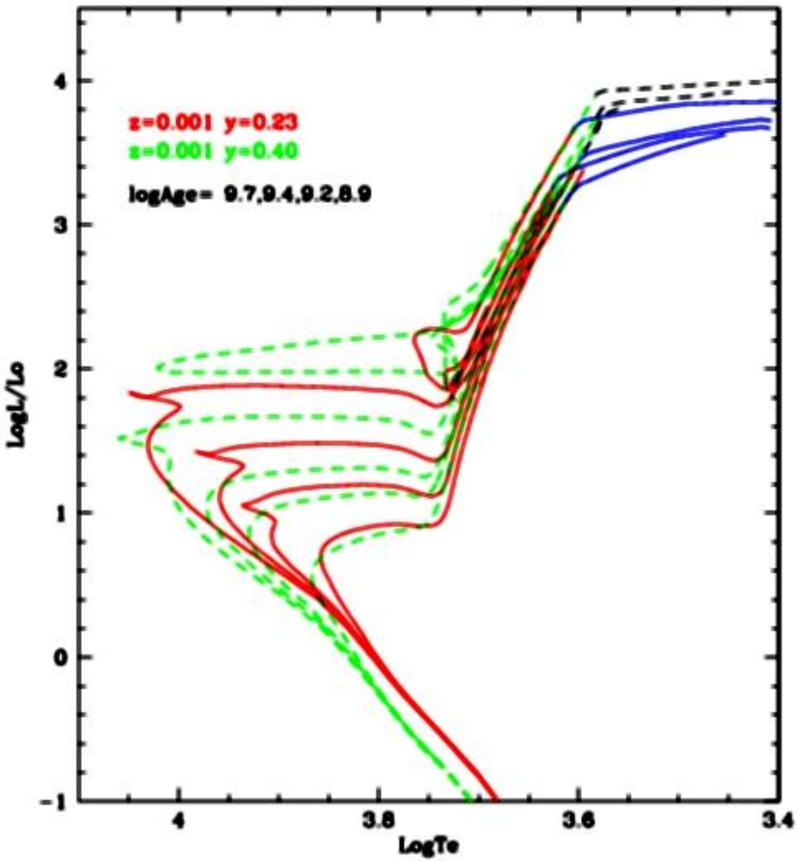


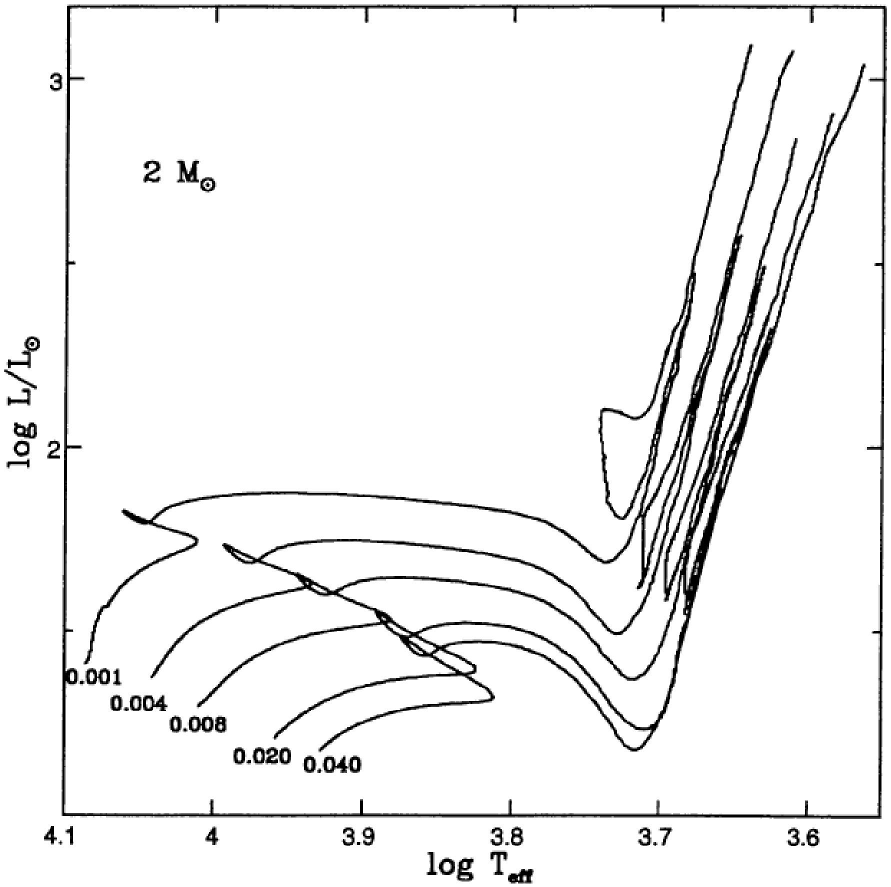
Isochrones for 10 Myr



For hot stars practically no dependency on [Fe/H]

Metallicity - isochrones





Different He abundances – [Z] constant

Schaller et al., 1993, A&AS, 101, 415