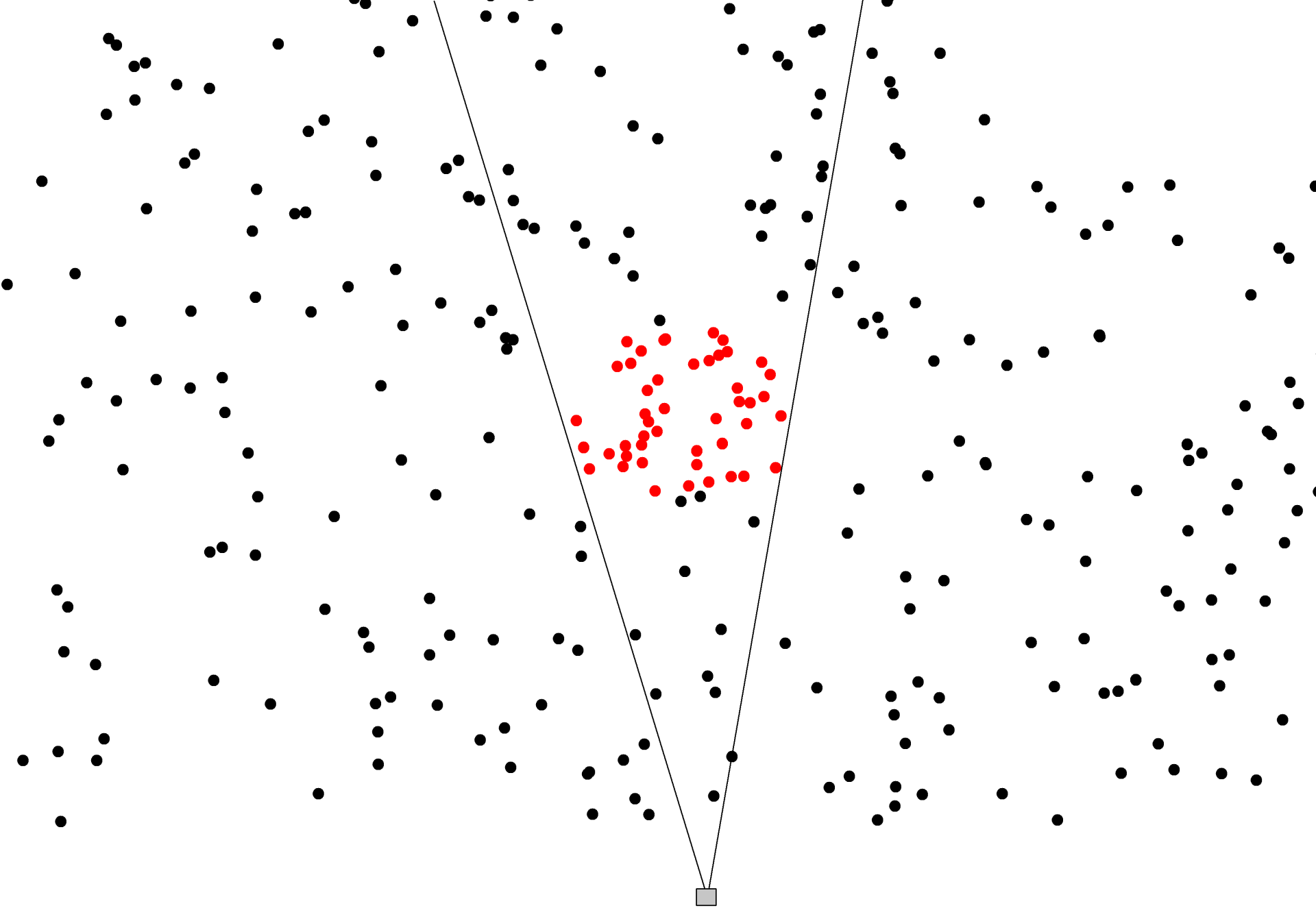


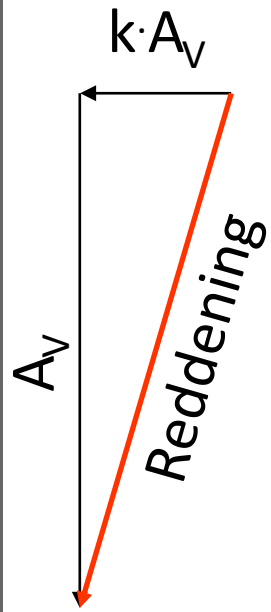
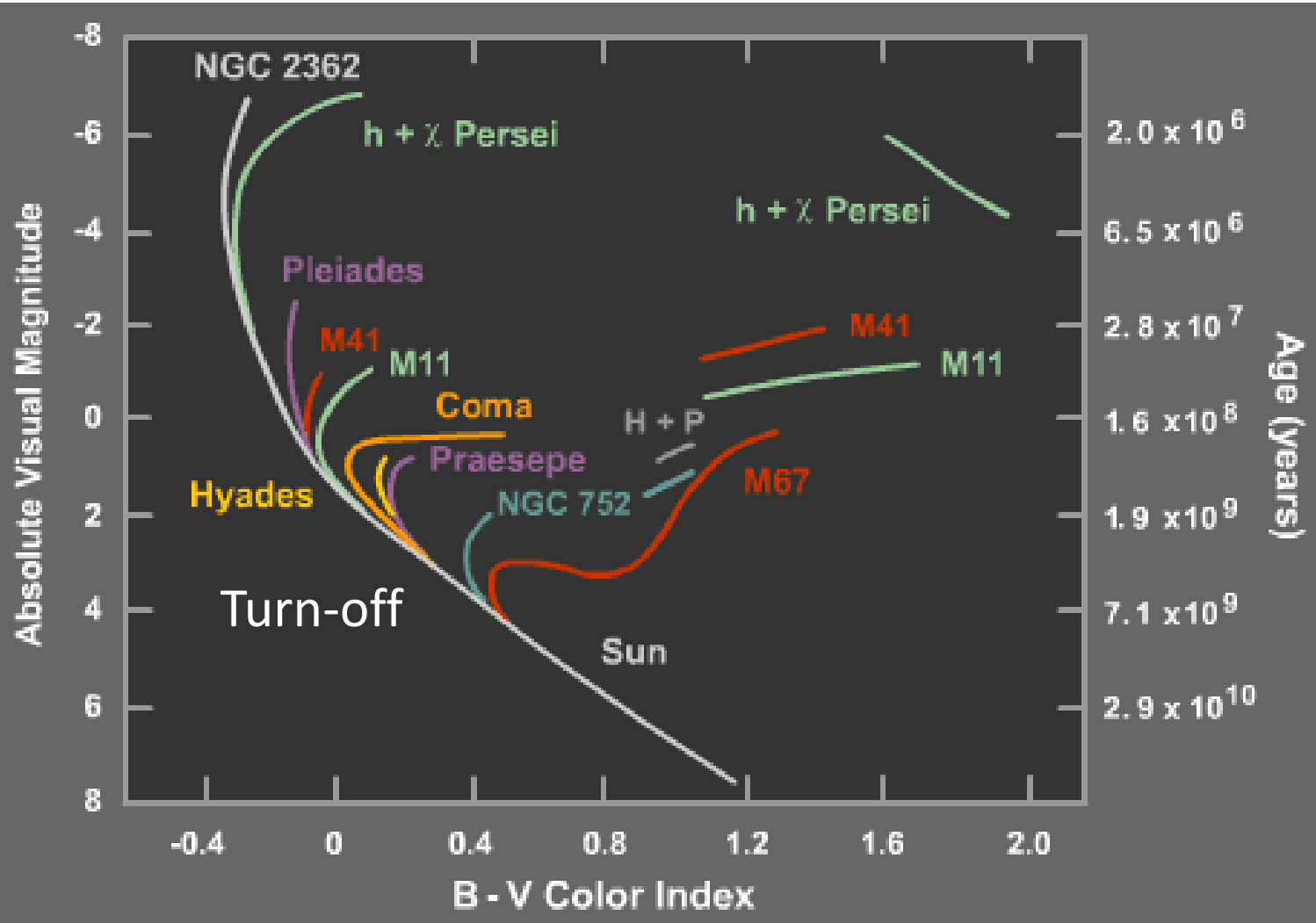
# The cluster parameters

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

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



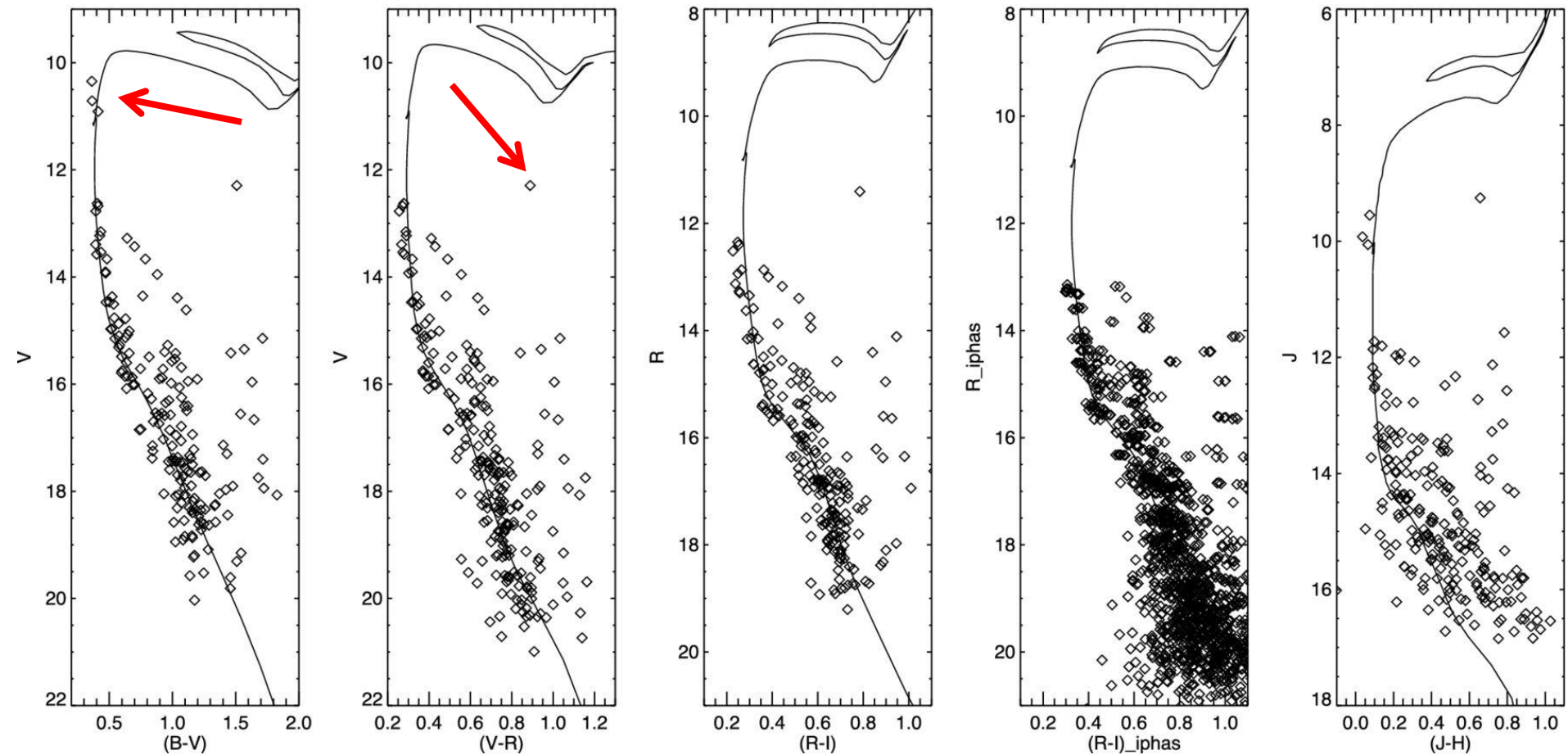
Distance:  $V_0 - M_V$

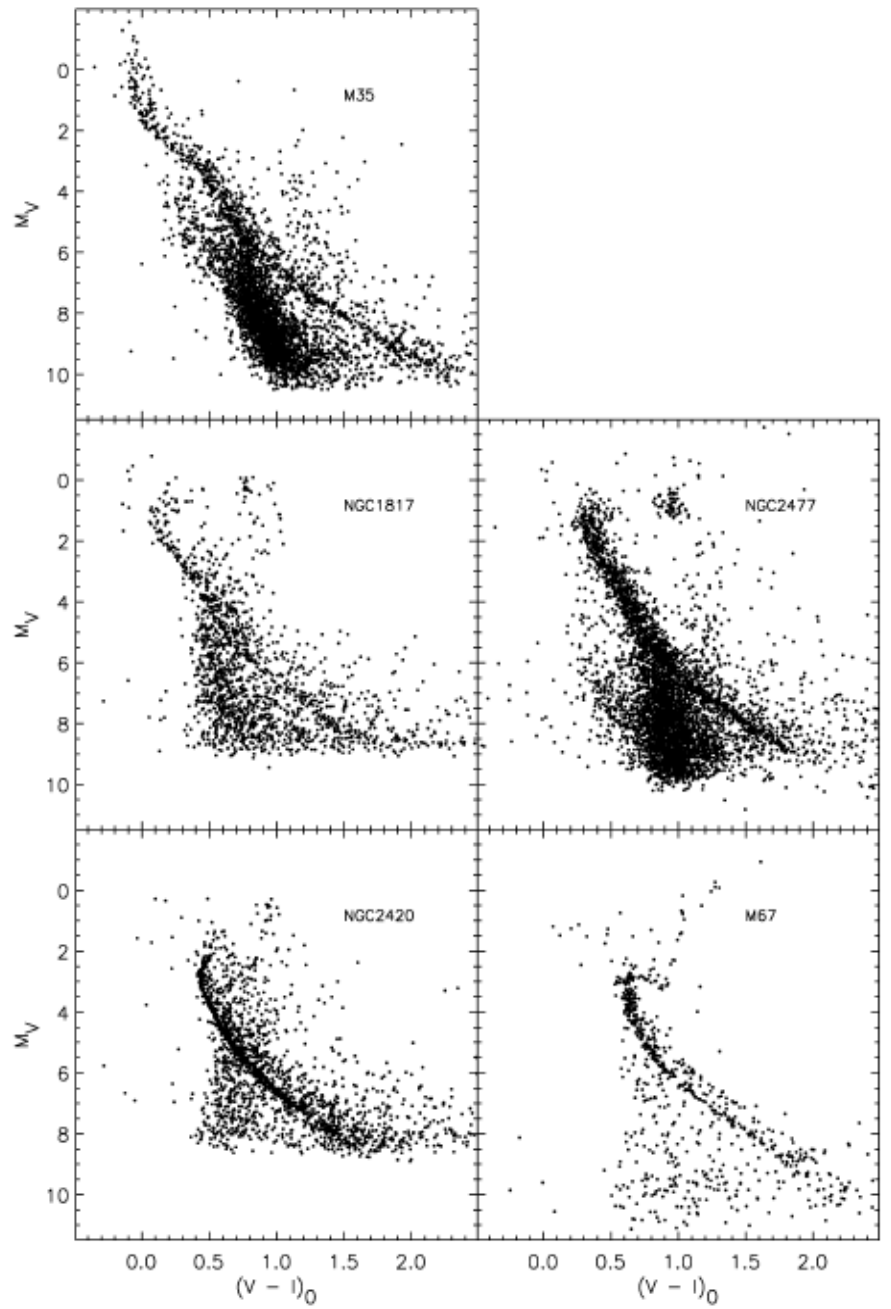
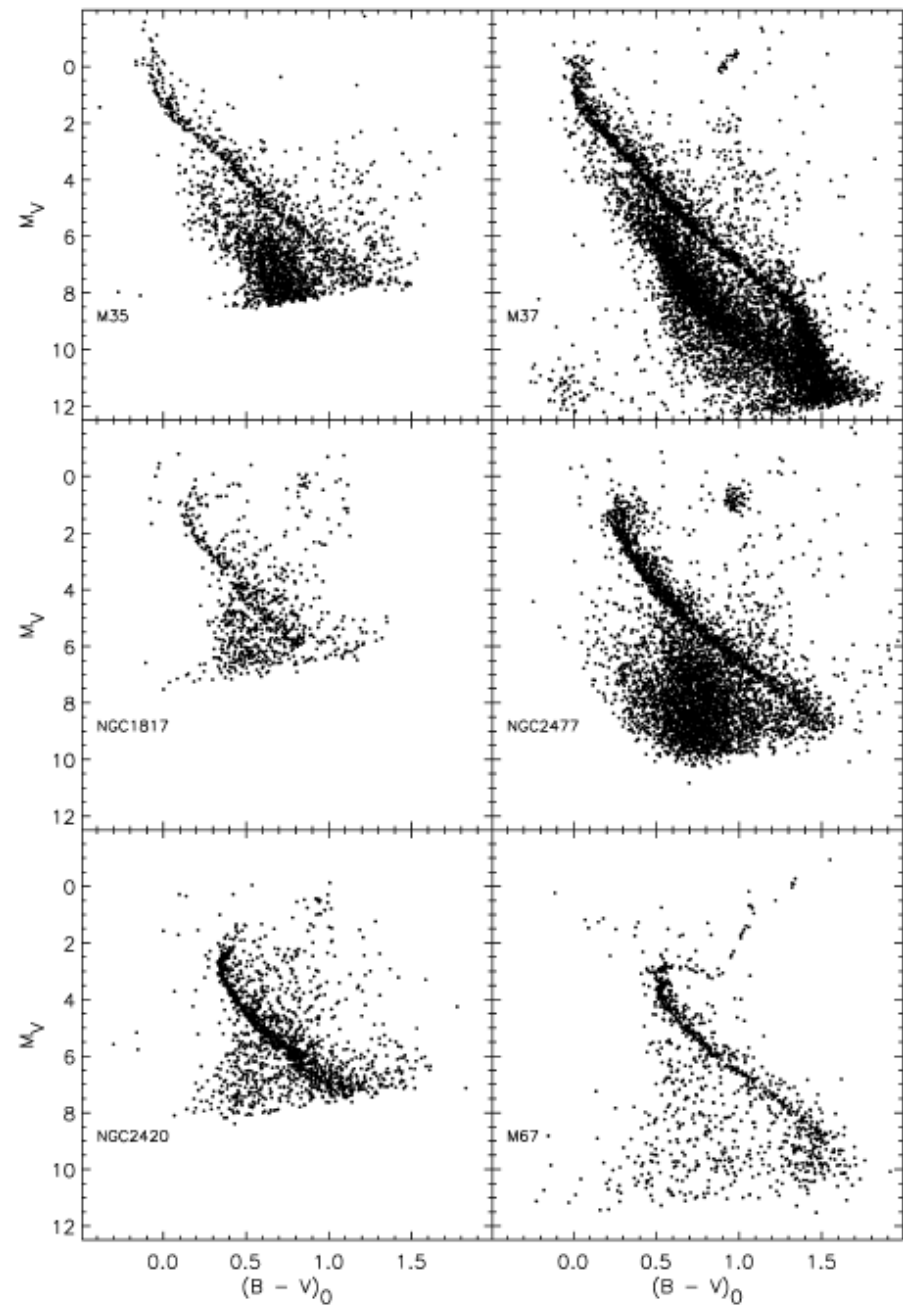


HR Diagrams for Various Open Clusters

# Color – Magnitude - Diagram

Different CMDs for **one open cluster**





# 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,  $\beta$
  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- $T_{\text{eff}}$  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

$$\theta = b_0 + b_1 C + b_2 C^2 + b_3 [\text{Fe}/\text{H}] + b_4 [\text{Fe}/\text{H}]^2 + b_5 [\text{Fe}/\text{H}] C \quad (1)$$

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

**Be aware of the extinction!**

**Table 1.** Coefficients  $b_0, \dots, b_5$  of the colour- $T_{\text{eff}}$  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)	$\sigma_{T_{\text{eff}}}$ (K)	N	$b_0$	$b_1$	$b_2$	$b_3$	$b_4$	$b_5$
Dwarf stars									
$(\text{BP} - \text{RP})_0$	[0.38–1.51]	61	445	0.4988	0.4925	-0.0287	0.0193	-0.0017	-0.0384
$(\text{BP} - \text{G})_0$	[0.17–0.72]	77	429	0.4800	1.3160	-0.4957	-0.0086	-0.0020	-0.0444
$(\text{G} - \text{RP})_0$	[0.17–0.79]	68	438	0.5623	0.5422	0.3069	0.0367	-0.0019	-0.0829
$(\text{BP} - \text{K})_0$	[0.64–3.24]	47	454	0.5375	0.1967	-0.0002	0.0268	0.0006	-0.0150
$(\text{RP} - \text{K})_0$	[0.34–1.75]	54	444	0.5451	0.3739	-0.0120	0.0289	0.0026	-0.0185
$(\text{G} - \text{K})_0$	[0.52–2.53]	51	446	0.5576	0.2191	0.0095	0.0334	0.0014	-0.0182
Giant stars									
$(\text{BP} - \text{RP})_0$	[0.34–1.80]	83	229	0.5403	0.4318	-0.0085	-0.0217	-0.0032	0.0040
$(\text{BP} - \text{G})_0$	[0.13–1.00]	106	218	0.5156	1.3488	-0.6976	-0.0105	-0.0020	-0.0181
$(\text{G} - \text{RP})_0$	[0.21–0.84]	86	190	0.5056	0.8788	0.0107	0.0216	0.0023	-0.0030
$(\text{BP} - \text{K})_0$	[0.69–3.98]	52	233	0.5670	0.1829	-0.0004	0.0030	-0.0009	-0.0034
$(\text{RP} - \text{K})_0$	[0.35–2.26]	64	235	0.5764	0.3601	-0.0237	0.0350	0.0000	-0.0245
$(\text{G} - \text{K})_0$	[0.56–3.06]	66	230	0.5444	0.2747	-0.0118	0.0387	0.0024	-0.0117

# Photometric calibrations

## Empirical photometric calibration of the *Gaia* red clump: Colours, effective temperature, and absolute magnitude★

L. Ruiz-Dern, C. Babusiaux, F. Arenou, C. Turon, and R. Lallement

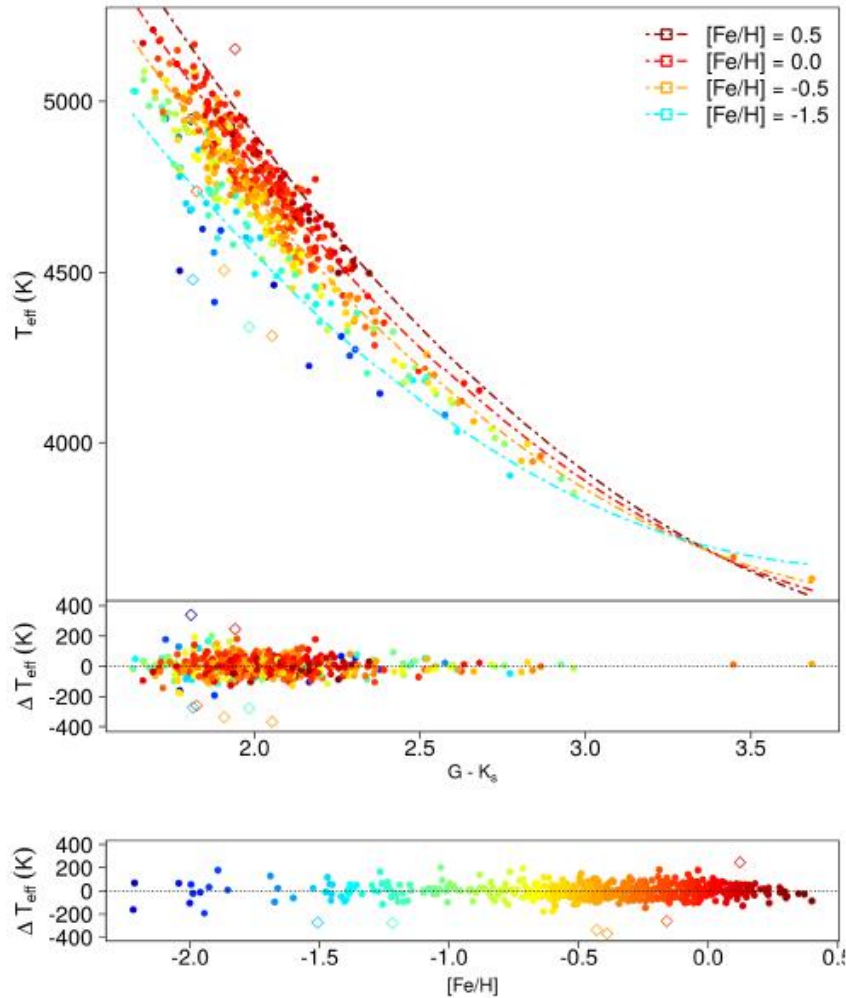
**Table 1.** Coefficients and range of applicability of colour versus  $G - K_s$  relations,  $Y = a_0 + a_1 (G - K_s) + a_2 (G - K_s)^2 + a_3 [\text{Fe}/\text{H}] + a_4 [\text{Fe}/\text{H}]^2 + a_5 (G - K_s) [\text{Fe}/\text{H}]$ .

Colour	$G - K_s$ range	[Fe/H] range	$a_0$	$a_1$	$a_2$	$a_3$	$a_4$	$a_5$	RMS	%outliers	$N$
$B - G$	[1.6, 2.4]	[-1.4, 0.4]	$0.583 \pm 0.180$	$-0.046 \pm 0.187$	$0.215 \pm 0.049$	$0.144 \pm 0.006$	–	–	0.02	17.9	230
$B - V$	[1.6, 2.4]	[-1.4, 0.4]	$-0.094 \pm 0.017$	$0.552 \pm 0.009$	–	$0.129 \pm 0.005$	–	–	0.02	10.4	251
$B - J$	[1.6, 2.4]	[-1.5, 0.4]	$-0.117 \pm 0.041$	$1.432 \pm 0.021$	–	$0.153 \pm 0.011$	–	–	0.03	12.9	176
$B - K_s$	[1.6, 2.4]	[-1.5, 0.4]	$-0.161 \pm 0.038$	$1.757 \pm 0.020$	–	$0.141 \pm 0.011$	–	–	0.02	9.3	254
$G - H_p$	[1.6, 2.4]	[-1.5, 0.4]	$0.029 \pm 0.009$	$-0.270 \pm 0.005$	–	$-0.023 \pm 0.003$	–	–	0.01	5.3	270
$G - V$	[1.6, 2.4]	[-1.5, 0.4]	$-0.286 \pm 0.104$	$0.191 \pm 0.107$	$-0.110 \pm 0.028$	$-0.017 \pm 0.003$	–	–	0.01	3.9	274
$G - B_T$	[1.6, 2.4]	[-1.4, 0.4]	$-0.375 \pm 0.257$	$-0.194 \pm 0.267$	$-0.218 \pm 0.069$	$-0.201 \pm 0.009$	–	–	0.03	12.7	241
$G - V_T$	[1.6, 2.4]	[-1.5, 0.4]	$-0.261 \pm 0.115$	$0.122 \pm 0.119$	$-0.109 \pm 0.031$	$-0.034 \pm 0.006$	$-0.016 \pm 0.007$	–	0.01	3.5	272
$G - J$	[1.6, 3.6]	[-4.8, 1.0]	$0.256 \pm 0.021$	$0.510 \pm 0.019$	$0.027 \pm 0.004$	$0.016 \pm 0.002$	$0.005 \pm 0.001$	–	0.02	0.2	2178
$V - J$	[1.6, 2.4]	[-1.5, 0.4]	$-0.028 \pm 0.026$	$0.880 \pm 0.013$	–	–	–	–	0.03	2.4	200
$V - K_s$	[1.6, 2.4]	[-1.5, 0.4]	$0.326 \pm 0.231$	$0.786 \pm 0.237$	$0.112 \pm 0.061$	$0.019 \pm 0.008$	–	–	0.01	2.1	279
$J - K_s$	[1.6, 3.6]	[-4.8, 1.0]	$-0.227 \pm 0.024$	$0.466 \pm 0.021$	$-0.023 \pm 0.005$	$-0.016 \pm 0.002$	$-0.005 \pm 0.001$	–	0.02	0.1	2180
$B_T - V_T$	[1.6, 2.4]	[-1.5, 0.4]	$-0.247 \pm 0.023$	$0.713 \pm 0.012$	–	$0.175 \pm 0.007$	–	–	0.03	8.0	254
$g - r$	[1.6, 3.1]	[-2.4, 0.4]	$-0.263 \pm 0.010$	$0.521 \pm 0.005$	–	$0.079 \pm 0.006$	$0.015 \pm 0.004$	–	0.03	8.8	465
$g - i$	[1.6, 3.1]	[-1.4, 0.4]	$0.280 \pm 0.084$	$0.057 \pm 0.079$	$0.163 \pm 0.018$	$0.063 \pm 0.005$	–	–	0.03	13.5	282
$r - i$	[1.6, 3.1]	[-1.4, 0.4]	$0.236 \pm 0.050$	$-0.171 \pm 0.047$	$0.095 \pm 0.011$	–	–	–	0.02	2.2	364
$G - W1$	[1.6, 3.2]	[-2.4, 0.5]	$0.099 \pm 0.043$	$0.948 \pm 0.040$	$0.019 \pm 0.009$	$0.006 \pm 0.004$	$0.007 \pm 0.003$	–	0.03	0.4	1666
$W1 - W2$	[1.6, 3.2]	[-2.4, 0.5]	$0.065 \pm 0.039$	$-0.051 \pm 0.038$	$-0.014 \pm 0.009$	$0.049 \pm 0.015$	$0.007 \pm 0.002$	$-0.028 \pm 0.008$	0.02	0.1	1657
$W2 - W3$	[1.6, 3.2]	[-2.4, 0.5]	$-0.228 \pm 0.032$	$0.240 \pm 0.029$	$-0.038 \pm 0.006$	–	–	–	0.03	0.1	1671
$H - W2$	[1.6, 3.2]	[-2.4, 0.5]	$0.025 \pm 0.008$	$0.032 \pm 0.004$	–	$0.009 \pm 0.004$	$0.016 \pm 0.003$	–	0.03	0.4	1137

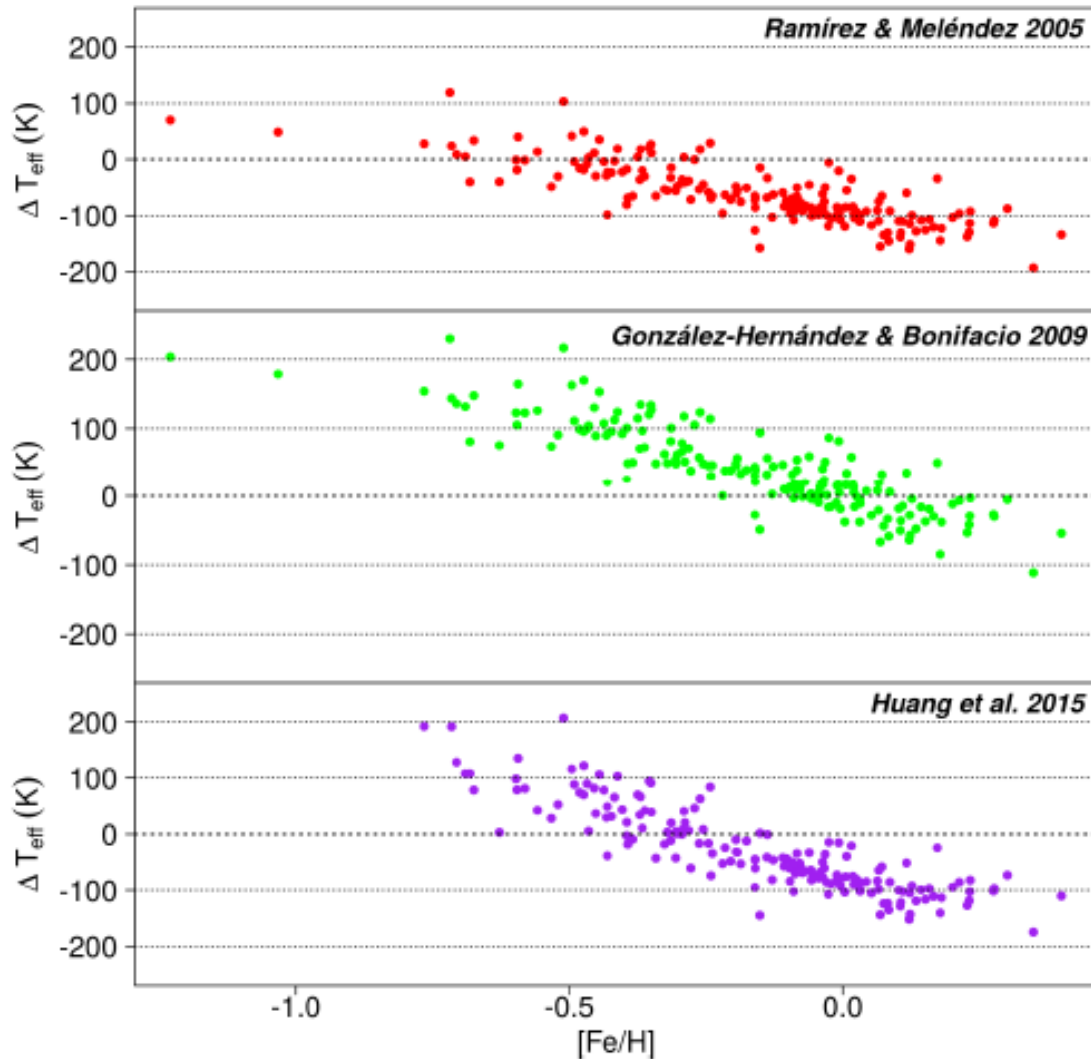


# Photometric calibrations

Final calibration



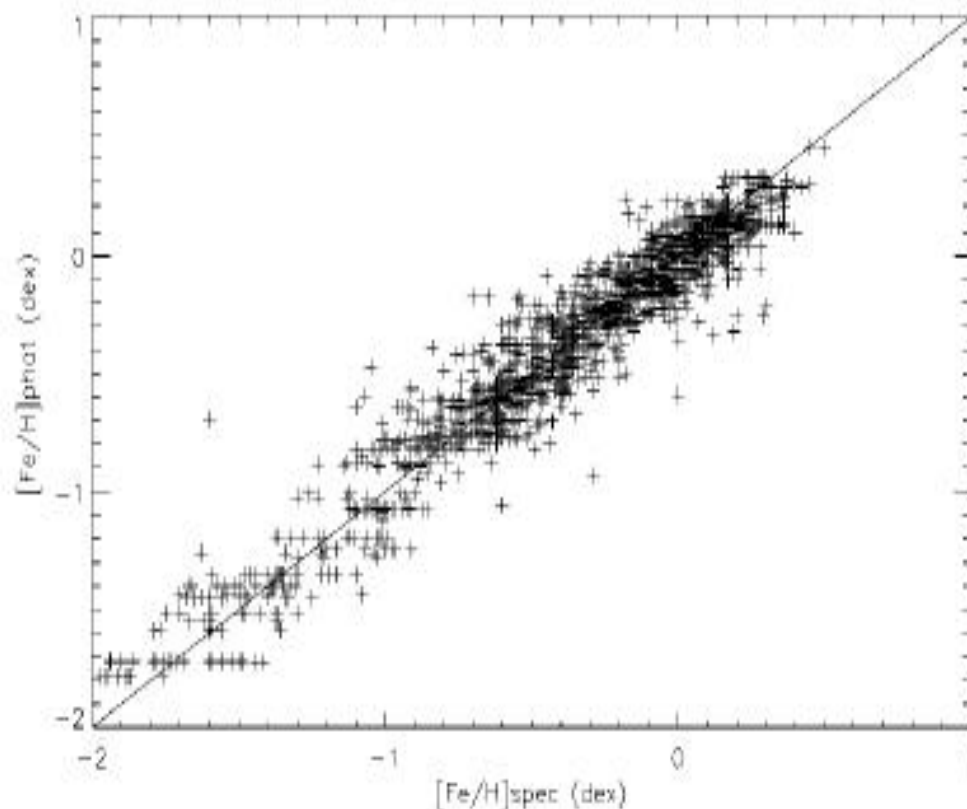
# Photometric calibrations



Comparison  
with other  
calibrations

# Photometric calibrations

Error:  $\pm 0.10$  dex



$$[\text{Fe}/\text{H}]_{\text{phot}} = -10.424602 + 31.059003(b-y)$$

$$+ 42.184476m_1 + 15.351995c_1$$

$$- 11.239435(b-y)^2 - 29.218135m_1^2$$

$$- 11.457610c_1^2 - 138.92376(b-y)m_1$$

$$- 52.033290(b-y)c_1 + 11.259341m_1c_1$$

$$- 46.087731(b-y)^3 + 26.065099m_1^3$$

$$- 1.1017830c_1^3 + 138.48588(b-y)^2m_1$$

$$+ 39.012001(b-y)^2c_1$$

$$+ 23.225562m_1^2(b-y) - 69.146876m_1^2c_1$$

$$+ 20.456093c_1^2(b-y) - 3.3302478c_1^2m_1$$

$$+ 70.168761(b-y)m_1c_1$$

# How to derive cluster parameters?

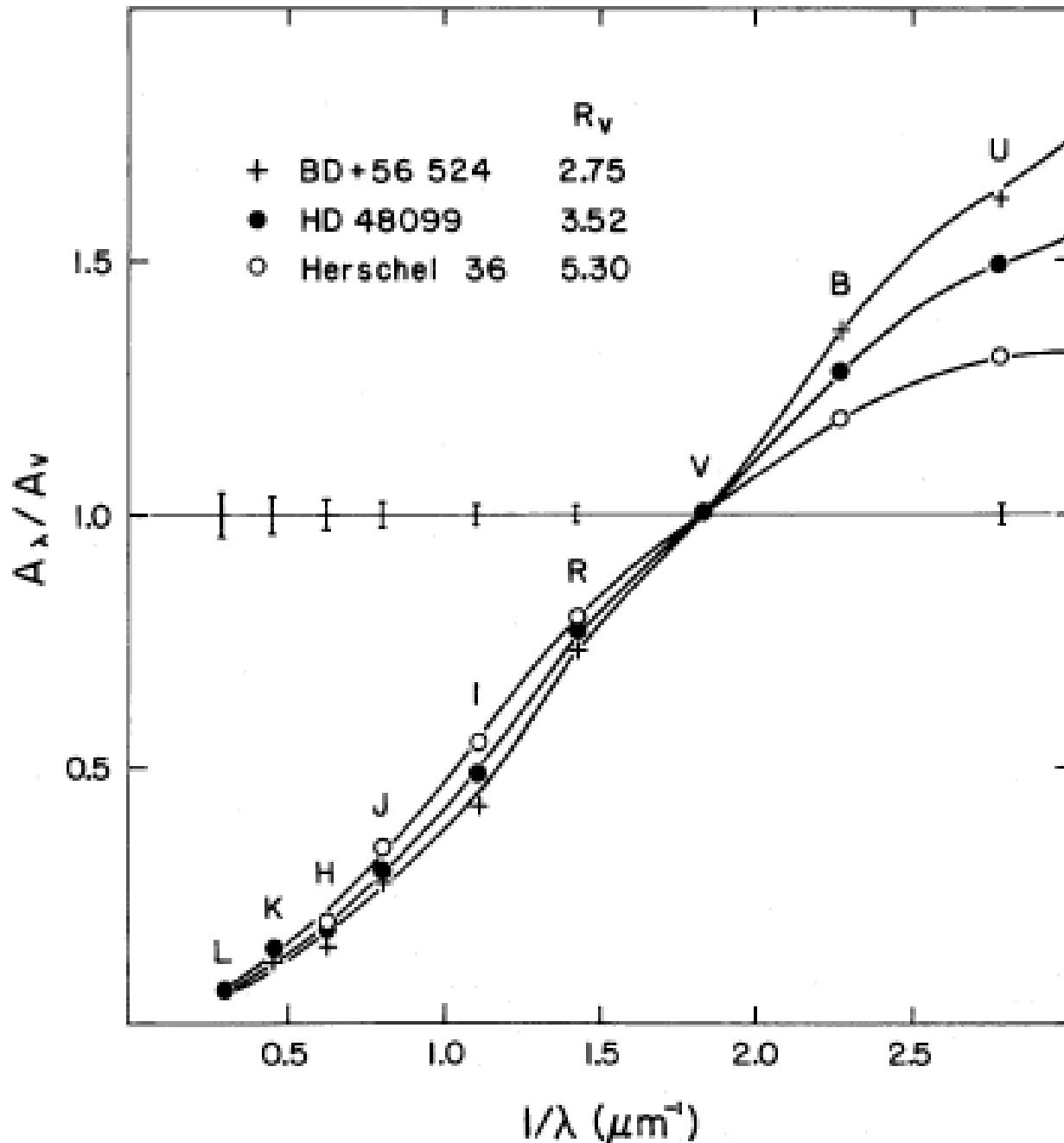
- Use as much as possible available indices
- Check the literature for published values as least as a starting point
- First try it with a “standard set” of data
- Automatic procedures available, but be careful

# Absorption = Extinction = Reddening

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



Important parameter:

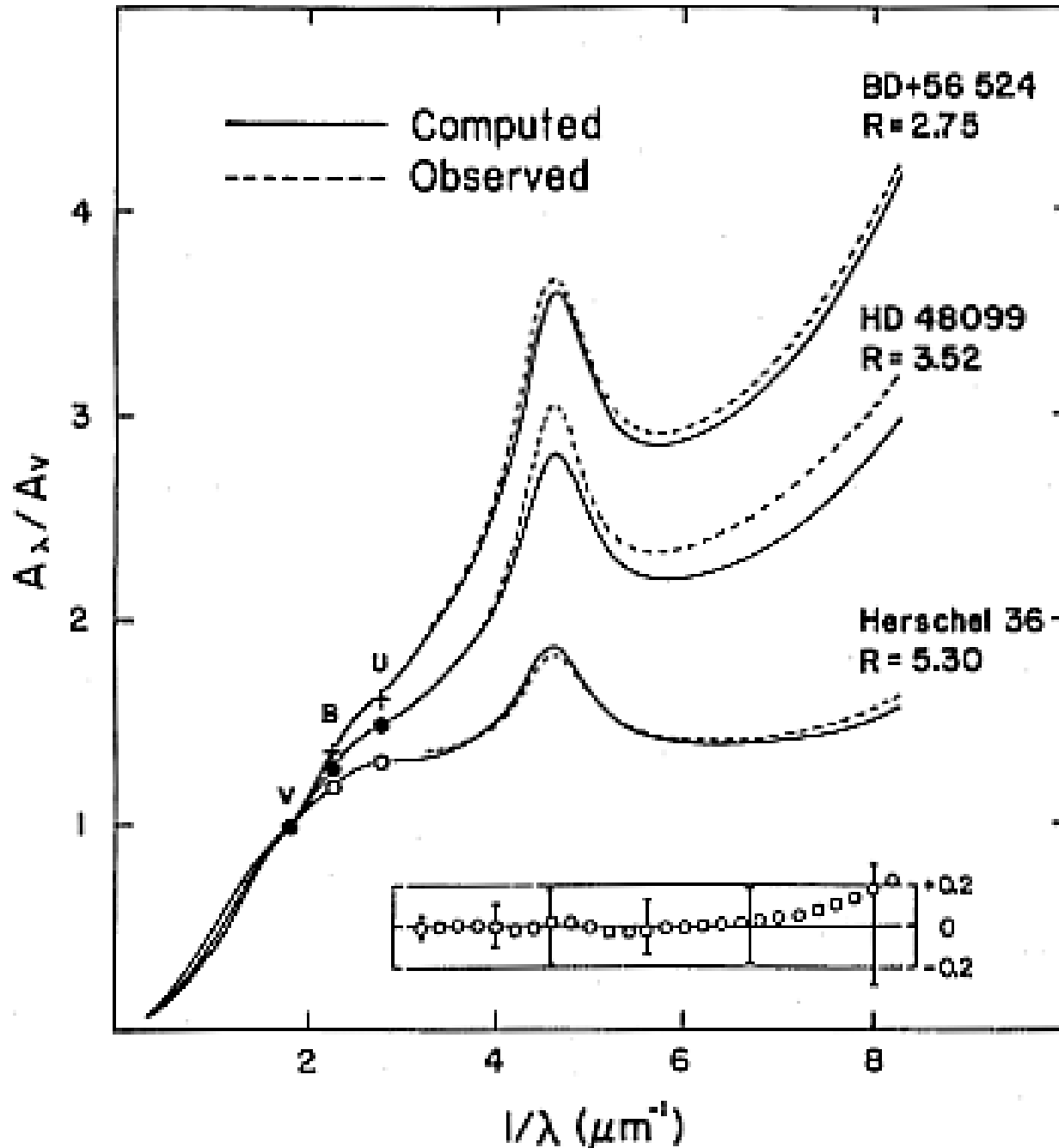
$$R_V = A_V/E(B-V)$$

Normalization factor

Standard value used is 3.1

Be careful, different values used!

Depending on the line of sight

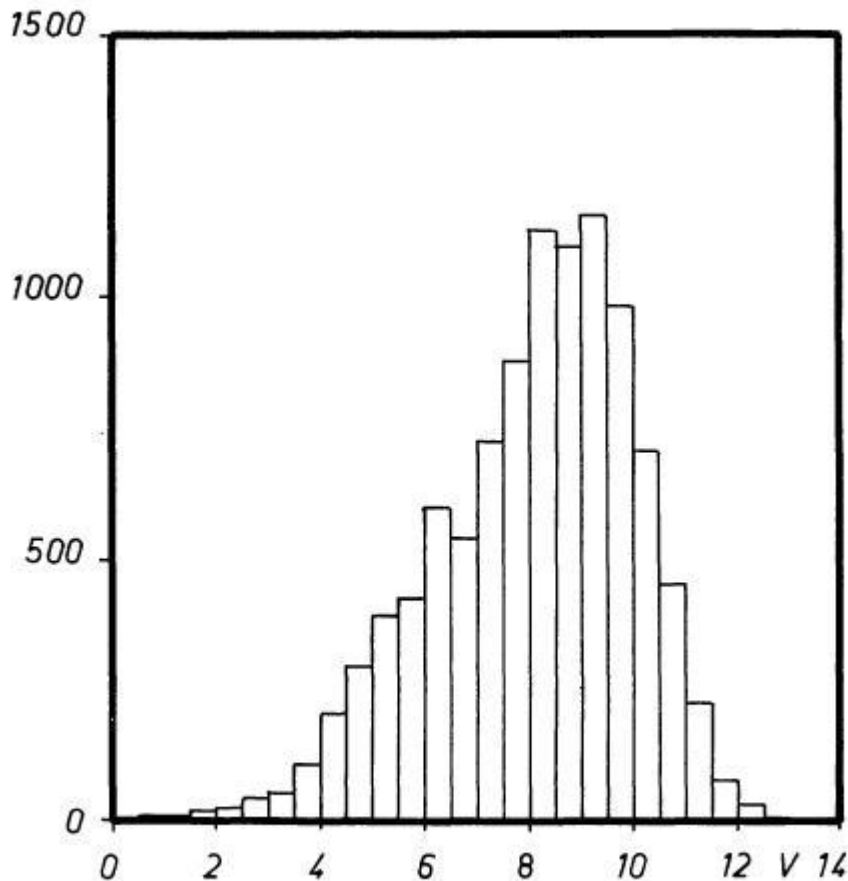


Dependency of  
the extinction  
from  $R_V$



# How to derive the reddening?

- Non-Isochrone approach: from photometric and spectroscopic observations



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

Take all available UBV and Strömngren  $\beta$  photometry

MK classifications

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

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

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

For  $R$  we take the value 3.1.

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

$$V - M_v - A_v = 5 \lg r - 5. \quad (3)$$

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

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

Bailer-Jones,  
1996, PhD,  
Cambridge  
University

SpT	Spectral Type	II	II/III	III	III/IV	IV	IV/V	V	
		<b>Absolute Magnitude</b>							
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	

Assume  $V = 10$  mag  
and no reddening

O5:  $-5.6 \Rightarrow 13\ 000$  pc

A0:  $+1.0 \Rightarrow 630$  pc

G0:  $+4.5 \Rightarrow 125$  pc

M0:  $+8.9 \Rightarrow 15$  pc

Assume  $V = 20$  mag  
and no reddening

O5:  $-5.6 \Rightarrow 1.3$  Mpc

A0:  $+1.0 \Rightarrow 63$  kpc

G0:  $+4.5 \Rightarrow 12.5$  kpc

M0:  $+8.9 \Rightarrow 1.5$  kpc

24	A6	-2.65	-1.45	1.15	1.35	1.60	1.95	2.30
25	A7	-2.60	-1.40	1.20	1.50	1.80	2.10	2.40
26	A8	-2.60	-1.40	1.30	1.65	2.05	2.25	2.50
27	A9	-2.55	-1.35	1.40	1.75	2.10	2.35	2.60
28	F0	-2.50	-1.30	1.50	1.85	2.20	2.45	2.70
29	F2	-2.50	-1.30	1.60	2.00	2.40	2.75	3.10
30	F3	-2.40	-1.20	1.65	2.10	2.45	2.90	3.35
31	F5	-2.30	-1.10	1.70	2.10	2.50	3.05	3.60
32	F6	-2.25	-1.05	1.75	2.15	2.55	3.18	3.80
33	F7	-2.20	-1.00	1.75	2.15	2.60	3.30	4.00
34	F8	-2.20	-1.00	1.75	2.20	2.80	3.50	4.20
35	G0	-2.10	-0.95	1.70	2.15	2.90	3.70	4.45
36	G1	-2.05	-0.90	1.70	2.10	3.00	3.80	4.70
37	G2	-2.00	-0.90	1.60	2.10	3.00	3.90	4.80
38	G3	-2.00	-0.85	1.60	2.05	3.05	4.00	5.00
39	G5	-2.00	-0.85	1.60	2.00	3.10	4.15	5.20
40	G6	-2.00	-0.80	1.50	2.00	3.15	4.23	5.30
41	G8	-2.00	-0.80	1.35	1.95	3.20	4.35	5.50
42	K0	-2.00	-0.80	1.20	1.87	3.20	4.50	5.80
43	K1	-2.00	-0.85	1.00	1.80	3.30	4.70	6.10
44	K2	-2.00	-0.90	0.80	1.80	3.30	4.80	6.30
45	K3	-2.00	-1.00	0.60	1.80	3.40	5.00	6.60
46	K4	-2.10	-1.00	0.20	-	-	-	6.90
47	K5	-2.20	-1.00	0.00	-	-	-	7.50
48	M0	-2.40	-1.00	-1.10	-	-	-	8.90
49	M1	-2.50	-1.10	-0.40	-	-	-	9.60
50	M2	-2.50	-1.10	-0.60	-	-	-	10.30
51	M3	-2.50	-1.20	-0.70	-	-	-	10.80
52	M4	-2.50	-1.20	-0.80	-	-	-	11.40
53	M5	-2.50	-1.30	-0.90	-	-	-	12.30
54	M6	-2.50	-1.30	-1.00	-	-	-	13.20
55	M7	-2.50	-1.40	-1.10	-	-	-	14.00
56	M8	-2.50	-1.50	-1.20	-	-	-	16.50
57	M9	-	-	-	-	-	-	-

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

$\beta$ (mag)	$M_v(\beta)$ (mag)	$\beta$ (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  $\beta$   
index

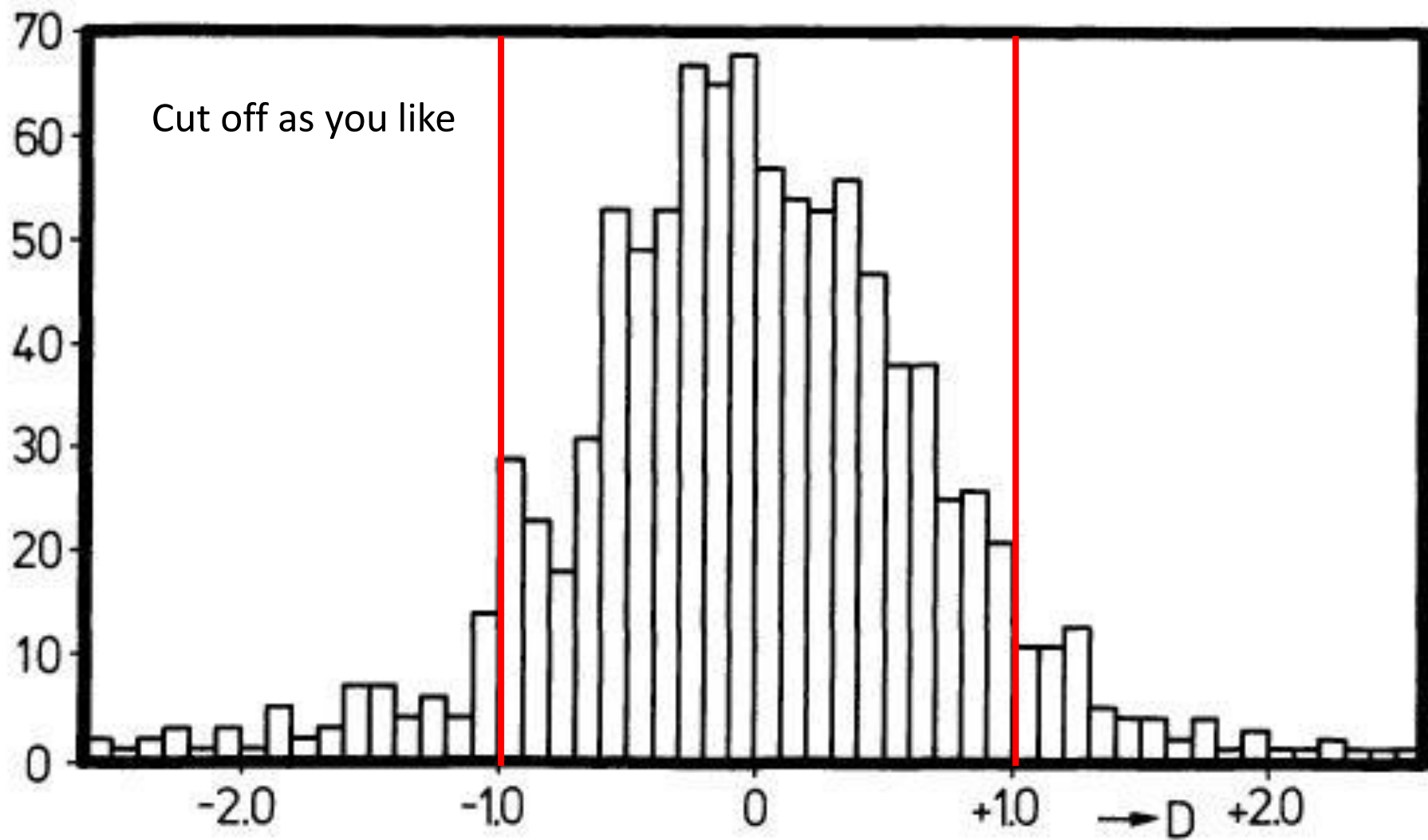
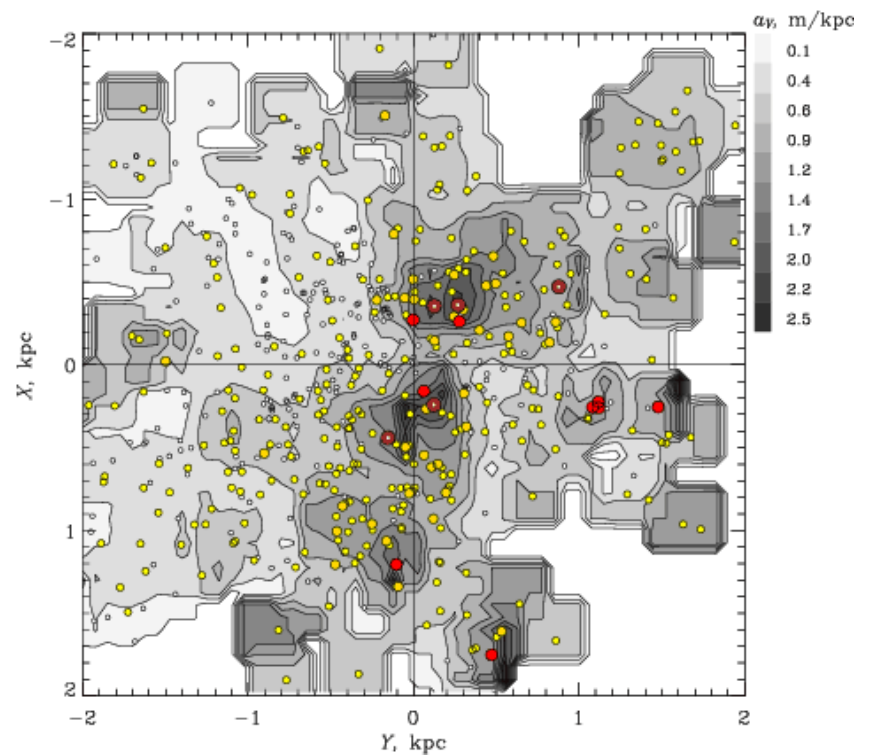
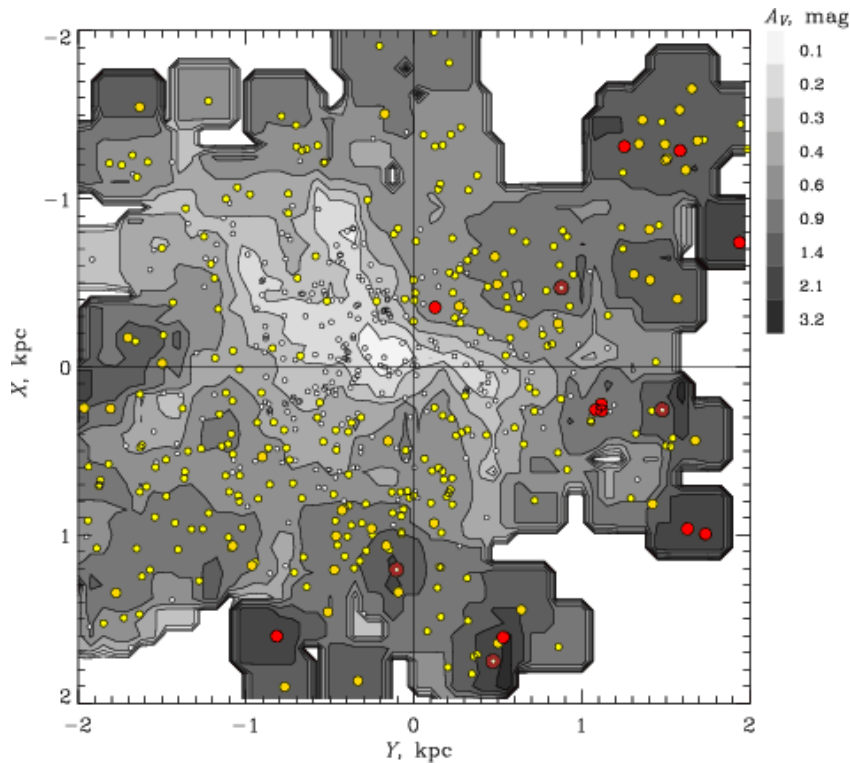


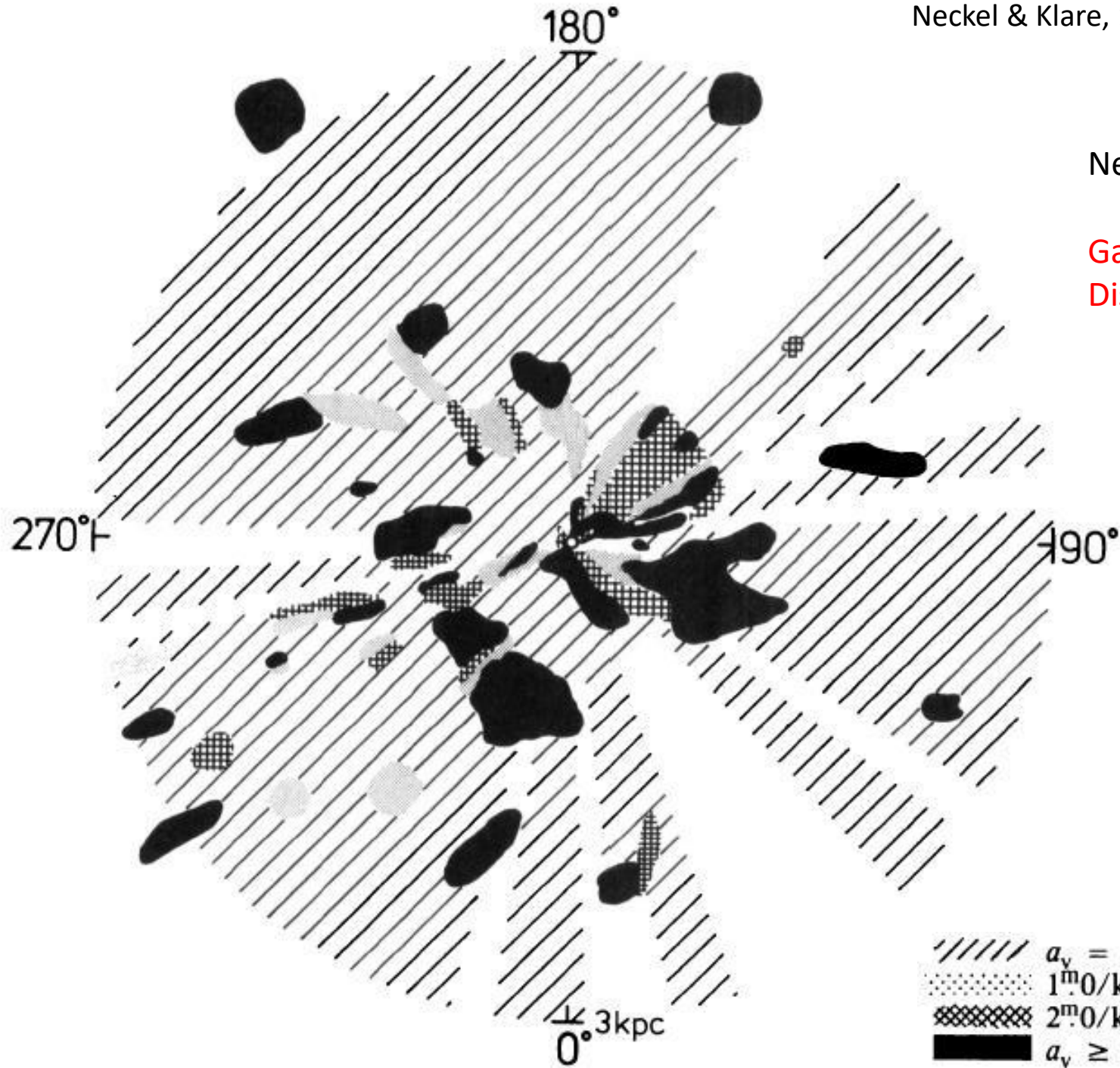
FIGURE 4. — Frequency distribution of the differences between the distance moduli derived from  $UBV + MK$  and  $UBV + \beta$  data.

# Reddening Maps

<http://argonaut.skymaps.info/>

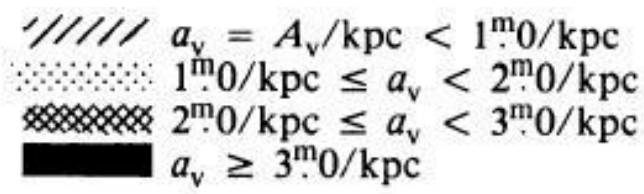
<http://www.univie.ac.at/p2f>





Needed:

Galactic coordinates  
Distance from Sun





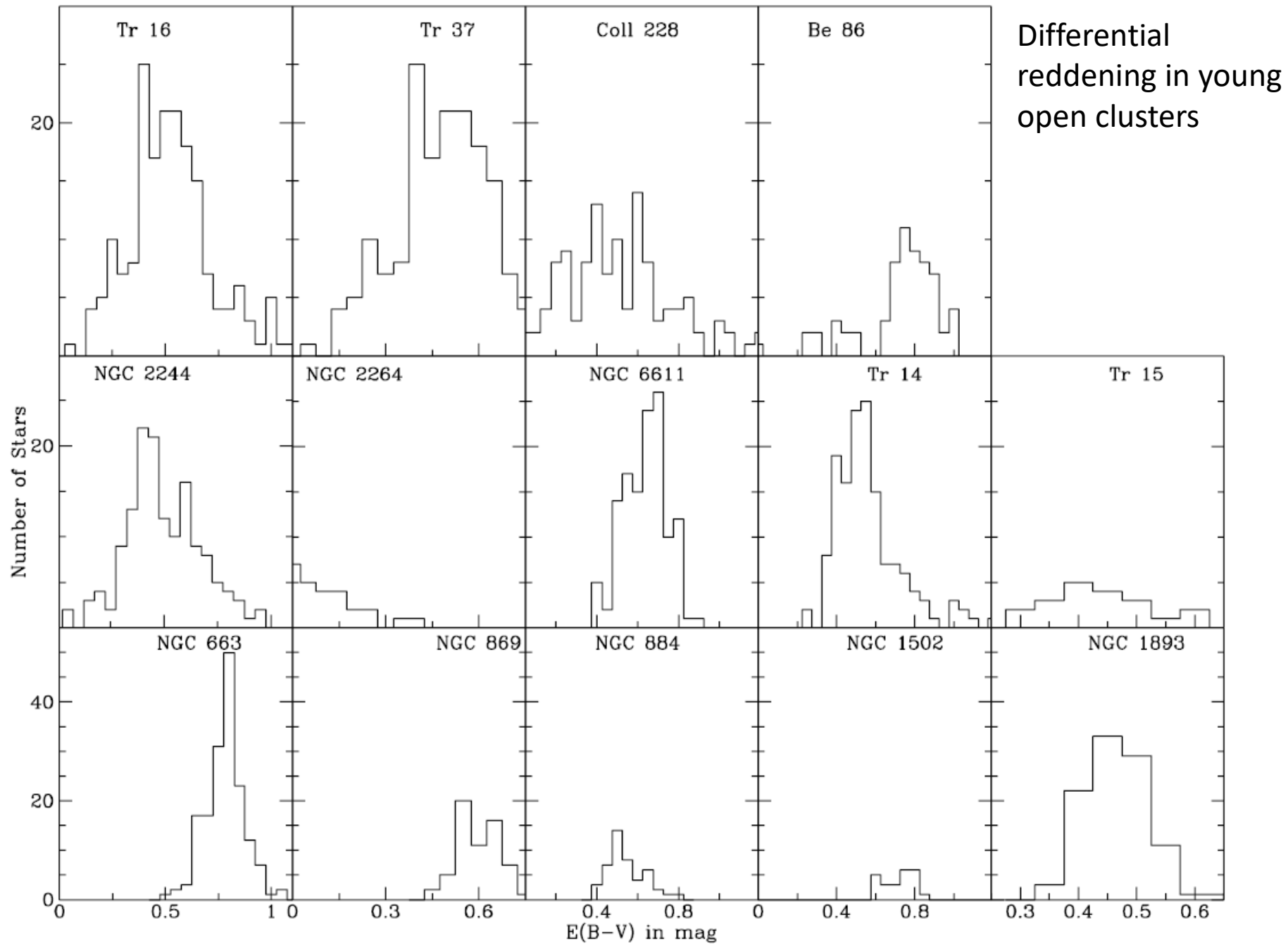
# Haffner 18

Age about 8 Myr

$d = 6000$  pc

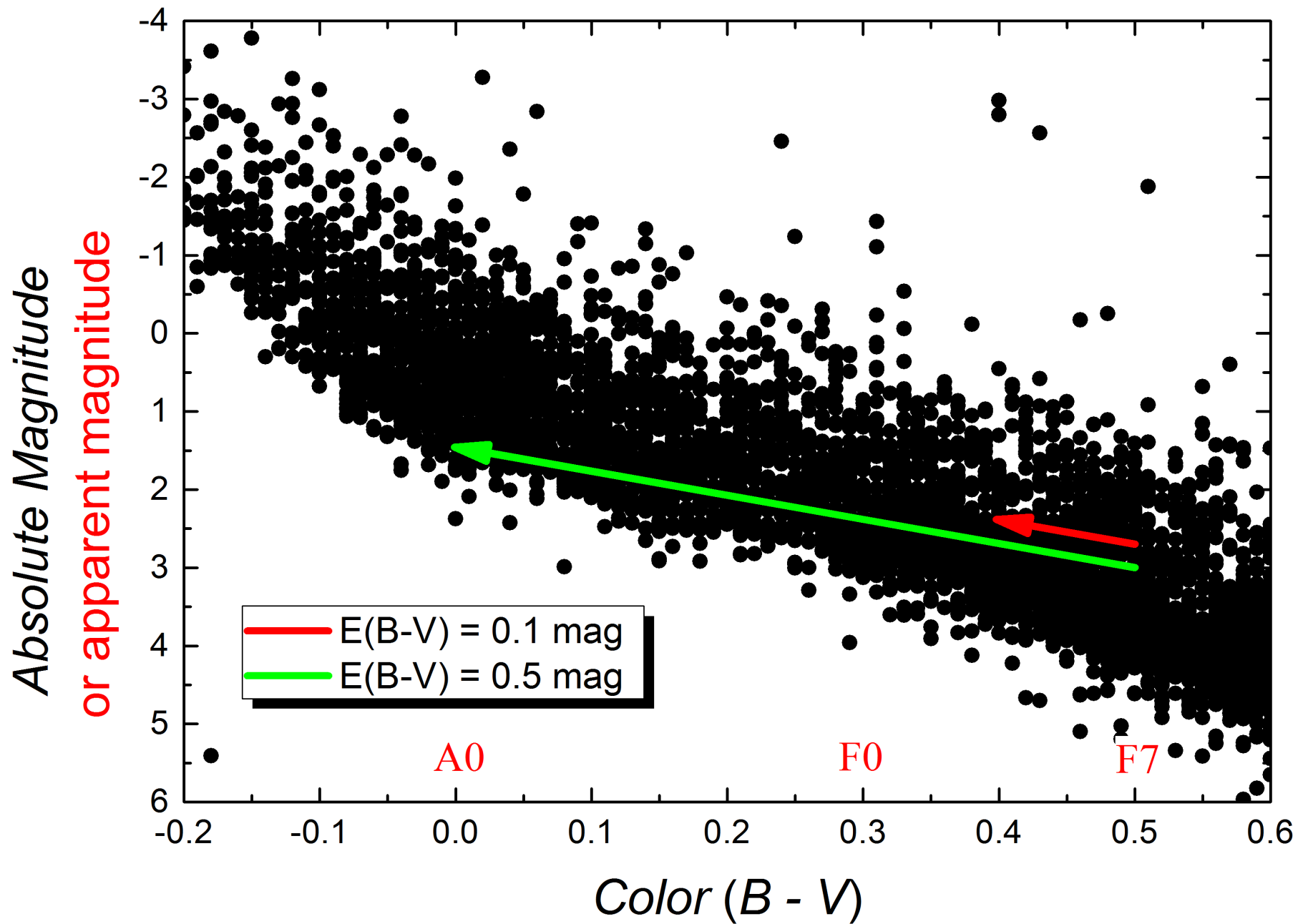
differential  
extinction within  
the cluster

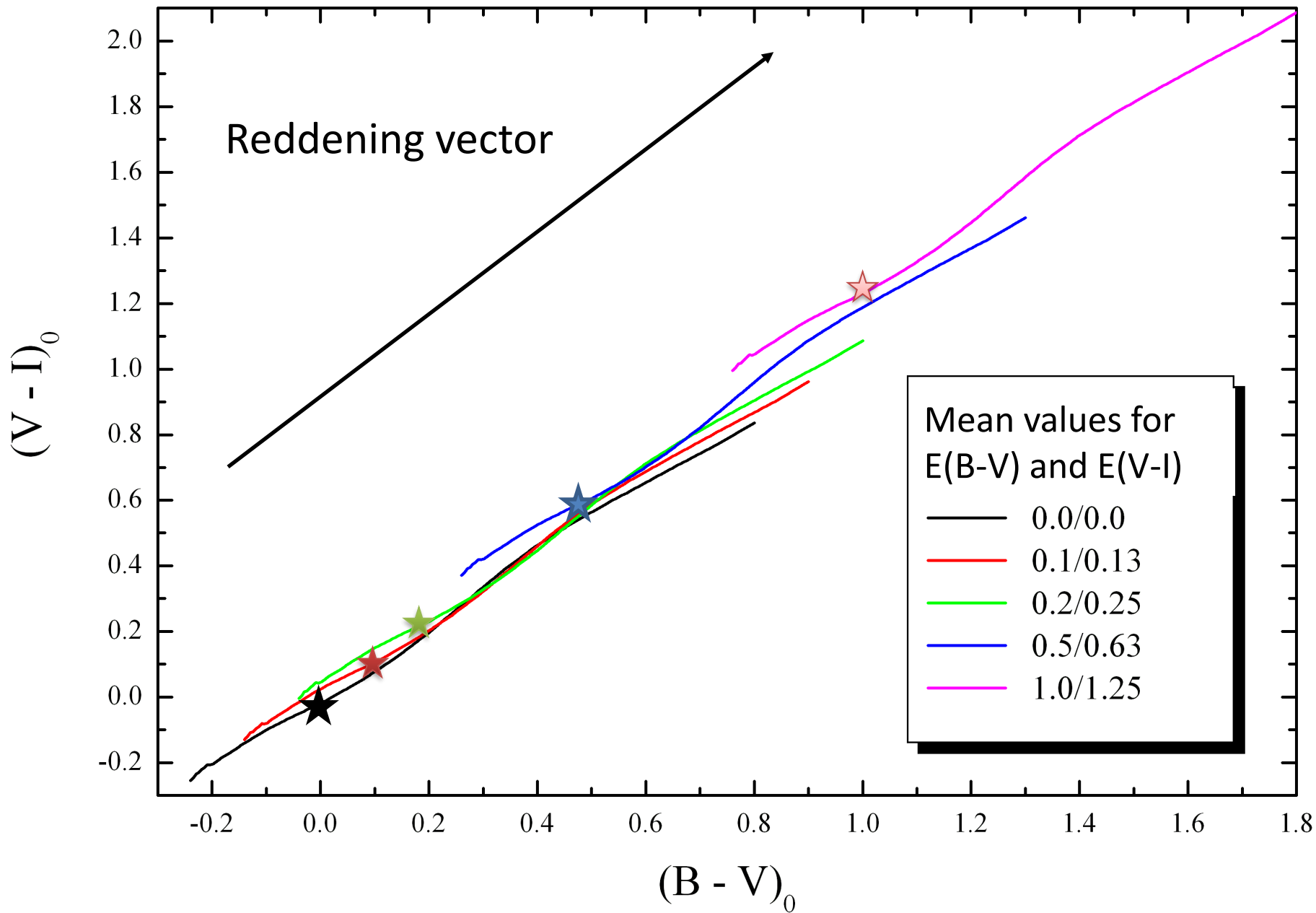




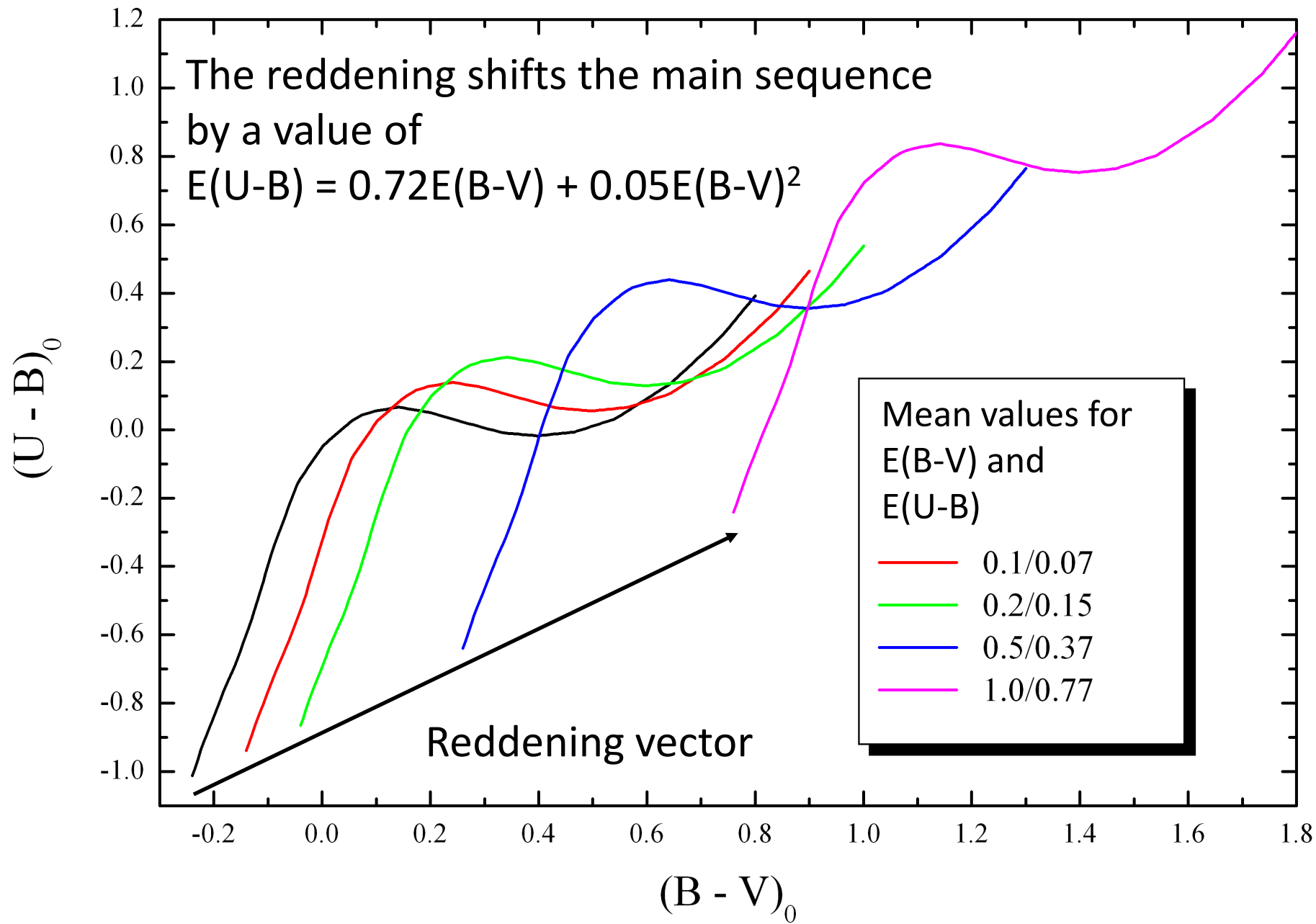
# Determination of the reddening - Isochrones

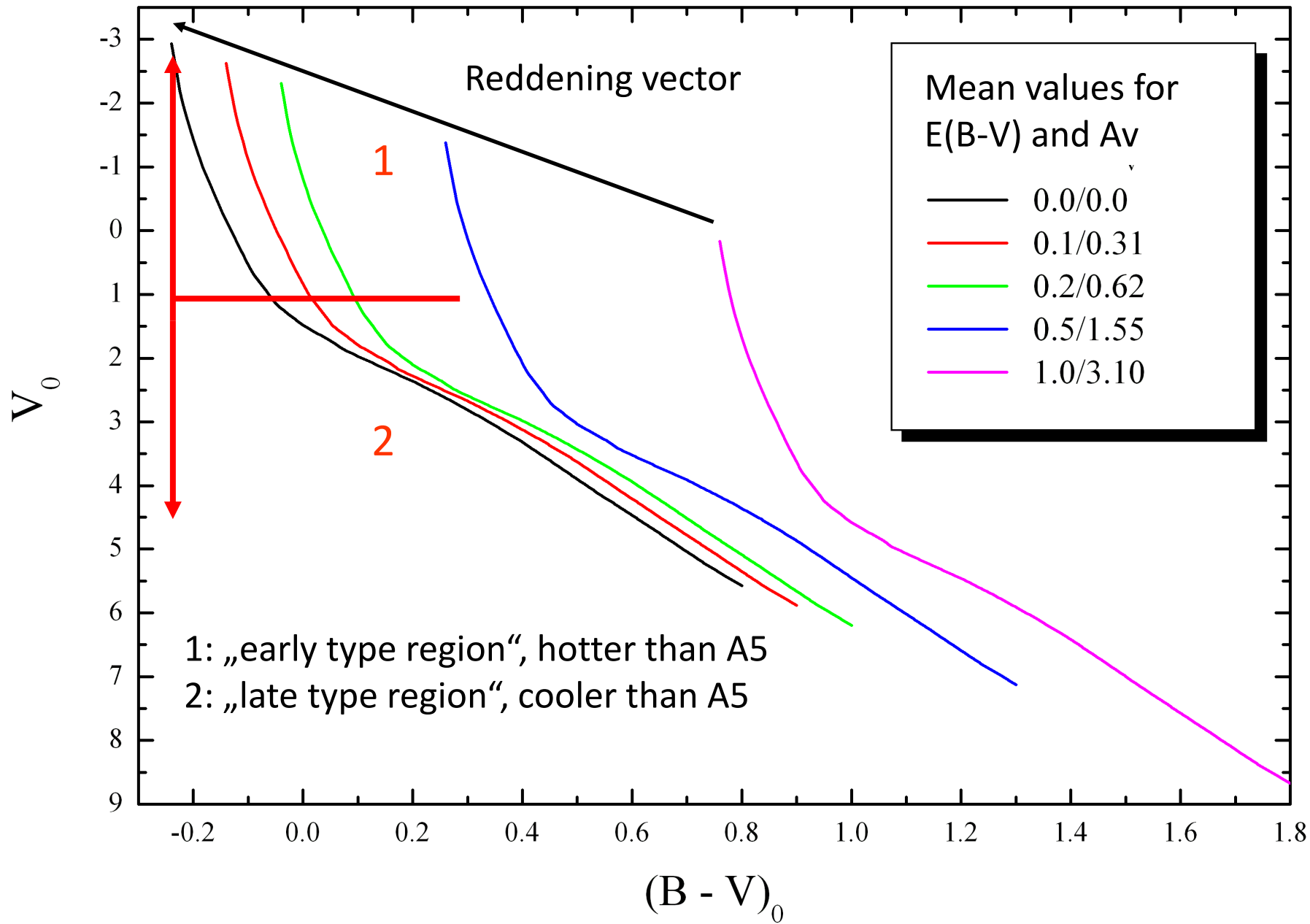
- From two temperature sensitive parameters, the determination of the reddening is **not** possible
- You need one “other” observational index
- First choices:  $(U - B)$ ,  $(u - b)$ ,  $[X]$ ,  $\beta$
- Normally, you only have V, J, H, K, and so on

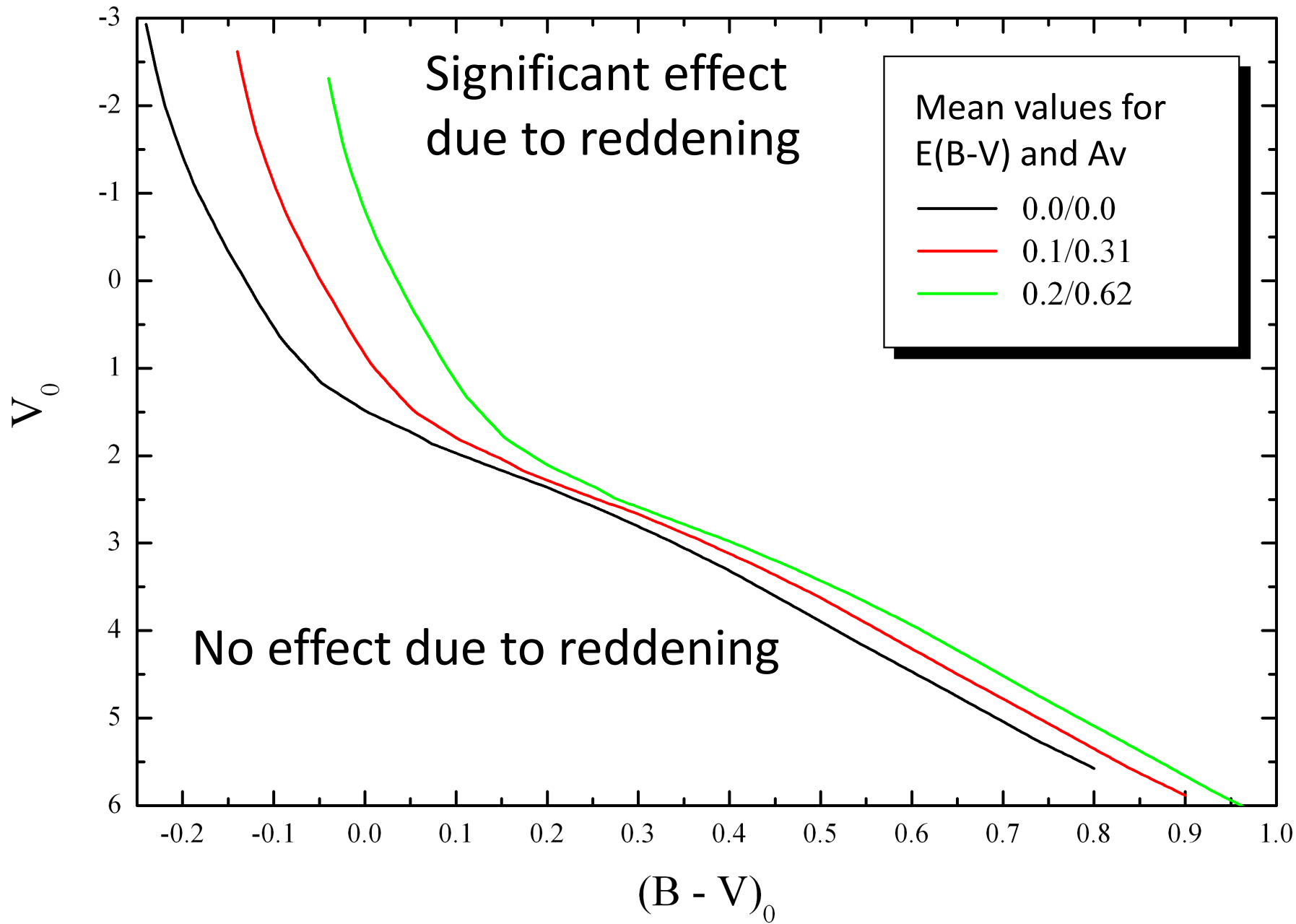




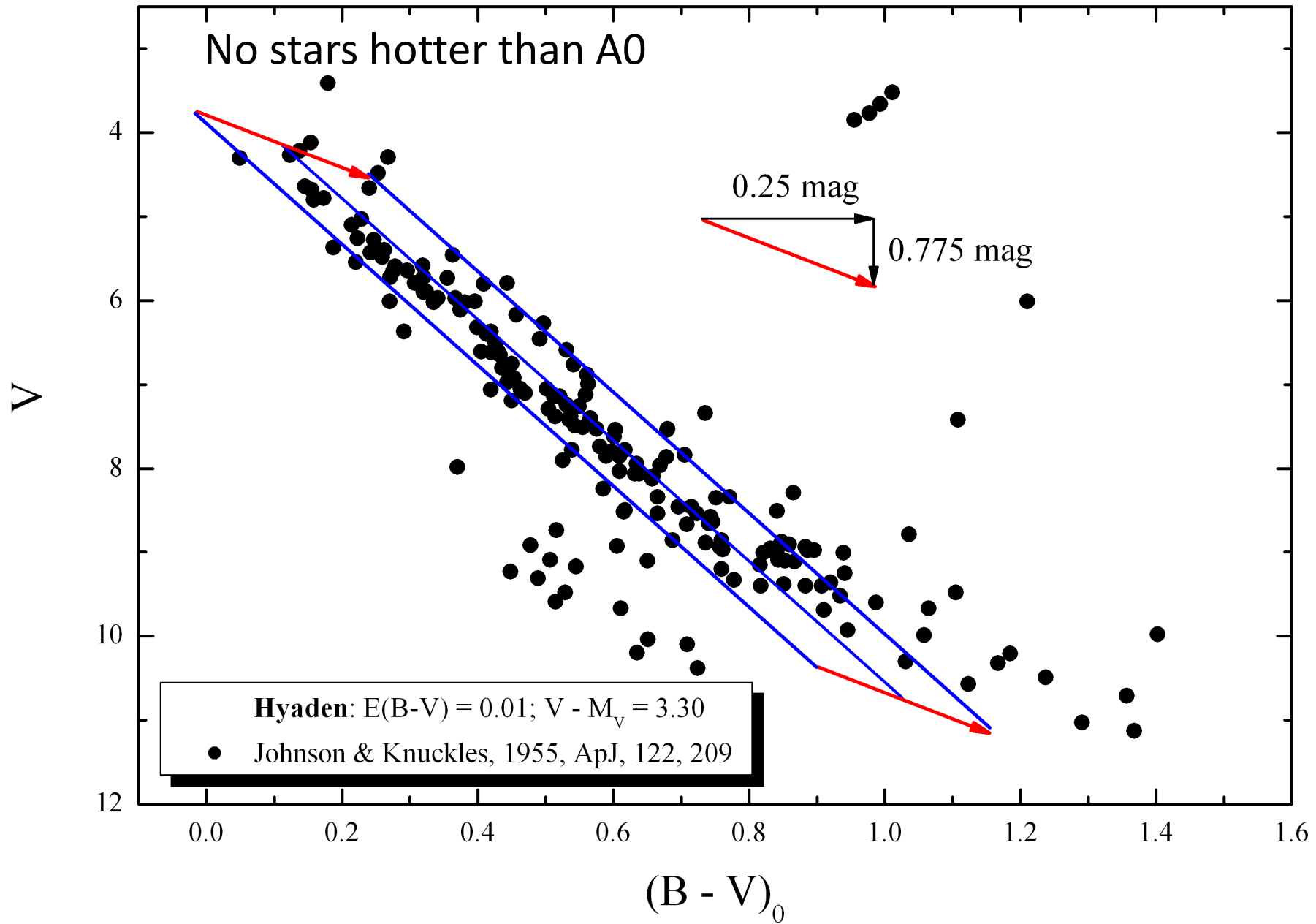
You would need a spectral information

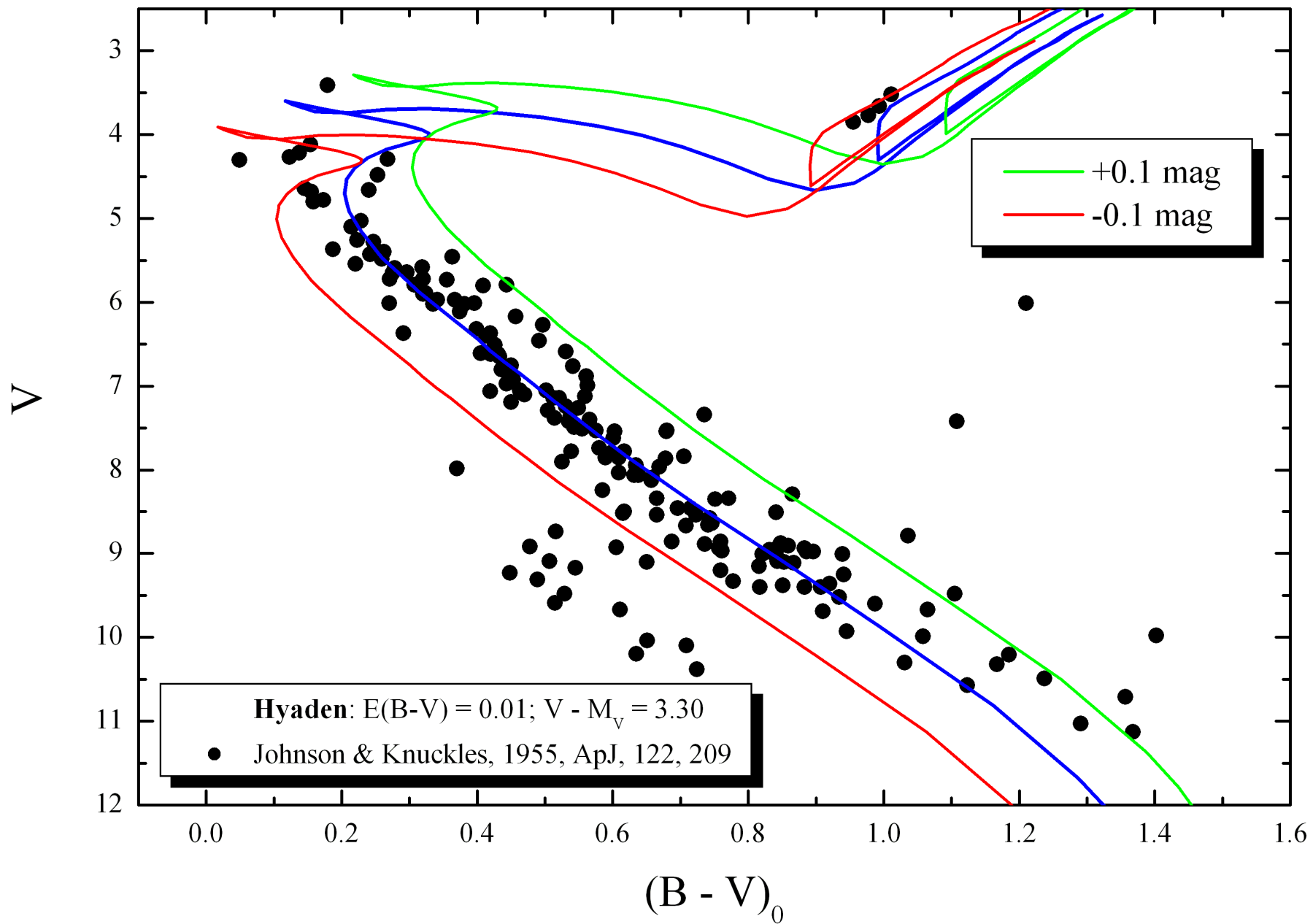


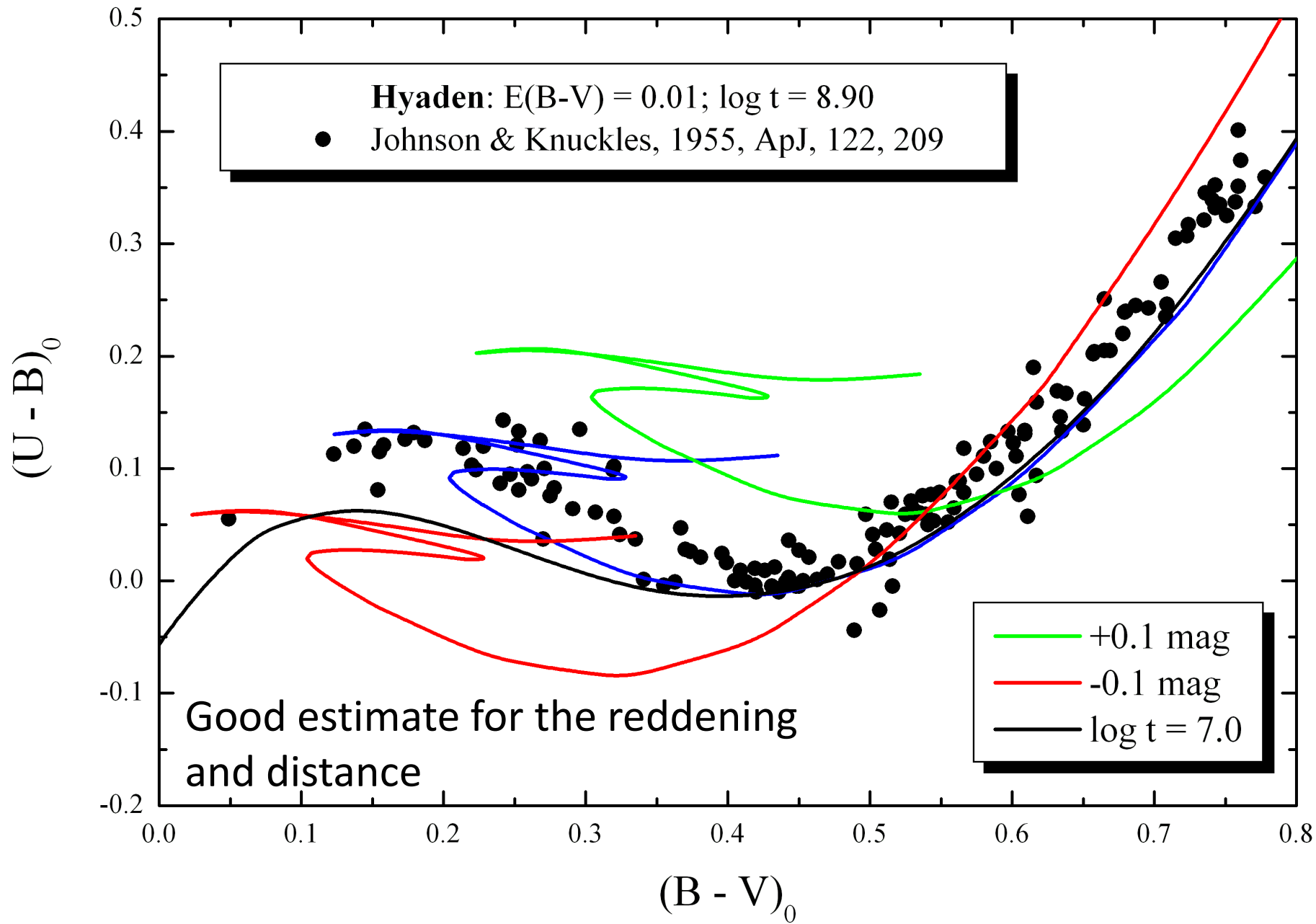












4. **Extinction values and distances.** — The visual extinction  $A_v$  can be derived from

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

For  $R$  we take the value 3.1.

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

$$V - M_v - A_v = 5 \lg r - 5. \quad (3)$$

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

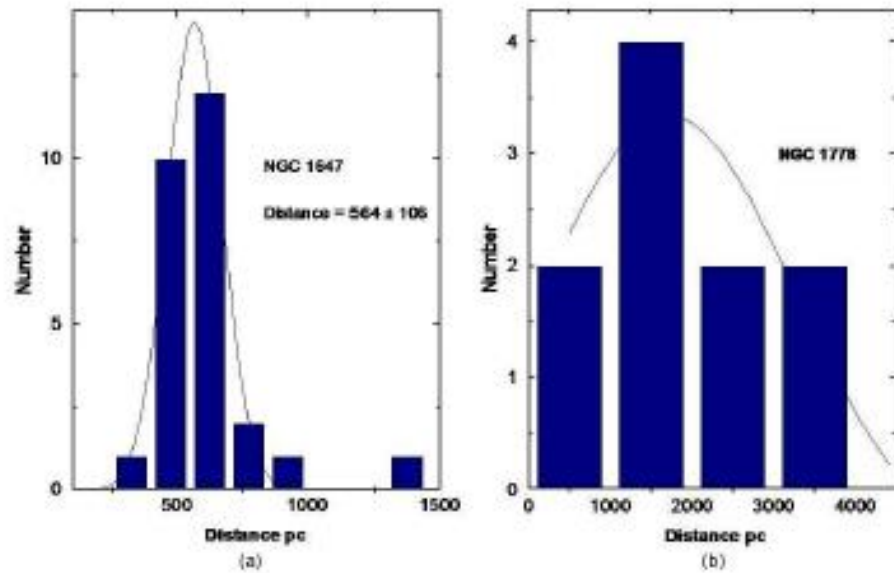
$$D = (V - M_v(\text{MK}) - A_v(\text{UBV}, \text{MK})) - (V - M_v(\beta) - A_v(\text{UBV}, \beta)). \quad (4)$$

# 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!

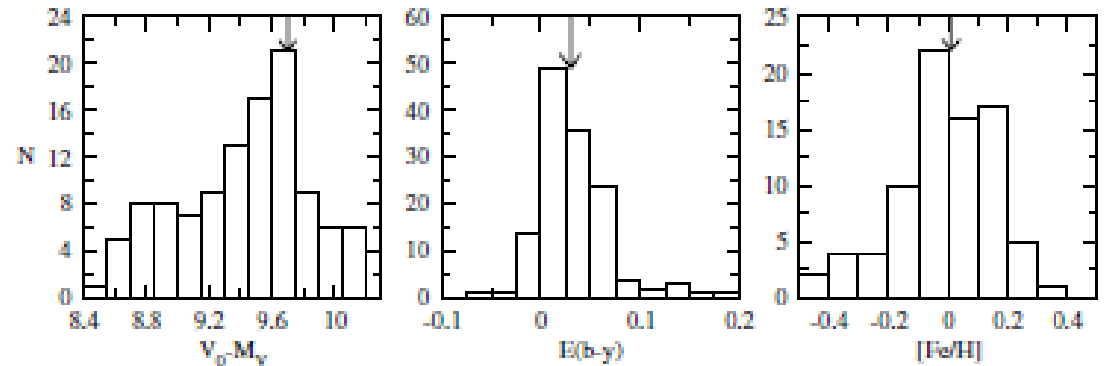
# How to determine the DM?

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



Guerrero et al., 2011, RMxAA, 47, 185

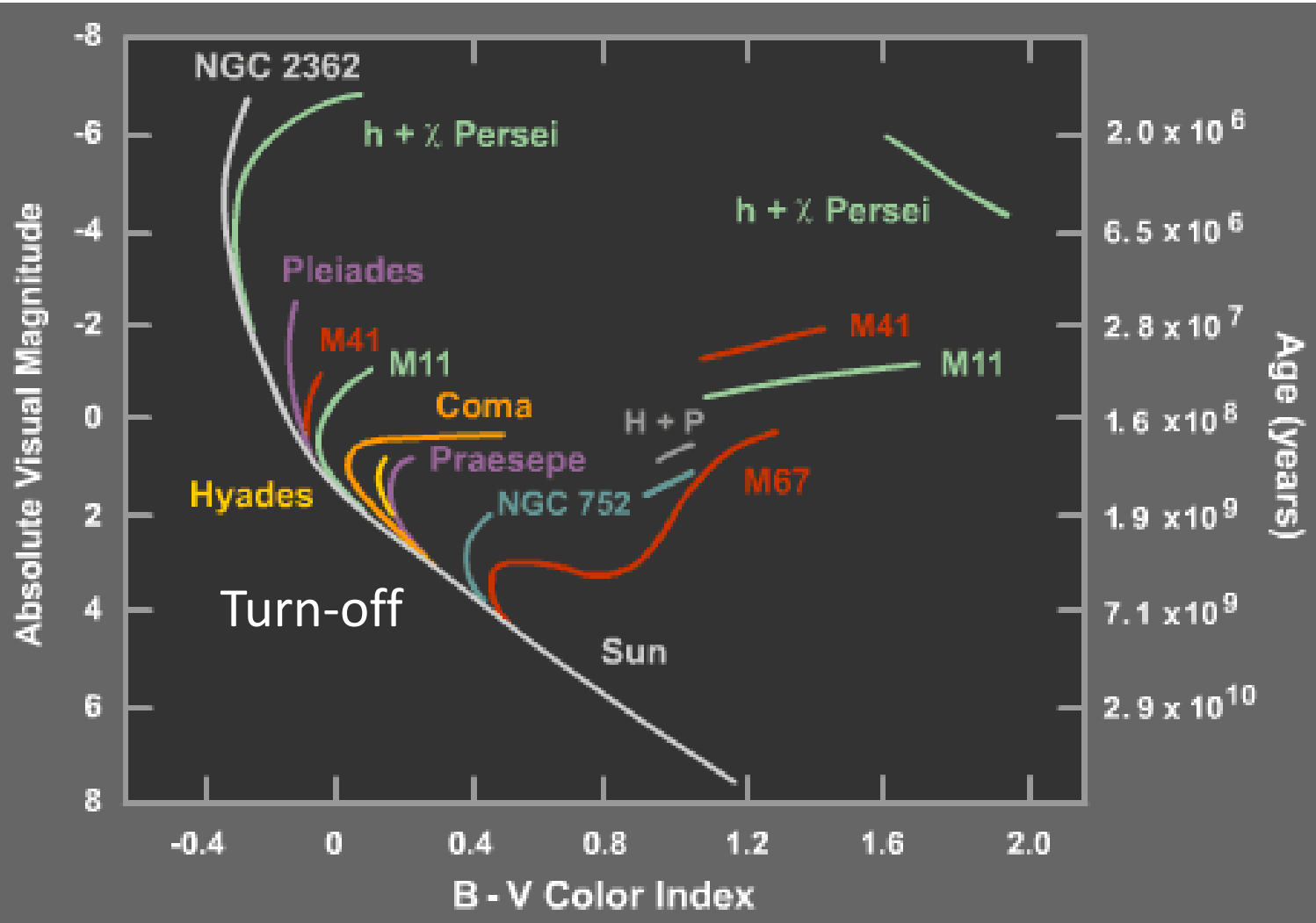
Fig. 3. Histogram of the distances for the stars in the direction of (a) NGC 1647 and (b) NGC 1778. The thin line is a Gaussian fit to the data.



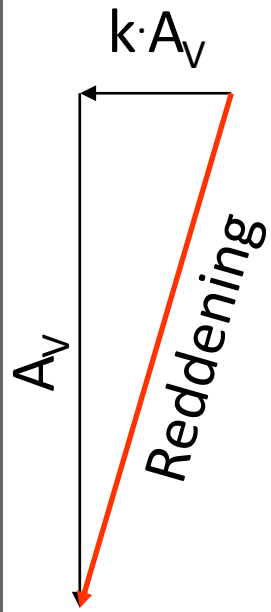
Balaguer-Núñez et al., 2007, A&A, 470, 585

Fig. 9. The histograms of the distance modulus, reddening and metallicity of the selected member stars of M 67 with  $H_\beta$  measurements. The arrows indicate the mean values adopted for the cluster.

Distance:  $V_0 - M_V$



HR Diagrams for Various Open Clusters

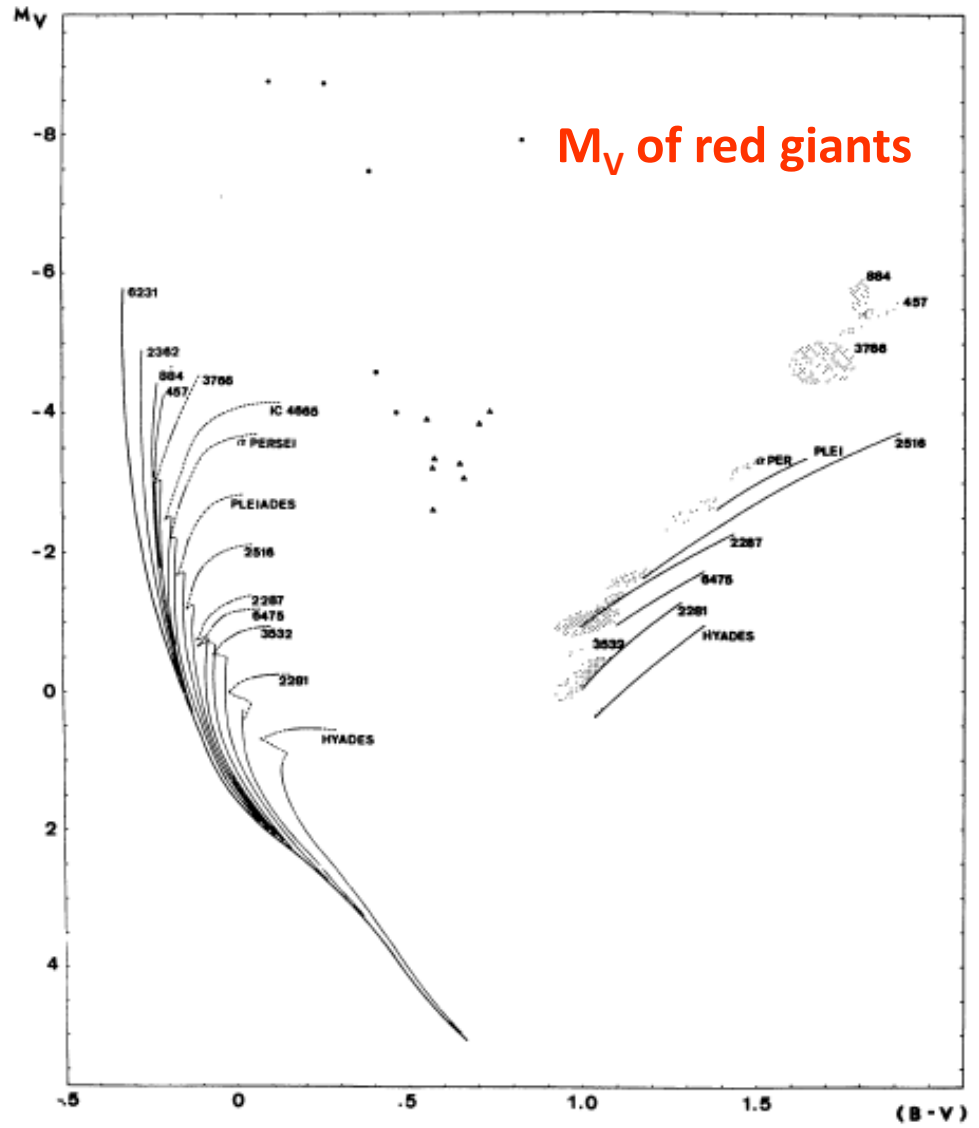
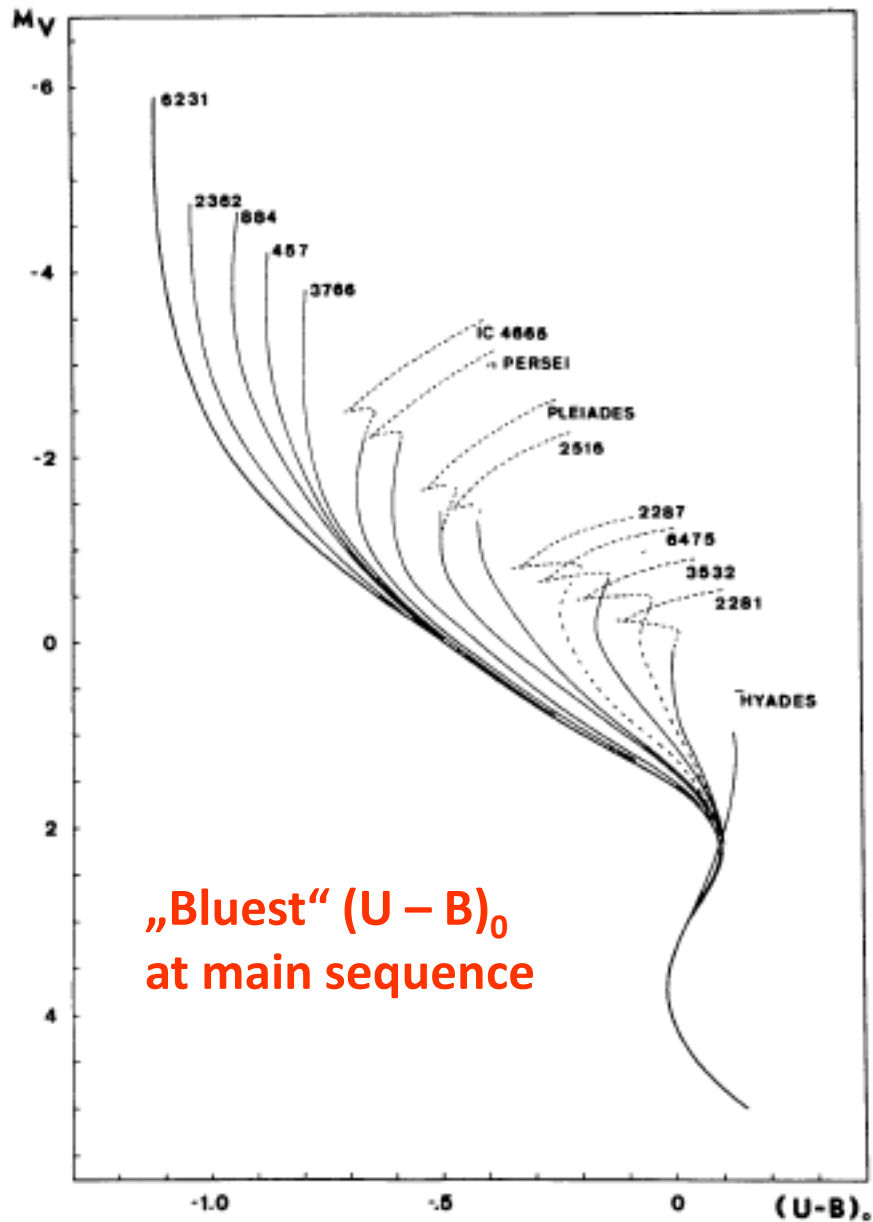




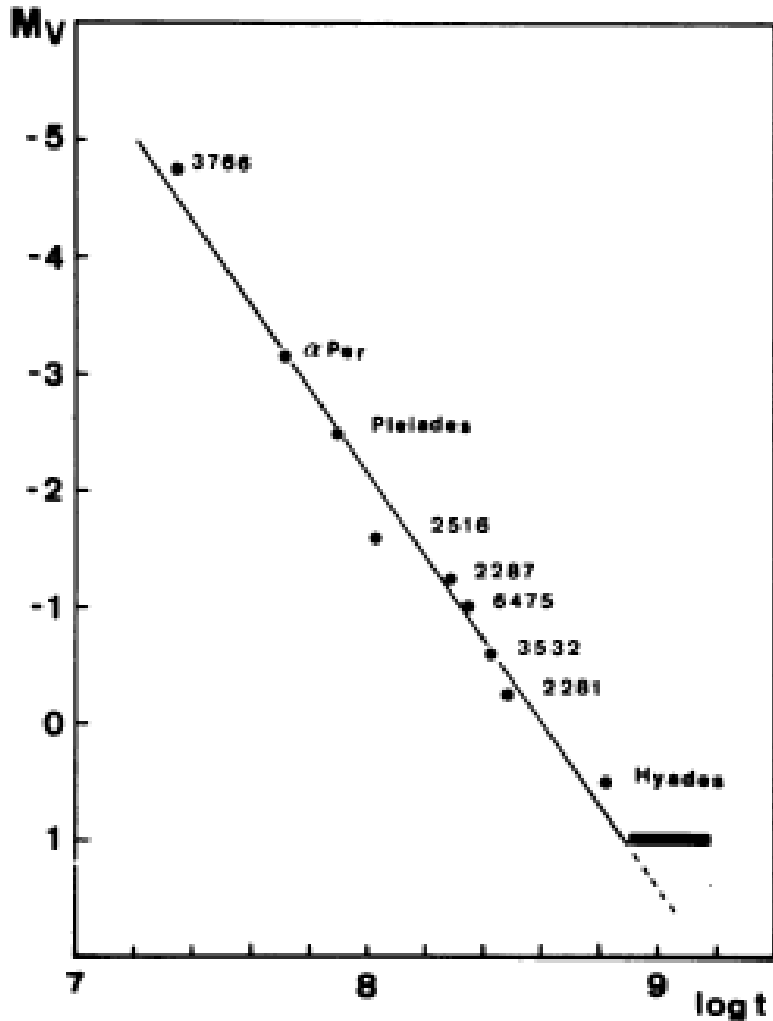
# Turn off point

- 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

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



Dereddened indices



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

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.

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**

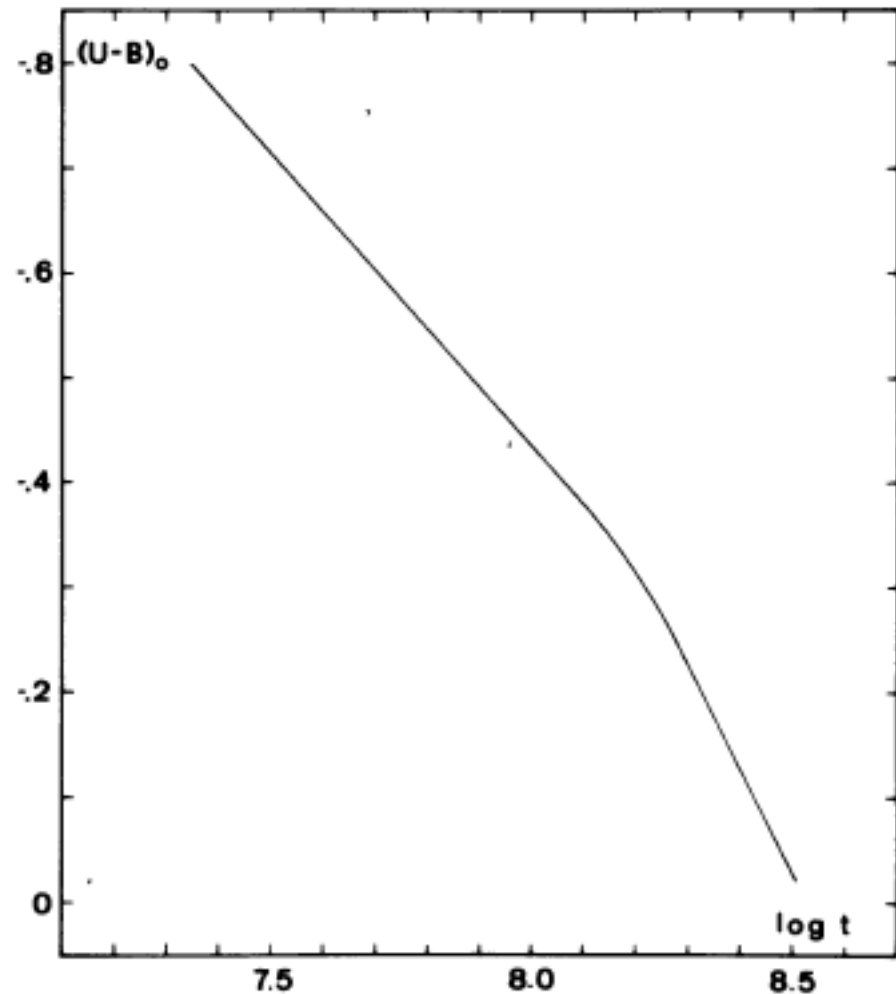
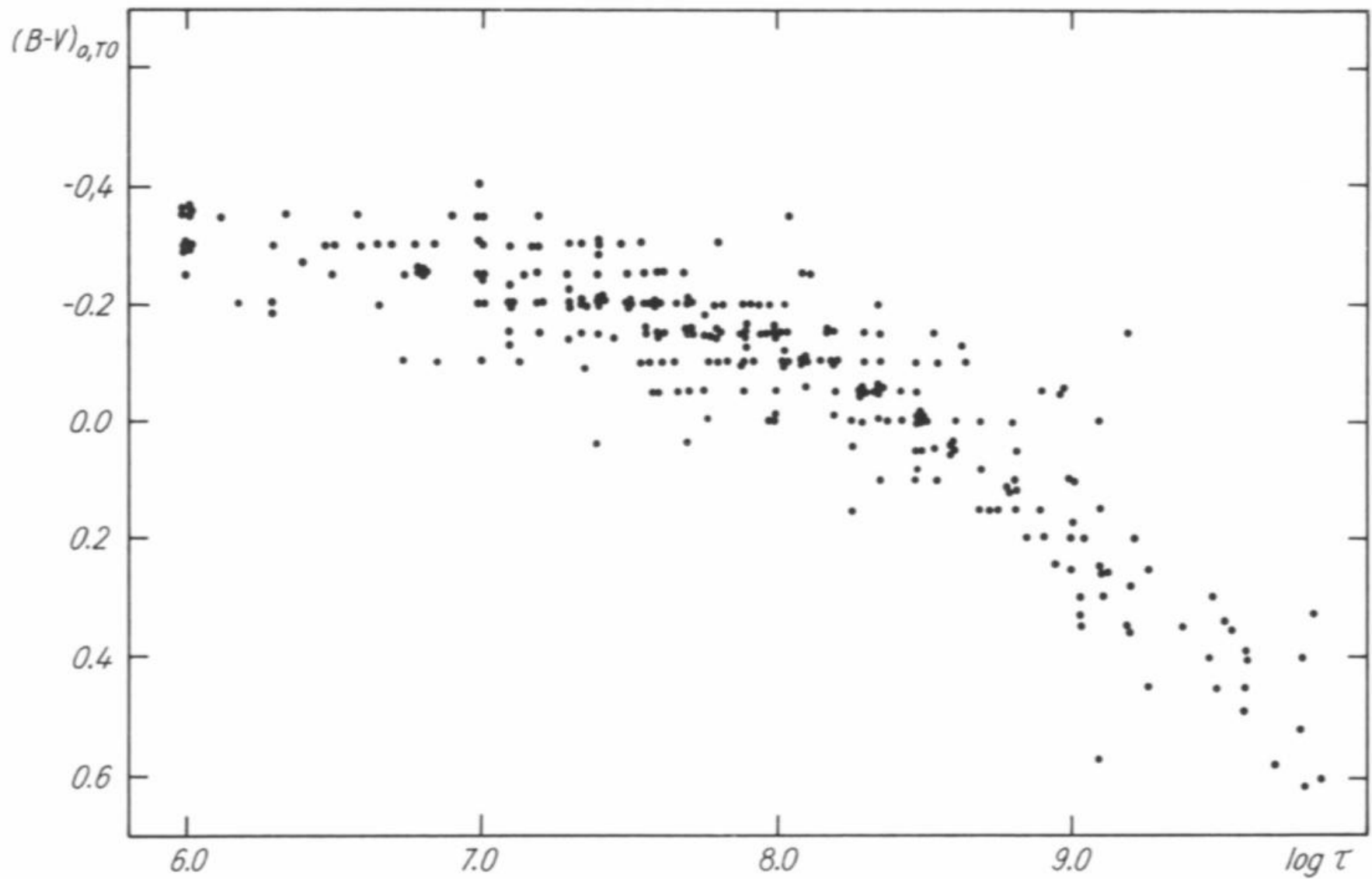


Fig. 6. Calibration of the bluest  $(U-B)_0$  on the main sequence in terms of age ( $\log t$ )

$$\begin{aligned}
 -.80 &\leq (U-B)_0 < -.35 & \log t &= 1.795(U-B)_0 + 8.785 \\
 -.28 &\leq (U-B)_0 < .00 & \log t &= 0.813(U-B)_0 + 8.487
 \end{aligned}$$



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

# Calculation of Isochrones

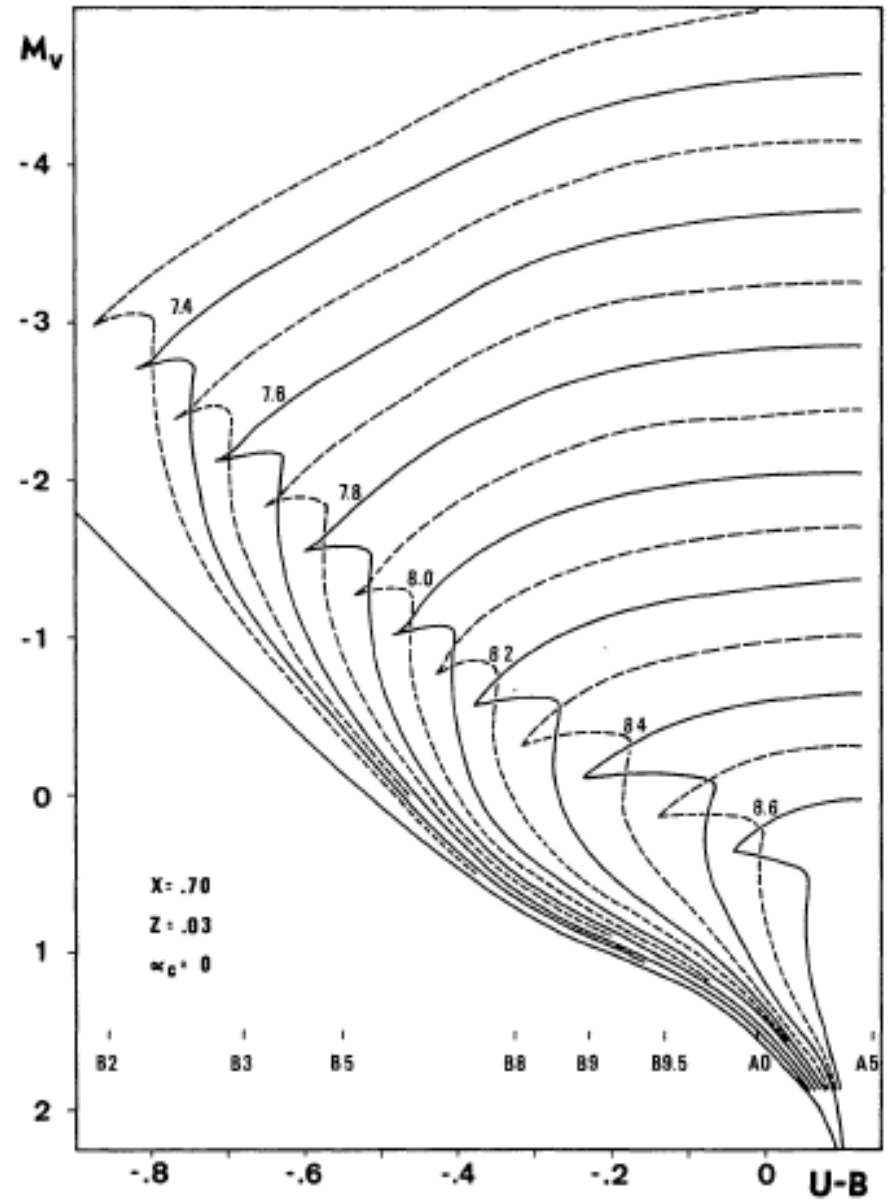
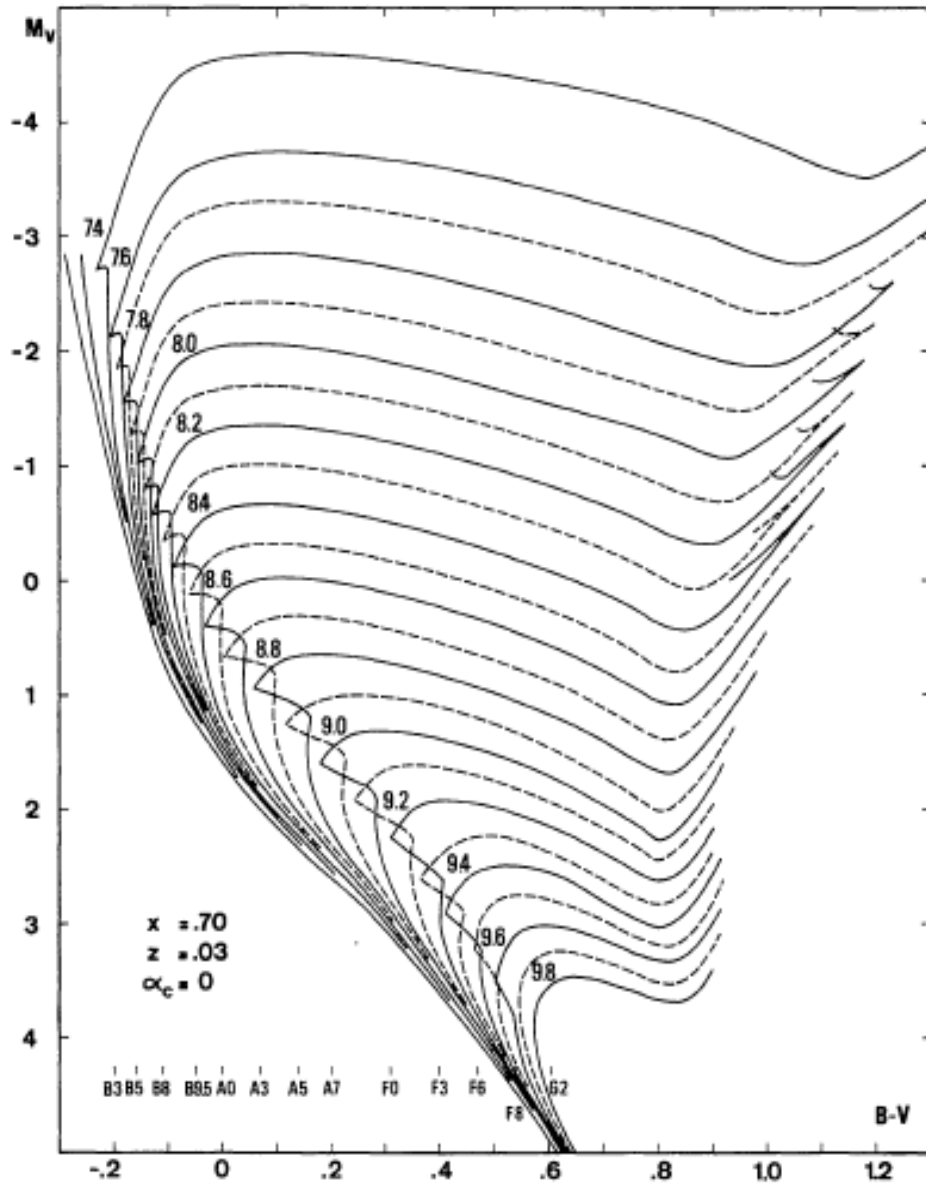
The calculation of theoretical isochrone (= lines of equal age) is done with stellar atmospheres

Free parameter : Metallicity [X, Y, Z]

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

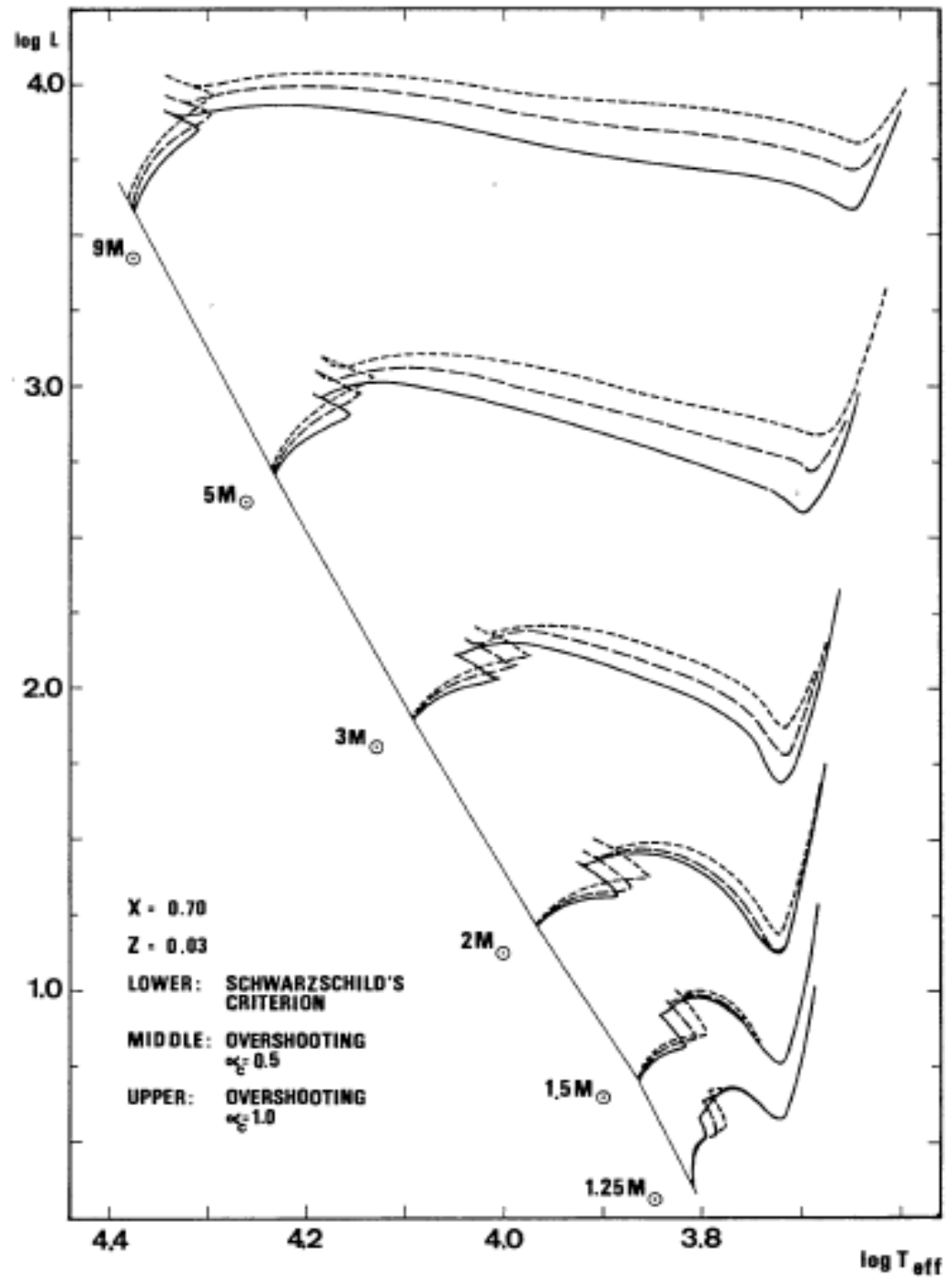
# Which astrophysical “parameters” are important?

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





# Different treatment of convection

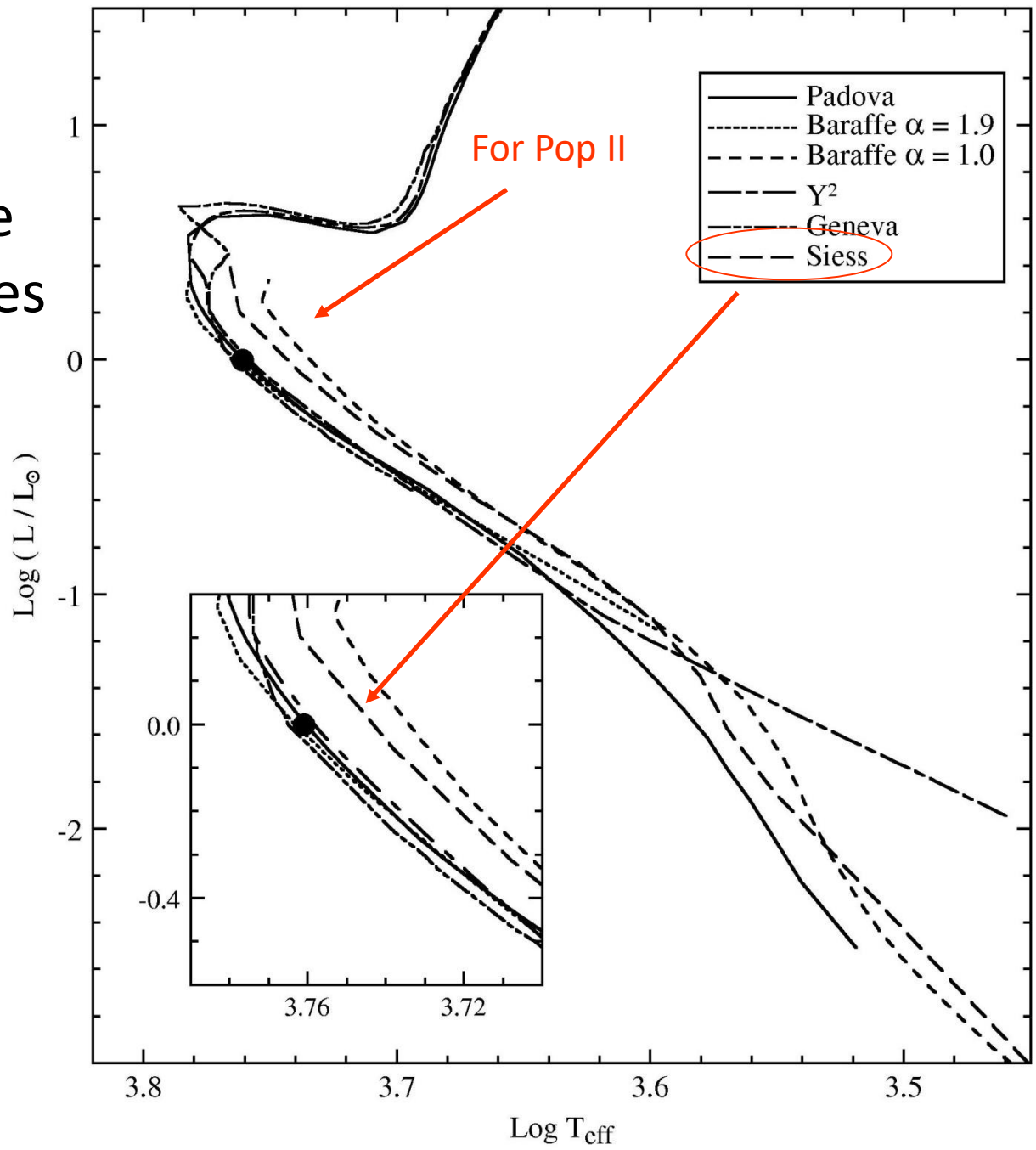


# A comparison of isochrone sets

- Grocholski & Sarajedini (2003, MNRAS, 345, 1015) compared the following isochrones:
  1. “Padova”: Girardi et al., 2002, A&A, 391, 195
  2. Baraffe: Baraffe et al., 1998, A&A, 337, 403
  3. “Geneva”: Lejeune & Schaerer, 2001, A&A, 366, 538
  4. Y<sup>2</sup>: Yi et al., 2001, ApJS, 136, 417
  5. Siess: Siess et al., 2000, A&A, 358, 593

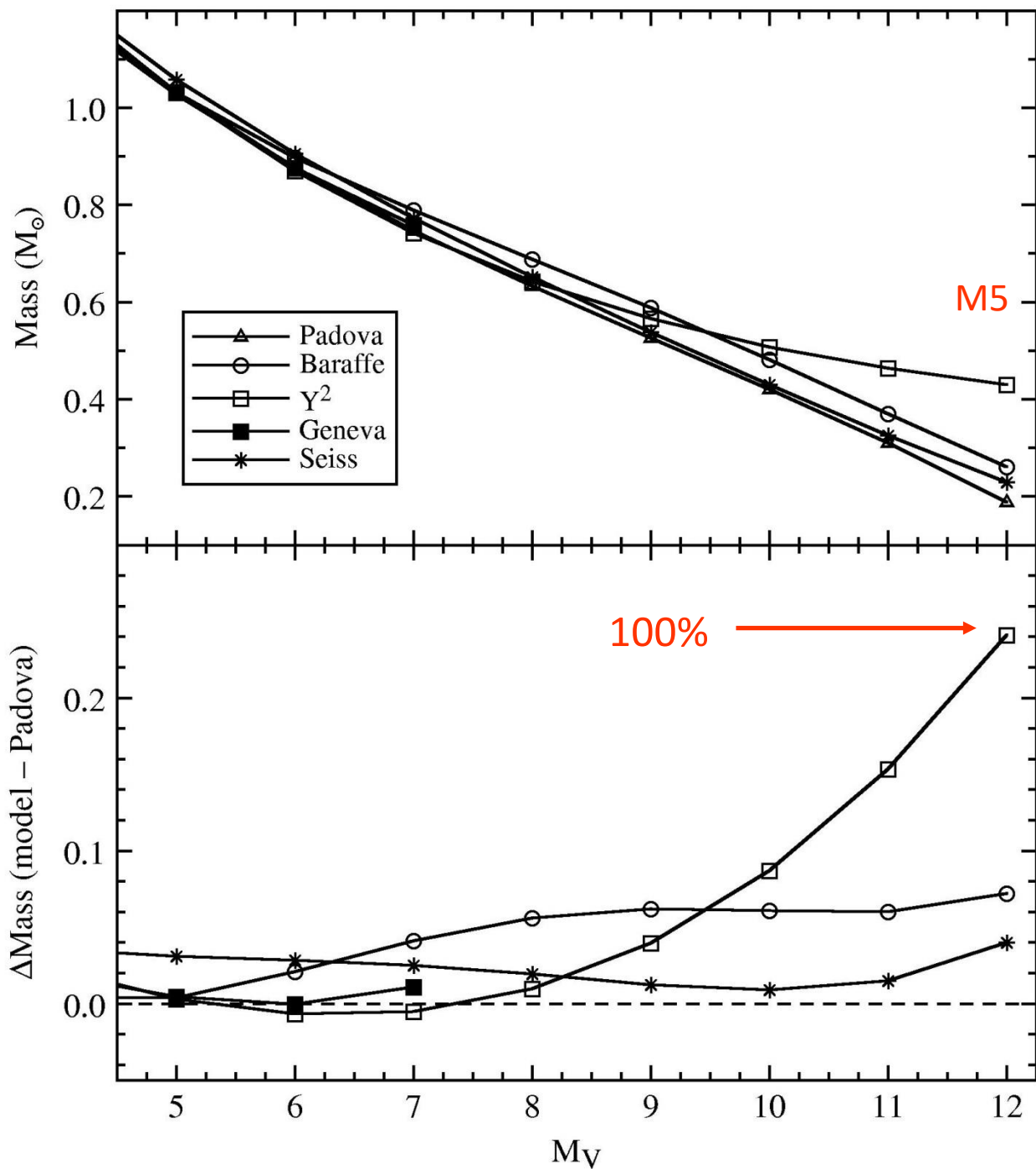
The location of the Sun with isochrones of 5 Gyr

Isochrones by Siess et al. (1997) seem “to have a problem”



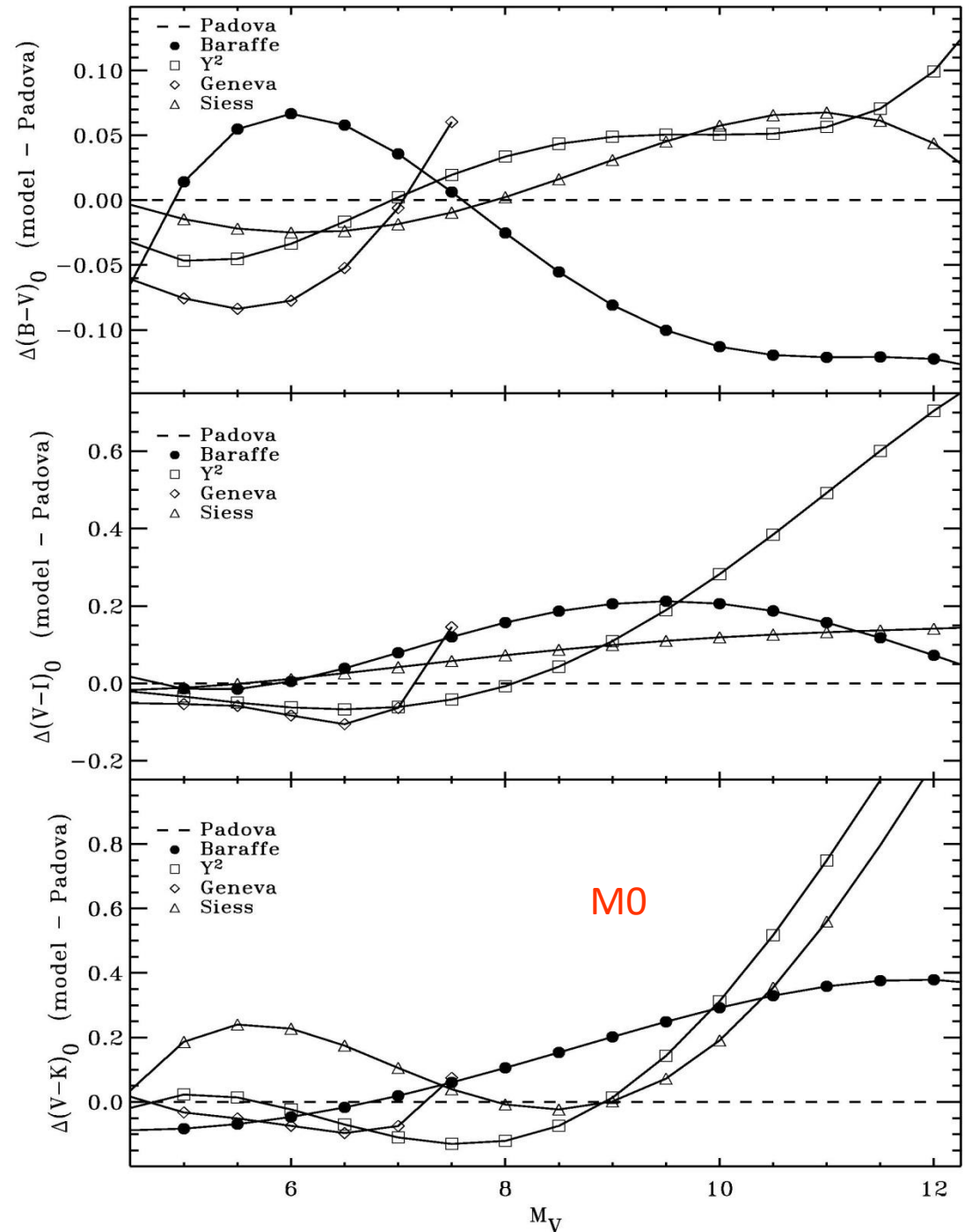
Comparison of  
different masses  
for a constant  $M_V$

Zero line is the  
isochrone of the  
Padova group



Comparison of different color indices for a constant  $M_V$

Zero line is the isochrone of the Padova group



Name	Available photometry	Log age	$E(B - V)$	[Fe/H]
M35 (NGC 2168)	<i>UBV RI JHK<sub>S</sub></i>	8.17	0.19	-0.160
M37 (NGC 2099)	<i>... BV... JHK<sub>S</sub></i>	8.73	0.27	0.089
NGC 1817	<i>... BV RI JHK<sub>S</sub></i>	8.80	0.26	-0.268
NGC 2477	<i>UBV... JHK<sub>S</sub></i>	9.04	0.23	0.019
NGC 2420	<i>... BV RI JHK<sub>S</sub></i>	9.24	0.05	-0.266
M67 (NGC 2682)	<i>UBV RI JHK<sub>S</sub></i>	9.60	0.04	0.000

Used  
Photometry

Parameters from the literature

Cluster	Padova	Baraffe	Geneva	Y <sup>2</sup>	Siess	Twarog et al.
M35 (NGC 2168)	10.16	10.41	9.81	9.91	9.96	10.30
M37 (NGC 2099)	11.55	11.40	11.50	11.35	11.75	11.55
NGC 1817	12.10	12.30	11.90	11.85	12.00	12.15
NGC 2477	11.55	11.60	11.30	11.15	11.45	11.55
NGC 2420	12.12	12.45	11.95	11.90	12.07	12.10
M67 (NGC 2682)	9.80	9.80	9.60	9.45	9.65	9.80

log t, E(B-V) and [Fe/H] fixed, only  
Distance modulus determined

Value from the  
literature

Cluster	Padova	Baraffe	Geneva	Y <sup>2</sup>	Siess	Twarog et al.
M35 (NGC 2168)	10.16	10.41	9.81	9.91	9.96	10.30
M37 (NGC 2099)	11.55	11.40	11.50	11.35	11.75	11.55
NGC 1817	12.10	12.30	11.90	11.85	12.00	12.15
NGC 2477	11.55	11.60	11.30	11.15	11.45	11.55
NGC 2420	12.12	12.45	11.95	11.90	12.07	12.10
M67 (NGC 2682)	9.80	9.80	9.60	9.45	9.65	9.80

## Transformation in distances [pc]

- M35: 1148 [916,1208]; -20% +5%
- M37: 2042 [1905,2239]; -7% +10%
- NGC 1817: 2692 [2344,2884]; -13% +7%
- NGC 2477: 2042 [1698,2089]; -17% +2%
- NGC 2420: 2630 [2399,3090]; -9% +17%
- M67: 912 [776,912]; -15% +0%
- Mean values: -13(5)% +7(6)%, for one free parameter!

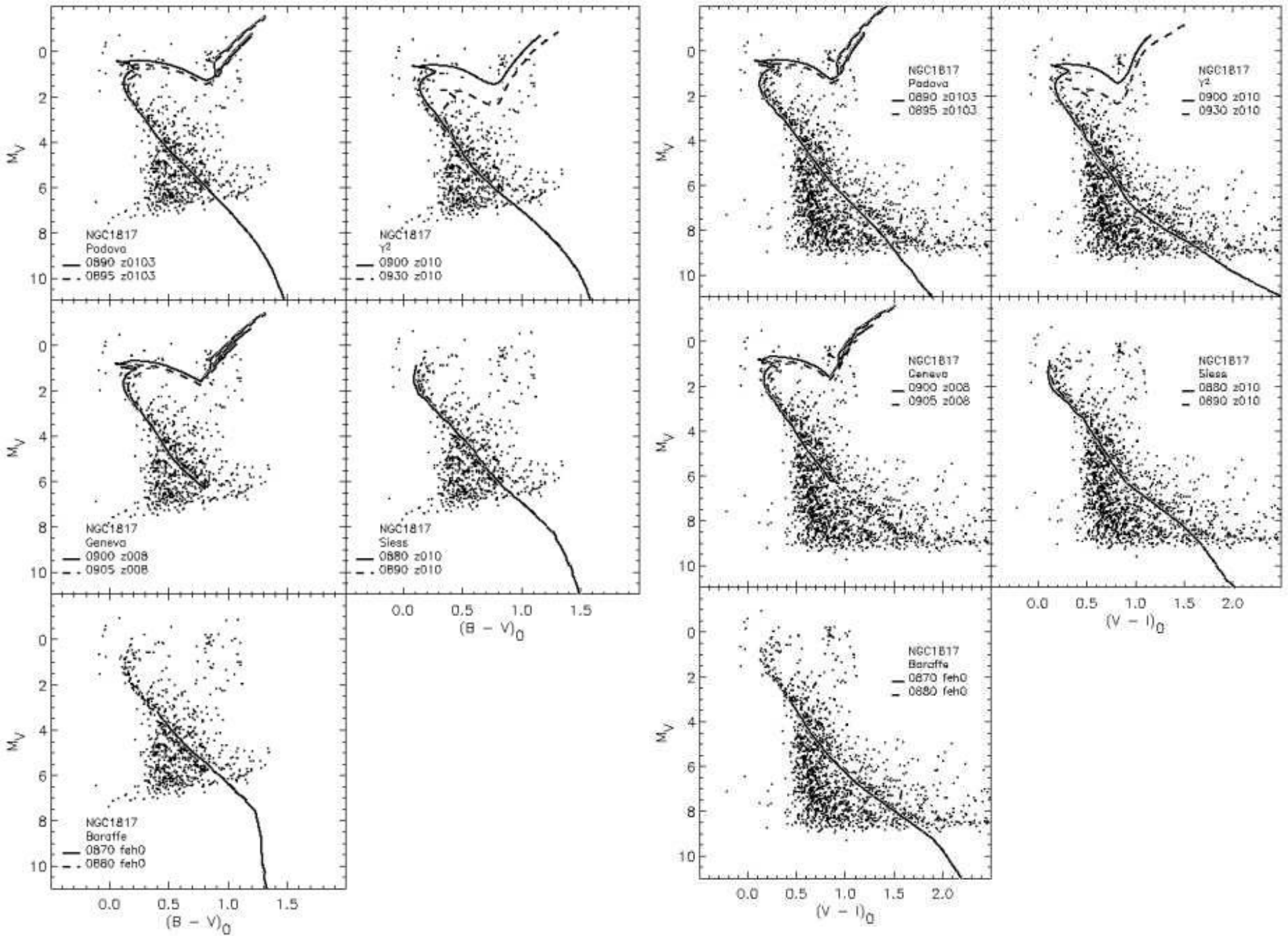
Cluster	Padova	Baraffe	Geneva	Y <sup>2</sup>	Siess	Twarog et al.
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NGC 2477	11.55	11.60	11.30	11.15	11.45	11.55
NGC 2420	12.12	12.45	11.95	11.90	12.07	12.10
M67 (NGC 2682)	9.80	9.80	9.60	9.45	9.65	9.80

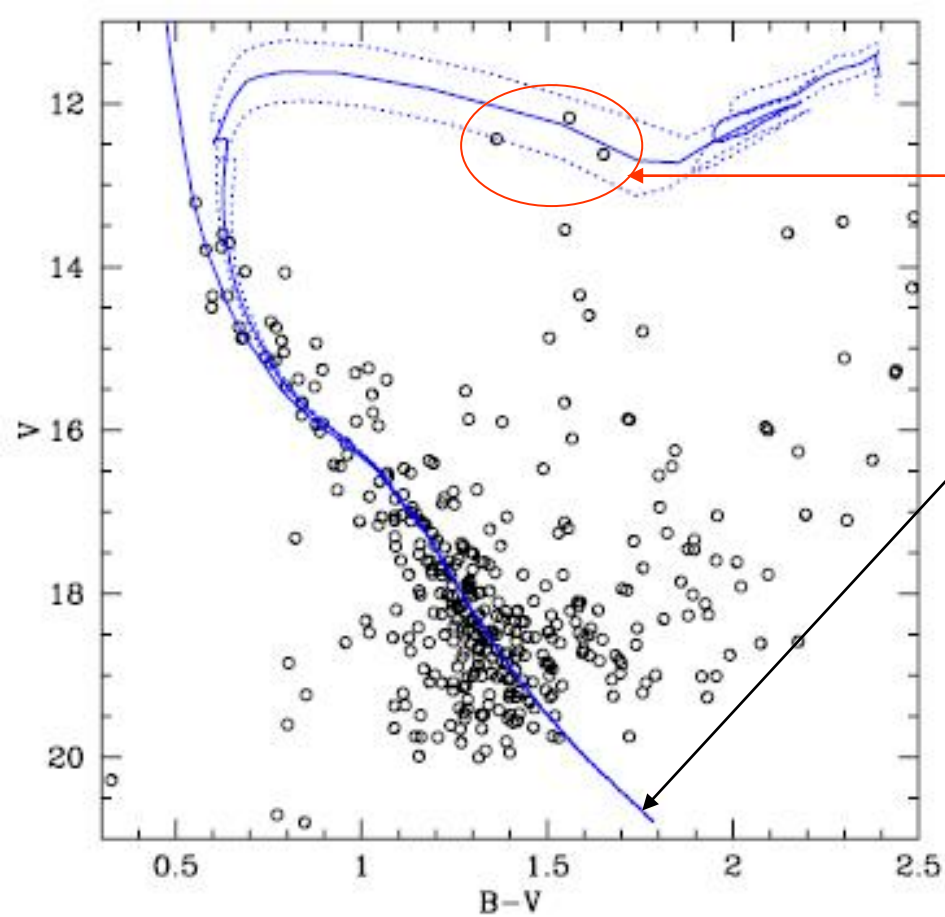
In a statistical point-of-view: **significant**

For a given reddening, metallicity and age, the isochrones by Baraffe et al. yield **significantly brighter** and Yi et al. **significantly fainter** absolute magnitudes .

In addition, the isochrones by Siess et al. **do not** reproduce the location of the Sun correctly.

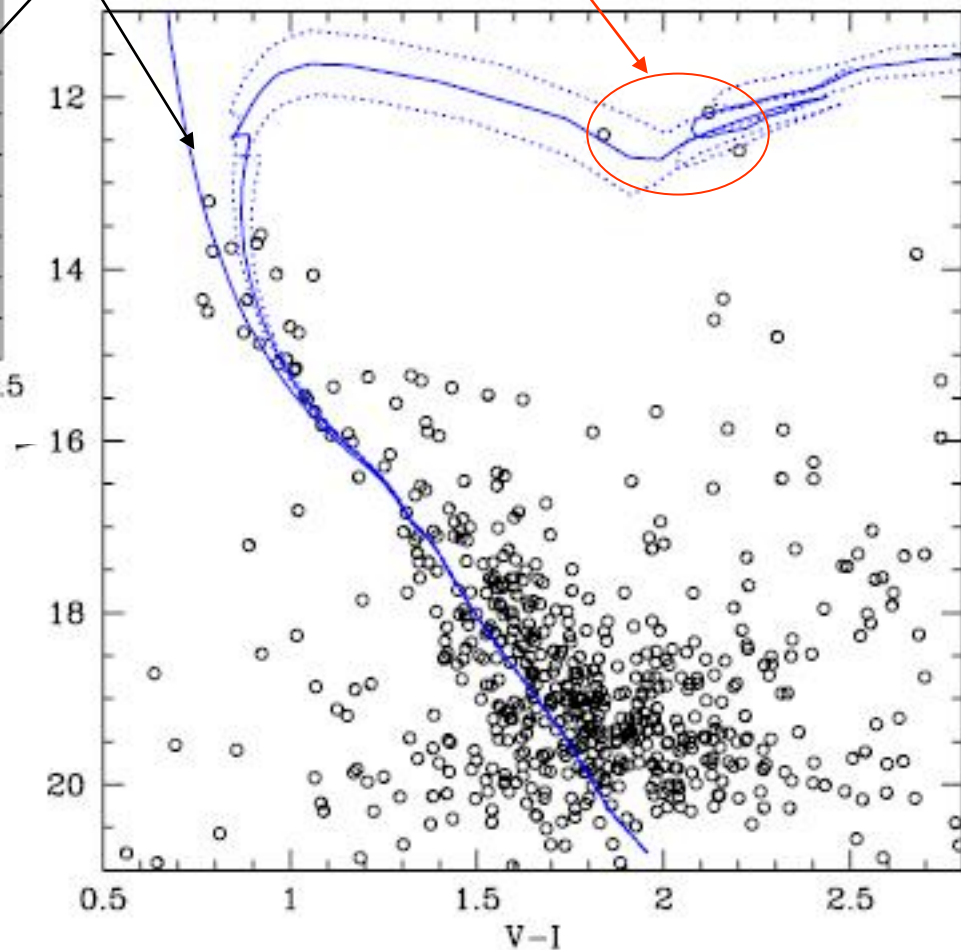






Age determination ONLY  
based on these three  
stars

log t = 7.0



Isochrones for  $[Z] = 0.040$   
and  $\log t = 8.0, 8.1$  und  $8.2$

Result:  $t = 130^{+40}_{-30}$  Myr  
 $E(B-V) = 0.75(5)$  mag  
 $V - M_V = 14.00(25)$  mag

# Automatic Methods

Jorgensen & Lindegren, 2005, A&A, 436, 127

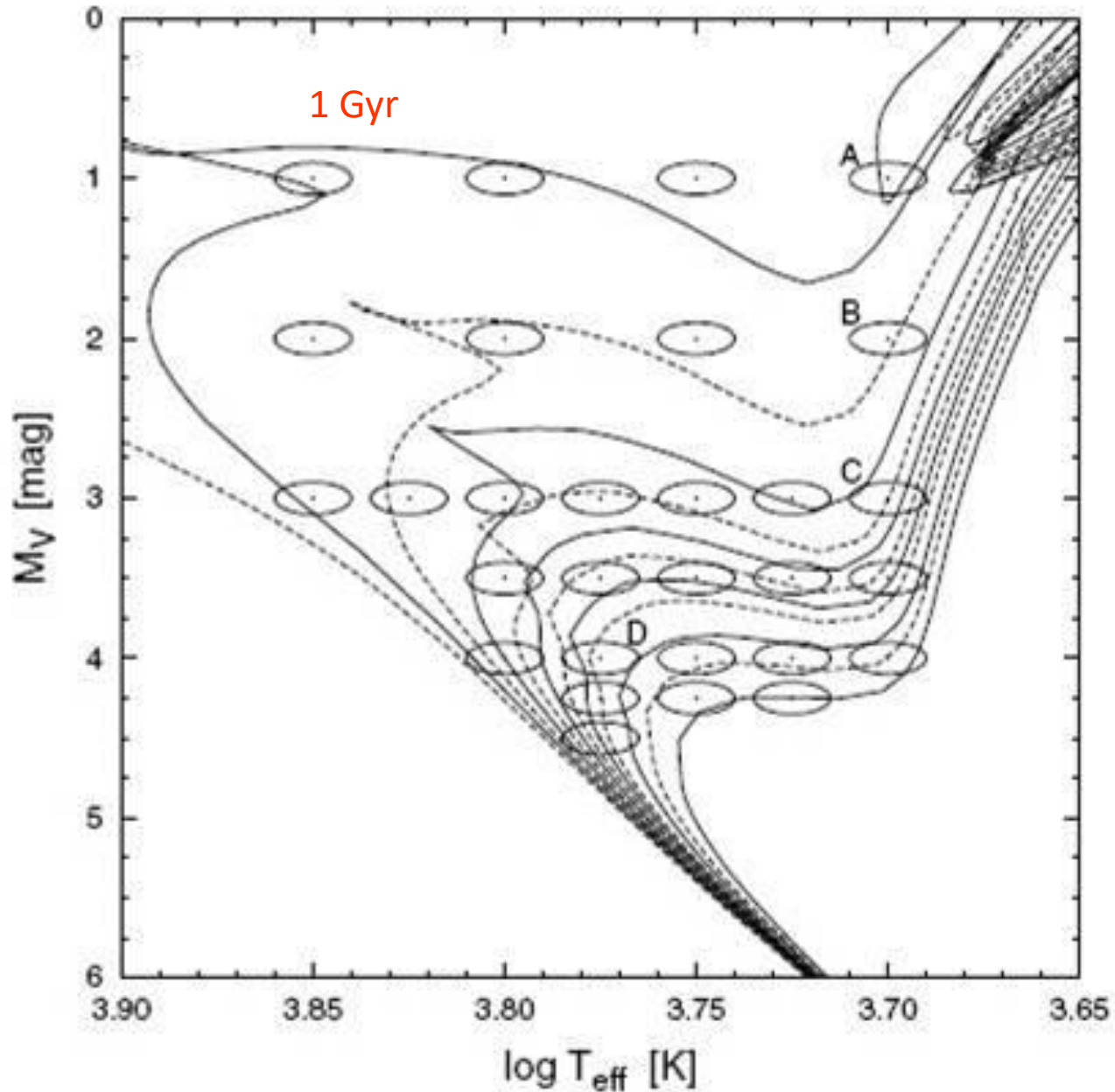
Definition of different „important“ areas (Box) in the CMD. Do this allocation as you like.

Turn-off point, location of the red giant clump, and so on.

Count the number of stars in each box.

Warning: you always „lose“ stars because of discrete boxes.

Only for  $t > 300$  Myr



# Other methods

- <https://github.com/hektor-monteiro/OCFit>
- <https://asteca.readthedocs.io/en/latest/>
- An et al., 2007, ApJ, 655, 233
- Buckner & Froebrich, 2013, MNRAS, 436, 1465
- Fernandes et al., 2012, A&A, 541, A95
- Frayn & Gilmore, 2003, MNRAS, 339, 887
- Kharchenko et al., 2005, A&A, 438, 1136
- Monteiro et al., 2010, A&A, 516, A2
- Oliveira et al., 2013, A&A, 557, A14
- Pinsonneault et al., 2003, ApJ, 598, 588

# Metallicity - Basics

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

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

# Metallicity - designations

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

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

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

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

# Metallicity – designations

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

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

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

$[\text{Fe}/\text{H}]$	$[\text{Z}]$	$[\text{Fe}/\text{H}]$	$[\text{Z}]$	$[\text{Fe}/\text{H}]$	$[\text{Z}]$
-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, ...)

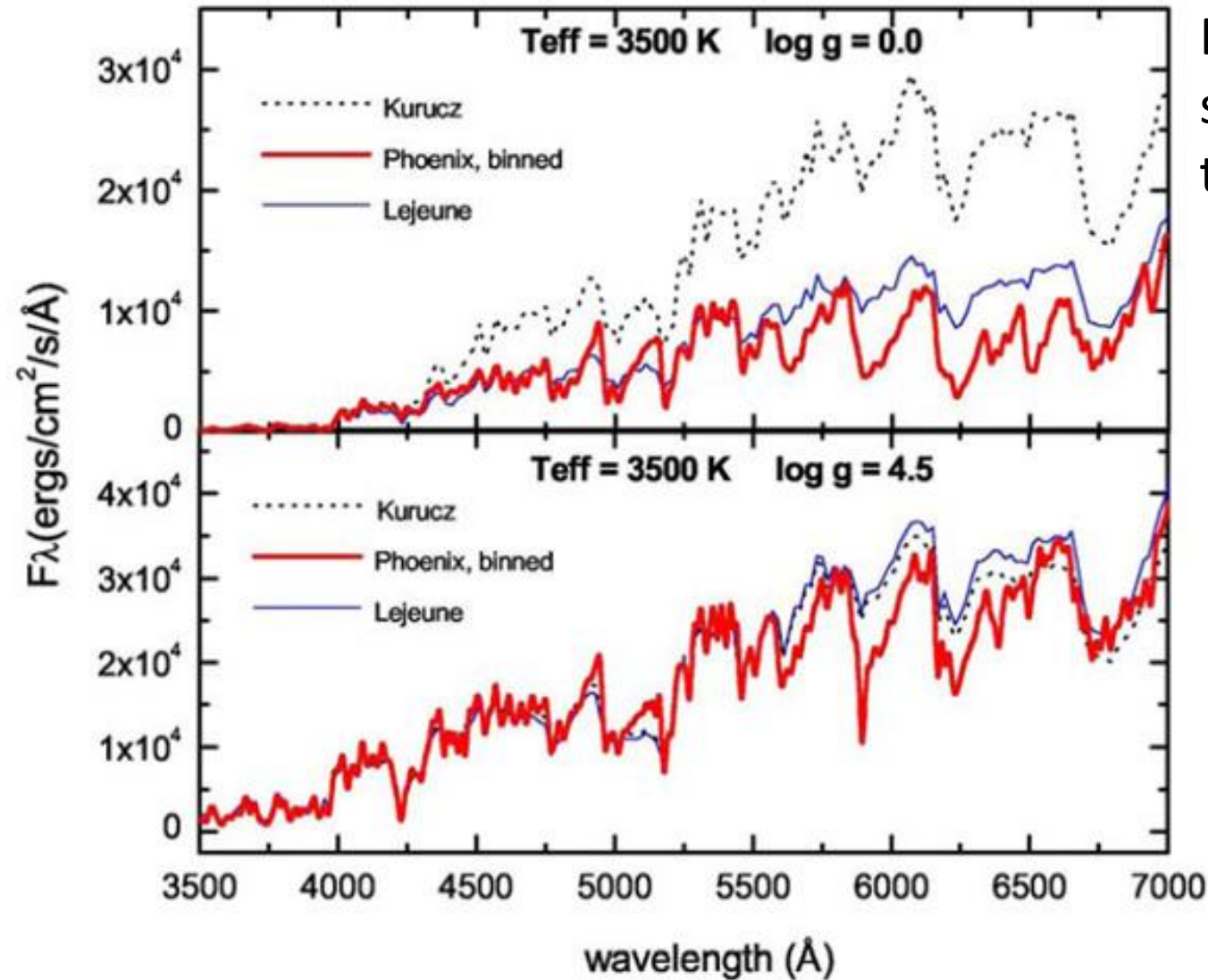
# Abundance analysis - Sun

- *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/](http://www.arm.ac.uk/~csj/software_store/)
- **Workshop:** [http://astro.physics.muni.cz/events/spec\\_ws\\_2017/](http://astro.physics.muni.cz/events/spec_ws_2017/)

# Stellar atmospheres



Different synthesized stellar spectra “for the same star”

# Abundance - Sun

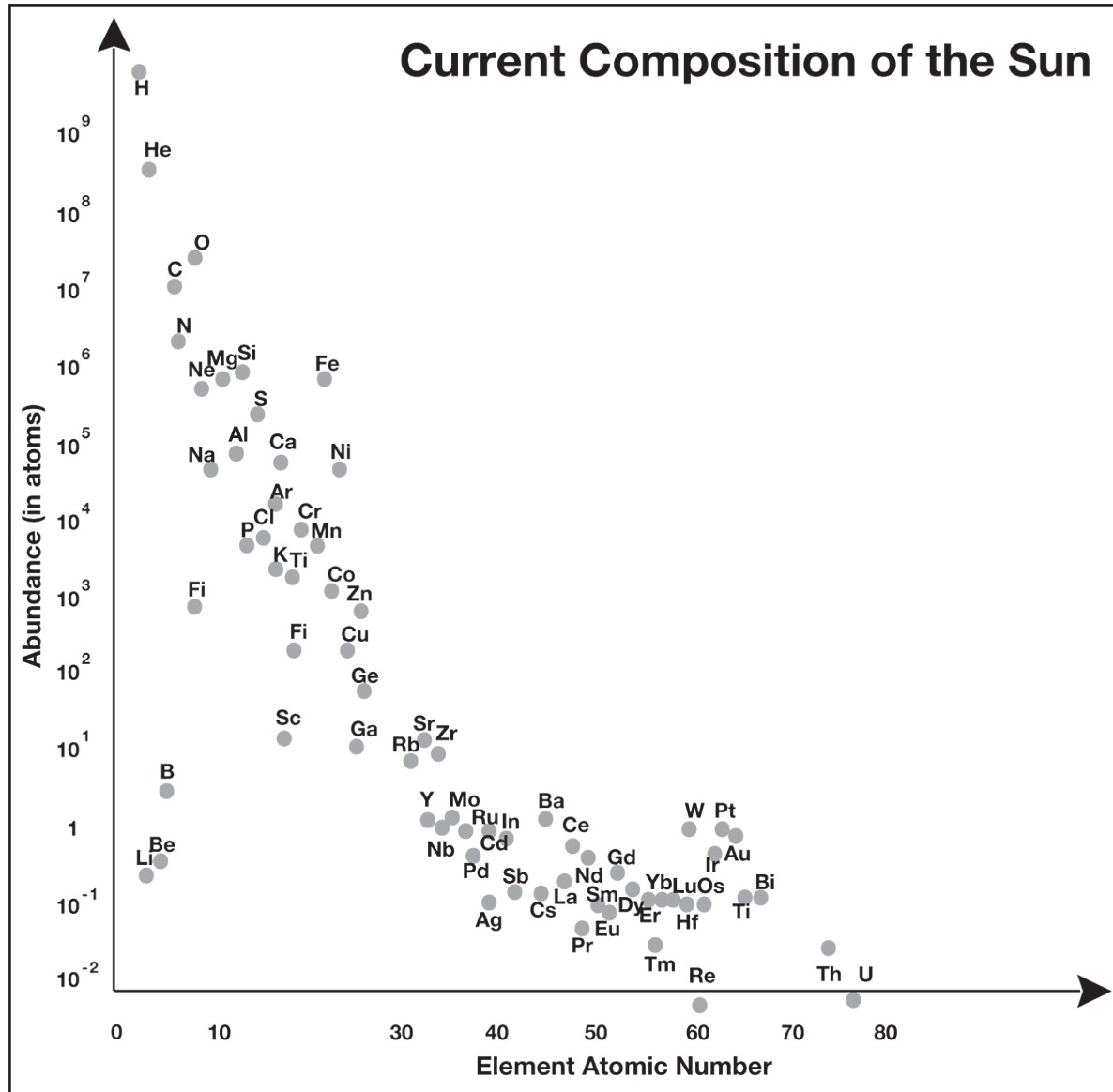
- Problems with
  - Hydrogen
  - Helium
  - Elements with only a few lines
  - Elements with only weak lines
- LTE versus NLTE (Local Thermodynamic Equilibrium )

# Abundance - Sun

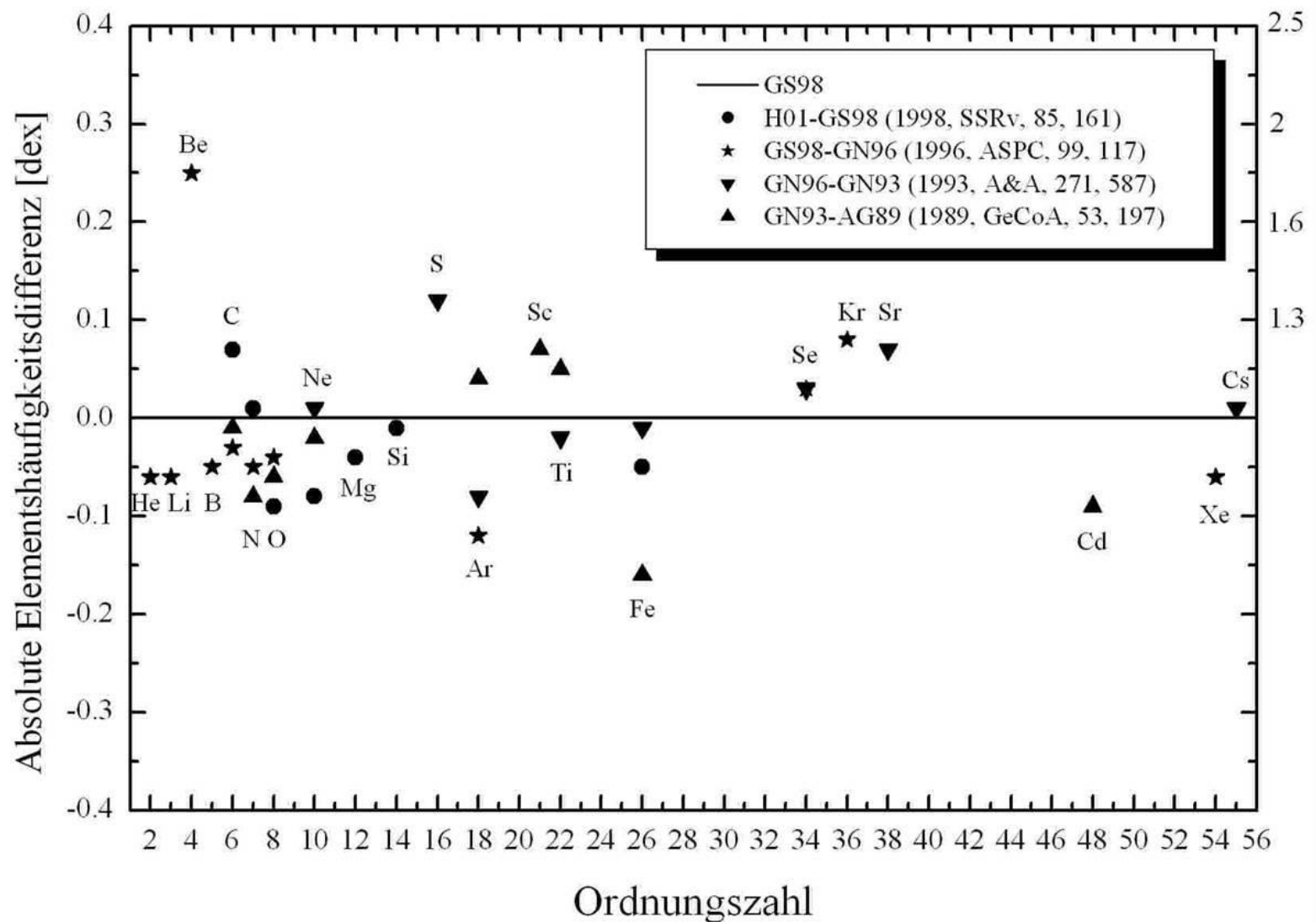
Asplund et al.

Elem.	Photosphere	Meteorites	Elem.	Photosphere	Meteorites	Elem.	Photosphere	Meteorites	Elem.	Photosphere	Meteorites
1	H	12.00	8.22 ± 0.04	44	Ru	1.75 ± 0.08	1.76 ± 0.03	67	Ho	0.48 ± 0.11	0.47 ± 0.03
2	He	[10.93 ± 0.01]	1.29	45	Rh	0.91 ± 0.10	1.06 ± 0.04	68	Er	0.92 ± 0.05	0.92 ± 0.02
3	Li	1.05 ± 0.10	3.26 ± 0.05	46	Pd	1.57 ± 0.10	1.65 ± 0.02	69	Tm	0.10 ± 0.04	0.12 ± 0.03
4	Be	1.38 ± 0.09	1.30 ± 0.03	47	Ag	0.94 ± 0.10	1.20 ± 0.02	70	Yb	0.84 ± 0.11	0.92 ± 0.02
5	B	2.70 ± 0.20	2.79 ± 0.04	48	Cd		1.71 ± 0.03	71	Lu	0.10 ± 0.09	0.09 ± 0.02
6	C	8.43 ± 0.05	7.39 ± 0.04	49	In	0.80 ± 0.20	0.76 ± 0.03	72	Hf	0.85 ± 0.04	0.71 ± 0.02
7	N	7.83 ± 0.05	6.26 ± 0.06	50	Sn	2.04 ± 0.10	2.07 ± 0.06	73	Ta		-0.12 ± 0.04
8	O	8.69 ± 0.05	8.40 ± 0.04	51	Sb		1.01 ± 0.06	74	W	0.85 ± 0.12	0.65 ± 0.04
9	F	4.56 ± 0.30	4.42 ± 0.06	52	Te		2.18 ± 0.03	75	Re		0.26 ± 0.04
10	Ne	[7.93 ± 0.10]	-1.12	53	I		1.55 ± 0.08	76	Os	1.40 ± 0.08	1.35 ± 0.03
11	Na	6.24 ± 0.04	6.27 ± 0.02	54	Xe	[2.24 ± 0.06]	-1.95	77	Ir	1.38 ± 0.07	1.32 ± 0.02
12	Mg	7.60 ± 0.04	7.53 ± 0.01	55	Cs		1.08 ± 0.02	78	Pt		1.62 ± 0.03
13	Al	6.45 ± 0.03	6.43 ± 0.01	56	Ba	2.18 ± 0.09	2.18 ± 0.03	79	Au	0.92 ± 0.10	0.80 ± 0.04
14	Si	7.51 ± 0.03	7.51 ± 0.01	57	La	1.10 ± 0.04	1.17 ± 0.02	80	Hg		1.17 ± 0.08
15	P	5.41 ± 0.03	5.43 ± 0.04	58	Ce	1.58 ± 0.04	1.58 ± 0.02	81	Tl	0.90 ± 0.20	0.77 ± 0.03
16	S	7.12 ± 0.03	7.15 ± 0.02	59	Pr	0.72 ± 0.04	0.76 ± 0.03	82	Pb	1.75 ± 0.10	2.04 ± 0.03
17	Cl	5.50 ± 0.30	5.23 ± 0.06	60	Nd	1.42 ± 0.04	1.45 ± 0.02	83	Bi		0.65 ± 0.04
18	Ar	[6.40 ± 0.13]	-0.50	62	Sm	0.96 ± 0.04	0.94 ± 0.02	90	Th	0.02 ± 0.10	0.06 ± 0.03
19	K	5.03 ± 0.09	5.08 ± 0.02	63	Eu	0.52 ± 0.04	0.51 ± 0.02	92	U		-0.54 ± 0.03
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
								24	Cr	5.64 ± 0.04	5.64 ± 0.01
								25	Mn	5.43 ± 0.05	5.48 ± 0.01
								26	Fe	7.50 ± 0.04	7.45 ± 0.01
								27	Co	4.99 ± 0.07	4.87 ± 0.01
								28	Ni	6.22 ± 0.04	6.20 ± 0.01
								29	Cu	4.19 ± 0.04	4.25 ± 0.04
								30	Zn	4.56 ± 0.05	4.63 ± 0.04
								31	Ga	3.04 ± 0.09	3.08 ± 0.02
								32	Ge	3.65 ± 0.10	3.58 ± 0.04
								33	As		2.30 ± 0.04
								34	Se		3.34 ± 0.03
								35	Br		2.54 ± 0.06
								36	Kr	[3.25 ± 0.06]	-2.27
								37	Rb	2.52 ± 0.10	2.36 ± 0.03
								38	Sr	2.87 ± 0.07	2.88 ± 0.03
								39	Y	2.21 ± 0.05	2.17 ± 0.04
								40	Zr	2.58 ± 0.04	2.53 ± 0.04
								41	Nb	1.46 ± 0.04	1.41 ± 0.04
								42	Mo	1.88 ± 0.08	1.94 ± 0.04

# Abundance - Sun



# Abundance - Sun





# 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
<b>Present-day photosphere:</b>				
Anders & Grevesse (1989) <sup>a</sup>	0.7314	0.2485	0.0201	0.0274
Grevesse & Noels (1993) <sup>a</sup>	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
<b>Proto-solar:</b>				
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

<sup>a</sup> 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).

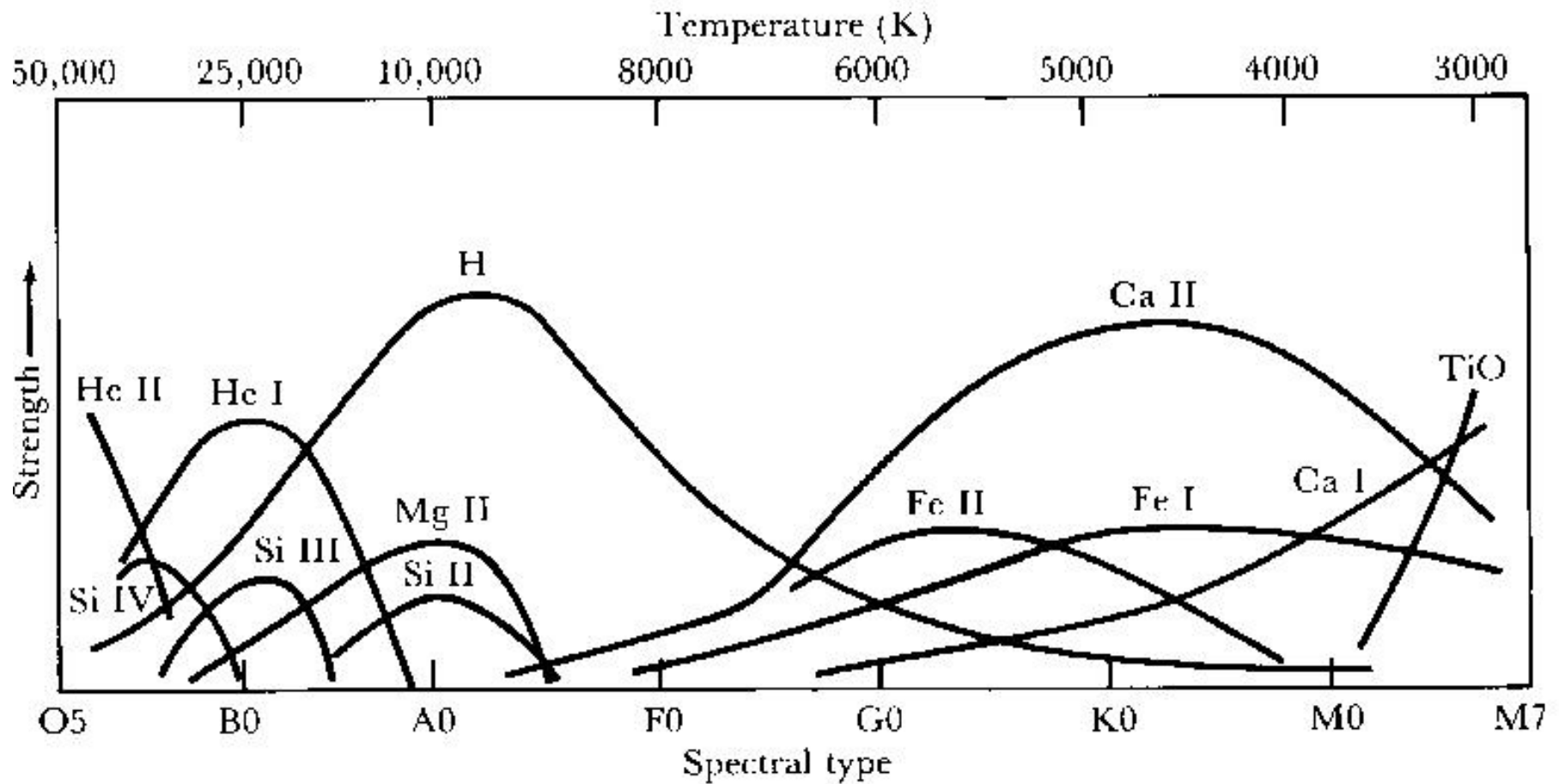
Table 2. Transformation of [Fe/H] to [Z] using  $[Y] = 0.23 + 2.25[Z]$  from Girardi et al. (2000) applied in this work.

[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		

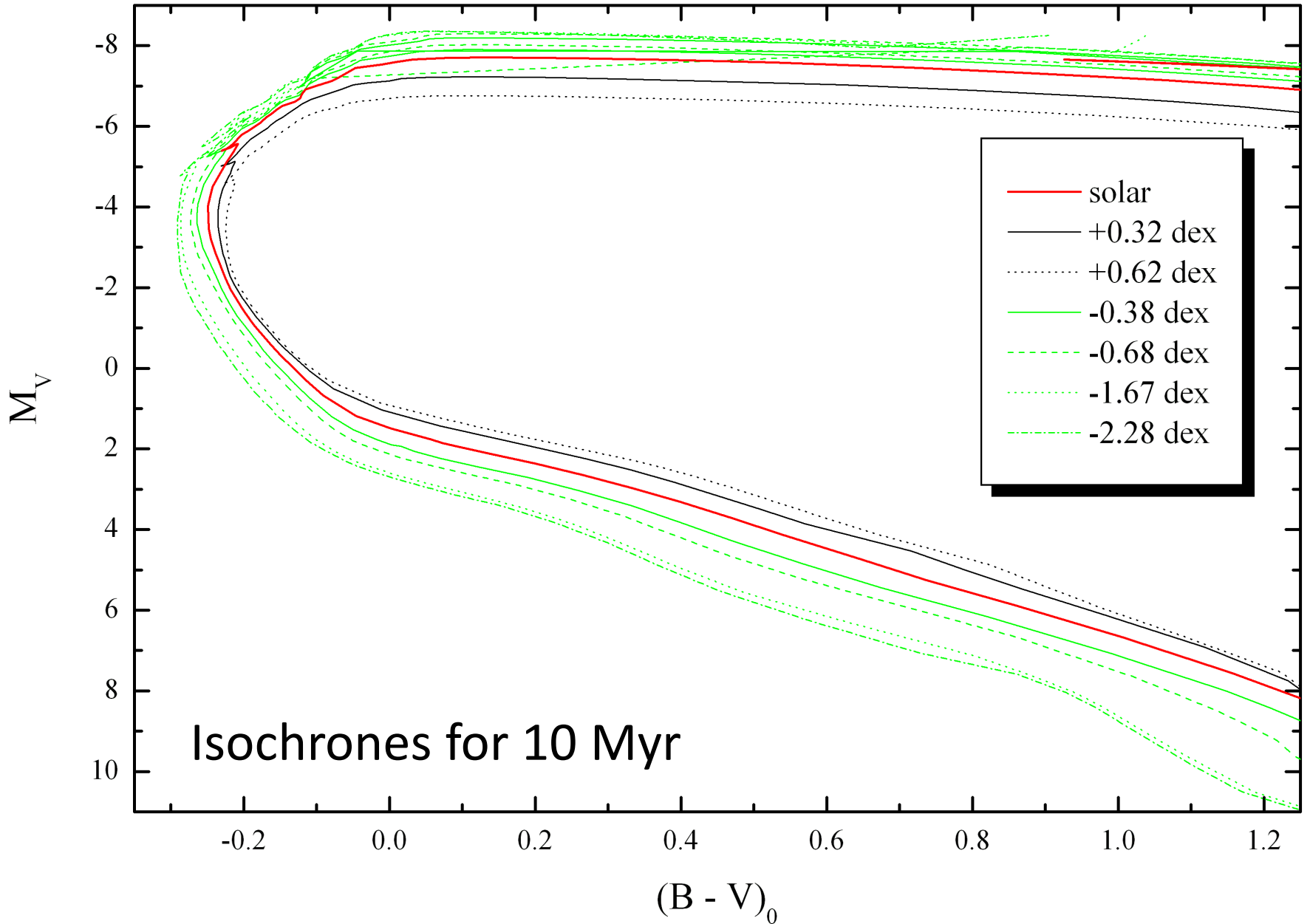
# Determination of the metallicity

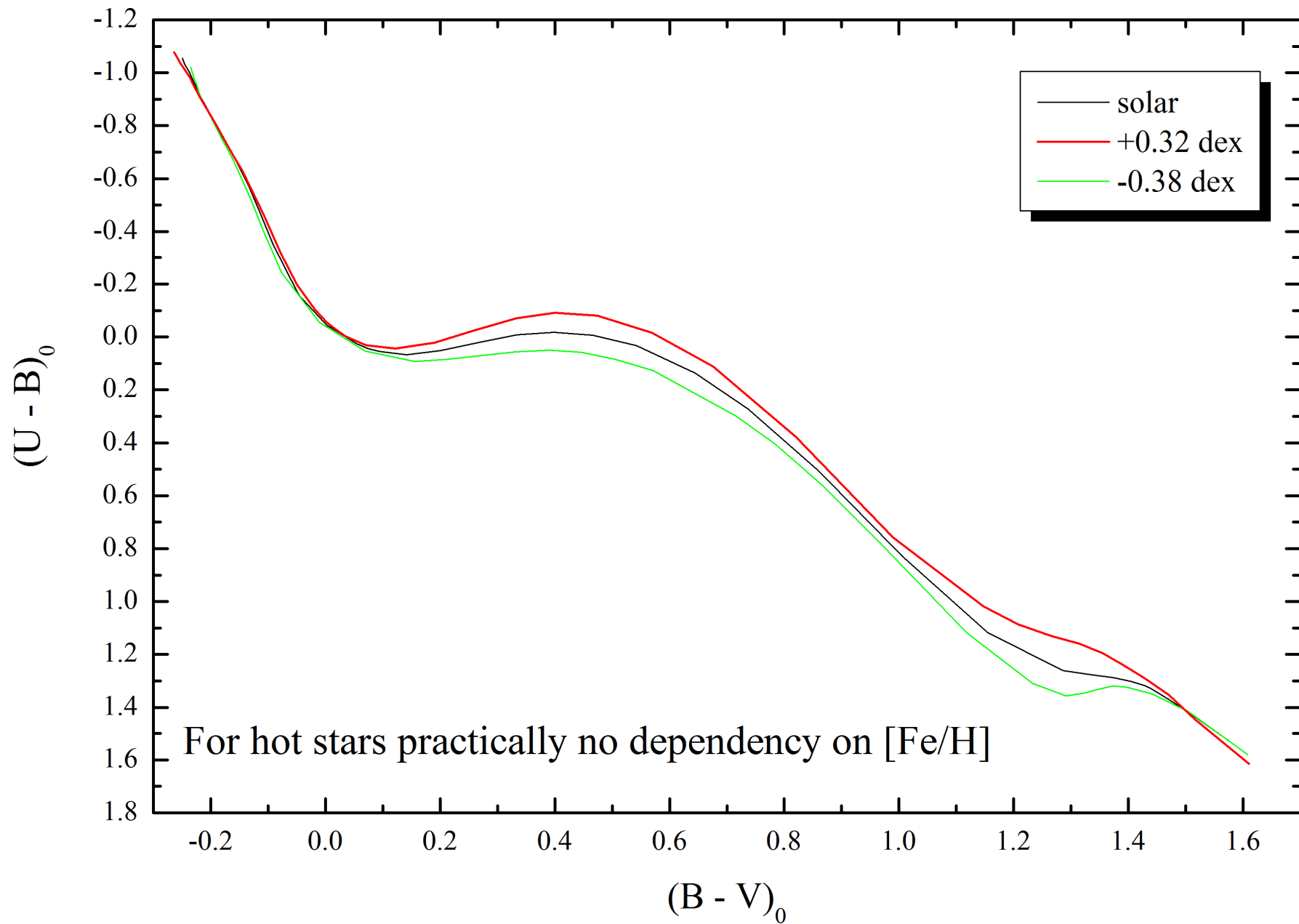
- The determination of the metallicity can be done in three ways:
  1. Spectroscopic abundance analysis
  2. Fitting of isochrones
  3. Photometric calibrations
- ESO- Gaia survey:  
<https://www.gaia-eso.eu/>

# „Metals“ in stars

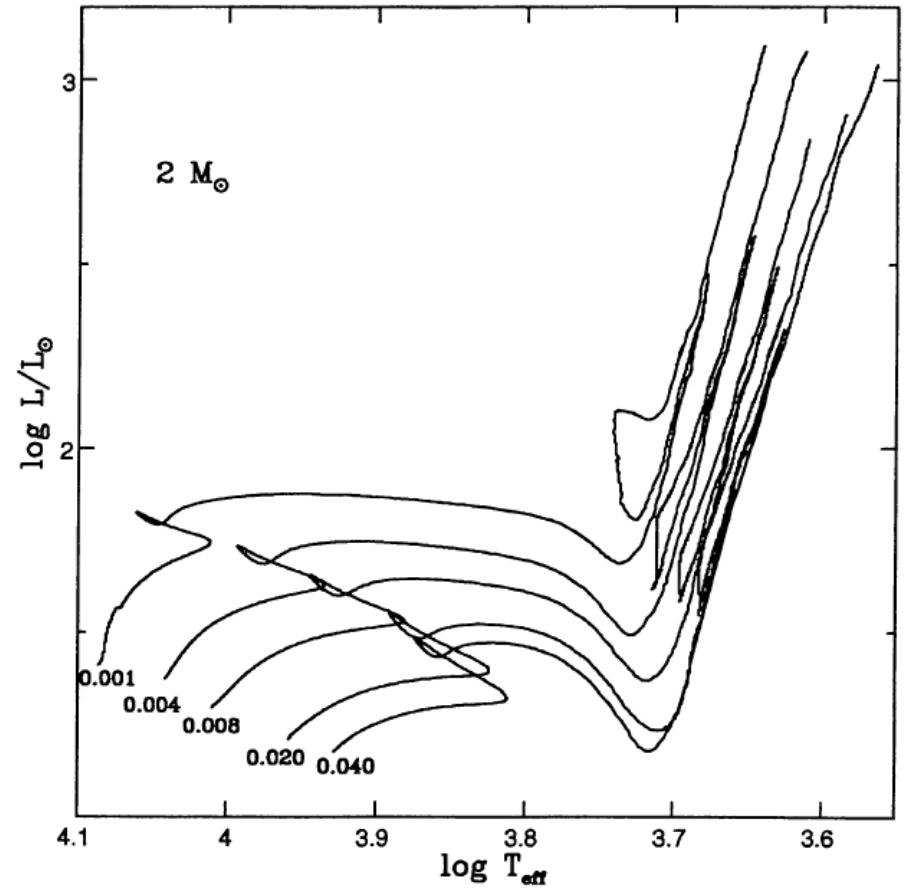
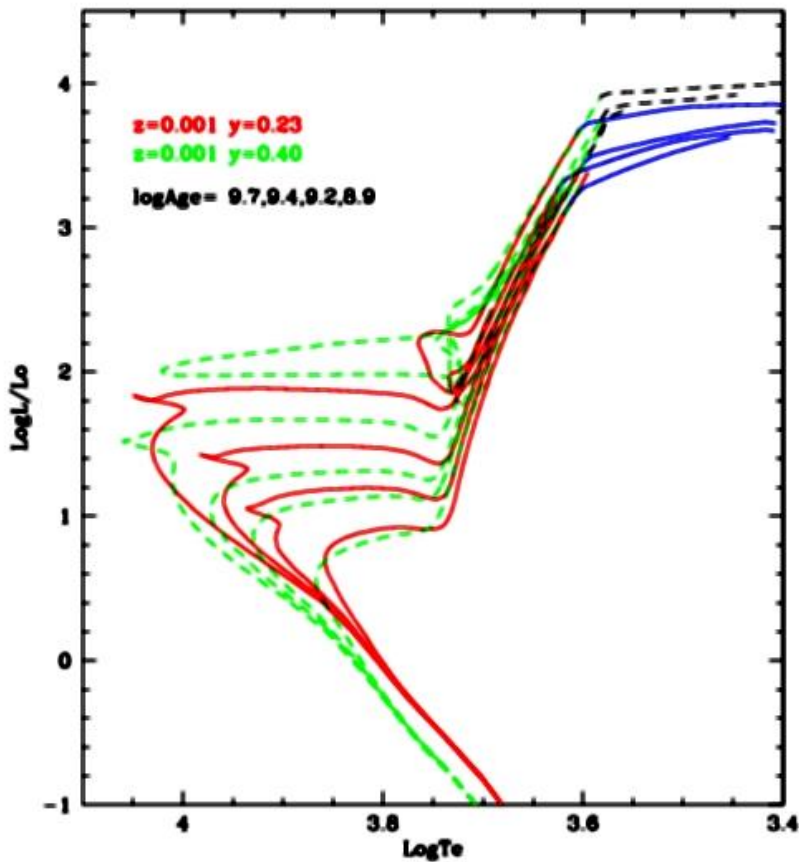


# Metallicity => different opacity





# Metallicity - isochrones



Different He abundances –  $[Z]$   
constant

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