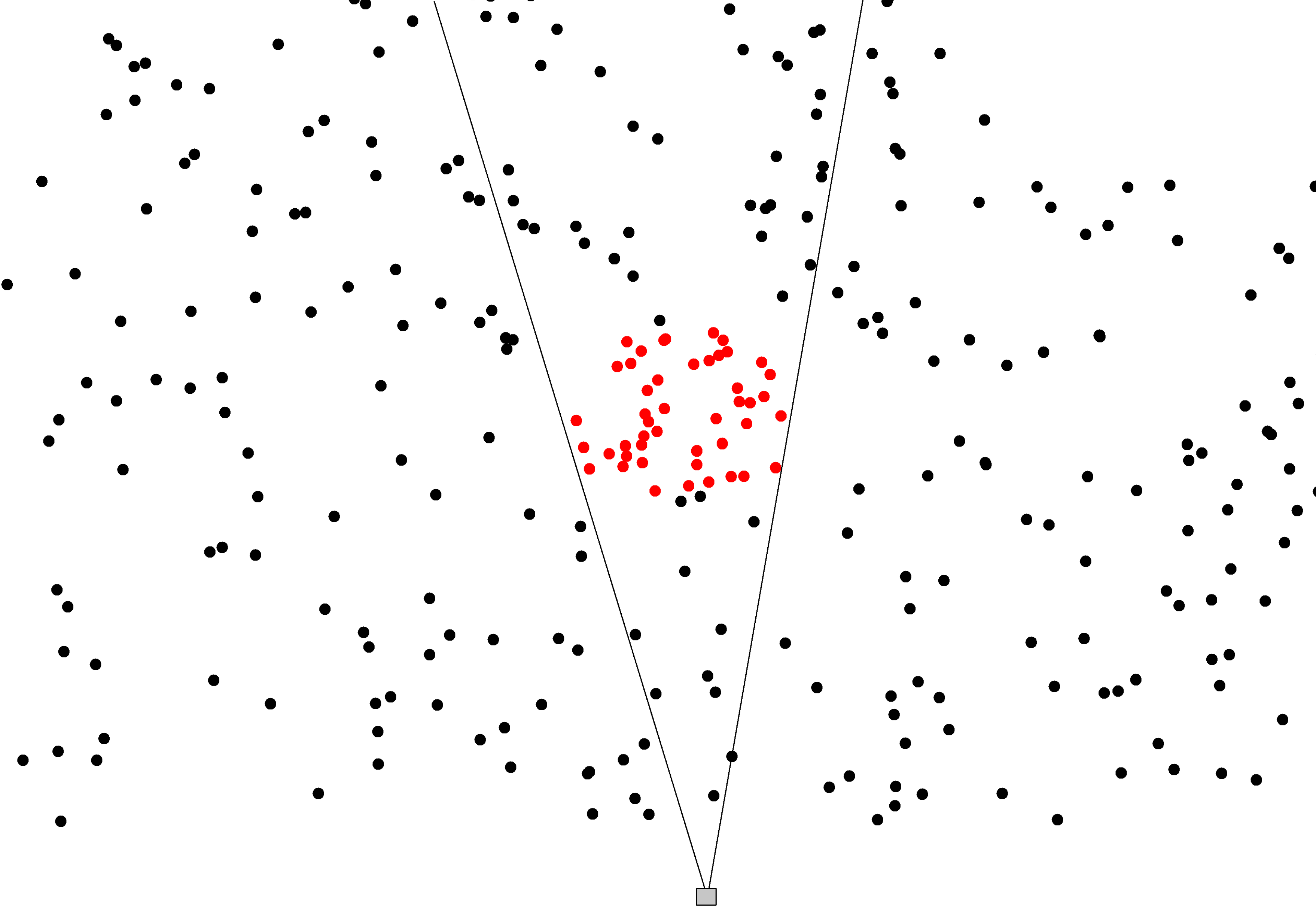
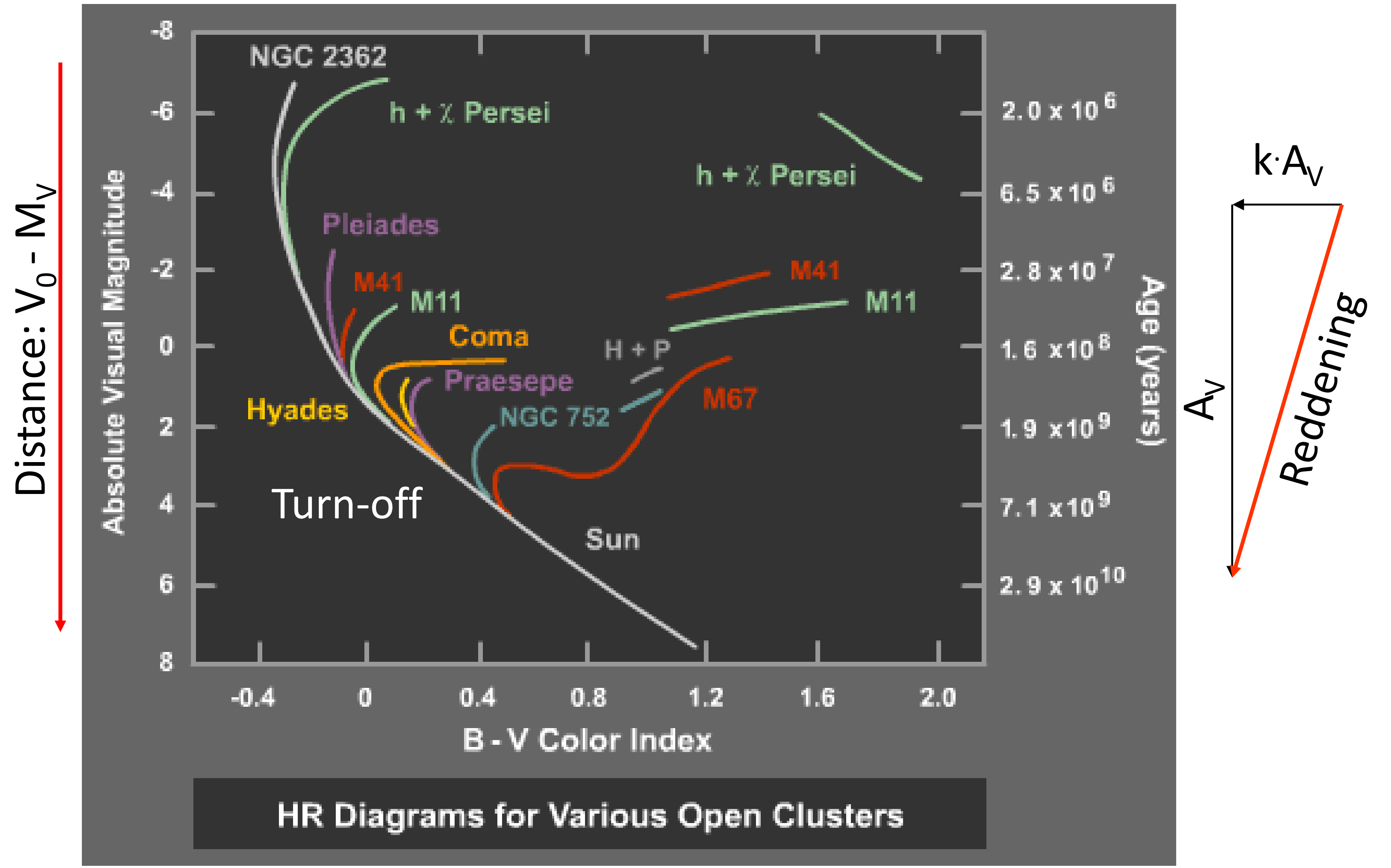
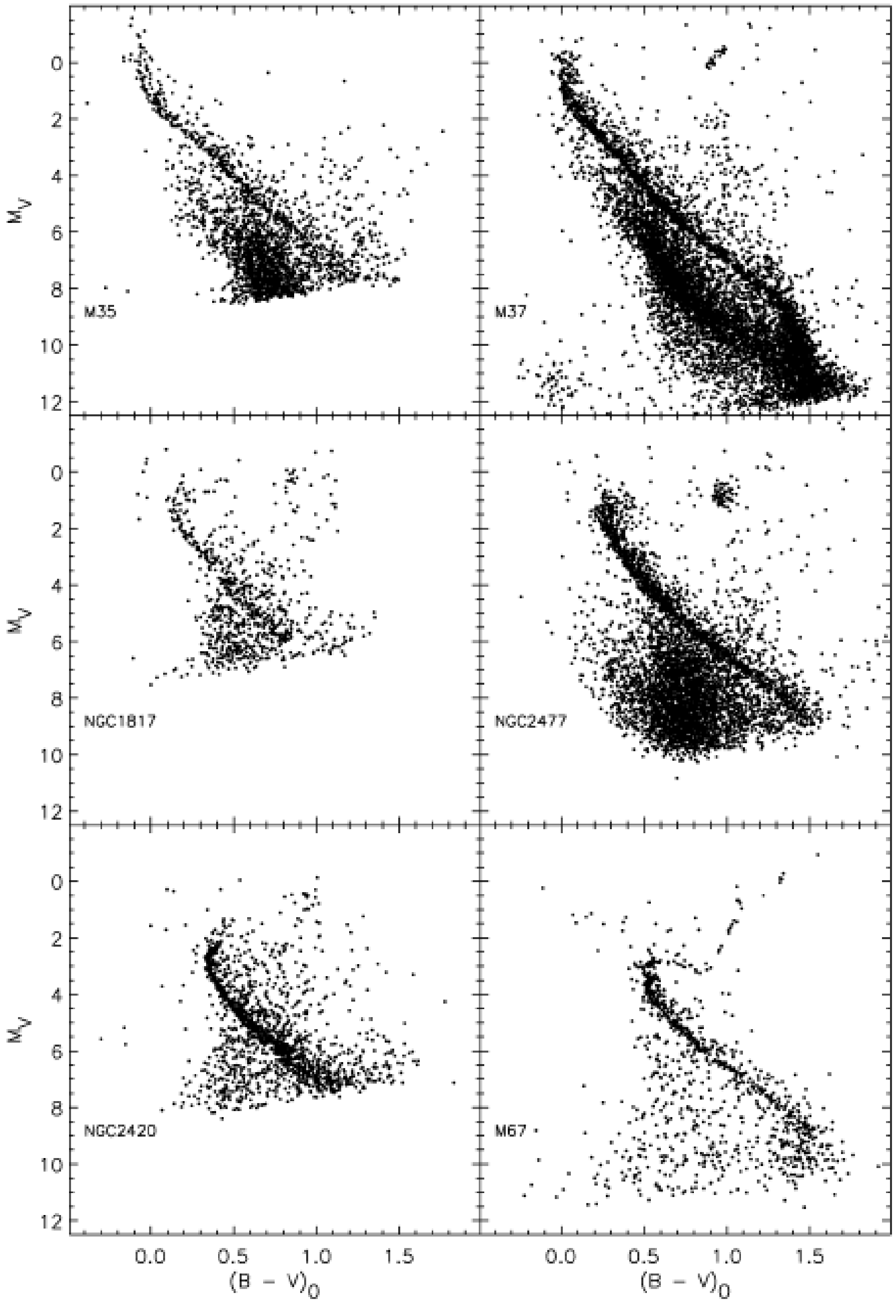
The cluster parameters

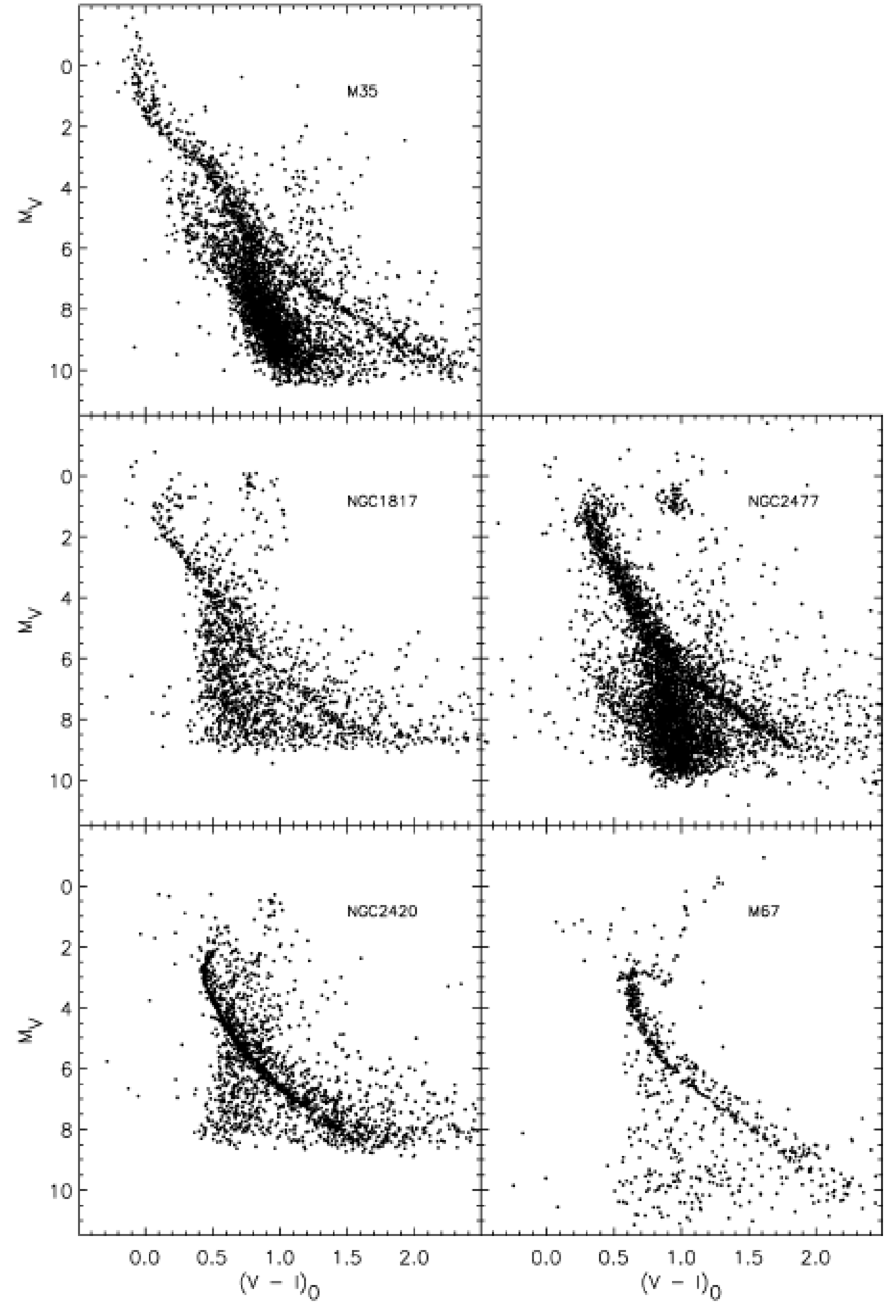
1. Reddening
2. Distance modulus
3. Age
4. Metallicity

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




Distance: V_0 - M_V
Absolute Visual Magnitude
-8
-6
-4
-2
0
2
4
6
8
NGC 2362
h + χ Persei
h + χ Persei
Pleiades
M41
M11
M41
M11
Coma
H + P
Praesepe
Hyades
NGC 752
M67
Turn-off
Sun
-0.4
0
0.4
0.8
1.2
1.6
2.0
B - V Color Index
2.0×10^6
6.5×10^6
2.8×10^7
1.6×10^8
1.9×10^9
7.1×10^9
2.9×10^{10}
Age (years)
HR Diagrams for Various Open Clusters
$k \cdot A_V$
A_V
Reddening



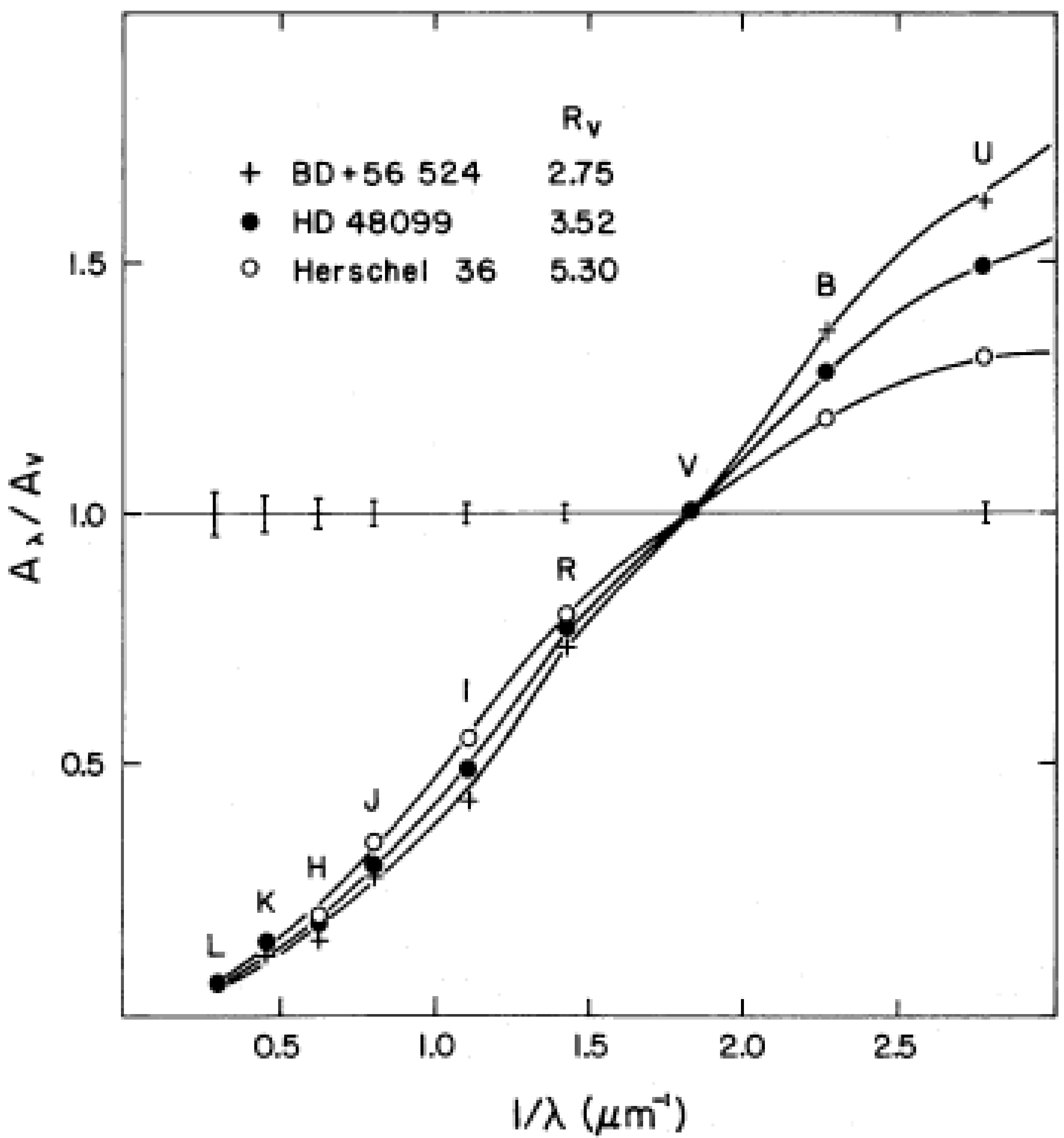


Grocholski & Sarajedini, 2003, MNRAS, 345, 1015

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

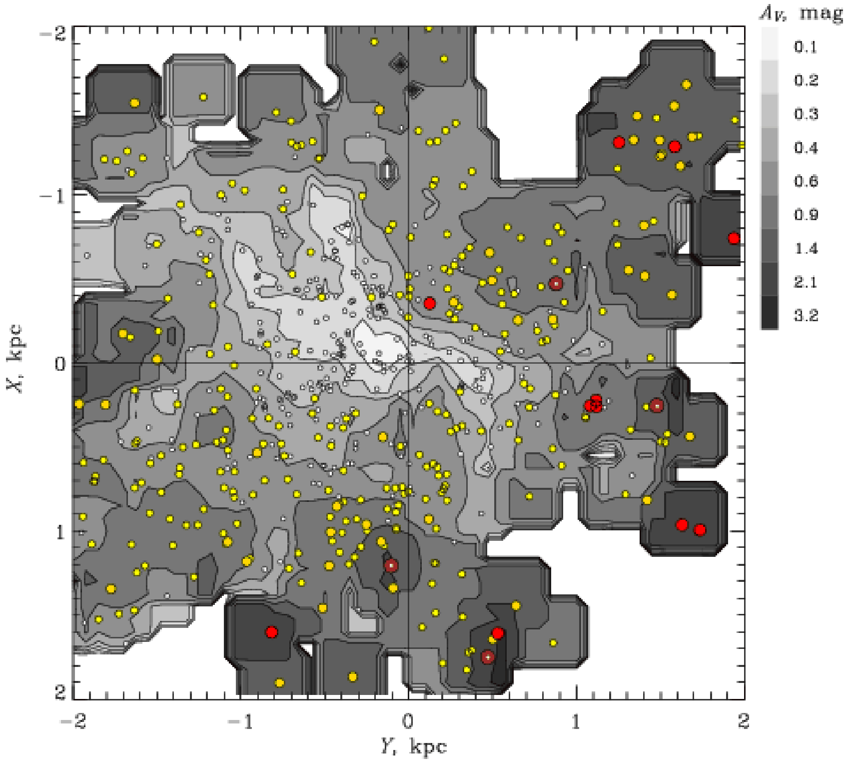
Standard value used is 3.1

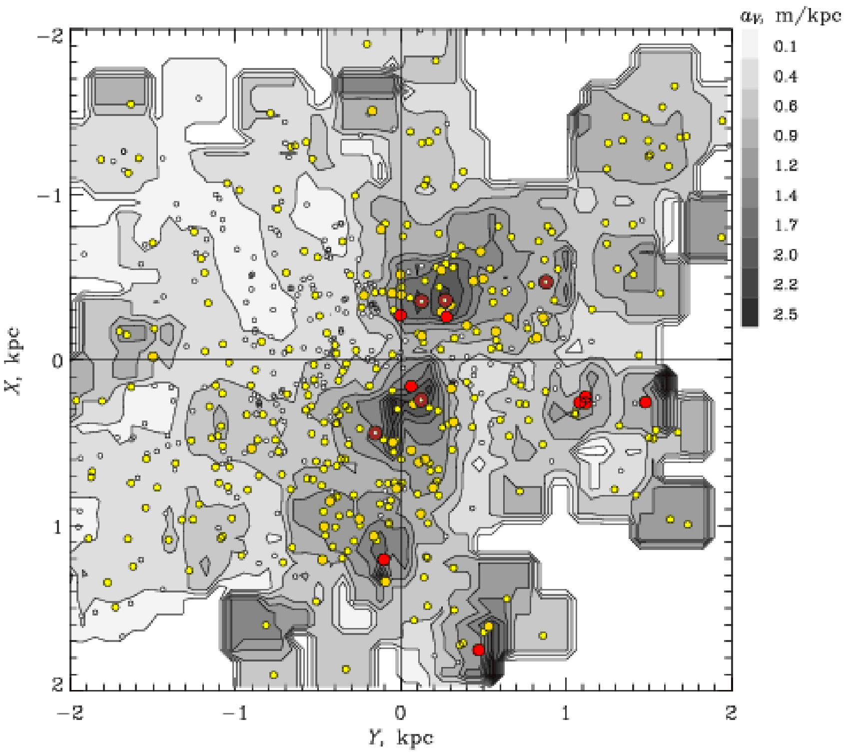
Be careful, different values used!

Depending on the line of sight

Reddening Maps

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

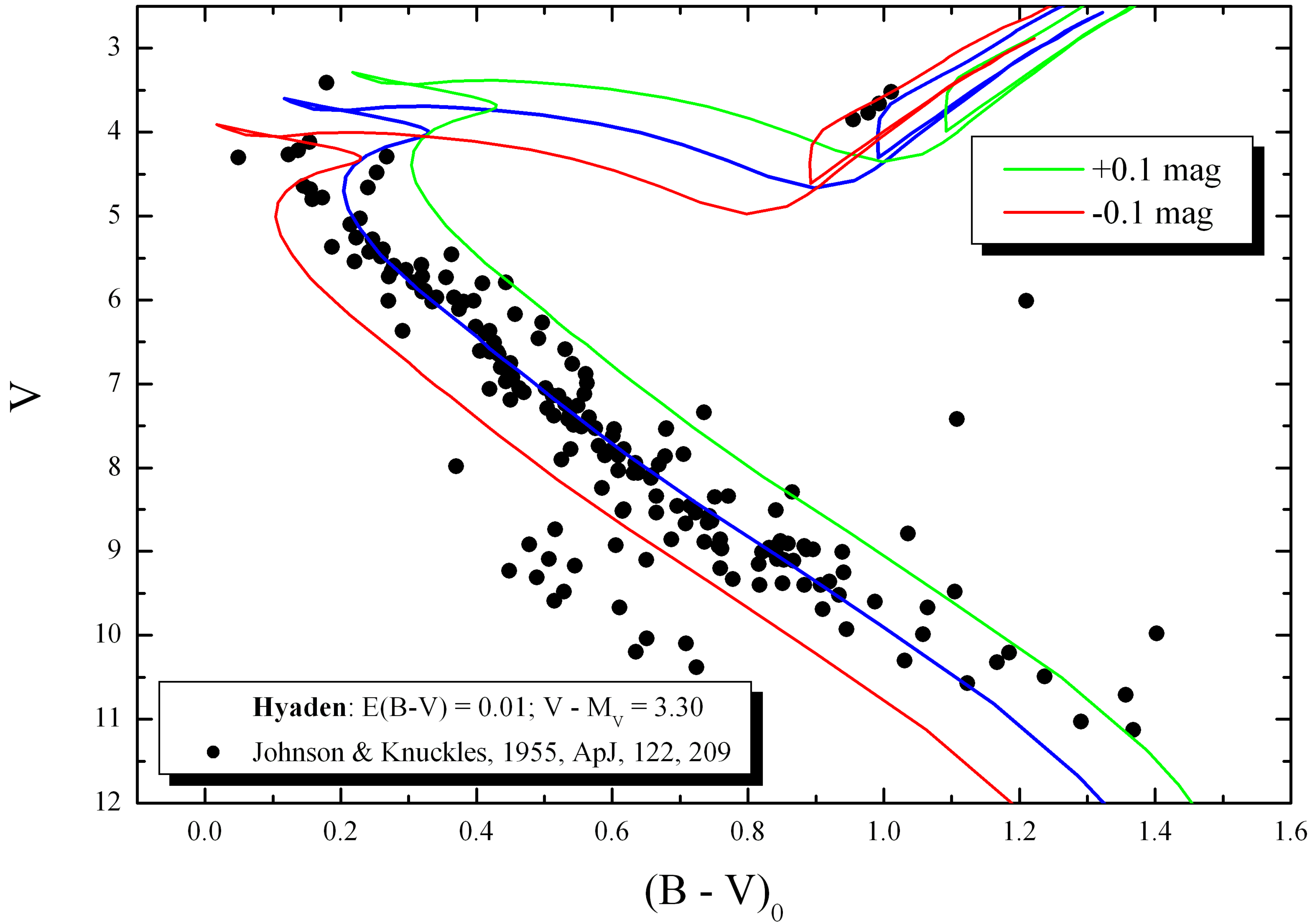




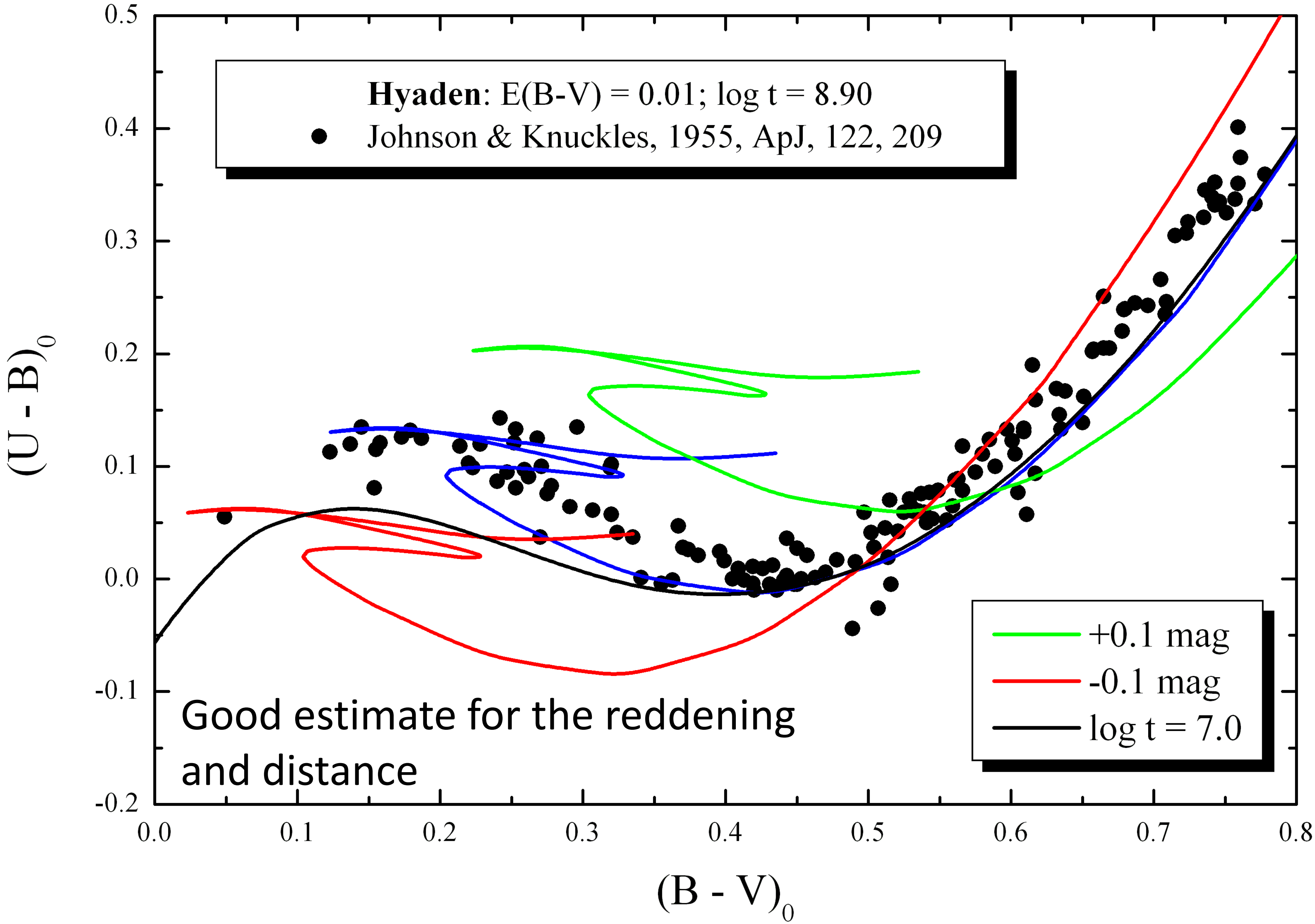
Piskunov et al., 2006, A&A, 445, 545

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



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

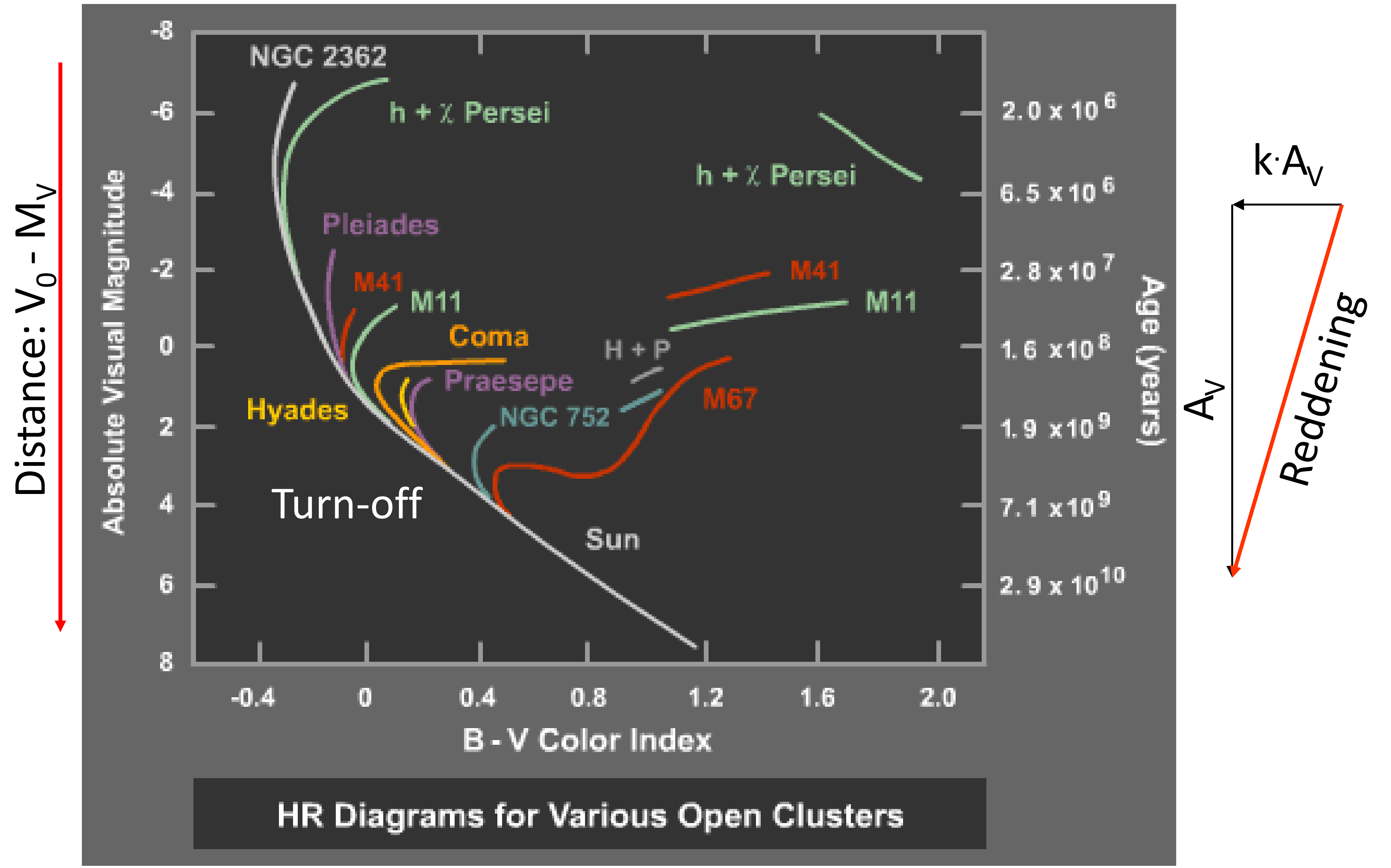

Hyaden: E(B-V) = 0.01; log t = 8.90
Johnson & Knuckles, 1955, ApJ, 122, 209
+0.1 mag
-0.1 mag
log t = 7.0
Good estimate for the reddening and distance
(U - B)0
(B - V)0
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8

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



Distance: $V_0 - M_V$
Absolute Visual Magnitude
-8
-6
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-2
0
2
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8
NGC 2362
h + χ Persei
h + χ Persei
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M41
M11
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H + P
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B - V Color Index
2.0 x 10 6
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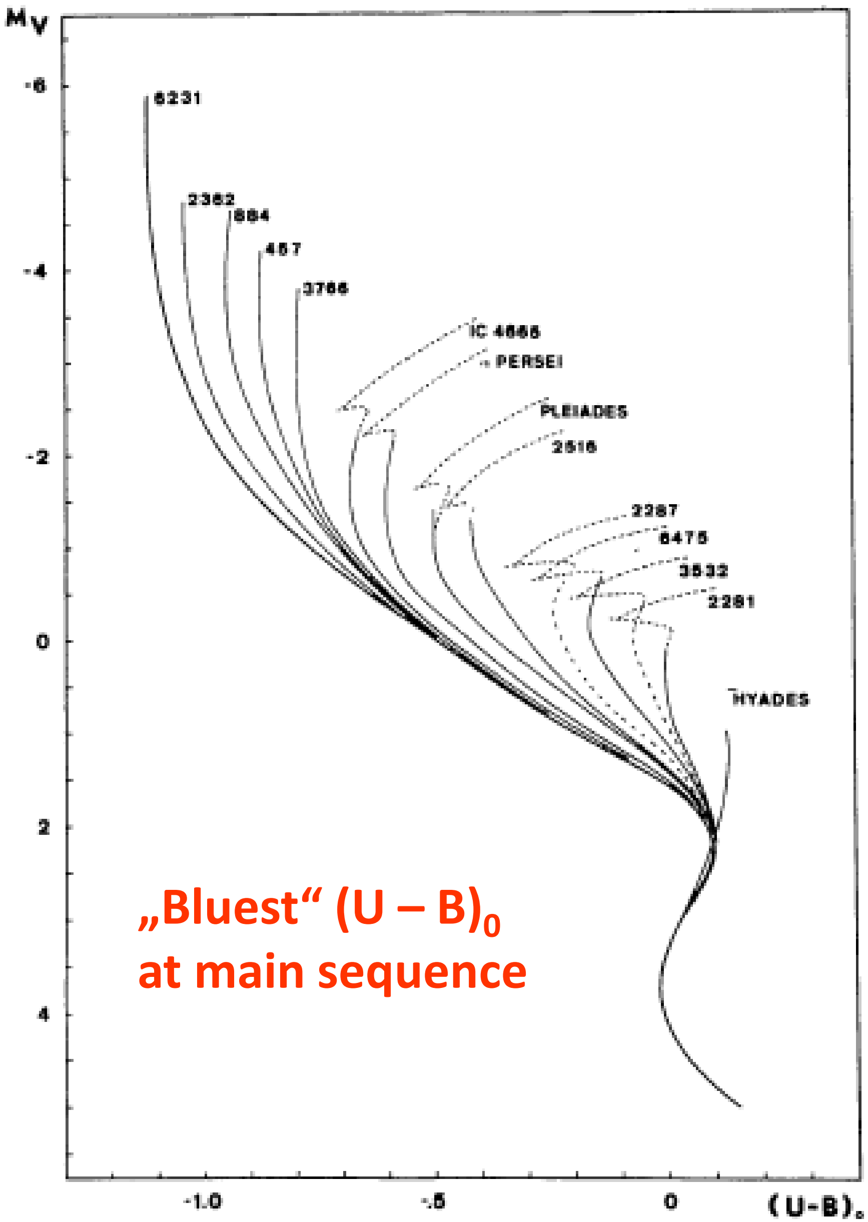
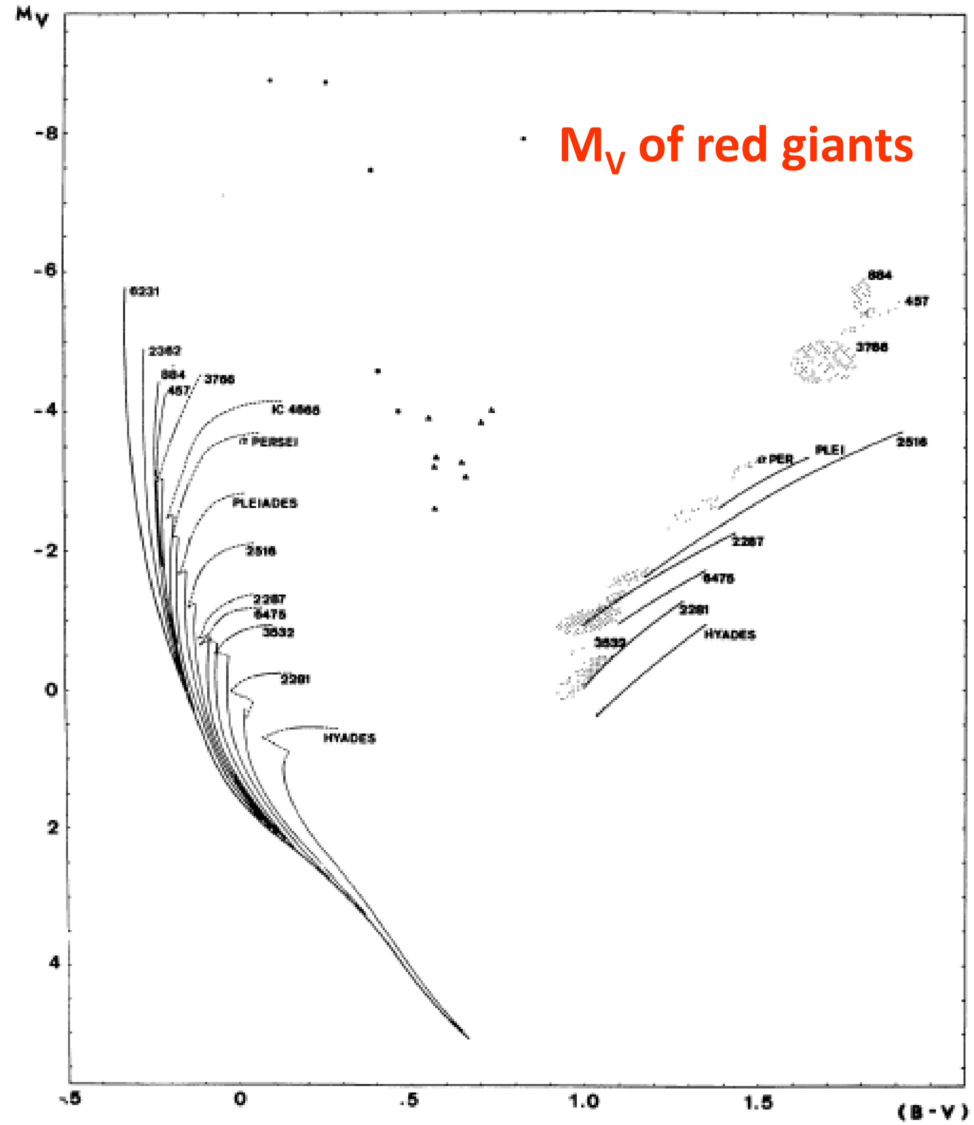
1.6 x 10 8
1.9 x 10 9
7.1 x 10 9
2.9 x 10 10
Age (years)
HR Diagrams for Various Open Clusters
$k \cdot A_V$
A_V
Reddening

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

Mermilliod, 1981, A&A, 97, 235

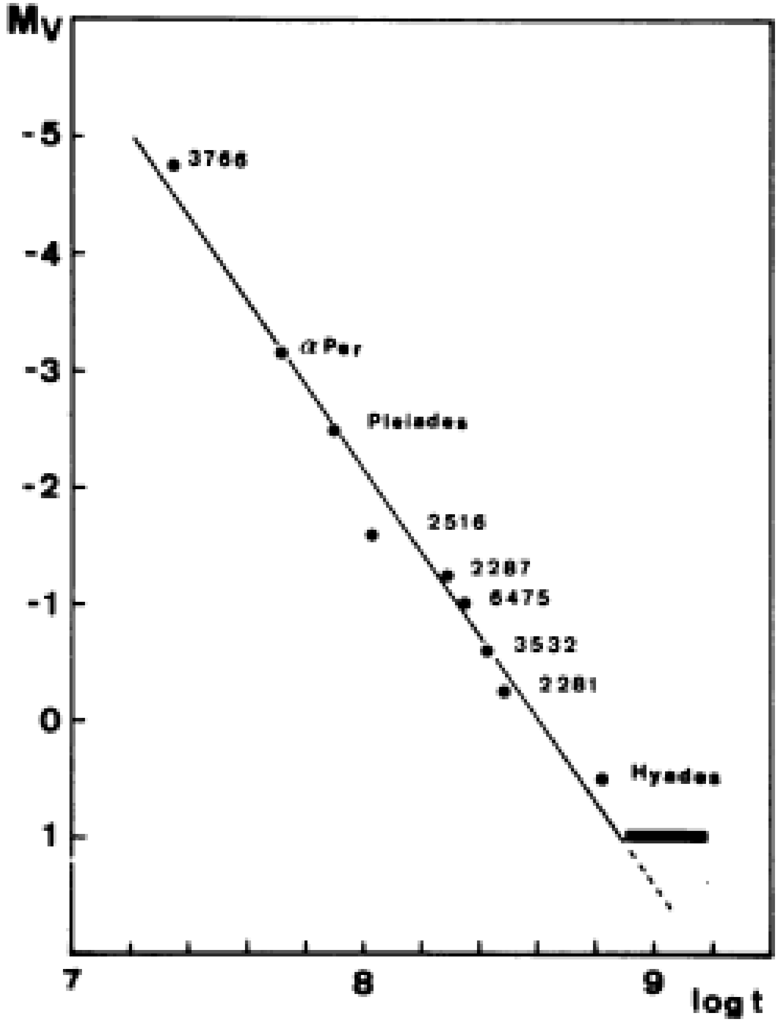


Fig. 7. Relation between the mean absolute magnitude of the red giant concentrations and log t. The darkened area at M_V=+1. indicates the position of the clump in old clusters.

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**

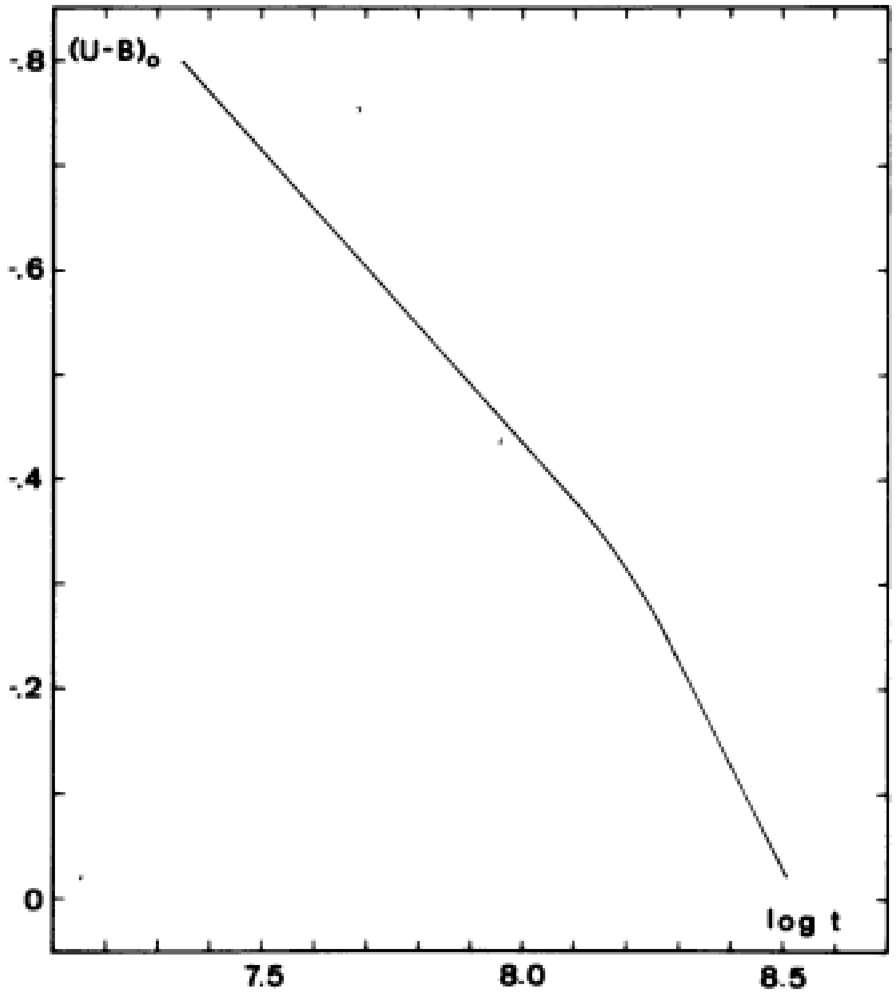
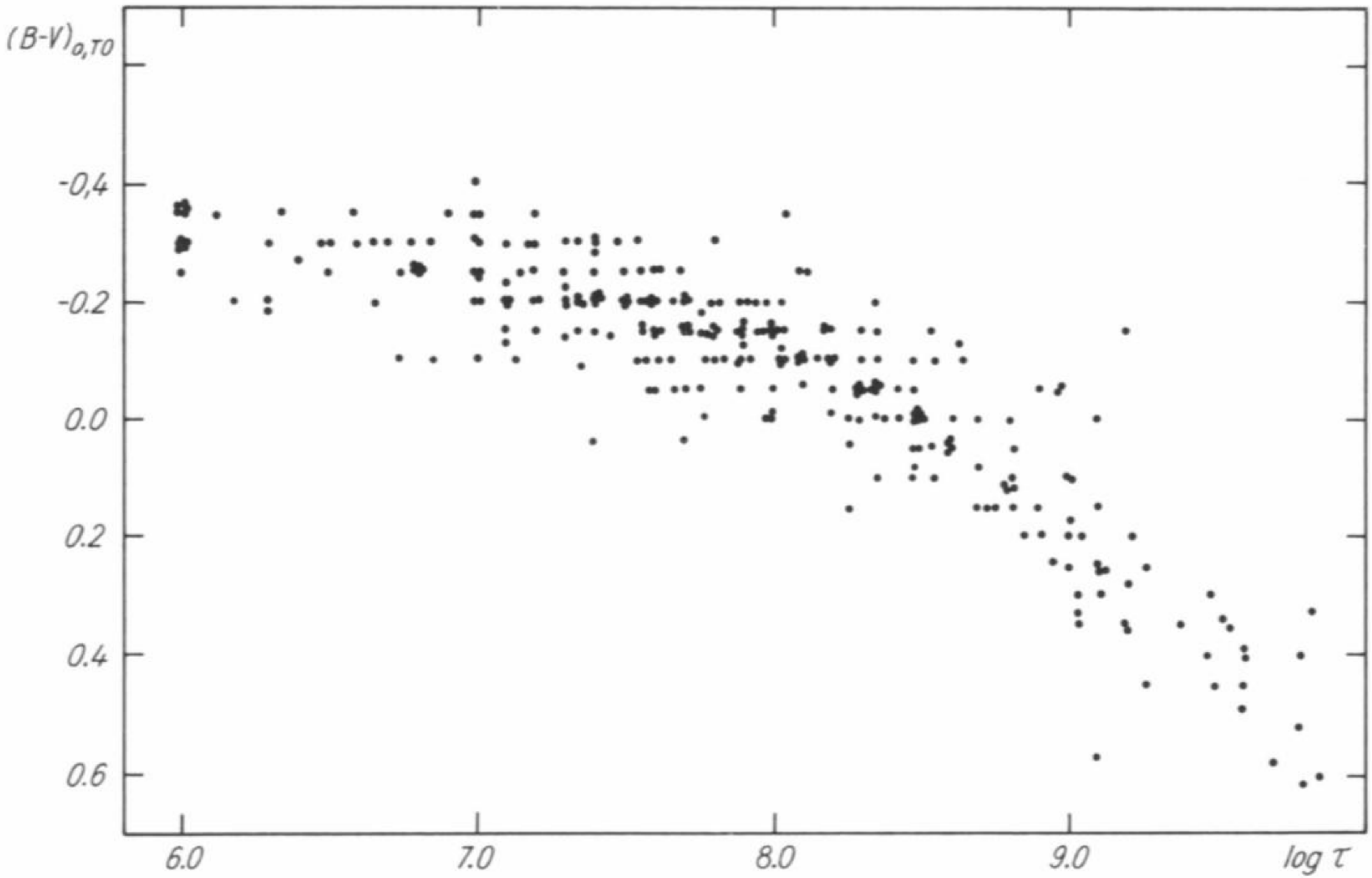


Fig. 6. Calibration of the bluest $(U-B)_o$ on the main sequence in terms of age (log t)

$$-.80 \leq (U-B)_o < -.35 \quad \log t = 1.795(U-B)_o + 8.785$$
$$-.28 \leq (U-B)_o < .00 \quad \log t = 0.813(U-B)_o + 8.487$$



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

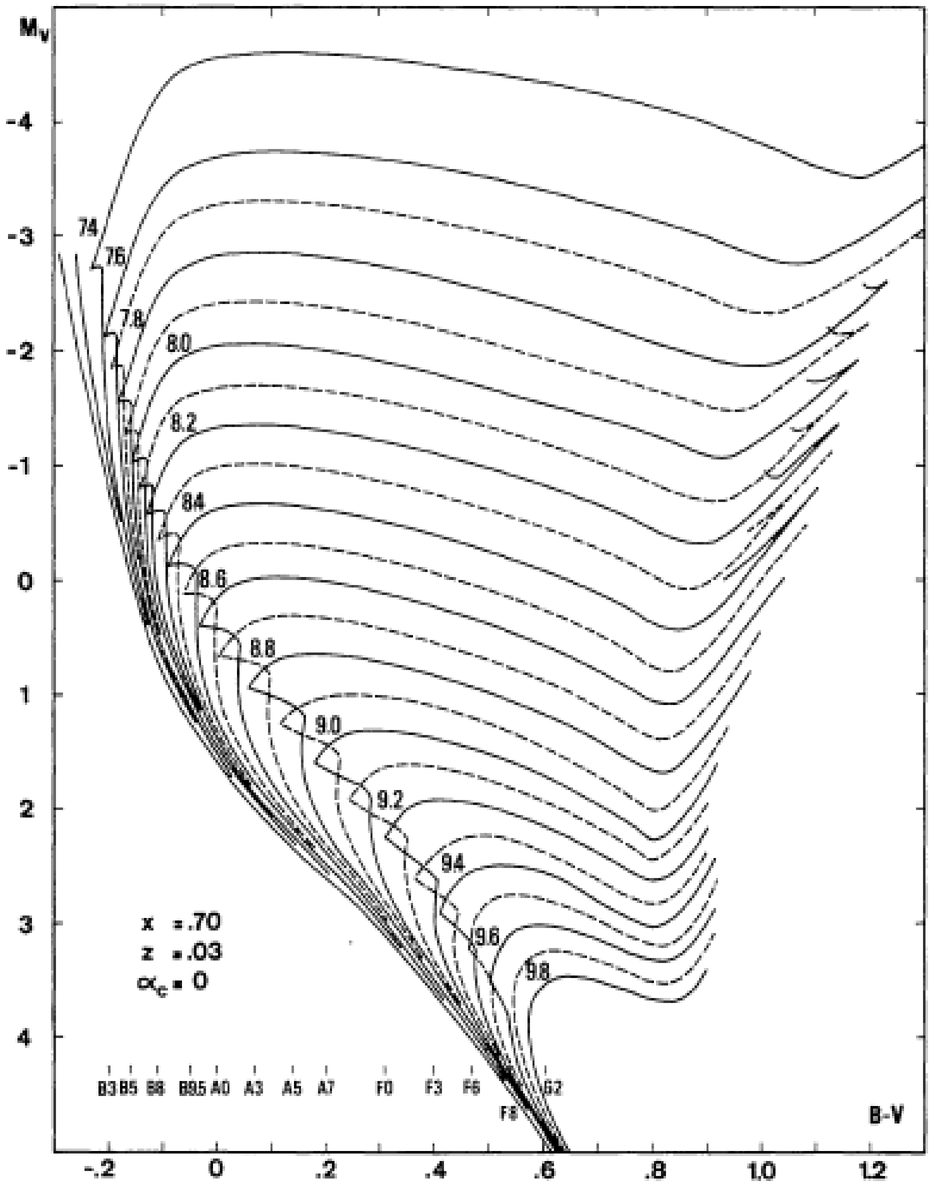
Free parameter : Metallicity [X, Y, Z]

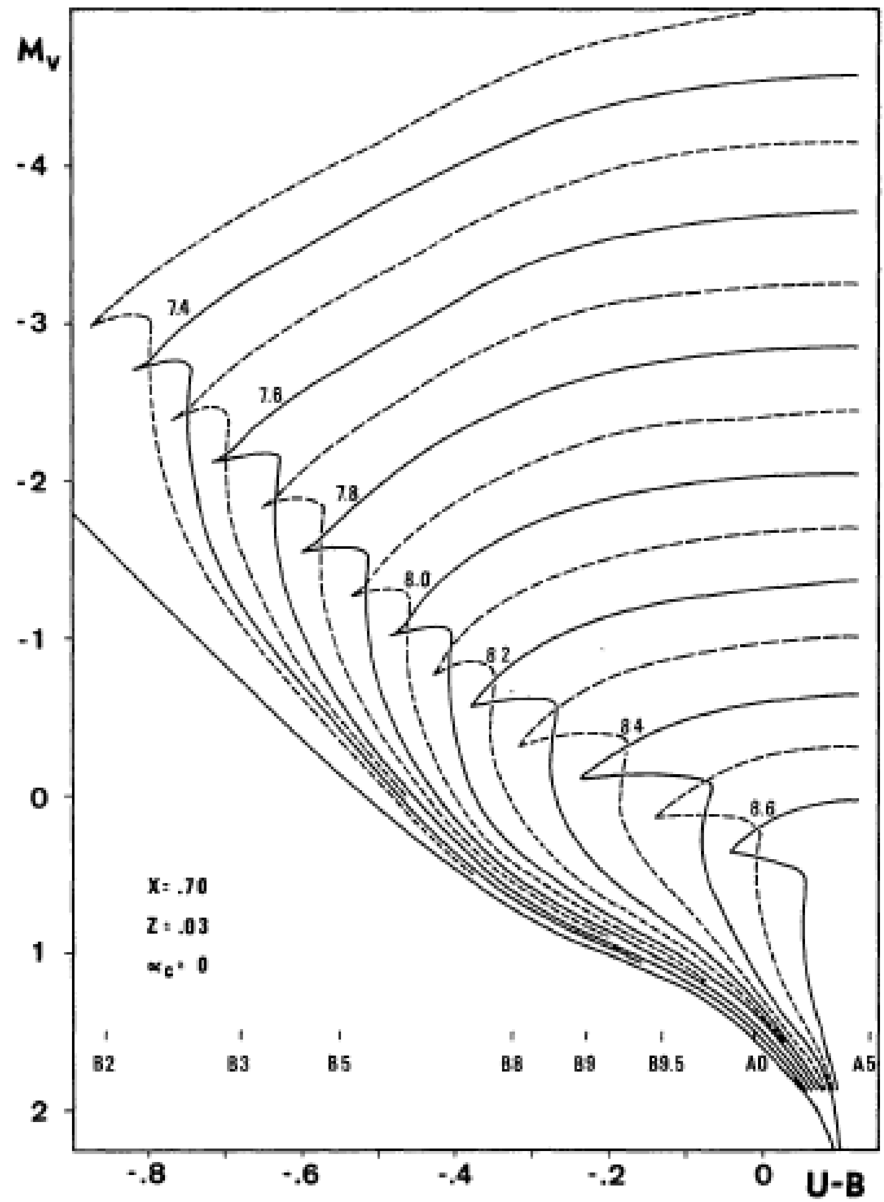
1. Zero Age Main Sequence $[T_{eff}, L]_0$
2. Chemical and gravitational evolution
3. $[T_{eff}, L](t)$
4. Adequate stellar atmosphere = **PHYSICS**
5. Absolute fluxes
6. Folding with filter curves
7. Colors, absolute magnitudes and so on

Which astrophysical “parameters” are important?

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

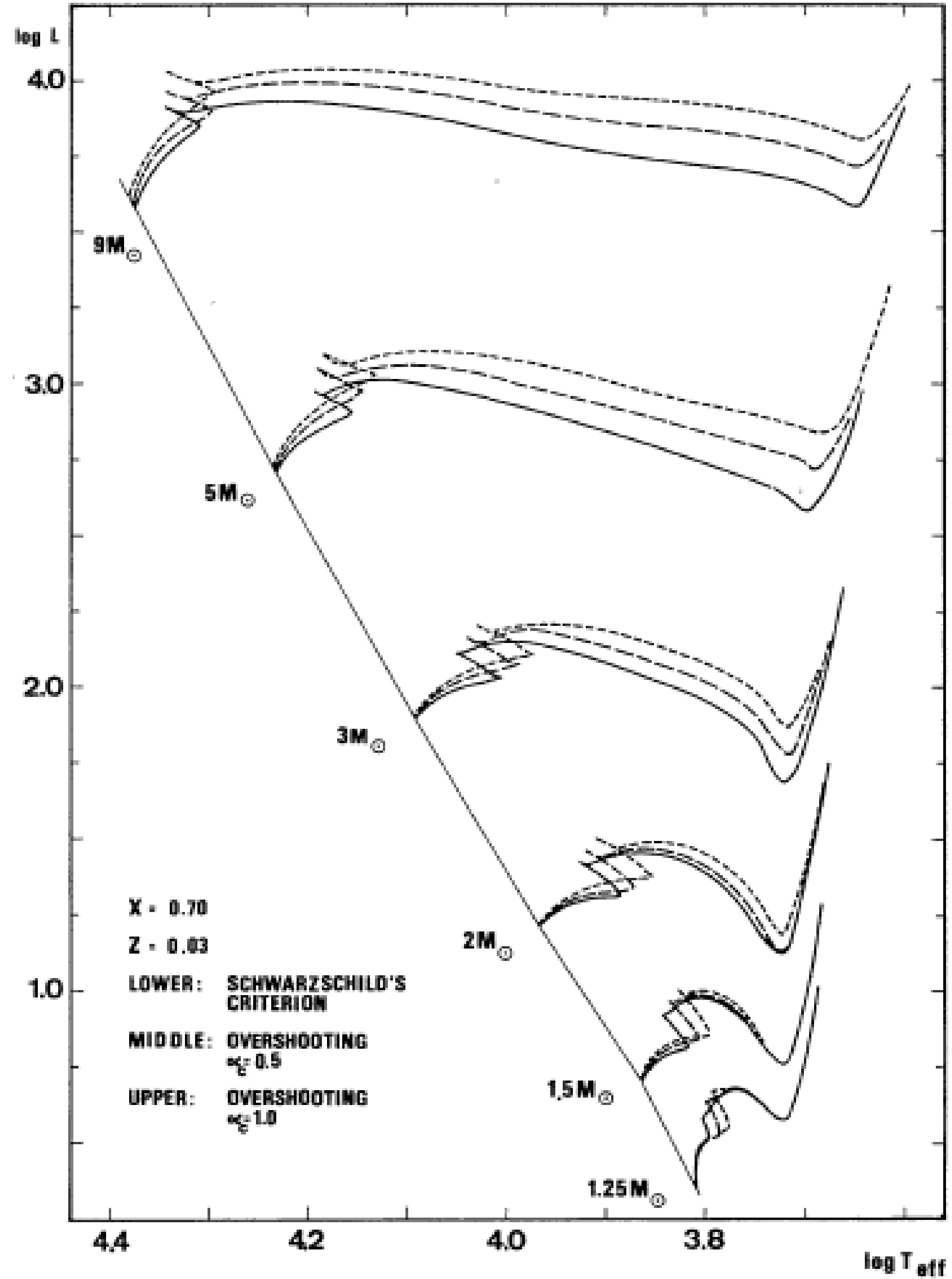
Maeder & Mermilliod, 1981, A&A, 93, 136





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

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^2: Yi et al., 2001, ApJS, 136, 417
  5. Siess: Siess et al., 2000, A&A, 358, 593

Automatic Methods

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

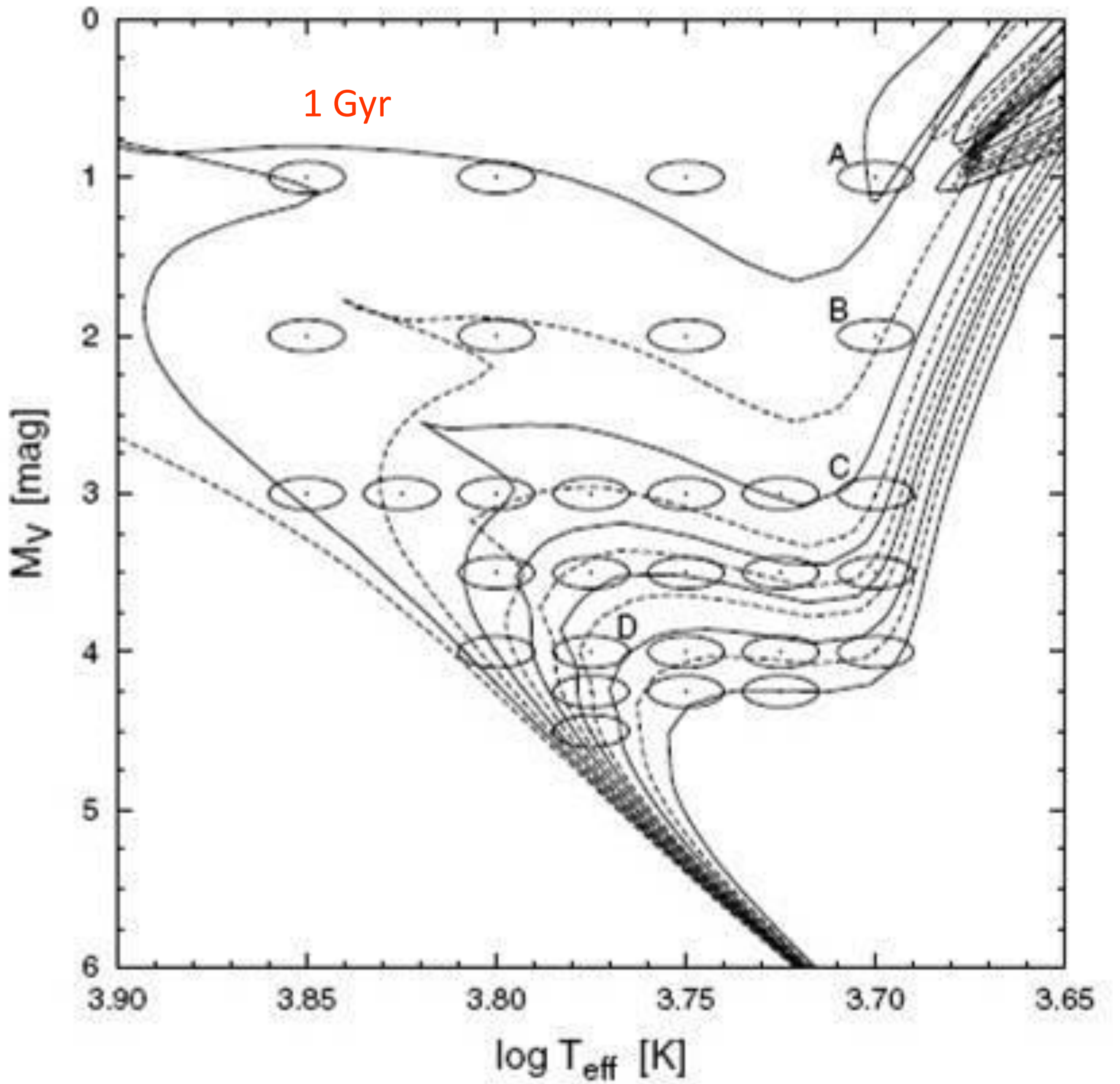
Definition of different „important“ areas (Box) in the CMD. Do this allocation as you like.

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“

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

Metallicity - designations

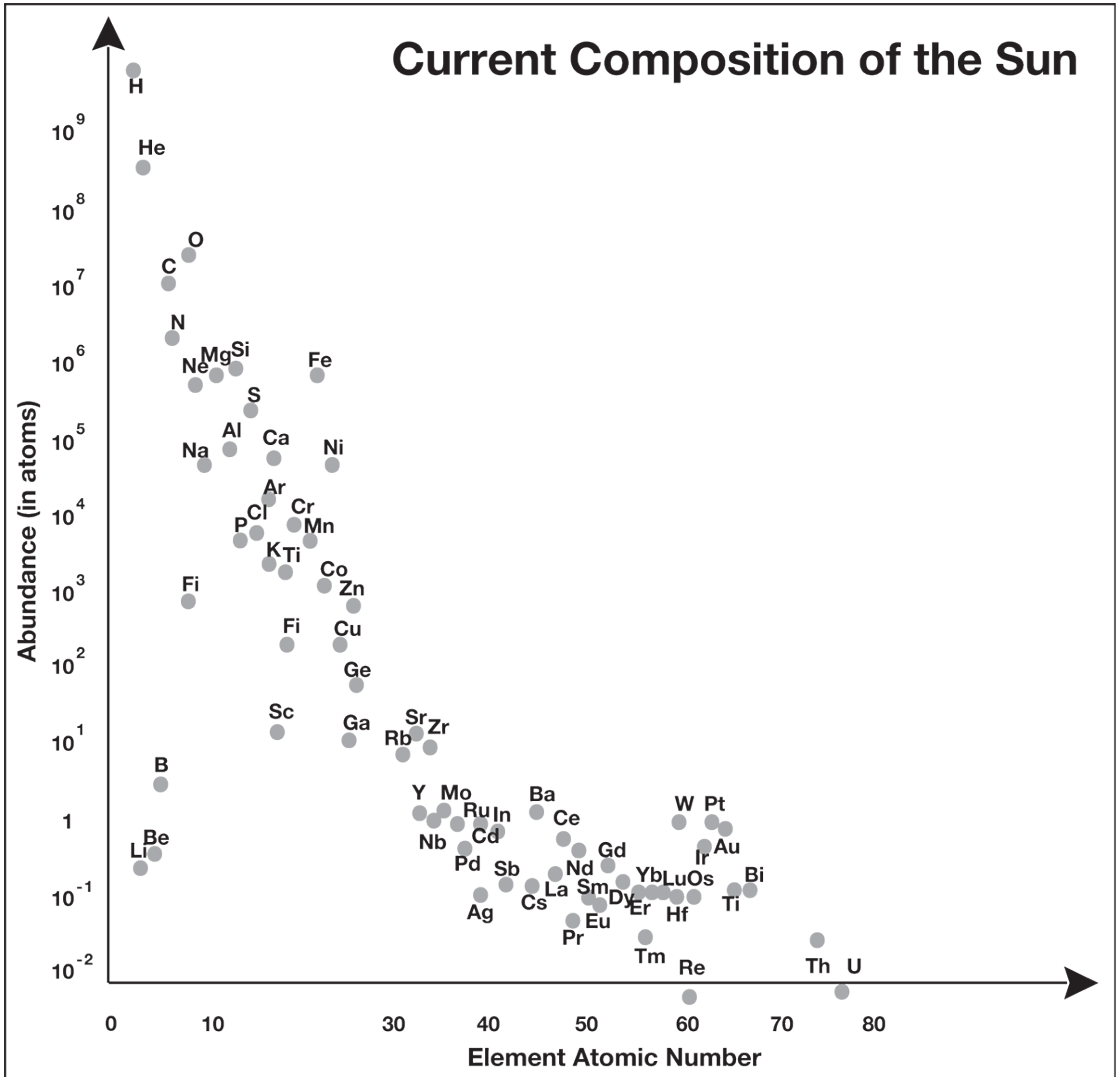
- [dex], e.g. [Fe/H] = -0,5 dex

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 - Sun



Asplund et al.

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

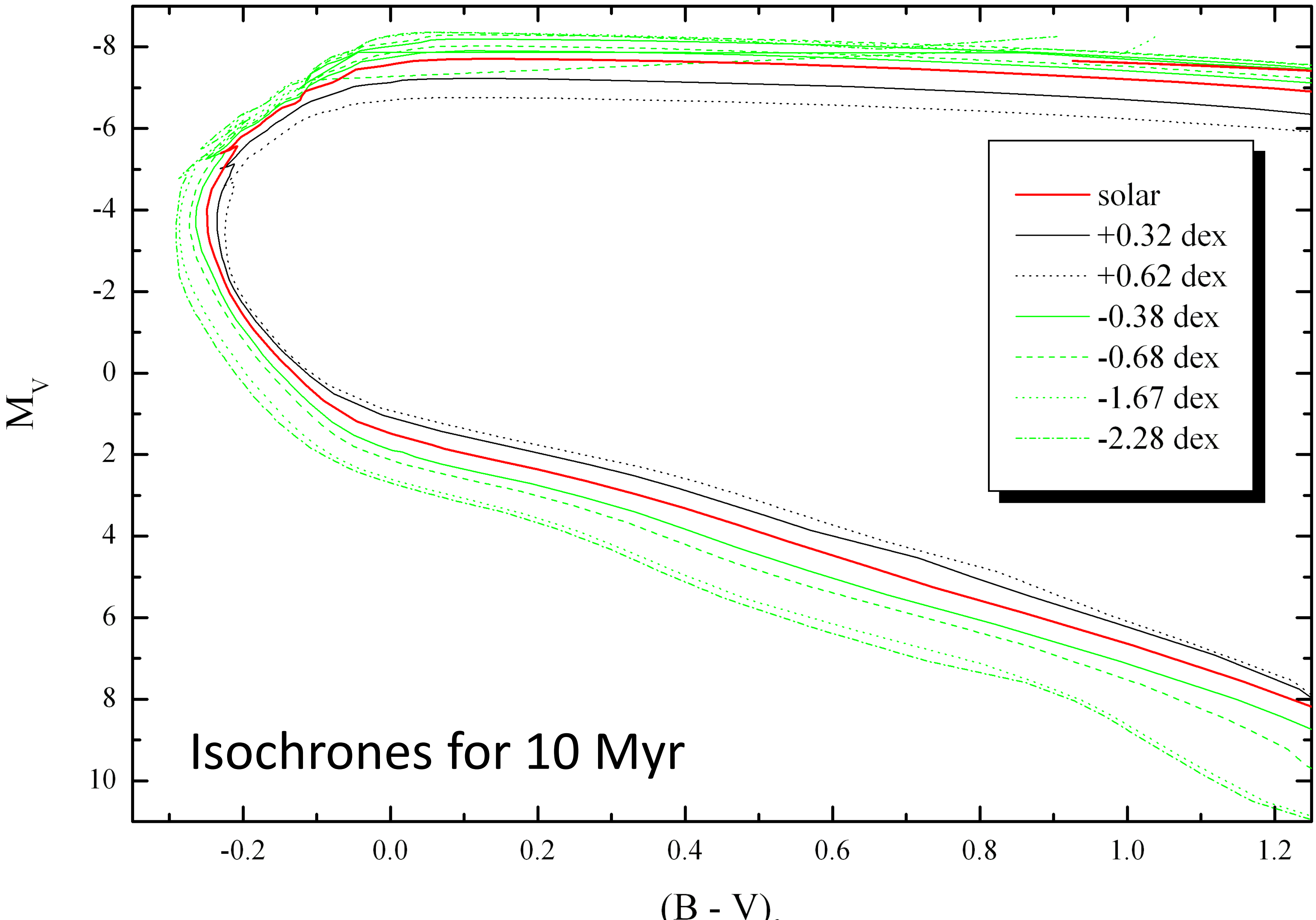
[a] The He abundances given in Anders & Grevesse (1989) and Grevesse & Noels (1993) have here been replaced with the current best estimate from helioseismology (Sect. 3.9).

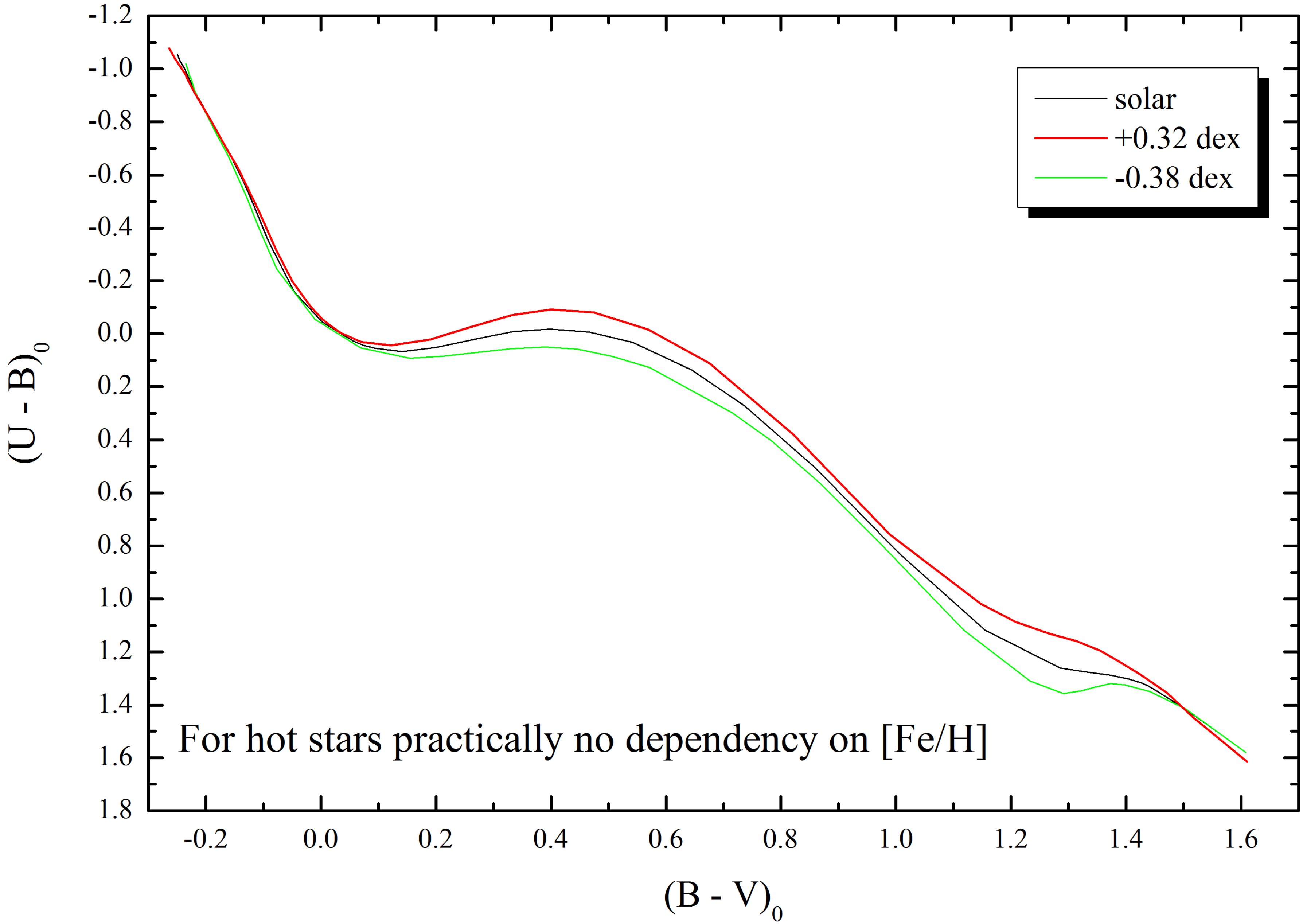
Table 2. Transformation of [Fe/H] to [Z] using $[Y] = 0.23 + 2.25[Z]$ from Girardi et al. (2000) applied in this work.

[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		

Asplund et al.

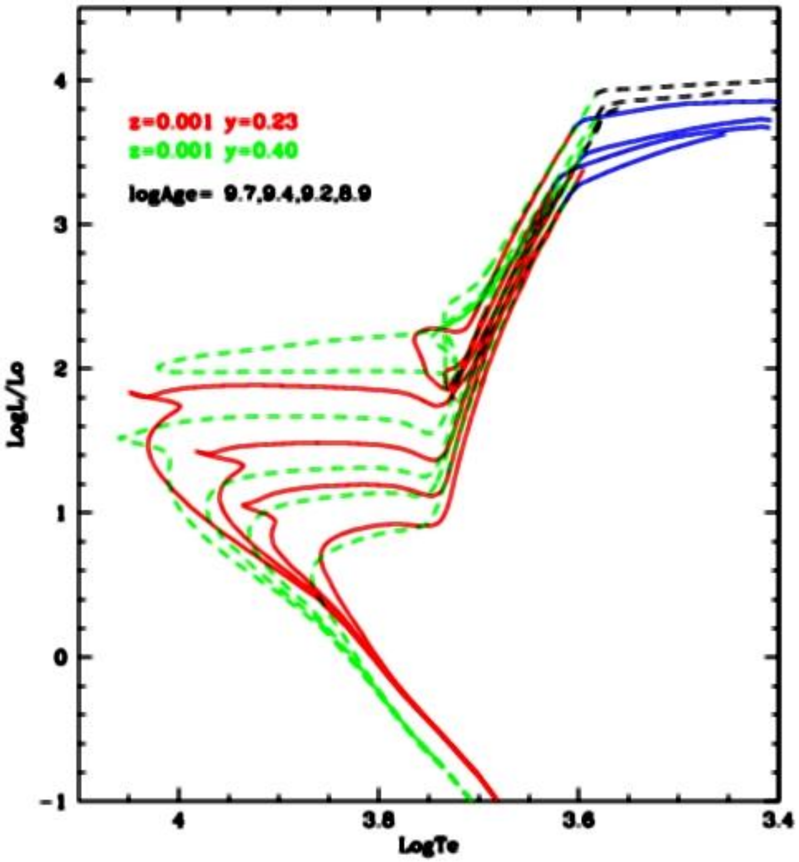
Metallicity => different opacity

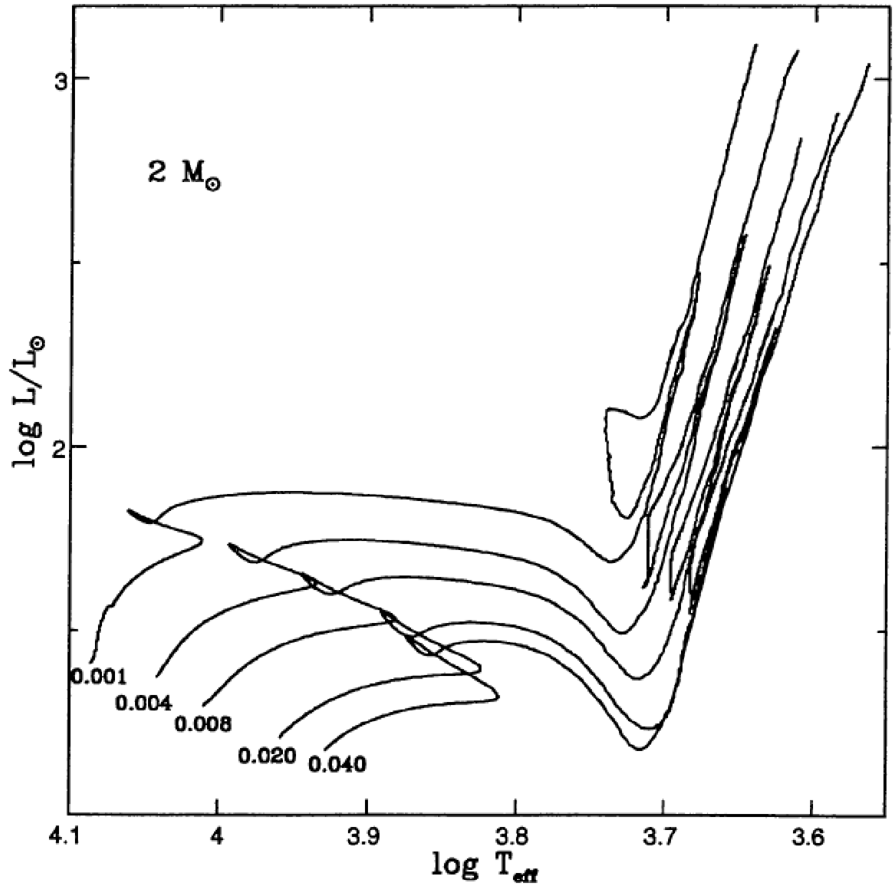




solar
+0.32 dex
-0.38 dex
For hot stars practically no dependency on [Fe/H]
(U - B)0
(B - V)0
-1.2
-1.0
-0.8
-0.6
-0.4
-0.2
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
-0.2
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6

Metallicity - isochrones

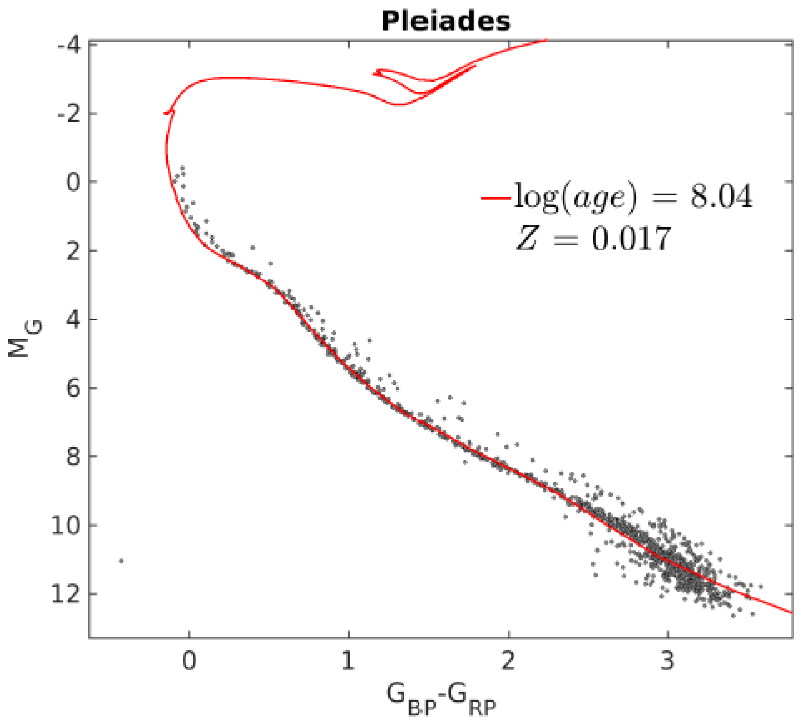


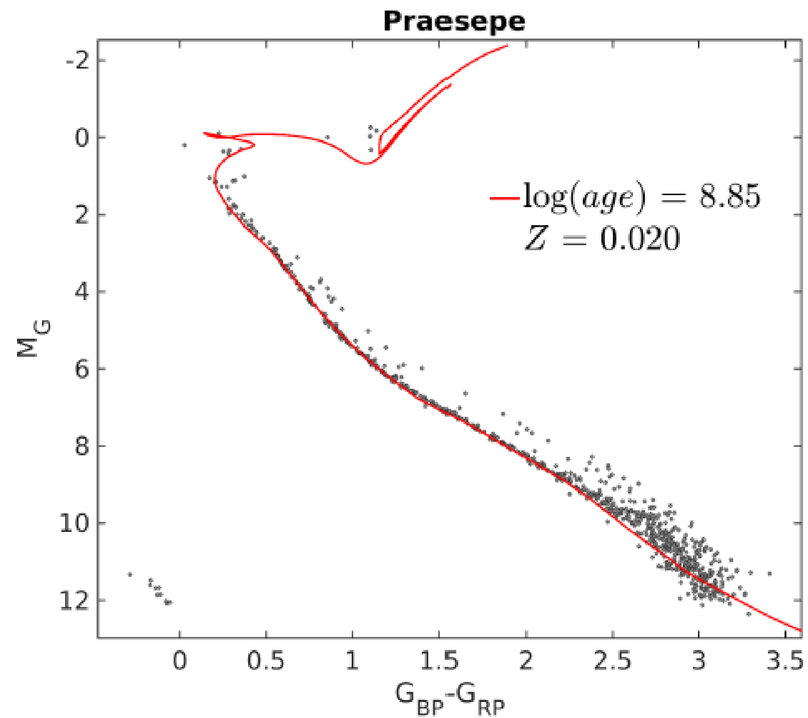


Different He abundances – [Z] constant

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

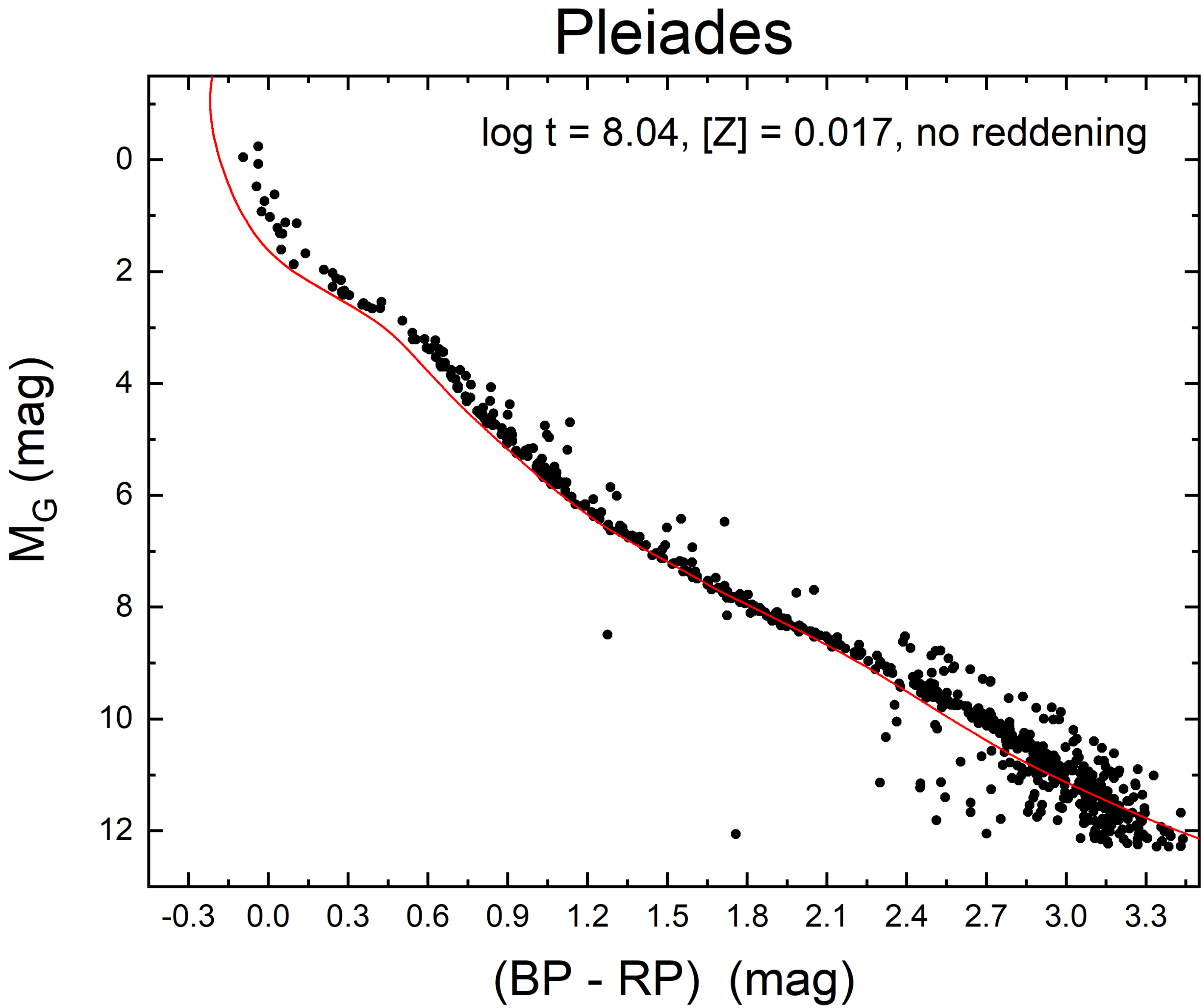
Color-Magnitude Diagram





Gaia Collaboration, 2018, A&A, 616, A10

Color-Magnitude Diagram



Color-Magnitude Diagram