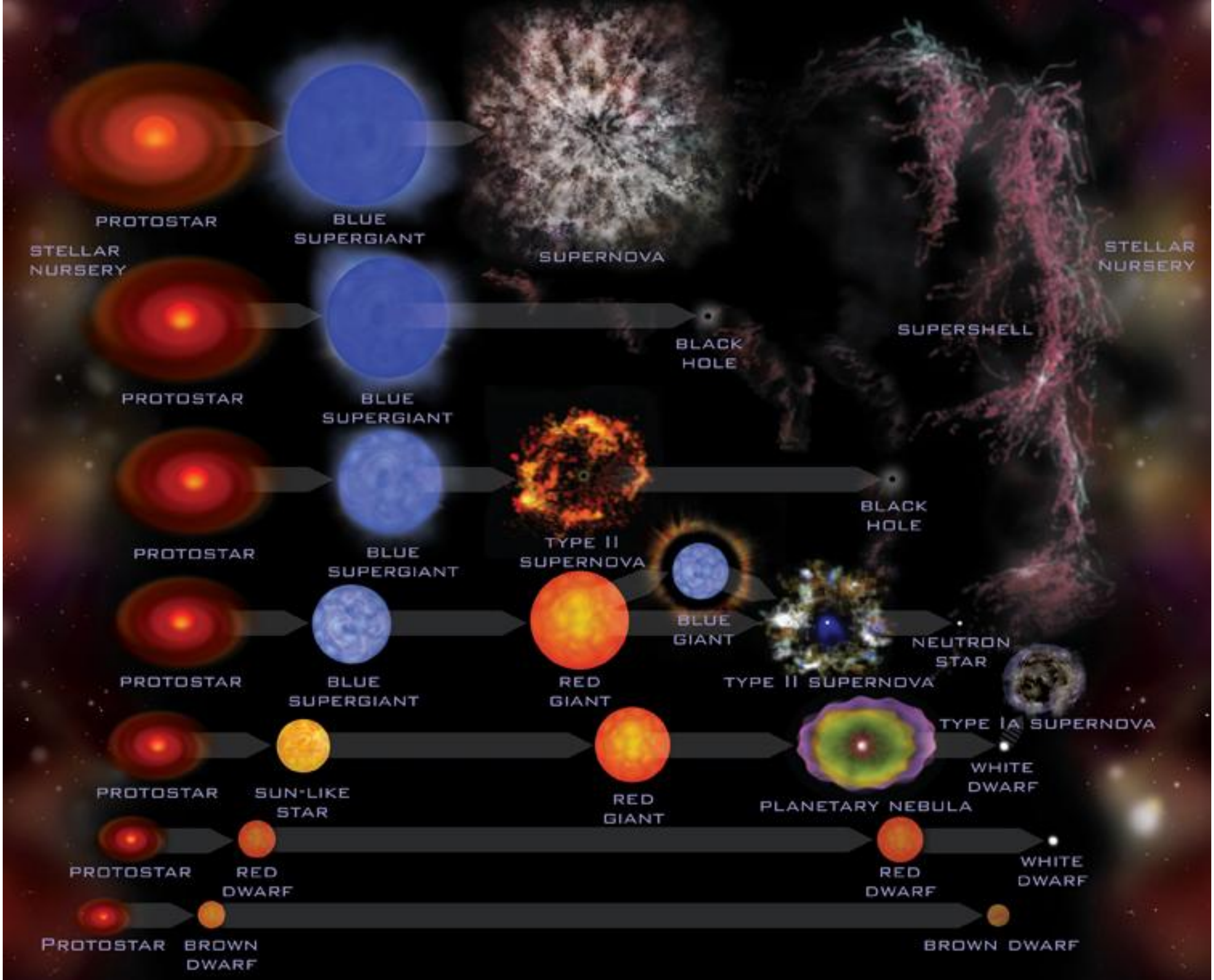
Evolution of Star Clusters

- Star Clusters form with the following characteristics
  1. **Total Mass**: IMF
  2. **Metallicity**
  3. **Kinematics of the Cluster center**: location within the Galaxy
  4. **Internal velocity dispersion**
- How does a Star Cluster evolve with these starting parameters?

- Each member (= star) evolve “as an individual”, some important topics
    1. Binary Evolution
    2. Mass Loss (hot stars)
    3. AGB Evolution
    4. Planetary Nebula (cool stars)
    5. Supernovae explosions
- In Star Clusters, collisions are very uncommon (see later), almost no new multiple (binary) systems form during the later evolution
- Star Clusters follow Galactic Rotation


PROTOSTAR
BLUE SUPERGIANT
SUPERNOVA
STELLAR NURSERY
STELLAR NURSERY
SUPERSHELL
PROTOSTAR
BLUE SUPERGIANT
BLACK HOLE
PROTOSTAR
BLUE SUPERGIANT
TYPE II SUPERNOVA
BLACK HOLE
PROTOSTAR
BLUE SUPERGIANT
RED GIANT
BLUE GIANT
TYPE II SUPERNOVA
NEUTRON STAR
TYPE IA SUPERNOVA
PROTOSTAR
SUN-LIKE STAR
RED GIANT
PLANETARY NEBULA
WHITE DWARF
PROTOSTAR
RED DWARF
RED DWARF
WHITE DWARF
PROTOSTAR
BROWN DWARF
BROWN DWARF

Calculation of Isochrones

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

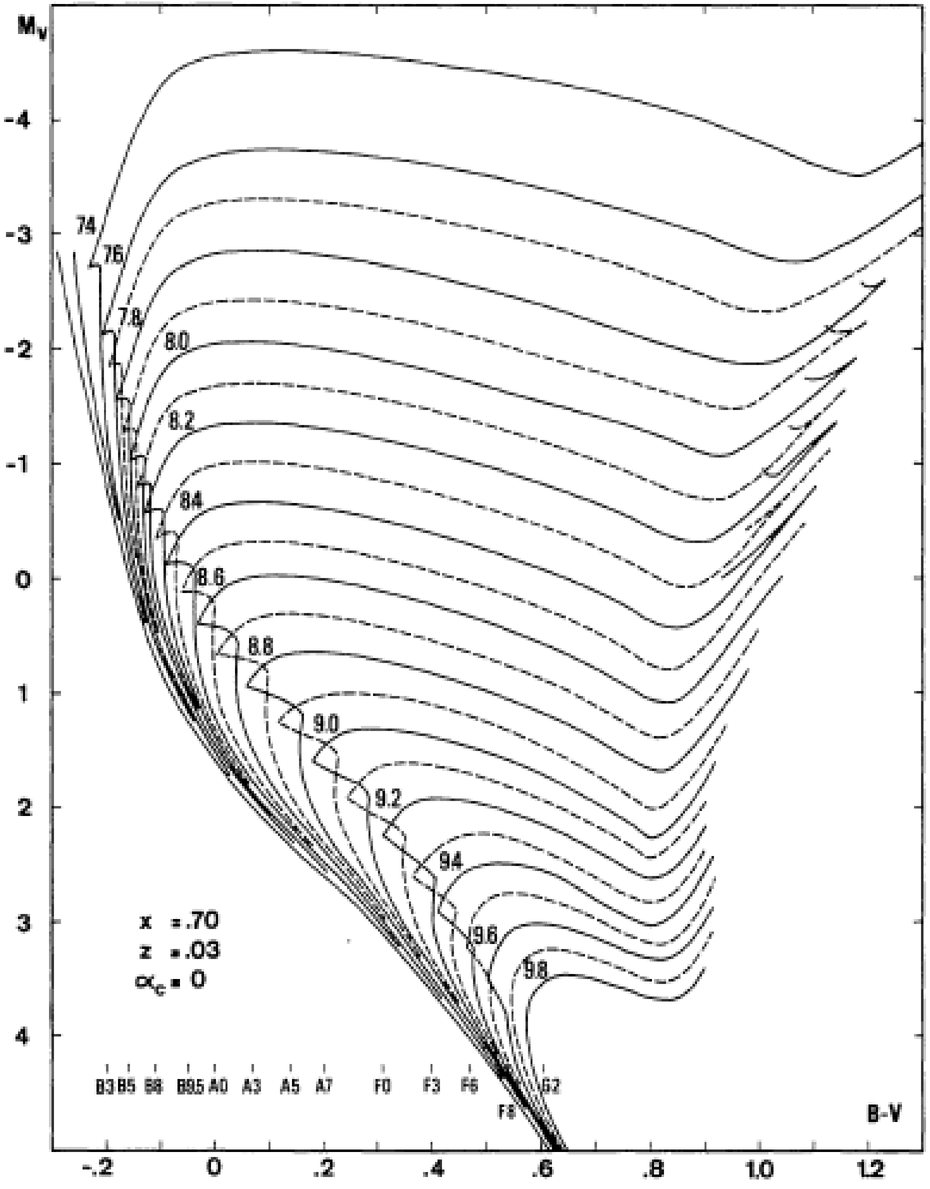
Free parameter : Metallicity [X, Y, Z]

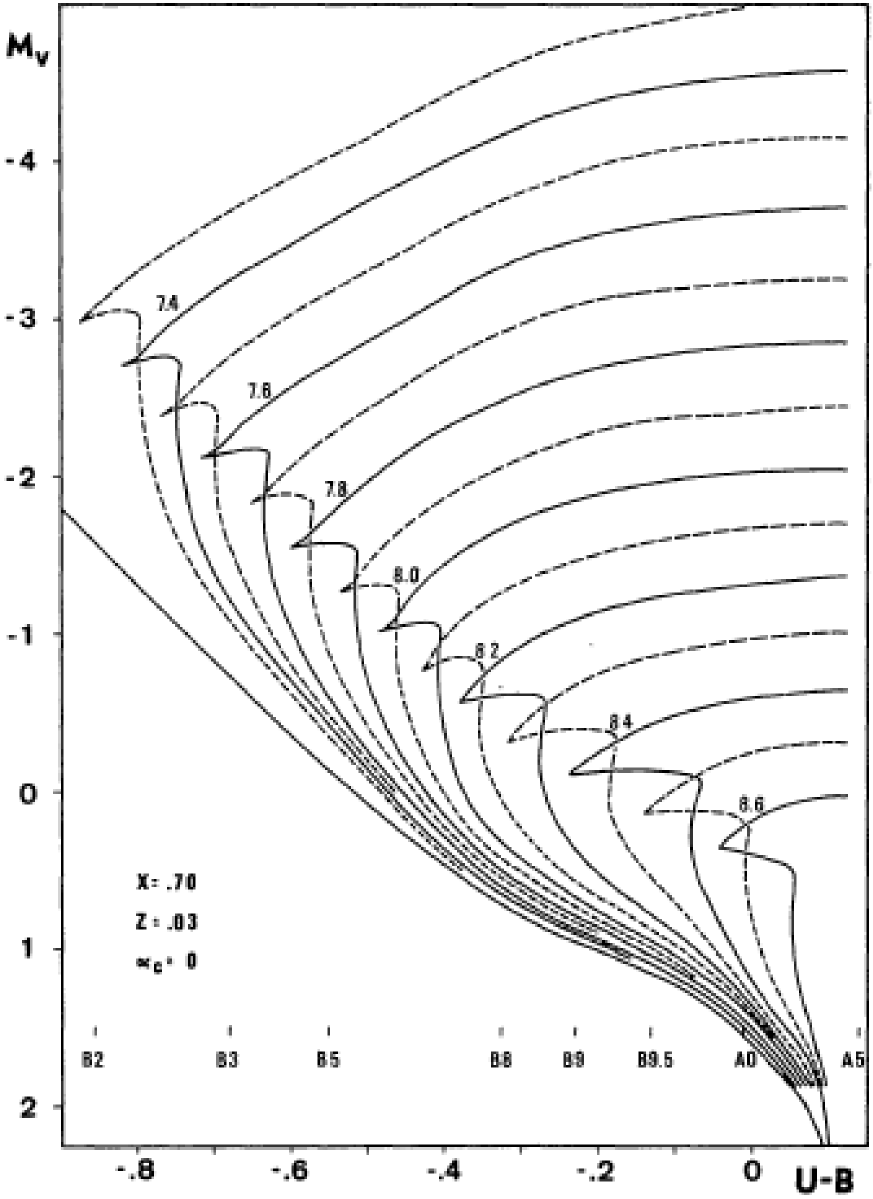
1. Zero Age Main Sequence $[T_{eff}, L]_0$
2. Chemical and gravitational evolution
3. $[T_{eff}, L](t)$
4. Adequate stellar atmosphere = **PHYSICS**
5. Absolute fluxes
6. Folding with filter curves
7. Colors, absolute magnitudes and so on

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





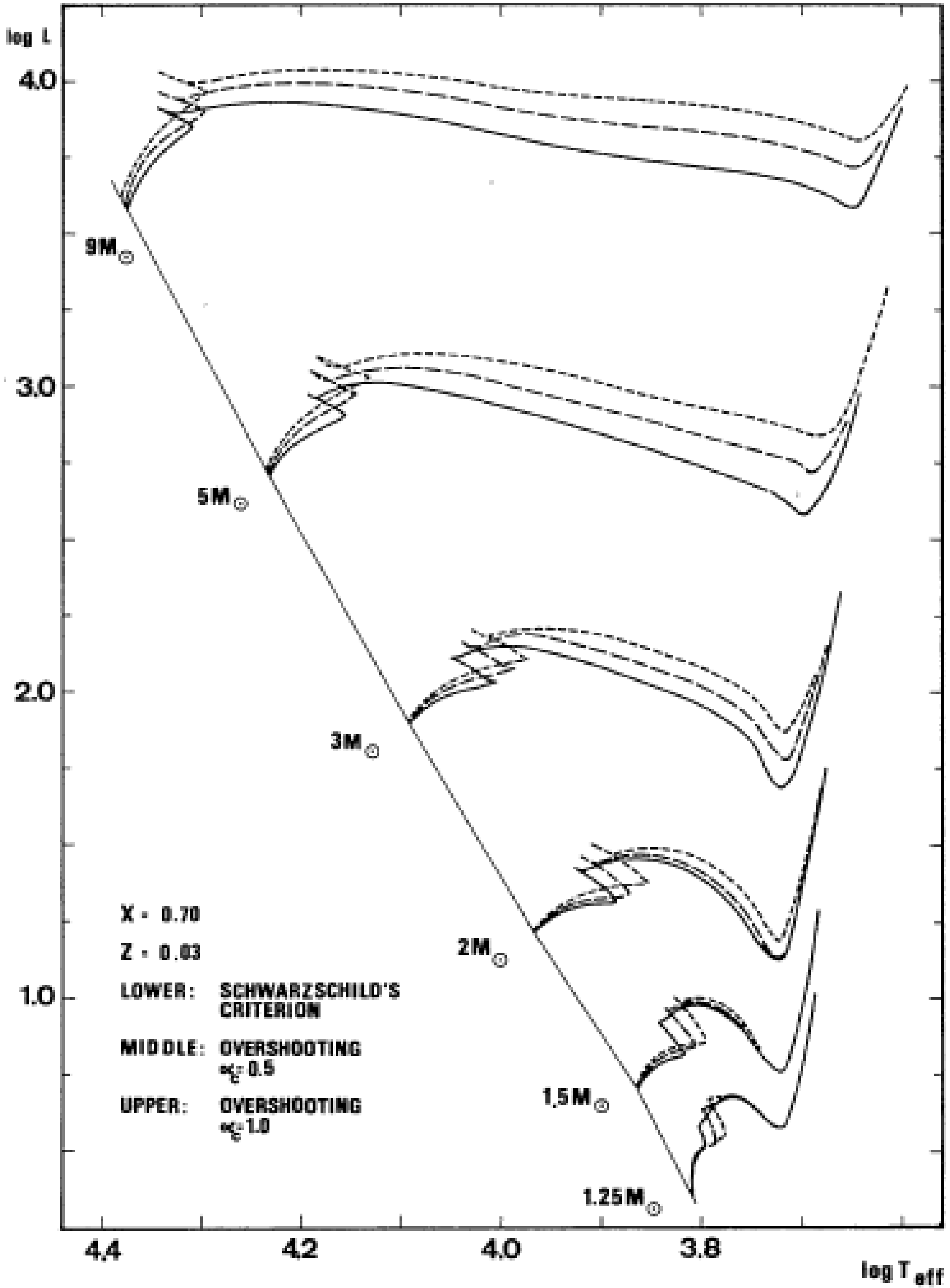
Maeder & Mermilliod, 1981, A&A, 93, 136

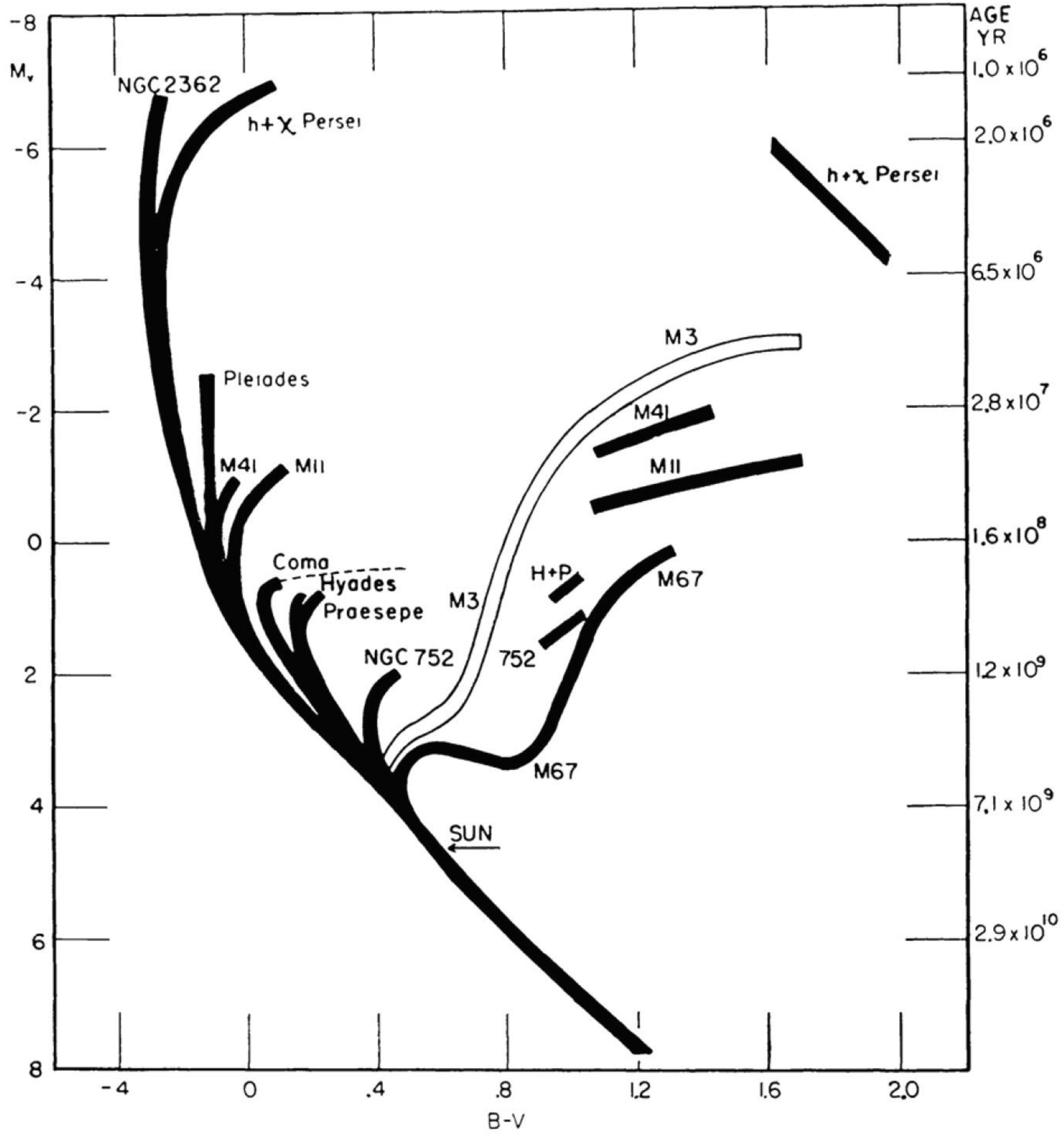
Differences of the isochrones due to different models of convection

Treatment of the other parameters has similar effects

Conclusion:
Everyone can calculate and publish his/her own set of isochrones

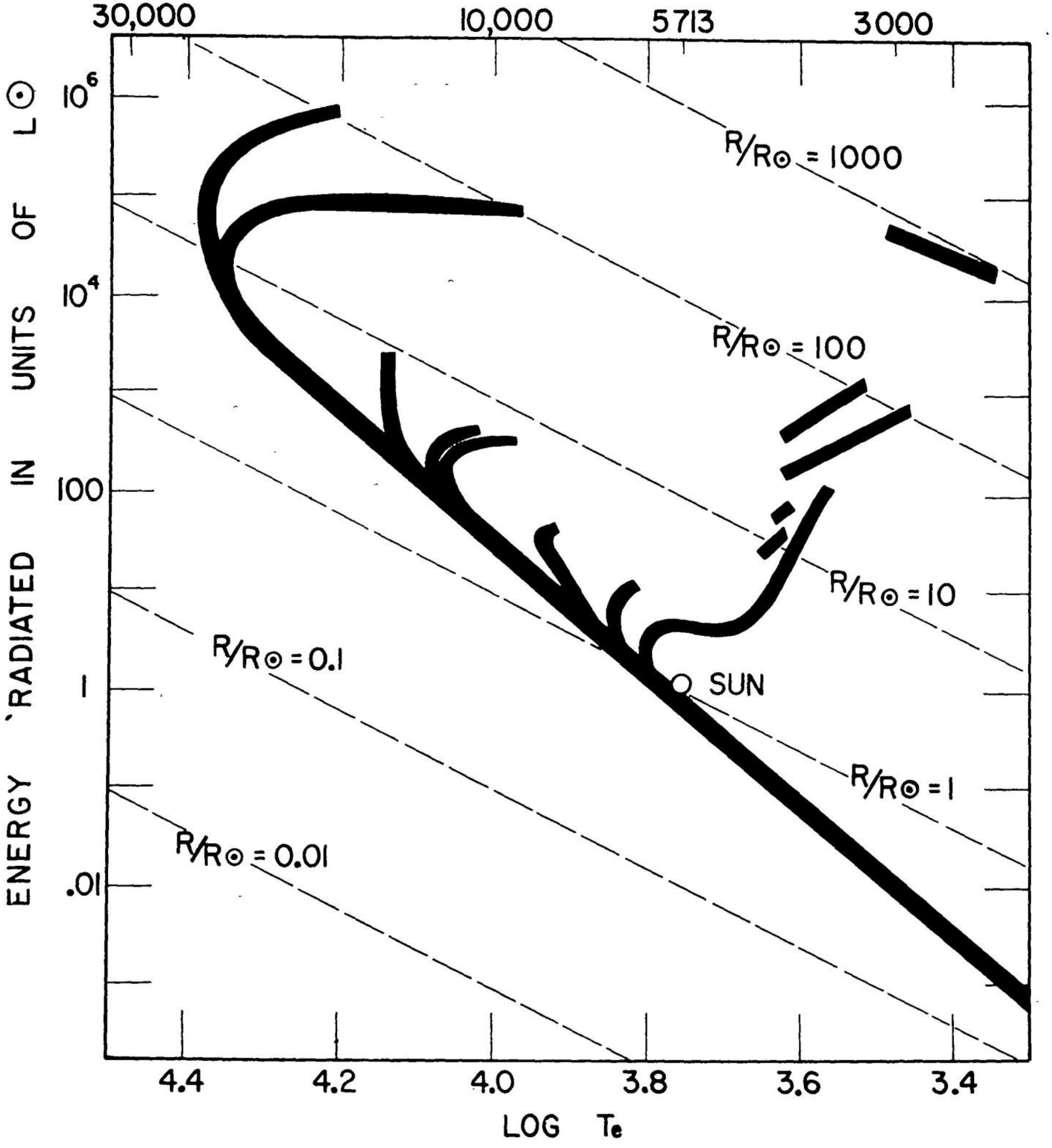
Later we will compare different sets of published isochrones





Sandage, 1958, RA, 5, 41

„The Color-Magnitude Diagrams of Galactic and Globular Clusters and their Interpretation as Age Groups"

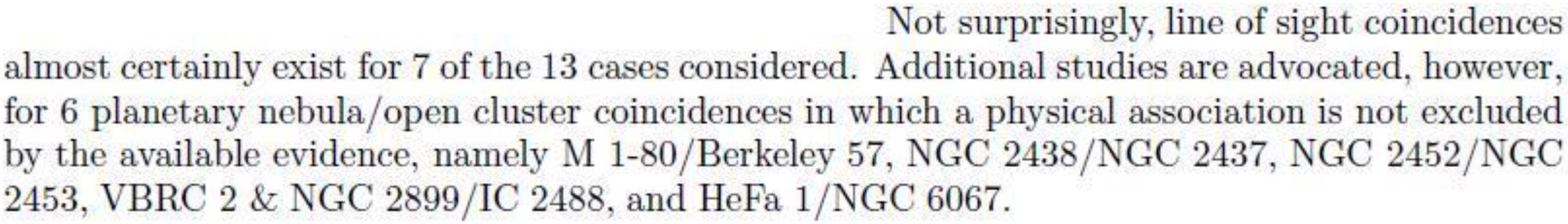


Sandage, 1958, RA, 5, 41

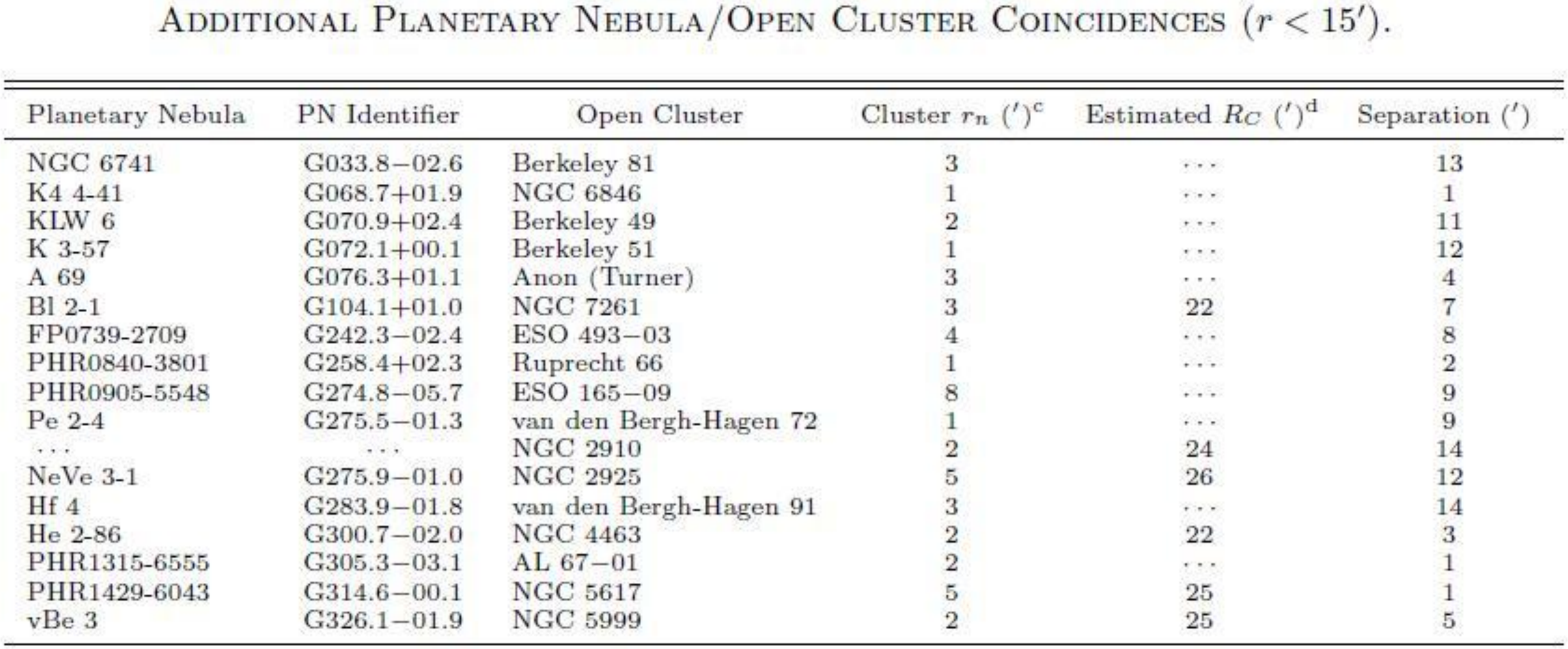
„The Color-Magnitude Diagrams of Galactic and Globular Clusters and their Interpretation as Age Groups"

Planetary Nebula

Majaess et al., 2007, PASP, 119, 1349



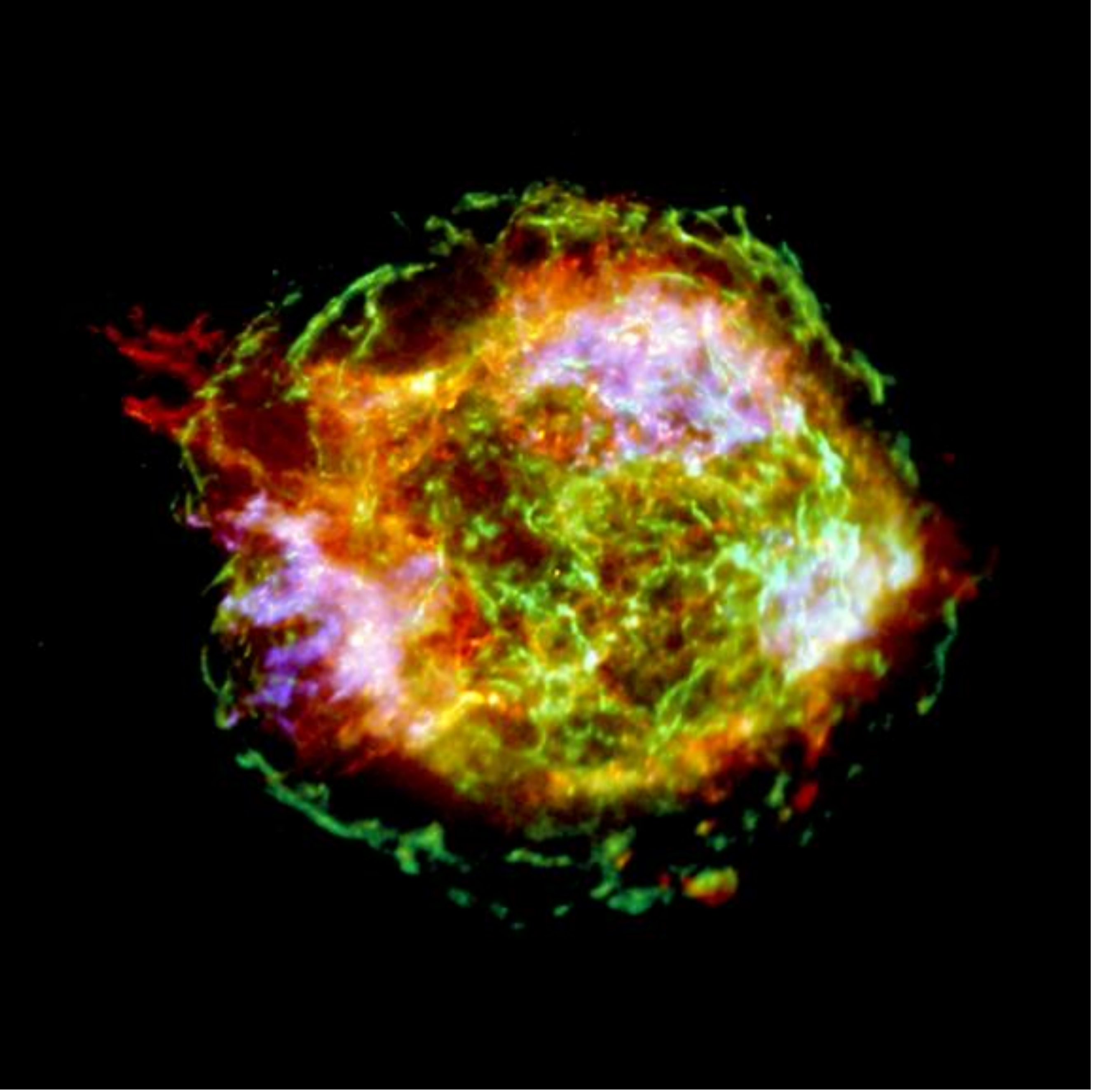
Not surprisingly, line of sight coincidences almost certainly exist for 7 of the 13 cases considered. Additional studies are advocated, however, for 6 planetary nebula/open cluster coincidences in which a physical association is not excluded by the available evidence, namely M 1-80/Berkeley 57, NGC 2438/NGC 2437, NGC 2452/NGC 2453, VBRC 2 & NGC 2899/IC 2488, and HeFa 1/NGC 6067.



ADDITIONAL PLANETARY NEBULA/OPEN CLUSTER COINCIDENCES ($r < 15'$).

Planetary Nebula	PN Identifier	Open Cluster	Cluster r_n ($'$)^c	Estimated R_C ($'$)^d	Separation ($'$)
NGC 6741	G033.8−02.6	Berkeley 81	3	...	13
K4 4-41	G068.7+01.9	NGC 6846	1	...	1
KLW 6	G070.9+02.4	Berkeley 49	2	...	11
K 3-57	G072.1+00.1	Berkeley 51	1	...	12
A 69	G076.3+01.1	Anon (Turner)	3	...	4
Bl 2-1	G104.1+01.0	NGC 7261	3	22	7
FP0739-2709	G242.3−02.4	ESO 493−03	4	...	8
PHR0840-3801	G258.4+02.3	Ruprecht 66	1	...	2
PHR0905-5548	G274.8−05.7	ESO 165−09	8	...	9
Pe 2-4	G275.5−01.3	van den Bergh-Hagen 72	1	...	9
...	...	NGC 2910	2	24	14
NeVe 3-1	G275.9−01.0	NGC 2925	5	26	12
Hf 4	G283.9−01.8	van den Bergh-Hagen 91	3	...	14
He 2-86	G300.7−02.0	NGC 4463	2	22	3
PHR1315-6555	G305.3−03.1	AL 67−01	2	...	1
PHR1429-6043	G314.6−00.1	NGC 5617	5	25	1
vBe 3	G326.1−01.9	NGC 5999	2	25	5

PNs exist in Open Clusters



Important topic of how SN explosions affect the cluster evolution

Shockwaves
Mass flow

Statistically, SN explosions are rather common

From Chandra, Diameter 10 lightyears

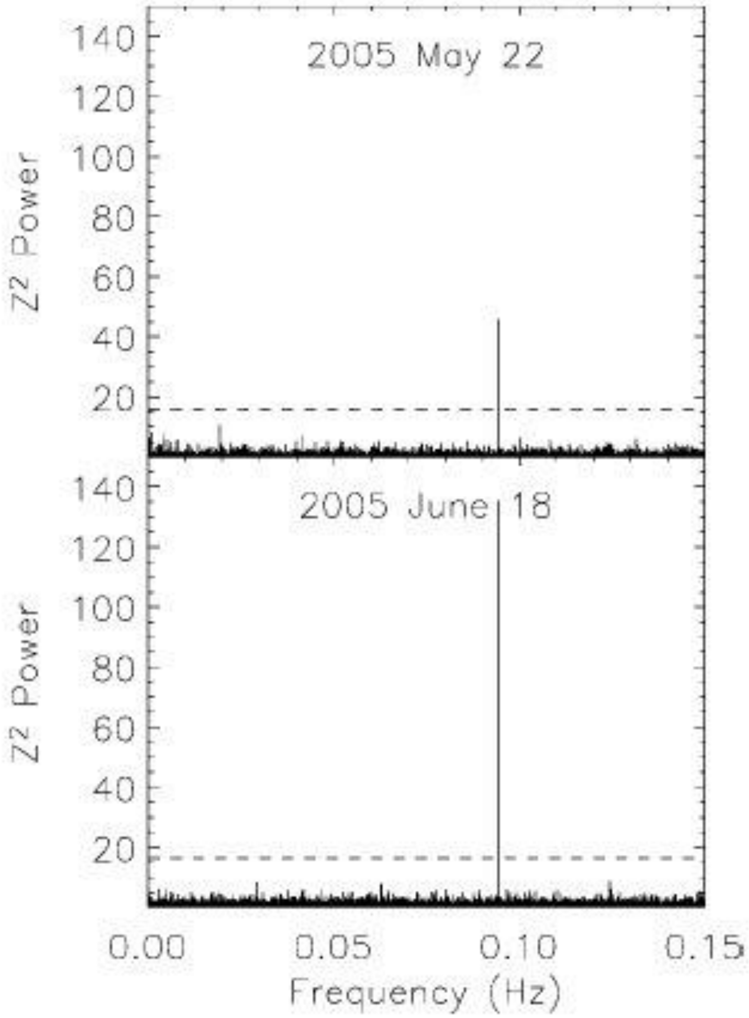
SN Remnants

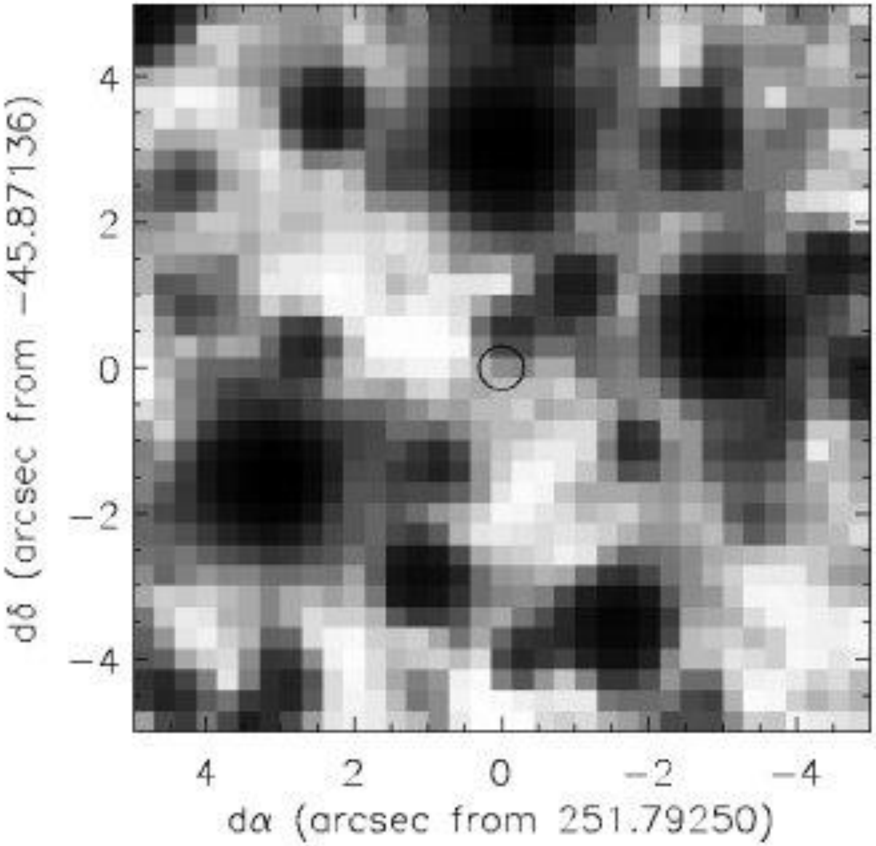
- Catalogue of galactic SNRs: http://www.mrao.cam.ac.uk/surveys/snrs/
- 273 entries
- Complete (!) list of papers for Open Clusters
  1. Pauls, 1977, A&A, 59, L13: NGC 559?
  2. Kuner, 1978, ApJ, 219, L13: **Tr 18** and 21?
  3. Peterson et al., 1988, MNRAS, 235, 1439: Lynga 1, Pismis 20, Stock 14, and Trumpler 21, none conclusive

- There was no SN directly in a Star Cluster observed, yet
- We have to search for Neutron stars, Pulsars or x-ray Binaries
- These objects are extremely faint in the optical regime
- The newest generation of x-ray satellites gave us the first hints that such objects exist in Star Clusters

Muno et al., 2006, ApJ, 636, L41: **Westerlund 1**

d = 5200 pc, log t < 6.4

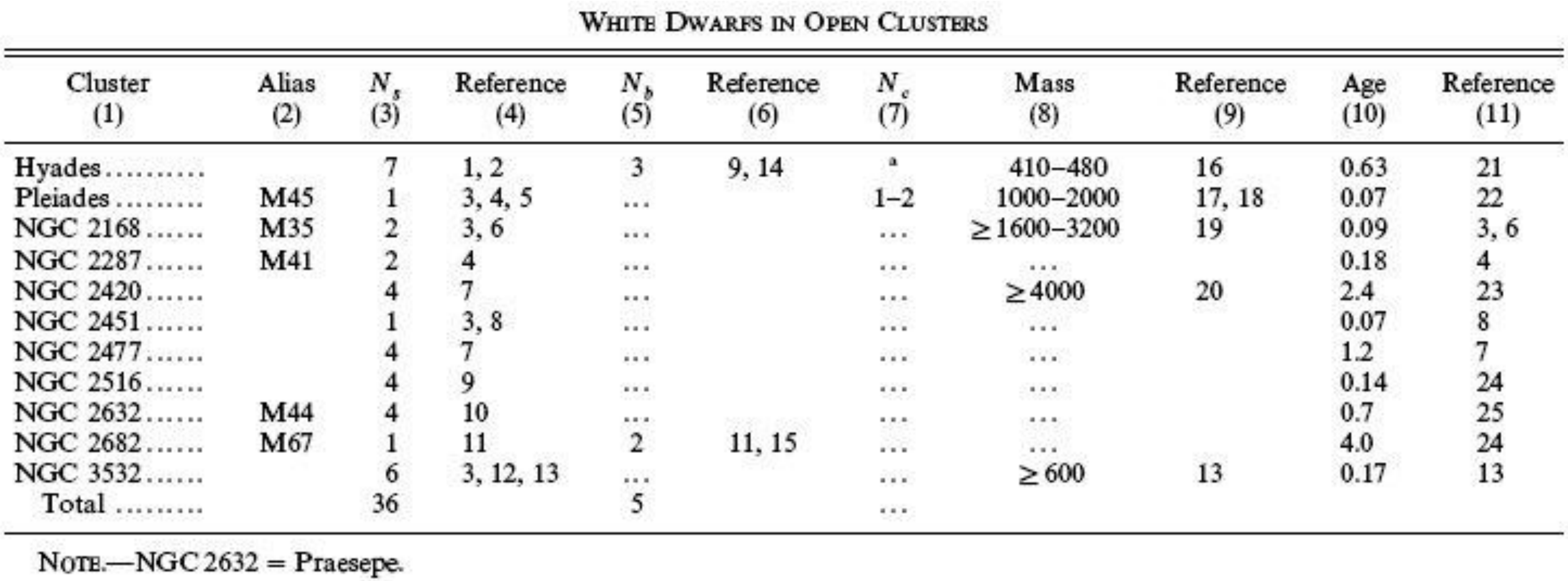




Pulsar, V fainter than 25th mag

- White Dwarfs were detected in Open Clusters
- The number is compatible with a common stellar evolution scenario, but the membership determination is very difficult
- The absolute magnitude of WDs is about 10 magnitudes fainter than the corresponding Main Sequence
- Still no reliable data about the number of the binary fraction is available

von Hippel, 1998, AJ, 115, 1536



WHITE DWARFS IN OPEN CLUSTERS

Cluster (1)	Alias (2)	N_s (3)	Reference (4)	N_b (5)	Reference (6)	N_c (7)	Mass (8)	Reference (9)	Age (10)	Reference (11)
Hyades		7	1, 2	3	9, 14	[a]	410–480	16	0.63	21
Pleiades	M45	1	3, 4, 5	...		1–2	1000–2000	17, 18	0.07	22
NGC 2168	M35	2	3, 6	...		...	$\geq$1600–3200	19	0.09	3, 6
NGC 2287	M41	2	4	...		...	...		0.18	4
NGC 2420		4	7	...		...	$\geq$4000	20	2.4	23
NGC 2451		1	3, 8	...		...	...		0.07	8
NGC 2477		4	7	...		...	...		1.2	7
NGC 2516		4	9	...		...	...		0.14	24
NGC 2632	M44	4	10	...		...	...		0.7	25
NGC 2682	M67	1	11	2	11, 15	...	...		4.0	24
NGC 3532		6	3, 12, 13	...		...	$\geq$600	13	0.17	13
Total		36		5		...				

NOTE.—NGC 2632 = Praesepe.

Single Multiple

In total, 41 WDs until 1998 found, no firm improvement after that

Why do Star Clusters dissipate?

Virial Theorem: $$2E_{kin} = -\Omega$$

Kinetic Energy: $$2E_{kin} = n \cdot m_i \cdot \bar{v}^2 = M \cdot \bar{v}^2$$

$\bar{v} \ldots$ mean v of the members

relative to the cluster center

Potential Energy: $$\Omega = -\frac{1}{2} \cdot \frac{G \cdot M^2}{\bar{R}^2}$$

yielding: $$\bar{v}^2 = \frac{G \cdot M}{2\bar{R}^2}$$

Escape Velocity: $\bar{v}_{\infty}^{2} = 4 \cdot \bar{v}^{2}$

Collisions: $t_{coll} \approx \dfrac{1}{\rho \cdot \sigma \cdot \Delta\bar{v}}$

Density ρ and Cross Section σ:

$$\rho = \frac{N}{\bar{R}^{3}} \qquad \sigma = 4\pi \cdot R_{*}^{2} \Rightarrow t_{coll} = \frac{\bar{R}^{3}}{4\pi \cdot N \cdot R_{*}^{2} \cdot \Delta\bar{v}}$$

Example of a typical Open Cluster:

$$N = 1000, \Delta\bar{v} = 10\mathrm{kms}^{-1}, \mathrm{R}_{*} = 2.5R_{Sun}, \bar{\mathrm{R}} = 5\mathrm{pc}$$

$t_{coll} = 10^{25}\mathrm{s}$ => Collisions play no role

Even in the most inner core parts, collisions are highly improper, but could occur

Conclusions:

1. Binary and Multiple systems are not results of collisions in later stages but form already at the very beginning
2. Members do, in general, not escape due to collisions (swing-by effect), but their peculiar velocity component is part of the cluster formation or due to a SN

Crossing Time: $t_{cross} = \frac{\overline{R}}{\Delta v}$

$$\Delta v = 10\mathrm{kms}^{-1} \text{ and } \overline{\mathrm{R}} = 5\mathrm{pc} \Rightarrow t_{cross} = 4.9 \cdot 10^{8}\, yr$$

Members can escape from a Star Cluster on a relatively short time scale

Reason: Velocity dispersion caused by the cluster formation and SN events

Tidal Forces due to Differential Galactic Rotation

Total Mass of the Milky Way: M_{G} = 2x10^{11} M(Sun)

Gravitational acceleration of the complete Star Cluster g_{G} and the individual member g_{*} :

$$g_G = \frac{G \cdot M_G}{R_{GC}^2} \qquad g_* = \frac{G \cdot M_G}{\left(R_{GC} - r\right)^2}$$

The difference of these two values, is the force, of which “the Galaxy” tries to pull away a star from the cluster

$$g_{G,*} = \frac{2 \cdot G \cdot M_G \cdot r}{R_{GC}^3} \text{ for } r << R_{GC}$$

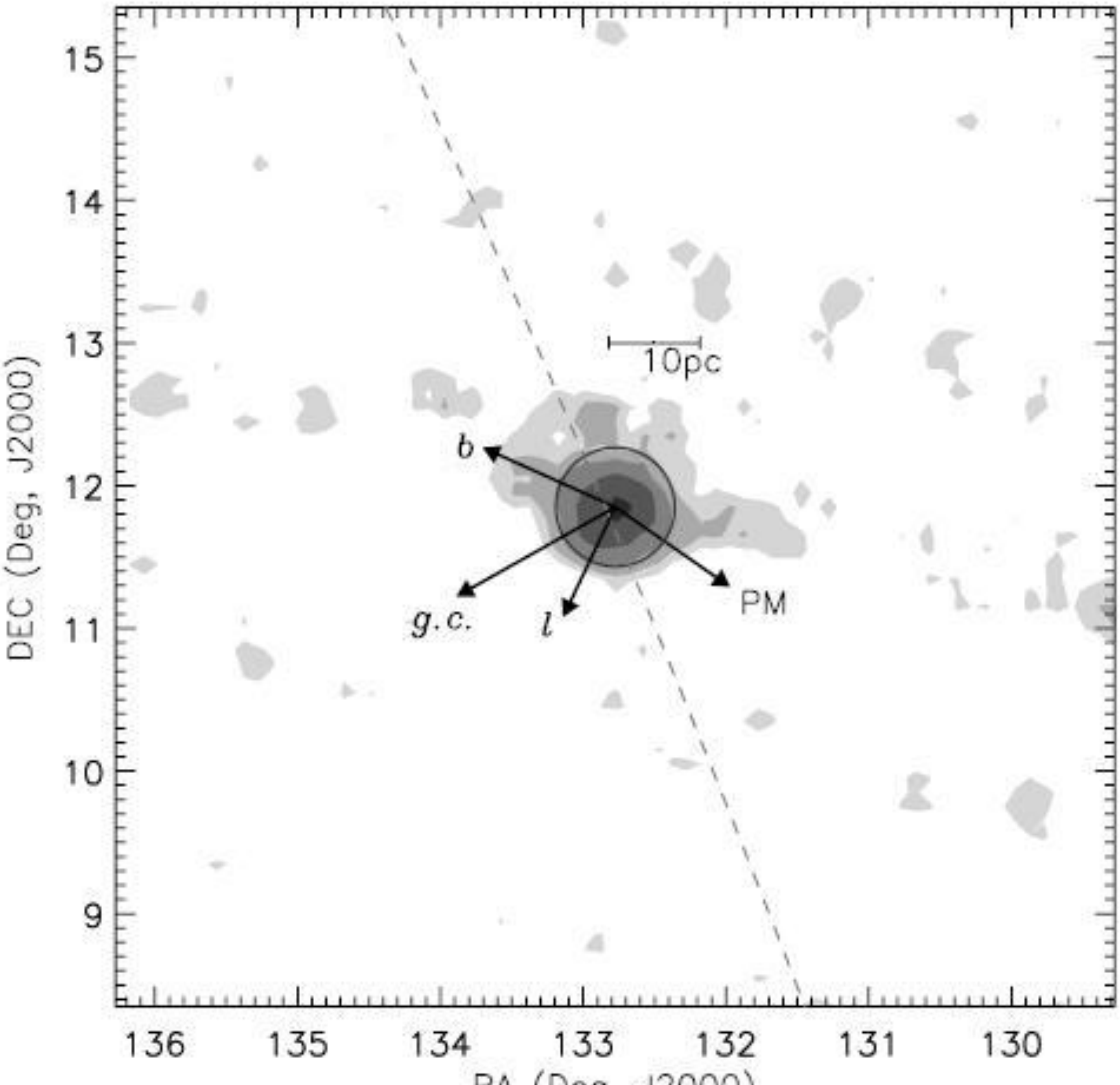
On the other side we have the gravitational force of the Open Cluster. The stability radius r_S is defined as:

$$\frac{2 \cdot G \cdot M_G \cdot r_S}{R_{GC}^3} = \frac{G \cdot M_{OC}}{r_s^2} \Rightarrow r_S = R_{GC} \cdot \left(\frac{M_{OC}}{2M_G} \right)^{1/3}$$

$$r_S = 10.9 \cdot \left(\frac{M_{OC}}{1000} \right)^{1/3} \quad \text{for } R_{GC} = 8\,\mathrm{kpc\,in}\,[\mathrm{M_{Sun}}, \mathrm{pc}]$$

For 1000 M(Sun) => Diameter 20 pc

M67



Davenport &
Sandquist,
2010, ApJ,
711, 559

Summary

- Star Cluster dissipate because of
  1. Differential Galactic Rotation
  2. Internal Velocity Dispersion
  3. Collisions in the first few Myrs
  4. SN Explosions and corresponding Shock Waves
  5. (Collisions with “Field Stars”)
- Explains the existence of Globular Clusters
- Valid for all Spiral Galaxies

Initial Mass Function

- The „Initial Mass Function“ (IMF) describes the mass distribution for a population of stars when they are formed together
- Relevant astrophysics:
  1. Size, total mass and metallicity of the initial GMC
  2. Fragmentation of the GMC
  3. Conservation of the angular momentum
  4. Local and global magnetic fields
  5. Accretion in the Pre-Main Sequence phase
- The only observational parameter for the test of stellar formation and evolution models
- We observe a luminosity function which has to be transformed to the IMF

Initial Mass Function

- Several most important questions are still not solved
  1. Is the IMF homogeneous within the Milky Way?
  2. Is the IMF constant throughout time?
  3. What is the influence of the local and global magnetic field on the IMF?
  4. What is the influence of the local and global metallicity on the IMF?
- Current answer to 1. and 2.: YES
- Current answer to 3. and 4.: UNKNOWN

Initial Mass Function

The IMF $\theta(m)$, often called „Present-Day Mass Function" (PDMF), is defined as:

$$dN = \theta(m)\, dm$$

dN is the number of all stars per cubic parsec on the *main sequence* with a mass between M and (M + dm).

But we observe not the masses of stars but their magnitudes (relative and absolute) or luminosities.

So we have to define the luminosity function and transform it into the IMF.

Luminosity function

The luminosity function $\Psi(M_V)$, is defined as:

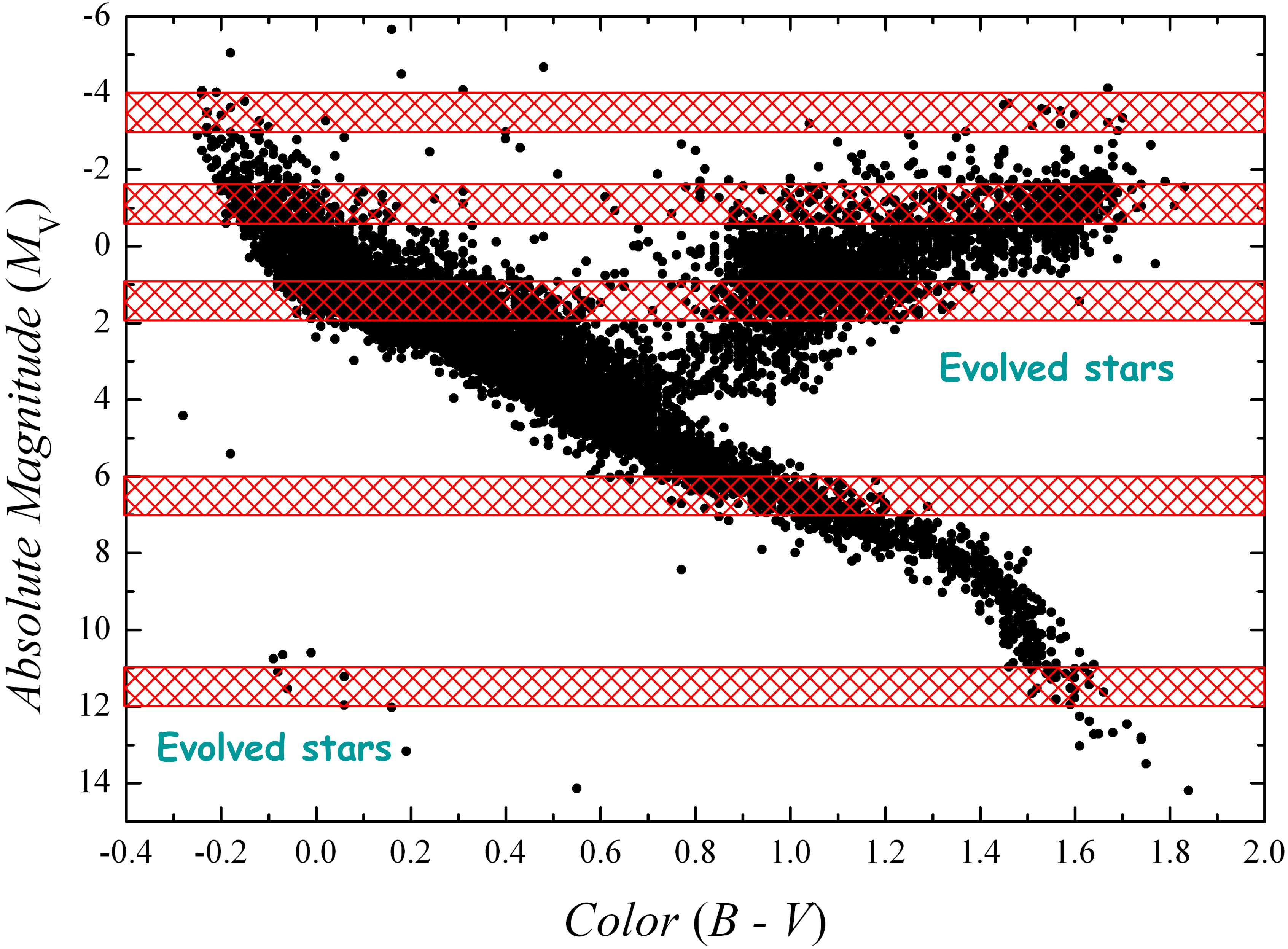
$$dN = -\Psi(M_V)\, dM_V$$

dN is is the number of all stars per cubic parsec on the *main sequence* with an absolute magnitude between M_V and $(M_V + dM_V)$. The transformation to the IMF is given as:

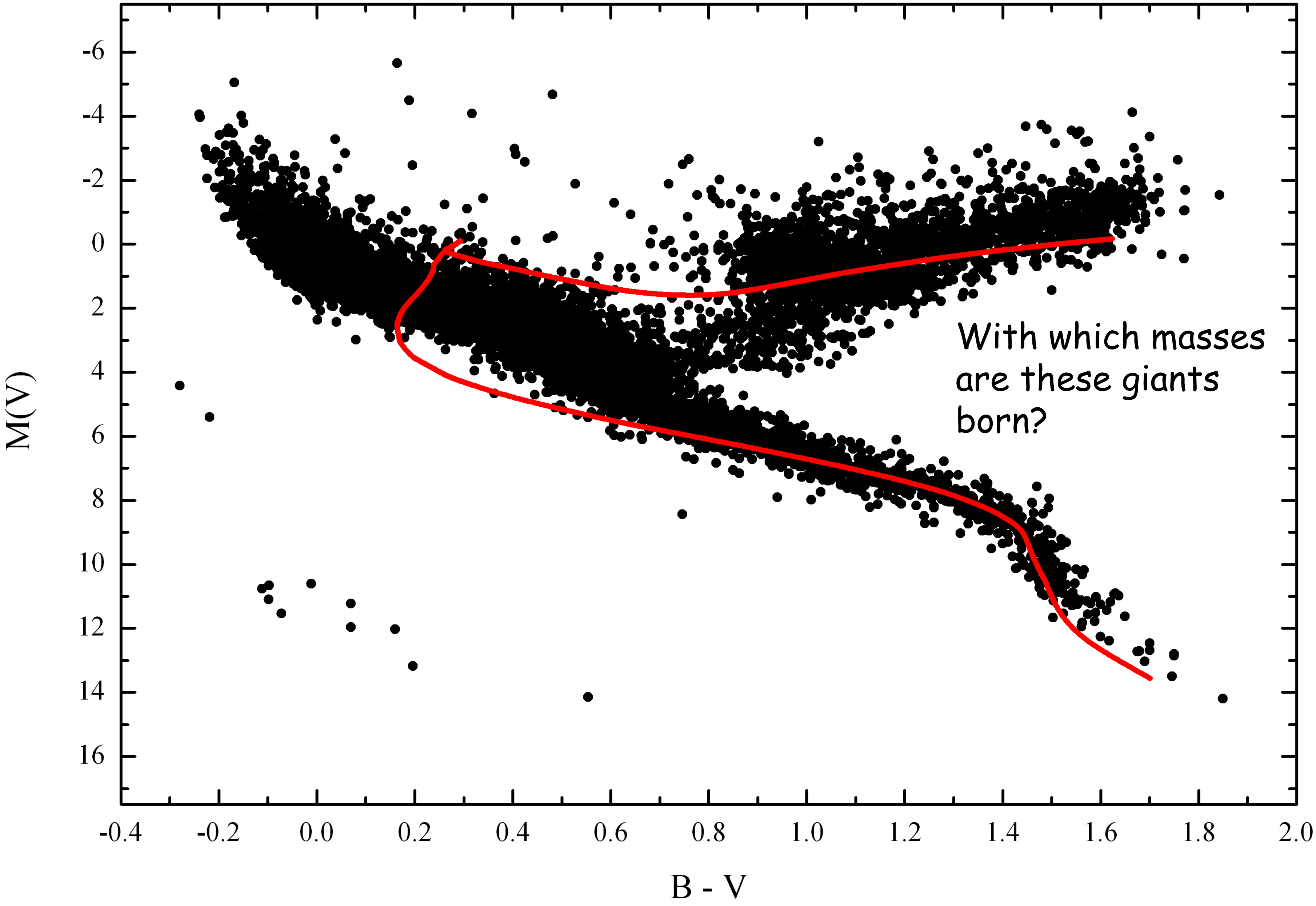
$$\theta(m) = -\Psi(M_V)[dm(M_V)/dM_V]^{-1}$$

The second term is the derivation of the Mass-Luminosity function $m(M_V)$. It is depending on the age (t), metallicity (Z) and rotation (v_{rot})

$$m(M_V) = m(M_V, Z, t, v_{rot})$$



In each row (M_V + dM) there is a mixture of main sequence and evolved objects. For the IMF, we need the main sequence only.



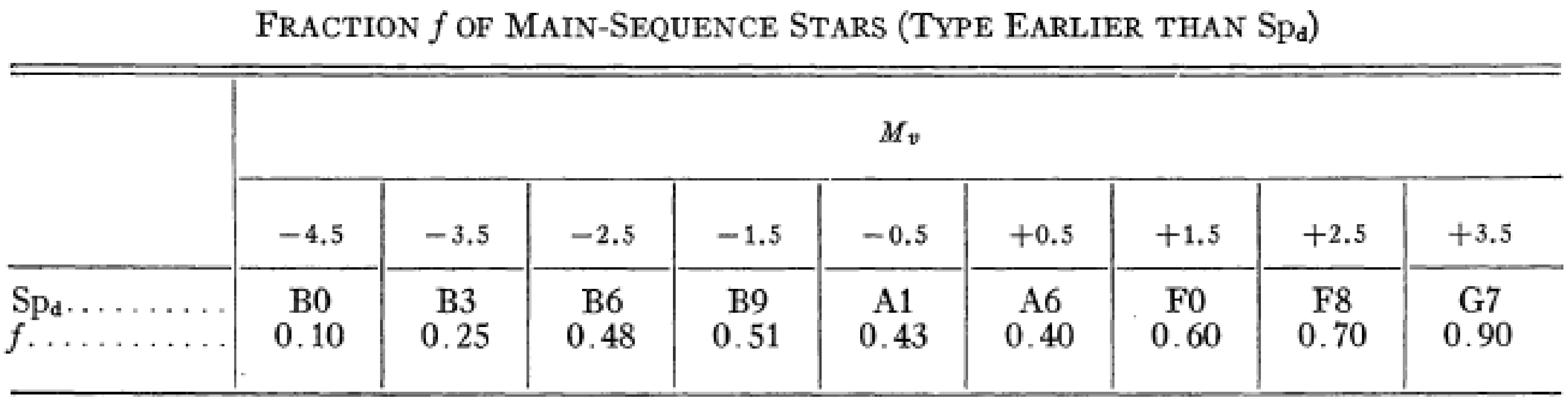
With which masses are these giants born?

Correction of the observations

We have to correct the complete observations for the evolved objects. There are three possibilities:

1. Take a statistical sample with a well known luminosity function (clusters)
2. Take a statistical sample with well known photometric magnitudes and distances
3. Take isochrones = theoretical star evolution = models based on observations = circular argument

All these methods are not self consistent and always introduce an unknown error to the analysis



FRACTION f OF MAIN-SEQUENCE STARS (TYPE EARLIER THAN Sp_d)

	M_v								
	−4.5	−3.5	−2.5	−1.5	−0.5	+0.5	+1.5	+2.5	+3.5
Sp_d	B0	B3	B6	B9	A1	A6	F0	F8	G7
f	0.10	0.25	0.48	0.51	0.43	0.40	0.60	0.70	0.90

Salpeter, 1955, ApJ, 121, 161

Results of classical spectral classification, only 10% of stars with M_V = -4.5 mag are on the main sequence!

These values are depending on the chosen sample for the spectral classification and which classification scheme is applied.

The errors are rather large.

The mathematical correction of the IMF is as follows.

Assume that the Milky Way was formed at t = 0 and has a present age of t_G. Within a time interval of (t,t+dt) and a mass interval (m,m+dm), per cubic parsec, there are

$$dN = \xi(m,t)dm\, b(t)dt$$

Stars newly formed. b(t) describes the time dependency of the IMF and is normalized to One:

$$\frac{1}{t_G}\int_0^{t_G} b(t)dt = 1$$

Stars which stay on the main sequence for $t(m) < t_G$ have left it already, if they were not formed within the time interval $[t_G - t(m)]$.

The number of stars which are still on the main sequence is therefore

$$\Theta(\mathrm{m}) = \xi(\mathrm{m}) \cdot \frac{1}{\mathrm{t}_G} \begin{cases} \displaystyle\int_{\mathrm{t}_G - t(m)}^{\mathrm{t}_G} \mathrm{b(t)dt} & \text{for } t(m) < t_G \\ \displaystyle\int_{0}^{\mathrm{t}_G} \mathrm{b(t)dt} & \text{for } t(m) \geq t_G \end{cases}$$

$\xi(m)$ is called the „time-averaged" IMF. For low mass stars, typically below 0.5 M(sun), one finds that

$$\theta(m) = \xi(m) \times \text{Term}$$

Special cases:

- Time constant IMF: $b(t) = 1$
- All stars were formed at the same time (t_0), e.g. for star clusters because $t_{CL} \ll t_G$: $b(t) = t_{CL}\, \delta(t - t_0)$

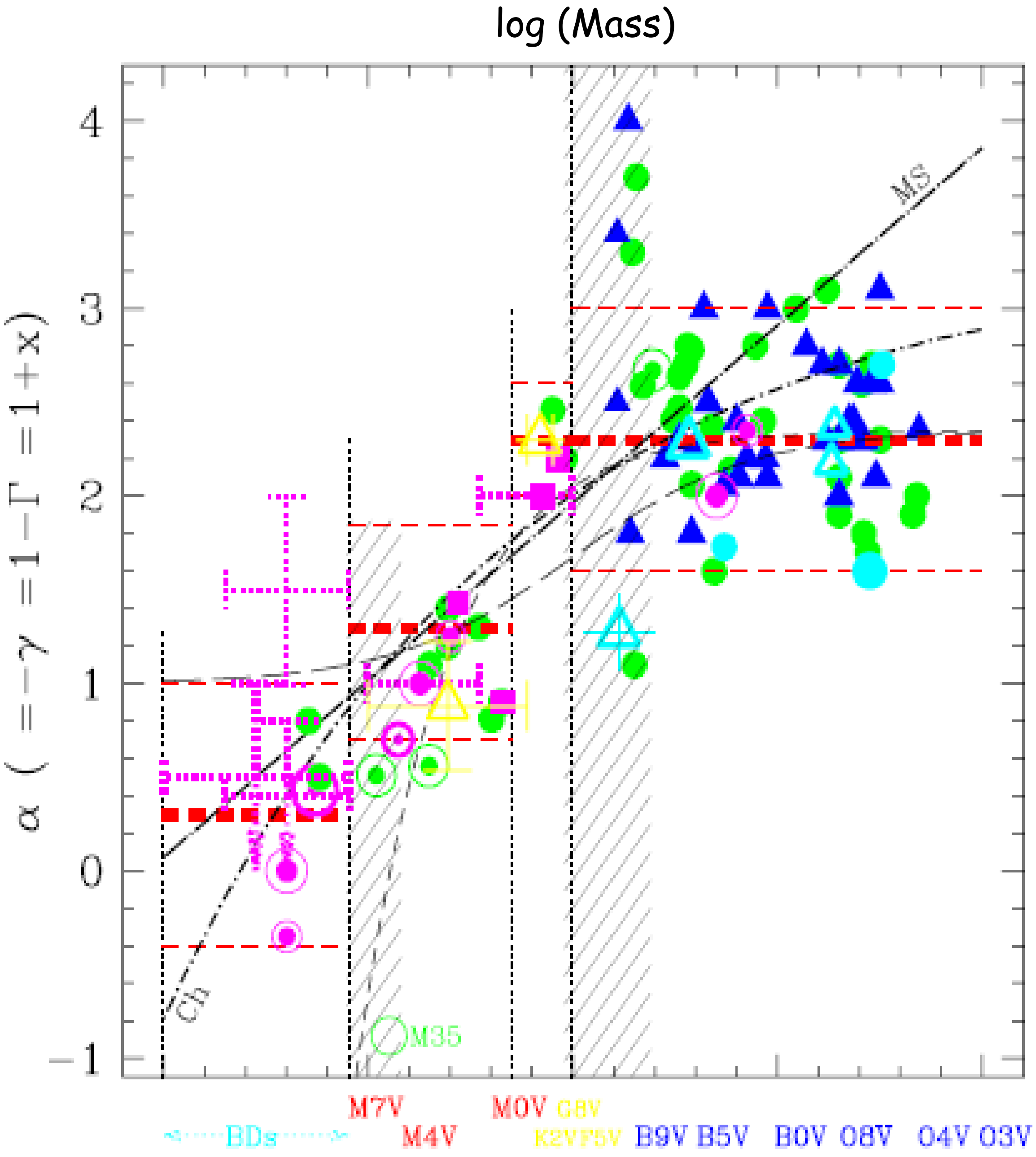
All observations have to be normalized to one “standard system” which means essentially to one “time scale”.

The observations show, that this heuristic law describes them very well

$\theta(m) \approx m^{-\Gamma}$ Salpeter law (1955)

Star cluster are one of the most important observational test for the IMF because they, normally, have well defined ages, distances and metallicities. However, the errors are still quiet large.

But there is still no homogeneous IMF determination for open clusters taking into account the available data.



Kroupa, 2002, Science, 295, 82

Mean value for different masses

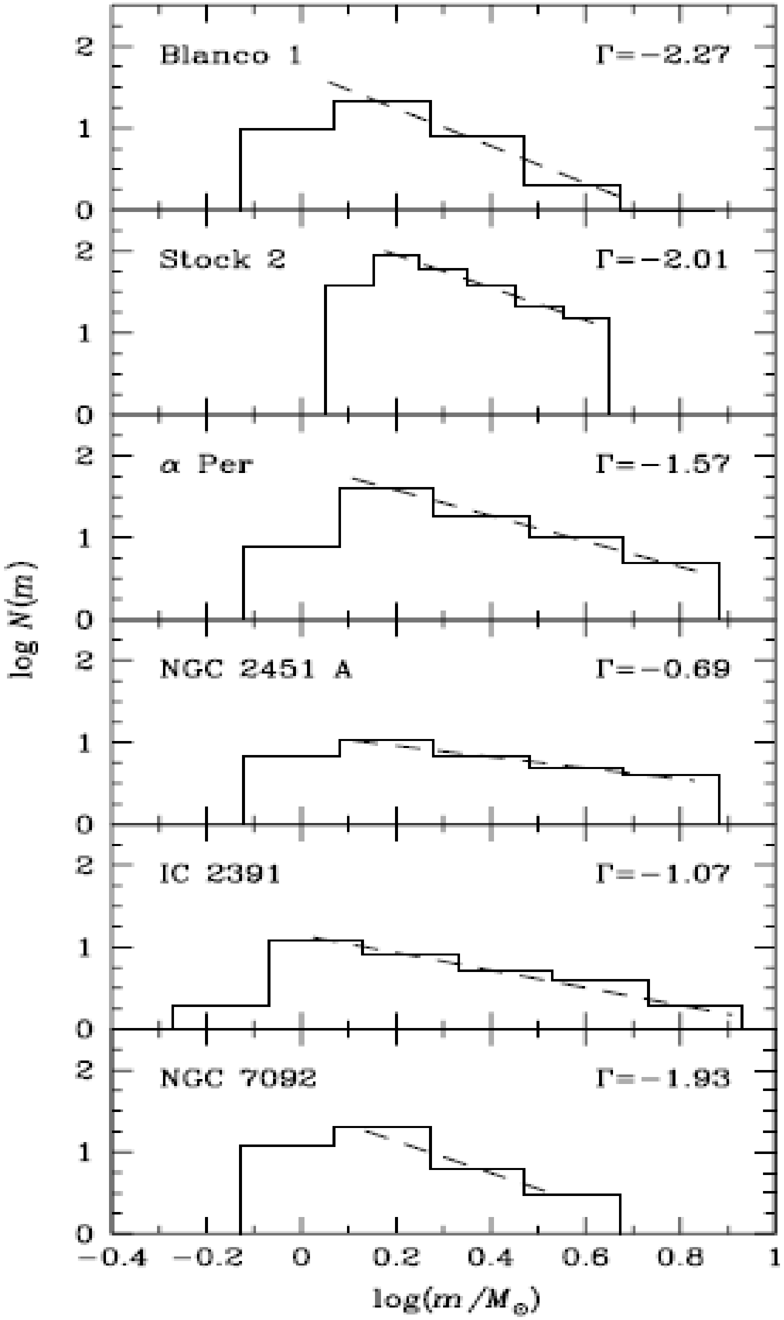
$$\Gamma = \begin{array}{ll} -0.2 \pm 0.3 & \text{for 0.1 to 1 } M_\odot \\ -1.7 \pm 0.5 & \text{for 1–10 } M_\odot \\ -1.3 \pm 0.5 & \text{for 10–100 } M_\odot \end{array}$$

The number of stars increases at lower masses

Cook Book to generate the IMF from Johnson BV observations for a star cluster

1. V versus B-V diagram
2. If possible select only members or generate a Hess diagram
3. Determine Age, distance and reddening
4. M_V versus $(B-V)_0$ diagram
5. Determine masses from isochrones, i.a. transform M_V and $(B-V)_0$ to masses
6. Estimate the lower and upper mass limits
7. Estimate meaningful mass bins
8. Plot histogram over the selected mass interval
9. Derive the IMF and/or Γ
10. Loop 4. to 8. with isochrones +- error
11. Estimate the error of the IMF from 10.

TYCHO2 data



cluster	$(m-M)_0$ [mag]	E_{B-V} [mag]	t Myr	$\underline{d}$ [′]
Blanco 1*	6.8	0.03	50	105
Stock 2	7.5	...	100	260
α Per*	6.3	0.09	20	255
Pleiades*	5.6	0.05	75	300
NGC 2451 A*	6.4	0.00	20	140
IC 2391*	5.8	0.00	20	110
Praesepe*	6.0	0.00	650	195
IC 2602*	5.8	0.03	10	185
NGC 7092	7.6	0.12	70	170

cluster	# stars	Γ	mass range [$M_\odot$]	V_T range [mag]
Blanco 1	34	-2.27 ± 0.70	[1.1; 4.8]	[6.1; 11.4]
Stock 2	204	-2.01 ± 0.40	[1.5; 4.1]	[7.6; 11.0]
α Per	70	-1.57 ± 0.44	[1.1; 6.8]	[5.0; 10.5]
Pleiades	127	-1.99 ± 0.39	[1.0; 4.1]	[5.0; 10.9]
NGC 2451 A	27	-0.69 ± 0.63	[1.3; 6.8]	[4.8; 10.0]
IC 2391	29	-1.07 ± 0.53	[1.1; 8.1]	[3.5; 10.7]
NGC 7092	25	-1.93 ± 1.24	[1.4; 3.4]	[6.5; 9.9]

Sanner & Geffert, 2001, A&A, 370, 87