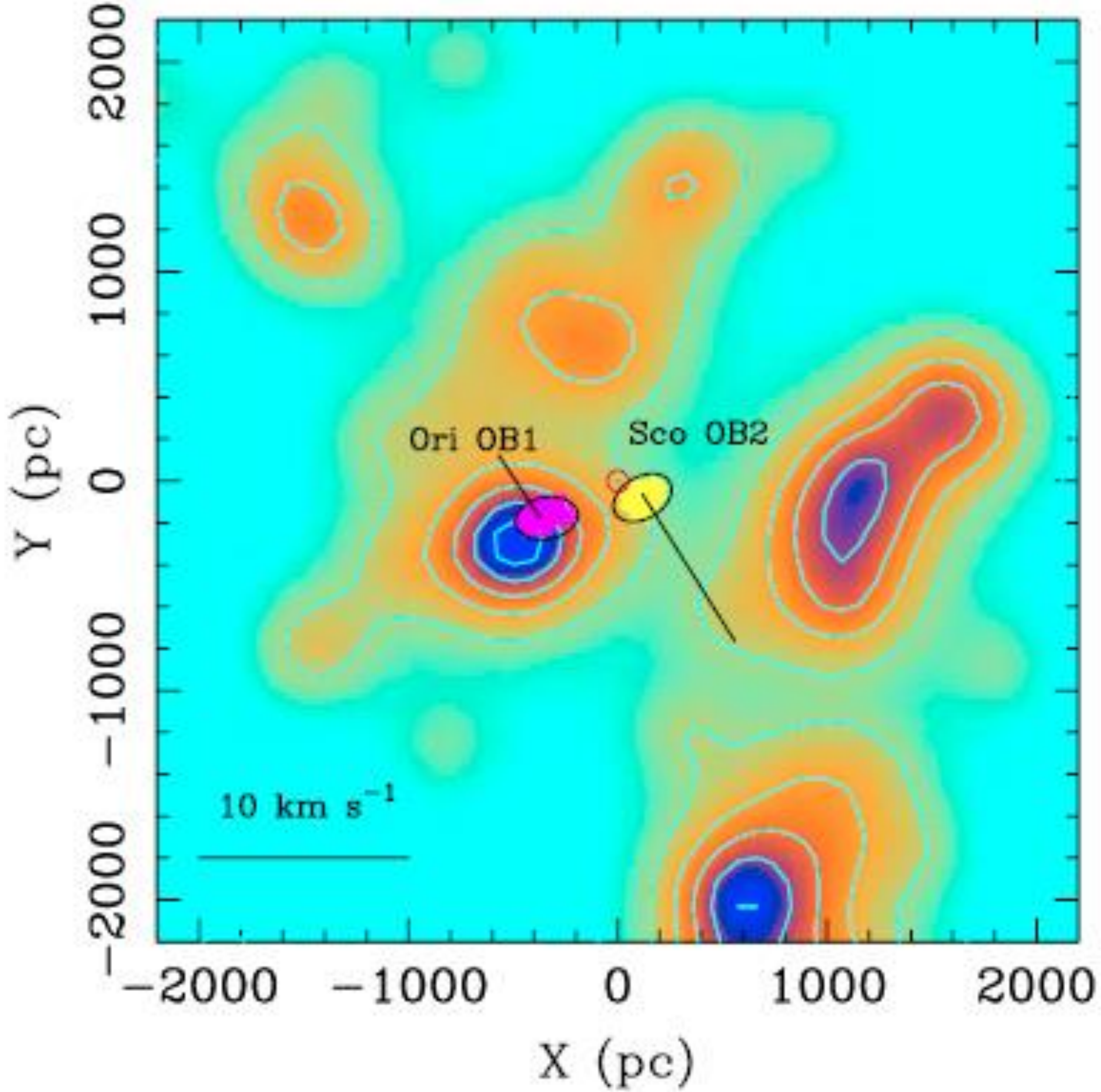
Cluster formation

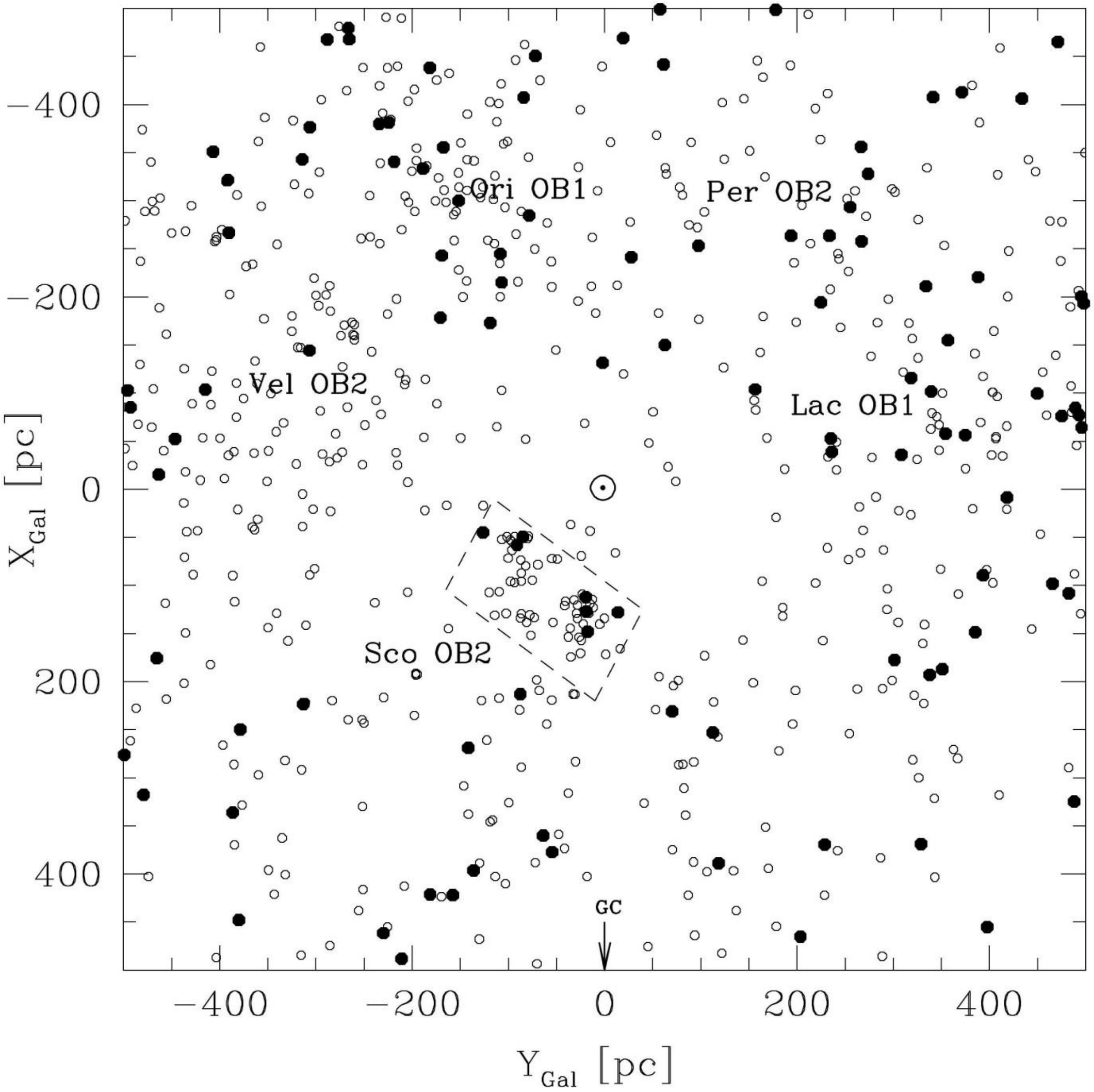
- Observations versus Models
- Important parameters
  1. Time scale
  2. Total mass
  3. Initial Mass Function
  4. Velocity distribution
  5. Binary fraction
  6. Diameter
  7. Density distribution

Heuristic Approach

- We know of 14 Open Clusters which are younger than 10 Myrs within 1000 pc around the Sun (Source: WEBDA)
- There are also five star forming regions
- Open Clusters still have to form within the solar vicinity
- Total masses: up to 40 000 M(sun)
- Stable for some Gyrs
- Evolutionary theory has to explain these facts



Distribution of young open clusters and star forming regions from Alfaro et al., 2009, Ap&SS, 324, 141



Stars hotter than B0 and B0 to B2

Distribution of star forming regions from Preibisch & Mamajek, 2008, Handbook of Star Forming Regions, Volume II

Orion Nebula, Distance about
450 pc, Total Mass about
5000 M(sun), Diameter about 3 pc

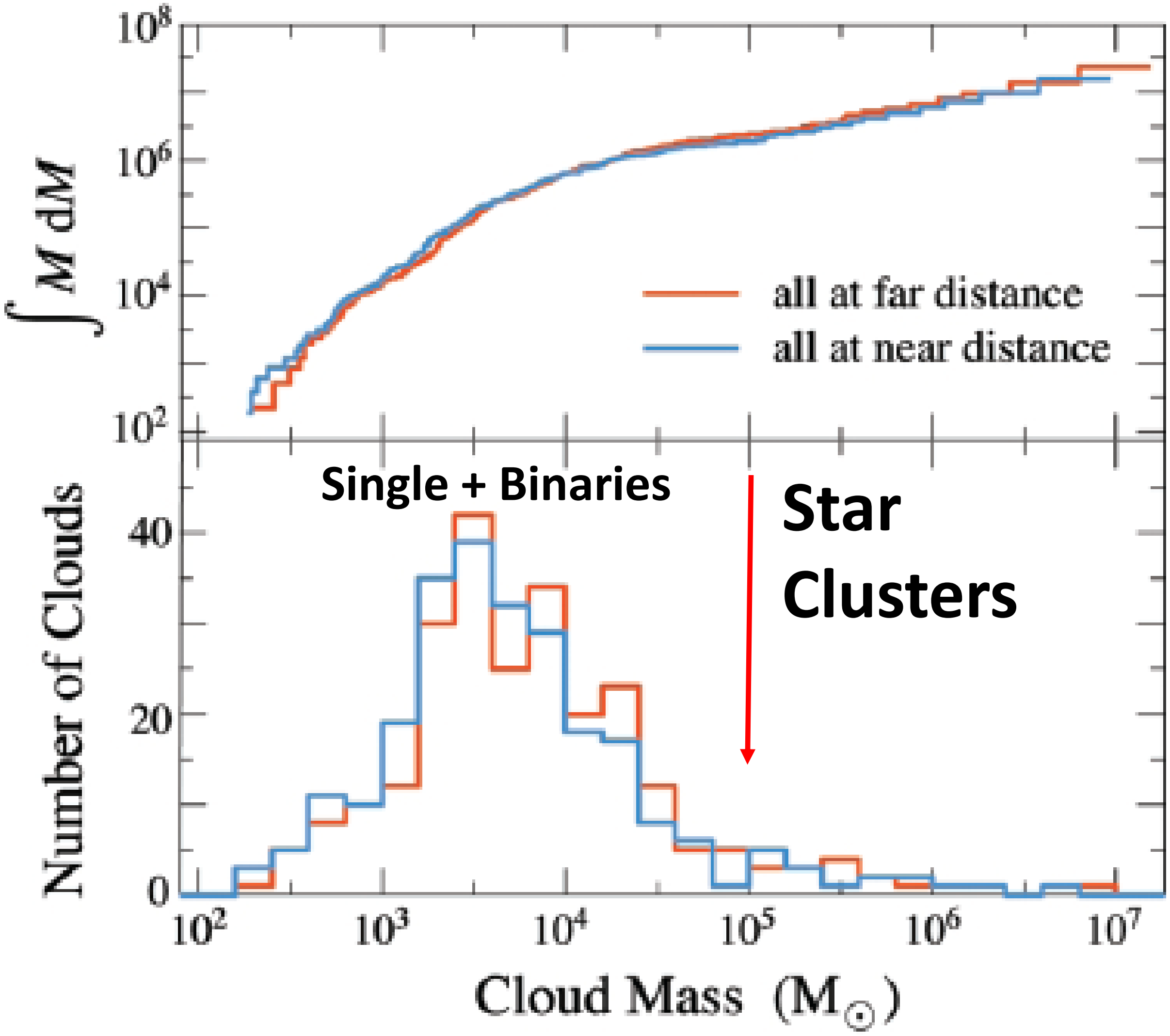
M11, NGC 6705: Total Mass
About 10000 M(sun), 200 Myr

Giant Molecular Clouds

- Star Clusters can only form within „Giant Molecular Clouds“ (GMC) with a high enough initial mass
- The stellar formation rate in the solar neighborhood is very low
- But still there have to exist several GMCs to form Star Clusters
- Is the formation process the same for all observed Galaxy types?

Giant Molecular Clouds

Stark & Lee, 2006, ApJ, 641, L116



Single + Binaries

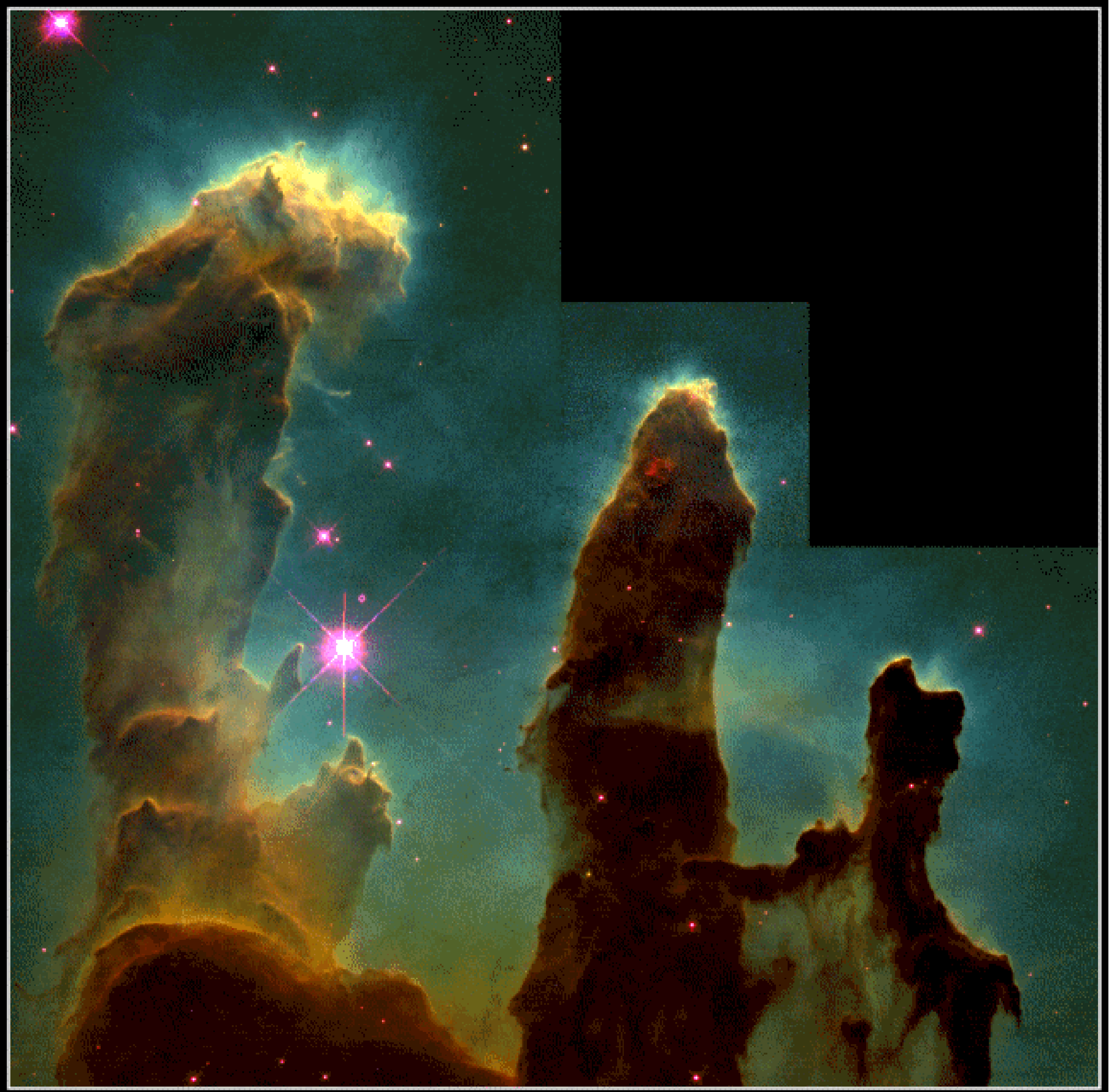
Star Clusters

Recent investigation of the ^{13}CO Gas within 2000 pc around the Sun

The number of young OCLs can be very well explained

Formation rate of 0.45 OCLs per kpc^{-2} Myr^{-1} in the galactic disk within 2 kpc around the Sun

Battinelli & Capuzzo-Dolcetta, 1991, MNRAS, 248, 76



Gaseous Pillars • M16 HST • WFPC2

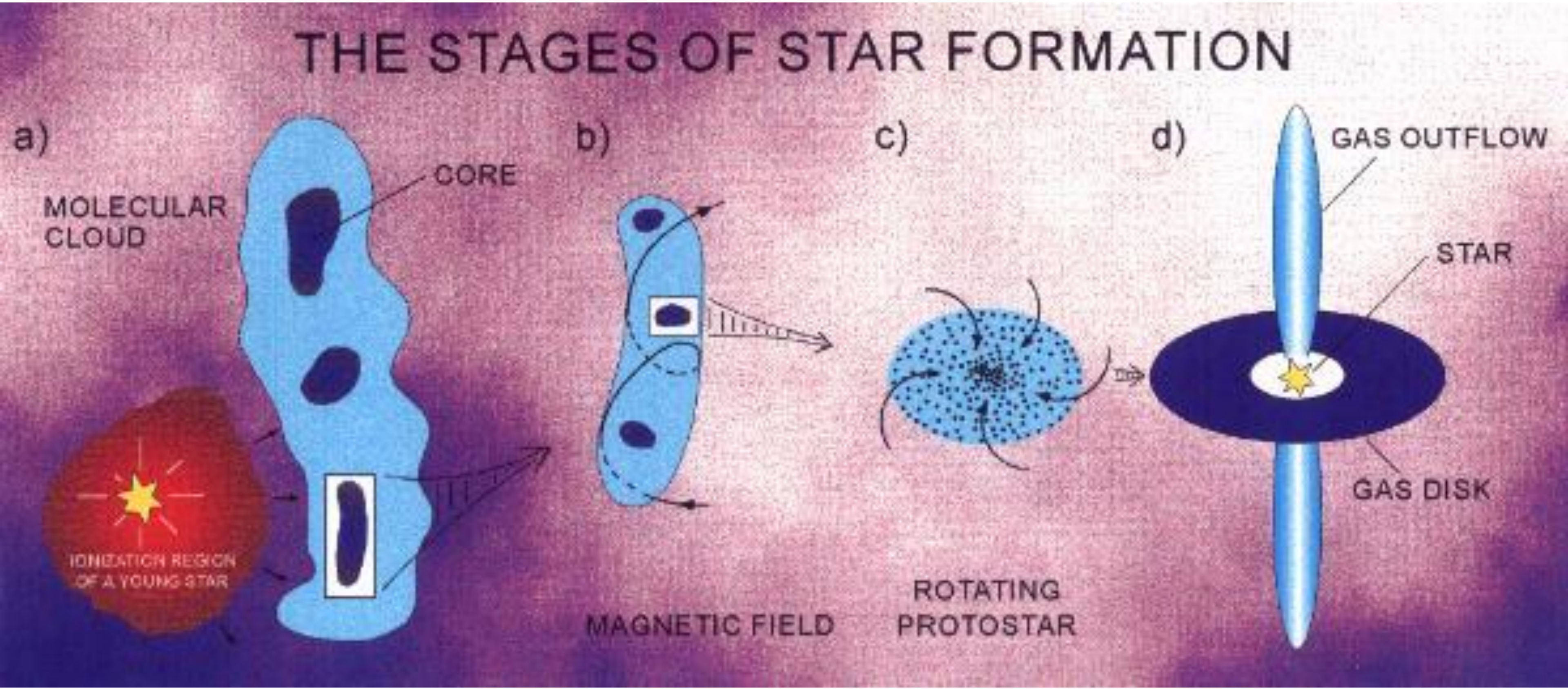
PRC95-44a • ST ScI OPO • November 2, 1995
J. Hester and P. Scowen (AZ State Univ.), NASA

NGC 6611 (M16)

d = 1750 pc
t = 8 Myr

Star formation „live“

Star formation



Gravitation „wins“ Magnetic field, Shock wave Protostar

← FREE GAS → ← NO FREE GAS →

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?

Initial Mass Function

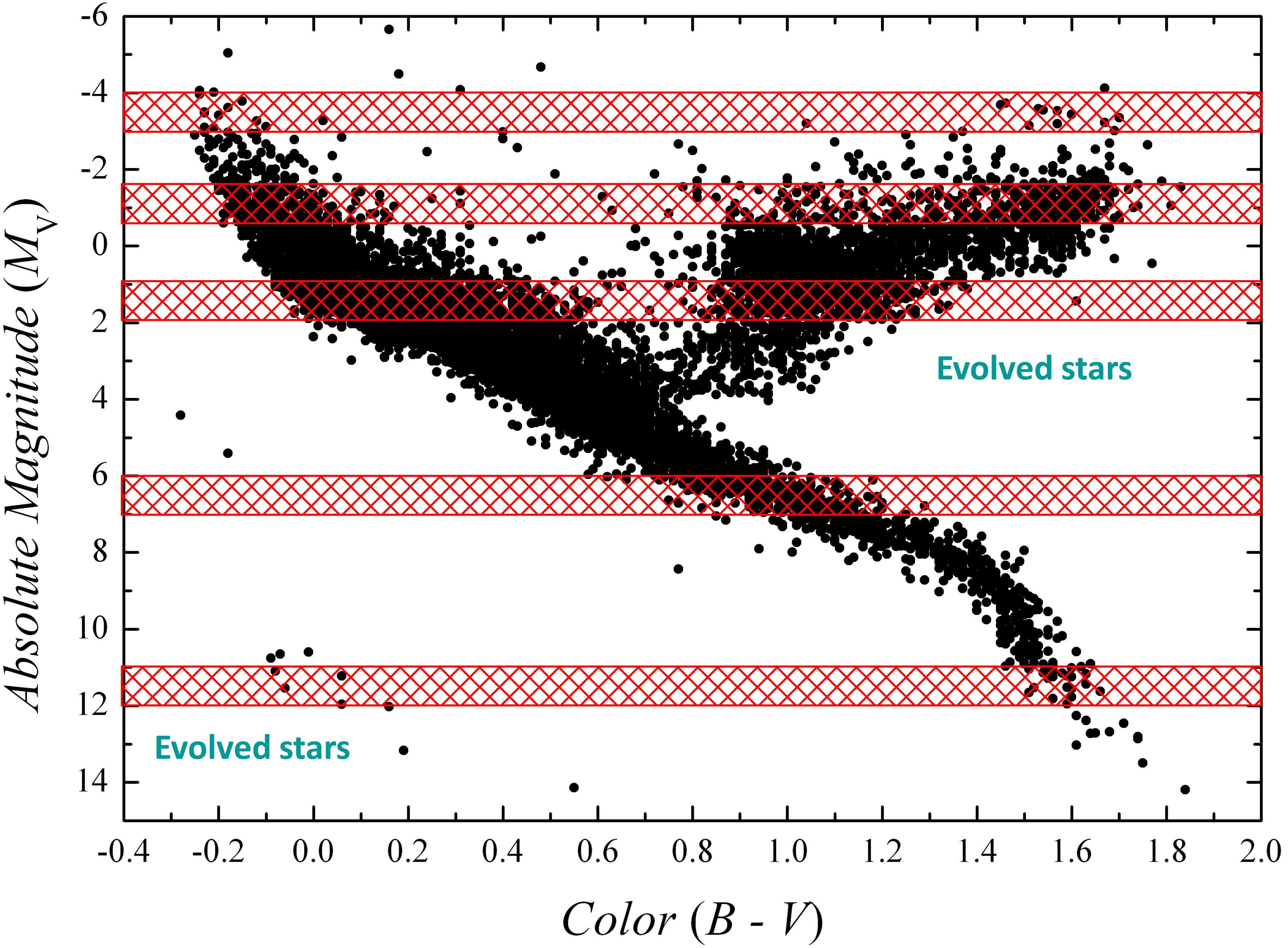
The IMF $\theta(m)$, often called „Present-Day Mass Function“ (PDMF), is defined as:

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

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.



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.

Luminosity function

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

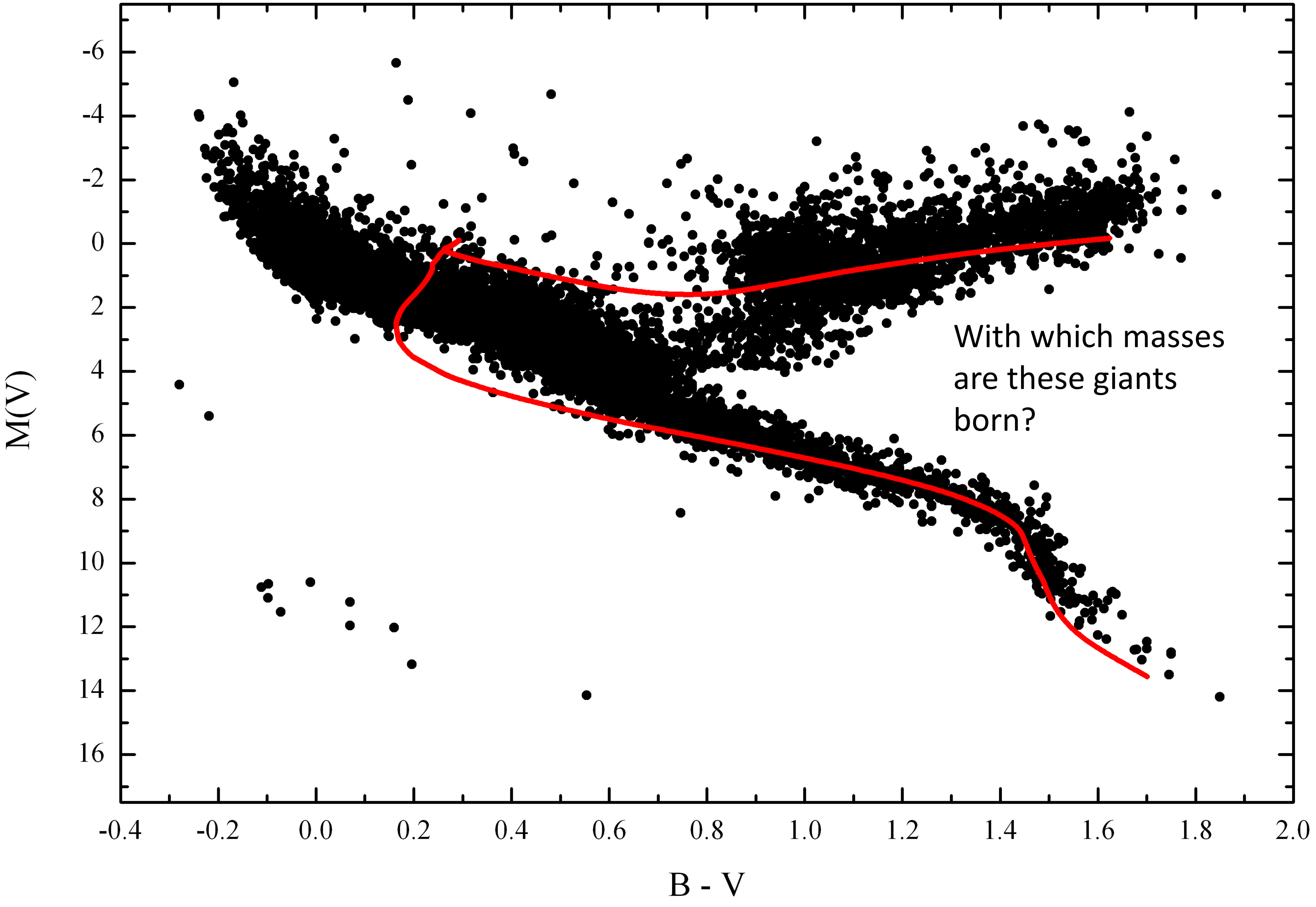
$$dN = -\Psi(M_V)\, dM_V$$

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})

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



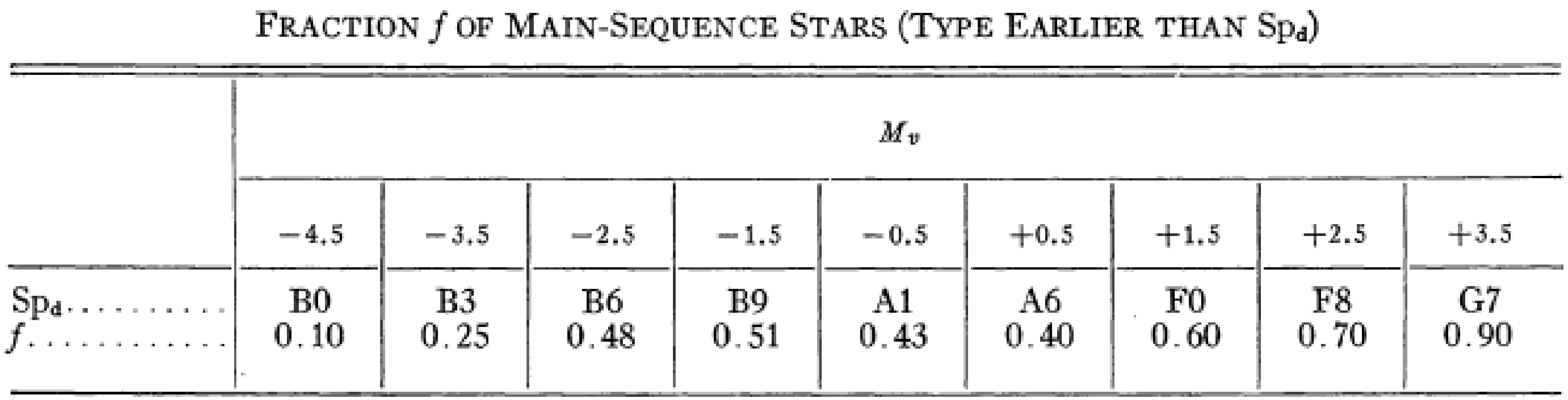
With which masses are these giants born?

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.

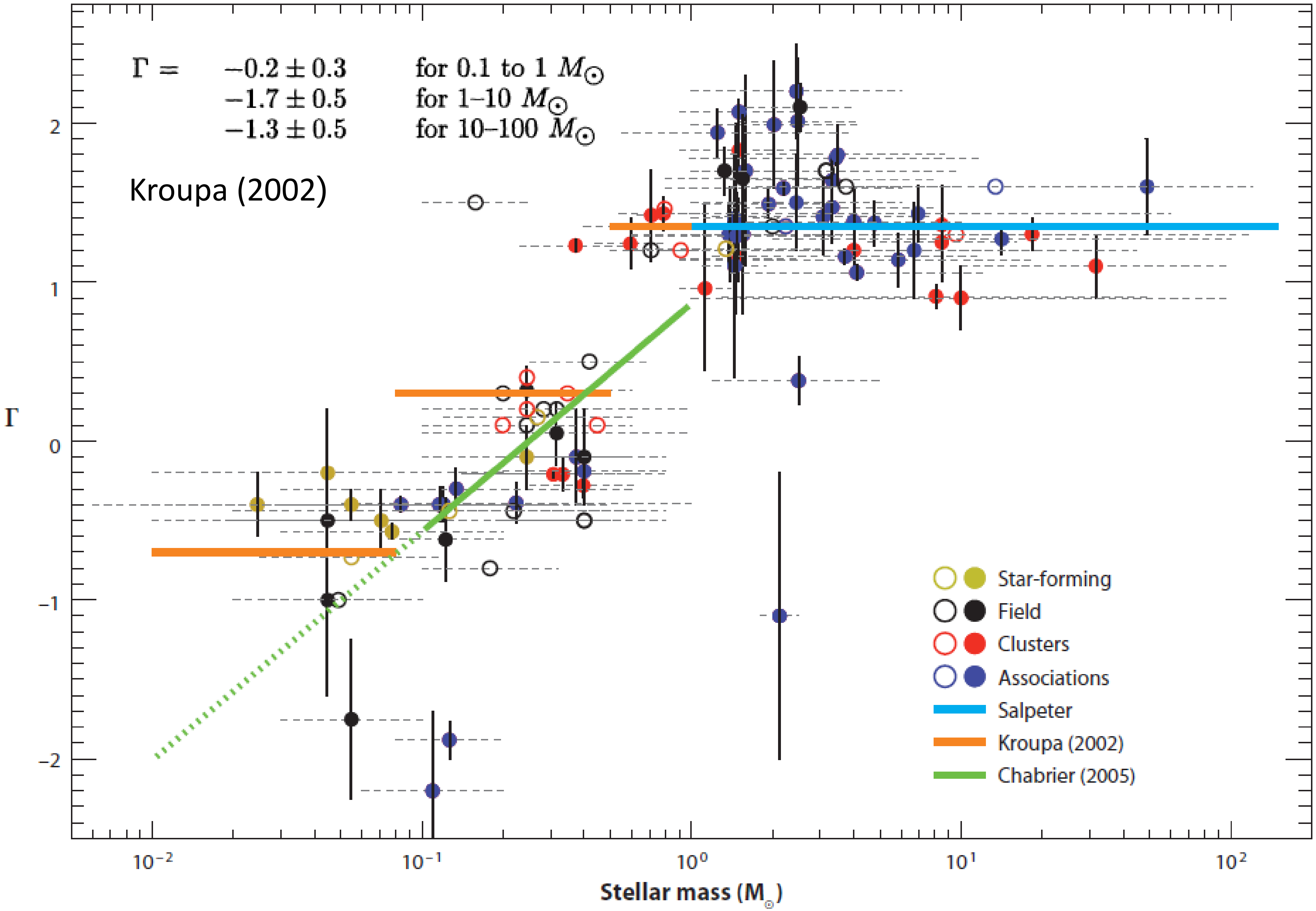
All observations have to be normalized to one “standard system” which means essentially to one “time scale”.

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

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

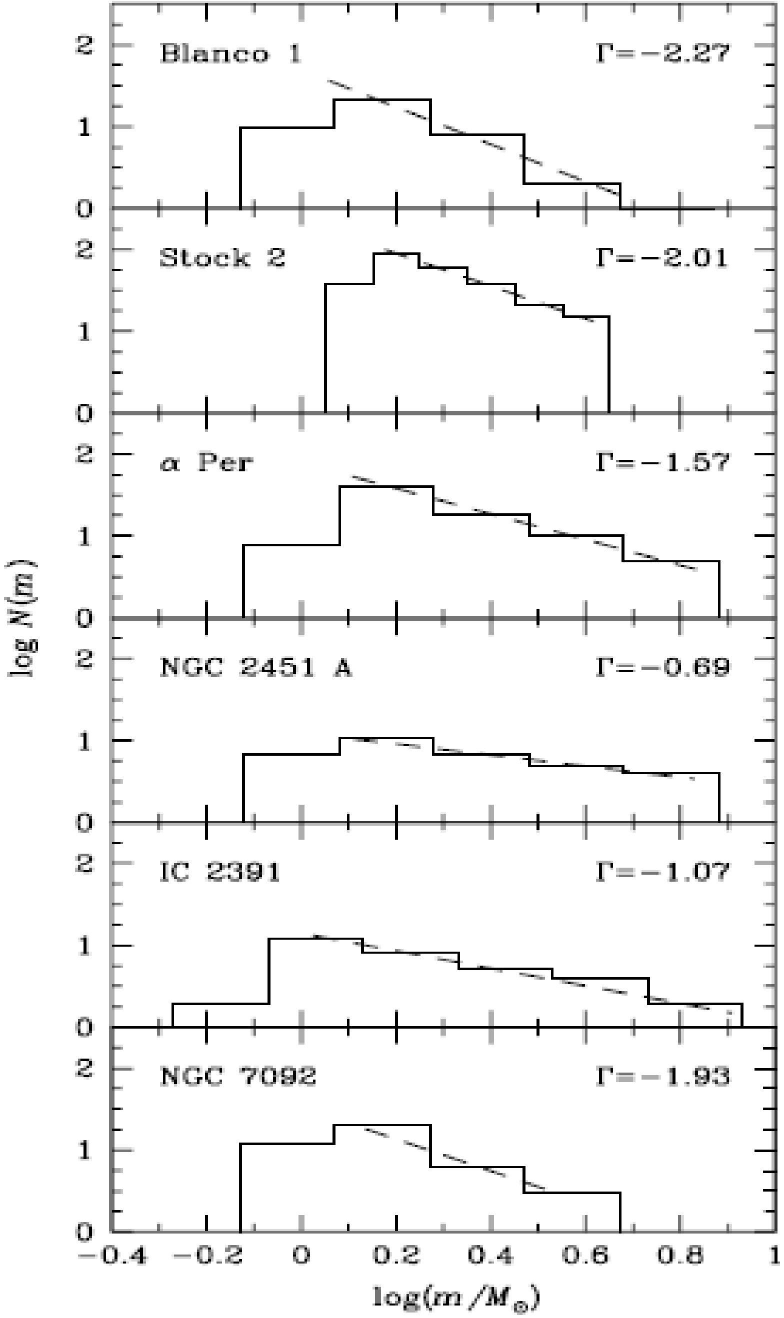
Star cluster are one of the most important observational test for the IMF because they, normally, have well defined ages, distances and metallicities. However, the errors are still quiet large.

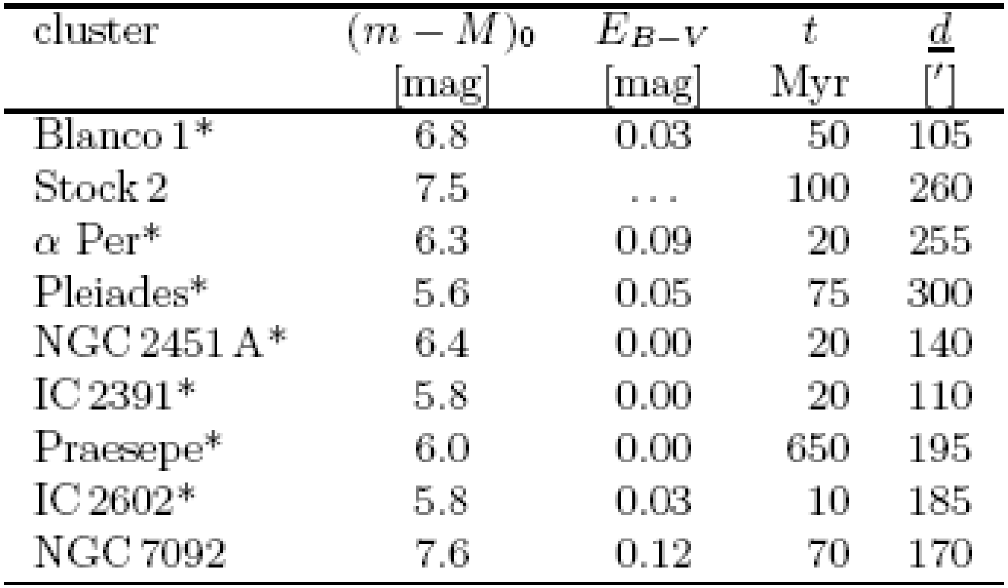
But there is still no homogeneous IMF determination for open clusters taking into account the available data.



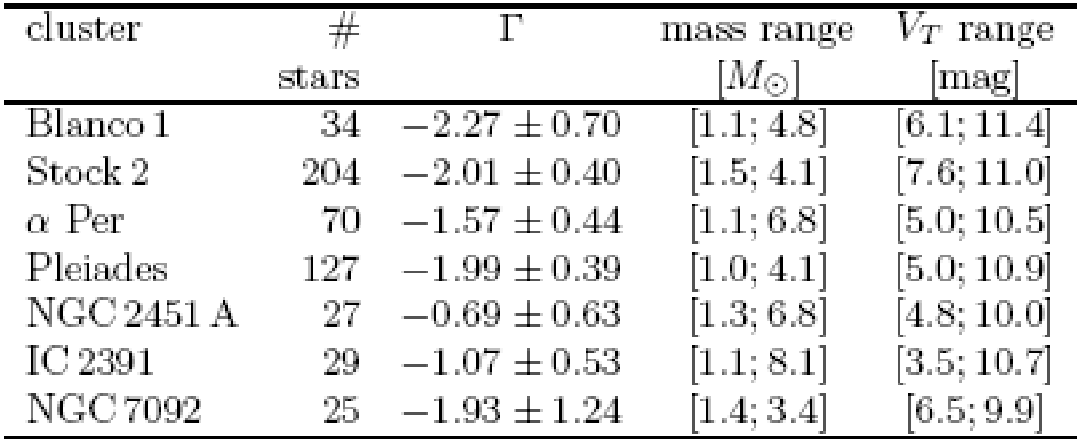
Bastian et al, 2010, Annual Review of Astronomy and Astrophysics, 48, 339

TYCHO2 data





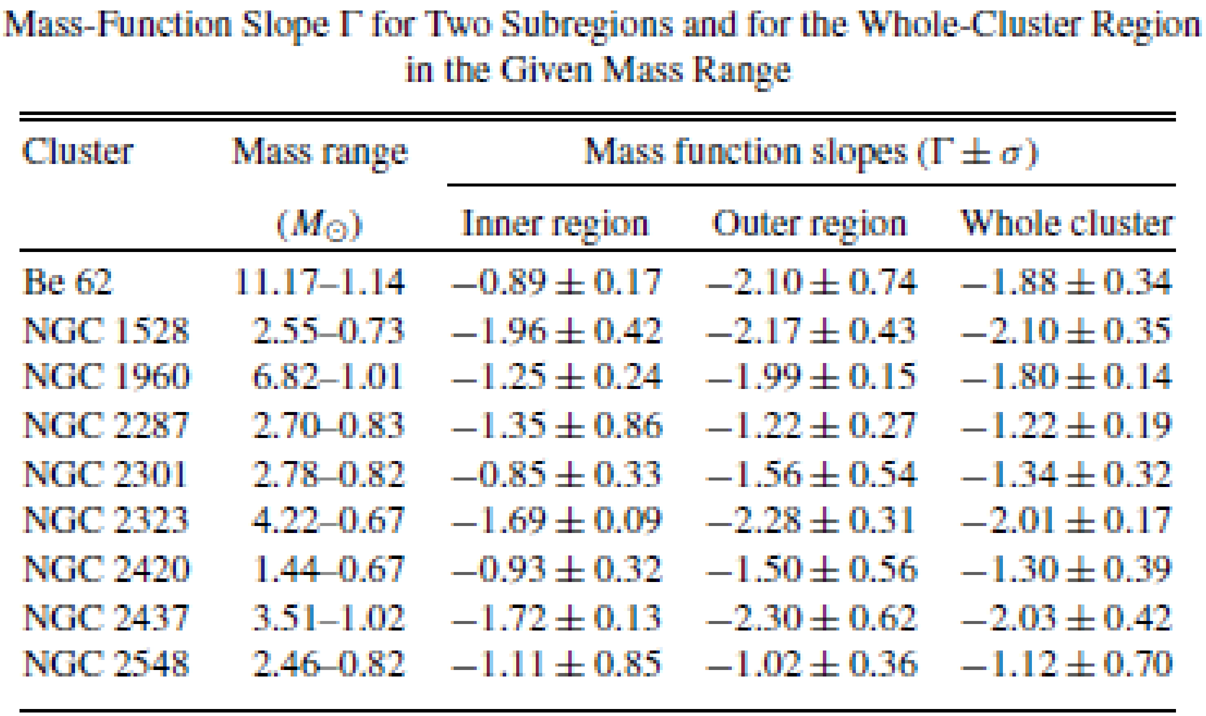
cluster	$(m-M)_0$ [mag]	E_{B-V} [mag]	t Myr	d [′]
Blanco 1*	6.8	0.03	50	105
Stock 2	7.5	...	100	260
α Per*	6.3	0.09	20	255
Pleiades*	5.6	0.05	75	300
NGC 2451 A*	6.4	0.00	20	140
IC 2391*	5.8	0.00	20	110
Praesepe*	6.0	0.00	650	195
IC 2602*	5.8	0.03	10	185
NGC 7092	7.6	0.12	70	170



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

Saurabh et al., 2008, AJ, 135, 1934



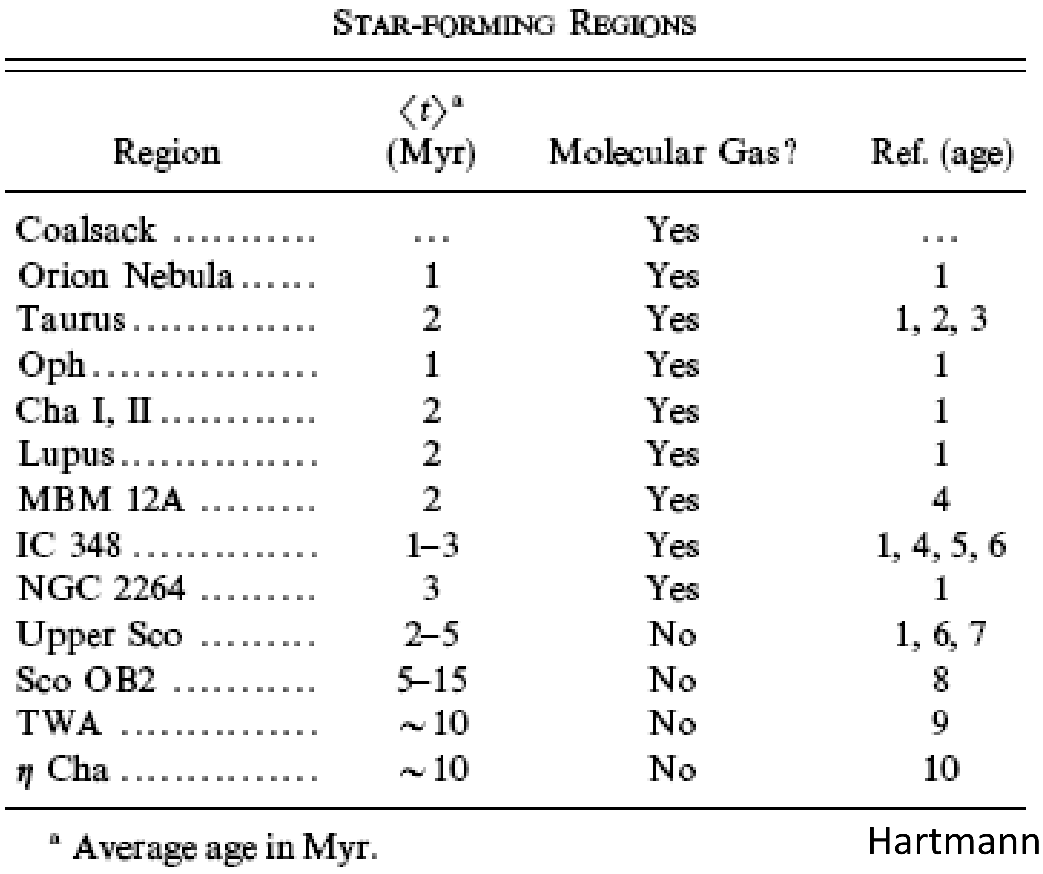
Mass-Function Slope Γ for Two Subregions and for the Whole-Cluster Region in the Given Mass Range

Cluster	Mass range	Mass function slopes ($\Gamma \pm \sigma$)		
	($M_\odot$)	Inner region	Outer region	Whole cluster
Be 62	11.17–1.14	-0.89 ± 0.17	-2.10 ± 0.74	-1.88 ± 0.34
NGC 1528	2.55–0.73	-1.96 ± 0.42	-2.17 ± 0.43	-2.10 ± 0.35
NGC 1960	6.82–1.01	-1.25 ± 0.24	-1.99 ± 0.15	-1.80 ± 0.14
NGC 2287	2.70–0.83	-1.35 ± 0.86	-1.22 ± 0.27	-1.22 ± 0.19
NGC 2301	2.78–0.82	-0.85 ± 0.33	-1.56 ± 0.54	-1.34 ± 0.32
NGC 2323	4.22–0.67	-1.69 ± 0.09	-2.28 ± 0.31	-2.01 ± 0.17
NGC 2420	1.44–0.67	-0.93 ± 0.32	-1.50 ± 0.56	-1.30 ± 0.39
NGC 2437	3.51–1.02	-1.72 ± 0.13	-2.30 ± 0.62	-2.03 ± 0.42
NGC 2548	2.46–0.82	-1.11 ± 0.85	-1.02 ± 0.36	-1.12 ± 0.70

Typical values and errors

Star formation

- The detection of free Gas in a Star Cluster is an excellent indicator for the time scale of continuous stellar formation



STAR-FORMING REGIONS

Region	$\langle t \rangle^a$ (Myr)	Molecular Gas?	Ref. (age)
Coalsack	...	Yes	...
Orion Nebula	1	Yes	1
Taurus	2	Yes	1, 2, 3
Oph	1	Yes	1
Cha I, II	2	Yes	1
Lupus	2	Yes	1
MBM 12A	2	Yes	4
IC 348	1–3	Yes	1, 4, 5, 6
NGC 2264	3	Yes	1
Upper Sco	2–5	No	1, 6, 7
Sco OB2	5–15	No	8
TWA	~10	No	9
η Cha	~10	No	10

[a] Average age in Myr.

Star formation lasts 3 to 4 Myrs and is continuous

This is also the "intrinsic" error of an age determination

Hartmann et al., 2001, ApJ, 562, 852

Numerical simulation of star formation in Giant Molecular Clouds

- Hypothesis: the formation of all members of a star cluster is continuous for 3 to 4 Myrs within one GMCs
- Is this a realistic approach?
- Is it possible to simulation the formation of star clusters and compare the results with observational data within the solar vicinity?

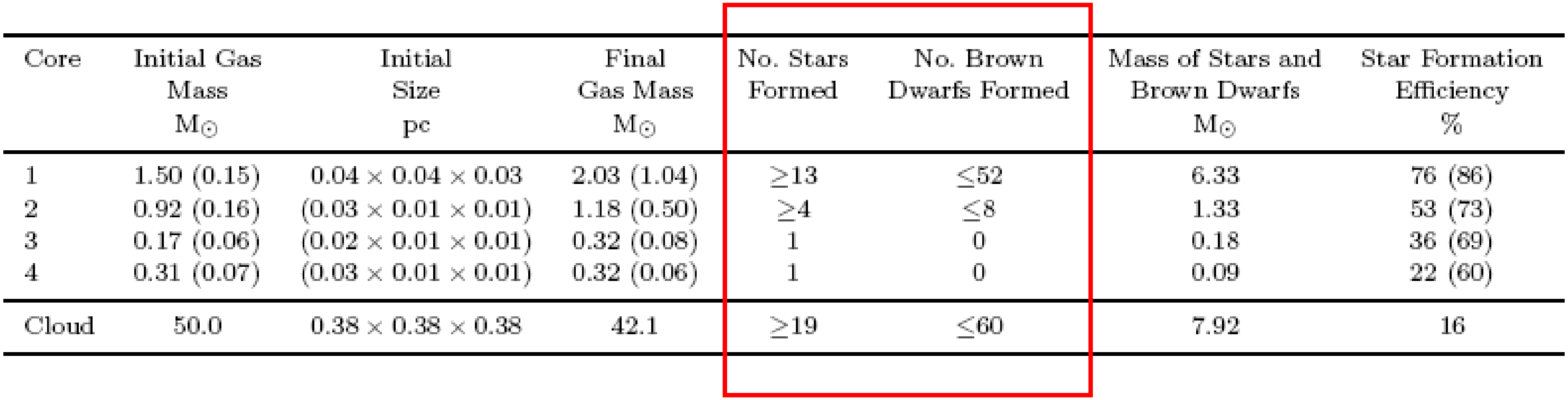
Numerical simulation of star formation in Giant Molecular Clouds

- Detailed paper by Bate & Bonnell, 2005, MNRAS, 356, 1201
- Basis: Orion Nebula and Taurus star forming region
- “Complete” astrophysical numerical simulation including Shock Waves, dynamical parameters and 3D-Hydrodynamics, Jeans Mass < 1 M(sun)
- The numerical simulations are astonishing close to the observations

Numerical simulation of star formation in Giant Molecular Clouds

Input parameter:

1. Mass (GMC) = 50 M(sun), limited by CPU time
2. Diameter = 0.375 pc, limited by CPU time
3. Time for the gravitational collapse: 19000 years
4. Random turbulence field with a 3D Gaussian distribution

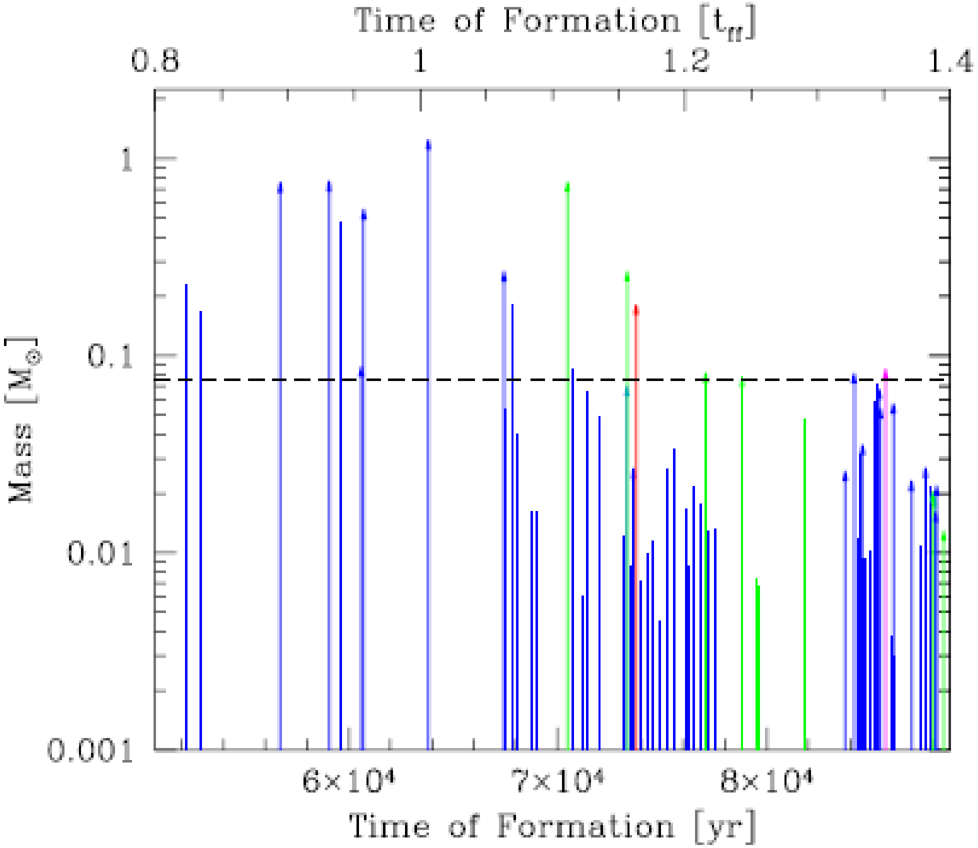


Core	Initial Gas Mass $M_\odot$	Initial Size pc	Final Gas Mass $M_\odot$	No. Stars Formed	No. Brown Dwarfs Formed	Mass of Stars and Brown Dwarfs $M_\odot$	Star Formation Efficiency %
1	1.50 (0.15)	$0.04 \times 0.04 \times 0.03$	2.03 (1.04)	$\geq$13	$\leq$52	6.33	76 (86)
2	0.92 (0.16)	$(0.03 \times 0.01 \times 0.01)$	1.18 (0.50)	$\geq$4	$\leq$8	1.33	53 (73)
3	0.17 (0.06)	$(0.02 \times 0.01 \times 0.01)$	0.32 (0.08)	1	0	0.18	36 (69)
4	0.31 (0.07)	$(0.03 \times 0.01 \times 0.01)$	0.32 (0.06)	1	0	0.09	22 (60)
Cloud	50.0	$0.38 \times 0.38 \times 0.38$	42.1	$\geq$19	$\leq$60	7.92	16

„Stars“: Mass > 0.084 M(sun)
Brown Dwarfs: Mass < 0.084 M(sun), no Hydrogen burning

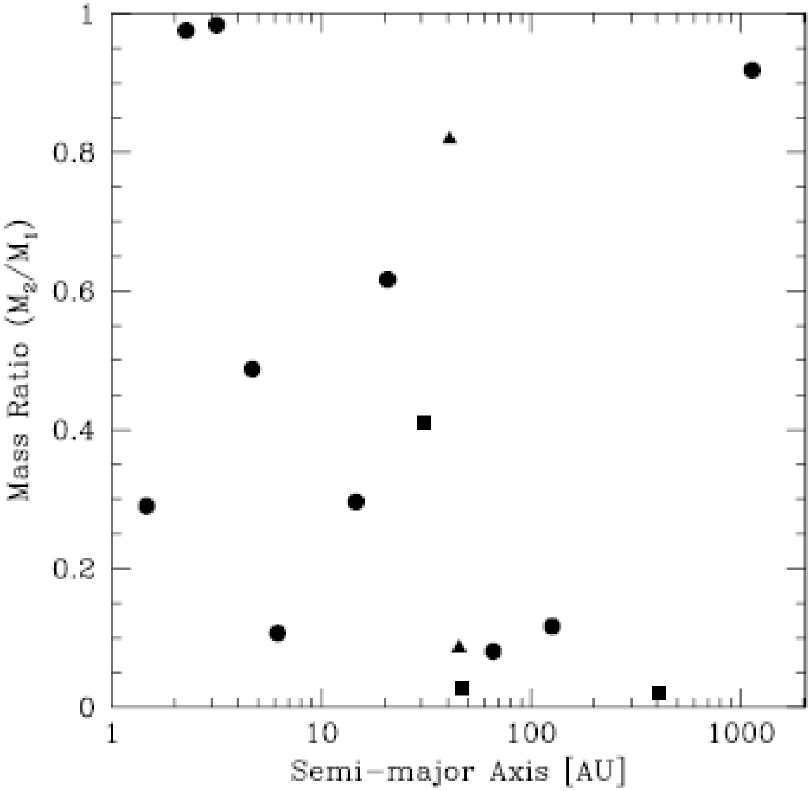
More low mass stars formed due to the IMF

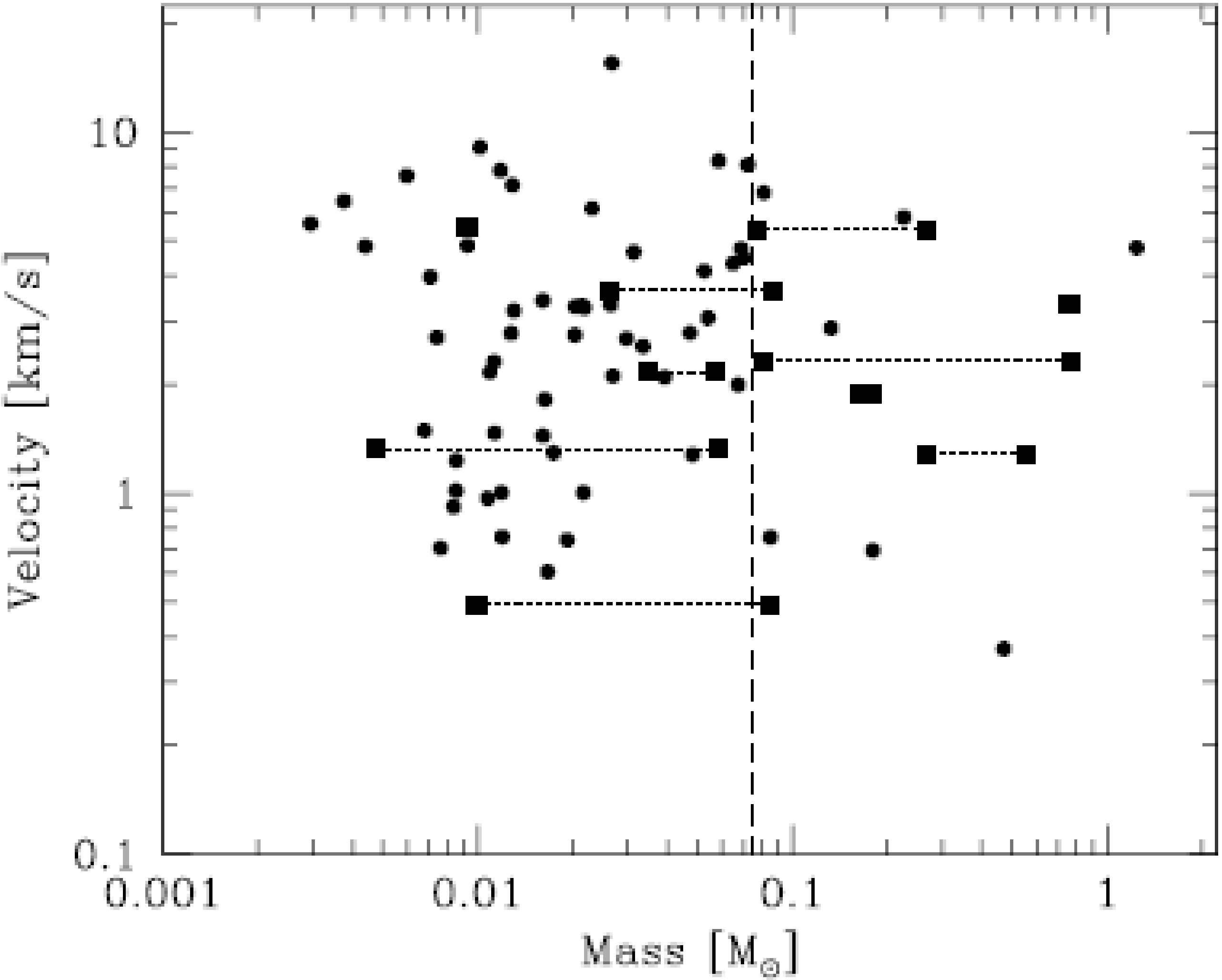
For star clusters it is essential to know the internal velocity distribution because of their evolution (see later)



Continuous star formation in time

The formation of Binary systems





Binaries are connected with a line

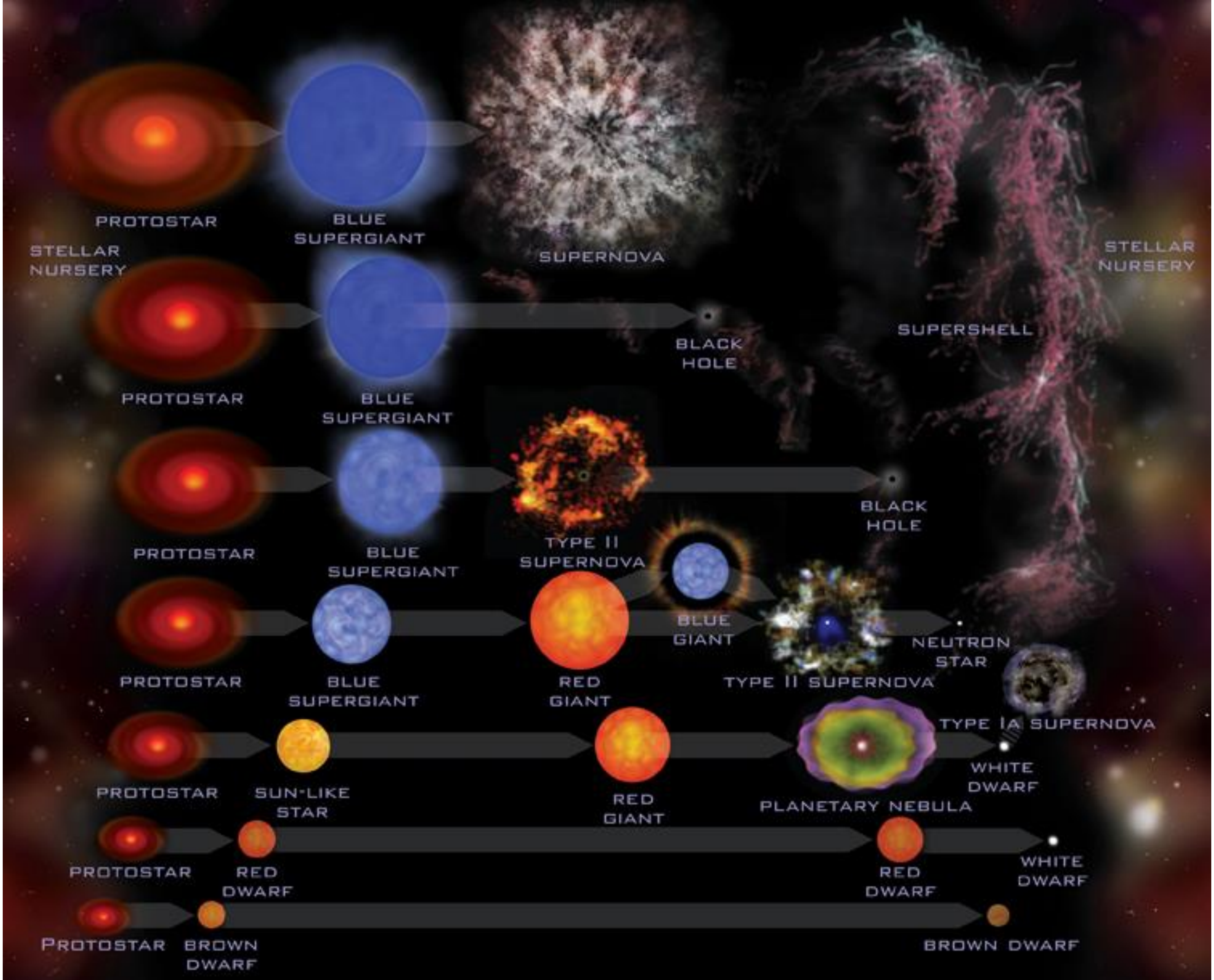
The rms velocity dispersion of the simulations is 4.3 km s^{-1}
Such observational data for d > 500 pc are still not available => Gaia satellite mission

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**

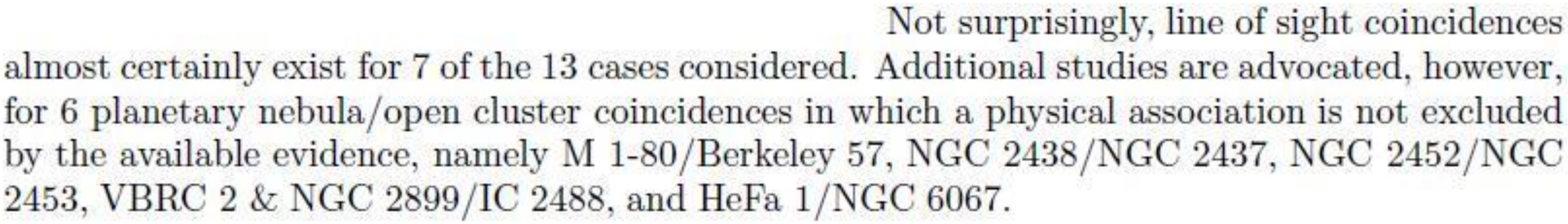
- How does a Star Cluster evolve with these starting parameters?

- 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, normally, follow Galactic Rotation

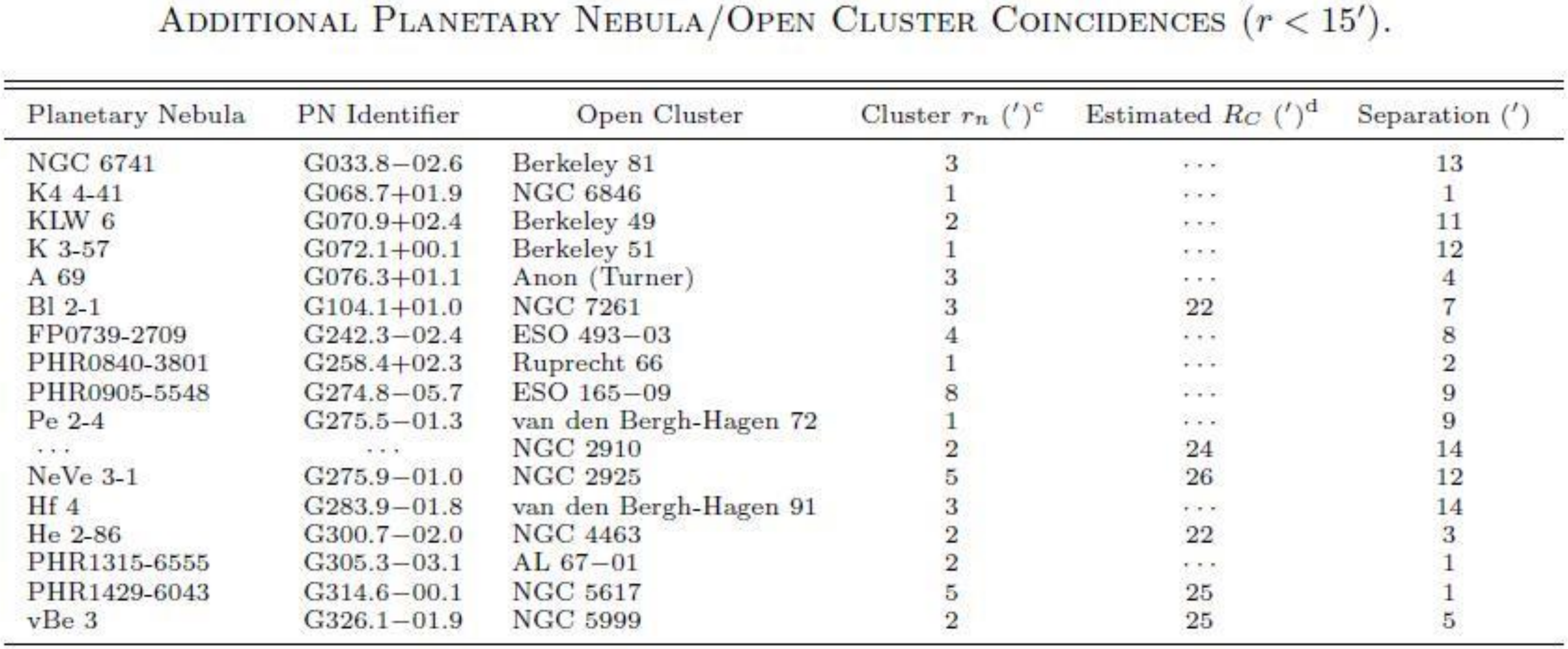

PROTOSTAR
BLUE SUPERGIANT
SUPERNOVA
STELLAR NURSERY
PROTOSTAR
BLUE SUPERGIANT
BLACK HOLE
SUPERSHELL
STELLAR NURSERY
PROTOSTAR
BLUE SUPERGIANT
TYPE II SUPERNOVA
BLACK HOLE
PROTOSTAR
BLUE SUPERGIANT
RED GIANT
BLUE GIANT
TYPE II SUPERNOVA
NEUTRON STAR
TYPE IA SUPERNOVA
PROTOSTAR
SUN-LIKE STAR
RED GIANT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

Planetary Nebulae

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



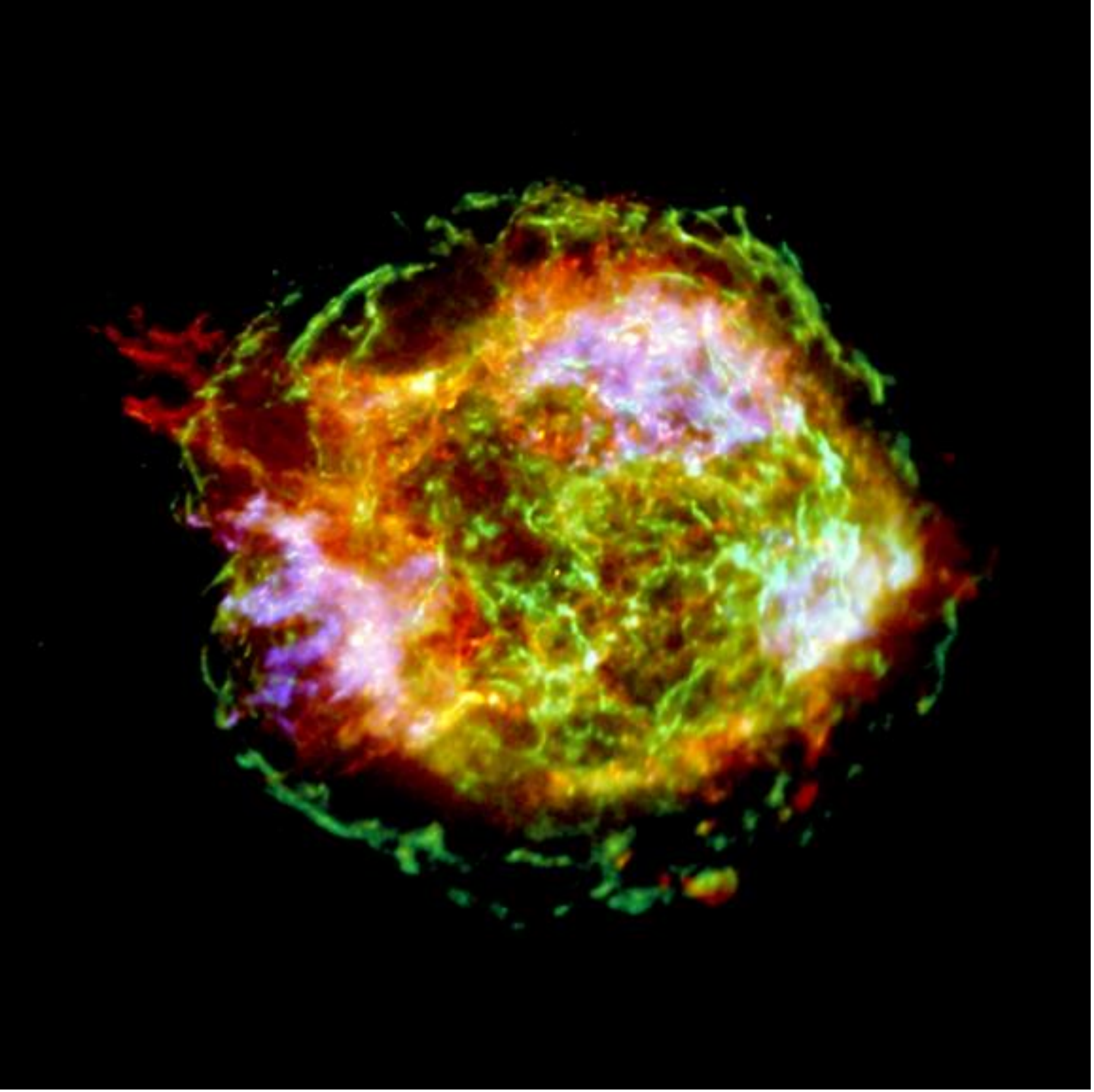
Not surprisingly, line of sight coincidences almost certainly exist for 7 of the 13 cases considered. Additional studies are advocated, however, for 6 planetary nebula/open cluster coincidences in which a physical association is not excluded by the available evidence, namely M 1-80/Berkeley 57, NGC 2438/NGC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



From Chandra, Diameter 4 pc

Important topic of how SN explosions affect the cluster evolution

Shockwaves
Mass flow

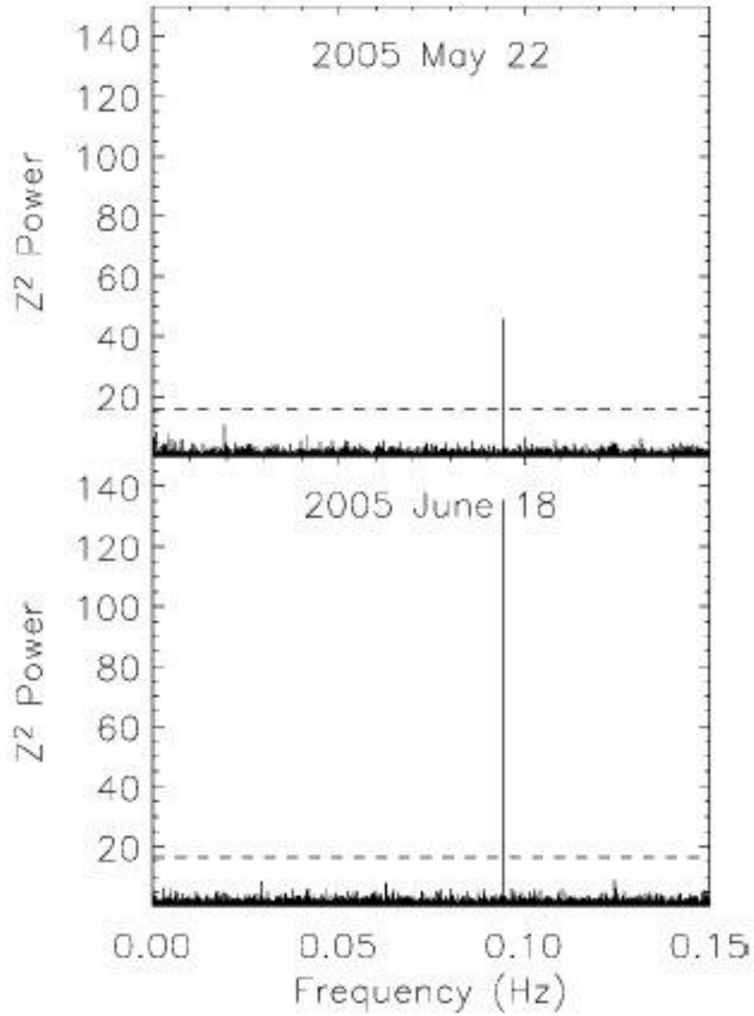
Statistically, SN explosions are rather common

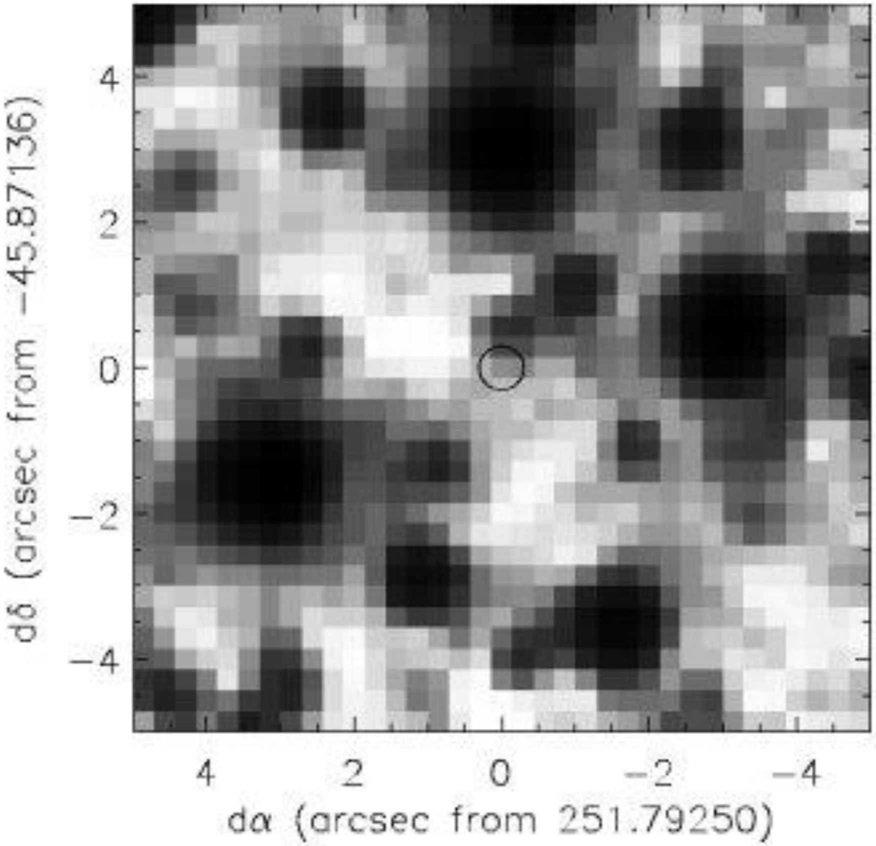
SN Remnants

- Catalogue of galactic SNRs: http://www.mrao.cam.ac.uk/surveys/snrs/
- 274 entries
- Complete list of papers for Open Clusters
  1. Pauls, 1977, A&A, 59, L13: NGC 559?
  2. Kumar, 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

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

d = 5200 pc, log t < 6.4

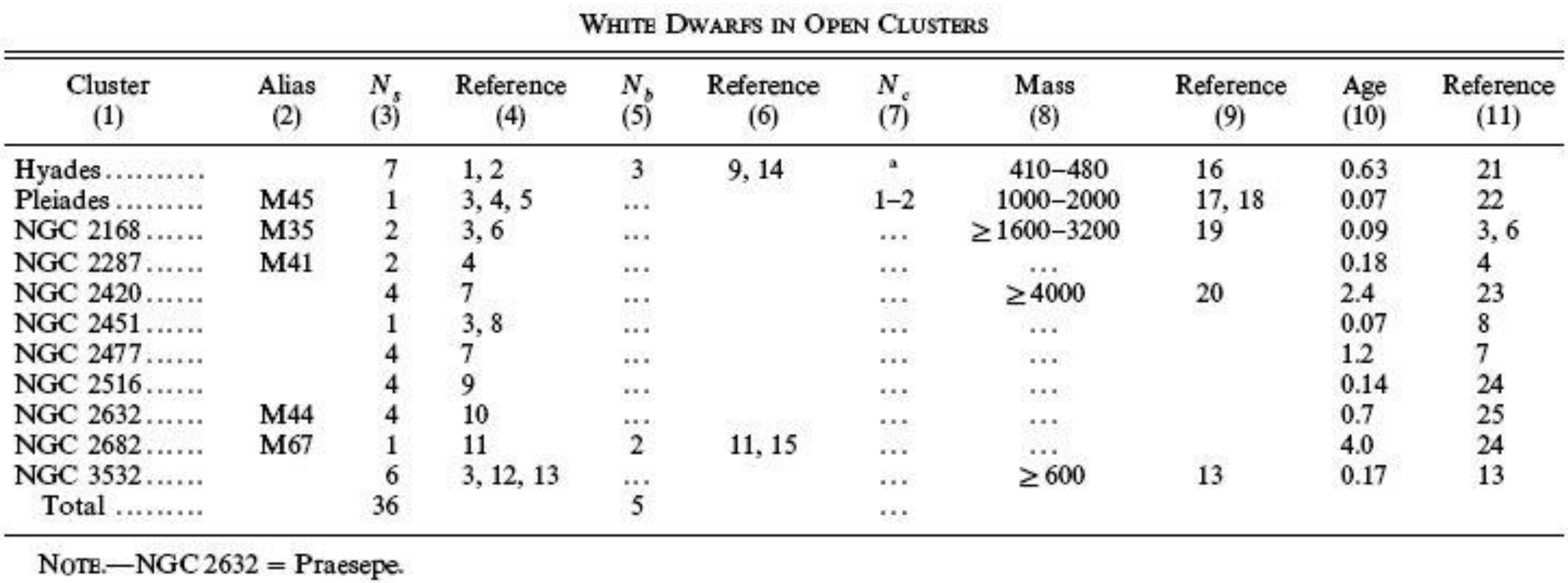




Pulsar, V fainter than 25th mag

- 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

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	...		...	≥1600–3200	19	0.09	3, 6
NGC 2287	M41	2	4	...		...	...		0.18	4
NGC 2420		4	7	...		...	≥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	...		...	≥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: $$2E_{kin} = n \cdot m_i \cdot \bar{v}^2 = M \cdot \bar{v}^2$$

$\bar{v}$ … 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: $t_{coll} \approx \frac{1}{\rho \cdot \sigma \cdot \Delta\bar{v}}$

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: $M_G = 2 \times 10^{11}$ 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

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

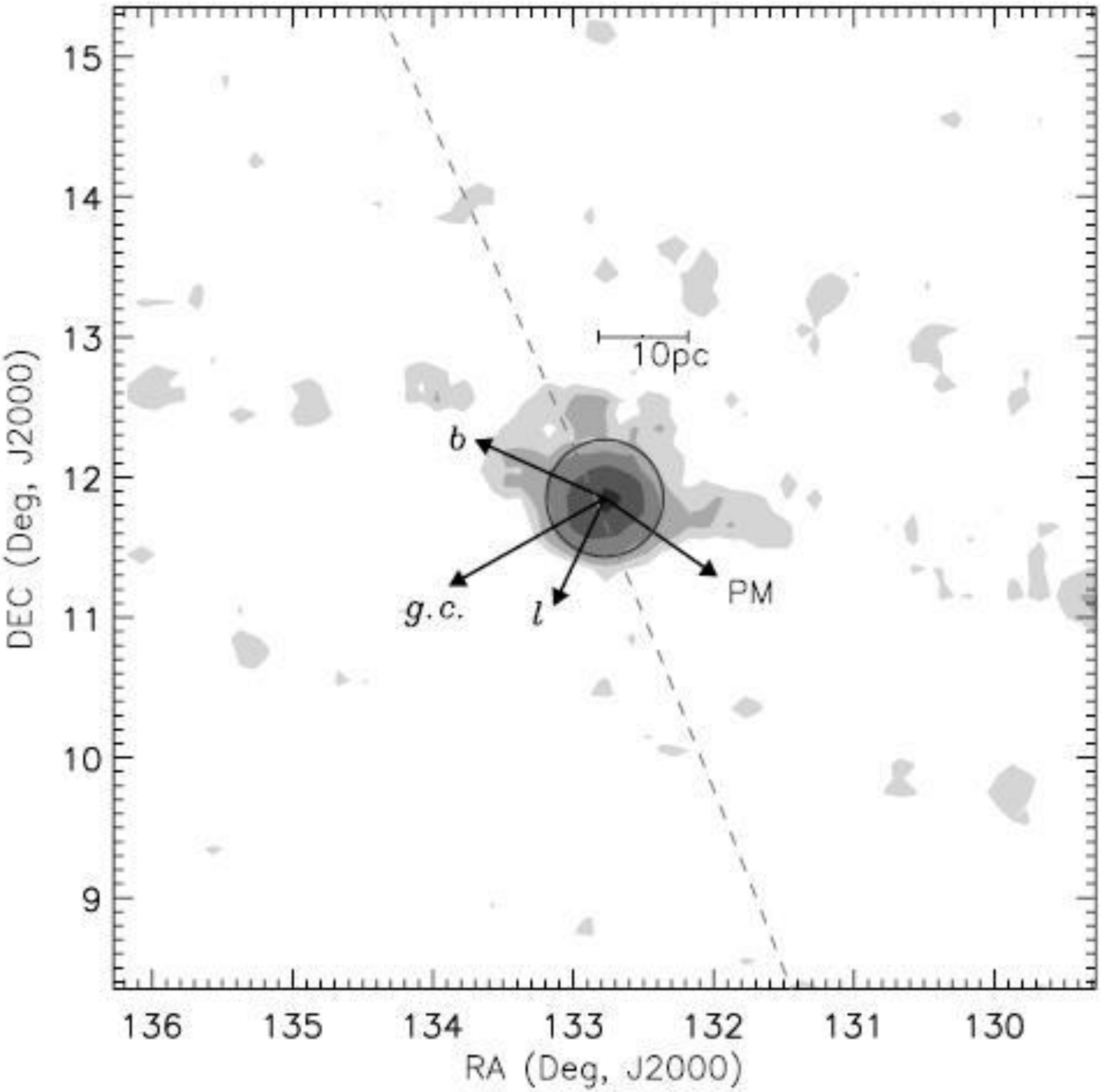
On the other side we have the gravitational force of the open cluster. The stability radius r_S is defined as:

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

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

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