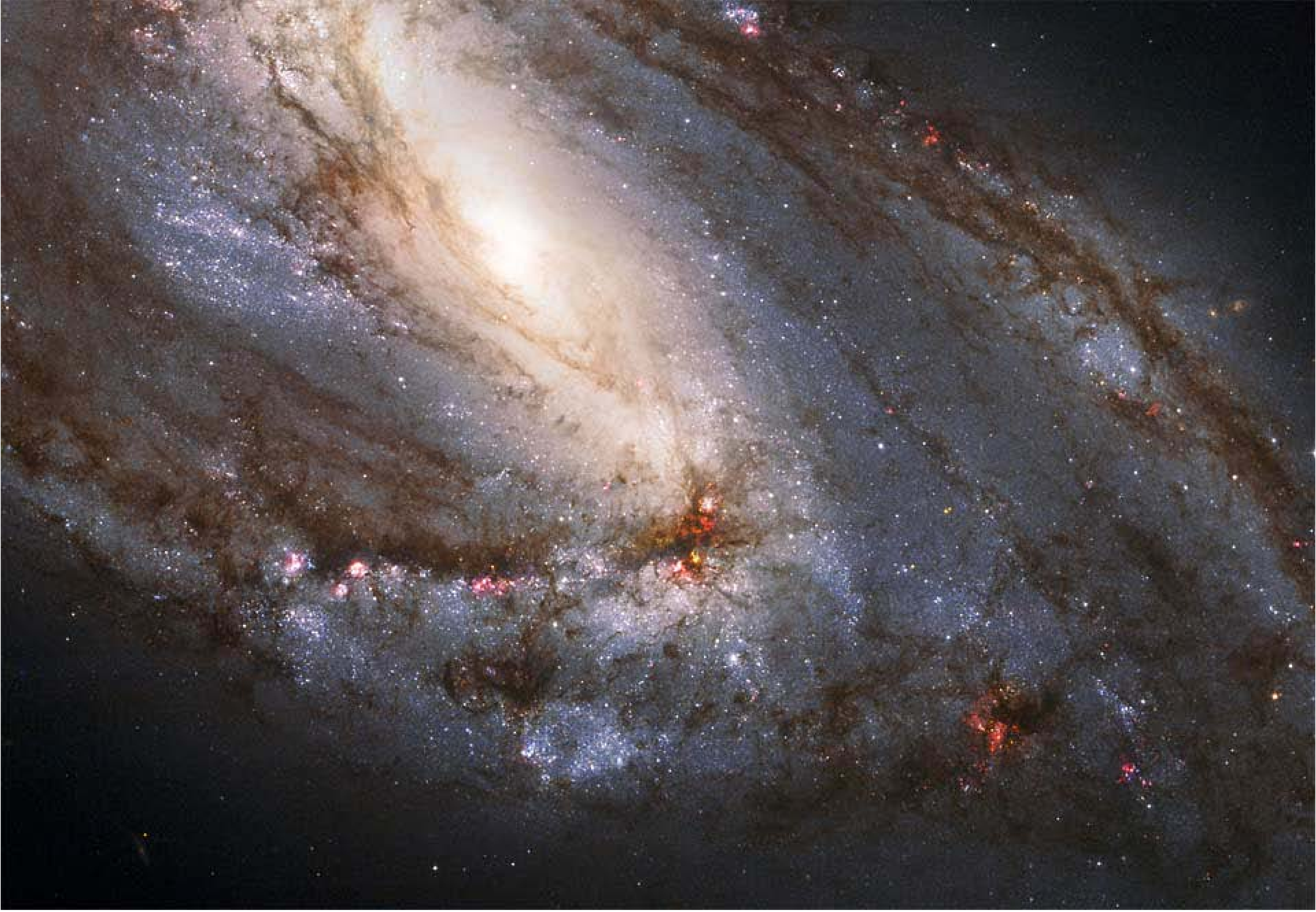
Star Cluster - Syllabus

- Definition and characteristics of Star Clusters
    1. Open Clusters
    2. Globular Clusters
    3. Stellar Associations
    4. Moving Groups
- Formation and Evolution
- Observational and "theoretical" techniques:
    1. Membership determination
    2. Isochrone fitting
    3. Integrated spectra

- Future challenges
  1. GAIA
  2. E-ELT
  3. Large Scale Surveys

- All slides as .pdf files on Server for download
- Written exam on the 3th of June



M66 (10 Mpc away): HST – NASA, Press release, 08.04.2010

What can we learn from Star Clusters?

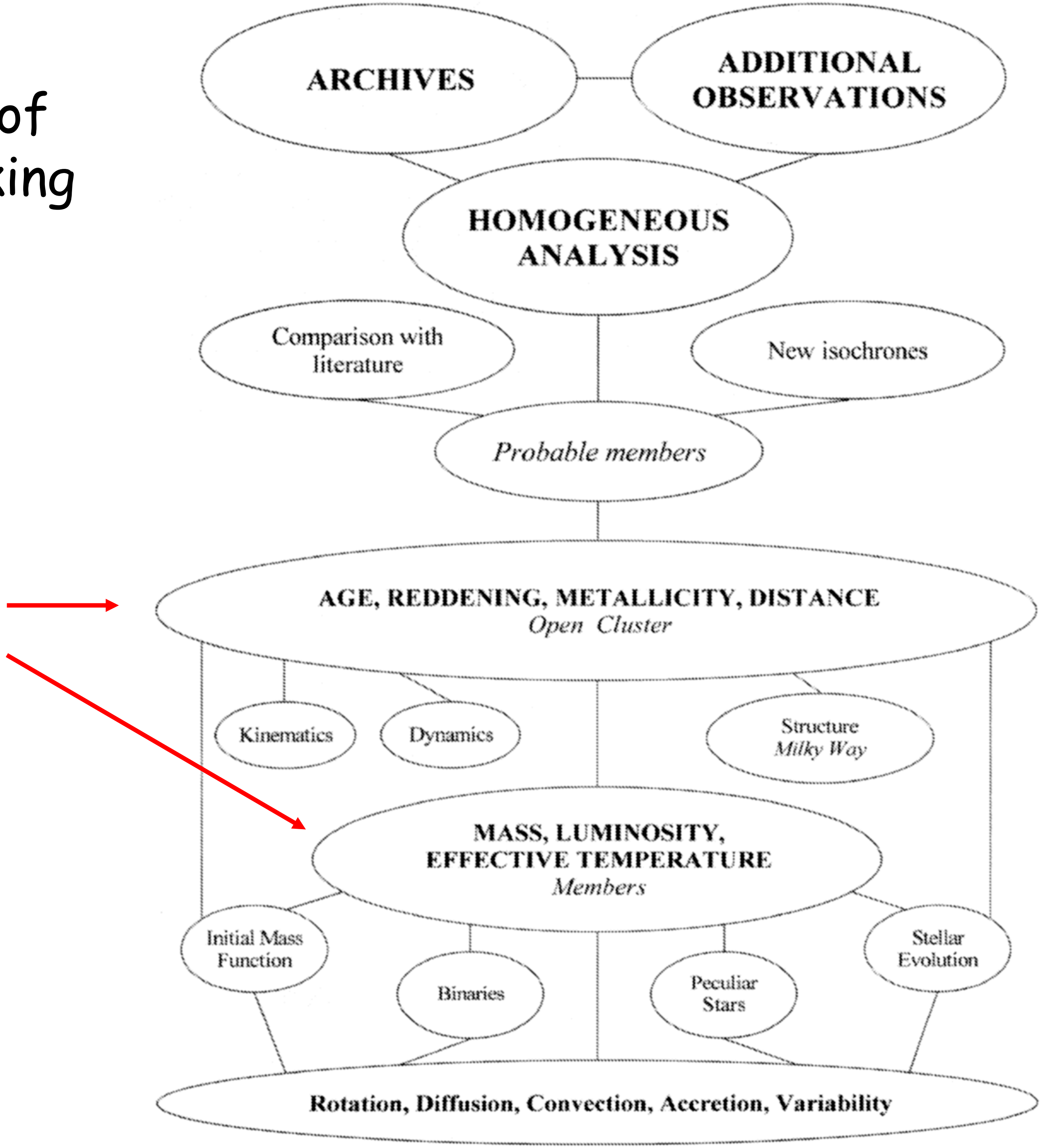
- There are two point of views which perfectly supplement each other

1. The Star Cluster as global aggregate
2. Each member as single stellar object

- We are able to study local and global characteristics simultaneously

- The Star Cluster as global aggregate
  1. Distance, age, reddening and metallicity
  2. Kinematics und dynamics
  3. Initial Mass Function
  4. Star formation and evolution
  5. Global characteristics of a Galaxy
- Members as single stars
  1. Special star groups: CP, Blue Stragglers, (Super)giants, Binaries, Wolf-Rayet Stars, Variable stars, post-AGB, HB stars, …
  2. Test of most astrophysical models and theories

Floating chart of a possible working example



Comparison of different models and calibrations possible

Two working examples:

1. Metallicity:
   - From isochrones for the complete cluster
   - From Strömgren uvbyβ photometry for individual members
2. Reddening:
   - From the shift of the ZAMS
   - From isochrone fitting
   - From photometric calibrations of different filter systems

Definition of Star Clusters

Star clusters are physically related groups of stars held together by mutual
gravitational attraction.

The number of all star clusters in the Milky Way is about 10 000 but only about 2000 in catalogues. Much less Globulars than Open ones, about 160 only.

Working Hypothesis

All members of an individual star cluster are born within one Giant Molecular Cloud over a time scale of some few Myrs

What are the immediate conclusions?

All members of an individual star cluster have:

- ***Identical distance from the Sun:*** +- The volume expansion of the cluster
- ***Identical age:*** +- Time scale of star formation
- ***Identical metallicity:*** +- Inhomogeneities of the initial GMC and the chemical evolution of the giant branch
- ***Identical kinematical characteristics:*** +- Intrinsic spread
  - Radial velocity
  - Proper motion

Clusters in Spiral Galaxies

- In Spiral Galaxies as in our Milky Way we can clearly distinct between
  1. Young clusters in the disk (Open Clusters)
  2. Old clusters in the halo (Globular Clusters)
- For other types of Galaxies, for example the LMC and SMC, this simple classification is not valid any more.

Characteristics – Open Clusters

- **Age:** 1 Myr – 5 Gyr
- **Metallicity:** -1.0 to +0.6 dex compared to the Sun
- **Distance from the Sun:** > 45 pc
- **Mass range of the members:** 0.08 to 100 M(sun)
- **Total masses:** up to 40000 M(sun)
- **Absolute linear diameter:** 2 to 20 pc

Characteristics – Globular Clusters

- **Age:** up to the age of the host galaxy
- **Metallicity:** -0.5 to -2.5 dex compared to the Sun
- **Distance from the Sun:** > 2000 pc
- **Mass range of the members:** 0.08 to 20 M(sun)
- **Total masses:** up to 10^6 M(sun)
- **Absolute linear diameter:** up to 100 pc

Star Associations and Moving Groups

Besides classical star clusters according to our definition there are also

- Moving Groups
- Stellar Associations
- (Star Forming regions)

There is a continuous transition between star clusters and these three types of stellar aggregates

Stellar Association

- Concentration of specific star groups, for example O, B or T Tauri Sterne, significant higher than in the galactic vicinity
- Overall density equal to surrounding
- Short life time, only about 10 Myrs because not gravitionally bound
- Diameters up to 200 pc
- Example: Orion OB1 association

Moving Group

- Simplified: “dissipating star clusters“
- Density as the surrounding
- Still “same motion“, weak gravitionally bound
- Diameters up to 400 pc

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

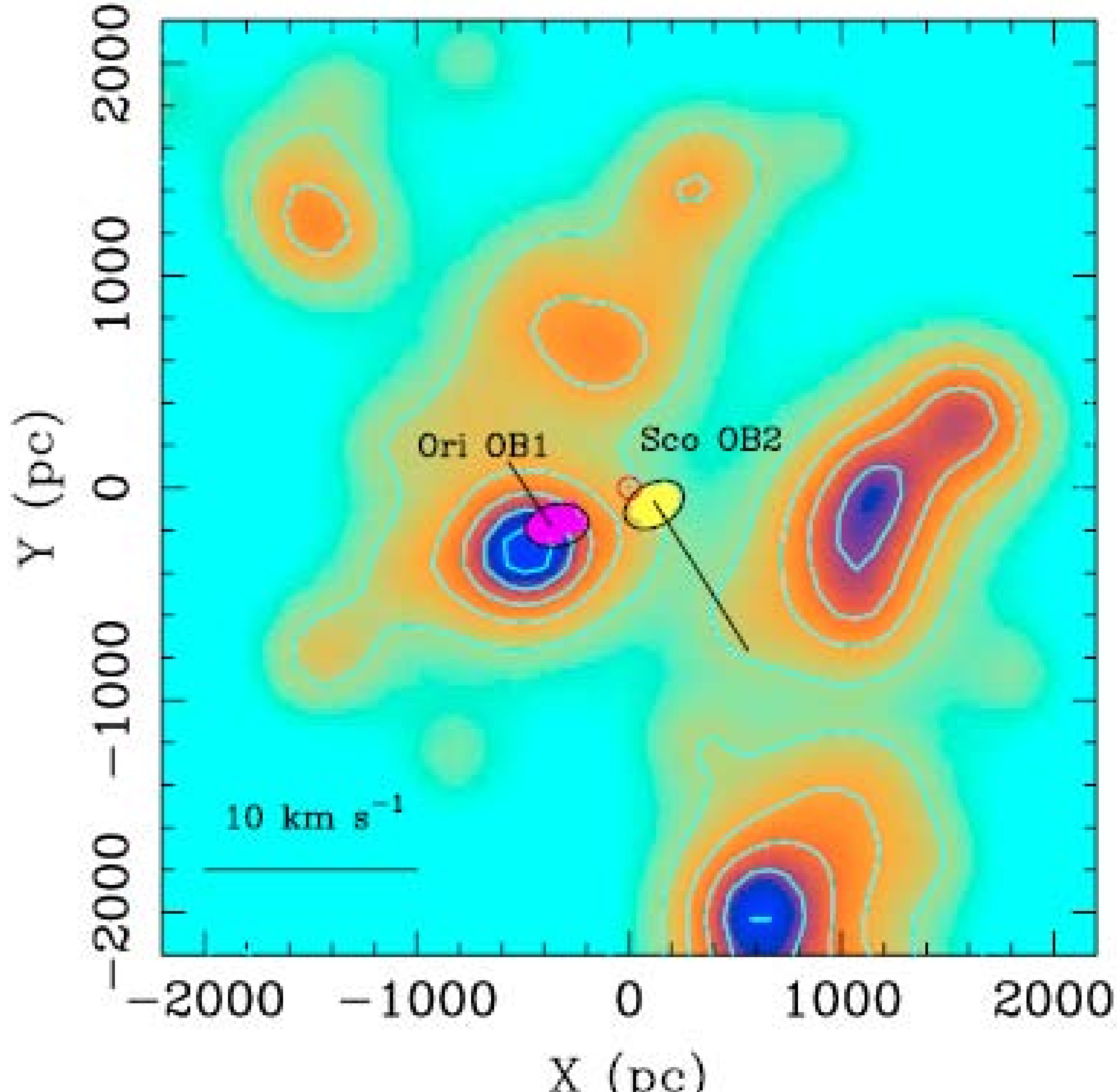
Heuristic Approach

- 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

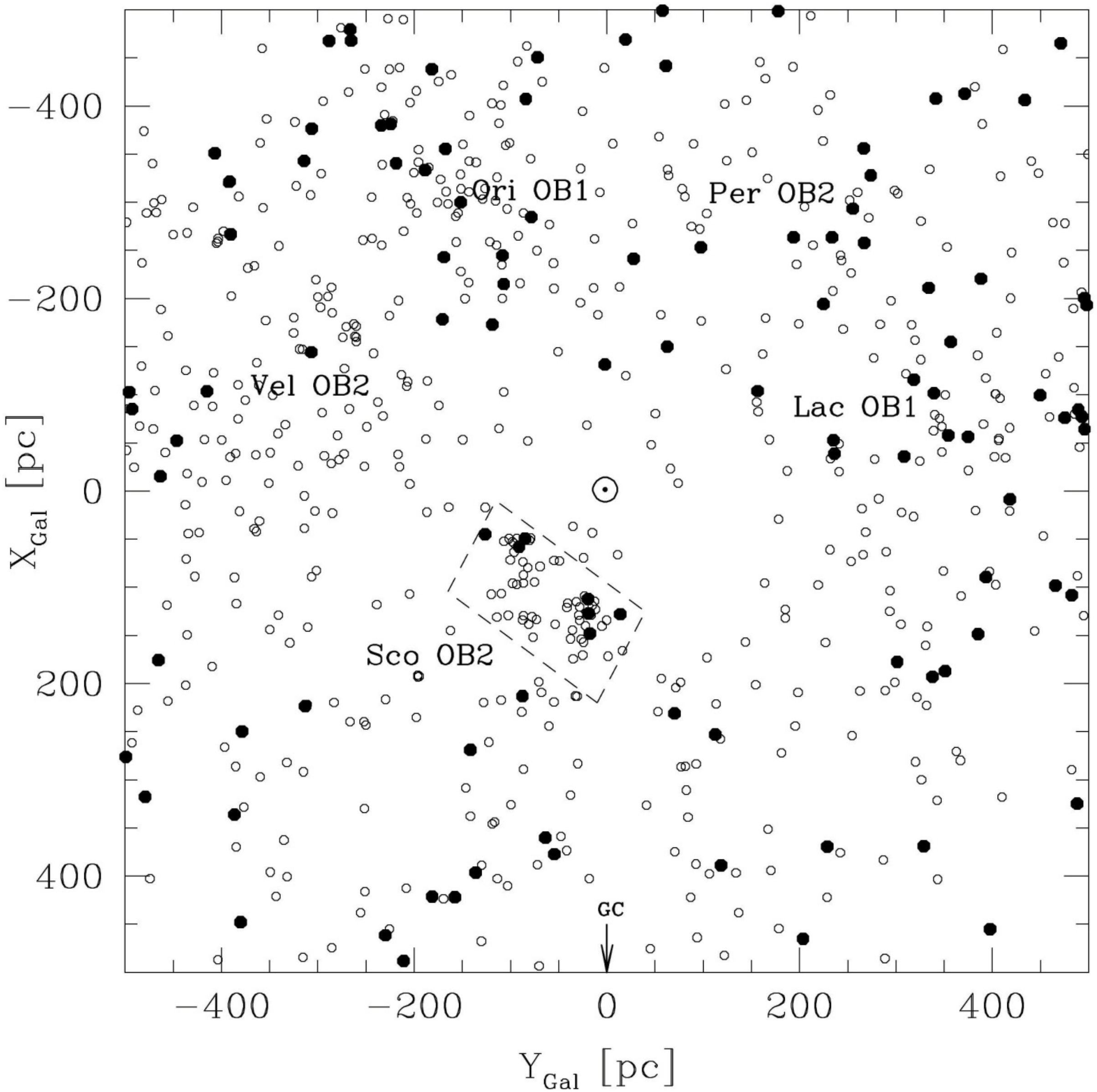
Clusters selected

Cluster_name	RA_2000_Dec		l	b	Dist	Mod	EB-V	Age	ST	Z	Diam	Fe/H	MRV	pm RA	pm Dec
Mamajek 1	08 42 06	-79 01 38	292.482	-21.654	97	4.93	0.00	6.9		-35.8	40.0		+16.1	-30.00	+27.80
Collinder 70	05 35 31	-01 06 00	205.03	-17.35	391	8.09	0.04	6.71		-116.6	180.0		19.49	0.36	-0.68
ASCC 24	06 28 44	-07 01 11	216.64	-8.23	400	8.44	0.14	6.96		-57.3	42.0		16.35	-5.55	-4.05
ASCC 16	05 24 35	+01 47 59	200.98	-18.35	460	8.59	0.09	6.93		-144.8	74.4		0.75	+0.75	-0.18
NGC 1980	05 35 24	-05 54 35	209.51	-19.60	550	8.86	0.05	6.67	B1	-184.5	25.2		25.34	0.83	-0.36
Bochum 14	18 02 00	-23 41 00	6.388	-0.499	578	13.48	1.508	6.996		-5.0	2.0				
NGC 2264	06 40 58	+09 53 42	202.936	2.196	667	9.28	0.051	6.954	O7	25.6	39.0	-0.15	+25.5	-1.13	-3.80
ASCC 122	22 33 14	+39 36 36	95.91	-15.90	700	9.53	0.10	6.98		-191.8	86.4		-8.17	-0.29	-4.19
Collinder 419	20 17 59	+40 43 12	78.07	2.79	740	10.40	0.34	6.85	B2	36.0	30.0		-8.19	-2.56	-6.99
ASCC 79	15 19 11	-60 43 47	320.04	-2.86	800	10.01	0.16	6.86		-39.9	62.4		4.03	-2.67	-4.10
IC 5146	21 53 24	+47 16 00	94.383	-5.495	852	11.49	0.593	6.00	B1	-81.6	20.0			-1.77	-1.70
Lynga 14	16 55 04	-45 14 00	340.919	-1.089	881	14.15	1.428	6.712		-16.7	3.0				
Ruprecht 119	16 28 15	-51 30 00	333.276	-1.879	956	11.67	0.570	6.853		-31.3	8.0			-1.15	-1.80
NGC 6383	17 34 48	-32 34 00	355.690	0.041	985	10.89	0.298	6.962	O7	0.7	20.0		+7.00	+1.58	-2.00

Several spurious entries like the “ASCC clusters”



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



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

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

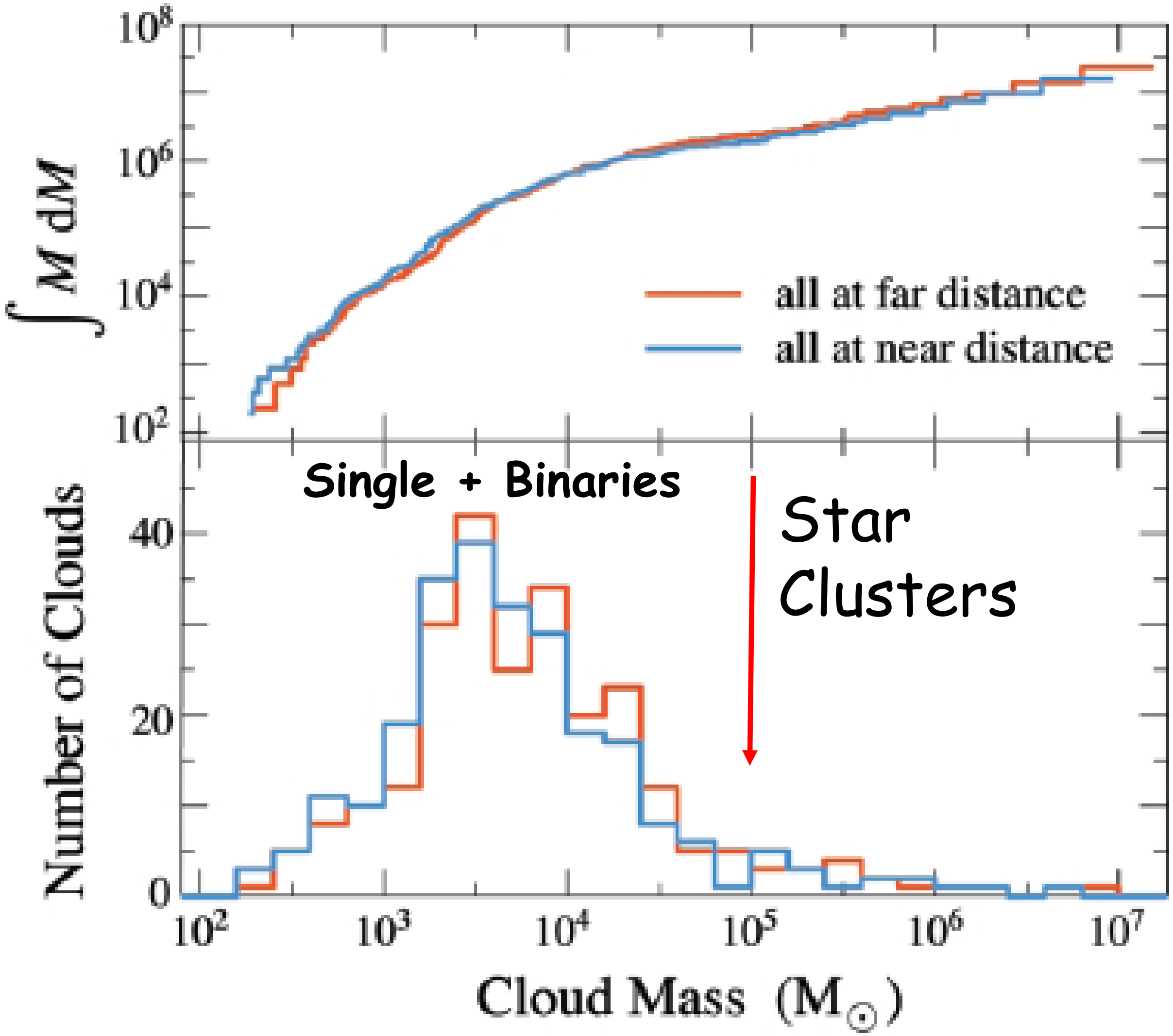
M11, NGC 6705: Total Mass ca.
10000 M(sun), 200 Myr

Giant Molecular Clouds

- Star Clusters can only form within „Giant Molecular Clouds“ (GMC) which have enough initial mass
- The stellar formation rate in the solar neighborhood is very small
- 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

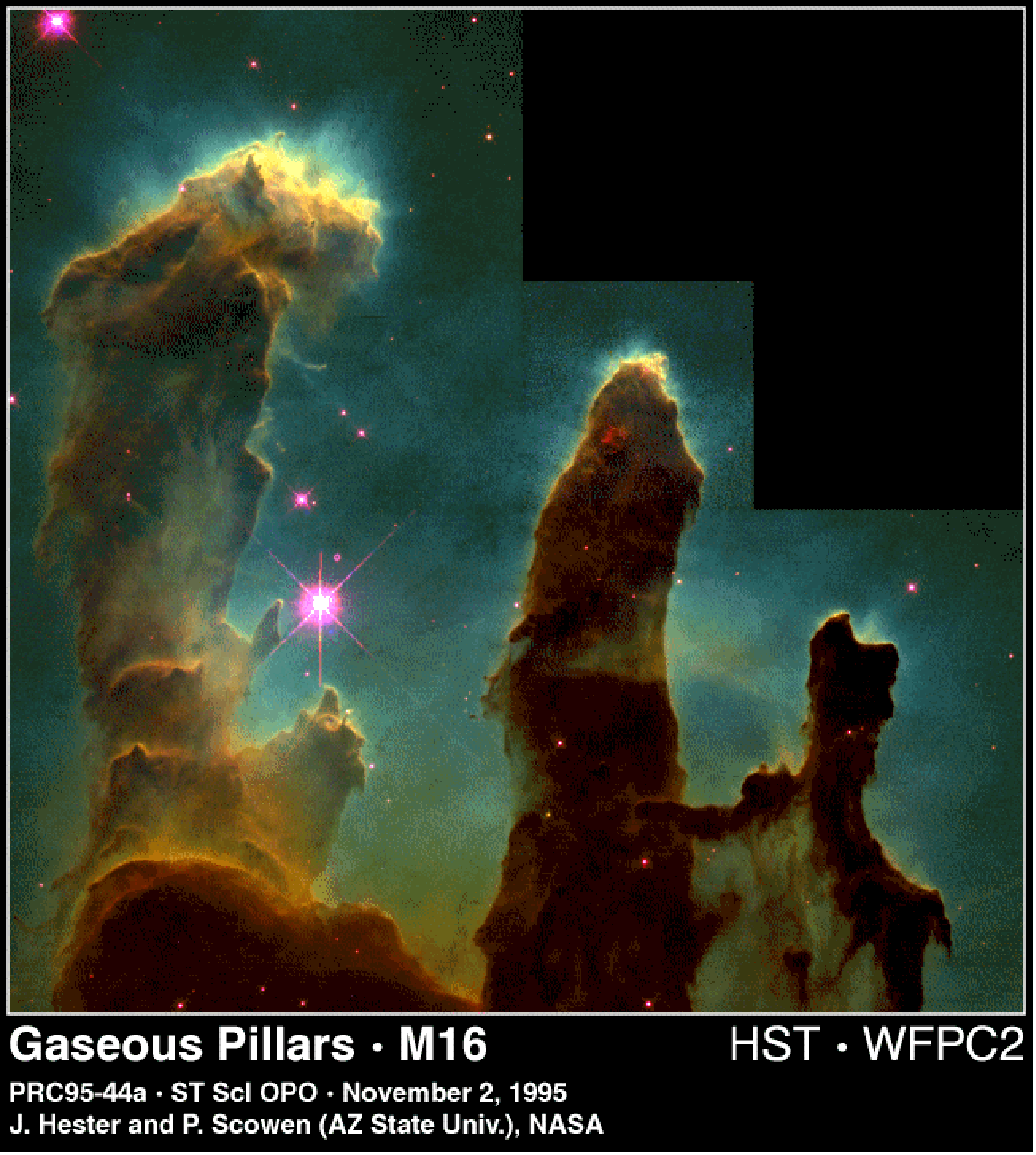


New investigation of the ^{13}CO Gas within 2000 pc around the Sun

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

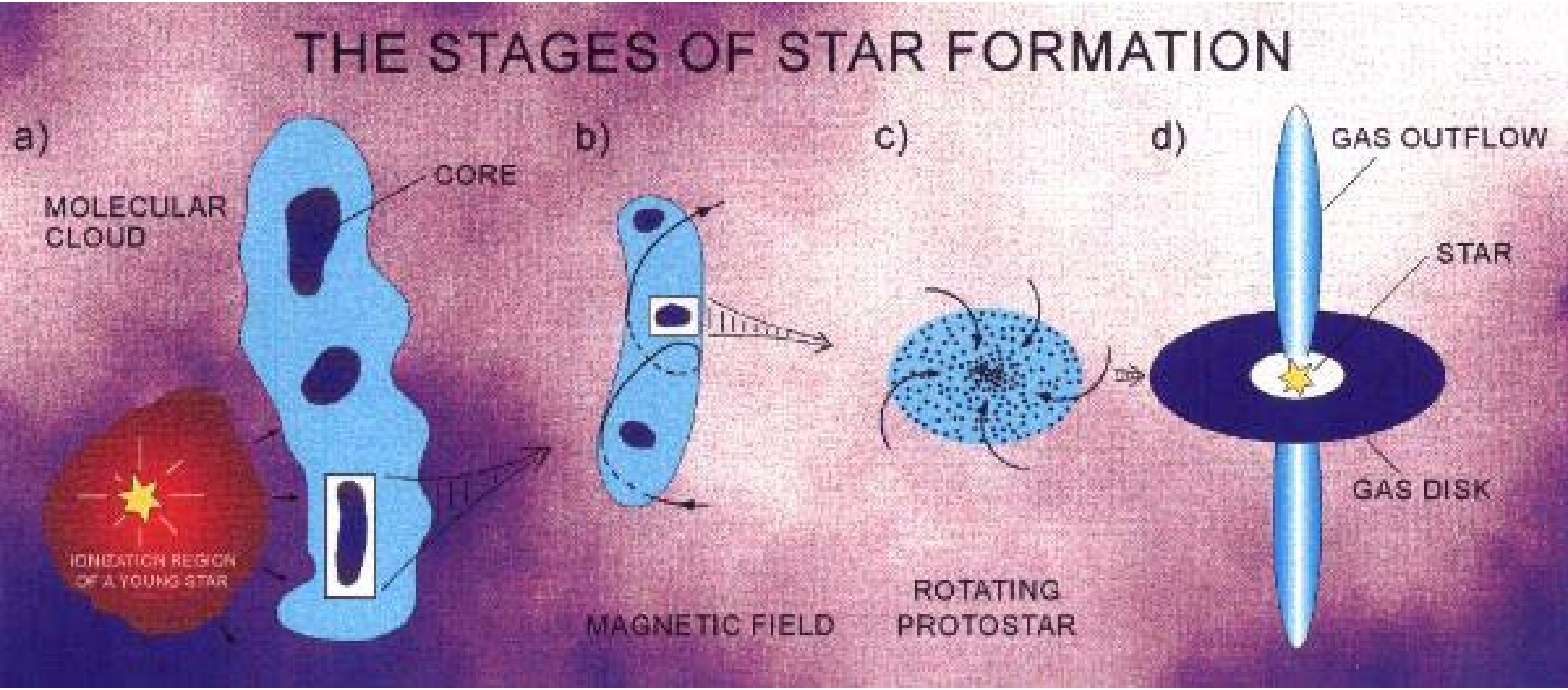


NGC 6611 (M16)

d = 1750 pc
t = 8 Myr

Star formation „live“

Star formation



Gravitation „wins“ Magnetic field, Shock waves Protostar

FREE GAS NO FREE GAS

Star formation

- The detection of free Gas in a Star Clusters 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 clusters 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:

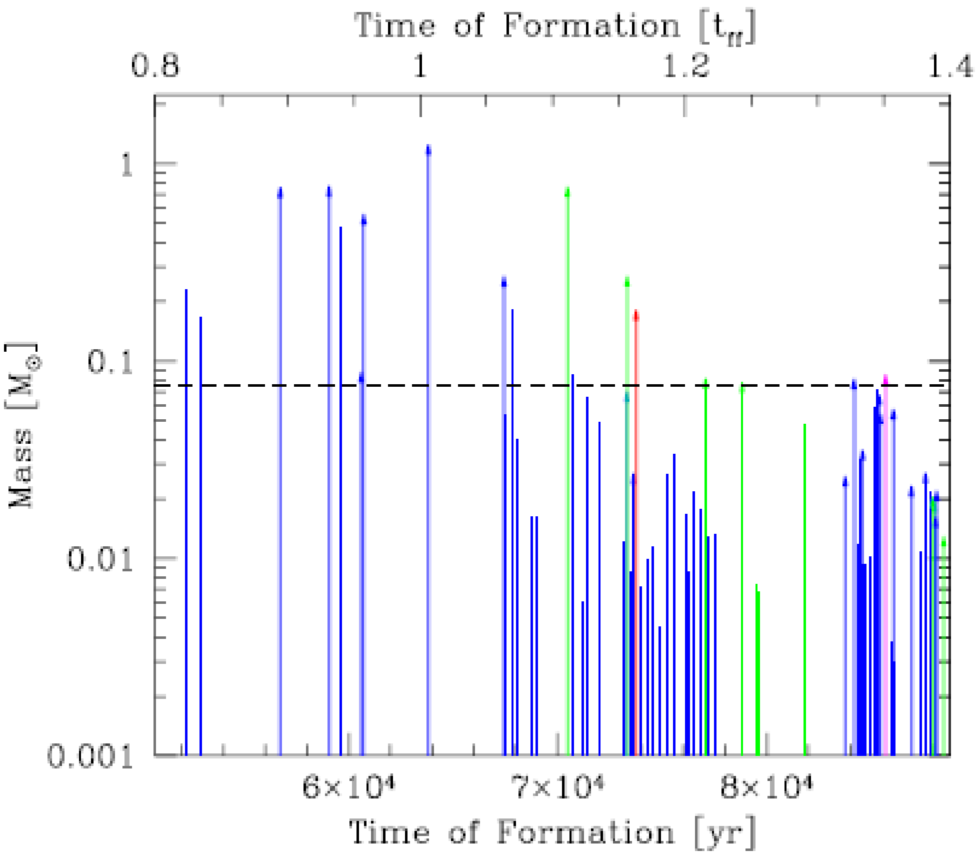
1. Mass (GMC) = 50 M(sun), limited by CPU time
2. Diameter = 0.375 pc, limited by CPU time
3. Time for the gravitational collapse: 19000 years
4. Random turbulence field with a 3D Gaussian distribution

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)	≥ 13	≤ 52	6.33	76 (86)
2	0.92 (0.16)	$(0.03 \times 0.01 \times 0.01)$	1.18 (0.50)	≥ 4	≤ 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	≥ 19	≤ 60	7.92	16

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

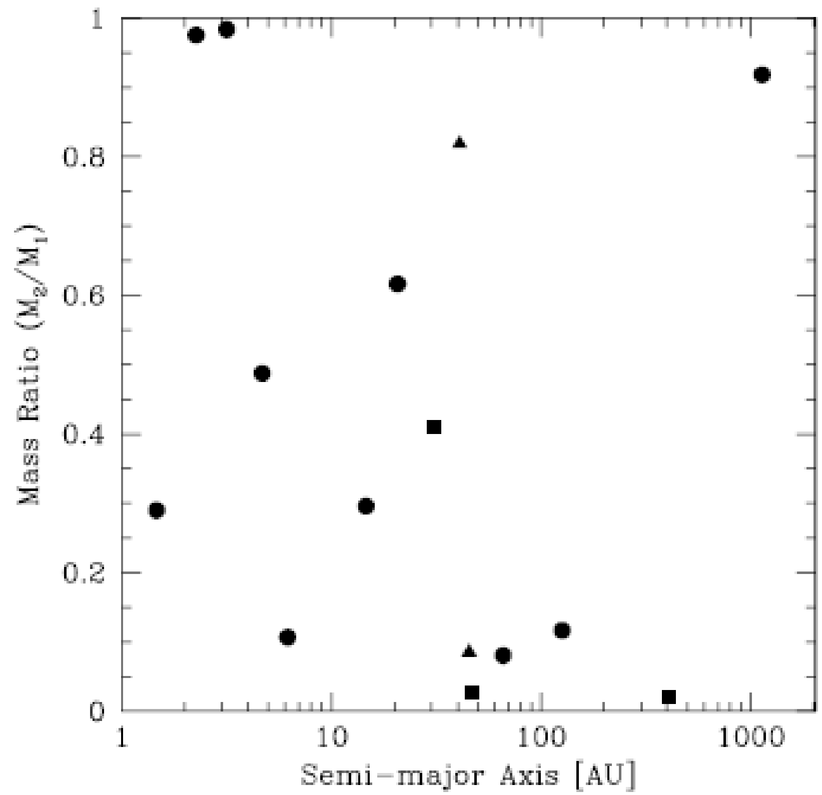
More low mass stars formed due to the IMF

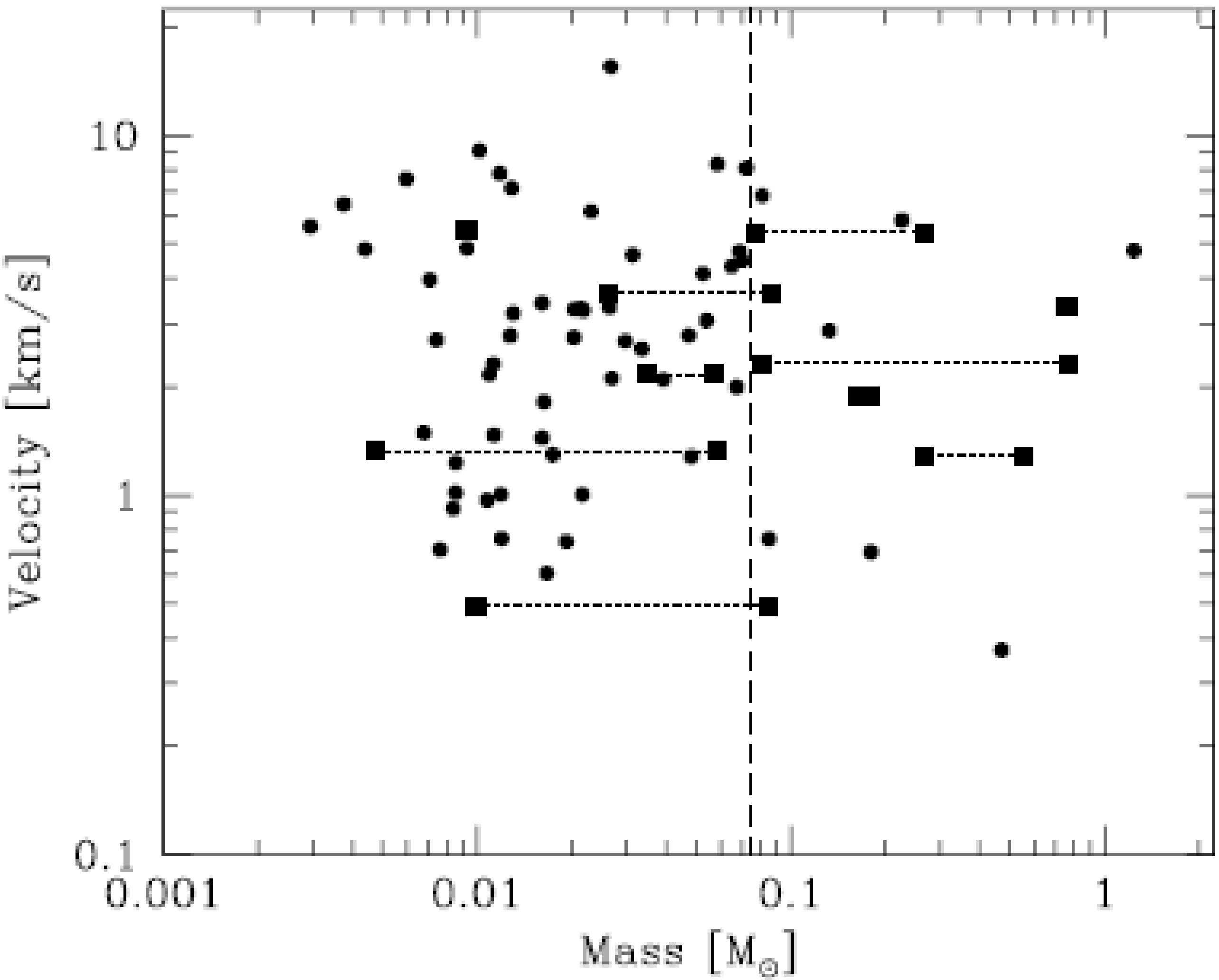
For star clusters it is essential to know the internal velocity distribution because of their evolution (see later)



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