Open clusters and associations in the Gaia era

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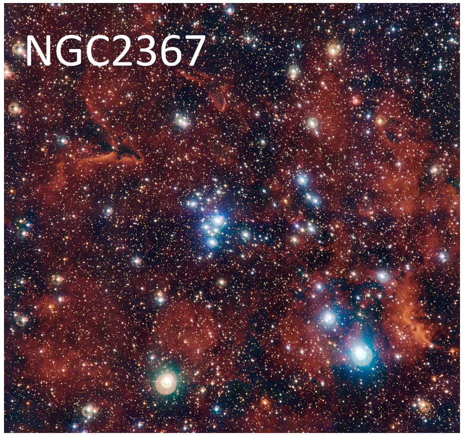
Overview

I. Definition and global properties
II. Statistical properties of cluster members
III. What will we learn from Gaia?



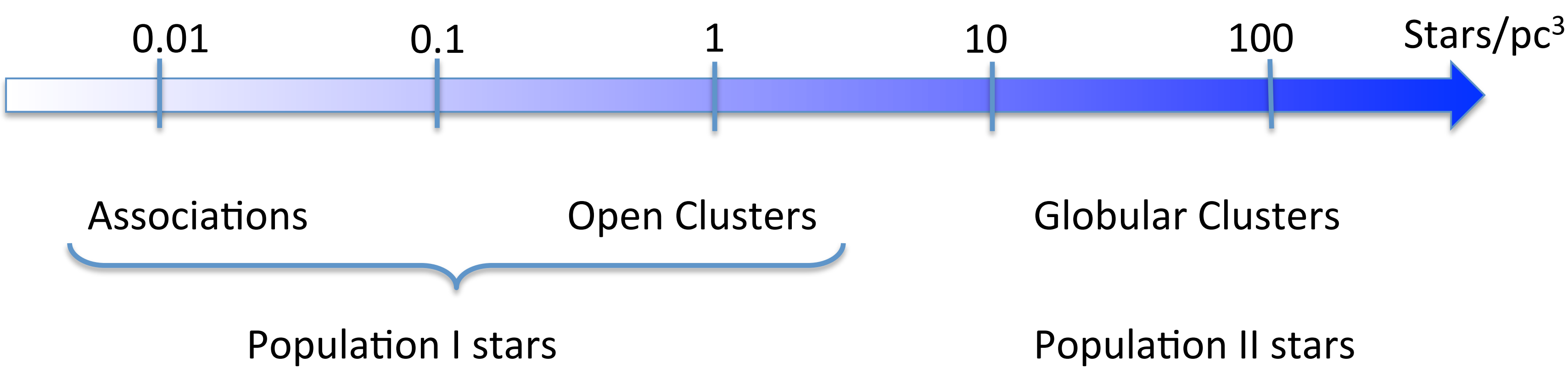
I. Definition and global properties

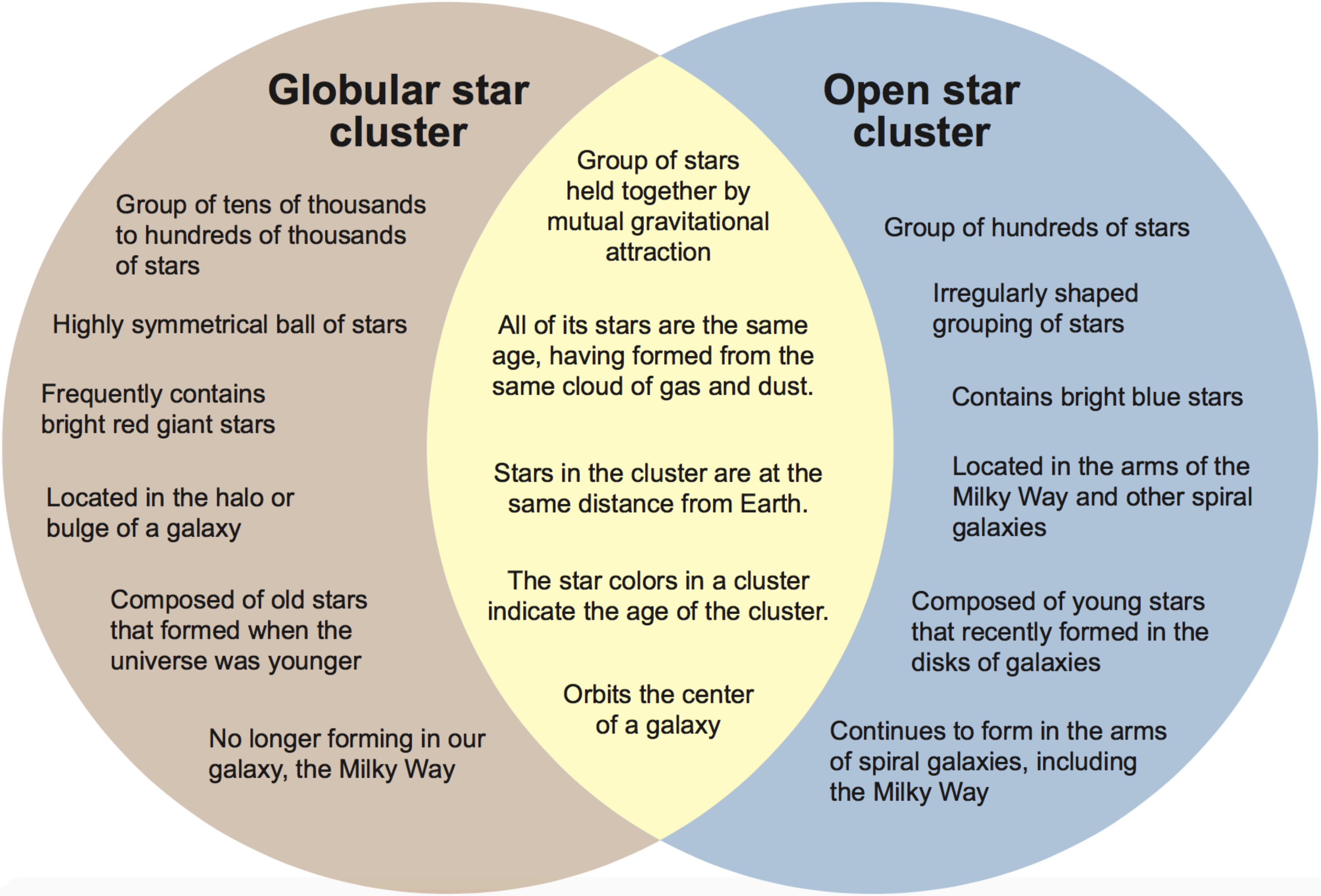
- Definition and description
- Dynamical state
- Distinct modes of star formation ?
- Dissolution into the field, timescales
- Membership studies: HR diagram + biases

Definition

Physically associated groups of young (pop. I) stars, moving together through the Galaxy, and sharing the same origin.

- Open cluster: clear concentration of young stars above the surrounding stellar background, gravitationally bound
- Association: unbound group with higher than normal density of a given O-B stars or T-Tauri stars (OB / T – associations)




Globular star cluster
Open star cluster
Group of tens of thousands to hundreds of thousands of stars
Highly symmetrical ball of stars
Frequently contains bright red giant stars
Located in the halo or bulge of a galaxy
Composed of old stars that formed when the universe was younger
No longer forming in our galaxy, the Milky Way
Group of stars held together by mutual gravitational attraction
All of its stars are the same age, having formed from the same cloud of gas and dust.
Stars in the cluster are at the same distance from Earth.
The star colors in a cluster indicate the age of the cluster.
Orbits the center of a galaxy
Group of hundreds of stars
Irregularly shaped grouping of stars
Contains bright blue stars
Located in the arms of the Milky Way and other spiral galaxies
Composed of young stars that recently formed in the disks of galaxies
Continues to form in the arms of spiral galaxies, including the Milky Way

Open Clusters

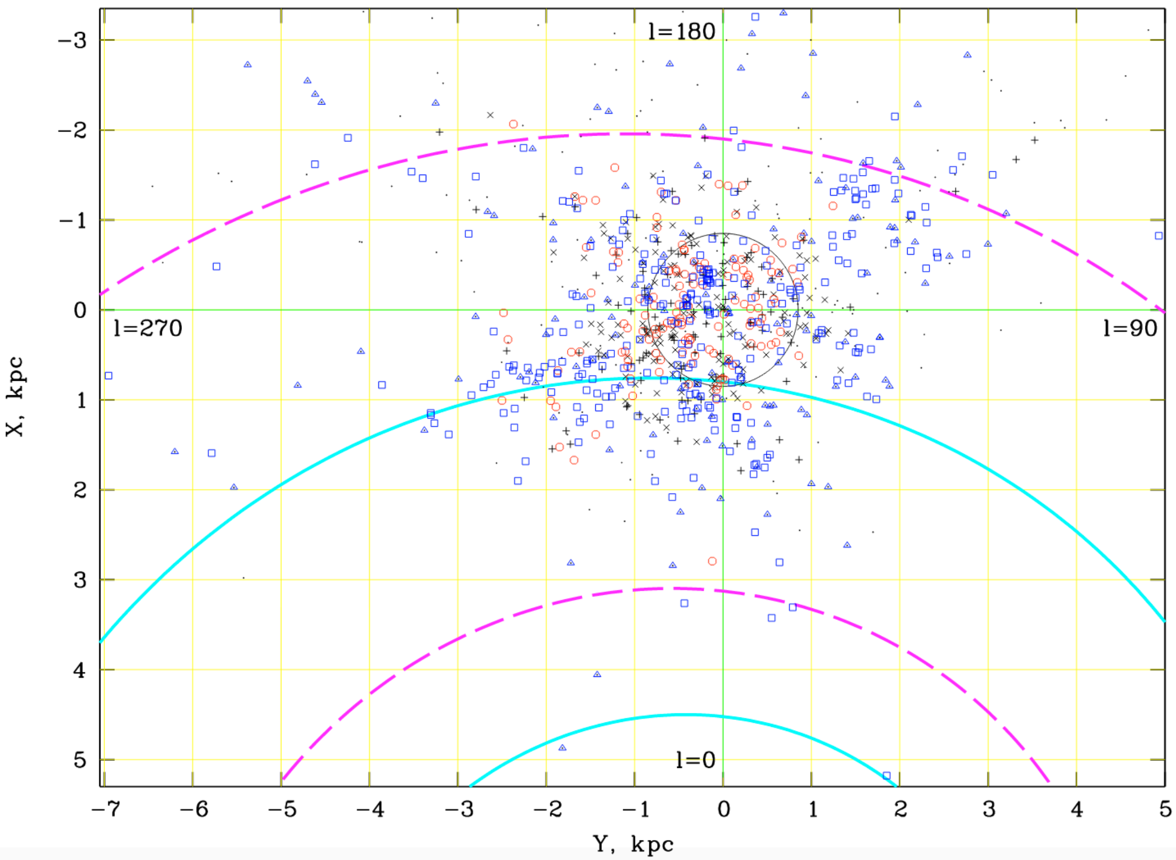
- Located in the disk of our Galaxy
- Young stars (Population I, metallicity ~solar)
- 10 to 10^4 stars per cluster
- ~ 1-10 pc in diameter (no strong correlation with number of members, nor age)
- Average star density ~ 0.1 to 10 stars/pc^3
- Loosely bound, stay together for <10^8-10^9 yr
- Irregularly shaped
- ~ 3000 known in the Galaxy (but a lot more to be found – maybe up to 10^5 in the Galaxy)
- Examples: Pleiades, Hyades, Praesepe…

Catalogs (not complete…)

- Lund catalog (Lynga 1982, 1987, Janes & Adler 1982, Janes et al. 1988): ~1200 clusters
- **WEBDA database** (Mermilliod 1995): photometry, spectroscopy, bibliography + specific informations
- Baumgardt et al. (2000) based on Hipparcos: ~200 clusters
- Loktin et al. (2001, 2003, 2004) based on Tycho2: ~350 clusters
- **DAML02 catalog** (Dias et al. 2002-2014)) based on Hipparcos + Tycho2 + UCAC4: ~2200 clusters with diameters, distance, age + ppm, Vrad, metallicity (http://www.wilton.unifei.edu.br/ocdb/)
- Catalogue of Open Cluster Data (**COCD**, Kharchenko et al. 2005, 2004) based on ASCC-2.5, Hipparcos + Tycho: ~650 clusters with distances, motions, sizes, ages, luminosities and masses, complete up to ~800pc
- SAI Open Clusters Catalog (Glushkova et al. 2010; http://ocl.sai.msu.ru/): ~200 clusters
- Milky Way Star Clusters (**MWSC**, Kharchenko et al. 2013, 2012) based on PPXML: ~2800 clusters with size, proper motion, distance, colour excess, age + Vrad; complete up to 1.8kpc for log t <9

Distribution in the galactic disk

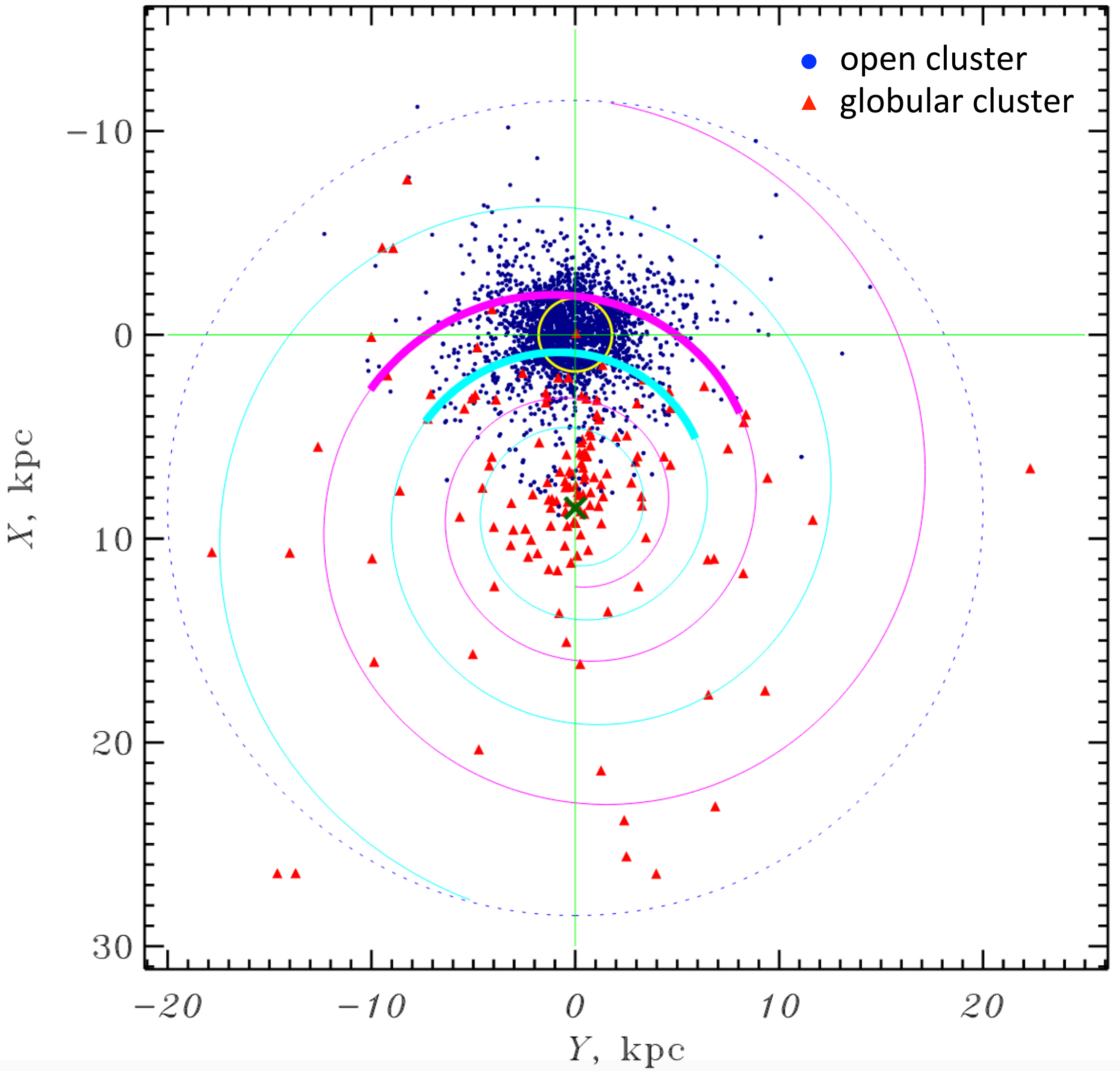
Distribution of DAML open clusters in the XY-plane centered at the location of the Sun (Piskunov et al. 2006)



Complete to ~850 pc

Fluctuations in the spatial and velocity distributions → 3 cluster complexes

Distribution of MWSC clusters in the XY-plane centered at the location of the Sun (Kharchenko et al. 2013)



~2800 clusters

Complete to ~1.8 kpc

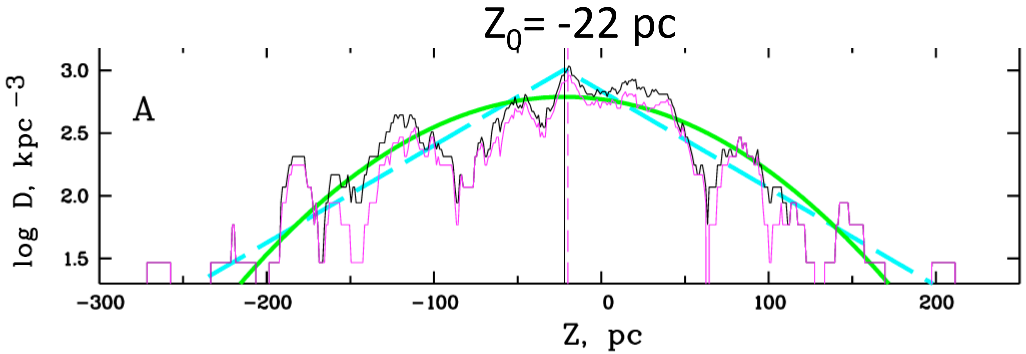
Estimated number of ~10^5 open clusters in the Galactic disk.

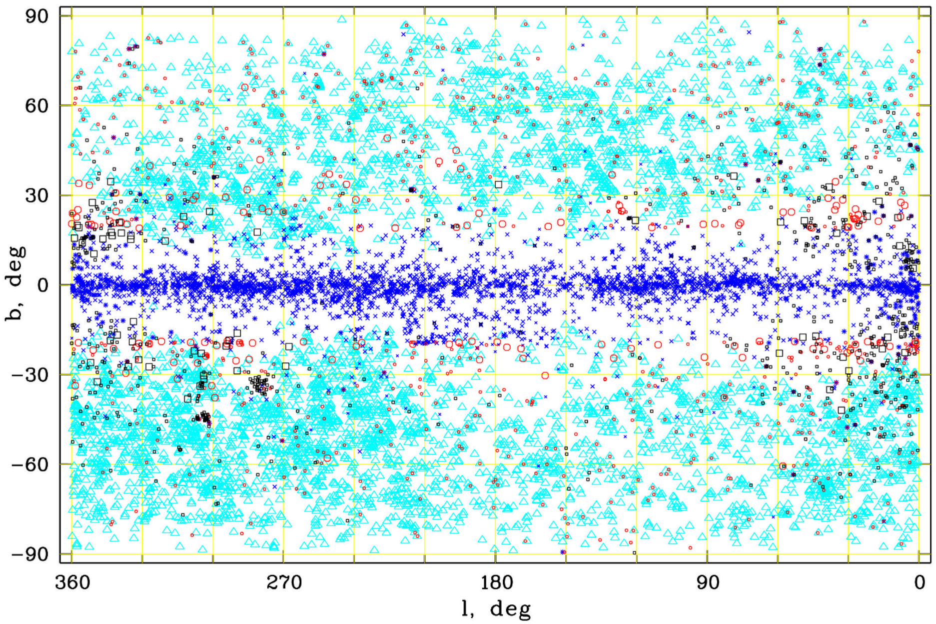
Height scale

$$D(Z) = D(Z_0)\exp\left\{-\frac{|Z - Z_0|}{h_Z}\right\}$$

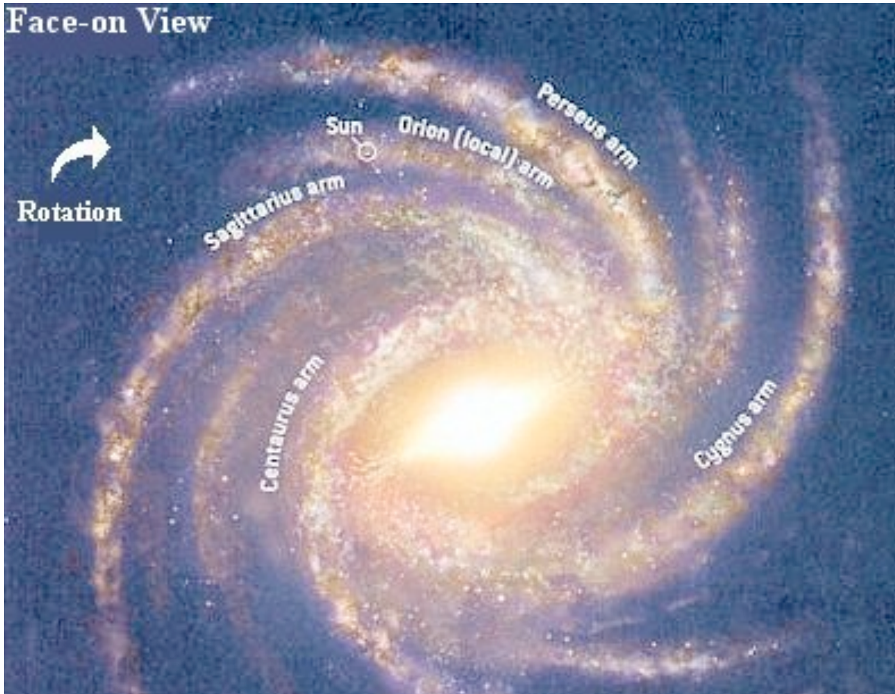
Relatively flat distribution

$h_Z = 56 \pm 3$ pc (Piskunov et al. 2006)

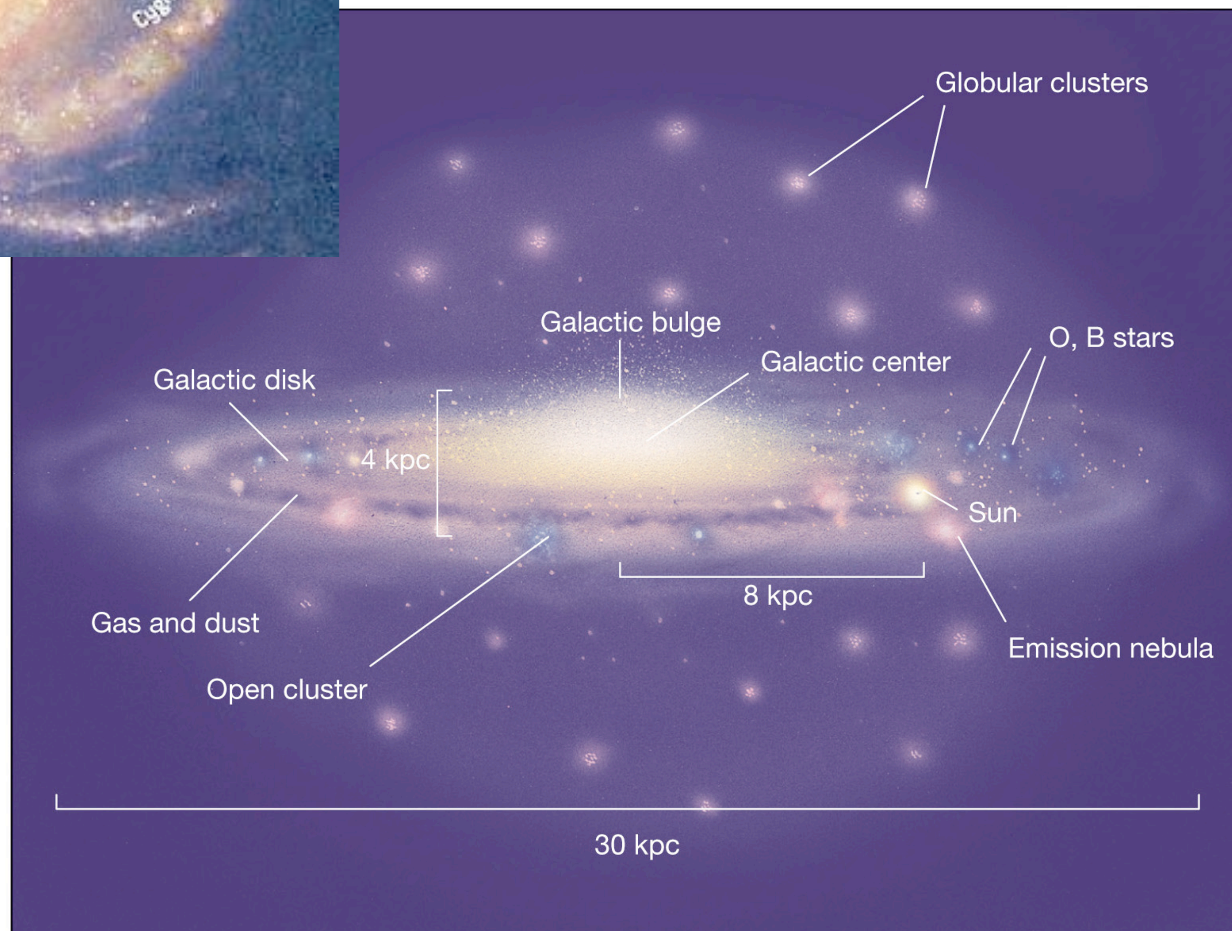




Blue crosses: Distribution of all MWSC open clusters and candidates in Galactic coordinates (Scholz et al. 2015)



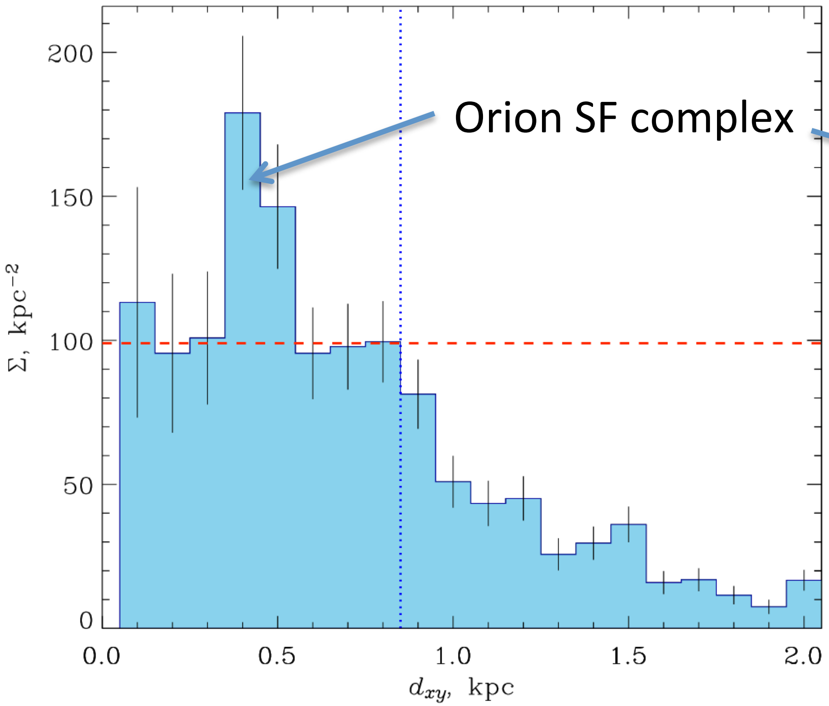
ASTRONOMY: A Beginner's Guide to the Universe 4th Edition; Chaisson & McMillan



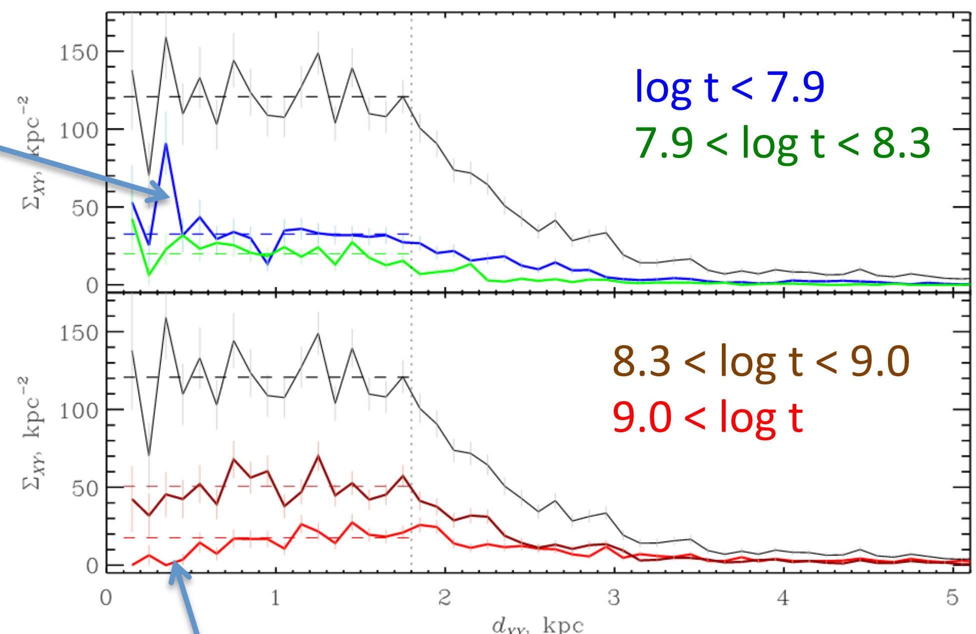
Global properties

Open cluster surface density Σ vs projected distance to the Sun d_{xy}

(256 clusters, Piskunov et al. 2006)

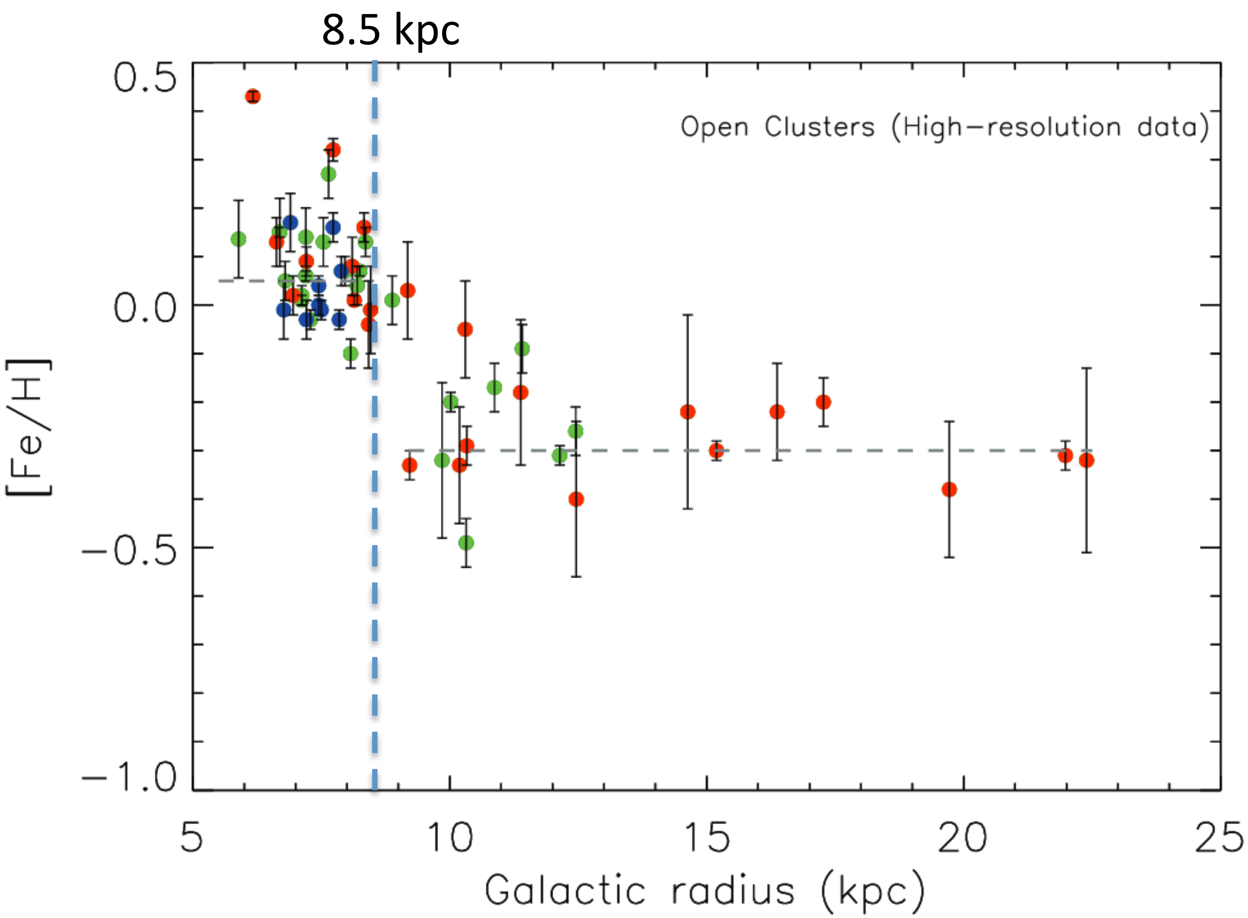


(MWSC, Kharchenko et al. 2013)



Apparent lack of >1Gyr cluster near the Sun :
larger scale height or artefact (e.g. Schmeja et al. 2014)

Metallicity distribution



(Lépine et al. 2011)

Abrupt decrease of metallicity around 8.5kpc, corresponding to the corotation radius of the main spiral structure.

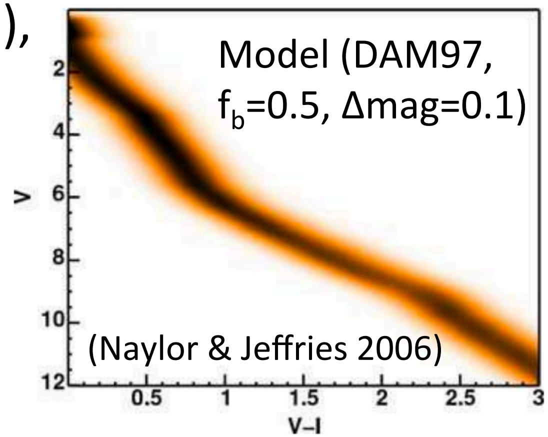
Void of gas acting as a barrier: gas chemical evolution independant on each side.

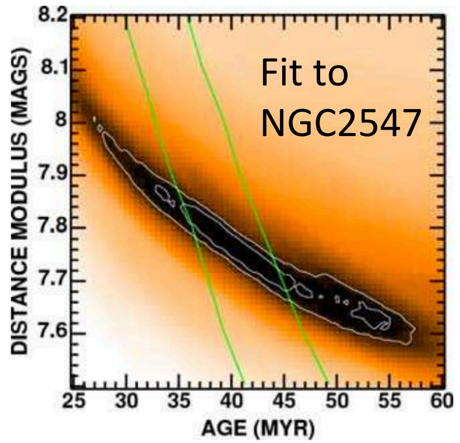
Age and distance determination

- Statistical measurement:

Isochrone fitting → age, distance, extinction and metallicity

e.g. τ^2 fitting (Naylor & Jeffries 2006), Cross-entropy optimization (Monteiro et al. 2010, 2011, Dias et al. 2012)



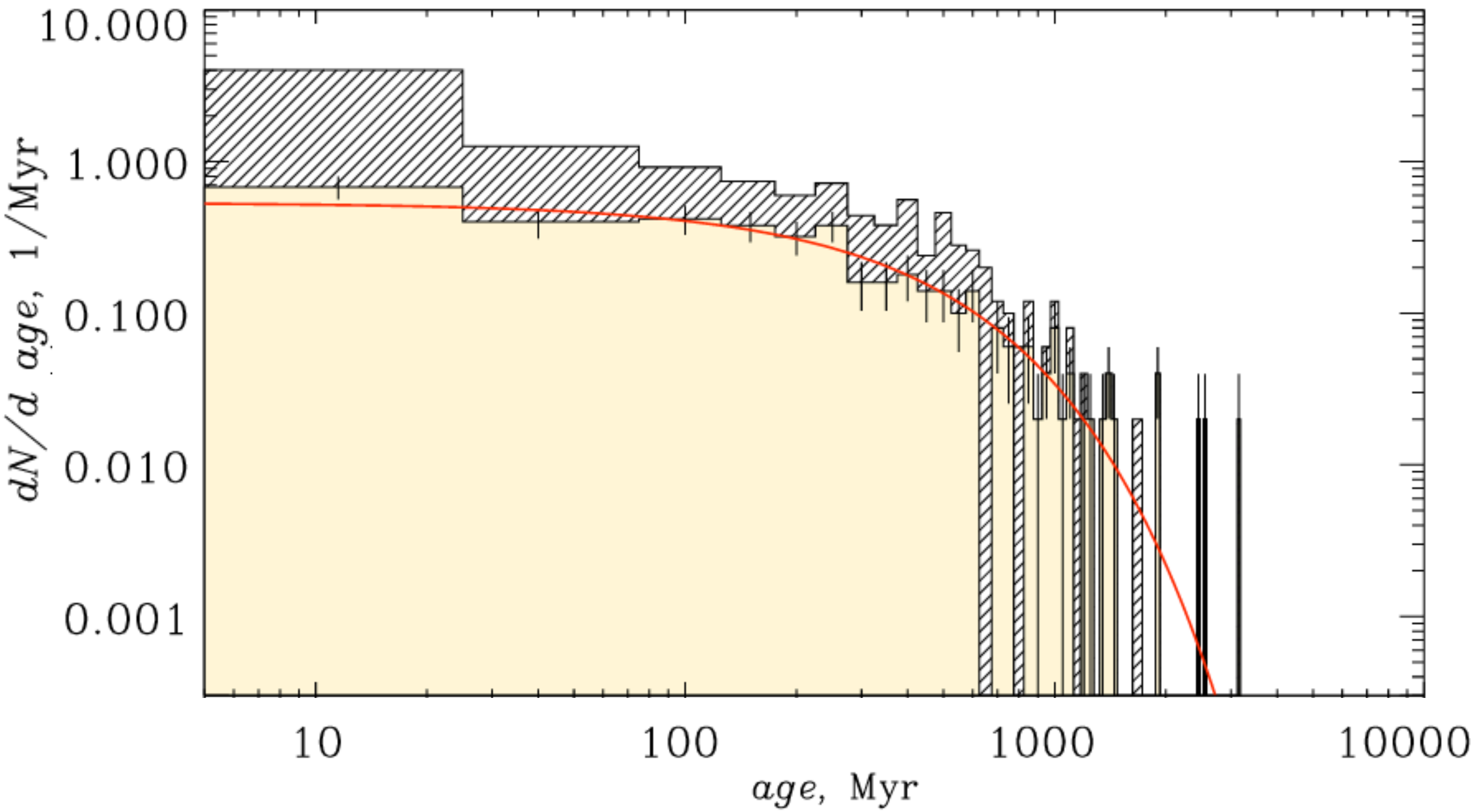


- Individual measurement on cluster members:

Parallaxes → distance

Lithium depletion boundary → age

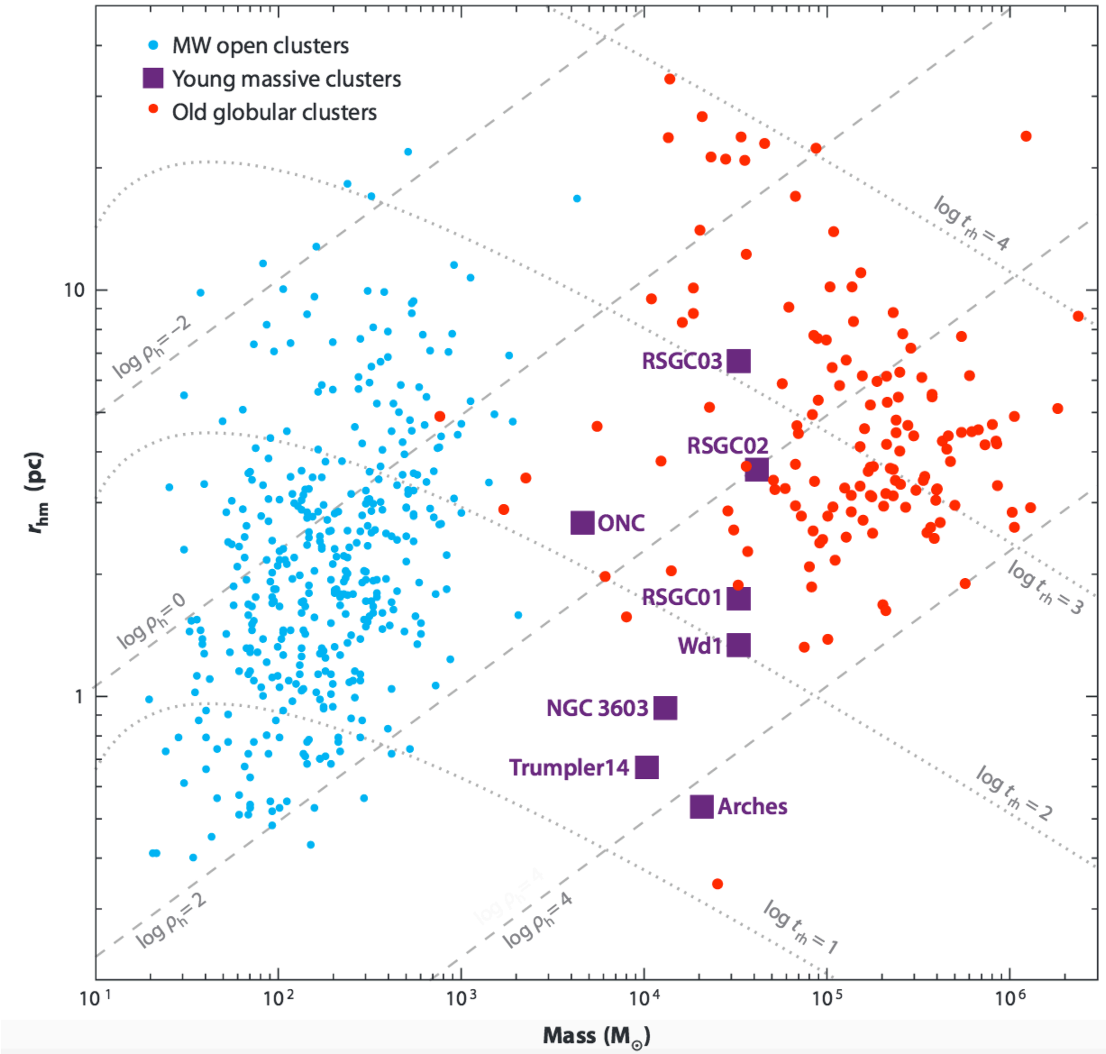
Age distribution



<850 pc sample (Piskunov et al. 2006):

- Mean age of local clusters: ~200 Myr
- Cluster lifetime: 322 ± 31 Myr

Radius distribution



(Portegies-Zwart et al. 2010)

- Half mass radius between ~1-10 pc
- Mean radius ~2 pc
- No correlation with mass nor age

Mass determination

Cluster mass determination:

- Sum up individual cluster member masses : requires a complete census)
- « Virial » masses estimated from radius and velocity dispersion : requires accurate σ_v

$$M_{vir} = \frac{R\sigma_V^2}{G}$$

- « Tidal » masses (King 1962) : requires accurate tidal radius estimate

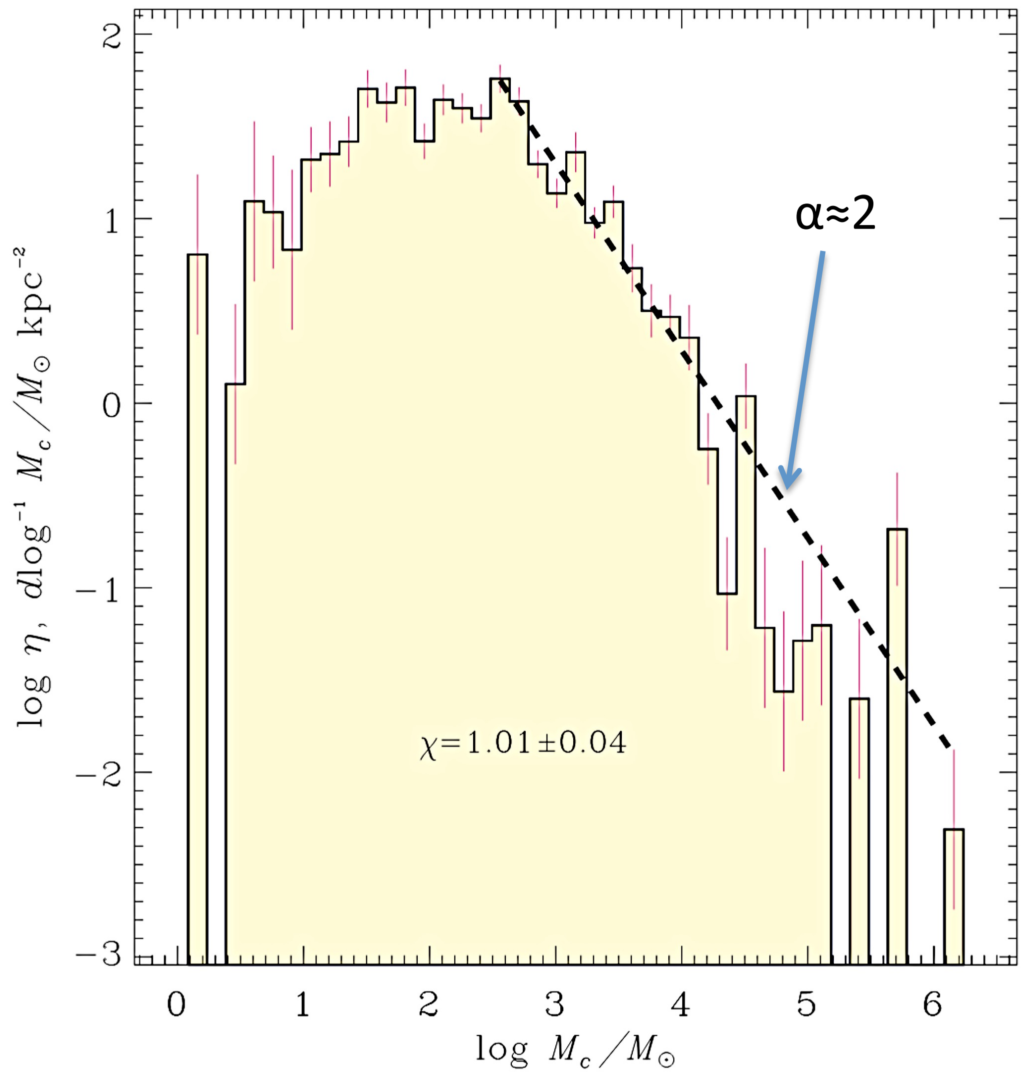
$$M_{tidal} = \frac{4A(A-B)r_t^3}{G}$$

Cluster mass function

Present day mass function of Galactic open clusters based on 440 local clusters (mag-limited sample, Piskunov et al. 2008):

→ $dN_c/dM_c \sim M_c^{-\alpha}$ with $\alpha \approx 2$

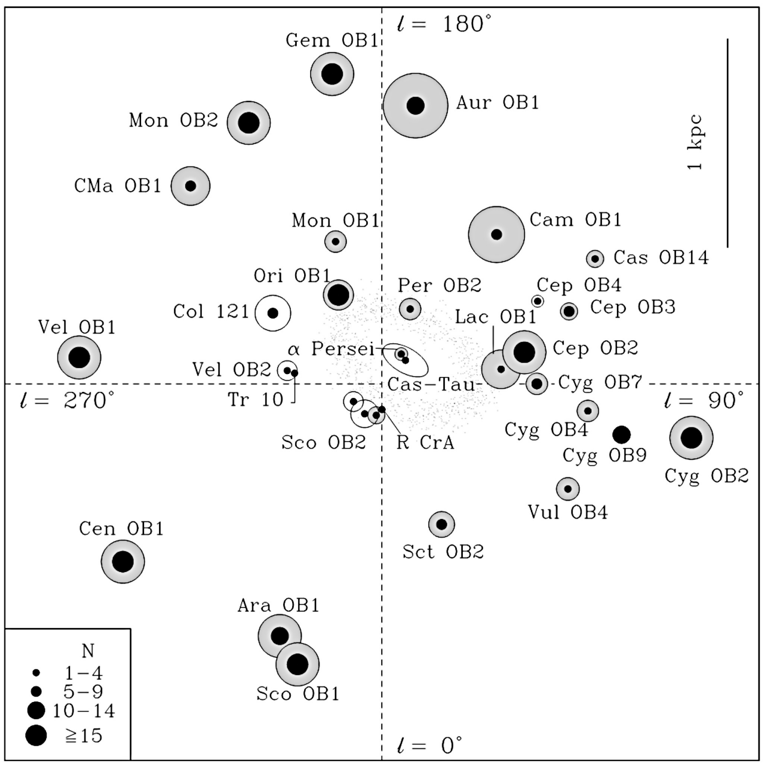
→ Average mass ~700 M_{sun}



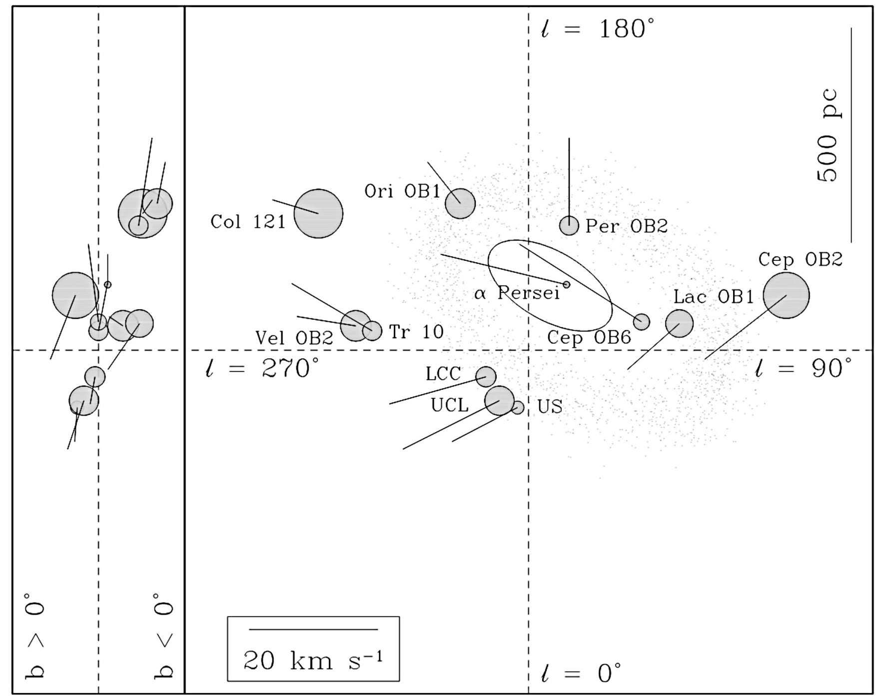
Associations

- Located in the spiral arms of our galaxy
- Young stars (Population I, metallicity ~solar)
- ~ 10 to 1000 stars per association
- ~ 100 - 200 pc in diameter
- Star density ~ 0.01 stars/pc^3
- **Gravitationally unbound**, disperse rapidly
- Irregularly shaped
- ~ 80 known O-B associations in the Galaxy
- Complete census of faint members difficult due to their diffuse nature
- Examples: Orion O-B Association, TW Hydra, β Pic

OB associations

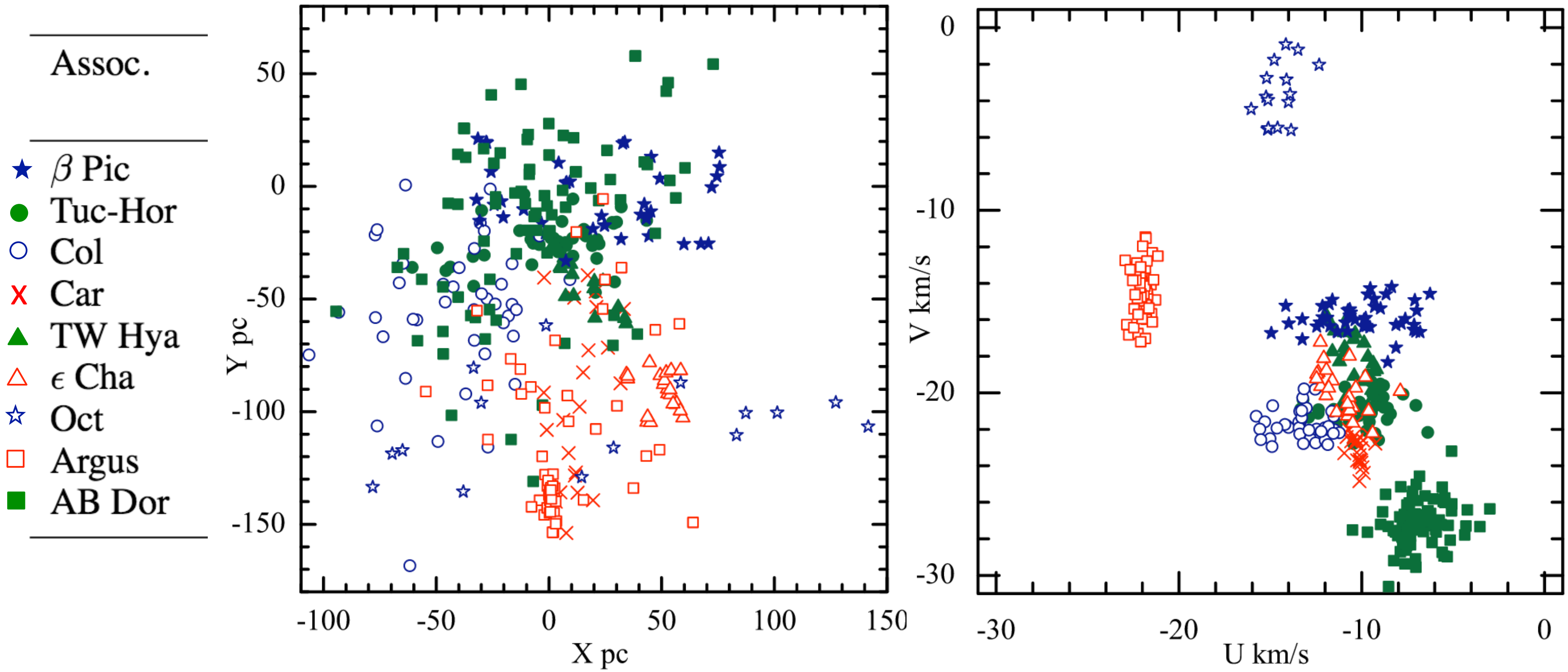


Pre-Hipparcos OB associations



Kinematically detected OB associations by Hipparcos within 1kpc (de Zeeuw et al. 1999)

Loose nearby associations



(Torres et al. 2008)

Distance of nearby associations

- Members of nearby associations can be spread all over the sky and may not share the same distance (distance range ~ mean distance)

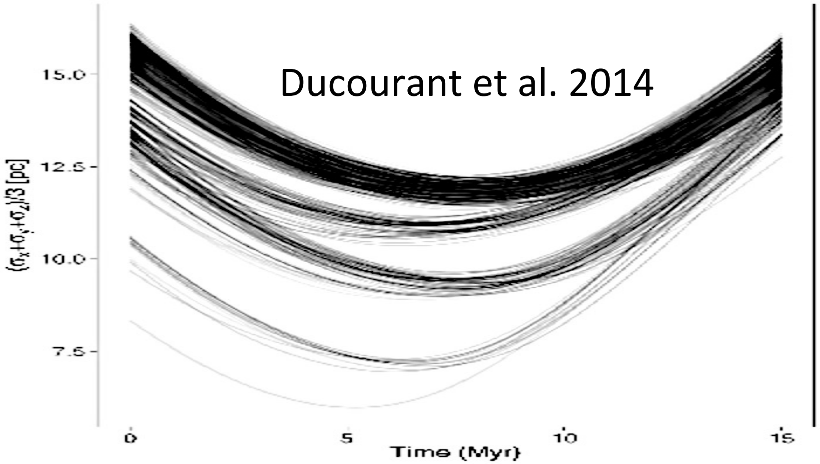
→ Need for individual parallax measurement

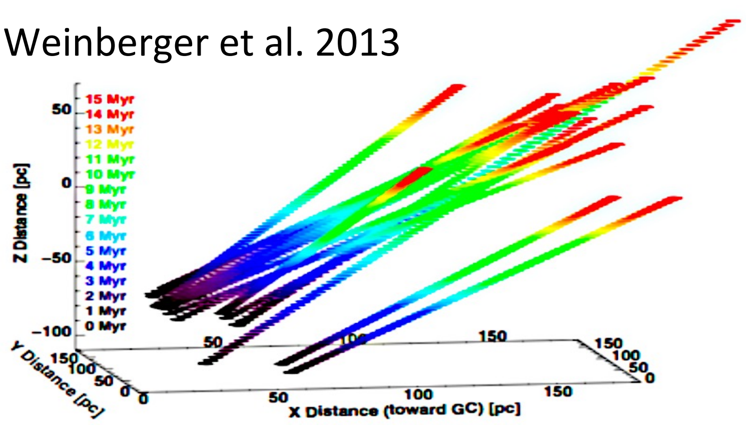
Assoc.	X [pc]	X Range [pc]	Y [pc]	Y Range [pc]	Z [pc]	Z Range [pc]	D [pc]	Age [Myr]
β Pic	20	-32/76	-5	-33/21	-15	-29/-1	31±21	10
Tuc-Hor	3	-61/43	-24	-47/-4	-35	-44/-30	48±7	30
Col	-42	-106/9	-56	-168/1	-47	-99/6	82±30	30
Car	14	-2/33	-94	-154/-39	-17	-33/5	85±35	30
TW Hya	15	2/34	-44	-61/-26	21	10/27	48±13	8
ϵ Cha	50	34/60	-92	-105/-78	-28	-44/-12	108±9	6
Oct	22	-79/142	-106	-138/-60	-68	-85/-38	141±34	20?
Argus	5	-55/64	-115	-154/-6	-18	-67/8	106±51	40
AB Dor	-6	-94/73	-14	-131/58	-20	-66/23	34±26	70

Age of nearby associations

- Isochrone fitting on distance corrected H-R diagram
- Lithium depletion boundary
- **Kinematic age:** traceback analysis to find the time when members were closest
  - **Beta Pic**: kinematic age 13-58 Myr (Mamajek & Bell 2014)
  - **TWA**: kinematic age ~7.5Myr +/- 0.7 Myr (Ducourant et al 2014)

  However Weinberger et al. (2013): no common formation point → formed from an extended filament, not necessarily coeval (3-23 Myr)





Moving groups

- Moving groups: stars sharing the same velocity but not necessarily a common origin (e.g. Hyades moving group) ≠ associations !
- Beware of older associations, e.g. ABDor (~120 Myr): lots of contaminants due to resonant trap in the Galaxy (Famaey et al. 2008)

  → Need to use other criteria than kinematics to assess association membership (e.g. Barenfeld et al. 2013): chemical composition, age, 3D velocity

In this lecture, I focus on clusters and associations and always assume that members have the same origin.

Summary of average parameters

	Globular clusters	Open clusters	OB associations
Numbers of clusters:			
Catalogued	147	1200	70
Likely Galactic total	200	10^5	> 1000
Typical Sizes (pc):			
Core radius (median)	1.0	—	unbound
Tidal radius (median)	35	—	unbound
Apparent diameter	—	4	> 100
Masses ($M_\odot$):			
Minimum	10^4	10	1000
Maximum	10^6	10^4	10^4
Ages (yr):			
Minimum	8×10^9	5×10^6	5×10^6
Maximum	16×10^9	9×10^9	2×10^7
Metallicities ([Fe/H]):			
Range	−2.3 to +0.2	−0.7 to 0.3	Pop I

Cluster vs. Association

- Is there any prefered mode ?
- Where do the disk stars come from ? cluster or association, or both ?
- Do clusters and associations form similarly but evolve differently ?
- Are associations formed from the halo of embedded clusters?
- Are clusters linked to associations via triggered star formation (e.g. ρ-Oph and USco) ?
- Do they form from different physical conditions (density, turbulence, magnetic field) ?
- How does the cluster/association environment affect the stellar properties ?

How to distinguish them

- A cluster is virialised if $2T + U = 0$
- It is bound if $T + U < 0$

$$U = -\frac{GM^2}{R} \text{ and } T = \frac{1}{2} M \sigma_V^2$$

$$\text{A system is bound if } \sigma_V < \sqrt{2}\ \sigma_V^{vir} = \sqrt{2\frac{GM}{R}}$$

- Virialized system: $\sigma_V = \sigma_V^{vir}$ → bound
- Subvirial system: $\sigma_V < \sigma_V^{vir}$ → bound
- Supervirial system: $\sigma_V > \sigma_V^{vir}$ → ??

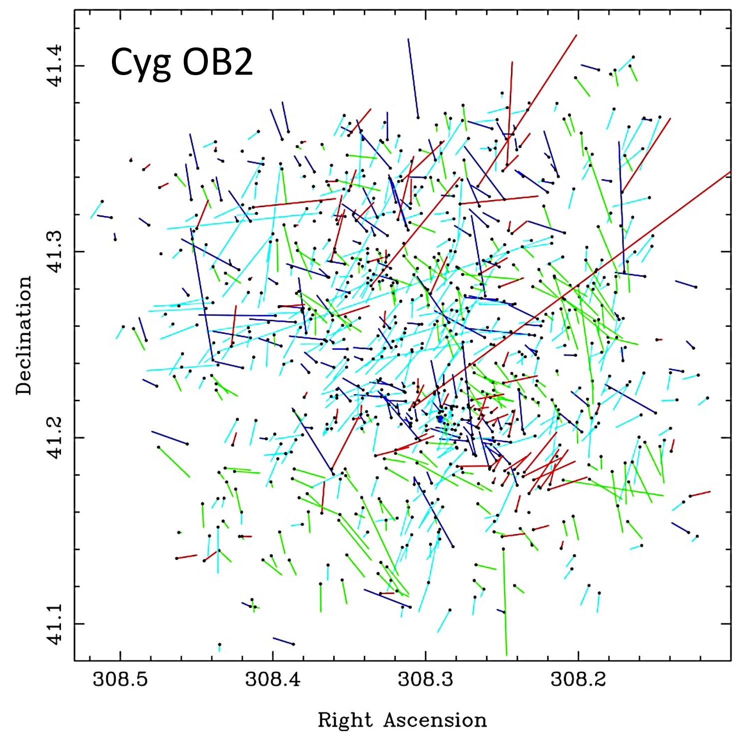
→ Need to estimate M_C and R_C

→ and to measure σ_V with a good accuracy (<1km/s)

Some examples

σ_V needs to be corrected from bias introduced by binaries (e.g. Cottaar & Henault-Brunet 2014, Cottaar et al. 2012)

- **Westerlund 1** subvirial (Cottaar et al. 2012): strongly bound
- **NGC3603** about virialized (Pang et al. 2013): bound ?
- **IC348** supervirial but probably bound thanks to the gas mass (Cottaar et al. 2015)
- **Cyg OB2** unbound (Kimiki et al. 2007, 2008; Wright et al. 2014), but no coherent expansion pattern on large scale



Other diagnosis

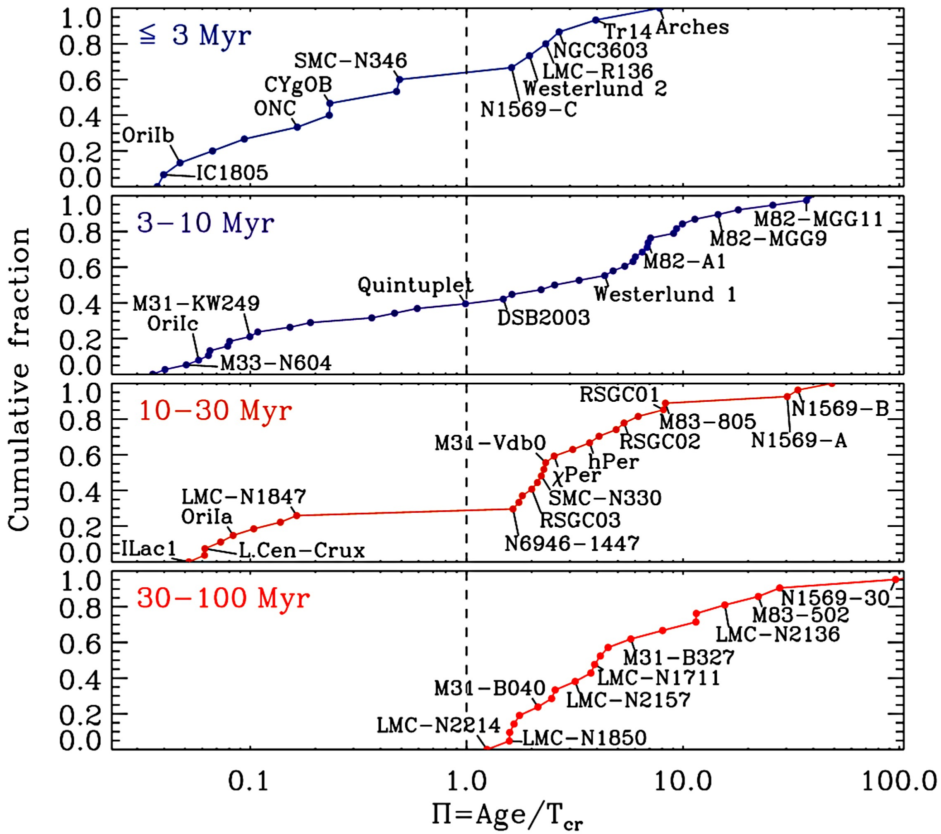
Proposed distinction between star cluster and association (Gieles & Portegies-Zwart 2011) – useful if we cannot measure σ_V :

π = age / t_{cross} > 1 → cluster

At young ages (<10 Myr):

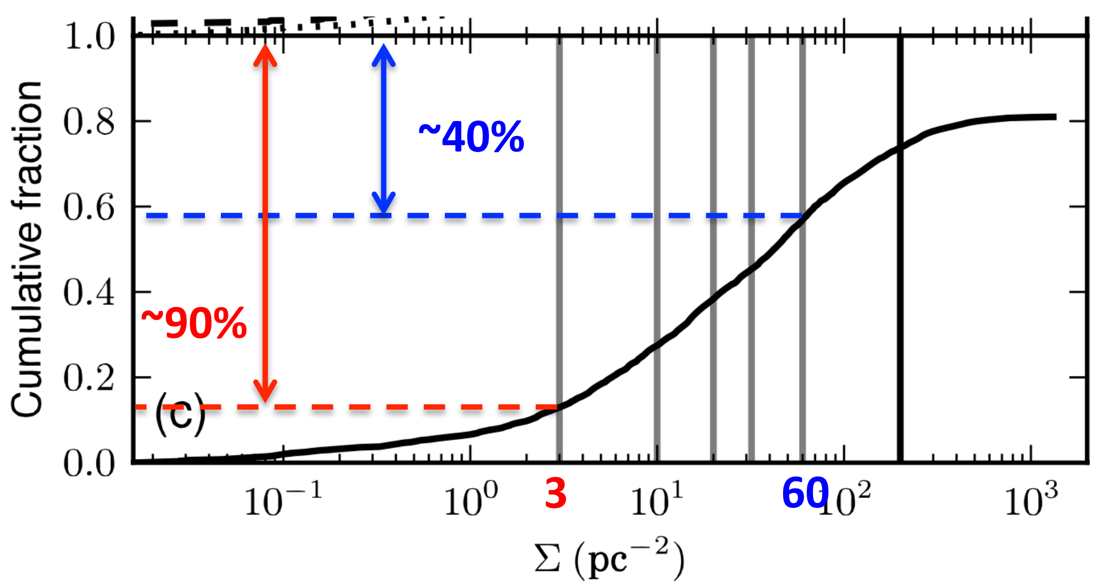
- Not a clear diagnosis
- A continuous distribution between clusters and associations

~10Myr: development of a gap



Distribution of YSOs

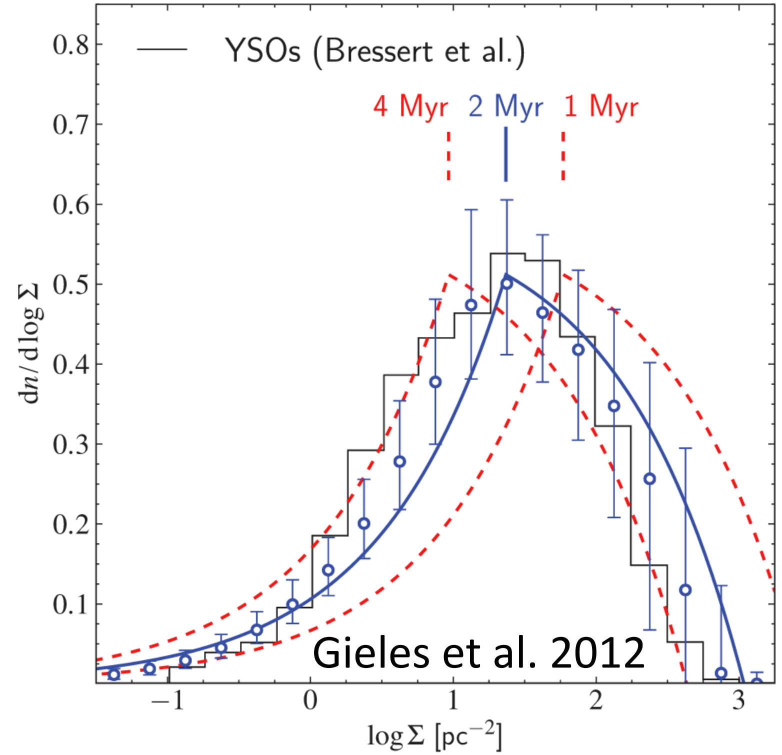
- Smooth distribution of surface densities
- No evidence for several discrete mode of star formation. Smooth transition between clusters and associations
- 40-90% of stars form in clusters depending on the density cutoff
- <26% of stars in dense clusters affected by their neighbours



Cumulative fraction of YSO (class I & II) surface densities, based on a <500pc sample (Bressert et al. 2010)

Cluster dissolution

- Clusters are loosing stars and are expanding and dissolving
- The distribution of YSO surface density distribution can be reproduced by a simple model where all stars form in bound clusters which expand by 2-body relaxation
- Moreover, a dissolving cluster and especially the escaped members may look like an association



→ The present day number (and mass) of bound clusters needs to be corrected from evolution efffect if we want to know where the disk population comes from.

Dynamical timescales

Crossing time: $t_{cross} = \dfrac{R}{\sigma_V}$

- If virial equilibrium: $\sigma_V = \sigma_V^{vir} \approx \sqrt{\dfrac{GM}{R}}$

  and $t_{cross} \approx \sqrt{\dfrac{R^3}{GM}} = 14.25\sqrt{\left(\dfrac{R}{1\text{pc}}\right)^3 \left(\dfrac{1M_{sun}}{M}\right)}\ \text{Myr}$

For a typical open cluster: R~4pc and M~1000 M_{sun} → t_{cross}~3-4Myr

The denser the cluster, the shorter is t_{cross} : $t_{cross} \approx \sqrt{\dfrac{R^3}{GM}} \propto \dfrac{1}{\sqrt{G\rho}}$

- Significance:
  - Time to respond to the global gravitational potential
  - Timescale to approach virial equilibrium
  - Timescale of orbital motions in virial equilibrium, « mixing time »
  - For an unbound system, t_{cross} corresponds to a dissolution timescale

Dynamical timescales

(two-body) relaxation time: $t_{relax} \approx 0.1 \dfrac{N}{\ln N} t_{cross}$

For a typical open cluster (N~1000): t_{relax} ~ $15t_{cross}$ ~ 50 Myr

But for small groups (N<100): t_{relax} ~ t_{cross}

- Significance:
  - time to change the star velocity vector by ~ 90 deg
  - Time such that $(\Delta E/E)_{star} \approx 1$
  - Timescale to transfer energy of orbital motion

- Consequences:
  - Energy equipartition: $m_i \langle v_i^2 \rangle = m_j \langle v_j^2 \rangle$
  - Mass segregation: more massive stars tend to have smaller velocities and sink to the center of the cluster

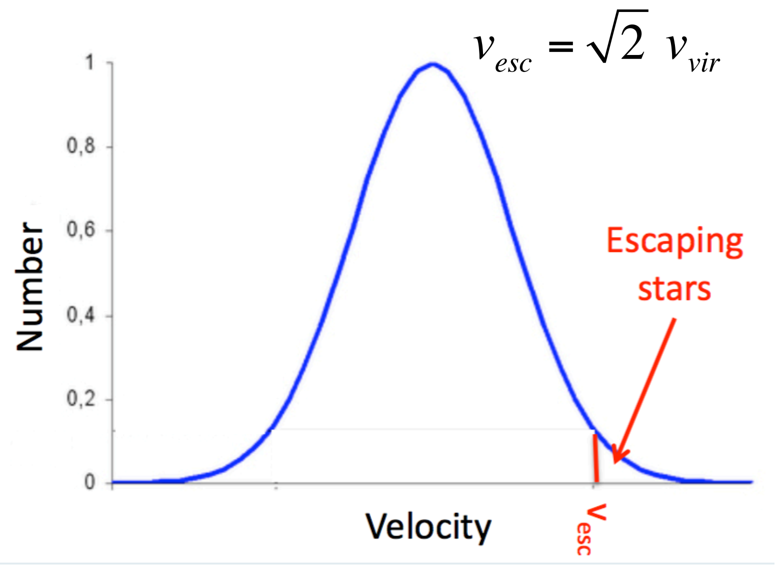
Dynamical timescales

Evaporation time: t_{evap}

- two-body relaxation → exchange of energy amongst stars. If at some moment a star becomes unbound (kinetic + potential energy > 0), it will escape the cluster.

  $t_{evap} \sim 100\ t_{relax}$

  (~1% of stars lost within 1 t_{relax})

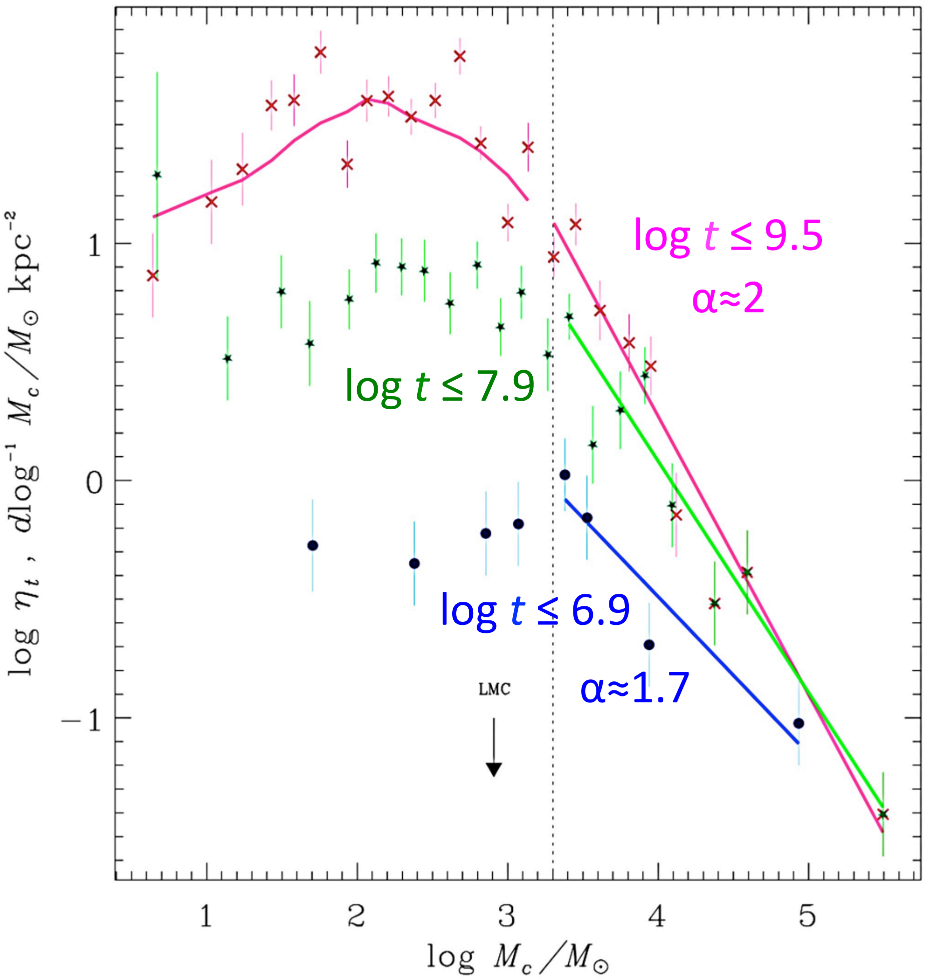


- Evaporation accelerated by tidal effect (e.g. passages of nearby giant molecular clouds or spiral density waves)

  → $t_{evap} \sim 10\ t_{relax}$

  $t_{evap} \sim t_0 (M_i/M_{sun})^{0.62}$ (Lamers et al. 2005, Gieles et al. 2004)

Cluster mass function evolution



Piskunov et al. 2008

- Steepening of the mass function with age due to stellar evolution and dynamical evolution.
- Typical cluster mass loss: 3-14 $M_{sun}Myr^{-1}$
- cluster formation rate: ~0.4 $kpc^{-2}Myr^{-1}$

Where does the disk come from?

- Assuming α~2 and a mean cluster mass of ~700 M_{sun}, ~10% of disk stars were cluster members (Piskunov et al. 2006)
- Taking into account the cluster mass loss, and assuming α~1.7 and an average birth mass ~4500 M_{sun}, ~40% of disk stars were cluster members (Piskunov et al. 2008)
- Lada & Lada (2003): the majority of stars form in embedded clusters based on their SF rate

→ ~half of the clusters do not survive the embedded phase

To be taken with cautious: based on a local (<1.8kpc) sample and a few 1000 clusters over ~10^5 expected in the disk.

Moreover depends on the embedded cluster definition.

Analysis of cluster members

Look at their properties (IMF, spatial distribution, binarity…) in various environments to:

- Look for similarities/differences with the field population to know where the disk stars are from
- Investigate star formation variation/universality
- Study the influence of neighbours on individual properties
- Understand the cluster dynamical evolution
- …

→ **Need for clean and complete samples of cluster members**

→ **Membership analysis** (but be aware that contamination and uncompleteness are always present…)

Summary of lecture 1

- Open clusters and associations are young (pop I), relatively low mass ($10\text{-}10^4\ M_{sun}$) stellar groups located in the galactic disk
- They can be used to investigate the galactic disk properties (structure, kinematics, metallicity gradient) – but be aware that we know only a limited sample
- Cluster catalogs provide position, apparent extension, proper motion, Vrad, metallicity and **estimate** of distance, mass and age
- Clusters are bound / associations are unbound
- Need very accurate σ_V to investigate the cluster dynamical state
- Probably a smooth transition between clusters and associations
- Still unclear to know what are the cluster/association contributions to the disk population
- Is there any prefered mode of star formation ?
- How do we go from embedded cluster to open cluster/association ?

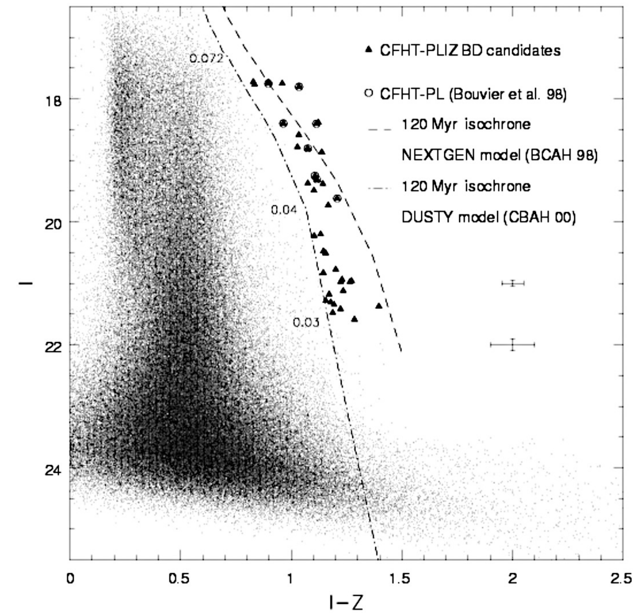
II. Statistical properties of young cluster population

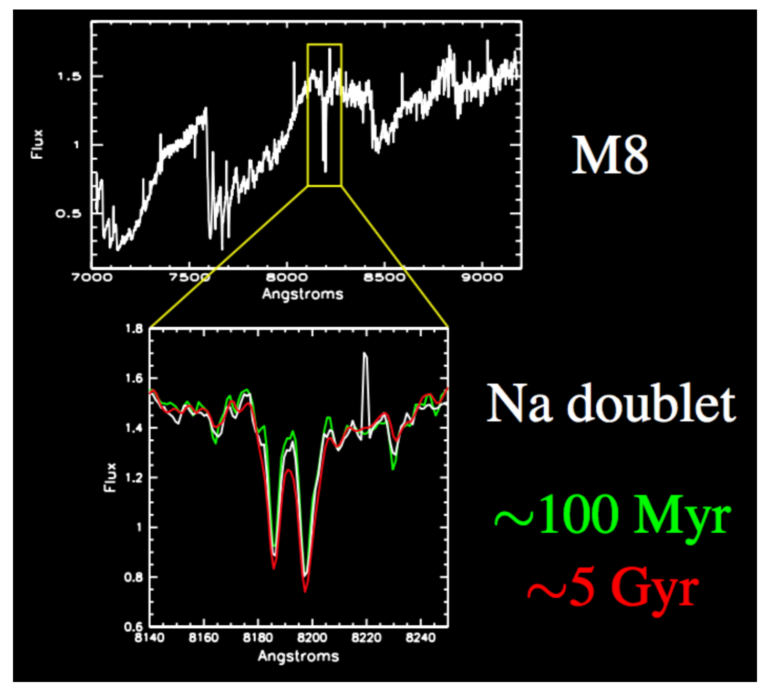
- Membership analysis
- IMF
- Multiplicity
- Substructures (spatial and kinematics)

Membership criteria

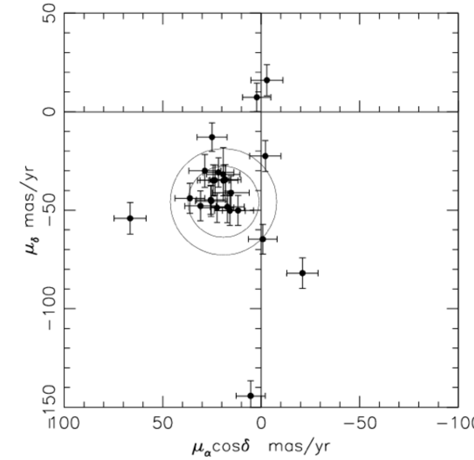
Clusters: homogeneous populations from low to high mass stars (same distance, age, [Fe/H])

- Cluster locus in HR diagram: colour, luminosity
- Spectral type
- Youth indicators: gravity sensitive spectral features, Lithium, activity
- Kinematics: Vrad, proper motion





Proper motion

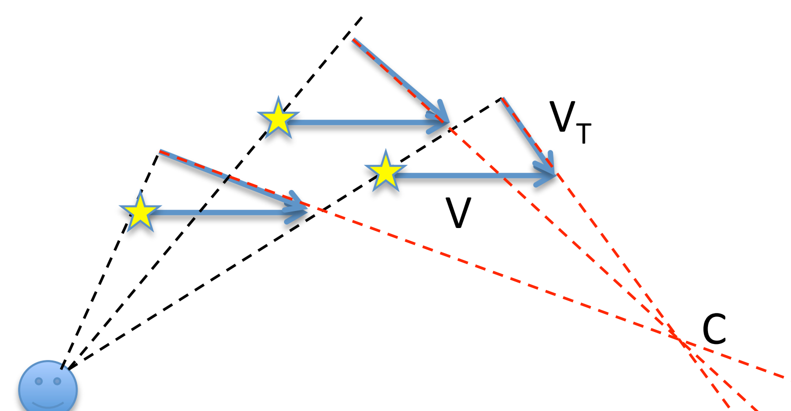


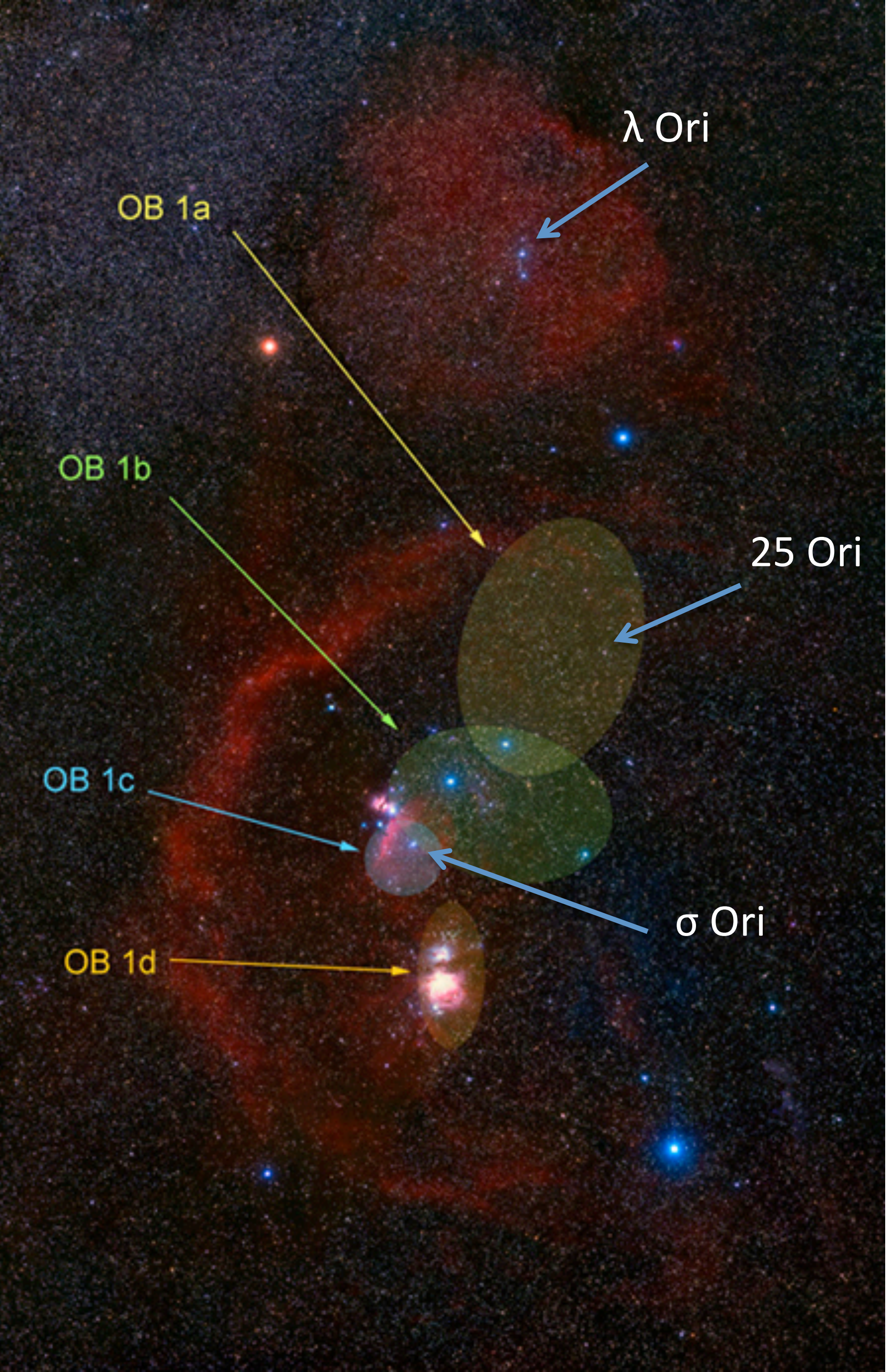
- Star clusters require a low velocity dispersion for their survival (δv = 1 km/s gives δd = 1 pc in 1 Myr)
- Typical σ_V ~ 1 km/s → **cluster members have essentially the same space motion $V = (V_{rad}, V_T)$ even after escaping the cluster**
- Proper motion: $\mu = V_T / 4.74\, d$

  where V_T is the transverse velocity and *d* is the cluster distance

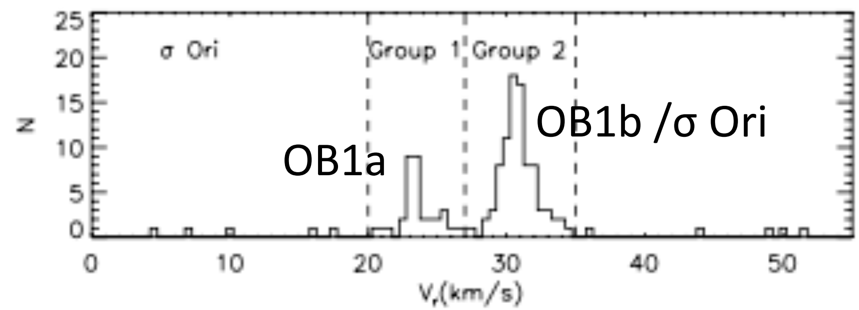
→ Powerful tool for membership **IF** the cluster has a large motion

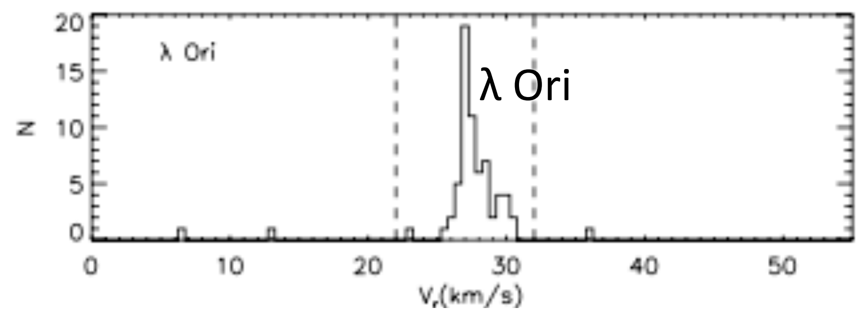
Convergent point analysis:
Depth effect implies proper motion gradient from front to back. Motions appear to converge to a point in the sky

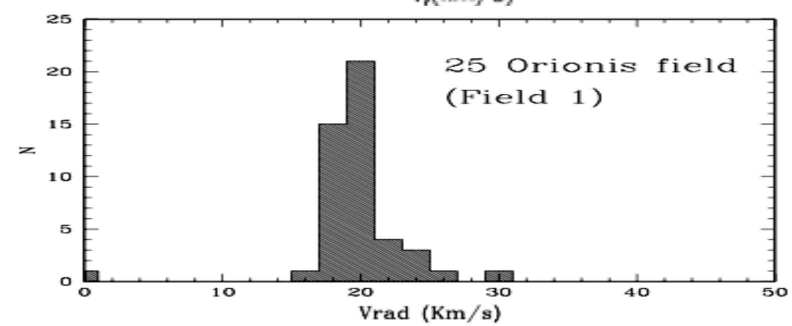




V_{rad} in Orion





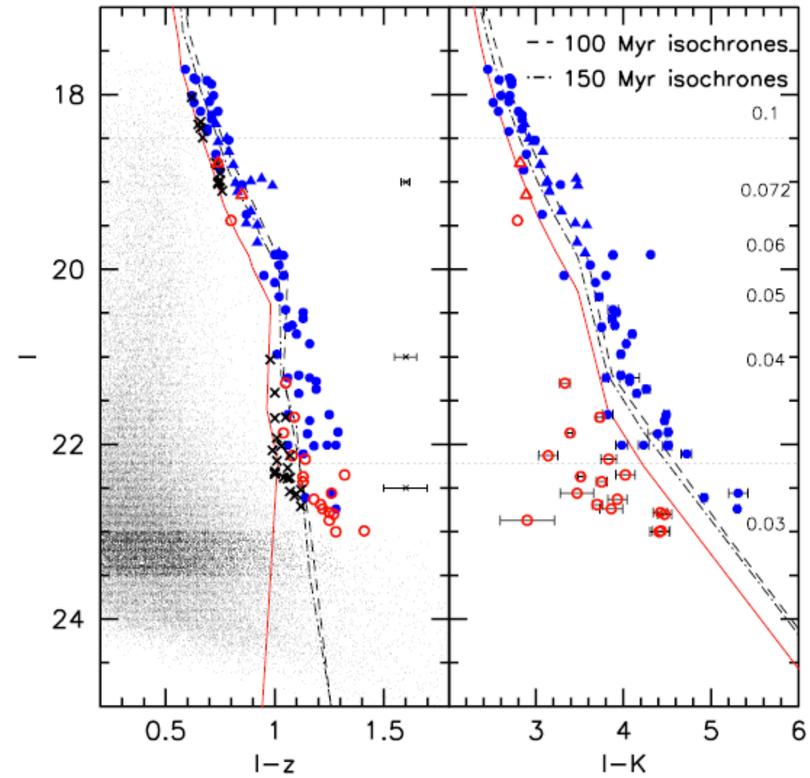


(Jeffries et al. 2006, Briceno et al. 2007, Maxted et al. 2008, Sacco et al. 2008)

On the « old-fashioned » (but still fine) method to find members

1- Photometric selection of cluster members:

e.g. Blanco 1
(Moraux et al. 2008)



2- Confirmation of candidates status :

follow-up observations to confirm membership

What we thought could be a better way…

Membership probabilities (Sanders 1971)

$$P_c(i) = \frac{\Phi_c(i)}{\Phi(i)}$$

$\Phi_c(i)$ ← cluster distribution

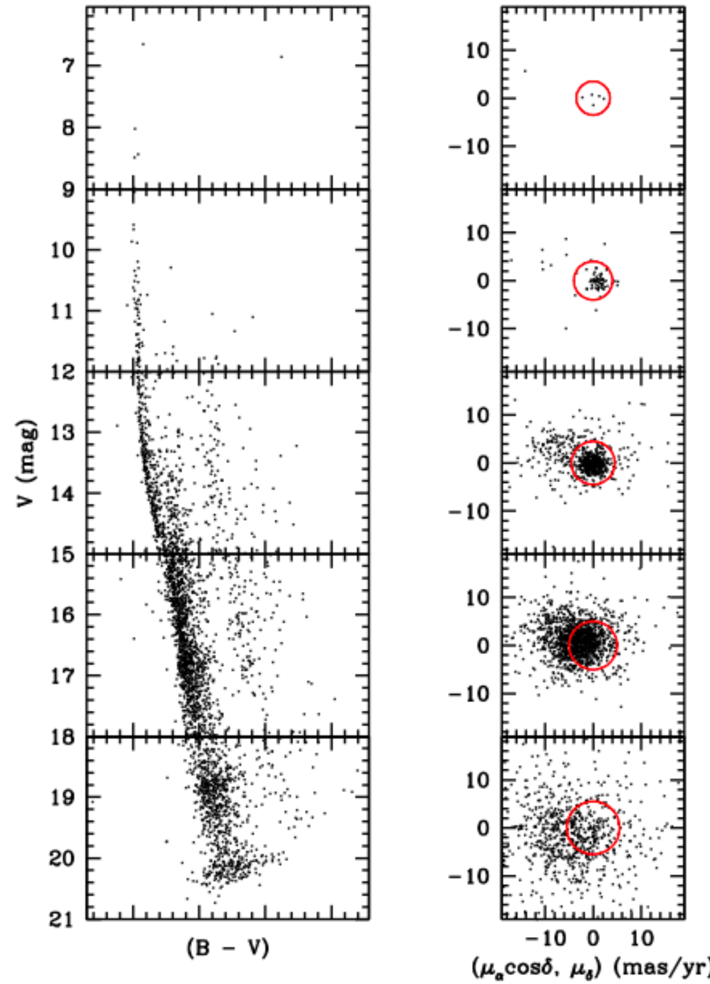
$\Phi(i)$ ← field + cluster distribution

But contrast with field decreases at fainter magnitude → a single probability cut at all mag misses faint members

Disentangling bona-fide low luminosity cluster members is challenging

→ contamination/uncompleteness

NGC3766 (Yadav et al. 2013)



« Modern » methods

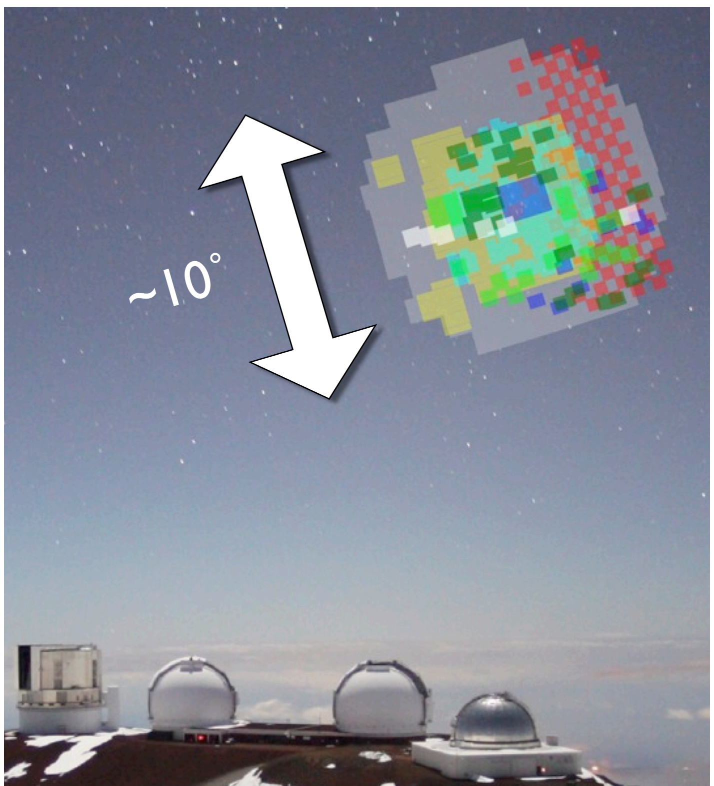
Bayesian analysis (e.g. Sarro et al. 2014, Malo et al. 2013, Rizzuto et al. 2011) based on positions, proper motions, magnitudes, colors…

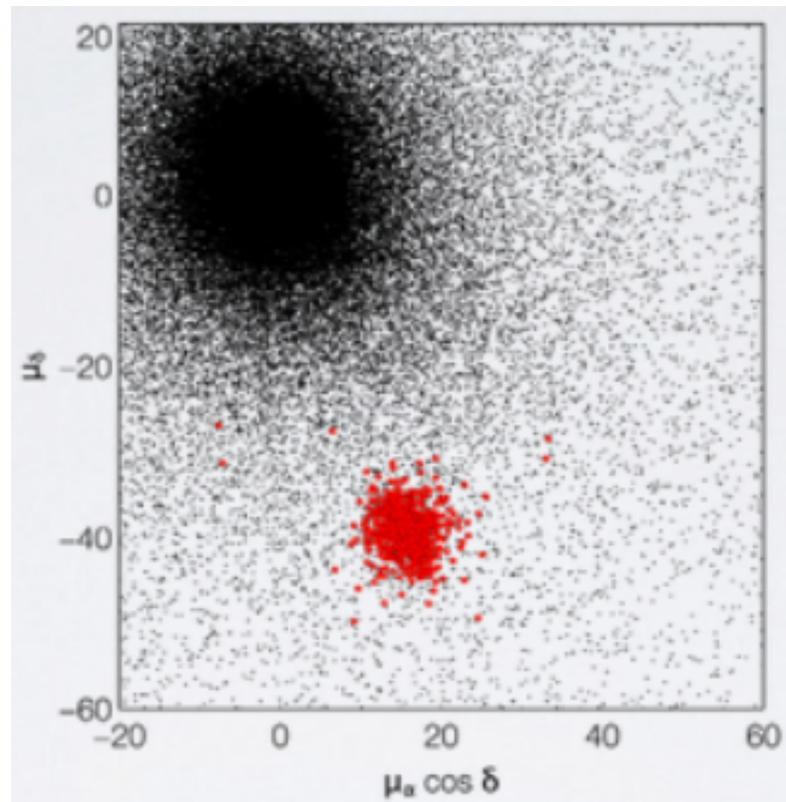
- Full treatment of uncertainties, censored data
- Use of empirical sequences (using principal curve analysis)
- Coherent and homogeneous membership probabilities
- Scalable to more dimensions: V_{rad}, variability, chemistry, rotation …

Example on the Pleiades

Proper motion study from the DANCe project:

- 15 yr time baseline using all archival data (9 instruments)
- Very accurate proper motion: <1mas/yr down to i~23 (Bouy et al. 2013)



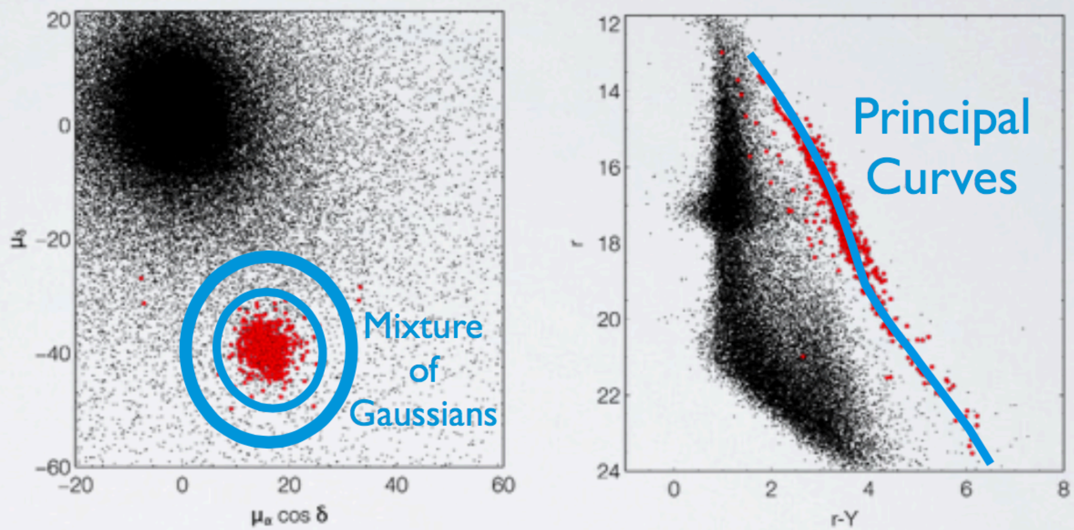


Example of the Pleiades

1

Best set of:
- luminosities
+
- colors

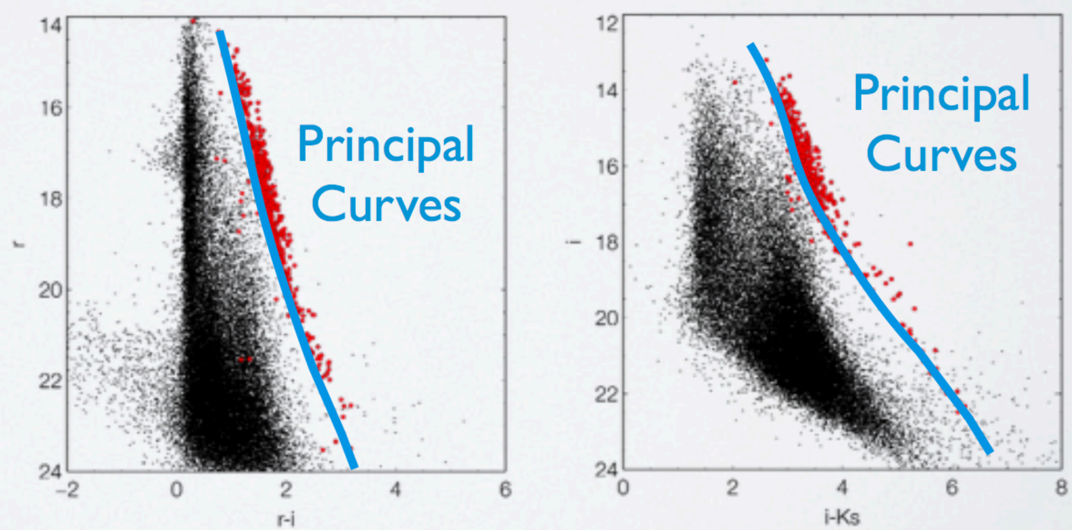
is found using **Bayesian Information Criterion**



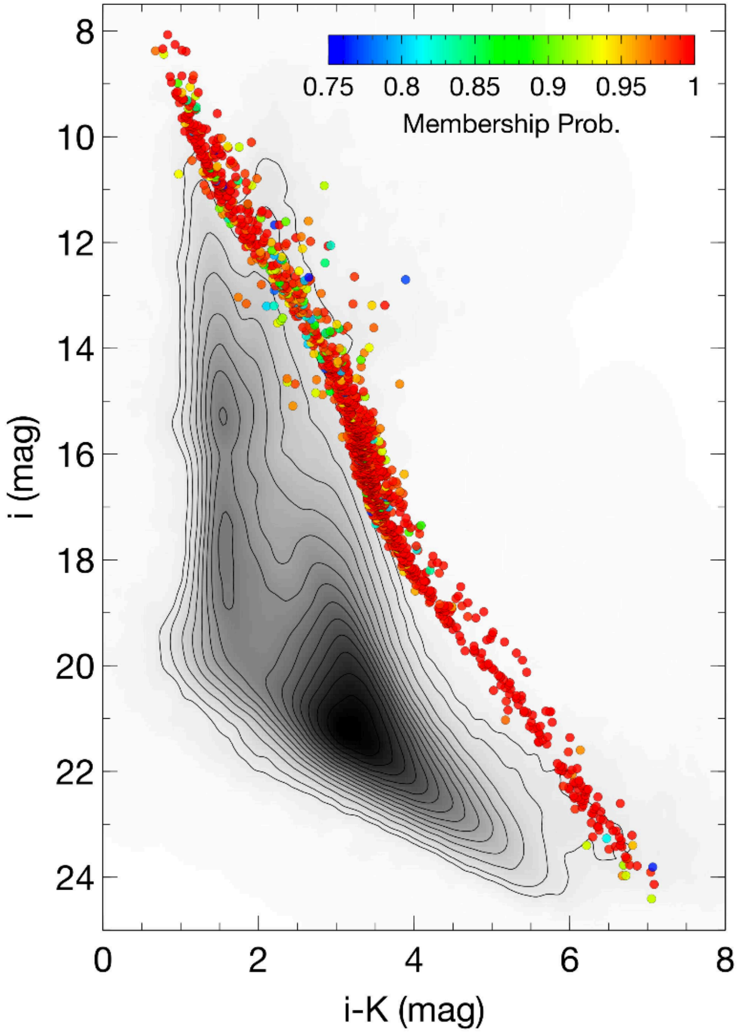
(Sarro et al. 2014)

2

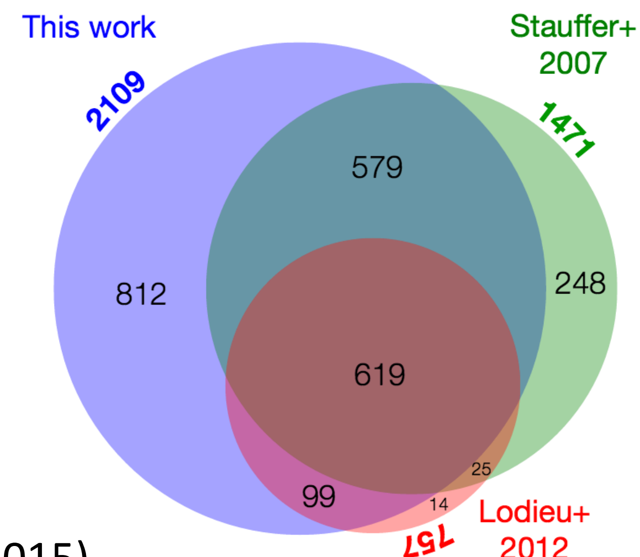
Fit Locus in astrometric + photometric space



Example of the Pleiades



~2100 members
50% more than previous studies even though the Pleiades has been intensively studied !!



(DANCe project; Bouy et al. 2015)

IMF

Introduction

- Initial Mass Function: relative number of stars at birth as a function of their mass

→ Product of star formation process

→ Structure and evolution of galaxies

→ Evolution of clusters

Recent reviews: Bastian et al. 2010, Jeffries 2012, Kroupa 2012, Luhman 2012, Offner et al. 2014

Usual functional forms

- Power-law: $\chi(m) = dN/dm \propto m^{-\alpha}$

Or $\Phi(\log m) = dN/d\log m \propto m^{-\Gamma}$ with $\alpha = \Gamma+1$

Salpeter 1955: $\alpha = 2.35$ ($\Gamma = 1.35$)

Kroupa 2001: segmented power-law

- Log-normal: $\phi(m) \sim e^{-\frac{(\log m - \log m_c)^2}{2\sigma^2}}$ Miller & Scalo 79

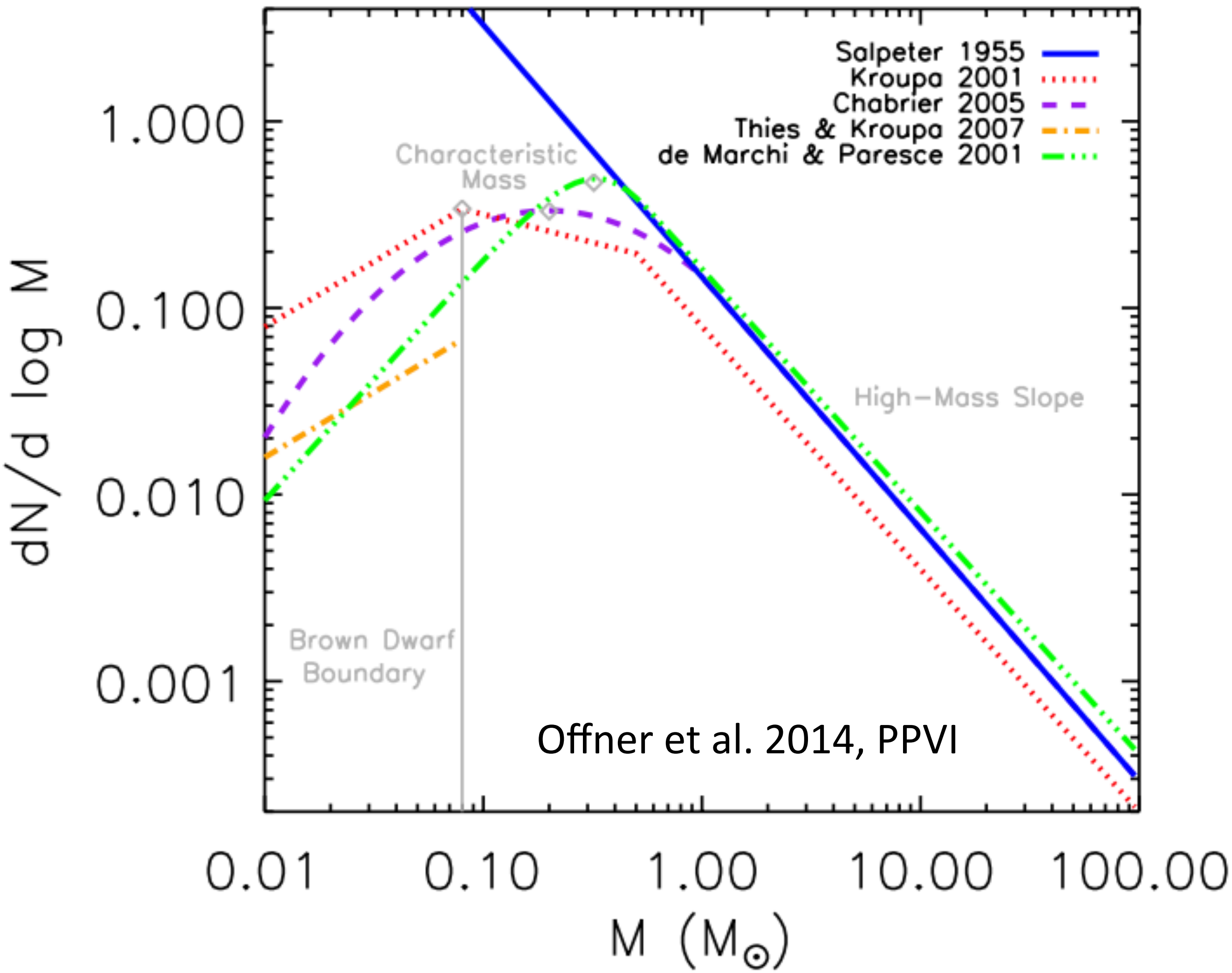
Chabrier 2005: log-normal + Salpeter above 1Msun

- Tapered power-law: $\chi(m) = \frac{dN}{dm} \propto m^{-\alpha}\left[1 - e^{(-m/m_p)^{\beta}}\right]$

De Marchi et al. 2005

See also e.g. Cartwright & Whitworth 2012, Maschberger 2013, Basu et al. 2015

Usual functional forms



Offner et al. 2014, PPVI

Methodology

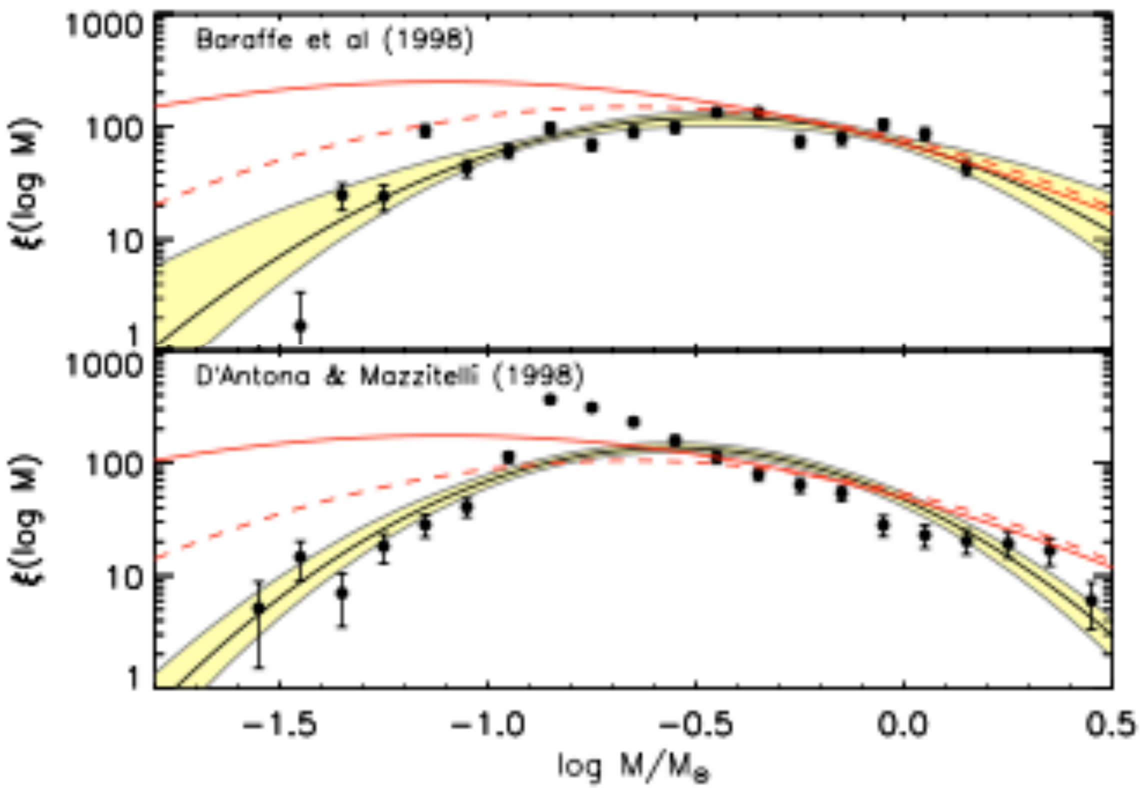
1. Determination of the luminosity function (LF)
   - Take your favorite cluster member sample
   - Assess contamination and completeness
   - Correct for extinction if necessary
2. Convert LF to Present Day Mass Function (PDMF)
   - Depends on distance, age, extinction law
   - Convert spectral type to temperature
   - Convert magnitudes to luminosity (with distance and BC correction)
   - Convert Teff and/or Luminosity (HR diagram) to mass
3. Convert PDMF to IMF
   - Correct for star formation history, stellar evolution, dynamical evolution
   - (Correct for binarity)

Observational uncertainties on the luminosity function (LF)

- **Contamination** of photometric surveys by field stars (dwarfs, giants) and/or extragalactic objects (galaxies, quasars)
- **Uncompleteness** of magnitude- and/or volume-limited surveys, in particular when the extinction is spatially variable
- **Biases** (Malmquist, mass segregation) and **low number statistics** (Poisson, binning)
- **Multiplicity**, crowding, missed objects (e.g. near bright stars)

Theoretical uncertainties on the present day mass function (PDMF)

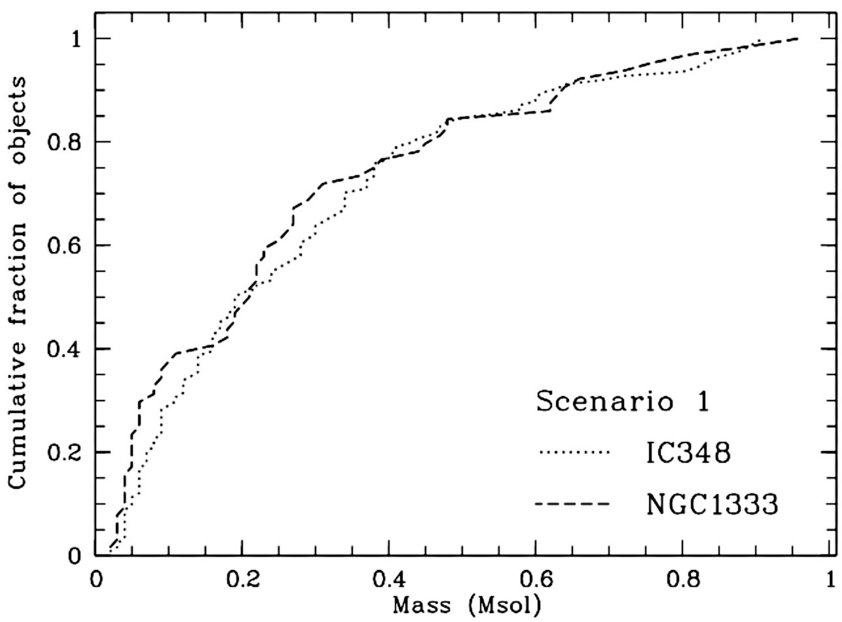
- **Mass-luminosity relationship**: LF→PDMF
  - Model-dependent (e.g. ONC, Da Rio et al.2012)

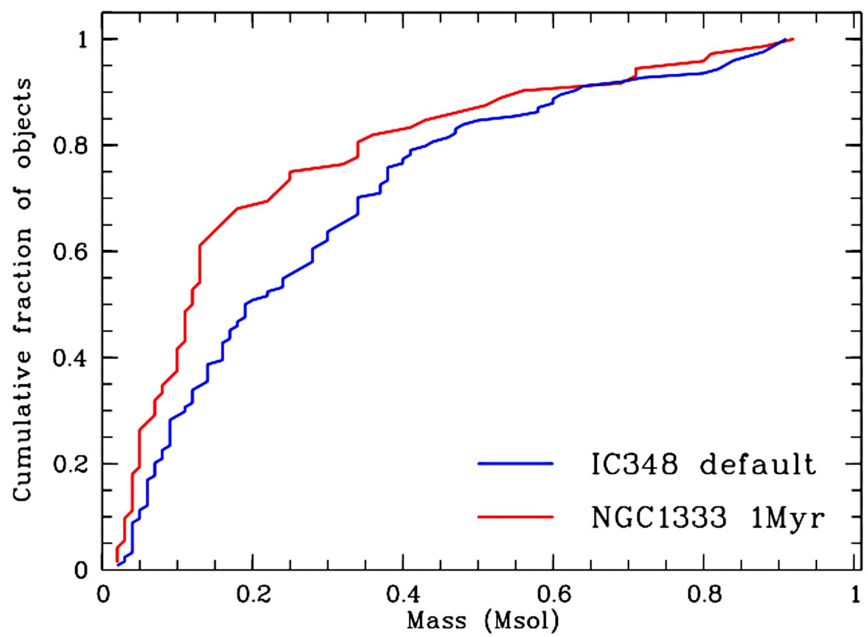


Theoretical uncertainties on the present day mass function (PDMF)

- **Mass-luminosity relationship**: LF→PDMF
  - Model-dependent (e.g. ONC, Da Rio et al.2012)
  - Age and distance dependent (e.g. Scholz et al. 2013)

Default parameters for IC348 & NGC1333: 3 Myr, 300pc

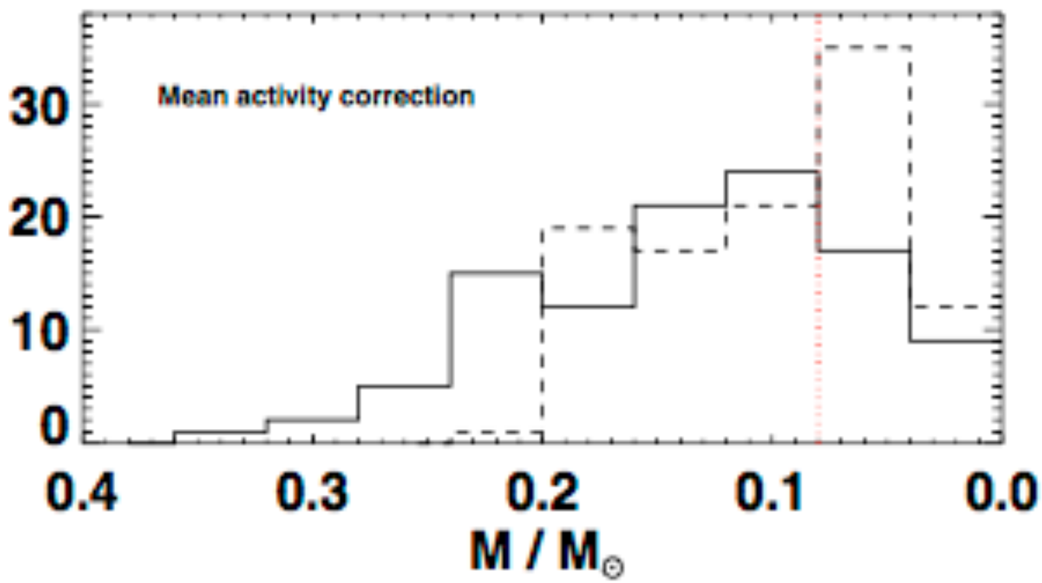




Theoretical uncertainties on the present day mass function (PDMF)

- **Rotation** can inflate the radius and and affect the luminosity
- **Magnetic activity** (chromosphere, cool spots) inflates the radius and reduces T_{eff} (hence, mass estimate) of low mass stars (e.g. Mohanty et al. 2009, Stassun et al. 2012, 2014)

UpperSco (Stassun et al. 2014)



Theoretical uncertainties on the present day mass function (PDMF)

- **Accretion history** may affect the early evolution (<10Myr) of young stars (cf. Baraffe et al. 2009)

$$L_{\rm add} = \alpha\epsilon\frac{GM\dot{M}}{R};\;\; L_{\rm acc} = \epsilon(1-\alpha)\frac{GM\dot{M}}{R}.$$

  - $\alpha \ll 1$: most accretion energy is radiated away
  - $\alpha = 1$: accretion energy is absorbed by the protostar/BD

Models suggest that accretion may affect the early evolution of low-mass stars and BDs prior to 10 Myr **only if $\alpha \ll 1$**

Different luminosity → different mass estimate

Theoretical uncertainties on the IMF (PDMF → IMF)

- Star formation rate assumption to correct the field PDMF
- Stellar evolution: death of high mass stars
- Dynamical evolution due to 2-body interaction in clusters:

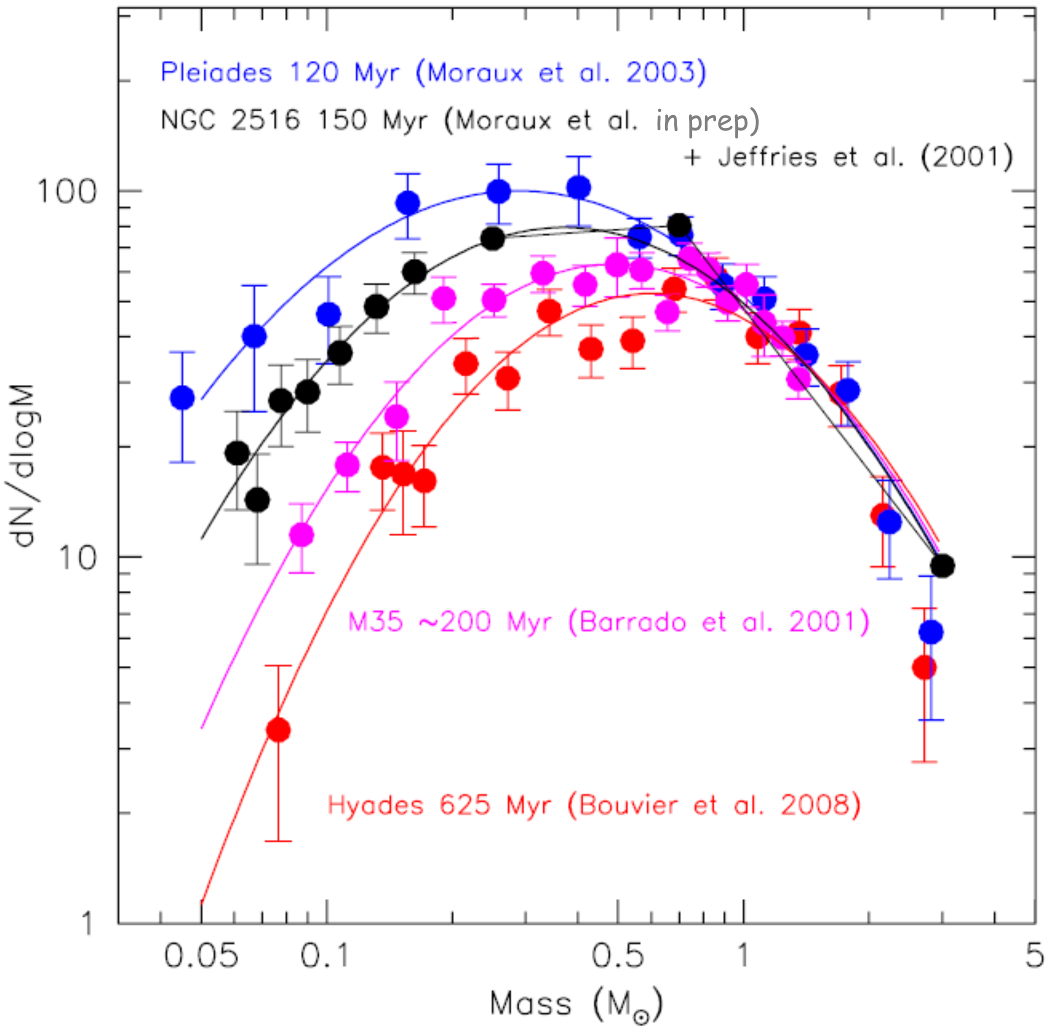
  → Mass segregation:

  Deficit of low mass objects in cluster center compared to peripheric area (to be accounted for in the cluster MF)

  → Preferential loss of low mass members:

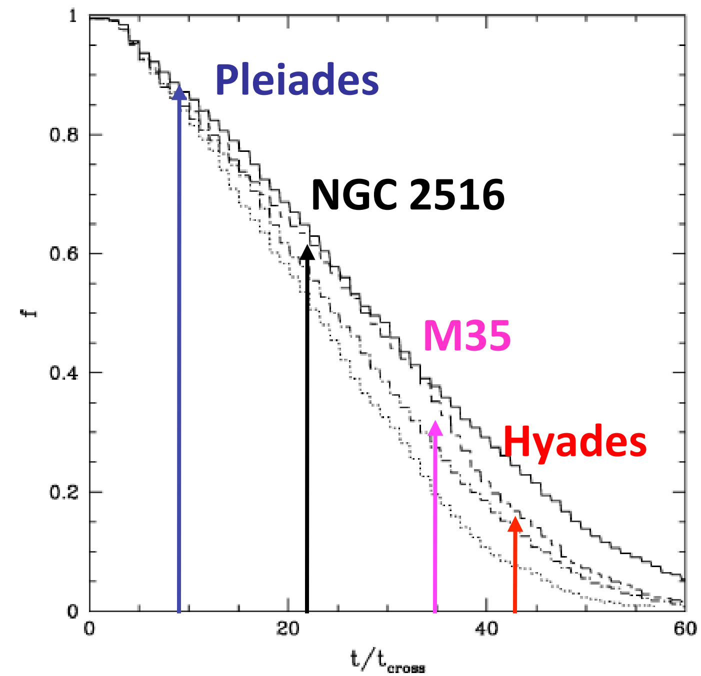
  Deficit of low mass stars and BDs in dynamically relaxed clusters (age > $t_{dyn} = (N/8\ln N)\, R/\sigma_v$) : characteristic mass shifted to higher value

Evolution of the cluster MF



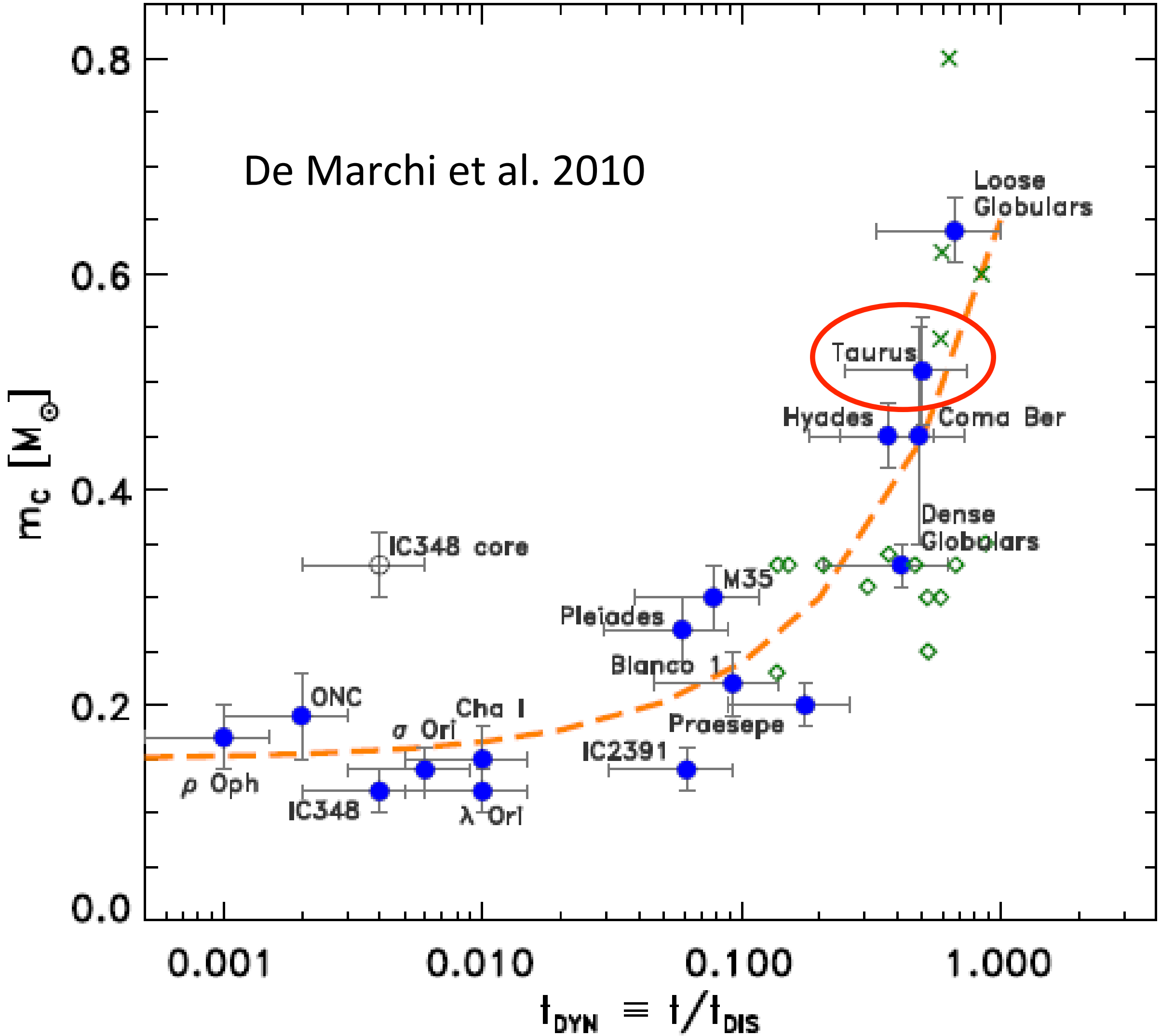
Dynamical evaporation of VLM stars and BD

Fraction of BD vs. time (Nbody models)



Adams et al. 2002

MF peak mass as a function of time

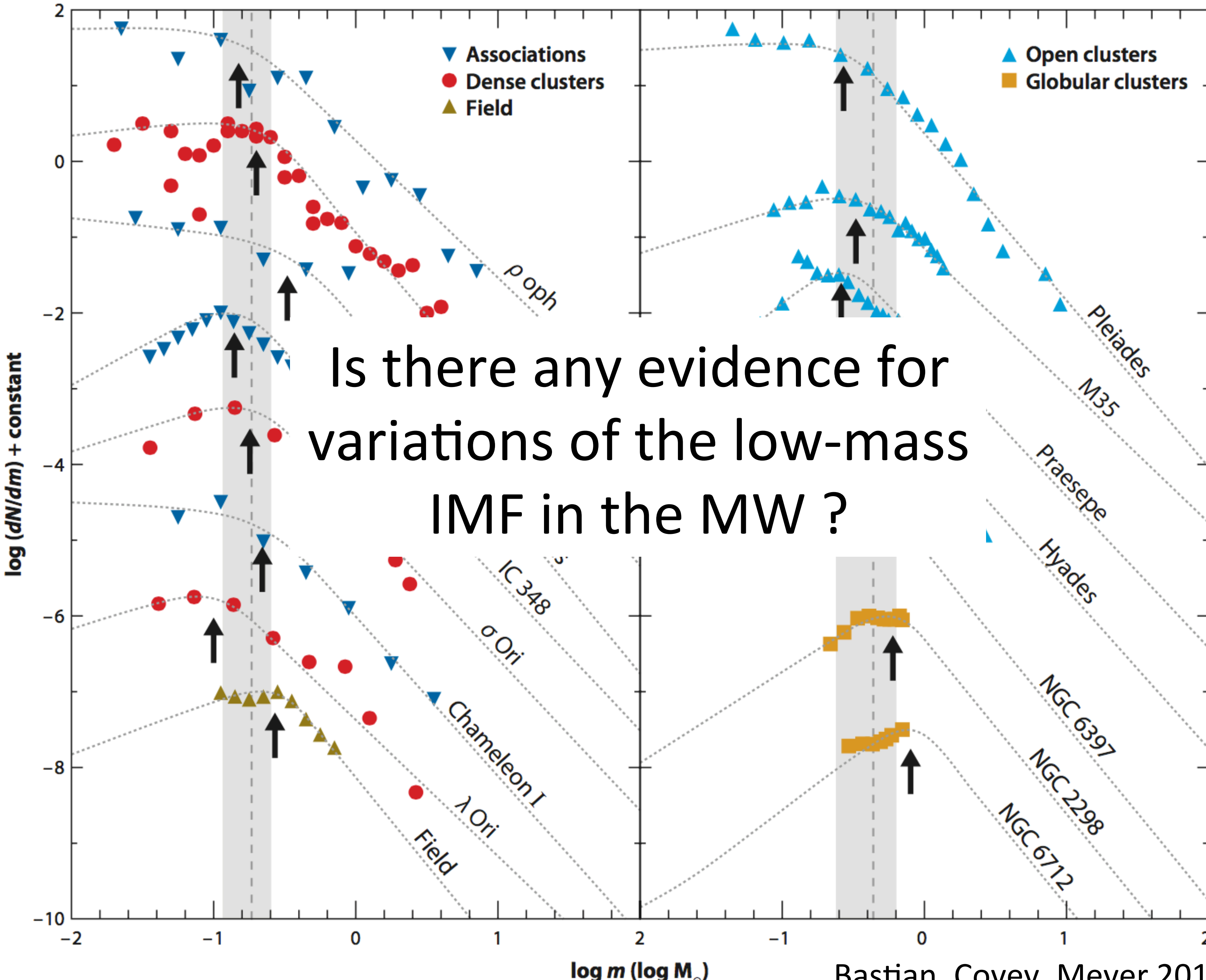


What matters is the cluster age **relative to its dynamical time**

Dense clusters evolve fast

as well as low-N clusters (N~10)

$t_{rlx} = (N/8 \ln N)\, R/\sigma_v$



Is there any evidence for variations of the low-mass IMF in the MW ?

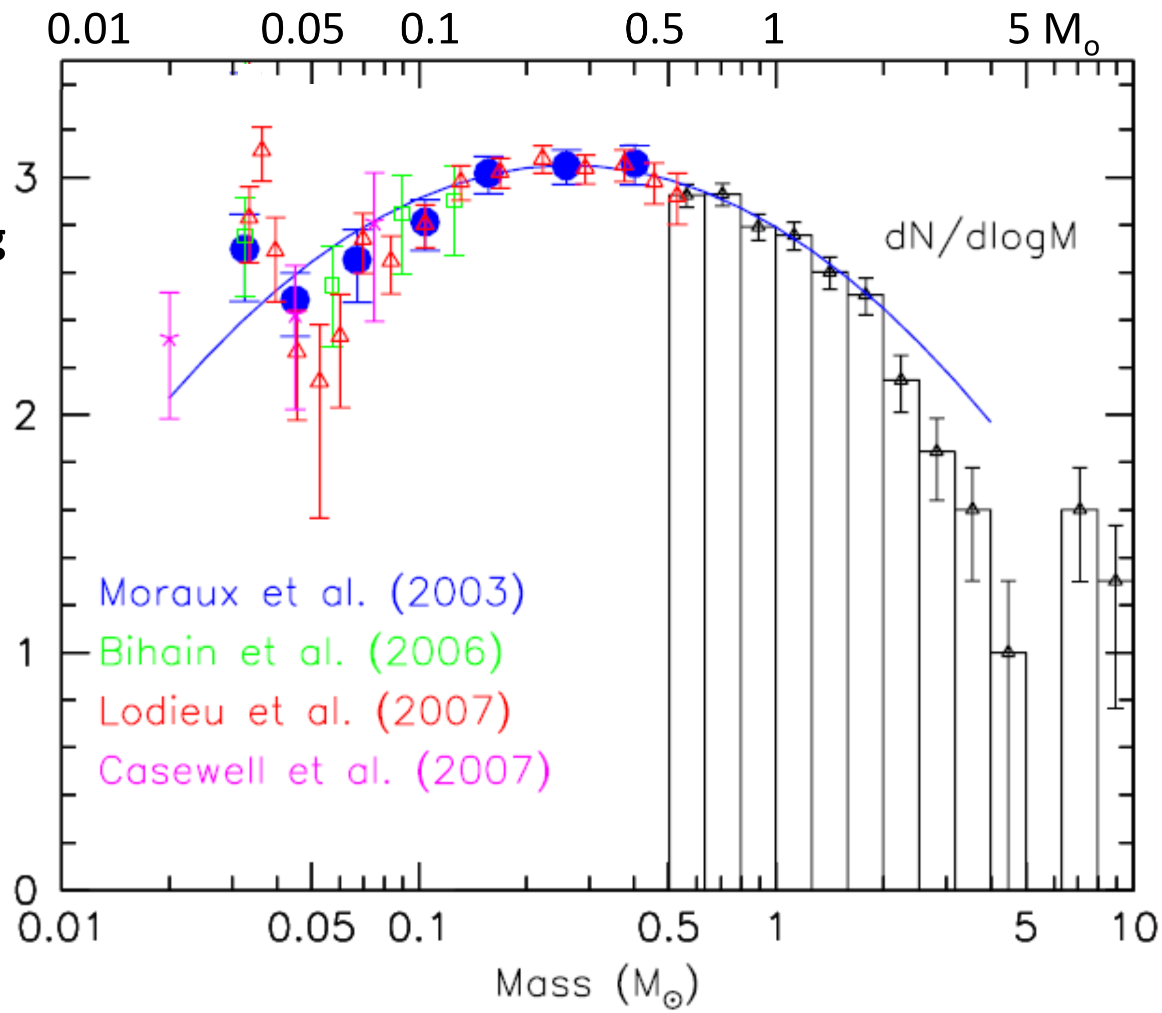
Bastian, Covey, Meyer 2010

The Pleiades : a benchmark cluster

Distance = 120-130 pc

Lithium age = 125 +/- 8 Myr
(Stauffer et al. 1998)

Star / BD boundary @ I ~ 17.8 mag
(Bouvier et al. 1998)



System MF
(unresolved binaries)

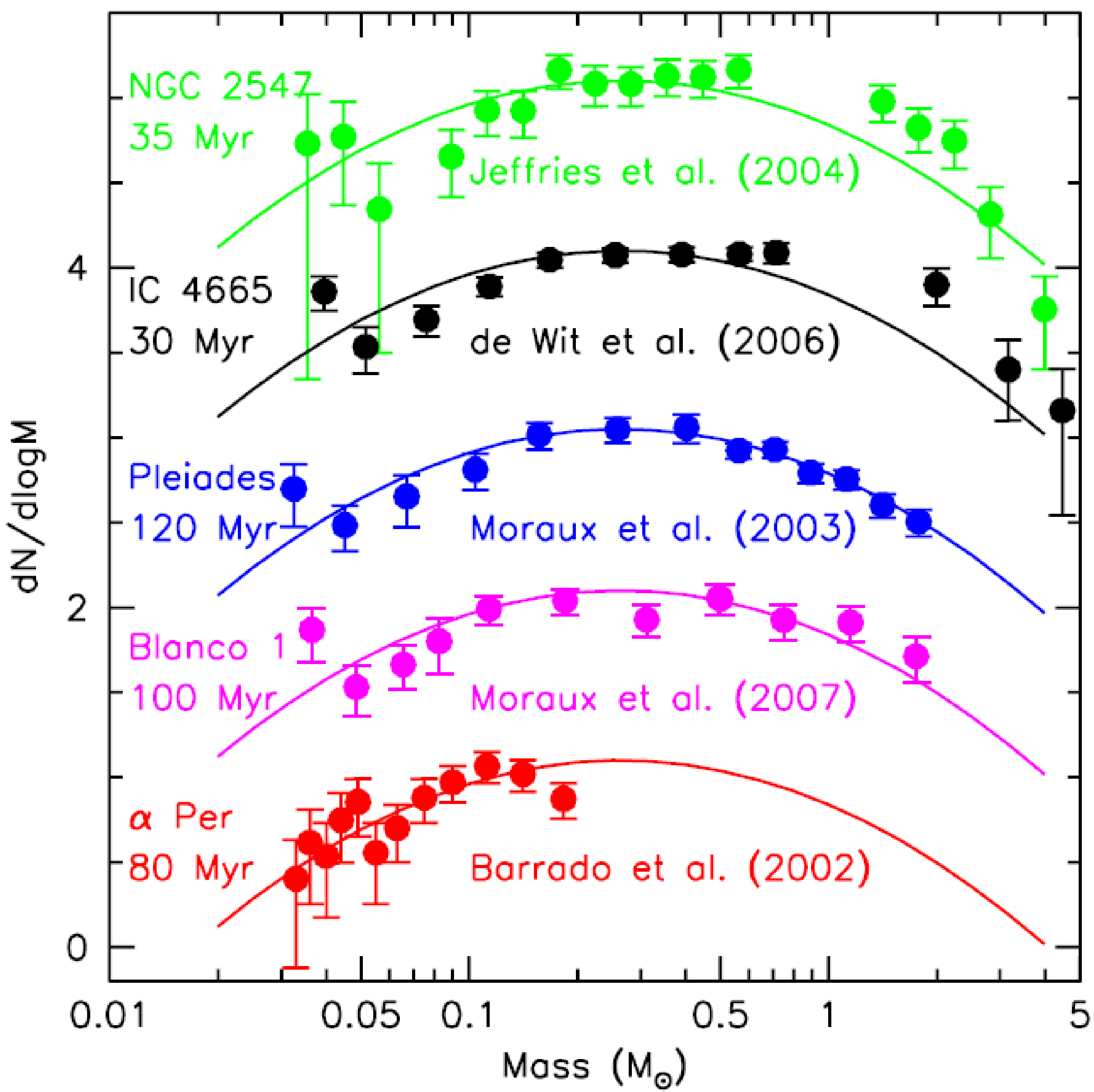
Lognormal fit :

m_c = 0.25 Mo
σ = 0.52

$$\phi(m) \sim e^{-\frac{(\log m - \log m_c)^2}{2\sigma^2}}$$

(See also Lodieu et al. 2012 and Bouy et al. 2015)

Young Open Cluster PDMF



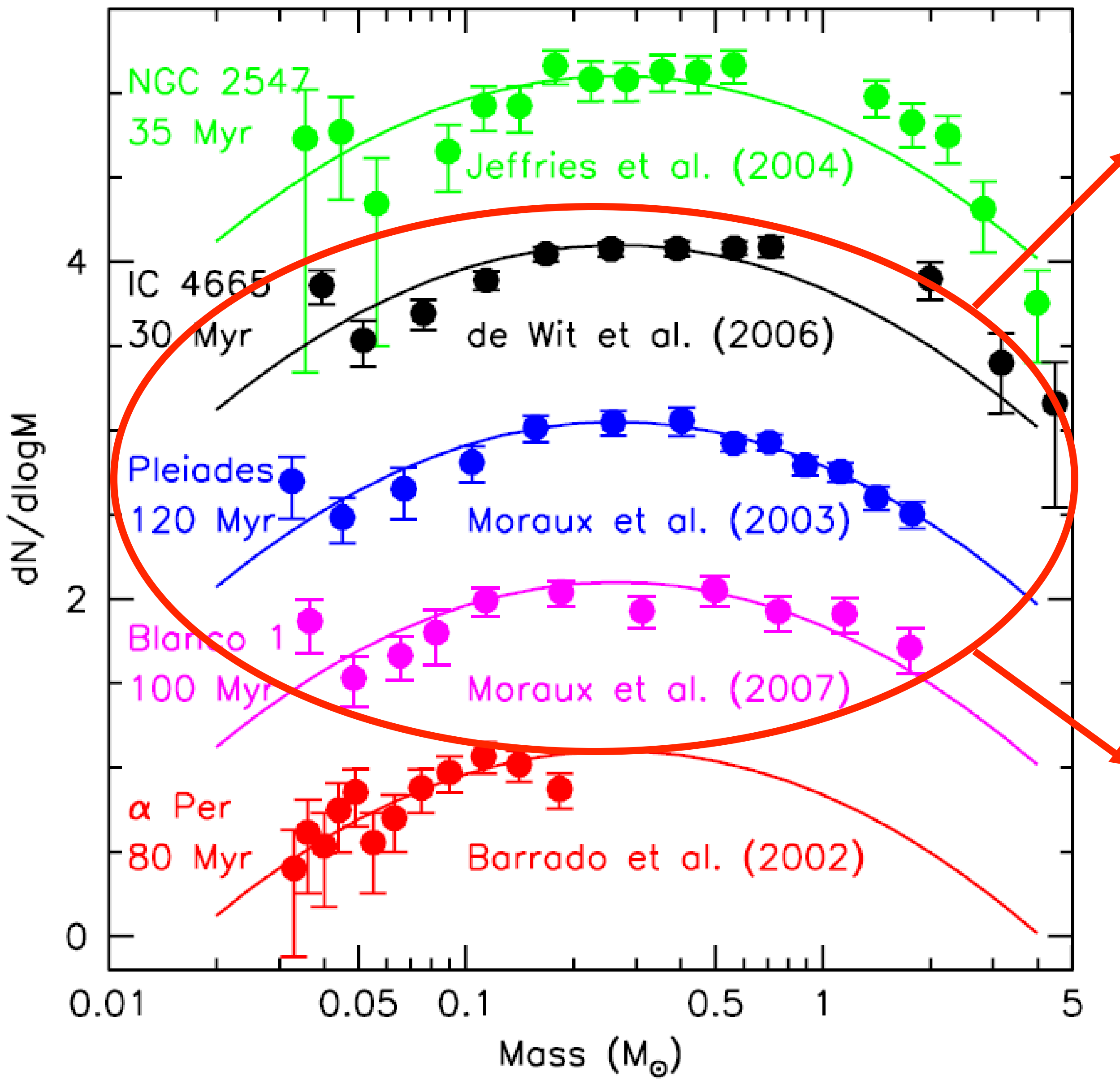
System MF
(unresolved binaries)

All observed YOC MFs consistent within errors with Pleiades lognormal fit in the mass range **~0.03-2.0 Mo**

$$\phi(m) \sim e^{-\frac{(\log m - \log m_c)^2}{2\sigma^2}}$$

m_c ~ 0.25 Mo
σ ~ 0.5-0.6

Combining the YOC MFs



System MF
(unresolved binaries)

Same group

Same instrument

Same analysis

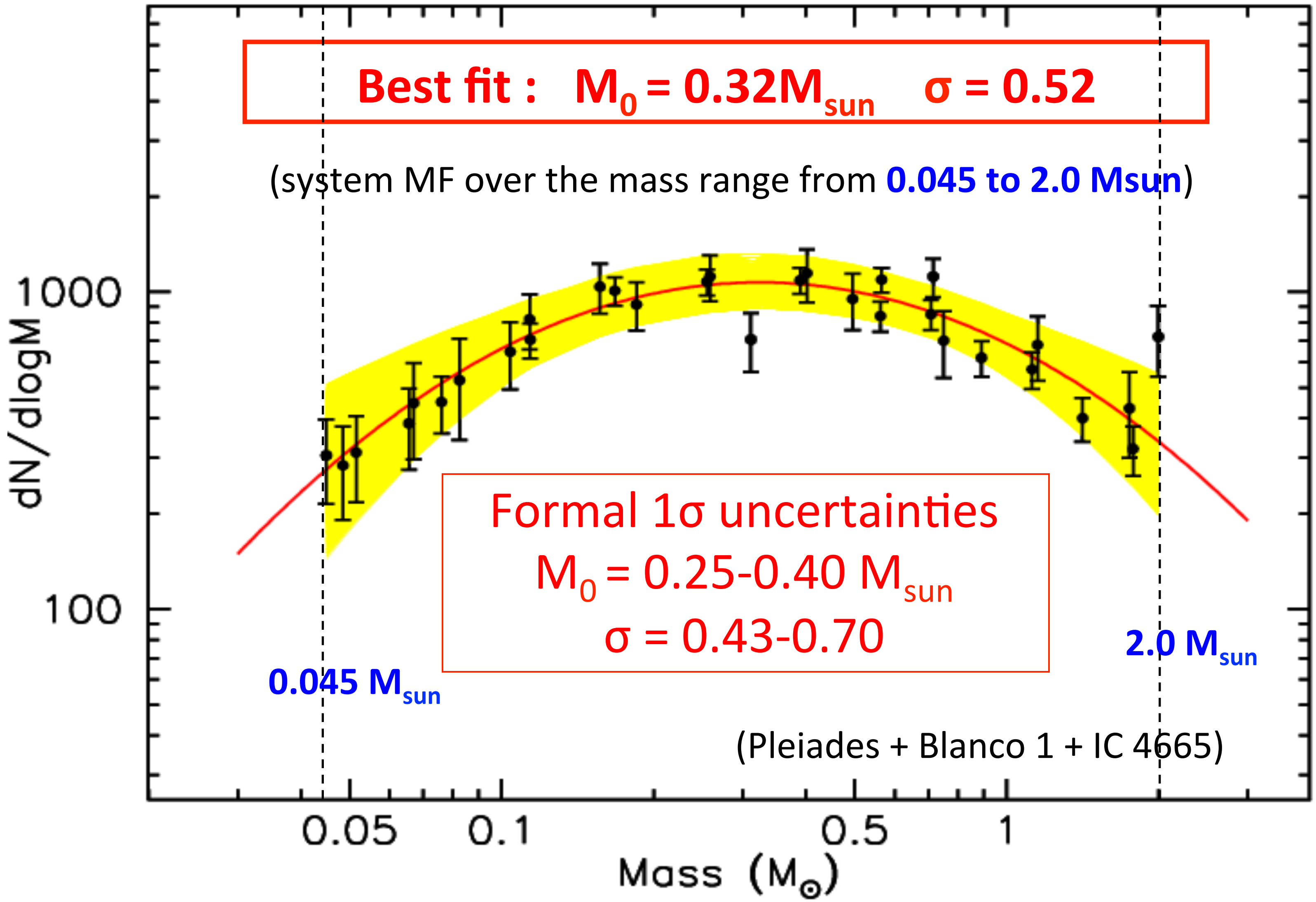
Same corrections (e.g. mass segregation)

Same models for M-L relationship

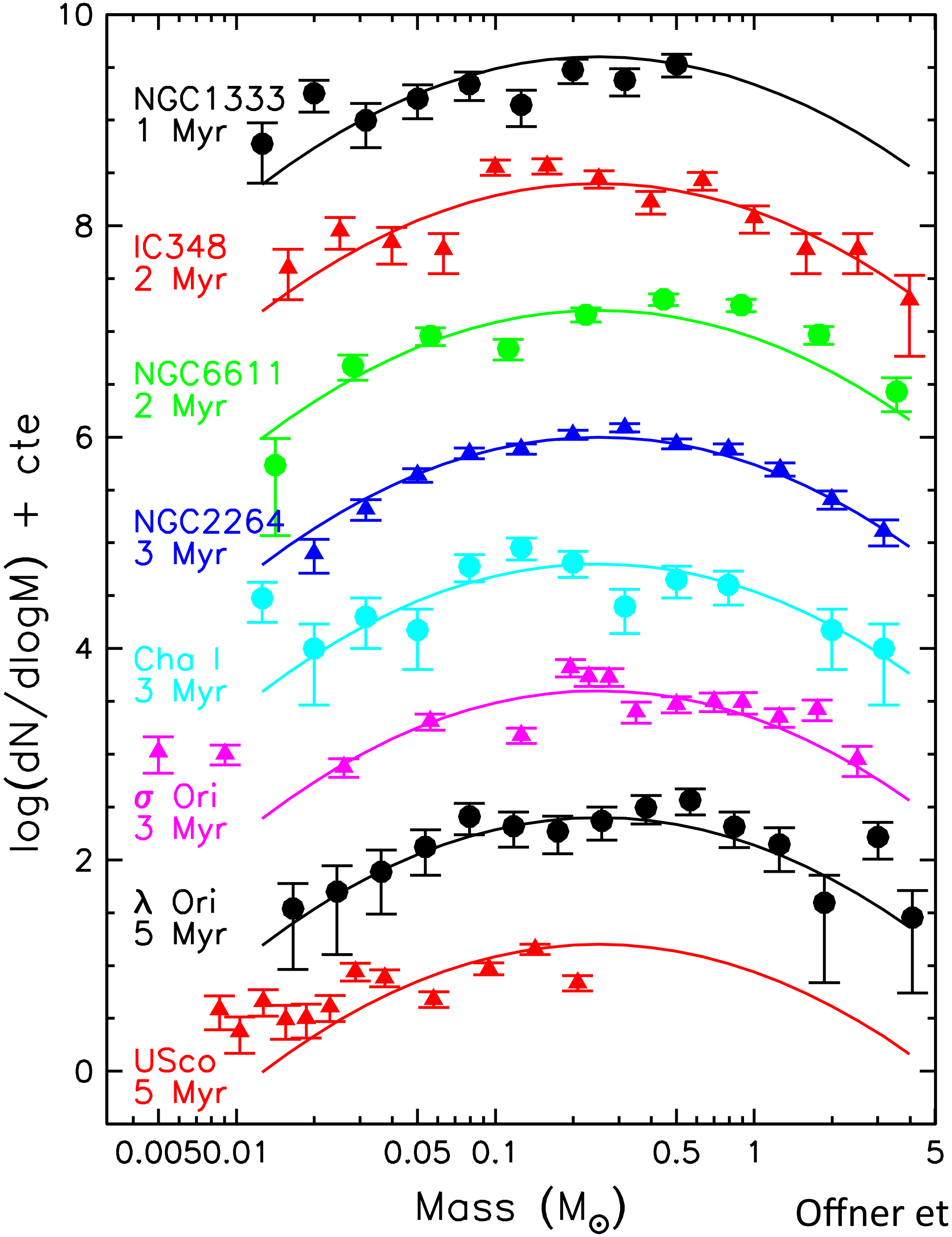
(Same referee ?)

Allows the derivation of an internally-consistent MF for young open clusters

A log-normal fit to the YOC MF



SFRs MF



System MF
(unresolved binaries)

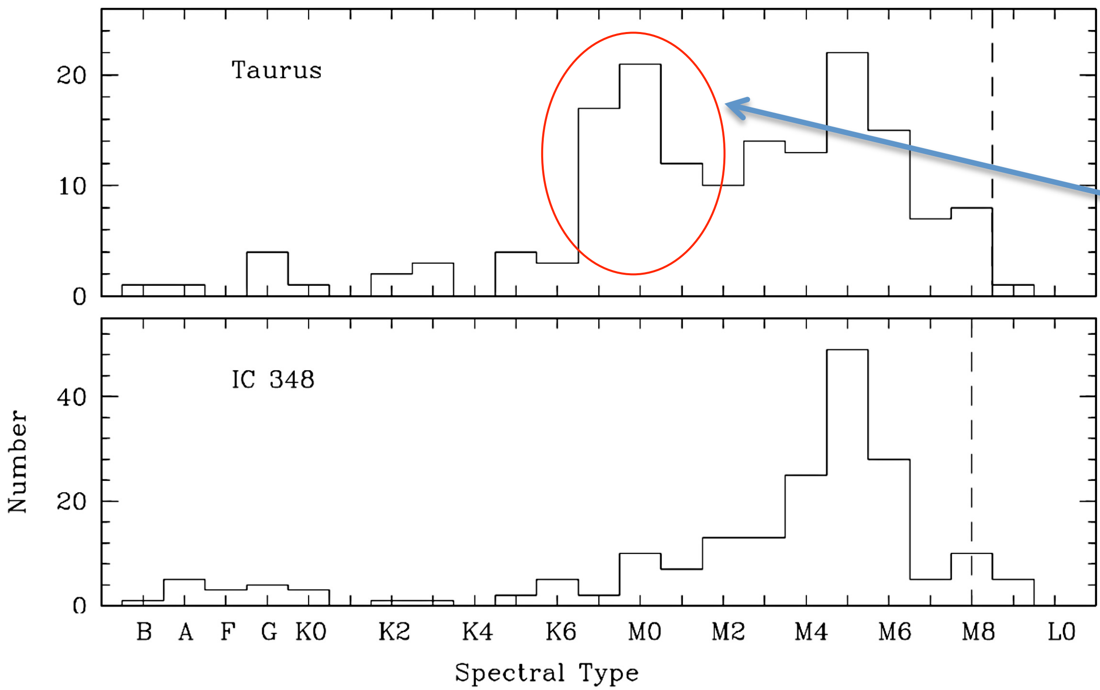
Similar MF for 0.03 – 3 Msun
(consistent with the Pleiades given the uncertainties)

m_c ~ 0.25 Mo
σ ~ 0.5-0.6

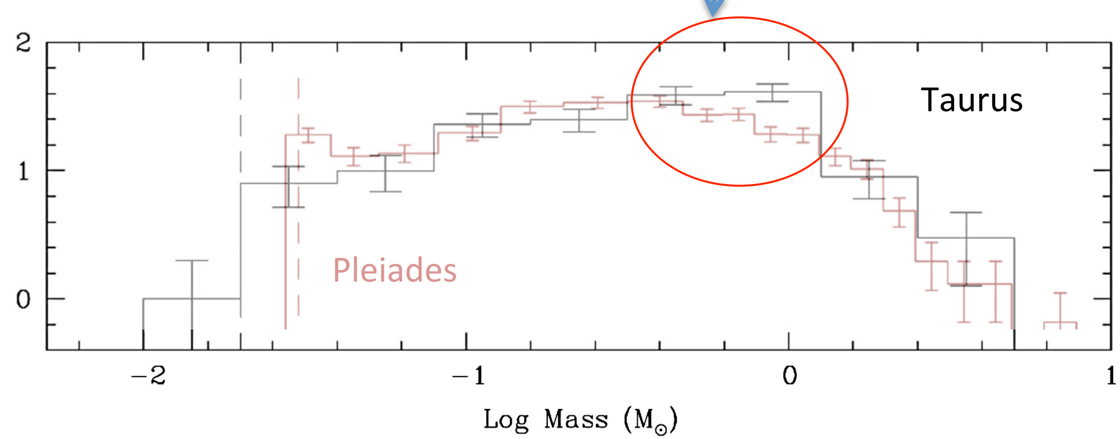
→ A universal IMF down to 0.03 Msun ?

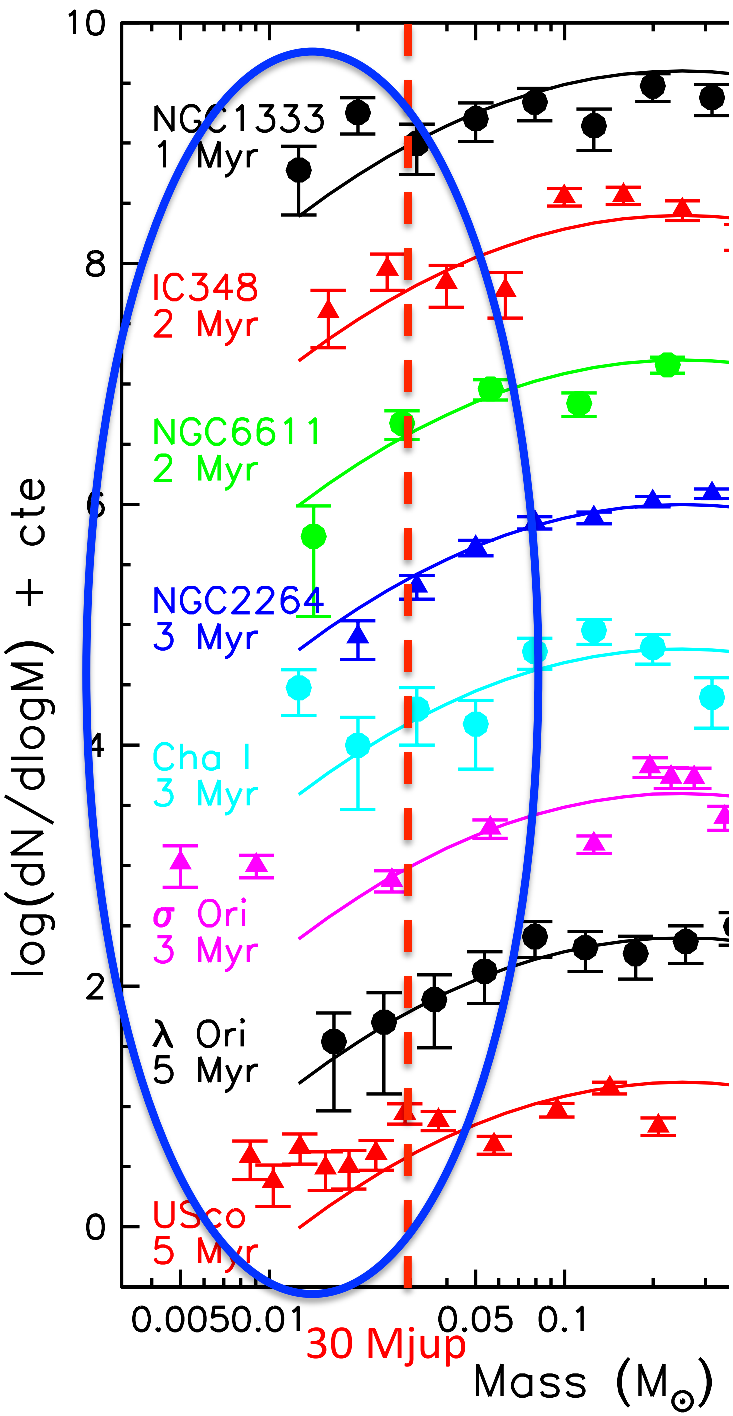
Offner et al. 2014, PPVI

Taurus



Excess of late-K, early-M stars (adapted from Luhman 2012)





The lower MF

System MF
(unresolved binaries)

Hint for variations at lower masses (<30 M_{jup}) ?

<u>Issues:</u>

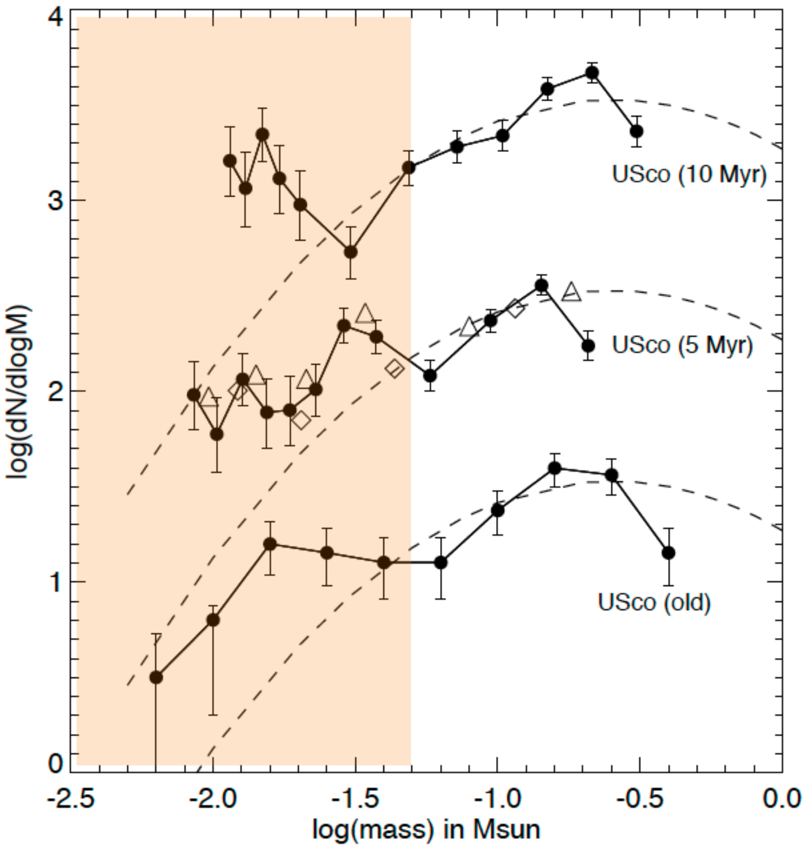
Residual contamination ?
Incompleteness?
Mass segregation ?

Uncertain mass-luminosity relationship at very low masses and young ages

Offner et al. 2014, PPVI

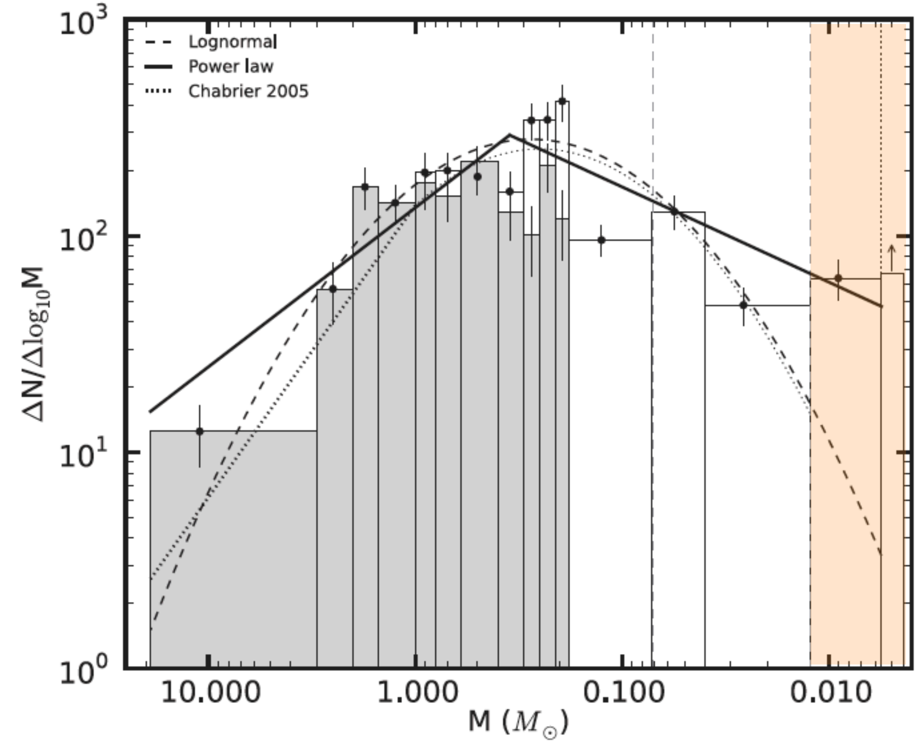
Hint for variations below 0.03Msun?

Upper Sco



Lodieu 2013, MNRAS, 431, 3222

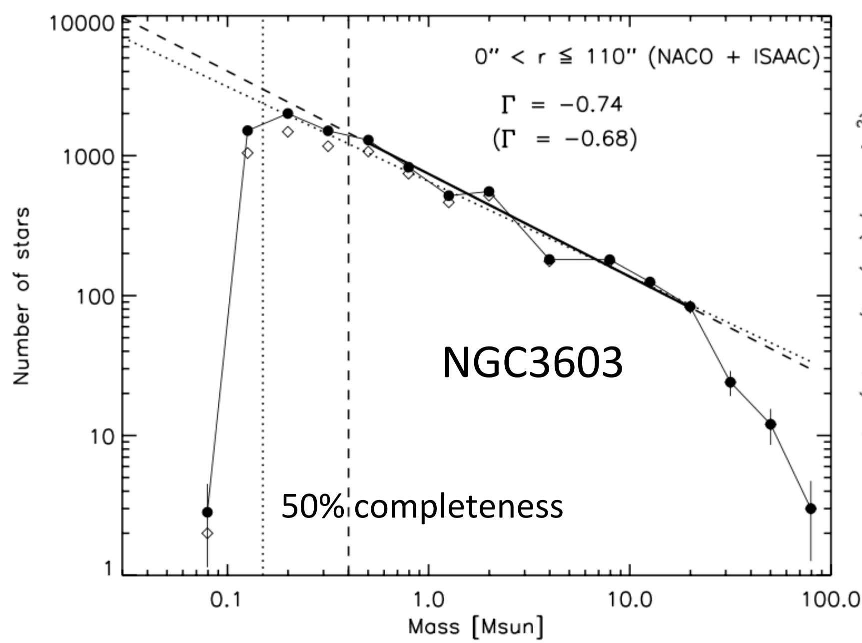
σ Ori

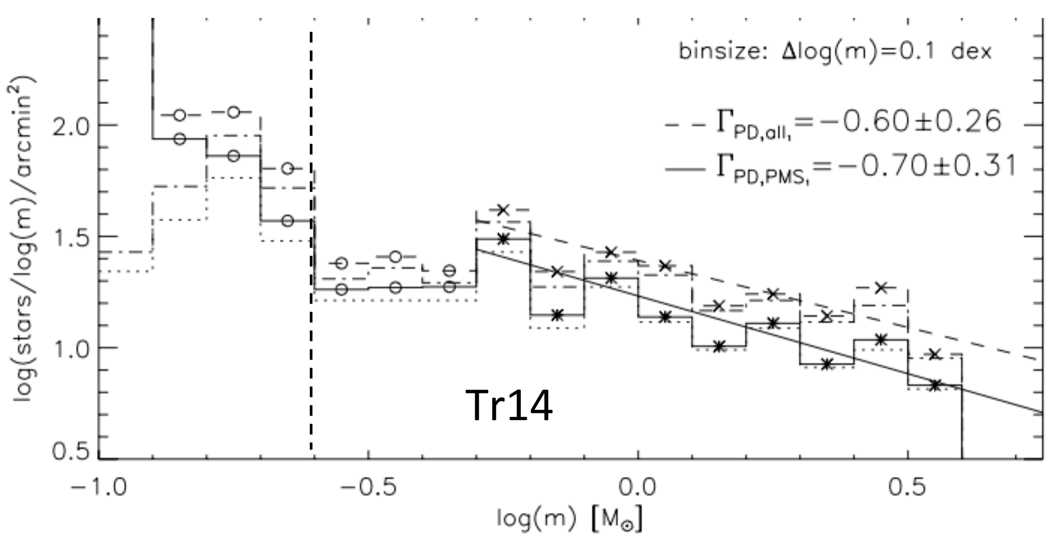


Peña Ramírez et al. 2012, ApJ, 754, 30

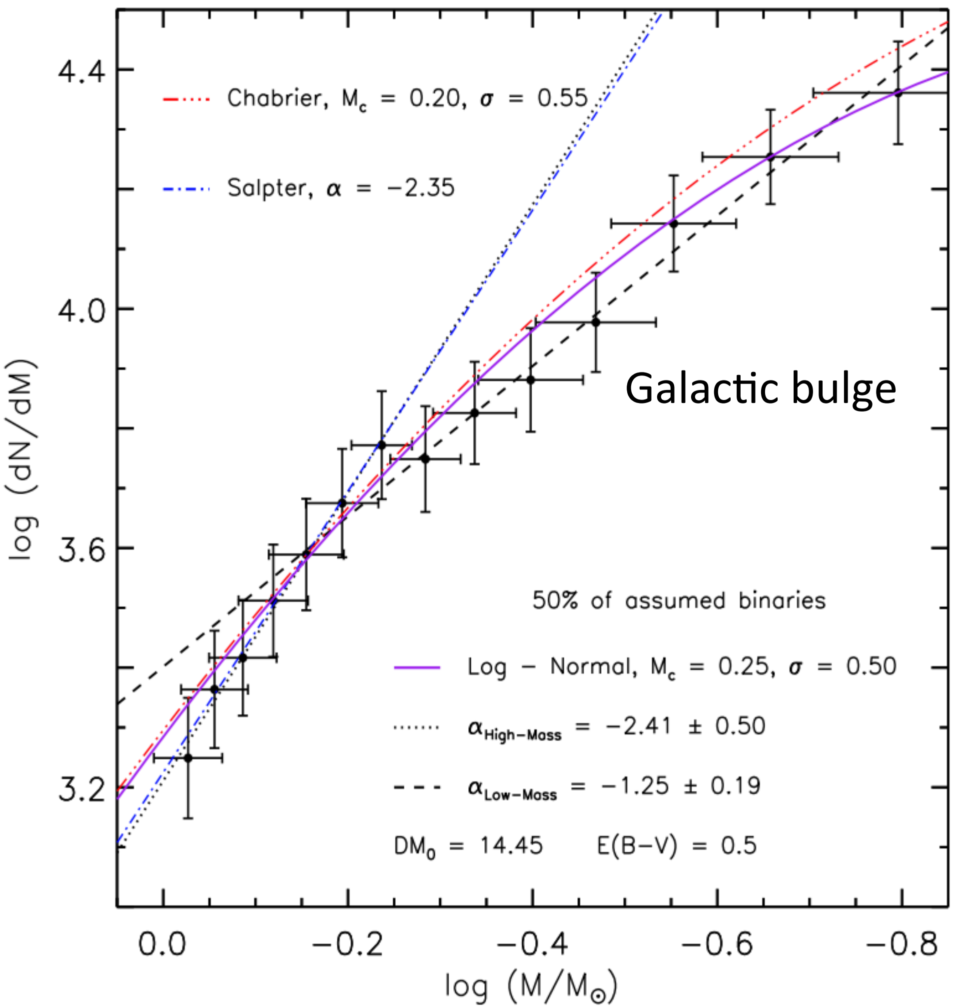
Young massive clusters

- Arches, Quintuplet, Westerlund 1: MF determined for m > 1Msun (e.g. Habibi et al. 2012, Lim et al. 2013, Hussman et al. 2012)
- NGC3603: no turnover before 0.4Msun (Γ ~ 0.7 – 0.9 ; Harayama et al. 2008, Stolte et al. 2006)
- Tr14: turnover at 0.5Msun (Rochau et al. 2011)





Galactic bulge and gobular clusters



Calamida et al. 2015

- Bulge MF consistent with disk (Calamida et al. 2015)
- Similar results for GC (e.g. NGC2298, NGC6712, De Marchi et al. 2007)
- But very small mass range: 0.2-0.8 Msun

Summary on the low mass IMF

- Little evidence for cluster-to-cluster variations (except maybe for Taurus) over the mass range **0.03-1.0 Msun**:

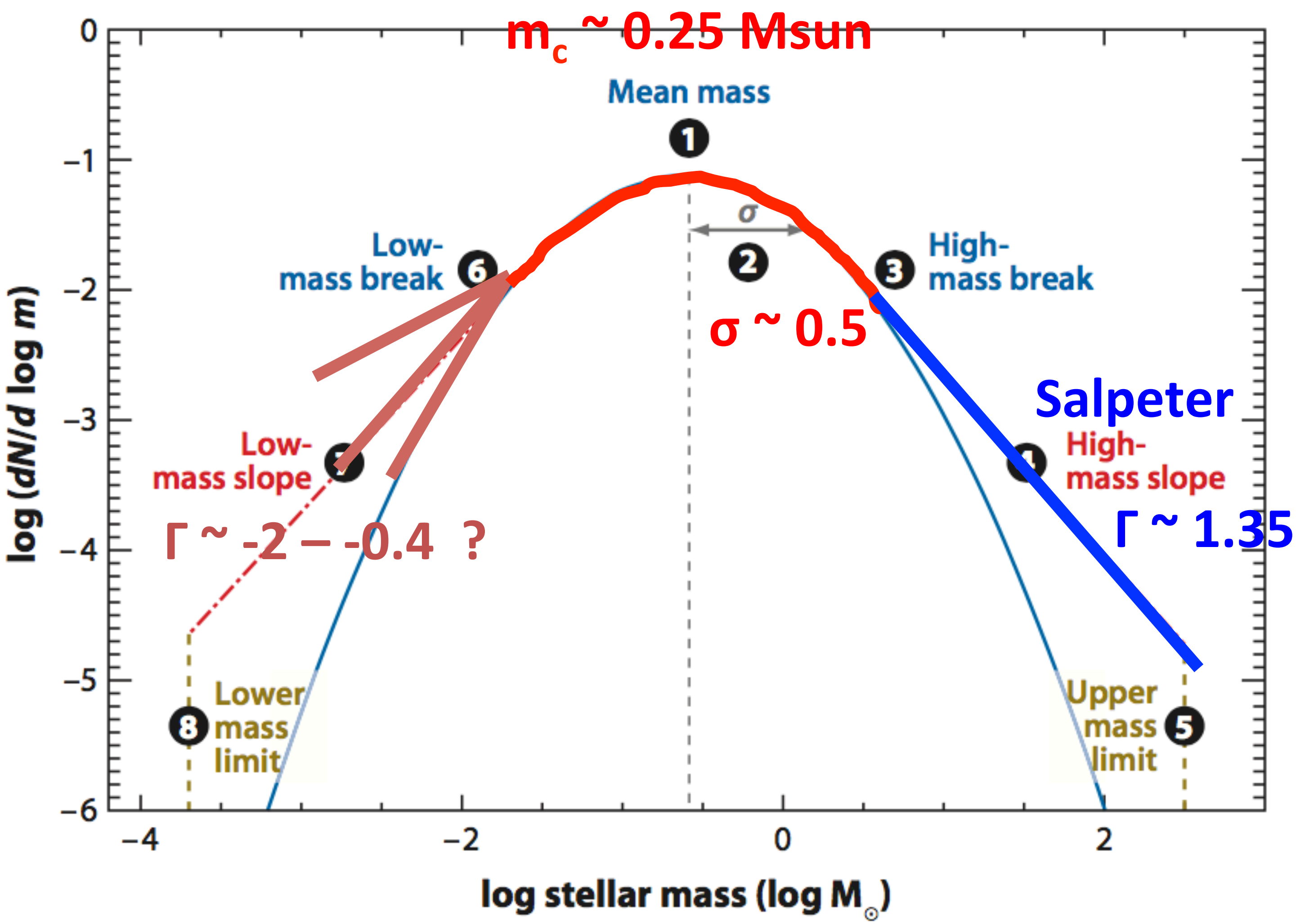
Lognormal mass distribution with m_c~0.25Msun, σ~0.5

- Consistent with the field MF **down to 0.1 Msun**, and also perhaps down to 0.03 Msun ?
- Galactic bulge and GC MF also similar for 0.2-0.8 Msun → little effect of metallicity ?
- Need more data in young massive clusters (ELTs)

→**A universal IMF at least down to 0.03 Msun ?**

- Variations below 0.03 Msun ? Low-mass cut-off ?

adapted from Bastian, Covey, Meyer 2010



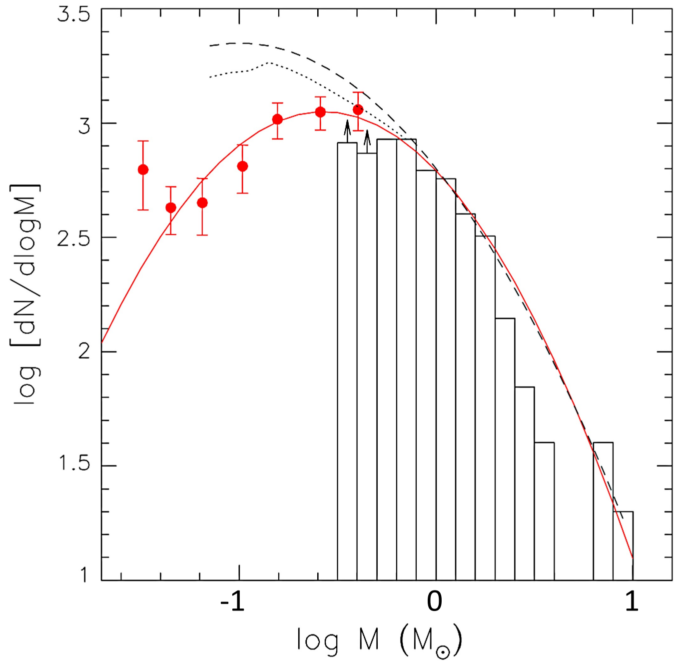
Multiplicity

Multiplicity frequency

- Outcome of star formation process
- Affect the single star IMF estimate at low masses

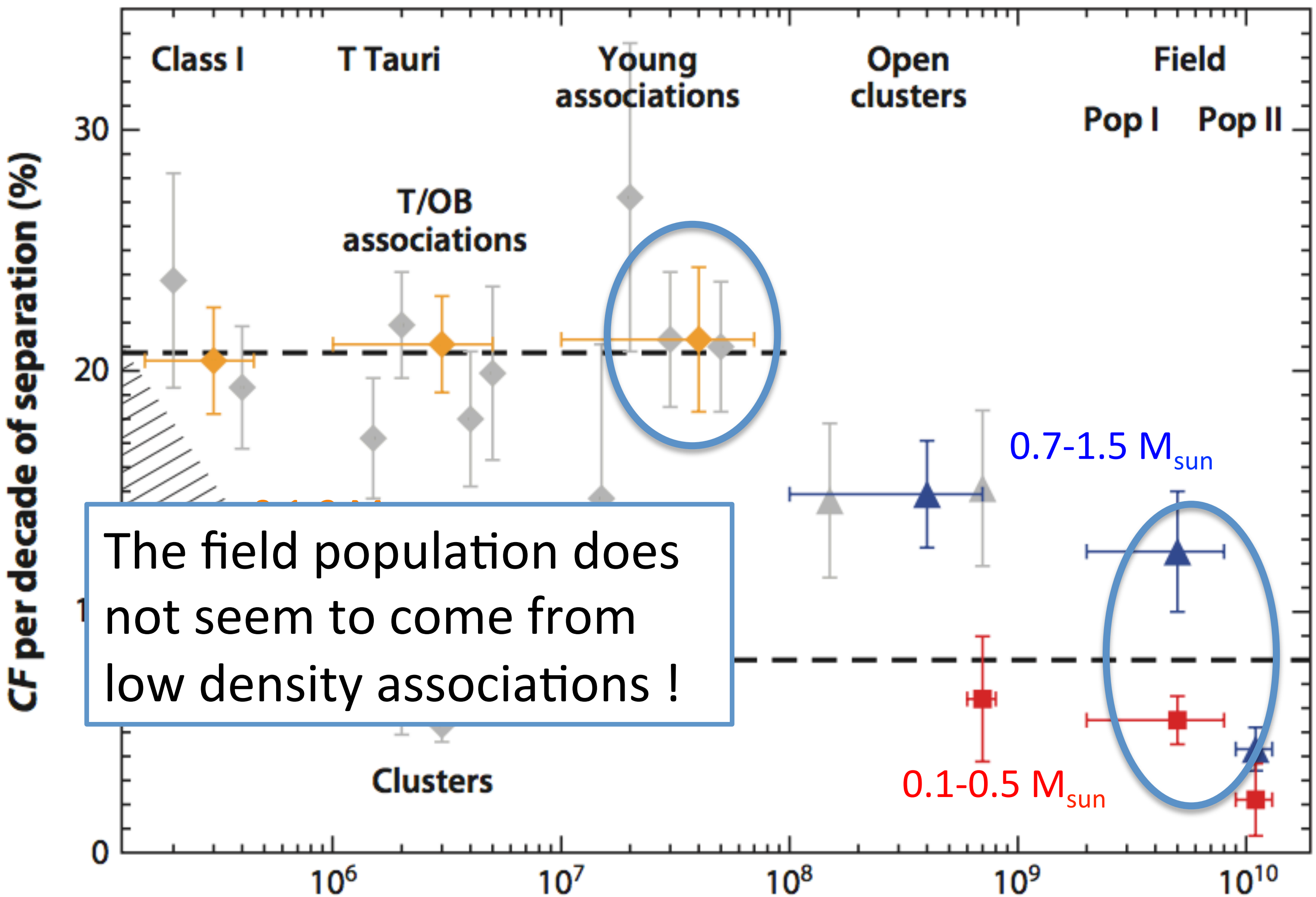
- If the IMF is universal,

does it imply the multiplicity frequency is also universal ?



Moraux et al. (2003)

Visual companion frequency (10-2000AU)



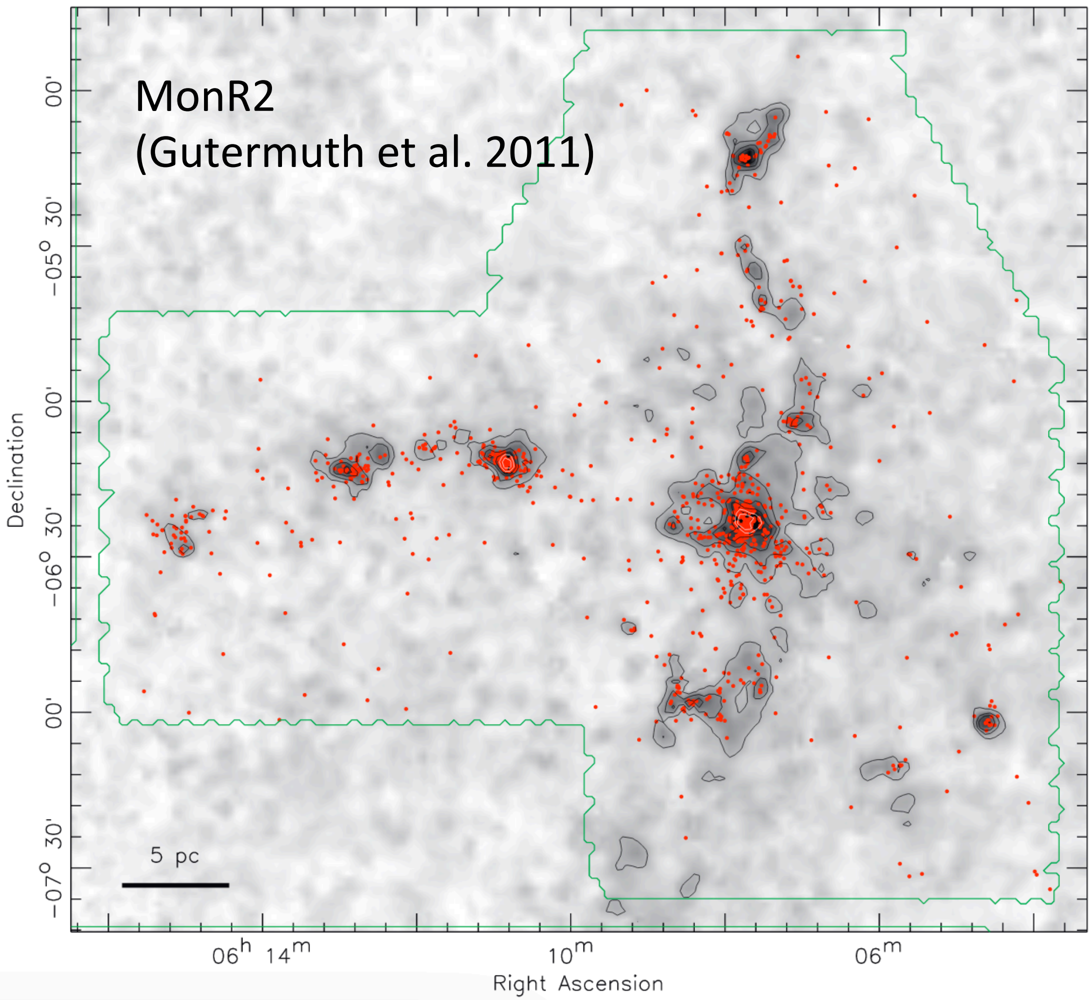
Duchêne & Kraus 2013

Substructures

II. Statistical properties of young cluster population

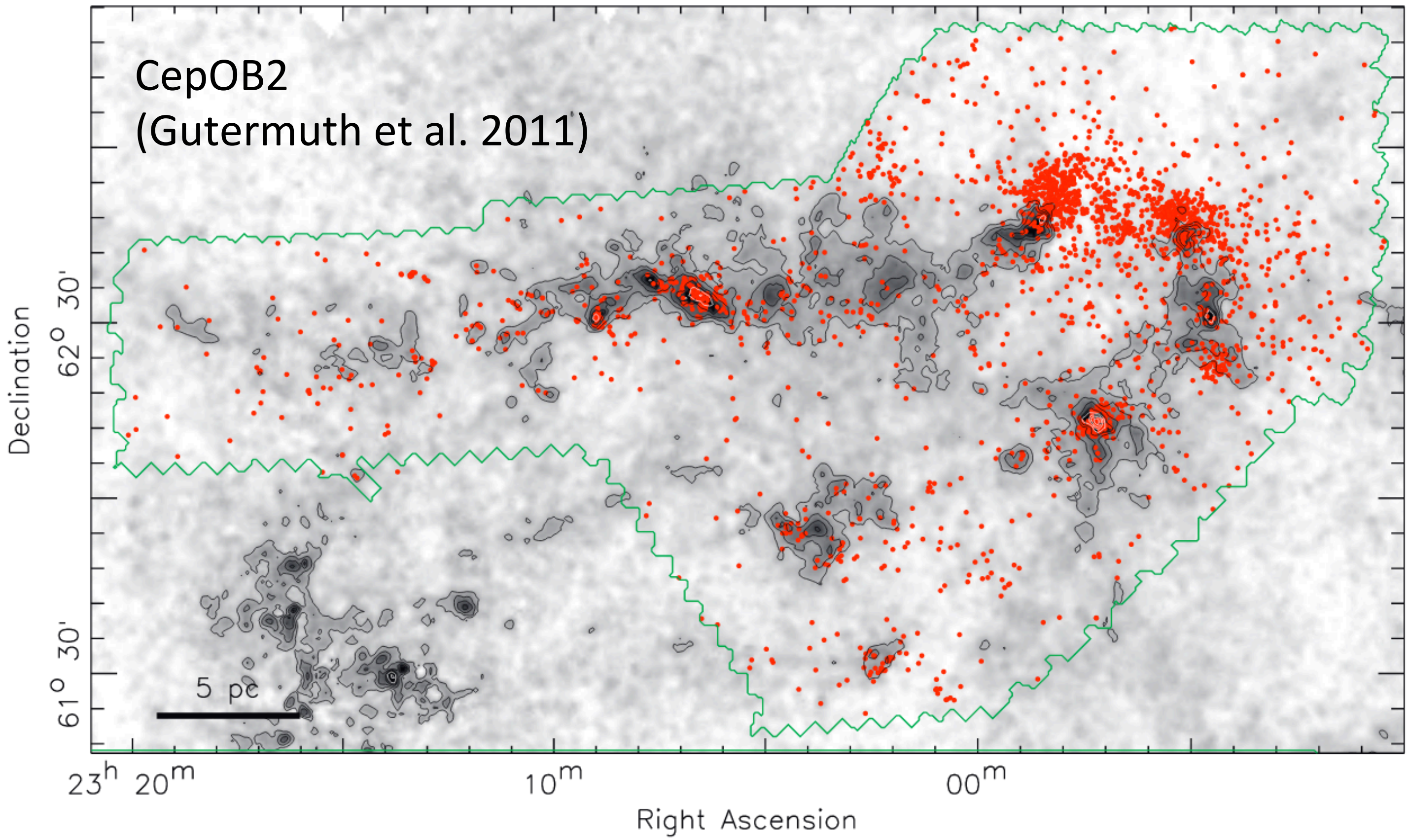
- Membership analysis
- IMF
- Multiplicity
- **Substructures (spatial and kinematics)**

Spatial distribution



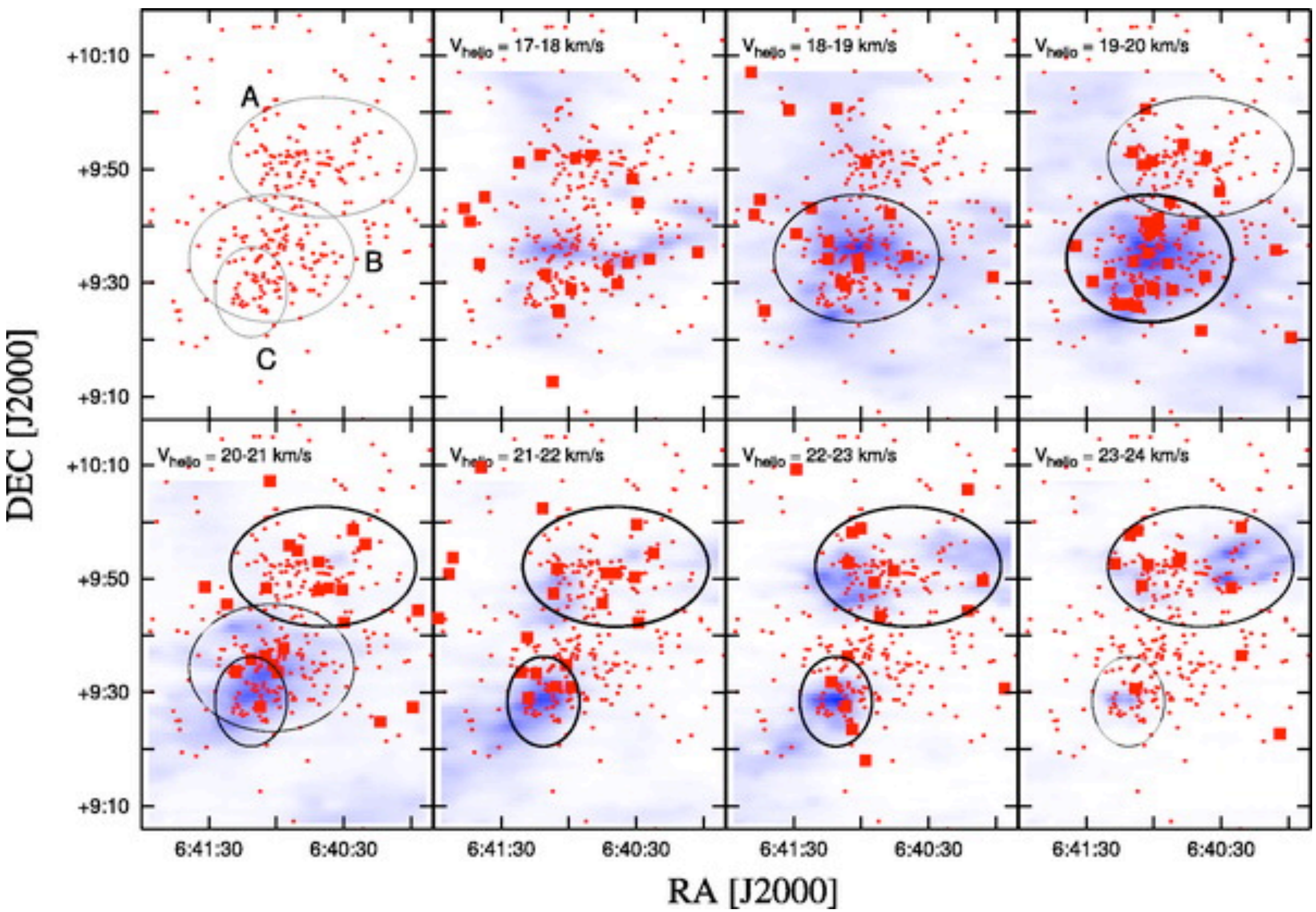
- Presence of substructures
- Clusters are found in the regions of highest extinction

Spatial distribution



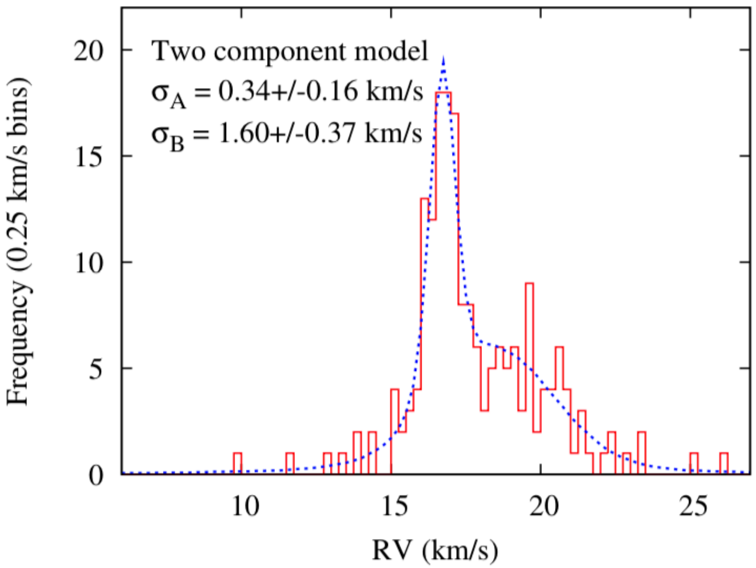
Large clusters are offset from extinction. OB stars have already dispersed much of the local natal cloud material

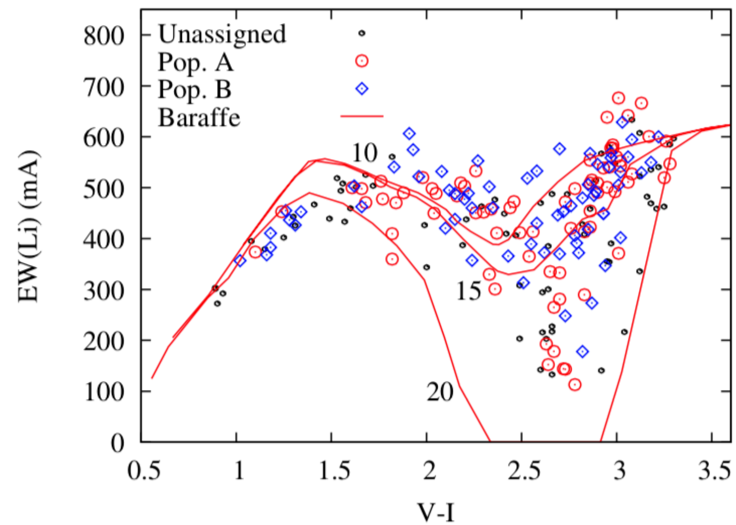
Kinematic distribution



NGC2264 (Furesz et al. 2006)

Gamma Velorum (Jeffries et al. 2014)





2 dynamically independent populations

- Pop A : v= 16.7km/s, σ=0.3km/s, ~virialized
- Pop B : v= 18.9km/s, σ=1.6km/s, superviral

Pop A younger by 1-2 Myr, closer by ~10pc, more centrally condensed around Υ^2 Vel

- Pop A = bound remnant of dense cluster ?
- Pop B = scattered population ? Spread over several degrees (up to NGC2547, Sacco et al. 2015)?

Substructure characterization

Minimum spanning tree
(Gower & Ross 1969)

- Q parameter : $Q = \frac{\bar{m}}{\bar{s}}$

(Cartwright & Whitworth 2004)

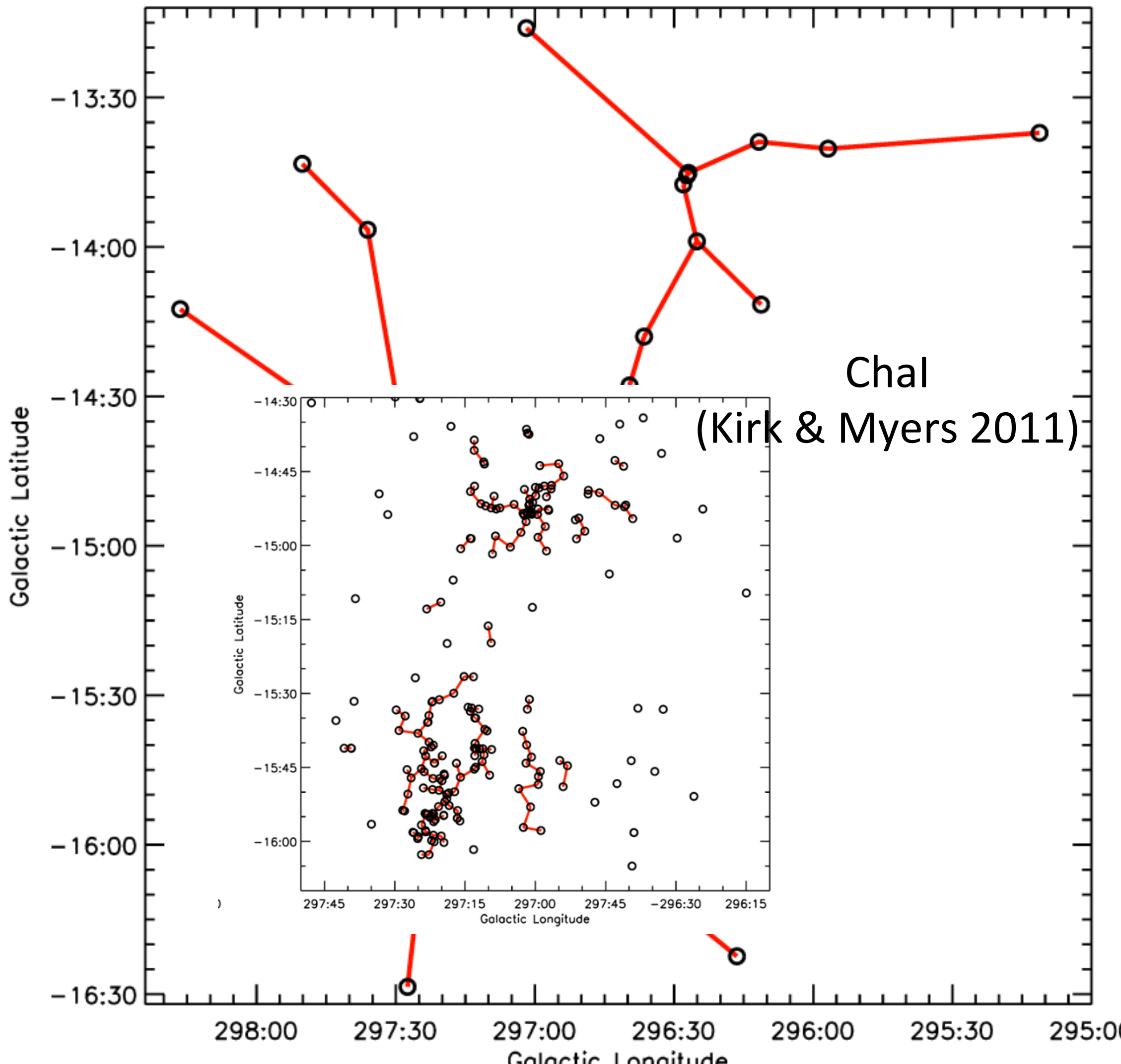
Q>0.8: smooth

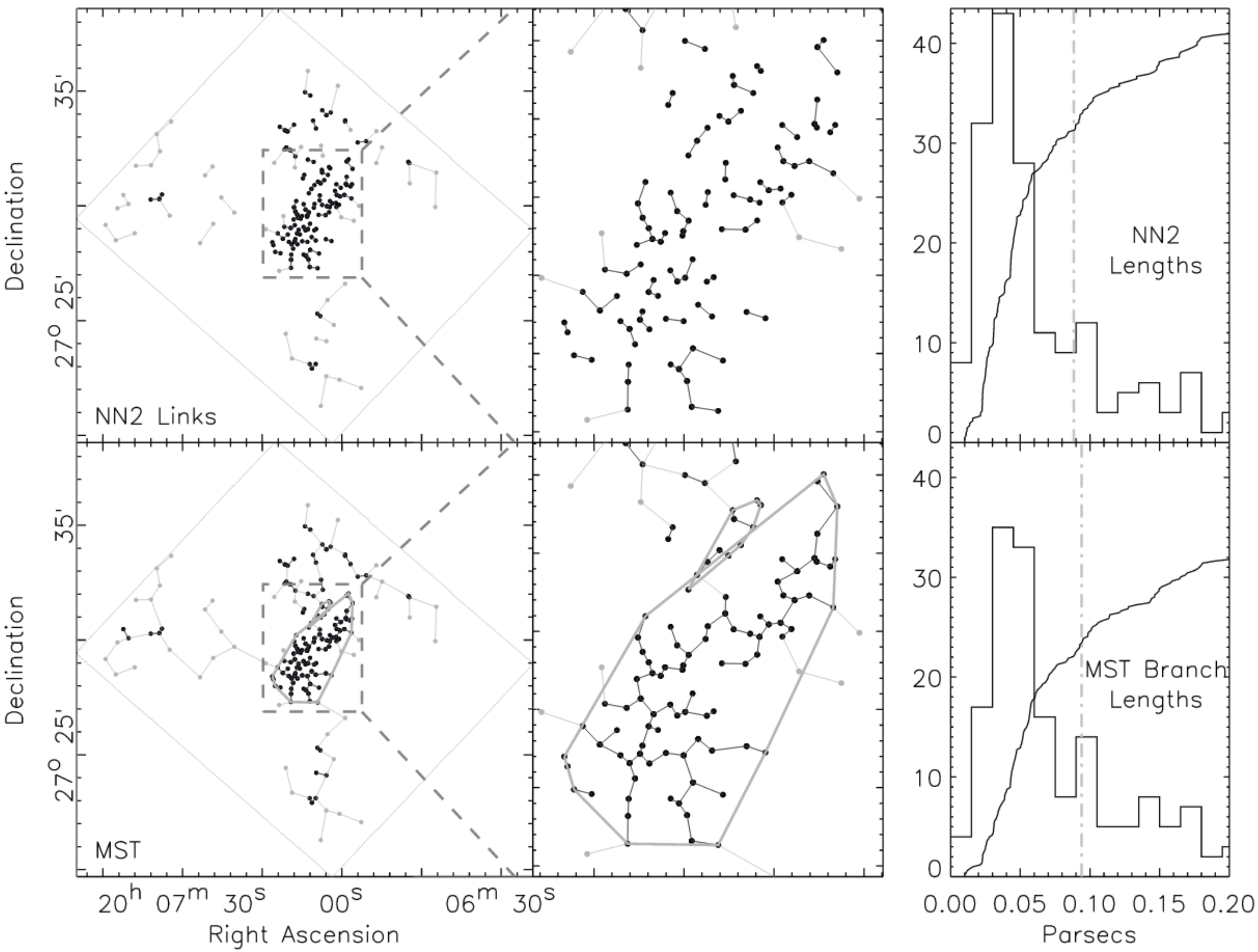
Q<0.8: substructured

- Cutoff at a given length

threshold to identify groups (Gutermuth et al. 2009):

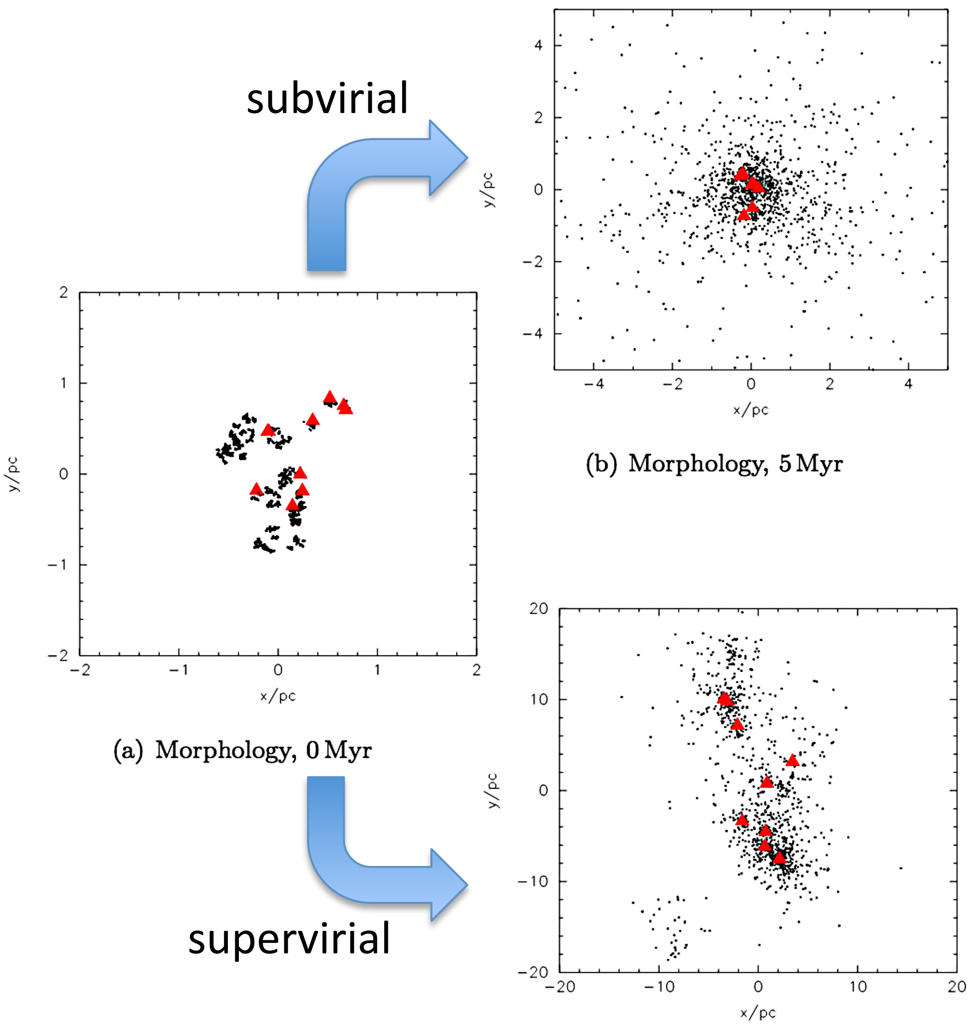
more massive stars tend to be toward the center





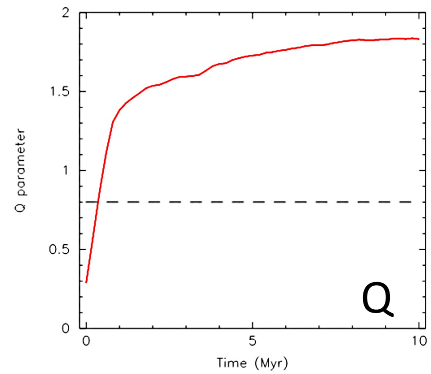
Source linkage diagrams using both the NN2 links (top) and MST (bottom), using IRAS 20050+2720 as an example (Gutermuth et al. 2009)

Substructure evolution



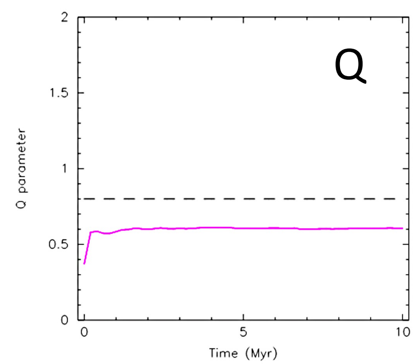
(a) Morphology, 0 Myr

(b) Morphology, 5 Myr



(l) Evolution of Q–parameter

Clusters become smooth on dynamical timescale



Unbound associations do not mix globally

Parker et al. 2014

Mass segregation

- Primordial / dynamical ?
- Timescale for dynamical mass segregation ~ t_{relax}
- Seen in young clusters such as the ONC ! (Hillenbrand 1997)
- Mass segregation can occur on a dynamical time t_{cross} if starting with substructures (Allison et al. 2009, Vesperini et al. 2009)

Summary of lecture 2

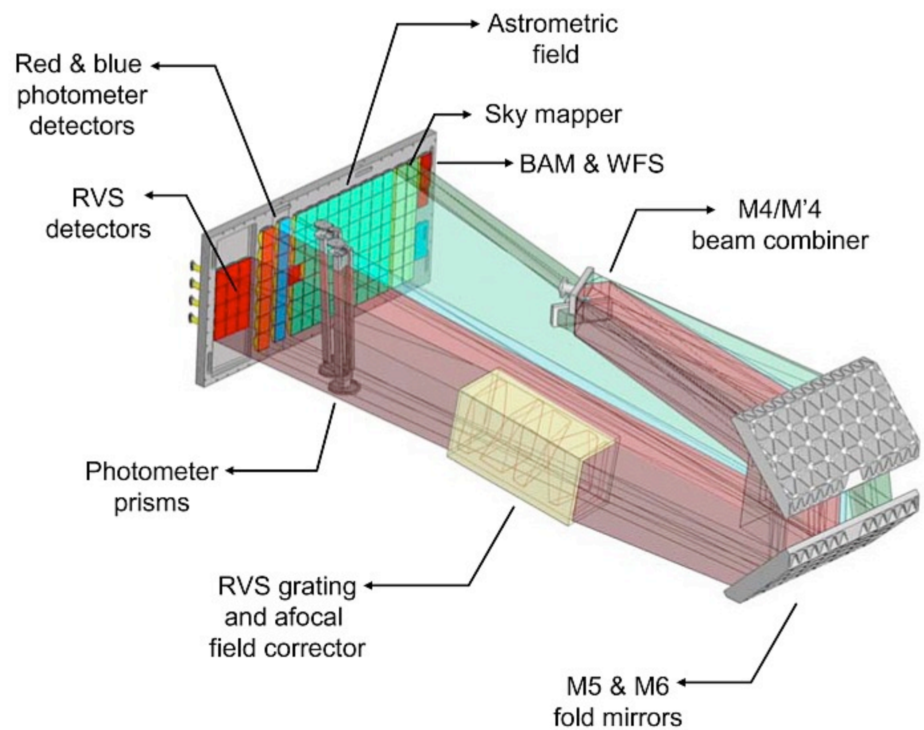
- A universal IMF down to $0.03M_{sun}$
- Where does the field population come from ?
- Low mass clusters seem to form as a collection of stellar aggregates
- Association/cluster = evolution of these groups ?
- Mass segregation primordial/dynamical ?

III. What will we learn from Gaia?

- Gaia mission
- Clusters and Gaia
- Complementary studies

Gaia

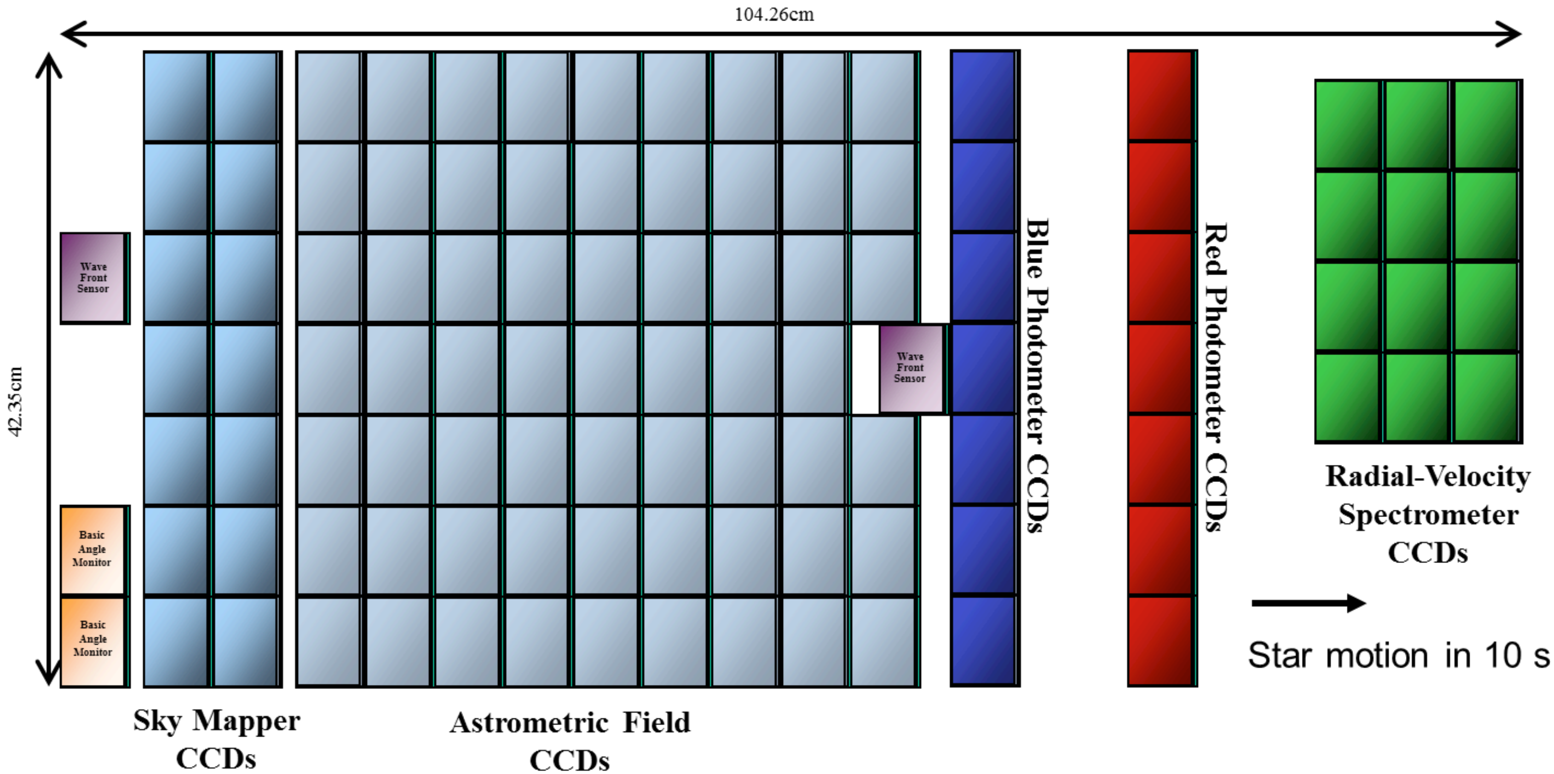
- Micro-arcsecond global astrometry for ~1 billion stars down to G~20 mag
- + asteroids, Kuiper-belt objects, quasars, supernovae, etc.
- 5-year mission
- 3 instruments:
  - Astrometric
  - Photometric
  - spectroscopic



credit: EADS Astrium

19/12/13: launch
18/07/14: end of commissioning. Gaia starts routine operations
12/09/14: Gaia discovers its 1st supernova

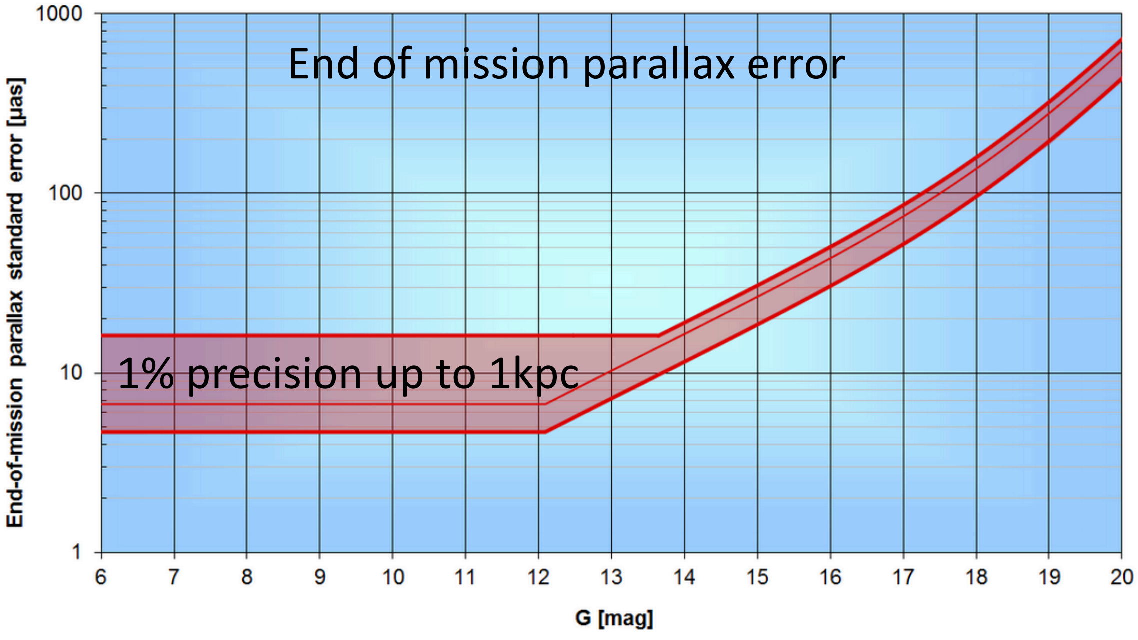
Focal Plane



- continuously scanning → high precision in the scanning direction
- object densities up to 36,000 stars per square degree. In denser regions, only the brightest objects will be observed

Astrometric instrument

- 62 CCD of 4500×1966 pixels
- pixel size of 10 µm (59 mas) in the scanning direction
- Each star will be seen ~70 times
- Position, parallax and proper motion for each object (G<20)



End of mission astrometric performance

- Scanning laws:
  - $\sigma_0 = 0.743 \cdot \sigma_\pi$
  - $\sigma_\mu = 0.526 \cdot \sigma_\pi$

- End of mission sky-average astrometric performance:

G	< 12	13	14	15	16	17	18	19	20	
σ_0	5.0	7.7	12.3	19.8	32.4	55.4	102	208	466	µas
σ_π	6.7	10.3	16.5	26.6	43.6	74.5	137	280	627	µas
σ_μ	3.5	5.4	8.7	14.0	22.9	39.2	72.3	147	330	µas/yr

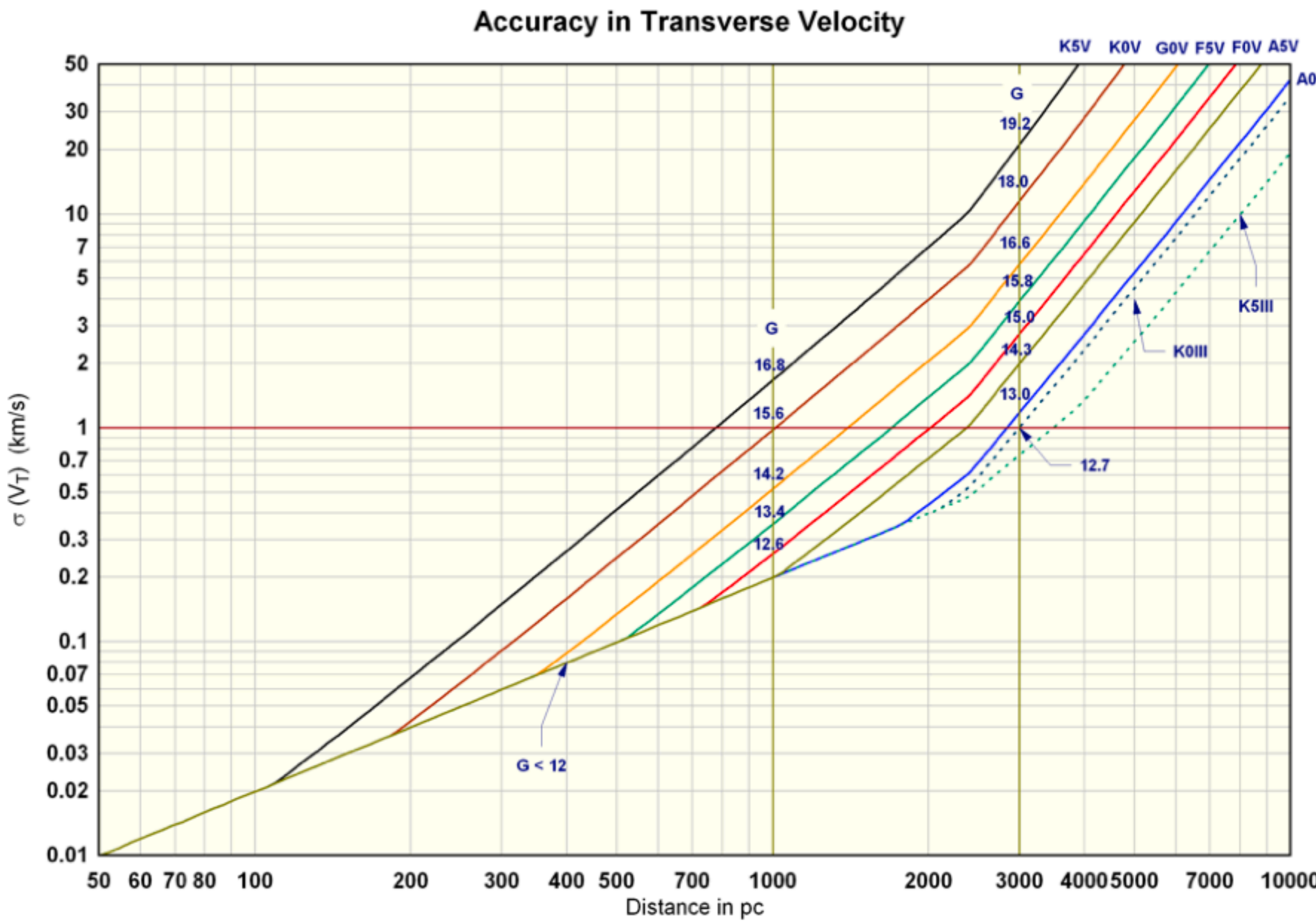


Figure courtesy of Francois Mignard

Photometric instrument

- blue (330-680nm) and red (640-1050nm) photometers
- low-resolution, spectro-photometric measurements
- enable chromatic corrections of the astrometric observations
- astrophysical classification
- astrophysical characterisation

Accuracy of AP estimation
(Bailer-Jones et al. 2013)

	G mag	$T_{\rm eff}$ K	A_0 mag	$\log g$ dex	[Fe/H] dex
A stars	9	340	0.08	0.43	0.86
	15	260	0.06	0.38	0.93
	19	400	0.15	0.51	0.74
F stars	9	150	0.06	0.36	0.36
	15	170	0.07	0.38	0.33
	19	630	0.35	0.37	0.60
G stars	9	140	0.07	0.31	0.14
	15	140	0.07	0.22	0.16
	19	450	0.33	0.45	0.65
K stars	9	100	0.09	0.26	0.19
	15	90	0.08	0.26	0.21
	19	230	0.23	0.36	0.48
M stars	9	60	0.13	0.15	0.21
	15	70	0.14	0.29	0.25
	19	90	0.13	0.17	0.29

Spectroscopic instrument

- Radial-velocity spectrometer (RVS), covering 12 CCDs (3×4)
- high-resolution spectra for G_{RVS} < 16 mag (~150 million stars)
- radial velocities using cross-correlation technique
- astrophysical information (reddening, T_{eff}) for G_{RVS} < 12 mag
- element abundances for G_{RVS} < 11 mag (~2 million stars)

	G_{RVS} mag	T_{eff} K	$\log g$ dex	[M/H] dex
Thin disk dwarfs	10	60	0.08	0.09
	13	70	0.12	0.09
	15	270	0.39	0.30
Thick disk dwarfs	10	70	0.11	0.09
	13	110	0.17	0.12
	15	350	0.43	0.29
Halo giants	10	70	0.17	0.15
	13	90	0.28	0.17
	15	340	0.86	0.38

Accuracy of AP estimation
(Bailer-Jones et al. 2013)

Spectral type	V [mag]	Radial-velocity error [km s^{-1}]
B1V	7.5	1
	11.3	15
G2V	12.3	1
	15.2	15
K1III-MP (metal-poor)	12.8	1
	15.7	15

Gaia releases

1. Summer 2016:
   – positions and G-mag for 90% of the sky (single-star like)
   – Hundred Thousand Proper Motion (stars in common with Hipparcos)
2. Early 2017:
   – 5 astrometric parameters, 90% of the sky (single-star like)
   – BP/RP photometry
   – Mean RV (if no variation) for bright stars
3. 2017/2018:
   – astrophysical parameters, binary orbital solution, mean RV
4. 2018/2019:
   – variable star classification, non single stars
5. 2022:
   – final astrometric, photometric and RV catalogues for all stars (single, non-single, variables), exo-planet list, ground-based observations

Clusters and Gaia

- Identification of new galactic clusters/associations
- Complete census of cluster members + look for escapers
- Individual distance for each member
  - better HR diagram and constraint for evolutionary model
  - 3D-view of the cluster, look for substructures
- Proper motion
  - Dynamical state (expansion/contraction/virialised)
  - Rotation
  - Kinematic structures, constrain star formation

→ 5 (+1)-D view of nearby clusters (<1kpc) and galactic disk

Gaia's limitation

- Astrometry limited down to G~20 mag
- Cannot deal with extinction
- No precise RV for G>12

→ Complementary data are required for RV and proper motion at fainter magnitudes and in extincted regions

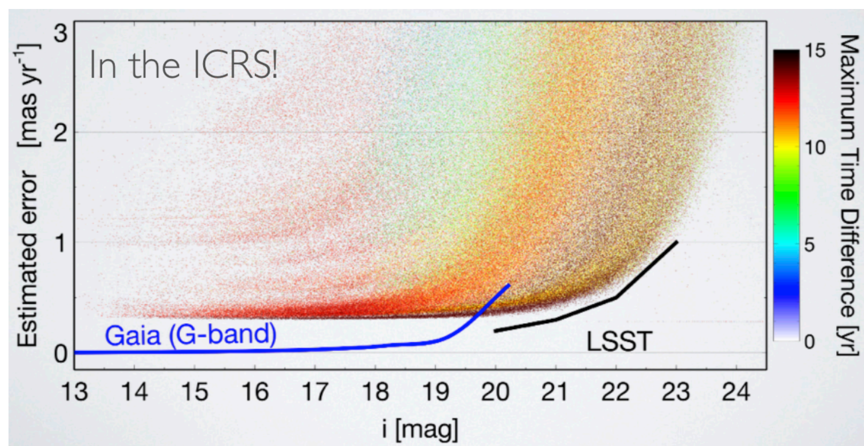
RV studies

- RAVE:
  - AAO/UK Schmidt, 6dF MOS, 9<I<13
  - RV (accuracy: 1-2km/s) + stellar parameters (Teff, log g, metallicity)
- GES (Gaia-ESO Survey)
  - VLT/FLAMES GIRAFFE + UVES
  - **RV accuracy ~0.3km/s down to V~19**
  - Many nearby clusters
- APOGEE:
  - NIR spectroscopic survey (H-band, <13 mag)
  - **RV (accuracy <150m/s)** + abundances
  - **IN-SYNC project**: NGC1333 (Foster et al.), IC348, NGC2264, ONC
  - Plan to observe more clusters with APOGEE-II, including the LMC

+ PI observations (VLT/FLAMES, MMT/Hectochelle,…)

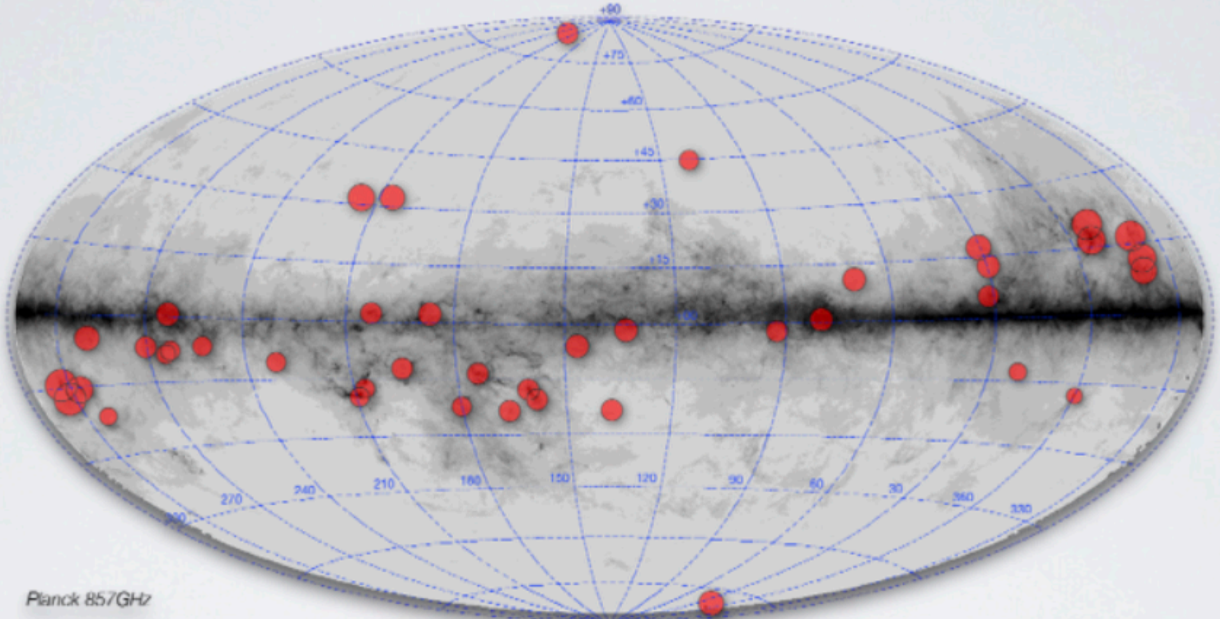
Complementary ppm studies

- UKIDSS: down to K~19, time baseline <5yrs, accuracy ~5mas/yr
- **Pann-STARRS**: 99% of northern stars down to 24th mag every few days, complete census within 100pc
- **DANCE**: archival data + new PI observations, time baseline up to 15 yrs, very accurate proper motion: <1mas/yr down to i~23 (Bouy et al. 2013)



- PI observations (VLT/NACO, Keck Laser guide stars AO, HST for distant young massive clusters)

PERSPECTIVES



Planck 857GHz

"FAST" ASSOCIATIONS				
Name	**Age [Myr]**	**Dist. [pc]**	**μRA [mas/yr]**	**μDec [mas/yr]**
Pleiades	120	120	-35	-15
CrA	1	130	-35	51
η Cha	9	100	-30	28
Cha I, II & III	3	140	-20	-5
Upper Sco	5	125	-9	-24
α Per	50	180	24	-26
IC2391	55	155	-25	23
IC2602	50	145	-22	10
Lupus	3	140	-17	-27

"FAST" ASSOCIATIONS				
Name	**Age [Myr]**	**Dist. [pc]**	**μRA [mas/yr]**	**μDec [mas/yr]**
Praesepe	650	180	-36	-13
Ophiuchus	1	145	-10	-25
Taurus	3	140	-8	-25
Blanco 1	100	210	19	4
Hyades	625	40	90	-20
γ Velorum	5	350	-6	10
NGC2451	50	300	-10	4

"SLOW" ASSOCIATIONS		
Name	**Age [Myr]**	**Distance [pc]**
Cygnus OB2		2000
IC348	3	350
NGC1333	1	350
Serpens	3	450
ONC	1	400
NGC1980	10(?)	400(?)
NGC2264	5	670
IC4665	40	350
λ-Ori	5	400
σ-Ori	5	350

Future facilities

- WHT/WEAVE: R=5000-20000, 2°diameter, 800 fibers, 2016
- VISTA/4MOST: R=5000-20000, 4 sq.deg., 2400 fibers, 2018

- **LSST**: 8.4m telescope, FOV 3.5° diameter, southern sky, each star 1000 times in 10yrs, 1st science in ~2020
- E-ELT CAM/MIR for distant young massive clusters

- Next astrometric mission ?

Proposal for an M4 mission: Theia (Gaia's daughter)

FOV ~0.5°, differential astrometry, down to R~25

Contact: Fabien.Malbet@obs.ujf-grenoble.fr

Conclusion

- Gaia + follow-up data will revolutionize our view of nearby clusters (6D structure + internal dynamics)
- Key to understand formation and evolution of stellar clusters

- We need to get ready to interpret the coming data !

→ **statistical tools** to analyse clusters in >6D dimensions (position, velocity, photometry…)

→ **hydro + N-body simulations** to follow cluster early evolution (gas + stars)

Young stellar clusters with ELT/JWST

Unprecedented sensitivity (ELT, JWST) combined to spatial resolution (ELT)

→ Access to crowded/distant regions for the 1st time: test the dependence on density and metallicity of the star forming process

→ Characterization of very faint/multiple objects become possible

- Center of massive star forming regions
- Low mass population in the LMC/SMC
- Small separation / low-q / ultra-cool visual binaries in young nearby clusters
- Atmospheres of young planetary mass objects