STAR CLUSTERS

Lezione V- Fisica delle Galassie

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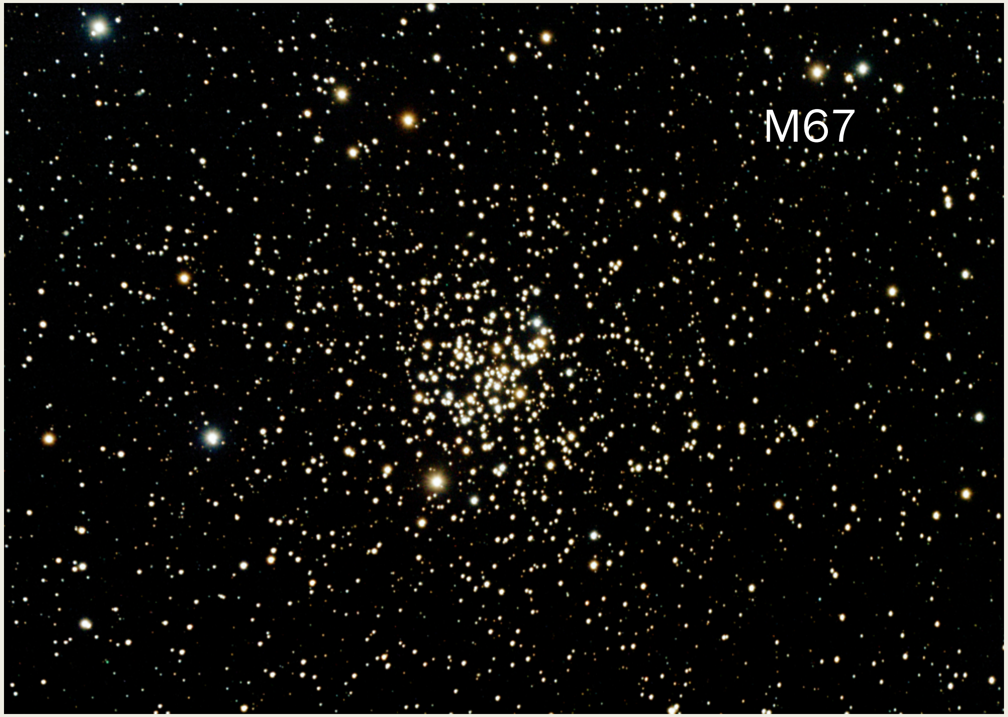
Summary

- What is a stars cluster?
- Types of clusters
- Observational properties
- Formation star clusters
- Properties of star clusters in equilibrium
- Dispersion mechanims

What is a star cluster?

Historical definition based on observations: Concentration of stars with a surface density above the stellar background that are located at the same distance

Modern definition: Group of stars located approximately at the same distance and gravitationally bound



Why clusters are important for studying the Galaxy

1. Stellar birthplaces

2. Best laboratories to study stellar evolution

3. Tracers of the chemical properties of the Galactic disc (Open clusters)

4. Relics of the early phases of the Galaxy formation (Globular clusters)

Different type of clusters

Open Clusters

<u>Properties</u>

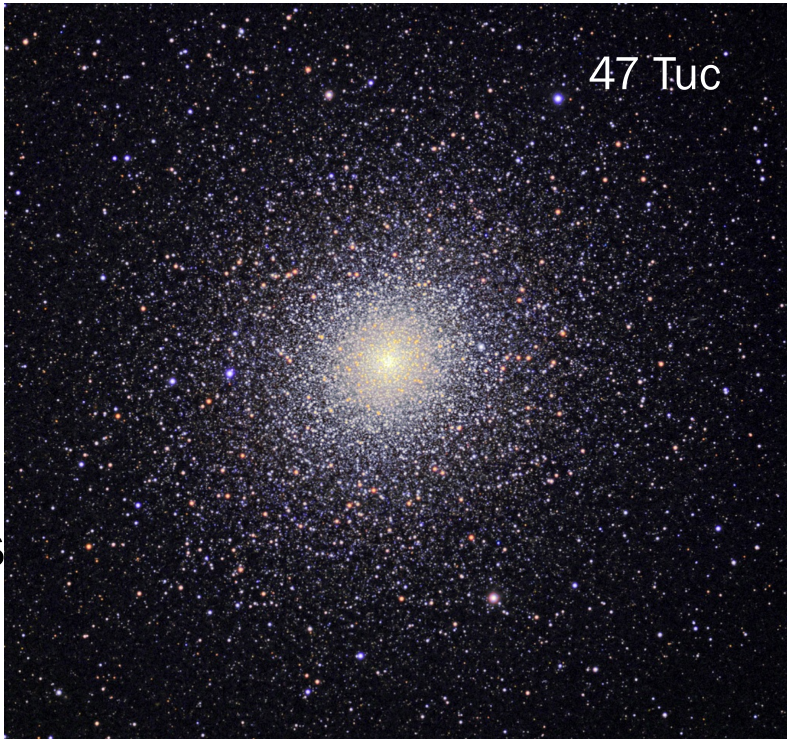
Density: 0.1-10^2 stars pc^{-3}
Mass: 10^2-10^3 $M_\odot$
Age: 0.01-10 Gyr
Median Age: 0.3 Gyr
Gravitationally bound
Location: Galactic disc
Almost coeval
Chemically homogeneous

Different type of clusters

Globular Clusters

Properties

Density: 10^3-10^4 stars pc^{-3}
Mass: 10^4-10^6 $M_\odot$
Age: 10-12 Gyr
Gravitationally bound
Not chemically homogeneous
Location: Galactic Halo
Almost coeval(???)



Different type of clusters

Embedded clusters/star forming regions

Properties

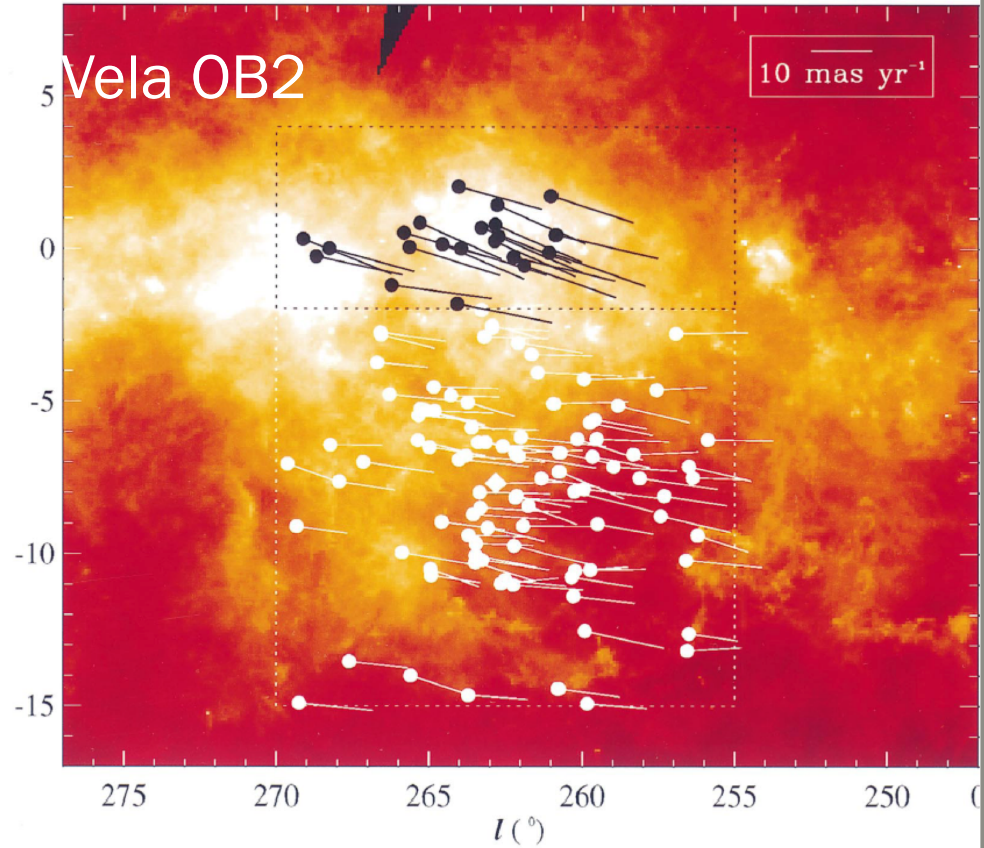
Density: 0.1-10^2 stars pc^{-3}
Mass: 10^2-10^3 $M_\odot$
Age: 0-10 Myr
Location: Galactic Disc
Almost coeval
Composed of Gas+dust+stars
Bound and unbound

Different type of clusters

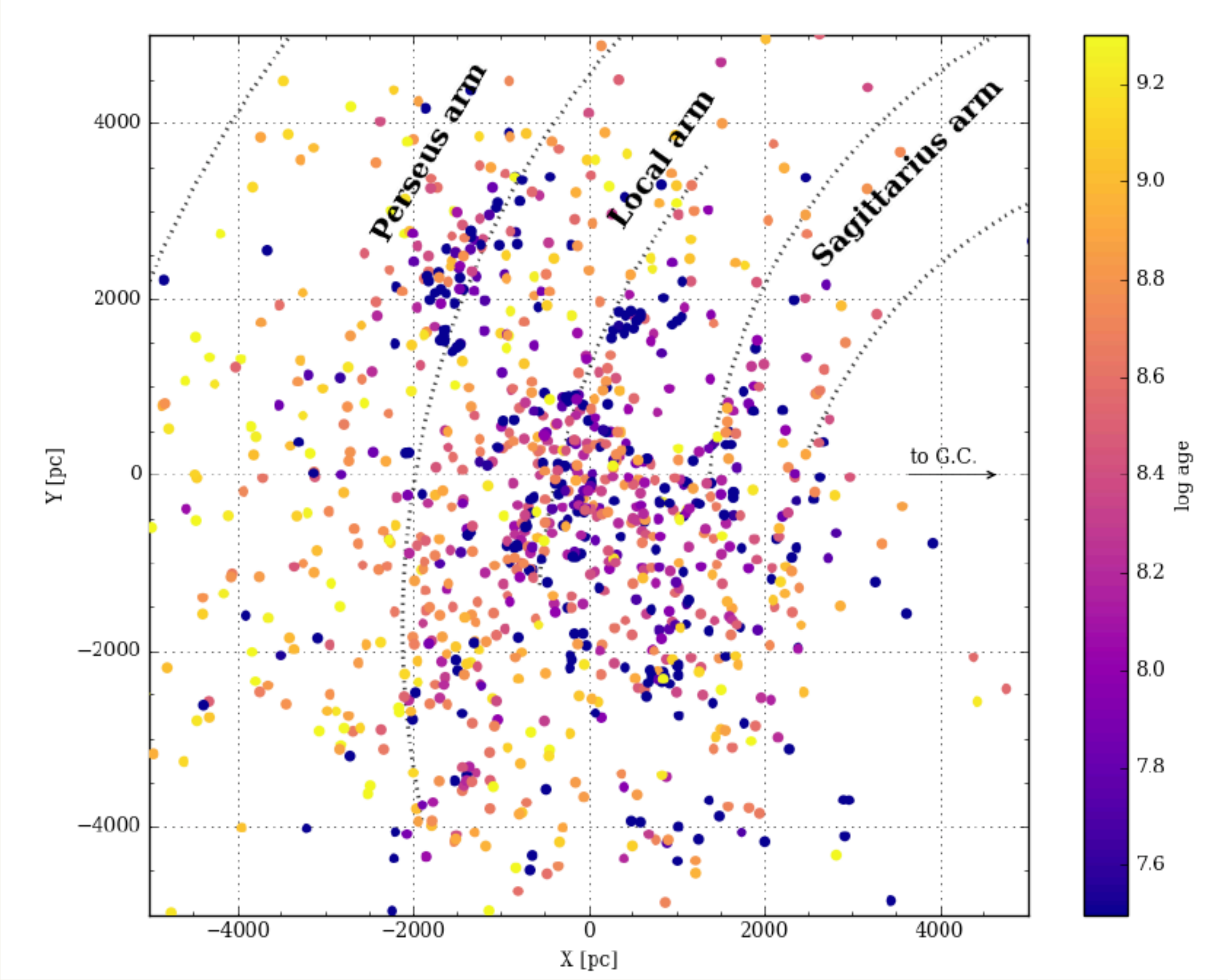
Stellar associations

Properties

Density: 0.1-10^2 stars pc^{-3}
Mass: 10-10^3 $M_\odot$
Age: 10-12 Gyr
Gravitationally bound
Not chemically homogeneo
Location: Galactic Halo
Almost coeval(???)
They are not clusters

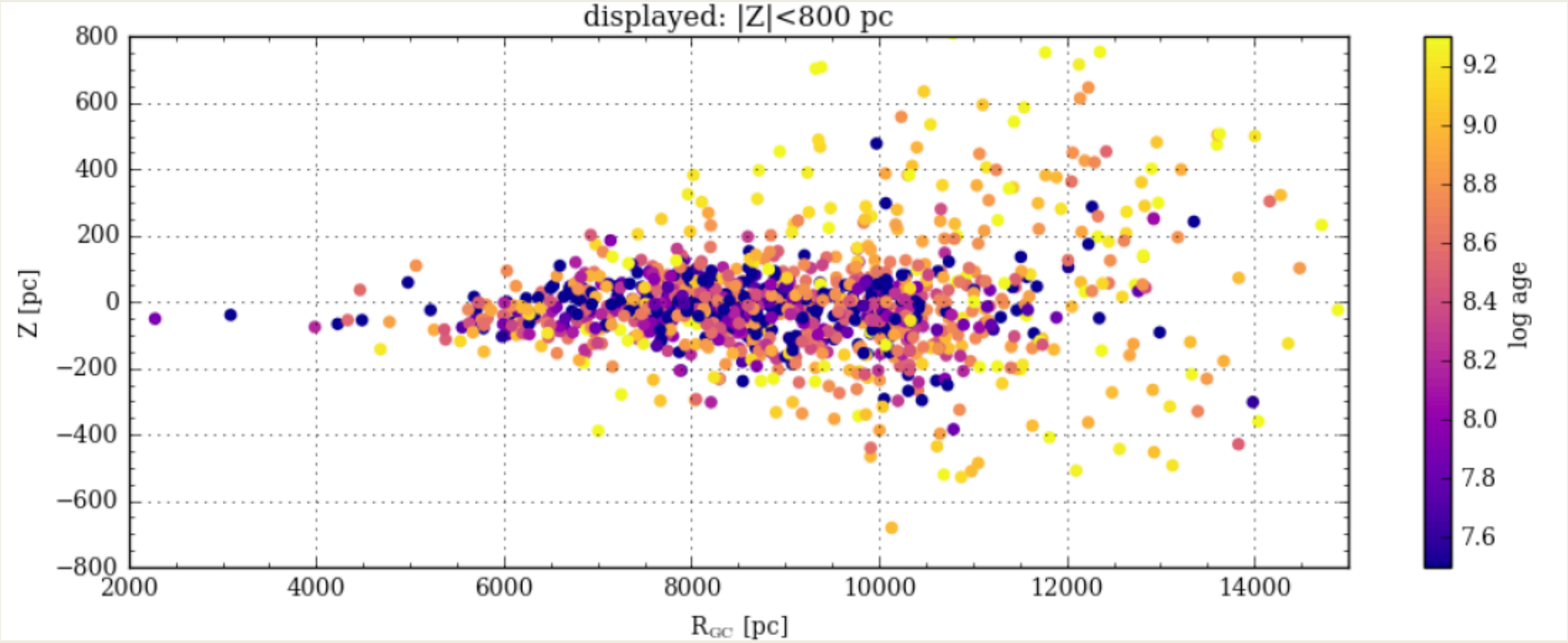


Open Clusters in the Galactic disc



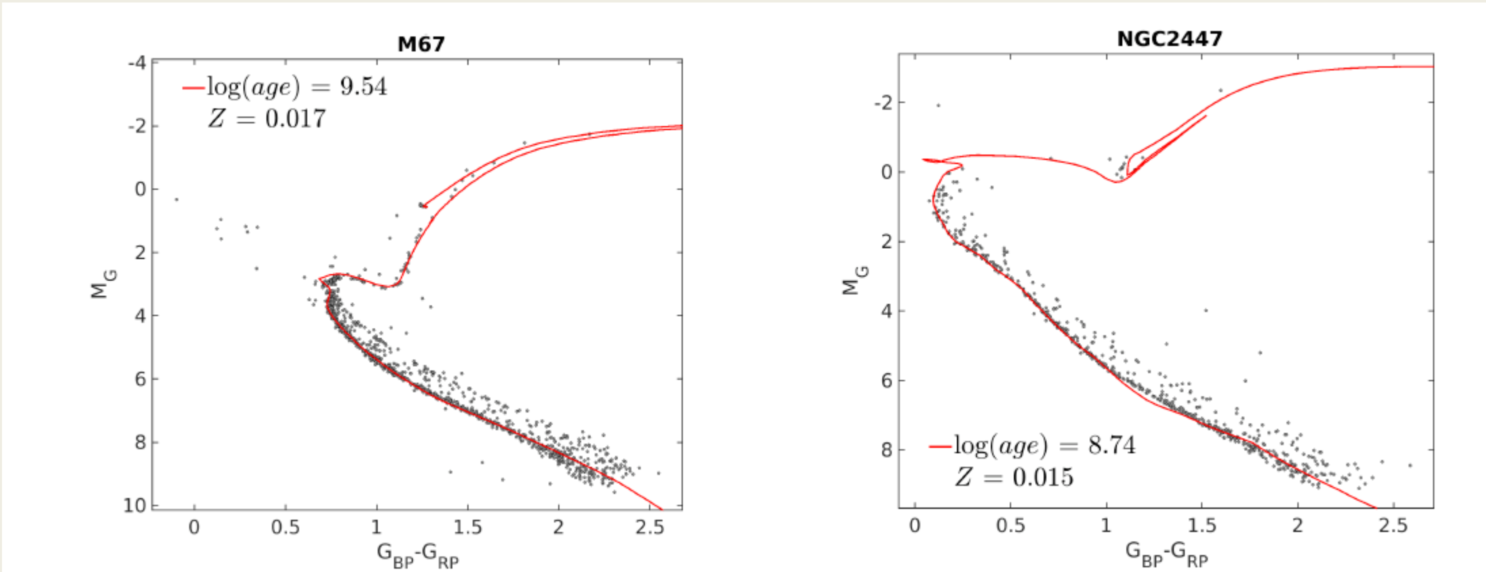
Cantat-Gaudin et al. (2018)

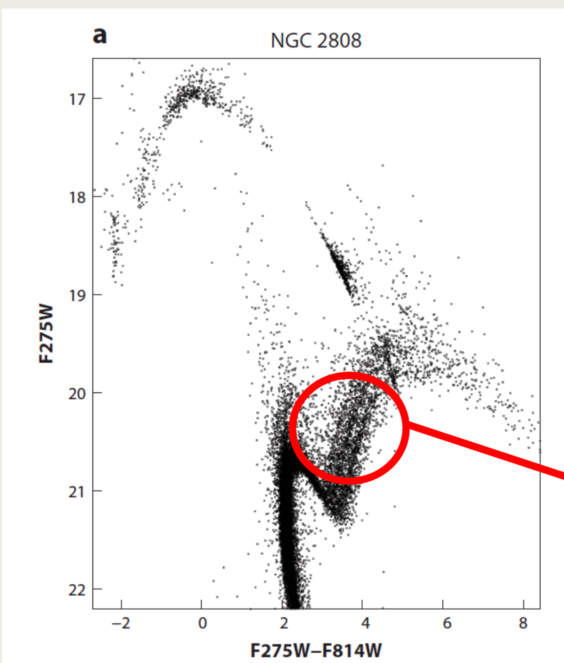
Open Clusters in the Galactic disc



Cantat-Gaudin et al. (2018)

HR diagram of star clusters





HR diagram of OCs is fitted with a single isochrone (see Babusieaux et al. 2018)

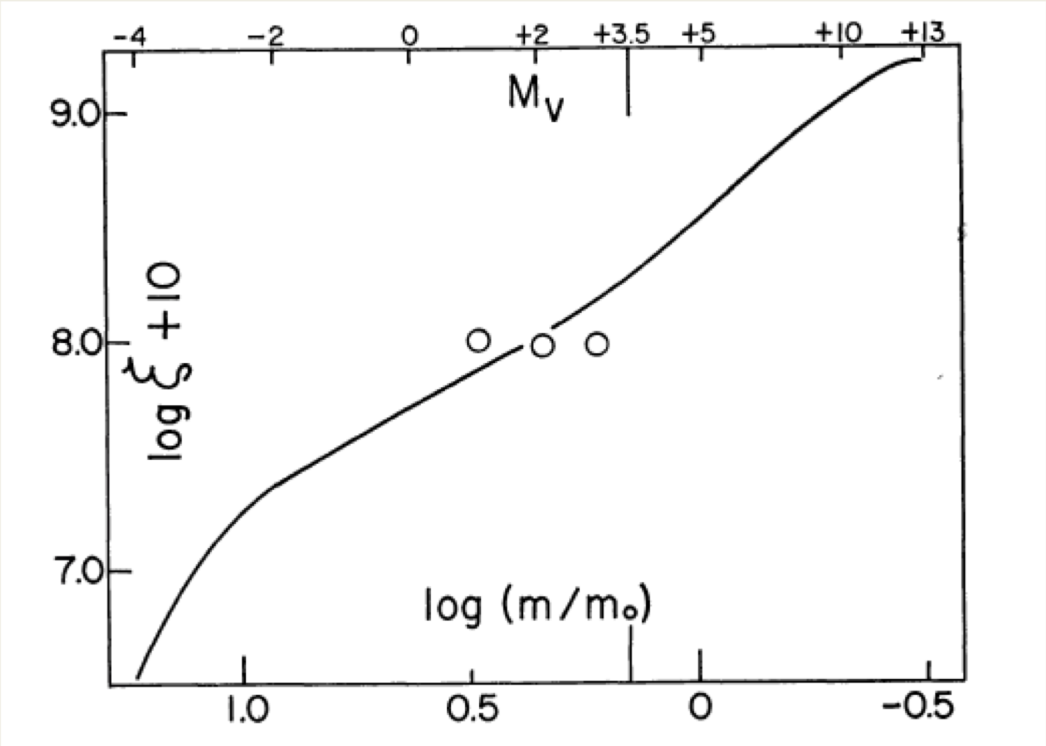
HR diagram of GCs cannot be fitted with a single isochrone. Very complex and debated problem (see Bastian and Lardo 2018)

(Initial) Mass Function

$$\phi(\log m) = \frac{dN}{d\log m}$$

$$\chi(m) = \frac{dN}{dm}$$

⇩



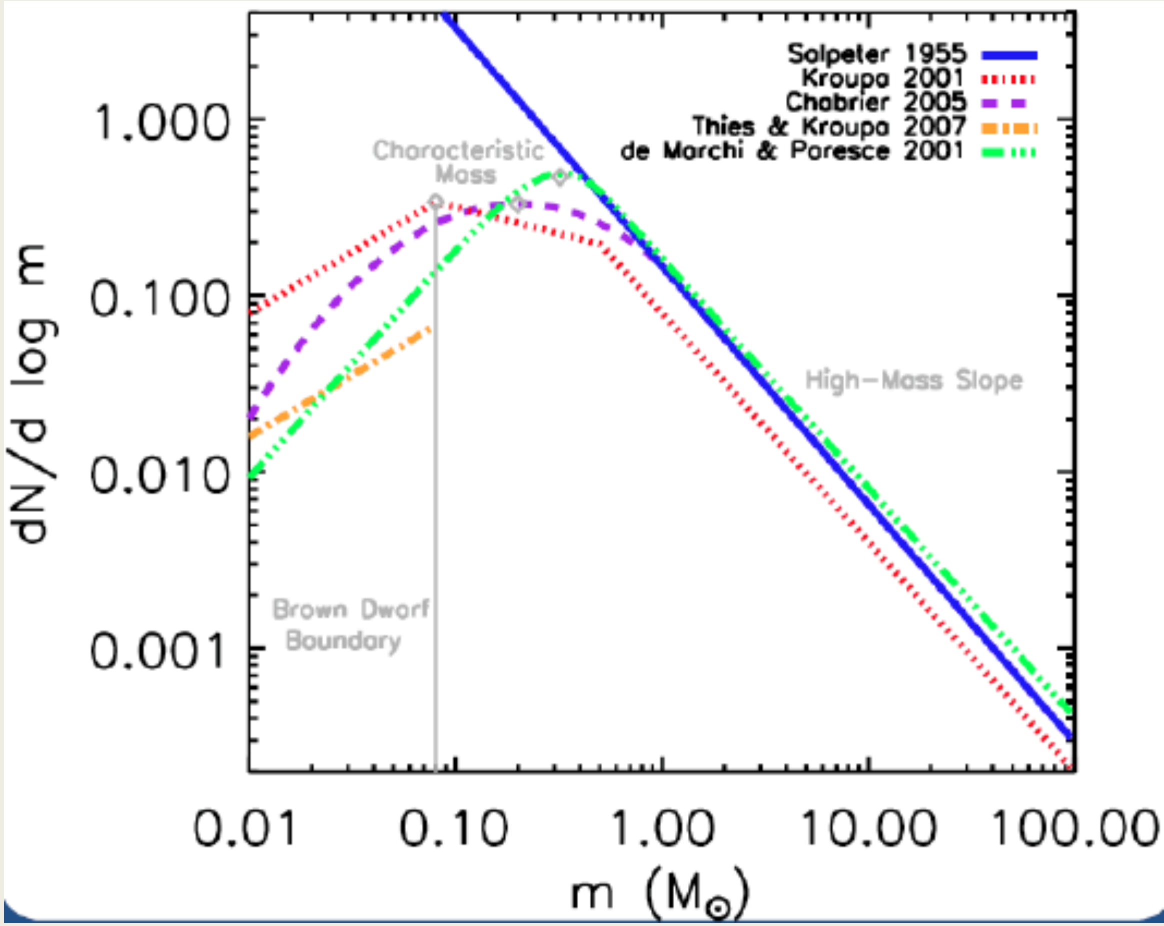
$$\phi(\log m) = m^{-\alpha} = m^{-1.35}$$

(Salpeter 1955)

$(\mathrm{m} > 1\ M_{\odot})$

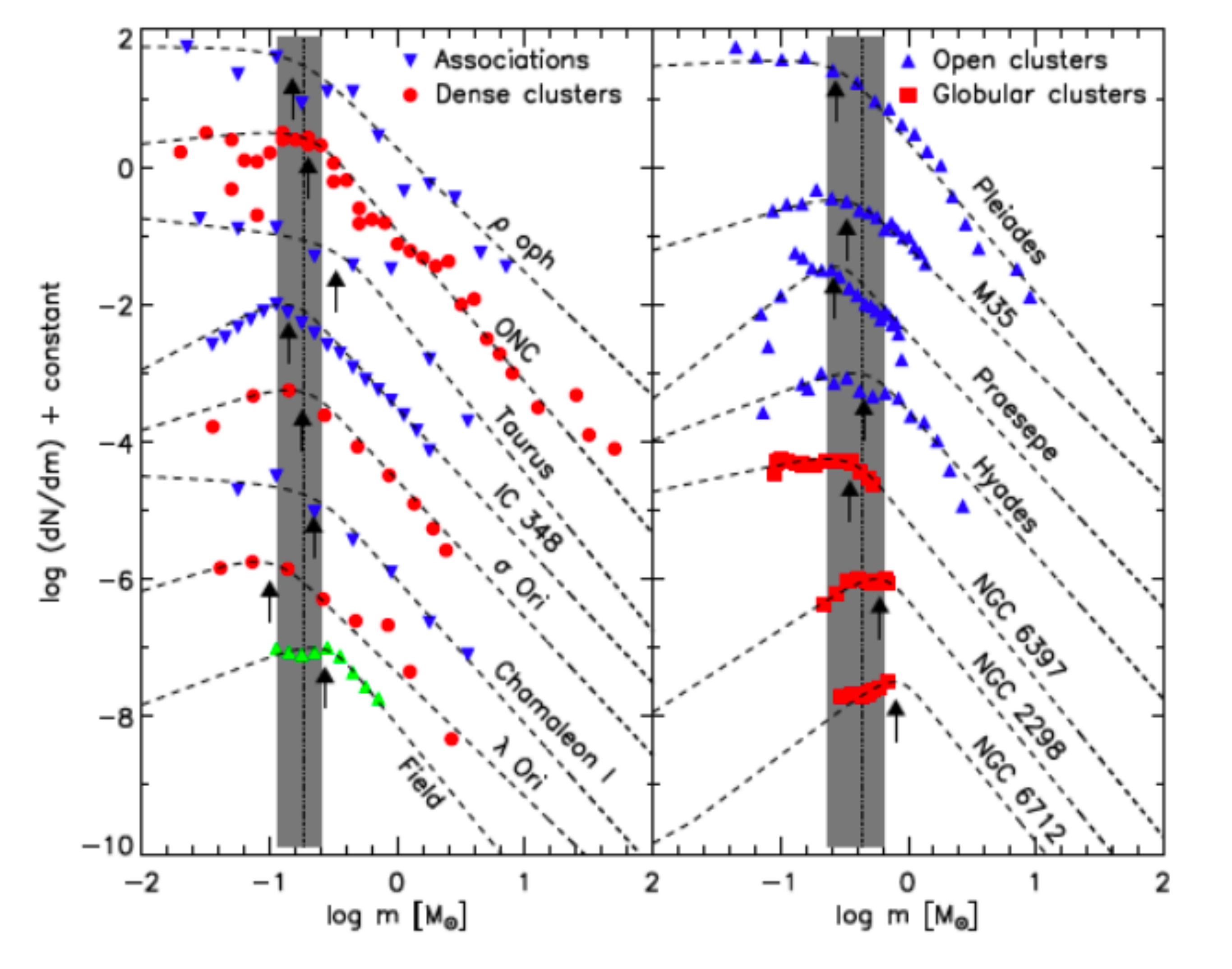
Initial Mass Function

- Salpeter (1955) Power law
- Kroupa (2001) Multiple Power Law
- Chabrier (2005) Power law+log-Normal
- De Marchi & Paresce(2001) Tapered power law



(Offner 2014)

Universality of the IMF



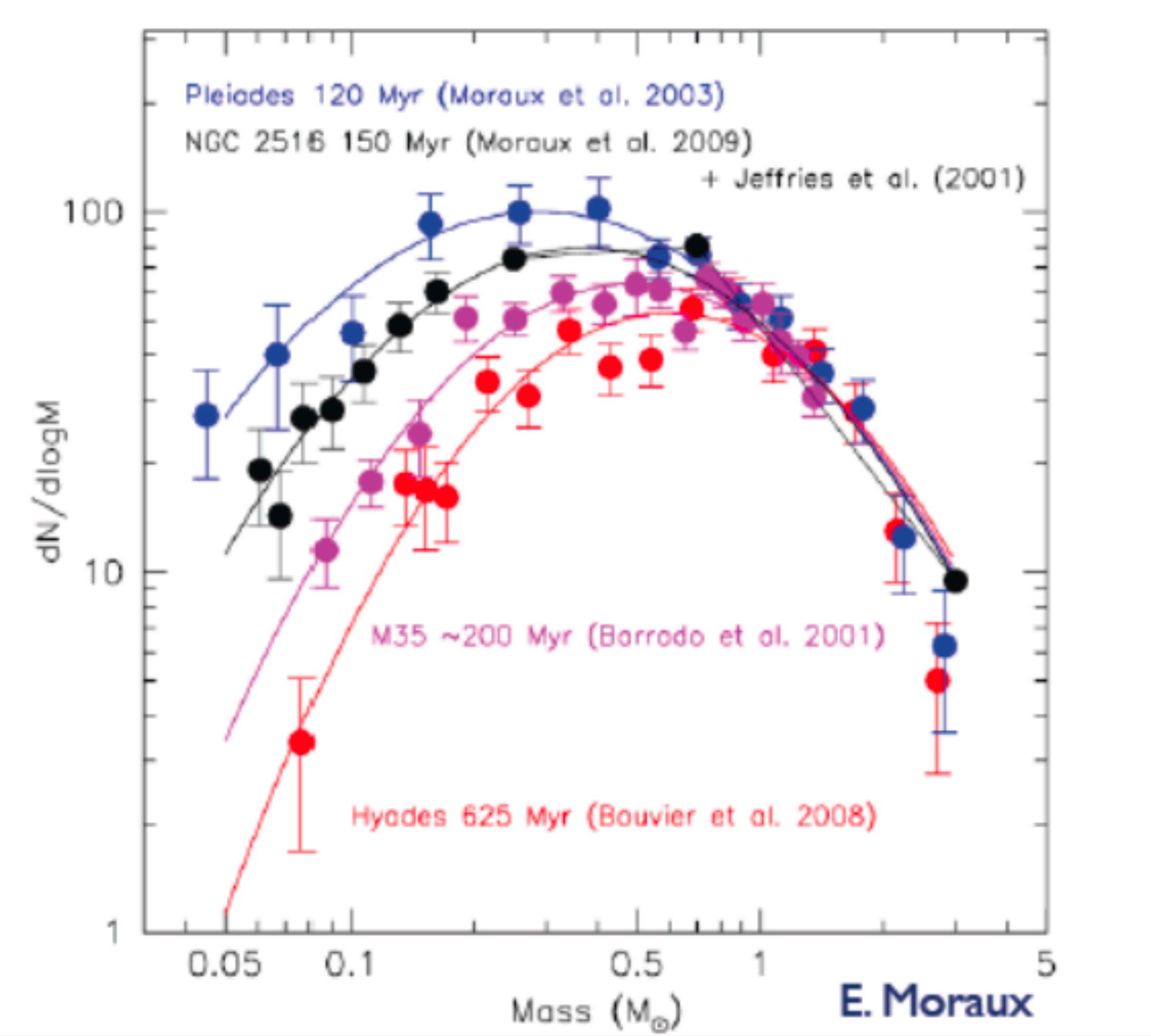
(Bastian et al. 2010)

MF in star clusters

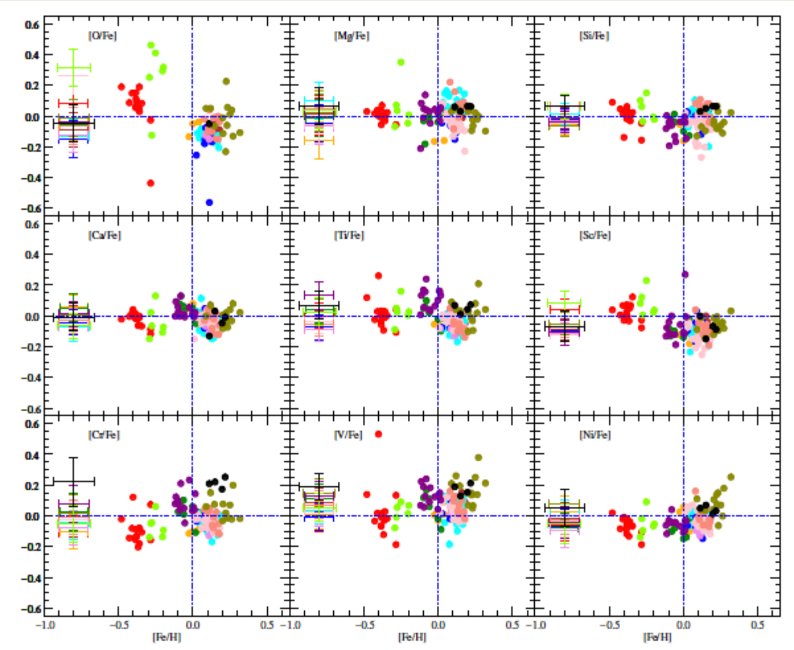
IMF
+
Dynamical evolution
+
Stellar evolution

⬇

MF of star clusters



Chemical abundances in star clusters



Open clusters are chemically homogeneous (e.g. Magrini et al. 2017)

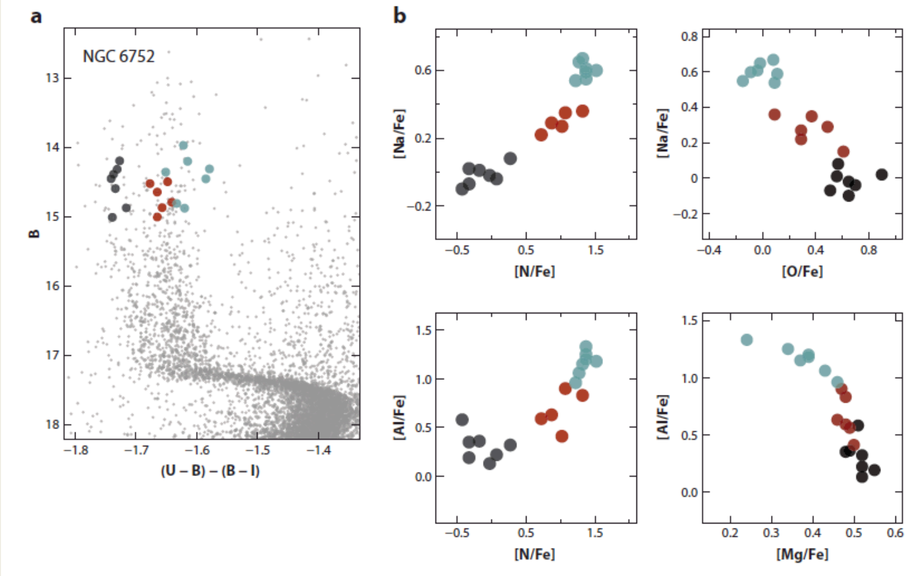
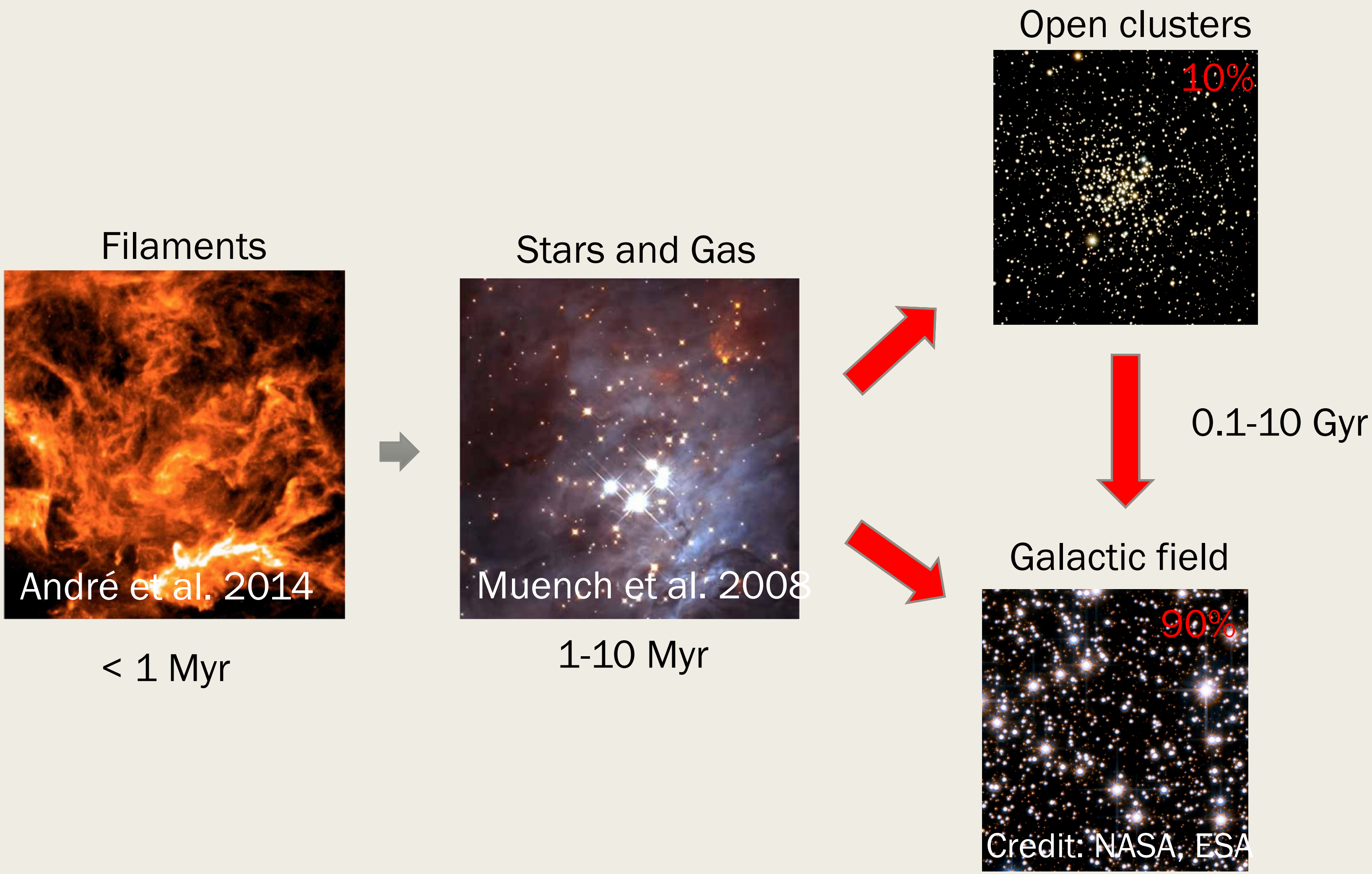


Figure 1

Globular clusters are not chemically homogeneous (e.g. Bastian & Lardo 2018)

Very complex issue non yet solved

Formation and evolution of star clusters



Collisional vs. Collisionless systems

Collisional systems: The dynamical evolution of the system is influenced by the interactions among its particles

Collisionless systems: Interaction among particles are negligible

Star clusters
are collisional systems

Galaxies
are collisionless systems

Crossing Time

Time necessary to cross the system

$$t_{cross} = \frac{R}{v}$$

$$t_{cross} \approx t_{dyn} \approx \sqrt{G\rho}$$

Open Clusters

R$\sim 3\ pc\ v\sim\ 0.5\ km\ s^{-1}$

$t_{cross}\sim 5\ Myr$

Globular Clusters

R$\sim 10\ pc\ v\sim\ 5\ km\ s^{-1}$

$t_{cross}\sim 2\ Myr$

Relaxation Timescale

Time necessary for a stars in a system to lose memory of its initial condition

$$t_{rlx} = \frac{N}{8 \ln N} t_{cross} = \frac{N}{8 \ln N} \frac{R}{v}$$

Number of stars

Crossing time

R= radius

v = velocity

COLLISIONAL SYSTEMS

$t_{rlx} < lifetime$

Open Clusters

N$\sim 10^3$ R$\sim 3\ pc$ $v\sim 0.5\ km\ s^{-1}$

$t_{rlx} \sim 100\ Myr$

Globular Clusters

N$\sim 10^5$ R$\sim 10\ pc$ $v\sim 5\ km\ s^{-1}$

$t_{rlx} \sim 2\ Gyr$

COLLISIONLESS SYSTEMS

$t_{rlx} > lifetime$

Galaxy

N$\sim 10^{11}$ R$\sim 20\ kpc$ $v\sim 100 - 300\ km\ s^{-1}$

$t_{rlx} \gg Hubble\ time$

(Binney and Tremaine 2008)

Evaporation Timescale

$\langle v_e^2 \rangle^{1/2} = 2\langle v^2 \rangle^{1/2}$

Escape Velocity

Open Clusters

$t_{rlx} \sim 100\ Myr$
$t_{evp} \sim 14\ Gyr$

Globular Clusters

$t_{rlx} \sim 2\ Gyr$
$t_{evp} \gg Hubble\ time$

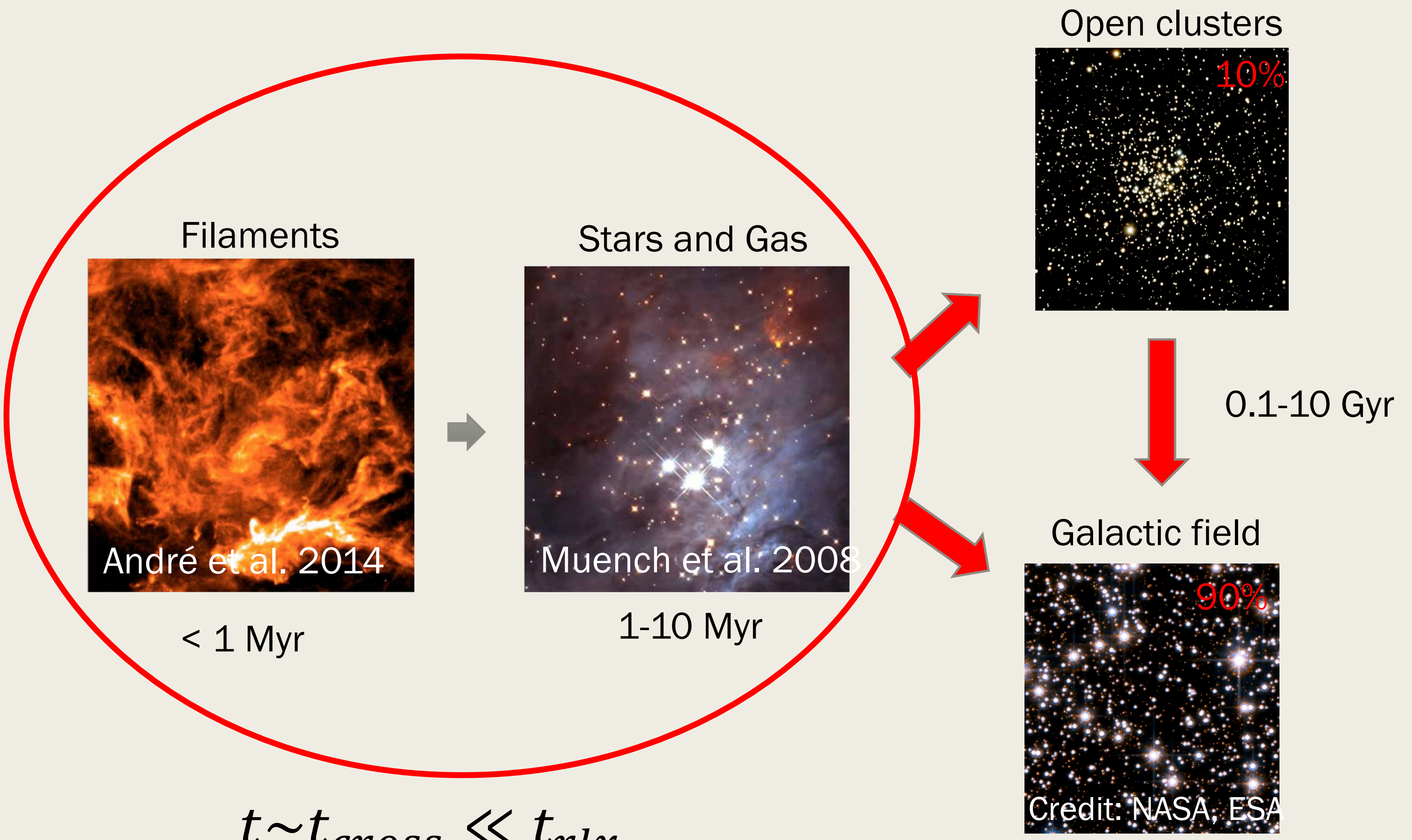
$\gamma = 8\times10^{-3}$

fraction of of particles exceeding escape velocity in a Maxellian distribution

$$\frac{dN}{dt} = -\frac{\gamma N}{t_{rlx}} = -\frac{N}{t_{evp}}$$

$$t_{evp} \approx 140 t_{rlx}$$

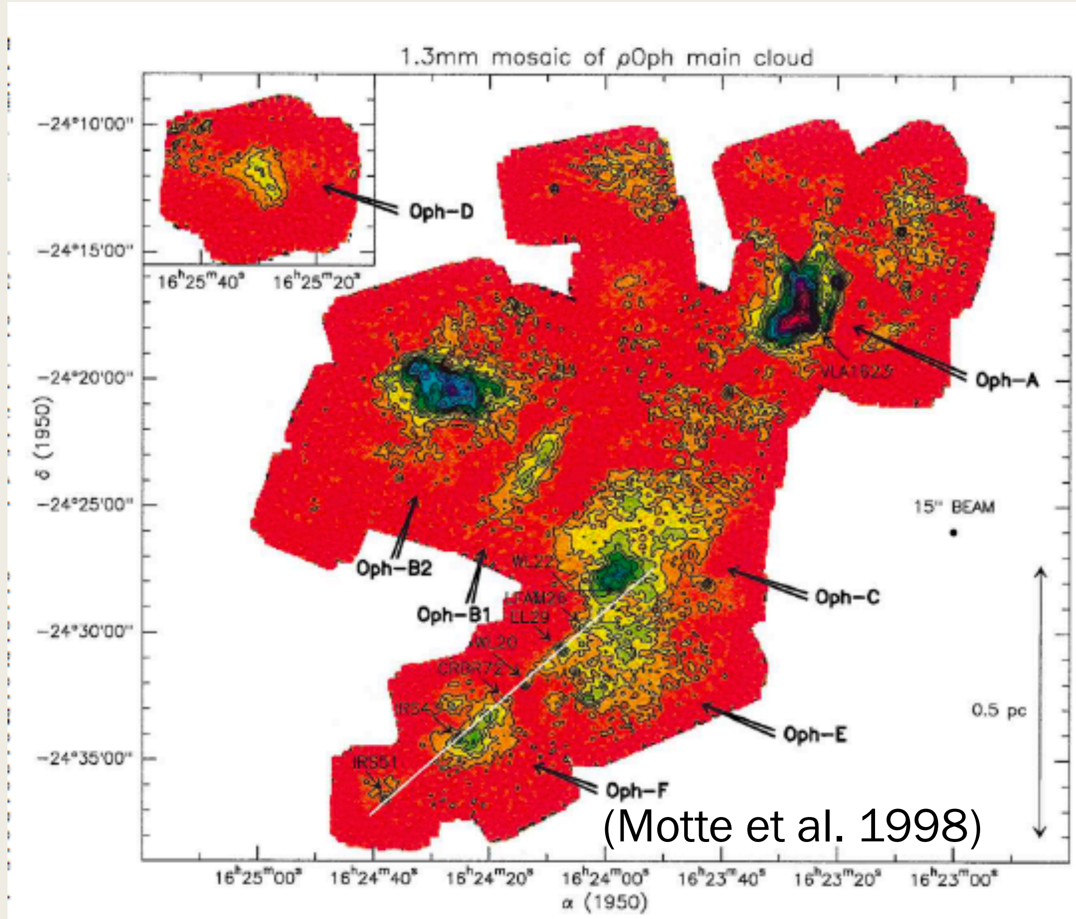
The Formation of star clusters



$$t \sim t_{cross} \ll t_{rlx}$$

The Formation of star clusters

Stars form from the fragmentation and collapse of Giant (10^4-10^5 $M_\odot$) and cold (T=10-20 K) molecular clouds



(Motte et al. 1998)

Denser part of the cloud collapse and fragment

1. New born stellar systems are highly structured
2. New born stars inherit the chemical content of the parental cloud

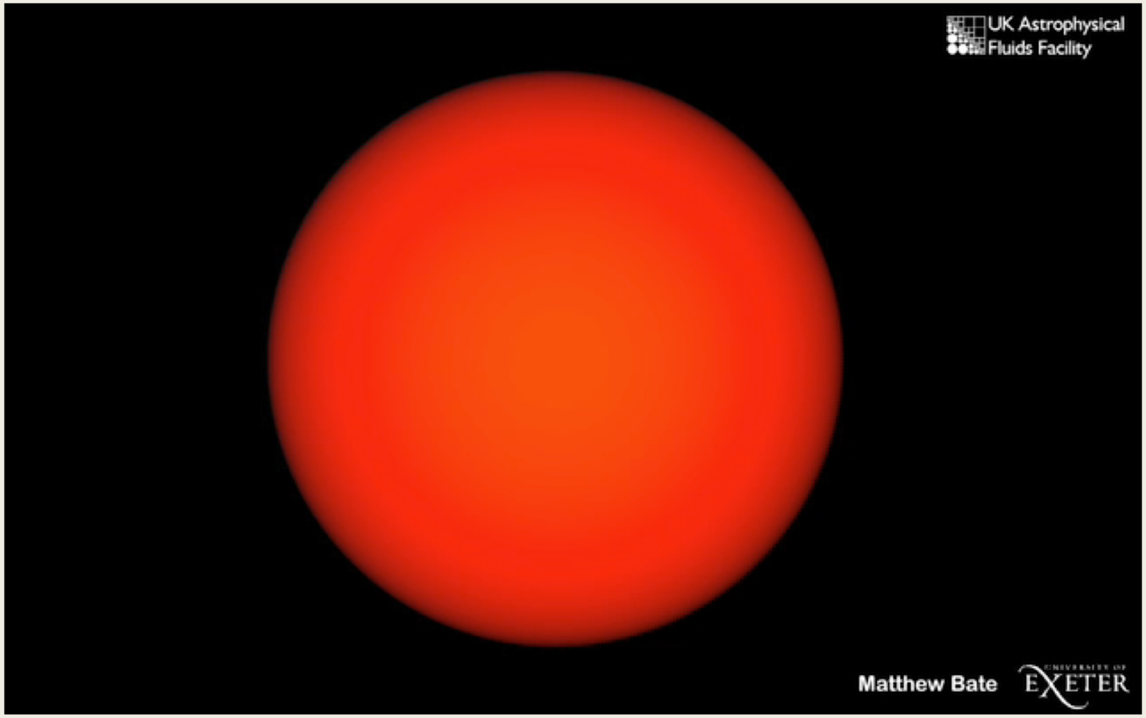
Molecular cloud and early stages of star formation discussed in the course “Fisica del mezzo interstellare

The Formation of Star Clusters

- Self Gravity
- Turbolence
- ISM Chemistry
- Radiative Transfer

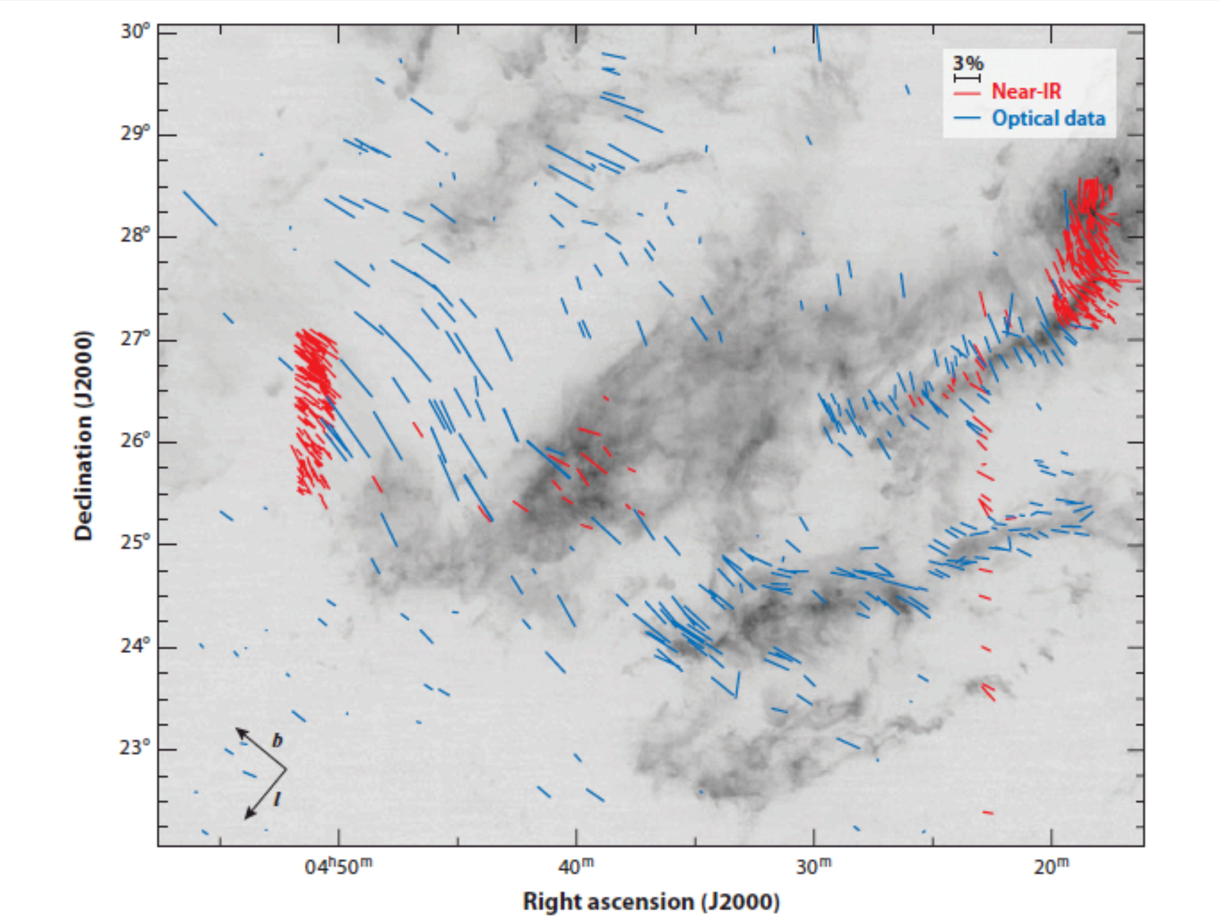
⇓

Very complex and high demanding simulations



The Formation of star clusters

Magnetic fields play a role in the star formation process both at large and low scale



(Chapman et al. 2011)

Very often neglected in simulation

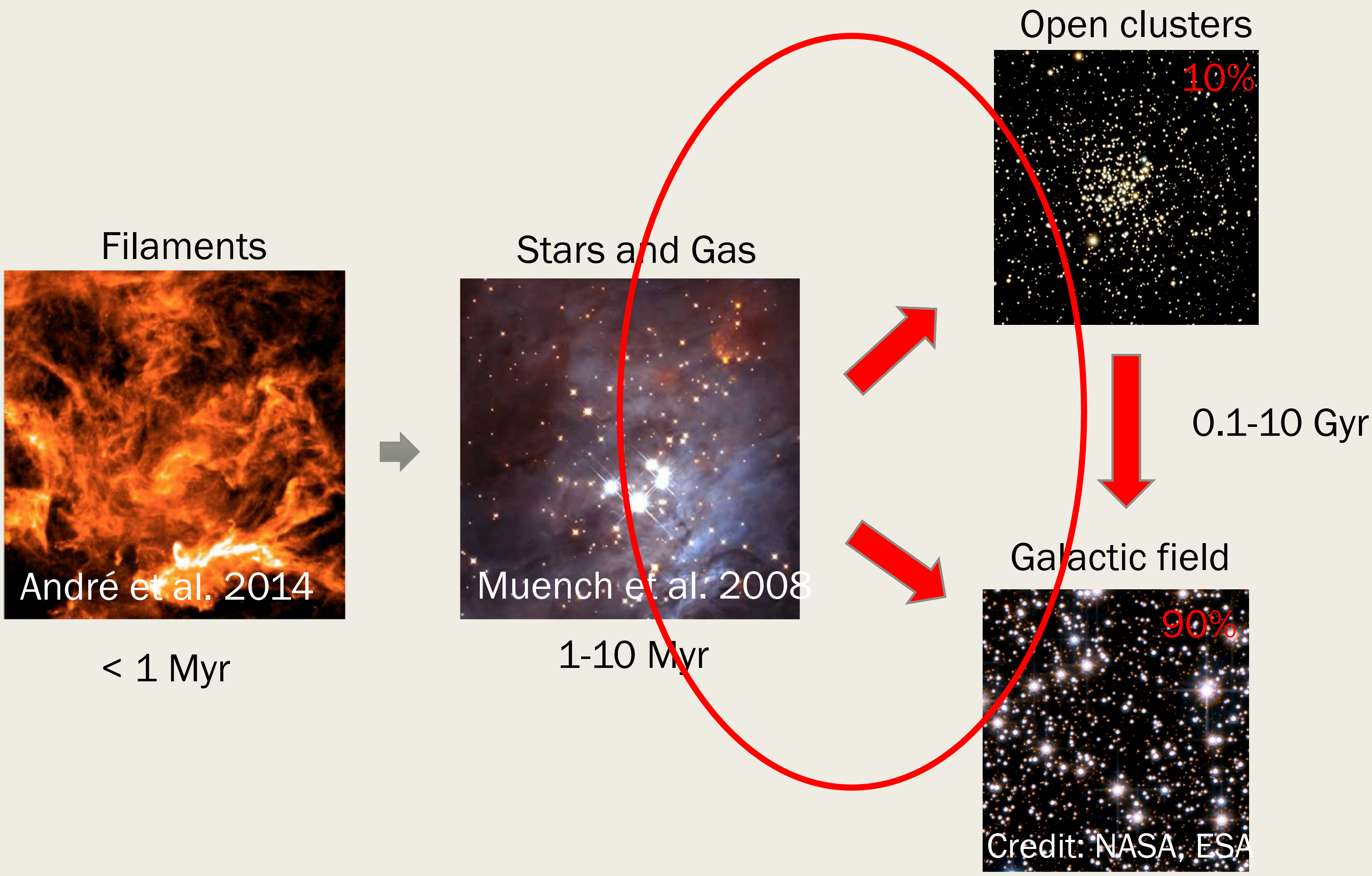
The Formation of star clusters

<u>Feedback from new born stars</u>

- Supernova explosion
- Stellar wind
- Radiation pressure
- Protostellar jets
- Ionization

These processes may trigger or quench star formation but are not considered in simulations

Infant mortality of star clusters

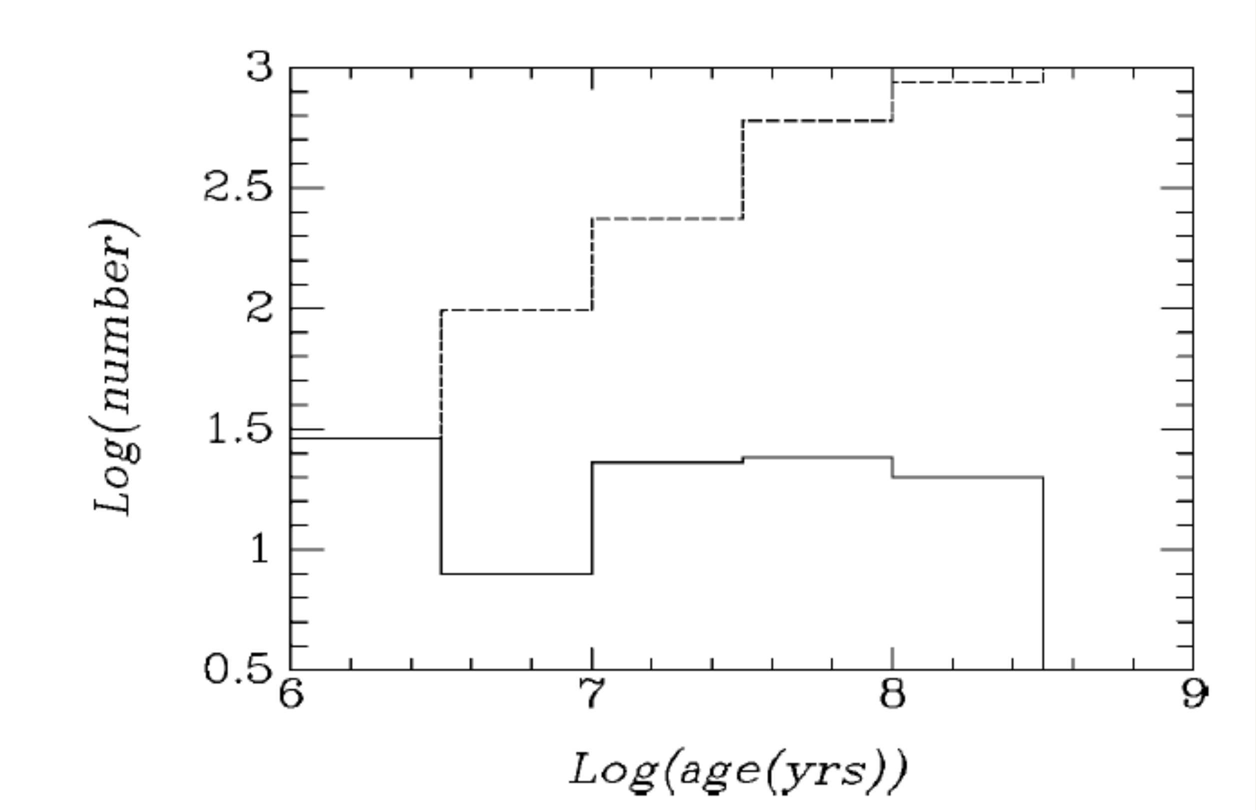


$$t_{cross} < t \leq t_{rlx}$$

Infant Mortality

Predicted number of OC

Observed number of OC

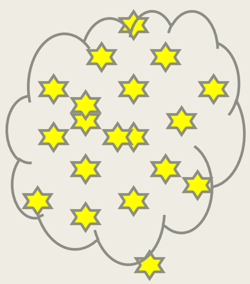


(Lada & Lada 2002)

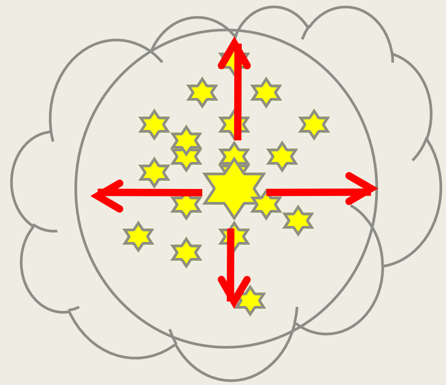
Most of the clusters disperse within 10-100 Myr

Residual Gas Expulsion Scenario

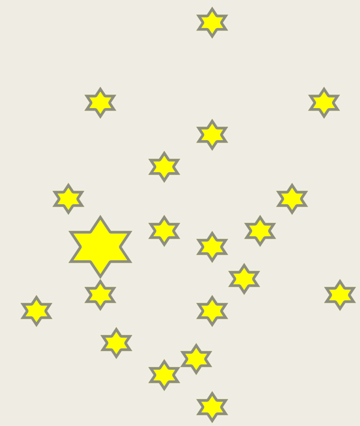
Embedded clusters in Virial Equilibrium



Feedback from massive stars swept out the gas



Supervirial unbound clusters disperse



(e.g., Hills 1980. Kroupa et al. 2001, Goodwin & Bastian 2006, Baumgardt & Kroupa 2009)

Residual Gas Expulsion Scenario: Hills model

Star Formation Efficiency

$$\varepsilon = \frac{M_{stars}}{M_{stars} + M_{gas}}$$

Total Energy

$$E = T + U$$

Virial Equilibrium

$$U = -2T$$

$$U = -\frac{GM^2}{R}$$

$$T = \frac{1}{2}MV^2$$

$$M' = \varepsilon M$$

$$T \propto M$$

$$\mathrm{U} \propto M^2$$

→

$$T' = \varepsilon T$$

$$U' = \varepsilon^2 \mathrm{U}$$

→

$$E' = \varepsilon T + \varepsilon^2 \mathrm{U}$$

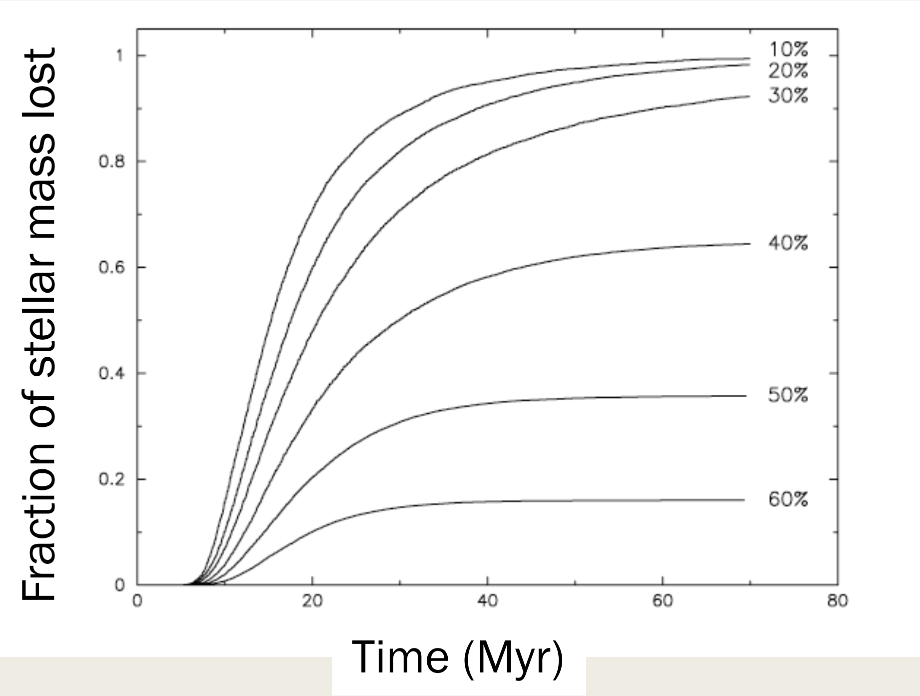
$$E' = \varepsilon\left(\varepsilon - \frac{1}{2}\right)\mathrm{U}$$

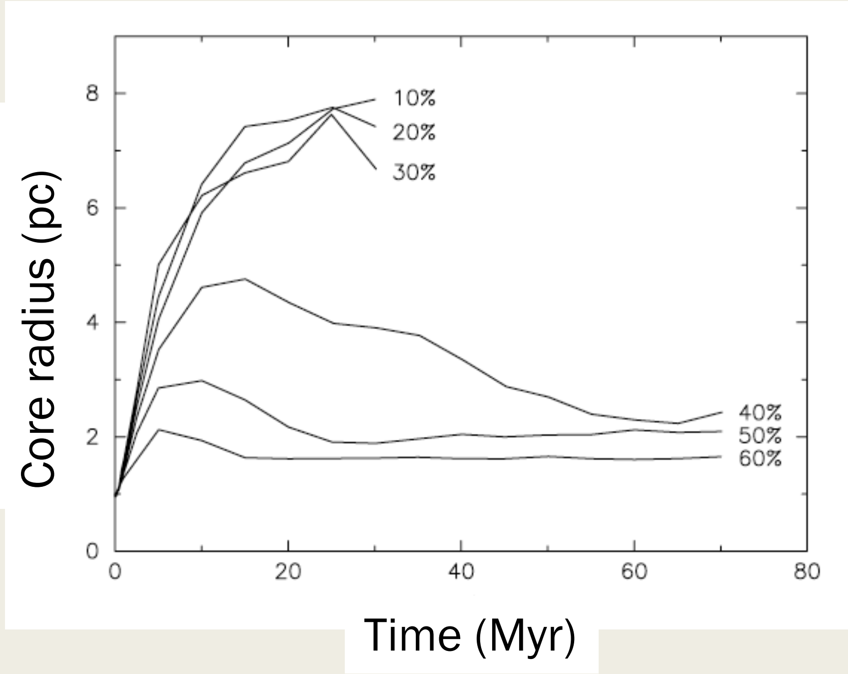
$\varepsilon > 0.5\,, E' < 0$ BOUND

$\varepsilon < 0.5\,, E' > 0$ UNBOUND

(Hills 1980)

Residual Gas Expulsion Scenario: N-body simulations





$\varepsilon > 0.3$ Cluster survive

(Goodwin & Bastian 2006)

$\varepsilon < 0.3$ Cluster disperse

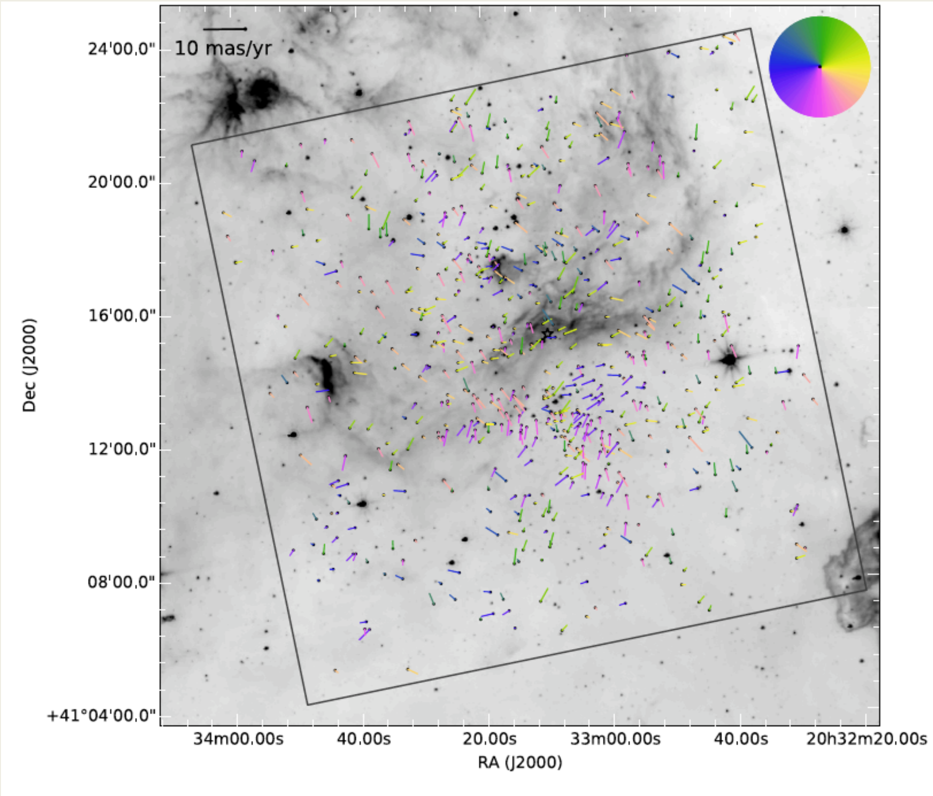
Issues with the Residual Gas Expulsion Scenario

<u>Observational evidence against the model</u>

- Observed star formation efficiency $\varepsilon < 0.1$
- Kinematic properties of stellar associations disagree with the model

<u>Issues with the N-body simulations</u>

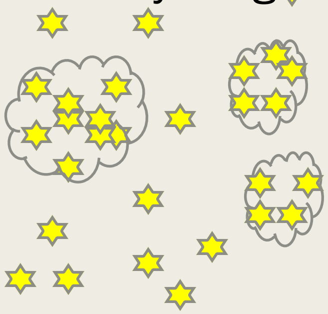
- Irrealistic intial conditions (embedded clusters not spherically symmetric)
- Gas expulsion not instantaneous



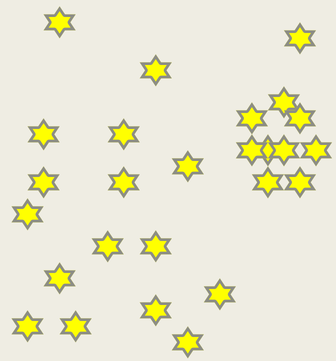
(Wright wt al. 2016)

Cluster evolution : Alternative Scenarios

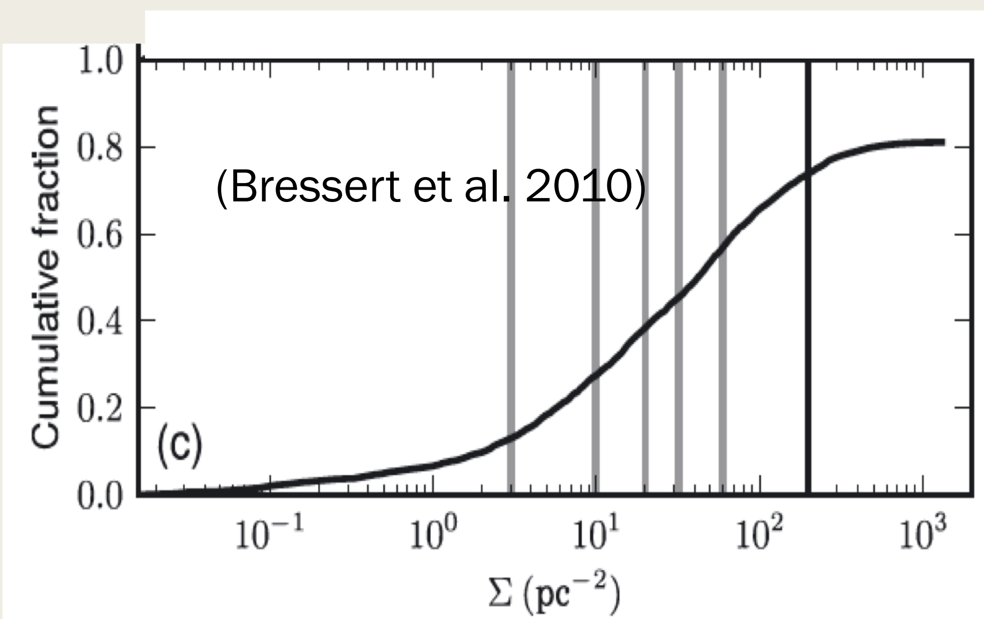
Hierarchical structure spanning large density range



Evolution driven by two-body interaction and feedback is not relevant



Survival of the cluster may depend on intial conditions and outer gravitational field



(e.g., Bressert et al. 2010, Kruijessen et al. 2012, Parker & Dale 2013, Dale et. al 2015)

Stationary equilibrium

$$t > t_{rlx}$$

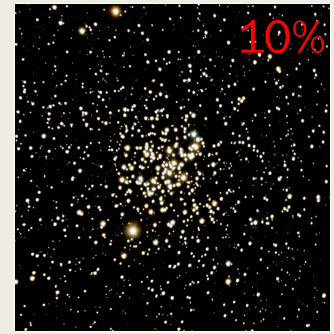
Filaments

< 1 Myr

Stars and Gas

1-10 Myr

Open clusters



0.1-10 Gyr

Galactic field

King surface density profile

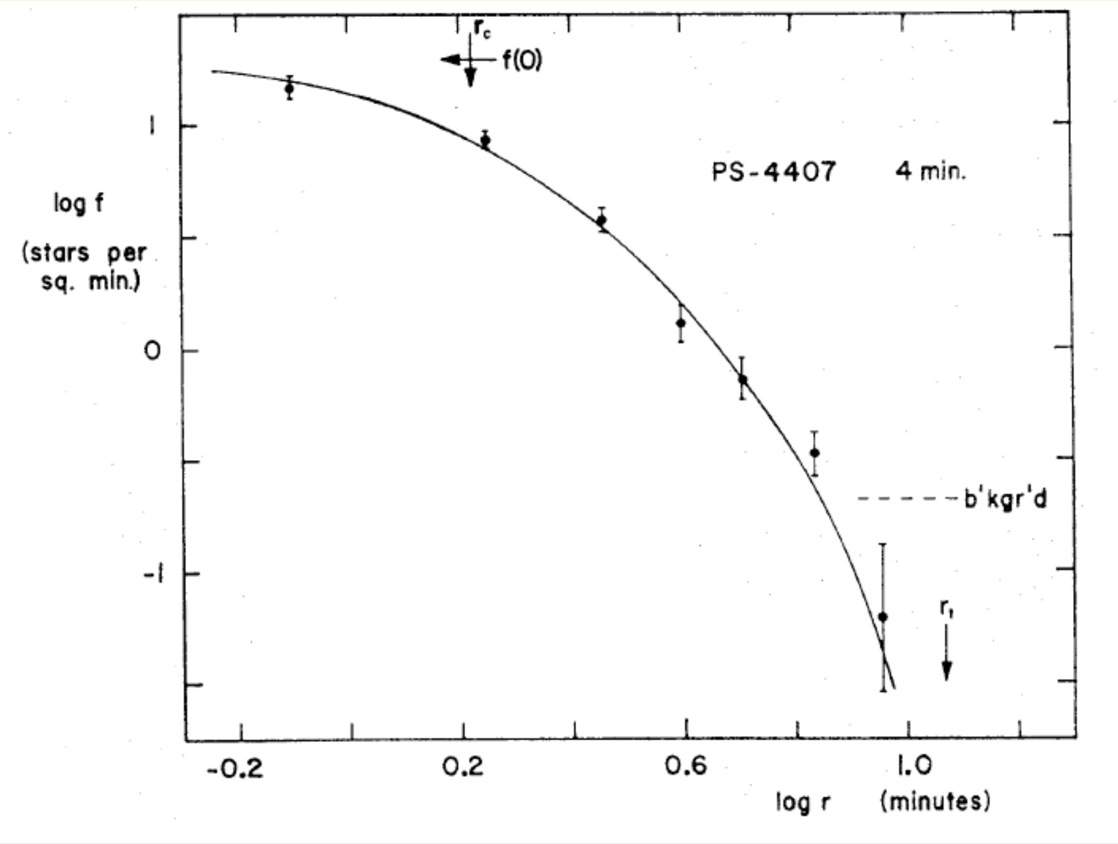
$$\Sigma(r) = \Sigma_0 \left(\frac{1}{(1 + (r/r_c)^2)^{1/2}} - \frac{1}{(1 + (r_t/r_c)^2)^{1/2}} \right)^2$$

Surface density (stars/arcsec^2)

At the core radius r_c
$\Sigma(r) \sim 0.5 \Sigma(0)$

At the tidal radius r_t
$\Sigma(r) \sim 0$

Concentration
$c = \log_{10}(r_t/r_c)$



(King 1962)

Stationary equilibrium

1. Gravitational potential slowly varying

2. Gravitational potential and distribution function slowly varying

3. Spherical symmetry

Distribution Function

$$f(\boldsymbol{x}, \boldsymbol{v}, t)$$

Boltzmann Equation

$$\frac{df}{dt} = \frac{\partial f}{\partial t} + \sum_i \frac{\partial f}{x_i} + \sum_i \frac{\partial f}{v_i}$$

Poisson Law

$$\nabla^2 \phi(\boldsymbol{x}) = 4\pi G\rho$$

$$\frac{1}{r^2}\frac{d}{dr}\left(r^2 \frac{d\phi(r,t)}{dr}\right) = 4\pi G\rho$$

Isothermal sphere equilibrium

$$E = \frac{1}{2}mv^2 + \phi(r)$$

$$f = Ke^{-BE}$$

$$B = \frac{3}{v_m^2}$$

$$\rho(r) = Cr^{-2}$$

$$M(r) = Ar$$

Problems

1. Infinte density at r=0

2. Infinite total mass

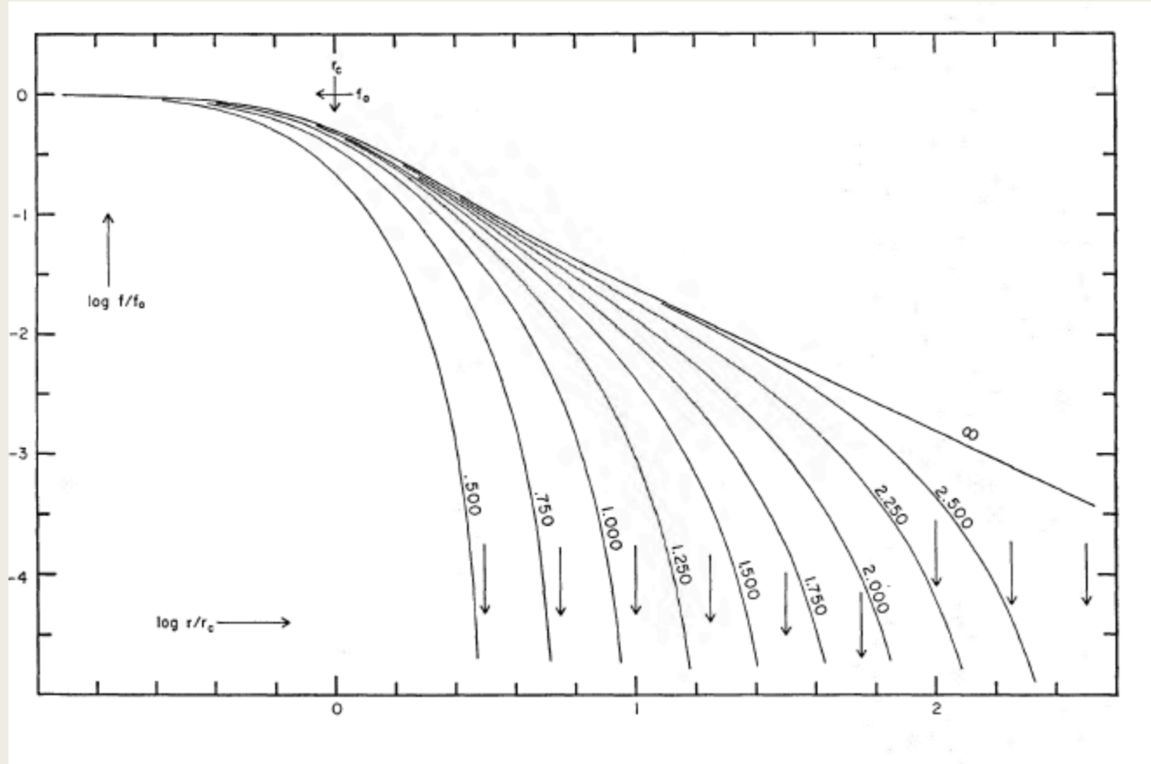
King Models

Core radius

$$\rho(0) = \rho_0$$

$$\rho(r_0) \cong 0.5\rho_0$$

Lowered Isothermal



(King 1966)

$$f=\begin{cases} K(e^{-BE} - e^{-BE_0}) & if\ E < E_0 \\ 0 & if\ E < E_0 \end{cases}$$

Cluster truncated due to the effect of the gravitational field of the Galaxy

Virial equilibrium

$$U + 2T = 0$$

U → Potential Energy

T → Kinetic Energy

(isotropic systems)

$$T = \frac{1}{2} M \langle v^2 \rangle = \frac{3}{2} M\sigma^2$$

M → Mass

v → velocity

σ → Velocity dispersion

$$r_{vir} = \frac{GM^2}{2|U|}$$

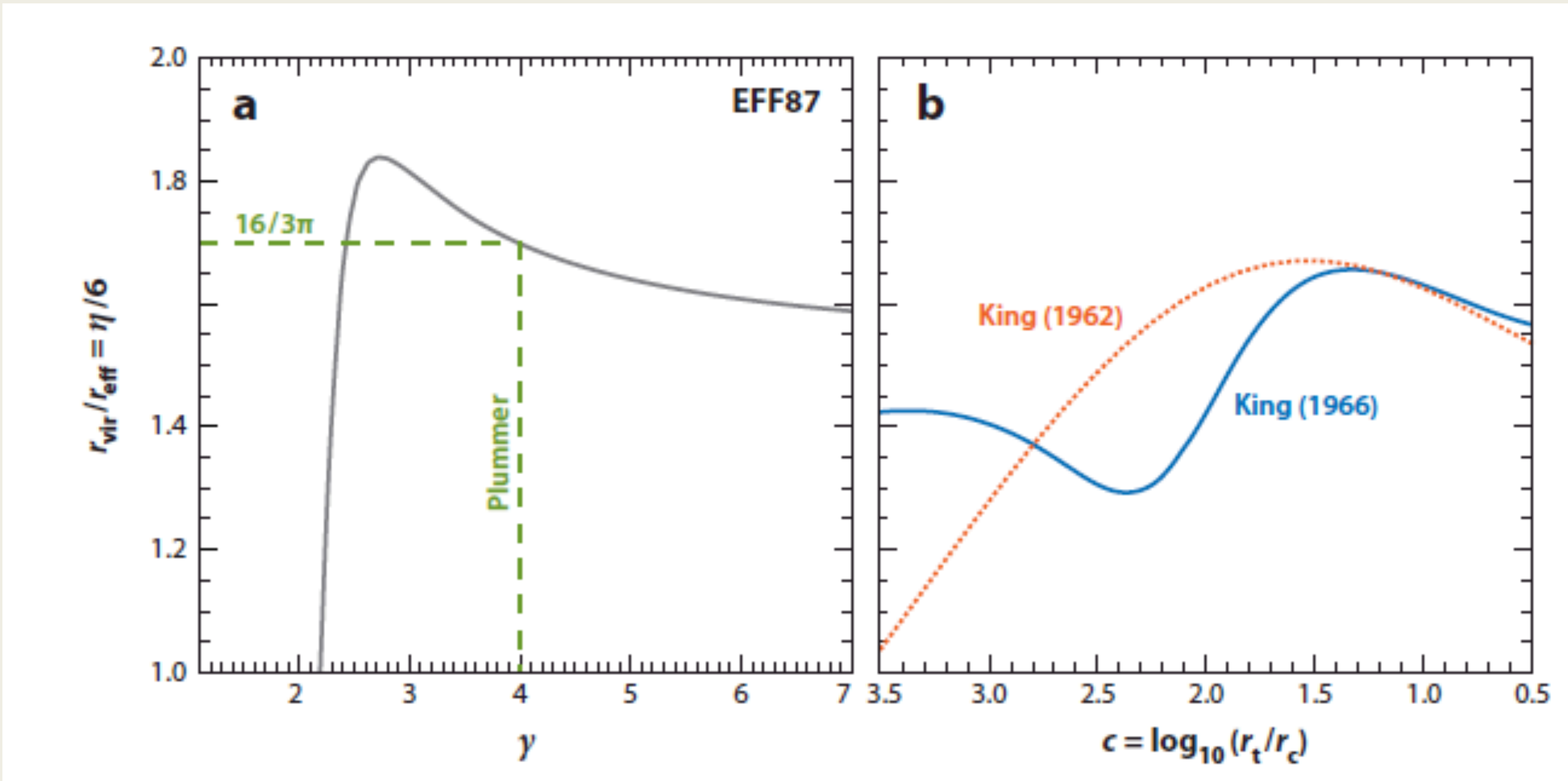
r_{vir} → Virial radius

$$\eta = 6\frac{r_{vir}}{r_{hm}}$$

r_{hm} → Half mass radius

$$\sigma^2 = \frac{GM}{\eta r_{hm}}$$

Virial equilibrium

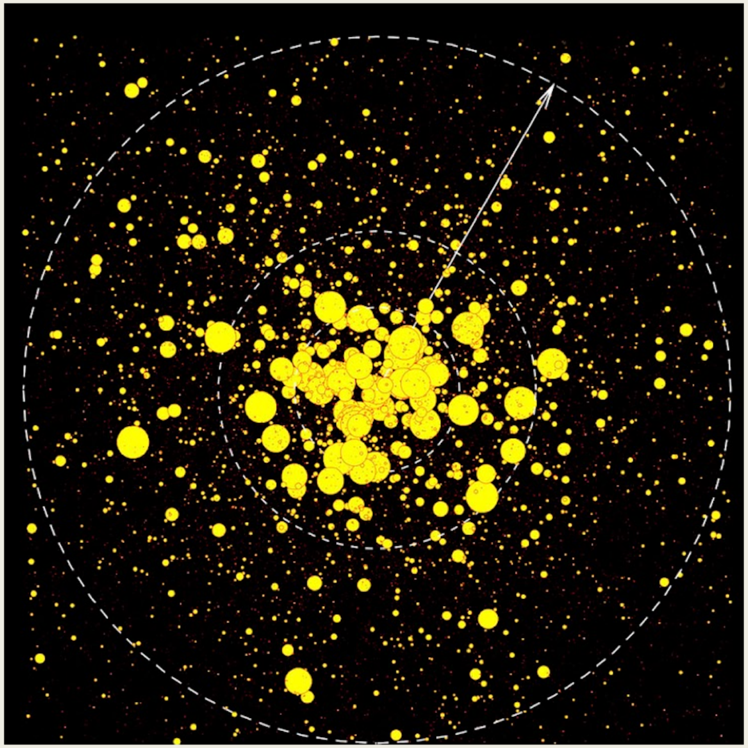


Elson, Fall & Freeman (1987)

$$\Sigma(r) = \Sigma(0)\left(1 + \frac{r^2}{a^2}\right)^{-\gamma/2}$$

Mass Segregation

Massive stars tend to be more concentrated toward the center with respect to low mass stars



1. Primordial Origin

2. Dynamical evolution

Energy equipartition and mass segregation

Energy equipartition ➡ $m_i v_i^2 = m_j v_j^2$ ➡ $v \propto m^{-1/2}$

Massive stars slower, therefore tend to concentrate in the center

Origin of the mass segregation?

Althought Spitzer (1969) showed that:

Population 1

$m = m_1 \quad total\ mass = M_1$

Population 2

$m = m_2 \quad total\ mass = M_2$

$m_2 \gg m_1, \qquad M_2 \gg M_2$

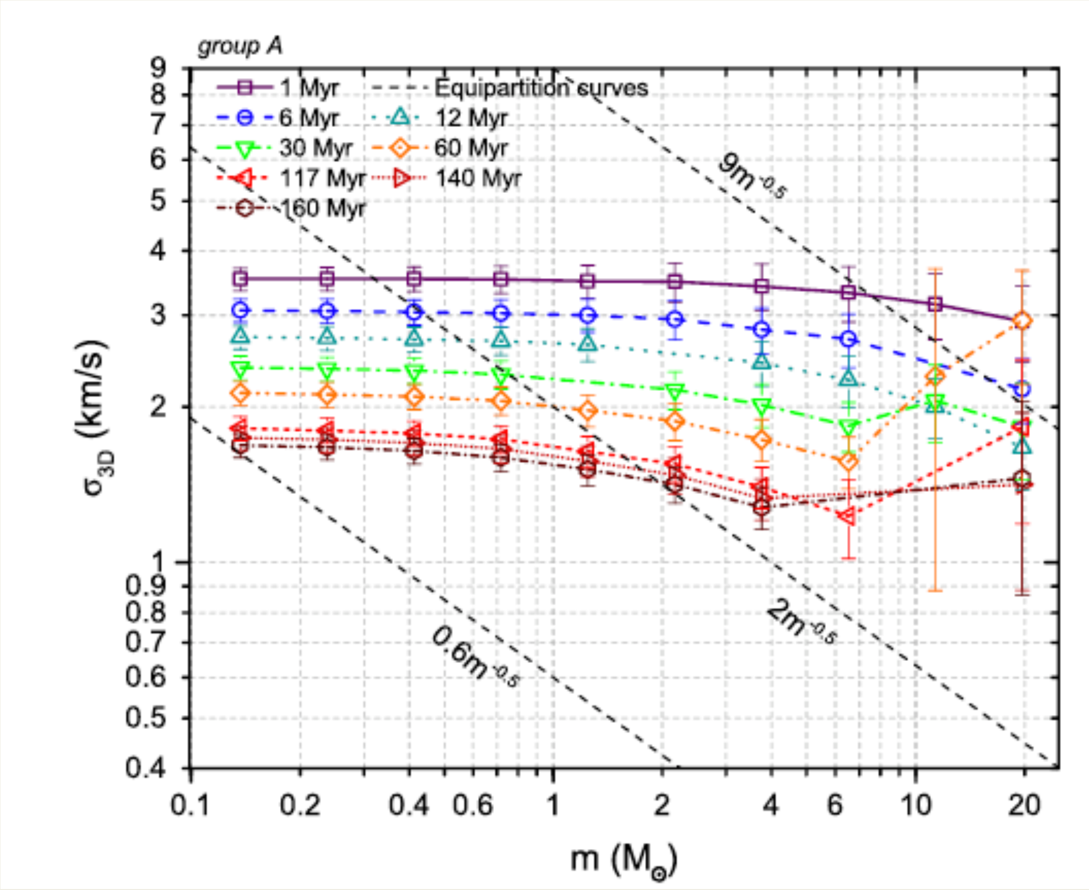
➡

Equipartition is possible only if:

$$M_2 < 0.16 M_1 \left(\frac{m_2}{m_1}\right)^{-3/2}$$

Energy equipartition and mass segregation

Simulations show that neither OC or GC reach equipartition



(Spera et al. 2017)