Stellar populations and star clusters as galactic building blocks

Lecture 2
Constraints from star-formation events a non-varying IMF ?

Selected Chapters on Astrophysics
Charles University, Praha,
November & December 2015

Pavel Kroupa
Argelander Institute for Astronomy (AIfA) University of Bonn

Lecture 1 :
The stellar IMF : solar neighbourhood as average IMF
theoretical expectations : a *variable IMF*

Lecture 2 :
The stellar IMF : constraints from star-forming events **:**
a non-varying IMF ?

Lecture 3 :
The integrated galactic initial mass function (IGIMF) : a new theory
How to calculate the stellar population of a galaxy.

Lecture 4 :
The stellar binary population**:** deriving the birth distribution functions
Binary dynamical population synthesis**:** the stellar populations of galaxies

The IMF
is the key
to our understanding
of the matter cycle
in the Universe.

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Counting stars => LF => PDMF => IMF

$$\Psi(M_{\mathrm{V}}) = -\frac{dm}{dM_{\mathrm{V}}}\,\xi(m)$$

\+ binaries
\+ main sequence stars

corrections for stellar evolution

✓ peak in LF => m-M_V relation

✓ nearby LF ≠ distant LF

? MW-field (Scalo) IMF index
≠ star-cluster/association (Salpeter/Massey) IMF index

star-formation theory (*Jeans-mass vs self-regulation*) :
? - expect IMF variation with density and metallicity
? - unable to account for IMF shape

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The solution found for the IMF *unifies* the two LFs for late-type stars.
This MF is an average or *bench mark* **:**
a *mixture* of many populations comprising the MW disk characterised by $\tau \approx 5\,\mathrm{Gyr}$ and $[\mathrm{Fe/H}] \approx -0.3$.

. . . so let's study stellar populations that are known to have formed in "one go",

i.e. truely co-eval and mono-metallicity, i.e. *simple stellar populations*.

... is a variation (e.g. with metallicity) about the bench mark evident **?**

Clusters

Clusters

Advantages: Stars have same d, τ, z .

But . . .

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Clusters

Advantages: Stars have same d, τ, z .

Disadvantages: If young (to avoid dynamical evolution) need *pre-main sequence models,* and $f_{\rm mult}$ *high*.

If main-sequence age then have *substantial dynamical evolution*.

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The Problem of Youth:

Wuchterl & Tscharnuter (2000)

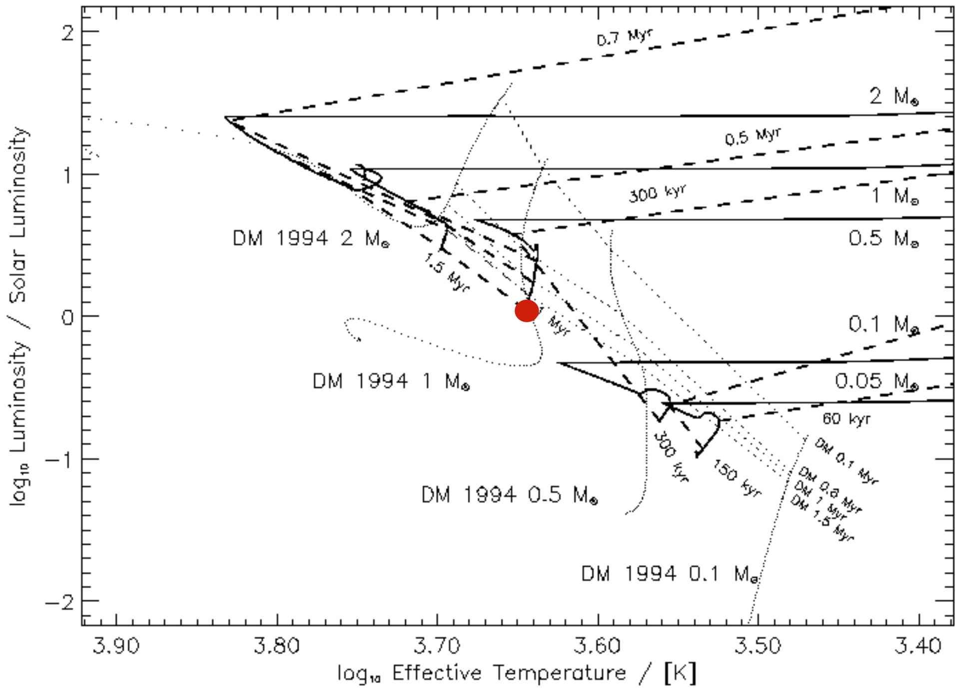

Fig. 4. Hertzsprung-Russell diagram for the early pre-main sequence evolution of 0.05, 0.1, 0.5, 1 and 2 $M_\odot$ cloud fragments (*full lines*), detail of Fig 3. The *dashed* lines are isochrones for the collapse tracks, labelled with the respective ages. Zero age is defined here as the moment when the respective cloud fragment becomes optically thick and the interior thermally locked as the first photosphere forms (Rosseland mean optical depth reaches 2/3). Quasi-hydrostatic tracks for 0.1, 0.5, 1 and 2$M_\odot$, (*dotted tracks*) and the corresponding isochrones for 0.1, 0.6, 1 and 1.5 Myr, (*dotted lines labelled with ages*) (D'Antona and Mazzitelli 1994, 'Alexander + MLT'-case, $\alpha_{ML} = 1.4$) are shown for comparison. Note that, e.g., 0.5 $M_\odot$ at 1 Myr (collapse) corresponds to 1 $M_\odot$ at 1.5 Myr (classical).

Consider an observed star ● :

Classical:

$1\ M_\odot$

> 1.5 Myr

Collapse:

$0.5\ M_\odot$

1 Myr

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Example:

The **Orion Nebula Cluster**

(ONC)

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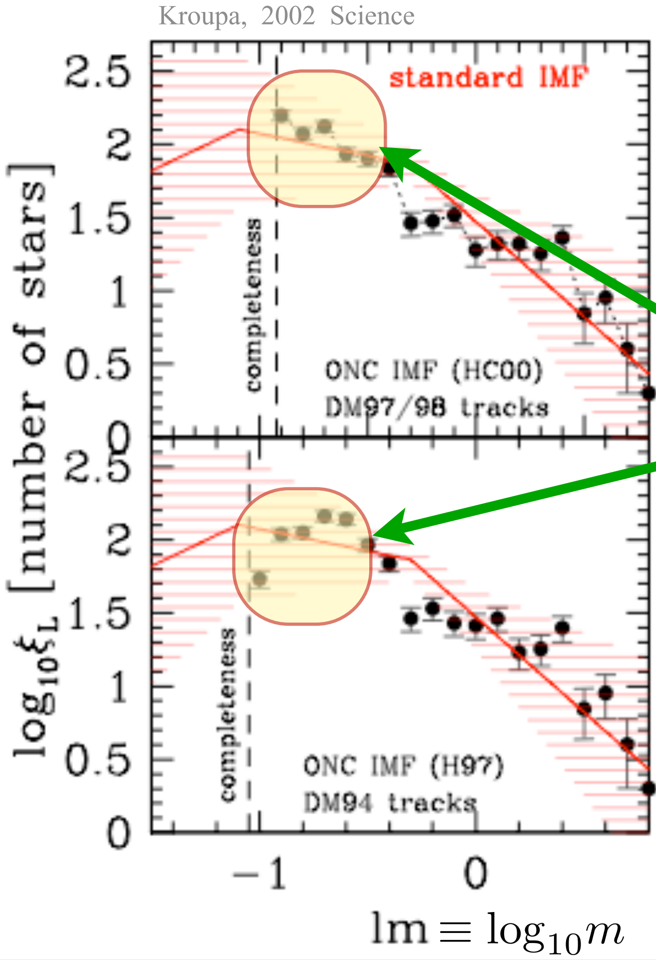

Uncertainties due to pre-main sequence tracks

e.g. the ONC : 1 Myr old

Shape differs for the same data !

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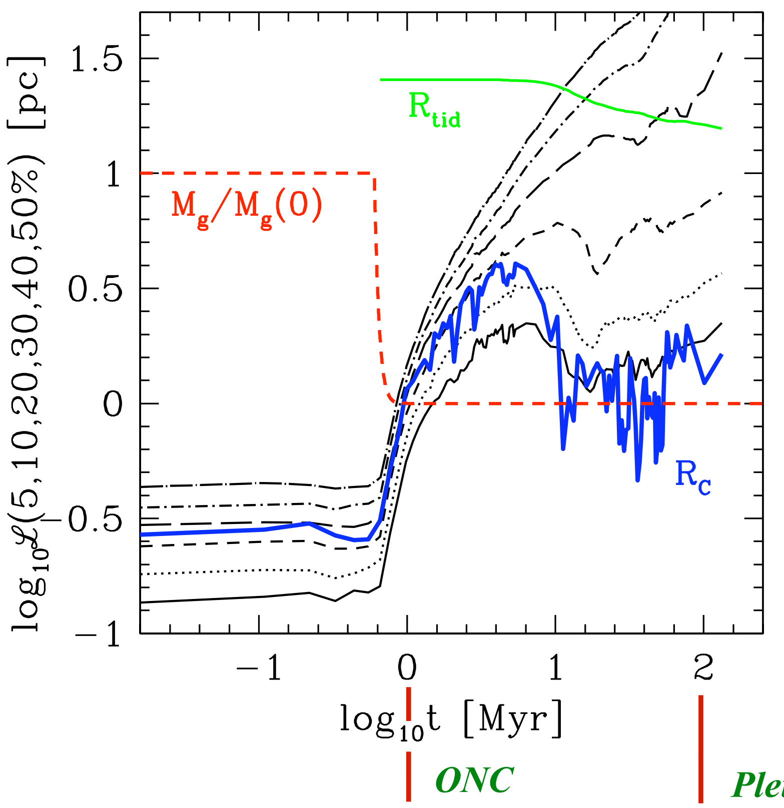
Uncertainties due to very early violent evolution of star clusters



Modell :

$N = 10^4$ (stars + BDs)

$f = 1$

$\epsilon = 33\,\%$

$\tau_{gas} \lesssim t_{cross}$

Kroupa, Aarseth & Hurley (2001)

$\xi_{cluster}(m) \neq \xi(m)$

already by ≈ 1 Myr ?

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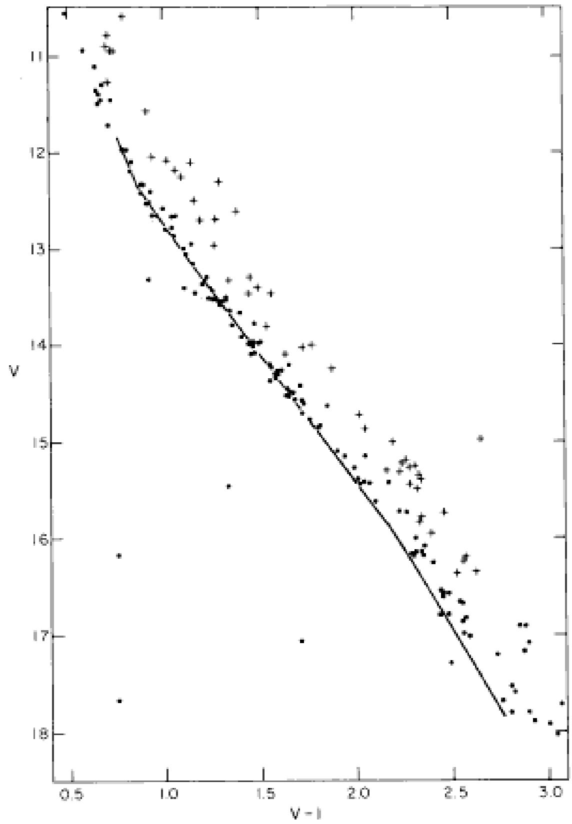

FIG. 7.—Same as Fig. 1, except that the main-sequence line has been shifted downward by 0.25 mag. The larger symbols in this diagram denote stars identified as photometric binaries.

Uncertainties due to binaries in clusters

Pleiades (Stauffer 1984; Kaehler 1999)

$d = 126\mathrm{pc}$, age $= 100\mathrm{Myr}$

Stauffer $f_{\mathrm{phot}} \approx 0.26$

Kaehler $f_{\mathrm{phot}} \approx 0.6 - 0.7$ possible

The binary fraction f evolves with time :

$$f = \mathrm{fn}\left(\frac{t}{t_{\mathrm{cross}}}\right)$$

but $t_{\mathrm{cross}} = \mathrm{fn}(t)$

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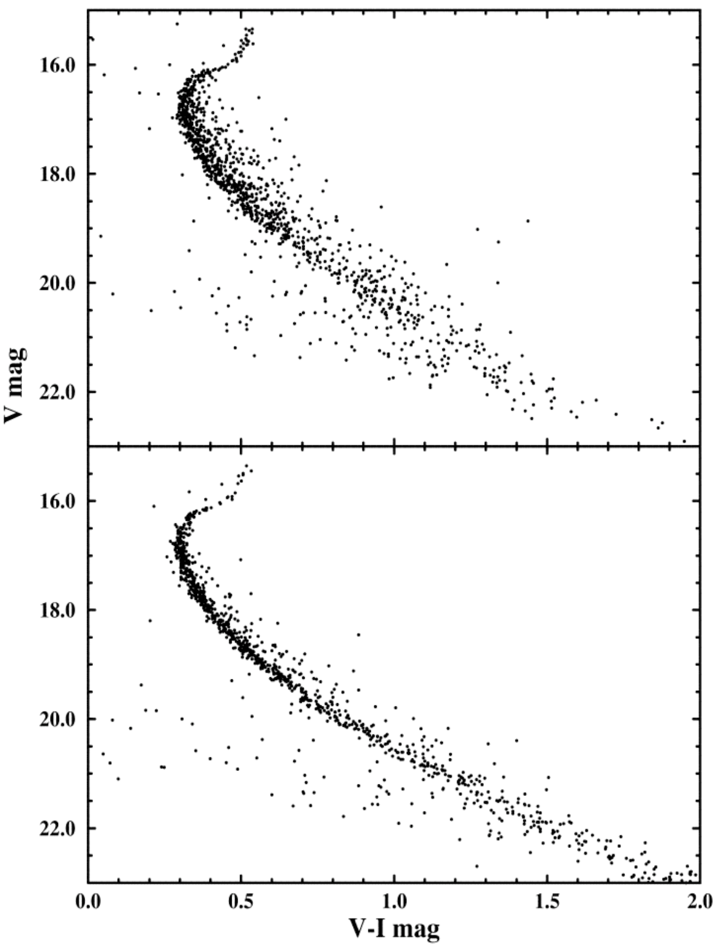

GC *NGC6752*

(Rubenstein & Bailyn 1997)

inner core: $0.15 \lesssim f_{\mathrm{phot}} \lesssim 0.4$

outer region: $f_{\mathrm{phot}} \lesssim 0.16$

Generally:

$f_{\mathrm{GC}} < f_{\mathrm{popI}}$

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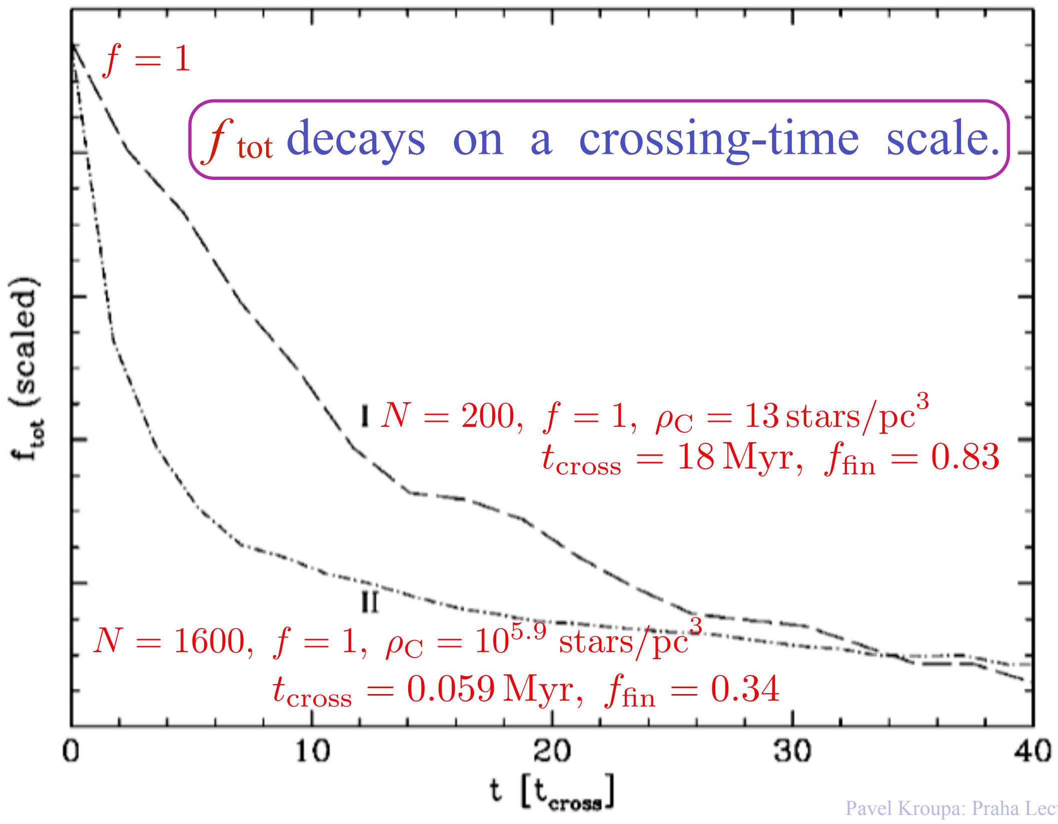
N-body Models of Binary-Rich Clusters

(Kroupa 1995, Kroupa 2000)



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N-body and analytical Models of Binary-Rich Clusters

(Marks, Kroupa, Oh 2011)

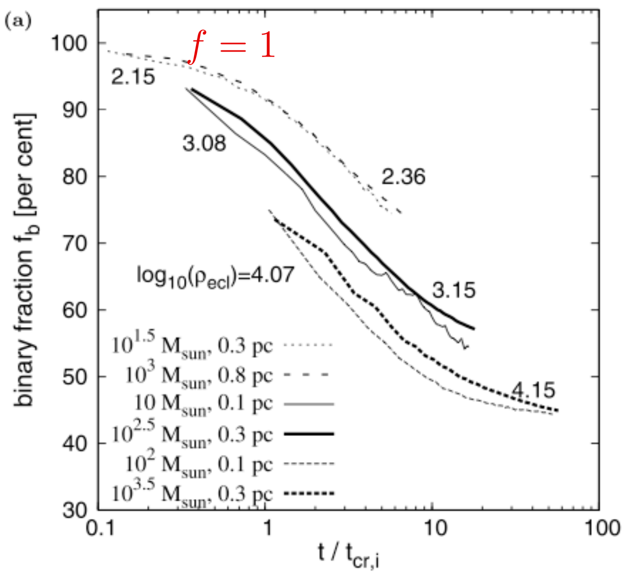

Figure 3. Time evolution of the binary fraction in some model clusters in dependence of (a) the number of crossing-times and (b) the number of relaxation times. Models having the same density ($t_{\rm cr} \propto \rho_{\rm ecl}^{-0.5}$) in panel (a) evolve their binary fraction in the same way, while the corresponding tracks in panel (b) lie apart. Models with similar initial velocity dispersion but different $t_{\rm cr}$ and $t_{\rm rel}$ follow similar tracks in panel (b). In panel (a) the numbers are $\log_{10}(\rho_{\rm ecl}/M_\odot\ \rm pc^{-3})$ and in panel (b) the numbers are $\sigma_{\rm ecl}^2/\rm km^2\ s^{-2}$.

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N-body and analytical Models of Binary-Rich Clusters

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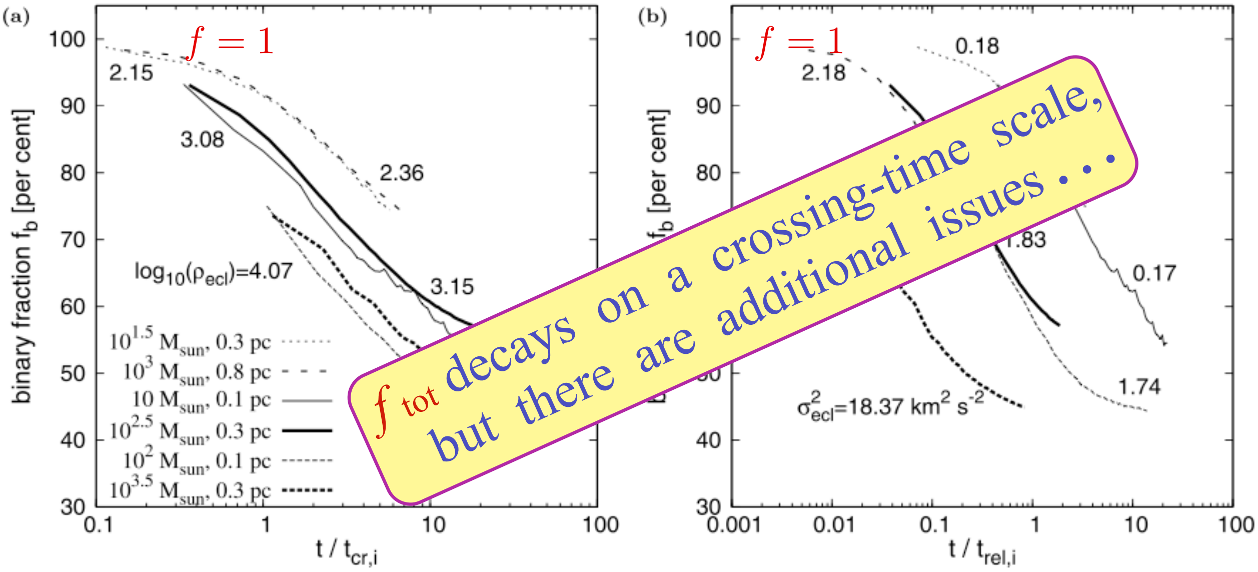

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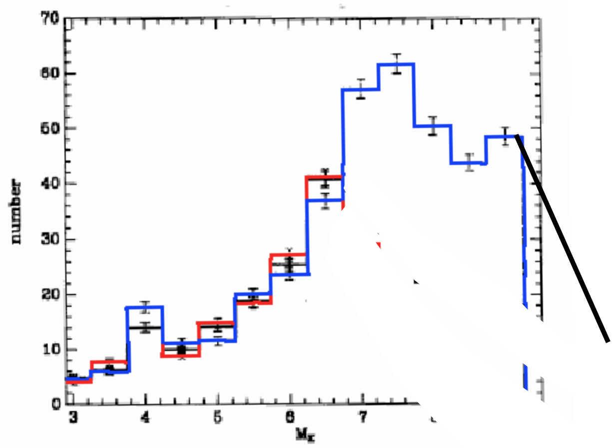
N-body Models of Binary-Rich Clusters

(Kroupa 1995)

$f = 1$ $\qquad 20 \times (N = 400\,\text{stars})$



individual-star LF $\qquad t = 0$

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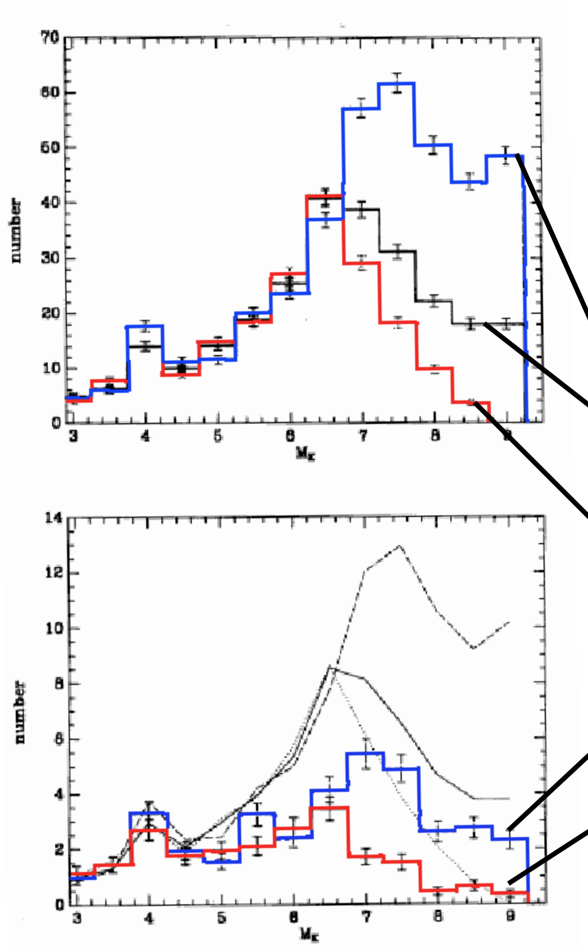

N-body Models of Binary-Rich Clusters

(Kroupa 1995)

$f = 1 \qquad 20 \times (N = 400\,\mathrm{stars})$

individual-star LF $\quad t = 0$

system LF $\quad t = 10^9$ yr, $f = 0.48$

system LF $\quad t = 0$, $f = 1$

In the cluster :

individual-star LF

system LF $\longrightarrow$ $\xi_{\mathrm{obs}}(m) \neq \xi_{\mathrm{true}}(m)$

$t = 44\, t_{\mathrm{cross}} = 5 \times 10^8$ yr

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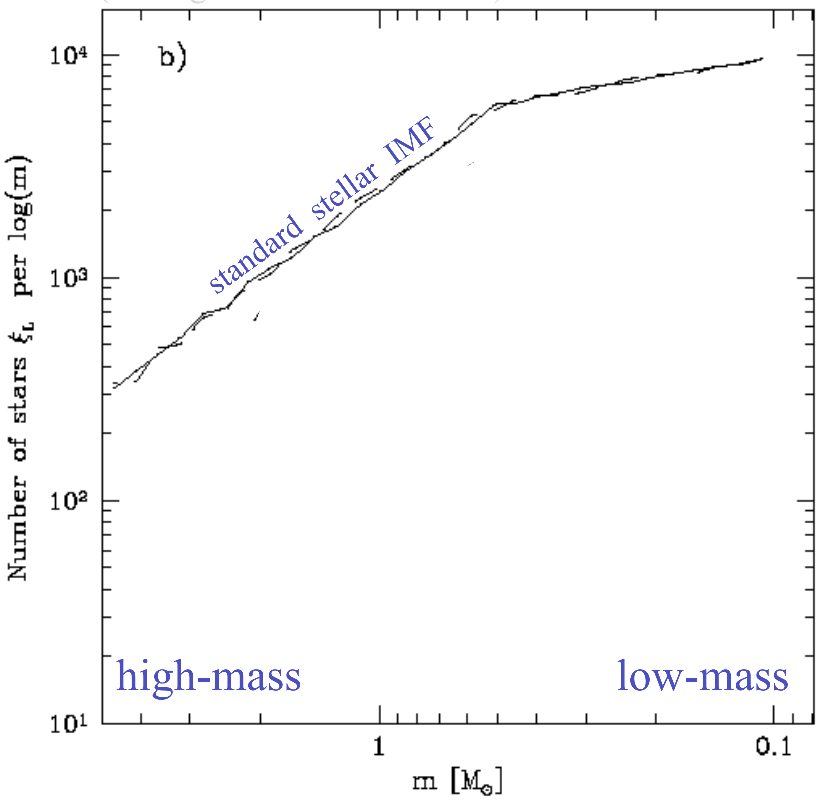
MF(t) due to cluster evolution

(Baumgardt & Makino 2003)



$f = 0$

——— $N = 1.28 \times 10^5$

– – – – $4 \times (N = 8000)$

t = 0
t = 0.3 Tdiss
t = 0.6 Tdiss
t = 0.9 Tdiss

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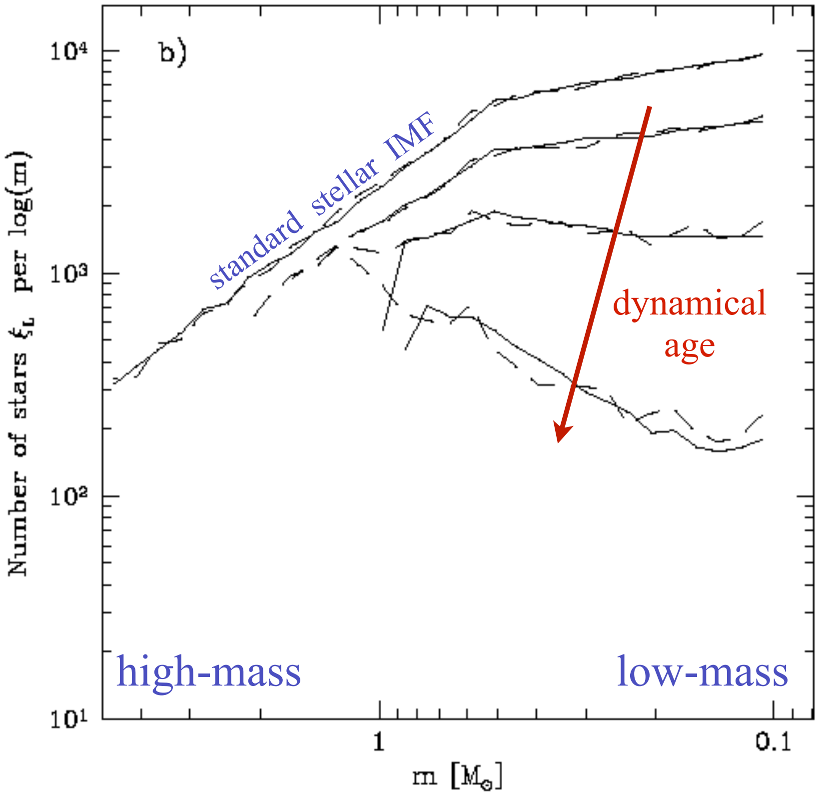
MF(t) due to cluster evolution

(Baumgardt & Makino 2003)



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$4 \times (N = 8000)$

t = 0

t = 0.3 Tdiss

t = 0.6 Tdiss

t = 0.9 Tdiss

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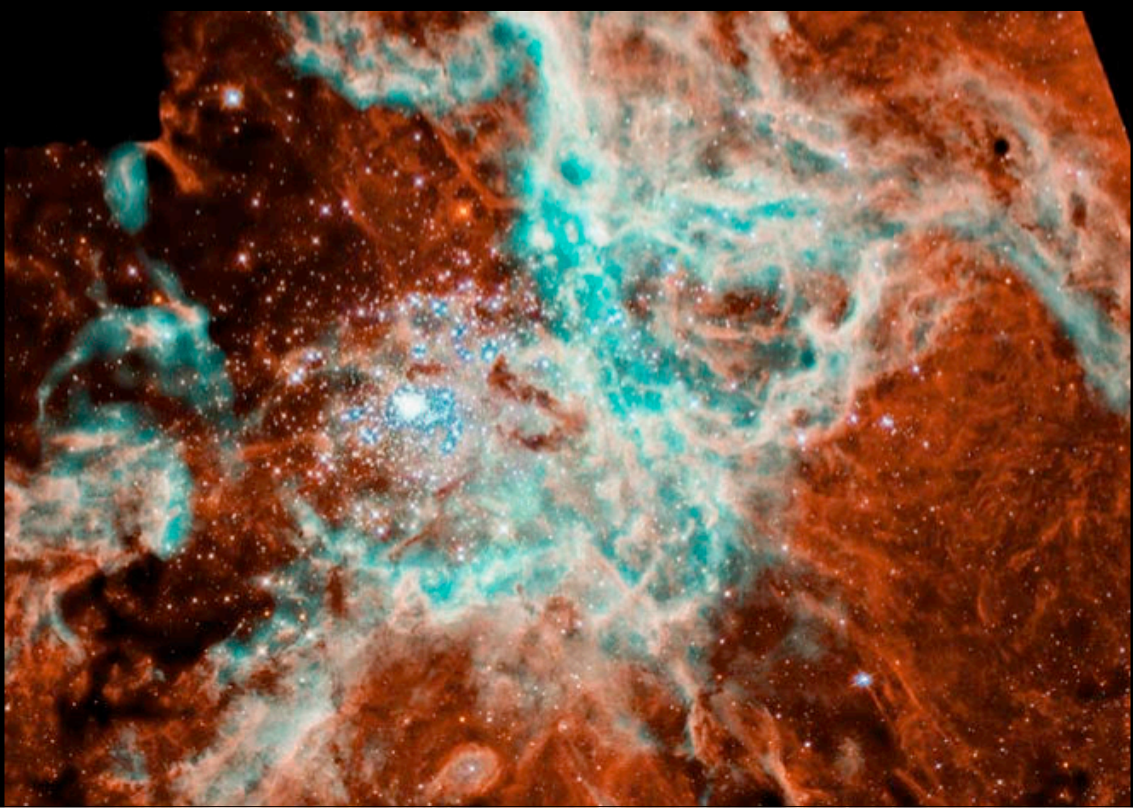
Massive stars in clusters



OB stars in clusters / HII regions

Two competing processes:

Mass segregation $t_{\rm msgr} \approx 2 \left(\frac{m_{\rm av}}{m_{\rm massive}}\right) t_{\rm relax}$ $t_{\rm relax} = \frac{21}{\ln(0.4N)} \left(\frac{M_{\rm ecl}}{100\,M_\odot}\right)^{\frac{1}{2}} \left(\frac{1\,M_\odot}{m_{\rm av}}\right) \left(\frac{R_{0.5}}{1\,{\rm pc}}\right)^{\frac{3}{2}}$	***e.g.*** $t_{\rm relax} \approx 0.6\,{\rm Myr}$ for pre-exposed ONC ↓ $t_{\rm msgr} \approx 0.12\,{\rm Myr} \ll$ age of ONC

Core decay $t_{\rm decay} \approx N_{\rm m} \times t_{\rm core,cross}$ $t_{\rm cross}^{\rm core} \approx 5 \left(\frac{M^{\rm core}}{100\,M_\odot}\right)^{-\frac{1}{2}} \left(\frac{R_{0.5}^{\rm core}}{1\,{\rm pc}}\right)^{\frac{3}{2}}$	***e.g.*** $R_{\rm core} \approx 0.02\,{\rm pc}$, $M_{\rm core} \approx 150\,M_\odot$ $t_{\rm cross}^{\rm core} \approx 1.2 \times 10^4\,{\rm yr}$ ↓ $t_{\rm decay} \approx 10^4 - 10^5\,{\rm yr} \ll$ age of ONC

(Pflamm-Altenburg & Kroupa 2006)

Note:

46 % of all O stars are runaways;

17.4 % of all O stars have v>30 km/s;

(Stone 1991)

4 % of B stars are runaways.

10% of all runaway O stars are binaries.

(Gies & Bolton 1986)

⟶ Qualitative consistency with ***dynamical ejections*** from cluster cores. (Clarke & Pringle 1995; Pflamm-Altenburg & Kroupa 2006; Oh, Kroupa & Pflamm-Altenburg 2015)

Note:

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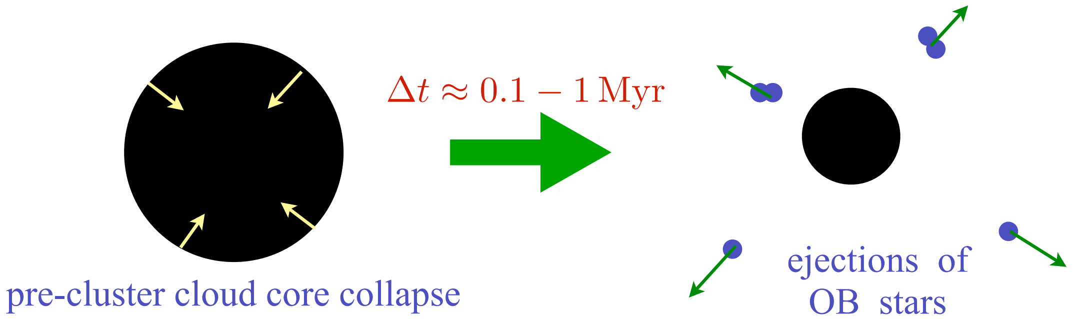


Extracting the IMF for individual clusters is therefore an impossible task.

Kroupa et al. 2013 :

It should be noted that the IMF is not a measurable quantity: Given that we are never likely to learn the exact dynamical history of a particular cluster or population, it follows that we can *never* ascertain the IMF for any individual cluster or population. This can be summarized concisely with the following theorem:

The IMF Unmeasurability Theorem

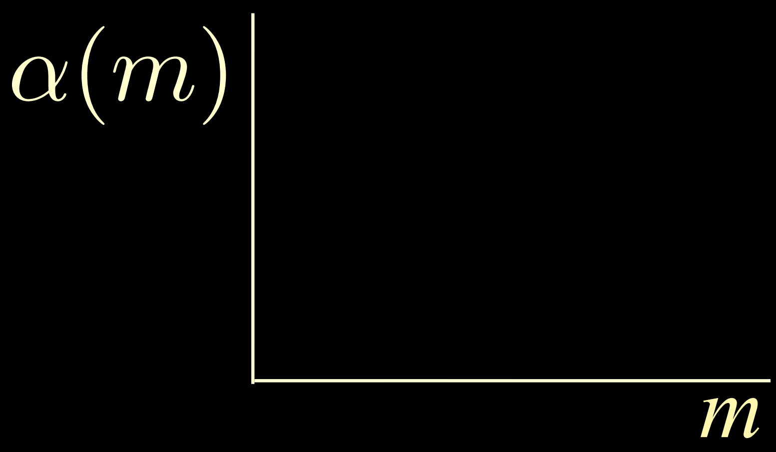
The IMF cannot be extracted directly for any individual stellar population.

Proof: For clusters younger than about 1 Myr, star formation has not ceased, and the IMF is therefore not assembled yet, and the cluster cores consisting of massive stars have already dynamically ejected members (Pflamm-Altenburg and Kroupa 2006). Massive stars ($m \gtrsim 30\, M_\odot$) leave the main sequence before they are fully assembled (Maeder and Behrend 2002). For clusters with an age between 0.5 and a few Myr, the expulsion of residual gas has lead to a loss of stars (Kroupa et al. 2001). Older clusters are either still loosing stars due to residual gas expulsion or are evolving secularly through evaporation driven by energy equipartition (Vesperini and Heggie 1997; Baumgardt and Makino 2003). There exists thus no time when all stars are assembled in an observationally accessible volume (i.e., a star cluster). An observer is never able to access all phase-space variables of all potential members of an OB association. The field population is a mixture of many star-formation events whereby it can practically not be proven that a complete population has been documented. □

. . . **but :** use measurements of the IMF
in *many star clusters* as
the basis for a
statistical analysis **:**

The alpha-plot

$$\xi(m) \propto m^{-\alpha(m)}$$



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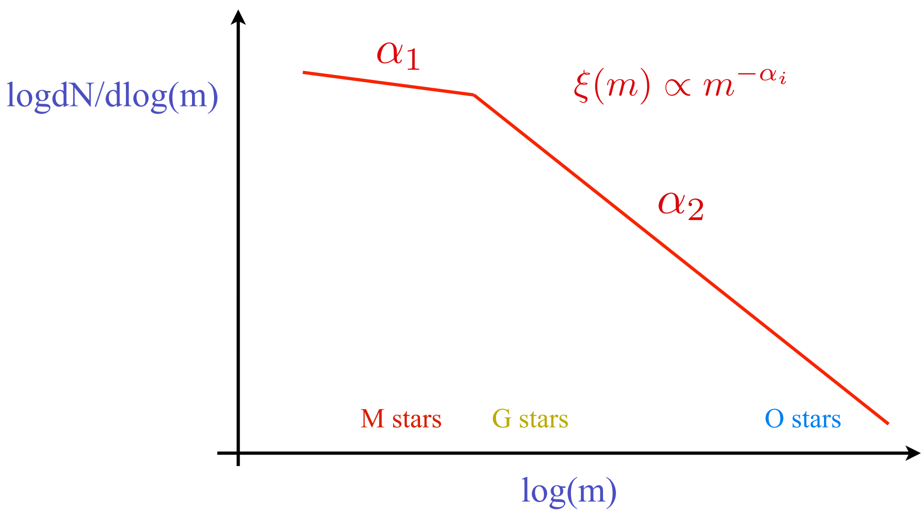
IMF = the distribution of stellar masses born together.

$$\xi(m)\, dm = dN = \text{Nr. of stars in interval } [m, m+dm]$$



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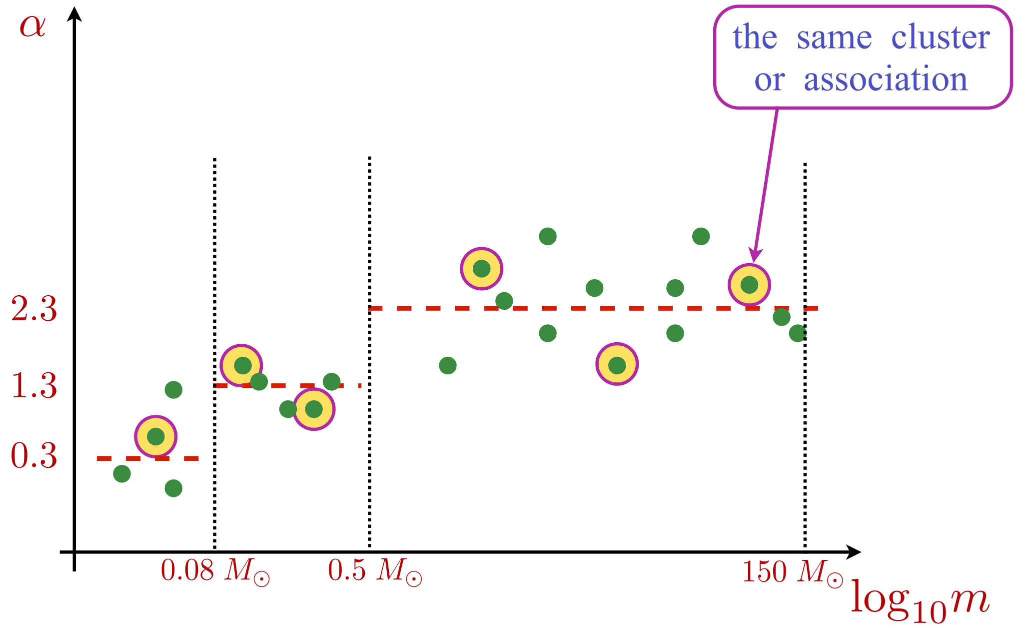
The alpha plot : $\xi(m) \propto m^{-\alpha(m)}$

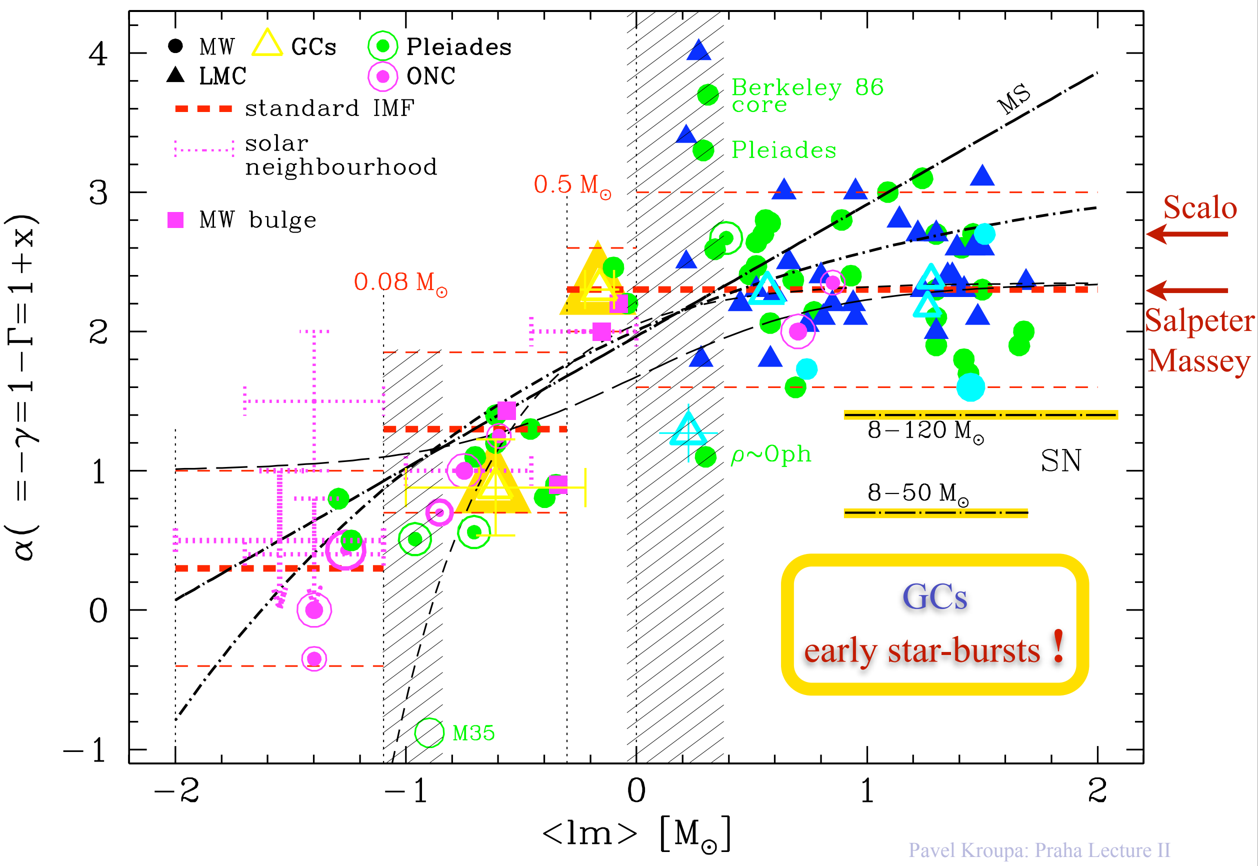
(Scalo 1998; Kroupa 2001)



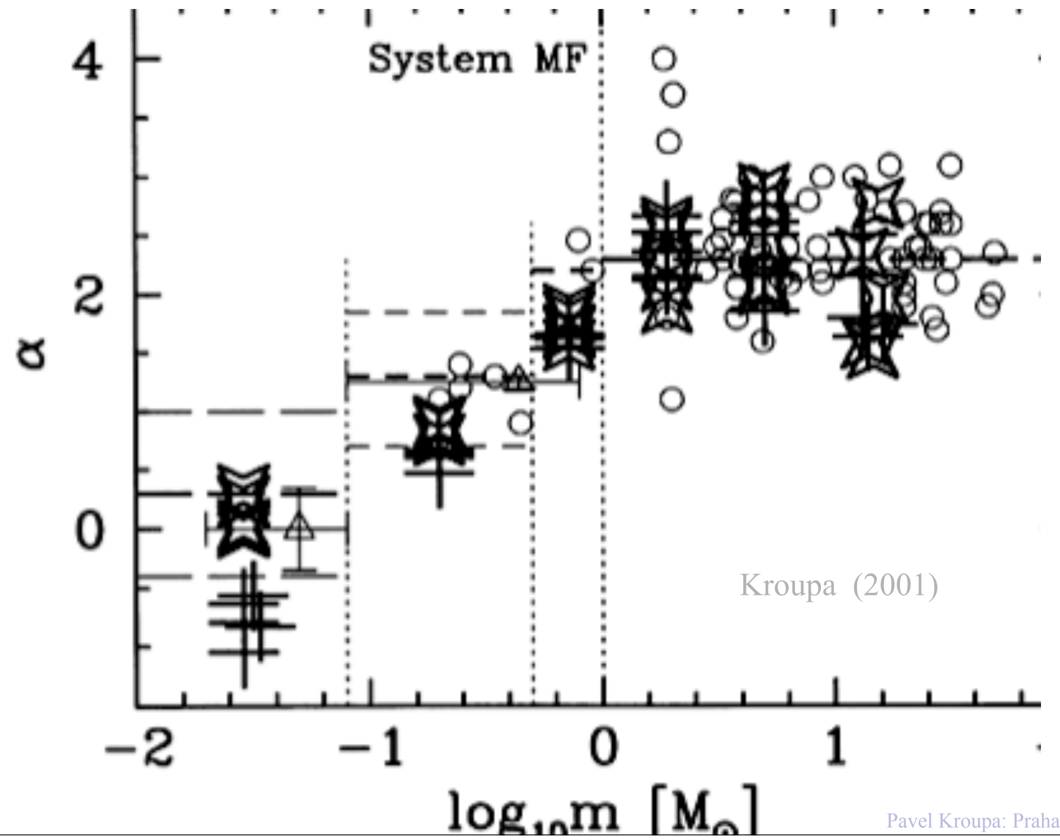
Good working hypothesis: *The IMF is universal.*

It is the same, *independent* of the *physical conditions* of star formation.

The α - plot $\xi(m) \propto m^{-\alpha(m)}$



The theoretical alpha plot for clusters with $N = 3000$ stars



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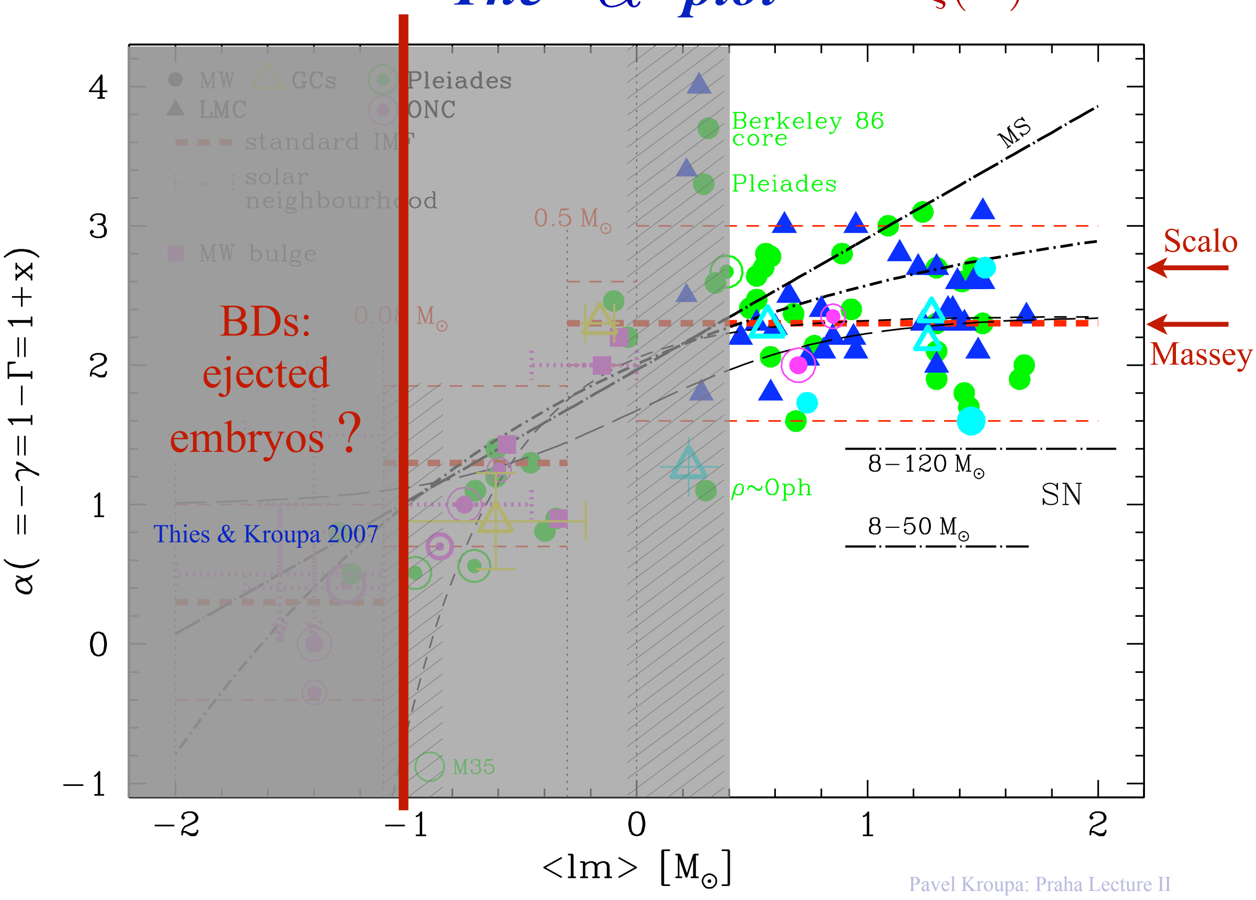
The α - plot $\xi(m) \propto m^{-\alpha(m)}$



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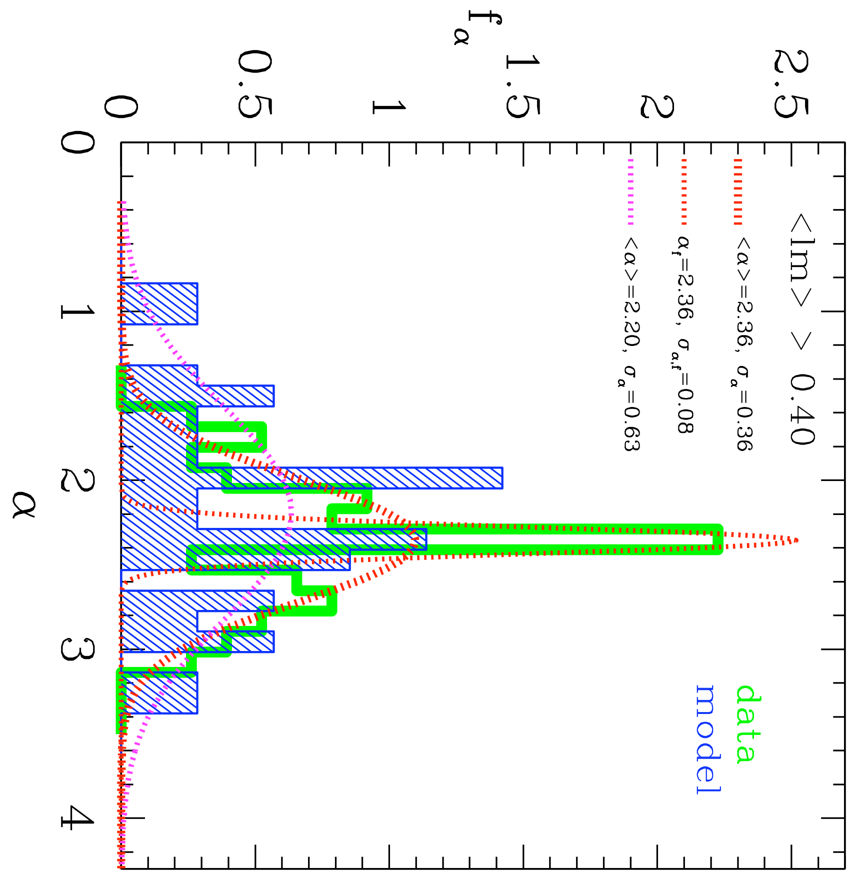

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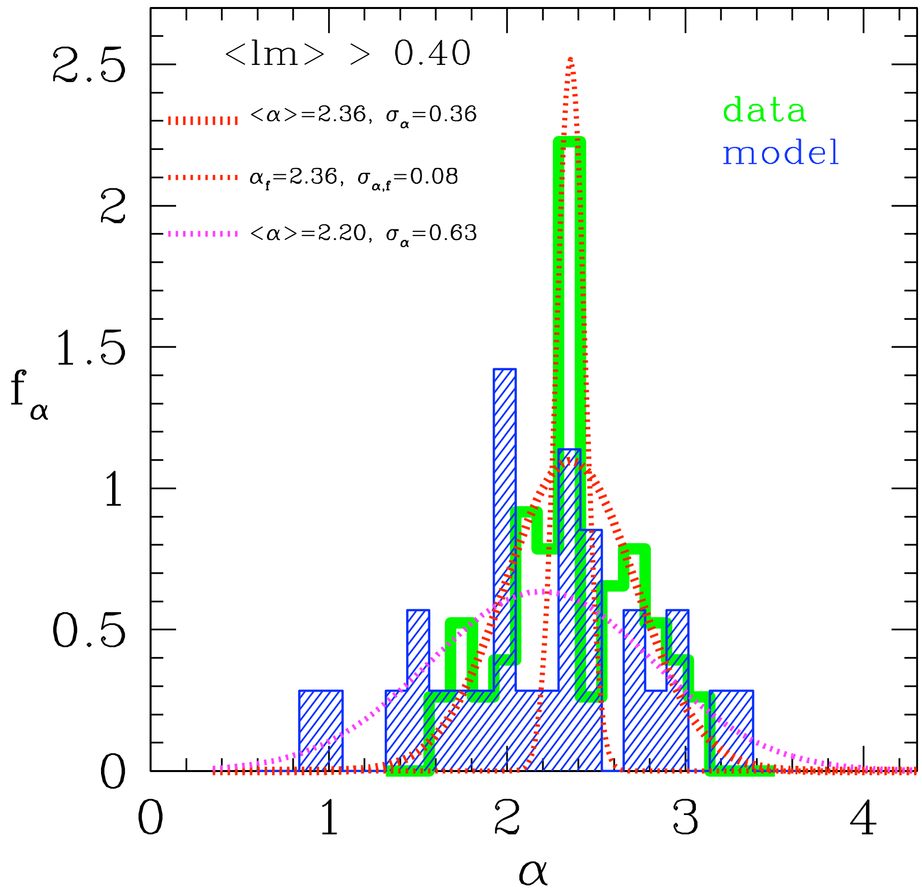

Kroupa 2002

1. No asymmetry

→

binaries cannot resolve the *Scalo vs Massey* discrepancy.

2. Model *worse* than data **!?**

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Observations

of well-resolved populations

show

the IMF to be universal !

More precisely : the available star-by-star data (until about 2009: Dabringhausen et al.) indicated no systematic variation nor did the observationally deduced dispersion of alpha values violate the expected statistical variation, turning out to be even smaller in fact.

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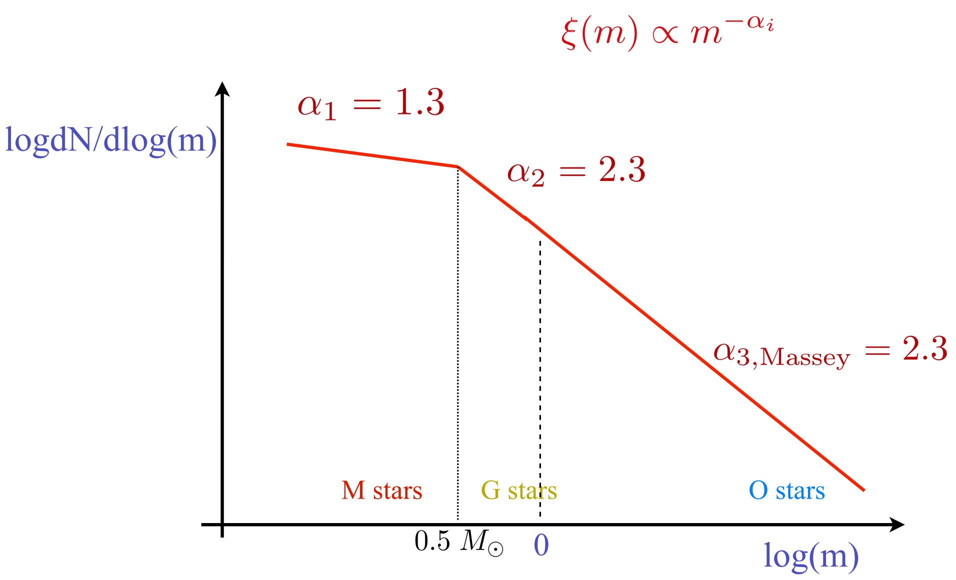
→ universal "canonical" *two-part* power-law IMF :



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According to the standard/canonical stellar IMF :

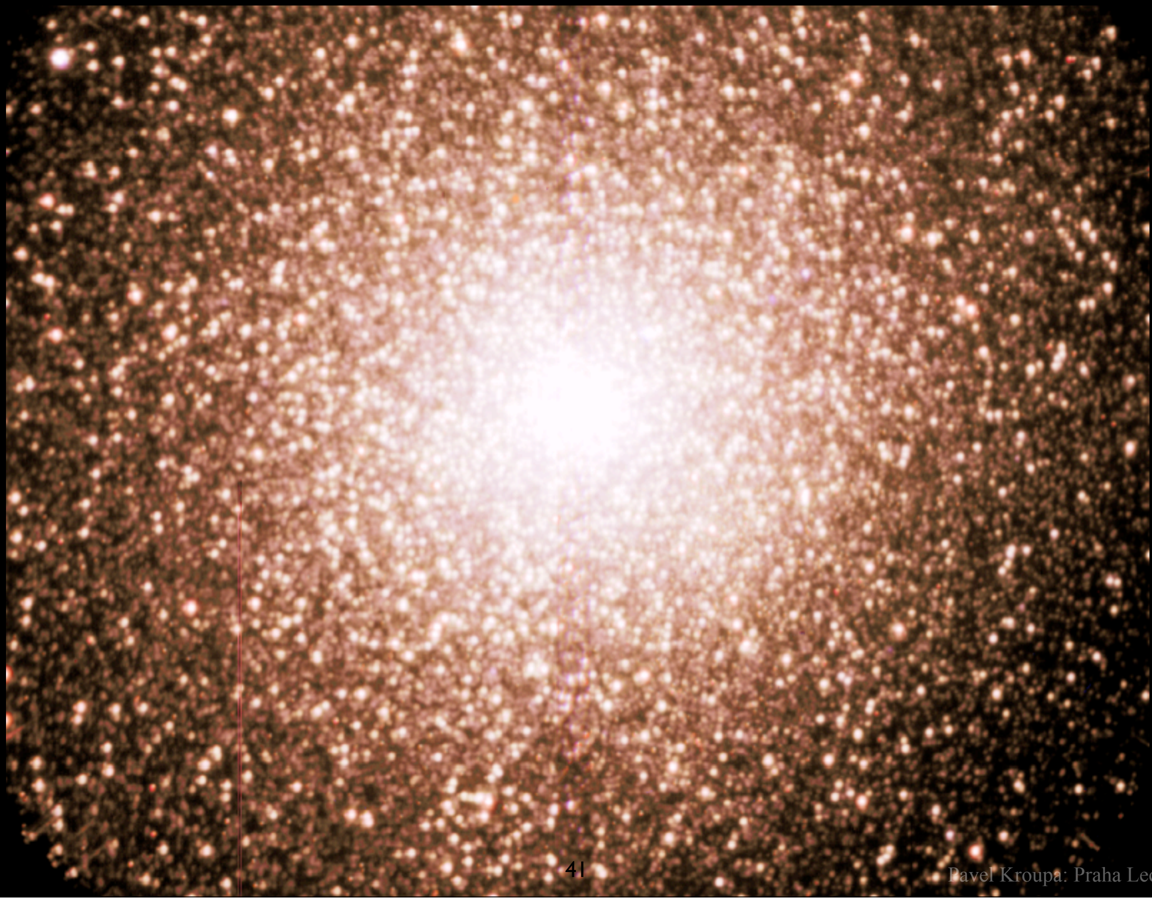
Kroupa et al. 2013

mass range $[M_\odot]$	% by number	% by mass
0.01 - 0.08	37,2	4,1
0.08 - 0.5	47,8	26,6
0.5 - 1	8,9	16,1
1 - 8	5,7	32,4
8 - 120	0,40	20,8
$<m>$	0,38 $M_\odot$	

But :

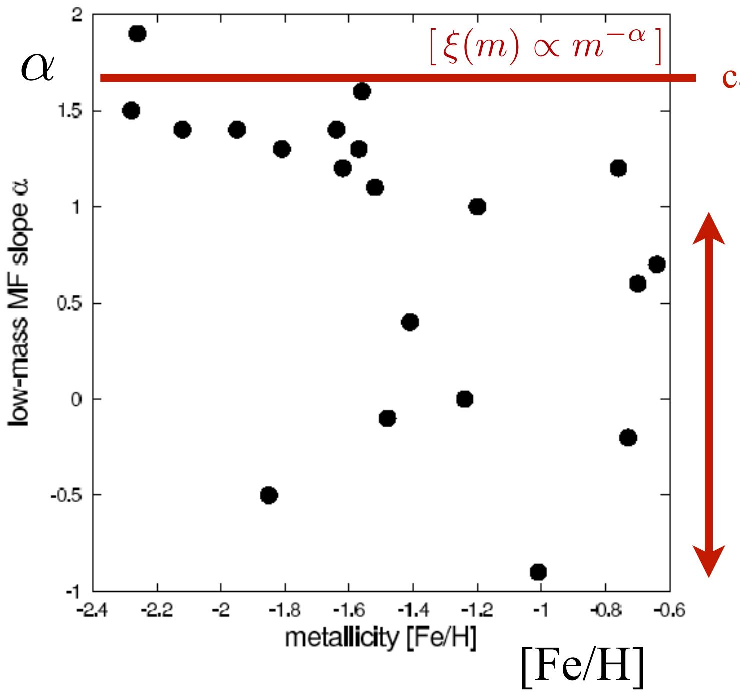
Recent evidence for systematic IMF variation with [Fe/H] ?

47 Tucannae $N \approx 10^6$ age $\approx$ 11 Gyr



A sample of 20 Galactic GCs with solid global MF measurements from deep HST or VLT data.

(de Marchi, Paresce & Pulone 2007)

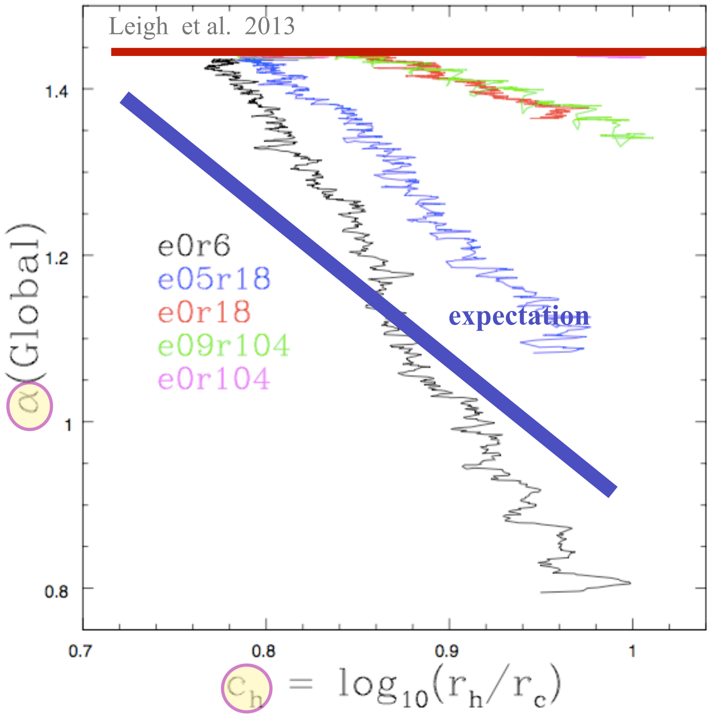


canonical (universal) IMF

Bottom-light MF **:**
(fewer low-mass stars)

but trend with [Fe/H] opposite to theoretical expectation from SF **!**

The expected evolution of the MF in the alpha - concentration diagramme



canonical (universal) IMF

normal
low-mass star population

too few
low-mass stars

low-concentration clusters ought
to be
dynamically less evolved

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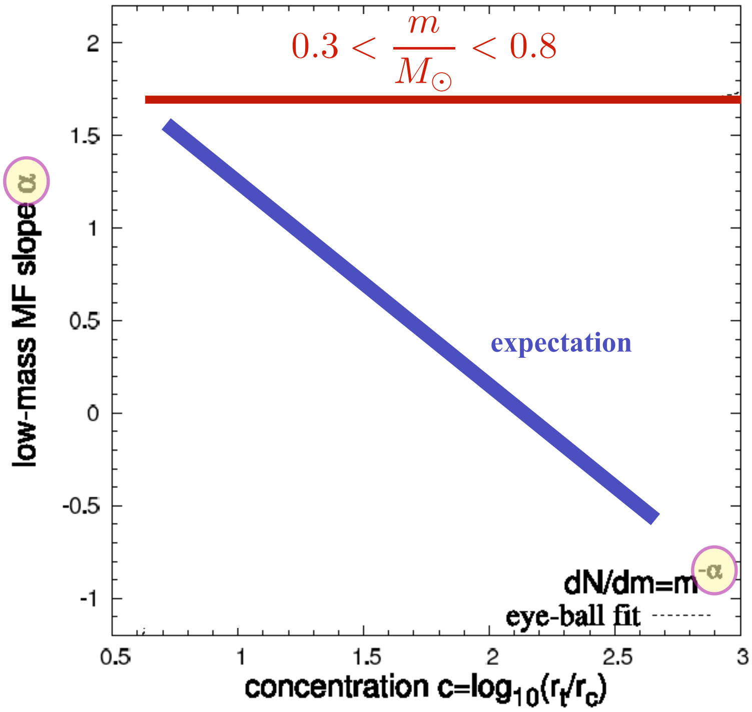
The expected evolution of the MF in the alpha - concentration diagramme



canonical (universal) IMF

normal
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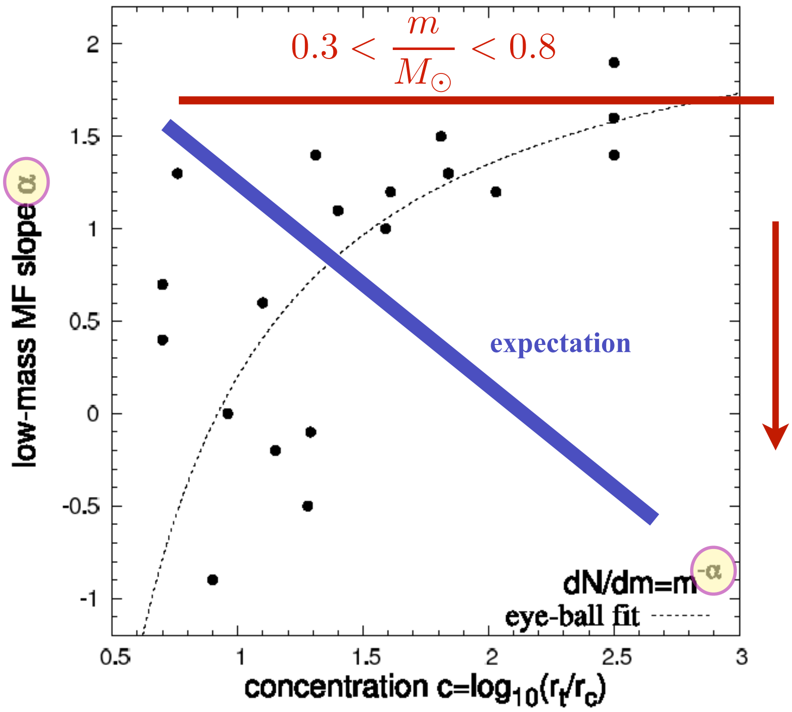
A sample of 20 Galactic GCs with solid global MF measurements from deep HST or VLT data.

(de Marchi, Paresce & Pulone 2007)



canonical (universal) IMF

normal
low-mass star population

too few
low-mass stars

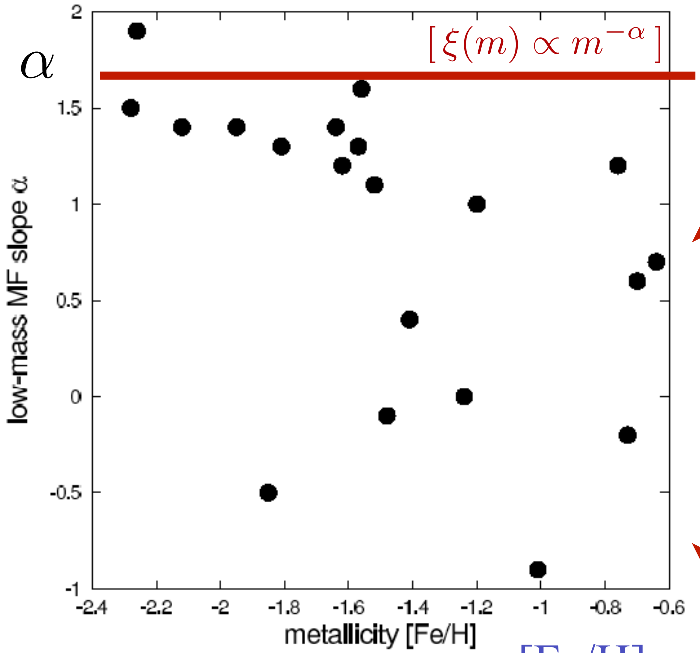
low-concentration clusters ought to be dynamically less evolved

Thus we have encountered
a ***new problem*** :

Dynamics not understood **?**
or
unexpected variation of IMF **?**

A sample of 20 Galactic GCs with solid global MF measurements from deep HST or VLT data.

(de Marchi, Paresce & Pulone 2007)



[Fe/H]

canonical (universal) IMF

Bottom-light MF **:**

but trend with [Fe/H] opposite to theoretical expectation from SF **!**

Instead **:** consistent with *residual gas expulsion.*

(Marks, Kroupa & Baumgardt 2008)

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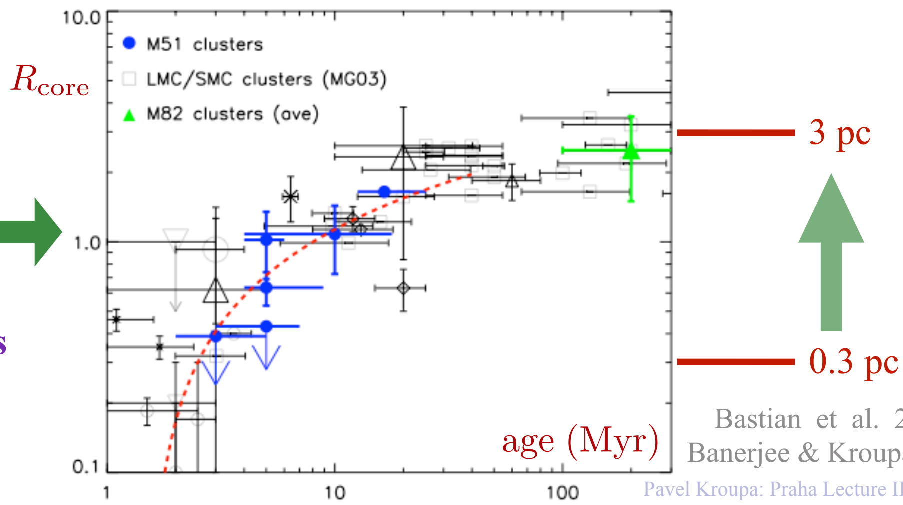
Cluster formation :

star-formation efficiency $\epsilon = \dfrac{M_{\rm ecl}}{M_{\rm ecl} + M_{\rm gas}} \lesssim 0.4$

(*eg.* Lada & Lada 2003)

vel.disp. of cluster in dyn.equil. prior to gas expulsion $\sigma \approx \sqrt{\dfrac{G\, M_{\rm ecl}}{\epsilon\, R}}$

rapid cluster expansion & stellar loss



Bastian et al. 2008
Banerjee & Kroupa 2015

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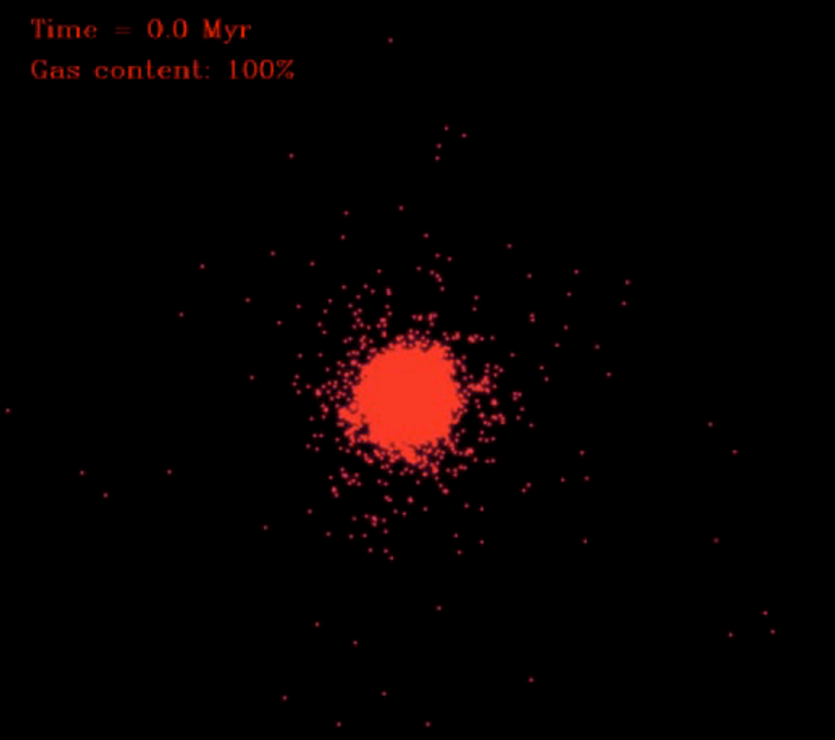
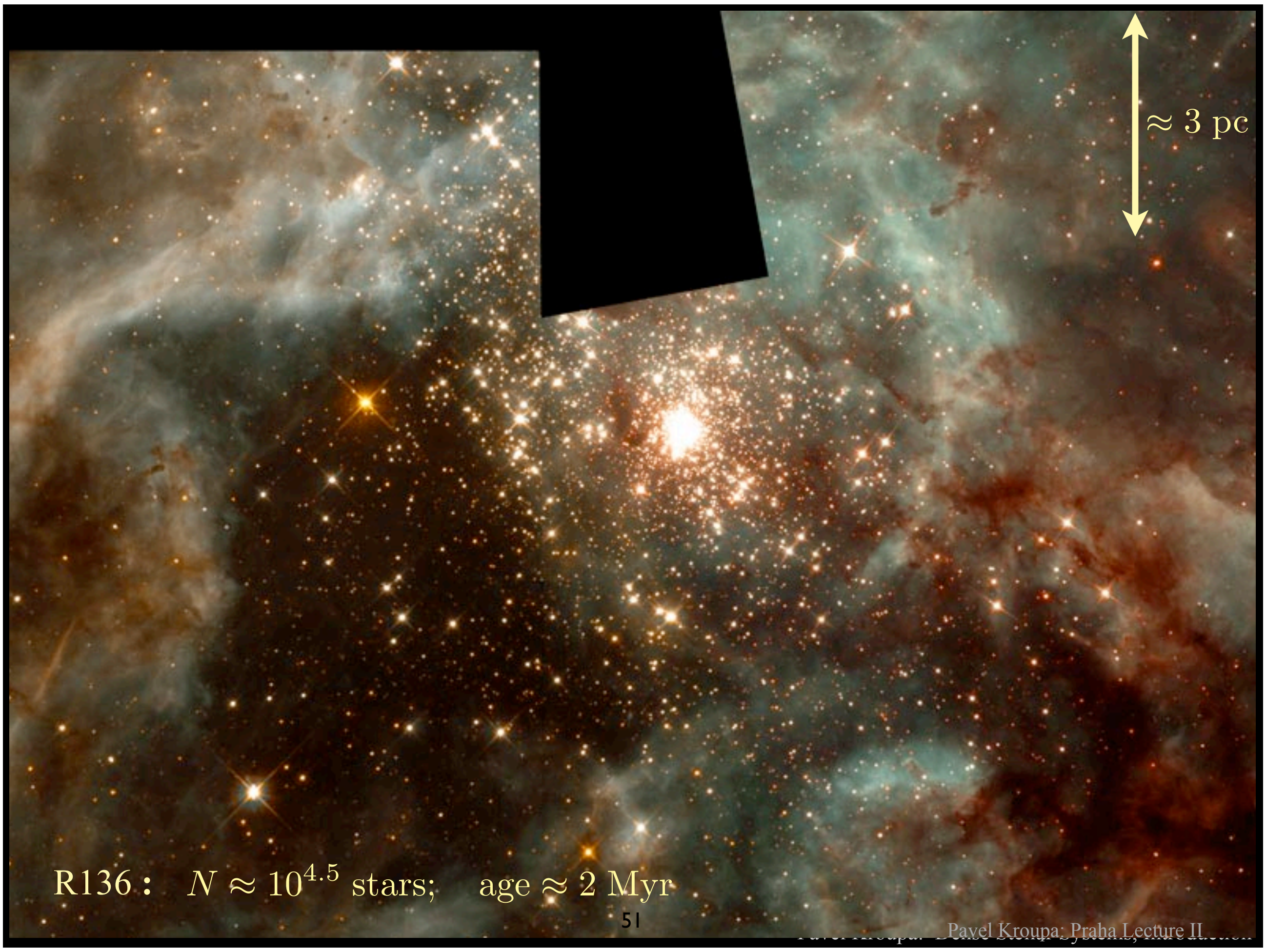
Cluster reaction to sudden gas removal :



Holger Baumgardt

ONC : $N \approx 5000$ stars; $\rho_C \approx 10^5$ stars/pc^3; age ≈ 1 Myr


≈ 3 pc
R136 : $N \approx 10^{4.5}$ stars; age ≈ 2 Myr
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gas expulsion

+

mass segregation

!

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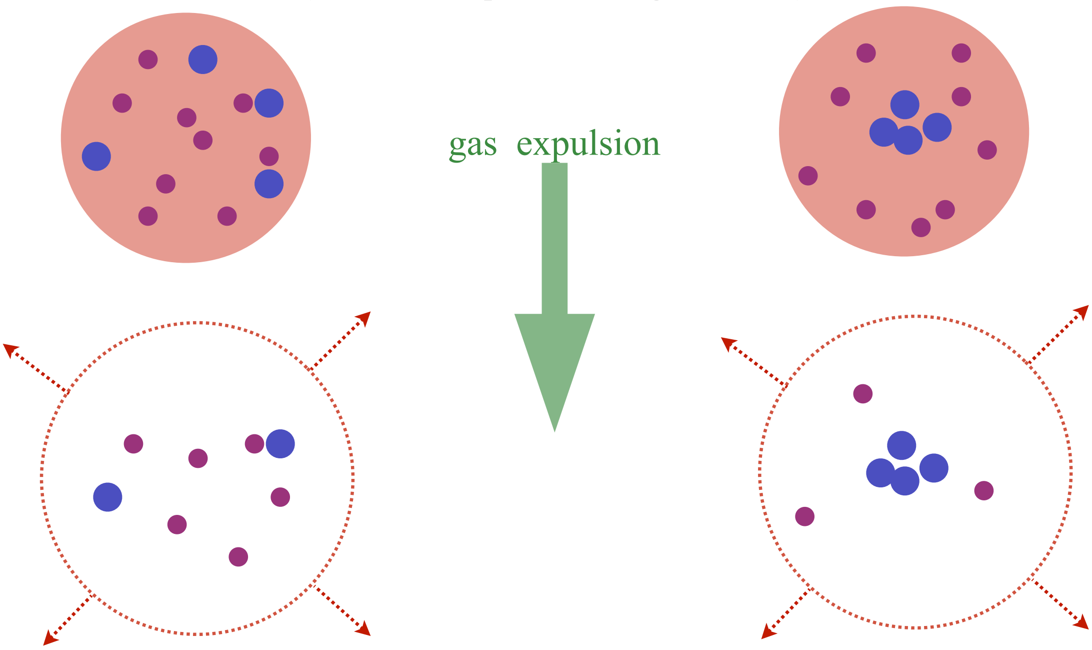
Nbody models of binary rich initially mass segregated clusters with redisual gas expulsion after birth

(Marks, Kroupa & Baumgardt 2008)



stellar loss independent of mass

loose mostly low-mass stars

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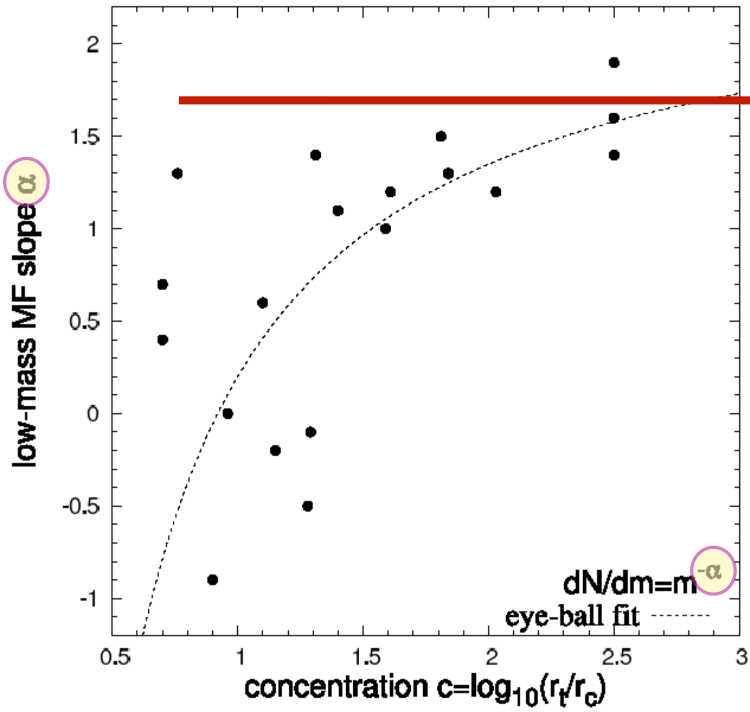
A sample of 20 Galactic GCs with solid global MF measurements from deep HST or VLT data.

(de Marchi, Paresce & Pulone 2007)



canonical (universal) IMF

low-mass star deficient MF

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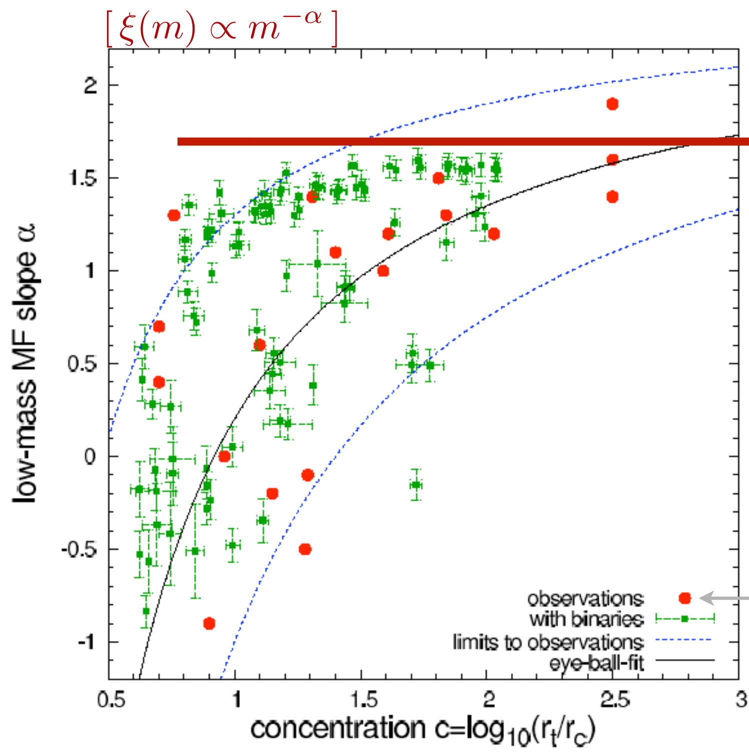
Nbody models of binary rich initially mass segregated clusters with redisual gas expulsion after birth

(Marks, Kroupa & Baumgardt 2008)

$[\xi(m) \propto m^{-\alpha}]$



input (universal) IMF

for
residual gas expulsion
+
mass segregated clusters

(de Marchi, Paresce & Pulone 2007)

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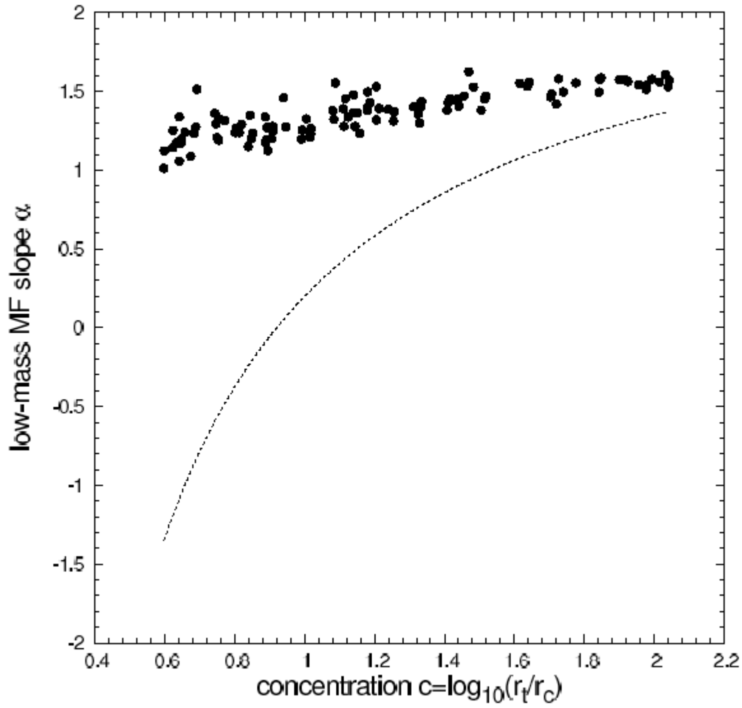
Nbody models of binary rich initially mass segregated clusters with redisual gas expulsion after birth

(Marks, Kroupa & Baumgardt 2008)



for
residual gas expulsion
without
mass segregation

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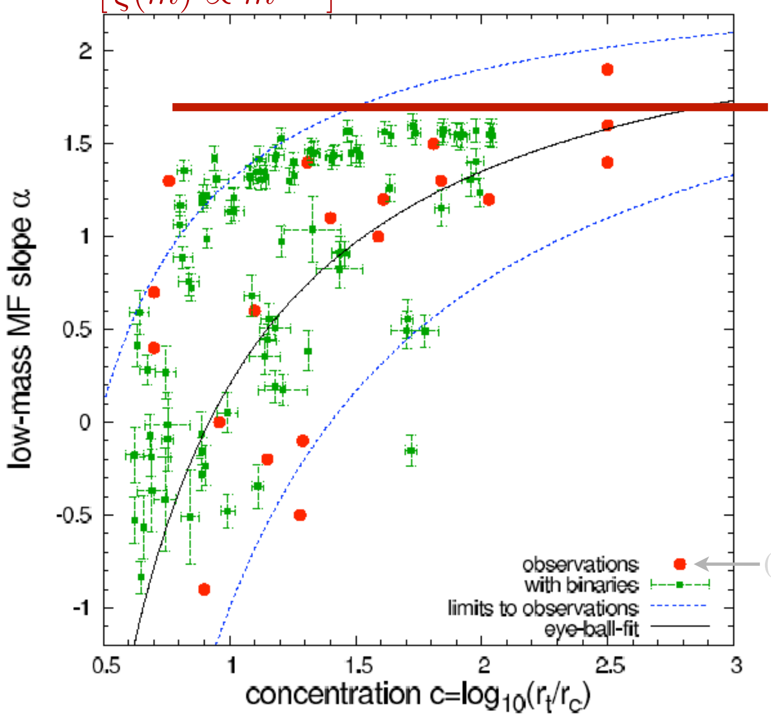
Nbody models of binary rich initially mass segregated clusters with redisual gas expulsion after birth

(Marks, Kroupa & Baumgardt 2008)

$[\xi(m) \propto m^{-\alpha}]$



input (universal) IMF

for
residual gas expulsion
+
mass segregated clusters

(de Marchi, Paresce & Pulone 2007)

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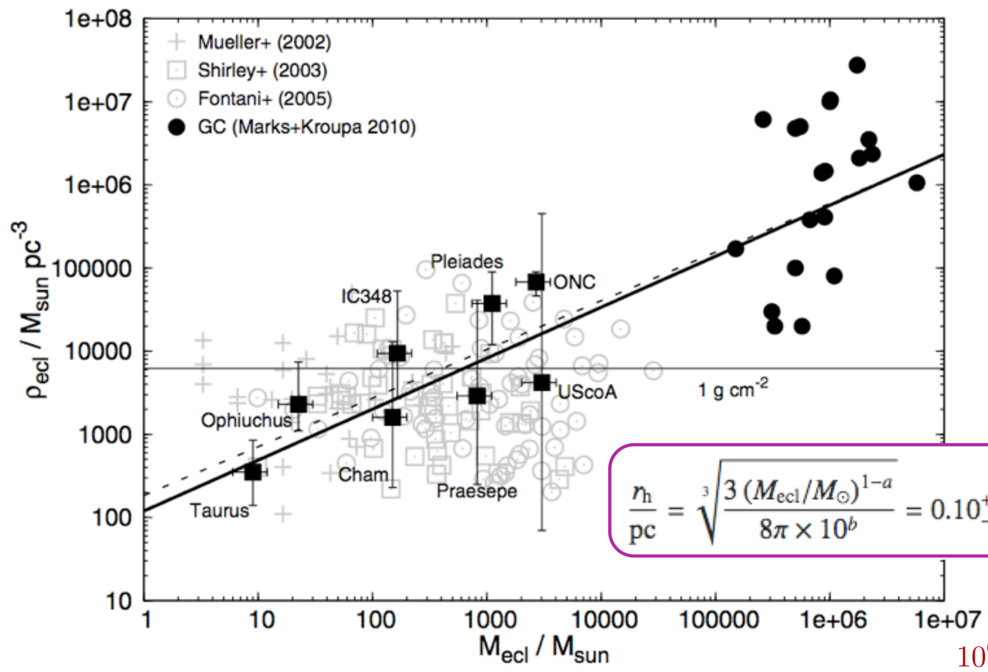
The GCs would have formed very compact

Marks & Kroupa 2012



$$\frac{r_h}{\mathrm{pc}} = \sqrt[3]{\frac{3\,(M_{\rm ecl}/M_\odot)^{1-a}}{8\pi \times 10^b}} = 0.10^{+0.07}_{-0.04} \times \left(\frac{M_{\rm ecl}}{M_\odot}\right)^{0.13\pm0.04}$$

Example:
$10^6\, M_\odot \rightarrow r_{\rm h} = 0.6\,\mathrm{pc}$

Fig. 6. Constraints on the initial volume-densities within the half-mass radius and masses derived in this work for the seven clusters (filled squares) versus the initial stellar mass. The indicated errors in mass correspond to the observationally inferred present-day mass on the left end of a bar and two times the present-day mass on its right end, to be understood as an estimator of the possible initial-mass range. Filled circles are Galactic GCs as in Fig. 5. Underlaid as grey symbols are data of molecular cloud clumps of Mueller et al. (2002, crosses), Shirley et al. (2003, squares), and Fontani et al. (2005, circles) as collated by Parmentier & Kroupa (2011). These are known to have already begun forming stars. The clump masses have been multiplied with a star-formation efficiency of one-third to compare to the stellar masses and densities inferred in the present work. The thin solid black-line is the threshold for massive-star formation evaluated by Krumholz & McKee (2008, 1 g cm^{-2}, see the text). The thick solid black-line is a least squares fit to both the young cluster and GC data (Eq. (6)), implying that there is a mass-radius relation (Eq. (7)) for star cluster-forming cloud clumps. The dashed line shows the result when the GCs are excluded from the fit.

The GCs would have formed very compact

Marks et al. 2012

Does the canonical IMF produce enough energy to blow out enough residual gas to expand the GC sufficiently early on ?

Mon. Not. R. Astron. Soc. **422,** 2246–2254 (2012) doi:10.1111/j.1365-2966.2012.20767.x

Evidence for top-heavy stellar initial mass functions with increasing density and decreasing metallicity

Michael Marks,[1,2★†] Pavel Kroupa,[1] Jörg Dabringhausen[1] and Marcel S. Pawlowski[1]

Does the canonical IMF produce enough energy to blow out enough residual gas to expand the GC sufficiently early on **?**

Develop a simple model : Marks et al. 2012

The rate by which radiative plus mechanical energy from all stars is deposited in the interstellar medium (ISM) is

$$\dot{E} = \int_{0.08\,\mathrm{M}_\odot}^{m_{\max}} \dot{E}_*(m)\,\xi(m)\,\mathrm{d}m\ , \tag{8}$$

where $\xi(m)\,\mathrm{d}m$ is the number of stars in the interval $[m, m+\mathrm{d}m]$ and $\dot{E}_*(m)$ is the total energy output by a single star of mass m. This energy can be calculated from (see Baumgardt, Kroupa & Parmentier 2008)

$$\log_{10} \dot{E}_*/\mathrm{erg\,Myr}^{-1} = 50 + 1.72\left(\log_{10} m/\mathrm{M}_\odot - 1.55\right)\ , \tag{9}$$

i.e. the contribution through low-mass stars is negligible. Within a gas-removal time-scale, τ_M, an amount of energy equivalent to $E_{\mathrm{OB}}^{\tau_M}(\alpha_3) = \dot{E}(\alpha_3)\cdot\tau_M$ is released by massive stars. The provided energy depends on the shape of the stellar IMF (equation 8) and therefore on the choice of α_3 and $m_{\max}$. The latter has been found to have a negligible influence on the results and is arbitrarily chosen as $m_{\max} = 120\,\mathrm{M}_\odot$.

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Energy input required by OB stars is difference in binding energies before and after gas removal, after which the cluster expands to a final radius :

Marks et al. 2012

$$E_{\mathrm{OB}}^{\mathrm{req}} = E_{\mathrm{in}} - E_{\mathrm{fin}}$$

$$E_{\mathrm{bin}} = \frac{3\pi}{32}\frac{G\,M_{\mathrm{pl}}}{r_{\mathrm{pl}}}$$ binding energy of Plummer model $$r_{\mathrm{pl}} = \frac{1}{1.305}\,r_{\mathrm{h}}$$

before gas blow out :

$$M_{\mathrm{pl}} = M_{\mathrm{cl}}$$

after gas blow out :

$$M_{\mathrm{pl}} = M_{\mathrm{ecl}} \qquad r_{\mathrm{h,fin}} = r_{\mathrm{h,init}}\frac{M_{\mathrm{cl}}}{M_{\mathrm{ecl}}} \qquad \epsilon = \frac{M_{\mathrm{ecl}}}{M_{\mathrm{cl}}}$$

Results: will be shown shortly together with two other entirely independent constraints.

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Top-heavy IMF in UCDs ?

the M/L ratio

(ultra-compact dwarf galaxies)

Properties of Ultra Compact Dwarf galaxies (UCDs)

UCDs occur mostly in galaxy clusters

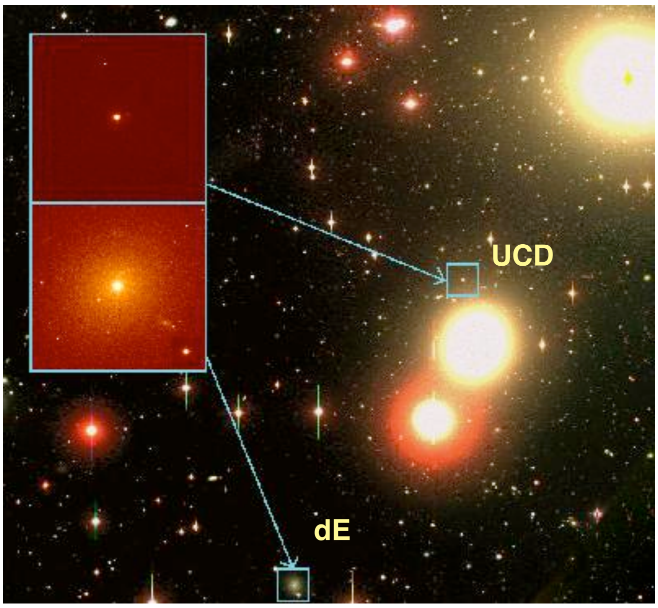

Image by M. Hilker

From close distance, a UCD probably looks similar to this:

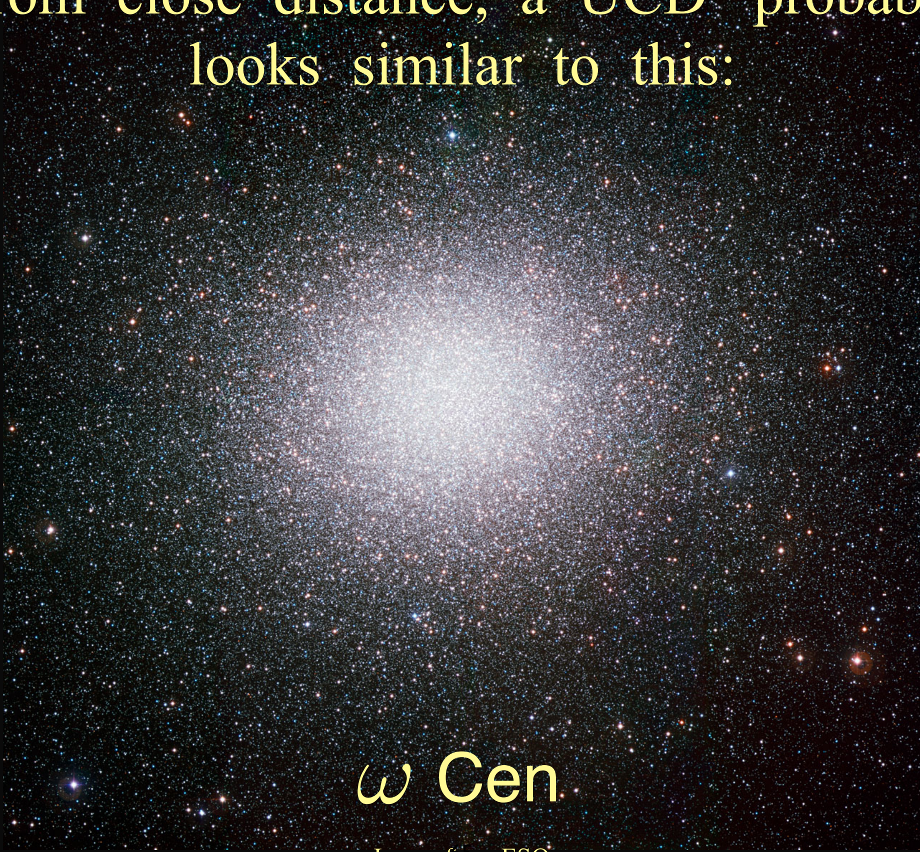

Image from ESO

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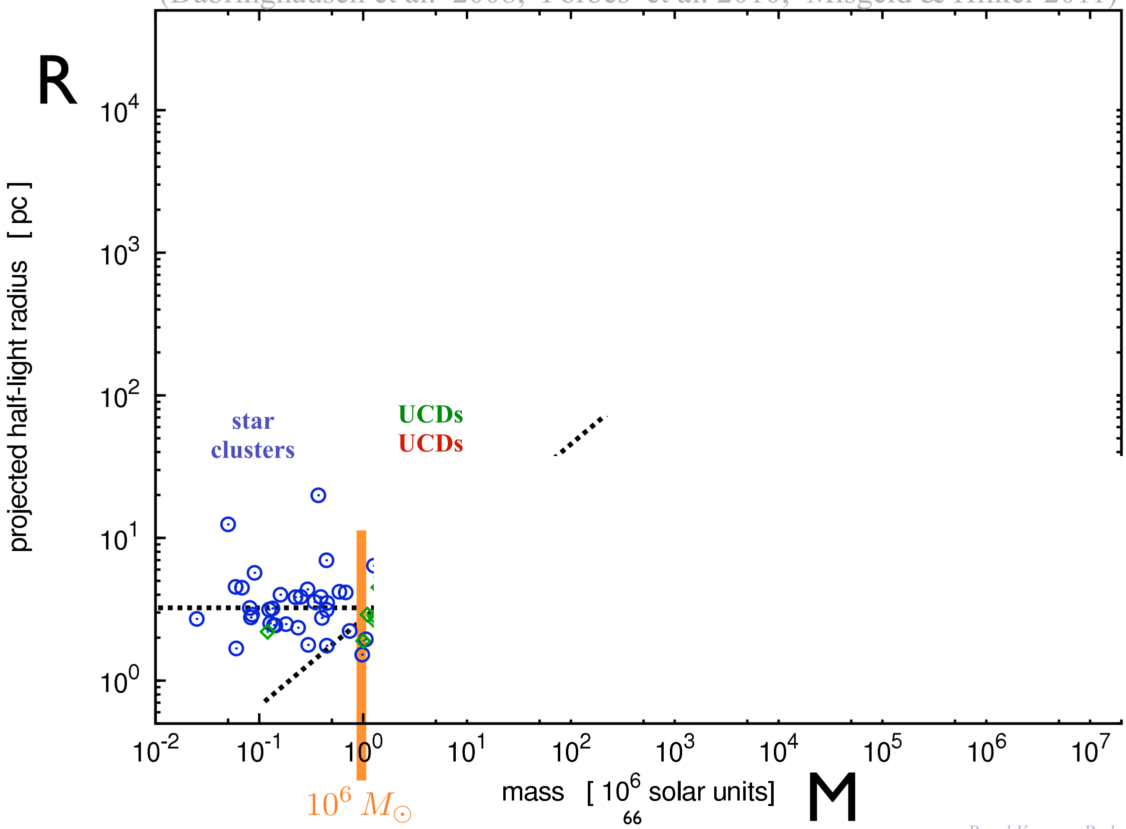
Radius vs mass : Spheroidal / pressure-supported Systems

(Dabringhausen et al. 2008; Forbes et al. 2010; Misgeld & Hilker 2011)



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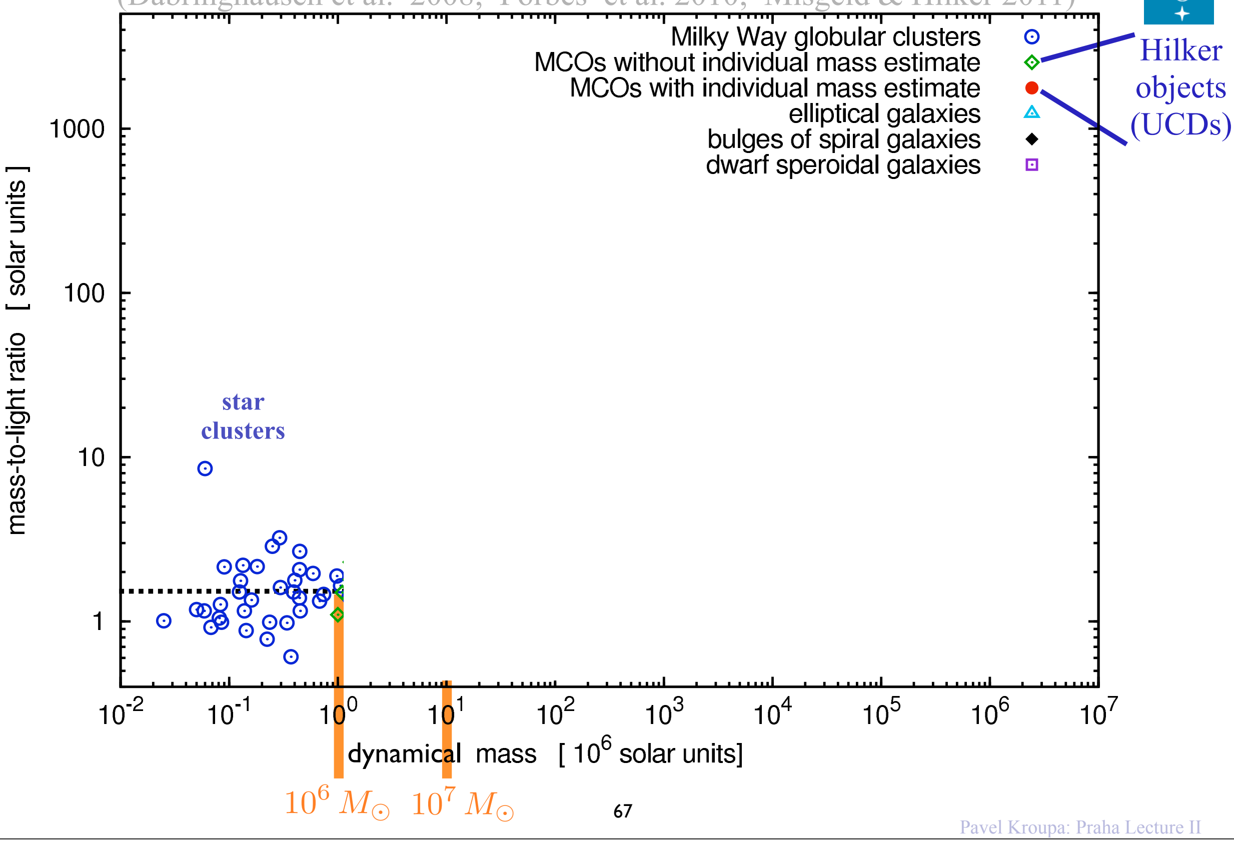
M/L vs mass :

(Dabringhausen et al. 2008; Forbes et al. 2010; Misgeld & Hilker 2011)



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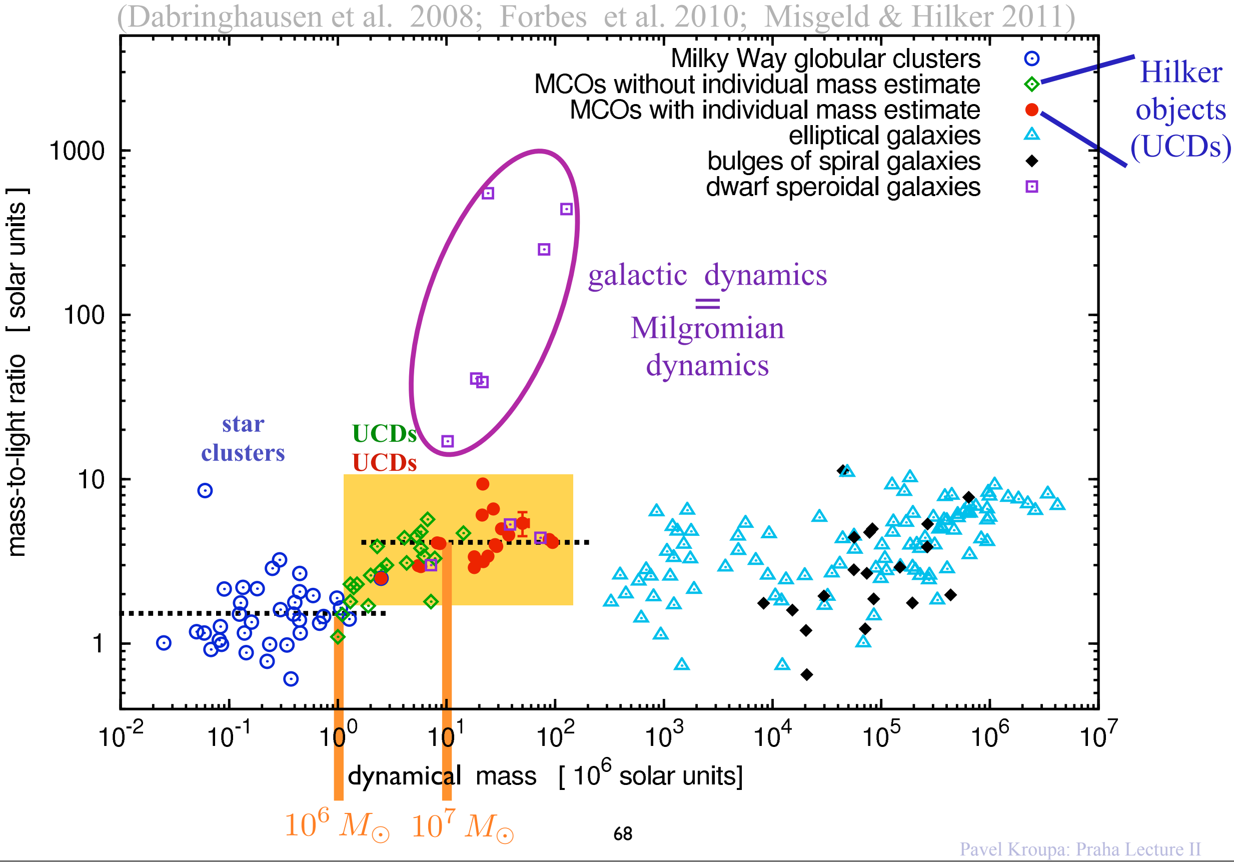
M/L vs mass :

(Dabringhausen et al. 2008; Forbes et al. 2010; Misgeld & Hilker 2011)



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UCDs cannot be dominated by exotic Dark Matter
because they are too compact.

(Murray 2009)

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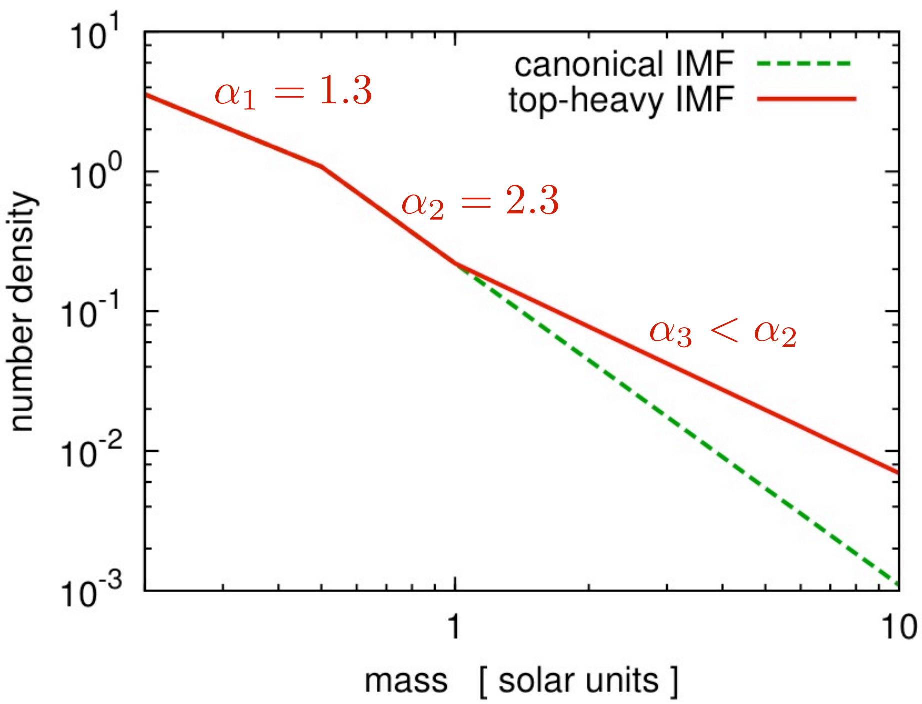
Is a top-heavy IMF a viable possibility ?

... it would provide many dark remnants



Seek α_3 such that M/L is accounted for.

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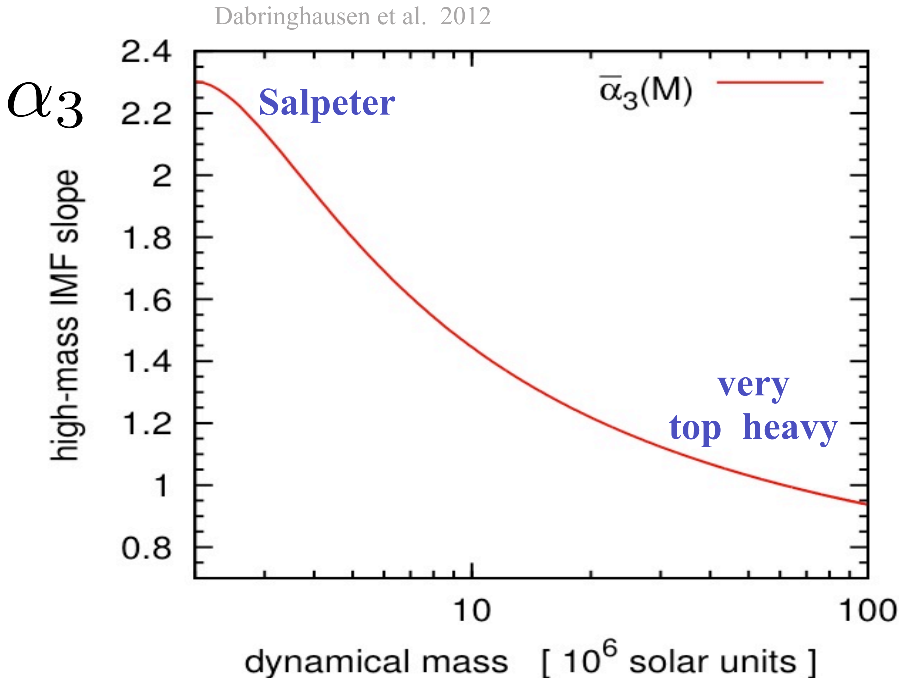
Top-heavy IMF is a viable possibility !

This solution accounts for the M/L vs L data for UCDs :



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Top-heavy IMF in UCDs ?

luminous X-ray binaries

Another clue to top-heavy IMFs :
Abundance of neutron stars

Compared to one with the canonical IMF, a stellar system with a top-heavy IMF should have *many neutron stars*.

Thus, it can have many binary systems where a neutron star accretes matter from a close companion star, so called *low-mass X-ray binaries* (LMXBs).

Low-mass X-ray binaries

LMXBs make neutron stars visible as bright X-ray sources.

The creation of LMXBs is driven by encounters involving stars and neutron stars - such encounters can make binaries close enough for accretion from the star to the neutron star.

The frequency of such encounters is measured by the encounter rate :

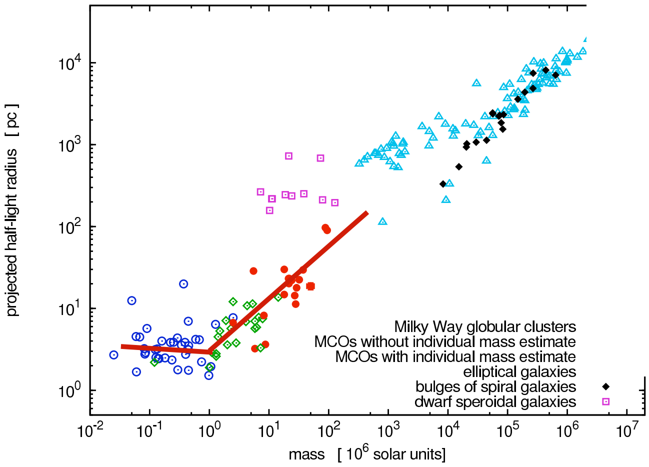
$$\Gamma \propto \frac{n_{\rm s}\ n_{\rm ns}\ r_{\rm c}^3}{\sigma}$$

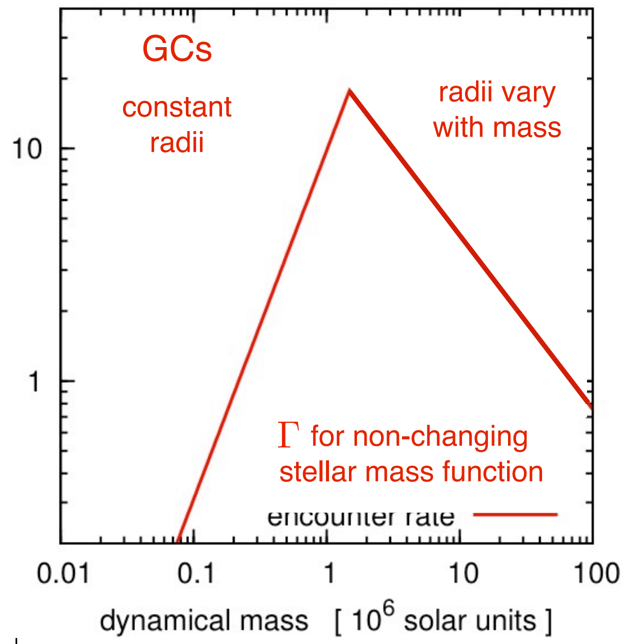
(Verbunt 2003)

LMXBs in globular clusters and UCDs in Virgo

The encounter rate is given as

$$\Gamma \propto \frac{n_{\rm s}\, n_{\rm ns}\, r_{\rm c}^3}{\sigma}.$$





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LMXBs in globular clusters and UCDs in Virgo

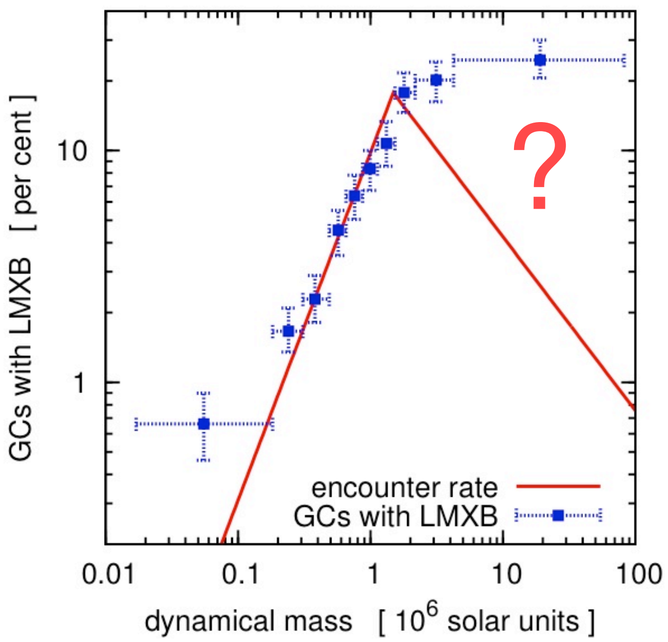
The encounter rate is given as

$$\Gamma \propto \frac{n_{\rm s}\, n_{\rm ns}\, r_{\rm c}^3}{\sigma}.$$

Is there an IMF, such that the probability for an LMXB in a UCD is consistent with their observed occurrence ?

A changing IMF

=> changing $n_{\rm s}, n_{\rm ns}, \sigma$



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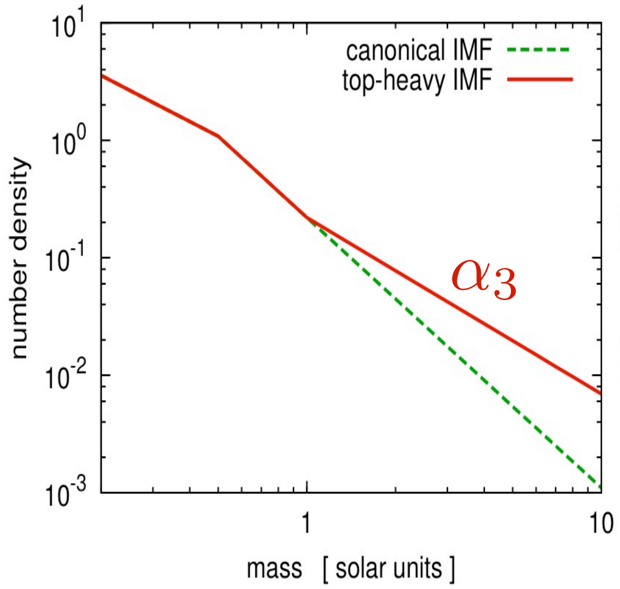
There is such an IMF !



(Dabringhausen et al. 2012)

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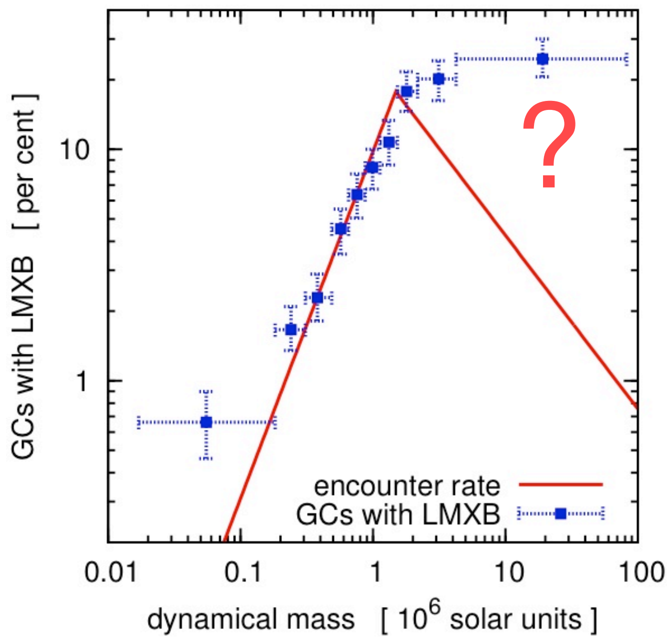
LMXBs in globular clusters and UCDs in Virgo



(Dabringhausen et al. 2012)

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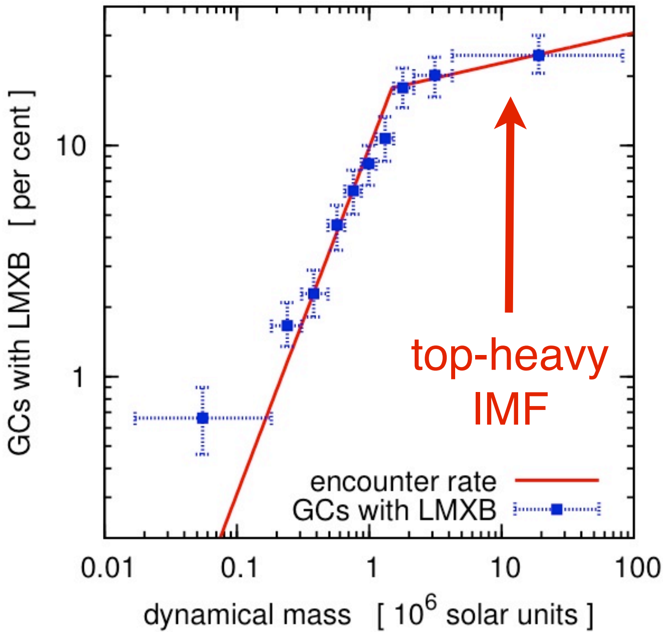
(Dabringhausen et al. 2012)



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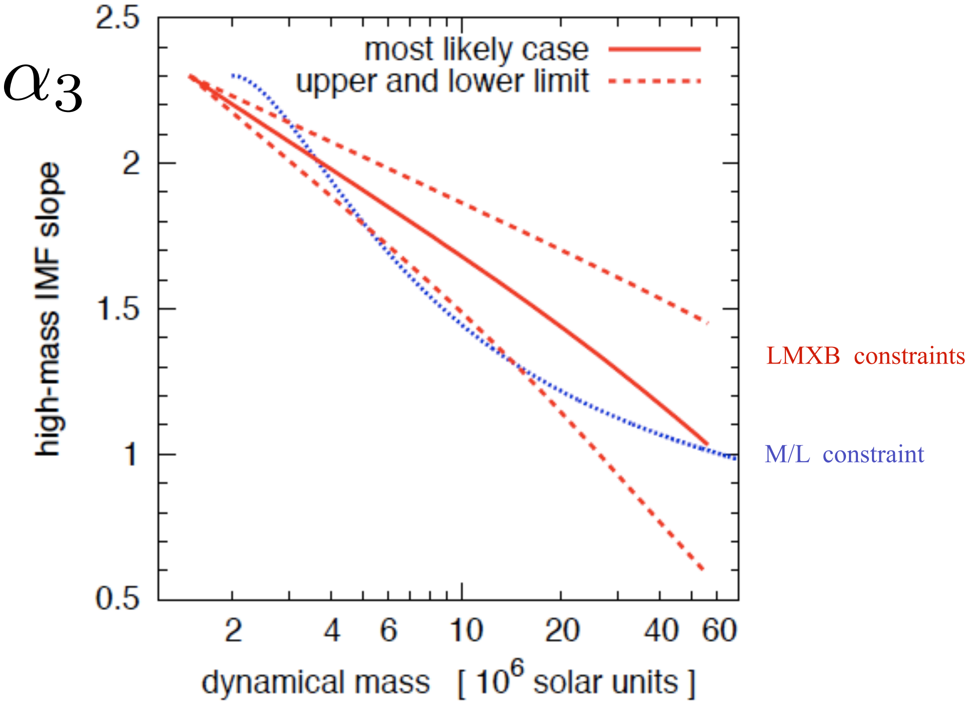
a systematically varying IMF in UCDs thus emerges . . .



(Dabringhausen et al. 2012)

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Top-heavy IMF in UCDs ?

can they survive evolution?

Would UCDs with a top-heavy IMF survive their early evolution?

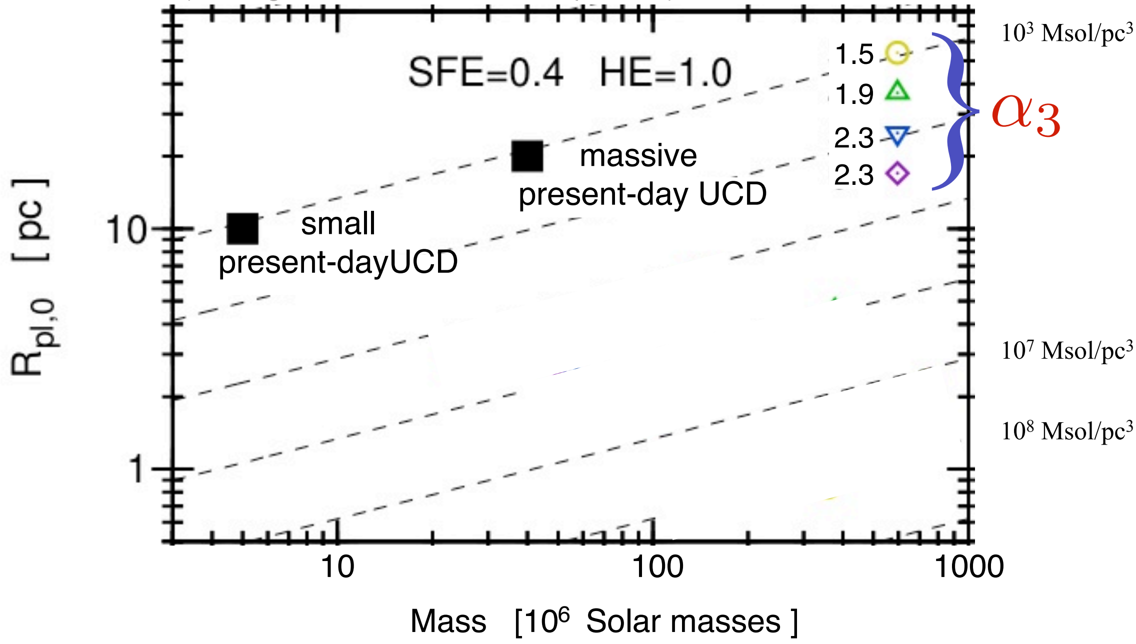
Perform N-Body simulations of UCDs with mass-loss through gas expulsion and stellar evolution

↓

UCDs can also form with top-heavy IMFs, but this implies extreme initial conditions for them. (Dabringhausen, Fellhauer & Kroupa 2010)

Initial parameters thereby implied for UCDs

(Dabringhausen, Fellhauer & Kroupa 2010)



Consider a UCD with some $10^7\,M_\odot$ today

Initially, it may have had:

- A mass of some $10^8\,M_\odot$ . . .
- ... but a half-mass radius of only a few pc! (expansion through mass-loss!)
- ... A population of 10^6 O-stars...
- ...with a total luminosity of $10^{11}\,L_\odot$.

Putting it all together . . .

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Putting GCs and UCDs together:

top-heavy IMFs at high star-formation rate density and low metallicity !

What we know from observation :

Globular clusters : deficit of low-mass stars increases with decreasing concentration

→ disagrees with dynamical evolution

→ correlate energy needed to expell residual gas with number of OB stars required.

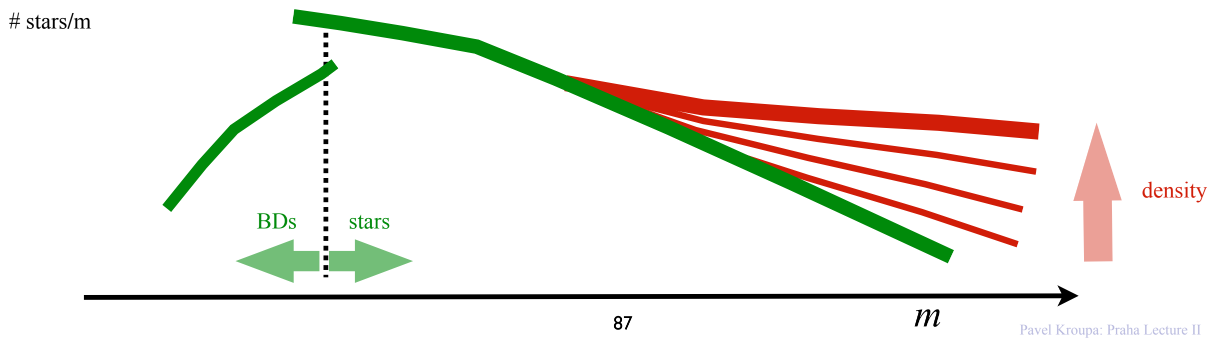
UCDs : higher dynamical M/L ratios

→ cannot be exotic dark matter => top-heavy IMF

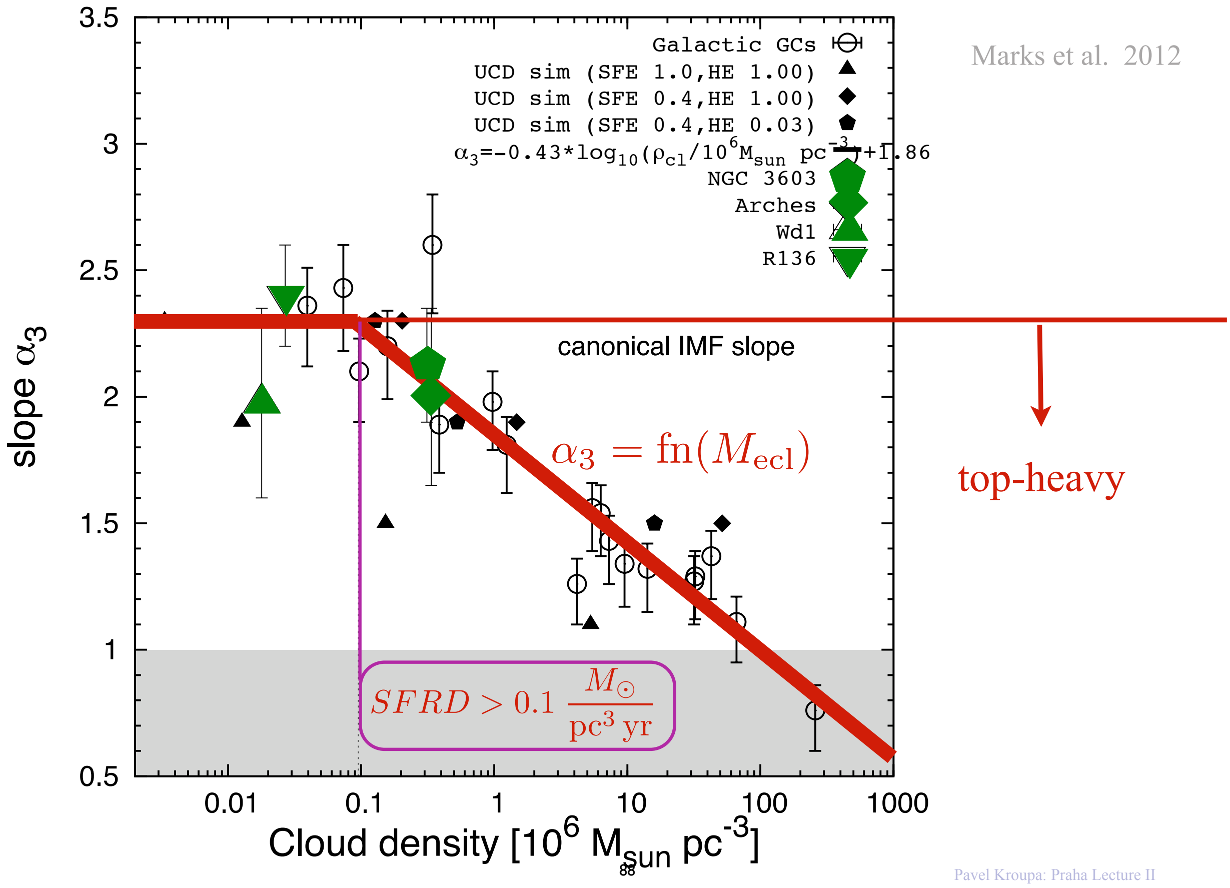
UCDs : larger fraction of X-ray sources than expected

→ no explanation other than many remnants => top-heavy IMF

What this implies :

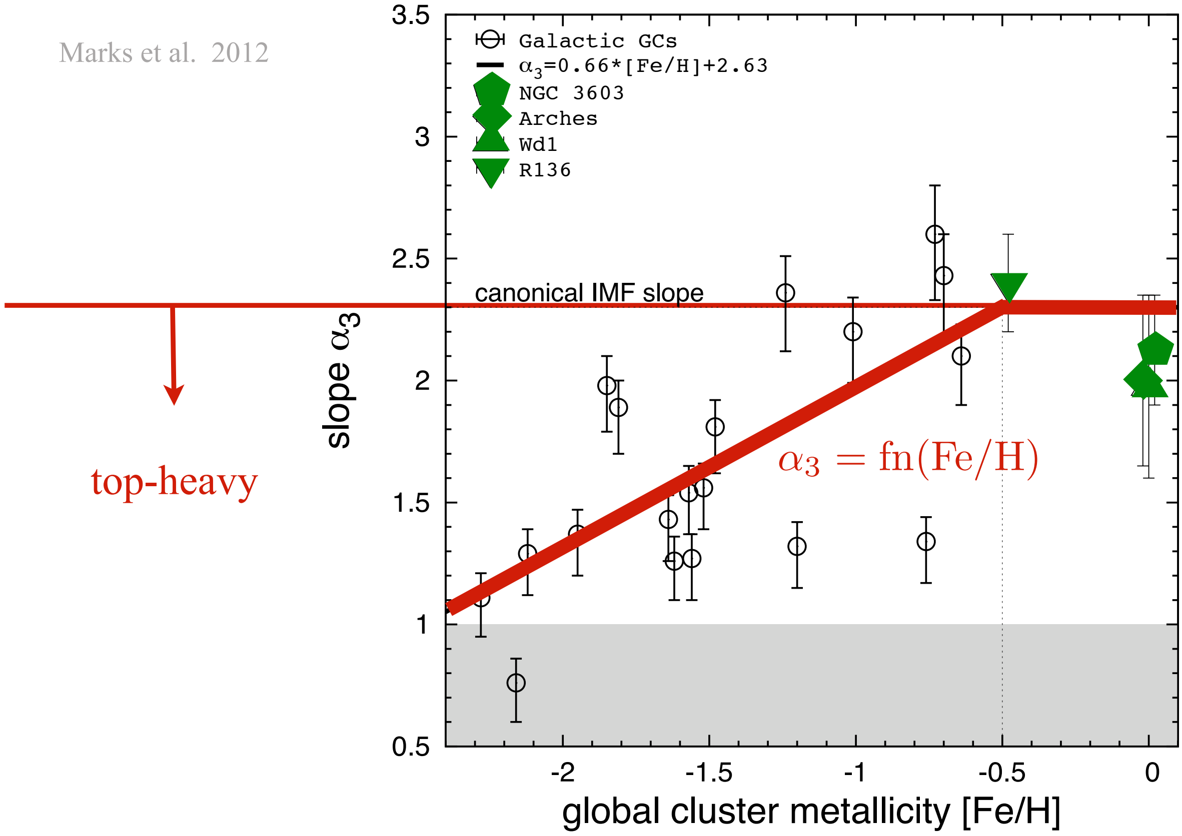


Top-heavy IMF in extreme-density environments :



Top-heavy IMF in extreme-density environments :

Marks et al. 2012



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Top-heavy IMF in extreme-density environments :

THE STELLAR IMF DEPENDENCE ON DENSITY AND METALLICITY: Resolved stellar populations show an invariant IMF (Eq. 55), but for $SFRD \gtrsim 0.1\, M_\odot/(\mathrm{yr\ pc}^3)$ the IMF becomes top-heavy, as inferred from deep observations of GCs. The dependence of α_3 on cluster-forming cloud density, ρ, (stars plus gas) and metallicity, [Fe/H],can be parametrised as

$$\begin{aligned} &\alpha_3 = \alpha_2, && m > 1\, M_\odot \;\wedge\; x < -0.89, \\ &\alpha_3 = -0.41 \times x + 1.94, && m > 1\, M_\odot \;\wedge\; x \geq -0.89, \\ &x = -0.14\,[\mathrm{Fe/H}] + 0.99 \log_{10}\left(\rho / \left(10^6\, M_\odot\, \mathrm{pc}^{-3}\right)\right). && \end{aligned} \tag{65}$$

Marks et al. 2012
Kroupa et al. 2013 (arXiv:1112.3340)

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Counting stars => LF => PDMF => IMF

Remember :

$$\Psi(M_{\rm V}) = -\frac{dm}{dM_{\rm V}}\,\xi(m)$$

+ binaries
+ main sequence stars

corrections for stellar evolution

✓ peak in LF => m-M_V relation

✓ nearby LF ≠ distant LF

? MW-field (Scalo) IMF index

≠ star-cluster/association (Salpeter/Massey) IMF index

star-formation theory (*Jeans-mass vs self-regulation*) :

? - expect IMF variation with density and metallicity

? - unable to account for IMF shape

Counting stars => LF => PDMF => IMF

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END of

Lecture 2