The stellar initial mass function from star formation and in galaxies

Harnack Haus Berlin on
Stars, Planets and Galaxies
13.-18. April 2018

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Charles University in Prague

c/o Argelander-Institut für Astronomie
University of Bonn

Issues which affect the determination of the IMF :

1) The IMF does not exist !

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2) What we call the IMF is a mathematical "hilfskonstrukt"
Star-formation "hilfskonstrukt" $\neq$ galaxy-wide "hilfskonstrukt"

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the stellar mass-to-light relation
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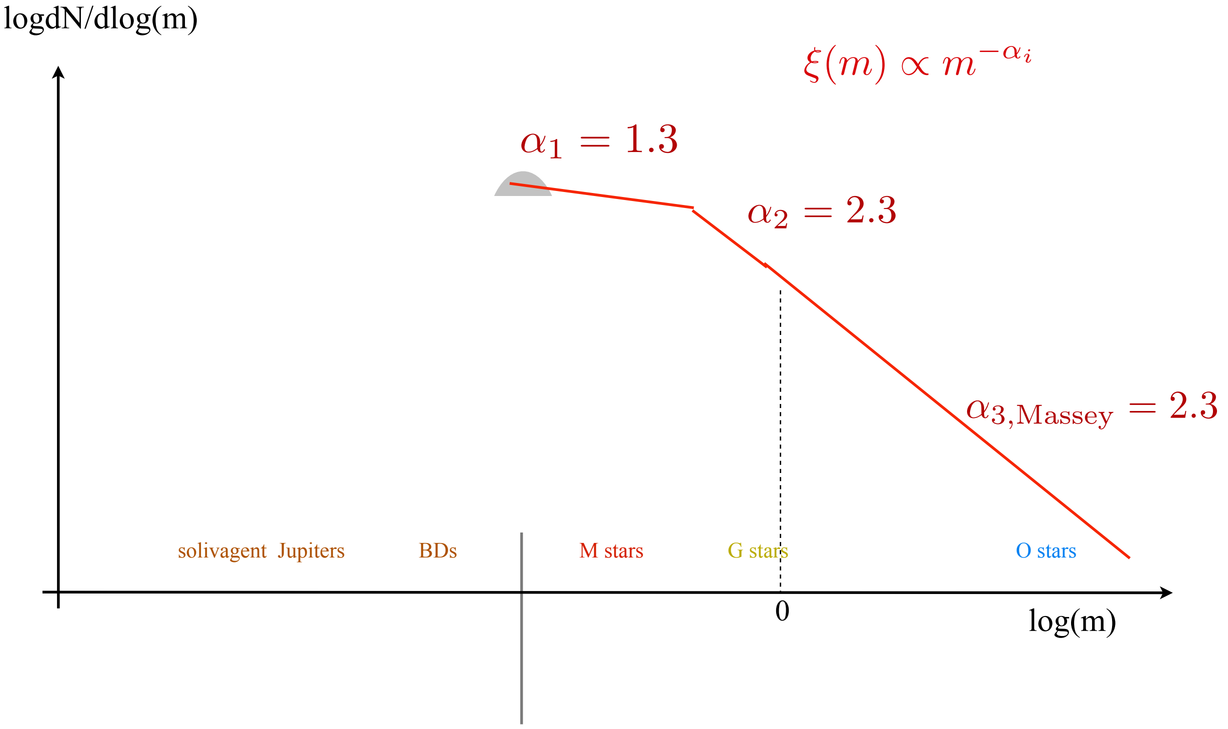
the most massive star in birth clusters
IMF = probability density distr.function
or an optimally sampled distribution function ?
evidence for top-heavy IMF in extremely massive star burst "clusters"
implications of this for the IMF of whole galaxies.

discontinuous four-part power-law IMF :



discontinuity: Thies & Kroupa (2007, 2008), Parker & Goodwin (2010)

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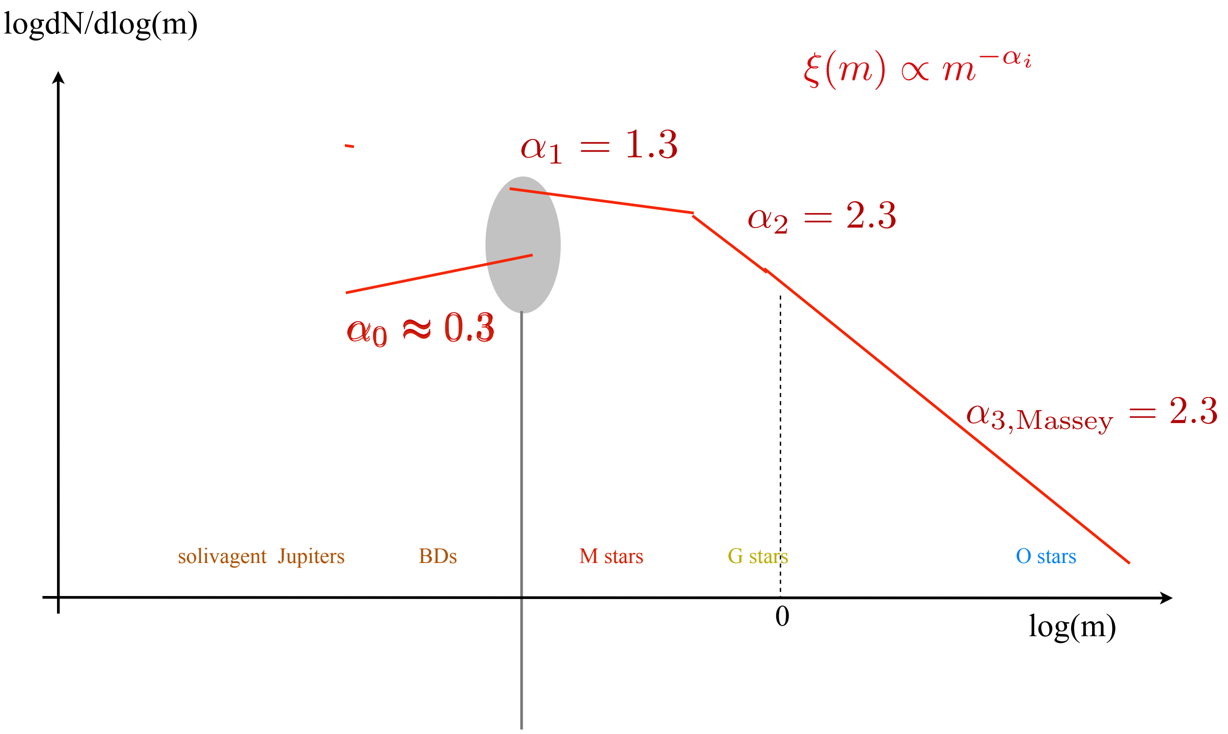

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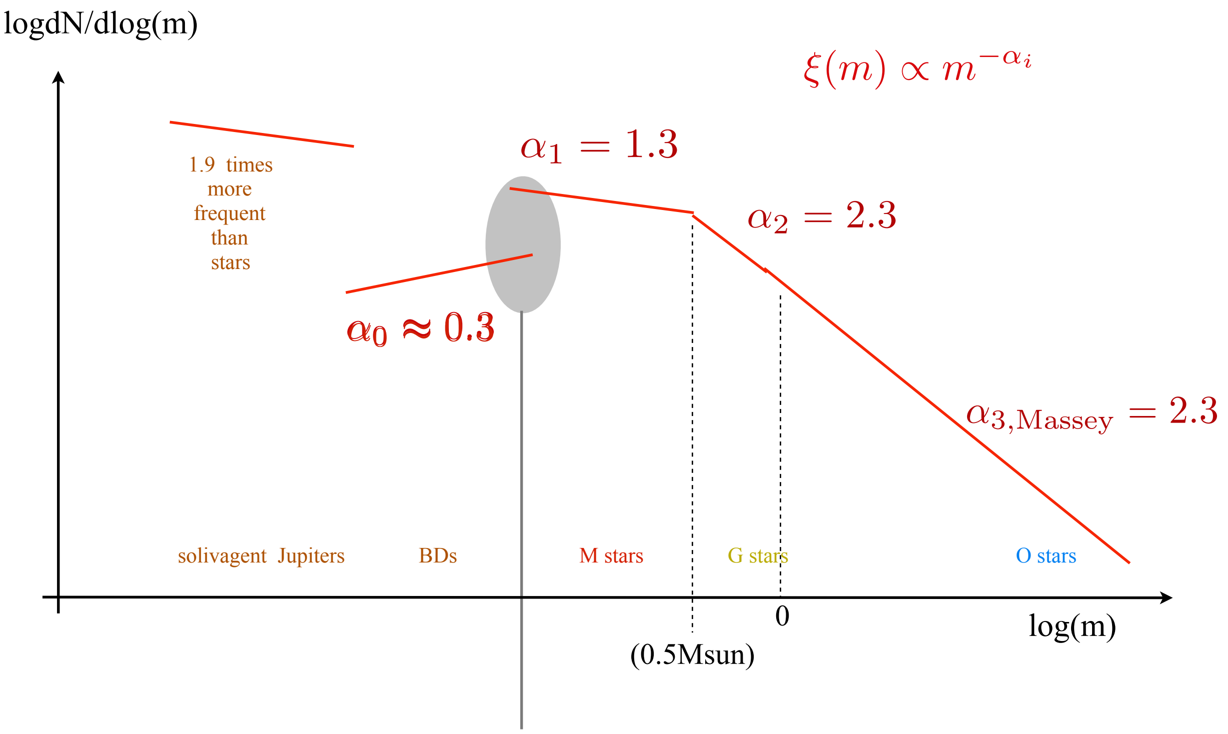

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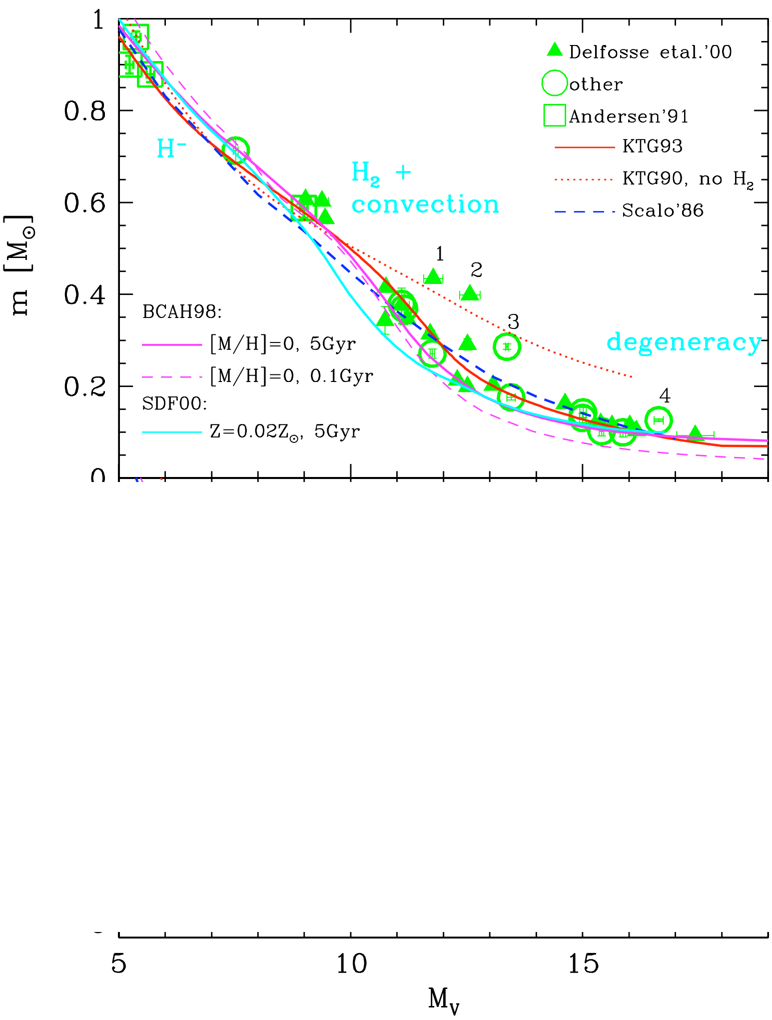
The mass-luminosity relation of low-mass stars

Kroupa, Tout & Gilmore 1990;
Kroupa, 2002, *Science*

$$\Psi(M_V) = -\frac{dm}{dM_V}\,\xi(m)$$



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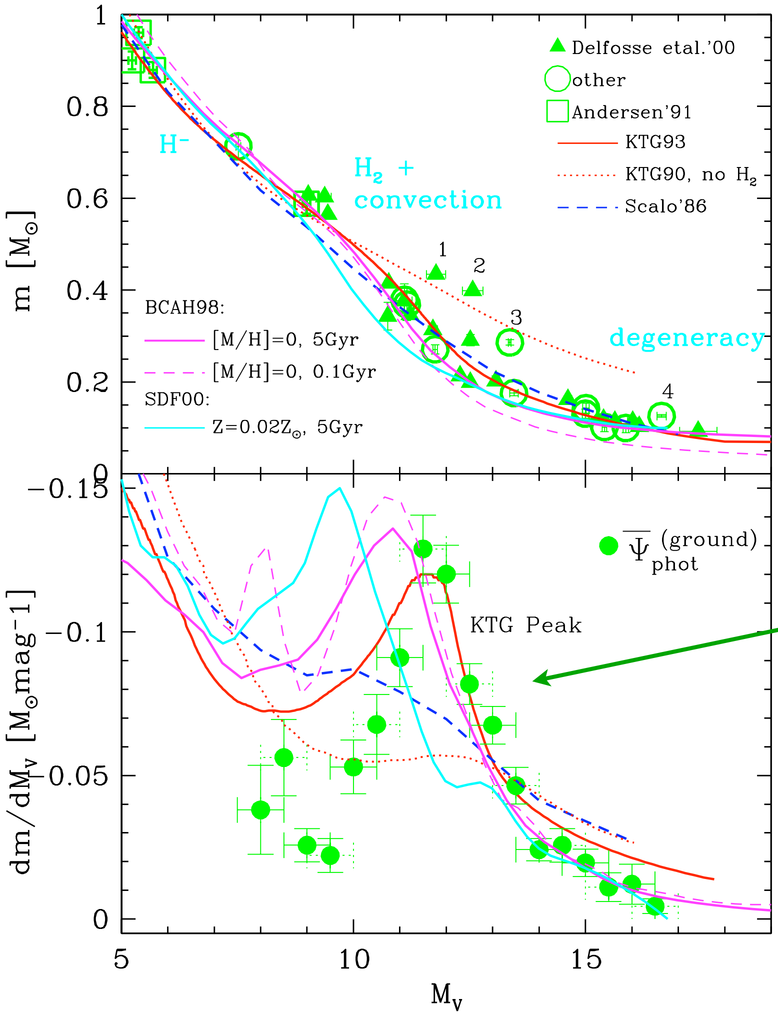

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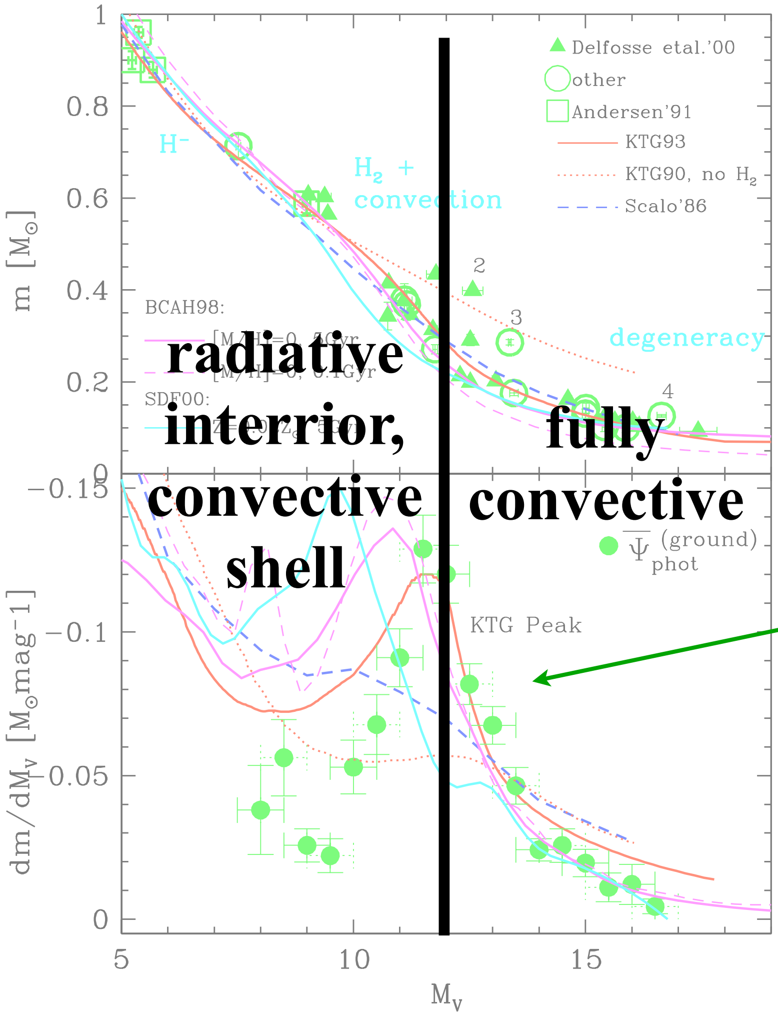
1. position
2. width
3. amplitude

all agree !



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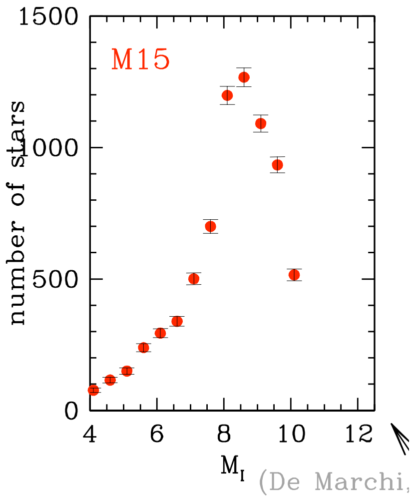

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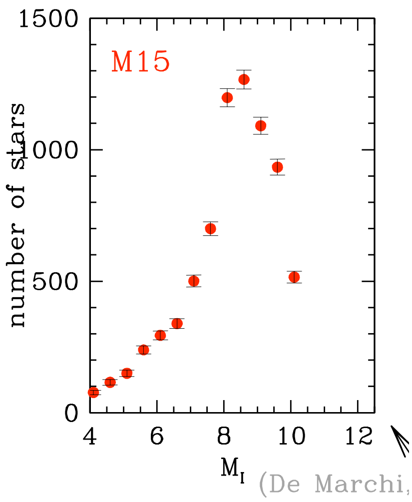
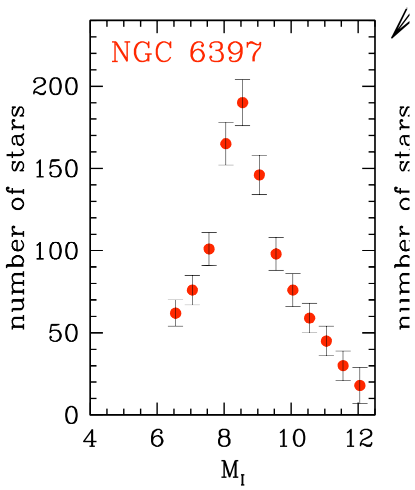
By counting stars we look into their internal constitution !

Peak in LF is not due to MF turnover,

because the formation of pre-stellar cores is independent of the physics of stellar interiors.





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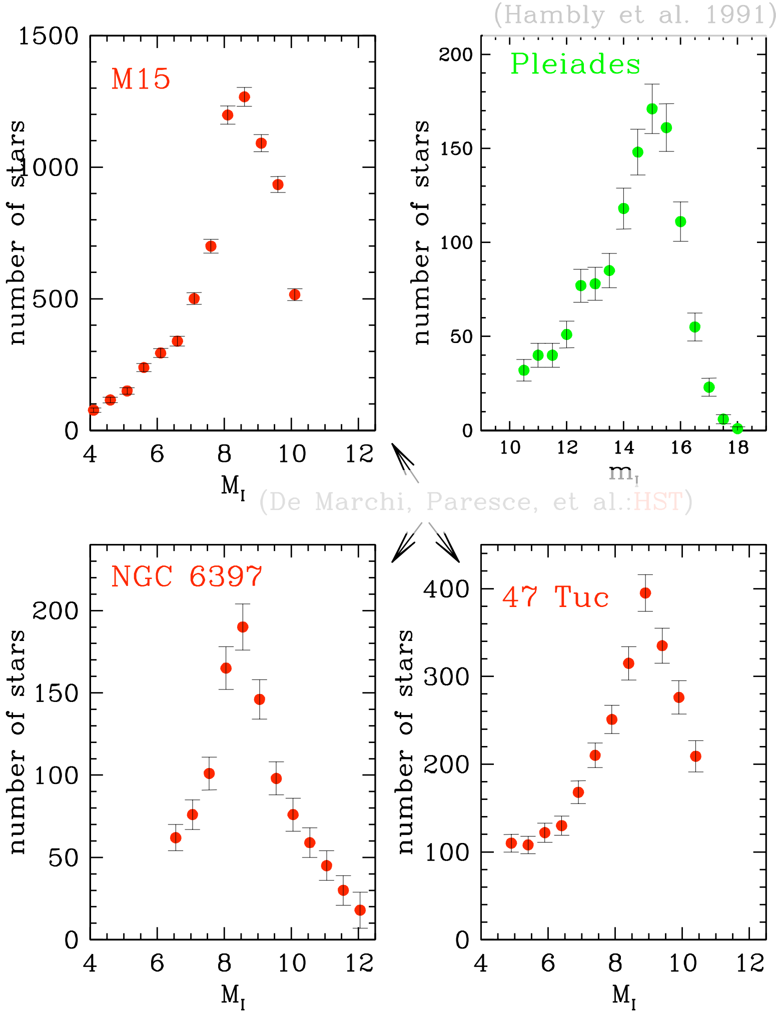

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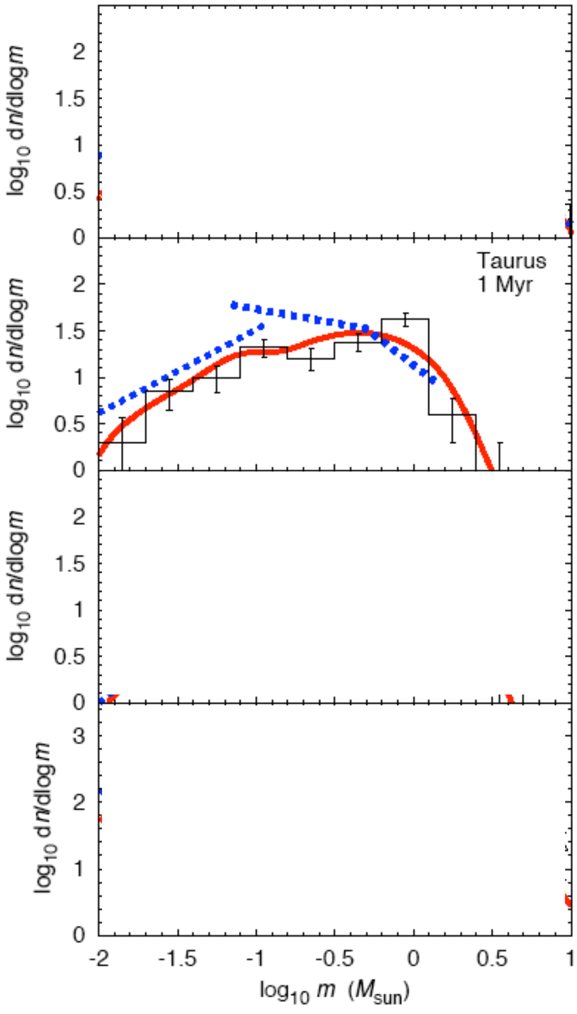


(Thies & Kroupa 2007)

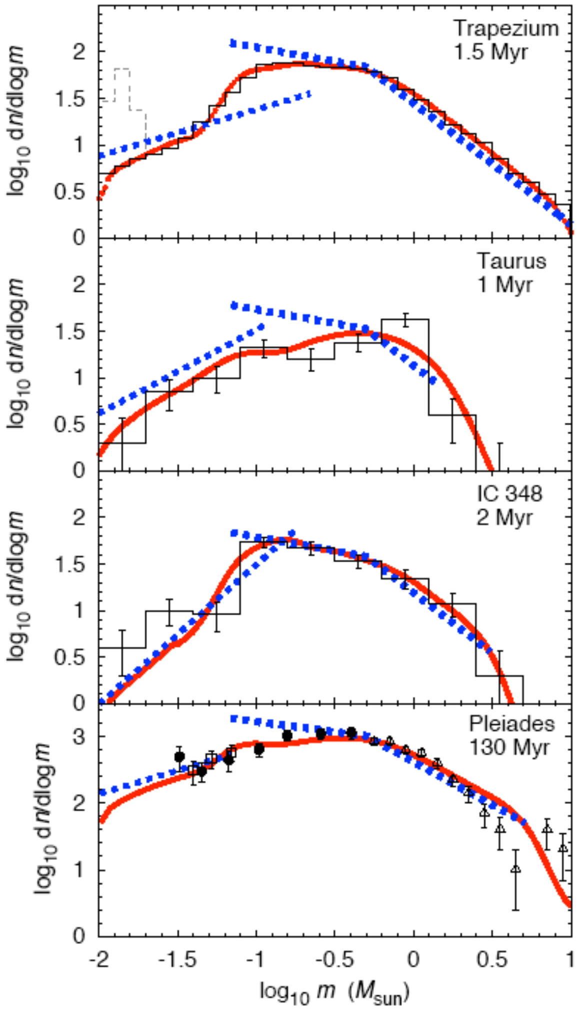
Standard (universal) IMF in stellar regime.

Similar IMF in brown dwarve regime $\alpha \approx 0.3 \pm 0.3$

Discontinuity near $\approx 0.08\ M_\odot$

$\mathcal{R} = 0.2 \pm 0.05$ BDs per star

One brown dwarve forms per 5 stars !



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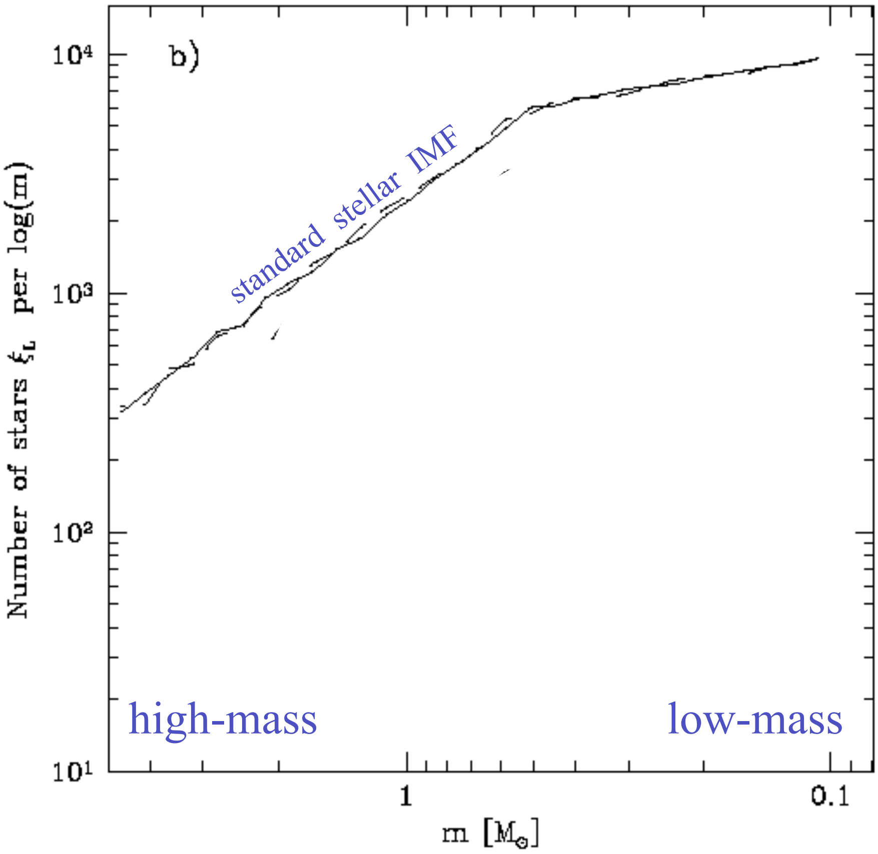
MF(t) due to cluster evolution

(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

P. Kroupa: University of Bonn / Charles University

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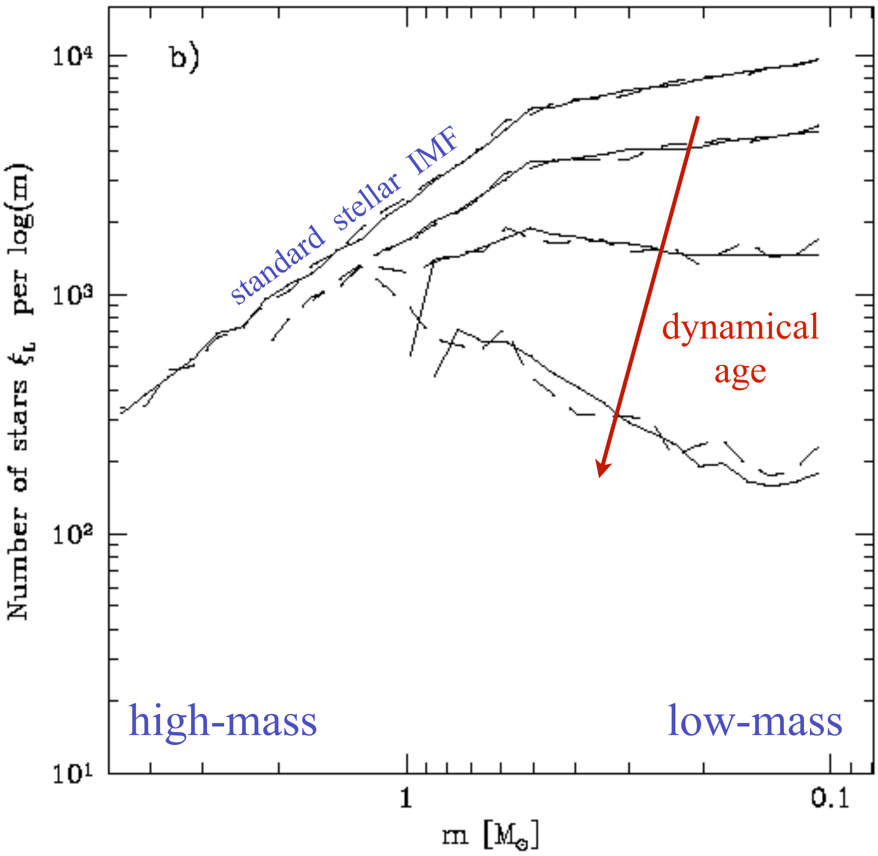

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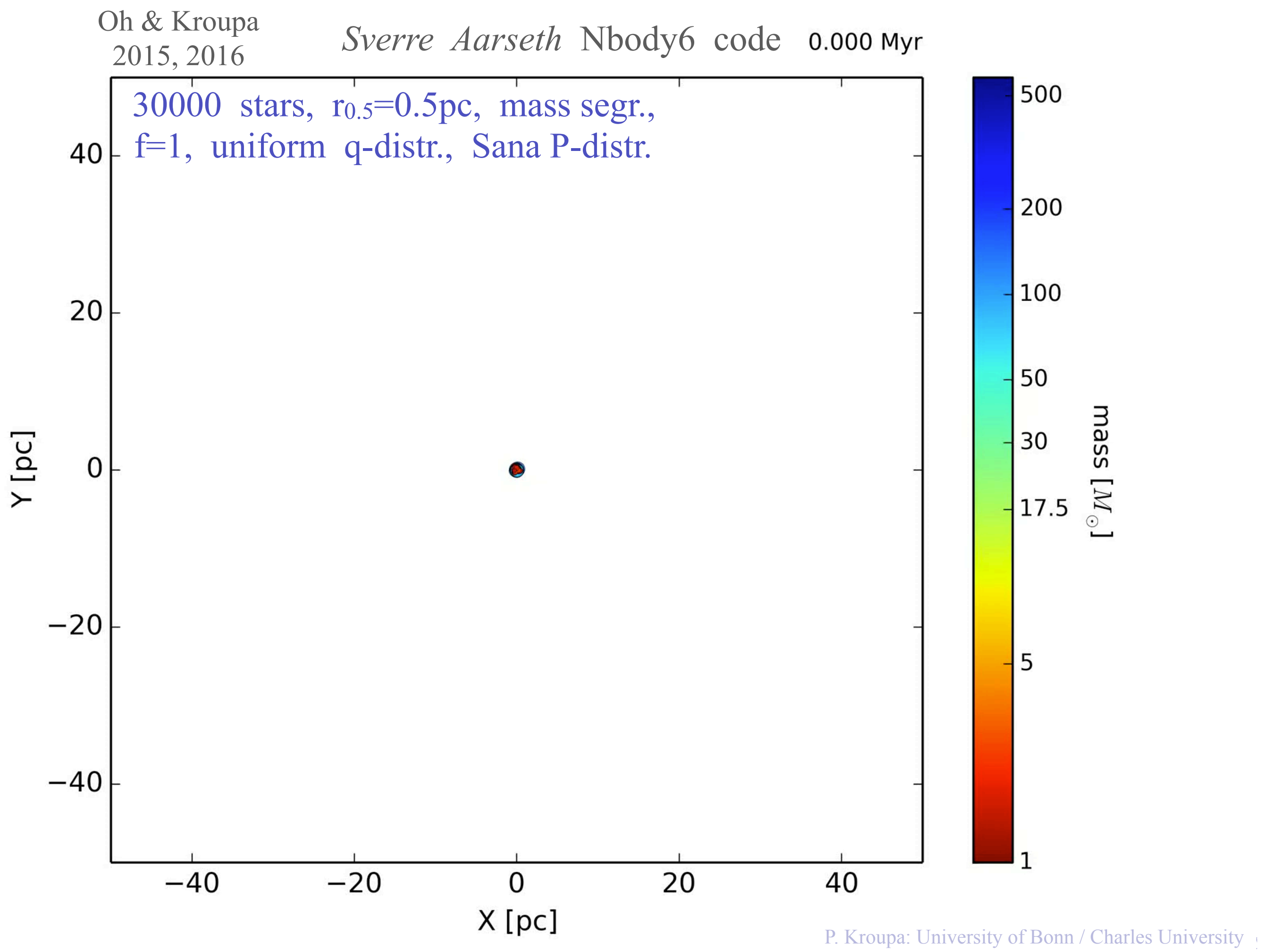
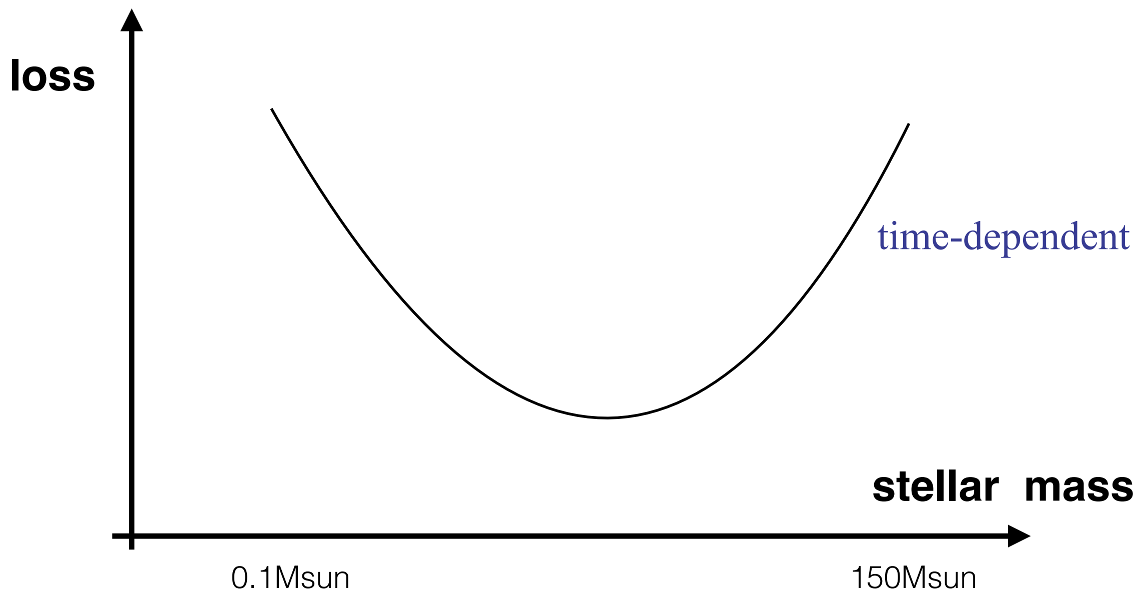


Clusters depopulate themselves
off low-mass stars and high mass stars.



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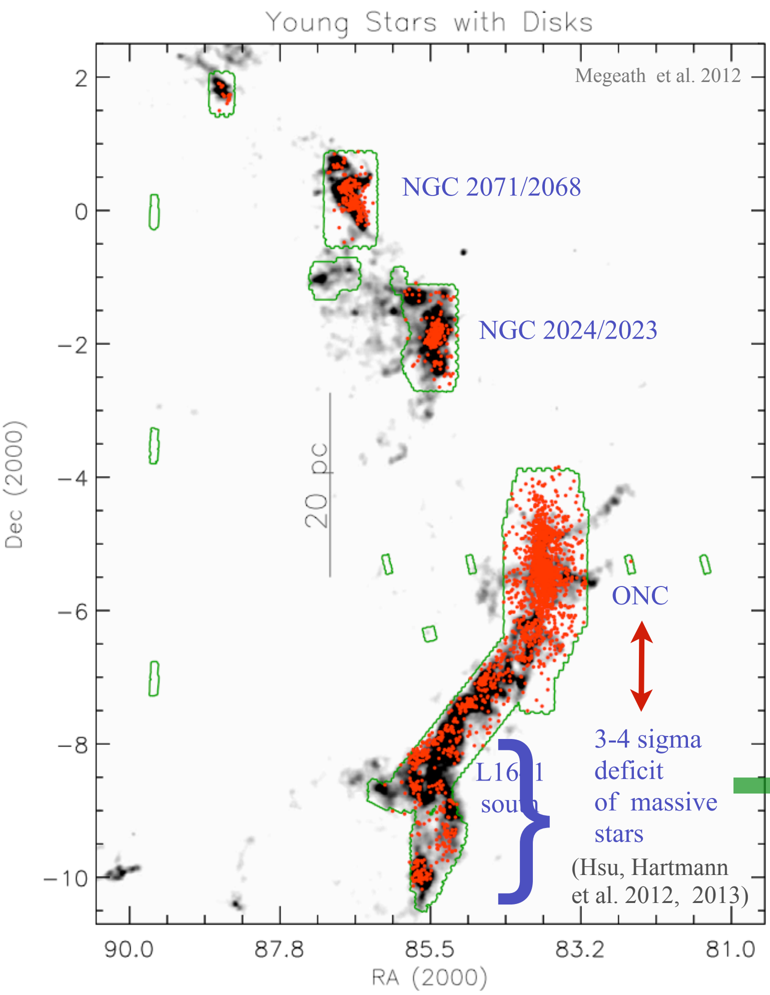


Lack of O stars

Many small / low-mass groups or clusters do not yield the same IMF as one massive cluster

stochastic IMF in each group is ruled out.

Pavel Kroupa: University of Bonn / Charles Universit

What is an optimally sampled distribution function ?

Given the *mass reservoir* in stellar mass M_{ecl},
starting with the most massive star,
select the next most massive such that
M_{ecl} is distributed over the distribution function
without Poisson scatter.

Kroupa et al. 2013
Schulz, Pflamm-Altenburg & Kroupa 2015
Yan et al. 2017

The above ansatz can be extended to a discretized optimal distribution of stellar masses: Given the mass, M_{ecl}, of the population, the following sequence of individual stellar masses yields a distribution function which exactly follows $\xi(m)$,

$$m_{i+1} = \int_{m_{i+1}}^{m_i} m\,\xi(m)dm, \quad m_L \le m_{i+1} < m_i, \quad m_1 \equiv m_{max}. \tag{4.9}$$

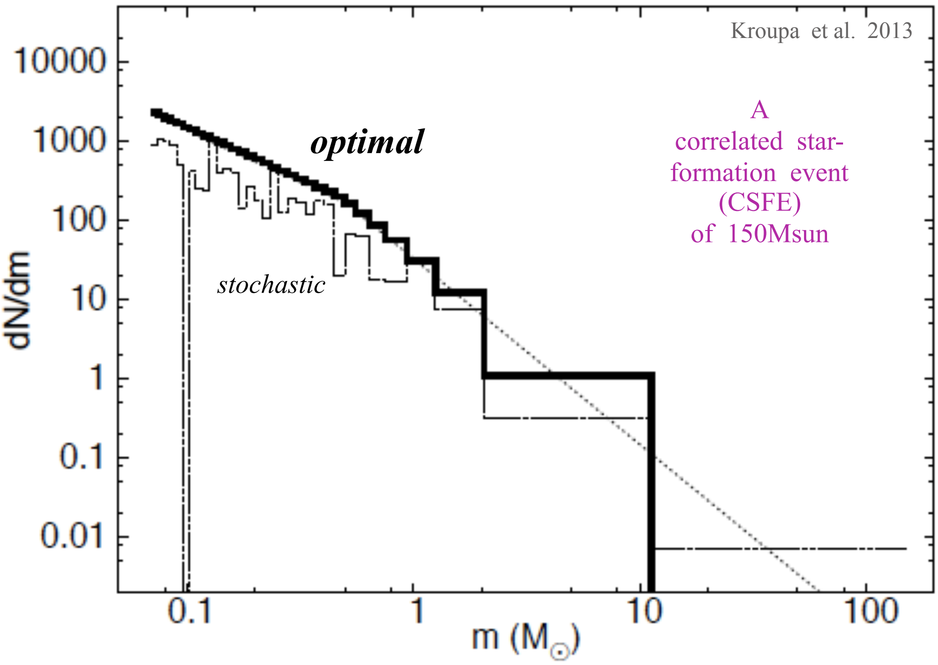
The normalization and the most massive star in the sequence are set by the following two equations:

$$1 = \int_{m_{max}}^{m_{max*}} \xi(m)\,dm, \tag{4.10}$$

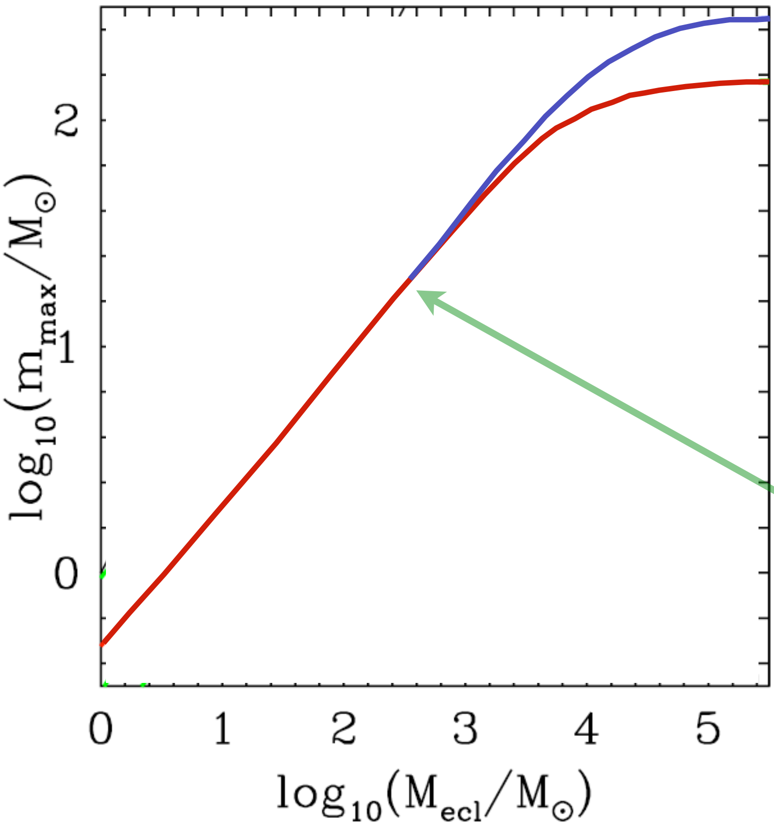
with

$$M_{ecl}(m_{max}) - m_{max} = \int_{m_L}^{m_{max}} m\,\xi(m)\,dm \tag{4.11}$$

as the closing condition. These two equations need to be solved iteratively. An excellent approx-



An important consequence of optimal sampling



$m_{\max}* = 300\,M_\odot$

$m_{\max}* = 150\,M_\odot$

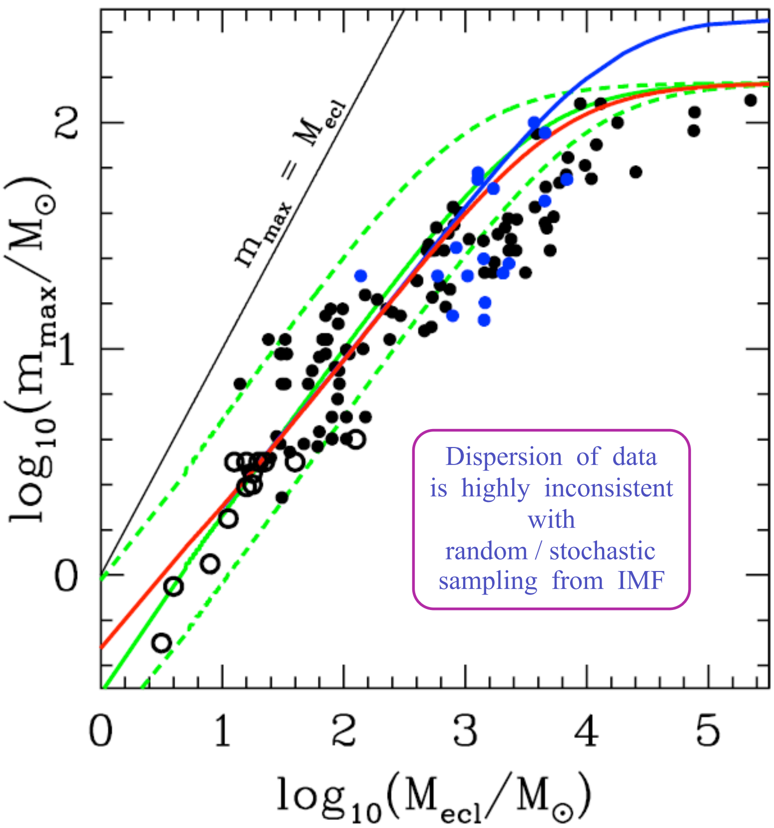
$$1 = \int_{m_{\max}}^{m_{\max *}} \xi(m)\, dm$$

$$M_{\rm ecl} = \int_{m_{\rm l}}^{m_{\max}} m\, \xi(m)\, dm$$

$$m_{\max} = \mathrm{fn}(M_{\rm ecl})$$

an m_{max} -- Mecl relation

Weidner & Kroupa 2005, 2006; Weidner et al. 2010, 2013; Kroupa et al. 2013; Kirk & Myers, 2010, 2012; Hsu, Hartmann et al. 2012, 2013; Ramirez Alegria, Borossiva et al. 2016



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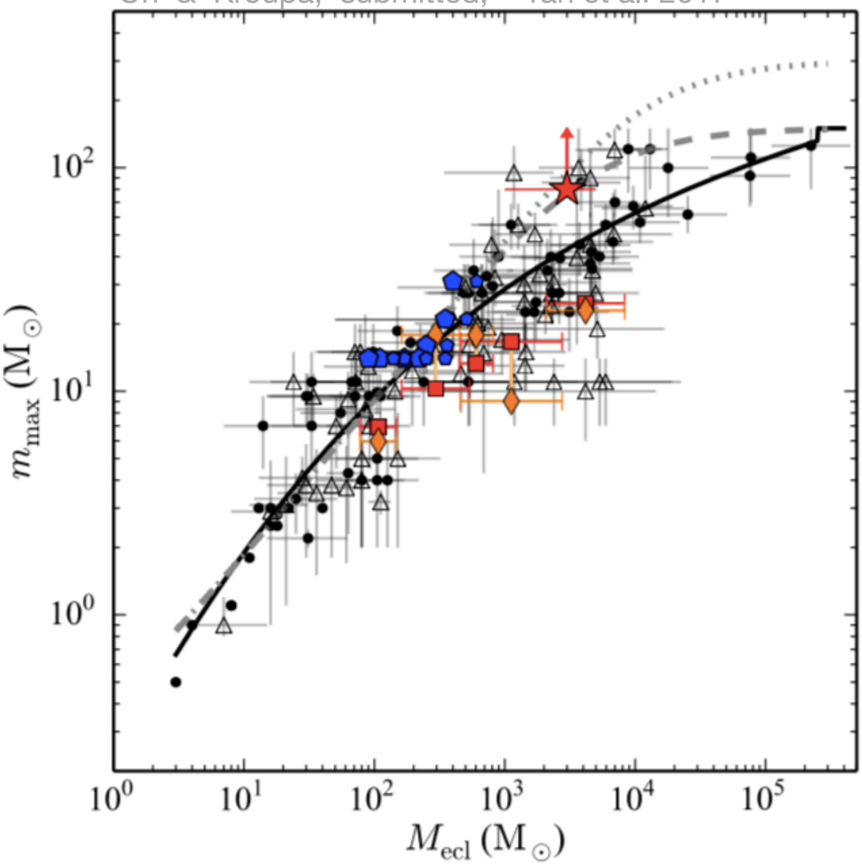
Confirmation

Oh & Kroupa, submitted; Yan et al. 2017



"isolated" O stars in LMC

Stephens et al. 2017

Open clusters:

Ram´ırez Alegr´ıa et al. (2016).

Real young populations
are *not stochastic ensembles*
from invariant distr. functions

the star-formation hilfskonstrukt ~~**an invariant probability density distribution function**~~

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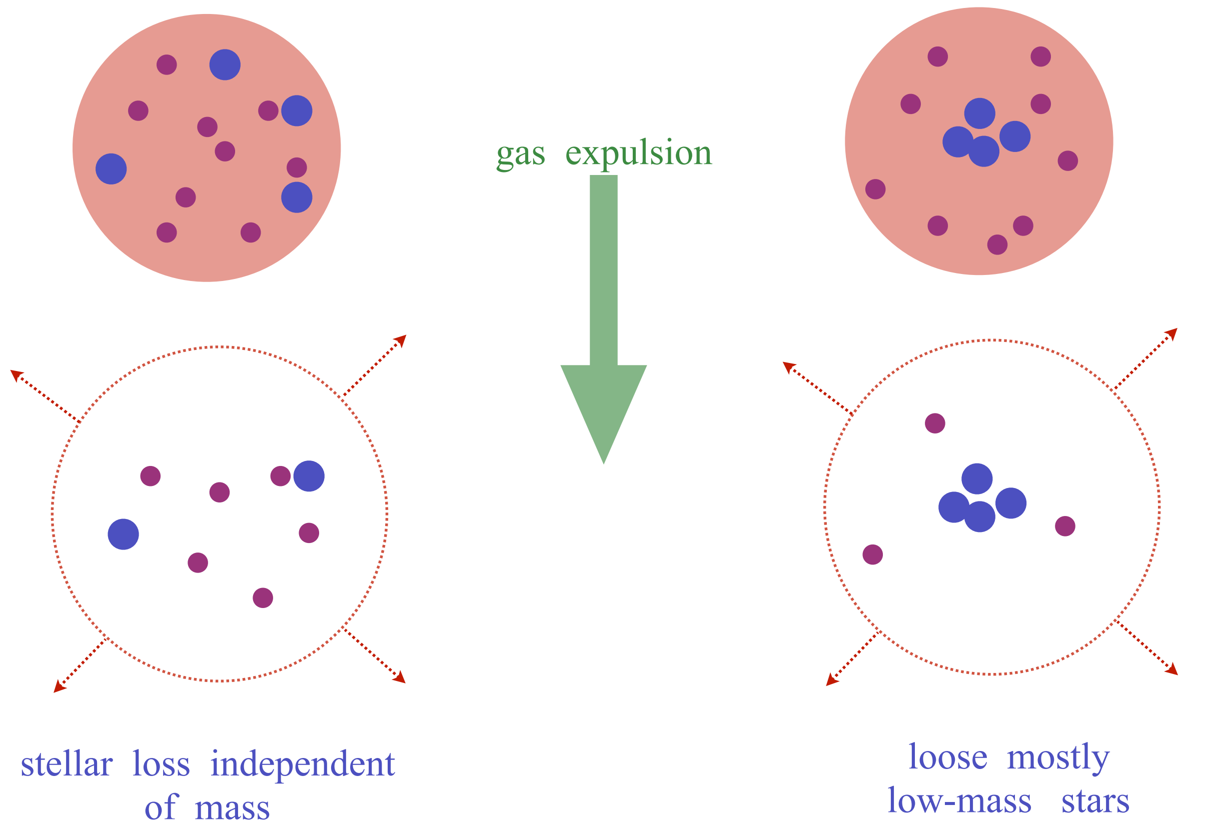
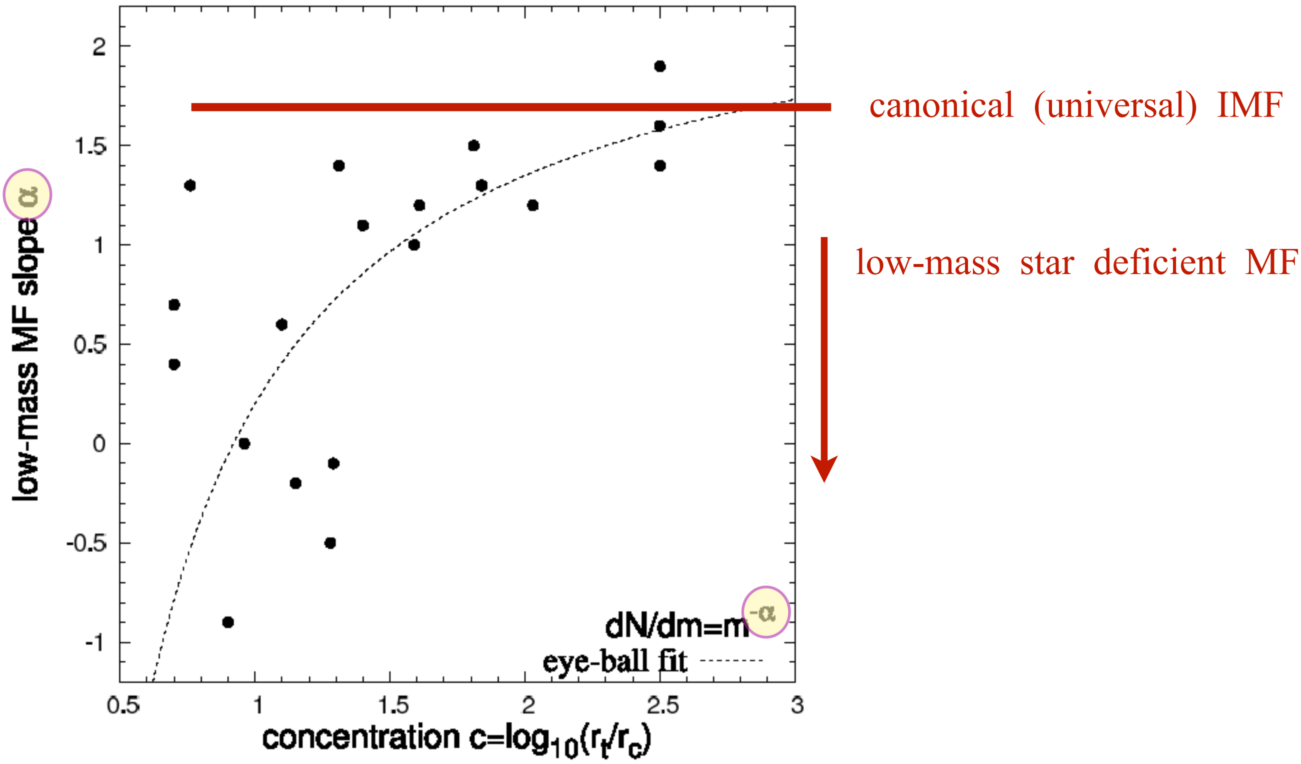
Nbody models of binary rich initially mass segregated clusters with redisual gas expulsion after birth

(Marks, Kroupa & Baumgardt 2008)



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

(de Marchi, Paresce & Pulone 2007)



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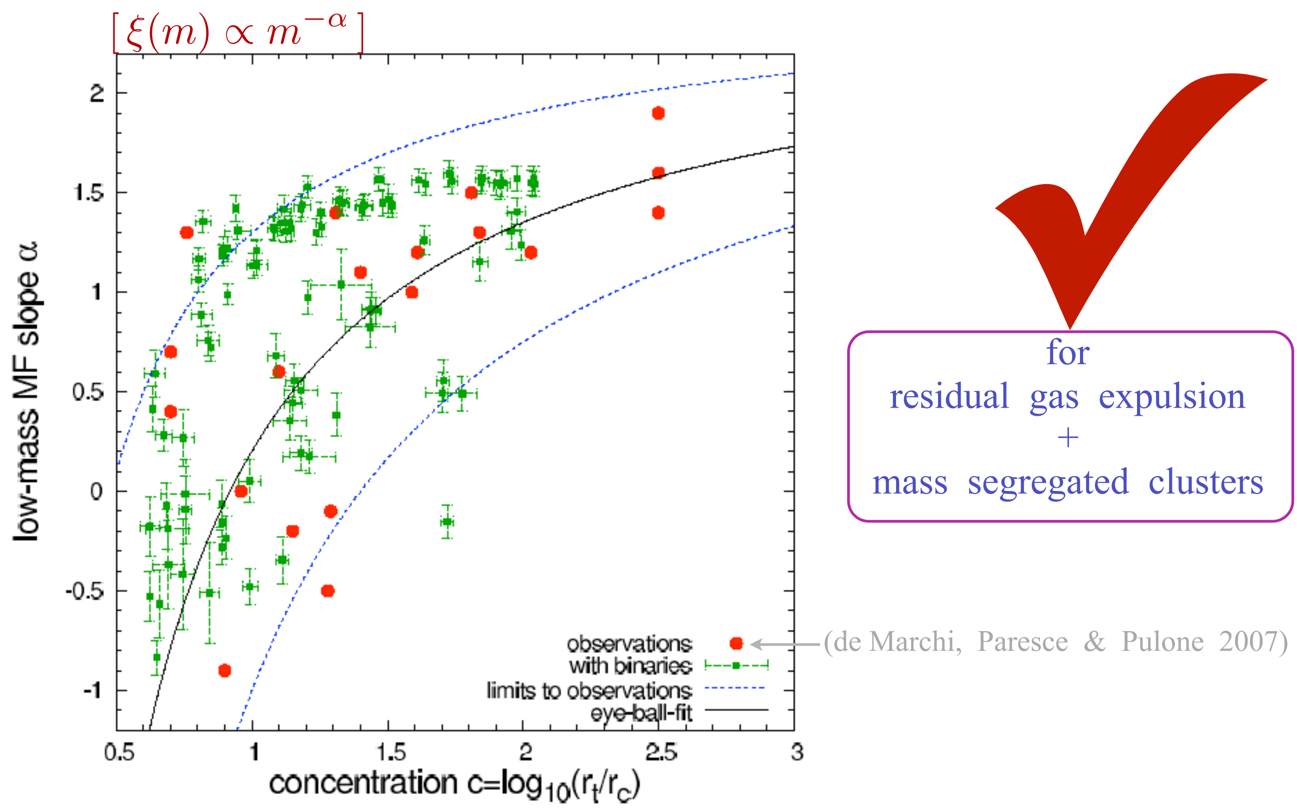


Top-heavy IMF in extreme-density environments :

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

$$\begin{aligned} \alpha_3 &= \alpha_2, & m > 1\,M_\odot \quad \wedge \quad x < -0.89, \\ \alpha_3 &= -0.41 \times x + 1.94, & m > 1\,M_\odot \quad \wedge \quad x \geq -0.89, \end{aligned}$$

$$x = -0.14\,[\mathrm{Fe/H}] + 0.99 \log_{10}\left(\rho/\left(10^6\,M_\odot\,\mathrm{pc}^{-3}\right)\right). \tag{65}$$

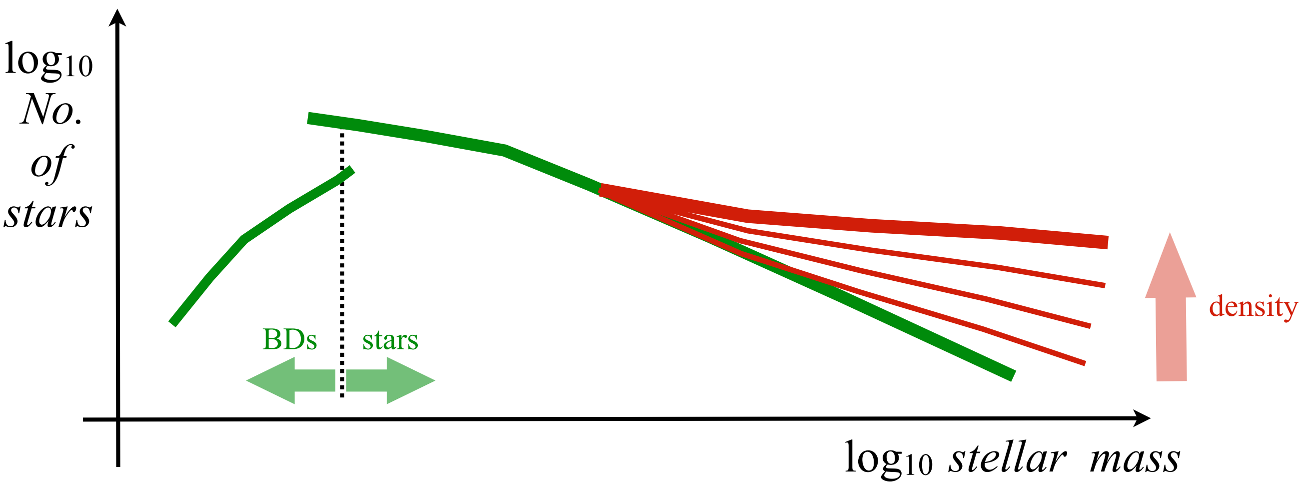
Marks et al. 2012
Kroupa et al. 2013 (arXiv:1112.3340)

Star-counts: Correct star-counts in R136 for ejected stars
→ IMF in R136 top-heavy (Banerjee & Kroupa 2012)

Excess of massive stars in whole 30Dor region
(Schneider et al. 2018)

Top-heavy IMF in Magellanic Bridge cluster NGC796
(Kalari et al. 2018)

What this implies :



Using for $m < 1\,M_\odot$

$$\alpha_{1,2} = \alpha_{1/2c} + 0.5 \left[\frac{\mathrm{Fe}}{\mathrm{H}}\right]$$

estimated from resolved MW populations
(Kroupa 2001)

where the canonical
solar-abundance values are
$\alpha_{1c} = 1.3 \quad 0.07 < m/M_\odot < 0.5$
$\alpha_{2c} = 2.3 \quad 0.5 < m/M_\odot < 1.3$

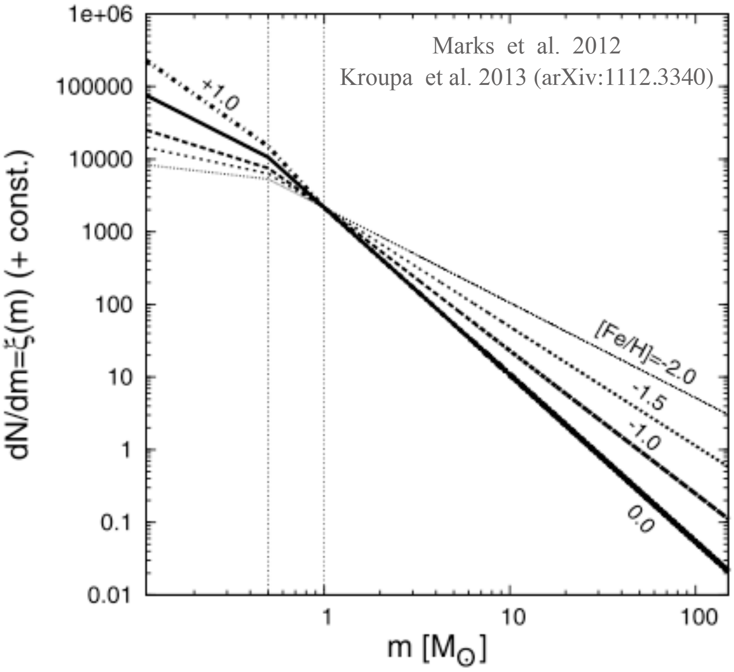


Figure 5. Suggested shape of the stellar IMF for different metallicities, [Fe/H] (not taking into account the density dependence of the IMF). The IMFs are scaled such that their values agree at $m = 1\,M_\odot$. Above $1\,M_\odot$ the IMF slope is determined by the present work (Fig. 4, equation 11). Below $1\,M_\odot$ the parametrization is determined by Kroupa (2001, equation 12), whose results suggest tentative evidence that more metal-rich environments produce relatively more low-mass stars. Note that only the metallicity dependence is shown, but not the dependence on mass (Fig. 2) or density (Fig. 3).

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Composite Stellar Populations

Stars form in a clustered mode (Lada & Lada 2003; Megeath et al. 2016).
Thus, the **I**ntegrated **G**alactic **I**MF follows from

IGIMF = $\sum$ of IMFs (in all clusters)

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$$\xi_{\rm IGIMF}(m,t) = \int_{M_{\rm ecl,min}}^{M_{\rm ecl,max}(SFR(t))} \xi(m \le m_{\rm max}(M_{\rm ecl}))\ \xi_{\rm ecl}(M_{\rm ecl})\, dM_{\rm ecl}$$

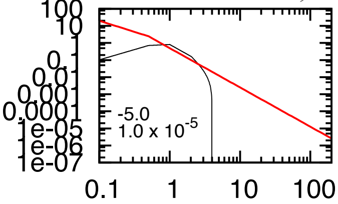
Kroupa & Weidner (2003); Weidner & Kroupa (2005, 2006)
Yan, Jerabkova & Kroupa (2017); Jerabkova et al. (2018)

Natural explanation of the
mass-metallicity relation,
radial Halpha cutoff
vs UV extended disks
of galaxies
and many other problems in
understanding galaxies.

Jerabkova et al. 2018; Yan, Jerabkova et al. 2017; Fontanot et al. 2017;
and recent papers by Simone Recchi et al.; Sylvia Ploeckinger et al.
and previous papers by Koeppen et al., Pflamm-Altenburg et al., Weidner et al.

The IGIMF for galaxies with different SFRs & [Fe/H]

Jerabkova et al., 2018 submitted



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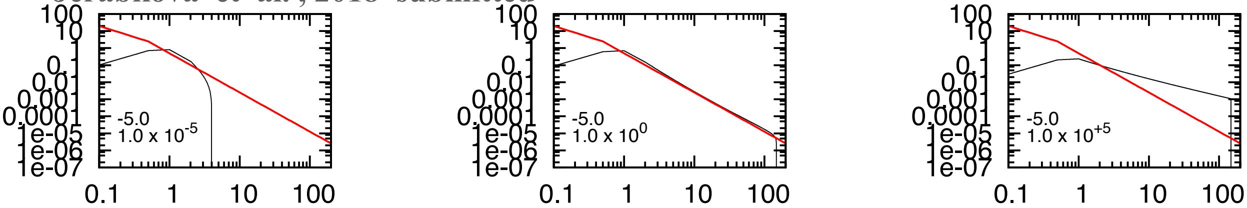

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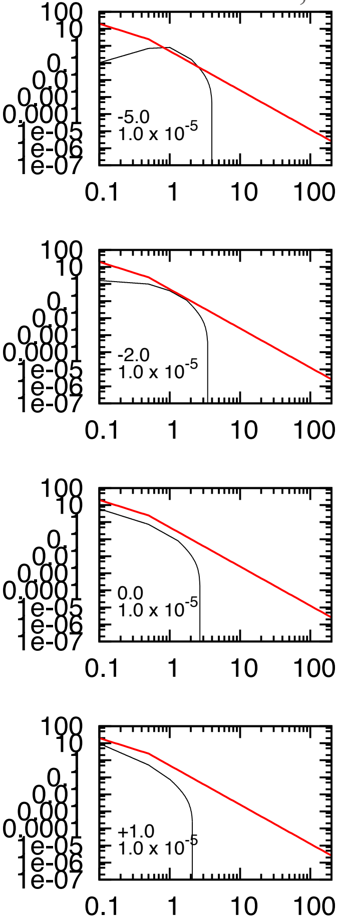

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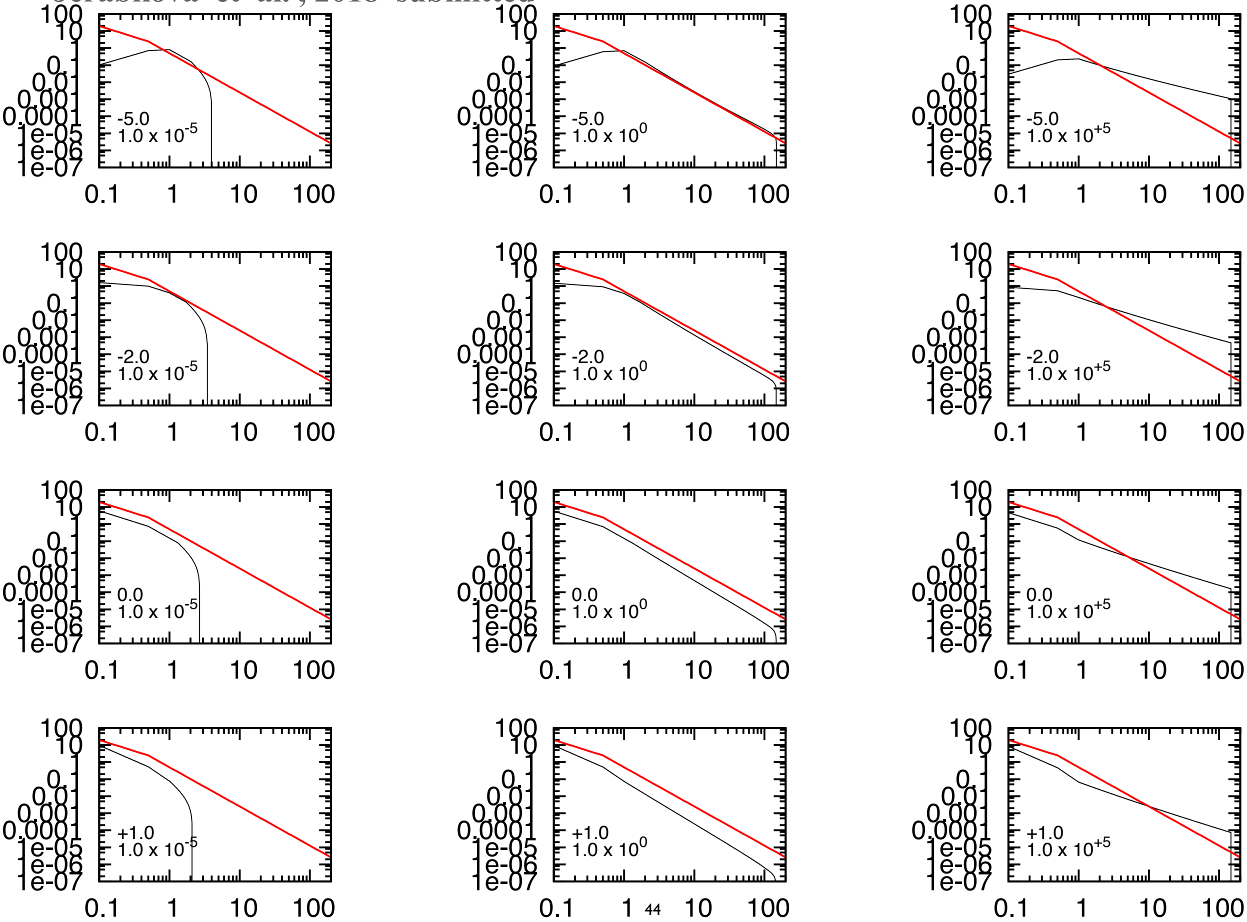

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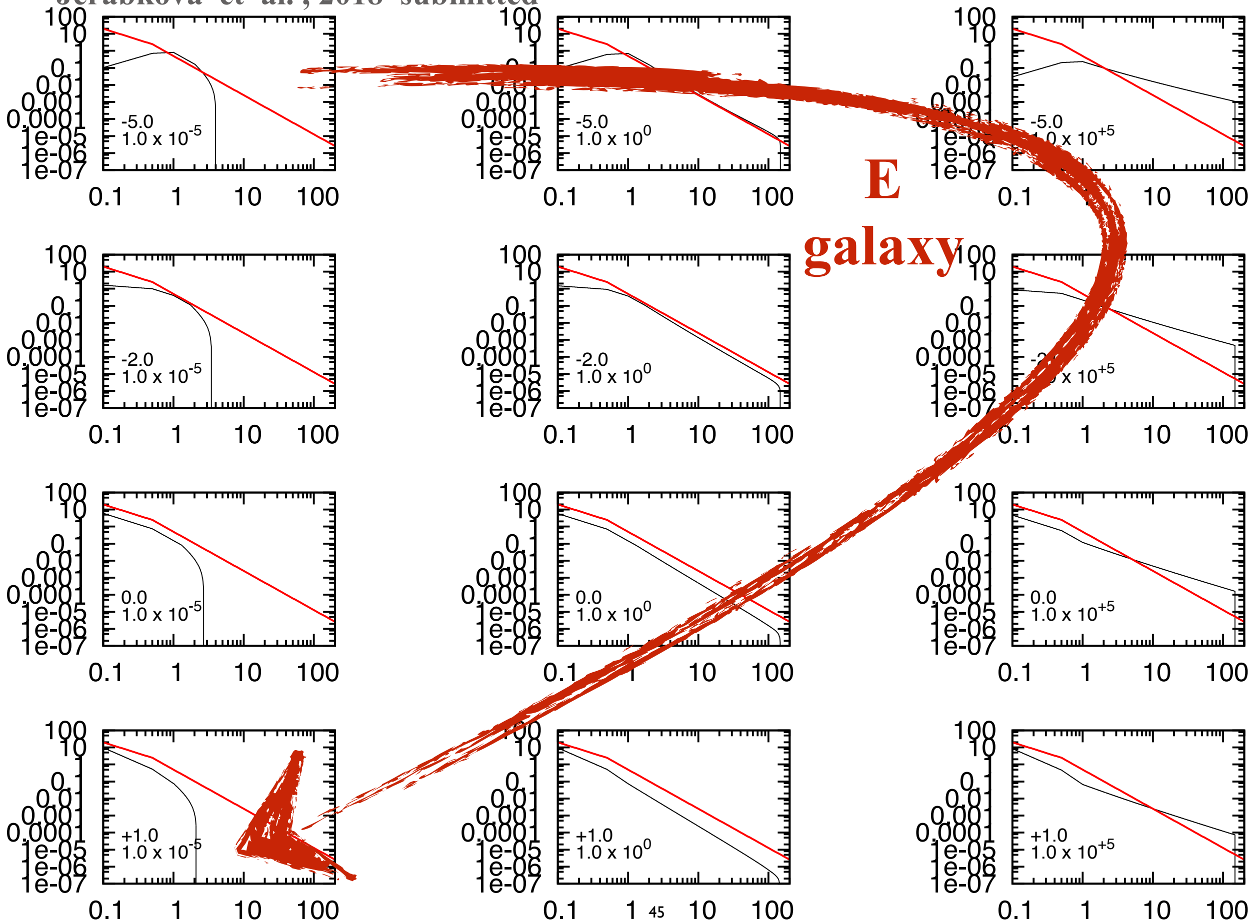
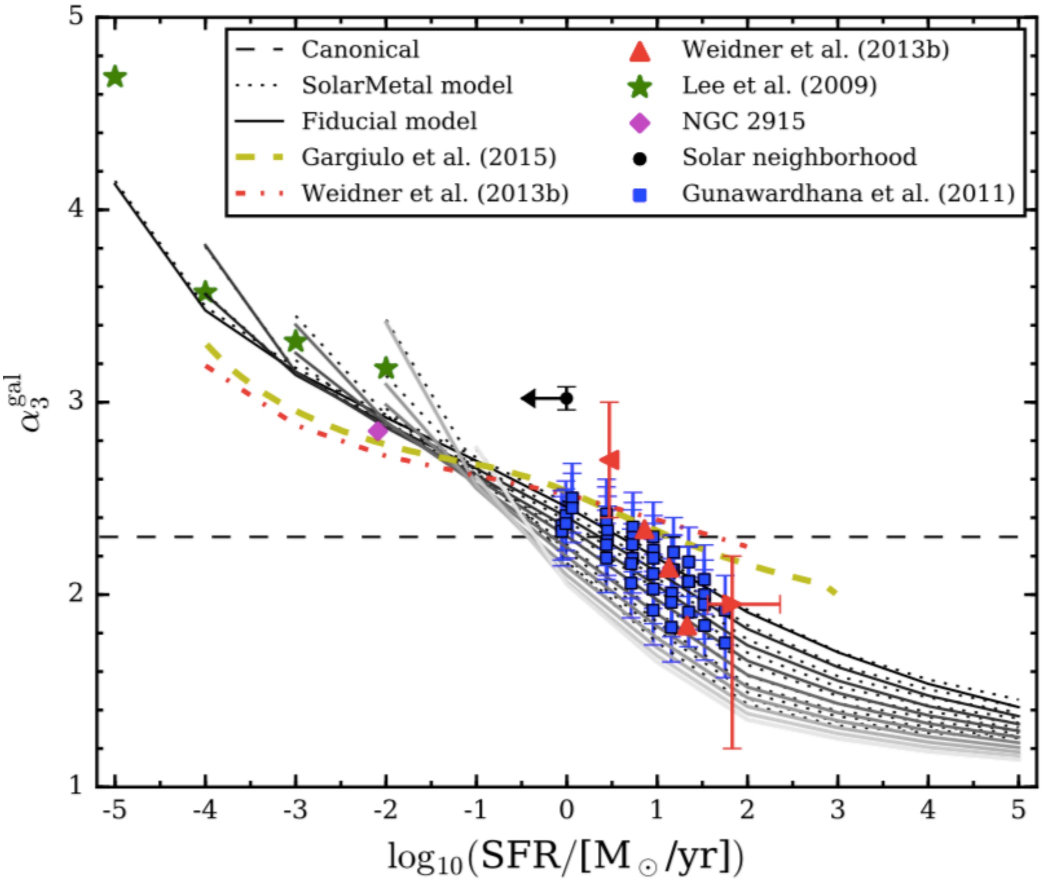


Yan, Jerabkova & Kroupa 2017; see also Weidner et al. 2013



E galaxies formed with top-heavy IMFs

confirming Matteucci (1994) !

and see recent work by Vazdekis

Kennicutt et al. (1994) SFR relation (for a pure Salpeter power-law IMF betw. 0.1 and 100 Msun)

$$\cancel{\mathrm{SFR(total)} = \frac{L_{\mathrm{H}\alpha}}{1.26 \times 10^{41}\ \mathrm{erg\ s^{-1}}}\ M_{\odot}\ \mathrm{yr}^{-1}.} \qquad (14)$$

$\cancel{SFR \propto L_{H_\alpha}}$ ~~always for all galaxies~~

$$L_{\mathrm{H}\alpha} = \mu\ 3.0207 \times 10^{-12}\ \mathrm{erg}\ N_{\mathrm{ion}}/\delta t, \qquad (3)$$

$$N_{\mathrm{ion},\delta t} = \int_{m_{\mathrm{low}}}^{m_{\mathrm{max}}} \xi_{\mathrm{IMF}}(m) N_{\mathrm{ion},\delta t}(m)\, dm, \qquad (2)$$

$\mu = 1$ (Pflamm-Altenburg et al. 2007)

Jerabkova et al. 2018

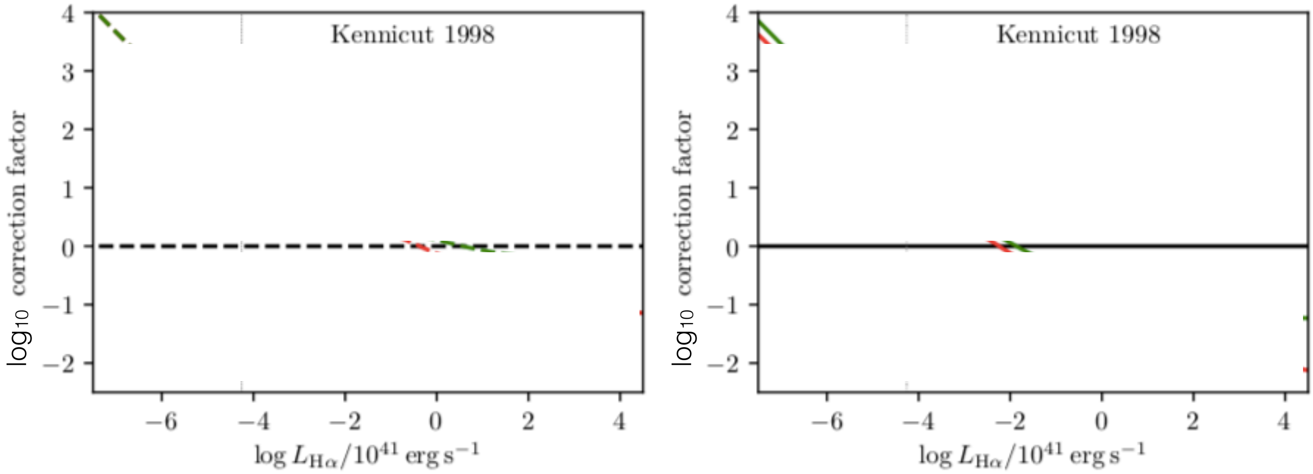
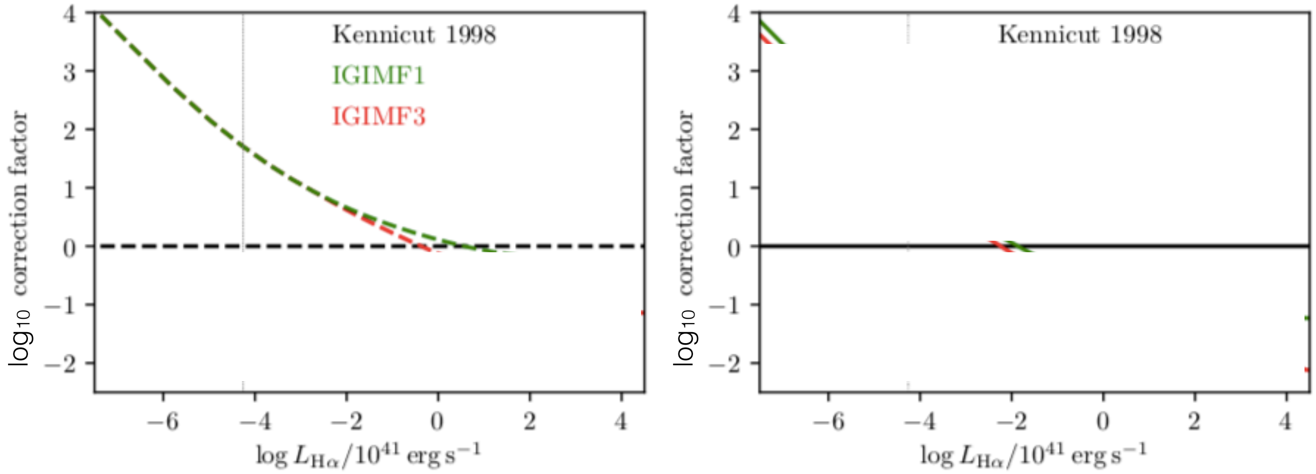


Fig. 8. Corrections to the Kennicutt SFR–Hα relation. The true (IGIMF) SFRs are divided by the Kennicutt value, for the same *Hα* flux and for the IGIMF models and metallicities shown in Fig. 7. The Hα flux of LeoP is shown by the vertical dotted line in both panels. The two panels demonstrate that dwarf galaxies wth Hα fluxes near 10^{36} erg/s have a SFR which is more than 100 times larger than that suggested by the Kennicutt relation, while massive or profusely star-forming galaxies with Hα $\approx 10^{44}$ erg/s have SFRs which can be 10–100 times smaller than given by the traditional Kennicutt relation. This has major implications for understanding galaxy formation and evolution.

Jerabkova et al. 2018



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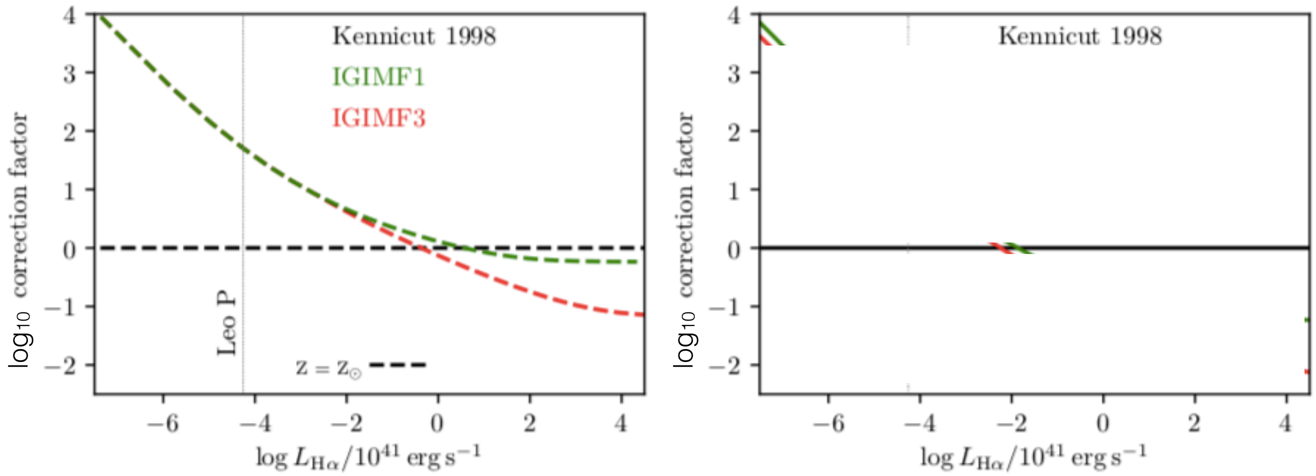

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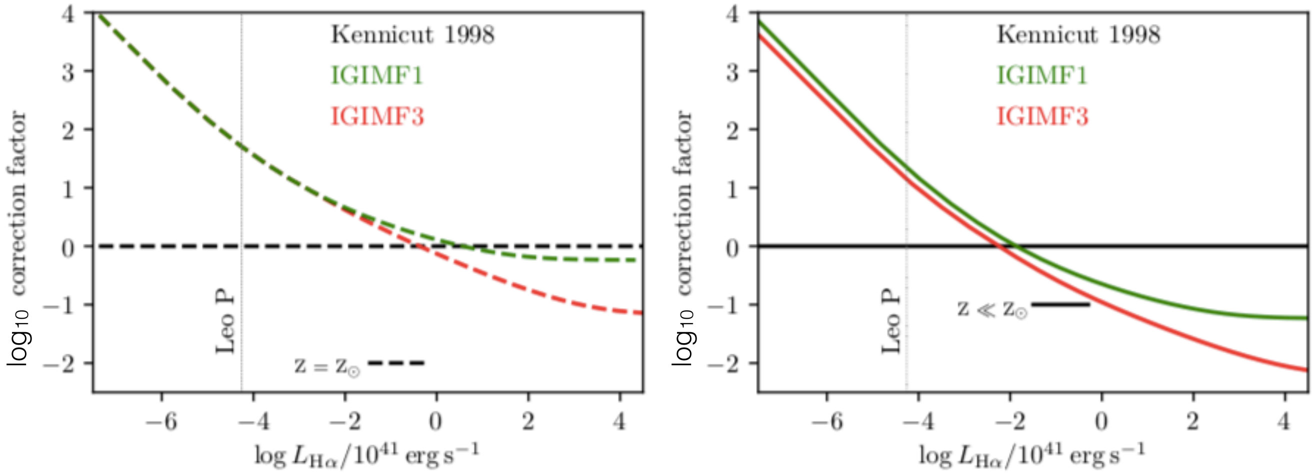

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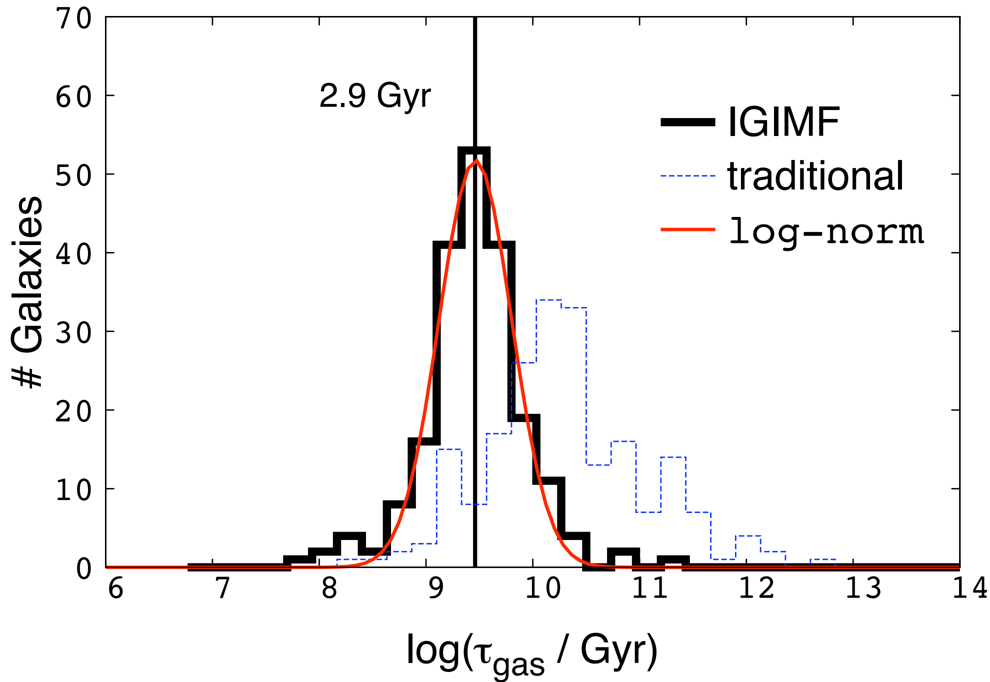
IGIMF theory → constant gas depletion time-scale ! for galaxies with $10^5 \lesssim \frac{M_{gas}}{M_\odot} \lesssim 10^{11}$



Pflamm-Altenburg, Weidner & Kroupa (2007); Pflamm-A. & Kroupa (2009)

for all late-type galaxies $10^6 \lesssim \frac{M_{gas}}{M_\odot} \lesssim 10^{11}$ **2.9 Gyr** ?

Dwarf galaxies have the same star-formation efficiencies as L* galaxies

$$\boxed{SFR = \frac{1}{3\,\mathrm{Gyr}}\, M_{\mathrm{neutral\ gas}}}$$

i.e. every 10 Myr a galaxy transforms 0.3 % of its neutral gas mass into stellar mass.

Conclusions

What we call the IMF is a mathematical "hilfskonstrukt"

This "hilfskonstrukt" is
an optimally sampled distribution function
(star formation is not probabilistic but
highly self-regulated)

This "hilfskonstrukt" varies with physical conditions

Star-formation "hilfskonstrukt" $\neq$ galaxy-wide "hilfskonstrukt"

Important implication for galaxy evolution (& cosmology)