IMF variations at the lowest and highest masses

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11.07.2013

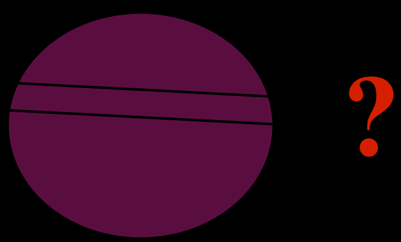
SpS 12: *A fresh look at the stellar IMF*

EWASS 2013, Turku, Finland

The low-mass system end

Brown Dwarfs vs

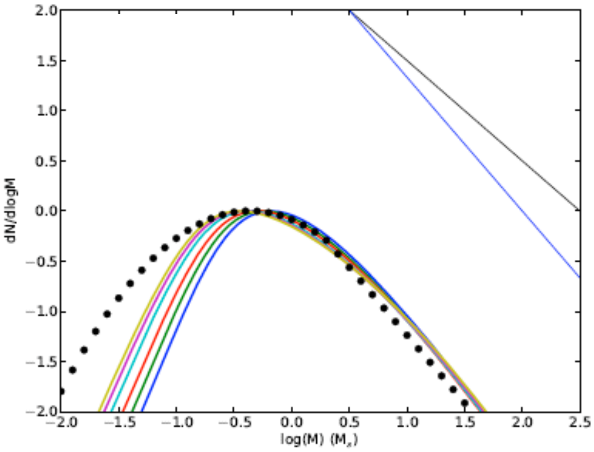
Stars



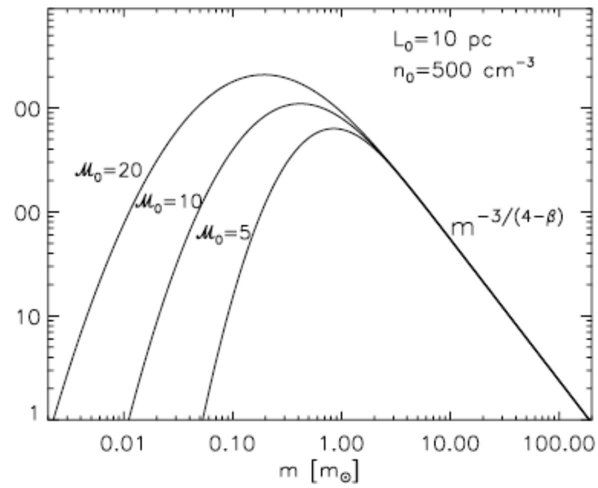
Mass distribution of gravitationally unstable cores generated by the process of turbulent fragmentation.

Cloud fragmentation predicts ***too few BDs*** **:**

Hennebelle & Chabrier 2008, Hennebelle'12



Padoan & Nordlund 2002



Significant deficit of theoretical BDs and IMF is ***not a log-normal***

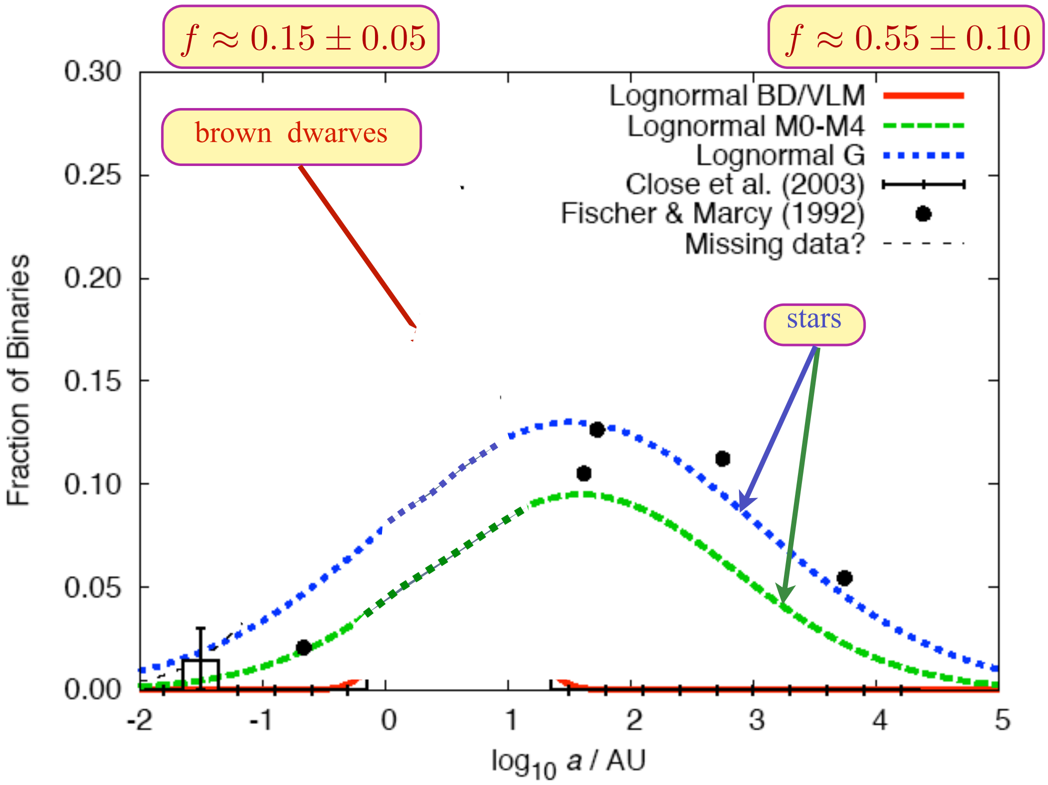
But the observed BDs must come from somewhere.

There must be an additional source of BDs.

Is this true?

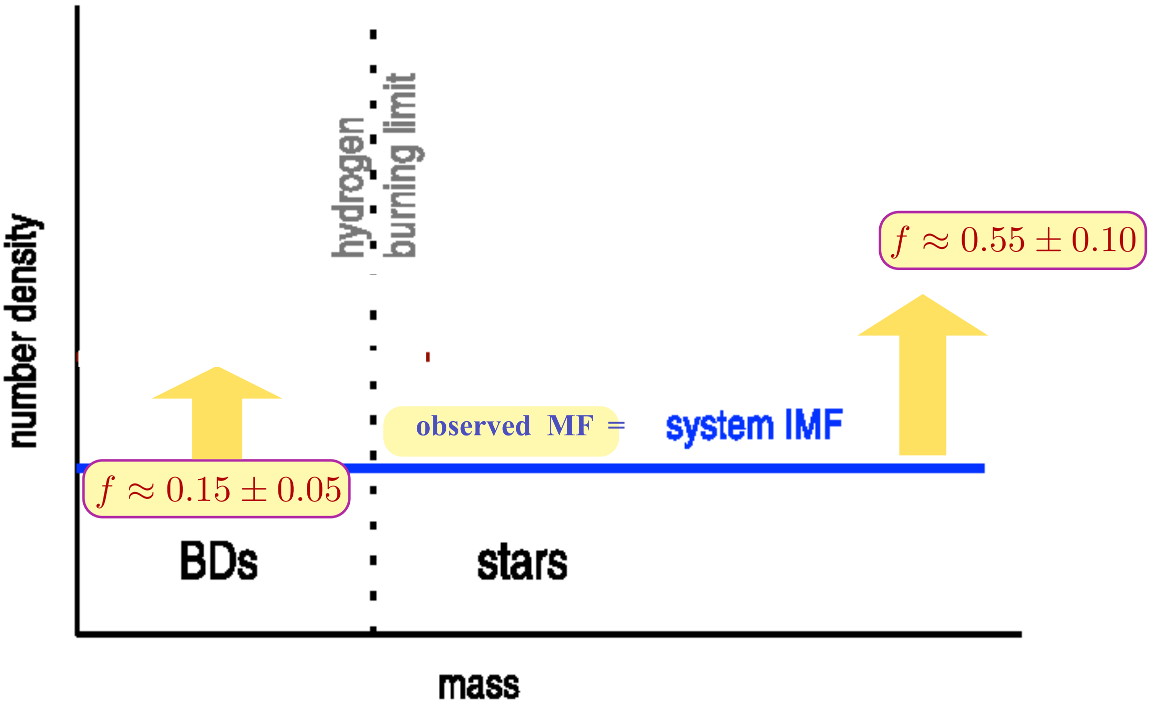
Letting aside pure theory, lets see what can be learned from observational data :

The semi-major axis distributions of BDs and stars differ :



... this implies that BDs and stars
are
different populations;
they have a
different dynamical history **!**

Correcting the observed IMF for unresolved components



What we know from observation :

Brown dwarf desert ⟷ (nearly) only star - star binaries

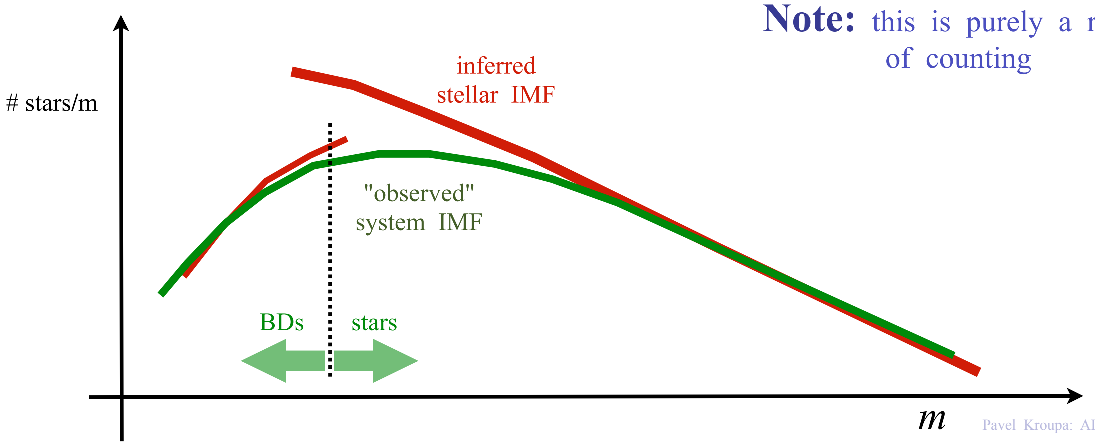
Binary fraction among stars in MW > **50 %** (100 % in dynamically young systems, 50 % in dynamically evolved systems, e.g. open clusters, Galactic field)

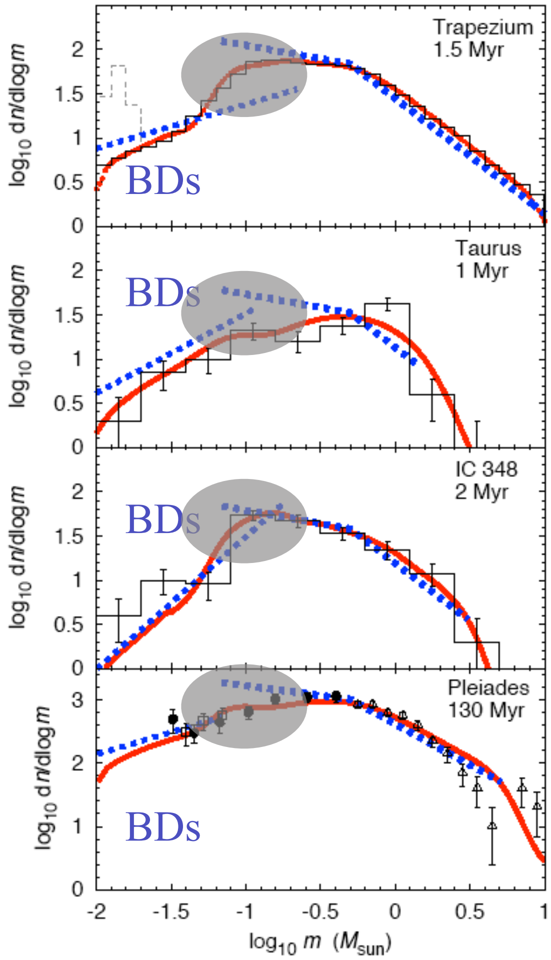
Approx. flat mass-ratio distribution for $0.2 < \frac{m_{\rm primary}}{M_\odot} < {\rm few}$

BD - BD binary fraction $\approx 15\,\%$

What this implies :

Note: this is purely a result of counting

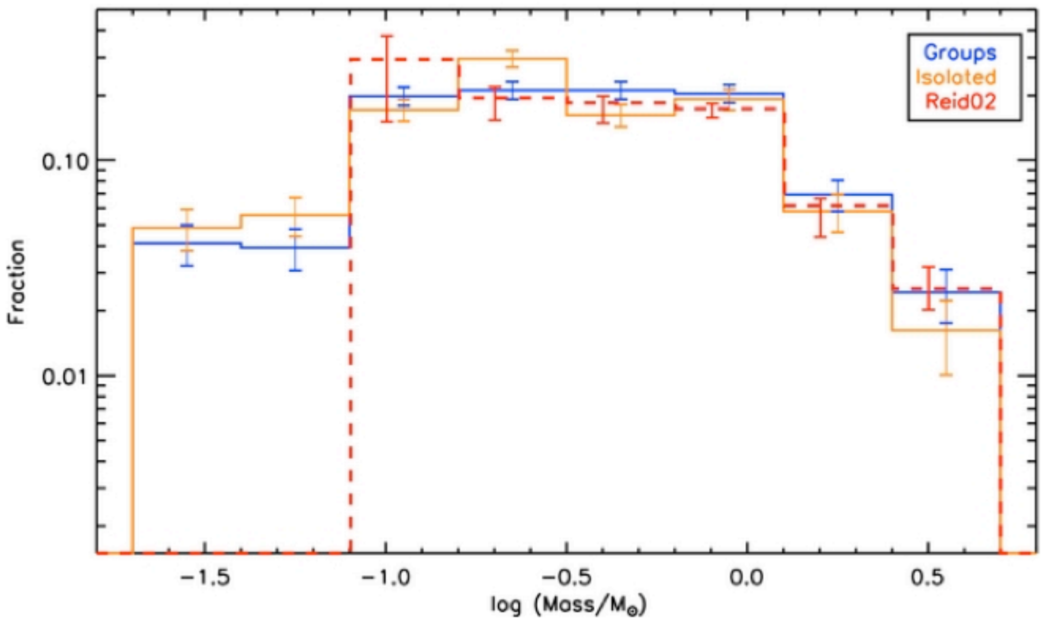


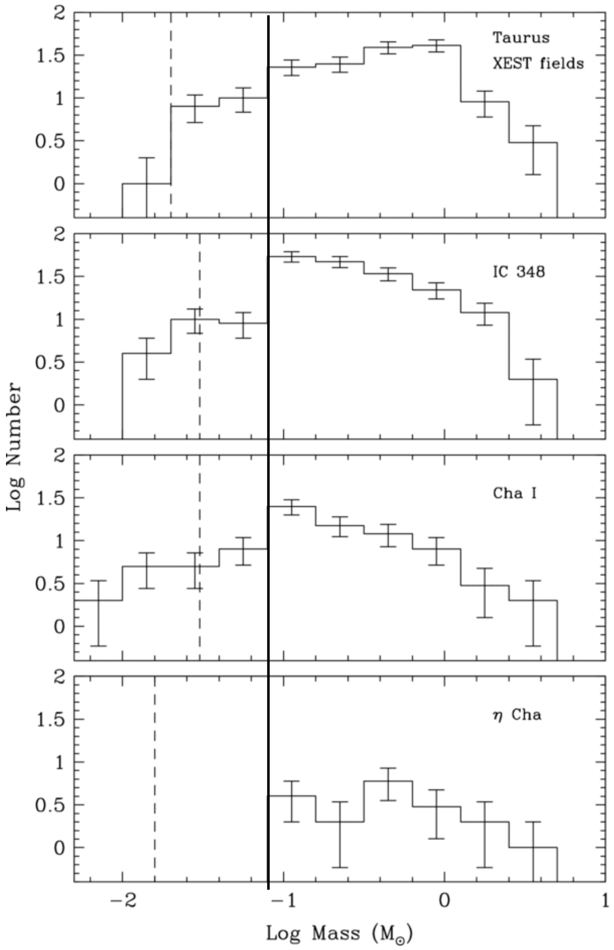


Correcting the observed IMF for unresolved components

(Thies & Kroupa 2007, 2008)

Kirk & Myers 2012





Luhman et al. 2009

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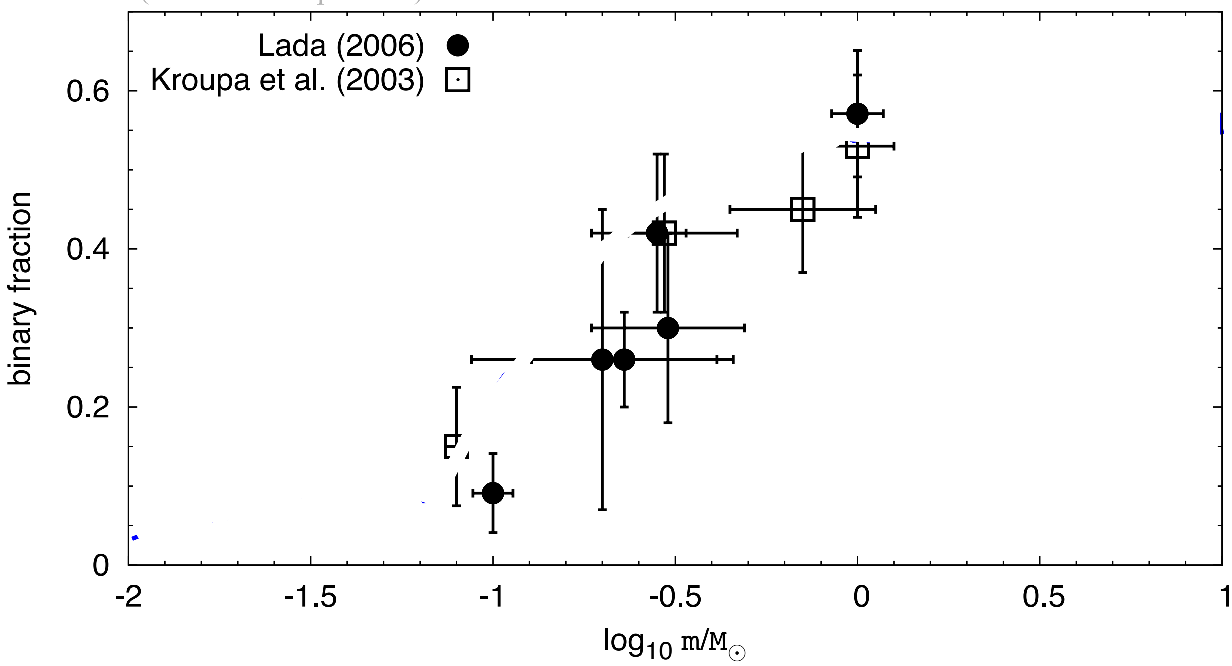
The binary fraction as a function of primary mass

(Thies & Kroupa 2007)



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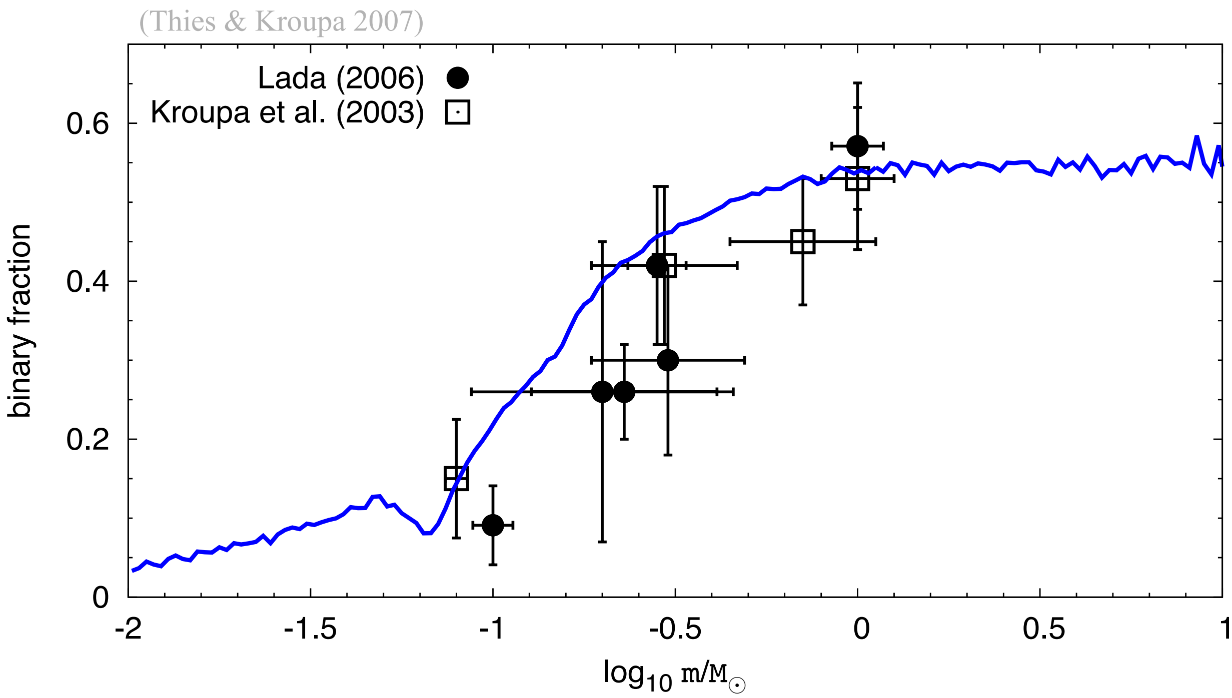
The binary fraction as a function of primary mass



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Induced BD Formation in Star Clusters

Towards explaining the BD population

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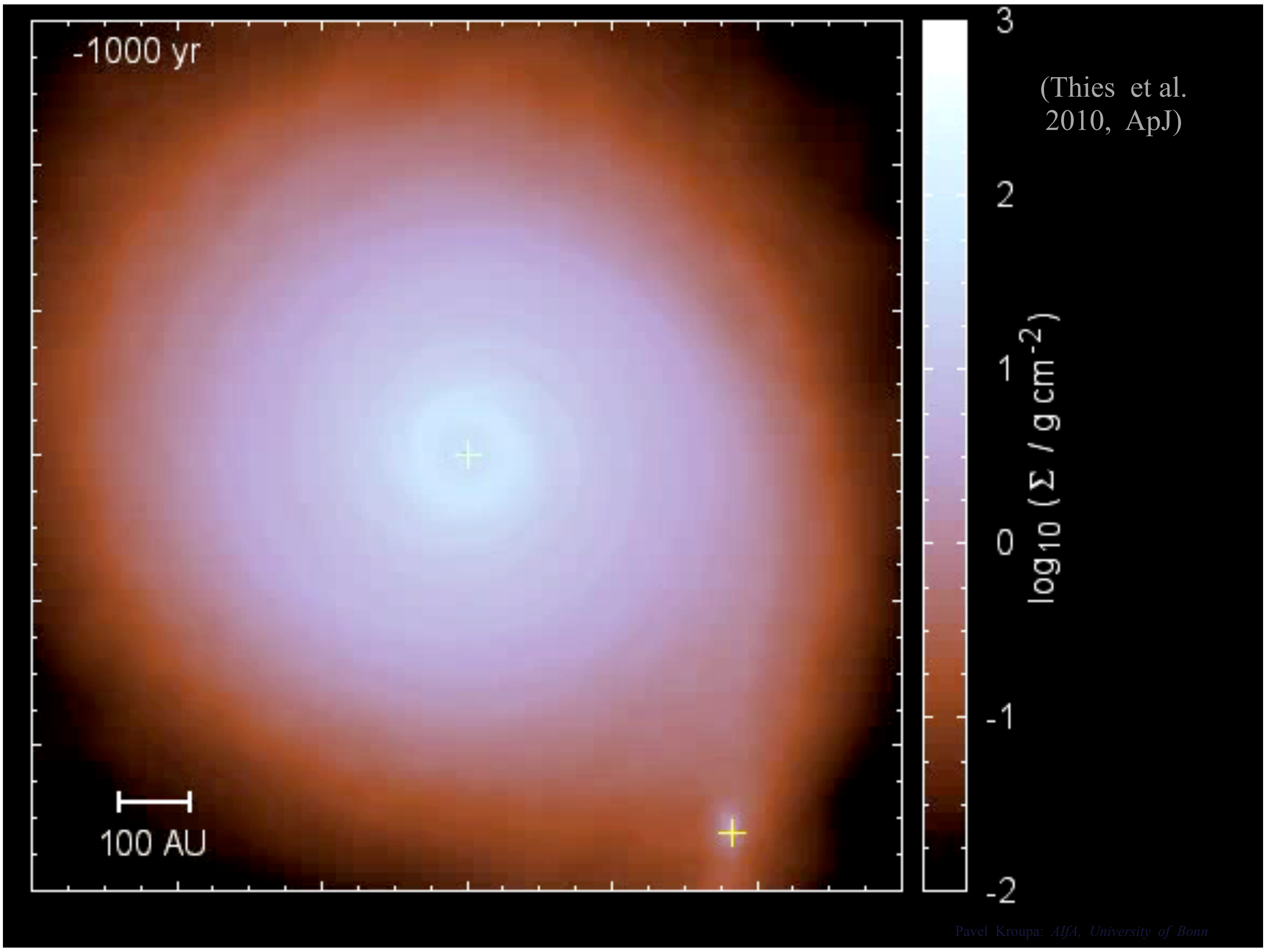
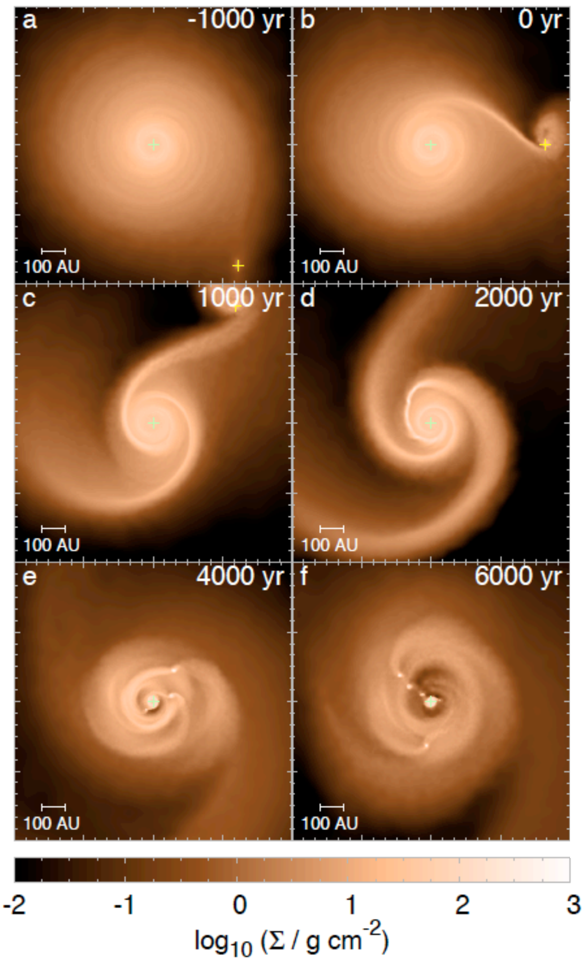
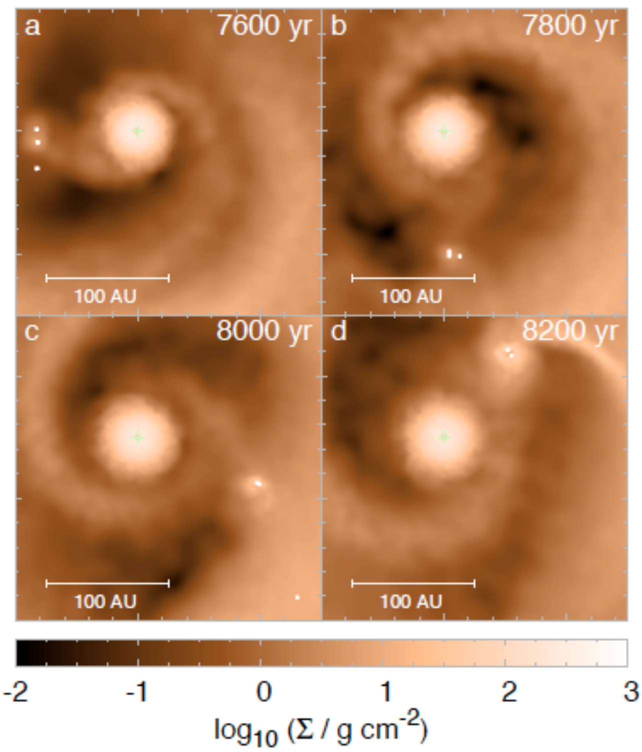


Thies, Kroupa, Goodwin, Stamatellos, Whitworth 2010



Basu & Vorobyov 2012



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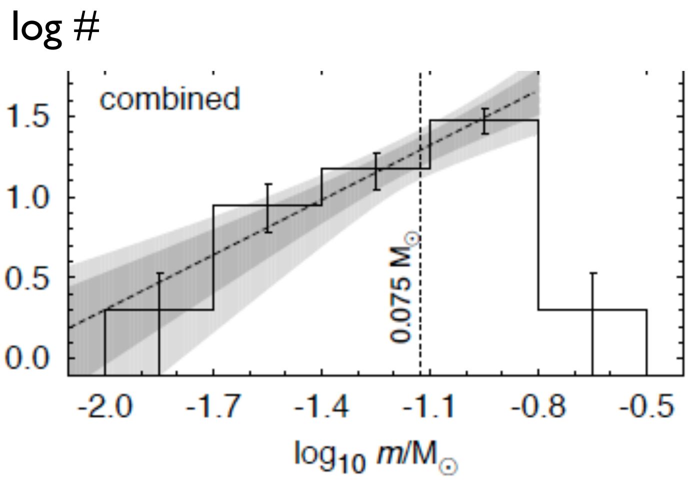
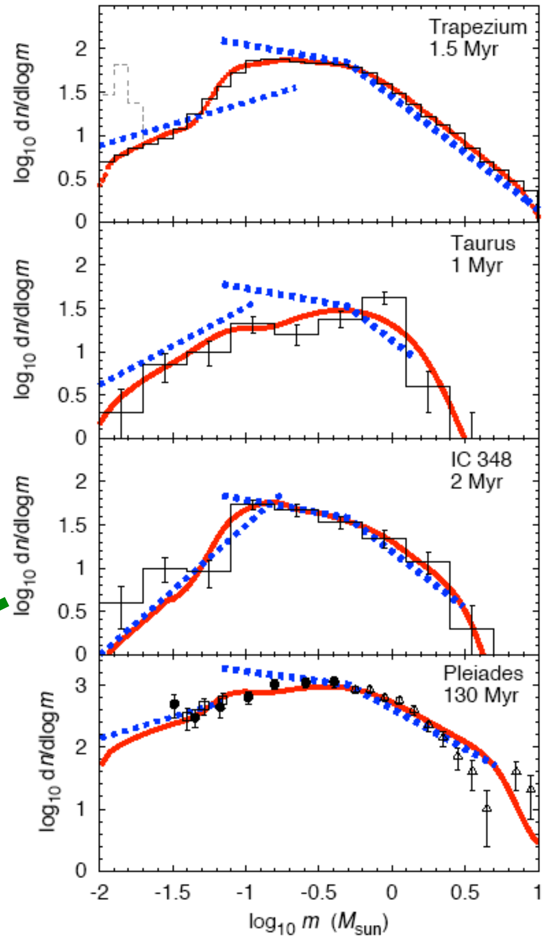
Thies et al. 2010





18 DRAGON computations :
58 BD & VLMS sinks formed

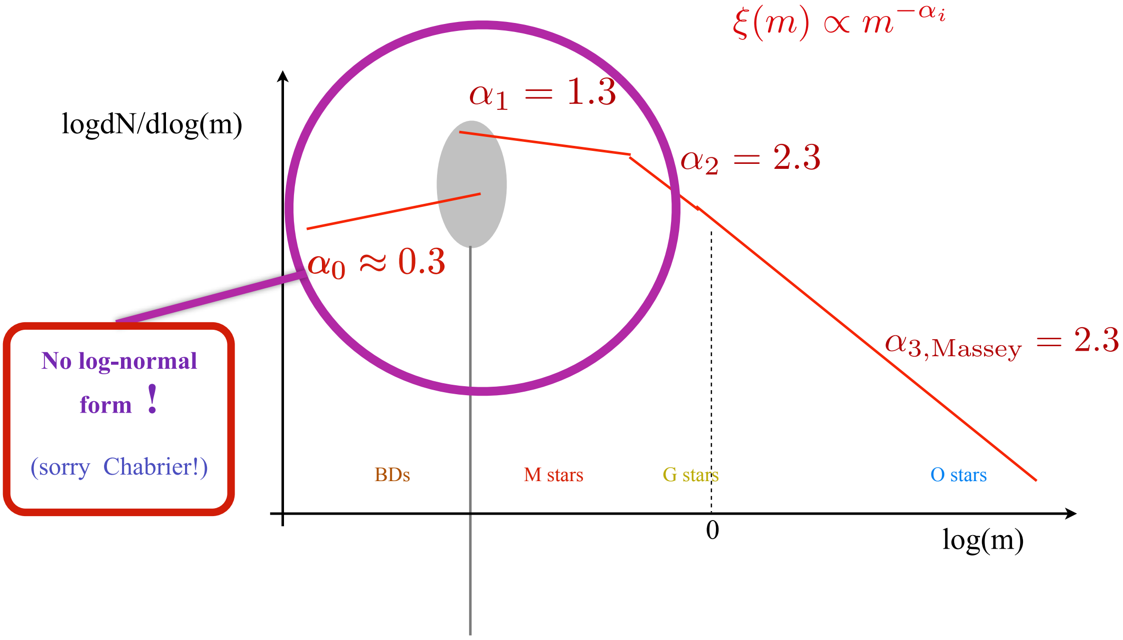
$\alpha_{BD} = 0.1^{+0.3}_{-0.4}$

convergence of theory and observation (when correctly interpreted !).

Pavel Kroupa: *Sternwarte, University of Bonn*

new universal / canonical discontinuous three-part power-law IMF :

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



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

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Ingo Thies
(AIfA, Bonn)

Bottom-heavy IMFs

in metal-rich

environments / in E galaxies ?

Low-mass stars in E galaxies

confirmation of a trend already known ?

With increasing metallicity, SF may be producing increasingly "bottom heavy" IMFs :

$$\alpha \approx 1.3 + 0.5[\mathrm{Fe/H}]; \quad m < 0.7 M_\odot$$

Kroupa 2001, 2002

Find long-sought *cooling flow population* of low-mass stars using gravity-sensitive spectral lines :

Kroupa & Gilmore 1994

With increasing E-galaxy mass, IMFs in E galaxies indeed seem to become increasingly "bottom heavy".

$$\alpha = 3.41 + 2.78[\mathrm{Fe/H}] - 3.79[\mathrm{Fe/H}]^2; \quad 0.1 < m/M_\odot < 100$$

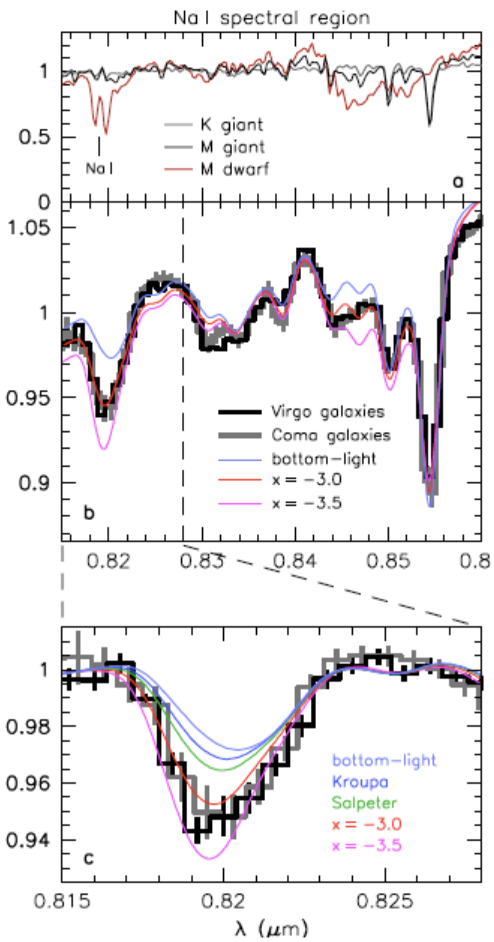
Cenarro et al. 2003
see also van Dokkum & Conroy 2011

A substantial population of low mass stars in luminous elliptical galaxies

Pieter G. van Dokkum[1] & Charlie Conroy[2 3] (Nature)

[1] Astronomy Department, Yale University, New Haven, CT, USA
[2] Department of Astrophysical Sciences, Princeton University, Princeton, NJ, USA
[3] Harvard-Smithsonian Center for Astrophysics, Cambridge, MA, USA

The stellar initial mass function (IMF) describes the mass distribution of stars at the time of their formation and is of fundamental importance for many areas of astrophysics. The IMF is reasonably well constrained in the disk of the Milky Way[1] but we have very little direct information on the form of the IMF in other galaxies and at earlier cosmic epochs. Here we investigate the stellar mass function in elliptical galaxies by measuring the strength of the Na I doublet[2,3] and the Wing-Ford molecular FeH band[4,5] in their spectra. These lines are strong in stars with masses $\lesssim 0.3\,M_\odot$ and weak or absent in all other types of stars.[5–7] We unambiguously detect both signatures, consistent with previous studies[8] that were based on data of lower signal-to-noise ratio. The direct detection of the light of low mass stars implies that they are very abundant in elliptical galaxies, making up $> 80\,\%$ of the total number of stars and contributing $> 60\,\%$ of the total stellar mass. We infer that the IMF in massive star-forming galaxies in the early Universe produced many more low mass stars than the IMF in the Milky Way disk, and was probably slightly steeper than the Salpeter form[9] in the mass range $0.1 - 1\,M_\odot$.



Salpeter x= -2.35

The Initial Mass Function of Stars: Evidence for Uniformity in Variable Systems

Pavel Kroupa 2002, Science

The distribution of stellar masses that form in one star formation event in a given volume of space is called the initial mass function (IMF). The IMF has been estimated from low-mass brown dwarfs to very massive stars. Combining IMF estimates for different populations in which the stars can be observed individually unveils an extraordinary uniformity of the IMF. This general insight appears to hold for populations including present-day star formation in small molecular clouds, rich and dense massive star-clusters forming in giant clouds, through to ancient and metal-poor exotic stellar populations that may be dominated by dark matter. This apparent universality of the IMF is a challenge for star formation theory, because elementary considerations suggest that the IMF ought to systematically vary with star-forming conditions.

However, there may be some IMF variation for very-low-mass stars. Present-day star-forming clouds typically have somewhat higher metal-abundances $\{\log_{10}(Z/Z_\odot) \approx [Fe/H] \approx +0.2\}$ compared to 6 Ga ago ($[Fe/H] \approx -0.3$) (*73*). This is the mean age of the population defining the average IMF. The data in the empirical alpha-plot indicate that some of the younger clusters may have a single-star IMF that is somewhat steeper than the average IMF if unresolved binary-stars are corrected for (*58*). Clouds with a larger [Fe/H] appear to produce relatively more very-low-mass stars. This is tentatively supported by the M35 result (Fig. 4) and by the typically flatter MFs in globular clusters (*50*) that have $[Fe/H] \approx -1.5$. The recent finding that the old and metal-poor ($[Fe/H] \approx -0.6$) thick-disk population has a flatter IMF below 0.3 $M_\odot$ with $\alpha \approx 0.5$ (*74*) also supports this assertion. If such a systematic effect is present, then for $m \lesssim 0.7\ M_\odot$

$$\alpha \approx 1.3 + \Delta\alpha[Fe/H] \quad (3)$$

with $\Delta\alpha \approx 0.5$. Many IMF measurements are needed to verify if such a variation exists because it is within the present uncertainty in

Have van Dokkum & Conroy thus found this suggested trend with metallicity ?

Saglia et al. 2002, "*The Puzzlingly Small Ca II Triplet Absorption in Elliptical Galaxies*", ApJ

Abstract: " . . . (2) *The steepening of the IMF at low masses* required to lower the CaT* and CaT indices to the observed values is *incompatible* with the measured FeH index at 9916 Å and the dynamical mass-to-light ratios of elliptical galaxies. . . . "

?

Smith & Lucey 2013, "*A giant elliptical galaxy with a lightweight initial mass function*", MNRAS, in press, aph/1306.4983

Abstract: ". . . A *"heavyweight" IMF*, with a mass twice as large as the Kroupa case, *is firmly excluded*. Such an IMF has been proposed for more distant elliptical lenses, and also to explain strong dwarf-star spectral features, in particular the NaI 8200-Ang doublet. A FORS2 far-red spectrum shows that this feature is as strong in ESO325-G004 as it is in other high-sigma ellipticals, suggesting tension between dwarf-star indicators and lensing-mass constraints for this galaxy."

?

Jeong, Yi, Kyeong et al. 2013, "*On the nature of sodium excess objects, I. Data and observed trends*", ApJS, in press, aph/1307.1472

Abstract: "...we find that models used to reproduce the NaI8190 line strengths that adopt *a bottom-heavy IMF* are *not able to reproduce* the observed NaD line strengths. By comparing the observed NaD, Mgb and Fe5270 line strengths with those of the models, we identify a plausible range of parameters. In these models, the majority of early-type NEOs are alpha-enhanced ([a/Fe]~0.3), metal-rich ([Z/H]~0.3) and especially Na-enhanced ([Na/Fe]~0.3). Enhanced Na abundance is a particularly compelling hypothesis for the increase in the strength of the NaD line index in our early-type NEOs."

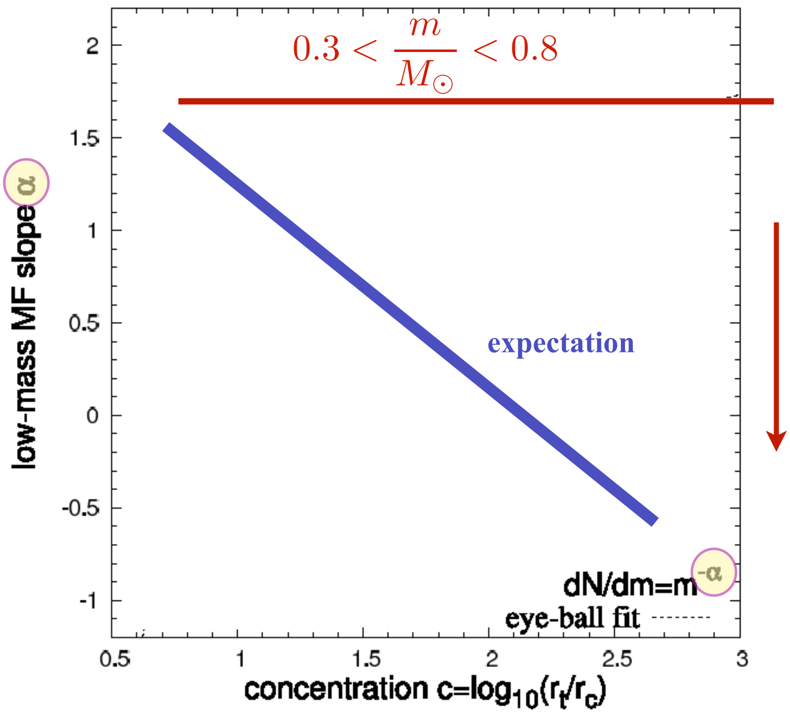
?

Top-heavy IMF

Globular Clusters ?

(ancient star bursts)

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



canonical (universal) IMF

normal
low-mass star population

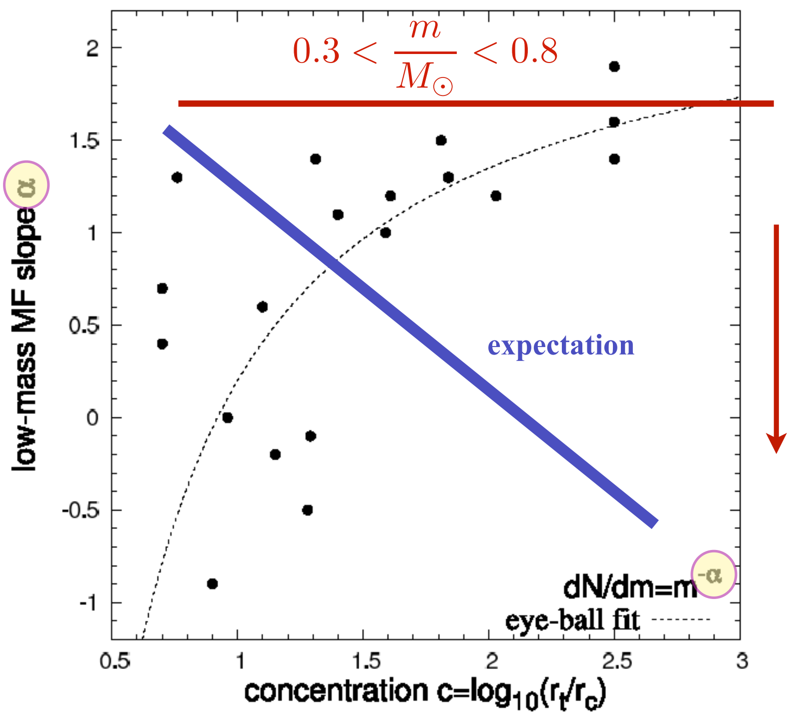
too few
low-mass stars

low-concentration clusters ought to be
dynamically less evolved

Pavel Kroupa: *AIfA, University of Bonn*

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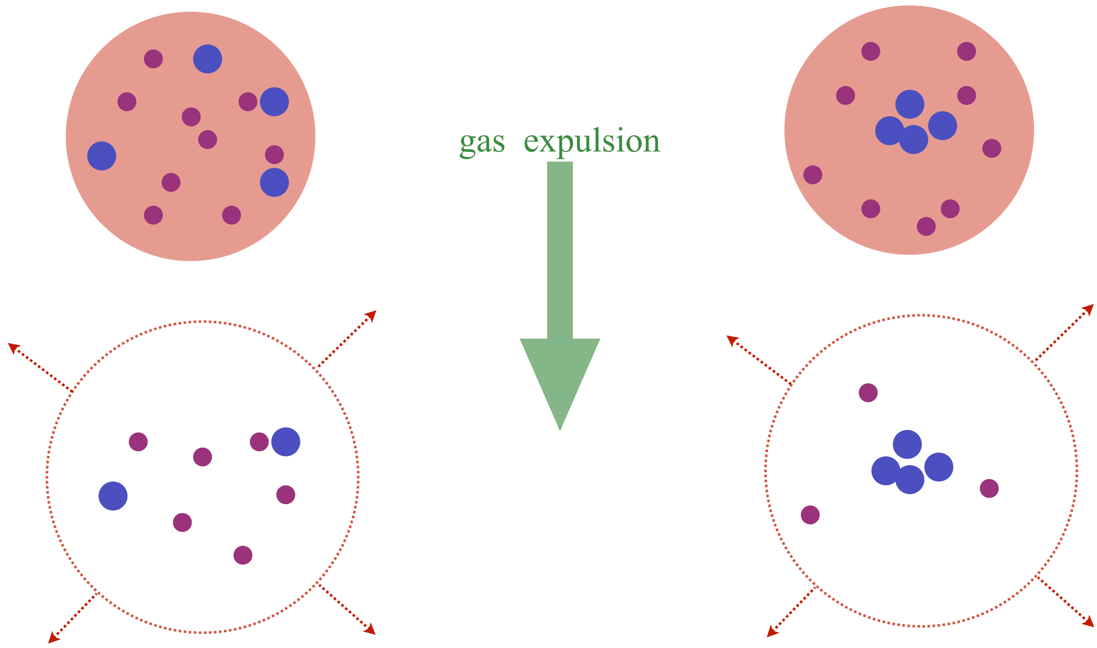
Nbody models of binary rich initially mass segregated clusters with redisual gas expulsion after birth

(Marks, Kroupa & Baumgardt 2008)

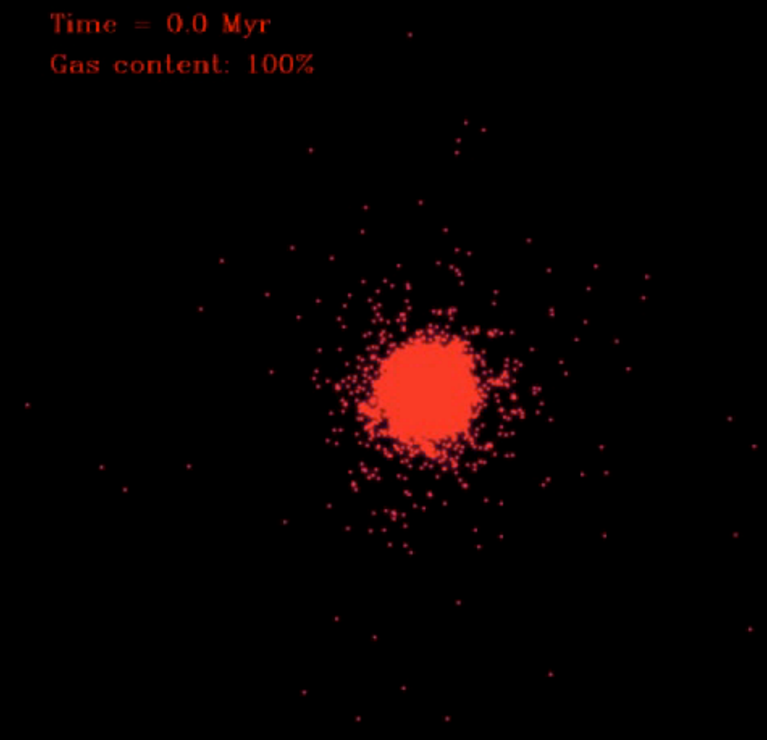


stellar loss independent of mass

loose mostly low-mass stars

Cluster reaction to thermal gas removal :

(movie by Baumgardt)



Baumgardt & Kroupa 2007, Bastian & Goodwin . . .

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

(Marks, Kroupa & Baumgardt 2008)

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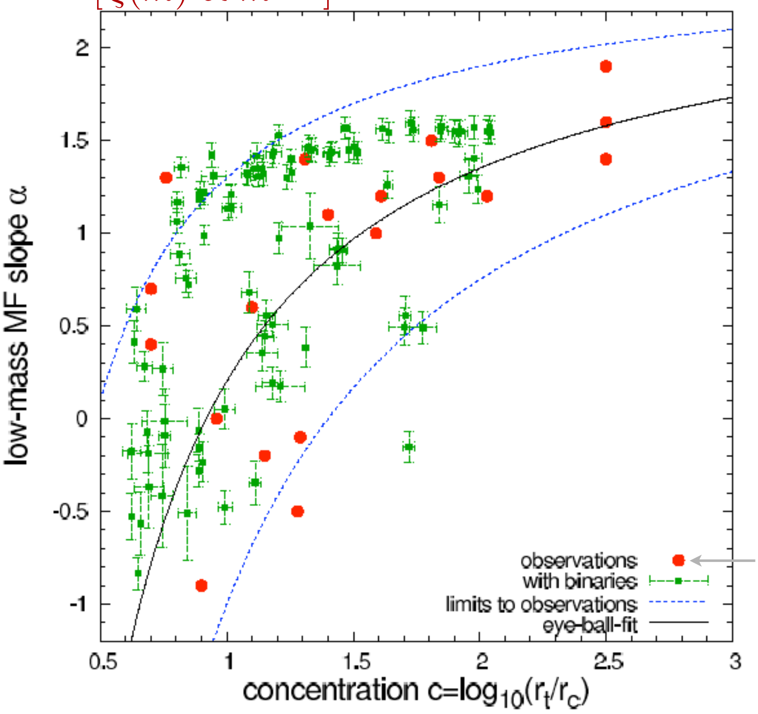
Nbody models of binary rich initially mass segregated clusters with redisual gas expulsion after birth

(Marks, Kroupa & Baumgardt 2008)

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



(de Marchi, Paresce & Pulone 2007)

for
residual gas expulsion
+
mass segregated clusters

Implications for the IMF :

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.

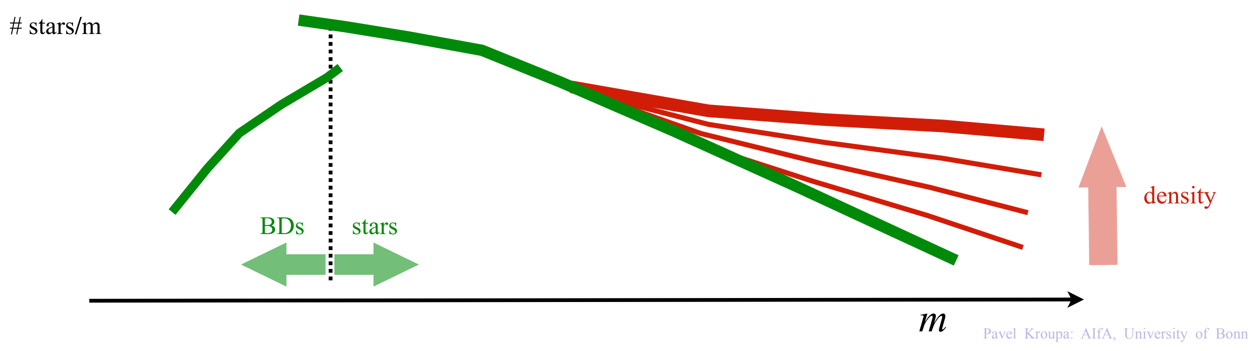
UCDs : higher dynamical M/L ratios

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

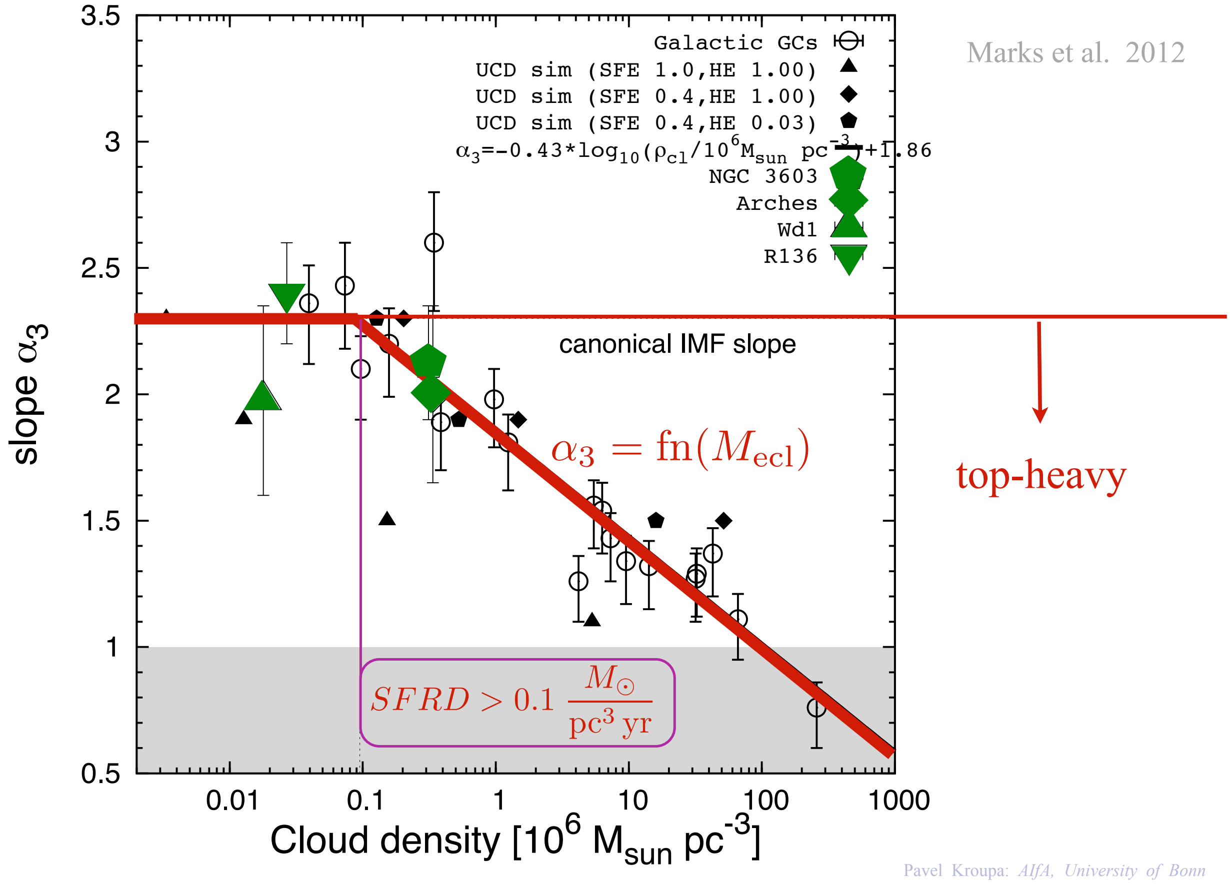
UCDs : larger fraction of X-ray sources than expected

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

What this implies :



Top-heavy IMF in extreme-density environments :

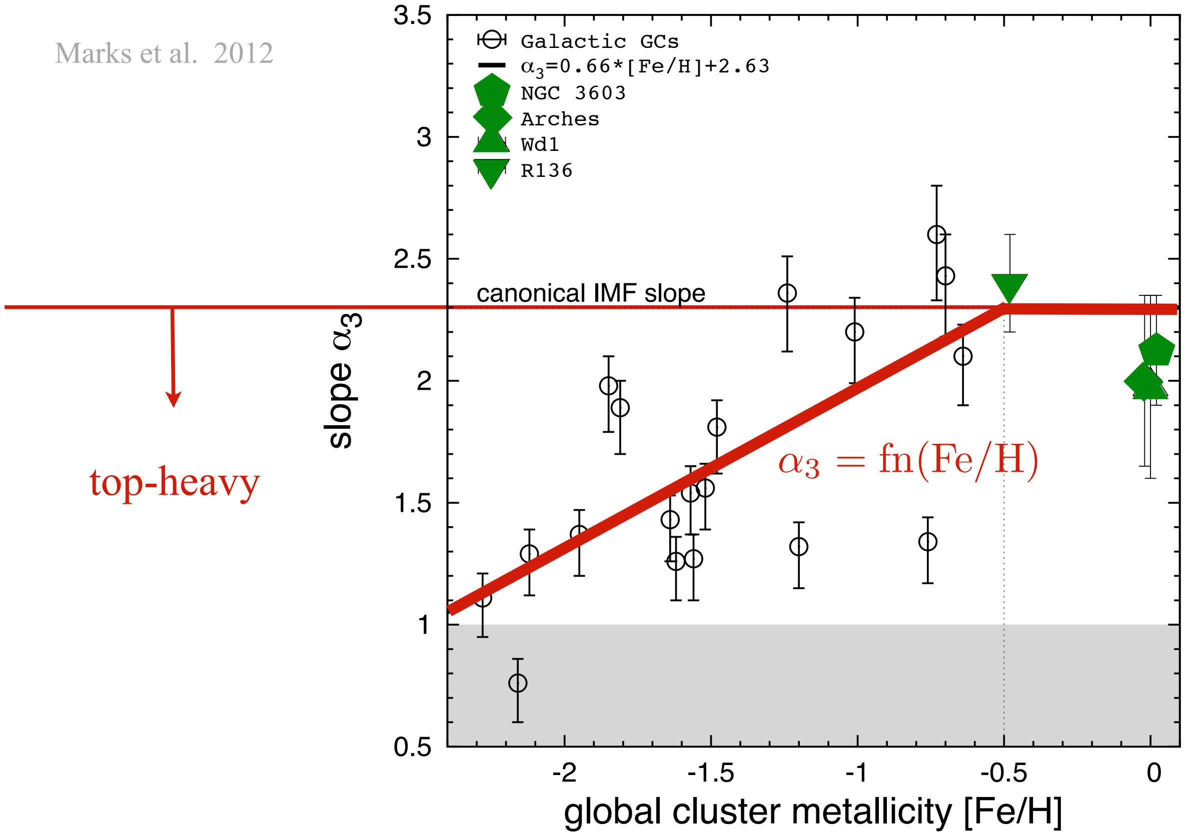


Marks et al. 2012

Pavel Kroupa: *AIfA, University of Bonn*

Top-heavy IMF in extreme-density environments :

Marks et al. 2012



Pavel Kroupa: *AIfA, University of Bonn*

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)

Michael Marks
(PhD: March 2012, Bonn)

Joerg Dabringhausen
(PhD 2013, Bonn)

The IGIMF

Pavel Kroupa: *AIfA, University of Bonn*

Composite Stellar Populations

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

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

Kroupa & Weidner (2003); Weidner & Kroupa (2005, 2006)
Vanbeveren (1982)

adding-up all IMFs
in all clusters !
The LEGO principle

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IGIMF = ∑ of IMFs (in all clusters)

Natural explanation of the mass-metallicity relation of galaxies
and many other problems in understanding galaxies.

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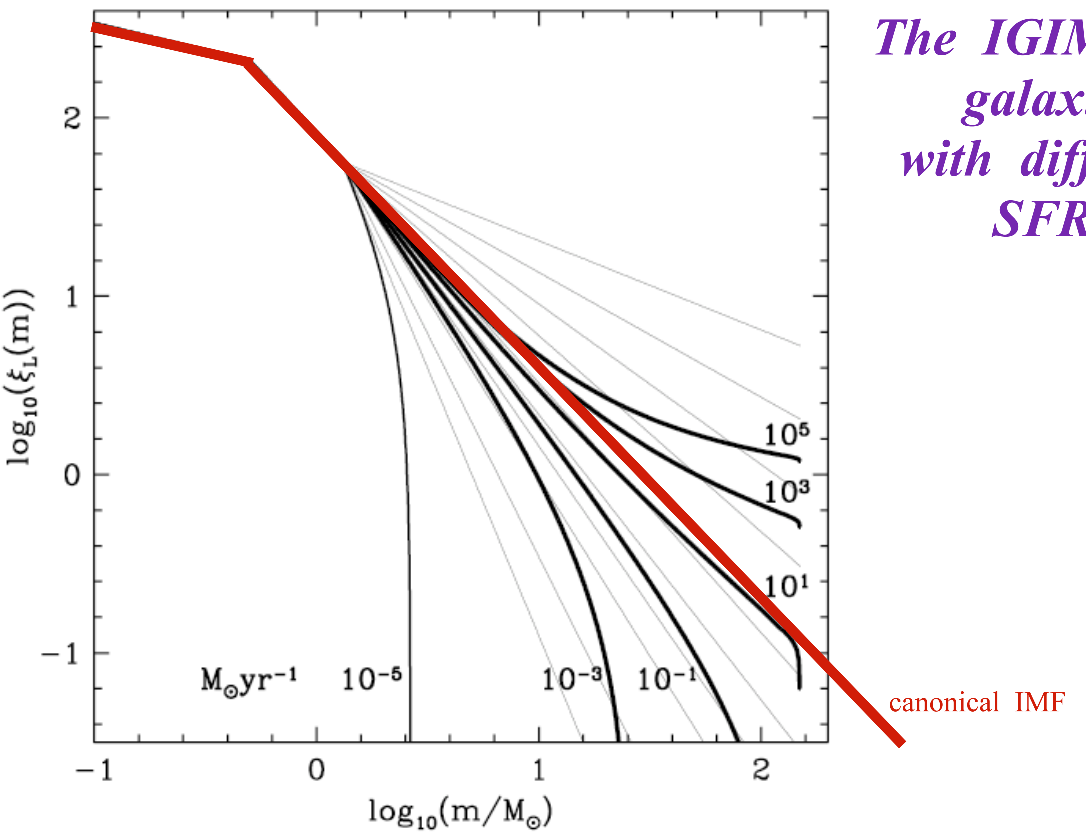
Weidner et al. 2013; Kroupa et al. 2013



The IGIMF for galaxies with different SFRs

46

Pavel Kroupa: *AIfA, University of Bonn*

Jan Pflamm-Altenburg
(AIfA, Bonn)

Carsten Weidner
(IAC, Tenerife)

47

Dice or no dice ?

Is star formation optimal
or purely stochastic?

Two extremes :

The IMF is an invariant
probability density distribution function

stochastic sampling

variations among
on-site IMFs

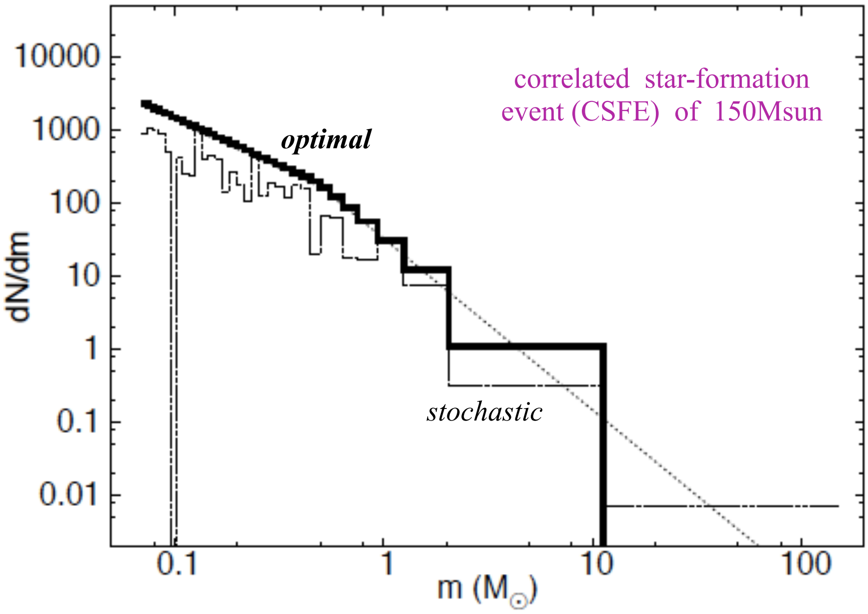
(nature plays dice, anything goes)

The IMF is an invariant
distribution function

optimal sampling

on-site IMFs
completely invariant

(nature does not play dice;
rules there are)



Kroupa et al. 2013
150 page IMF review
(astro-ph/1112.3340)

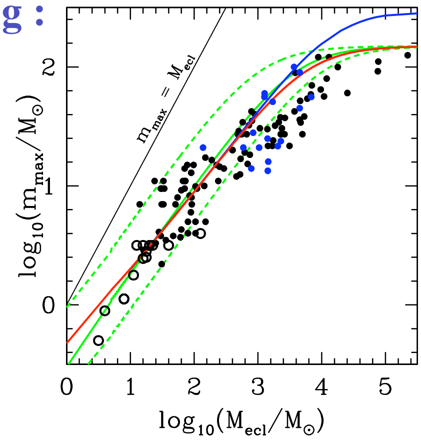
Remember:
observational data always
have substantial
measurement errors.

These bring-in a
substantial
stochastic element,
even if nature were
to be optimal.

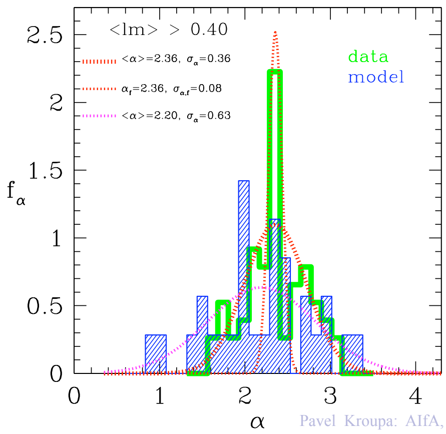
Pavel Kroupa: AIfA, University of Bonn

Nature appears to be closer to optimal sampling :

Tight $m_{\rm max}(M_{\rm ecl})$ relation :



Small dispersion of α_3 values :



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Conclusions

- The *stellar IMF* is found to be *surprisingly invariant* (Bastian et al. 2010; but see Marks et al. 2012; Kroupa et al. 2013)
- *BDs* follow *their own MF* -- stellar/BD MF discontinuous -- about 1 BD forms per 5 stars
- Bottom-heavy IMFs in E galaxies**:** very controversial / theoretically not understood
- Some *globular clusters* have *damaged MFs* --> clues to their formation
- GCs (+UCDs) ==> evidence for top-heavy IMF in starbursts
- IGIMF then becomes top heavy for SFR > 10MSun/yr
- Optimal sampling !