Evidence for systematic IMF variability

"ESO@50 - the first 50 years of ESO"

September 3 - 7, 2012
ESO, Garching

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

The observationally derived
IMF of stars
places firm constraints
on the
cosmological matter cycle.

arXiv:1112.3340v2 [astro-ph.CO] 29 Jan 2012

Kroupa et al. 2012
(150 page IMF review)

Stellar Systems and Galactic Structure, 2012
Vol. V, Planets, Stars & Stellar Systems, ed. by Gilmore, G.

The stellar and sub-stellar IMF of simple and composite populations

Pavel Kroupa[1], Carsten Weidner[2,3], Jan Pflamm-Altenburg[1], Ingo Thies[1], Jörg Dabringhausen[1], Michael Marks[1] & Thomas Maschberger[4,5]

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[2] *Scottish Universities Physics Alliance (SUPA), School of Physics and Astronomy, University of St. Andrews, North Haugh, St. Andrews, Fife KY16 9SS, UK*

[3] *Instituto de Astrofsica de Canarias, C/ Vía Láctea, s/n, E38205 La Laguna (Tenerife), Spain*

[4] *Institute of Astronomy, Madingley Road, Cambridge CB3 0HA, UK*

[5] *Institut de Planétologie et dAstrophysique de Grenoble, BP 53, F-38041 Grenoble Cédex 9, France*

l, University of Bonn

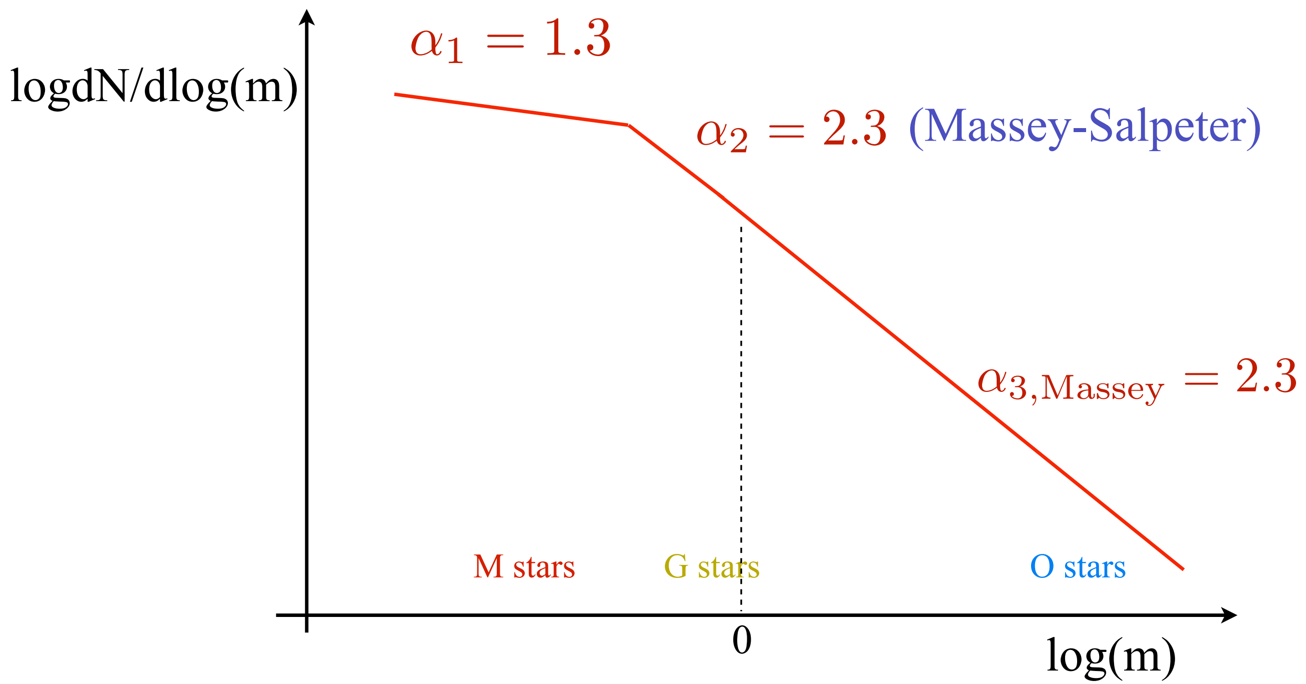
Good working hypothesis: *The IMF is universal.*

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

But see The IMF Unmeasurability Theorem

***canonical / standard / universal two-part power-law IMF*:**

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



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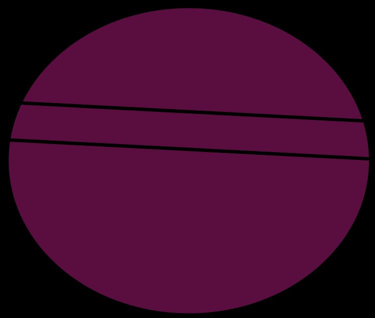
The low-mass system end

Brown Dwarfs vs

Stars



?

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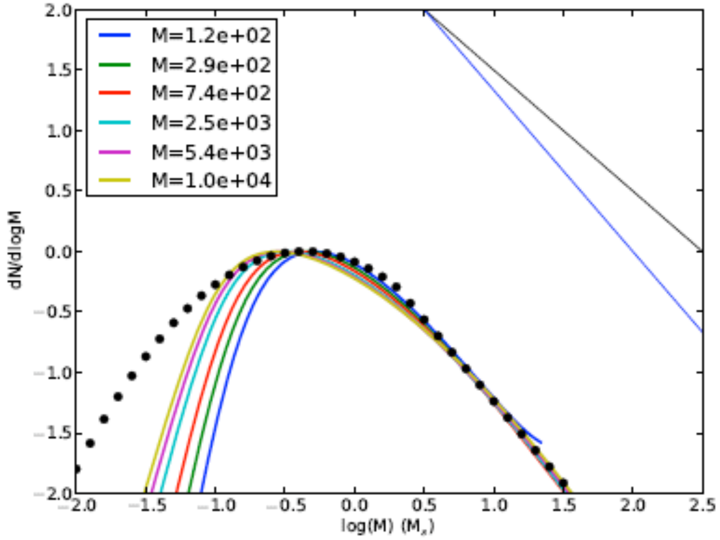
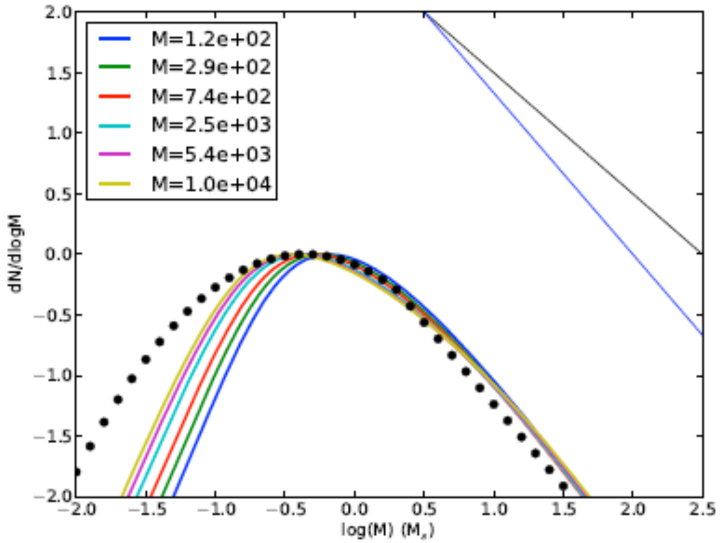
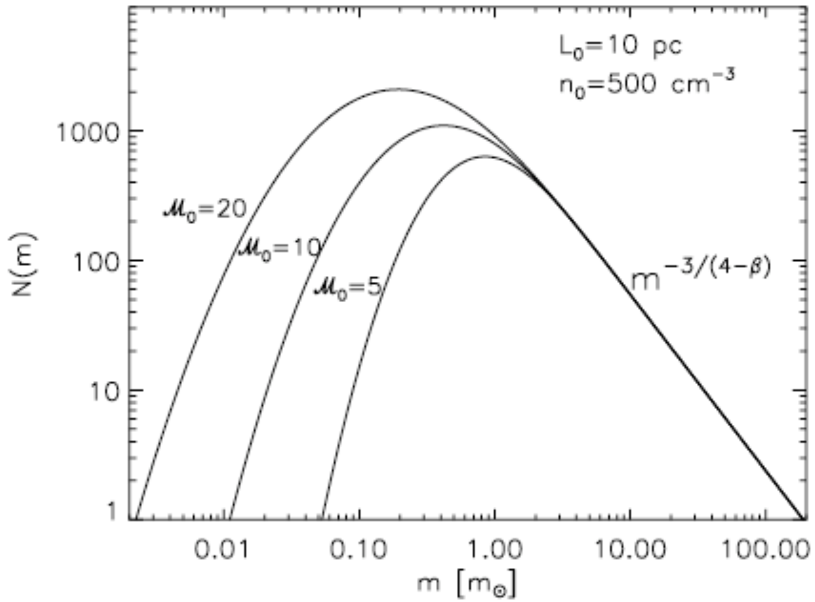
Cloud fragmentation predicts too few BDs

Hennebelle 2012





Padoan & Nordlund 2002



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

Hennebelle 2012

Cloud fragmentation predicts too few BDs

"Our model reproduces well . . . an initial mass function that is i) very close to the Chabrier IMF"

Padoan & Nordlund 2002

"given the success of the present model in predicting the observed shape of the stellar IMF"

→ recent IMF work sociologically driven

What we know from observation :

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

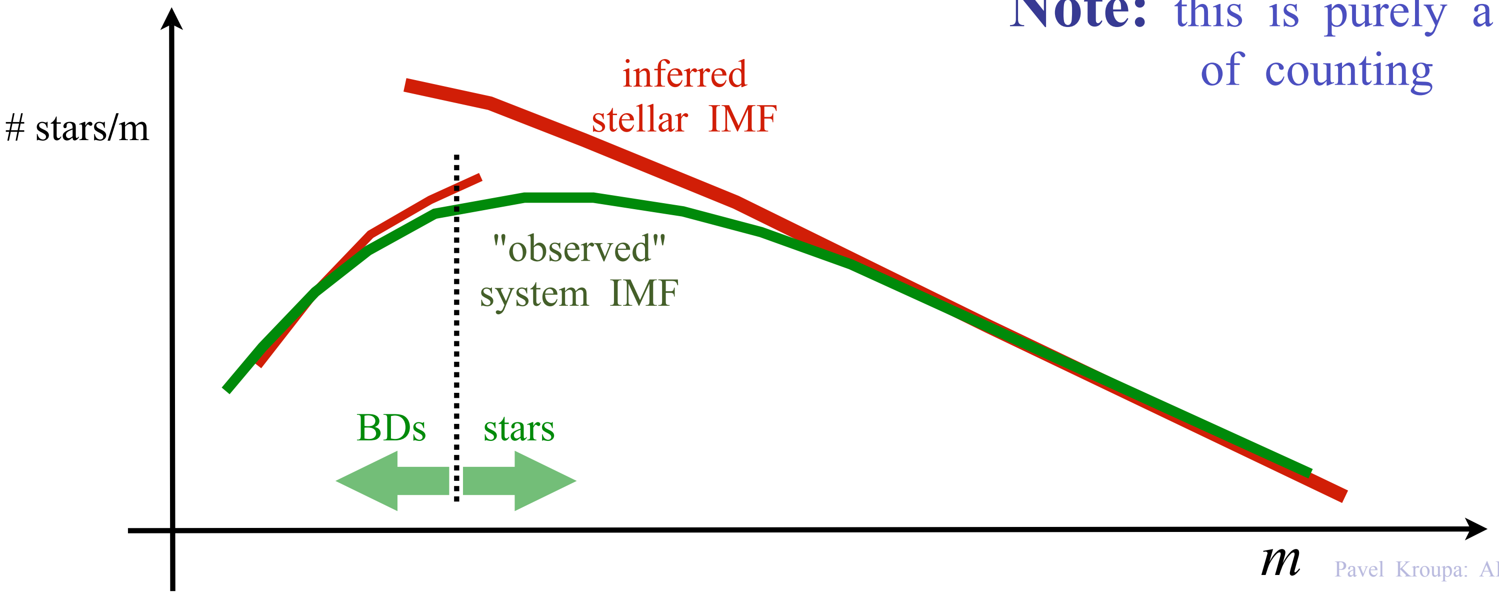
Binary fraction among stars in MW **> 50 %** (100 % in dynamically young systems, 50 % in dynamically evolved systems, e.g. open clusters, Galactic field)

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

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

What this implies :

Note: this is purely a result of counting



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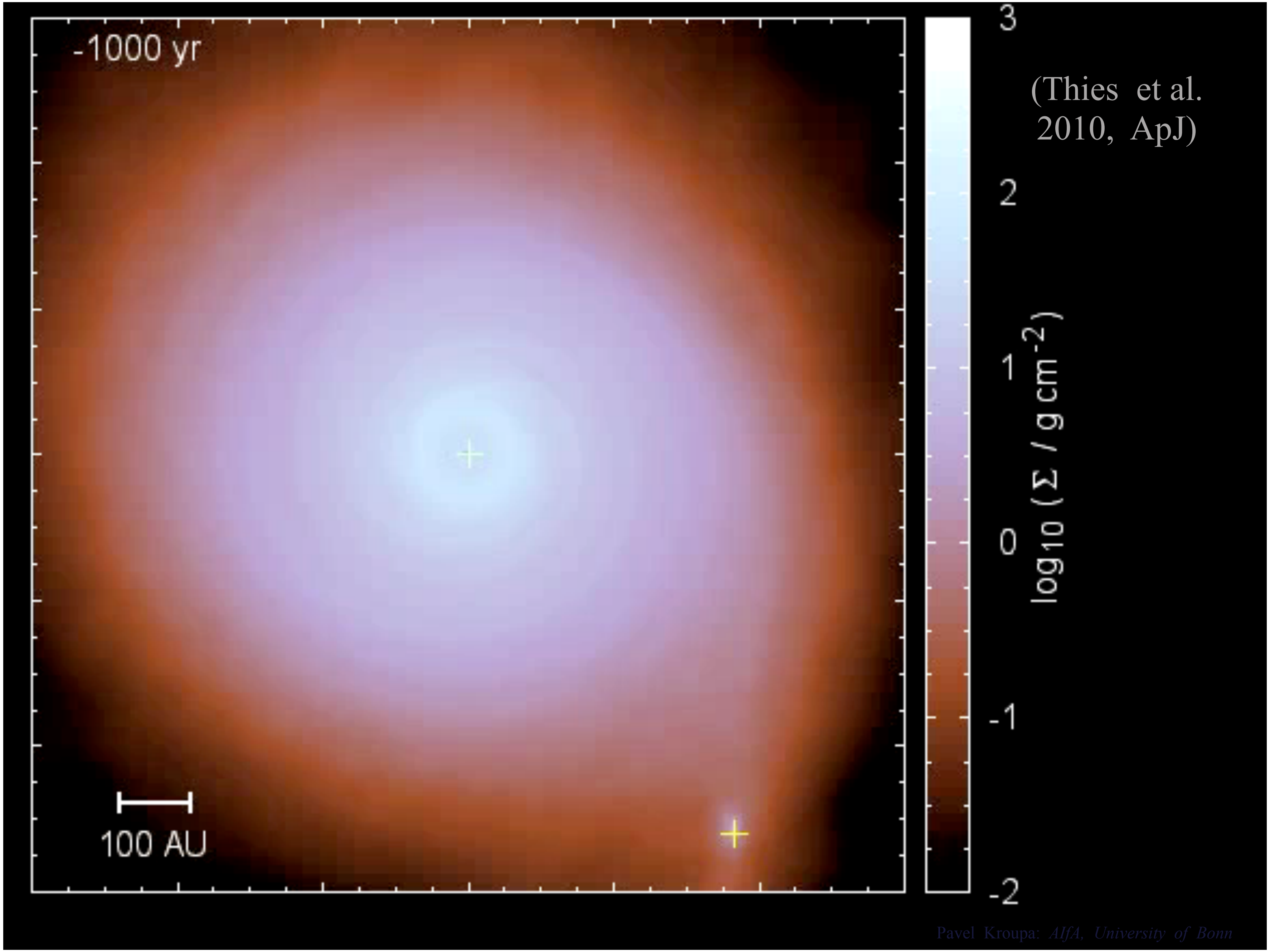
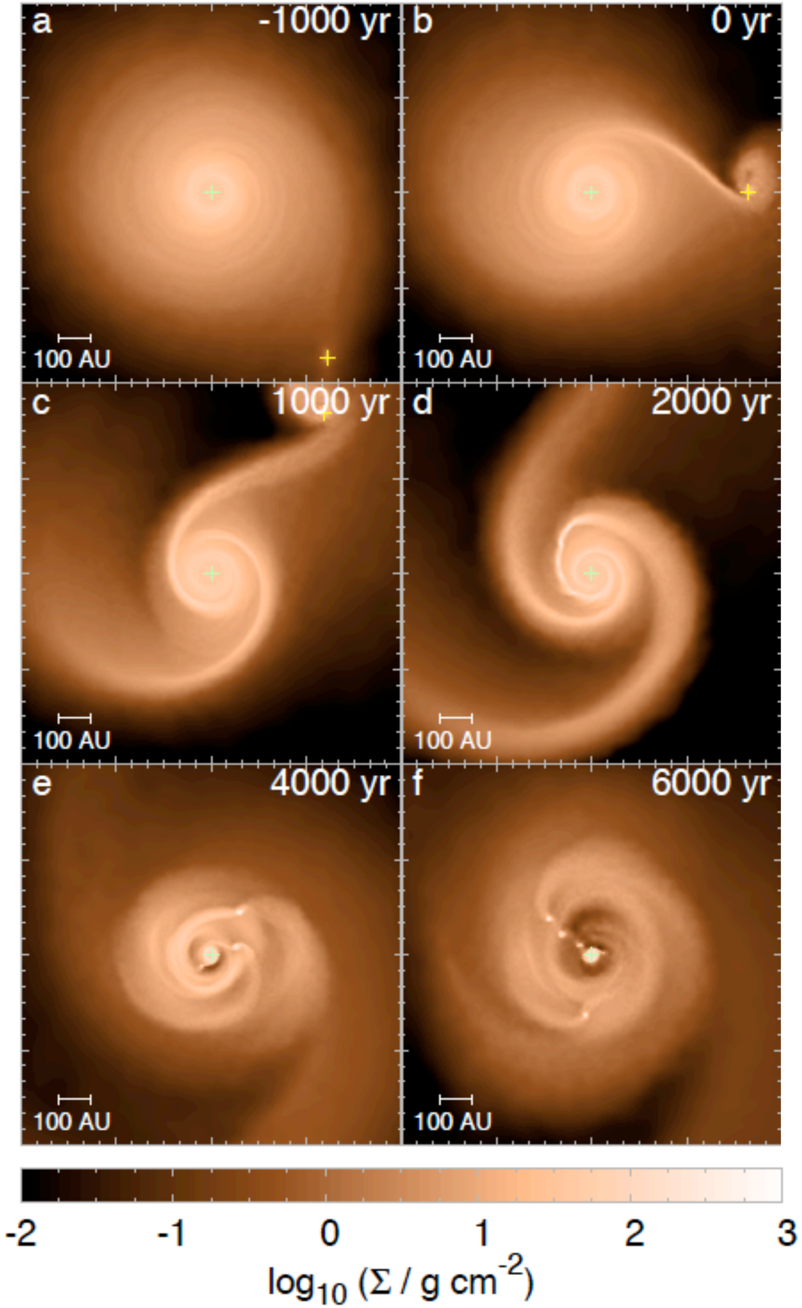
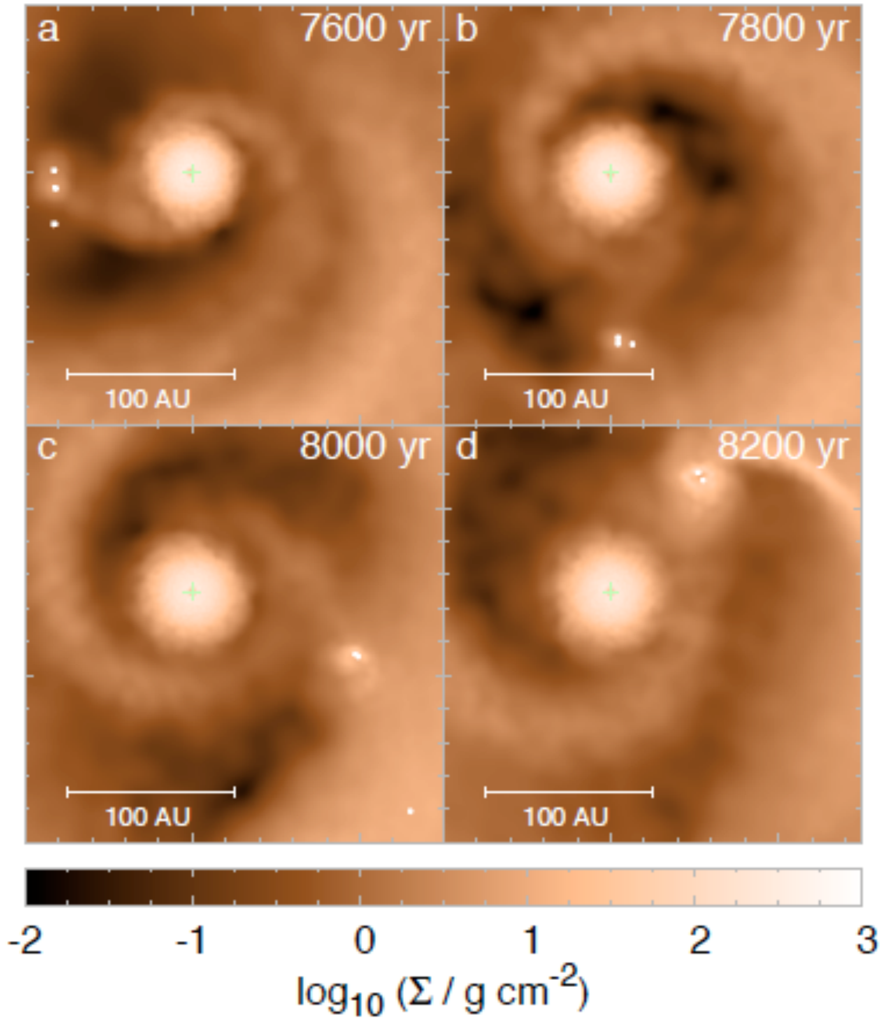

-1000 yr
100 AU
3
2
1
0
-1
-2
log10 (Σ / g cm-2)
(Thies et al. 2010, ApJ)
Pavel Kroupa: AIfA, University of Bonn

Thies, Kroupa, Goodwin, Stamatellos, Whitworth 2010



Basu & Vorobyov 2012



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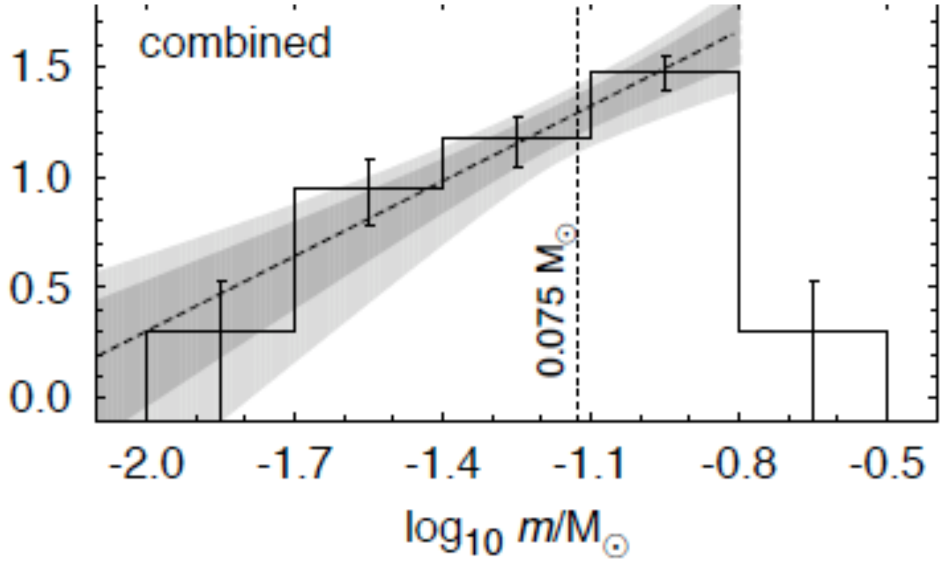
Thies et al. 2010

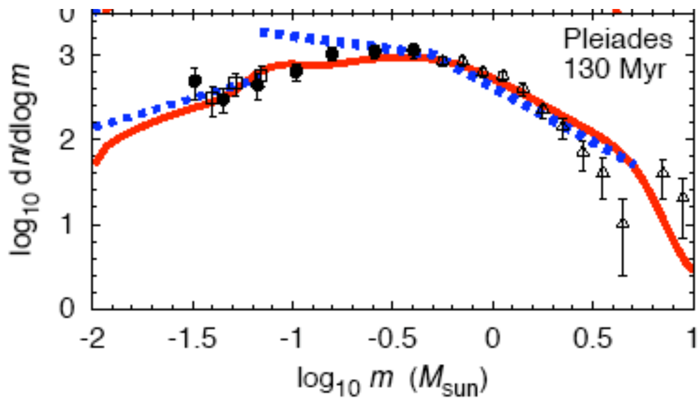
log #



18 DRAGON computations :
58 BD & VLMS sinks formed

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

convergence of theory and observation (correctly interpreted !).



Pavel Kroupa: Sternwarte, University of Bonn

Thies et al. 2010

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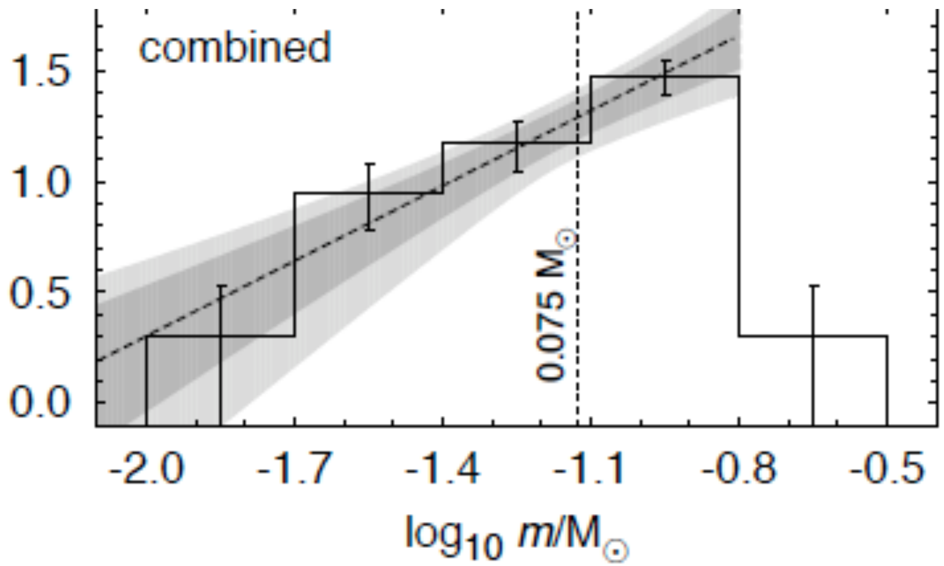

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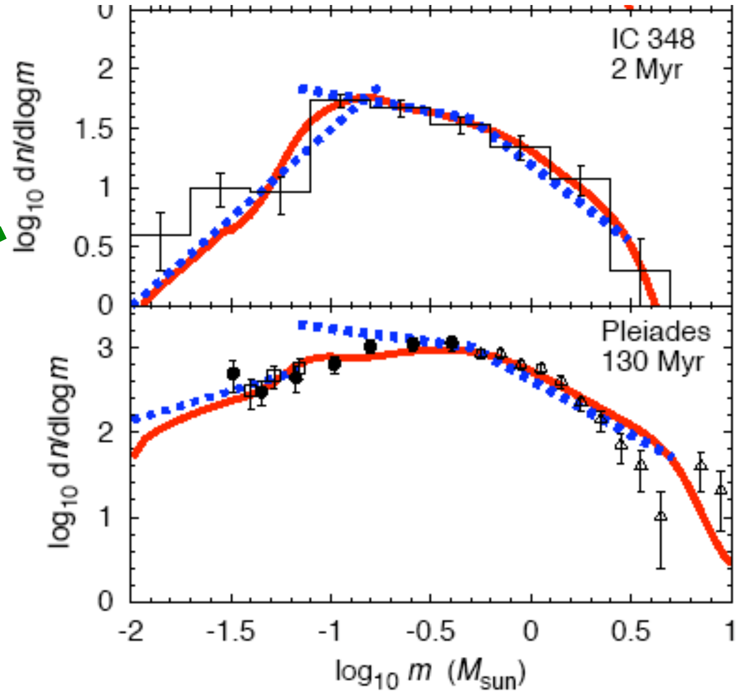

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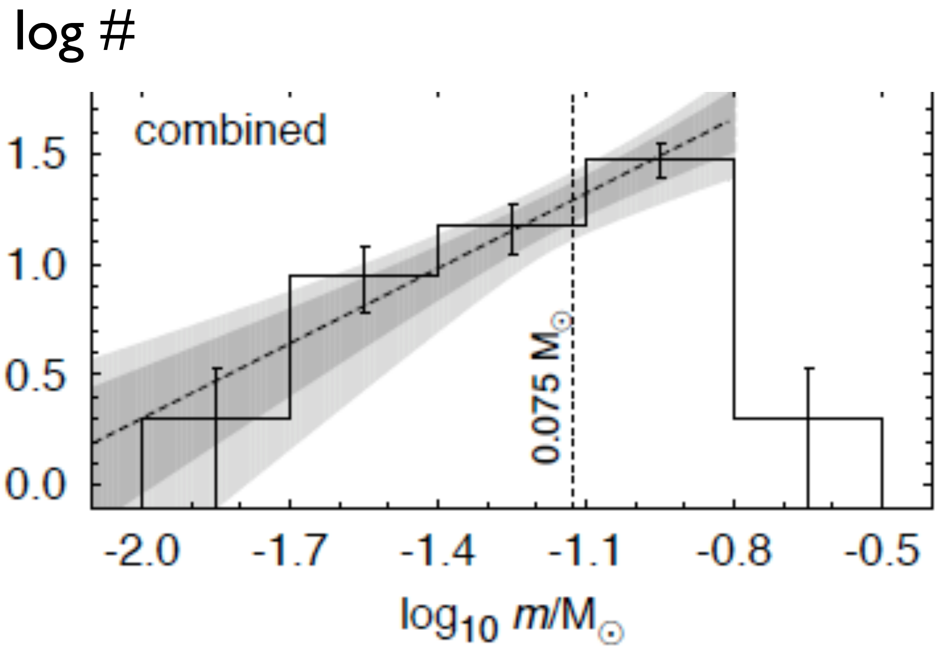
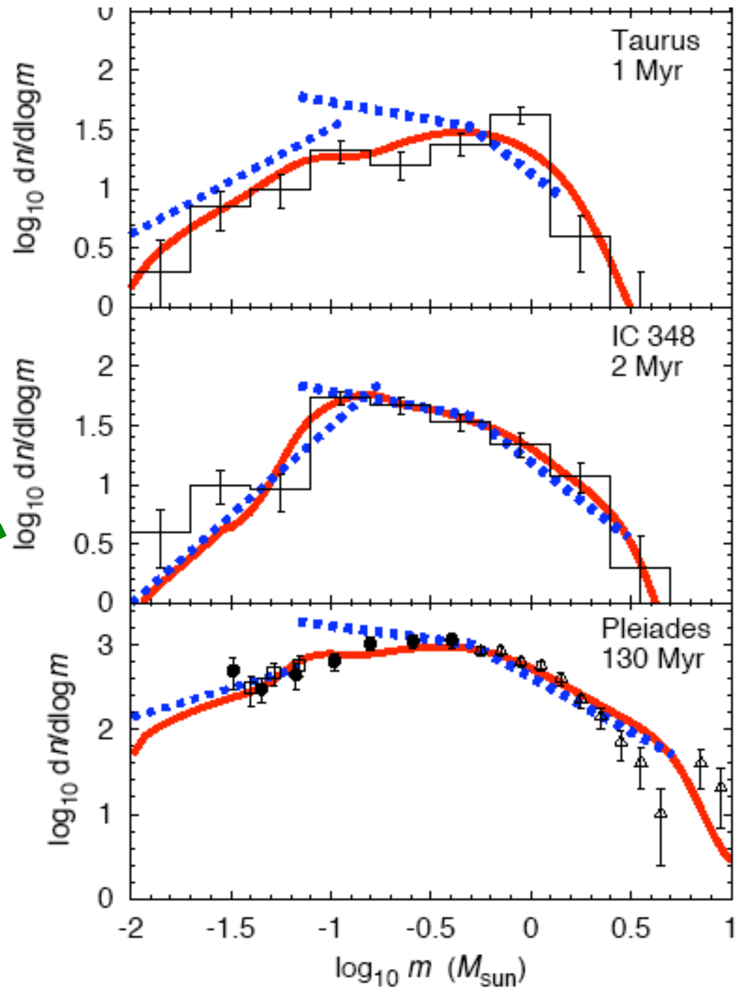
Thies et al. 2010





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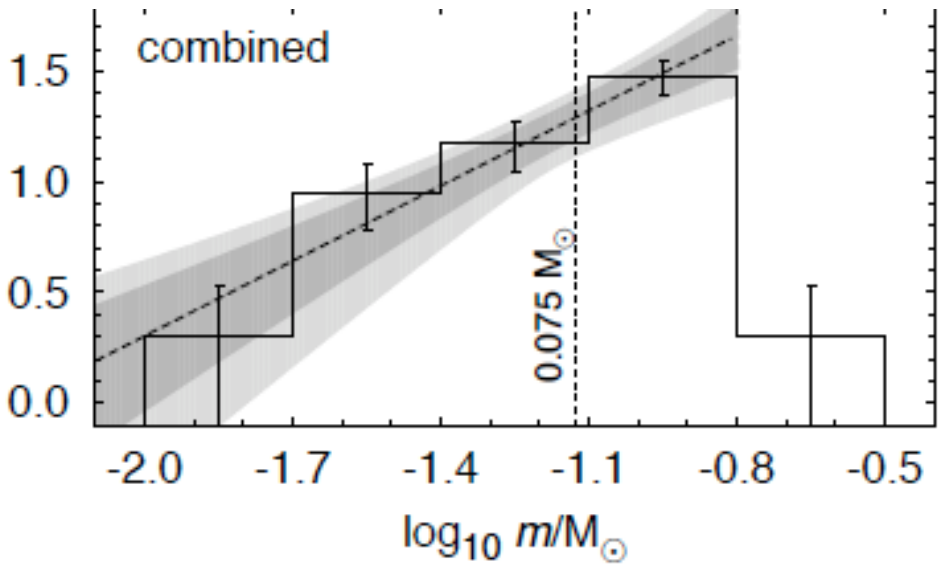

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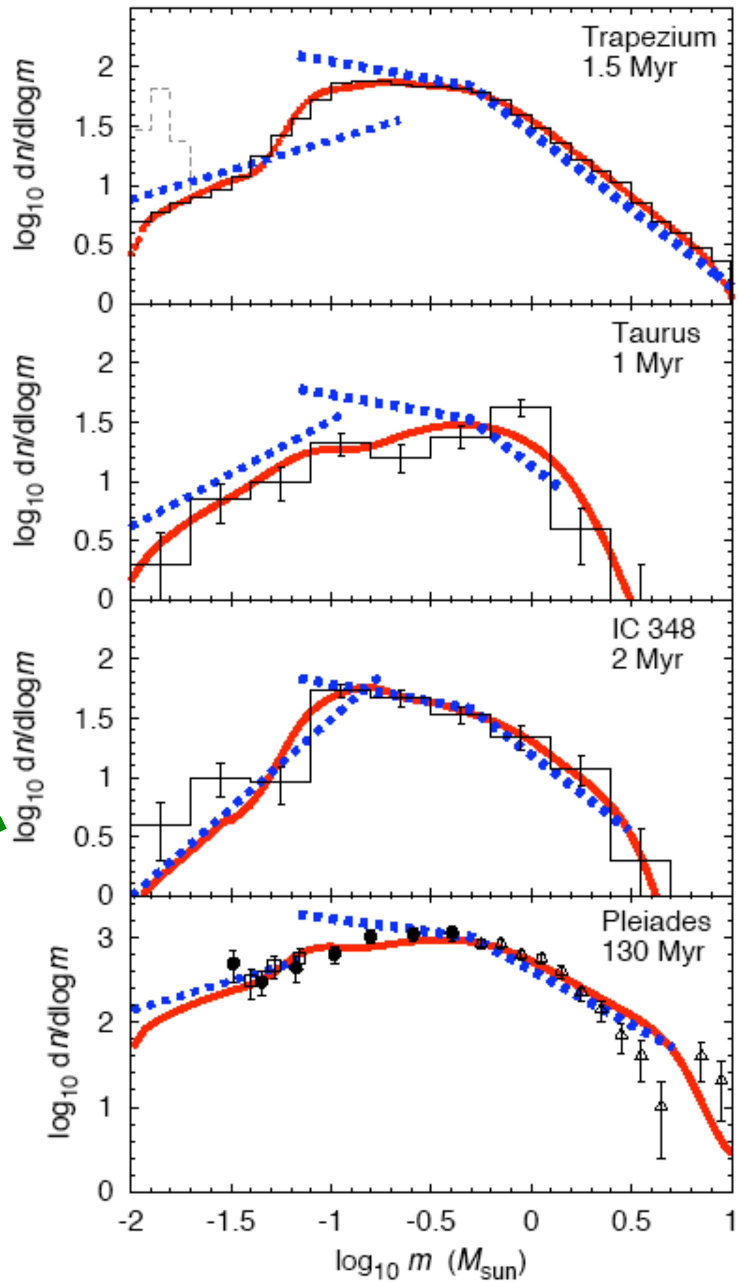
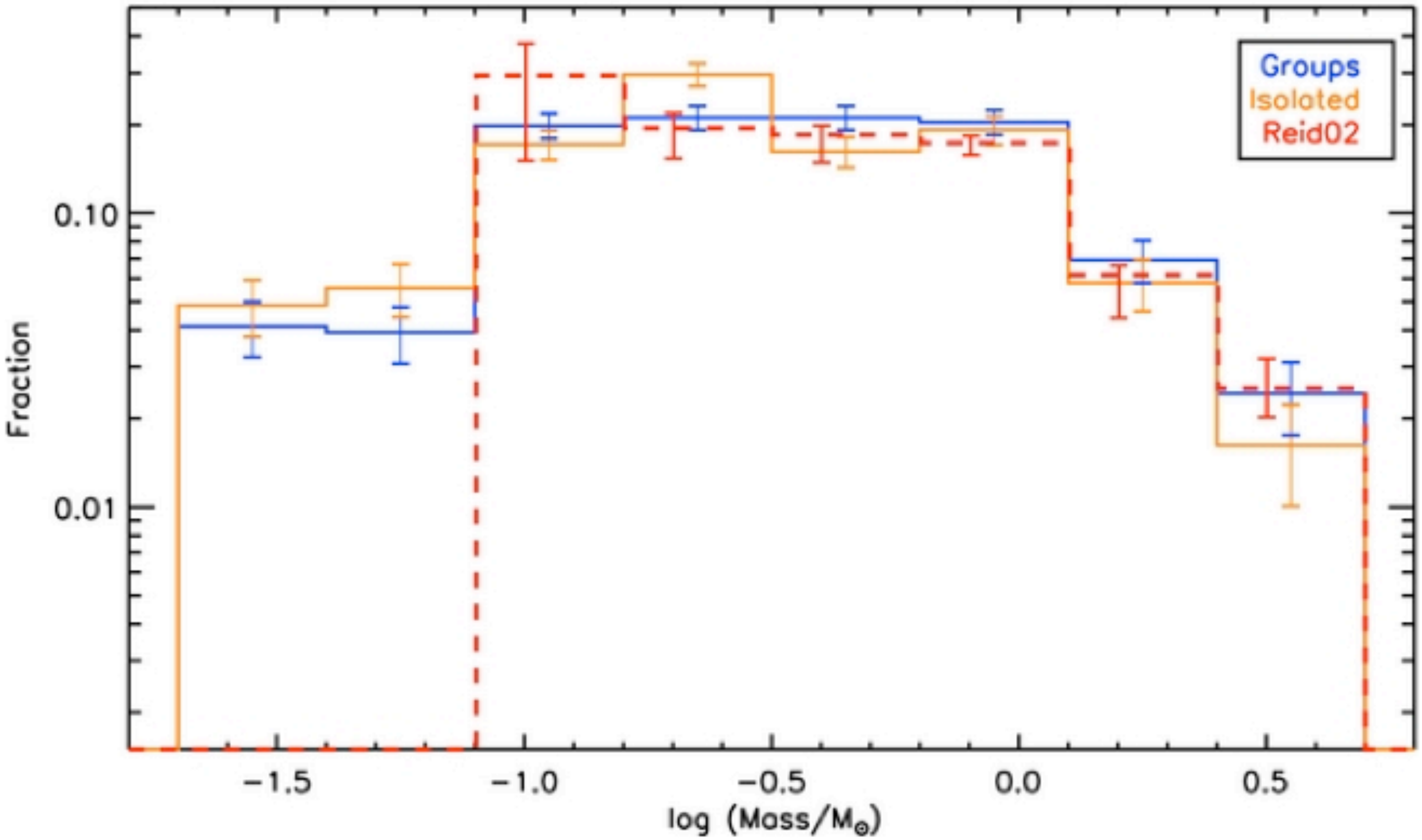
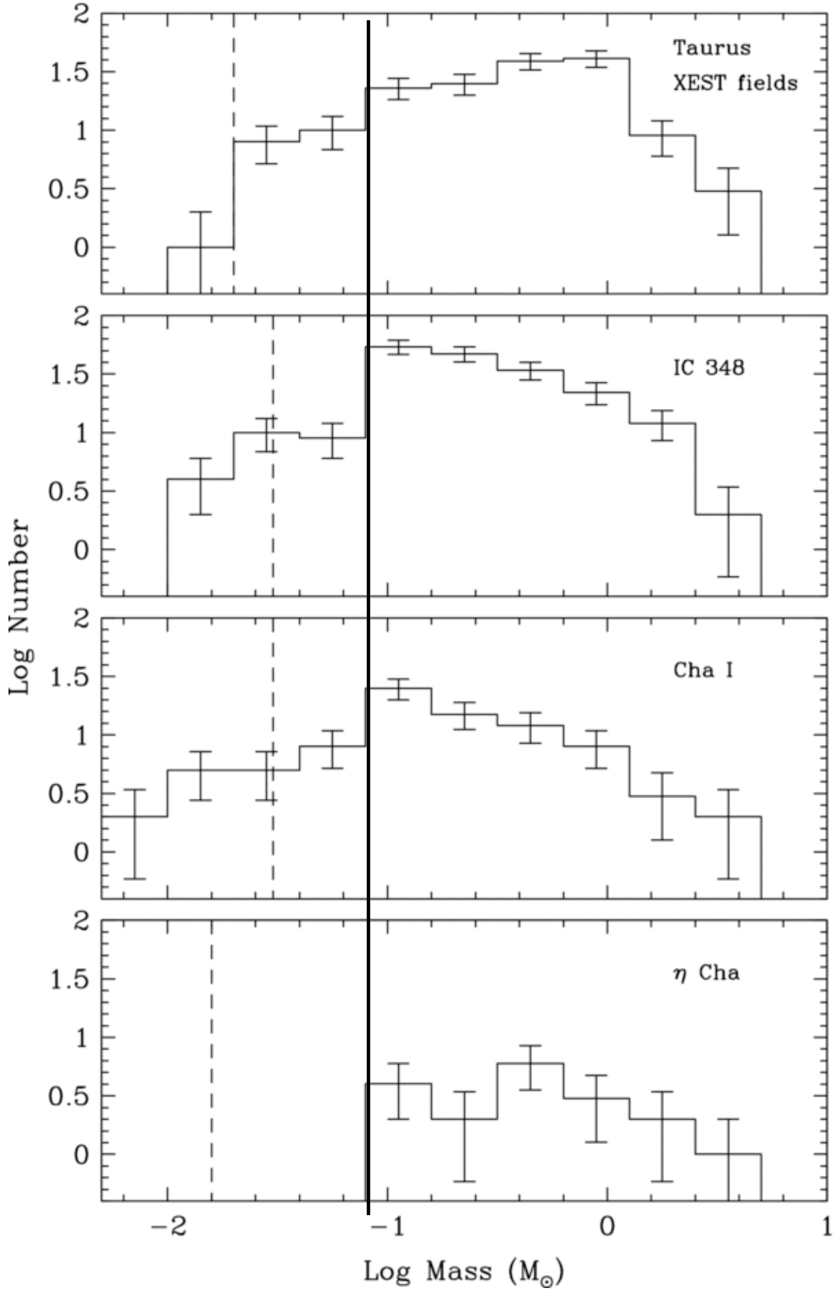


Kirk & Myers 2012





Luhman et al. 2009

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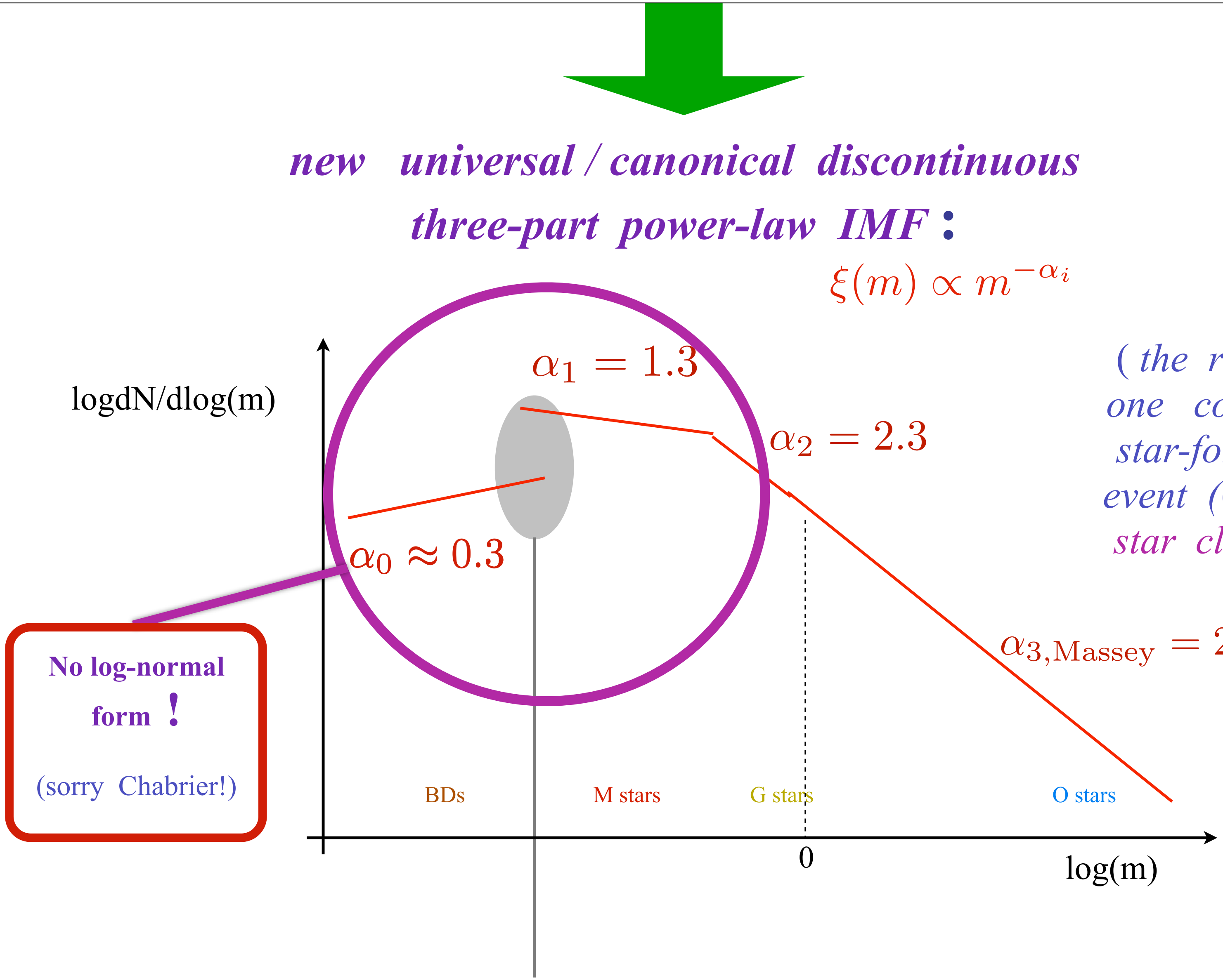
new universal / canonical discontinuous three-part power-law IMF :

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



(the result of one correlated star-formation event (CSFE) - star cluster !)

discontinuity: Thies & Kroupa (2007, 2008)

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Ingo Thies
(AIfA, Bonn)

ESO data !

e.g. :

Bouvier et al., 2008, "*Brown dwarfs and very low mass stars in the Hyades cluster: a dynamically evolved mass function*", EMMI

Moraux et al. 2007, "*The lower mass function of the young open cluster Blanco 1 : from 30 Mjup to 3 Msun*", FORS2, SOFI

Nürnberger & Petr-Gotzens 2002, "*Infrared observations of NGC 3603. I. New constraints on cluster radius and Ks-band luminosity function*", ISAAC

Muench et al. 2002, "*The Luminosity and Mass Function of the Trapezium Cluster: From B Stars to the Deuterium-burning Limit*", SOFI

Bottom-heavy IMFs

in metal-rich

environments / in E galaxies ?

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

ESO data !

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

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. **. . .** "

?

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IMF variation :

the canonical IMF

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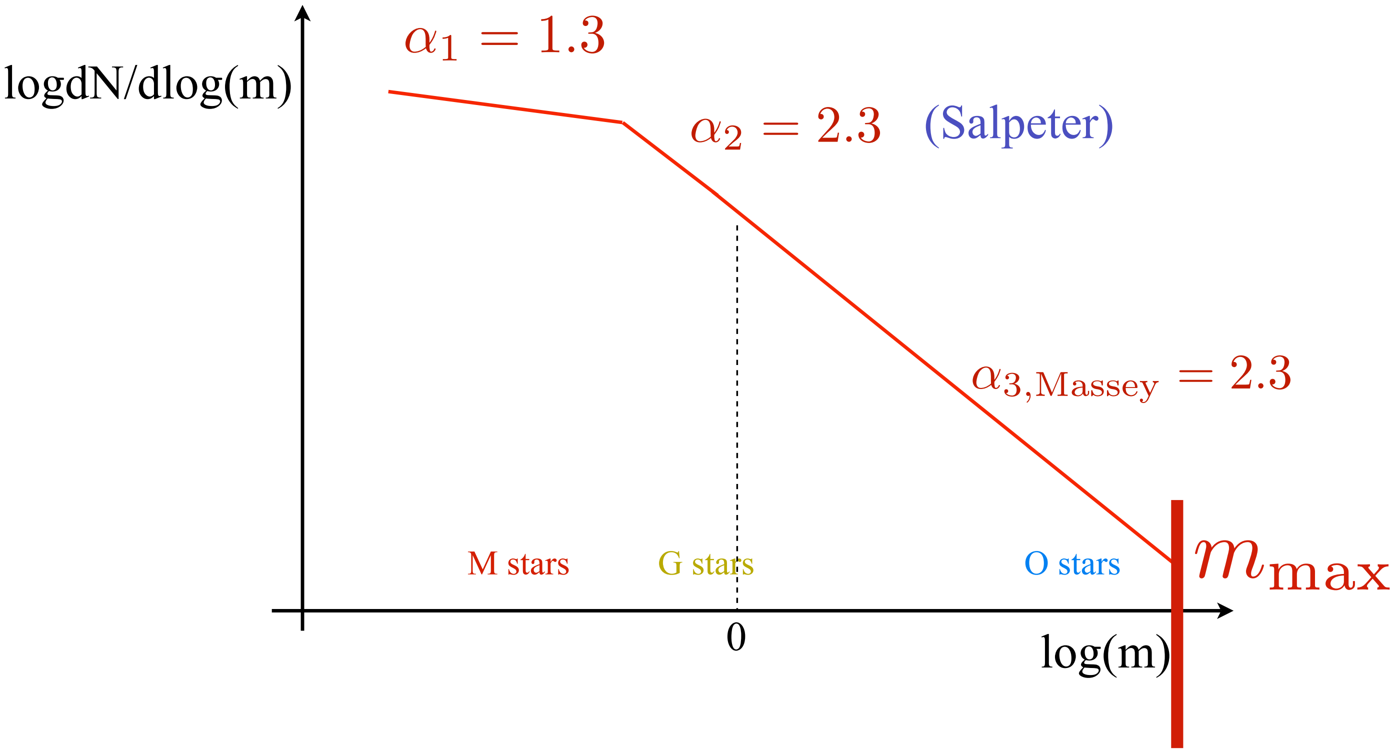
Remember : *canonical / standard / universal two-part power-law stellar IMF* **:**

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



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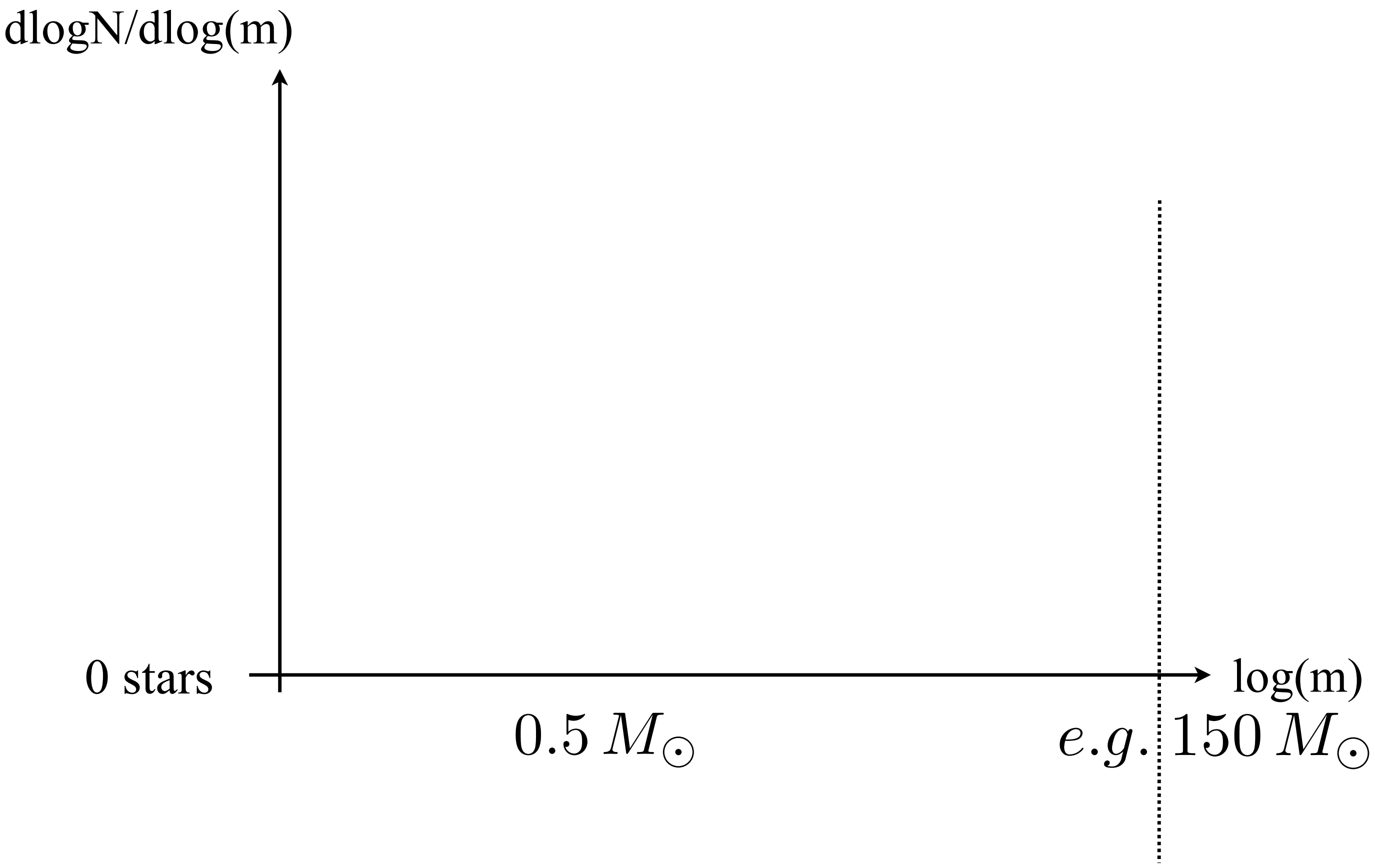
. . . So :

Variation of the canonical / standard / universal IMF ?



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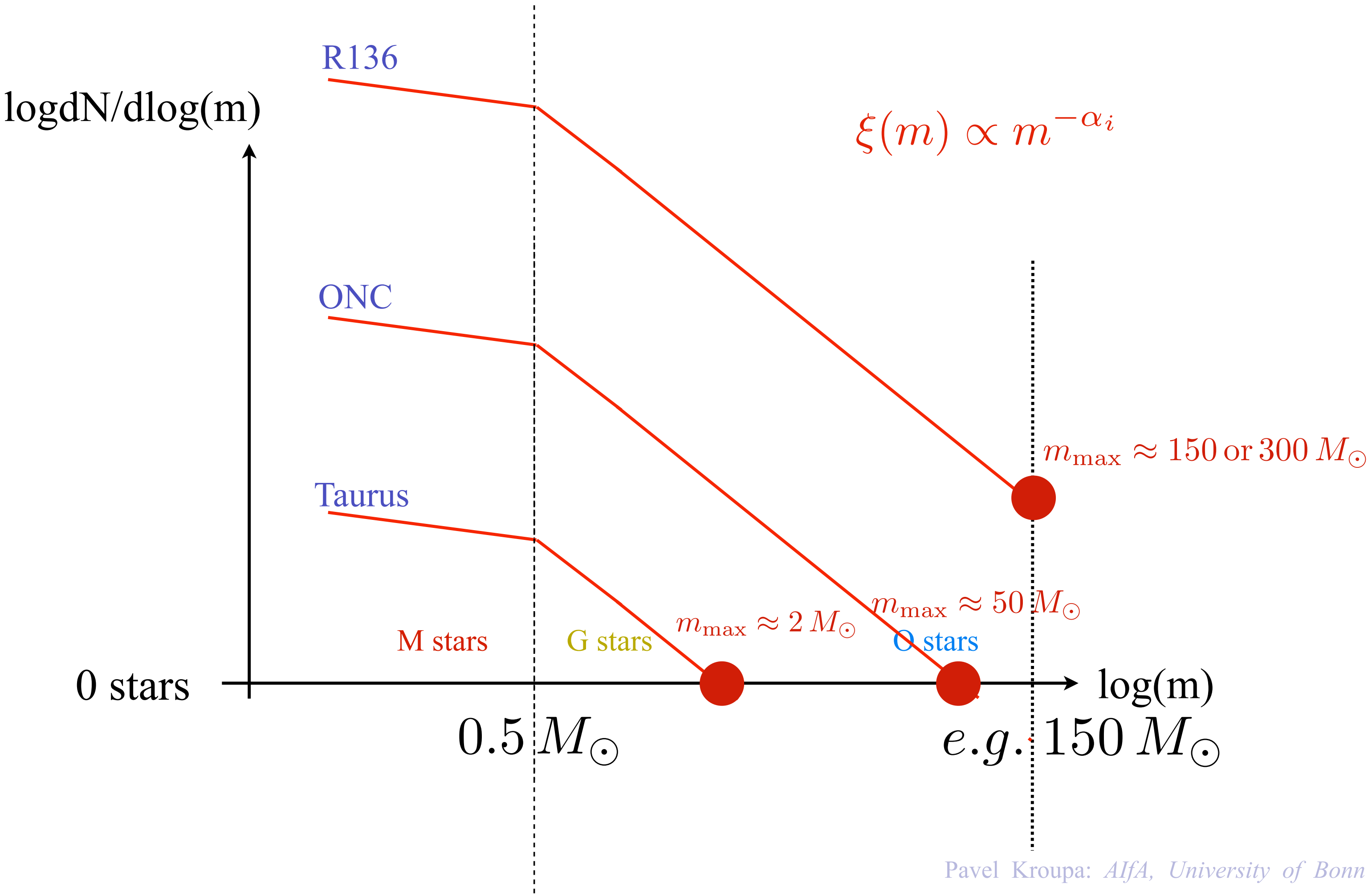
. . . *So* :

Variation of the canonical / standard / universal IMF ?



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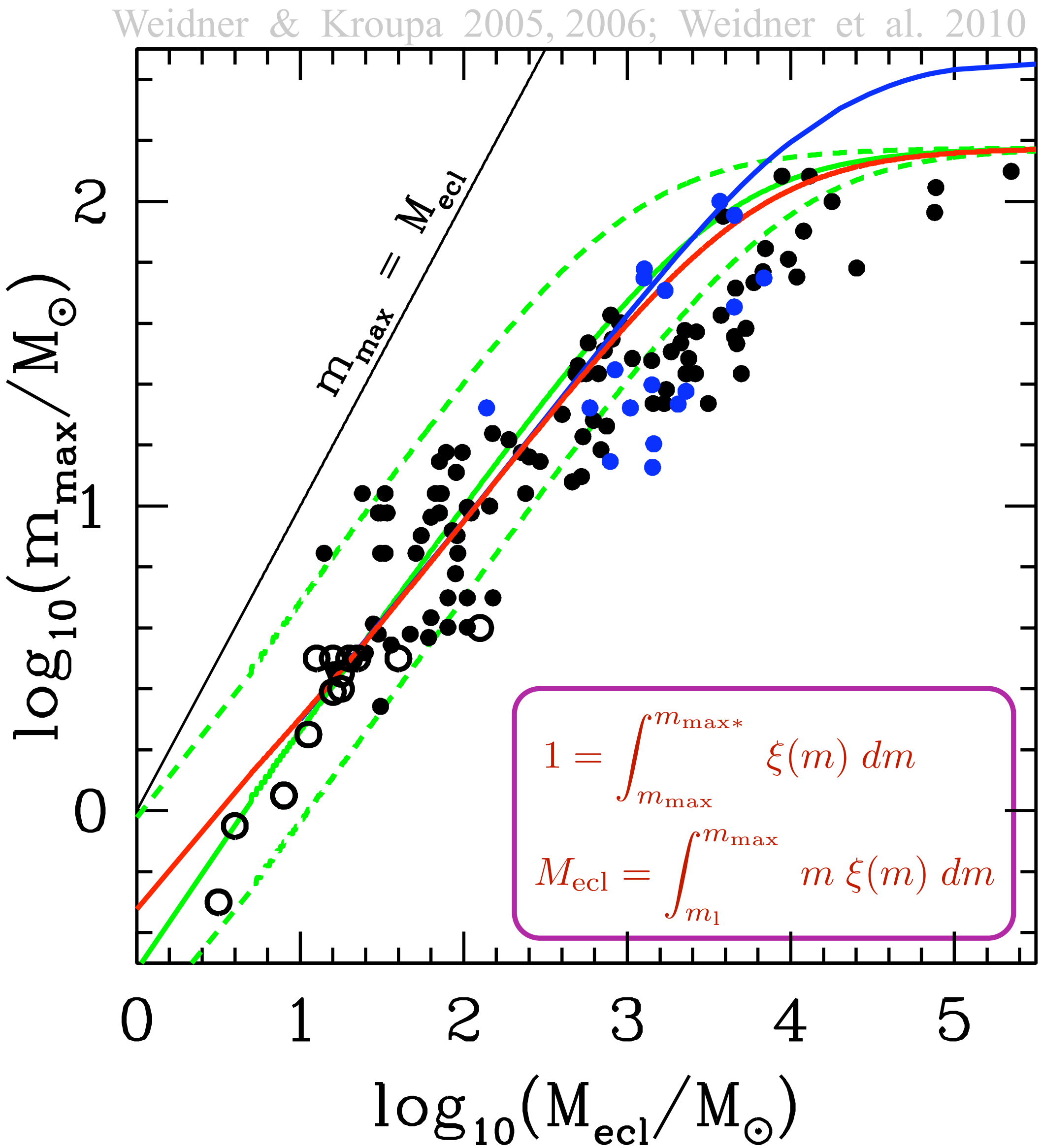
The $m_{\max}(M_{\rm ecl})$ *relation*



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

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

$m_{\max *} = 300\, M_\odot$
(Crowther, Schnurr et al. 2010)

physical maximum stellar mass ?

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

(Weidner & Kroupa 2004;
Figer 2005;
Oey & Clarke 2005,
Koen 2006;
Maiz Appelaniz et al. 2007)

ESO data !

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Top-heavy IMF

Globular Clusters ?

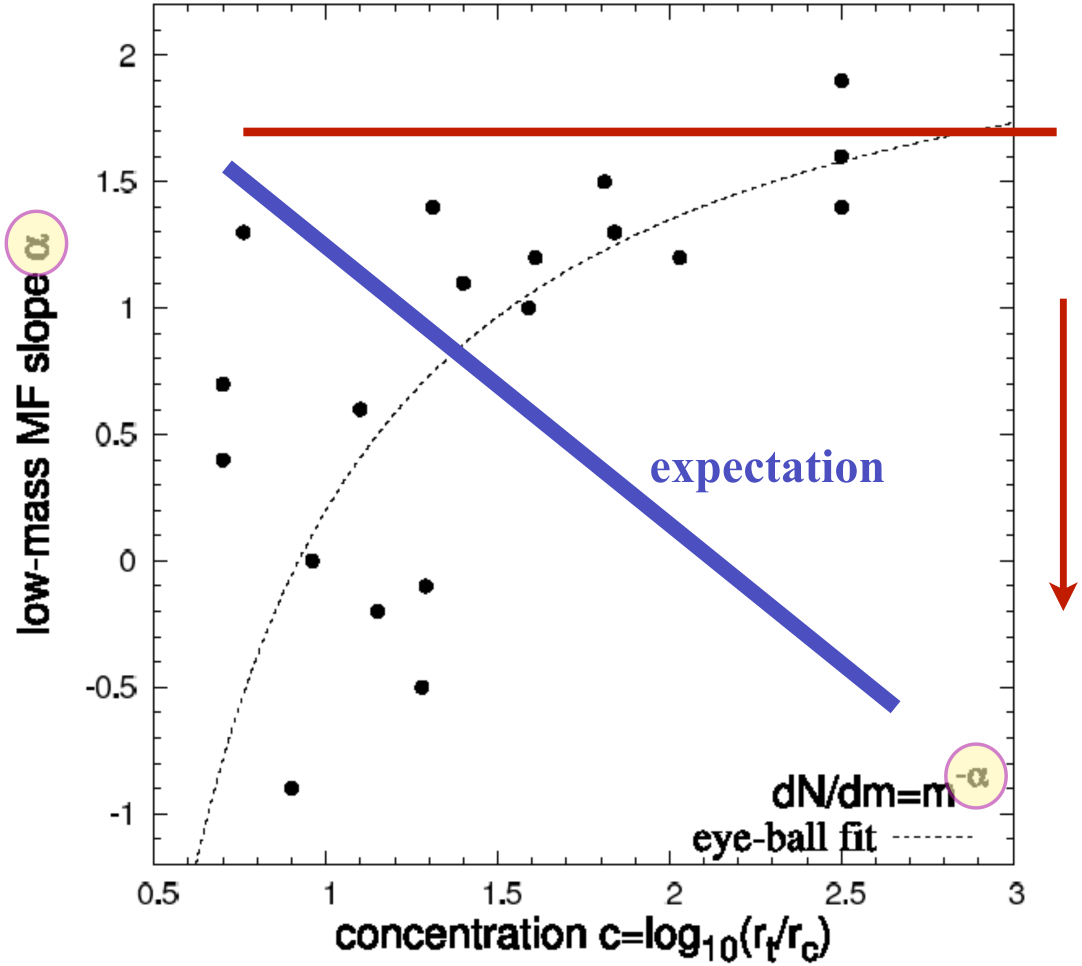
(ancient star bursts)

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

(de Marchi, Paresce & Pulone 2007)

One of the most important recent MF papers!

ESO data!



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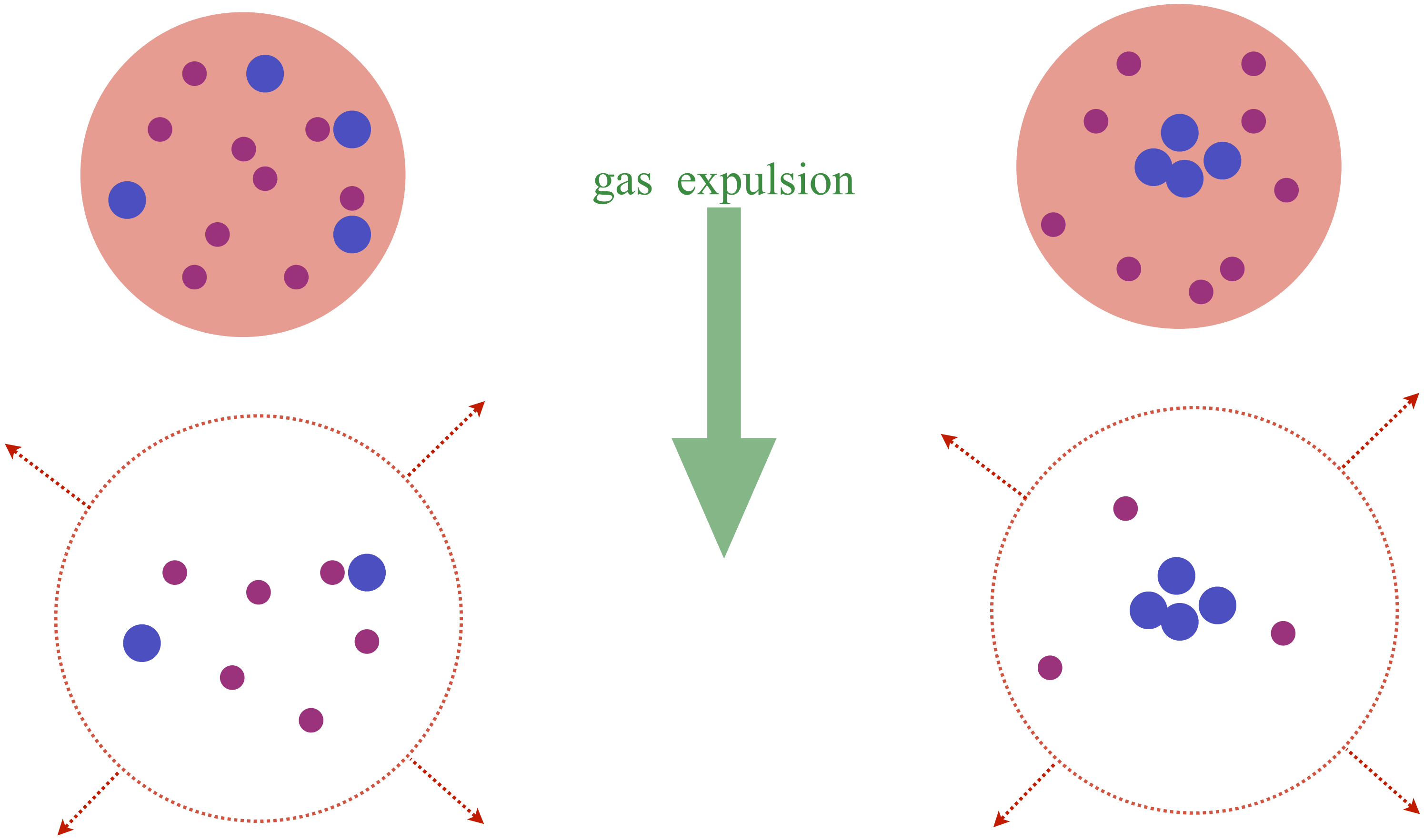
Nbody models of binary rich initially mass segregated clusters with redisual gas expulsion after birth

(Marks, Kroupa & Baumgardt 2008)

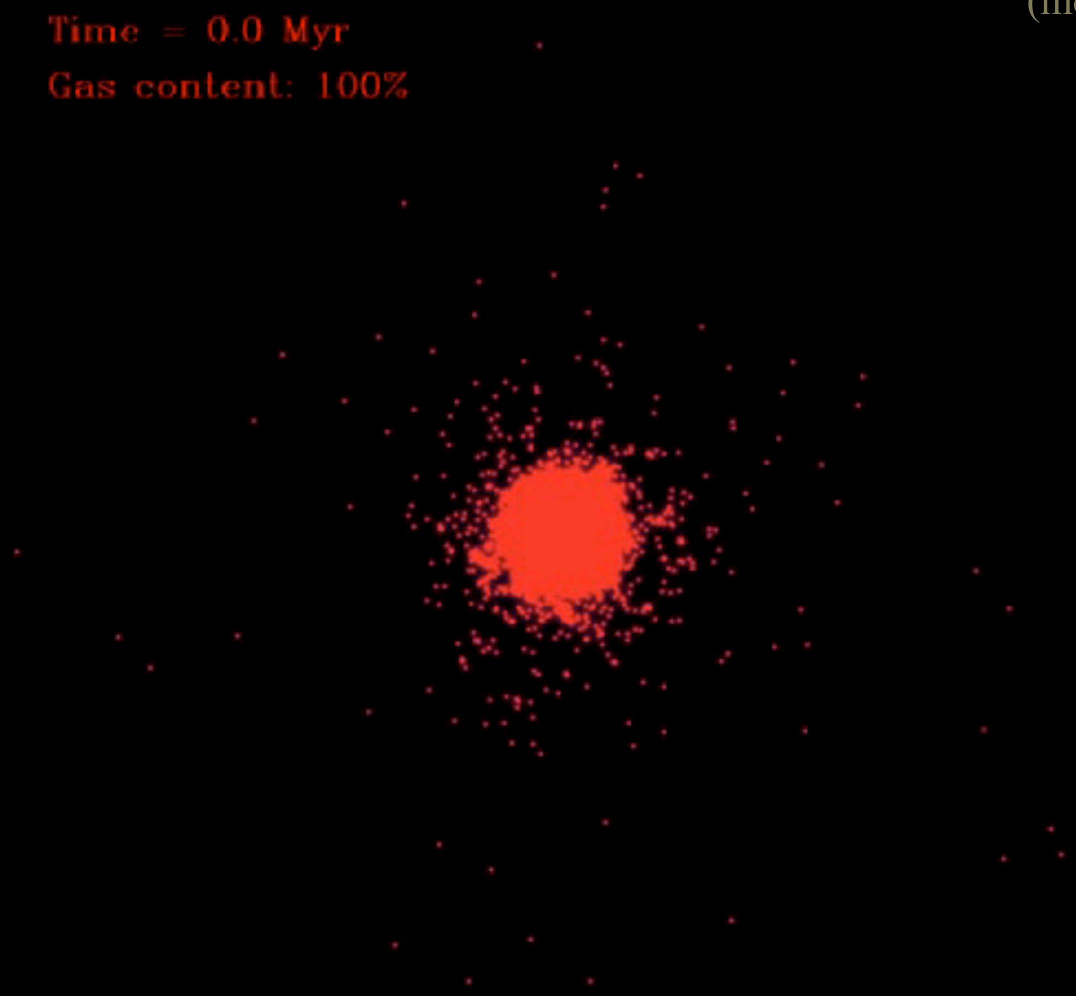


stellar loss independent of mass

loose mostly low-mass stars

Cluster reaction to sudden 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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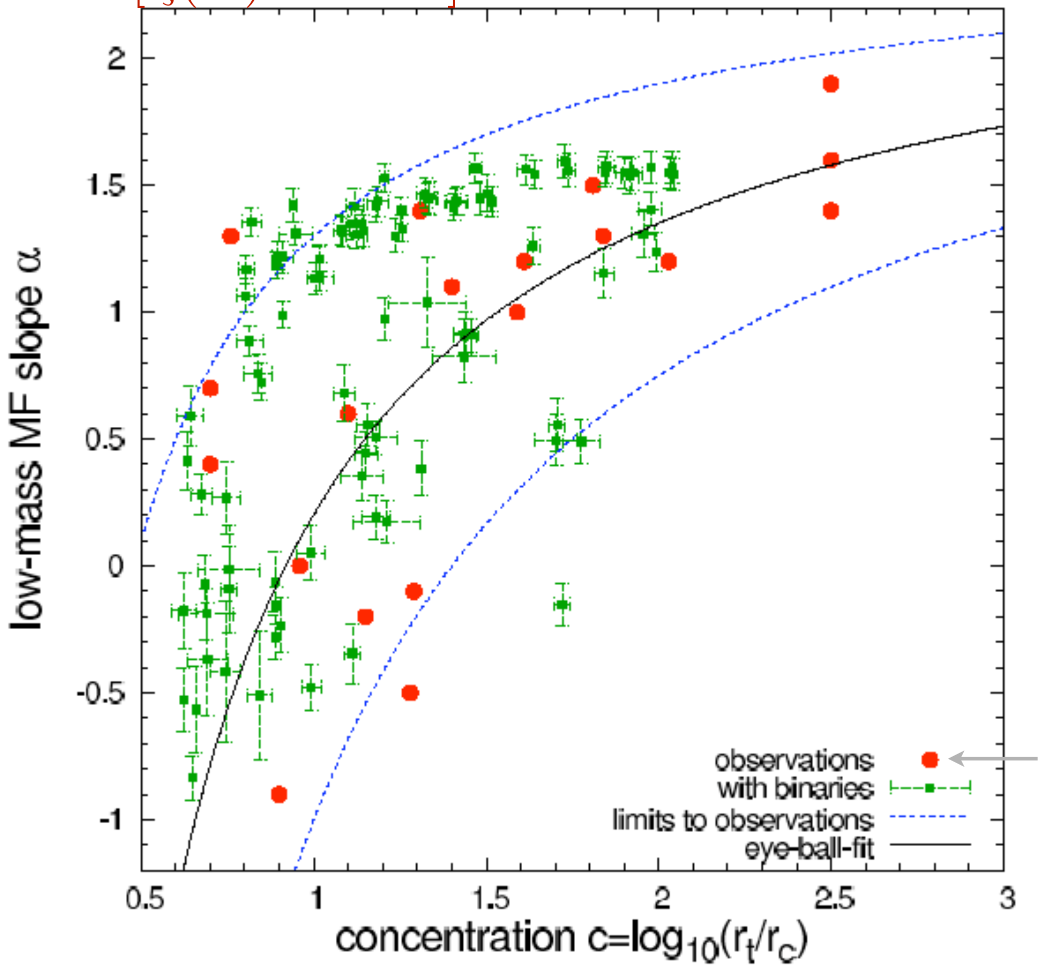
Nbody models of binary rich initially mass segregated clusters with redisual gas expulsion after birth

(Marks, Kroupa & Baumgardt 2008)

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



(de Marchi, Paresce & Pulone 2007)

for
residual gas expulsion
+
mass segregated clusters

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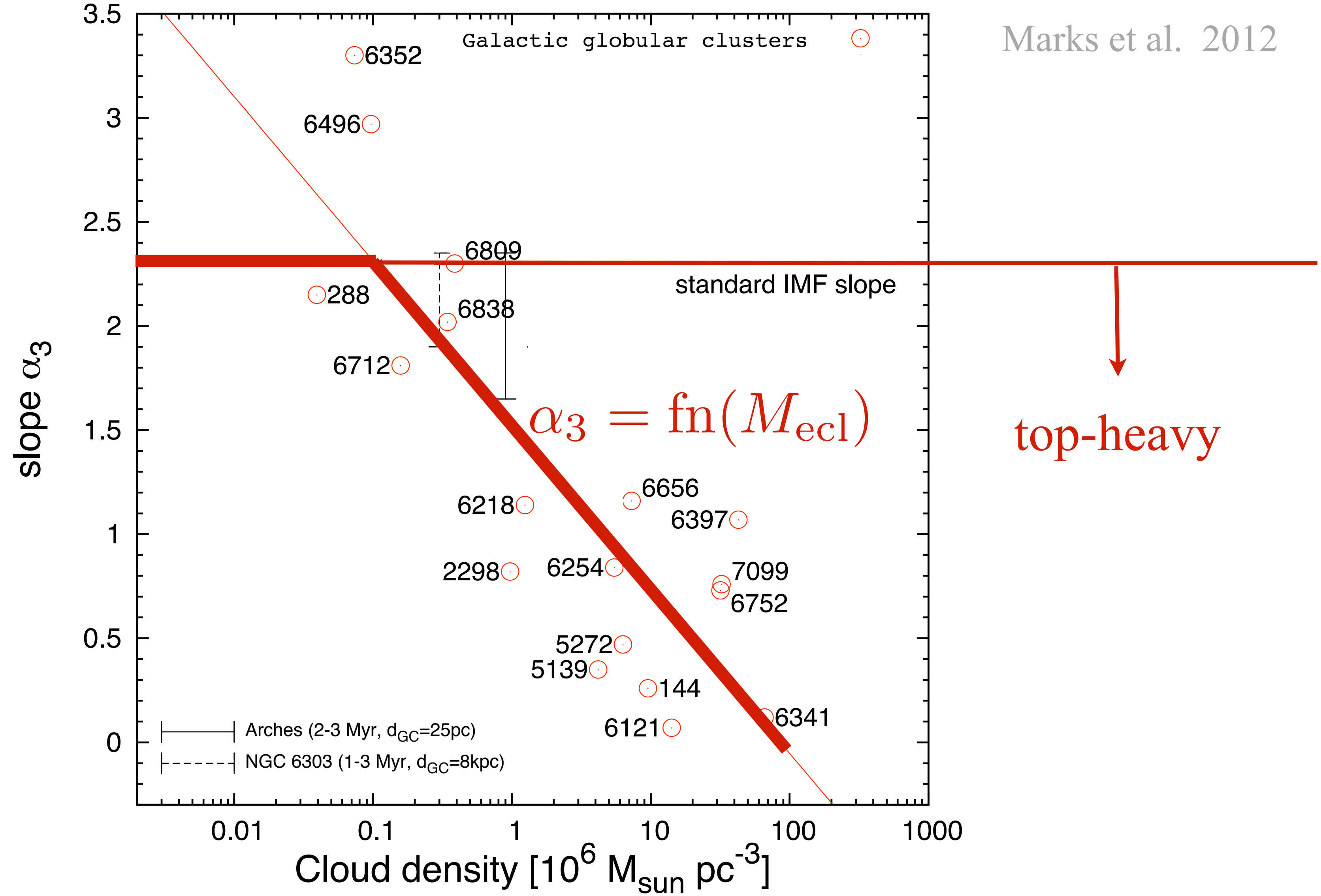
Top-heavy IMF in extreme-density environments :

Marks et al. 2012



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Michael Marks
(AIfA, Bonn)

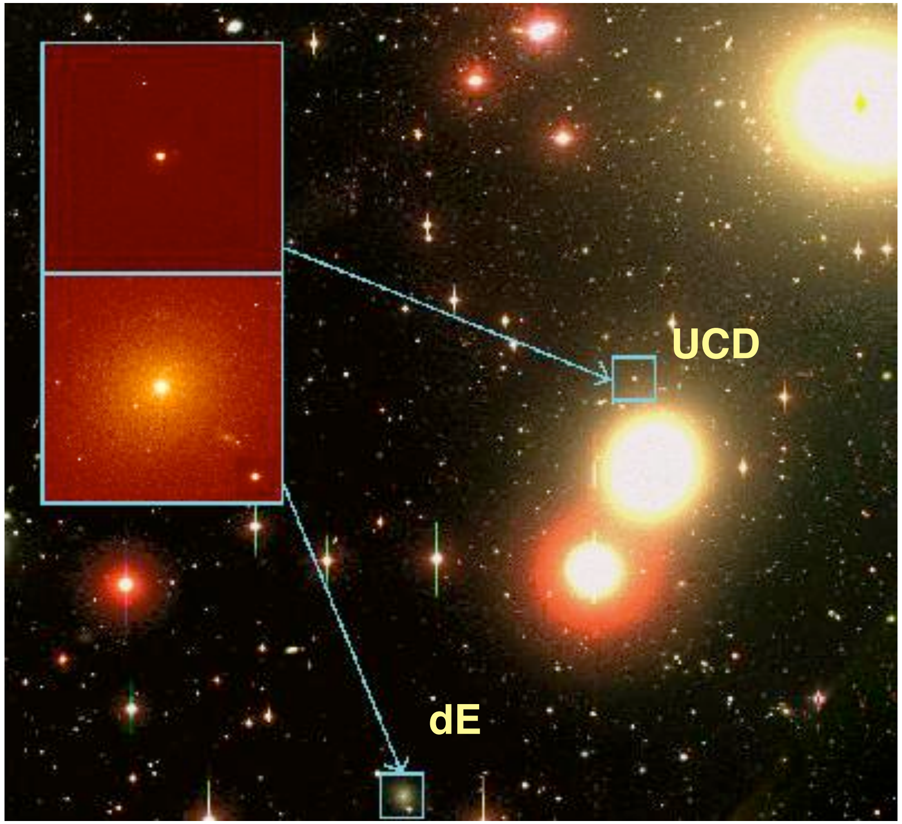
Top-heavy IMF in UCDs ?

the M/L ratio

(ultra-compact dwarf galaxies)

Pavel Kroupa: *AIfA, University of Bonn*

Properties of Ultra Compact Dwarf galaxies (UCDs)

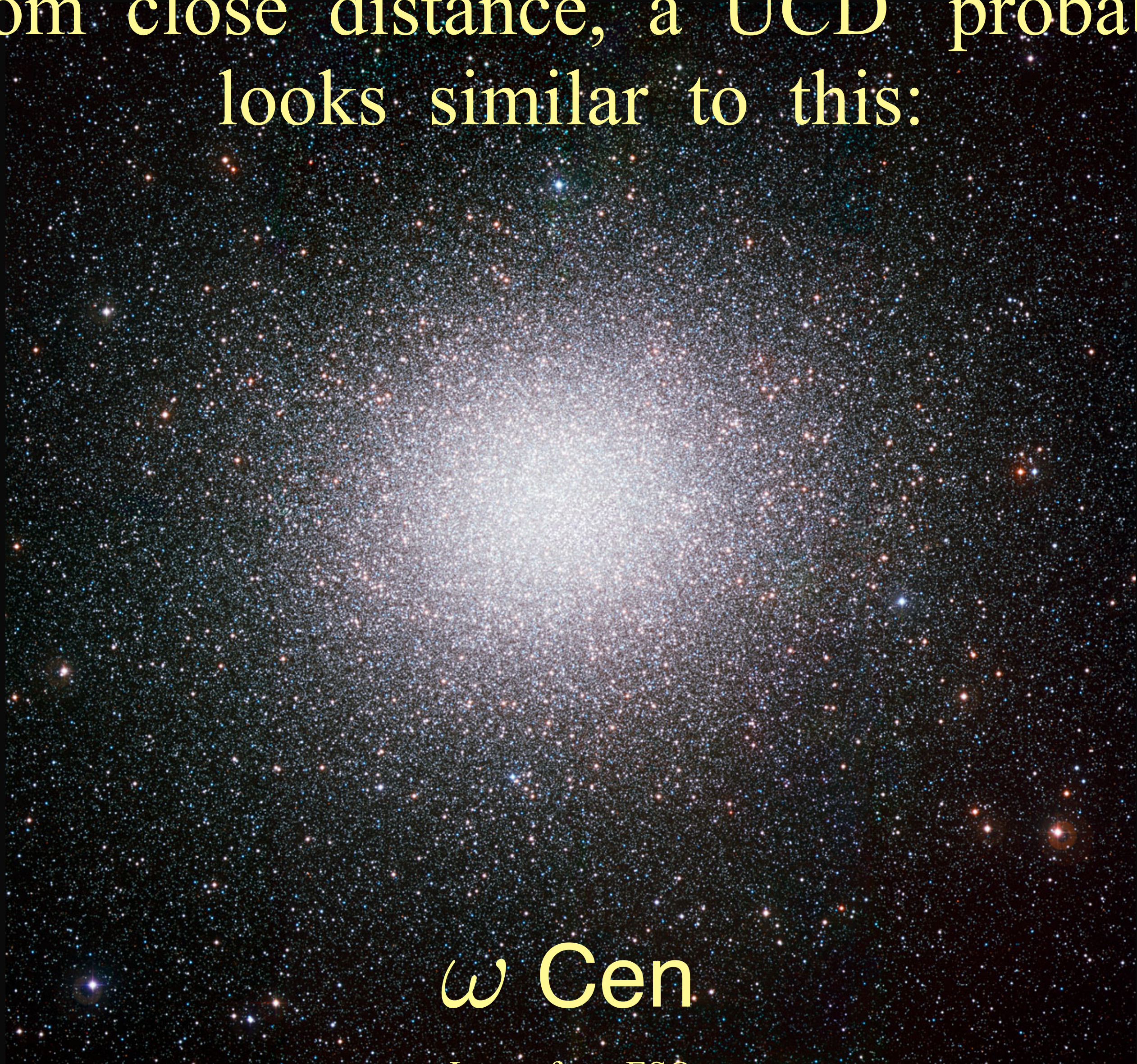


UCDs occur mostly in galaxy clusters

Image by M. Hilker

Pavel Kroupa: *AIfA, University of Bonn*

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



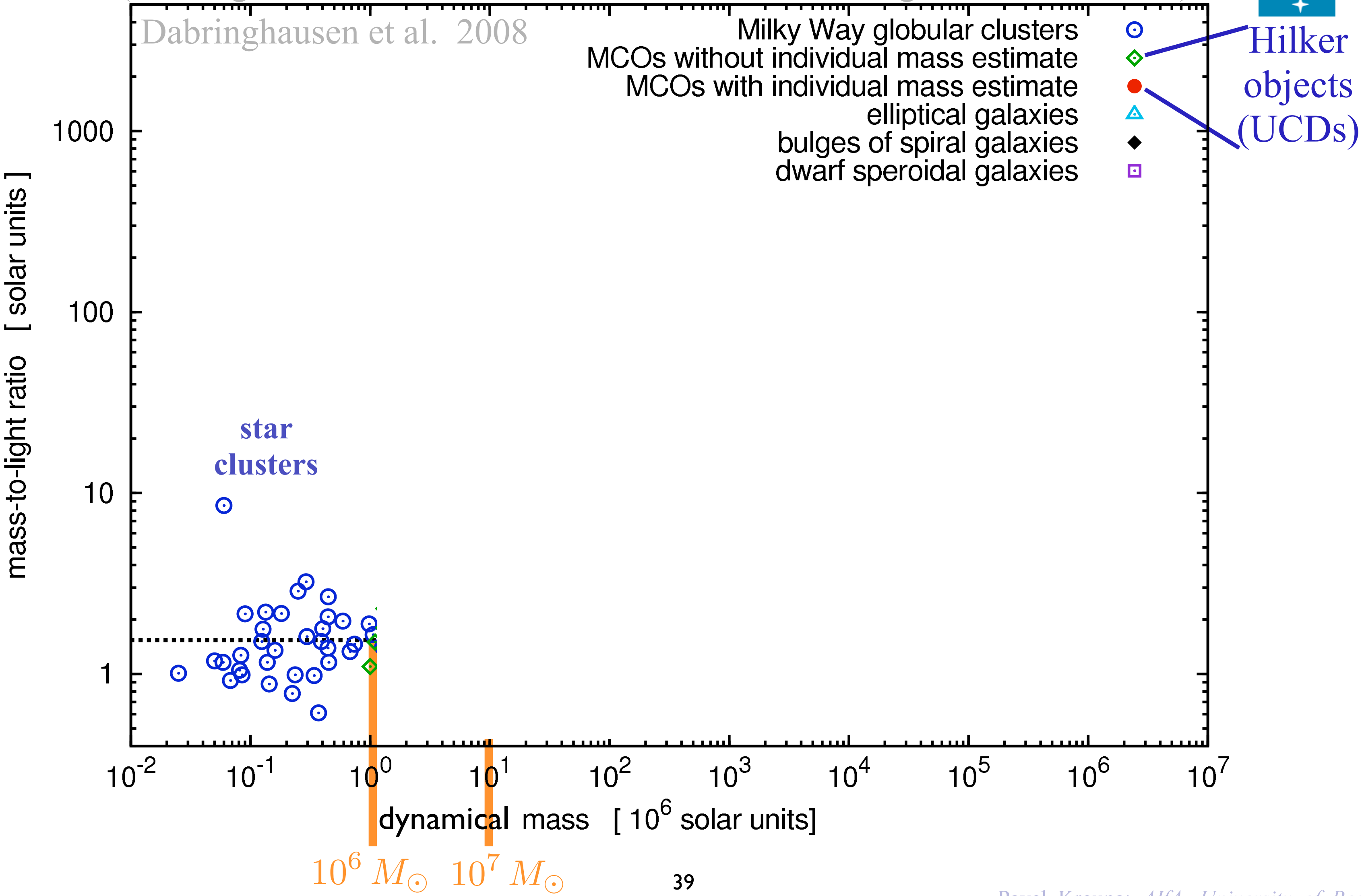
ω Cen

Image from ESO

Pavel Kroupa: *AIfA, University of Bonn*

M/L vs mass :

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



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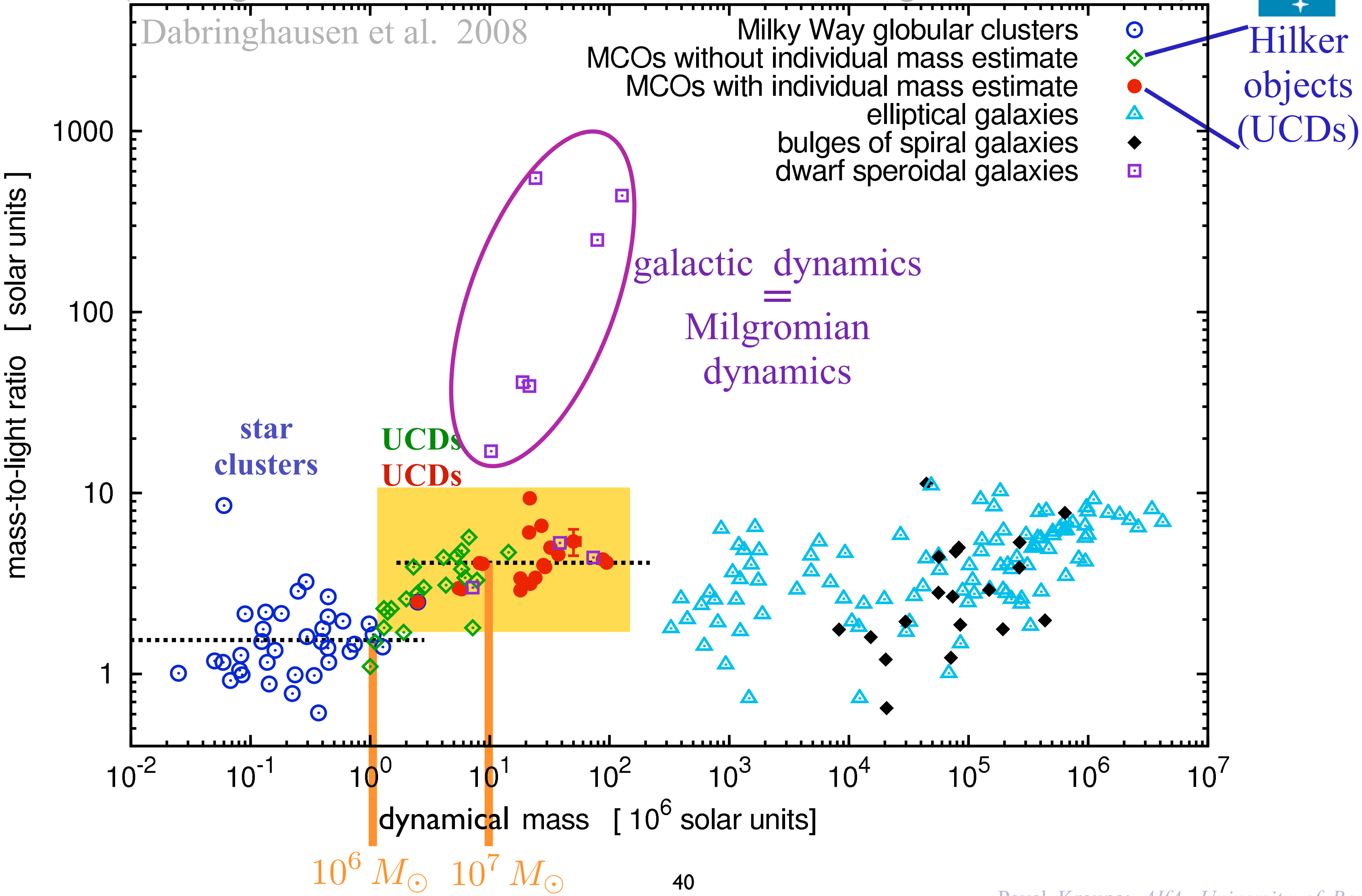
M/L vs mass :

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



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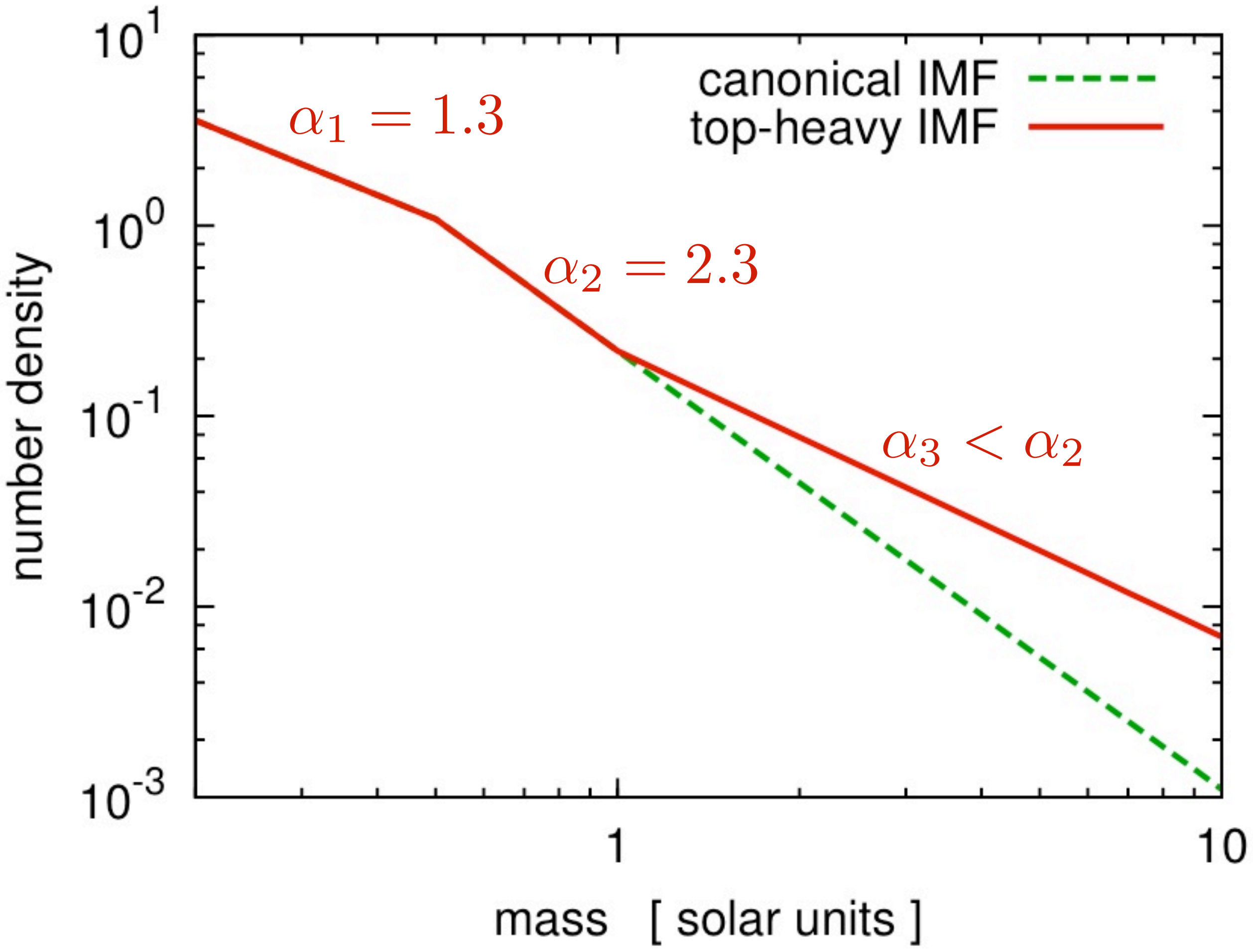
Is a top-heavy IMF a viable possibility ?

. . . it would provide many dark remnants



Seek α_3 such that M/L is accounted for.

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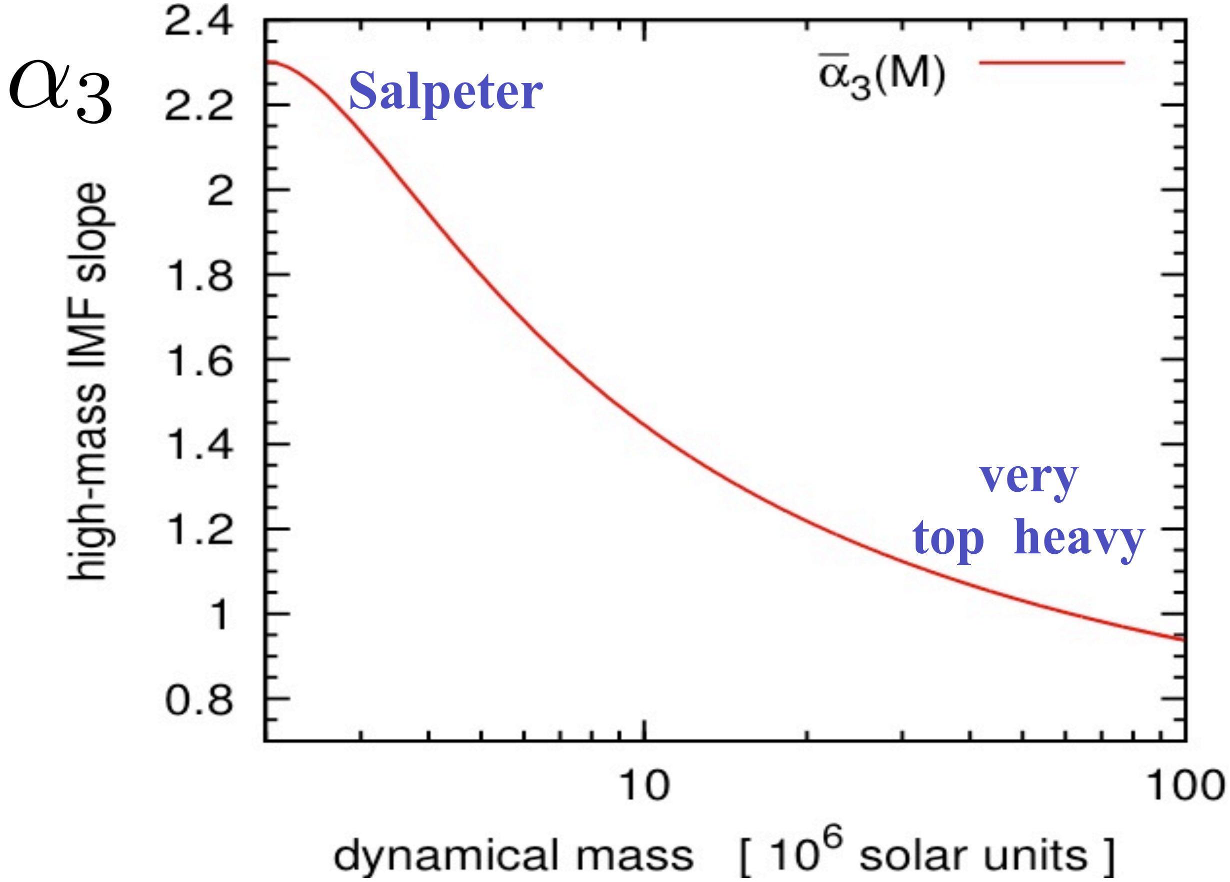
Top-heavy IMF is a viable possibility !

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

Dabringhausen et al. 2012



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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 :

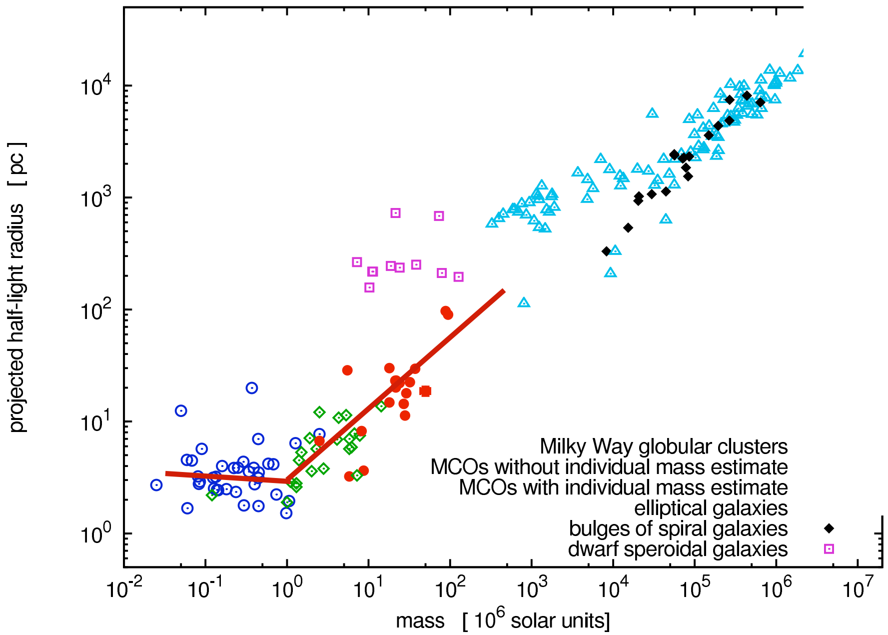
$$\Gamma \propto \frac{n_{\rm s}\; n_{\rm ns}\; r_{\rm c}^3}{\sigma}$$

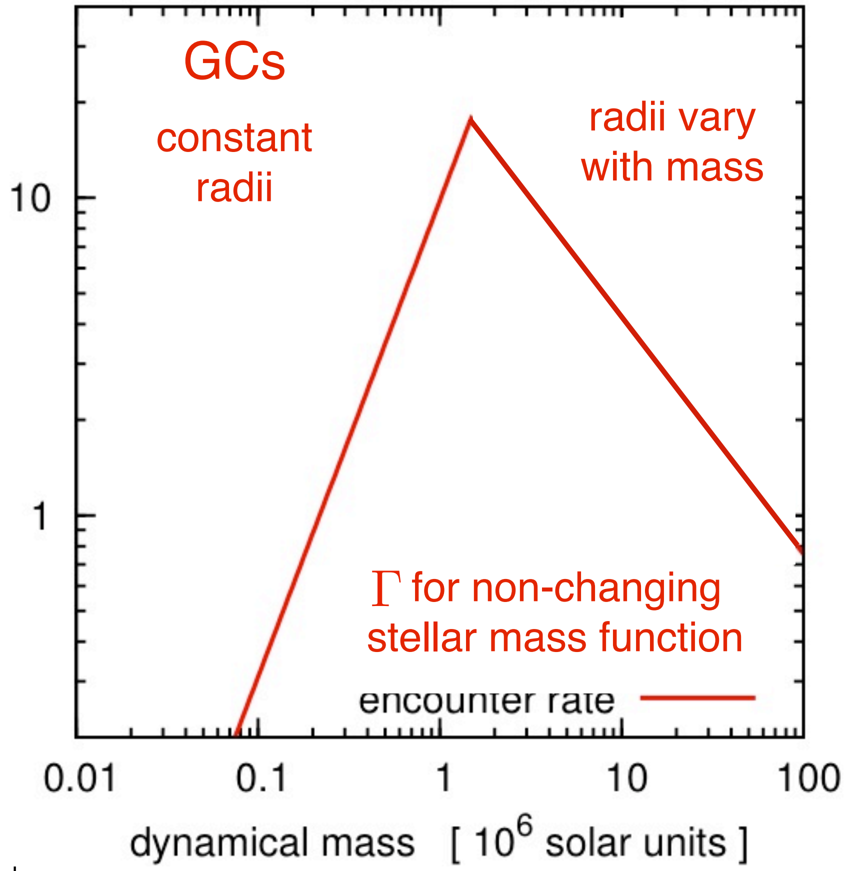
(Verbunt 2003)

LMXBs in globular clusters and UCDs in Virgo

The encounter rate is given as

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





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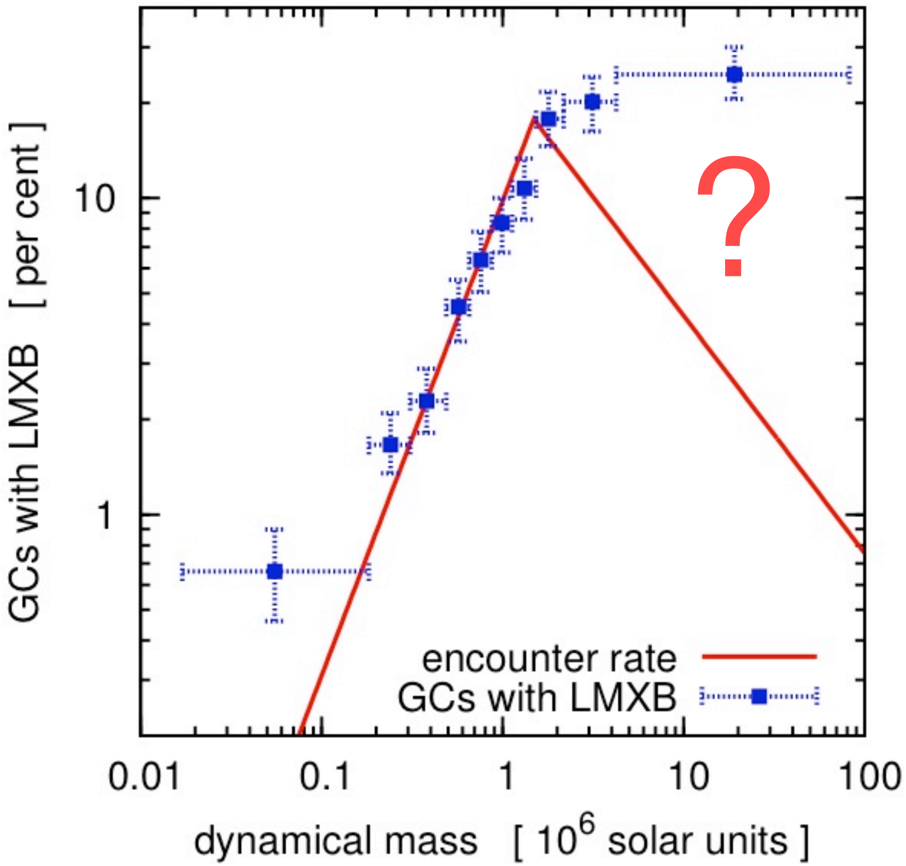
LMXBs in globular clusters and UCDs in Virgo

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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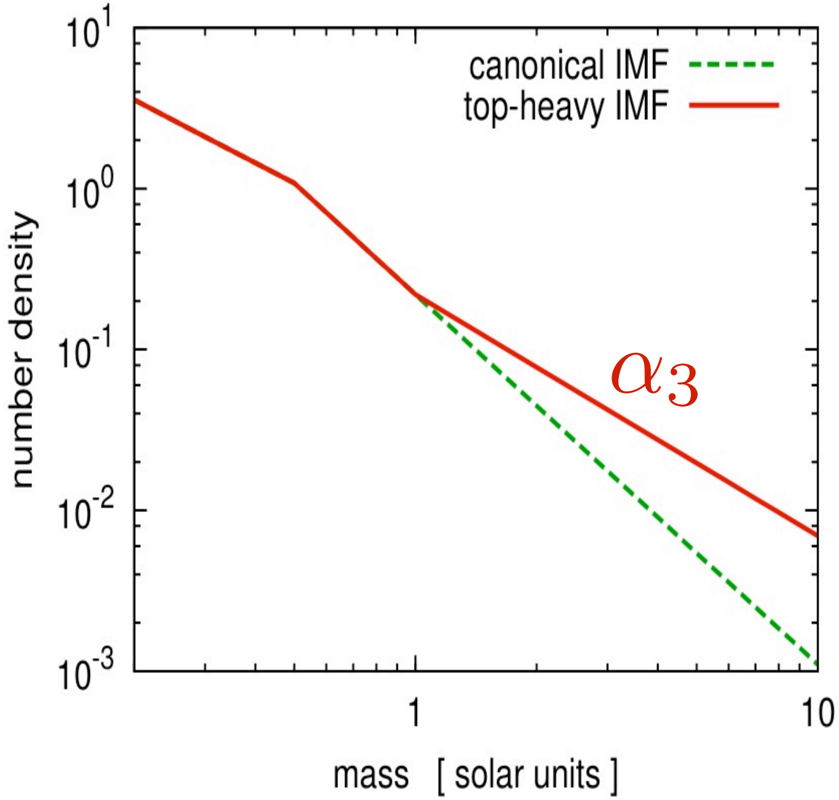
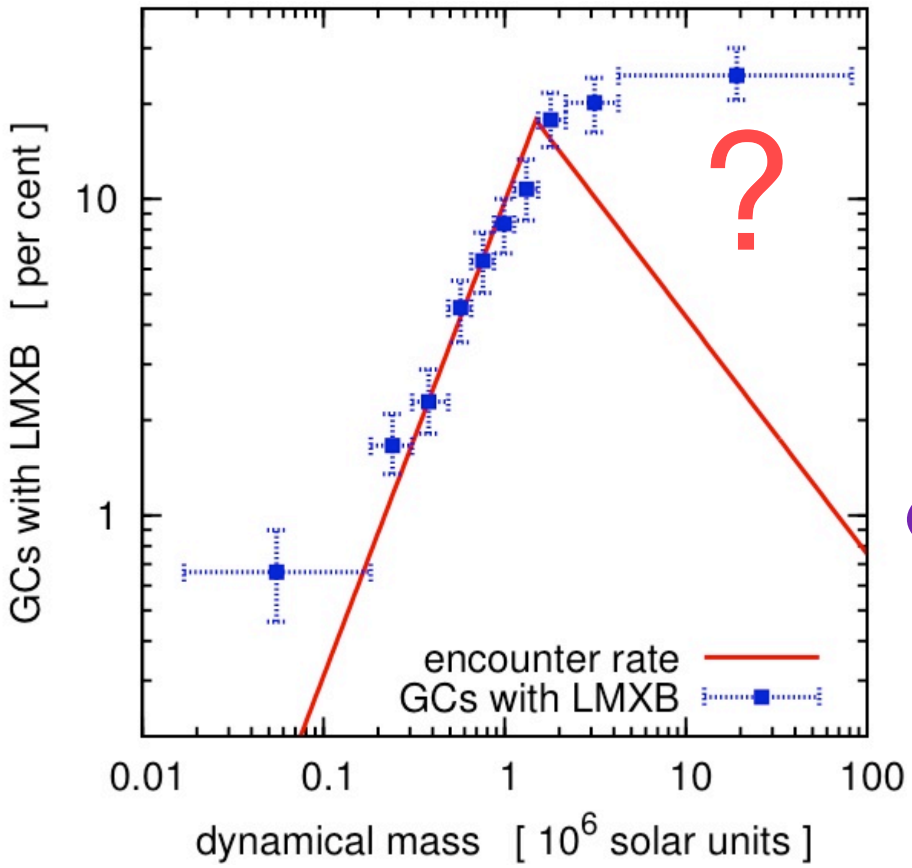
There is such an IMF !



(Dabringhausen et al. 2012)

LMXBs in globular clusters and UCDs in Virgo

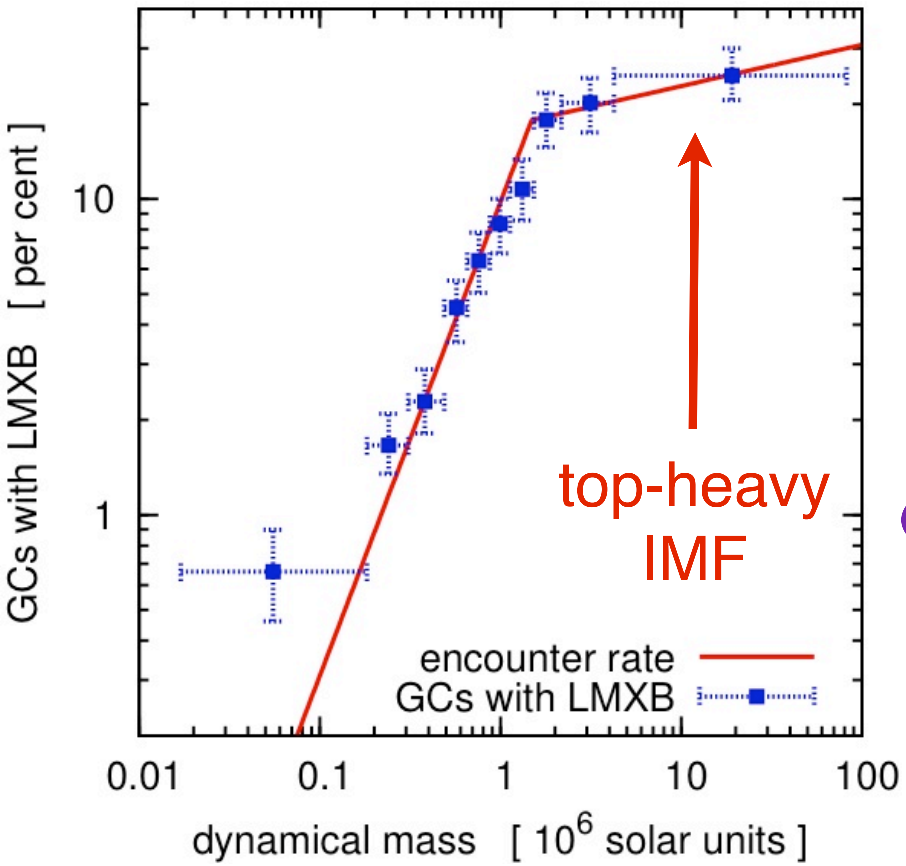


(Dabringhausen et al. 2012)

ESO data !

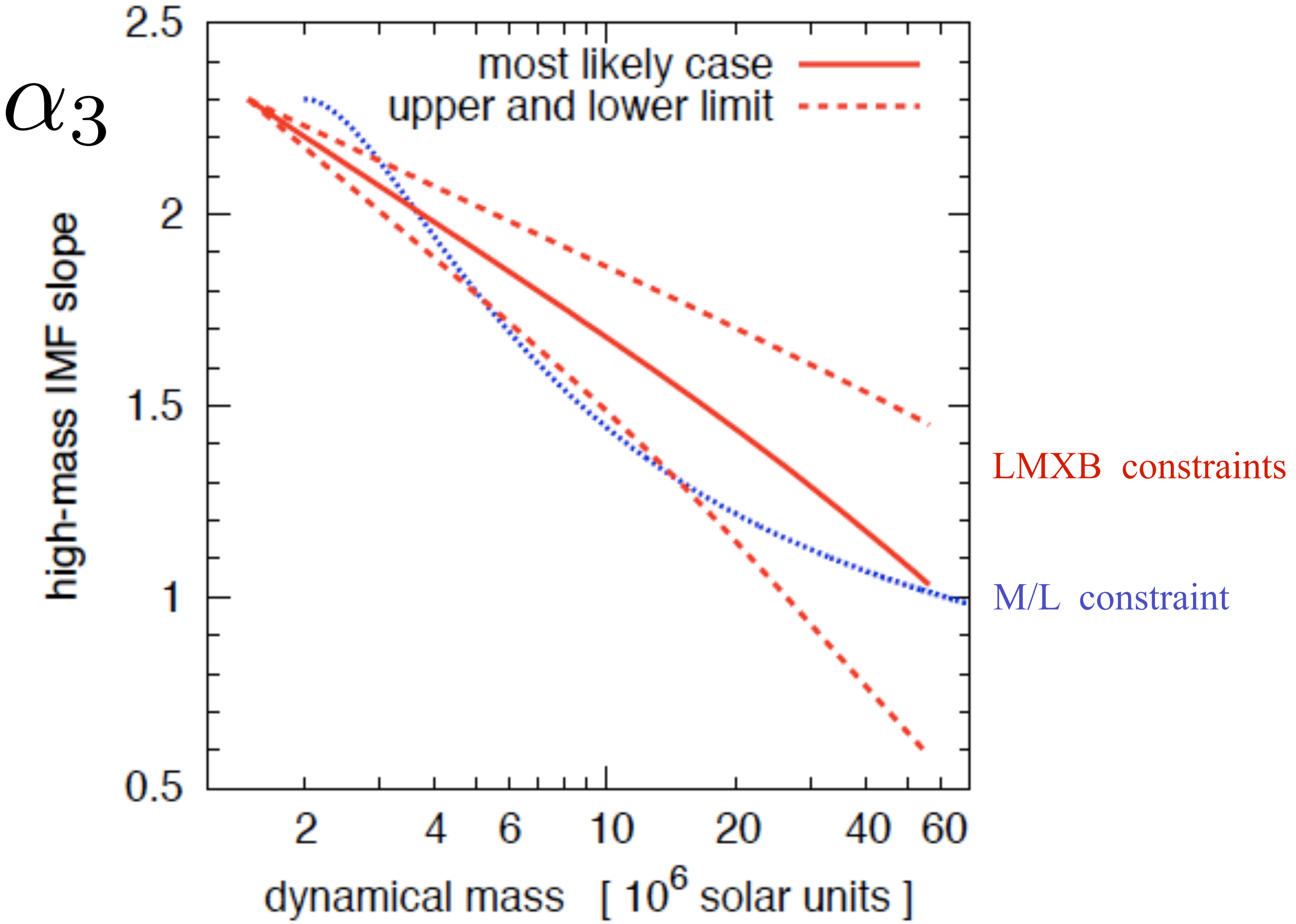
Pavel Kroupa: *AIfA, University of Bonn*

(Dabringhausen et al. 2012)



ESO data !

a systematically varying IMF in UCDs thus emerges . . .



(Dabringhausen et al. 2012)

Joerg Dabringhausen
(AIfA, Bonn)

ESO data !
e.g. :

Maraston et al., 2004, "*The dynamical mass of the young cluster W3 in NGC 7252. Heavy-weight globular cluster or ultra compact dwarf galaxy?*", UVES

Sollima et al. 2007, "*The mass function of ω Centauri down to 0.15 Msolar*", FORS1

Chilingarian et al., 2008, "*Stellar population constraints on the dark matter content and origin of ultra-compact dwarf galaxies*", FLAMES-GIRAFFE

Chilingarian et al., 2012, "*Dynamical versus stellar masses of ultracompact dwarf galaxies in the Fornax cluster*", FLAMES-GIRAFFE

Putting GCs and UCDs together:

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

Pavel Kroupa: *AIfA, University of Bonn*

Putting it all together . . .

Pavel Kroupa: *AIfA, University of Bonn*

What we know from observation :

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

→ disagrees with dynamical evolution

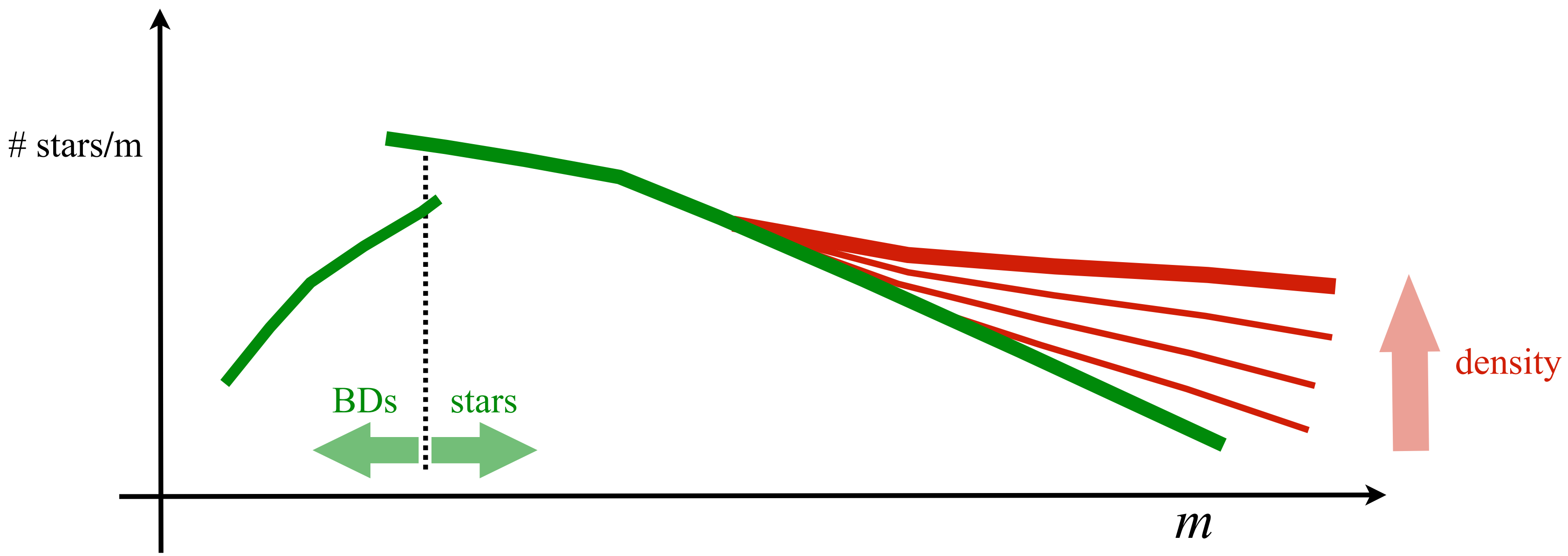
UCDs : higher dynamical M/L ratios

→ cannot be exotic dark matter

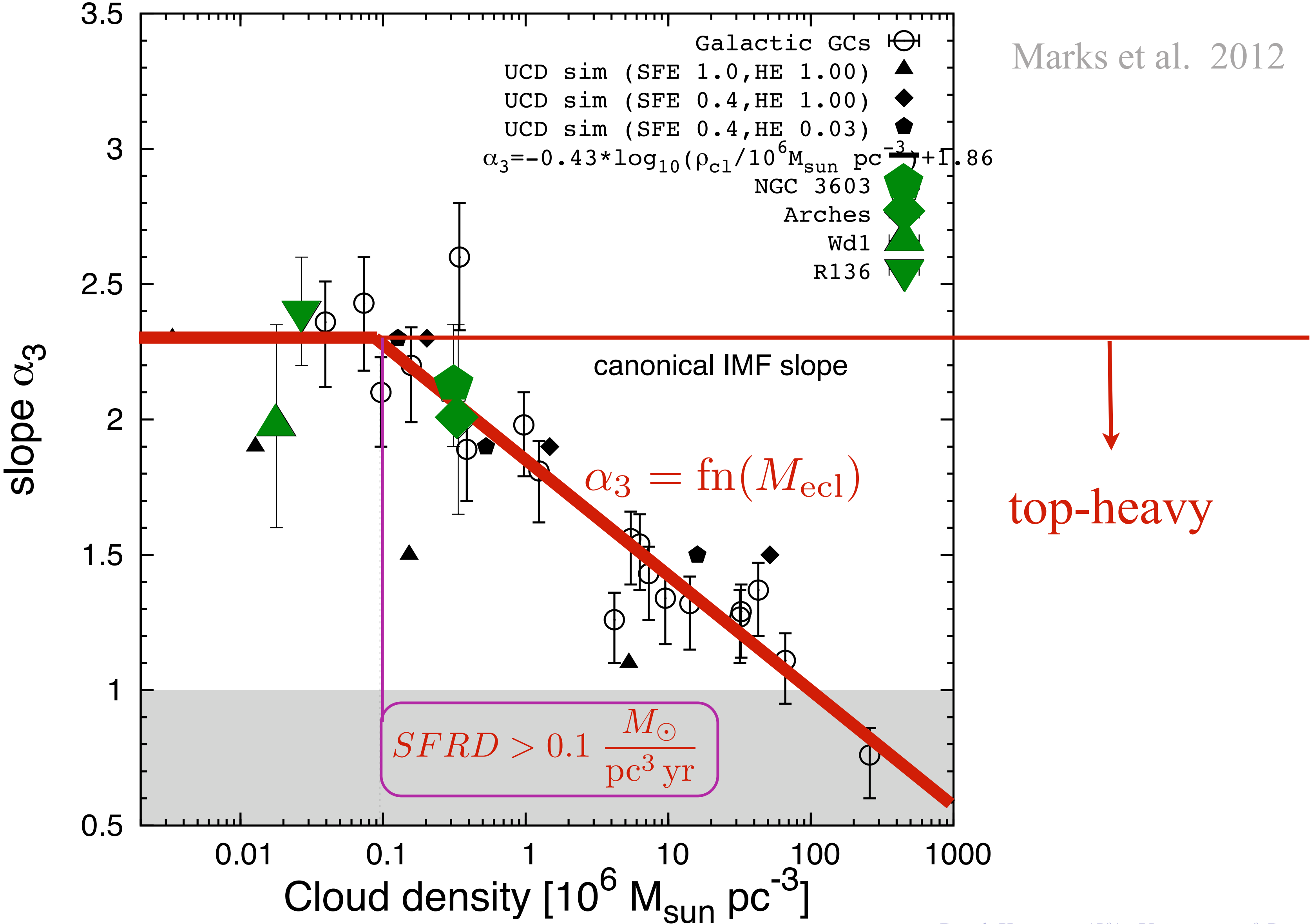
UCDs : larger fraction of X-ray sources than expected

→ no explanation other than many remnants

What this implies :



Top-heavy IMF in extreme-density environments :



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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

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

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

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ESO data ! e.g. :

Selman et al. 1999, "*The ionizing cluster of 30 Doradus. III. Star-formation history and initial mass function*",

Cassasus et al. 2000, "*The luminosity function of galactic ultra-compact H II regions and the IMF for massive stars*",

Clark et al. 2005, "*On the massive stellar population of the super star cluster Westerlund 1*",
EMMI, SUSI2

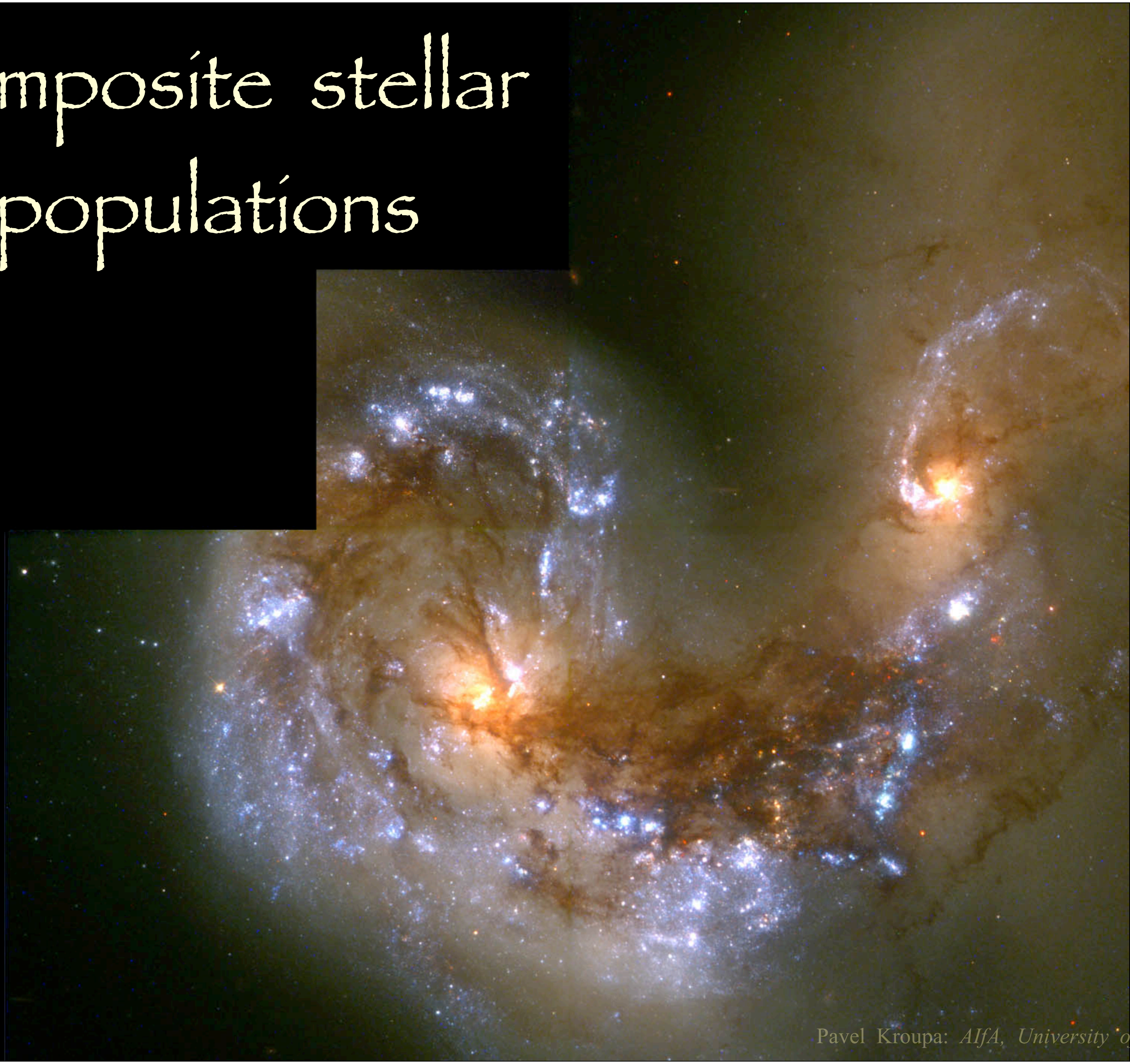
Selman & Melnik 2005, "*The IMF of the field population of 30 Doradus*", WFI

Maness et al., 2007, "*Evidence for a Long-standing Top-heavy Initial Mass Function in the Central Parsec of the Galaxy",* SINFONIE, SPIFFI

Harayama, Eisenhover et al. 2008, "*The Initial Mass Function of the Massive Star-forming Region NGC 3603 from Near-Infrared Adaptive Optics Observations*", ISAAC, NACO

Bartko et al., 2010, "*An Extremely Top-Heavy Initial Mass Function in the Galactic Center Stellar Disks*", LaserGuideStarFacility, SINFONI

Composite stellar populations



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The

IGIMF

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Composite Stellar Populations

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

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

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

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

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IGIMF $= \sum$ ***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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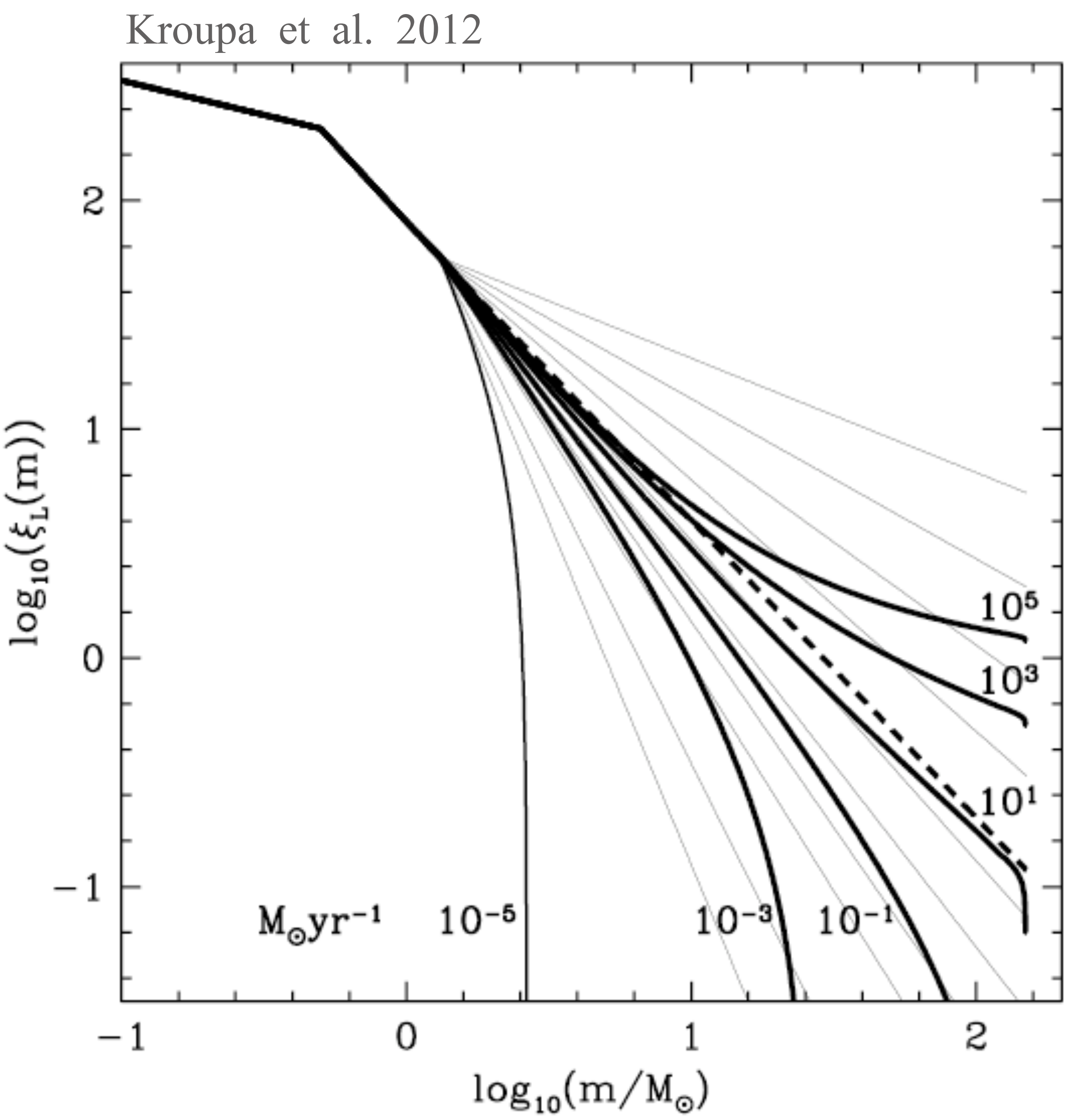

The IGIMF for galaxies with different SFRs

64

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Jan Pflamm-Altenburg
(AIfA, Bonn)

Carsten Weidner
(IAC, Tenerife)

Dice or no dice ?

Is star formation optimal
or purely stochastic?

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Two extremes :

The IMF is an invariant
probability density distribution function

stochastic sampling

variations among
on-site IMFs

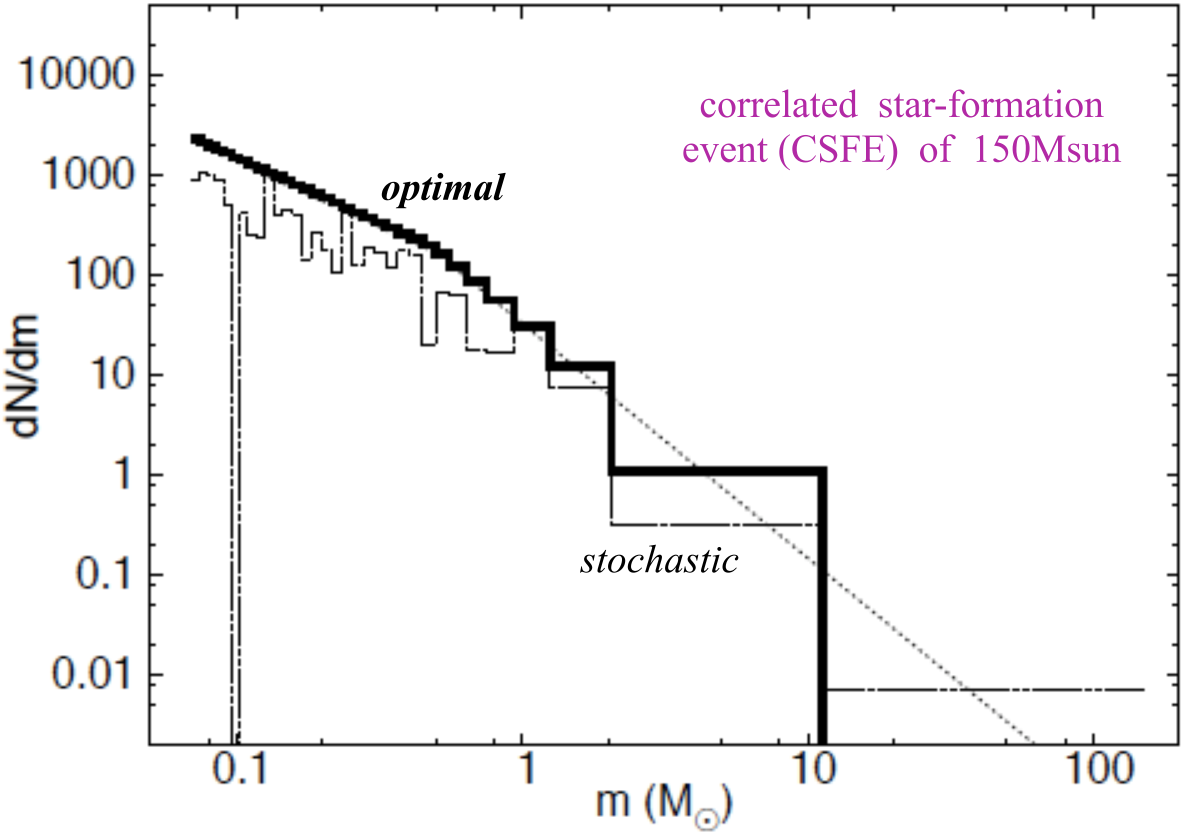
(nature plays dice, anything goes)

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. 2012
(150 page IMF
review : astro-ph)

Remember:
observational data always
have substantial
measurement errors.

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

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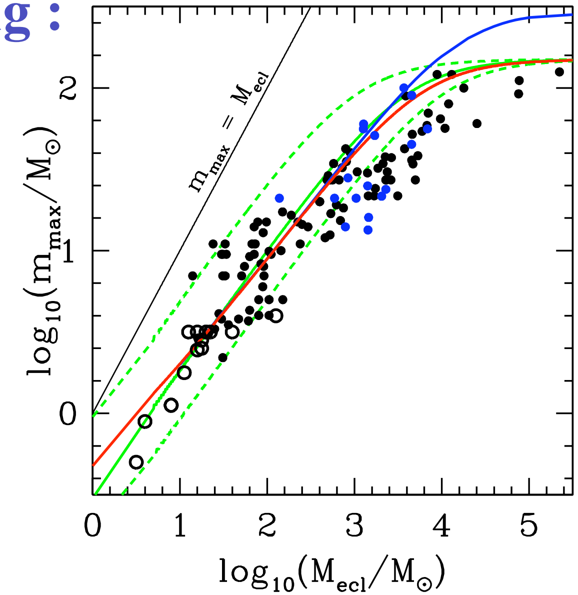
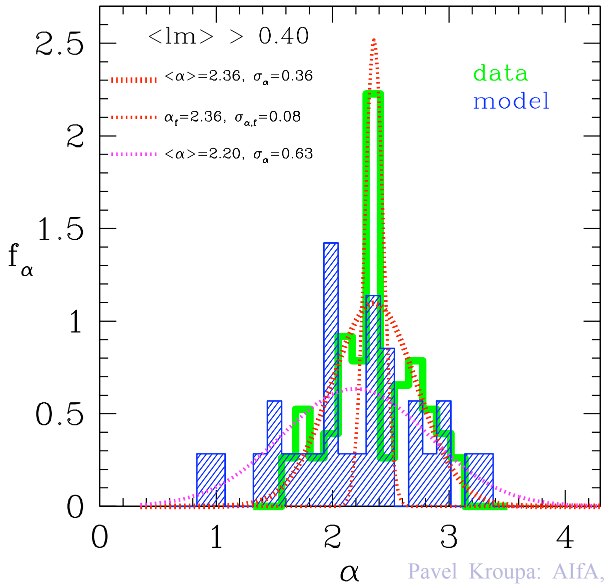
Nature appears to be closer to optimal sampling :

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



Small dispersion of α_3 values :



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arXiv:1112.3340v2 [astro-ph.CO] 29 Jan 2012

Kroupa et al. 2012
(150 page IMF review)

Stellar Systems and Galactic Structure, 2012
Vol. V, Planets, Stars & Stellar Systems, ed. by Gilmore, G.

The stellar and sub-stellar IMF of simple and composite populations

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[3] *Instituto de Astrofsica de Canarias, C/ Vía Láctea, s/n, E38205 La Laguna (Tenerife), Spain*

[4] *Institute of Astronomy, Madingley Road, Cambridge CB3 0HA, UK*

[5] *Institut de Planétologie et dAstrophysique de Grenoble, BP 53, F-38041 Grenoble Cédex 9, France*

l, *University of Bonn*

Conclusions

- Binary correction → stars and BDs must have their own (separate) IMFs (no log-normal IMF)
  - Implications for formation proccess

- For star-forming pc-scale systems with $M_{\rm ecl} < 10^5\, M_\odot$ the IMF varies, but trivially so : IMF is form invariant but $m_{\rm max} = {\rm fn}(M_{\rm ecl})$

- For star-forming pc-scale systems with $M_{\rm ecl} > 10^6\, M_\odot$ the IMF may be top-heavy : $SFRD > 0.1 \, \frac{M_\odot}{{\rm pc}^3\,{\rm yr}}$
  - Independent arguments lead to virtually the same variation of α_3 with $M_{\rm ecl}$:
    - Deficit of LMS in fluffy GCs
    - The increased M/L ratio of UCDs
    - The fraction of UCDs with LMXBs

- Whole galaxies : IGIMF = ∑ IMFs in all star formation events
  - New understanding of galaxies.

- Nature: Stochastic vs Optimal Sampling ?

ESO telescopes and staff
contributed essentially to the results obtained to-date
on understanding the rules of star formation
and the IMF in particular.

Indeed, from my own experience the ESO facility stands as
the perhaps finest astronomical observatory in existence.

Conclusions

- Binary correction → stars and BDs must have their own (separate) IMFs (no log-normal IMF)
  - Implications for formation proccess

- For star-forming pc-scale systems with $M_{\rm ecl} < 10^5\, M_\odot$ the IMF varies, but trivially so : IMF is form invariant but
  $m_{\rm max} = {\rm fn}(M_{\rm ecl})$

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  $SFRD > 0.1 \, \frac{M_\odot}{{\rm pc}^3\, {\rm yr}}$

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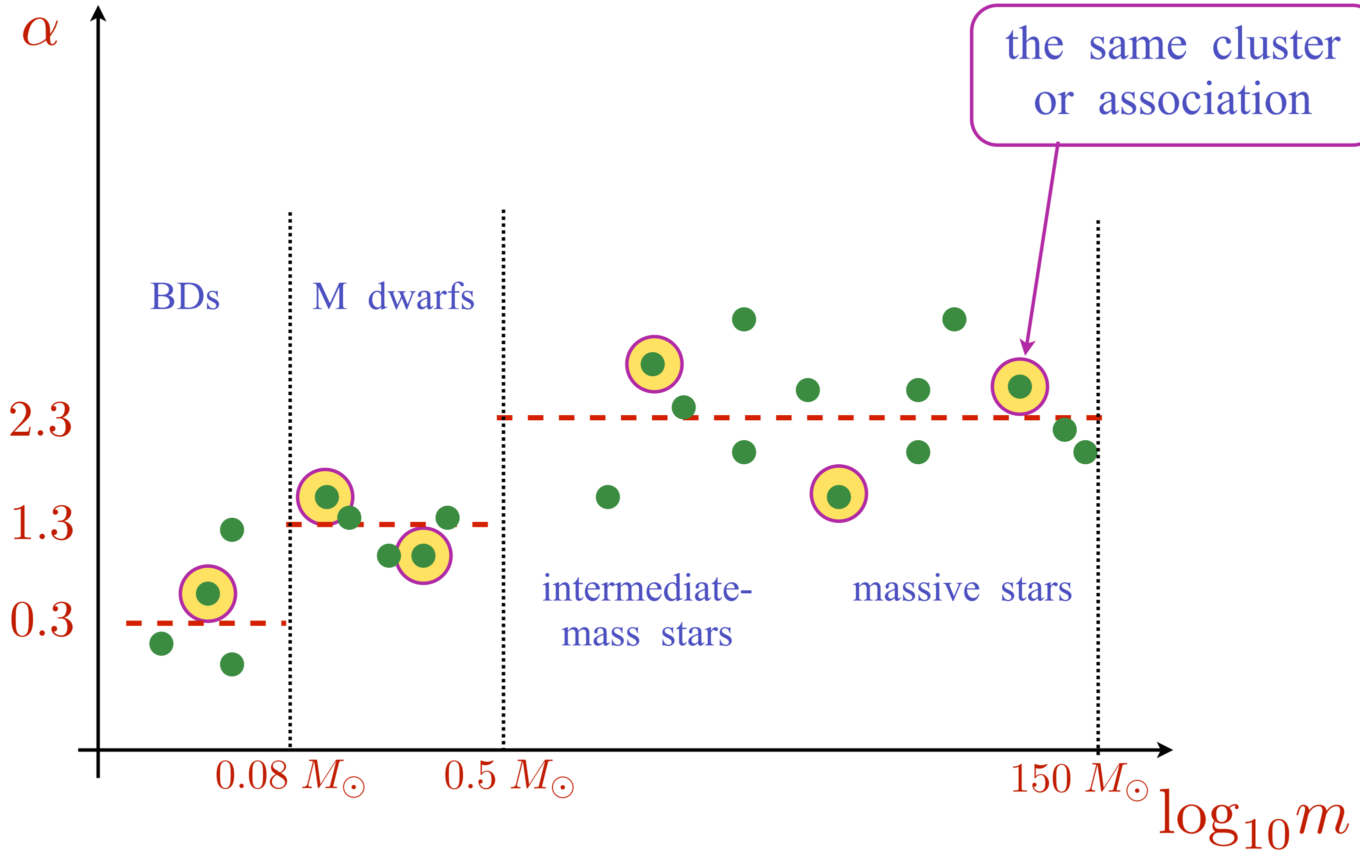
- Whole galaxies : IGIMF = $\sum$ IMFs in all star formation events
  - New understanding of galaxies.

- Nature: Stochastic vs Optimal Sampling ?

THE END

The alpha plot : $\xi(m) \propto m^{-\alpha(m)}$ (Scalo 1998; Kroupa 2001)



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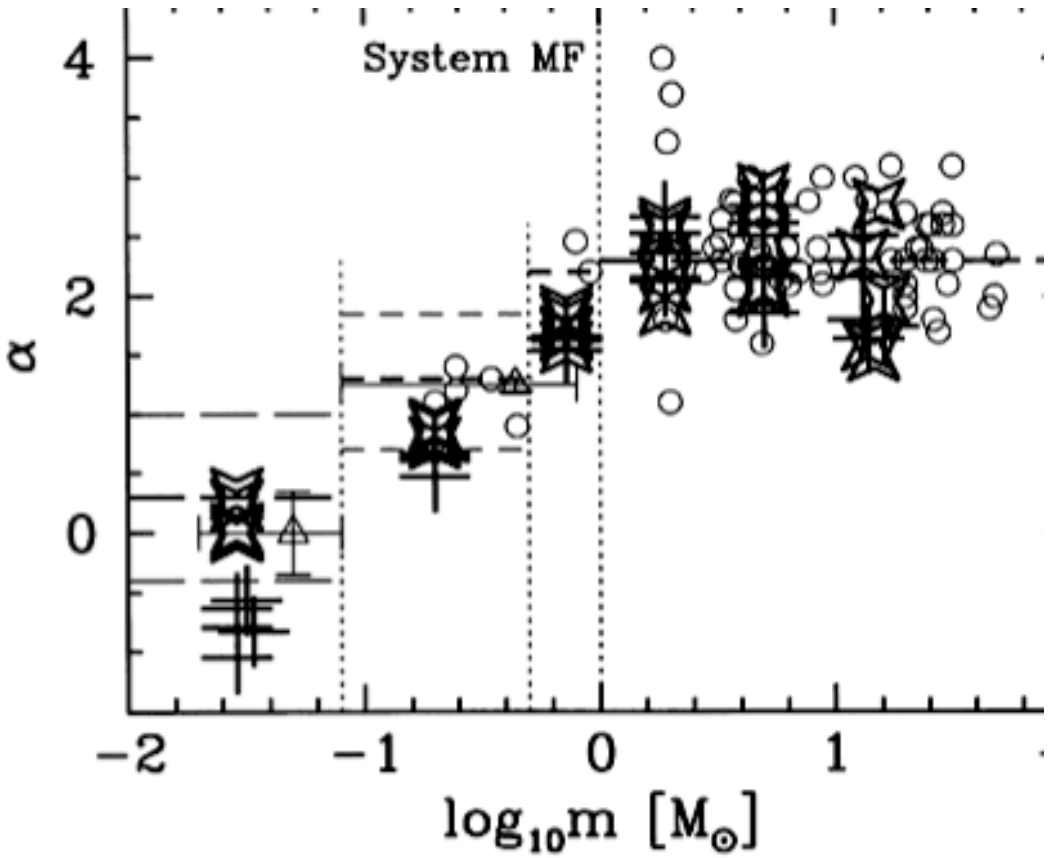
The theoretical alpha plot for clusters with $N = 3000$ stars

Kroupa (2001)



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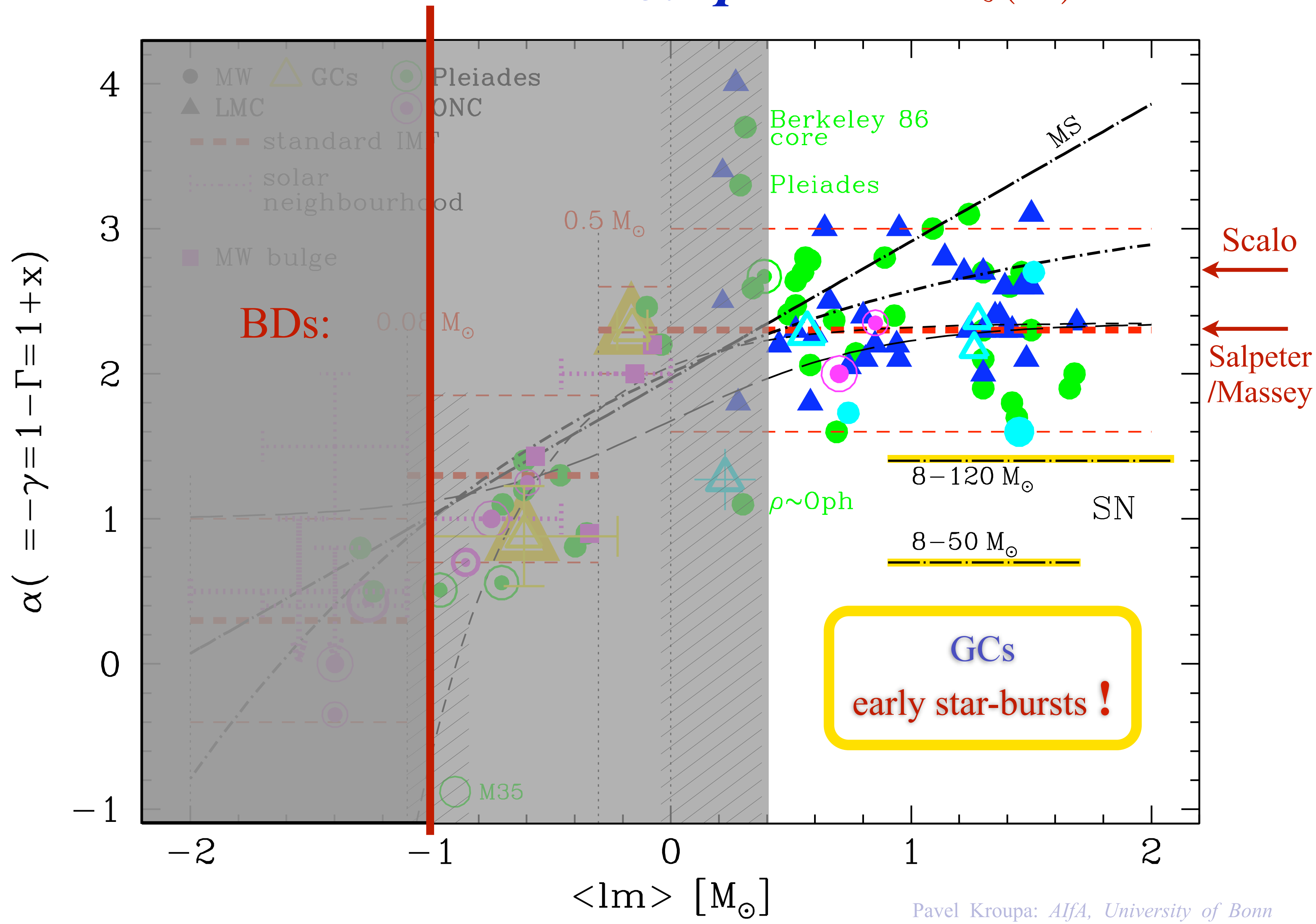
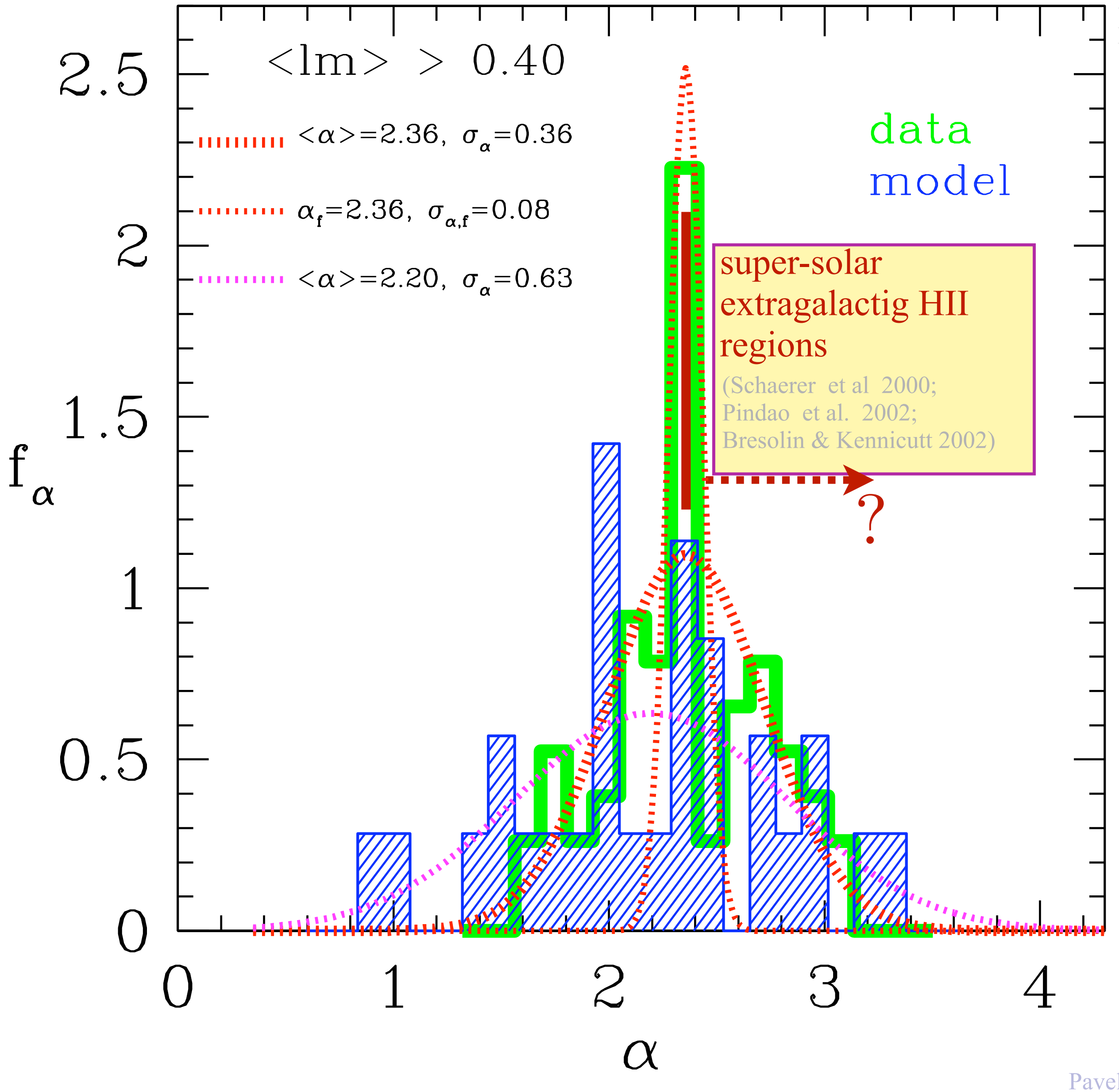
The α- plot $\xi(m) \propto m^{-\alpha(m)}$



Kroupa 2002;
Weidner & Kroupa 2006



1. No assymetries and sharp Salpeter/Massey peak.

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

3. *Super-solar HII* region have Salpeter/Massey IMF (perhaps a little steeper?). ***But*** what about *runaways*?

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THE END Final

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