# The systematically varying stellar IMF and some implications thereof

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**Looking into the stars by just counting them**

We have $dN = \Psi(M_V)\, dM_V$ = # of stars with $M_V \in [M_V, M_V + dM_V]$

$dN = \xi(m)\, dm$ = # of stars with $m \in [m, m + dm]$

Kroupa, Tout & Gilmore 1990

since $$\frac{dN}{dM_V} = -\frac{dm}{dM_V}\,\frac{dN}{dm}$$

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

the **observable** ($\Psi(M_V)$), the **obstacle** ($\frac{dm}{dM_V}$), the **target** ($\xi(m)$)

Strong sharp maximum near $M_V \approx 11.5$, $M_I \approx 8.5$

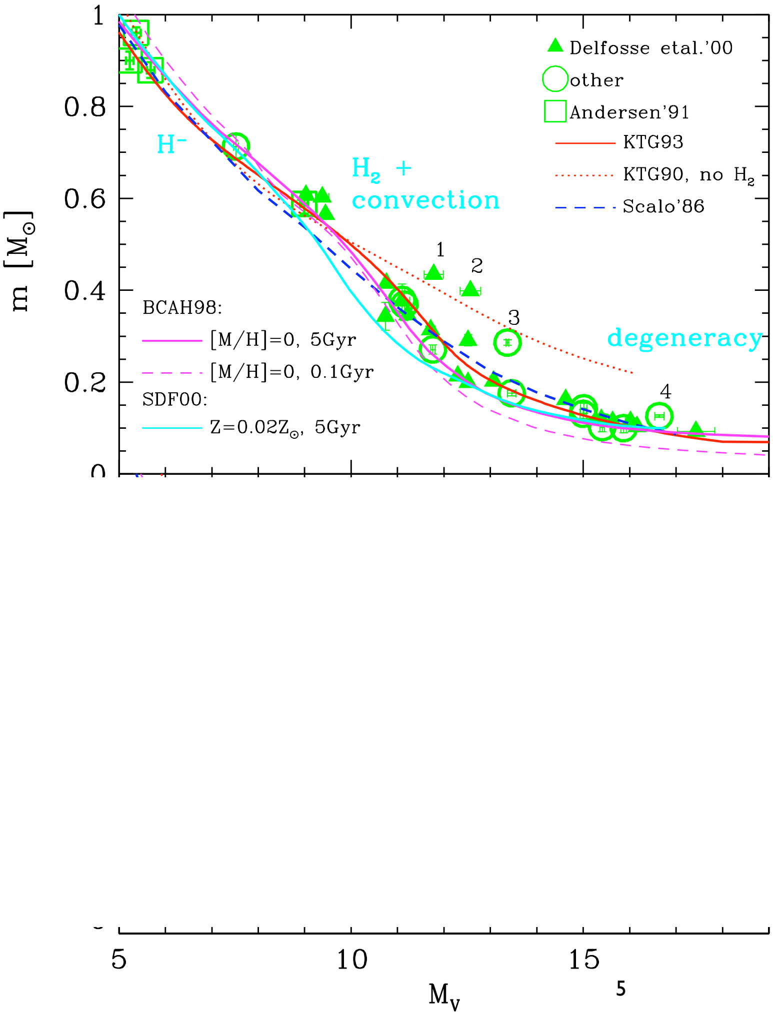




## *The mass-luminosity relation of low-mass stars*

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

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




# *The mass-luminosity relation of low-mass stars*

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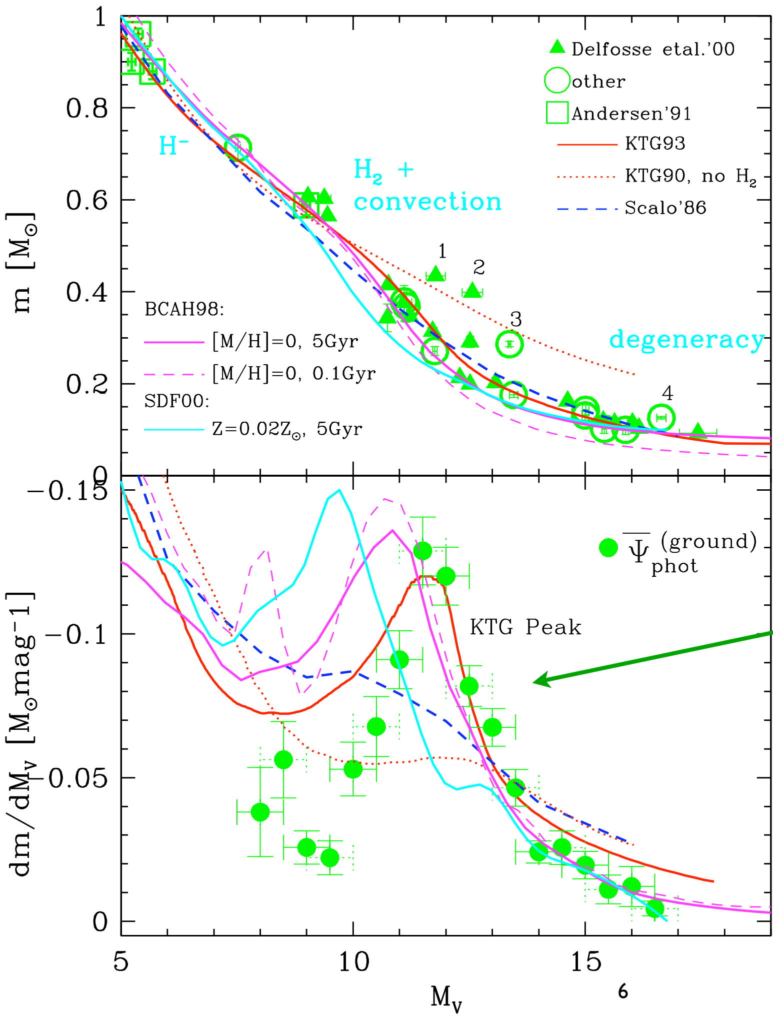


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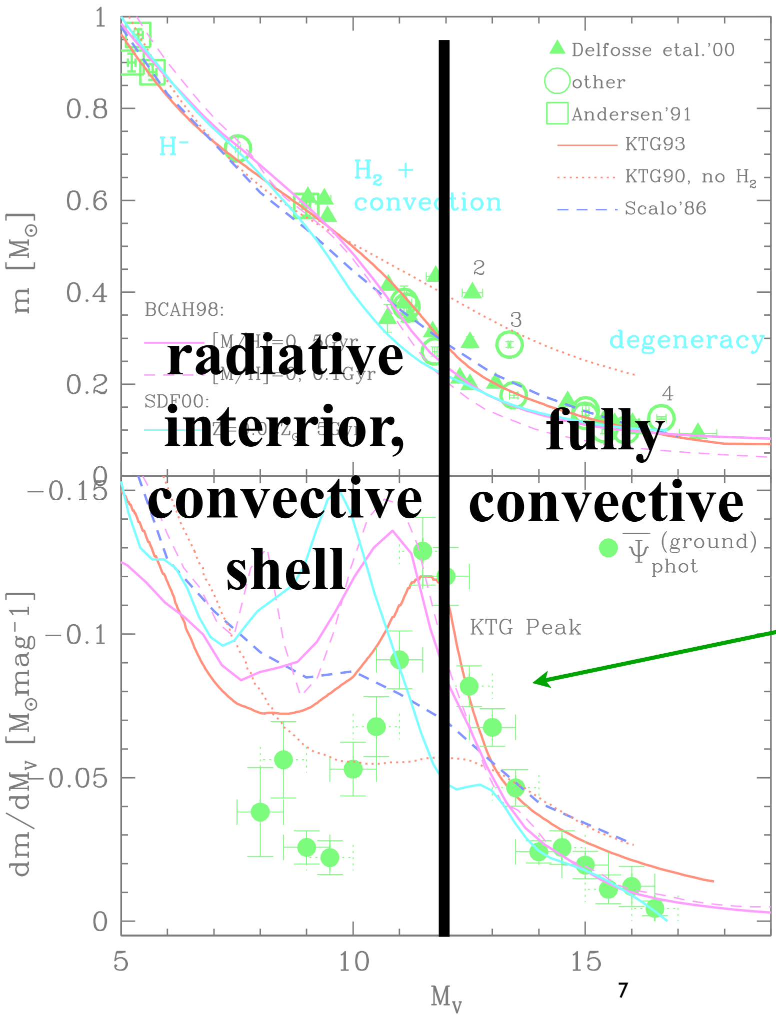
$$\Psi(M_{\rm V}) = -\frac{dm}{dM_{\rm V}}\,\xi(m)$$

1. position
2. width
3. amplitude

*all* agree !



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2. width
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*all* agree **!**



# The Galactic-field IMF

## There are ***two luminosity functions*** for the solar neighbourhood

**I.** Count stars nearby to Sun

Obtain $M_V$ and $d$ from trigonometric parallax

⟶ Well observed individual stars but *small numbers at faint end* ($\Psi_{near}$)

**II.** Deep (100 - 300 pc) pencil-beam photographic/CCD surveys

Formidable data reduction ($10^5$ images $\longrightarrow \approx 100$ stars)

Obtain $M_V$ and $d$ from photometric parallax

⟶ Large # of stars but *poor resolution* (2"-3") and *Malmquist bias* ($\Psi_{phot}$)



## The possibility of *dark matter* in the *Galactic disk*

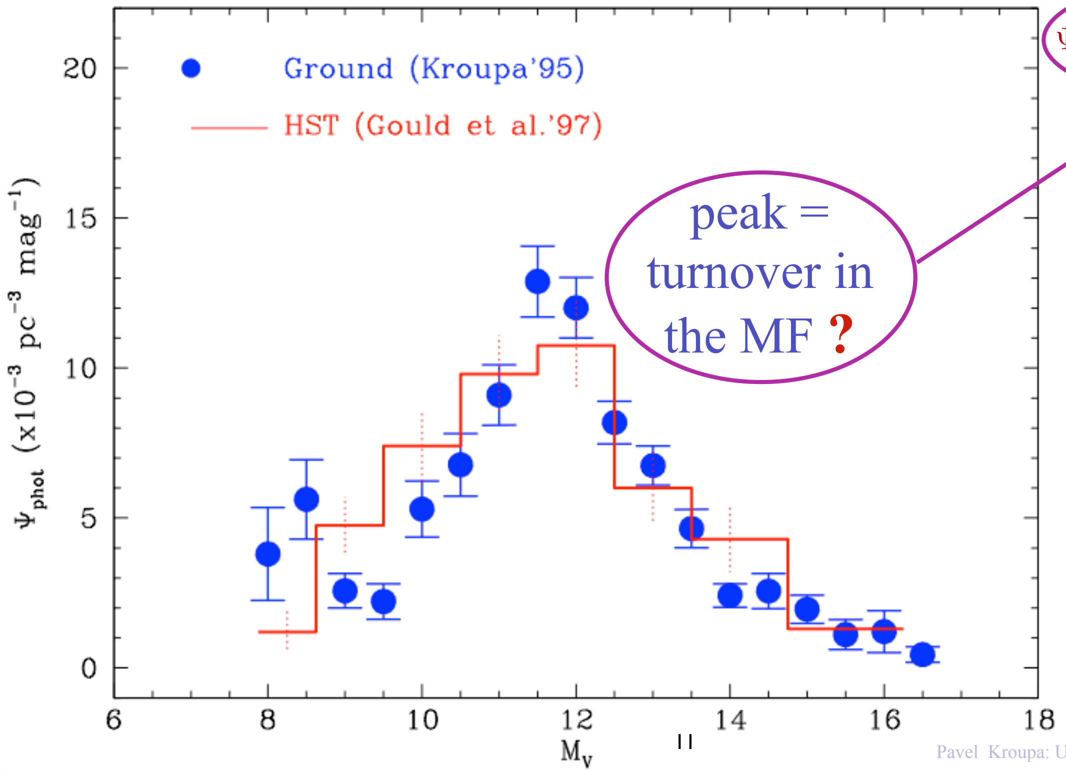
(Bahcall 1984)

⟶ Many surveys of type II (pencil-beams) to constrain the LF :

| | | |
|---|---|---|
| ground | Reid & Gilmore | 1982 |
| | Gilmore, Reid & Hewett | 1985 |
| | Hawkins & Bessell | 1988 |
| | Leggett & Hawkins | 1988 |
| | Stobie, Ishida & Peacock | 1989 |
| | Tinney, Reid & Mould | 1993 |
| | Kirkpatrick et al. | 1994 |
| HST | Gould, Bahcall & Flynn | 1997 |
| | Zheng, Flynn, Gould et al. | 2001 |

$\Psi_{phot}$
- independent of direction
- maximum (peak) at $M_V \approx 12$

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

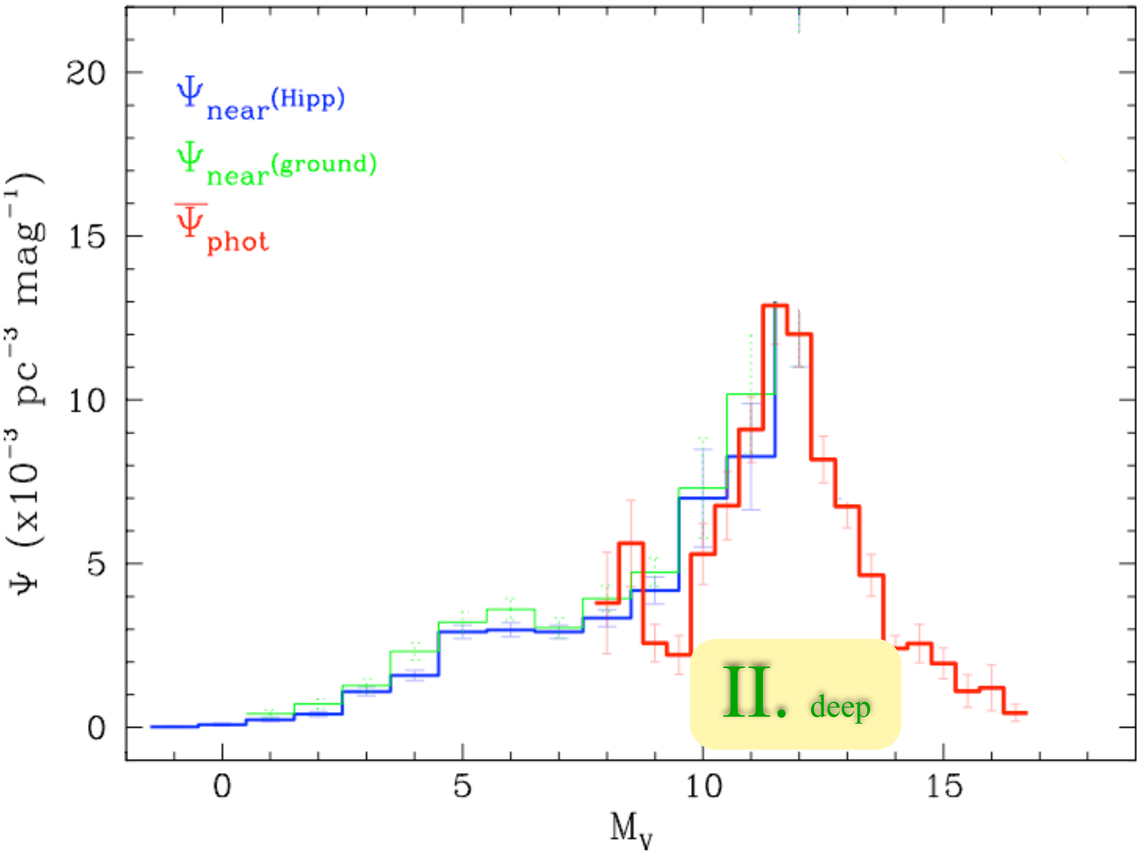



see also Bochanski et al. (2010, AJ)



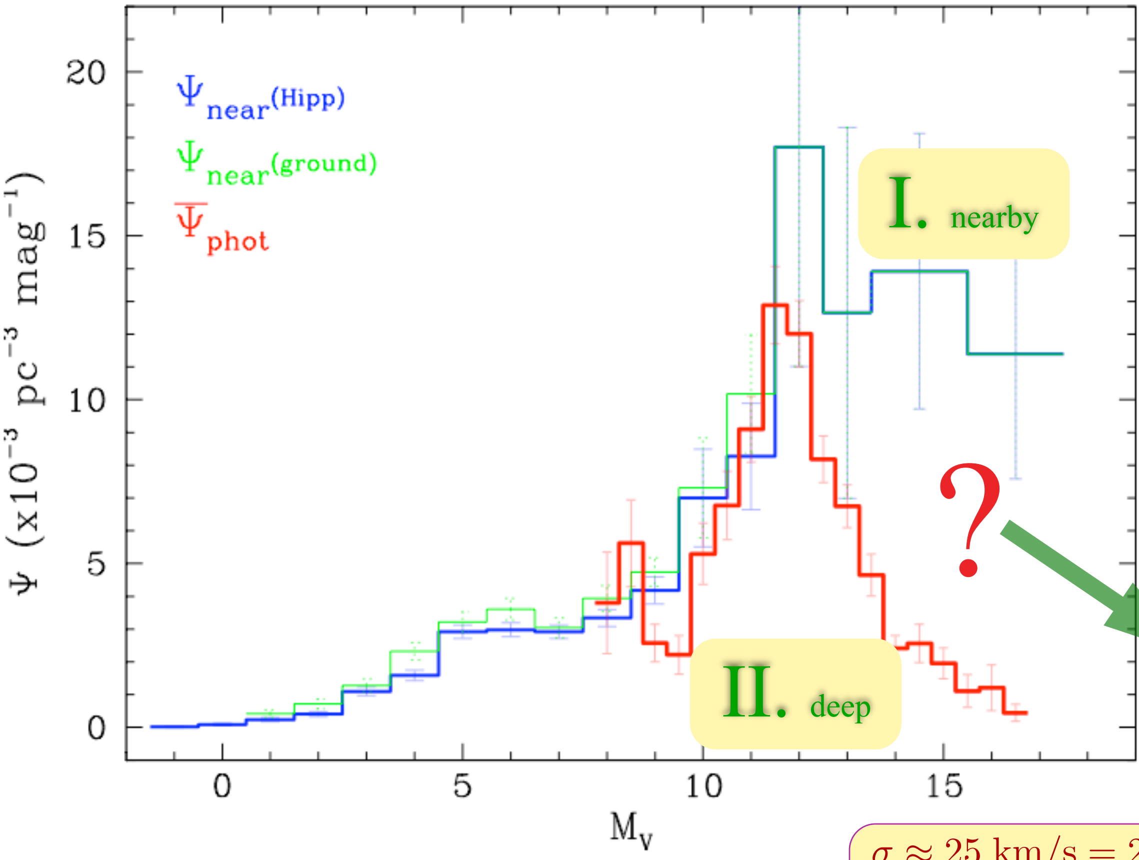
## Two solar-neighbourhood samples:

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



## BUT: two solar-neighbourhood samples:

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




Stellar samples should be *well-mixed*:

$$\sigma \approx 25\ \mathrm{km/s} = 250\ \mathrm{pc/10Myr}$$





# Problem :

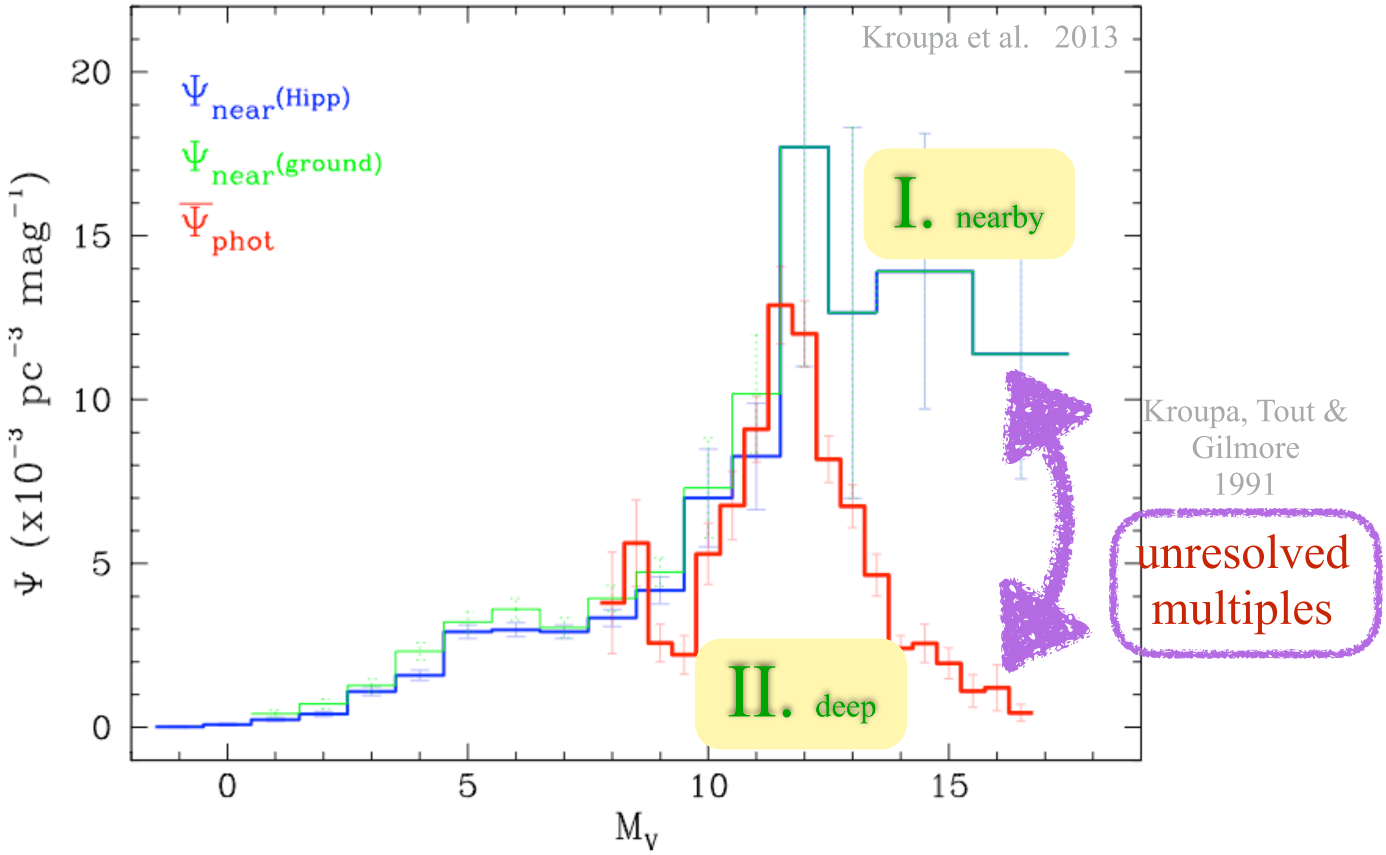
The nearby and deep LFs are not equal.

→ *Which* *LF* do we use to calculate the *MF* ?

$$\xi(m) = -\left(\frac{dm}{dM_V}\right)^{-1} \Psi(M_V)$$

# Two solar-neighbourhood samples:

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







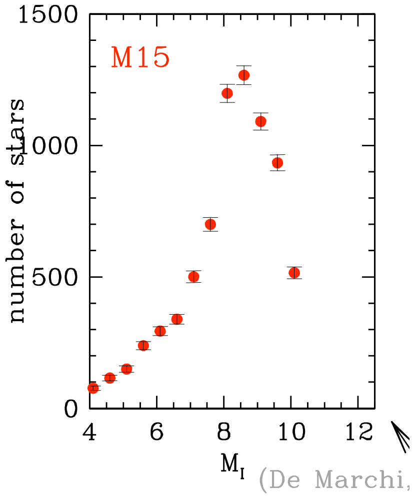

## The IMF in star clusters



Pavel Kroupa: University of Bonn / Charles University

Kroupa 2002
Science

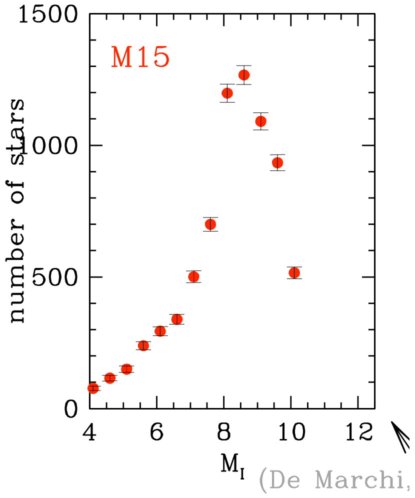
$$\Psi(M_V) = -\frac{dm}{dM_V}\,\xi(m)$$

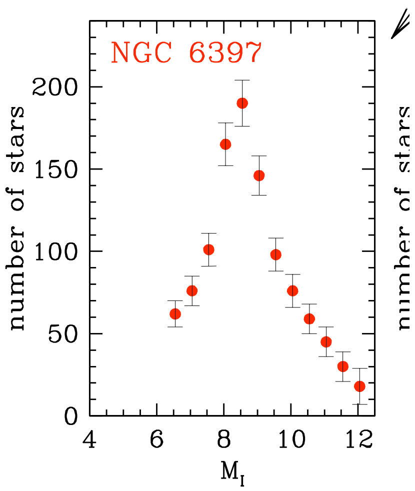





Kroupa 2002
Science

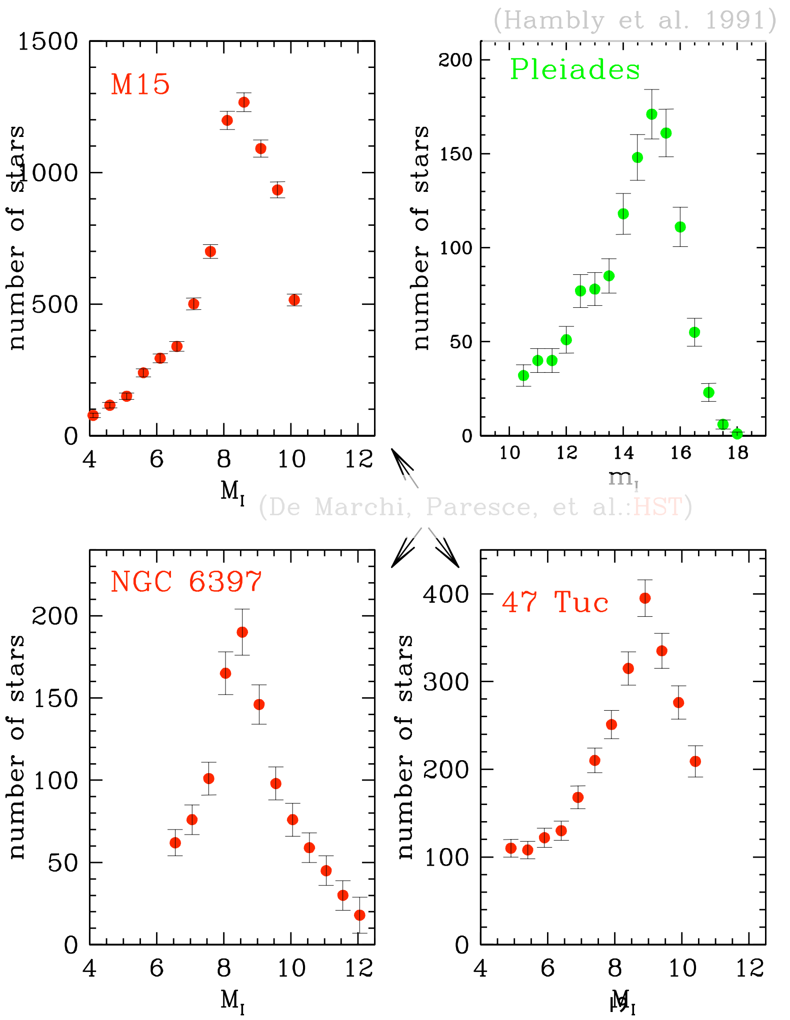
$$\Psi(M_V) = -\frac{dm}{dM_V}\,\xi(m)$$



Kroupa 2002
Science

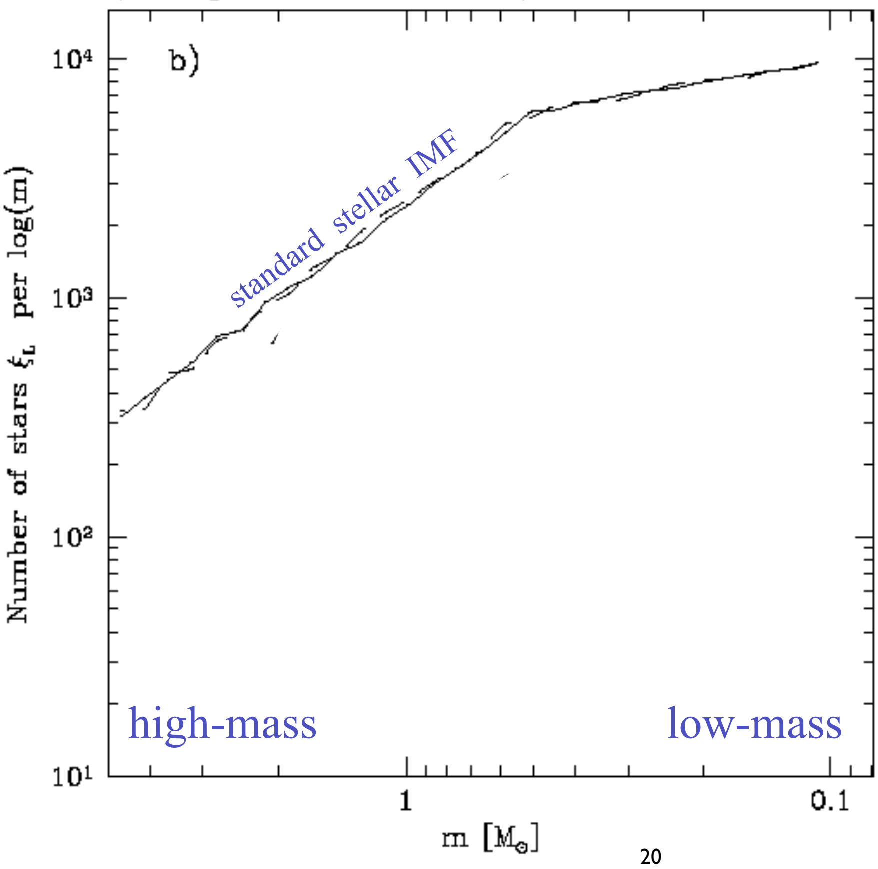
$$\Psi(M_V) = -\frac{dm}{dM_V}\,\xi(m)$$






# *MF(t) due to cluster evolution*

(Baumgardt & Makino 2003)




$f = 0$

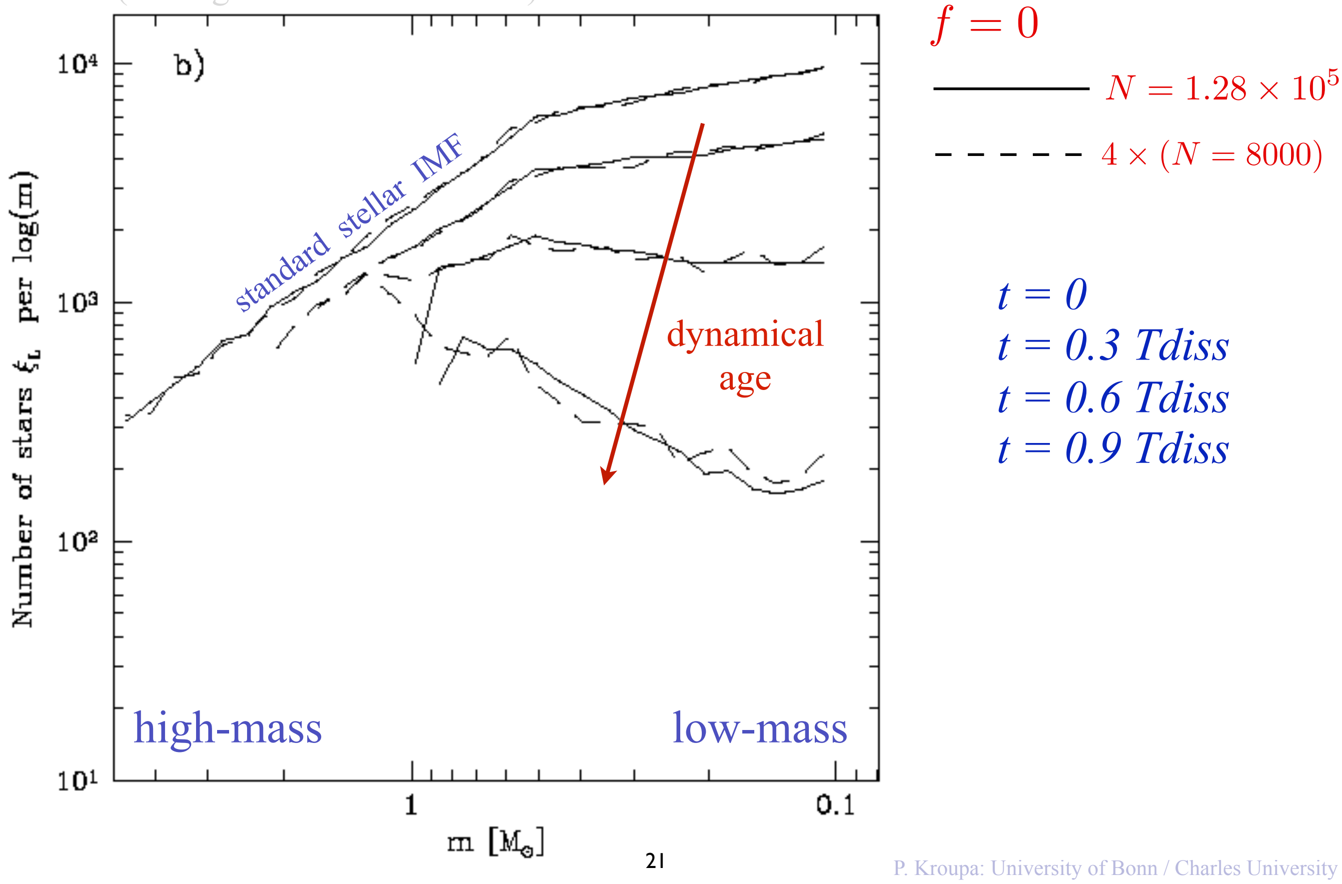
——— $N = 1.28 \times 10^5$

- - - - $4 \times (N = 8000)$

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

# MF(t) due to cluster evolution

(Baumgardt & Makino 2003)





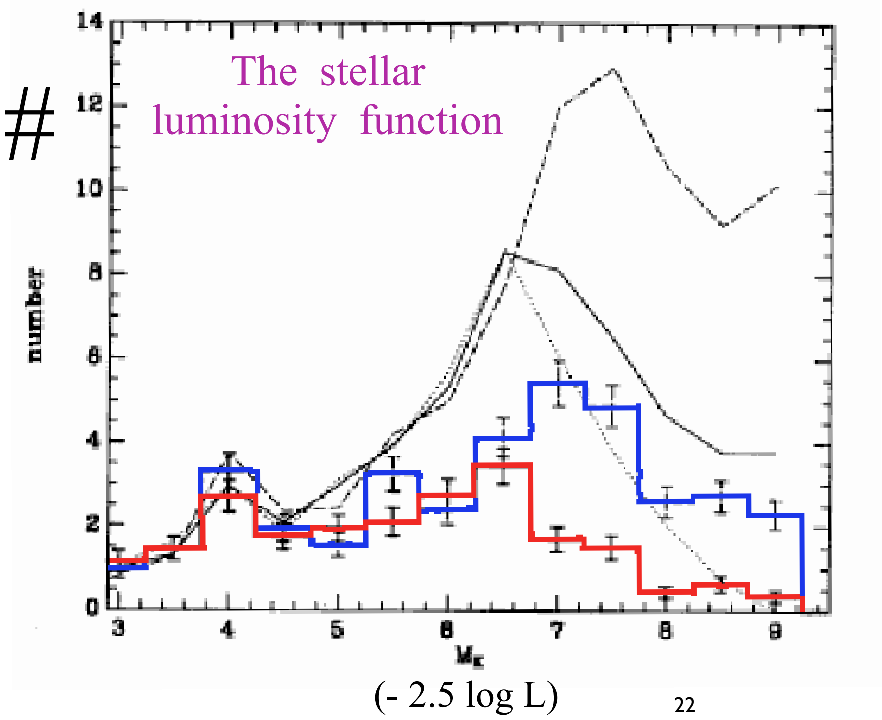



# N-body Models of Binary-Rich Clusters

(Kroupa 1995)

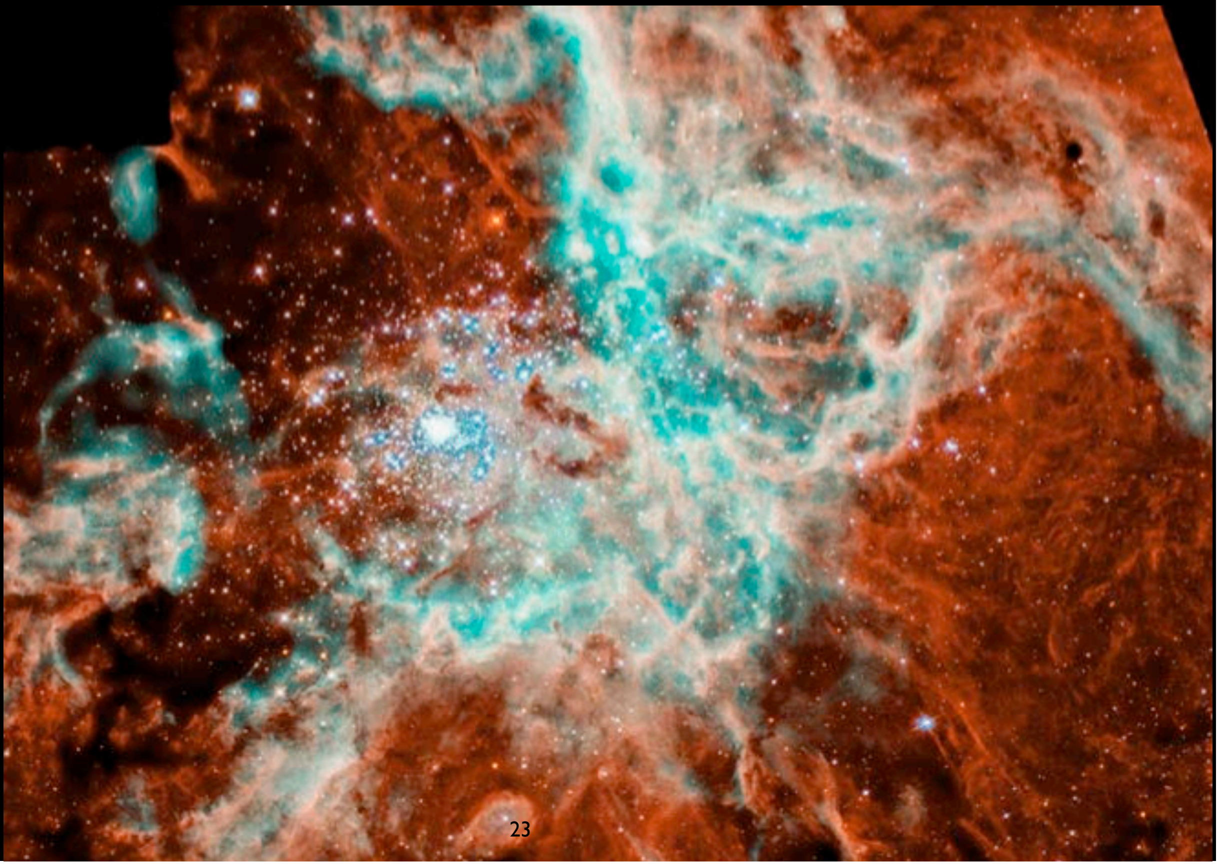
$20 \times (N = 400\,\text{stars})$

$f = 1$




$\xi_{\text{obs}}(m) \neq \xi_{\text{true}}(m)$

## Massive stars in very young clusters





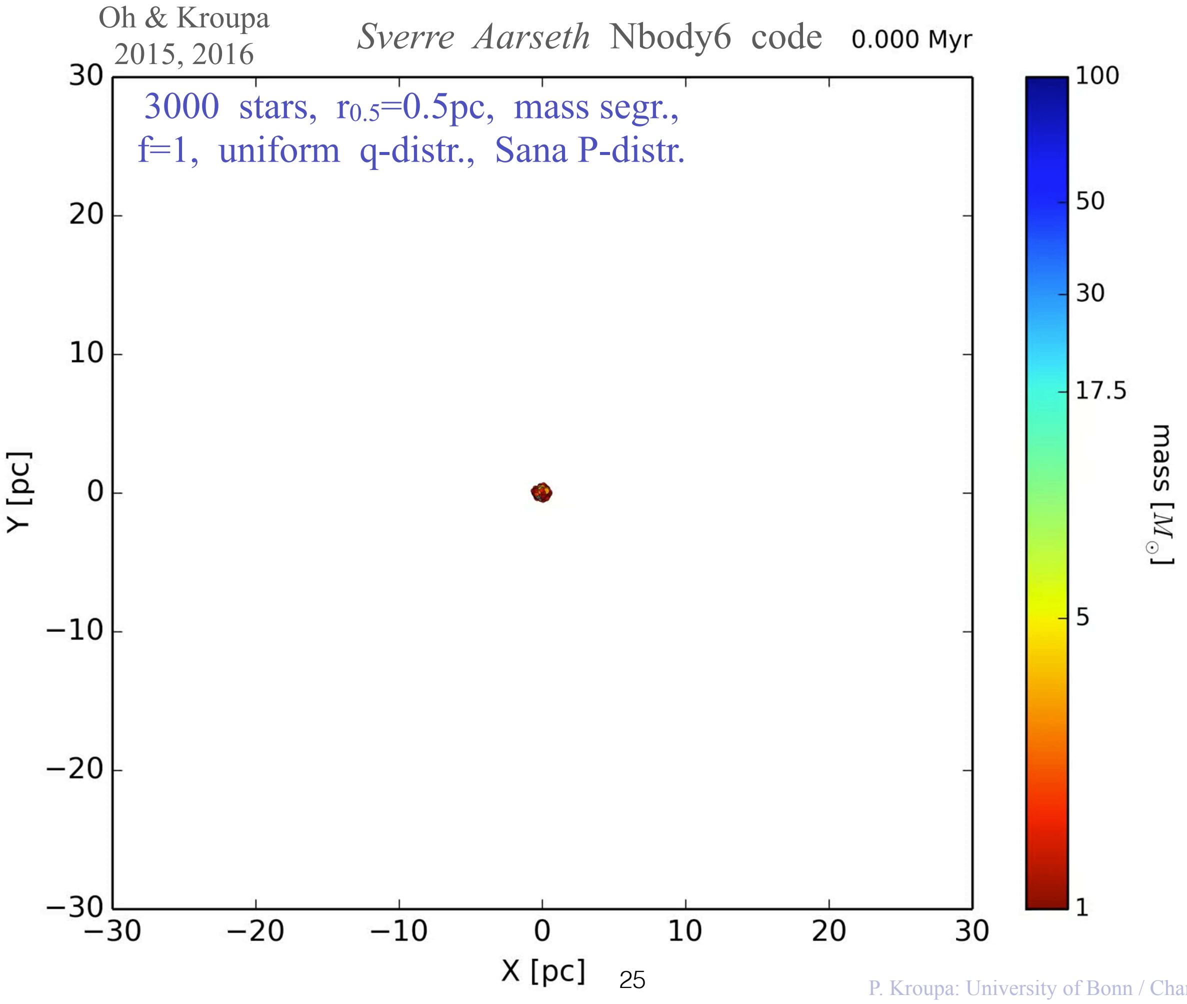
# *OB stars in clusters / HII regions*

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 |

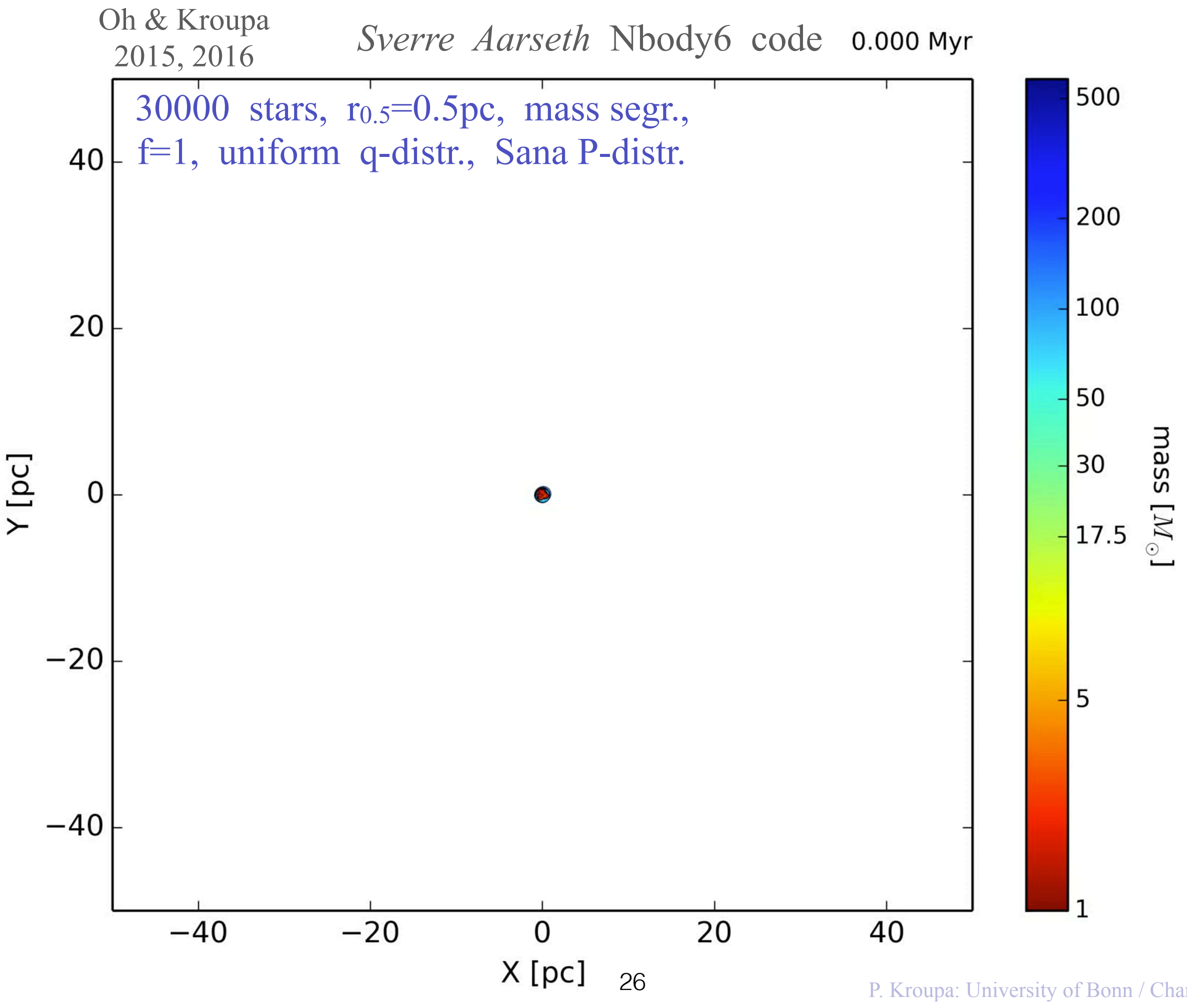
| | |
|---|---|
| ***Core decay*** $$t_{\rm decay} \approx N_{\rm m} \times t_{\rm core,cross}$$ $$t^{\rm core}_{\rm cross} \approx 5 \left(\frac{M^{\rm core}}{100\, M_\odot}\right)^{-\frac{1}{2}} \left(\frac{R^{\rm core}_{0.5}}{1\,{\rm pc}}\right)^{\frac{3}{2}}$$ | ***e.g.*** $R_{\rm core} \approx 0.02\,{\rm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

(Pflamm-Altenburg & Kroupa 2006)





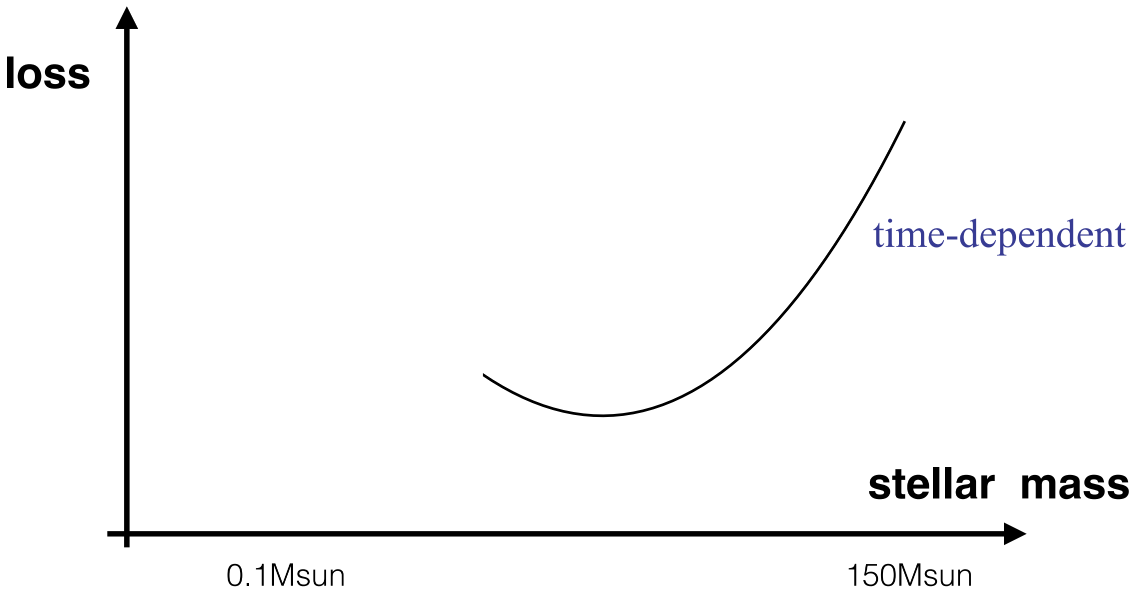

P. Kroupa: University of Bonn / Charles University






P. Kroupa: University of Bonn / Charles University

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

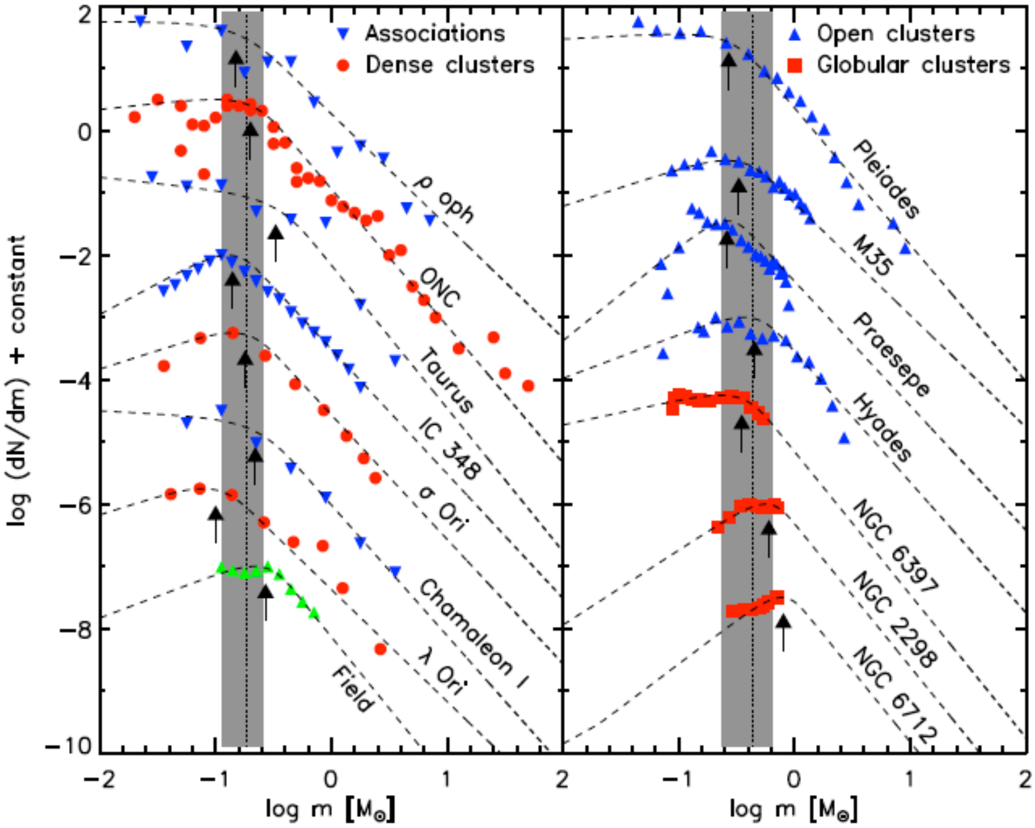







**Thus, stellar-dynamical processes**
**are**
**extremely important**
when determining the IMF shape!!

Bastian et al. 2010




**The IMF appears largely invariant** (in MW CSFEs / embedded clusters)

Kroupa 2001, 2002

Bastian, Covey, Meyer, 2010, ARAA

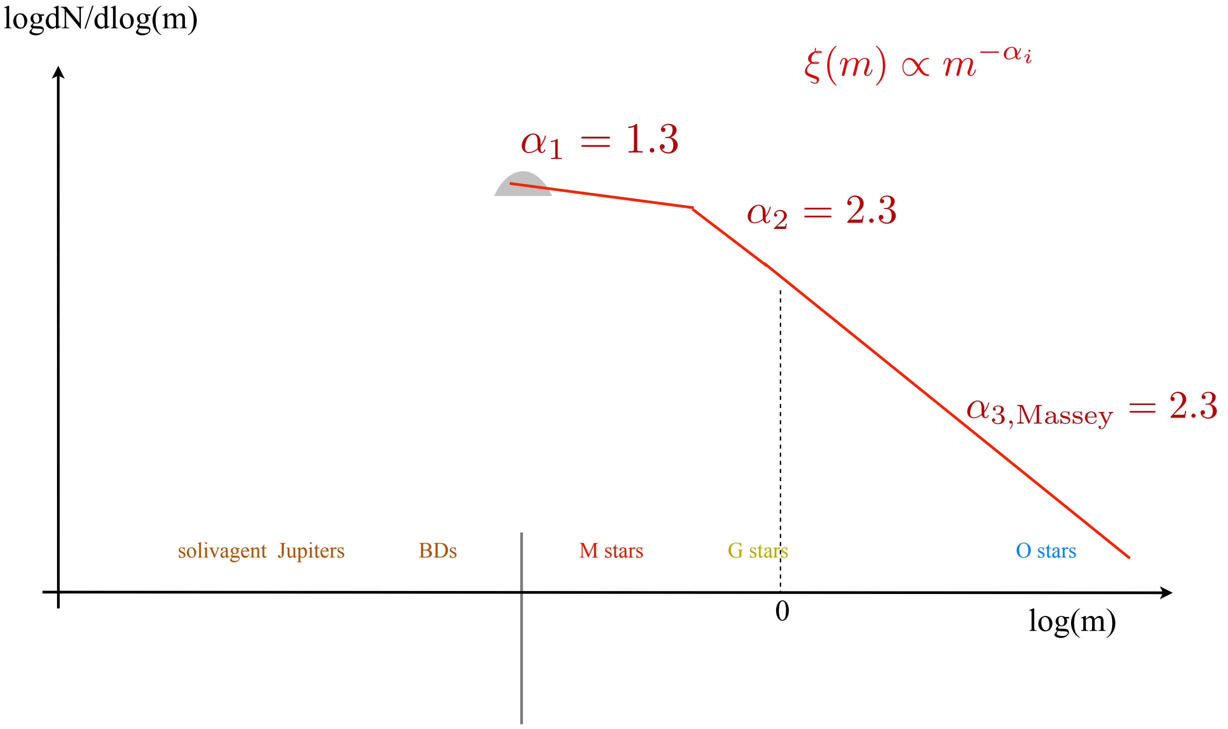
Kroupa et al., 2013

Offner et al., 2014, PPVI



# The invariant canonical IMF

***the canonical IMF*:**

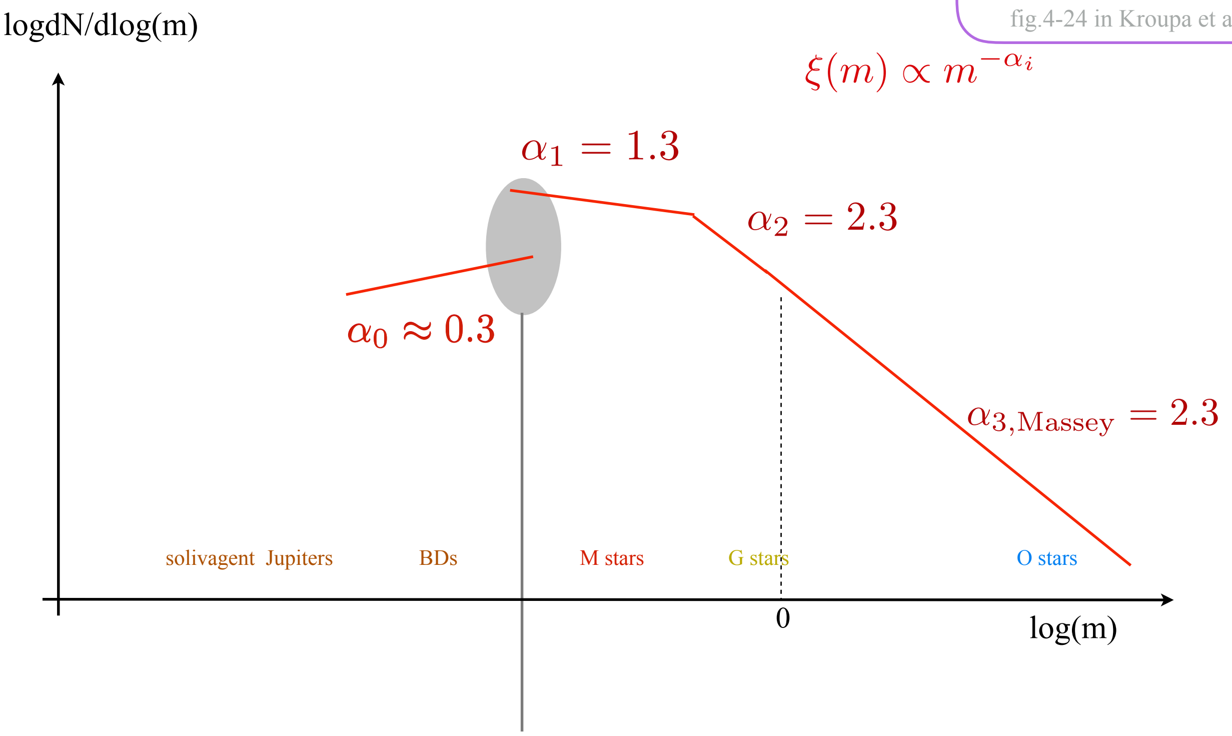



discontinuity: Thies & Kroupa (2007, 2008), Parker & Goodwin (2010)



***the canonical IMF*:**

Rederived later by Chabrier
---
essentially identical result to the canonical IMF
fig.4-24 in Kroupa et al. 2013



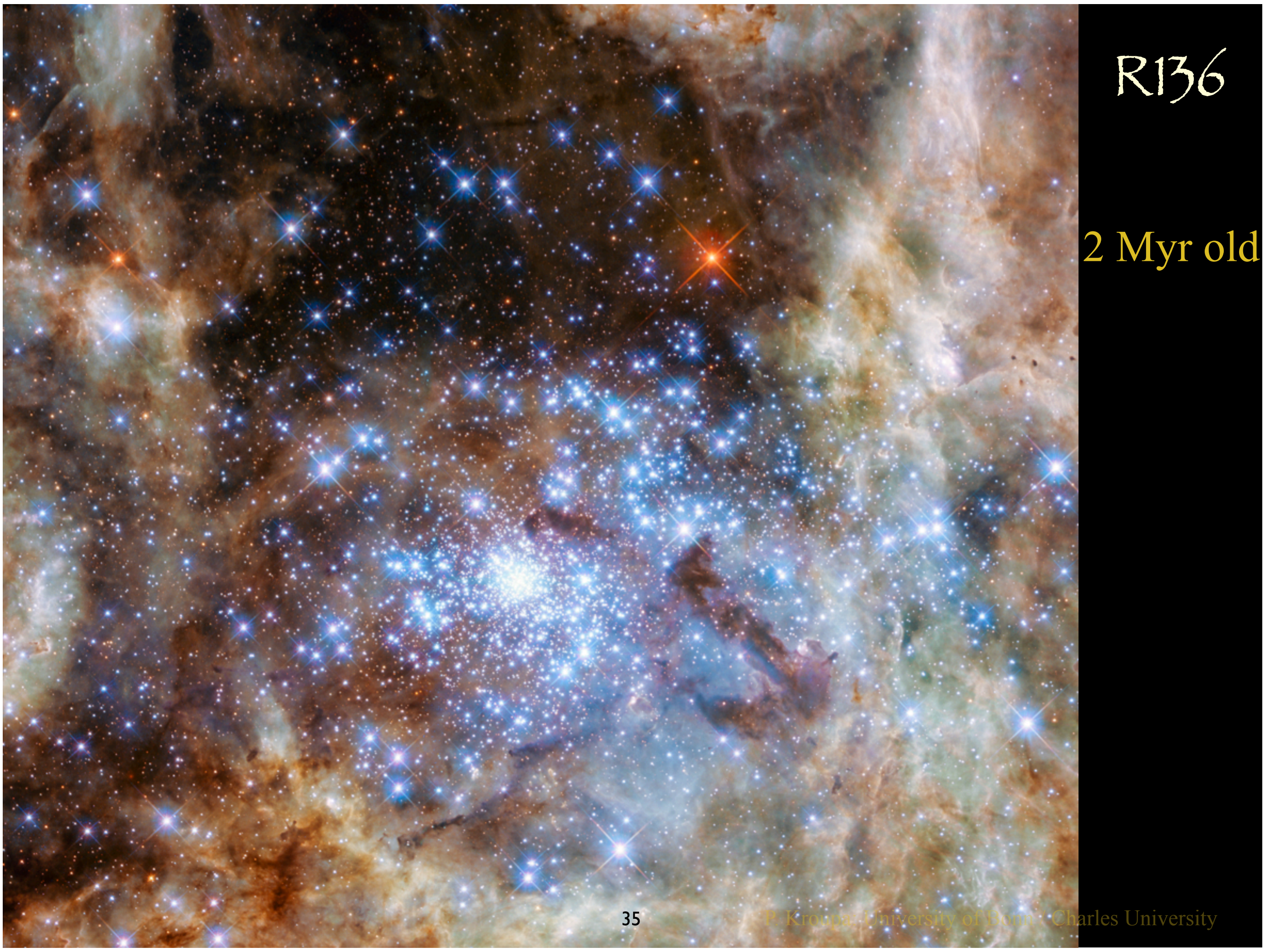

discontinuity: Thies & Kroupa (2007, 2008), Parker & Goodwin (2010)

# Hints towards a variable IMF




Some subtle hints for a systematically varying IMF
are available at high masses

**Star-counts:** Correct star-counts in R136 for ejected stars




## Some subtle hints for a systematically varying IMF are available at high masses

**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)

GCs in M31: more top-heavy IMF at lower metallicity
(Zonoozi et sl. 2016; Haghi et al. 2017)

## *What we know from observation :*

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

→ disagrees with dynamical evolution (Marks et al. 2012)





# *GCs*
# *(extreme star burst "clusters")*

**gas expulsion**

**+**

**mass segregation**

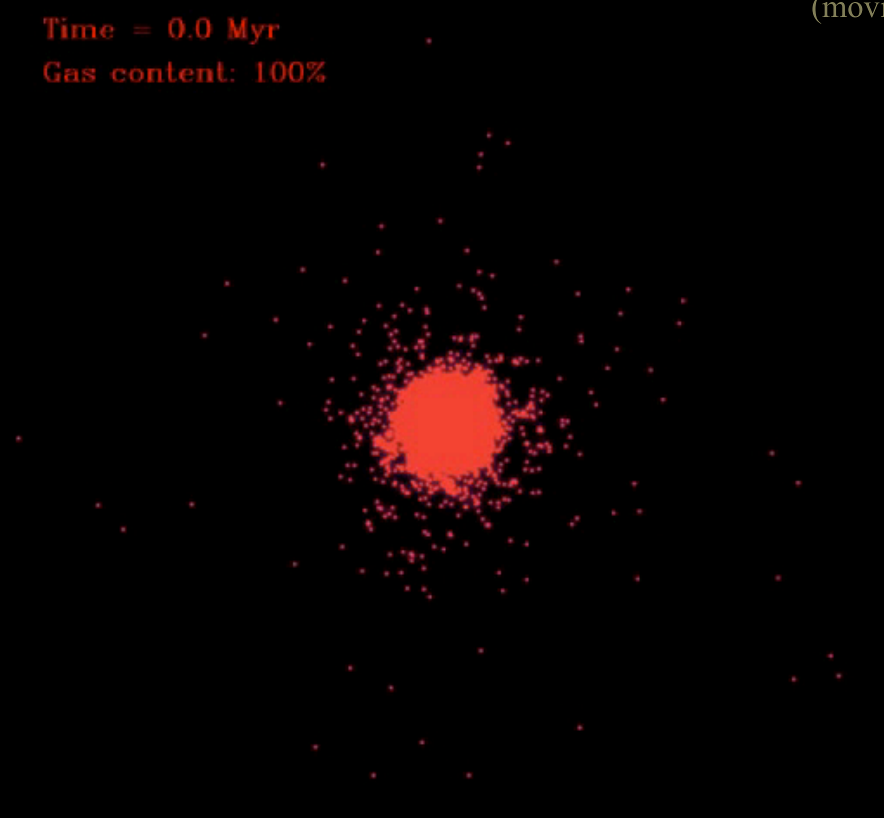
**!**





## *Cluster reaction to thermal gas removal :*

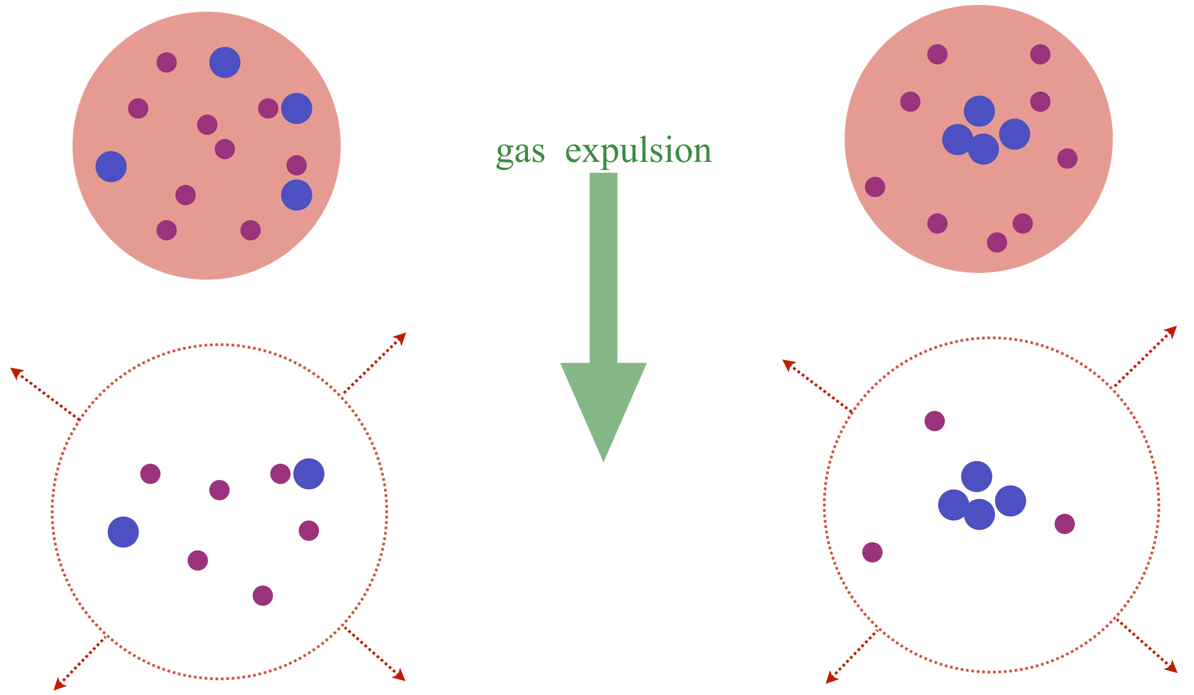
(movie by Baumgardt)




Baumgardt & Kroupa 2007

## *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



## *What we know from observation :*

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

→ disagrees with dynamical evolution (Marks et al. 2012)
(need gas expulsion from mass-segregated clusters)

UCDs : higher dynamical M/L ratios (Dabringhausen et al. 2009)

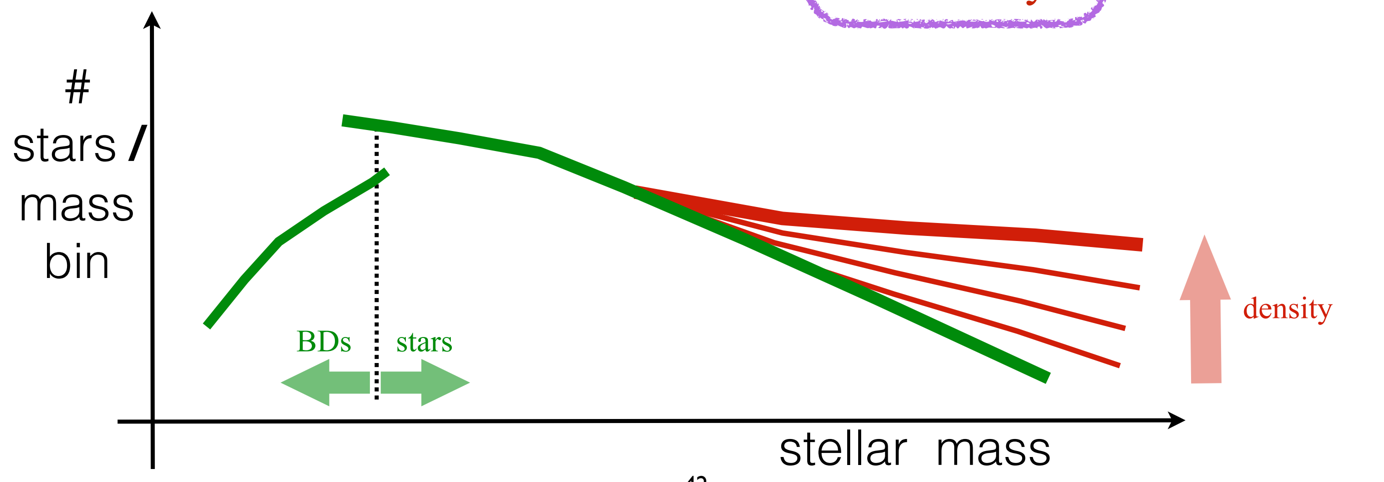
→ cannot be exotic dark matter

UCDs : larger fraction of X-ray sources than expected (Dabringhausen et al. 2012)

→ no explanation other than many remnants

mutual consistency !!

## *What this implies :*



Thus

IMF = IMF($Z$, $SFRD$)

$Z$=metallicity, $SFRD$=star-formation rate density





## 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 $\alpha_3$ on cluster-forming cloud density, $\rho$, (stars plus gas) and metallicity, [Fe/H],can be parametrised as

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

Z

Marks et al. 2012
Kroupa et al. 2013

Top-heavy IMF
and
"quasars"
a la
Tereza Jerabkova



***UCDs*** ( = Hilker objects)

***(extremely extreme star burst "clusters")***

# *Properties of ultra compact dwarf galaxies (UCDs)*

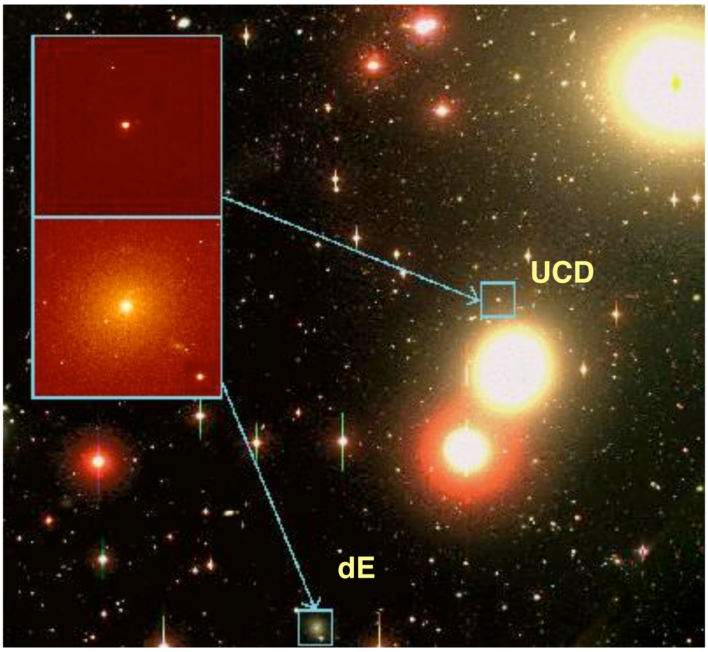



Image by M. Hilker

UCDs occur mostly in galaxy clusters





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


Image from ESO

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

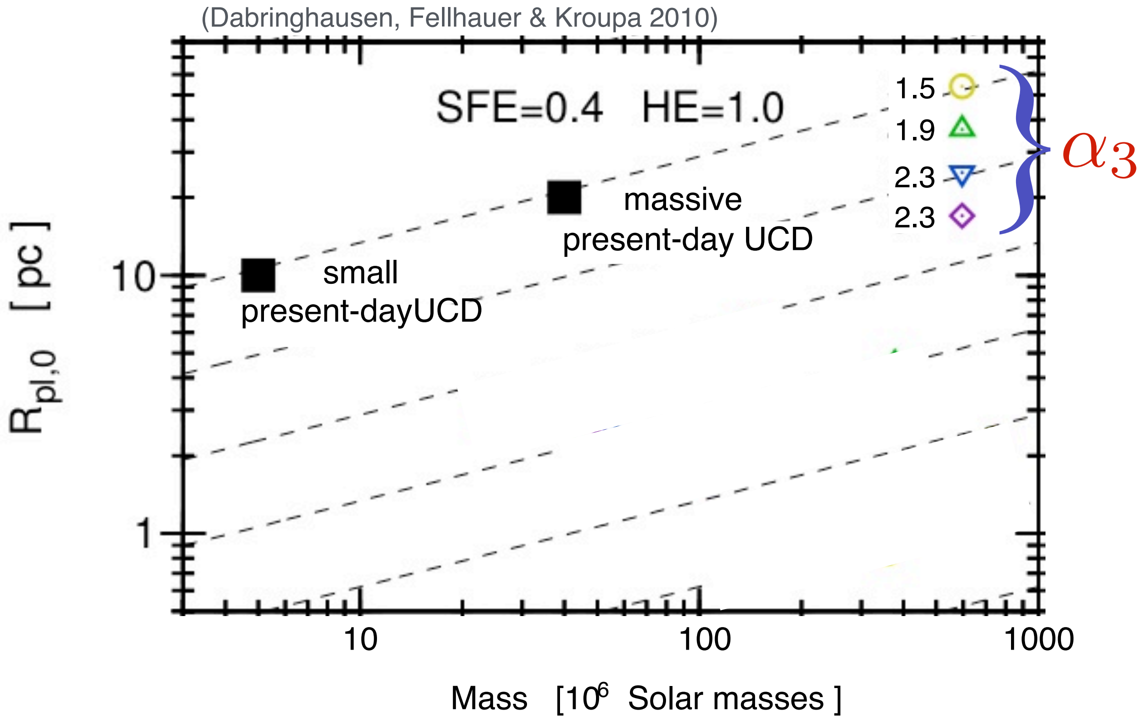
Perform N-Body simulations of UCDs with mass-loss through gas expulsion and stellar evolution

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*



## *Can this IMF variation be confirmed?*

---> probe conditions at high redshift

scouting work by

*Tereza Jerabkova*

**ESO student of the year**

with ESO staff of the year

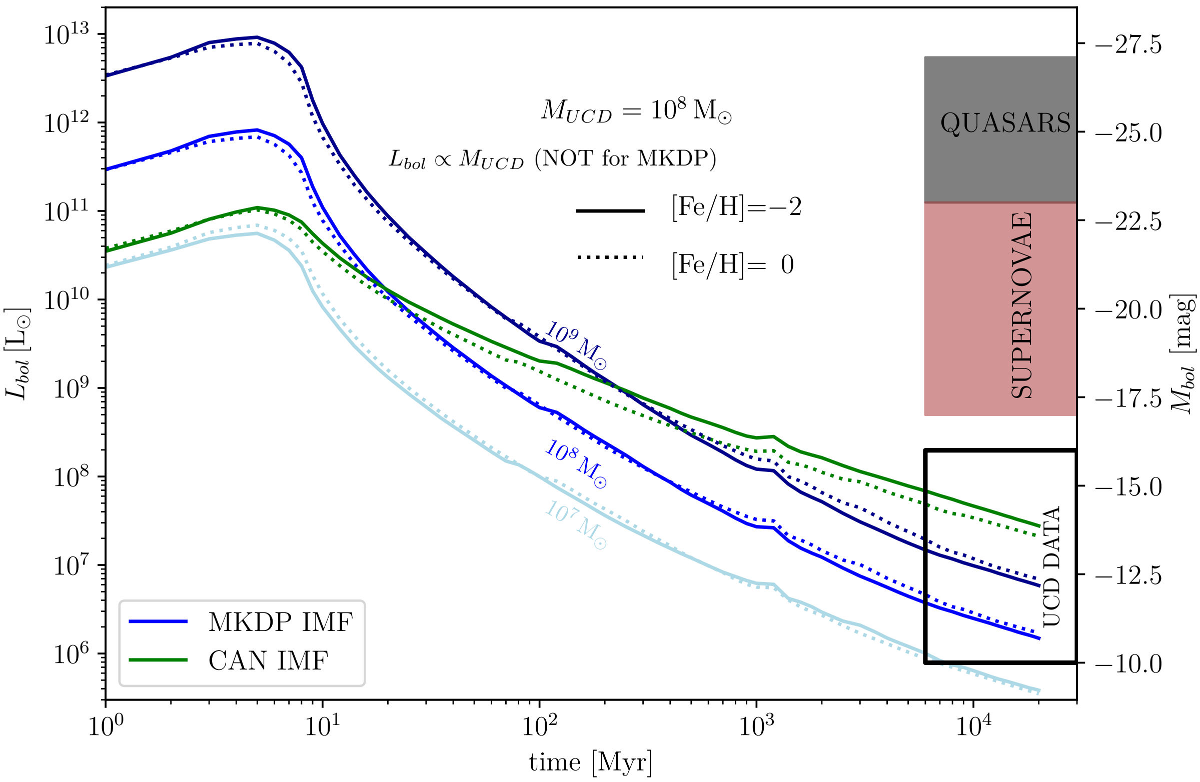
(Chris Harrison and Michael Hilker)

*ESO Annual Report 2018*

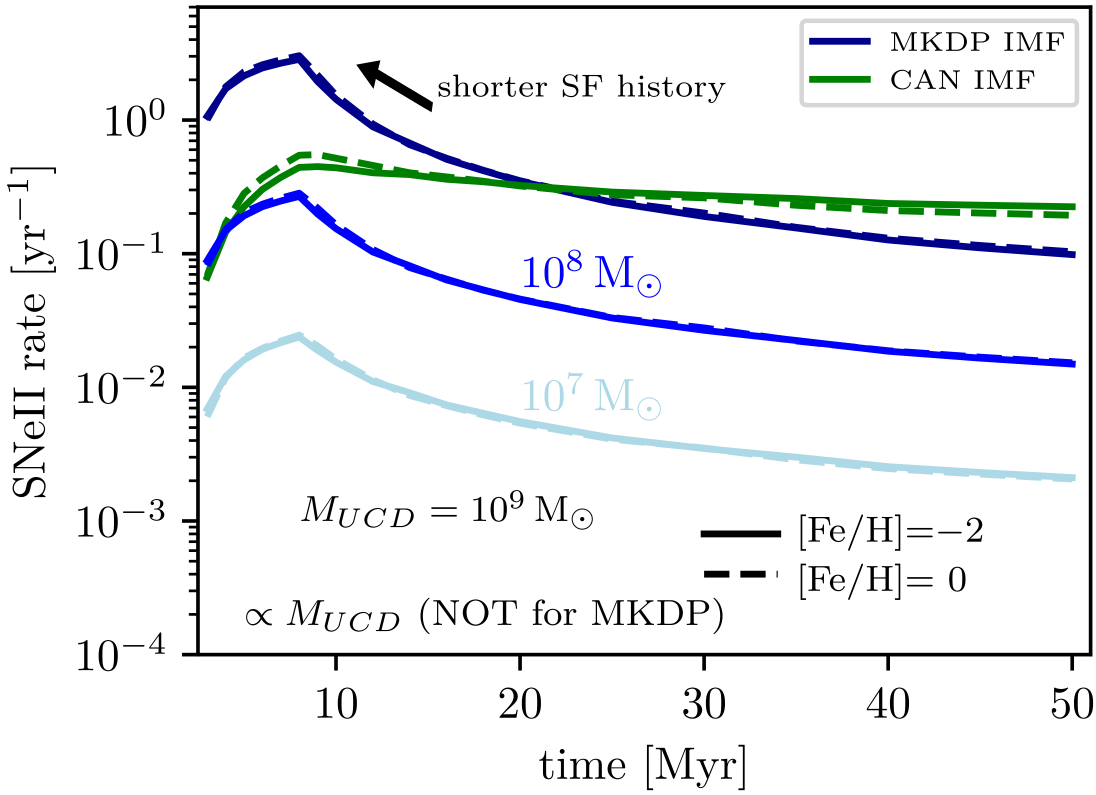


## ===> Quasar-like objects   Jerabkova et al. 2017

The redshift dependent photometric properties are calculated as predictions for *James Webb* Space Telescope (JWST) observations.



Jerabkova et al. 2017








# Conclusions

The IMF is not observable (it is a mathematical "hilfsconstruct")

This hilfsconstruct is not a probability distribution function.

Significant evidence that the IMF varies with Z and rho.

The galaxy-wide IMF (the gwIMF) changes with SFR,
as expected.

Testbed: extremely star-bursting clusters (UCDs) at high-z.

**Are some/most quasars at very high z merely young UCDs ?**

Jerabkova et al. 2017