Stellar populations and star clusters as galactic building blocks

Lecture 1

Derivation of the IMF
Expected variations

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

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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

Knowing how many stars
and of which type are born
is the pre-requisite
to understanding the formation
of structure in matter.

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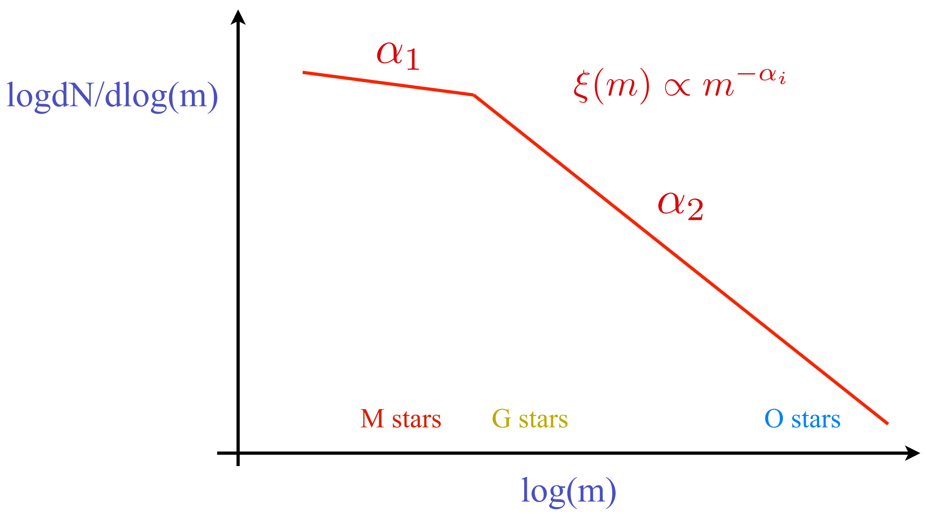
IMF = the distribution of stellar masses born together.

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



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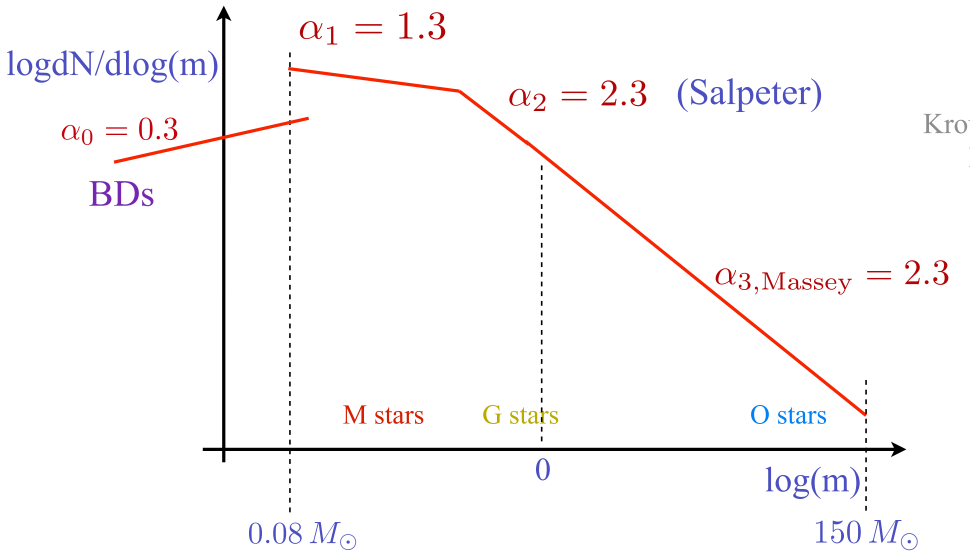
canonical / standard / universal

two-part power-law stellar IMF :

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



Kroupa et al. 2013
IMF Review

Why is the stellar Initial Mass Function (IMF) important ?

To know how much dark mass is in faint stars

To understand the matter cycle

To understand how shining-matter is distributed

As a boundary condition for star-formation theory

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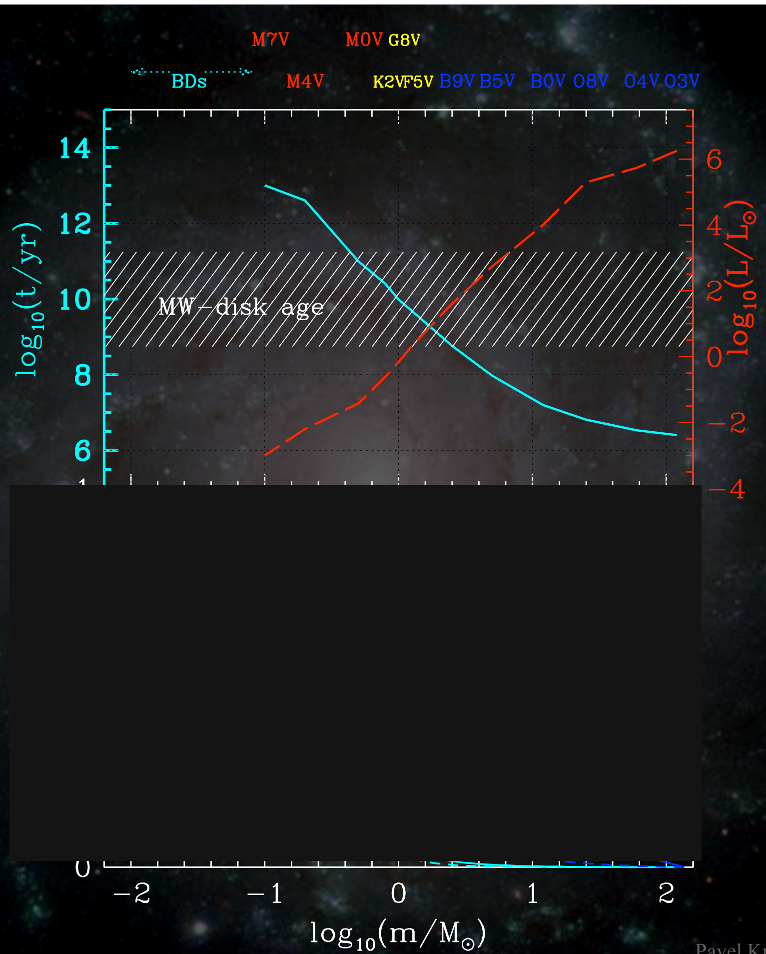

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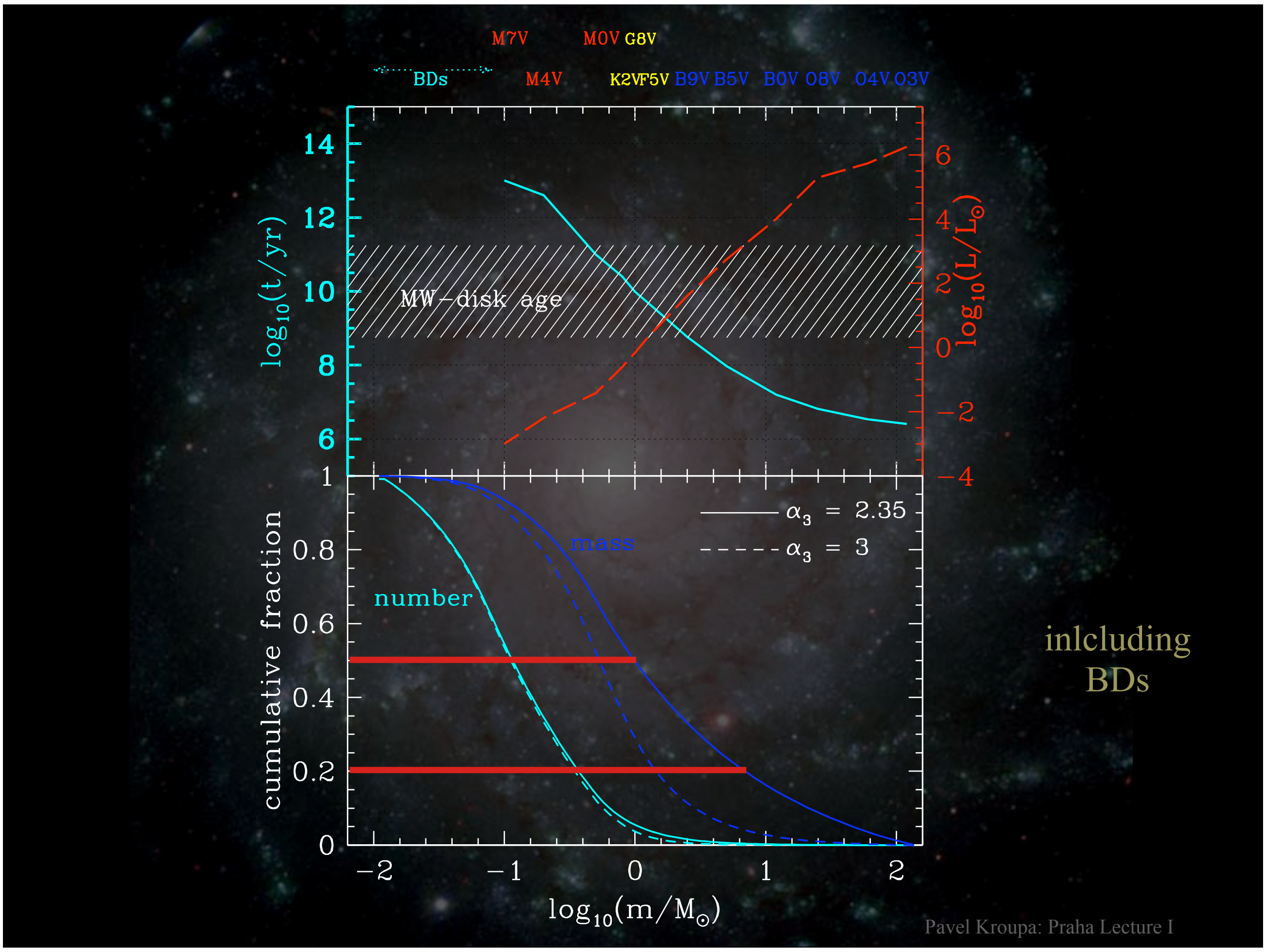

O star

$N = 1$stars

$M = 63\, M_\odot$
$L = 10^6\, L_\odot$
$\tau = 10^{6.2}\, yr$

$R = 20\, R_\odot$
$T_e = 35000\, K$

G star

$N = 10^{4.1}$ stars

$M = 1\, M_\odot (= 2 \times 10^{33}\, g)$
$L = 1\, L_\odot (= 3.8 \times 10^{33}\, erg/s)$
$\tau = 10 \times 10^9\, yr$

$R = 1\, R_\odot (= 7 \times 10^{10}\, cm)$
$T_e = 5000\, K$

M star

$N = 10^{5.5}$ stars

$M = 0.15\, M_\odot$
$L = 10^{-2.5}\, L_\odot$
$\tau > 10^{11}\, yr$

$R = 0.20\, R_\odot$
$T_e = 3300\, K$

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1 000 000 M stars combine to

100 000 $M_\odot$ but only

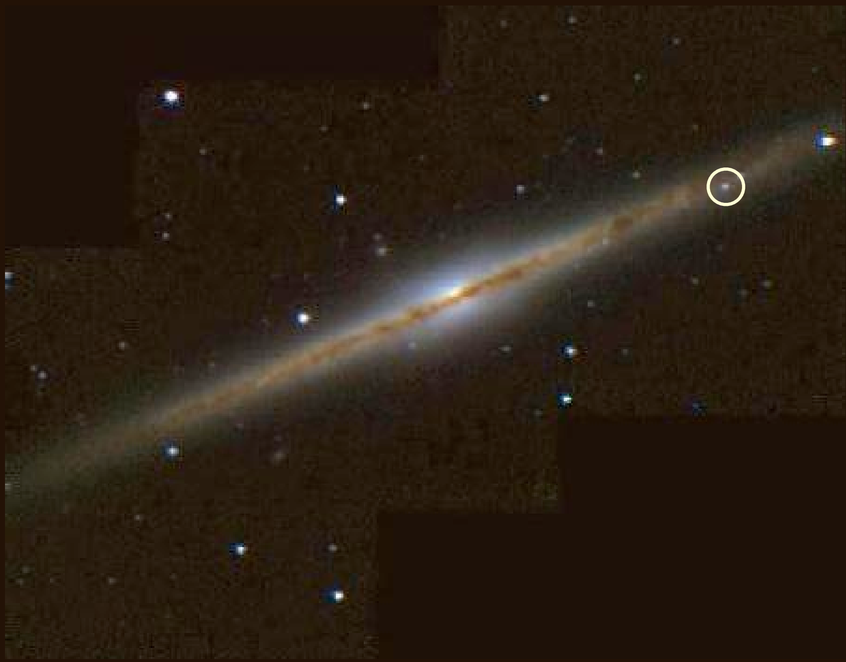
$10^{3.5}\,L_\odot \ll L_{\rm O\ star}$

One O star ($60\,M_\odot$) out-shines 10^8 M stars ($10^7\,M_\odot$).

From these numbers it becomes immediately apparent that it is of much importance to know the shape of the IMF below about $1\,M_\odot$

This forces us to
count the stars
in our
immediate solar neighbourhood.

The solar neighbourhood



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The distribution of stars

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 $m \in [m, m + dm]$

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

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

the **observable** the **target**

the **obstacle**

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

I. Count stars nearby to Sun (within 5 pc for M dwarfs; 20 pc for G dwarfs)

Obtain M_V and d from trigonometric parallax

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

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

I. Count stars nearby to Sun (within 5 pc for M dwarfs; 20 pc for G dwarfs)

Obtain M_V and d from trigonometric parallax

$\longrightarrow$ Well observed individual stars but *small numbers at faint end* (Ψ_{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

$\longrightarrow$ Large # of stars but *poor resolution* (2”-3”) and *Malmquist bias* (Ψ_{phot})

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

(Bahcall 1984)

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

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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

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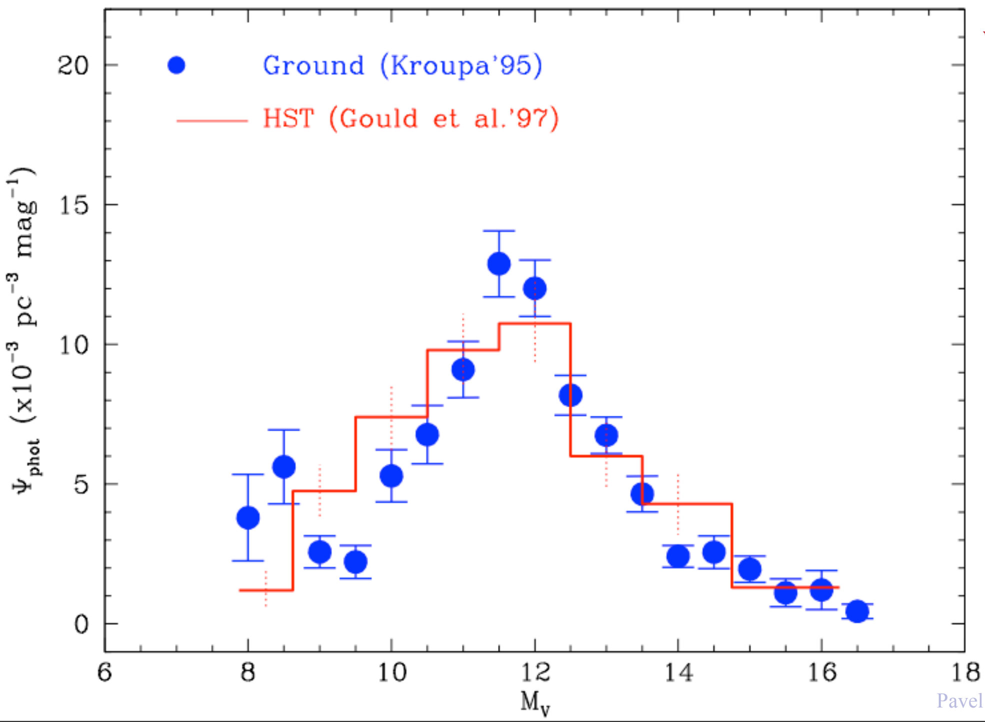
Ψ_{phot} { - independent of direction
- maximum (peak) at $M_V \approx 12$



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

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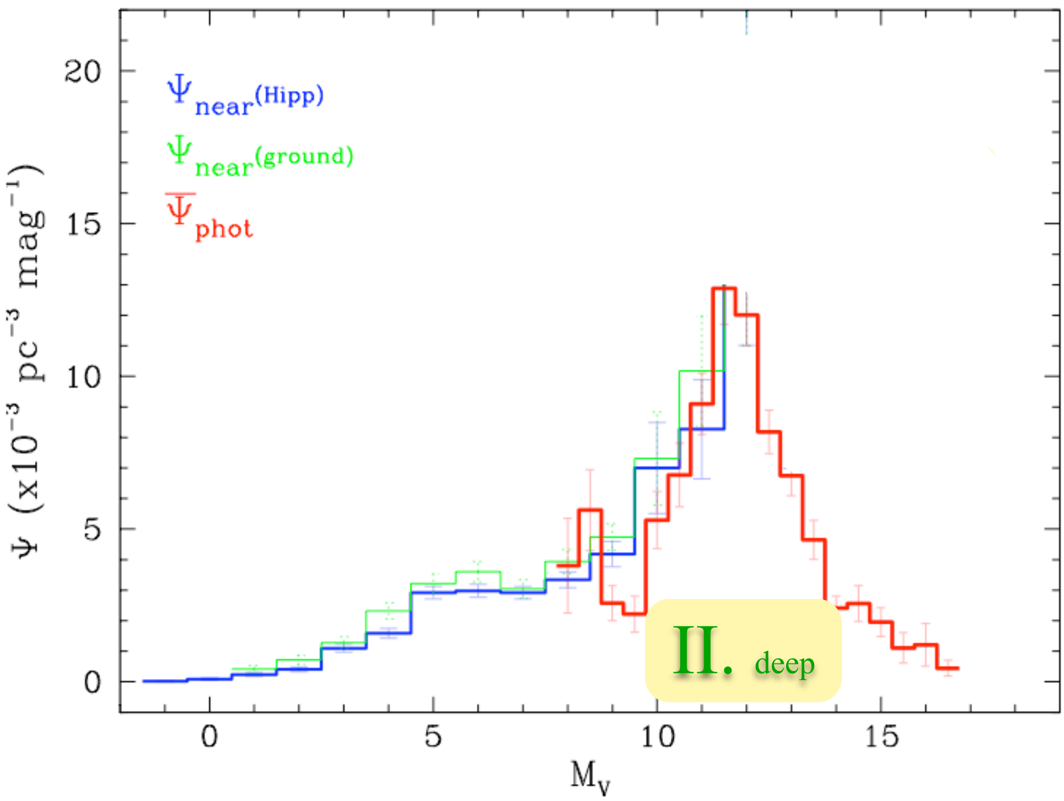
Two solar-neighbourhood samples:

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



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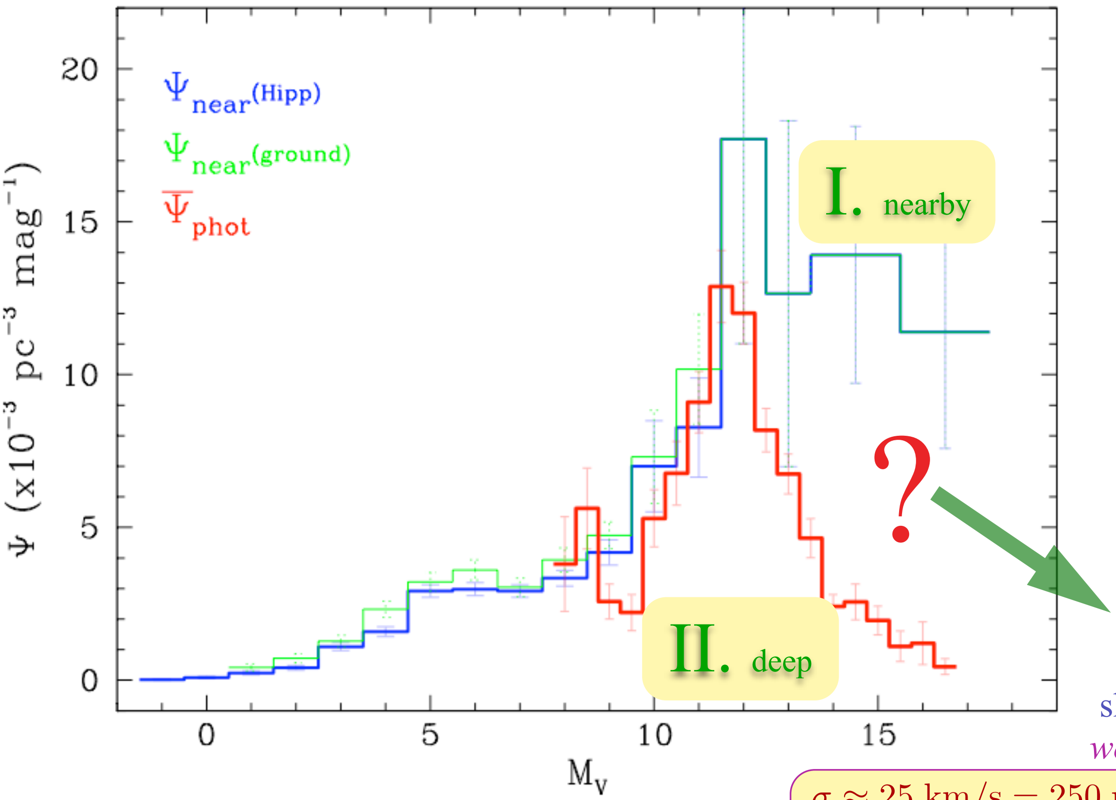


Stellar samples should be *well-mixed*:

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

So . . . who thought merely counting stars is boring ?

Problem :

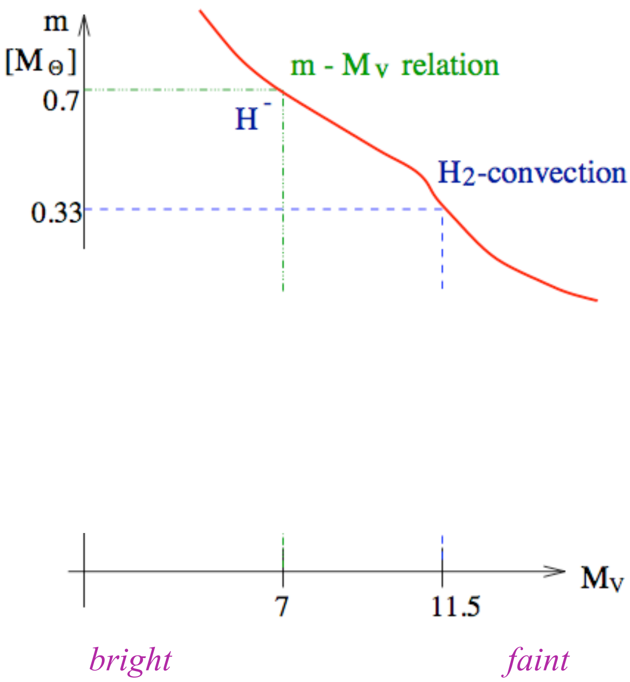
The nearby and deep LFs are not equal.

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

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

Understand ***detailed shape*** of LF from fundamental principles :

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



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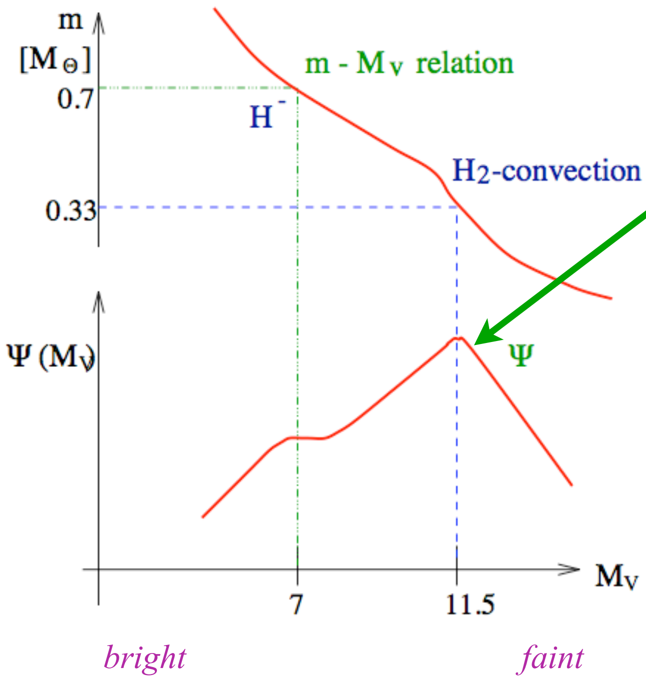

Kroupa, Tout & Gilmore 1991

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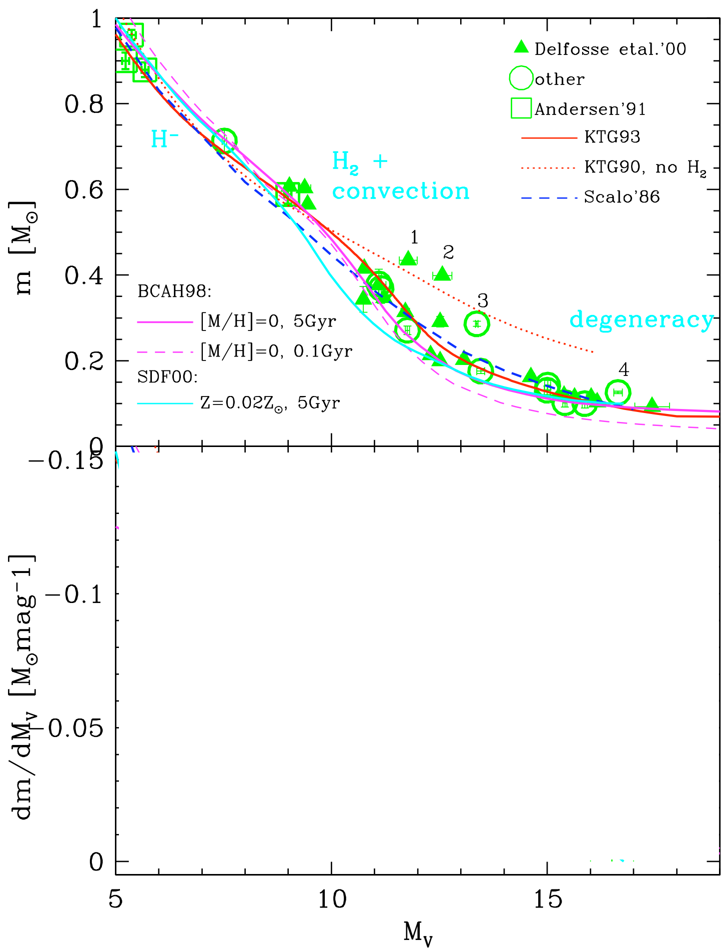

The mass-luminosity relation of low-mass stars

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

Kroupa, 2002, *Science*

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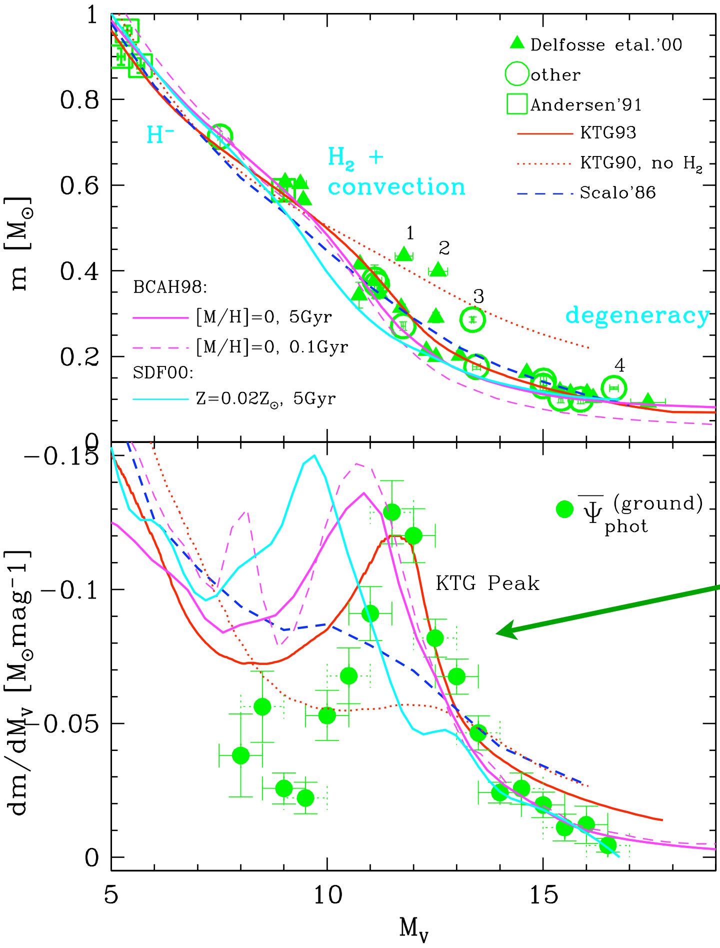

The mass-luminosity relation of low-mass stars

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

1. position
2. width
3. amplitude

all agree !

Kroupa, 2002, *Science*

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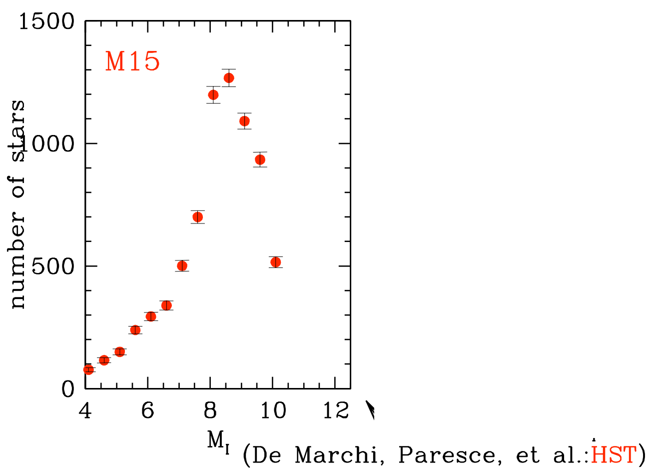

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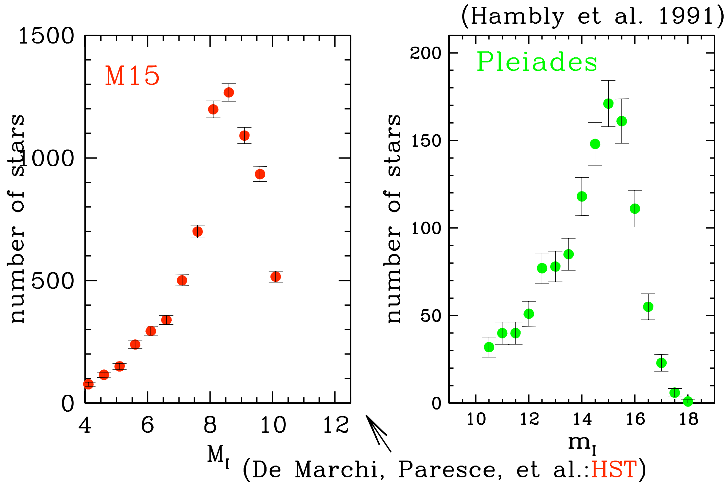

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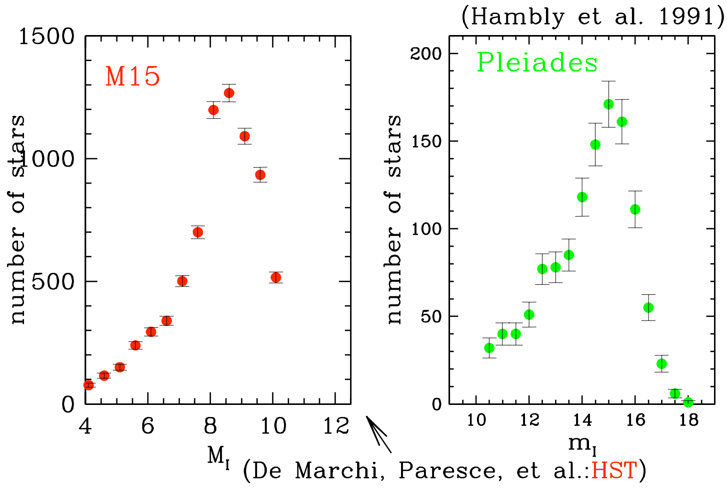

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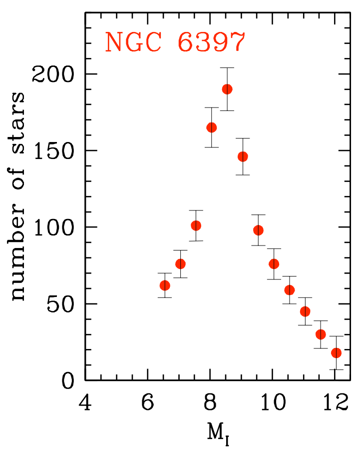

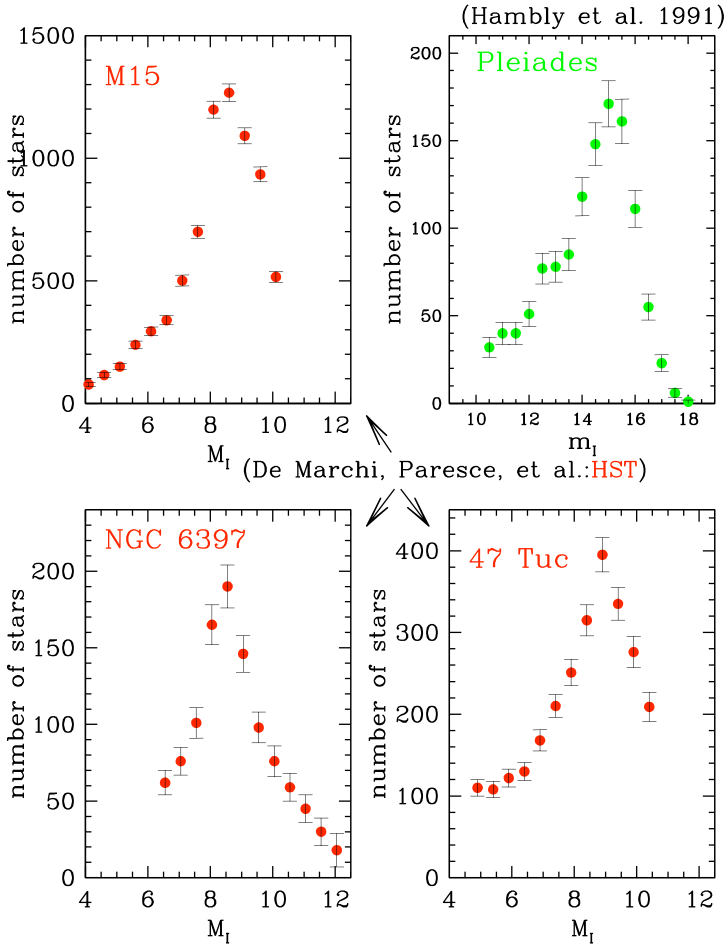

$$\Psi(M_V) = -\frac{dm}{dM_V}\,\xi(m)$$

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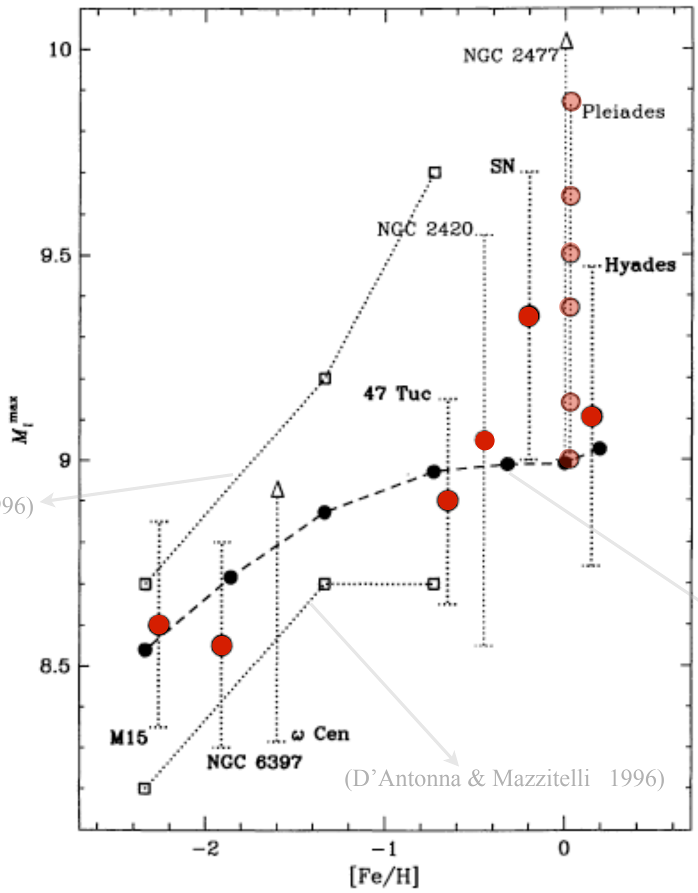
Location of the maximum of the LF with [Fe/H]



(van Hippel, Gilmore et al. 1996;

Kroupa & Tout 1997)

(D'Antonna & Mazzitelli 1996)

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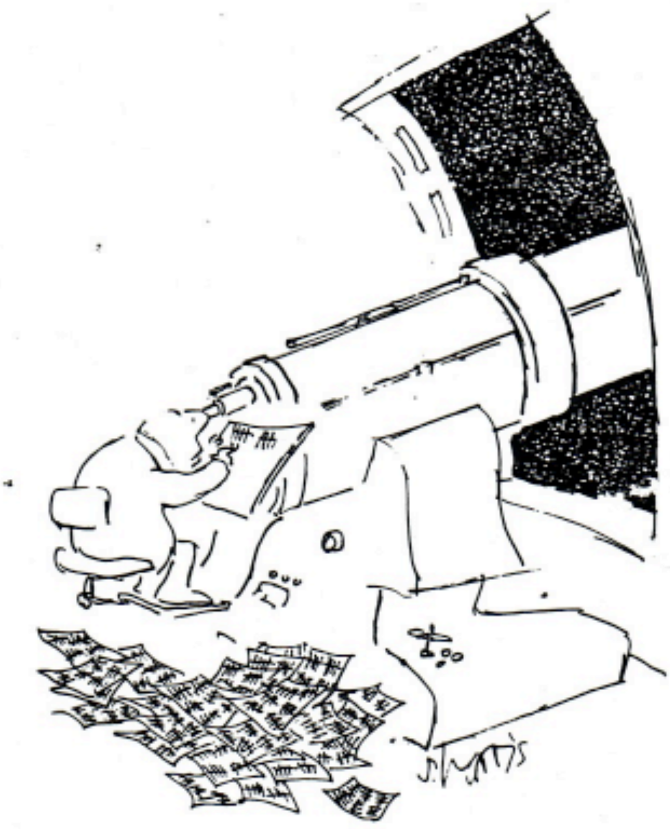
The maximum near

$M_{\rm V} \approx 12; \; M_{\rm I} \approx 9$

is universal

and well understood.



By counting the stars
on the sky
we look into
the constitution
of their interiors !

The maximum near

$M_V \approx 12;\ M_I \approx 9$

is universal

and well understood.

But we are still trying to understand the

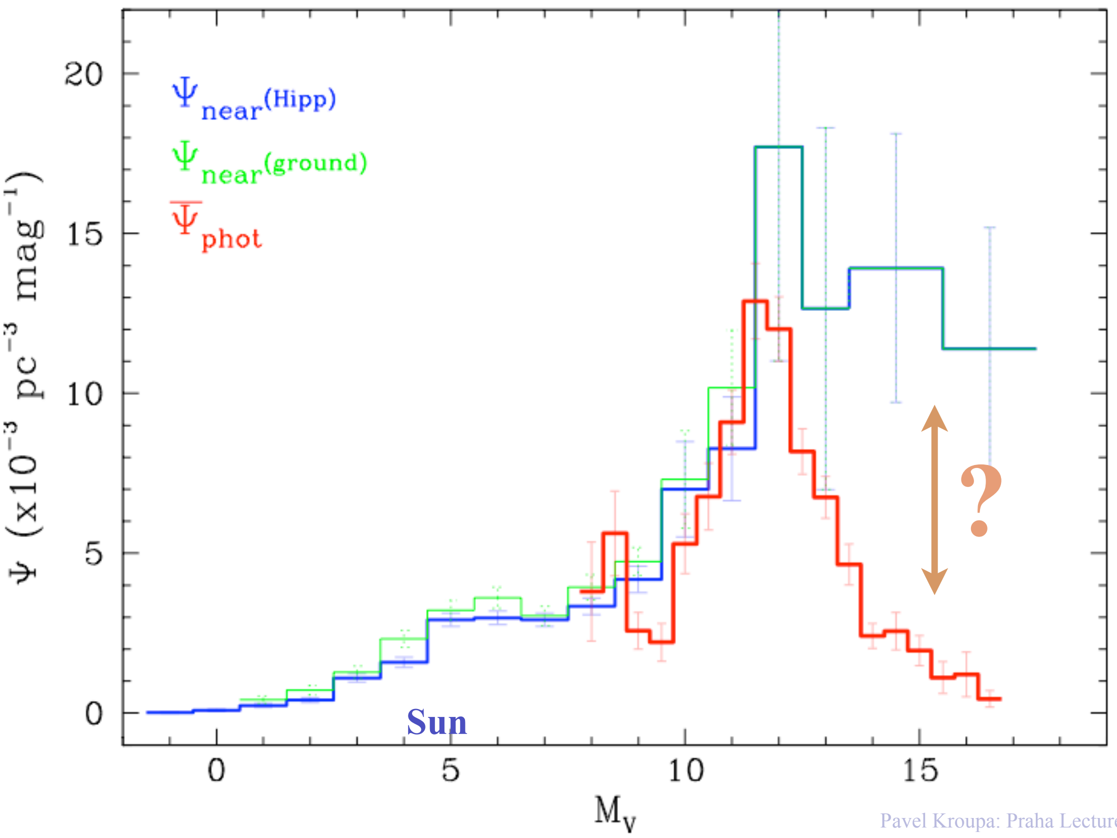
Problem :

the local LF discrepancy...

Two solar-neighbourhood samples:

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

. . . understand the peak, but a problem remains . . .



Multiple systems :

Nearby-sample:

- stars are well resolved and
- individually well-scrutinised.

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Multiple systems :

Nearby-sample:

- stars are well resolved and
- individually well-scrutinised.

Distant (pencil-beam) samples:

- poor resolution
- but even if formally resolved, faint companions are missed because
  - differing survey distance limits for primary and companion(s)
  - glare

- unresolved multiples appear closer

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Multiple systems :

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$\longrightarrow$ bias in density estimates

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Multiple systems :

Counting example: Observer sees 100 systems:

unknown is that
- 40 are *binaries*
- 15 are *triples*
- 5 are *quadruples*

$$\longrightarrow \quad f_{\rm mult} = \frac{40+15+5}{100} = 0.60$$

but 85 (= 40 + 2x15 + 3x5) stars are missed.

$\longrightarrow$ *Correct treatment* of this important bias *solves* the LF discrepancy !

(Kroupa, Tout & Gilmore 1991, 1993)

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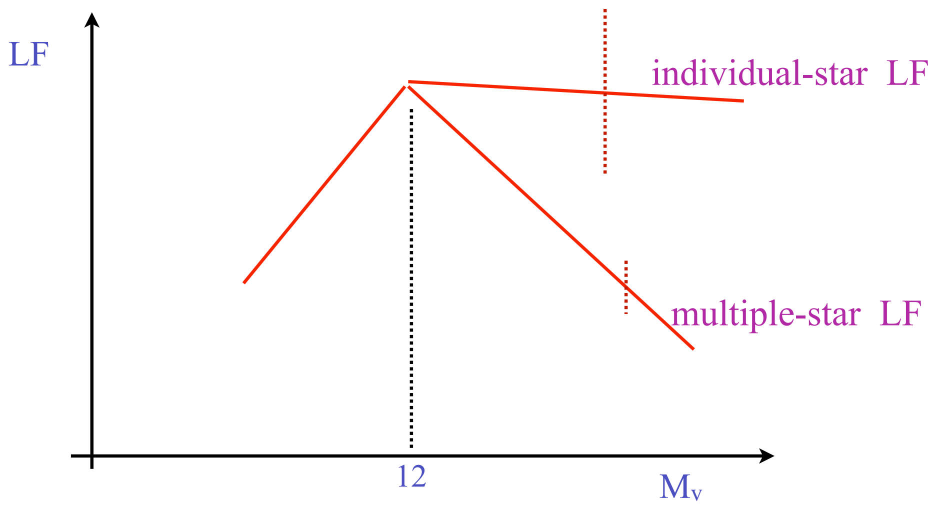
Find the *one* MF
which fits *both* LFs :



get MF directly but large uncertainty

small uncertainty but need info on binaries

We need to perform a
full star-count analysis
by modelling
the spatial distribution of stars, their
masses, multiplicity, ages, metallicities
and luminosities,
as well as the
observational biases and uncertainites.

That is, we make a *model galaxy* in the computer and observe the computer model with computer telescopes and computer survey equipment.

The mass of an isolated star

$$m = f(l, \tau, z, \vec{s})$$

$l =$ primary observable

$\tau = f\,(\mathrm{sfh})$

$z = f\,(M_{\mathrm{gal}}, \mathrm{sfh})$

$\vec{s} = f\,(m, \tau, \text{viewing angle})$

Stars with same l may have different

$\tau,\quad z,\quad \vec{s}$

and thus different m .

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Is there one MF which fits both Ψ_{near} and Ψ_{phot} ?

Model:

1) Cosmic scatter (Malmquist bias), pre-main sequence contraction, main-sequence evolution, SFH, Galactic-disk structure. Each star has m, d, τ, z .

2) A fraction f of systems are *unresolved multiples* with random masses from some pre-defined $\xi(m):\ 0.08 \le m/M_\odot \le 1$.

3) Compute Ψ_{near}, Ψ_{phot} and h for different $\xi(m) \longrightarrow \xi_{\mathrm{best}}(m)$ = “KTG93 IMF”.

(Kroupa, Tout & Gilmore 1990, 1991, 1993; Zheng et al. 2001; Chabrier 1999)

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Dynamical Population Synthesis:

(Kroupa 1995)

Assume all stars form as binaries in typical open clusters:

$R \approx 0.8$ pc, $N \approx 800$ stars

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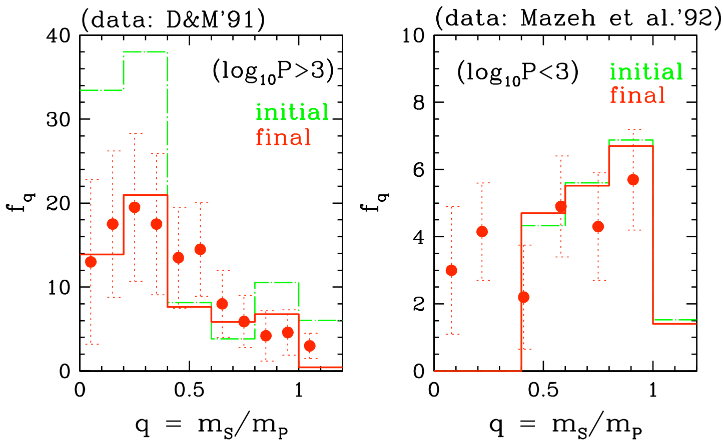

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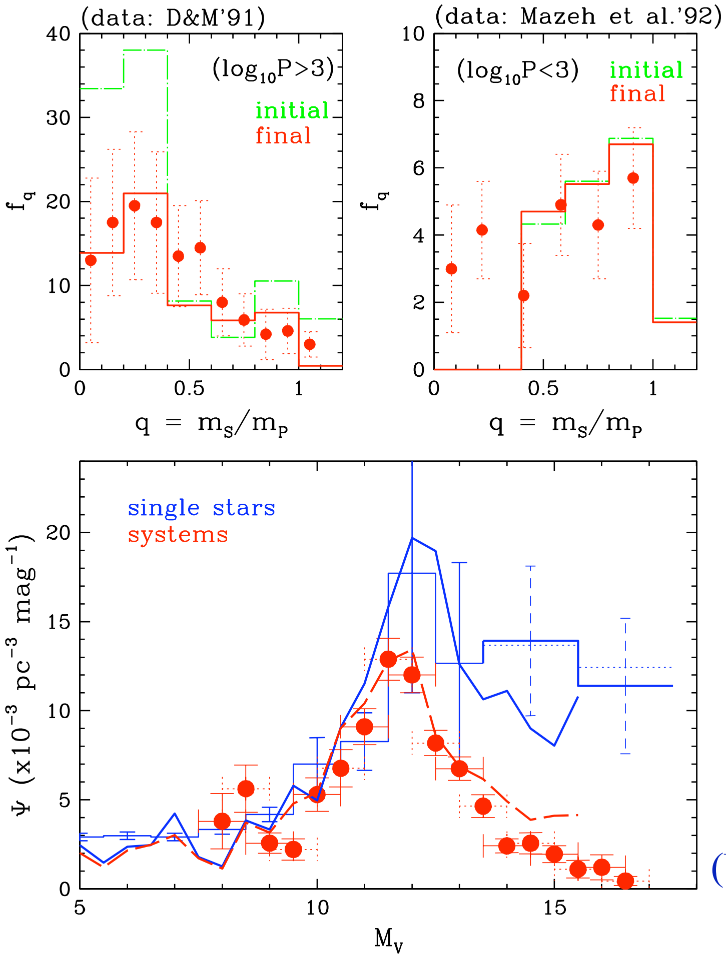


Dynamical Population Synthesis:

(Kroupa 1995)

Assume all stars form as binaries in typical open clusters:

$R \approx 0.8$ pc, $N \approx 800$ stars

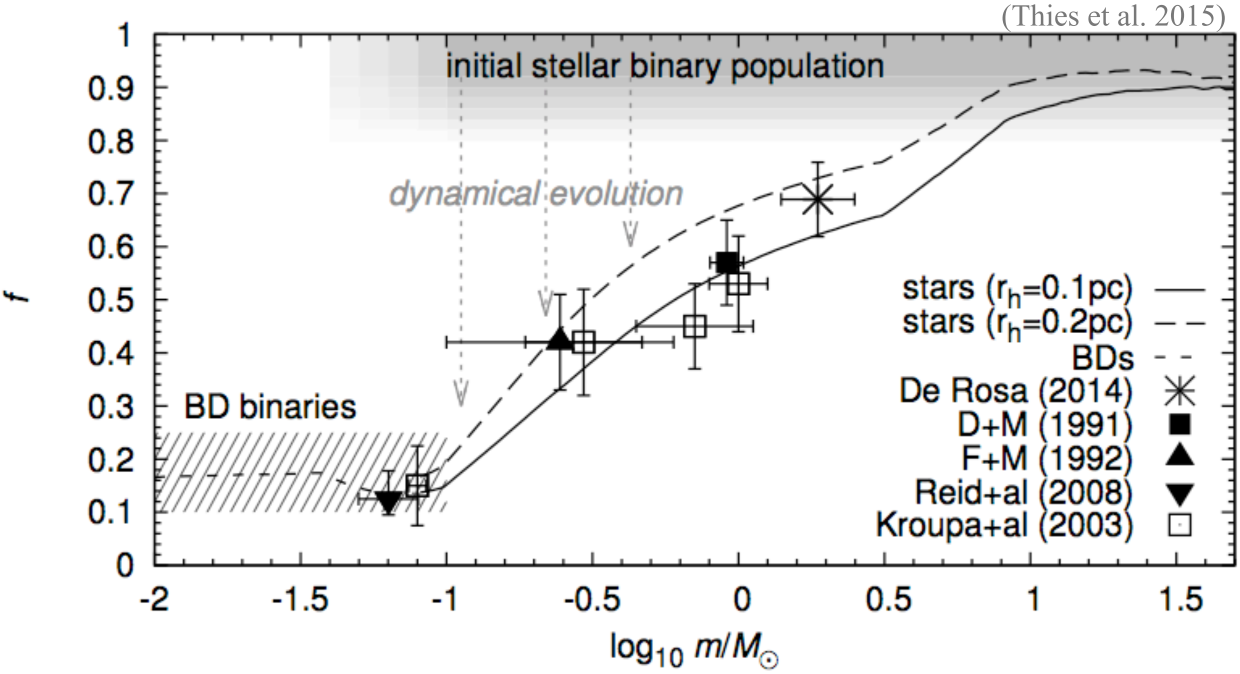
(Using KTG93 MLR)

Binary fraction as a function of *primary mass*:

Compute many cluster models assuming all stars are born in binaries.
The clusters evaporate their stars which become the Galactic field.

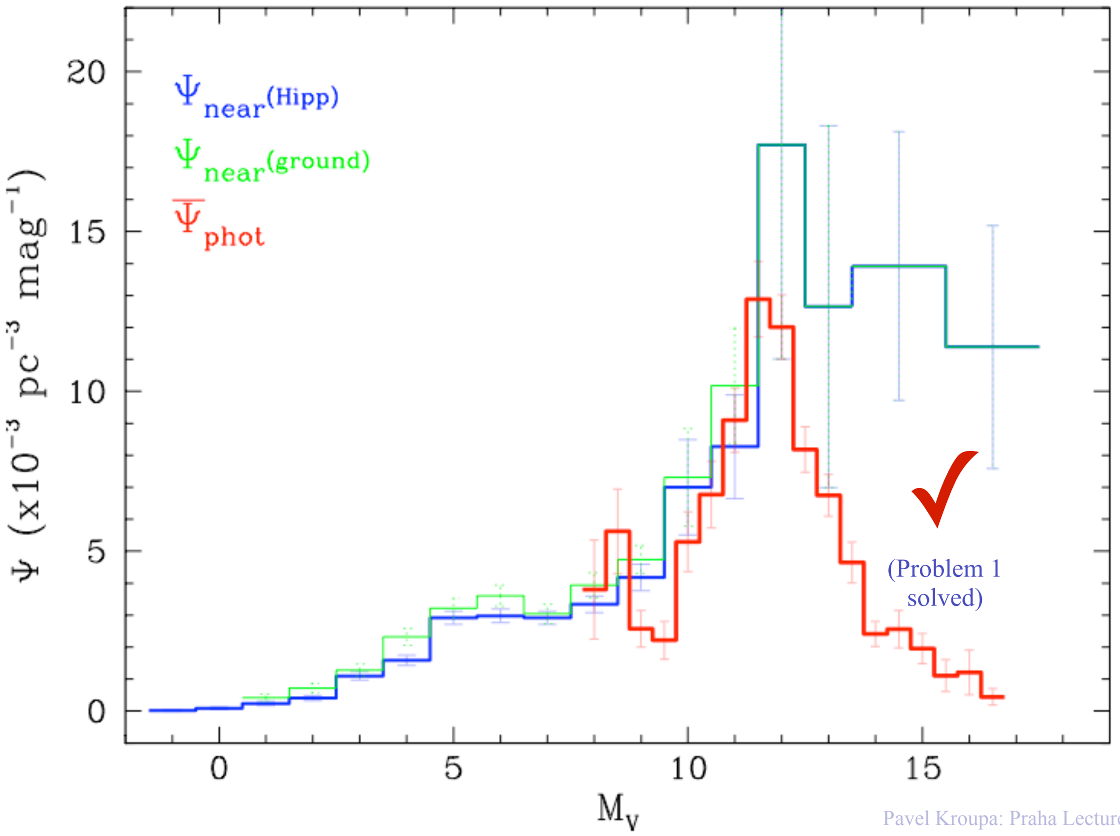
"Observe" this Galactic field in the computer . . .

(Thies et al. 2015)



Two solar-neighbourhood samples:

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



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Resultant Galactic-field MF:

After : - understanding the MLR

- modelling faint star-counts

(Malmquist bias, unresolved binaries, photometric parallax)

- dynamical population synthesis

(N-body calculations of binary-rich clusters)

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

$$\alpha_1 = 1.3 \pm 0.5, \quad 0.08 \le m/M_\odot < 0.5$$

$$\alpha_2 = 2.3 \pm 0.3, \quad 0.5 \le m/M_\odot < 1$$

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

(Kroupa, Tout & Gilmore 1993; Kroupa 1995; Reid, Gizis & Hawley 2002)

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Resultant Galactic-field MF

for low-mass stars :

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

$$\alpha_1 = 1.3 \pm 0.5, \quad 0.08 \le m/M_\odot < 0.5$$
$$\alpha_2 = 2.3 \pm 0.3, \quad 0.5 \le m/M_\odot < 1$$

. . . *unifies* the two LFs.

(Kroupa, Tout & Gilmore 1993; Kroupa 1995;
Reid, Gizis & Hawley 2002; cf. Chabrier 2003)

Resultant Galactic-field MF

for low-mass stars :

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

$$\alpha_1 = 1.3 \pm 0.5, \quad 0.08 \le m/M_\odot < 0.5$$
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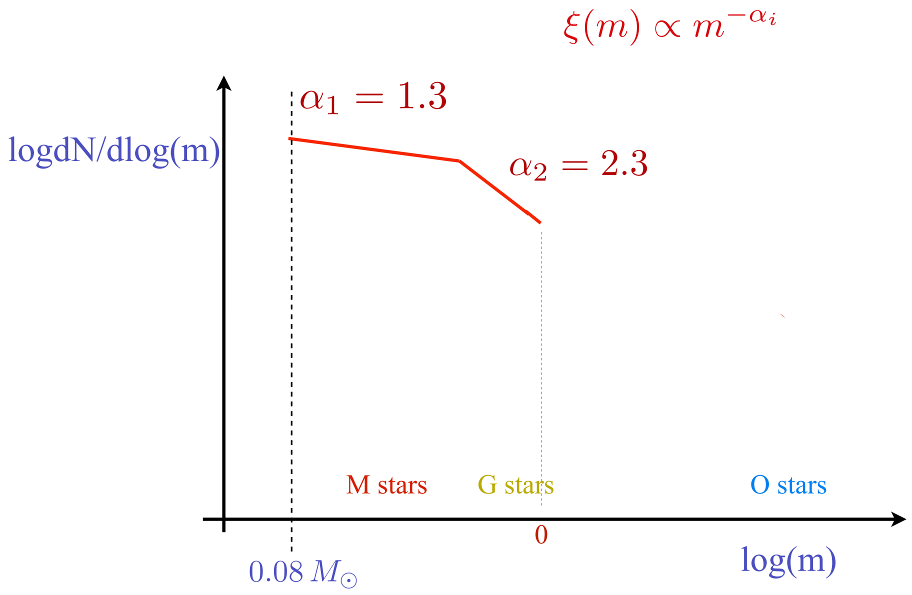
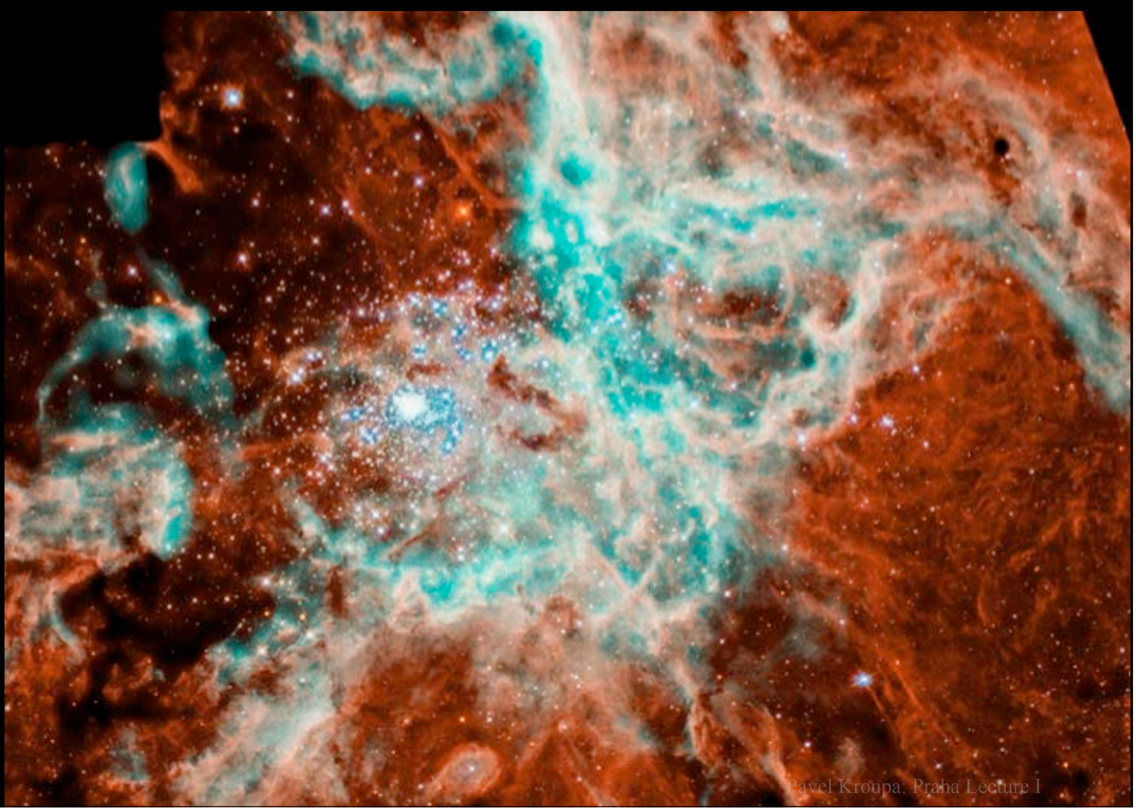
Note: Chabrier (2003) proposes a *log-normal IMF*. This is more physical in principle, since nature does not make discontinuous slopes. An extension to $m \gtrsim 1\, M_\odot$ still requires a power-law though, loosing the advantage.

Here: *prefer* the above *two-part power-law* formulation because it is easier to work with, and because it has been demonstrated to excellently fit the LF.



No diverging mass in faint stars !!

Massive stars



Massive stars

Scalo (1986): A very detailed study of local star-counts together with assumptions about the SFH, spatial structure of the MW disk and stellar evolution corrections

$$\longrightarrow \boxed{\alpha_3 \approx 2.7, \quad 1 \lesssim m/M_\odot}$$

Thus, the *standard Galactic-field IMF* (KTG93) becomes

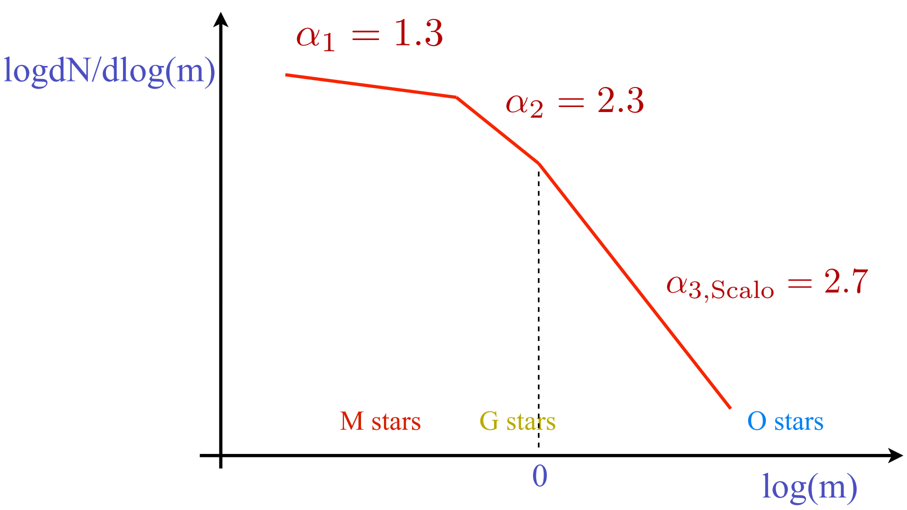
$$\xi(m) \propto m^{-\alpha_i}$$

$$\alpha_1 = 1.3 \pm 0.5, \quad 0.08 \leq m/M_\odot < 0.5$$
$$\alpha_2 = 2.3 \pm 0.3, \quad 0.5 \leq m/M_\odot < 1$$
$$\alpha_3 = 2.7, \quad 1 \leq m/M_\odot$$

(Kroupa, Tout & Gilmore 1993 = KTG93)

The standard field-star (KTG93) IMF :

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



Note: it is not a Salpeter power-law **!!** Salpeter's analysis was done in 1954-1955 and is only valid for stars between 0.4 and 10 $M_\odot$.

Massey (various papers): A rigorous *spectroscopic* study of OB associations and clusters in the MW, LMC, SMC

(for massive stars only a *very small fraction* of $L_{\rm bol}$ emerges in the *optical*.)

Steps: - *spectroscopy* and *photometry* to get

$T_{\rm eff}$, BC, $L_{\rm bol}$, redenning

$\downarrow$

- HRD + isochrones $\longrightarrow$ ***initial stellar masses***

Massey (1995) finds for OB associations & clusters
(IMF only determined for stars with $\tau_{\rm ms} \geq \tau =$ age of population)

1)

SMC	LMC	MW
Z = 0.002	0,008	0,02
$\alpha_3 = 2.3 \pm 0.1$	2.3 ± 0.1	2.1 ± 0.1
$\xi(m) =$	$\xi(m) =$	$\xi(m)$

$\longrightarrow$ $\alpha_{3,\rm OB\ ass} < \alpha_{3,\rm Scalo}$ **?**
2.3 2.7

2) Independence of density:

Massey 1995

Example: R136 in LMC

central density $\rho_C \approx 10^5$ stars/pc^3

> 39 O3 stars !

$$\alpha_3 = 2.35 \pm 0.15$$

Thus, the *standard Galactic-field IMF* is

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

$\alpha_1 = 1.3 \pm 0.5, \quad 0.08 \le m/M_\odot < 0.5$

$\alpha_2 = 2.3 \pm 0.3, \quad 0.5 \le m/M_\odot < 1$

$\alpha_3 = 2.7, \quad 1 \le m/M_\odot$ (*Scalo*)

KTG93

But, the *standard stellar IMF* is

?

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

$\alpha_1 = 1.3 \pm 0.5, \quad 0.08 \le m/M_\odot < 0.5$

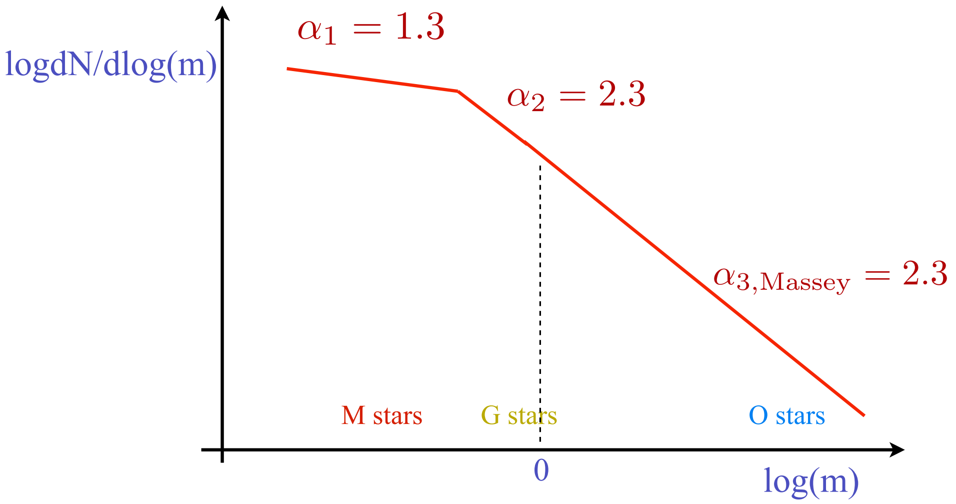
$\alpha_2 = 2.3 \pm 0.3, \quad 0.5 \le m/M_\odot < 1$

$\alpha_3 = 2.3, \quad 1\,M_\odot \le m$ (*Massey*)

Kroupa 2001

two-part power-law IMF :

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



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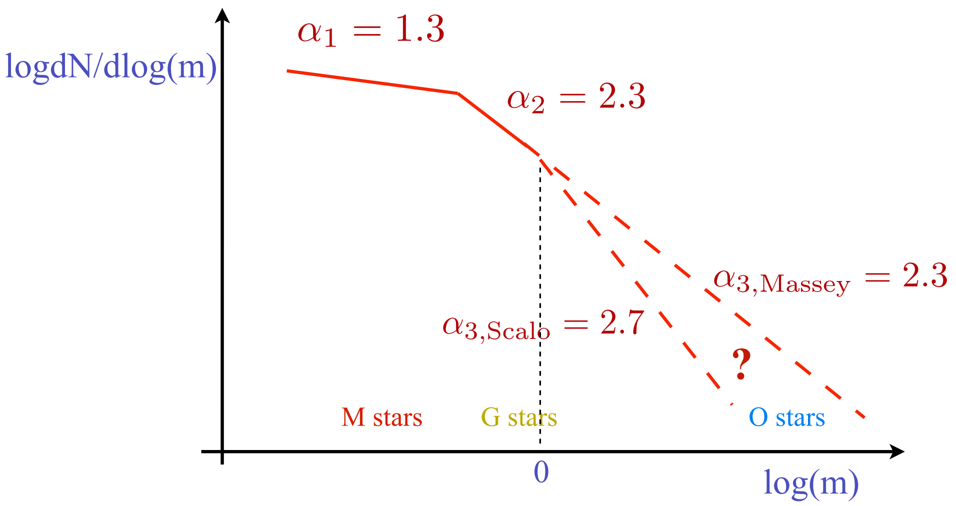
$\alpha_{3,\mathrm{OB\ ass}} < \alpha_{3,\mathrm{Scalo}}$?
2.3 2.7

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



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Problem 2:

The stellar IMF in the
Galactic-field
and in
OB associations/star clusters
is not equal.

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Not One
but
Two
or even
Many More

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Multiplicity of massive stars

(towards understanding the "*Scalo vs Massey problem*")

Most massive stars are in
binary ($\mathcal{B}$),
triple ($\mathcal{T}$) or
quadruple ($\mathcal{Q}$) systems.

Def: *The companion star fraction:*

$$CSF = \frac{\mathcal{B} + 2\,\mathcal{T} + 3\,\mathcal{Q}}{\mathcal{S} + \mathcal{B} + \mathcal{T} + \mathcal{Q}}$$

(*cf* Reipurth & Zinnecker 1993)

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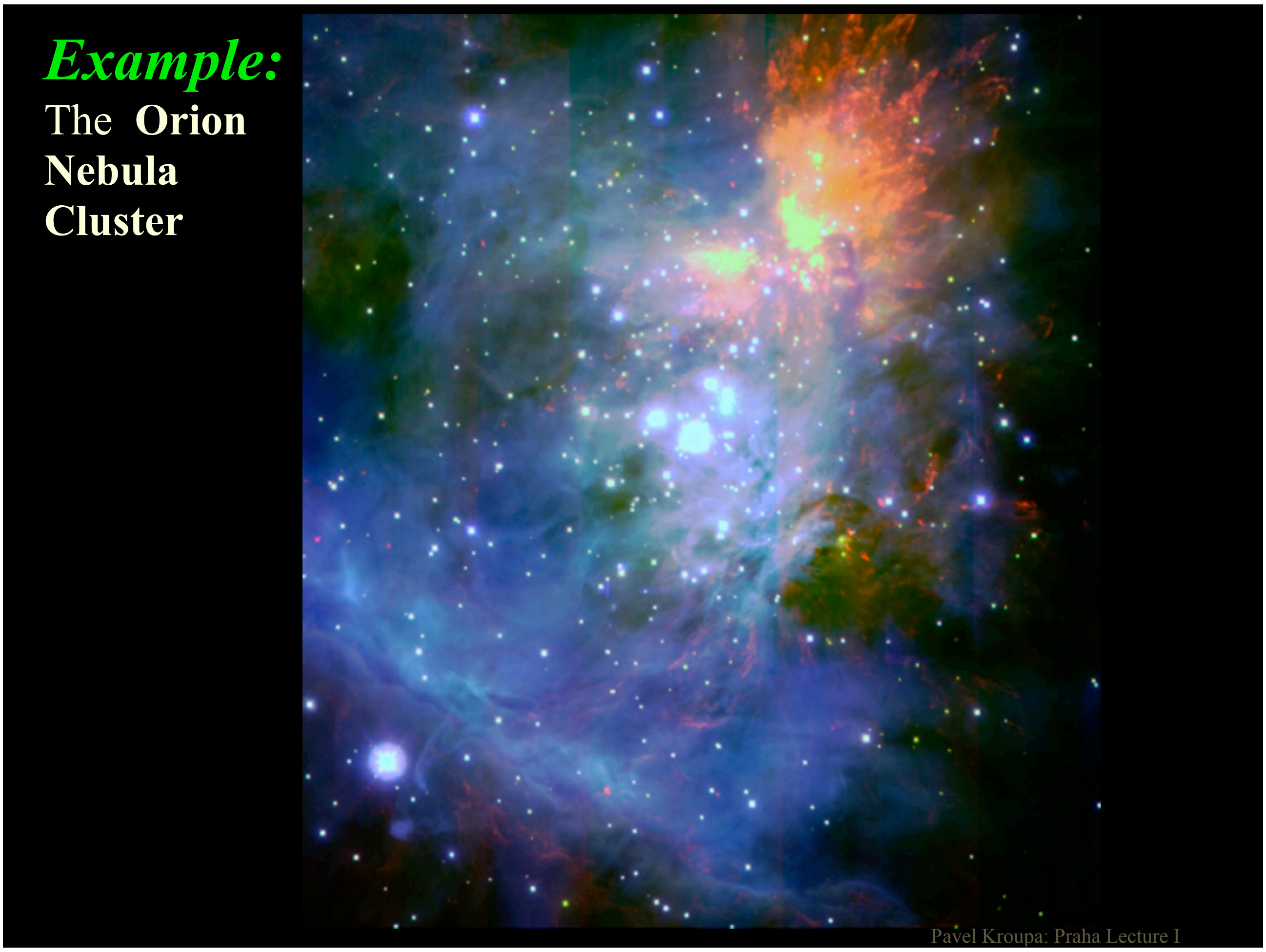

Example: The **Orion Nebula Cluster** (≈ 1 Myr)

The multiplicity of the 8 most massive stars:
(Preibisch et al. 1999)

θ^1 Ori A	$\mathcal{T}$	
θ^1 Ori B	$\mathcal{Q}$	
θ^1 Ori C	$\mathcal{B}$	– the exciting star
θ^1 Ori D	$\mathcal{S}$	
θ^2 Ori A	$\mathcal{T}$	
θ^2 Ori B	$\mathcal{S}$	
LP Ori	$\mathcal{T}$	
ν Ori	$\mathcal{T}$	

$$\longrightarrow \quad CSF = \frac{1+8+3}{2+1+4+1} = 1.5$$

separation $\lesssim 1$ AU – 1000 AU
mass-ratios $0.1 \lesssim q \leq 1$

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Multiplicity of massive stars

$$CSF = \frac{\mathcal{B}+2\,\mathcal{T}+3\,\mathcal{Q}}{\mathcal{S}+\mathcal{B}+\mathcal{T}+\mathcal{Q}}$$

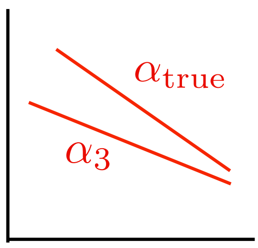
Compare

ONC OB stars: $CSF = 1.5$

pre-main-sequence low-mass stars: $CSF = 1$

Galactic-field late-type stars $CSF = 0.5$

But $CSF \geq 1 \longrightarrow$ $\boxed{\alpha_{\rm true} > \alpha_3 \text{ (true steeper IMF) ?}}$



Sagar & Richtler 1991: $\alpha_{\rm true} \geq 2.7\,(2-14\,M_\odot)$

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Multiplicity of massive stars

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The influence of multiple stars on the high-mass stellar initial mass function and age dating of young massive star clusters

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ABSTRACT

The study of young stellar populations has revealed that most stars are in binary or higher order multiple systems. In this study, the influence on the stellar initial mass function (IMF) of large quantities of unresolved multiple massive stars is investigated by taking into account the stellar evolution and photometrically determined system masses. The models, where initial masses are derived from the luminosity and colour of unresolved multiple systems, show that even under extreme circumstances (100 per cent binaries or higher order multiples), the difference between the power-law index of the mass function (MF) of all stars and the observed MF is small ($\lesssim$0.1). Thus, if the observed IMF has the Salpeter index $\alpha = 2.35$, then the true stellar IMF has an index not flatter than $\alpha = 2.25$. Additionally, unresolved multiple systems may hide between 15 and 60 per cent of the underlying true mass of a star cluster. While already a known result, it is important to point out that the presence of a large number of unresolved binaries amongst pre-main-sequence stars induces a significant spread in the measured ages of these stars even if there is none. Also, lower mass stars in a single-age binary-rich cluster appear older than the massive stars by about 0.6 Myr.

Unresolved binaries do not affect the high-mass end of the IMF .

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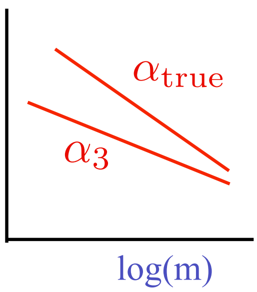
Multiplicity of massive stars

$\alpha_{\rm true} > \alpha_3$ **?**
(true steeper IMF)



Can unresolved multiple systems solve this problem **?**

NO !

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Thus

Is the *Scalo* value ($\alpha_{3,\,\mathrm{Scalo}} = 2.7$) the *true stellar IMF* ?

Is the Salpeter/Massey IMF $\boxed{\alpha_3 = 2.3}$ *true stellar IMF* ?

Constraint on star-formation theory
and chemical and spectro-photometric evolution of
galaxies . . .

Which, IMF are you or I to use ?

Next, turn to theory - can theory help ?

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Questions :

What is the *shape*
of the IMF ?

Is this stellar IMF
universal ?

Or does it vary among
OB associations / star clusters ?

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Origin of the stellar IMF
& its required variation :

$\alpha \xrightarrow[\text{theory}]{} \Omega$

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The Jeans Mass :

(simplified argument)

(Sir James Hopwood Jeans, 1933-1946)

One begins with a *spherical gaseous region* of radius *R*, mass *M*, and with a gaseous sound speed c_s.

Imagine that we *compress the region slightly*.

It takes a sound-crossing time, t_s , for sound waves to cross the region, and attempt to push back and re-establish the system in pressure balance. At the same time, gravity will attempt to contract the system even further, and will do so on a free-fall time, t_{ff} .

When $t_s < t_{ff}$, pressure forces win, and the system *bounces back* to a stable equilibrium.

When $t_s > t_{ff}$, gravity wins, and the region undergoes gravitational collapse. .

The *condition for gravitational collapse* is therefore $t_s > t_{ff}$

It can be shown that the *resultant Jeans mass* (the mass within the Jeans length) is approximately **:**

$$M_{\rm Jeans} \propto T^{\frac{3}{2}}\ \rho^{-\frac{1}{2}}$$

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The *Jeans mass* depends on *temperature* and *density* :

$$M_{\rm Jeans} \propto T^{\frac{3}{2}}\ \rho^{-\frac{1}{2}}$$

(e.g. Bonnell, Larson & Zinnecker 2006)

Metallicity dependence through atomic/molecular line cooling and thermal emission from dust;

ambient T higher at larger z setting *minimum possible* T at given cosmological epoch.

Metallicity dependence through atomic/molecular line cooling and thermal dust emission.

$M_{\rm Jeans}$ = characteristic mass scale of star formation decreases with increasing [Z/H] . (Larson 1998)

Characteristic mass *smaller* in *higher-metallicity* environments than for solar-neighbourhood stars.

On the other hand . . .

The *Jeans mass* has “virtually nothing to do with the masses of forming stars”.

There exists structure in molecular clouds on all scales - no *single characteristic density* can be identified, thus “no single Jeans mass exists”. (Adams & Fatuzzo 1996)

The *conditions in molecular clouds* define the set of initial conditions for regional collapses, while the *balance* between *accretion rate* and *stellar feedback* regulates the transformation of these initial conditions to the final stellar masses.

metallicity dependence through temperature (sound speed).

metallicity dependence through coupling of radiation to matter.

(Adams & Laughlin 1996)

Note: *Feedback* must play the *dominant physical role* because most of the gravitationally assembled matter is dispersed by it ($sfe < 0.5$).

Different theories on origin of stellar masses :

- The *Jeans mass* depends on *temperature* and *density* :
  $M_{\text{Jeans}} \propto T^{\frac{3}{2}}\ \rho^{-\frac{1}{2}}$ (e.g. Bonnell, Larson & Zinnecker 2006)

- Stars define their own masses through *accretion* and *feedback* . (Adams & Fatuzzo 1996; Adams & Laughlin 1996)

The different theoretical approaches
have in common that
higher-metallicity environments should produce
lighter stars on average.

$$Z \uparrow \quad \longrightarrow \quad m \downarrow$$

Can this be seen in the measured IMF **?**

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Different theories on origin of stellar masses :

- The *Jeans mass* depends on *temperature* and *density* :
  $M_{\text{Jeans}} \propto T^{\frac{3}{2}}\ \rho^{-\frac{1}{2}}$ (e.g. Bonnell, Larson & Zinnecker 2006)

- Stars define their own masses through *accretion* and *feedback* . (Adams & Fatuzzo 1996; Adams & Laughlin 1996)

No empirical evidence of this has been found **!**

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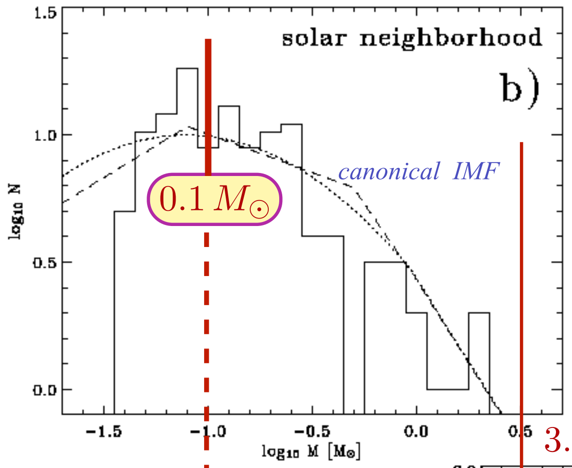
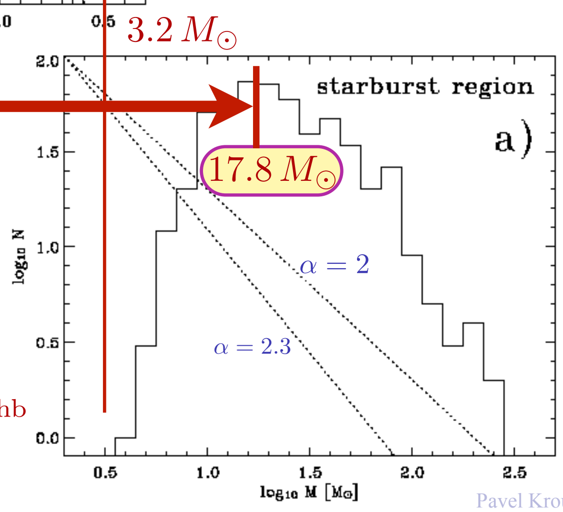


Star formation in
solar-neighbourhood:
state-of-the art
SPH simulations

Klessen, Spaans & Japsen
(2006)



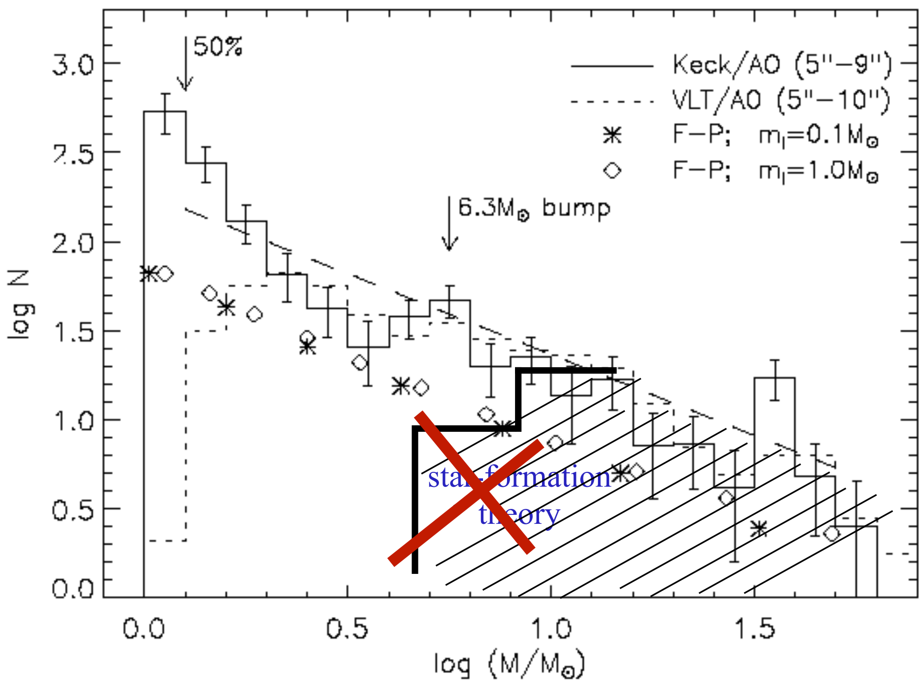
Star formation near
Galactic centre

$T_{\rm gas/dust} \approx 3 \times T_{\rm solar\ neighb}$

$\rho_{\rm gas} \approx 10 \times \rho_{\rm solar\ neighb}$

$SFR \approx 100 \times SFR_{\rm solar\ neighb}$

But : Kim, Figer, Kudritzki, Najarro
(2006, a few days on astro-ph after *Klessen et al.* **!**)



Keck-imaging of the Arches cluster
+
dynamical modelling (mass segregation)

$\alpha_{3,\rm Arches} \approx 2.0 - 2.1$
$\approx$ Salpeter/Massey
!

Star formation theory

fails

to account for the basic (non)-behaviour of the IMF we see in the heavens **!**

Origin of the stellar IMF
& its required variation :

$\alpha \longrightarrow \Omega$

observations

Origin of IMF

(Motte, Andre & Neri 1998)

1.3 mm continuum mapping of Oph ρ.

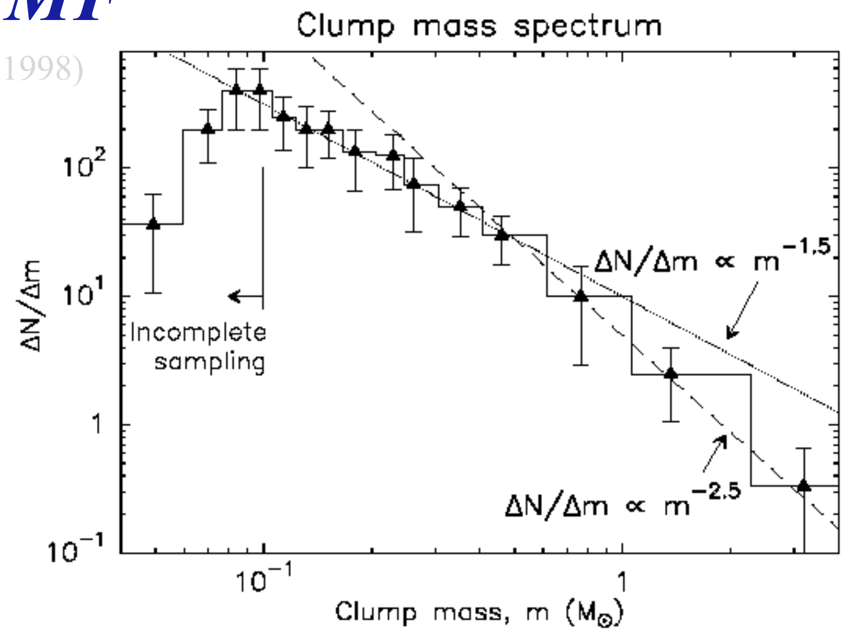


Fig. 5. Frequency distribution of masses for 60 small-scale clumps extracted from the mosaic of Fig. 1 (solid line). The dotted and long-dashed lines show power laws of the form $\Delta N/\Delta m \propto m^{-1.5}$ and $\Delta N/\Delta m \propto m^{-2.5}$, respectively. The error bars correspond to $\sqrt{N}$ counting statistics.

Origin of IMF

(Motte, Andre et al. 2001)

850 μm and 450 μm mapping of NGC 2068 and 2071.

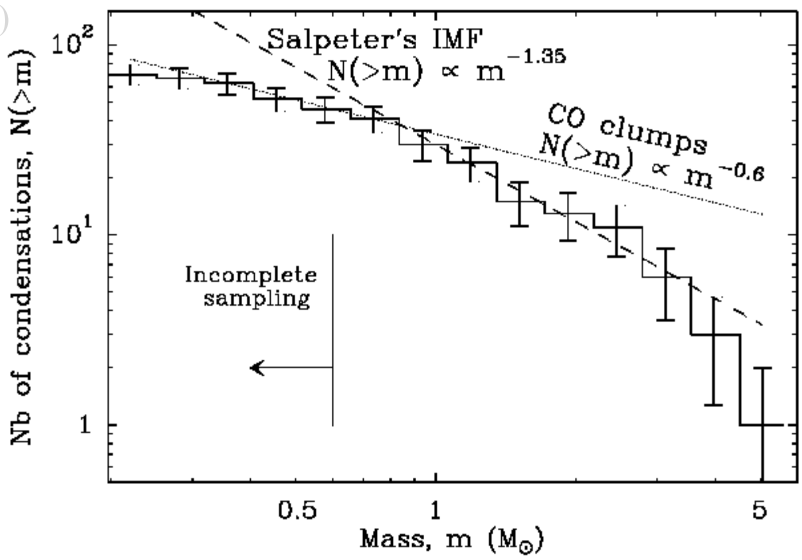
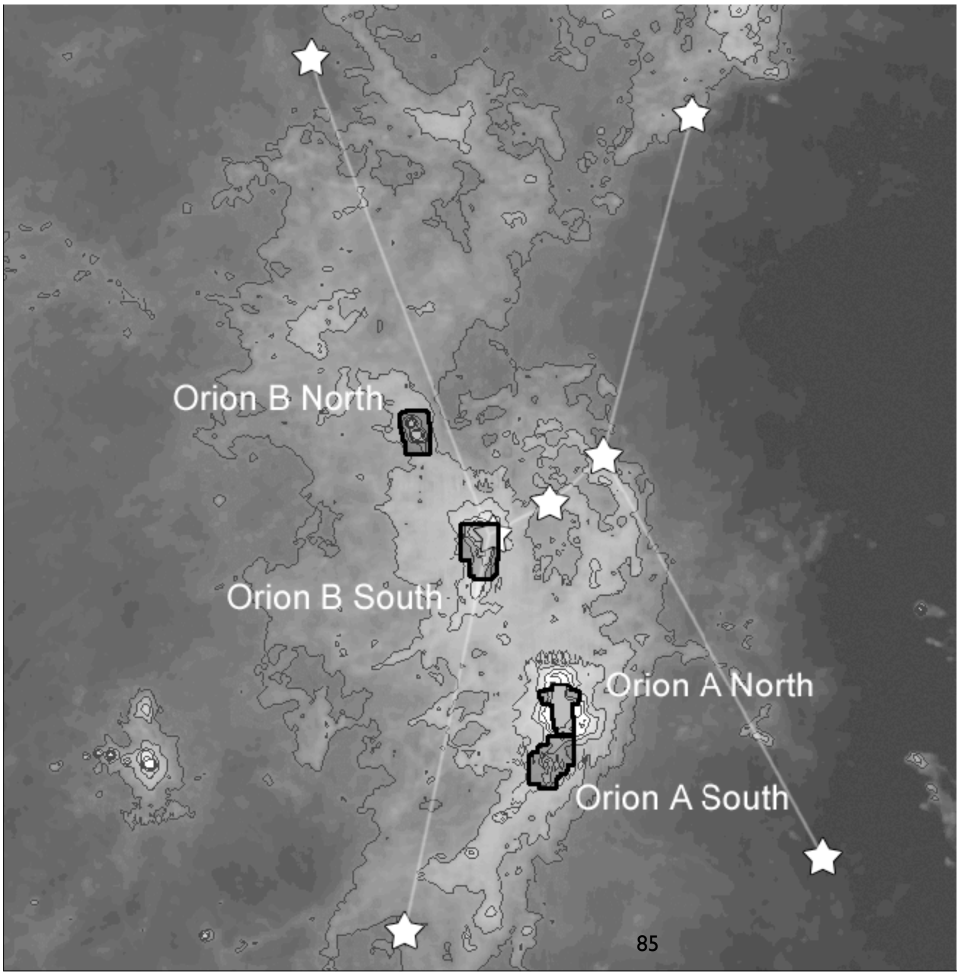


Fig. 3. Cumulative mass distribution of the 70 pre-stellar condensations of NGC 2068/2071. The dotted and dashed lines are power-laws corresponding to the mass spectrum of CO clumps (Kramer et al. 1996) and to the IMF of Salpeter (1955), respectively. The error bars correspond to $\sqrt{N}$ counting statistics.



Nutter & Ward-Thompson 2006

IRAS 100 micro meter map of the Orion molecular cloud

Nutter & Ward-Thompson (2006, aph/0611164)

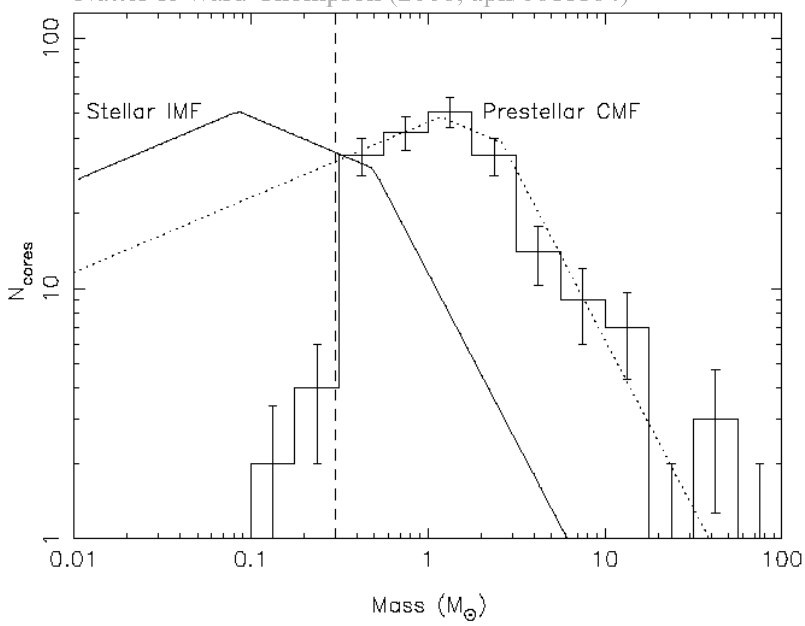


Figure 6. The core mass function for the Orion AN and Orion BN regions. The average completeness limit for the two regions is shown as a dashed line. A three-part stellar IMF, normalised to the peak in N of the CMF, is overlaid as a thin solid line. The dotted line shows a three-part mass function with the same slopes as the IMF (see text for details).

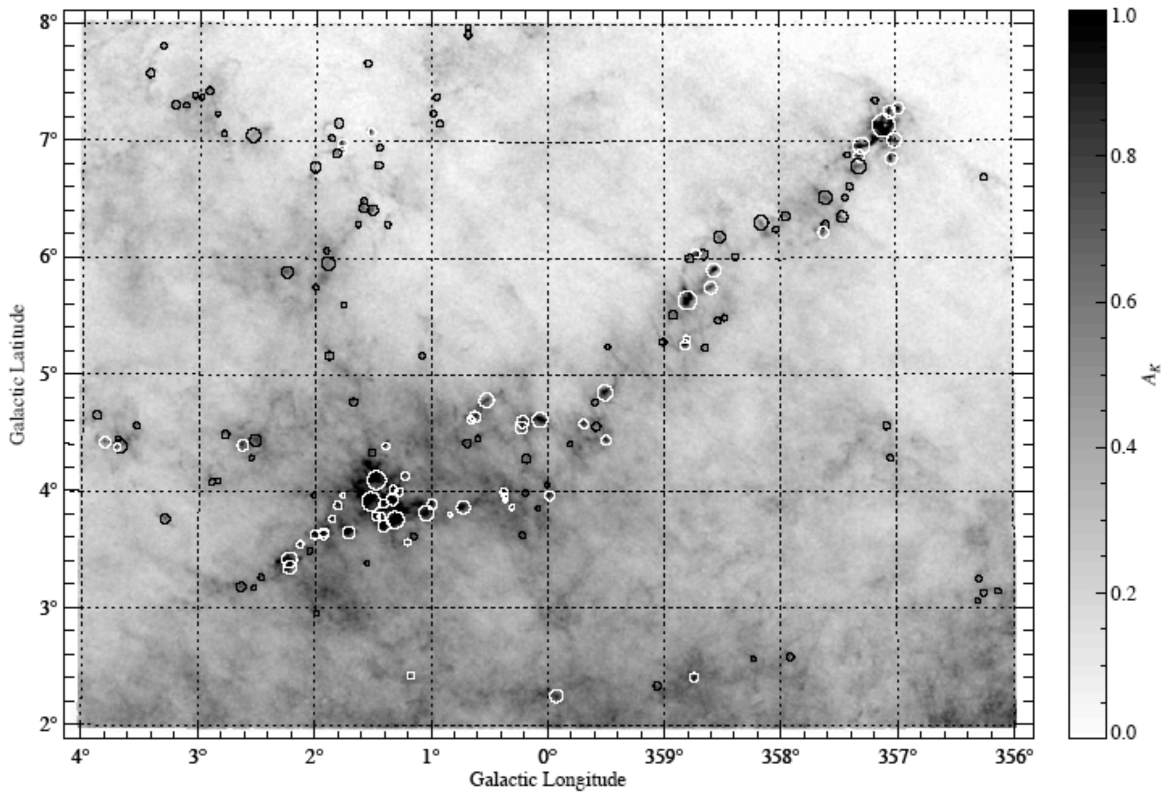


Fig. 1. Dust extinction map of the Pipe nebula molecular complex from Lombardi et al. (2006). This map was constructed from near-infrared observations of about 4 million stars in the background of the complex. Approximately 160 individual cores are identified within the cloud and are marked by an open circle proportional to the core radius. Most of these cores appear as distinct, well separated entities. Alves, Lombardi & Lada (2006)

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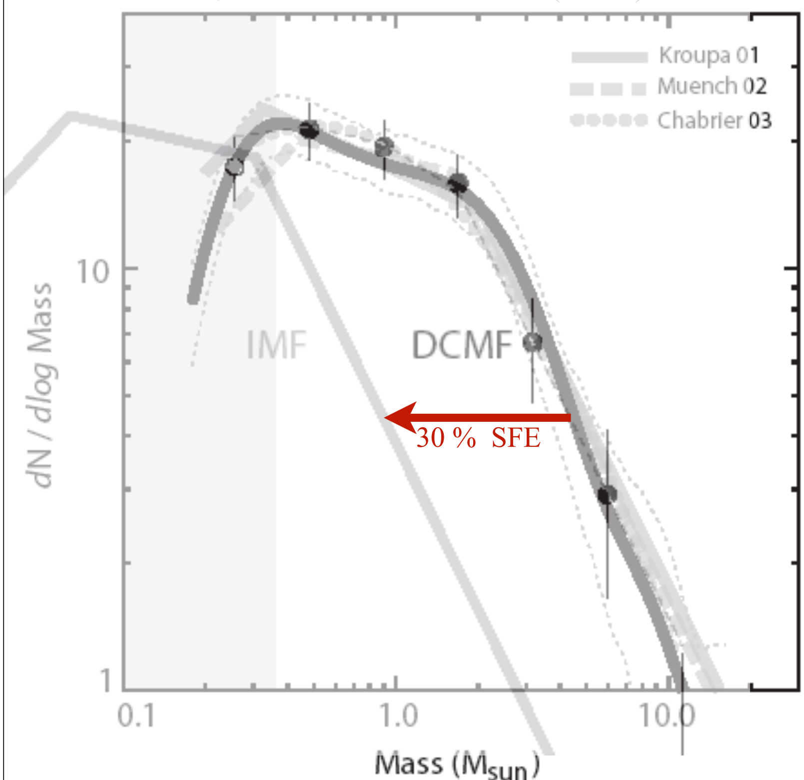
Alves, Lombardi & Lada (2006)



Similar work and results by
Motte, Andre
Nutter, Ward-Thompson
Testi, Sargent

The **shape** of the
molecular cloud-core MF
is
indistinguishable
to the
stellar IMF !

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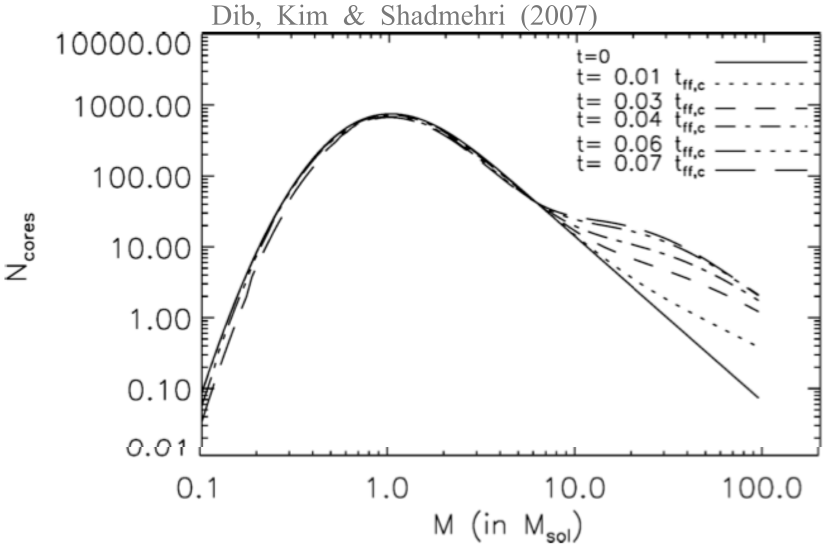
IMF becomes top heavy with increasing density :

Dib, Kim & Shadmehri (2007)



Models of coalescing and collapsing cloud cores in a dense proto cluster.

Schematic IMF (Bonnell, Larson & Zinnecker 2006, PPV)

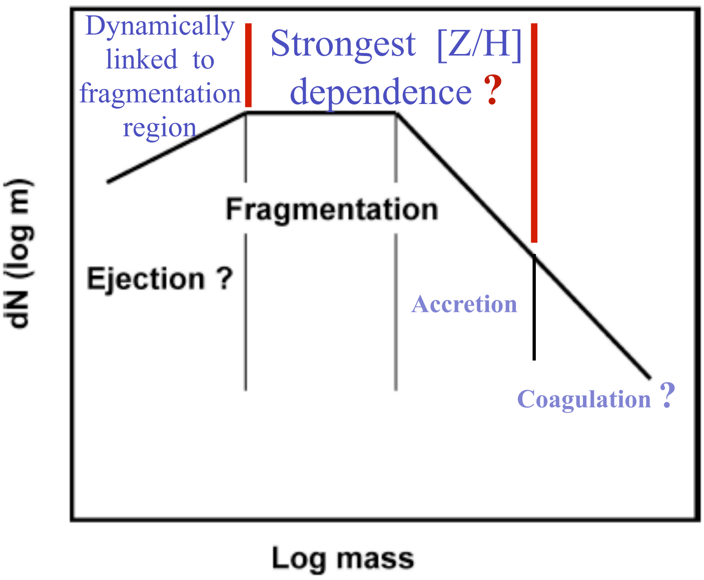


Fig. 11.— A schematic IMF showing the regions that are expected to be due to the individual processes. The peak of the IMF and the characteristic stellar mass are believed to be due to gravitational fragmentation, while lower mass stars are best understood as being due to fragmentation plus ejection or truncated accretion while higher-mass stars are understood as being due to accretion.

Elmegreen (2004) also proposes a *three-part IMF*.

Is a *consensus* emerging on the *fundamental physics* active in the *three mass regimes* ?

But then, what about the [Z/H] dependence ?

END of

Lecture 1