Stellar populations and star clusters as galactic building blocks

Lecture 3
The IGIMF and implications

Selected Chapters on Astrophysics
Charles University, Praha,
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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, and implications.

Lecture 4 :

The stellar binary population**:** deriving the birth distribution functions
Binary dynamical population synthesis**:** the stellar populations of galaxies

The IMF
is the key
to our understanding
of the matter cycle
in the Universe.

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Counting stars => LF => PDMF => IMF

Remember :

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

\+ binaries
\+ main sequence stars

corrections for stellar evolution

✓ peak in LF => m-M_V relation

✓ nearby LF ≠ distant LF

? MW-field (Scalo) IMF index
≠ star-cluster/association (Salpeter/Massey) IMF index

star-formation theory (*Jeans-mass vs self-regulation*) **:**
✓ - expect IMF variation with density and metallicity
? - unable to account for IMF shape

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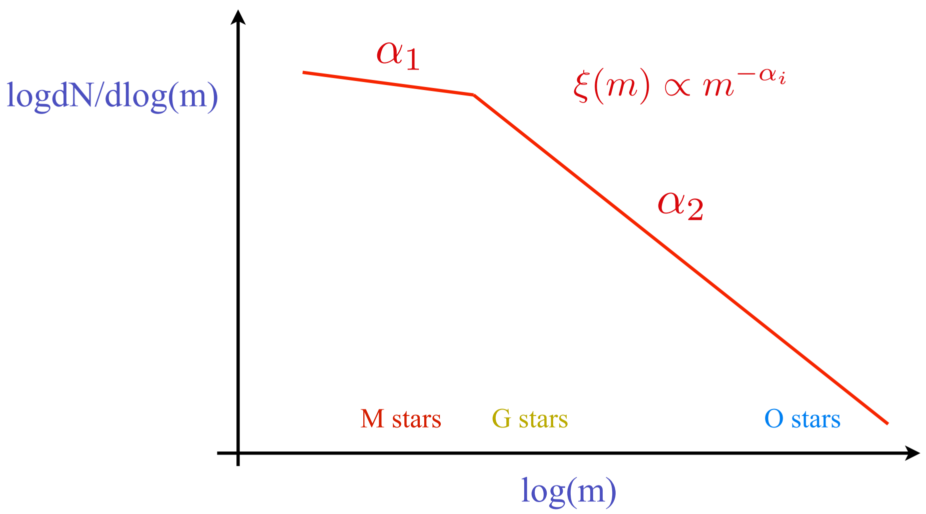
Recap

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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Observations

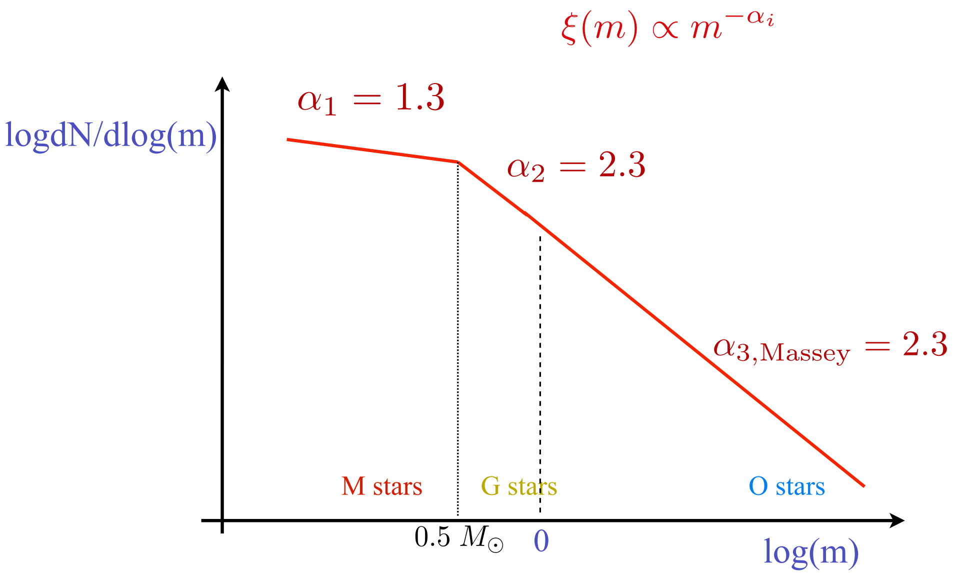
of well-resolved populations

show

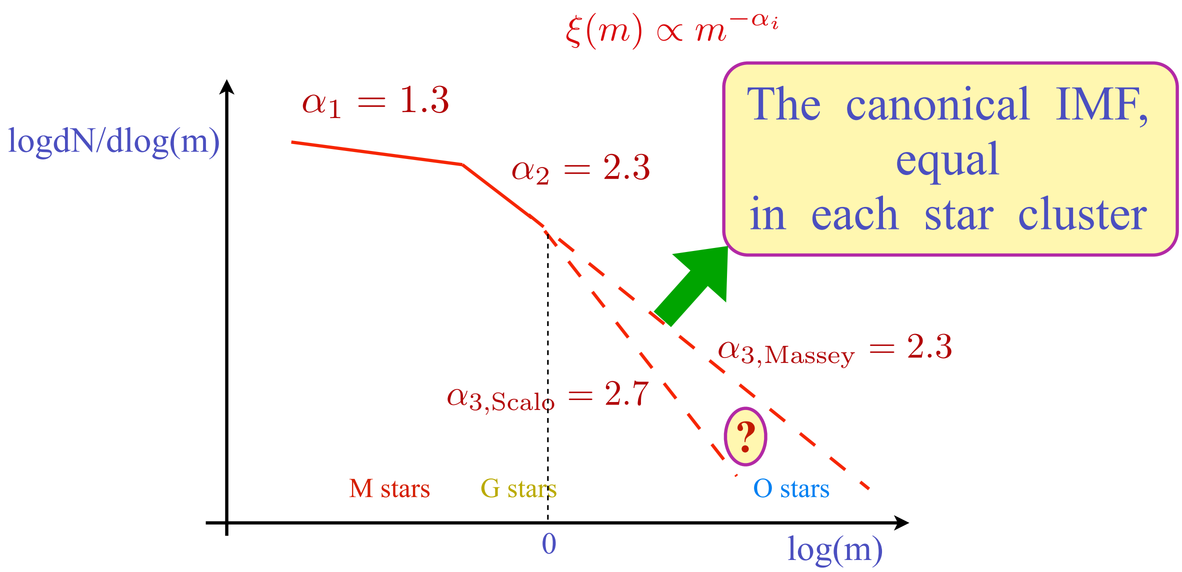
the IMF to be universal **!**

(except under extreme conditions - see Lecture II)

universal "canonical" *two-part* power-law IMF **:**



Return to the Scalo / Massey-Salpeter discrepancy :



back to **Problem 2:**

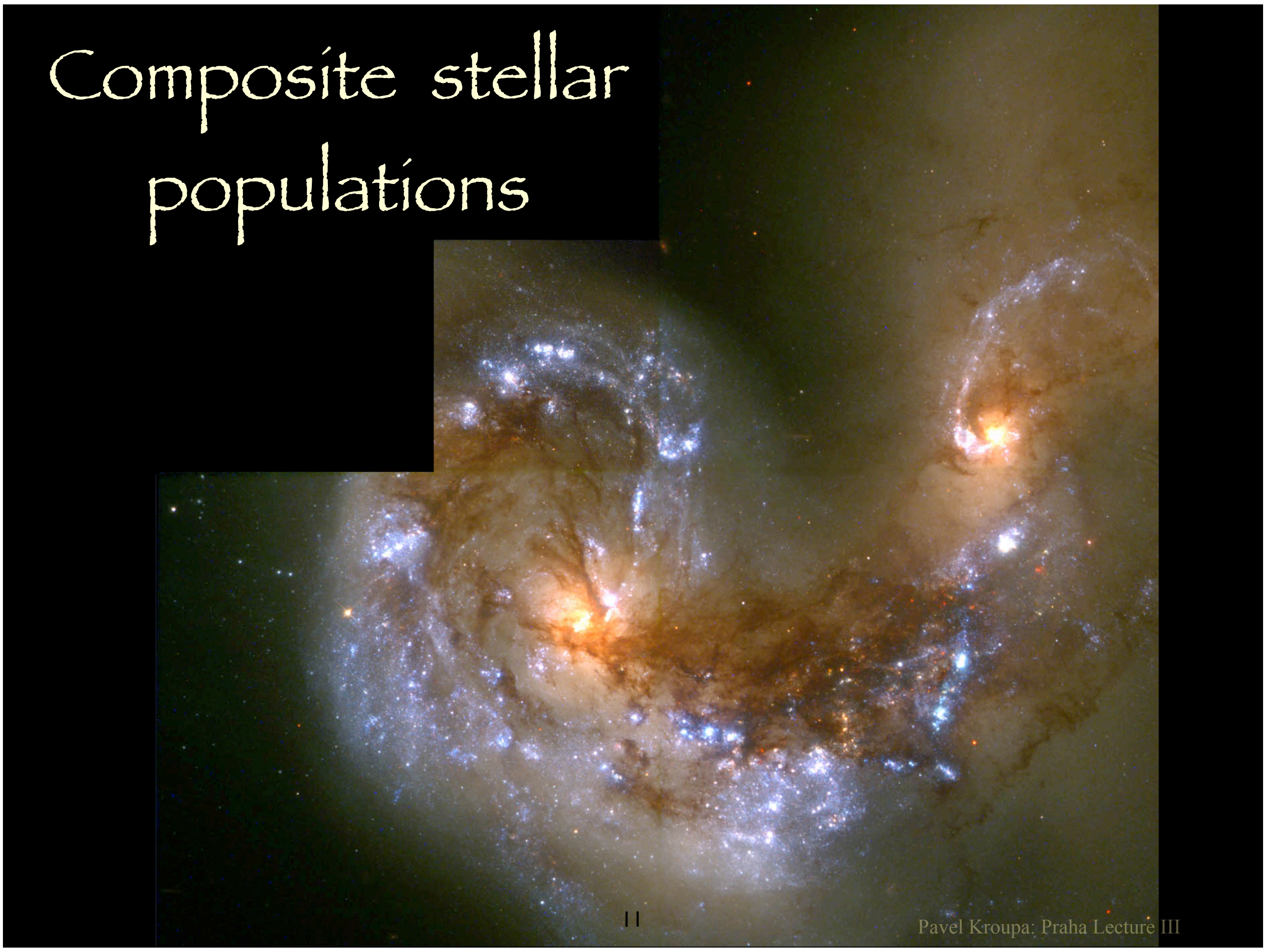
(see Lecture I)

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

$\alpha_3 = 2.7$

$\alpha_3 = 2.3$

Composite stellar populations



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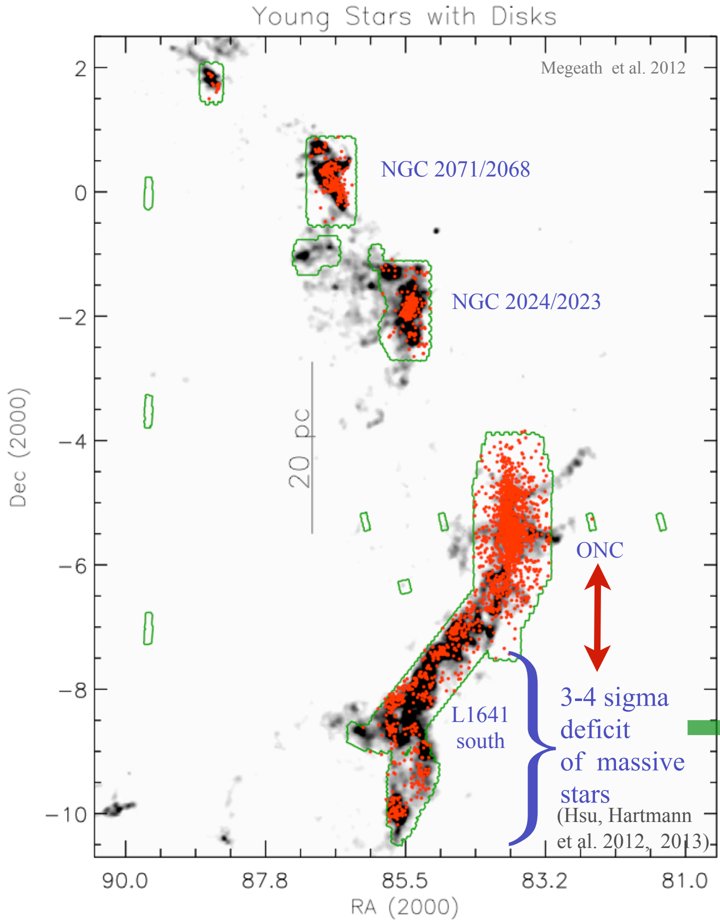

Clustered star formation

(see also Lada & Lada 2003)

and
lack of O stars :

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

stochastic IMF in each group disfavoured.

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Composite Stellar Populations

Stars form in clusters (Lada & Lada 2003).
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)

adding-up all IMFs in all clusters !

Vanbeveren (1982)

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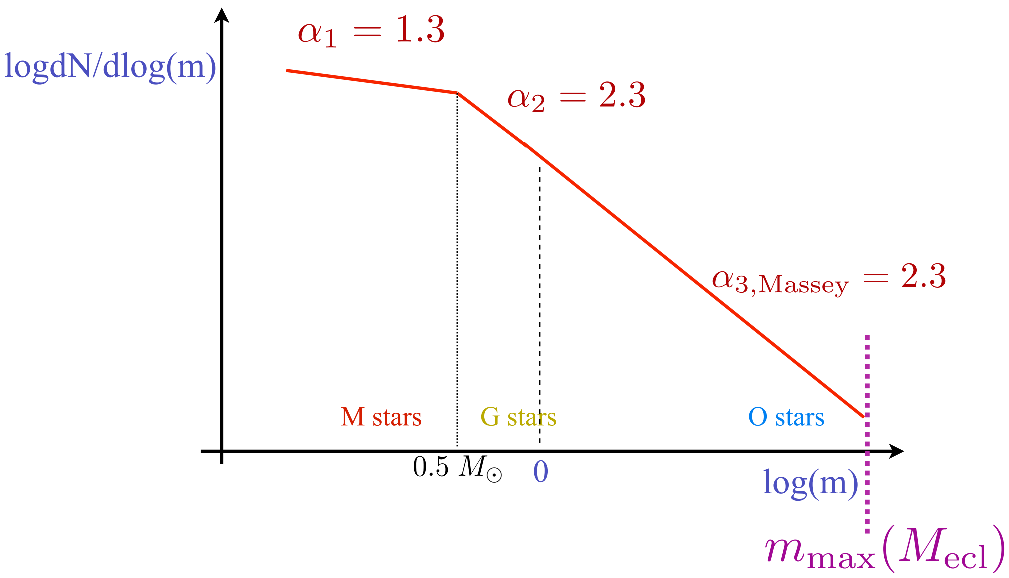
The universal "canonical" *two-part* power-law IMF :

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



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Kroupa & Weidner (2003), Weidner & Kroupa (2005, 2006)

The embedded-cluster MF (ECMF) :

$\xi_{\rm ecl} \propto M_{\rm ecl}^{-\beta}; \quad \beta \approx 2-2.4$

solar-neighbourhood (Lada & Lada 2003)	few 10 $M_\odot$ – 1000 $M_\odot$
LMC & SMC (Hunter et al. 2003)	$10^3\ M_\odot - 10^4\ M_\odot$
Antennae (Zhang & Fall 1999)	$10^4\ M_\odot - 10^6\ M_\odot$

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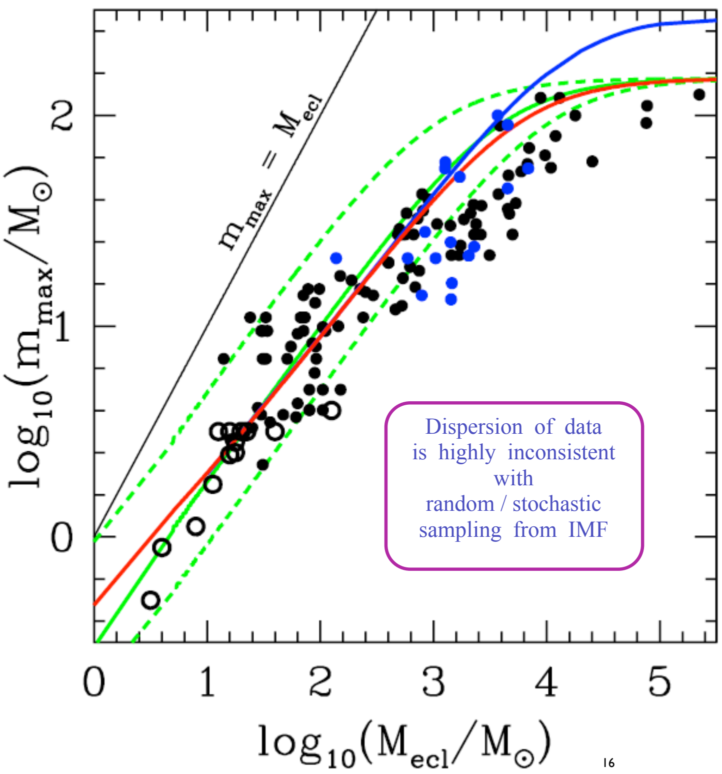
The $m_{\rm max}(M_{\rm ecl})$ *relation*

Weidner & Kroupa 2005, 2006;
Weidner et al. 2010, 2013; Kroupa et al. 2013;
Kirk & Myers, 2010, 2012; Hsu, Hartmann et al. 2012, 2013;
Megeath et al. 2015



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

$m_{\rm max*} = 150\,M_\odot$ physical upper mass limit ?
(Weidner & Kroupa 2004;
Figer 2005;
Oey & Clarke 2005,
Koen 2006;
Maiz Appelaniz et al. 2007)

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

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

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

an mmax -- Mecl relation

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Composite Stellar Populations

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

Kroupa & Weidner (2003); Weidner & Kroupa (2005)

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Correlated star formation events building up a galaxy

(i.e. embedded clusters = building blocks; Kroupa, 2005ESASP.576..629K)

The total mass in stars formed in a galaxy over time δt is $M_{\rm tot} = SFR \times \delta t$

But $M_{\rm tot} = \int_{M_{\rm ecl,min}}^{M_{\rm ecl,max}} \xi_{\rm ecl}(M_{\rm ecl})\, M_{\rm ecl}\, dM_{\rm ecl}$

For $M_{\rm ecl,min} = 5\ M_\odot$ and with $1 = \int_{M_{\rm ecl,max}}^{M_{\rm ecl,max*}} \xi_{\rm ecl}(M_{\rm ecl})\, dM_{\rm ecl}$

where $M_{\rm ecl,max*} \approx 10^7\ M_\odot$

Thus $\boxed{M_{\rm ecl,max} = {\rm fn}(SFR)}$

What is *delta t* ?

The galaxy-wide time-scale of transforming the ISM via molecular clouds into a new stellar population (Egusa et al. 2004; 2009).

Disappearance of large molecular clouds around young star clusters (Leisawitz 1989).
(see also Schulz et al. 2015)

→ $\boxed{\delta t \approx 10\ {\rm Myr}}$

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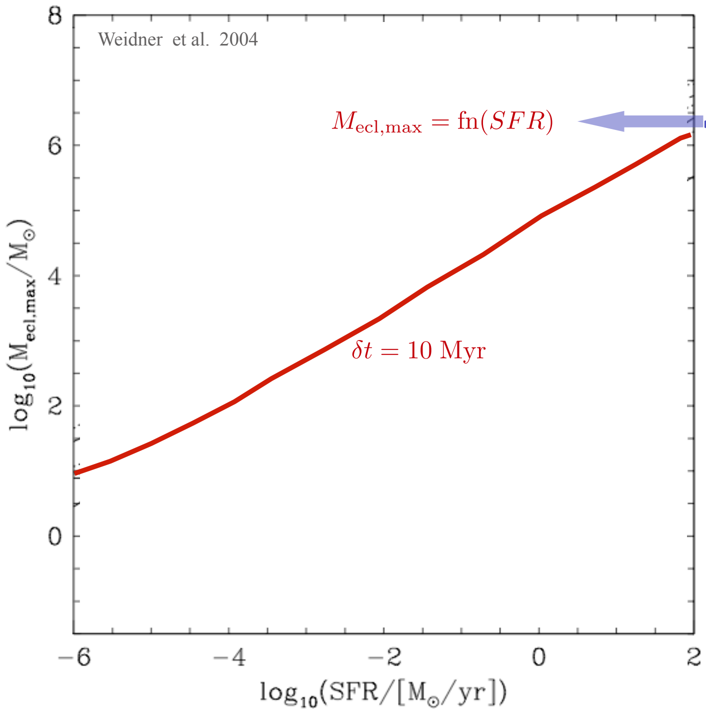

$M_{\rm tot} = SFR \times \delta t$

$$M_{\rm tot} = \int_{M_{\rm ecl,min}}^{M_{\rm ecl,max}} \xi_{\rm ecl}(M_{\rm ecl})\, M_{\rm ecl}\, dM_{\rm ecl}$$

$$1 = \int_{M_{\rm ecl,max}}^{M_{\rm ecl,max*}} \xi_{\rm ecl}(M_{\rm ecl})\, dM_{\rm ecl}$$

$\delta t = 10$ Myr

$M_{\rm ecl,min} = 5\ M_\odot$

$M_{\rm ecl,max*} \approx 10^7\ M_\odot$

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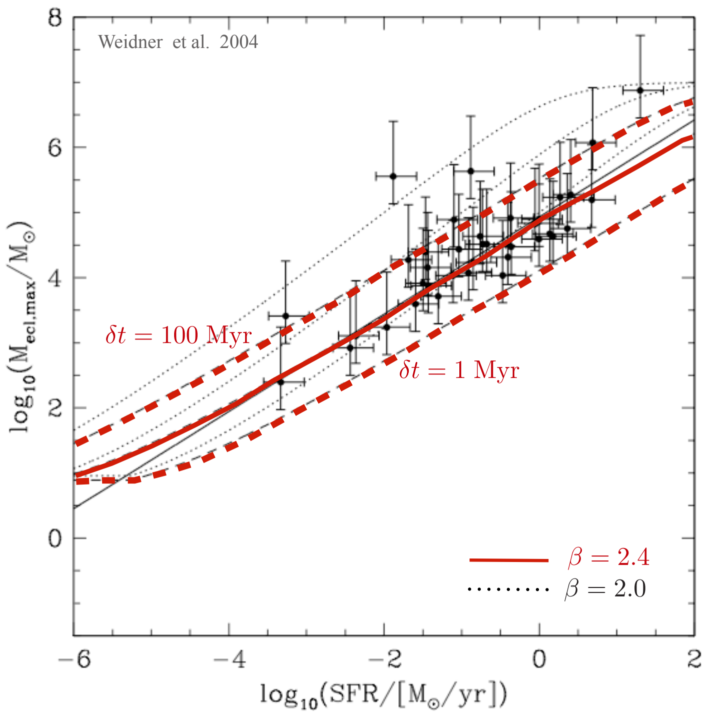

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THE ASTROPHYSICAL JOURNAL LETTERS, 775:L38 (6pp), 2013 October 1

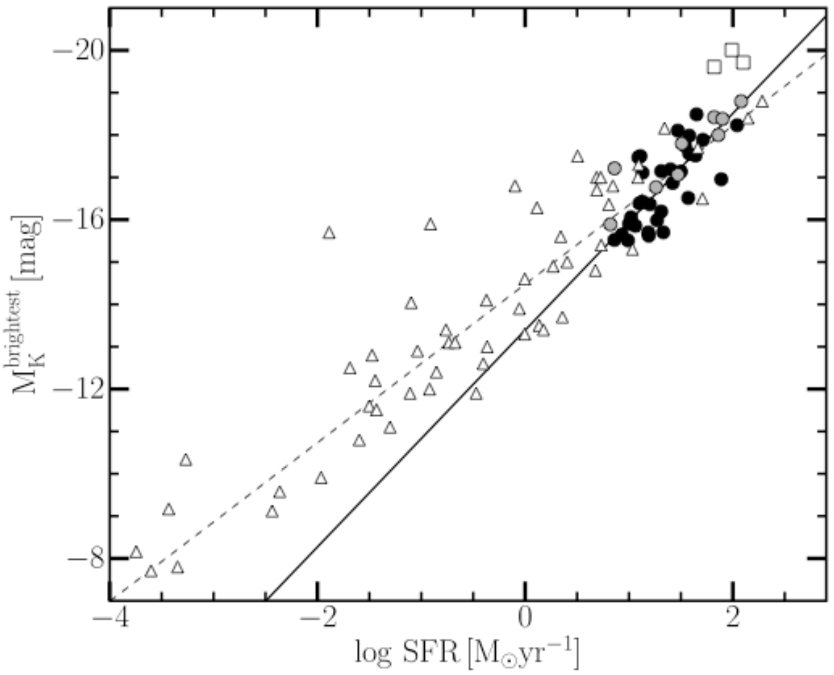

Figure 4. $M^{brightest}$–SFR relation with data from literature (the triangles; Adamo et al. 2011 and references therein) added to the present work (symbols as in Figure 1). The solid line is our best fit of Equation (3) and the dashed line is the fit from Weidner et al. (2004) to the optical V-band data after a constant $V - K = 2$ conversion.

Randriamanakoto, Escala, et al. 2013,

"In particular, the scatter in the relation is smaller than expected from pure random sampling strongly suggesting physical constraints."

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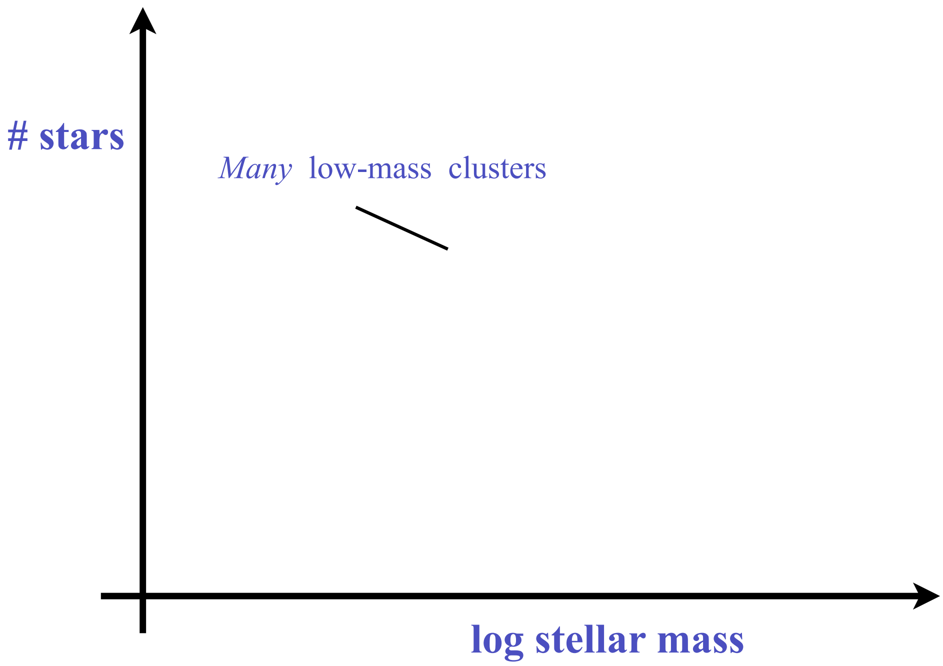
IGIMF = $\sum$ *of IMFs (in all CSFEs/ embedded clusters)*

Why is the IGIMF different to the IMF ?



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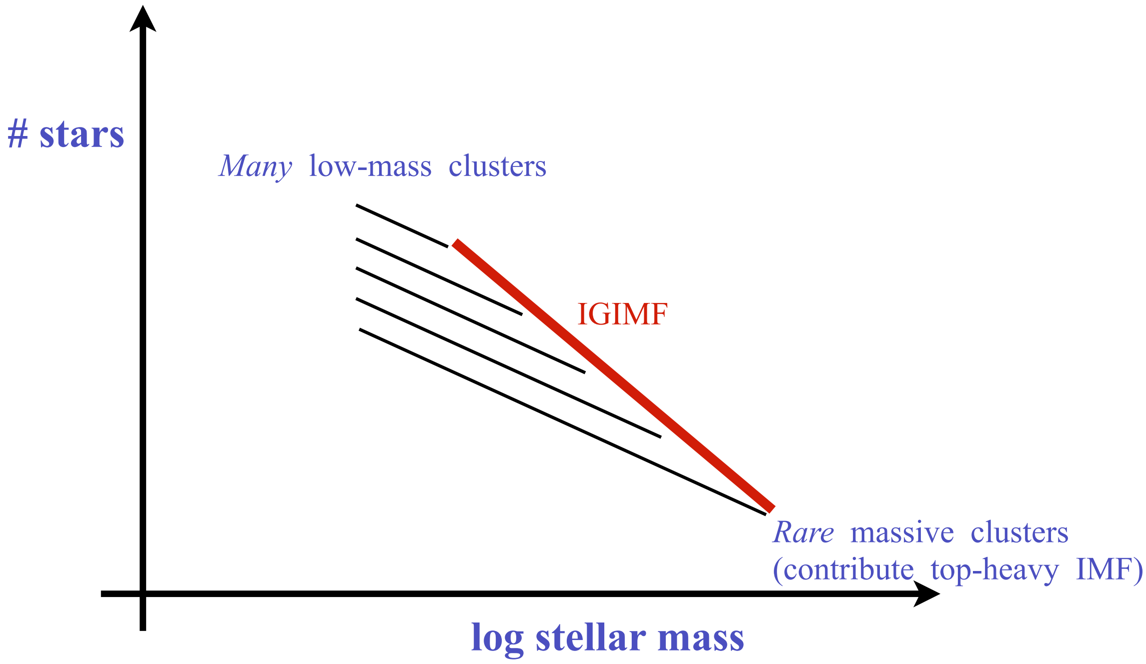
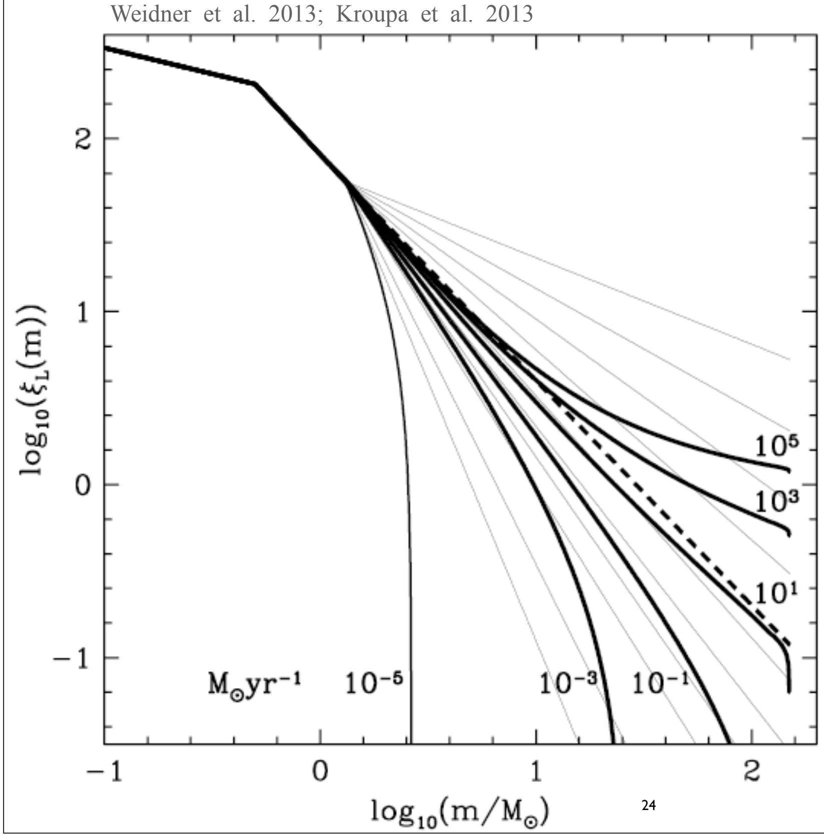


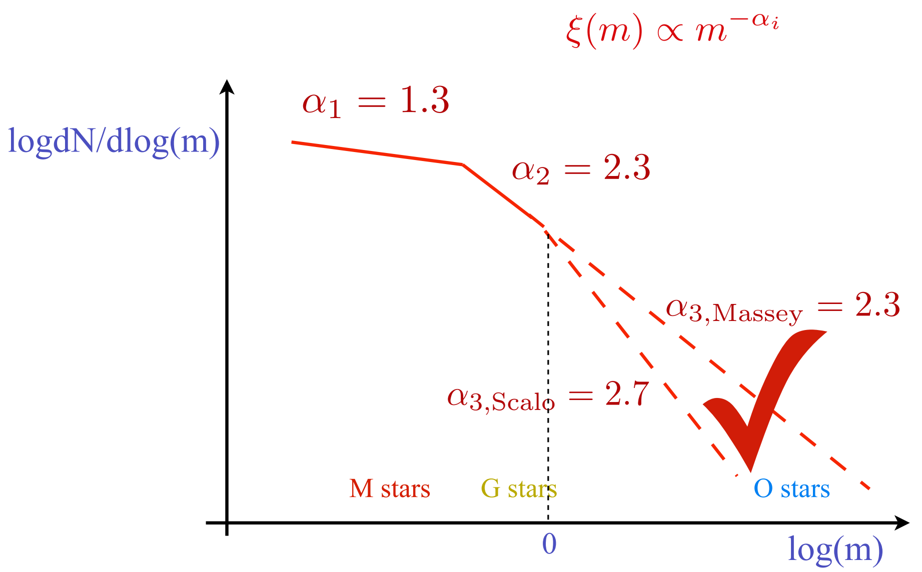
$$\xi_{\rm IGIMF}(m,t) = \int_{M_{\rm ecl,min}}^{M_{\rm ecl,max}(SFR(t))} \xi(m \le m_{\rm max}(M_{\rm ecl}))\ \xi_{\rm ecl}(M_{\rm ecl})\, dM_{\rm ecl}$$

Weidner et al. 2013; Kroupa et al. 2013



The IGIMF for galaxies with different SFRs

Return to the Scalo / Massey-Salpeter discrepancy :



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Recall:

Salpeter/Massey : $\alpha_3 = 2.3$ for individual clusters and OB associations

but

Scalo : $\alpha_3 = 2.7$ from Galactic-field star-counts

Independent evidence :

Tinsley 1980
Kennicutt 1983
Portinari et al. 2000
Romano et al. 2005

$2.5 \lesssim \alpha_3 \lesssim 2.7$

based on *spectro-photometric* and/or *chemical-evolution* modelling of the MW disk.

Reid et al. 2002 : $\alpha_3 = 2.5 - 2.8$ from Galactic-field star counts.

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Composite stellar populations have a steeper IMF than the stellar IMF :

Further observational evidence for steep galaxy-wide massive star IMF

MW disk : $\alpha = 2.5 - 2.7$ (Kennicutt 198n; Scalo 1986; Reid et al. 2002)

LSBs : bottom heavy IMF (Lee et al. 2005, MNRAS)

Dwarf NGC4214 : $\alpha > 2.8$ (Ubeda et al. 2007, AJ

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Counting stars => LF => PDMF => IMF

Remember :

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corrections for stellar evolution

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star-formation theory (*Jeans-mass vs self-regulation*) :
✓ - expect IMF variation with density and metallicity
? - unable to account for IMF shape

The IGIMF theory :

Natural explanation of the difference between the Scalo field IMF ($\alpha \approx 2.7$) and the stellar IMF ($\alpha \approx 2.3$).

Composite stellar populations can have a steeper IMF than the stellar IMF:

Further observational verification **?**

Use Hα flux to measure the number of $m > 10\,M_\odot$ stars forming. (see further below)

Use broad-band colours to measure the number of $m < 10\,M_\odot$ stars forming.

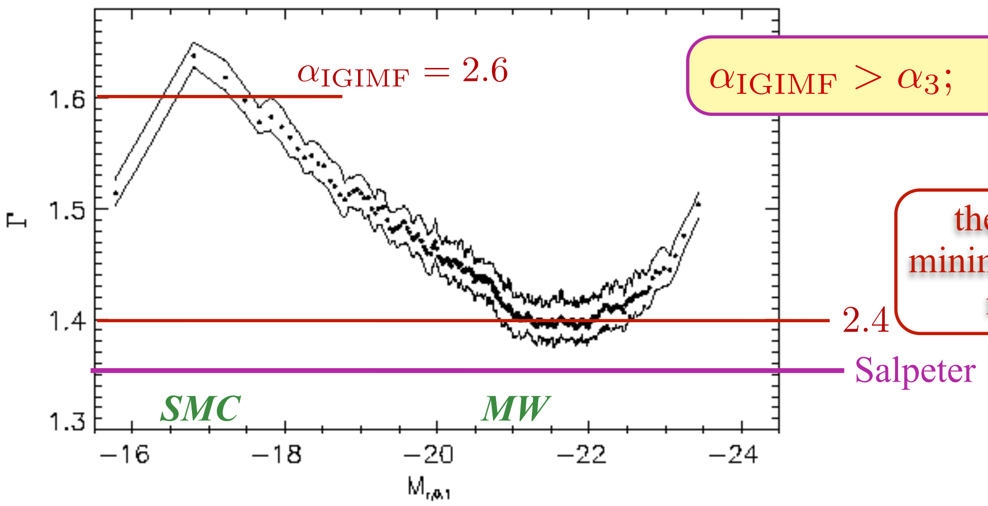
Observational constraints on the IMF in galaxies. (based on the method by Kennicutt 1983)

That is, use the count of ionising photons relative to bulk (optical) photons to estimate the slope of the galaxy-wide IMF (i.e. of the IGIMF) **:**

Composite stellar populations can have a steeper IMF than the stellar IMF:

Further observational verification **?**

$\alpha = \Gamma + 1$

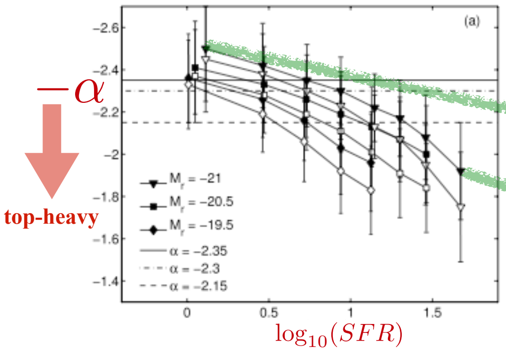


$\alpha_{\rm IGIMF} > \alpha_3; \quad m \gtrsim 1.3\,M_\odot$

theoretical minimal IGIMF model

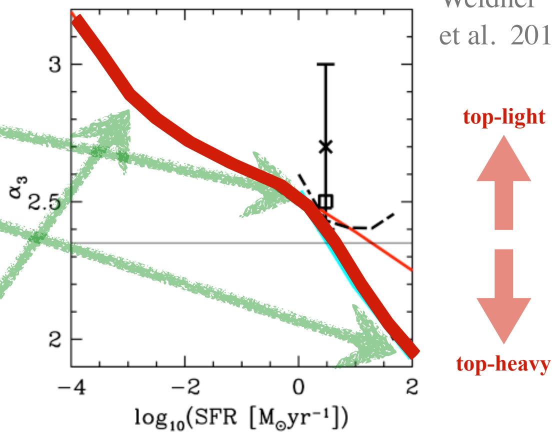
140 000 SDSS galaxies **:** Hoversten & Glazebrook (2007)

1660 *M. L. P. Gunawardhana et al.* ***2011***



IGIMF theory

Weidner et al. 2013



Very comparable / consistent results by

Hoversten E. A., Glazebrook K., 2008, ApJ, 675, 163

Meurer G. R. et al., 2009, ApJ, 695, 765

Lee, J. C. et al., 2009, ApJ, 706, 599

E galaxies
formed with
top-heavy IMFs

confirming Matteucci (1994) !

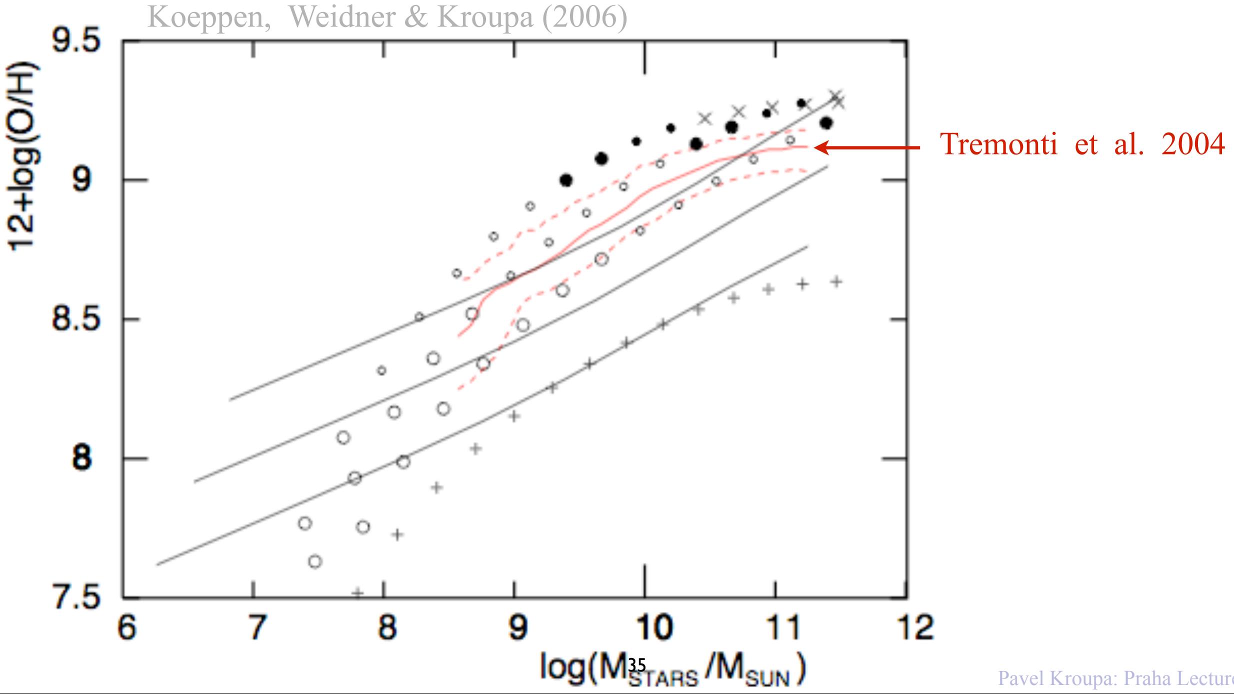
and see recent work by Vazdekis

Some implications

The mass-metallicity relation

The ***IGIMF theory*** naturally accounts for the *observed mass-metallicity relation* of galaxies !

Koeppen, Weidner & Kroupa (2006)



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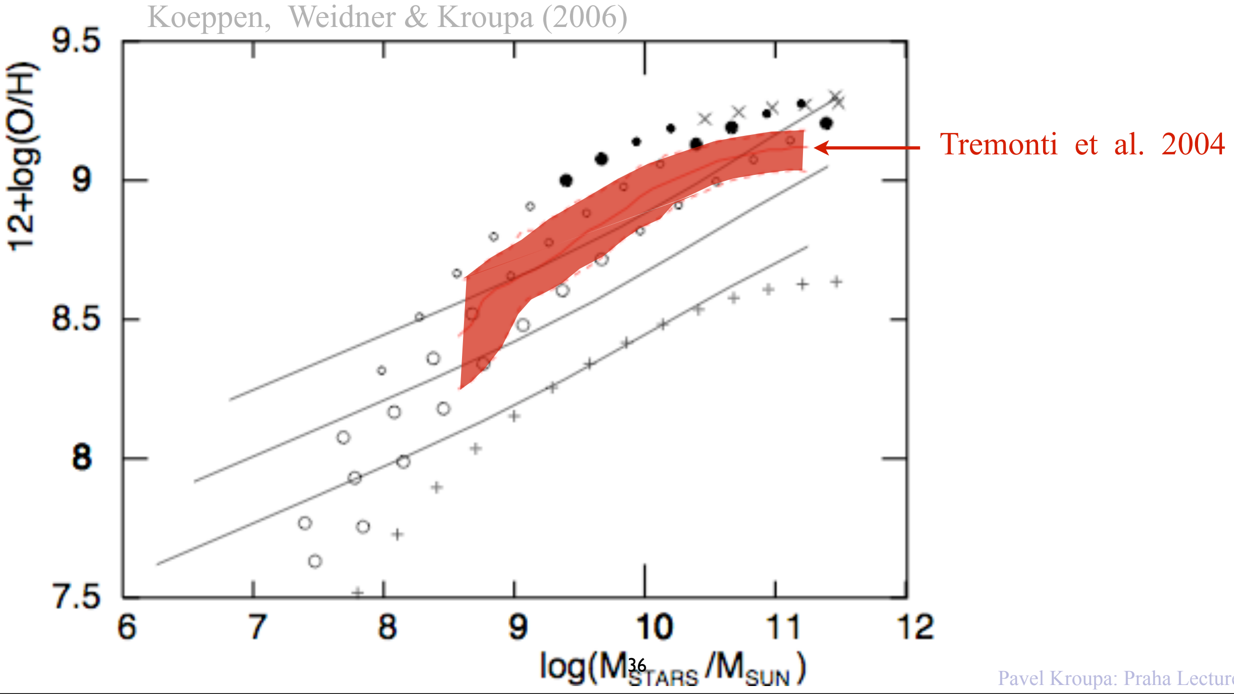

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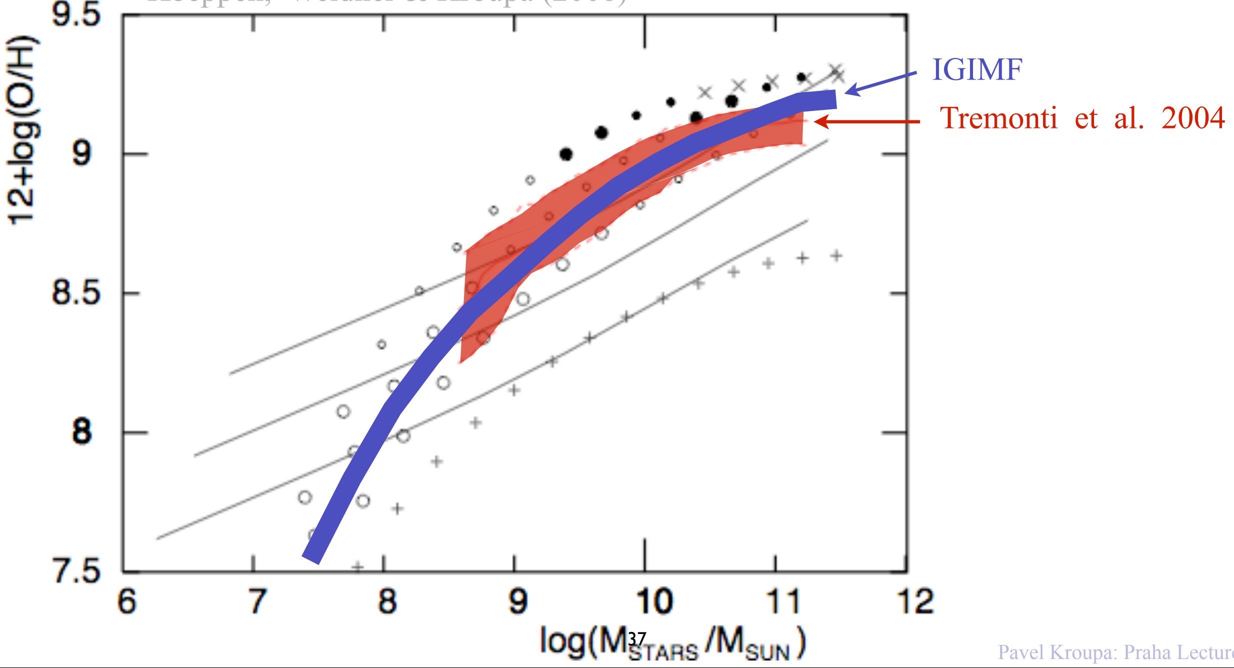

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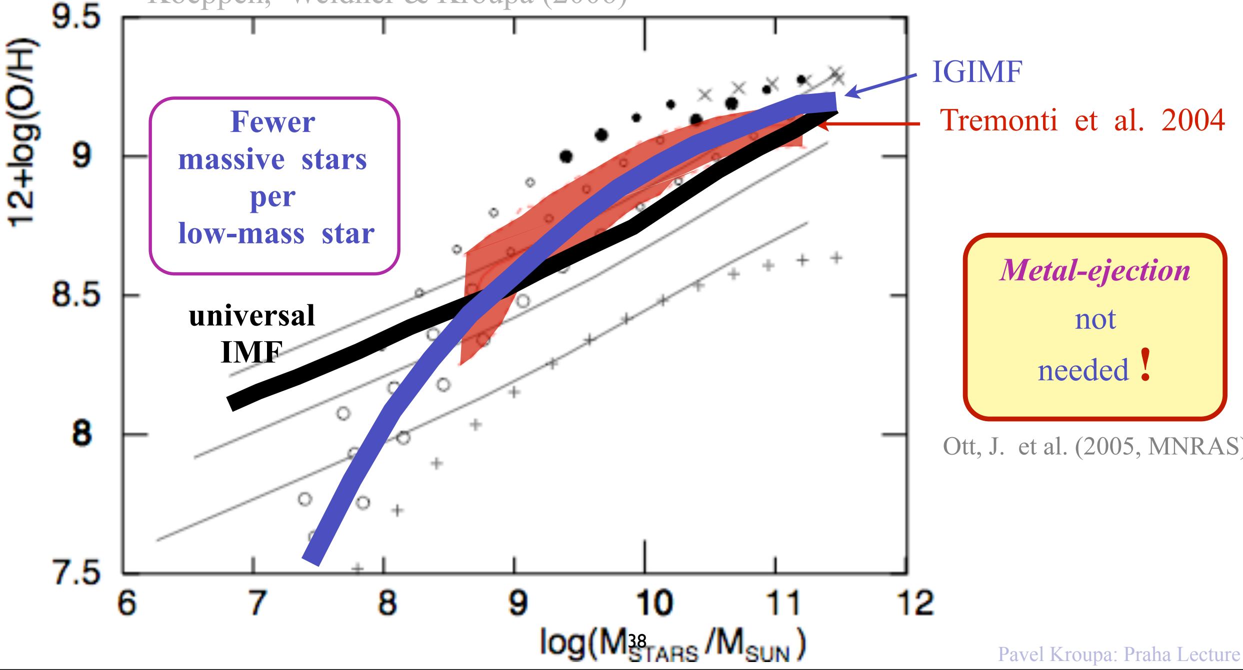

Metal-ejection not needed !

Ott, J. et al. (2005, MNRAS)

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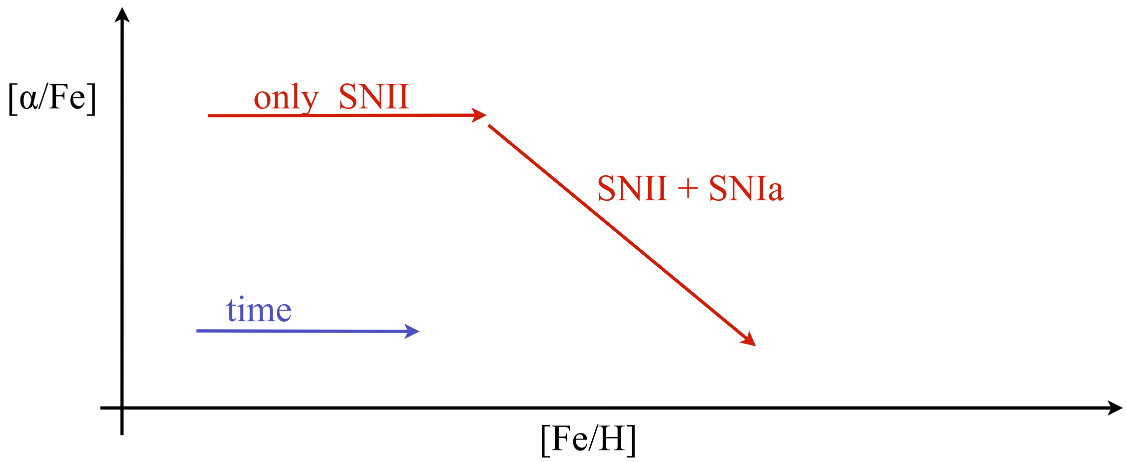
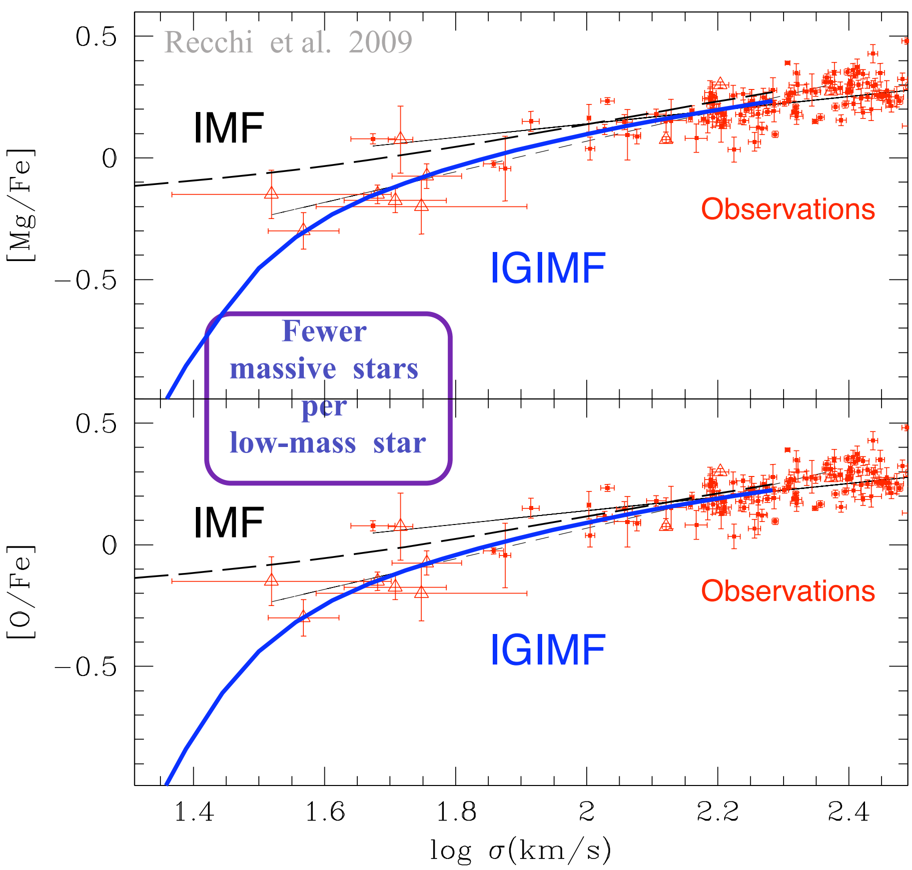
Chemical evolution of the interstellar medium (ISM) of a galaxy from which new stars form :

"alpha elements" (e.g. O, Mg) are injected into the inter stellar medium by SNII explosions.

Fe is injected into the inter stellar medium by SNII and SNIa explosions.





The ***IGIMF theory*** naturally accounts for the *observed* $[\alpha/\mathrm{Fe}] - \sigma$ *relation* of galaxies !

● Thomas et al. (2005)

△ Samson & Northeast (2008)

Metal-ejection not needed !

Ott, J. et al. (2005, MNRAS)

The IGIMF theory :

Natural explanation of the mass-metallicity relation of galaxies.

Some implications

The Halpha vs UV flux of galaxies

Kennicutt et al. (1994)

SFR relation

(for a pure Salpeter power-law IMF betw. 0.1 and 100 Msun)

$$\mathrm{SFR(total)} = \frac{L_{\mathrm{H}\alpha}}{1.26\times10^{41}\ \mathrm{erg\ s^{-1}}}\ M_\odot\ \mathrm{yr}^{-1}. \qquad (14)$$

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

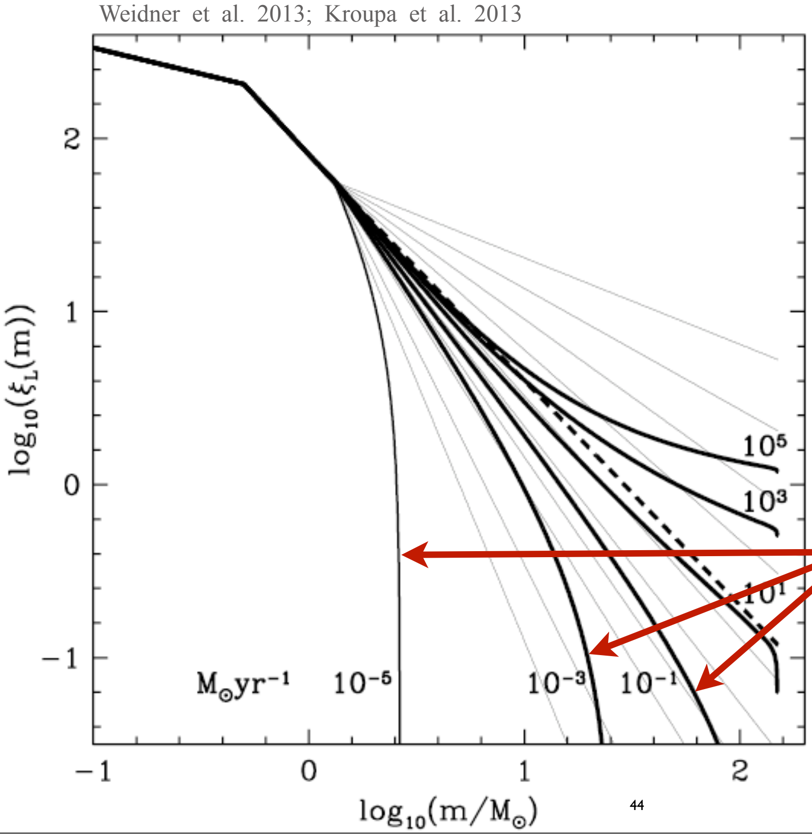
$$L_{\mathrm{H}\alpha} = \mu\ 3.0207\times10^{-12}\ \mathrm{erg}\ N_{\mathrm{ion}}/\delta t, \qquad (3)$$

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

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

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

Weidner et al. 2013; Kroupa et al. 2013



The IGIMF for galaxies with different SFRs

Expect :

IGIMF slope↑ with SFR↓

A further observational test

UV flux is sensitive to intermediate-mass stars with ages from 0 to 100 Myr.

A UV luminosity is therefore proportional to the SFR: $SFR_{UV} \propto L_{\rm UV}$
(Pflamm-Altenburg, Weidner & Kroupa 2009, submitted)

Hα luminosity is sensitive to massive stars ($m > 10\,M_\odot$) with life-times of a few Myr.

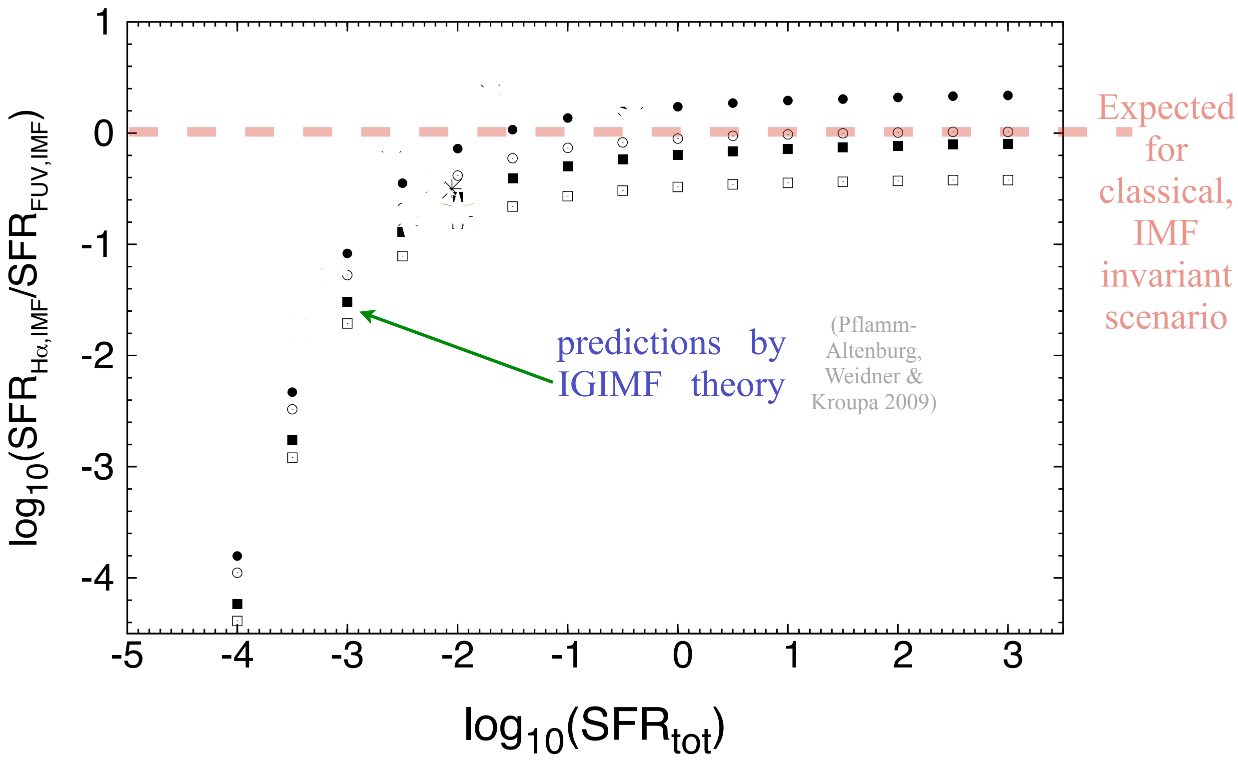
If the IMF=IGIMF and if it is invariant with the SFR (the classical, Kennicutt case), then expect

$$\boxed{\frac{SFR_{\rm H\alpha}}{SFR_{\rm UV}} = \text{const with } SFR}$$

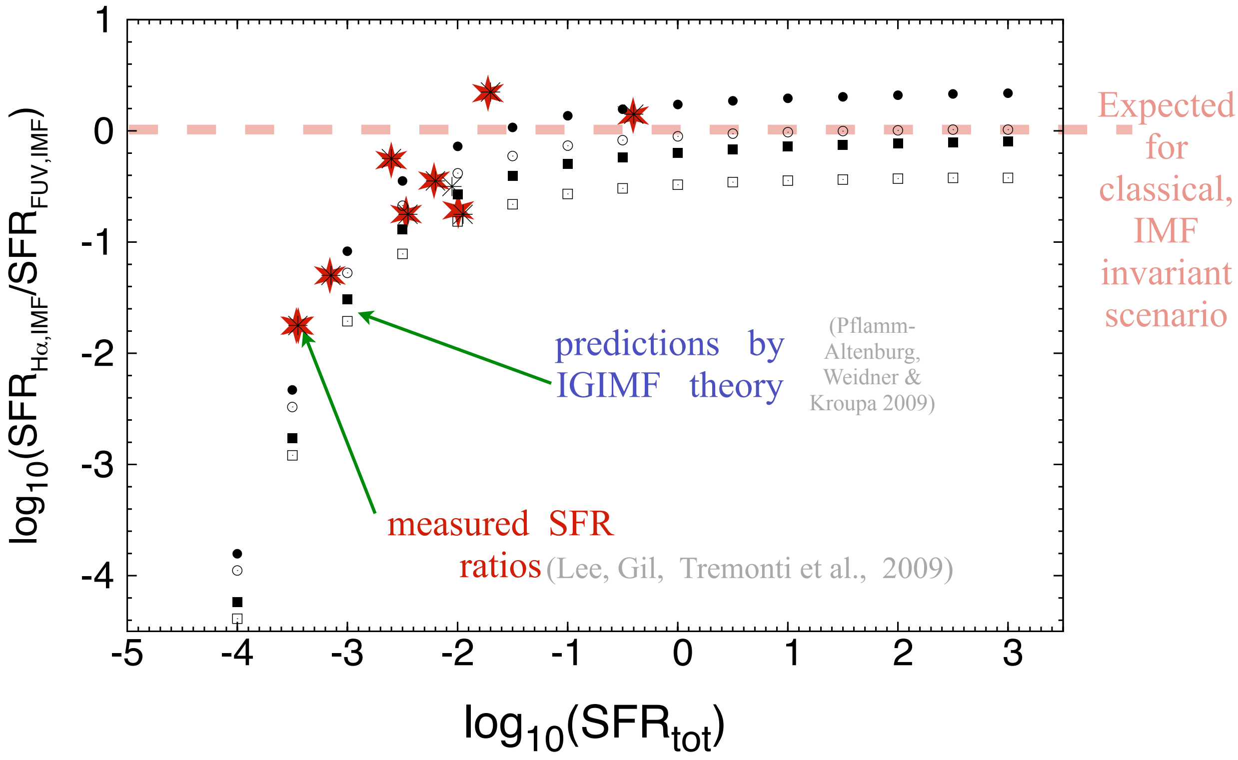
If the IMF≠IGIMF and if it varies with the SFR (the IGIMF-theory case), then expect

$$\boxed{\frac{SFR_{\rm H\alpha}}{SFR_{\rm UV}} \downarrow \text{ for } SFR \downarrow}$$

A further observational test



A further observational test



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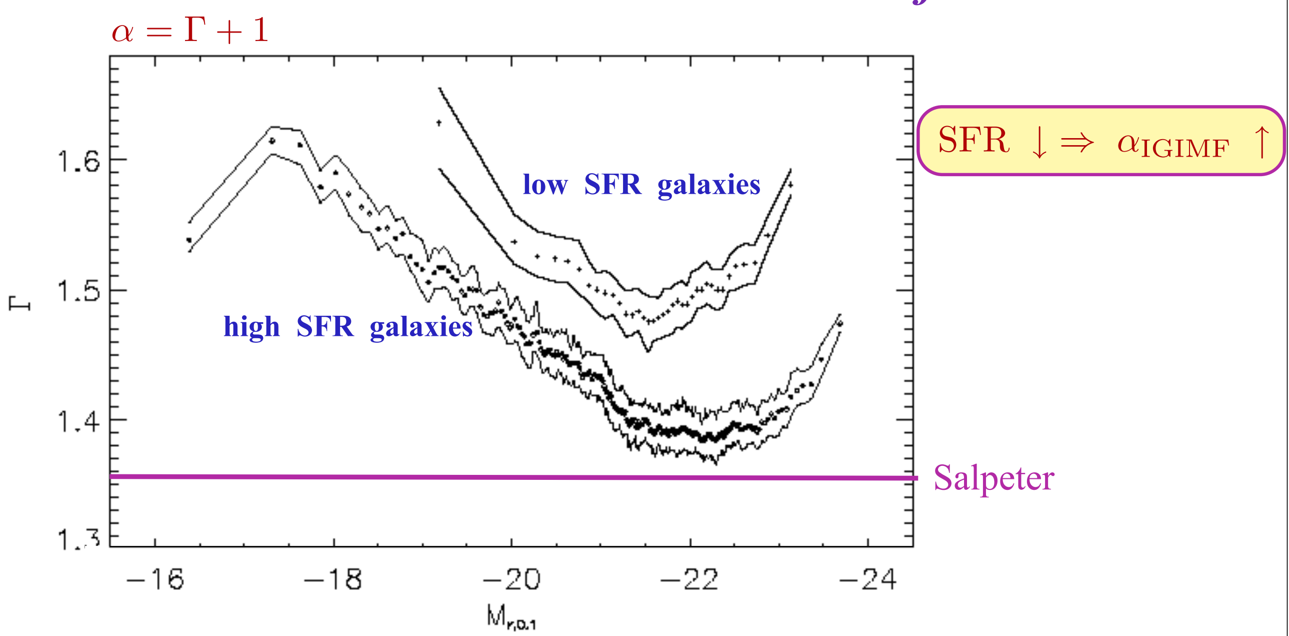
Composite stellar populations have a steeper IMF than the stellar IMF:

Observational verification **!!**



140 000 SDSS galaxies : Hoversten & Glazebrook (2007)

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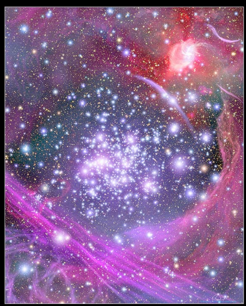
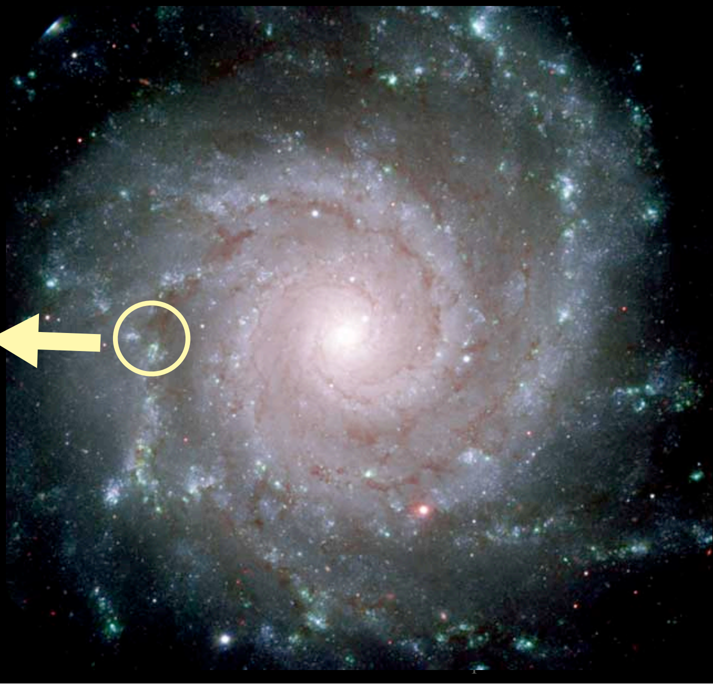
The *IGIMF theory* appears to be affirmed by observation.

Todo : compute Halpha / UV flux ratio for galaxies ith high SFRs.

Some implications

The radial cutoff
in Halpha/UV ratio
in disk galaxies

The local IGIMF and the radial star-formation cutoff in disk galaxies

$n \times$  $=$ 

Express the IGIMF in terms of local quantities :

(Pflamm-Altenburg & Kroupa 2008)

$$\Sigma_{\rm SFR}(x,y) = A\,\Sigma_{\rm gas}^{n}(x,y), \quad n=1$$
$$A^{-1} = 3\ {\rm Gyr}$$

(local Schmidt law, based on UV GALEX data) (Boissier et al. 2007; Zasov et al. 2005)

$$M_{\rm ecl,max,loc}(x,y) = M_{\rm ecl,max}\left(\frac{\Sigma_{\rm gas}(x,y)}{\Sigma_{\rm gas,0}}\right)^{\gamma}, \quad \gamma = 3/2$$

(ansatz - less massive clusters further out)

$$\xi_{\rm LECMF}(M_{\rm ecl},x,y) = \frac{dN_{\rm ecl}}{dM_{\rm ecl}\,dx\,dy}$$

$$\xi_{\rm LIGIMF}(m,x,y) = \int_{M_{\rm ecl,min}}^{M_{\rm ecl,max,loc}(x,y)} \xi_{M_{\rm ecl}}(m)\,\xi_{\rm LECMF}\,(M_{\rm ecl},x,y)\,dM_{\rm ecl}$$

= the local IGIMF = LIGIMF

. . . and study the emission of Hα photons as a function of local gas density and galactocentric radius . . .

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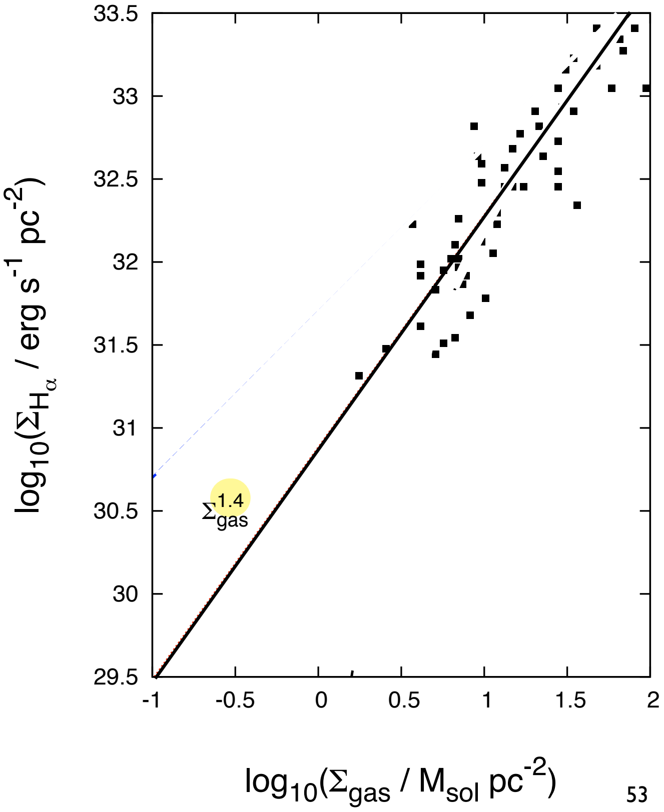
According to classical scenario (universal IMF=invariant IGIMF) :



- Hα surface luminosity vs local gas density at different radii in 7 disk galaxies .
  (Kennicutt ‘89 [data], ‘94, ‘98 [relation])

Hα emission scales with number of O stars, and IMF non-varying

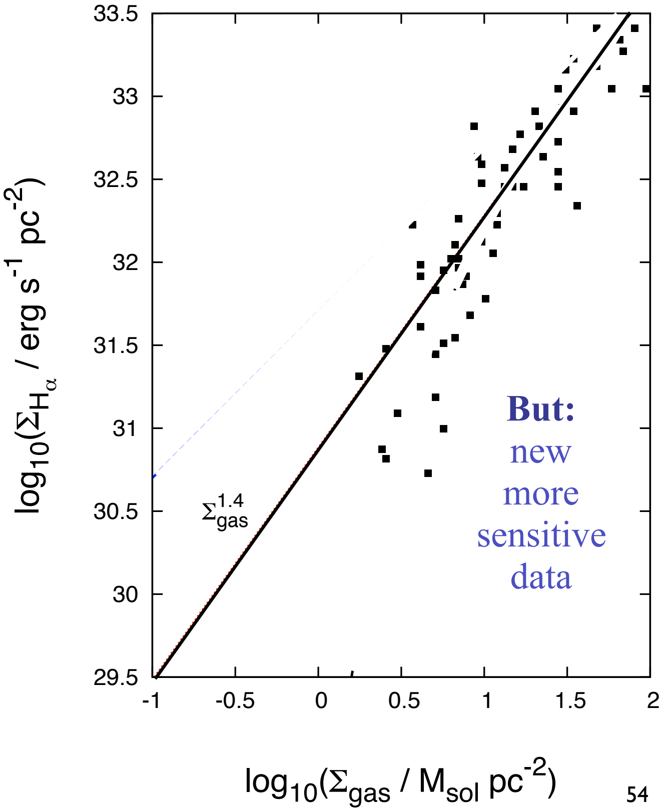
$\rightarrow$ $L_{\mathrm{H}\alpha} \propto SFR$

Measure Hα surface luminosity density and surface gas mass density.

$\rightarrow$ $\Sigma_{SFR,\mathrm{H}\alpha} \propto \Sigma_{\mathrm{H}\alpha} \propto \Sigma_{\mathrm{gas}}^{1.4}$

The Kennicutt SFR law.

According to classical scenario (universal IMF=invariant IGIMF) :



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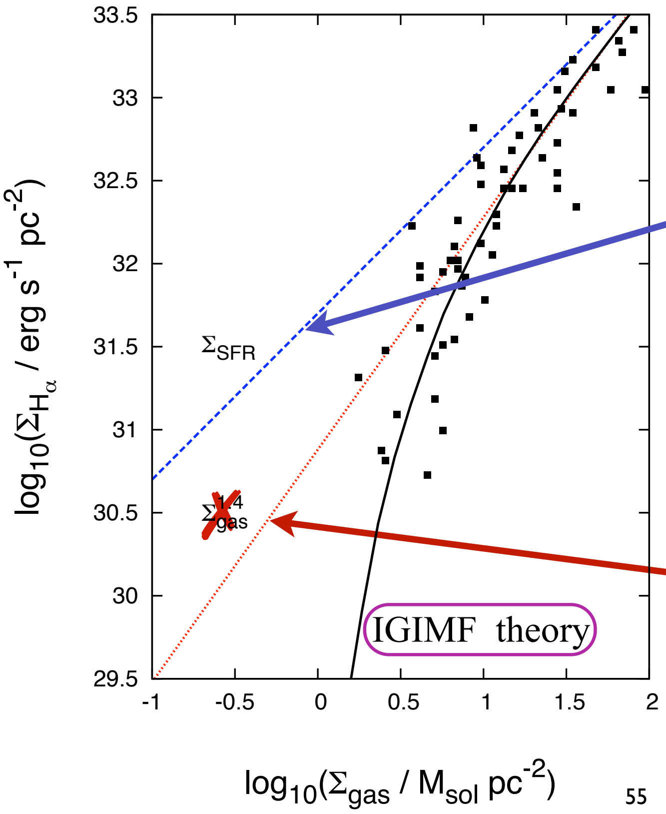
The Kennicutt SFR law.

Express the IGIMF in terms of local quantities :

(Pflamm-Altenburg & Kroupa 2008)



- Hα surface luminosity vs local gas density at different radii in 7 disk galaxies . (Kennicutt '89 [data], '94, '98 [relation])

True underlying SF density law :

$$\Sigma_{SFR} = \frac{1}{3\,\mathrm{Gyr}}\,\Sigma_{gas}$$ ✓

converted to Hα surface luminosity using standard (but wrong) linear (Kennicutt) Hα-SFR relation.

H$\alpha - \Sigma_{gas}$ relation based on standard (but wrong) Kennicutt SFR law $\Sigma_{SFR} = A\,\Sigma^{1.4}_{gas}$; ✗ it is a good (but wrong) fit to the bright data.

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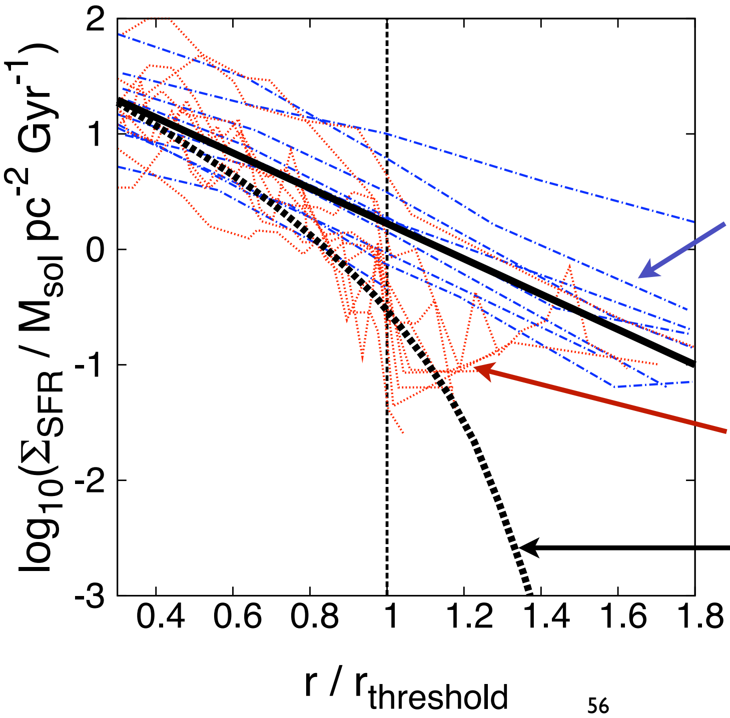
Express the IGIMF in terms of local quantities :

(Pflamm-Altenburg & Kroupa 2008)

9 observed disk galaxies :



SFR density from UV flux (Boissier et al. 2007)

(UV flux generated by intermediate-mass stars with ages 0-100 Myr, i.e not sensitive to O stars only !)

SFR density from Hα flux (Martin & Kennicutt 2001)

LIGIMF-theoretical Hα flux based on true law $\Sigma_{SFR} = A\,\Sigma_{gas}$

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The IGIMF theory :

Hα cutoff accounted for naturally.

True is $\Sigma_{\rm SFR} = \frac{1}{3\ {\rm Gyr}}\ \Sigma_{\rm gas}$

(i.e no radial cutoff in SF).

Theoretical models :

a threshold for star formation à la Hα cutoff

does not exist !

Some implications

The stellar-masss buildup times of dwarf galaxies

If dwarf galaxies would have as low SFRs as are implied by the standard theory (Kennicutt), then their blue-band luminosities are too high.

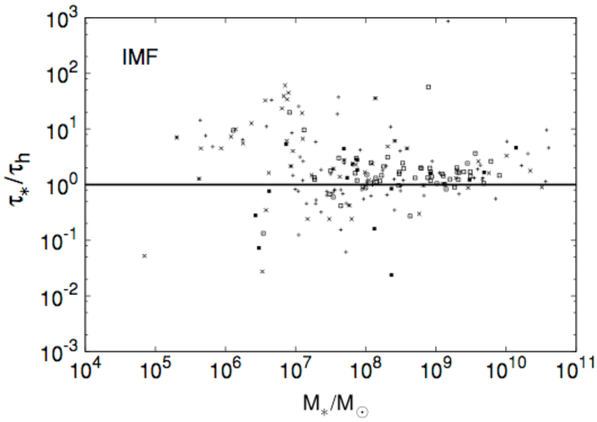


Figure 10. Stellar-mass buildup timescale in units of the Hubble time, τ_h = 13.7 Gyr, in dependence of the total stellar mass derived from the blue luminosity for a constant galaxy-wide IMF. Note that the buildup times for dwarf star-forming galaxies are longer than the ones for large disk galaxies. This implies that the SFRs of dwarf galaxies must have decreased faster over cosmic time than the SFRs of large disk galaxies. This is in contradiction to the finding of downsizing according to which the SFRs of large disk galaxies must have decreased faster over cosmic time than the SFRs of dwarf galaxies. The symbols are the same as in Figure 2.

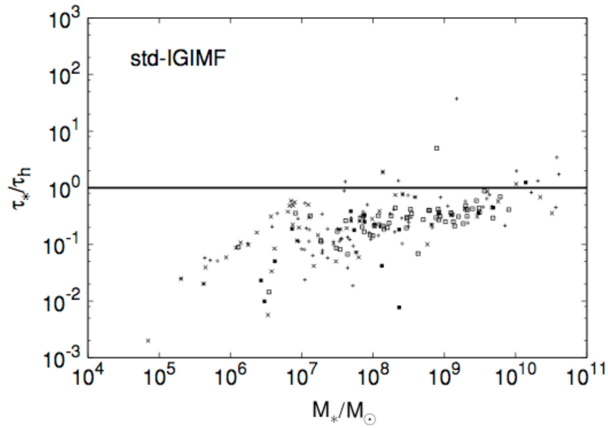


Figure 11. Same as Figure 10 but for the standard IGIMF. Note that the stellar-mass buildup times, which result from SFR calculations in the IGIMF context, decrease with decreasing galaxy mass. This suggest that the SFR may have been increasing slightly with time for dwarf galaxies or that they were forming stars over a more recent epoch while for massive disk galaxies the SFHs may be constant, which is in agreement with downsizing. The symbols are the same as in Figure 2.

Pflamm-Altenburg & Kroupa 2009, ApJ

Within the *IGIMF theory* (fewer massive stars at low SFRs) can the stellar masses of dwarf galaxies be formed within a Hubble time.

Some implications

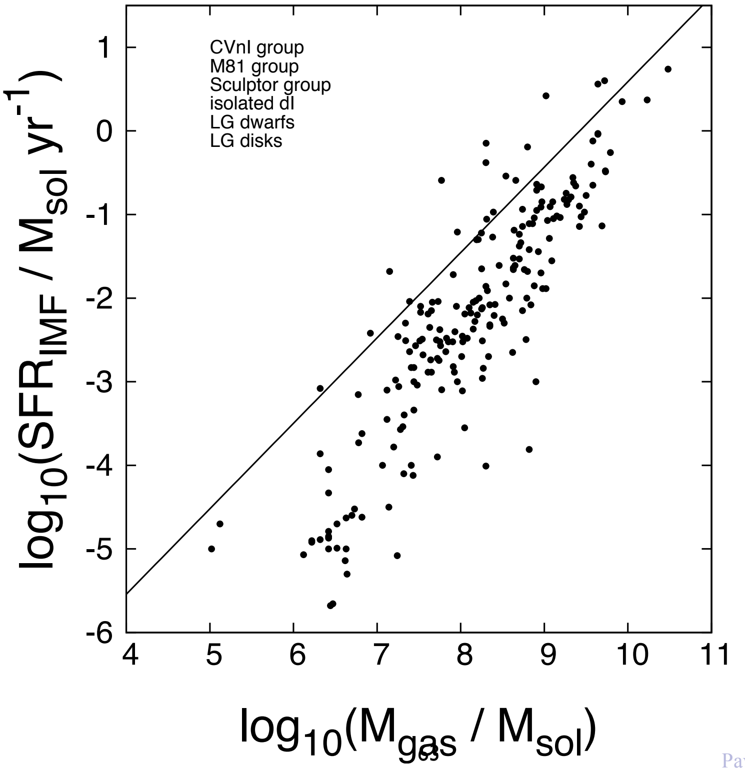
The gas-consumption time-scales
and
implications for the
matter cycle

The traditional view :

Dwarf galaxies as
modest consumers

SFR vs gas mass : **traditional**

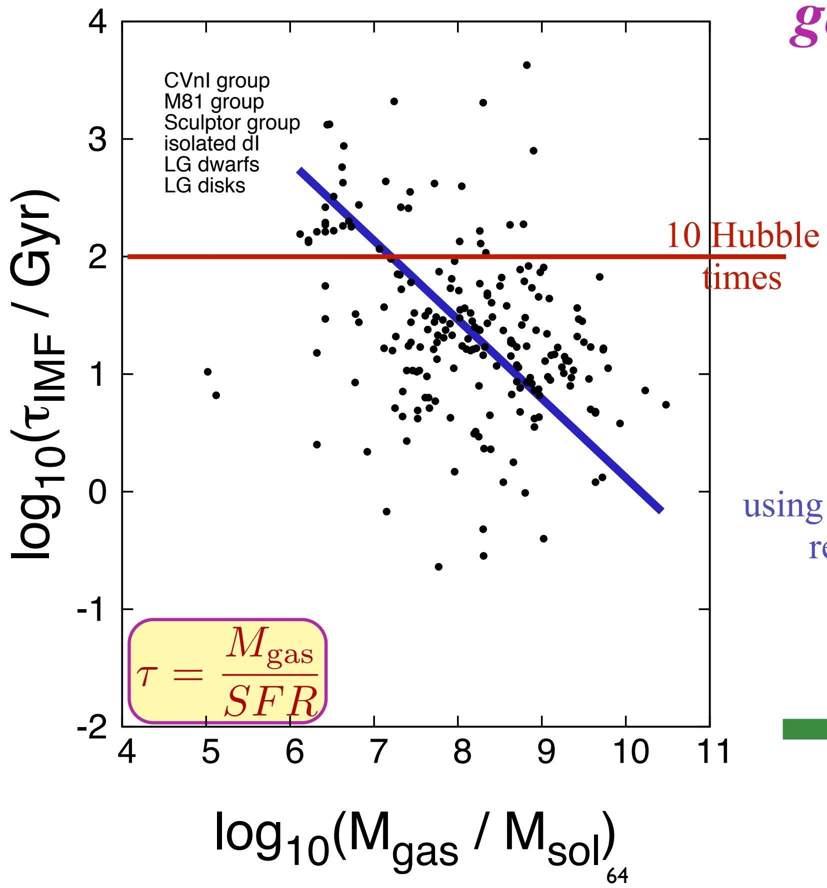
(using linear Kennicutt relation to convert Hα flux to SFR.)



Pflamm-Altenburg, Weidner & Kroupa (2007); Pflamm-Altenburg & Kroupa (2008)

Pflamm-Altenburg, Weidner & Kroupa (2007); Pflamm-A. & Kroupa (2008)

gas-consumption time scale vs gas mass



using Kennicutt relation

~~Dwarf galaxies consume their gas very carefully, very slowly !~~

According to the IGIMF theory :

Dwarf galaxies as insattiable consumers

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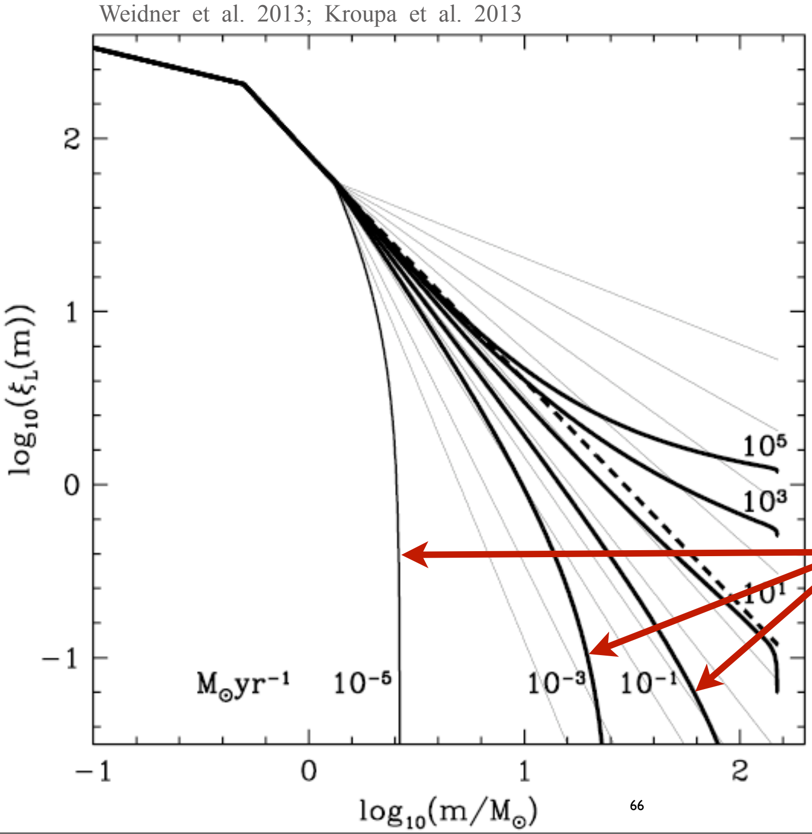
$$\xi_{\rm IGIMF}(m,t) = \int_{M_{\rm ecl,min}}^{M_{\rm ecl,max}(SFR(t))} \xi(m \le \underline{m_{\rm max}(M_{\rm ecl})})\ \underline{\xi_{\rm ecl}(M_{\rm ecl})}\, dM_{\rm ecl}$$

Weidner et al. 2013; Kroupa et al. 2013



Back to the integrated-galaxy view.

The IGIMF has fewer ionising photons !

Expect :

IGIMF slope↑ with SFR↓

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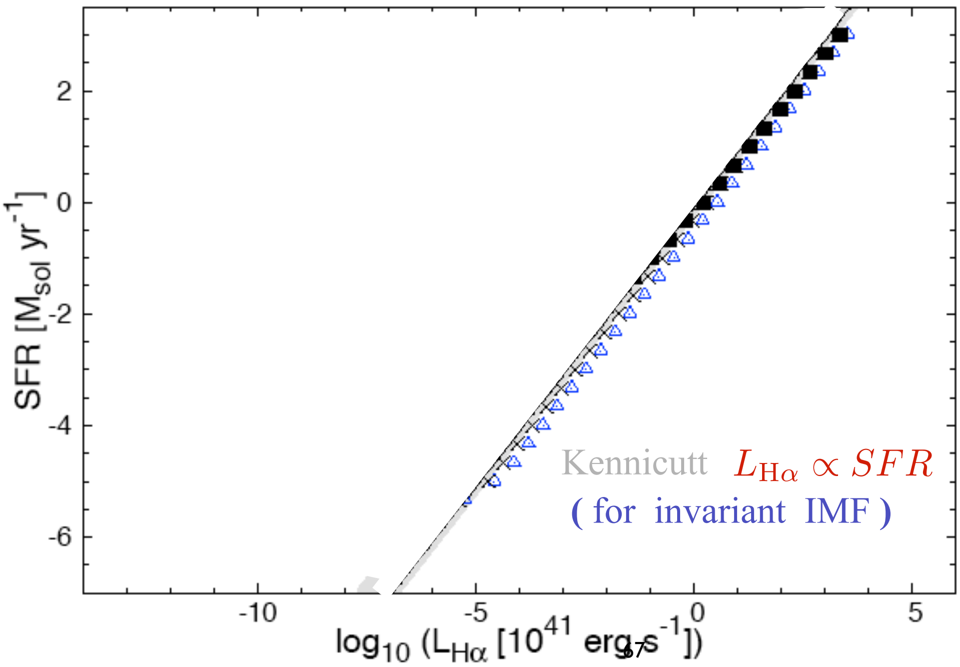
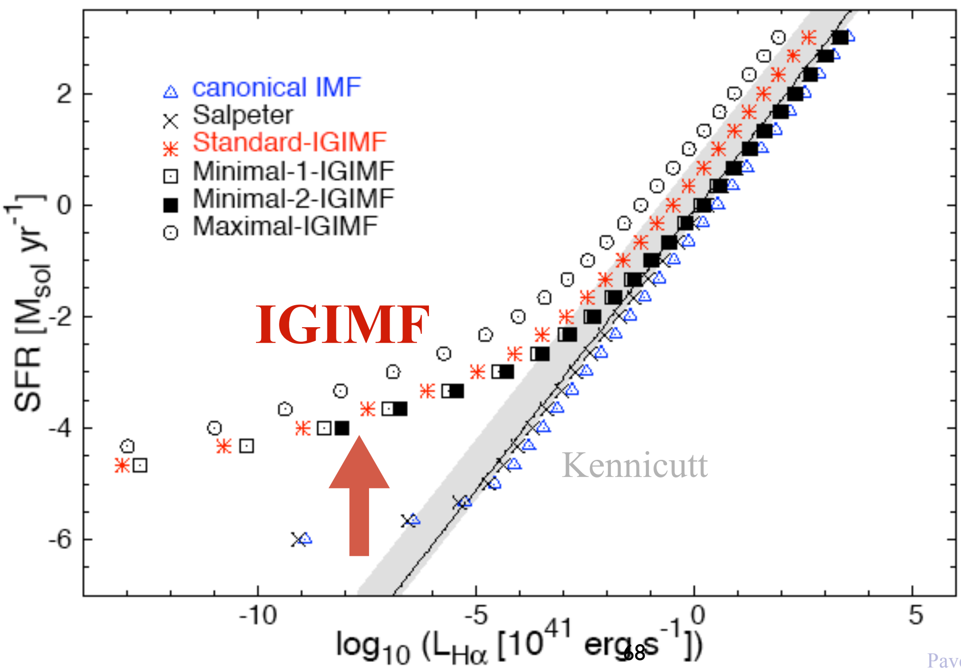
The ***variable IGIMF notion*** → revision of the $L_{\mathrm{H}\alpha} - SFR$ *relation* (the Kennicutt relation) !



Pflamm-Altenburg, Weidner & Kroupa (2007)

The ***variable IGIMF notion*** → revision of the $L_{\mathrm{H}\alpha} - SFR$ *relation* (the Kennicutt relation) !



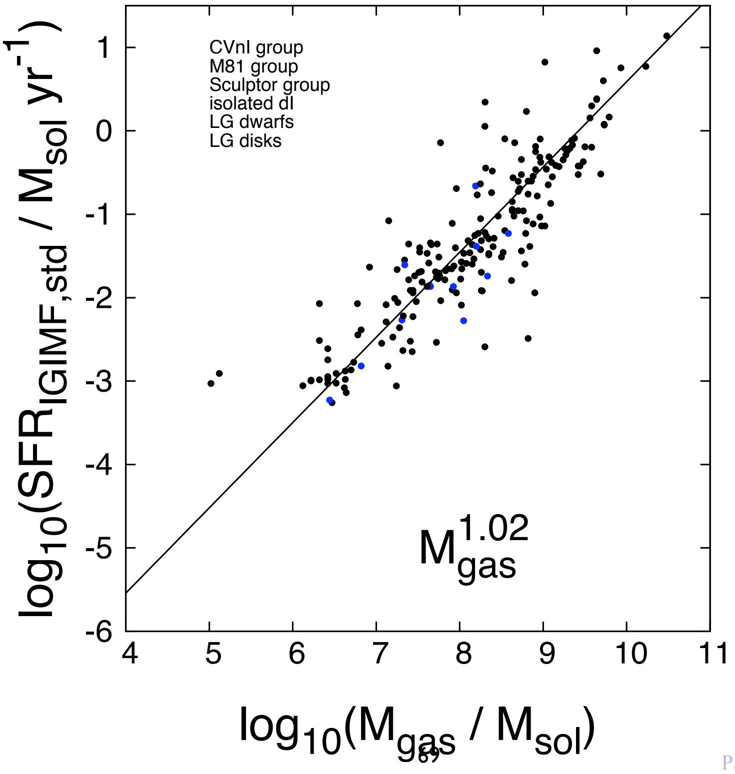
Pflamm-Altenburg, Weidner & Kroupa (2007)

Deficit of massive stars in the IGIMF

→ ***increased SFR***

SFR vs gas mass : **new**

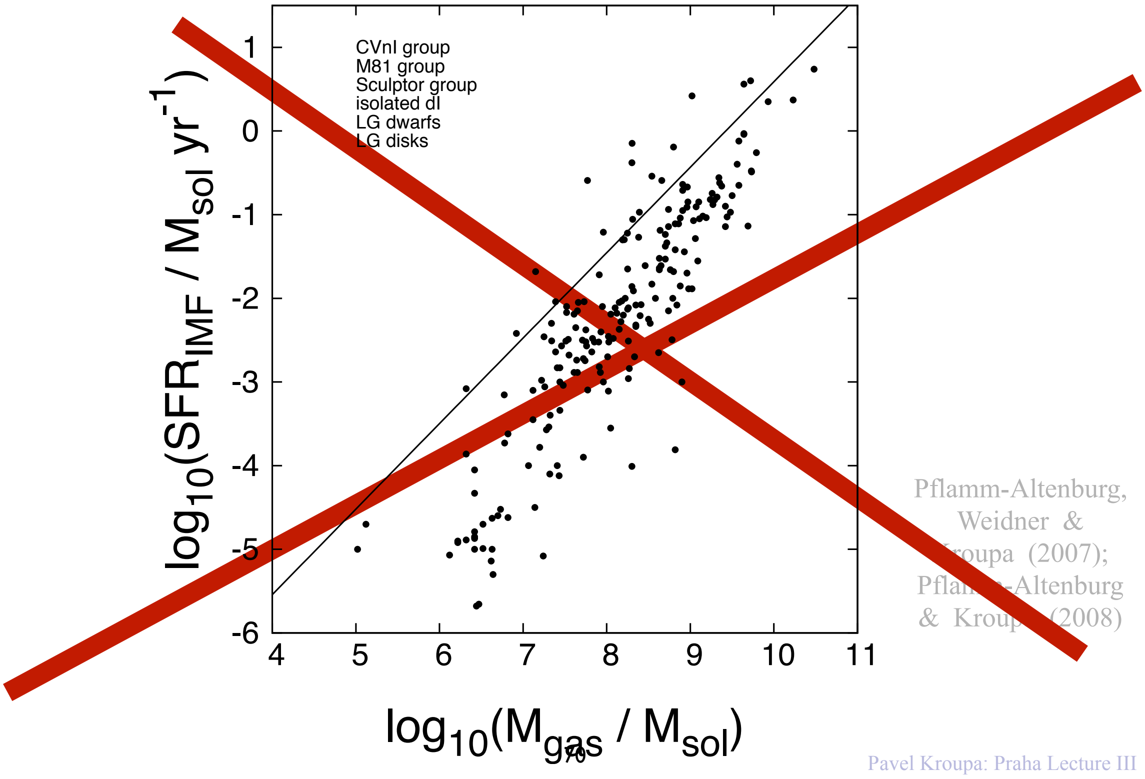
(using IGIMF theory)



Pflamm-Altenburg, Weidner & Kroupa (2007); Pflamm-Altenburg & Kroupa (2008)

SFR vs gas mass : **traditional (again)**

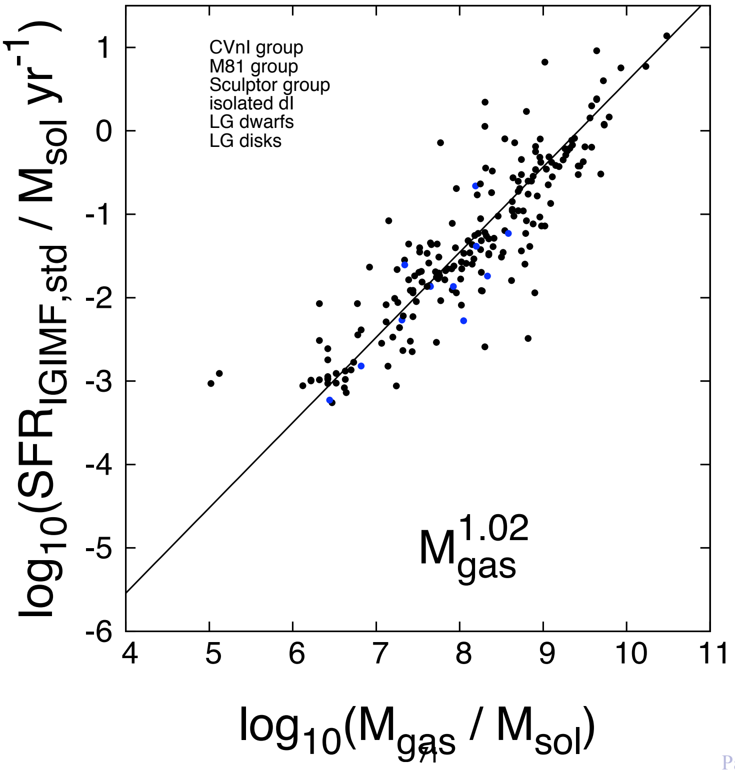
(using linear Kennicutt relation to convert $H\alpha$ flux to SFR.)



Pflamm-Altenburg, Weidner & Kroupa (2007); Pflamm-Altenburg & Kroupa (2008)

SFR vs gas mass : **new (again)**

(using IGIMF theory)

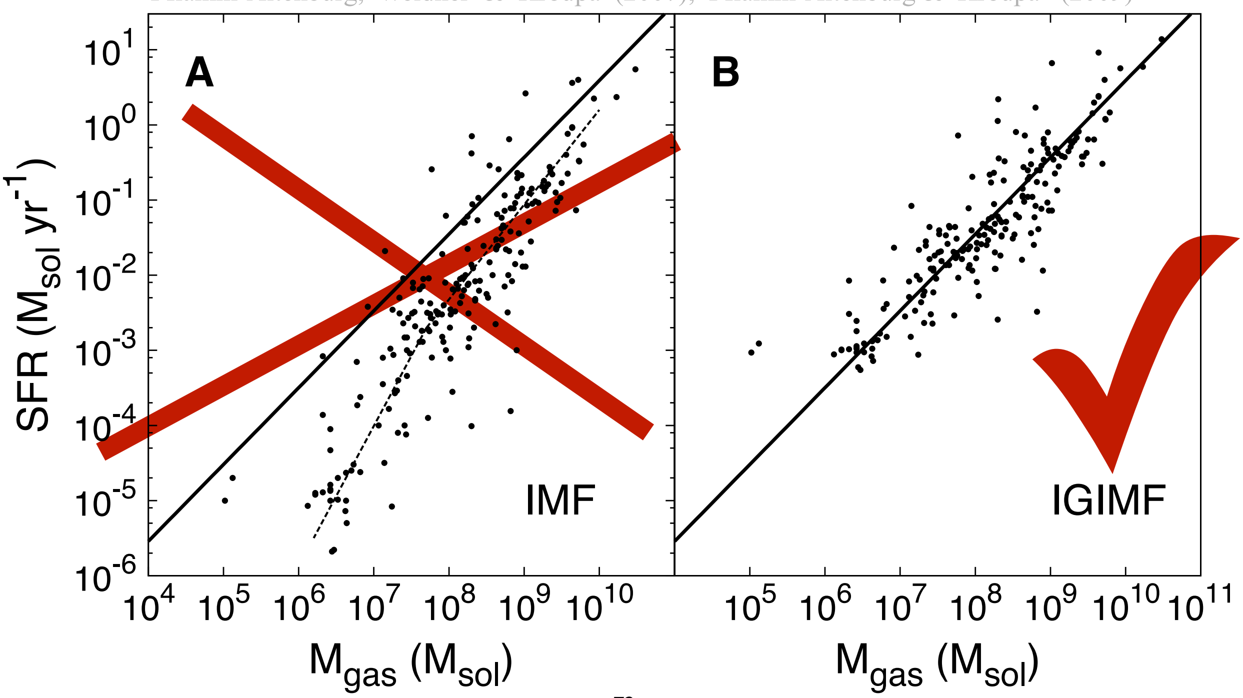


Pflamm-Altenburg, Weidner & Kroupa (2007); Pflamm-Altenburg & Kroupa (2008)

SFR vs gas mass :

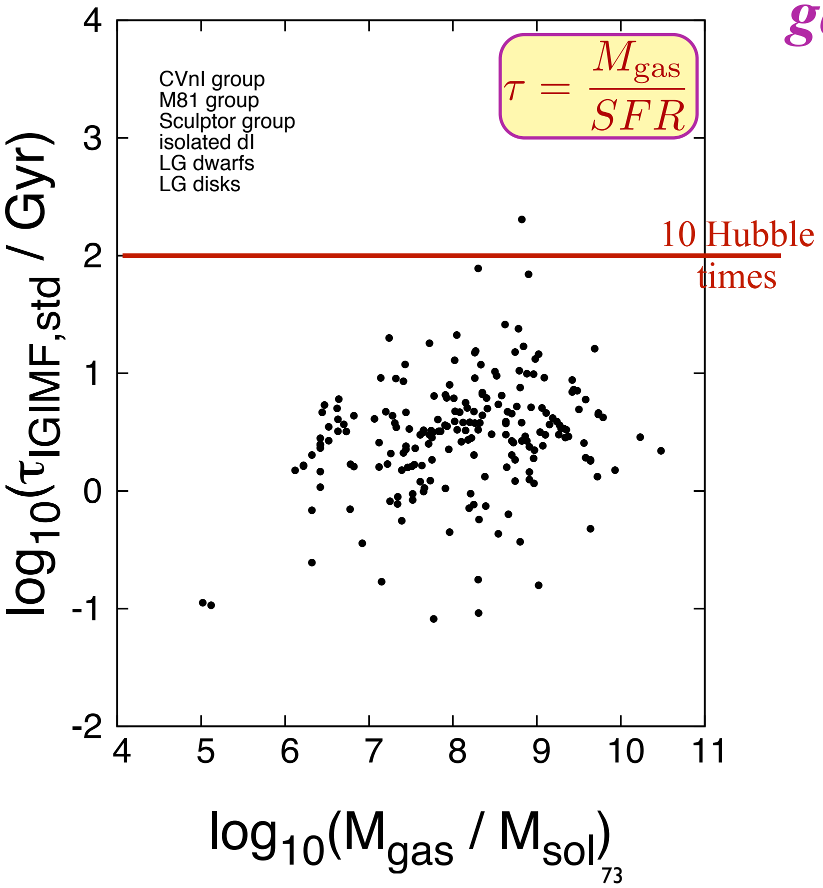
(traditional: invariant IMF) (using IGIMF theory)

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



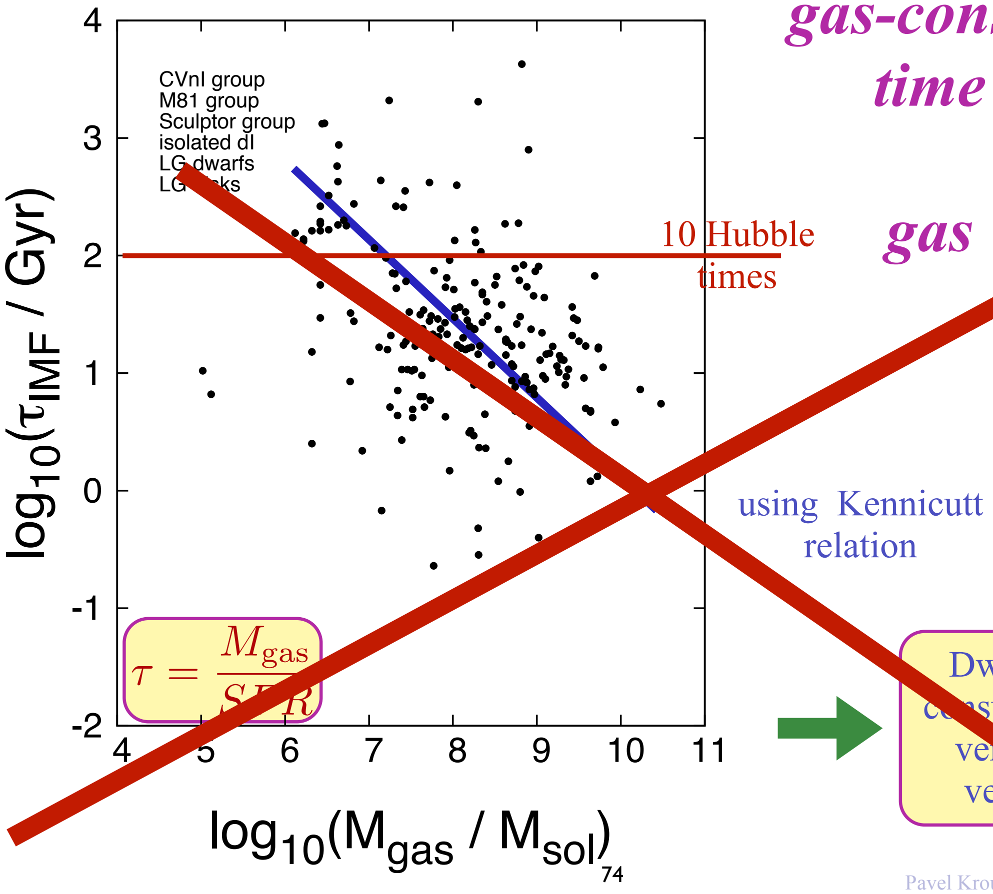
Pflamm-Altenburg, Weidner & Kroupa (2007); Pflamm-A. & Kroupa (2008)

gas-consumption time scale vs gas mass



Pflamm-Altenburg, Weidner & Kroupa (2007); Pflamm-A. & Kroupa (2008)

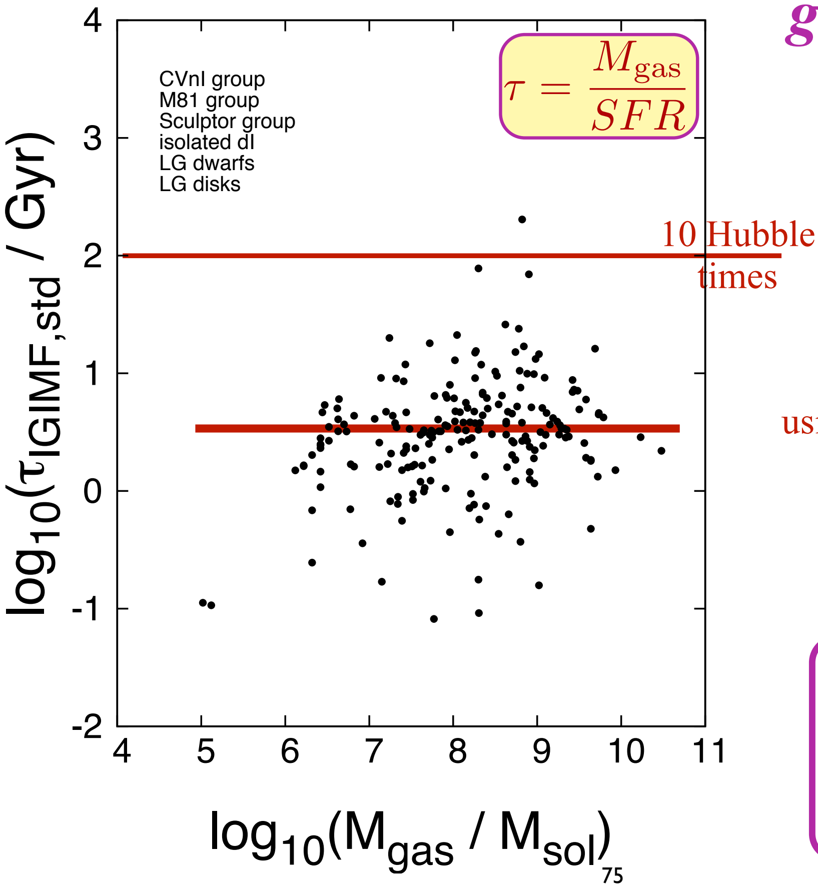
gas-consumption time scale vs gas mass



Dwarf galaxies consume their gas very carefully, very slowly !

Pflamm-Altenburg, Weidner & Kroupa (2007); Pflamm-A. & Kroupa (2008)

gas-consumption time scale vs gas mass

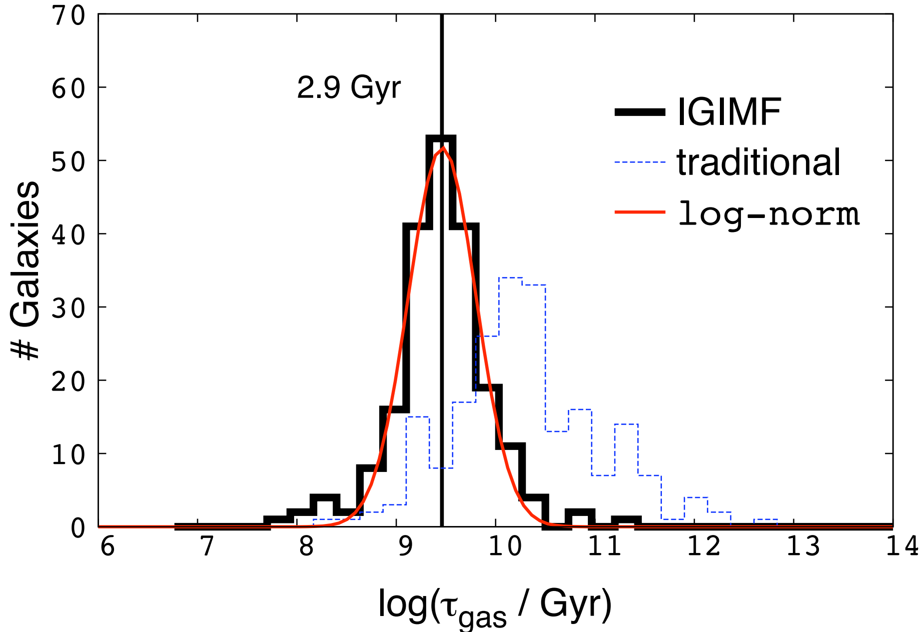


using IGIMF theory

IGIMF theory

constant gas depletion time-scale !

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



Pflamm-Altenburg, Weidner & Kroupa (2007); Pflamm-A. & Kroupa (2008)

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

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

Pflamm-Altenburg, Weidner & Kroupa (2007); Pflamm-A. & Kroupa (2008)

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

But

where is all the star-forming gas coming from at just the right rate **?**

Further work is required

These are possible research projects.

- Unify the local and the galaxy-wide / global IGIMFs (theoretical) .
- Compute Halpha/UV flux ratios, photometric properties and M/L ratios of galaxies with different SFRs and SFHs (theoretical)
- Test IGIMF theory via diret counts of O stars in nearby dwarf galaxies with low SFRs (see predictions in Weidner et al. 2013) :

Table 3. The expected number of O and B stars in a galaxy in dependence of the SFR of the galaxy. Columns 2 and 3 are the expected number of O and B stars for the canonical invariant IMF between the mass limits of 0.1 and 100 $M_\odot$. Columns 4–9 are the numbers for three different IGIMF models. Columns 4 and 5 are for IGIMF model I with constant $\alpha_3 = 2.35$ for the IMF and constant $\beta = 2$ for the ECMF. In columns 6 and 7 are the IGIMF model II that are top-heavy because $\alpha_3 = \mathrm{fn}(\rho_{\mathrm{ecl}})$ as described by equation (2). And for columns 8 and 9 (model III), α_3 varies as for columns 6 and 7 but also $\beta = \mathrm{fn}(\mathrm{SFR})$. In columns 4, 6 and 8 the B star numbers are given in fractions of column 2, while in columns 5, 7 and 9 the O star numbers are given in fractions of column 3. In order to, for example, calculate the actual number of expected O stars for IGIMF I with constant α_3 and β for a SFR of 1 $M_\odot$ yr^{-1} the 32 313 expected O stars from the canonical IMF have to be multiplied by 0.51 and therefore only 16 157 O stars are to be expected.

SFR ($M_\odot$ yr^{-1}) (1)	B 3–18 $M_\odot$ IMF (2)	O 18$^+$ $M_\odot$ IMF (3)	B 3–18 $M_\odot$ $\alpha_3 = 2.35$ $\beta = 2$ IGIMF I (4)	O 18$^+$ $M_\odot$ $\alpha_3 = 2.35$ $\beta = 2$ IGIMF I (5)	B 3–18 $M_\odot$ $\alpha_3 = \mathrm{fn}(\rho_{\mathrm{ecl}})$ $\beta = 2$ IGIMF II (6)	O 18$^+$ $M_\odot$ $\alpha_3 = \mathrm{fn}(\rho_{\mathrm{ecl}})$ $\beta = 2$ IGIMF II (7)	B 3–18 $M_\odot$ $\alpha_3 = \mathrm{fn}(\rho_{\mathrm{ecl}})$ $\beta = \mathrm{fn}(\mathrm{SFR})$ IGIMF III (8)	O 18$^+$ $M_\odot$ $\alpha_3 = \mathrm{fn}(\rho_{\mathrm{ecl}})$ $\beta = \mathrm{fn}(\mathrm{SFR})$ IGIMF III (9)
10^{-5}	4	0	0	0	0	0	0	0
10^{-4}	36	3	0.55	0	0.55	0	0.55	0
10^{-3}	356	31	0.66	0.04	0.66	0.04	0.66	0.04
10^{-2}	3559	313	0.77	0.25	0.77	0.25	0.77	0.25
10^{-1}	35 594	3135	0.83	0.40	0.83	0.40	0.83	0.40
10^{0}	355 939	31 347	0.86	0.51	**0.87**	**0.58**	**0.87**	**0.55**
10^{1}	3559 386	313 472	0.88	0.58	**0.90**	**0.88**	**1.06**	**1.31**
10^{2}	35 593 862	3134 724	0.90	0.64	**0.89**	**1.22**	**1.02**	**2.17**
10^{3}	355 938 622	31 347 240	0.91	0.68	**0.84**	**1.54**	**0.92**	**2.57**
10^{4}	3559 386 217	313 472 403	0.92	0.71	**0.79**	**1.80**	**0.82**	**2.84**

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END of Lecture 3

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