Radiation-driven and wind-blown HII Regions and the Energy Transfer Efficiency by Massive Stars

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Motivation: Massive stars affect ISM + galactic evolution most dominantly

✓ Energy: enormous luminosities in all evolutionary stages

⇒ Feedback: energy input vs. cooling

⇒ negative star-formation feedback

✓ Dynamics: energy release stirs-up the ISM

⇒ gas compression, turbulence, mixing, galactic winds

⇒ star-formation feedback positive + negative

✓ Chemistry: rapid release of mainly α elements thru SNe type II, but also CNO by WR winds

⇒ consequences for early enrichment of the Universe

2d models of radiation-driven + wind-blown HII Regions

Method:

- **2d radiation-HD numerical simulations, nested-grid code:**
- **e.g. for a 85 $M_\odot$ star: 6 levels, $\Delta x = 7.4 \times 10^{-3}$ … 0.24 pc**
- **stellar evolutionary models: Langer (Garcia-Segura et al. 1996)**
  Schaller et al. (1992)

Pub.s:

15 $M_\odot$ (Kroeger, 2007, PhD thesis)
35 $M_\odot$ (Freyer, G.H., Yorke, 2006, ApJ, 638, 262)
60 $M_\odot$ (Freyer, G.H., Yorke, 2003, ApJ, 593, 888)
85 $M_\odot$ (Kroeger, G.H., et al., 2006, A&A, 450, L5)

Aims:

Structure formation in observed HII regions:
therefore start with homogeneous surroundings

Energy deposit to the ISM ➔ galaxy evolution

Atmospheric evolution of a $M_* = 60\ M_\odot$ star

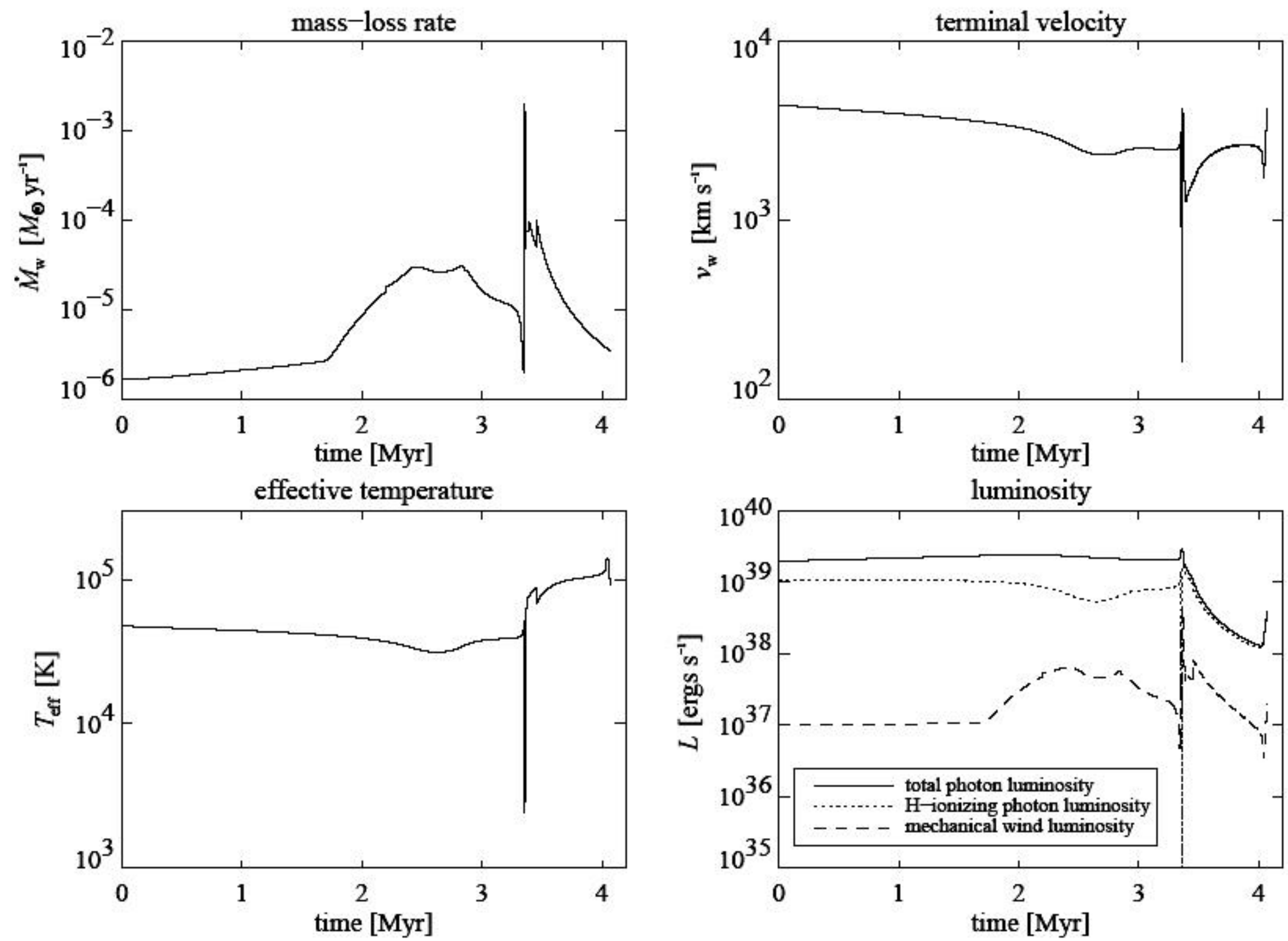


FIG. 2.—Time-dependent stellar parameters used as boundary conditions for the calculation of the 60 $M_\odot$ model: mass-loss rate (*top left*), terminal velocity of the wind (*top right*), effective temperature (*bottom left*), and luminosity (*bottom right*). All parameters are adopted from GML1.

60 M$_\odot$ Model

Freyer, G.H., Yorke (2003)

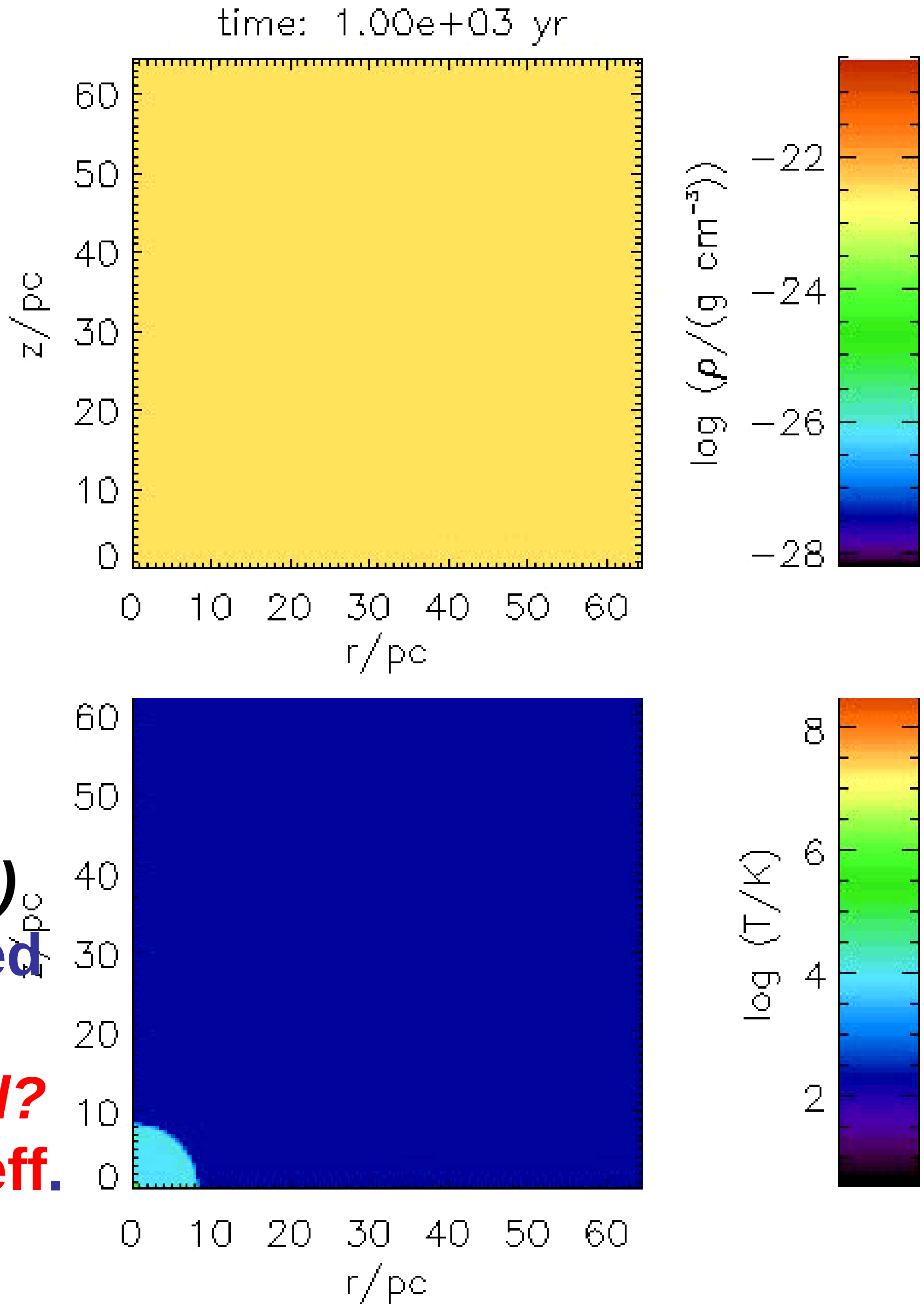
Model parameters:

M_{star} = 60 M$_\odot$

n_{ICM} = 20 cm^{-3} T_{ICM} = 200 K

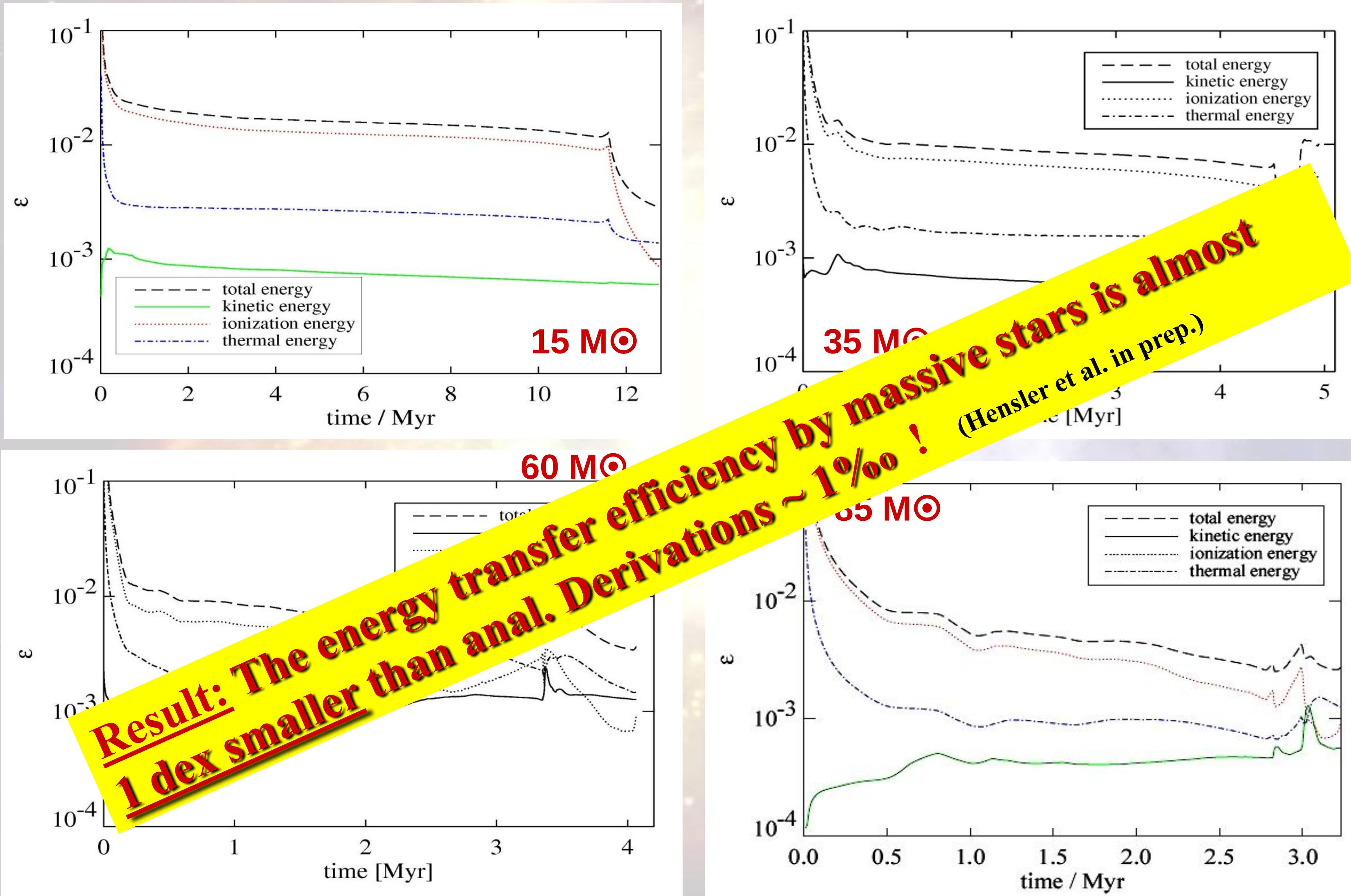
results:

- **Hot wind region**
- **The stellar wind produces Vishniac instab.,**
- **Ioniz. radiat. enhances finger-like structures*(obs.)***
- **Mixing of photo-evaporated gas with hot one:** ***abund. determ.? Rad. field?***
- **Very low energy transfer eff.**



Energy transfer efficiency ε

Def.: $\varepsilon = \frac{E}{\tau(L_{Lyc}+L_w)}$



Result: The energy transfer efficiency by massive stars is almost **1 dex smaller** than anal. Derivations ~ 1‰ ! (Hensler et al. in prep.)

Blowing in the Wind – The Impact of stellar Feedback at low Star-formation Rates in Models of Galaxy Evolution

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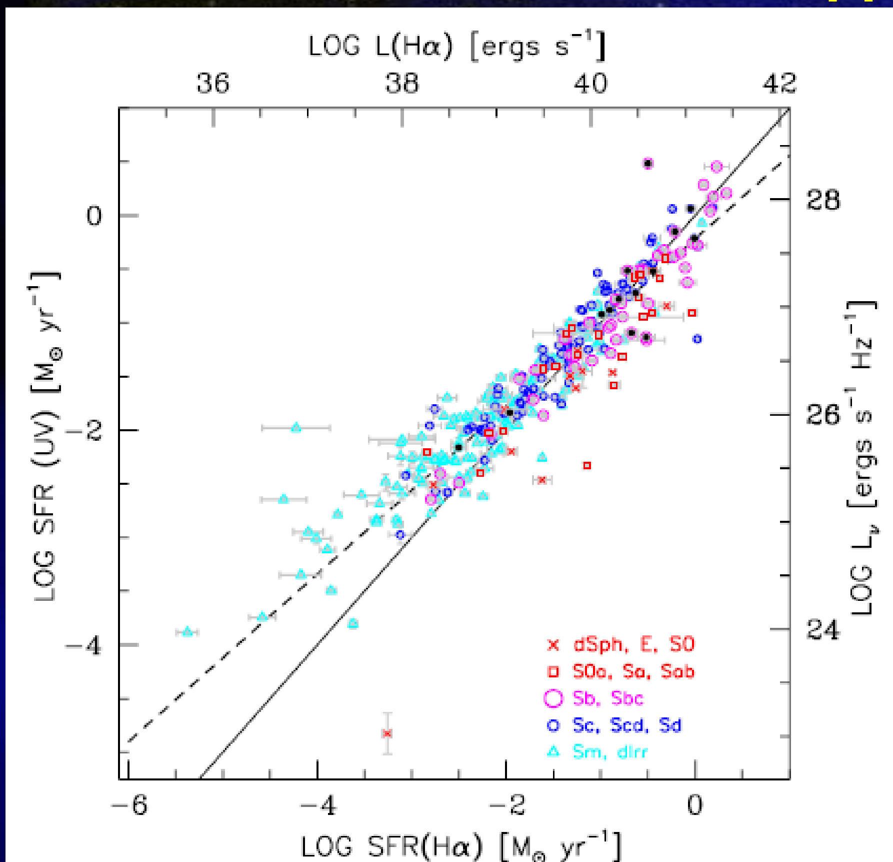
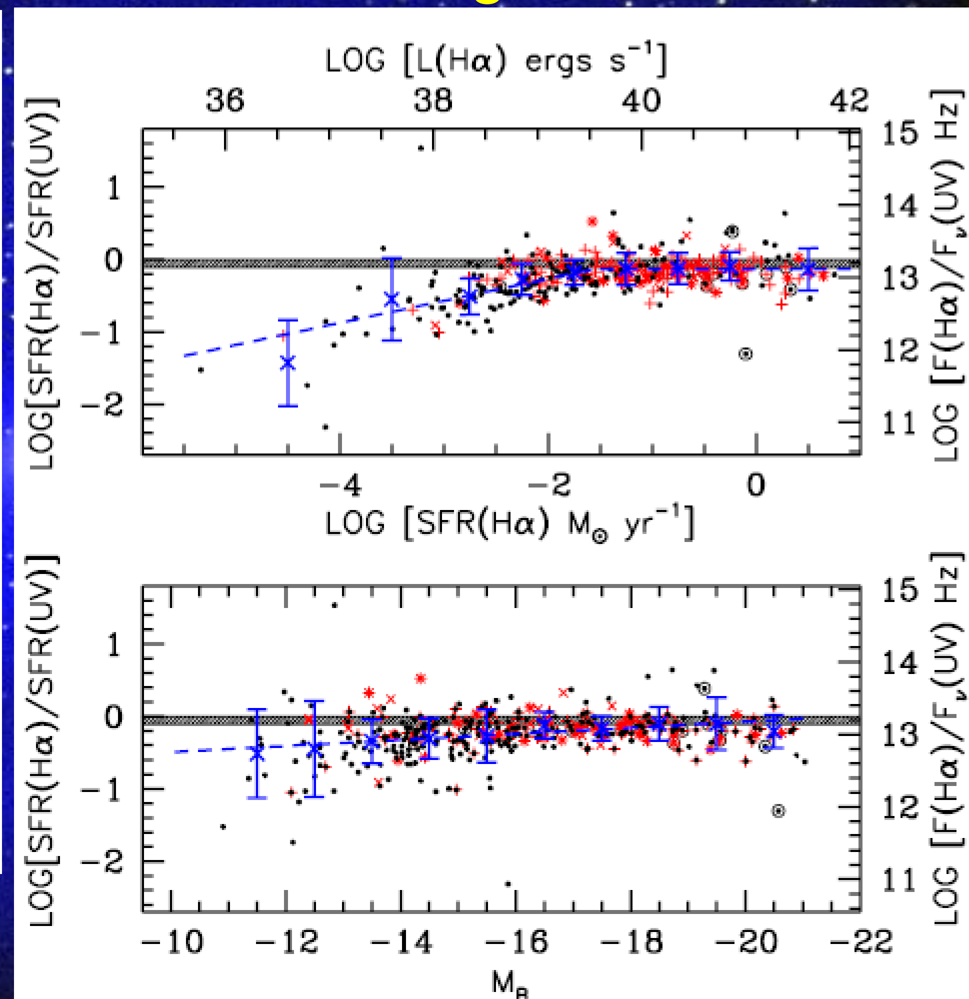
Star formation in DGs mostly at low rates

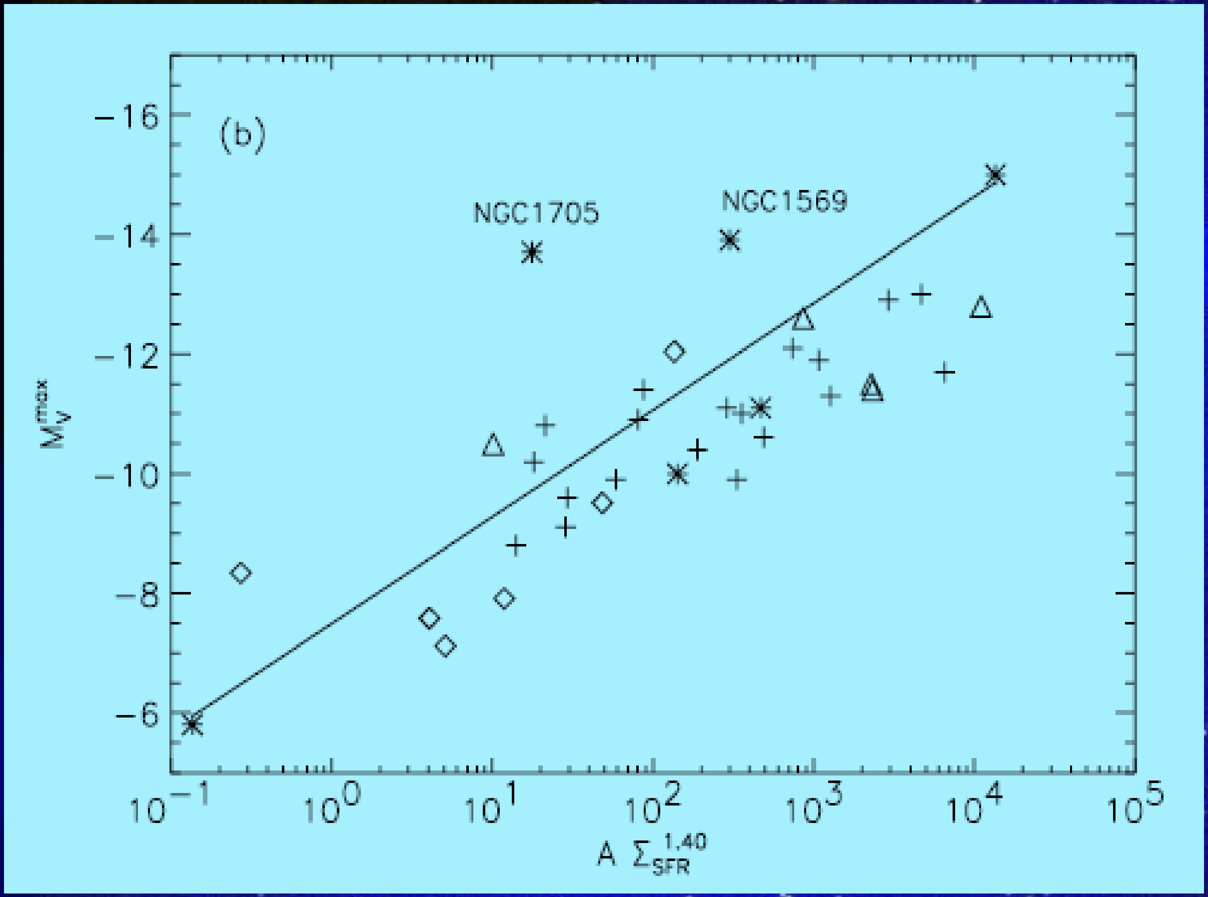
SFRs derived from indicators (massive stars normalized to IMF) Hα and UV begin to deviate below ~ $10^{-2}\ M_{\odot}\ yr^{-1}$.
Explanation: Hα preferably from higher-mass stars than UV ⇒ IMF not complete in uppermost mass range.





Lee et al., 2009, ApJ, 706

M_V of brightest star cluster vs. column SFR in various galaxies



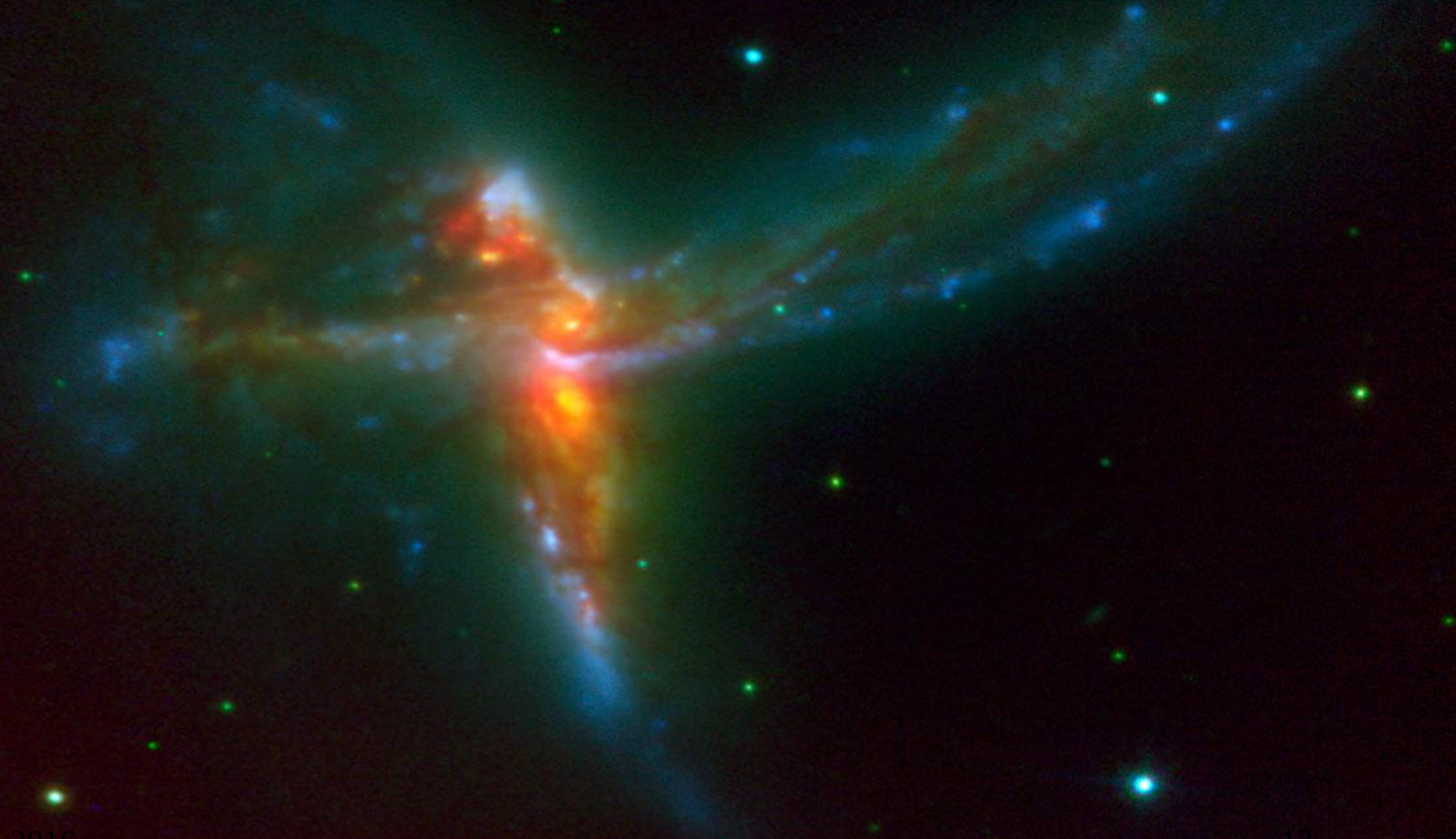
Max. V brightness of star clusters is correlated with the K-S SFR.

Exceptions are galaxies with starbursts forming super star clusters.

Larsen, 2002, AJ, 124

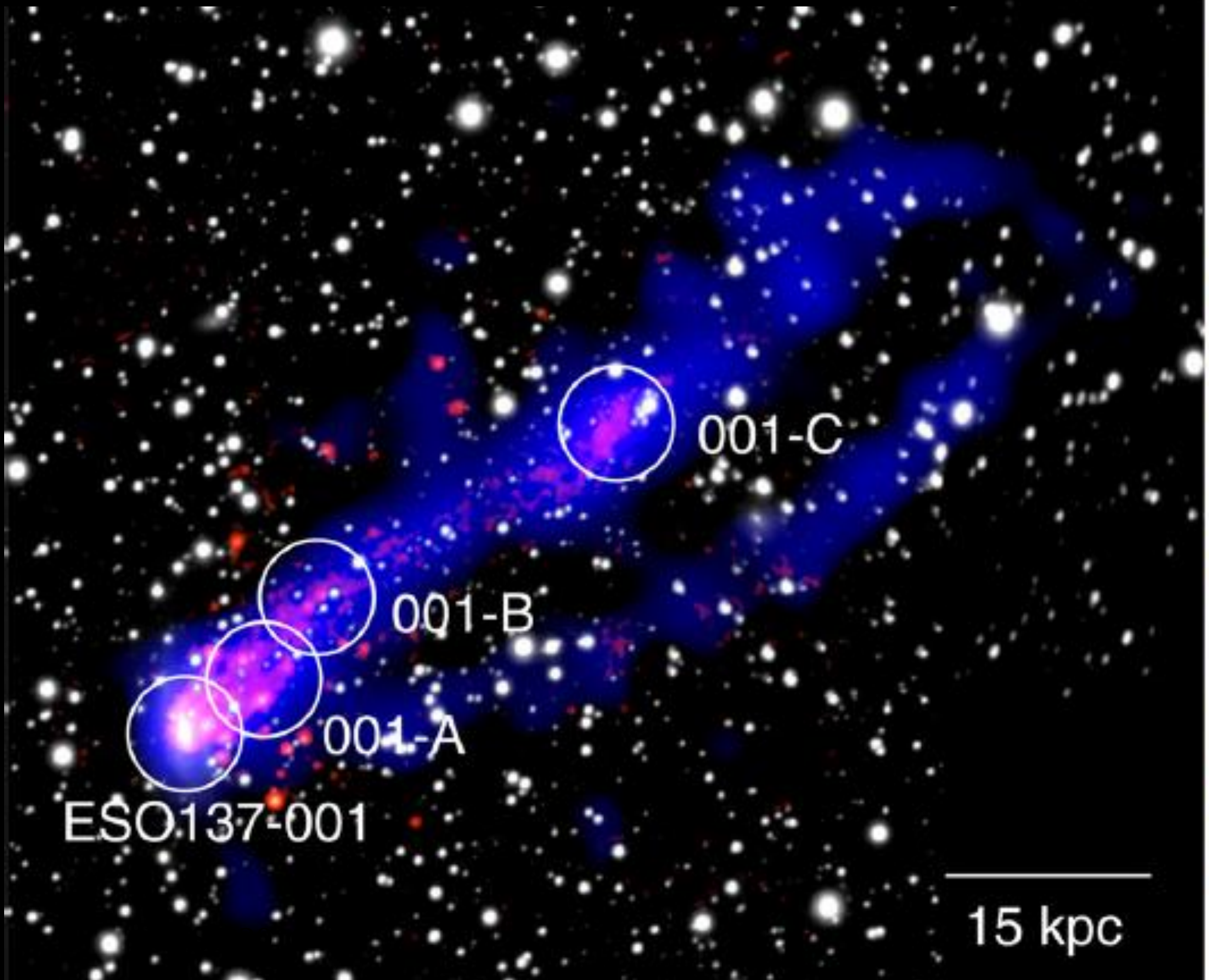
Tinker Bell Triplett: The “Bird”

Star formation in the tidal-tail blobs with rates ~ 10^{-4} … 10^{-3} $M_{\odot}$/yr



The detection of ESO 137-001

Star formation in the RPS blobs with rates of ~ 10^{-4} … 10^{-3} $M_{\odot}$/yr



Star-formation param.s in numerical models

- *Star-formation dependence*

  $\dot{\rho}_{SF} \propto \rho_g^k$

  + *physical criteria*
  - *Self-gravity*
  - *Density*
  - *~ n_{mol}*
  - *Temperature*
  - *Jeans mass*
  - ……
- *SF efficiency ε*

Feedback processes

- *Stellar winds: E + p*
- *Stellar radiation: E + P_{rad}*
- *Supernovae II: E + p(!)*
- *Supernovae Ia: E + p(!)*
- *PNe*

Free parameter:

Energy transfer efficiency ξ

$\xi_{Lyc+SW} \approx$ **0.1 … 1%** **(Hensler 2006)**

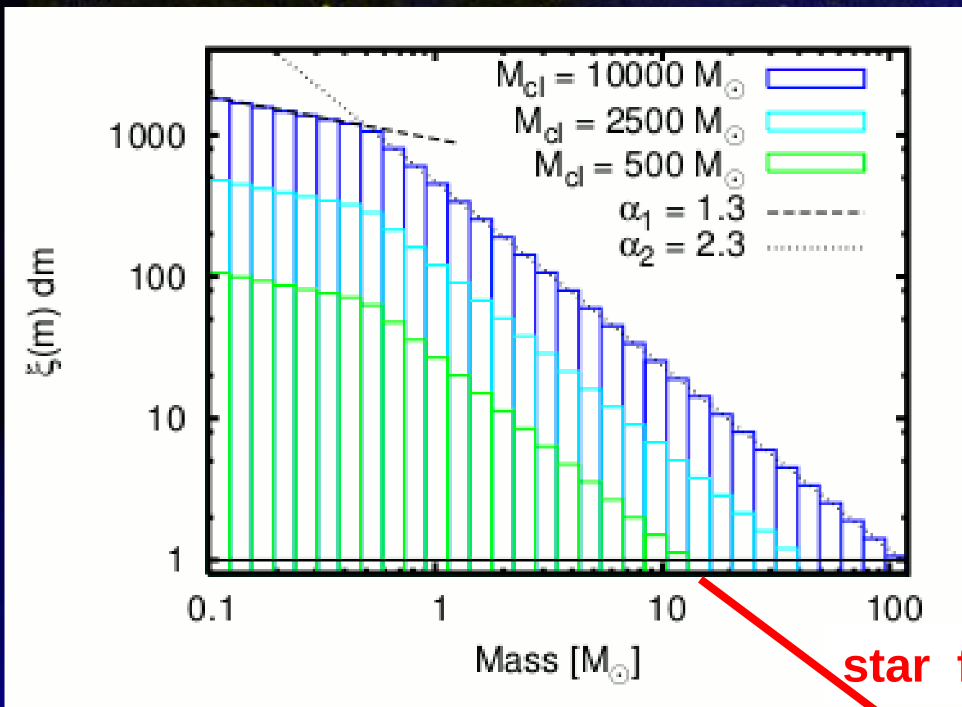
$\xi_{SNII} \approx$ **1 … 10%**

What about the IMF?

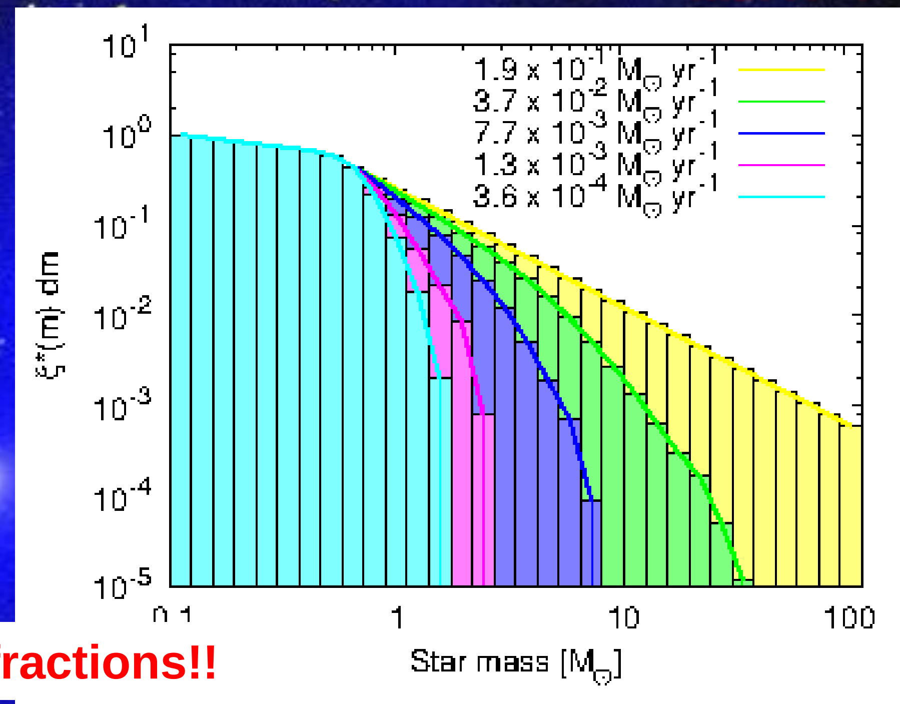
10^{-2} $M_\odot$/yr over 1 Myr ⇒ 10^4 $M_\odot$ star cluster, i.e. SF eff.=5% needs a cloud mass of $2 \cdot 10^5$ $M_\odot$!

Possibilities to fill the IMF according to the SFR/cloud mass

filled IMF reduced to star fraction



IMF truncated at upper mass interval with N=1



star fractions!!

Consequences of low SFR:

- **Filled IMF**: star fractions lead to SNII fractions ⇒ heating?
- **Truncated IMF**: less SF self-regulation? Longer lifetimes of heaviest stars. More low-mass stars! Low SNII rate! But also less SNII energy?

The IMF at low SFR in numerical simulations

At low SFR 3 possibilities emerge:

$$\text{IMF}: \quad \Phi(m) = \frac{dN(m)}{dm} \sim m^{-\alpha}$$

• ***a filled IMF*** **can lead to** ***N(Δm)*** **becoming fractions of stars only! i.e. for massive stars also** $N_{SNII}(\Delta m)$

$$N(\Delta m) = A \int_{\Delta m} \Phi(m)\, dm = A \int_{m_l}^{m_u} \Phi(m)\, dm$$

$$\text{SFR}: \quad M_*(\Delta m) = A \int_{m_l}^{m_u} m^{-\alpha+1}\, dm$$

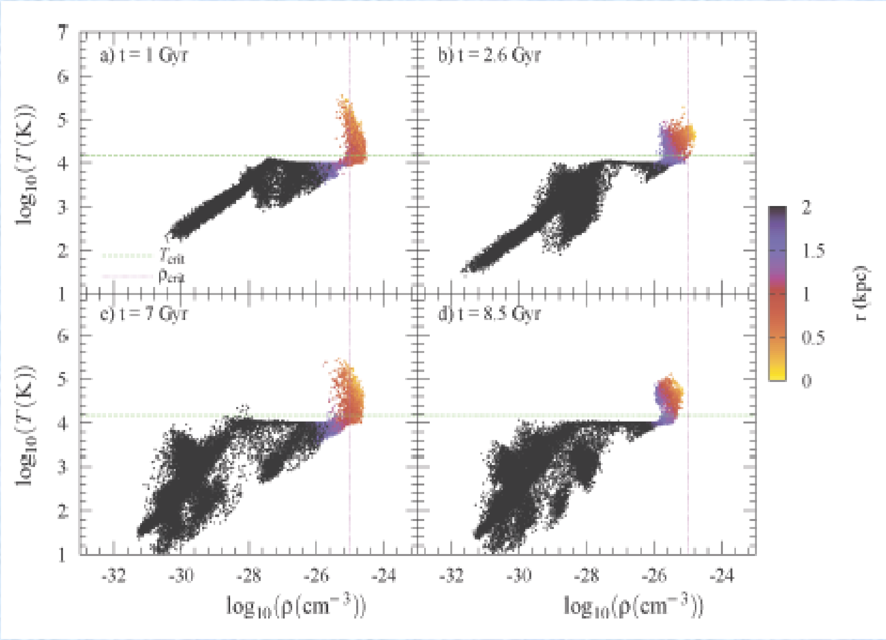
• ***The IMF is truncated***

$$\text{condition}: \; N(m_u) \geq 1$$

• ***A stochatic IMF allows for individual massive stars***

The effect of low n_{crit} on SF in DG models

$M_{gas,i} = 1.4 \times 10^8\ M_\odot$; $M_{DM} = 6.6 \times 10^8\ M_\odot$
$n_{crit} = 0.1\ cm^{-3}$

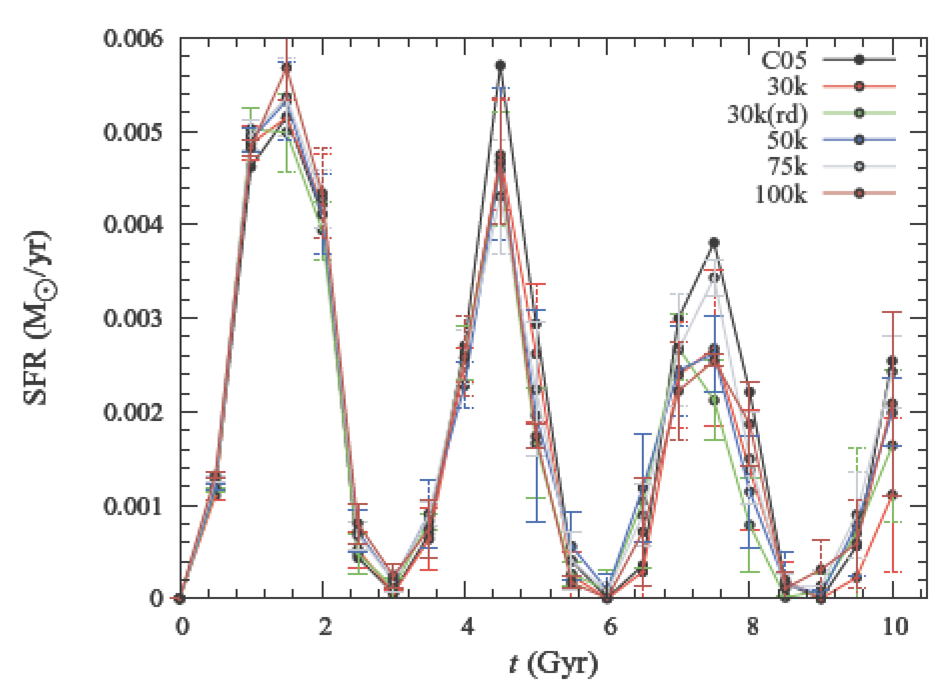


Valcke et al. (2008) MN, 389

Drawbacks for hr-SPH:

Too low density threshold leads to

⇒ **SFR distributed allover the disk,**
⇒ **low SFRs,**
⇒ **fractions of IMF, less energy feedback?**
⇒ **chemical yields mix locally;**
⇒ **physical state of the ISM?**



Issues:

SFR oscillates, DGs is 'breathing';
low metal. loss, high Z,
small radial Z gradients

Numerical Star-formation recipe

Star-formation self-regulation by stellar feedback

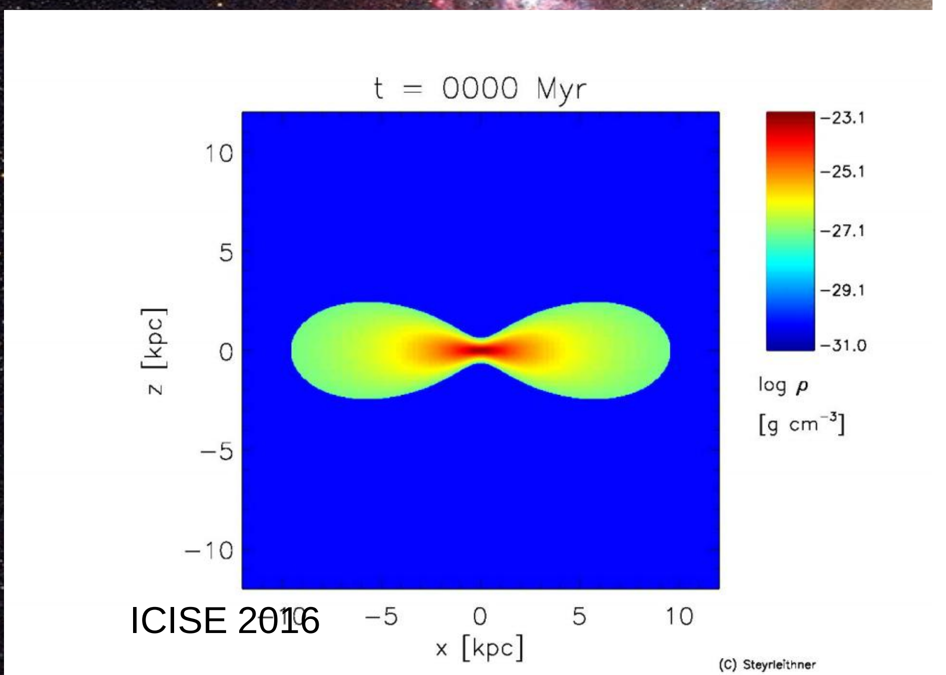
$M_{gas,i}$ = 1.4 x10^8 $M_\odot$; $M_{s,i}$ = 0
M_{DM} = 8.4 x10^8 $M_\odot$; v_{rot} = 30 km/s

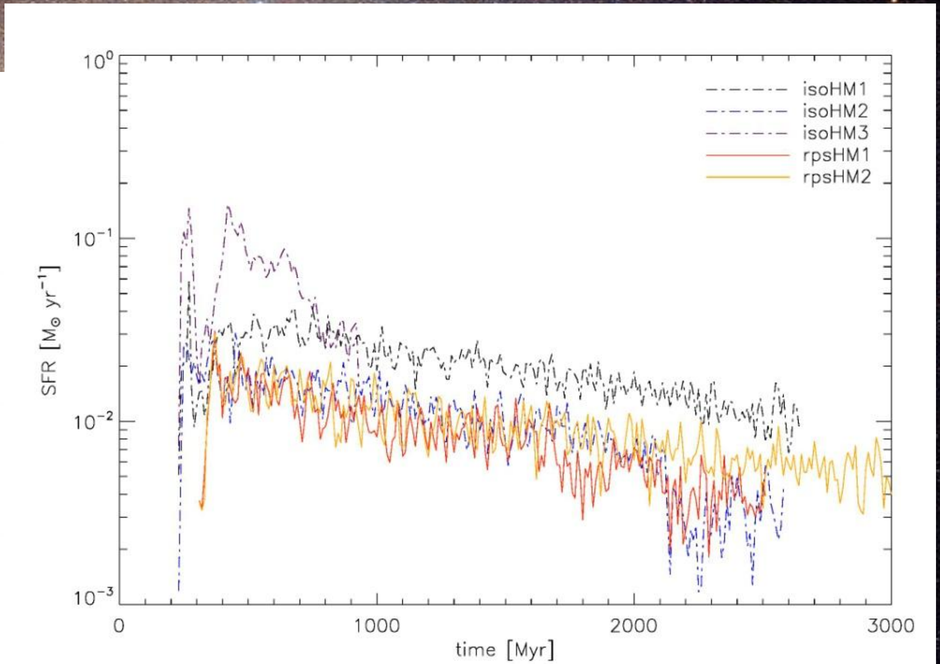
SF as in Köppen, Theis, G.H. (1998, *A&A*, 331)

$$\Psi(c,T_c) = C_n c^n \exp\{-T_c / 10^4 K\}$$

Low star-formation rate;
Massive-star bins not fully with N≥1;
No galactic wind!
SF concentrated to the central part.

AMR code FLASH





Steyrleithner et al. (2016)

Numerical IMF recipes and their issues on galaxy evolution

Star-formation self-reg.

stellar radiation+winds
chemistry

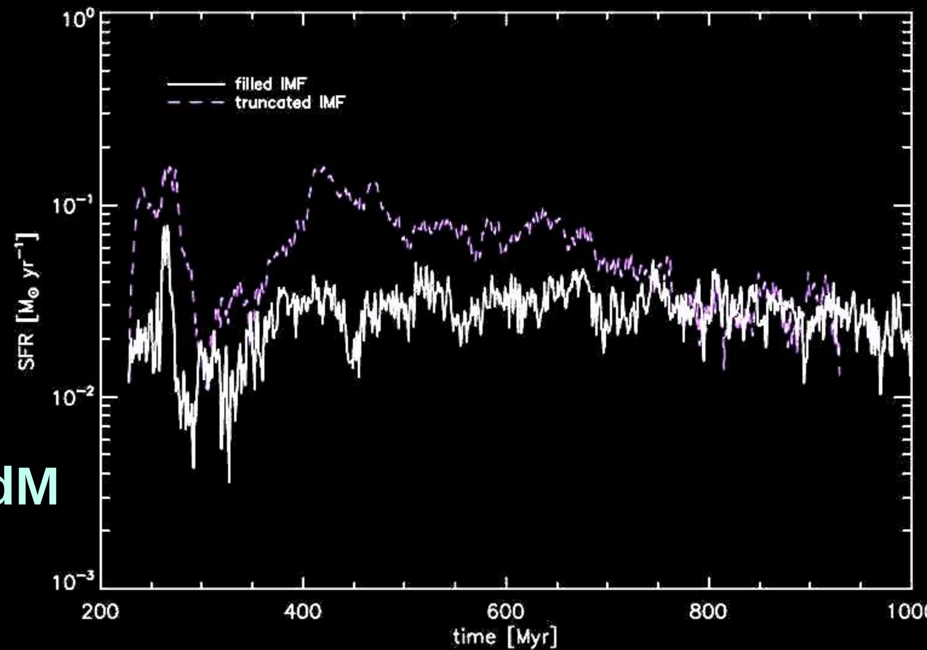
Stellar feedback

supernovae II
galactic winds

full IMF vs. truncated

Steyrleithner et al. (2016)

Energetic feedback by the IMFs

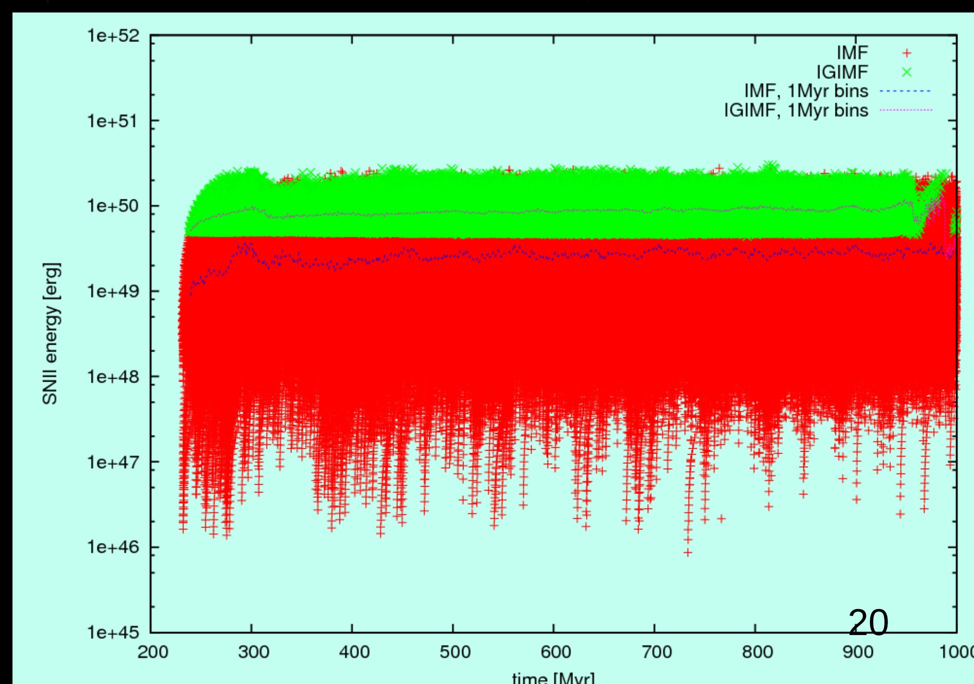


For a *truncated IMF* the massive-stars' specific radiative energy feedback is smaller than for a *filled IMF* because:

$L_{Lyc,tot} \sim N_{ms}(M)\, L_{Lyc}(M) \sim \int M^{-2.35}\, M^{\beta}\, dM$
$= \int M^{>0}\, dM$, $\beta = 4 \ldots 6$

The SNII energy, $\xi_{SN} \sim 5\%$
however, relates to the star number $N_{ms} \cdot e_{SN}$
$\Rightarrow$ a *filled IMF* produces $\leq 1 \cdot e_{SN}$ if

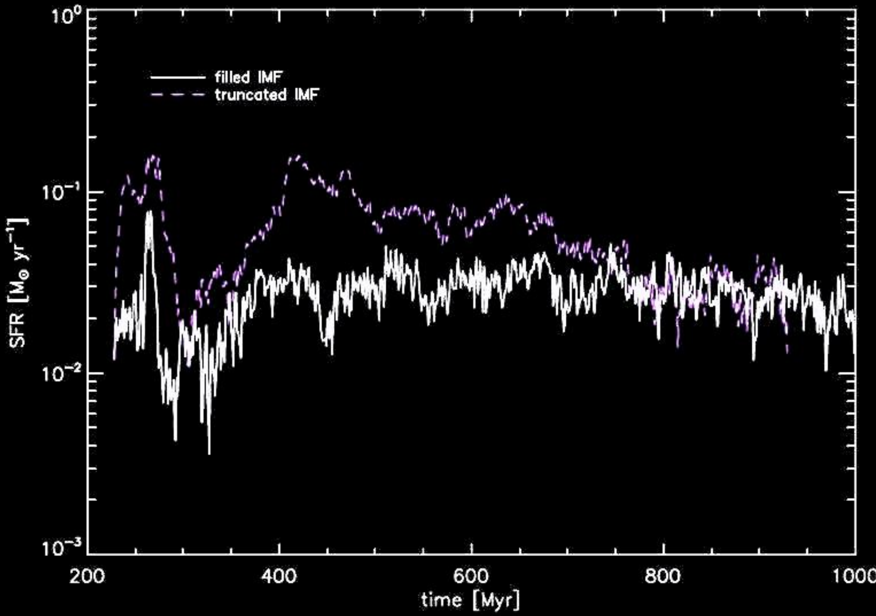
$M_{ms,tot} = \int^{ms} M\,(M)\,dM \leq \overline{M}_{ms}$



Then a *truncated IMF* releases more SNII energy than the sum of *filled IMF* mass fractions.

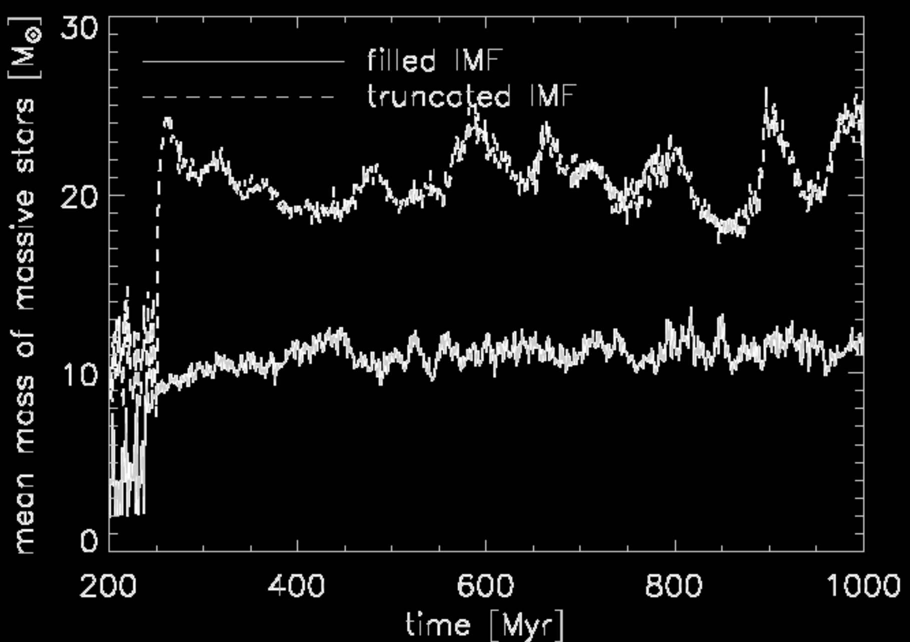
Steyrleithner et al. (2016)

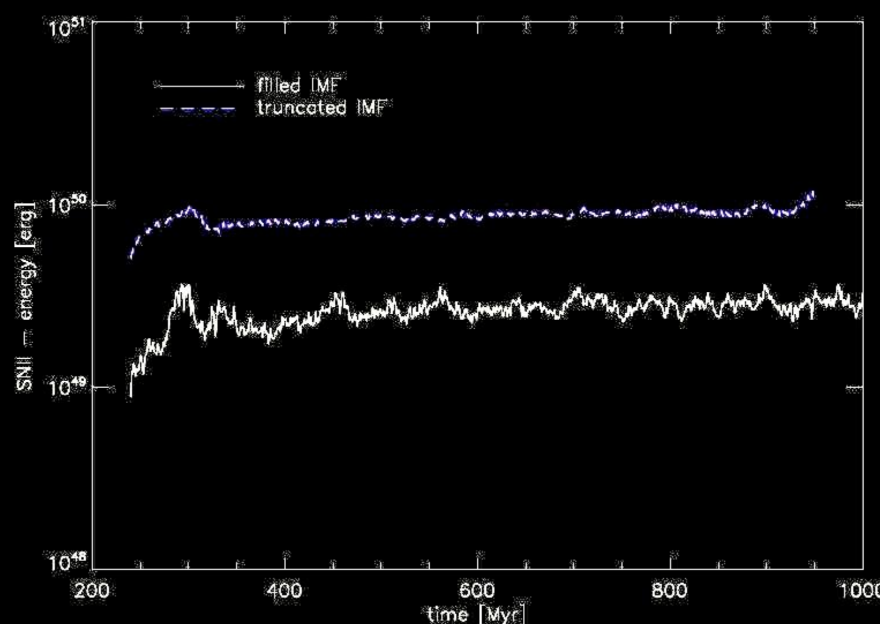
Energetic feedback by the IMFs



The *filled IMF* reaches mean masses of ~10 $M_\odot$ in the range [8,120] $M_\odot$.

In the *truncated IMF* model the mean mass is above 20 $M_\odot$.





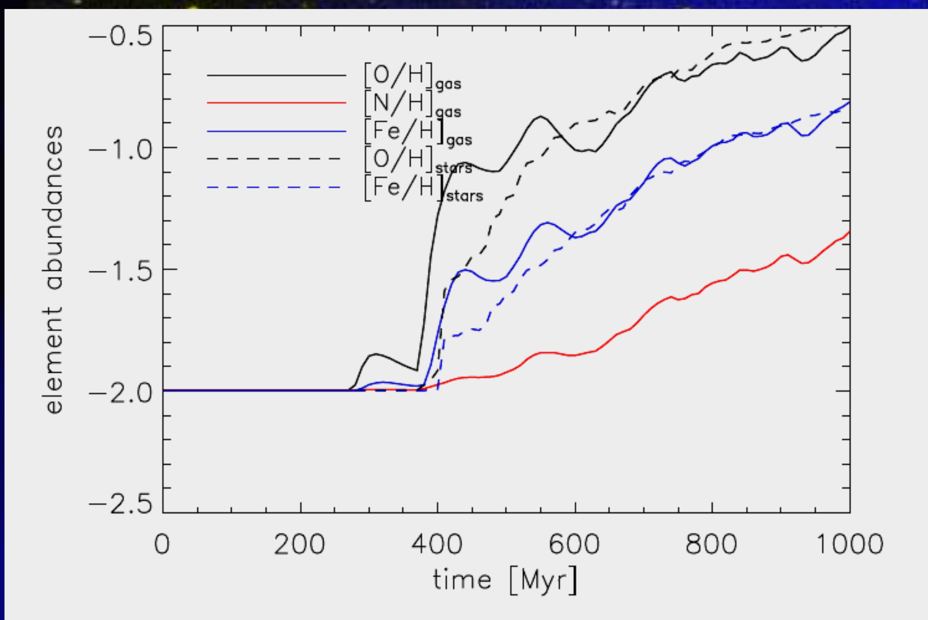
Steyrleithner et al. (2016)

Chemical feedback by the IMFs

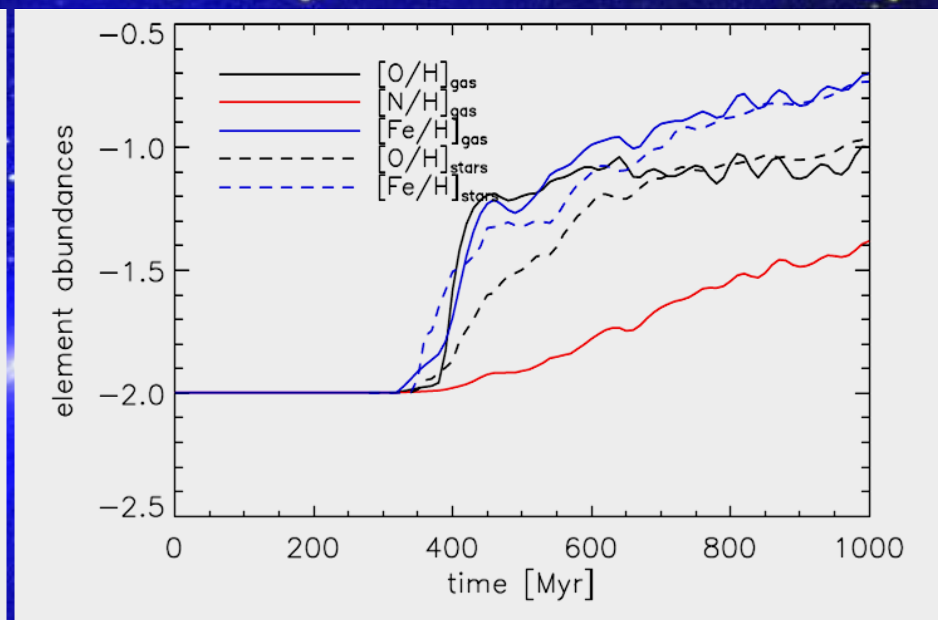
What do we expect?

In the case of lacking massive stars α-element yields should be reduced.

filled IMF



truncated IMF



For the *truncated IMF* [O/Fe] becomes < 0; observed e.g. in dSphs.

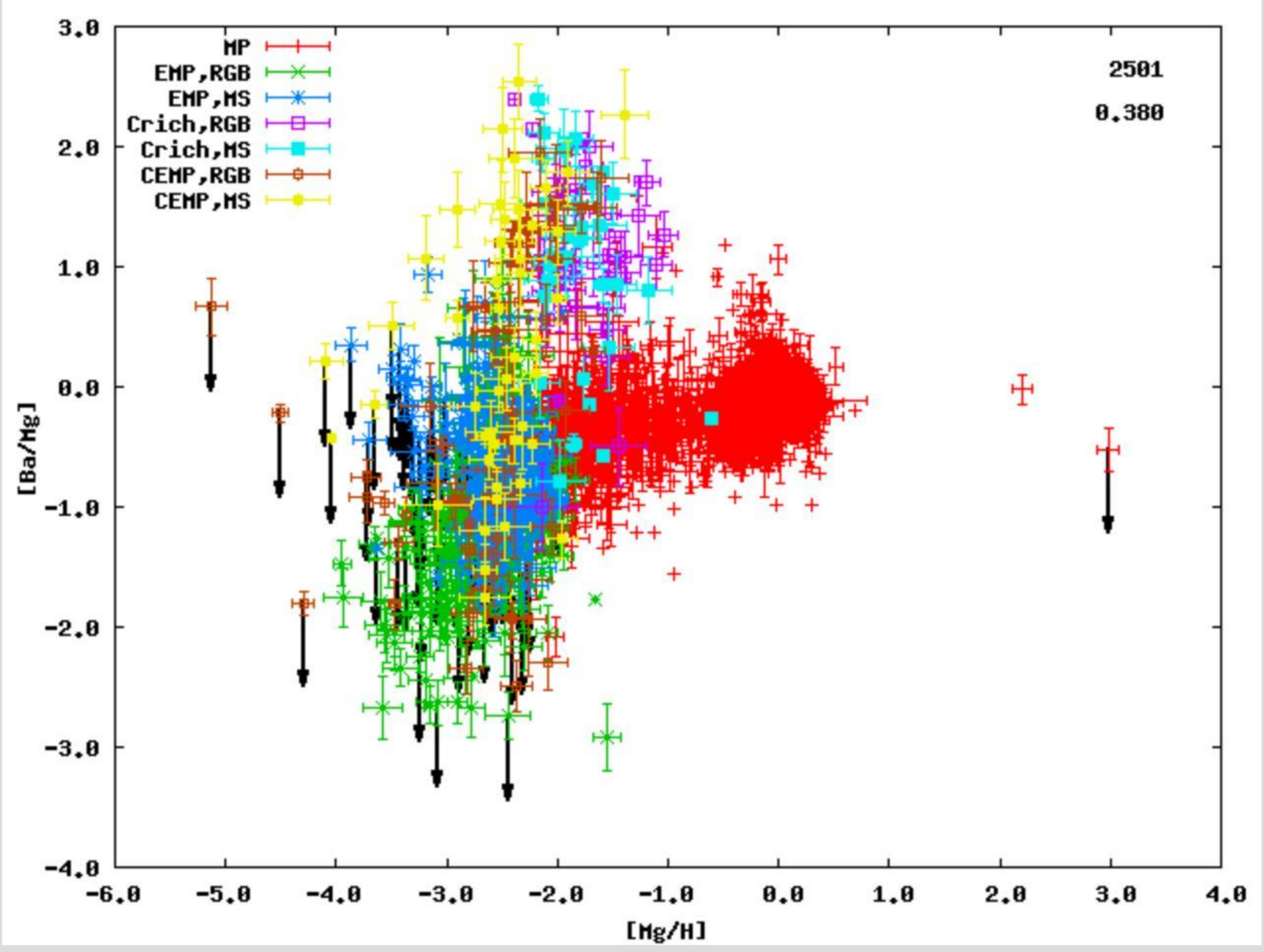
The same should be studied for Ba vs. Mg!

Steyrleithner et al. (2016)

Summary and Outlook

- ✓ At low SFRs the massive stellar IMF range is not filled!
- ✓ Careful study of their Ha-derived SFR necessary.
- ✓ At low SFRs the ansatz of *filled IMFs* in simulations underestimates the SNII feedback by o.o.m.
- ✓ Galactic winds can be driven even by a *truncated IMF*!
- ✓ SF self-regulation by stellar ion. rad. and winds works more efficient for *filled IMF*.
- ✓ *Truncated IMFs* change the feedback!
- ✓ Chemical yields of intermediate-mass vs. massive stars change abundance ratios!

Ba vs. Mg of MW halo stars



http://sagadatabase.jp/

IAU XXX GA

Vienna 2018

August 20-31