STScI - 14.10.2013

Local-Density-Driven Clustered Star Formation: Model and Implications

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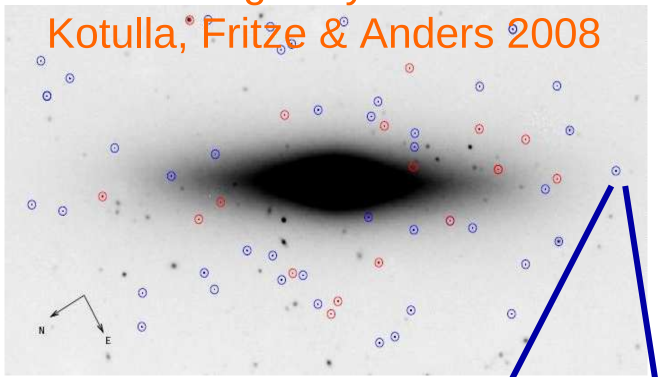
Star Clusters as Galaxy Evolution Tracers

Star Clusters: Why do I care?

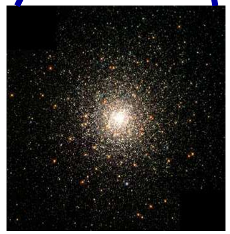
- **Identified on a one-by-one basis against the background of their host galaxy**
- **Cluster spectrophotometry ⟶ cluster age, cluster mass and cluster metallicity (estimates)**

Lenticular galaxy NGC4570
Kotulla, Fritze & Anders 2008



➧ Comprehensive view of galaxy-evolution over the past Hubble-Time:

- **Chemical evolution (cluster age vs. cluster metallicity)**
- **Interaction/merging history (cluster age distribution)**



To recover the star formation history of galaxies from their star clusters

- **Is the 'Holy Grail' of this quest**
- **But star clusters dissolve with time (= give off their stars to the field)**
- **Cluster age distribution of a galaxy is an <u>encoded</u> record of its star formation history**

Gas-Density Dependent Star Formation Efficiency

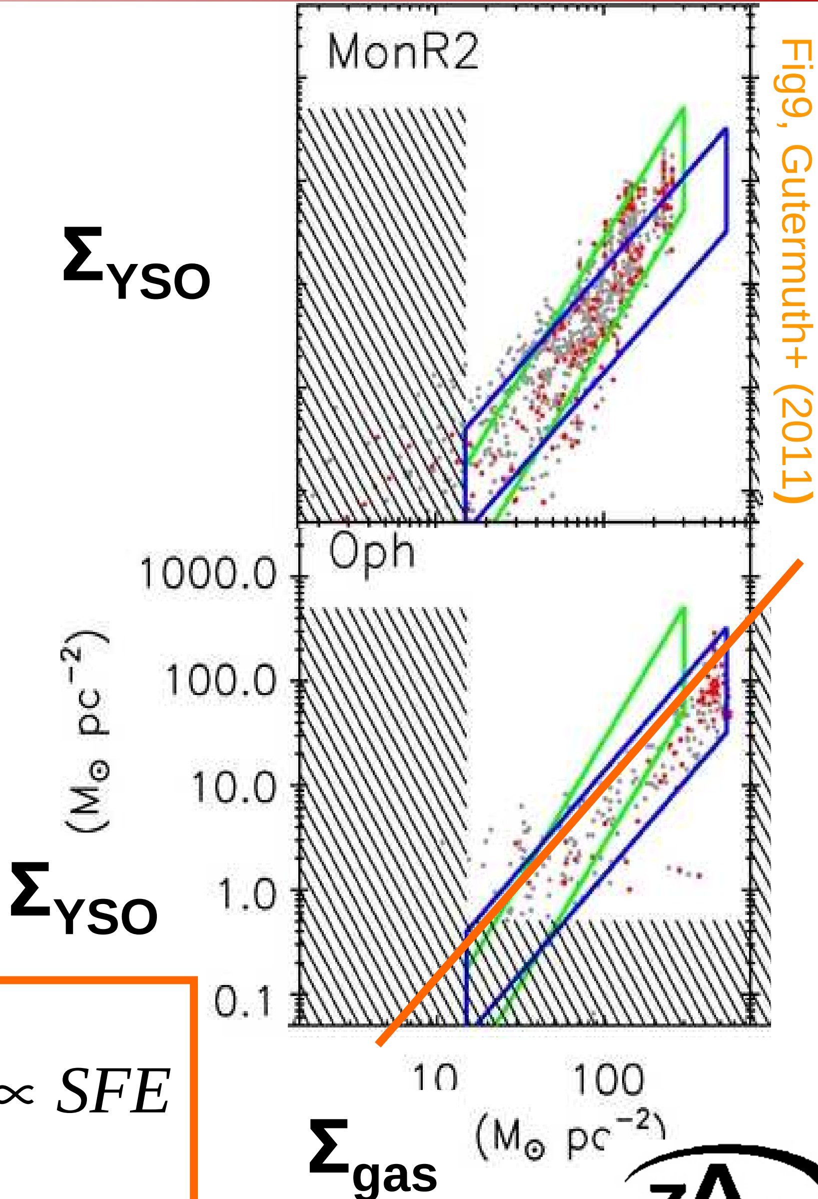
Dissolution rate of star clusters

- **Is heavily initial-conditions-driven**
- **Depends on the efficiency with which cluster progenitors convert their gas into stars**
- **The lower the efficiency, the greater the likelihood of dispersing the cluster stars into the field when the residual star-forming gas is expelled**

What does the Star Formation Efficiency of star-cluster progenitors depend on?

- **Recent observations of star-forming molecular clouds in the Solar Neighbourhood (Gutermuth et al. 2011) suggest a gas-density-dependent efficiency**

$$\Sigma_{gas} \propto \frac{\Sigma_{YSO}}{\Sigma_{gas}} \propto SFE$$



Star Formation Efficiency per Free-Fall Time (ε_{ff})

Star Formation Efficiency ε_{ff}
per Free-Fall Time τ_{ff}

$$\tau_{ff} = \sqrt{\frac{3\pi}{32\, G\, \rho_{gas}}}$$

Krumholz & McKee 2005

For any given time-span after the onset of star formation: molecular-gas regions of higher density achieve higher SFEs

- **Consequences on the scale of individual cluster-parent clumps?**
  - **molecular clumps have volume density gradients**
  - **SFE_{centre} >> $SFE_{outskirts}$ is expected**

- **Denser**
- **Faster**
- **Higher SFE**

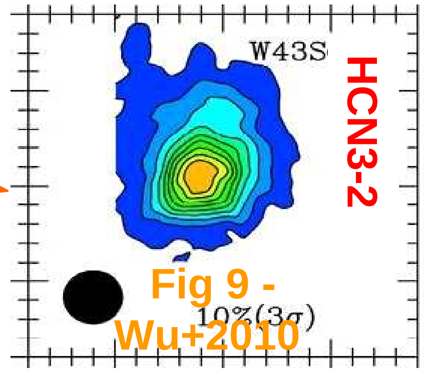
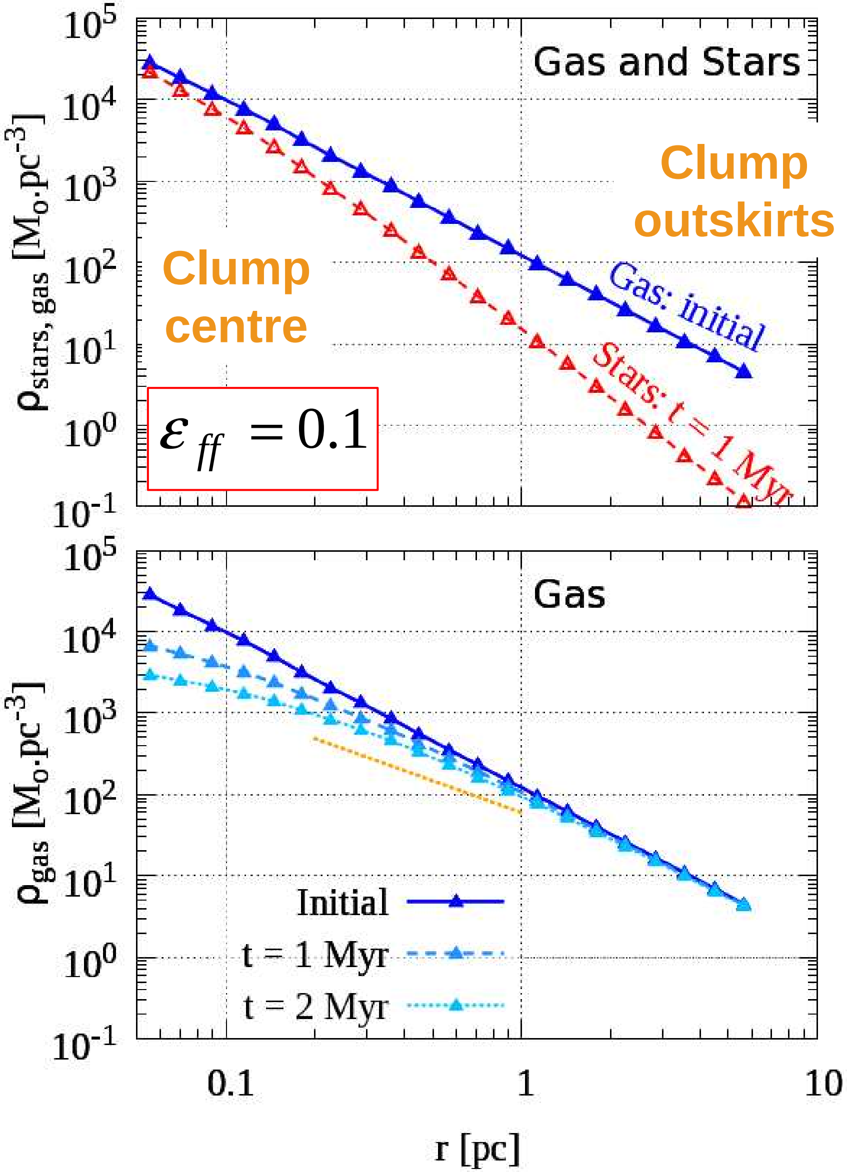


Fig 9 - Wu+2010

Star and Gas Volume Density Profiles



MonR2 cloud: M_{tot} = 25,800$M_\odot$

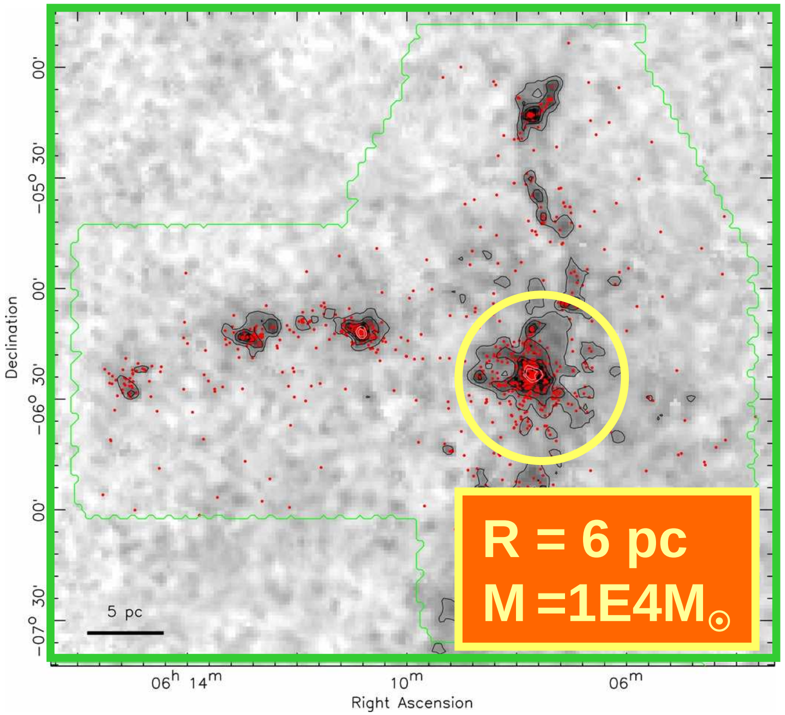
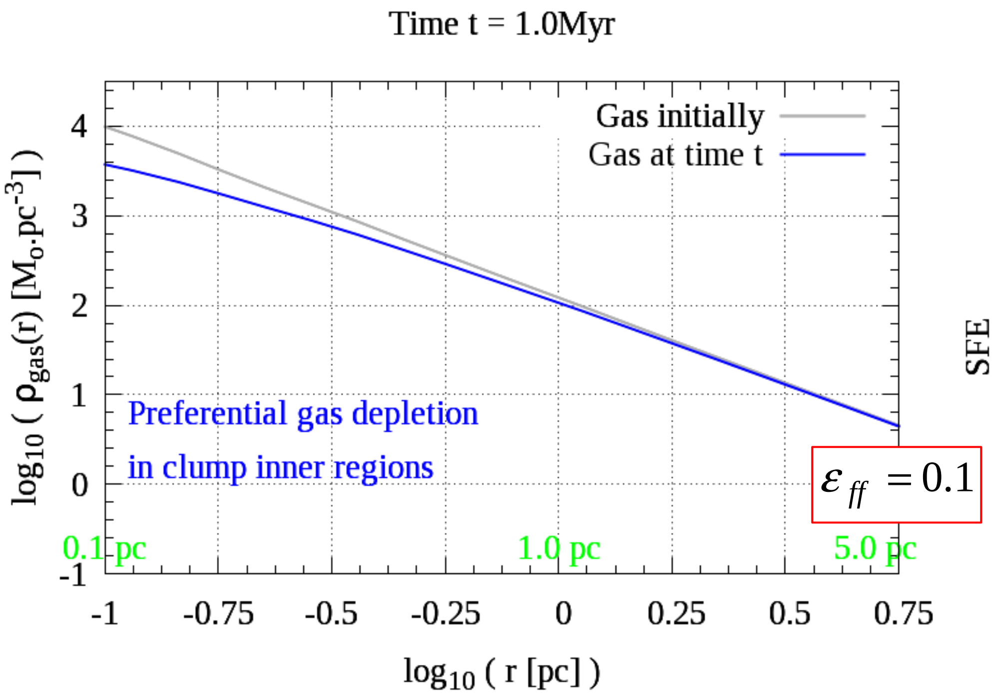


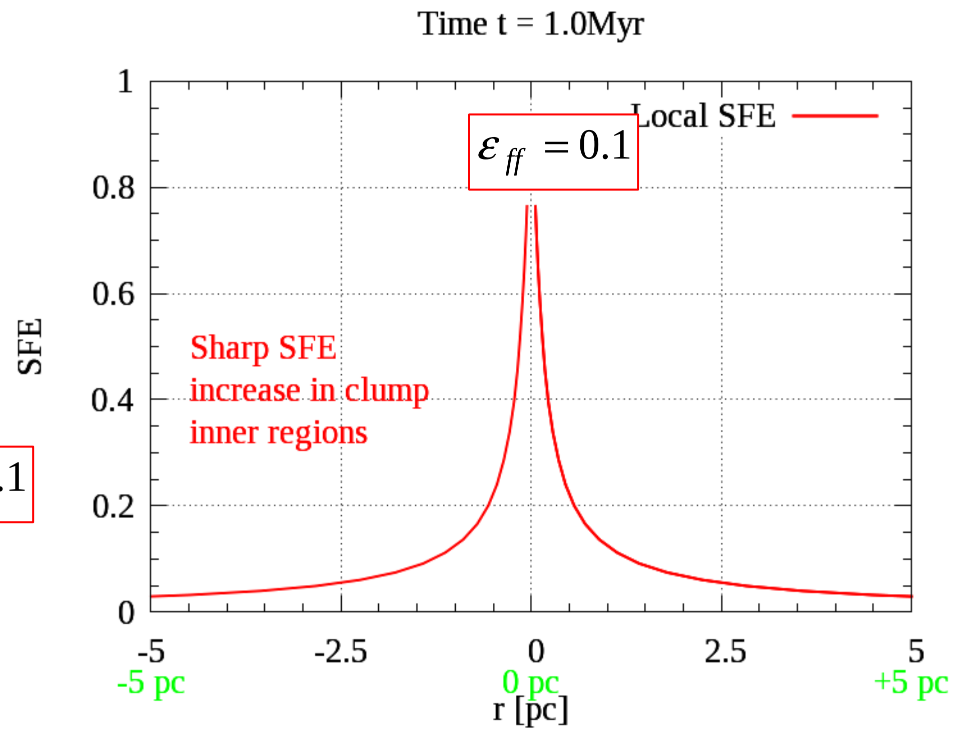
Fig1, Gutermuth+ (2011)

Density profiles:

- $\rho_{stars}(r)$ steeper than initial $\rho_{gas}(r)$
- $\rho_{gas}(r)$ gets shallower with time

Movie: Gas Depletion and SFE Increase





- **Measured mean SFE depends on:**
  - **Where (which spatial scale)?**
  - **When (time-span since SF onset)?**
- **Impact on cluster survivability after gas expulsion (low mean/global SFE does not necessarily imply cluster disruption -- see Adams 2001)**

Denser Means Faster: Local & Global

Denser means faster

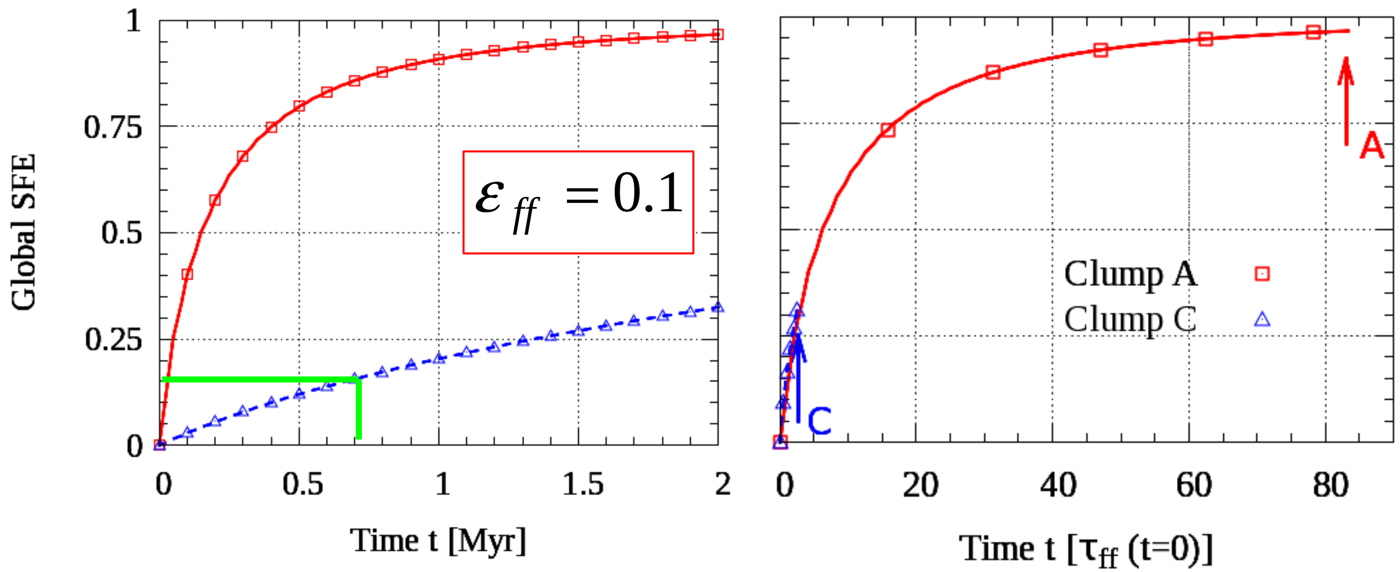
- **True on the local scale**
  → evolution of clump radial profiles (previous slide)
- **True on the global scale too**
  → evolution of the clump as a whole (this slide)
  → Conseq for cluster stellar age spreads

$$\text{Global } SFE(t) = \frac{M_{stars}(t)}{M_{clump}}$$

where $M_{stars}(t)$ is the stellar mass of the whole clump at time t

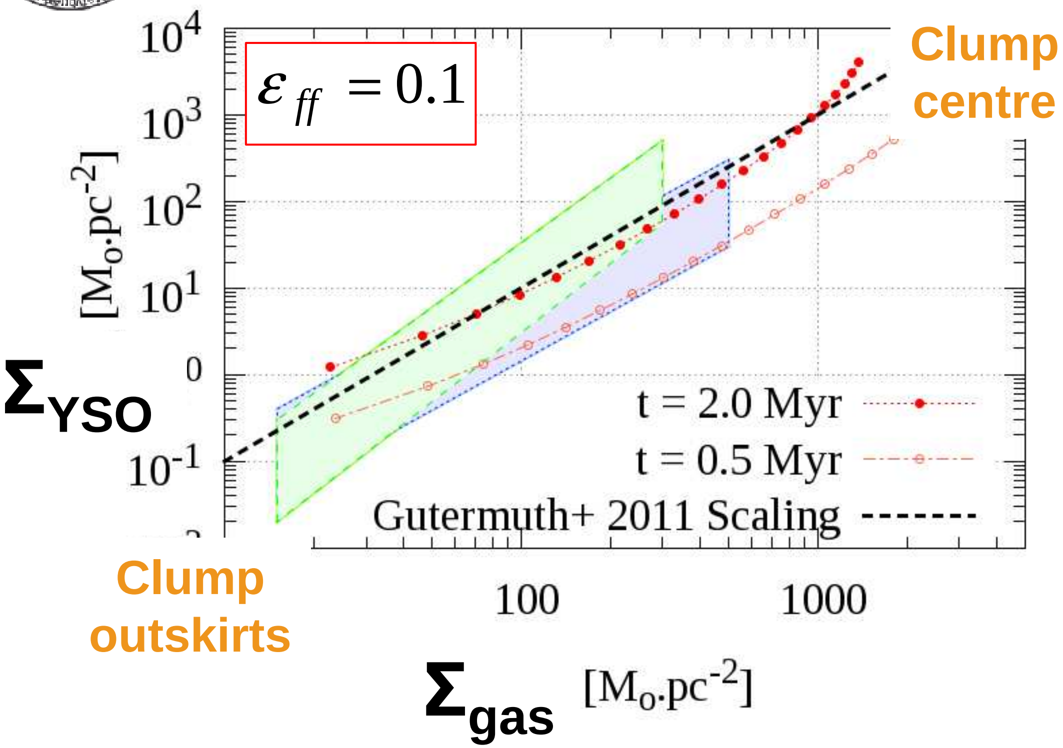
Clump A: $<\rho>= 10^5 M_\Theta \cdot pc^{-3}$, $\tau_{ff,t=0} = 0.02 Myr$

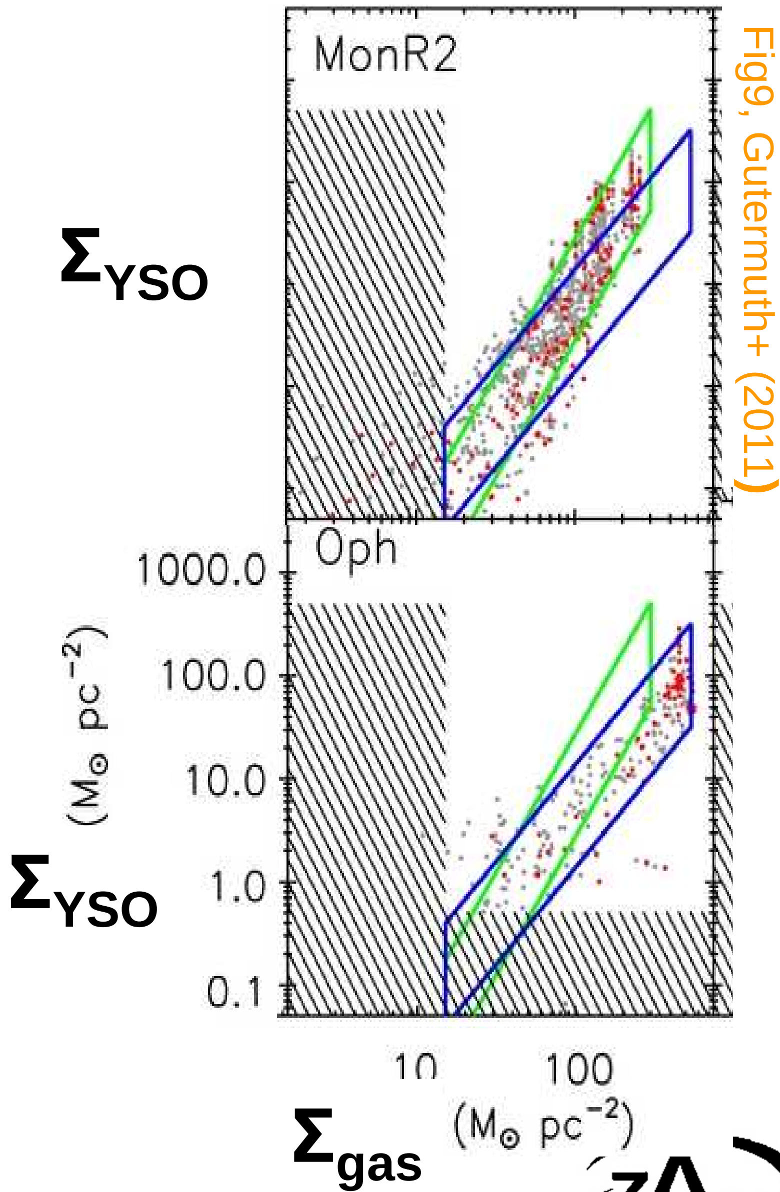
Clump C: $<\rho>= 10^2 M_\Theta \cdot pc^{-3}$, $\tau_{ff,t=0} = 0.74 Myr$



- Note that after $1\tau_{ff}$: Global SFE = 16%, not 10%
- Due to clump central mass concentration [PL(-2)] – see also Tan+ 2006 and Elmegreen 2011

Local Star Formation Law



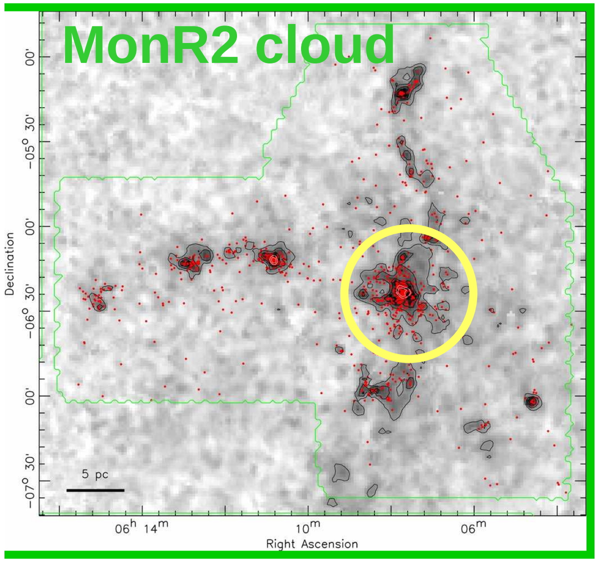


Relation between the local surface densities of molecular gas and YSOs:

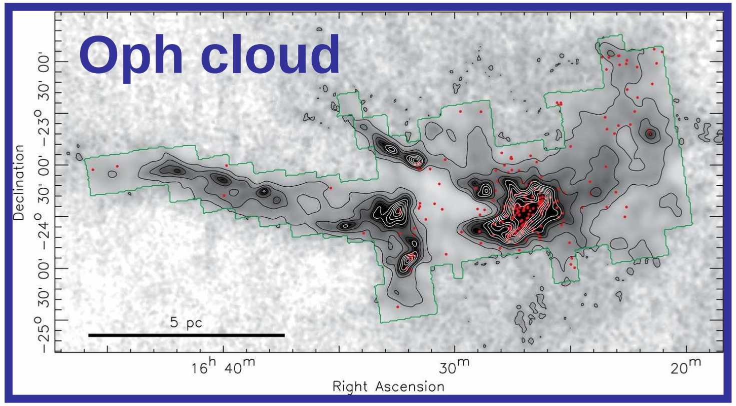
$$\Sigma_{YSO} \approx 10^{-3}\, \Sigma_{gas}{}^{2} \quad \text{at} \quad t = 2\text{Myr}$$

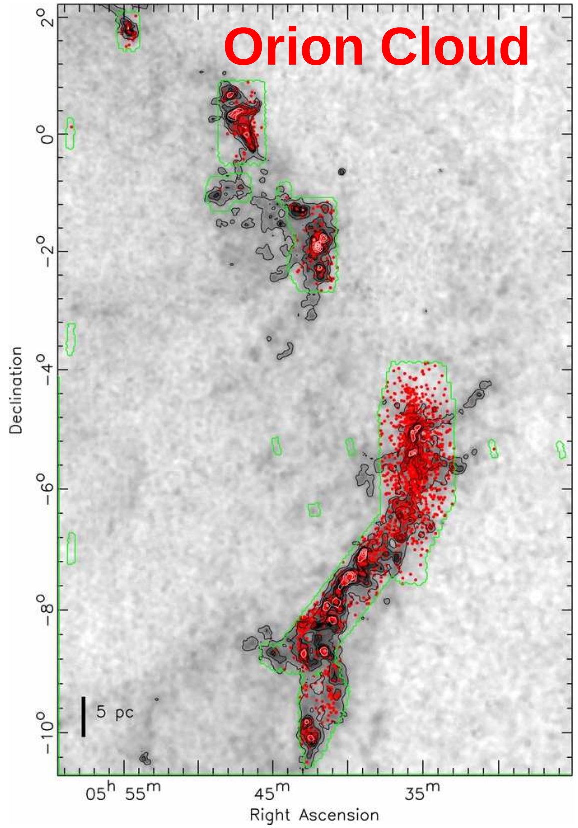
for the adopted M, R, ε_{ff}
(Parmentier & Pfalzner 2013)

Local Star Formation Law

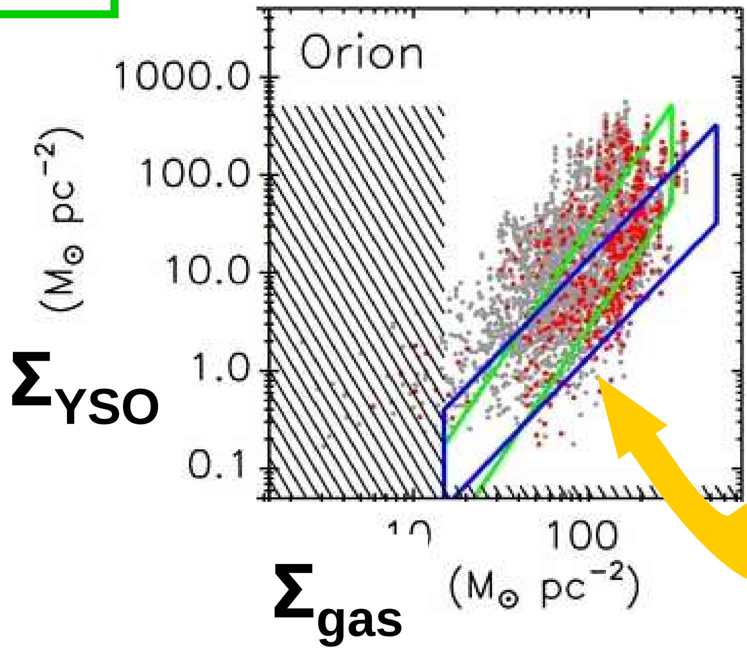


Figs 1,4,6,9, Gutermuth+(2011)





The model prediction is a <u>clump</u> SF law, <u>not a cloud</u> SF law

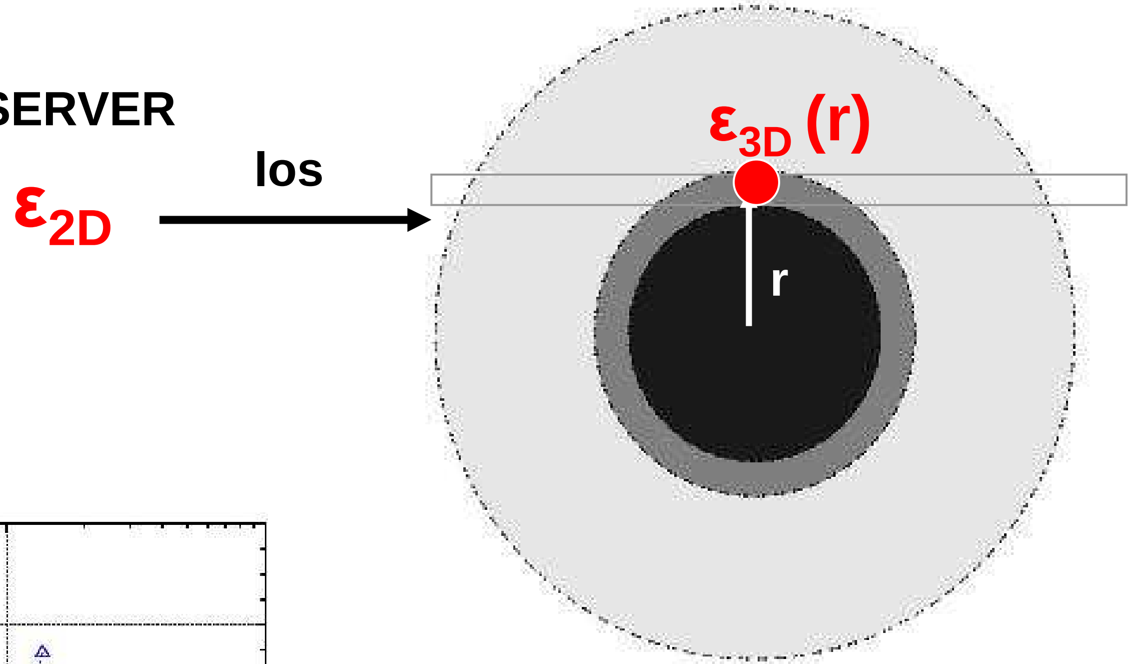


The Orion cloud is a collection of many clumps, hence the cloud-like aspect of its observed SF law

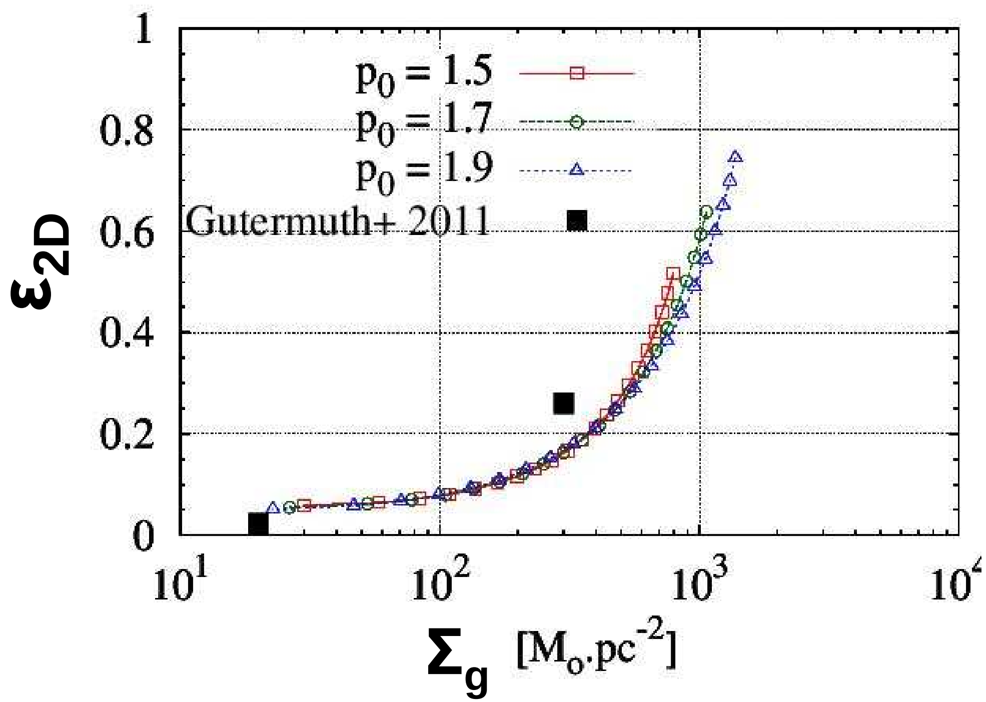
3D vs. 2D Perspectives – Measured ε_{2D}

- **Observed (2D) local efficiencies < Actual (3D) local efficiencies**

OBSERVER



$$\varepsilon_{2D} < \varepsilon_{3D}$$



ε_{2D} vs. residual gas Σ (as if observed)

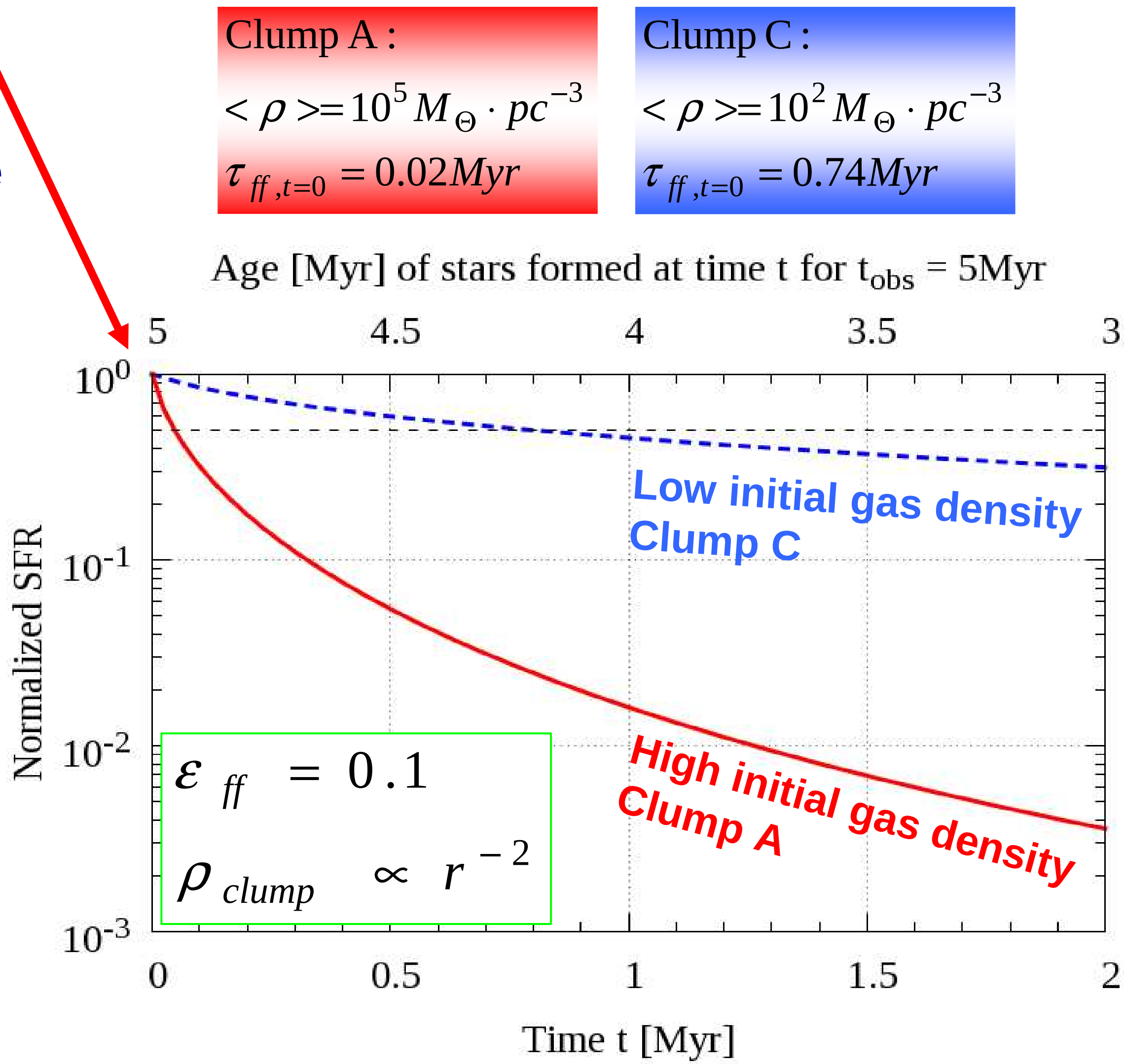
- **Gutermuth+(2011) obs ■**
- **Model → correct orders of mag despite simplifying hyp.**
  - **Spherical symmetry**
  - **Single power-law**

Denser Is Faster – Cluster Stellar Age Spreads

- **Clump SFR evolution normalized to initial value**
- **SFR decreases with time**
  - **$M_{gas}(t)$ decreases**
  - **$\tau_{ff}(t)$ gets longer**

- **Low-density Clump C:**
  - **shallow slope**
  - **slow evolution**
  - **limited SFR variations**

- **High-density Clump A:**
  - **steep slope**
  - **fast evolution**
  - **strong SFR variations**

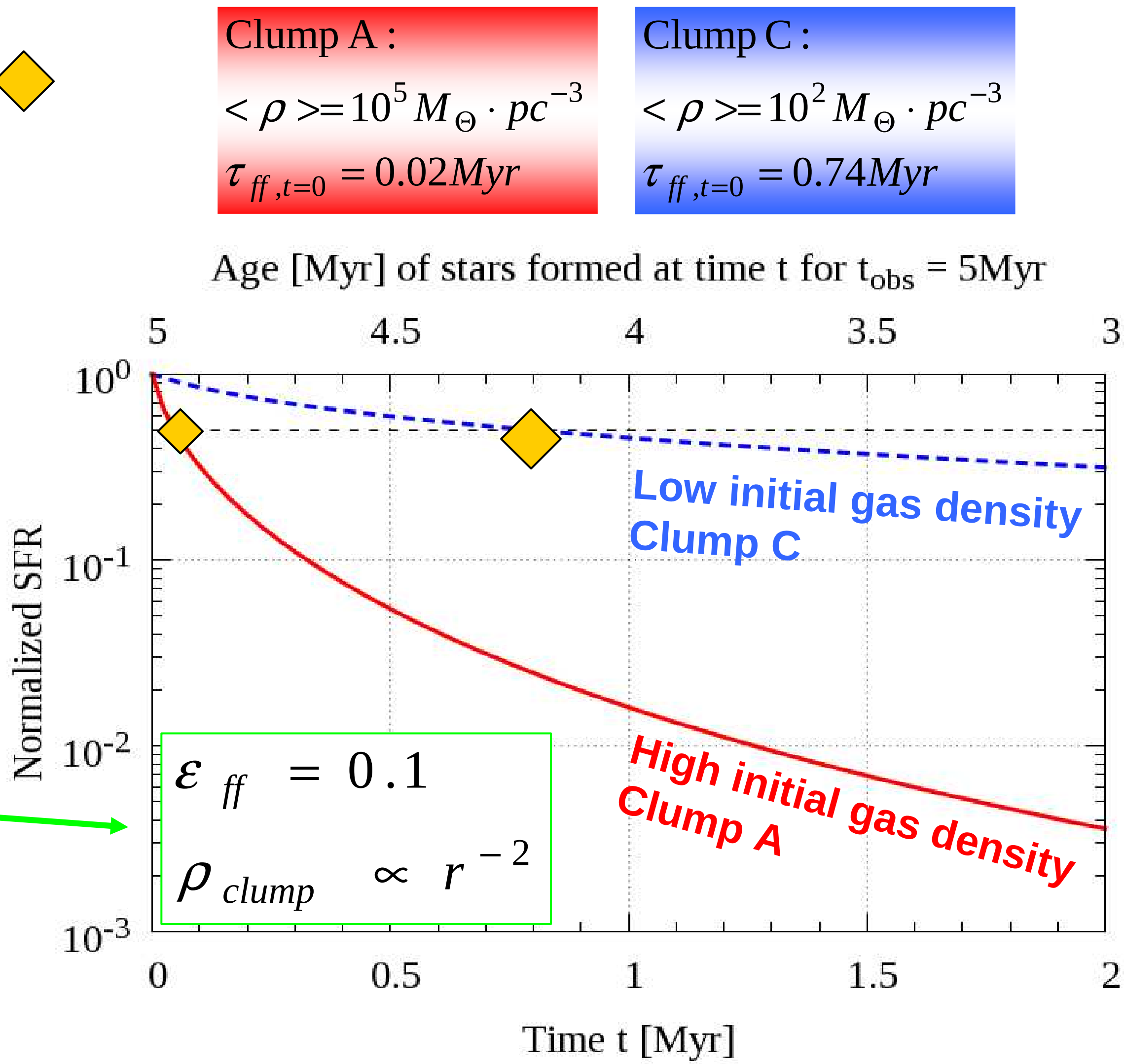


Parmentier, Pfalzner & Grebel (subm)

Denser is Faster – SFR Half-Life Time, $t_{1/2}$

- Half-life time of SFR, $t_{1/2}$:
  - in low-density gas
    → $t_{1/2}$ is long
  - in high-density gas
    → $t_{1/2}$ is short

- Half-life time of SFR, $t_{1/2}$, is a clump density indicator for given
  - star formation efficiency per free-fall time, ε_{ff} (smaller efficiency → slower)
  - clump density profile, ρ_{clump} (shallower → slower)



Parmentier, Pfalzner & Grebel (subm)

Clump SF Histories - Binning

- **Same models; different result presentation**
- **Assuming a SF duration of 2Myr, distribution of the stellar mass formed at t=2Myr as a function of time (bin size = 0.1Myr):**
- **Binning alone conceals the short SFR half-life time of high-density clumps; e.g.**

Clump A :

$$\left(t_{1/2} = 0.05 Myr\right) < \left(\text{Bin width} = 0.1 Myr\right)$$

  - **In case of high-density/fast-evolving clumps, only an upper limit (>≈0.1Myr, the bin size) to the half-life time is recovered**

Clump A :

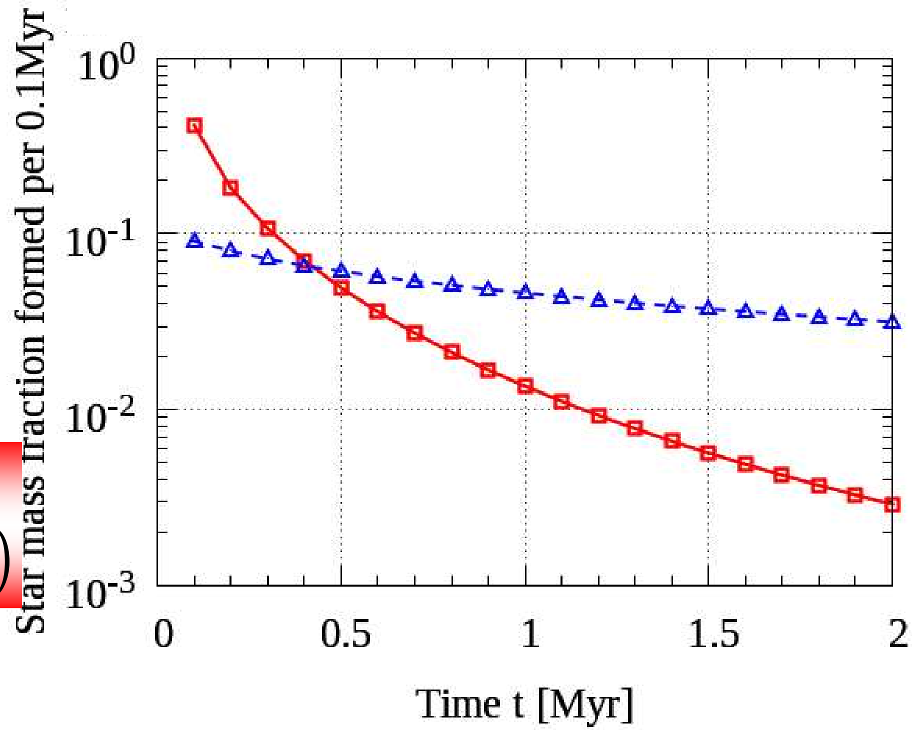
$< \rho >= 10^5 M_\Theta \cdot pc^{-3}$

$\tau_{ff,t=0} = 0.02 Myr$

Clump C :

$< \rho >= 10^2 M_\Theta \cdot pc^{-3}$

$\tau_{ff,t=0} = 0.74 Myr$

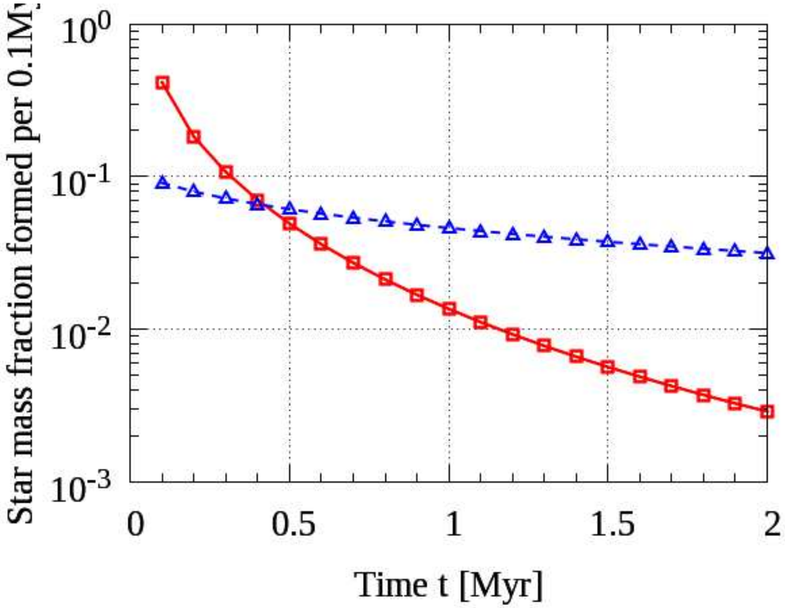


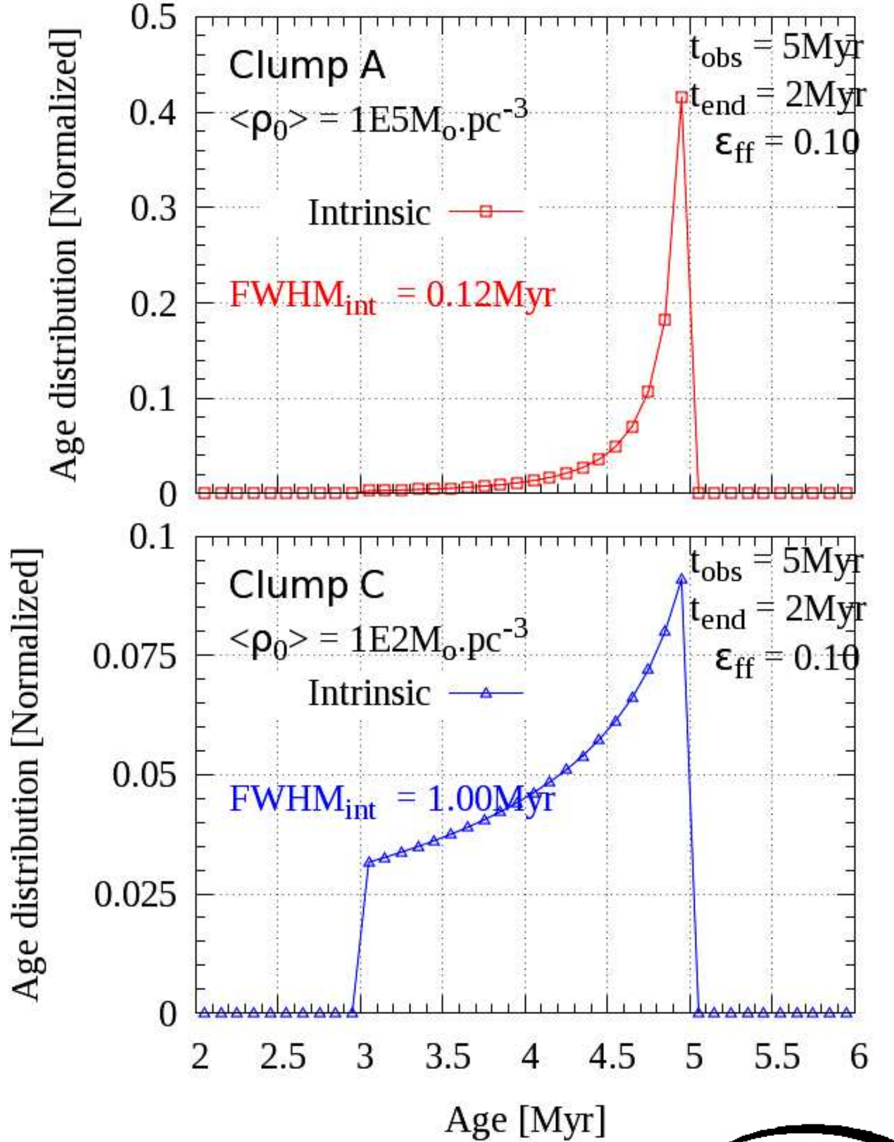
Parmentier, Pfalzner & Grebel (subm)

From Clump SFHs to Stellar Age Distributions

- **The SFR half-life time, $t_{1/2}$, is one driver of the FWHM of linear stellar age distributions in clusters**

Clump A :	Clump C :
$< \rho >= 10^5 M_\Theta \cdot pc^{-3}$	$< \rho >= 10^2 M_\Theta \cdot pc^{-3}$
$\tau_{ff,t=0} = 0.02 Myr$	$\tau_{ff,t=0} = 0.74 Myr$
$t_{1/2} = 0.05 Myr$	$t_{1/2} = 0.80 Myr$





Parmentier, Pfalzner & Grebel (subm)

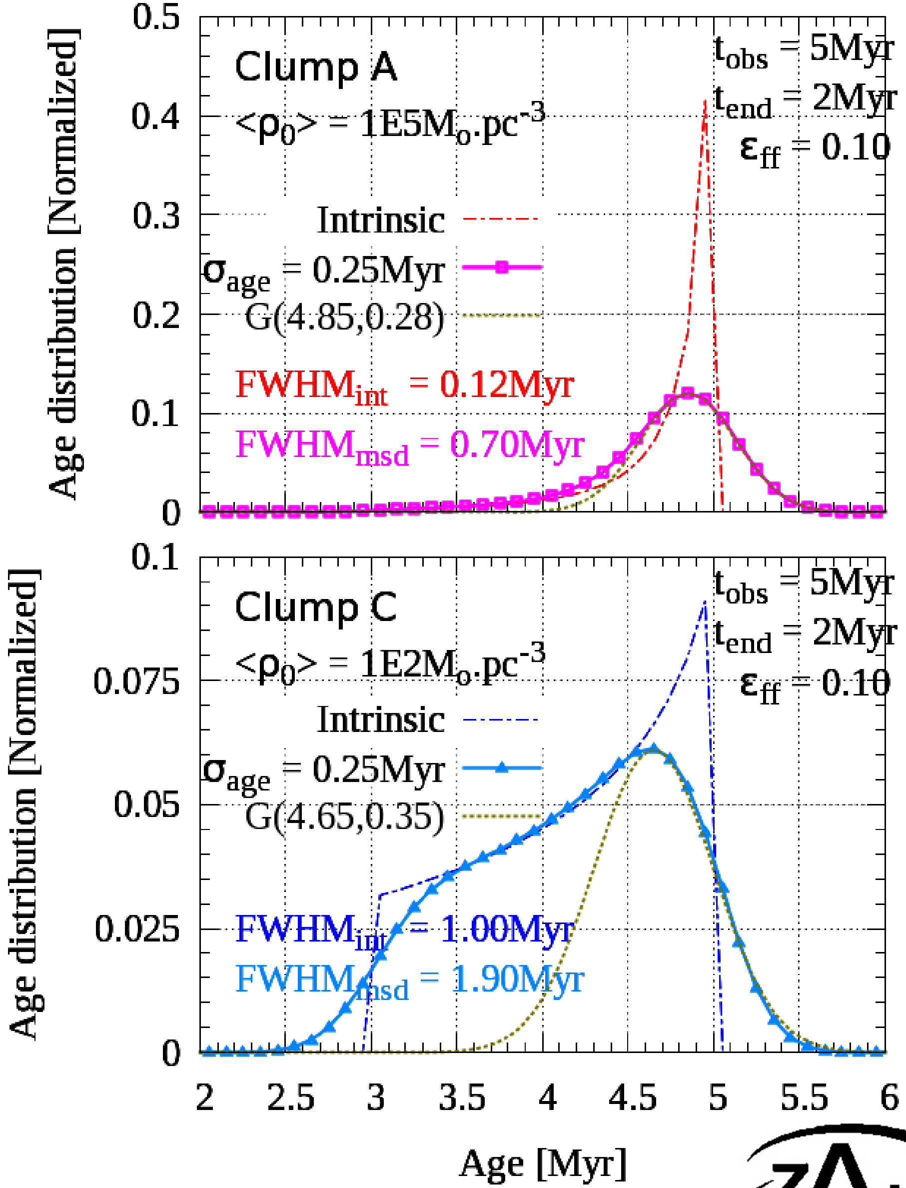
Measured Cluster Stellar Age Distributions

- **Impact of the uncertainty affecting individual star ages: measured FWHM larger than SFR half-life time , $t_{1/2}$ (in addition to binning effect)**

- **Denser Is Faster: Model outcomes consistent with stellar age spreads in Wd-1 and NGC3603 narrower than that of the ONC (Kudryavtseva+2012, Reggiani+2011)**

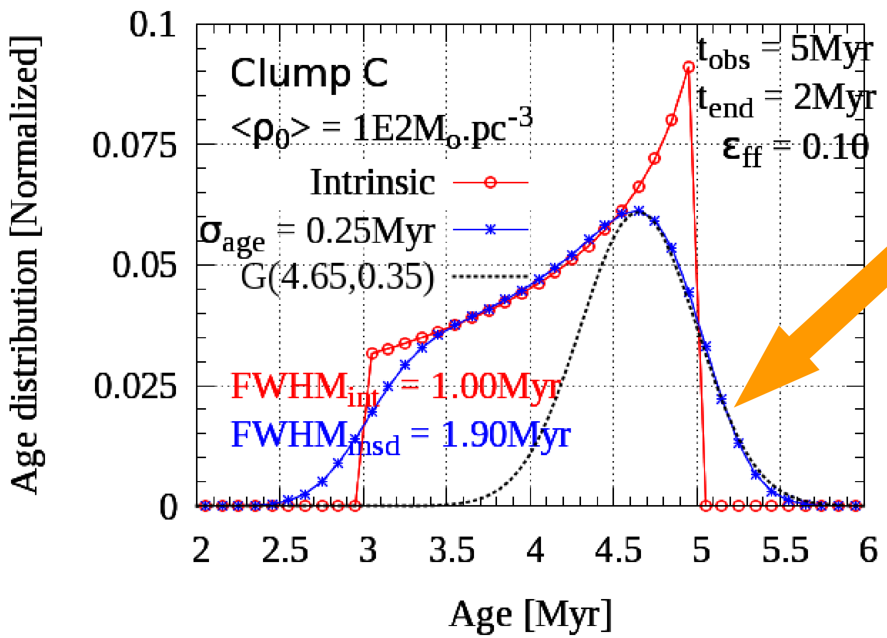
- **Stellar age distribution often quantified by its width. Other interesting parameters:**
  - **skewness**
  - **kurtosis (Jeffries+2011)**

- **Logarithmic stellar age distributions coming soon**



Stellar Age Distributions – A Comment

➤ **Observed accelerated SF on the old side of the age distribution could be the imprint of age errors**

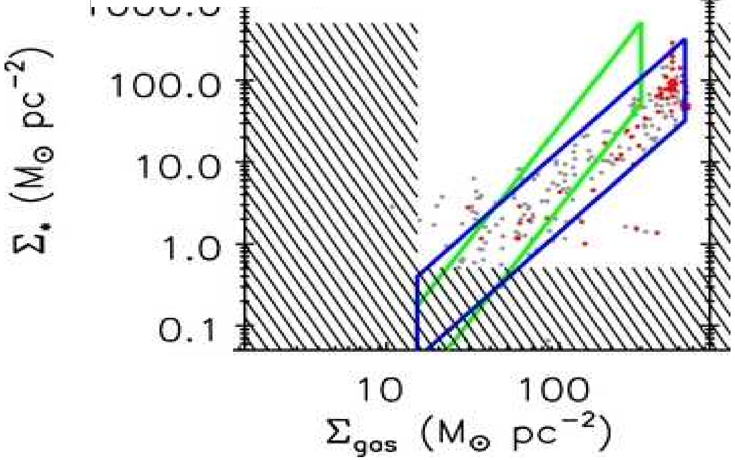


- **Accelerated SF 'a la' Palla & Stahler (2000)**
- **No intrinsic property of SFH**
- **Imprint of star age errors!!**
- **See review by Preibisch (2012)**

Conclusions

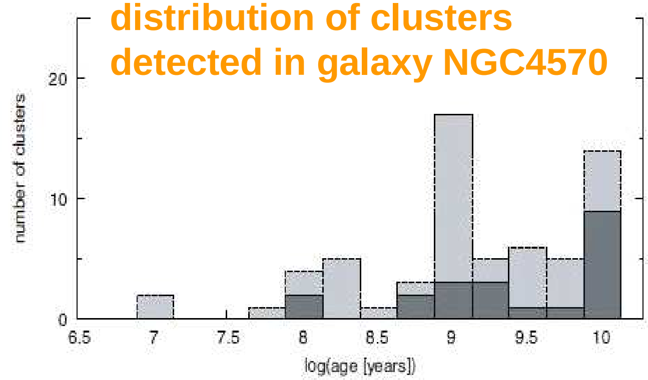
Multi-pc scale

Fig9, Gutermuth+ (2011)



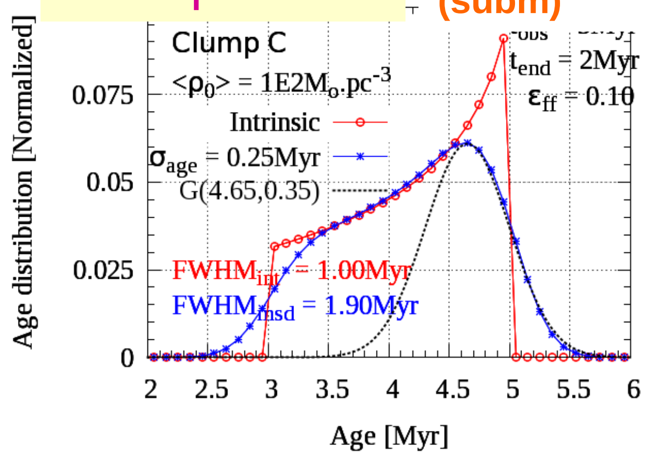
Multi-kpc scale

Fig4, Kotulla+ (2008) - Age distribution of clusters detected in galaxy NGC4570



Multi-pc scale

Parmentier+ (subm)



All these topics are related:

- High SFE in high-density gas
- Greater survivability of clusters formed out of high-density gas
- Narrow stellar age spreads for clusters formed out of high-density clumps

- **Slides:** wwwstaff.ari.uni-heidelberg.de/mitarbeiter/gparm/talks.html
- **Movies:** wwwstaff.ari.uni-heidelberg.de/mitarbeiter/gparm/movies.html