The Early Survival of (Globular) Star Clusters:

Easier Than We Thought!

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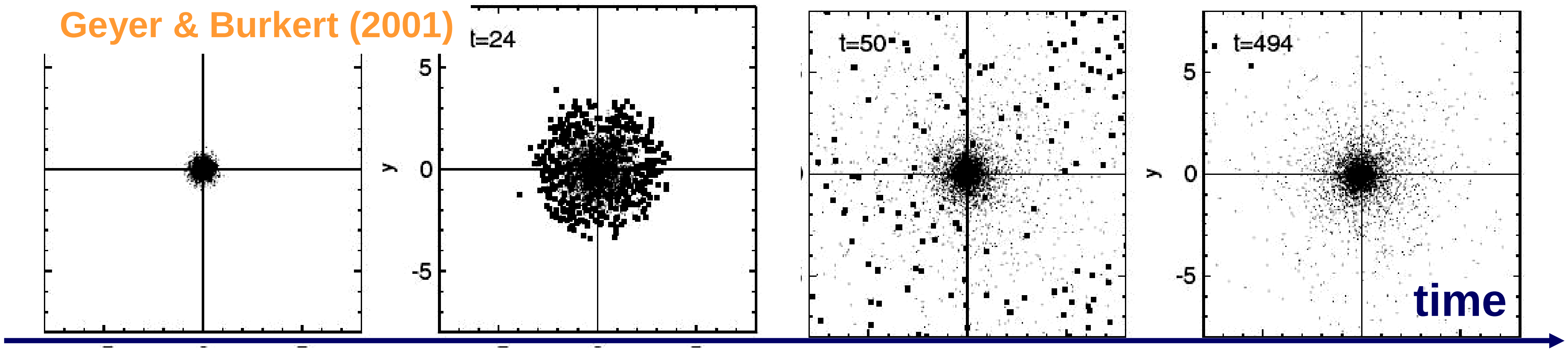
Germany

Post-Gas-Expulsion Cluster Evolution

SC Dynamical Response to the Expulsion of its Residual Star-Forming Gas
→ star-loss and expansion

Geyer & Burkert (2001)



- Time sequence of N-body simulations by Geyer & Burkert (2001):
- The SC does not necessarily survive
- The dynamical response of a star cluster to residual star-forming gas expulsion depends on many parameters:
  - *Global star formation efficiency (Hills 1980)*
  - *Gas expulsion time-scale, in crossing-time units (Lada et al. 1984)*
  - *Embedded cluster subvirial or not (Goodwin 2009)*
  - *External tidal field (cluster – galaxy volume density contrast) (Baumgardt & Kroupa 2007, Renaud et al 2008)*
  - *Additional external perturbations (e.g. spiral arms, GMCs) (Gieles et al. 2006)*

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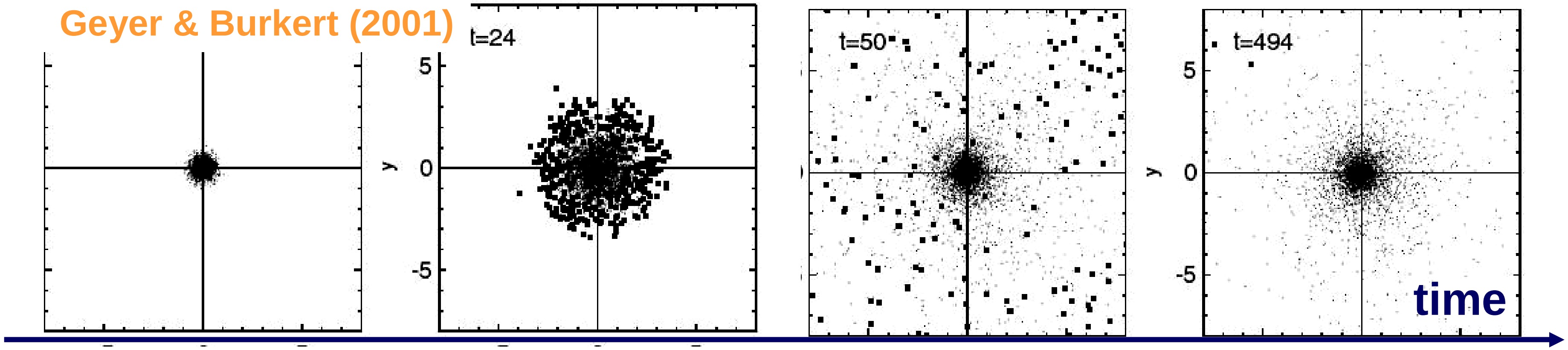

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How are the gas and stars of a nascent cluster distributed with respect to each other at gas expulsion?

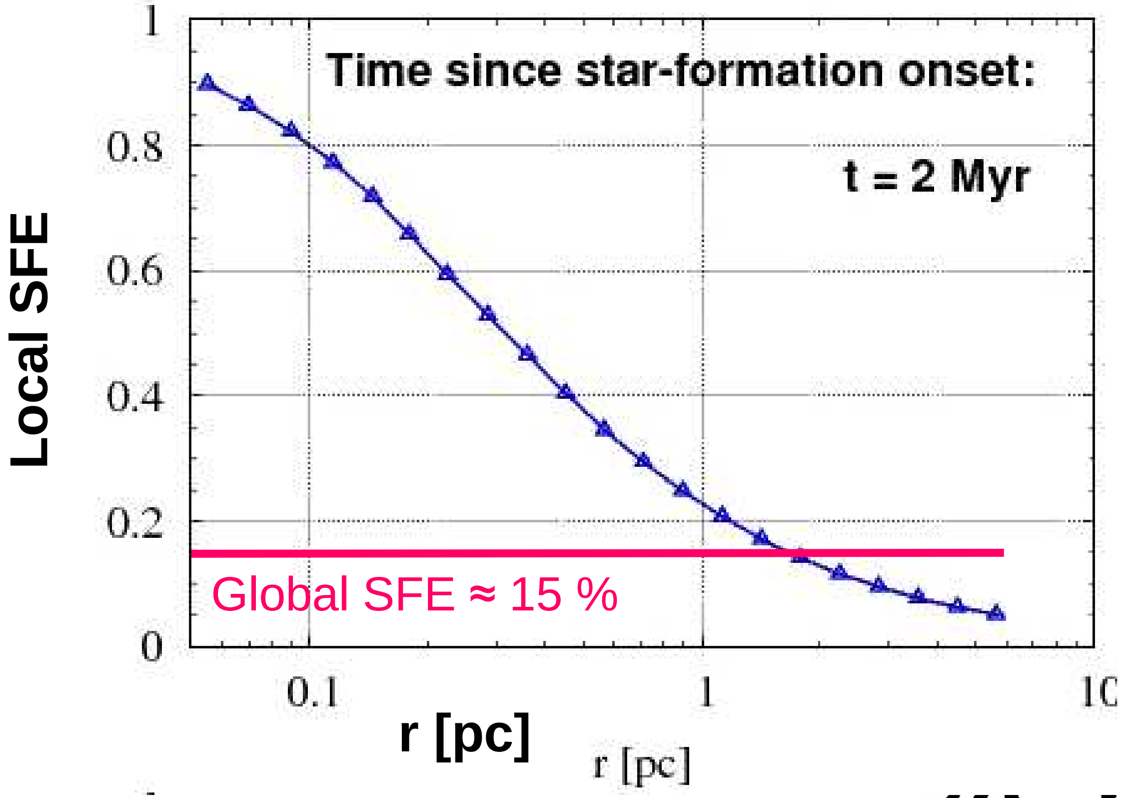
Post-Gas-Expulsion Cluster Evolution

Knowledge of the global star formation efficiency is not enough

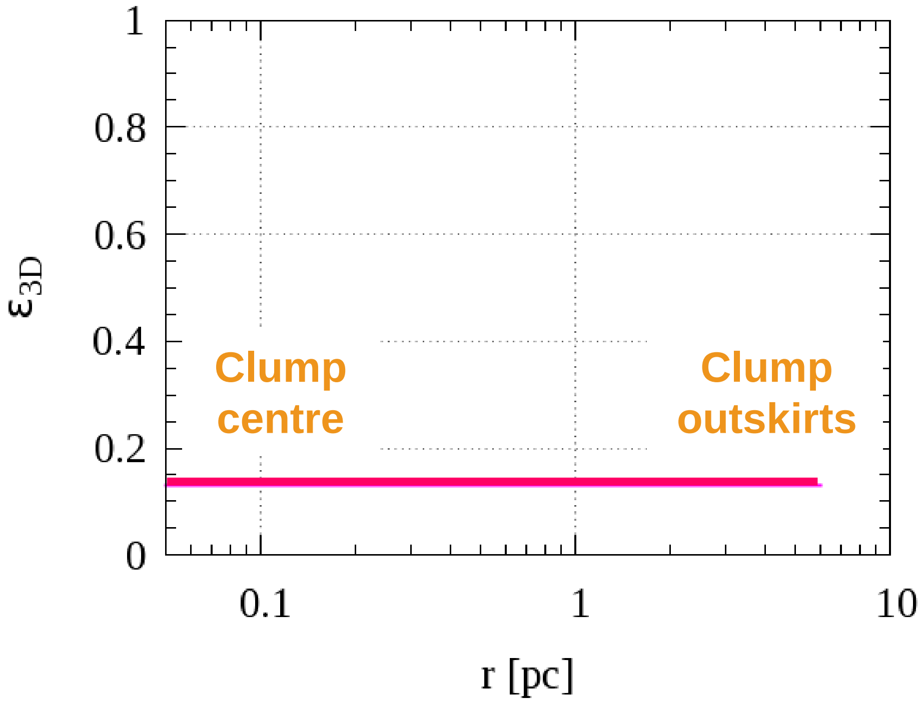
How are the gas and stars of a nascent cluster distributed with respect to each other at gas expulsion?

- Clump of molecular gas
  A. Is the gas converted into stars in a uniform manner?
     - Assumption on which the model presented in the previous slide builds
  B. Or: is star formation more efficient in the central regions of the protocluster?
     - Helps improve star cluster survival

Parmentier & Pfalzner 2013, Fig10



Scenario A – The Killer



Radially constant SFE:

- **Local SFE = Global SFE**
- **Cluster survival requires global SFE > 0.33**

Fraction of stars staying in a cluster after gas expulsion vs. global SFE at gas expulsion

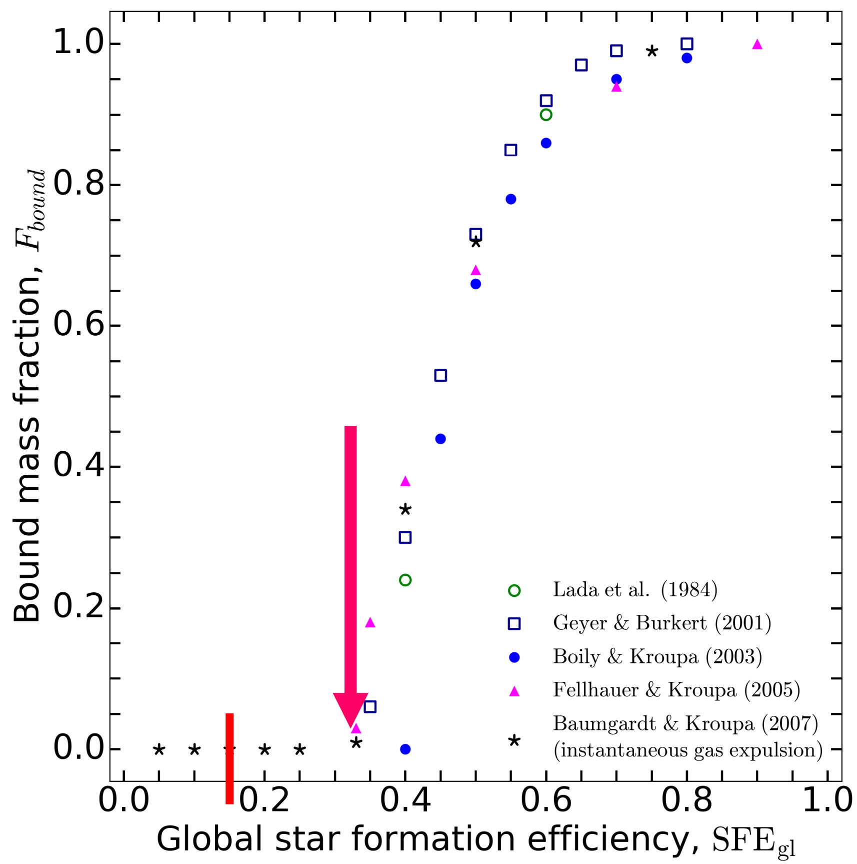
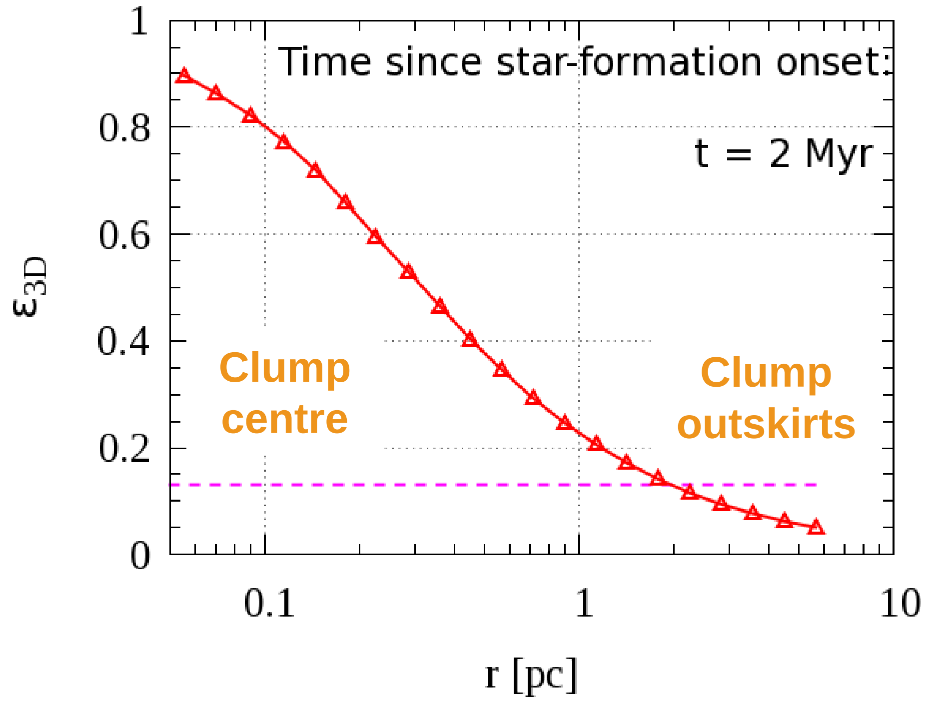


Fig. by Bek Shukirgaliyev (see also Fig.1, Parmentier & Gilmore 2007)

Scenario B – The Rescuer



Parmentier & Pfalzner 2013, Fig. 10

Radially-varying SFE:

- **Cluster survival despite low global SFE**

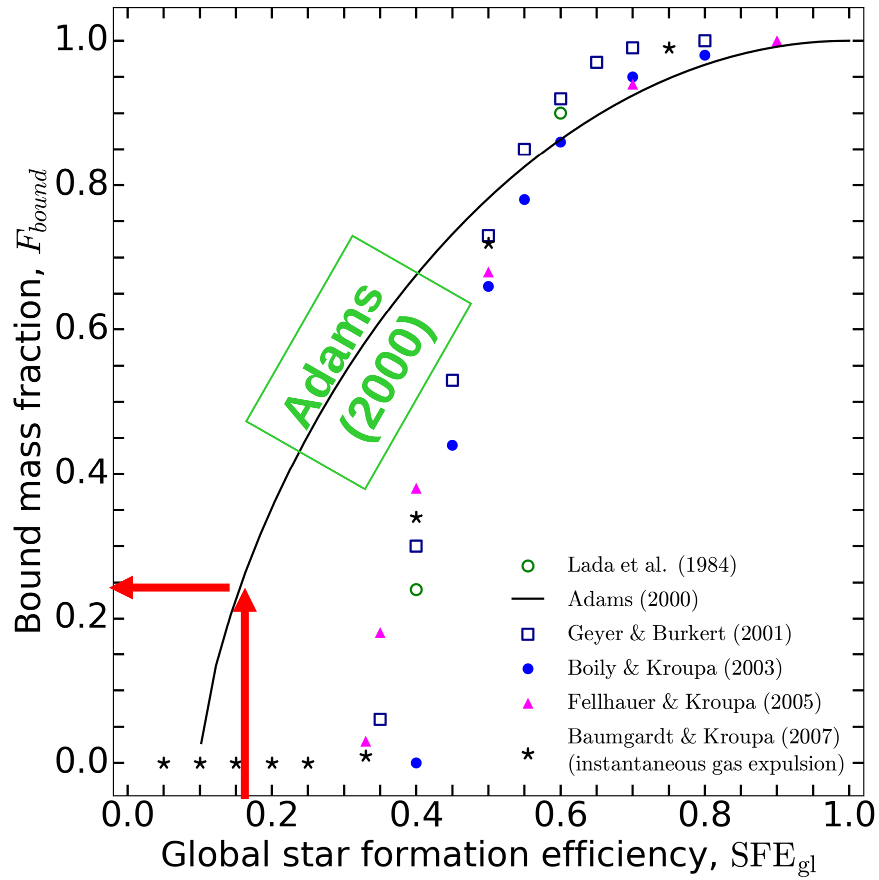
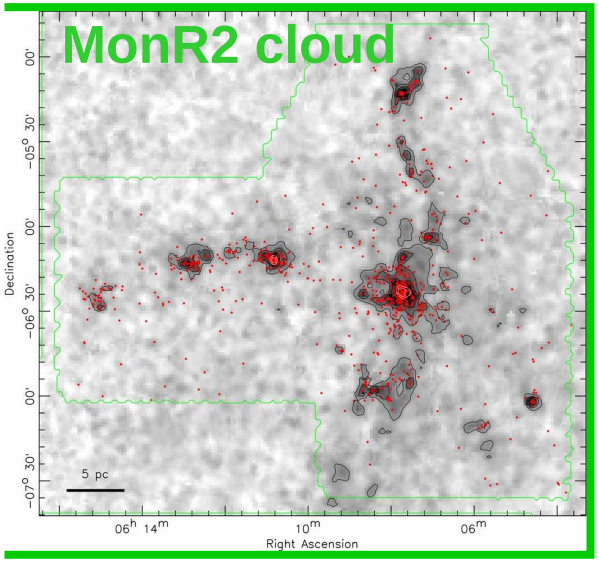


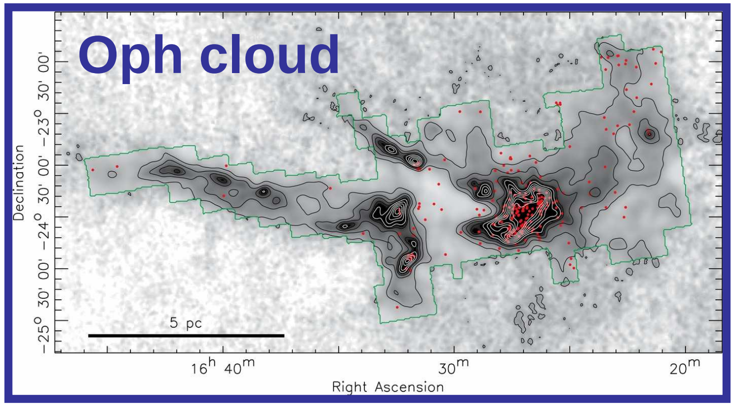
Fig. by Bek Shukirgaliyev

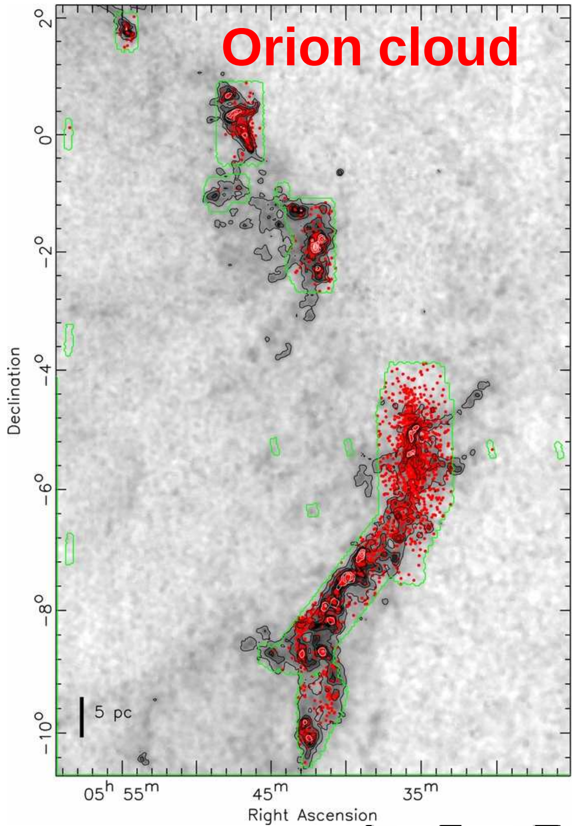
Cluster Formation: Insights from the Galactic Disk

- Early survival likelihood of star clusters depends heavily on initial conditions
- How can we distinguish between Scenario A and Scenario B?
- One possibility is to look at nearby molecular clouds in the disk of our Galaxy, where young stars can be counted



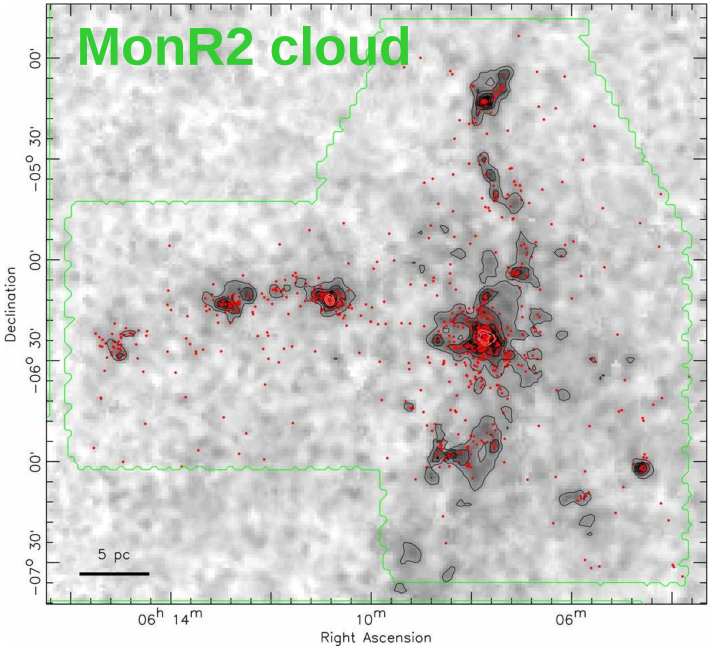
Figs 1,4,6 Gutermuth+(2011)





Gas-Density Dependent SFE: Observations

Fig. 1, Gutermuth+ (2011)



$$\Sigma_{YSO} \propto \Sigma_{gas}^2$$

Σ_{YSO}

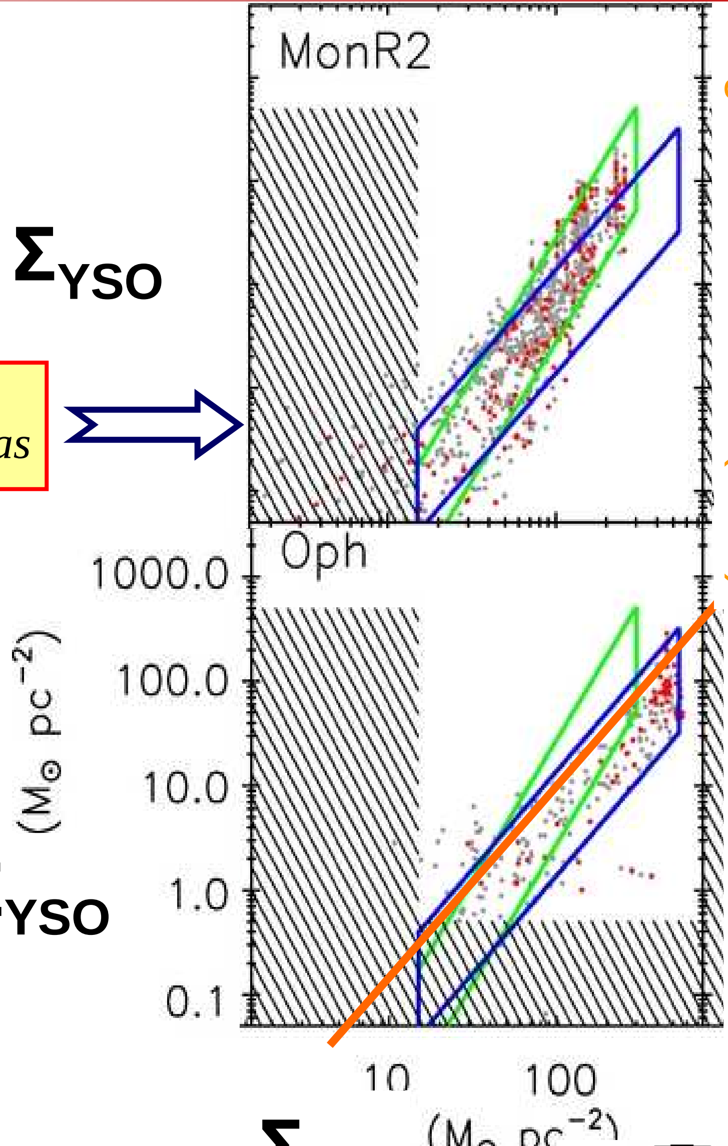


Fig. 9, Gutermuth+ (2011)

Σ_{gas}

$$\Sigma_{gas} \propto \frac{\Sigma_{YSO}}{\Sigma_{gas}} \propto \varepsilon_{2D}$$

Σ_{YSO}

- **Observations of molecular clouds in Solar Neighbourhood: local star formation efficiency does depend on gas density (see also Lombardi+2013, Lada+ 2013)**

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

- **Denser**
- **Faster**

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**

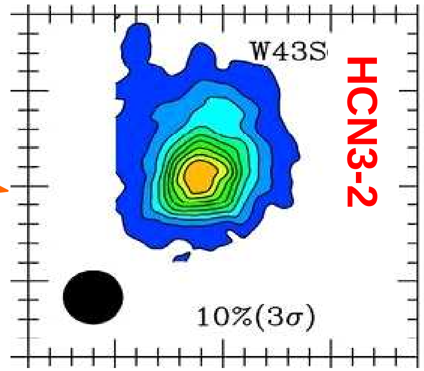
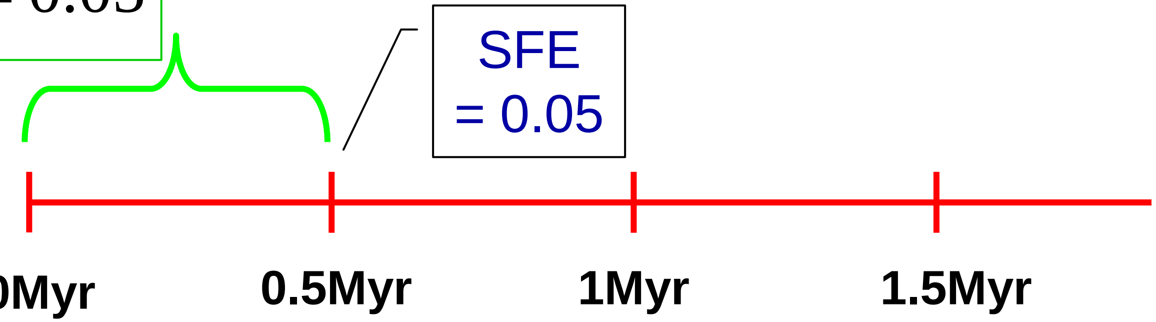


Fig 9 - Wu+2010

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

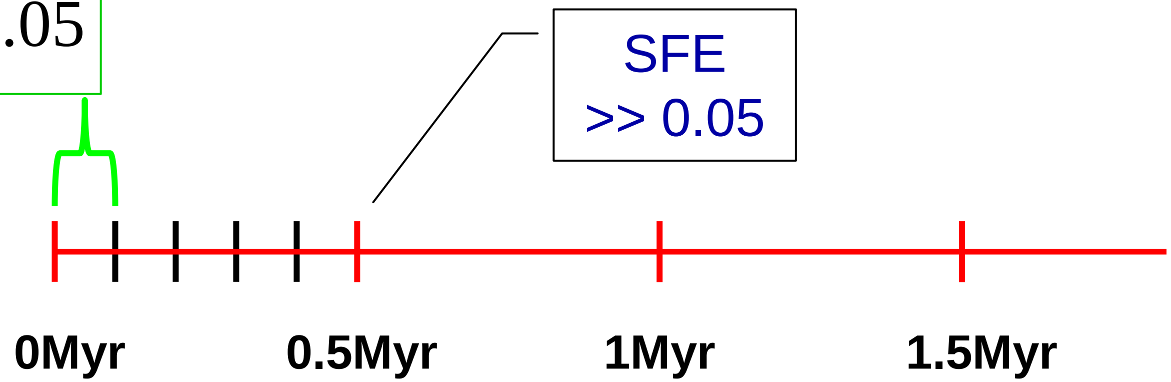
$$\tau_{ff,init} = 0.5 Myr$$
$$\rho \cong 300 M_{\Theta} \cdot pc^{-3}$$

$$\varepsilon_{ff} = 0.05$$



$$\tau_{ff,init} = 0.1 Myr$$
$$\rho \cong 10^4 M_{\Theta} \cdot pc^{-3}$$

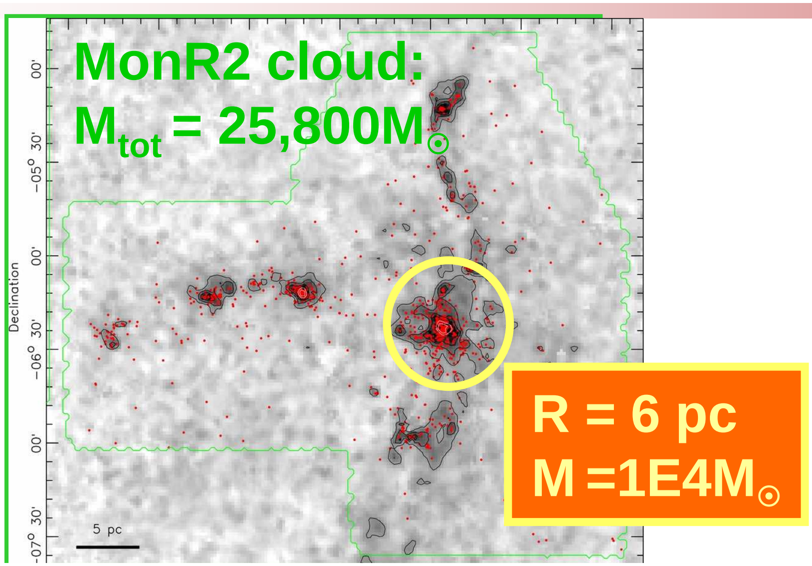
$$\varepsilon_{ff} = 0.05$$

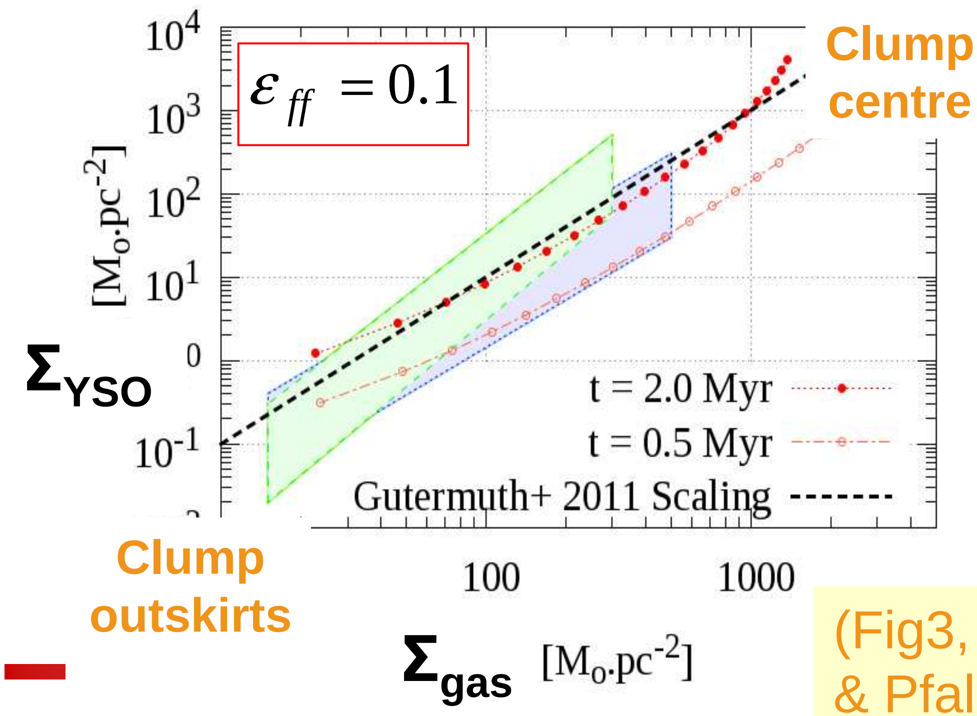


For any given physical time-span after the onset of star formation: molecular-gas regions of higher density achieve higher SFEs

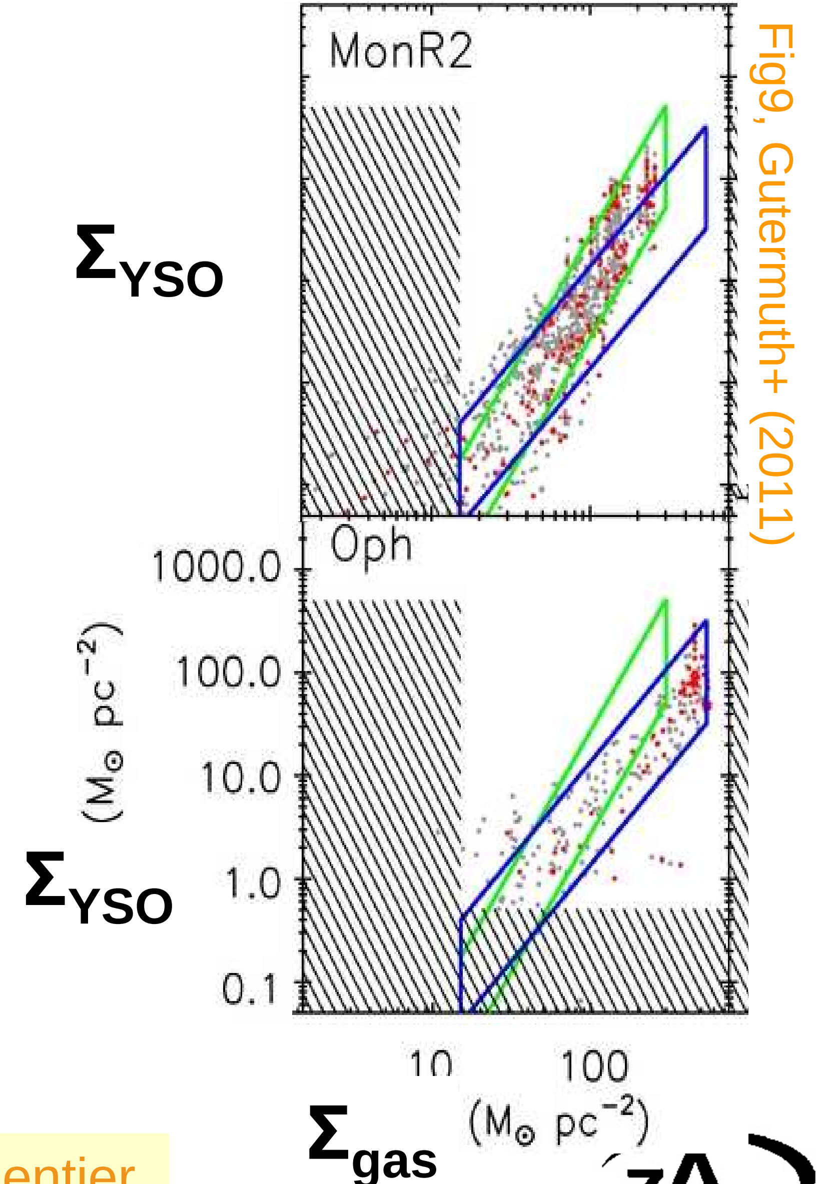
A star cluster does not care about how long the Earth takes to revolve around the Sun

Observations vs. Models



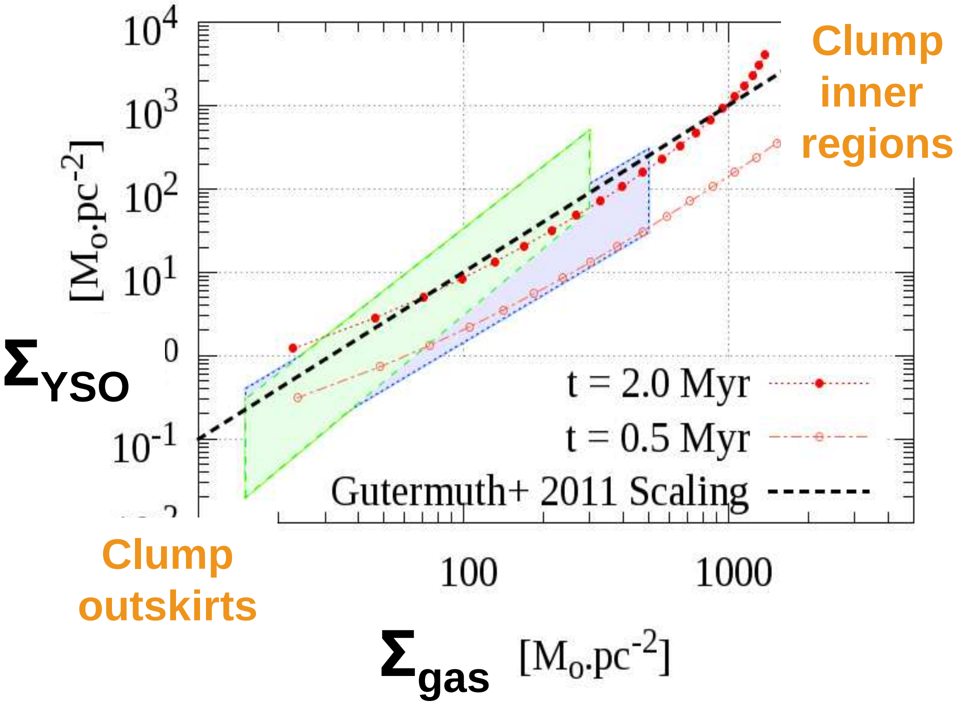


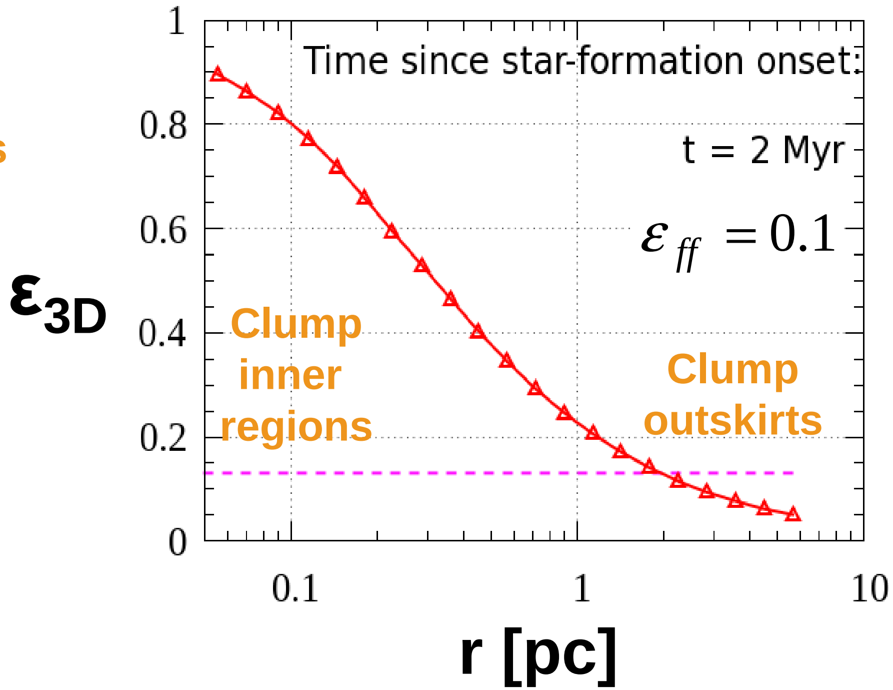
(Fig3, Parmentier & Pfalzner 2013)



Star Formation Relation and SFE Radial Variations

Figs 3 and 10, Parmentier & Pfalzner (2013)





Local Star Formation Relation:

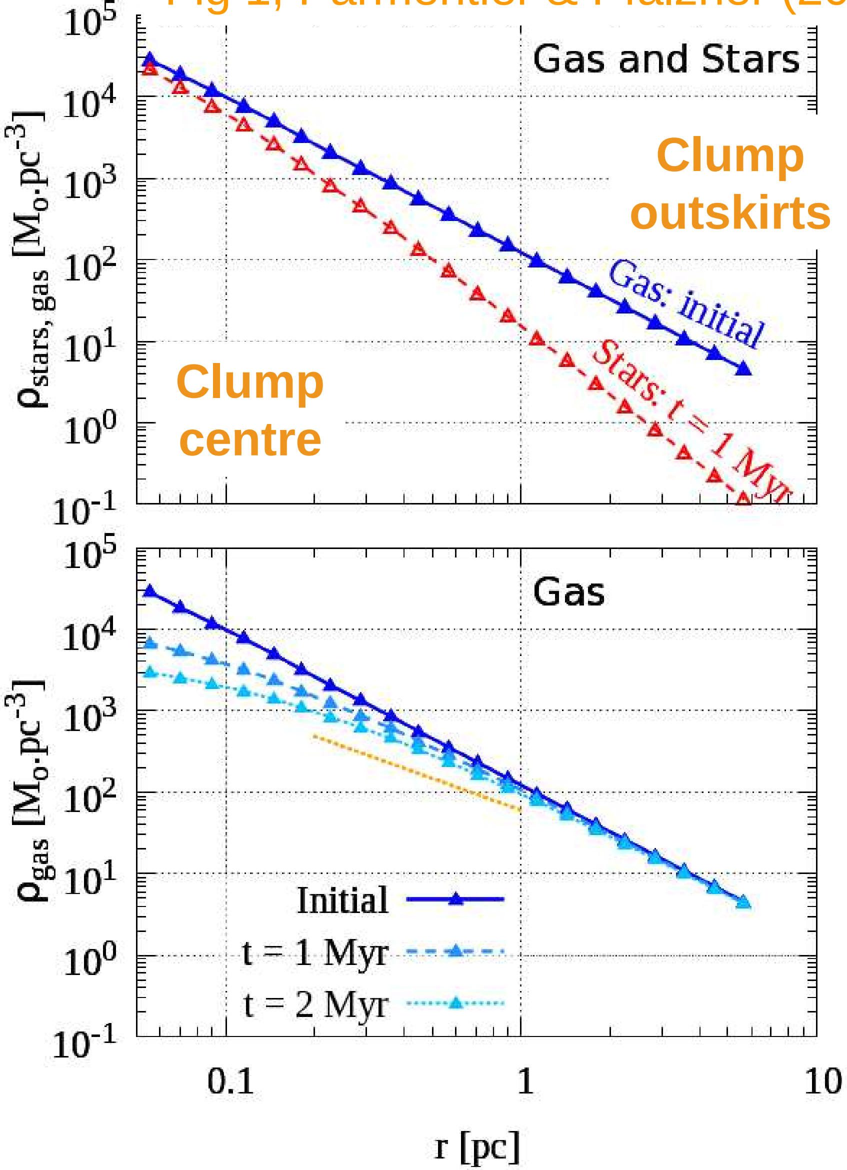
Superlinear / Quadratic

Local star formation efficiency :

ε_{3D}(inner) > ε_{3D}(outer)

Scenario B – the Rescuer – is the Winner

Fig 1, Parmentier & Pfalzner (2013)



- **Radial density profiles of the embedded cluster (stars only), of the residual gas, and of the initial gas** (Eqs 19-20 , Parmentier & Pfalzner 2013)

Residual gas

$$\rho_{gas}(t,r) = \left(\rho_0(r)^{-1/2} + \sqrt{\frac{8G}{3\pi}}\varepsilon_{ff}\, t \right)^{-2}$$

$$\rho_{ecl}(t,r) = \rho_0(r) - \left(\rho_0(r)^{-1/2} + \sqrt{\frac{8G}{3\pi}}\varepsilon_{ff}\, t \right)^{-2}$$

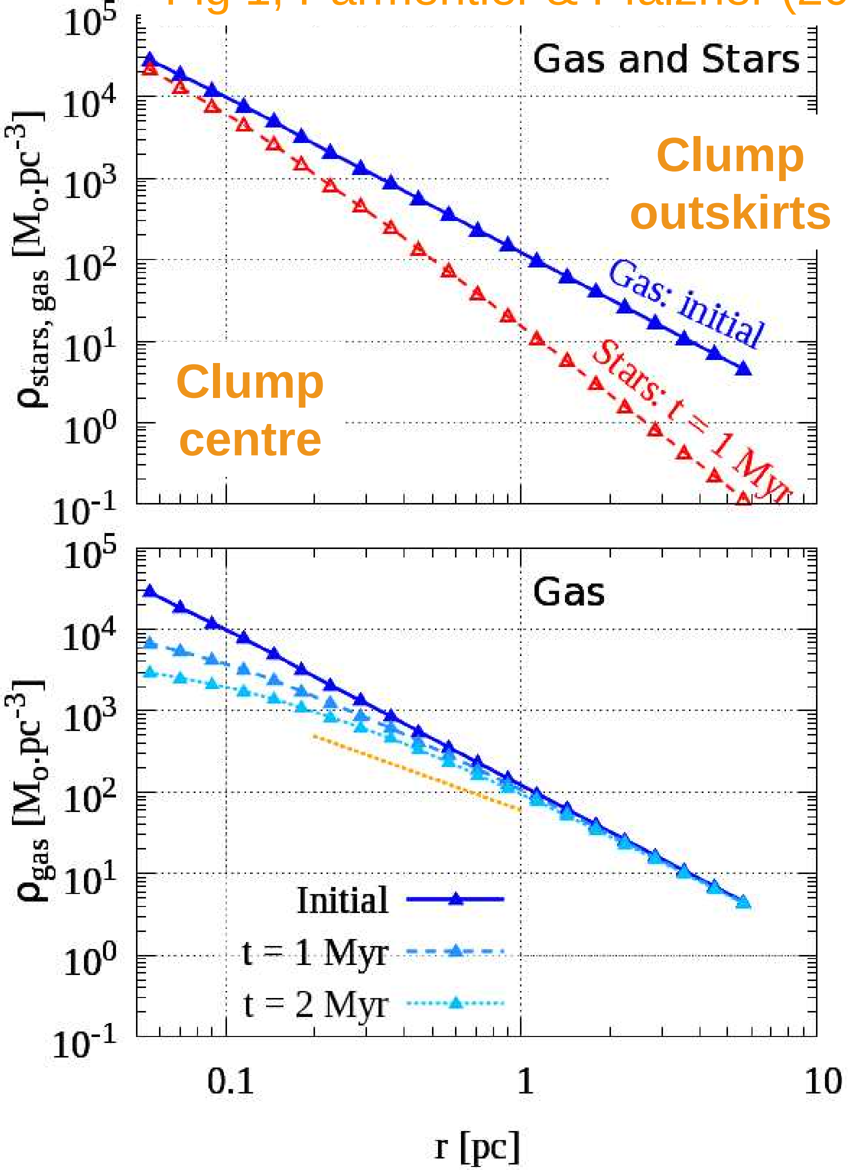
Stars **Initial gas**

- **Initial gas density profile $\rho_0(t)$**

$\rightarrow \rho_{ecl}(r,t)$, $\rho_{gas}(r,t)$

Implementing Rescuing/Winning Scenario

Fig 1, Parmentier & Pfalzner (2013)



- **Starting point: molecular clump**

$$\rho_0(r) \rightarrow \rho_{ecl}(t_{SF}, r) \text{ and } \rho_{gas}(t_{SF}, r)$$

$$\neq t_{SF} \rightarrow \neq SFE \rightarrow \neq cluster\ masses \rightarrow \neq r_t$$

$$\rightarrow \neq density\ profiles \rightarrow \neq r_h$$

- **Not straightforward to compare modeling outputs with earlier works**
- **To make life easier, starting point: embedded cluster with a given mass and given density profile**

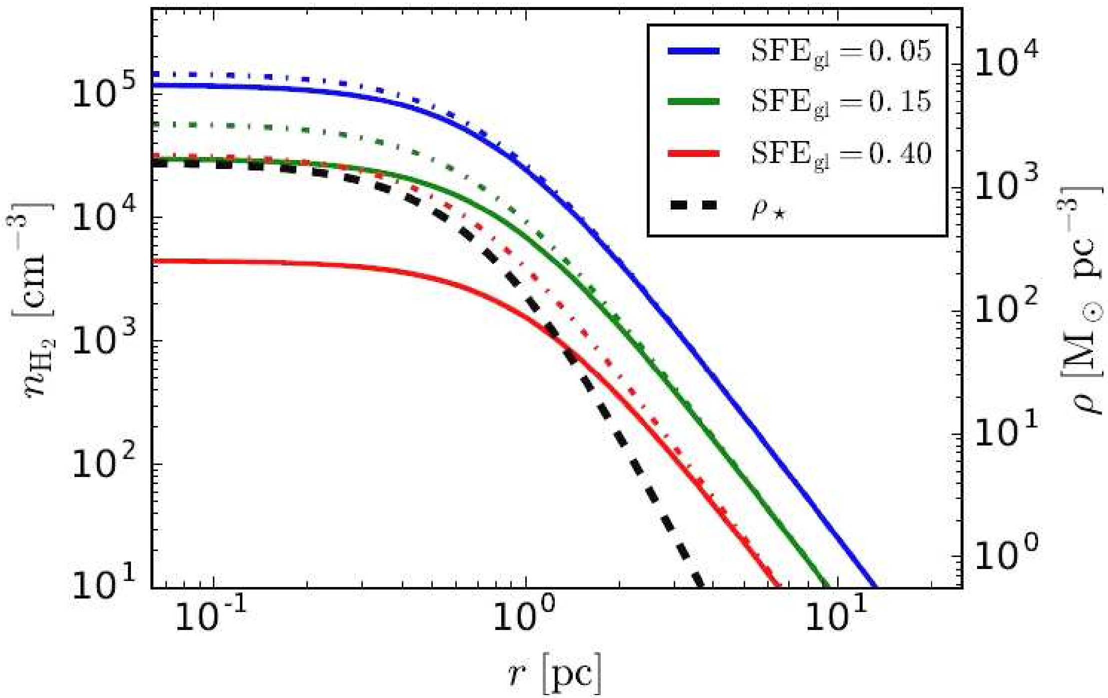
$\rho_{ecl}(r)$ with fixed

stellar mass / density profile

Given SFE $\rightarrow \rho_0(t_{SF}, r)$ and $\rho_{gas}(t_{SF}, r)$

Implementing Rescuing/Winning Scenario

Bekdaulet Shukirgaliyev

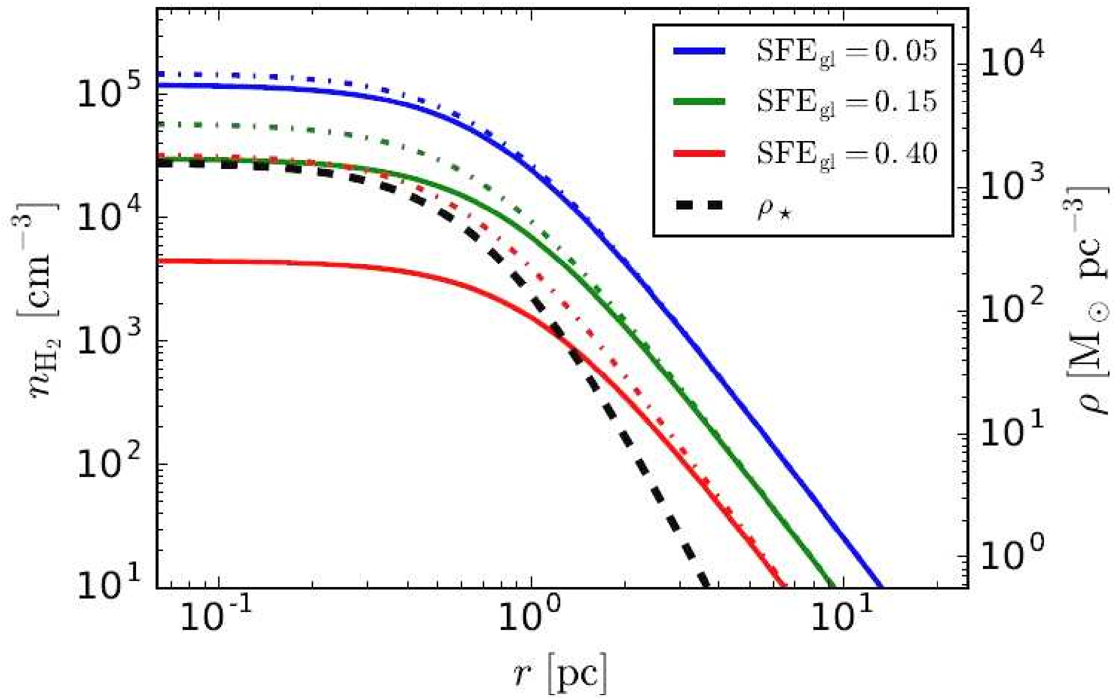


- **Density profile of embedded cluster is fixed to a Plummer profile**
- **Residual gas density profile recovered based on the formalism of Parmentier & Pfalzner (2013)**

$$\rho_{gas}(t_{SF}, r) = \left(\frac{1}{\sqrt{\rho_{gas}(r, t_{SF}) + \rho_{ecl}(r)}} + \underbrace{\sqrt{\frac{8G}{3\pi}} \varepsilon_{ff} t_{SF}}_{k} \right)^{-2}$$

Implementing Rescuing/Winning Scenario

Bekdaulet Shukirgaliyev



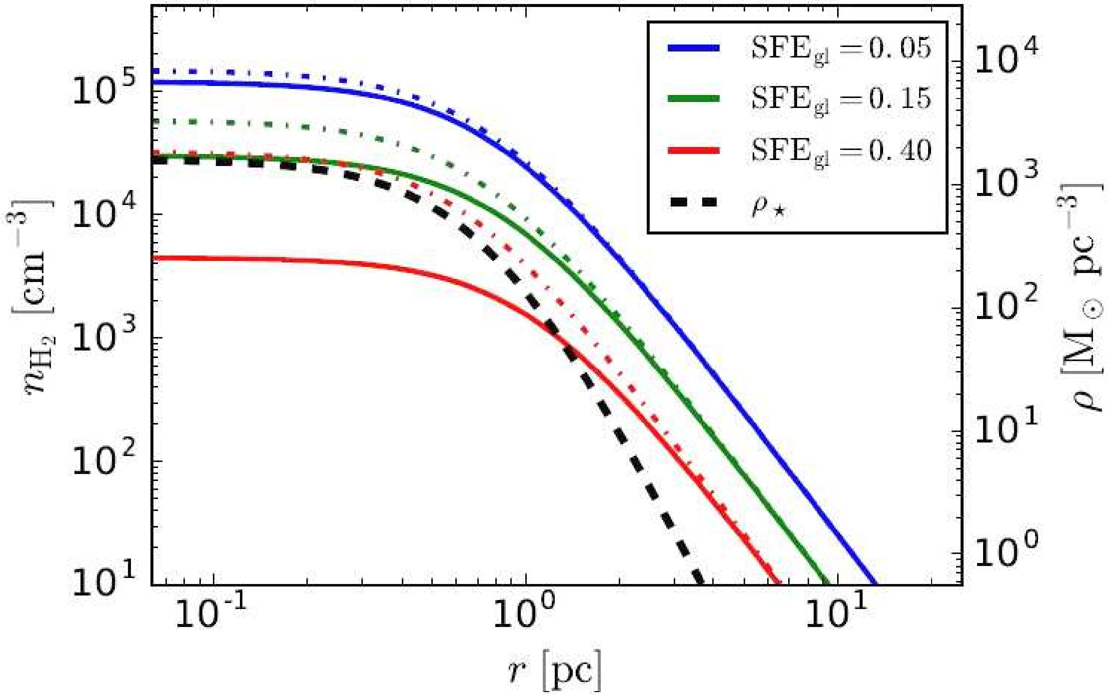
- **Density profile of embedded cluster is fixed to a Plummer profile**
- **Residual gas density profile recovered based on the formalism of Parmentier & Pfalzner (2013)**

$$k^4\rho_{gas}^4 - \left(4k^2 - 2k^4\rho_{ecl}\right)\rho_{gas}^3 - \left(6k^2\rho_{ecl} - k^4\rho_{ecl}^2\right)\rho_{gas}^2 - 2k^2\rho_{ecl}^2\rho_{gas} + \rho_{ecl}^2 = 0$$

- **Solution given as Eq A.7 of Shukirgaliyev et al., A&A, in press**

N-body Set-up for Rescuing/Winning Scenario

Bekdaulet Shukirgaliyev

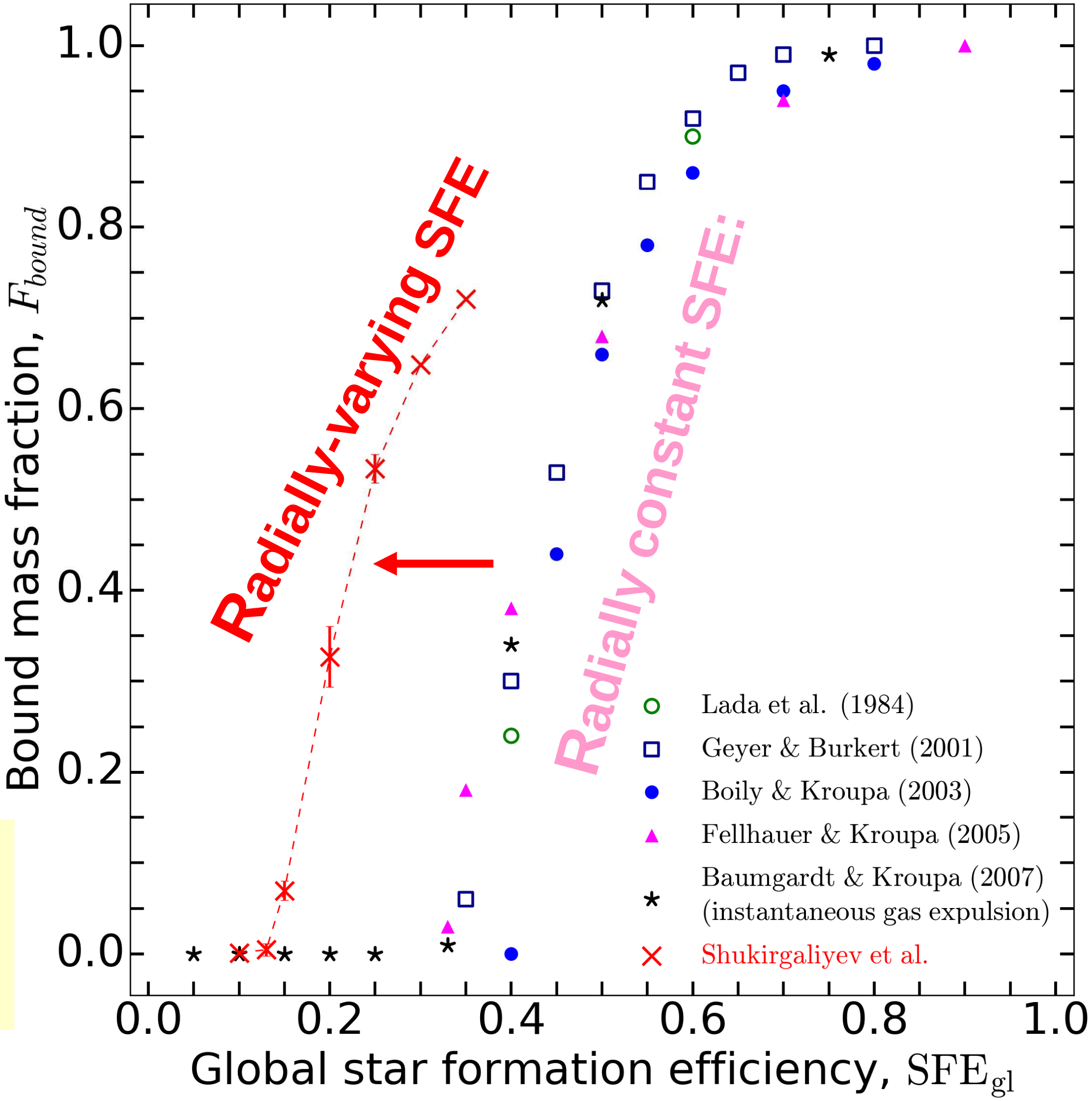


- Density profile of embedded cluster is fixed to a **Plummer profile**
- Residual gas density profile recovered based on the formalism of **Parmentier & Pfalzner (2013)**
- Residual gas $\rho_{gas}(r,t_{SF})$ accounted for as an external potential (using *mkhalo* by **McMillan & Dehnen 2007**)

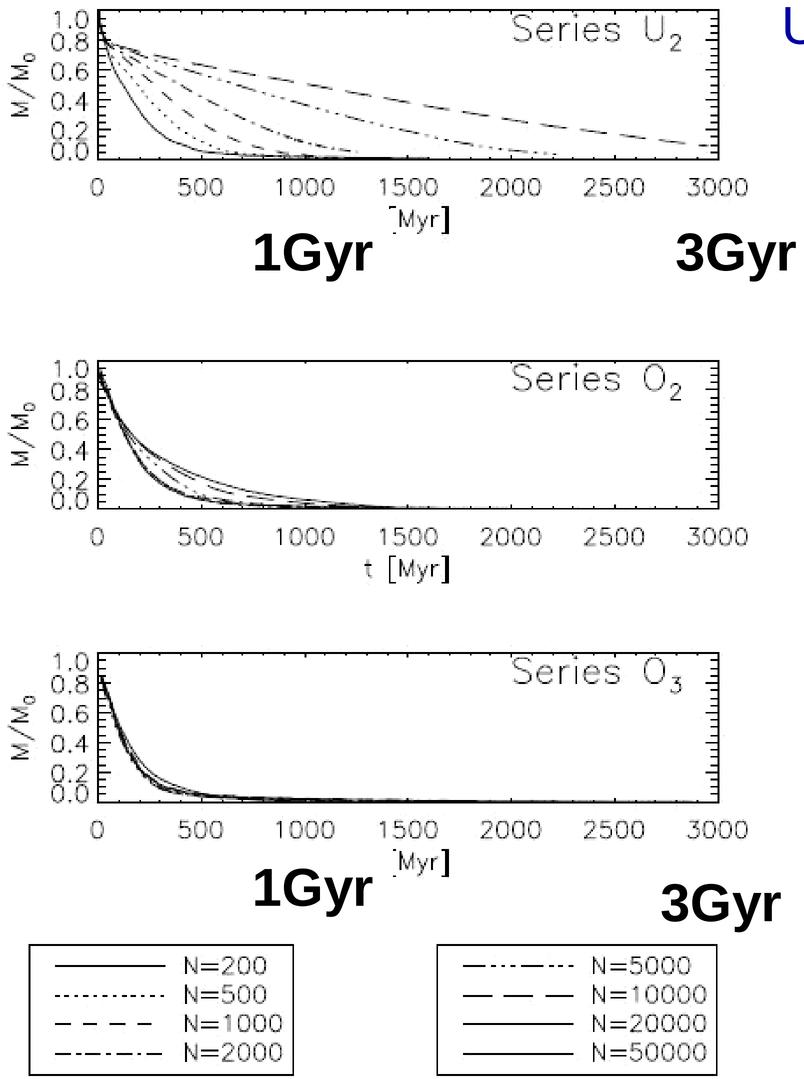
Results for Rescuing /Winning Scenario

Cluster survivability is strengthened (despite tidal-field inclusion)

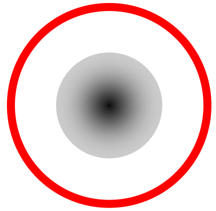
Shukirgaliyev, Parmentier, Berczik & Just, A&A, in press [http://xxx.lanl.gov/abs/1706.03228]



Mass-Dependent vs Mass-Independent Dissolution



Underfilling cluster (U2):
→ mass-dependent dissolution



$$\lambda' = \frac{r_{99\%}}{r_J} = 1/3$$

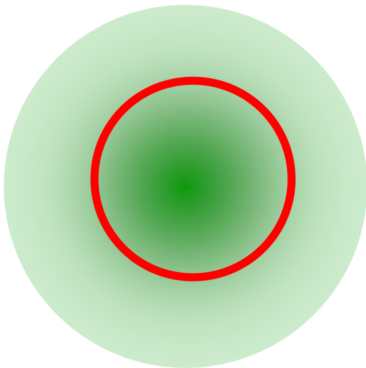
Jacobi radius:

$$r_J \propto \left(\frac{G M_{cl}(r_J)}{\Omega_c^2} \right)^{1/3}$$

Overfilling clusters (O2, O3):
→ mass-INdependent
(and faster: <1Gyr) dissolution

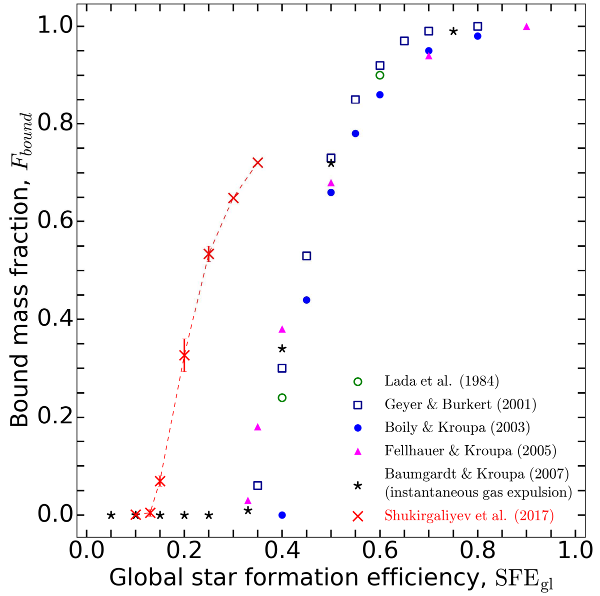
$$\lambda' = \frac{r_{99\%}}{r_J} = 2$$

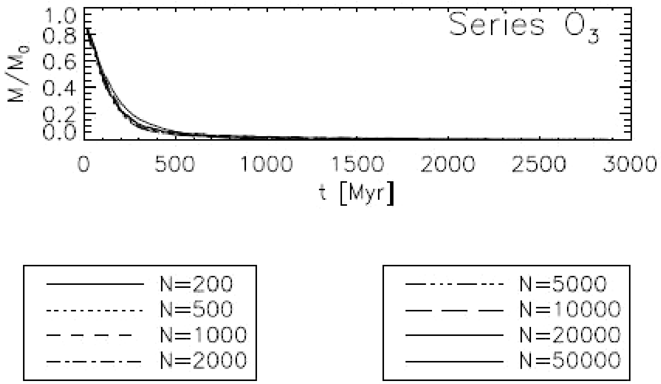
$$\lambda' = \frac{r_{99\%}}{r_J} = 3$$



Ernst, Berczik, Just & Noel 2015, Fig.5

Conclusions





- The survivability of clusters after gas expulsion is higher than previously expected, even in case of instantaneous gas expulsion

Shukirgaliyev, Parmentier, Berczik & Just, A&A, in press [http://xxx.lanl.gov/abs/1706.03228]

- Mass-dependent and mass-independent cluster dissolution co-exist during the first Gyr of evolution
- Keep in mind: star clusters expand after gas expulsion

Ernst, Berczik, Just & Noel 2015