Do the majority of stars form in gravitationally unbound groups?

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Two broad scenarios

Star formation in gravitationally bound embedded clusters

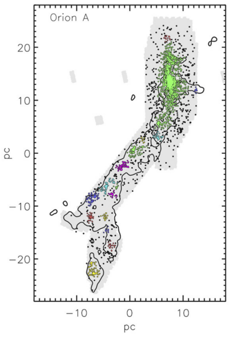
- Star clusters form as gravitationally bound and embedded by their natal gas.
- Massive stars disperse the cloud via photoionising radiation, radiation pressure, stellar winds, . . . , which leads to cluster expansion and the loss of a substantial fraction ($\gtrsim 50\%$) of its stars.
- The dense core revirialises forming an open star cluster while the rest of stars expands forming an unbound OB association (Lada+ 1984, Kroupa+ 2001, Baumgardt & Kroupa 2007).
- Some massive stars are ejected from the cluster in dynamical encounters (or supernovae), and these stars are observed far away from the cluster as runaway stars (Fujii & Portegies Zwart 2011, Oh+ 2015, Wang+ 2019).

Star formation in loose OB associations

- Stars form throughout a molecular cloud at various densities. Some stars are clustered but the majority is gravitationally unbound since their formation (Clark+ 2005, Elmegreen+ 2006).
- Young stellar groups expand mostly because they preserve the turbulent motions of their natal clouds.

Evidence for clusters as the main sites of star formation

- The majority of star formation in the Galaxy ($\gtrsim$ 50%) occurs in dense clusters (Carpenter+ 1995, Lada & Lada 2003, Bressert+ 2010, Winston+ 2020).
- The binary frequency of solar type stars in embedded clusters is $\gtrsim 0.8$, while it is 0.5 in the field. The decrease of binary frequency can be explained by the cluster environment (Kroupa 1995, Marks & Kroupa 2011).
- For many of the previously claimed isolated O stars in Magellanic clouds were found accompanying clusters of lower mass stars (Stephens+ 2017), indicating that $\gtrsim$ 95% of O stars form in clusters.



YSOs in the Orion A cloud (Megeath+ 2016).

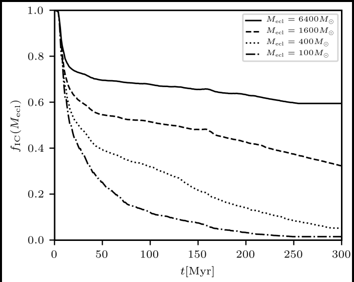
Evidence for distributed star formation

- In contrast, observations of many external galaxies suggest that they form only $\approx 10\%$ of stars in clusters (Goddard+ 2010, Adamo+ 2011, Johnson+ 2016).
- The semi-analytical estimate of Γ as a function of the star formation rate per unit area $\Sigma_{\rm SFR}$ ($\Gamma - \Sigma_{\rm SFR}$ theory; Kruijssen 2012) predicts that Γ to be a strong function of $\Sigma_{\rm SFR}$, with $\Gamma \approx 10\%$ for the Galaxy.
- Another observations (Chandar+ 2017, Fensch+ 2019) suggest higher fraction of stars forming in clusters (≈ 10 to 50%).

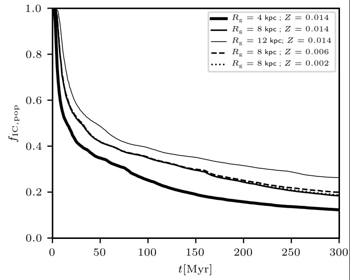
Present models

- We identified several questionable points in the $\Gamma - \Sigma_{\rm SFR}$ theory (the PDF of the star forming gas; the threshold of SF at $n \gtrsim 10^4\,{\rm cm}^{-3}$; neglecting star cluster dynamics; Dinnbier, F., Kroupa P., Anderson, R. I., 2022, A&A 660, 61) $\rightarrow$ we assume that all stars form in a population of star clusters ($\Gamma - 1$ model).
- The cluster mass range spans the interval from $50\,{\rm M}_\odot$ to $6400\,{\rm M}_\odot$; we extrapolate the results for clusters with mass $> 6400\,{\rm M}_\odot$ and down to $5\,{\rm M}_\odot$.
- The models are evolved by the code NBODY6 (Aarseth 2003) for $300\,{\rm Myr}$ (first $10\,{\rm Myr}$ are the most relevant).
- We calculate a large set (≈ 2500 simulations) of open star clusters experiencing early gas expulsion (SFE $= 1/3$), located at different galactocentric radii $R_{\rm g}$ and of different metallicity Z.

The fraction of stars in clusters for a single starburst

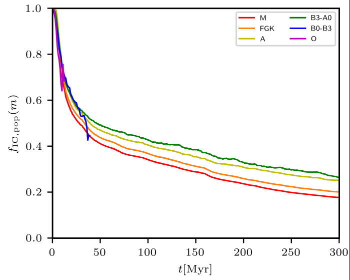


The fraction of stars located in clusters as a function of cluster mass and age.



The fraction of stars $f_{IC,pop}$ located in a whole population of clusters (of initial slope $\beta = -2$) as a function of their galactocentric radii R_g and metallicity Z (for clusters with $R_g = 8\,\mathrm{kpc}$).

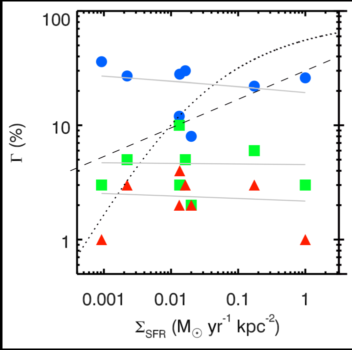
The fraction of stars in clusters for a single starburst



The fraction of stars located in clusters for stars of different spectral types.

- The earlier spectral type, the higher the probability of being found in a cluster.
- The exception are O-type stars because of their dynamical interactions producing runaway stars.

Comparison with observations



The fraction of stars located in star clusters of age $\lesssim 10\,\mathrm{Myr}$ (blue dots), $10\,\mathrm{Myr} < t < 100\,\mathrm{Myr}$ (green squares) and $100 < \,\mathrm{Myr} < 400\,\mathrm{Myr}$ (red triangles) (Chandar+ 2017).

- We aim at the Magellanic clouds because they present the largest difference between the observations of Chandar+ 2017 and the $\Gamma - \Sigma_{\mathrm{SFR}}$ relation.
- The data of Chandar+ 2017 are based on Hunter+ 2003, who identify star clusters visually.

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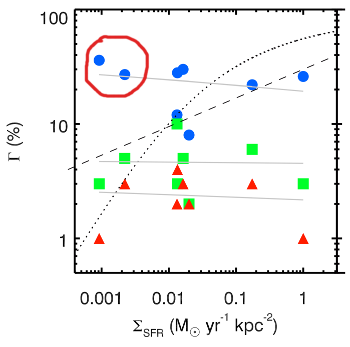

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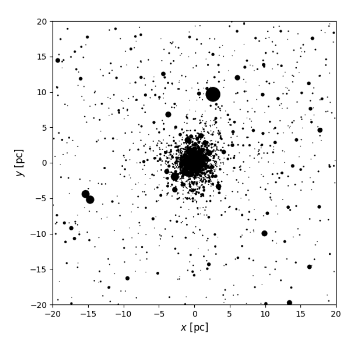
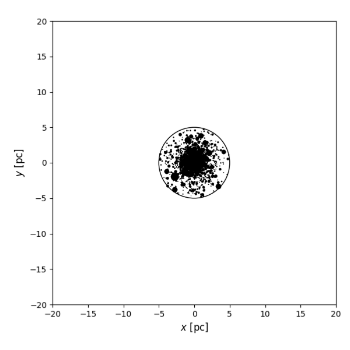


Cluster identification (initially $3200\,\mathrm{M}_\odot$ cluster).

- Hunter+ 2003: A star cluster must be distinguished from its background within a circle of radius $r_{\mathrm{search}} = 5.5\,\mathrm{pc}$.
- We define a cluster as a grouping of at least 10 stars earlier than sp. type F0 which fit in radius $r_{\mathrm{search}} = 5\,\mathrm{pc}$.
- We experiment also with $r_{\mathrm{search}} = 2\,\mathrm{pc}$.
- In total: 3840 stars

Comparison with observations



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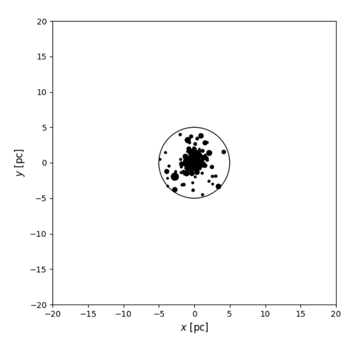

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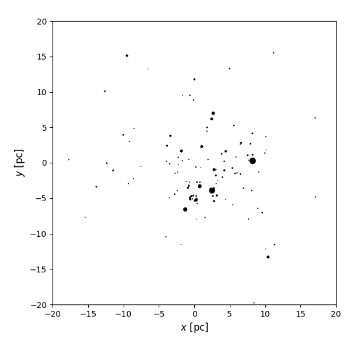
- In total: 163 stars $\rightarrow$ cluster detected.

Comparison with observations



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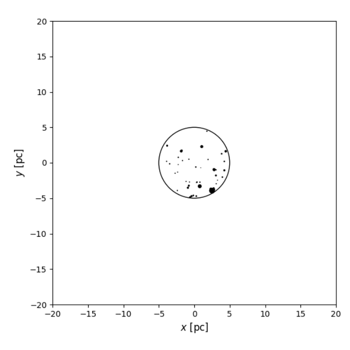
- We experiment also with $r_{\mathrm{search}} = 2\,\mathrm{pc}$.
- In total: 128 stars.

Comparison with observations



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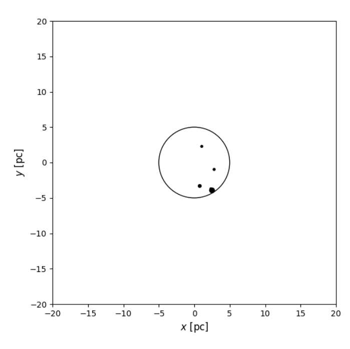
- We experiment also with $r_{\mathrm{search}} = 2\,\mathrm{pc}$.
- In total: 51 stars.

Comparison with observations



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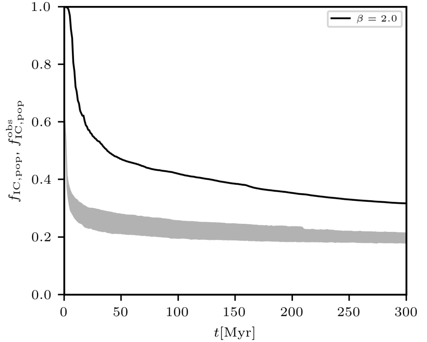
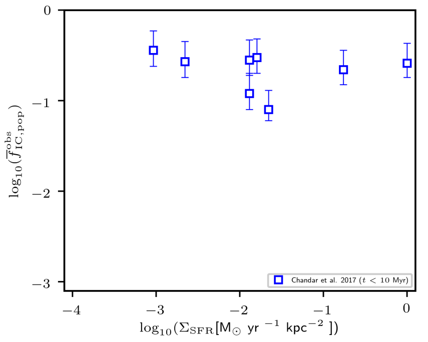
- In total: 5 stars $\rightarrow$ cluster is not detected.

Comparison with observations



- The solid line shows the physical fraction of stars located in clusters.
- The shaded area shows the approximate fraction of stars to be observed in clusters.
- The observed fraction of stars in clusters $f^{\rm obs}_{\rm IC,pop}$ is typically by a factor of 2 lower than $f_{\rm IC,pop}$.
- Γ is equivalent to the observed fraction of stars in clusters $\overline{f}^{\rm obs}_{\rm IC,pop}(t < 10\,{\rm Myr})$.

The estimated fraction of stars to be located in clusters



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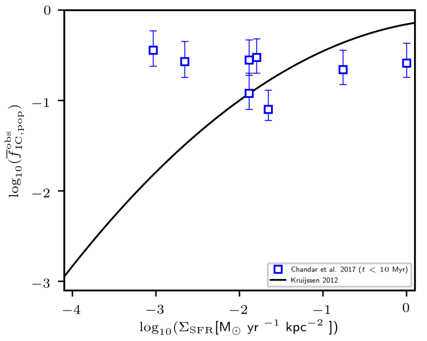

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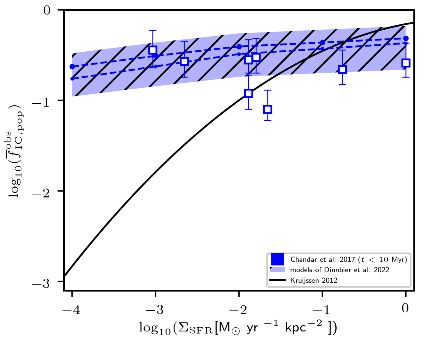

- We assume constant star forming rate.
- The dashed lines are estimates of NBODY6 simulations for $r_{\rm search} = 2\,{\rm pc}$ and $5\,{\rm pc}$, respectively.
- The shaded area represents the variation of $\beta = -1.8$ to $\beta = -2.2$ as suggested from the IGIMF theory (Weidner+2004, Jerabkova+ 2018).
- For the youngest clusters ($t \lesssim 10\,{\rm Myr}$), they agree with observations better than the $\Gamma - \Sigma_{\rm SFR}$ theory.

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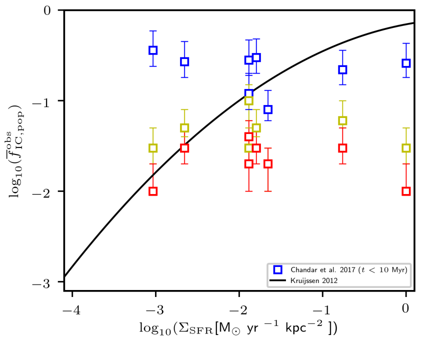

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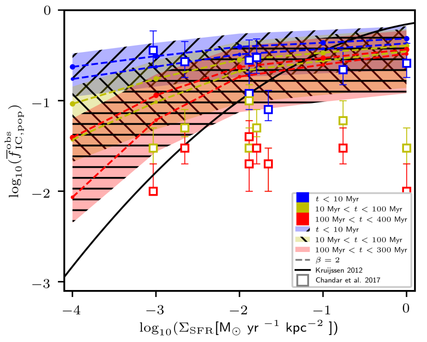

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- For the youngest clusters ($t \lesssim 10\,\mathrm{Myr}$), they agree with observations better than the $\Gamma - \Sigma_{\mathrm{SFR}}$ theory.
- Older clusters have less stars observed than predicted. This was reported in previous studies of cluster dispersal (Lamers+ 2005). Possible explanation is increased destruction in encounters with molecular clouds (Gielles+ 2006, Jerabkova+ 2021).

Summary

- We assume that all stars form in gravitationally bound embedded star clusters, which experience gas expulsion, and then lose stars due to their internal dynamics.
- The estimated fraction of stars which is supposed to be observed in clusters for this model agrees with observations better than the $\Gamma - \Sigma_{\rm SFR}$ theory.
- The present scenario leads to a weaker dependence of Γ on $\Sigma_{\rm SFR}$ than the $\Gamma - \Sigma_{\rm SFR}$ theory; the dependence is due to the fact that low $\Sigma_{\rm SFR}$ preferentially form lower mass clusters, which disperse fast.
- For more details, see Dinnbier, F., Kroupa P., Anderson, R. I., 2022, A&A 660, 61

Thank you for your attention