Volkswagen Trilateral Project
Dynamical Mechanisms of Accretion in Galactic Nuclei

The evolution of star clusters with centrally peaked star-formation efficiency

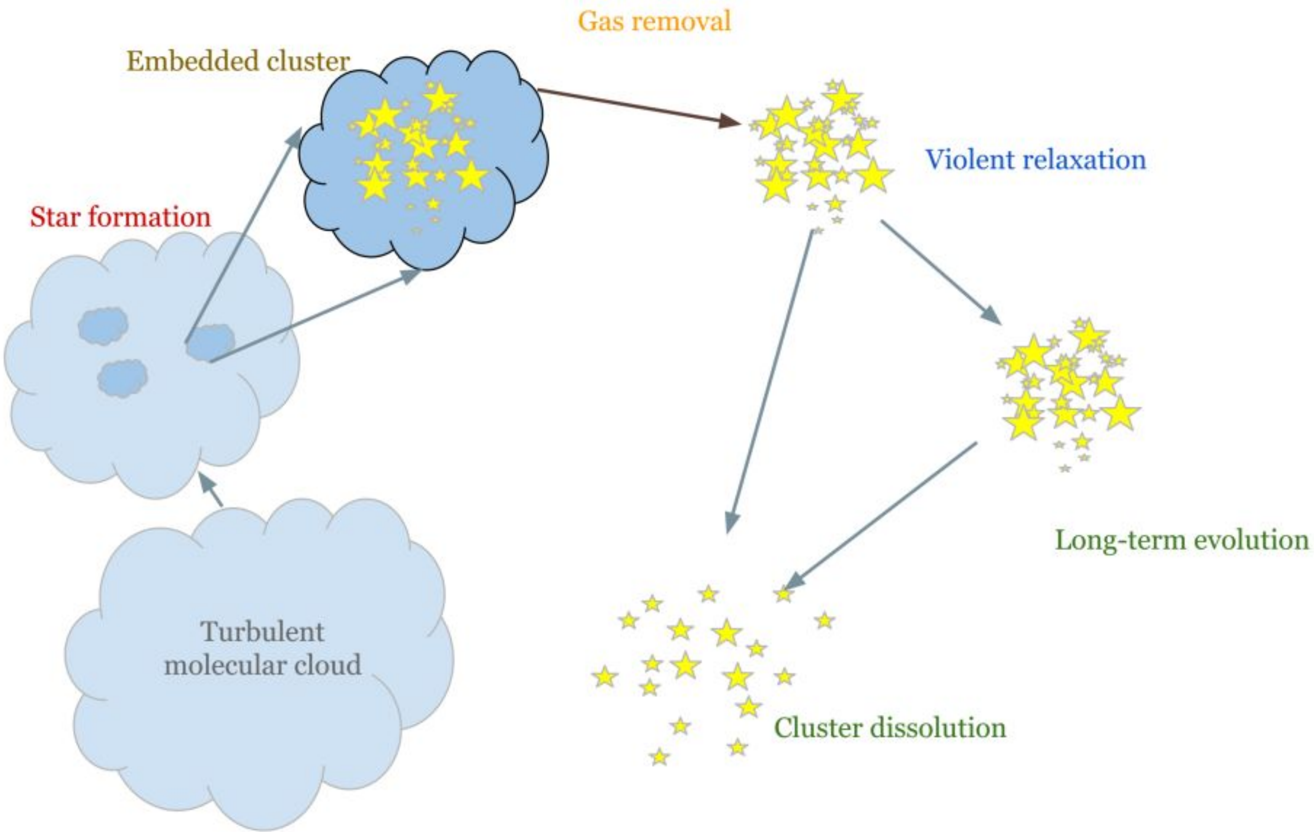
Bekdaulet Shukirgaliyev

Postdoc @
Energetic Cosmos Laboratory, Nazarbayev University

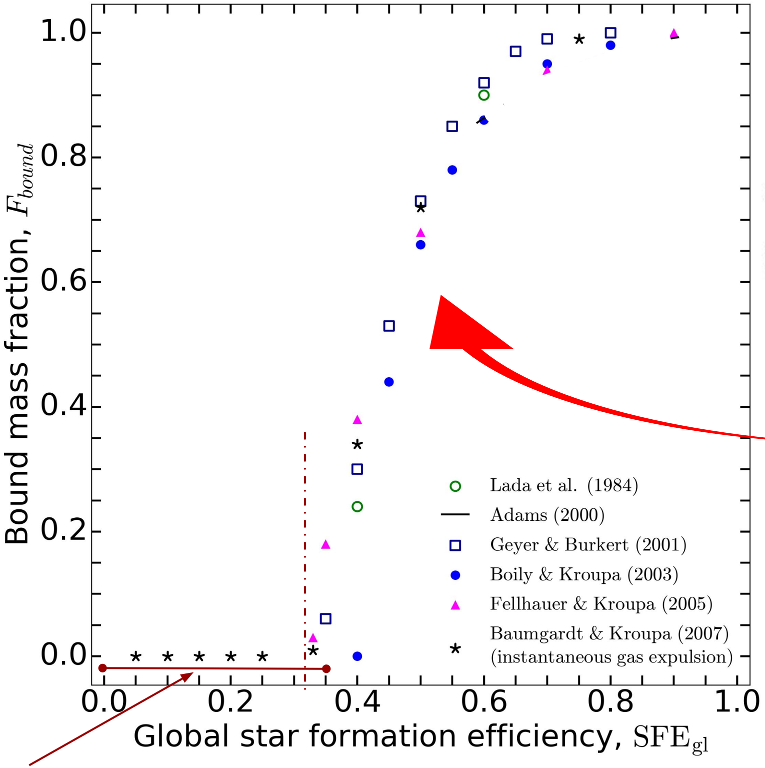
Senior Researcher (part-time) @
Fesenkov Astrophysical Institute

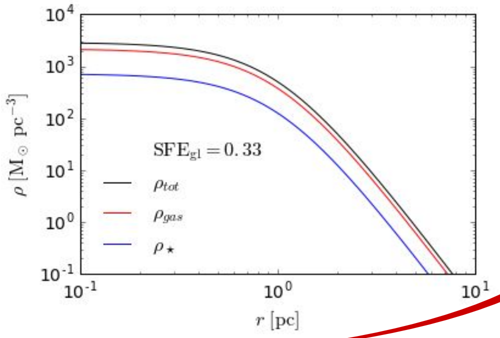
TO LEAD. TO INNOVATE.

The life of Star Clusters



Star cluster survivability

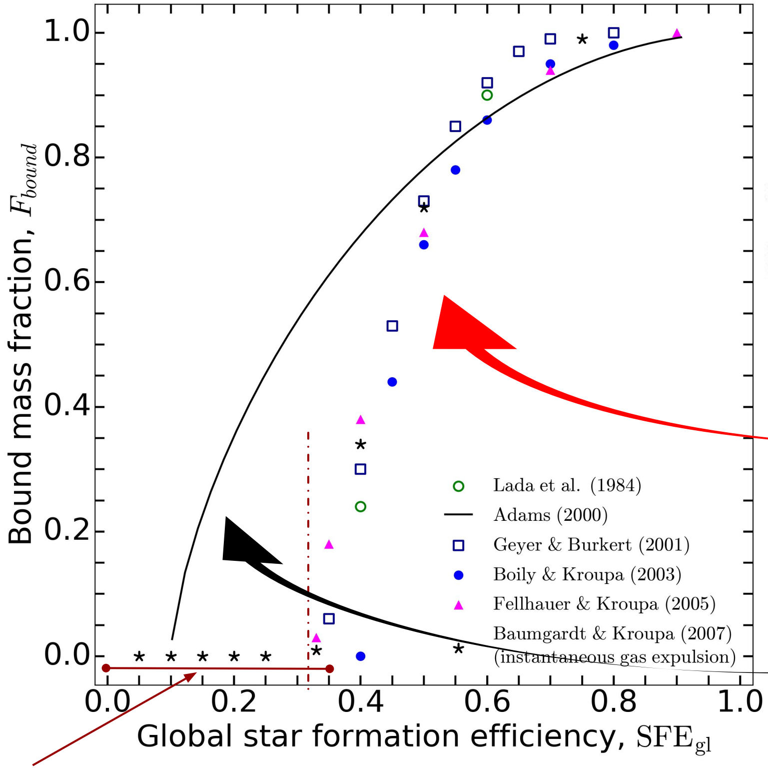


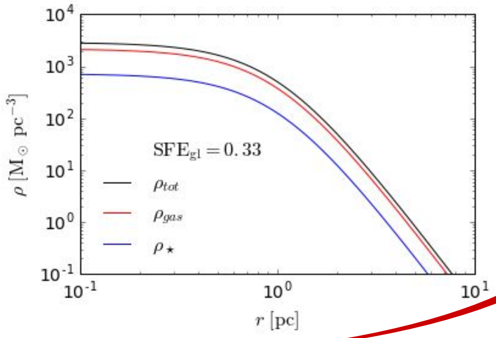


radially constant SFE

The observed global SFEs vary up to **30 %** (Lada & Lada 2003, Higuchi et al 2009, Evans et al. 2009, Murray 2011)

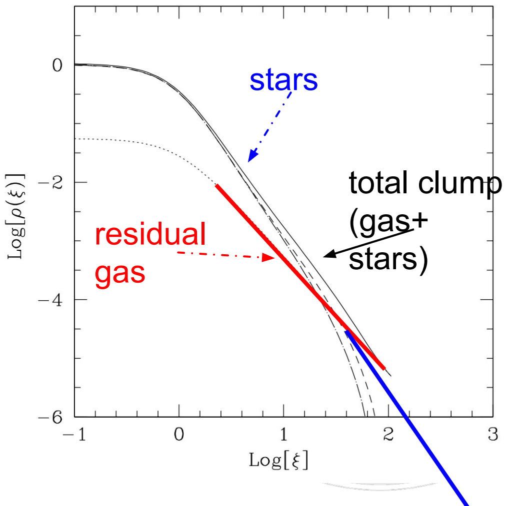
Star cluster survivability





radially constant SFE

SFE varies radially



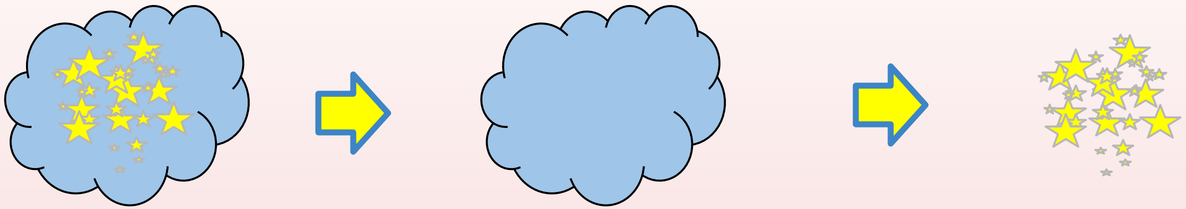
The observed global SFEs vary up to **30 %** (Lada & Lada 2003, Higuchi et al 2009, Evans et al. 2009, Murray 2011)

Cluster Formation

Parmentier & Pfalzner (2013)

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

$$\rho_0 = f(r)$$



$$\rho_0(r) = \rho_g(r,t) + \rho_\star(r,t)$$

$$\rho_\star(r,t) = \rho_0(r) - \rho_g(r,t)$$

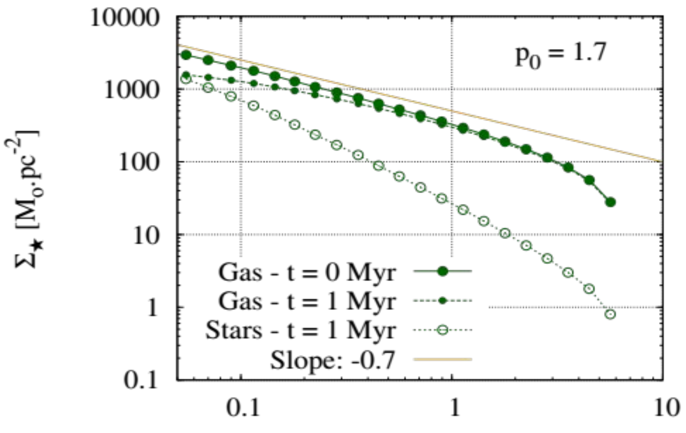
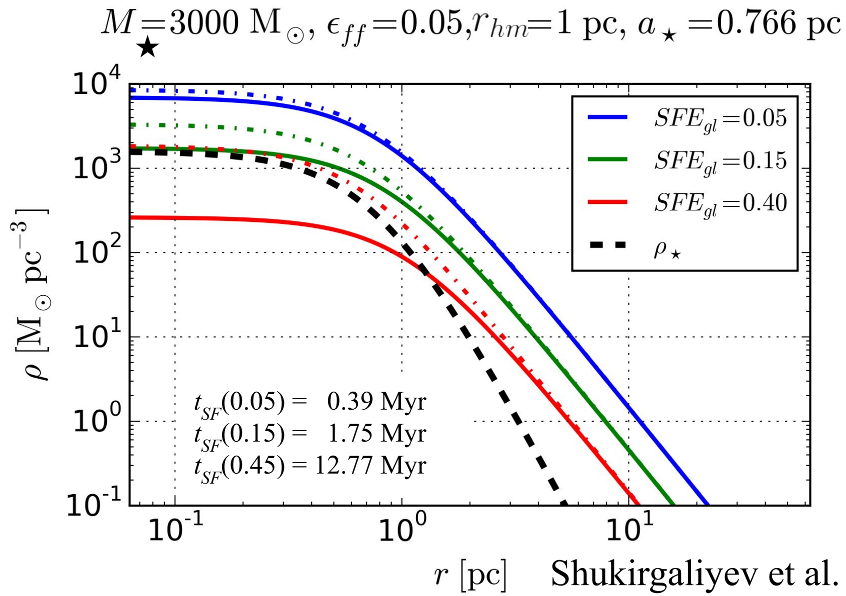


Fig 2 of Parmentier & Pfalzner (2013)

The shape of the stellar density profile is steeper than that of initial and residual star-forming gas

Initial Conditions
Density profiles of the Cluster components



Shukirgaliyev et al. (2017)

Initial conditions build on the local-density-driven cluster formation model of Parmentier & Pfalzner (2013).

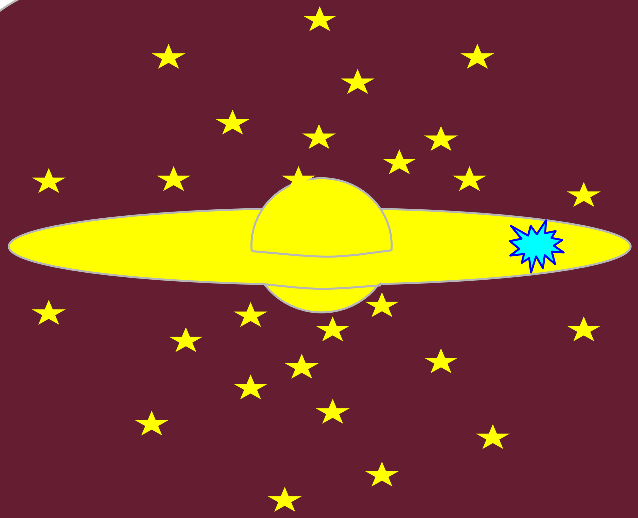
Star-formation efficiency per free-fall time is constant ϵ_{ff}=0.05.

Embedded cluster is in virial equilibrium within total (stars + gas) gravitational potential.

$$SFE_{gl} = \frac{M_\star}{M_\star + M_{gas}}$$

Density profiles of : Newly formed star cluster (black dashed line) corresponds to a Plummer model
Residual gas (solid lines)
Initial Clump (dash-dotted lines)

N-body simulations



MW like Galactic tidal field
(3-component Plummer-Kuzmin model)

Cluster masses:
$M_\star$ = 3k, 6k, 10k, 15k, 30k, 60k, 100k $M_\odot$

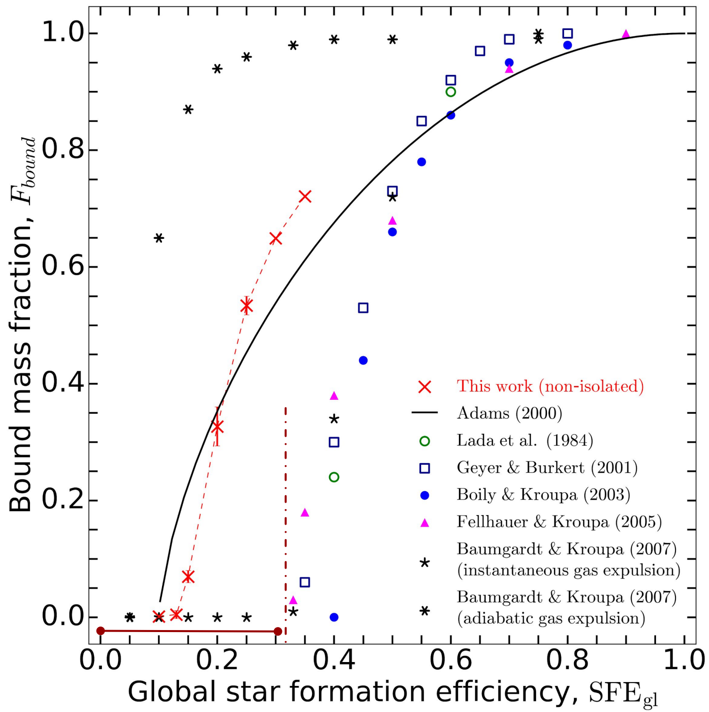
Global SFEs:
SFE_{gl} = 0.10, 0.13, 0.15, 0.20, 0.25

Circular orbit in Galactic disc plane at
R = 8 kpc

Stellar evolution - SSE with no SNe kick

We use phi-GRAPE/GPU code by Berczik et al. 2011 for simulations

The bound mass fraction vs global SFE



The observed global SFEs vary up to **30 %** (Lada & Lada 2003, Higuchi et al 2009, Evans et al. 2009, Murray 2011)

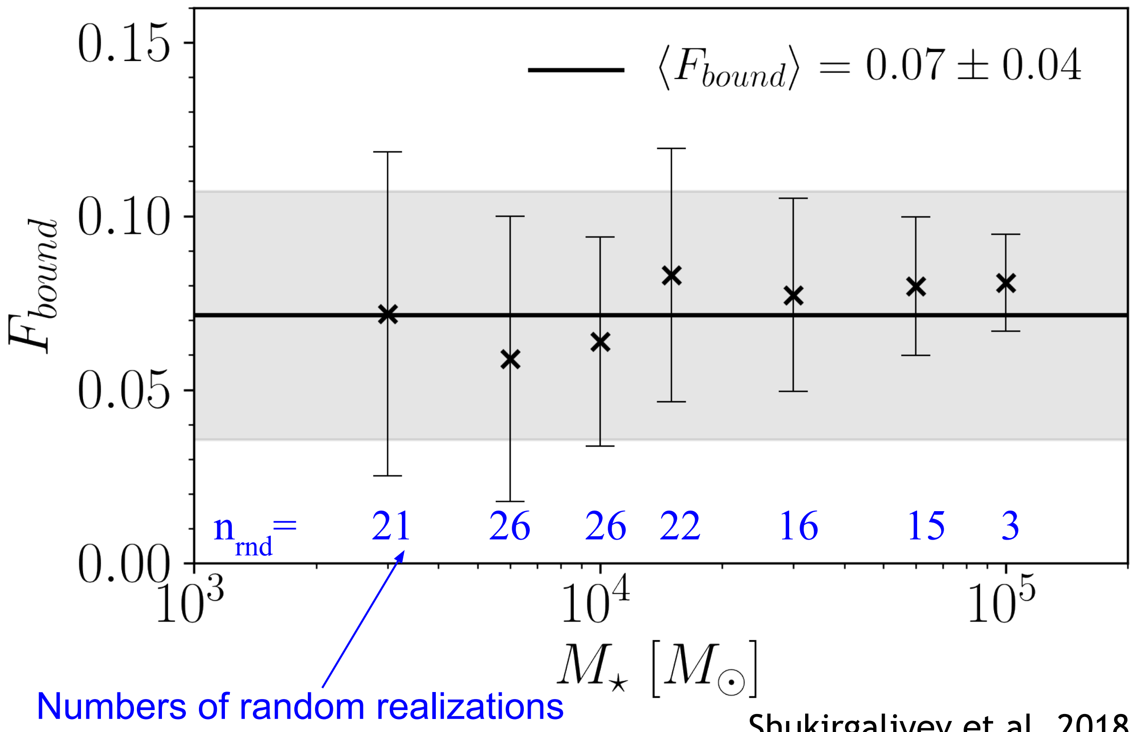
We have increased the resilience of the cluster to gas expulsion and
have addressed the mismatch between observations and theory in case of instantaneous gas expulsion

$$F_{bound} = \frac{M_J(t = 30\mathrm{Myr})}{M_\star}$$

M_J - stellar mass within Jacobi radius
$M_\star$ - cluster birth mass

Shukirgaliyev et al. 2017

Cluster survivability is independent of cluster mass



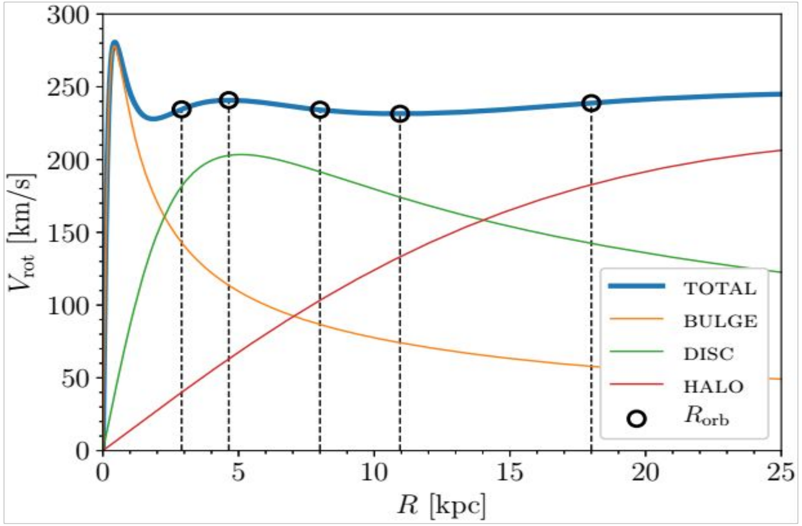
Shukirgaliyev et al. 2018

The distribution of bound mass fractions of random realizations of SFE_{gl}=0.15 models for a given cluster birth mass at *t*=30 Myr

The impact of Galactic tidal field

We vary the impact of the Galactic tidal field, characterized by the ratio between cluster half-mass radius and Jacobi radius, $\lambda = r_h/R_J$ in two ways (Shukirgaliyev et al 2019a):

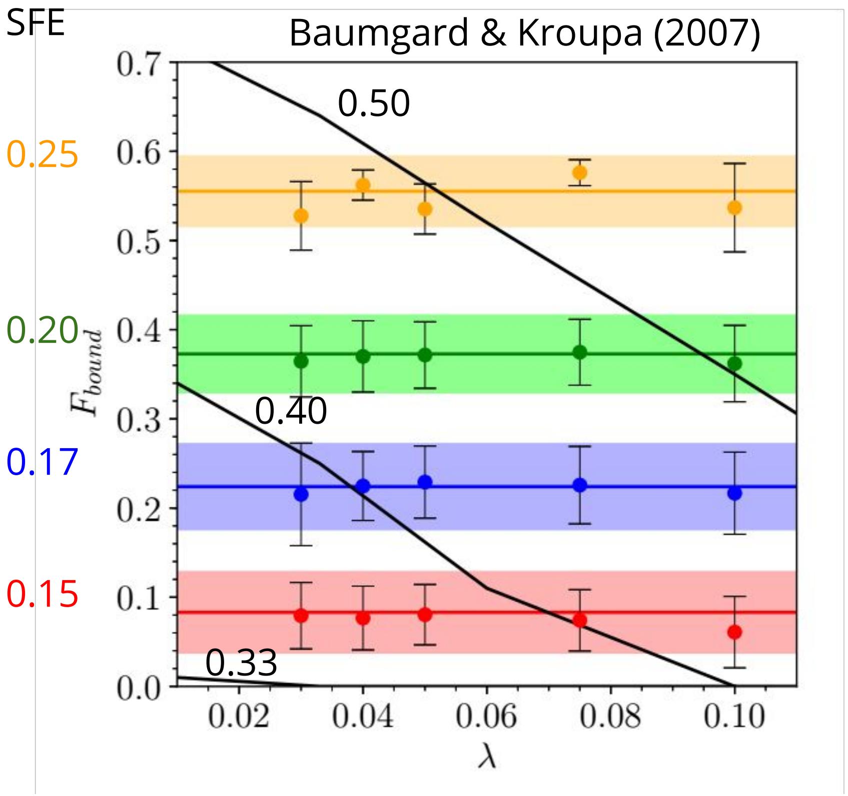
varying the galactocentric distance hence varying R_J

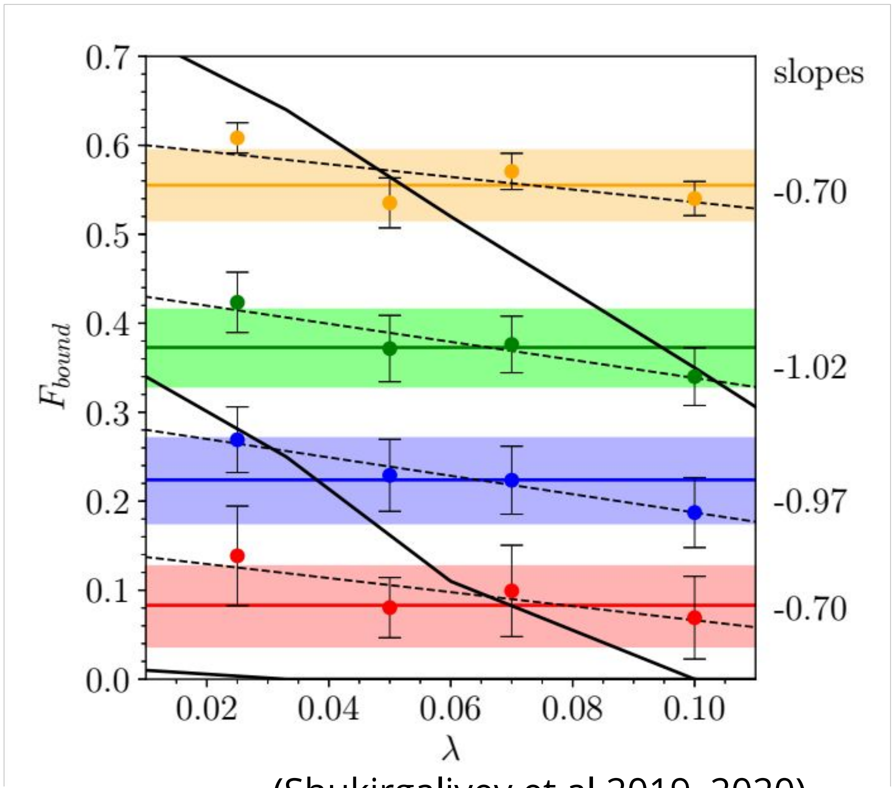


varying the cluster size hence varying r_h

R_{orb} [kpc]	λ
2.9	0.100
4.64	0.075
10.95	0.040
18.0	0.030
8.0	0.100
8.0	0.070
8.0	0.050
8.0	0.025

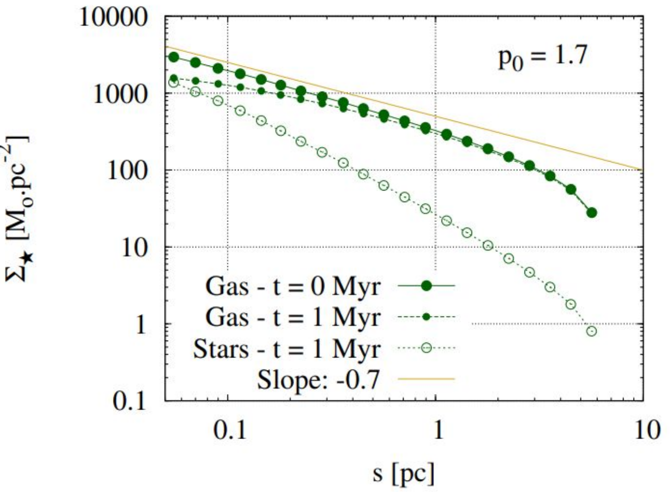
Clusters survive independent of the impact of the Galactic tidal field





(Shukirgaliyev et al 2019, 2020)

Difference between stars and gas density profiles



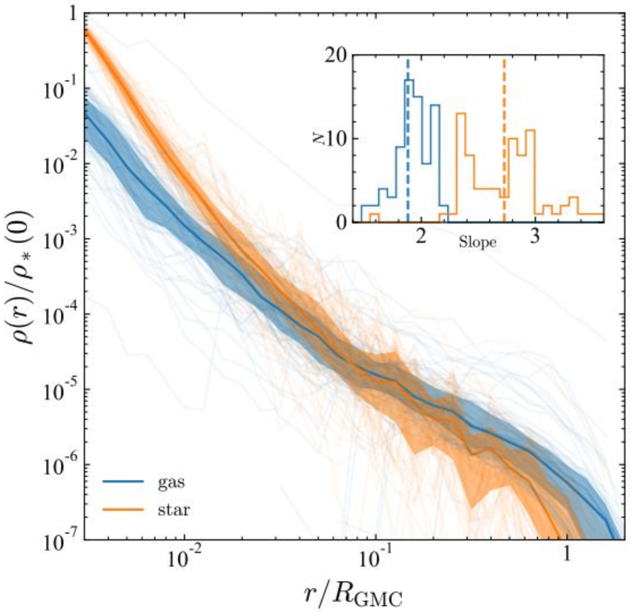
According to the Local-density-driven clustered star formation model of Parmentier & Pfalzner (2013), if stars and gas follow the power-law density profiles with indexes of p and q then

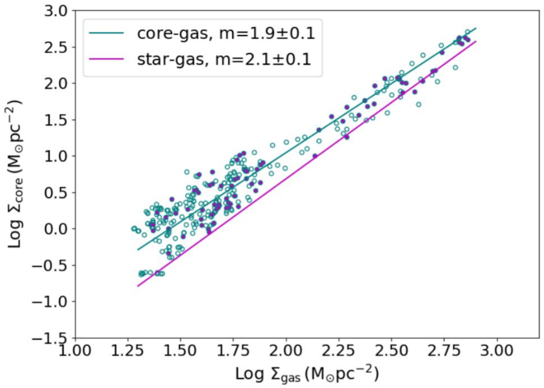
$$q = 3/2p$$

$$\rho_{gas}(r) \propto r^{-p}$$
$$\rho_\star(r) \propto r^{-q}$$

That is for p=2, q=3
for q=5, p=3.3

Hydrodynamical simulations of Li et al (2019) MNRAS 487:364





Gutermuth et al. 2011 (see also Pokhrel et al 2020) found the correlation between surface densities of stars and gas

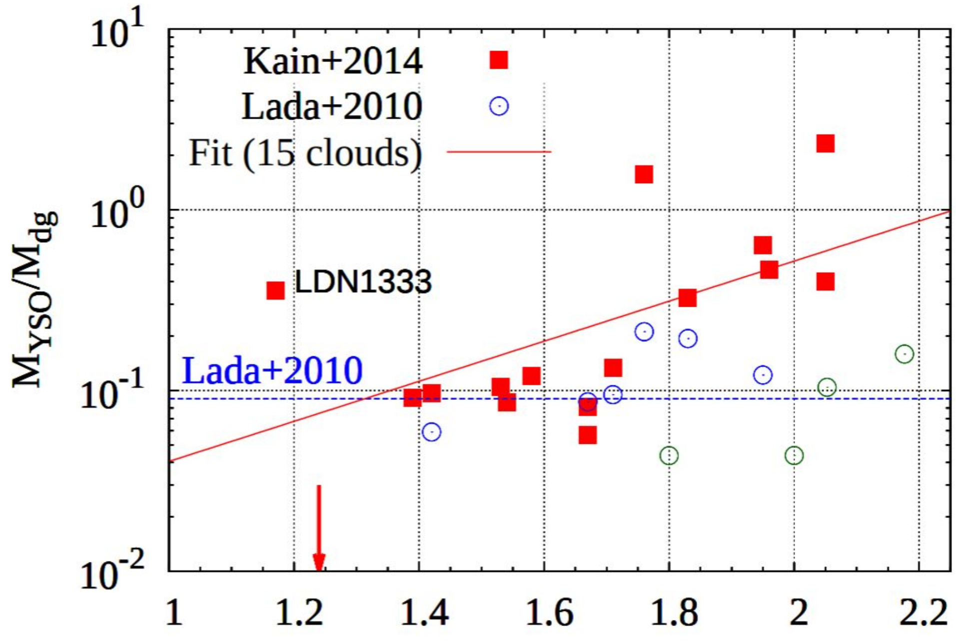
$$\Sigma_\star \propto \Sigma_{gas}^2$$

meaning that stars more concentrated to the center than gas in nearby star-forming regions

Gas density profiles from observations

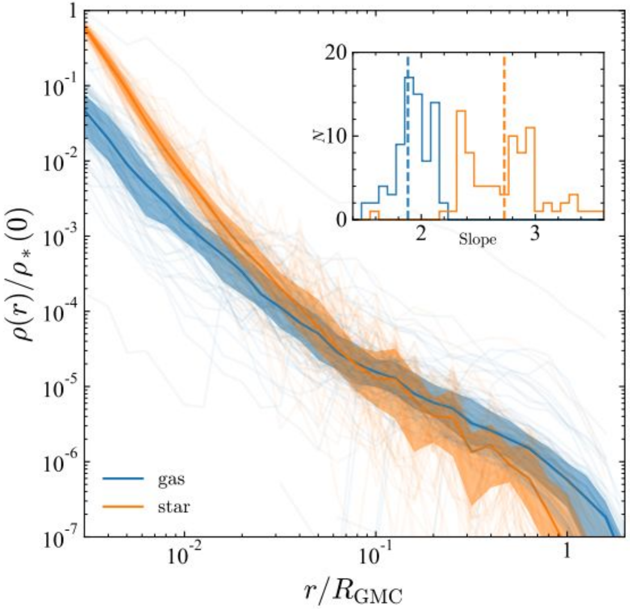
Observed dense gas clumps follow the power-law density profiles with indexes p varying from 1 to 2.2

$$\rho_{gas}(r) \propto r^p$$

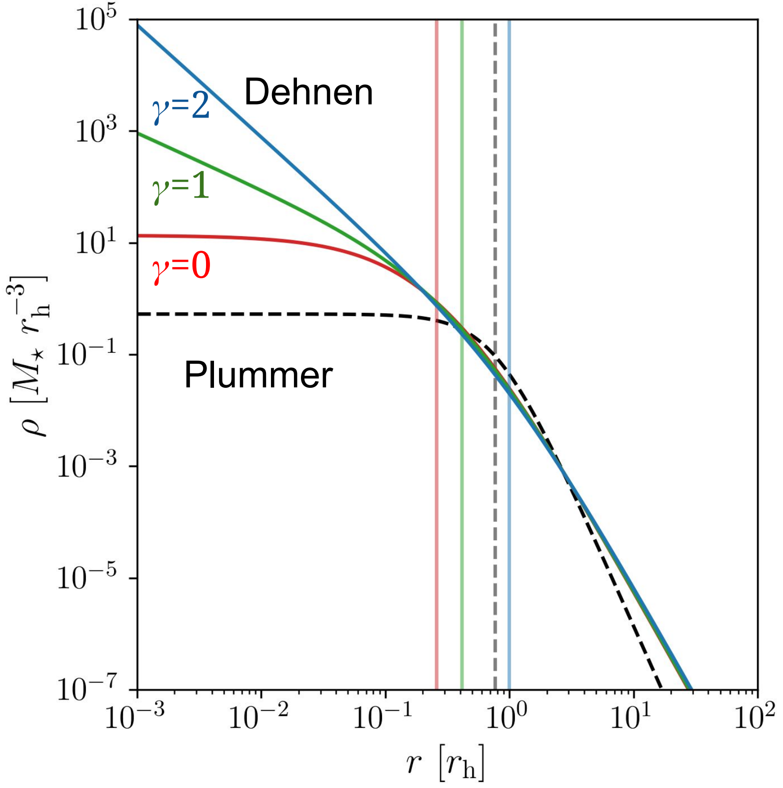


Parmentier & Pasquali (2020)

Hydrodynamical simulations of Li et al (2019) MNRAS 487:364



A family of Dehnen models vs Plummer model



Shukirgaliyev et al. (2021)

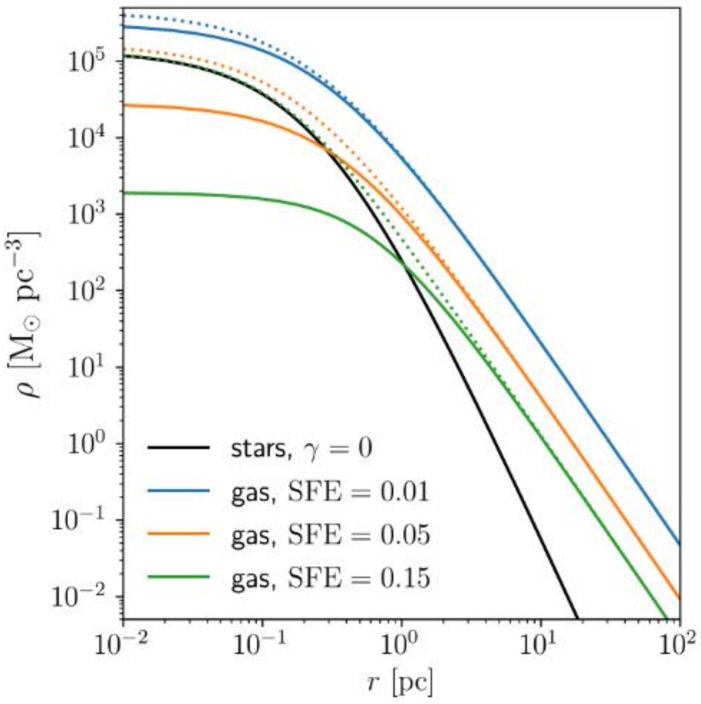
$$\rho_\star(r) = \frac{(3-\gamma)M_\star}{4\pi}\frac{a}{r^\gamma (r+a)^{4-\gamma}}$$

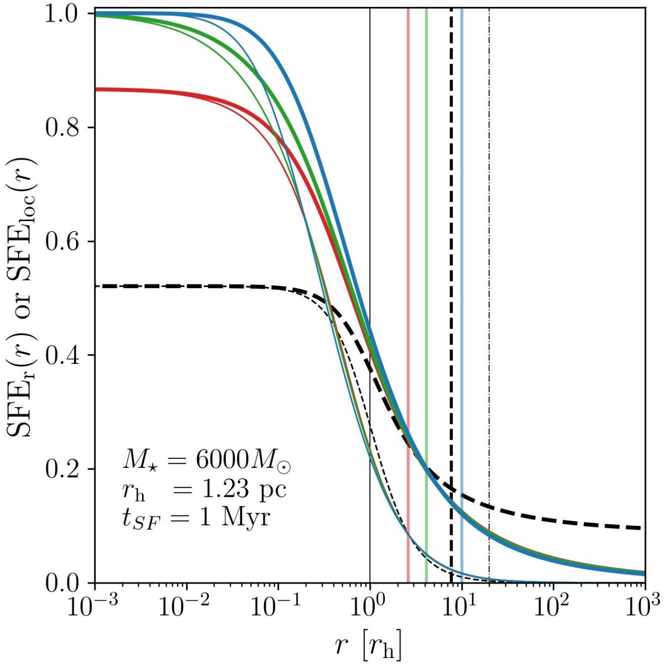
For Dehnen model the outer power-law profile has an index q=4, thus gas would have p=2.6

$$\rho_P(r) = \frac{3M_\star}{4\pi a_P^3}\left(1+\frac{r^2}{a_P^2}\right)^{-5/2}$$

For Plummer model the outer power-law profile has an index q=5, thus gas would have p=3.3

Density profiles and SFE profiles

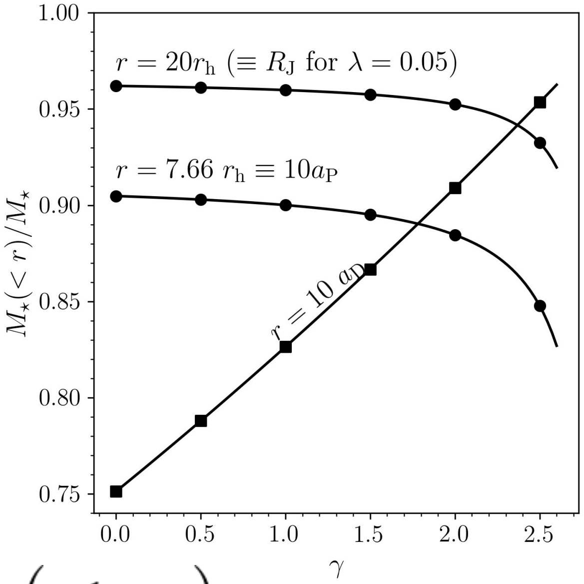




Shukirgaliyev et al. (2021)

Thin lines represent the *local SFE*
While thick lines show the *cumulative SFE*

How to measure SFE?



Effective SFE, (Q=0.5 -- virial equil.)
(Goodwin 2009)

$$\mathrm{eSFE} = \frac{1}{2Q}$$

Local stellar fraction
(Smith et al. 2011)

$$\mathrm{LSF} = \frac{M_\star(< r_\mathrm{h})}{M_\star(< r_\mathrm{h}) + M_\mathrm{gas}(< r_\mathrm{h})}.$$

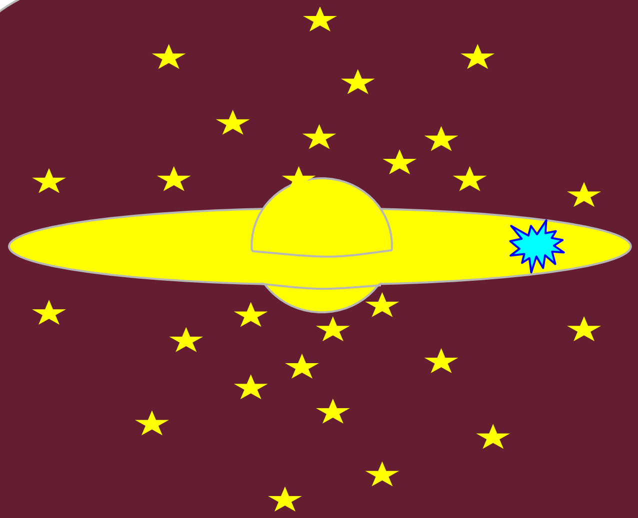
Global SFE (Dehnen model)

$$\mathrm{SFE_J} = \mathrm{SFE}_r(< R_J)$$

Global SFE (Plummer model)
(Shukirgaliyev et al. 2017)

$$\mathrm{SFE_{10}} = \mathrm{SFE}_r(< 10a_\star)$$

N-body simulations



MW like Galactic tidal field
(3-component Plummer-Kuzmin model)

Cluster mass: $M_{\star} = 6k\ M_{\odot}$

Global SFEs:
$SFE_{gl} = 0.03 - 0.3$ (Dehnen model)
$SFE_{Pl} = 0.13 - 0.25$ (Plummer model)

Circular orbit in Galactic disc plane at
$R = 8178$ pc

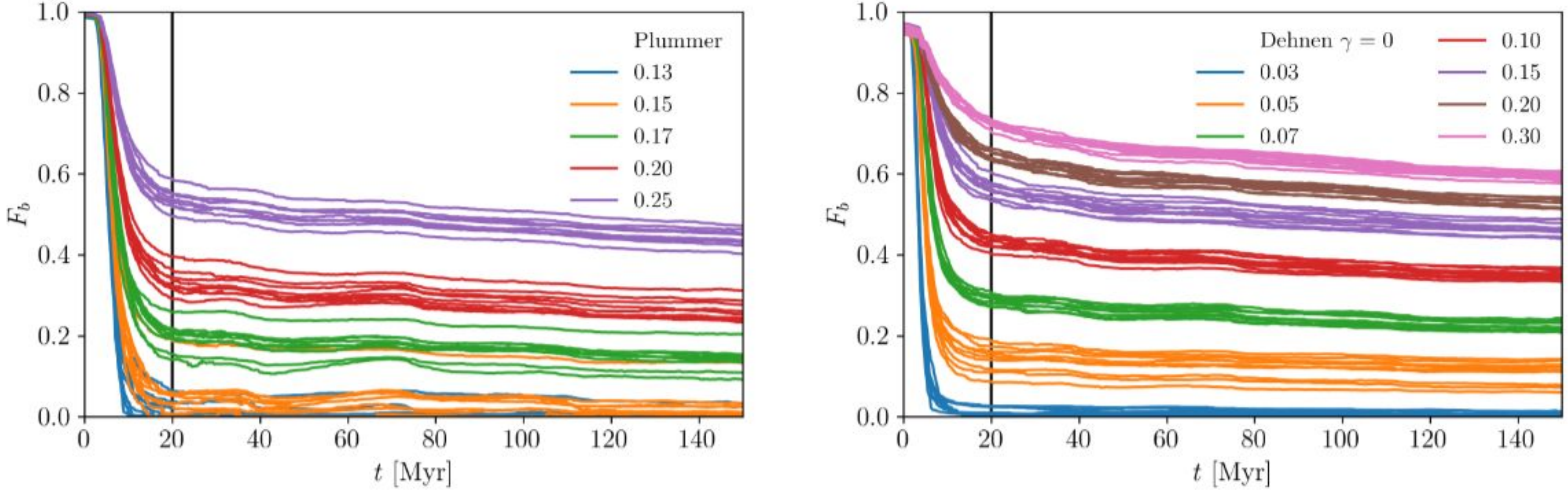
Stellar evolution - updated SSE with SNe kick

We use phi-GRAPE/GPU code by Berczik et al. 2011 for simulations

Bound mass fraction evolution

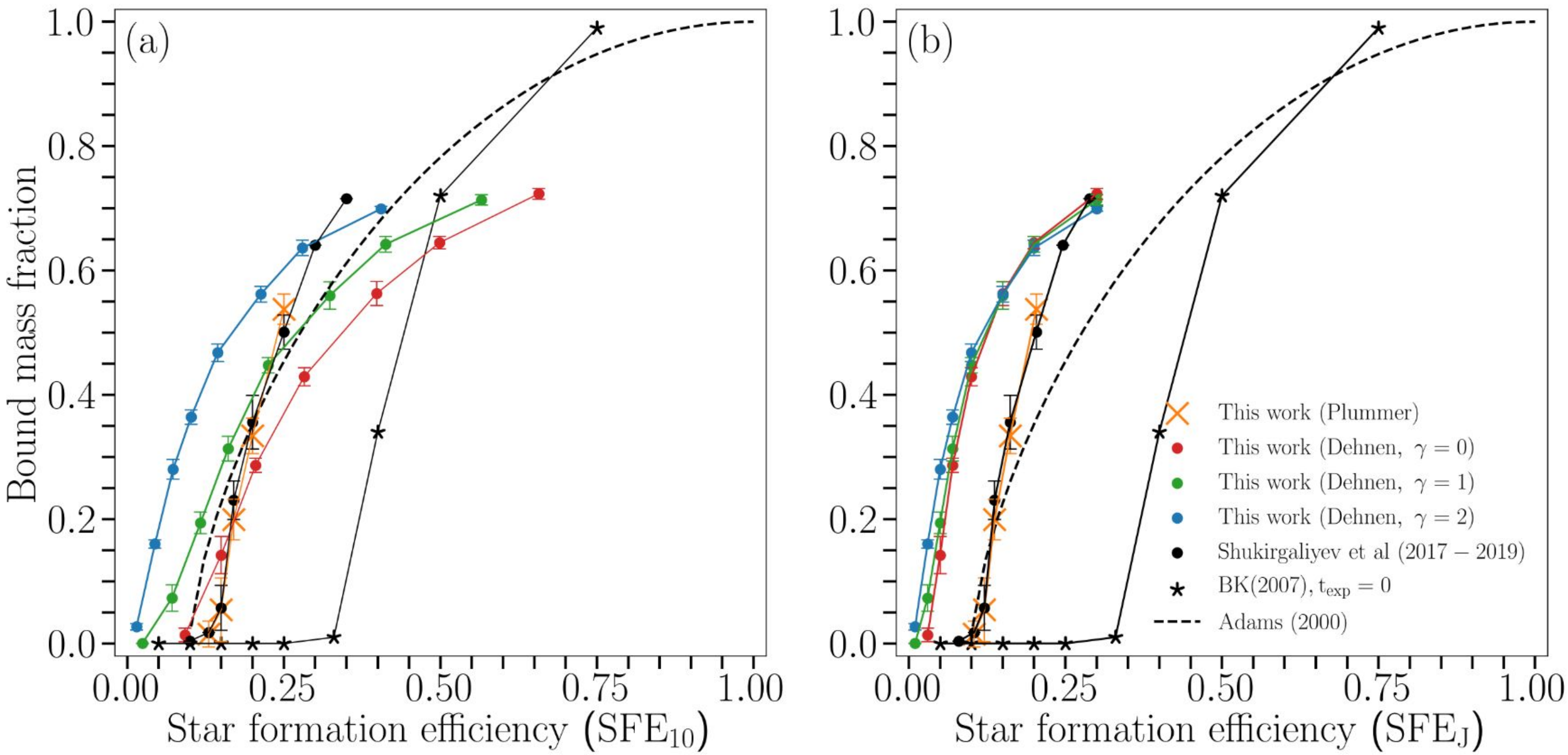
Violent relaxation ends at t=20 Myr

$$F_b(t) = \frac{M_J(t)}{M_\star}.$$



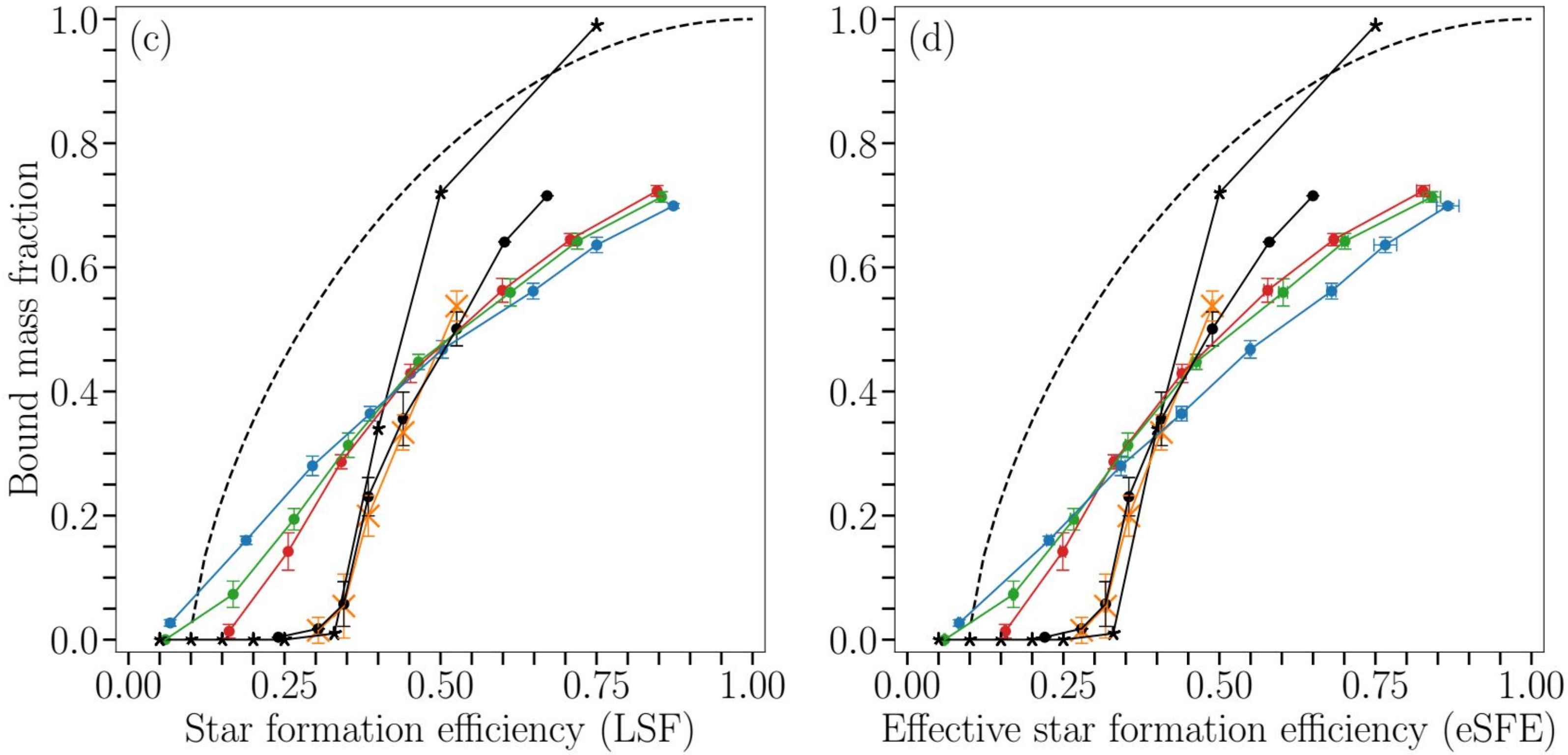
Shukirgaliyev et al. (2021)

The bound mass fraction vs global SFE



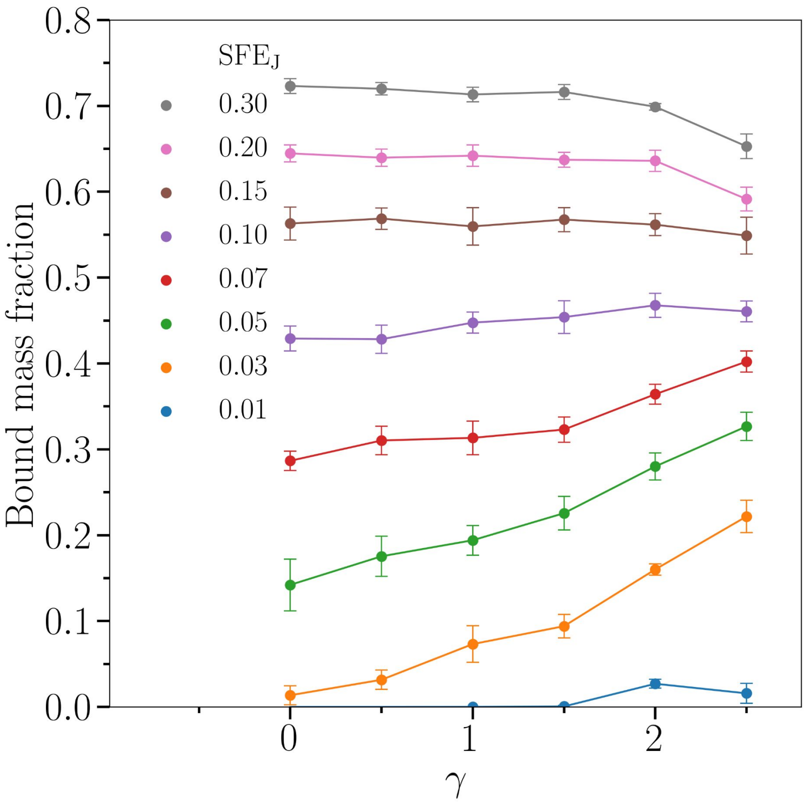
Shukirgaliyev et al. (2021)

The bound mass fraction vs global SFE



Shukirgaliyev et al. (2021)

The bound mass fractions for different Dehnen profiles



The steeper the inner power-law density slope (i.e. increasing γ), the higher the bound mass fraction retained by cluster after violent relaxation for SFE$_J$<0.10.

The opposite trend for SFE$_J$>0.10 is due to the fact that the scale radius of Dehnen clusters increases with γ, thus leaving the significant mass fraction beyond the Jacobi radius already at the time of gas expulsion

Conclusions

- The centrally peakes SFE profile helps star clusters to resist the instantaneous gas expulsion with observed values of the global SFE
- The violent relaxation lasts less than 30 Myrs after instantaneous gas expulsion.
- Star cluster survivability does not depend on the cluster stellar mass before gas expulsion, and depends only on SFE.

- Clusters with Dehnen profile survive the instantaneous gas expulsion much better than clusters with Plummer profile, both having equal mass and half-mass radii.

  That is the shallower the stellar density slope the lower the critical SFE to survive gas expulsion
- Dehnen models with steeper inner density profiles (cusp) can survive the gas expulsion with high bound fraction for very low values of SFE about few percent.

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Thank you very much for your attention!