UNIVERSITY OF HELSINKI

Helsinki Theoretical Extragalactic Research Group

Theoretical astrophysics at the University of Helsinki.

IMPRS-HD
IMPRS for Astronomy & Cosmic Physics
at the University of Heidelberg

Massive BH formation in Pop. III star clusters

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Agencia
Nacional de
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y Desarrollo
Ministerio de Ciencia,
Tecnología, Conocimiento
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LISA AWG meeting
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DAAD

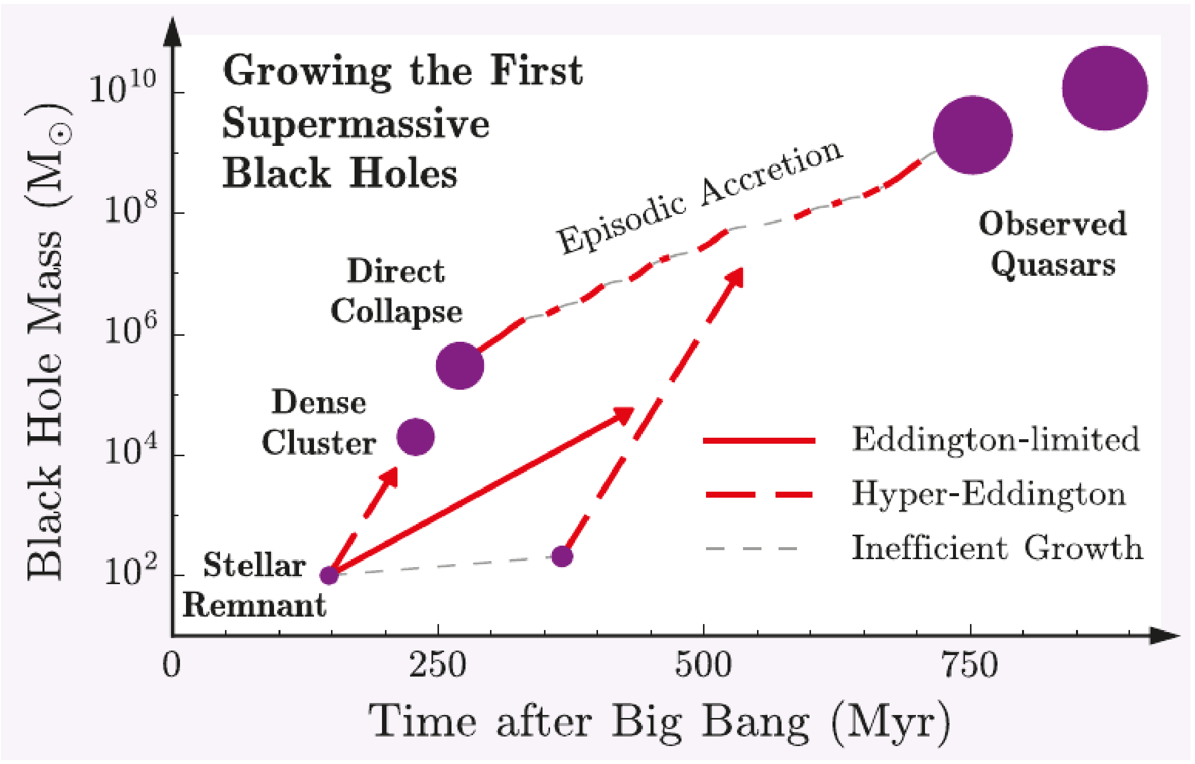
SMBHs in the early Universe

More than 200 Quasars detected at z>6

(Fan et al. 2001, Mortlock et al. 2011, Bañados et al 2018, Onoue et al. 2019)

With new JWST discoveries of 10^6 – 10^8 Msun BHs (Maiolino et al 2024, Matthee et al. 2024, Greene et al. 2024, Li et al. 2024)

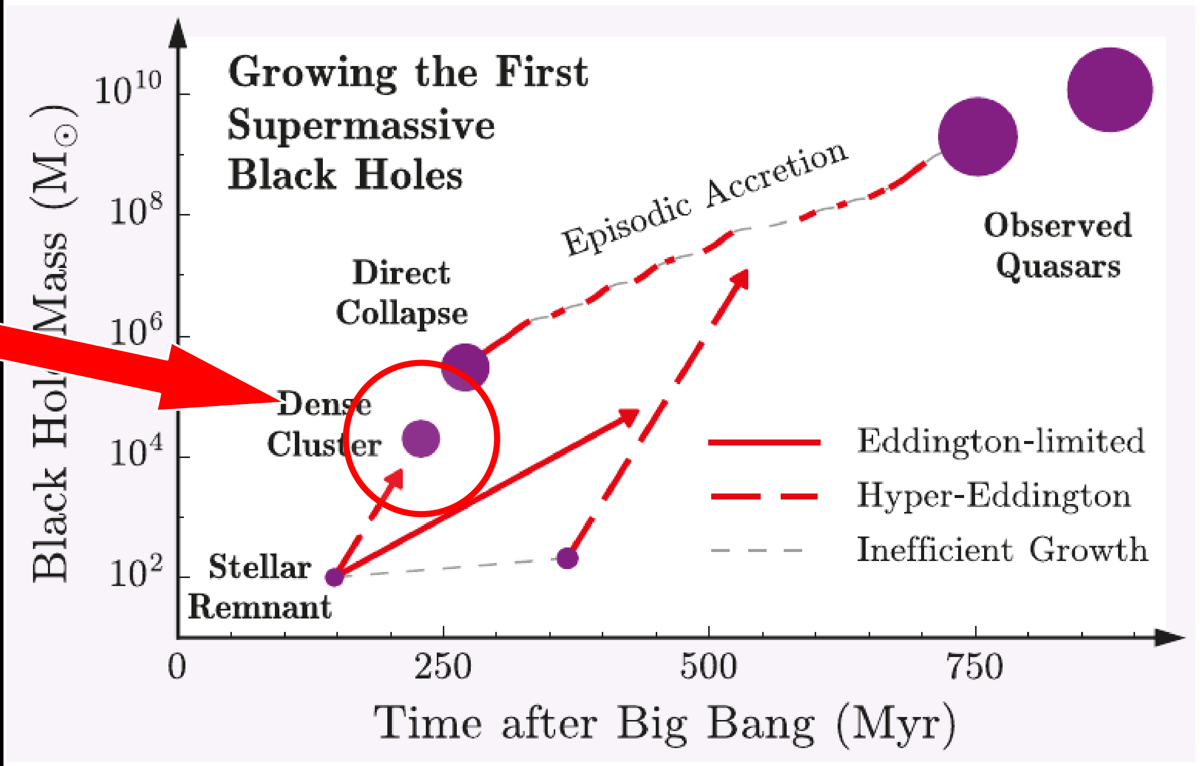
10^7-10^8 Msun BH at z~10.1 (Bogdán et al. 2023, Goulding et al. 2023)



Smith, Bromm & Loeb 2017

SMBHs in the early Universe

Further exploration of this channel is necessary



Smith, Bromm & Loeb 2017

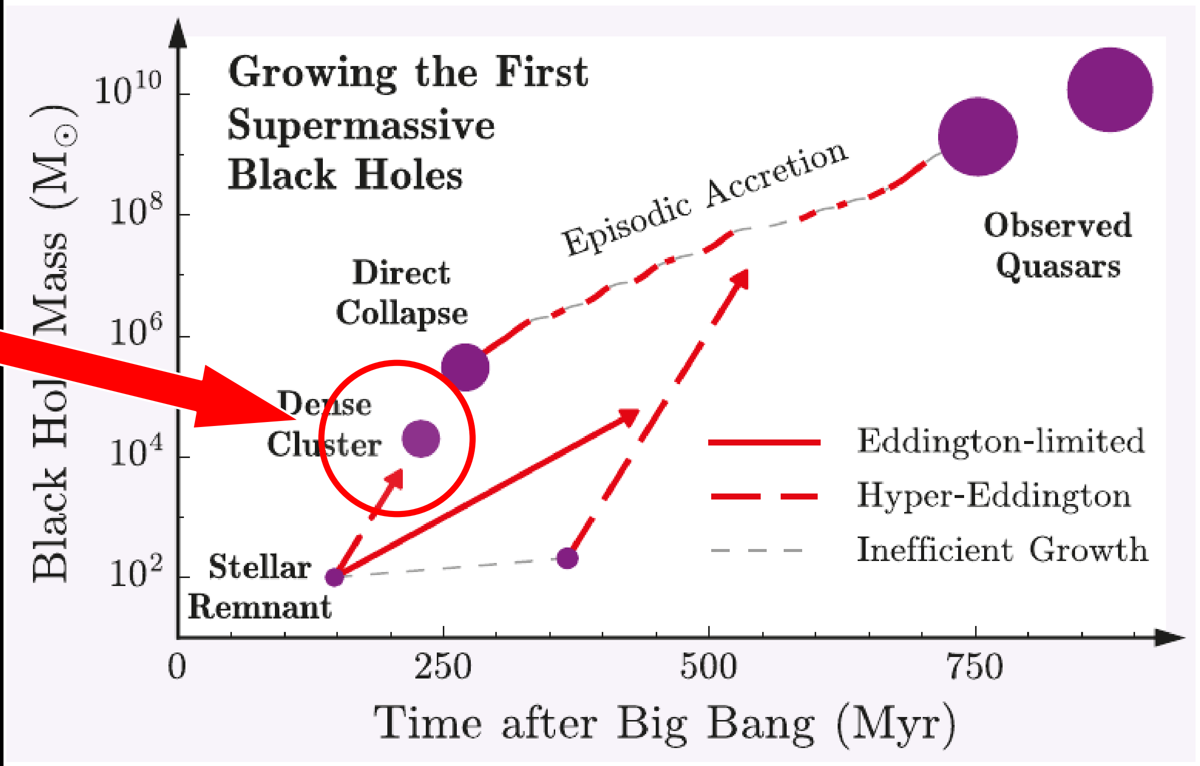
SMBHs in the early Universe

Runaway stellar collisions in young and dense star clusters (Portegies Zwart et al. 2004)

Models for the first Pop II star clusters (Katz et al. 2015, Sakurai et al. 2017)

See also Rantala et al. (2024) for IMBH formation in hierarchical SC formation

We want to improve the existing models for Pop III star clusters (Reinoso et al. 2018, Vergara et al. 2021, Wang et al. 2022)



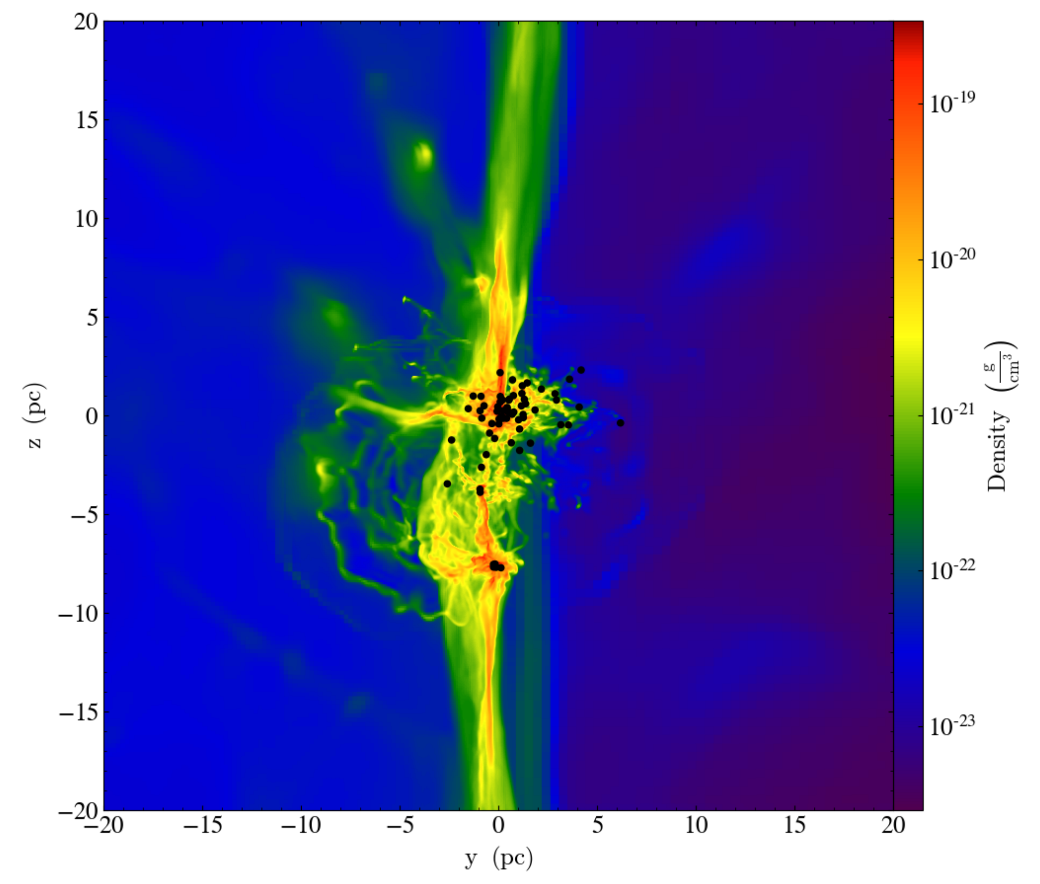
Smith, Bromm & Loeb 2017

Initial conditions

We take the output of a cosmological zoom-in simulation performed with the ENZO code (AMR).

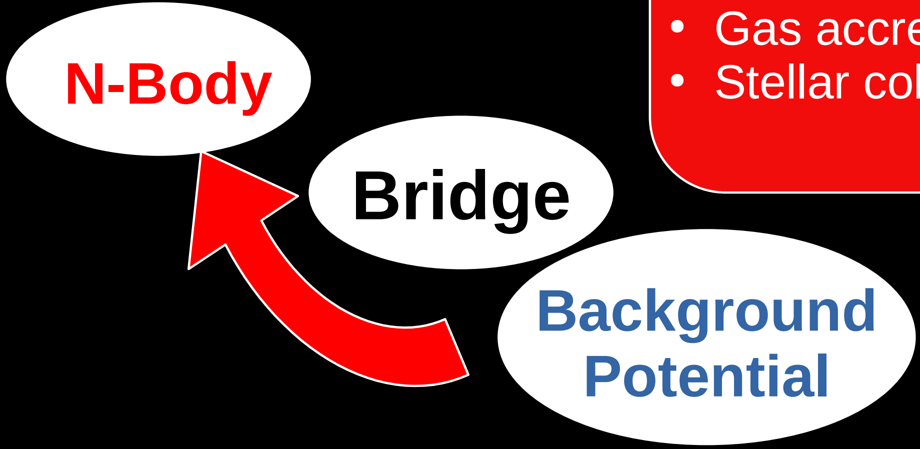
The simulation includes up to 18 refinement leves, resolving 0.01 pc scales of a 10^5 MSun (gas) minihalo.

Simulation also included sink particle creation, gas accretion, sink mergers, and radiation feedback.



Numerical Model

(Portegies Zwart et al. 2009,2013)



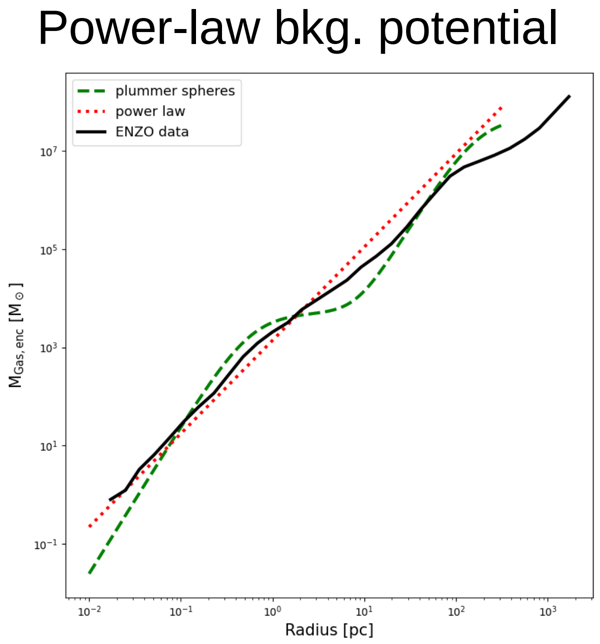
Bridge method (Fujii et al. 2007)

The model includes:

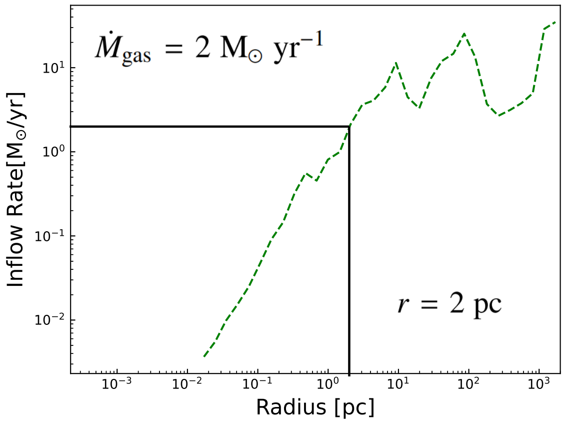
- Time-varying Bkg. Potential
- IMF
- Star formation
- Gas accretion by stars
- Stellar collisions & Mass loss

Evolve the system for a total of 2 Myr

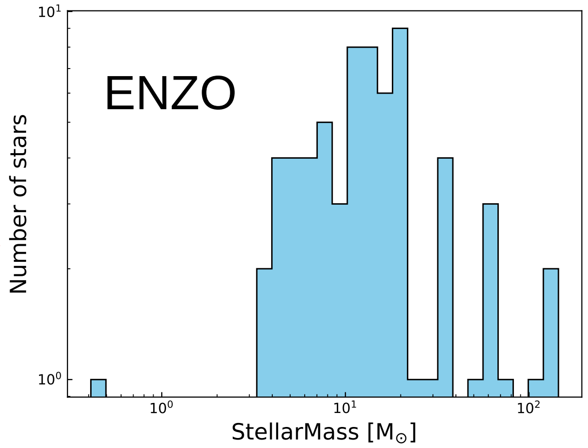
Modelling the gas & Star Formation



Power-law bkg. potential



Model the gas as a growing background potential



Continually insert new stars during the simulation & explore different values for the star formation efficiency

$$\epsilon_{\mathrm{SF}} = 0.1, 0.2, 0.3$$

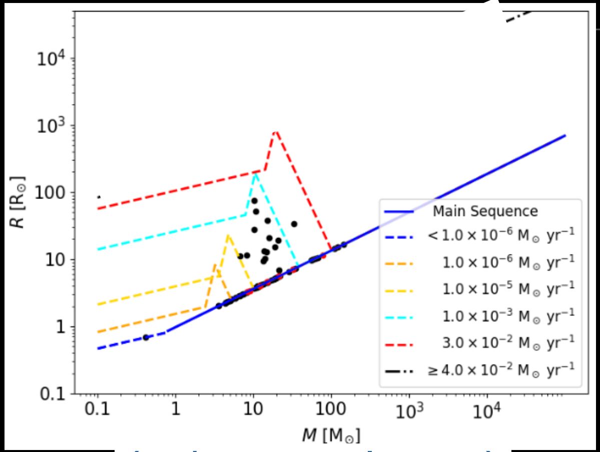
Construct IMF based on the ENZO runs

Gas accretion & Stellar collisions

Gas accretion onto stars

We assume that stars accrete at the Bondi-Hoyle rate

$$\dot{m} = \frac{4\pi G^2 m^2 \rho_0}{(v^2 + c_s^2)^{3/2}} \left(\frac{r_0}{r + r_{\rm bondi}} \right)^{\alpha}$$



(Reinoso et al. 2023)

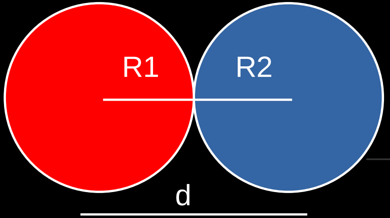
Including an accretion rate limit for MS stars

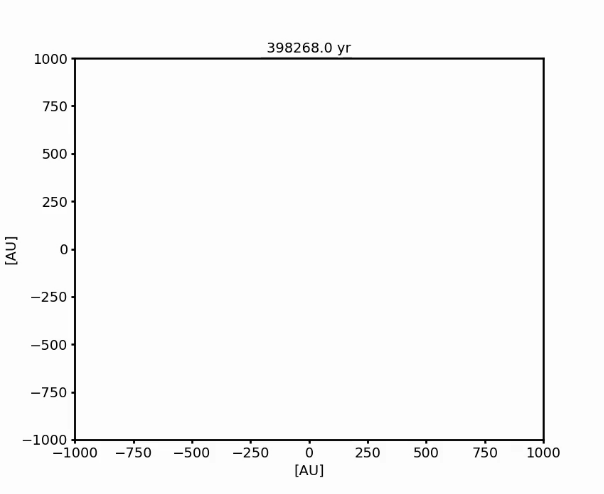
$$\dot{m}_{\rm max} = 10^{-4}\ M_\odot\ {\rm yr}^{-1}$$

Stellar collisions

Hit & stick approximation

$$d \leq R_1 + R_2$$



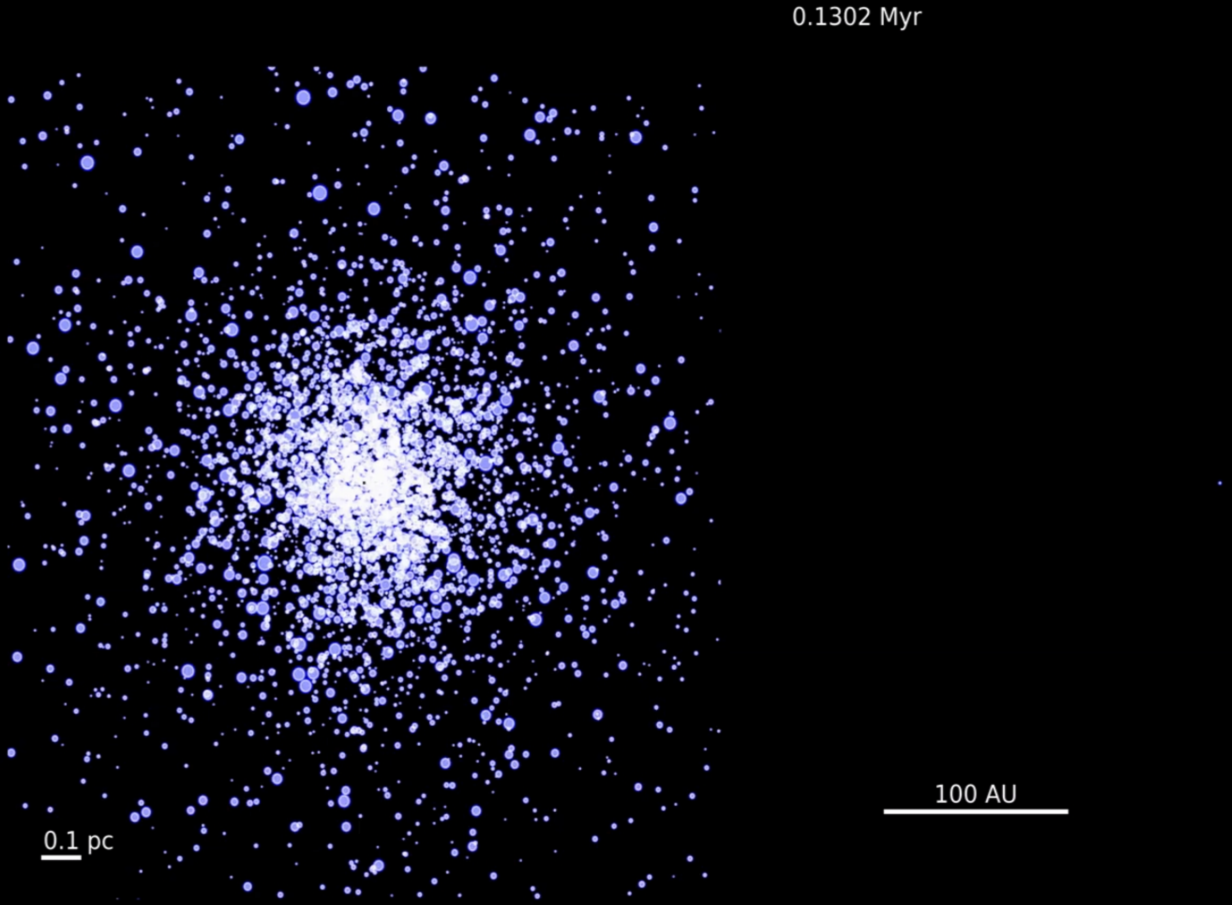


Mass loss during stellar collisions

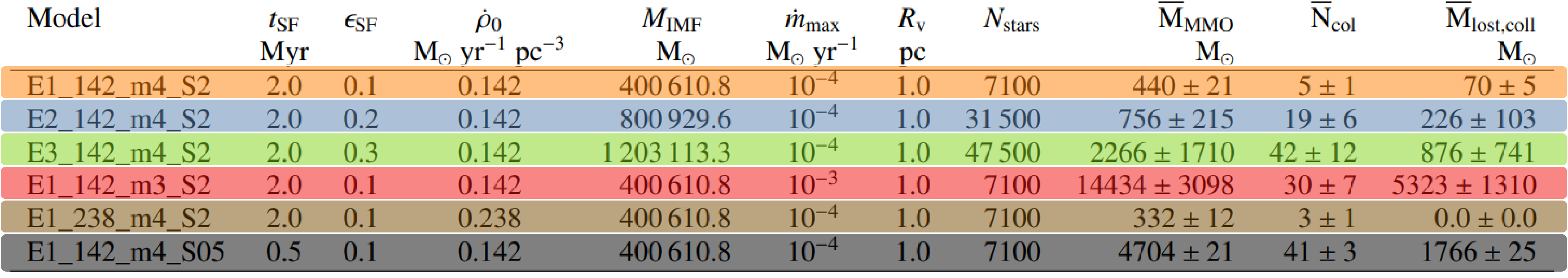
$$f_{\rm lost} = \frac{q}{1+q^2} \begin{cases} 0.243, & q < 0.4, \\ 0.3, & q \geq 0.4. \end{cases}$$

$$m_{\rm new} = (1 - f_{\rm lost})(m_1 + m_2).$$

Glebbeek et al. 2013

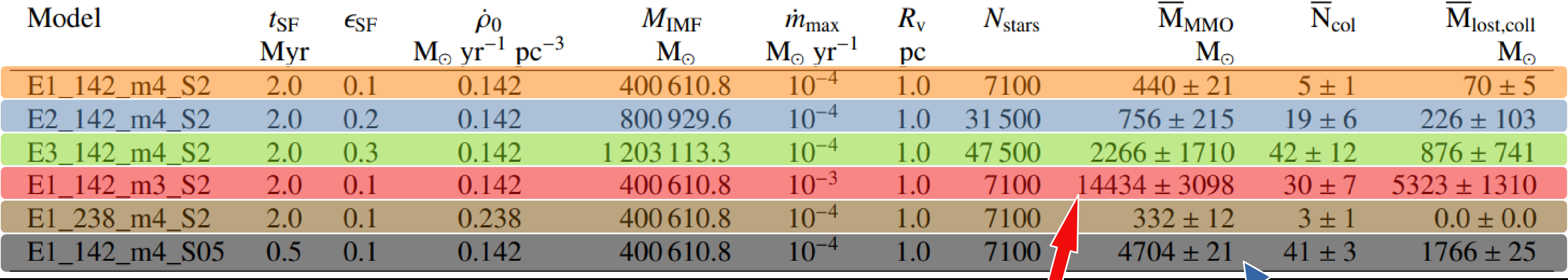

0.1302 Myr
0.1 pc
100 AU

The simulation set & Initial results



Model	$t_{\rm SF}$ Myr	$\epsilon_{\rm SF}$	$\dot{\rho}_0$ $M_\odot$ yr^{-1} pc^{-3}	$M_{\rm IMF}$ $M_\odot$	$\dot{m}_{\rm max}$ $M_\odot$ yr^{-1}	$R_{\rm v}$ pc	$N_{\rm stars}$	$\overline{\rm M}_{\rm MMO}$ $M_\odot$	$\overline{\rm N}_{\rm col}$	$\overline{\rm M}_{\rm lost,coll}$ $M_\odot$
E1_142_m4_S2	2.0	0.1	0.142	400 610.8	10^{-4}	1.0	7100	440 ± 21	5 ± 1	70 ± 5
E2_142_m4_S2	2.0	0.2	0.142	800 929.6	10^{-4}	1.0	31 500	756 ± 215	19 ± 6	226 ± 103
E3_142_m4_S2	2.0	0.3	0.142	1 203 113.3	10^{-4}	1.0	47 500	2266 ± 1710	42 ± 12	876 ± 741
E1_142_m3_S2	2.0	0.1	0.142	400 610.8	10^{-3}	1.0	7100	14434 ± 3098	30 ± 7	5323 ± 1310
E1_238_m4_S2	2.0	0.1	0.238	400 610.8	10^{-4}	1.0	7100	332 ± 12	3 ± 1	0.0 ± 0.0
E1_142_m4_S05	0.5	0.1	0.142	400 610.8	10^{-4}	1.0	7100	4704 ± 21	41 ± 3	1766 ± 25

The simulation set & Initial results



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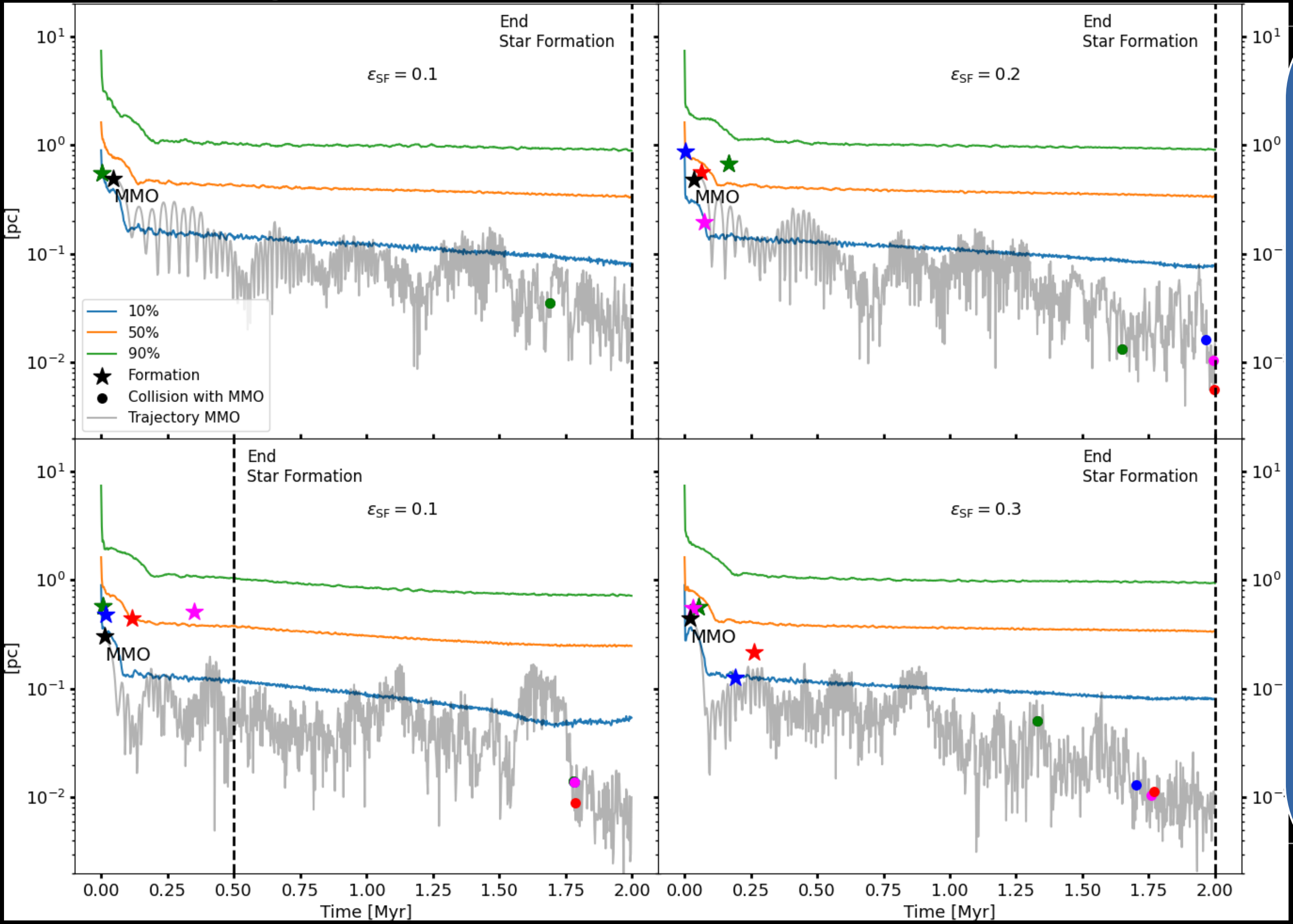
This is growth
by gas accretion

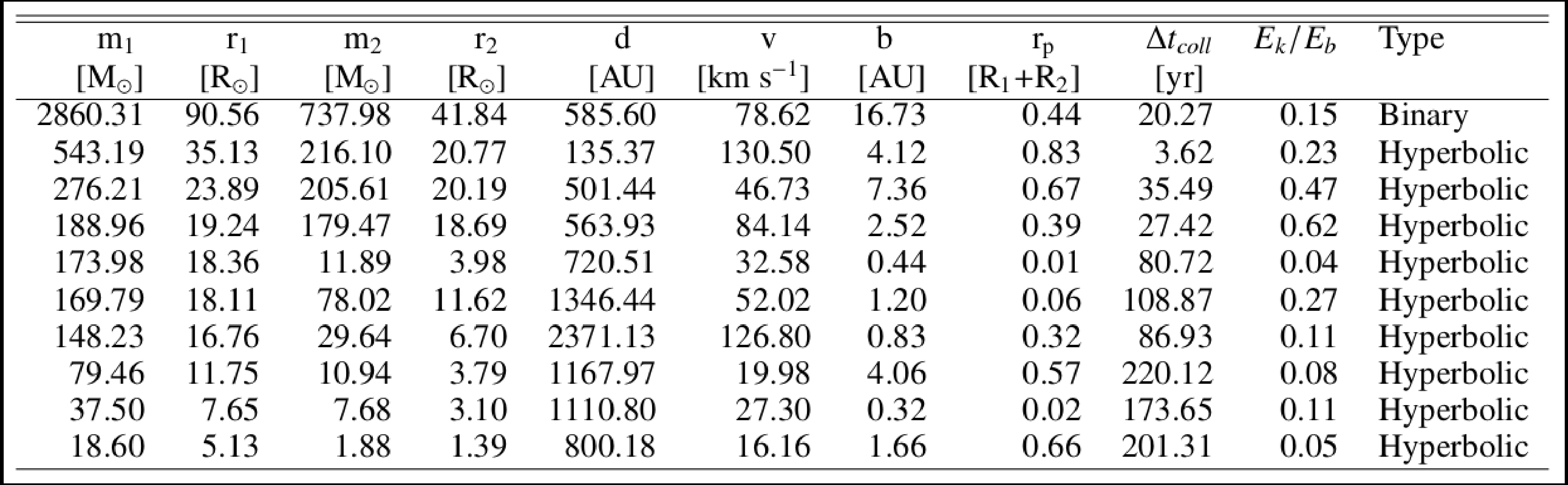
These clusters
experienced
core-collapse

Emergence of the MMOs



- A 80-150 MSun star that forms early (<50kyr) sinks to the cluster core
- The star gains ~200 Msun from gas accretion
- Stellar collisions start occurring close to the end of the simulation (>1.25 Myr)
- Stellar collisions involve MS stars with >80 MSun typically

A set of collisions from the simulations



m_1 $[M_\odot]$	r_1 $[R_\odot]$	m_2 $[M_\odot]$	r_2 $[R_\odot]$	d [AU]	v [km s^{-1}]	b [AU]	r_p $[R_1+R_2]$	Δt_{coll} [yr]	E_k/E_b	Type
2860.31	90.56	737.98	41.84	585.60	78.62	16.73	0.44	20.27	0.15	Binary
543.19	35.13	216.10	20.77	135.37	130.50	4.12	0.83	3.62	0.23	Hyperbolic
276.21	23.89	205.61	20.19	501.44	46.73	7.36	0.67	35.49	0.47	Hyperbolic
188.96	19.24	179.47	18.69	563.93	84.14	2.52	0.39	27.42	0.62	Hyperbolic
173.98	18.36	11.89	3.98	720.51	32.58	0.44	0.01	80.72	0.04	Hyperbolic
169.79	18.11	78.02	11.62	1346.44	52.02	1.20	0.06	108.87	0.27	Hyperbolic
148.23	16.76	29.64	6.70	2371.13	126.80	0.83	0.32	86.93	0.11	Hyperbolic
79.46	11.75	10.94	3.79	1167.97	19.98	4.06	0.57	220.12	0.08	Hyperbolic
37.50	7.65	7.68	3.10	1110.80	27.30	0.32	0.02	173.65	0.11	Hyperbolic
18.60	5.13	1.88	1.39	800.18	16.16	1.66	0.66	201.31	0.05	Hyperbolic

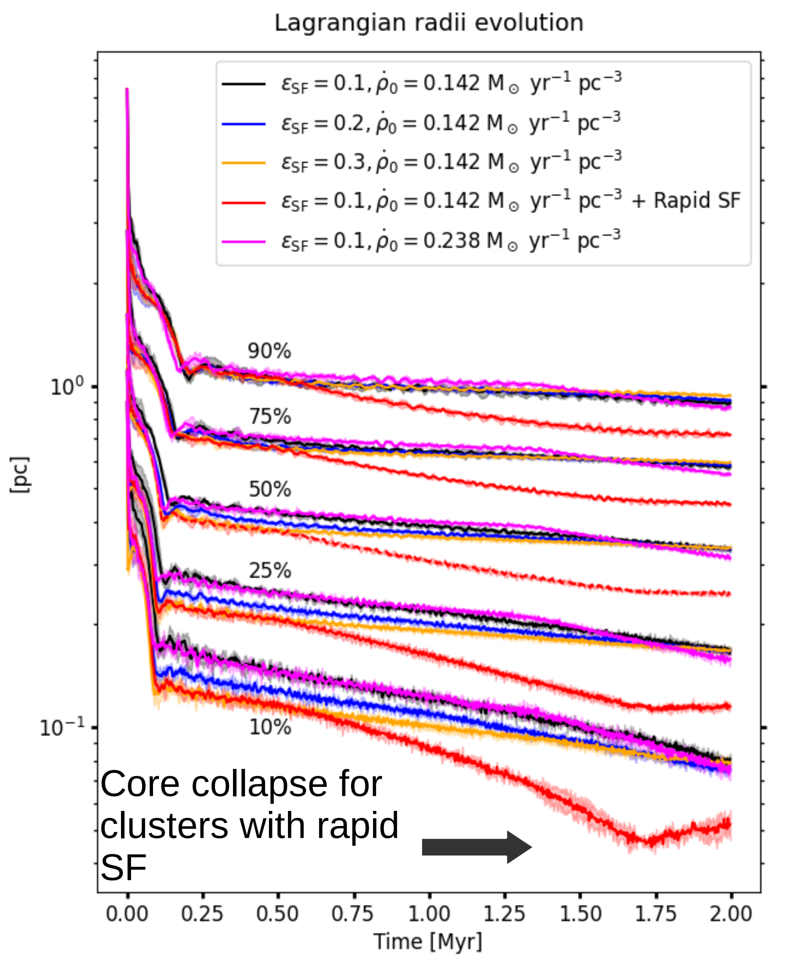
We hope that this can serve for producing realistic ICs for stellar collisions of high-mass stars during the formation of massive collision products. This would in turn improve our understanding of mass loss and stellar evolution during these events.

Summary

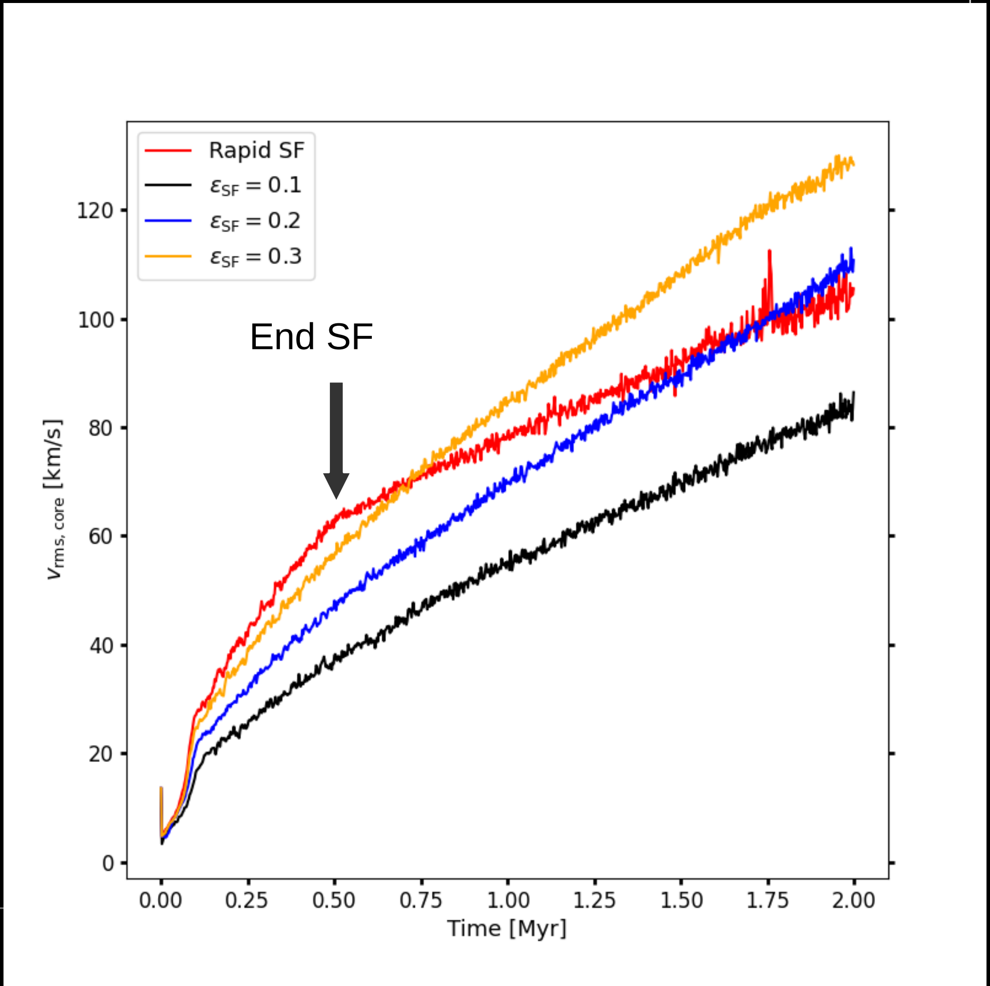
- Standard SF efficiency of 10% produces ~400 MSun BHs
- Higher SF efficiencies produce more massive BHs, approx. 2200 MSun for SF efficiency of 30%
- Continuous SF delays core-collapse in our models but when core-collapse occurs the final mass is a factor ~10 higher → Future models should improve the modelling of star formation

Reinoso, Latif, & Schleicher in prep.

Large scale evolution of the clusters



Core collapse for clusters with rapid SF



End SF