Formation of massive star cluster under radiative and stellar wind feedback: origins of extremely high N/O ratios and multiple stellar populations

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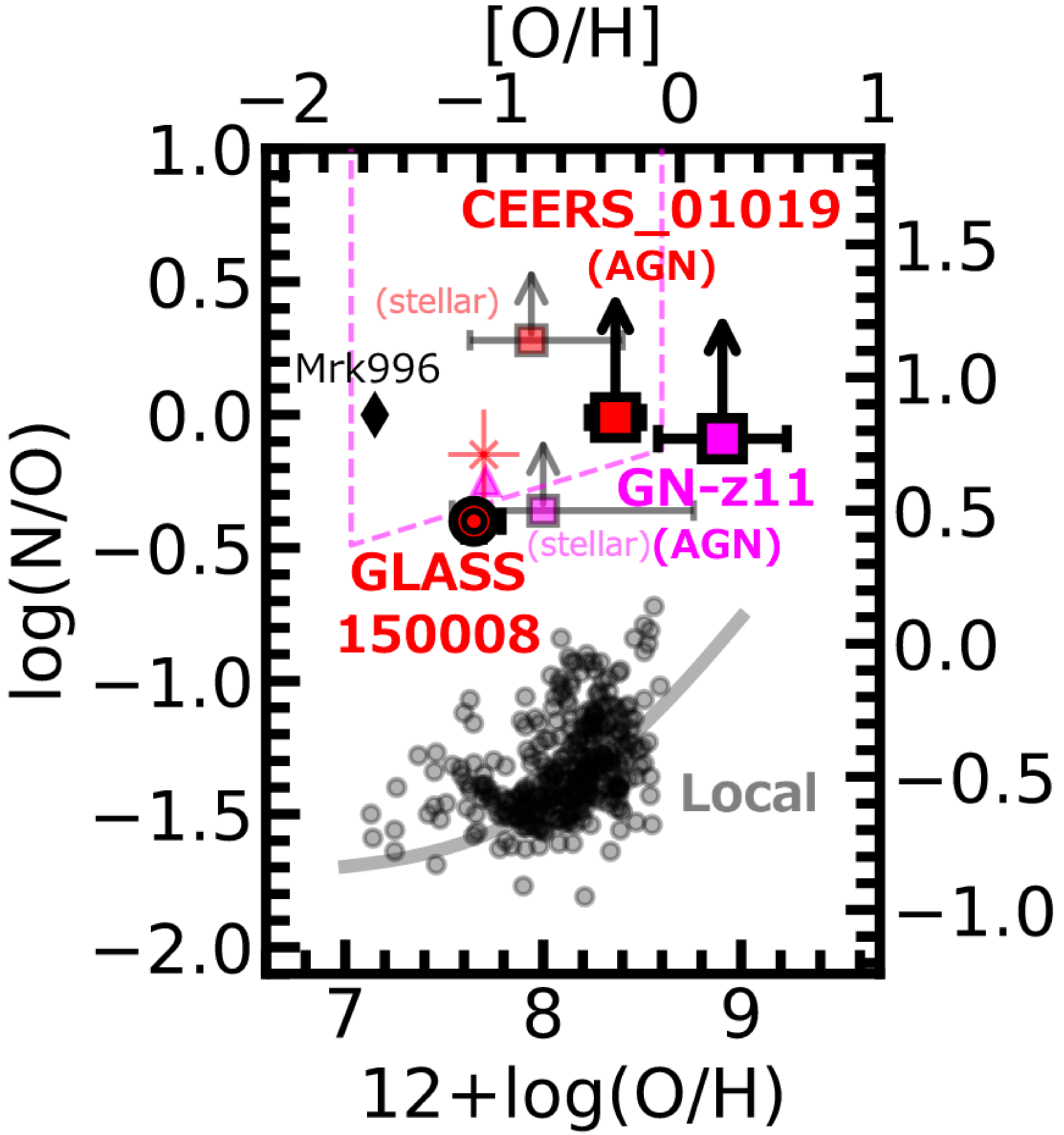
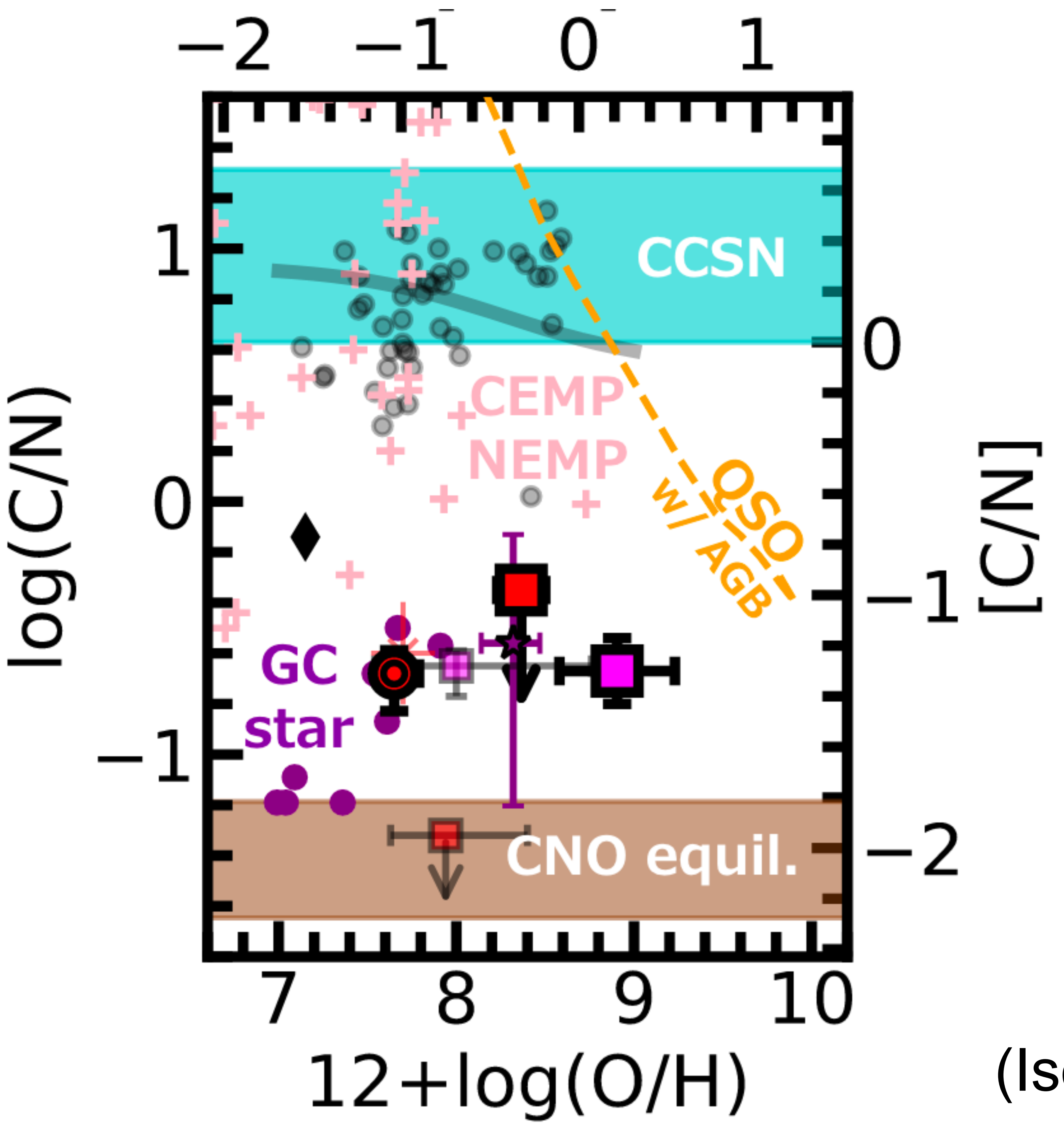
Supersolar N/O galaxies in the Early Universe

cf. Yuki's Talk

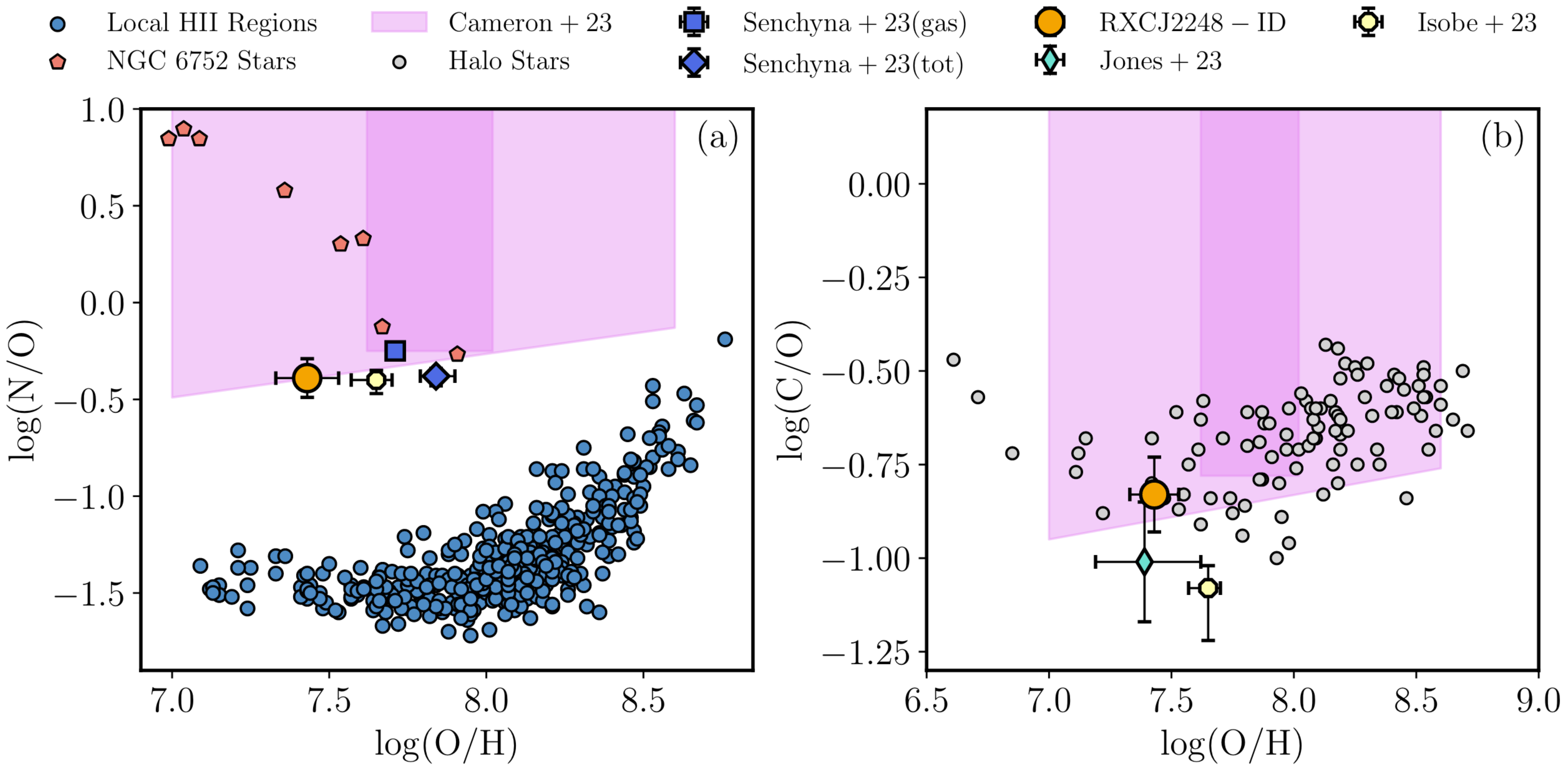


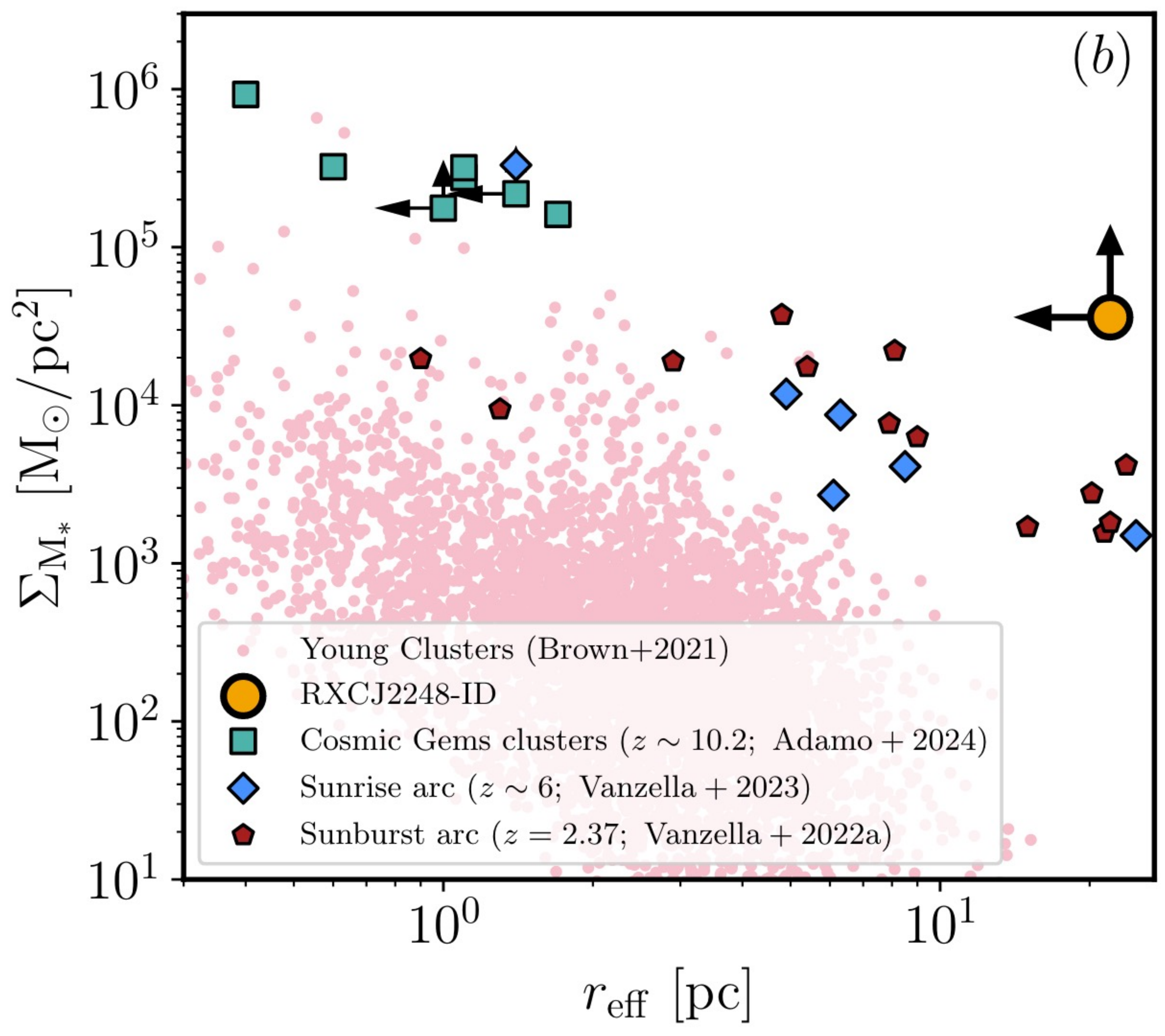


(Isobe+23)

(e.g., Bunker+23, Cameron+23, Senchyna+23)

Birthplaces of Globular Clusters (GCs) ?





(Topping+24)

[N/O] of observed galaxies are similar to GCs.

(e.g., GN-z11, Cameron+23, Senchyna+23)

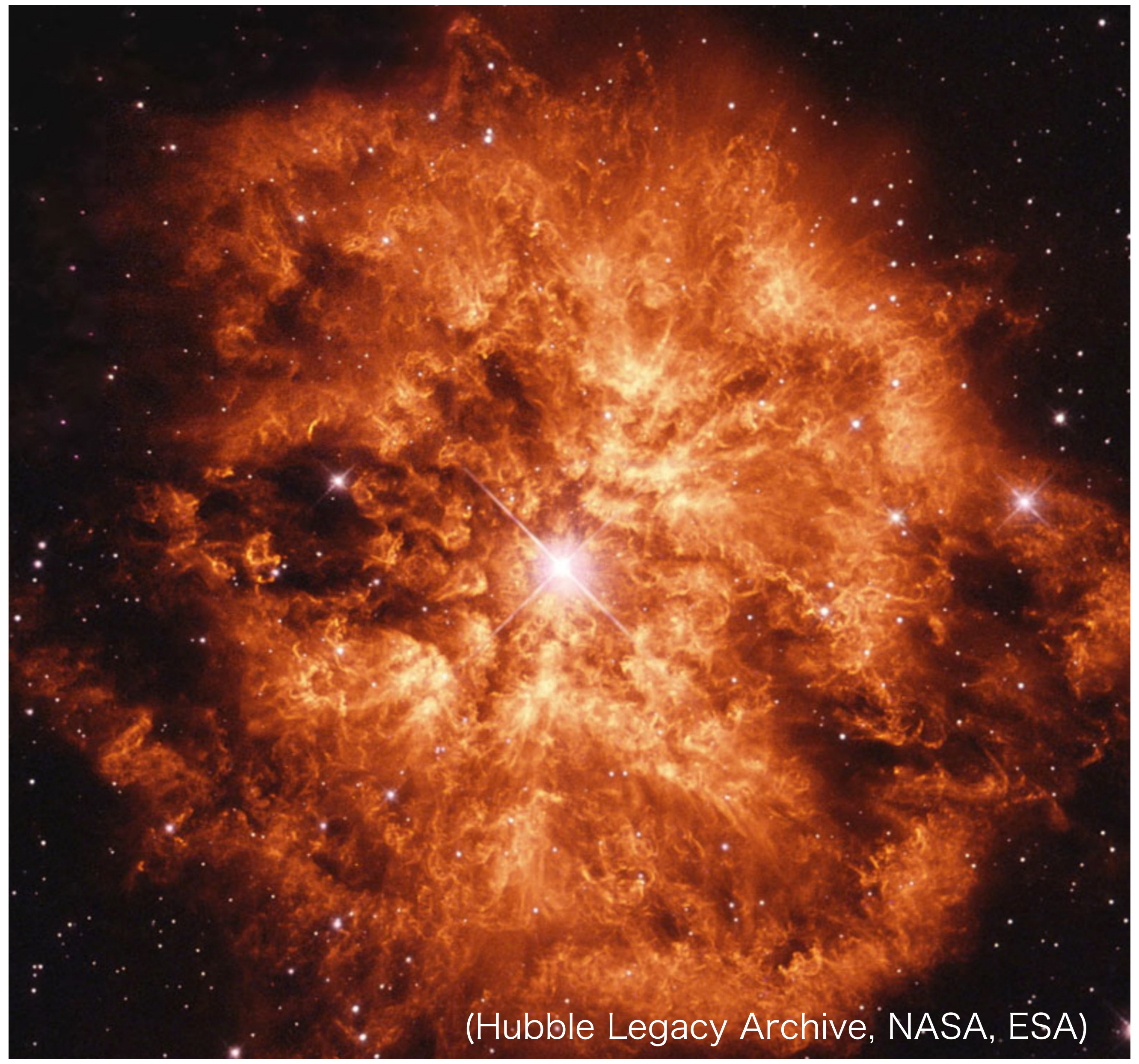
Supersolar N/O and compact star forming regions (< 20 pc) are also discovered.

(e.g., Adamo+24, Topping+24)

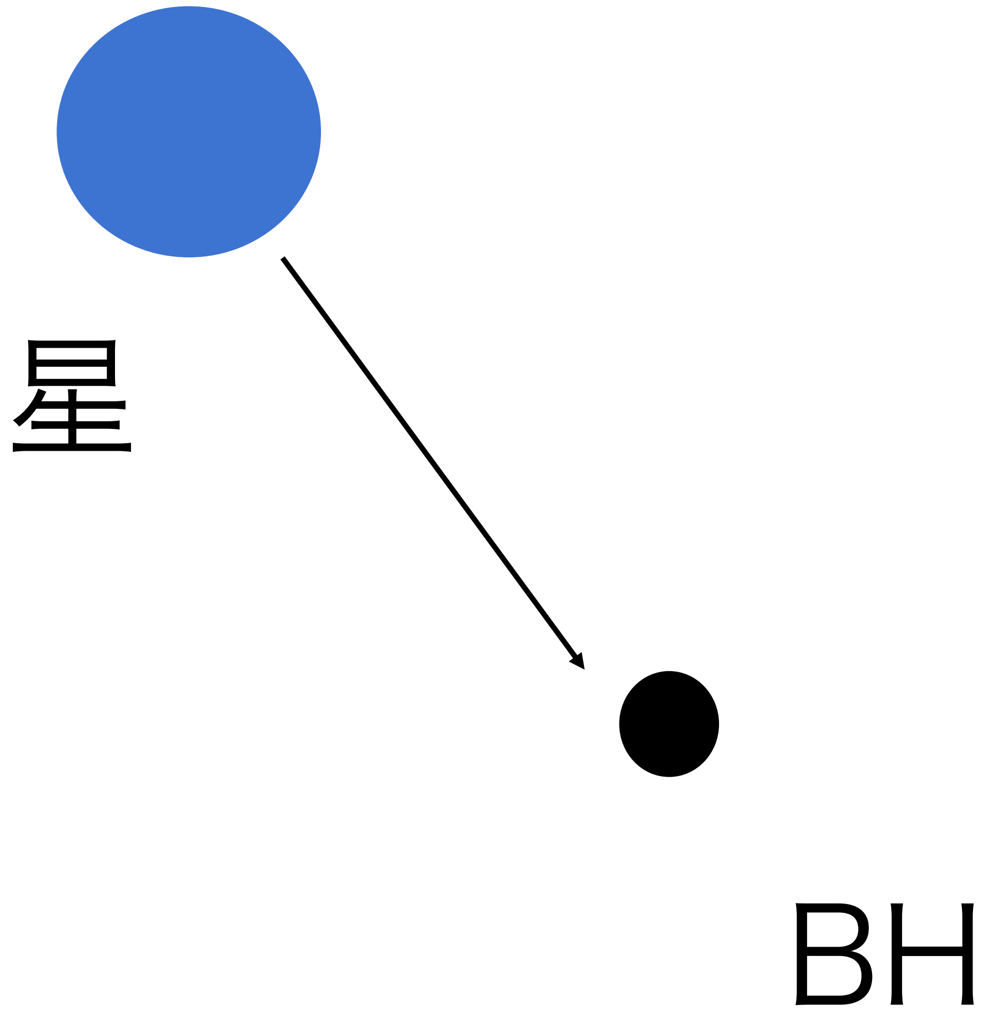
Nitrogen-enrichment scenarios

cf. Kuria's Talk

① Wolf-Rayet star

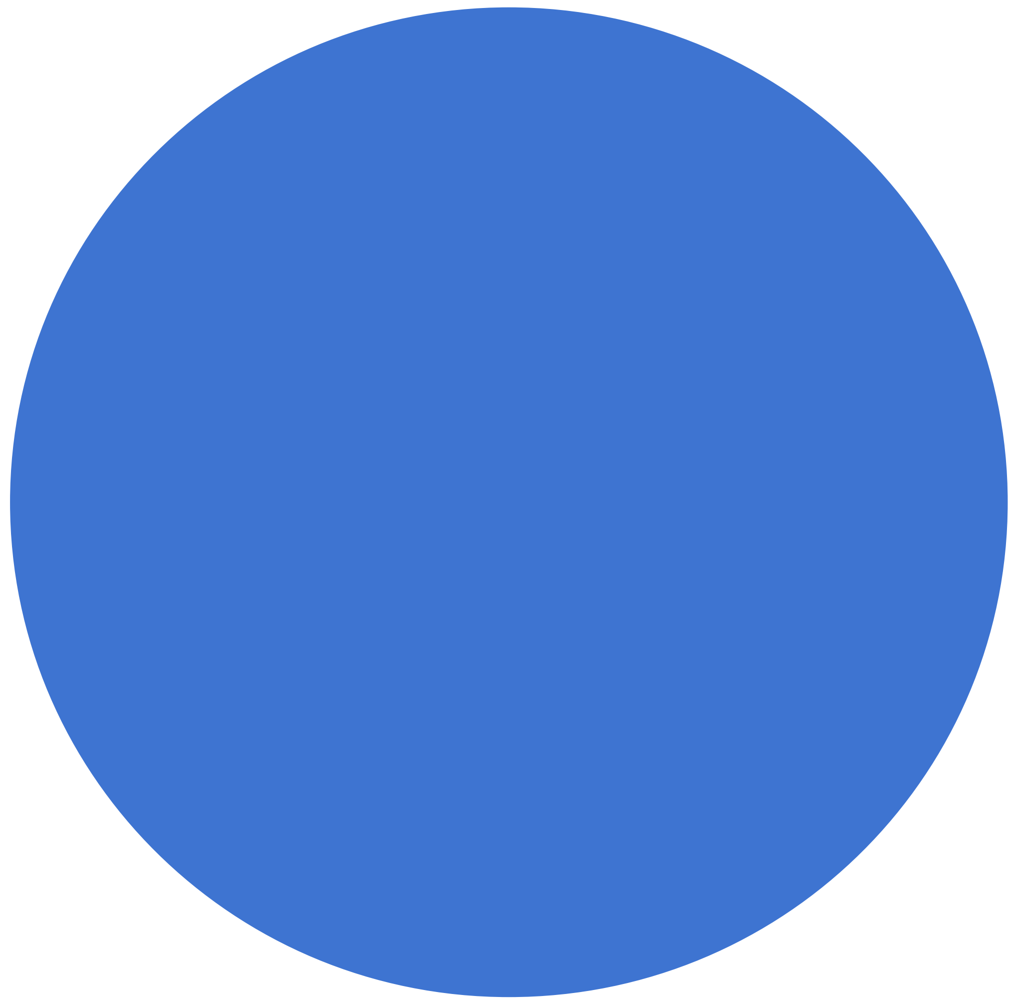


② Tidal disruption event



(Cameron+23, Watanabe+23)

③ Supermassive star

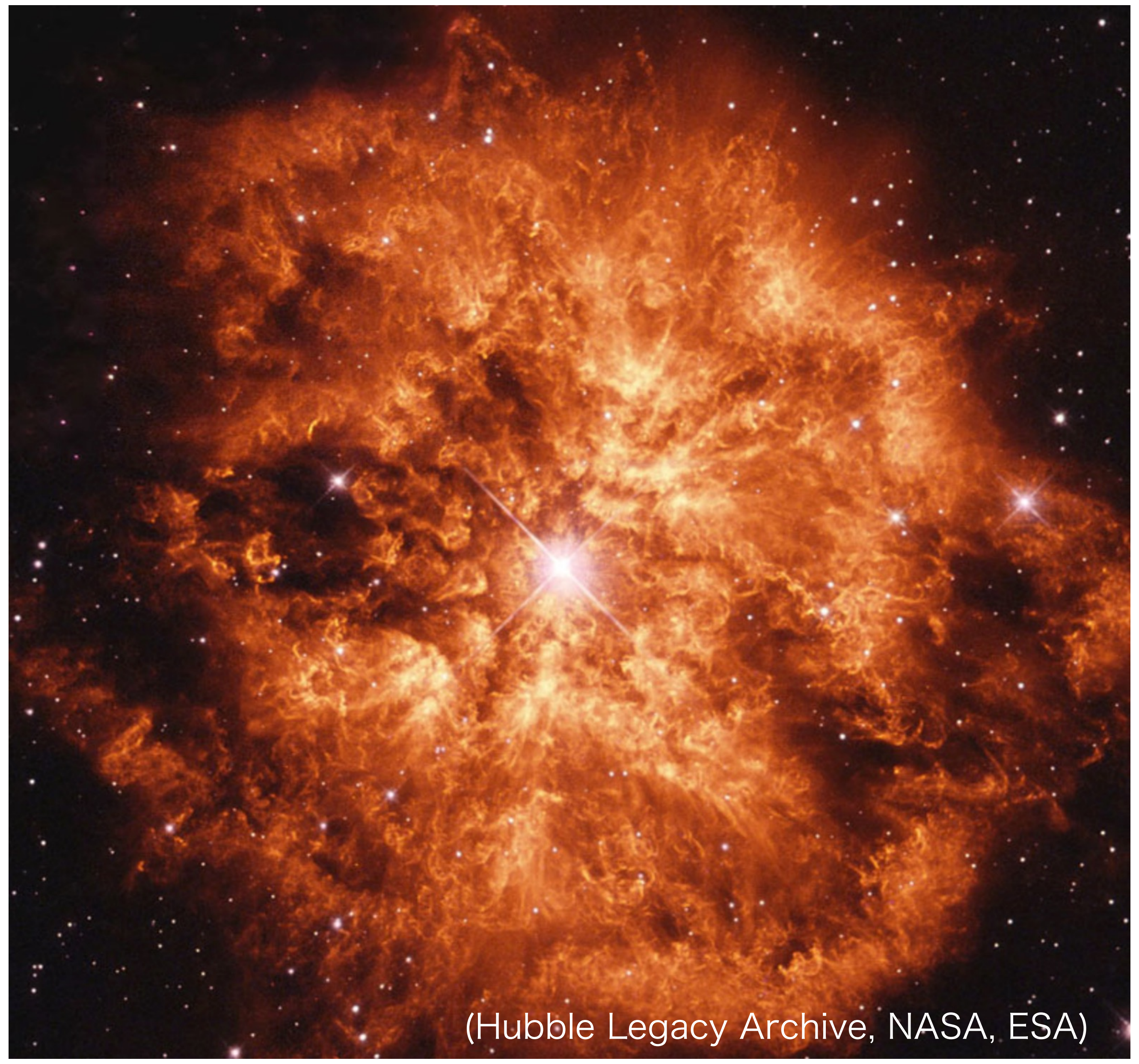


$M_* > 1000 M_\odot$

(Gieles+18, Charbonnel+23, Fujii+24)

Nitrogen-enrichment scenarios

① Wolf-Rayet star



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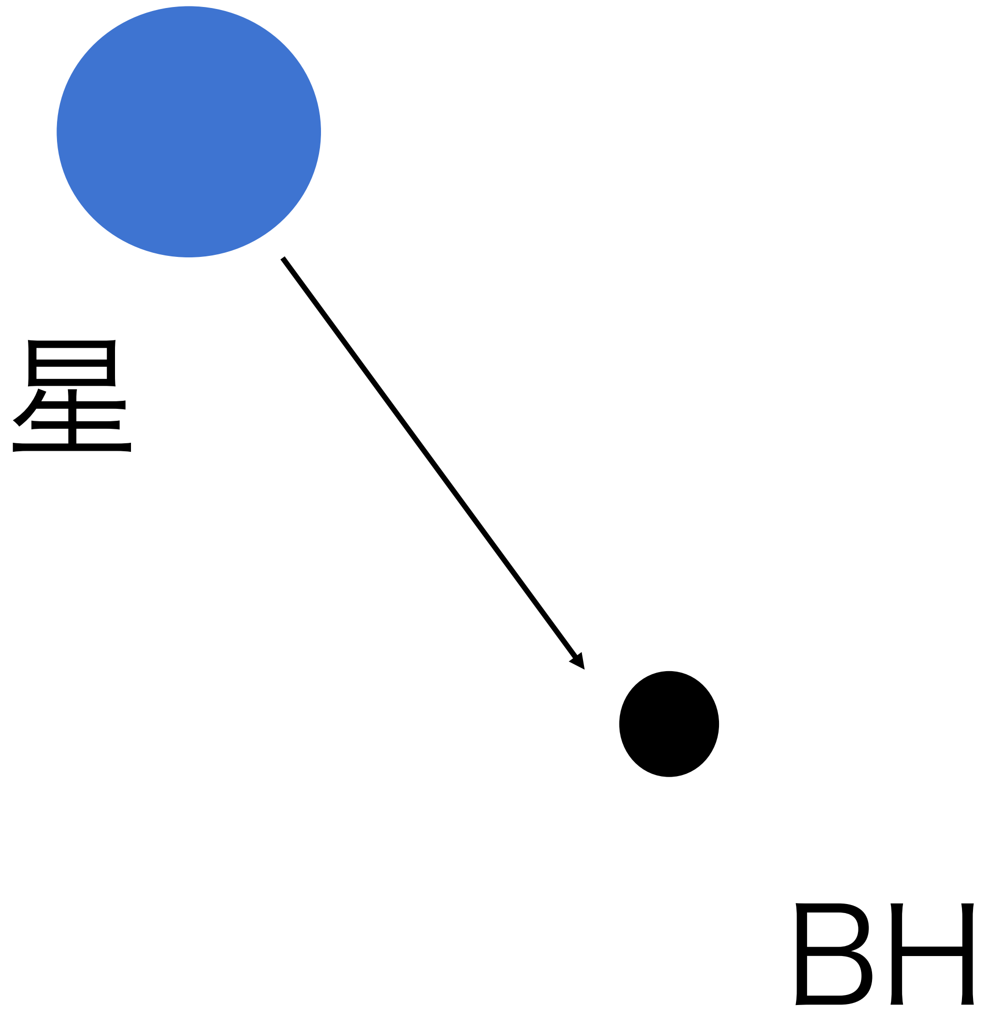

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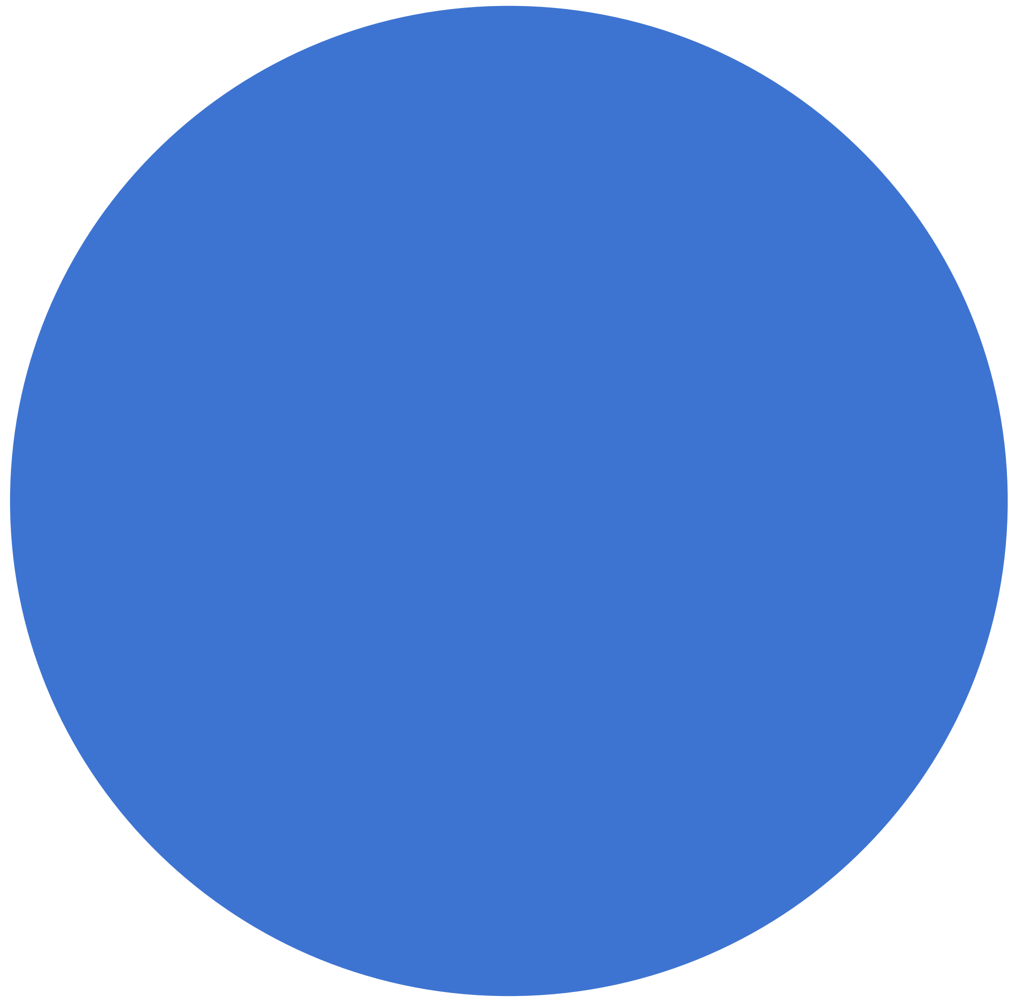


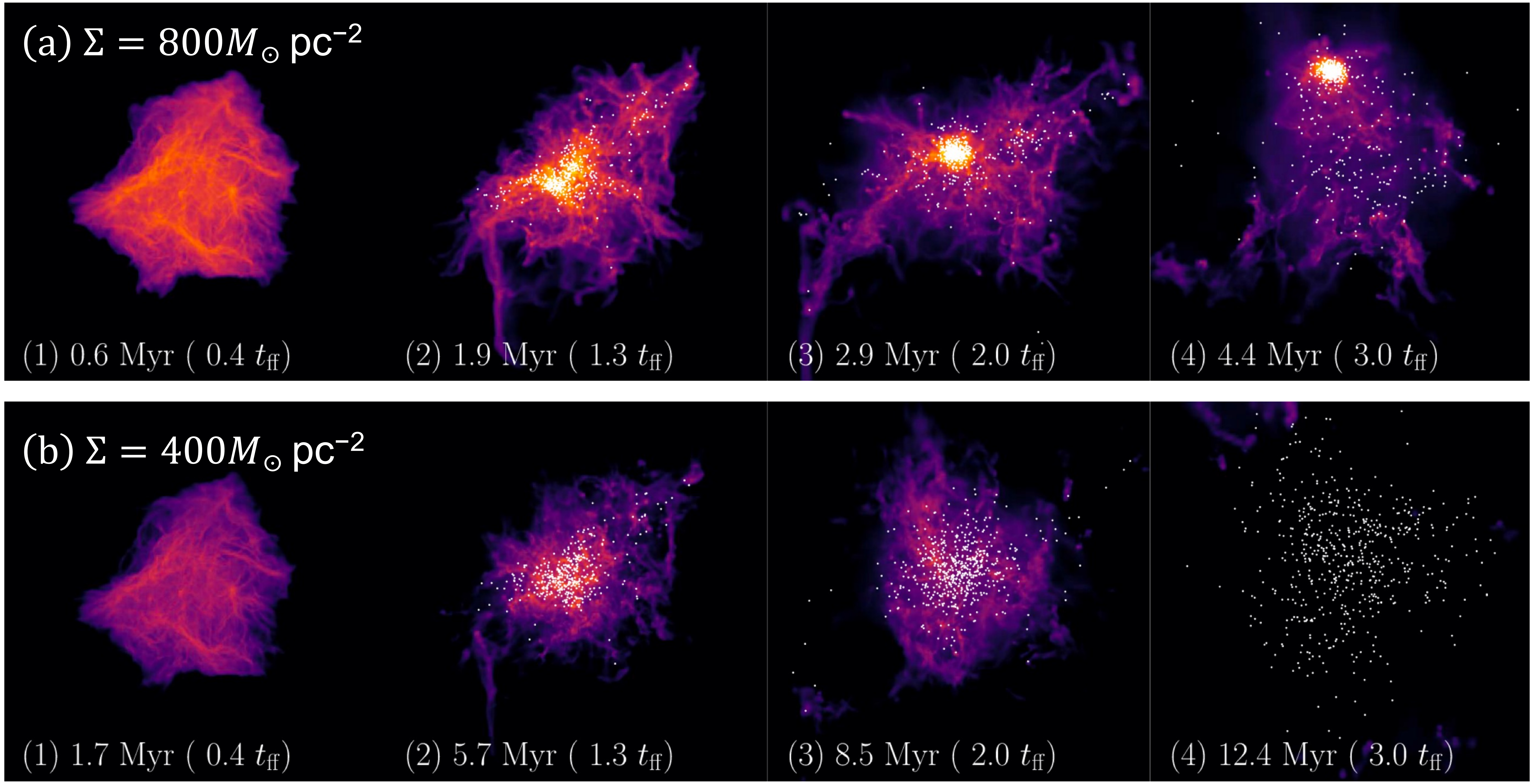
$M_* > 1000 M_\odot$

(Gieles+18, Charbonnel+23, Fujii+24)

We study metal enrichment by WR stars in star cluster formation.

Young massive star cluster (YMC) formation

Cloud mass: $10^6 M_\odot$

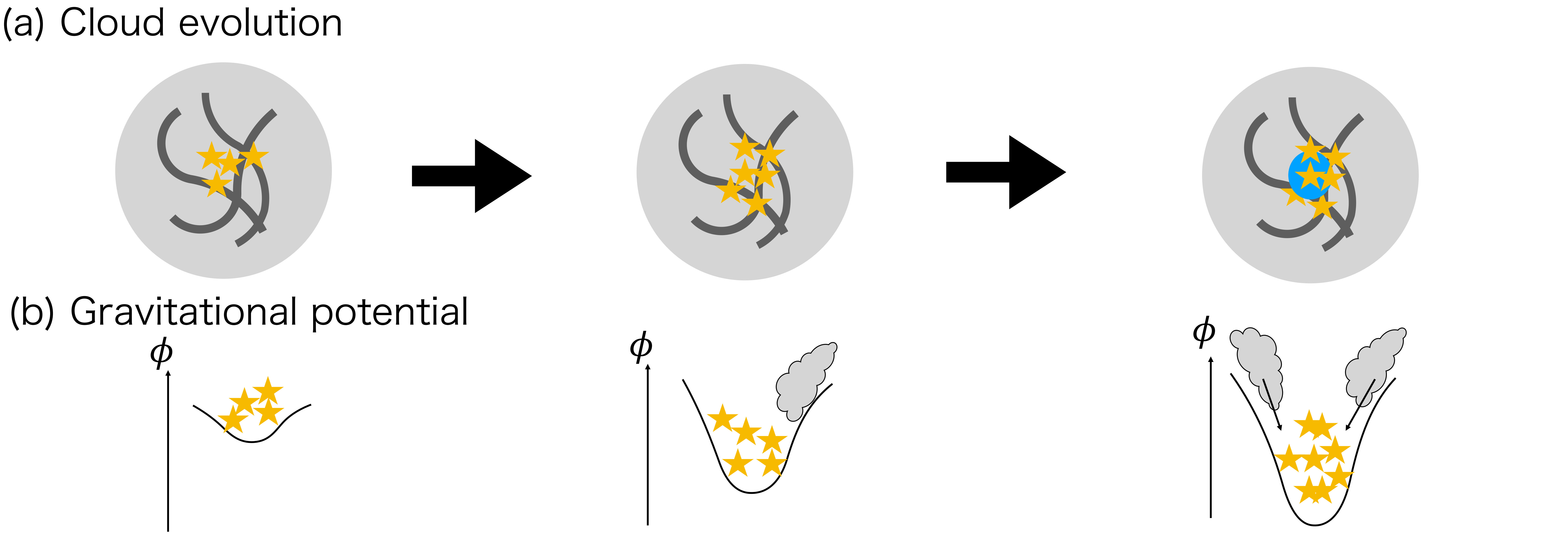


(HF & Yajima 2021)

In diffuse clouds, radiative feedback suppress compact star cluster formation.

YMC formation mechanism

(HF & Yajima 2021)



(1) Star formation starts

(2) Stars begin to gravitationally bind each other.

(3) Thermal pressure cannot push ambient gas.

Condition of YMC formation:

Velocity of expanding shell ($v_{\rm sh}$) < escape velocity from the core ($v_{\rm esc}$)

YMC formation mechanism

(HF & Yajima 2021)

(a) Cloud evolution

(b) Gravitational potential

(1) Star formation starts

(2) Stars begin to gravitationally bind each other.

(3) Thermal pressure cannot push ambient gas.

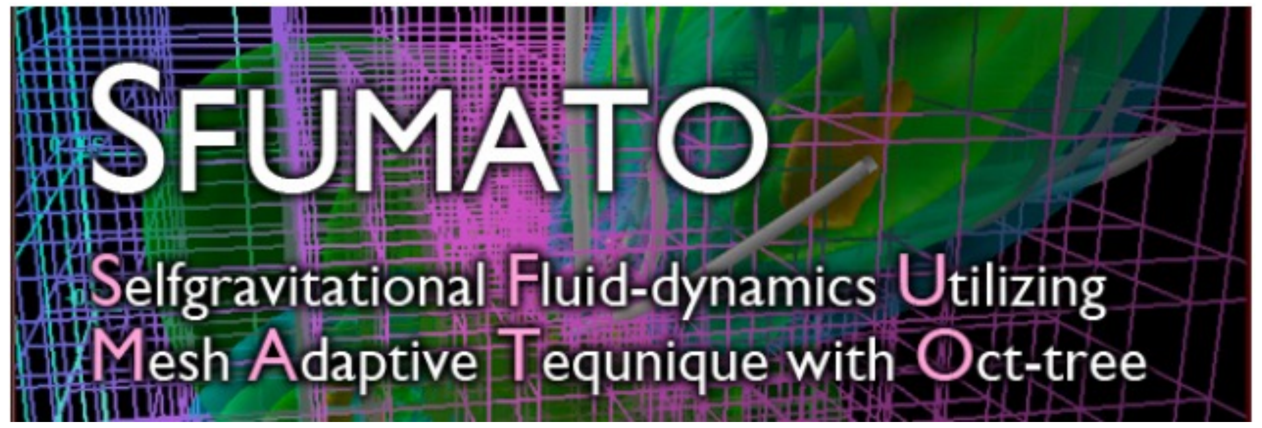
Condition of YMC formation:

$$\Sigma_{\rm cl} > \Sigma_{\rm thr} = 670 M_{\odot}{\rm pc}^{-2} \left(\frac{M_{\rm cl}}{10^6 M_{\odot}}\right)^{-1/5} \left(\frac{s_*}{10^{47} M_{\odot}^{-1} s^{-1}}\right)^{2/5} \left(\frac{T_{\rm HII}}{2.5\times10^4 {\rm K}}\right)^{28/25}$$

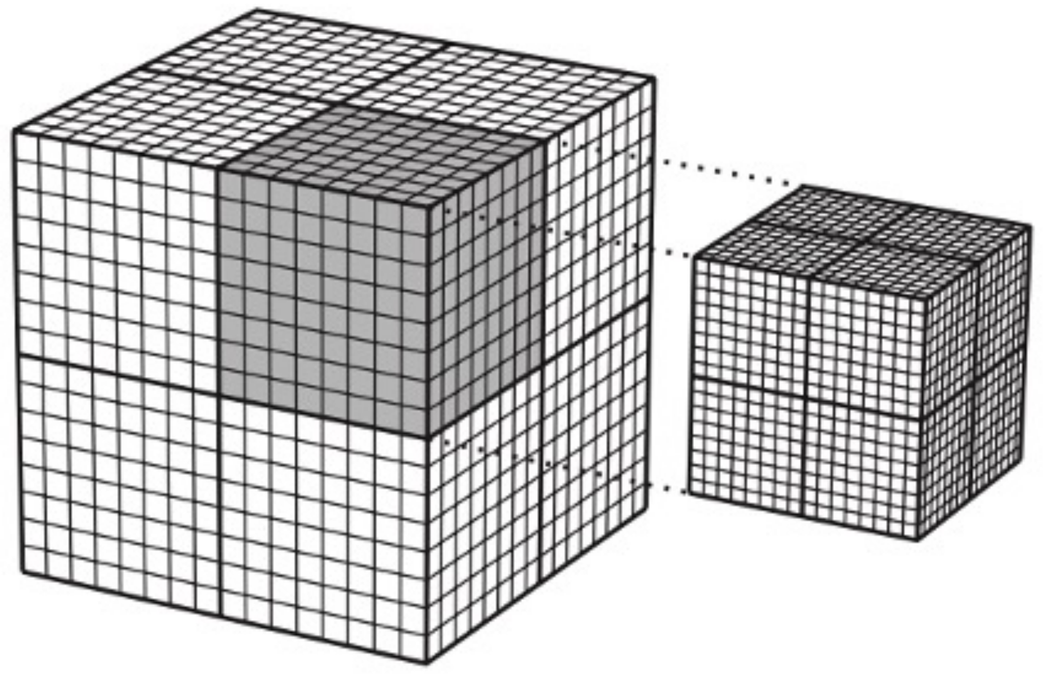
$M_{\rm cl}$: cloud mass, $\Sigma_{\rm cl}$: cloud surface density ($\Sigma_{\rm cl}=M_{\rm cl}/\pi R_{\rm cl}^2$), $R_{\rm cl}$: cloud radius

Simulation code:

Self-gravitational AMR (M)HD + Sink particles



(Matsumoto 2007, 2015)



Cell structures

Non-Equilibrium chemistry

H, H_2, H^+, H^-, H_2^+, e, CII, OI, OII, OIII, CO

Heating & Cooling

Photoionization & photodissociation heating
Line cooling (CII, CO, OI, OII, OIII), dust cooling
Chemical heating & cooling

Stellar evolution

Metal yield from SNe & stellar wind (He, N, C, O)
Stellar wind & SNe feedback
Direct collapse ($> 25 M_\odot$)
(Limongi & Chieffi 2018, Watanabe+23)
Mini-star cluster particles

(Sugimura et al. 2020, CO network: Nelson & Langer 1997)

Radiation transfer with moment method (M1-closure, reduced speed of light)

EUV photons
FUV photons (H_2, CO photodissociation)
Dust thermal emission

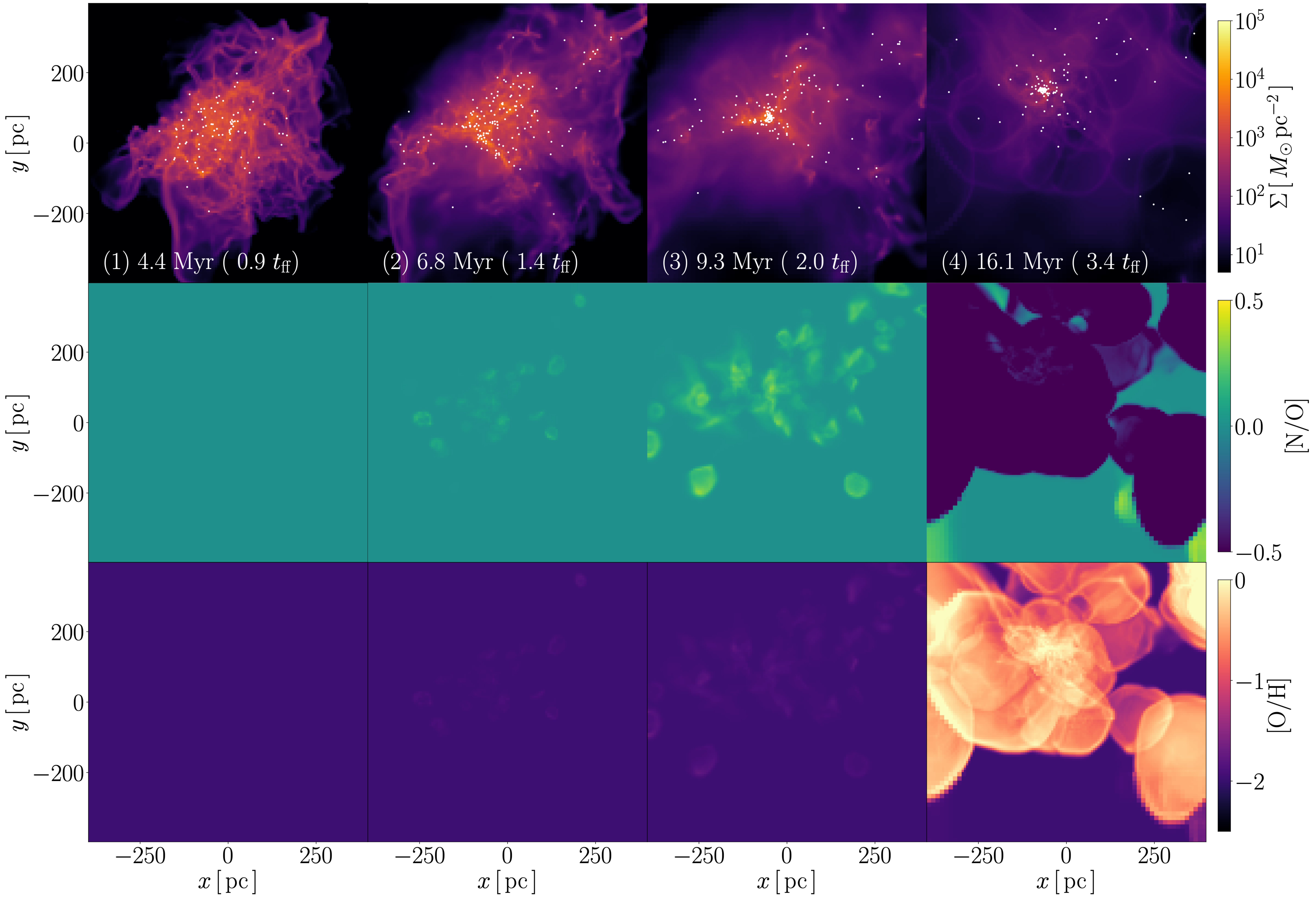
(Rosdahl+13, HF&Yajima 21)

Results:

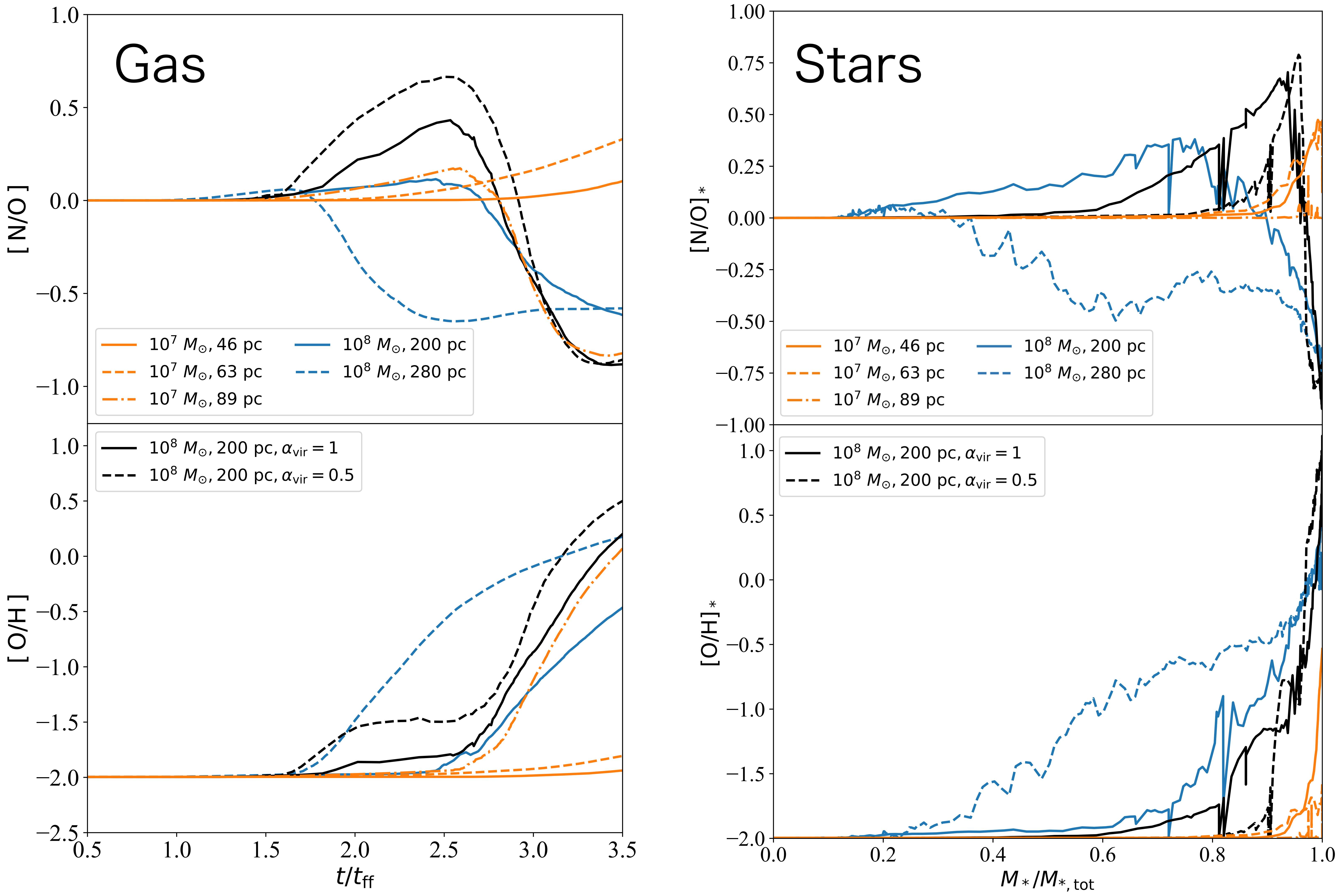
Cloud mass: $10^8 M_\odot$, Radius: $200\mathrm{pc}$, Metallicity: $10^{-2} Z_\odot$

Initial conditions: uniform density sphere with turbulence motions

Cloud mass: $10^8 M_\odot$, Radius: 200pc, Metallicity: $10^{-2} Z_\odot$

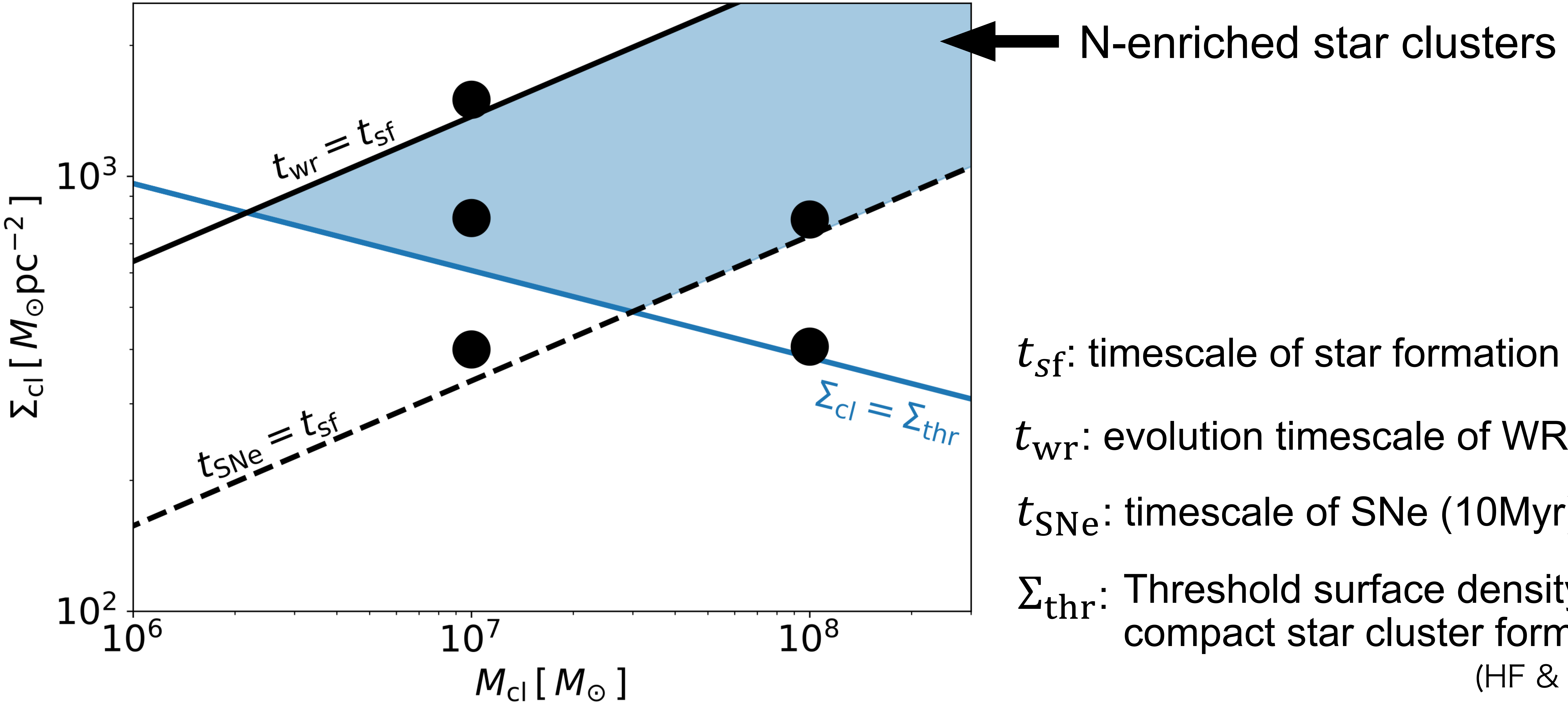


[N/O], [O/H]:



In compact clouds, nitrogen-enriched gas and stars are formed

Conditions of nitrogen enrichment in star cluster formation:



t_{sf}: timescale of star formation (2 tff)

t_{wr}: evolution timescale of WR stars (3Myr)

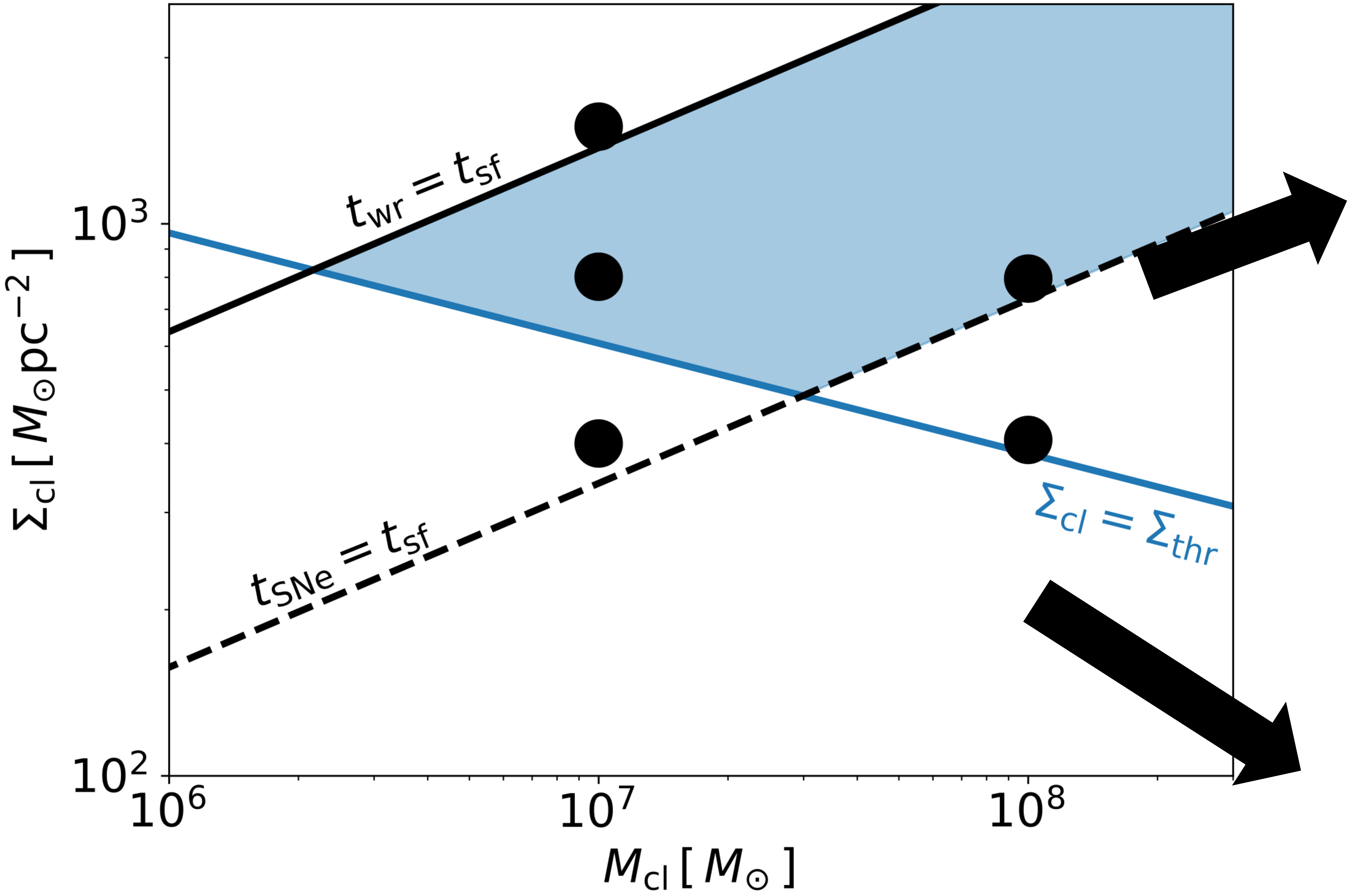
t_{SNe}: timescale of SNe (10Myr)

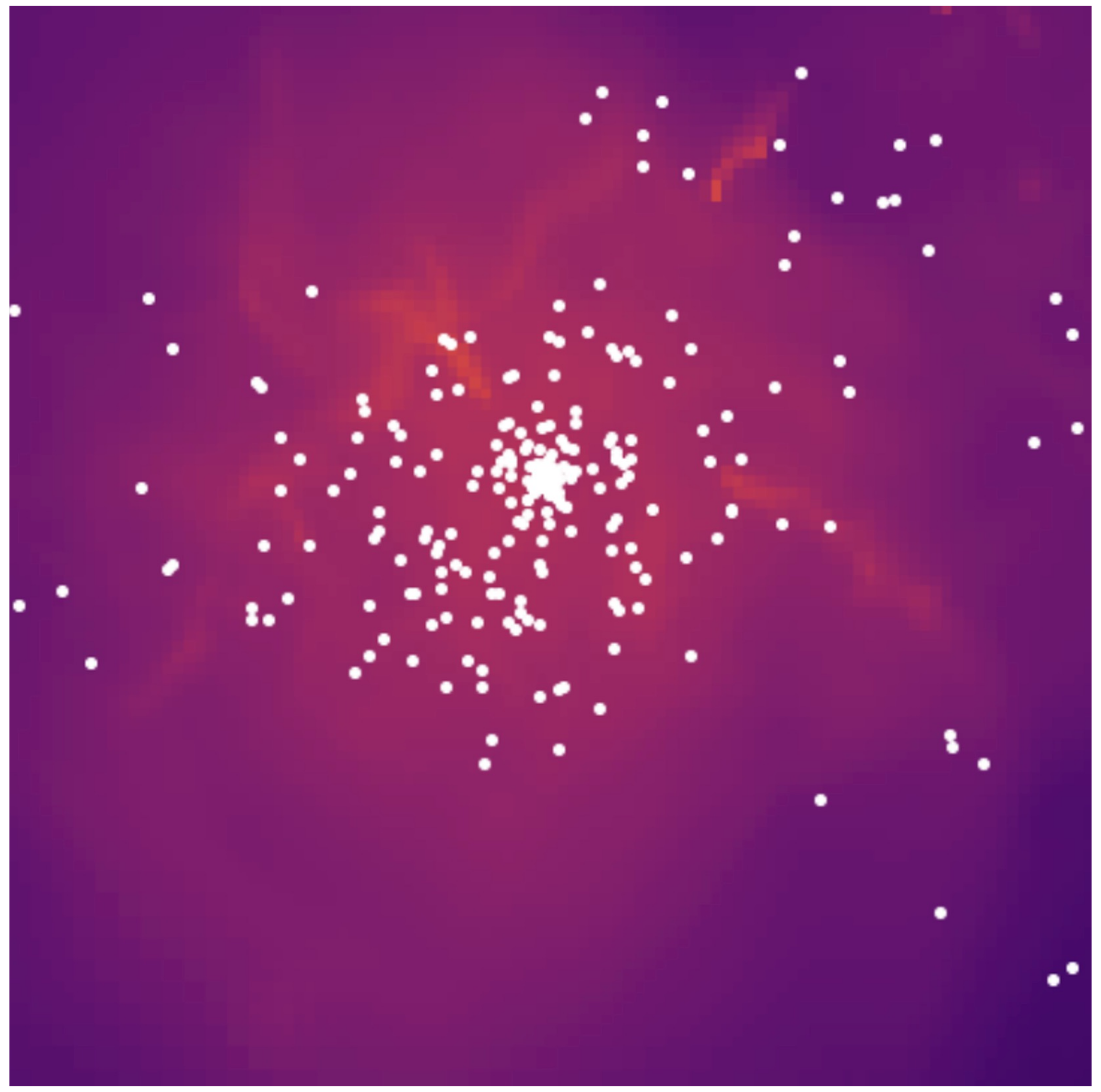
Σ_{thr}: Threshold surface density for compact star cluster formation

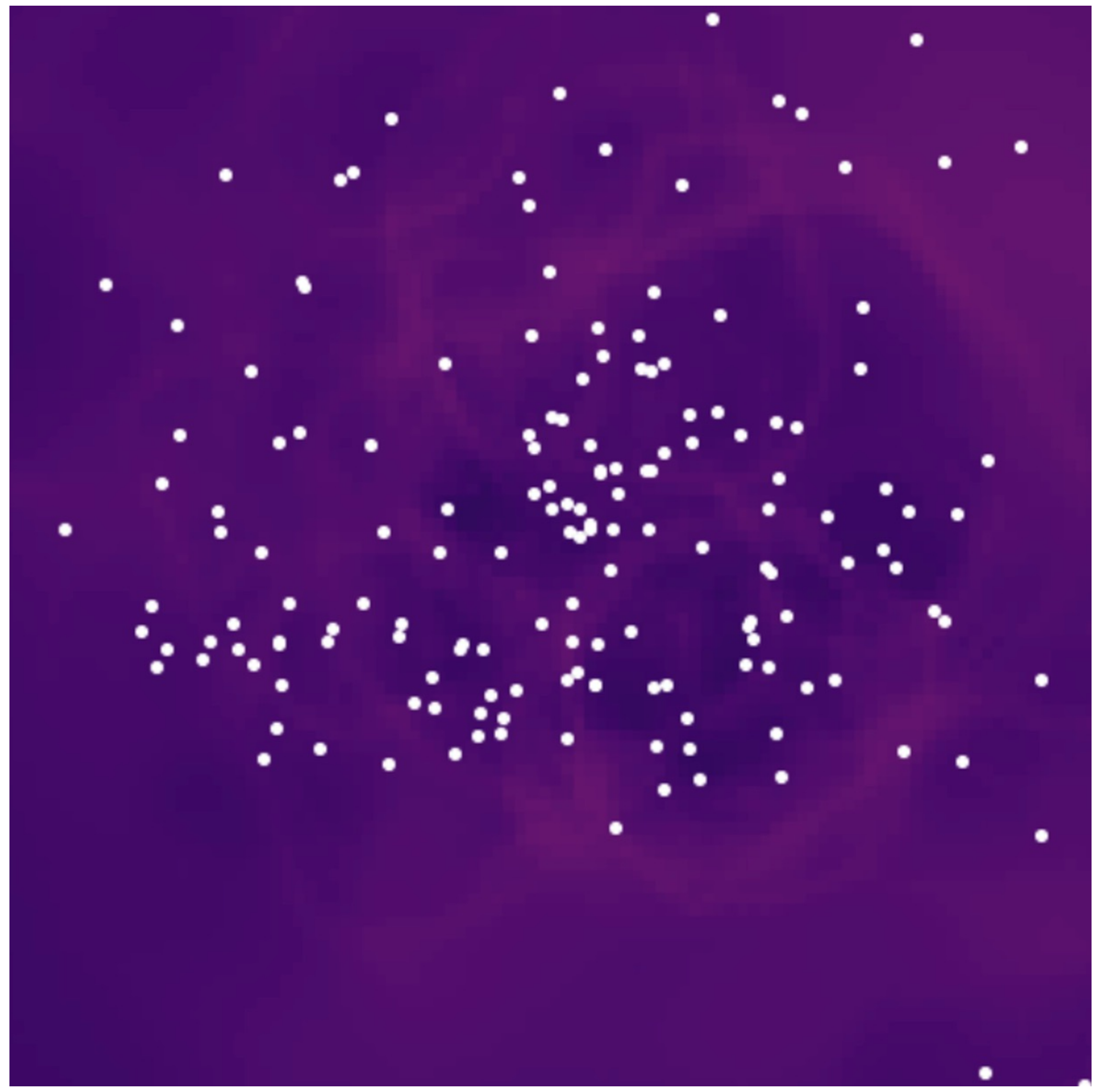
(HF & Yajima 2021)

M_{cl}: cloud mass, Σ_{cl} : cloud surface density ($\Sigma_{cl}=M_{cl}/\pi R_{cl}^2$), R_{cl} : cloud radius

Conditions of nitrogen enrichment in star cluster formation:







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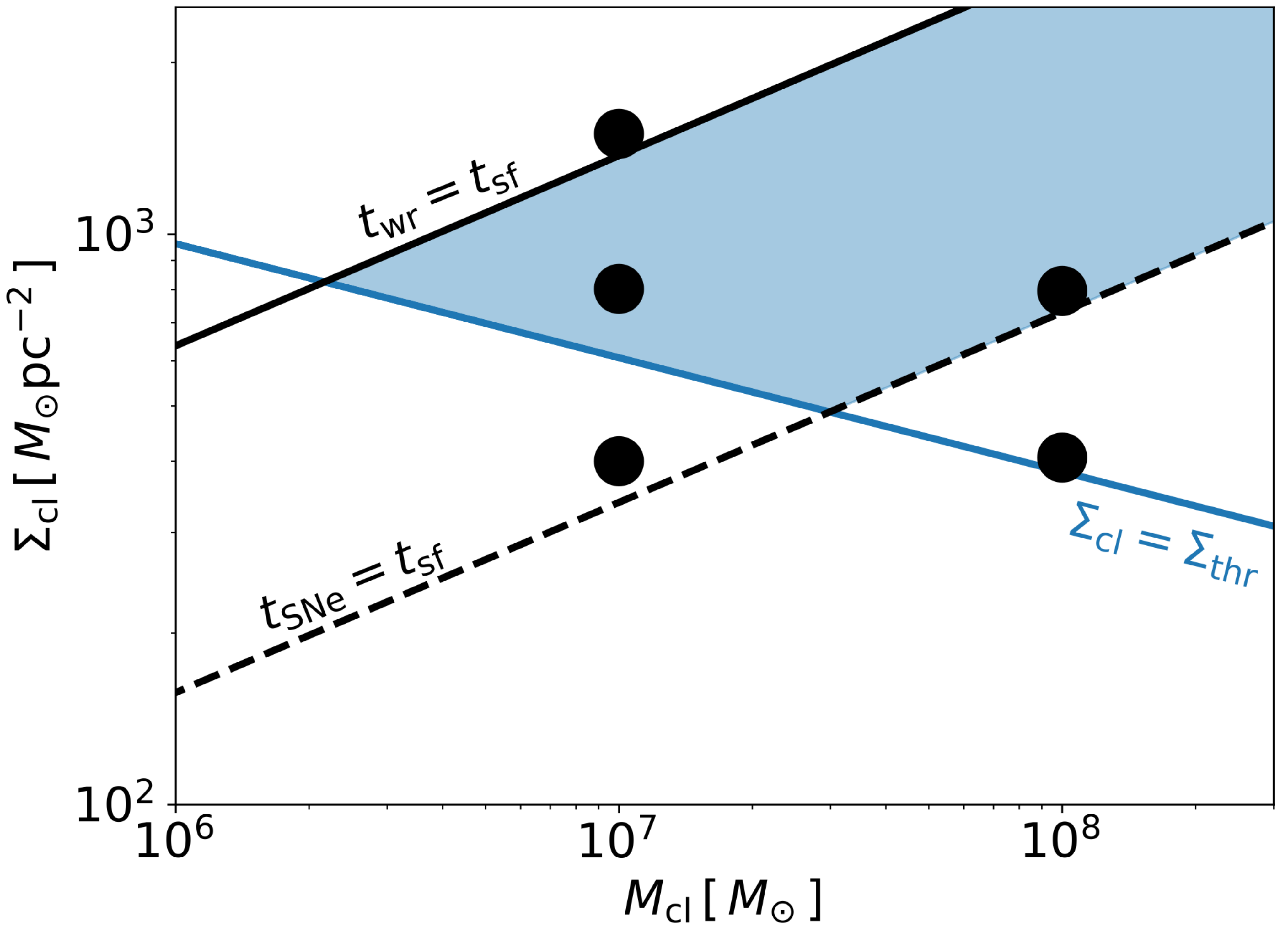

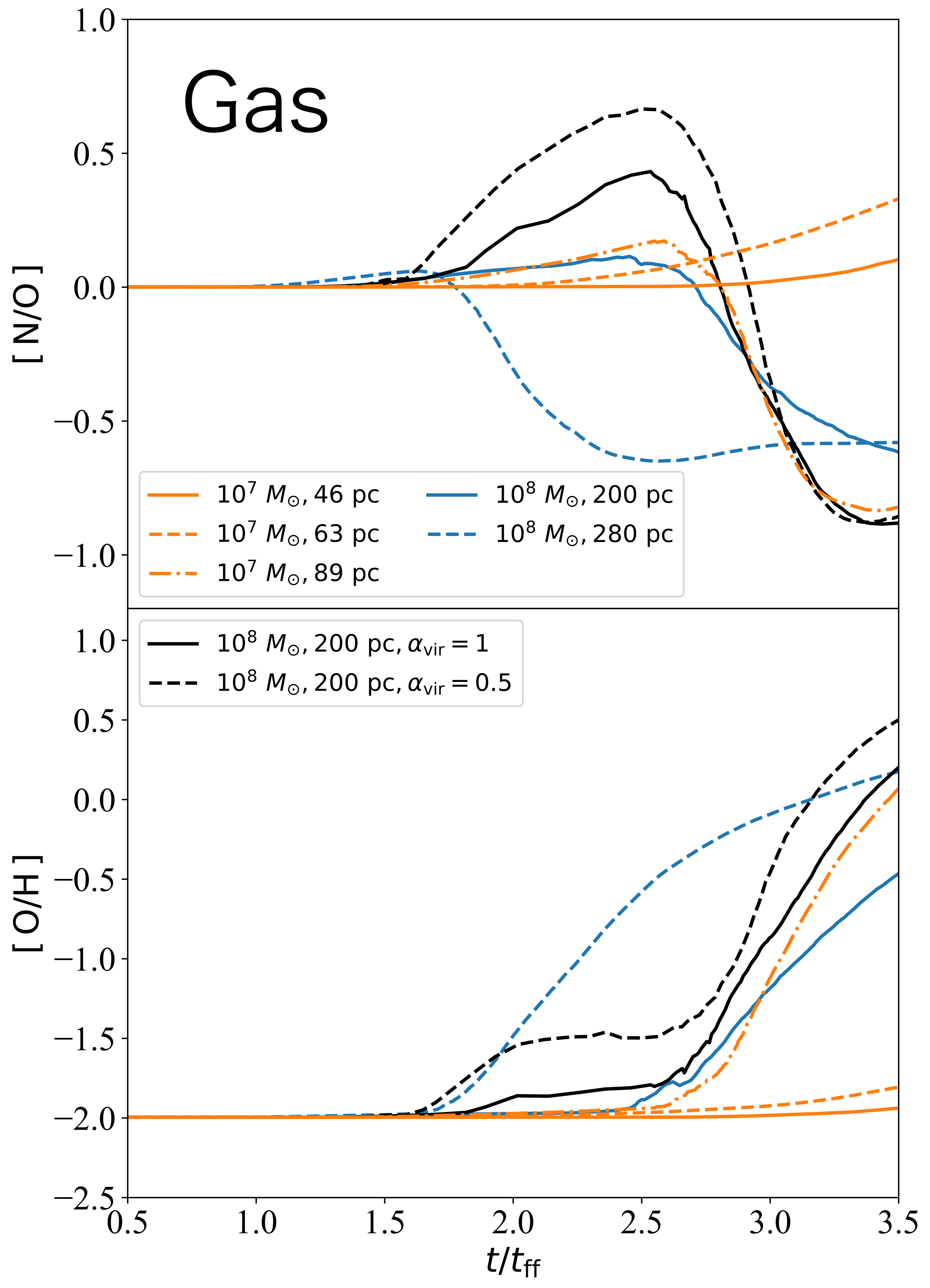

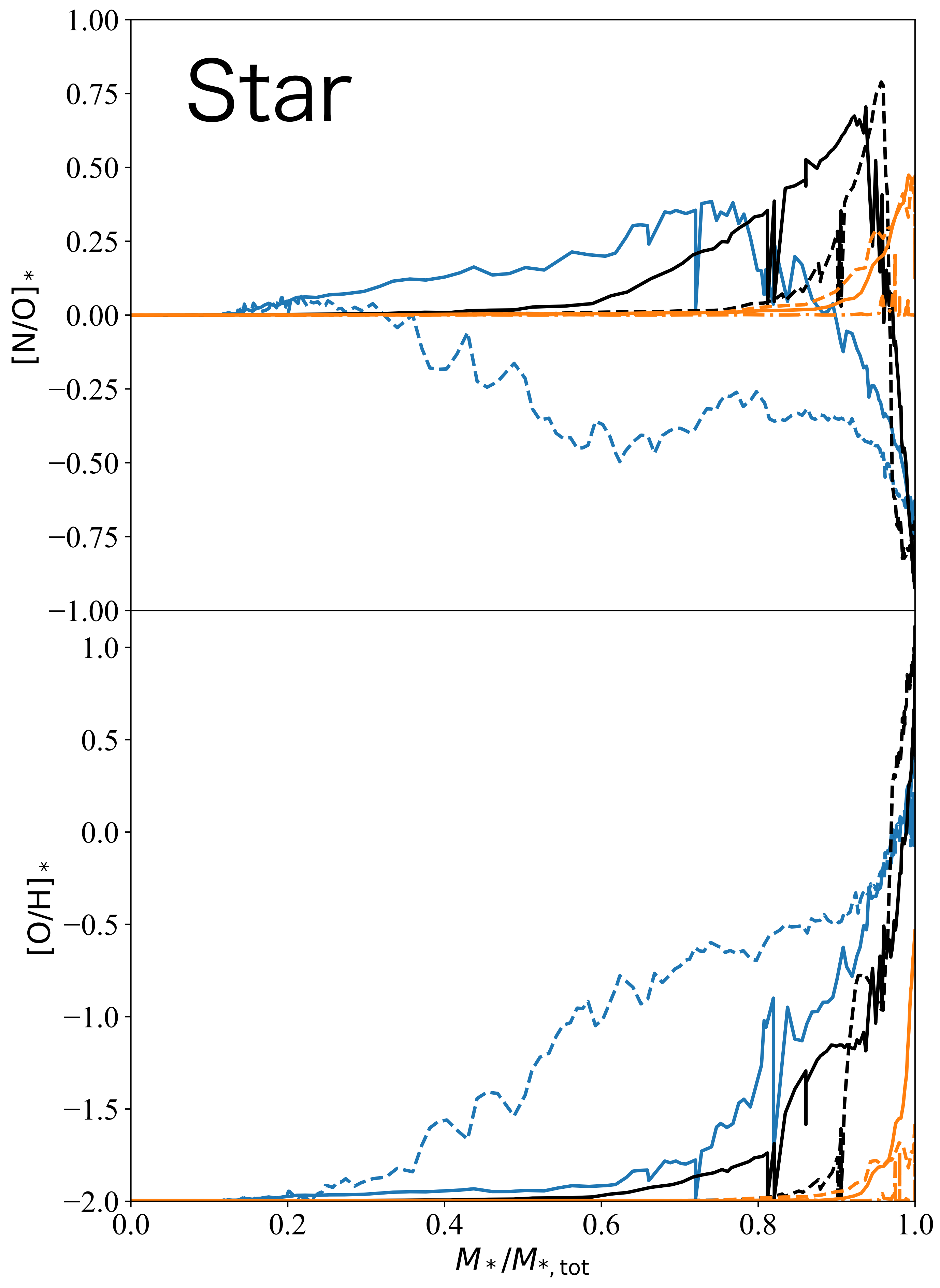

N-enriched stars form only in blue shaded regions.

Summary:

We perform simulations of star cluster formation including stellar wind and SNe feedback.

We found that recycling of ejected materials only when compact star cluster formation occurs.

We predicted that nitrogen-enriched star clusters need to be more massive than $10^6 M_{\odot}$.

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