宇宙初期のガス衝突による
大質量星団形成における紫外線強度の影響

Theoretical Astrophysics
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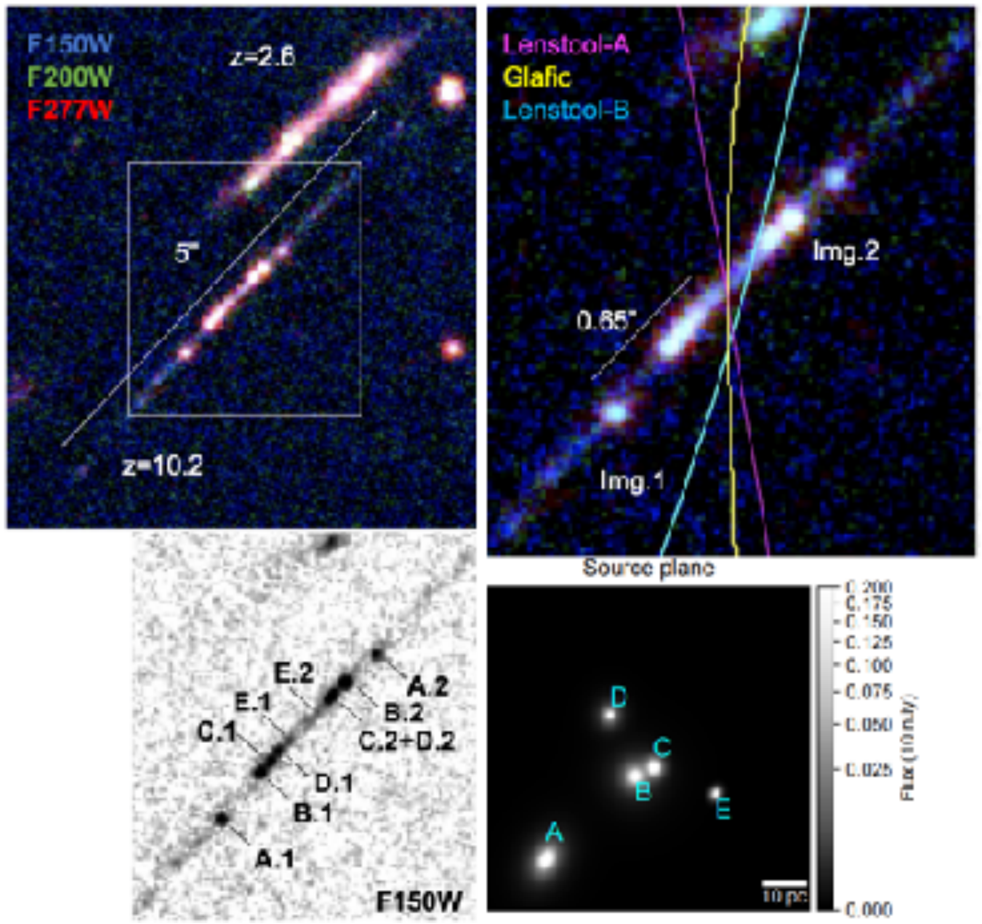
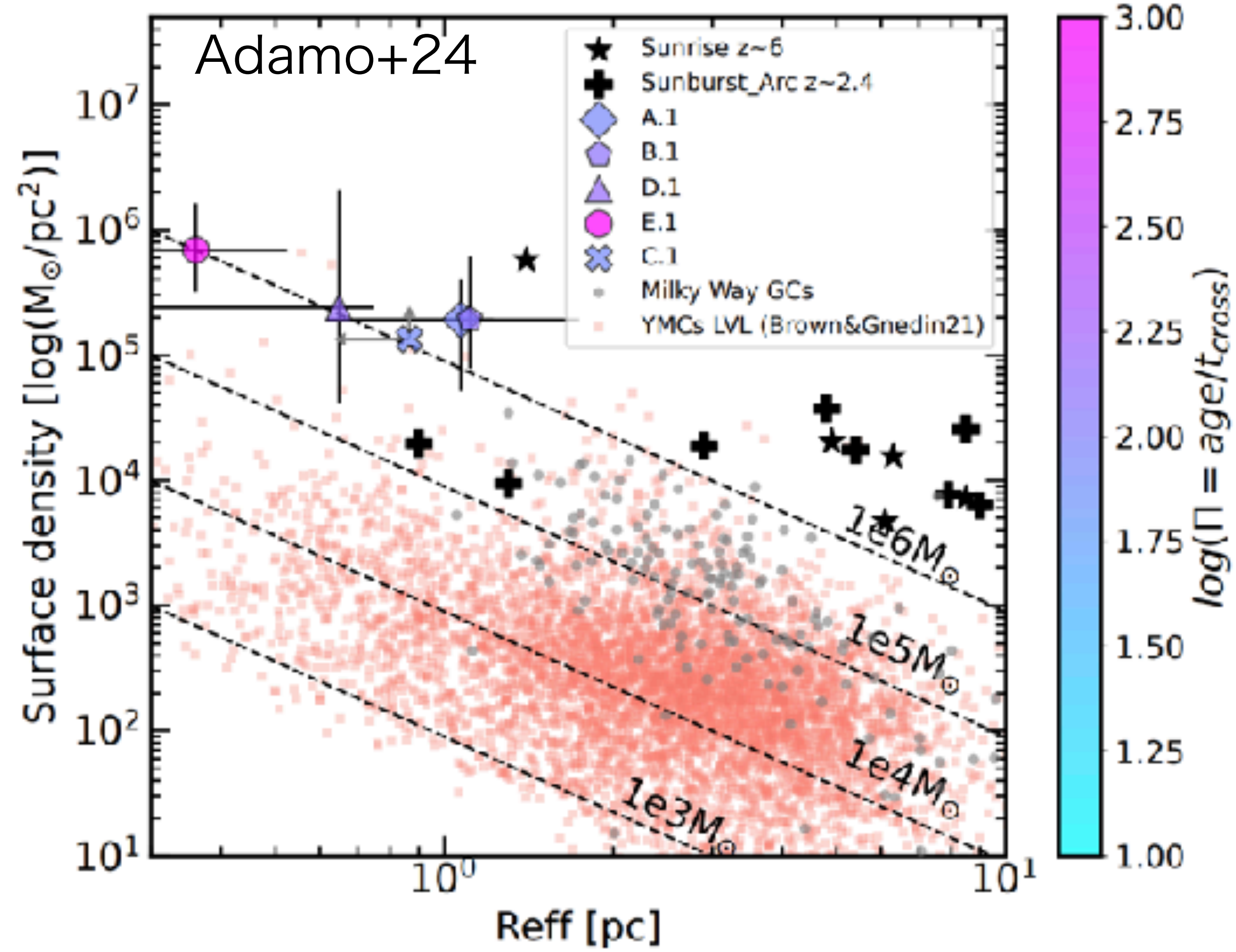
FSFG FUKUI @2025.12.02

Massive Star Clusters in Early Universe





✓ Star clusters observed by JWST

e.g., Vanzella+22, 23a, 23b, Adamo+24, Messa+25

Observation of gravitationally lensed galaxies by JWST

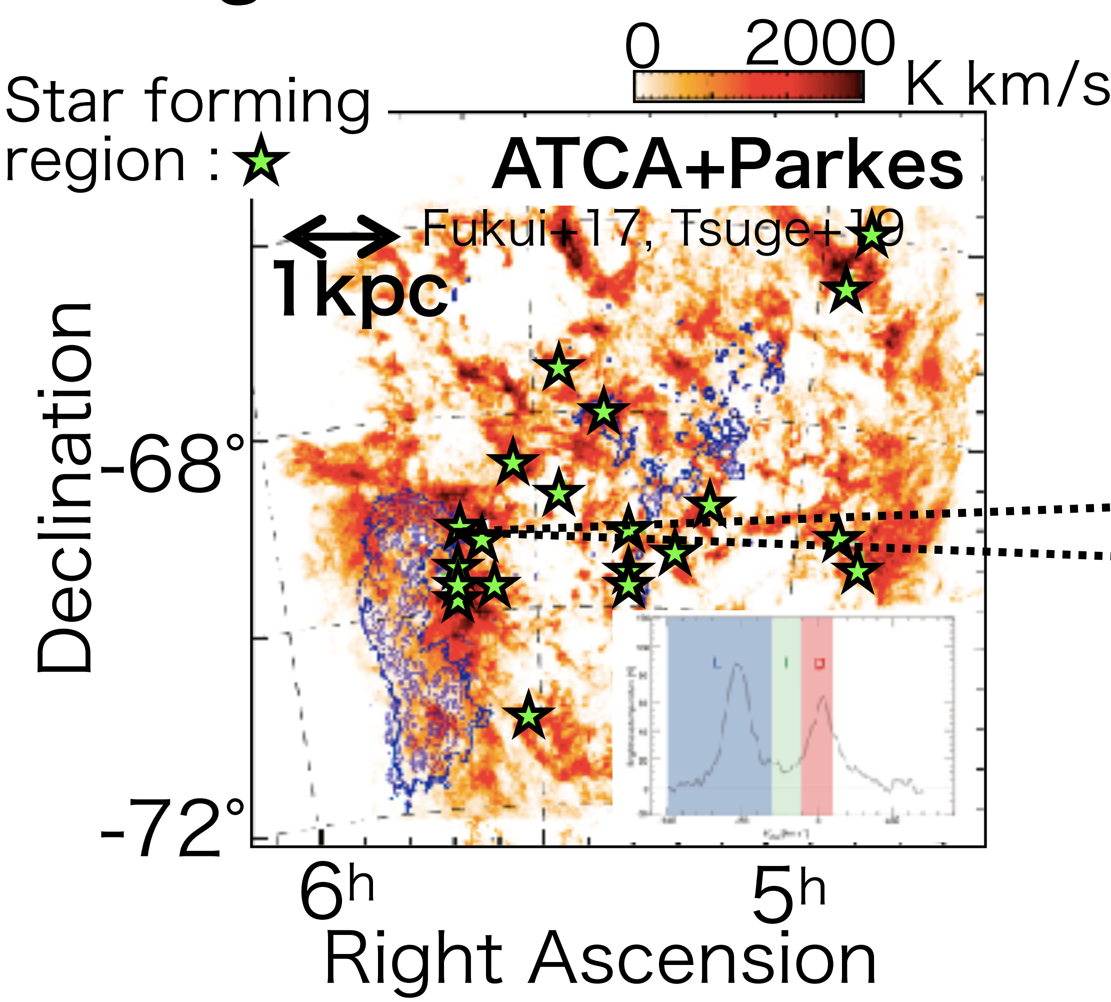
Star clusters with $M \sim 10^6\ \mathrm{M}_\odot$ are discovered at $z \sim 4-10$
→ Comparable to globular clusters >> YMCs in MW ($\sim 10^4\ \mathrm{M}_\odot$)

Massive star clusters account for $> 30\,\%$ of the galaxy's stellar mass.

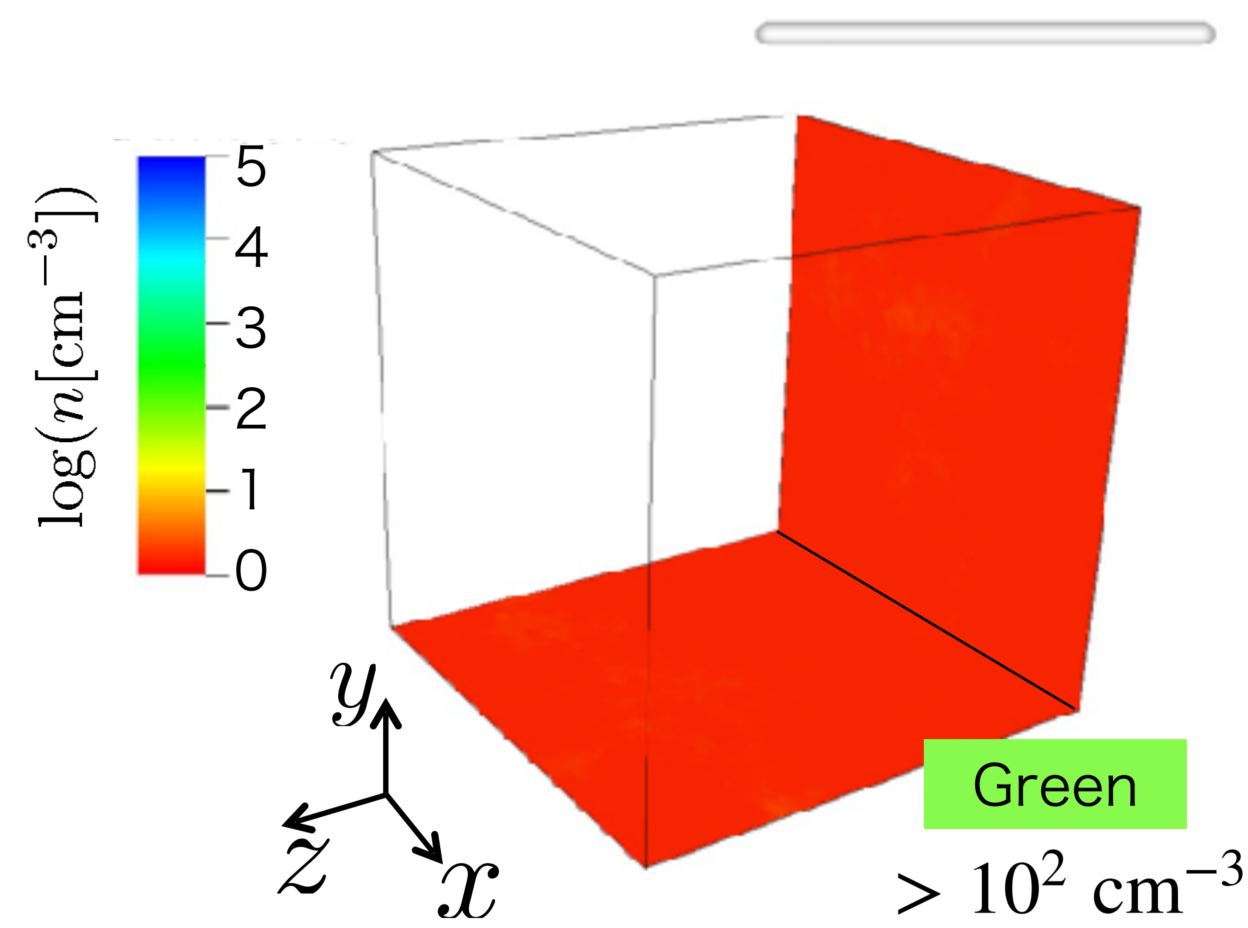
These clusters are key to understand galaxy formation

Massive Star Cluster Formation in the Local Universe

✓ HI-gas Obs. @LMC



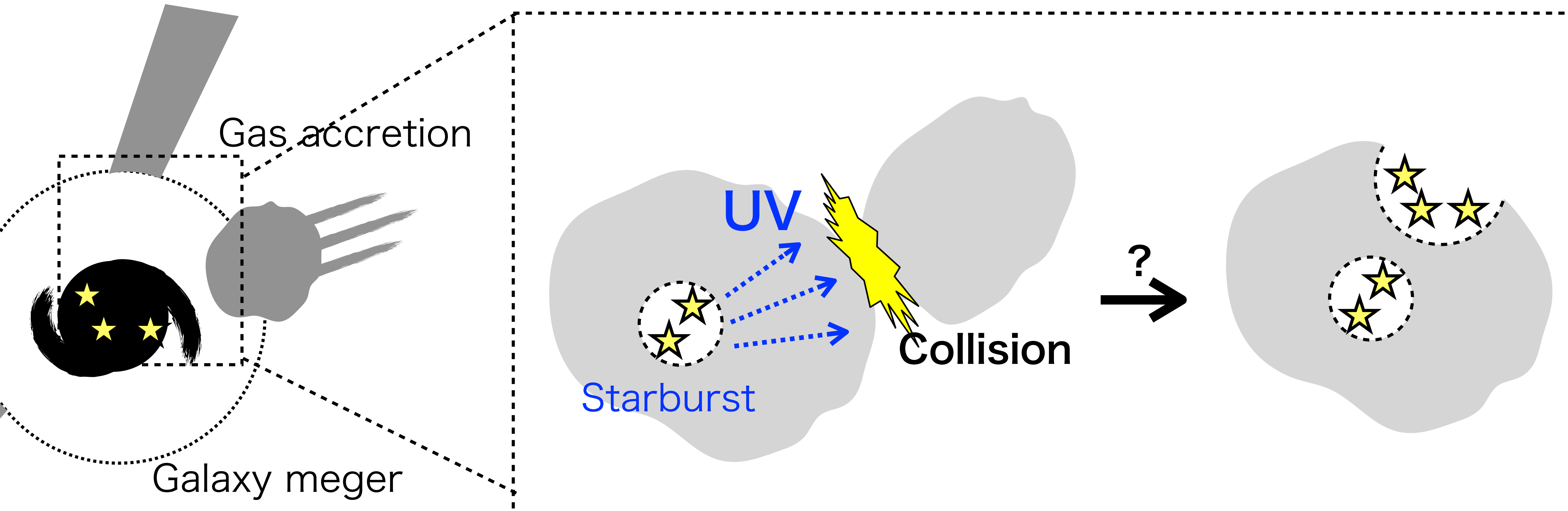
✓ Simulation Maeda+21,24



- High-velocity gas collisions produce a dense sheet
- Small clouds form via thermal instability
- **The clouds merge under gravity and form a massive, compact gas clump (~10^5 M_sun, L~6 pc)**

Massive star cluster formation via gas collisions in the early universe?

Purpose of This Study



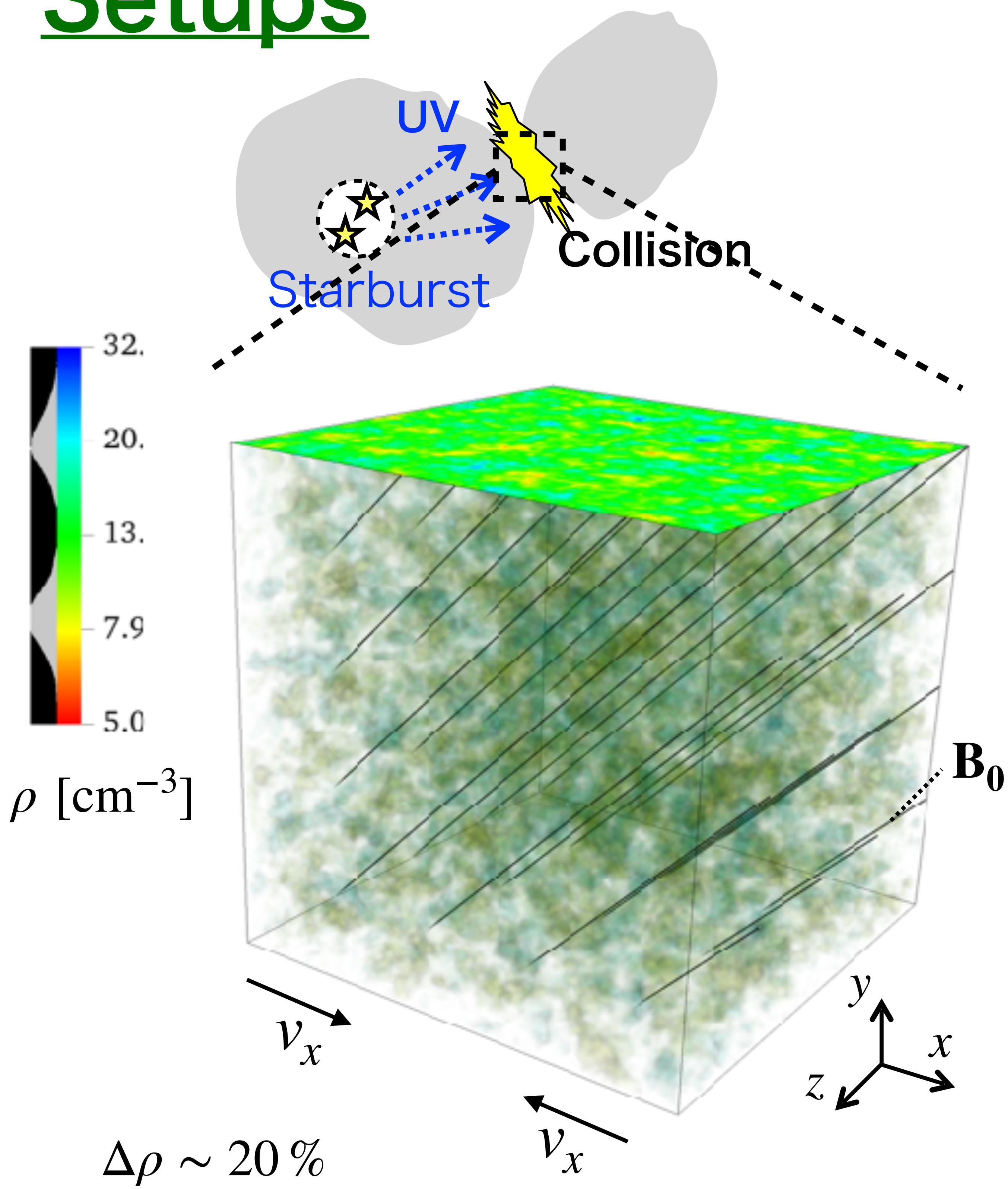
✓ More frequent galaxy mergers and interactions e.g., Harikane+24, Duan+24

✓ Shock-compressed gas from collisions forms massive star clusters via gravitational collapse Maeda+21, 24

✓ Post-shock properties depend on metallicity and UV intensity Inoue+15

Use simulations to study how colliding gas evolves and forms stars in low-metallicity, strong-UV environments

Setups



$\Delta\rho \sim 20\,\%$
$L_{\rm box} = 100$ pc
$\Delta x \sim 0.2$ pc

✓ Basic equations

MHD	cf. Inoue & Inutsuka 12
＋Heating/Cooling	Inoue & Inutsuka 12
＋Chemistry	Inoue & Omukai 15
＋Self-gravity	Maeda+24a
＋Feedback	Maeda+24b

Add the following cooling to Maeda+24b.

Free-Free	Draine+11
Recombination (H)	Draine+11
CIE	Gnat & Ferland 12

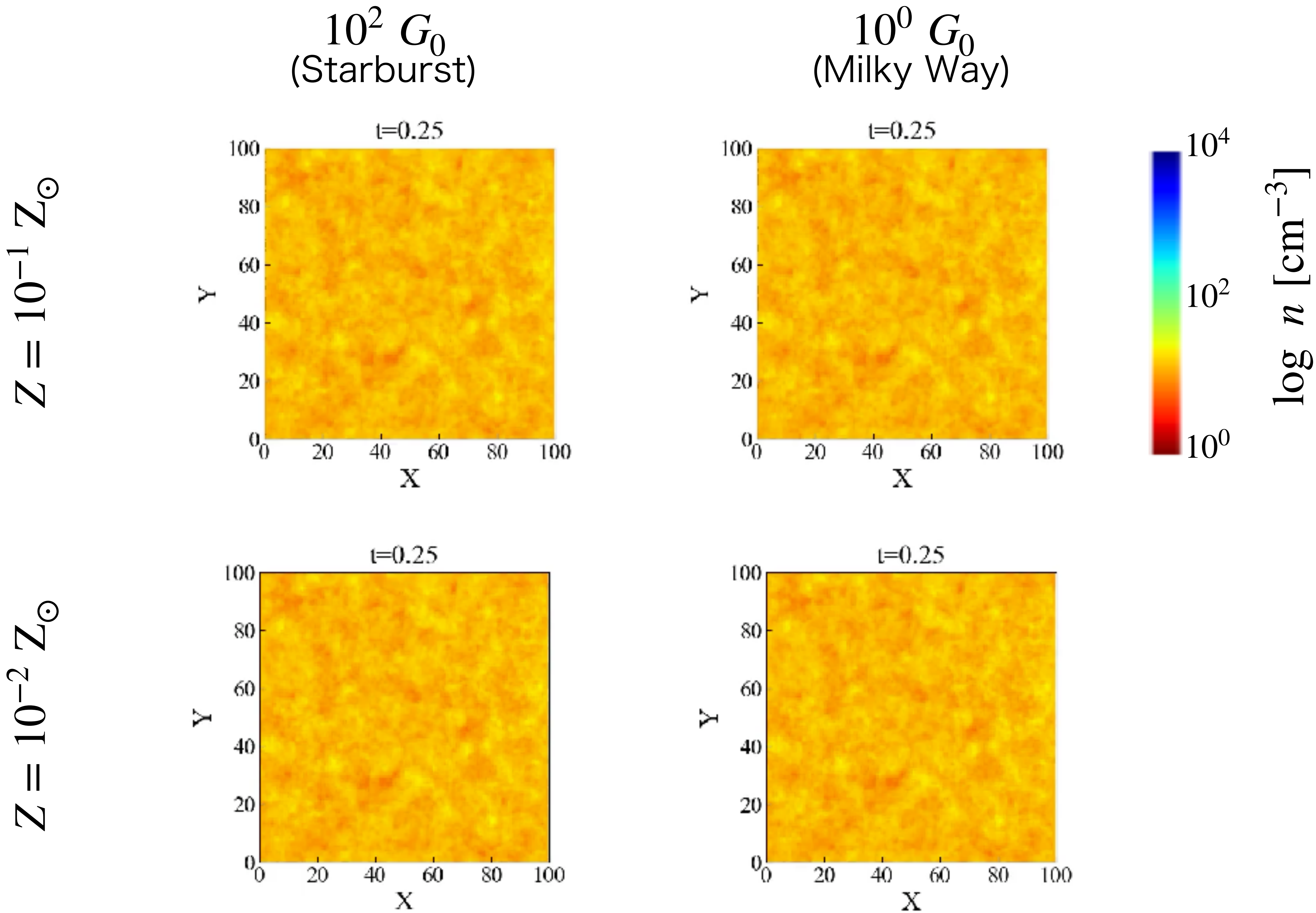
✓ Boundary condition

yz 面	Gas inflow
xy, zx 面	Periodic

✓ Initial condition

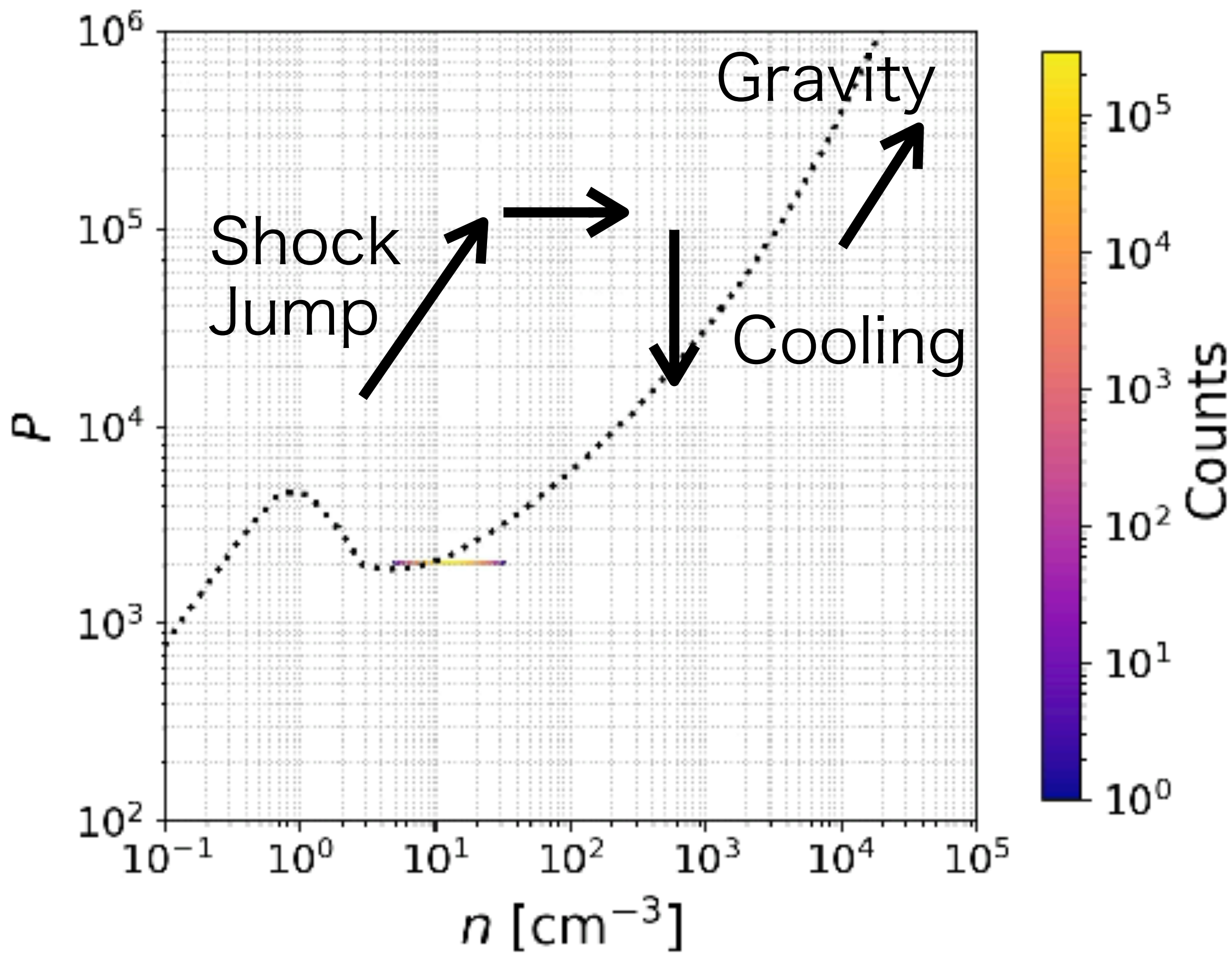
$v_{\rm rel} = 20$ km/s	: Velocity
$n_0 \sim 10$ cm^{-3}	: Density
$B_0 = 3\ \mu$G (45°)	: B-field
$Z = 10^{-1,-2,-3}\ Z_\odot$	: Metallicity
$F_{\rm UV} = G_0,\ 10^2 G_0$	: UV

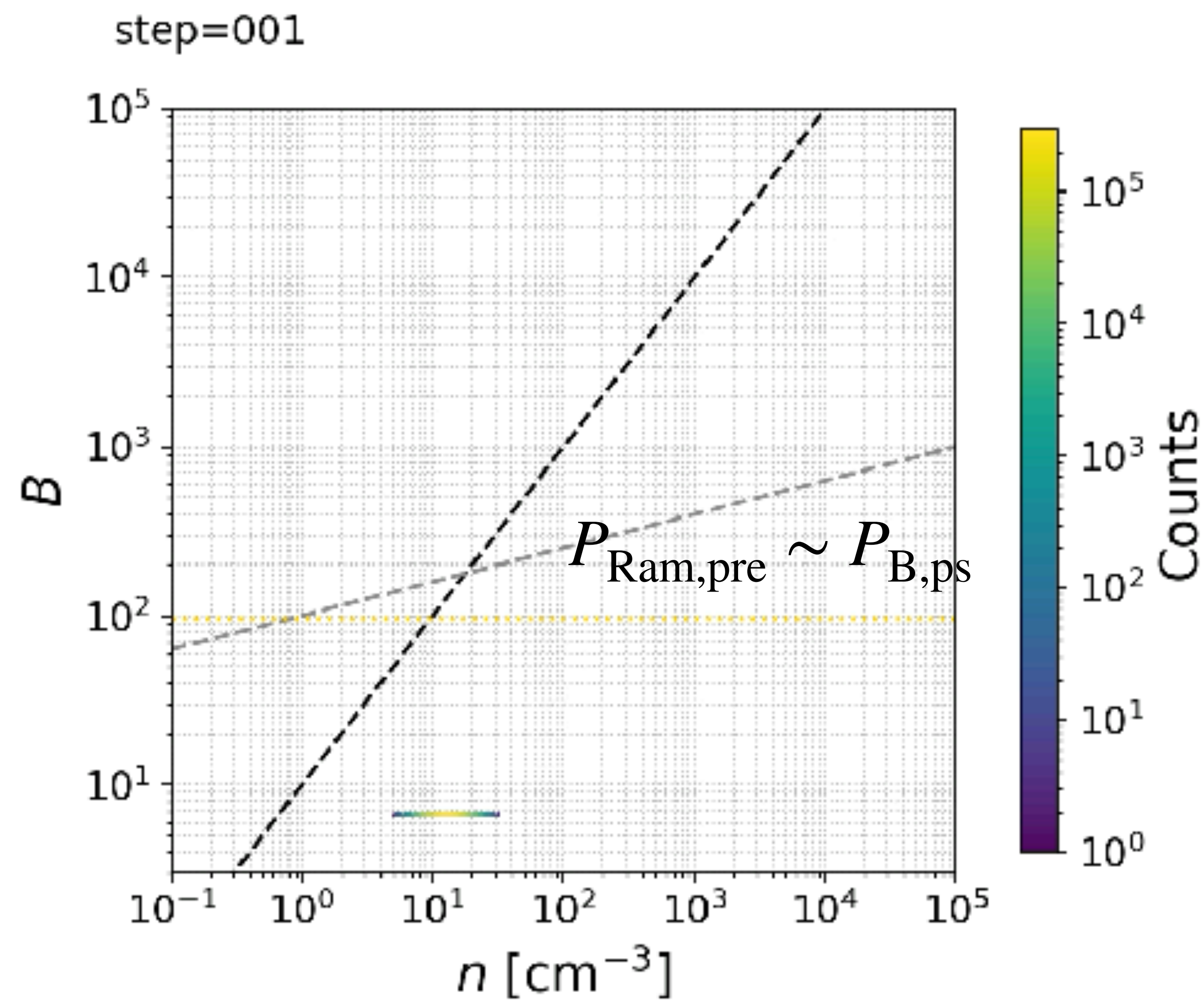
Gas Evolution under Different Metallicities and UV



Typical Post-shock Gas Evolution in Phase Diagram

➤ $10^{-2}\ Z_\odot$, $10^0\ G_0$ case





✓ Shock-compressed gas cools quickly and becomes dense

$$t_{\rm cool} \sim 0.24\ {\rm Myr} \left(\frac{Z}{10^{-2}\ Z_\odot}\right)^{-1} \left(\frac{n_{\rm ps}}{40\ {\rm cm^{-3}}}\right)^{-3/2} \left(\frac{p_{\rm ps}}{p_{\rm rm} = 10\ [/{\rm cc}] \times (10\ [{\rm km/s}])^2}\right)^{1/2}$$ Inoue+15

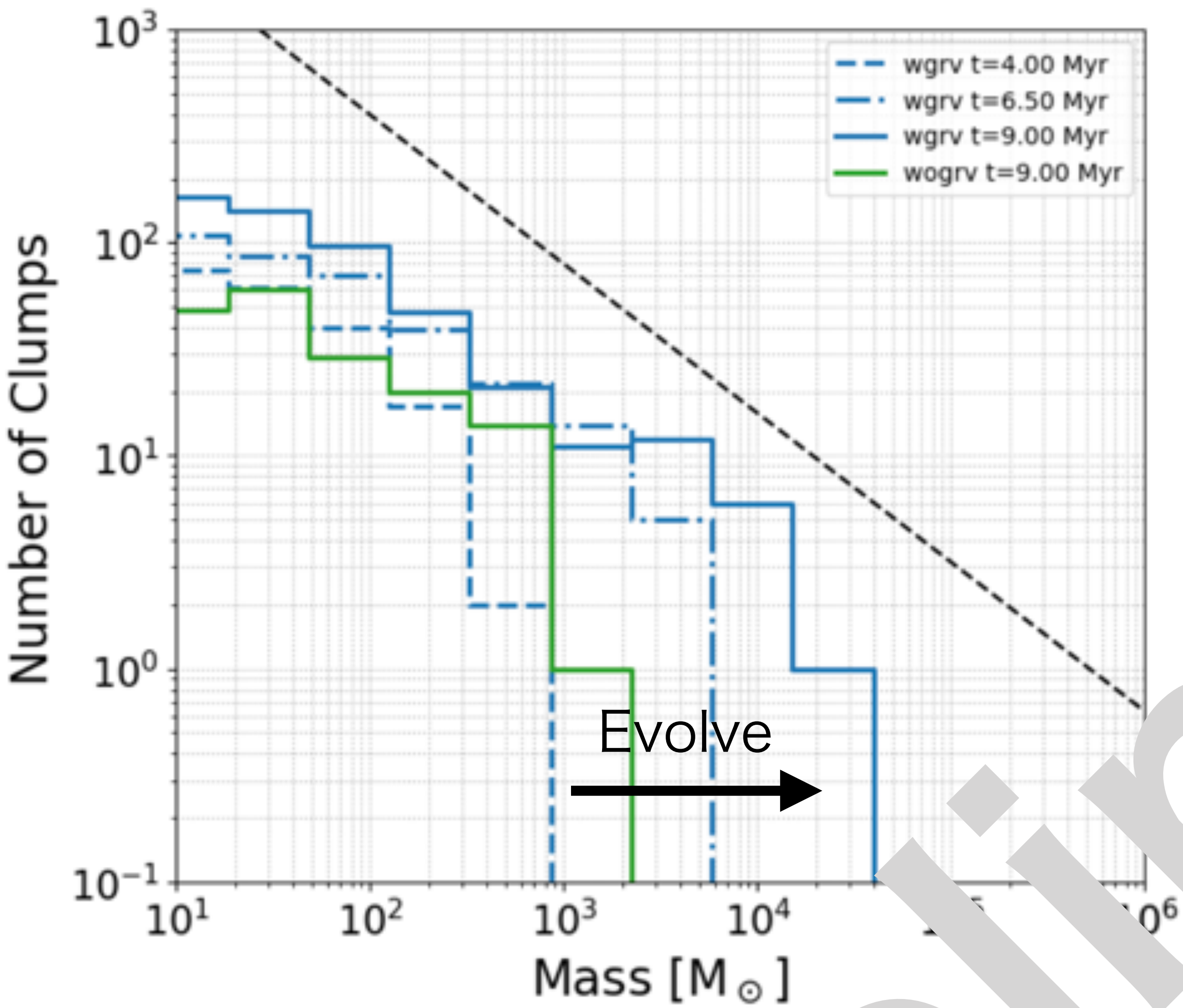
✓ Gas evolves nearly isochorically at $\rho_0 v_0^2 \sim B_{\rm ps}^2/8\pi$

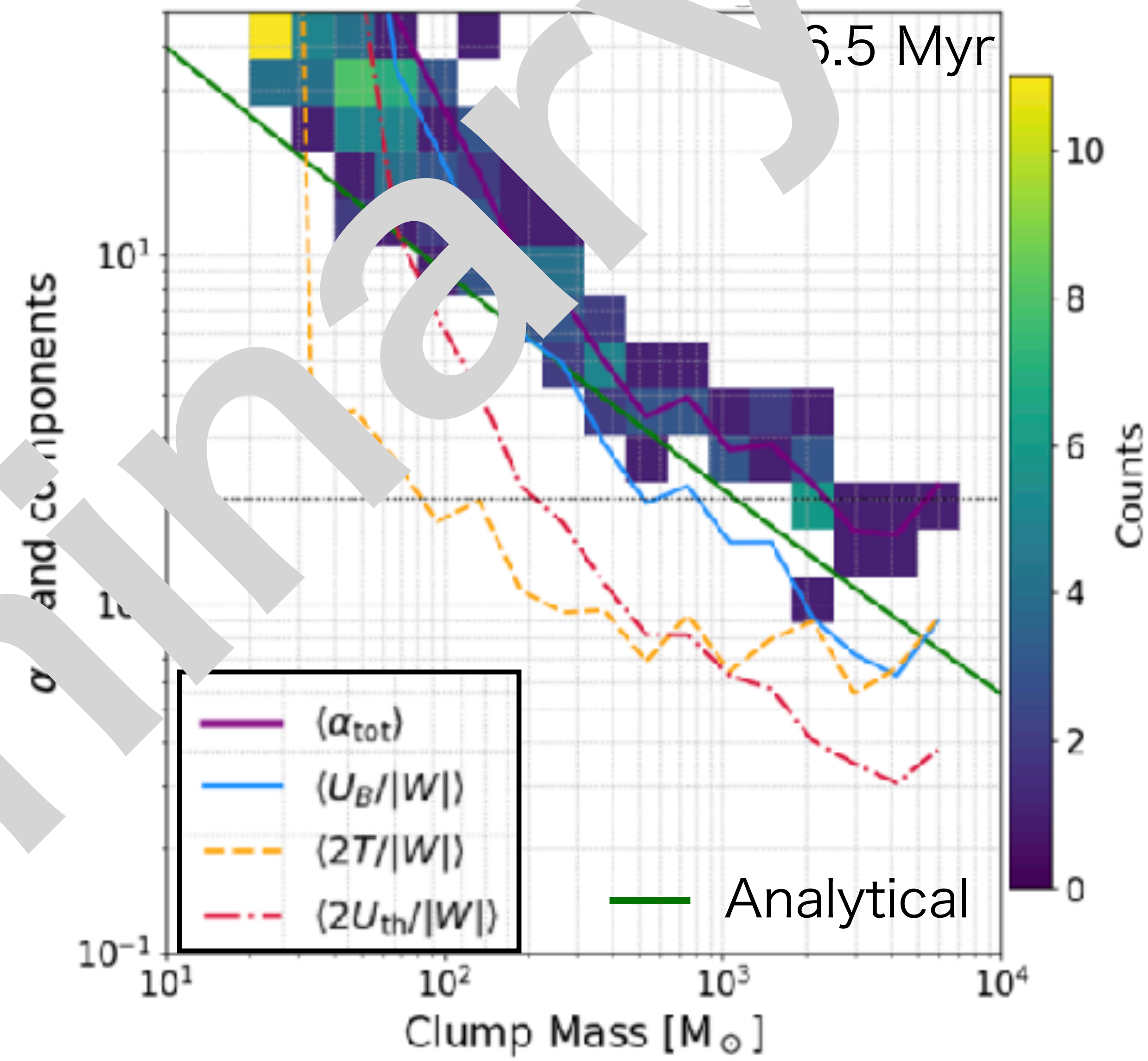
✓ The post-shock temperature settles onto the thermal equilibrium curve

Post-shock gas have strong B-field

Mass and Virial Parameter of Formed Cloud

➤ $10^{-2}\,Z_\odot$, $10^{0}\,G_0$ case





✓ The clump mass function evolves over time

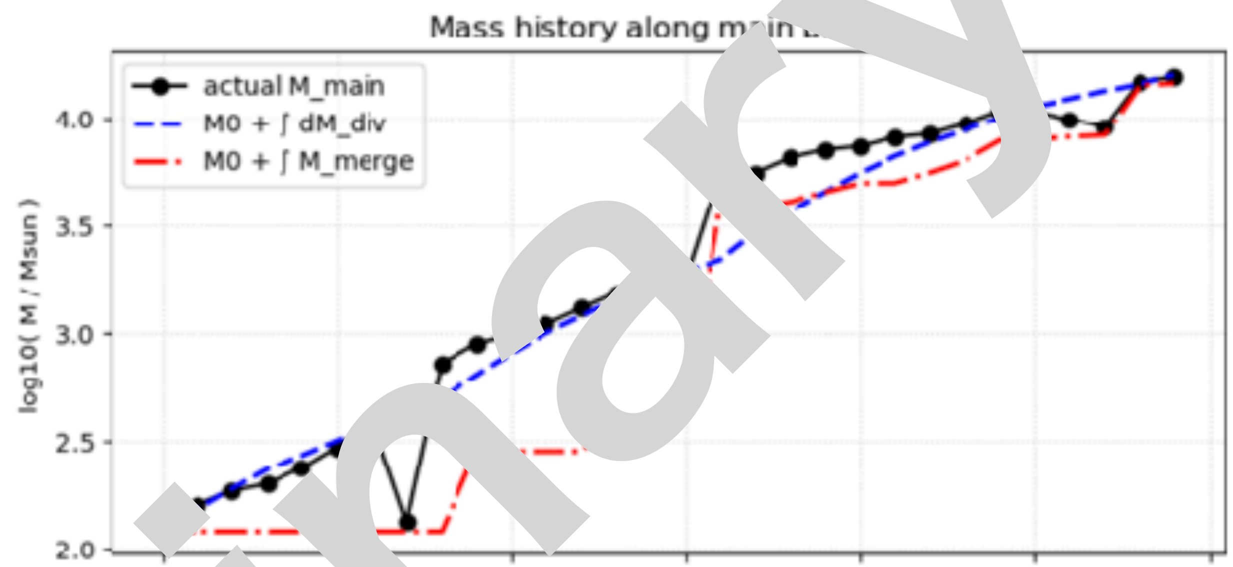
✓ The virial parameter of the formed clouds agrees well with the following (cf. Iwasaki+22)

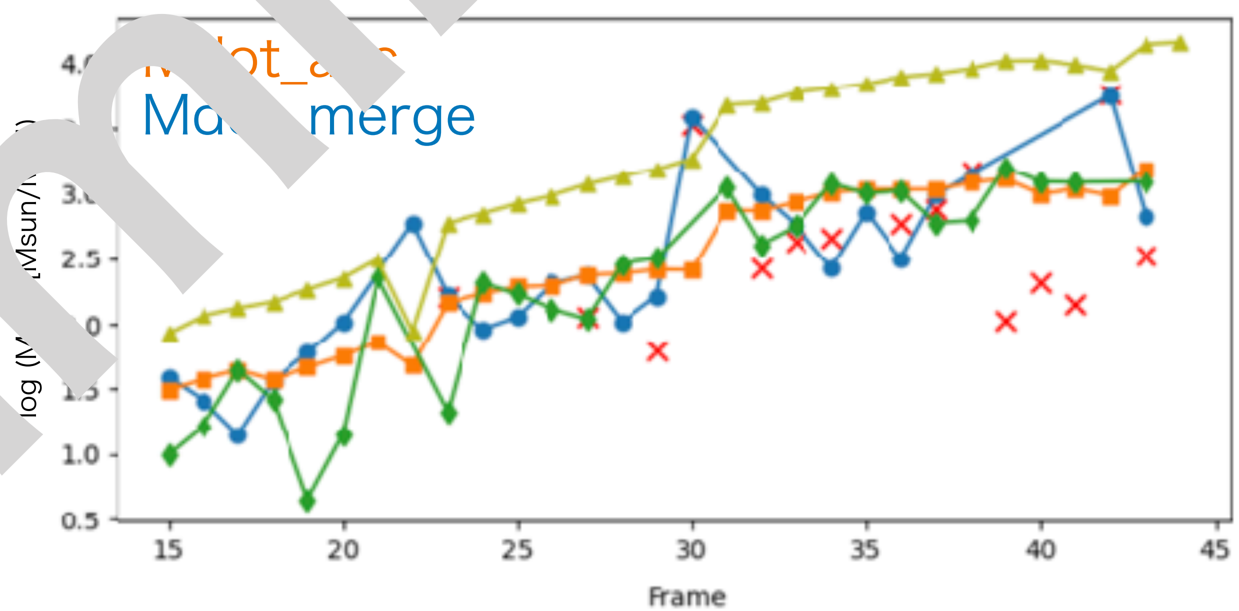
$$\alpha_{tot} = \frac{15M^{-2/3}\rho_{cl}^{-1/3}}{4\pi G}\left(\frac{1}{3}\rho_0 v_0^2 + \rho_{cl}\delta v^2 + \rho_{cl}c_s^2\right)$$

✓ massive clumps mainly supported by B-field

Gravitational collapse occurs when the Virial parameter ~ 1

Merger History of Most Massive Cloud



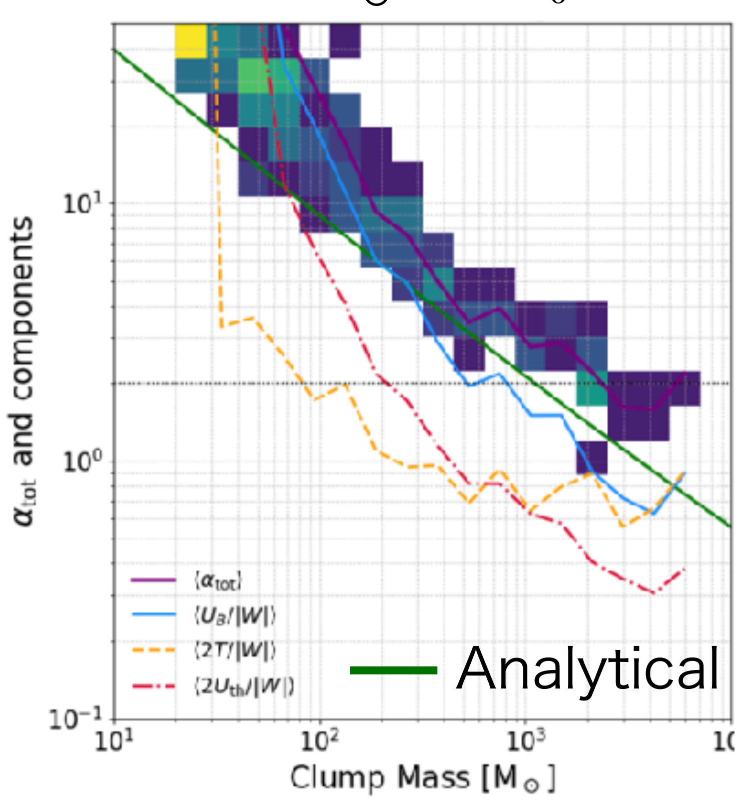


✓ The most massive gas clump forms through clump mergers and gas accretion

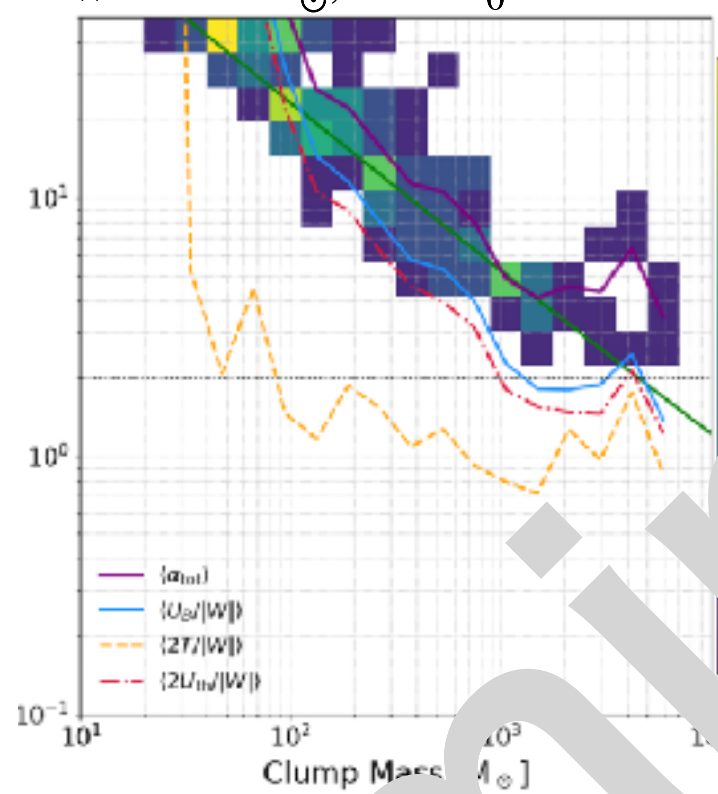
✓ A clump can undergo gravitational collapse once it reaches state $\alpha_{\rm tot} \sim 1$

UV and Metallicity Dependence of Formed Cloud

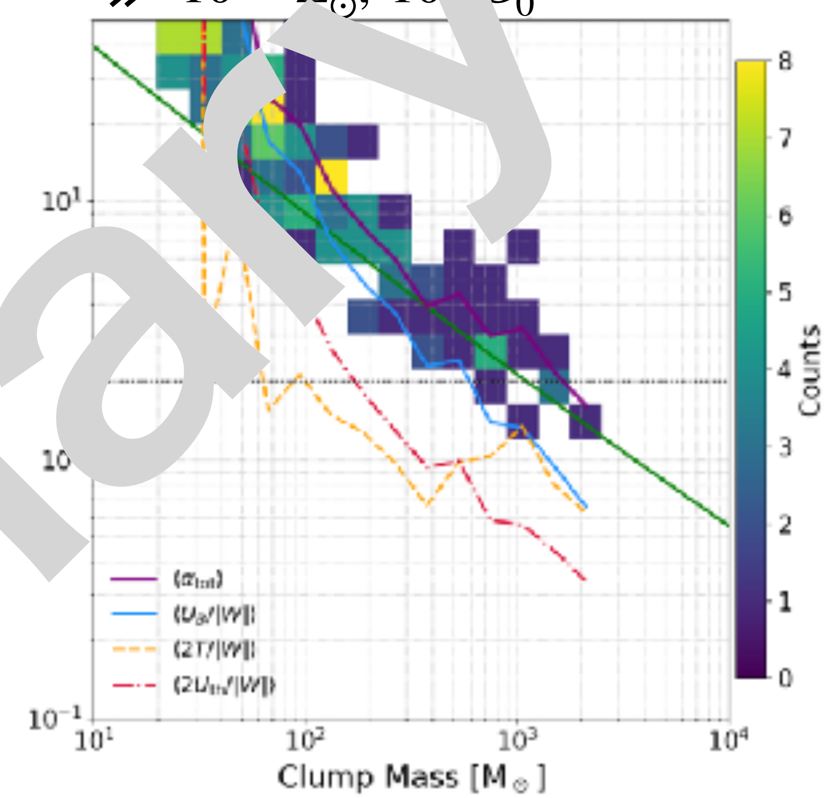
≫ $10^{-2}\ Z_\odot,\ 10^{0}\ G_0$



≫ $10^{-2}\ Z_\odot,\ 10^{2}\ G_0$

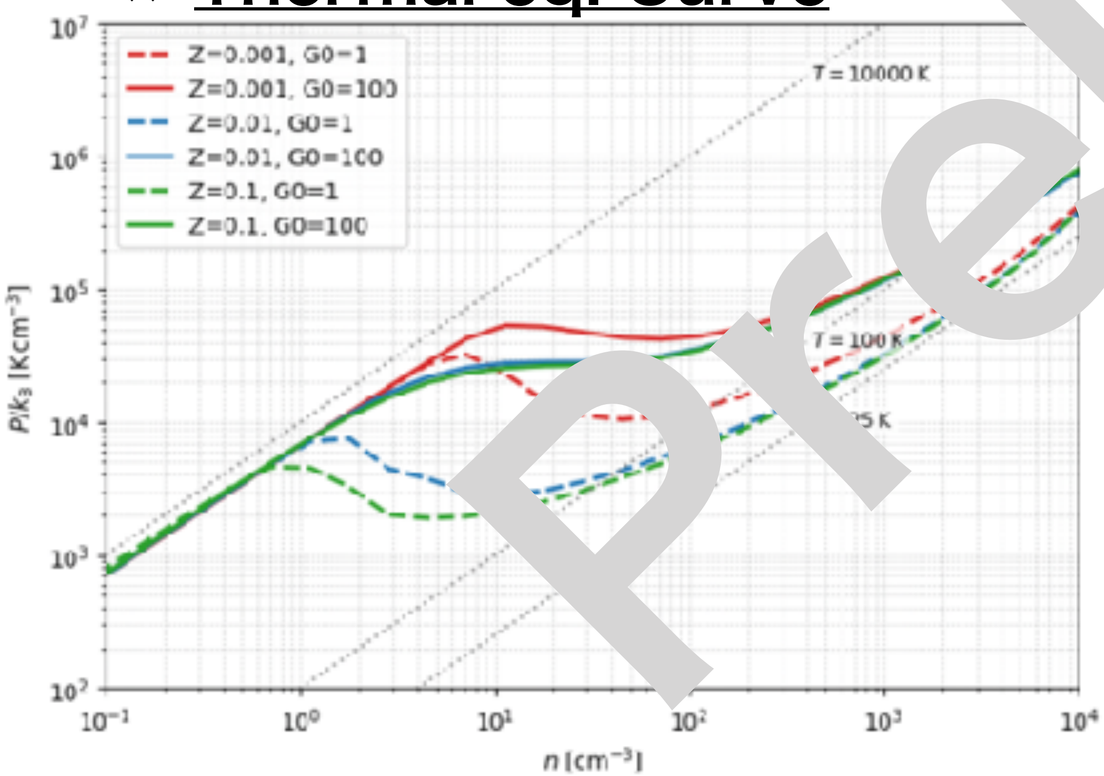


≫ $10^{-1}\ Z_\odot$, 10 G_0



The fraction of thermal support differs

≫ Thermal eq. Curve

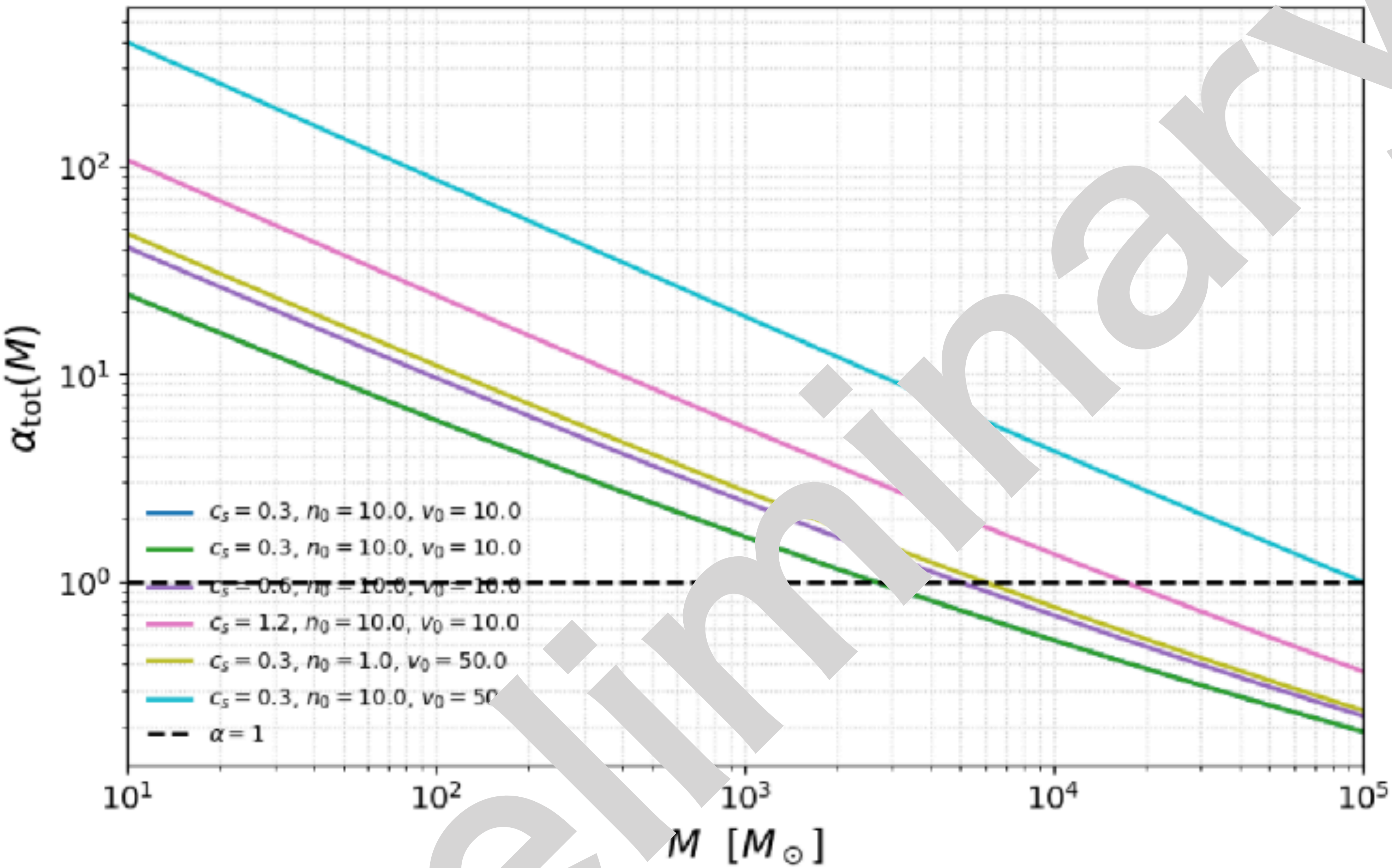


✓ Clump temperature? @ $n = 10^3$ /cc

More strongly depend on G0 due to
Metal cooling ~ Photo electric heating

✓ However, thermal support remains sub-dominant

Parameter Dependence of the Virial Parameter of Clumps



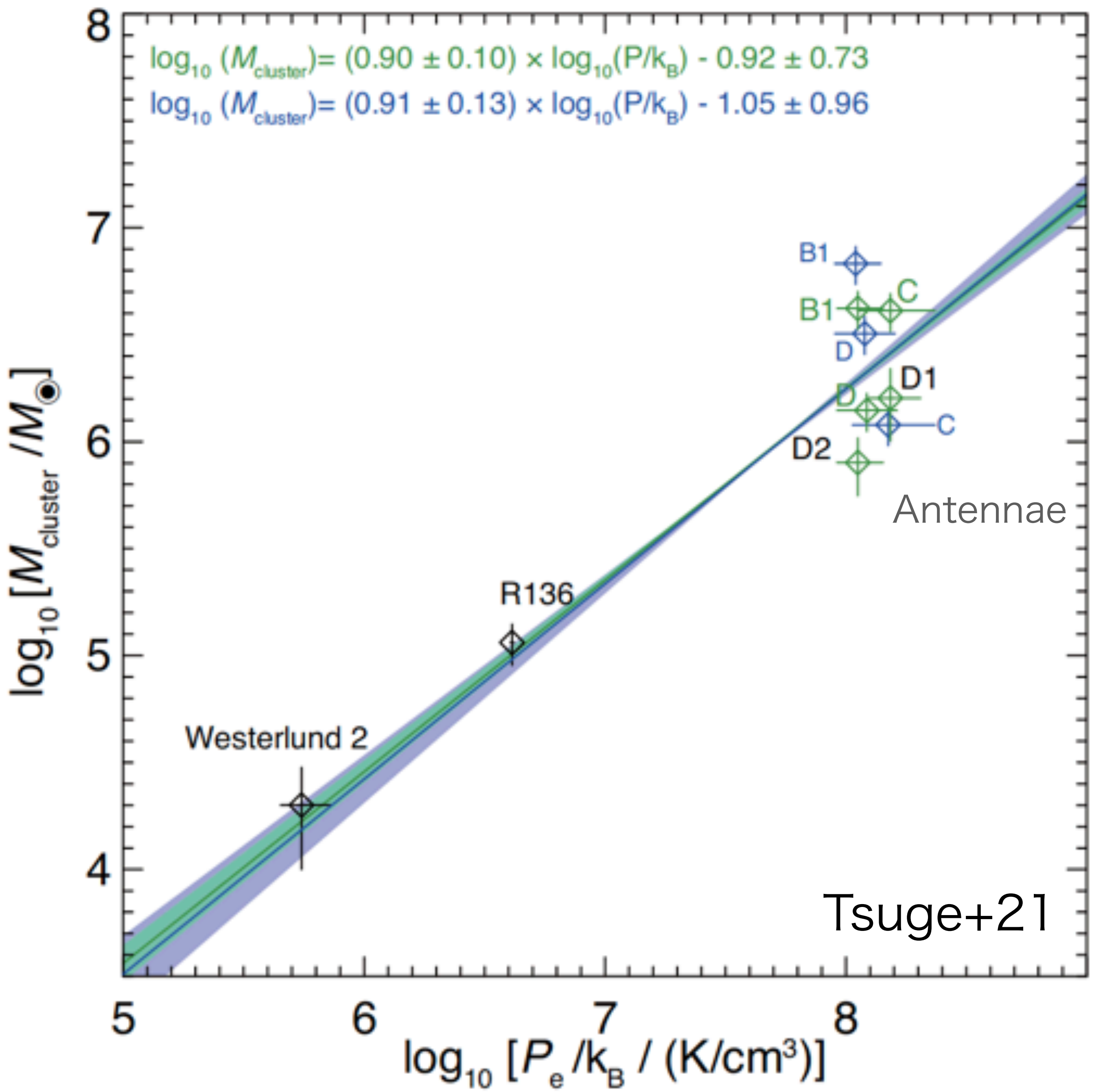
✓ A stronger ram pressure (fast collision) results in a larger Virial parameter

✓ The sound speed is determined by the metallicity and the UV field.

To estimate the clump mass that forms under given physical conditions.

Discussion: Cluster Mass in the Post-Shock Layer

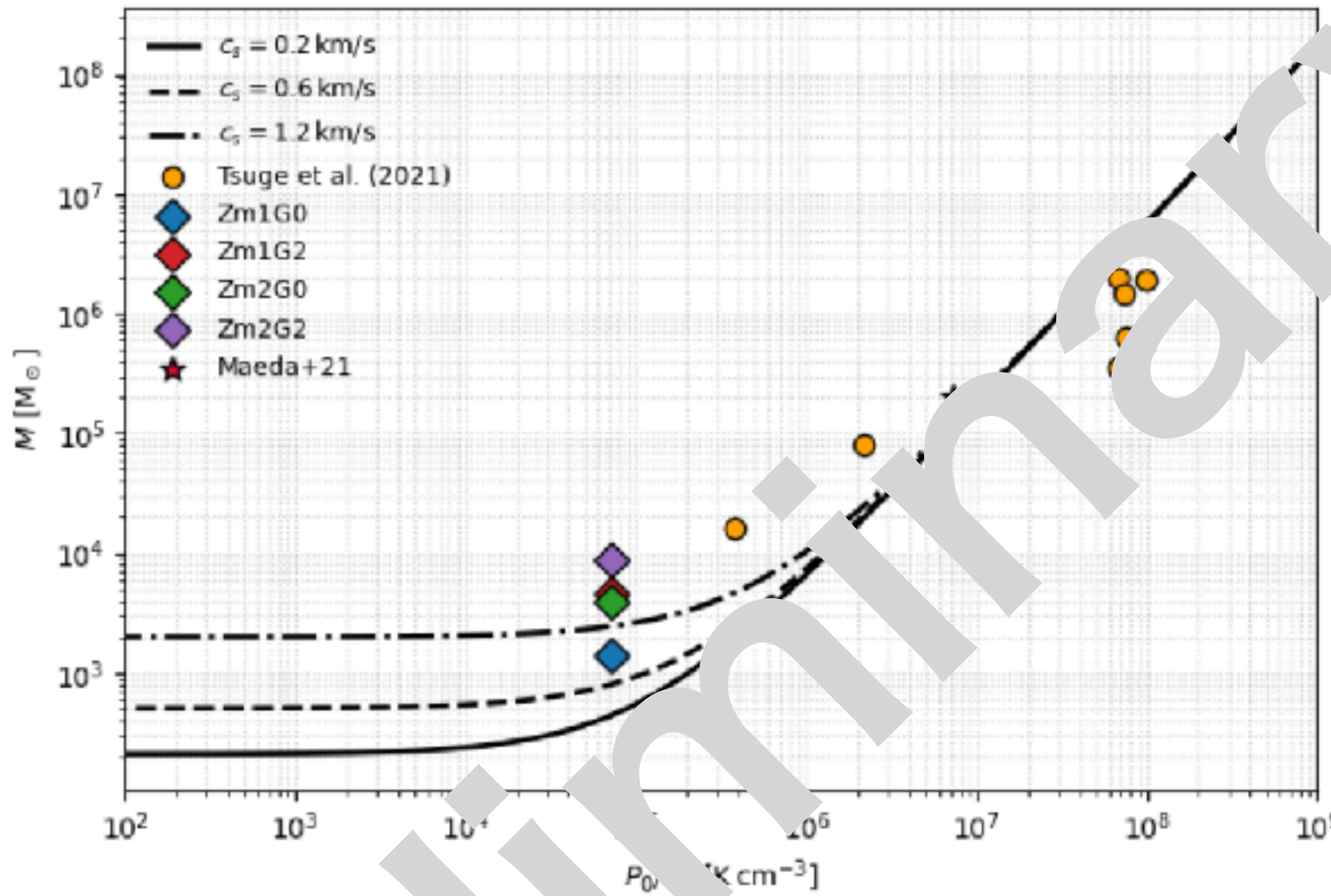
➤ **Observational trends in Young Massive Clusters (YMC)**



✓ YMCs that form in gas-collision regions

✓ A higher ram pressure by the collision tends to lead to the formation of more massive clusters

Discussion: Cluster Mass in the Post-Shock Layer



✓ Mass corresponding to a virial parameter of 1

✓ Trend of Tsuge+21 is explained by post-shock magnetic amplification

✓ Metallicity and UV dependences appear when the ram pressure is weak

Summary & Future Work

✓ Summary

- We investigated the formation of massive star clusters in environments with varying metallicity and UV radiation field strength.

- In $t_{\rm cool} < t_{\rm GI}$, massive gas clumps form through gravitational contraction of a sufficiently cooled sheet in all cases, resulting in only minor differences between metallicities.

- In environments with strong UV radiation, the CNM temperature is higher, leading to the formation of more massive star clusters.

✓ Future Work

- We investigate the dependence on magnetic field strength, magnetic-field orientation, and collision velocity.