ダークマター欠乏銀河の形成シミュレーション

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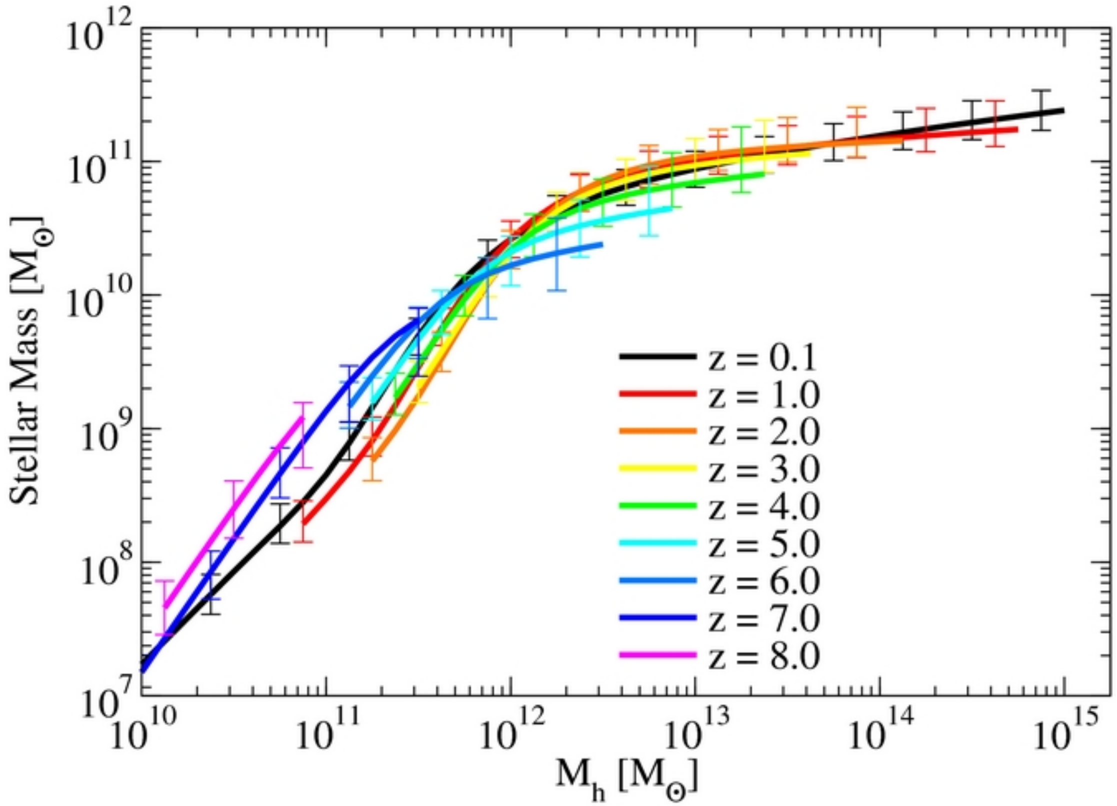
Stellar Mass – Halo Mass relation



(Behroozi et al. 2013)

Massive galaxy:

$$M_\star \sim 10^{10}\,\mathrm{M}_\odot$$
$$M_{\mathrm{DM}} \sim 10^{12}\,\mathrm{M}_\odot$$

Dwarf galaxy:

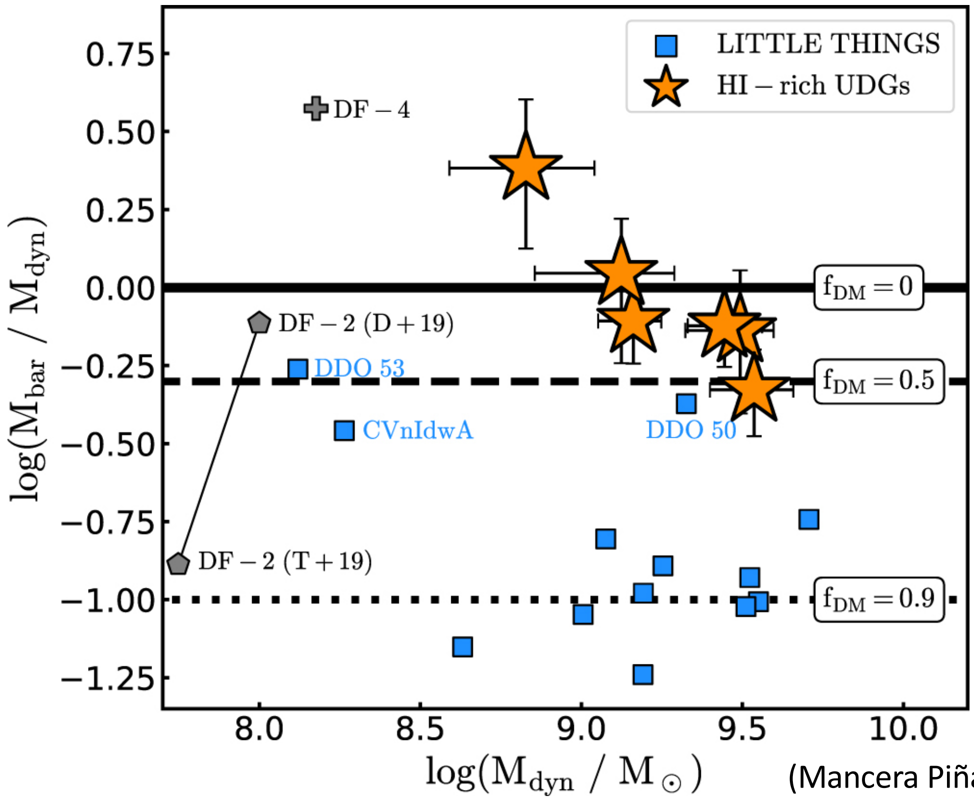
$$M_\star \sim 10^{8}\,\mathrm{M}_\odot$$
$$M_{\mathrm{DM}} \sim 5 \times 10^{10}\,\mathrm{M}_\odot$$

Recently, some galaxies were found to have $M_{\mathrm{baryon}} \sim M_{\mathrm{DM}}$.

= Dark Matter Deficient Galaxies (DMDGs)

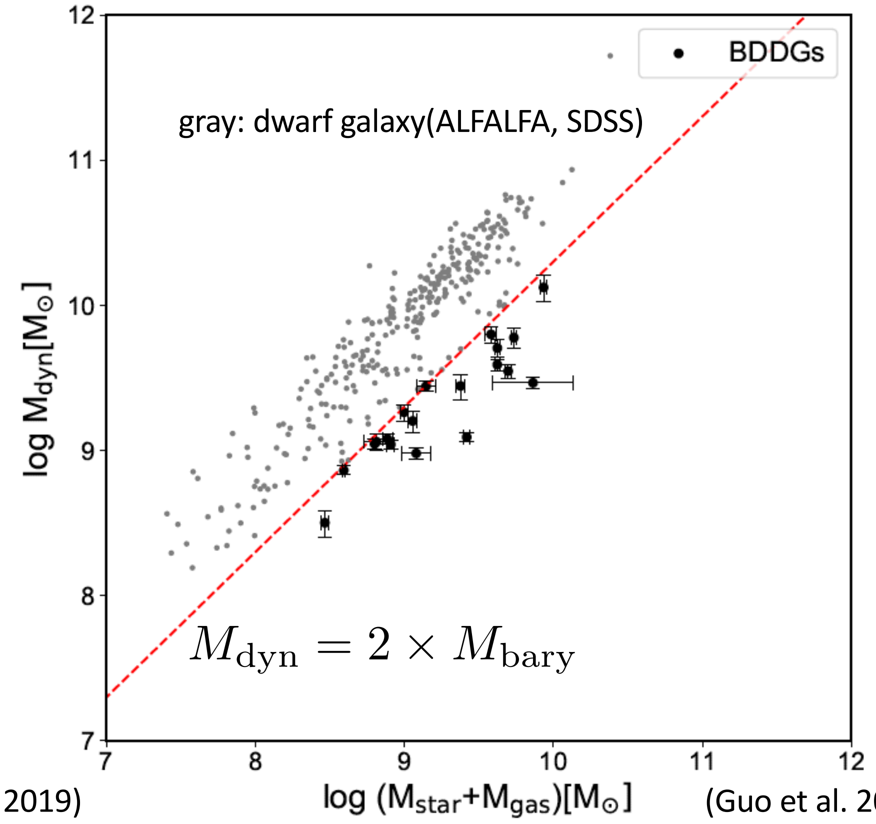
Observed DMDGs

NGC1052-DF2, NGC1052-DF4,
6 Baryon-dominated UDGs



(Mancera Piña et al. 2019)

19 Baryonic Dominated Dwarf Galaxies



(Guo et al. 2019)

Ultra Diffuse Galaxy (UDG): Low surface brightness ≈ Dwarf galaxy, Size ≈ the Milky Way

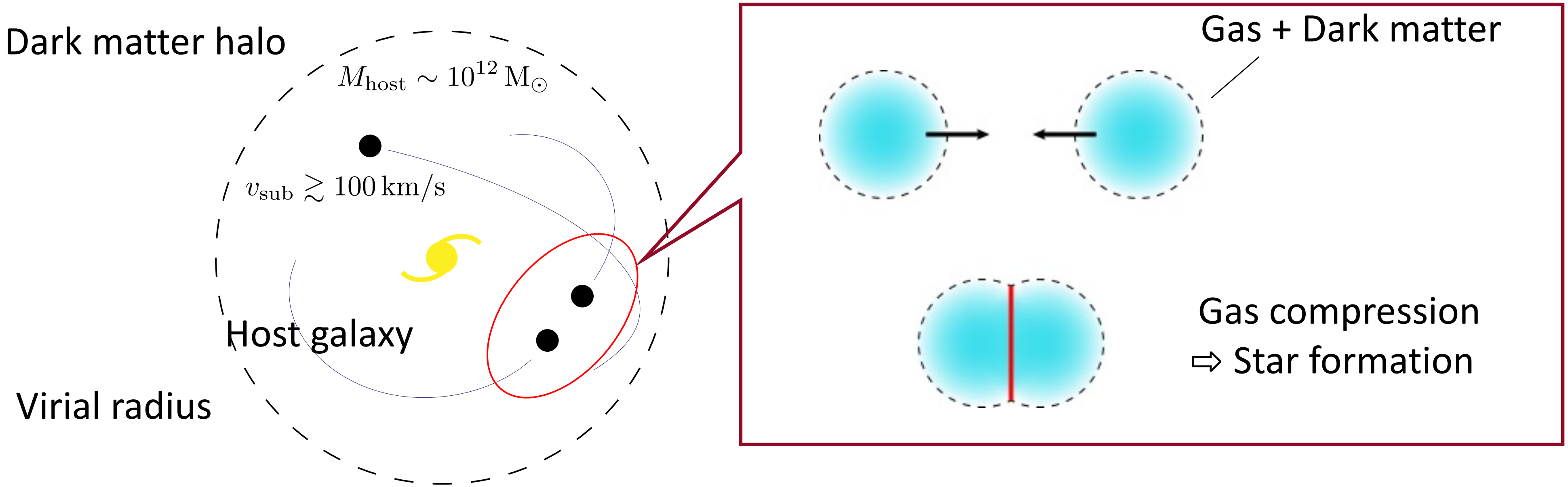
NGC1052-DF2: $r_{\rm eff} = 2.7\,{\rm kpc},\ M_\star = 1.0 \times 10^8\,{\rm M}_\odot,\ M_{\rm dyn} = 1.3 \times 10^8\,{\rm M}_\odot$

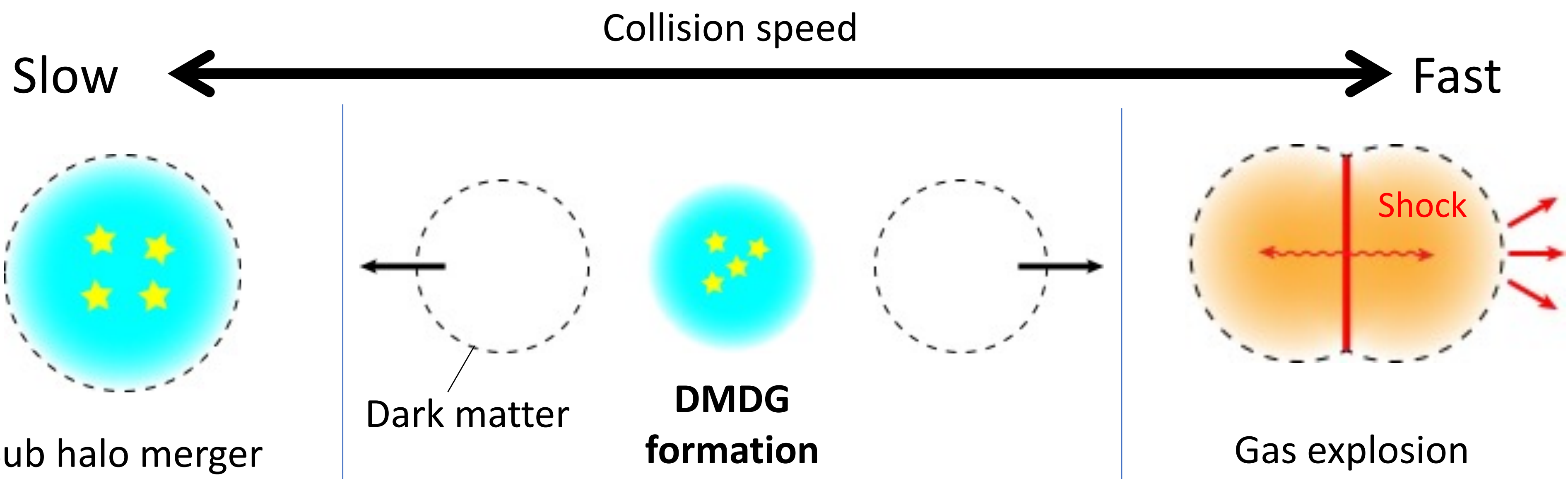
(Daniel et al. 2019)

In total, 27 DMDGs were discovered.

Formation scenario

DMDG could be formed in dark matter sub halo collision





Condition for dark matter to merge

Kinetic energy vs. Potential energy

$$\boxed{\frac{1}{2}mv^2 + m\Phi = 0}$$

m : Mass of a test particle
v : Velocity
Φ : Dark matter potential

Dark matter sub halo (DM + gas): $M_{\rm tot} = 10^{10}\,{\rm M}_\odot$ $\quad M_{\rm DM} : M_{\rm gas} \simeq 5.4 : 1$

Spherical NFW potential: $\Phi_{\rm NFW}(r) = -4\pi G\rho_0 r_{\rm s}^2 \frac{\ln(1 + r/r_{\rm s})}{r/r_{\rm s}}$

Virial radius: $R_{200} = \left(\frac{M_{\rm DM}}{4\pi\rho_{200}/3}\right)^{1/3}, \quad \rho_{200} = 200\rho_{\rm crit} = 200\frac{3H_0^2}{8\pi G}$

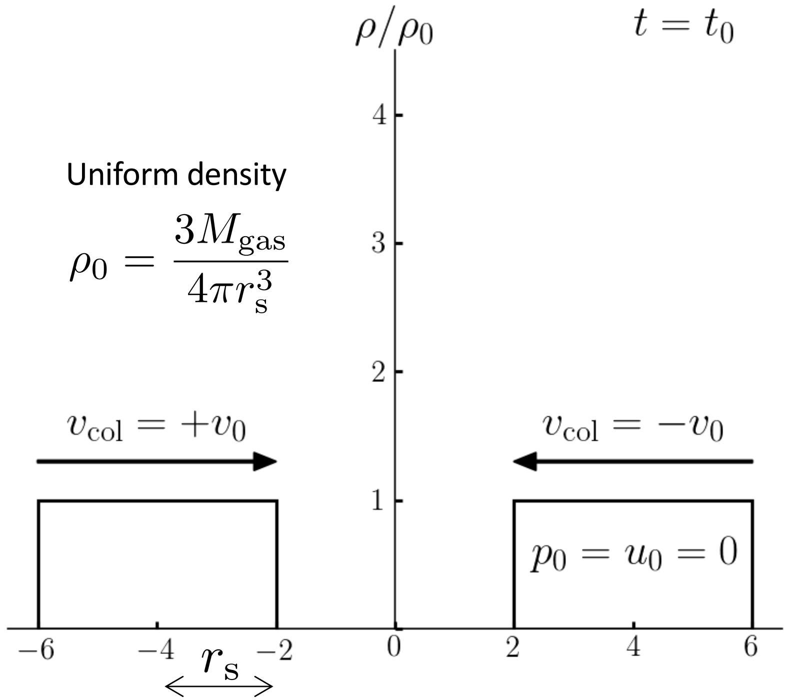
Scale radius: c-M relation (Prada et al. 2012)

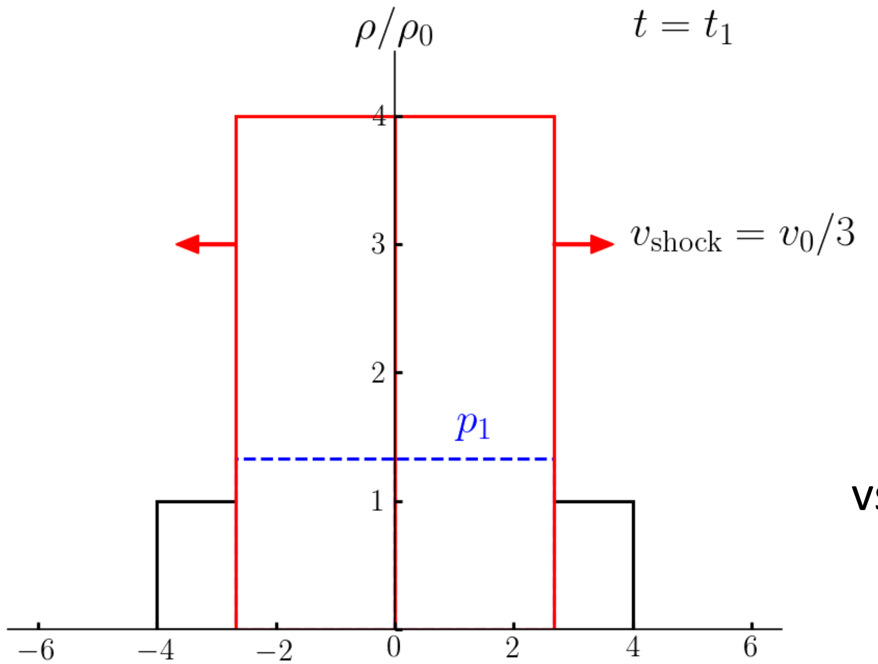
G : Gravitational constant
$r_{\rm s}$: Scale radius
$H_0 = 67.4\,{\rm km\,s^{-1}\,Mpc^{-1}}$

Result: $\boxed{v = 72\,{\rm km/s}}$

When $v_{\rm col} < 72\,{\rm km/s}$, dark matter sub halos merge.

Condition of gas explosion





Index 0: Initial Condition ($t = t_0$)

Index 1: Post Shock ($t = t_1$)

- ρ : Mass density
- p : Pressure
- u : Specific internal energy
- $v_{\rm col}$: Collision velocity
- $v_{\rm shock}$: Shock velocity
- γ : Specific heat ratio $= 5/3$

- **Strong shock**

$$\rho_1 = \frac{\gamma+1}{\gamma-1}\rho_0 = 4\rho_0$$

- Conversion of Kinetic Energy to Internal Energy

$$u_1 = \frac{1}{2}v_0^2, \quad v_1 = 0, \quad p_1 = \frac{4}{3}\rho_0 v_0^2$$

- Rankine-Hugoniot condition

$$\rho_0(-v_0 - v_{\rm shock}) = \rho_1(0 - v_{\rm shock})$$

$$v_{\rm shock} = \frac{1}{3}v_0$$

- Shock wave arrival time

$$v_{\rm shock}t_{\rm crit} = 2r_{\rm s} - v_0 t_{\rm crit}$$

$$\boxed{t_{\rm crit} = \frac{2r_{\rm s}}{v_0 + v_{\rm shock}}}$$

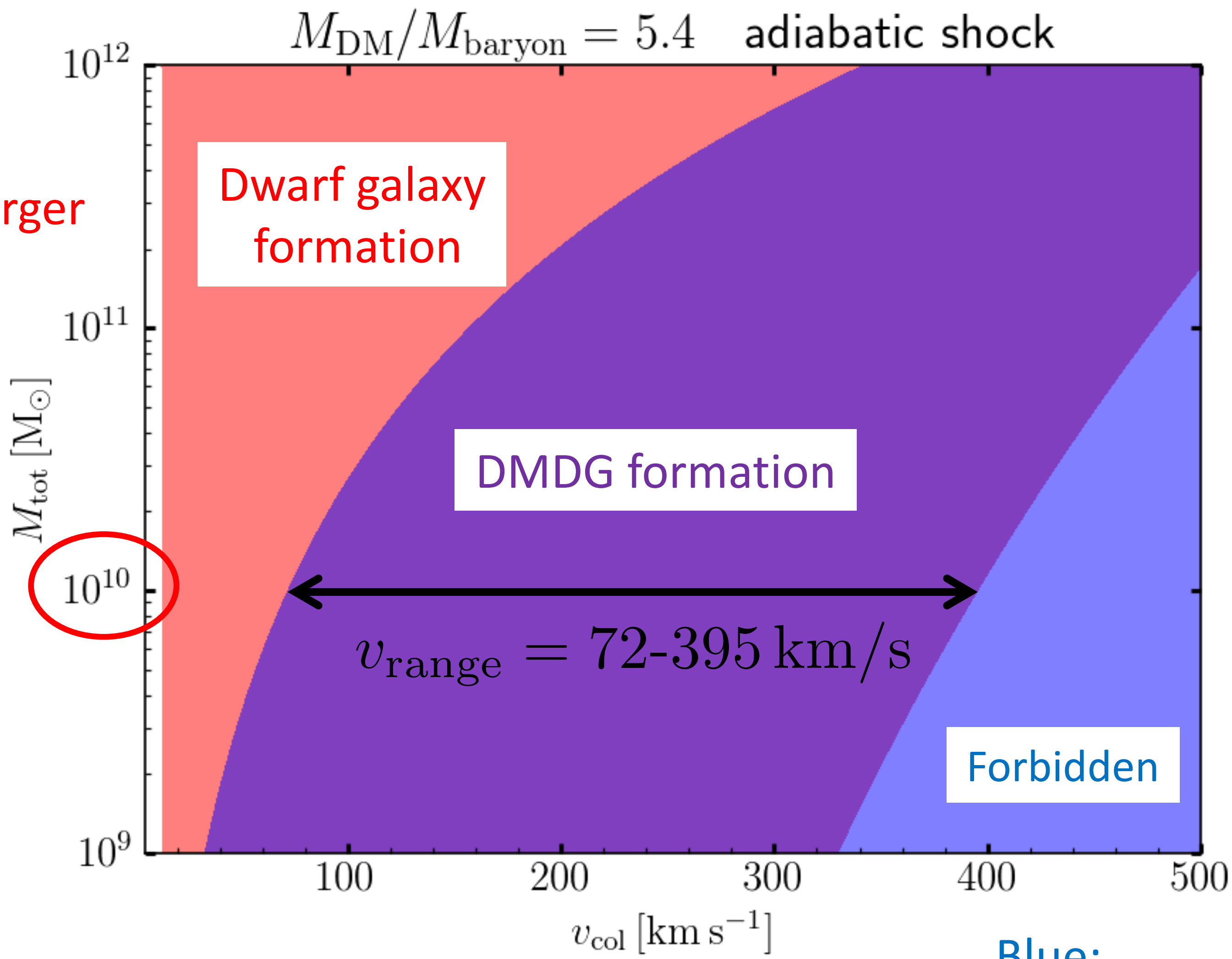
vs. Cooling time

$$t_{\rm cool} = \frac{k_{\rm B}T_1}{(\gamma-1)n_1\Lambda(T_1)}$$

- $k_{\rm B}$: Boltzmann constant
- T : Temperature
- n : Number density
- Λ : Cooling rate

Result: 1D physical model

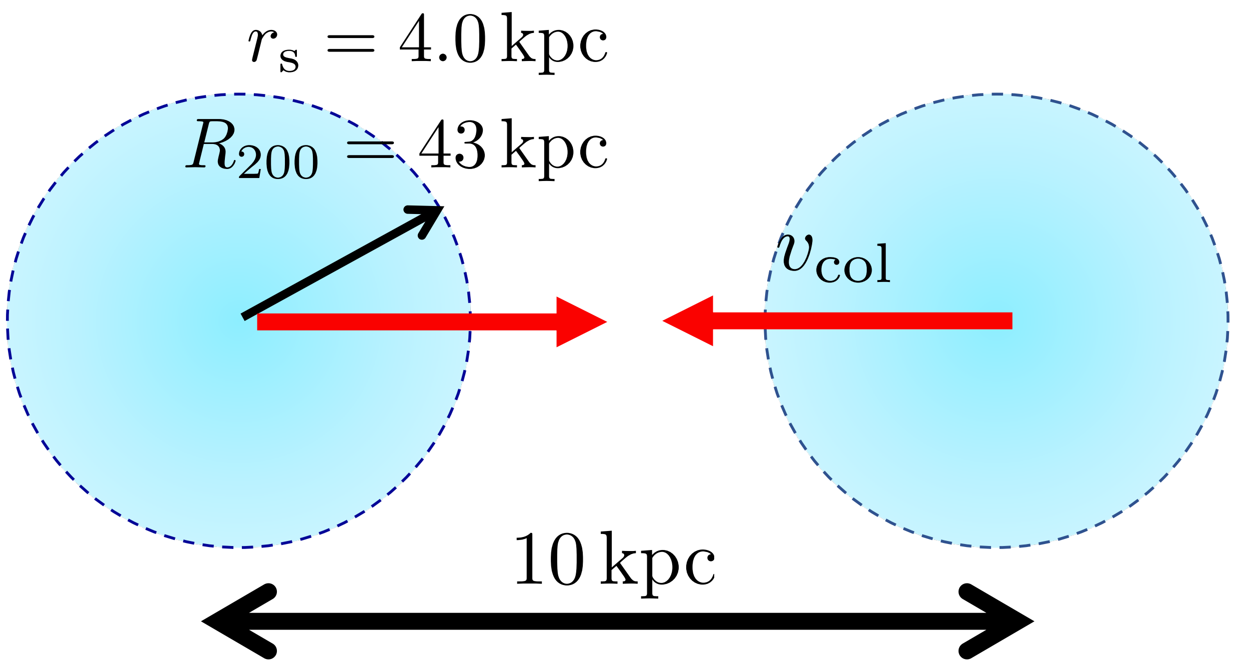
Red:
sub halo merger



Blue:
gas explosion by shock

Simulation set-up (N-body + SPH)

NFW dark matter and hydrostatic equilibrium gas



A dark matter sub halo

$$M_{\mathrm{tot}} = 10^{10}\,\mathrm{M}_\odot$$

$$M_{\mathrm{DM}} = 8.43 \times 10^{9}\,\mathrm{M}_\odot$$

$$M_{\mathrm{gas}} = 1.57 \times 10^{9}\,\mathrm{M}_\odot$$

$$M_{\mathrm{DM}} : M_{\mathrm{gas}} \simeq 5.4 : 1$$

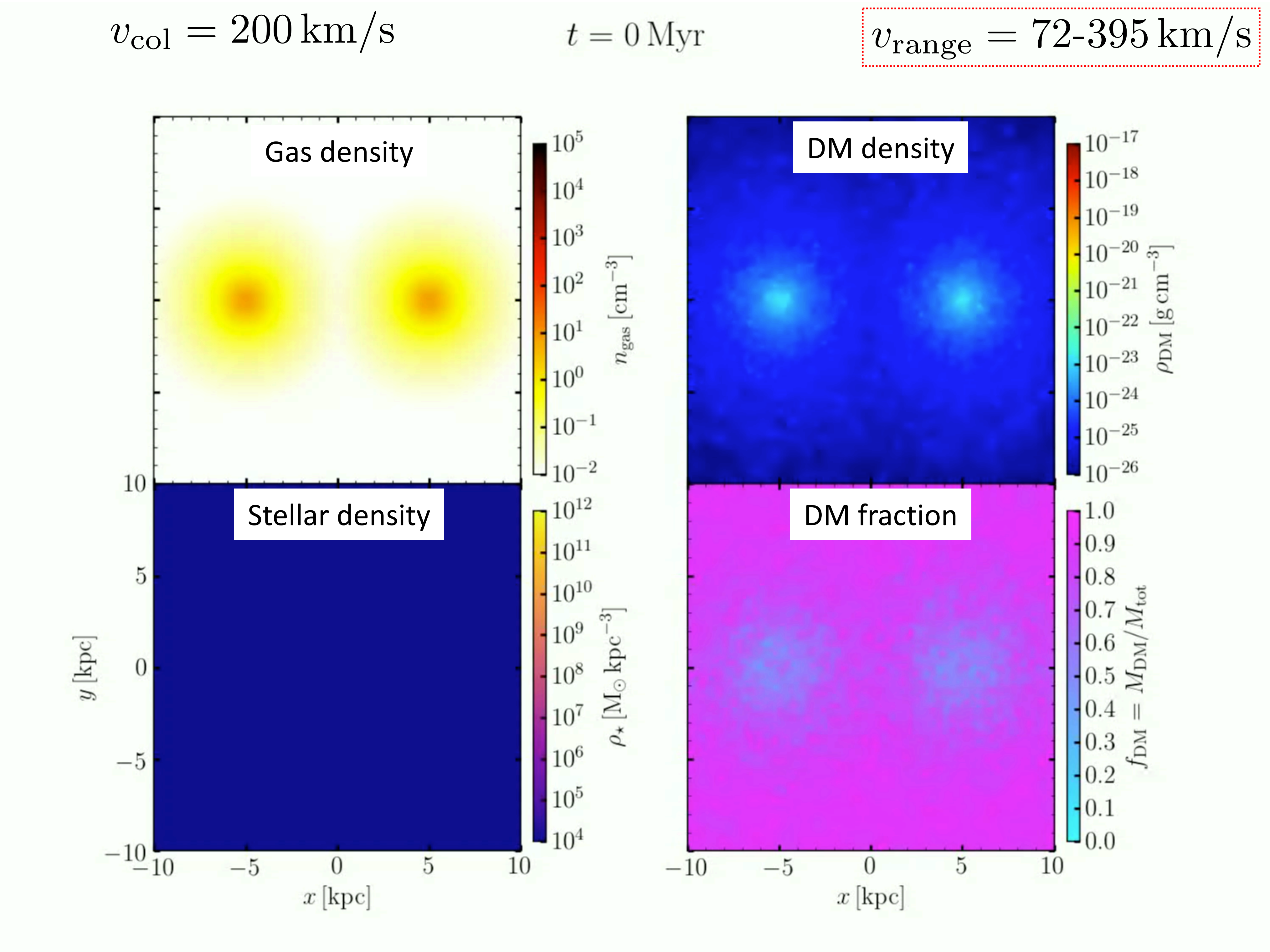
Primordial abundance gas

$$m_{\mathrm{SPH}} = m_{N\mathrm{body}} = 1.47 \times 10^{4}\,\mathrm{M}_\odot$$

- Numerical code: FDPS (Iwasawa et al. 2016, Namekata et al. 2018)
- **Cooling**: Exact Integration scheme (Townsend 2009)
- **Star formation** model (Katz 1996)
- **Supernova feedback** model (Mori et al. 1997)

$$v_{\mathrm{range}} = 72\text{-}395\,\mathrm{km/s}$$

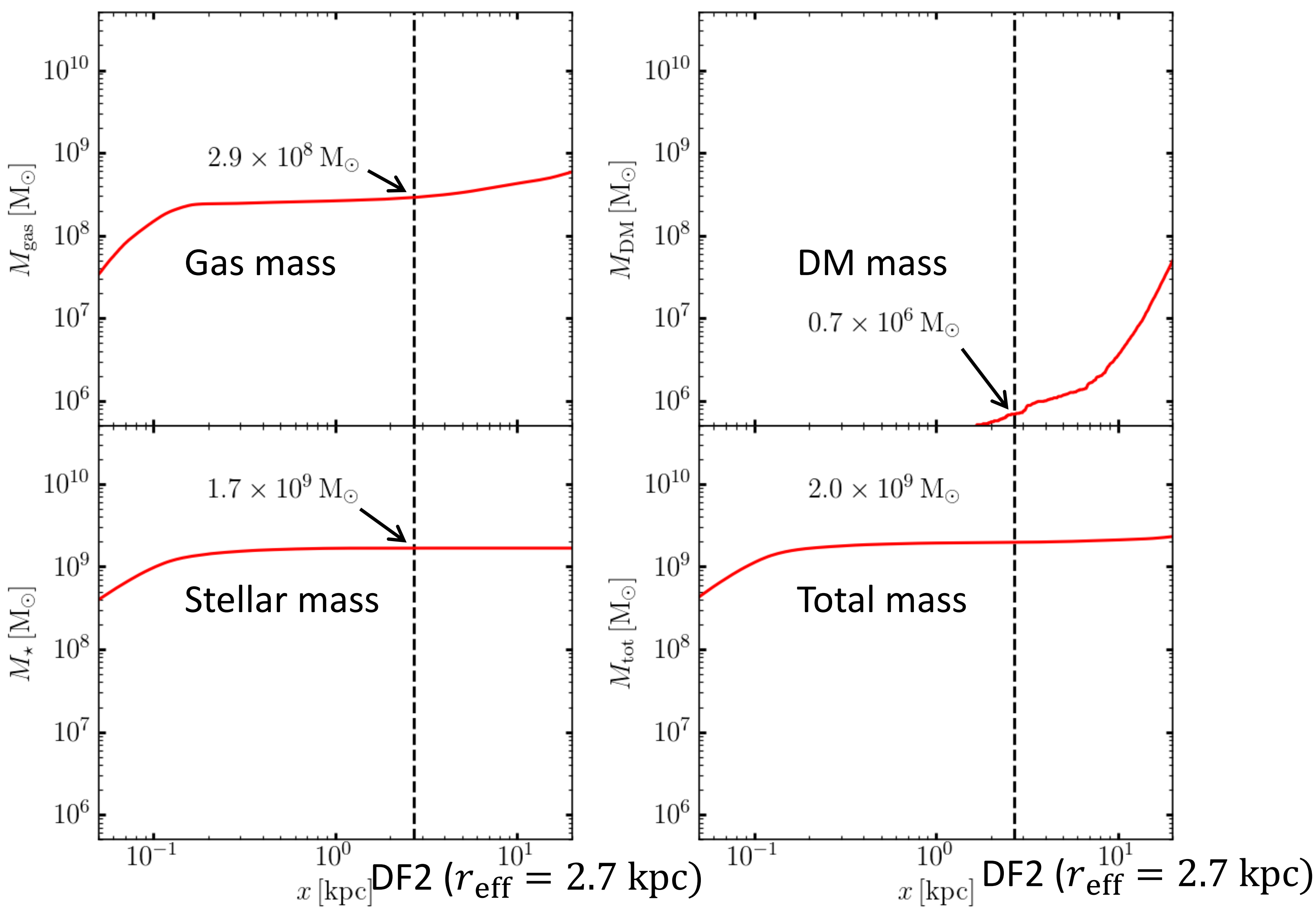
Collision velocity = $50, 200, 500, 700\,\mathrm{km/s}$

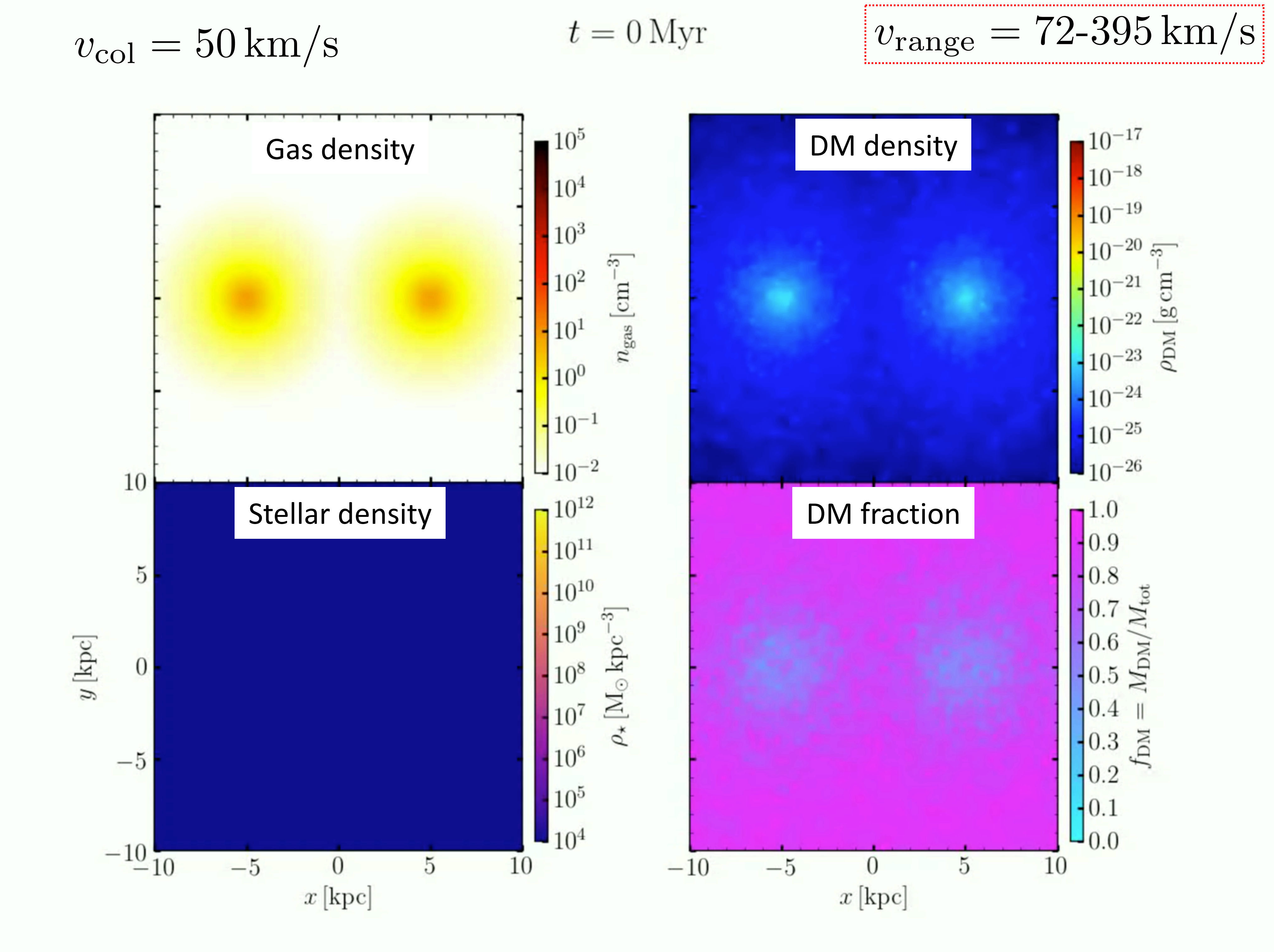


$v_{\rm col} = 200\,{\rm km/s}$
$t = 0\,{\rm Myr}$
$v_{\rm range} = 72\text{-}395\,{\rm km/s}$
Gas density
DM density
Stellar density
DM fraction
$n_{\rm gas}\,[{\rm cm}^{-3}]$
$\rho_{\rm DM}\,[{\rm g\,cm}^{-3}]$
$\rho_\star\,[{\rm M}_\odot\,{\rm kpc}^{-3}]$
$f_{\rm DM} = M_{\rm DM}/M_{\rm tot}$
x [kpc]
y [kpc]

Enclosed mass in the DMDG

$v_{\mathrm{col}} = 200\,\mathrm{km/s}$ $t = 280\,\mathrm{Myr}$





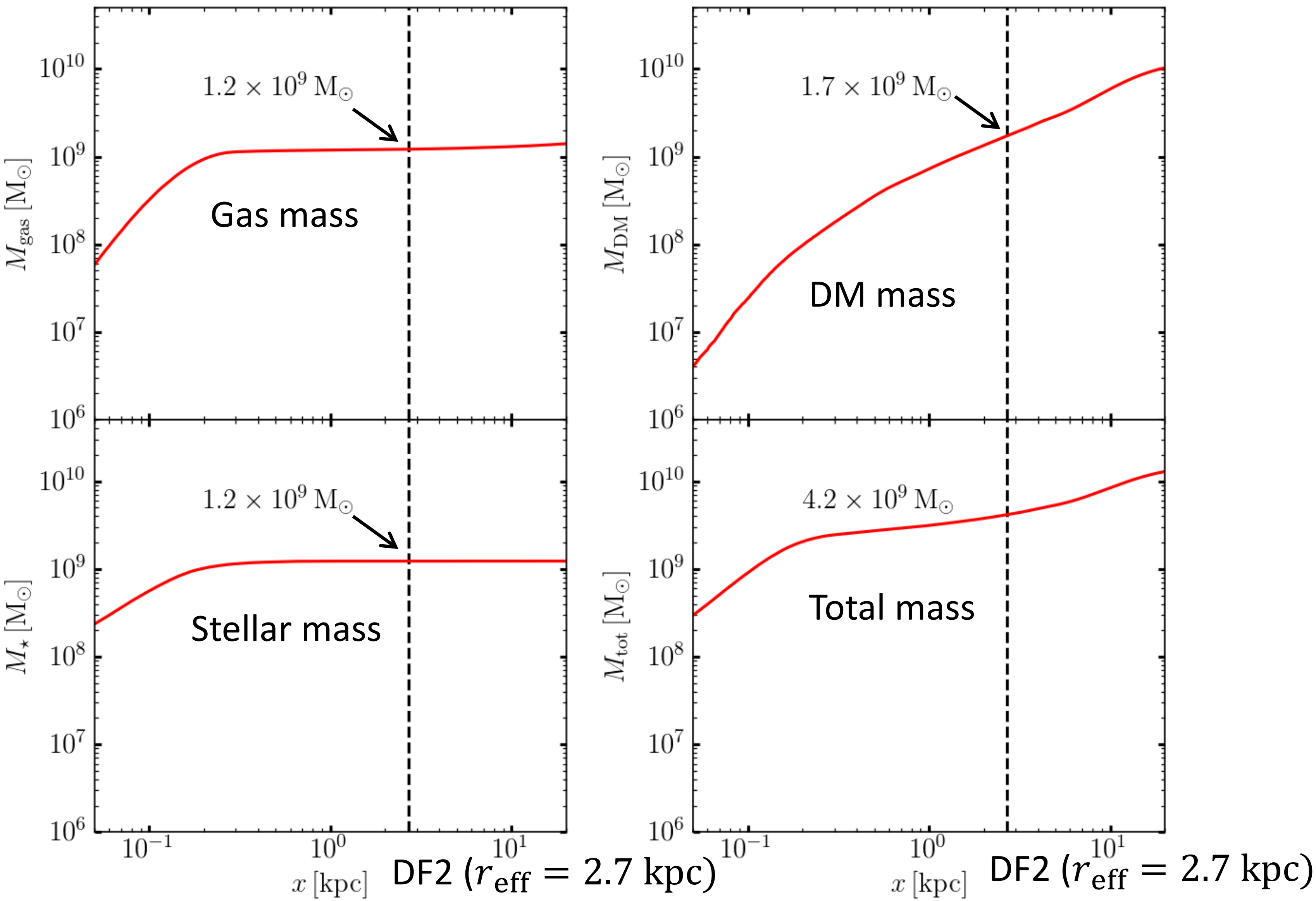
$v_{\mathrm{col}} = 50\,\mathrm{km/s}$
$t = 0\,\mathrm{Myr}$
$v_{\mathrm{range}} = 72\text{-}395\,\mathrm{km/s}$
Gas density
DM density
Stellar density
DM fraction
$n_{\mathrm{gas}}\,[\mathrm{cm}^{-3}]$
$\rho_{\mathrm{DM}}\,[\mathrm{g\,cm}^{-3}]$
$\rho_\star\,[\mathrm{M}_\odot\,\mathrm{kpc}^{-3}]$
$f_{\mathrm{DM}} = M_{\mathrm{DM}}/M_{\mathrm{tot}}$
x [kpc]
y [kpc]

$v_{\rm col} = 50\,{\rm km/s}$

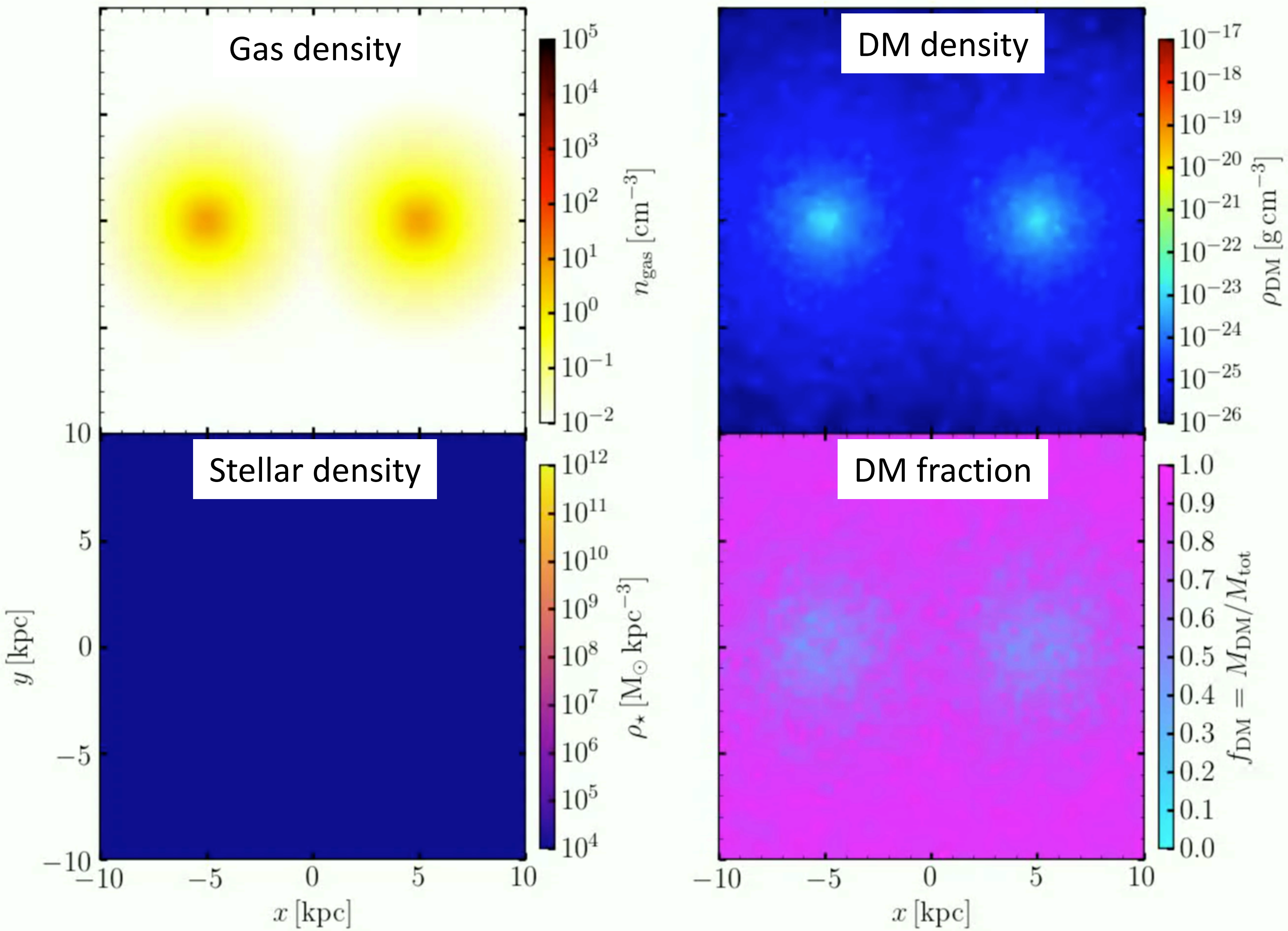
Enclosed mass

$t = 285\,{\rm Myr}$

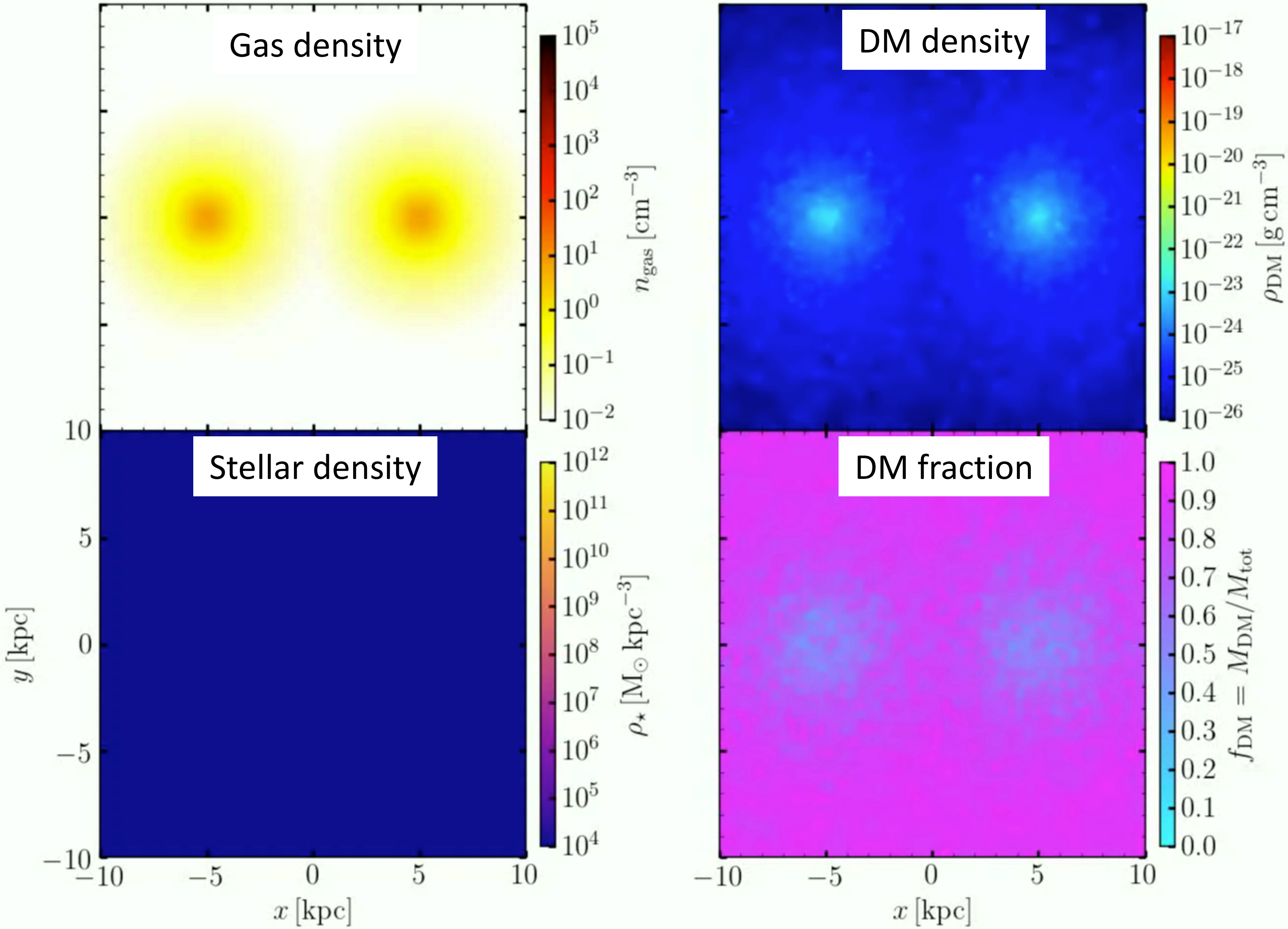
$v_{\rm range} = 72\text{-}395\,{\rm km/s}$



$v_{\rm col} = 700\,{\rm km/s}$ $t = 0\,{\rm Myr}$ $v_{\rm range} = 72\text{-}395\,{\rm km/s}$



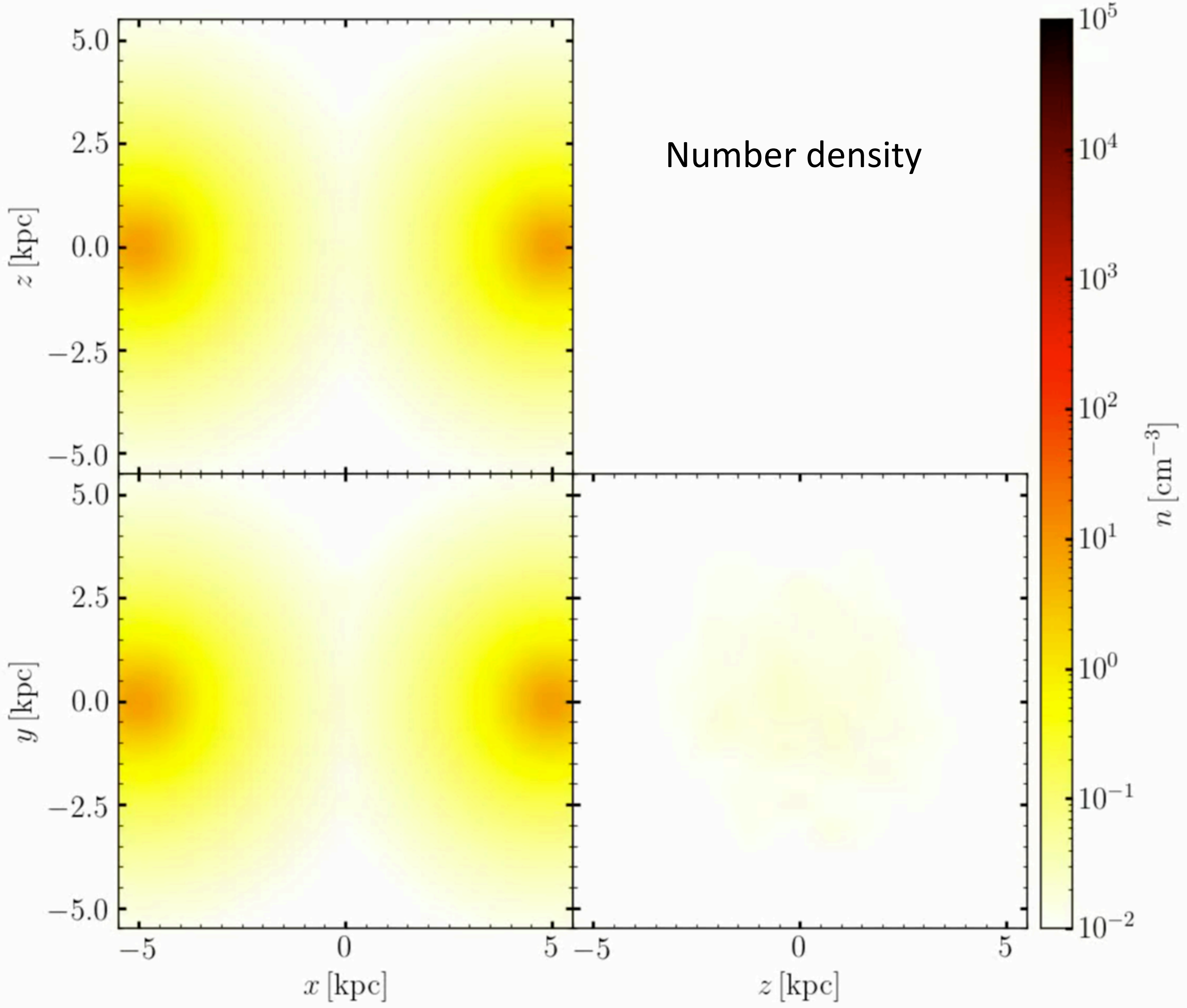
$v_{\mathrm{col}} = 500\,\mathrm{km/s}$ $t = 0\,\mathrm{Myr}$ $v_{\mathrm{range}} = 72\text{-}395\,\mathrm{km/s}$



$v_{\mathrm{col}} = 500\,\mathrm{km/s}$

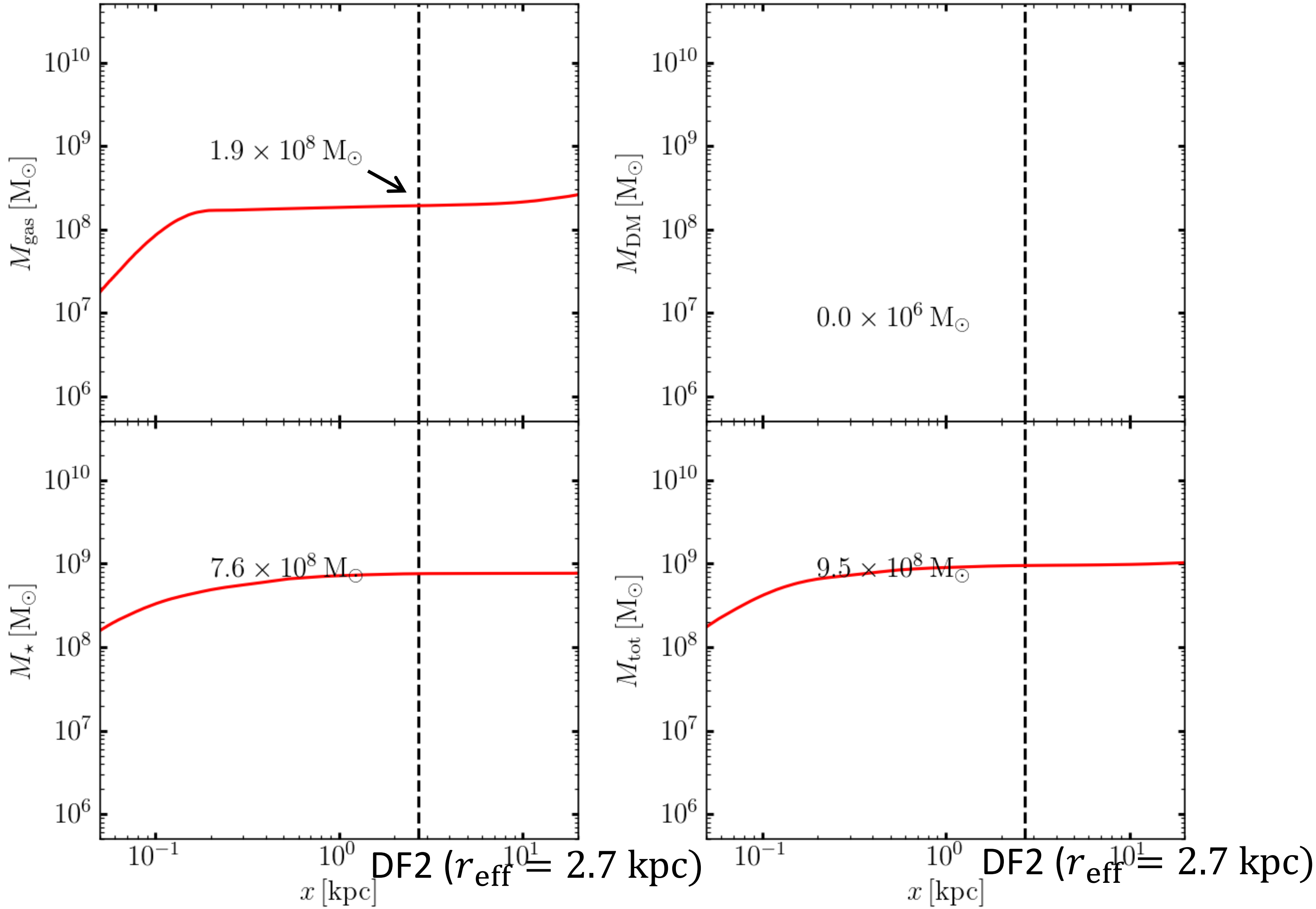
$t = 0\,\mathrm{Myr}$

$v_{\mathrm{range}} = 72\text{-}395\,\mathrm{km/s}$



Enclosed mass in the DMDG

$v_{\rm col} = 500\,{\rm km/s}$ $t = 280\,{\rm Myr}$



Summary

- We have discussed the formation process of a dark matter deficient galaxy (DMDG) using physical model.
- In simulation, DMDG could be formed by dark matter sub halo collision.

Future Work

- Change the initial condition to fit observed DMDGs.
  (dark matter sub halo mass, impact parameter, baryon-DM ratio…)
- Estimate the dark matter sub halo collision probability based on cosmological simulation.