On the ejecta properties of BQS or QS-BH merger

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Outline

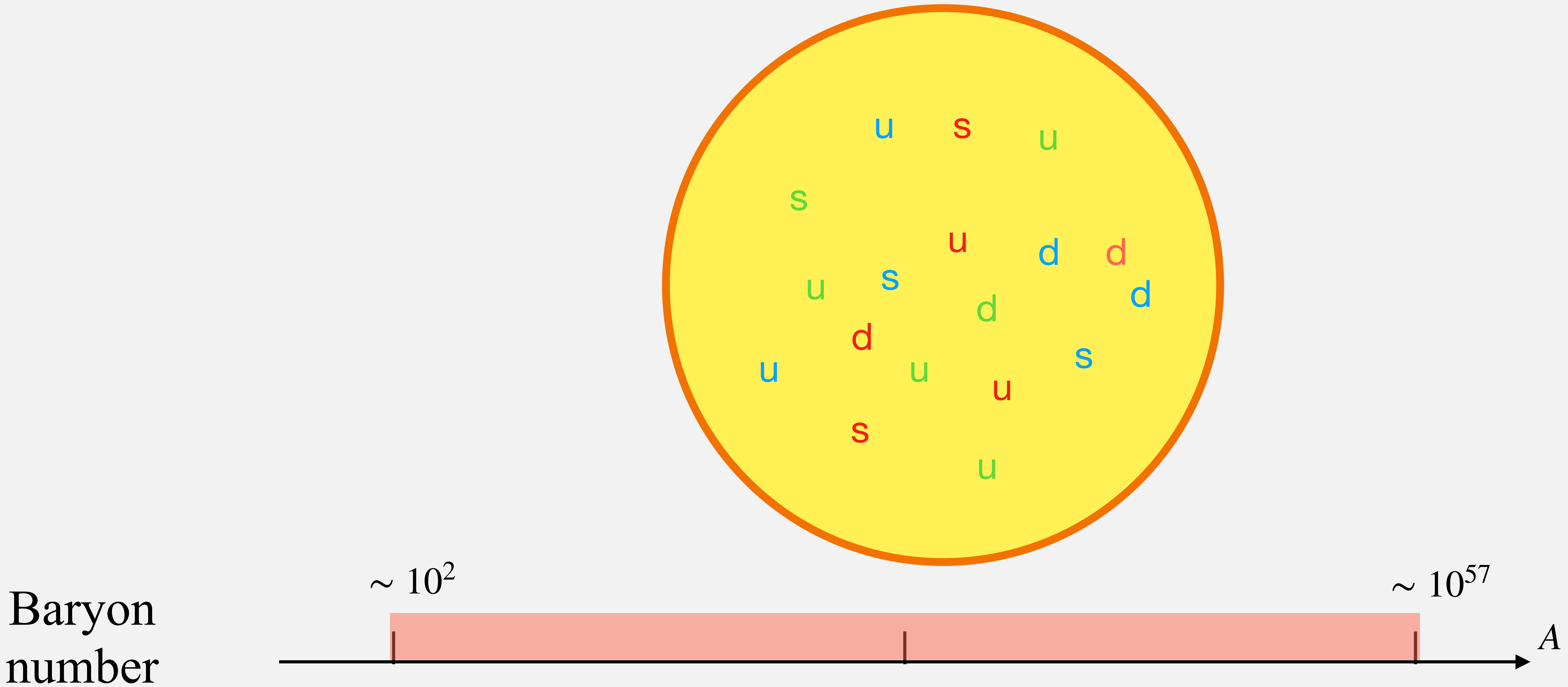
- ➡Introduction
- ➡Quark nugget evaporation & ejecta evolution
- ➡Results
- ➡Discussion & Conclusion

Quark star and quark nugget

Bodmer–Witten hypothesis: strange quark matter is the true ground state of strong interaction matter. (Bodmer 1971, Witten 1984)

$$\Delta E > m_n - m(^{56}Fe)/56 \approx 8.8\,\mathrm{MeV}$$

Then there should be stable quark nuggets and stable quark stars.



From quark nuggets to quark stars

Baryon density	$n_b = n_q/3 \simeq 0.3\,\mathrm{fm}^{-3}$
Quark chemical potential	$\mu \sim (\pi^2 n_q)^{1/3} \simeq 300\,\mathrm{MeV}$
Electron chemical potential	$\mu_e \sim \dfrac{m_s^2}{4\mu} \simeq 10\,\mathrm{MeV}$
Electron fraction	$Y_e \sim \dfrac{m_s^6}{192\mu^6} \simeq 10^{-5}(\dfrac{m_s}{100\mathrm{MeV}})^6$

Confirm or exclude them observationally ?

- Stellar properties: mass-radius relation, moment of inertia, tidal deformability, Kepler limit…

  （More measurements are needed, as well as more precise measurements.）

- In this talk, I focus on the ejecta from BQS or QS-BH mergers

  $T \gtrsim 1$ MeV: **nugget evaporation**

  $T \lesssim 1$ MeV: Nucleosynthesis ——> next talk by Yudong Luo

Basic scenarios in post-merger stage

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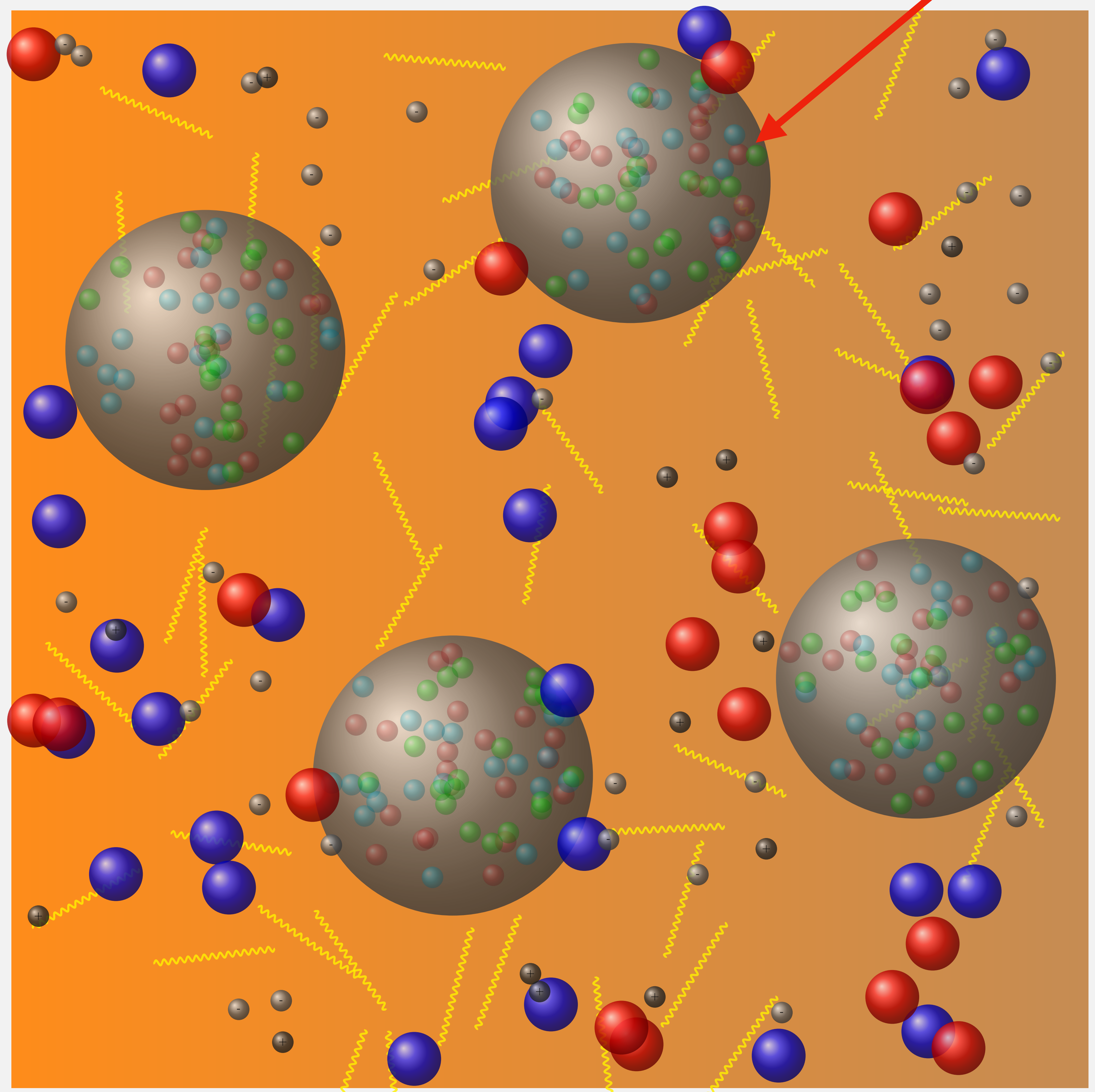
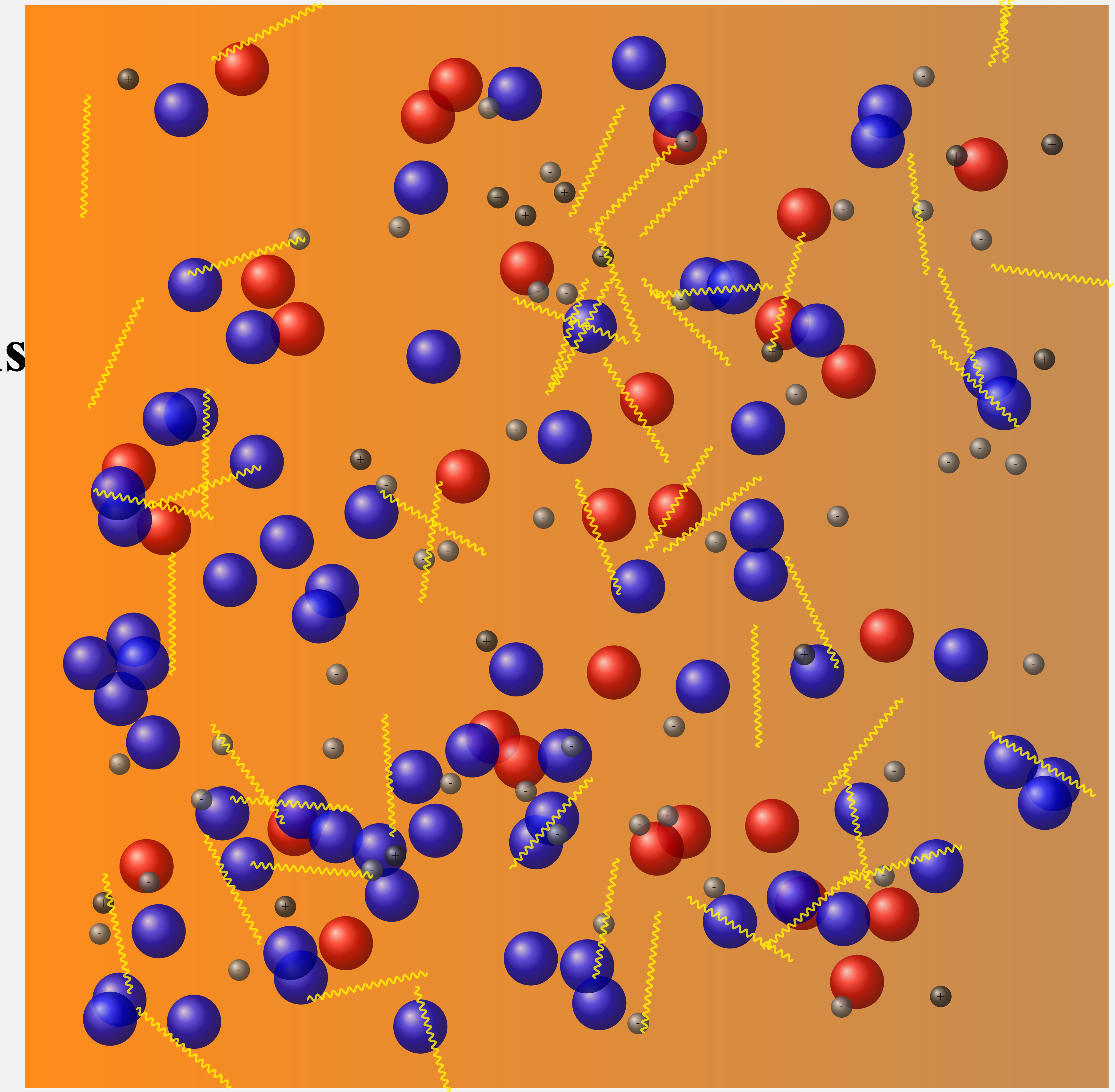
Nuggets + Gas

Initial A should be sufficiently large ($\gtrsim 10^{26}$), limited by surface tension (Bucciantini+2022)



If all evaporate to nucleons

Gas (like BNS)



Evaporation can be effectively suppressed in a dense environment

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- Previous studies on nugget evaporation suggest that the process could be sufficiently efficient.

  Alcock+1985, for early universe
  Bucciantini+2022, for BQS merger

- The evaporated nucleons will reach saturation, thereby suppressing further evaporation and allowing more quark nuggets to survive, the timescale of saturation is estimated as

$$\tau \sim 1.7 \times 10^{-13}\,\mathrm{s}\left(\frac{0.1\,\mathrm{fm}^{-3}}{n_B}\right)\left(\frac{10\,\mathrm{MeV}}{T}\right)^{1/2}\left(\frac{A}{10^{30}}\right)^{1/3}$$

In the early universe ($n_B \sim 10^{-11}\,\mathrm{fm}^{-3}, T \sim 100\,\mathrm{MeV}, A \sim 10^{36} - 10^{45}$), $\tau \sim 0.1 - 100\,\mathrm{s}$ is much longer than the cosmic expansion time $1/H \sim 10^{-4}\,\mathrm{s}$,

while in BQS merger ($n_B \sim 10^{-3}\,\mathrm{fm}^{-3}, T \sim 10\,\mathrm{MeV}, A \sim 10^{30}$), $\tau \sim 10^{-11}\,\mathrm{s}$ is much smaller than the ejecta expansion time $\tau_{\mathrm{expansion}} \sim 10^{-3}\,\mathrm{s}$.

Ejecta evolution

- Ejecta expansion ——> decreasing density, cooling of the gas temperature T $\longrightarrow$ $\tau_{\text{expansion}}$

- Nugget evaporation ——> cooling of the nugget T_s $\longrightarrow$ τ_{cooling}, $\tau_{\text{evaporation}}$

$$A \leftrightarrow (A-1) + n$$

$$A \leftrightarrow (A-1) + p$$

- Weak reactions

$$n + \nu_e \leftrightarrow p + e^-$$

$$n + e^+ \leftrightarrow p + \bar{\nu}_e$$

$$n \leftrightarrow p + e^- + \bar{\nu}_e$$

Equilibrium: a hot and dense state

$(\tau_{\text{cooling}} \ll \tau_{\text{expansion}}, \tau_{\text{evaporation}} \ll \tau_{\text{expansion}})$

Chemical equilibrium

$$\mu_n^{(N)} = \mu_n^{(G)}$$

$$\mu_p^{(N)} + \mu_e^{(N)} = \mu_p^{(G)} + \mu_e^{(G)}$$

$$\mu_n^{(G)} = \mu_p^{(G)} + \mu_e^{(G)}$$

Charge Neutrality

$$n_p^{(G)} = n_{e^-}^{(G)} - n_{e^+}^{(G)} = \frac{\mu_e^{(G)\,3}}{3\pi^2} + \frac{\mu_e^{(G)\,3} T^2}{3}$$

Temperature equilibrium

$$T_s = T$$

Baryon conservation

$$n_B = A n_A + n_n^{(G)} + n_p^{(G)}$$

$$\mu_{n,p}^{(G)} - m_{n,p} = T \ln \left[\left(\frac{2\pi}{m_{n,p} T} \right)^{3/2} \frac{n_{n,p}^{(G)}}{2} \right]$$

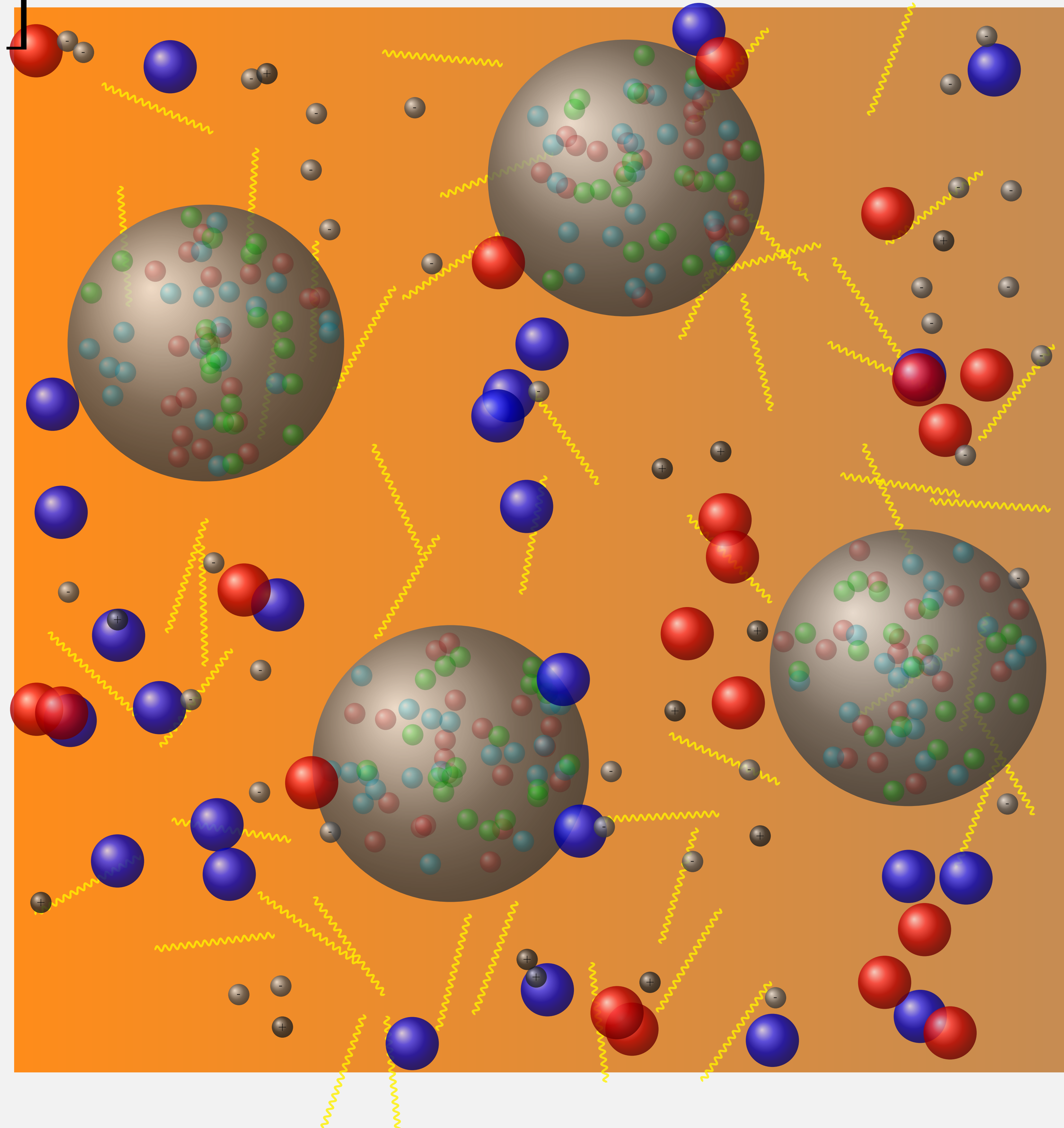
$$\mu_n^{(N)} = \mu_u + 2\mu_d$$

$$\mu_p^{(N)} = 2\mu_u + \mu_d$$

Recall the binding energy is

$$\Delta E \equiv m_n - \mu_n^{(N)} > 8.8\,\text{MeV}$$

Nuggets + Gas



Equilibrium: a hot and dense state

$(\tau_{\text{cooling}} \ll \tau_{\text{expansion}}, \tau_{\text{evaporation}} \ll \tau_{\text{expansion}})$

$$\cancel{\mu_n^{(N)} = \mu_n^{(G)}}$$

Chemical equilibrium

$$\cancel{\mu_p^{(N)} + \mu_e^{(N)} = \mu_p^{(G)} + \mu_e^{(G)}}$$

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~~Temperature equilibrium~~

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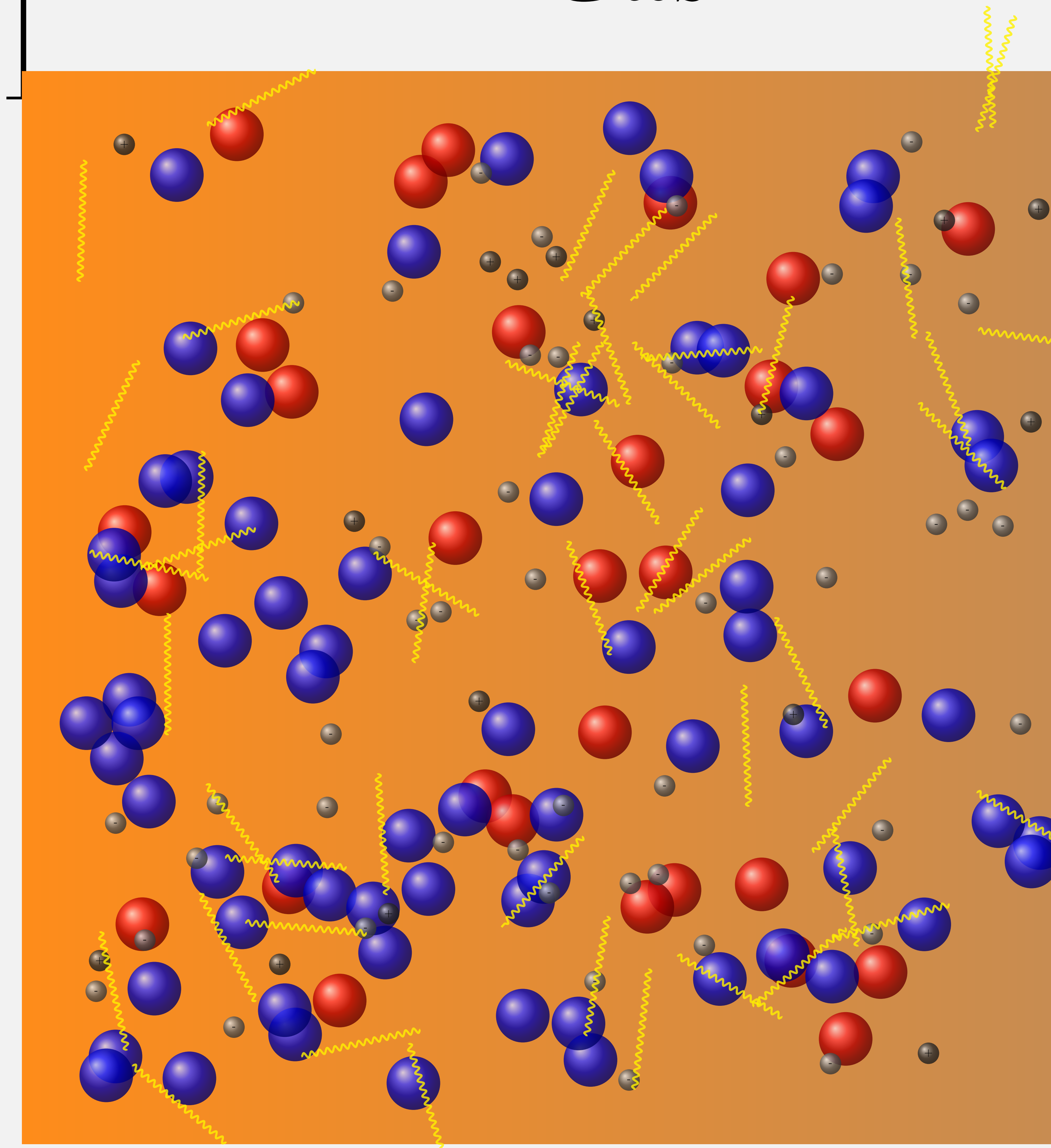
Gas



Out of equilibrium: thermal and chemical evolution

(Onset when $\tau_{\text{cooling}} \gtrsim \tau_{\text{expansion}}$ or $\tau_{\text{evaporation}} \gtrsim \tau_{\text{expansion}}$)

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Nugget temperature T_s

$$\frac{dU}{dt} = L_\nu + L_{n,p},$$

$$U \approx 3\pi^2 A T_s^2/2\mu_q$$

$$L_\nu = 4\pi R_s^2 \left[\frac{7\pi^2}{160}\right]\left[T^4 p(R_s,T) - T_s^4 p(R_s,T_s)\right]$$

$$L_{n,p} = -\frac{dN_{n,p}}{dt}(\Delta E + 2T),$$

Given density and gas temp. trajectories, these eqs. can be evolved to get the nugget temp. and also the fraction of gas

Baryon number A

$$\frac{dA}{dt} = -\frac{dN_n}{dt} - \frac{dN_p}{dt}$$

Free neutrons & protons

$$\frac{dN_{n,p}}{dt} = \left[\frac{dN_{n,p}}{dt}\right]_{A\leftrightarrow(A-1)+n} + \left[\frac{dN_{n,p}}{dt}\right]_{n\leftrightarrow p}$$

$$\left[\frac{dN_n}{dt}\right]_{A\leftrightarrow(A-1)+n} = n_n^{\text{eq}}\langle\sigma_n v_n\rangle_{T_s} - n_n\langle\sigma_n v_n\rangle_T,$$

$$\left[\frac{dN_p}{dt}\right]_{A\leftrightarrow(A-1)+p} = n_p^{\text{eq}}\langle\sigma_p v_p\rangle_{T_s} - n_p\langle\sigma_p v_p\rangle_T,$$

$$\left[\frac{dN_n}{dt}\right]_{n\leftrightarrow p} = -\left[\frac{dN_p}{dt}\right]_{n\leftrightarrow p} = -N_n\lambda_{e^+n} + N_p\lambda_{e^-p},$$

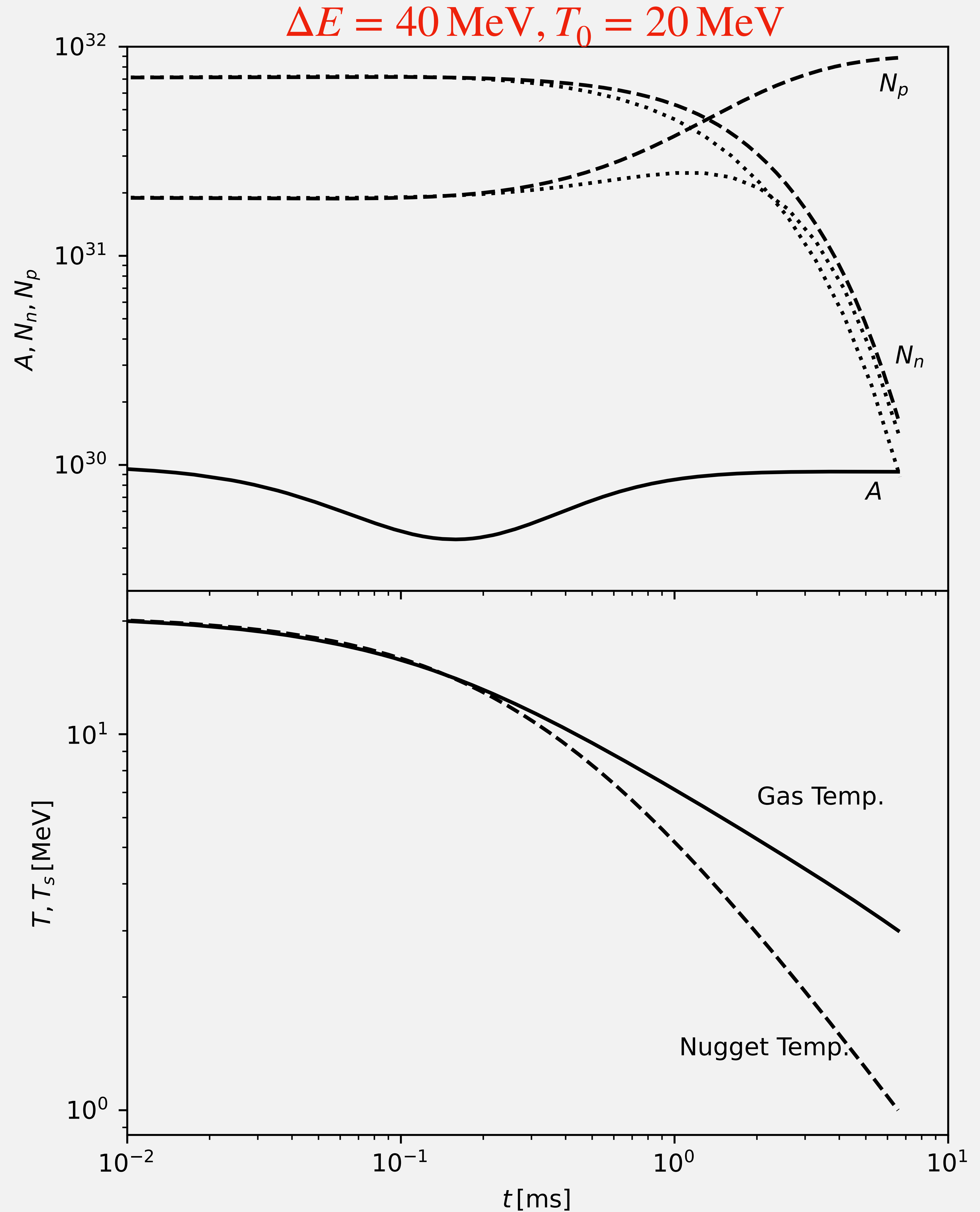
Applied to a homologous expansion model

$$\rho(t) = \frac{M_{\rm ej}}{(4\pi/3) v_{\rm ej}^3 (t+t_0)^3},$$

$$T(t) = T_0 \left(1 + \frac{t}{t_0}\right)^{-3(\gamma-1)}$$

$\gamma = 4/3$

we set ejecta mass $M_{\rm ej} = 0.01\, M_\odot$ and velocity $v_{\rm ej} = 0.1c$. We also set the initial density $\rho_0 = \rho(0) = M_{\rm ej}/(\frac{4\pi}{3} v_{\rm ej}^3 t_0^3) = 5 \times 10^{12}\,{\rm g/cm^3}$, which gives $t_0 = 0.33\,{\rm ms}$. T_0 is left to be a free parameter in our analysis.

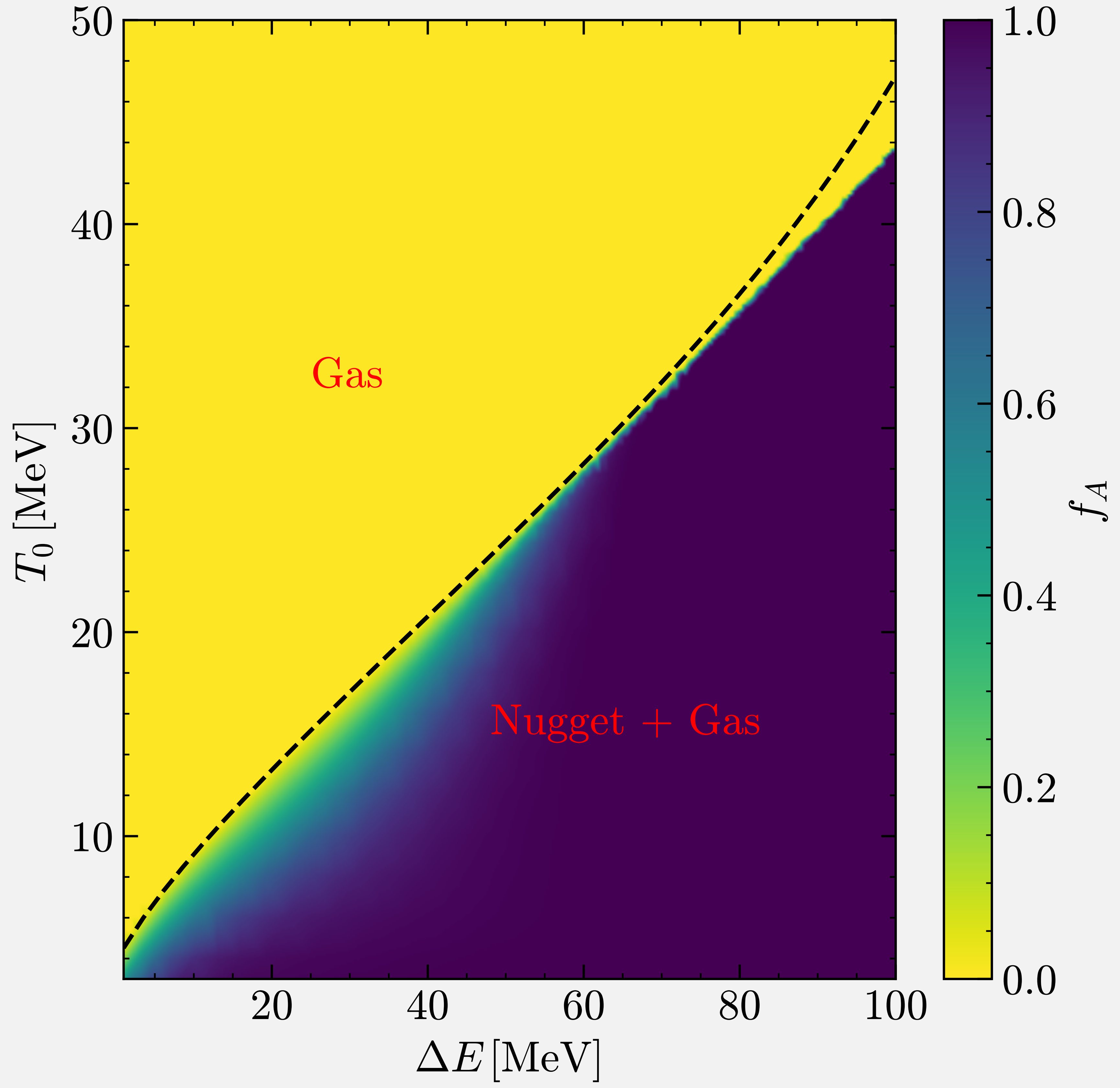


Applied to a homologous expansion model

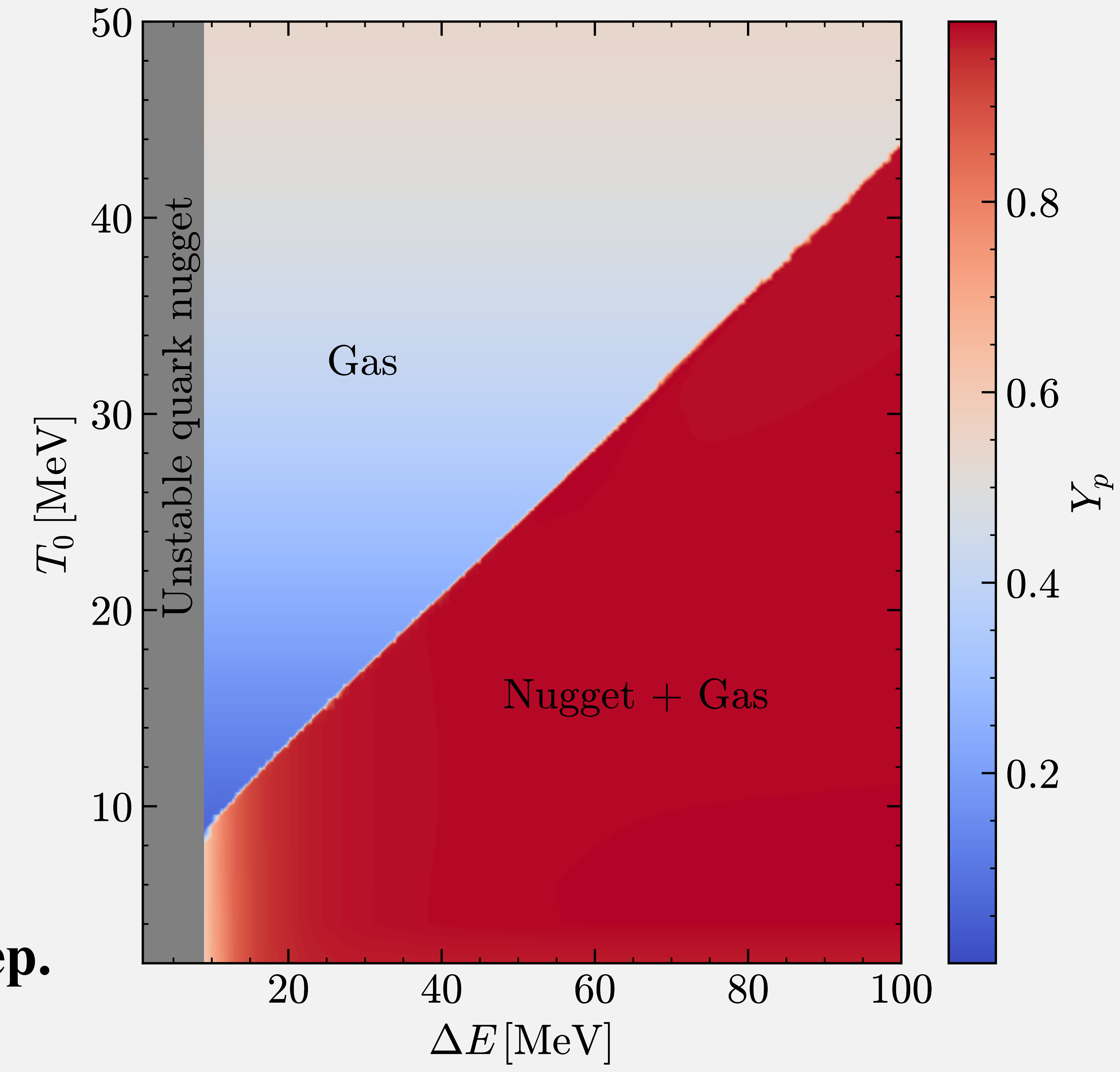
Properties at $T = 1\,\mathrm{MeV}$ when fixing $\rho_0 = 5\times10^{12}\,\mathrm{g/cm^3}, v_{ej} = 0.1c, M_{ej} = 0.01\,M_\odot$

(at this temp. the compositions almost freeze, and nucleosynthesis starts to play an important role)

Mass fraction of nugget $f_A \equiv \dfrac{An_A}{An_A + n_n + n_p}$



Proton fraction (in gas phase) $Y_p \equiv \dfrac{n_p}{n_n + n_p}$



ZQ Miao 2024, in prep.

Discussion & Conclusion

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√We explore the properties of ejecta from BQS mergers, with a detailed focus on both equilibrium and non-equilibrium processes during the ejecta expansion, including quark nugget evaporation and cooling.

√The ejecta properties are primarily determined by the binding energy of the quark nuggets and can differ significantly from those of a binary neutron star merger.

- Small binding energy —> a neutron-rich gas like a binary neutron star merger
- Large binding energy —> a low density, proton-rich gas + nuggets

√Maybe no kilonova can be produced in BQS merger, but need more reliable $T(t), \rho(t)$ inputs from simulations which reflect more details like shocks, and need further nucleosynthesis calculations —> talk by Yudong

Equation of state in equilibrium

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$$\rho = A m_n n_A + m_n n_n + m_p n_p$$

$$n_B = A n_A + n_n + n_p$$

$$P = n_n T + n_p T$$

if the temperature is too high, the quark nuggets may completely evaporate into nucleons, the boundary is determined by

$$n_B < n_n + n_p$$

Coulomb barrier & Proton cross section

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the nugget carries a net positive charge within its surface, creating a Coulomb barrier that protons must overcome to penetrate the nugget.

$$V(r) = \frac{3V_q}{\sqrt{6\alpha/\pi V_q (r - R_s)} + 4}, \quad r > R_s,$$

Penetration factor

$$\sigma_n = \pi R_s^2 \qquad \sigma_p = P(E)\sigma_n$$

$$P(E > E_c) = (1 - \frac{E_c}{E})^{1/2},$$

$$P(E < E_c) = (\frac{E_c}{E} - 1)^{1/2} \exp\left\{-2\sqrt{2m_p}\int_{R_s}^{R_0} [V(r) - E]^{1/2}\, dr\right\}. \qquad E_c = 3V_q/4$$

Applied to GRHD simulation results (Zhu & Rezzolla 2021)

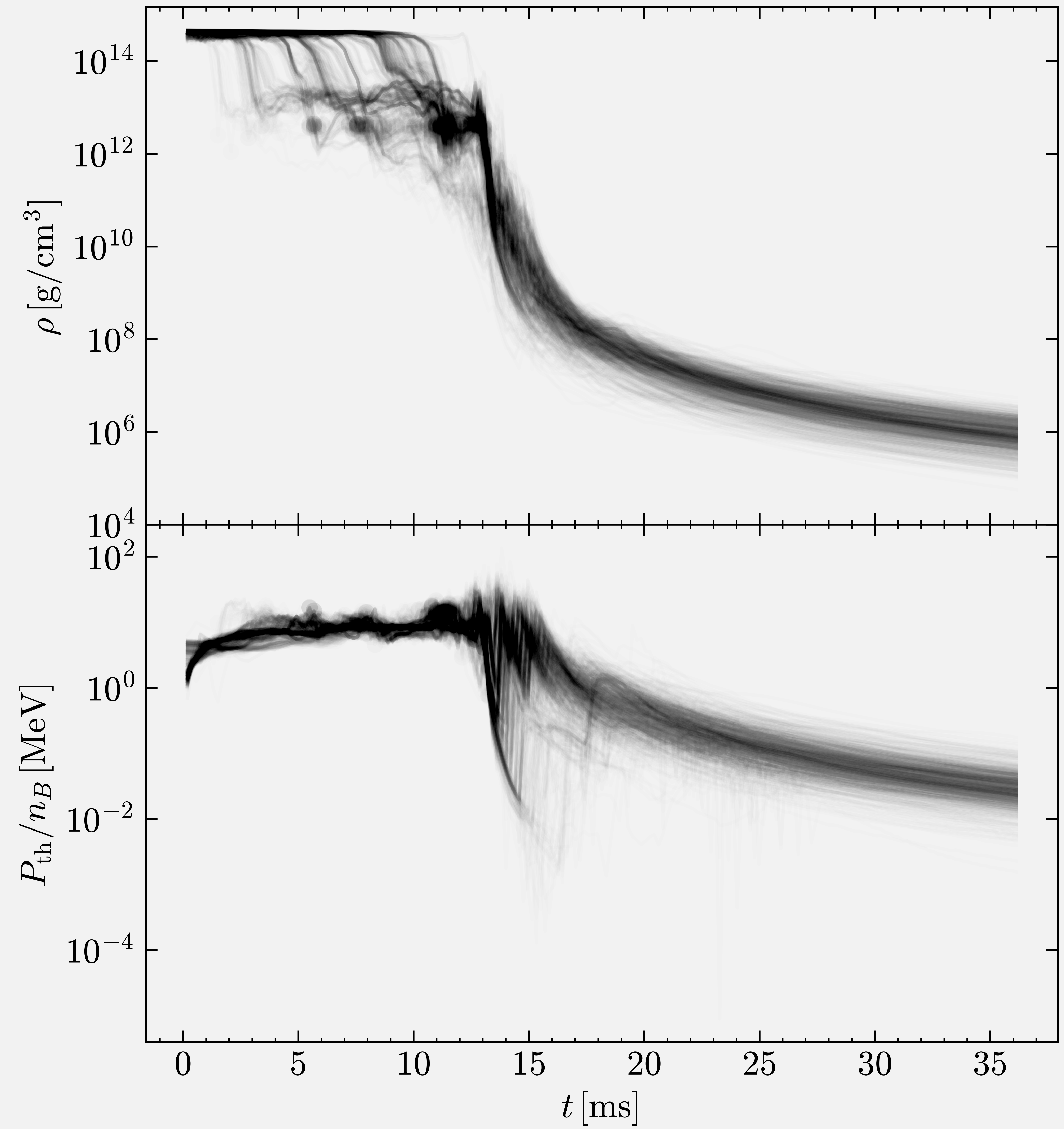
- Fully general-relativistic simulations of binary quark stars, equal mass $1.35M_\odot - 1.35M_\odot$

- A total of 1030 tracers, consist the trajectories of density and thermal pressure

- The pressure can be translated to temperature as

$$T = P_{th}/(n_n + n_p)$$

which should be calculated in each iteration step



Applied to GRHD simulation results (Zhu & Rezzolla 2021)

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