

Properties of quark star merger ejecta and the observational signature

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Based on: arXiv 2411.09013

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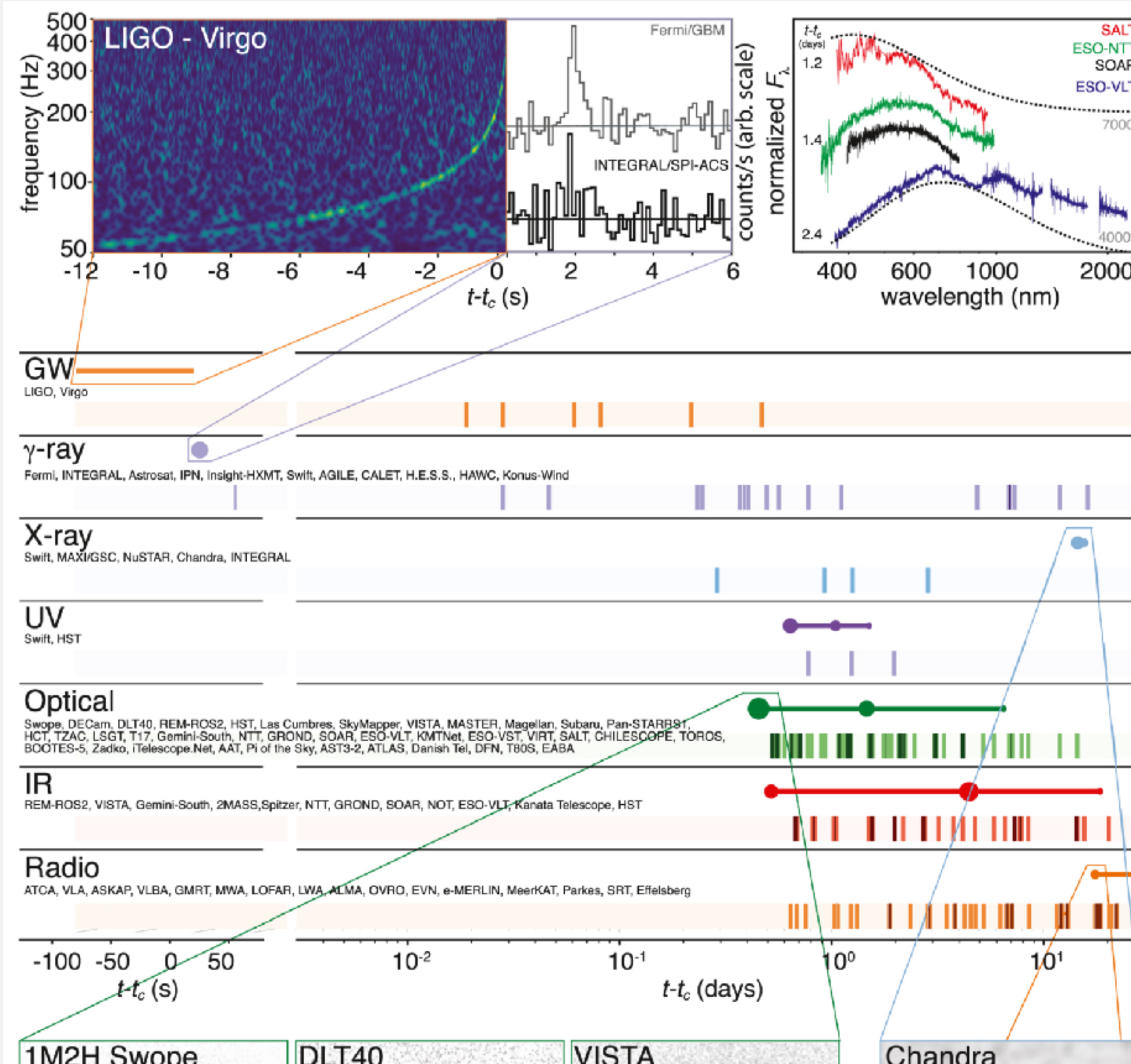
Outline

- ➡ **Background and motivation**
- ➡ **(Non-)equilibrium EoS of the ejecta**
- ➡ **Results & Discussion**

• First Binary Neutron Star Merger



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- GW170817
- GRB 170817A
- AT 2017gfo

Blue/Red kilonova

Neutron rich environment

R-process elements

• Quark star merger picture?



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PHYSICAL REVIEW D

VOLUME 4, NUMBER 6

15 SEPTEMBER 1971

Collapsed Nuclei*

A. R. Bodmer

Nuclear Physics Laboratory, Oxford, England

Bodmer–Witten hypothesis: strange quark matter is the true ground state of strong interaction matter

PHYSICAL REVIEW D

VOLUME 30, NUMBER 2

15 JULY 1984

Cosmic separation of phases

Edward Witten*

Institute for Advanced Study, Princeton, New Jersey 08540

(Received 9 April 1984)

A first-order QCD phase transition that occurred reversibly in the early universe would lead to a surprisingly rich cosmological scenario. Although observable consequences would not necessarily survive, it is at least conceivable that the phase transition would concentrate most of the quark excess in dense, invisible quark nuggets, providing an explanation for the dark matter in terms of QCD effects only. This possibility is viable only if quark matter has energy per baryon less than 938 MeV. Two related issues are considered in appendices: the possibility that neutron stars generate a quark-matter component of cosmic rays, and the possibility that the QCD phase transition may have produced a detectable gravitational signal.

Bodmer 1971, Witten 1984

• Quark star merger picture?



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Edward Witten*

Bodmer 1971, Witten 1984

Constraints on interquark interaction parameters with GW170817 in a binary strange star scenario

En-Ping Zhou,^{1,2} Xia Zhou,³ and Ang Li^{4,*}

The quark star model is not ruled out by GW170817

¹State Key Laboratory of Nuclear Science and Technology and School of Physics

Bayesian Inference of Strange Star Equation of State Using the GW170817 and GW190425 Data

Zhiqiang Miao¹, Jin-Liang Jiang^{2,3}, Ang Li¹, and Lie-Wen Chen⁴

¹Department of Astronomy, Xiamen University, Xiamen, Fujian 361005, People's Republic of China; liang@xmu.edu.cn

²Key

³School

⁴School of Physics

Interacting ud and uds quark matter at finite densities and quark stars

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Zhou EP, Zhou X., Li A. 2018,

ZQM, Jiang JL, Li A., Chen LW 2021,

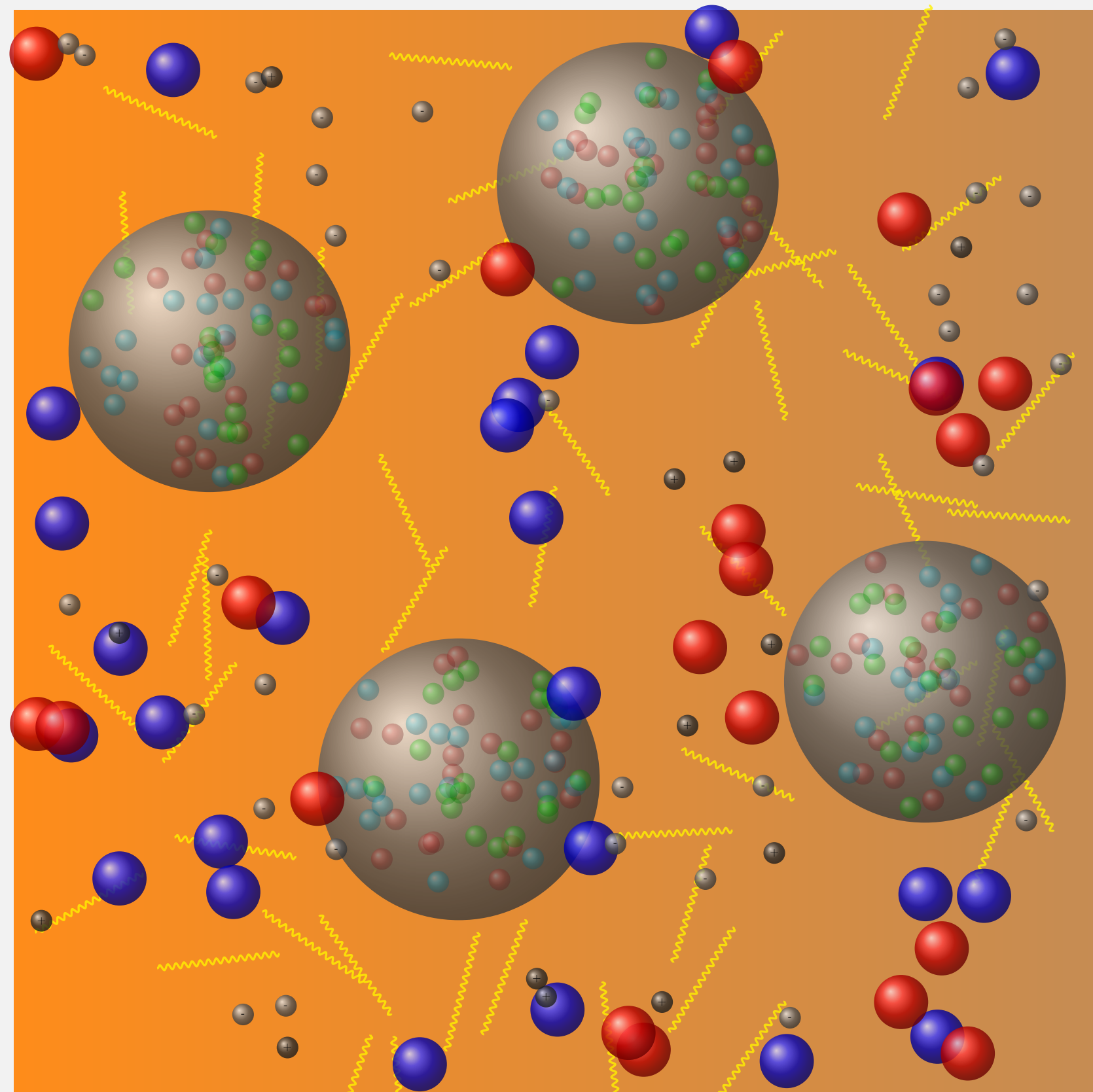
Yuan WL, Li A., **ZQM**, Zuo BJ, Bai Z. 2022

• What's the outcome of quark star merger



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Nuggets + Gas

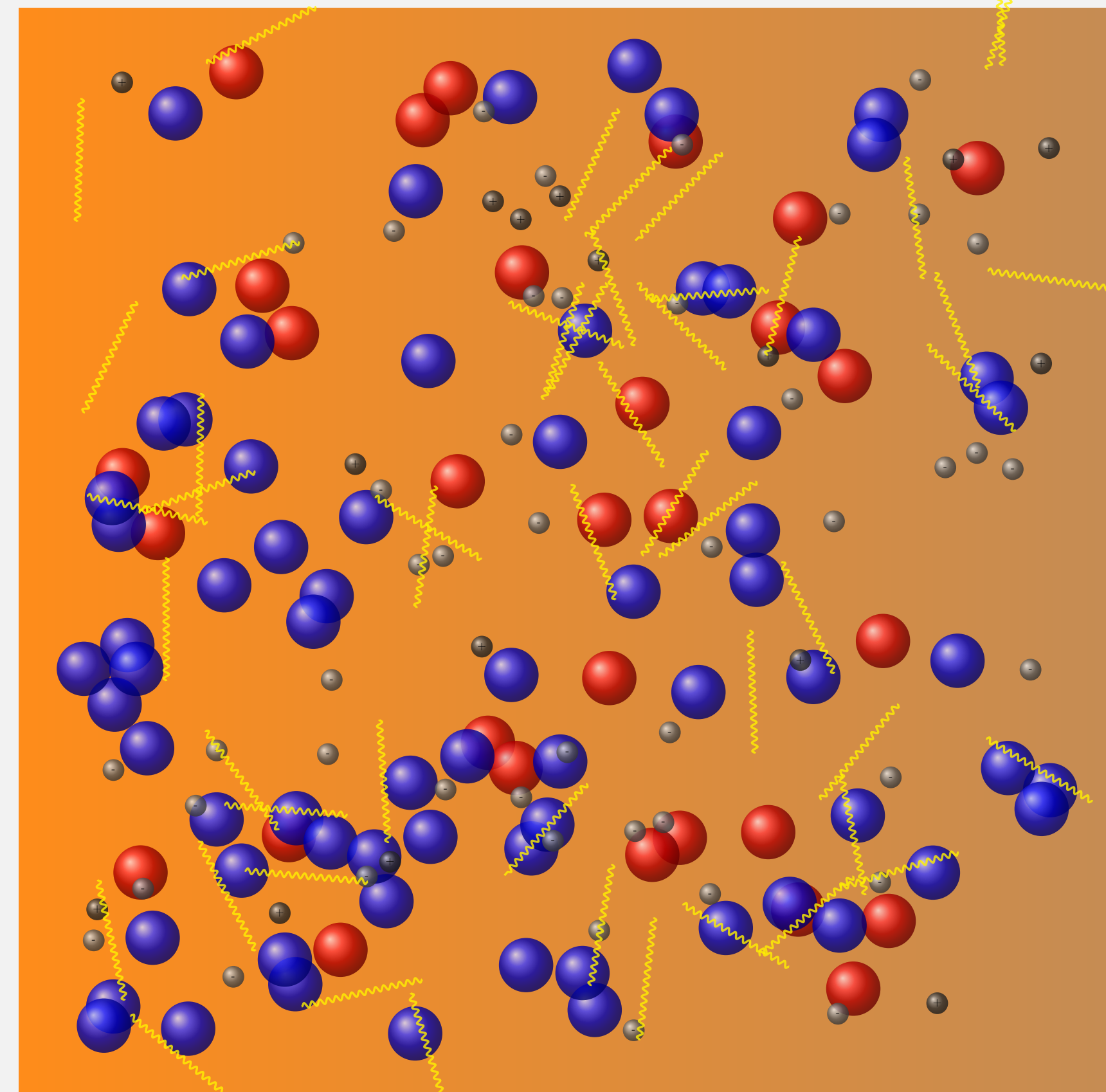


Maybe no kilonova

or

Gas

?



Maybe similar to neutron star merger

• Different stages



- $\rho \gtrsim \rho_s \sim 4 \times 10^{14} \text{ g/cm}^3$

Bulk quark matter, describe by (hot) quark matter EOS

- $0.01 - 0.1\rho_s < \rho < \rho_s, T \sim \mathcal{O}(10) \text{ MeV}$

Turbulence , fragmentation, collisions; hard to model

- $\rho \lesssim 0.01 - 0.1\rho_s, T \simeq 1 - \mathcal{O}(10) \text{ MeV}$

Quark nugget evaporation, cooling; ejecta expansion

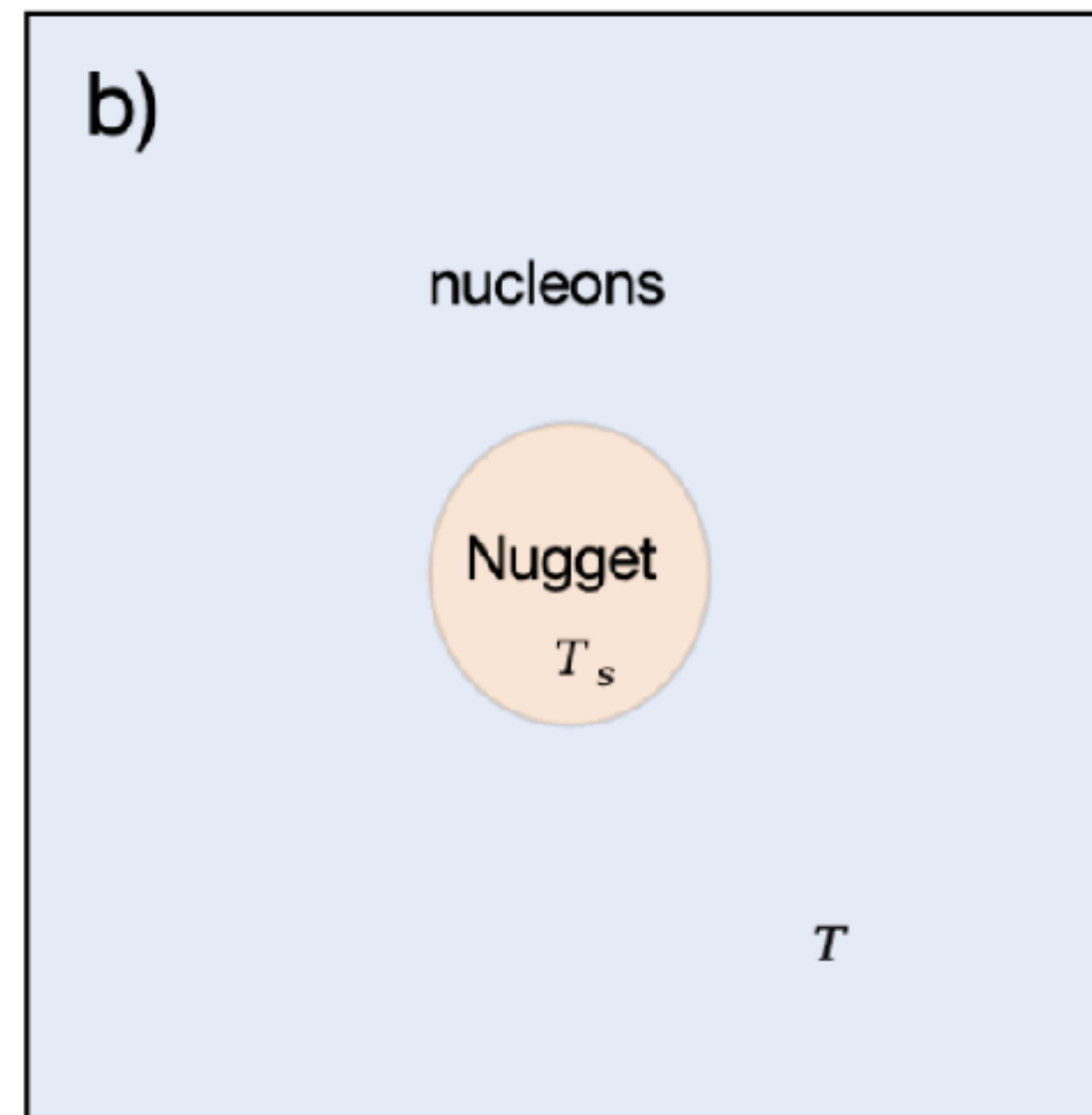
- Lower $\rho, T \lesssim 1 \text{ MeV}$

Nucleosynthesis

Assumptions



- The nugget should be large, with $A \gtrsim 10^{24}$, due to surface tension
- The physical picture of evaporation process



Saturation timescale

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

10



• Relevant Physical processes

• Ejecta expansion — —> decreasing density, cooling of the gas temperature T ———→ $\tau_{\text{expansion}} \gtrsim 1 \text{ ms}$

• Nugget evaporation — —> cooling of the nugget T_s ———→ $\tau_{\text{cooling}}, \tau_{\text{evaporation}}$

$@T \gtrsim 1 \text{ MeV}$

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

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

• Weak reactions

$@T \gtrsim 1 \text{ MeV}$

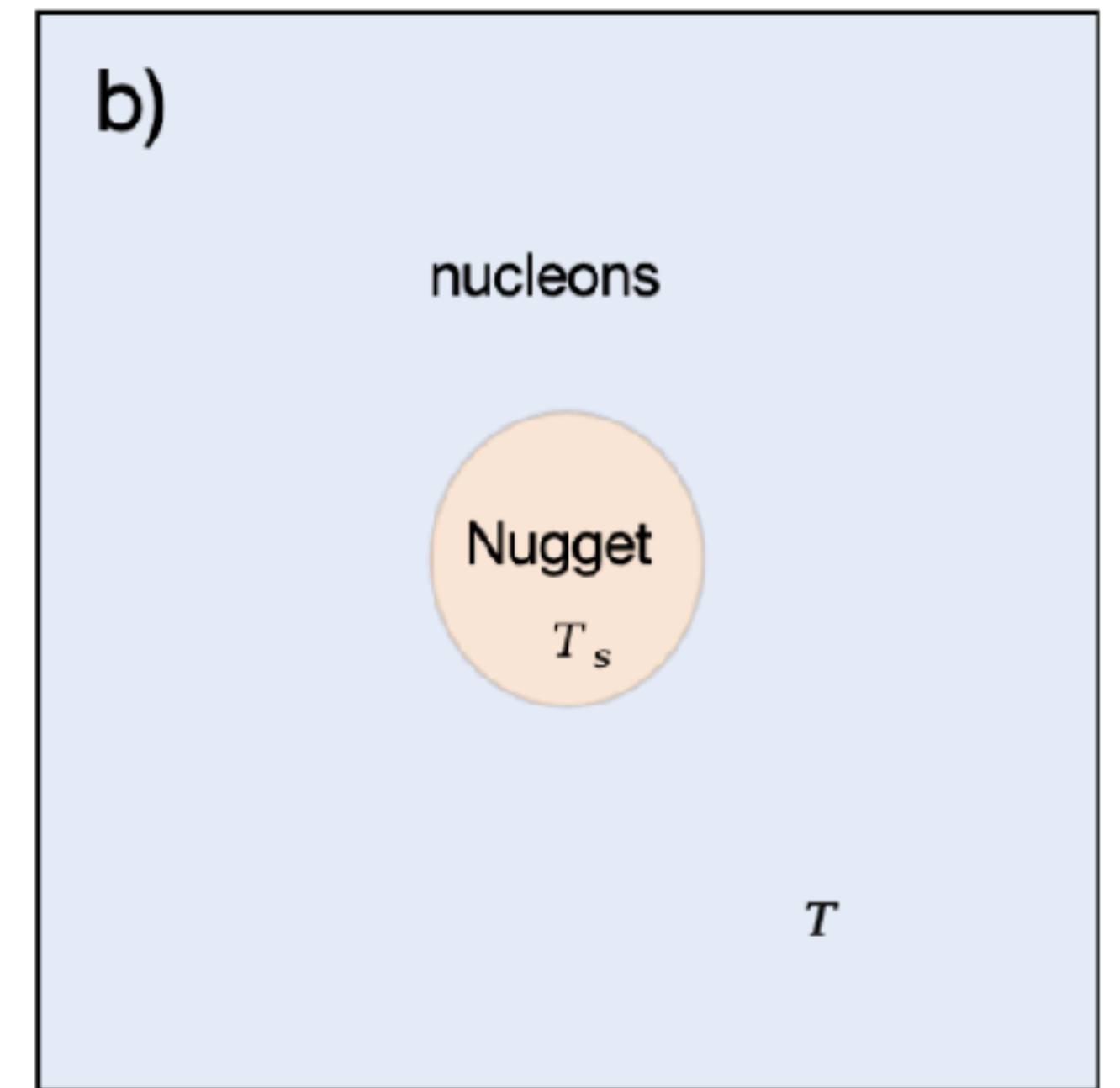
$$n + \nu_e \leftrightarrow p + e^-$$

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

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

• Nucleosynthesis

$@T \lesssim 1 \text{ MeV}$



Equilibrium equation of 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

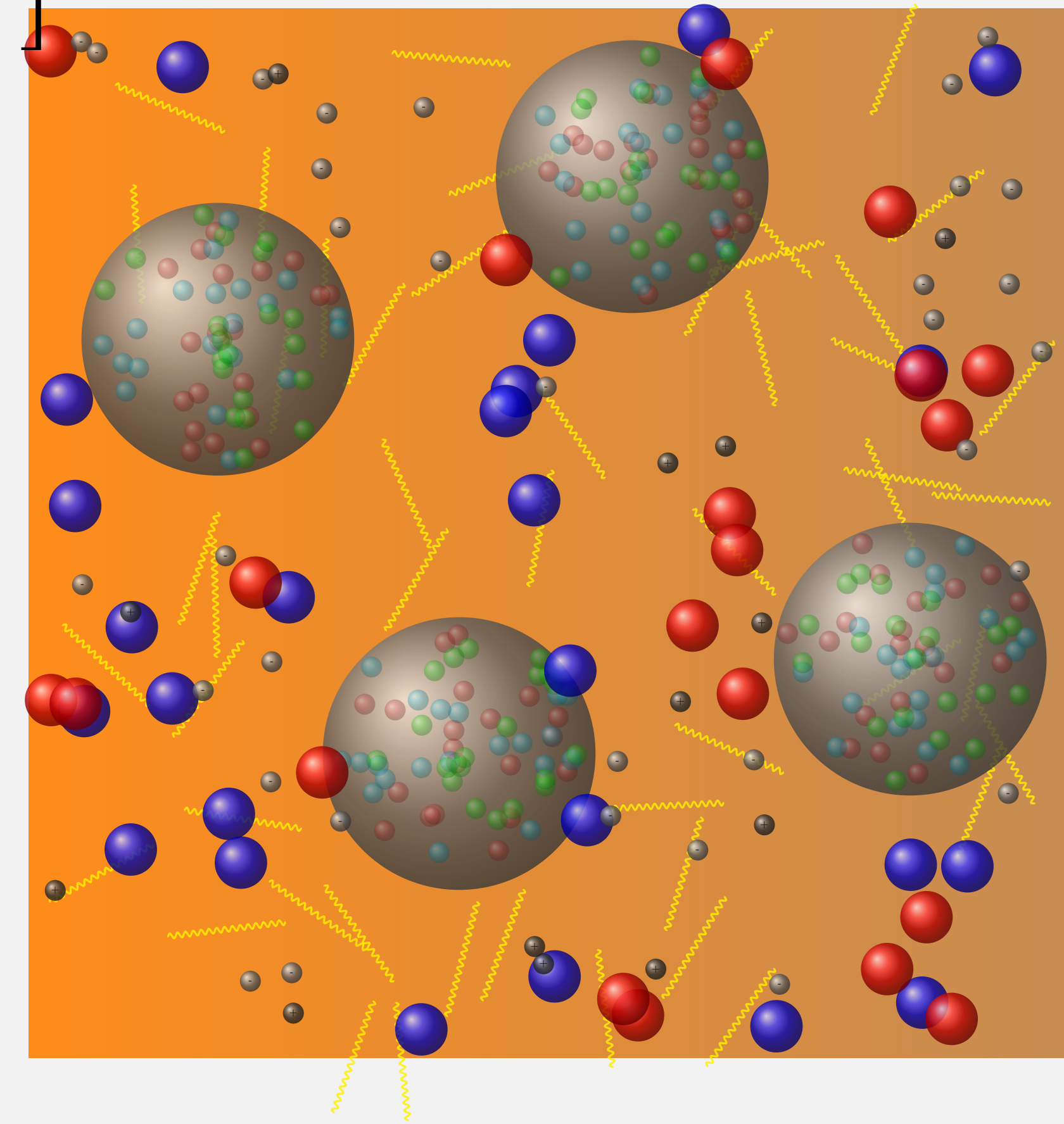
$$n_B = An_A + n_n^{(G)} + n_p^{(G)}$$

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

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

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

Nuggets + Gas



Recall the binding energy is

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

• Non-equilibrium EOS



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

Nugget
cooling

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

$$U \approx 3\pi^2 AT_s^2 / 2\mu_q$$

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

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

Evaporation

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

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

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

Proton neutron
conversion

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

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

Applied to a homologous expansion model

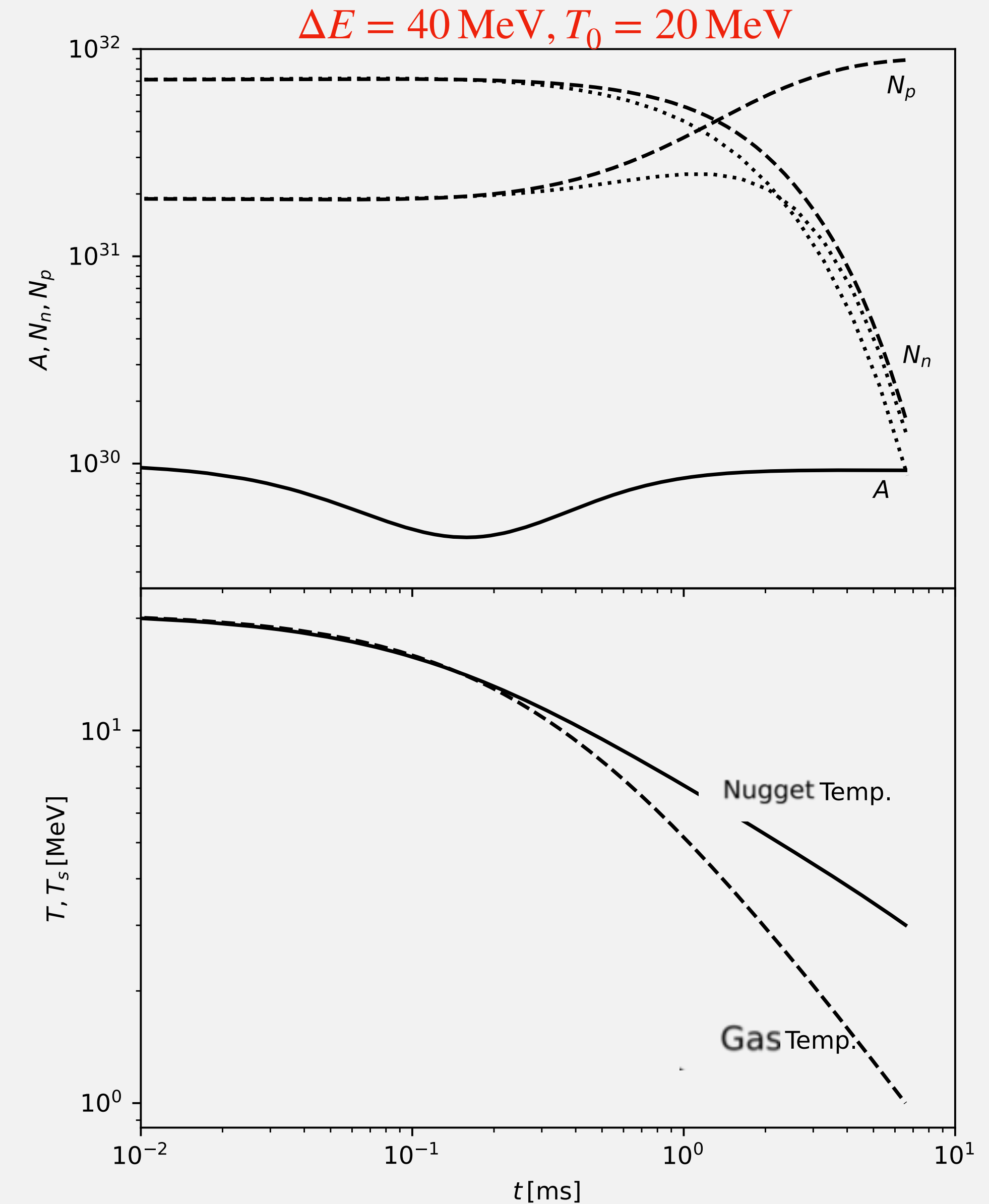
$$\rho(t) = \frac{M_{\text{ej}}}{(4\pi/3)v_{\text{ej}}^3(t+t_0)^3},$$

$$T(t) = T_0 \left(1 + \frac{t}{t_0}\right)^{-3(\gamma-1)} \quad \gamma = 4/3$$

$$M_{\text{ej}} = 0.01 M_{\odot}, v_{\text{ej}} = 0.1c, \rho_0 = \rho(0) = 5 \times 10^{12} \text{ g/cm}^3$$



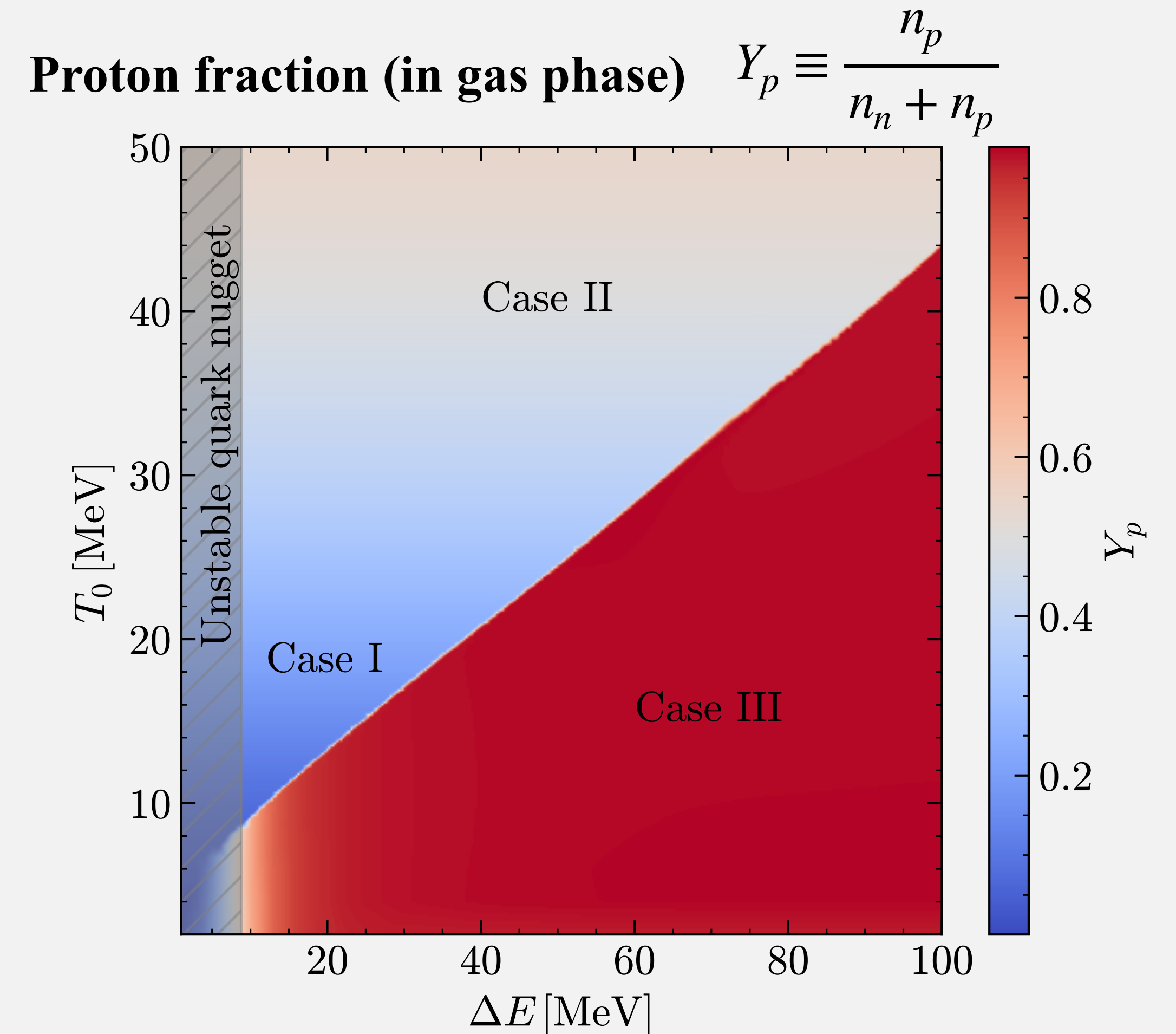
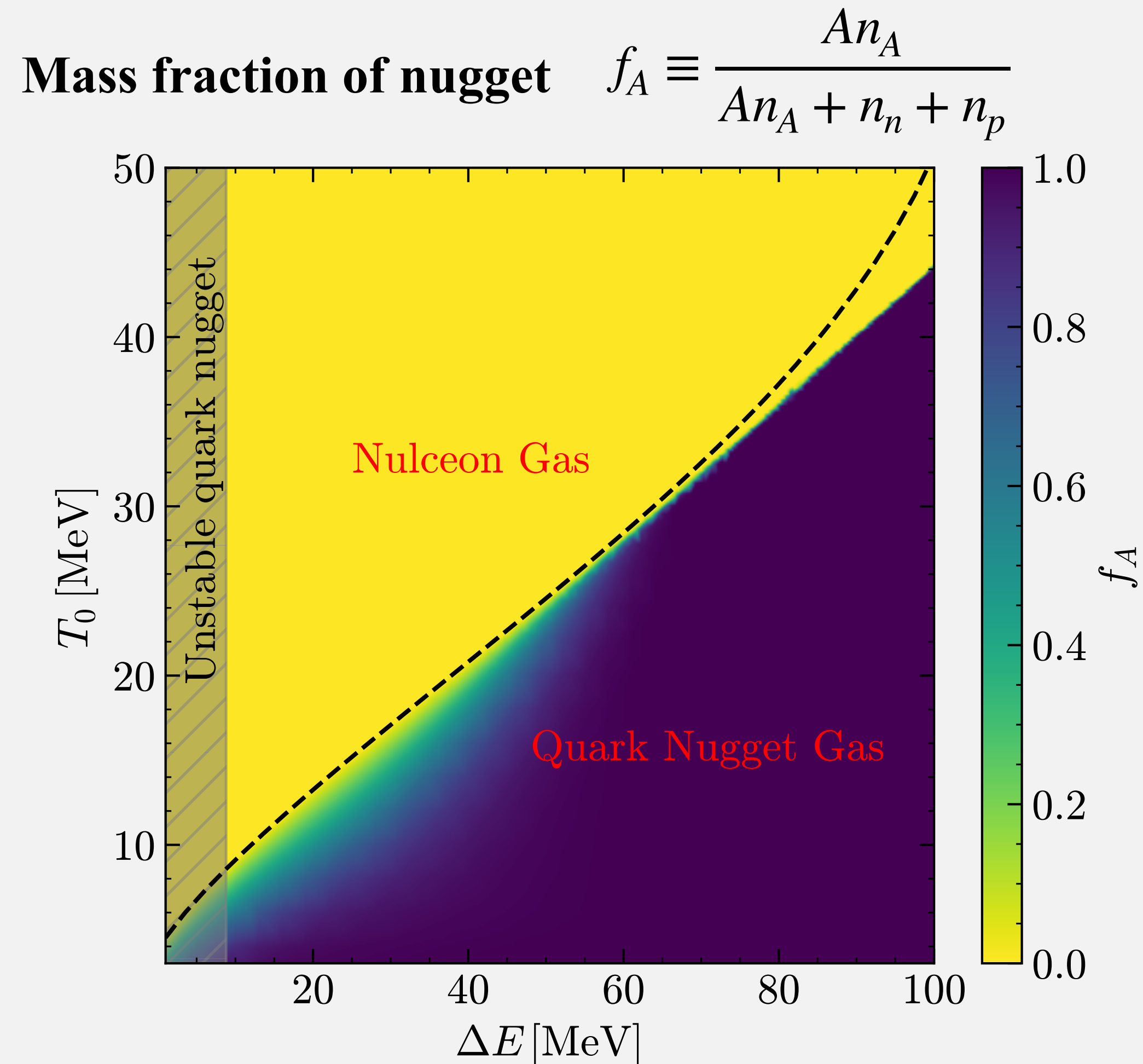
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Two fractions



Properties at $T = 1 \text{ MeV}$ when fixing $\rho_0 = 5 \times 10^{12} \text{ g/cm}^3$, $v_{ej} = 0.1c$, $M_{ej} = 0.01 M_\odot$
(at this temp. the compositions almost freeze, and nucleosynthesis starts to play an important role)



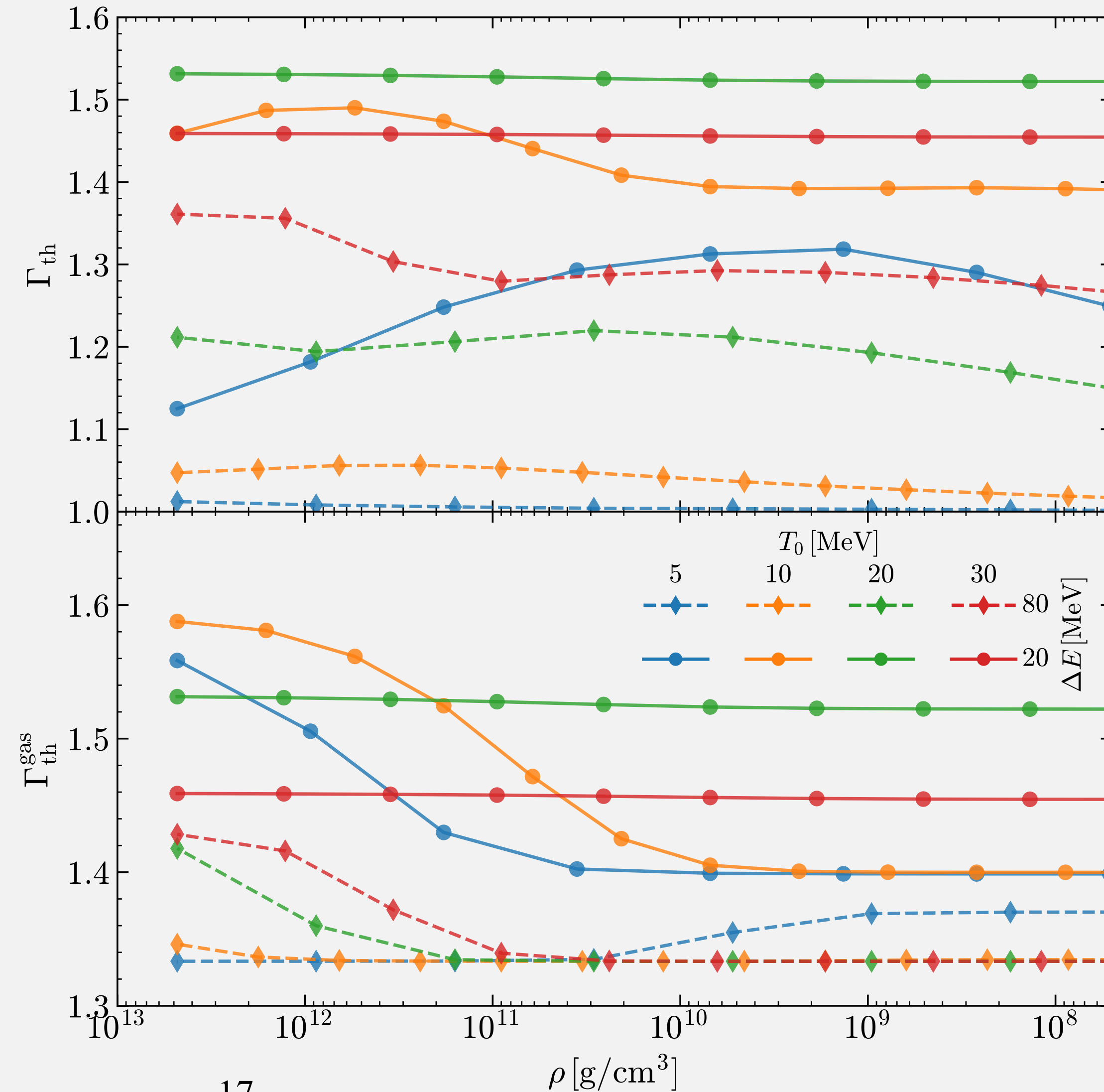
Equation of state of ejecta



$$\rho = Am_n n_A + m_n n_n + m_p n_p,$$

$$P_{\text{th}} = P_n + P_p + P_{e^+e^-} + P_\gamma,$$

$$\epsilon_{\text{th}} = \epsilon_A + \epsilon_n + \epsilon_p + \epsilon_{e^+e^-} + \epsilon_\gamma,$$



• Applied to BQS simulations

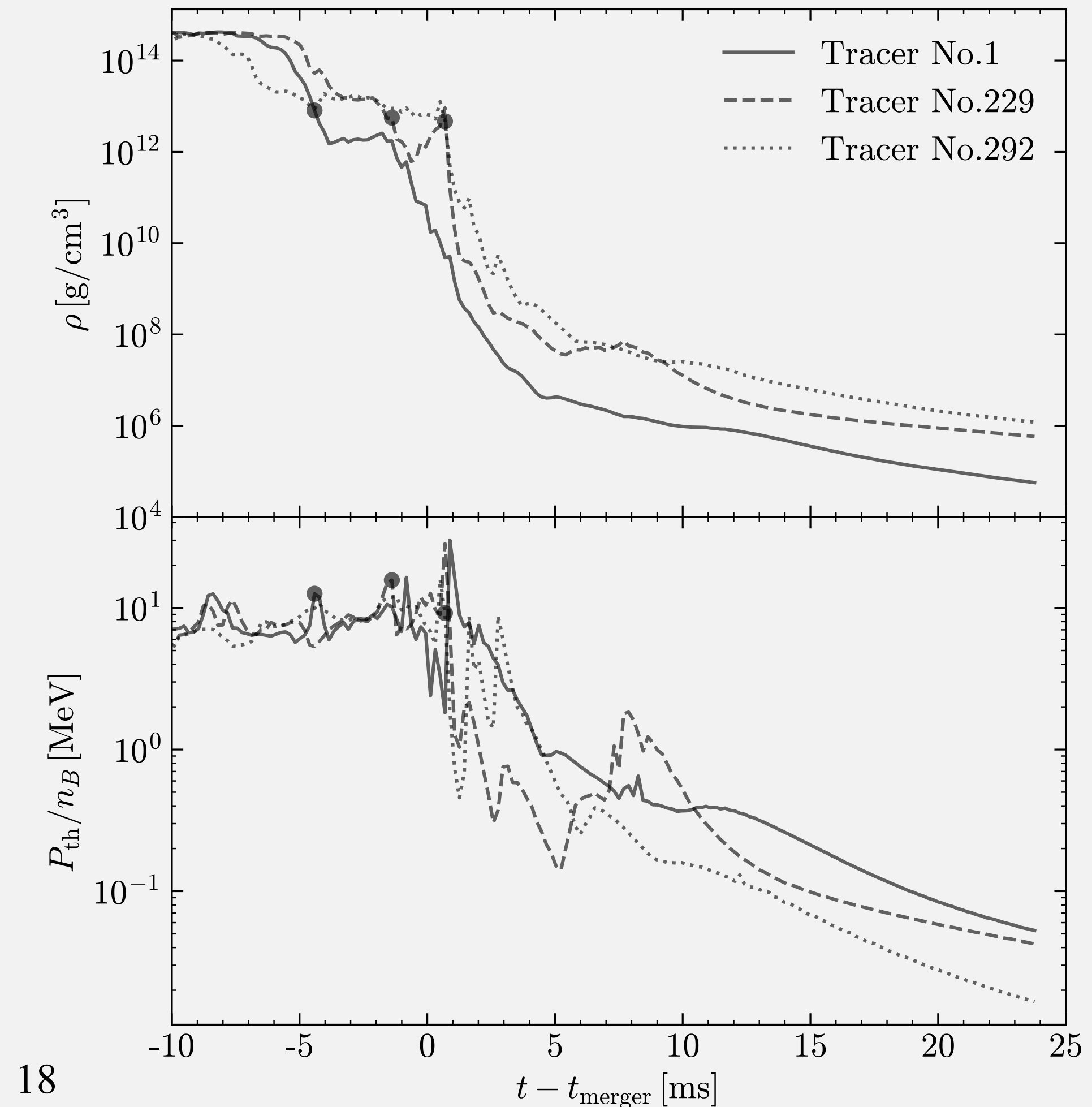
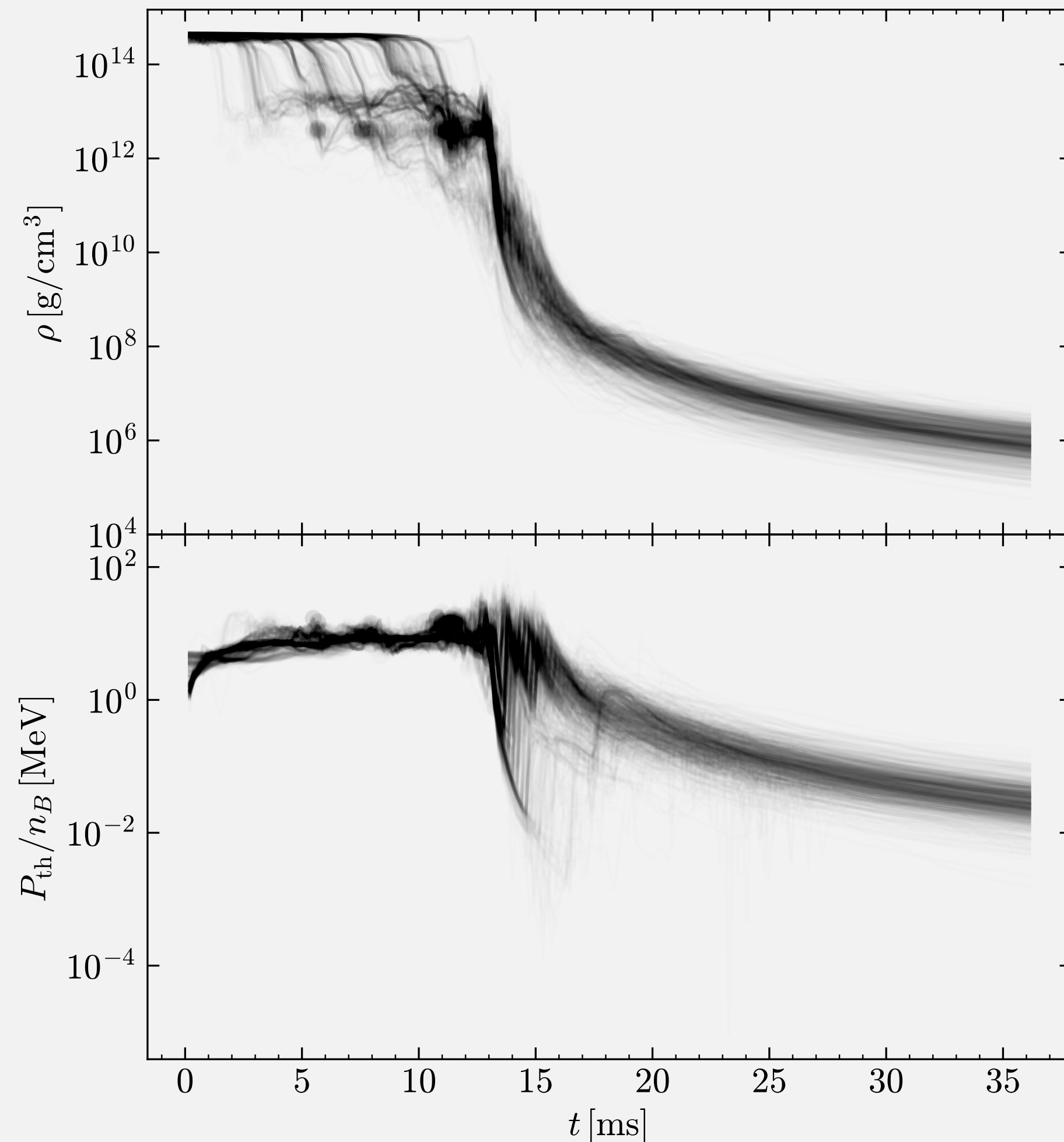


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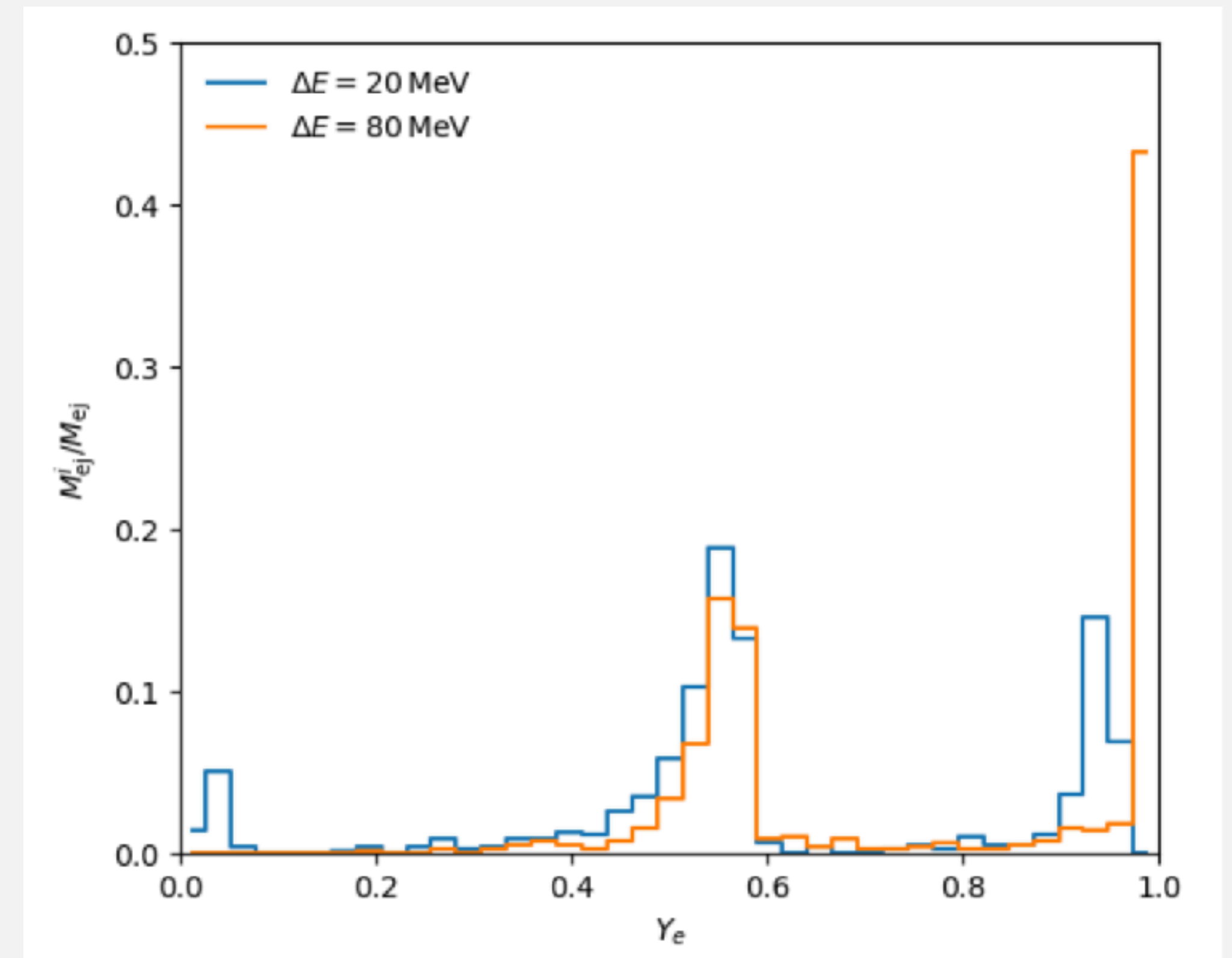
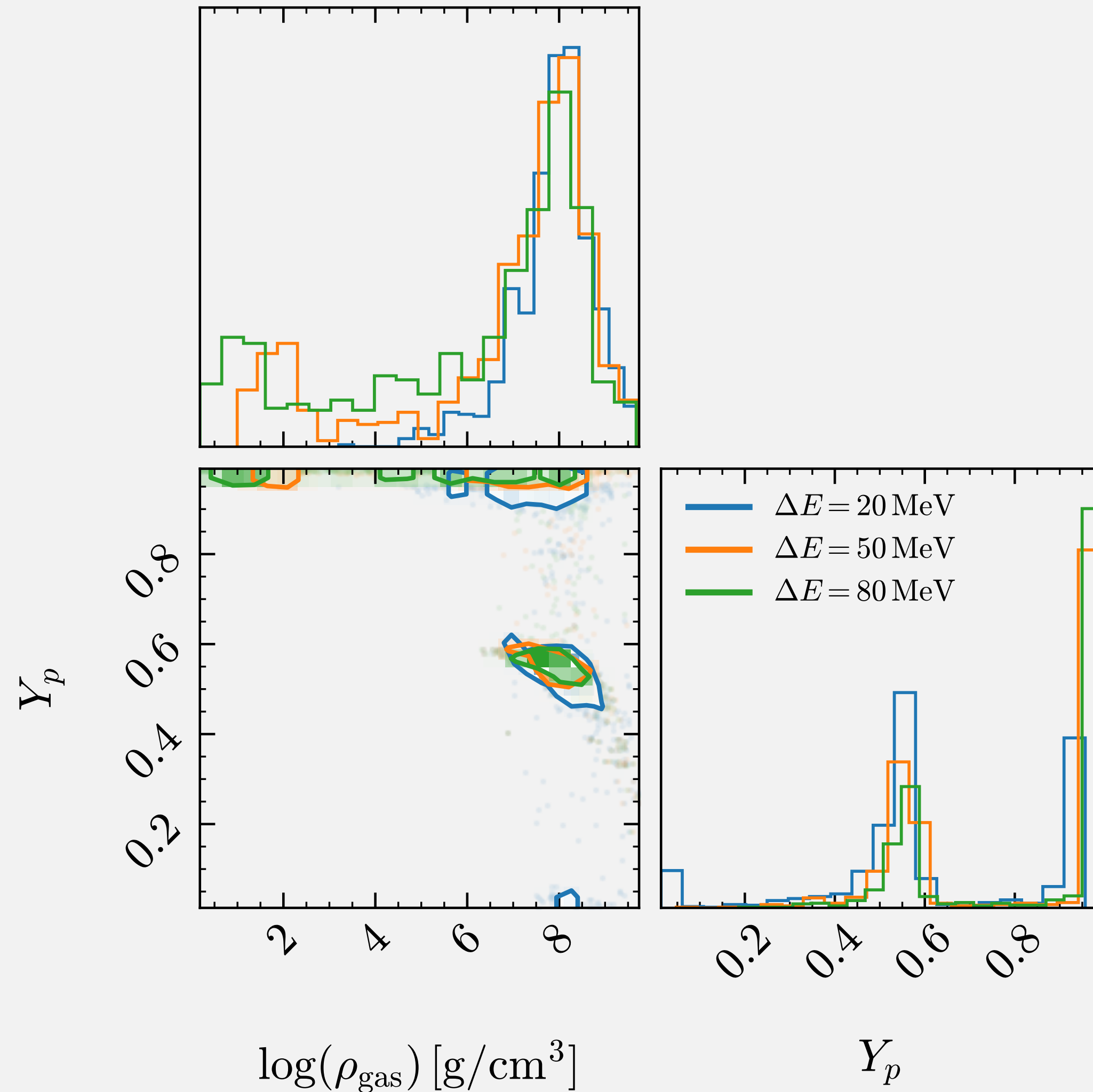
GRHD simulation from Zhu et al. PRD 2021

There are a total of 1030 tracers

In the simulation, they used $P_{\text{th}} = (\Gamma_{\text{th}} - 1)\epsilon$, $\Gamma_{\text{th}} = 7/4$



• Applied to BQS simulations



• Discussion & Conclusion



✓ The ejecta properties are primarily determined by the binding energy of the quark nuggets

Case I: a low Y_p ($\lesssim 0.2$) nucleon gas

Case II: a medium Y_p ($\sim 0.2 - 0.6$) nucleon gas

Case III: an extremely proton-rich ($Y_p \sim 1$) quark nugget gas.

✓ QS merger ejecta can differ significantly from those in NS mergers, possible for distinguishing btw them

✓ Need reliable BQS or QS-BH simulations, as well as nucleosynthesis and lightcurve calculations.

Thank you!

• 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

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

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

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

Applied to BQS simulations



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