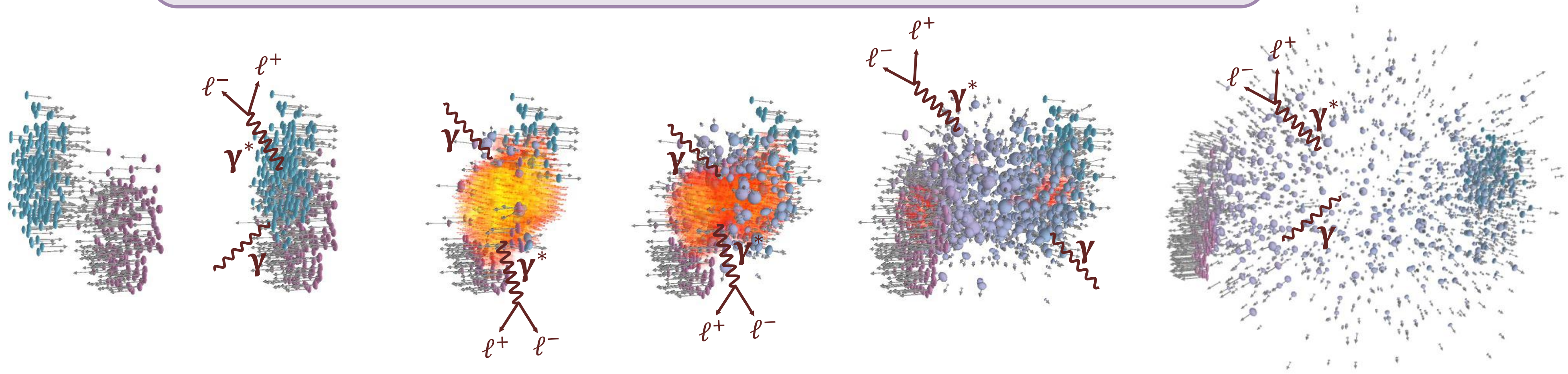
Dilepton Measurements with HADES as Probes of Hot and Dense Hadronic Matter

Niklas Schild for the HADES Collaboration

Motivation

Electromagnetic probes (γ, γ^*) penetrate strongly-interacting medium and can bring direct information to the detector



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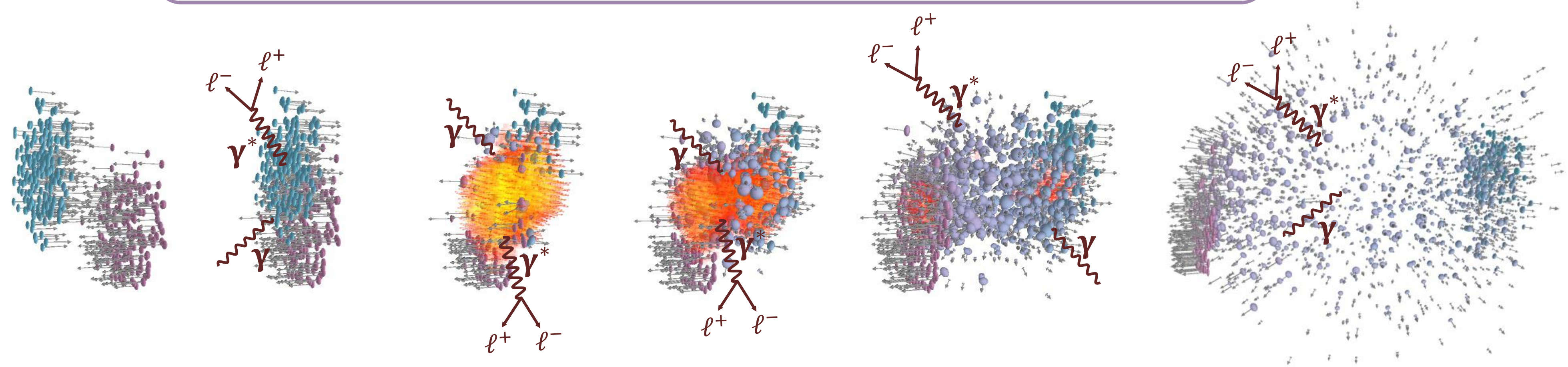


Allow many unique measurements

Signals of phase transition via lifetime and temperature measurement

Restoration of chiral symmetry

Degrees of freedom of the medium

Transport properties

Yet bring own set of challenges

Need to isolate contribution of interest

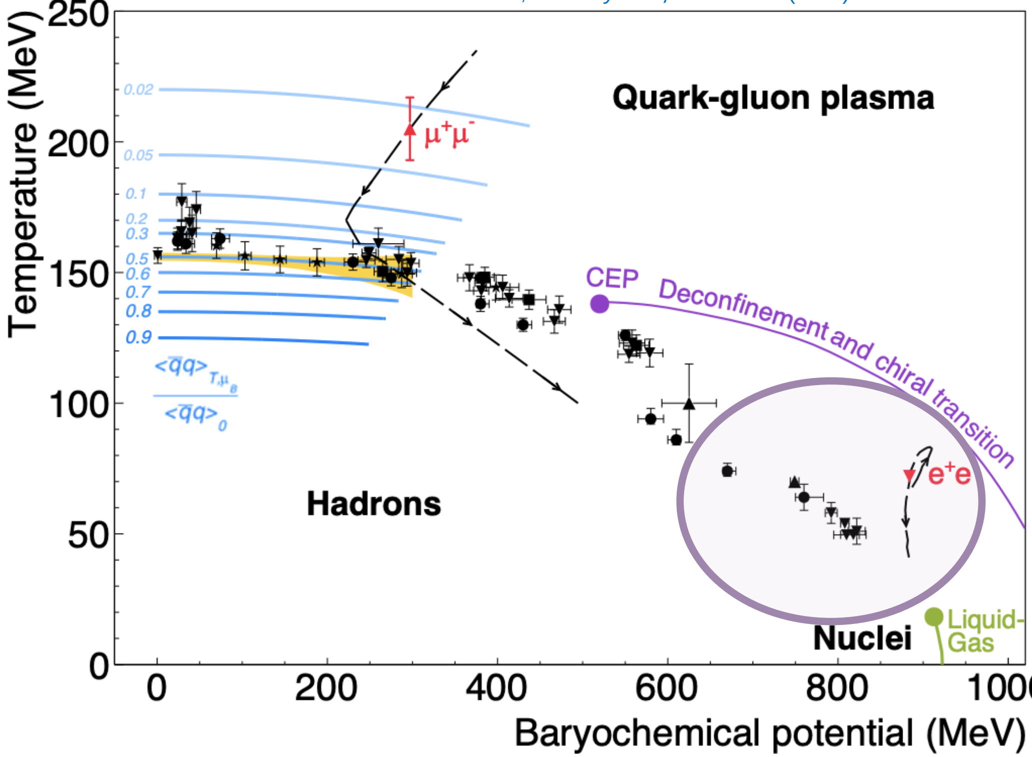
Rarity of events (BR ~ 10^{-5})

The High-Acceptance-Di-Electron-Spectrometer

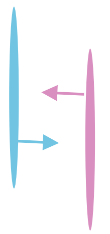
- **Heavy ion collisions** at $\sqrt{s_{NN}} = 2 - 3$ GeV
  - ⇨ Different collision dynamics compared to higher energies
- **Pion and nucleon beams**
  - ⇨ Reference measurements
  - ⇨ Inclusive and exclusive measurements

Explore region of QCD phase diagram with high net-baryon density and moderate temperatures

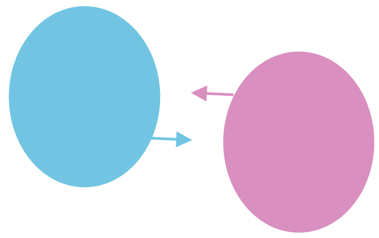
The HADES Collaboration, *Nat. Phys.* **15,** 1040–1045 (2019)



LHC energies $\sqrt{s_{NN}} = 2$ TeV
parton+parton collisions
Early Universe in the laboratory



Energies $\sqrt{s_{NN}} \cong 2 * m_N$ GeV
nuclear stopping
NS merger matter in the laboratory

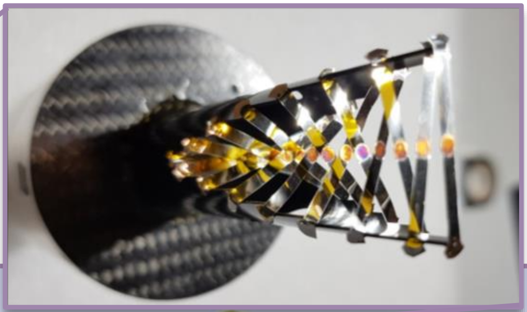


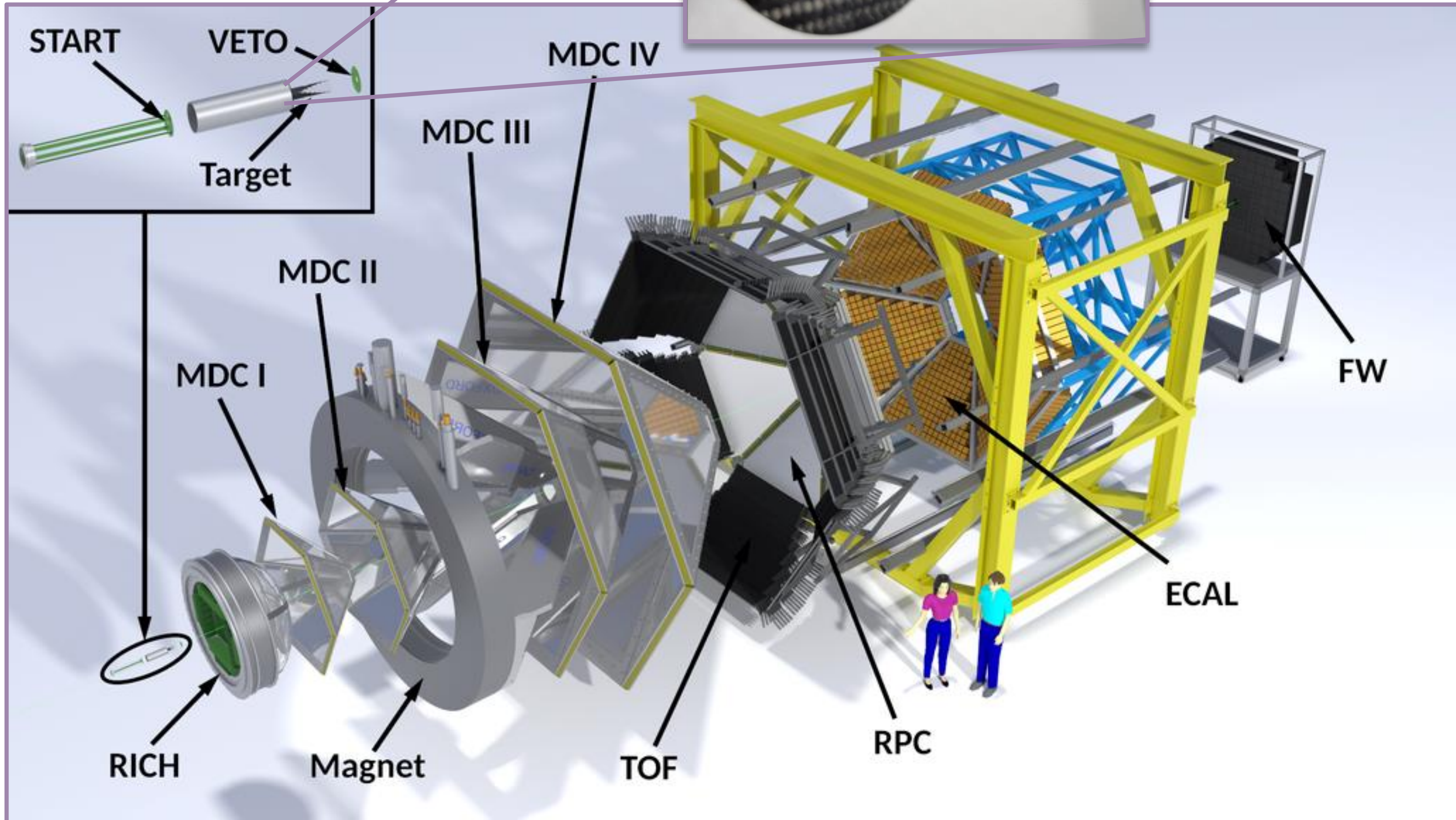
The High-Acceptance-Di-Electron-Spectrometer

- Designed with minimal material budget to reduce photon conversion
- Large angular coverage:

$$15° < \theta < 85°$$
$$0° < \phi < 360°$$

- Accepted trigger rate up to:
  - 16 kHz for heavy-ion collisions
  - 50 kHz with proton/pion beam
- Dedicated components for electron and positron identification





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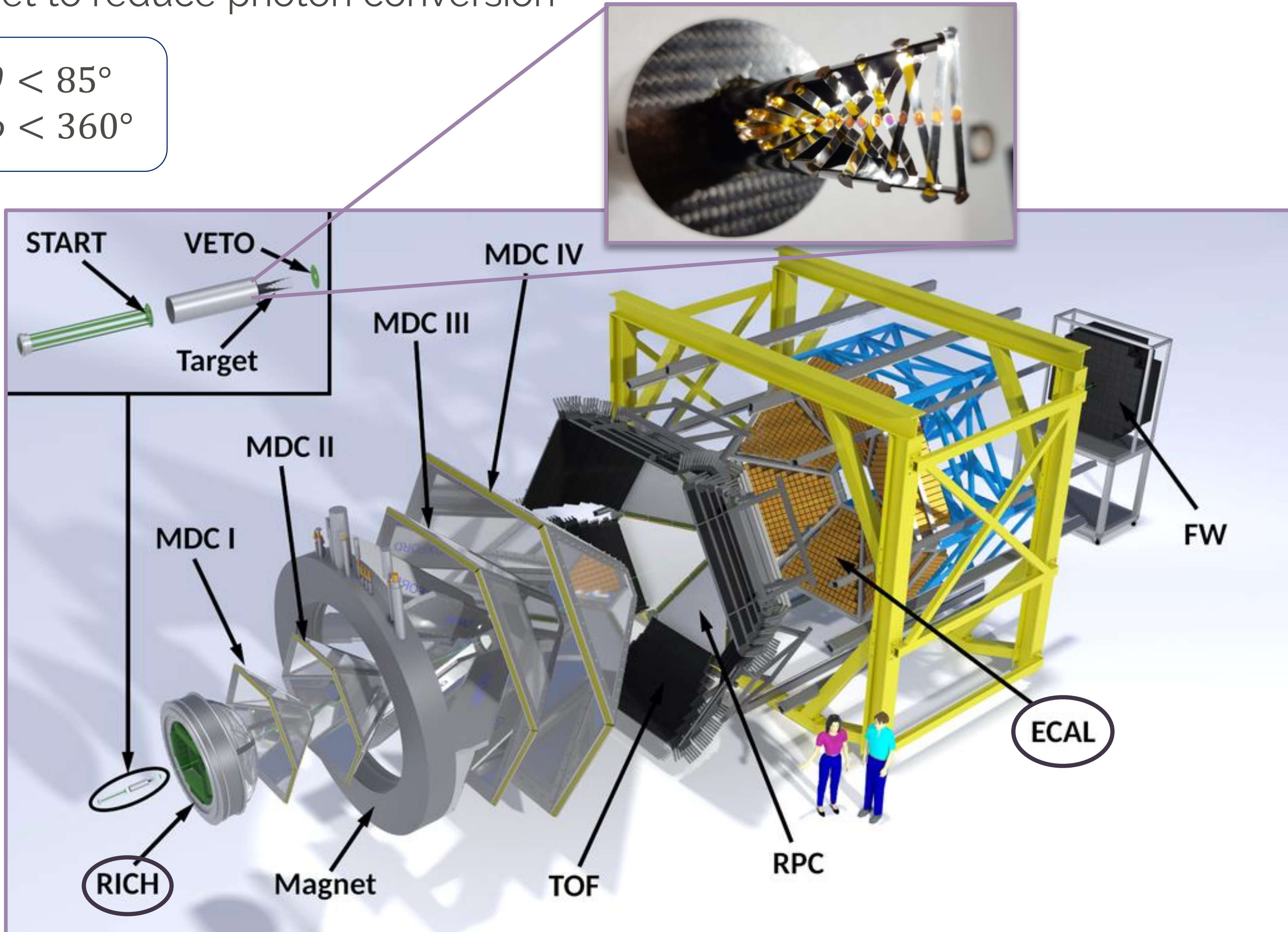

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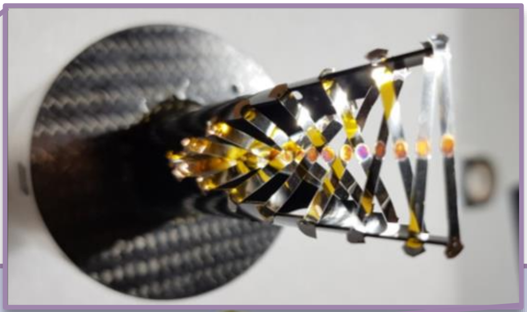
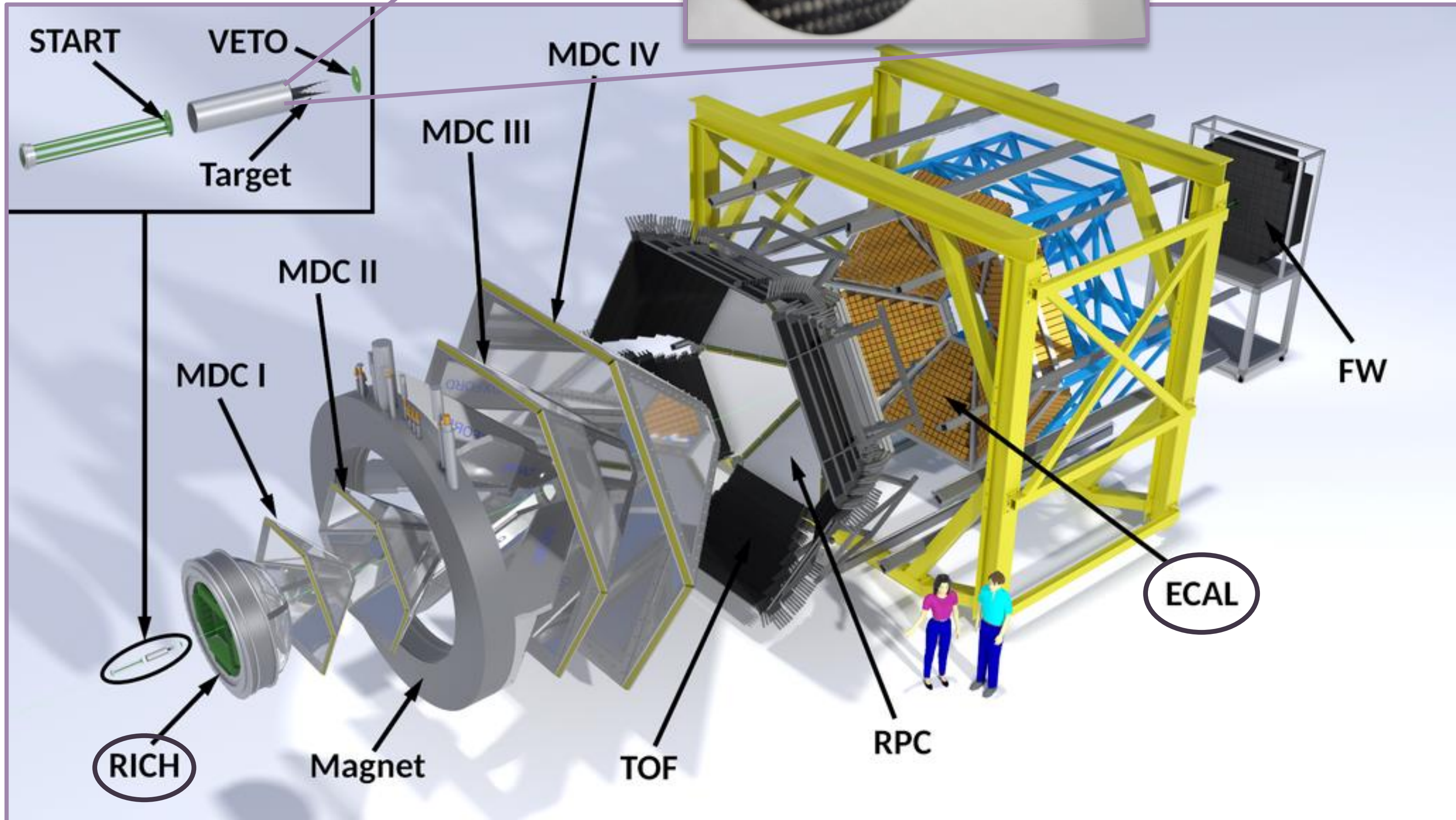




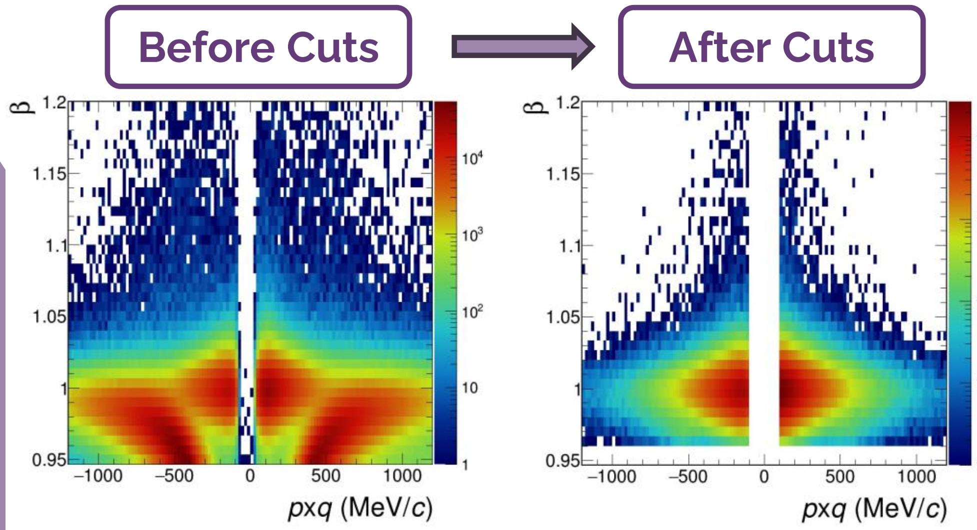
HADES allows reconstruction of electron sample with high effciency and high purity!

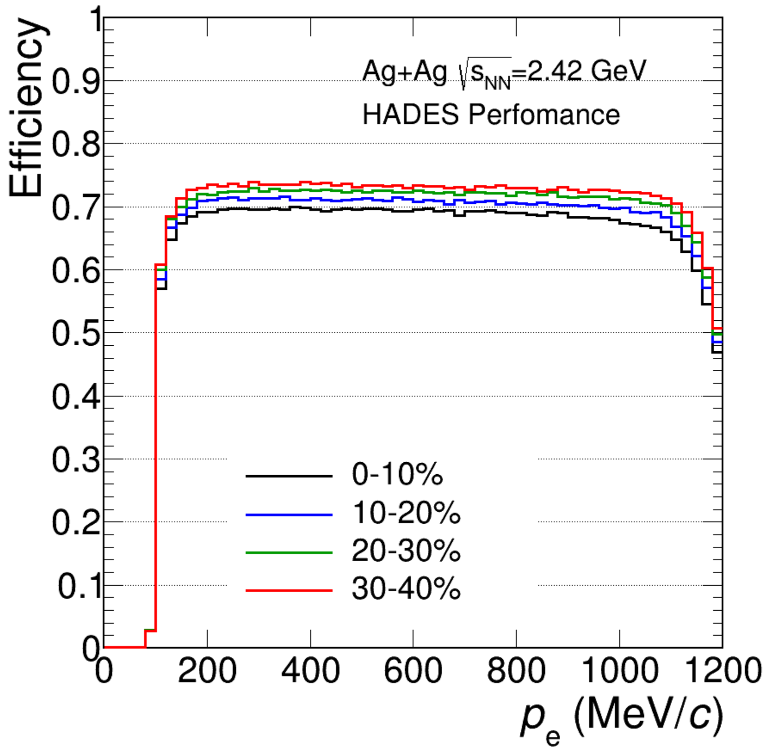
HADES – Lepton Identification Perfomance

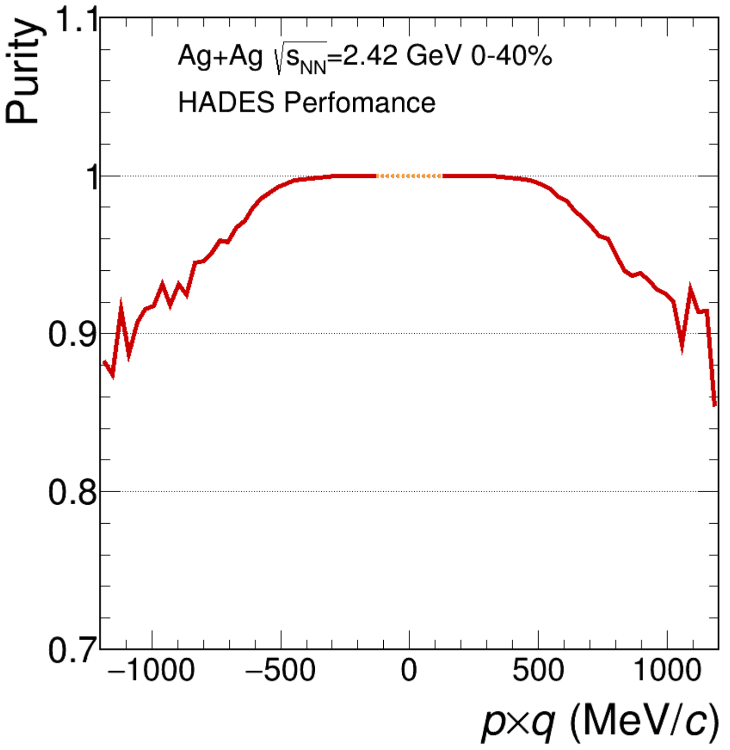
- Reconstruction efficiency ~ **70%**
- Purity above **95%** in relevant momentum region
- Hadron suppression of ~ $\mathbf{10^{-5}}$

Ag+Ag run in 2019

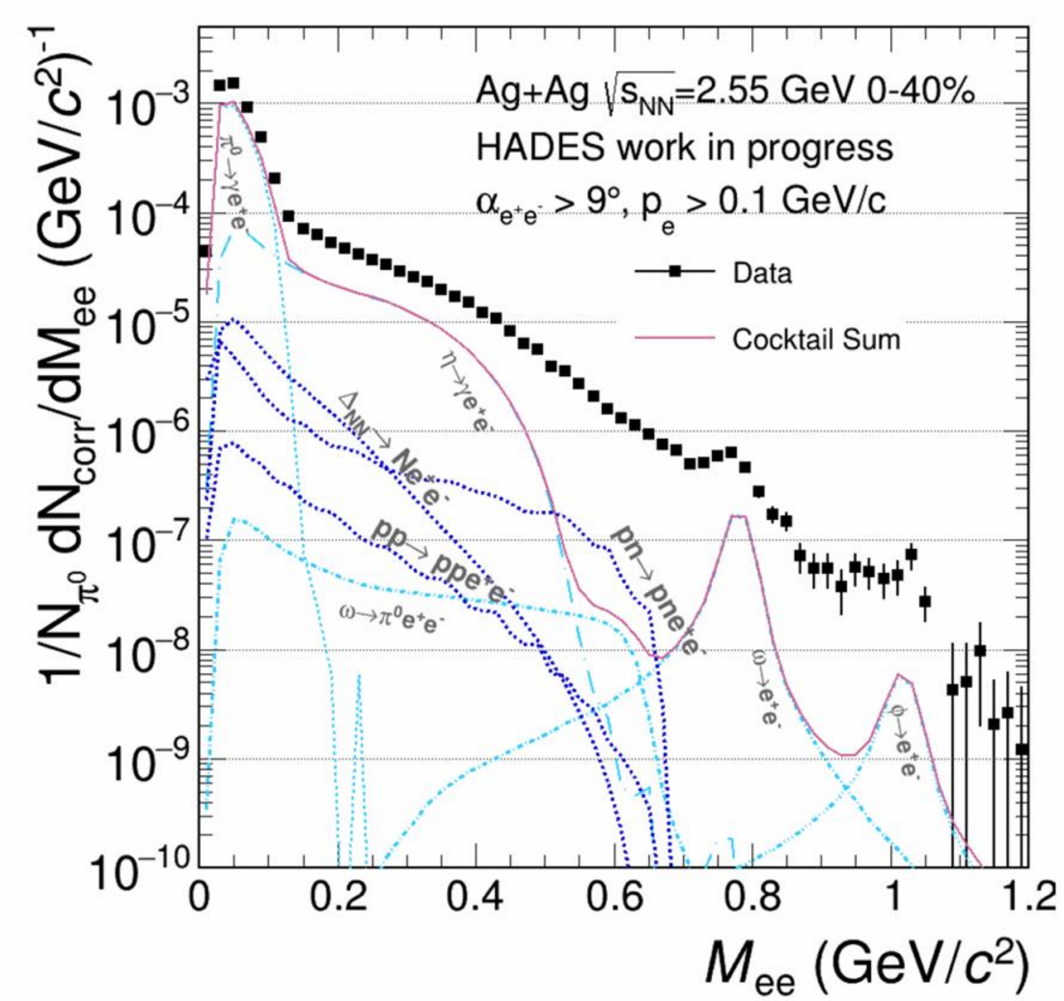
$N_{y*}^{rec} \approx 1.5 \cdot \mathbf{10^6}$ for $\sqrt{s_{NN}} = 2.55$ GeV (28 days)
$N_{y*}^{rec} \approx 1.5 \cdot \mathbf{10^5}$ for $\sqrt{s_{NN}} = 2.42$ GeV (3 days)

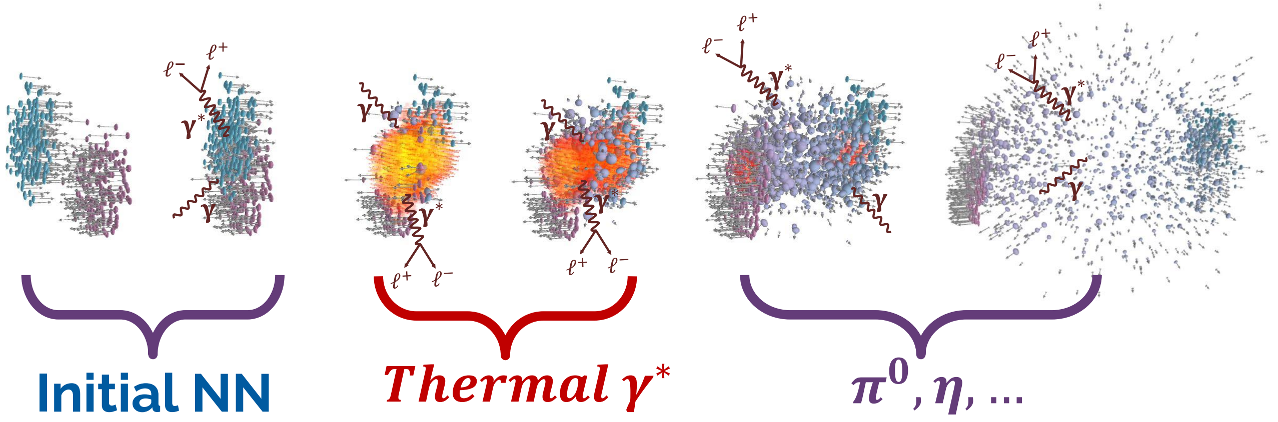






Dilepton – Invariant Mass Spectrum





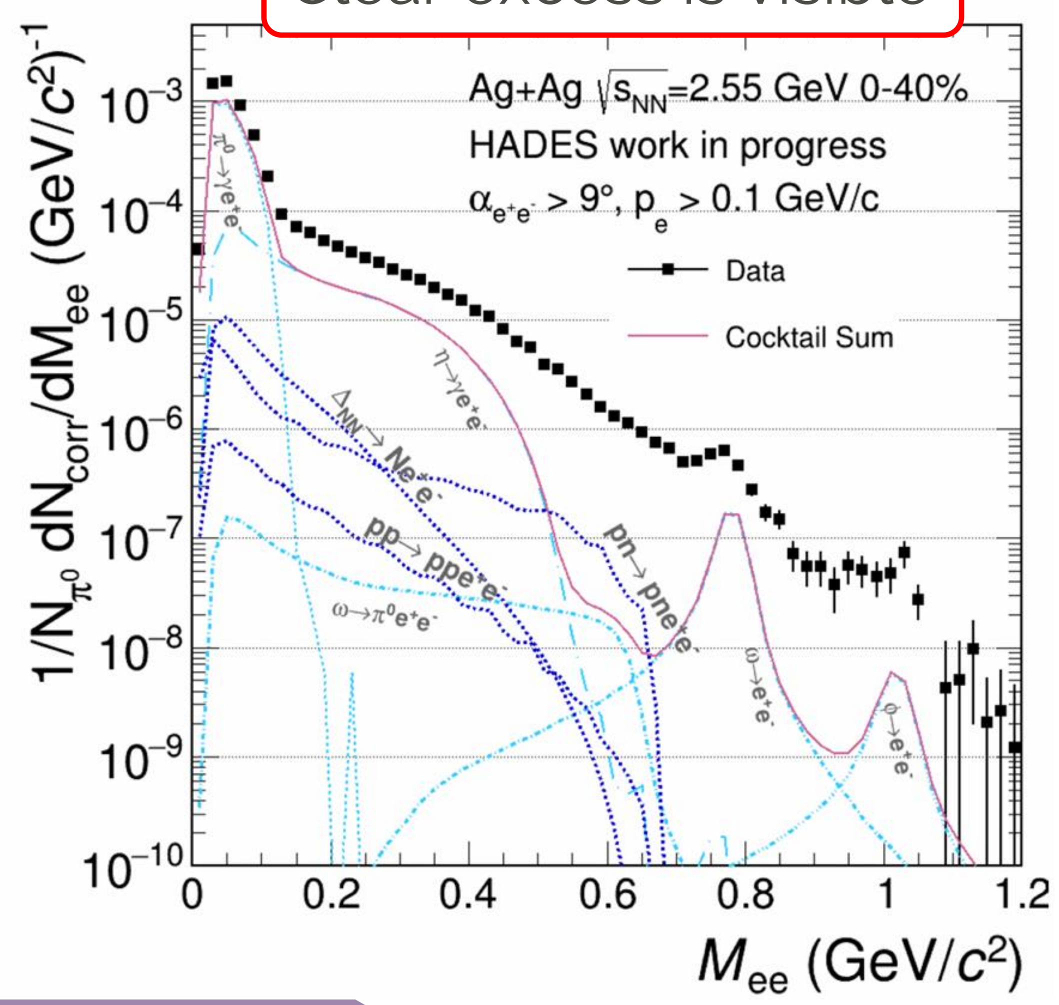
Measured signal is integral over whole evolution

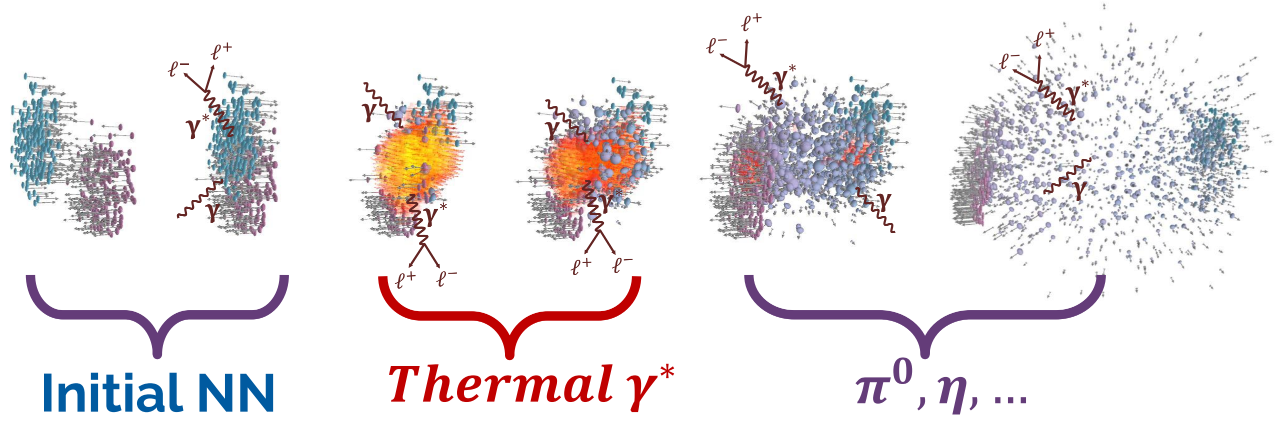
Isolate thermal contribution by subtraction of experimentally measured:

- Freeze-out cocktail $(\pi^0, \eta, \omega, \phi)$
- Initial NN reference spectrum
  - pp and $p(n)$ reactions

Dilepton – Invariant Mass Spectrum

Clear excess is visible





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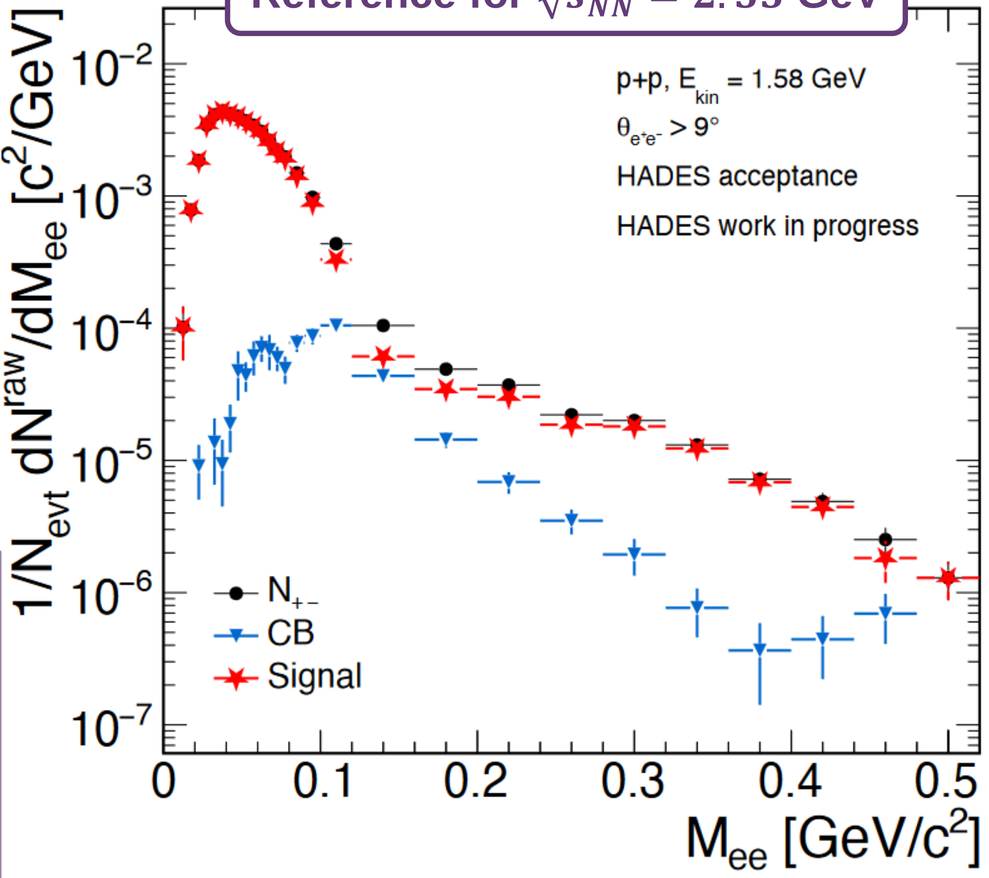
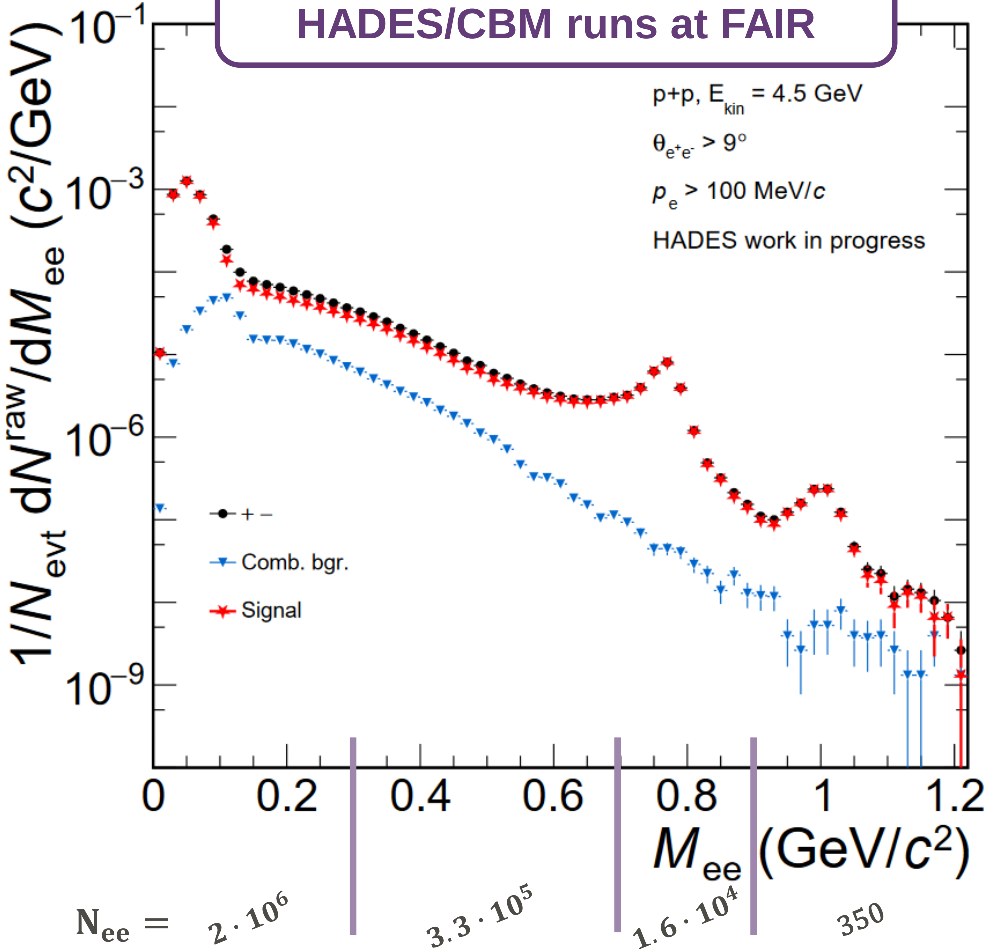
NN Reference Measurements

- Dedicated measurements of elementary collisions serve as reference
- High-statistics allow for multidifferential studies of cross sections

Reference for $\sqrt{s_{NN}} = 2.55$ GeV



Reference for future HADES/CBM runs at FAIR

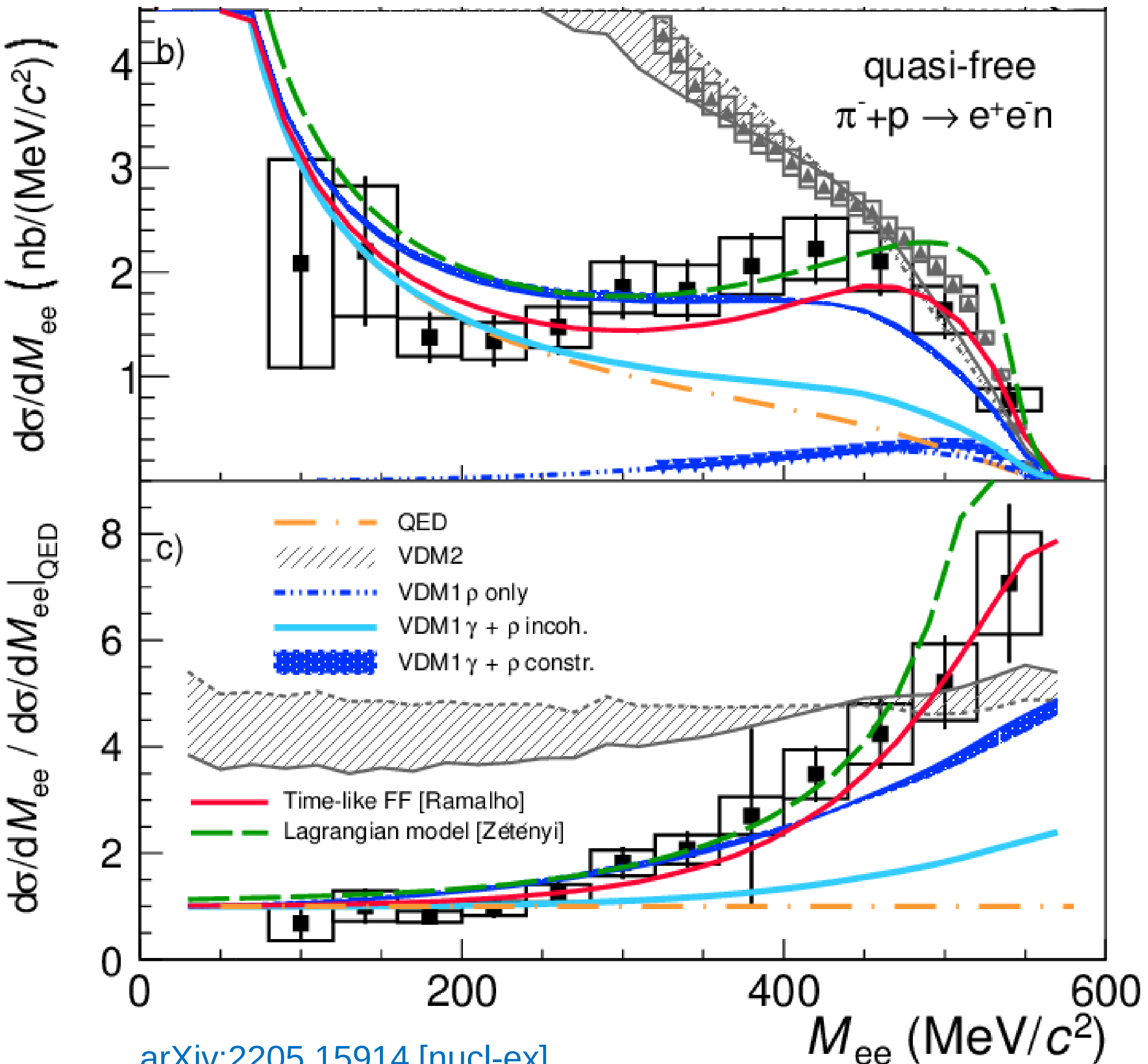


Pion Beam Measurements

- Study of Baryon-ρ coupling using pion-induced reactions

- $\pi^- + p \rightarrow n + e^+e^-$

➡ Provide crucial test of of Vector-Dominance-Model (VDM) models



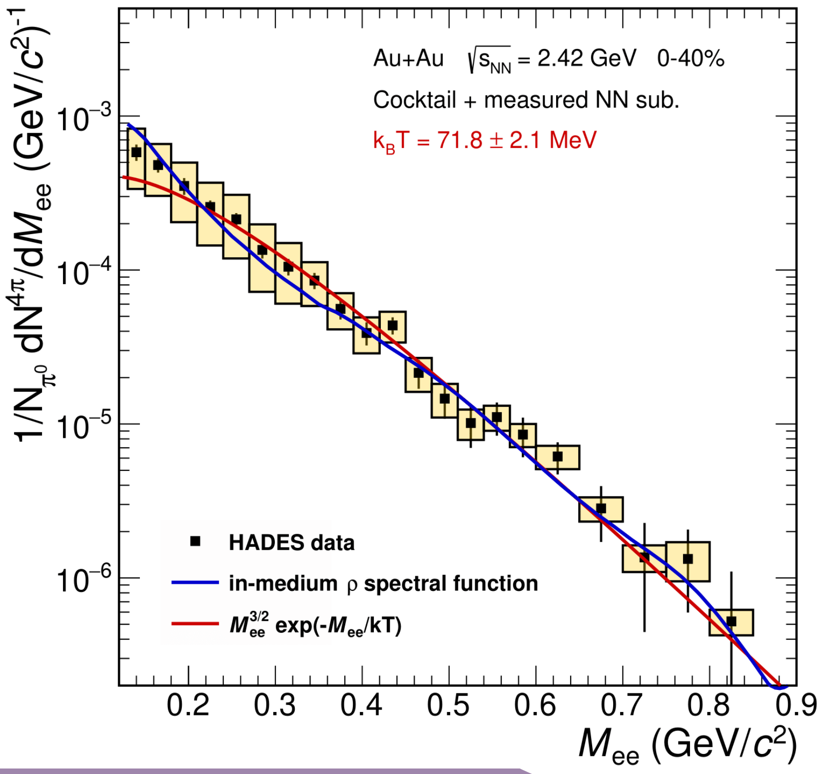
arXiv:2205.15914 [nucl-ex]

Dilepton Excess

$$\frac{dN_{ll}}{d^4x d^4q} = -\frac{\alpha_{em}^2}{\pi^3 M^2} L(M^2) f^B(q \cdot u; T)\ Im\Pi_{em}(M, q; \mu_B, T)$$

- Subtraction of reference and freeze-out sources reveals thermal excess
- Good agreement between data and theory predictions from coarse-grained (CG) UrQMD

Au+Au at $\sqrt{s_{NN}} = 2.42$ GeV



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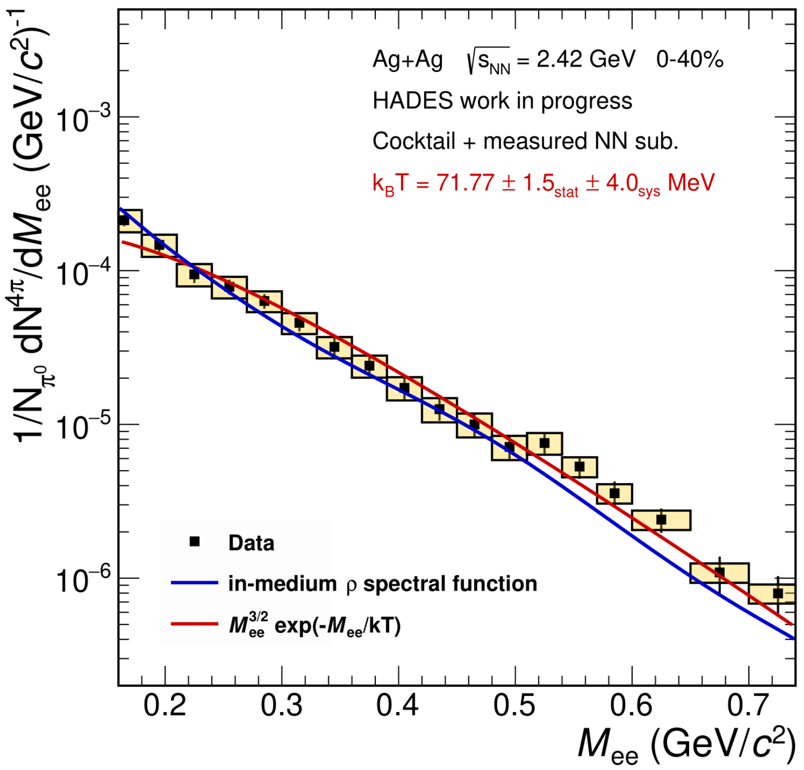

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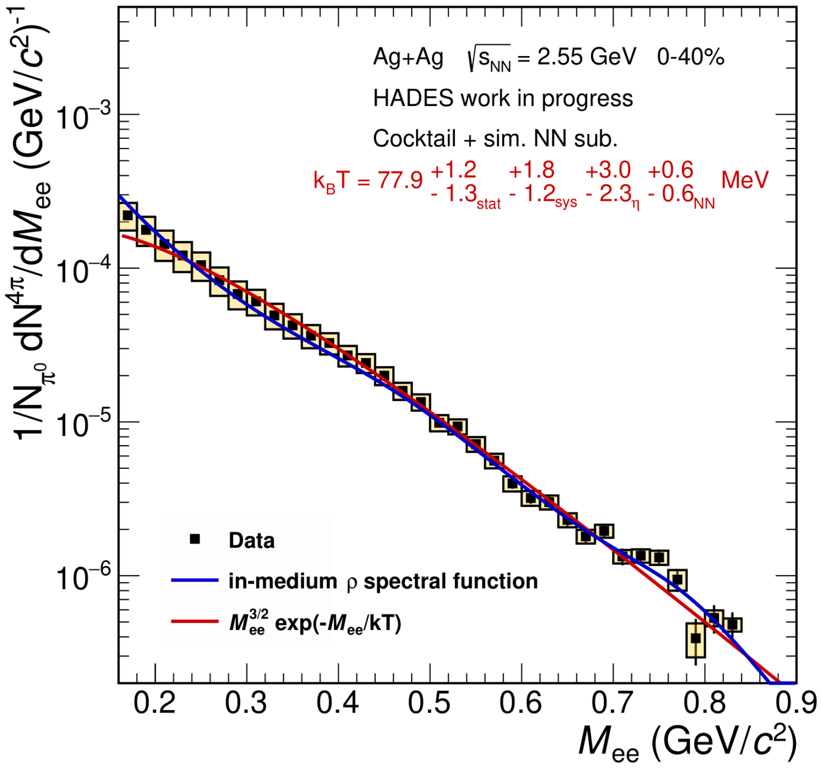
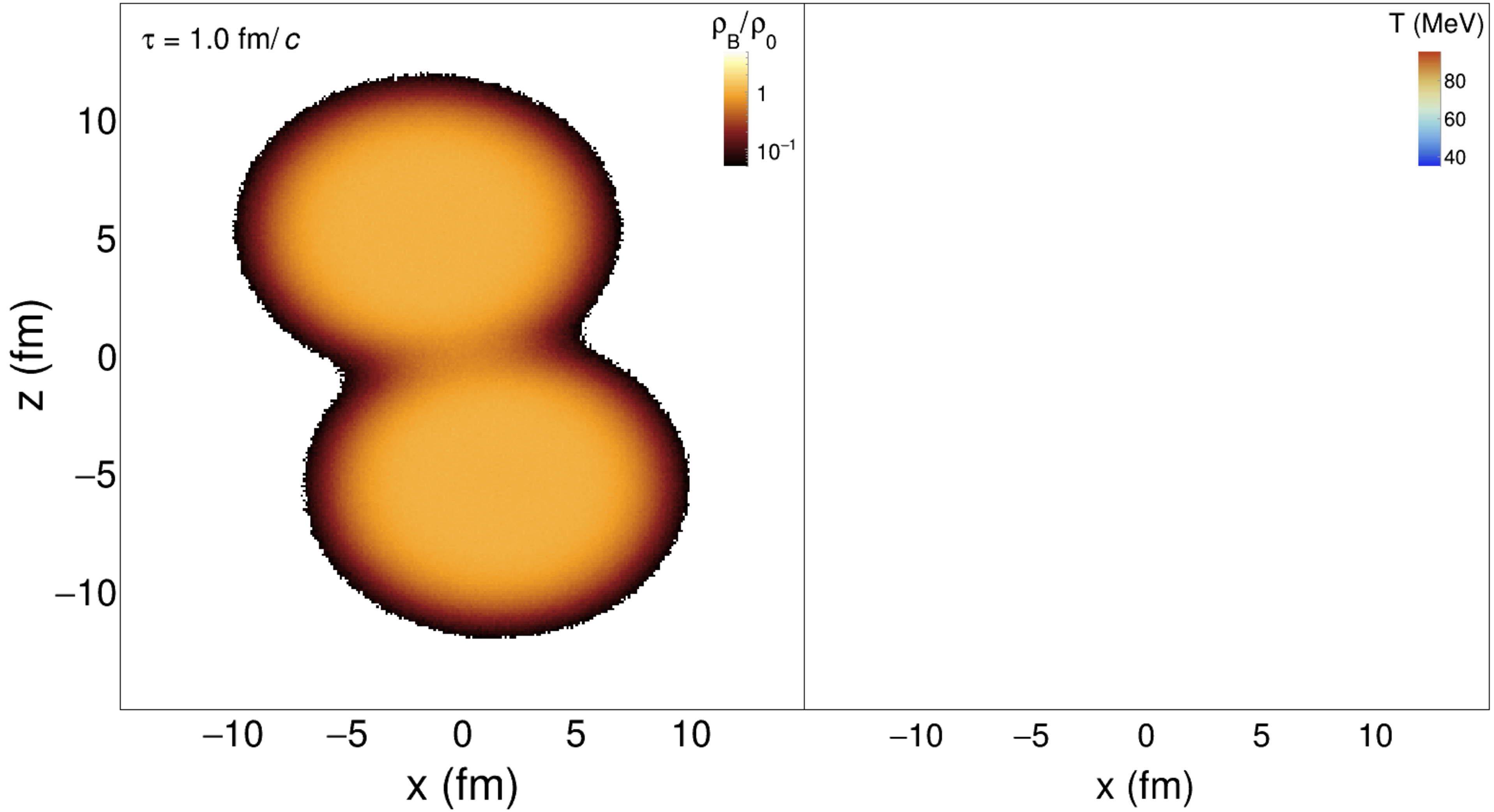


Eur.Phys.J.A 52 (2016) 5, 131

Simulated Profiles in Au+Au $\sqrt{s_{NN}} = 2.42$ GeV



F. Seck, M. Wiest

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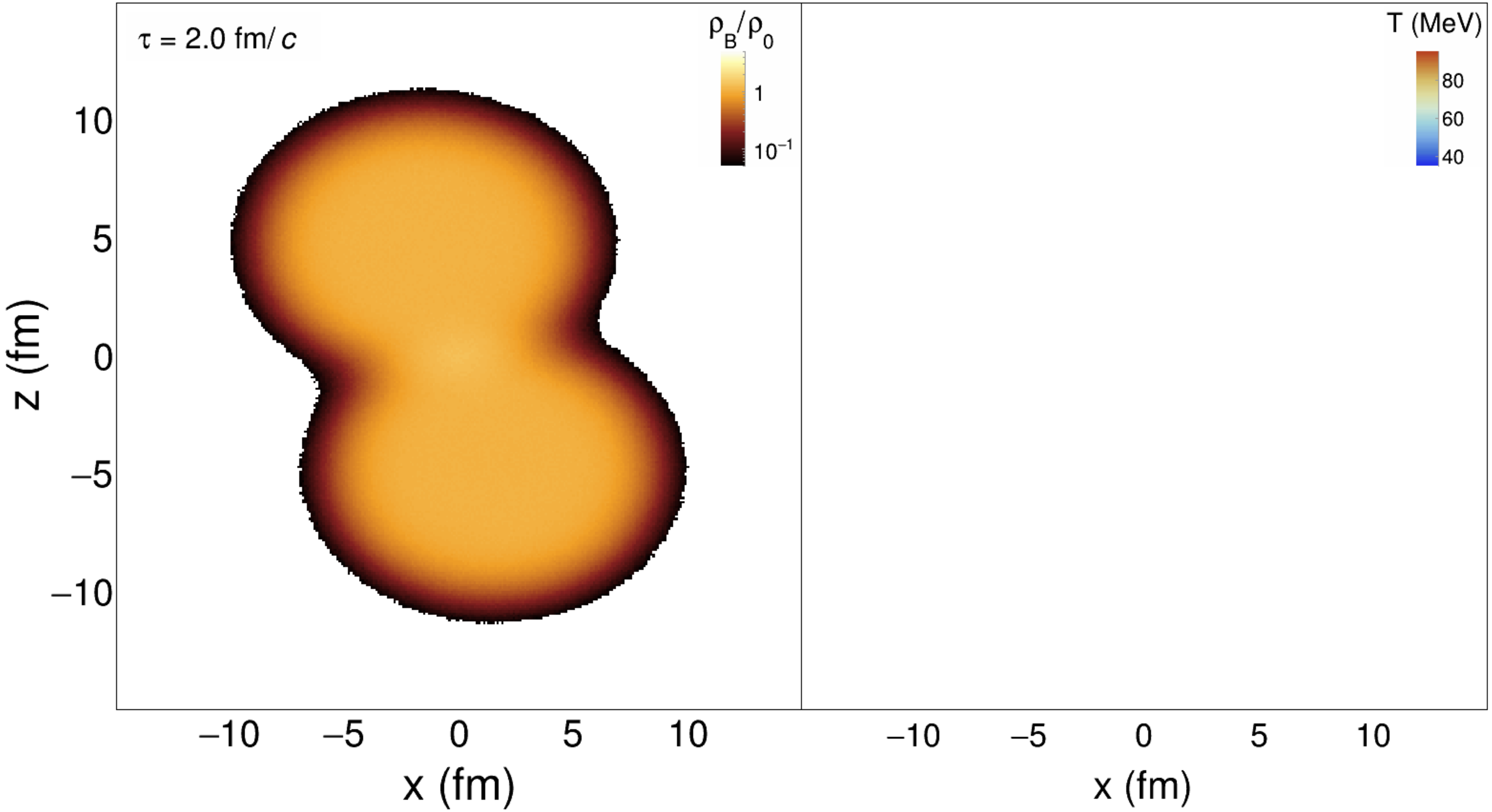

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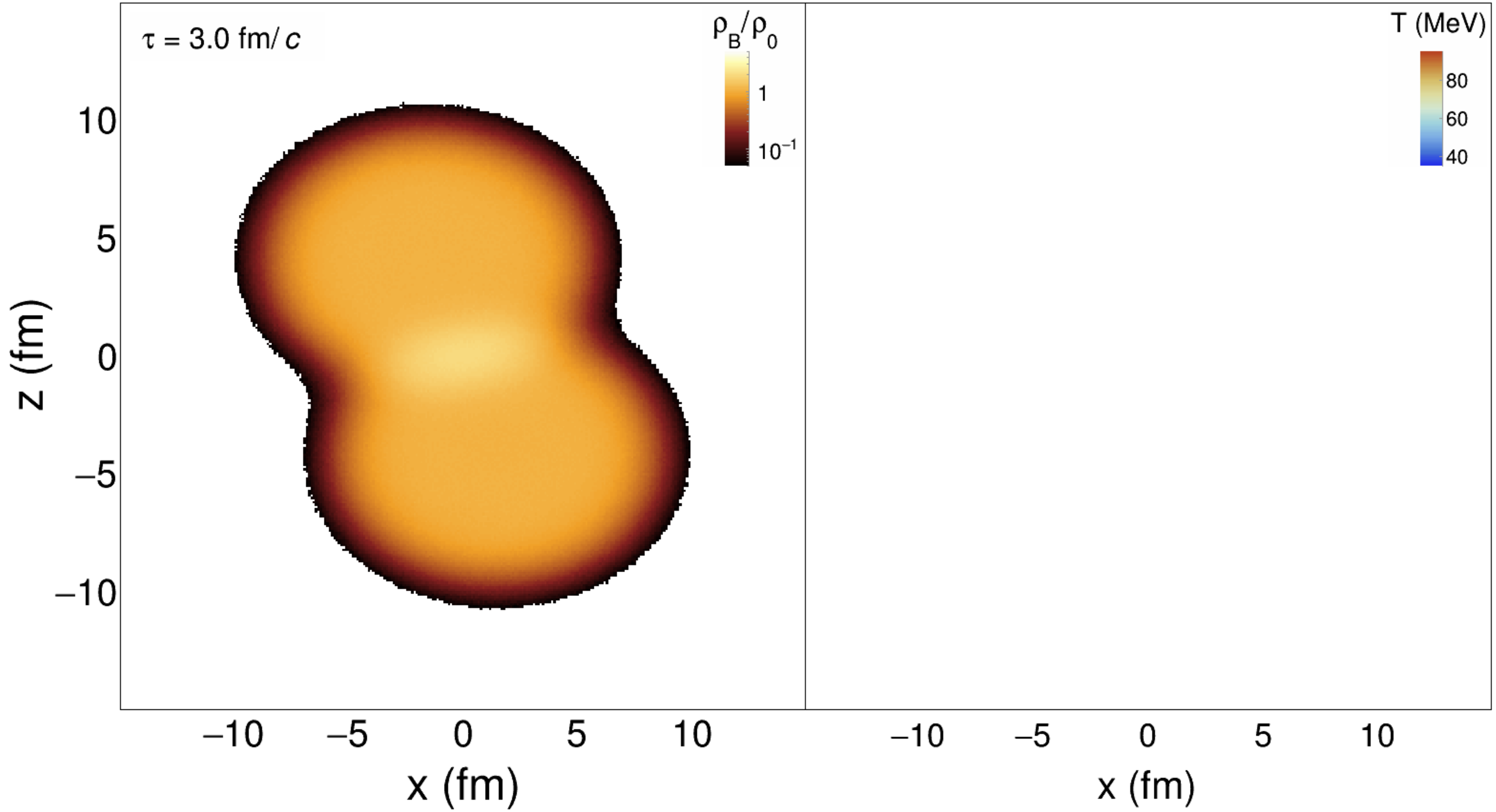

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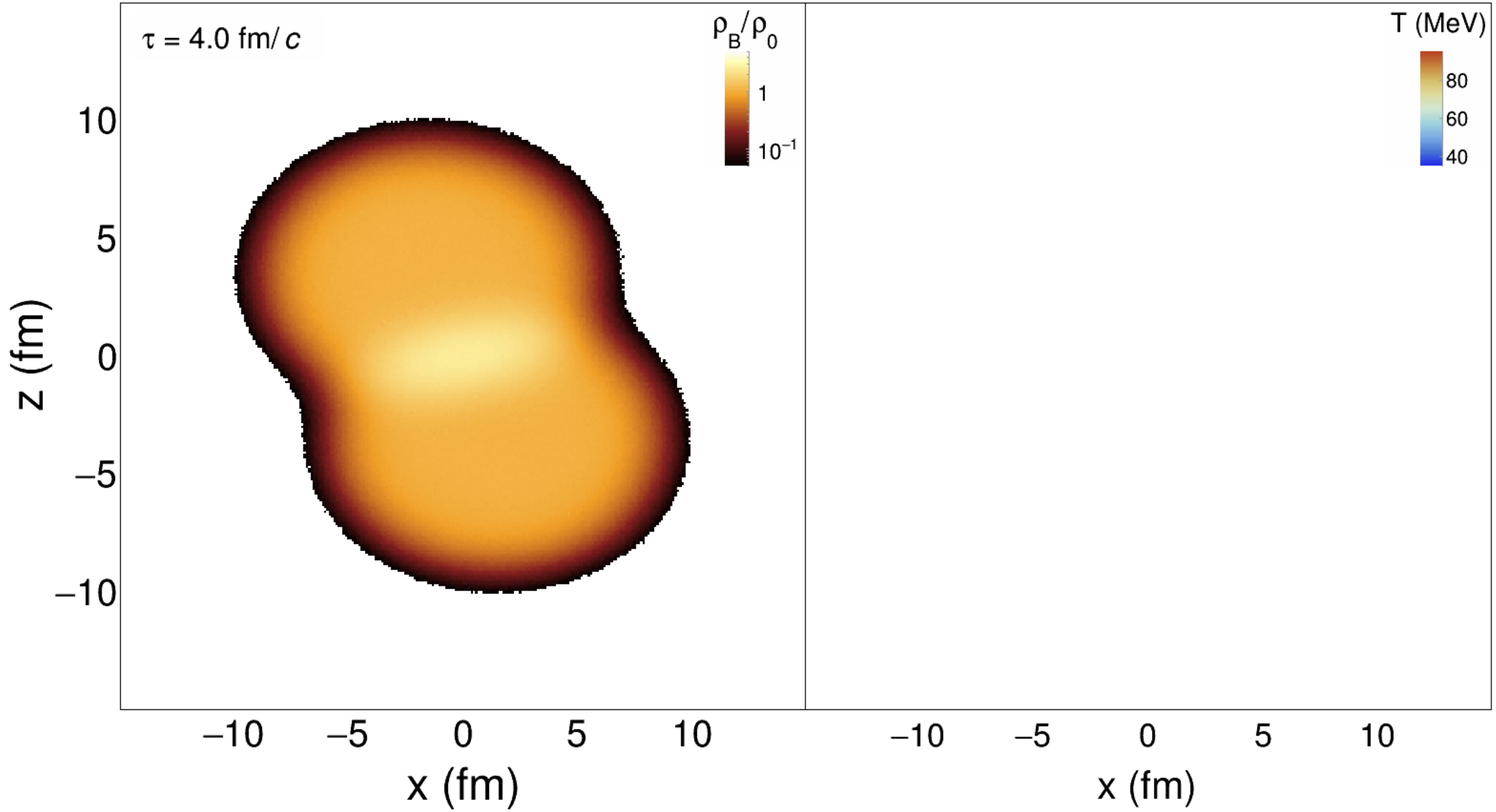

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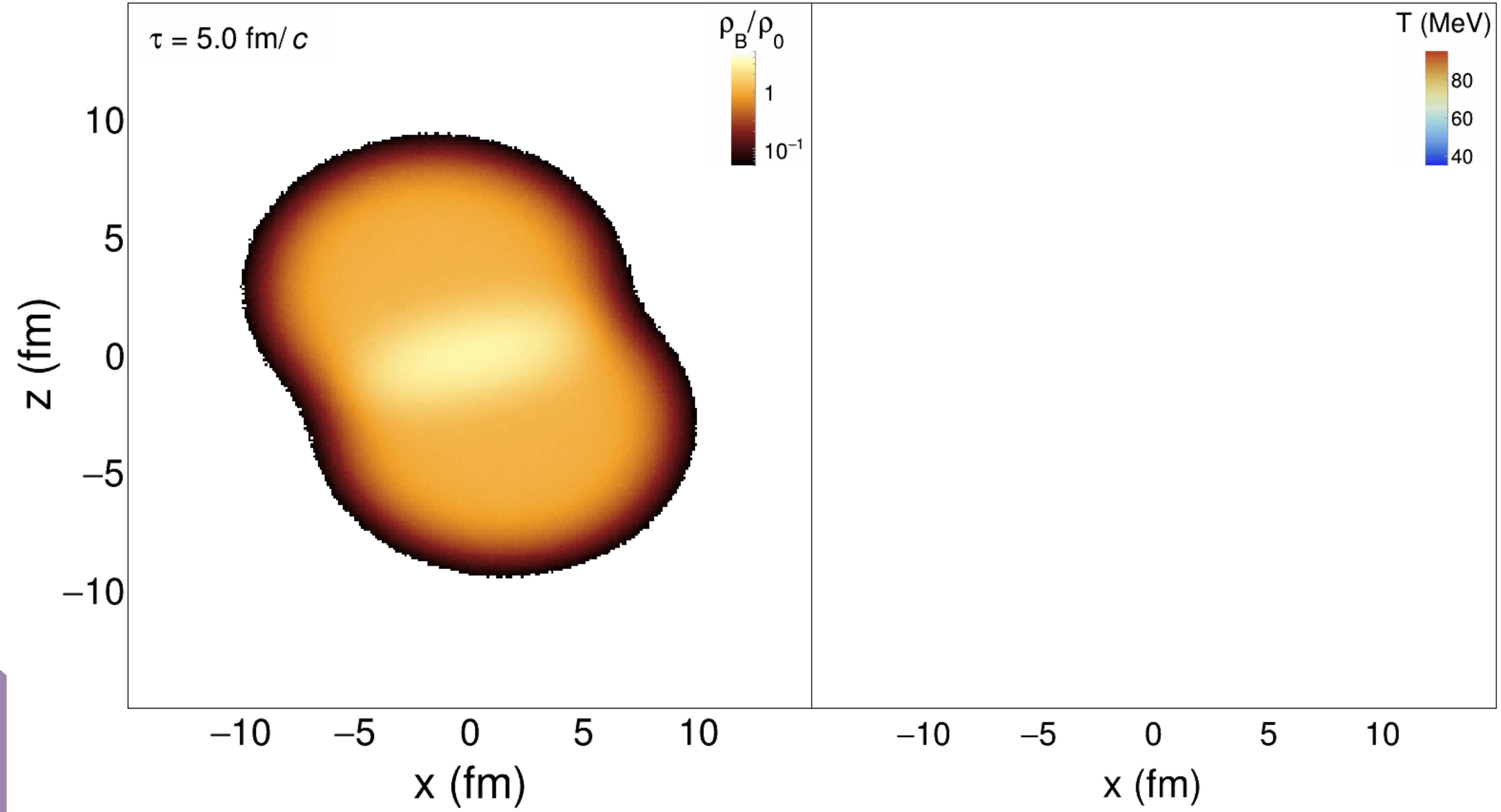

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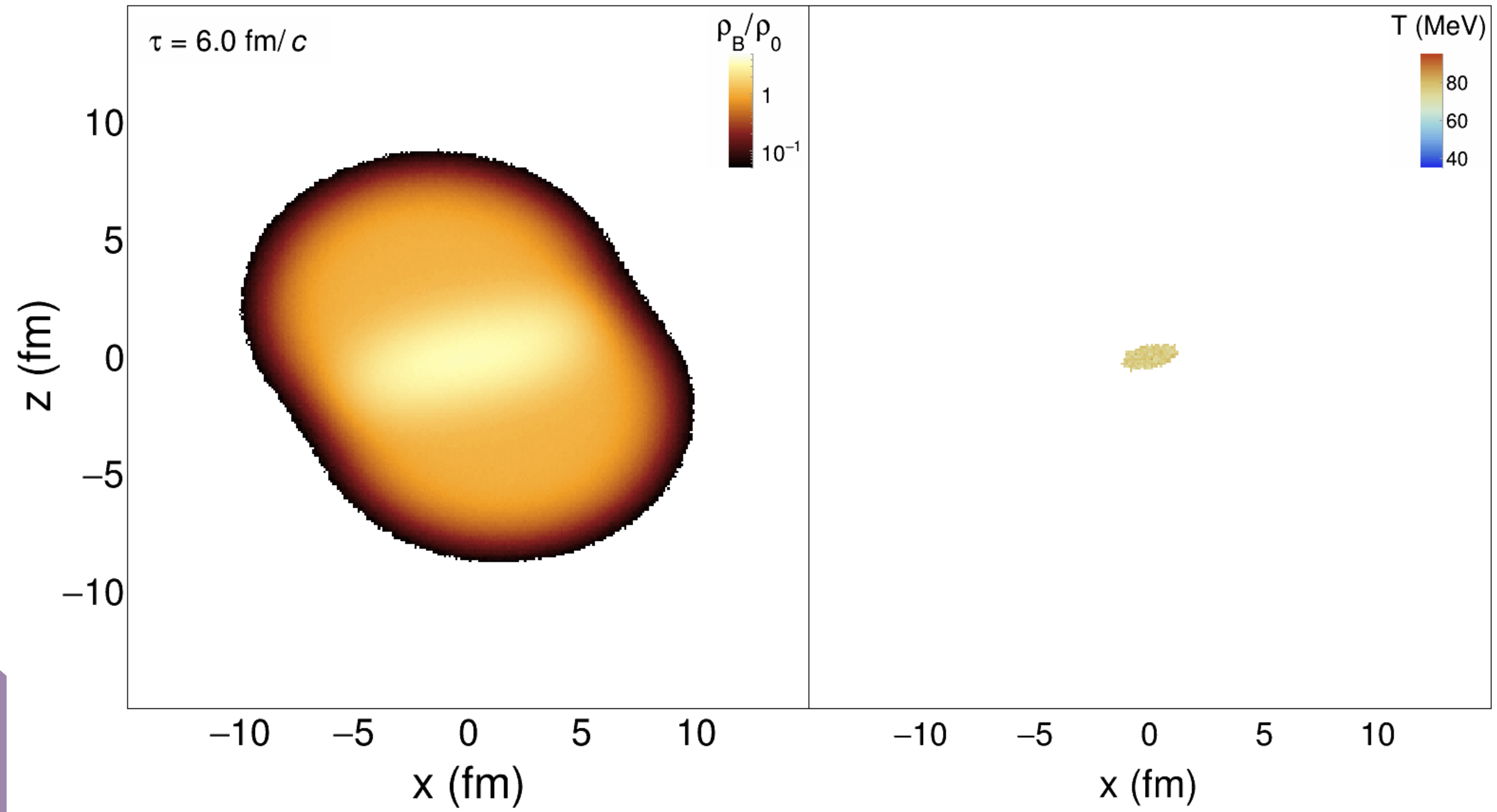

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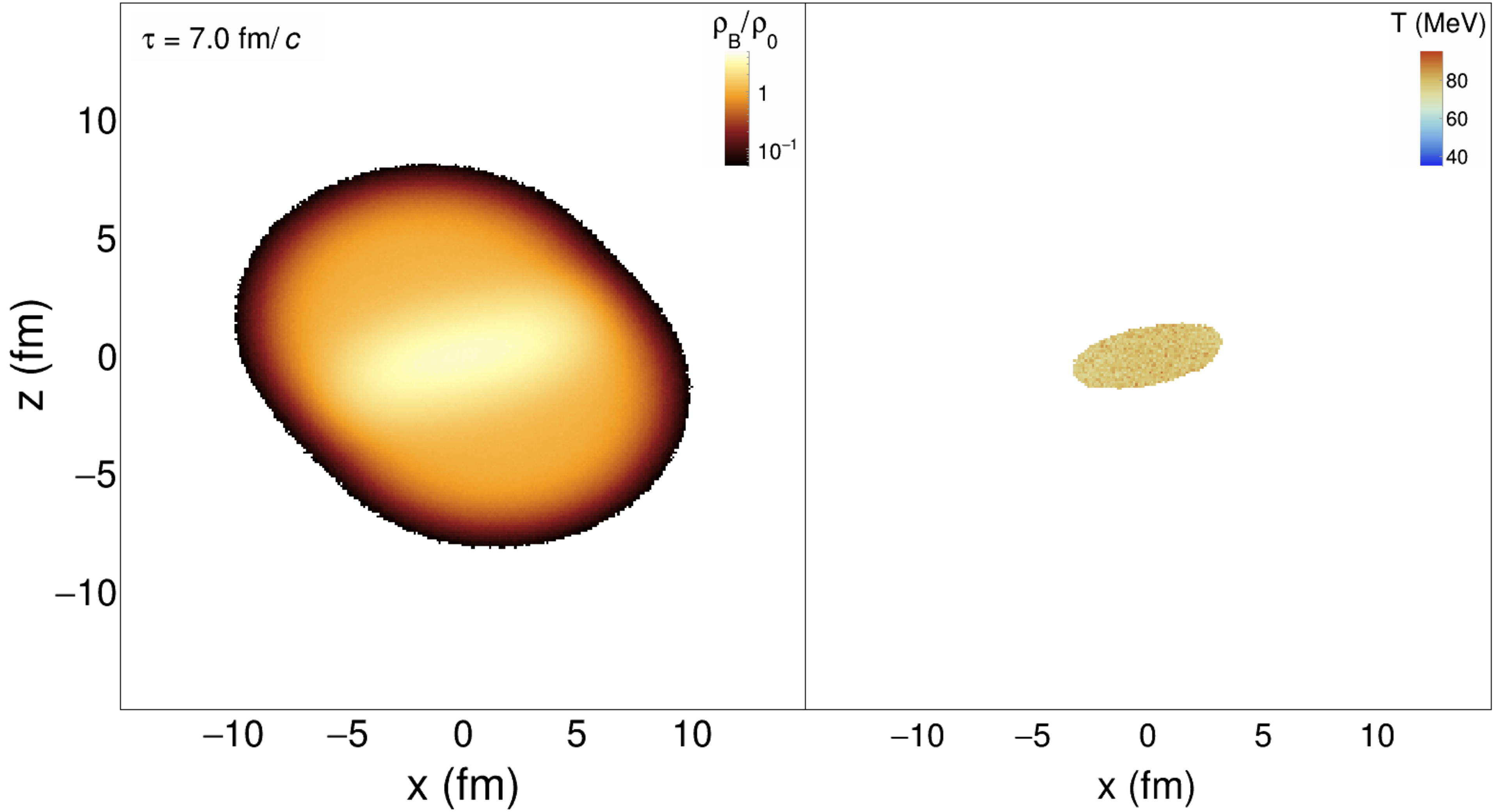

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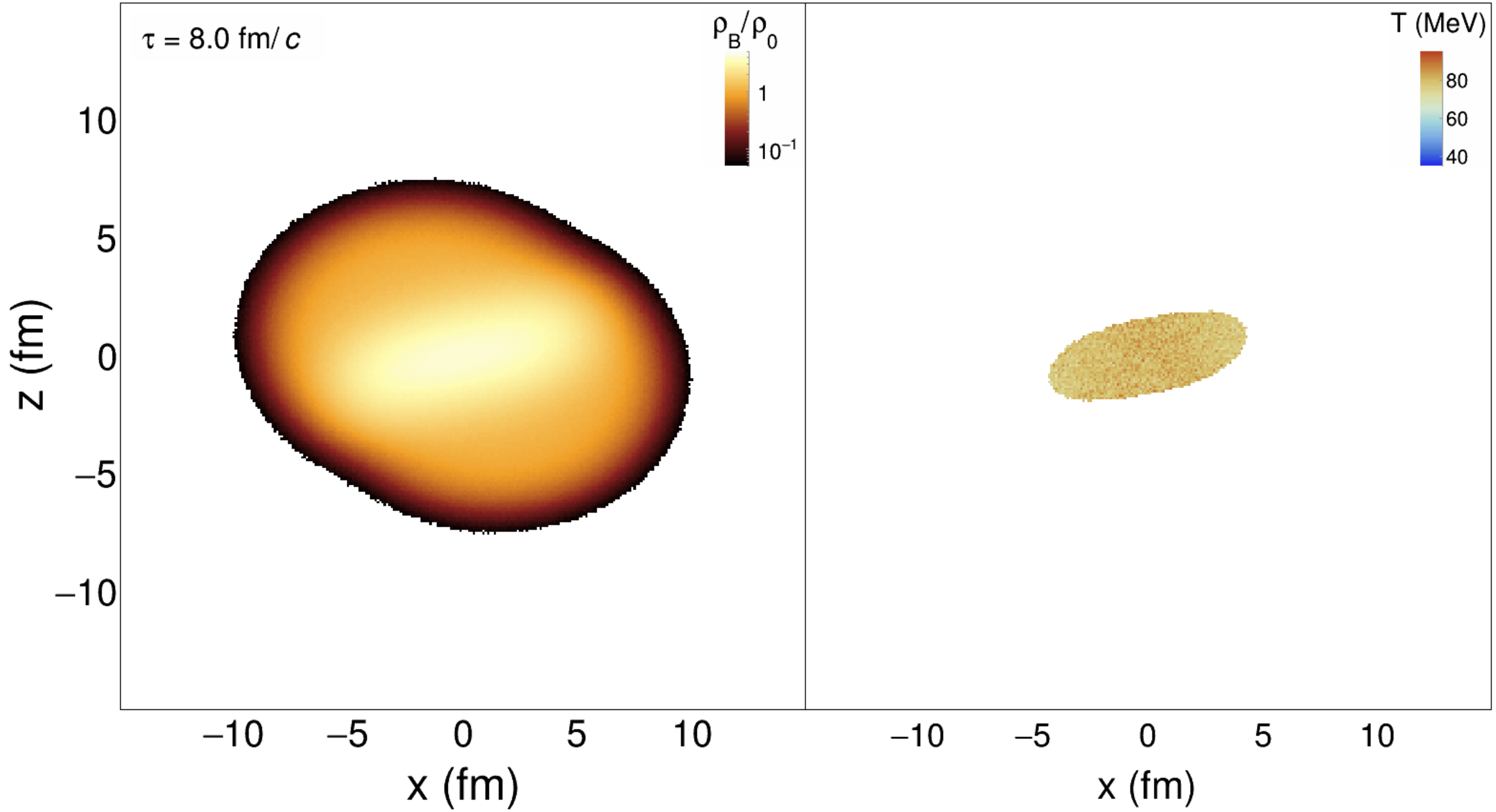

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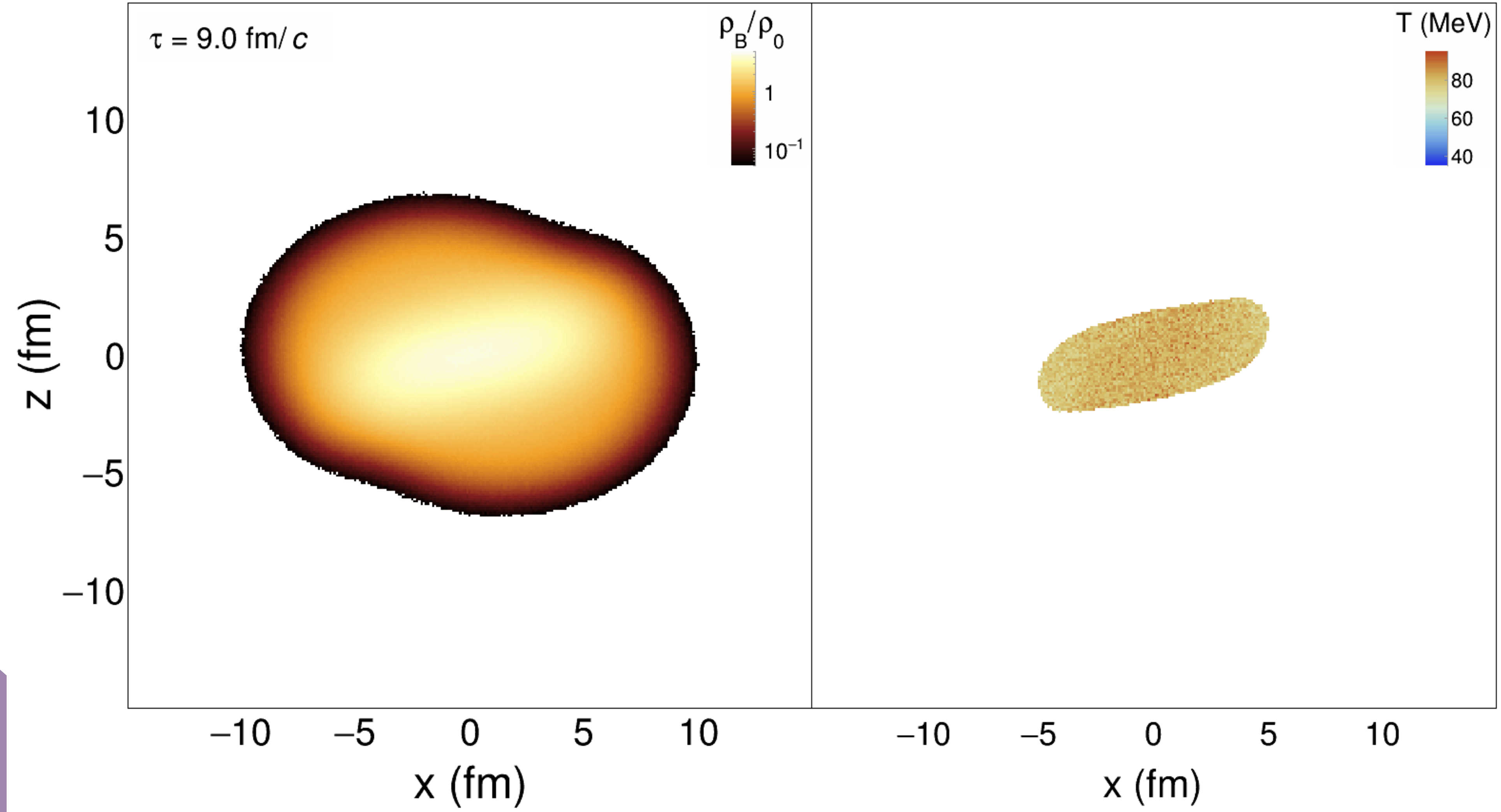

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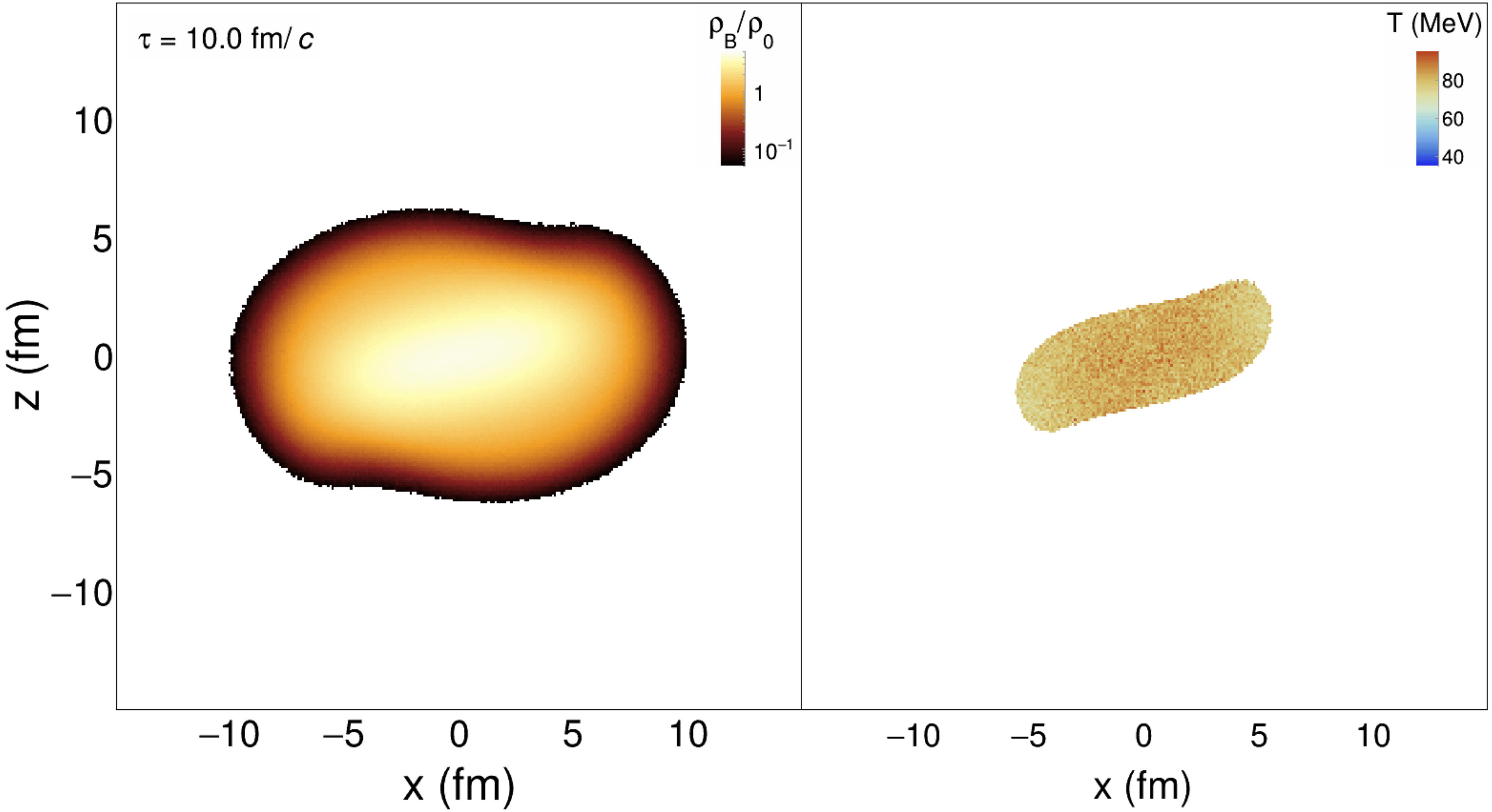

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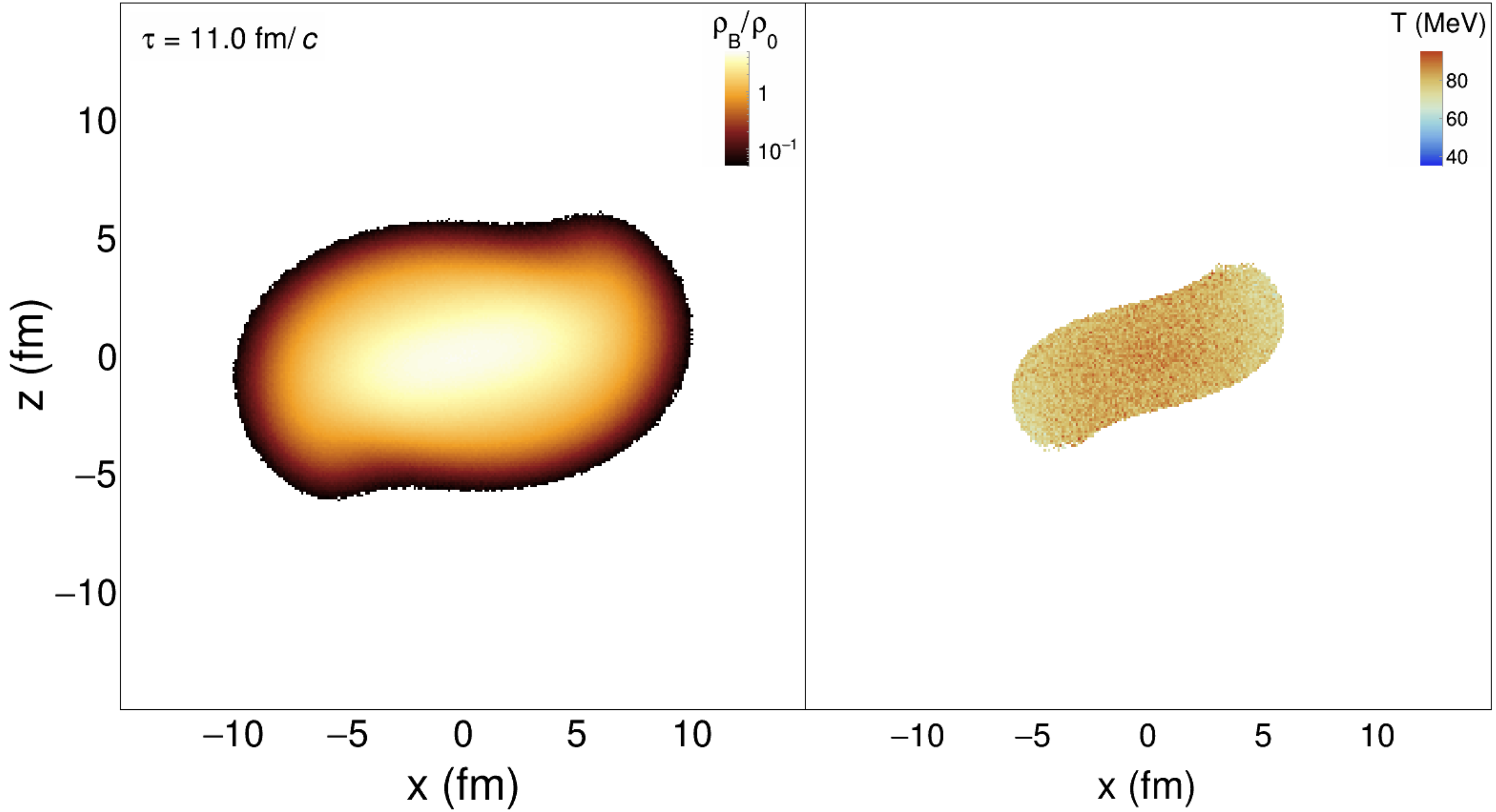

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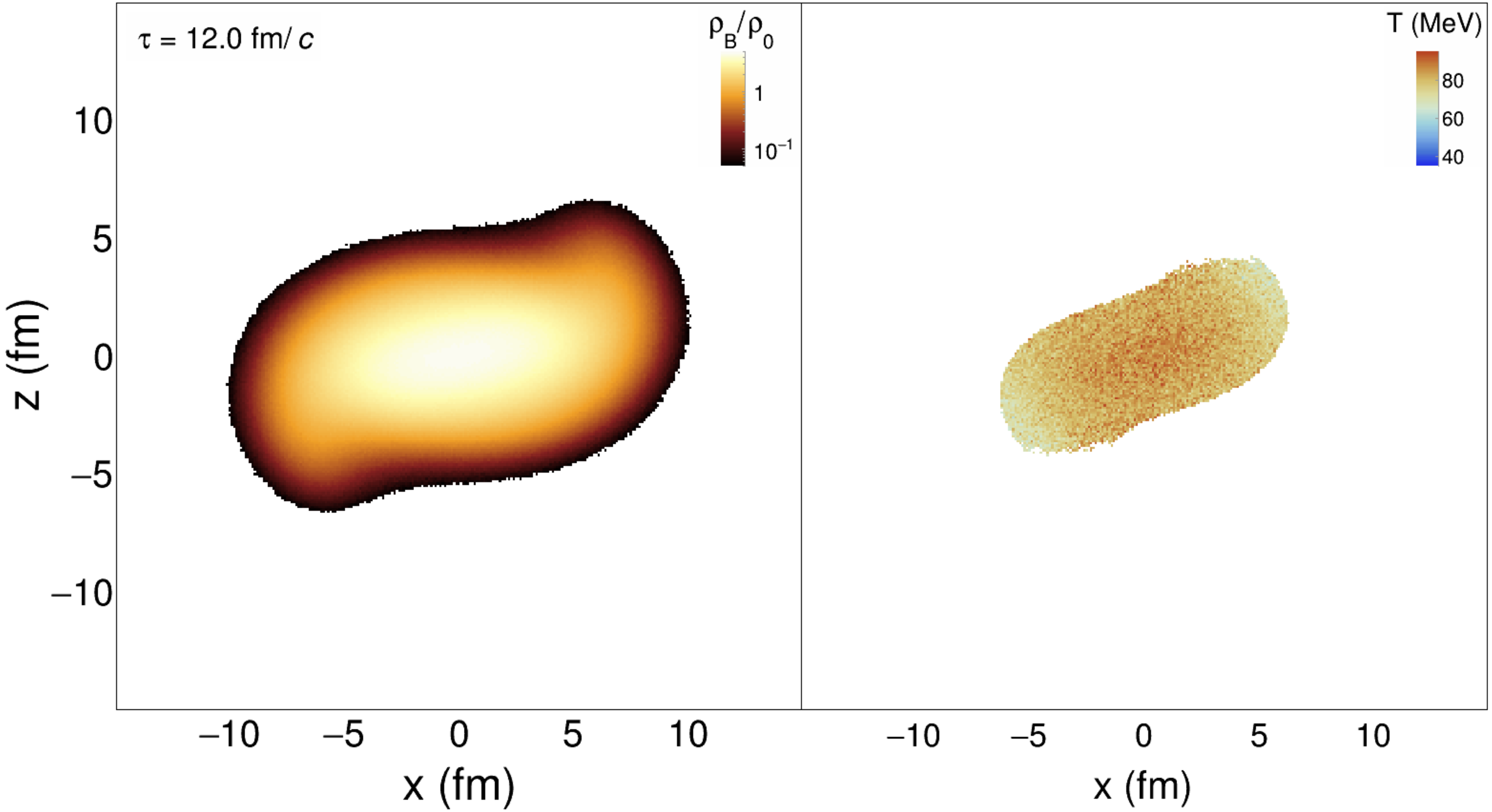

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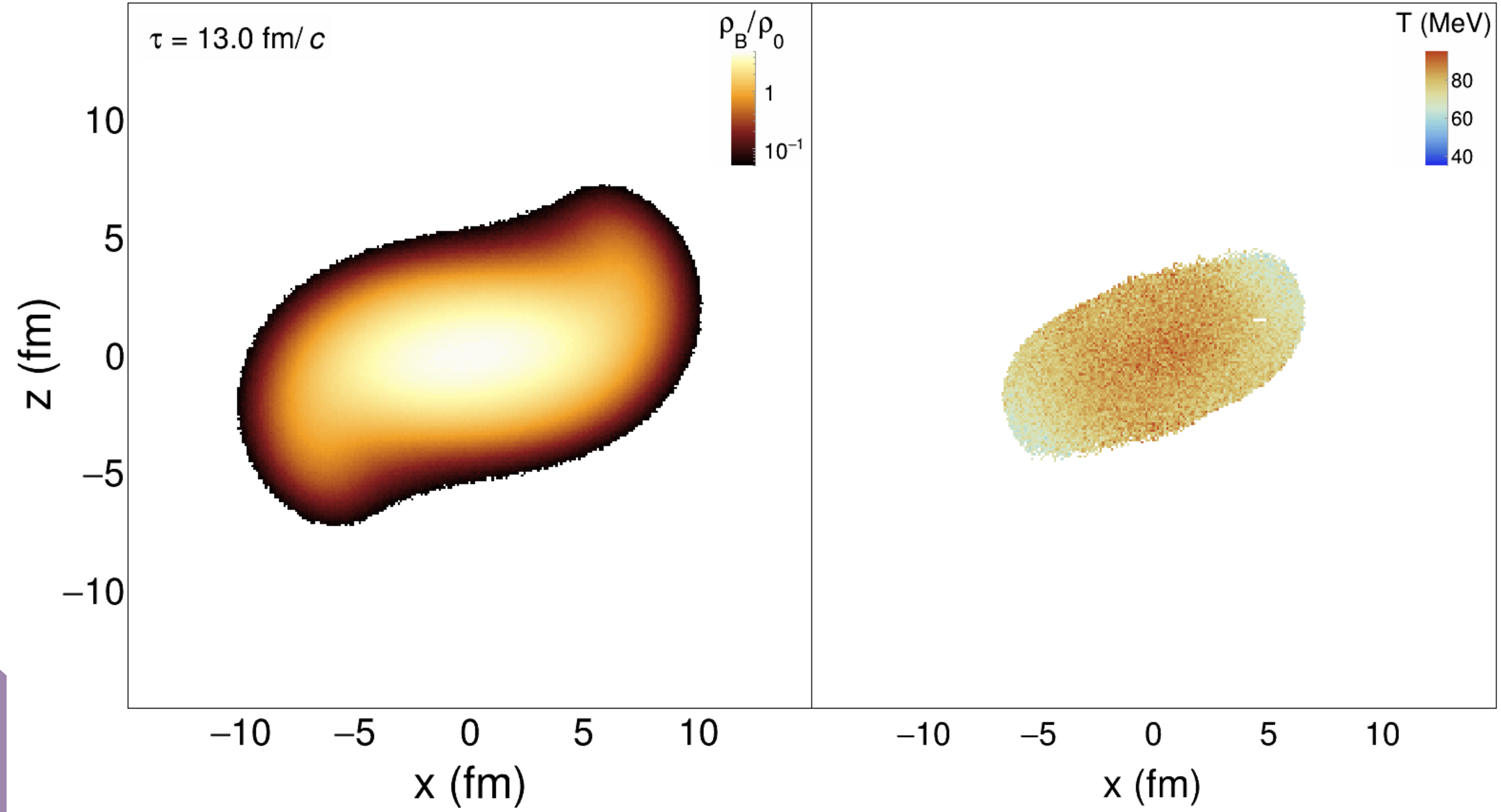

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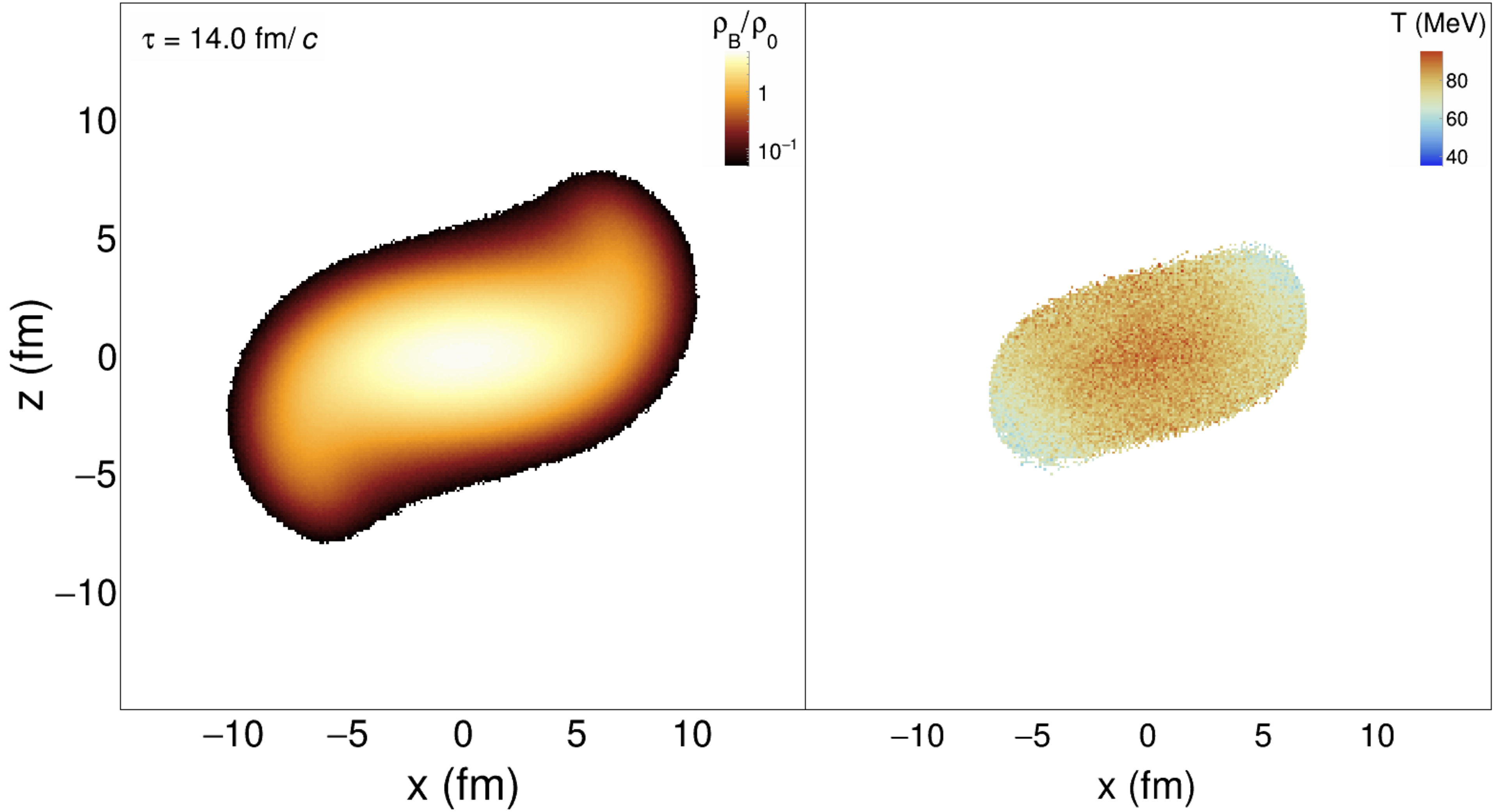

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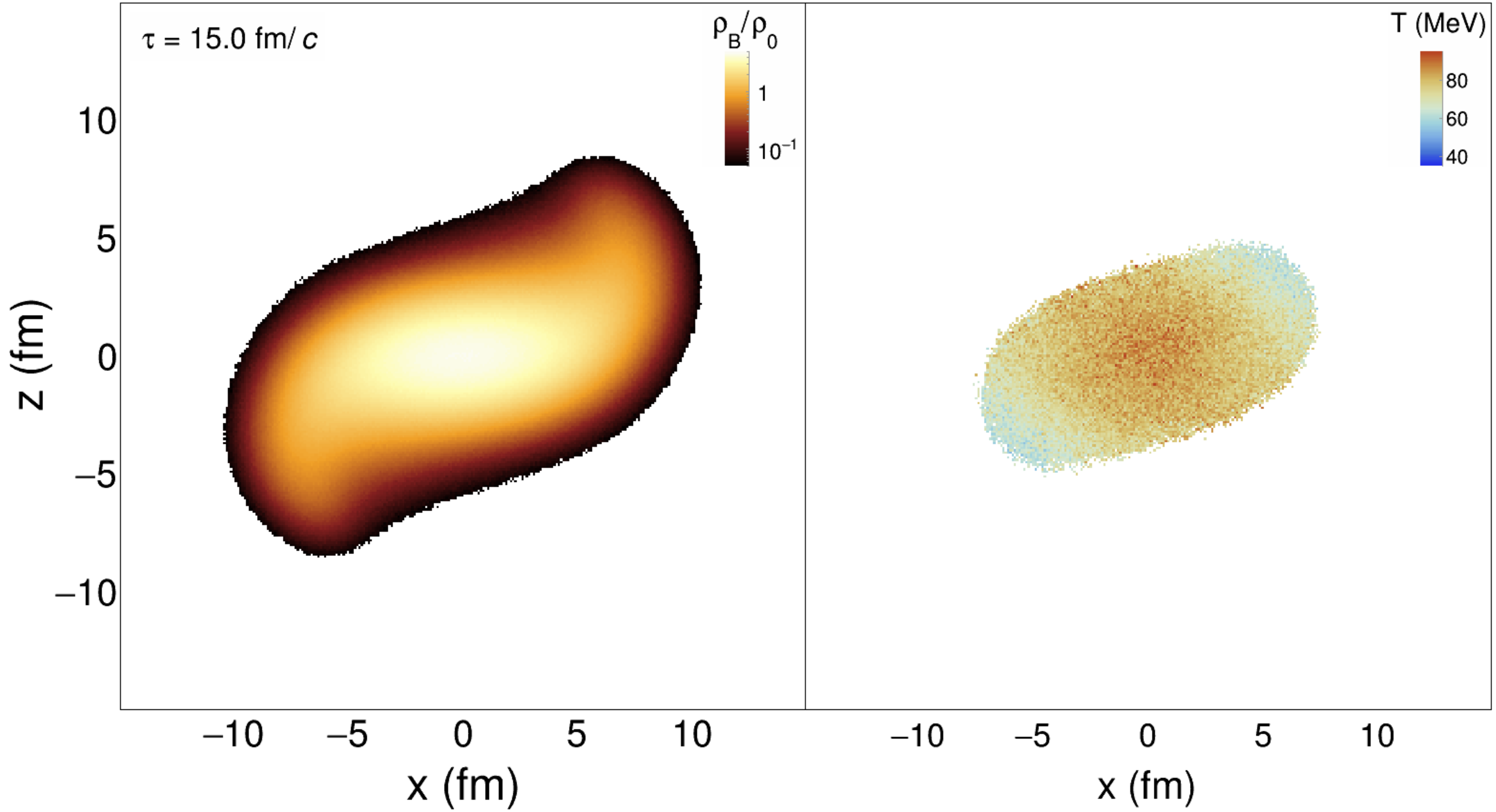

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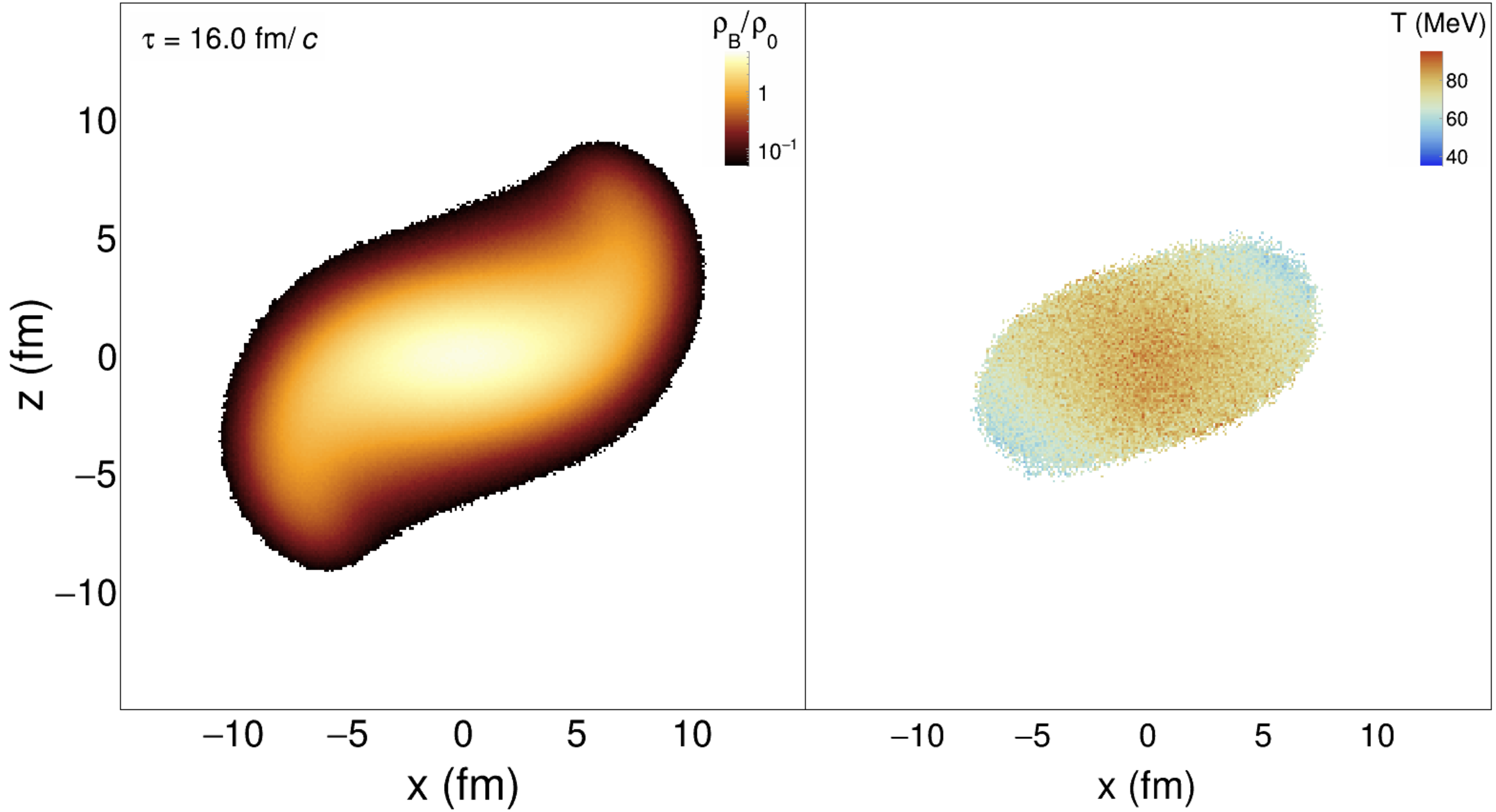

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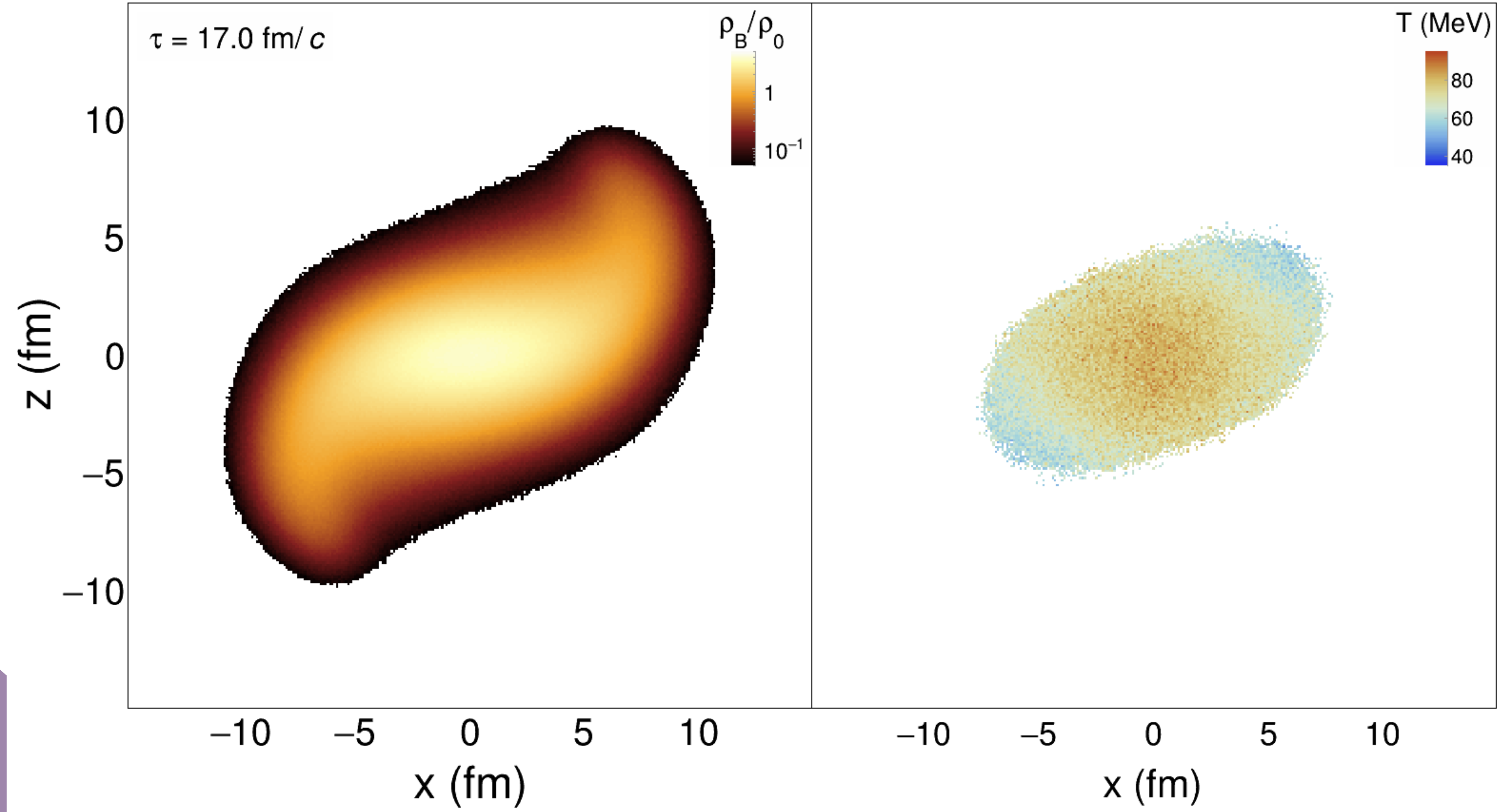

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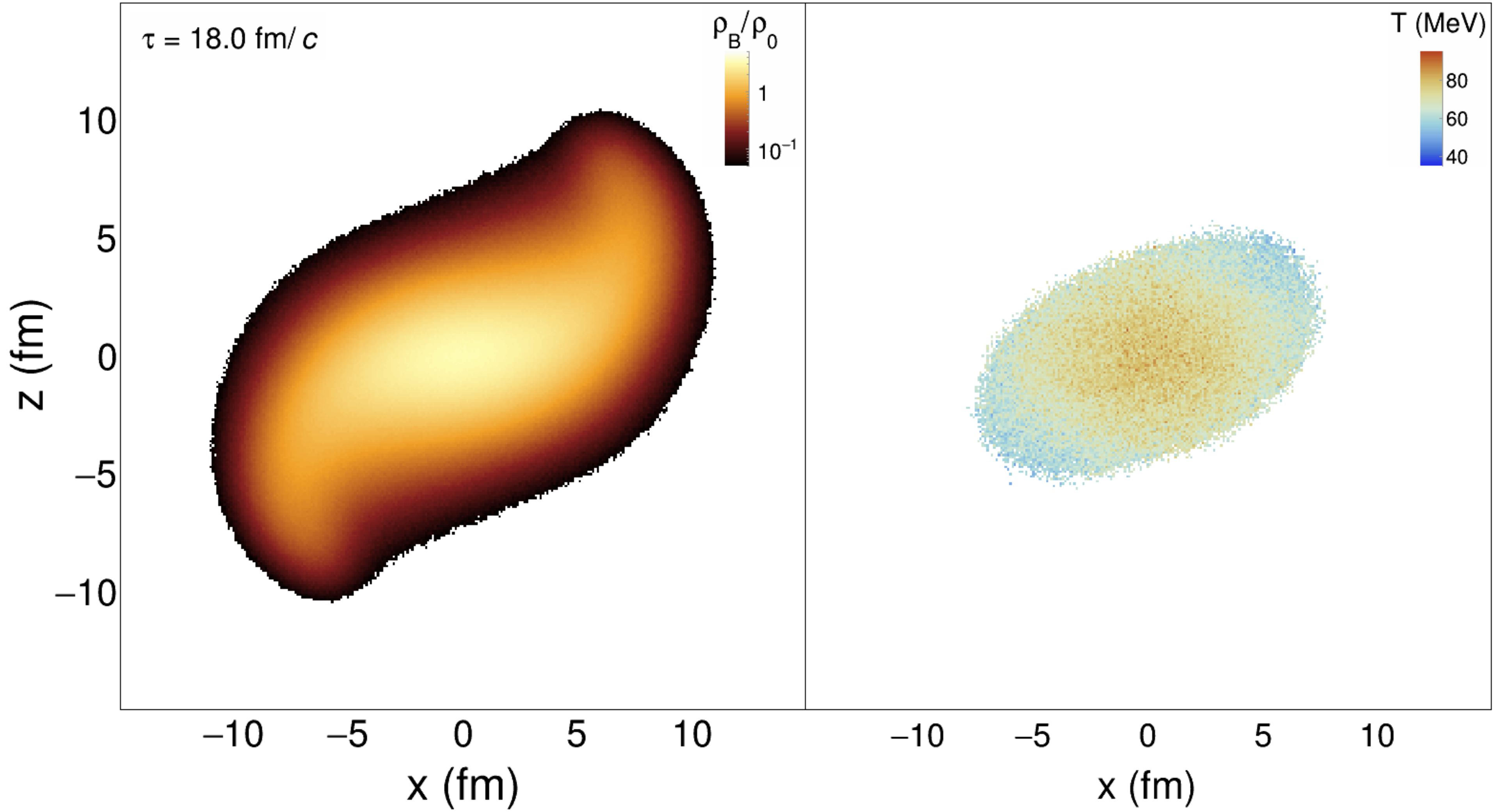

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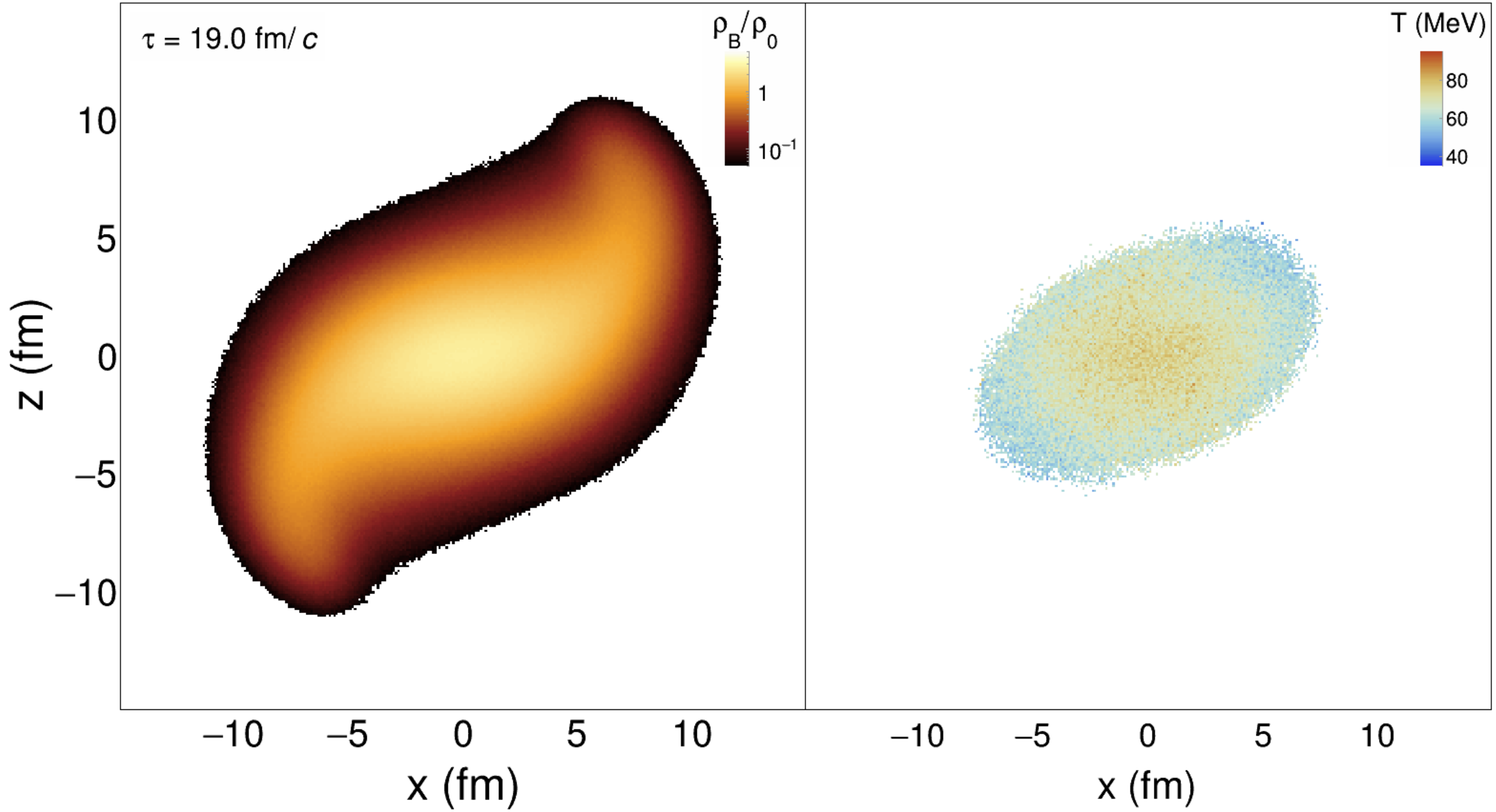

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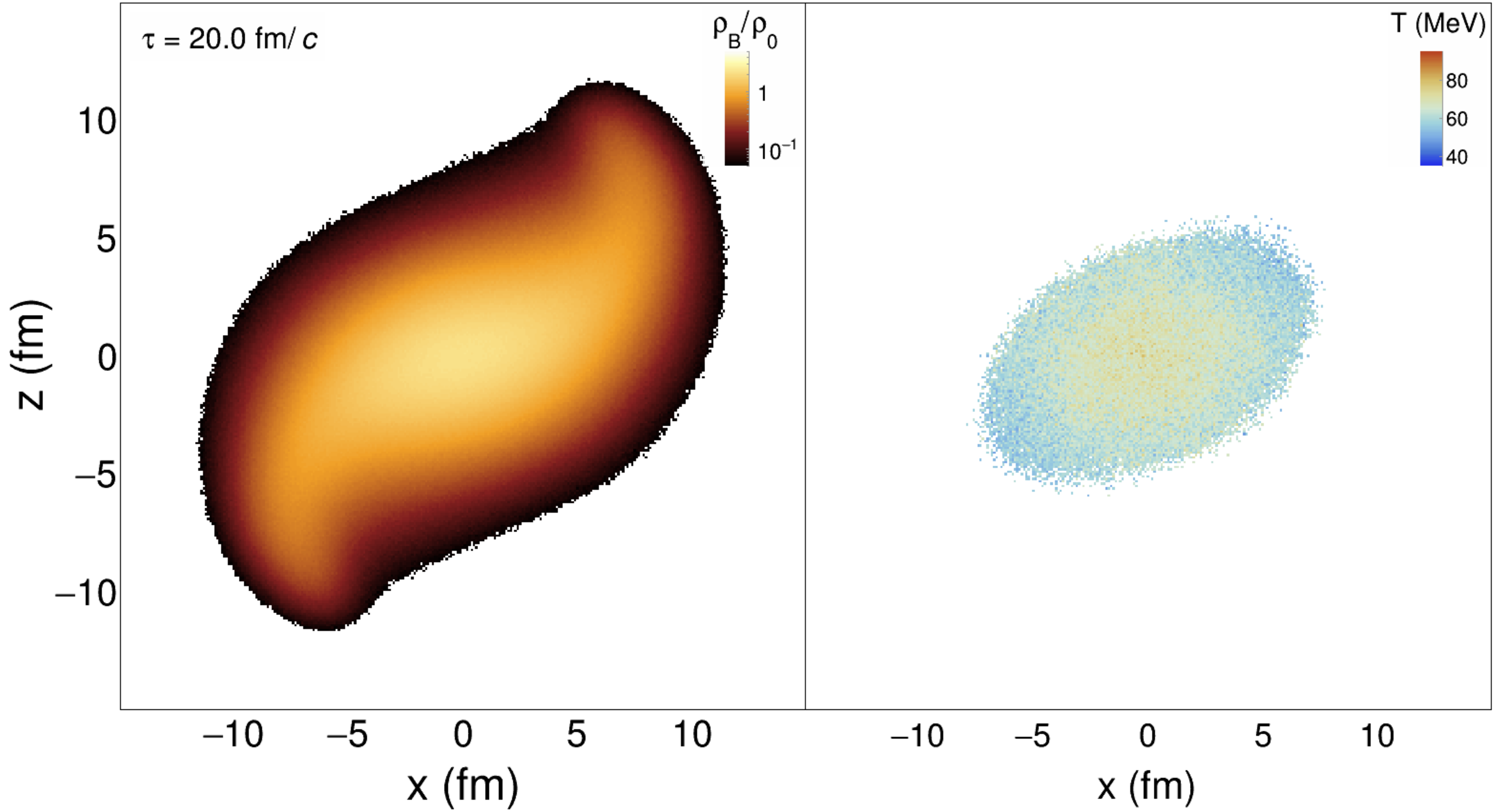

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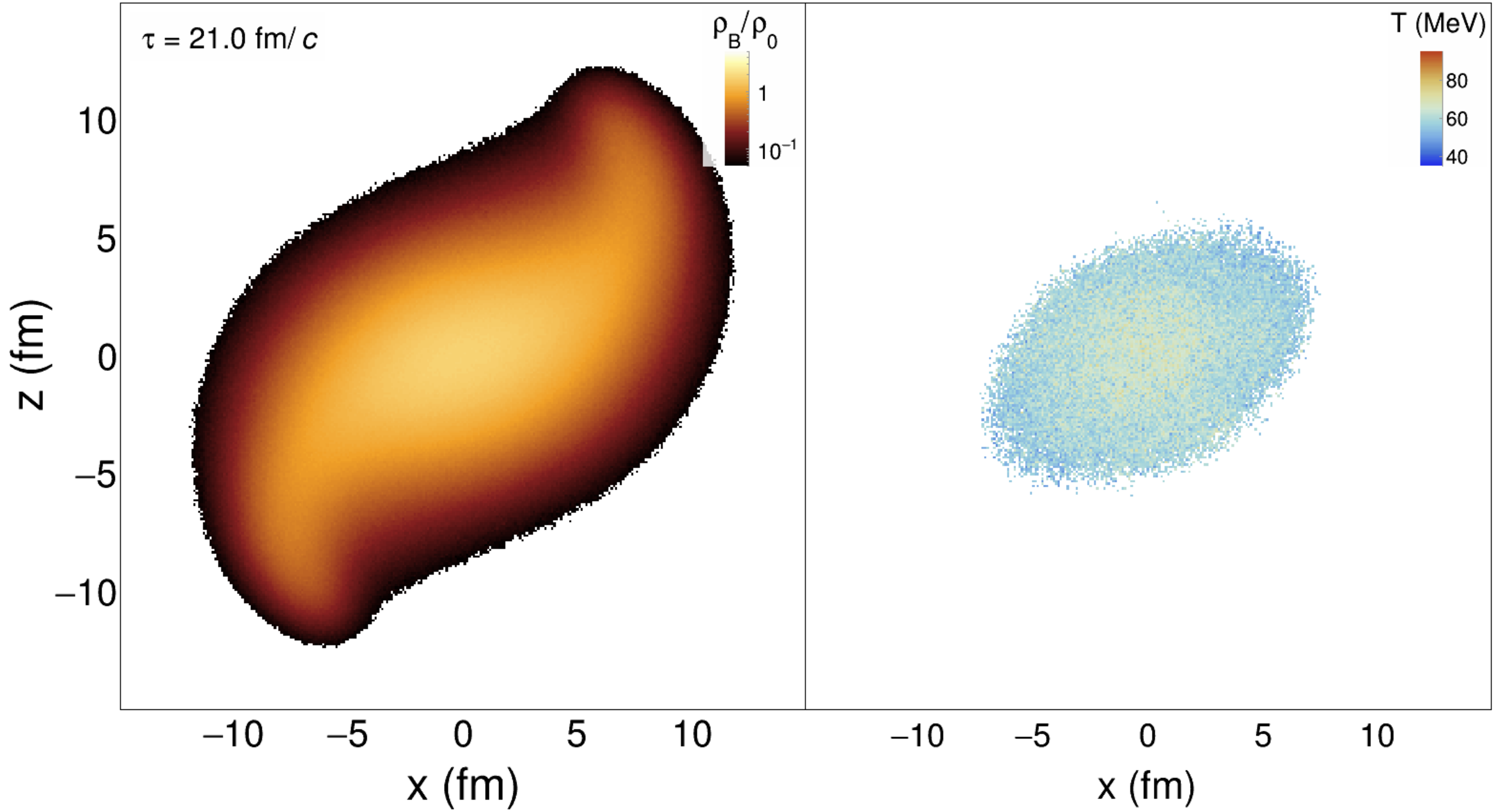

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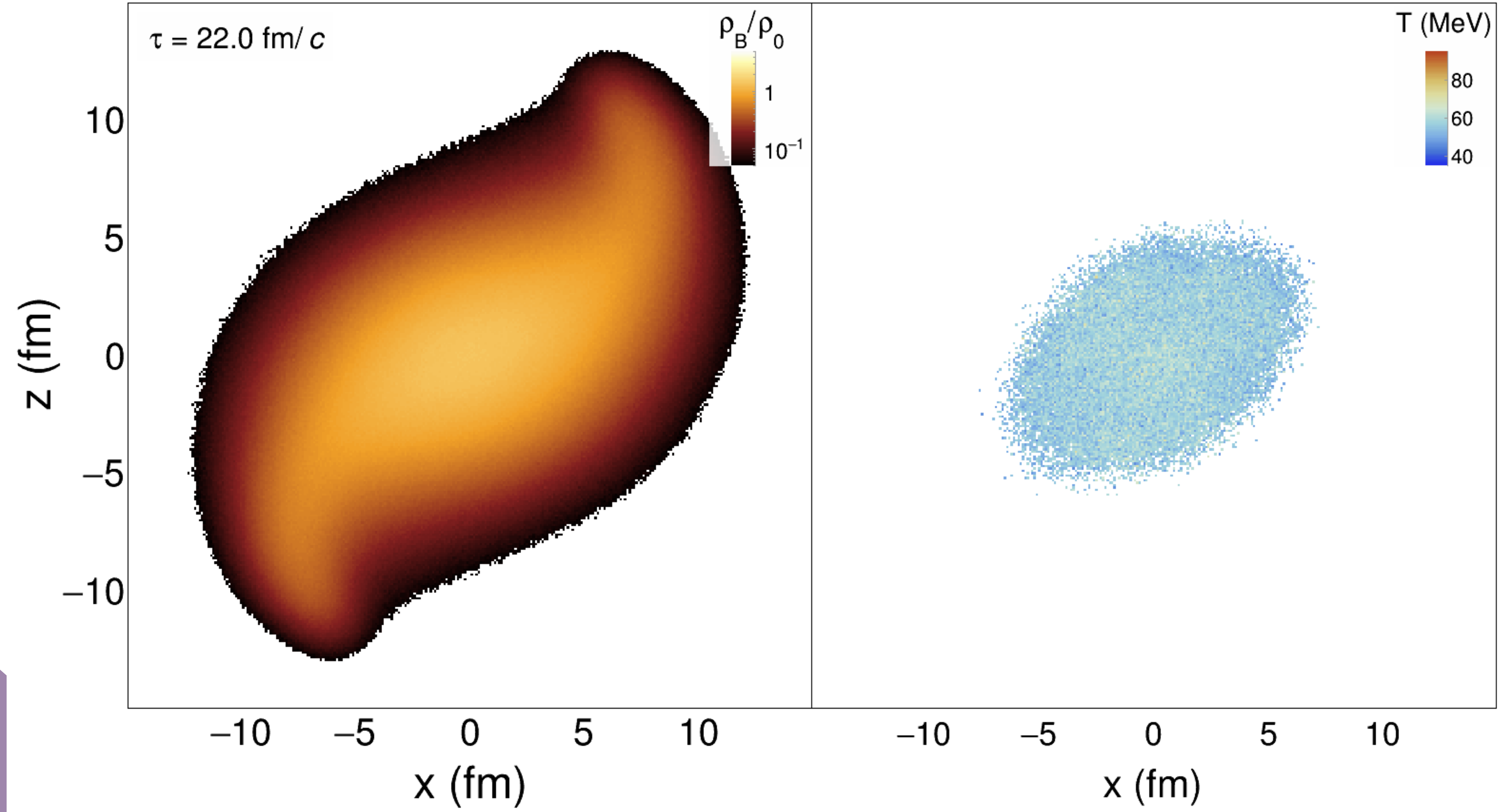

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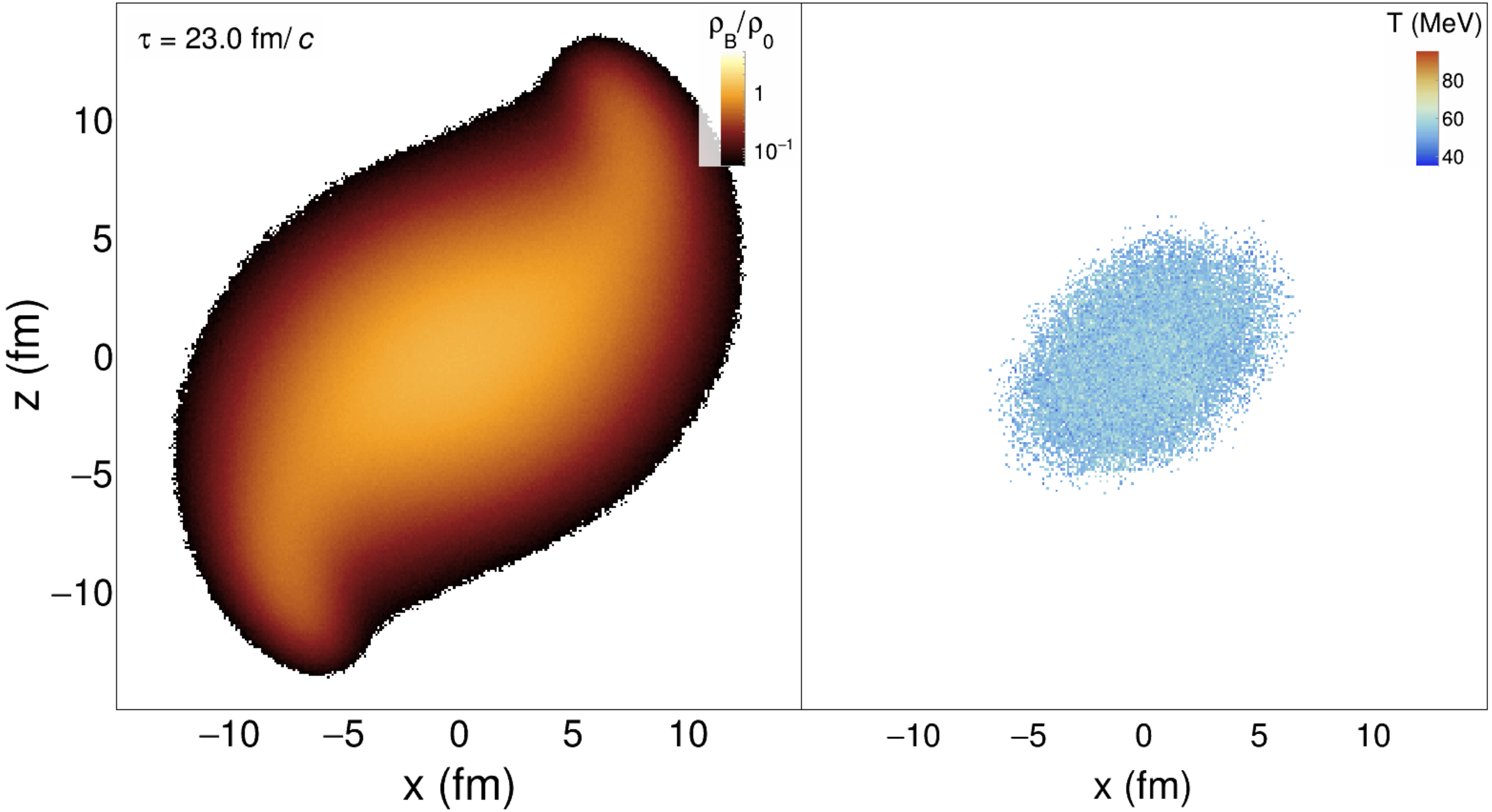

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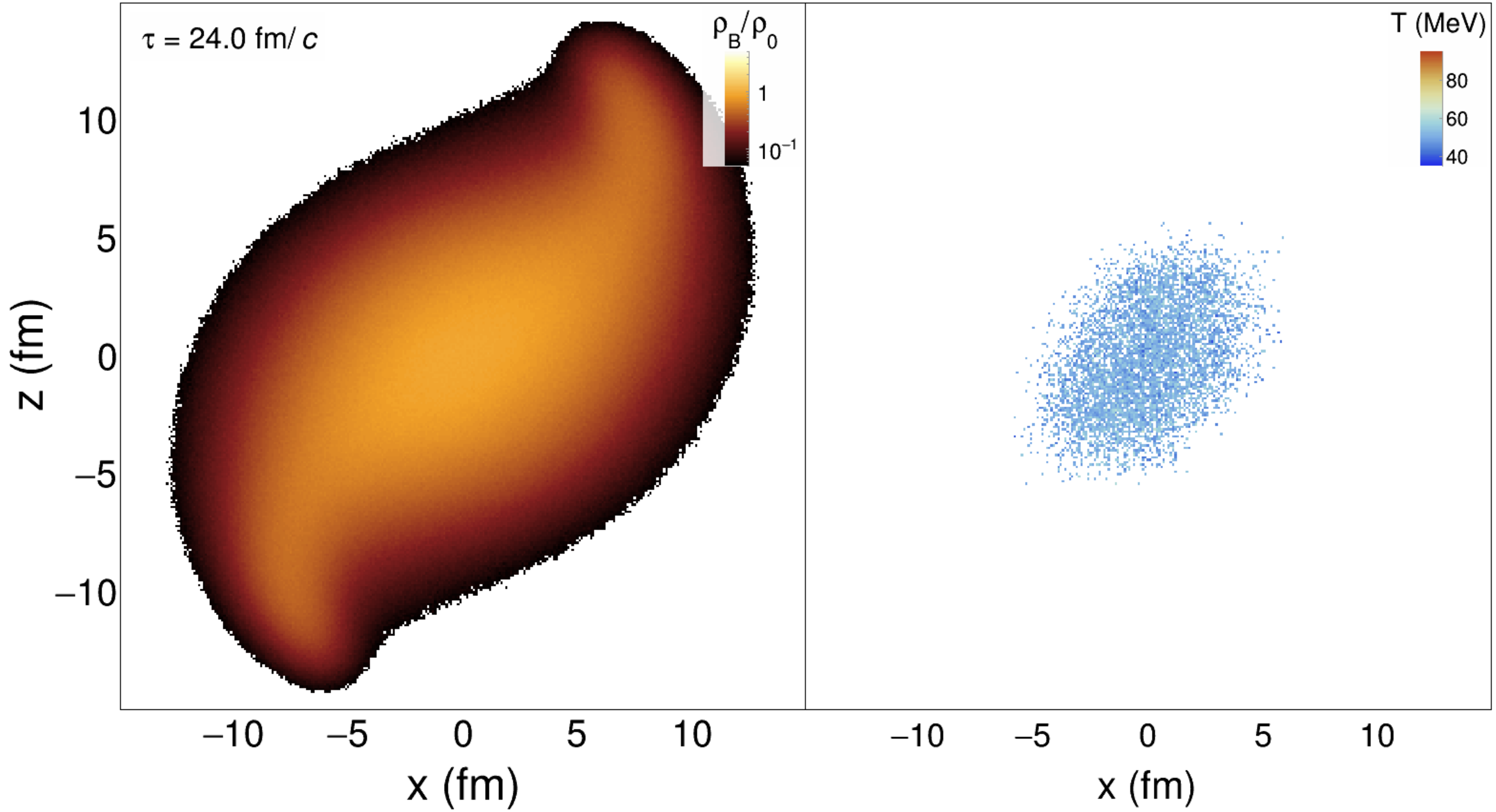

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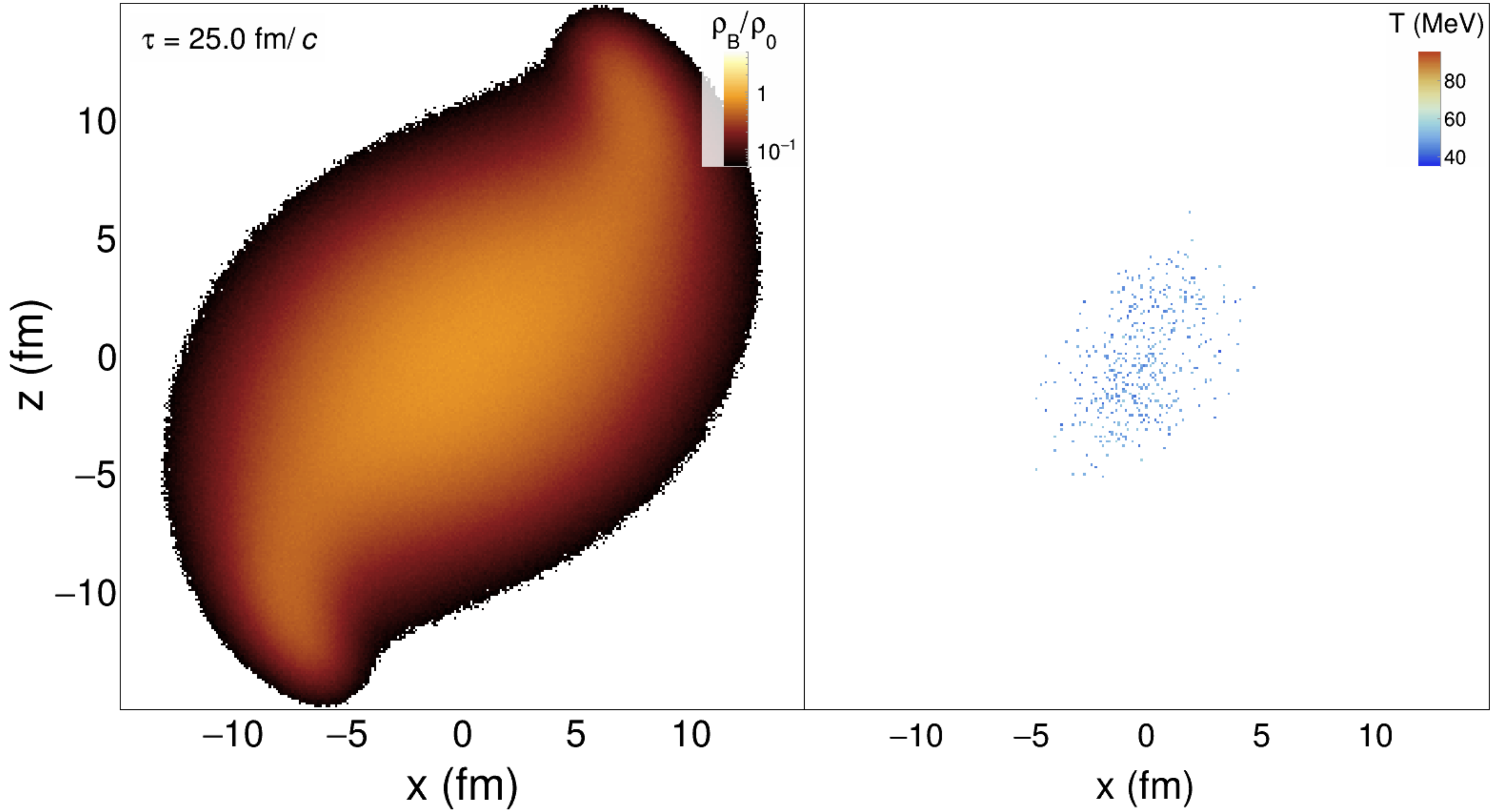

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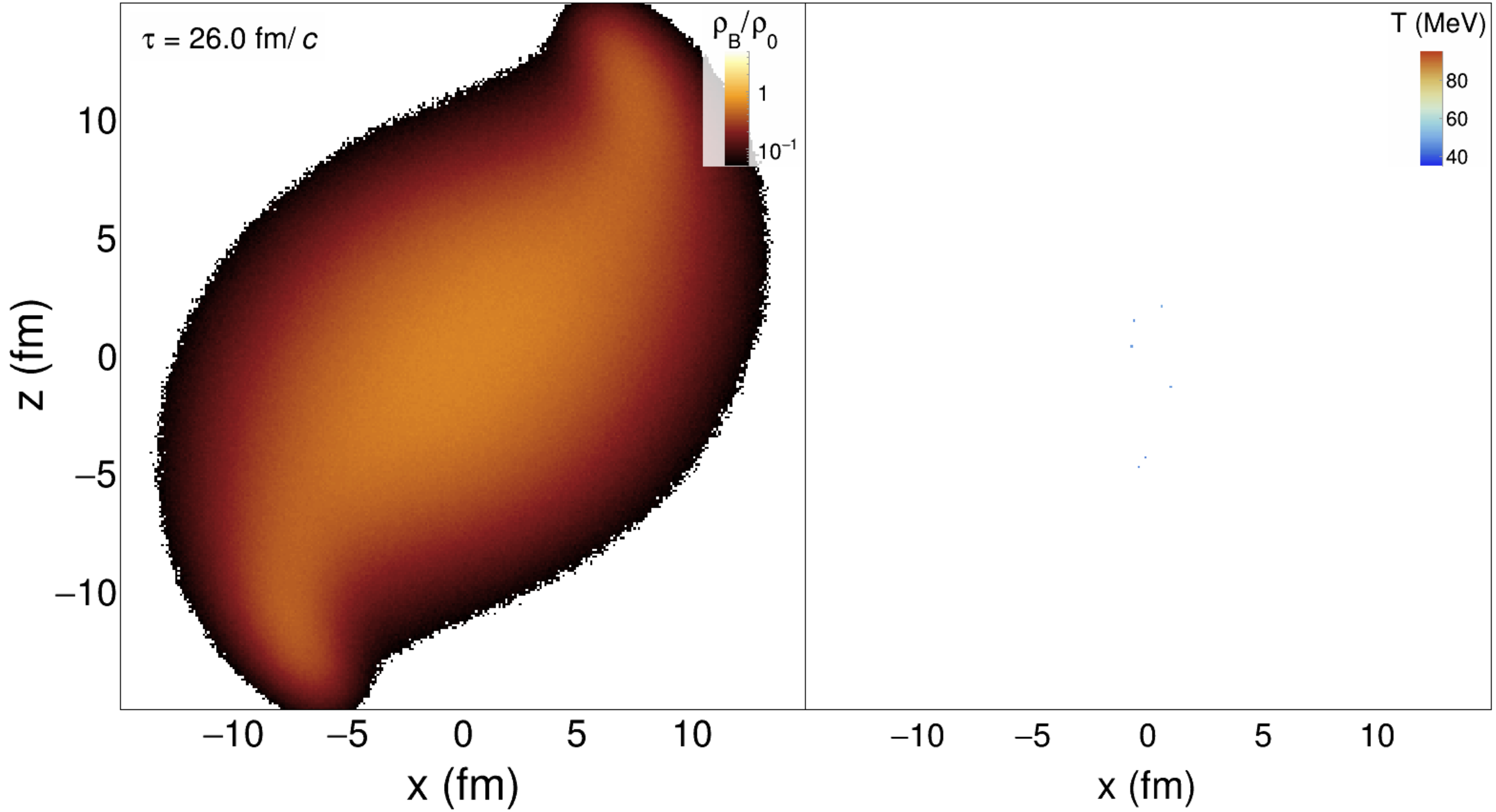

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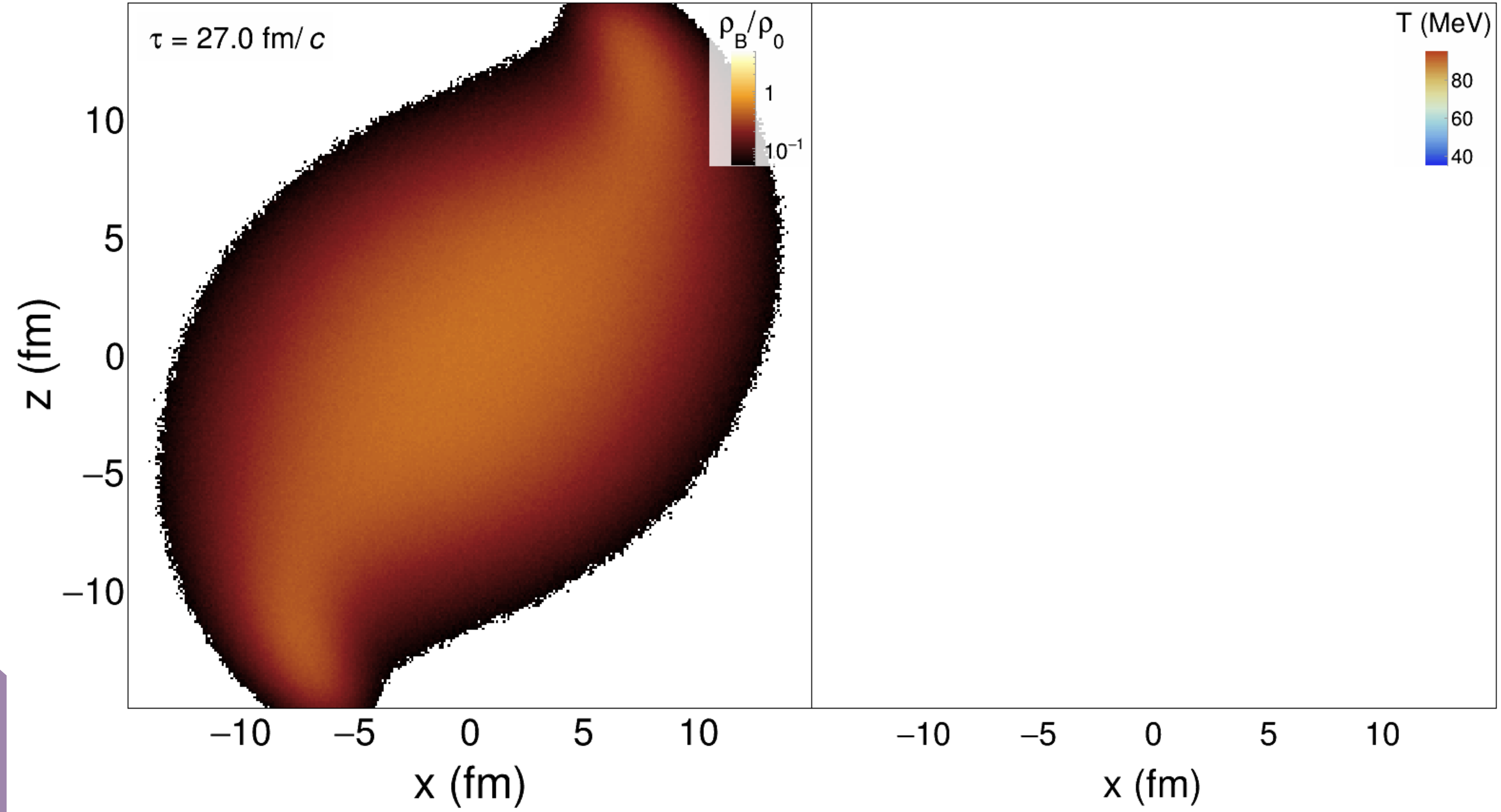

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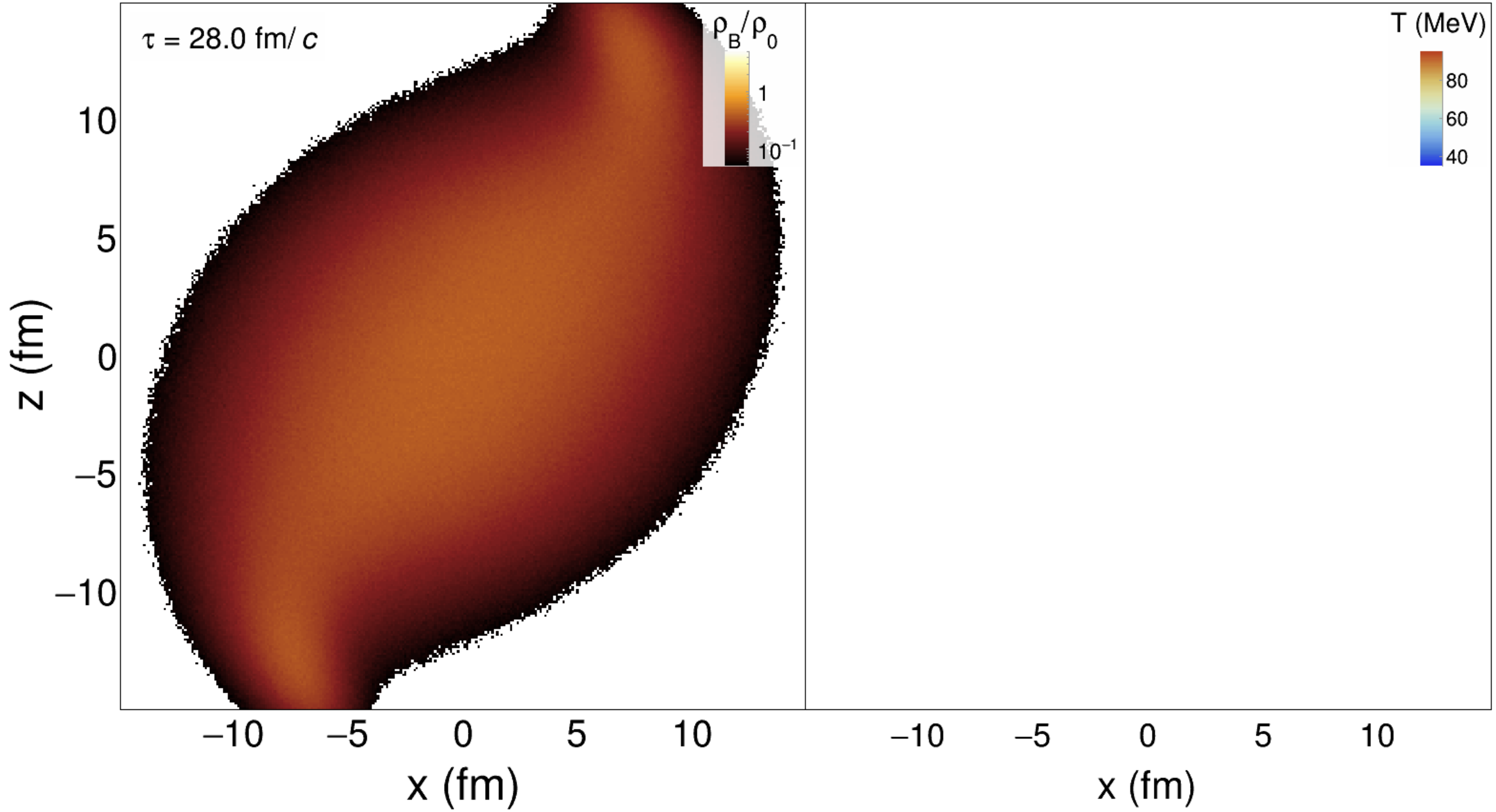

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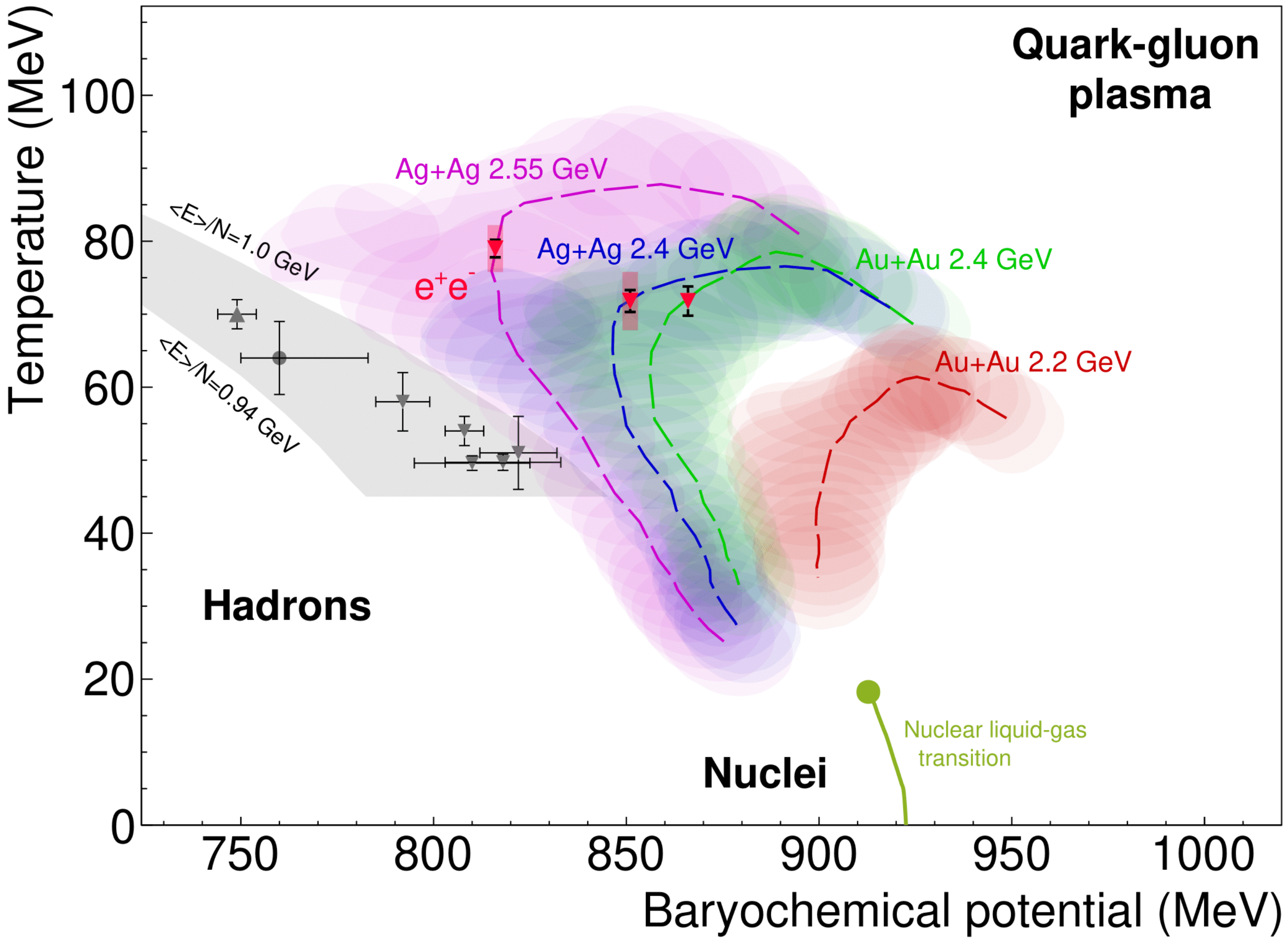
How Dileptons Probe the QCD Phase Diagram



- Trajectories from coarse-grained UrQMD
- Measured average temperatures from HADES well above universal freeze-out region
- Au+Au 2.2 GeV data collected in Feb-Mar 2024

Measured kT represents mean fireball temperature during hottest and densest collision stage

FO curve: J. Cleymans, K. Redlich, Nucl. Phys. A 661 (1999) 379
Au+Au 2.4 GeV data: HADES, Nature Phys. 15(2019) 1040
Eur.Phys.J.A 52 (2016) 5, 131
Phys.Rev.C 106 (2022) 1, 014904
Ag+Ag data: HADES preliminary
figure: F.Seck, T.Galatyuk

Investigating Collective Observables

Radial (isotropic) Flow

Anistropic Flow

Polarization

Investigating Collective Observables

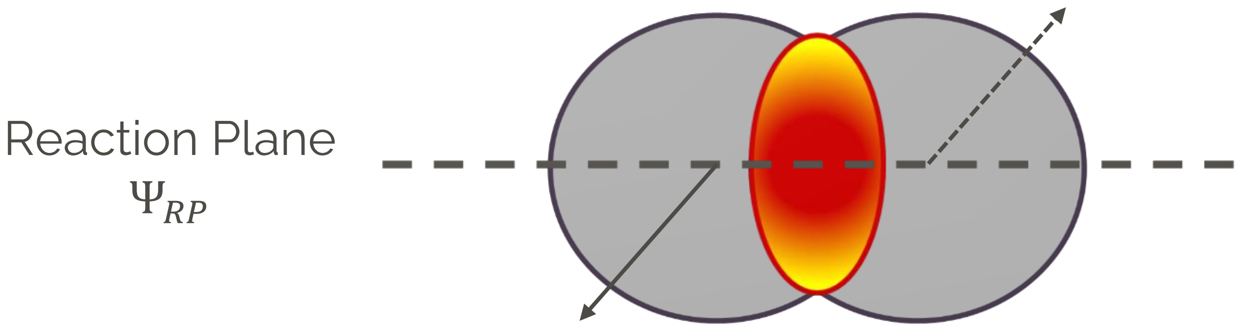
Radial (isotropic) Flow | **Anistropic Flow** | Polarization

$$\frac{dN}{d\Delta\varphi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos(n\,\Delta\varphi)$$

$$\Delta\varphi = \varphi - \Psi_{RP}$$

v_1: Directed Flow

v_2: Elliptic Flow



Investigating Collective Observables

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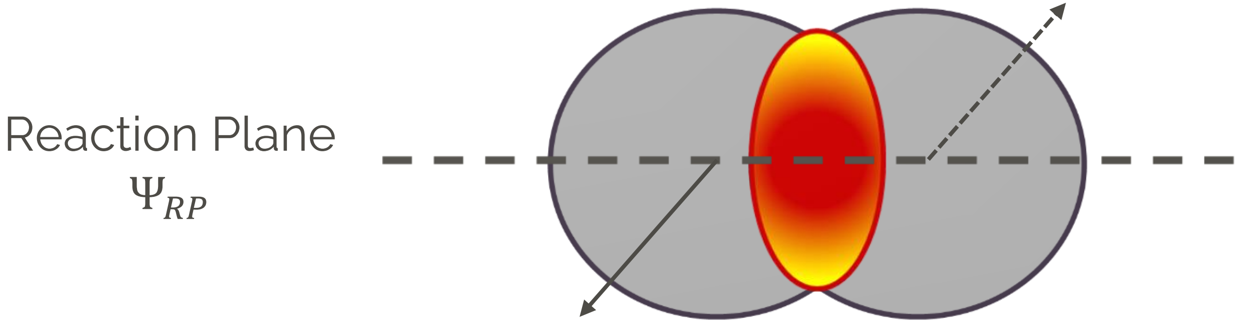
v_1: Directed Flow

v_2: **Elliptic Flow**



- Flow sensitive to EoS

Investigating Collective Observables

Radial (isotropic) Flow | Anistropic Flow | Polarization

$$\frac{dN}{d\Delta\varphi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos(n\,\Delta\varphi)$$

$$\Delta\varphi = \varphi - \Psi_{RP}$$

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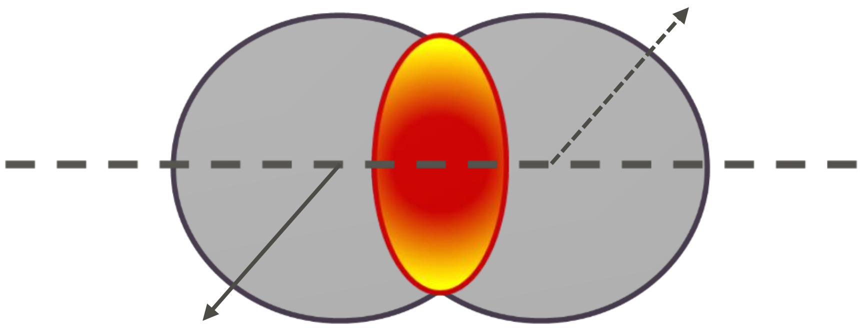
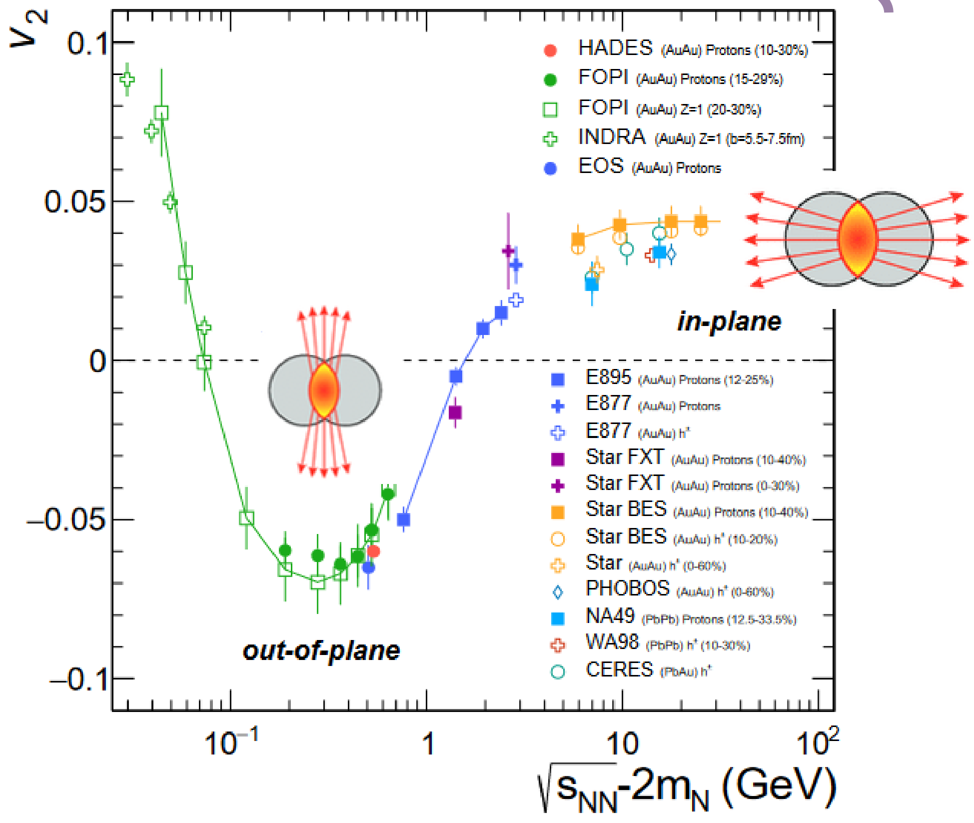
Reaction Plane Ψ_{RP}





- Flow sensitive to EoS

The HADES Collaboration, arXiv:2208.02740

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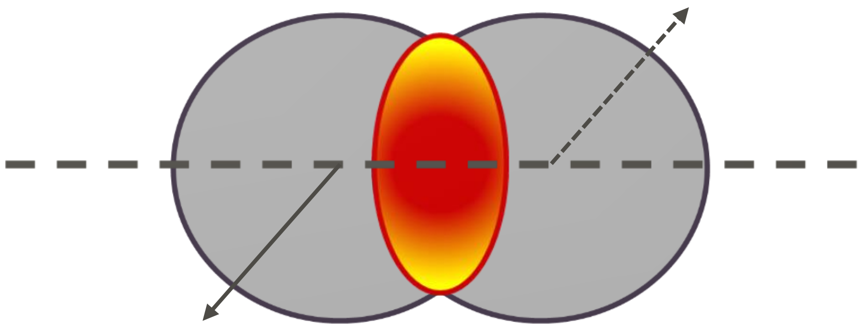
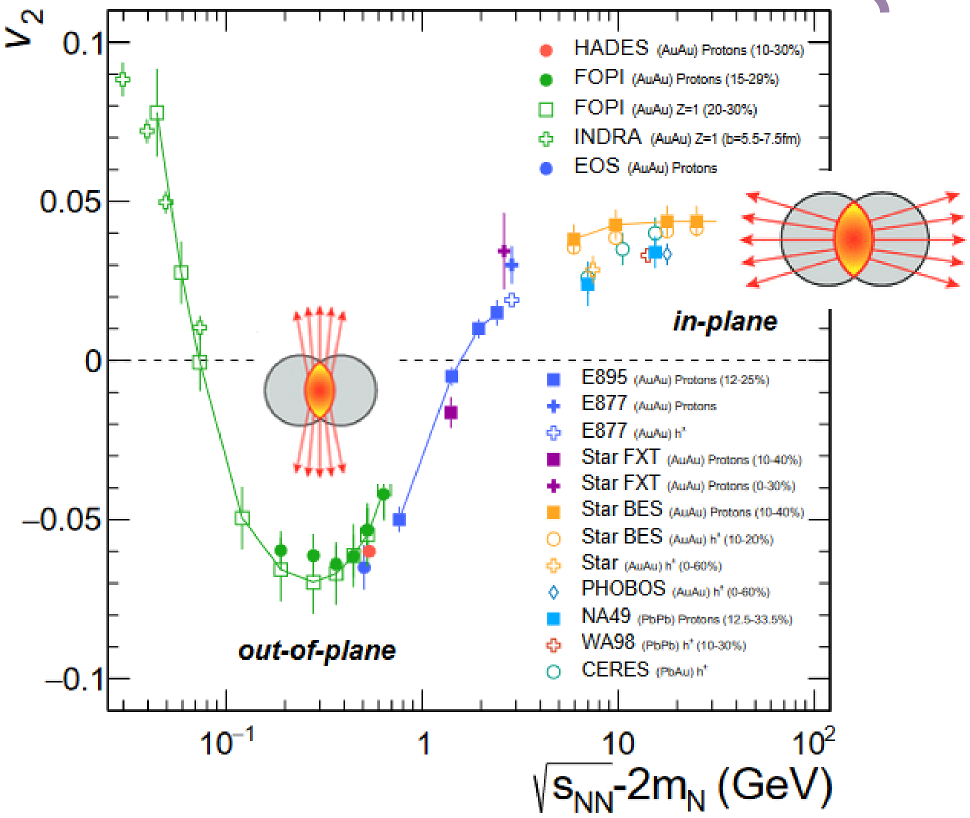
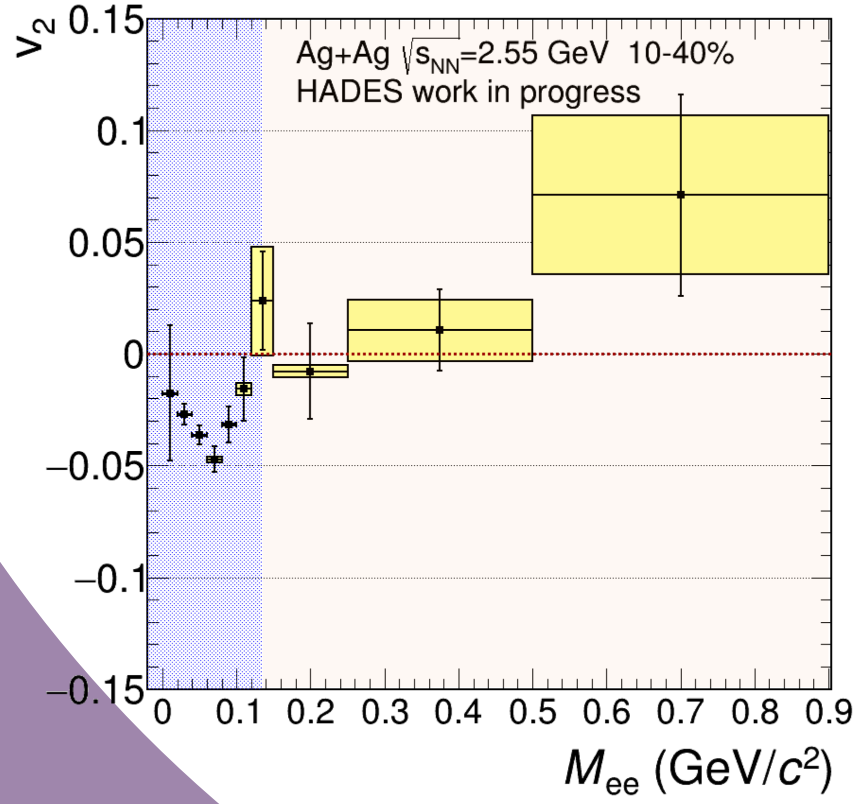




- Flow sensitive to EoS
- Dilepton may probe evolution of flow over time

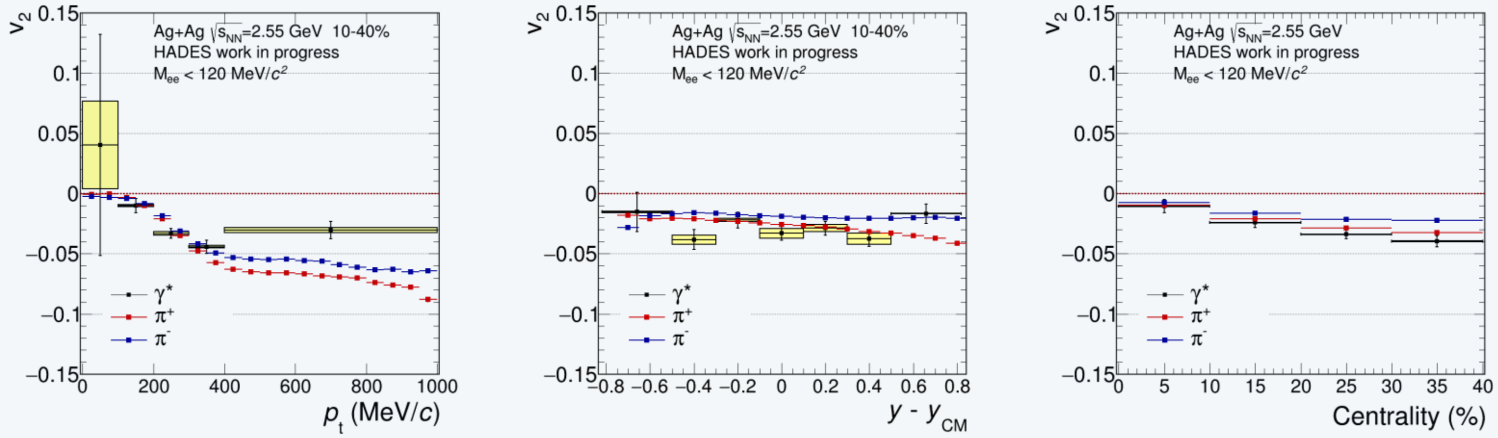
The HADES Collaboration, arXiv:2208.02740

Elliptic Flow of Dileptons



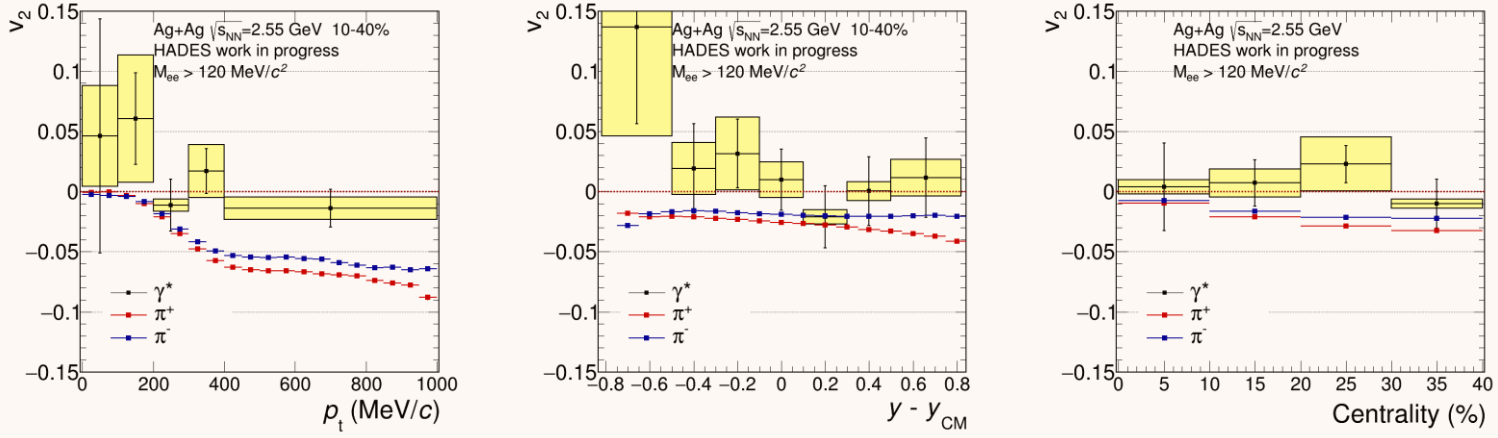
***M_{ee}* < 0.12 GeV/*c*²**: inclusive yield dominated by **π^0 decays**

⇨ Dilepton v_2 consistent with charged pion v_2



***M_{ee}* > 0.12 GeV/*c*²**: inclusive yield dominated by **thermal radiation**

⇨ Dilepton v_2 consistent with zero → early emission



Summary and Outlook

- HADES provides high-quality data of the di-electron production in elementary and heavy-ion collisions at SIS energy regime

Unique possibility to various observables:

- **Flow** to investigate the equation of station
- Establish **thermal nature** of the radiation

- Production Mechanism via **Polarisation**
- **QCD phase structure** at high μ_B with low momentum dileptons

- Exciting possibilities at future CBM experiment at FAIR with dedicated dilepton program

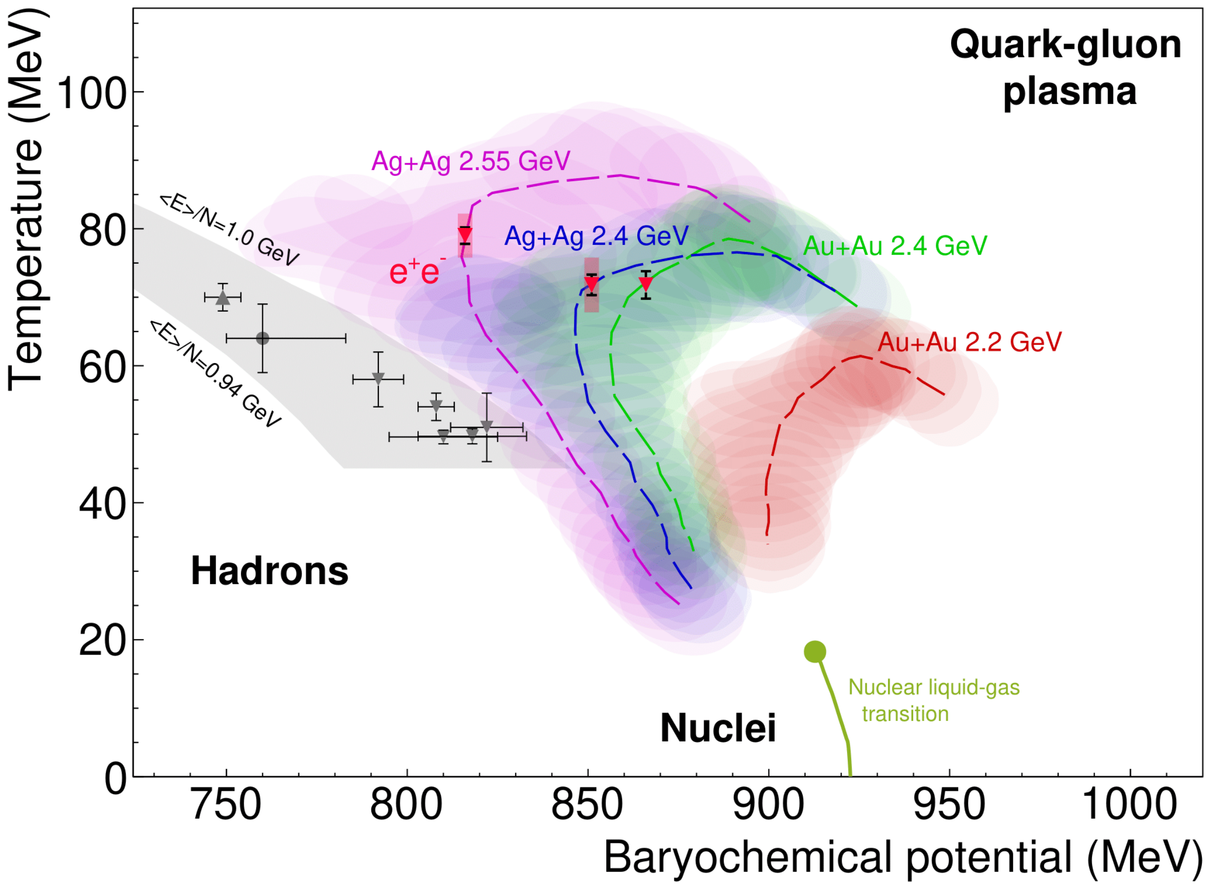


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figure: F.Seck, T.Galatyuk