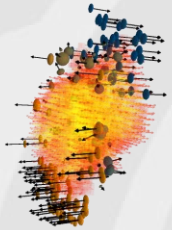
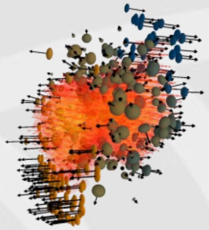
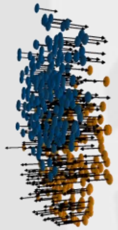
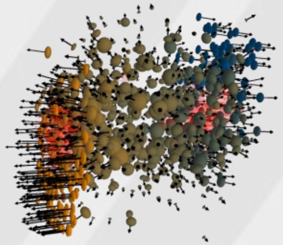
DECODING THE COMPOSITION OF QCD MATTER WITH THERMAL DILEPTONS

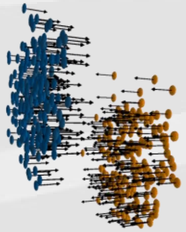




Florian Seck
(TU Darmstadt)







Dense Nuclear Matter EOS from Theory and Experiments
October 28 – November 01, FRIB

SEARCH FOR LANDMARKS IN THE QCD PHASE DIAGRAM

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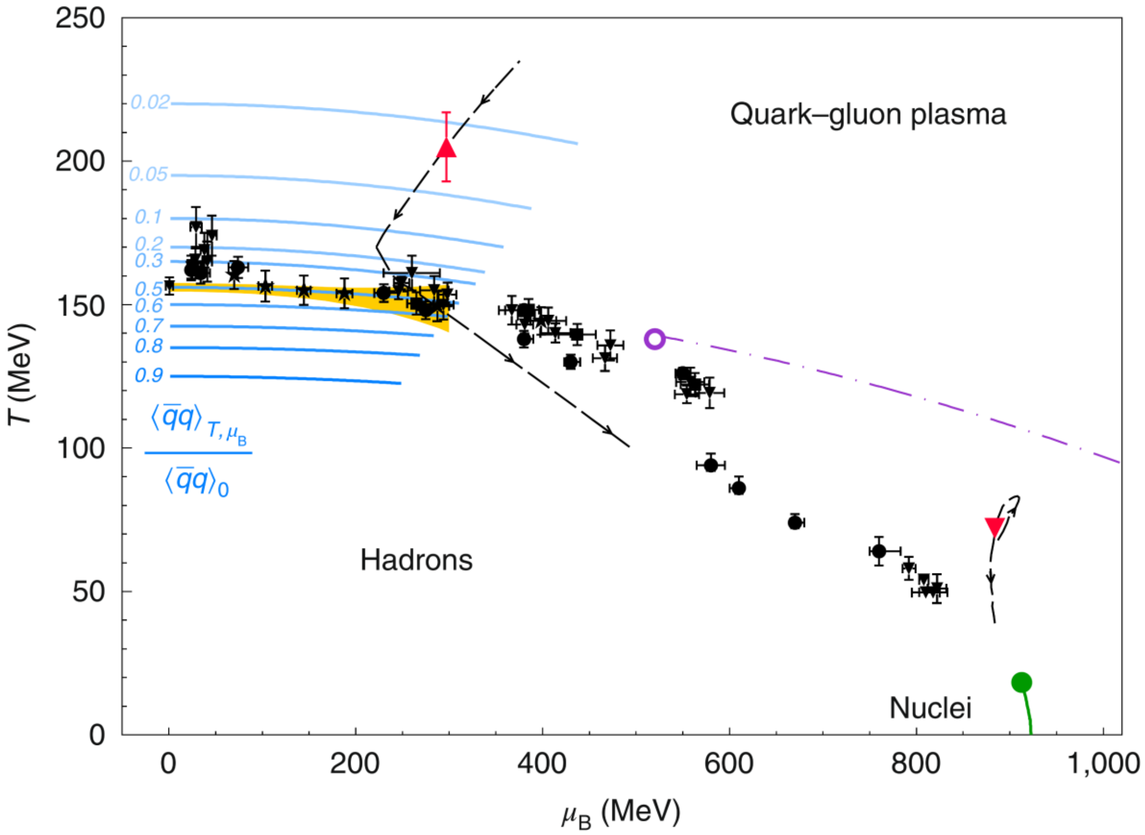
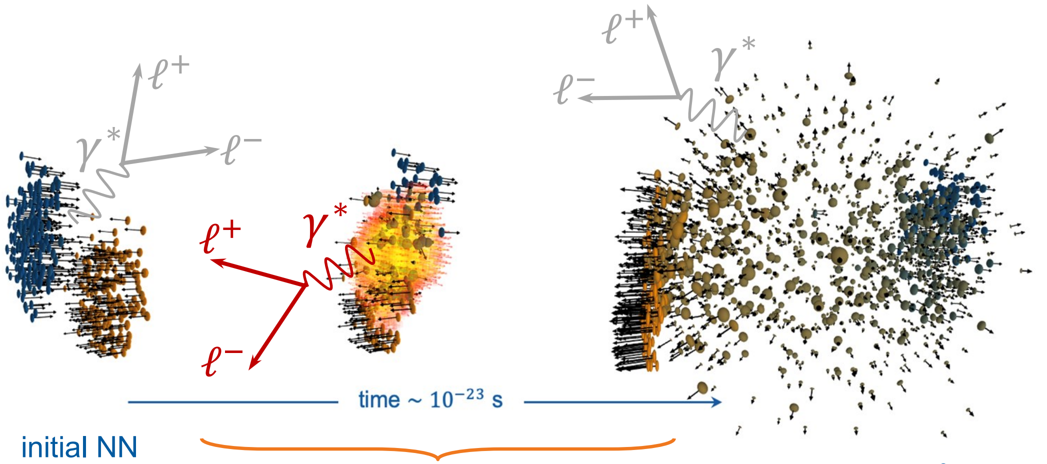
- Search for
  - Phase boundaries
  - Changes in microscopic degrees of freedom
  - Restoration of chiral symmetry
- Bulk observables and rare probes offer different tools to understand the nature of the matter created in HIC
- Electromagnetic radiation (γ, γ^*)
  - Reflects the whole history of a collision
  - No strong final state interaction
    ⇝ leaves reaction volume undisturbed
  - Virtual photons reconstructed via their dilepton decay
    ⇝ extra information: invariant mass

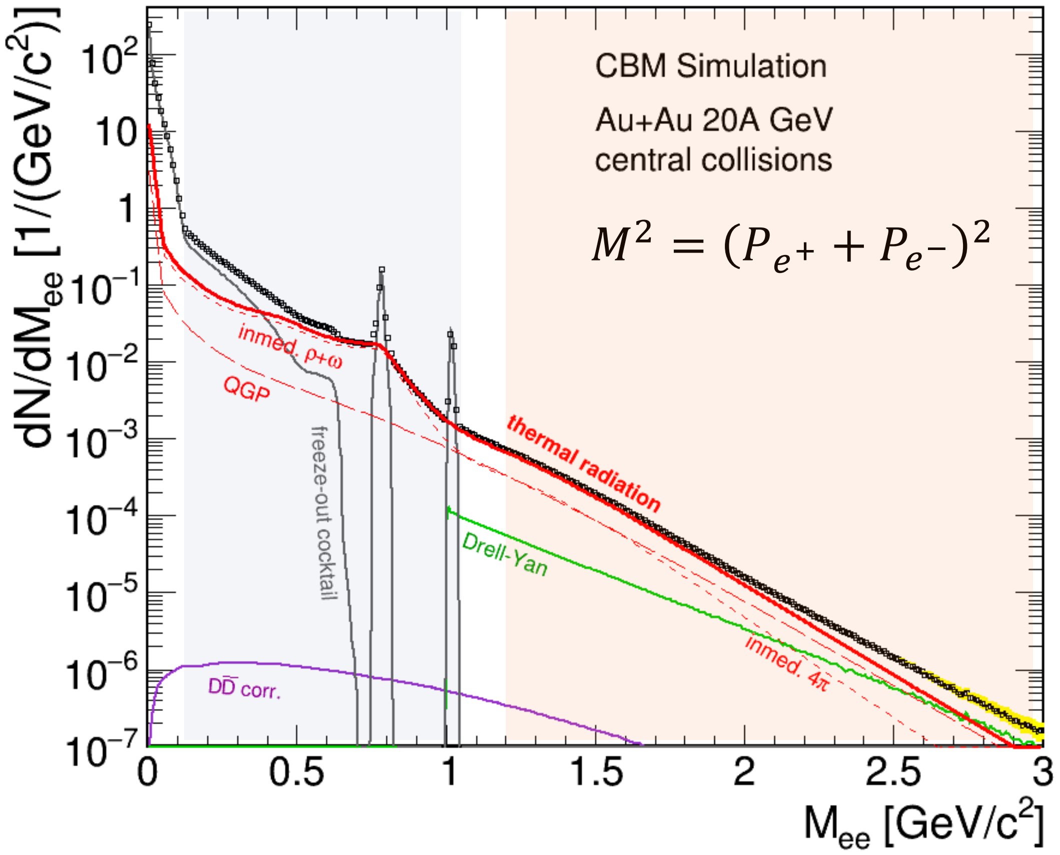
HADES, Nature Phys. 15 (2019) 1040



EXPERIMENTAL CHALLENGES

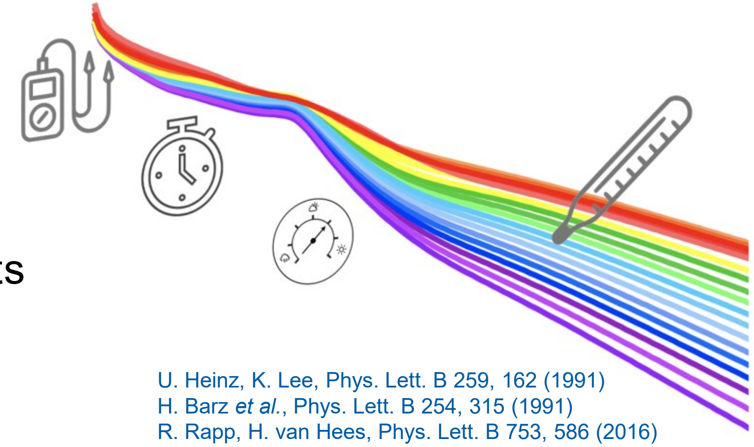
- Dileptons are rare probes
  - High interaction rates
  - Good signal-to-combinatorial background ratio (S/CB)
  - High acceptance (Mid-rapidity, low-$M_{\ell\ell}$, low-p_T coverage)
- Isolation of thermal radiation by subtraction of measured decay cocktail $(\pi^0, \eta, \omega, \varphi)$, Drell-Yan, $c\bar{c}$ $(b\bar{b})$





THERMAL DILEPTON RADIATION AS MULTIMETER OF THE FIREBALL

- Lifetime via low-mass yield
  → search for "**extra radiation**" due to latent heat around **phase transition** (& critical point?)
- Temperature via slope of invariant mass spectrum
  → **flattening** of caloric curve (T vs ε) sign for a **phase transition**
- Pressure anisotropies via dilepton flow
  → **access** to **EoS at high baryon density** via multi-differential measurements
- Spin polarization allows to distinguish different sources of thermal dileptons
  → **access** information on **production mechanism**
- Electric conductivity probed in the limit p_{ee} = 0 MeV/c, M_{ee} → 0 MeV/c^2
  → **access** to **transport properties** of QCD matter
- Access to exotic QCD phases
  → yield **enhancement** in vicinity of **color superconducting phase** (?)



Dileptons are rare probes → high-rate, high-efficiency detectors
→ HADES at GSI, CBM at FAIR

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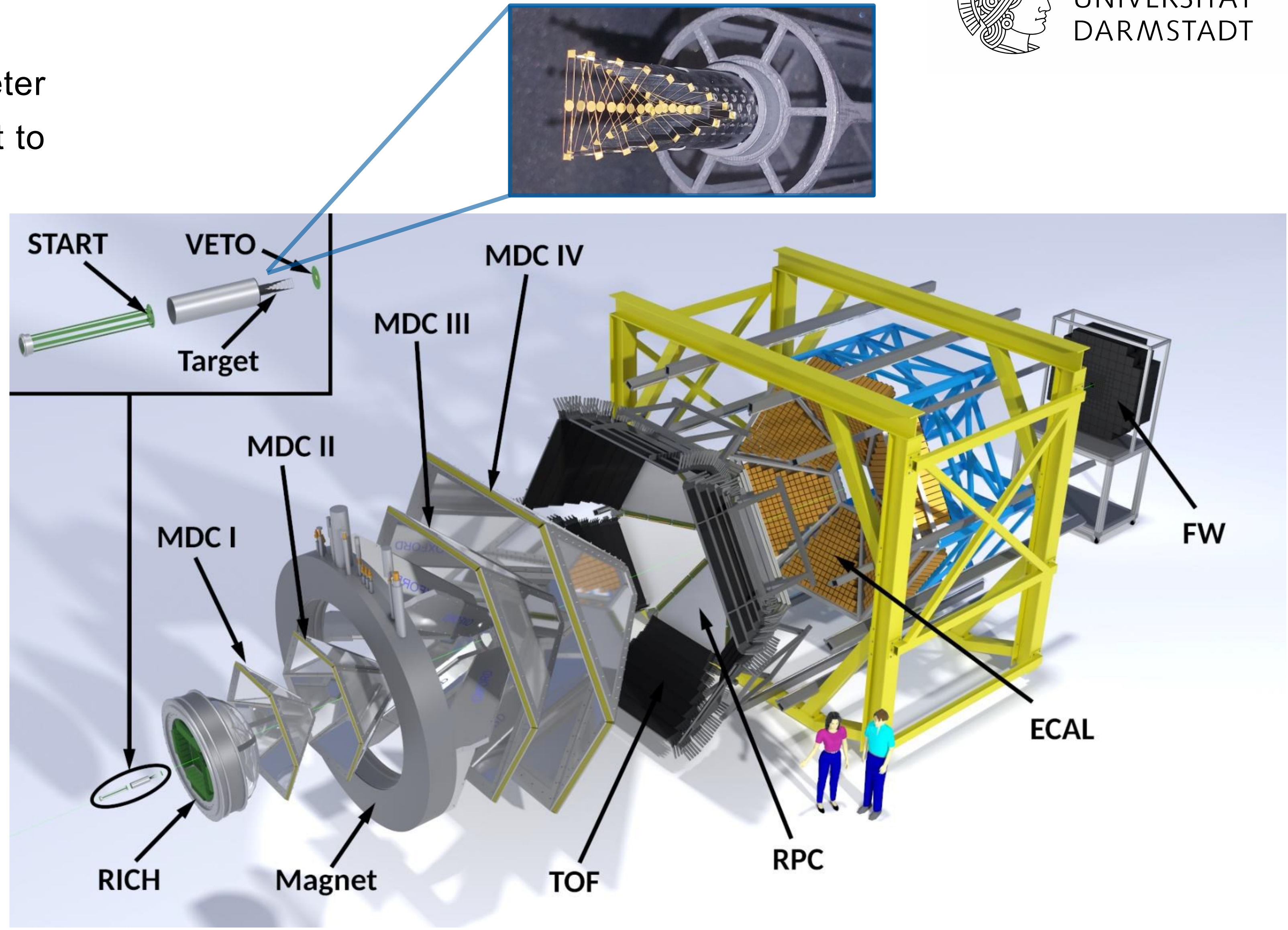
HADES EXPERIMENT AT GSI

- **H**igh-**A**cceptance **D**i-**E**lectron **S**pectrometer
- Designed with a minimal material budget to reduce conversion
- Large angular coverage:
  - $15^\circ < \theta < 85^\circ$
  - $0^\circ < \phi < 360^\circ$
- Accepted trigger rate up to
  - 16 kHz for heavy-ion collisions
  - 50 kHz with proton/pion beam
- Dedicated components for e^+/e^-:
  - Time-of-Flight measurements
  - Ring-Imaging Cherenkov Detector
  - Electromagnetic Calorimeter

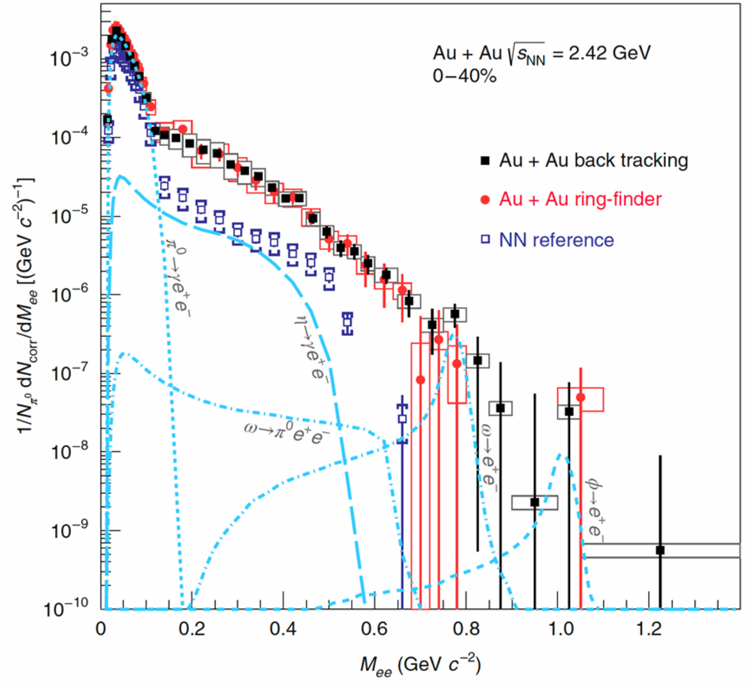
HADES allows for high efficiency and high purity electron sample



DILEPTON INVARIANT MASS SPECTRA FROM HADES

- Clear excess visible above contributions from initial NN reference and freeze-out cocktail

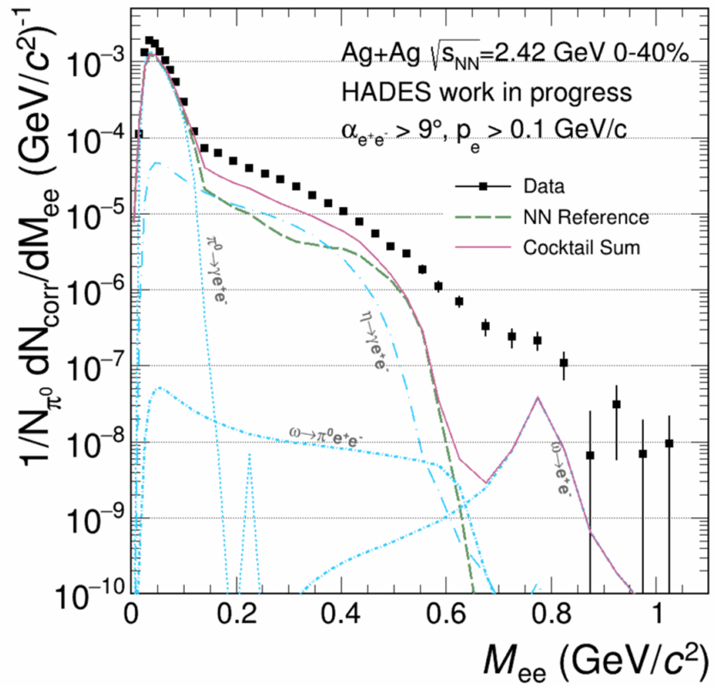
Au+Au at $\sqrt{s_{NN}} = 2.42$ GeV



HADES, Nature Phys. 15 (2019) 1040

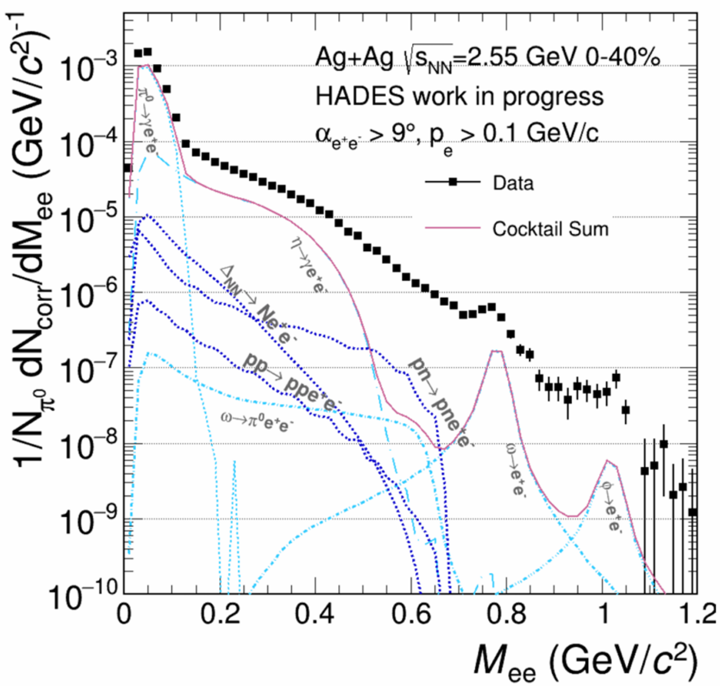
measured NN reference

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



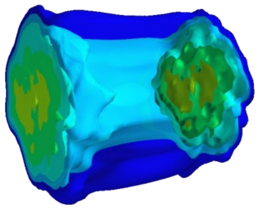
measured NN reference

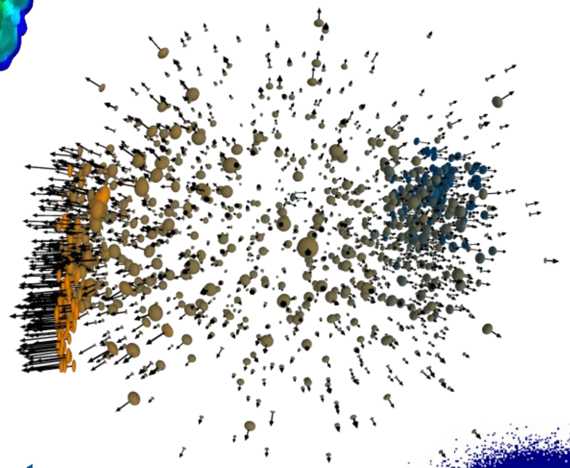
Ag+Ag at $\sqrt{s_{NN}} = 2.55$ GeV



simulated reference (GiBUU)
→ analysis of NN measurement at the same collision energy ongoing

DESCRIPTION OF THE SPACE-TIME EVOLUTION

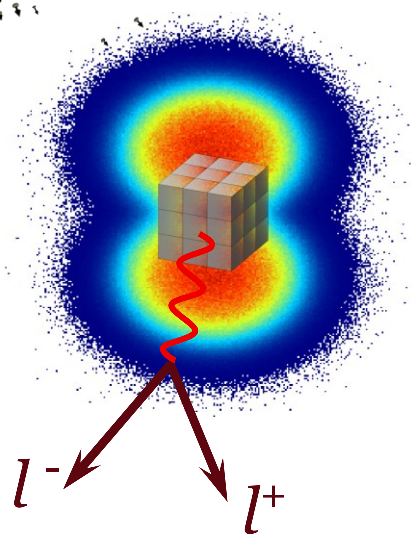




- Bulk observables are reasonably well described by simulations
  - Hydrodynamics at high collision energies
  - Microscopic transport model at low collision energies

- Pure transport simulations struggle to describe dilepton data
  - “shining” or time-integration method

- “Combination” of hydrodynamics and transport model: **coarse-grained transport**



- Simulate events with a transport model & take ensemble average to obtain smooth space-time distributions
- Divide space-time into 4-dim. cells
- Check if cell is thermalized (→ enough interactions)
- Extract baryon density ρ_B, medium velocity $\vec{u}$, and temperature T (→ m_T spectra of pions)
- Calculate dilepton rates based on these inputs per cell
- Space-time integration via summation of the contributions from all cells

BARYON DENSITY AND TEMPERATURE PROFILE IN AU+AU AT 1.23 AGEV

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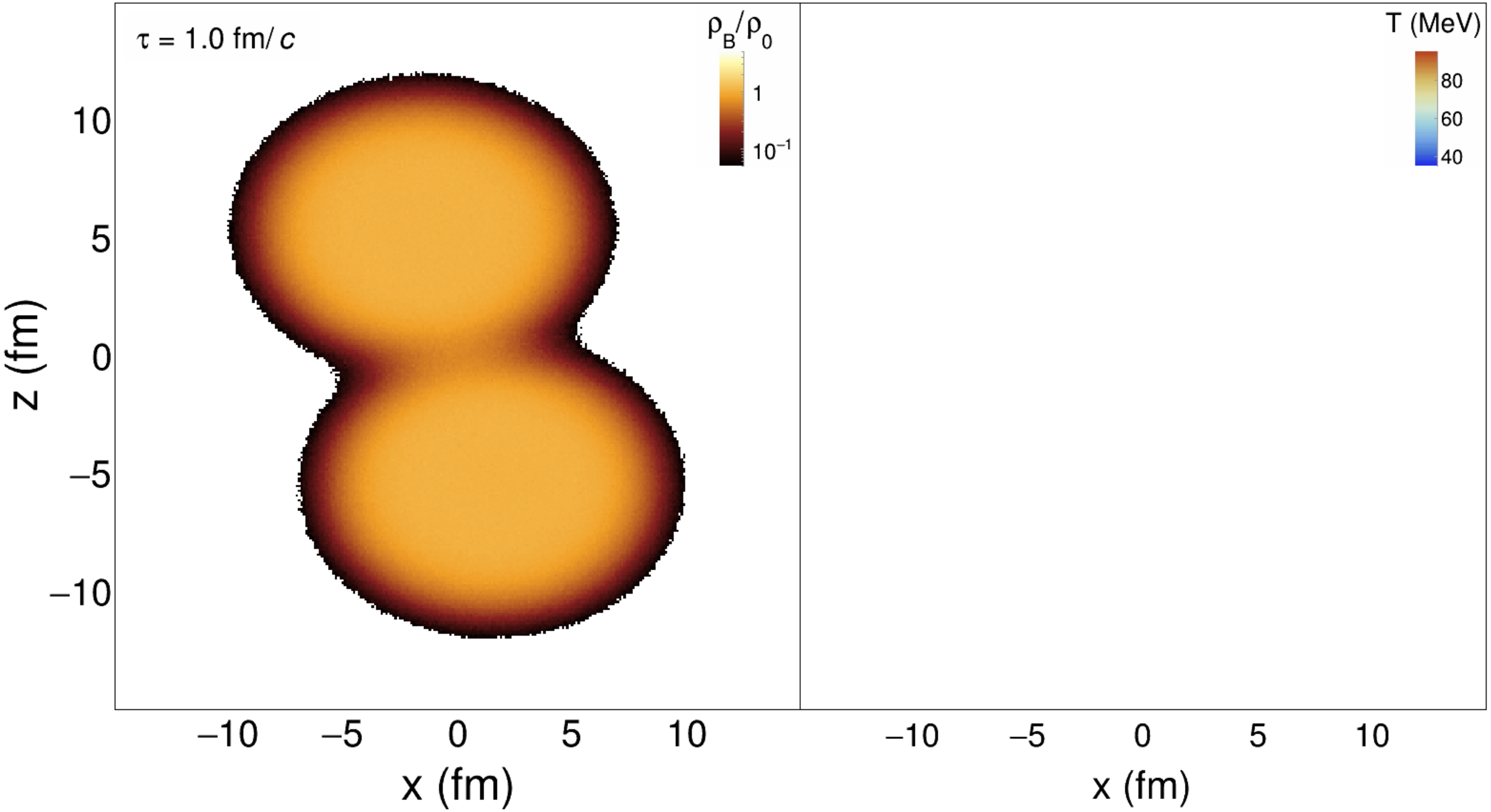

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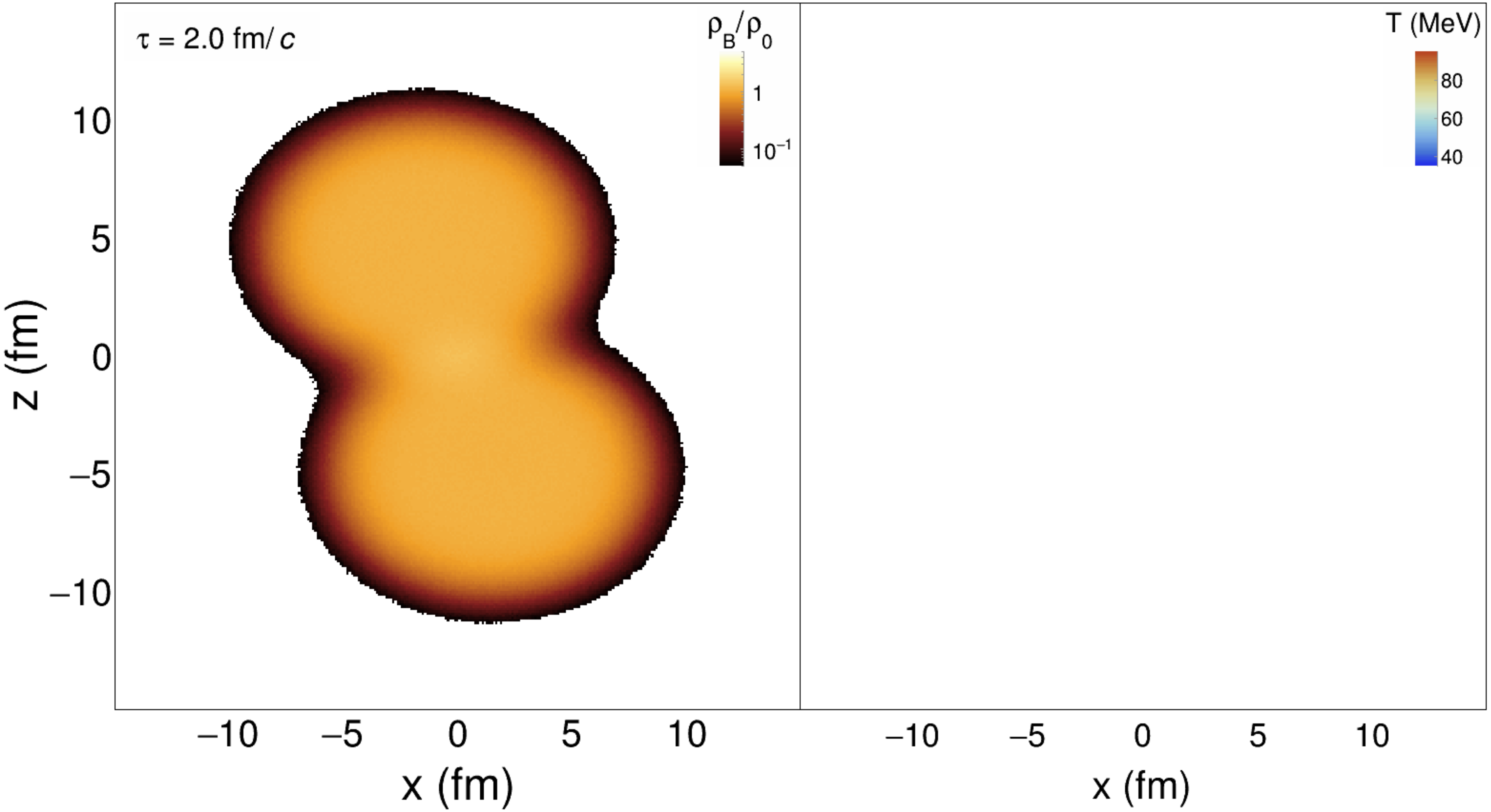

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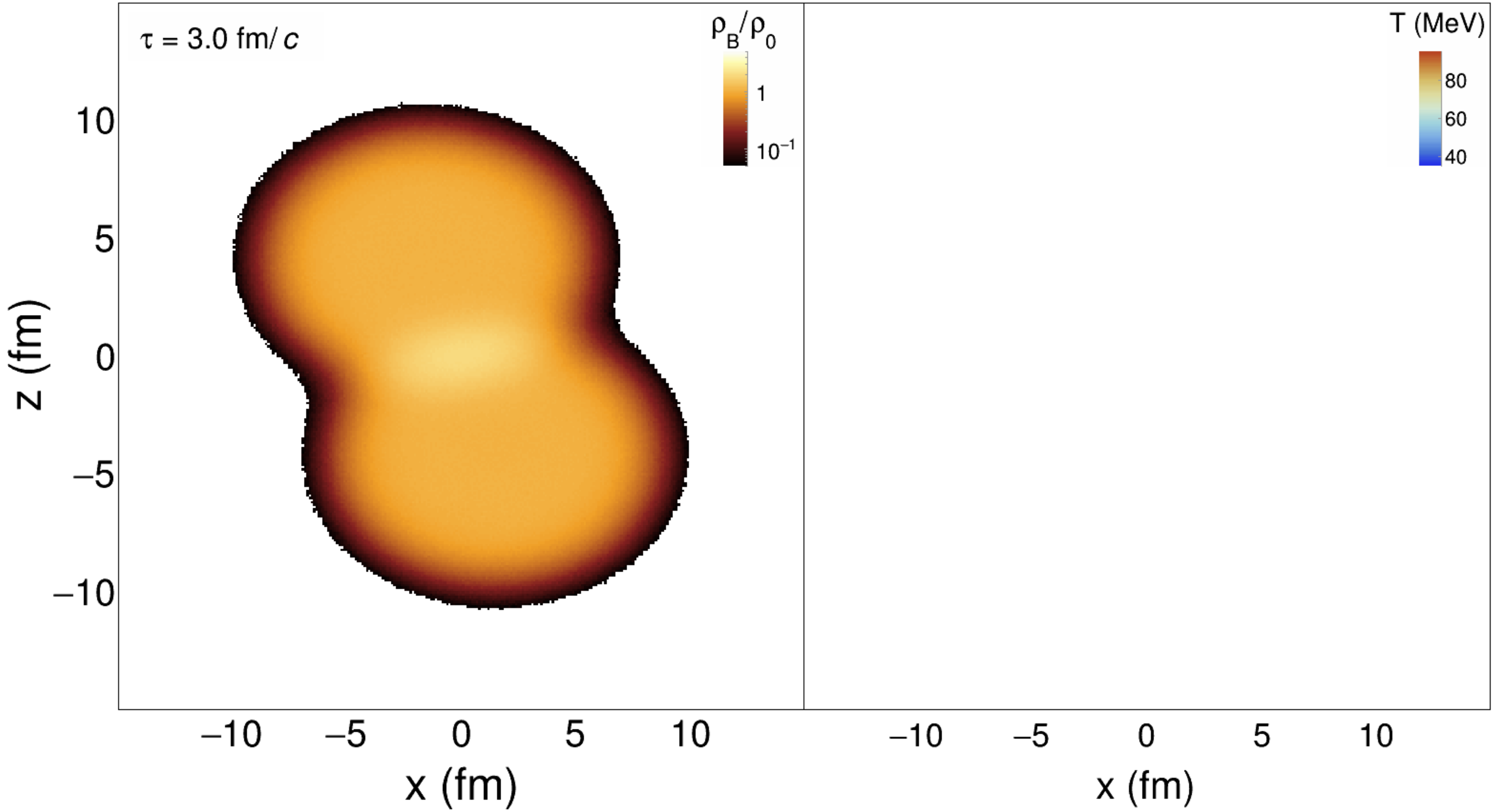

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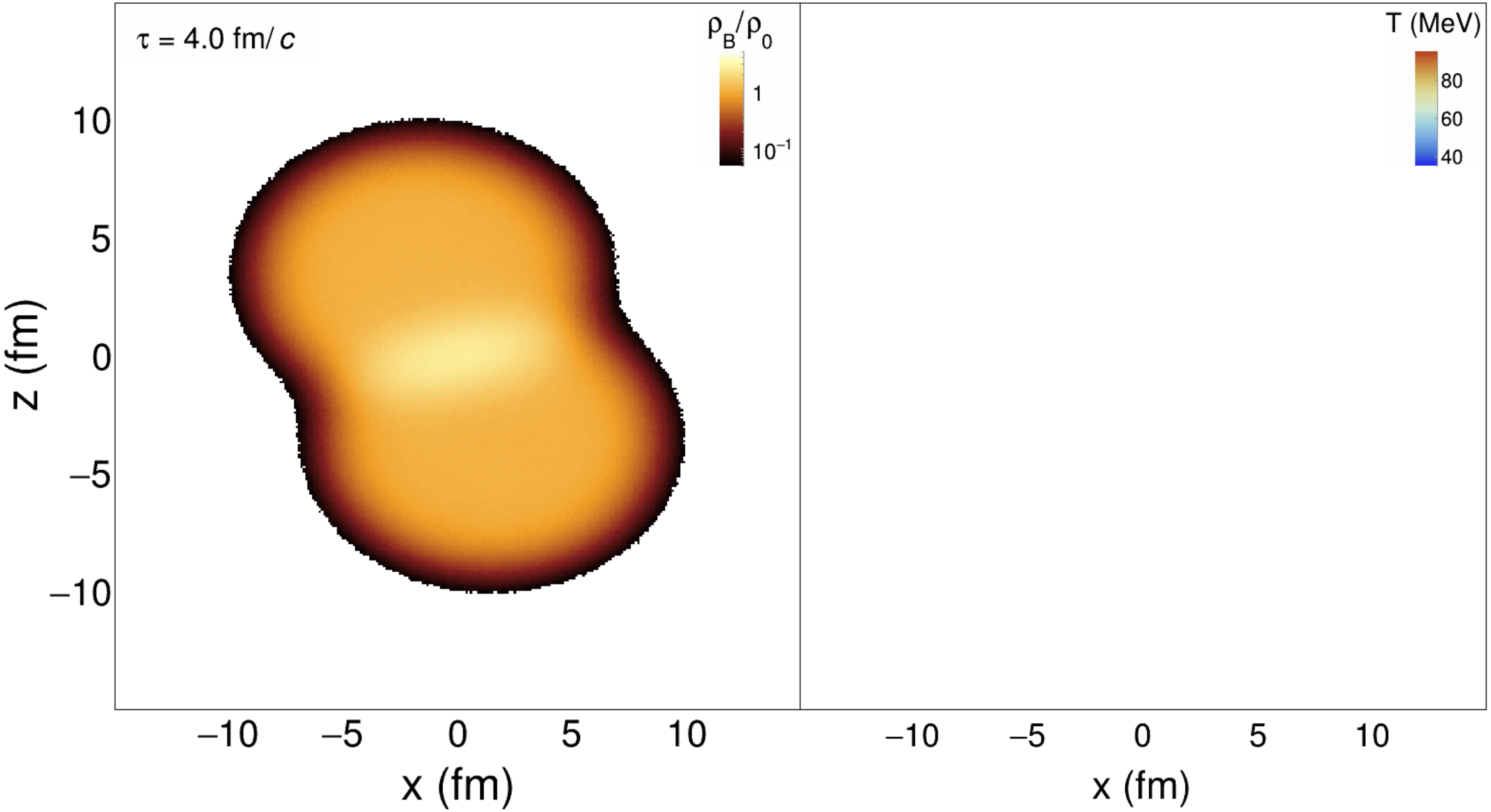

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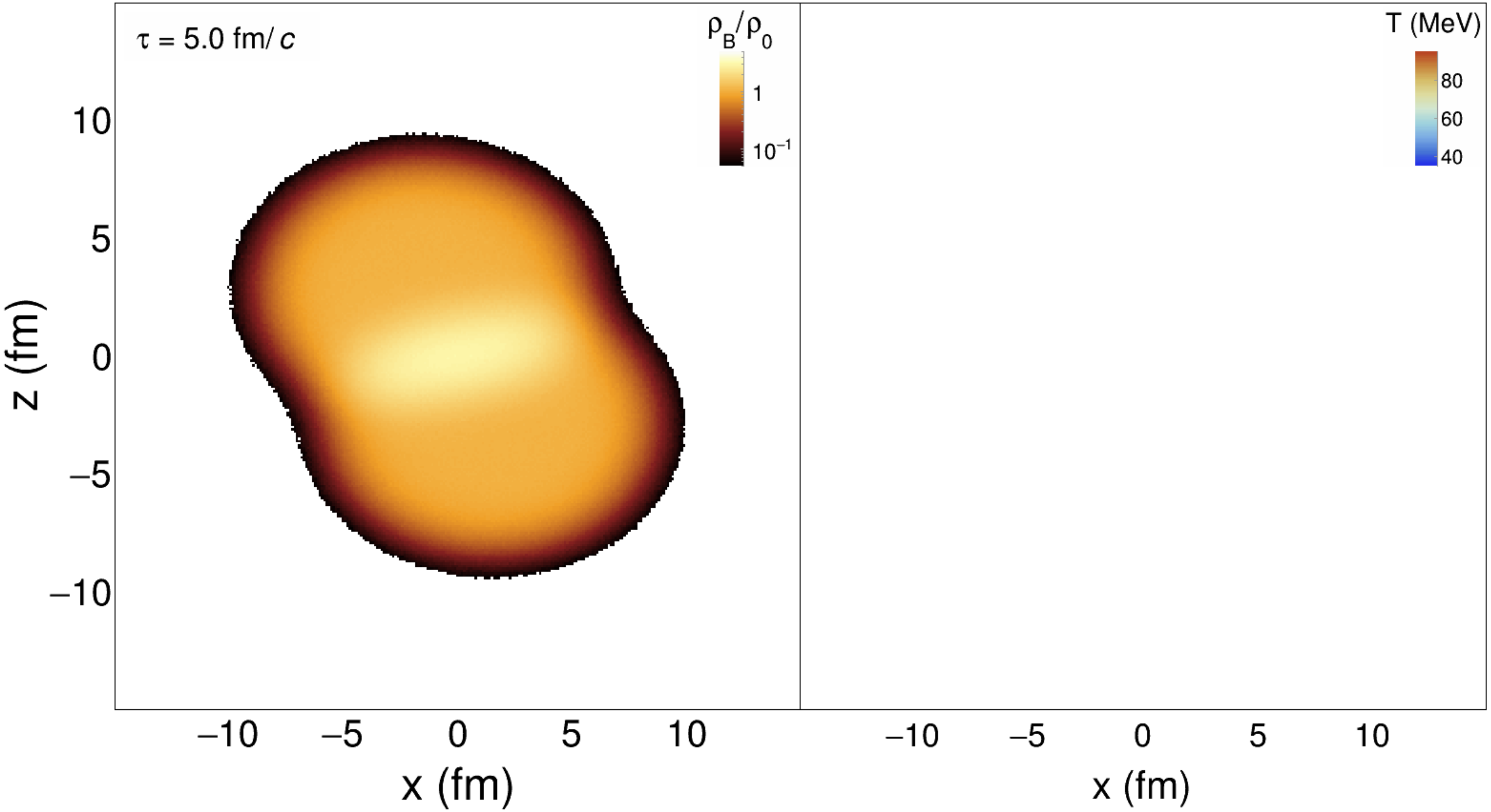

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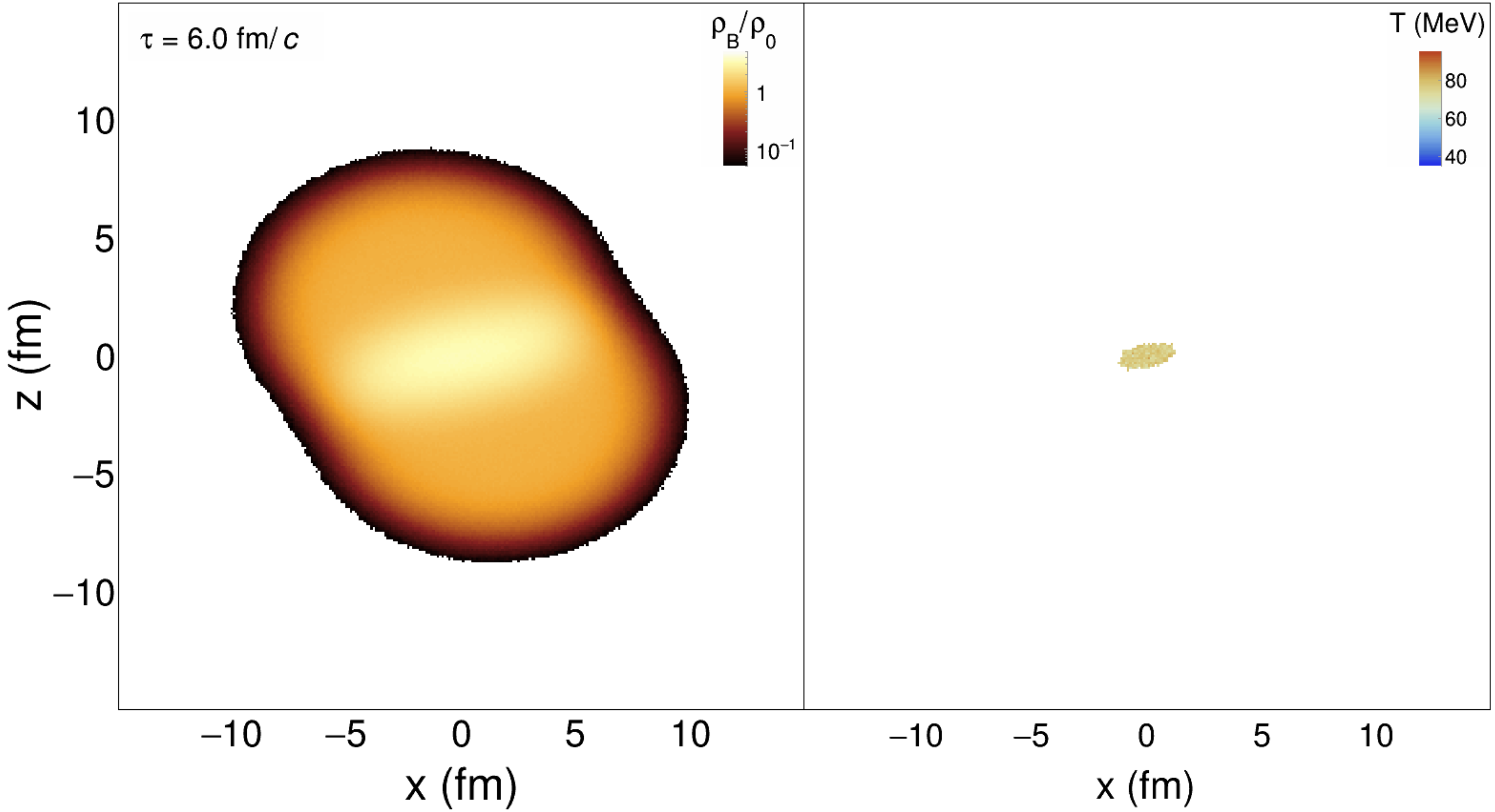

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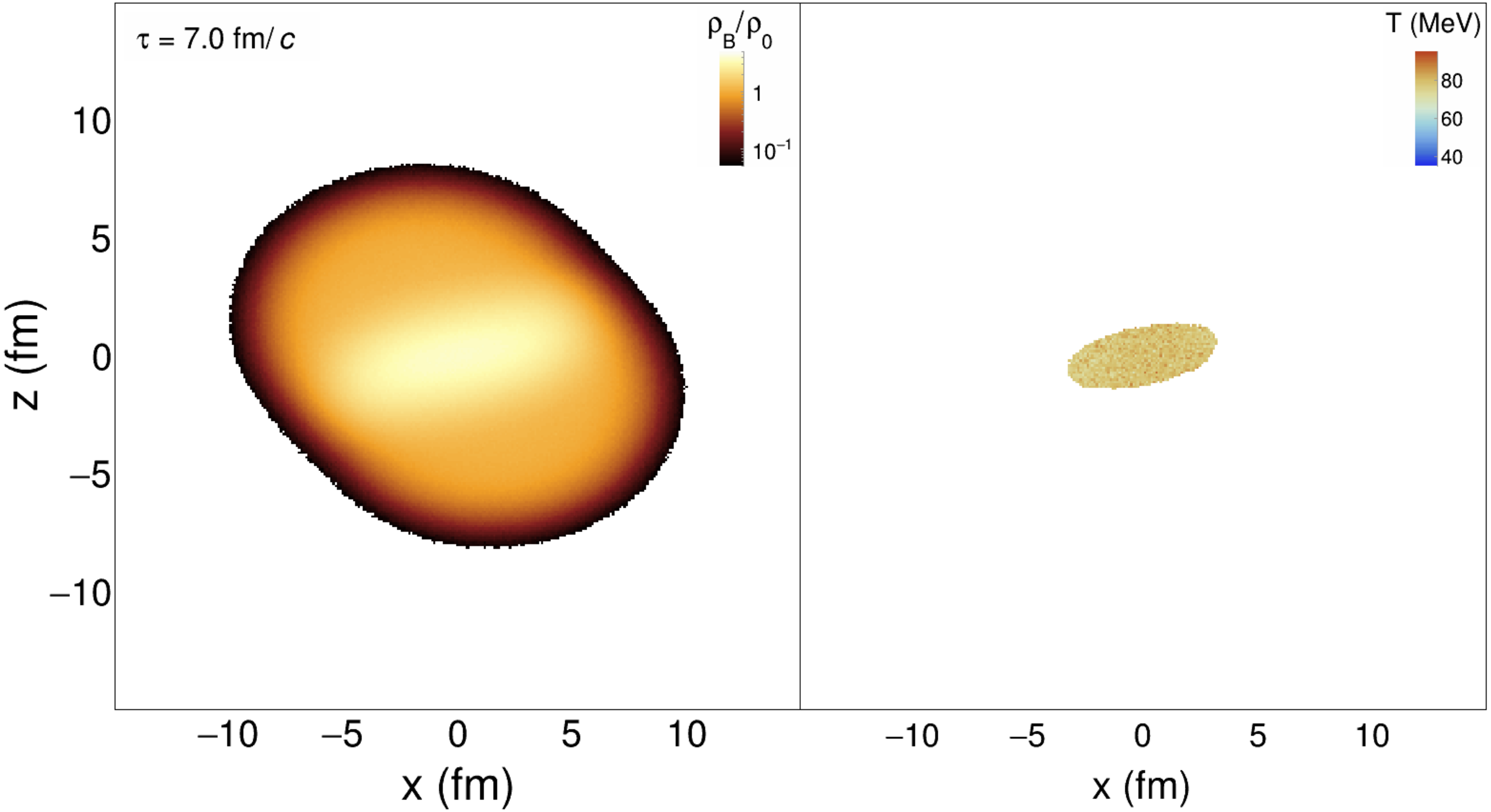

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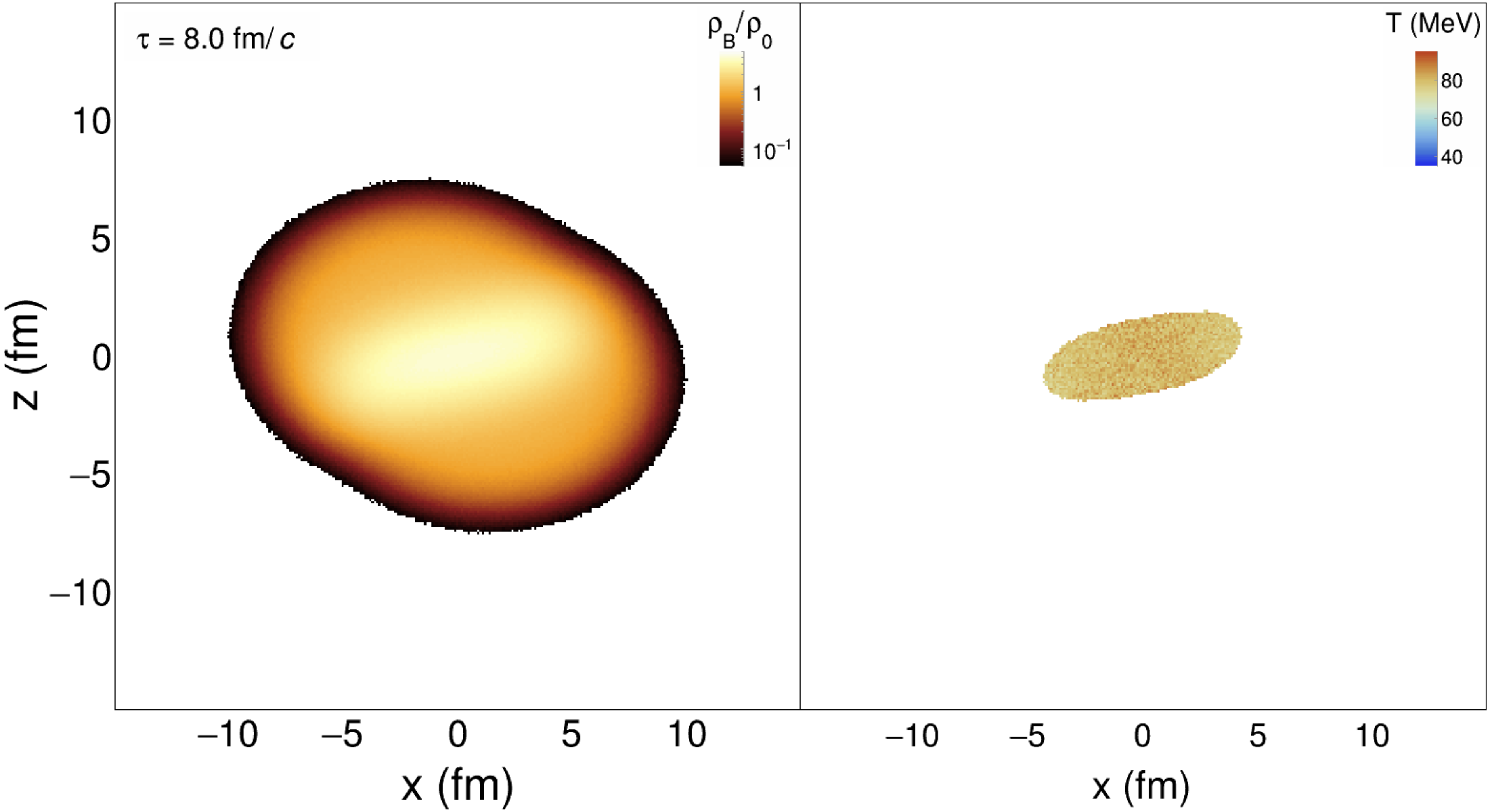

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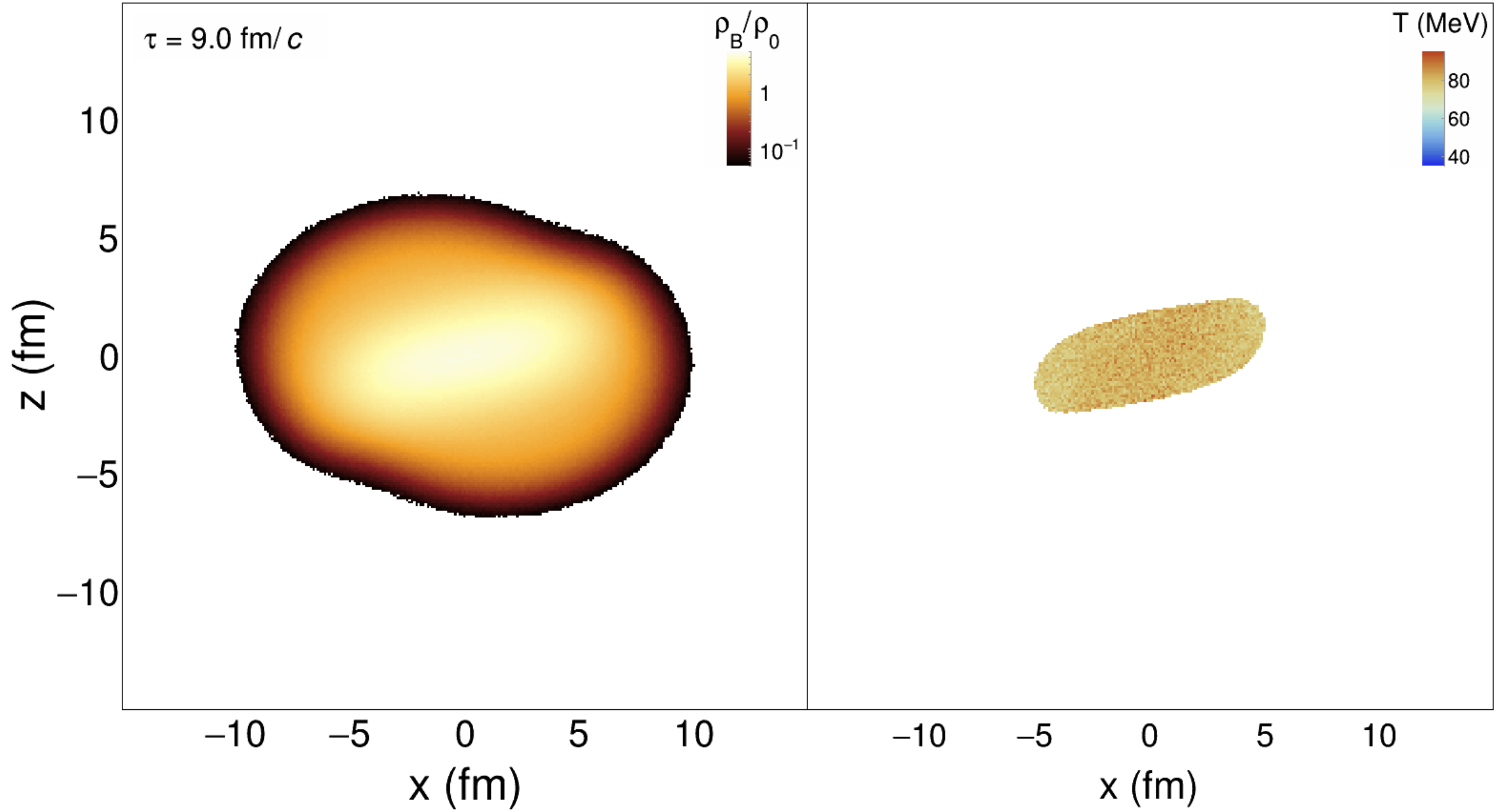

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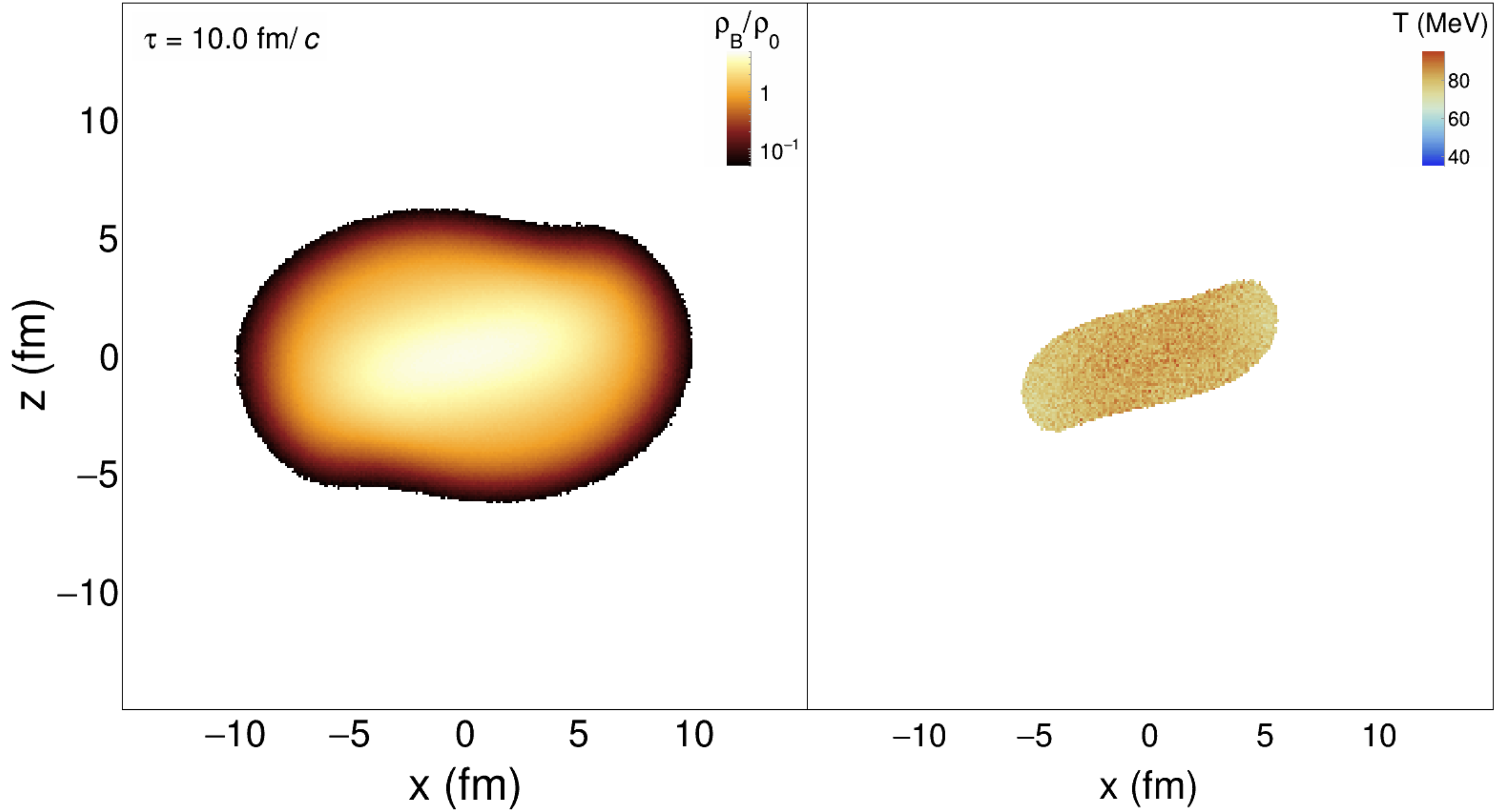

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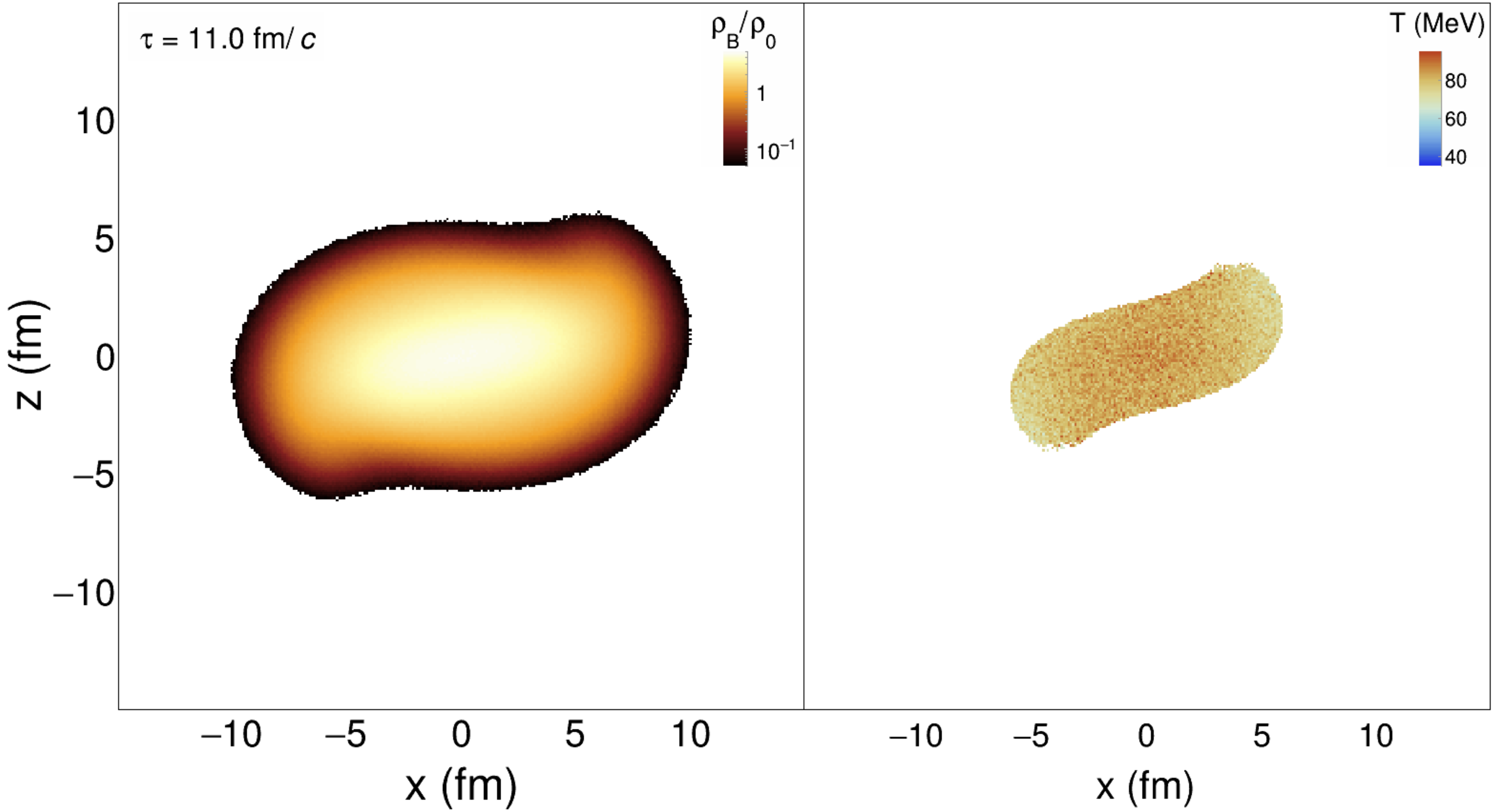

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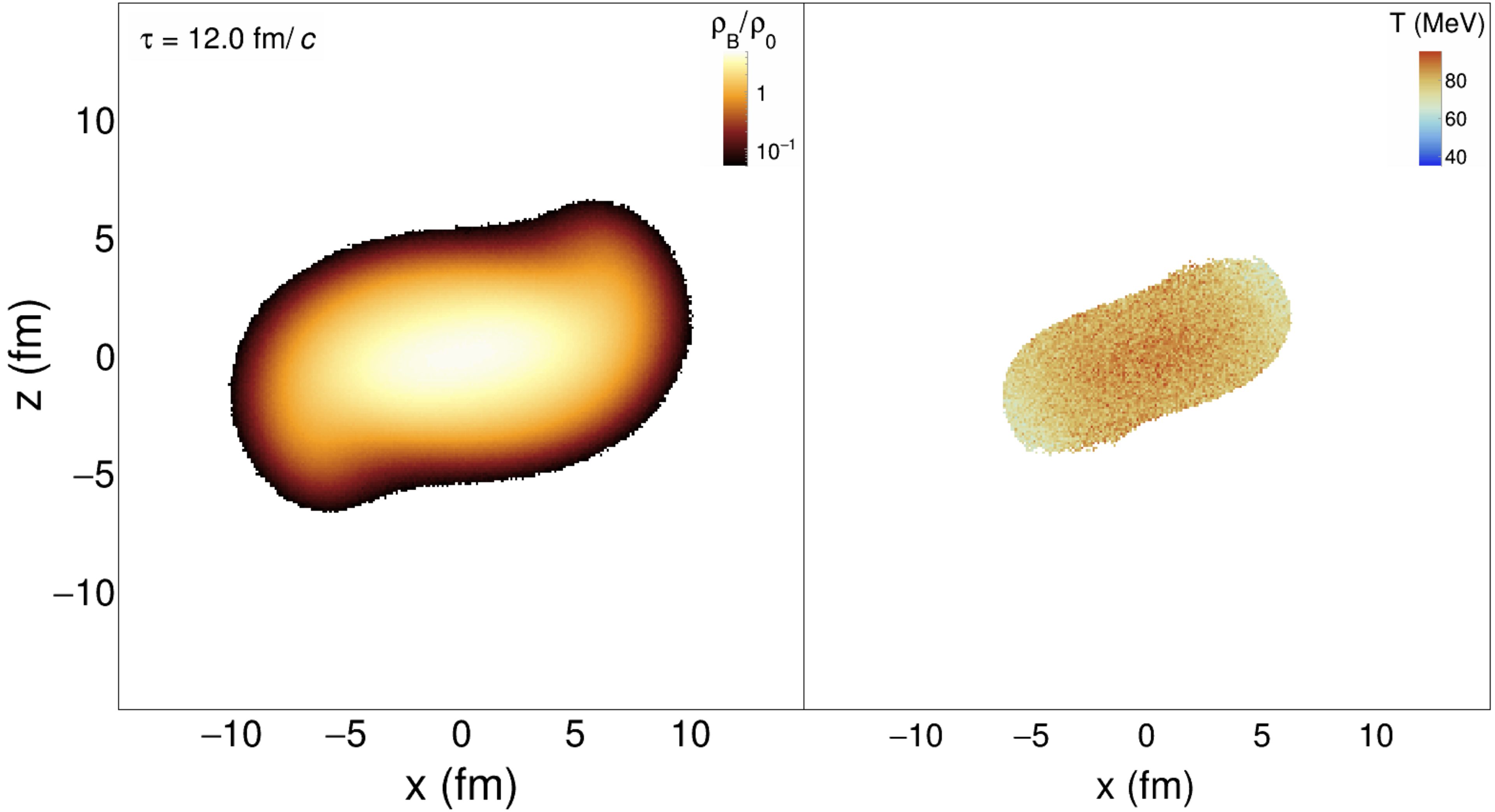

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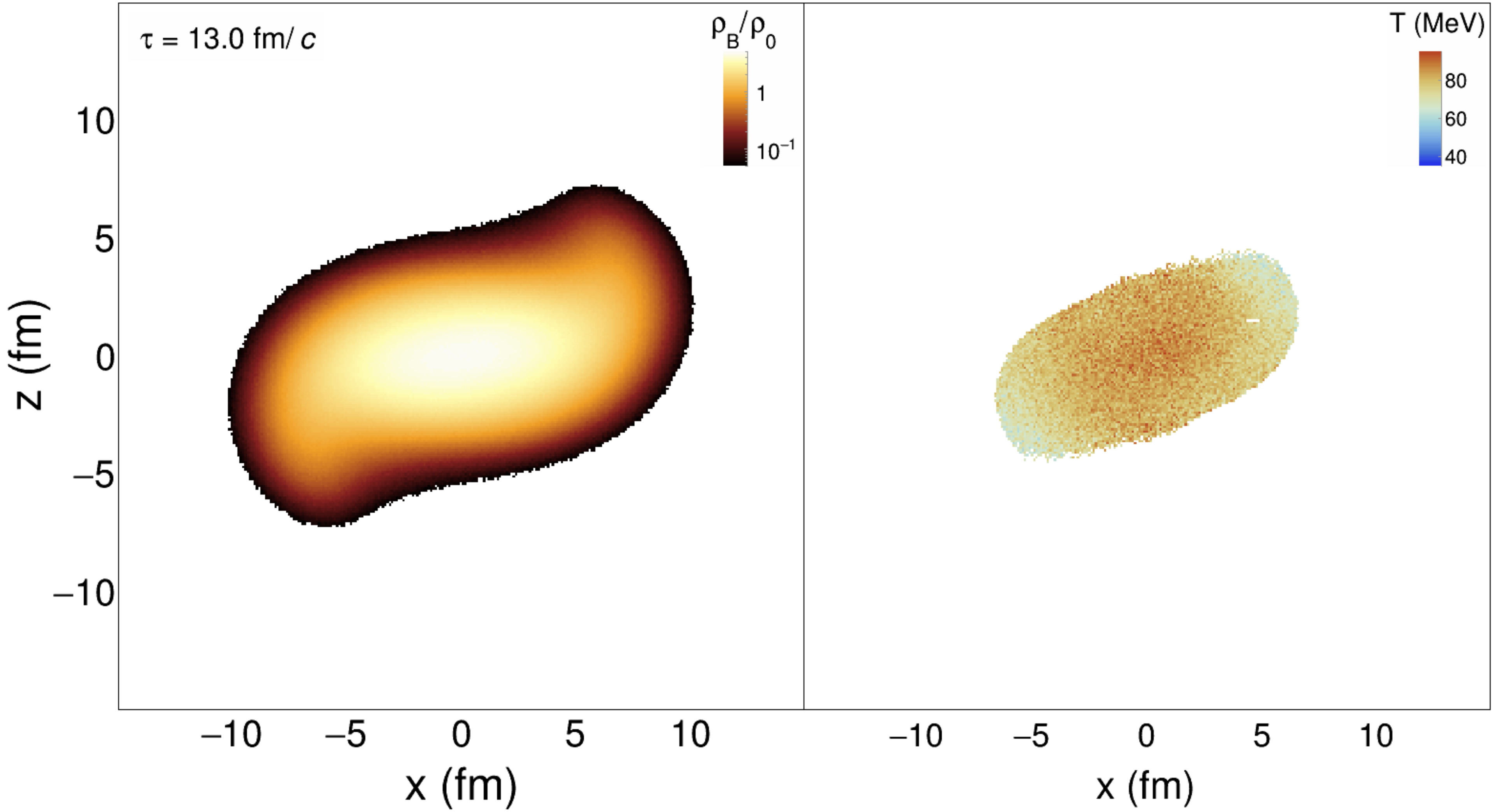

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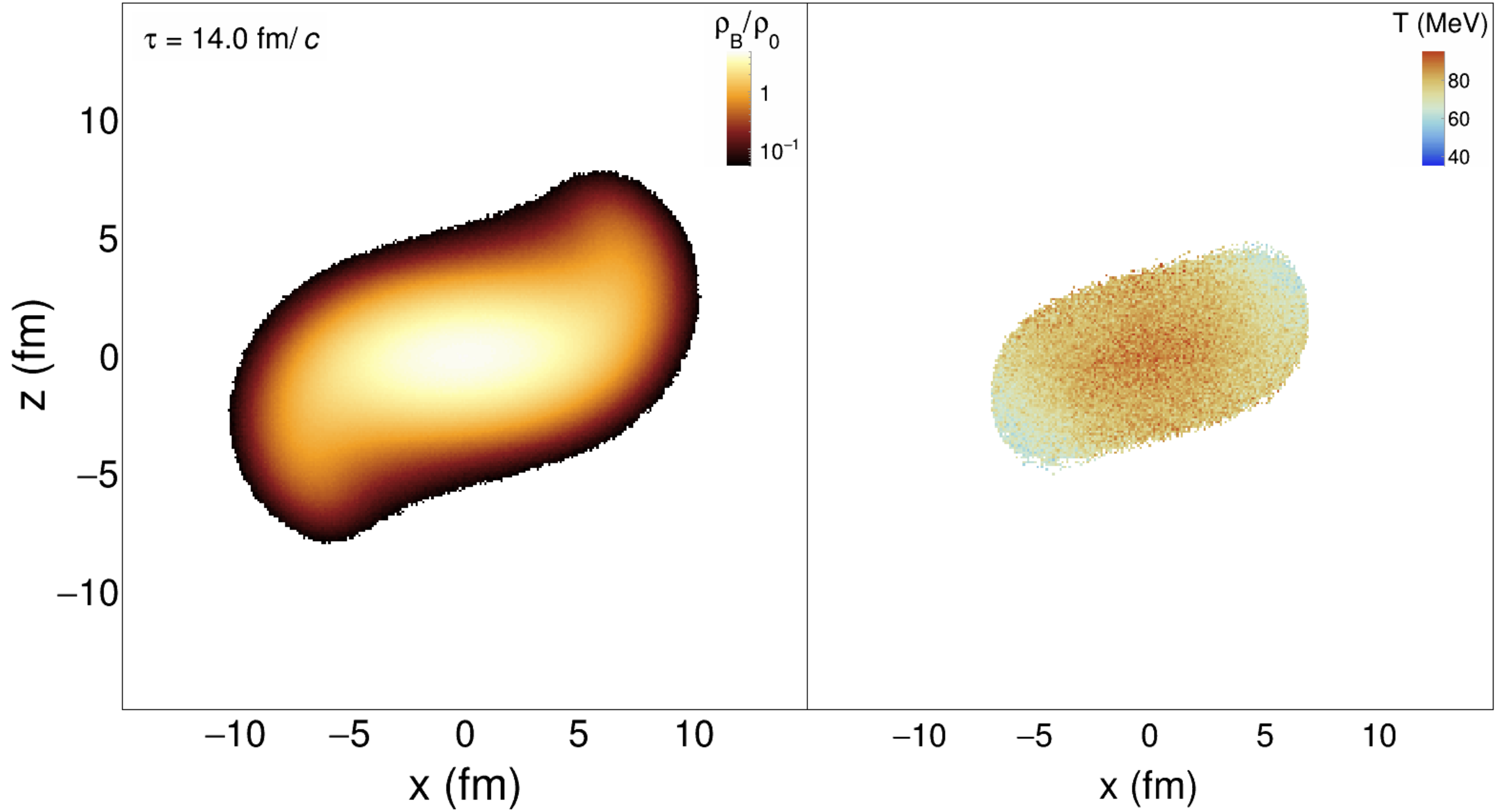

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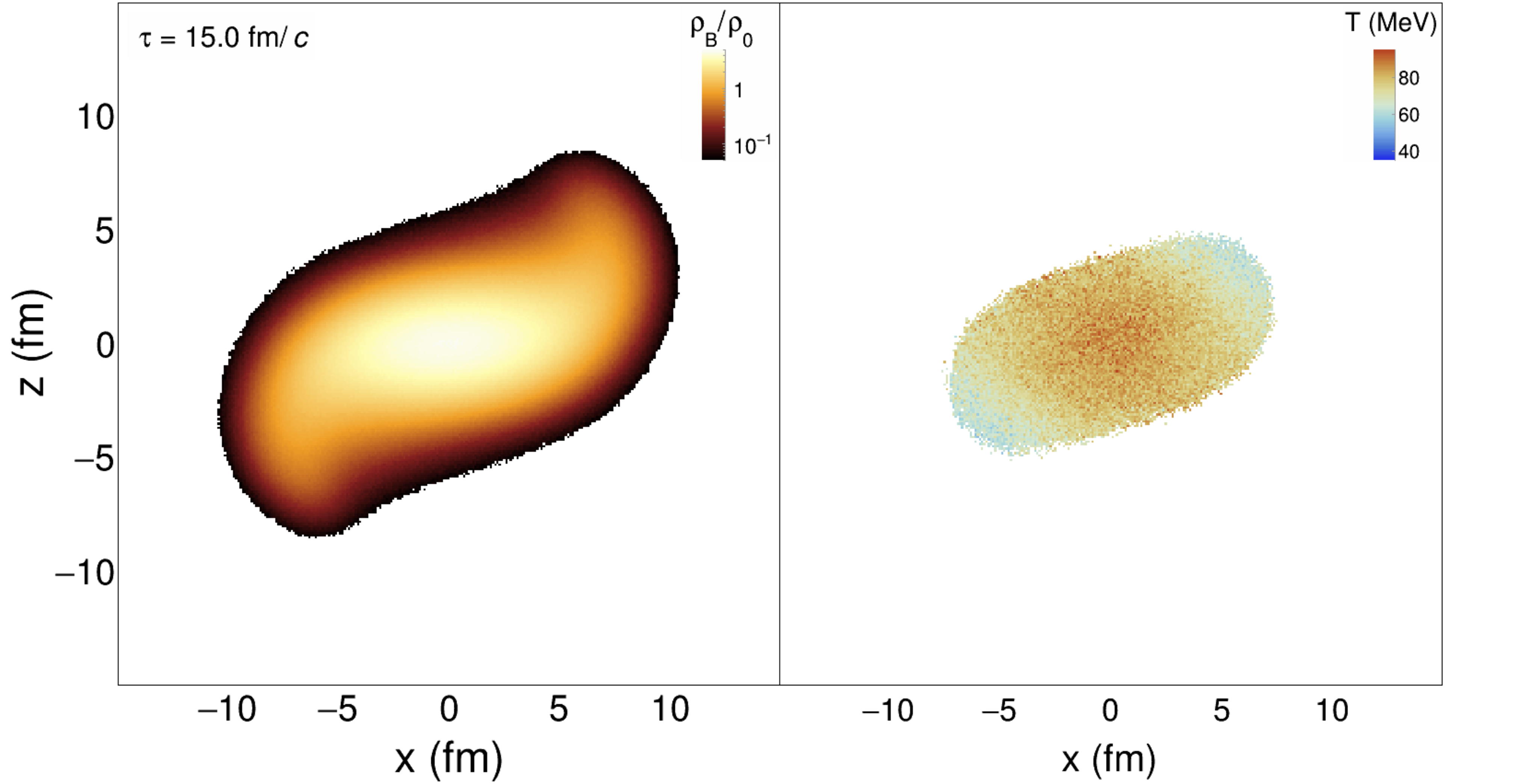

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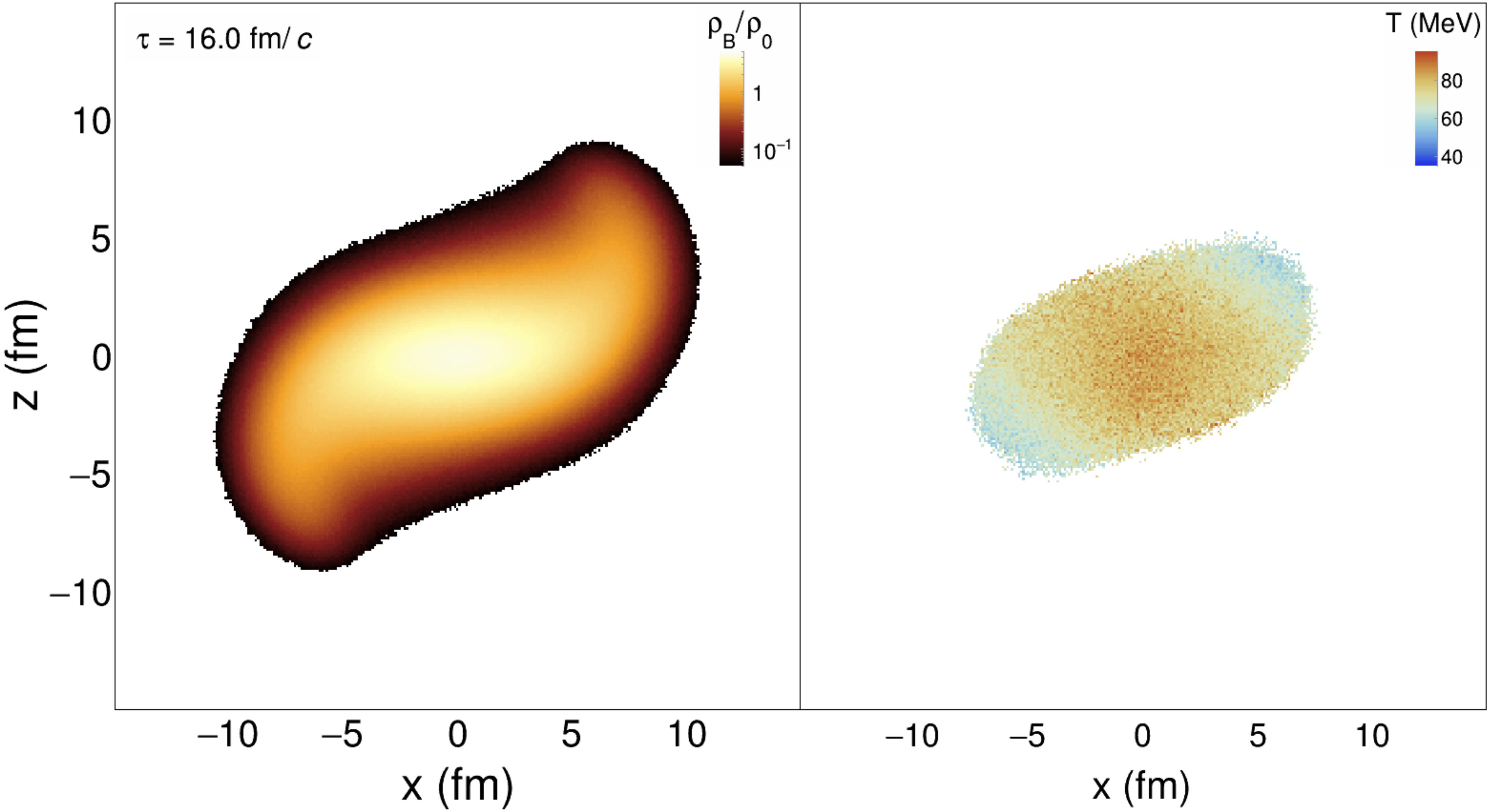

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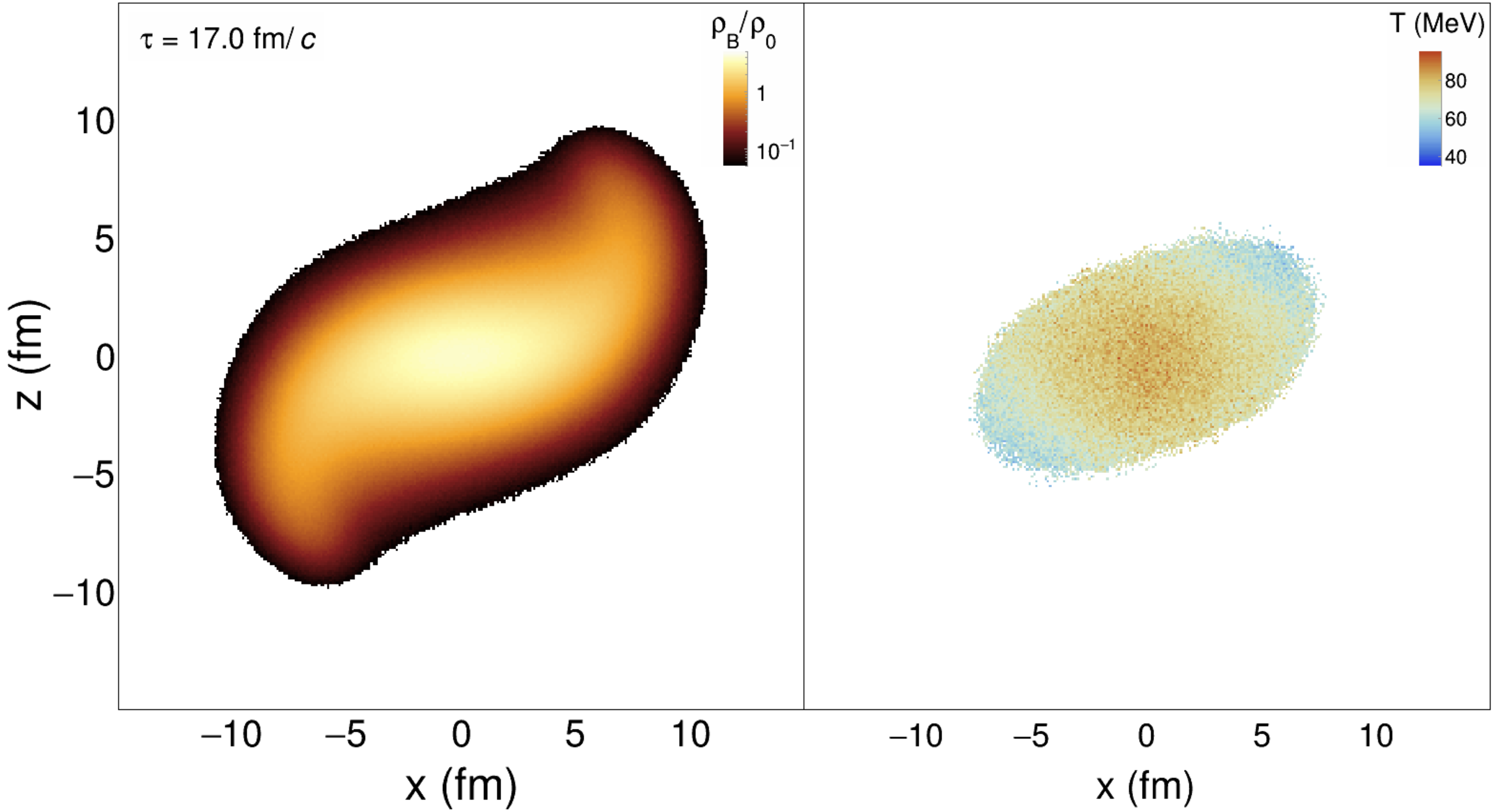

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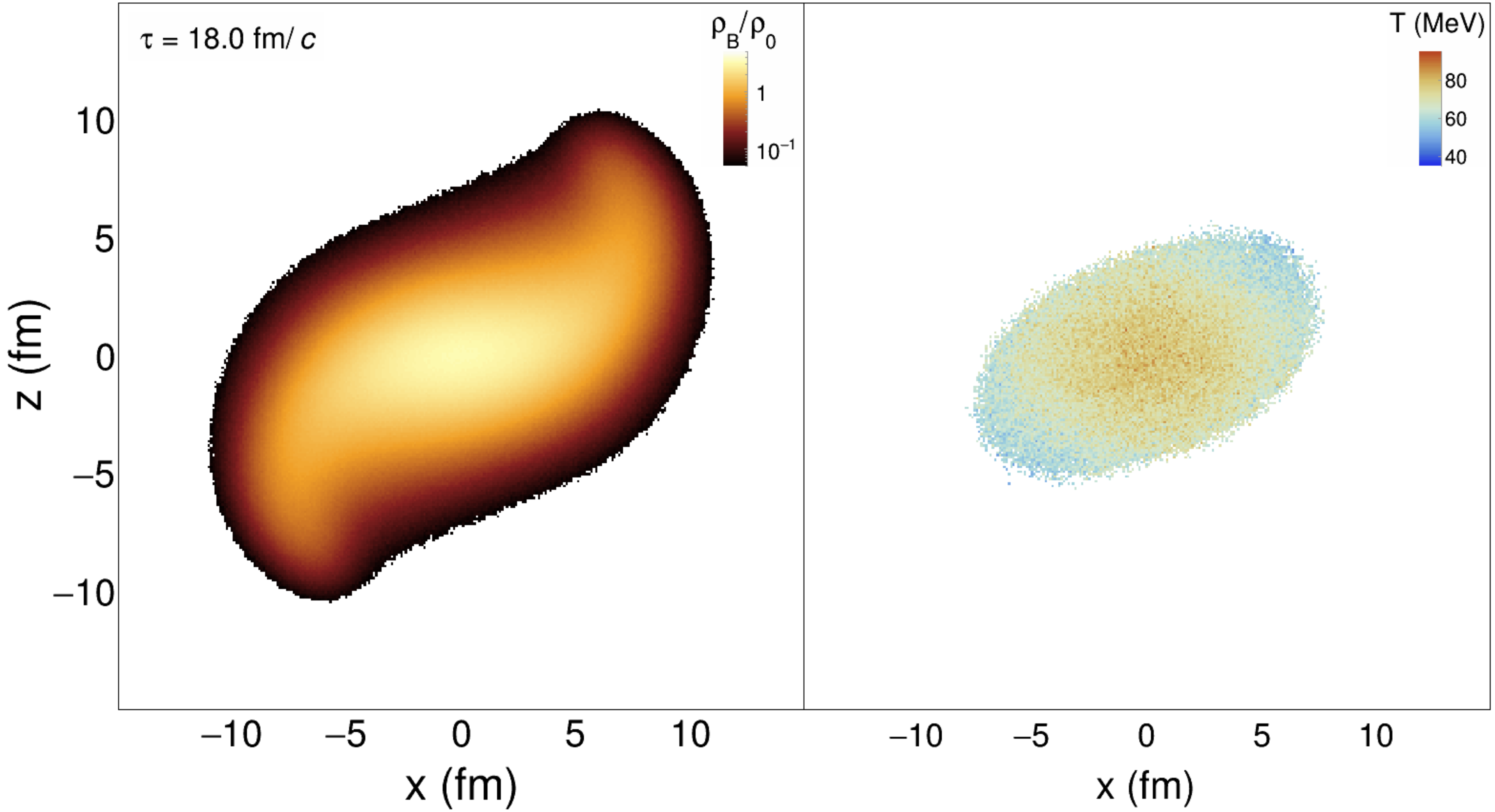

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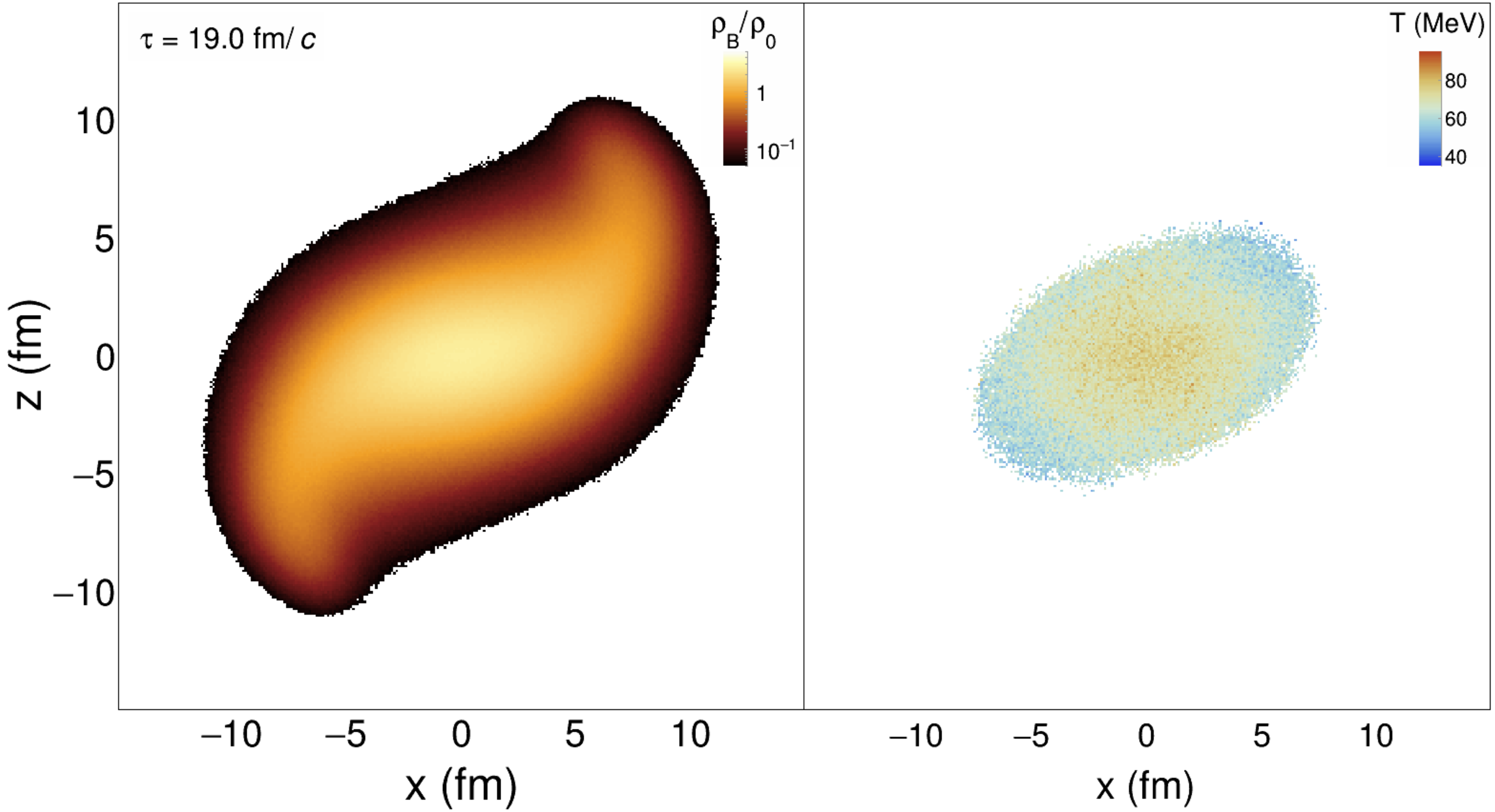

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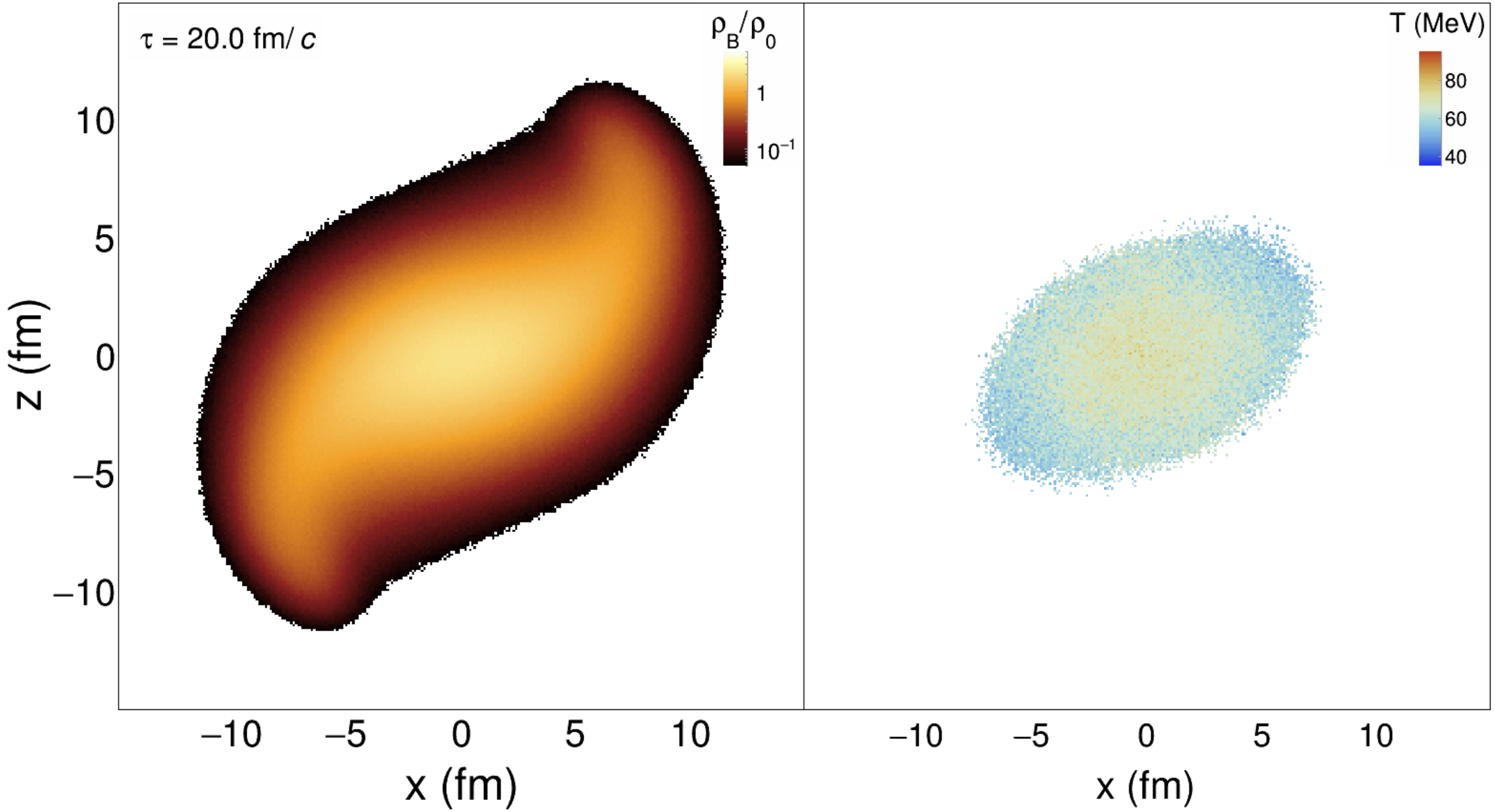

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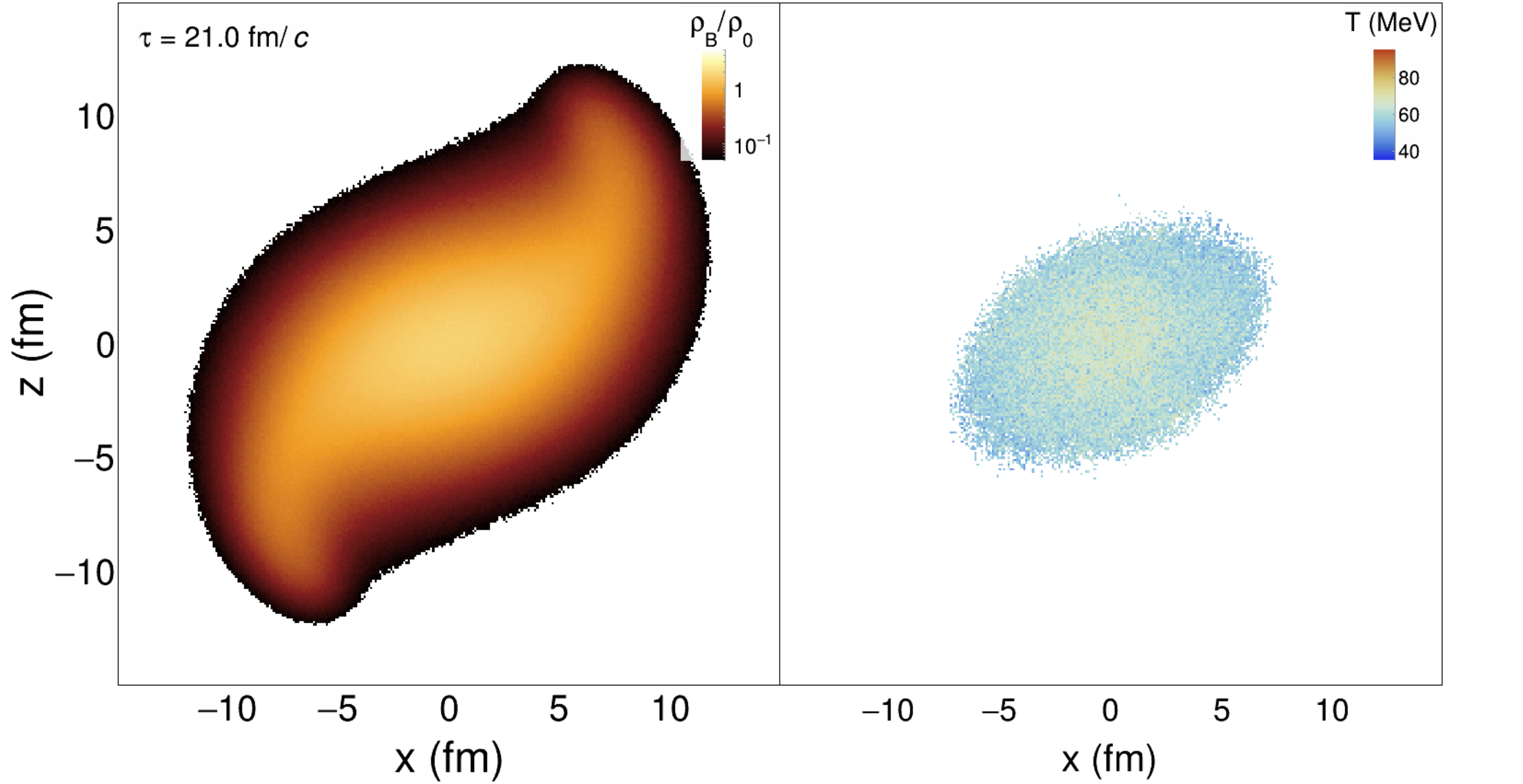

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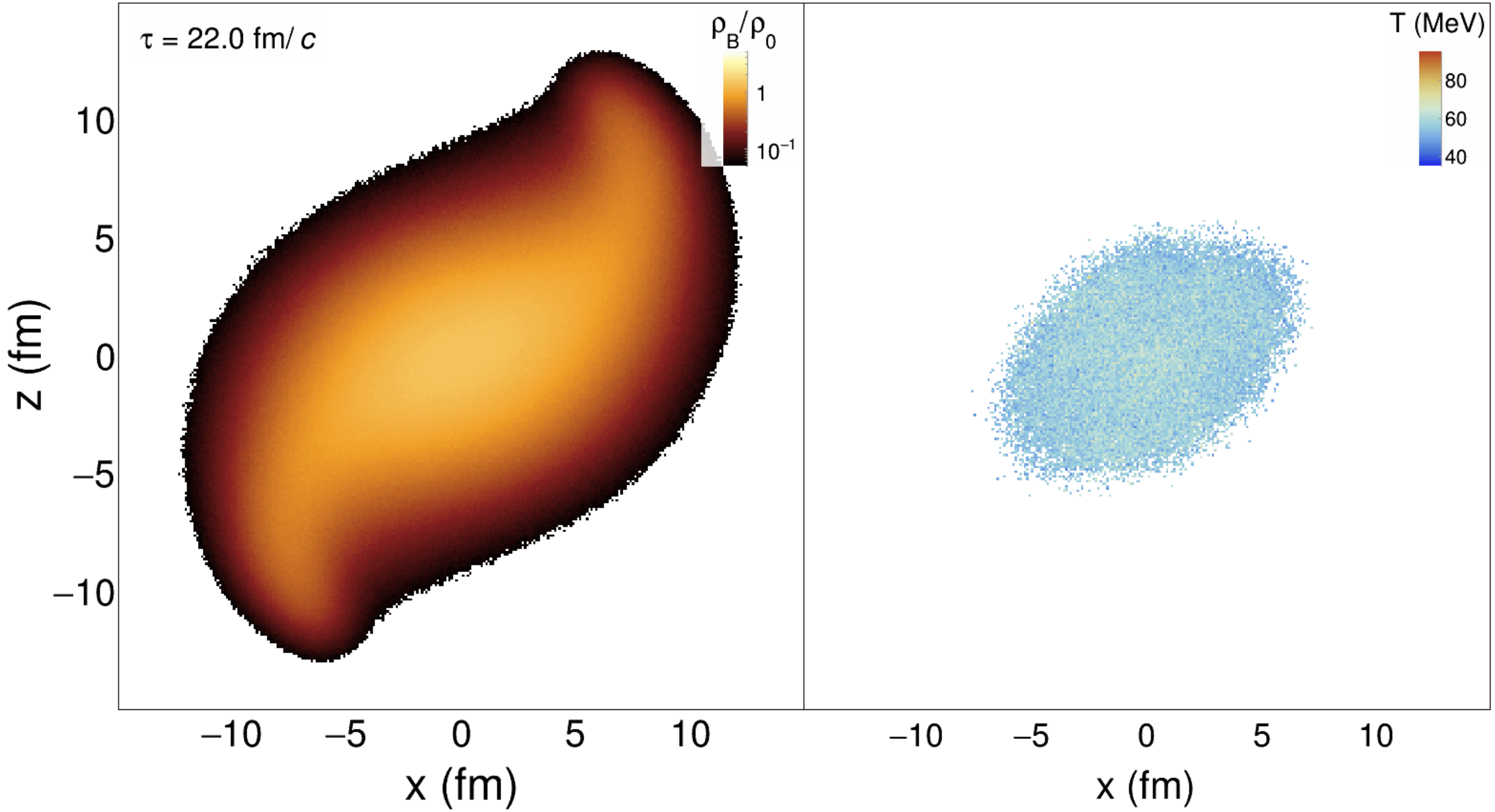

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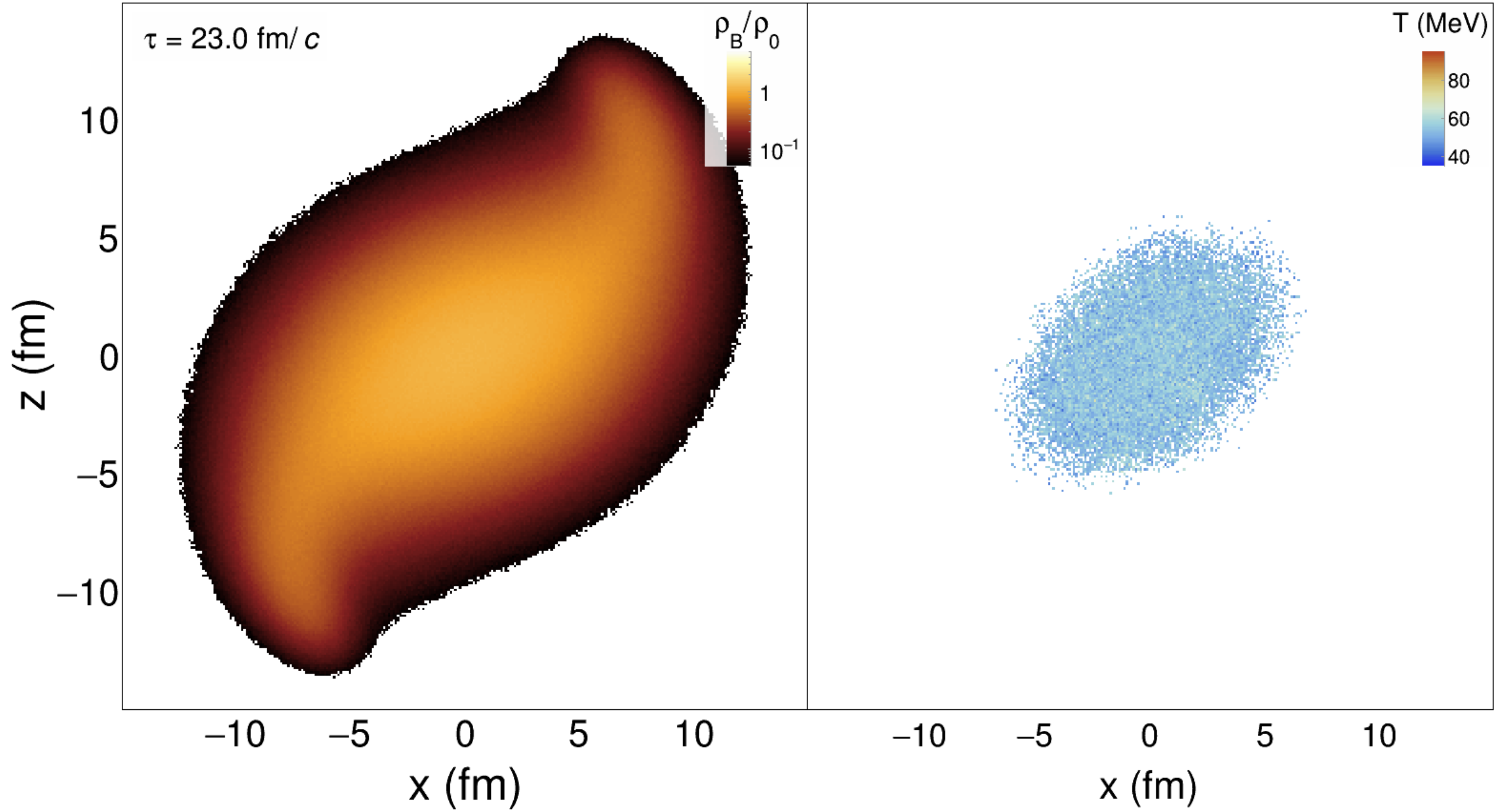

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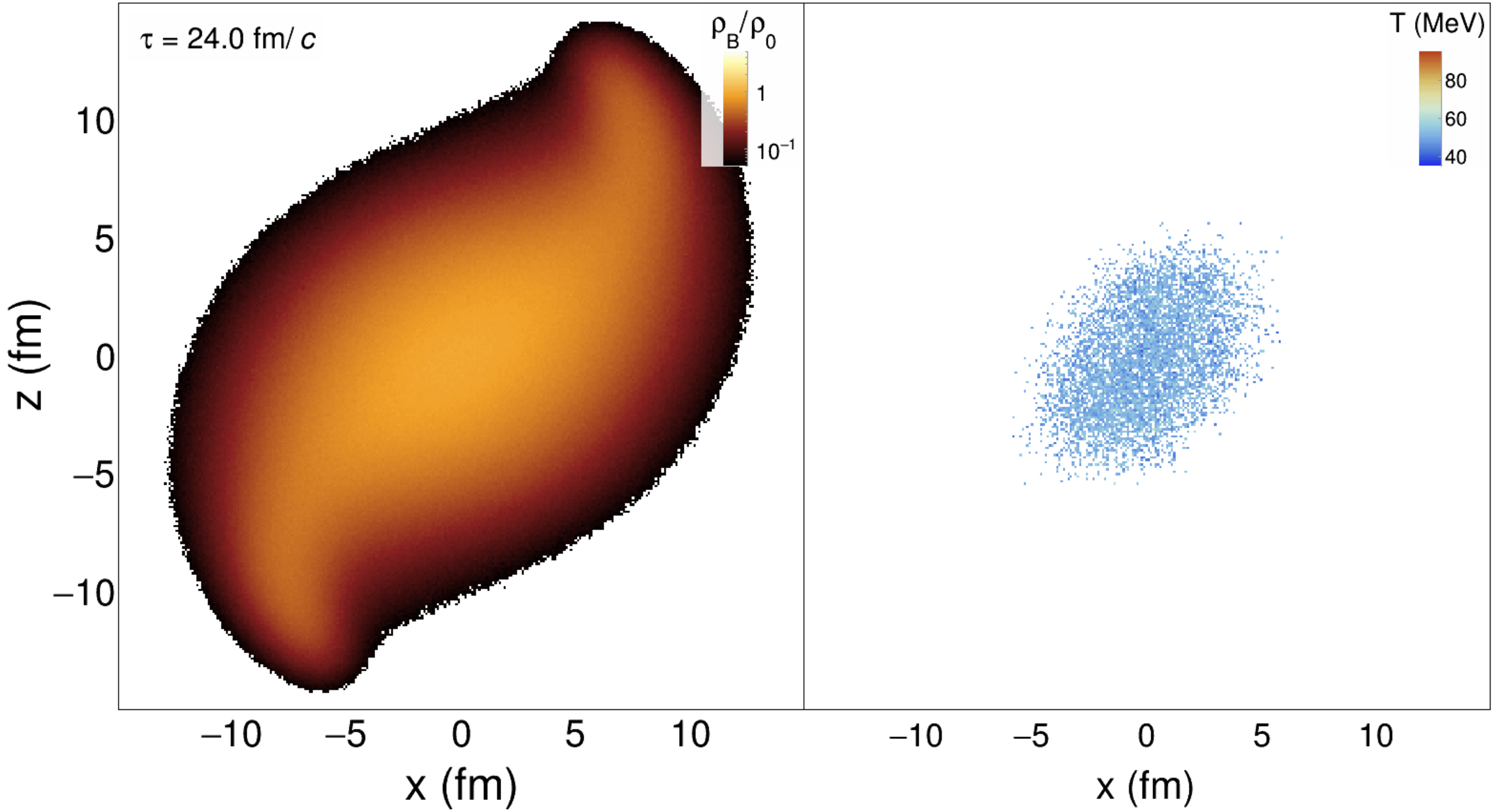

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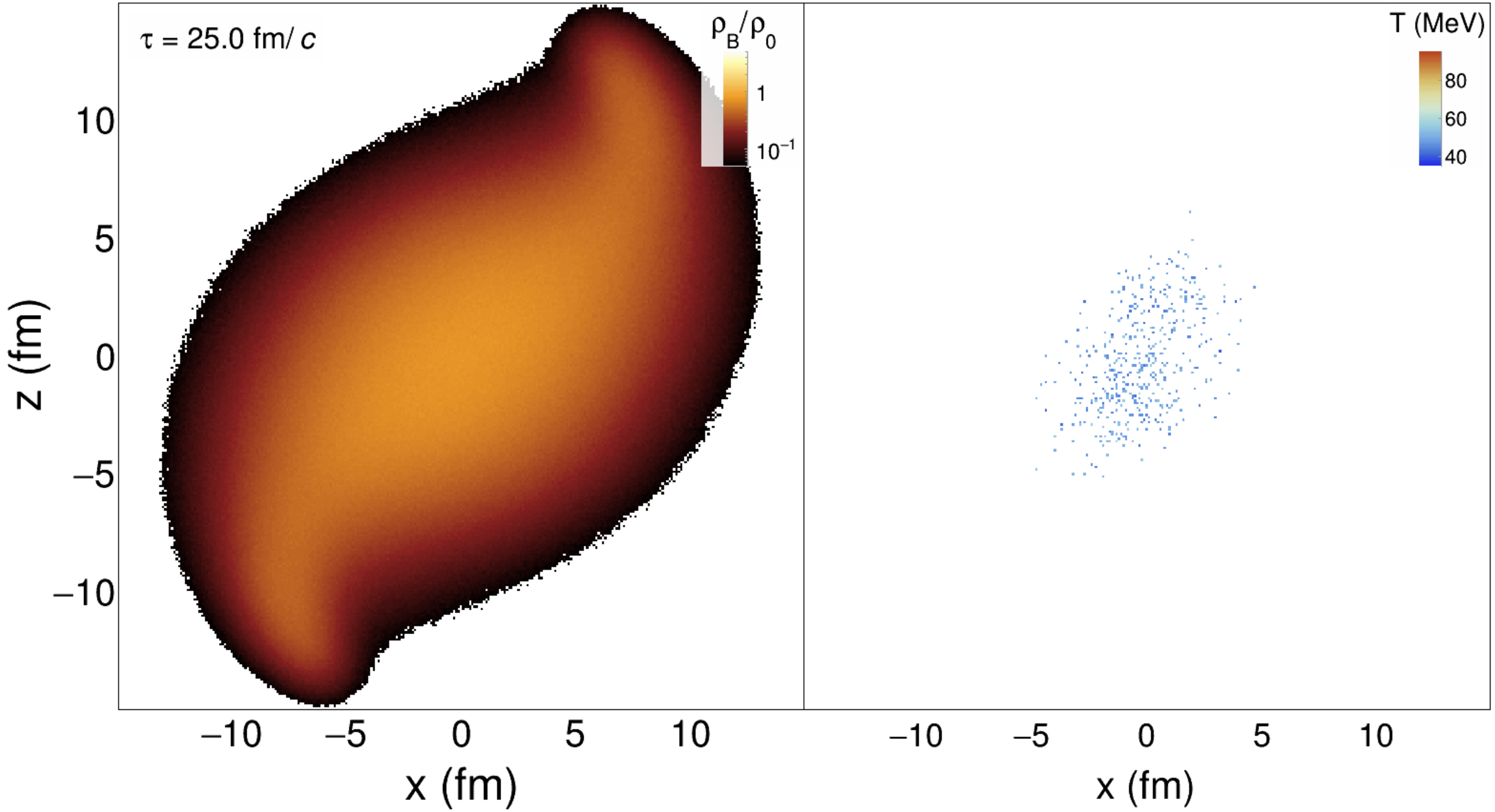

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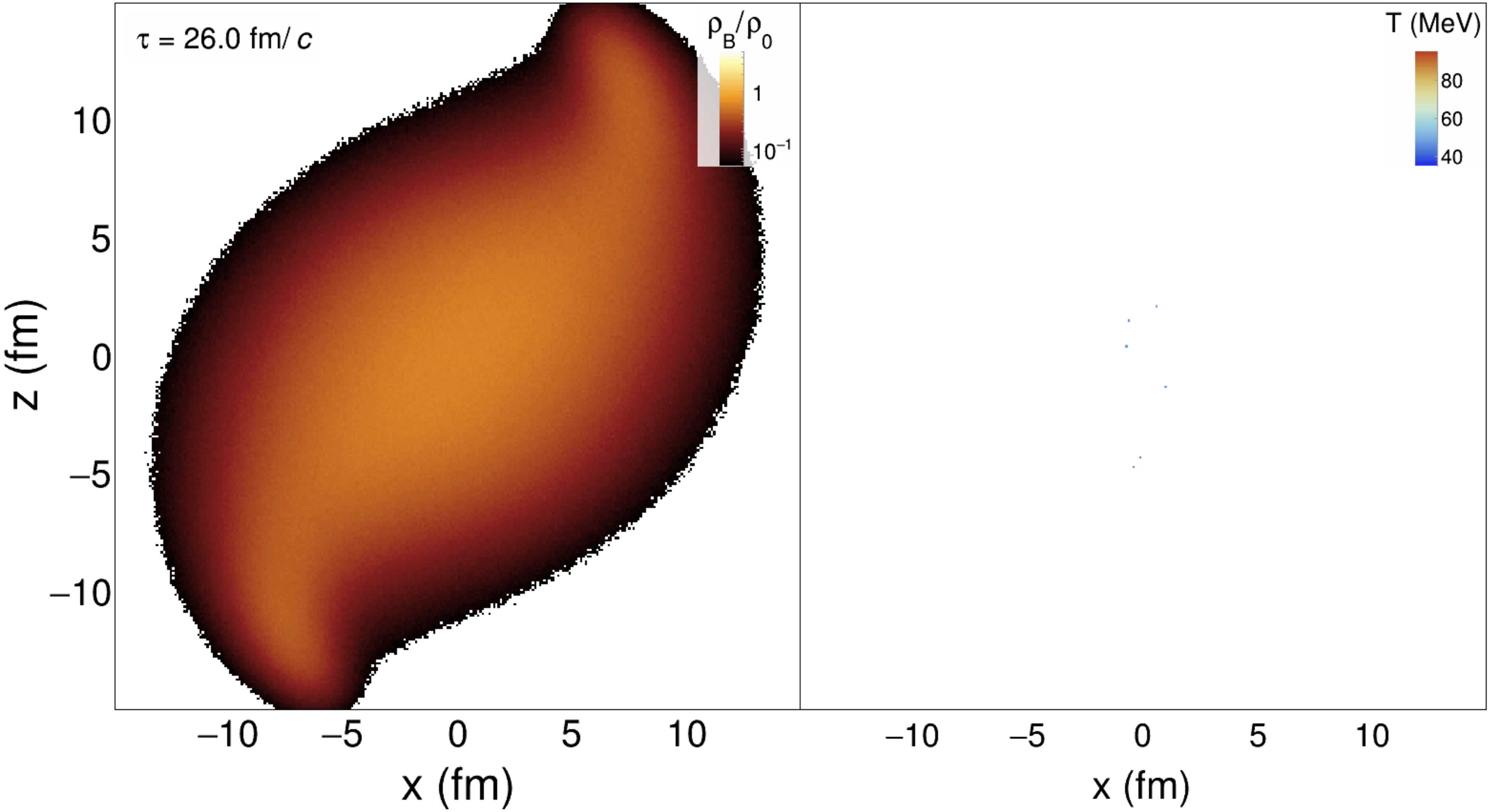

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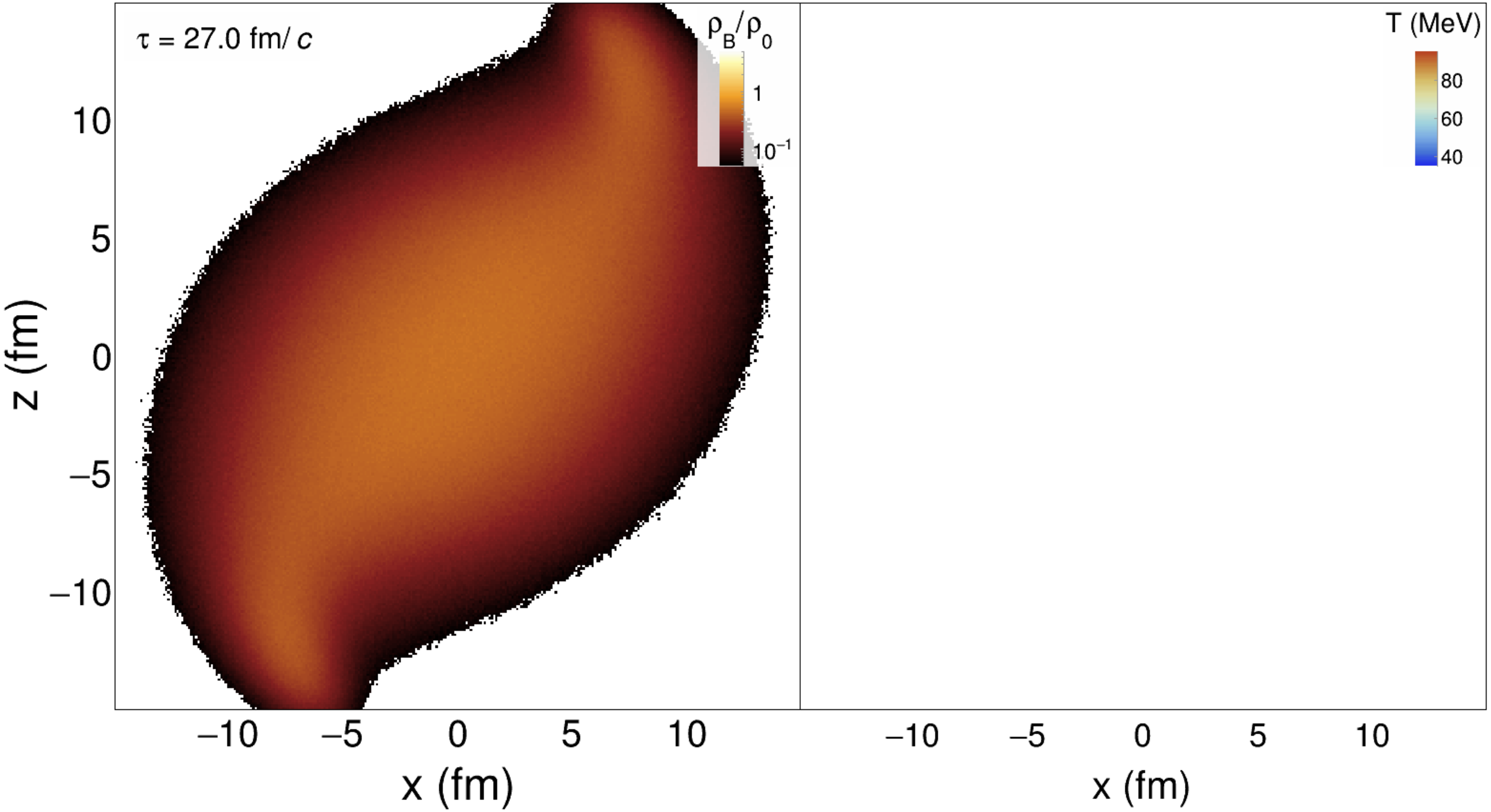

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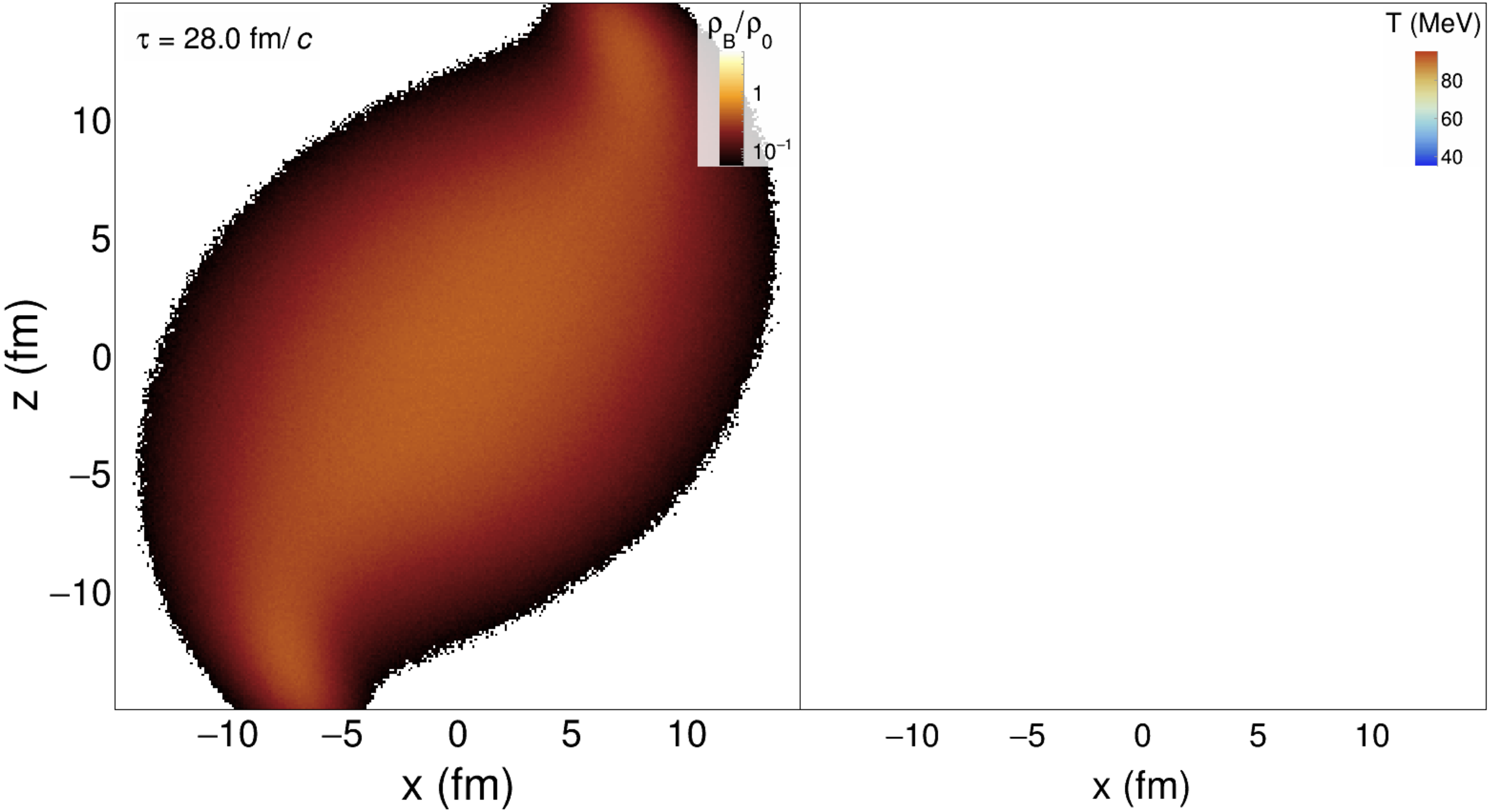


THERMAL DILEPTON PRODUCTION

Bose-Einstein distribution

electromagnetic spectral function

- McLerran-Toimela formula $$\frac{dN_{ll}}{d^4q d^4x} = -\frac{\alpha_{em}^2}{\pi^3}\frac{L(M^2)}{M^2} f^B(q_0,T)\, Im\Pi_{EM}(M,q,T,\mu_B)$$

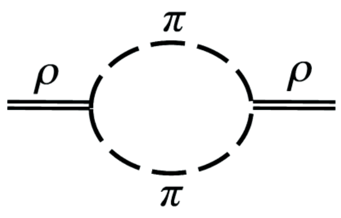
L. McLerran, T. Toimela, Phys. Rev. D 31 (1985) 545

- ρ-meson spectral function broadens
  - Additional contributions to the self-energy in the medium through coupling to (anti-)baryons and mesons

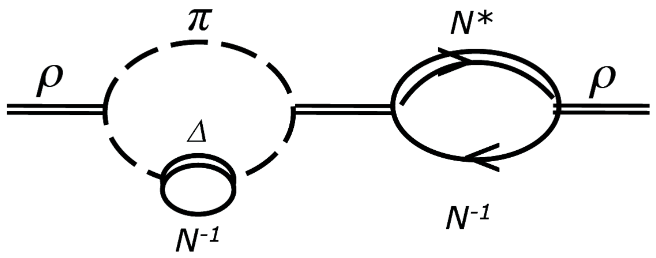
$$D_\rho(M,q;\mu_B,T) = \frac{1}{M^2 - m_\rho^2 - \Sigma_{\rho\pi\pi} - \Sigma_{\rho B} - \Sigma_{\rho M}}$$

- If $\frac{Im\Pi_{EM}}{M^2} \sim const.$ → thermometer

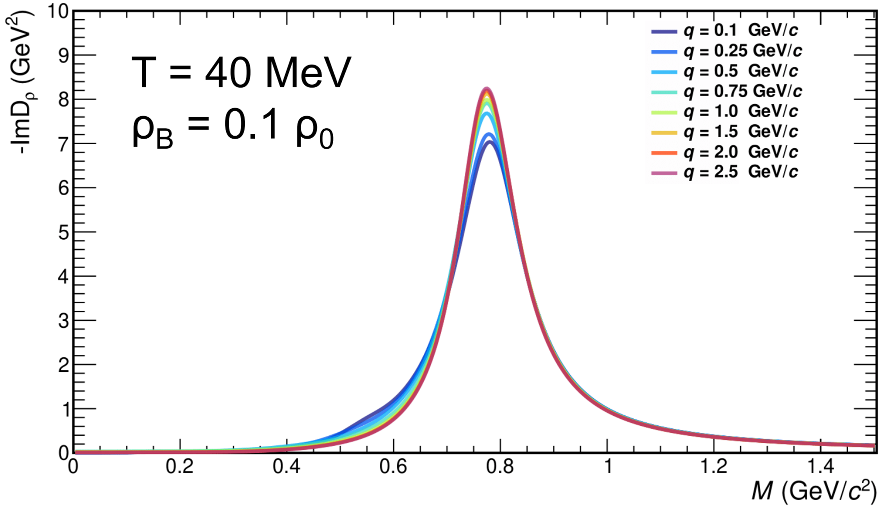
vacuum

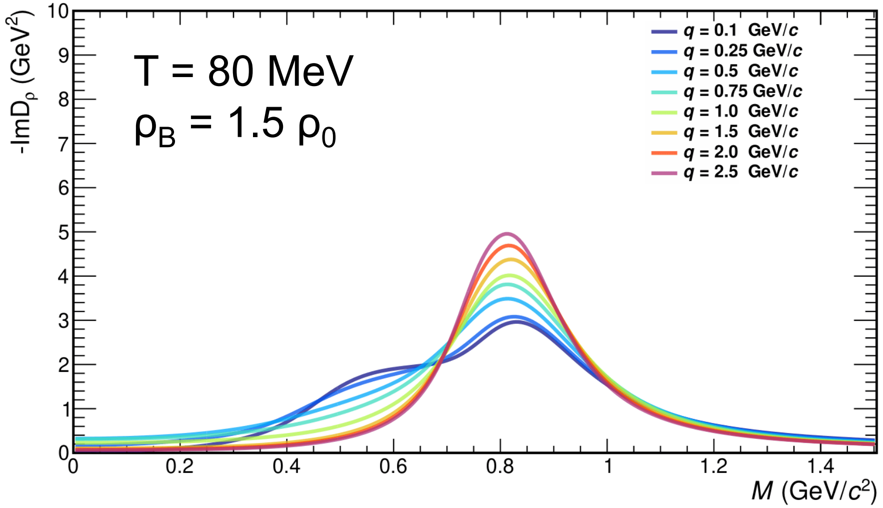


medium



R. Rapp, J. Wambach: Eur. Phys. J. A **6** (1999) 415

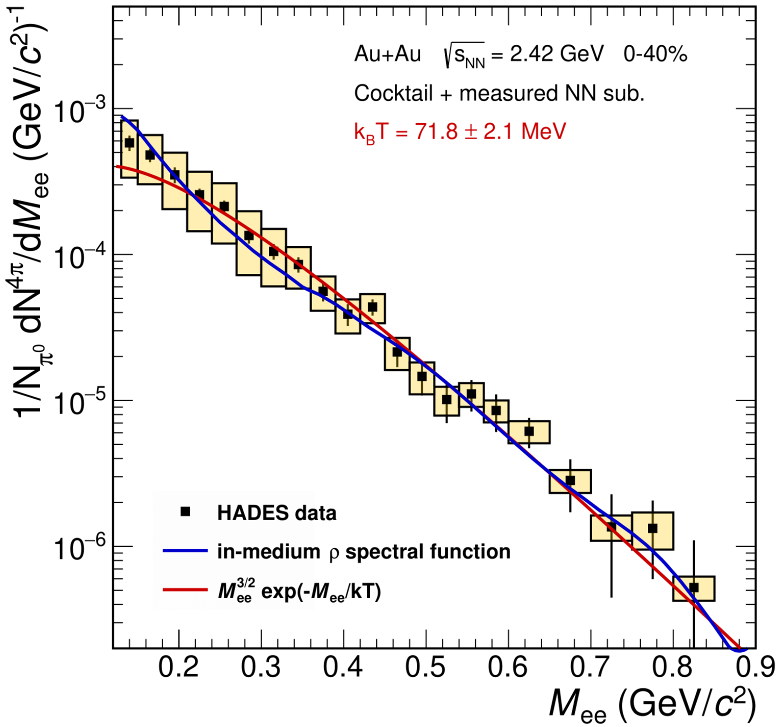




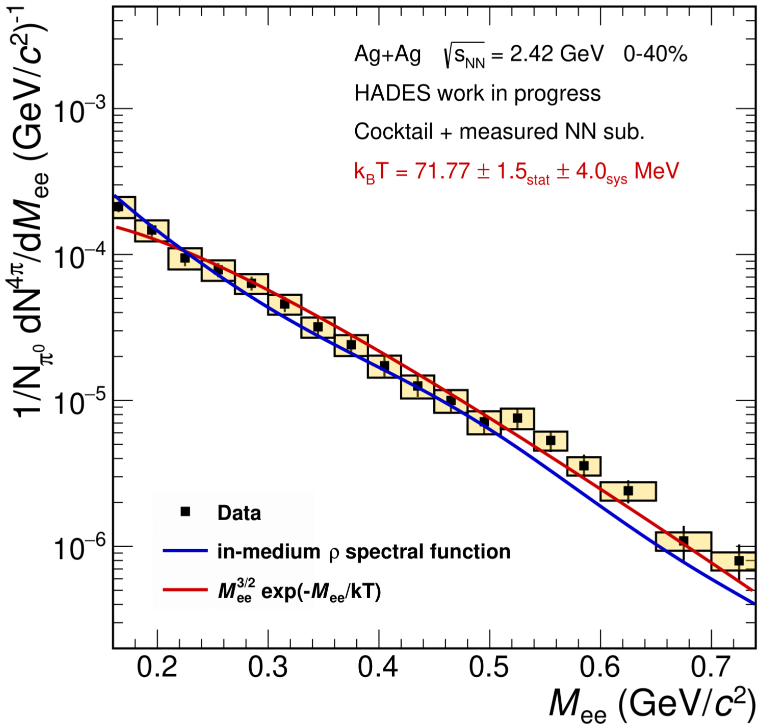
COMPARISON OF THERMAL EXCESS DATA WITH THEORY

- Good agreement between experiment and theory for excess radiation

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



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



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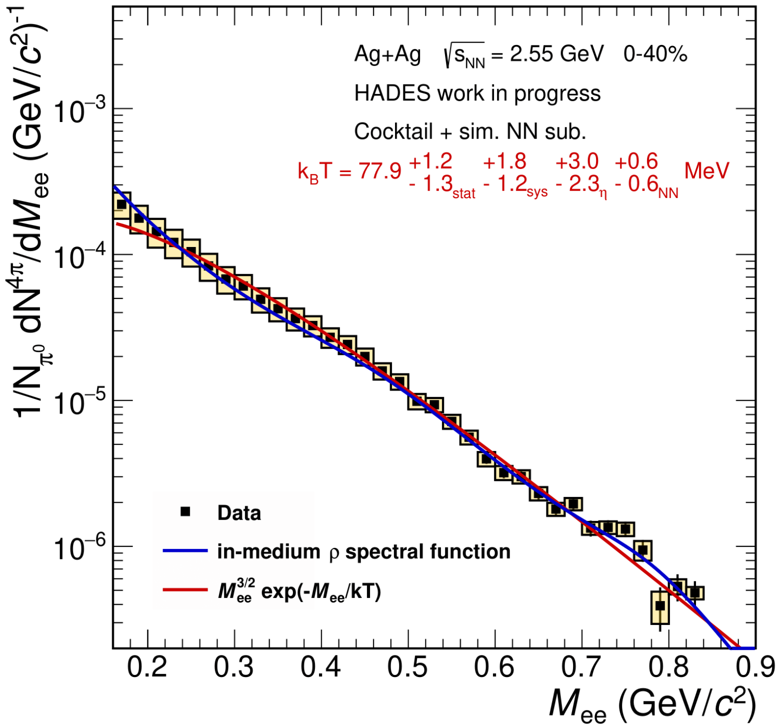


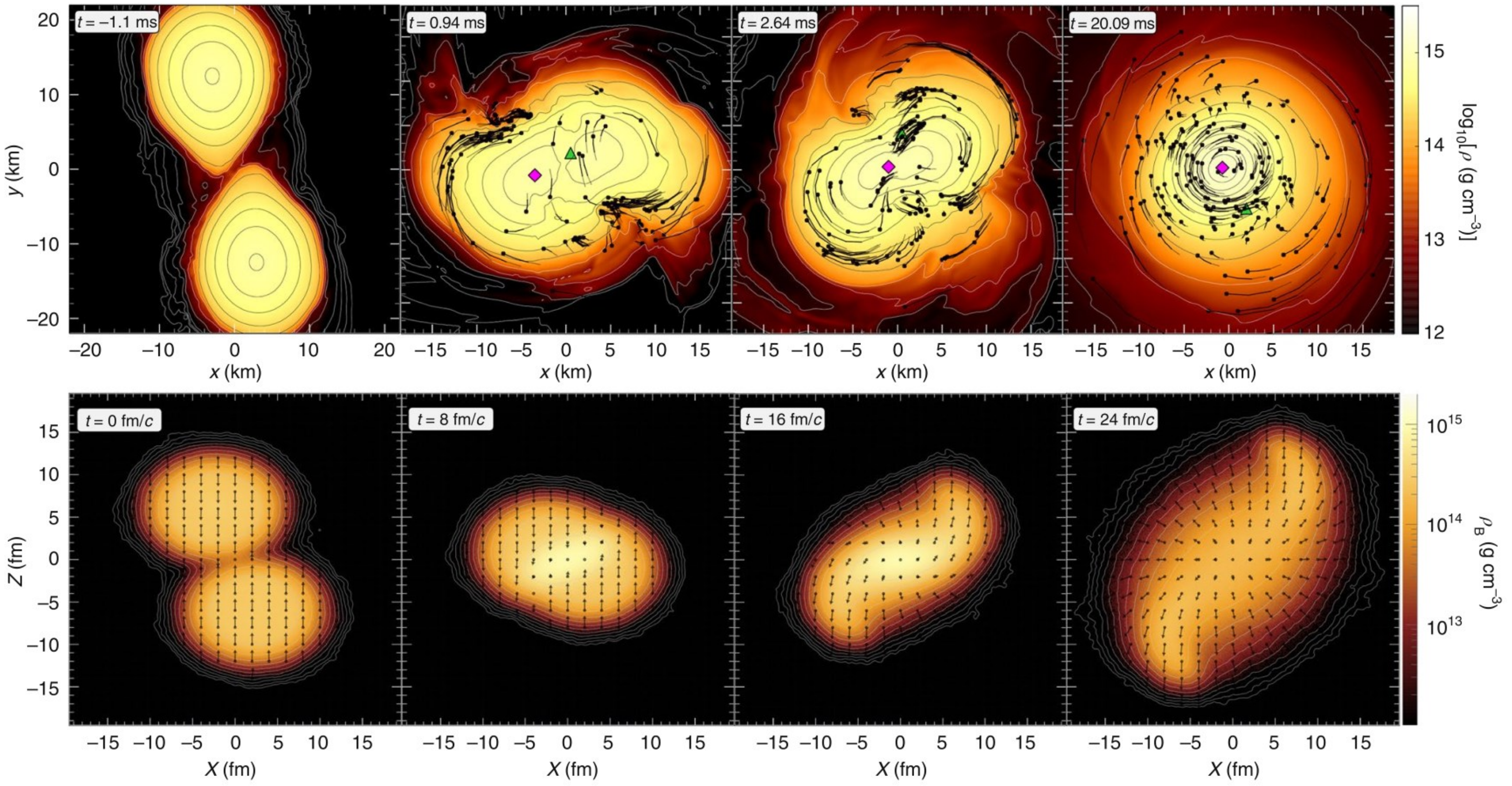
COSMIC MATTER IN THE LABORATORY

- Remarkable similarities between matter in neutron star mergers and HIC in the few GeV regime

- Laboratory studies of the matter properties (EoS) in compact stellar objects (neutron star mergers)

  M. Hanauske *et al.,* Particles 2 (2019) no.1
  L. Rezzolla *et al.,* Phys. Rev. Lett. 122 (2019) no. 6, 061101
  E. Most et al., Phys. Rev. D 107 (2023) 4, 043034

- What are the measurable consequences of phase transition and critical point in the QCD phase diagram?



HADES, Nature Phys. 15 (2019) 1040

EXCITATION FUNCTION OF THE LIFETIME OF THE FIREBALL

TECHNISCHE UNIVERSITÄT DARMSTADT

- Excess yield in LMR tracks fireball lifetime

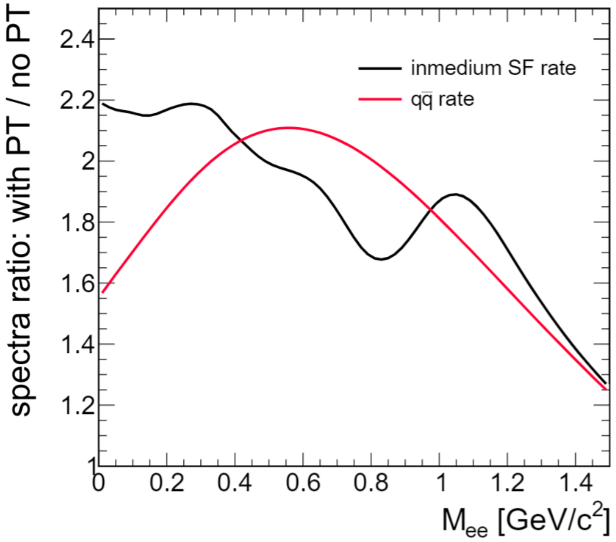
$$\tau_{Life} \propto \frac{N_{ll}}{N_{charged\ pions}}$$

R. Rapp & H. van Hees, Phys. Lett. B 753 (2016) 586-590

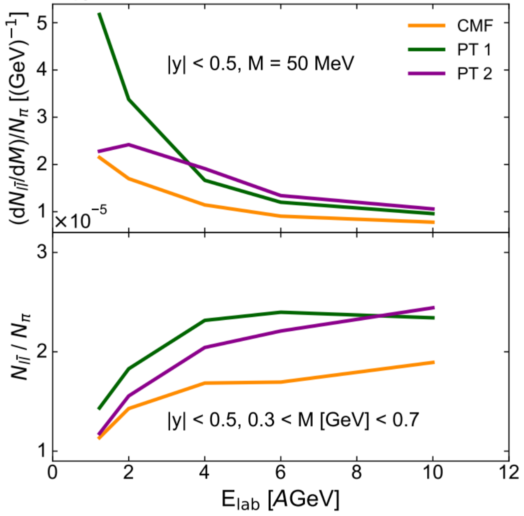
- Search for "**extra radiation**" due to latent heat around **phase transition** (& critical point?)

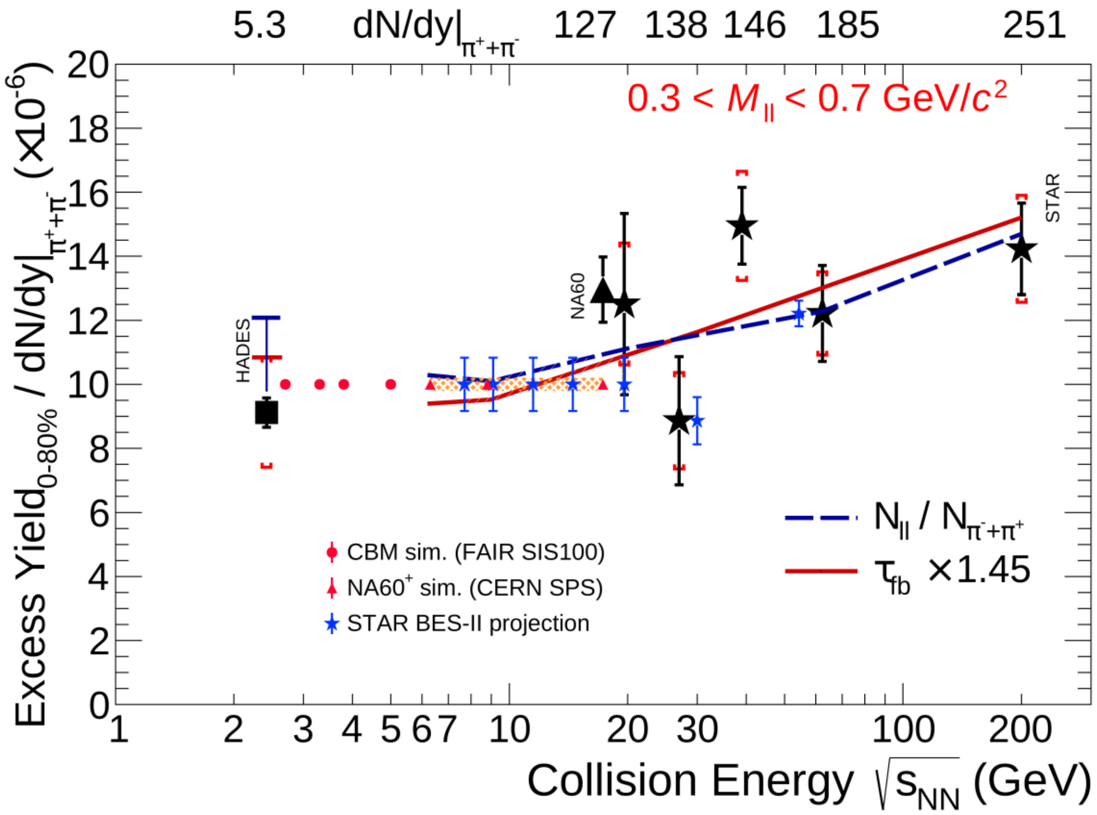
- 1st order phase transition could result in factor 2 larger yield
  - Detectable by current & future experiments

FS *et al.*, Phys. Rev. C 106 (2022) 1, 014904



O. Savchuk *et al.*, J. Phys G 104537 R2 (2023)





EXCITATION FUNCTION OF THE TEMPERATURE OF THE FIREBALL

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- Invariant mass slope measures radiating source temperature (free from blue-shift effects)

$$\frac{dN_{ll}}{dM} \propto (MT)^{\frac{3}{2}} \exp\left(-\frac{M}{T}\right)$$

R. Rapp & H. van Hees, Phys. Lett. B 753 (2016) 586-590

„black body radiation“

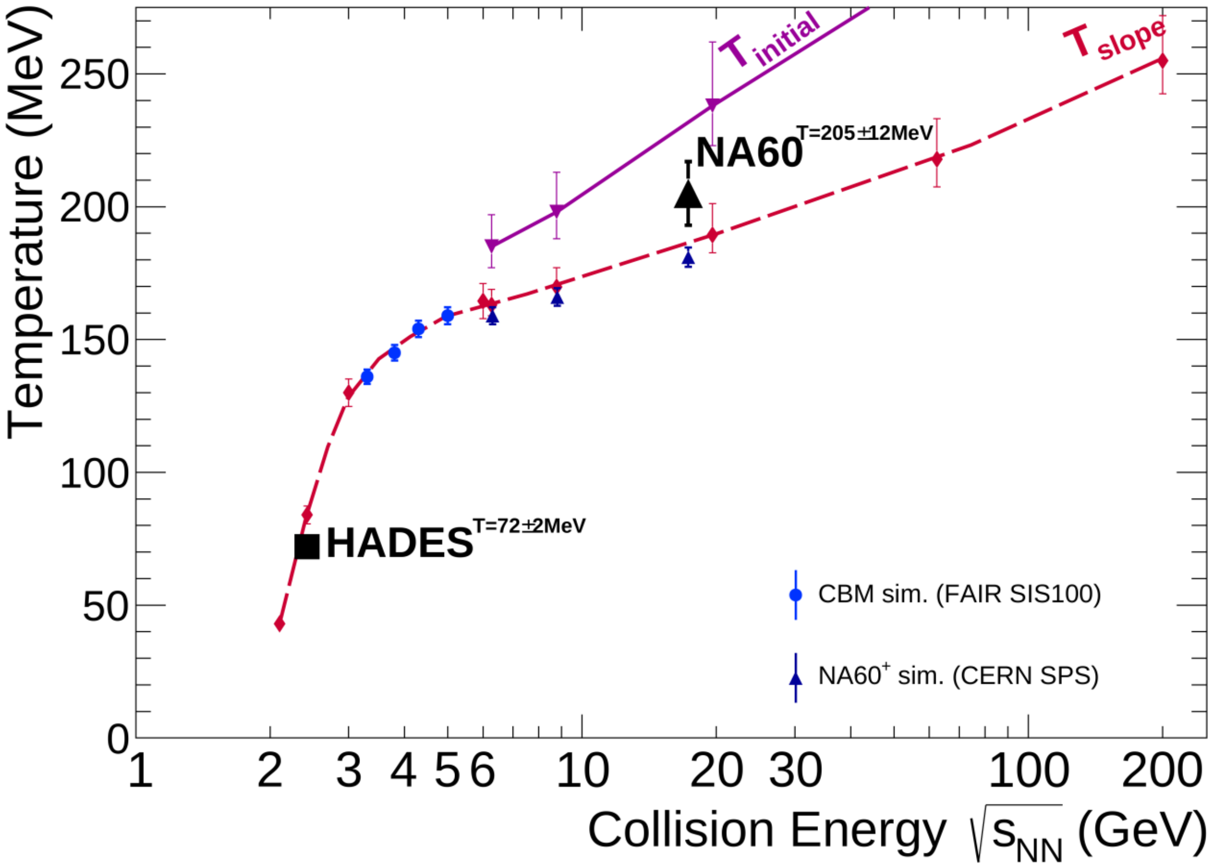
- Assumption: $\frac{Im\Pi_{EM}}{M^2} \sim$ constant
  - Generally justified in the IMR (M_{ee} > 1.5 GeV/c^2)
  - Strong melting of ρ meson allows temperature extraction in the LMR (M_{ee} = 0.3-0.7 GeV/c^2)

FS, T. Galatyuk et al., Eur. Phys. J. A 52 (2016) 5, 131

- T_{LMR} and T_{IMR} different:
  - T_{IMR} probes hottest regions
  - T_{LMR} probes average fireball temperature

Flattening of caloric curve (T vs ε)

→ evidence for a **phase transition**



NA60, AIP Conf. Proc. 1322 (2010) 1.
R. Rapp, H. van Hees, Phys.Lett.B 753 (2016) 586-590
HADES, Nature Phys. 15 (2019) 1040

DILEPTON FLOW

- Azimuthal anisotropies with respect to reaction plane

$$\frac{dN}{d\phi} \propto \left(1 + 2\sum_n v_n \cos(n\phi)\right), \text{ with } v_n = \langle \cos(n\phi) \rangle$$

- Interplay between medium 4-velocity u and temperature T

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

R. Chatterjee et. al, Phys. Rev. C 75 (2007) 054909
G. Vujanovic et al., Phys. Rev. C 89 (2014) 3, 034904

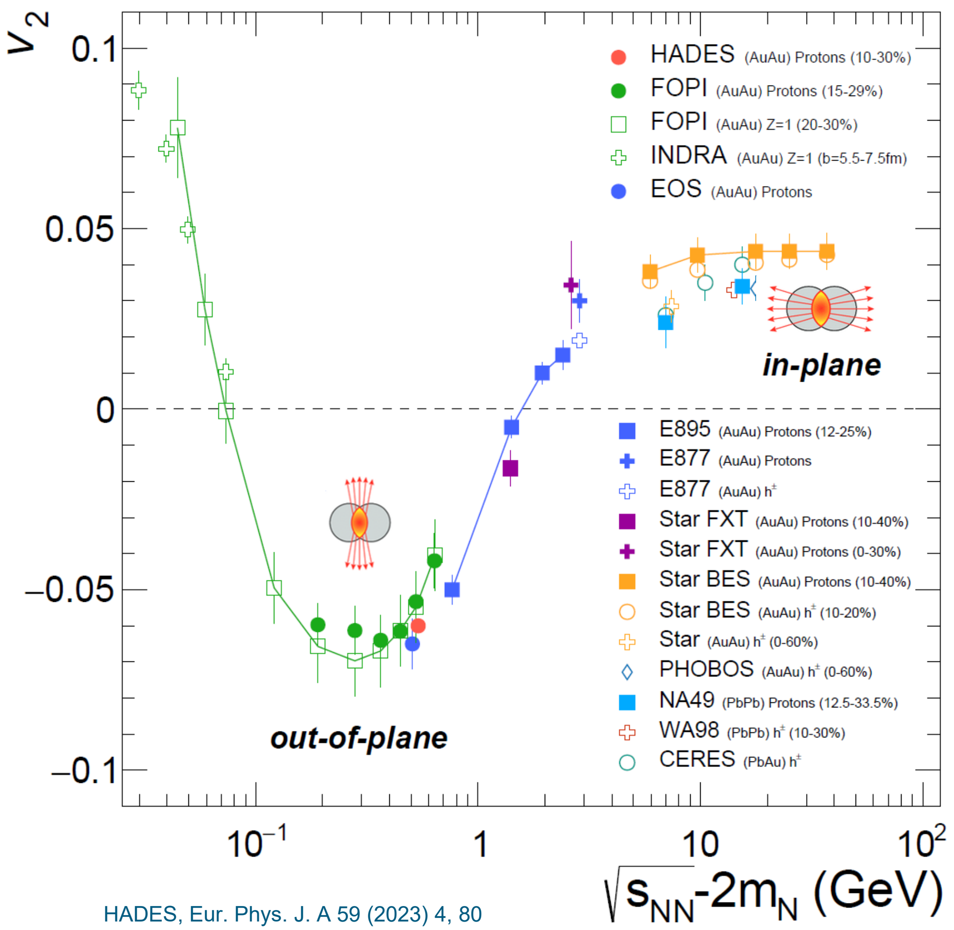
- Pressure anisotropies in underlying space-time evolution → collective velocities of medium cells

- Dileptons probe earlier times (high ρ_B, high T) compared to hadron flow

Possible sensitivity to the EoS at high density

T. Reichert *et al.*, Phys.Lett.B 841 (2023) 137947

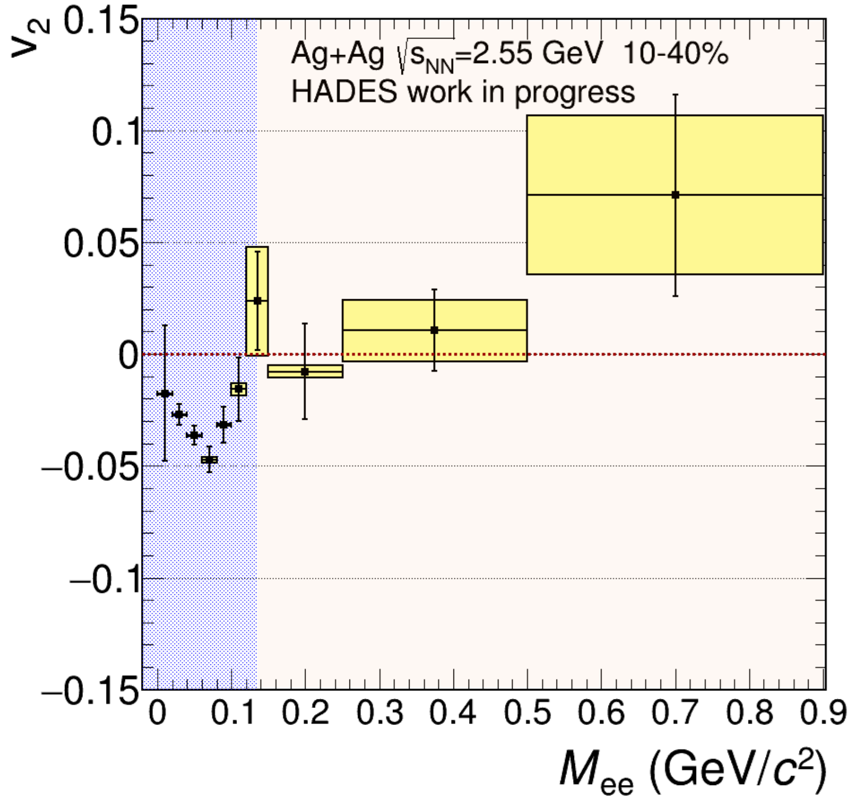
proton v_2



HADES, Eur. Phys. J. A 59 (2023) 4, 80

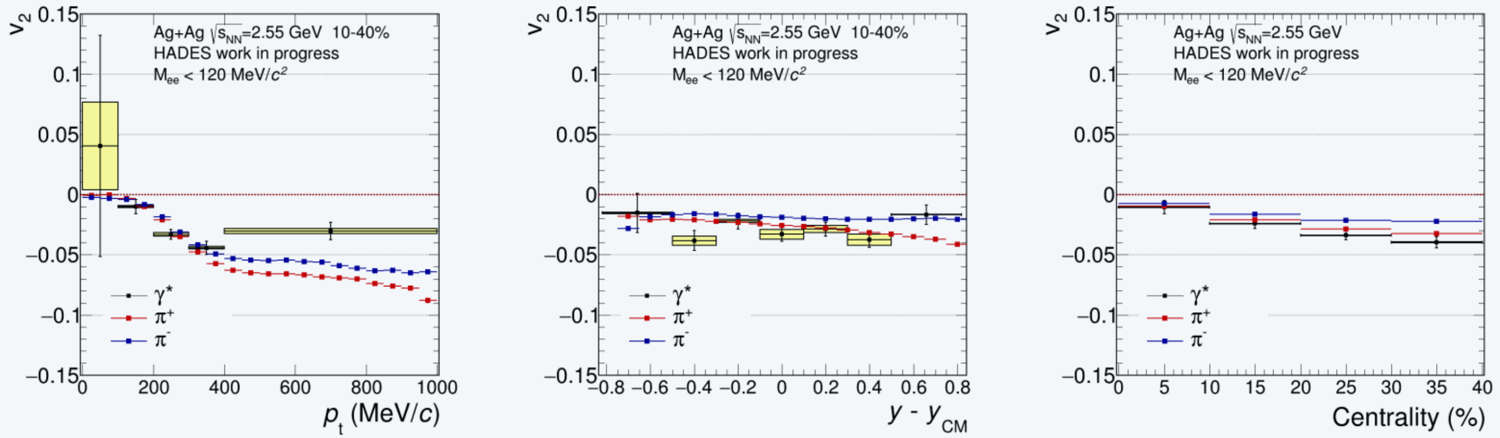
DILEPTON V2 IN AG+AG COLLISIONS

TECHNISCHE UNIVERSITÄT DARMSTADT



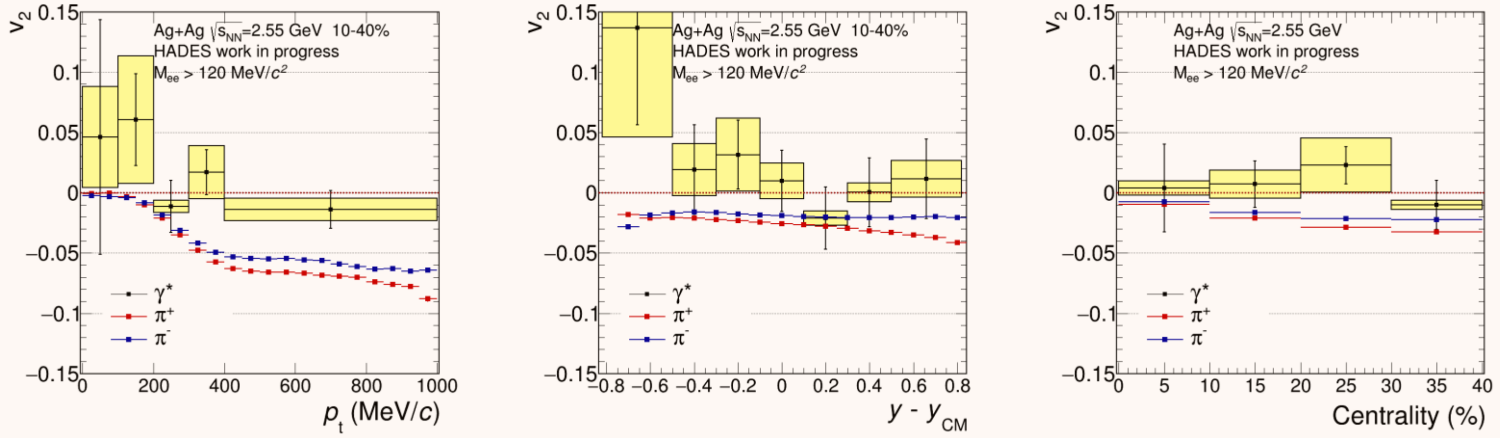
M_{ee} < 0.12 GeV/c^2: inclusive yield dominated by π^0 decays

- 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

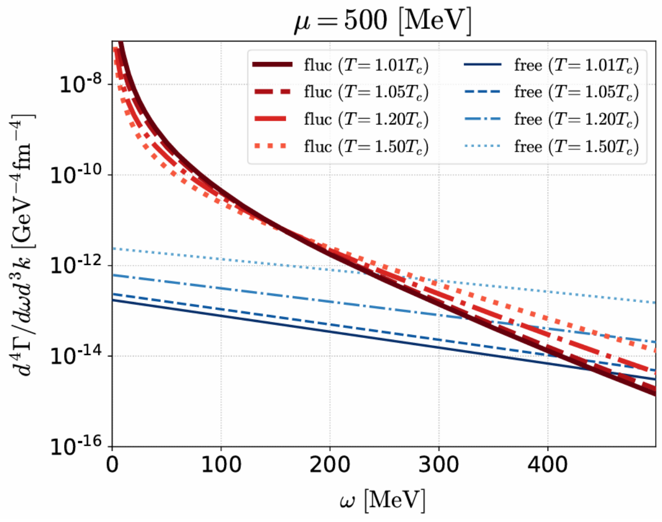


LOW-MASS LOW-MOMENTUM DILEPTONS

- Color superconductivity could manifest itself in an enhanced yield of low-energy dileptons
- Thermal dileptons encode information on matter properties
  - yield in p_{ee} = 0 MeV/c, $M_{ee} \rightarrow$ 0 MeV/c^2 limit proportional to electrical conductivity

- Large **theoretical uncertainty**
  → **experimental constraints** highly desirable

- Determines time evolution of electromagnetic fields generated by spectators
  - Important for effects related to presence of strong magnetic fields



T. Nishimura *et al.*, PTEP 2022 (2022) 9, 093D02
arXiv:2201.01963

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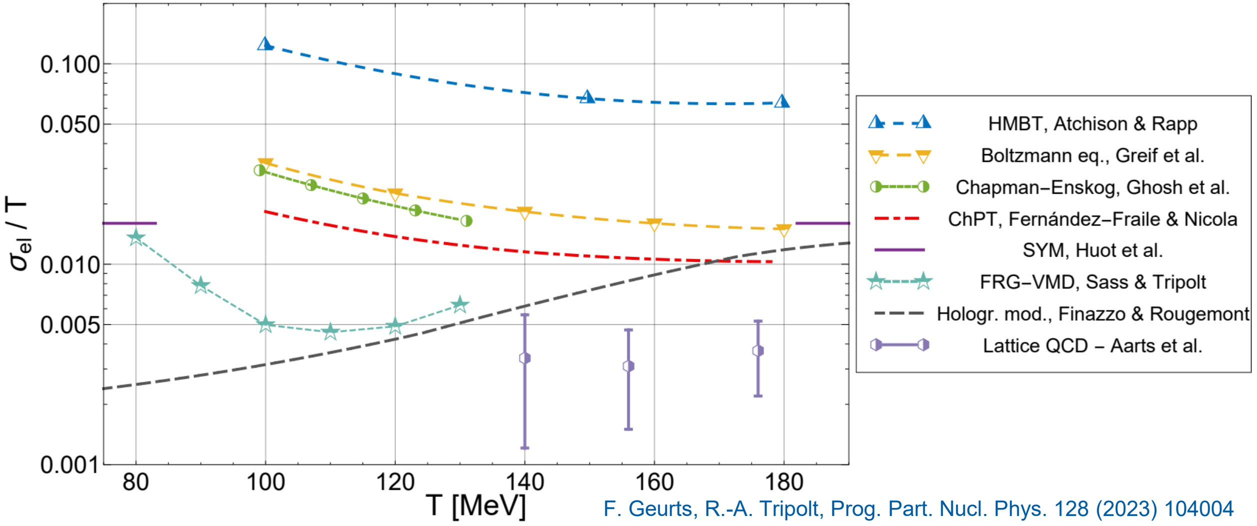


F. Geurts, R.-A. Tripolt, Prog. Part. Nucl. Phys. 128 (2023) 104004

electrical conductivity

$$\sigma_{el}(T) = -e^2 \lim_{q_0 \to 0} \frac{\rho_{EM}(q_0, \vec{q} = 0, T, \mu_B)}{q_0}$$

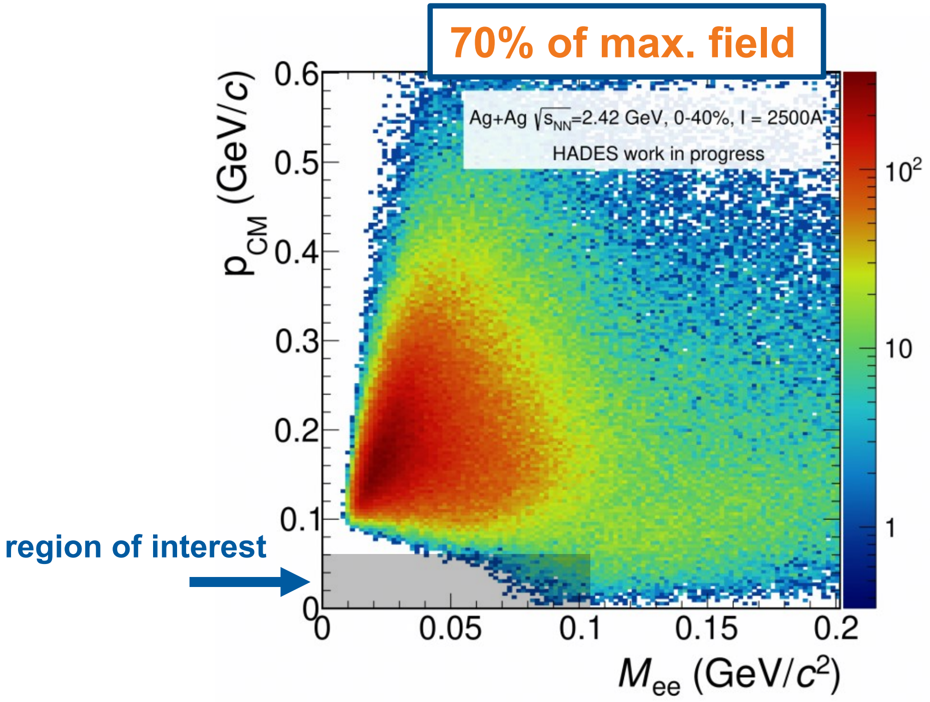
R. Kubo, J. Phys. Soc. Jap. 12 (1957) 570-586
G. Moore, J. Robert, arXiv:hep-ph/0607172 [hep-ph]

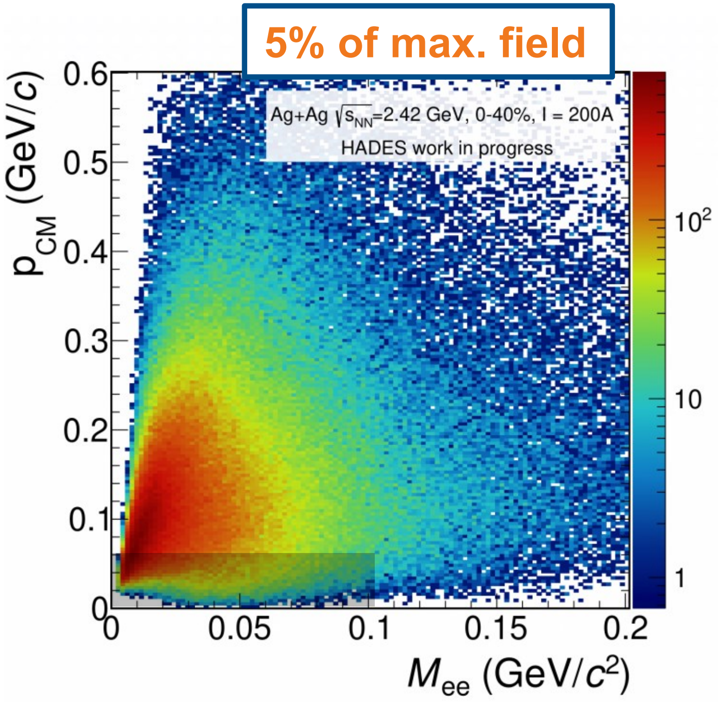
thermal dilepton emission rate

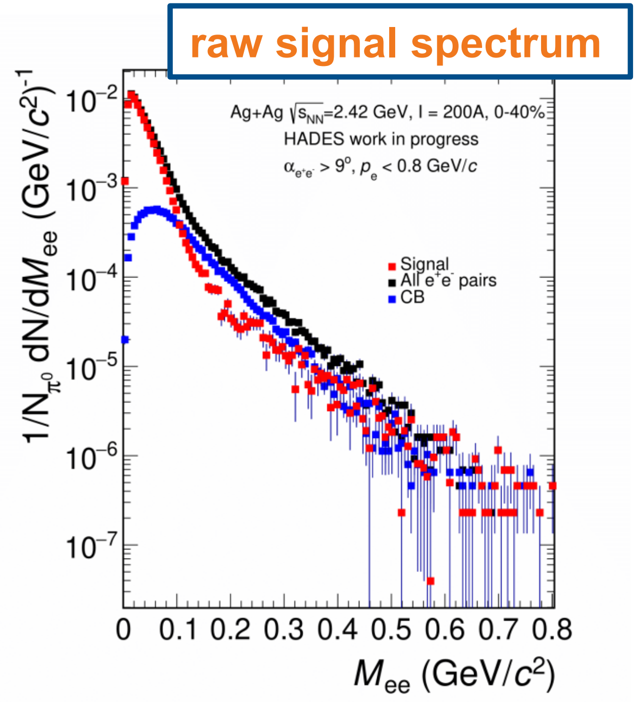
$$\frac{d^8N}{d^4q\, d^4x} = \frac{-\alpha_{EM}^2}{\pi^3 M^2} f_B(q_0, T) \underbrace{Im\Pi_{EM}(M, q, T, \mu_B)}_{\rho_{EM}}$$

EXPERIMENTAL CHALLENGES

- Low momentum lepton tracks bent out of acceptance by magnetic field
- Photon conversion suppressed via opening angle cut
- Physical background of π^0 and η mesons
- Step towards measurement:
  - Dedicated Ag+Ag test run at HADES with low magnetic field
  - New Au+Au at $\sqrt{s_{NN}}$ = 2.23 GeV data recorded this year with 50% B-field + low field run (5%) scheduled for 2025

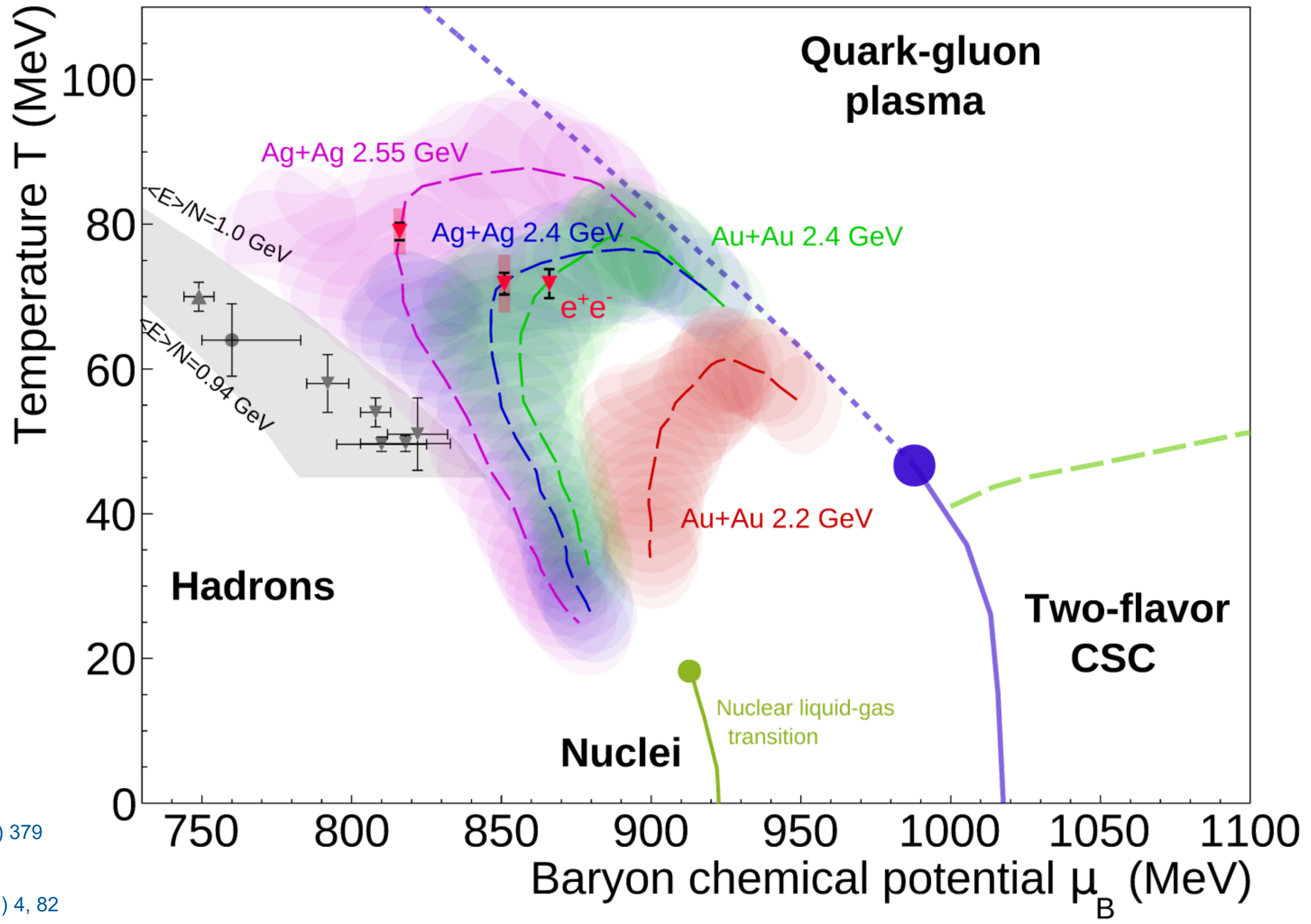






QCD PHASE DIAGRAM PROBED WITH DILEPTONS

- Trajectories from coarse-grained UrQMD
- Measured average temperatures from HADES well above universal freeze-out region
- Transition lines from two-flavor NJL model in mean-field approximation
  - Transition of chiral symmetry breaking
  - Transition to the two-flavor color superconducting (CSC) phase
- Collisions at $\sqrt{s_{NN}} = 2.2$ GeV (E_{kin}=800A MeV) might show sensitivity to precursor phenomena for the CSC phase



FO curve: J. Cleymans, K. Redlich, Nucl. Phys. A 661 (1999) 379
Au+Au 2.4 GeV data: HADES, Nature Phys. 15 (2019) 1040
Ag+Ag data: HADES preliminary
Transition curves: T. Nishimura *et al.*, Eur.Phys.J.A 60 (2024) 4, 82
Figure: FS, T.Galatyuk

VIRTUAL PHOTON POLARIZATION

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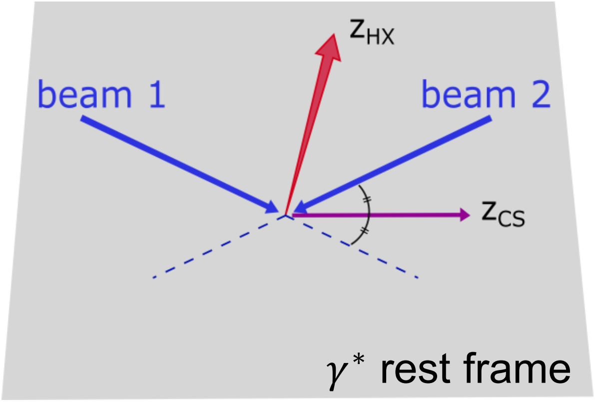
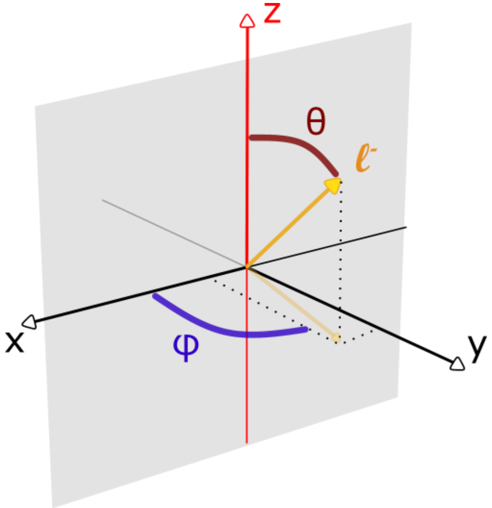
- Decompose spectral function using projectors for a spin-1 particle $\rho^{\mu\nu}_{EM} = \rho_L \, P^{\mu\nu}_L + \rho_T \, P^{\mu\nu}_T$ with $g_{\mu\nu} \, \rho^{\mu\nu}_{EM} = \rho_L + 2\rho_T$
- Angular distribution of single lepton in γ^* rest frame depends on polarization of γ^*

$$\frac{dN}{d^4x \, d^4q \, d\Omega} = \mathcal{N} \, (1 + \lambda_\theta \cos^2\theta + \lambda_\varphi \sin^2\theta \cos 2\varphi + \lambda_{\theta\varphi} \sin 2\theta \cos\varphi)$$

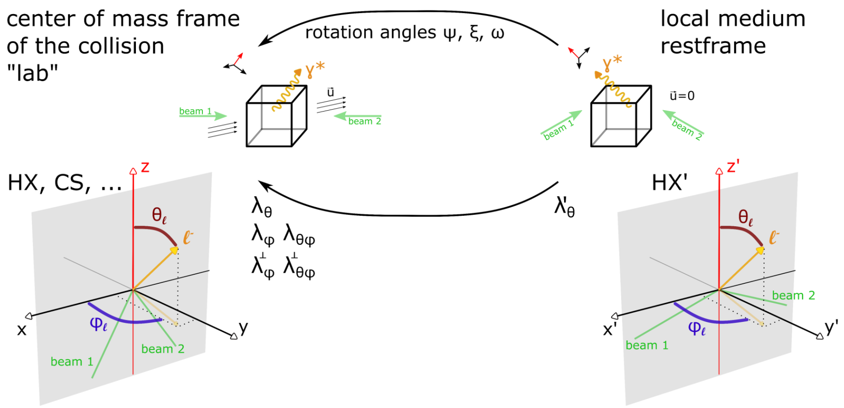
E. Speranza *et al.*, Phys. Lett. B 782, 395 (2018)
G. Baym *et al.*, Phys. Rev. C 95, 044907 (2017)
E. Bratkovskaya *et al.*, Phys. Lett. B 376, 12 (1996)

- Different virtual photon **production mechanisms** imprint different anisotropy parameters λ
- λ coefficients related to **difference** between **longitudinal and transverse components** of spectral function: $\lambda_\theta = \frac{\rho_T - \rho_L}{\rho_T + \rho_L}$
- Rotational symmetry of static thermal medium broken by virtual photon's momentum direction
- For moving medium: transform local coefficients to global frame accessible in experiment → comparison to data





FS et al., arXiv: 2309.03189
QM23 talk



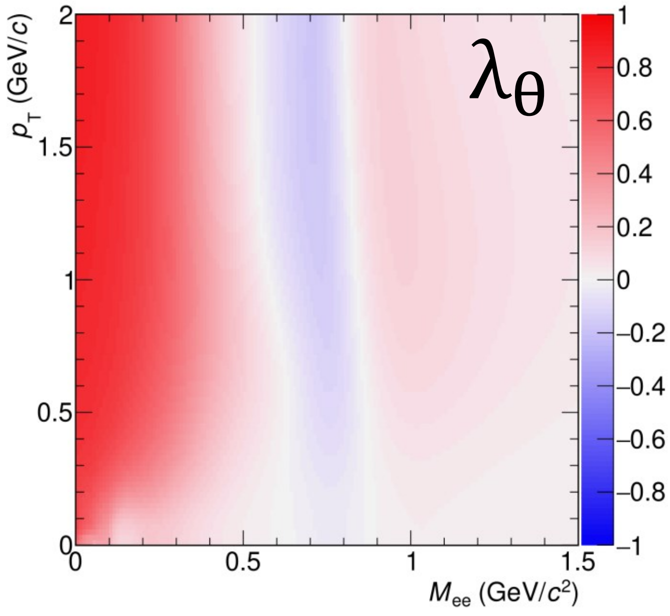
COMPARISON TO HADES DATA

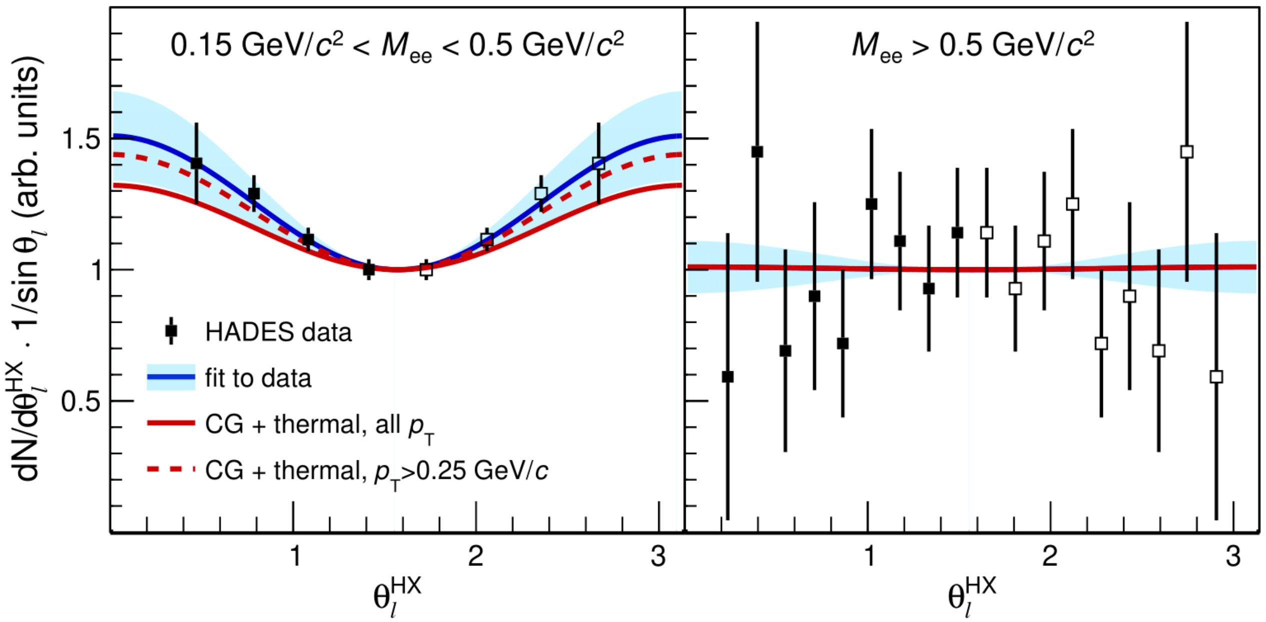
- HADES measured anisotropy coefficient λ_θ of excess radiation in Ar+KCl collisions at 1.76 AGeV ($\sqrt{s_{NN}} = 2.62$ GeV)

- Polarization largely survives evolution of the expanding medium

- **Best fit** to data gives $\lambda_\theta = 0.51 \pm 0.17$ and $\lambda_\theta = 0.01 \pm 0.10$ in the two mass windows
- **Calculation** result gives $\lambda_\theta = 0.32$ and $\lambda_\theta = 0.01$ respectively

HADES, Phys. Rev. C 84, 014902 (2011)
T. Galatyuk *et al.*, Eur. Phys. J. A 52, 131 (2016)
FS et al., arXiv: 2309.03189





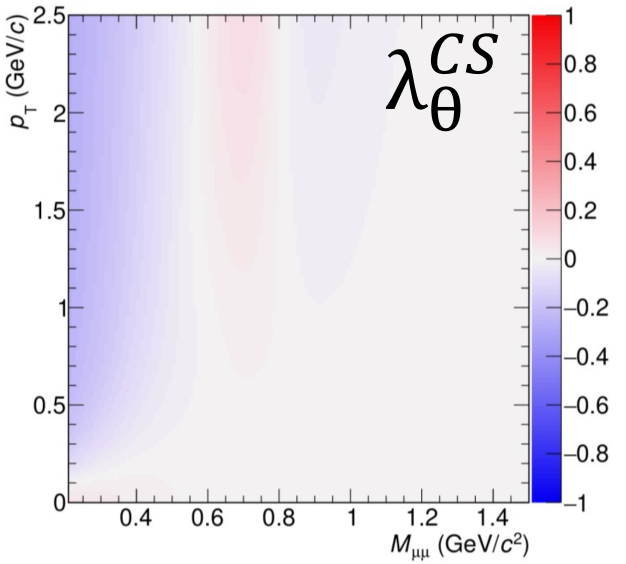
COMPARISON TO NA60 DATA

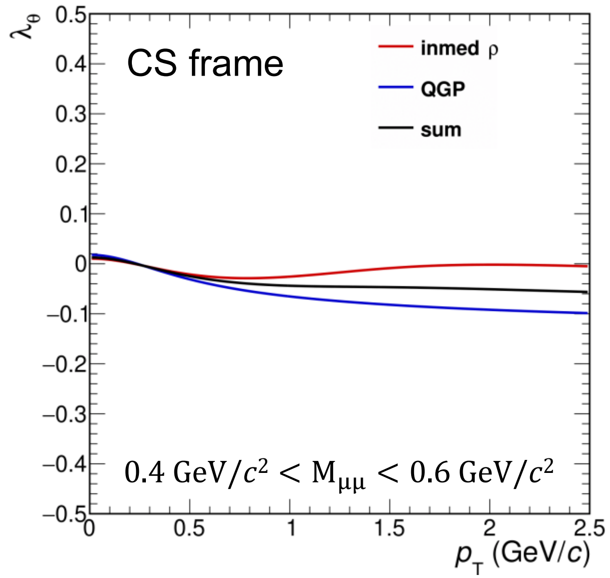
TECHNISCHE UNIVERSITÄT DARMSTADT

- NA60 measured polarization coefficients λ_θ, λ_φ and $\lambda_{\theta\varphi}$ of excess radiation in the CS frame in In+In collisions at 158 AGeV
- Space-time evolution via isentropic fireball model with transition from QGP to hadronic rates at T=170 MeV

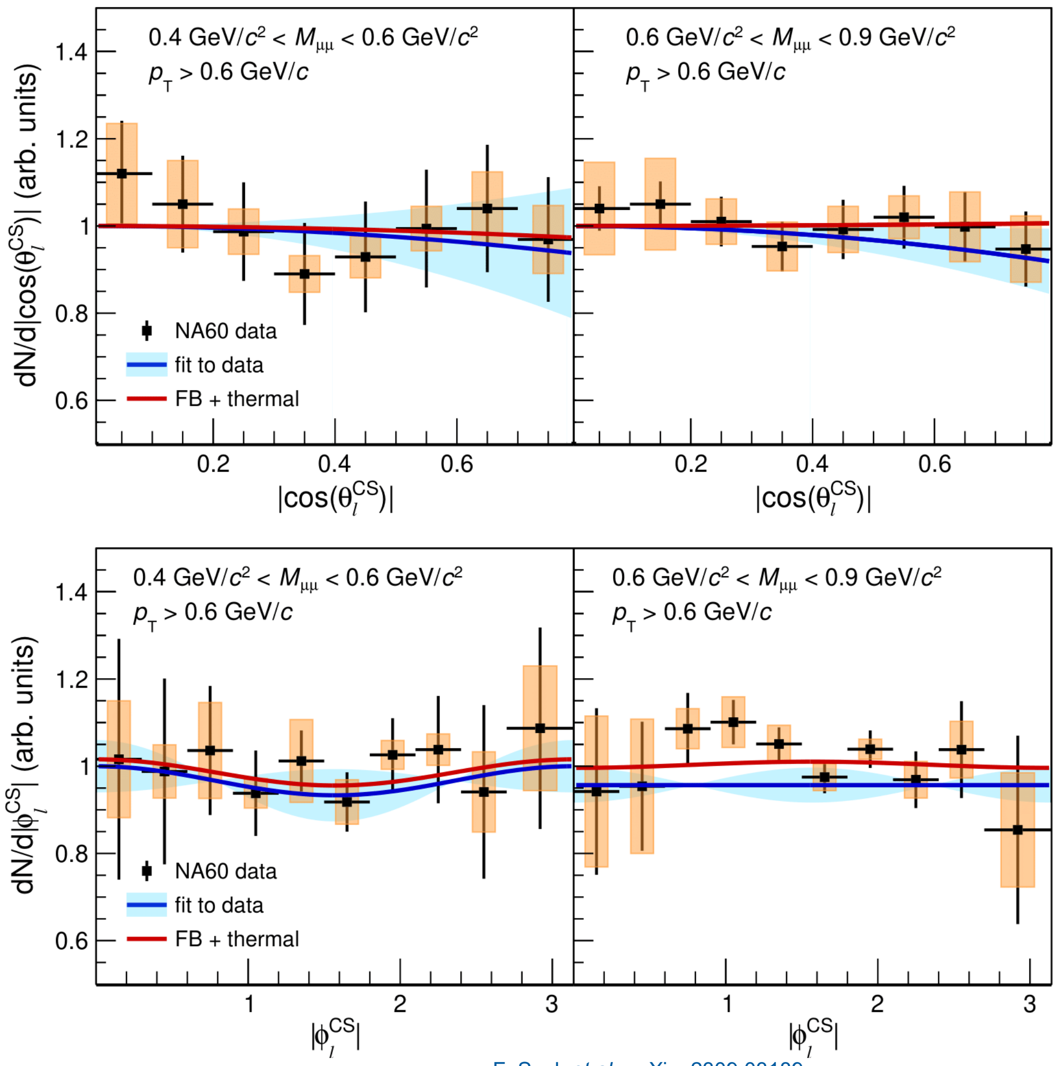
NA60, Phys. Rev. Lett. 96, 162302 (2006)
R. Rapp, H. van Hees, Phys. Lett. B 753, 586 (2016)

- Good agreement between data and theory → size and trend
- Near absence of a net polarization not related to thermal isotropy arguments





data points: NA60, Phys. Rev. Lett. 102, 222301 (2009)



F. Seck *et al.*, arXiv: 2309.03189

SUMMARY

TECHNISCHE UNIVERSITÄT DARMSTADT

- Unique possibility of characterizing the properties of baryon-rich matter with multi-differential measurements of penetrating probes
  - Establish thermal nature of the radiation
  - Flow, polarization, transport coefficients
  - Microscopic degrees of freedom and possible new phases at high μ_B

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

  (+ proton and light nuclei flow coefficients v_1 - v_6)
  - Au+Au at 1.23A GeV, Ag+Ag at 1.58 and 1.23A GeV
  - Energy scan: Au+Au at 200-400-600-800A MeV in March 2025 (including a dedicated run with low magnetic field)

- Big discovery potential with CBM in the near future

BACKUP

STEPS TO ISOLATE THERMAL RADIATION

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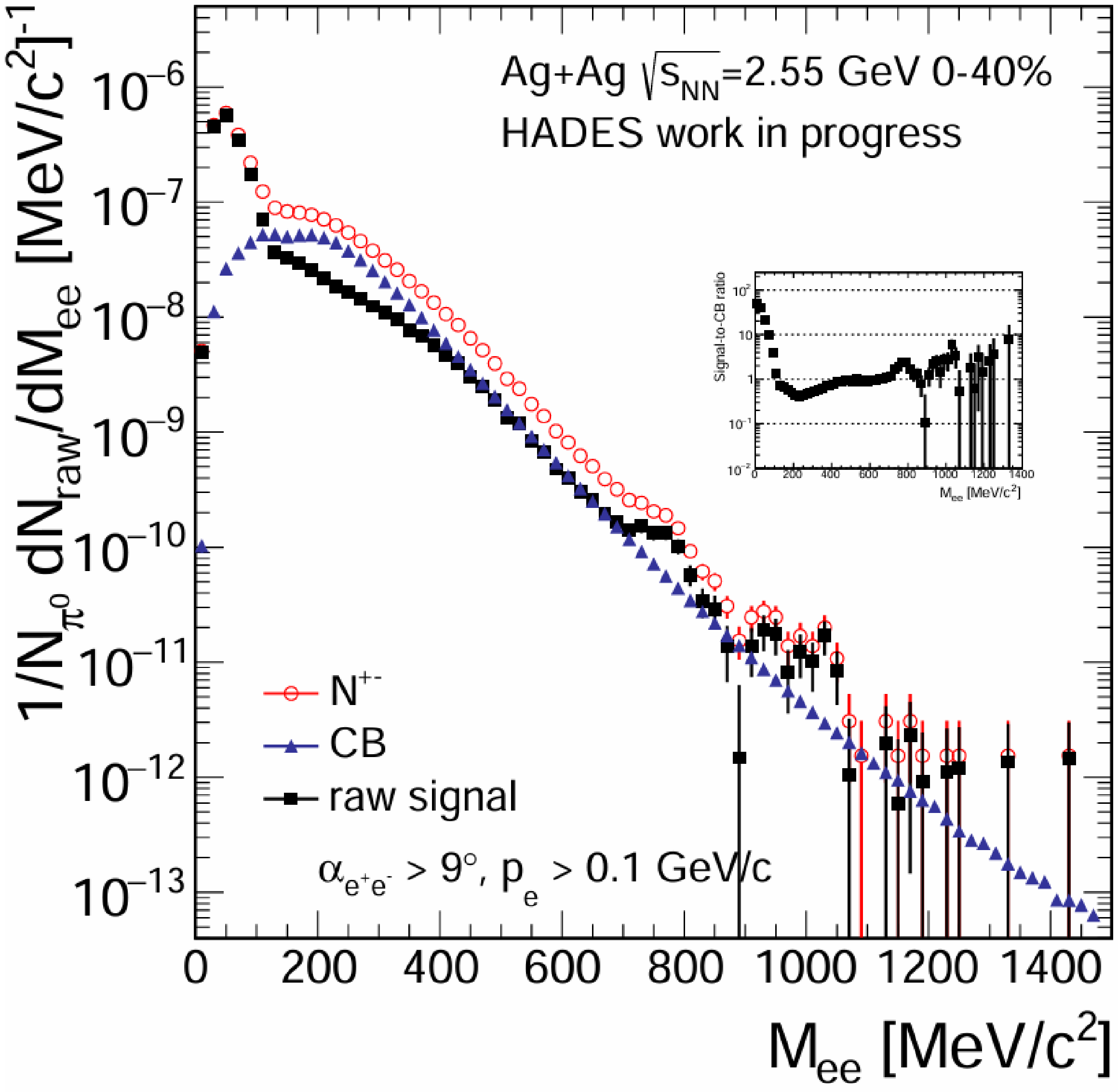
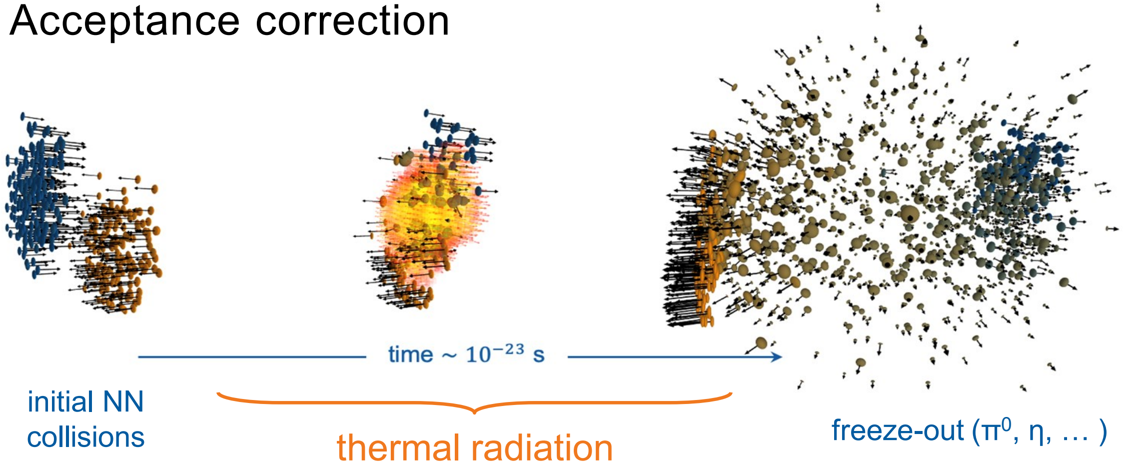
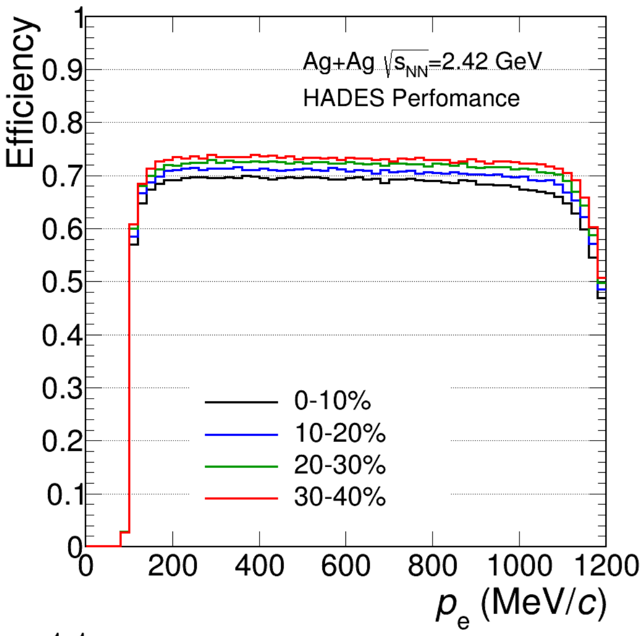


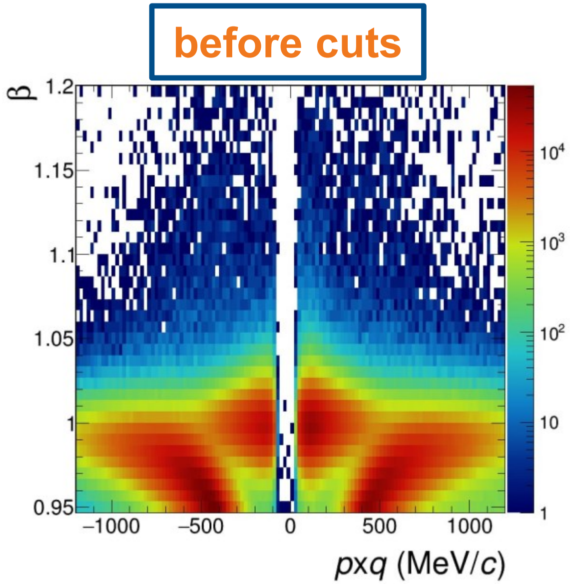
- RICH photodetector upgrade
  - Employing CBM at FAIR technology (CBM FAIR phase-0)
- Efficiency correction
- NN reference subtraction
- Freeze-out cocktail subtraction
  - Simulated using Pluto event generator with measured/estimated multiplicities
- Acceptance correction

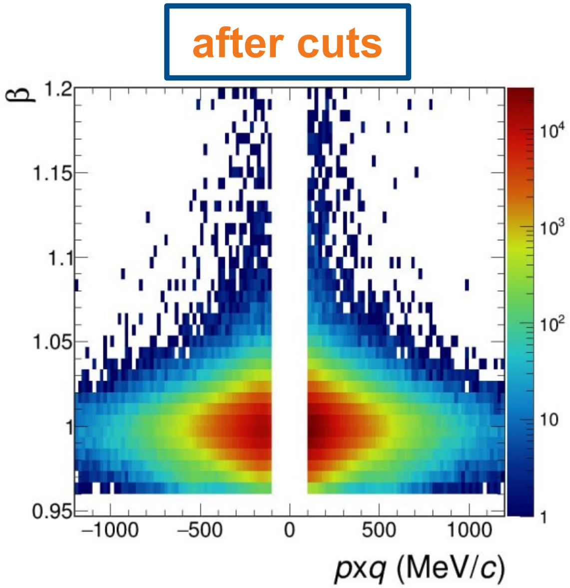


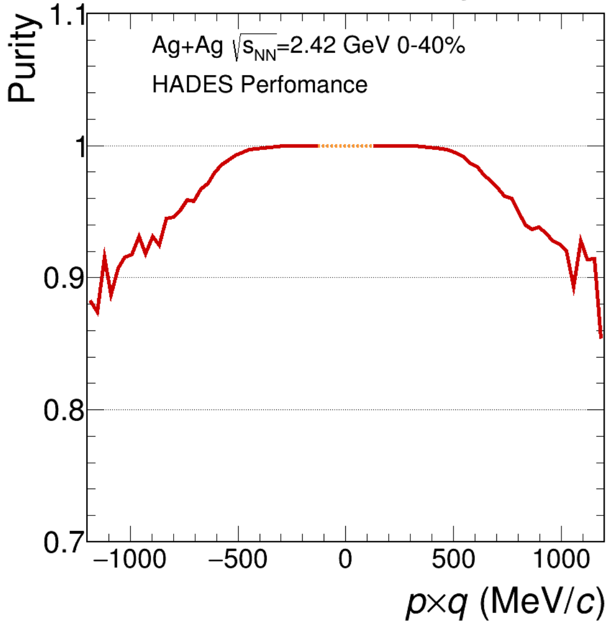
HADES LEPTON IDENTIFICATION PERFORMANCE

- Reconstruction efficiency ~ 70%
- Purity above 90%
- Hadron suppression of ~ 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)







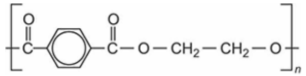


MEASUREMENT OF NN REFERENCE IN HADES

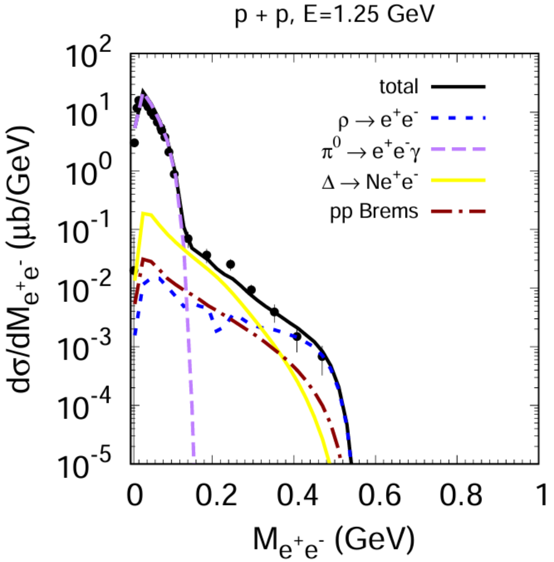
- p+p and d+p collisions at E_{kin} = 1.25 GeV
  - n+p reaction tagged by triggering on proton spectator

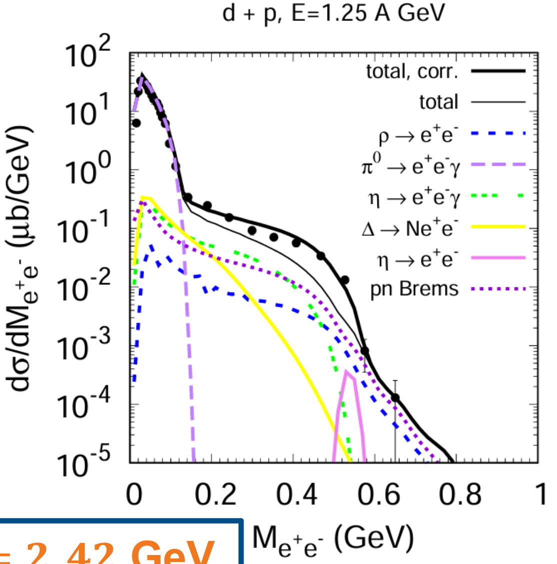
HADES, Phys. Lett. B 690 (2010) 118
A. Larionov *et al.*, Phys. Rev. C 102 (2021), 064913

- Ongoing analysis of p+p at E_{kin} = 1.58 GeV and 4.5 GeV
  - Empty target run p+C/p/O as proxy for p+p/p+n

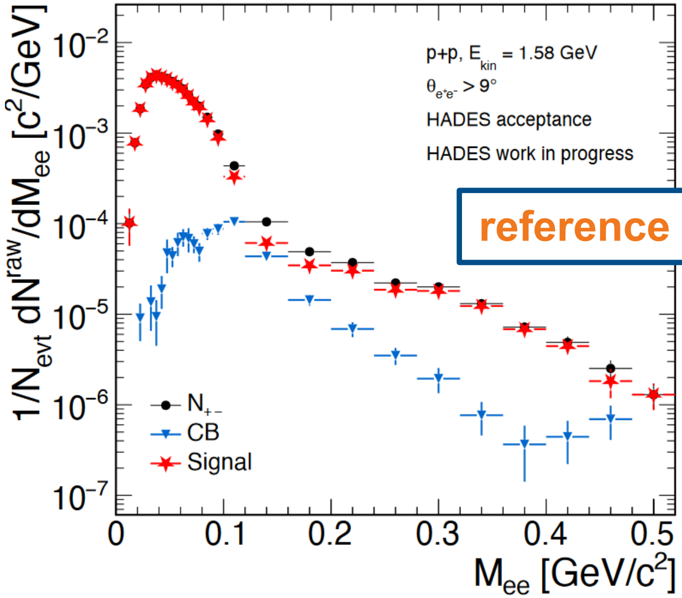


Mylar

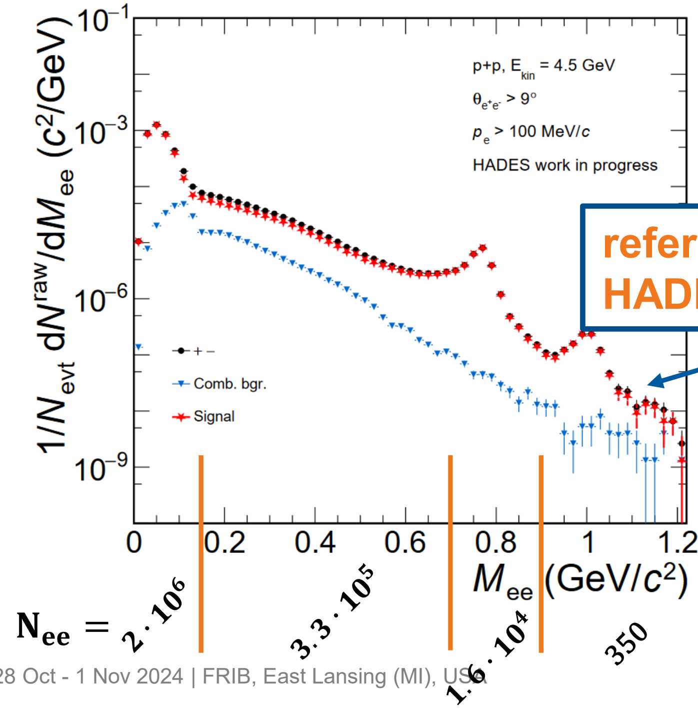




reference for $\sqrt{s_{NN}} = 2.42$ GeV



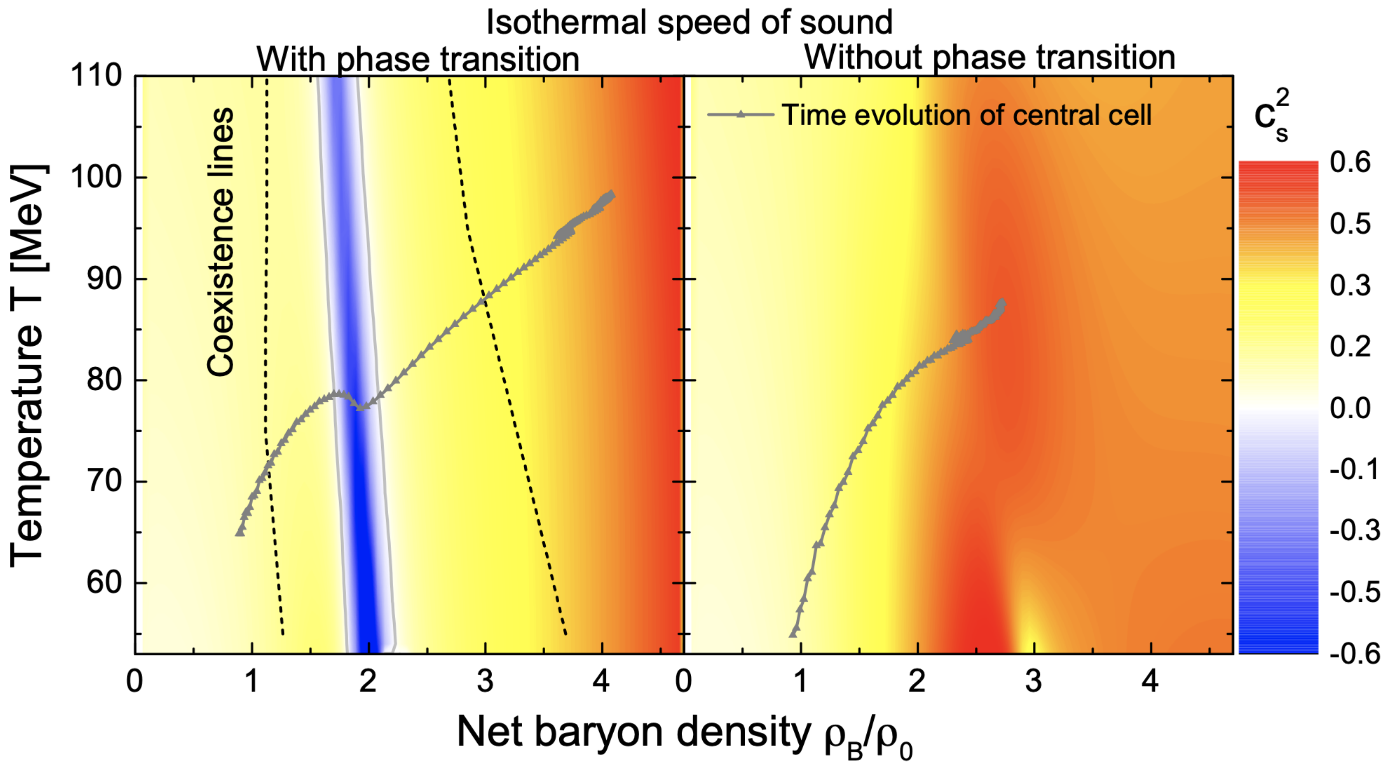
reference for $\sqrt{s_{NN}} = 2.55$ GeV



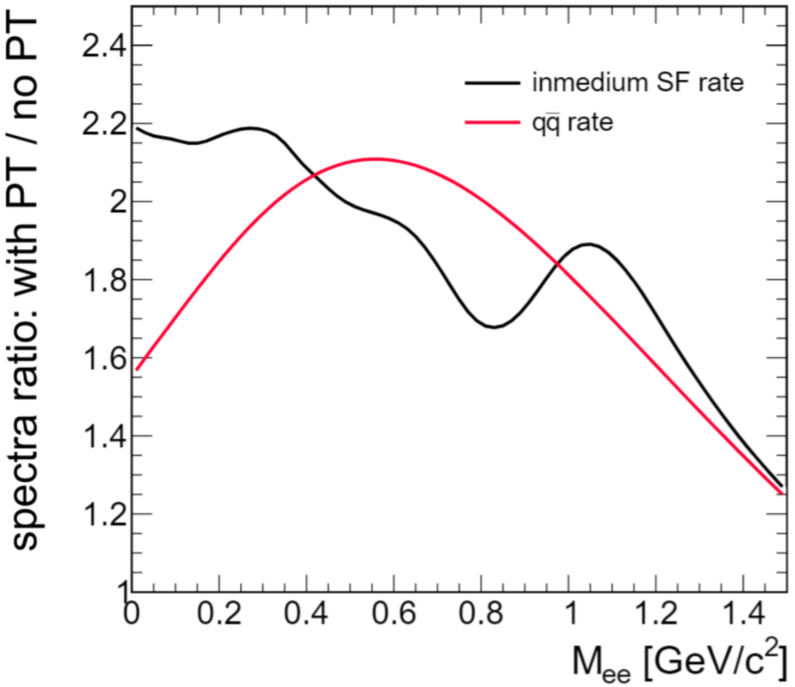
reference for future HADES/CBM runs at FAIR

TECHNISCHE UNIVERSITÄT DARMSTADT

- Ideal hydro simulations with and w/o first order nuclear matter – quark matter phase transition
- Chiral Mean Field model that matches lattice QCD at low μ_B and neutron-star constraints at high density



FS *et al.*, Phys. Rev. C 106 (2022) 1, 014904



STATIC THERMAL MEDIUM

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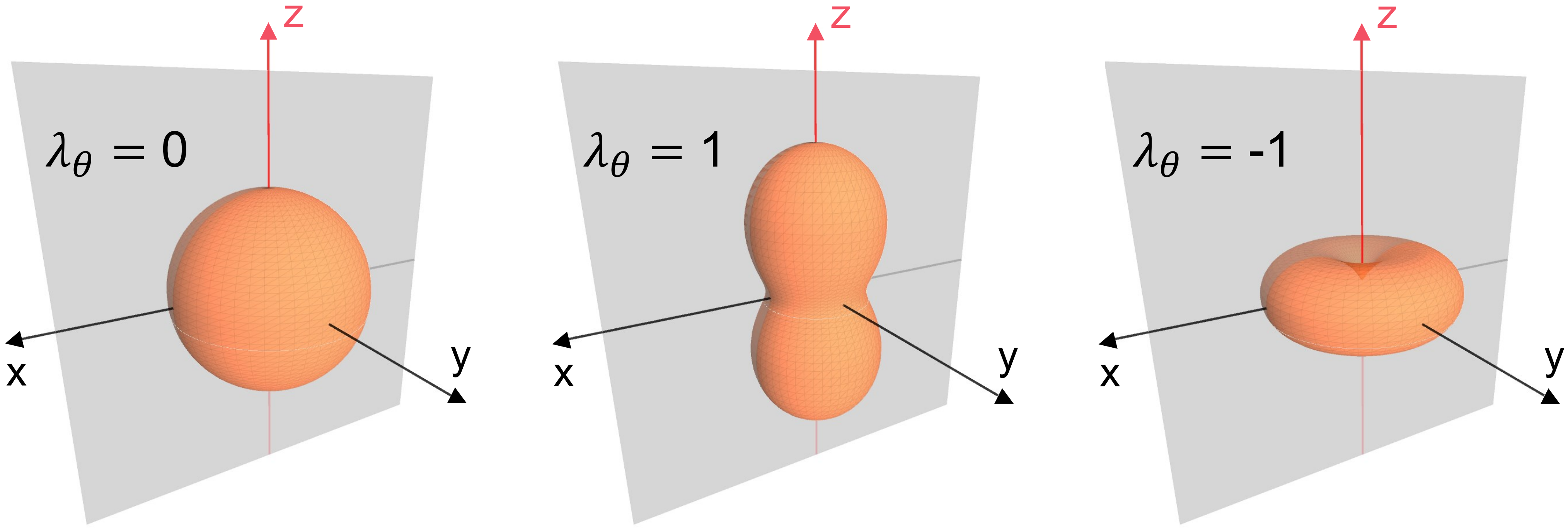
- Rotational symmetry only broken by virtual photon's momentum direction
- In the helicity frame HX the only non-zero coefficient is $\lambda_\theta = \frac{\rho_T - \rho_L}{\rho_T + \rho_L}$

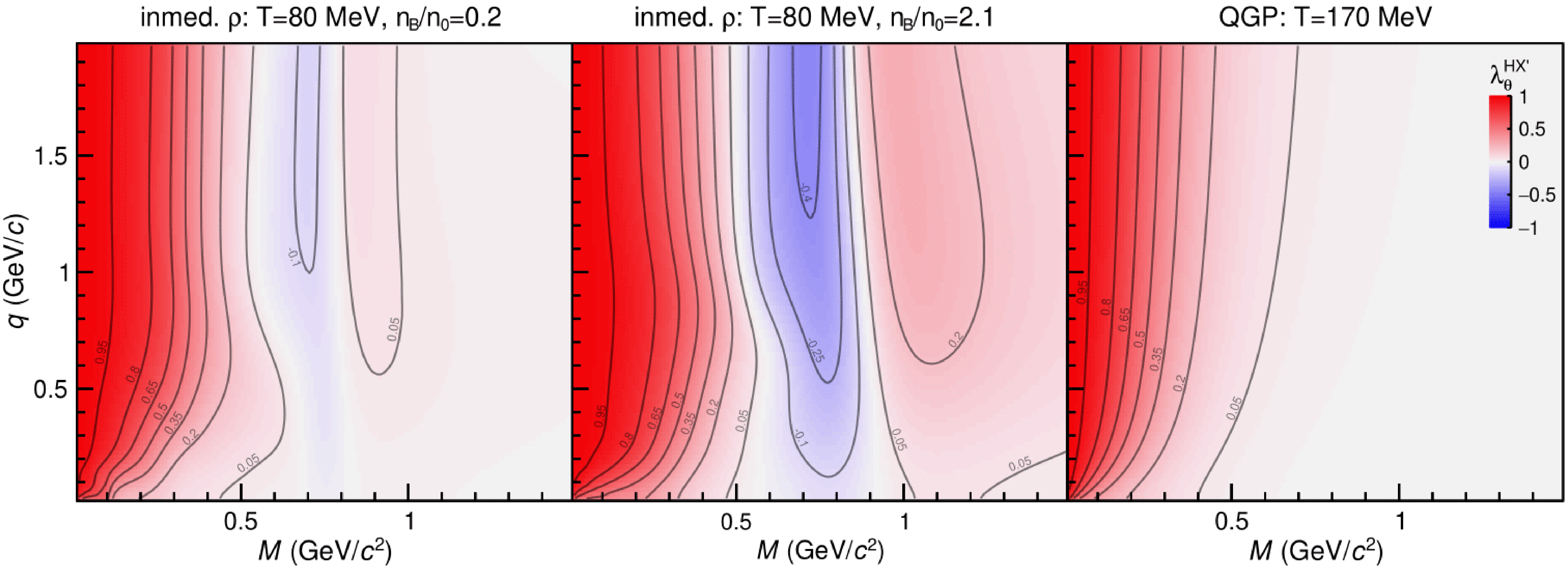
E. Speranza *et al.*, Phys. Lett. B 782, 395 (2018)
G. Baym *et al.*, Phys. Rev. C 95, 044907 (2017)



POLARIZATION IN STATIC MEDIUM

TECHNISCHE UNIVERSITÄT DARMSTADT

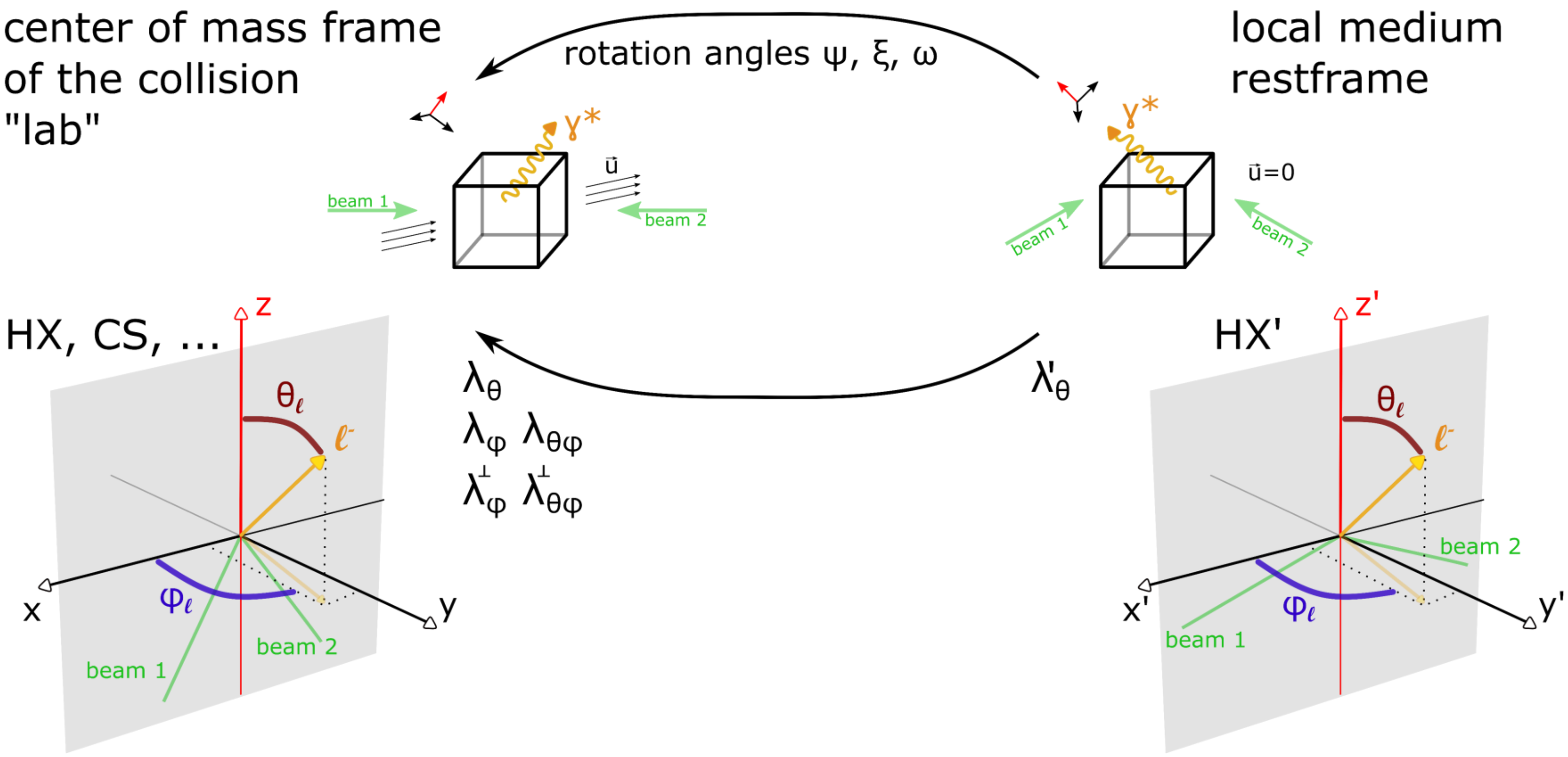
- Strong dependence on mass, momentum and baryon density for hadronic medium
- Rather small polarization for QGP except for M_{ee} < 0.5 GeV/c^2 approaching the photon point



FS *et al.*, arXiv: 2309.03189

POLARIZATION IN MOVING MEDIUM

- Helicity frames (HX') of individual local fluid cells misaligned
- Transform local coefficients to global frame → accessible to experiment: HX, CS, …



RESULTS FOR IN+IN COLLISIONS AT SPS ENERGIES

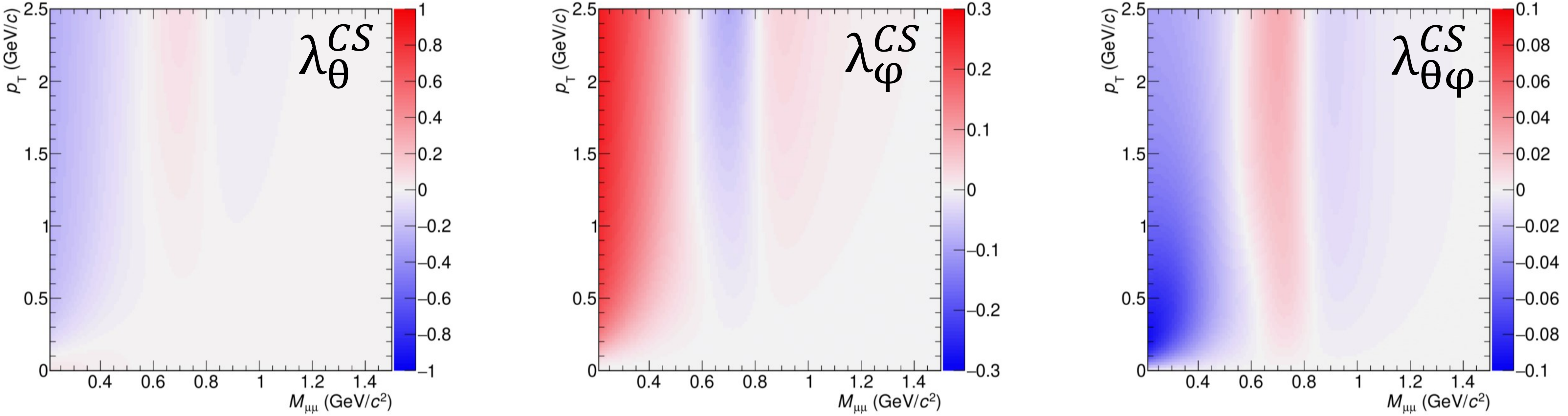
TECHNISCHE UNIVERSITÄT DARMSTADT

- NA60 measured polarization coefficients λ_θ, λ_φ and $\lambda_{\theta\varphi}$ of excess radiation in the CS frame in In+In collisions at 158 AGeV beam energy

NA60, Phys. Rev. Lett. 96, 162302 (2006)
R. Rapp, H. van Hees, Phys. Lett. B 753, 586 (2016)

- Space-time evolution via isentropic fireball model with transition from QGP to hadronic rates at T=170 MeV

- Strong dependence on the polarization frame as function of mass and momentum



COMPARISON TO NA60 DATA

- Good agreement between data and theory → size and trend

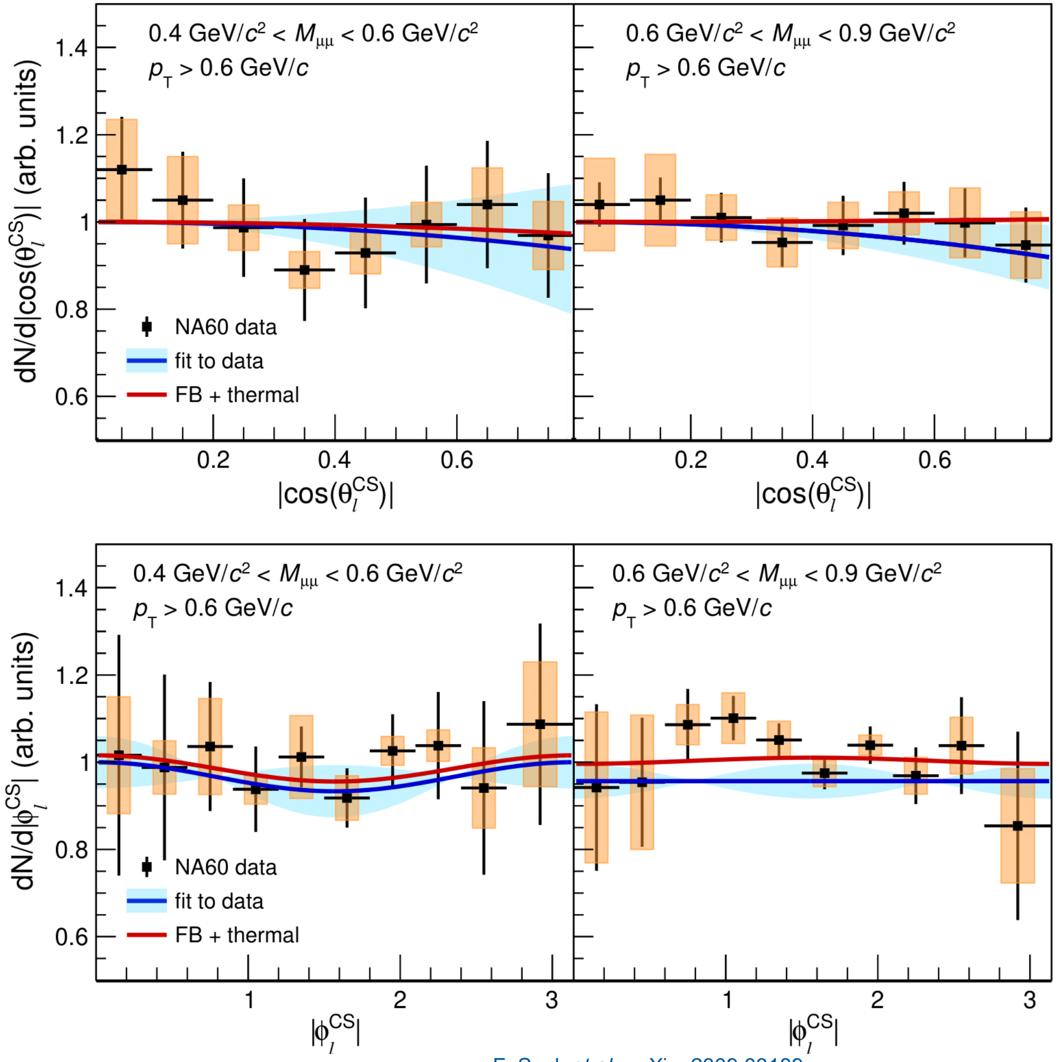
- Near absence of a net polarization
  - not related to thermal isotropy arguments
  - thermal properties of the EM spectral function

- **Best fit** to data gives $\lambda_\theta = -0.10 \pm 0.24$ and $\lambda_\theta = -0.13 \pm 0.12$ in the two mass windows
- **Calculation** results in $\lambda_\theta = -0.04$ and $\lambda_\theta = 0.01$ respectively

- **Best fit** to data gives $\lambda_\varphi = 0.05 \pm 0.09$ and $\lambda_\varphi = 0.00 \pm 0.06$ in the two mass windows
- **Calculation** results in $\lambda_\varphi = 0.04$ and $\lambda_\varphi = -0.01$ respectively

- **Best fit** to data gives $\lambda_{\theta\varphi} = -0.04 \pm 0.10$ and $\lambda_{\theta\varphi} = 0.05 \pm 0.03$ in the two mass windows
- **Calculation** results in $\lambda_{\theta\varphi} = -0.02$ and $\lambda_{\theta\varphi} = 0.01$ respectively

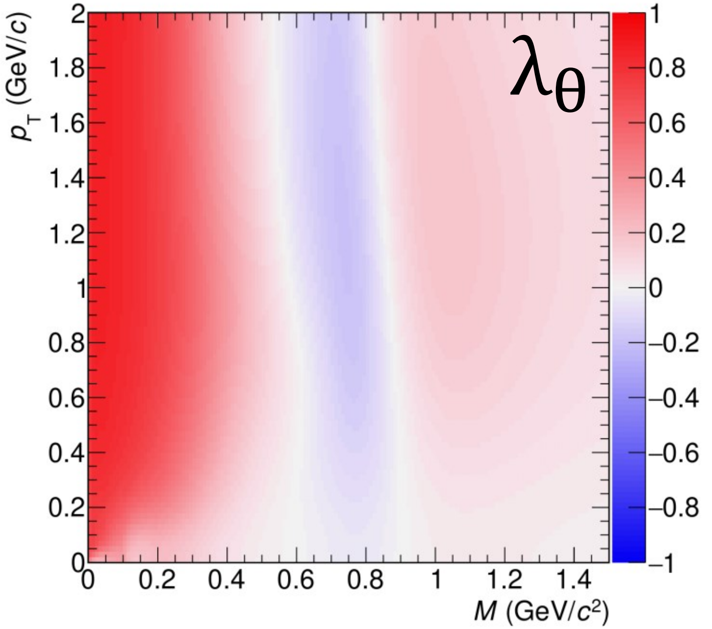
data points: NA60, Phys. Rev. Lett. 102, 222301 (2009)

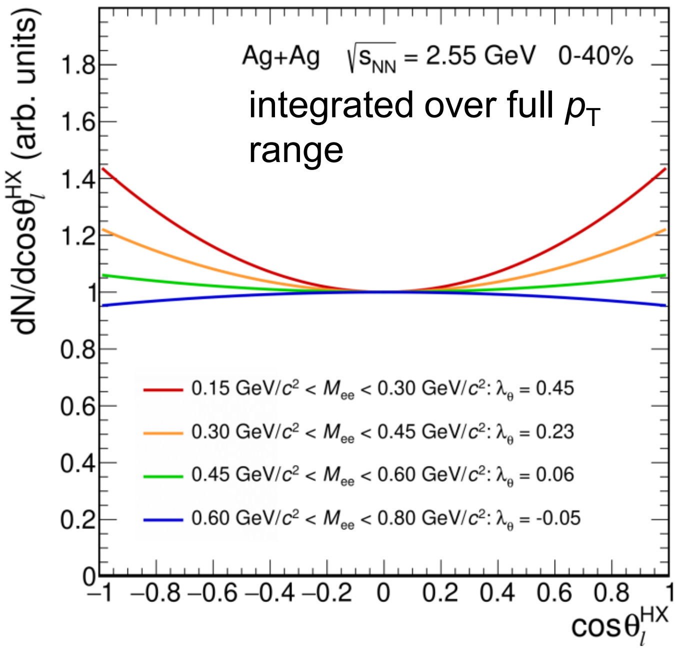


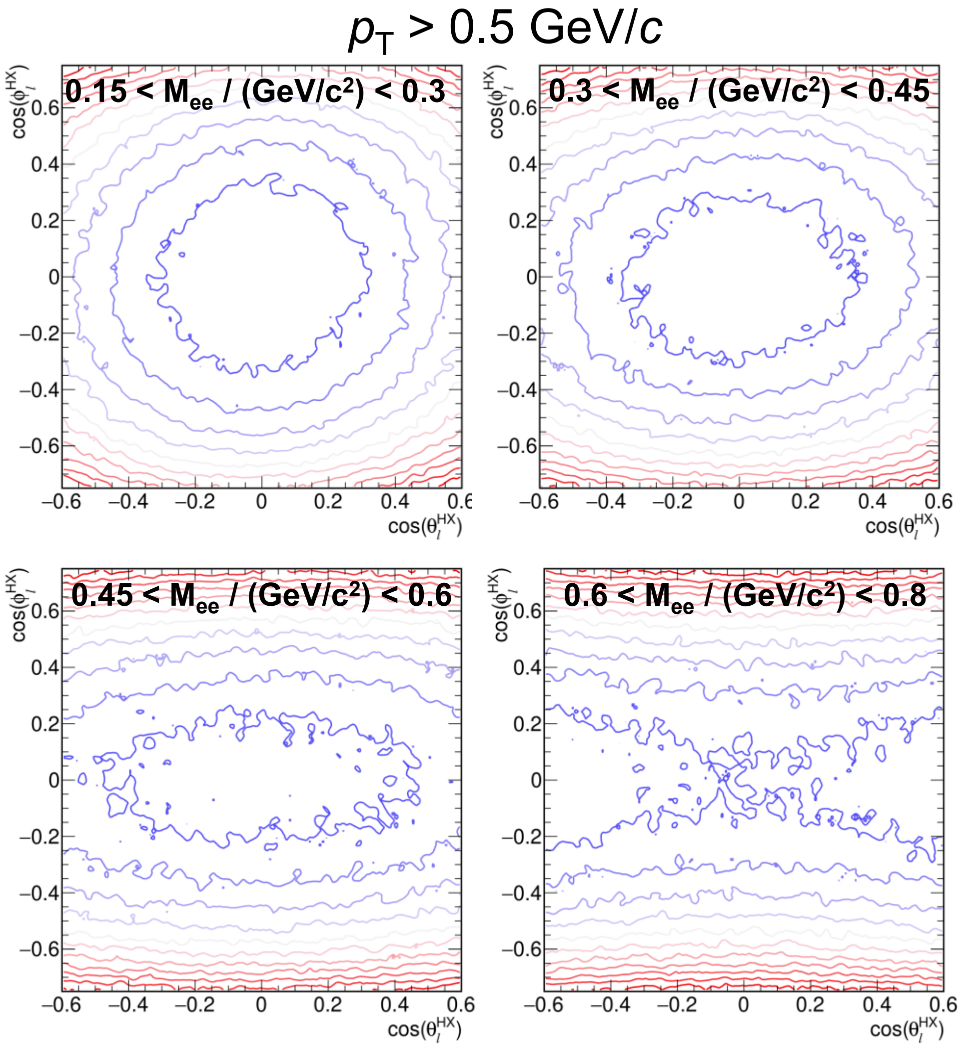
F. Seck *et al.*, arXiv: 2309.03189

PREDICTIONS FOR AG+AG COLLISIONS & FUTURE EXPERIMENTS

- Predictions for λ_θ in Ag+Ag at $\sqrt{s_{NN}} = 2.55$ GeV
- Anisotropy coefficients integrated over p_T in several mass ranges



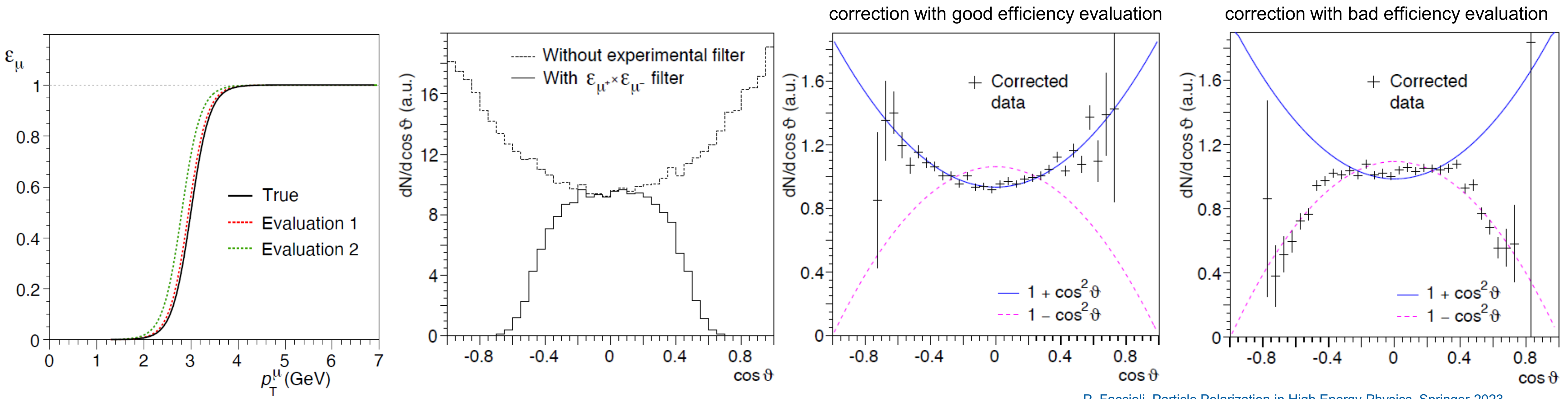




- Multi-differential measurements of the virtual photon polarization
  → large datasets needed: CBM, NA60+ and ALICE3
  - Search for onset of QGP
  - ρ-a_1 mixing vs. QGP around M_{ee} ~ 1.1 GeV

EXPERIMENTAL DIFFICULTIES

- Virtual photon polarization influences detection efficiency
- Efficiency + acceptance corrections need to be done carefully
- Wrong efficiency evaluation can lead to wrong sign of polarization



P. Faccioli, Particle Polarization in High Energy Physics, Springer 2023

PROSPECT OF DISENTANGLING HADRONIC AND PARTONIC SOURCES

TECHNISCHE UNIVERSITÄT DARMSTADT

- Polarization plays important role in exploring the mechanisms underlying EM emission
- Multi-differential measurements of the virtual photon polarization
  - resolve mass, p_T, rapidity, lepton emission angles θ_l, φ_l $\rightarrow$ large datasets needed
  - future high-rate experiments CBM, NA60+ and ALICE3