Rapidity scan with DCCI at LHC energy

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Sophia University[1], Akita International University[2]

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Rapidity Scan

Expected high baryon number density in forward rapidity in high-energy collisions

M. Li and J. I. Kapusta, Phys. Rev. C **99**, 014906 (2019)

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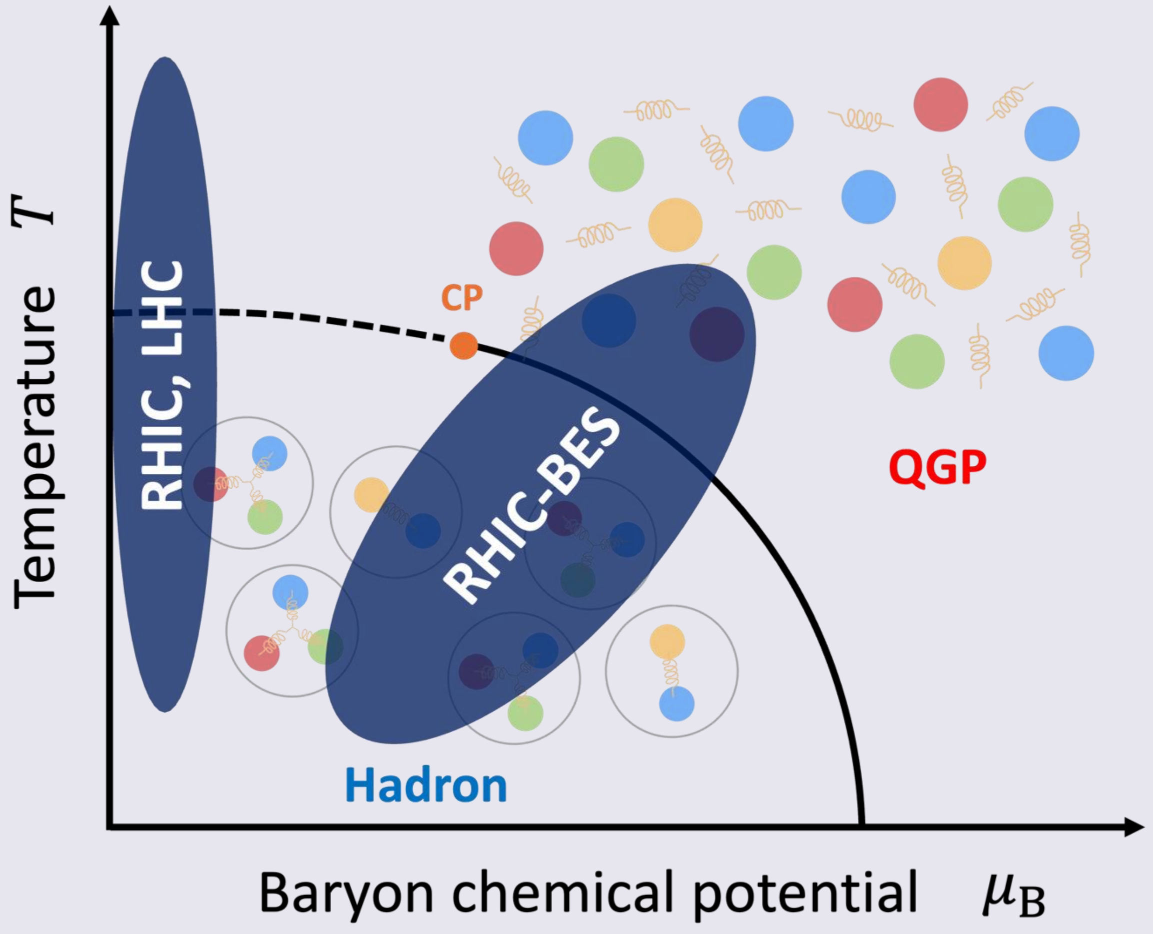
Access high baryon chemical potential region in the QCD phase diagram

Beam Energy Scan @ low energy ⟷ **Rapidity Scan @ high energy**

Complementary study of QCD phase diagram by BES and Rapidity Scan!

QCD phase diagram and experiments



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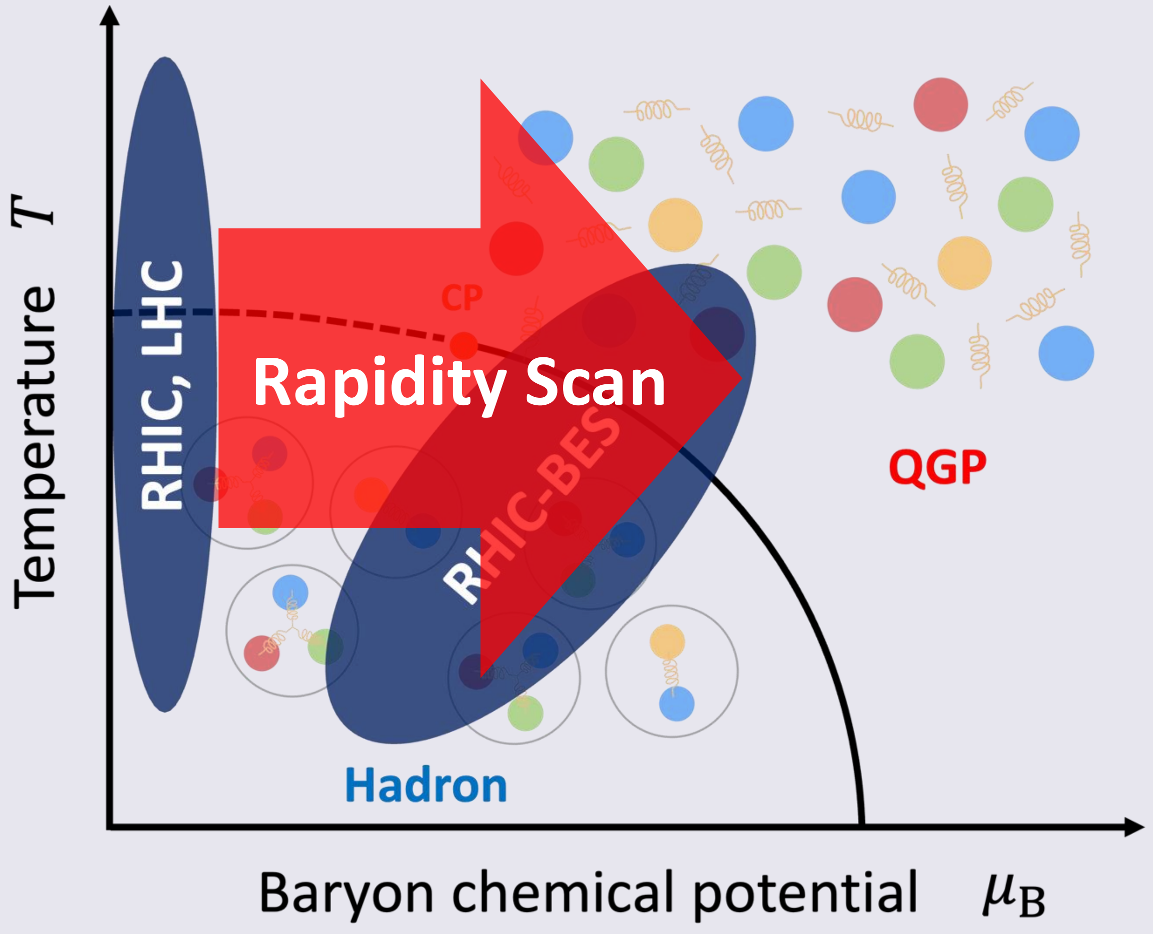

A fundamental question

How large baryon chemical potential is achieved as equilibrated matter in forward rapidity?

To answer the question, models must describe…

- Equilibrium and non-equilibrium components separately
- Fluidization of baryon number
- Hydrodynamic evolution of baryon number density

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→ **DCCI + finite n_{B} extension**

Introduction

▷ **Model**

Results

Summary and Outlook

Dynamical Core-Corona Initialization (DCCI) model

Y. Kanakubo *et al.*, Phys. Rev. C **105**, 024905 (2022)

Initial partons

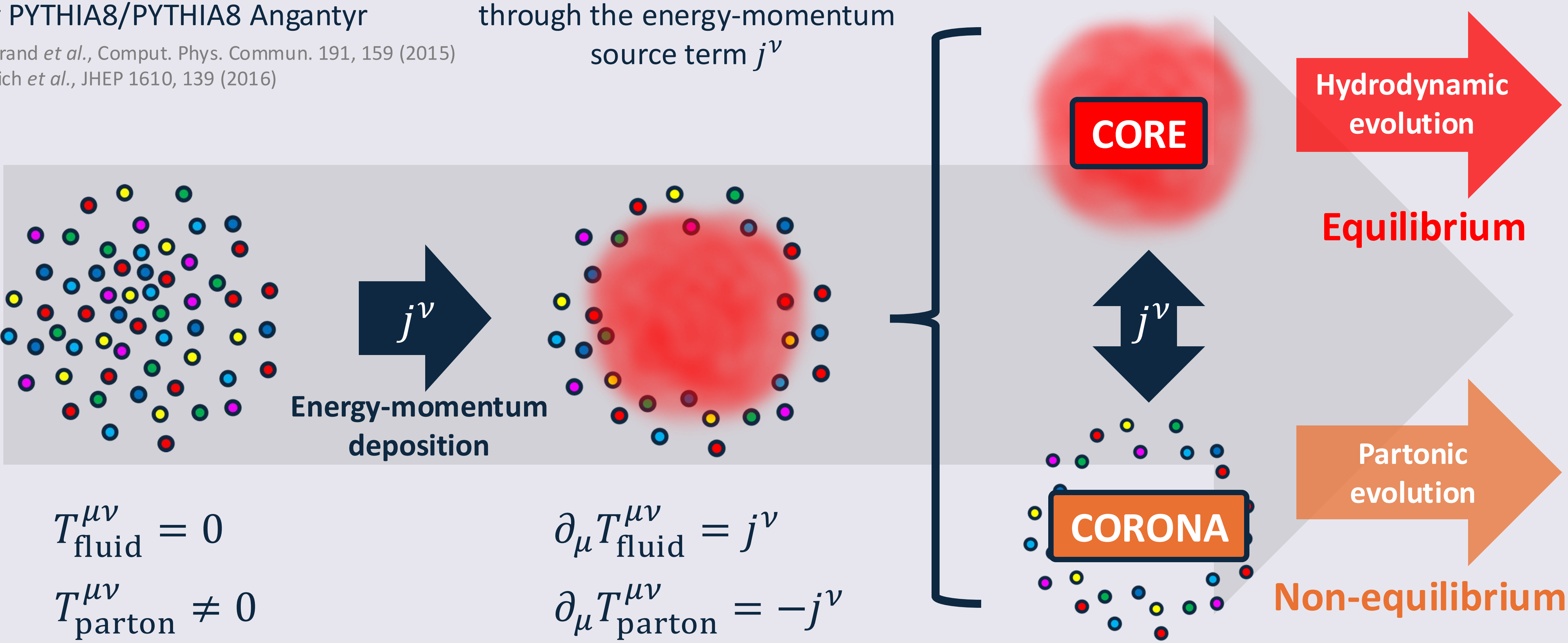
by PYTHIA8/PYTHIA8 Angantyr

T. Sjöstrand *et al.*, Comput. Phys. Commun. 191, 159 (2015)
C. Bierlich *et al.*, JHEP 1610, 139 (2016)

Dynamical initialization

through the energy-momentum source term j^ν

Core-corona picture



$$T^{\mu\nu}_{\mathrm{fluid}} = 0$$
$$T^{\mu\nu}_{\mathrm{parton}} \neq 0$$

$$\partial_\mu T^{\mu\nu}_{\mathrm{fluid}} = j^\nu$$
$$\partial_\mu T^{\mu\nu}_{\mathrm{parton}} = -j^\nu$$

Source terms

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Energy-momentum source term

Y. Kanakubo *et al*., Phys. Rev. C **105**, 024905 (2022)

$$\partial_\mu T^{\mu\nu}_{\mathrm{fluid}} = j^\nu$$

$$j^\nu = -\sum_i^{N_{\mathrm{parton}}} \frac{dp_i^\nu(t)}{dt} G(\boldsymbol{x} - \boldsymbol{x}_i(t))$$

p_i^ν: Four-momentum of i_{th} parton

G: Gaussian function $\boldsymbol{x}_i$: Position of i_{th} parton

When i_{th} parton deposits all energy = dead parton

Baryon number source term **New!!**

$$\partial_\mu N^\mu_{\mathrm{fluid}} = \rho$$

$$\rho = -\sum_j^{N_{\mathrm{dead}}} \frac{dB_j}{dt} G\left(\boldsymbol{x} - \boldsymbol{x}_j(t)\right)$$

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- **Phenomenological fluidization rate per particle in core-corona picture**

Low p_{T} / Dense → CORE

High p_{T} / Dilute → CORONA

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- **Phenomenological fluidization rate per particle in core-corona picture**

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- **Deposition of baryon number into the fluid**

  Thermalized baryon number in CORE

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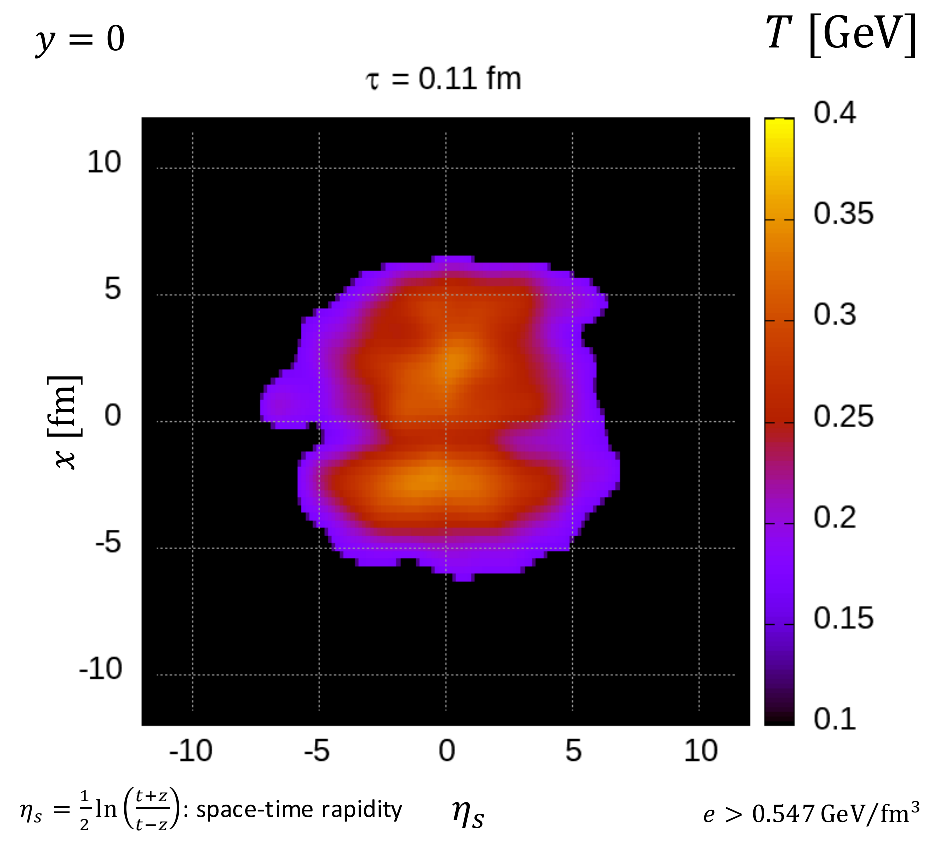
Space-time evolution of core

Pb+Pb 2.76 TeV, b = 2.46 fm
Single event

Temperature (longitudinal profile)



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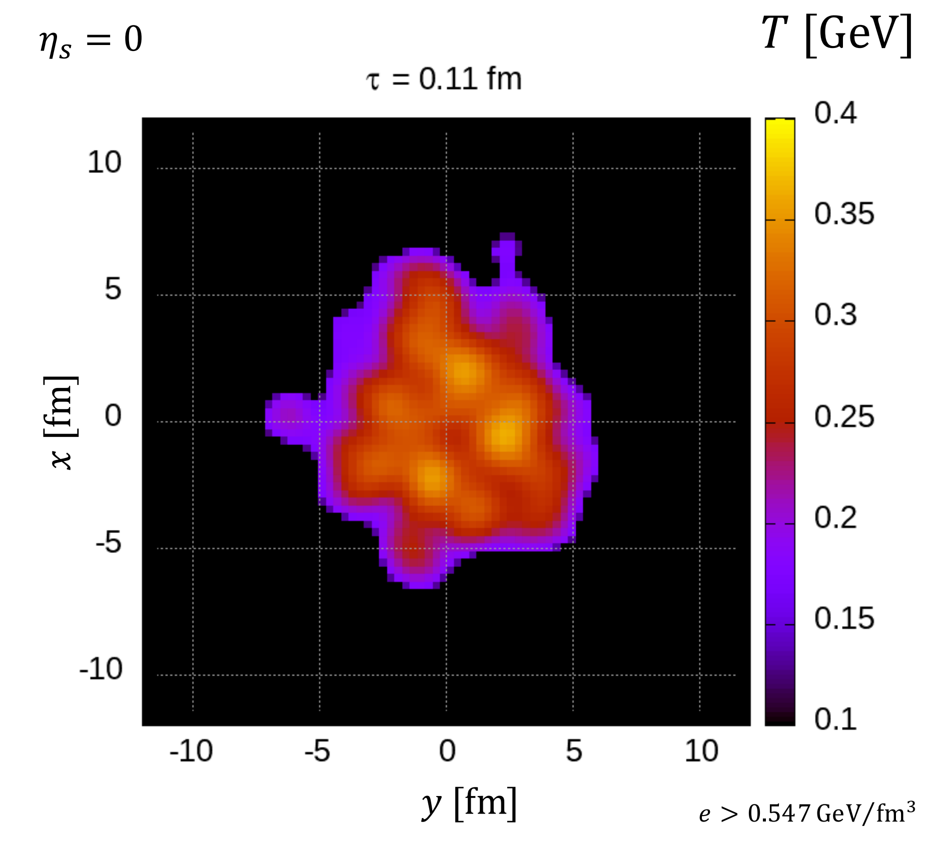

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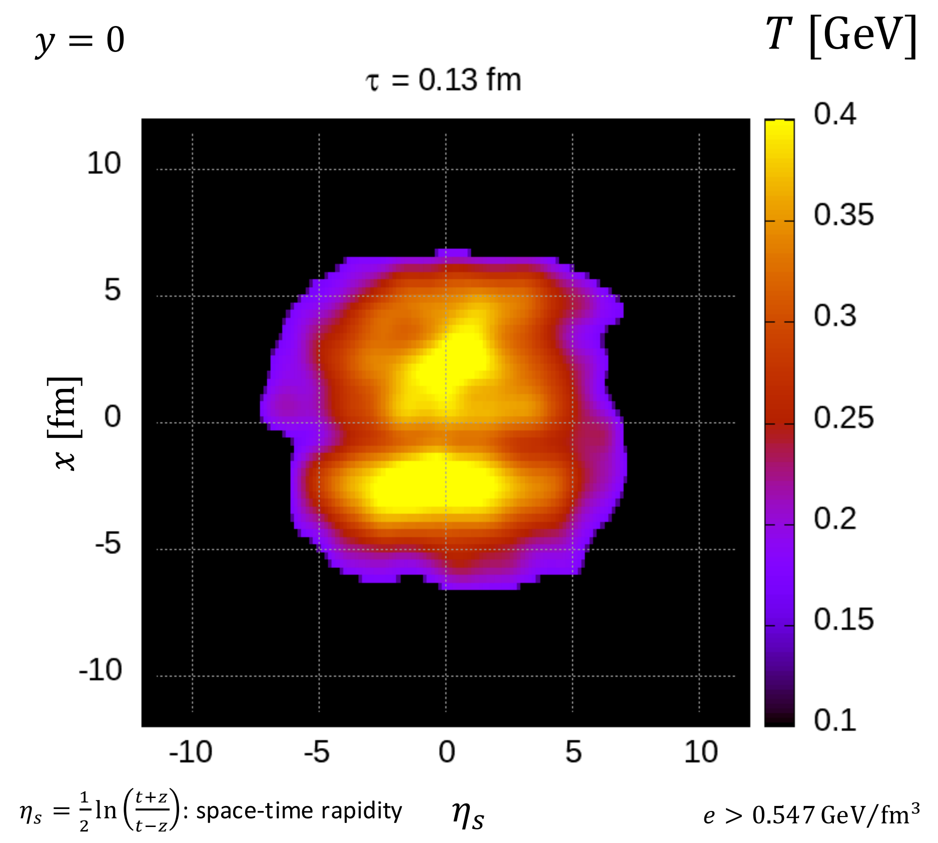

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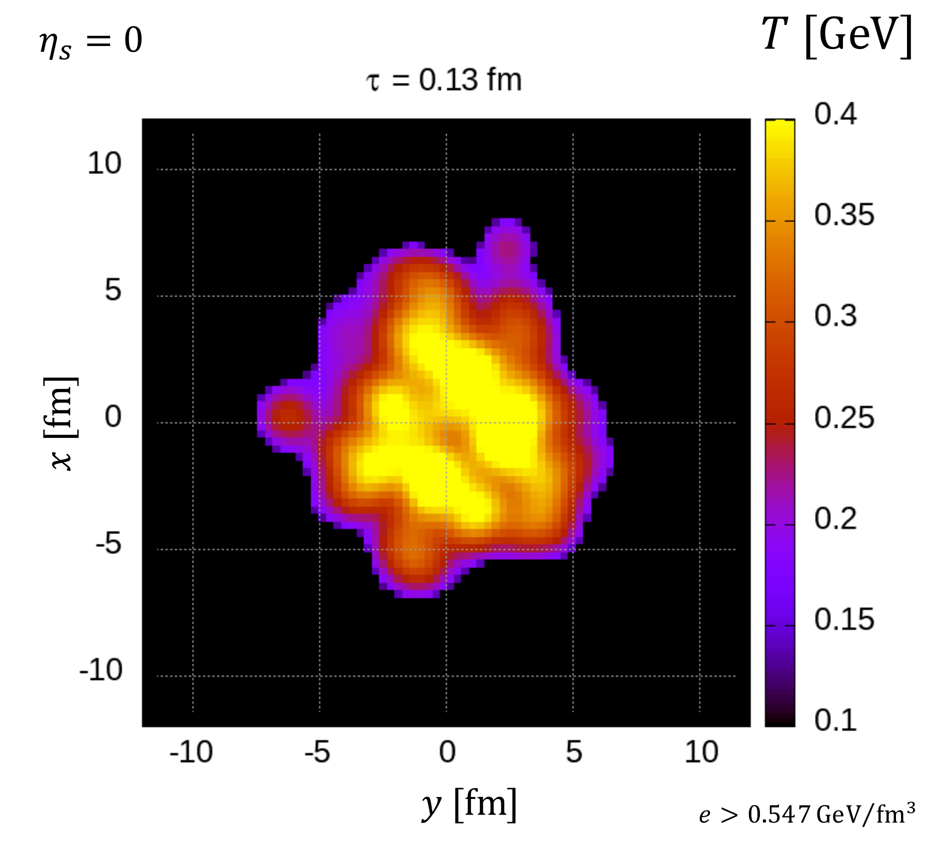

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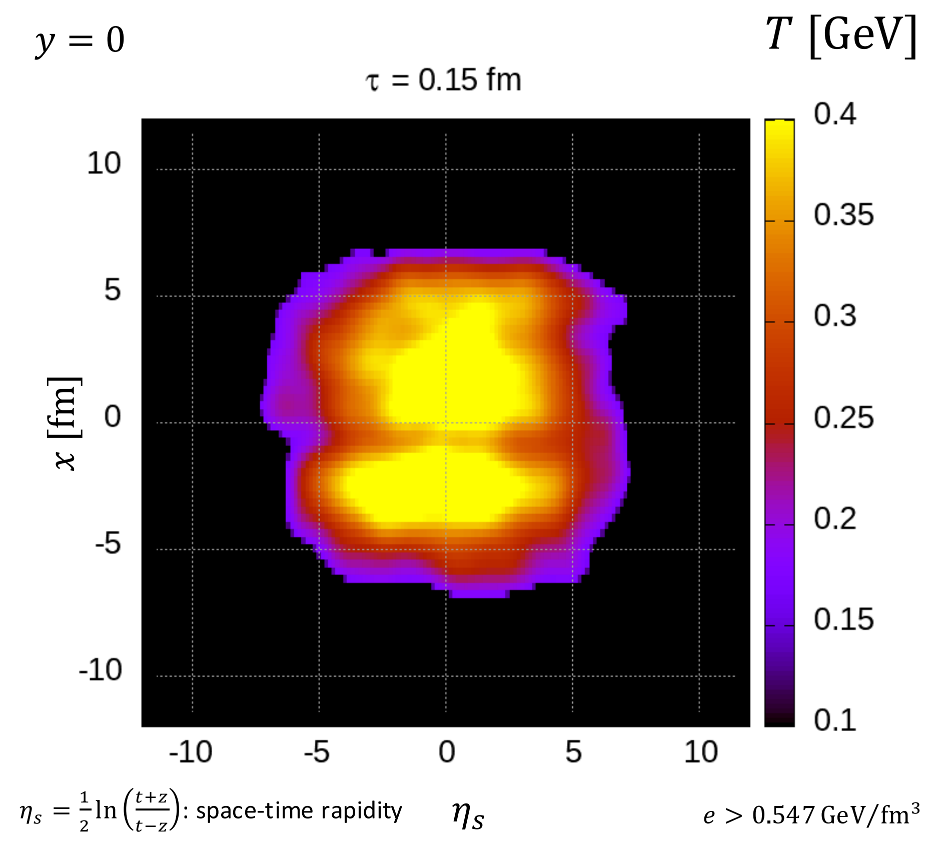

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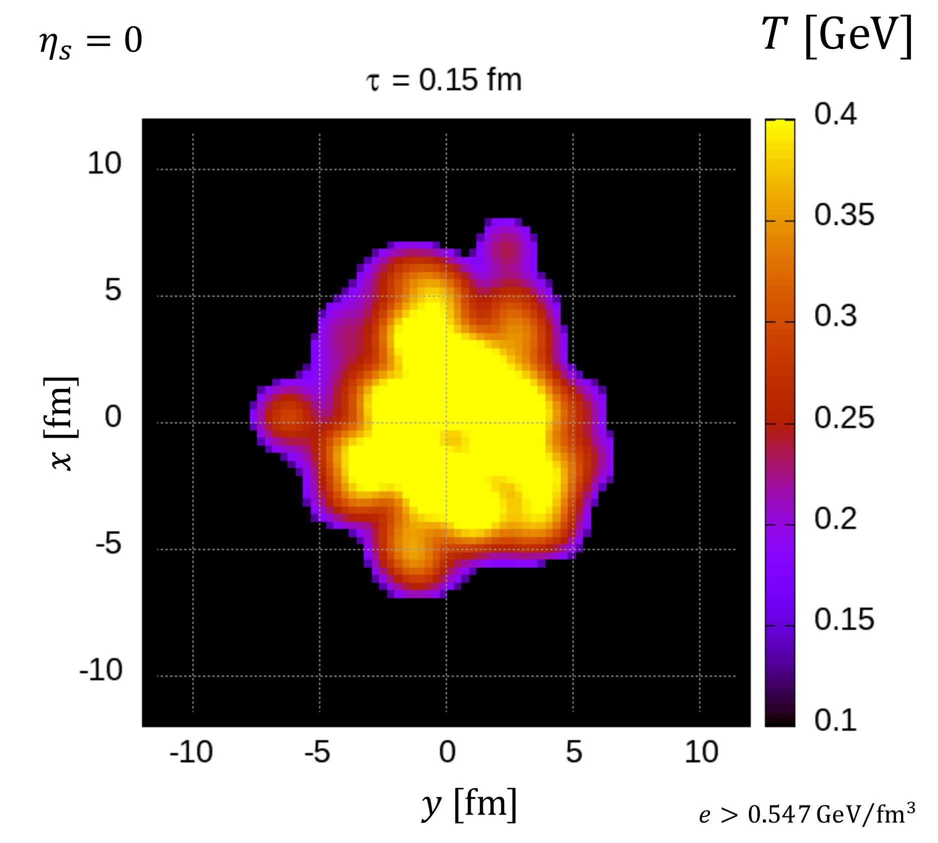

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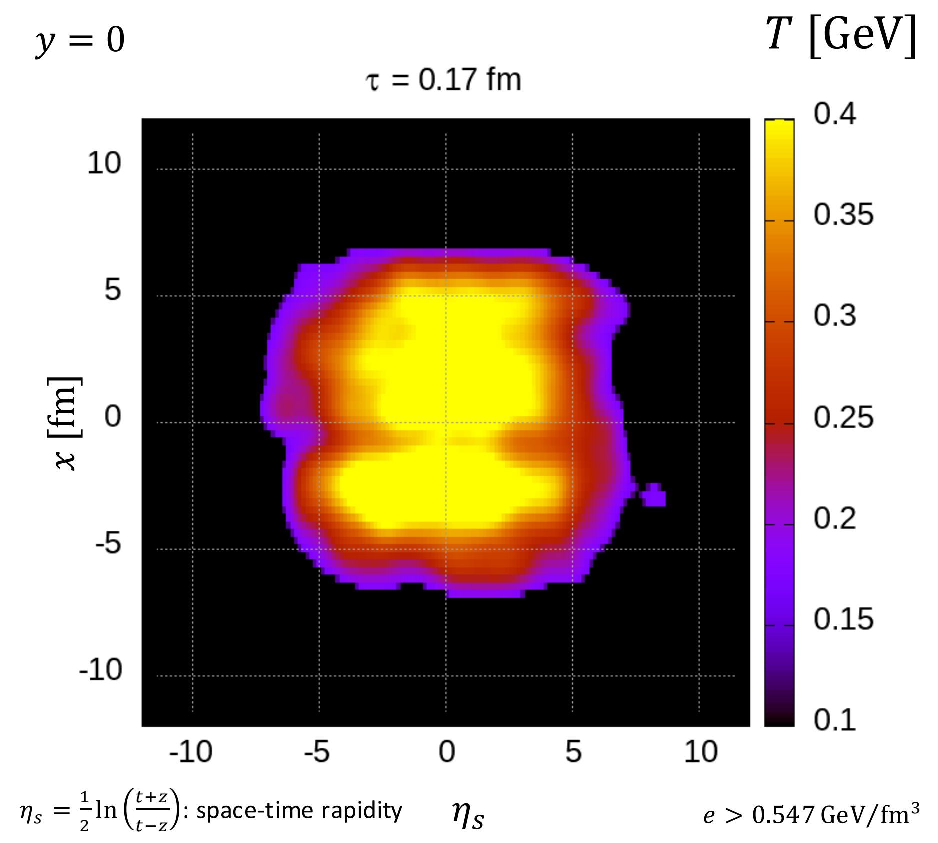

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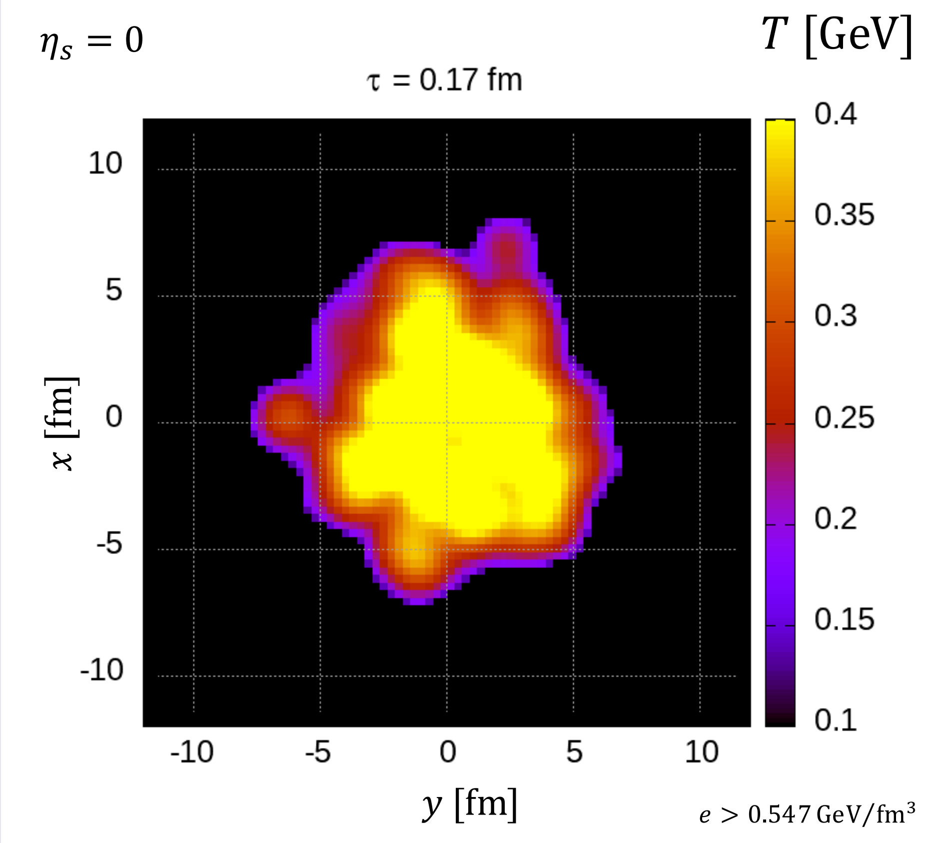

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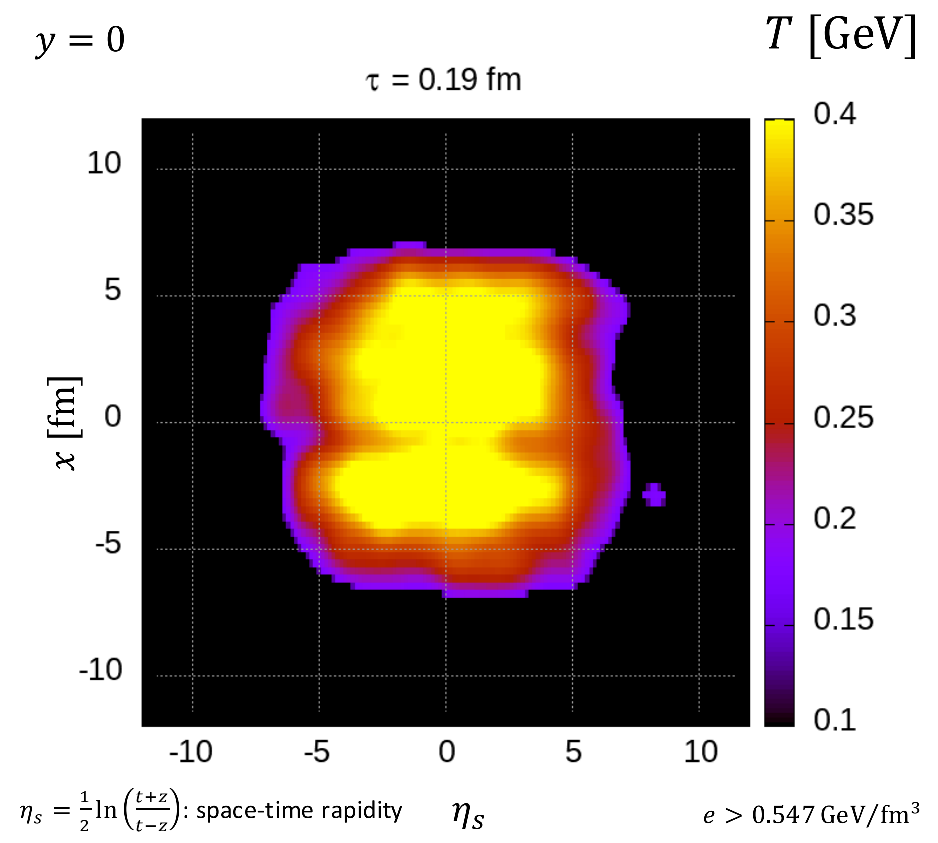

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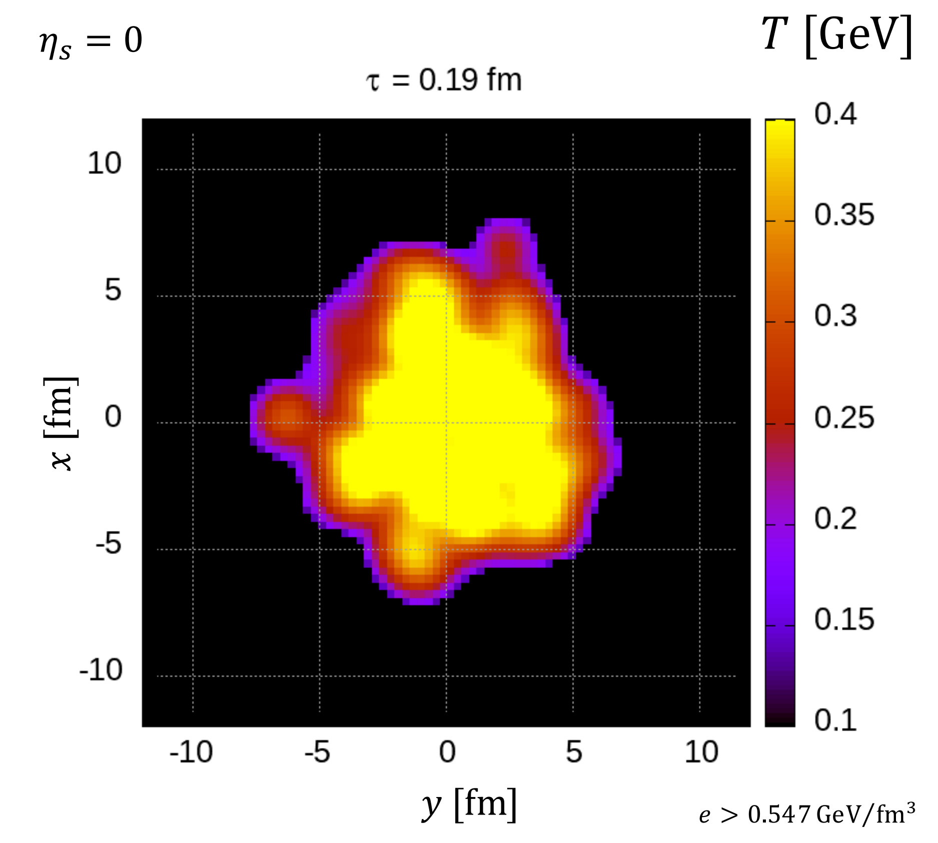

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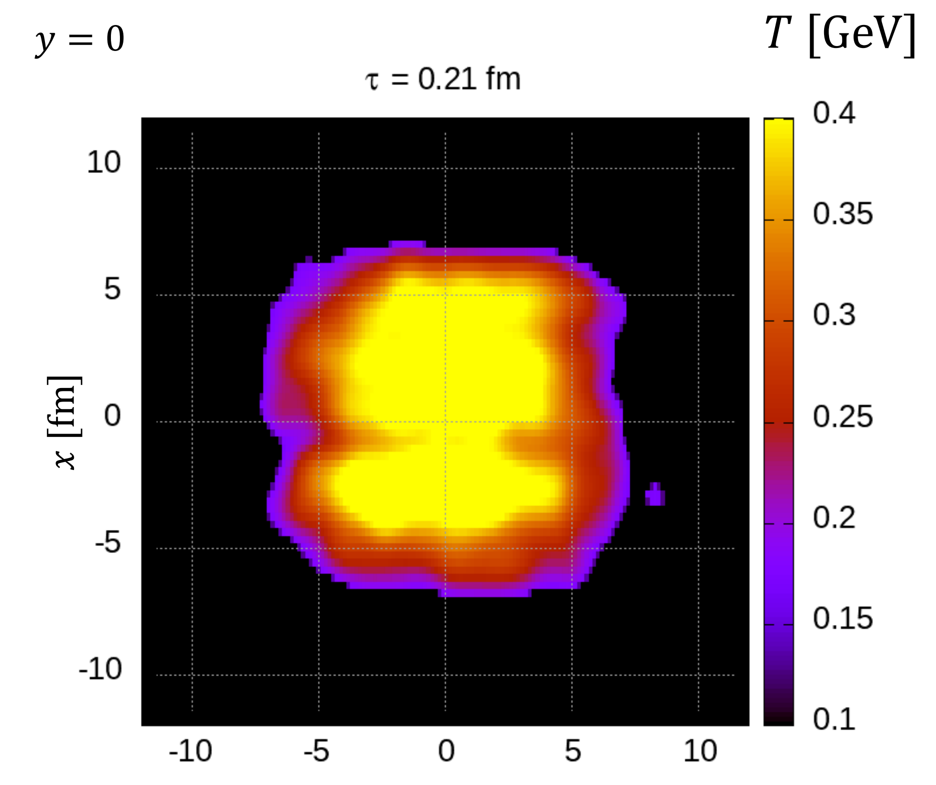

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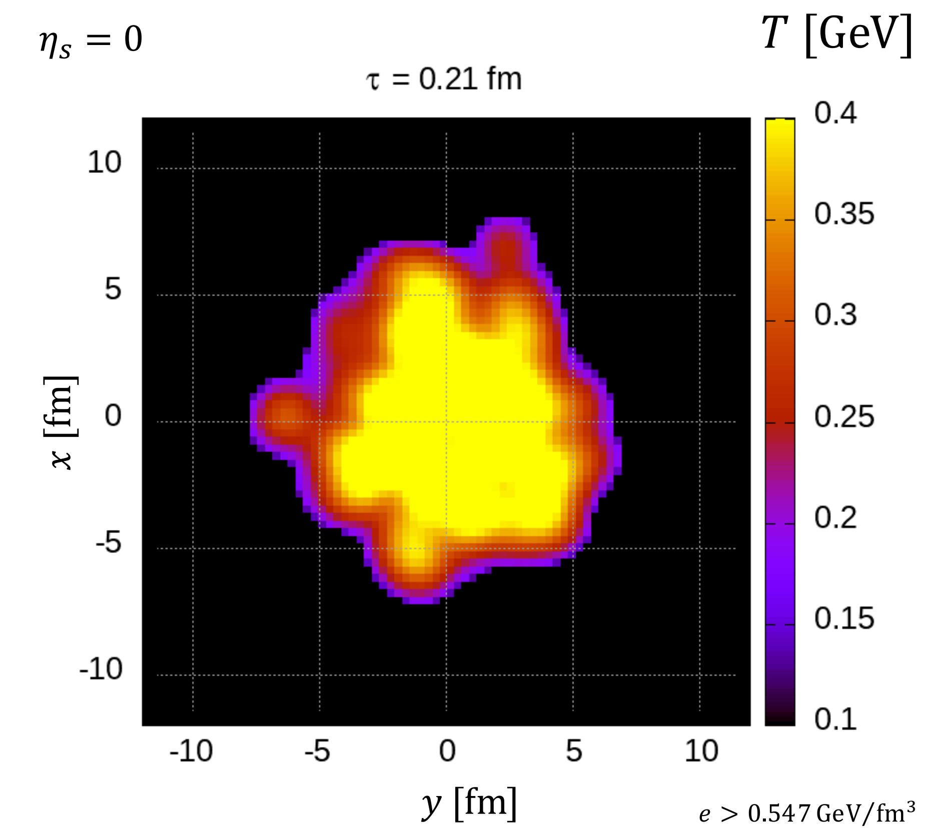

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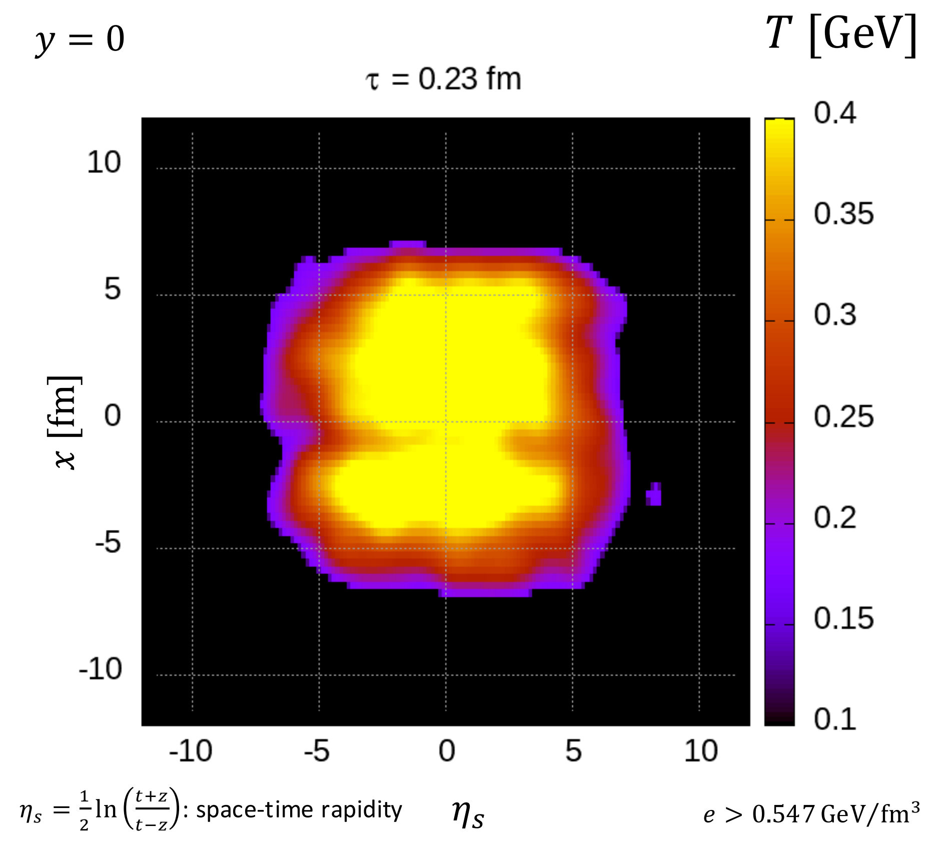

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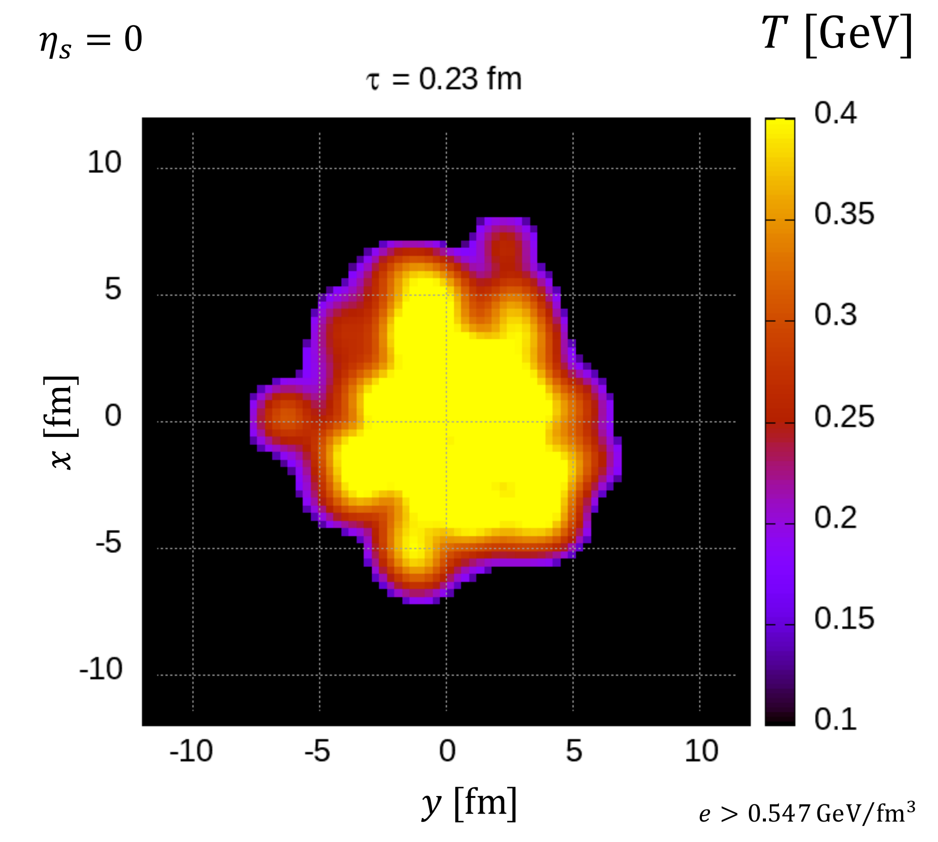

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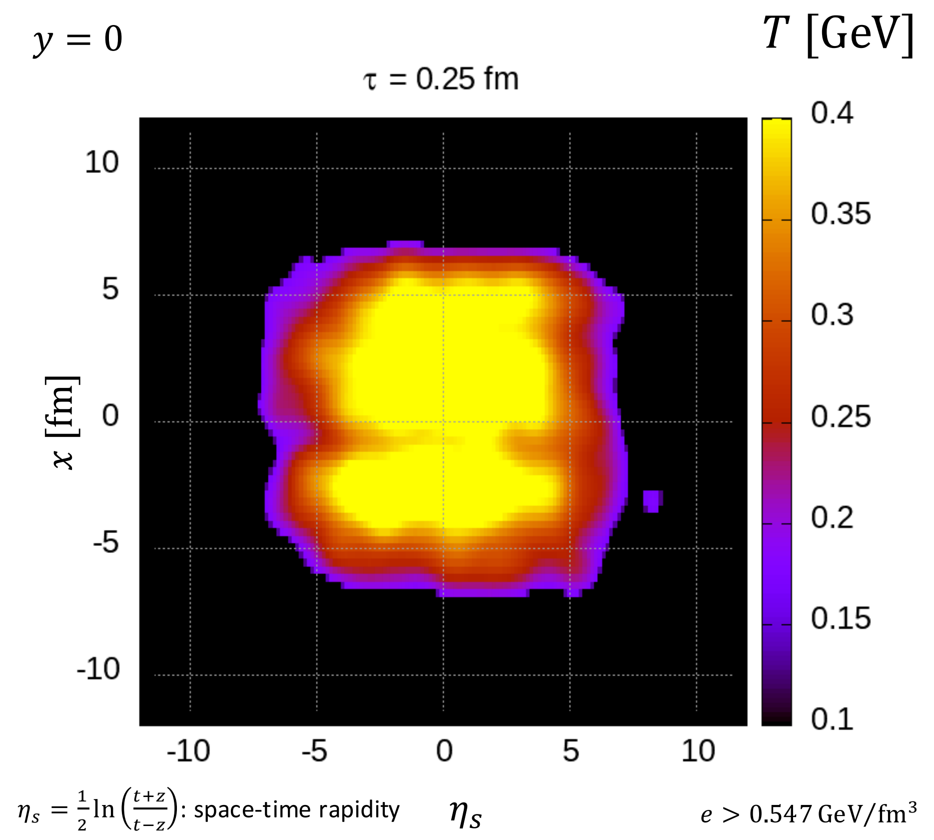

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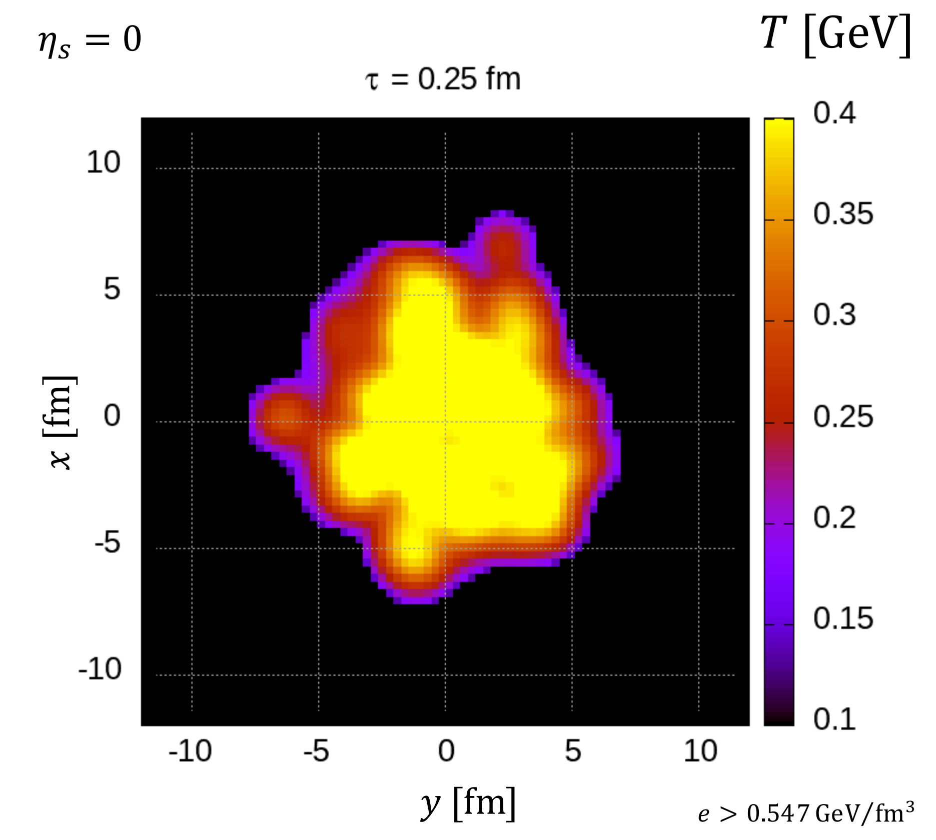

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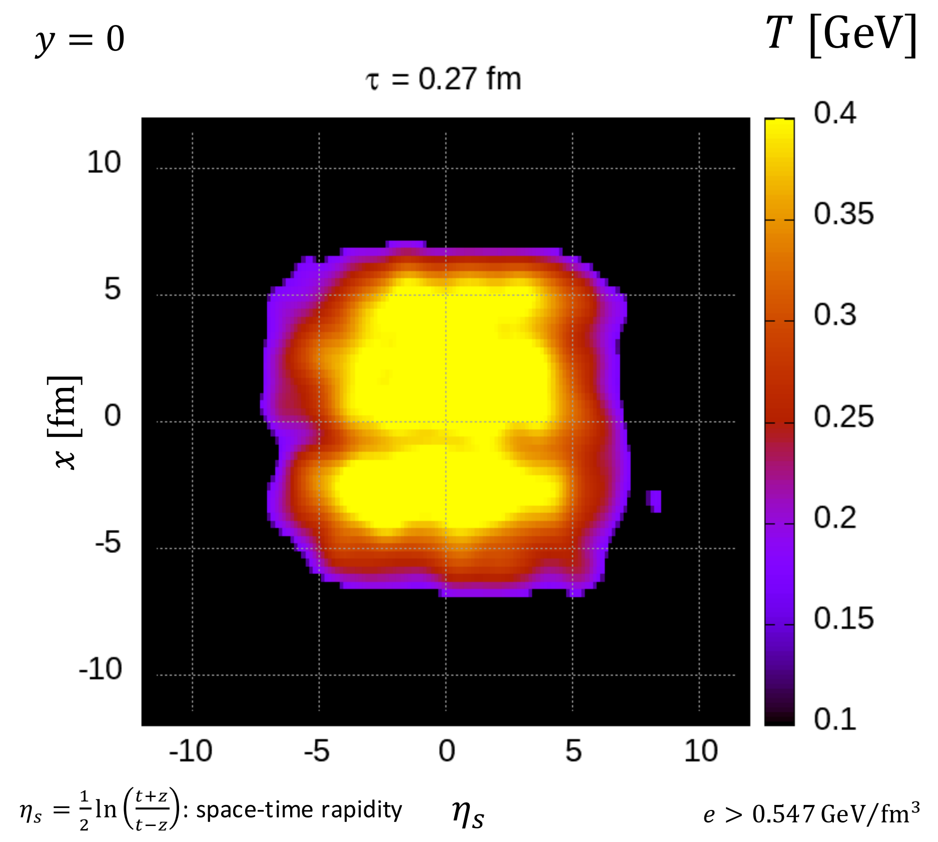

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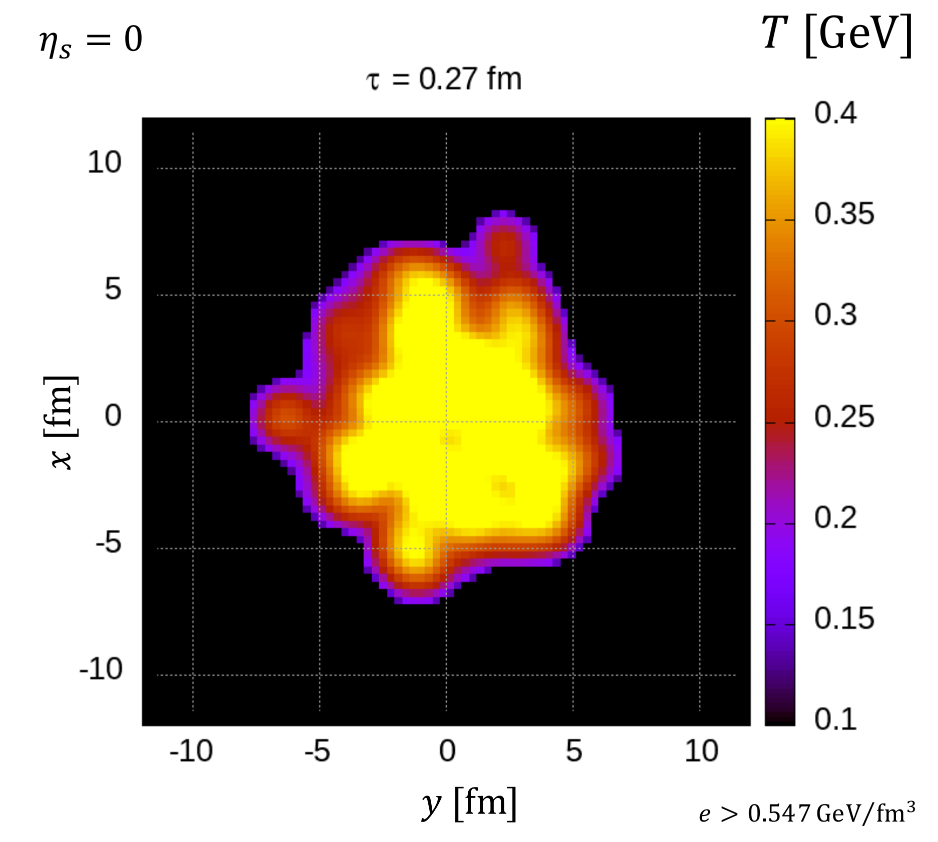

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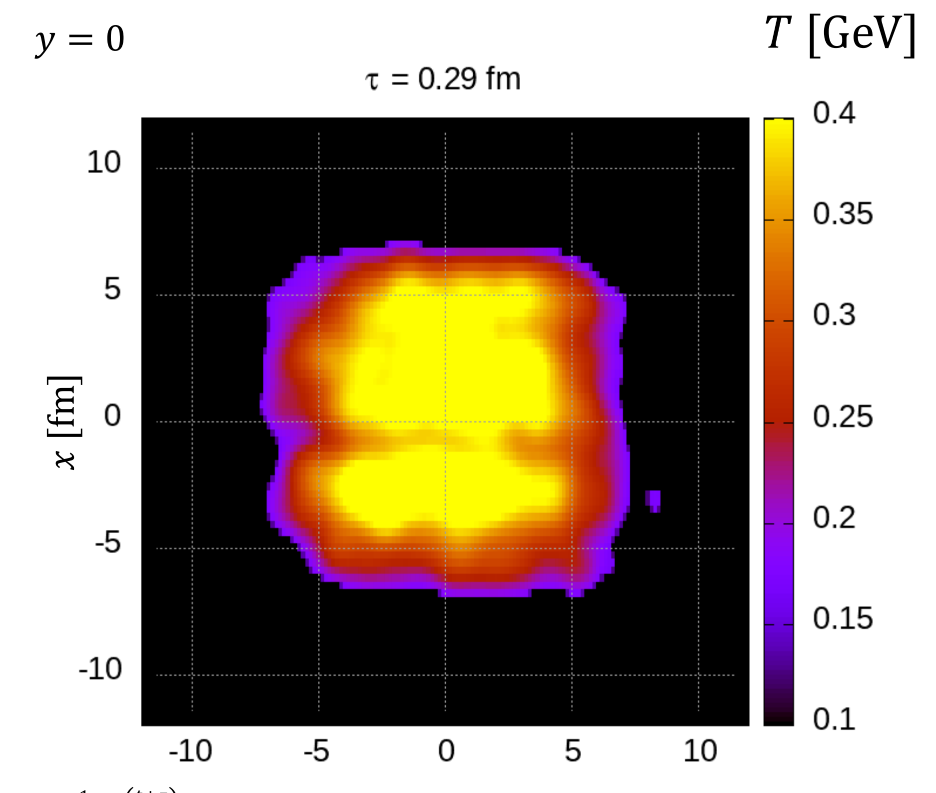

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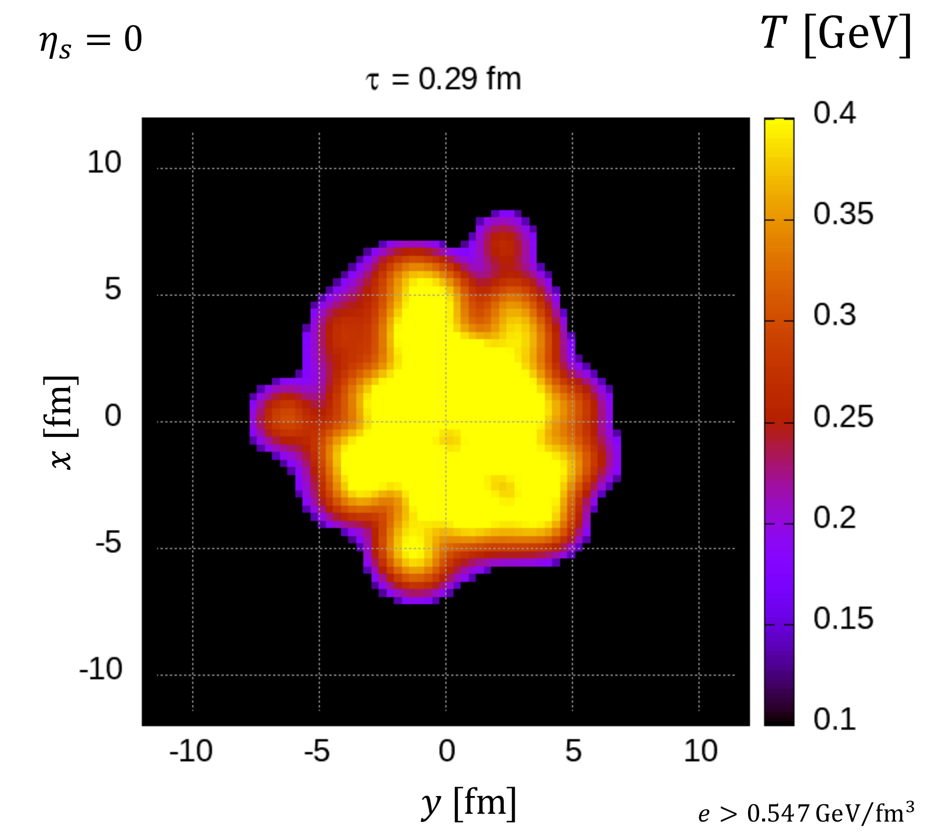

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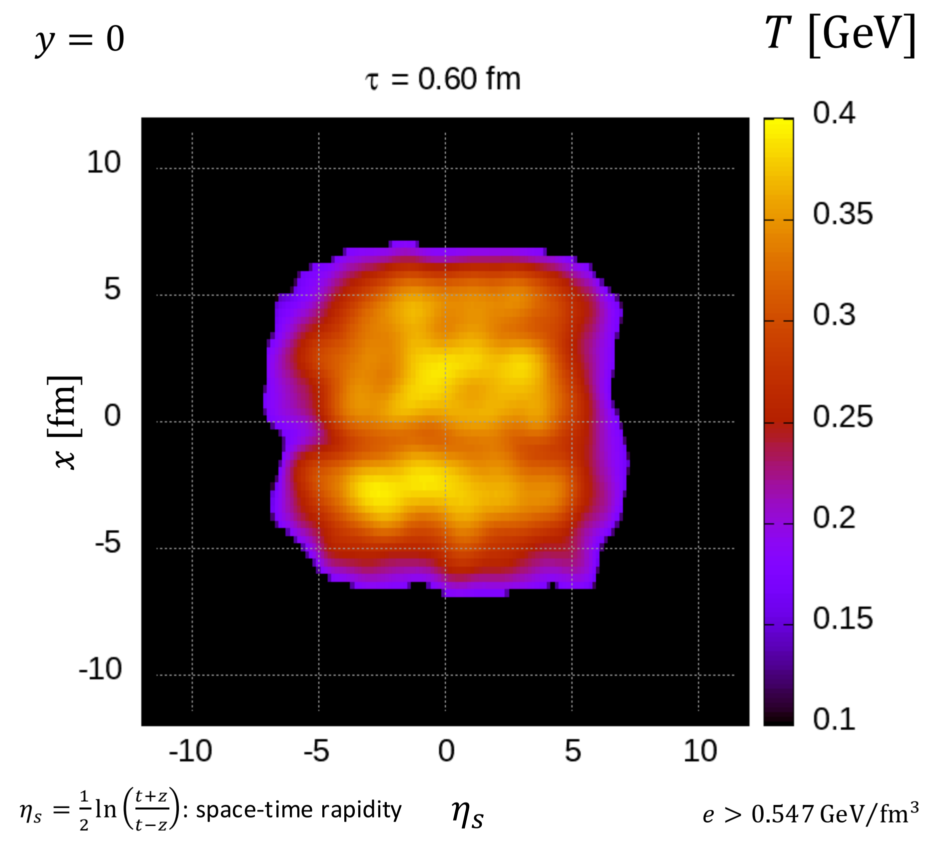

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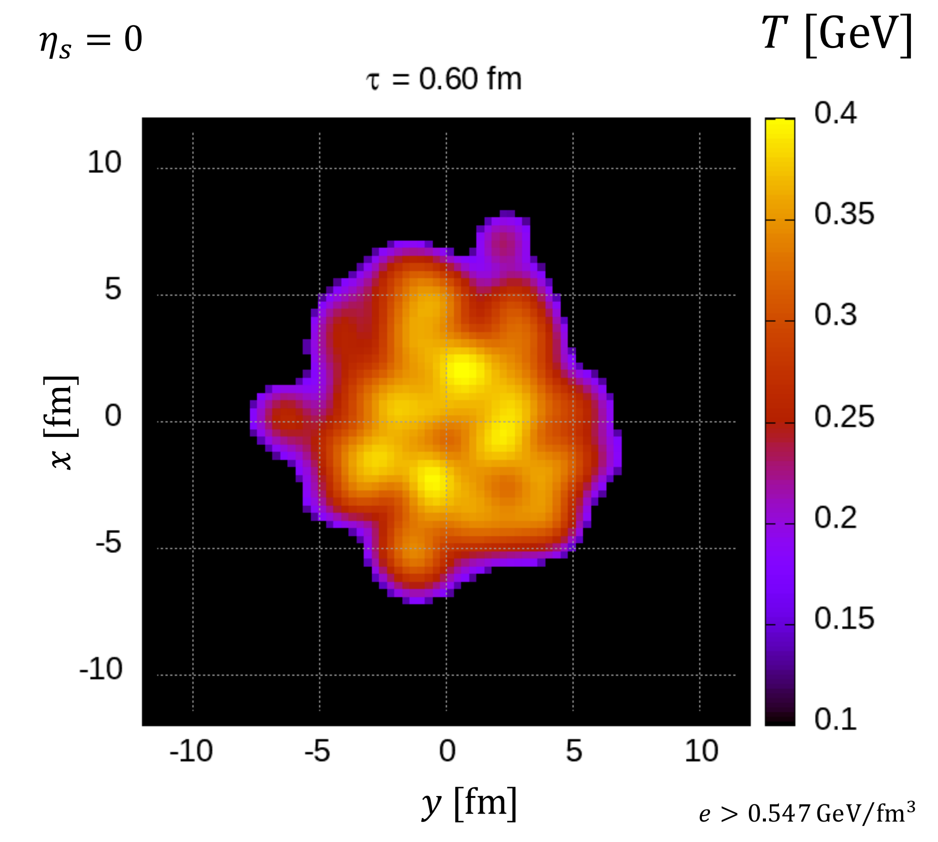

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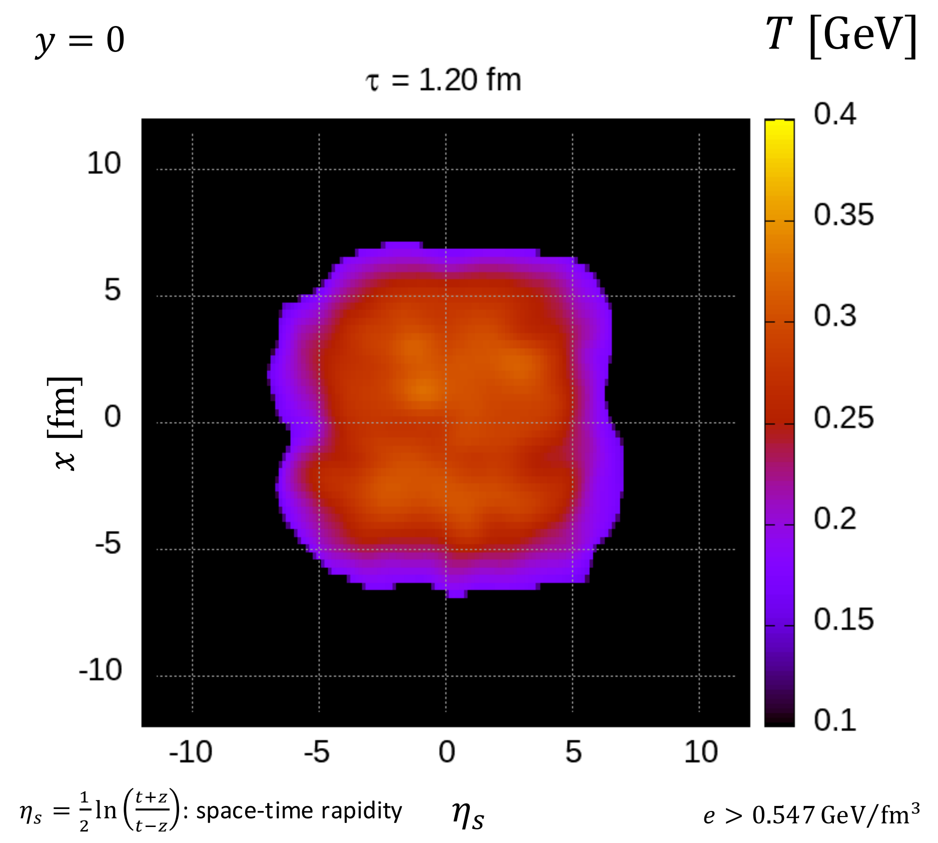

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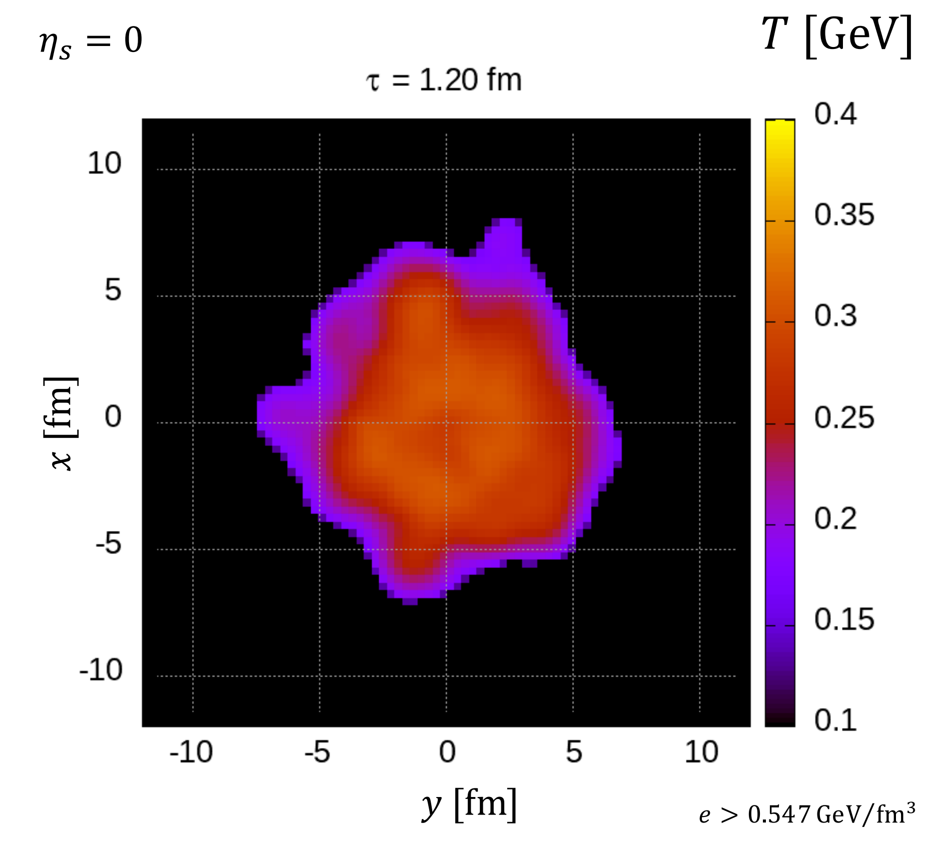

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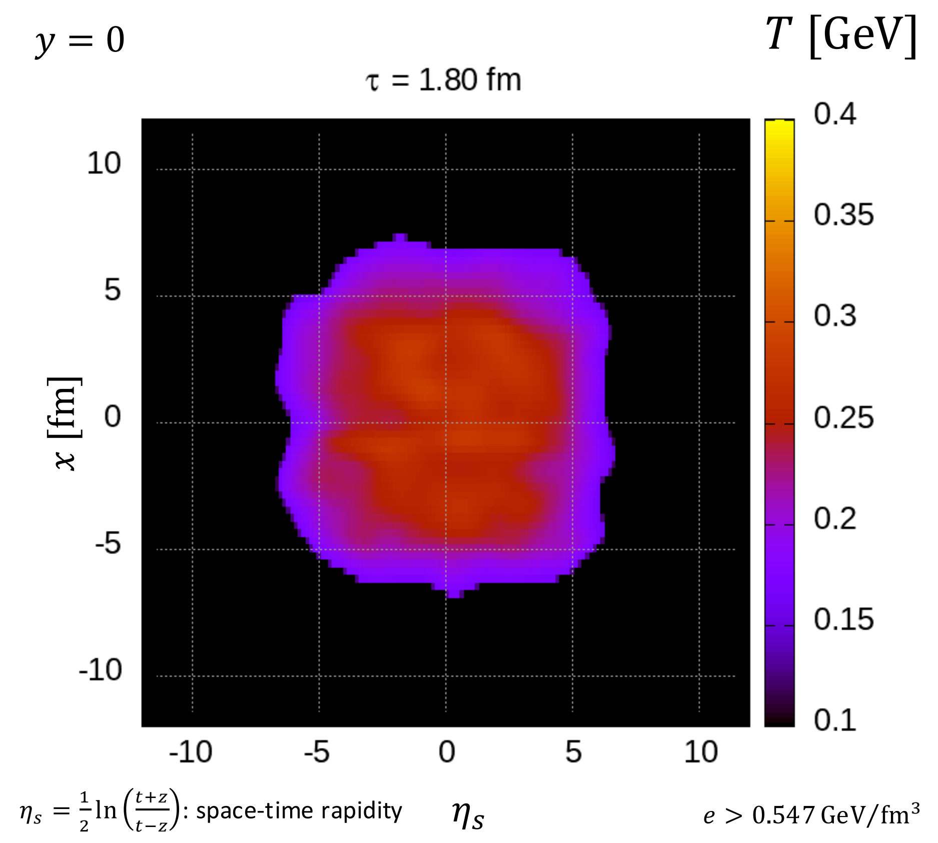

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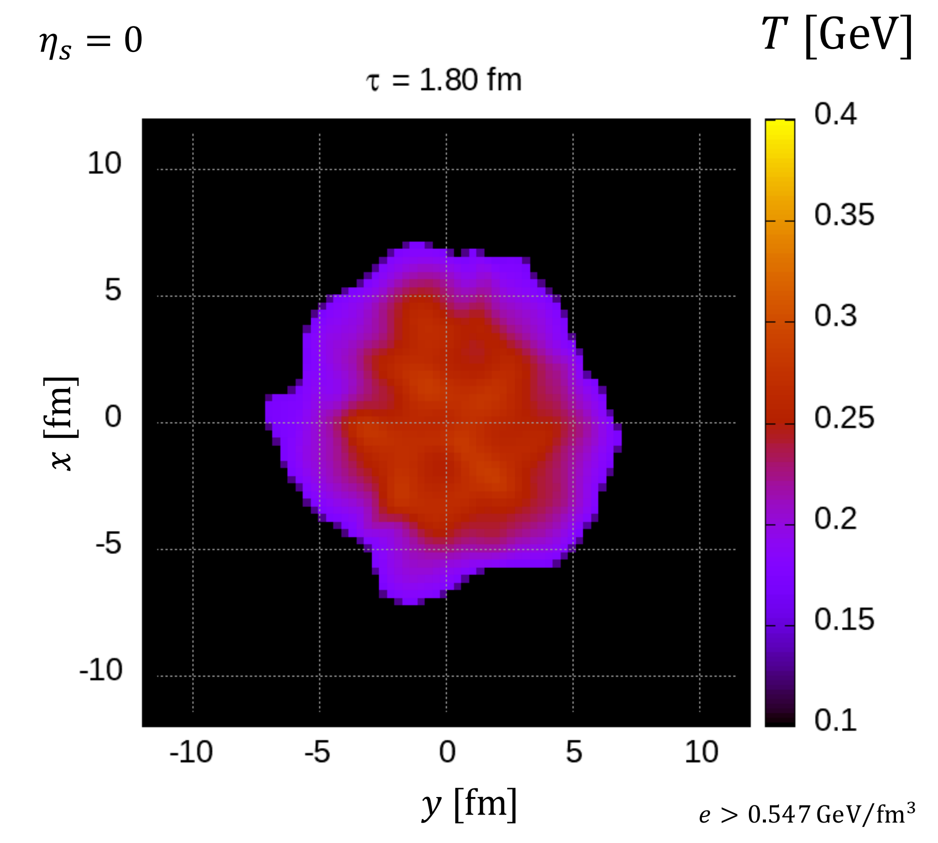

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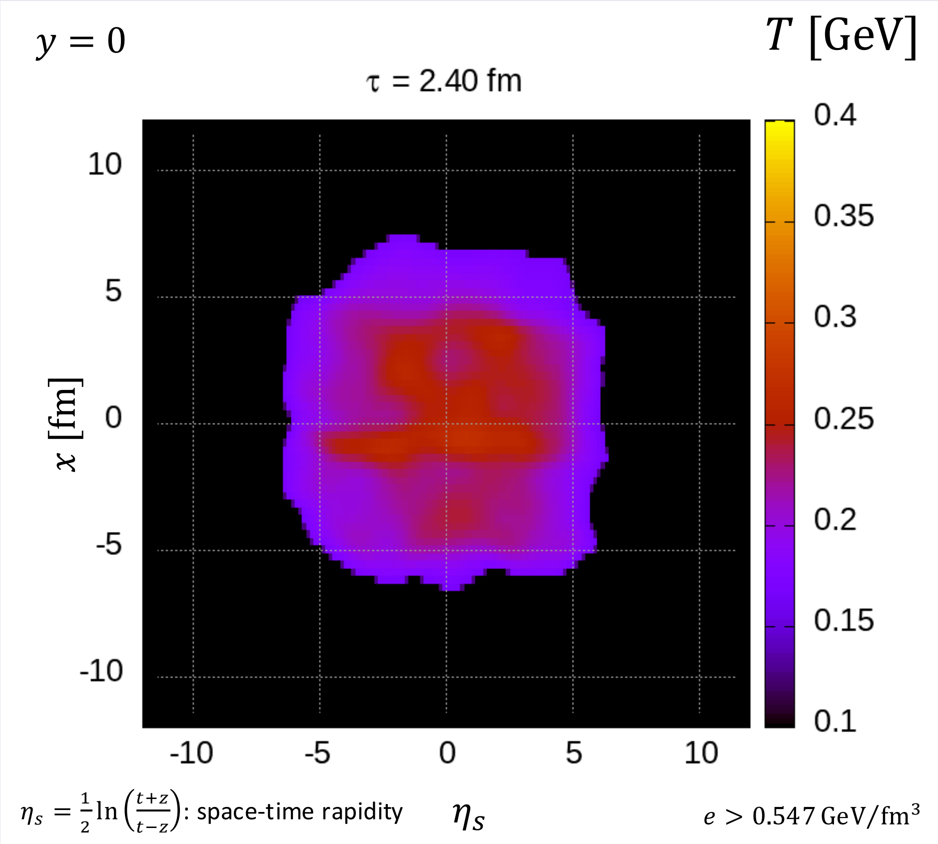

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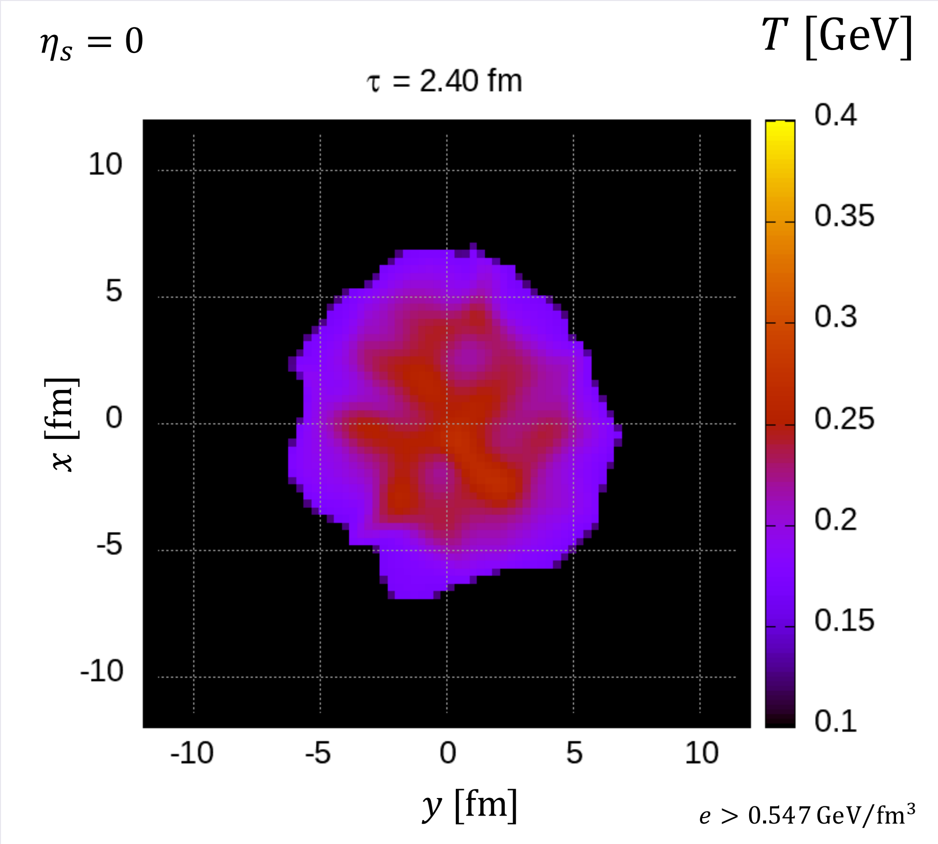

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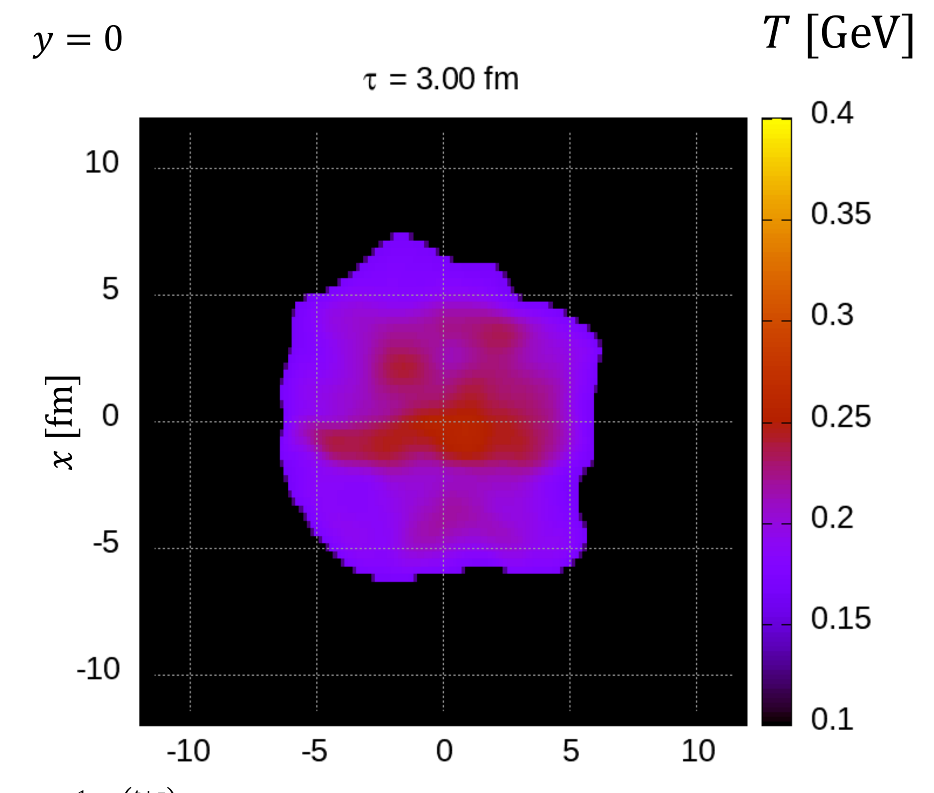

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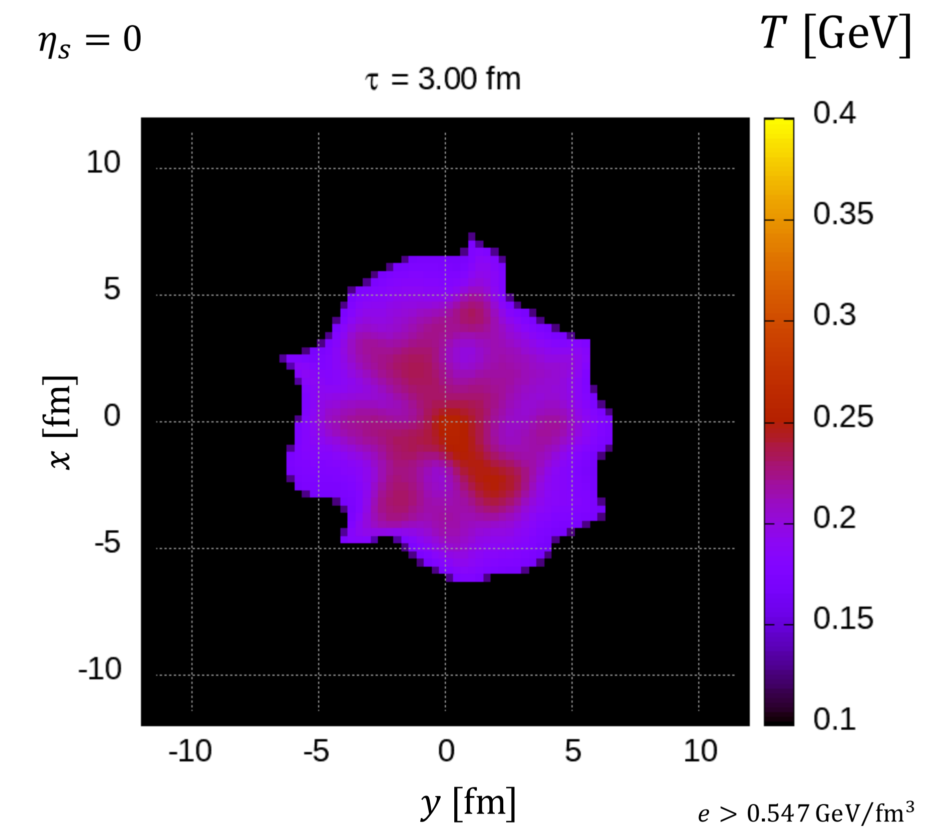

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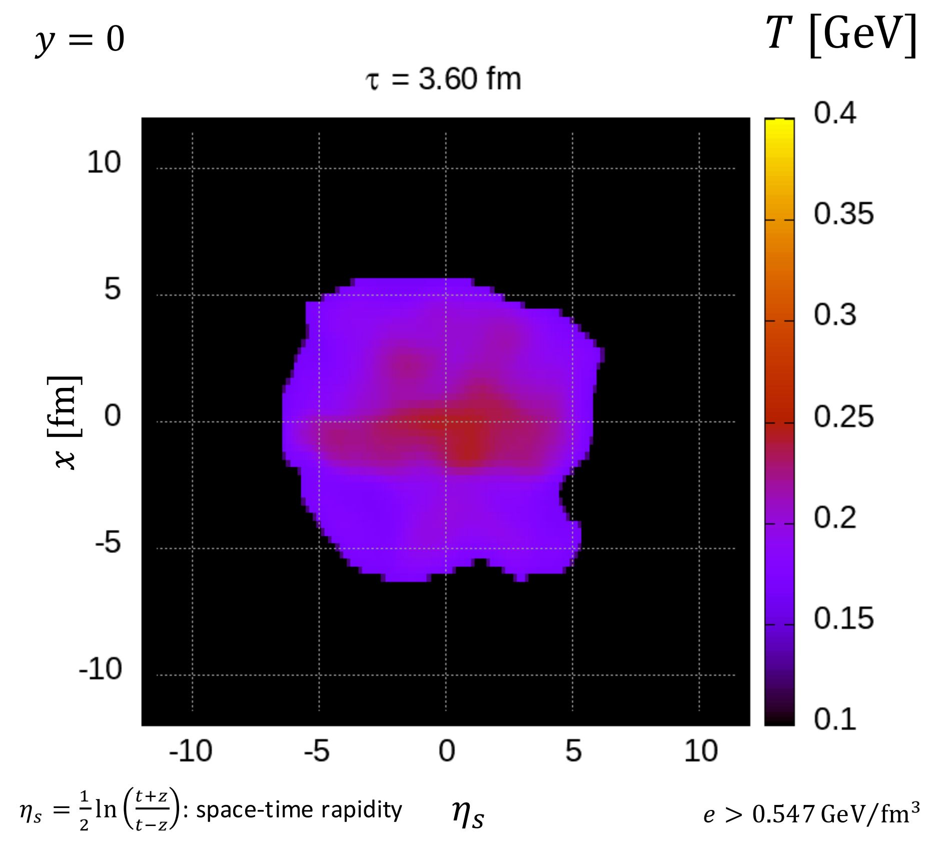

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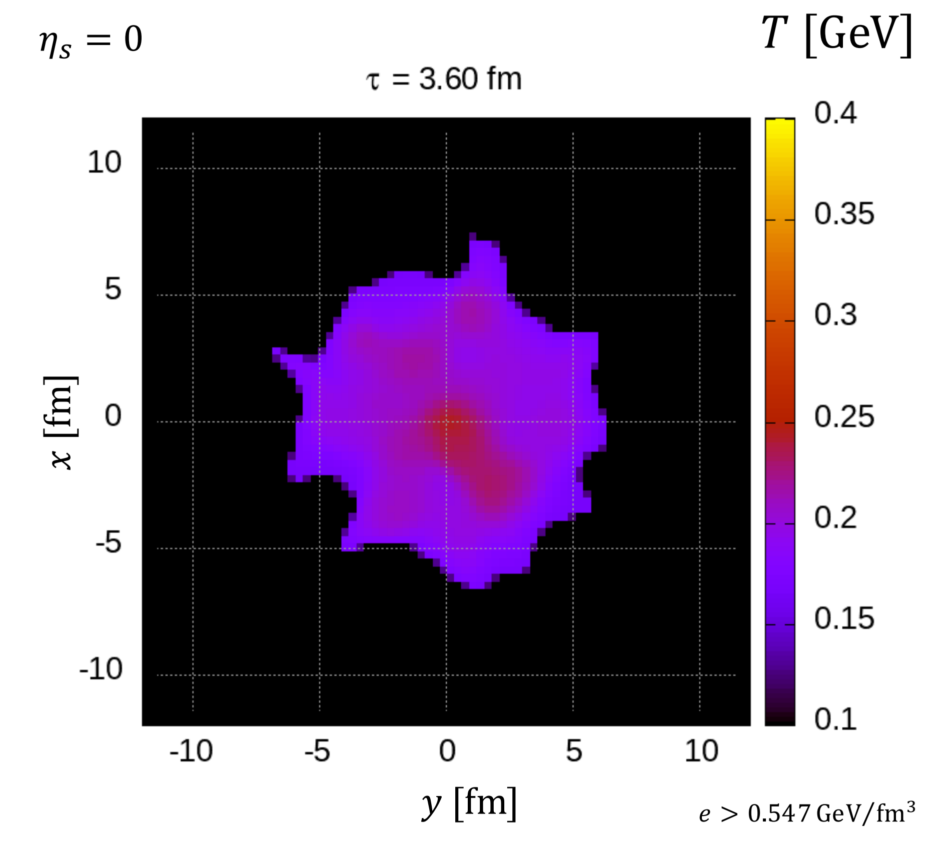

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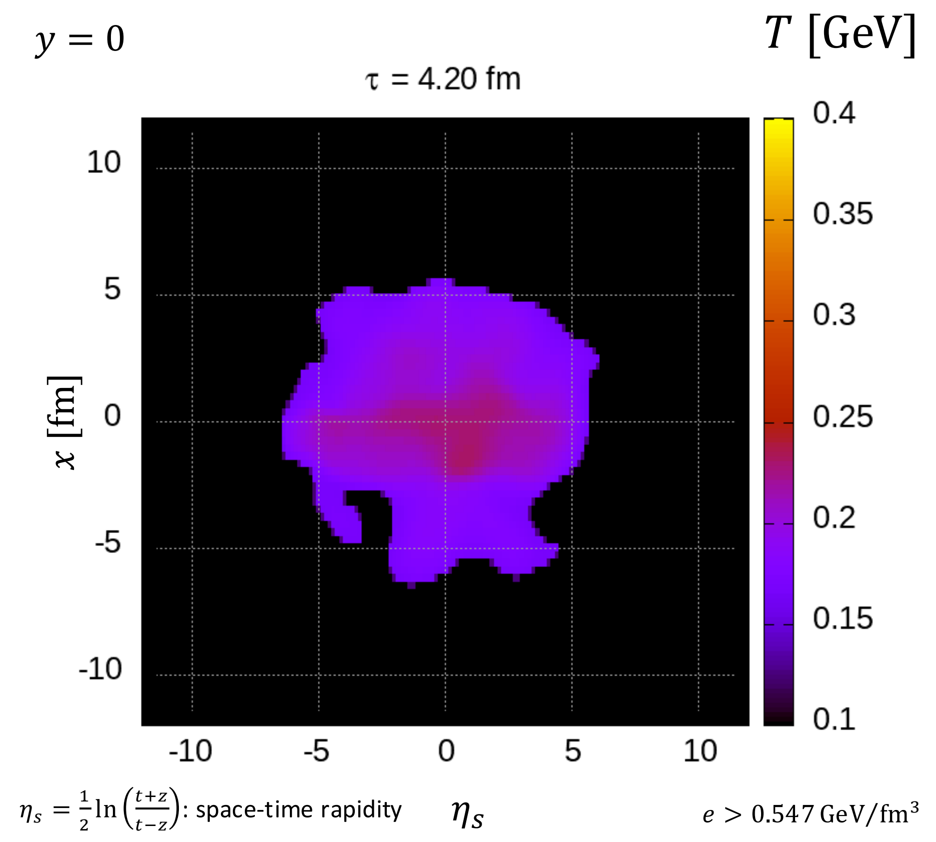

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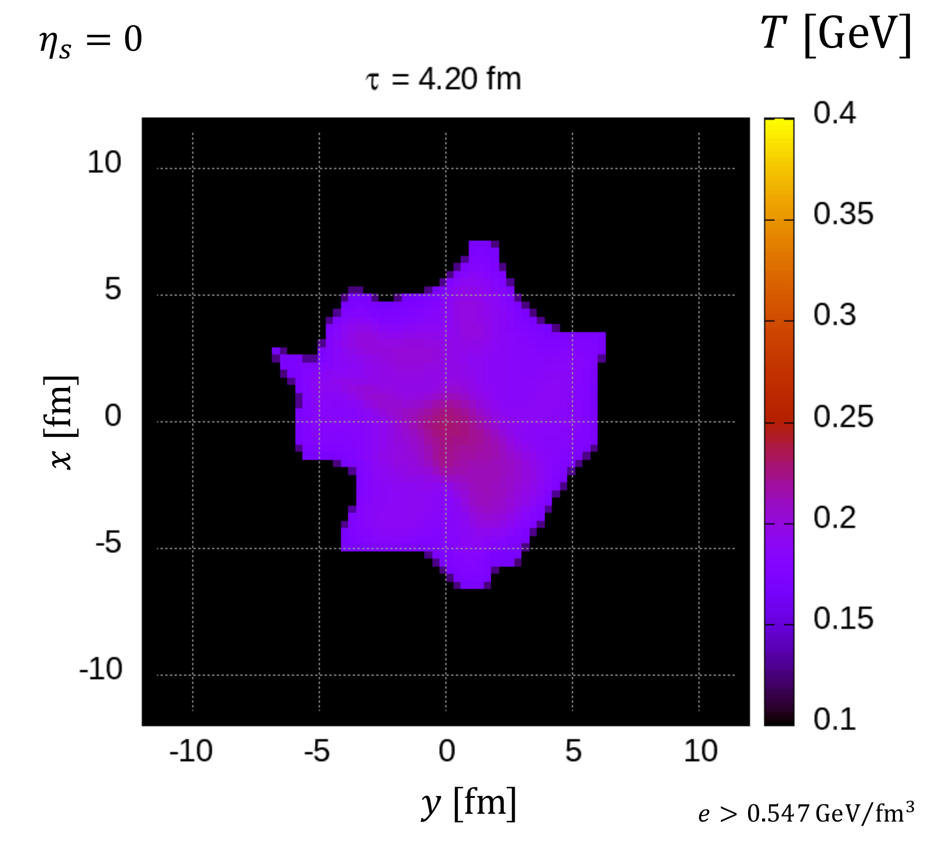

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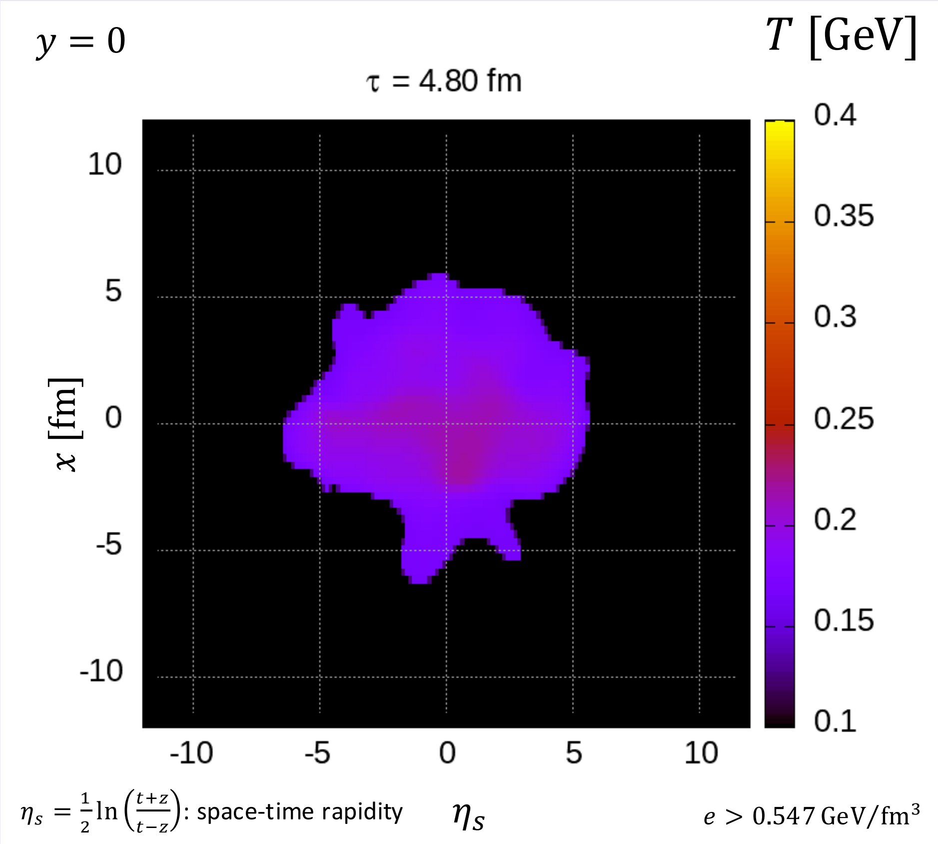

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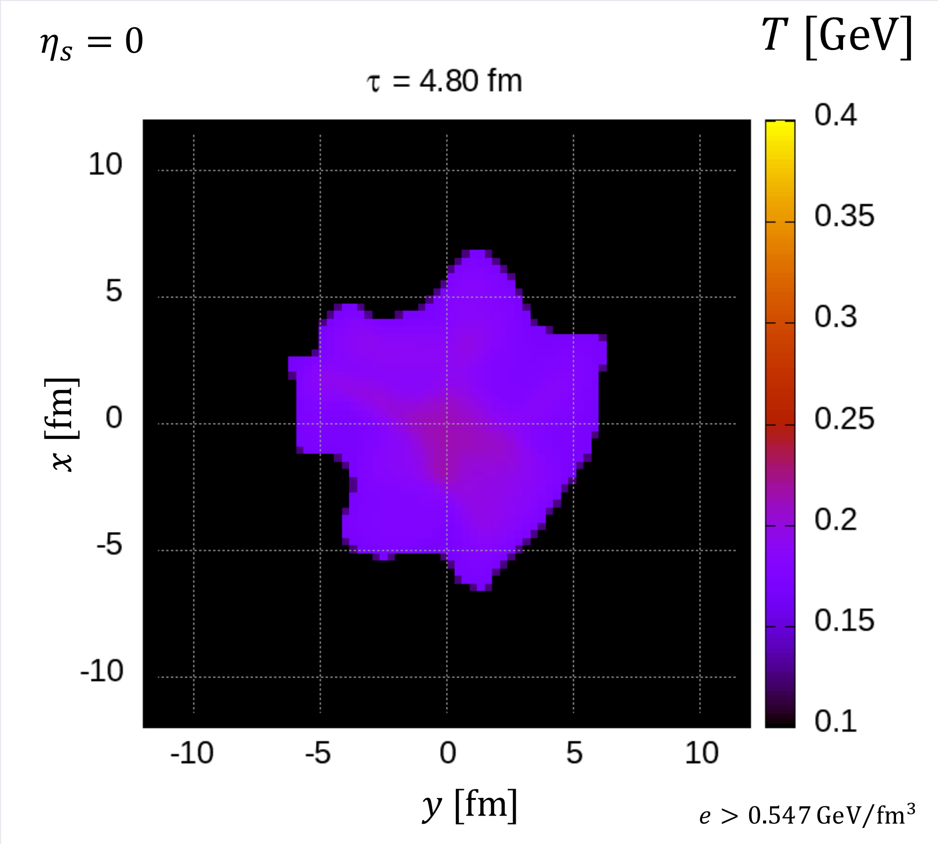

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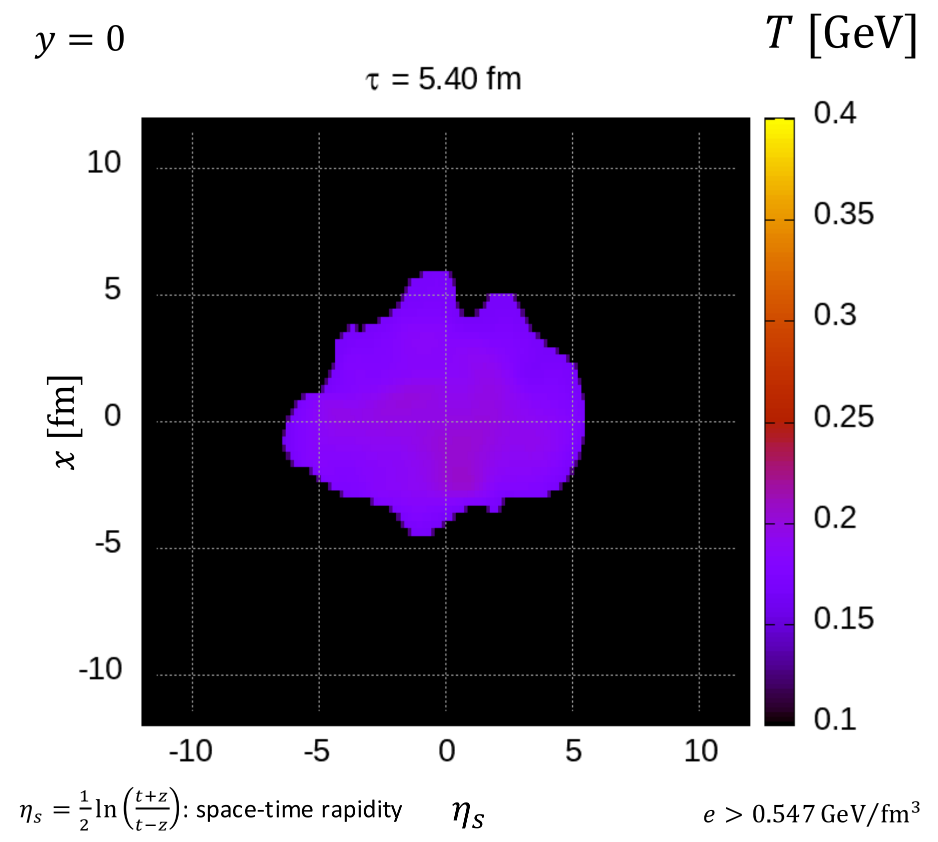

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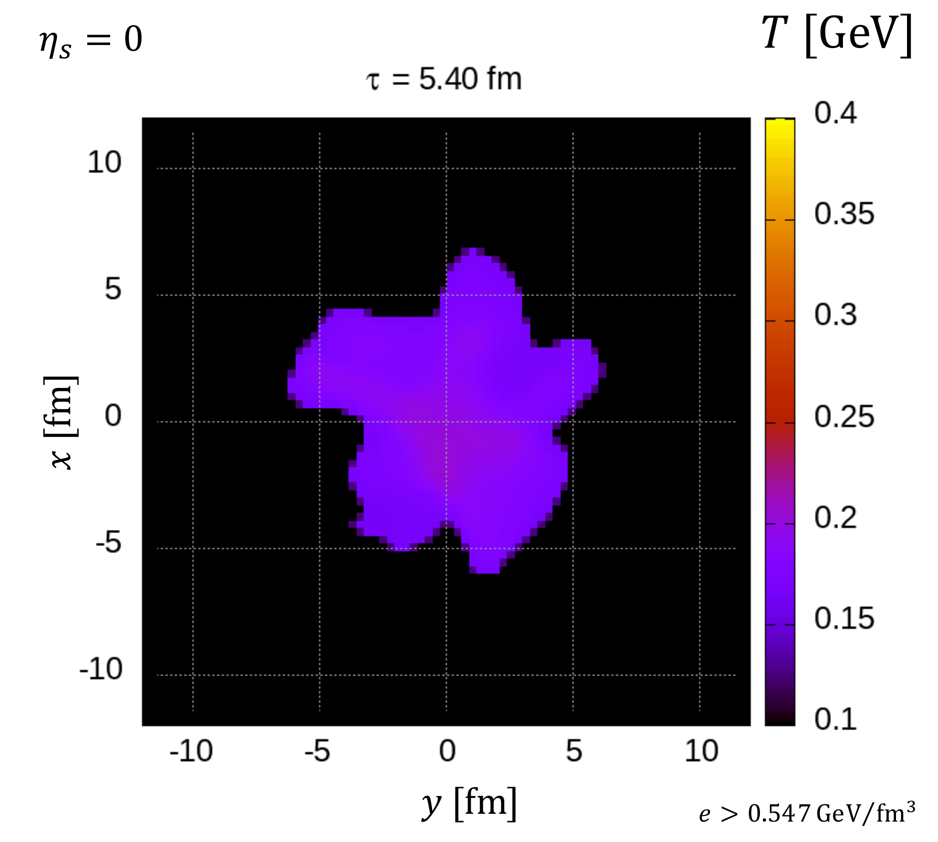

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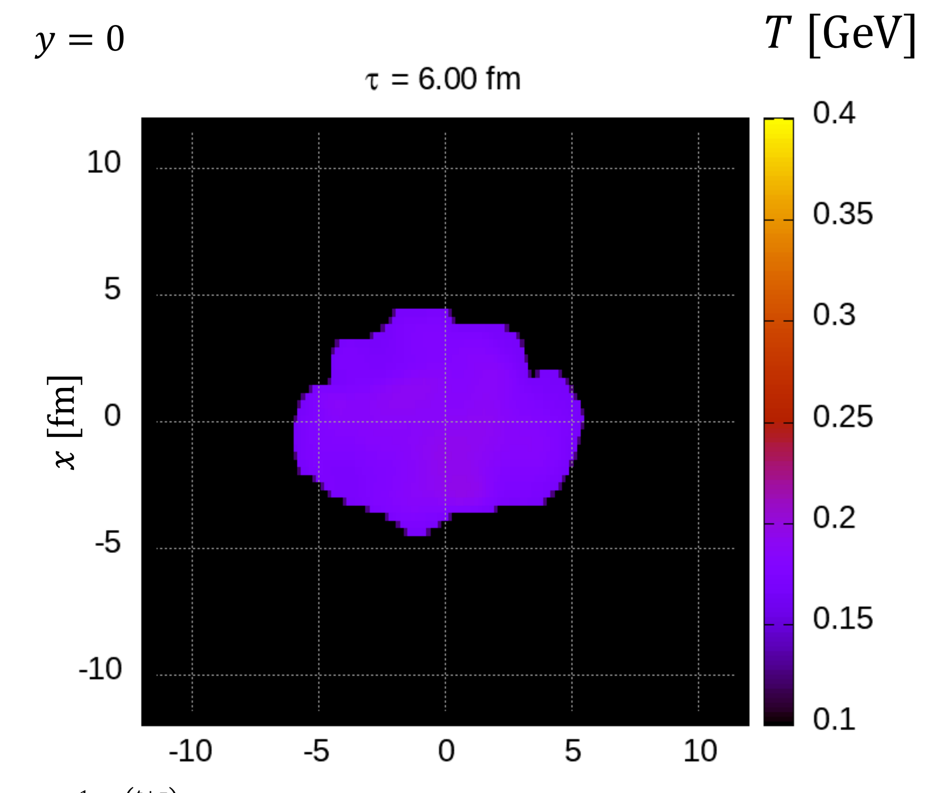

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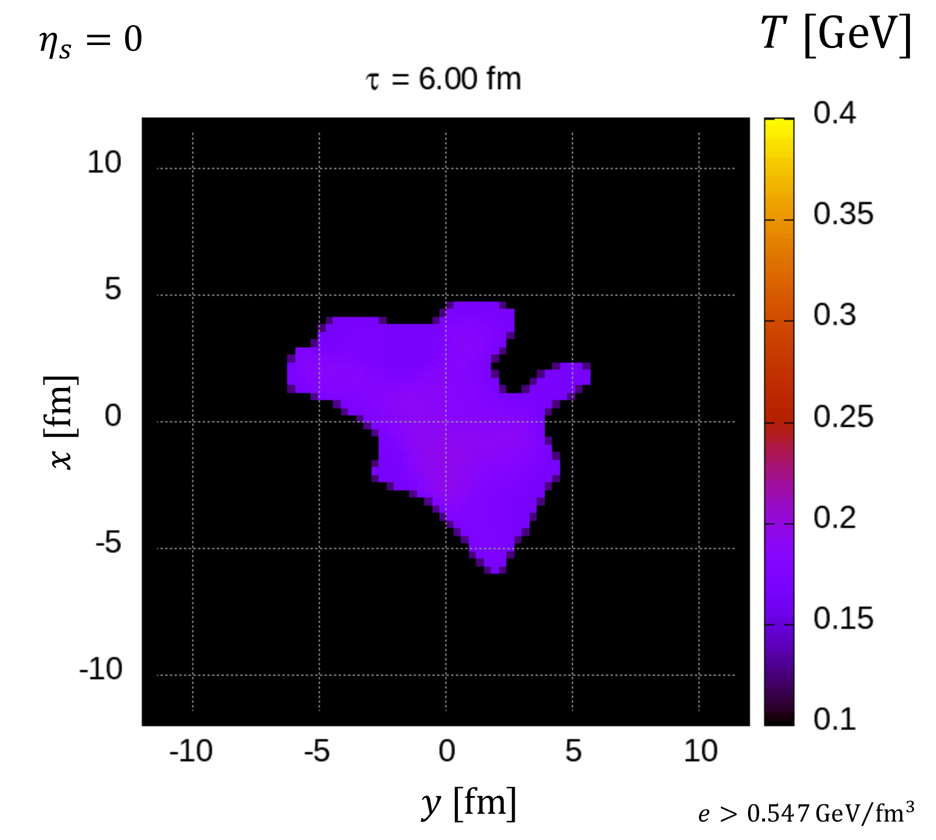

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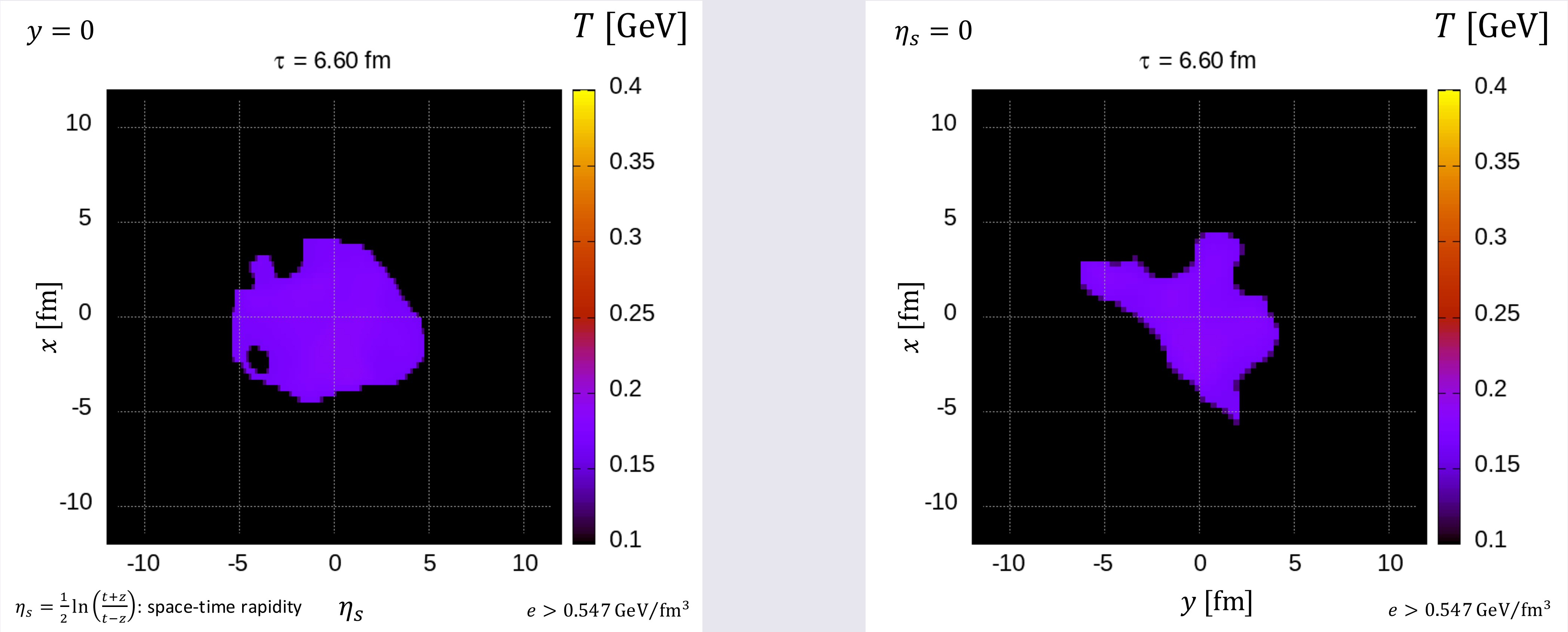
Temperature (longitudinal profile) | Temperature (transverse profile)



- Gradual formation of the core (QGP fluid) through the energy-momentum source term
- Alongside the fluid formation, the core cools down due to the hydrodynamic evolution

Space-time evolution of core

Pb+Pb 2.76 TeV, b = 2.46 fm
Single event

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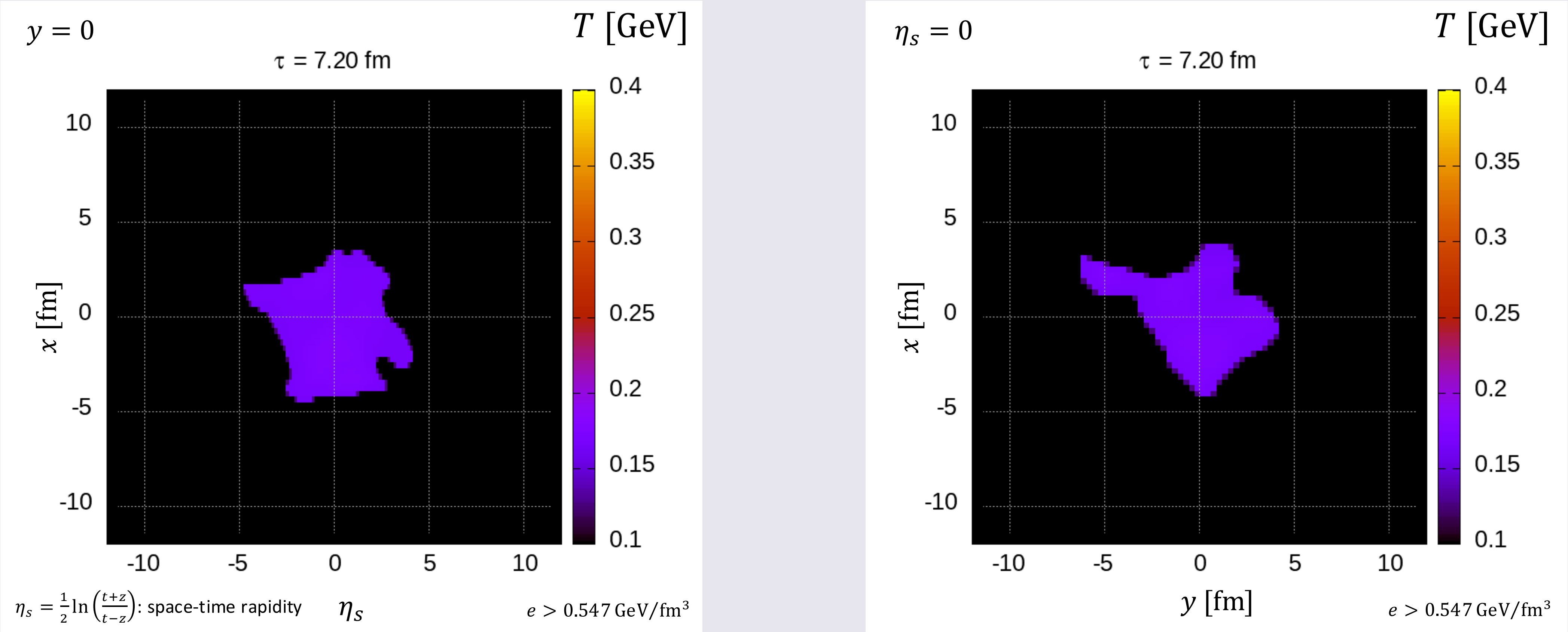

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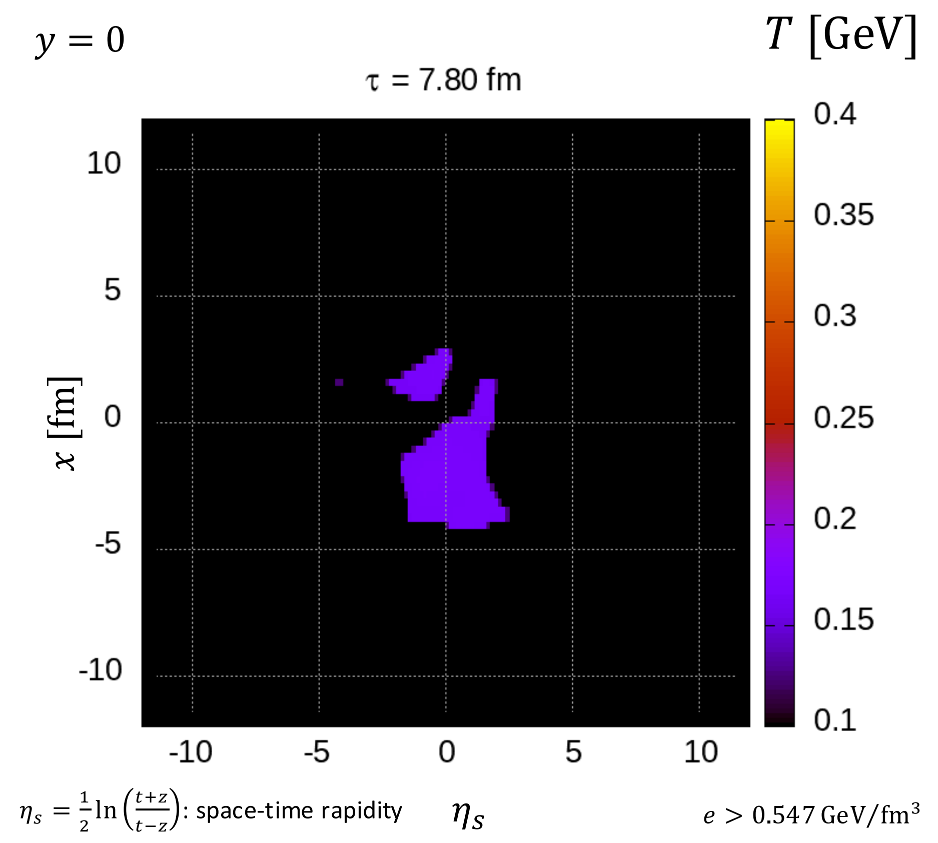
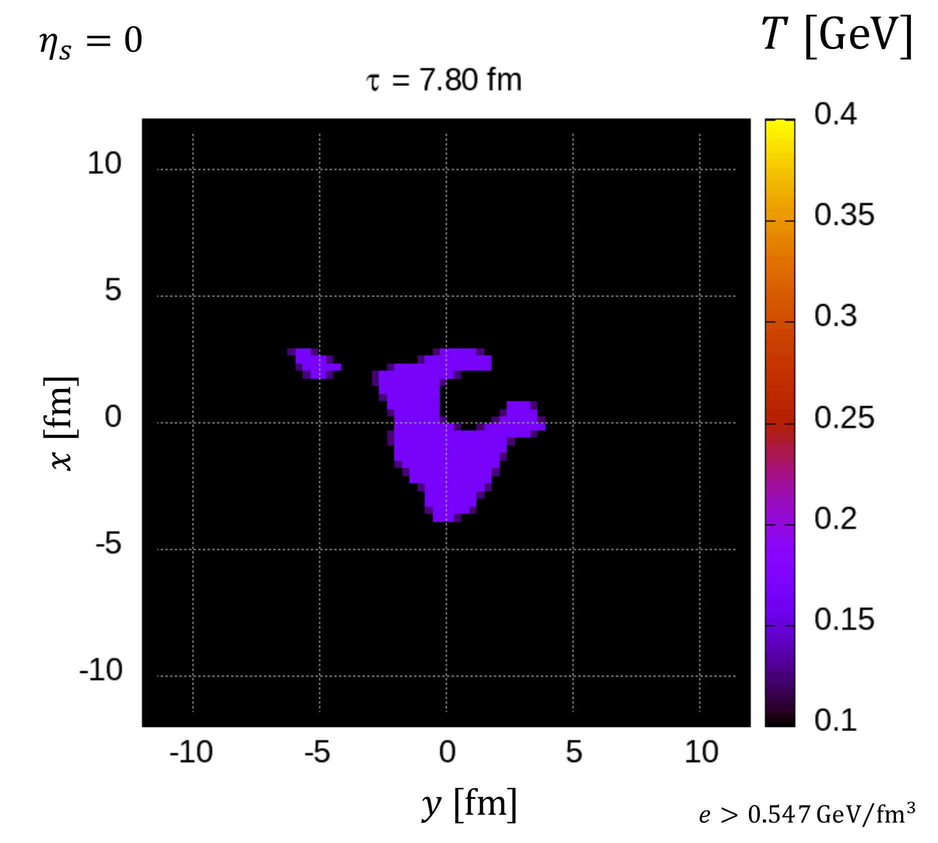


Temperature (transverse profile)



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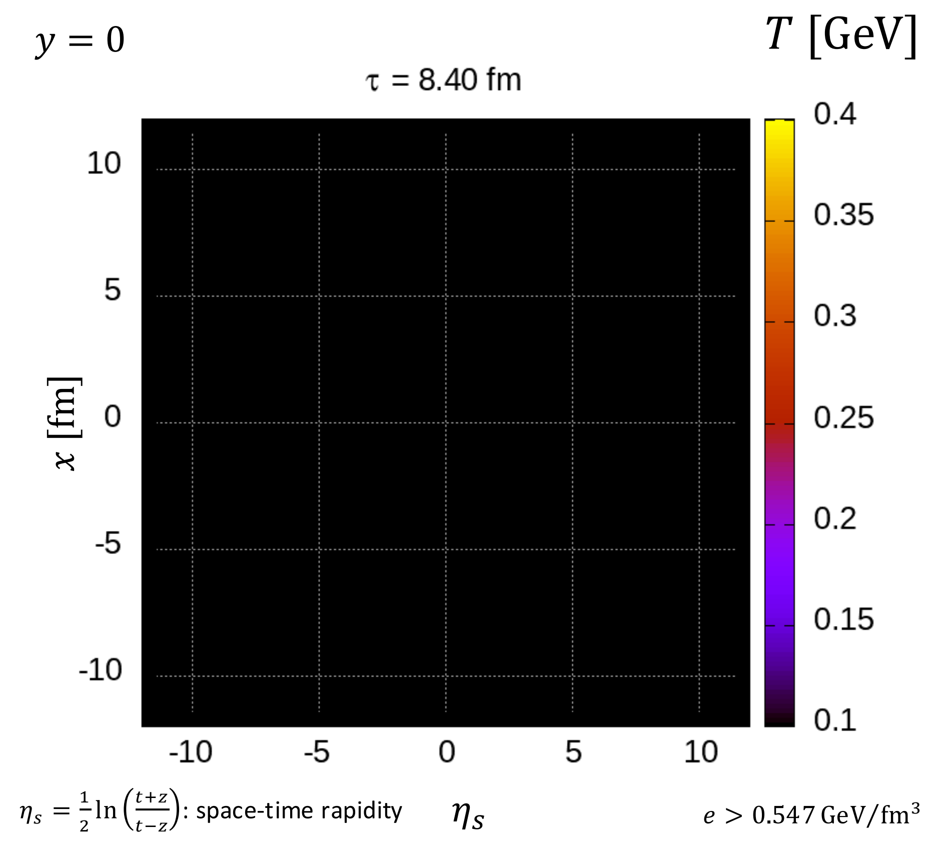
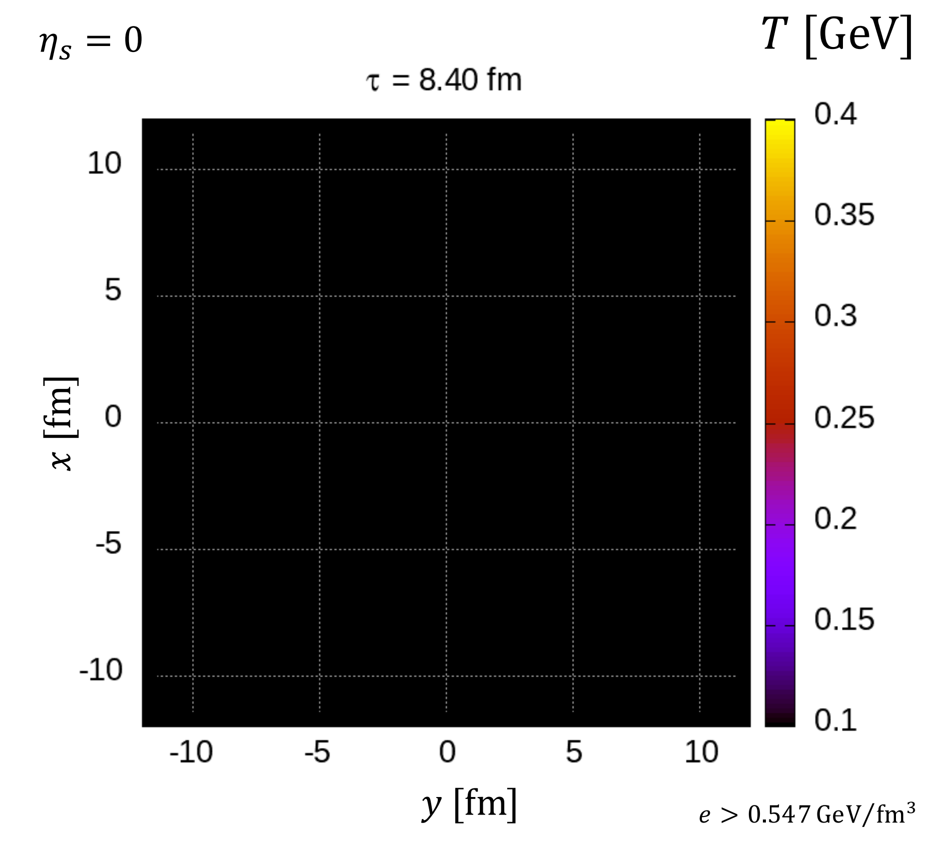


Temperature (transverse profile)



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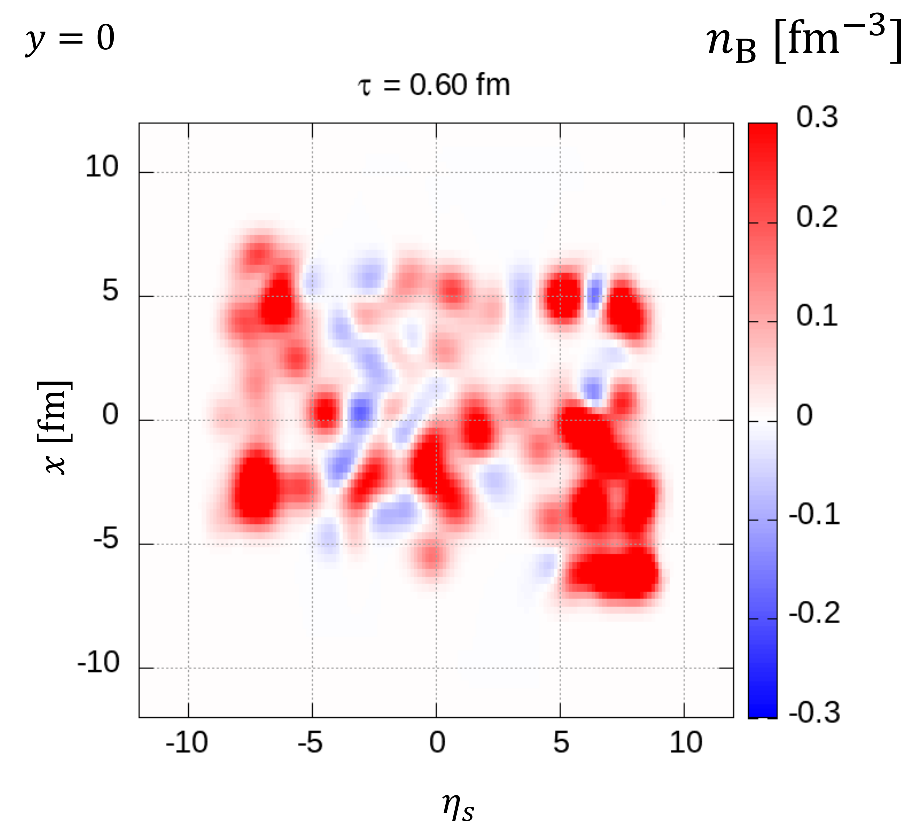
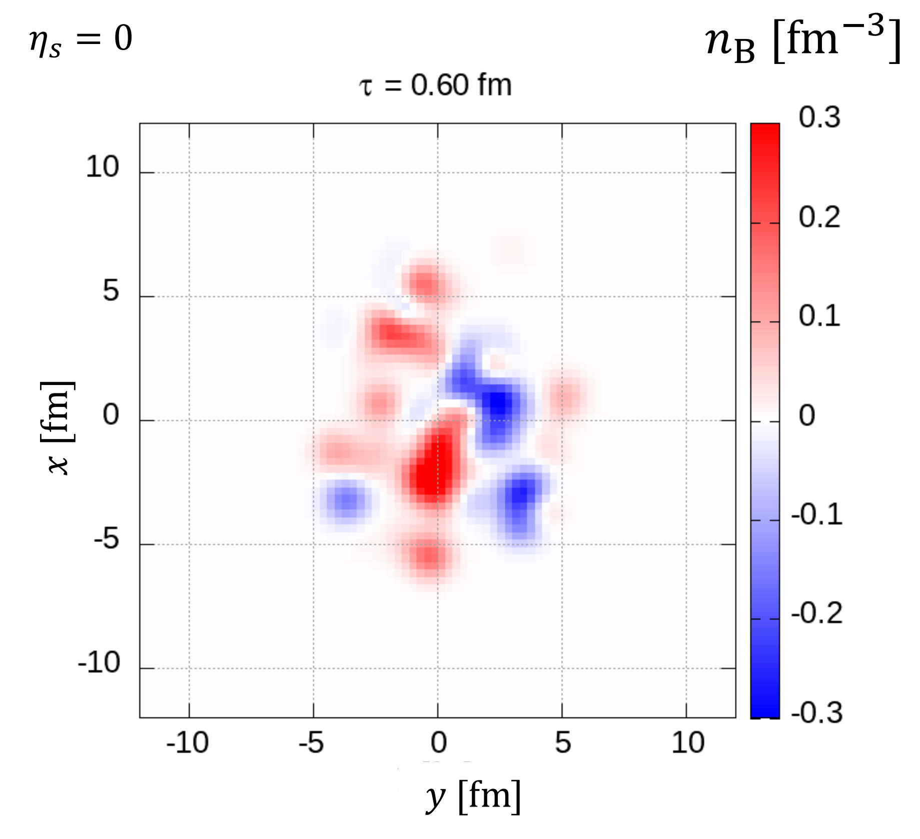
Baryon number density (longitudinal profile)



Baryon number density (transverse profile)



- Large baryon number density is realized in forward rapidities $5 \lesssim |\eta_s| \lesssim 10$

  cf.) $y_{\mathrm{beam}}(\sqrt{s_{\mathrm{NN}}} = 2.76\ \mathrm{TeV}) \approx 8$

- Large fluctuations of baryon number density even in midrapidity

  ➡ Negative n_B region appears

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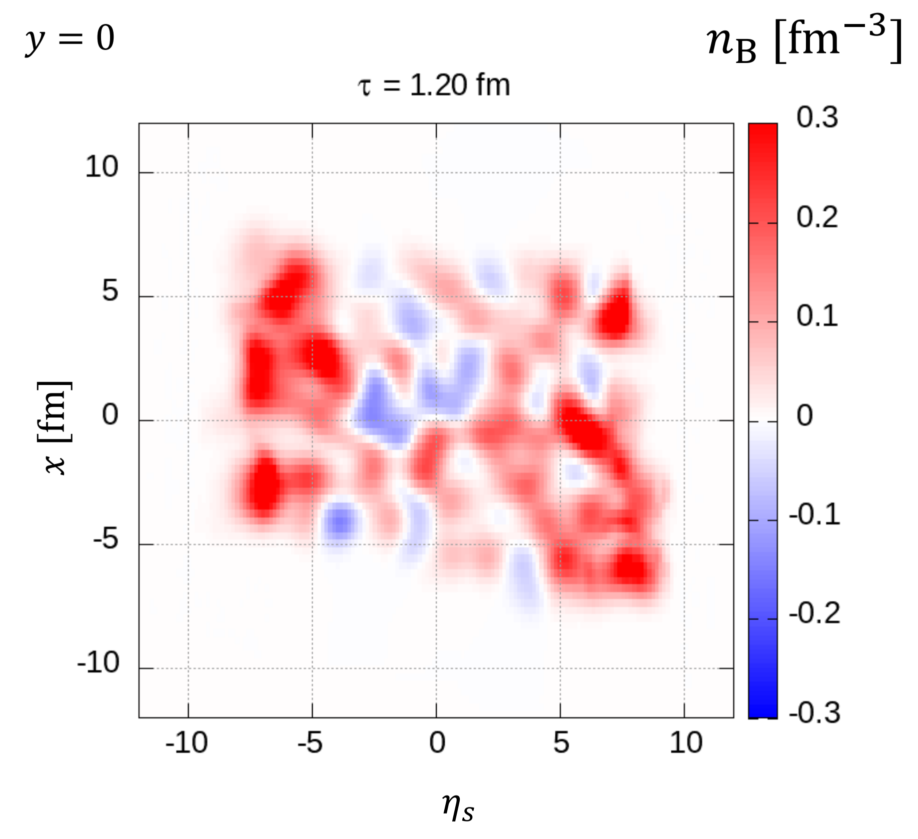
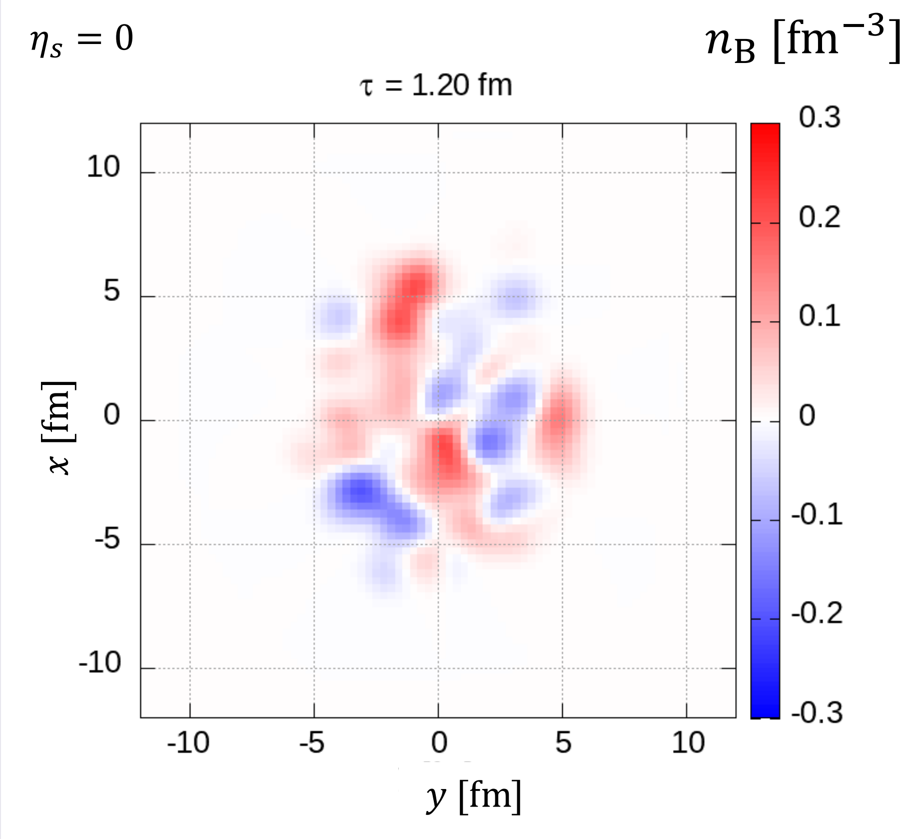


Baryon number density (transverse profile)



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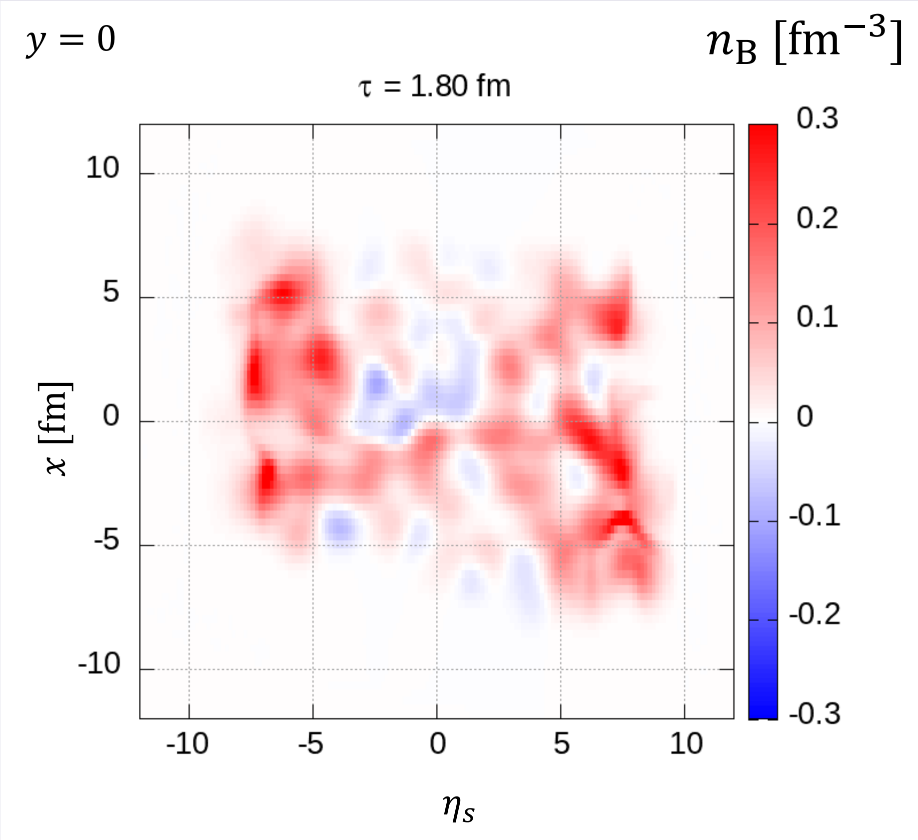
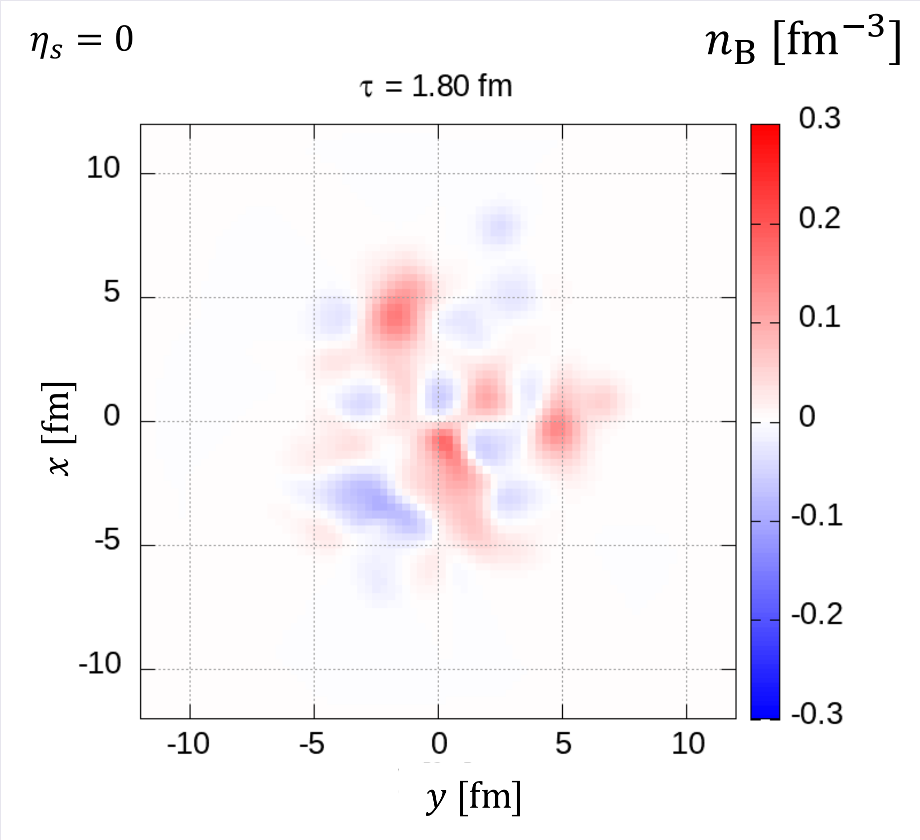


Baryon number density (transverse profile)



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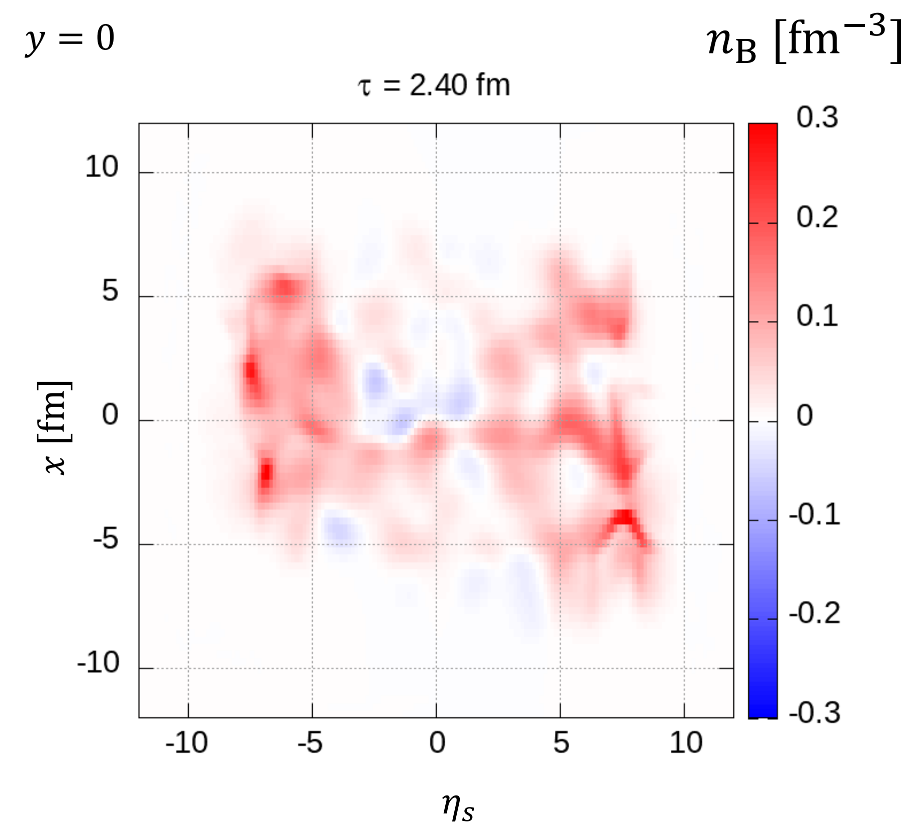

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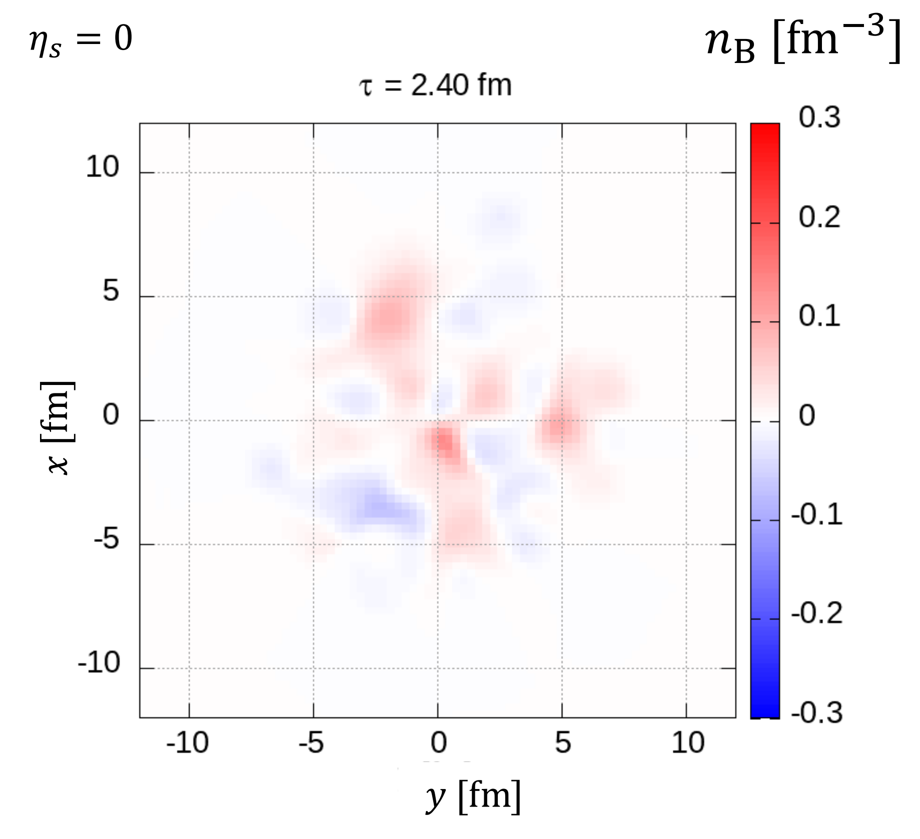

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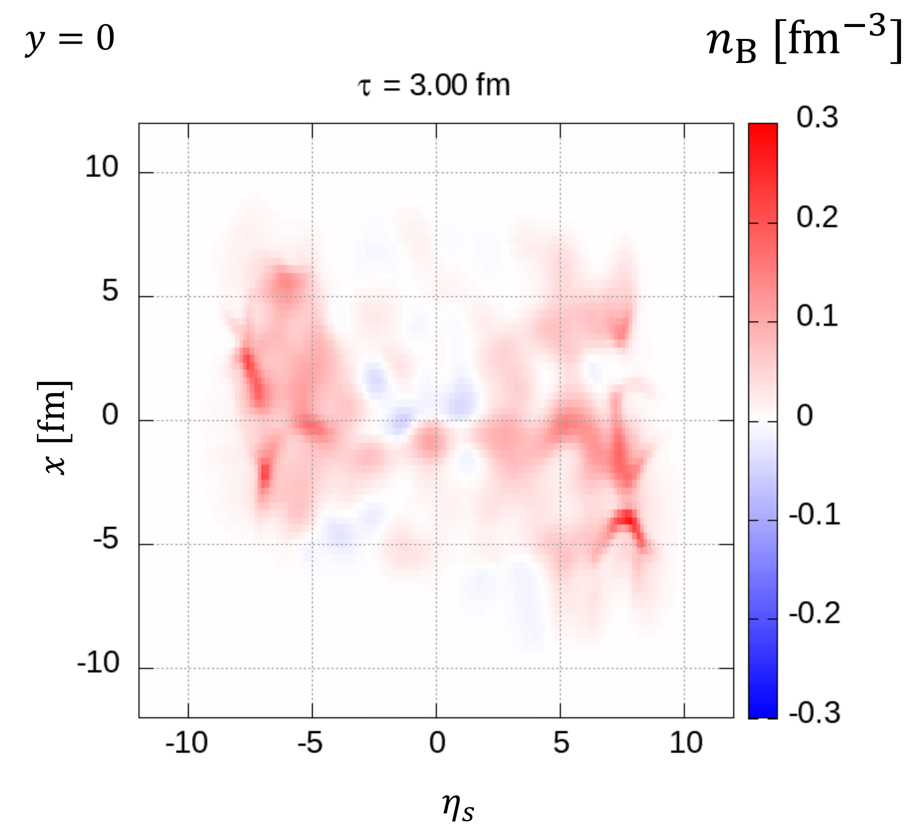

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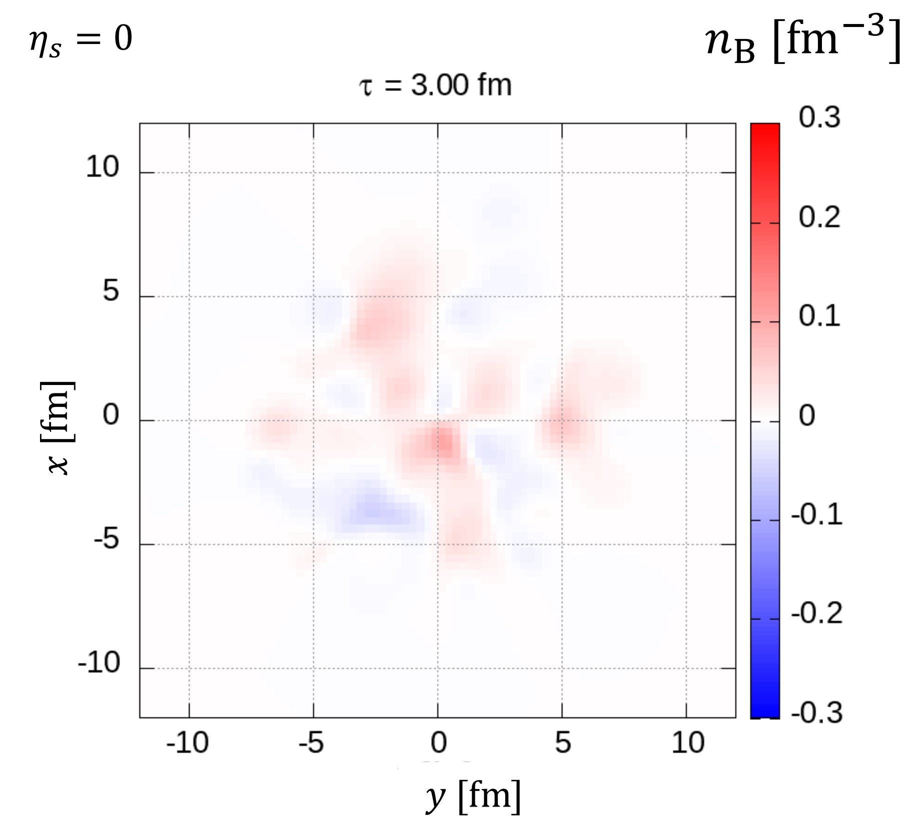

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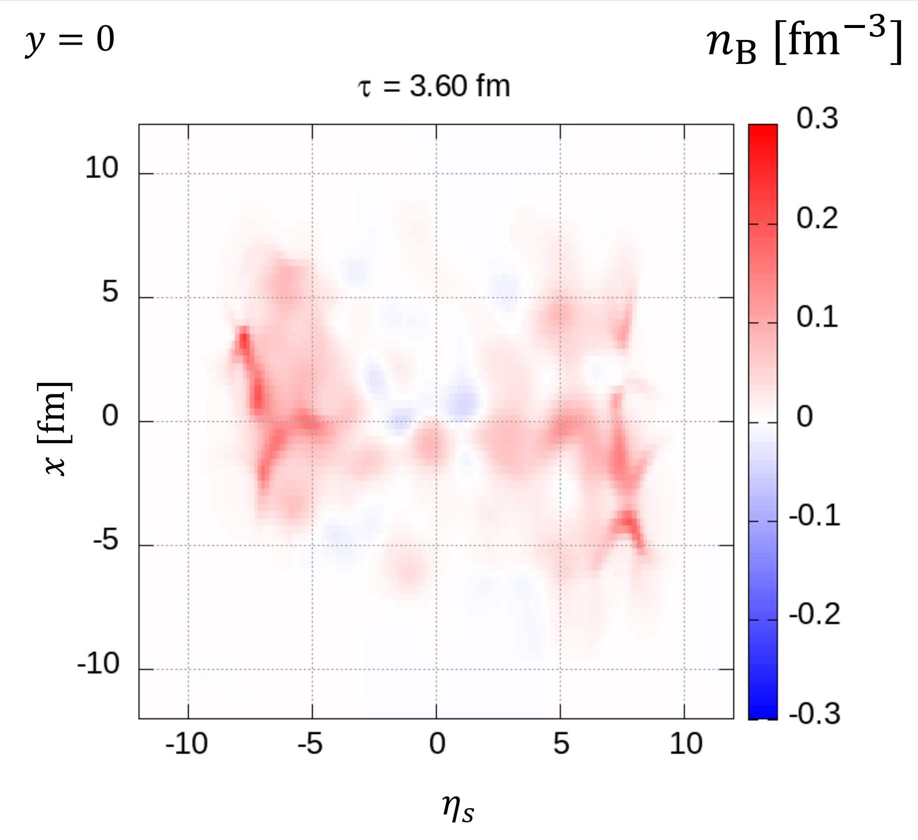

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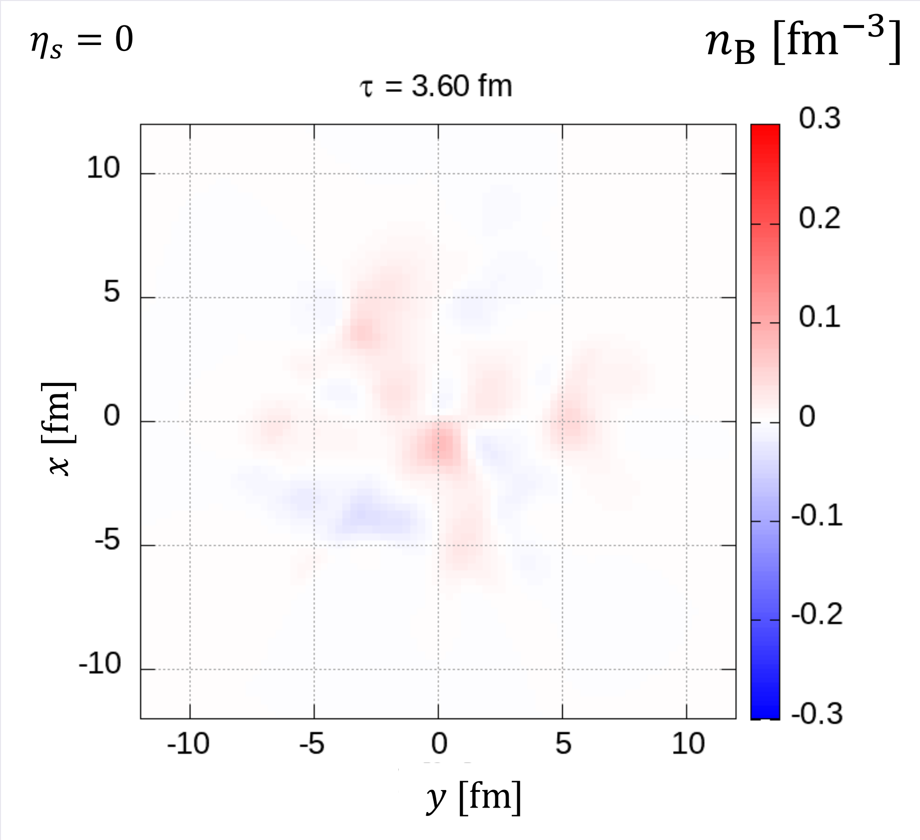

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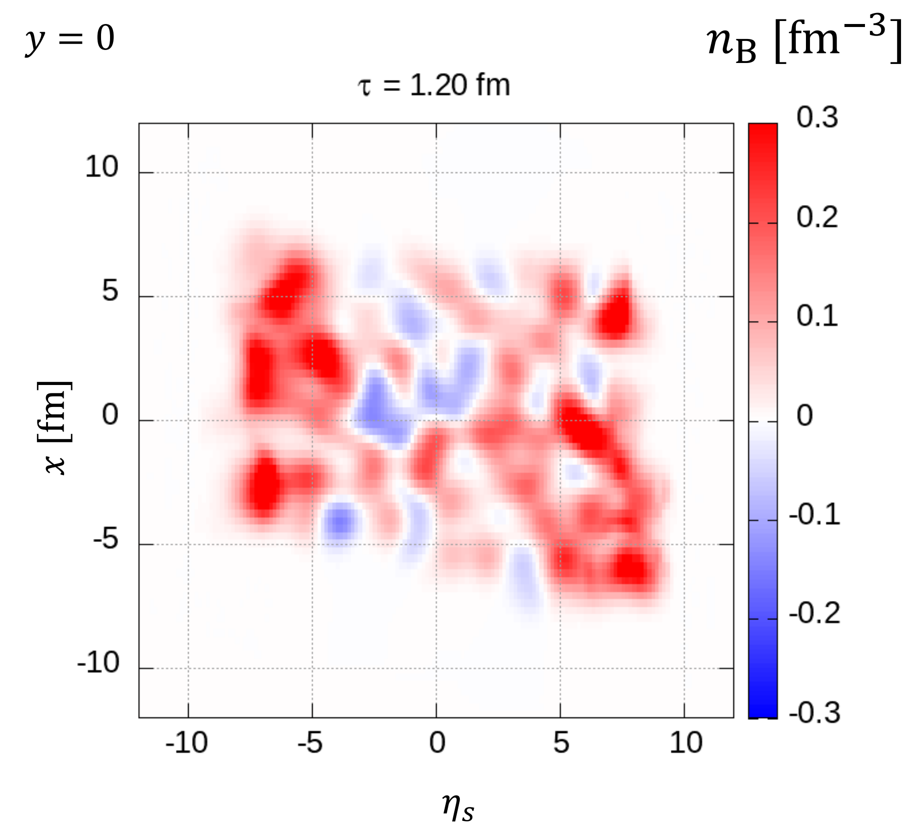

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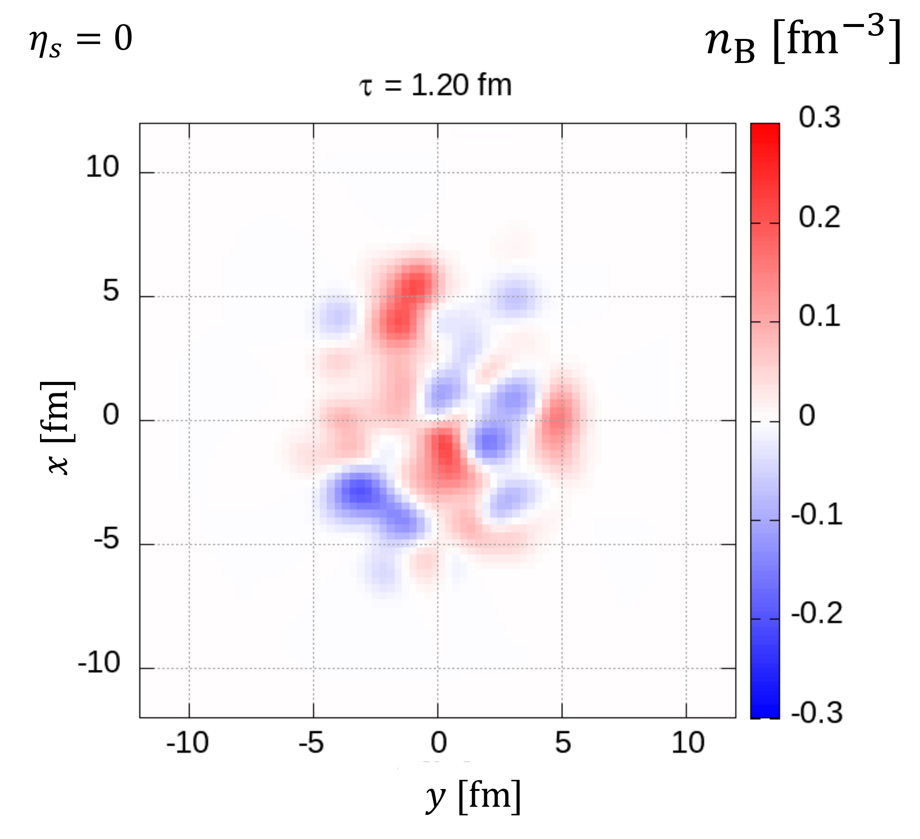

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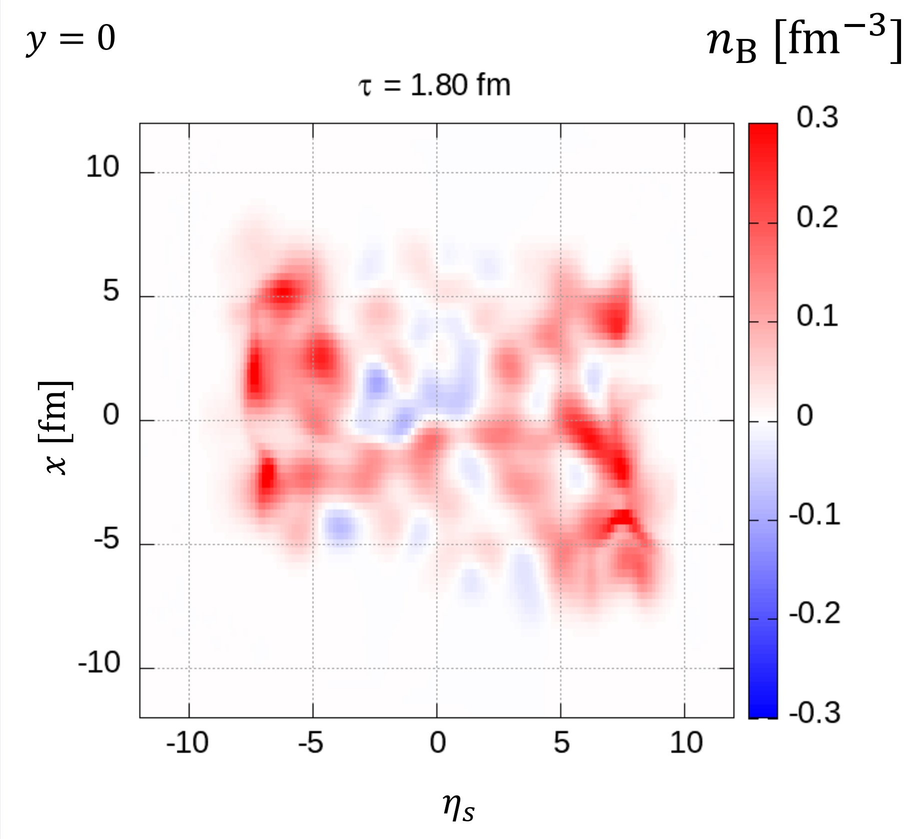

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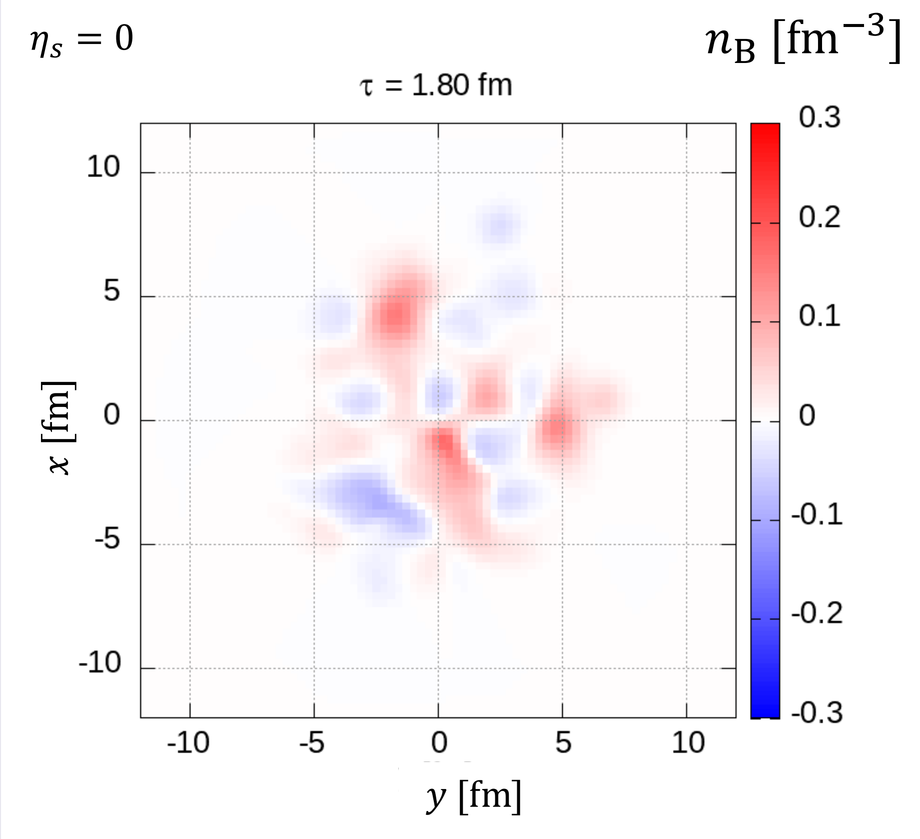

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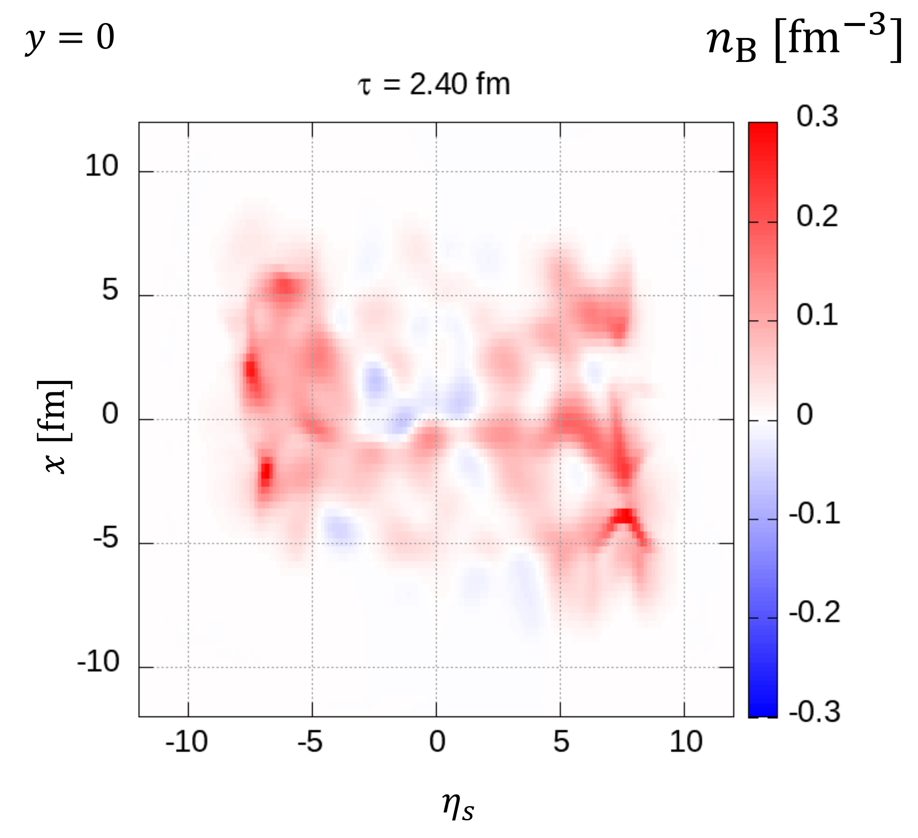

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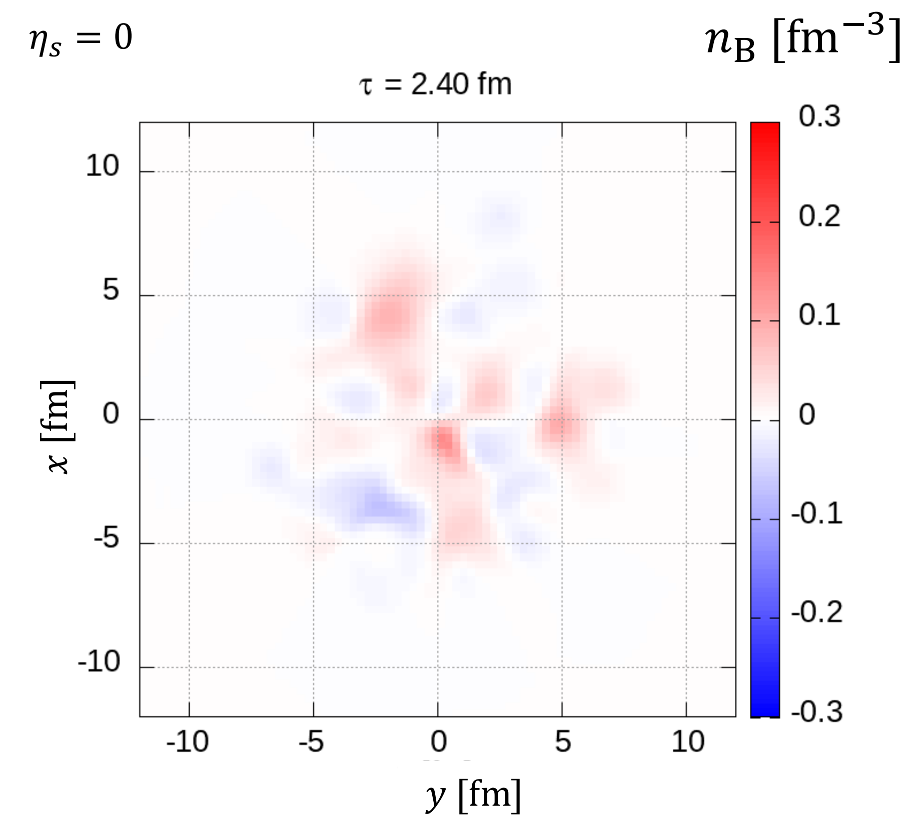

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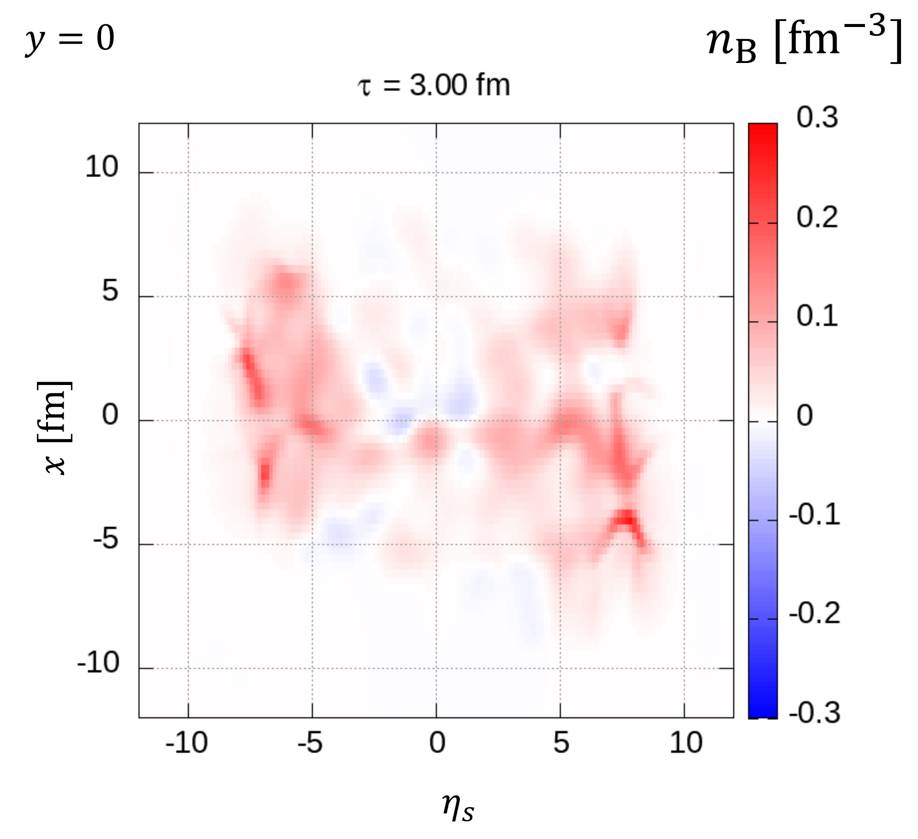

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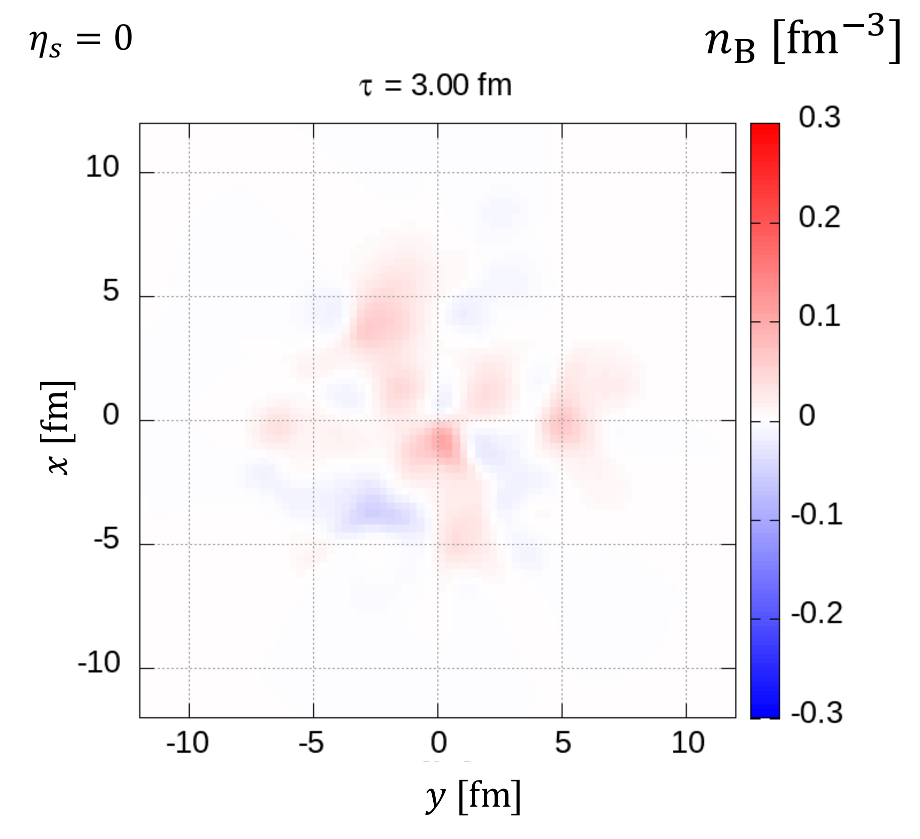

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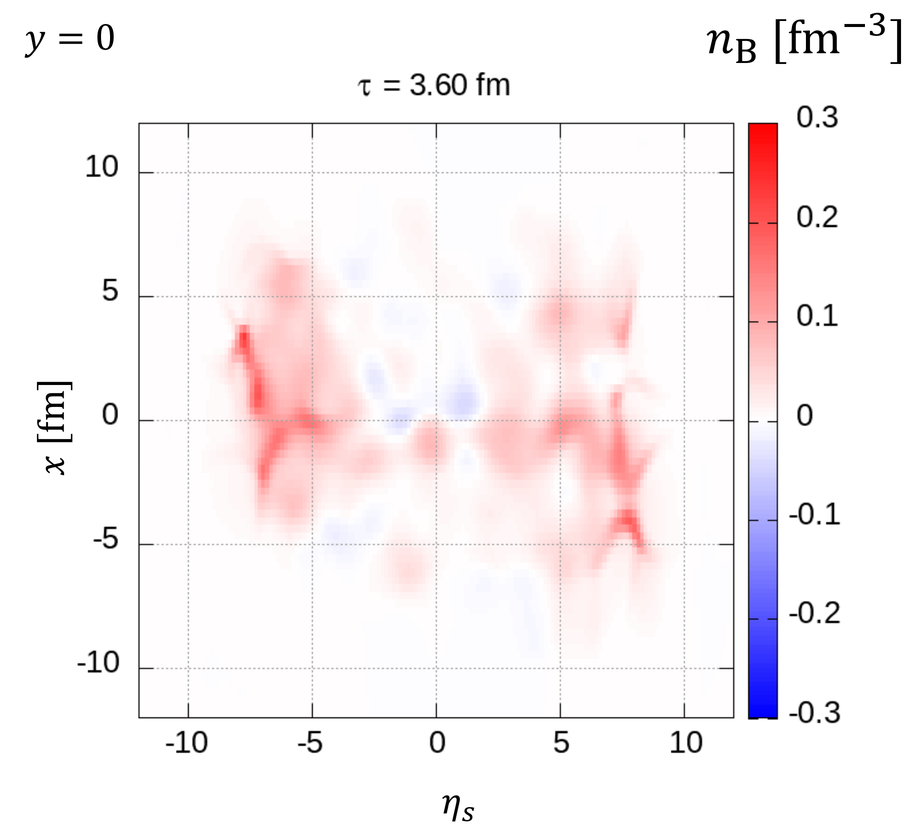

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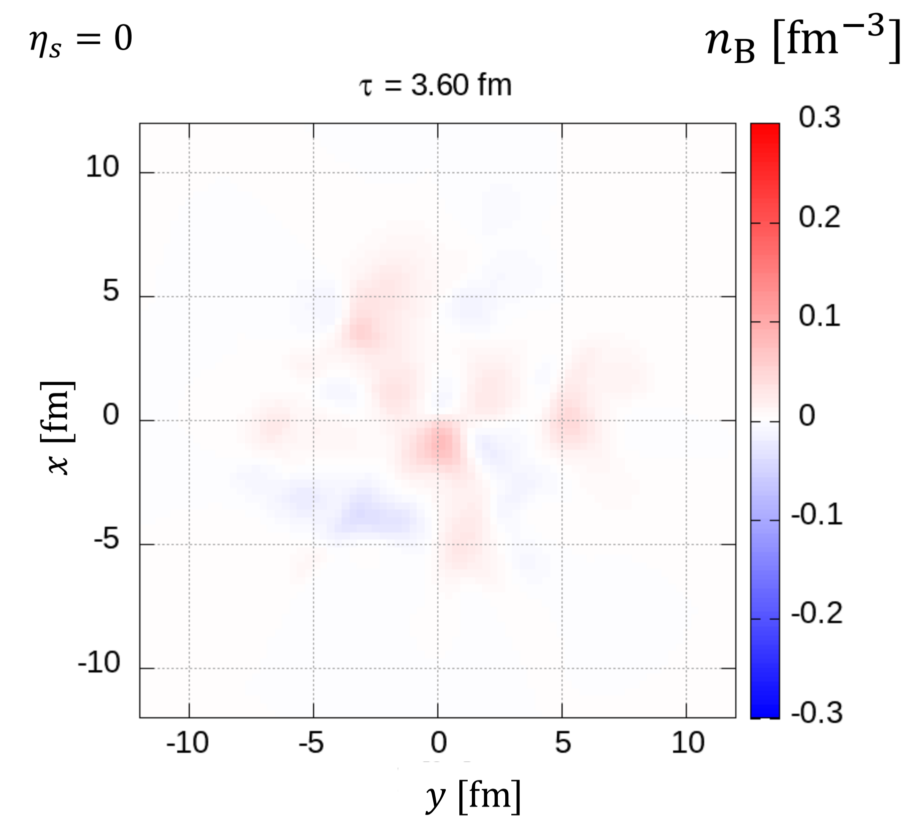

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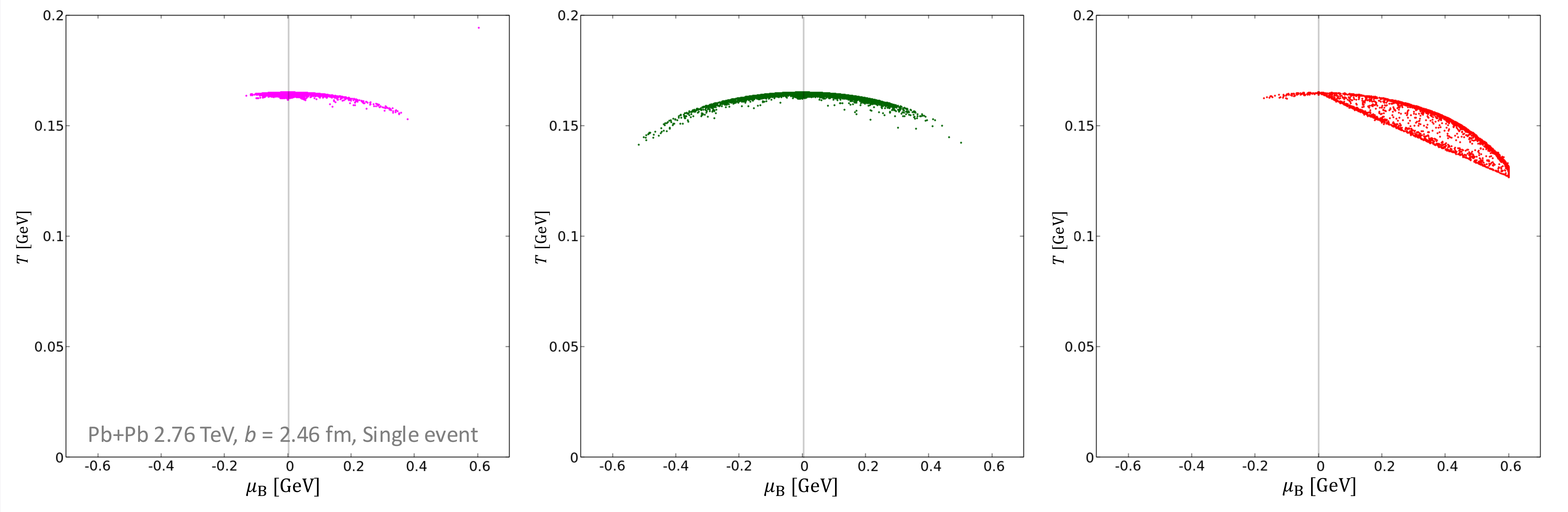
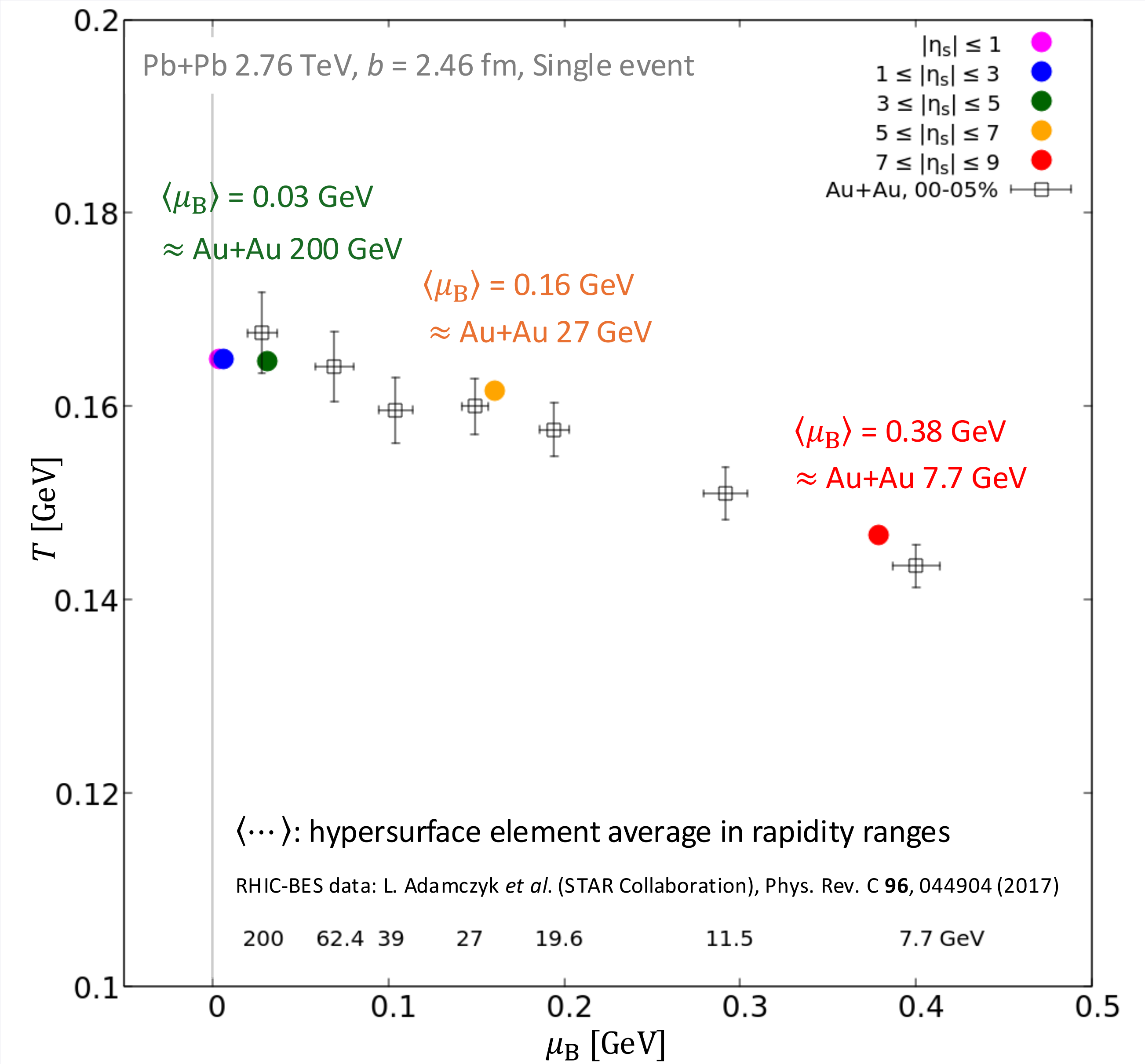
Rapidity dependence of freezeout hypersurface

$-1 \le \eta_s \le 1$ $3 \le \eta_s \le 5$ $7 \le \eta_s \le 9$



- Some hypersurface element has negative baryon chemical potentials
- Significantly large baryon chemical potentials in forward rapidities

Rapidity-averaged freezeout hypersurface



- Almost zero baryon chemical potential until $|\eta_s| \leq 5$
  - ➡ ≈ Au+Au 200 GeV
- Averaged-hypersurface in rapidity range $5 \leq |\eta_s| \leq 7$ exceeds $\mu_B = 100$ MeV
  - ➡ **≈ Au+Au 27 GeV**
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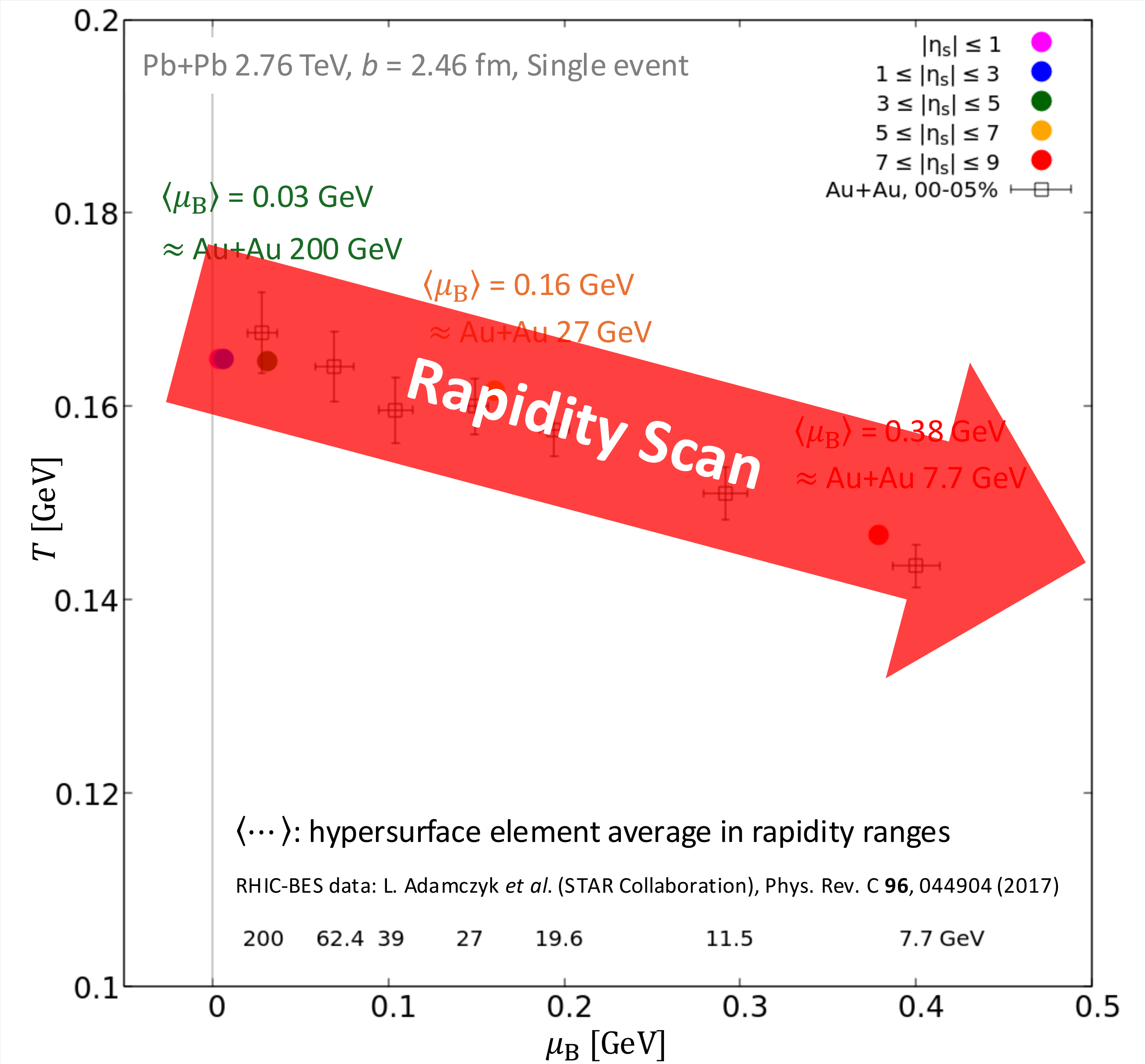

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Rapidity scan is a strong tool for exploring the QCD phase diagram!!

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Summary and Outlook

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Summary

- Extended the DCCI model to finite baryon number
  - ➡ descriptions of thermalized baryon number
  - ➡ Rapidity Scan!!
- Negative $n_{\mathrm{B}}(\mu_{\mathrm{B}})$ region appears due to the depositions of anti-quarks
- At LHC energies, high baryon chemical potentials are realized in forward rapidities

Outlook

- Centrality dependence
- Event-averaged analysis
- Baryon stopping

Backups

Rapidity-averaged freezeout hypersurface

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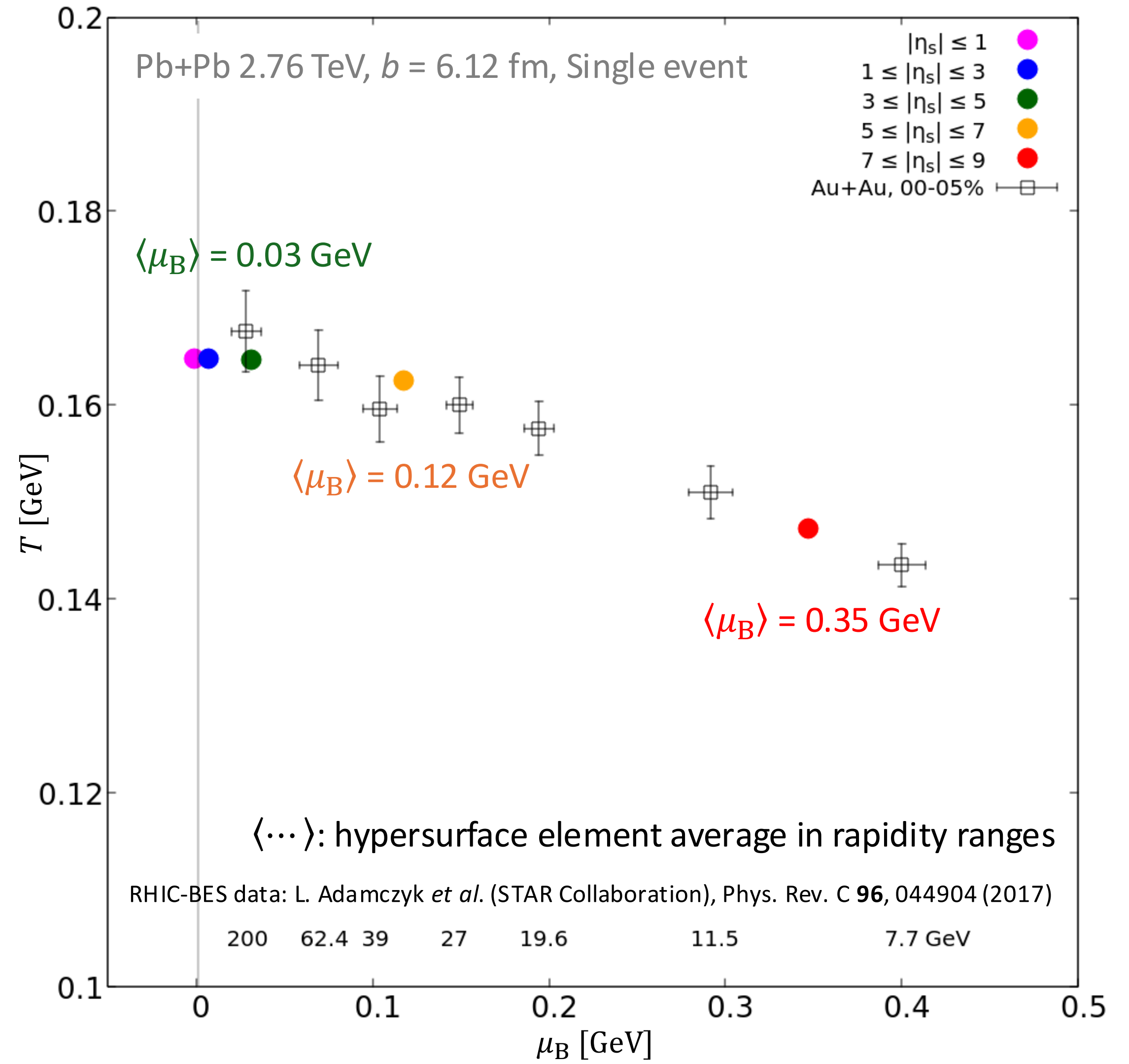
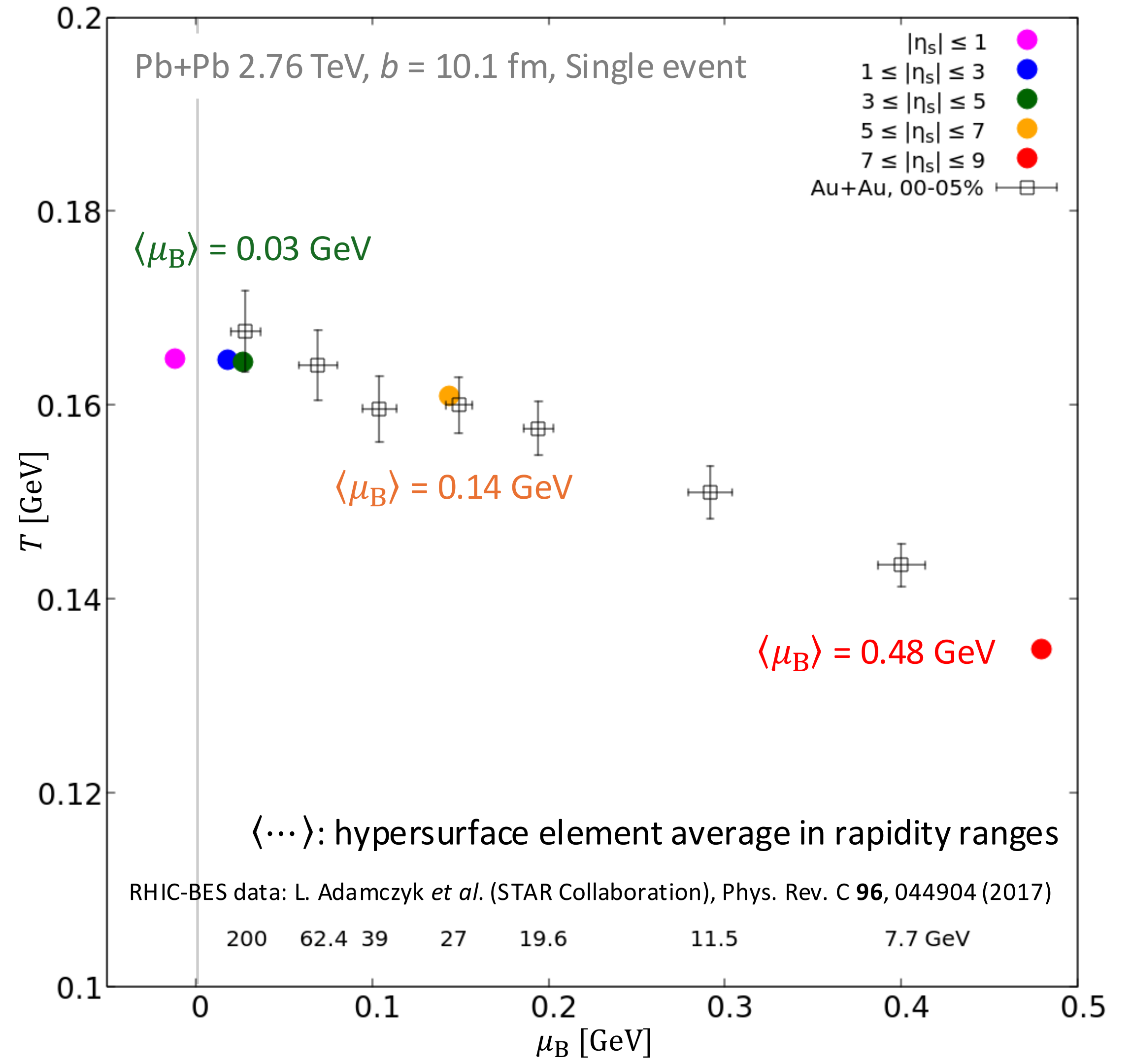
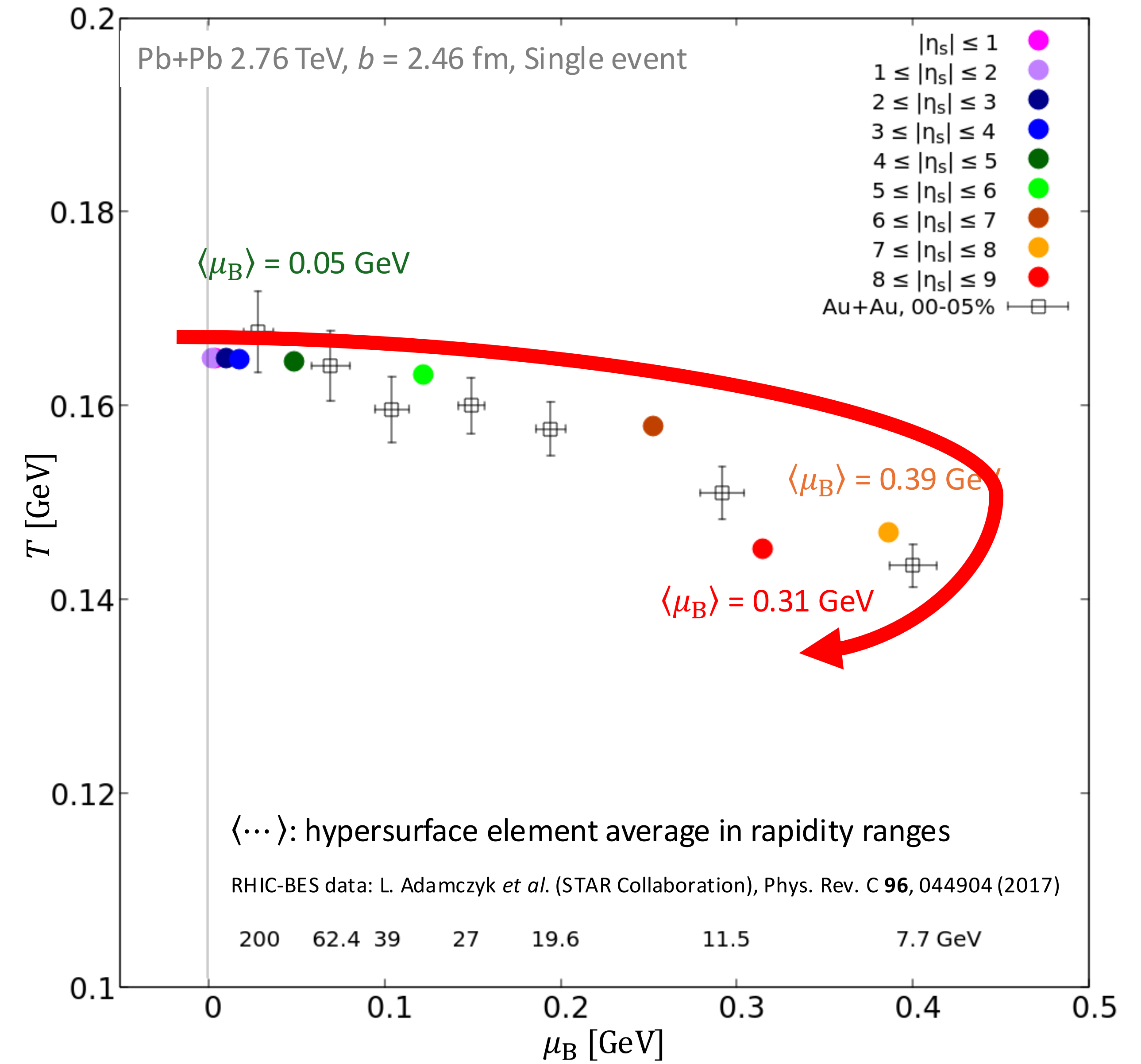
b = 6.12 fm



b = 10.1 fm



Rapidity-averaged freezeout hypersurface



- μ_{B} becomes maximum in $7 \leq |\eta_s| \leq 8$

cf.) $y_{\mathrm{beam}}\left(\sqrt{s_{\mathrm{NN}}} = 2.76\ \mathrm{TeV}\right) \approx 8$

Rapidity dependence of freezeout hypersurface

Pb+Pb 2.76 TeV, b = 6.12 fm, Single event

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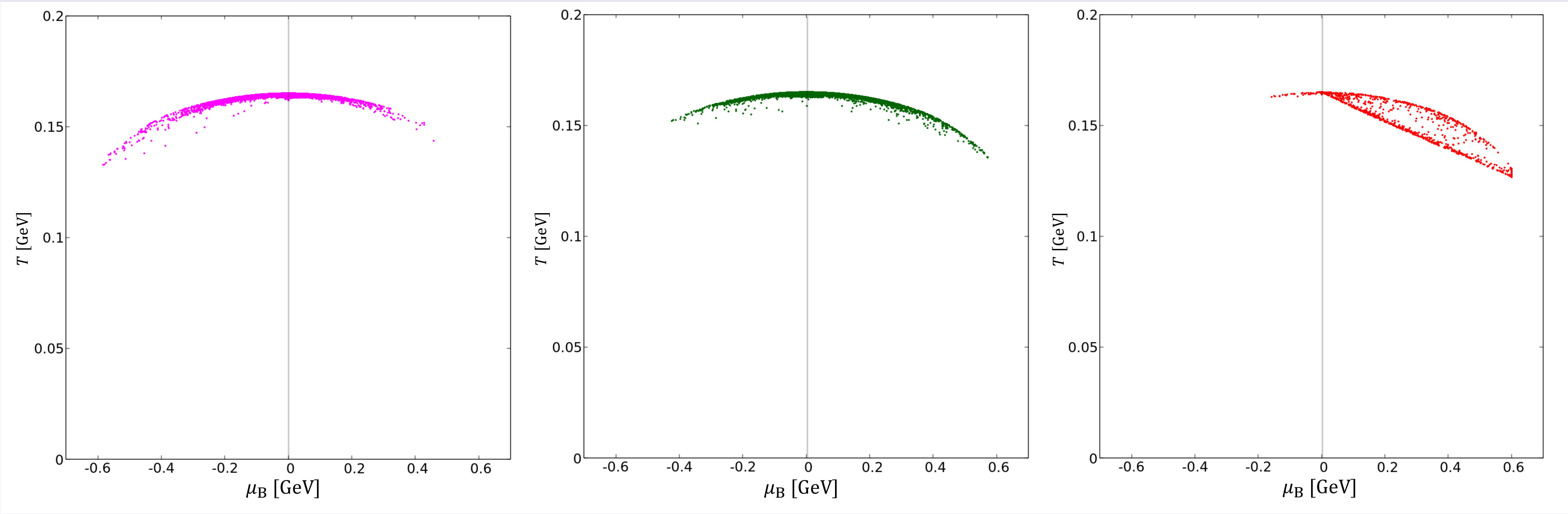

Rapidity dependence of freezeout hypersurface

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Pb+Pb 2.76 TeV, *b* = 10.1 fm, Single event

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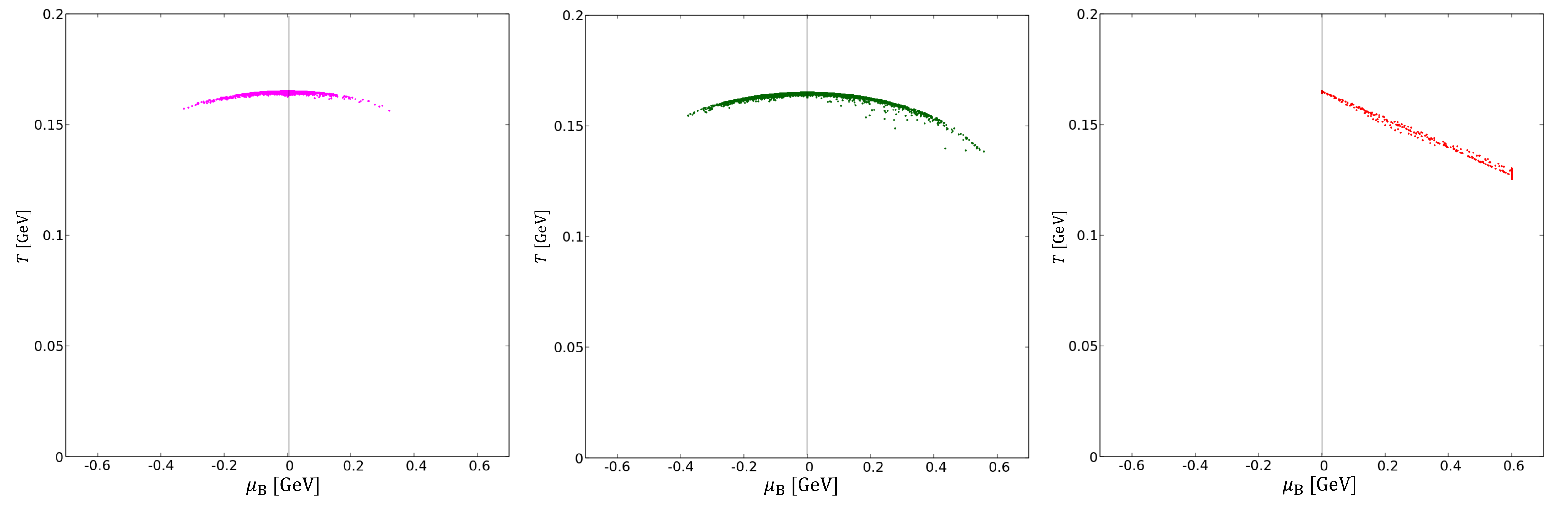

Space-time evolution of core

Pb+Pb 2.76 TeV, b = 6.12 fm
Single event

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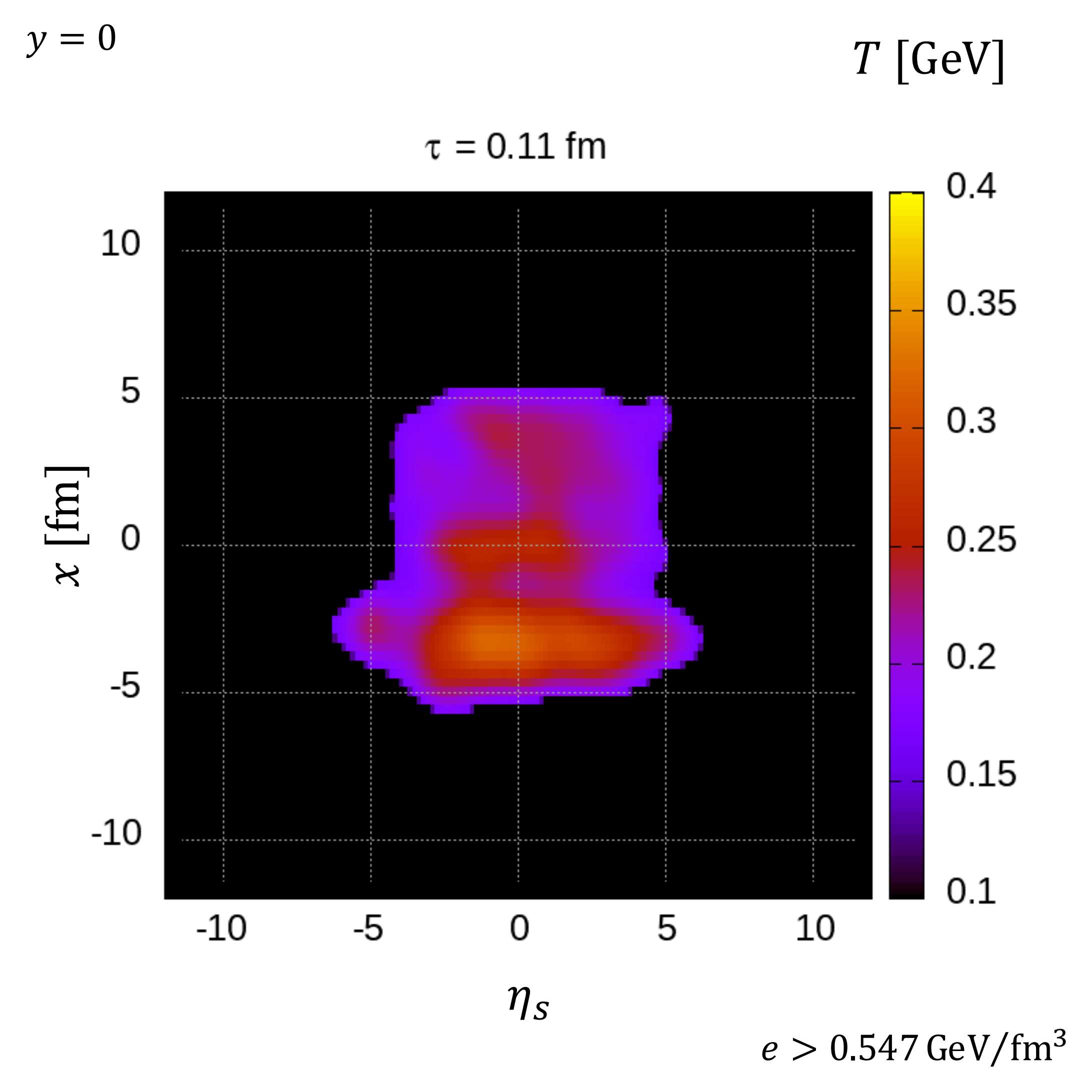
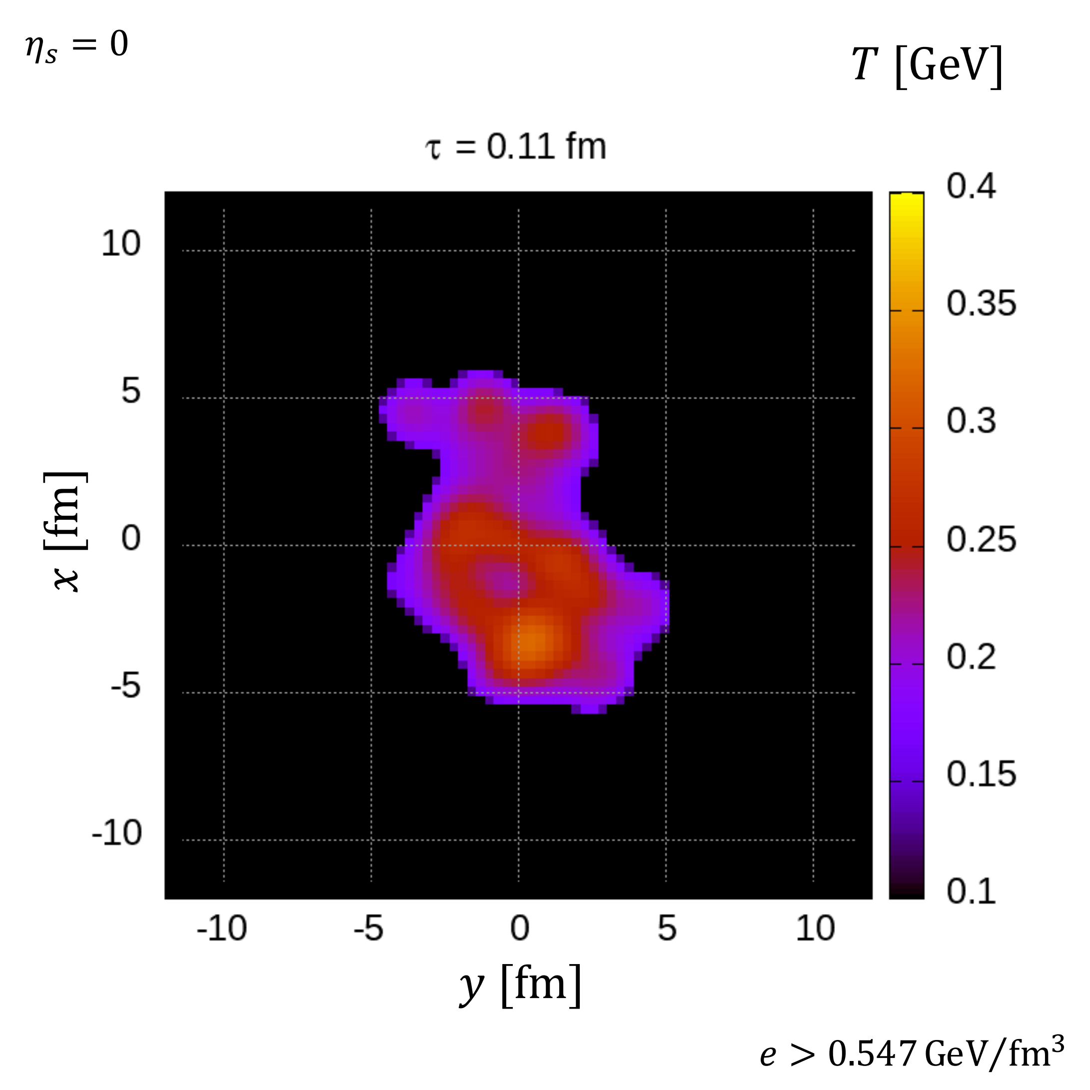
Temperature (longitudinal profile)



Temperature (transverse profile)



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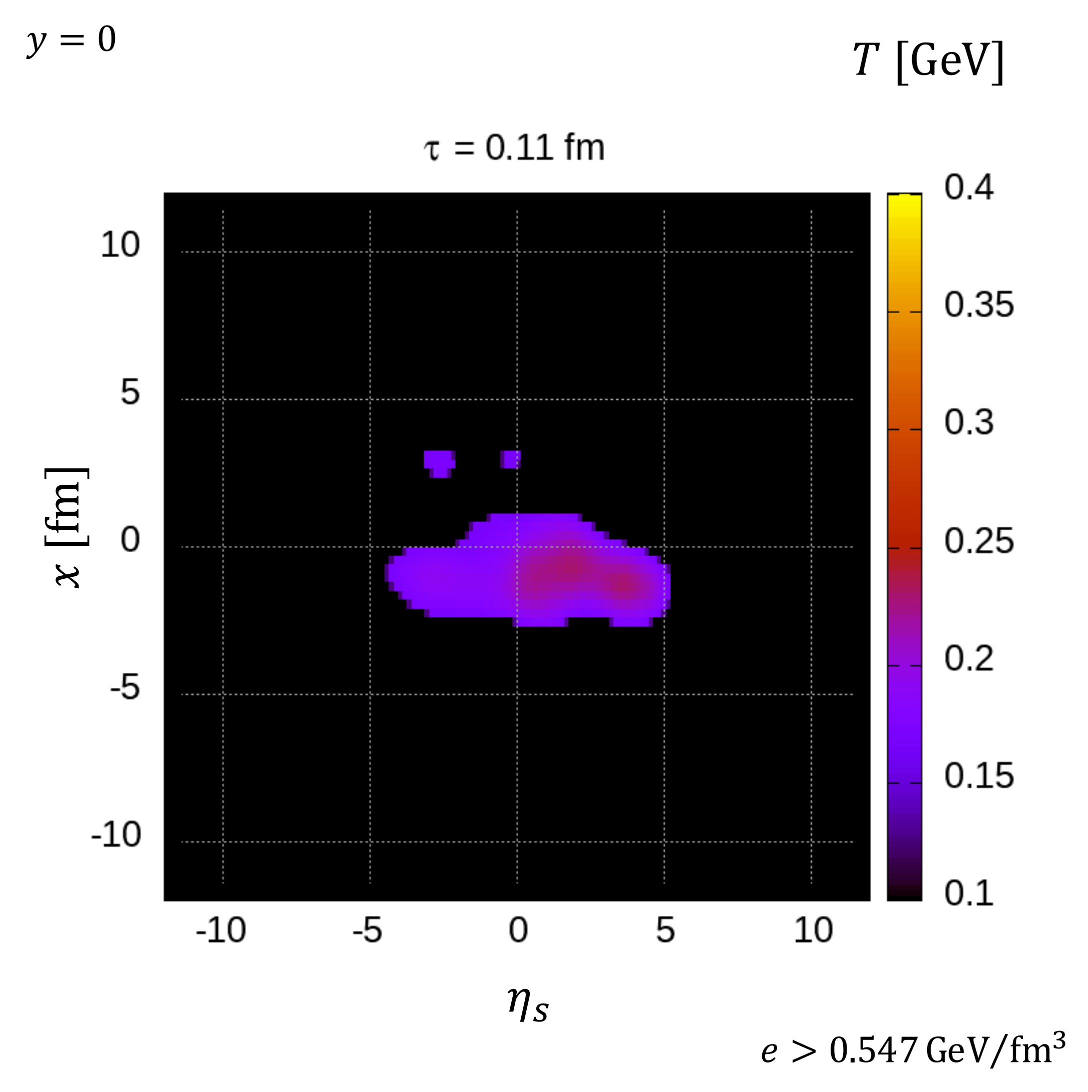

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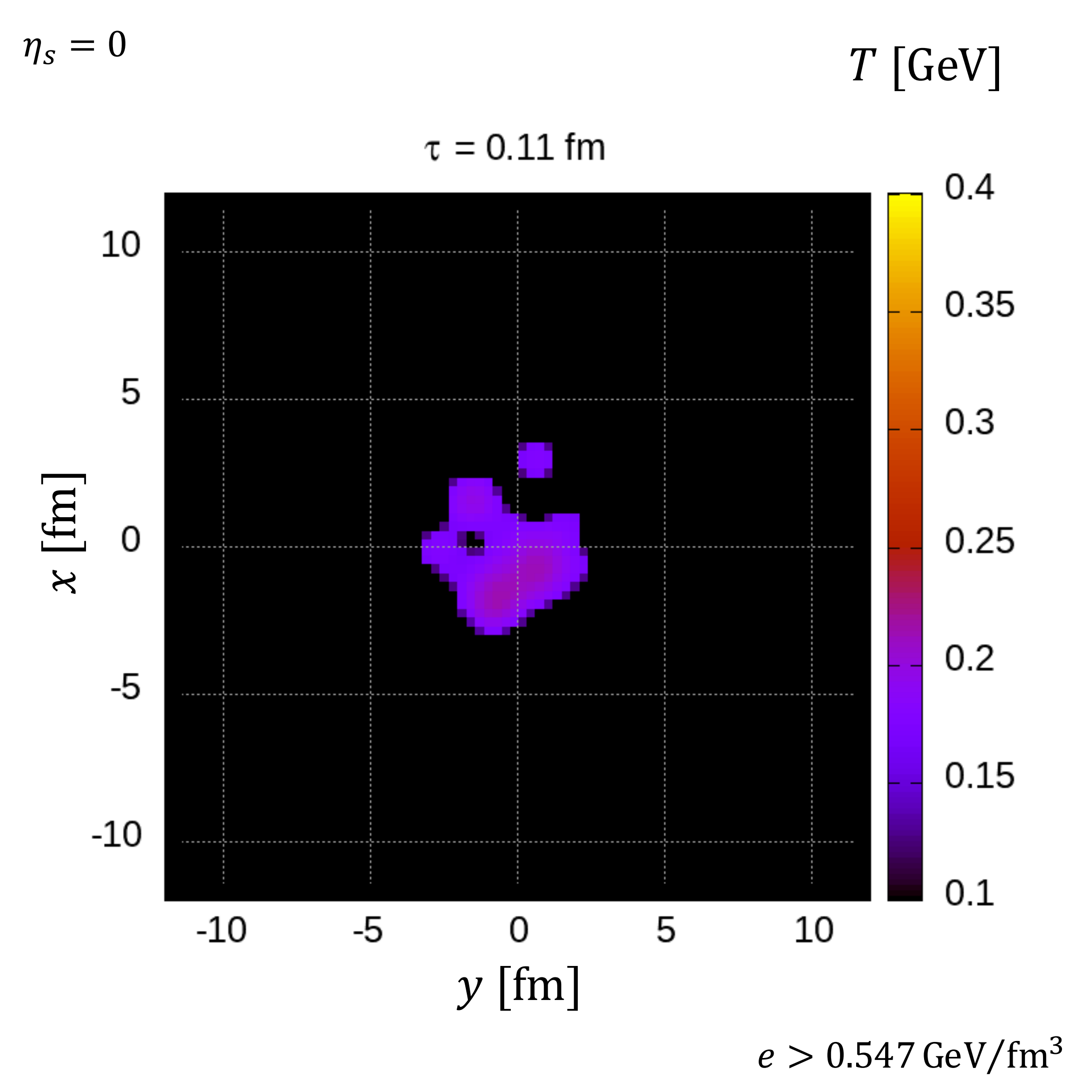

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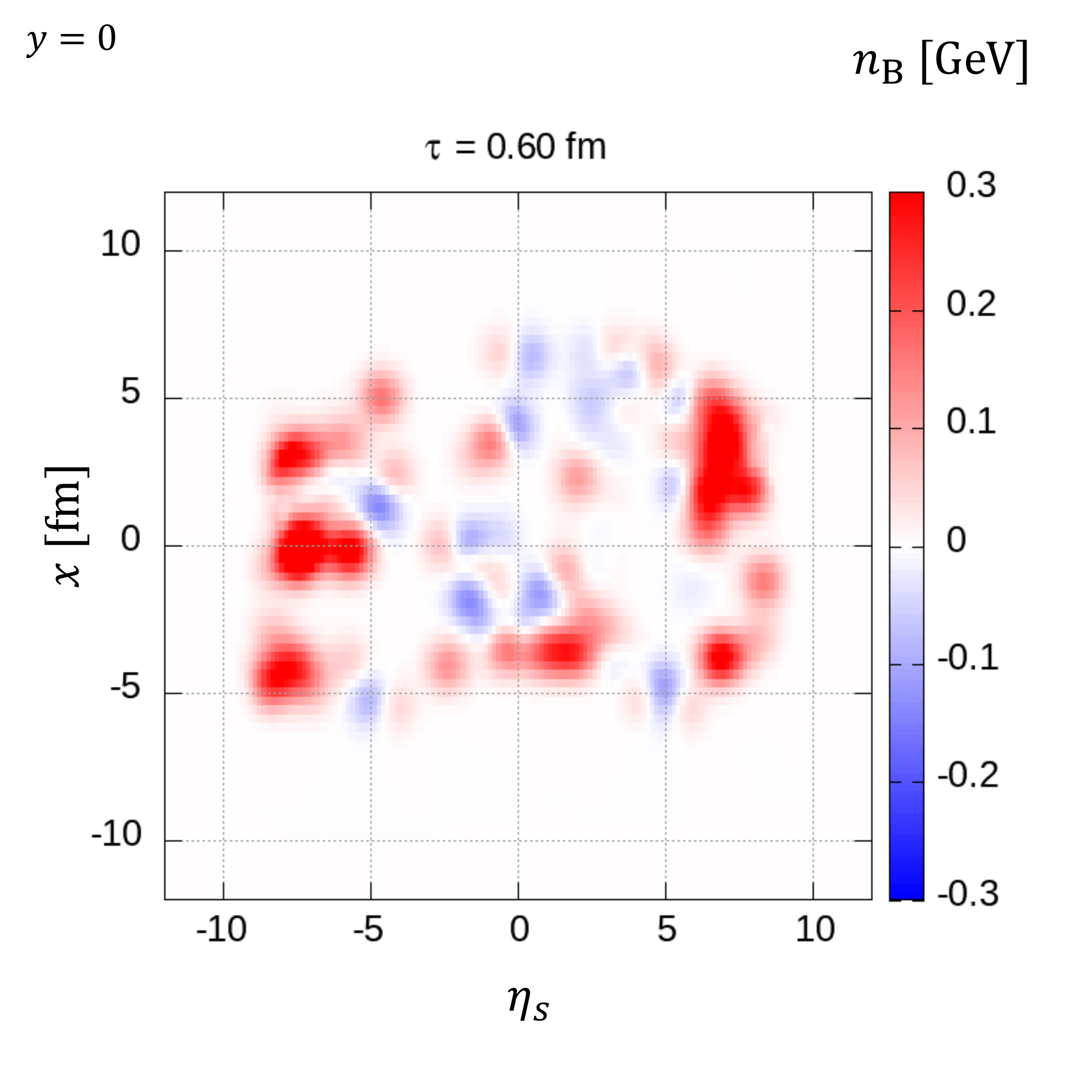

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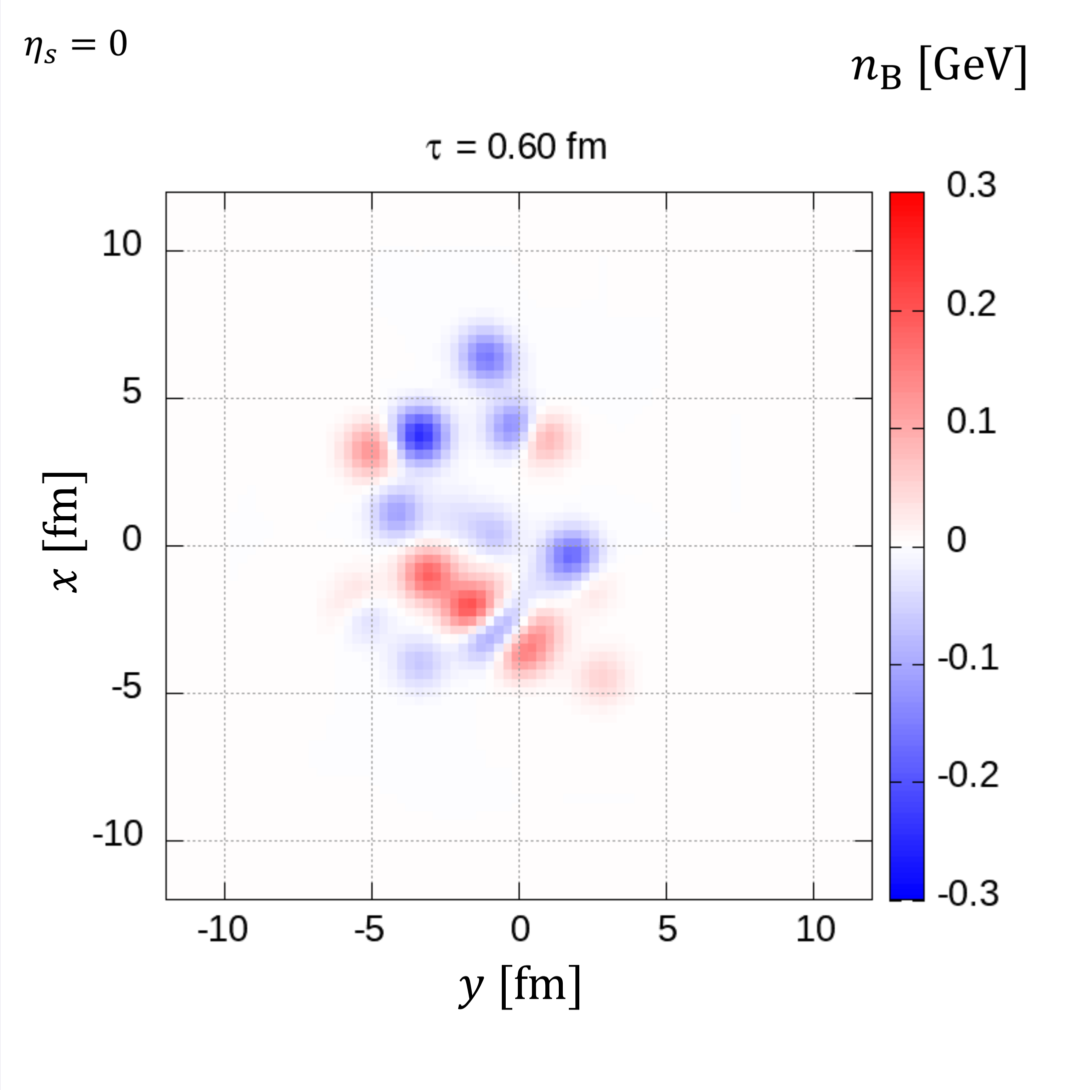

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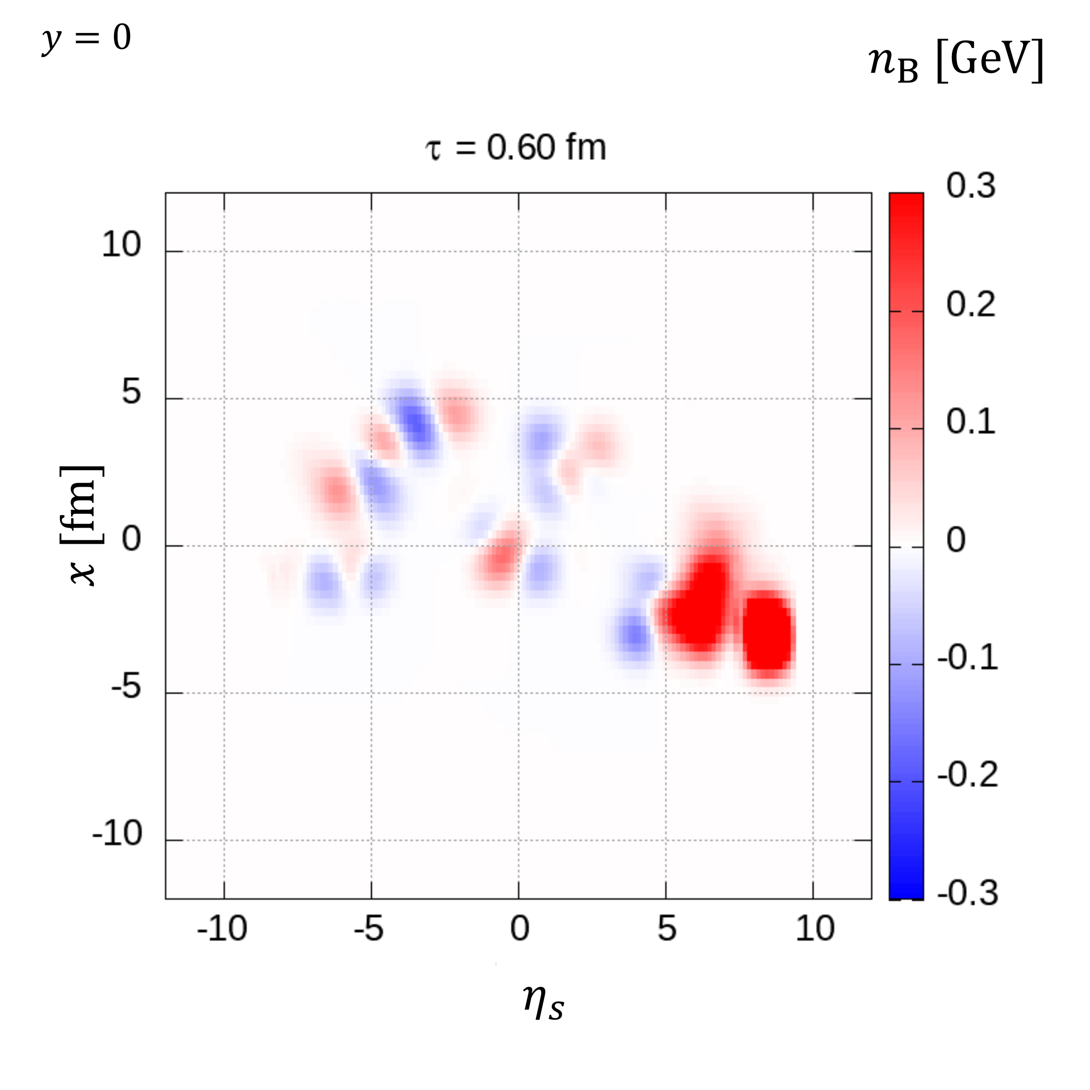

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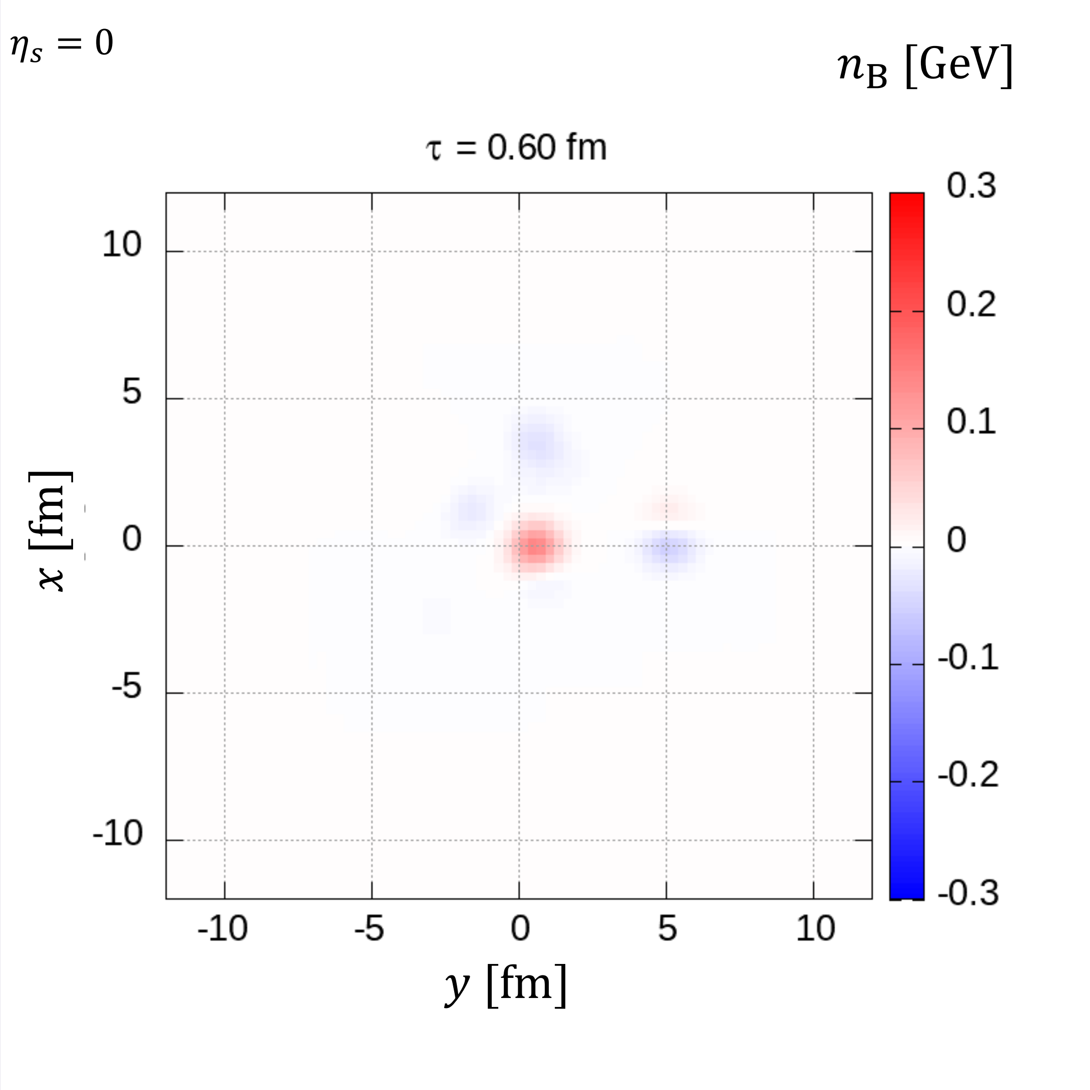

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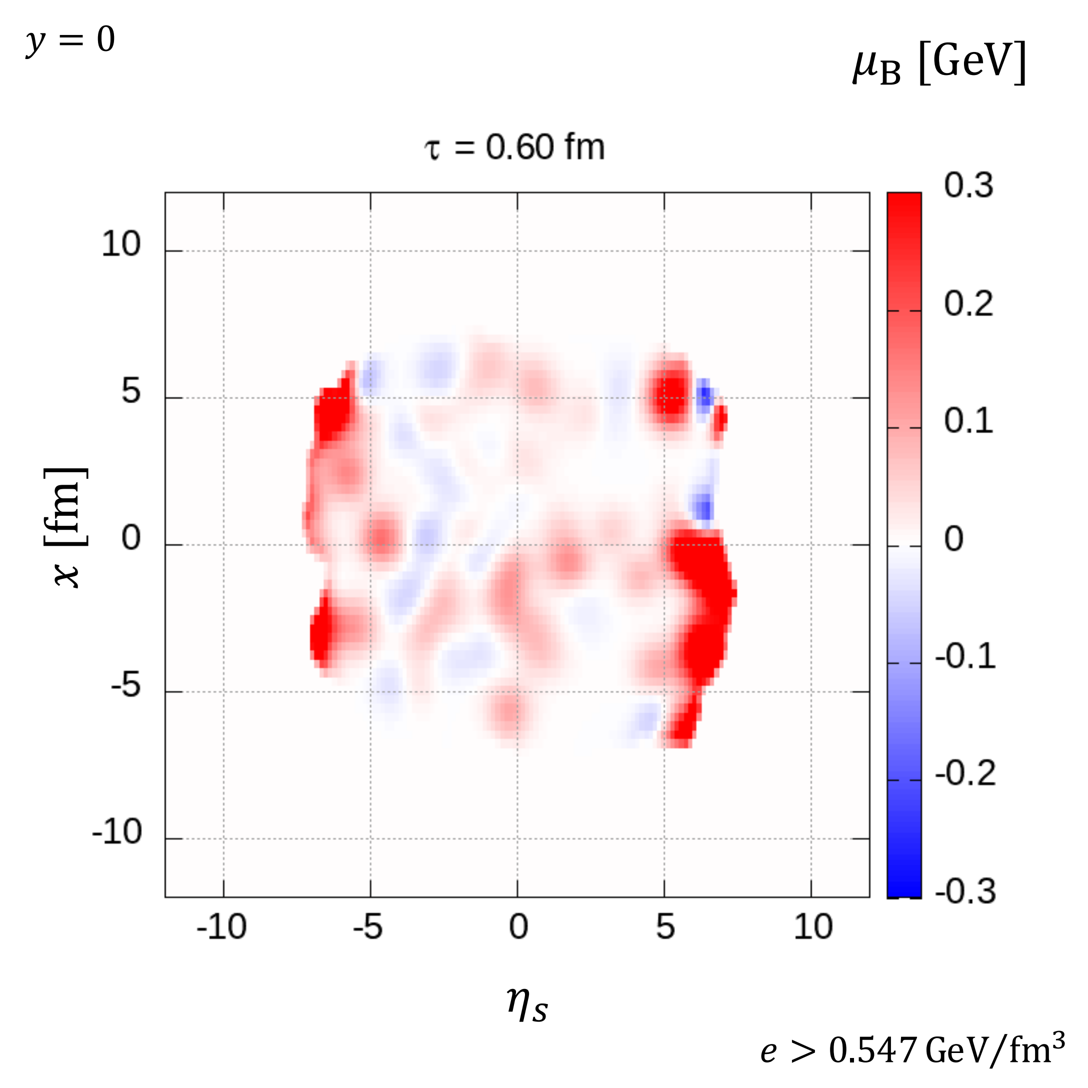
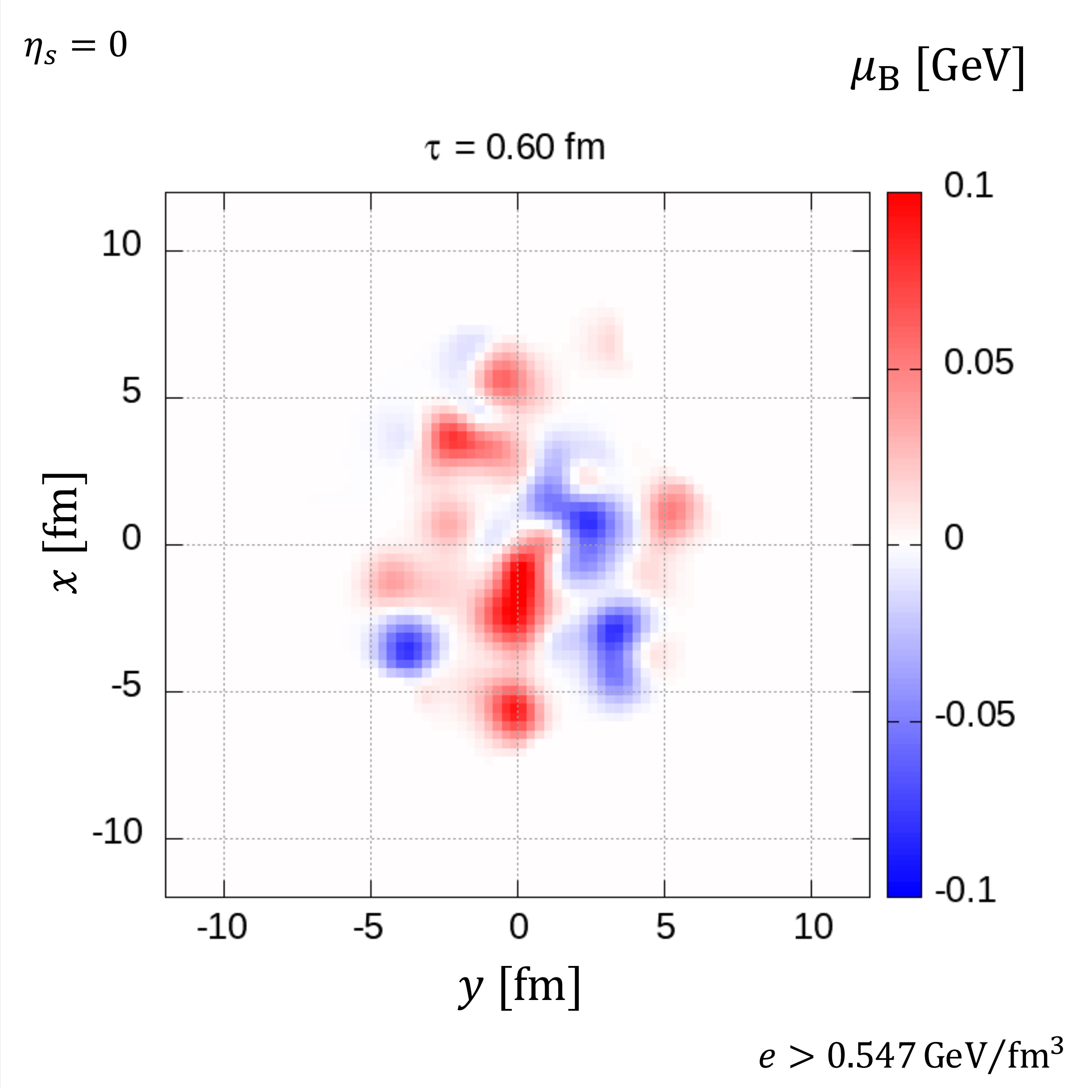
Baryon chemical potential (longitudinal profile)



Baryon chemical potential (transverse profile)



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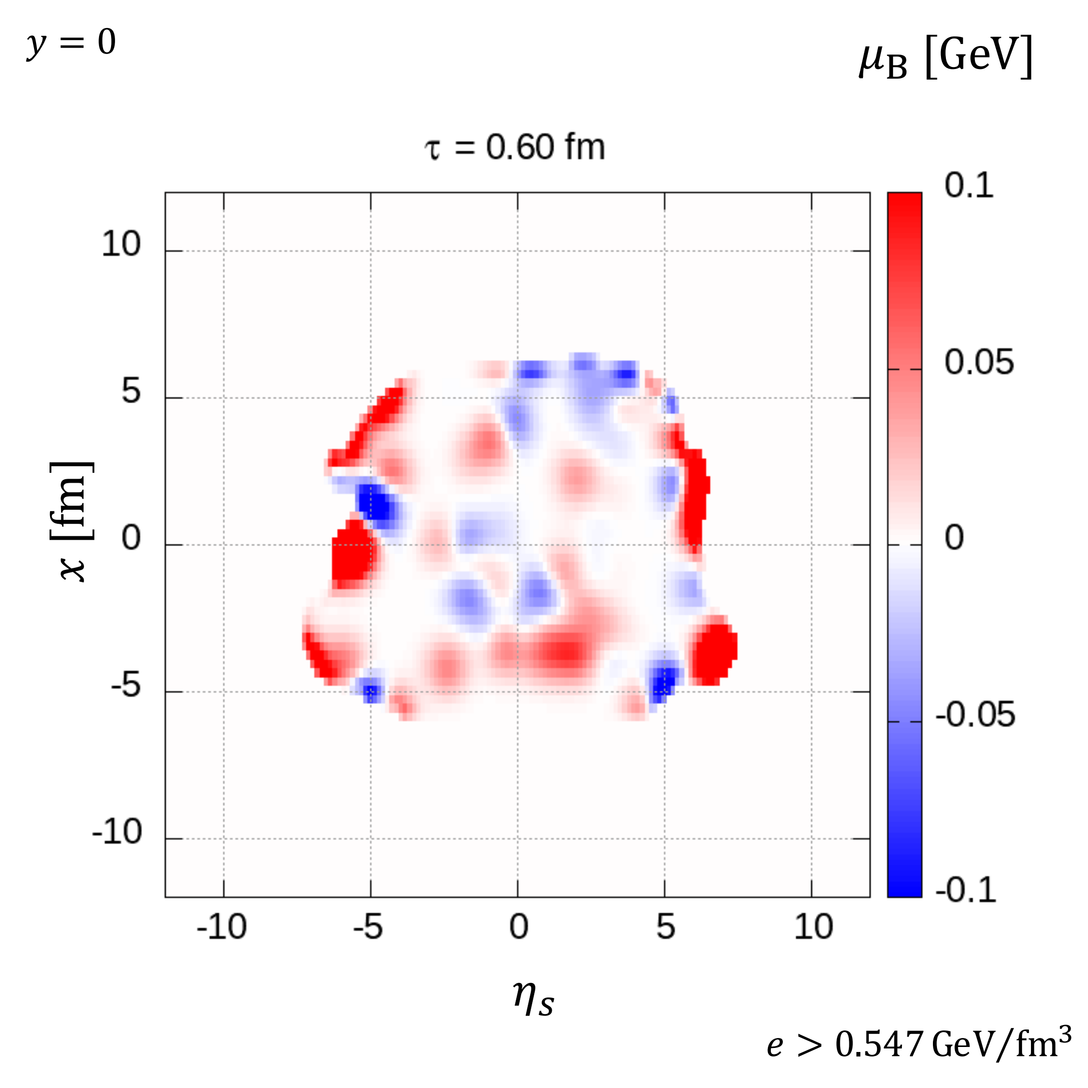

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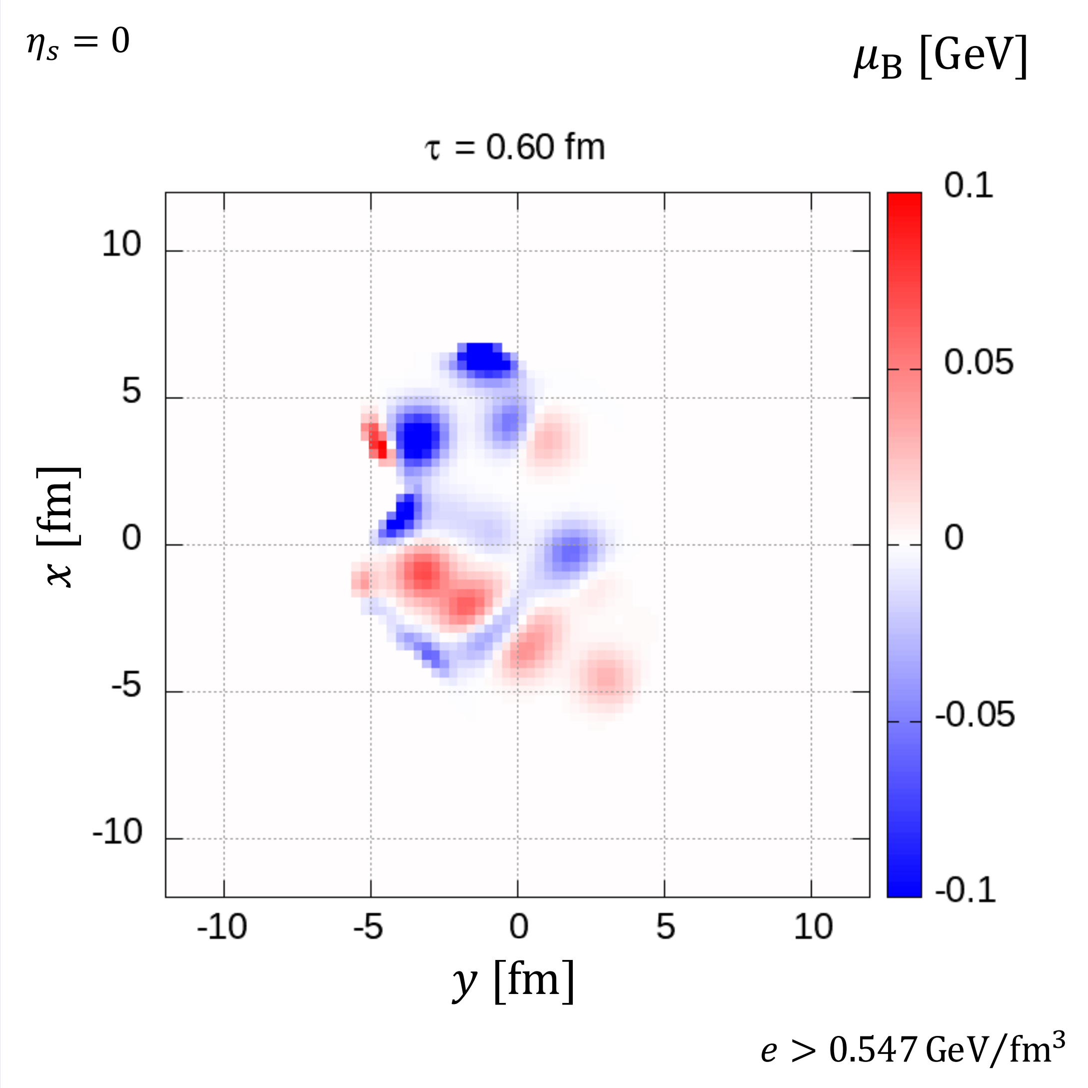

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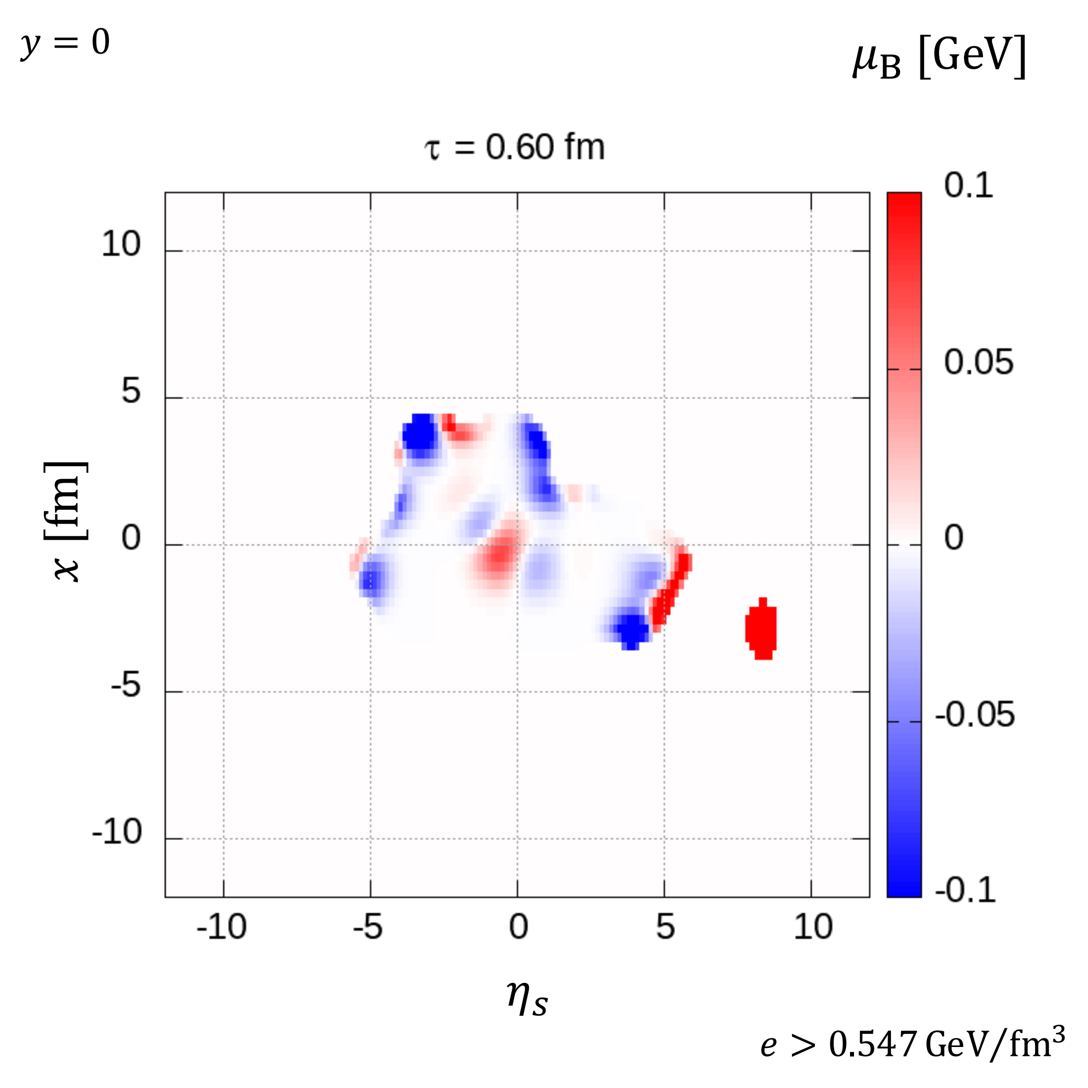
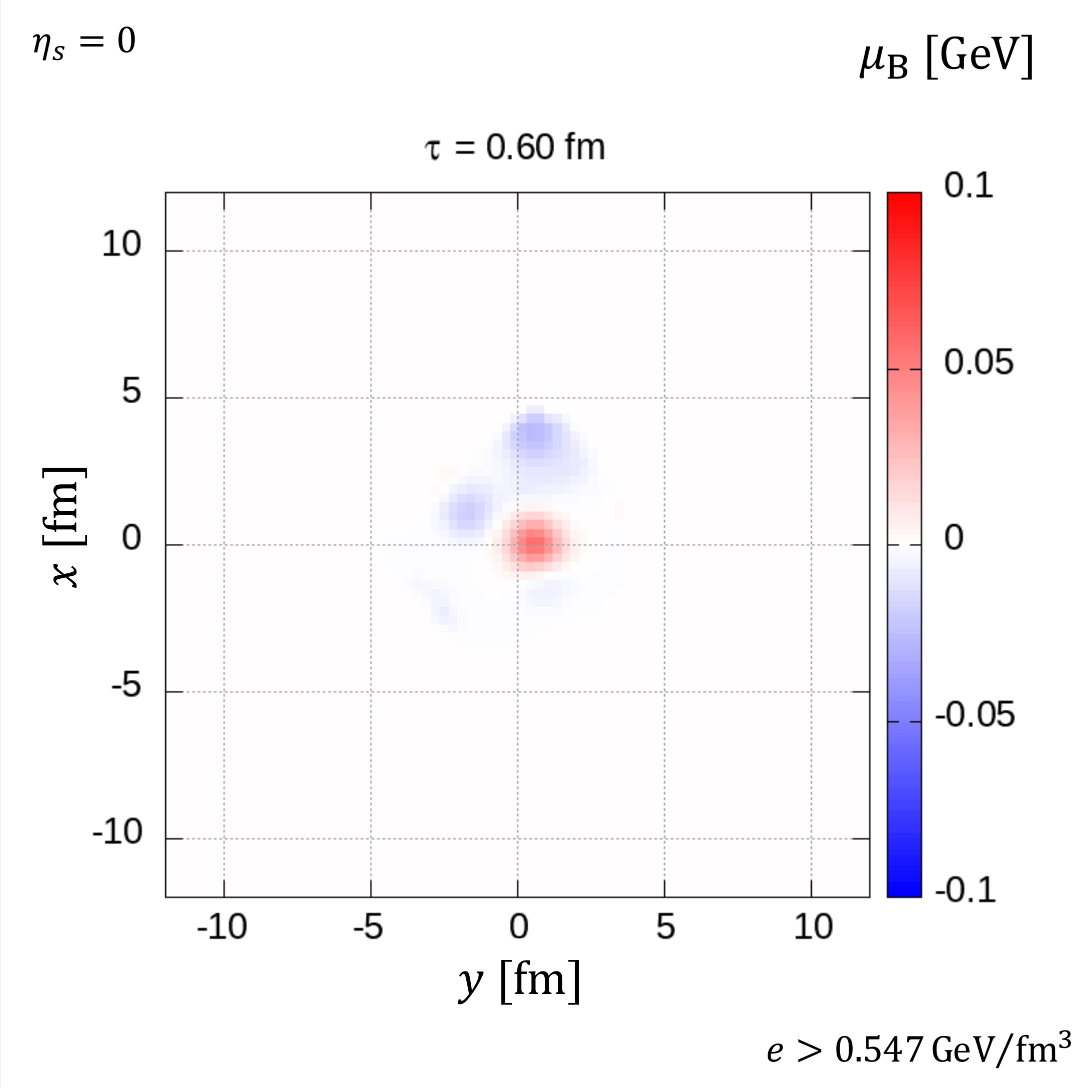
Baryon chemical potential (longitudinal profile)



Baryon chemical potential (transverse profile)



High baryon number density at LHC energies

Nuclear compression + CGC

Ming Li, Ph.D thesis, U. of Minesota (2018)

M. Li and J. I. Kapusta, Phys. Rev. C **99**, 014906 (2019)

- Solving classical gluon fields of receding nuclear remnants

  ⇨ Rapidity loss Δy of nucleons

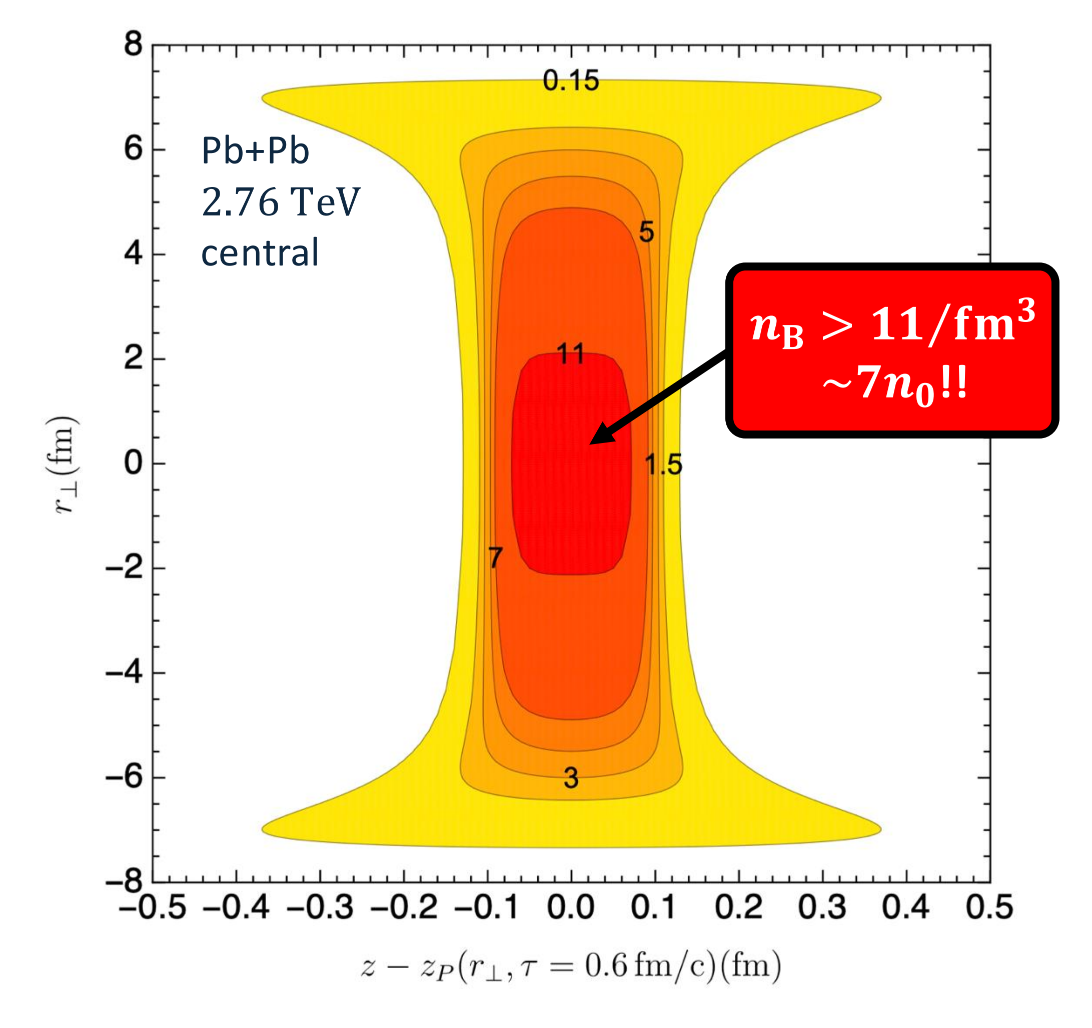
- Nuclear compression by Δy

$$n_{\mathrm{B}}(x,y,z) \approx e^{\Delta y} \rho_{\mathrm{A}}\left(x,y,ze^{\Delta y}\right)$$ @high energy

M. Gyulassy and L. P. Csernai, Nucl. Phys. A **460**, 723 (1986)

➡ **Extremely high baryon number density in the fragmentation regions of high-energy heavy ion collisions**

Baryon number density of compressed Pb



Source terms

Y. Kanakubo *et al.*, Phys. Rev. C **105**, 024905 (2022)

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Energy-momentum source term

$$\partial_\mu T^{\mu\nu}_{\mathrm{fluid}} = j^\nu$$

$$j^\nu = -\sum_i \frac{dp_i^\nu(t)}{dt} G(\boldsymbol{x} - \boldsymbol{x}_i(t))$$

p_i^ν: Four-momentum of i_{th} parton

G: Gaussian function $\boldsymbol{x}_i$: Position of i_{th} parton

When i_{th} parton deposit all energy = dead parton

Baryon number source term

New!!

$$\partial_\mu N^{\mu}_{\mathrm{fluid}} = \rho$$

$$\rho = -\sum_{i_{\mathrm{dead}}} \frac{dB_{i_{\mathrm{dead}}}}{dt} G\left(\boldsymbol{x} - \boldsymbol{x}_{i_{\mathrm{dead}}}(t)\right)$$

$B_{i_{\mathrm{dead}}}$: Baryon number of i_{dead}th parton

- Phenomenological fluidization rate per particle in core-corona picture

$$\frac{dp_i{}^\mu}{d\tau} = -\sum_j^{N_{\mathrm{scat}}} \rho_{i,j}\sigma_{i,j}\left|v_{\mathrm{rel},i,j}\right| p_i{}^\mu$$

$\rho_{i,j}$: Effective density of j_{th} seen from i_{th}

$\sigma_{i,j}$: Cross section between i_{th} and j_{th}

$v_{\mathrm{rel},i,j}$: Relative velocity between i_{th} and j_{th}

Low p_{T} / Dense ➡ **Core**

High p_{T} / Dilute ➡ **Corona**

NEOS-BQS

A. Monnai, B. Schenke and C. Shen, Phys. Rev. C **100**, 024907 (2019)

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Taylor expansion using Lattice results (high T)

$$\frac{P}{T^4} = \frac{P_0}{T^4} + \sum_{l,m,n} \frac{x^{B,Q,S}_{l,m,n}}{l,m,n} \left(\frac{\mu_B}{T}\right)^l \left(\frac{\mu_Q}{T}\right)^m \left(\frac{\mu_S}{T}\right)^n$$

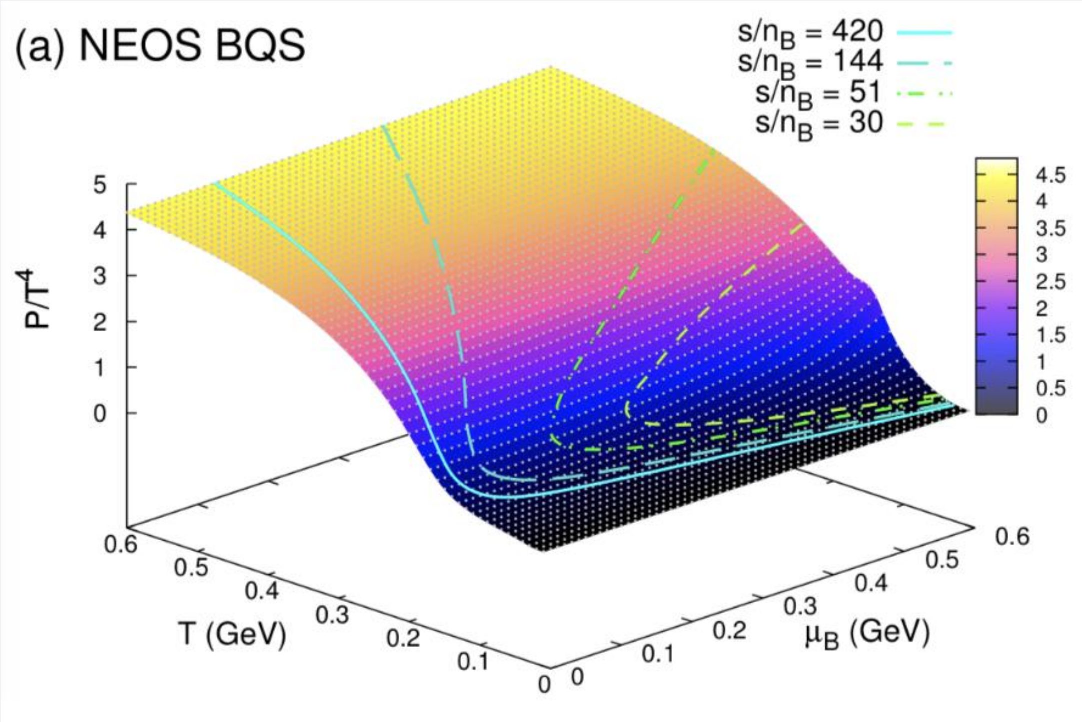
Hadron gas (low T)

$$P = \pm T \sum_i \int \frac{g_i d^3p}{(2\pi)^3} \ln\left[1 \pm e^{-(E_i-\mu_i)/T}\right]$$

$$= \sum_i \sum_k (\mp 1)^{k+1} \frac{1}{k^2} \frac{g_i}{2\pi^2} m_i^2 T^2 e^{k\mu_i/T} K_2\left(\frac{km_i}{T}\right)$$

CONNECT

$$\frac{P}{T^4} = \frac{1}{2}\left[1 - f(T,\mu_J)\right] \frac{P_{\mathrm{had}}(T,\mu_J)}{T^4} + \frac{1}{2}\left[1 + f(T,\mu_J)\right] \frac{P_{\mathrm{lat}}(T,\mu_J)}{T^4}$$



Constraints: $n_Q = 0.4 n_B, \quad n_S = 0$

$$e(T,\mu_B) = e(0.165\ \mathrm{GeV}, 0)$$
$$= 0.547\ \mathrm{GeV/fm^3}$$

➡ e_{sw} for core

Hydrodynamic module in DCCI

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Energy-momentum conservation

$$\partial_\mu T^{\mu\nu}_{\mathrm{fluid}} = j^\nu$$

$$T^{\mu\nu}_{\mathrm{fluid}} = e u^\mu u^\nu - p\Delta^{\mu\nu}$$ ← ideal hydro

$$j^\nu = -\sum_i \frac{dp_i^\nu(t)}{dt} G\left(\boldsymbol{x} - \boldsymbol{x}_i(t)\right)$$

Baryon number conservation

$$\partial_\mu N^{\mu}_{\mathrm{fluid}} = \rho$$

$$N^{\mu}_{\mathrm{fluid}} = n_{\mathrm{B}} u^\mu$$ ← ideal hydro

$$\rho = -\sum_{i_{\mathrm{dead}}} \frac{dB_{i_{\mathrm{dead}}}}{dt} G\left(\boldsymbol{x} - \boldsymbol{x}_{i_{\mathrm{dead}}}(t)\right)$$

$$G_{\mathrm{Milne}} = \frac{1}{\sqrt{2\pi\sigma_\eta^2\tau^2}} \exp\left(-\frac{\left(\eta_{s,\mathrm{parton}} - \eta_{s,i}\right)^2}{2\sigma_\eta^2}\right) \times \frac{1}{2\pi\sigma_{xy}^2} \exp\left(-\frac{\left(x_{\mathrm{parton}} - x_i\right)^2 + \left(y_{\mathrm{parton}} - y_i\right)^2}{2\sigma_{xy}^2}\right)$$

Default: $\sigma_\eta = 0.5$, $\sigma_{xy} = 0.6$ fm

RHIC-BES data

L. Adamczyk *et al*. (STAR Collaboration), Phys. Rev. C **96**, 044904 (2017)