

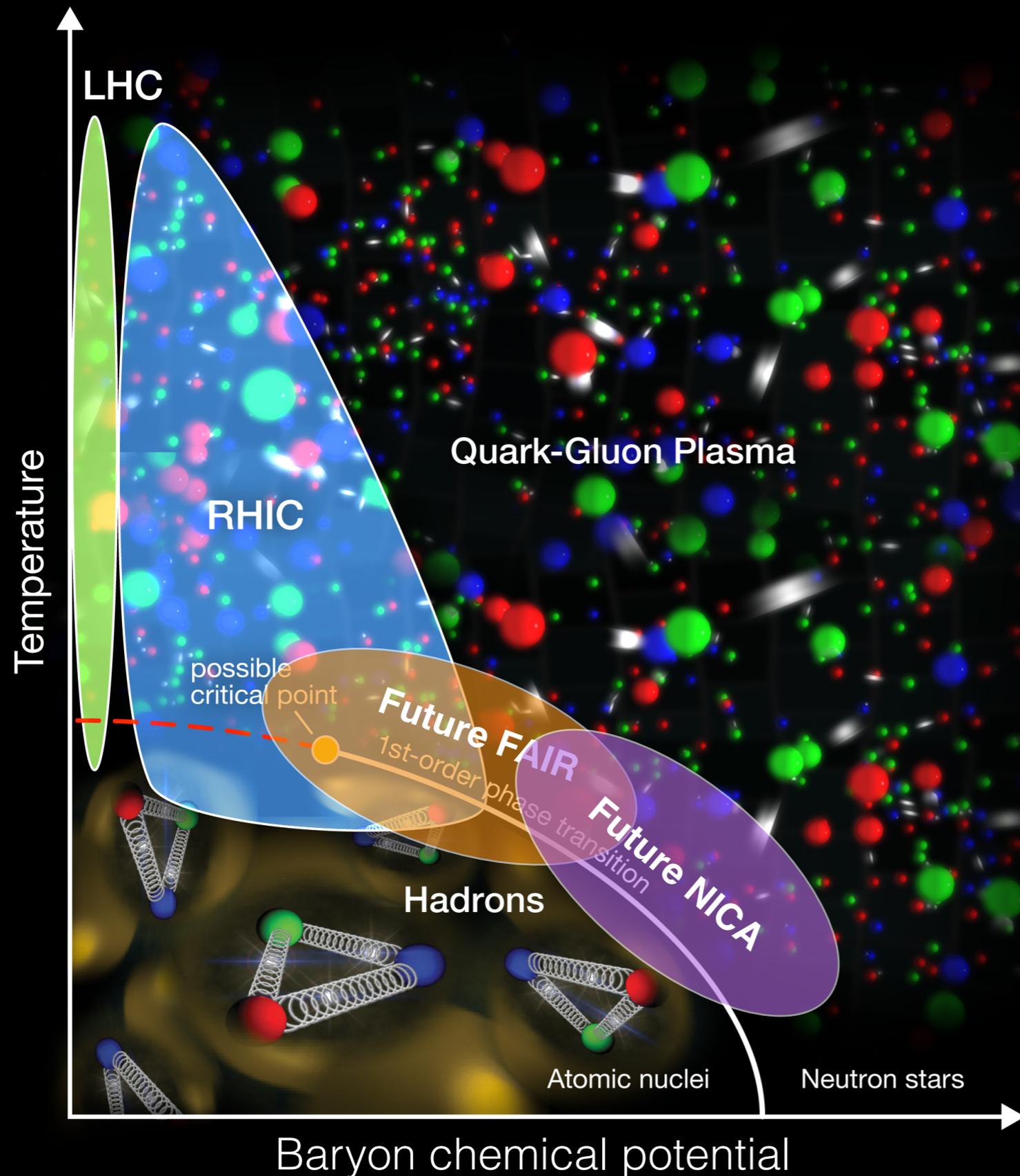


Dynamical initialization and hydrodynamic modeling of relativistic heavy-ion collisions

CHUN SHEN

In collaboration with
BJÖRN SCHENKE

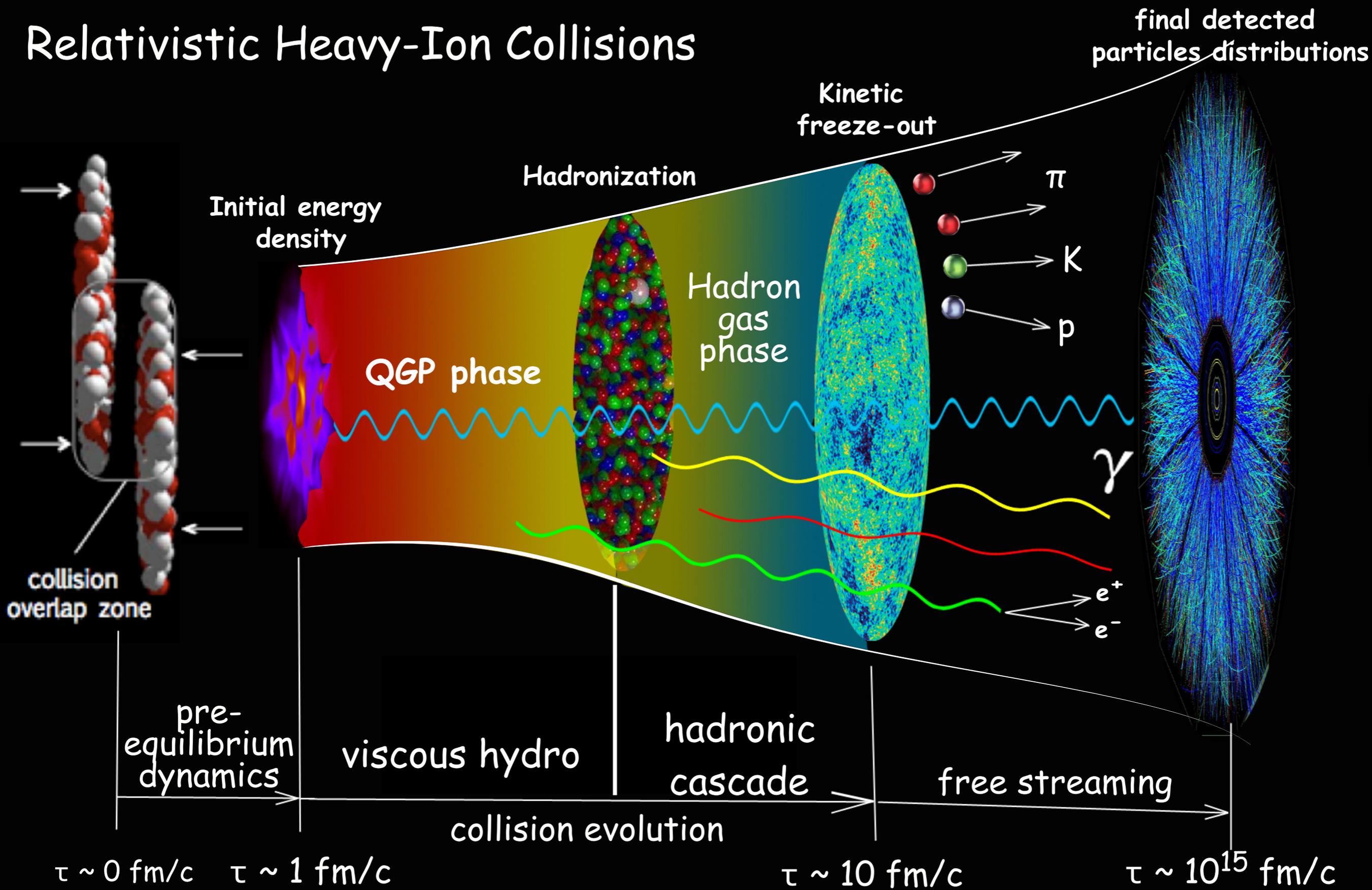
Phase diagram of hot nuclear matter



- What is the phase structure of nuclear matter
- What are the transport properties of the Quark-Gluon Plasma (QGP)
- Where is the critical point located

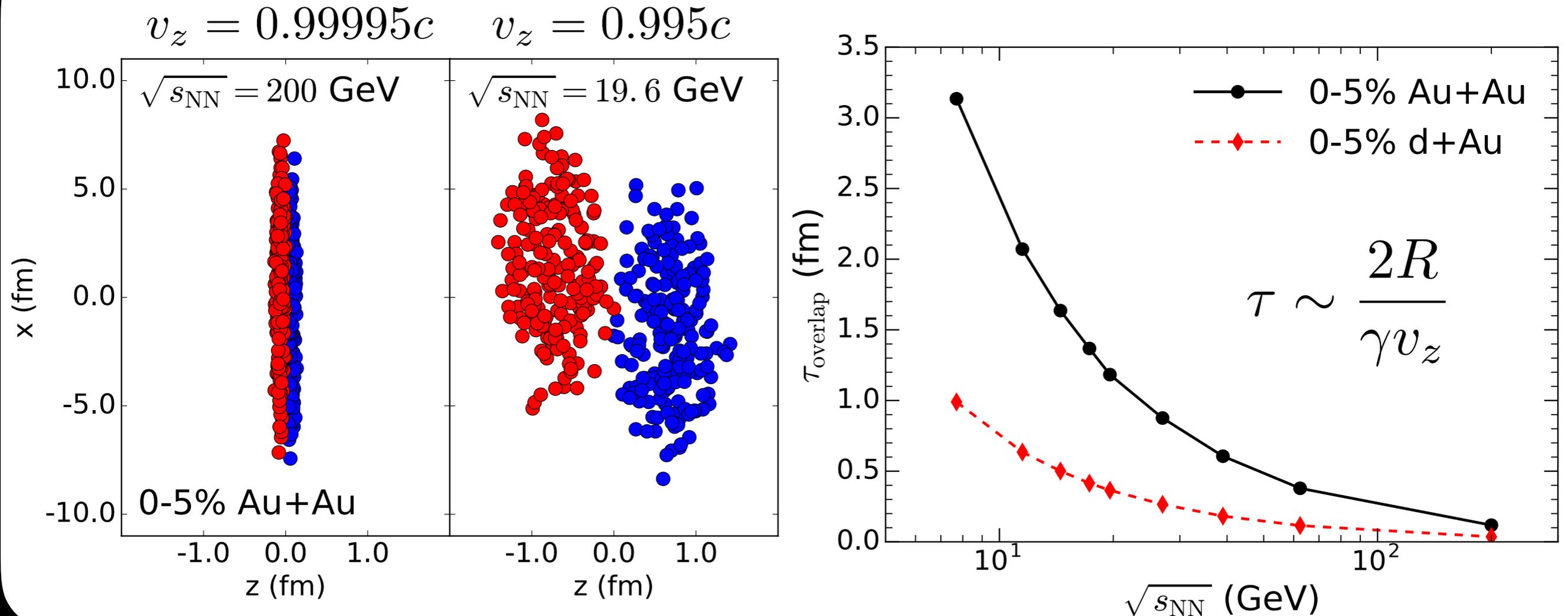
The picture is taken from <http://www.bnl.gov/newsroom/news.php? a=11446>

Relativistic Heavy-Ion Collisions



When to start hydrodynamics?

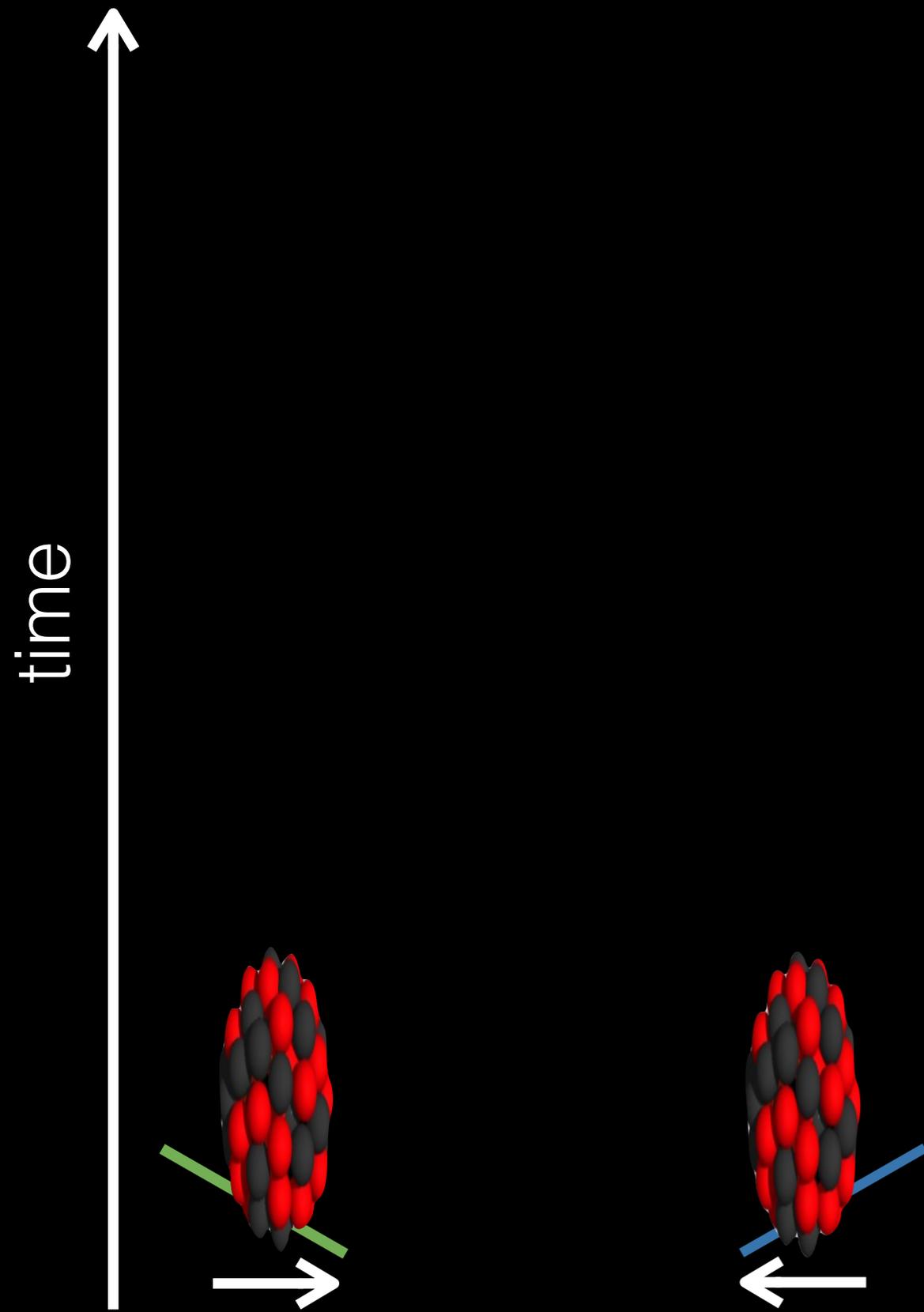
C. Shen and B. Schenke, Phys.Rev. C97 (2018) 024907



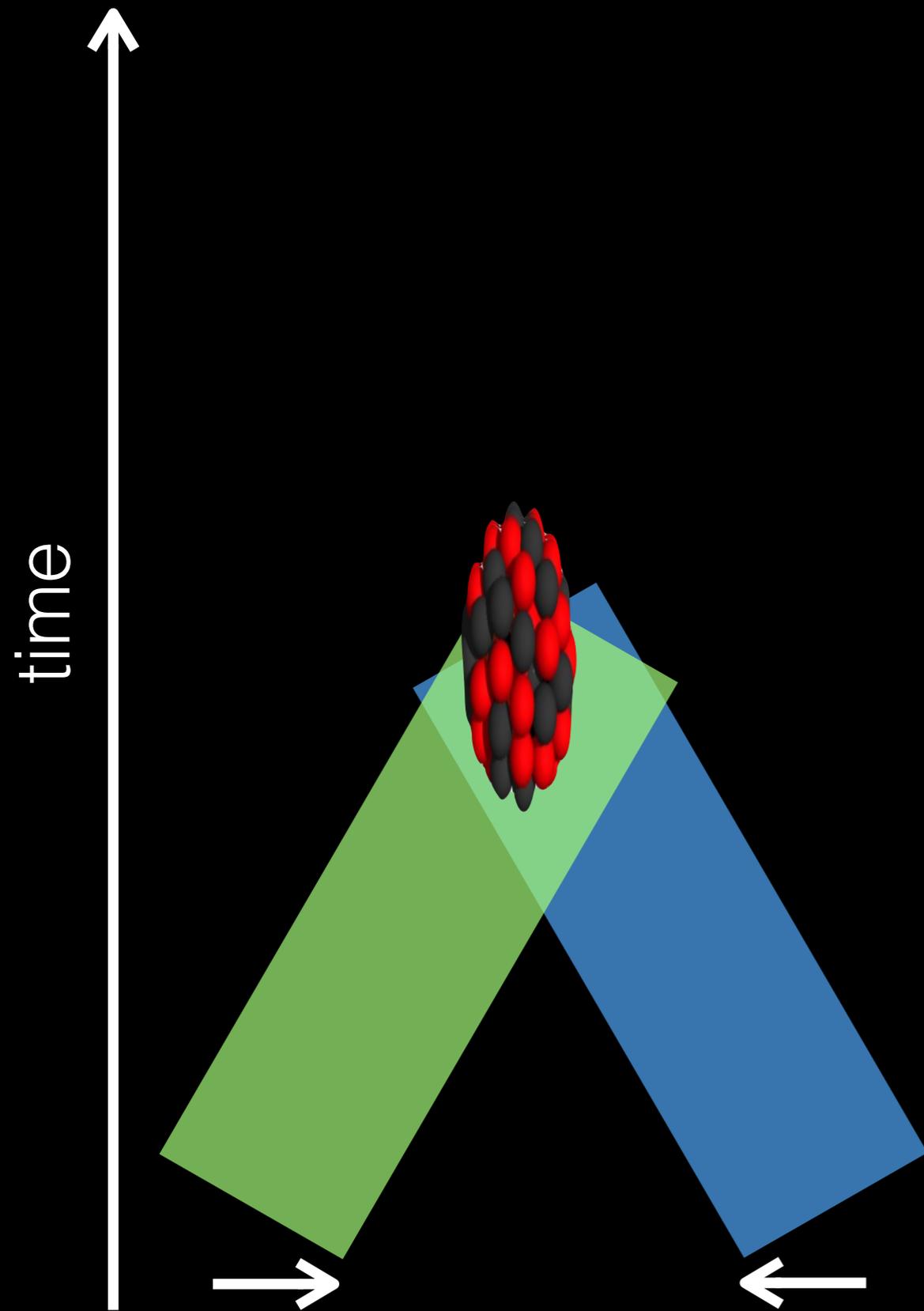
- Nuclei overlapping time is **large** at low collision energy
- **Pre-equilibrium dynamics** can play an important role

note: total evolution time ~ 10 fm

Model heavy-ion collisions in 3D

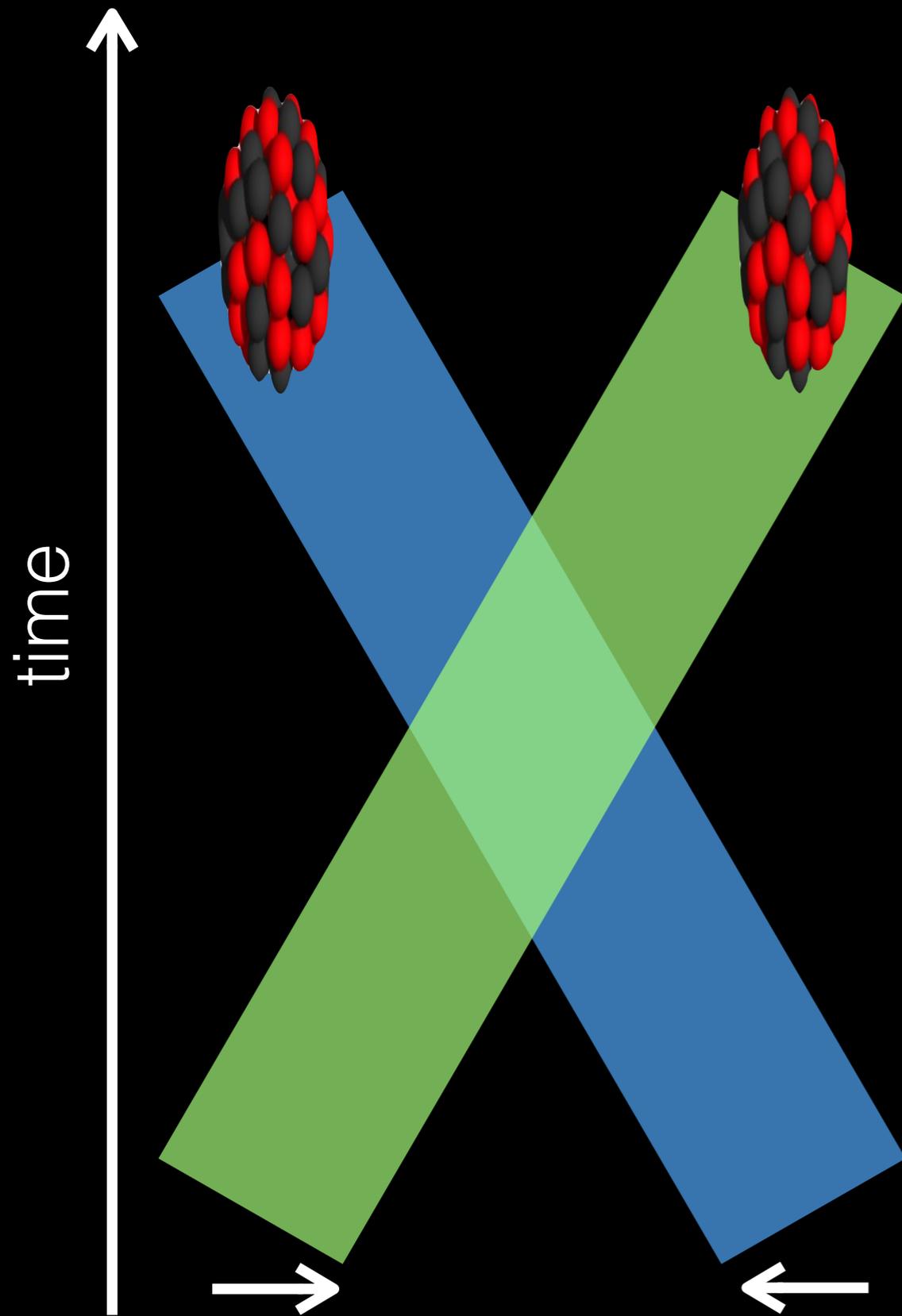


Model heavy-ion collisions in 3D

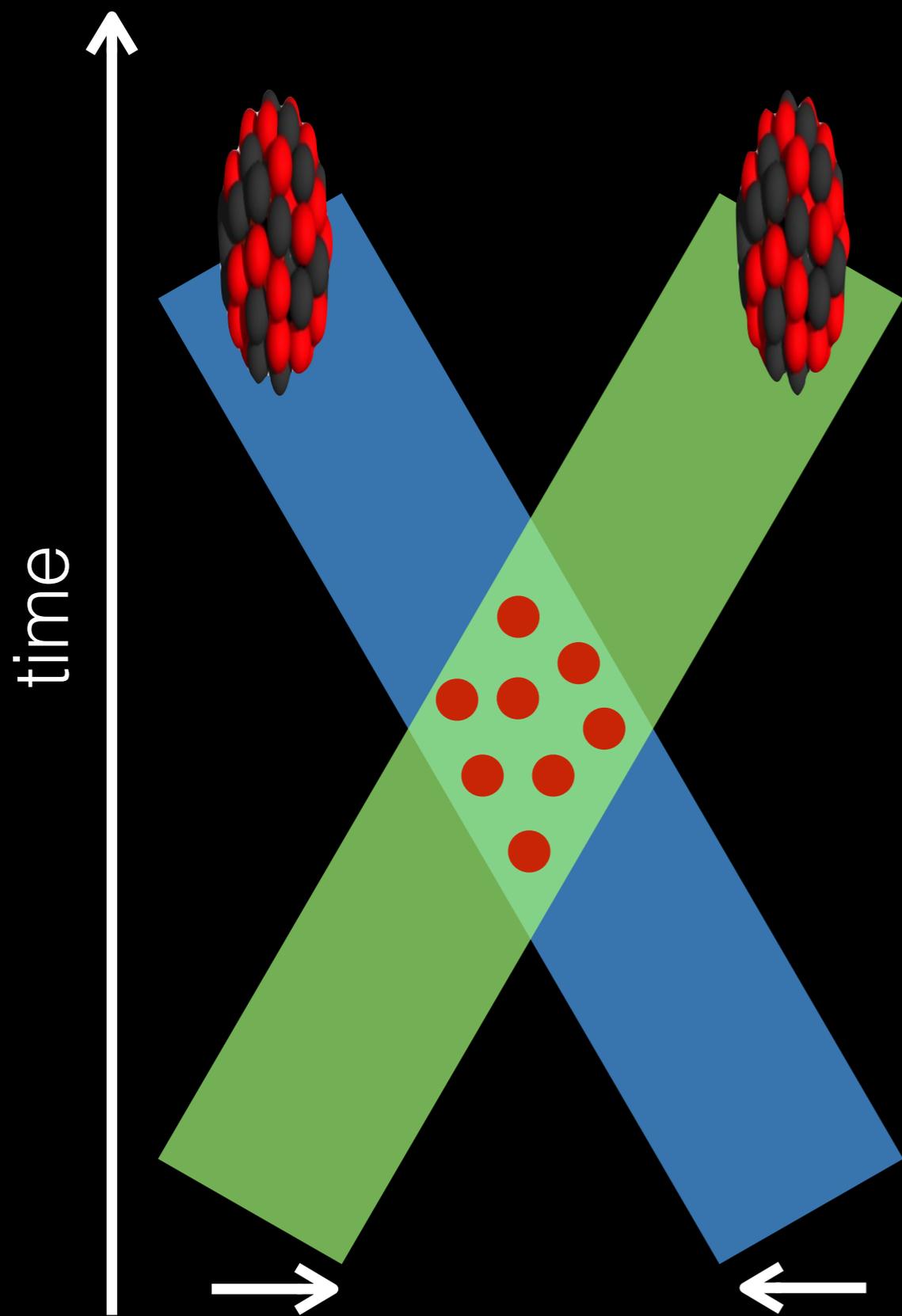


Model heavy-ion collisions in 3D

- The interaction zone is not point like



Model heavy-ion collisions in 3D

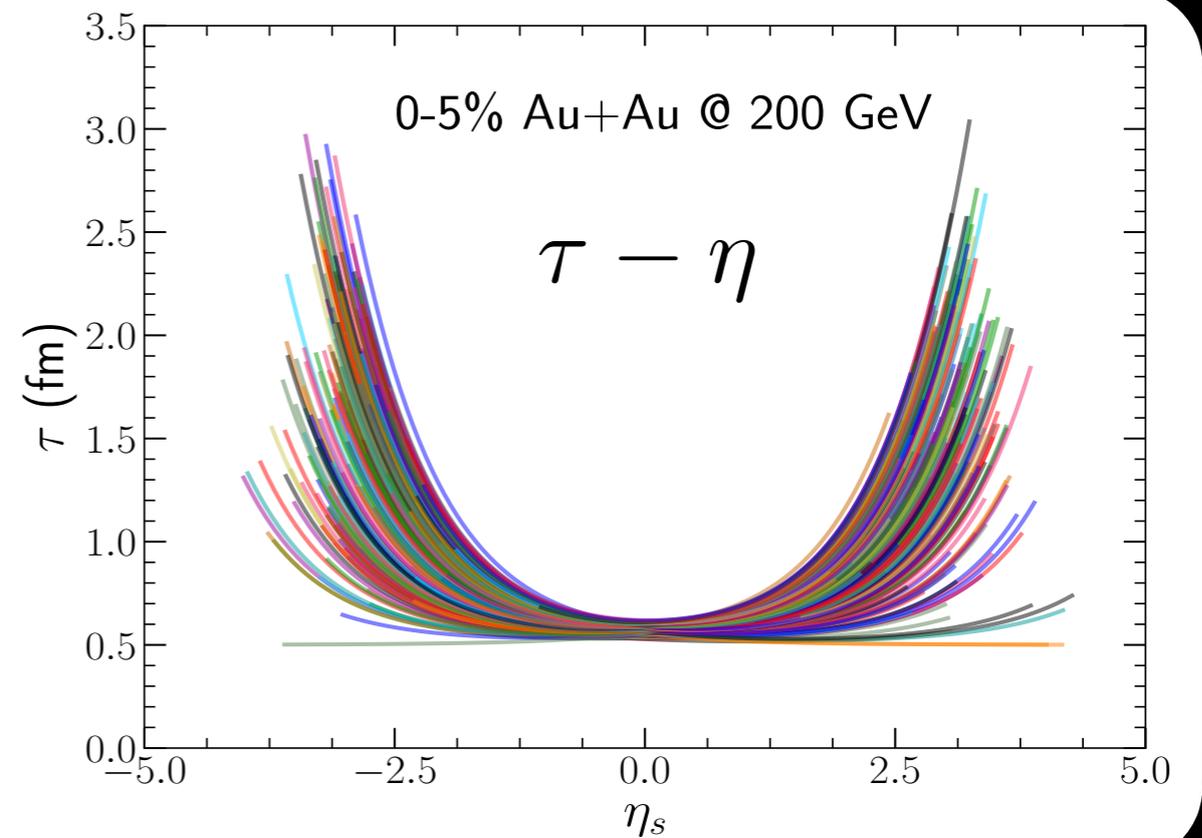
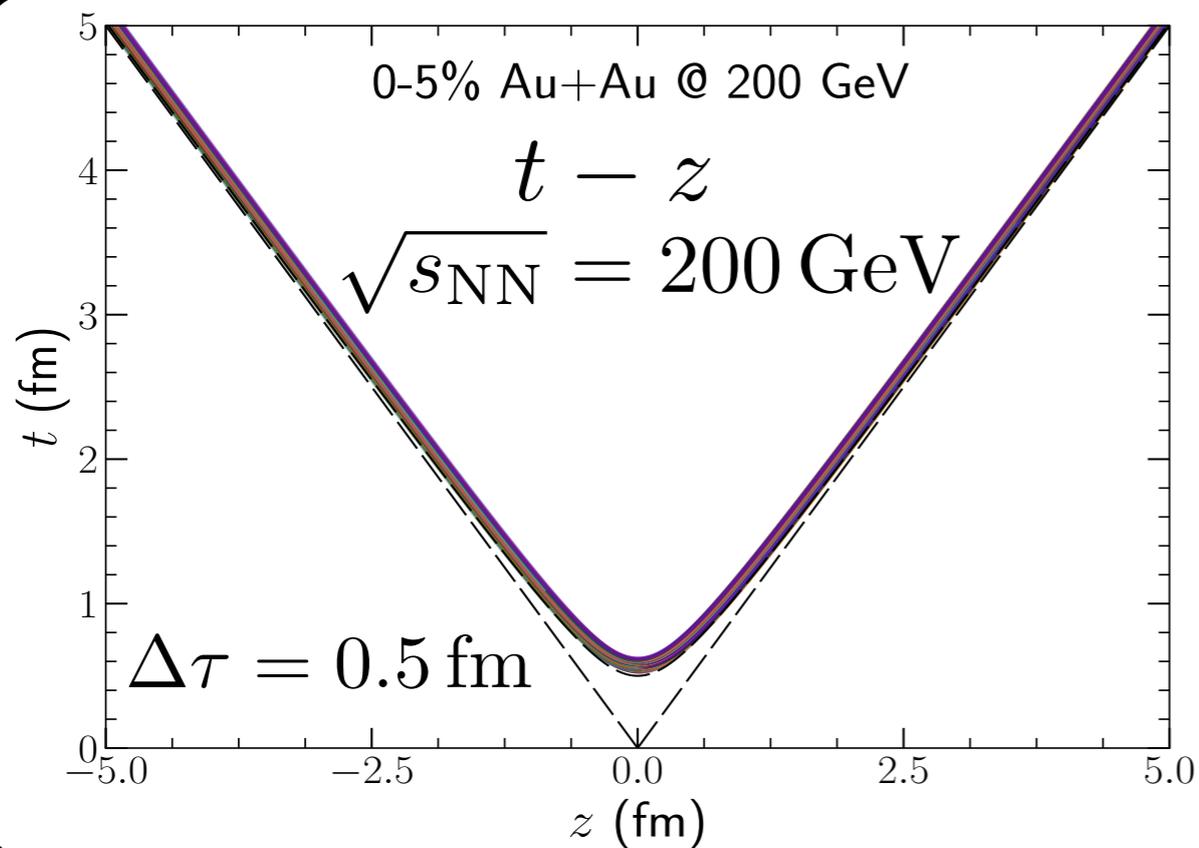


- The interaction zone is not point like
- The colliding nucleons are decelerated with a classical string model from binary collision points
- The lost energy and momentum from the decelerated nucleons are fed into hydrodynamic fields as source terms

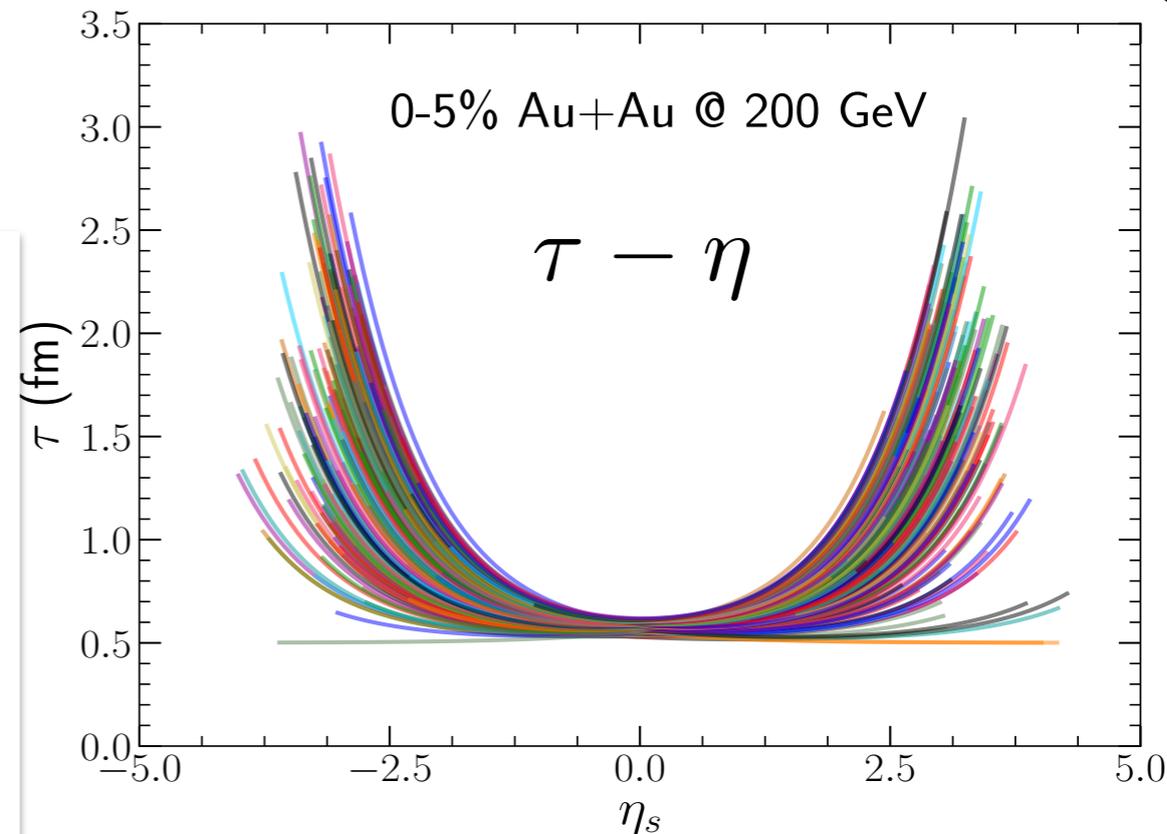
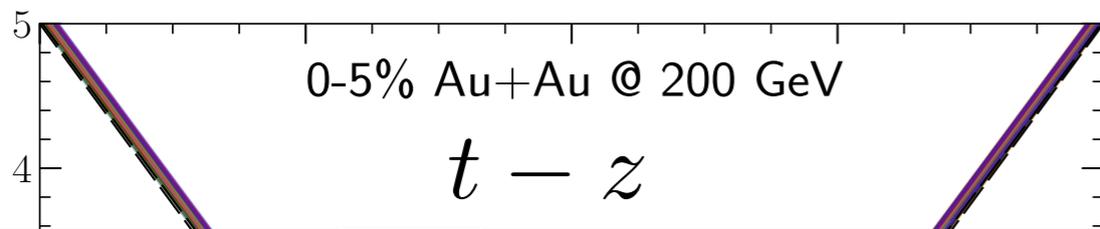
A. Bialas, A. Bzdak and V. Koch,
[arXiv:1608.07041 \[hep-ph\]](https://arxiv.org/abs/1608.07041)

C. Shen and B. Schenke,
[Phys.Rev. C97 \(2018\) no.2, 024907](https://arxiv.org/abs/1708.07504)

String space-time distribution

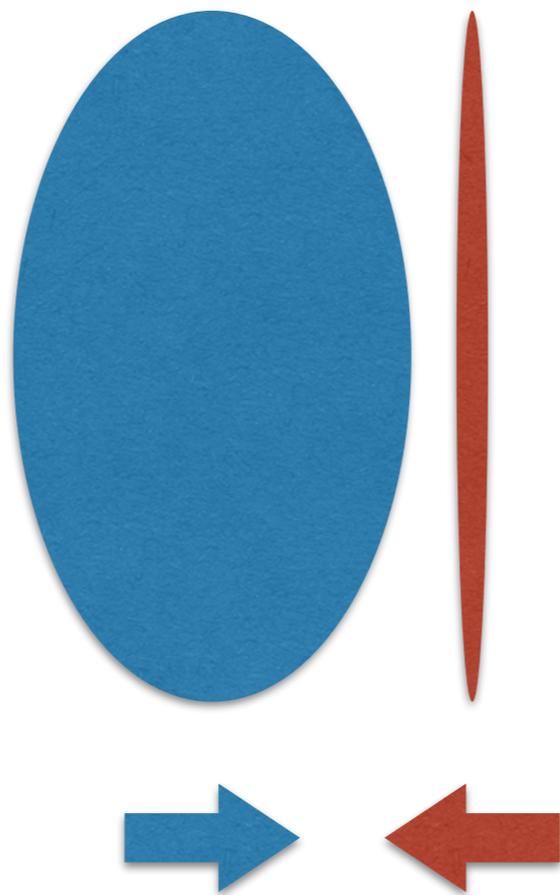
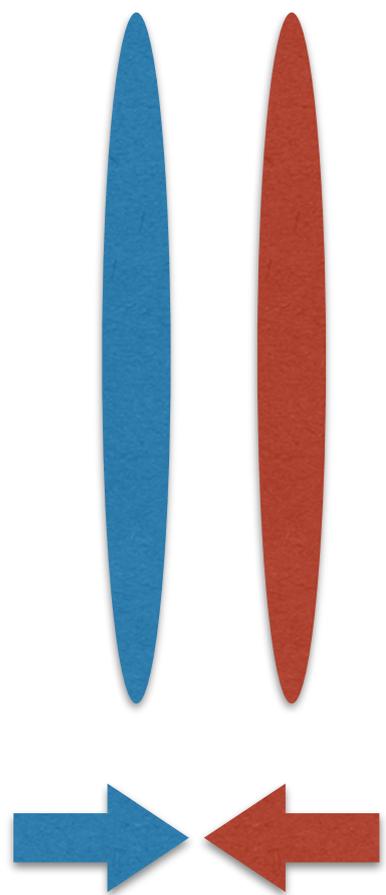


String space-time distribution

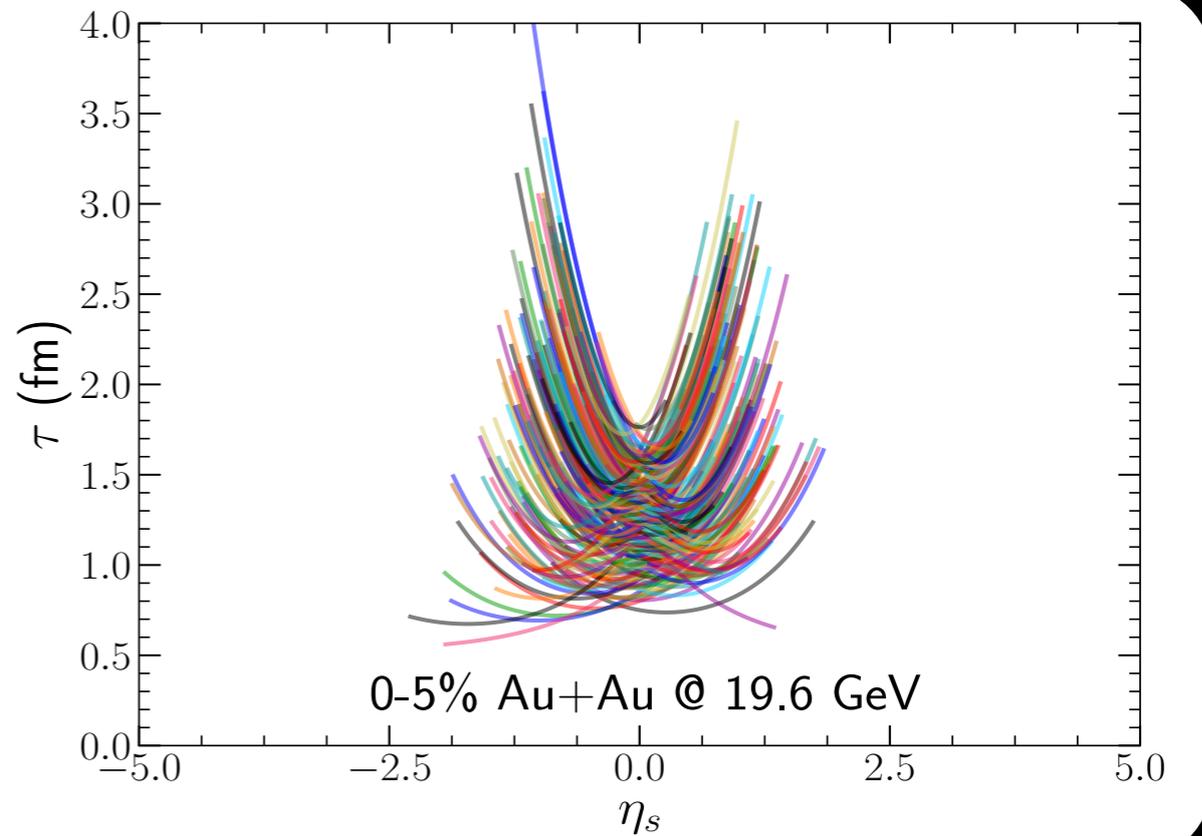
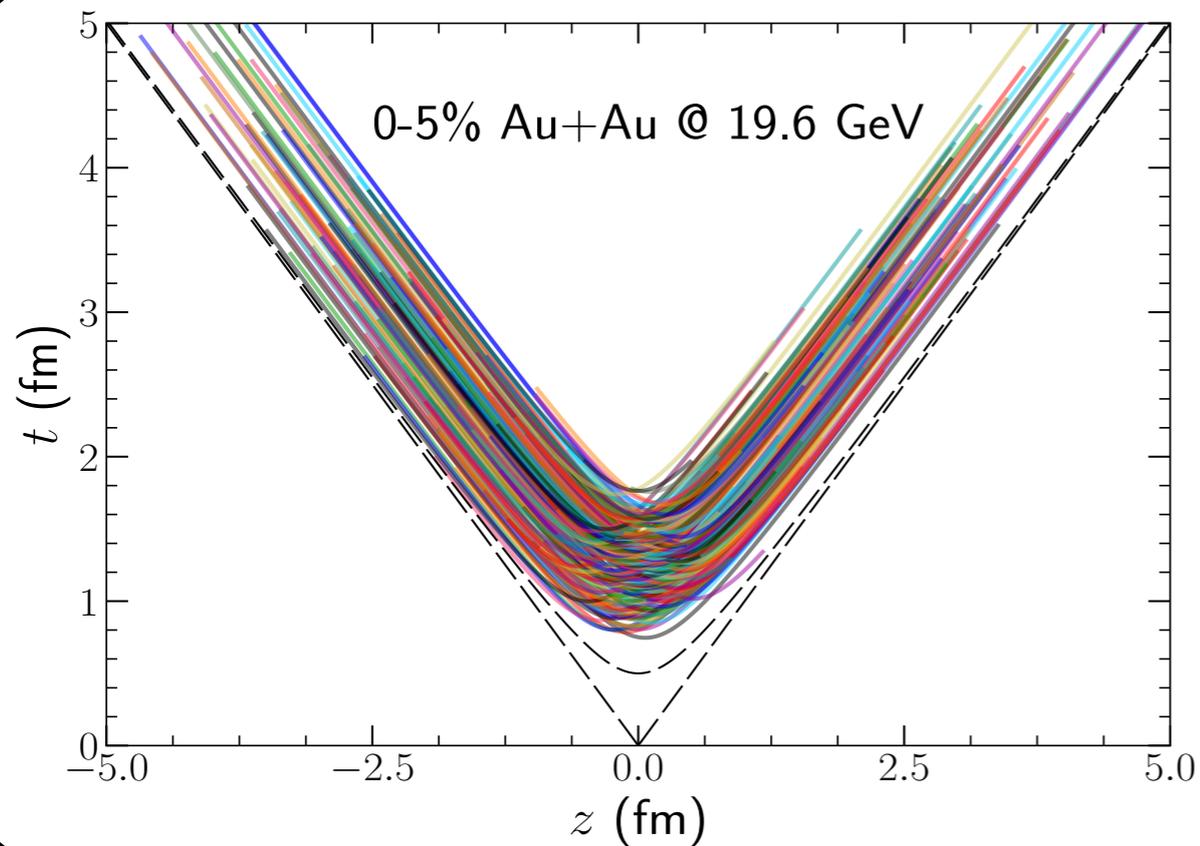
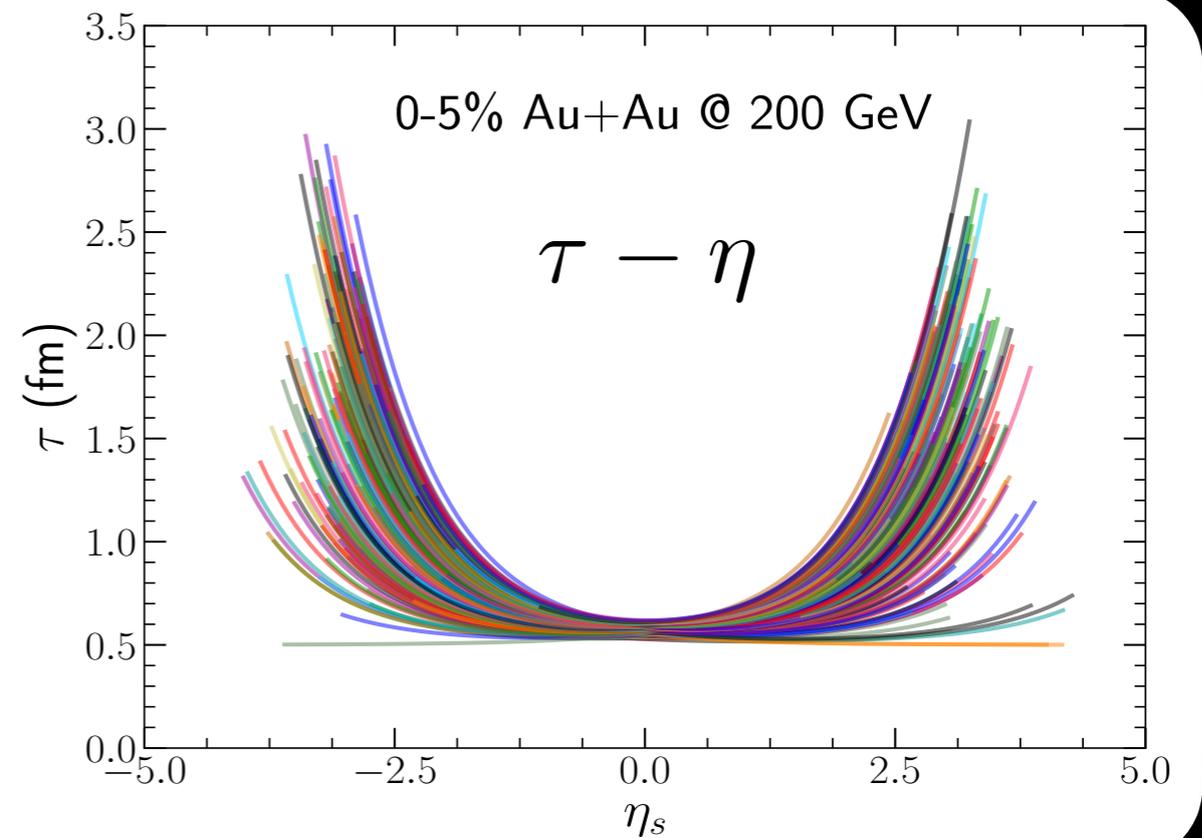
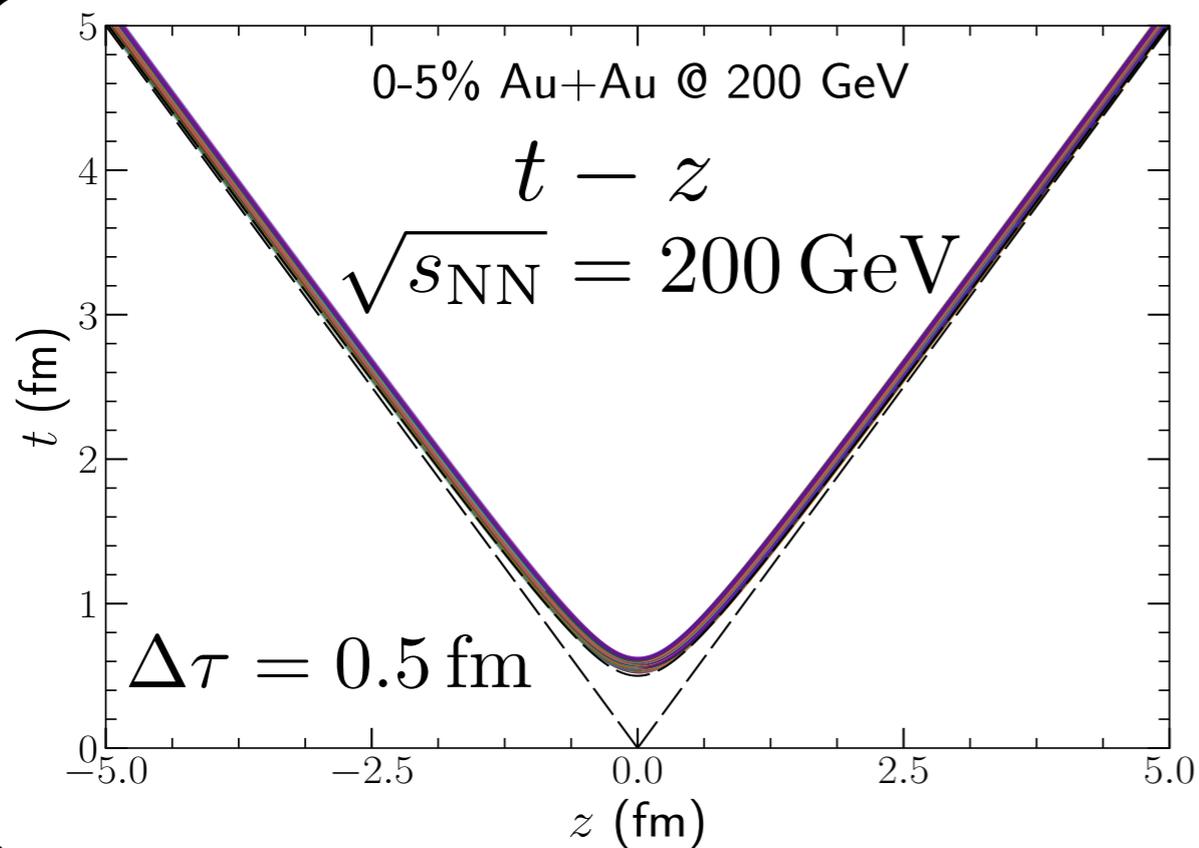


$\eta_s = 0$

$\eta_s = 3$

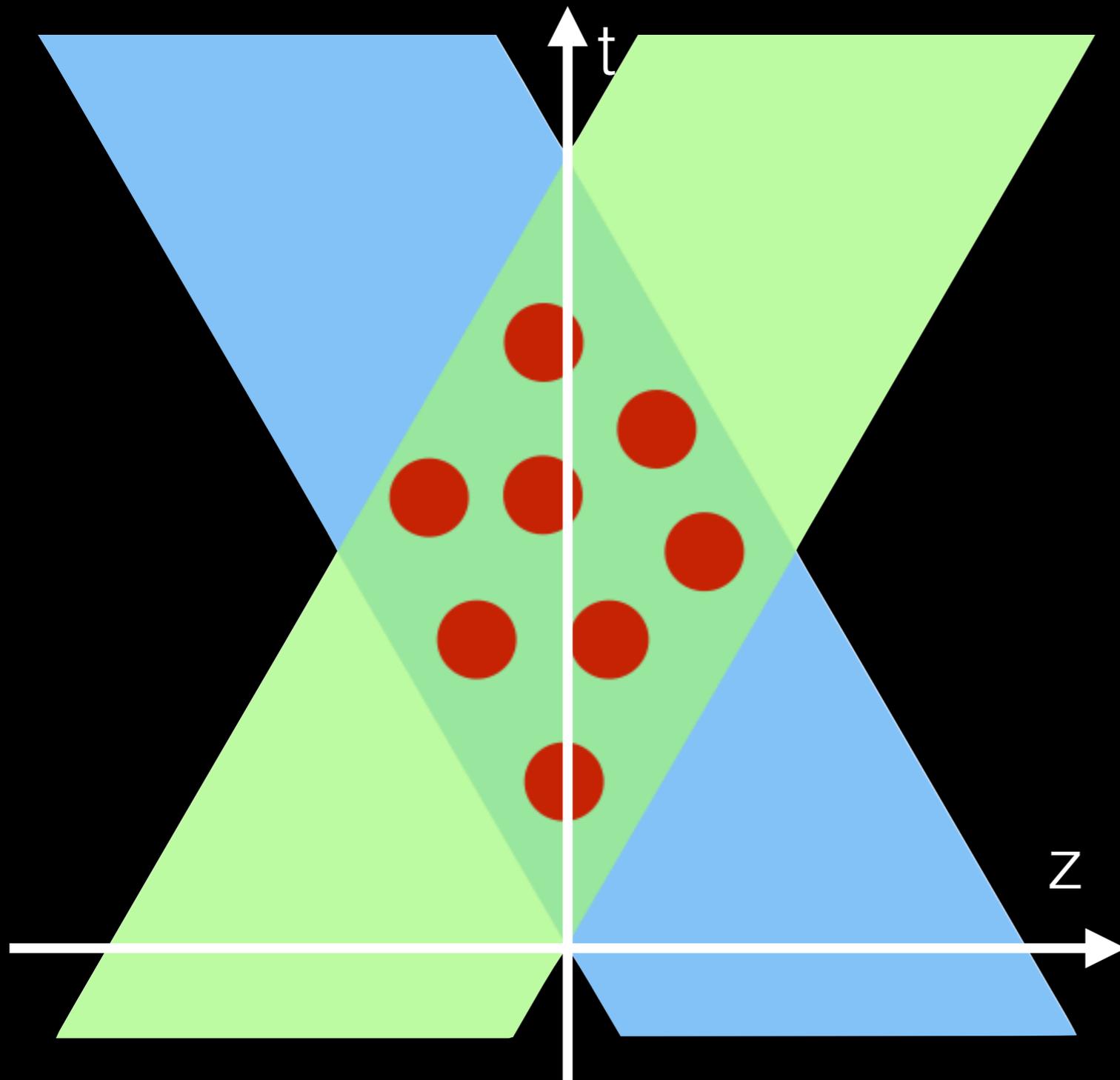


String space-time distribution



Hydrodynamics with sources

Energy-momentum current and net baryon density are fed into hydrodynamic simulation as source terms

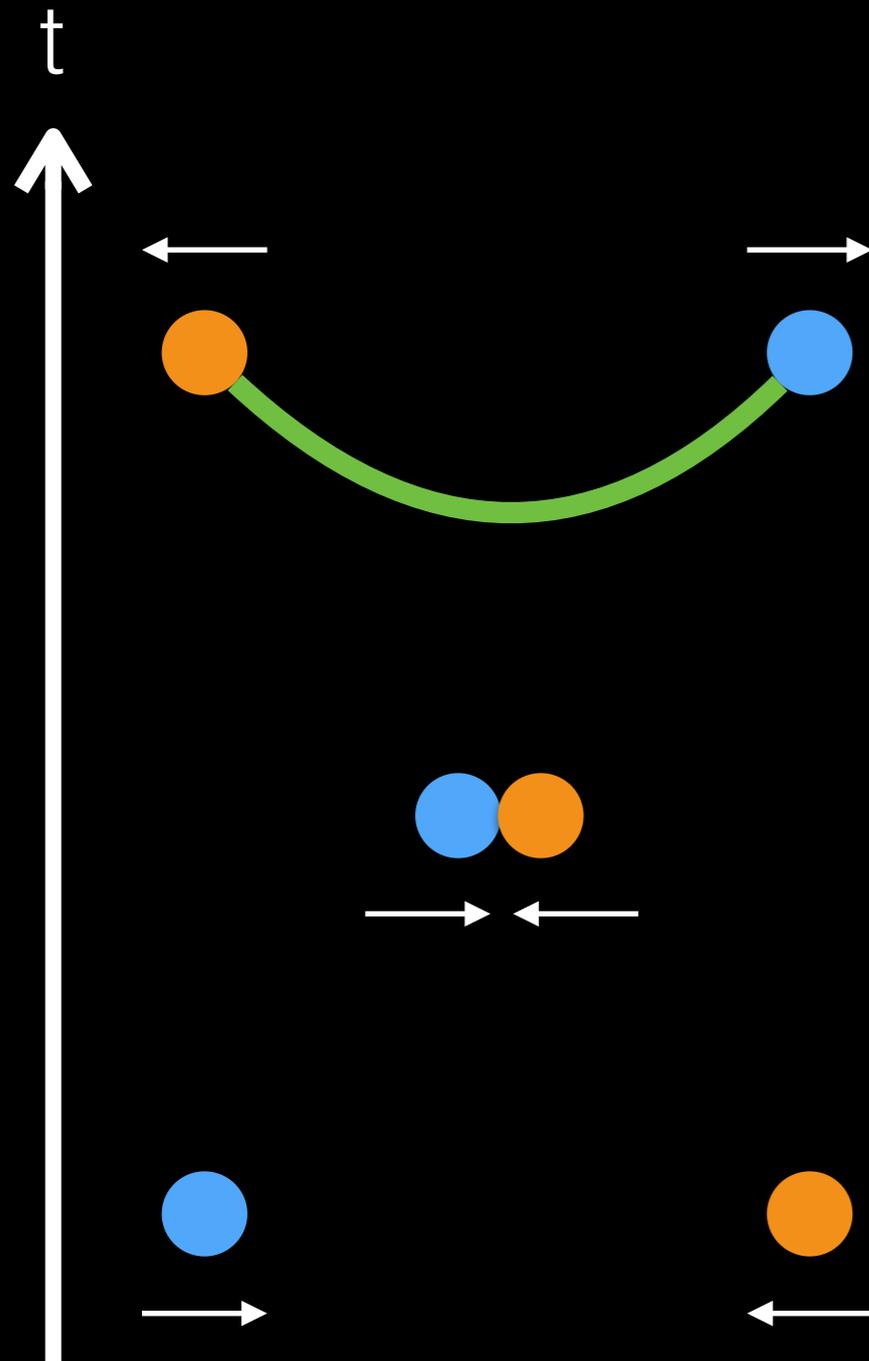


$$\partial_{\mu} T^{\mu\nu} = J_{\text{source}}^{\nu}$$
$$\partial_{\mu} J^{\mu} = \rho_{\text{source}}$$



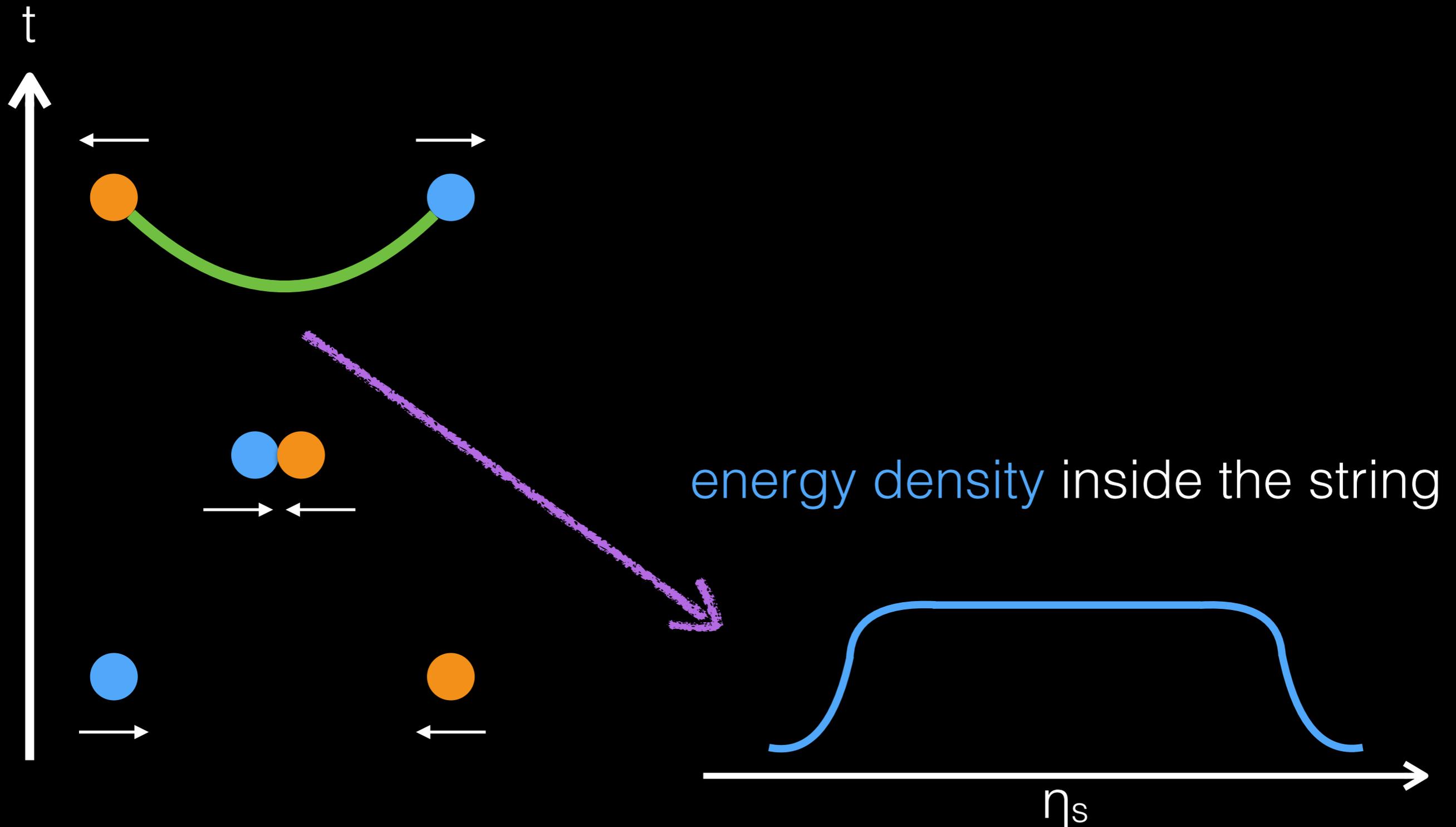
Details about the dynamical initialization

C. Shen and B. Schenke, Phys.Rev. C97 (2018) 024907



Details about the dynamical initialization

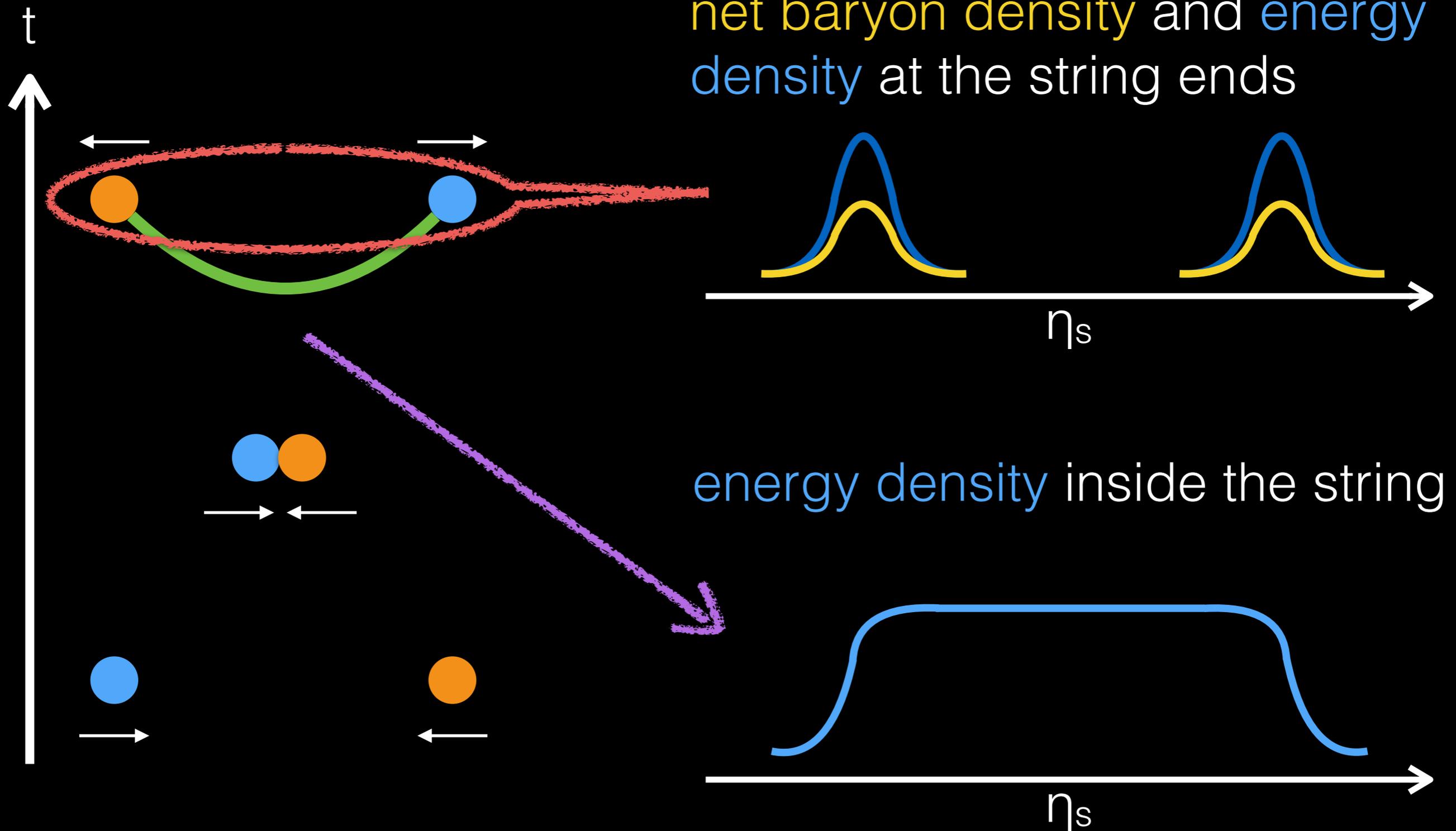
C. Shen and B. Schenke, Phys.Rev. C97 (2018) 024907



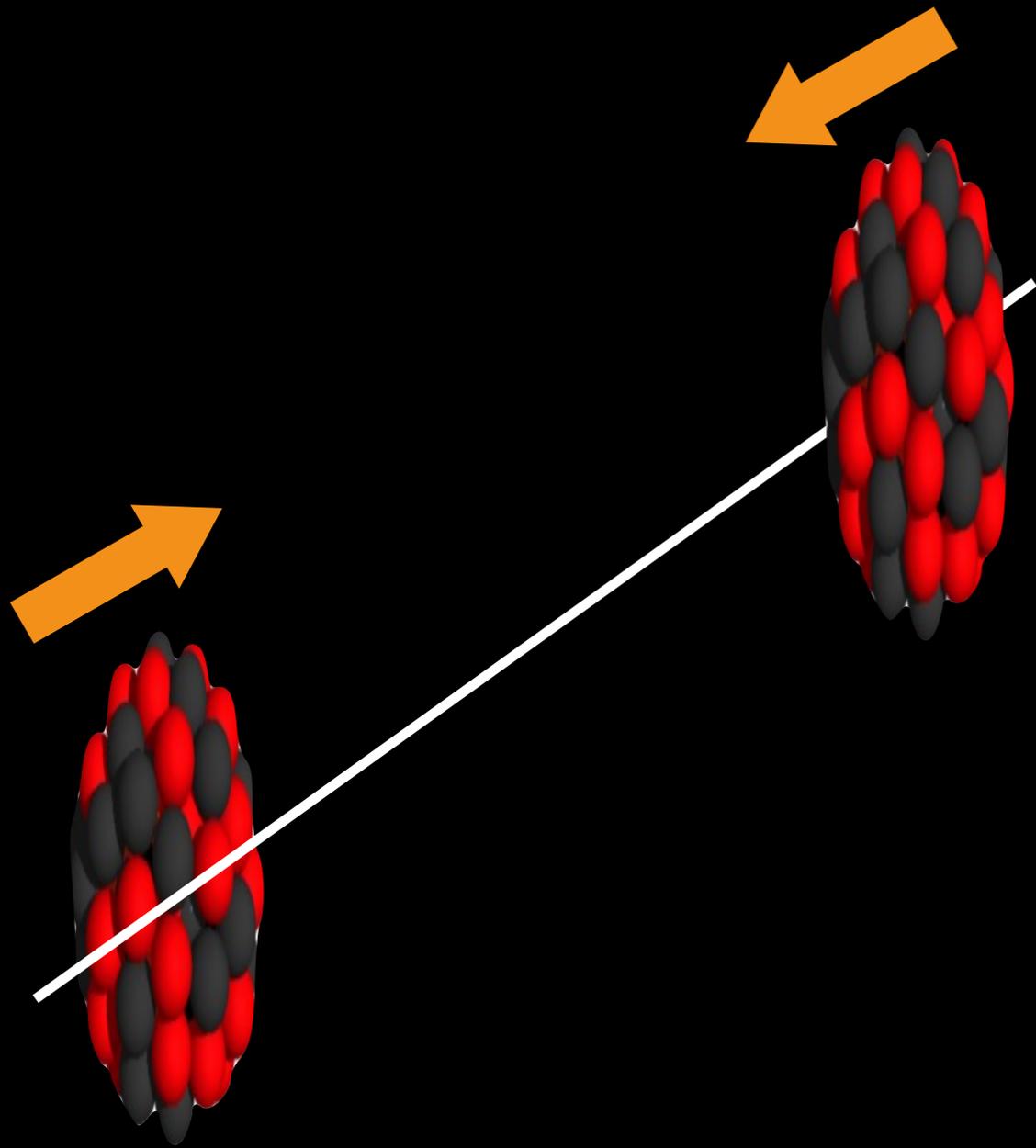
Details about the dynamical initialization

C. Shen and B. Schenke, Phys.Rev. C97 (2018) 024907

net baryon density and energy density at the string ends

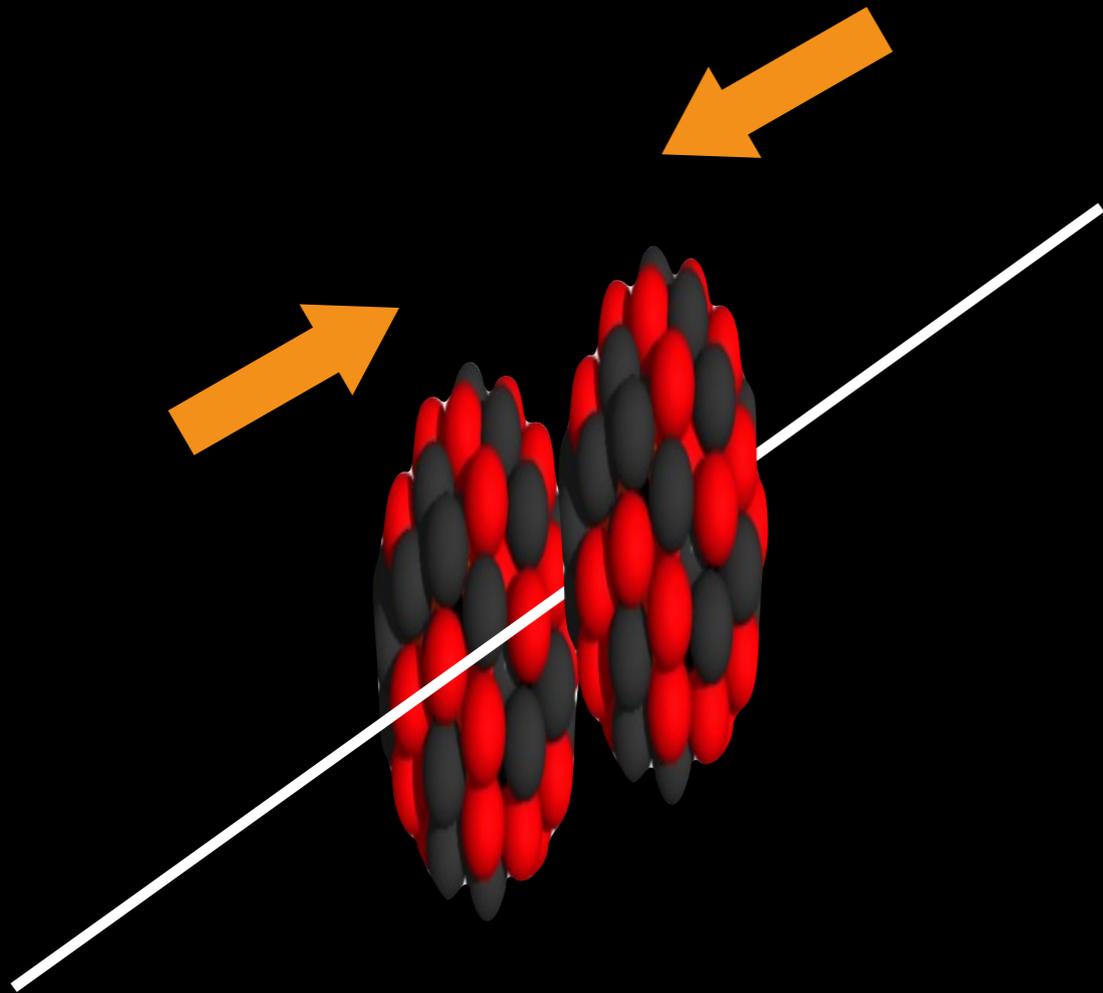


Hydrodynamical evolution with sources



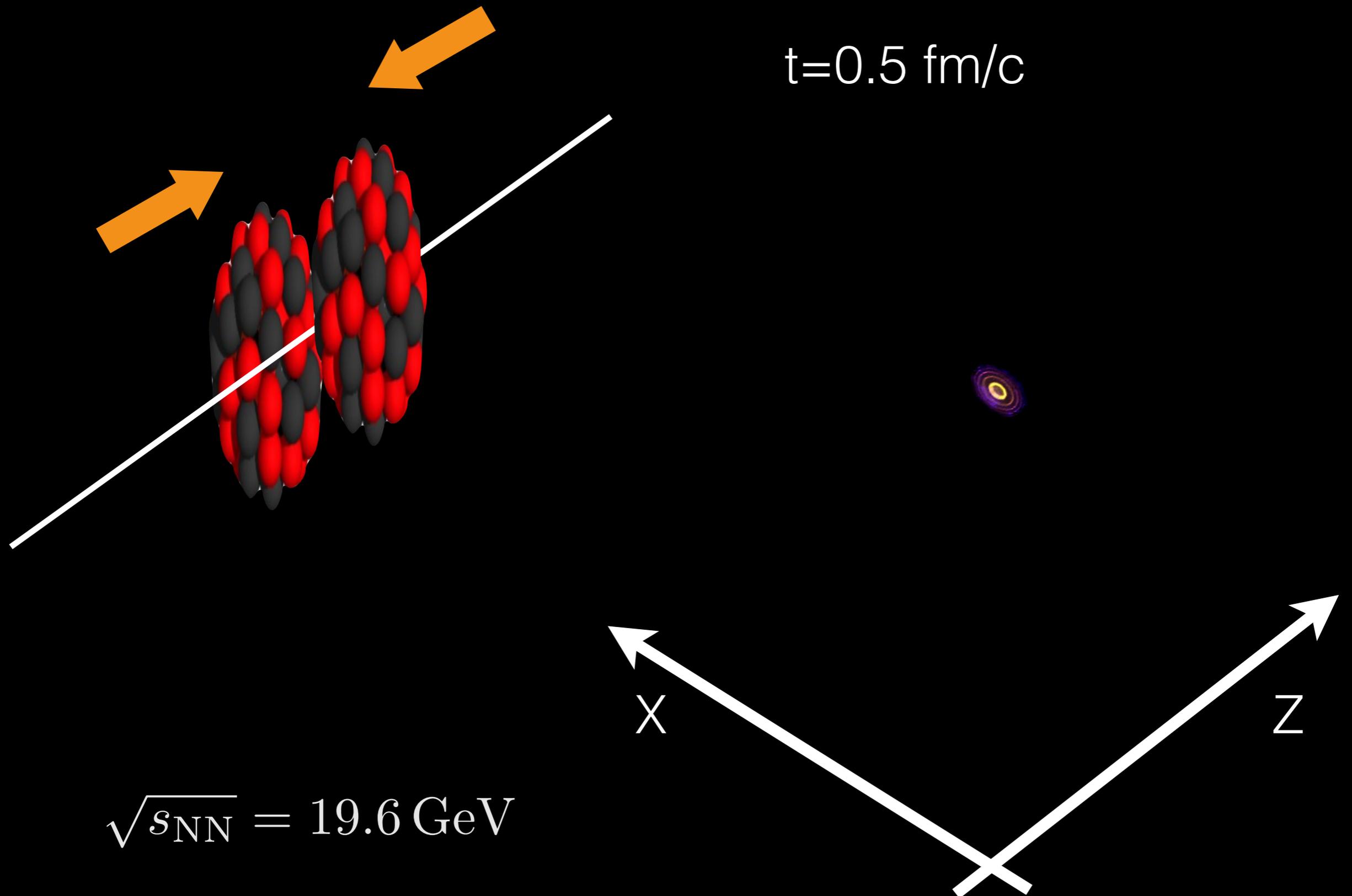
$$\sqrt{s_{\text{NN}}} = 19.6 \text{ GeV}$$

Hydrodynamical evolution with sources

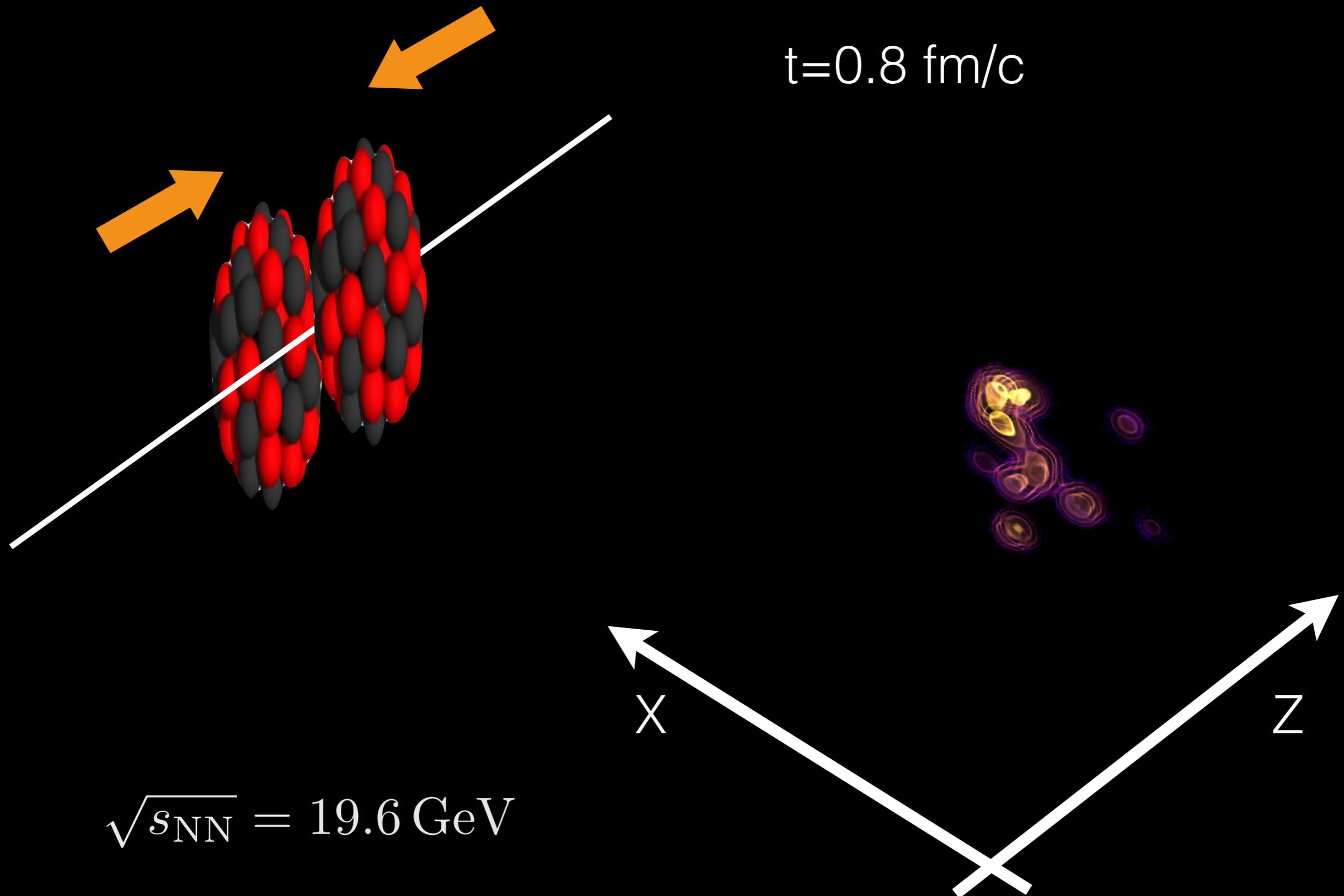


$$\sqrt{s_{\text{NN}}} = 19.6 \text{ GeV}$$

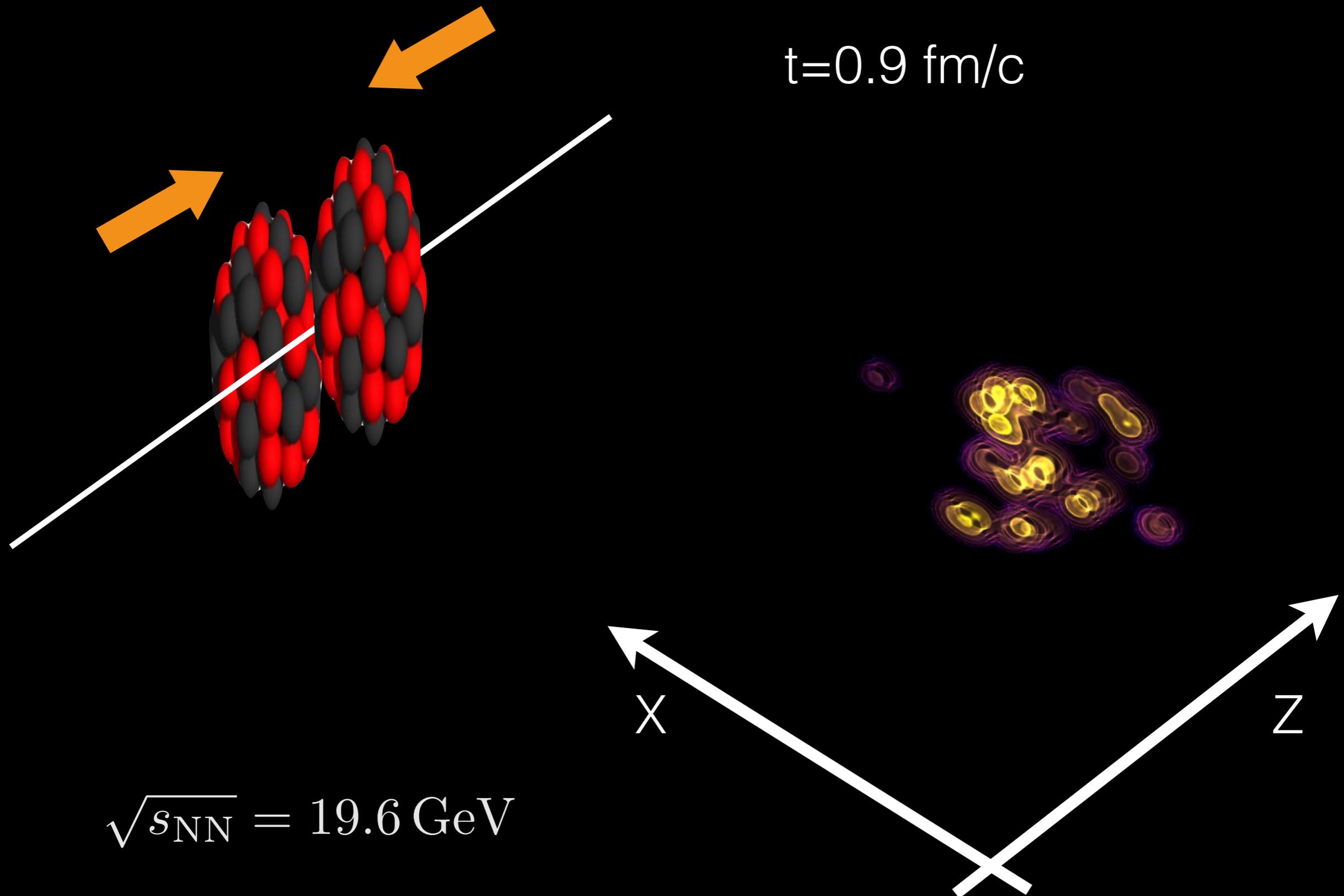
Hydrodynamical evolution with sources



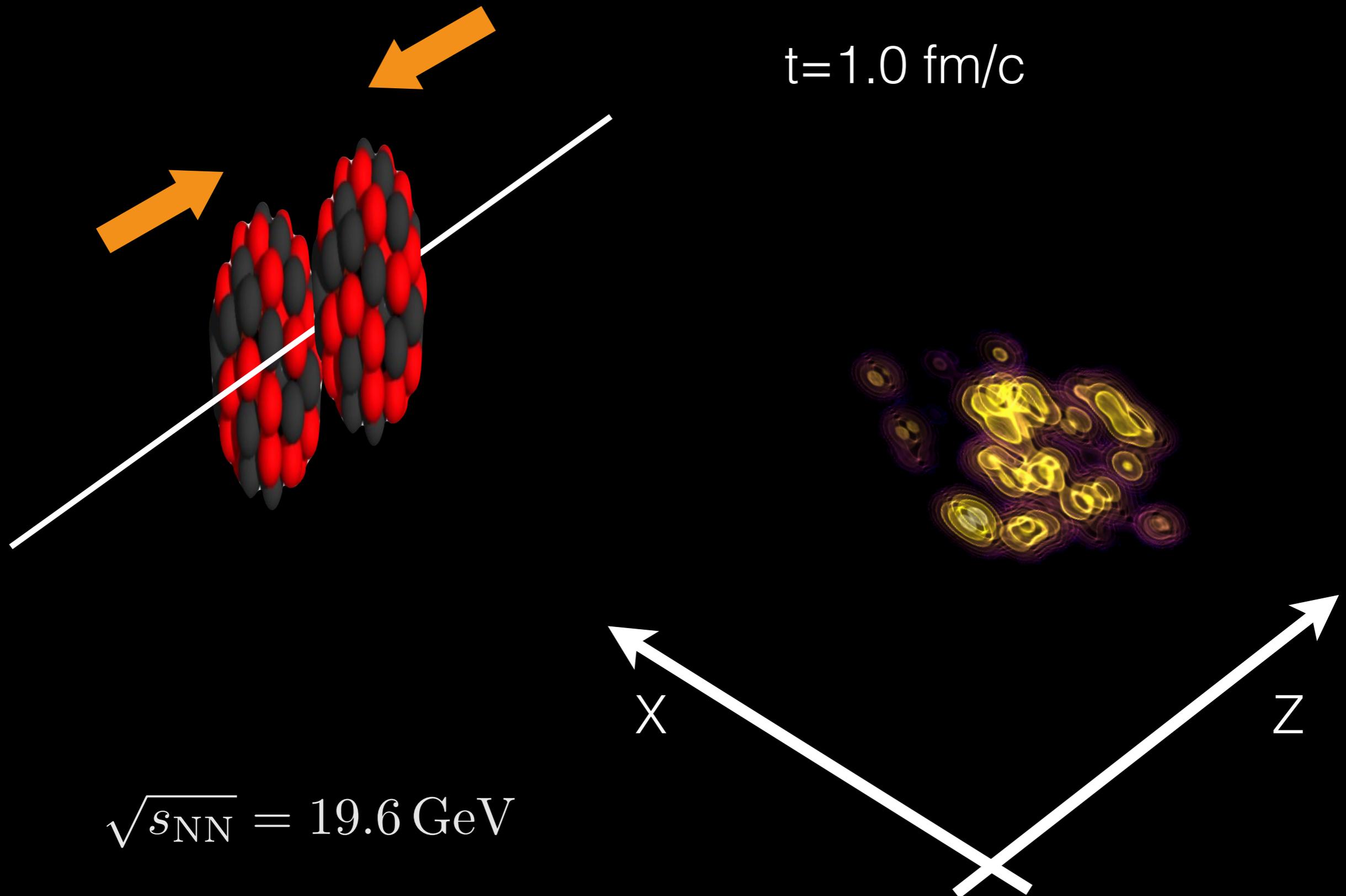
Hydrodynamical evolution with sources



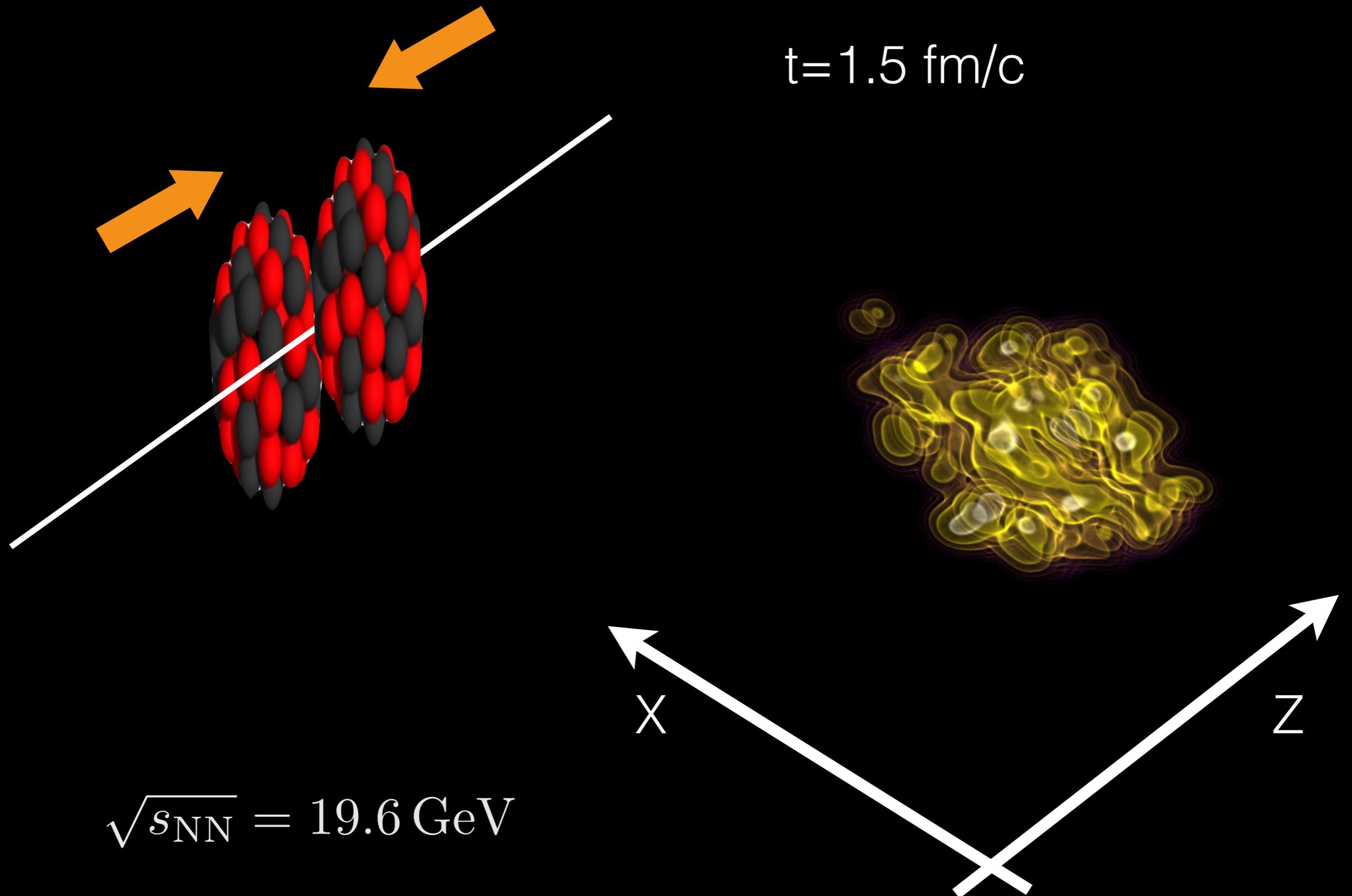
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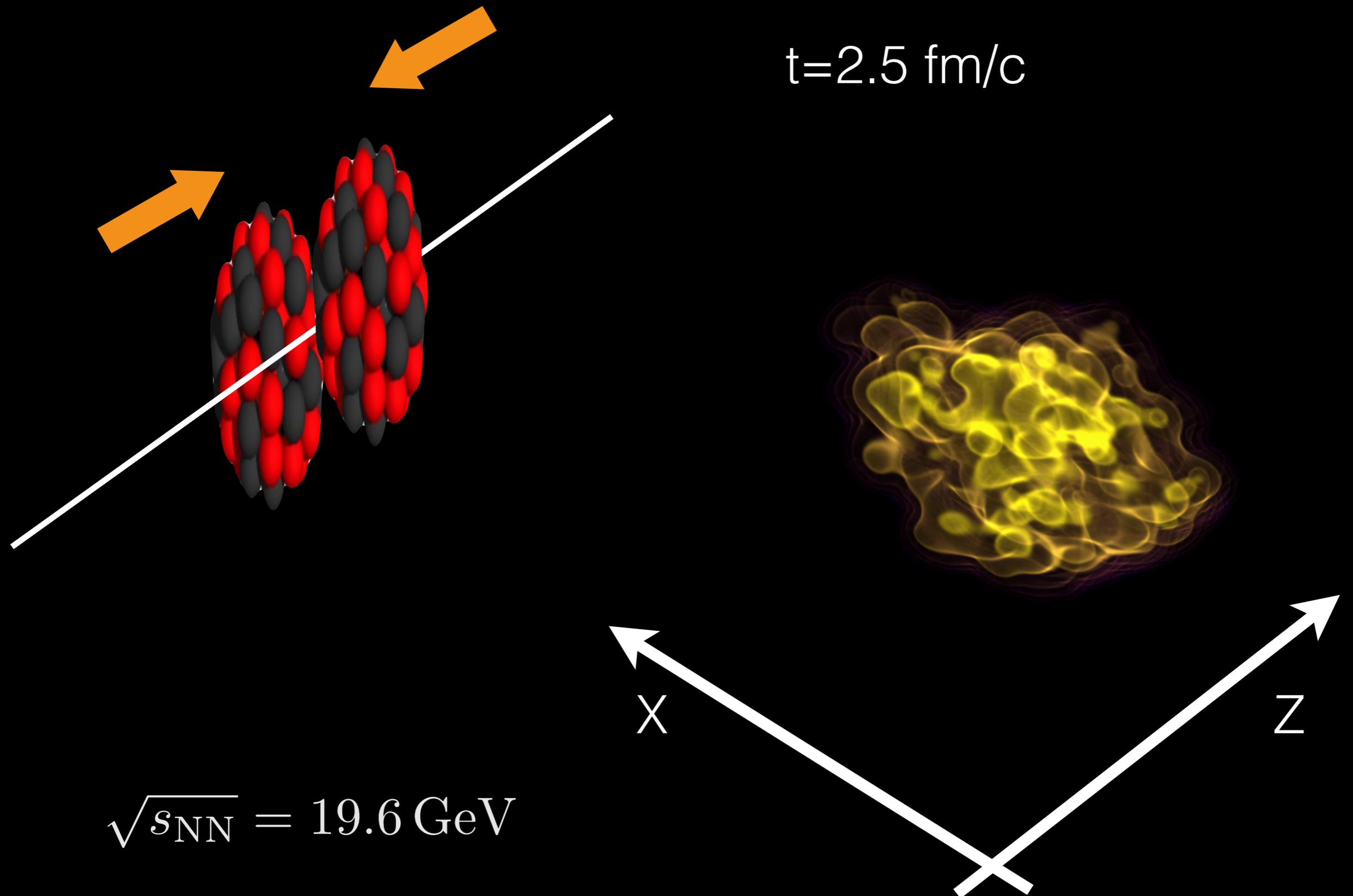
Hydrodynamical evolution with sources



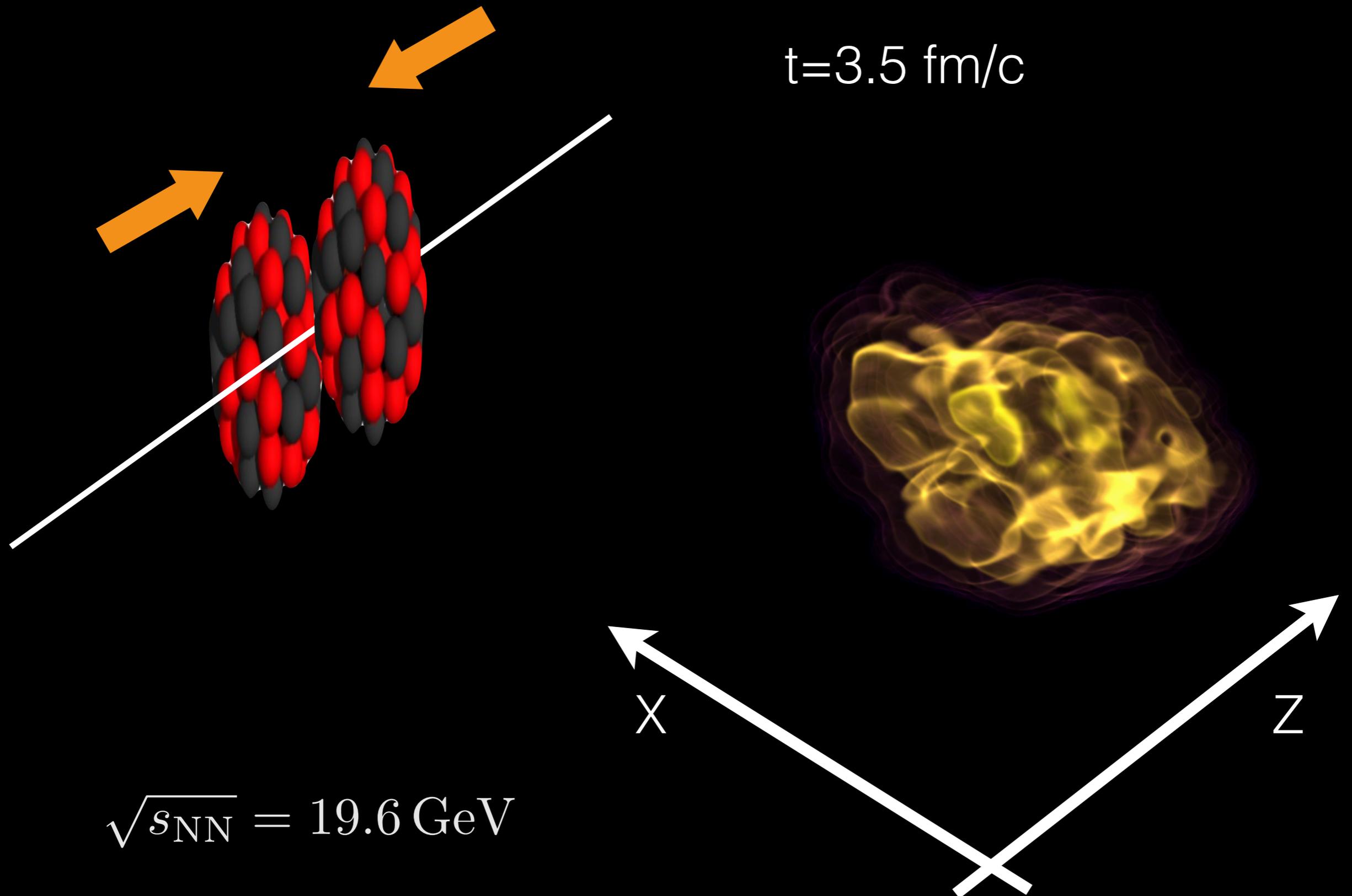
Hydrodynamical evolution with sources



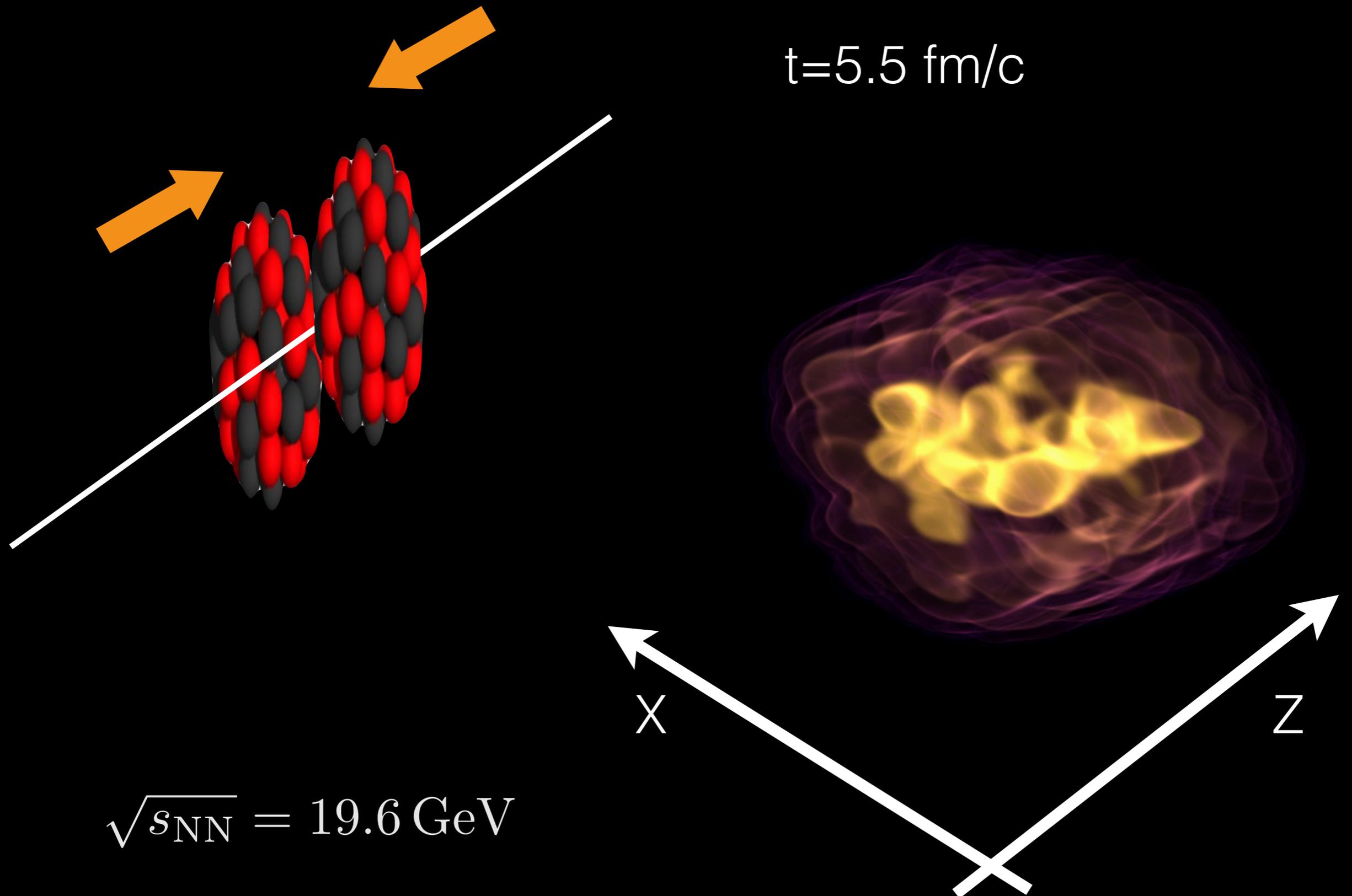
Hydrodynamical evolution with sources



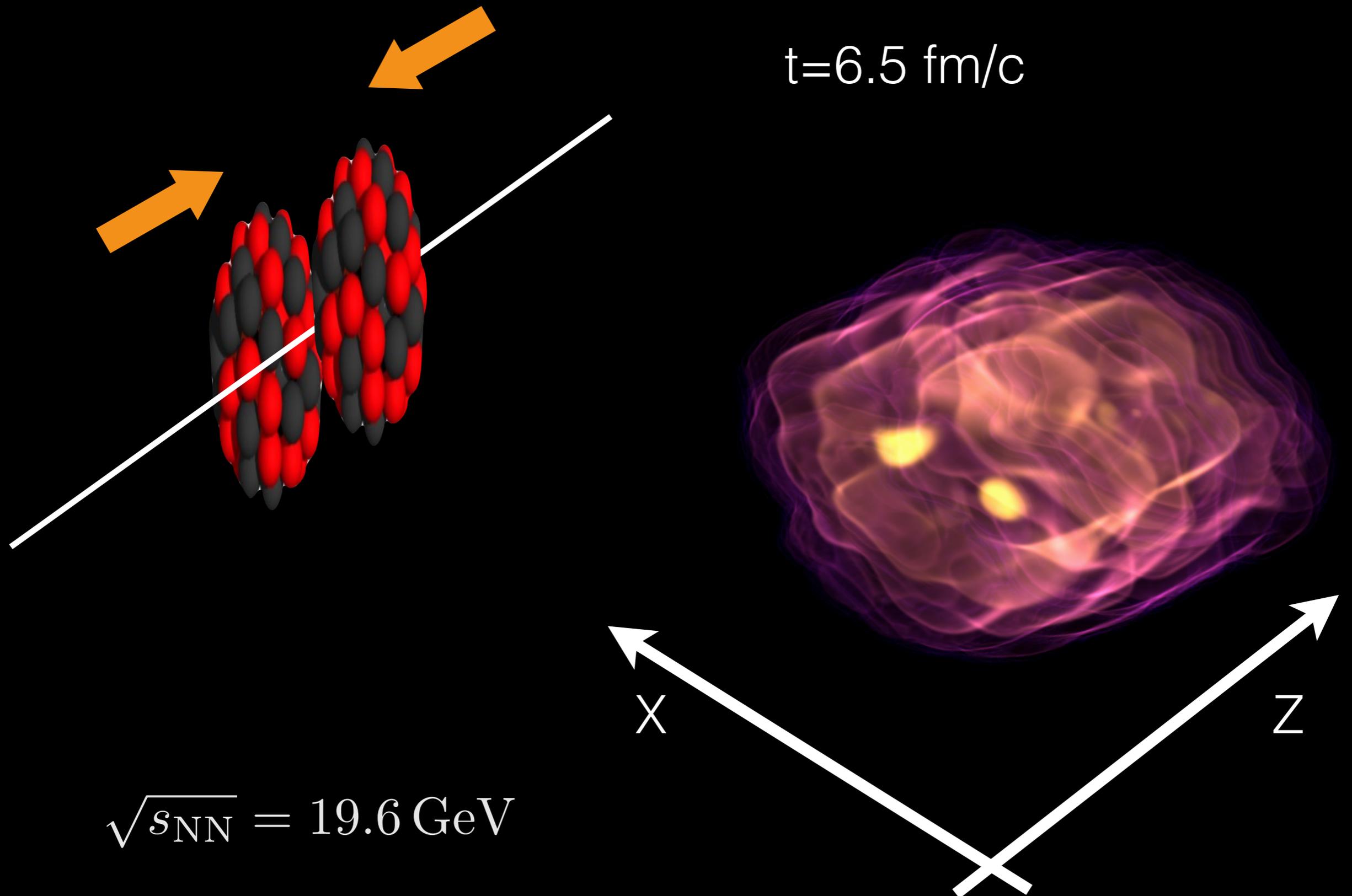
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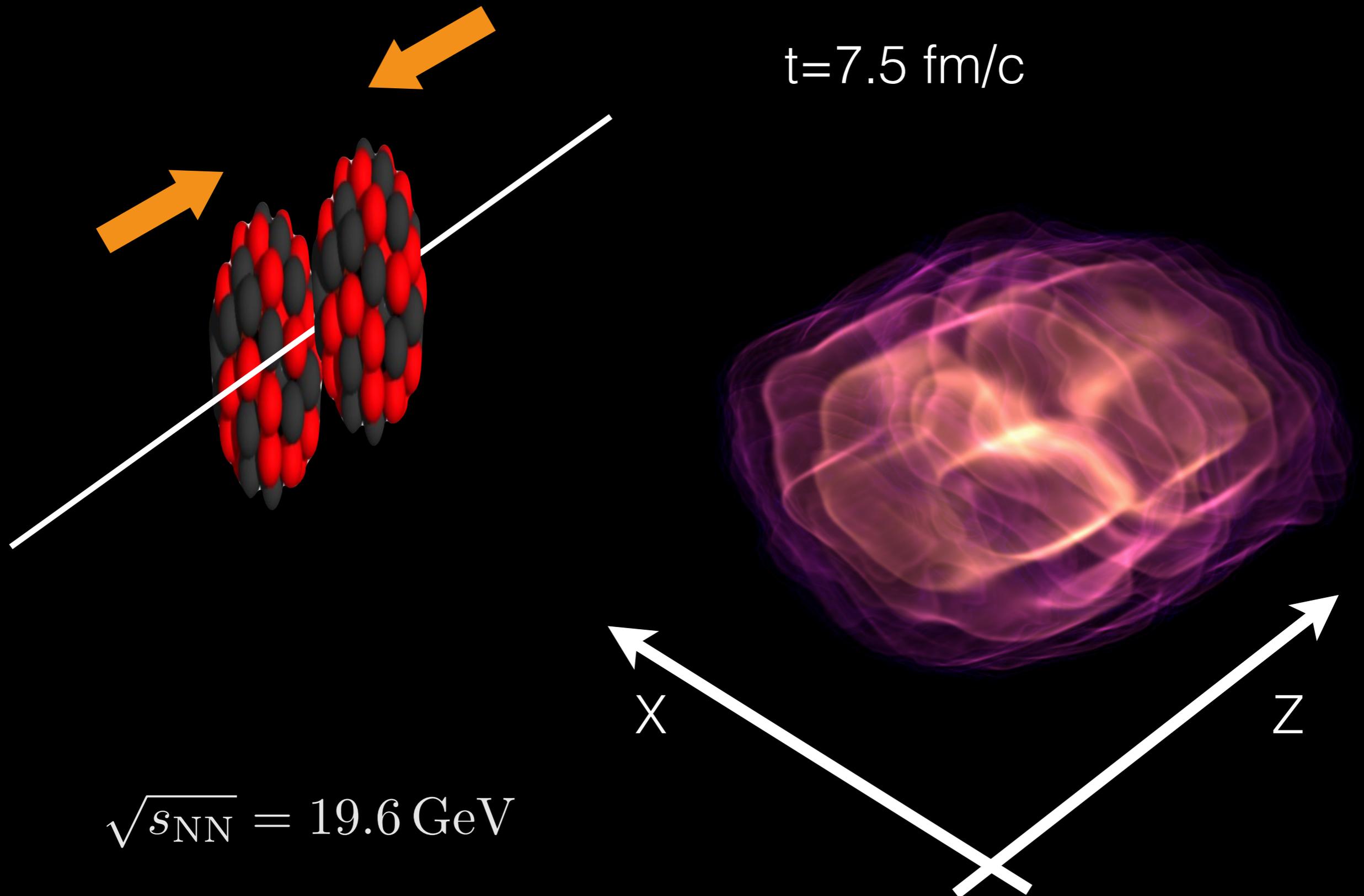
Hydrodynamical evolution with sources



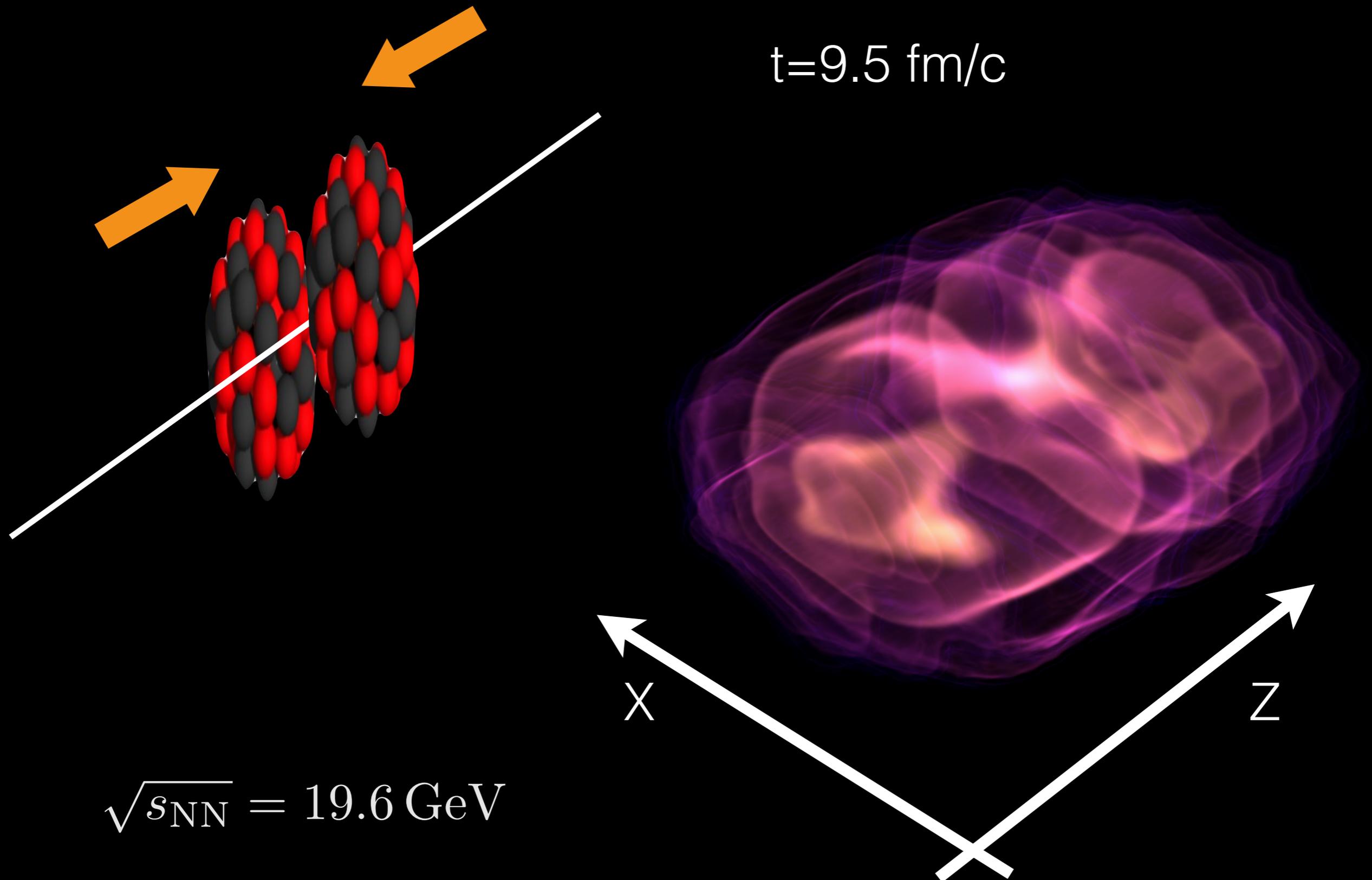
Hydrodynamical evolution with sources



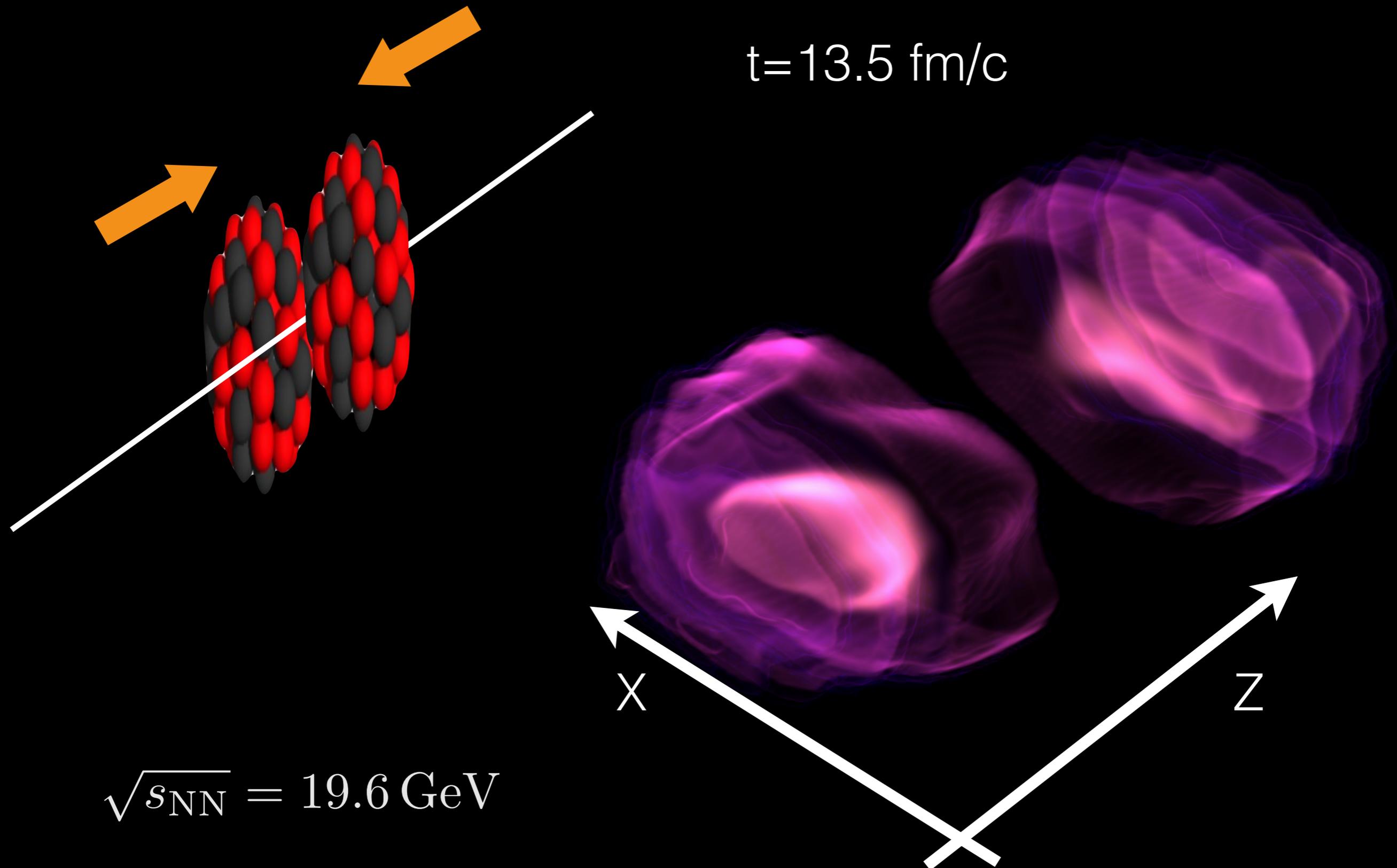
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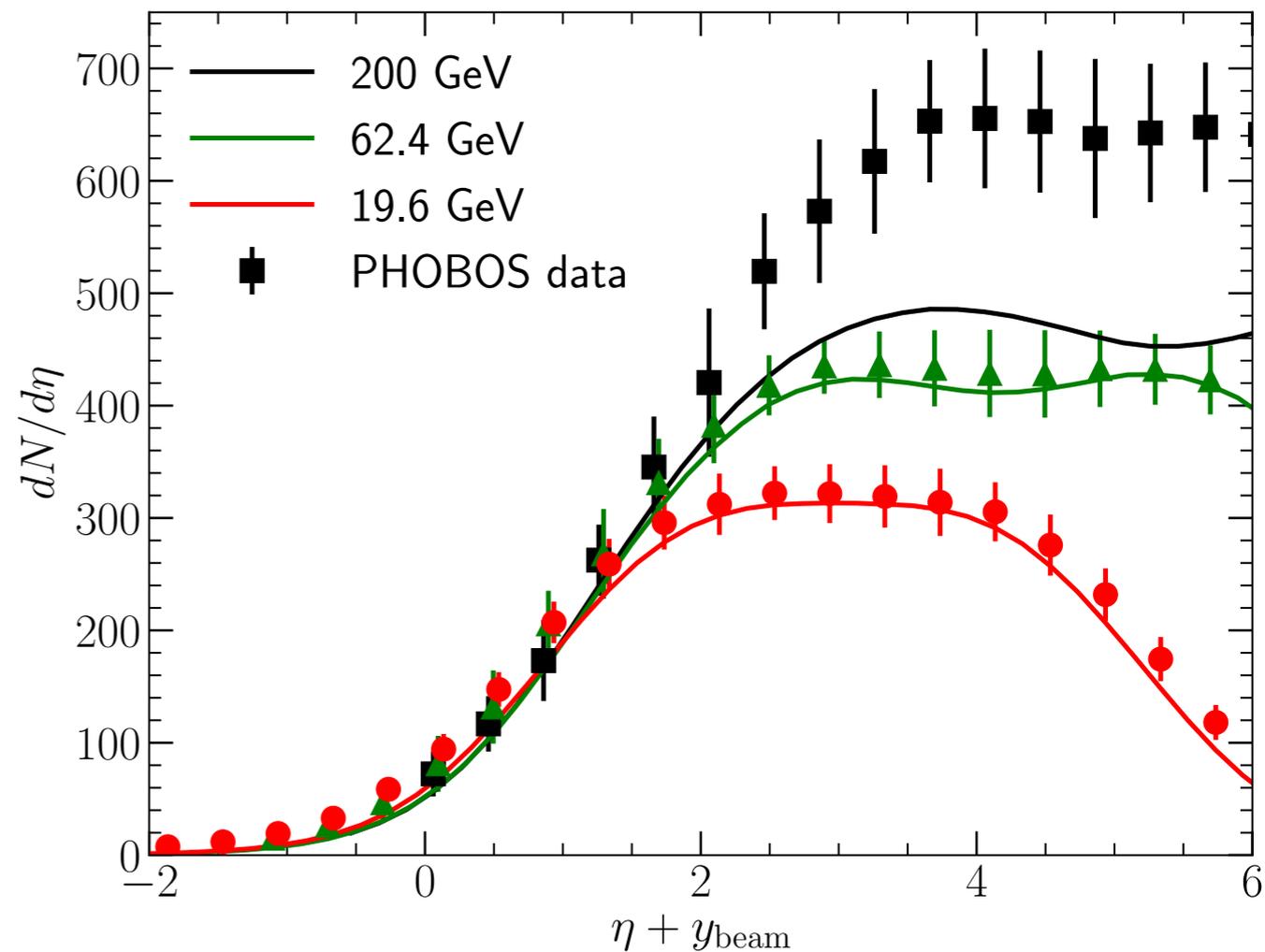
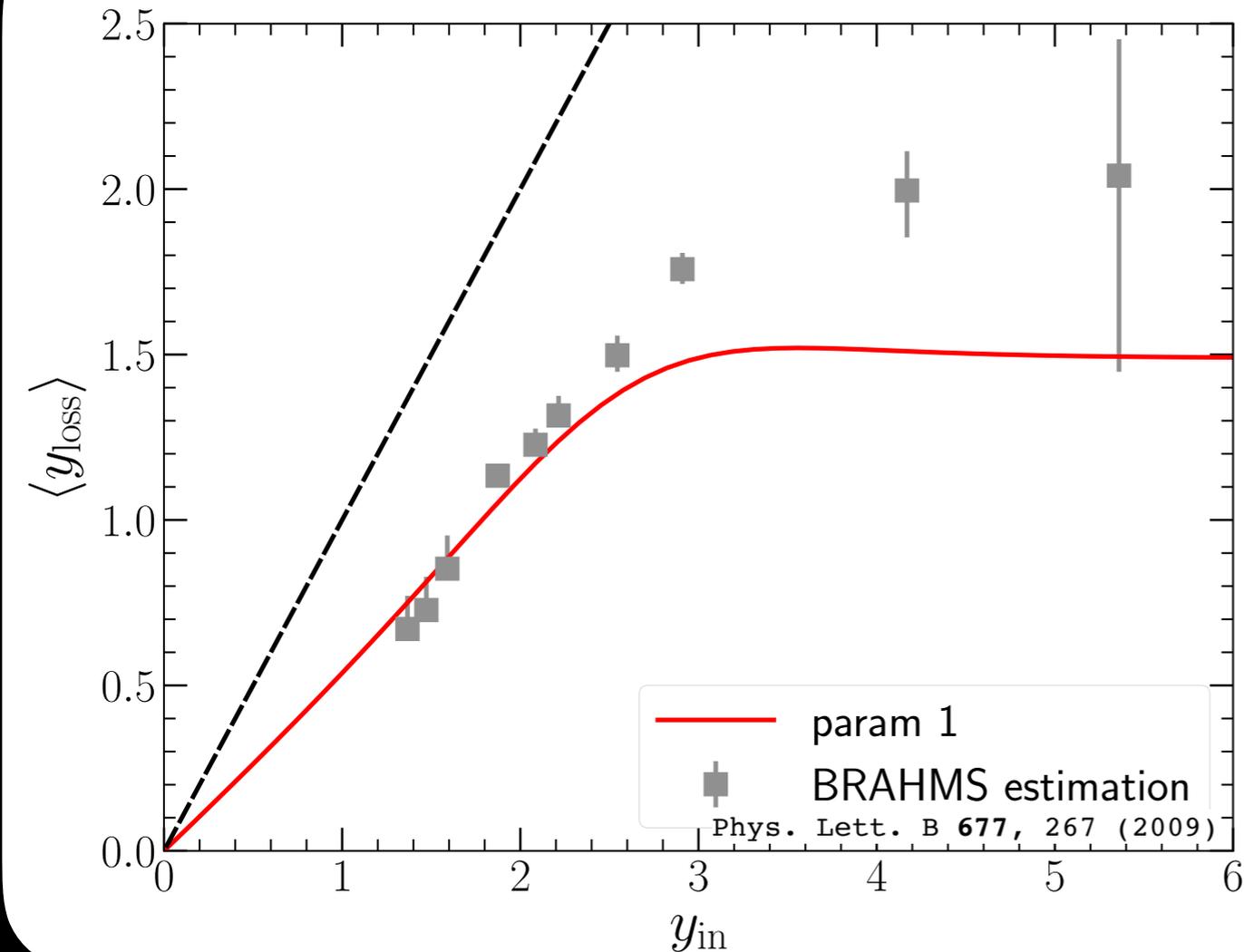
Hydrodynamical evolution with sources



Hydrodynamical evolution with sources

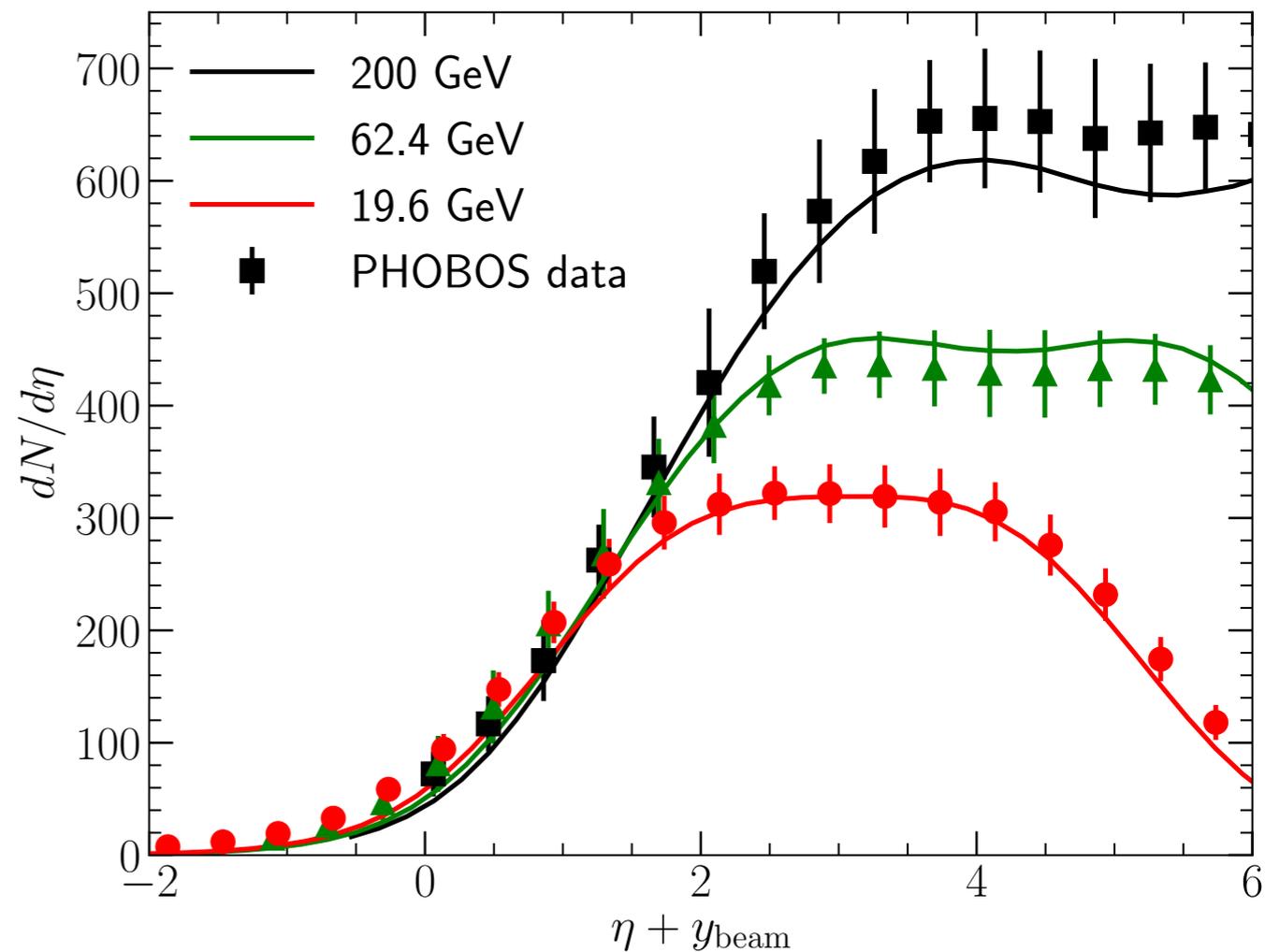
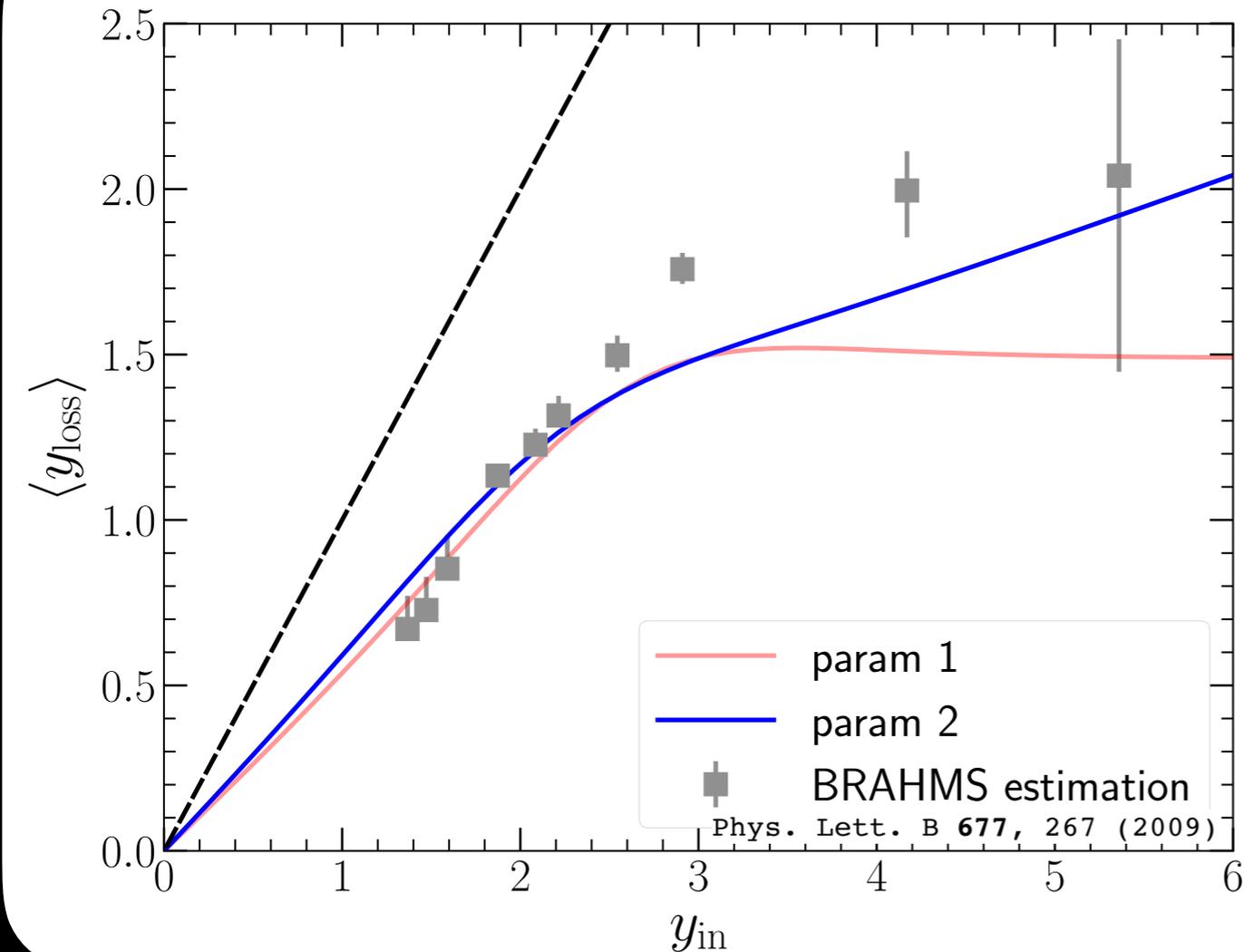


Model the baryon stopping



- The charged hadron rapidity distribution is sensitive to the parameterization of the baryon energy loss

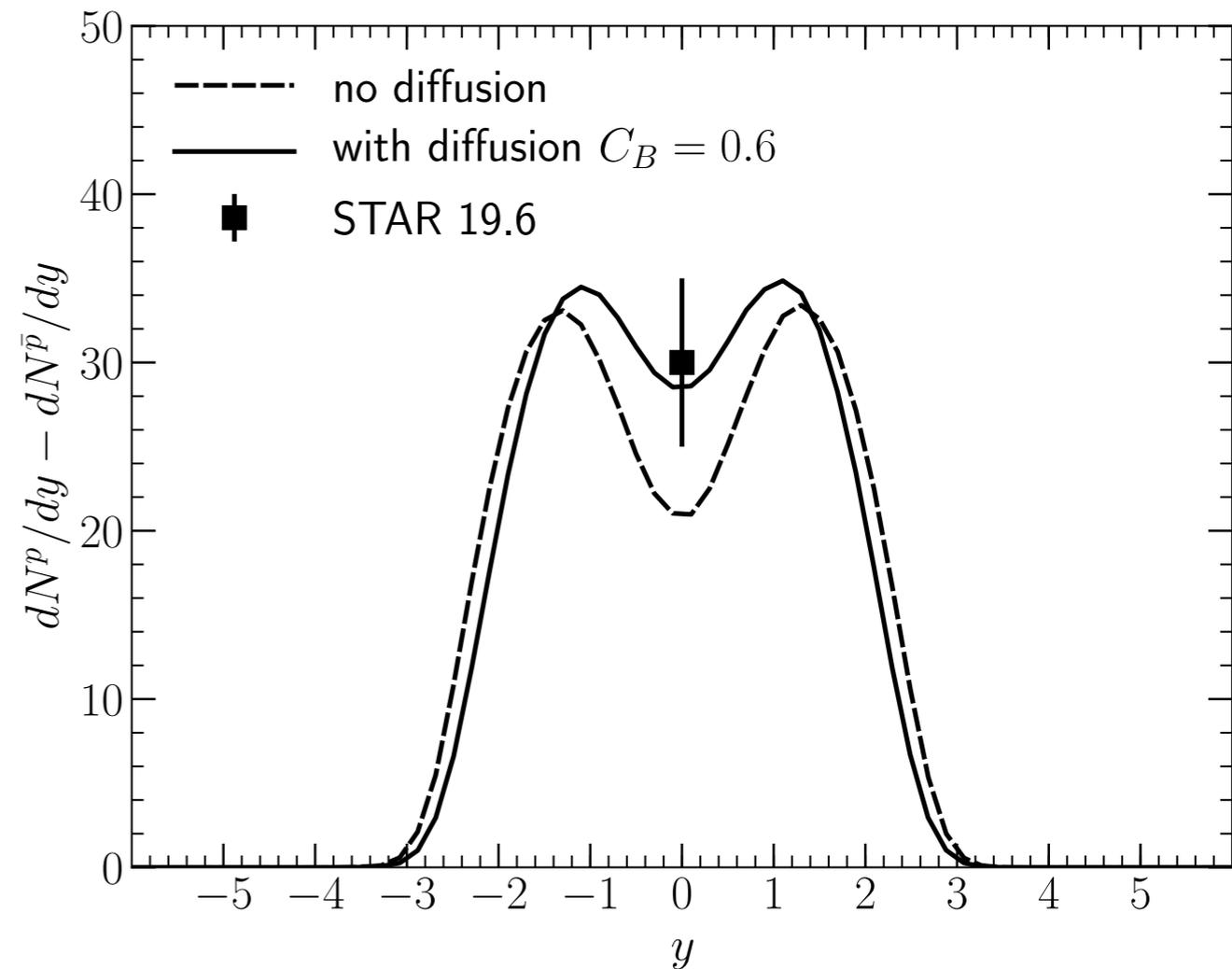
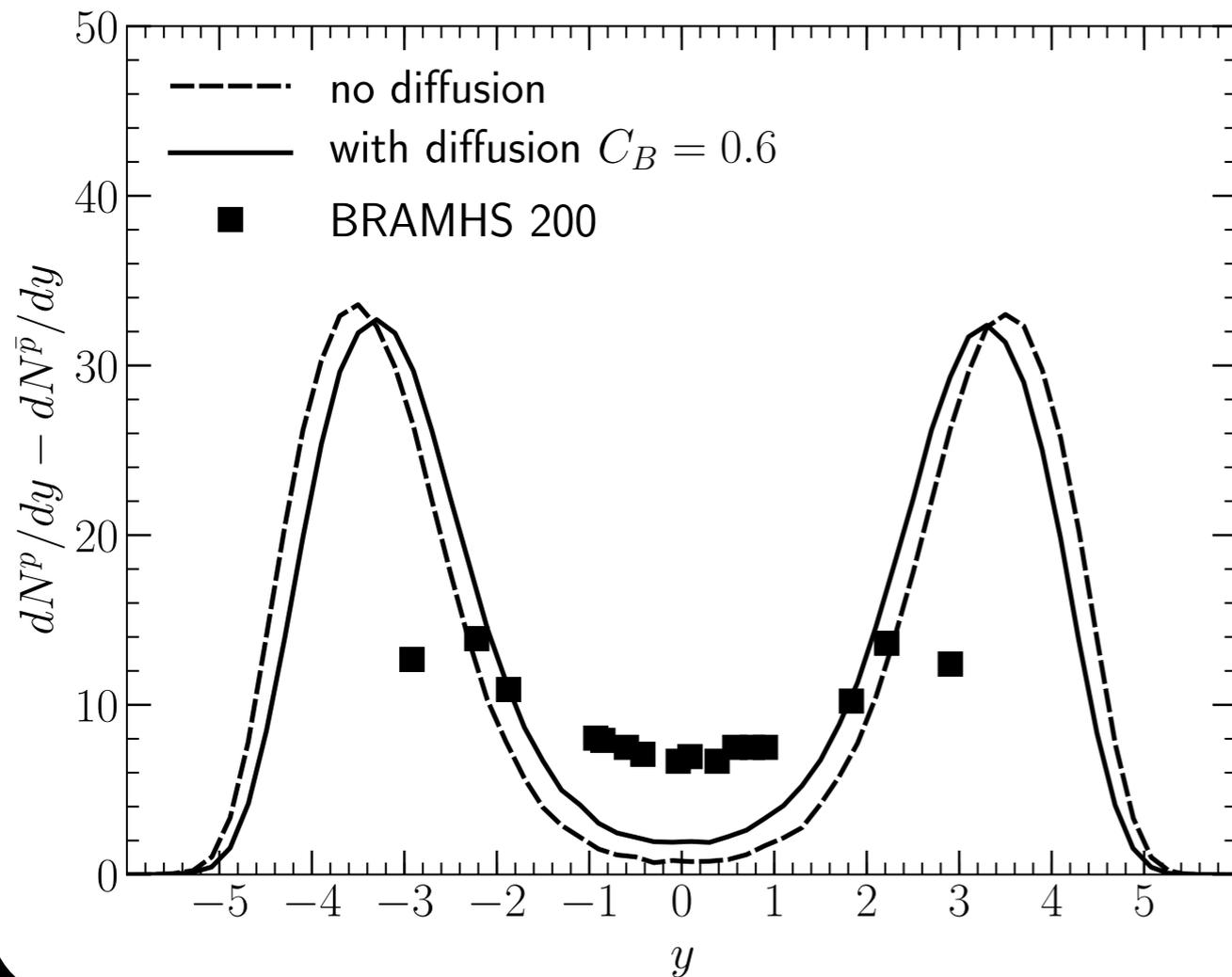
Model the baryon stopping



- The charged hadron rapidity distribution is sensitive to the parameterization of the baryon energy loss
- Understand how the collision energy is converted to particle production

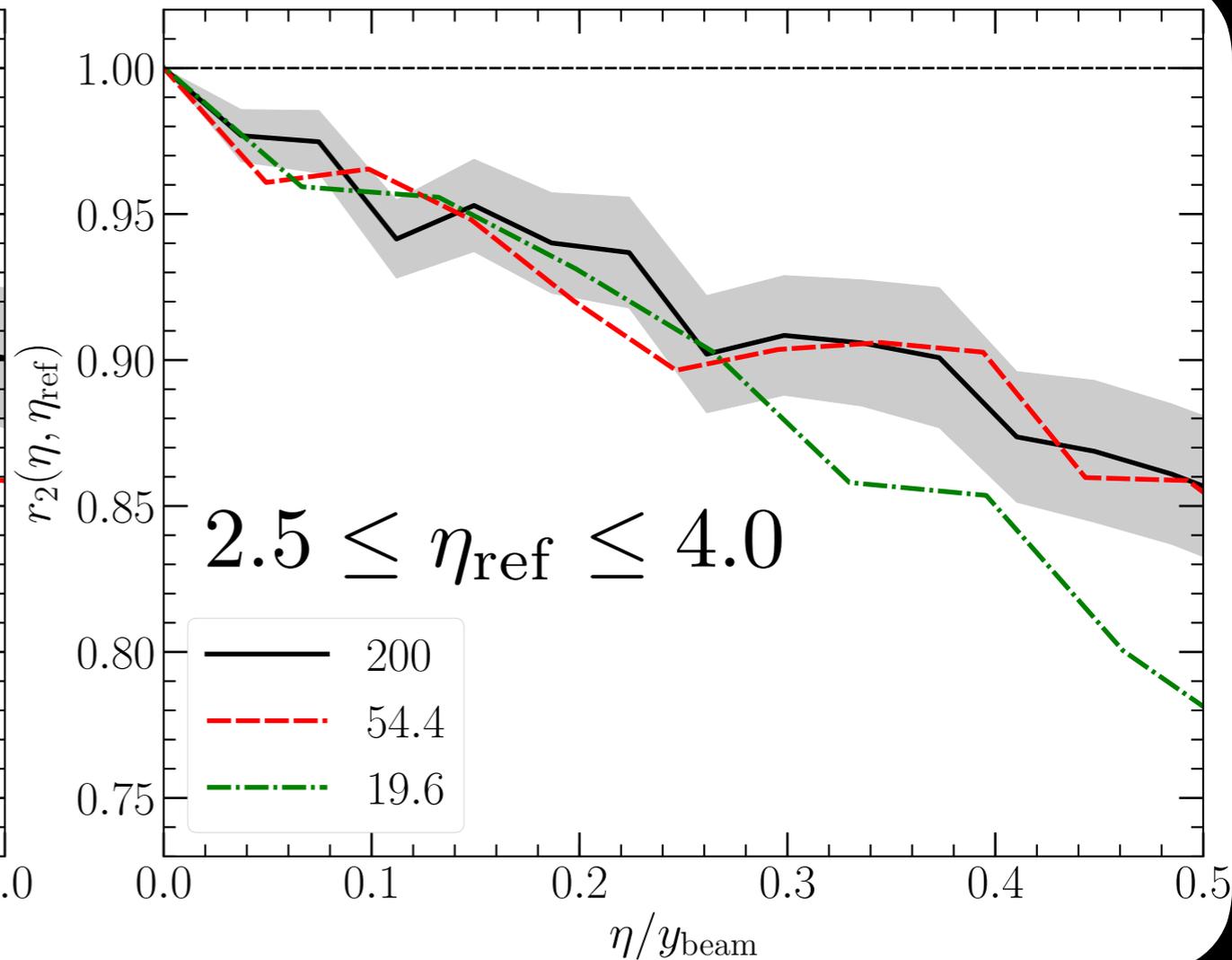
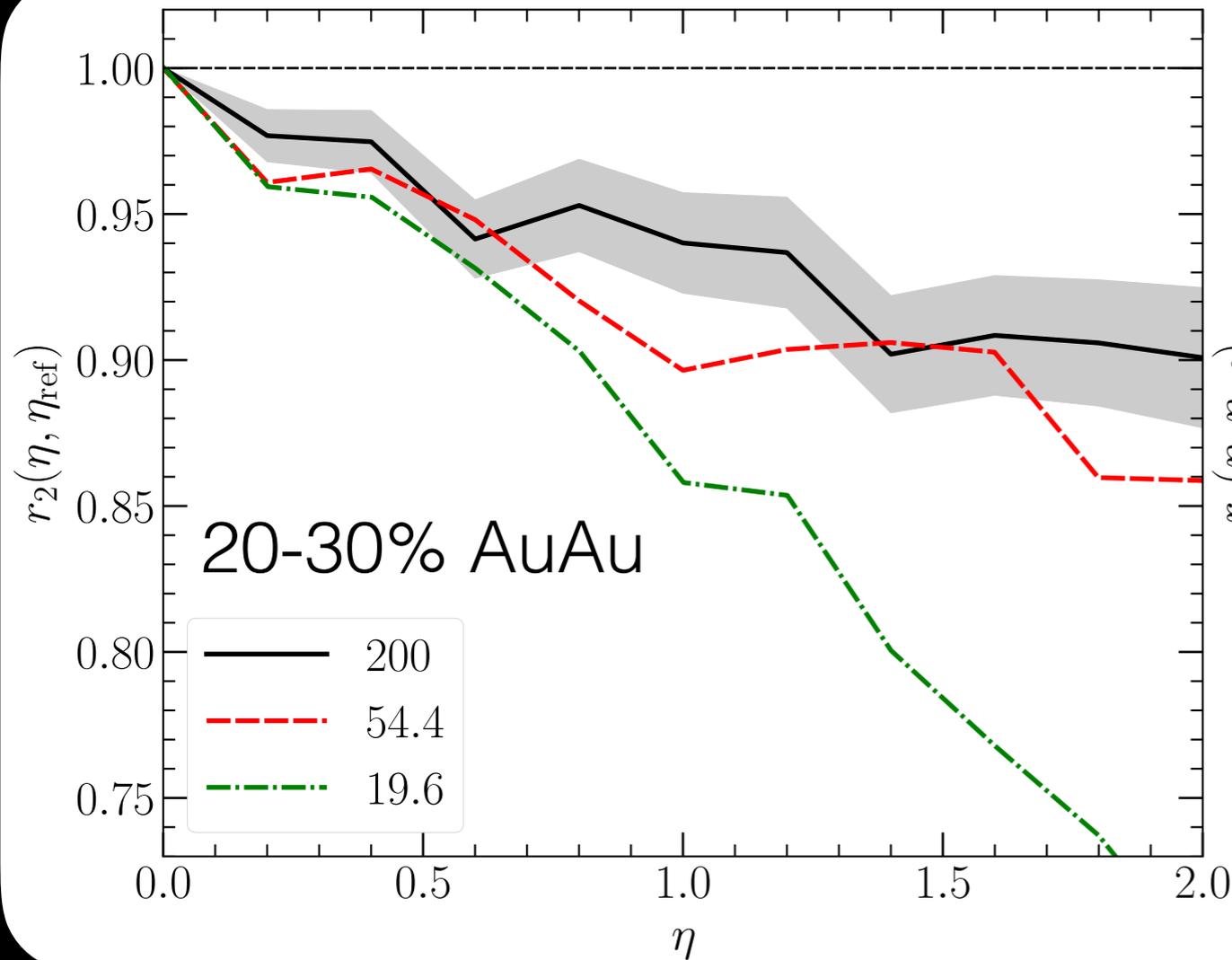
Net baryon rapidity distribution

G. Denicol, C. Gale, S. Jeon, A. Monnai, B. Schenke and C. Shen, arXiv:1804.10557 [nucl-th]



- Net baryon diffusion transports more baryon numbers to the mid-rapidity region
- Additional baryon fluctuations are needed at high collision energies

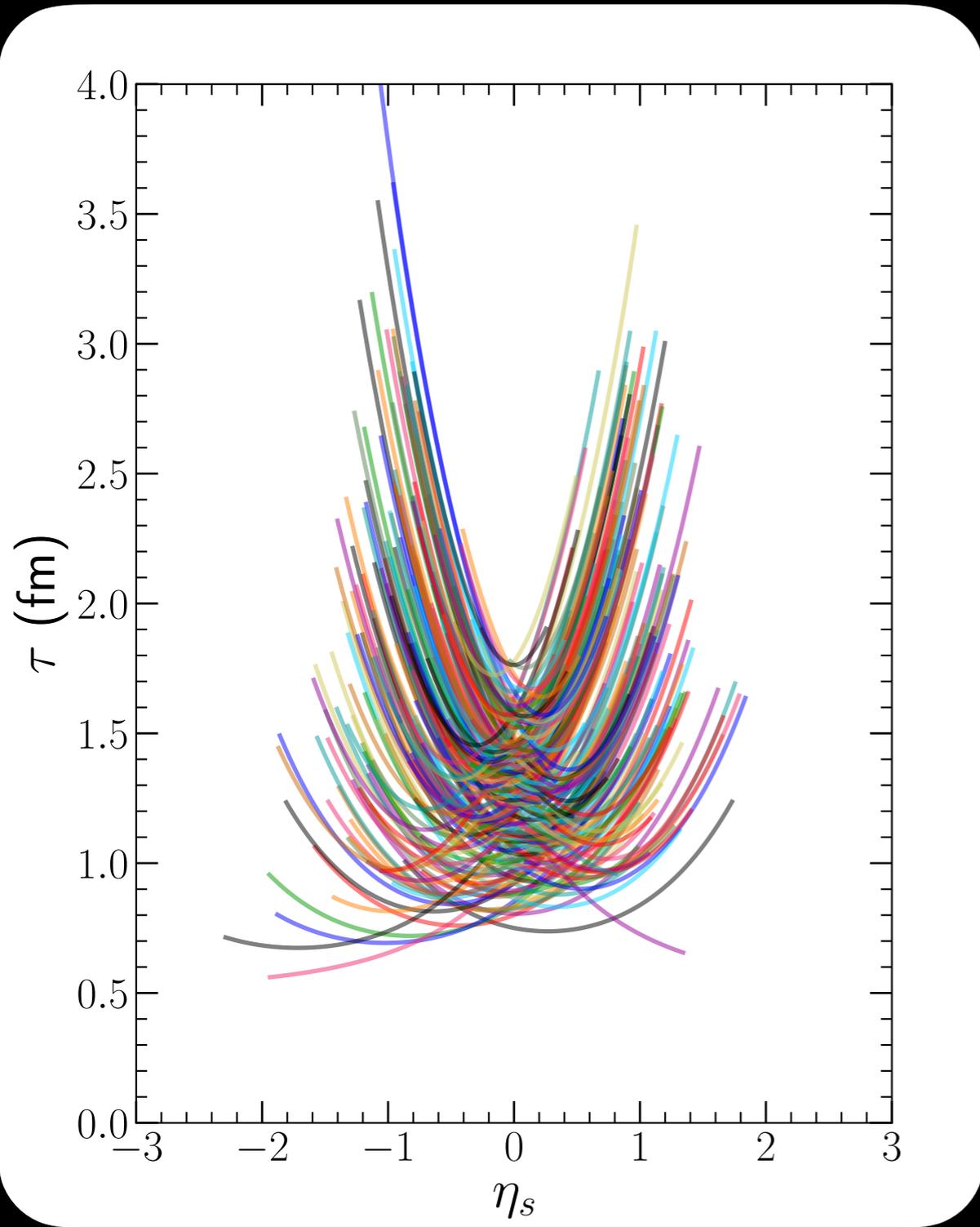
Longitudinal fluctuations



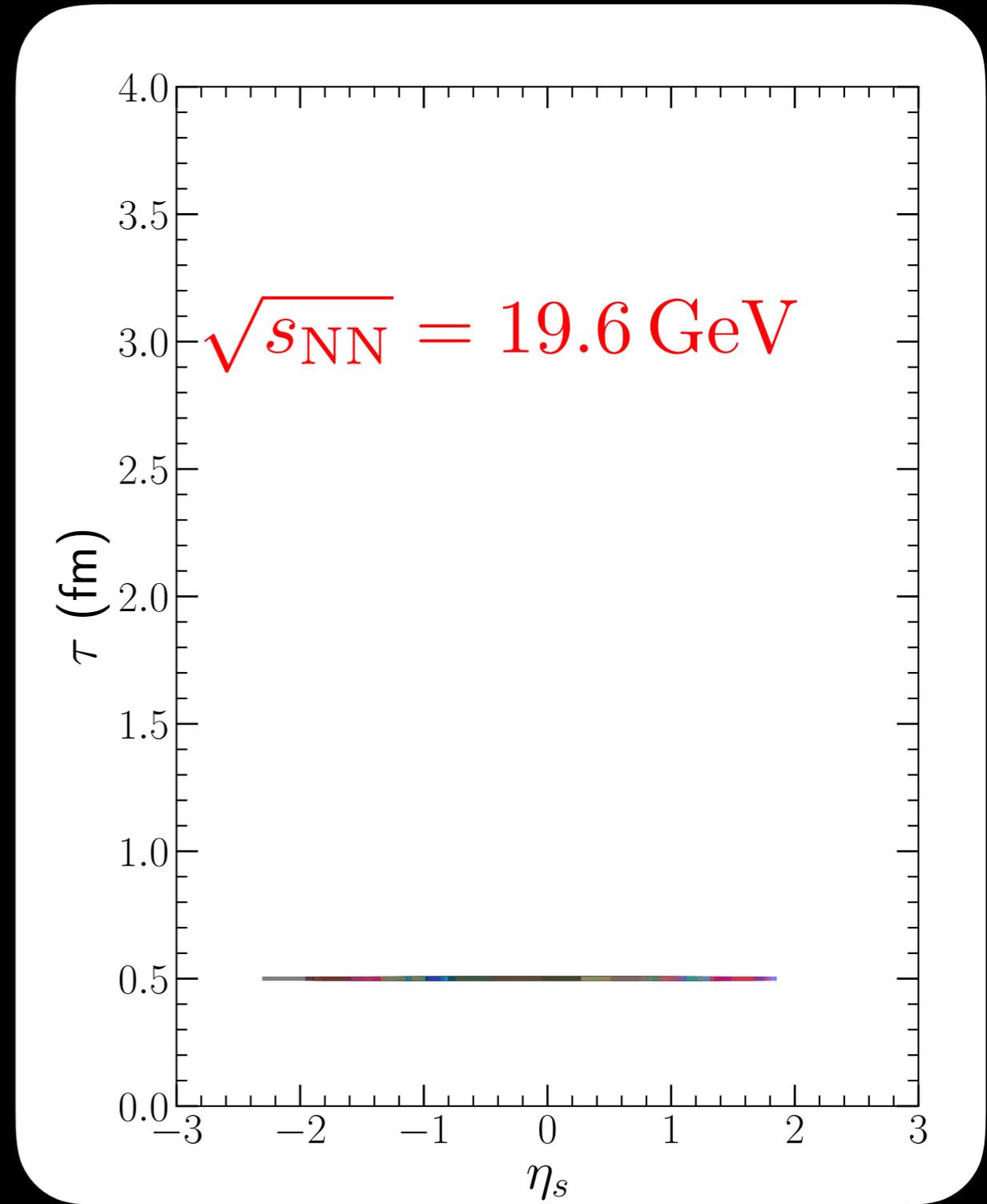
$$r_2(\eta, \eta_{\text{ref}}) = \frac{\langle v_2(-\eta)v_2(\eta_{\text{ref}}) \cos(2(\Psi_2(-\eta) - \Psi_2(\eta_{\text{ref}}))) \rangle}{\langle v_2(\eta)v_2(\eta_{\text{ref}}) \cos(2(\Psi_2(\eta) - \Psi_2(\eta_{\text{ref}}))) \rangle}$$

- Longitudinal fluctuations imprint themselves on the event-plane decorrelation ratios; The r_n ratio decorrelates faster at lower energy

Do we really need dynamical initialization?

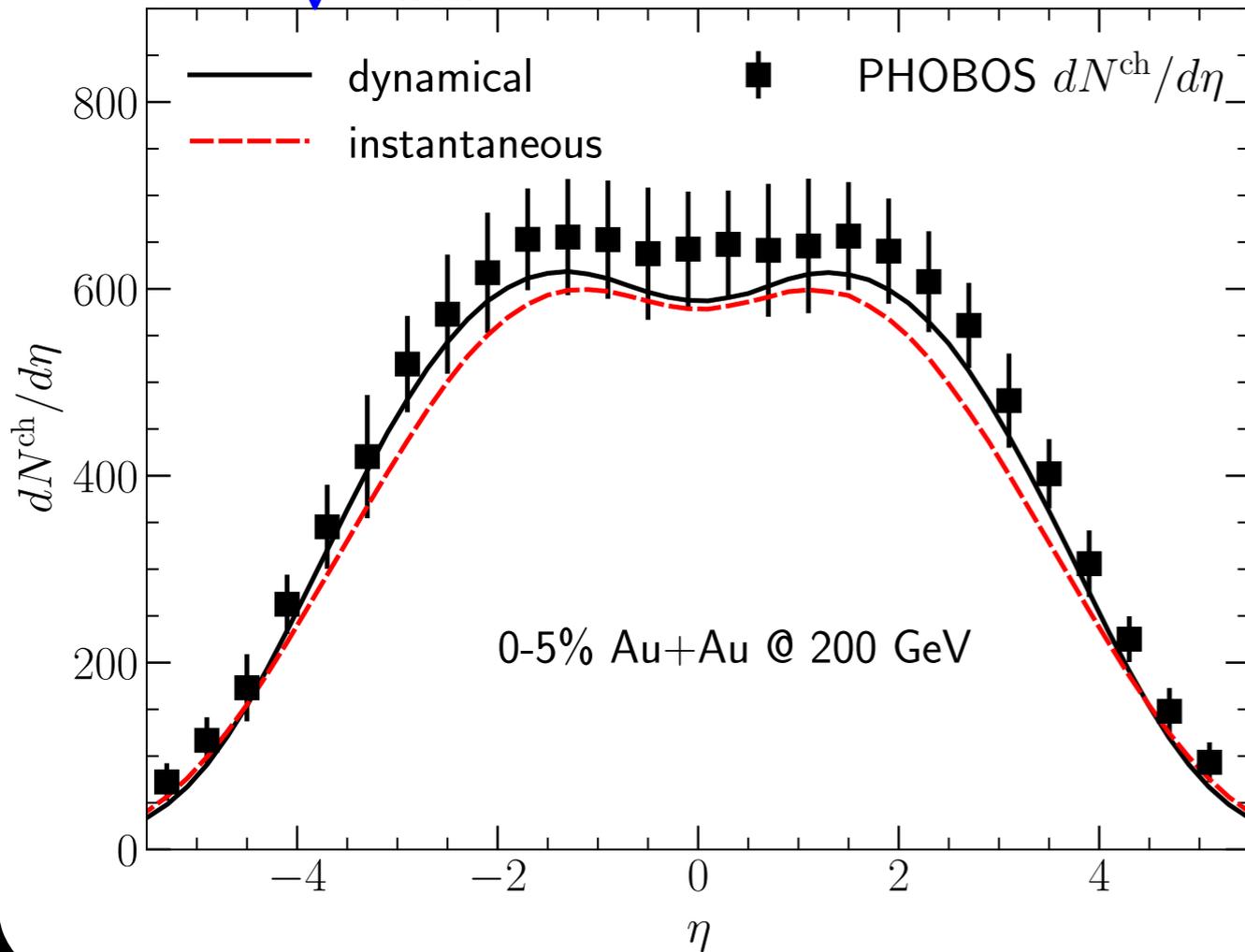


vs.

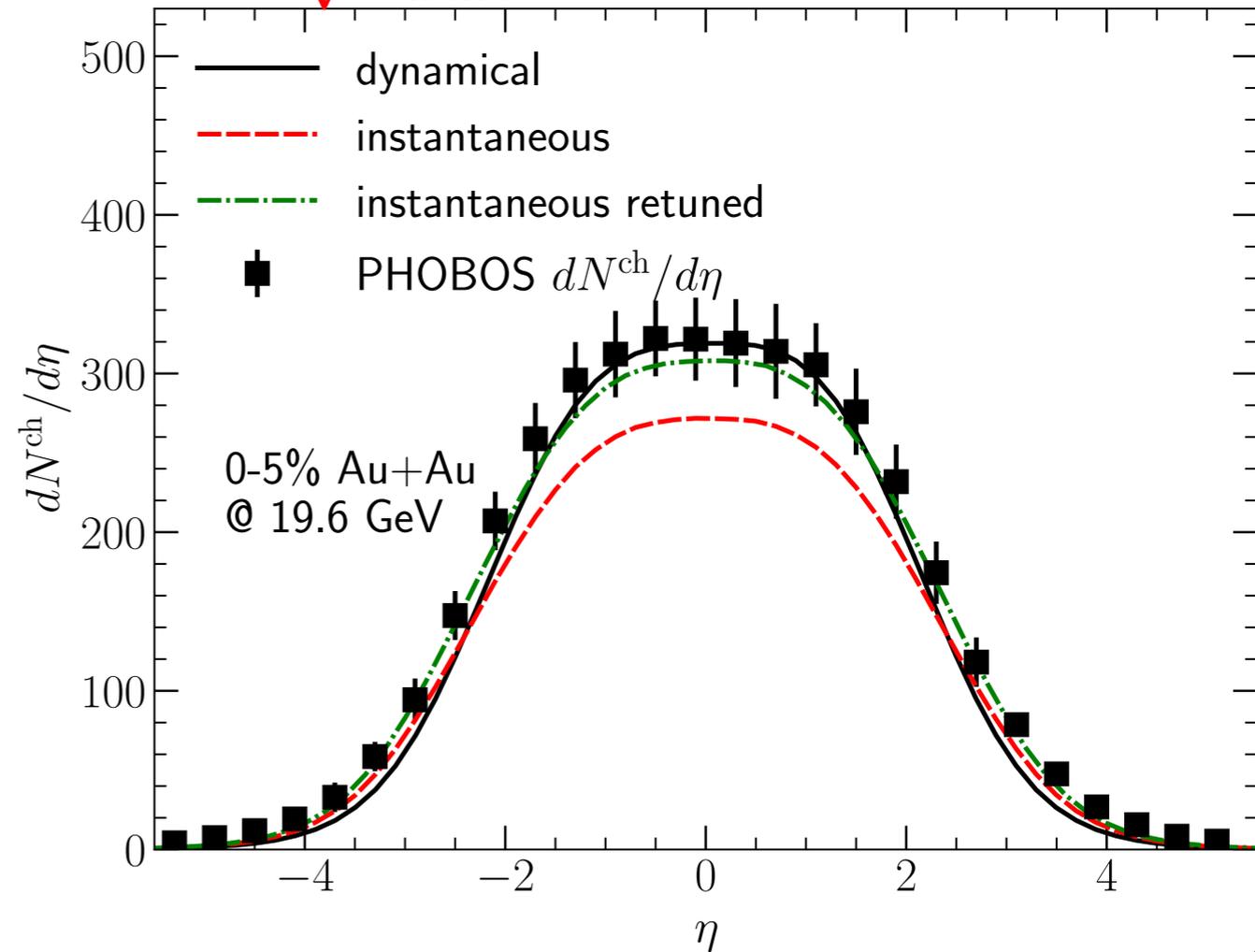


Dynamical vs instantaneous initialization

$\sqrt{s_{NN}} = 200 \text{ GeV}$

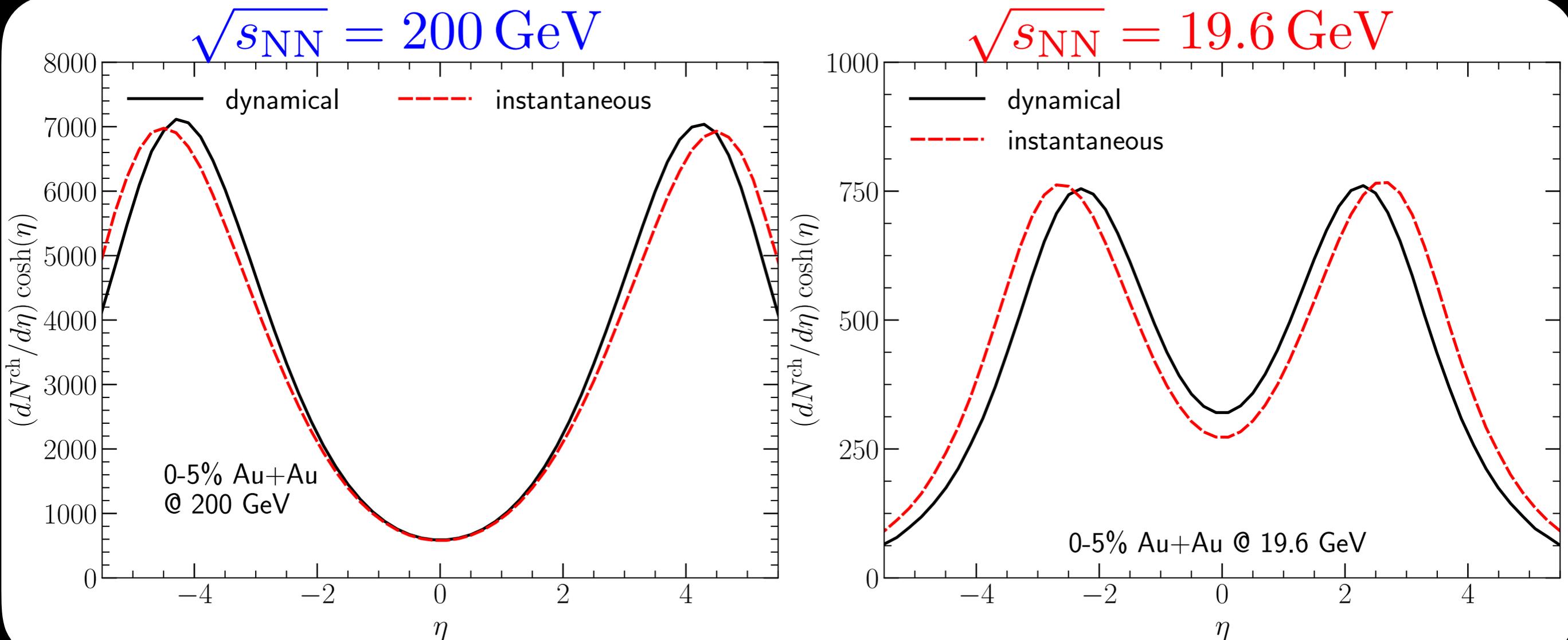


$\sqrt{s_{NN}} = 19.6 \text{ GeV}$



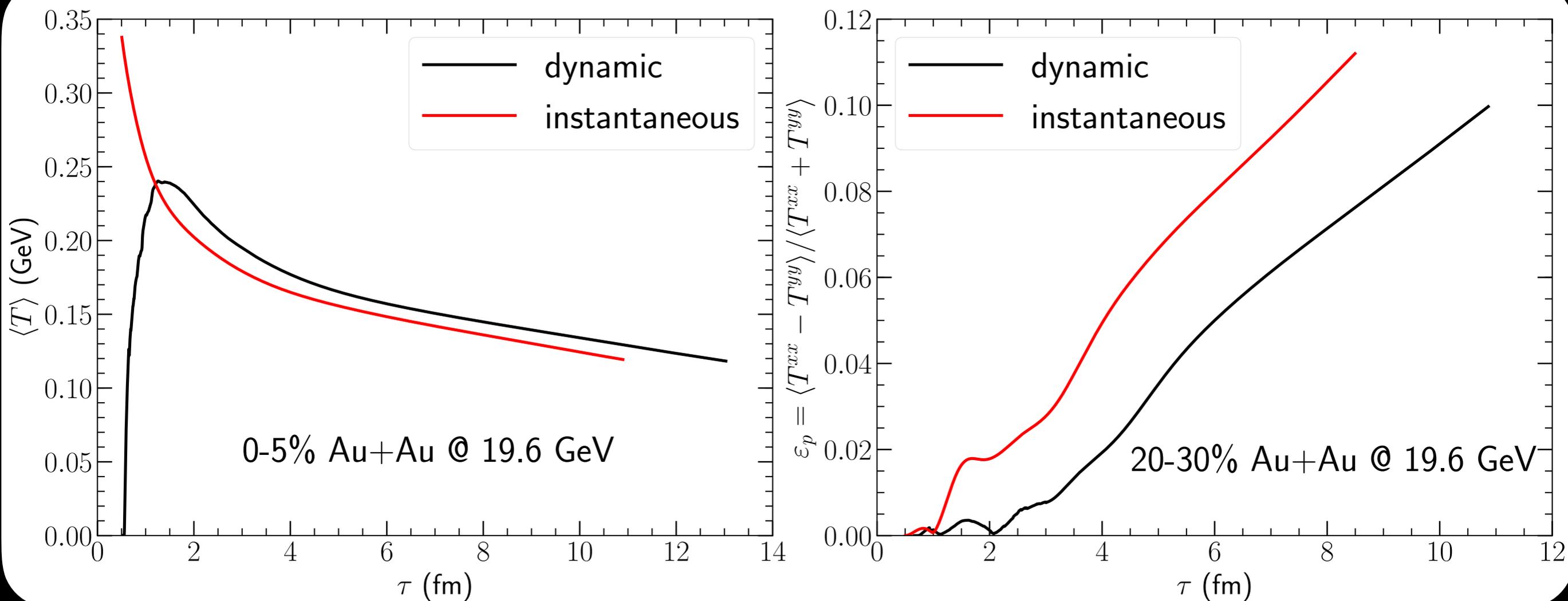
- With the same input collision energy, instantaneous initialization results in 10-15% smaller charged multiplicity at mid-rapidity at 19.6 GeV

Dynamical vs instantaneous initialization



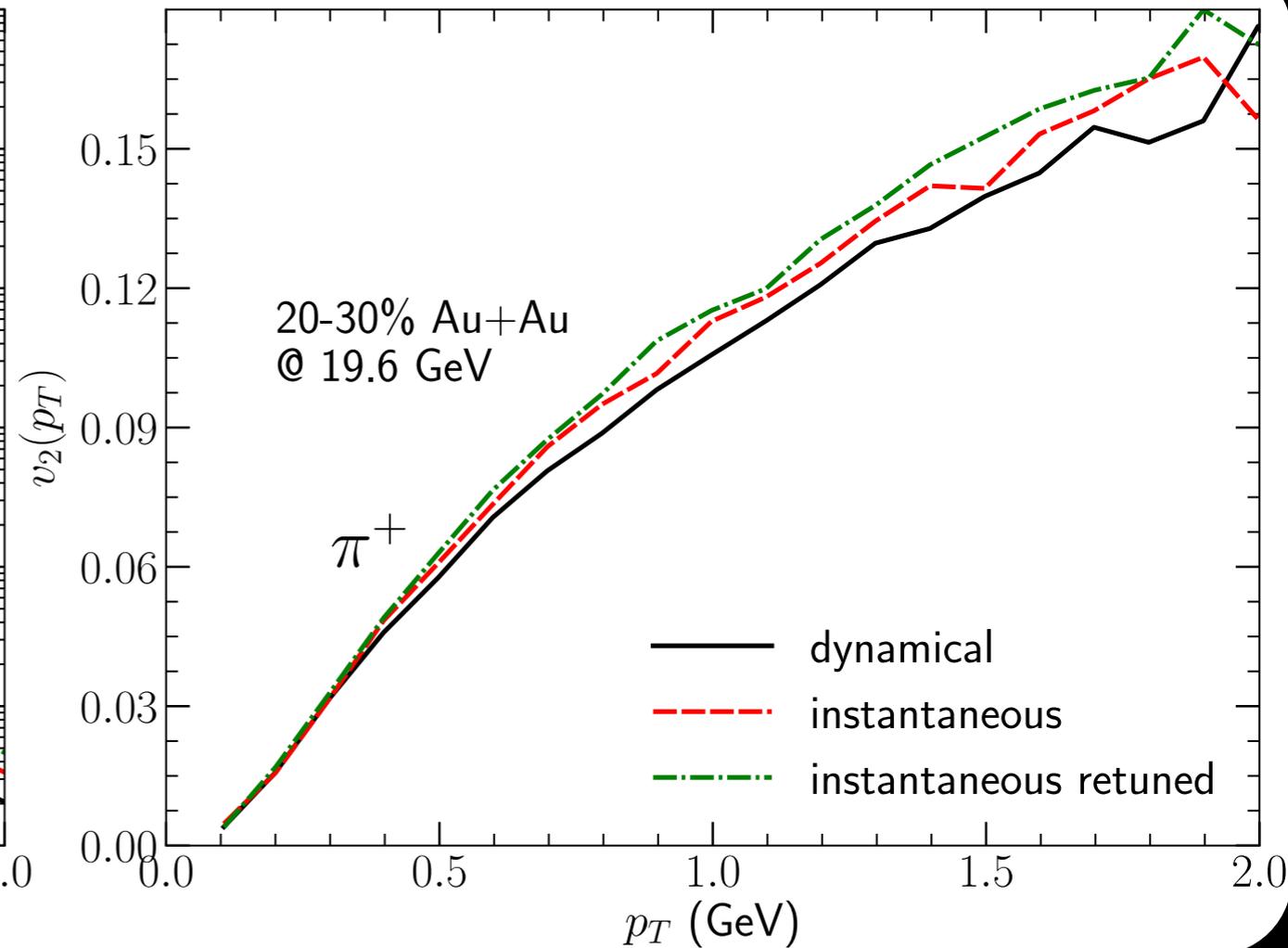
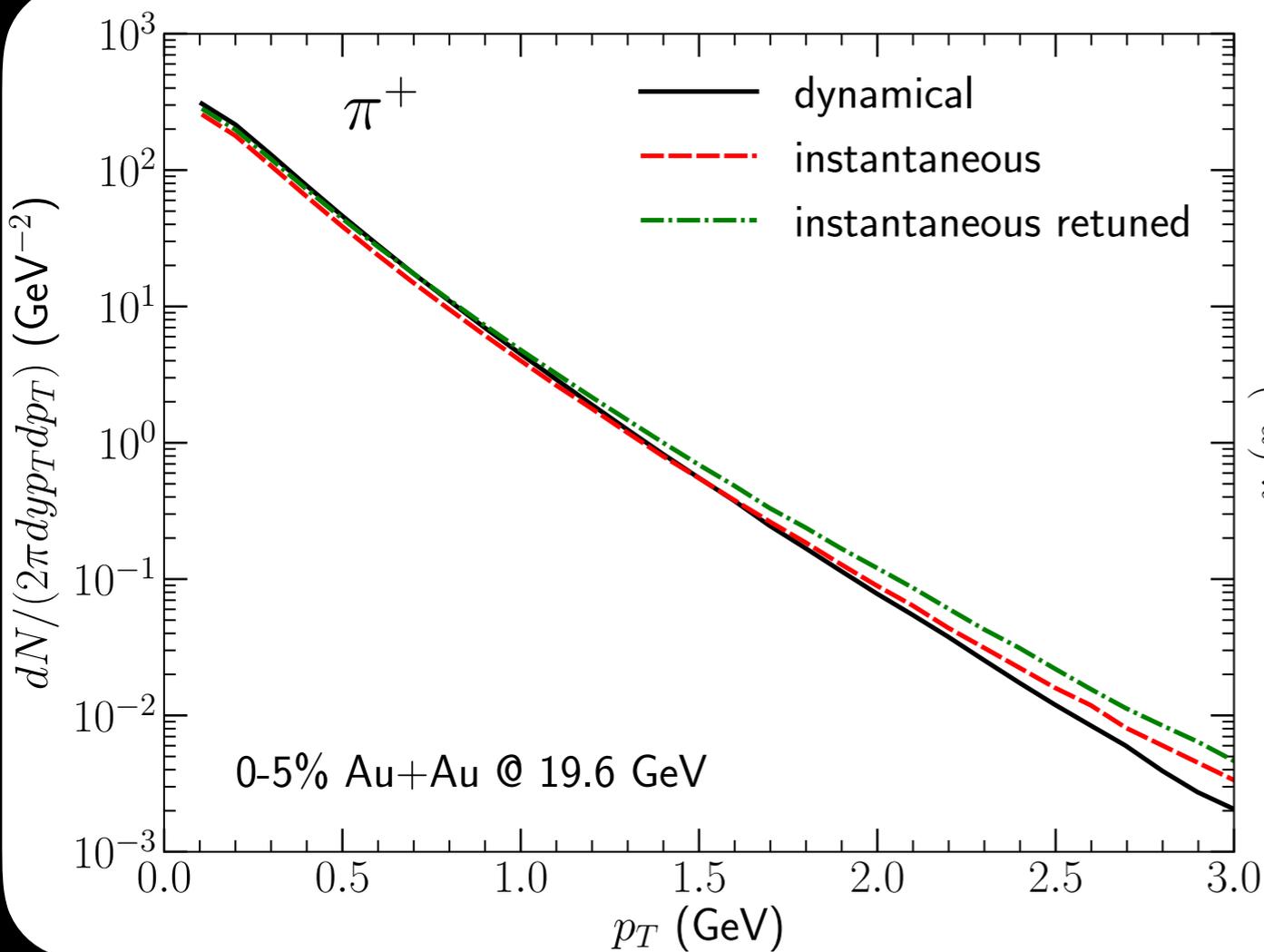
- Instantaneous initialization starts with an earlier longitudinal expansion and pushes more energy to the forward rapidity region

Transverse dynamics with sources



- Fireball lives ~ 2 fm longer with dynamical initialization compared to the instantaneous setup
- Hydrodynamic flow and its anisotropy develop slower with dynamical sources

Dynamical vs instantaneous initialization



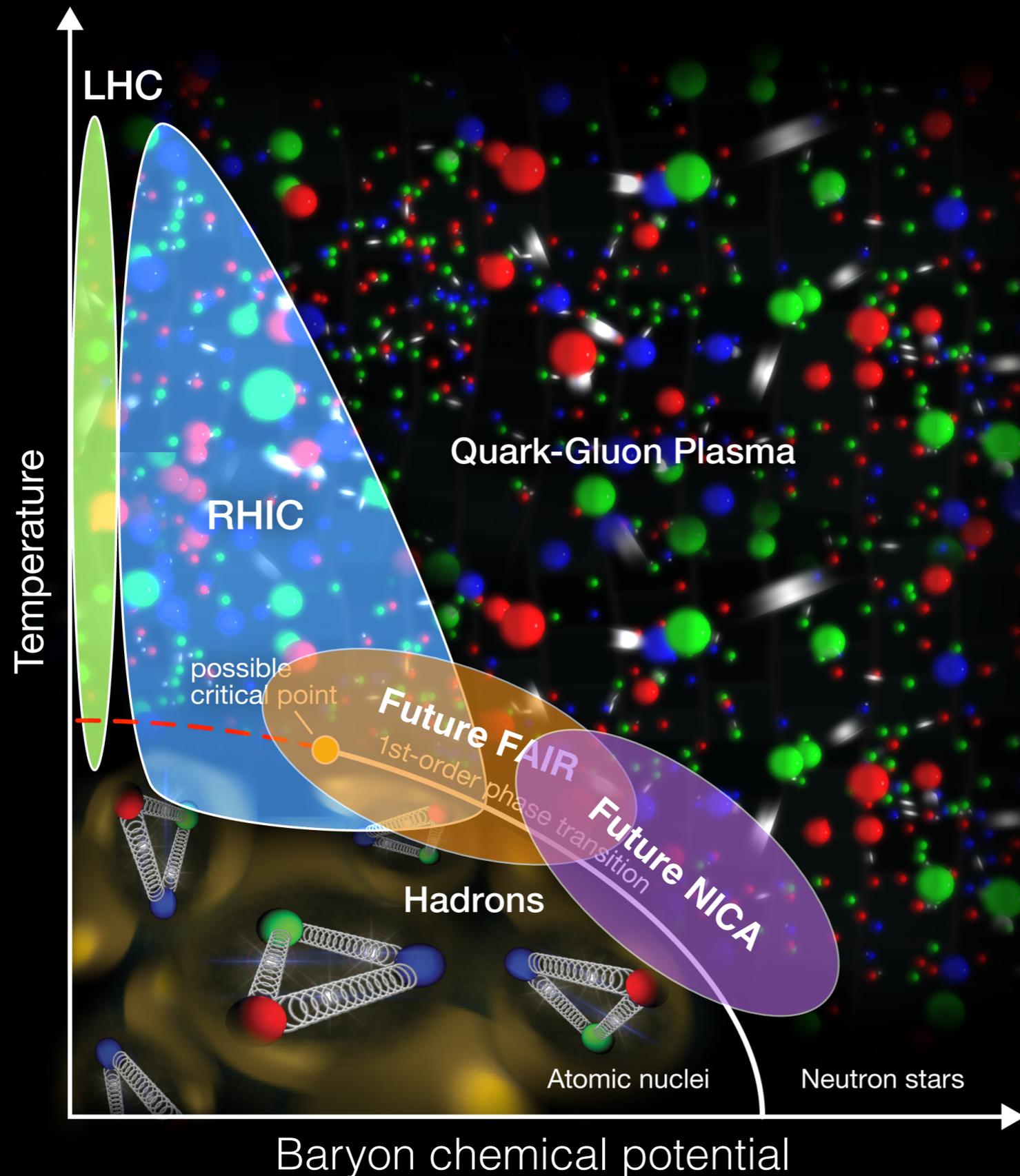
- Dynamical initialization results steeper particle spectra and smaller $v_2(p_T)$

5-10% less radial and elliptic flow

= 20-50% variation on extracted transport coefficients

See J-F. Paquet's talk on Monday 17:10
for the fingerprint of dynamical initialization on EM probes

Compass for the phase diagram

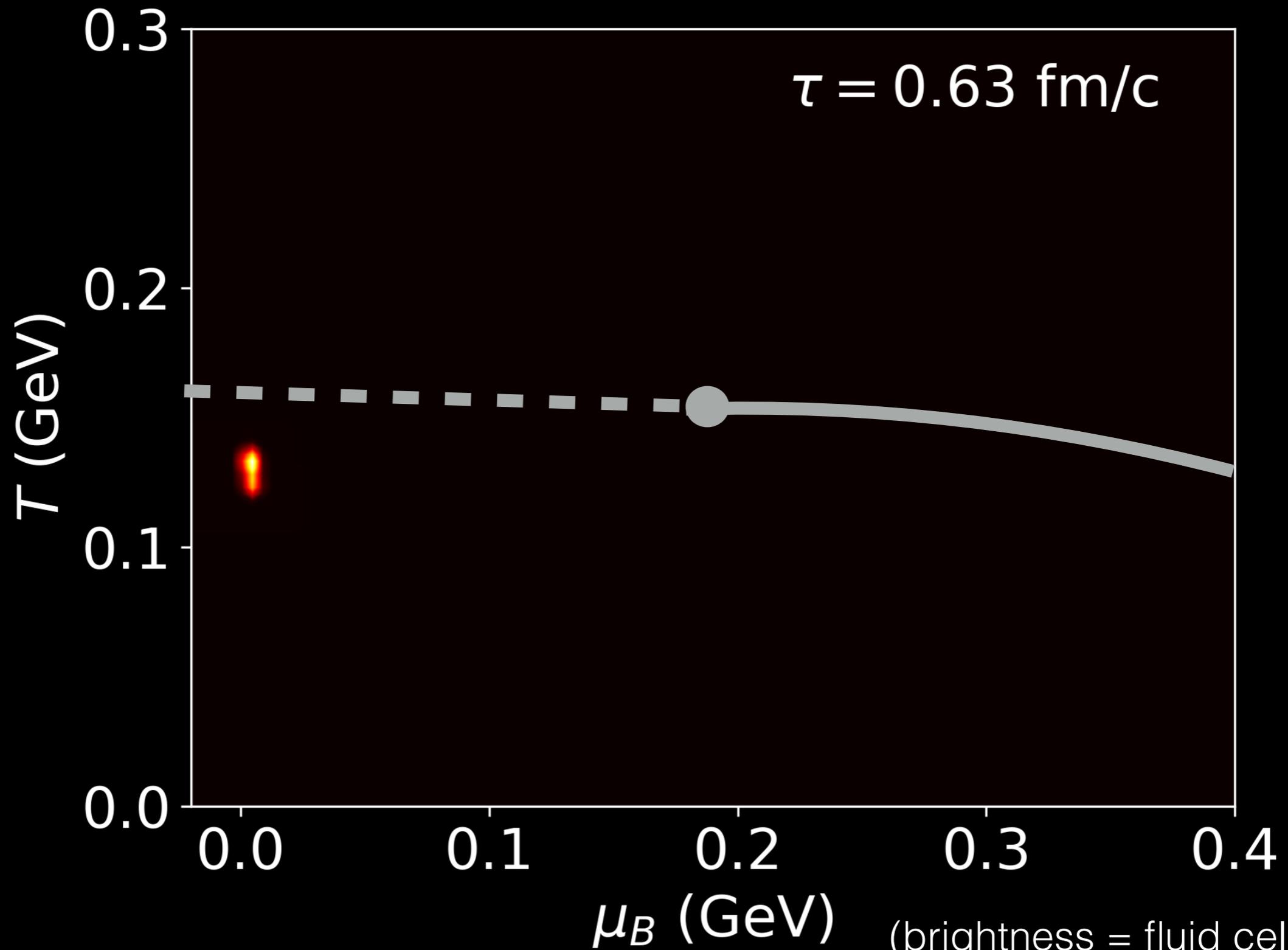


- Fireball trajectory
- How fast the fireball evolves

Essential information to understand how critical fluctuations go out-of-equilibrium

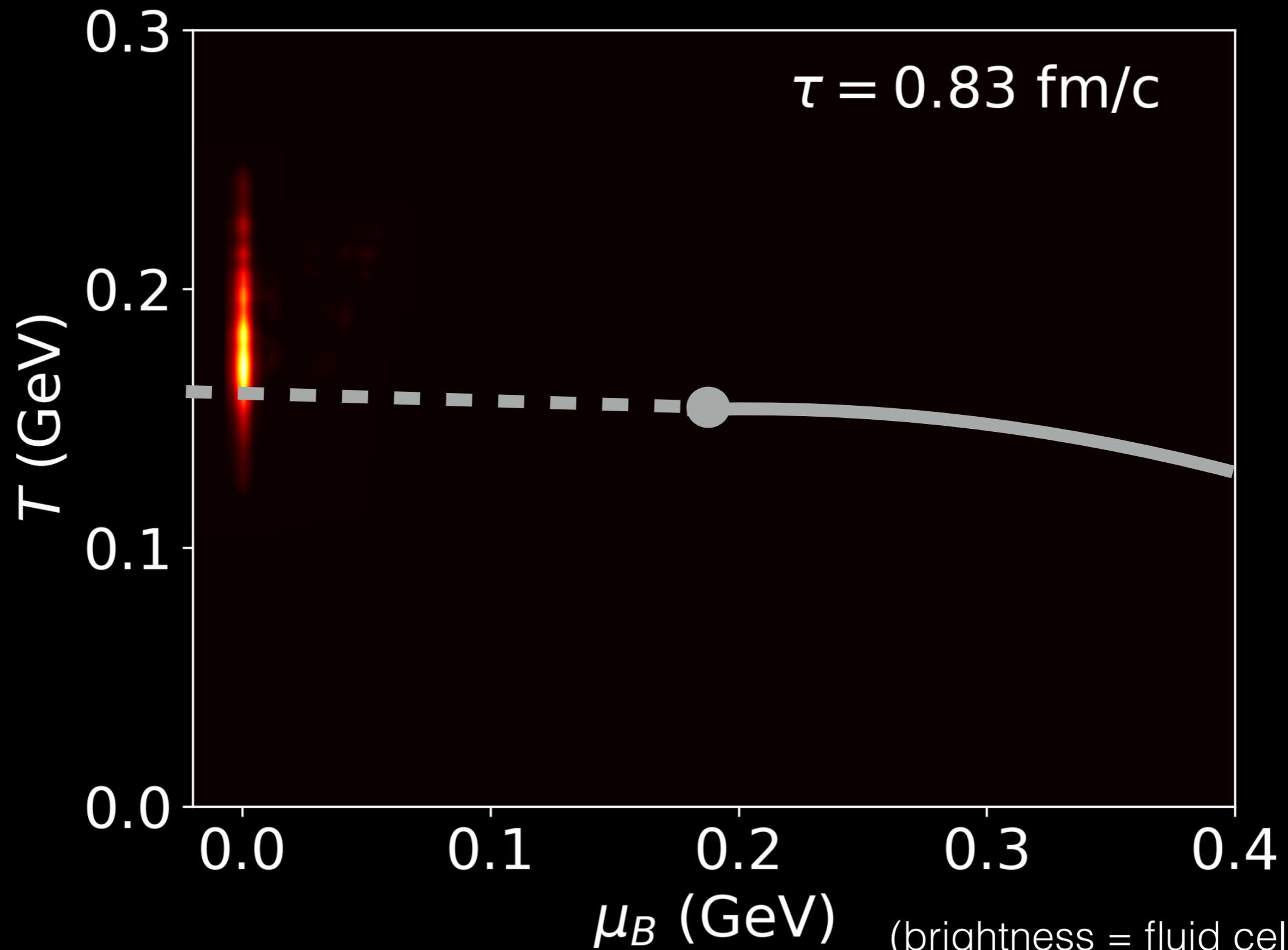
The picture is taken from <http://www.bnl.gov/newsroom/news.php? a=11446>

Sailing in the phase diagram



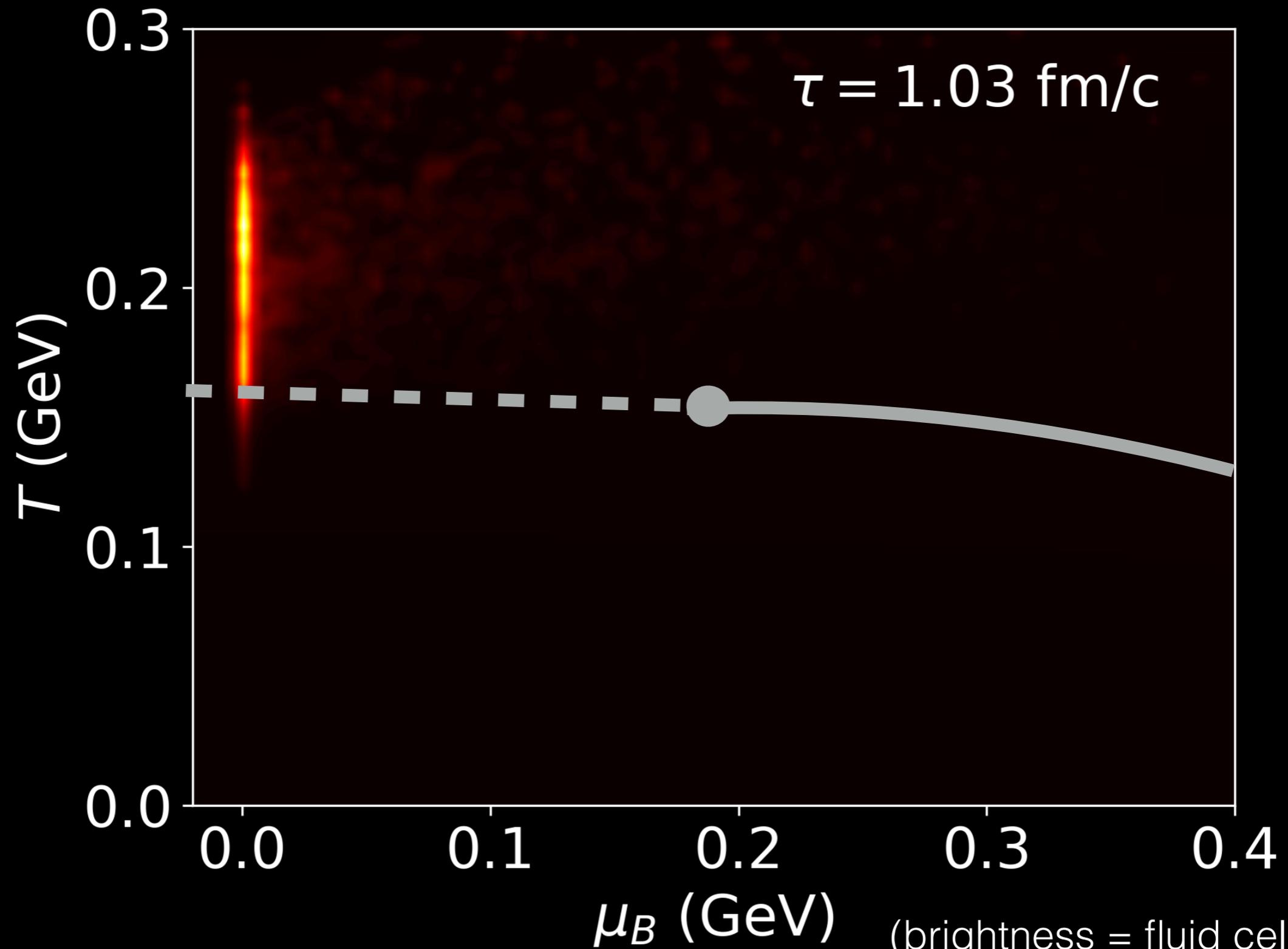
0-5% AuAu@19.6 GeV

Sailing in the phase diagram



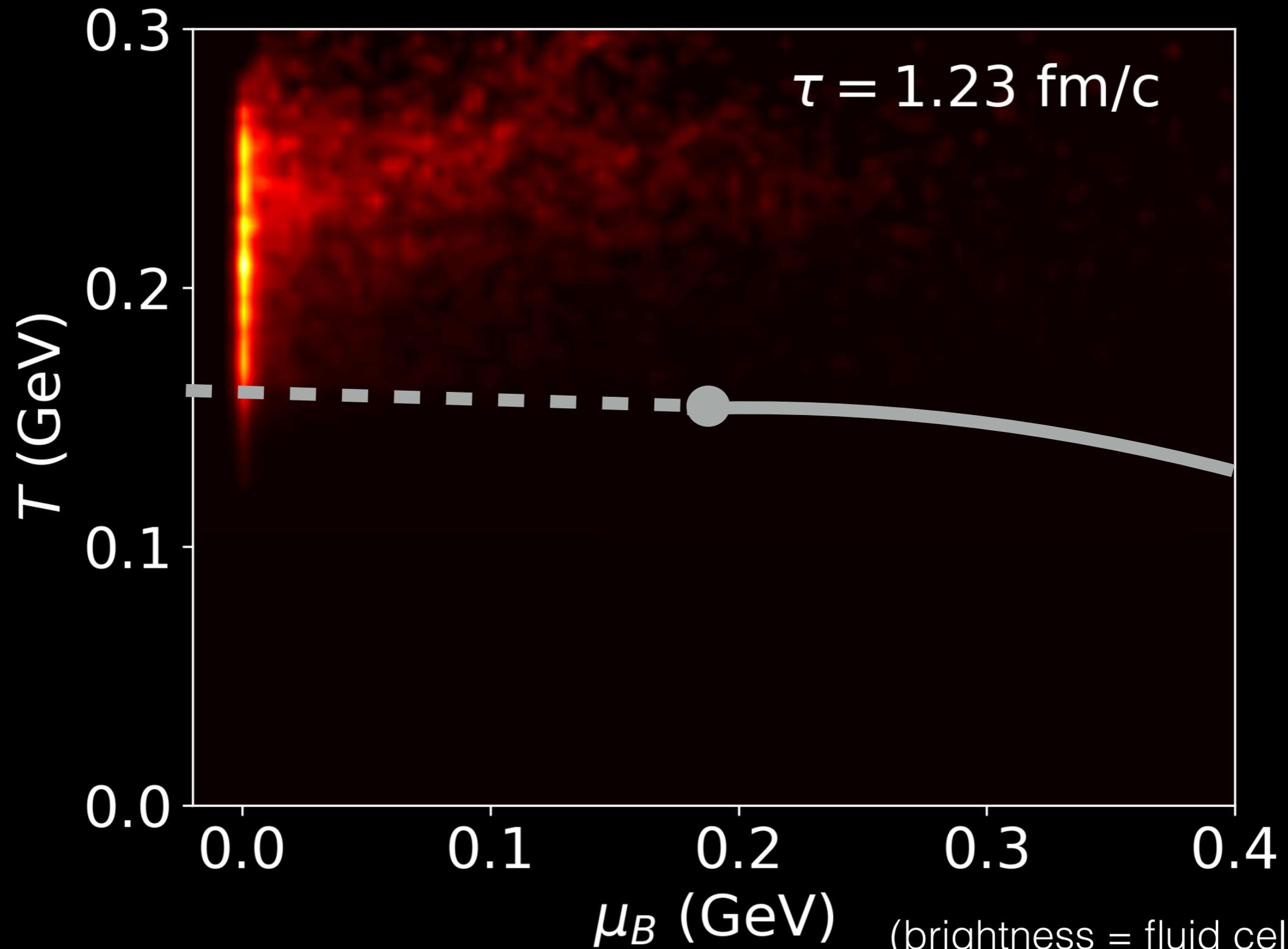
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Sailing in the phase diagram



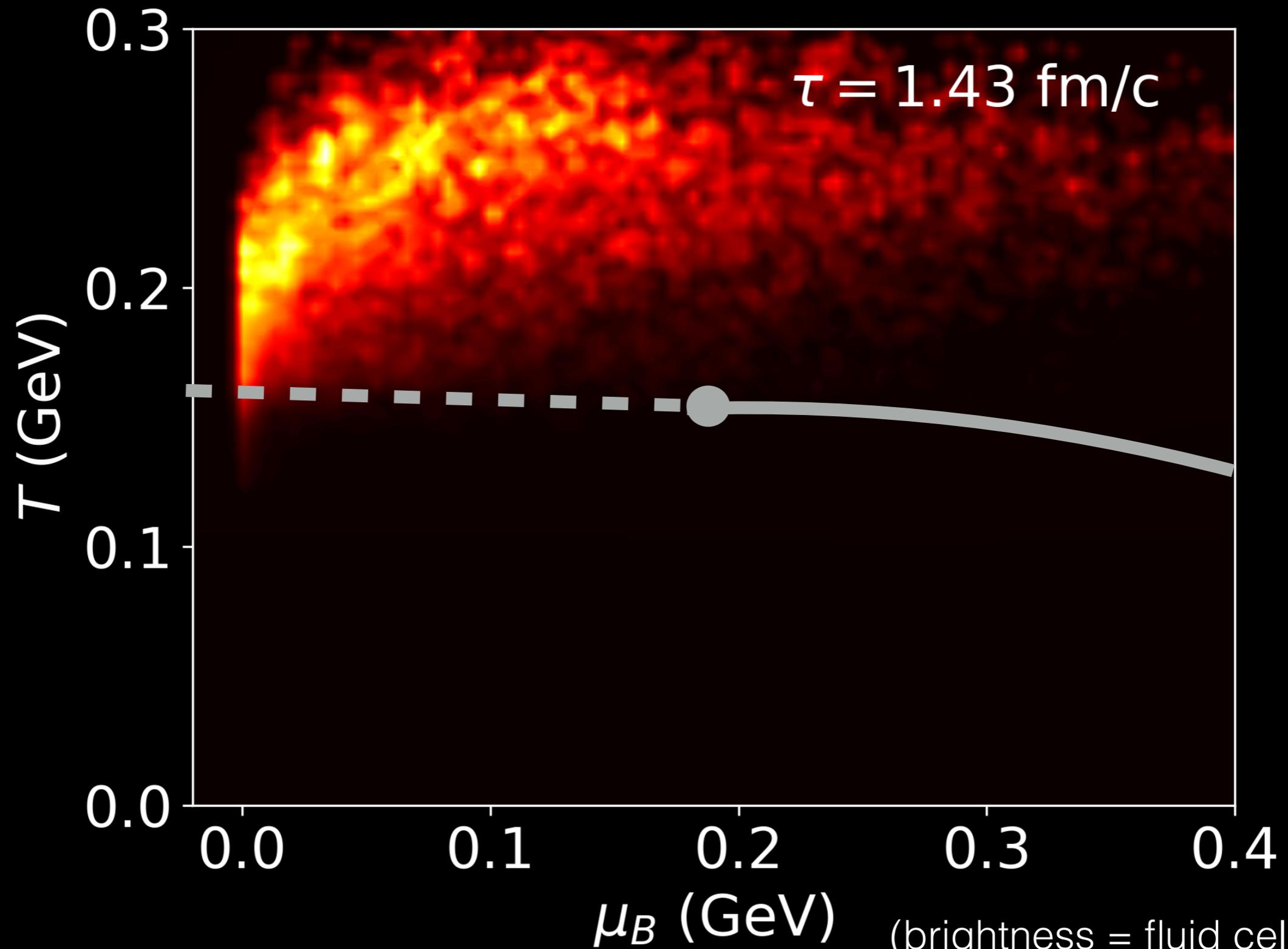
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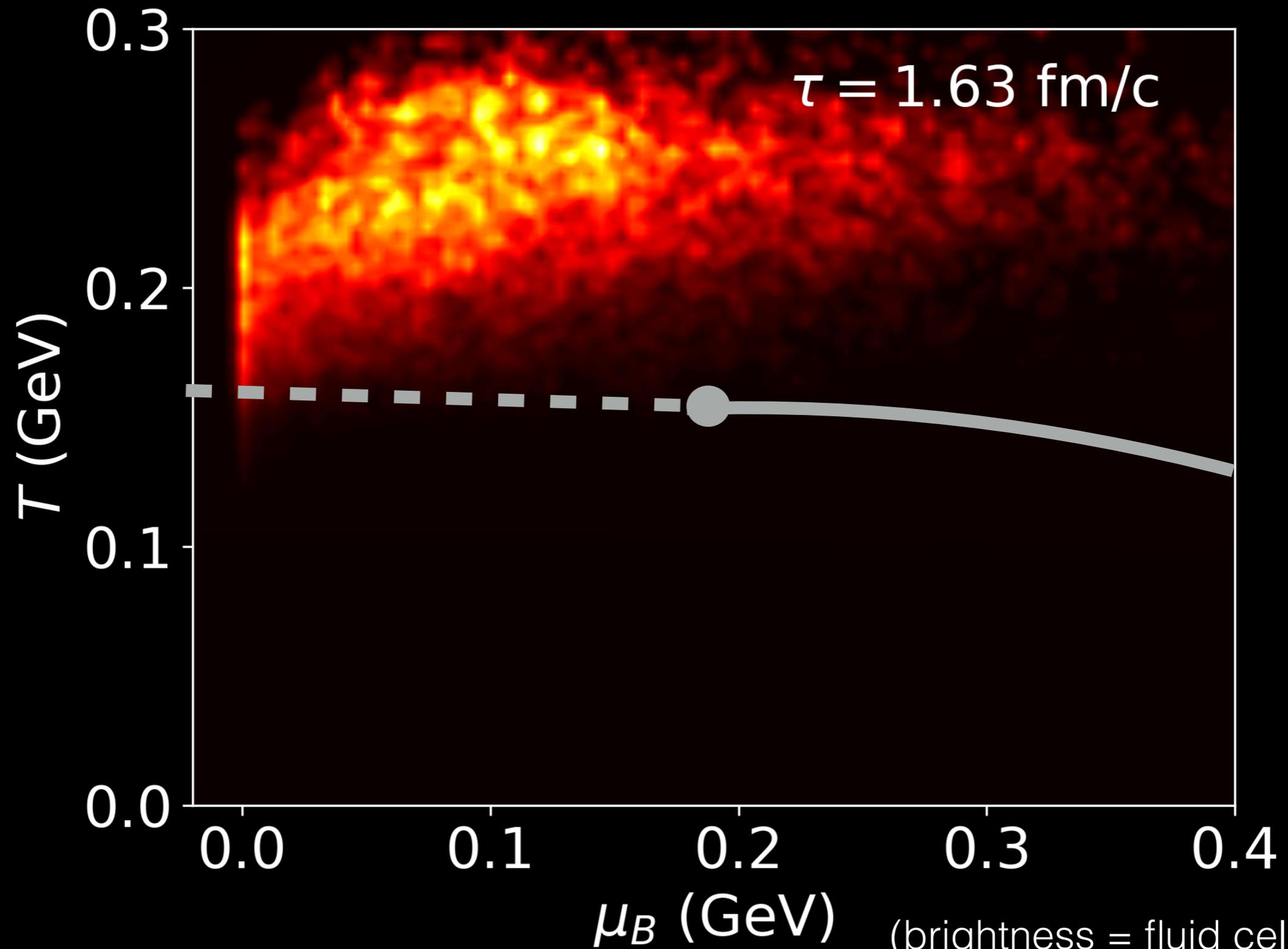
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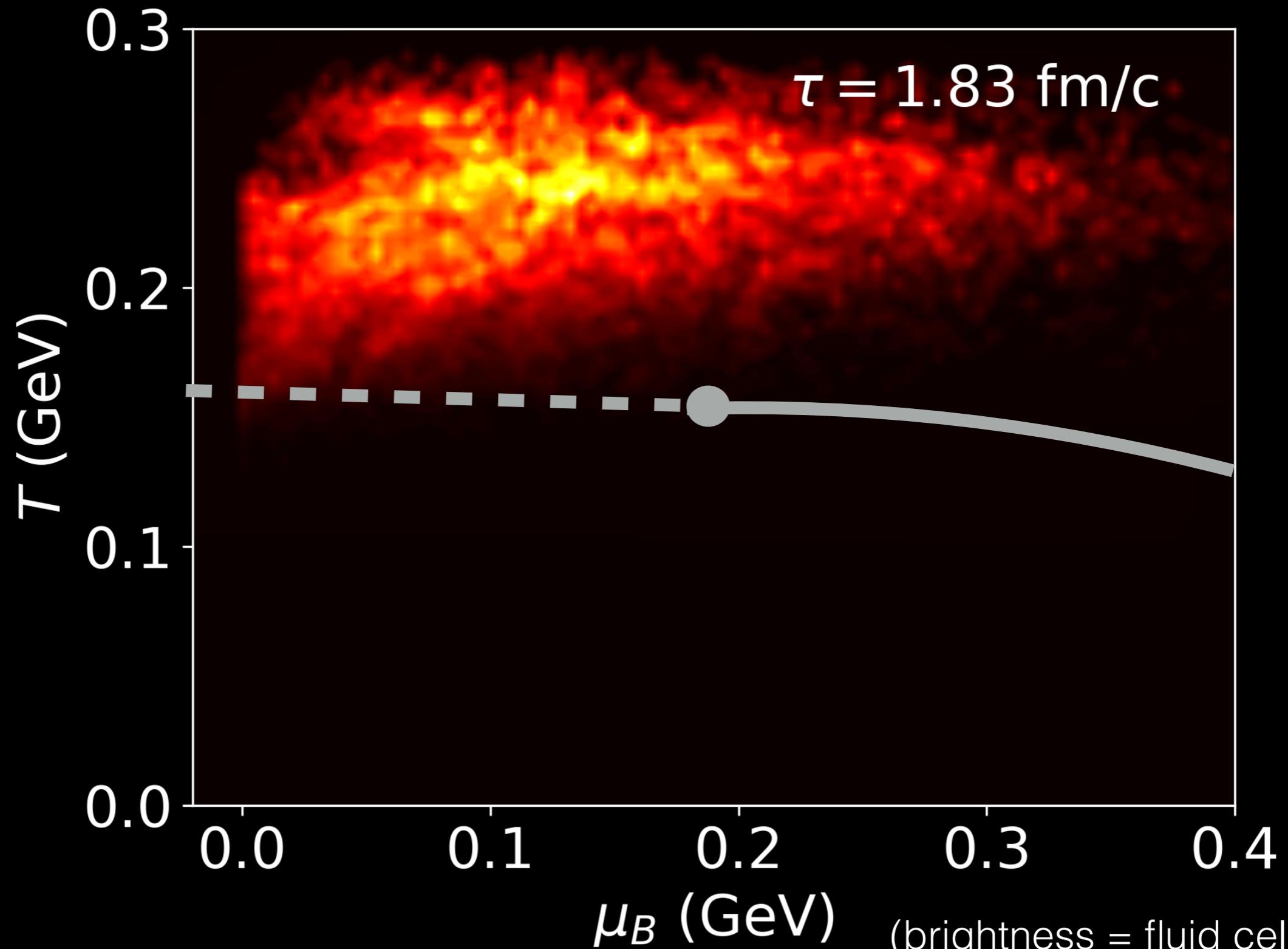
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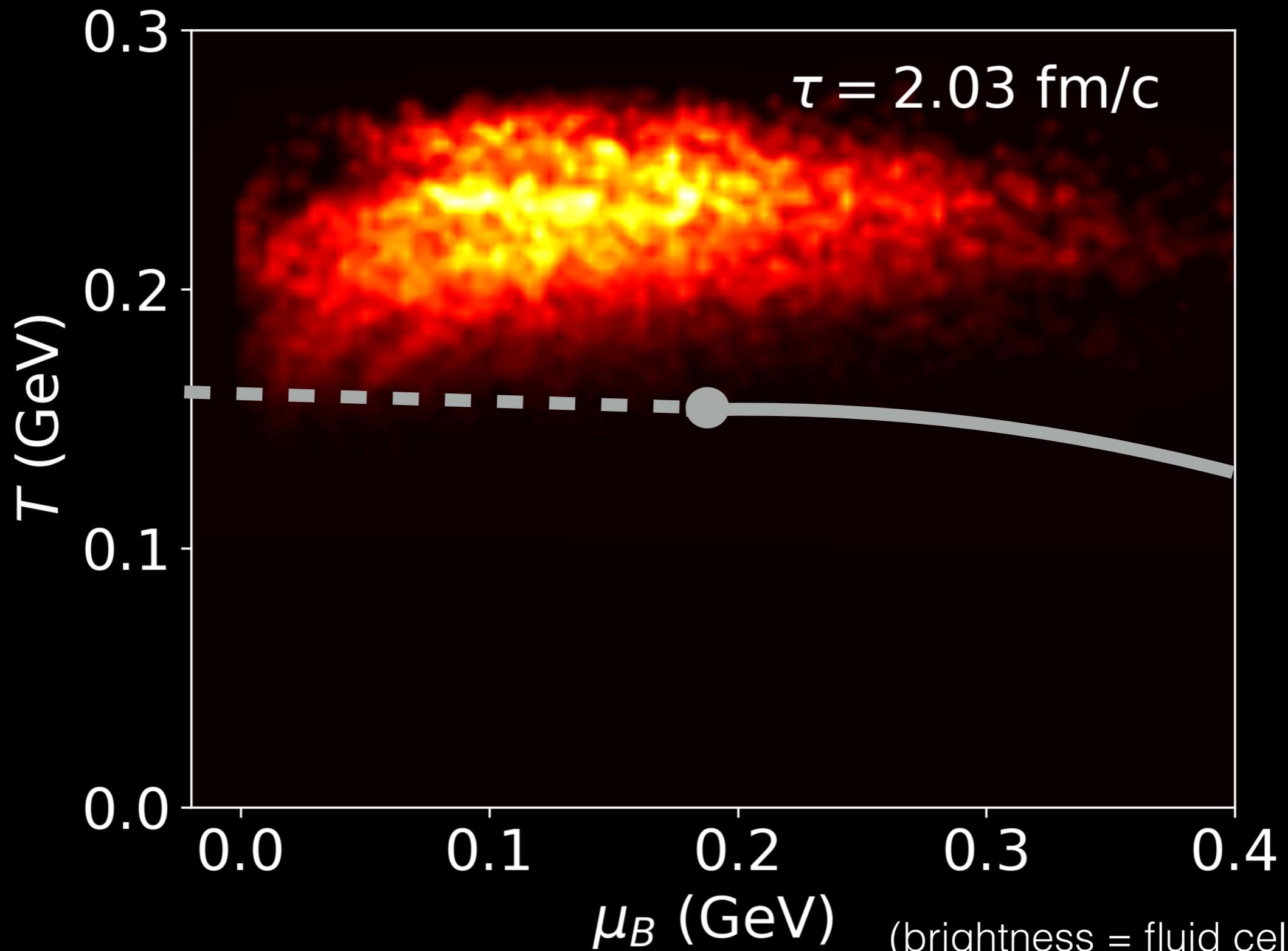
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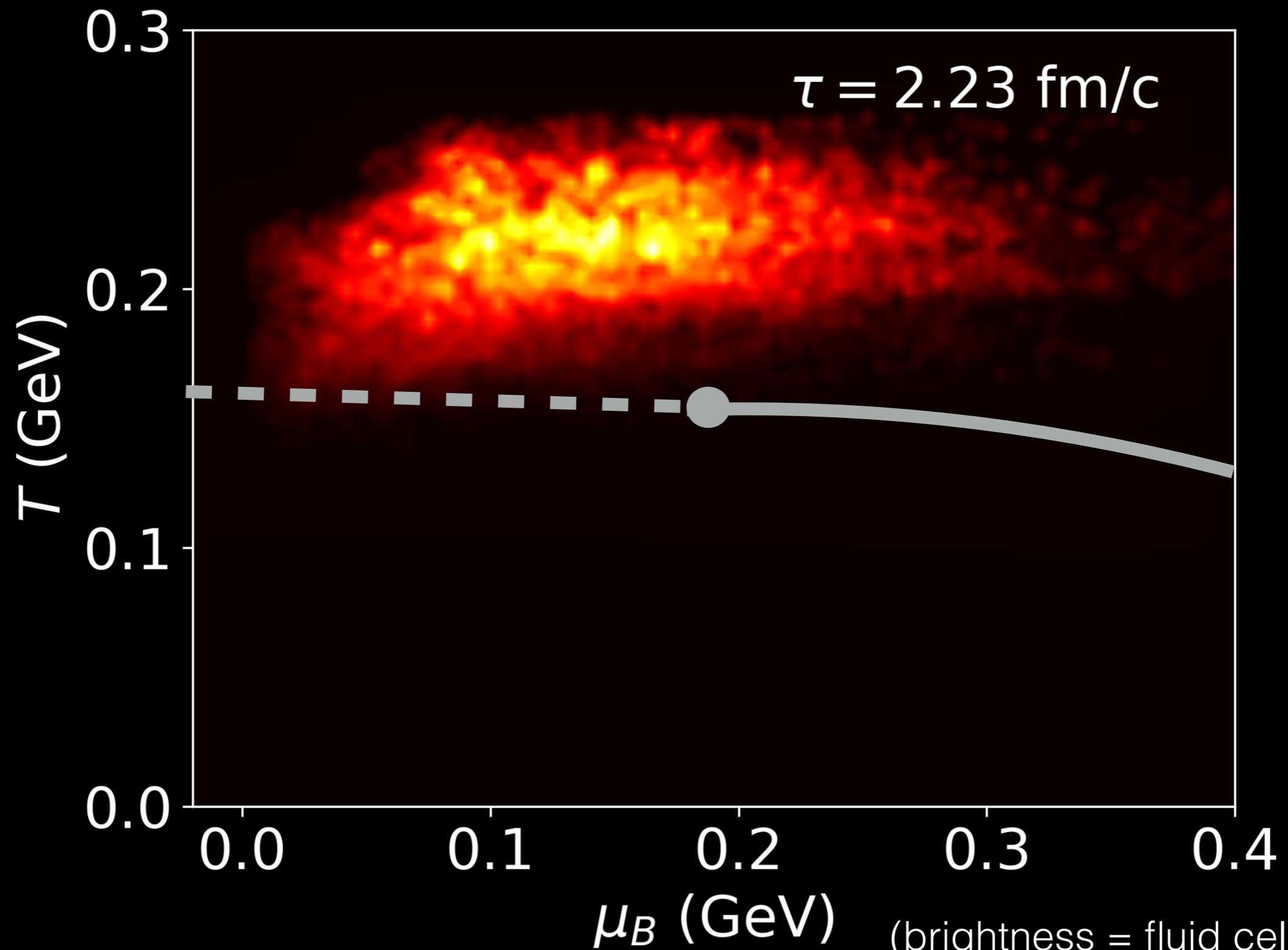
Sailing in the phase diagram



0-5% AuAu@19.6 GeV

(The critical point is only for eye guidance)

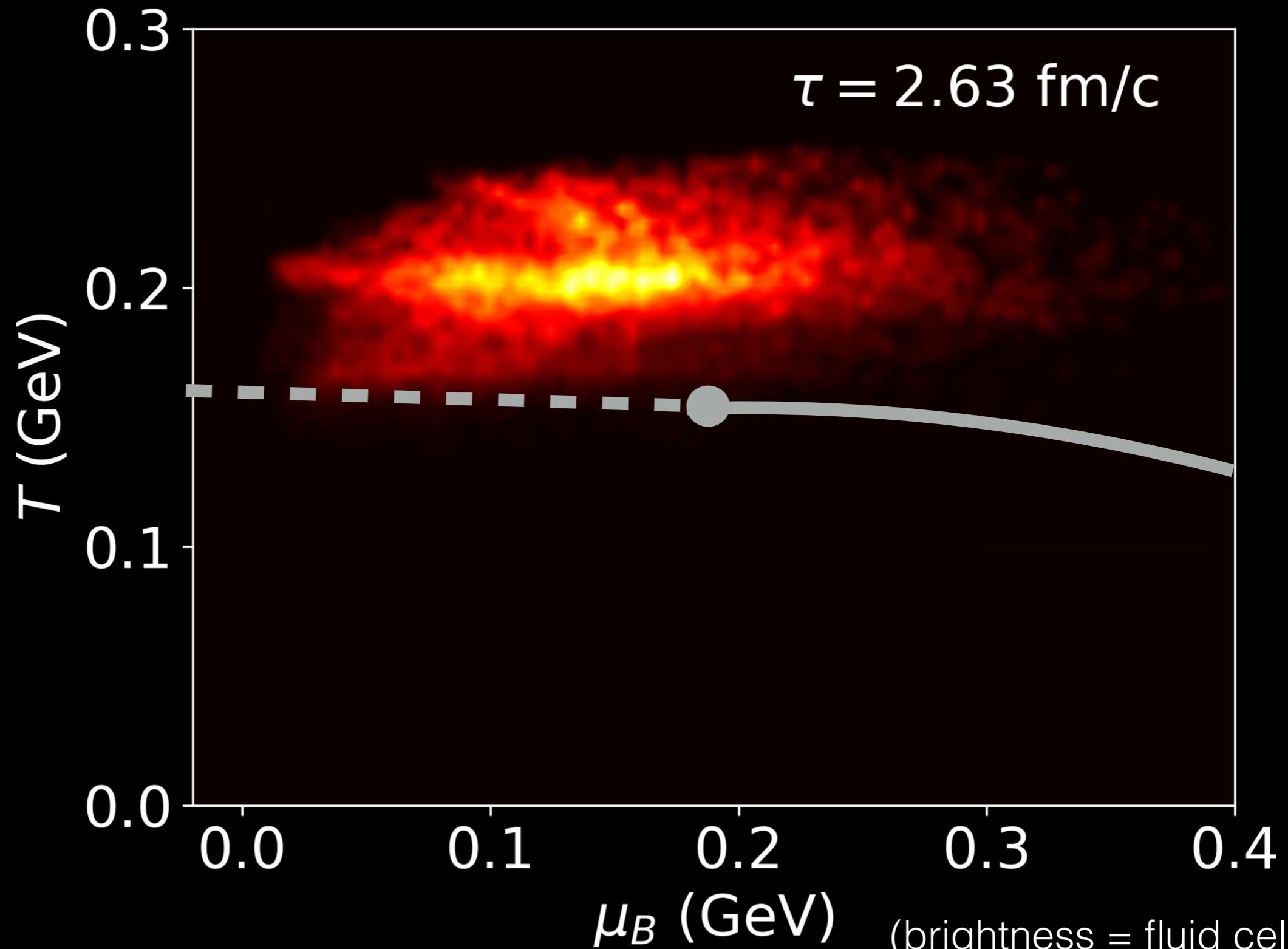
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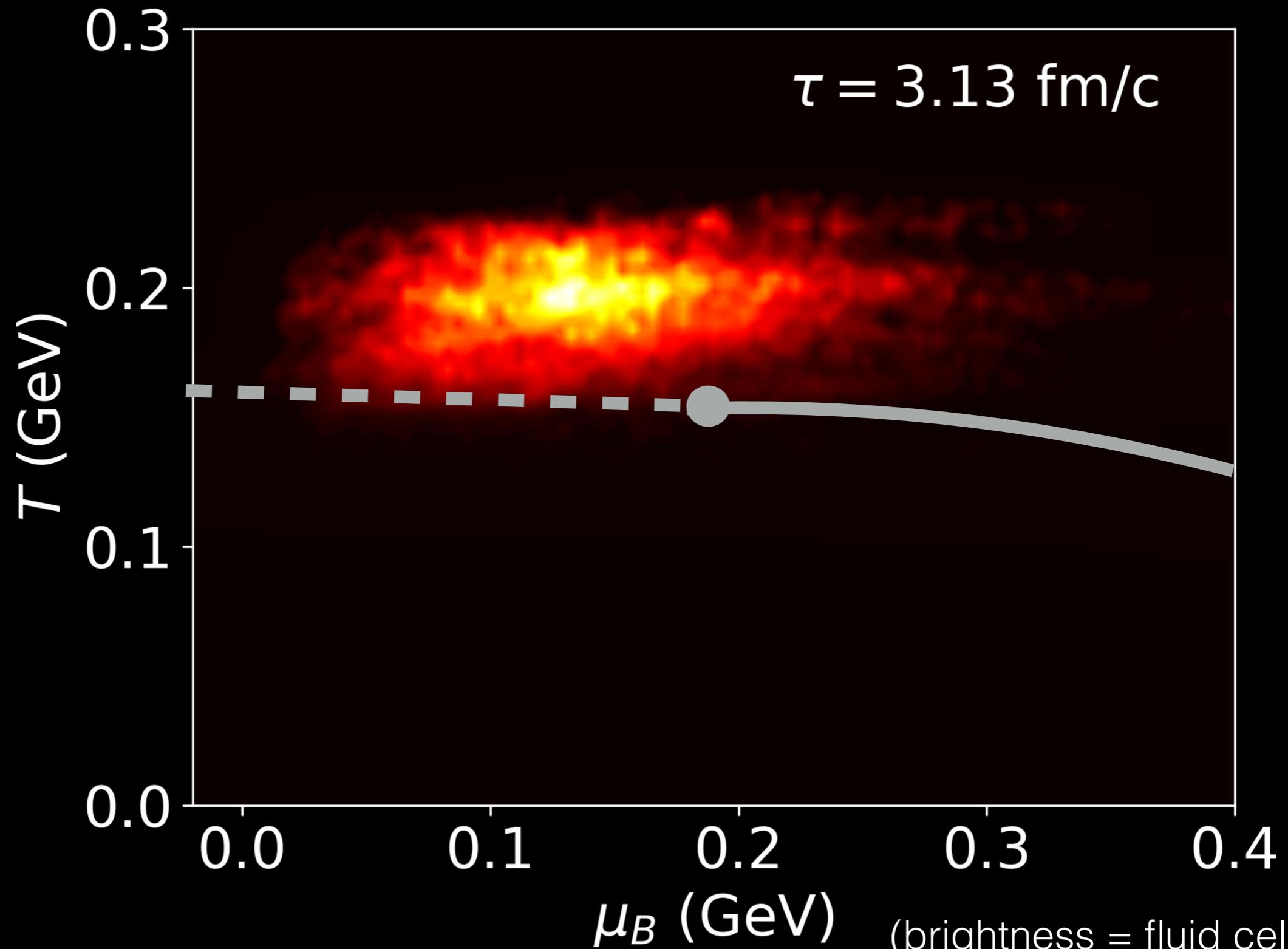
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Sailing in the phase diagram



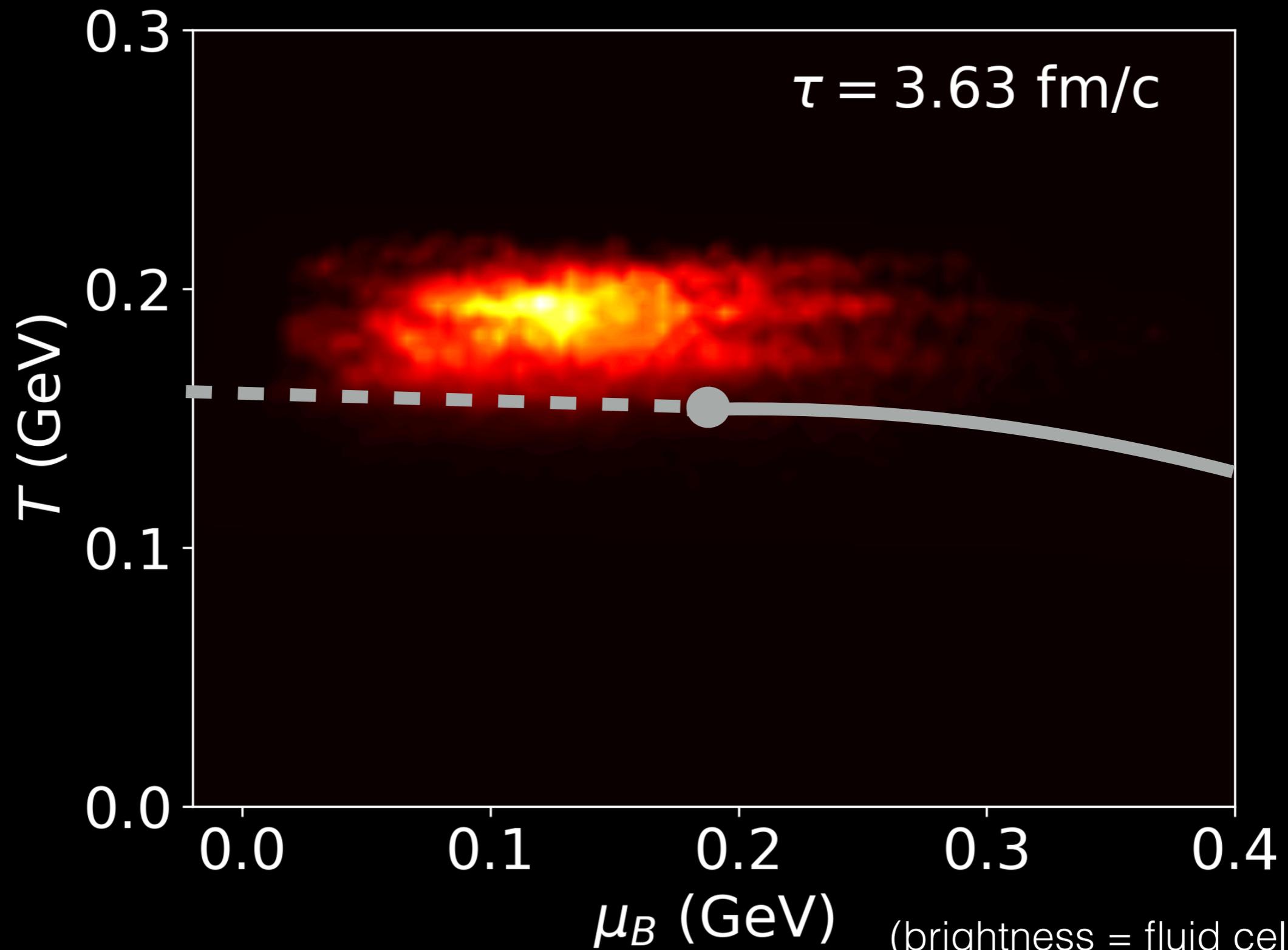
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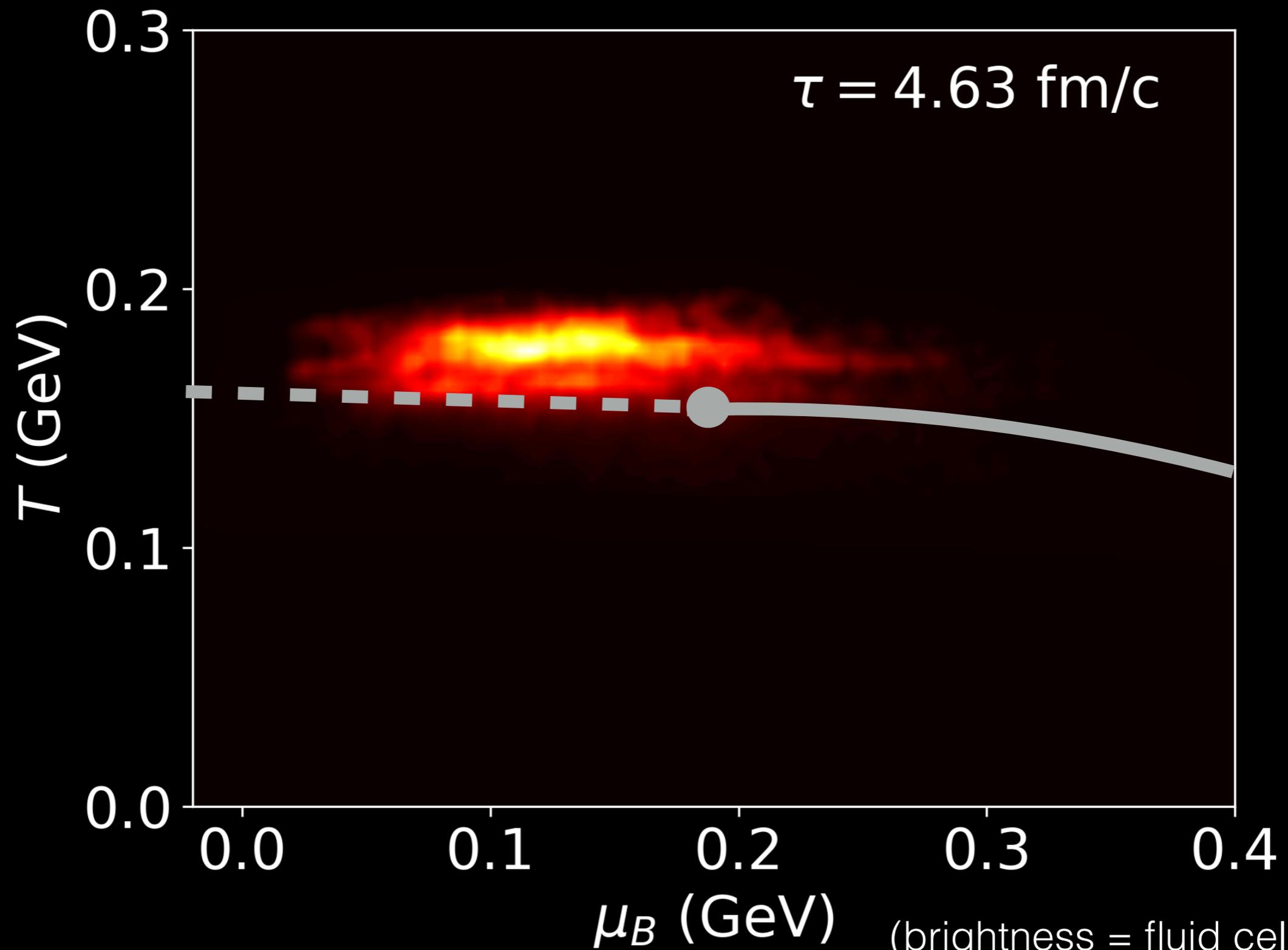
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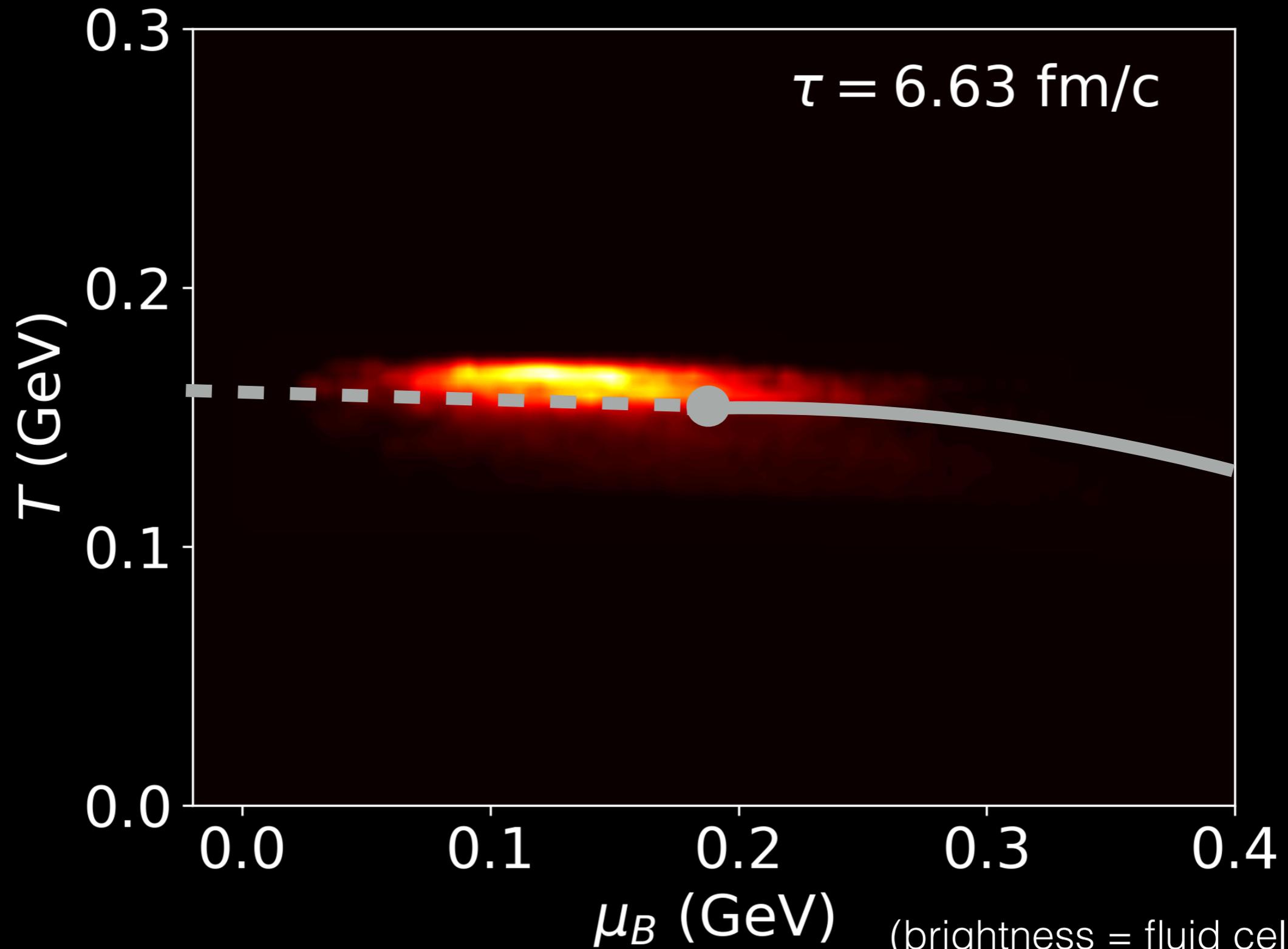
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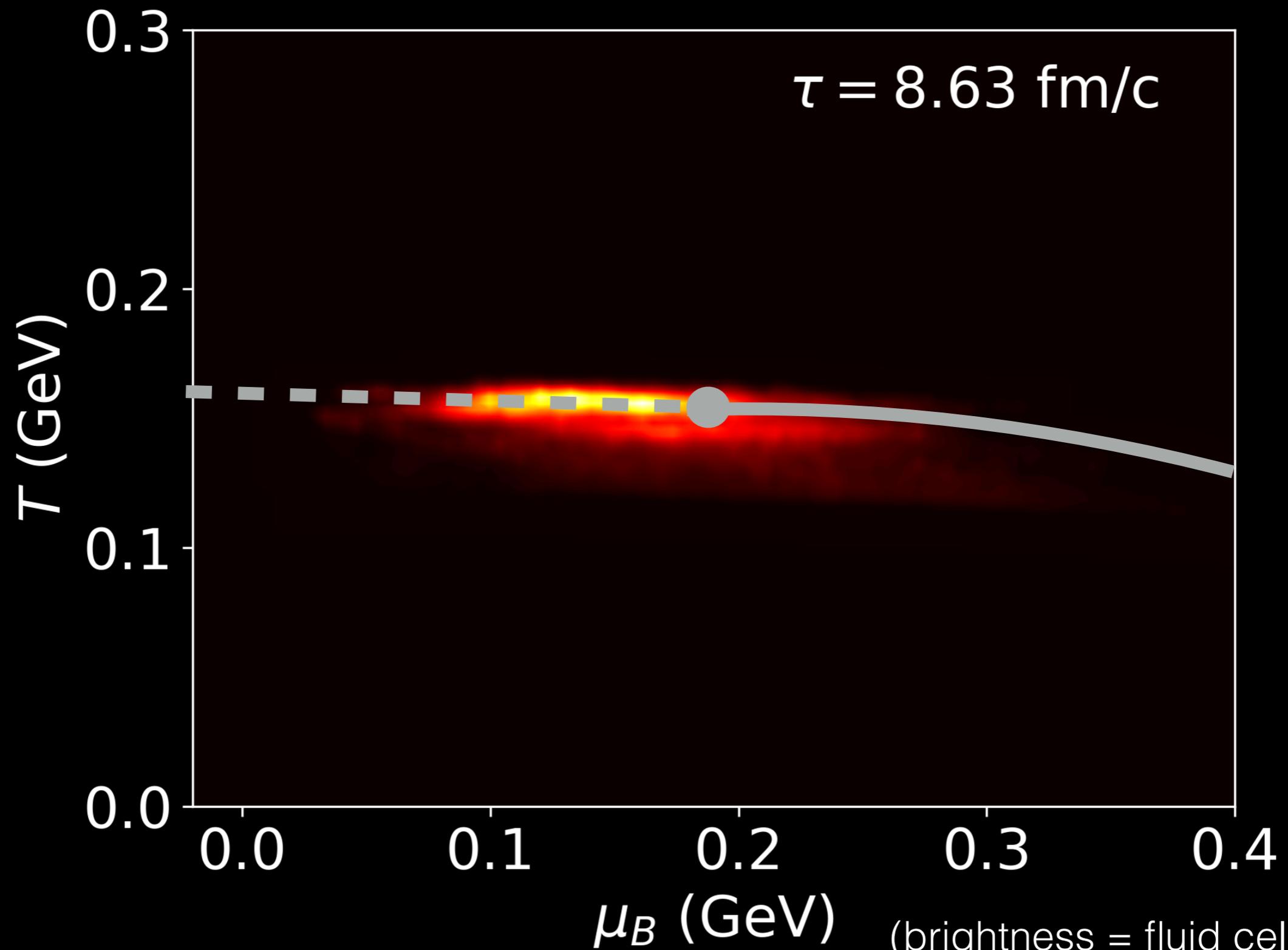
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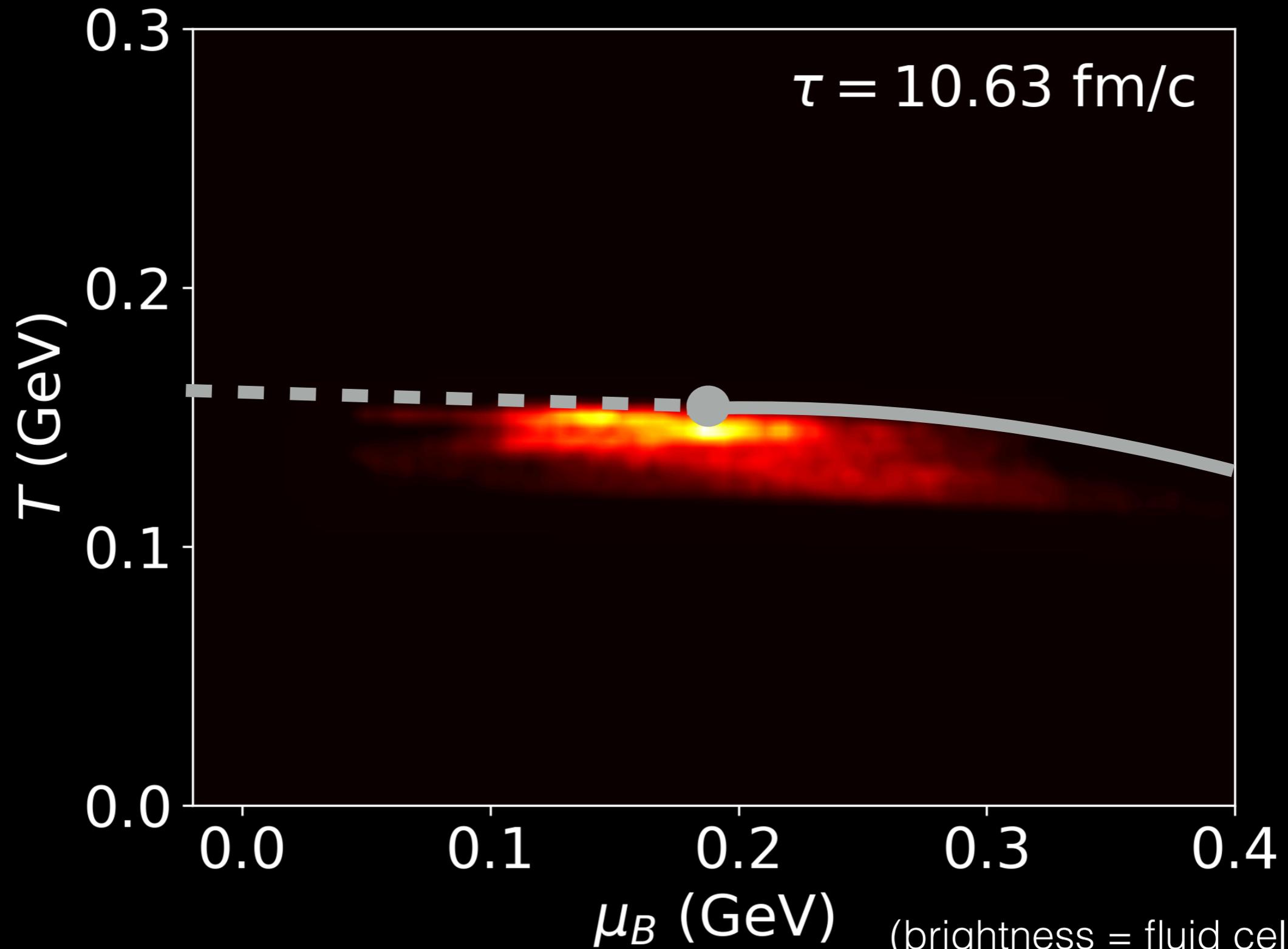
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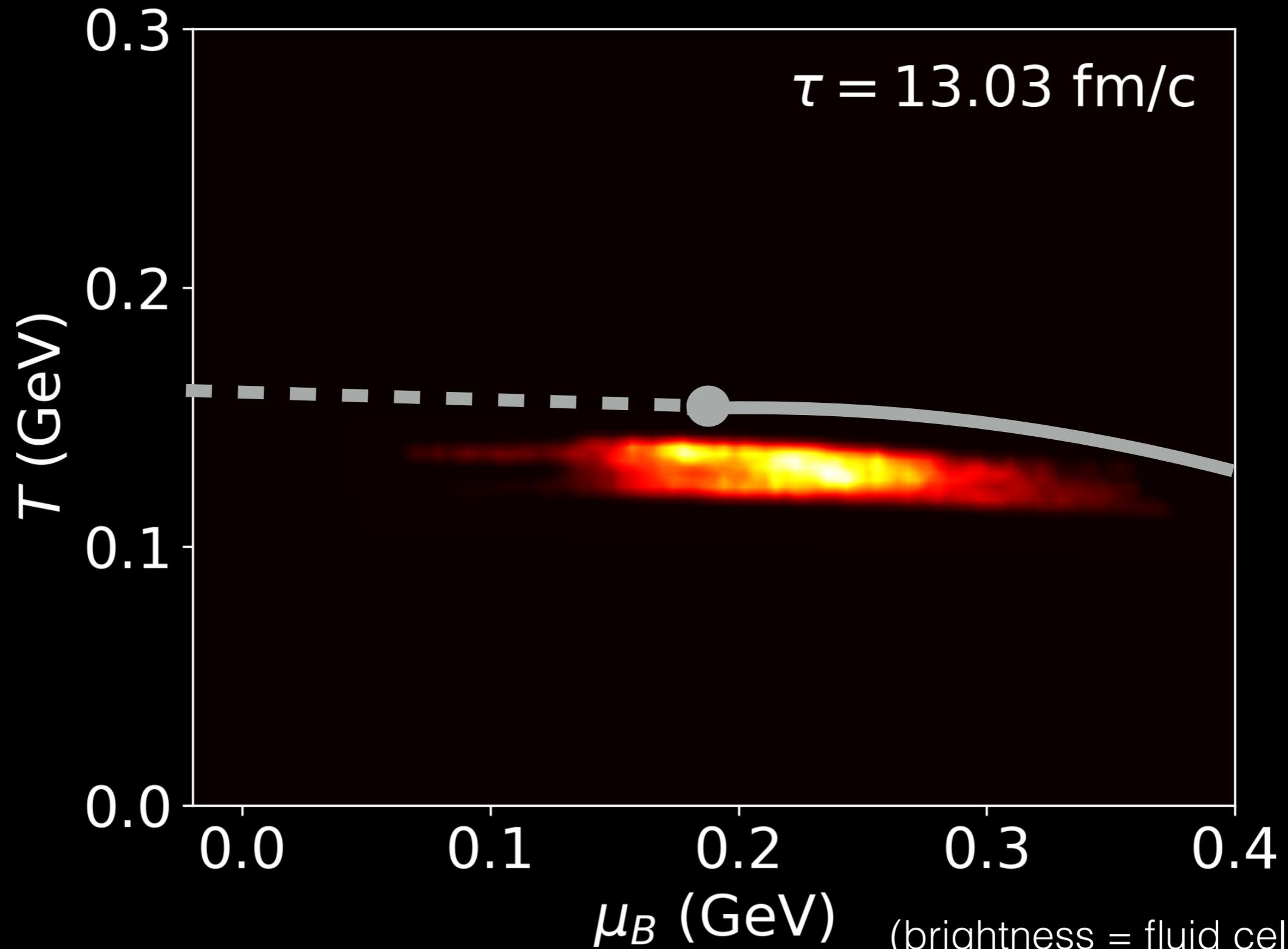
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Sailing in the phase diagram



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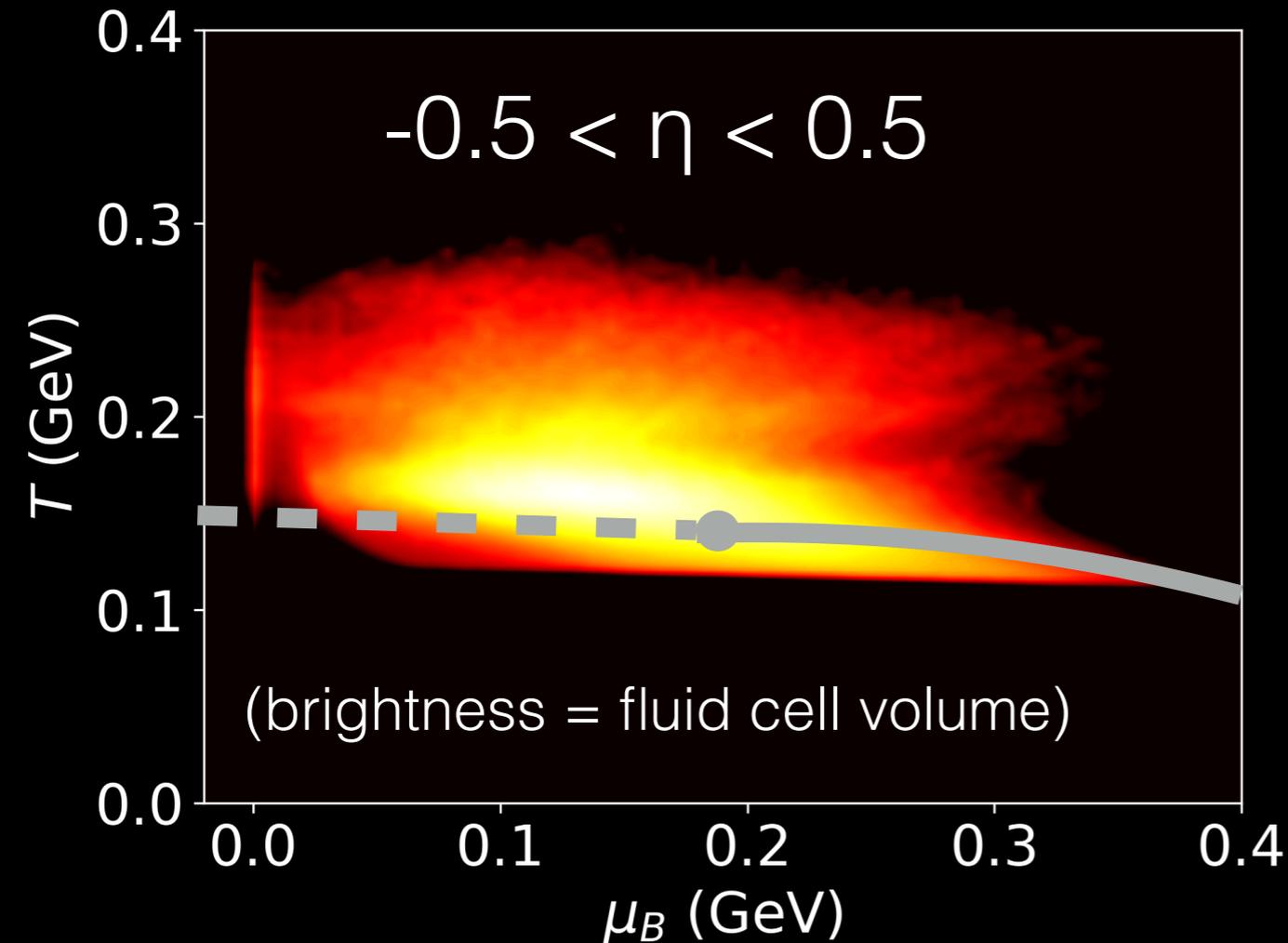


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0-5% AuAu@19.6 GeV

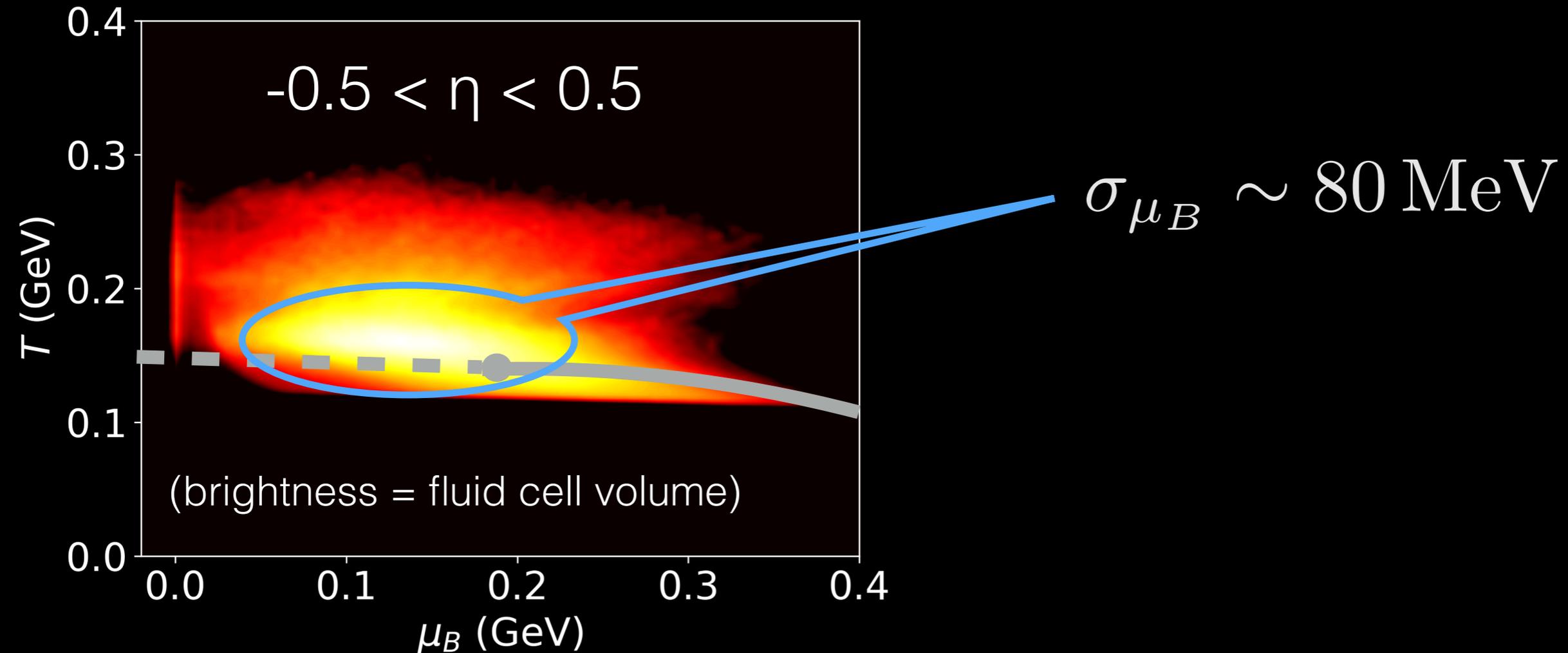


- The fireball trajectory and how fast it flows in the phase diagram are indispensable information for the search of the critical point

only from dynamical modelling

Sailing in the phase diagram

0-5% AuAu@19.6 GeV

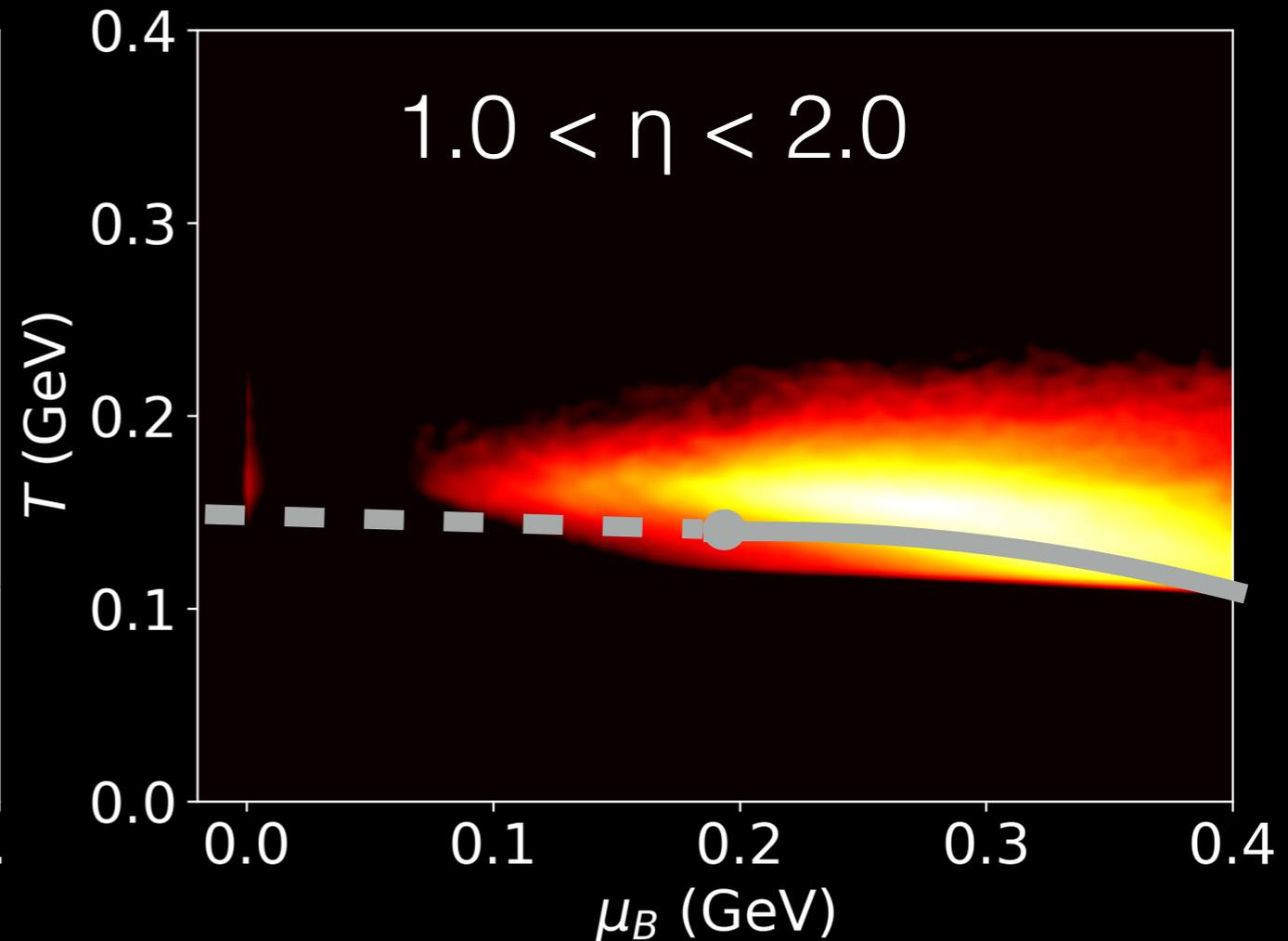
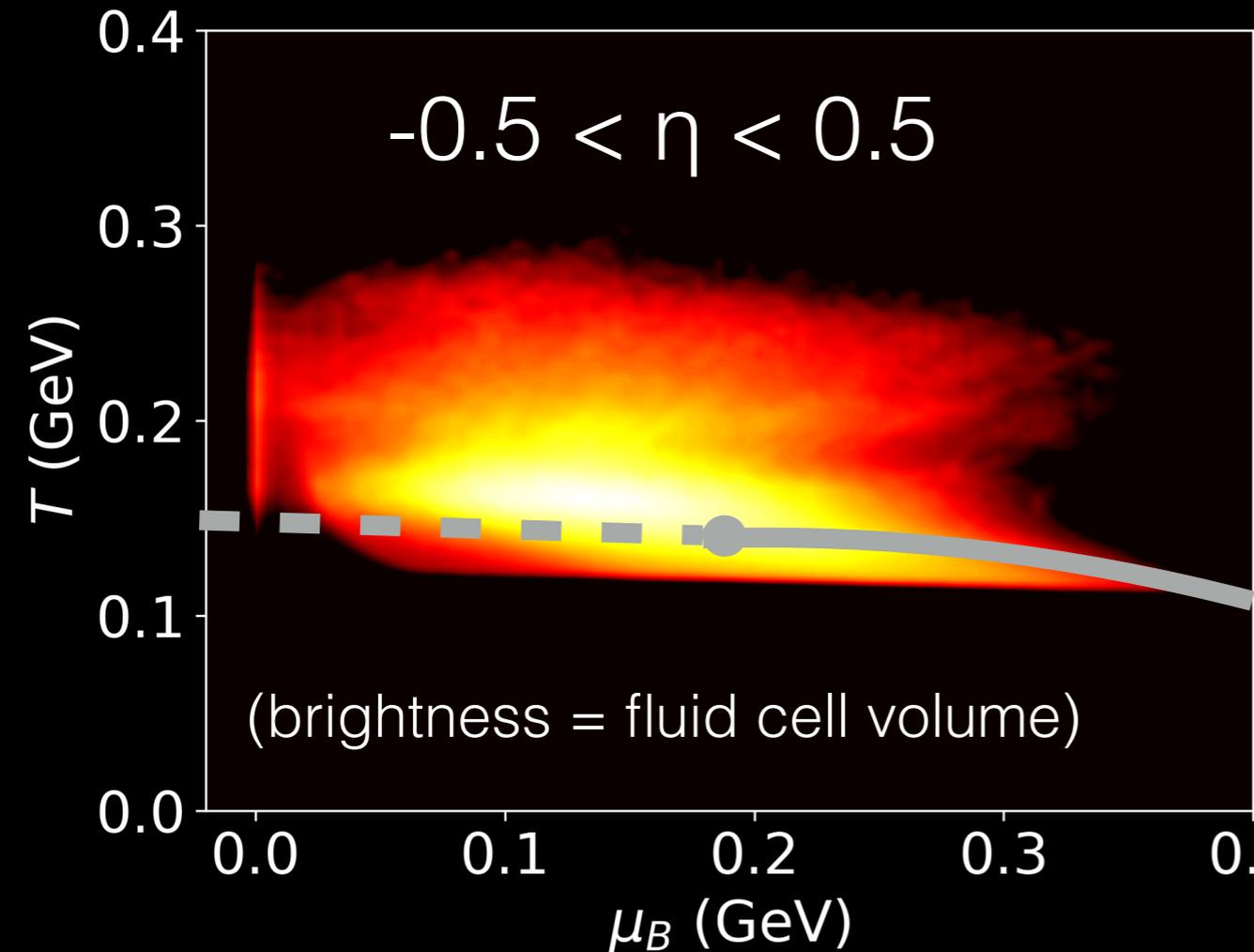


- The fireball trajectory and how fast it flows in the phase diagram are indispensable information for the search of the critical point

only from dynamical modelling

Sailing in the phase diagram

0-5% AuAu@19.6 GeV



- The selected rapidity window can serve as an experimental knob to systematically study the critical fluctuations in addition to collision energy

See J. Brewer's talk on Wednesday 9:40 for the rapidity dependence of cumulants

Conclusions

- We developed a **dynamical initialization** framework to study the early time evolution of heavy-ion collisions at the BES energies
 - full **(3+1)-d event-by-event** hydro with **net baryon current**
 - Important effect on the fireball evolution
- Dynamically modelling of relativistic heavy-ion collisions is the **cornerstone** of the search for the critical point of nuclear matter
- Future combination with the **Bayesian analysis** will help us to constrain the initial state and transport coefficients of the QGP in a baryon-rich environment

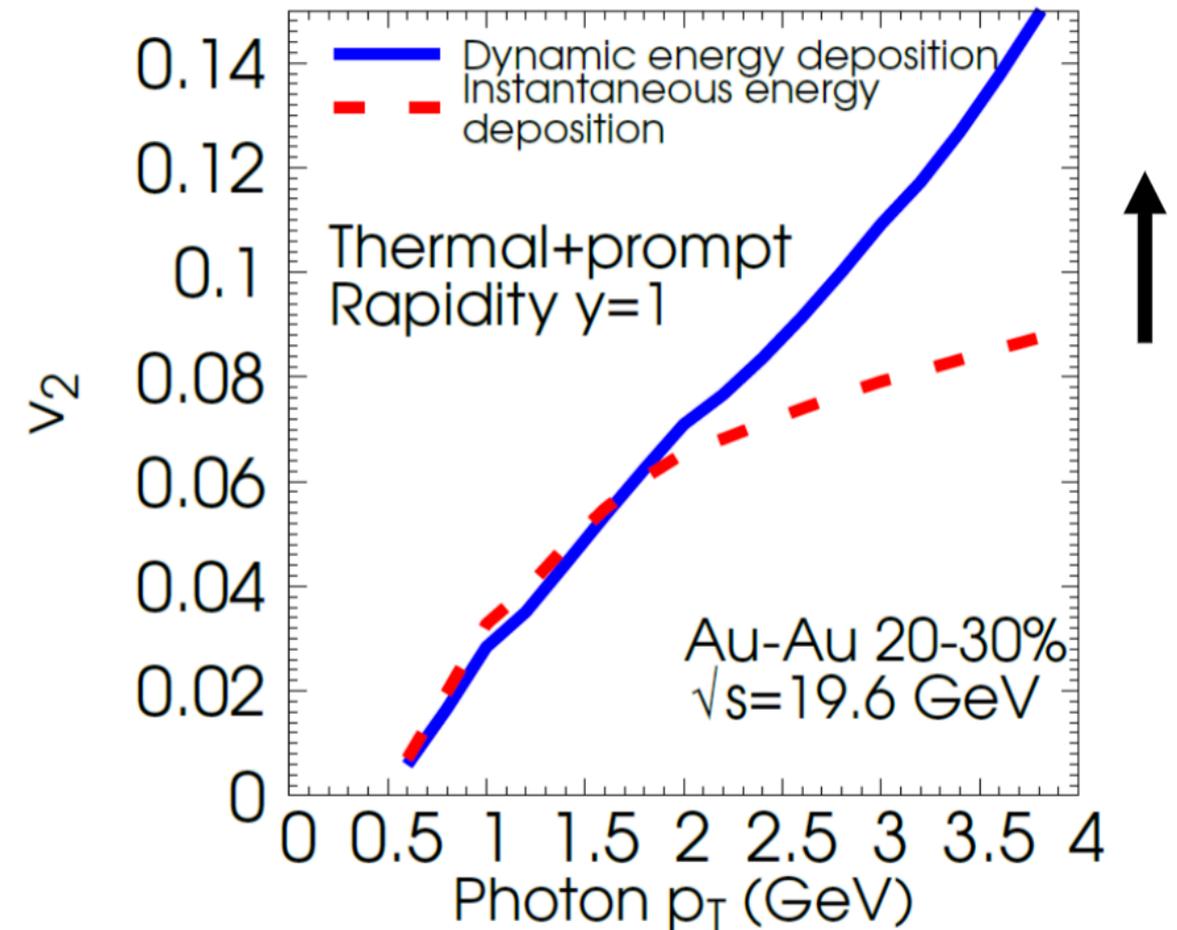
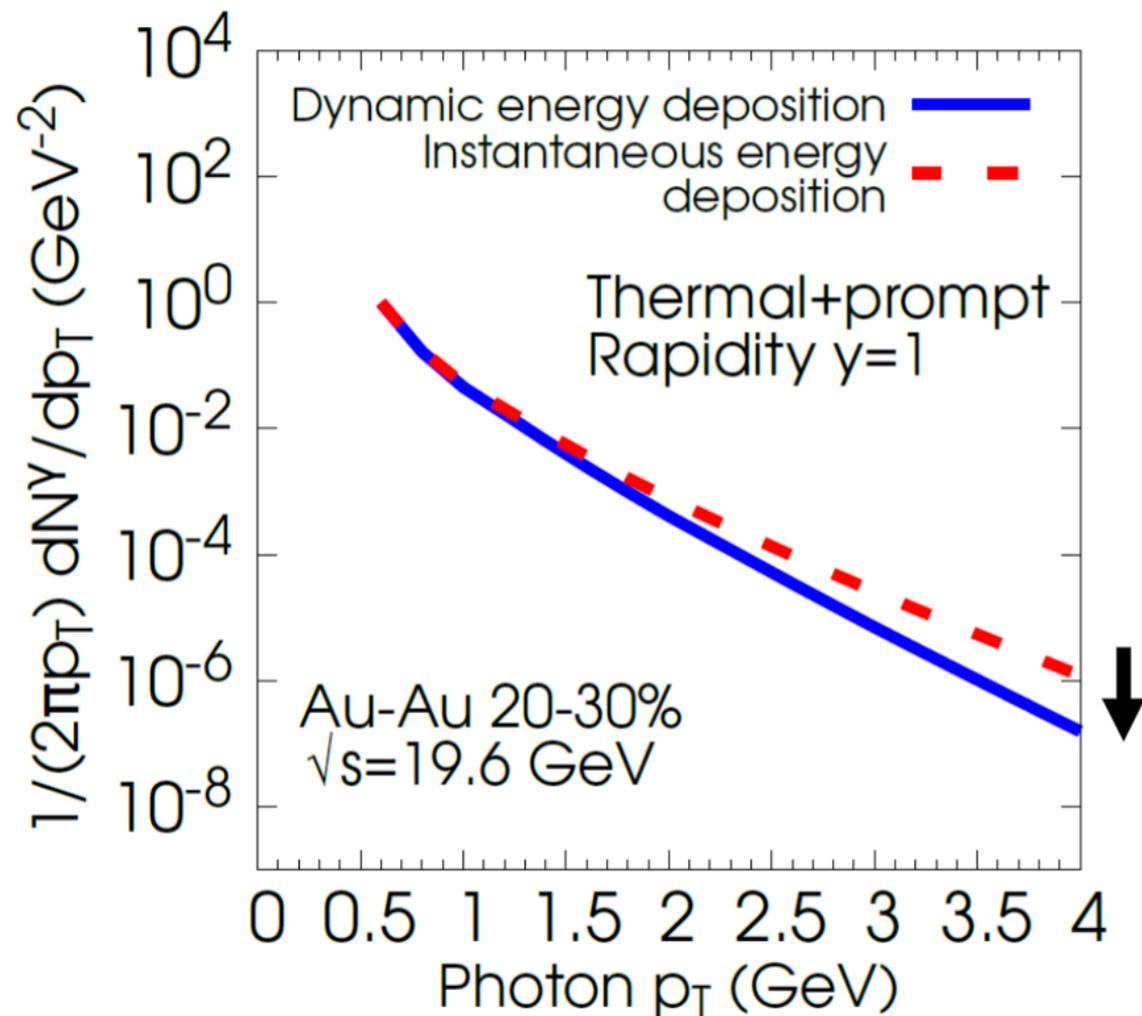


BACKUP

Dynamical initialization effect on EM probes

See J-F. Paquet's talk on Monday 17:10 for details

Thermal+prompt photons

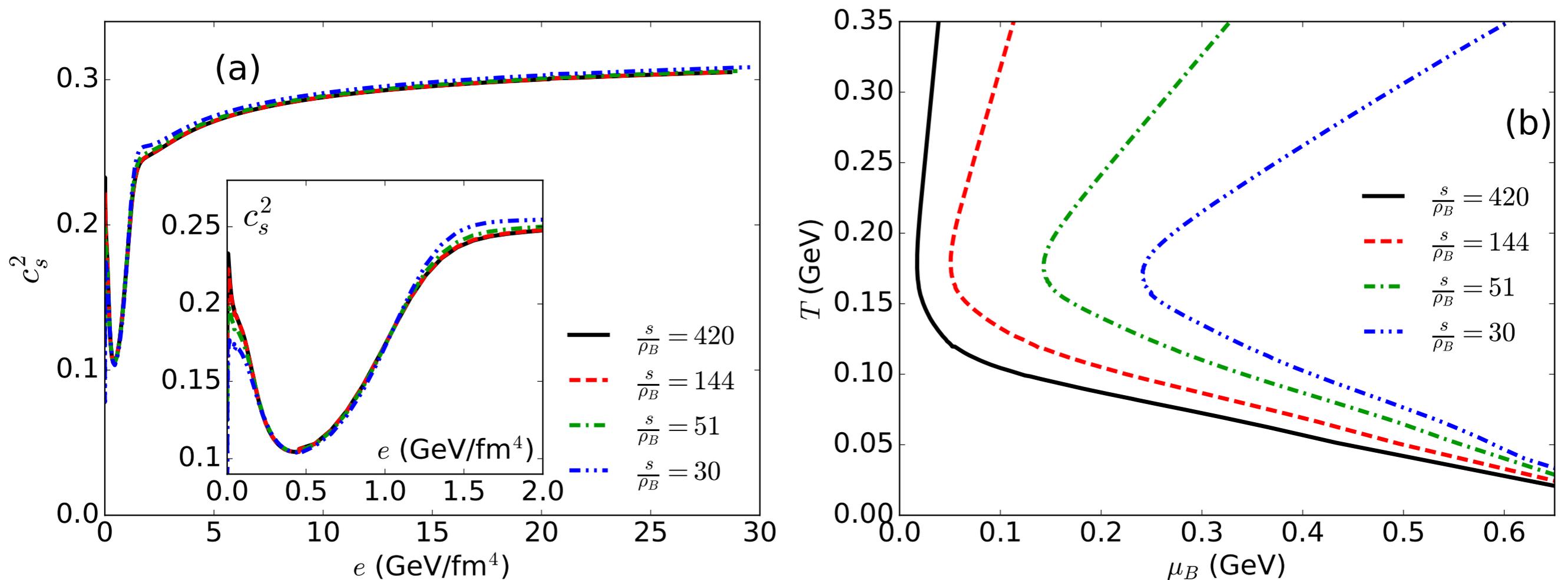


- Dynamical initialization results large direct photon v_2 at high p_T

space-time volume reduction at early time

EoS at finite μ_B

G. Denicol, C. Gale, S. Jeon, A. Monnai, B. Schenke and C. Shen, arXiv:1804.10557 [nucl-th]



High temperature:

- Lattice QCD EoS up to $\mathcal{O}(\mu_B^4)$

Low temperature:

- Glued with hadron resonance gas EoS

Hydrodynamics

Energy momentum tensor

G. Denicol, C. Gale, S. Jeon, A. Monnai, B. Schenke
and C. Shen, arXiv:1804.10557 [nucl-th]

$$T^{\mu\nu} = e u^\mu u^\nu - (P + \Pi) \Delta^{\mu\nu} + \pi^{\mu\nu}$$

$$\partial_\mu T^{\mu\nu} = T^{\mu\nu};_{;\mu} = 0$$

$$\Delta^{\mu\nu} = g^{\mu\nu} - u^\mu u^\nu$$

Conserved currents

$$J^\mu = n u^\mu + q^\mu$$

$$\partial_\mu J^\mu = 0$$

$$D = u^\mu \partial_\mu$$

$$\nabla^\mu = \Delta^{\mu\nu} \partial_\nu$$

$$\theta = \partial_\mu u^\mu$$

Dissipative part:

$$\Delta_{\alpha\beta}^{\mu\nu} D \pi^{\alpha\beta} = -\frac{1}{\tau_\pi} (\pi^{\mu\nu} - 2\eta \sigma^{\mu\nu}) - \frac{\delta_{\pi\pi}}{\tau_\pi} \pi^{\mu\nu} \theta - \frac{\tau_{\pi\pi}}{\tau_\pi} \pi^{\lambda\langle\mu} \sigma^{\nu\rangle}{}_\lambda + \frac{\phi_7}{\tau_\pi} \pi_\alpha^{\langle\mu} \pi^{\nu\rangle\alpha}$$

$$- \frac{\tau_{\pi\pi}}{\tau_\pi} \pi_\alpha^{\langle\mu} \sigma^{\nu\rangle\alpha} + \frac{\lambda_{\pi\Pi}}{\tau_\pi} \Pi \sigma^{\mu\nu}$$

$$D\Pi = -\frac{1}{\tau_\Pi} (\Pi + \zeta \theta) - \frac{\delta_{\Pi\Pi}}{\tau_\Pi} \Pi \theta + \frac{\lambda_{\Pi\pi}}{\tau_\Pi} \pi^{\mu\nu} \sigma_{\mu\nu}$$

$$\Delta^{\mu\nu} D q_\nu = -\frac{1}{\tau_q} (q^\mu - \kappa \nabla^\mu \frac{\mu_B}{T}) - \frac{\delta_{qq}}{\tau_q} q^\mu \theta - \frac{\lambda_{qq}}{\tau_q} q_\nu \sigma^{\mu\nu}$$

Transport coefficients

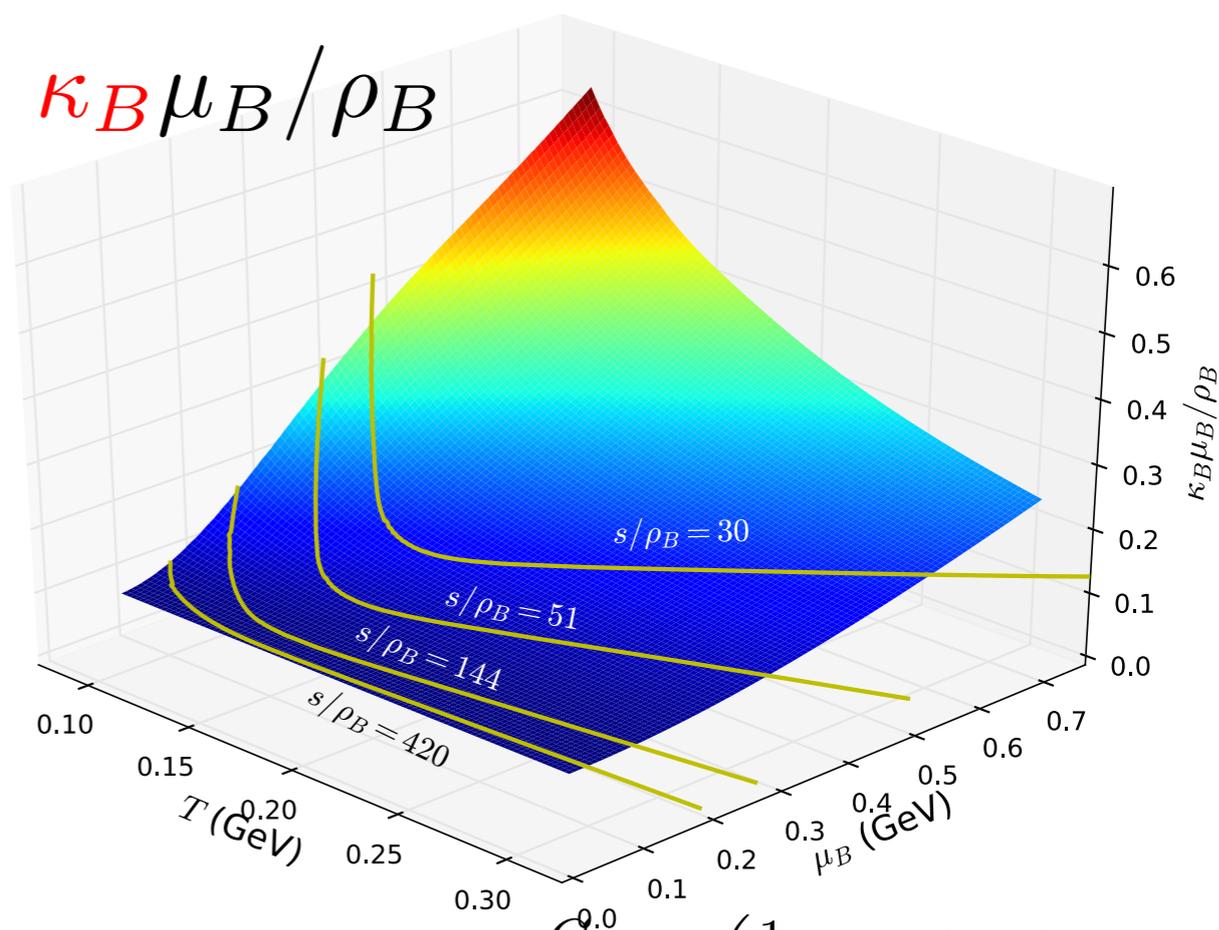
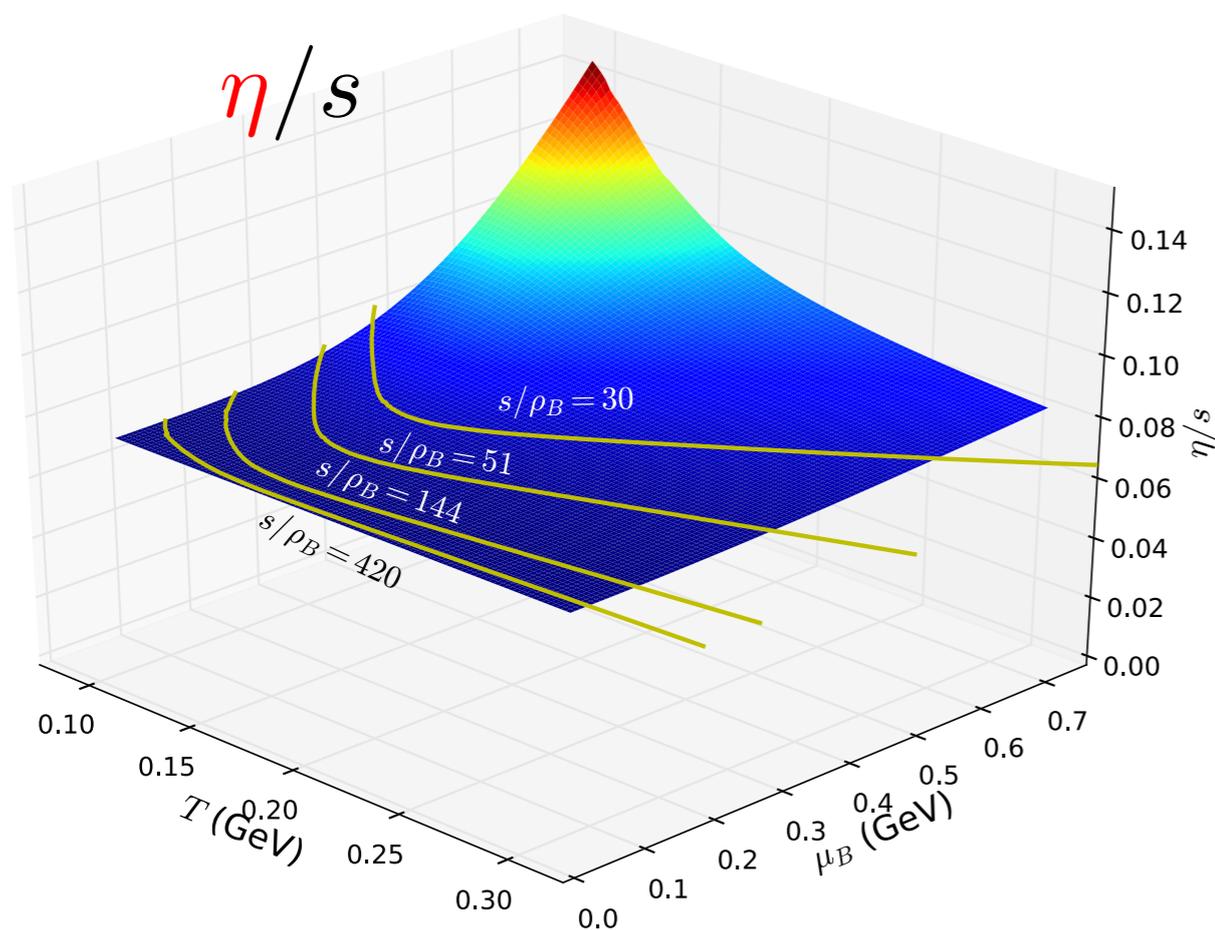
Dissipative part:

(relaxation time approximation)

$$\Delta_{\alpha\beta}^{\mu\nu} D\pi^{\alpha\beta} = -\frac{1}{\tau_\pi} (\pi^{\mu\nu} - 2\eta\sigma^{\mu\nu}) - \frac{\delta_{\pi\pi}}{\tau_\pi} \pi^{\mu\nu} \theta - \frac{\tau_{\pi\pi}}{\tau_\pi} \pi^\lambda \langle \mu \sigma^\nu \rangle_\lambda + \frac{\phi_7}{\tau_\pi} \pi_\alpha \langle \mu \pi^\nu \rangle_\alpha$$

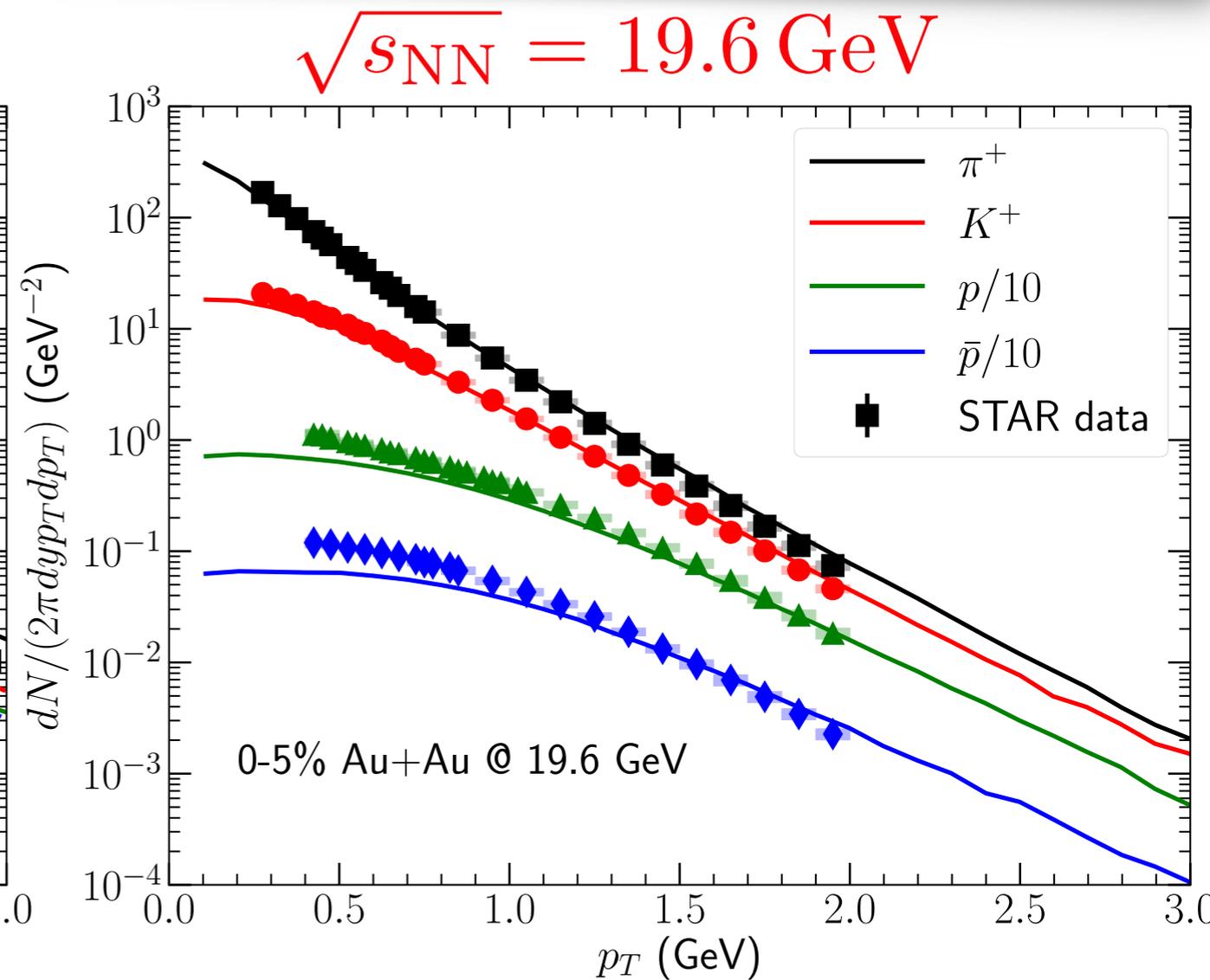
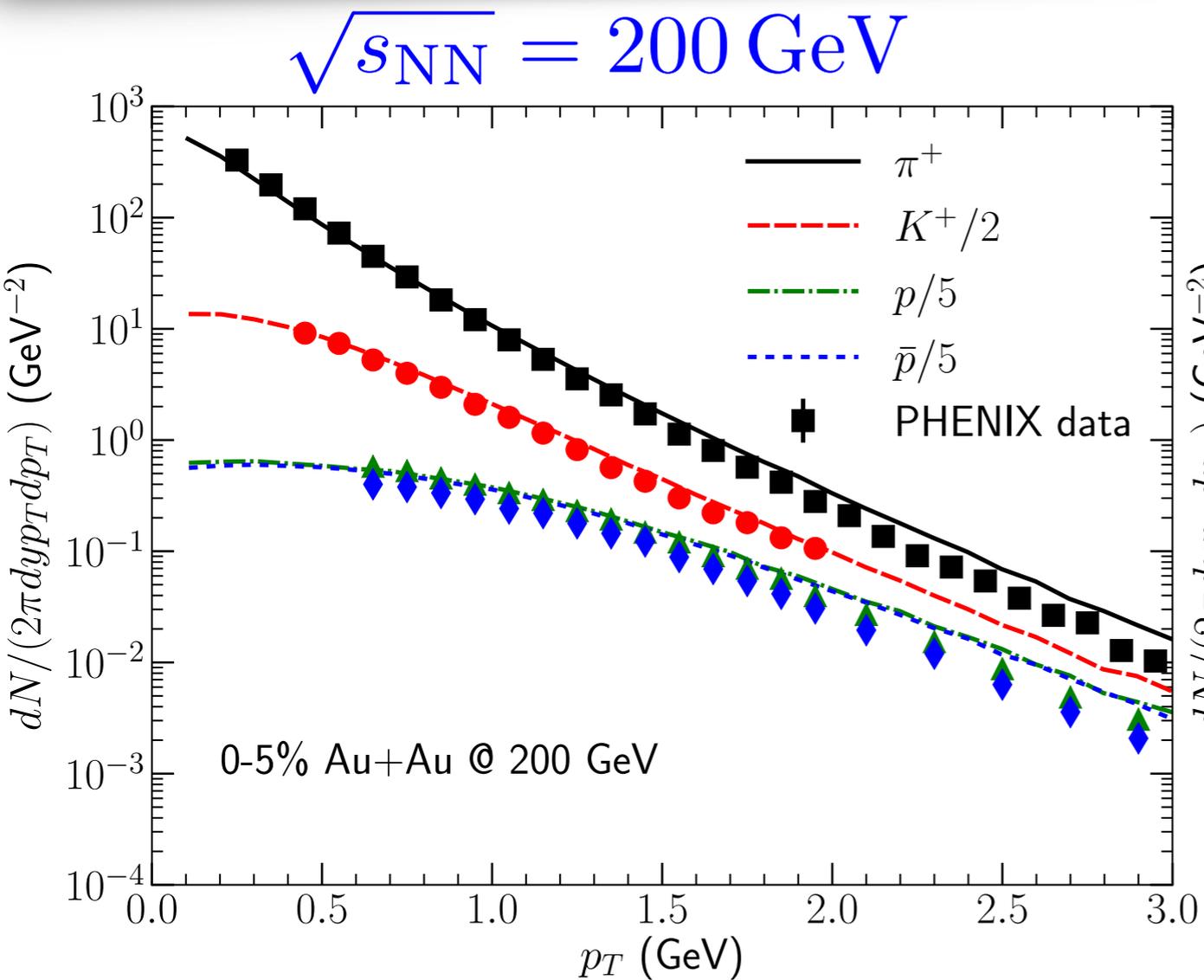
$$\Delta^{\mu\nu} Dq_\nu = -\frac{1}{\tau_q} (q^\mu - \kappa \nabla^\mu \frac{\mu_B}{T}) - \frac{\delta_{qq}}{\tau_q} q^\mu \theta - \frac{\lambda_{qq}}{\tau_q} q_\nu \sigma^{\mu\nu}$$

With non-zero μ , we choose $\tau_\pi = \tau_q = \frac{0.4}{T} \quad \frac{\eta T}{e + \mathcal{P}} = 0.08$



$$\kappa_B = \frac{C_B^{0,0}}{T} \rho_B \left(\frac{1}{3} \coth \left(\frac{\mu_B}{T} \right) - \frac{\rho_B T}{e + P} \right)$$

Transverse Dynamics

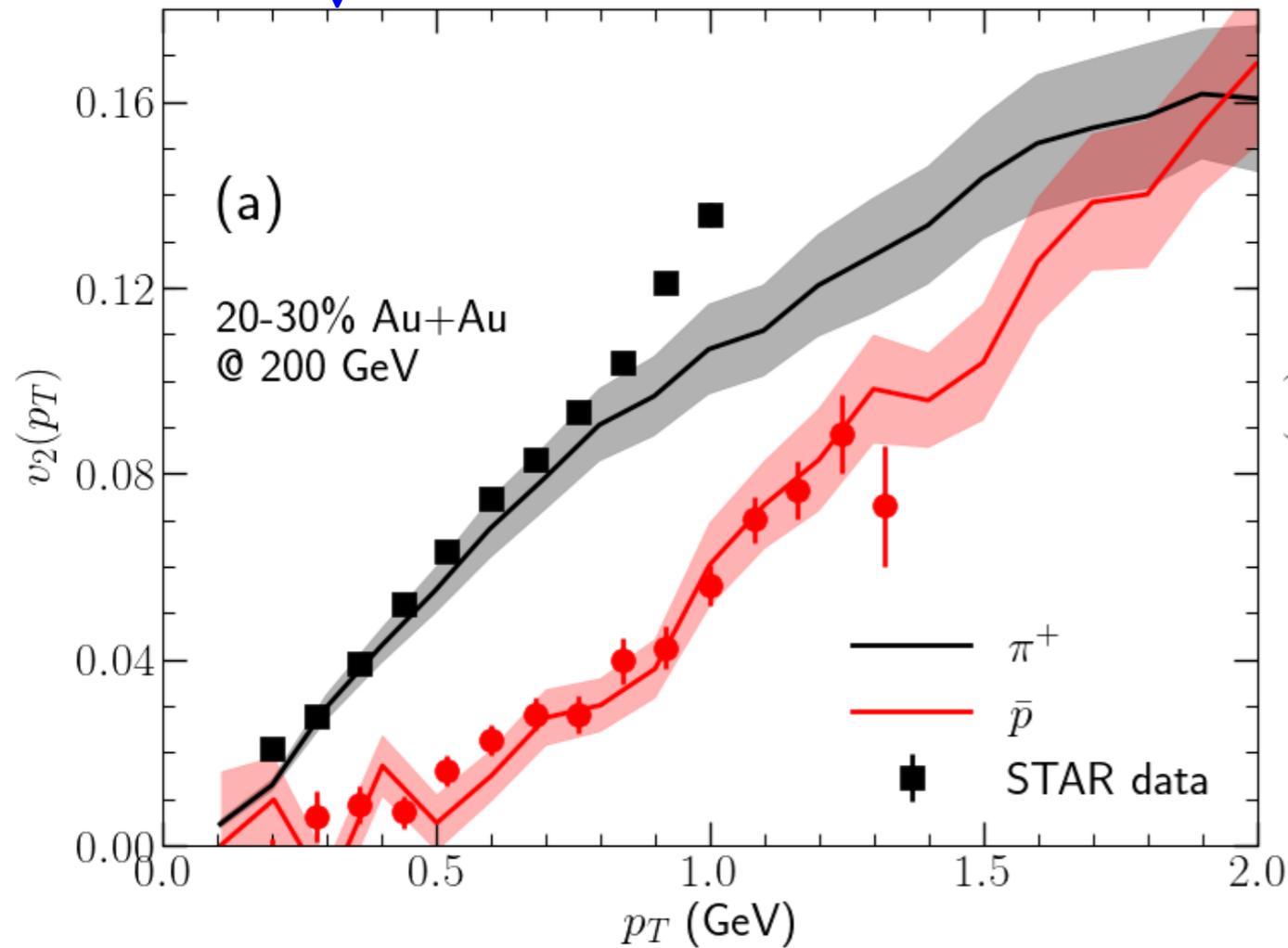


- Particle spectra are slightly flatter than the experimental data

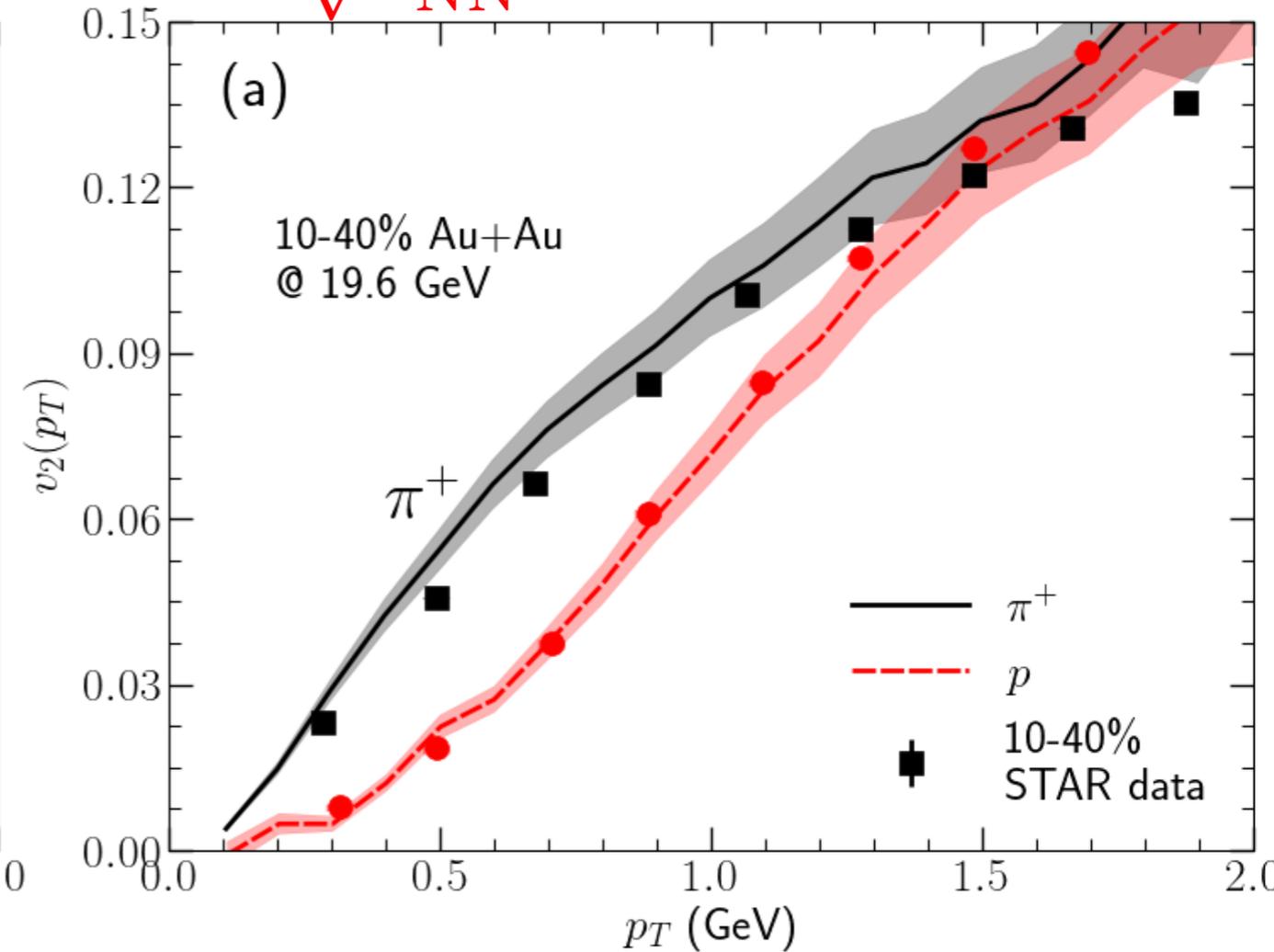
hot spot size, longer string breaking time, bulk viscosity?

Transverse Dynamics

$\sqrt{s_{NN}} = 200 \text{ GeV}$



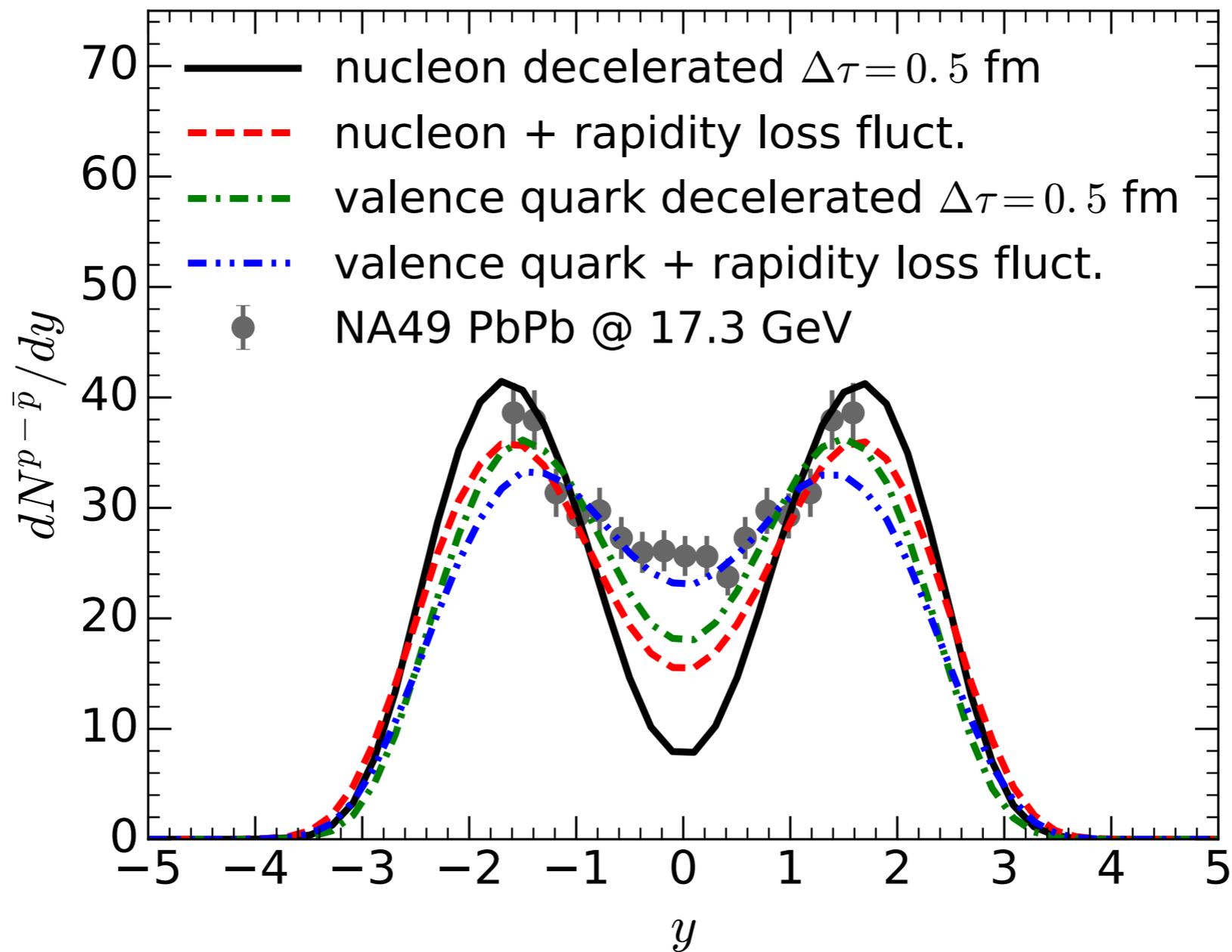
$\sqrt{s_{NN}} = 19.6 \text{ GeV}$



- Fair agreement of identified particle $v_2(p_T)$ at mid-rapidity
- Mass splitting is reproduced by the model

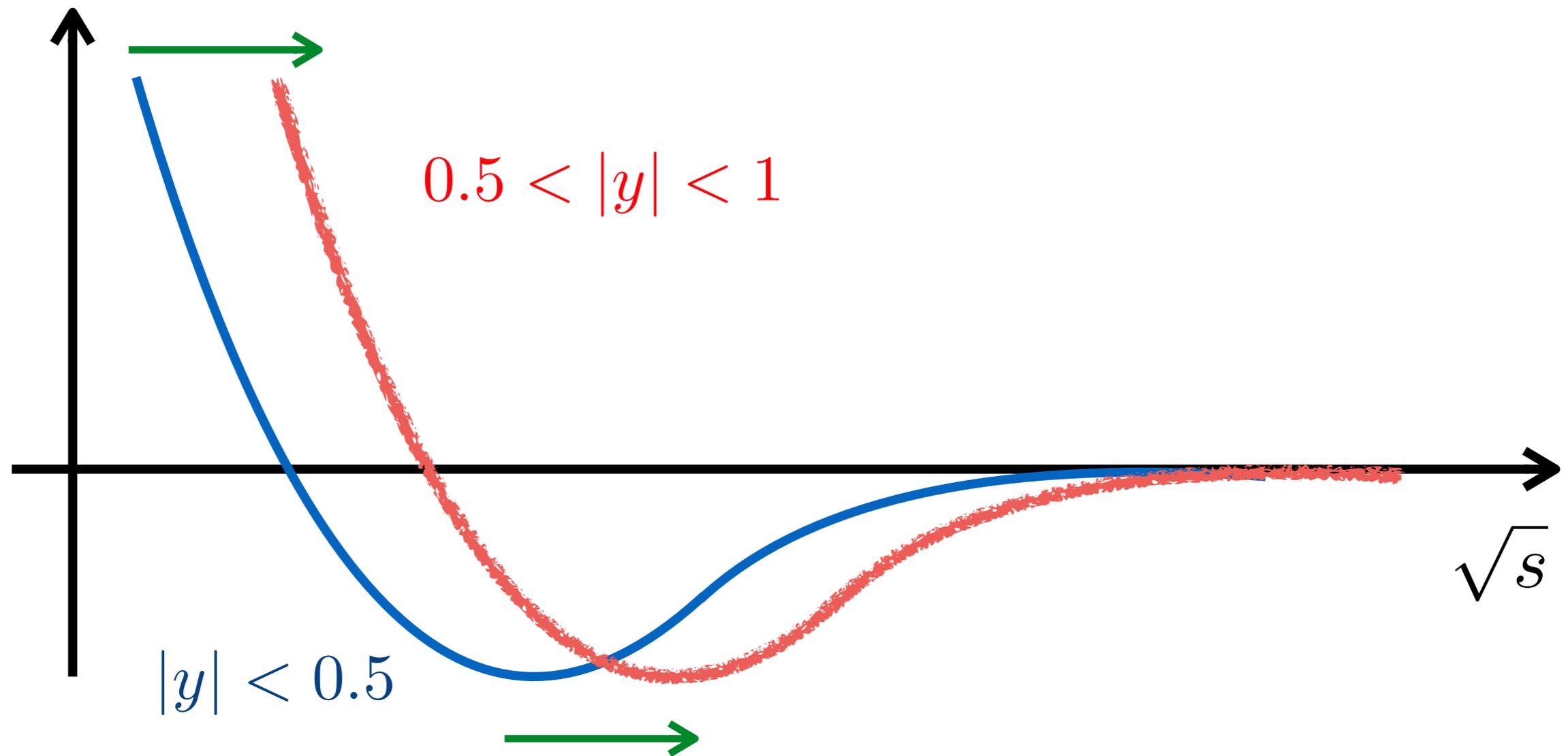
Net baryon rapidity distribution

C. Shen and B. Schenke, Phys.Rev. C97 (2018) 024907



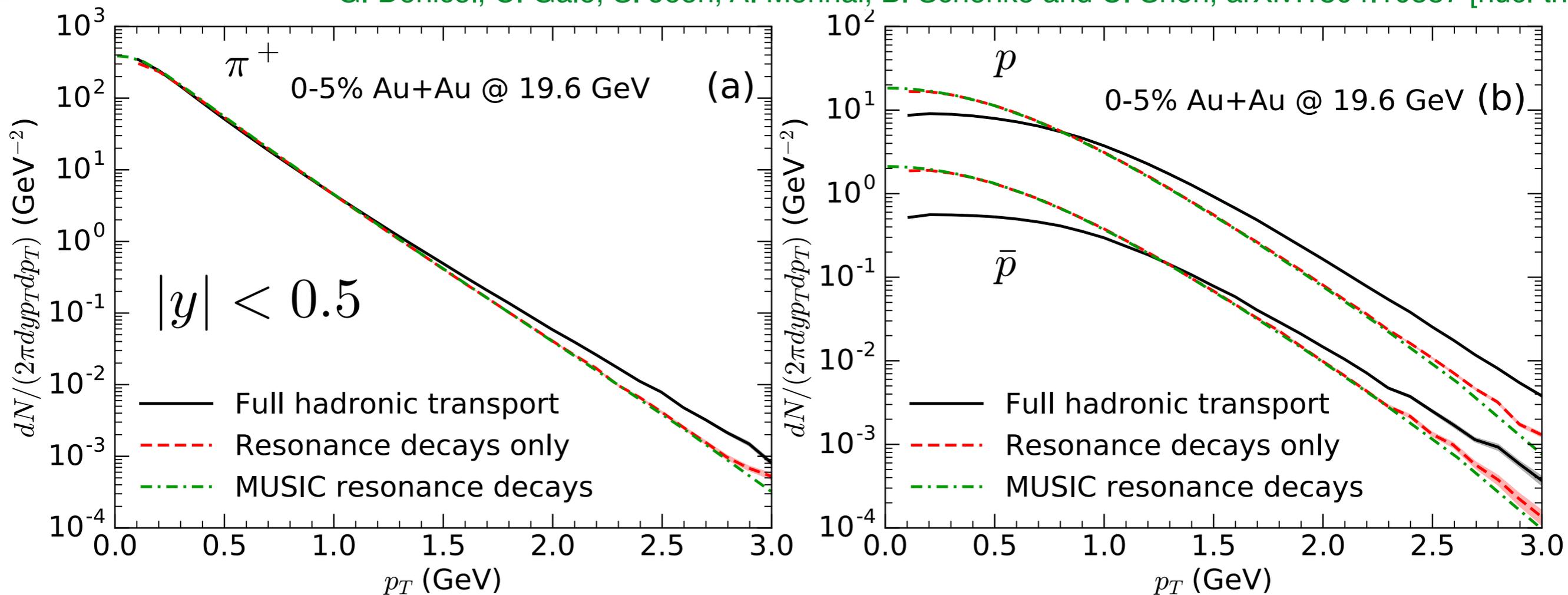
- The valence quark + rapidity loss fluct. model provides a reasonable net baryon rapidity distribution compared to the NA49 measurement

Mapping critical fluctuations with hydrodynamics



Effects of hadronic afterburner on pid spectra

G. Denicol, C. Gale, S. Jeon, A. Monnai, B. Schenke and C. Shen, arXiv:1804.10557 [nucl-th]

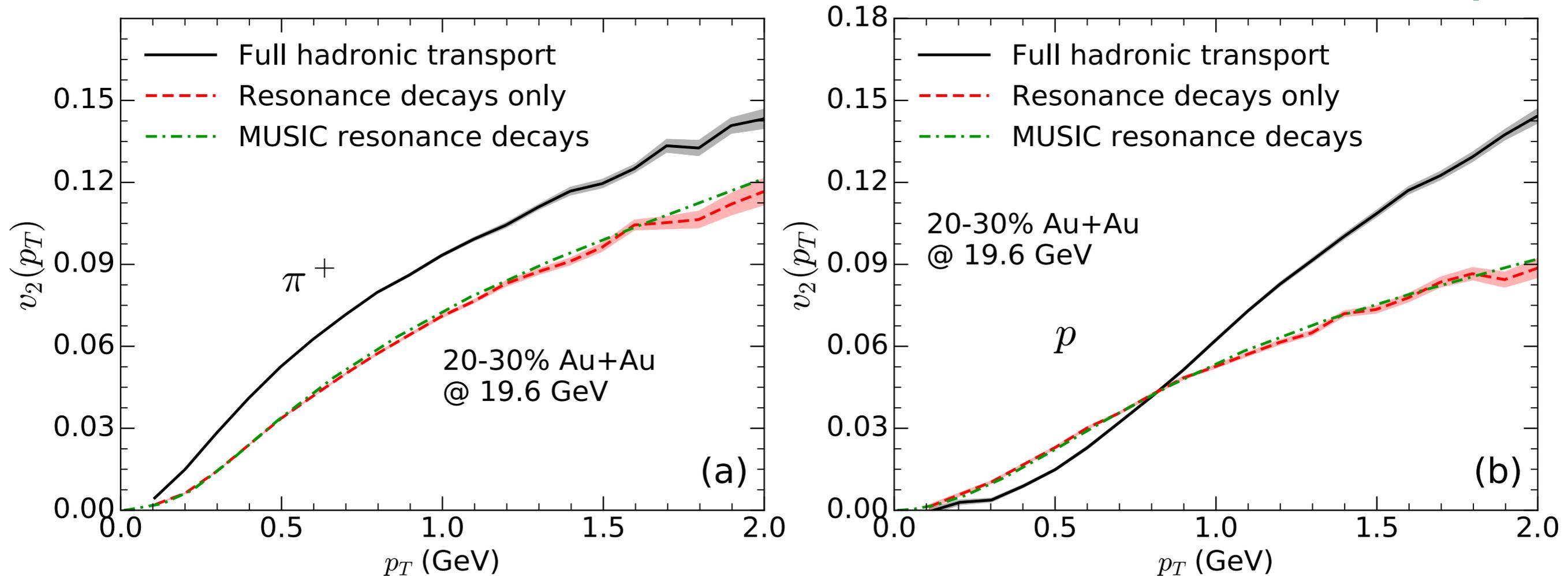


- Hadronic afterburner harden pion spectra at high p_T
- Heavy baryon spectra are largely affected

hadronic afterburner is essential for baryon spectra

Effects of hadronic afterburner on v_2

G. Denicol, C. Gale, S. Jeon, A. Monnai, B. Schenke and C. Shen, arXiv:1804.10557 [nucl-th]



- Hadronic afterburner increases pion v_2 ; converting the remaining spatial eccentricity to momentum anisotropy
- Proton $v_2(p_T)$ receives strong blue-shift effects in hadronic phase

hadronic afterburner is essential for particle v_2