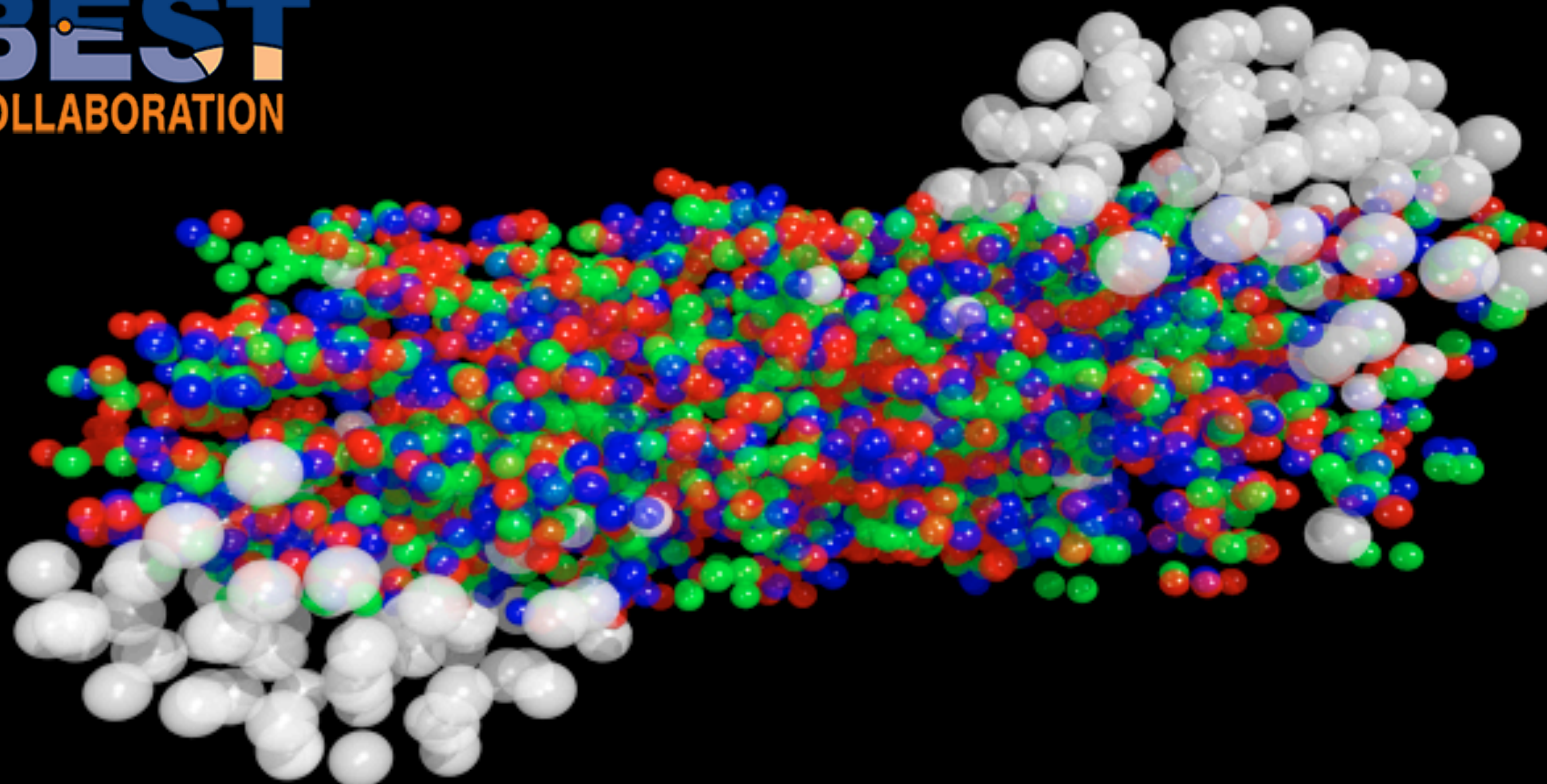
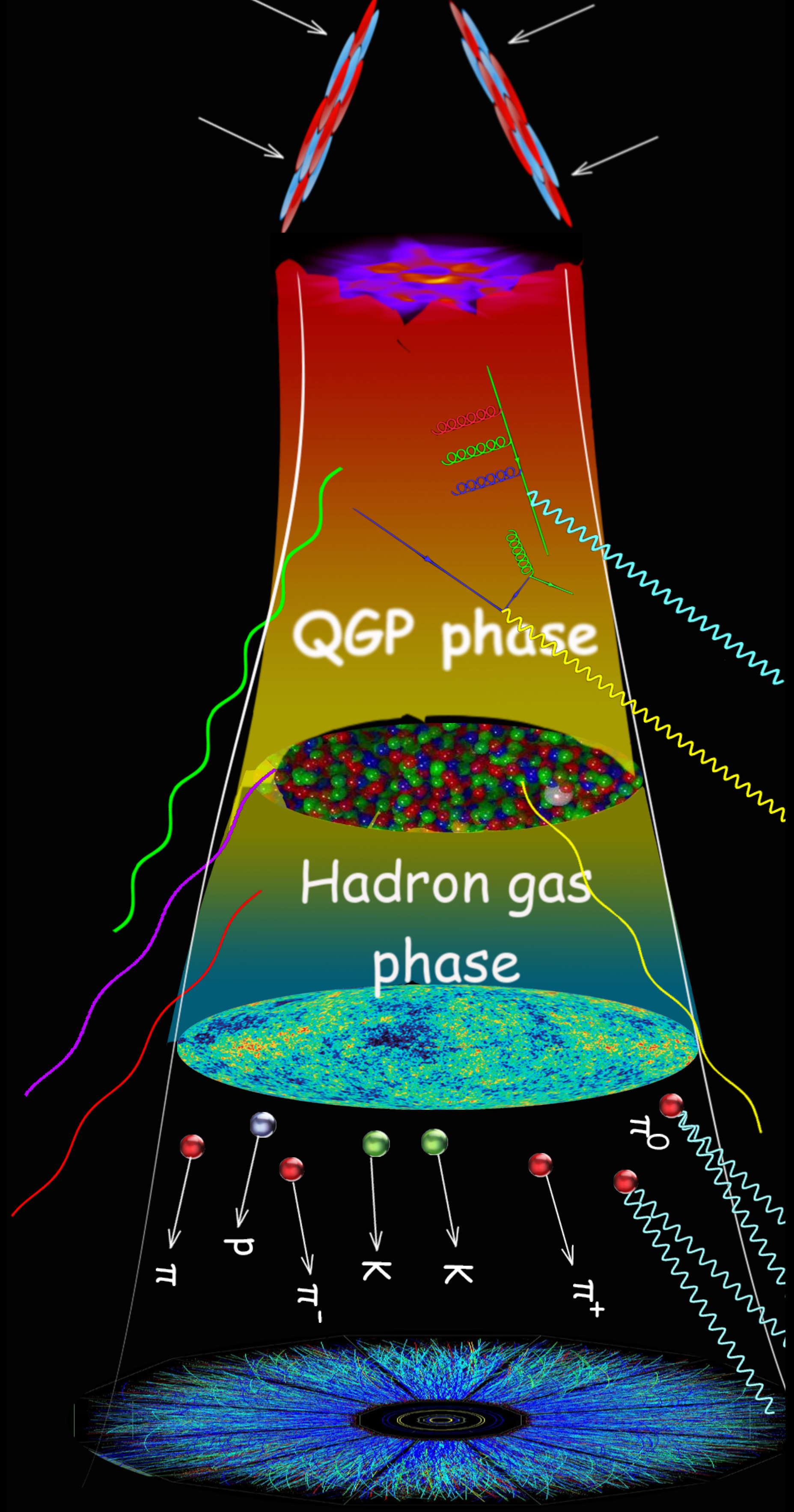


CHUN SHEN

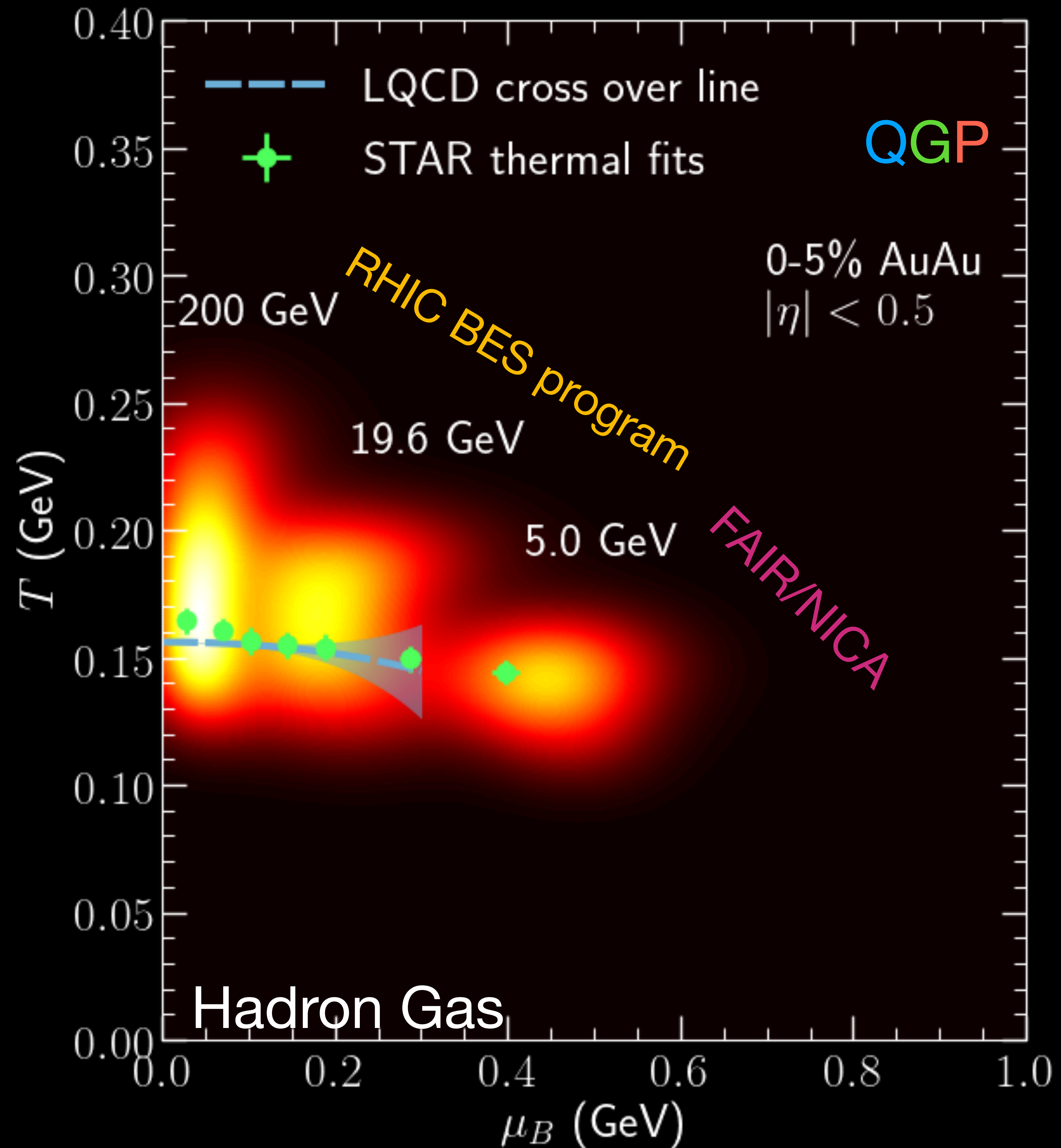
HYDRO PERSPECTIVES ON BES/LONGITUDINAL DYNAMICS

June 26, 2019 Columbia University

Initial Stages 2019



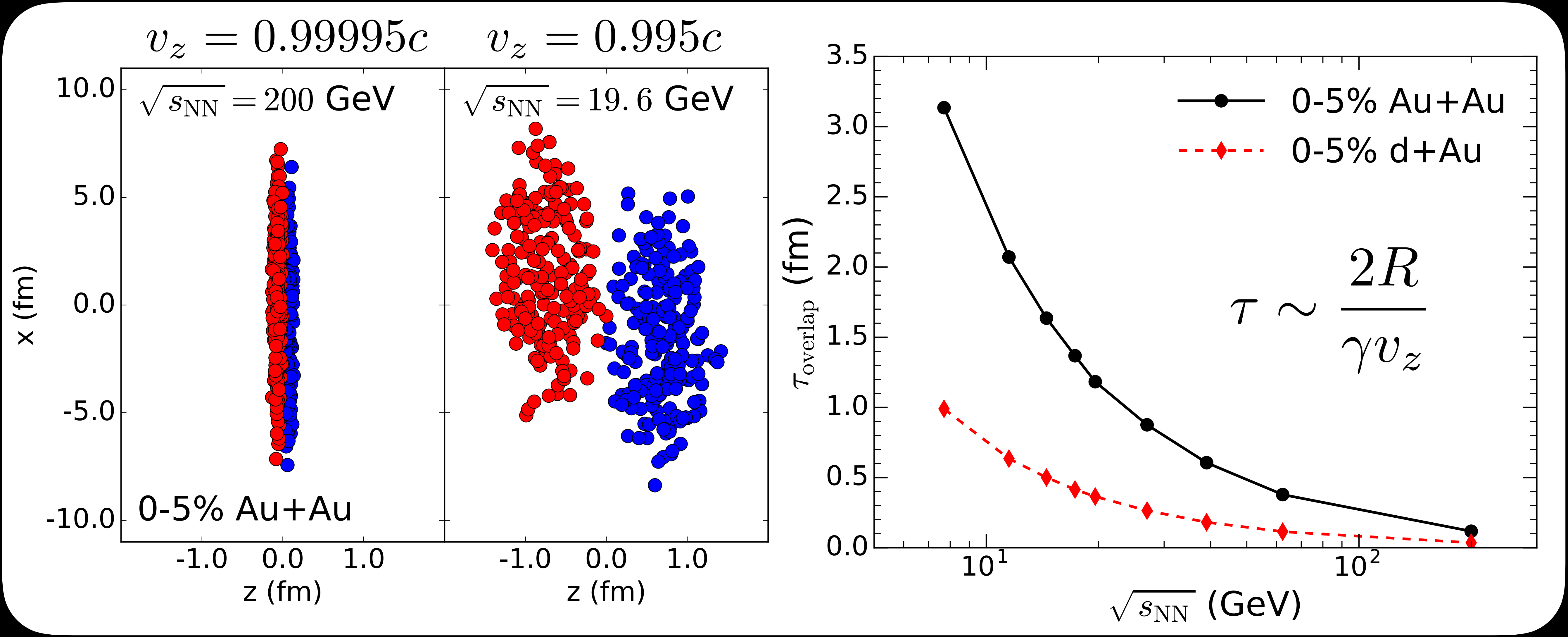
Relativistic Heavy-ion Collisions
QGP phase
Hadron gas phase
π
p
π⁻
K
K
π⁺
π⁰



LQCD cross over line
STAR thermal fits
QGP
0-5% AuAu
|η| < 0.5
200 GeV
RHIC BES program
19.6 GeV
5.0 GeV
FAIR/NICA
Hadron Gas
T (GeV)
μ_B (GeV)
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.0
0.2
0.4
0.6
0.8
1.0

Heavy-ion collisions at RHIC BES

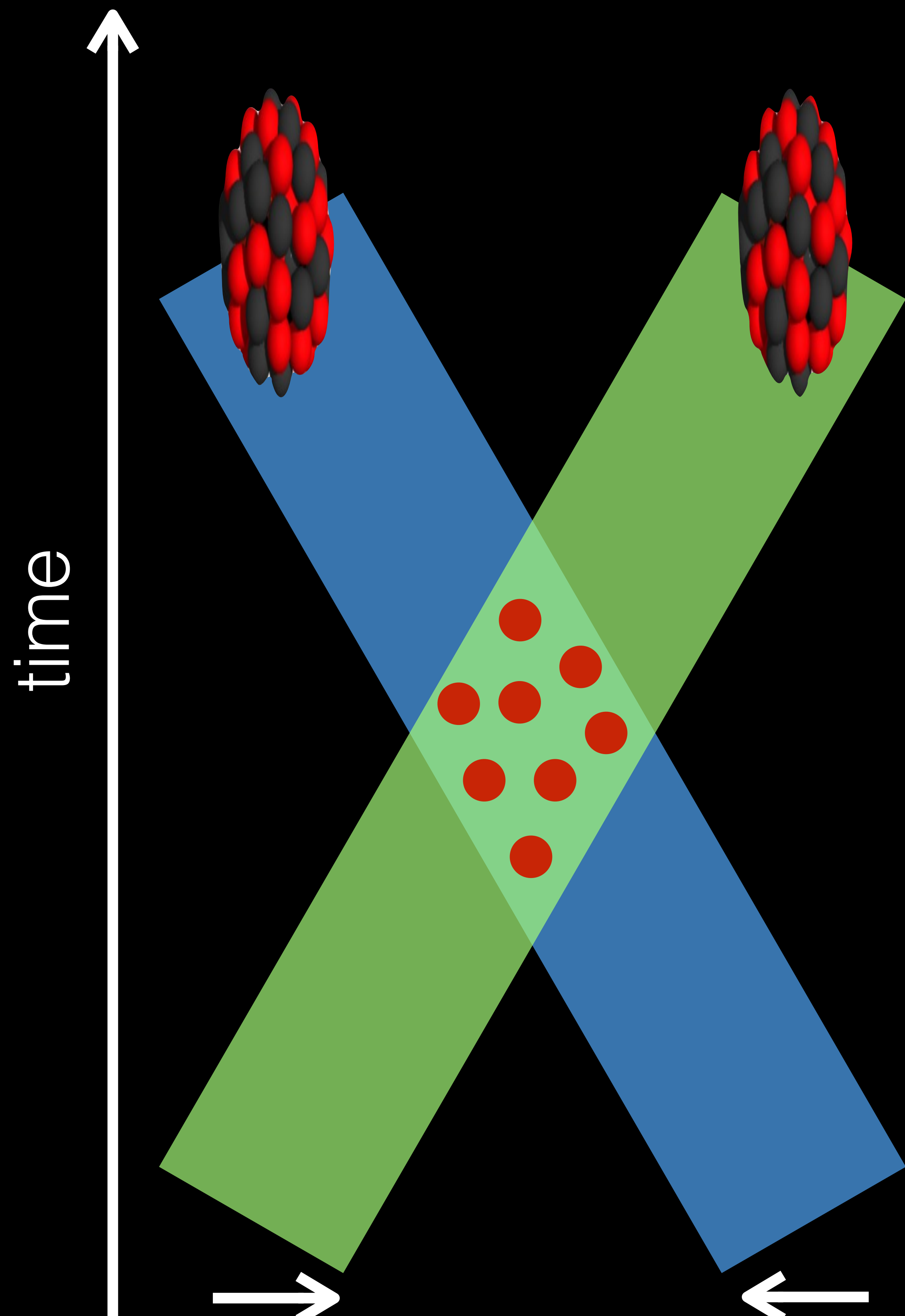
I. A. Karpenko, P. Huovinen, H. Petersen and M. Bleicher, Phys. Rev. C91 (2015) 064901
C. Shen and B. Schenke, Phys. Rev. C97 (2018) 024907



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

note: total evolution time ~ 10 fm

3D dynamics beyond the Bjorken paradigm



- String based initial condition

  A. Bialas, A. Bzdak and V. Koch, Acta Phys. Polon. B49 (2018)

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

- Transport model based initial condition

  I. A. Karpenko, P. Huovinen, H. Petersen and M. Bleicher, Phys. Rev. C91 (2015) 064901

  L. Du, U. Heinz and G. Vujanovic, Nucl. Phys. A982 (2019) 407-410

- Color Glass Condensate based model

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

  L. D. McLerran, S. Schlichting and S. Sen, Phys. Rev. D 99, 074009 (2019)

- Holographic approach at intermediate coupling

  Phys.Rev.Lett. 121 (2018) no.26, 261601

WILKE TUESDAY 15:20

Baryon stopping from CGC

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

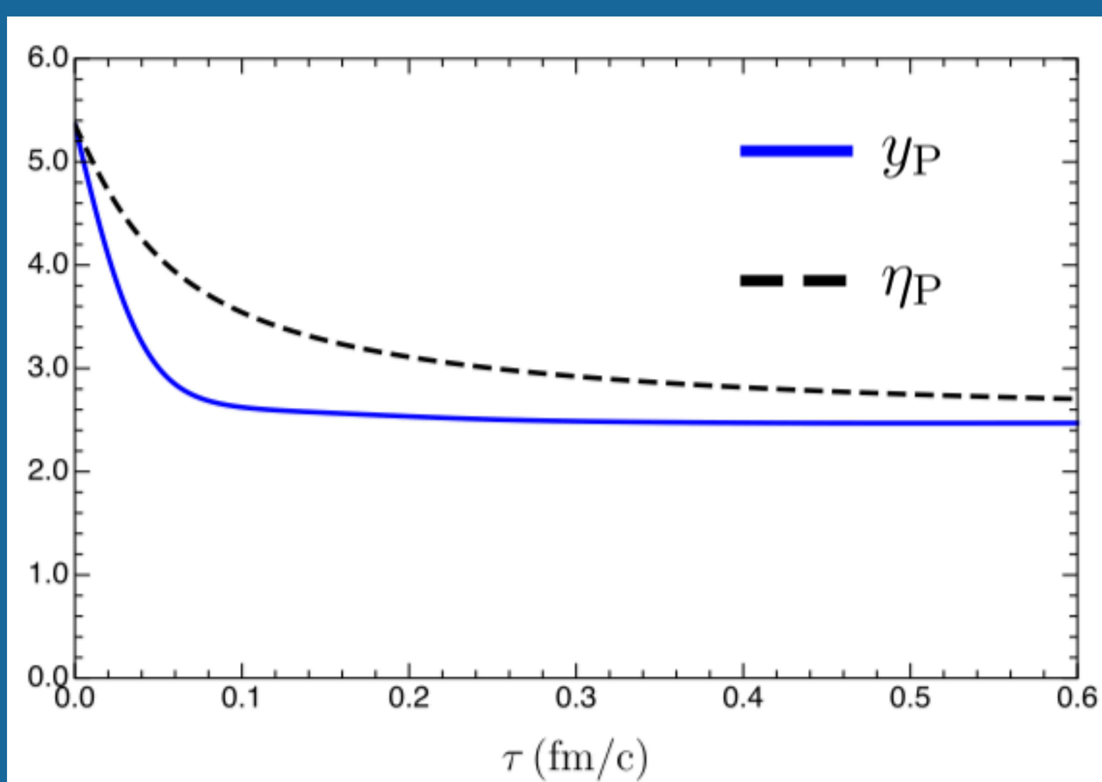
L. D. McLerran, S. Schlichting and S. Sen, Phys. Rev. D 99, 074009 (2019)

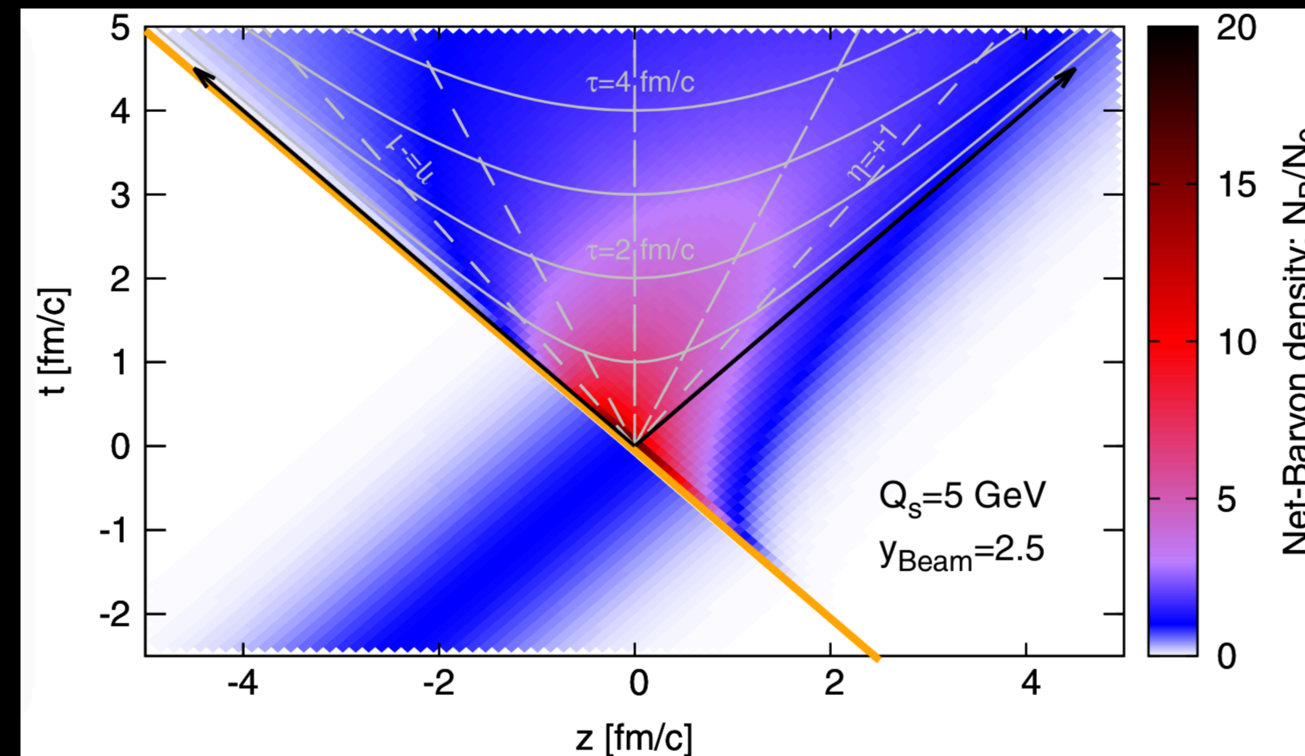
$$dP_p^\mu = -T^{\mu\nu}_{\rm glasma} d\Sigma_\nu$$

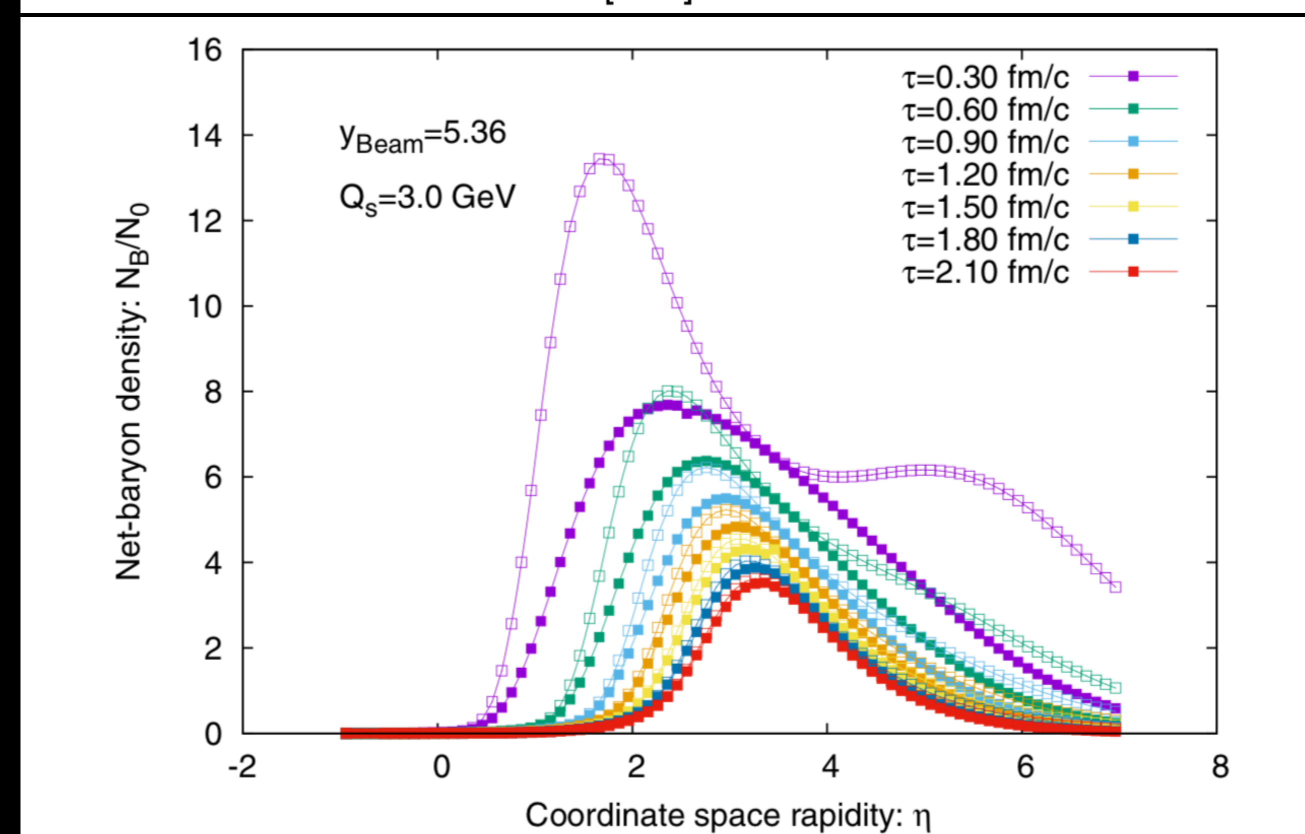
$$d\Sigma_\nu = (dz, 0, 0, -dt)$$

$$T^{\mu\nu}_{\rm glasma} =$$

$$\begin{pmatrix} A + B\cosh(2\eta) & 0 & 0 & B\sinh(2\eta) \\ 0 & A & 0 & 0 \\ 0 & 0 & A & 0 \\ B\sinh(2\eta) & 0 & 0 & -A + B\cosh(2\eta) \end{pmatrix}$$

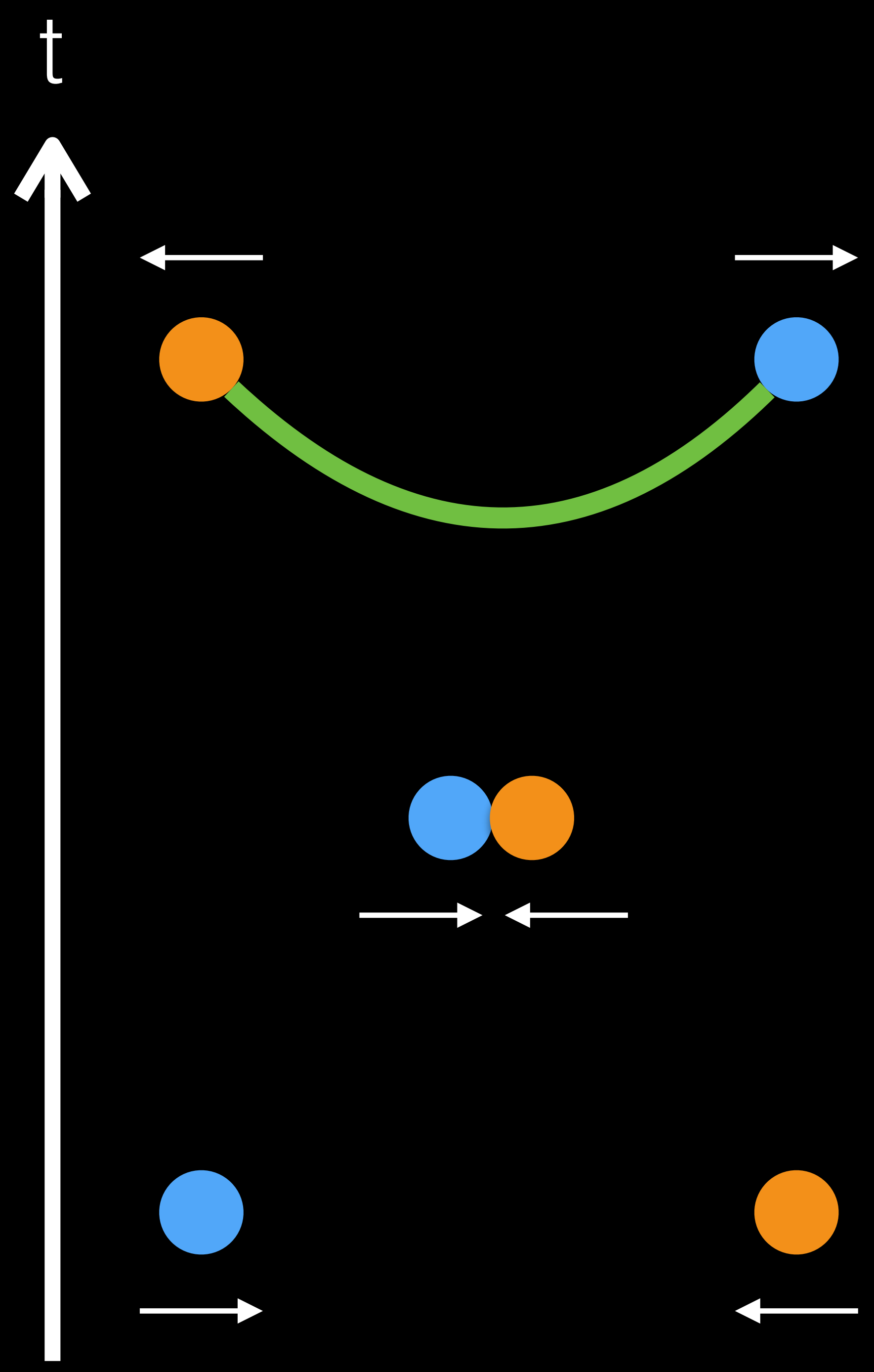






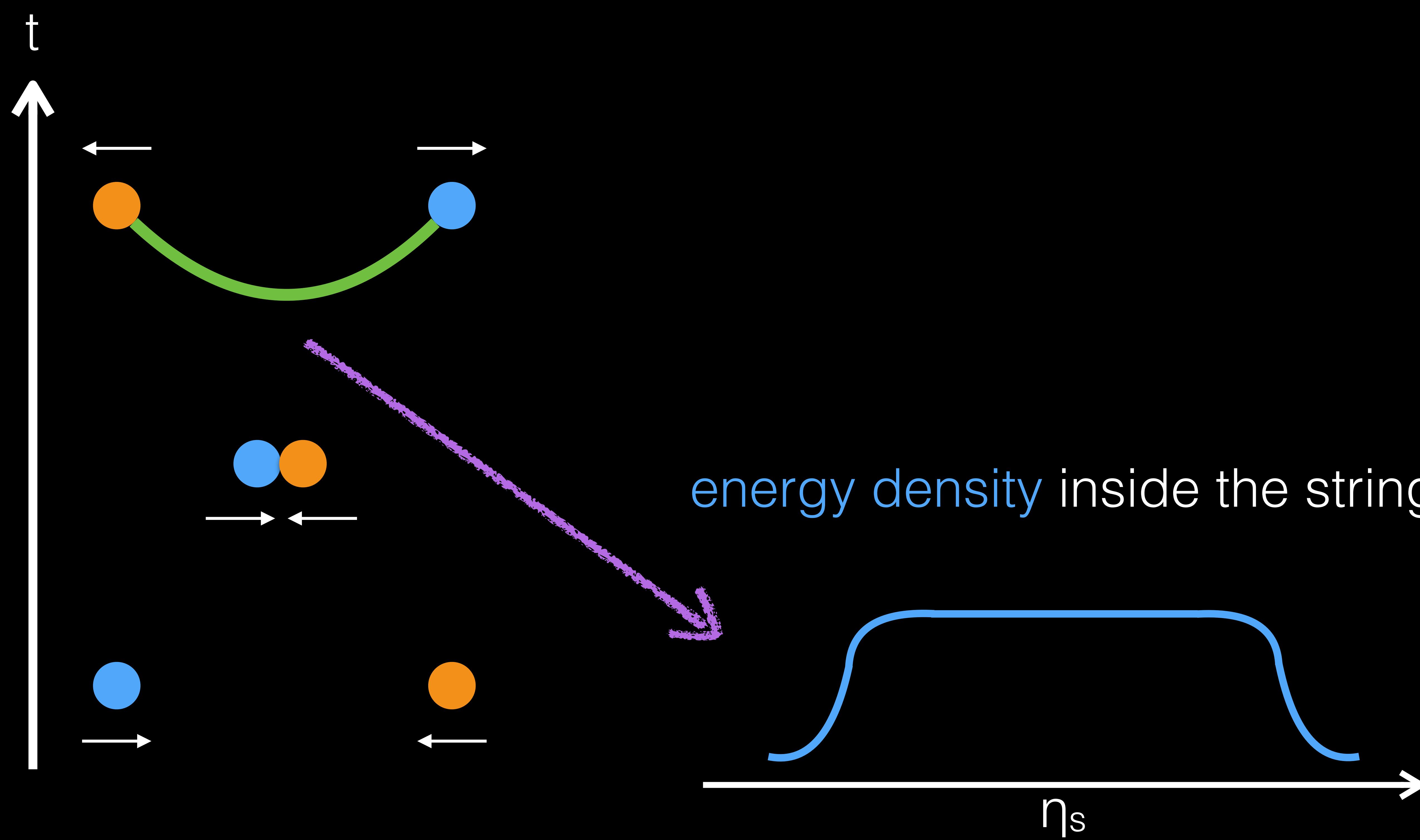
Details about the string-based model

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



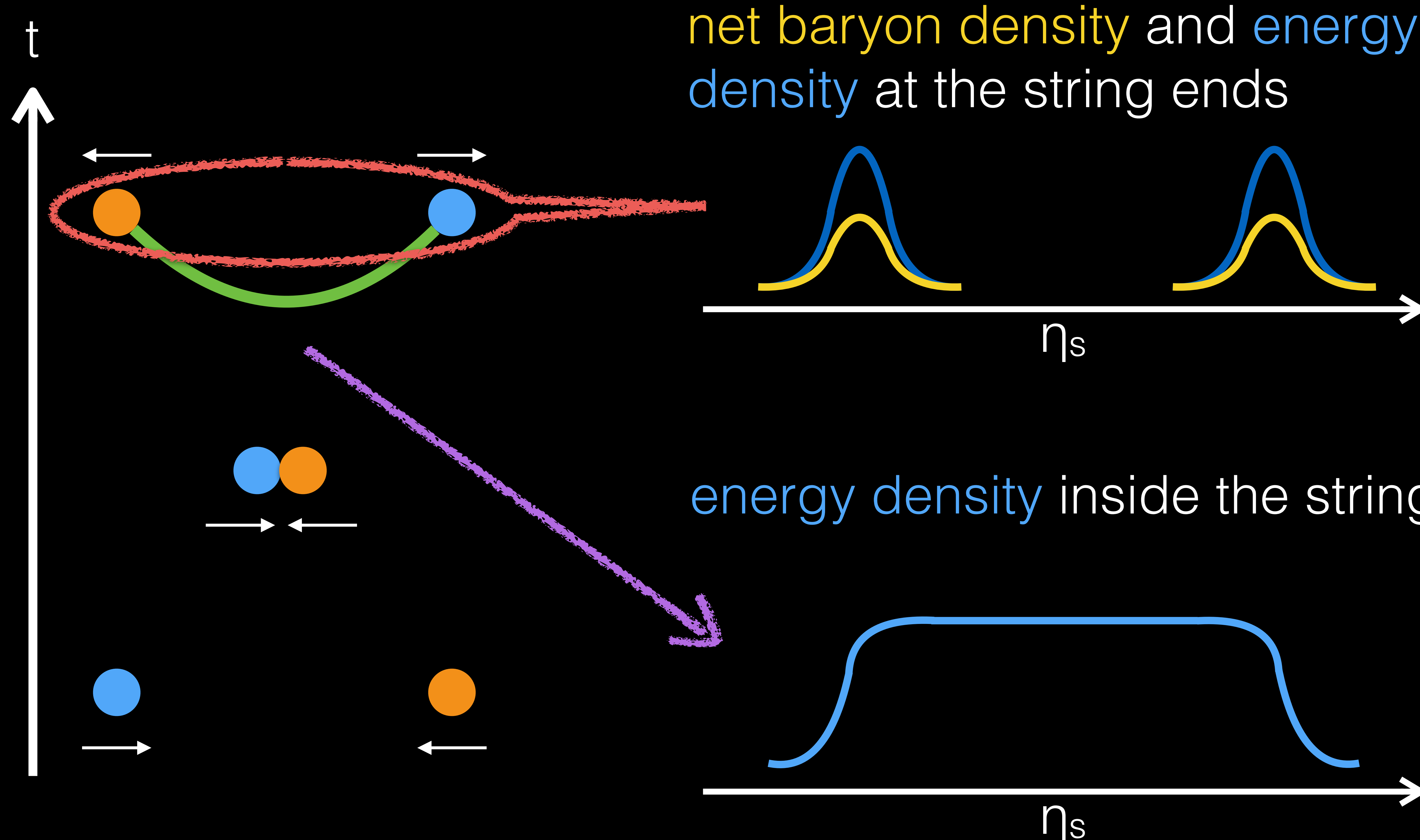
Details about the string-based model

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

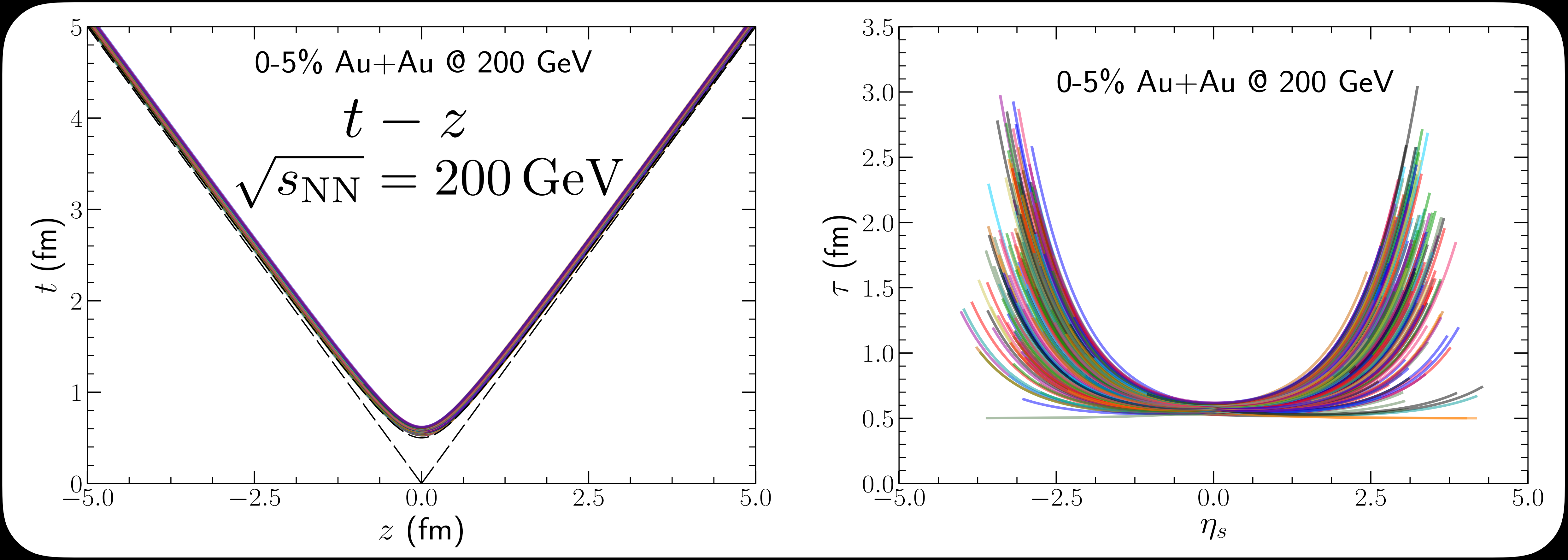


Details about the string-based model

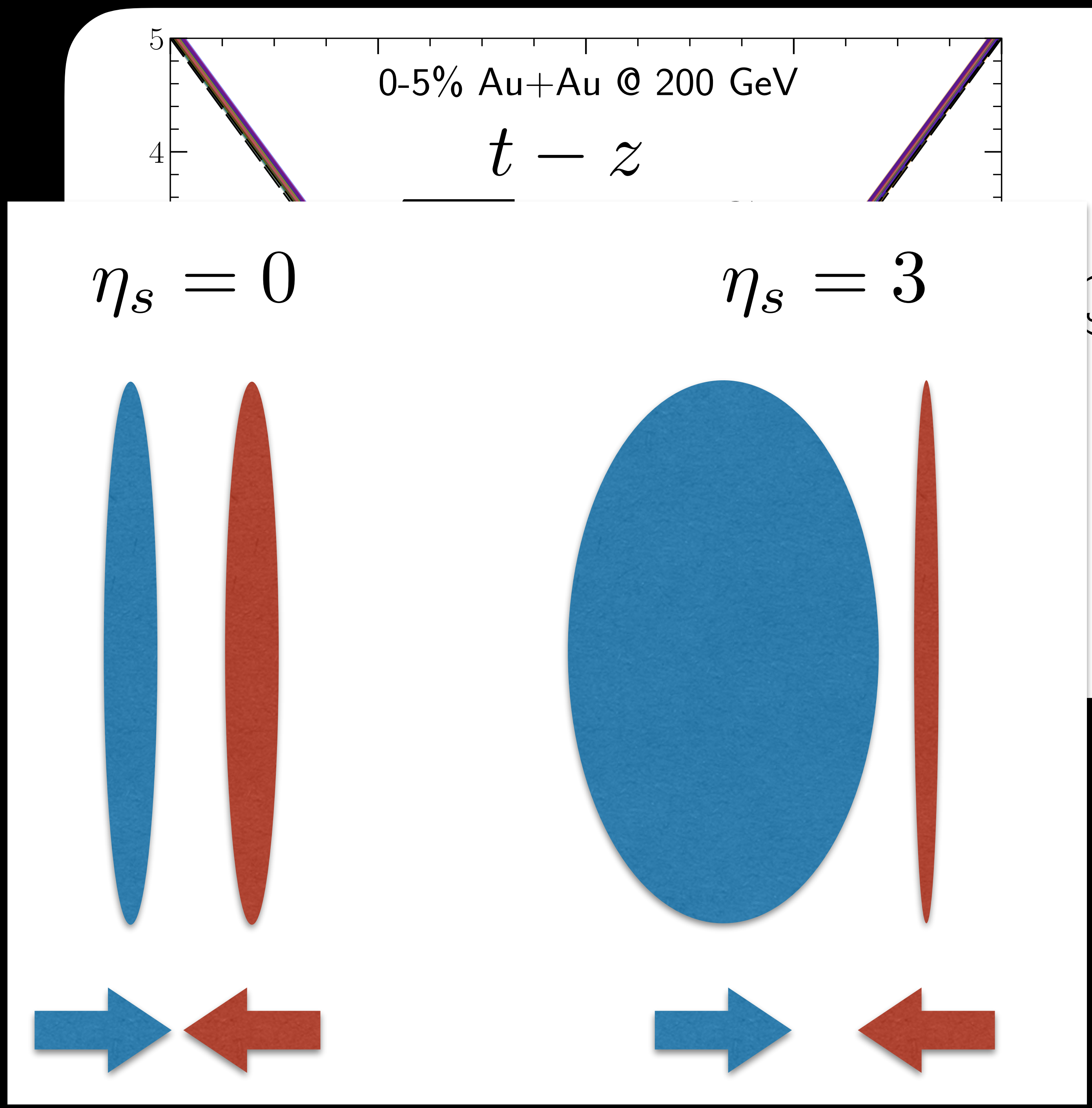
C. Shen and B. Schenke, Phys.Rev. C97 (2018) 024907

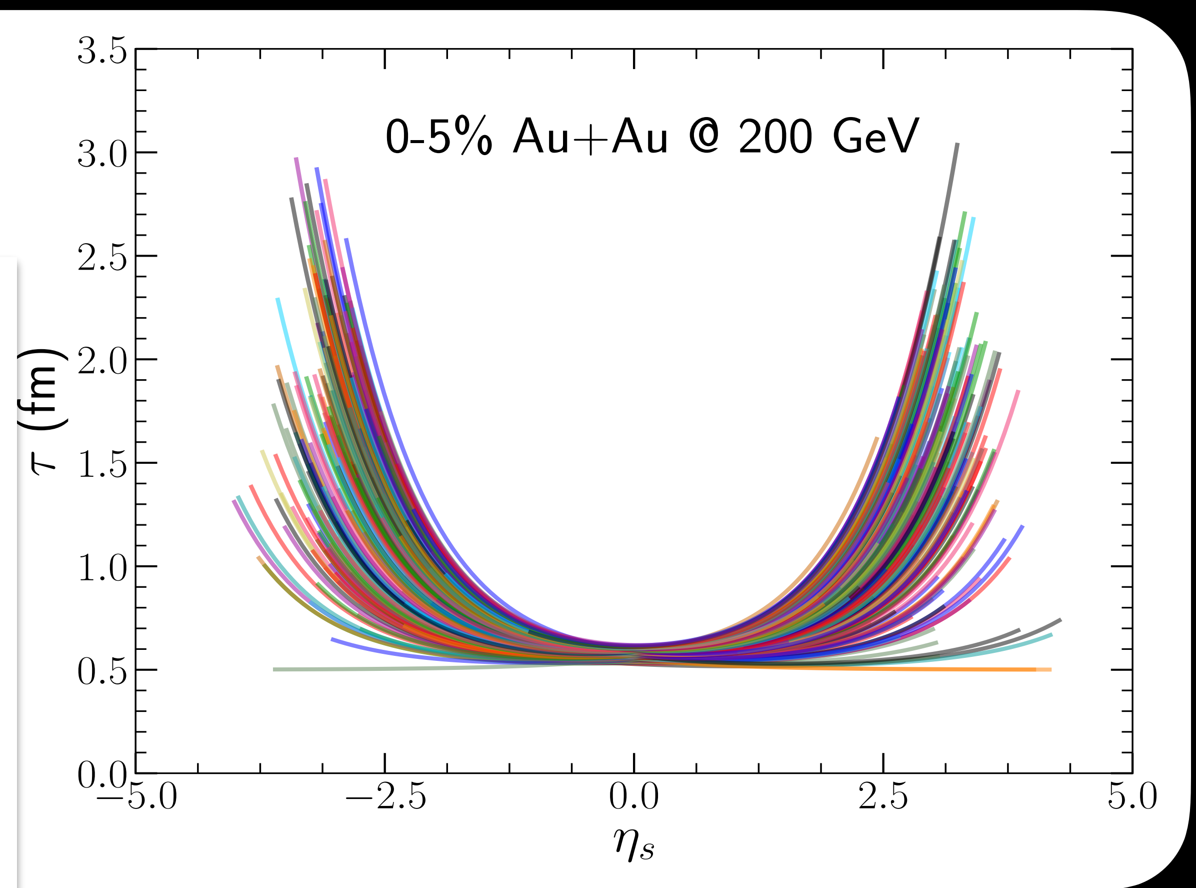


String space-time distribution

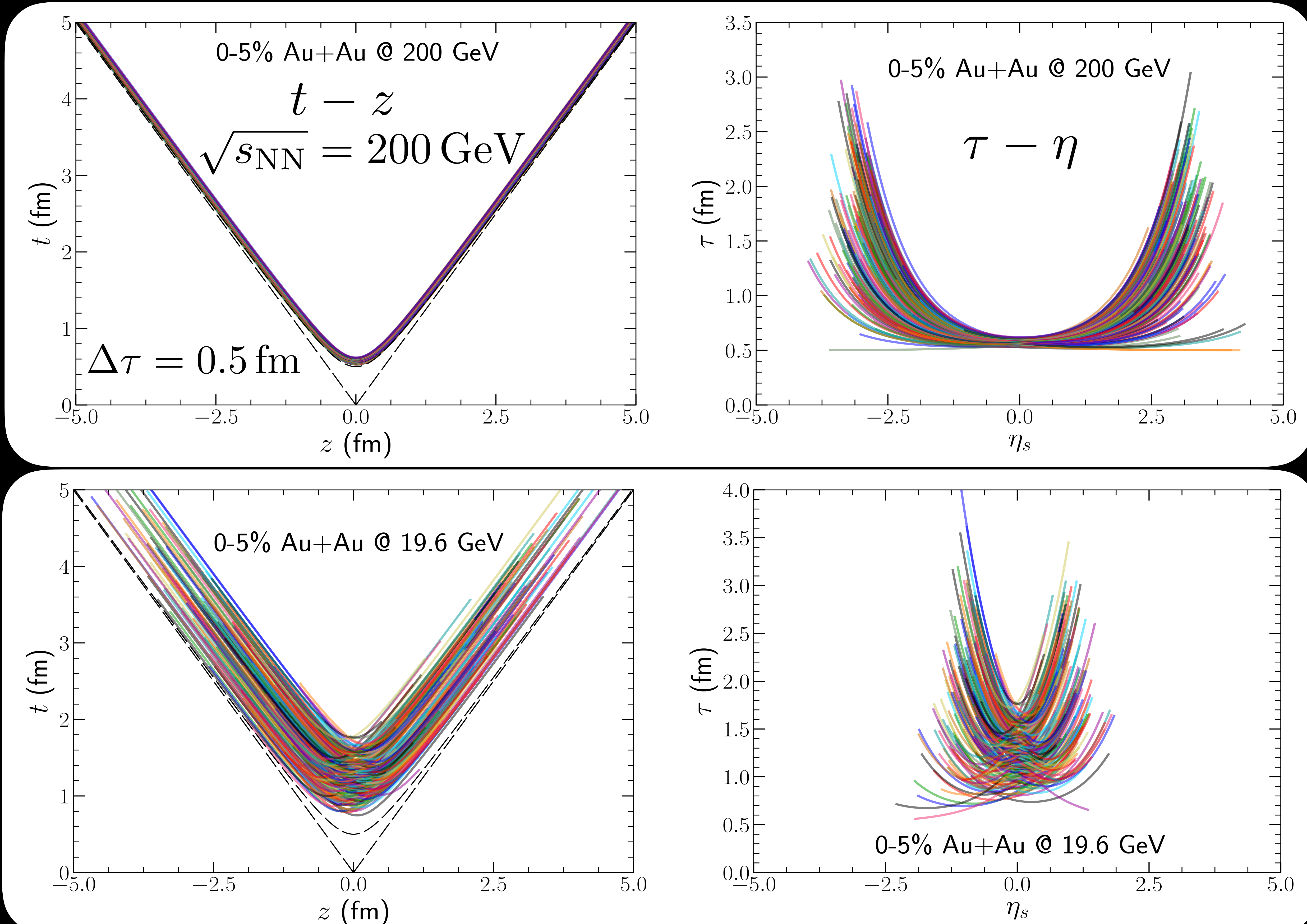


String space-time distribution



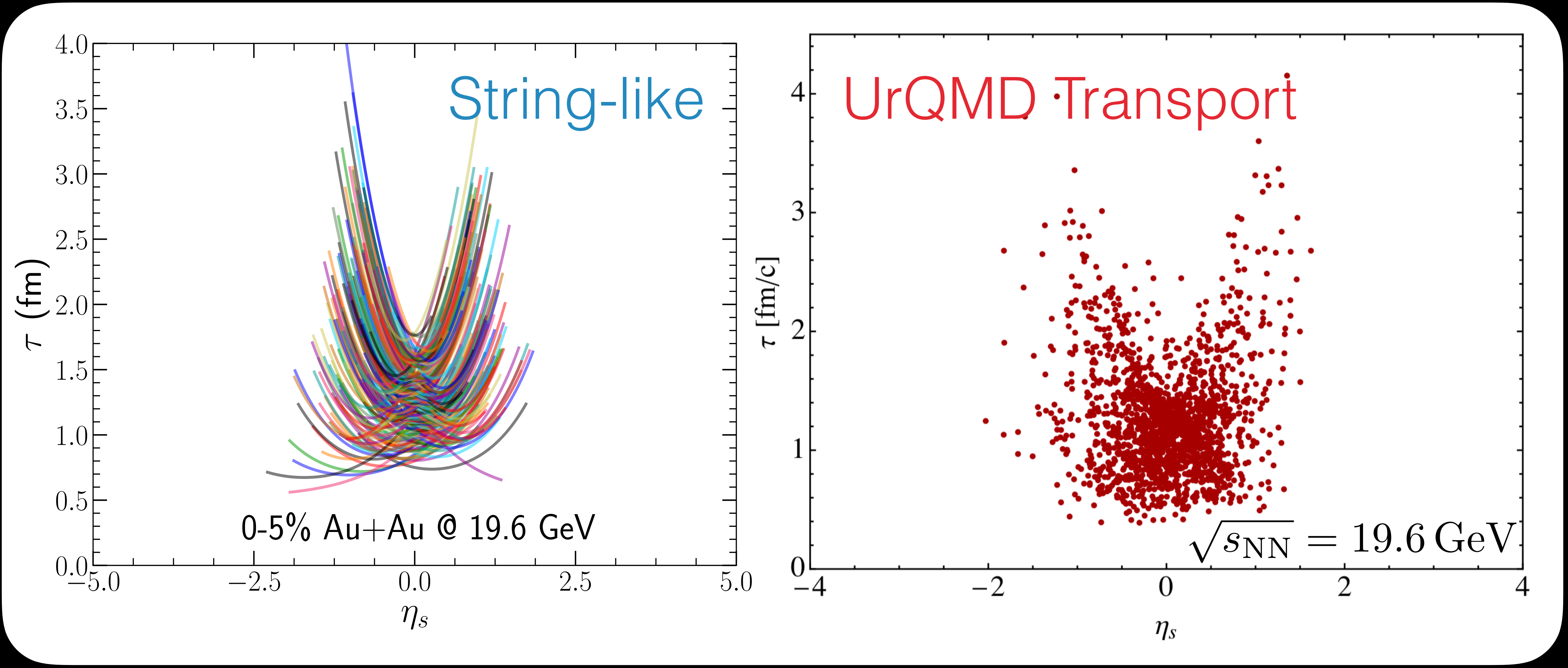


String space-time distribution



Energy-momentum space-time distribution

C. Shen and B. Schenke, Phys. Rev. C97 (2018) 024907
L. Du, U. Heinz and G. Vujanovic, Nucl. Phys. A982 (2019) 407-410

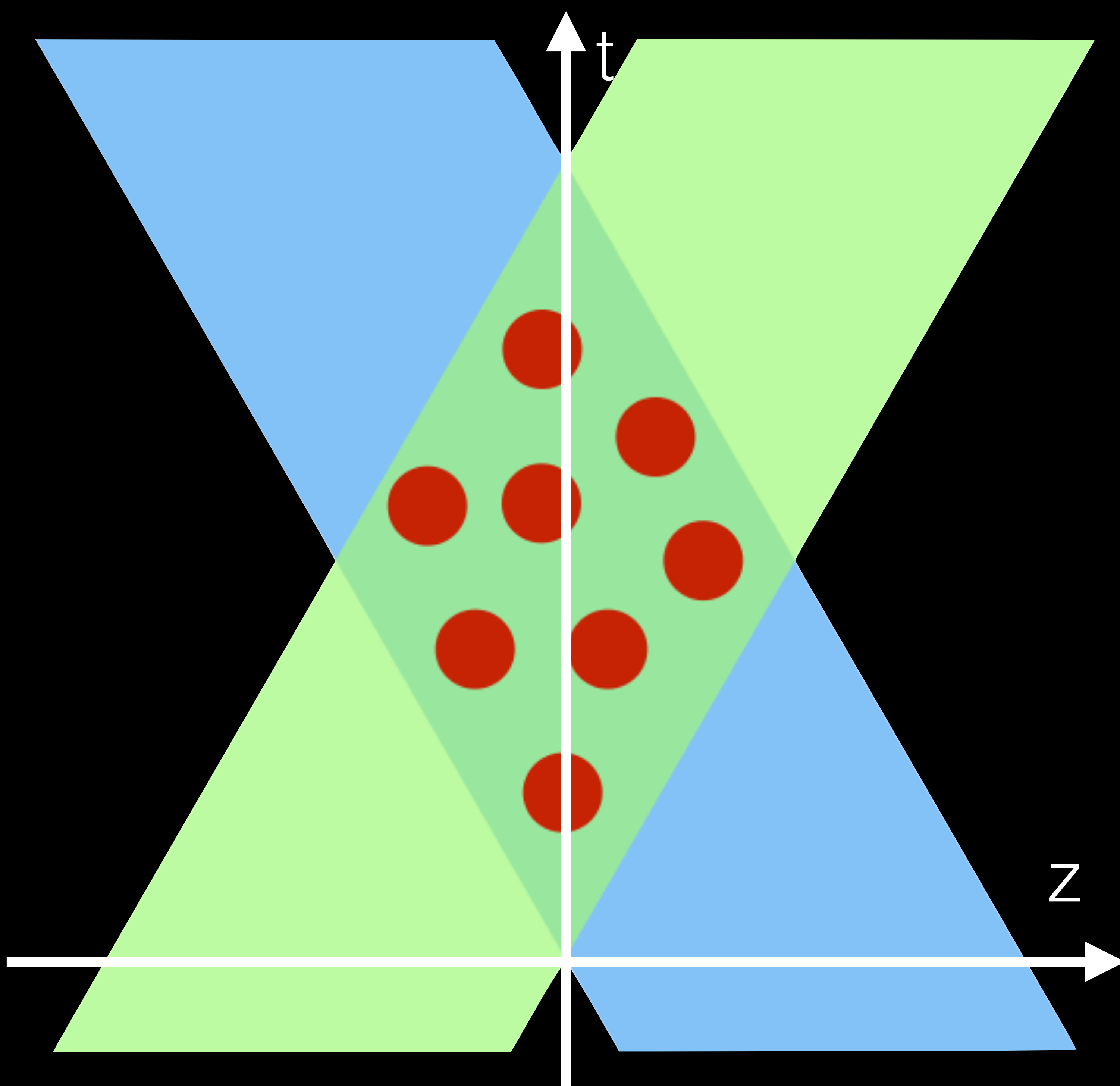


- An extended interaction zone for the energy-momentum sources from the 3D collision geometry

Dynamically interweaves with hydrodynamics

Hydrodynamics with sources

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



$$\partial_\mu T^{\mu\nu} = J^\nu_{\rm source}$$

$$\partial_\mu J^\mu = \rho_{\rm source}$$

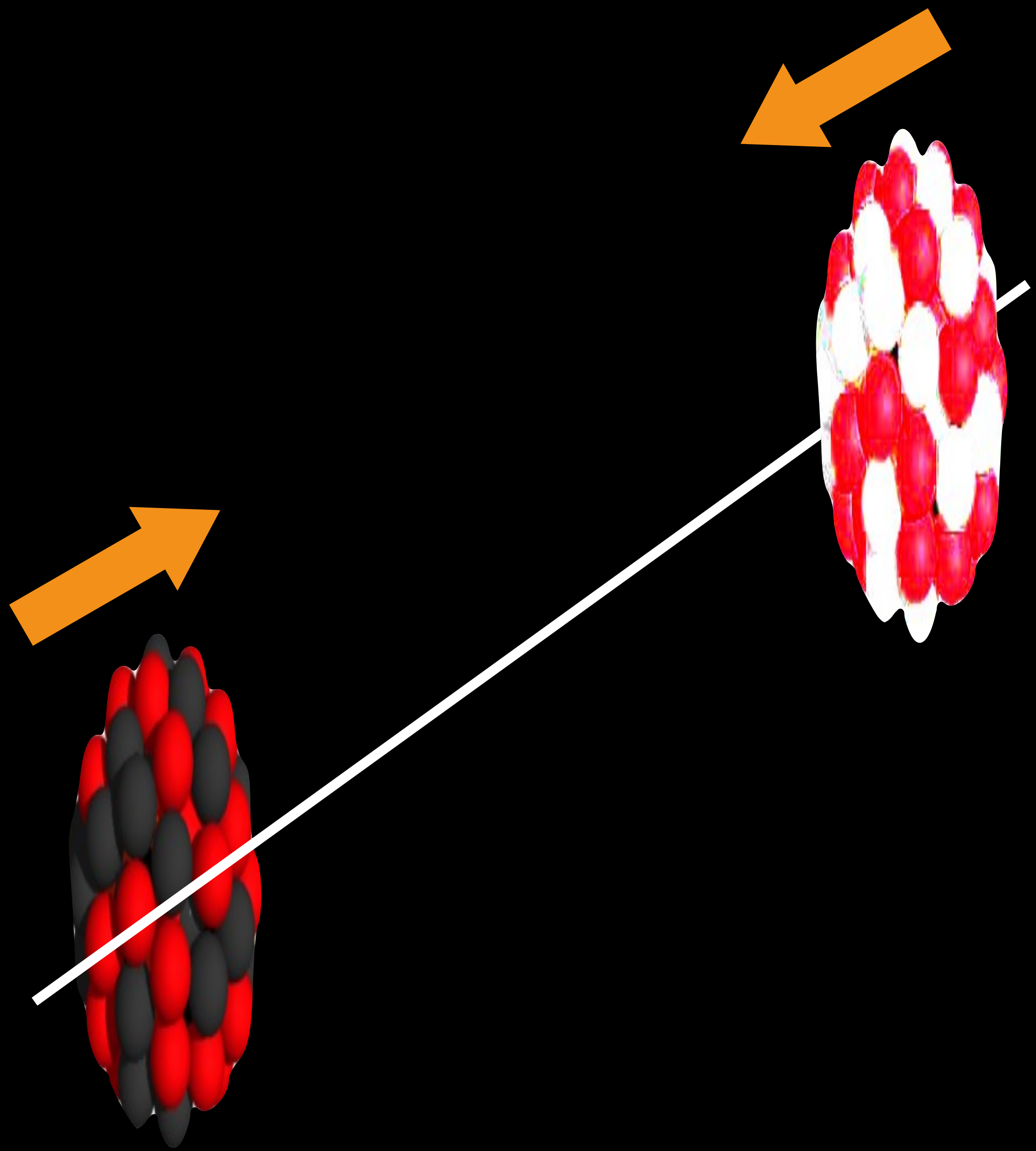
M. Okai, K. Kawaguchi, Y. Tachibana, and T. Hirano, Phys. Rev. C95, 054914 (2017)

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

L. Du, U. Heinz and G. Vujanovic, Nucl. Phys. A982 (2019) 407-410

Hydrodynamical evolution with sources

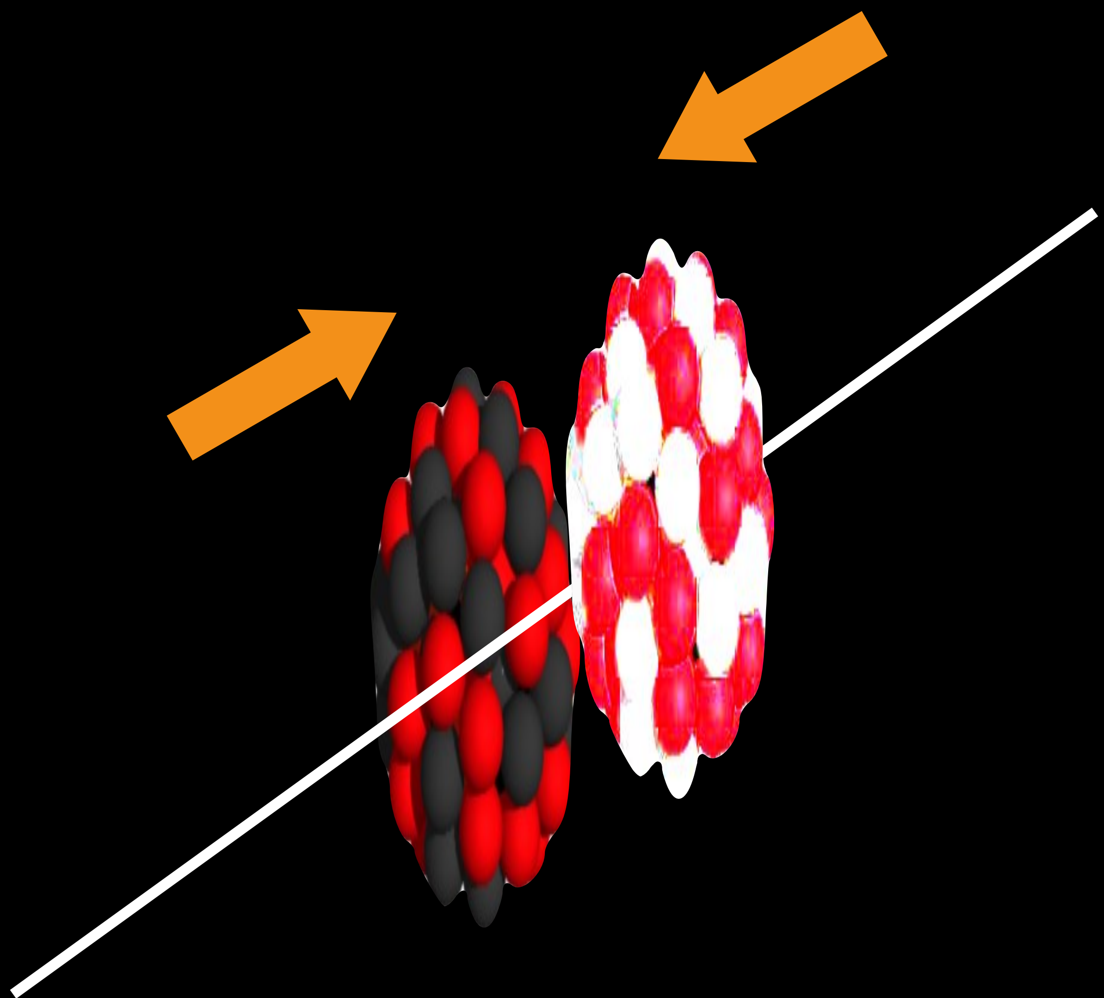
C. Shen and B. Schenke, Phys. Rev. C97 (2018) 024907



$\sqrt{s_{\mathrm{NN}}} = 19.6\,\mathrm{GeV}$

Hydrodynamical evolution with sources

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



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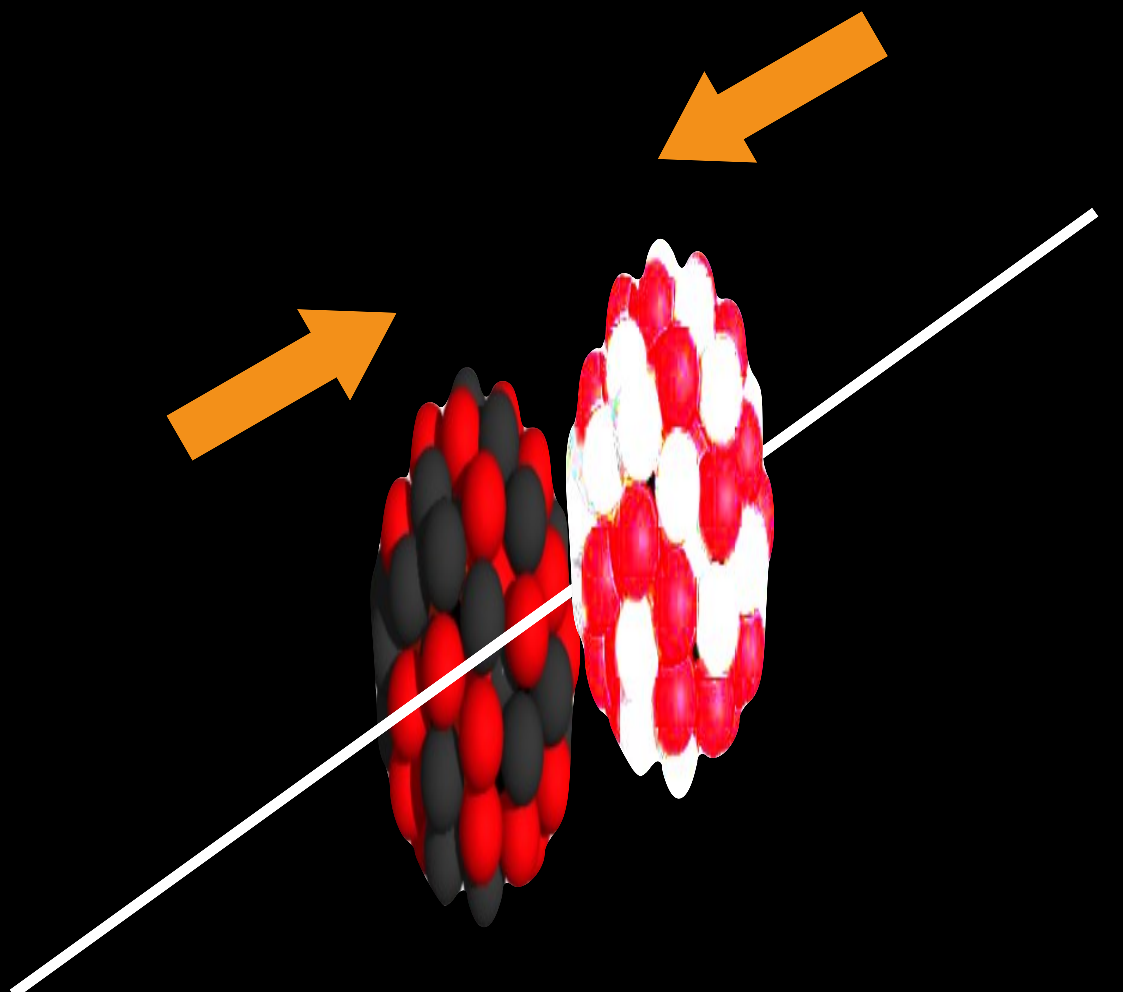
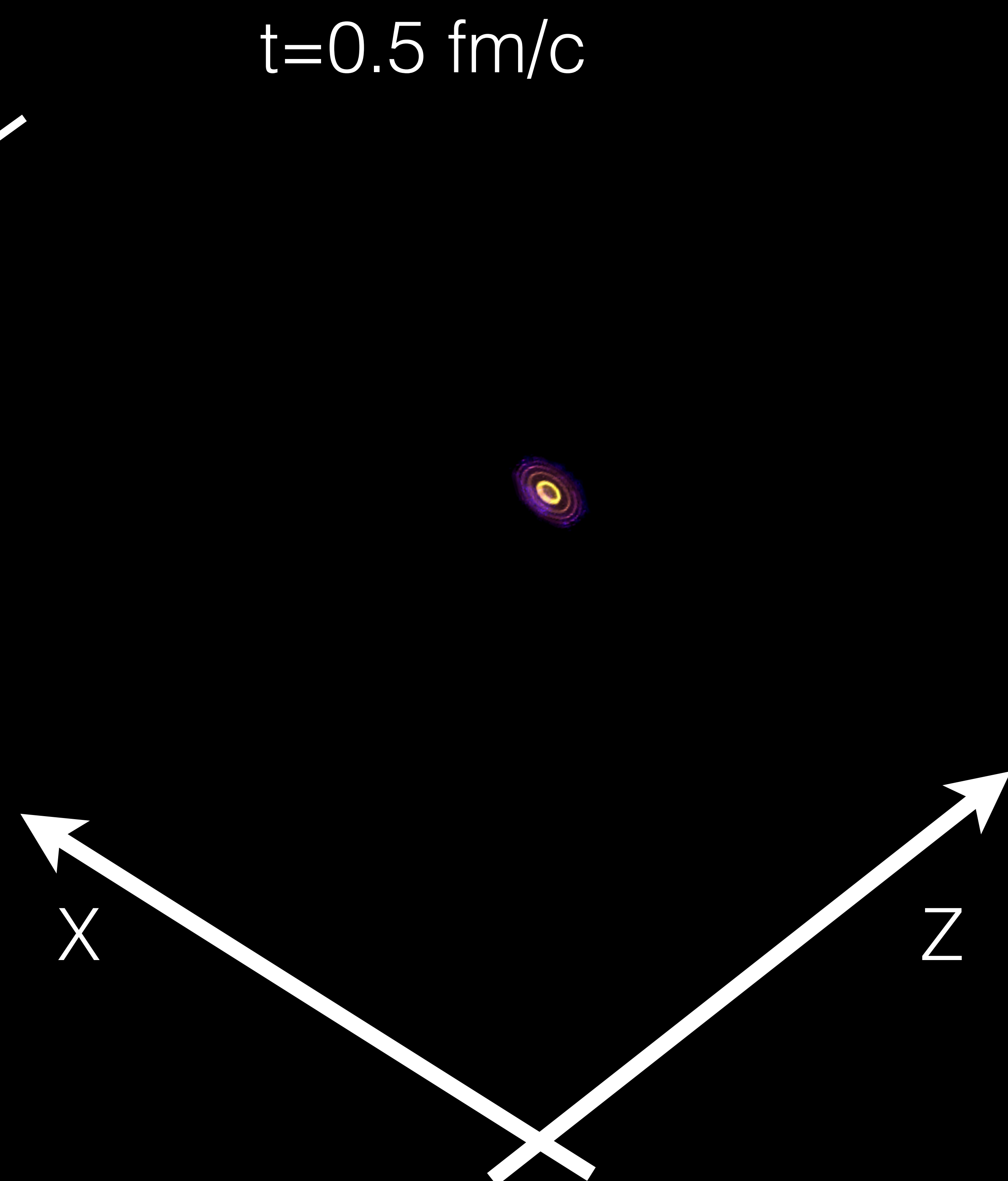
C. Shen and B. Schenke, Phys. Rev. C97 (2018) 024907





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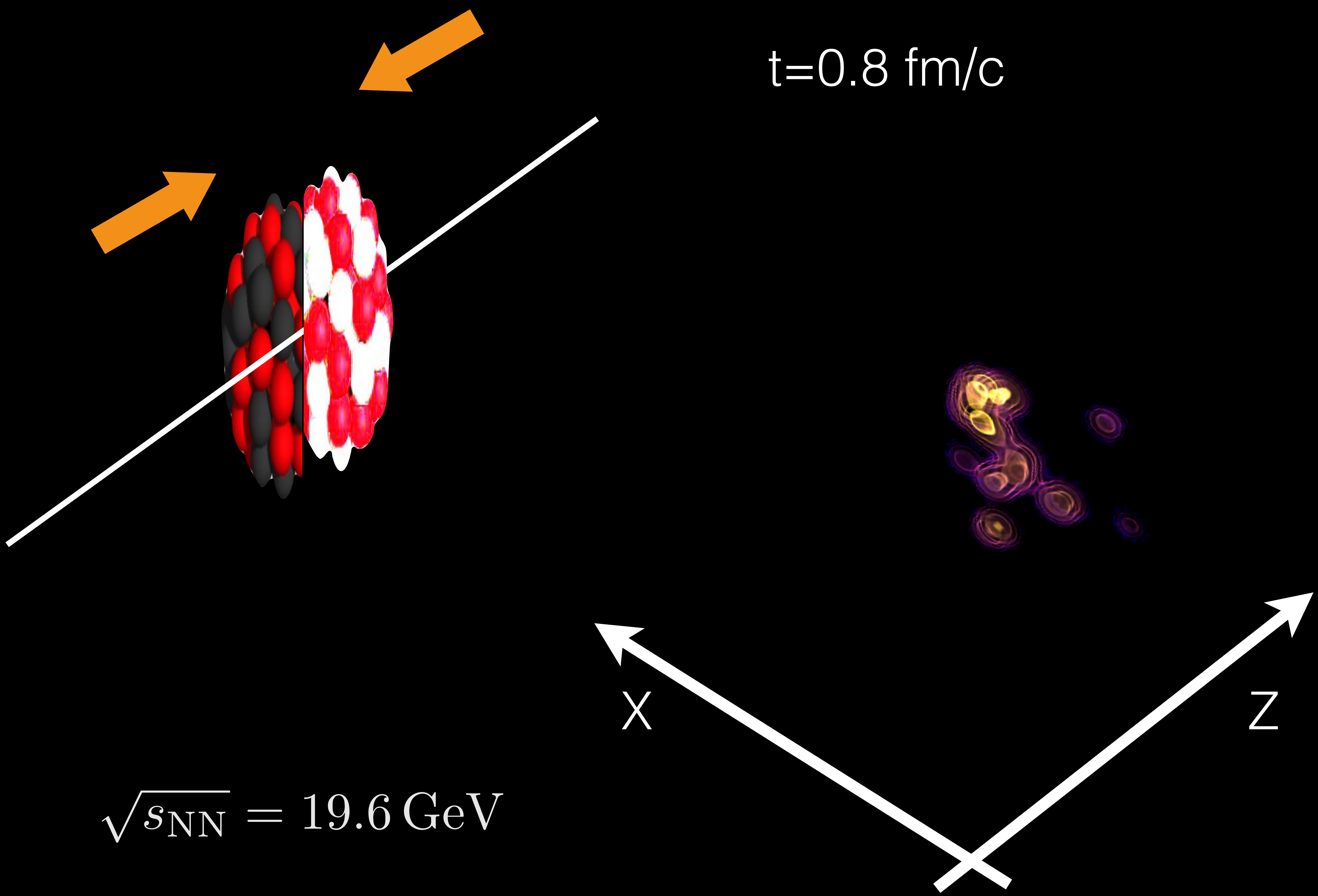
C. Shen and B. Schenke, Phys. Rev. C97 (2018) 024907



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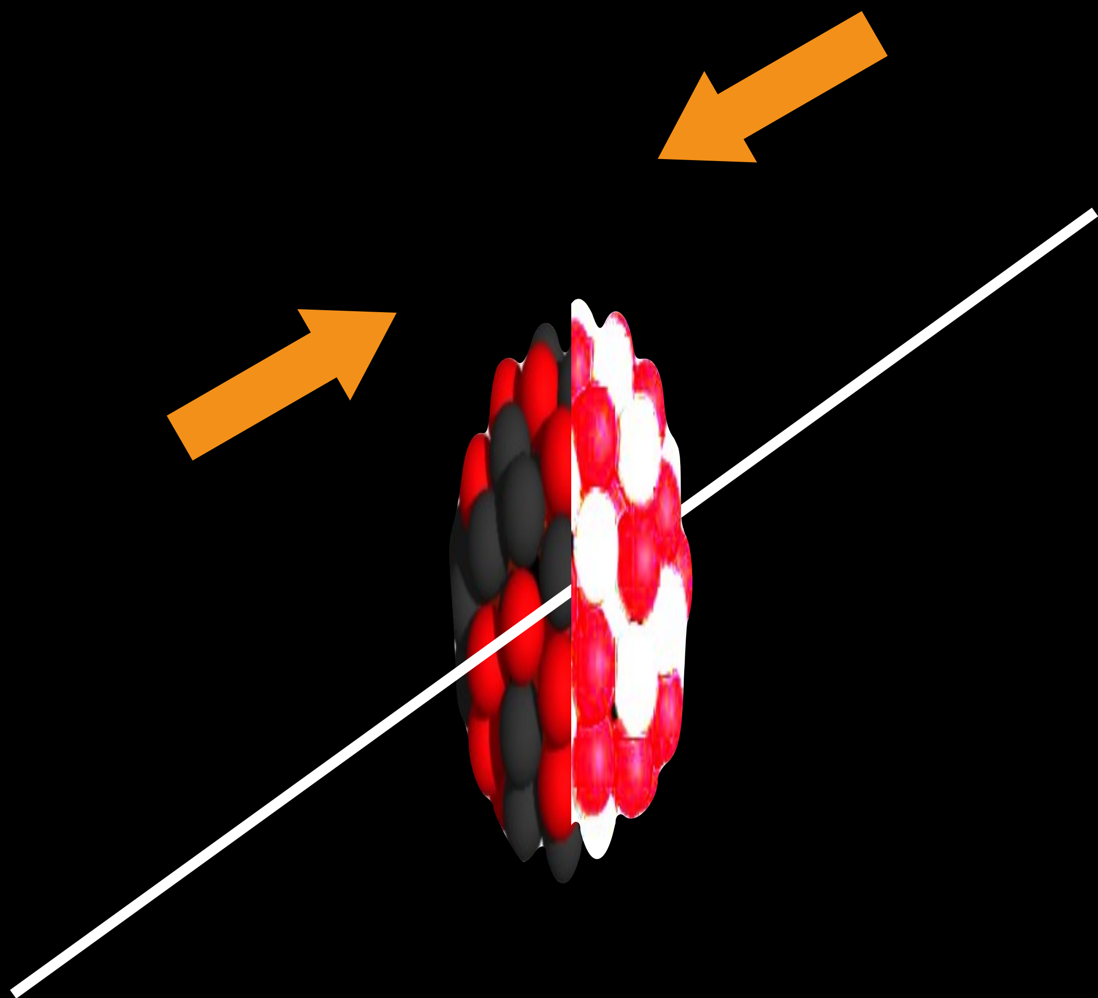
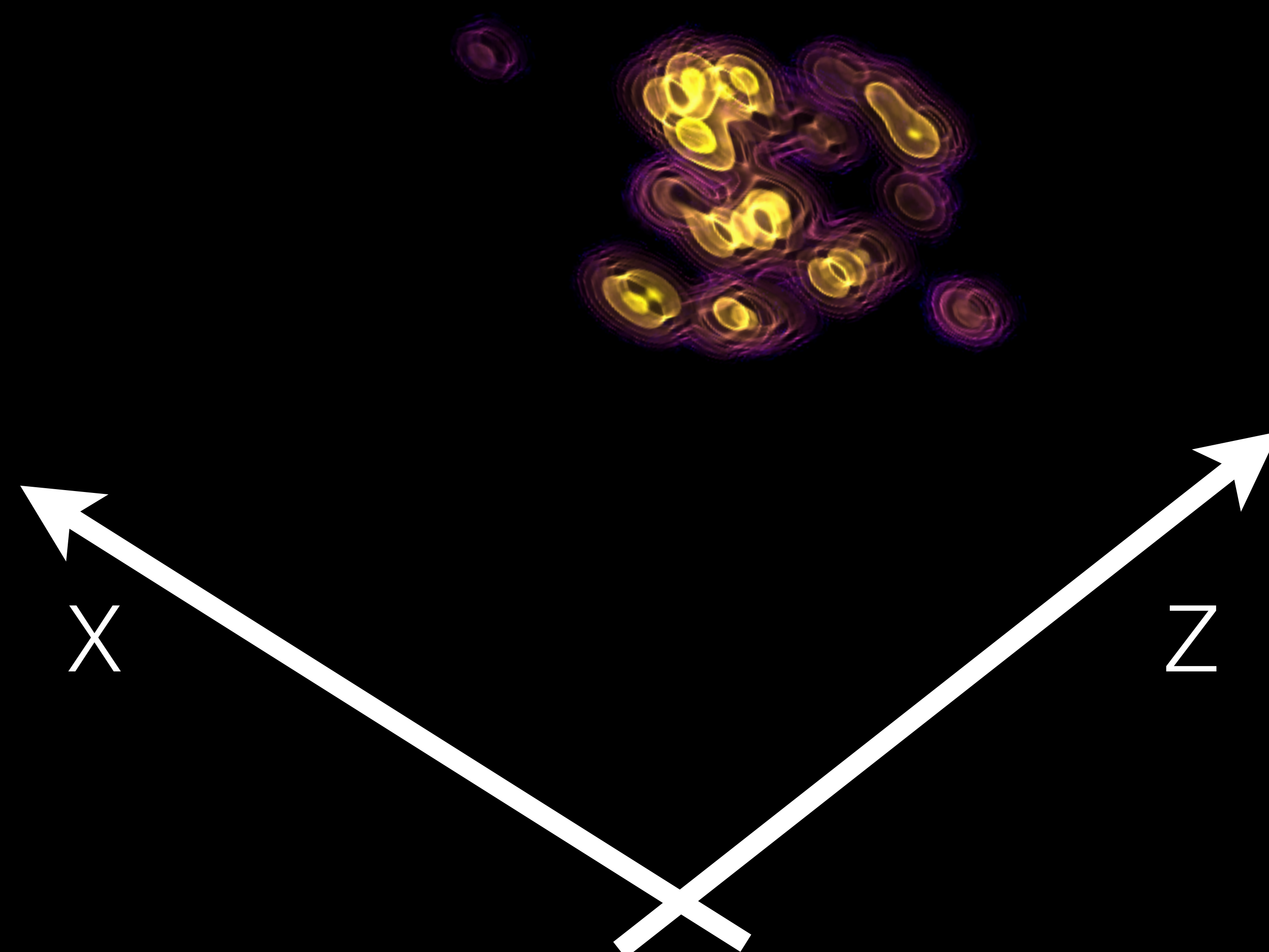
C. Shen and B. Schenke, Phys. Rev. C97 (2018) 024907



t=0.9 fm/c



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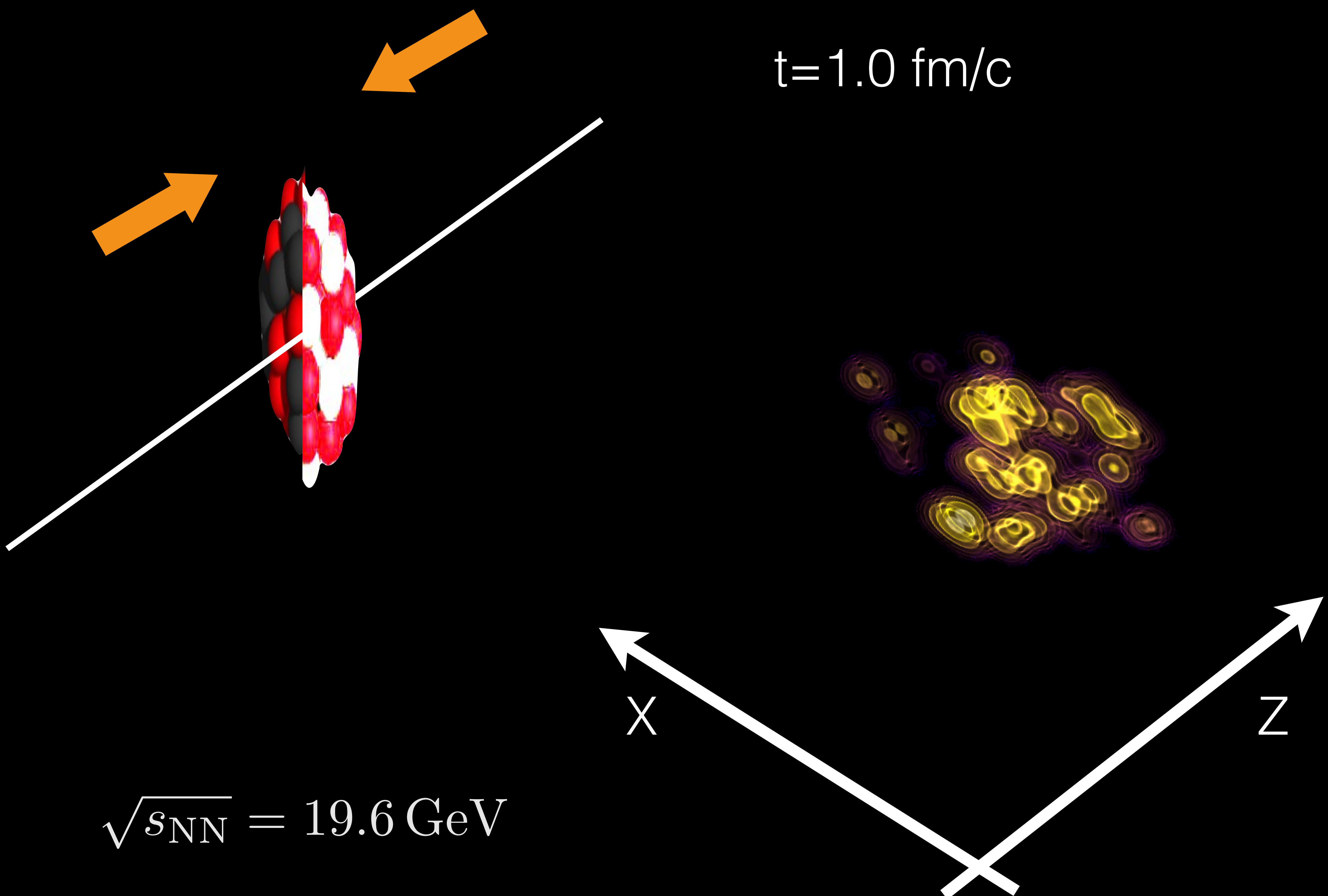
C. Shen and B. Schenke, Phys. Rev. C97 (2018) 024907



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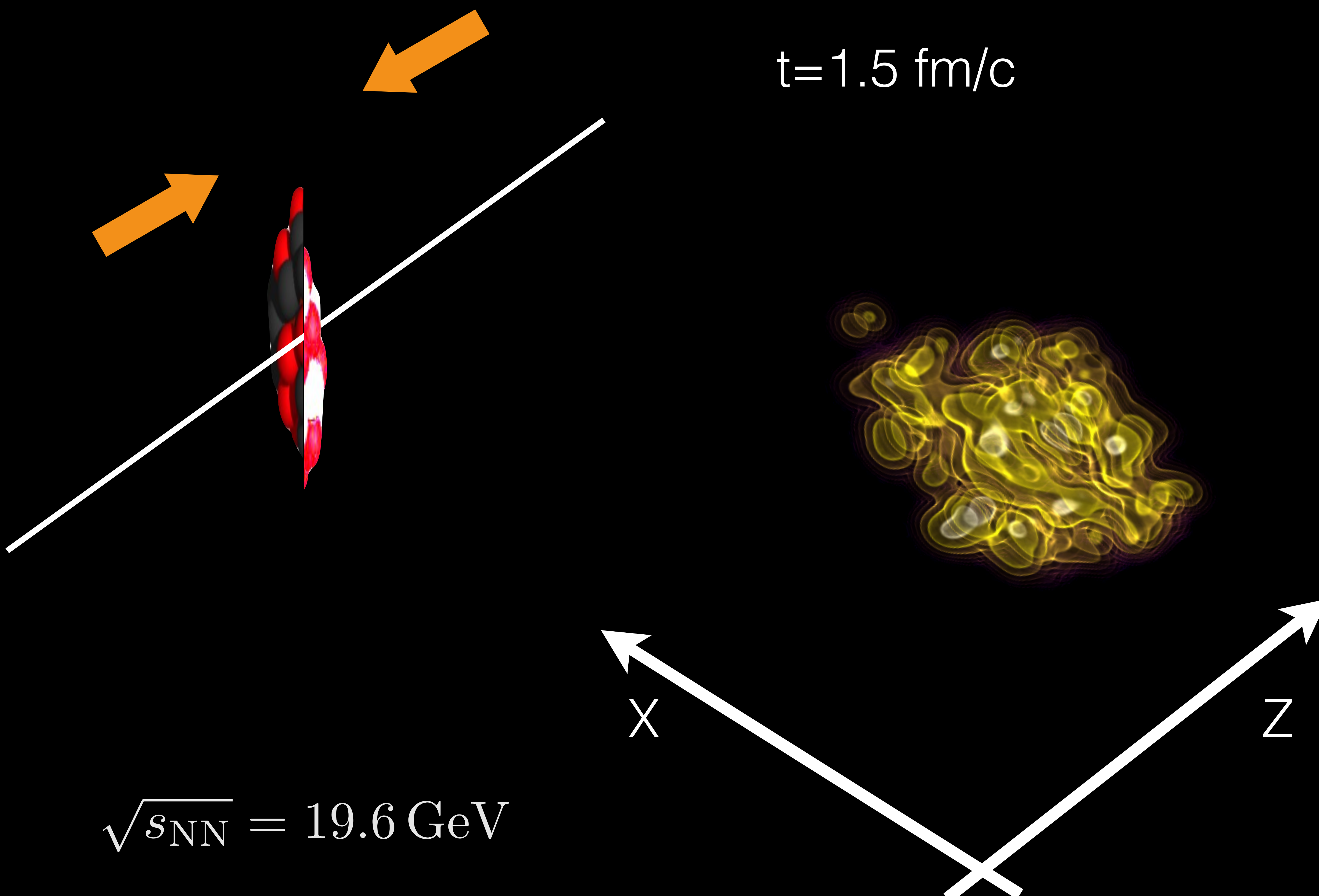

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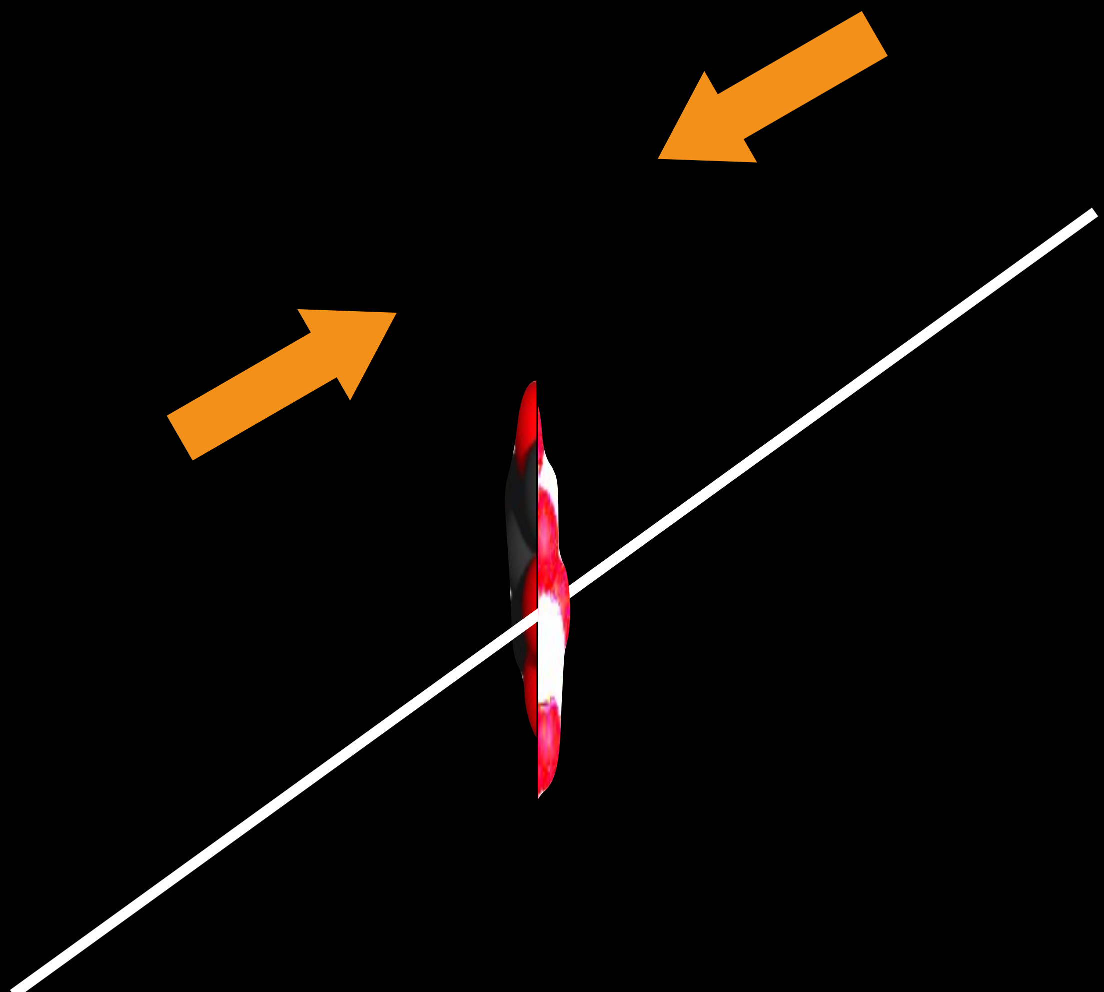

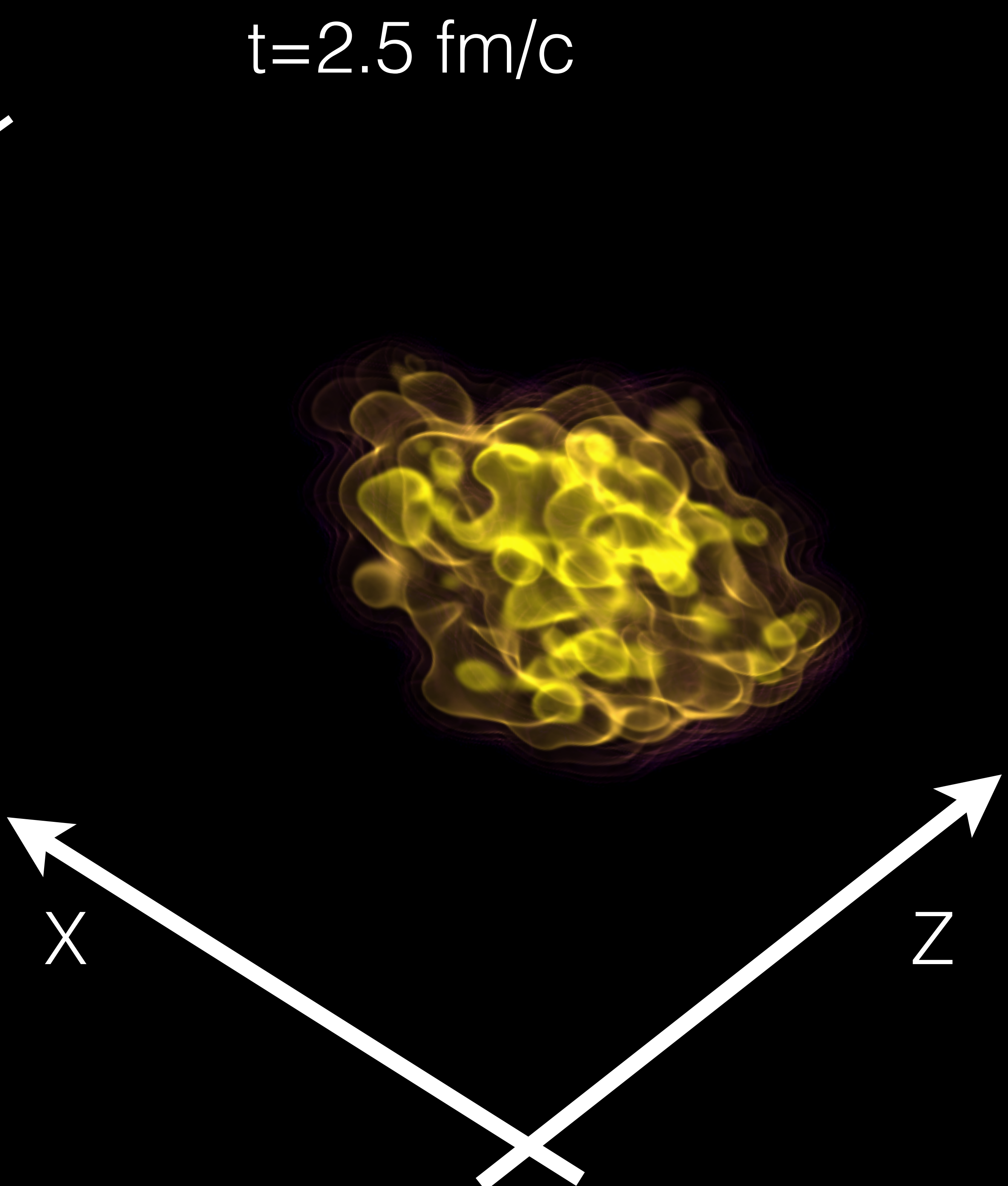

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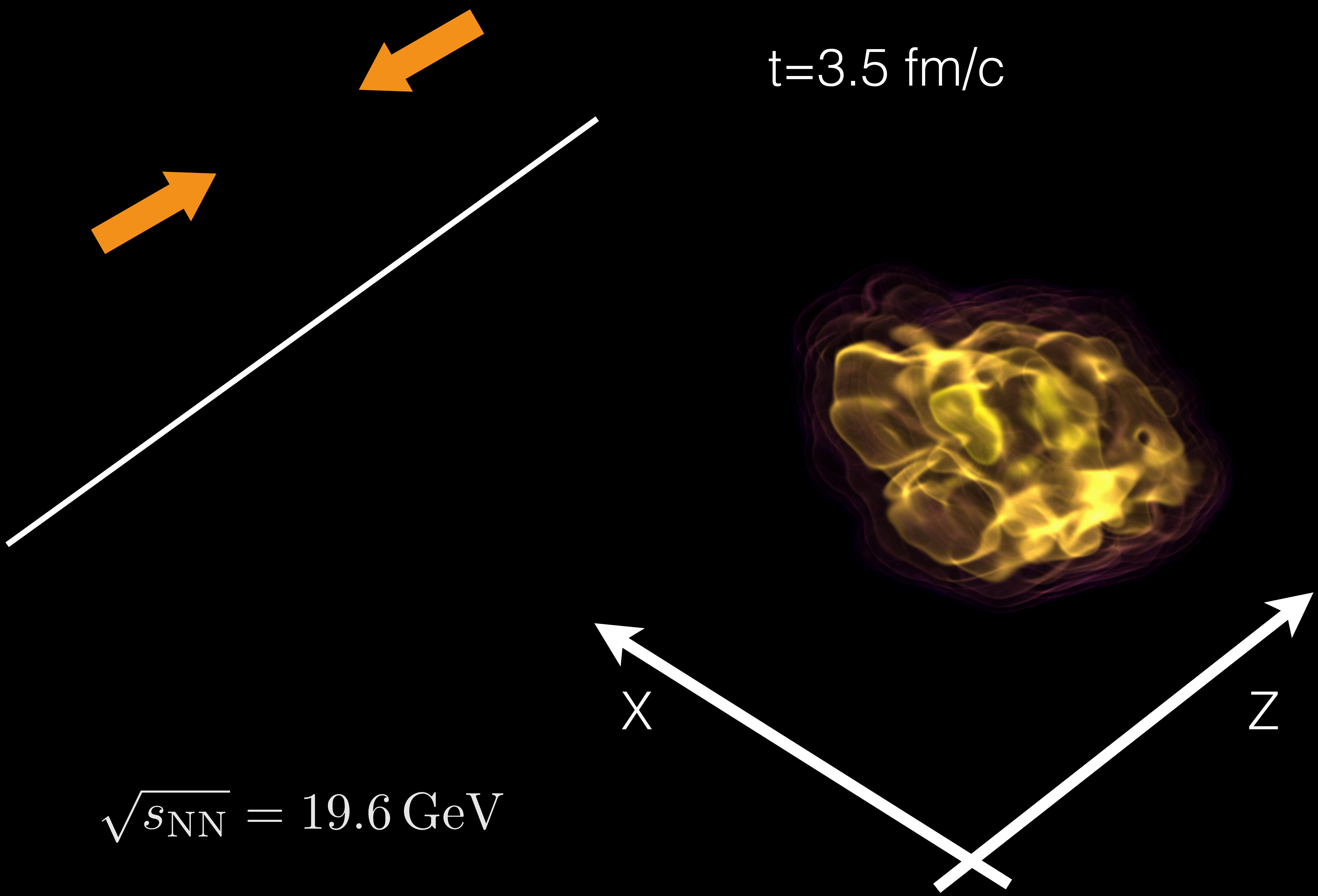
C. Shen and B. Schenke, Phys. Rev. C97 (2018) 024907



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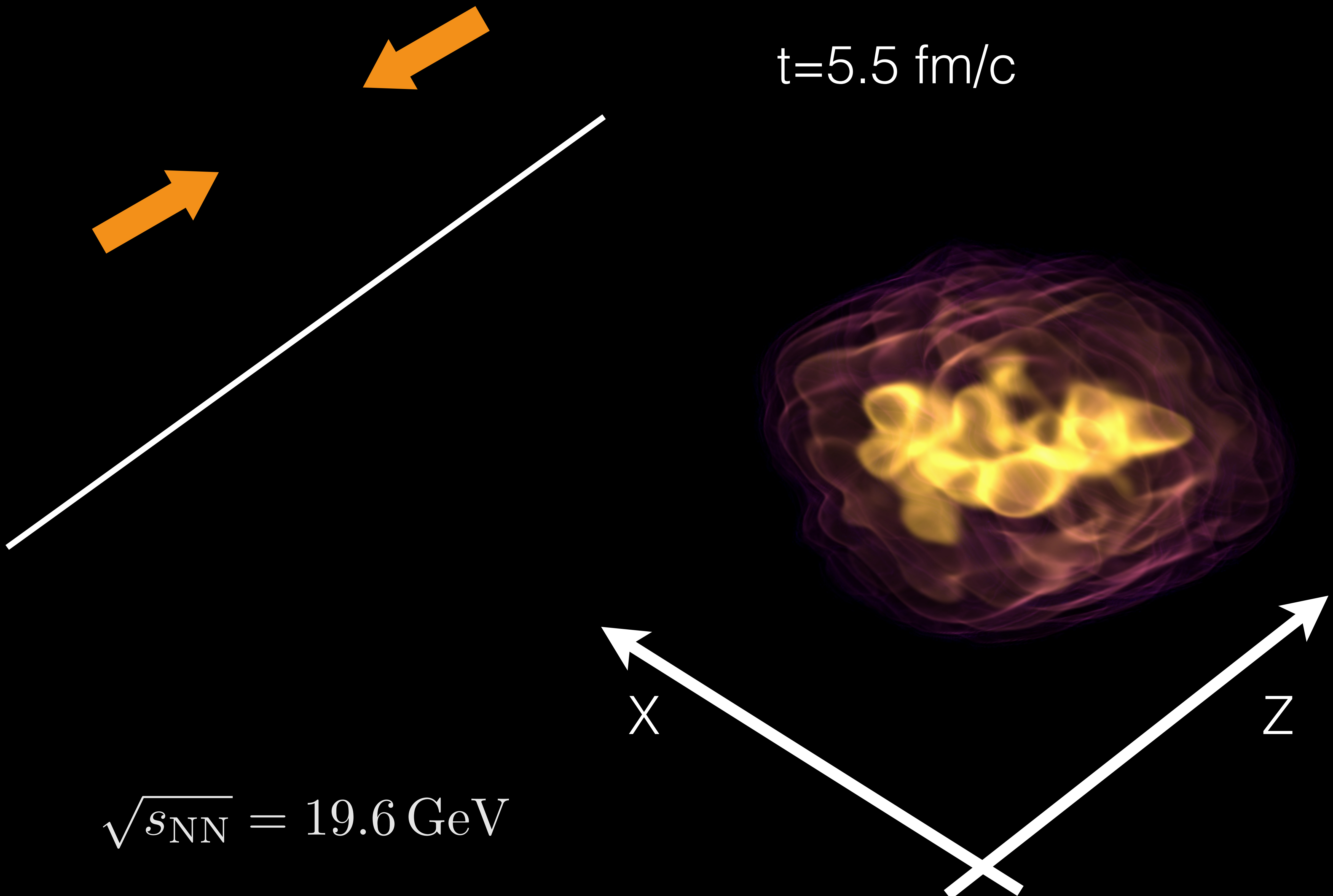
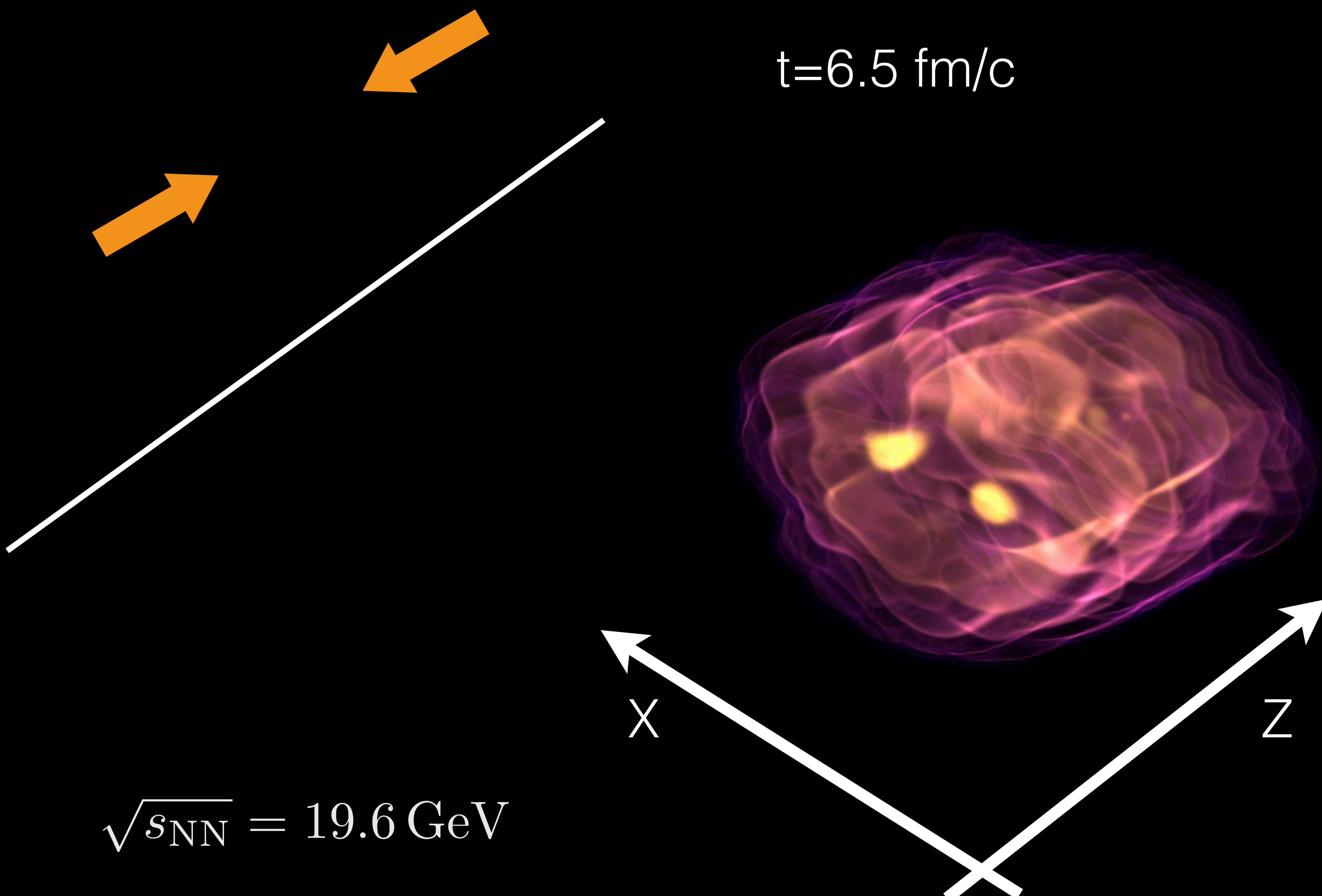
C. Shen and B. Schenke, Phys. Rev. C97 (2018) 024907



$\sqrt{s_{\rm NN}} = 19.6\,\mathrm{GeV}$

Hydrodynamical evolution with sources

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



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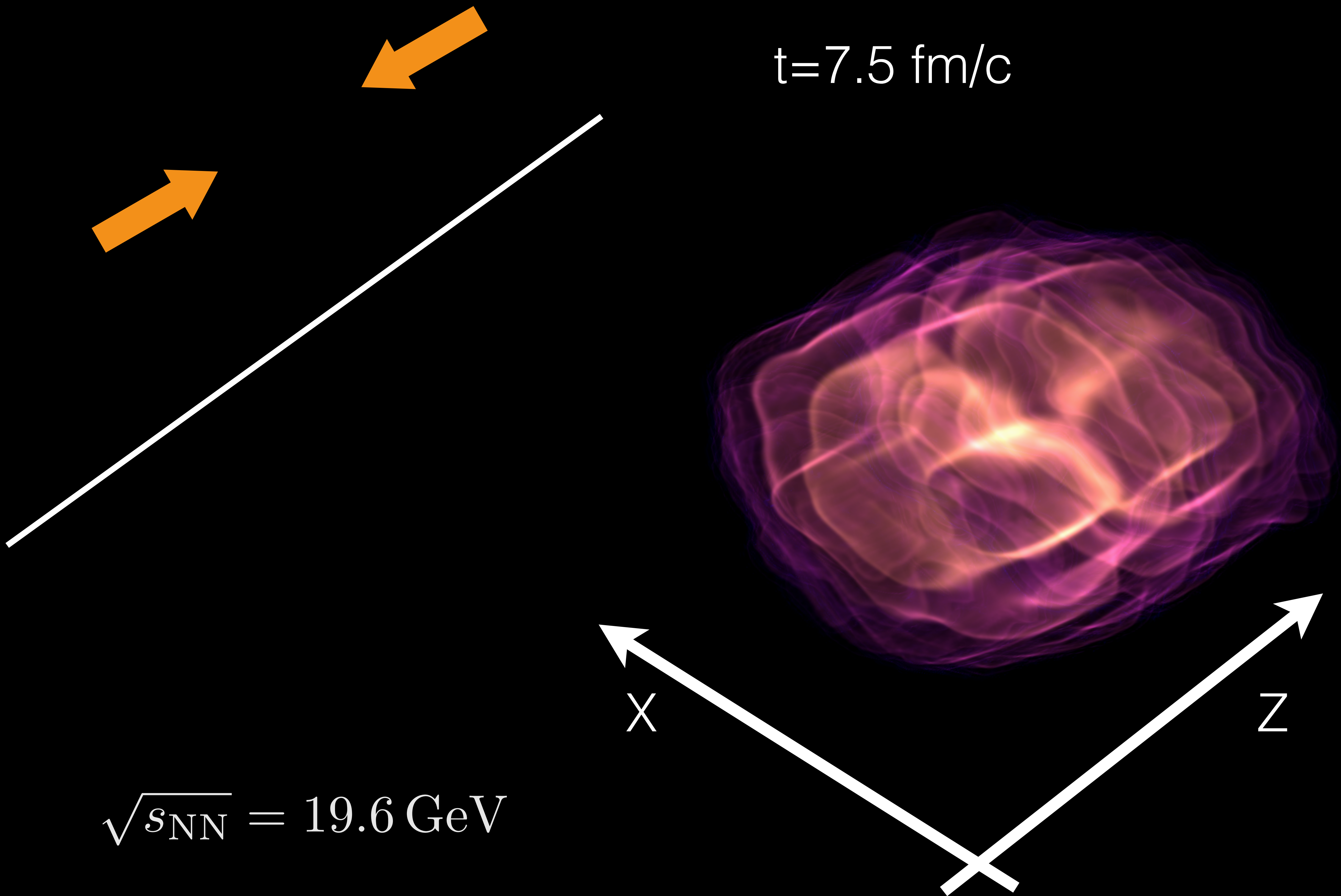
Hydrodynamical evolution with sources

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



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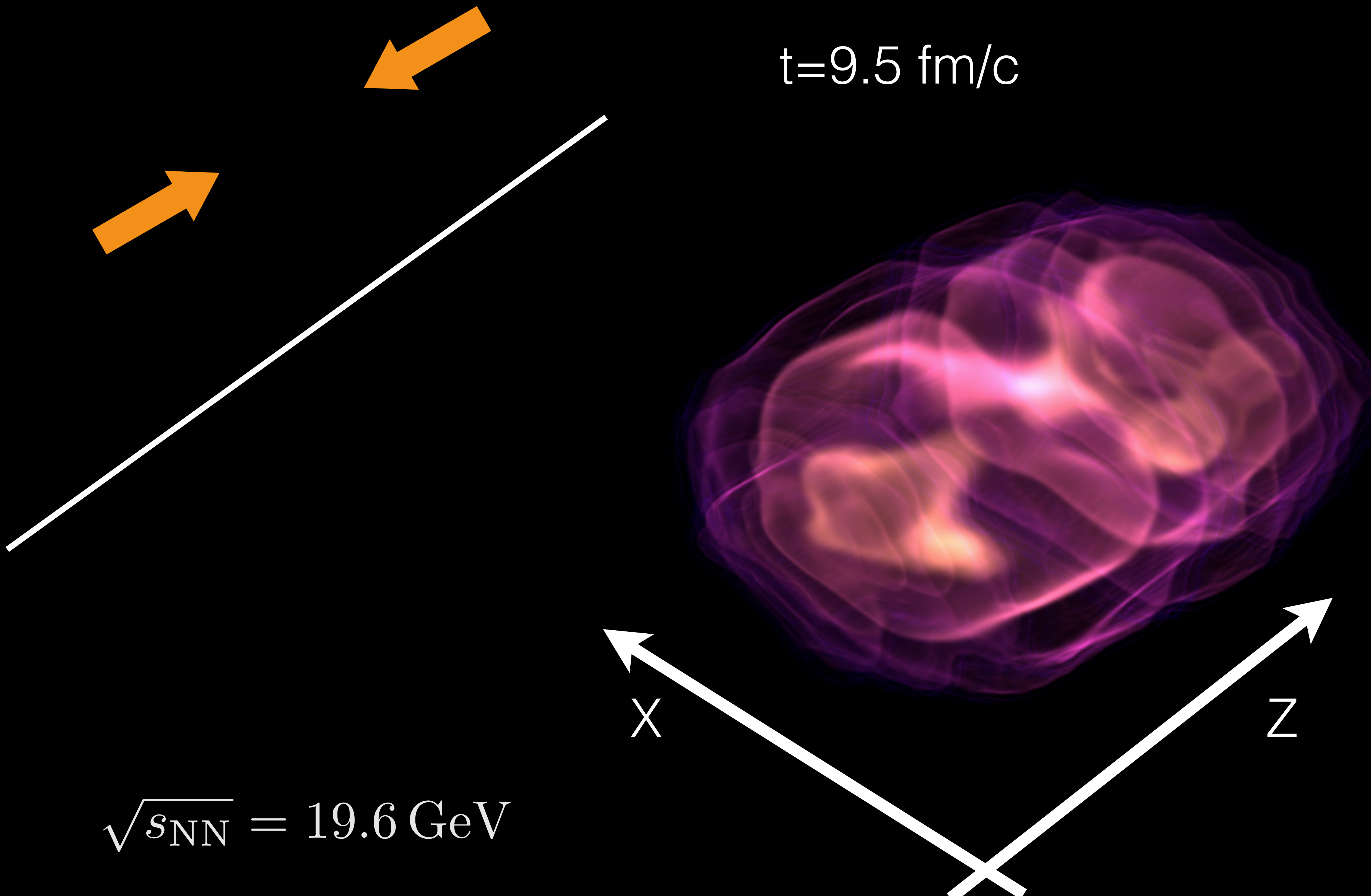
Hydrodynamical evolution with sources

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

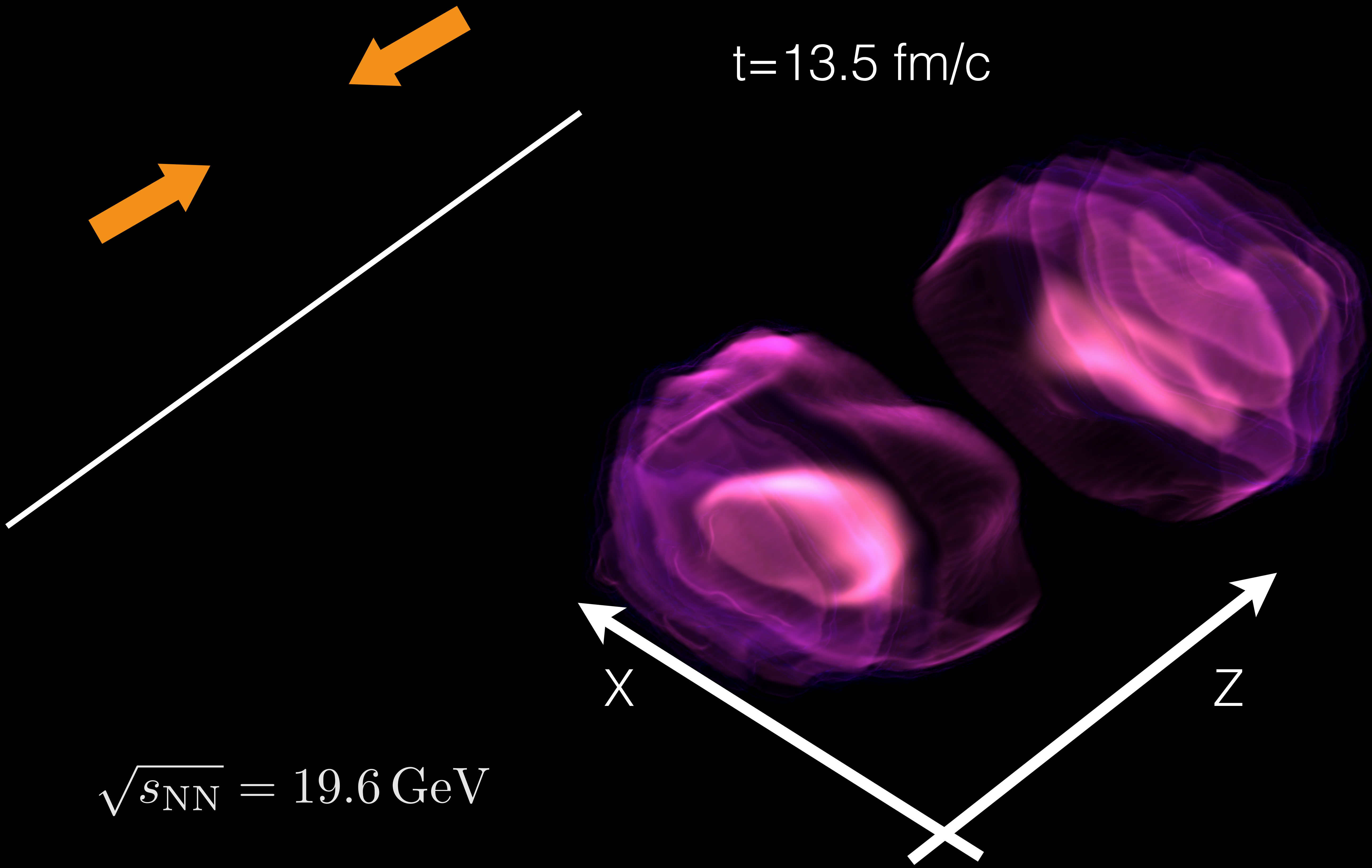


$$\sqrt{s_{\mathrm{NN}}} = 19.6\,\mathrm{GeV}$$

Hydrodynamical evolution with sources

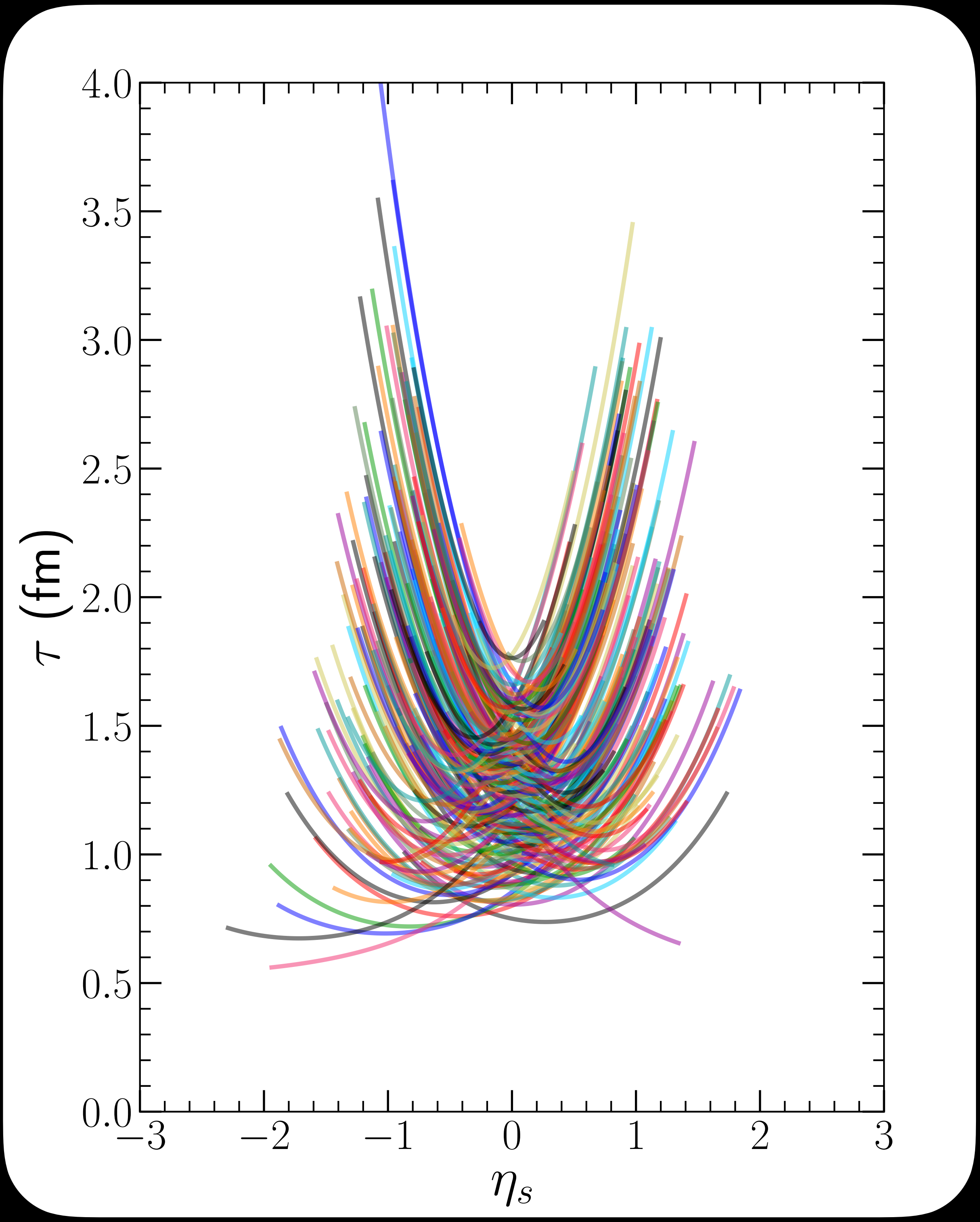
C. Shen and B. Schenke, Phys. Rev. C97 (2018) 024907

t=13.5 fm/c

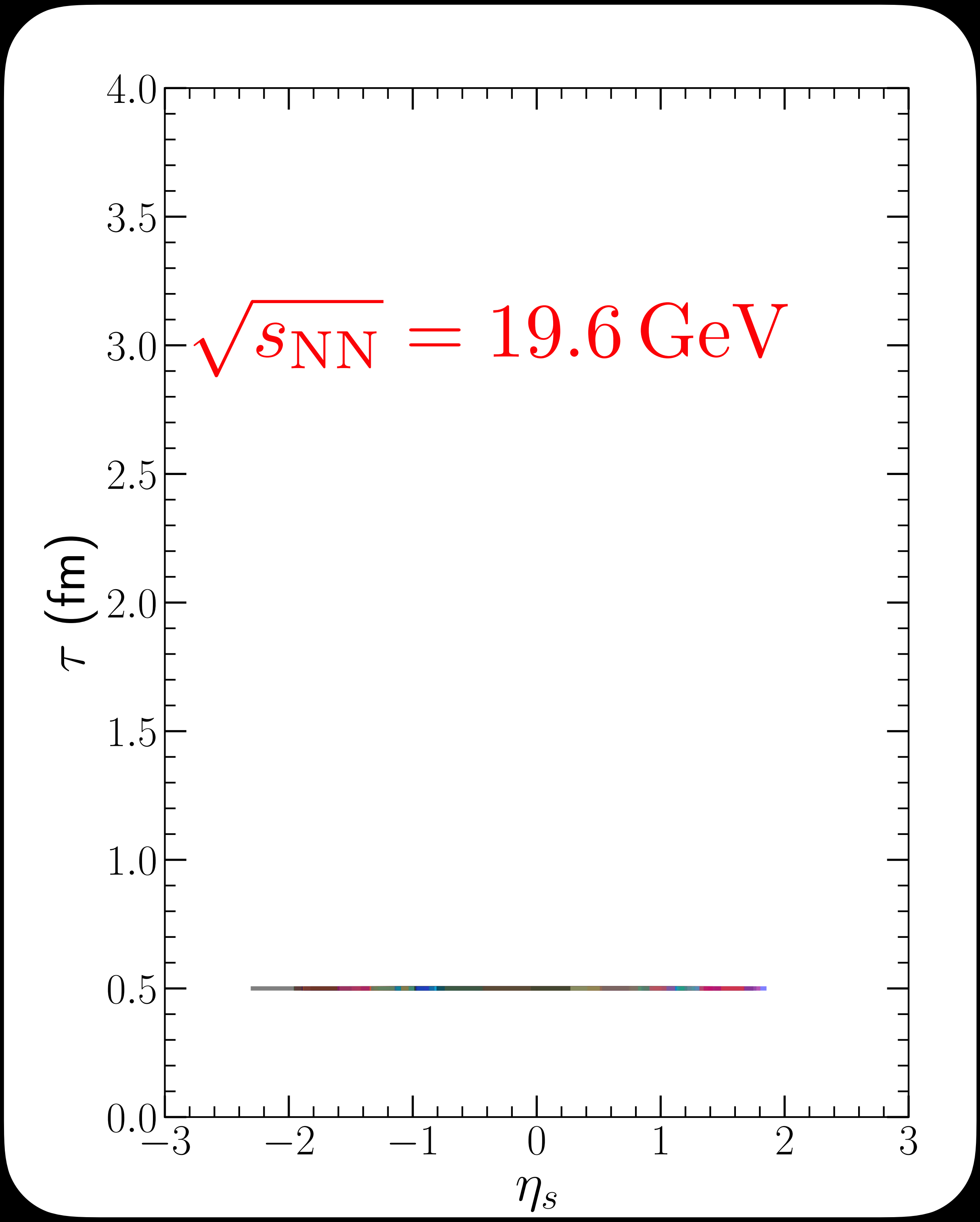


$$\sqrt{s_{\rm NN}} = 19.6\,\mathrm{GeV}$$

Can we see dynamical initialization in data?

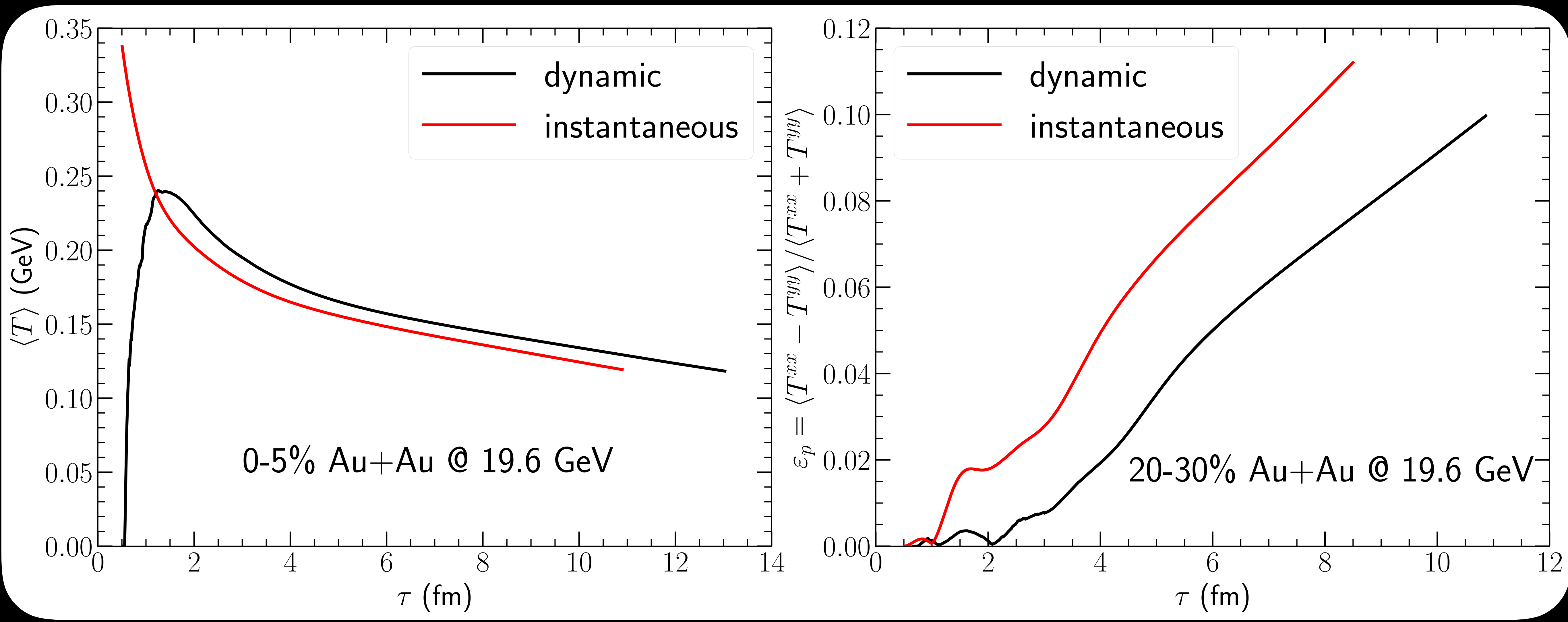


vs.



Transverse dynamics with sources

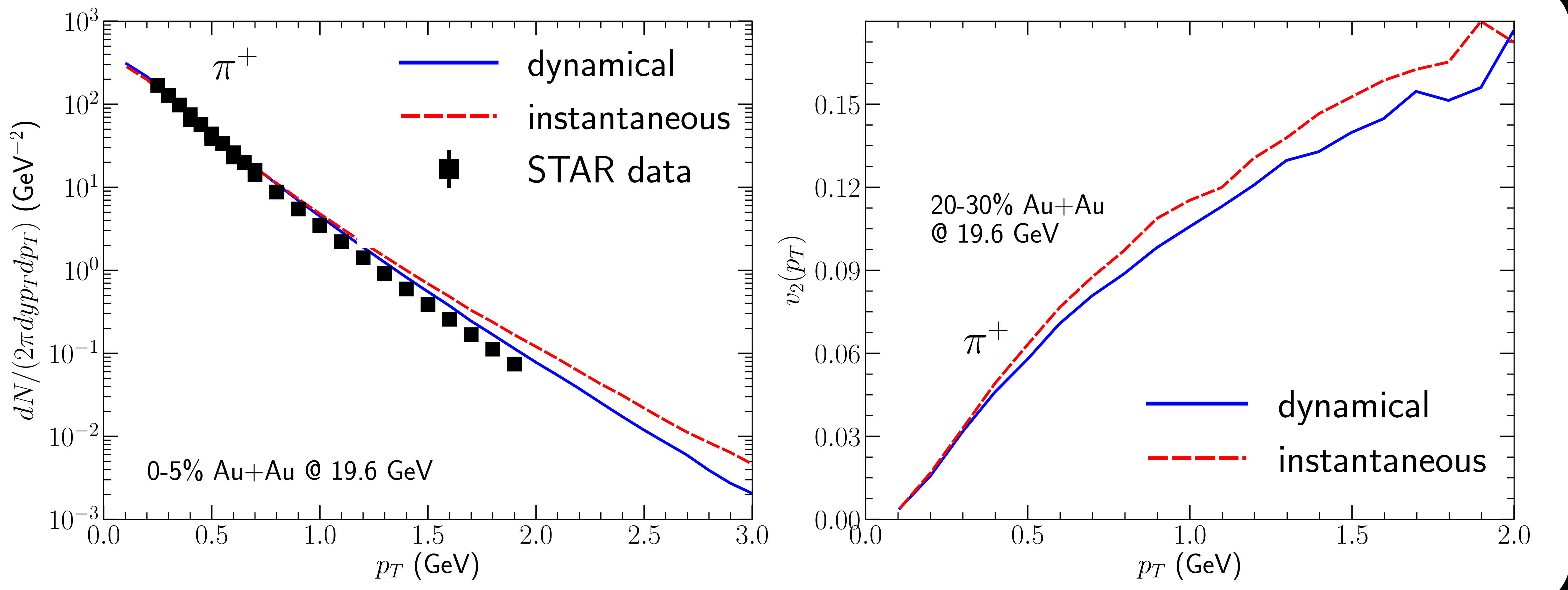
C. Shen and B. Schenke, arXiv:1807.05141 [nucl-th]



- 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

C. Shen and B. Schenke, arXiv:1807.05141 [nucl-th]



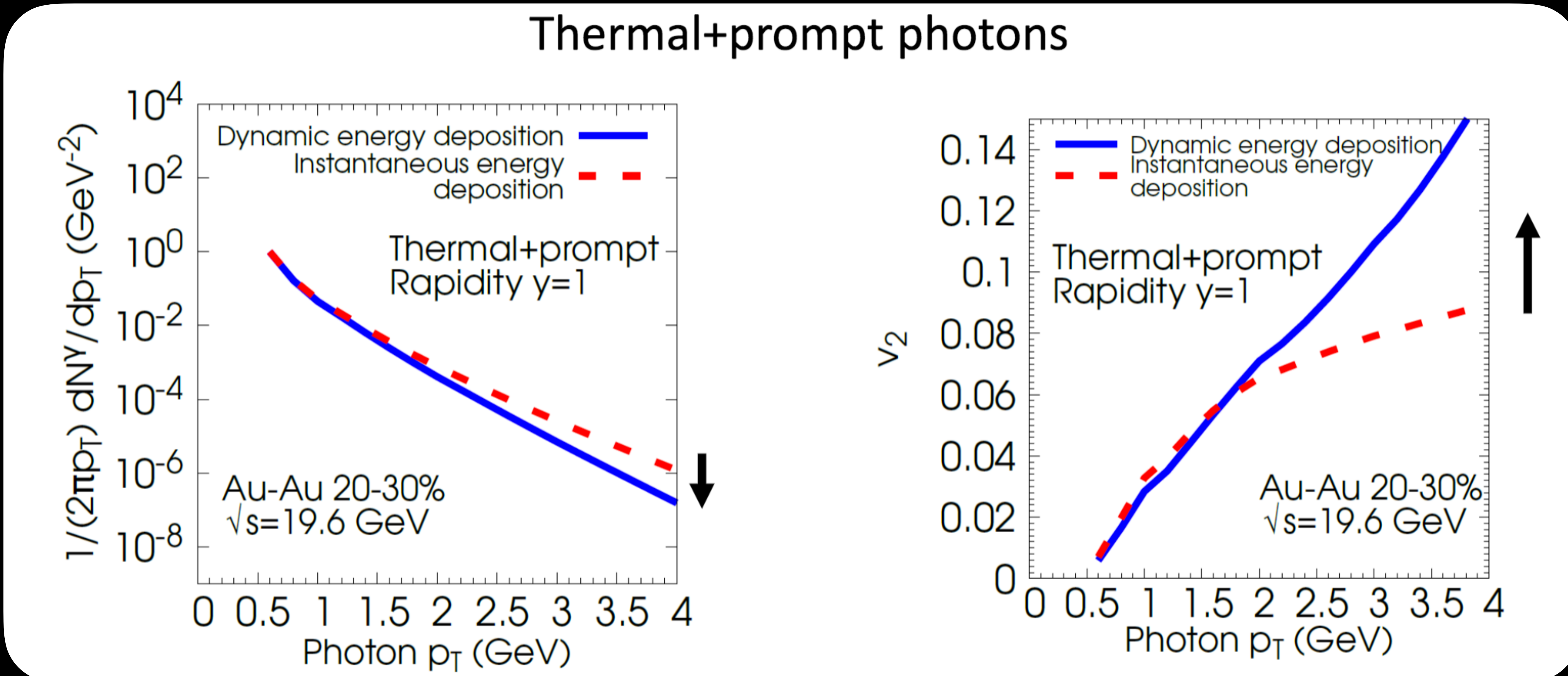
- Dynamical initialization results steeper particle spectra and smaller $v_2(p_T)$

5-10% less radial and elliptic flow

→ *~20-40% smaller shear viscosity*

Dynamical initialization effect on EM probes

C. Gale, S. Jeon, S. McDonald, J.F. Paquet and C. Shen, arXiv:1807.09326 [nucl-th]

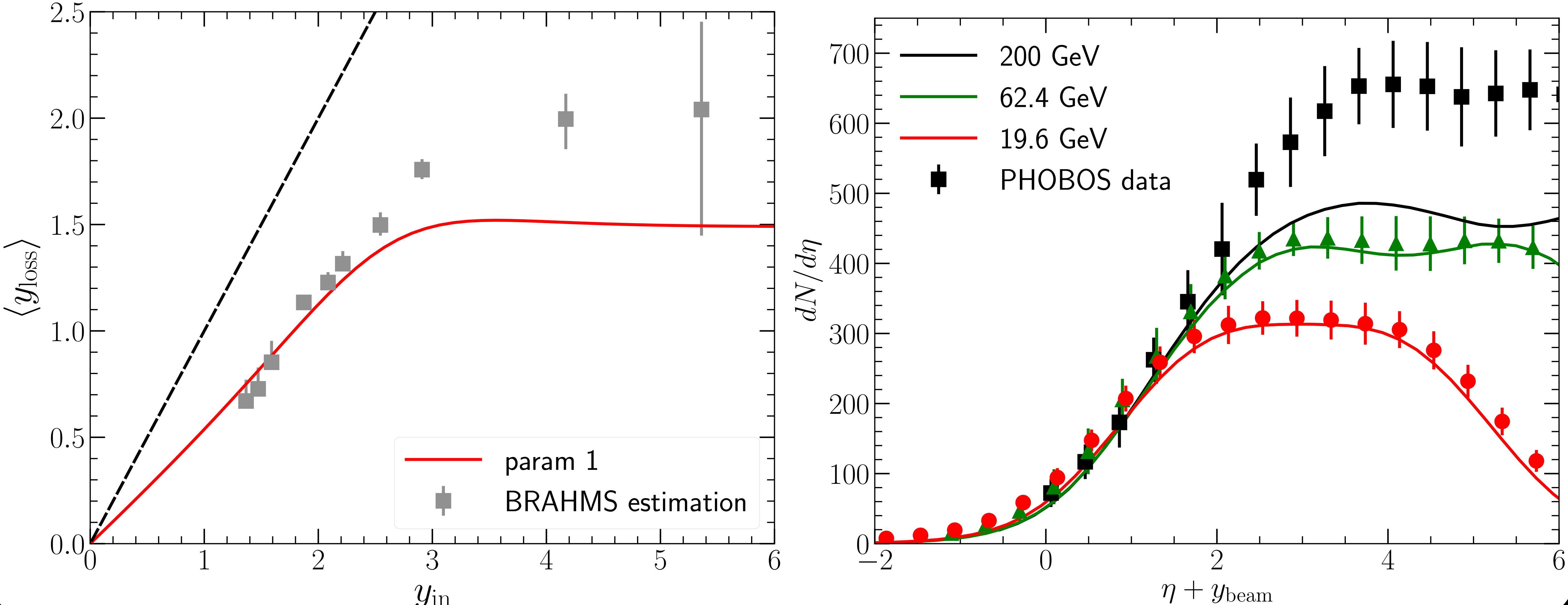


- Dynamical initialization results in large direct photon v_2 at high p_T

A large sensitivity to the early time dynamics

Quantify the baryon stopping

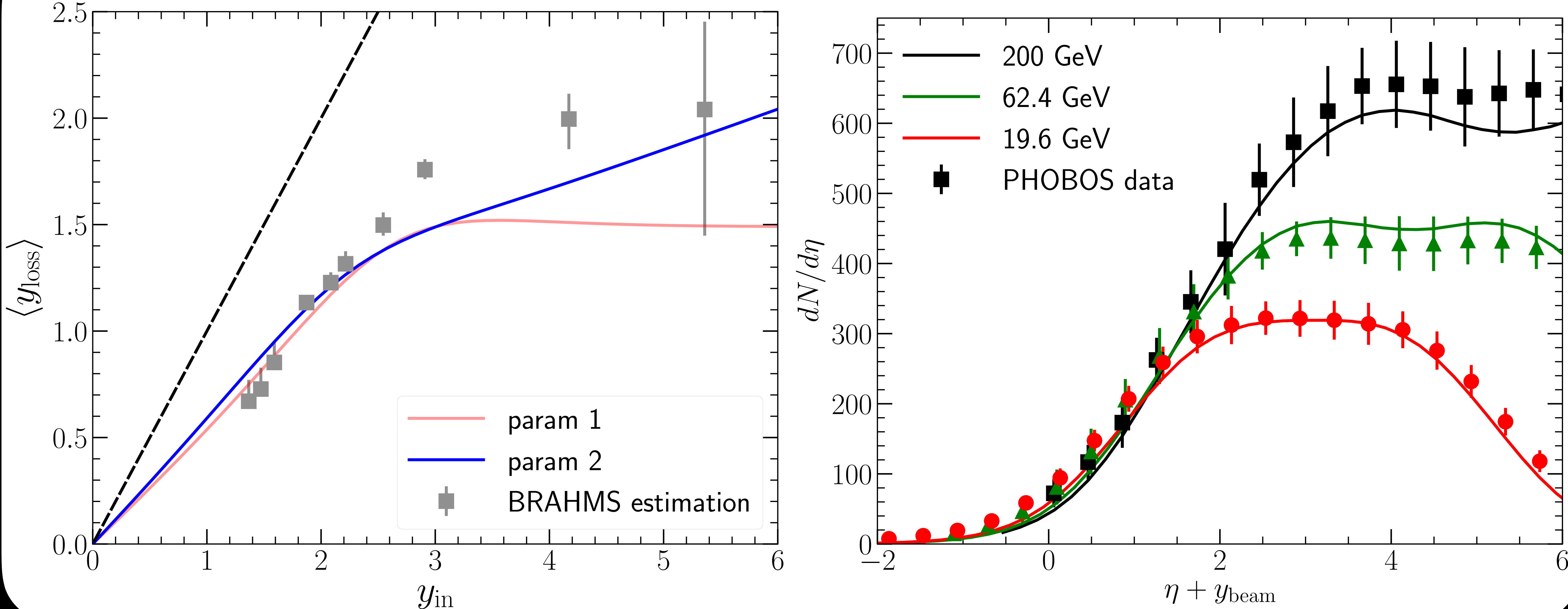
C. Shen and B. Schenke, Nucl. Phys. A982 (2019) 411-414



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

Quantify the baryon stopping

C. Shen and B. Schenke, Nucl. Phys. A982 (2019) 411-414

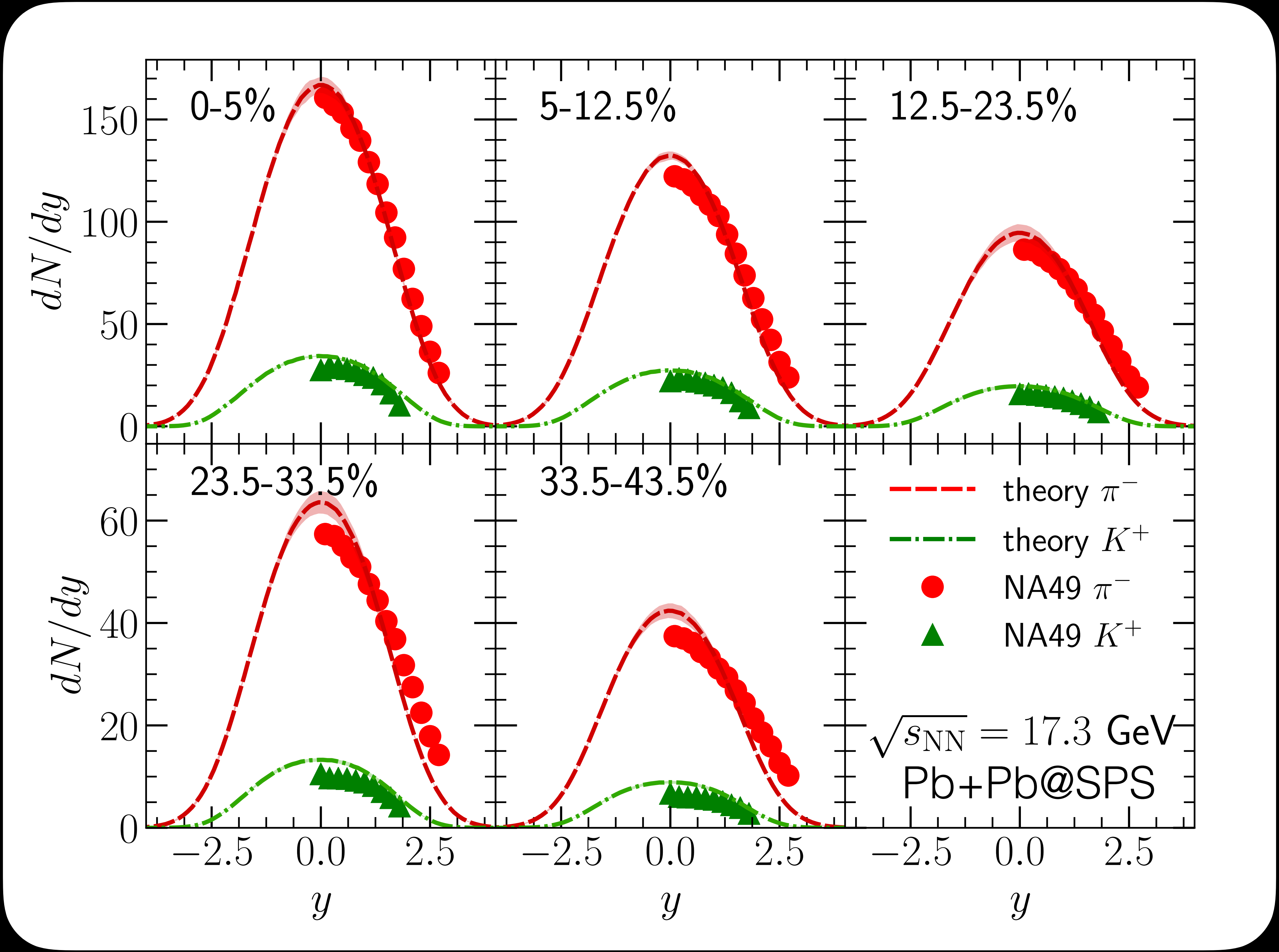


- Understand how the collision energy is converted to particle production

Bayesian analysis is underway to quantify baryon stopping

Towards "one fluid" to rule BES

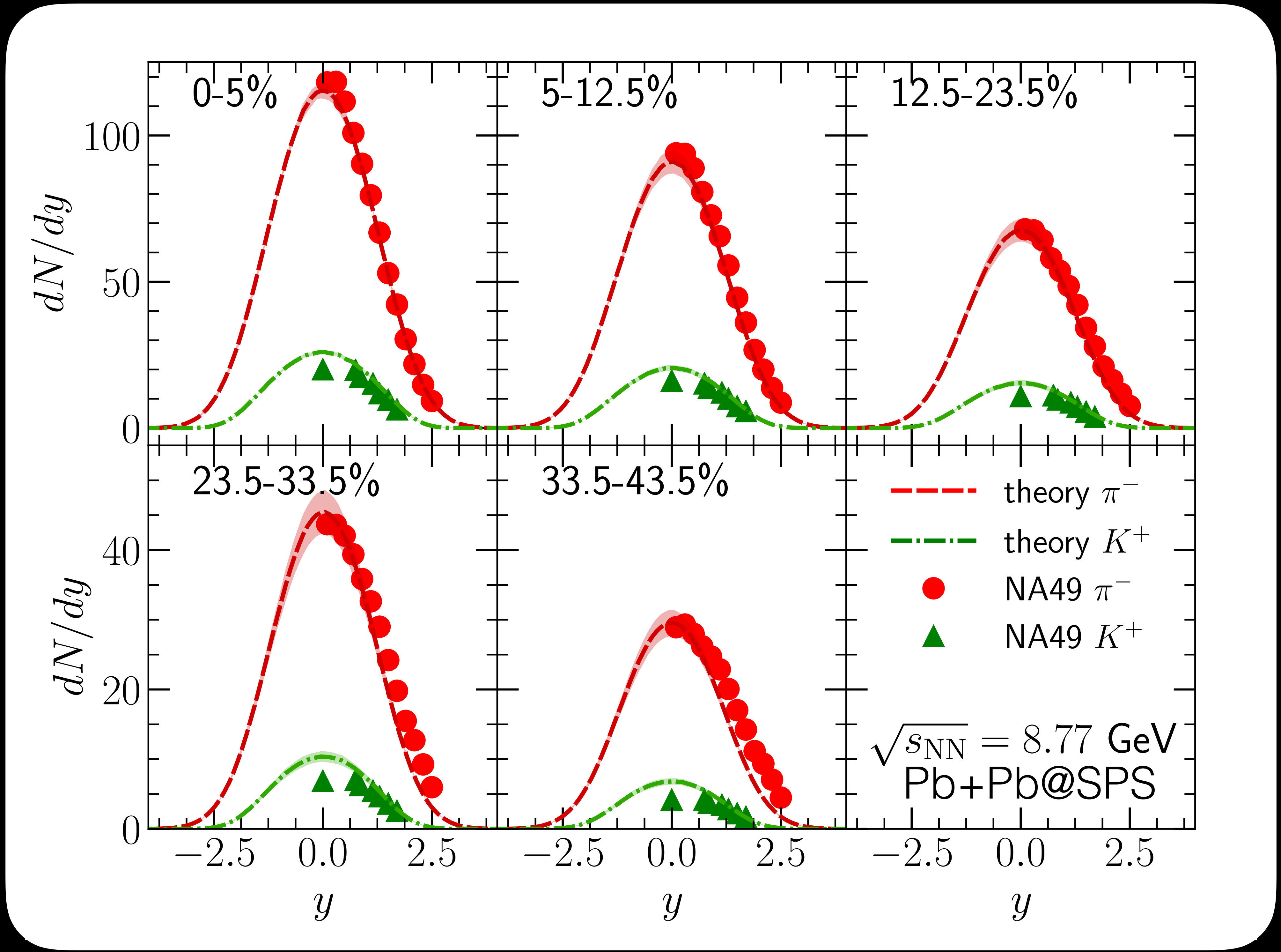
B. Schenke and C. Shen, in preparation



- No free parameters after fit to Au+Au 200, 62.4, and 19.6 GeV

Towards "one fluid" to rule BES

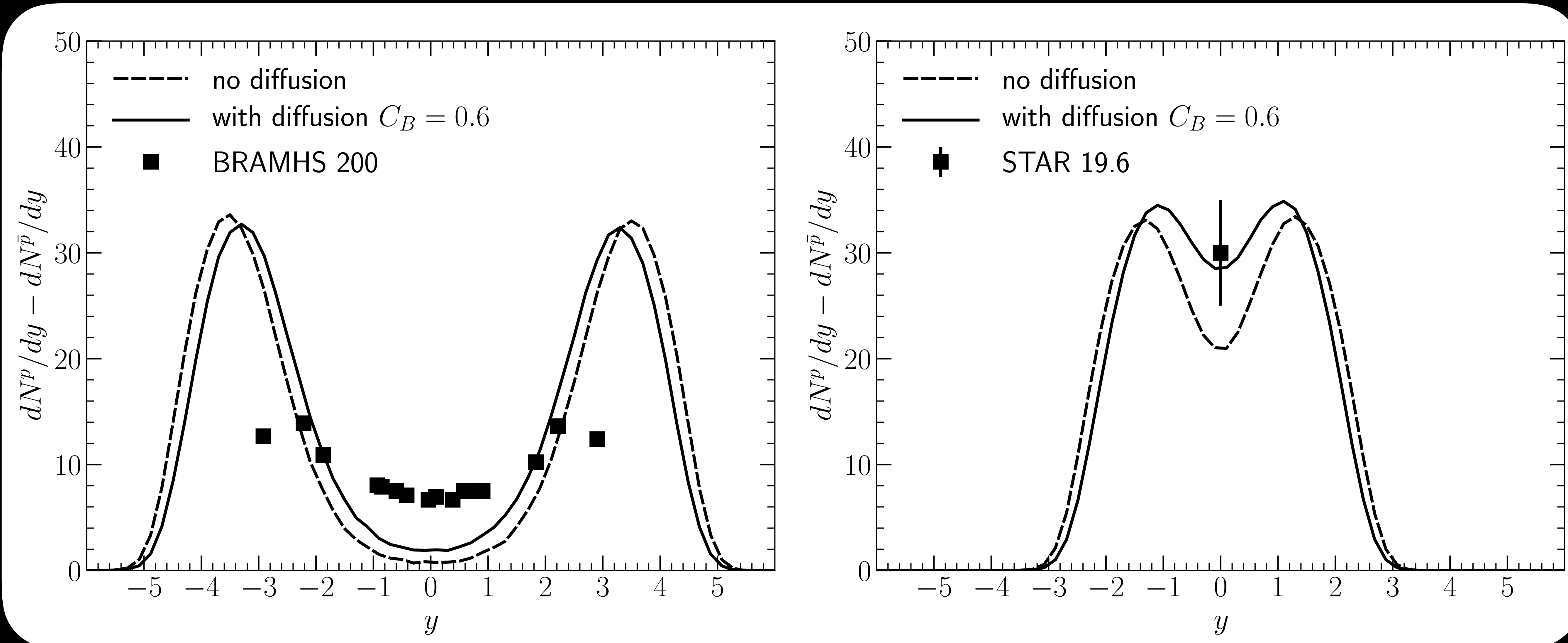
B. Schenke and C. Shen, in preparation



- No free parameters after fit to Au+Au 200, 62.4, and 19.6 GeV

Effects of net baryon diffusion

G. Denicol, C. Gale, S. Jeon, A. Monnai, B. Schenke and C. Shen, Phys. Rev. C98, 034916 (2018)
M. Li and C. Shen, Phys. Rev. C98, 064908 (2018)
L. Du, U. Heinz and G. Vujanovic, Nucl. Phys. A982 (2019) 407-410

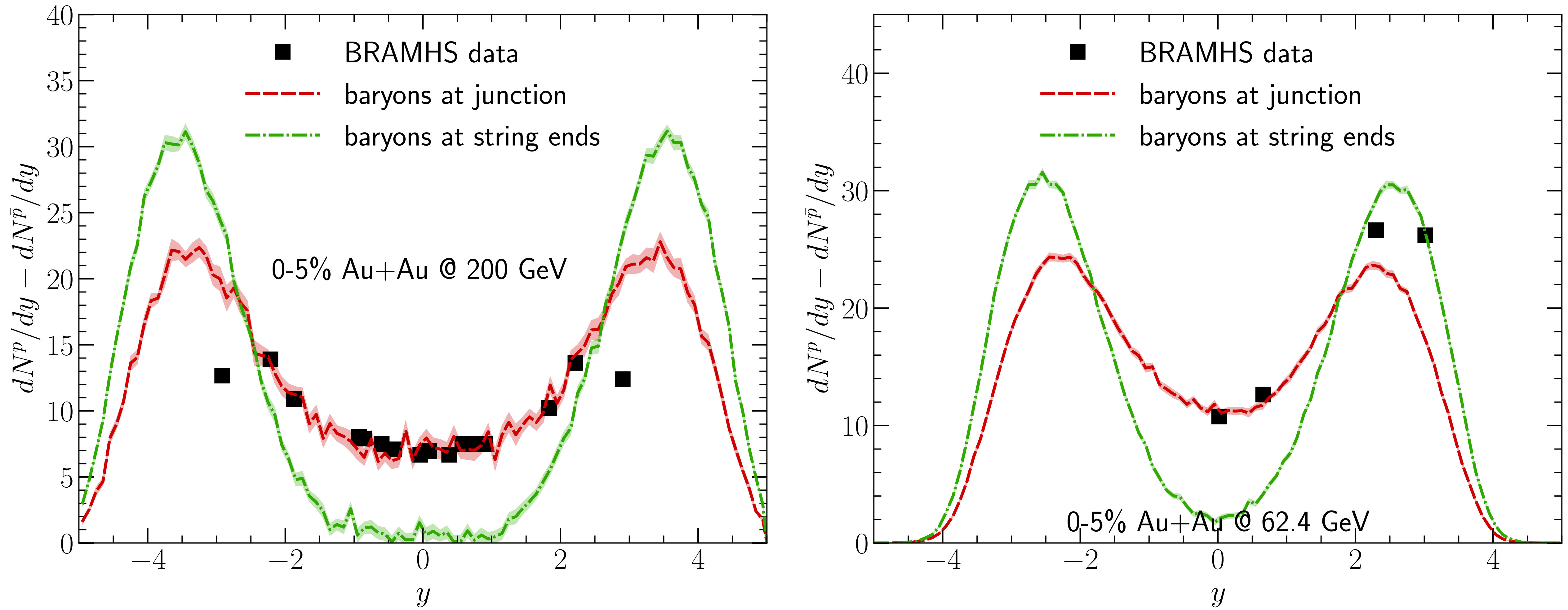


- Net baryon diffusion transports more baryon numbers to the mid-rapidity region

Not enough for high energy collisions

Initial state fluctuations of baryon positions

B. Schenke and C. Shen, in preparation



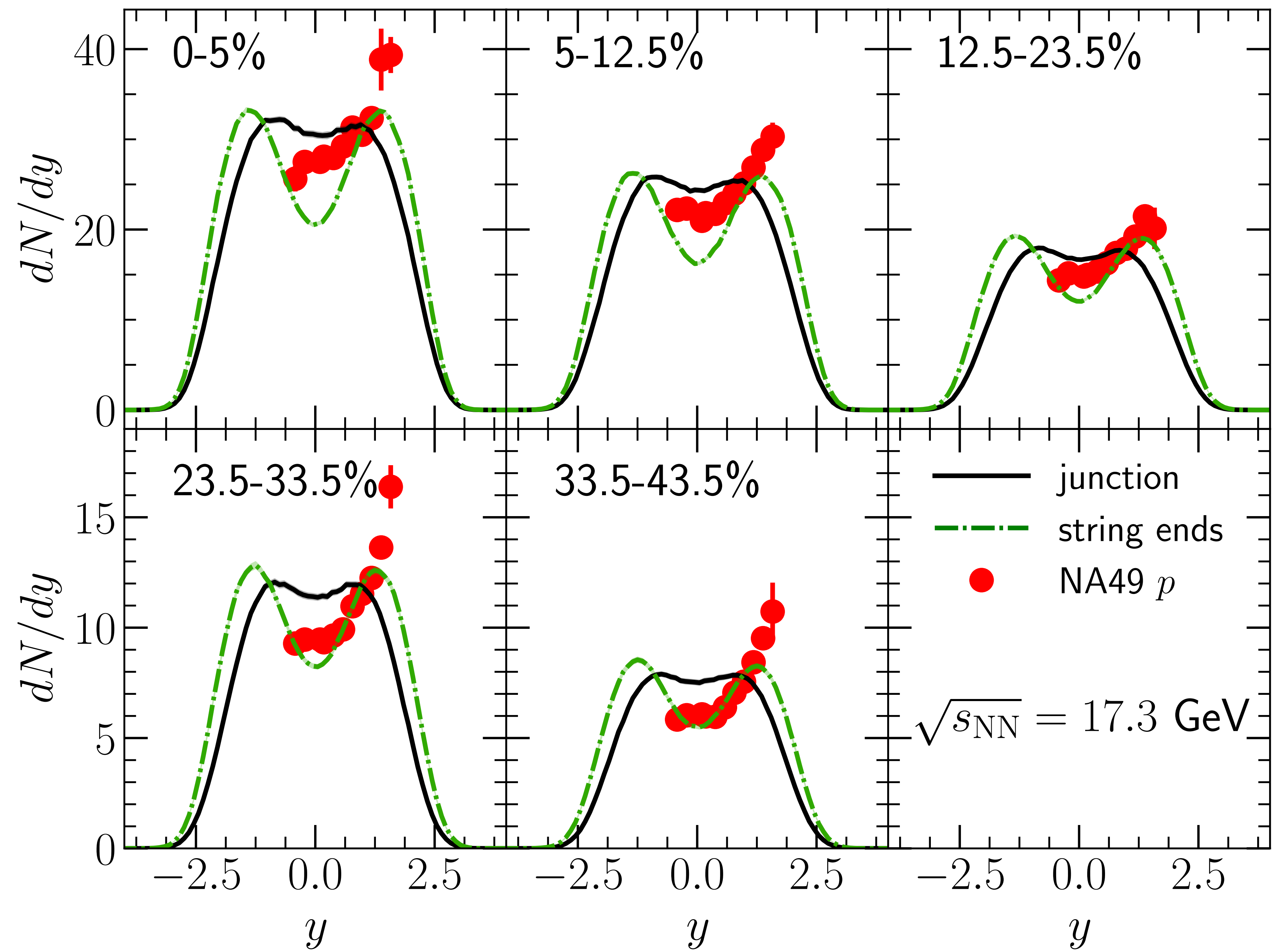
- Allowing the initial baryon density to fluctuate to string junctions improves description at high collision energies

D. Kharzeev, Phys. Lett. B 378, 238 (1996)

baryon diffusion vs. initial fluctuations

Towards "one fluid" to rule BES

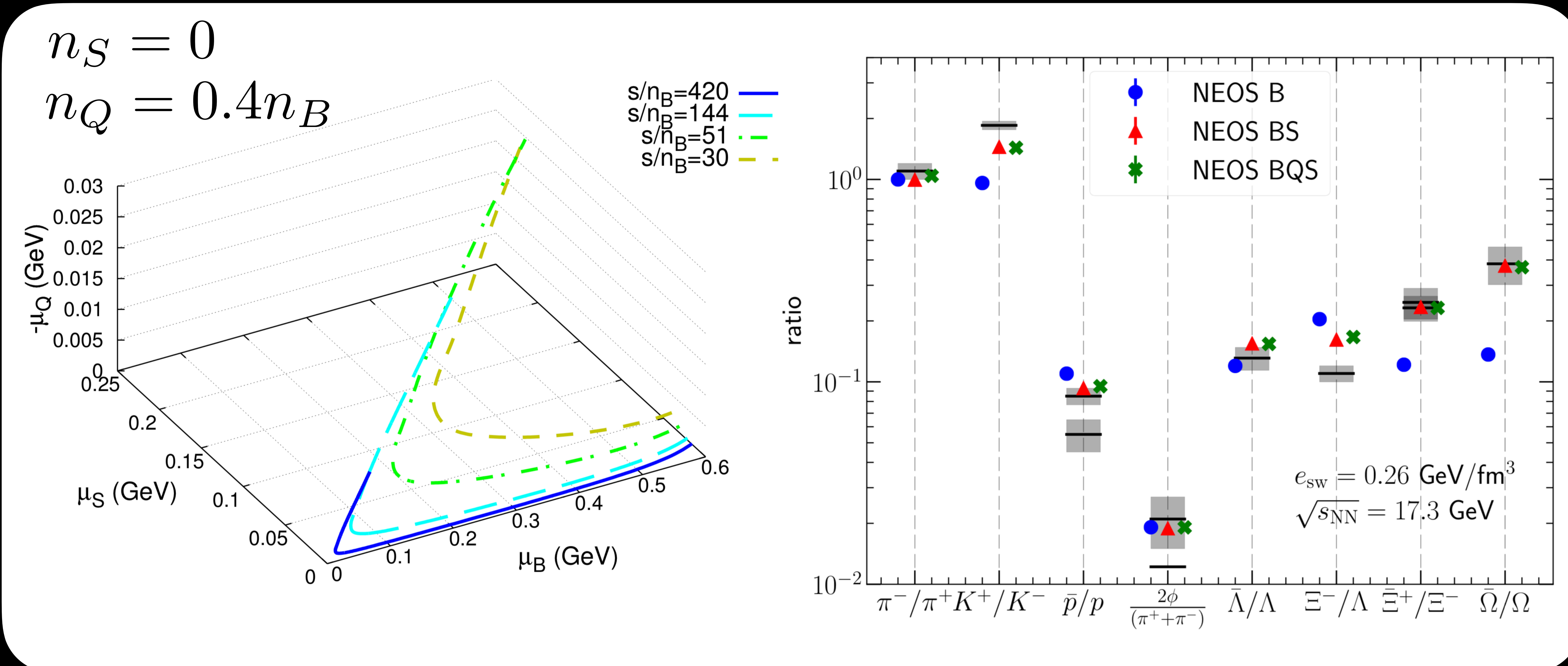
B. Schenke and C. Shen, in preparation



- Centrality dependence of proton distribution need further study

QCD Equation of State at finite densities

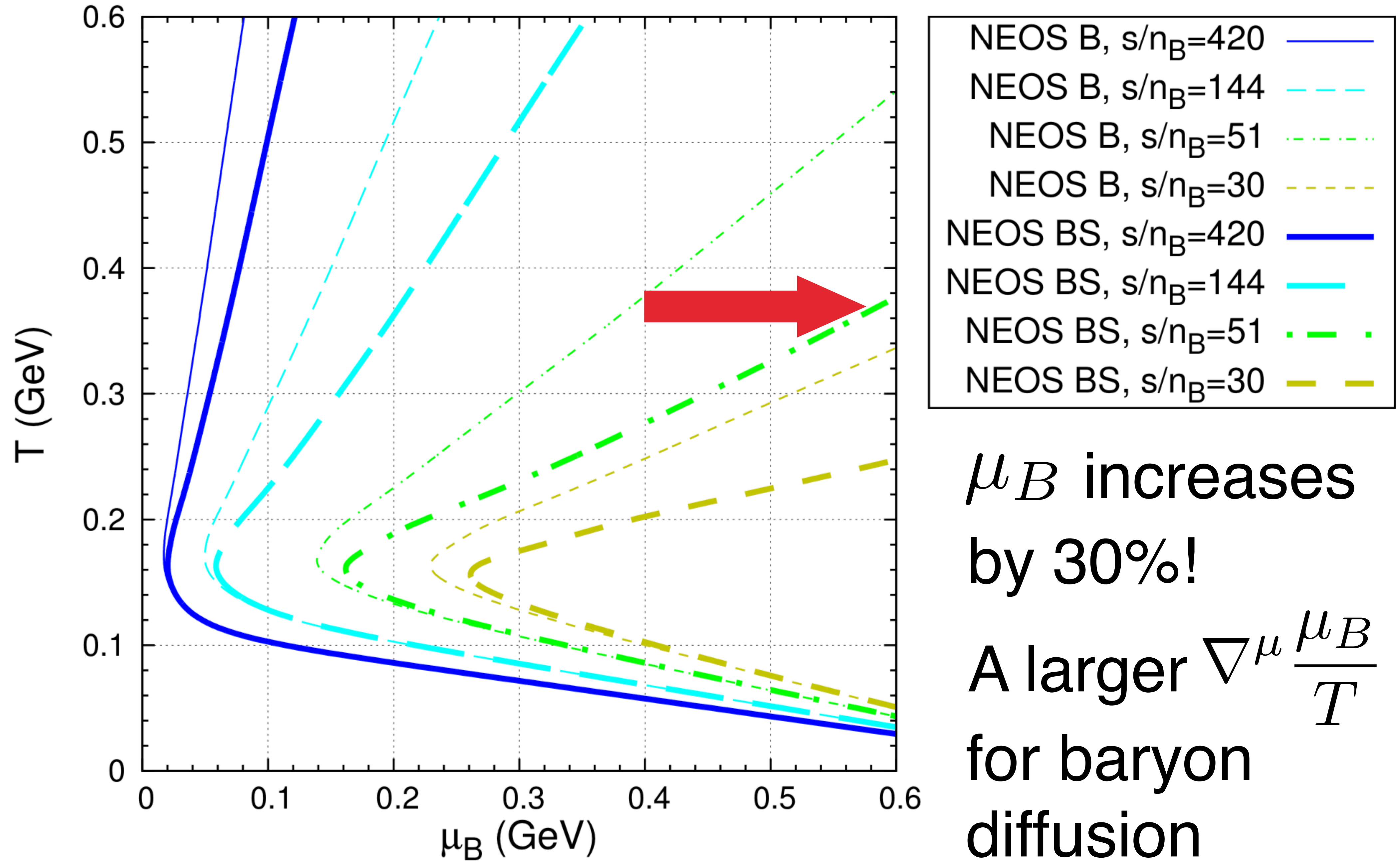
A. Monnai, B. Schenke and C. Shen, arXiv:1902.05095 [nucl-th]
J. Noronha-Hostler, P. Parotto, C. Ratti and J. M. Stafford, arXiv:1902.06723 [hep-ph]



- Lattice QCD EoS has been extended to non-zero net baryon, strangeness, and electric charges and implemented in the hydrodynamic framework

QCD Equation of State at finite densities

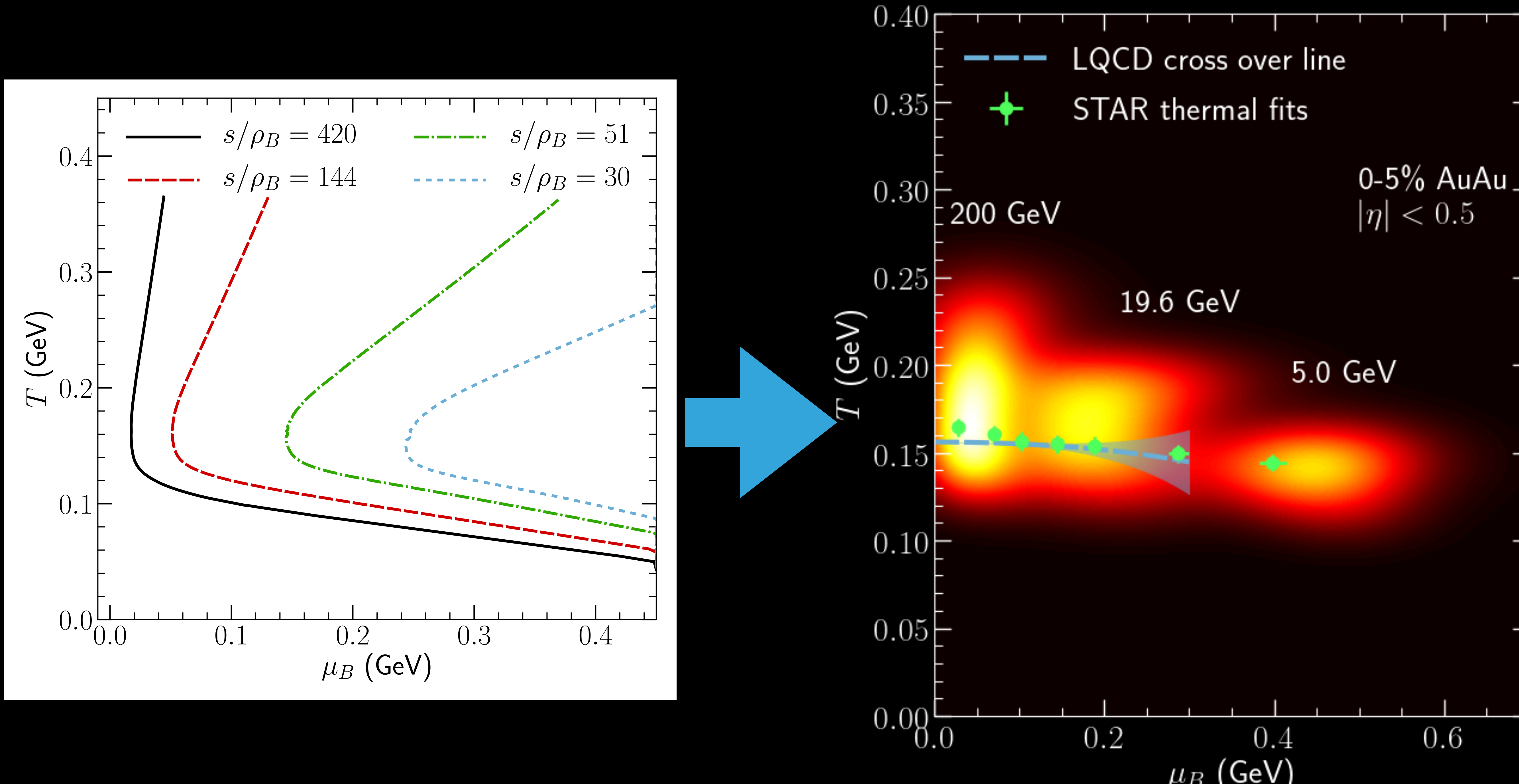
A. Monnai, B. Schenke and C. Shen, arXiv:1902.05095 [nucl-th]



- Strangeness neutrality yields the fireball trajectory significantly

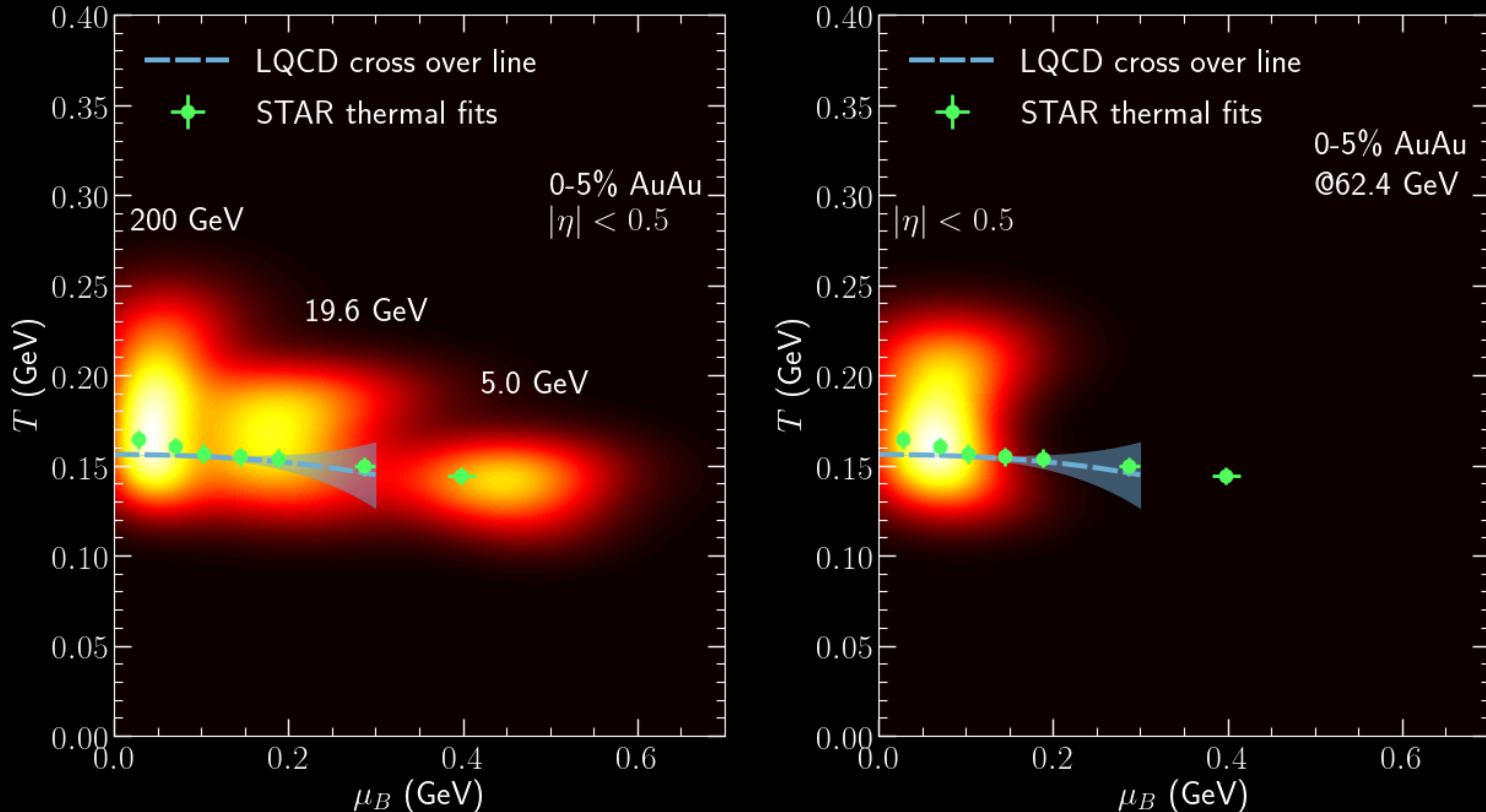
Poster: Travis Dore

Sailing in the QCD phase diagram



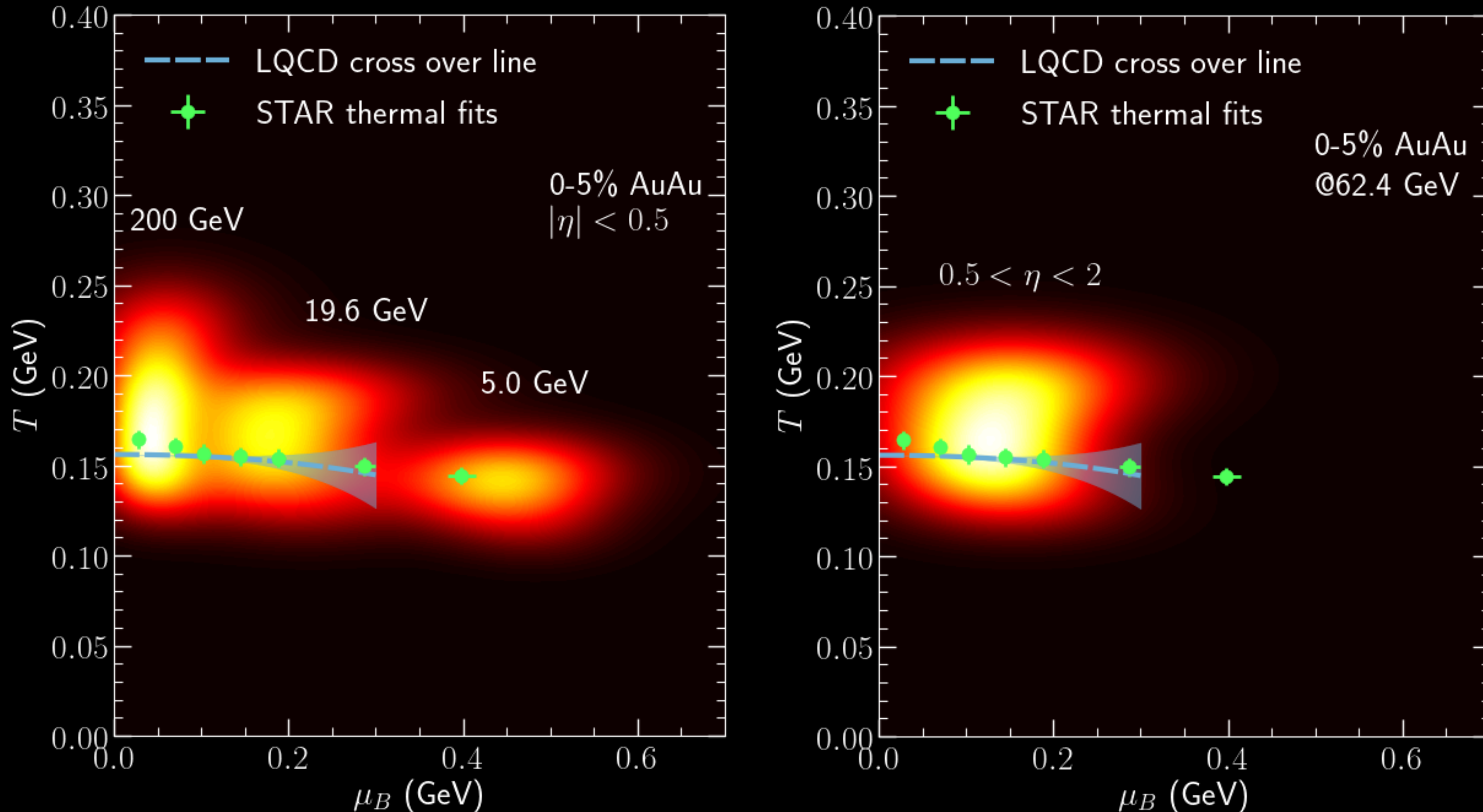
- The fireball trajectory and how fast it flows in the phase diagram are **indispensable** information for the search of the critical point

Sailing in the QCD phase diagram



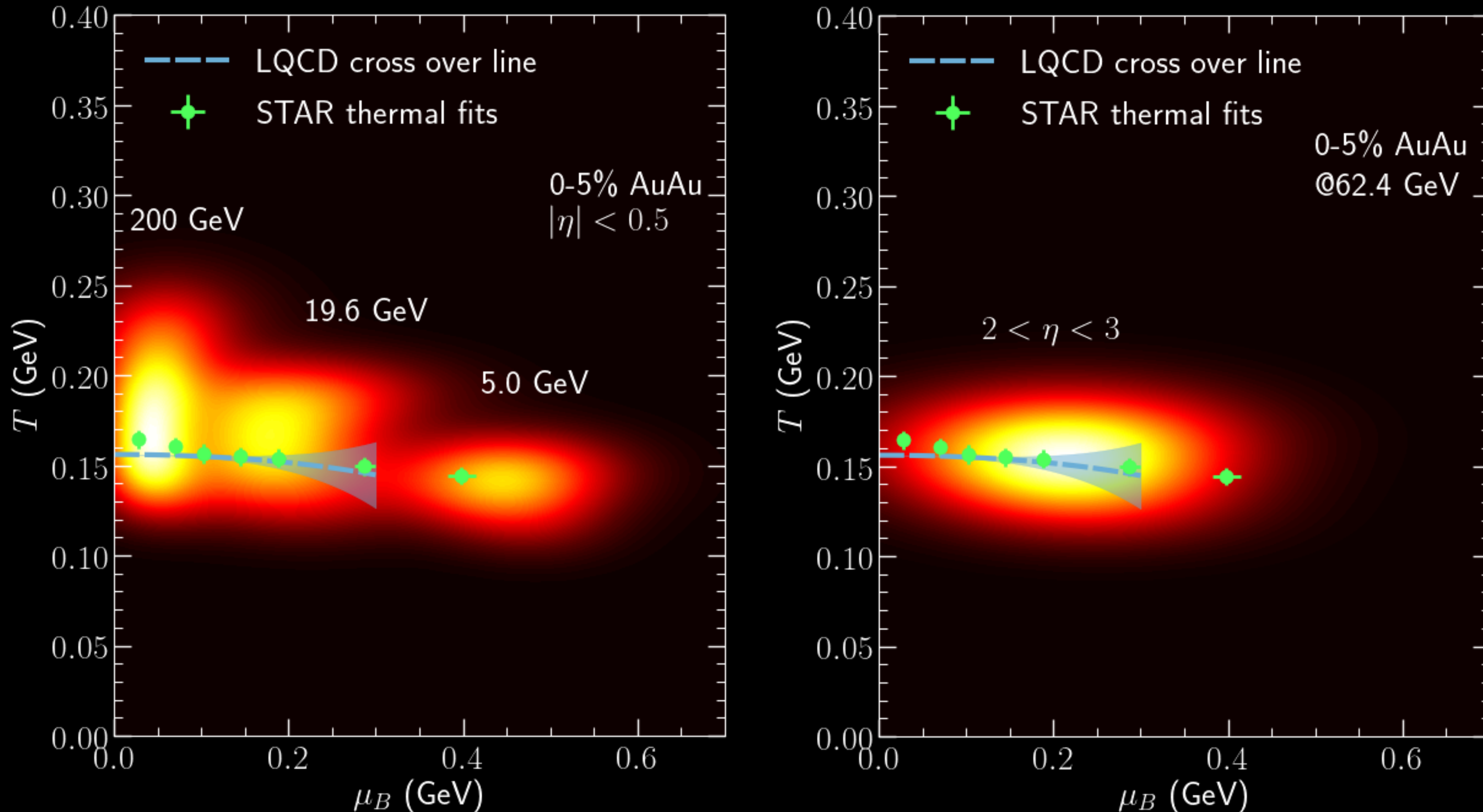
- Rapidity scan can be a second handle to explore QCD phase diagram

Sailing in the QCD phase diagram



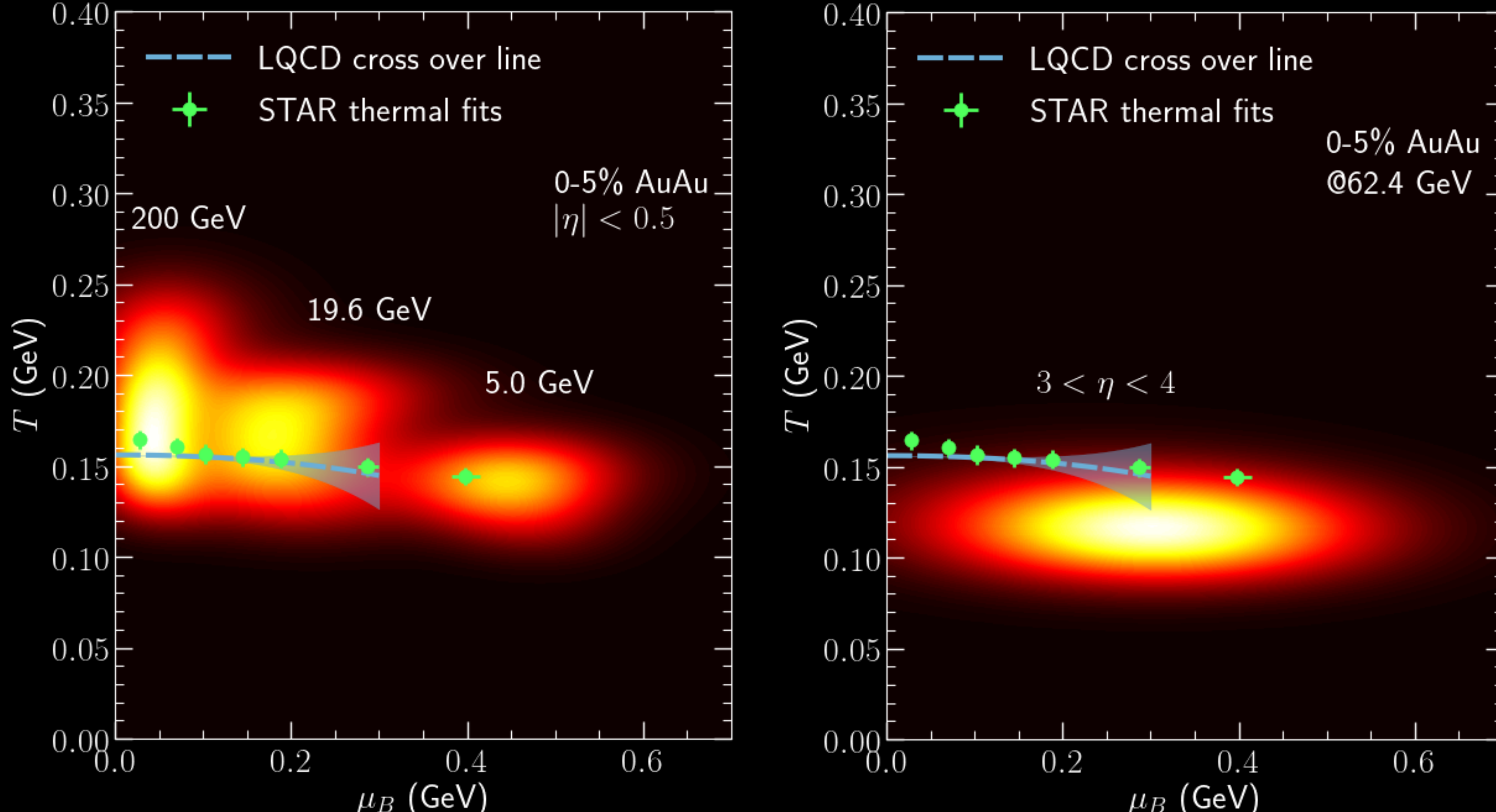
- Rapidity scan can be a second handle to explore QCD phase diagram

Sailing in the QCD phase diagram



- Rapidity scan can be a second handle to explore QCD phase diagram

Sailing in the QCD phase diagram



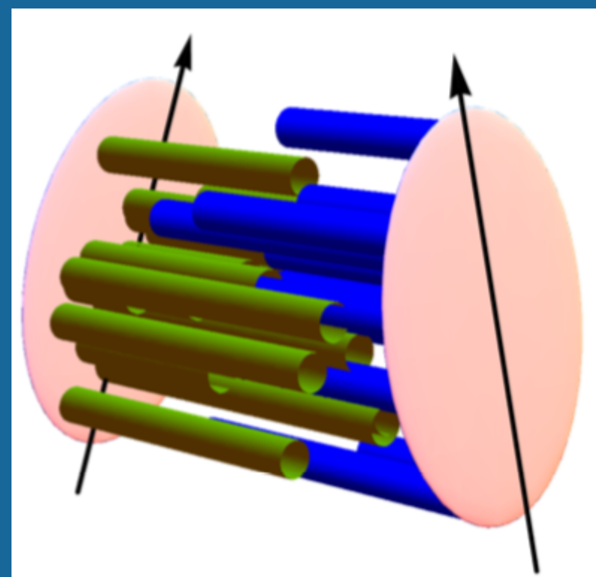
- Rapidity scan can be a second handle to explore QCD phase diagram

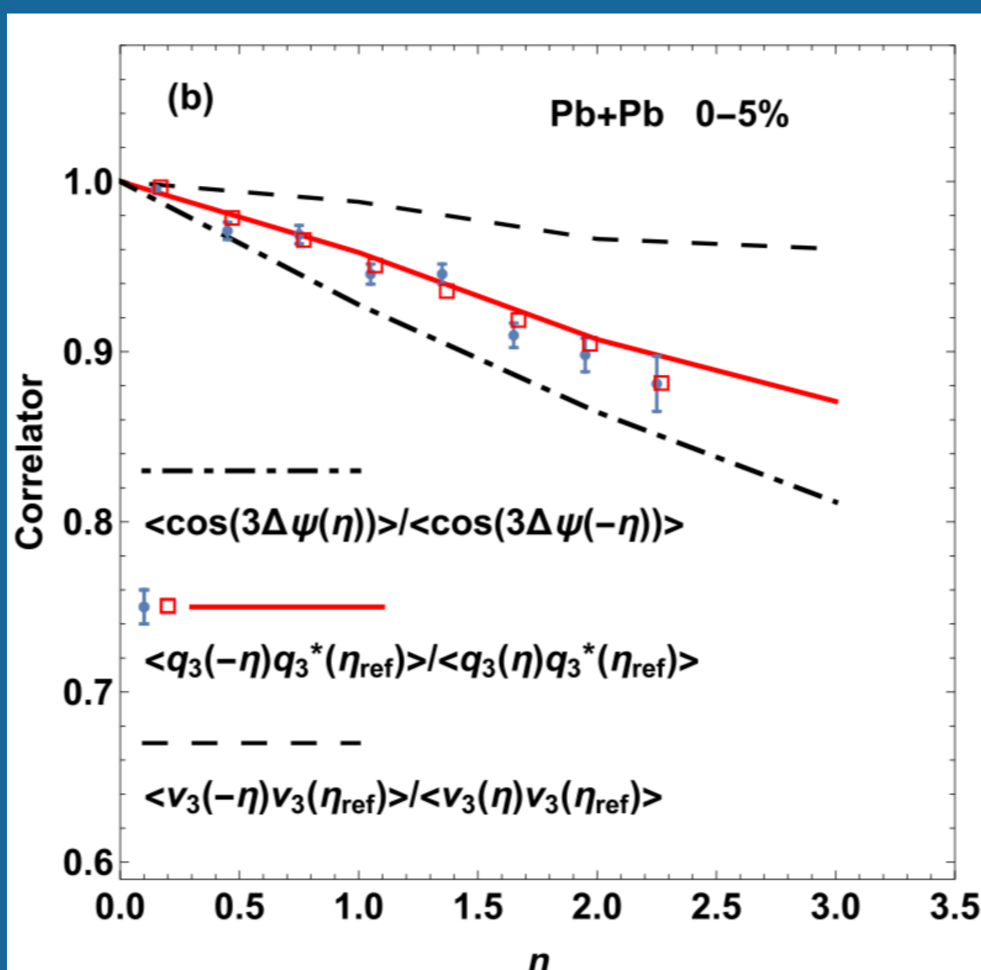
Longitudinal fluctuations

P. BOZEK TUESDAY 17:20

G. QIN TUESDAY 18:00

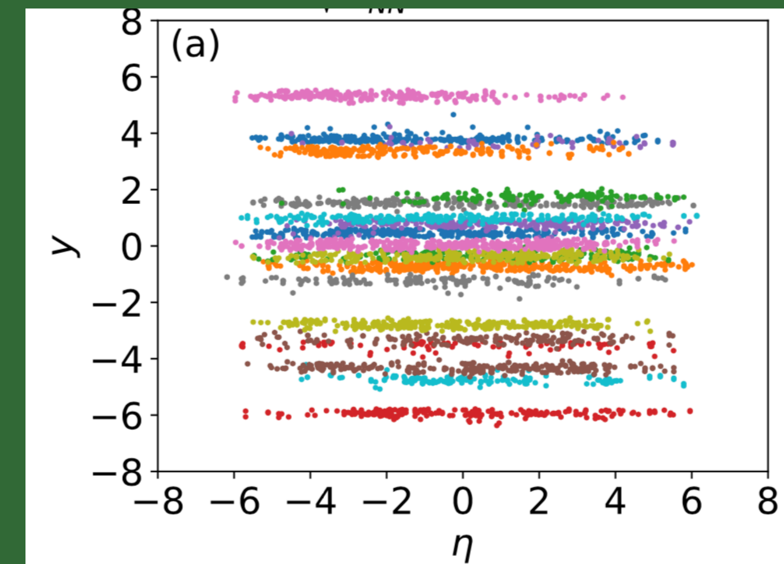
MCGlauber
Torque + eccentricity magnitude fluctuations

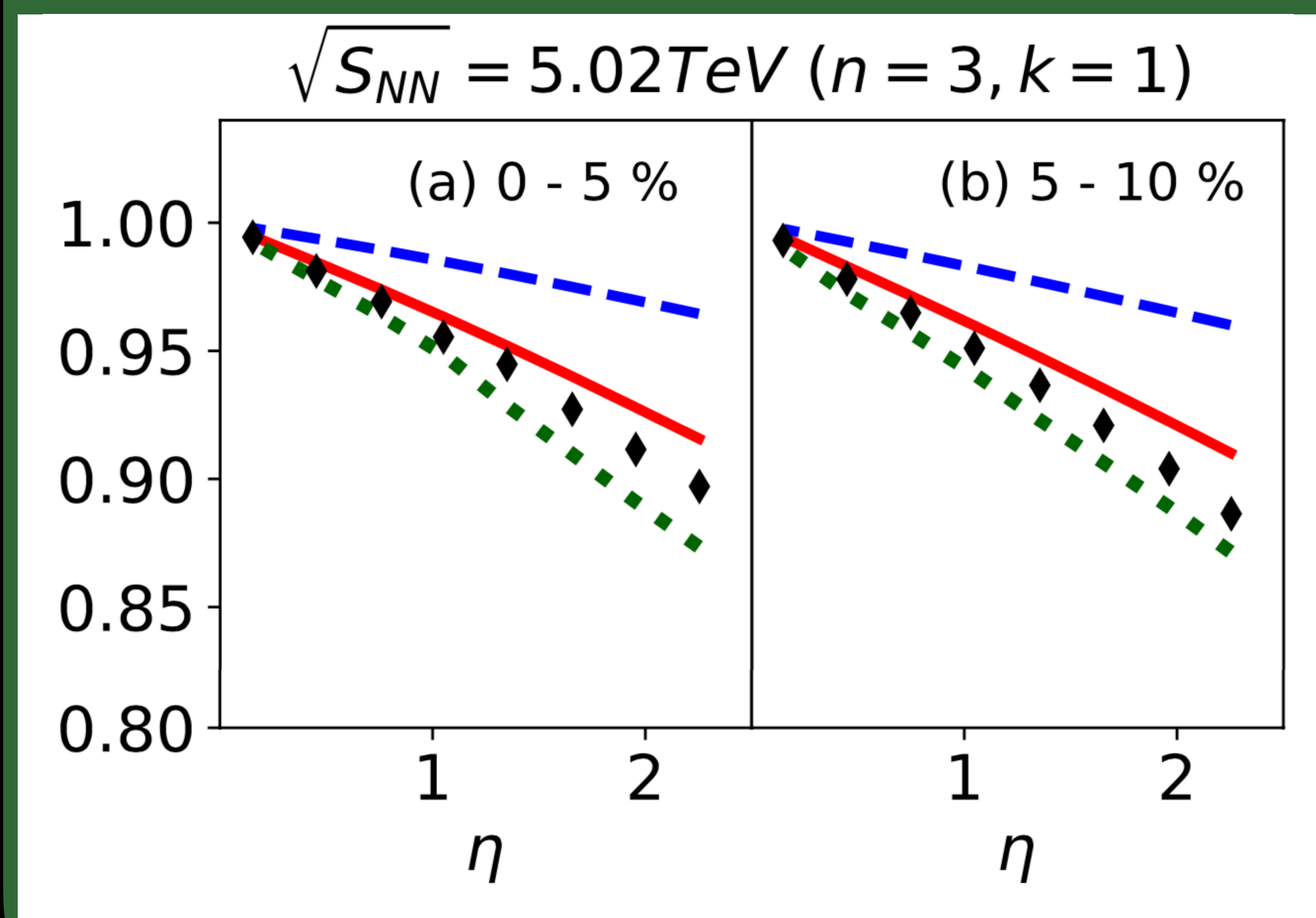




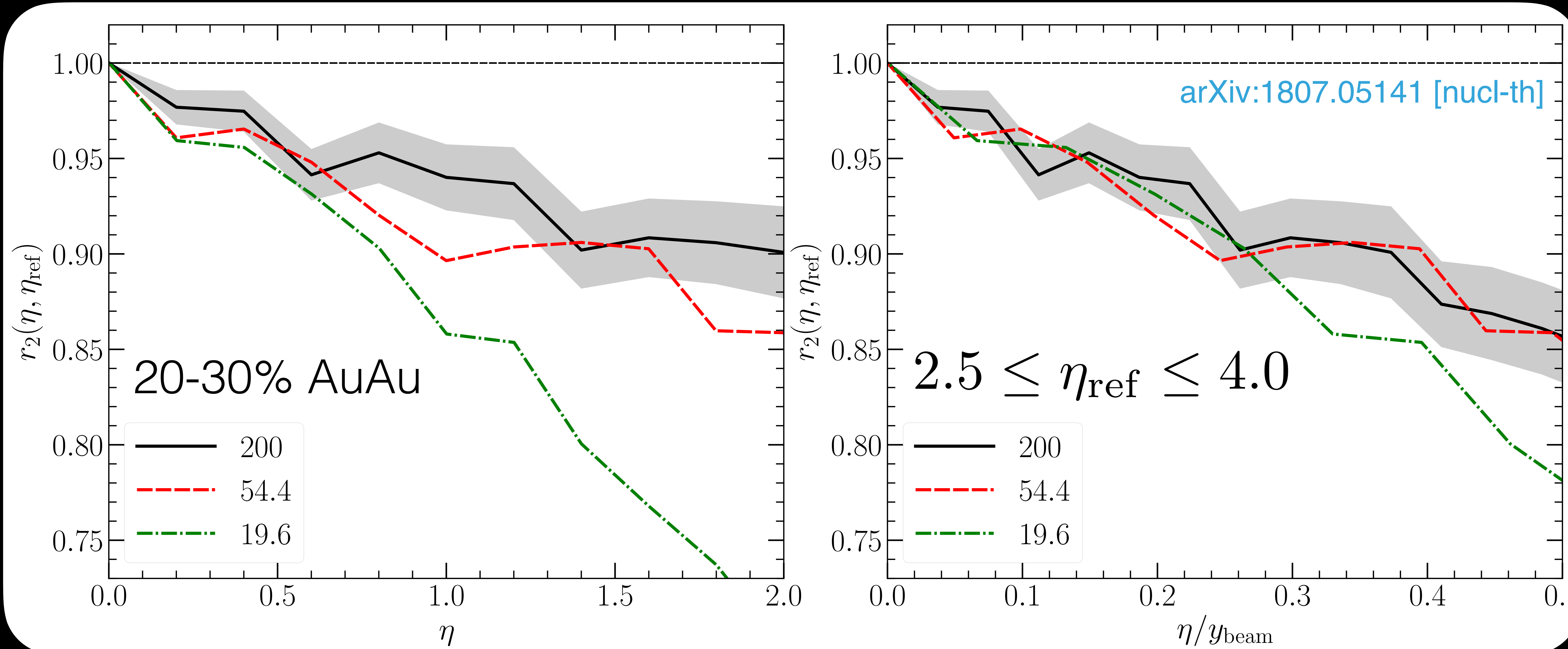
AMPT

Fluctuations from string breaking





Longitudinal fluctuations



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

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

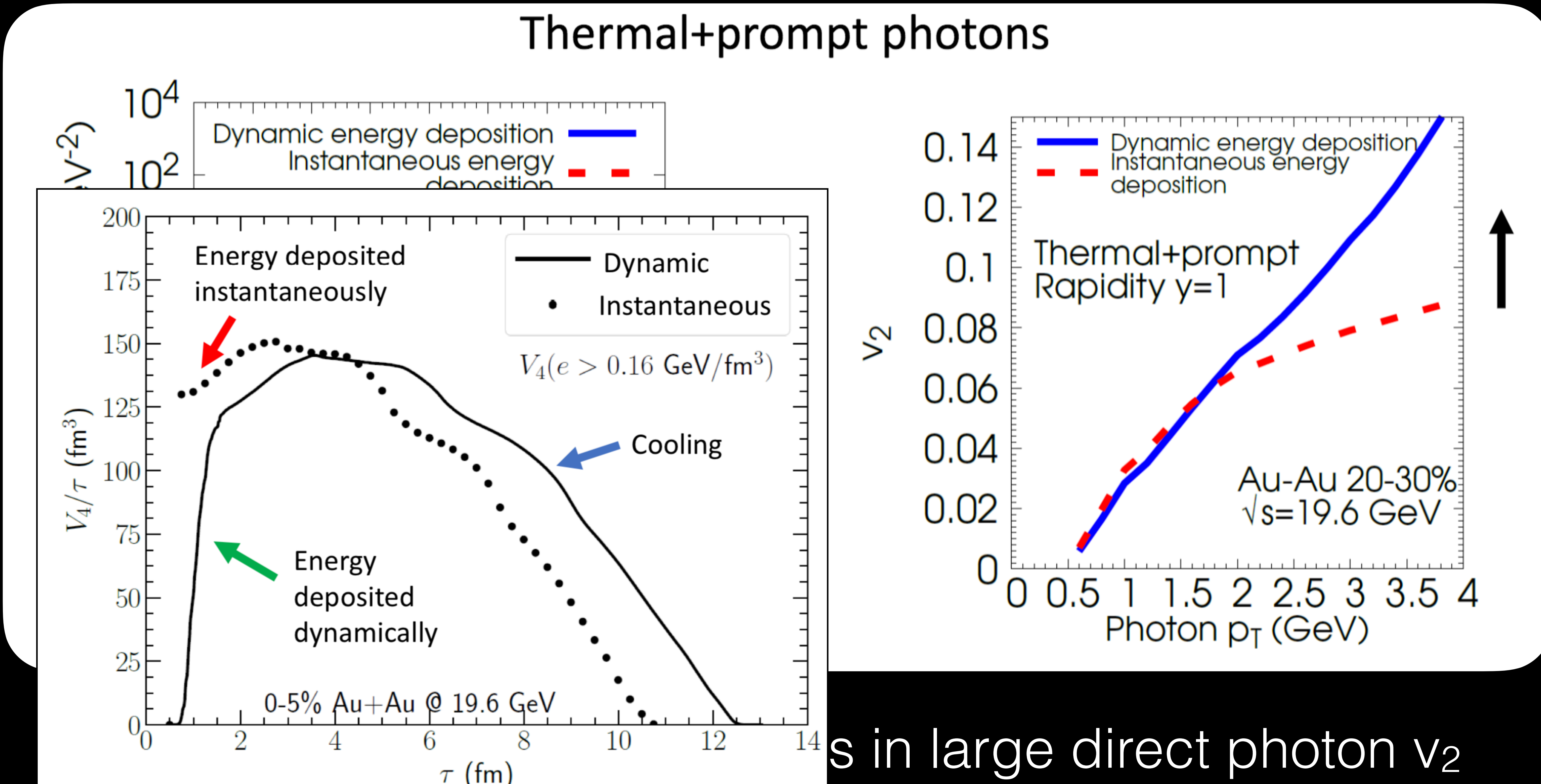
Summary and Outlook

- The hybrid framework of dynamical initialization for heavy-ion collisions at the RHIC BES energies enables
  - Elucidating the initial baryon stopping, hydrodynamic baryon diffusion, and hadronic baryon transport
  - Quantitative characterization of Quark-Gluon Plasma transport properties at finite baryon density via Bayesian analysis
- Realistic mapping of heavy-ion collisions to the QCD phase diagram for the search of critical behaviors at RHIC BES
- Longitudinal decorrelation measurements at different collision energies set strong constrains on longitudinal fluctuations in heavy-ion collisions


BACKUP

Dynamical initialization effect on EM probes

C. Gale, S. Jeon, S. McDonald, J.F. Paquet and C. Shen, arXiv:1807.09326 [nucl-th]

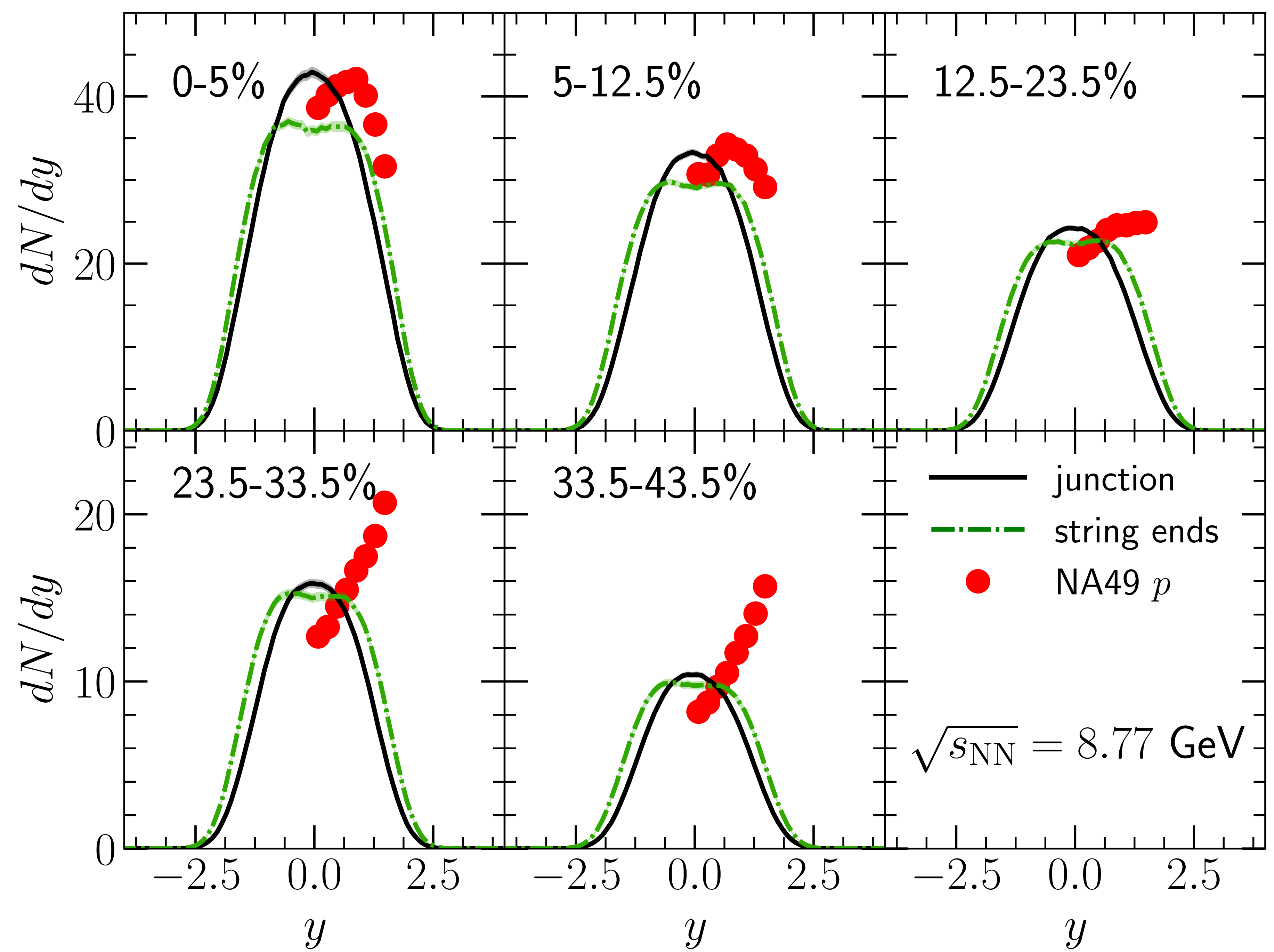


s in large direct photon v_2 at high p_T

A large sensitivity to the early time dynamics

Towards "one fluid" to rule BES

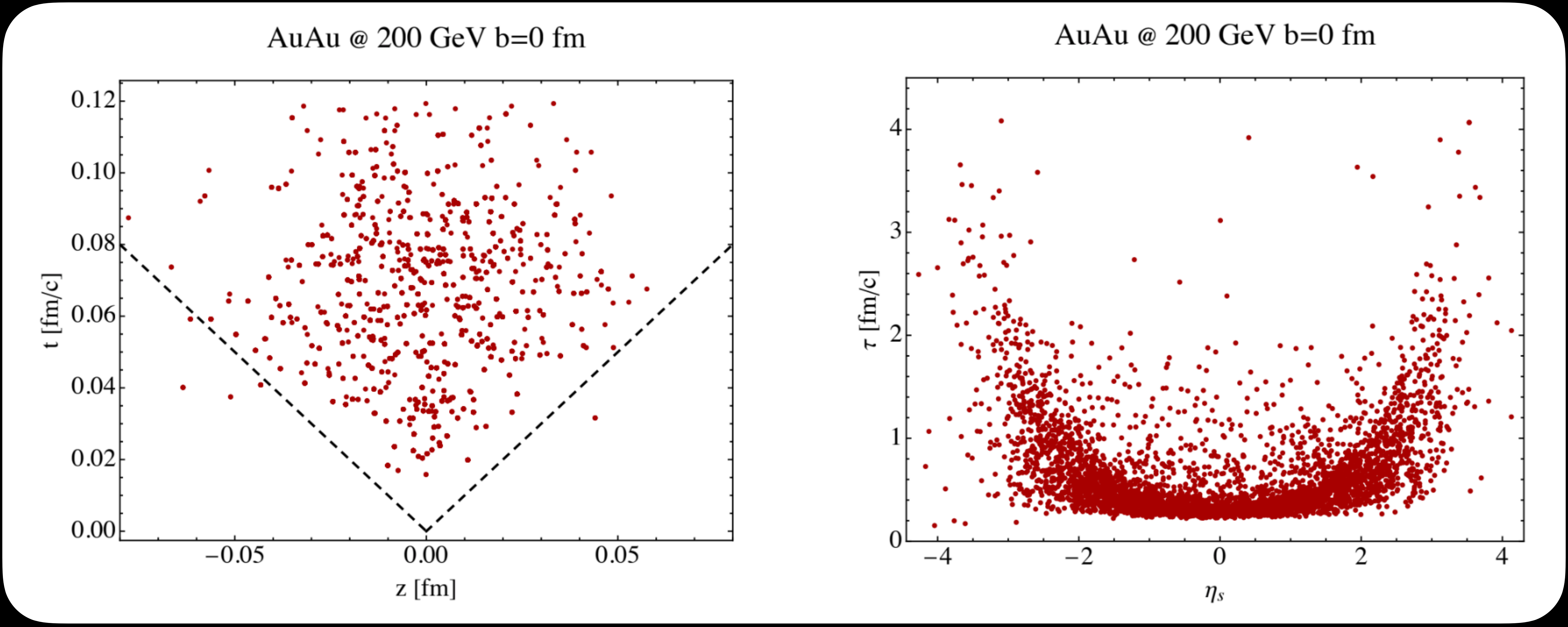
B. Schenke and C. Shen, in preparation



- Centrality dependence of proton distribution need further study

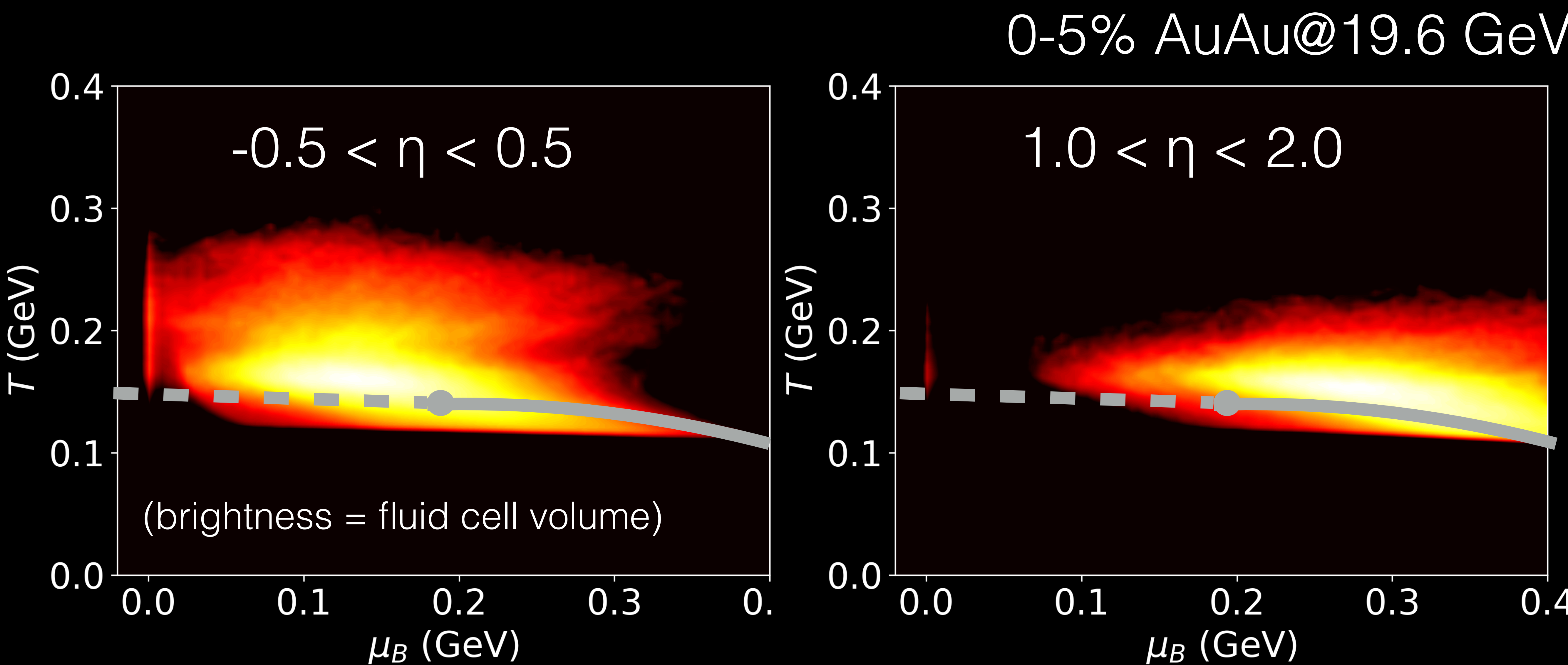
Dynamical initialization based on UrQMD

L. Du, U. Heinz and G. Vujanovic, Nucl. Phys. A982 (2019) 407-410



- A similar space-time distribution for the energy-momentum sources
- Contains additional fluctuations from string fragmentation

Sailing in the phase diagram



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

J. Brewer, S. Mukherjee, K. Rajagopal, Y. Yin, arXiv:1804.10215

Dissipative hydrodynamics

Energy momentum tensor

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

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

Conserved currents

$$J^\mu = nu^\mu + q^\mu$$

Equations of motion

$$\partial_\mu T^{\mu\nu} = 0 \quad \partial_\mu J^\mu = 0 \quad + \quad P(e, n)$$

Dissipative quantities are evolved with 2nd order Israel-Stewart type of equations

At Navier-Stokes limit,

$$\pi^{\mu\nu} \sim 2\eta\nabla^{\langle\mu}u^{\nu\rangle} \quad \Pi \sim -\zeta\partial_\mu u^\mu \quad q^\mu \sim \kappa\nabla^\mu\frac{\mu}{T}$$

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

Hydrodynamics

Energy momentum tensor

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

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

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

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:

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

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

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

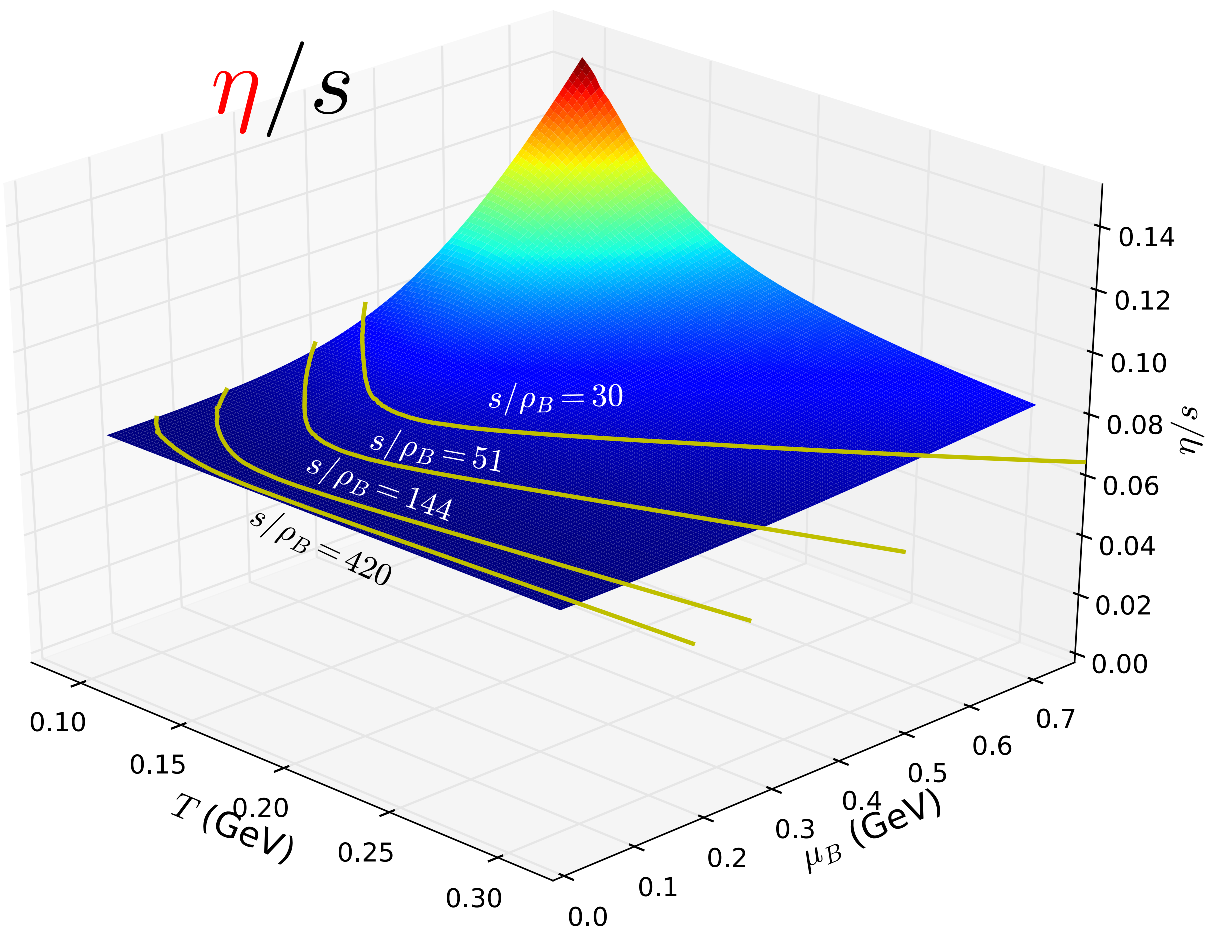
Transport coefficients

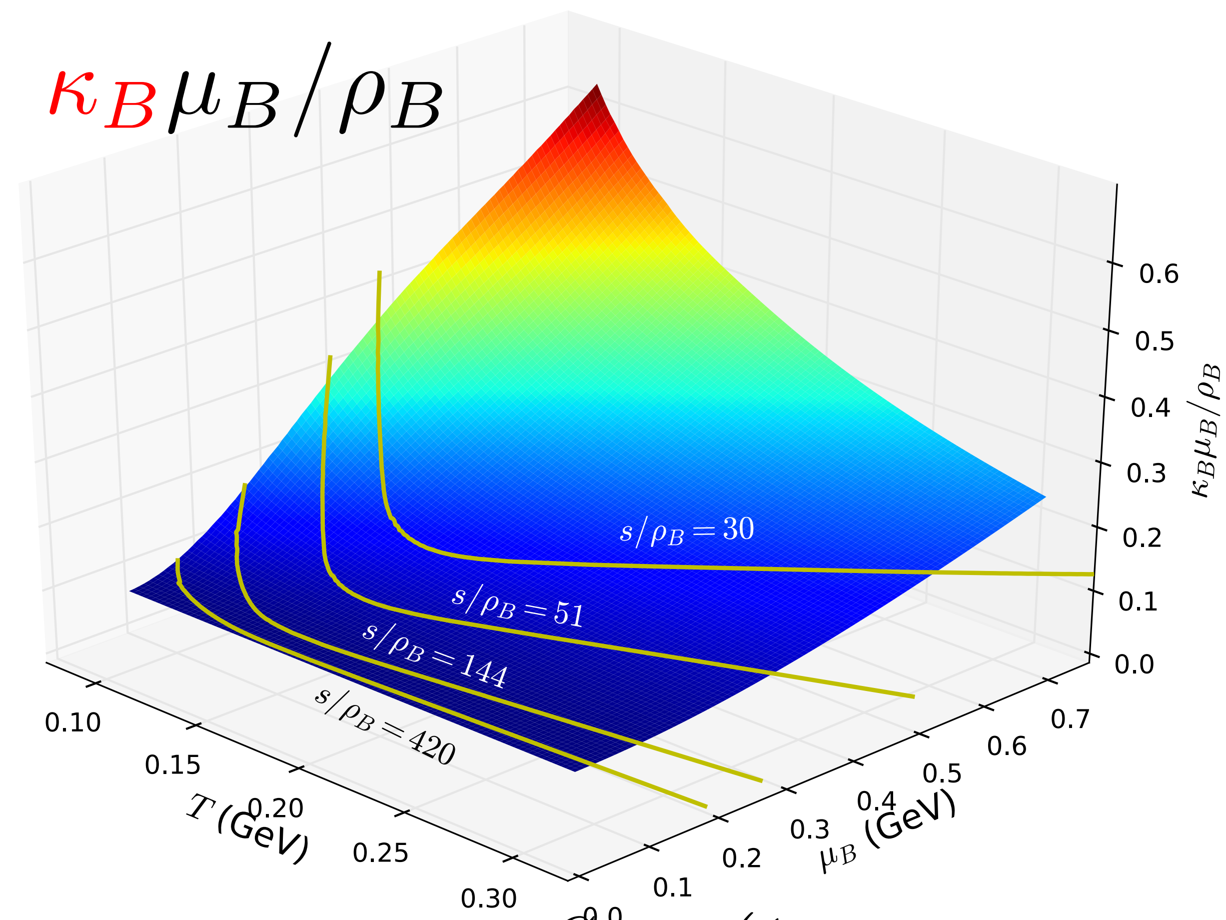
Dissipative part: (relaxation time approximation)

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

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

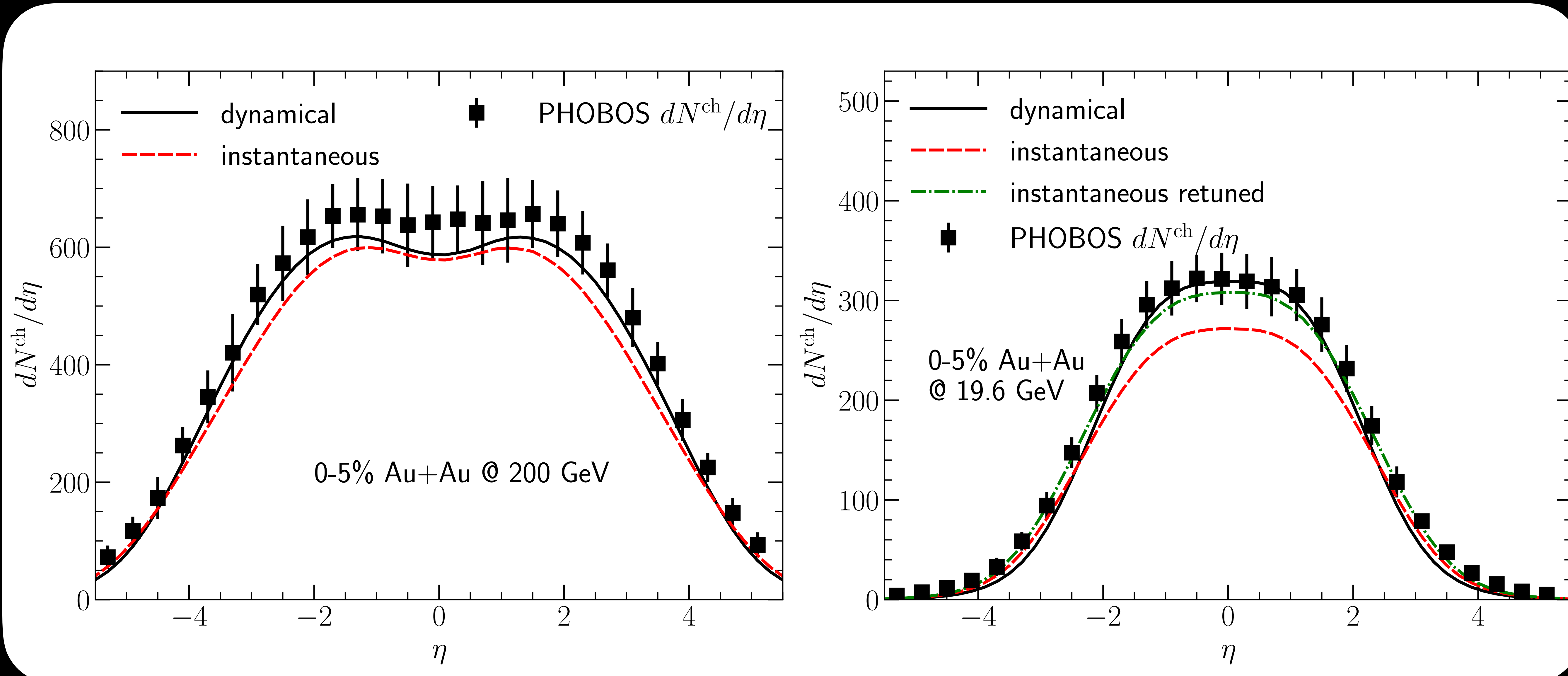
With non-zero μ, we choose $\tau_\pi = \tau_q = \frac{0.4}{T}$ $\quad \frac{\eta T}{e + \mathcal{P}} = 0.08$





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

Dynamical vs instantaneous initialization



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