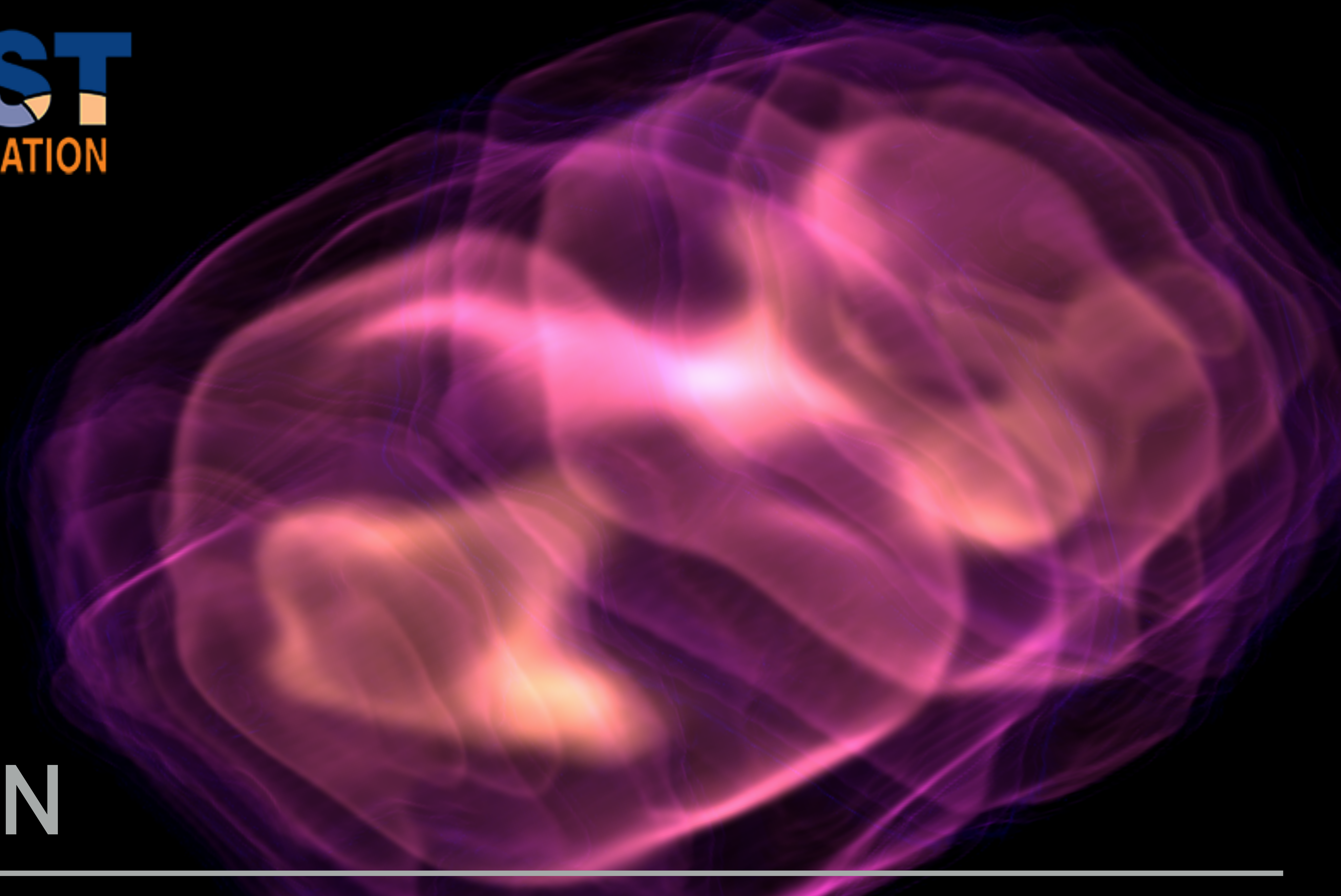


WAYNE STATE

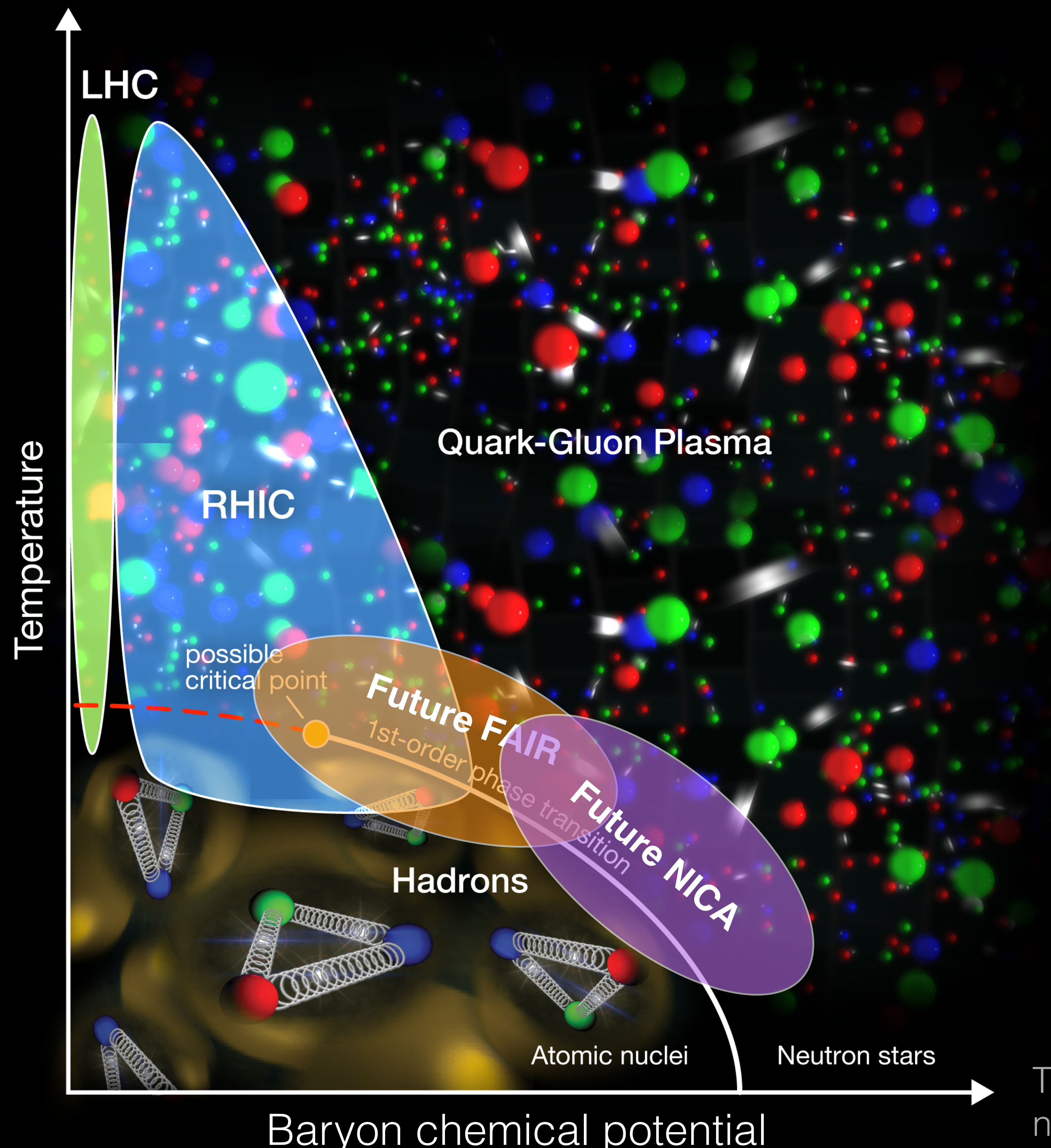
BEST COLLABORATION

CHUN SHEN

PHOTONS FROM BARYON-RICH FLUID AT BEAM ENERGY SCAN ENERGIES

Nov. 29 2018, ECT* Trento Italy

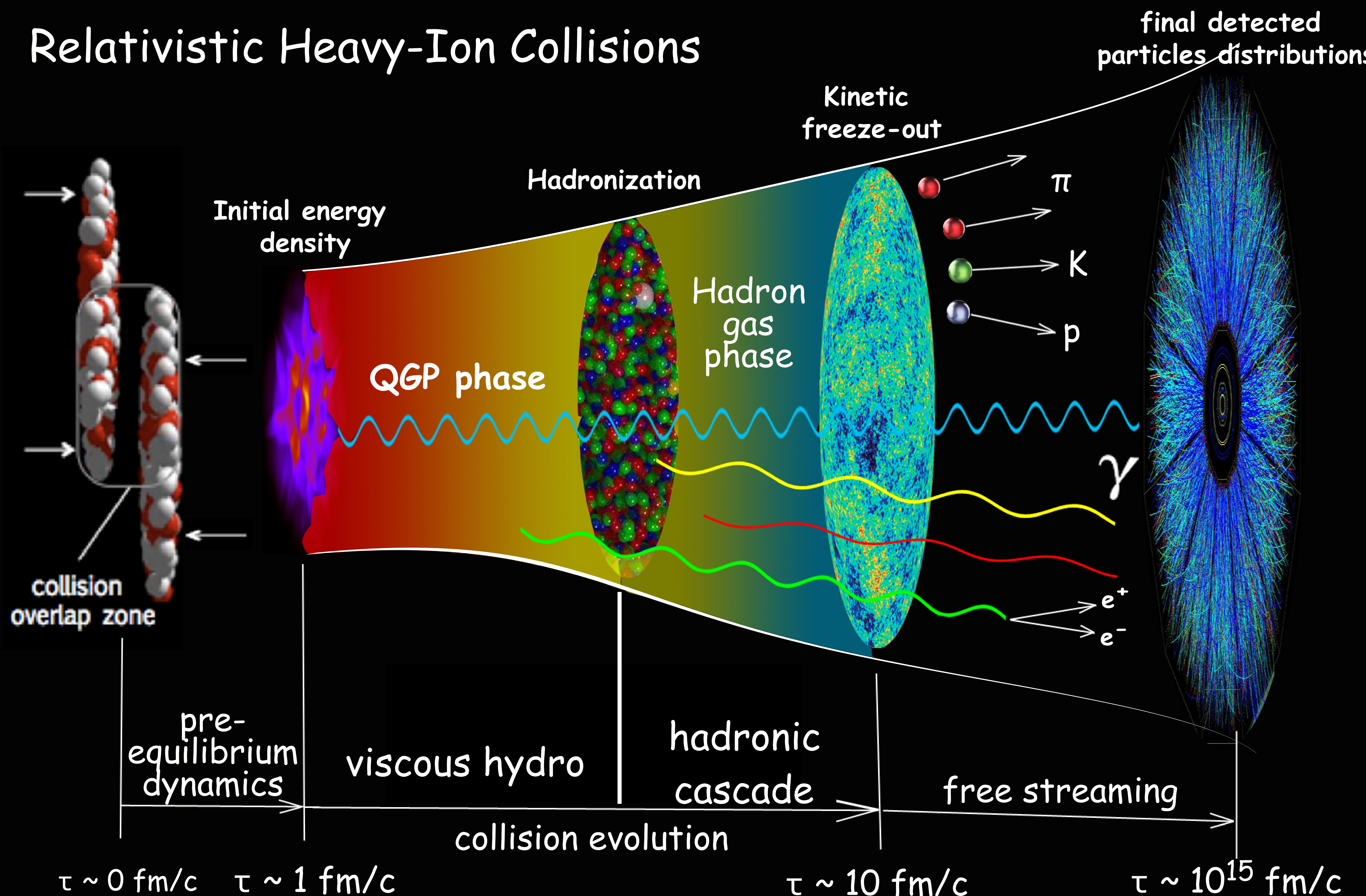
Phase diagram of hot nuclear matter



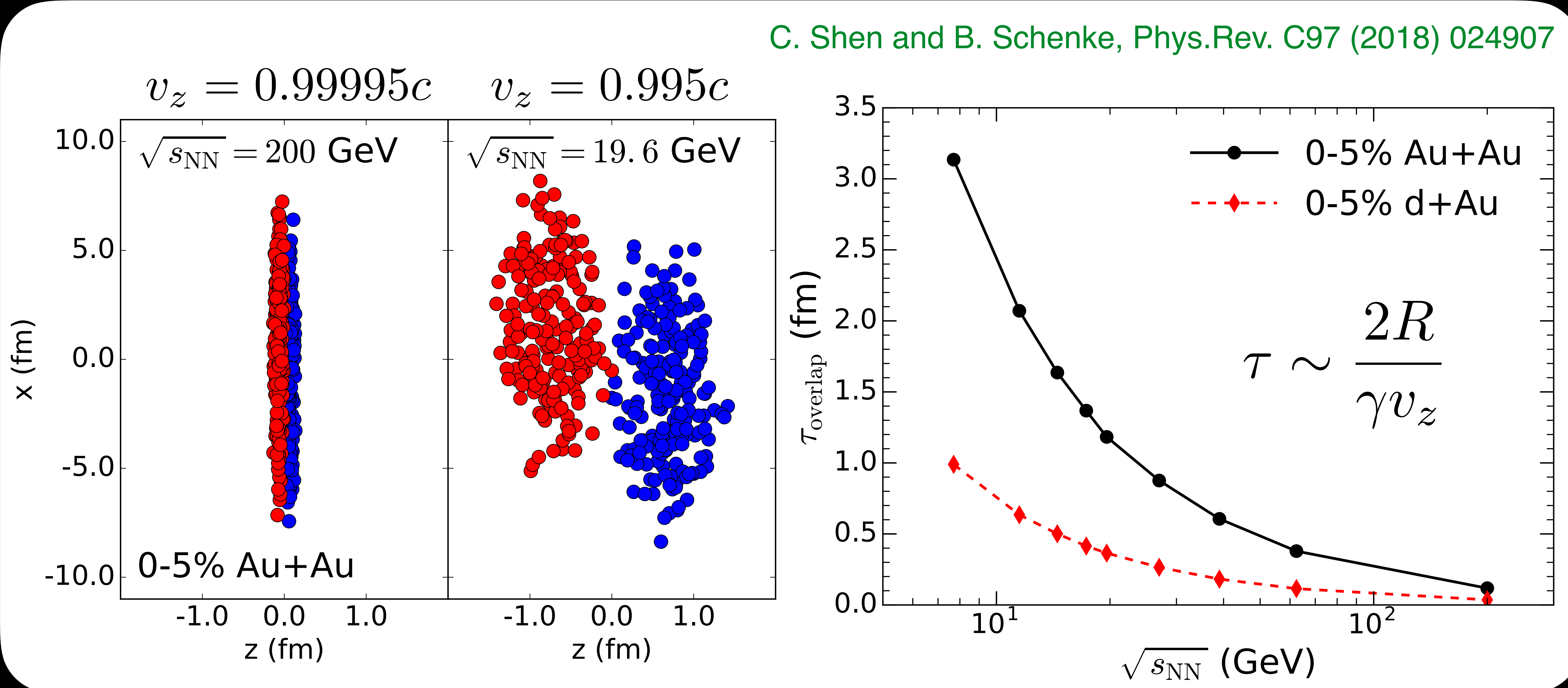
- What is the phase structure of nuclear matter
- What are the transport properties of the Quark-Gluon Plasma (QGP)
- Where is the critical point located

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

Relativistic Heavy-Ion Collisions



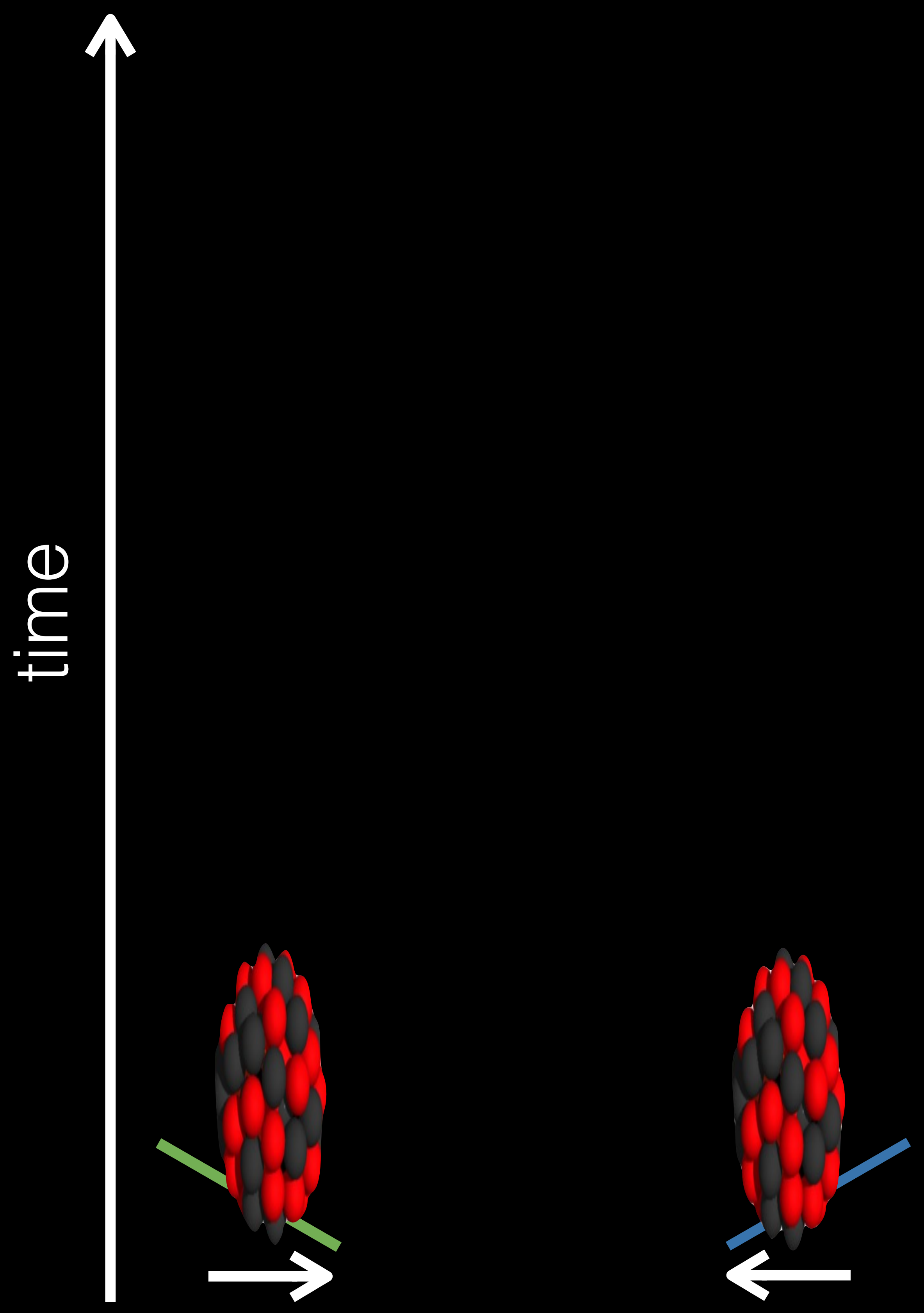
When to start hydrodynamics?



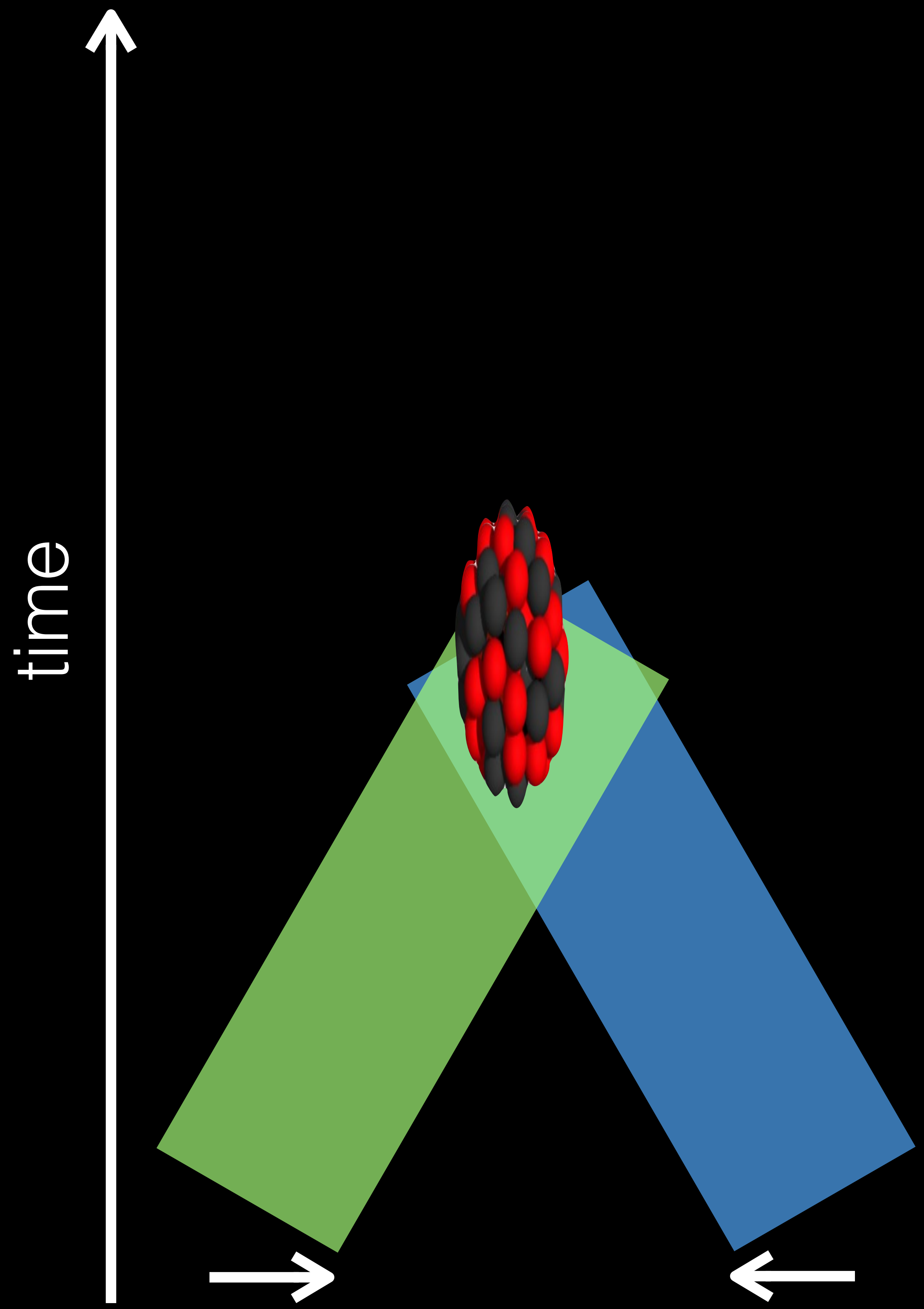
- Nuclei overlapping time is large at low collision energy
- Pre-equilibrium dynamics can play an important role

note: total evolution time ~ 10 fm

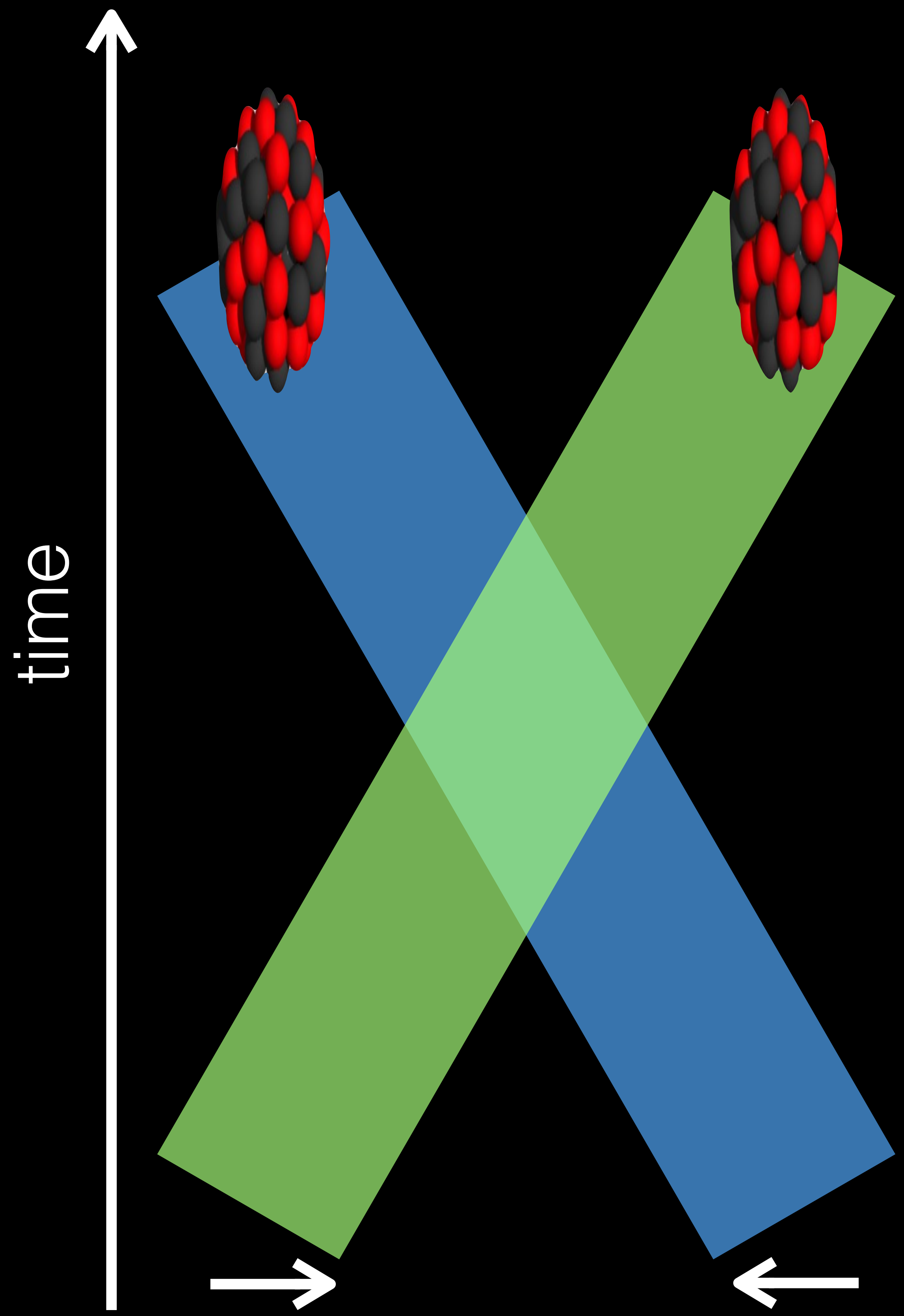
Model heavy-ion collisions in 3D



Model heavy-ion collisions in 3D

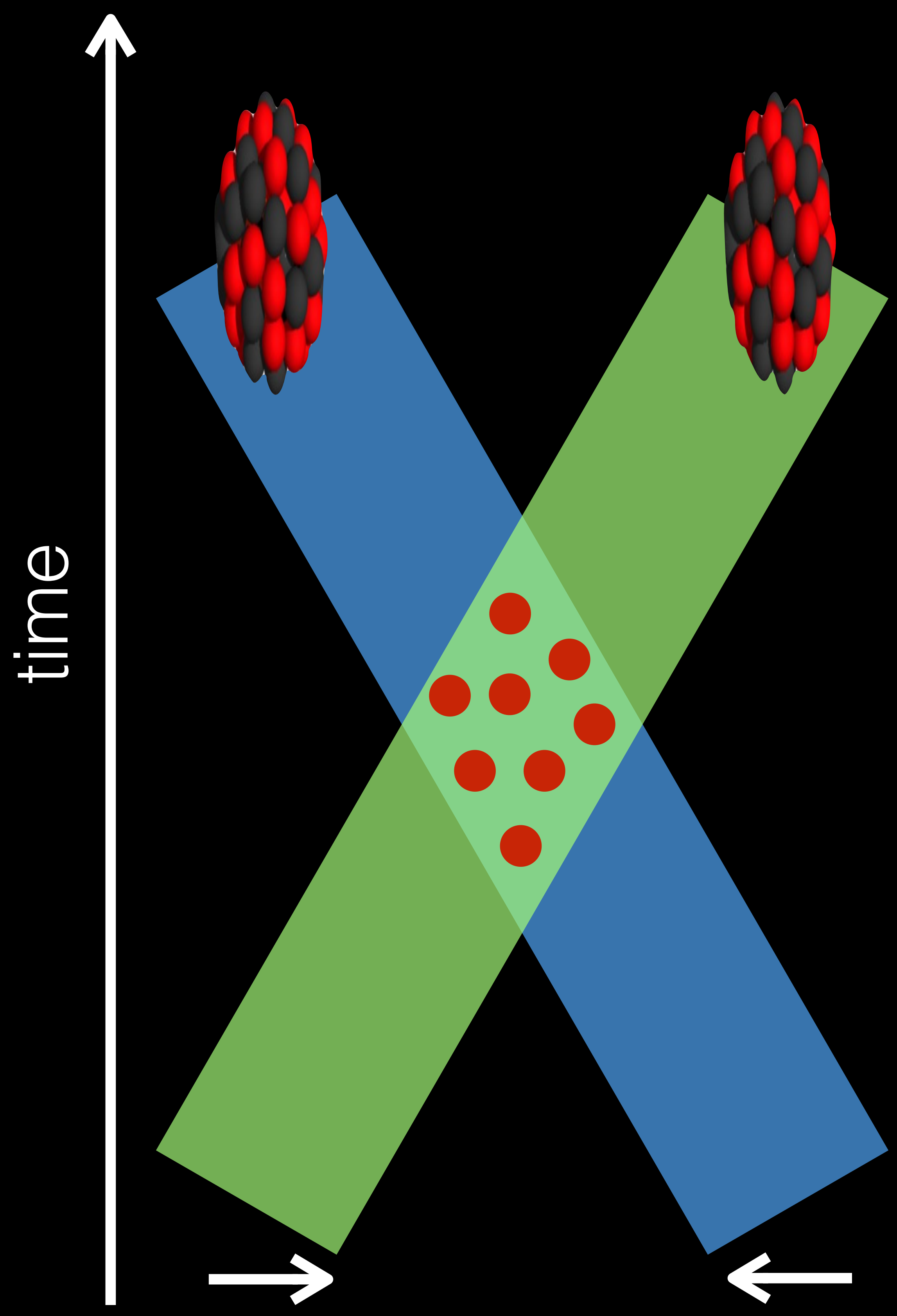


Model heavy-ion collisions in 3D



- The interaction zone is not point like

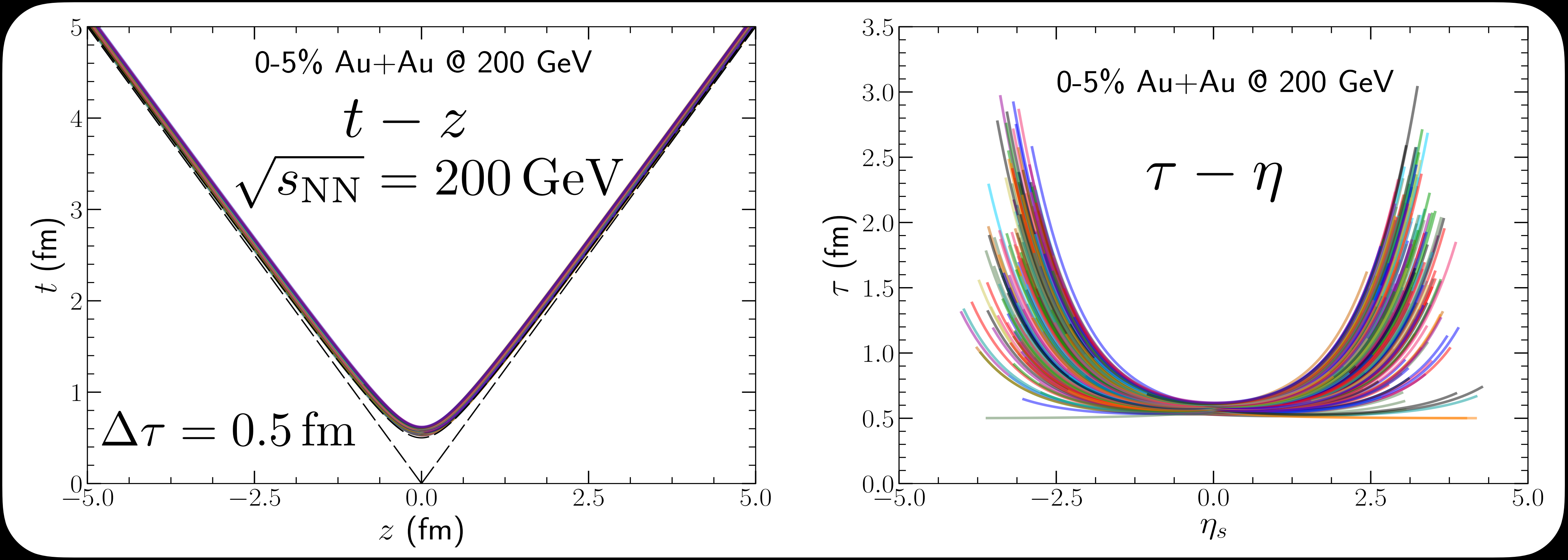
Model heavy-ion collisions in 3D



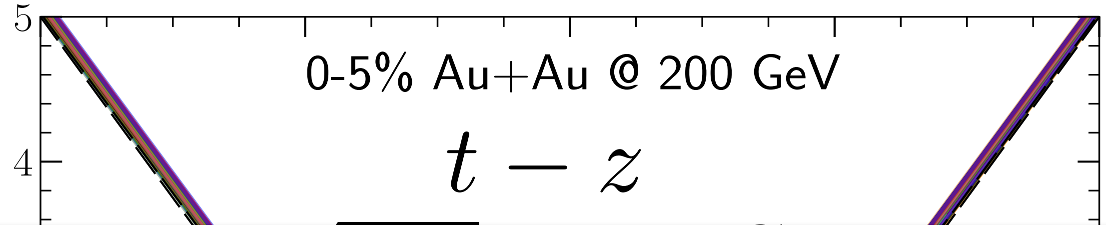
- The interaction zone is not point like
- The colliding nucleons are decelerated with a classical string model from binary collision points A. Bialas, A. Bzdak and V. Koch, arXiv:1608.07041 [hep-ph]
- The lost energy and momentum from the decelerated nucleons are fed into hydrodynamic fields as source terms

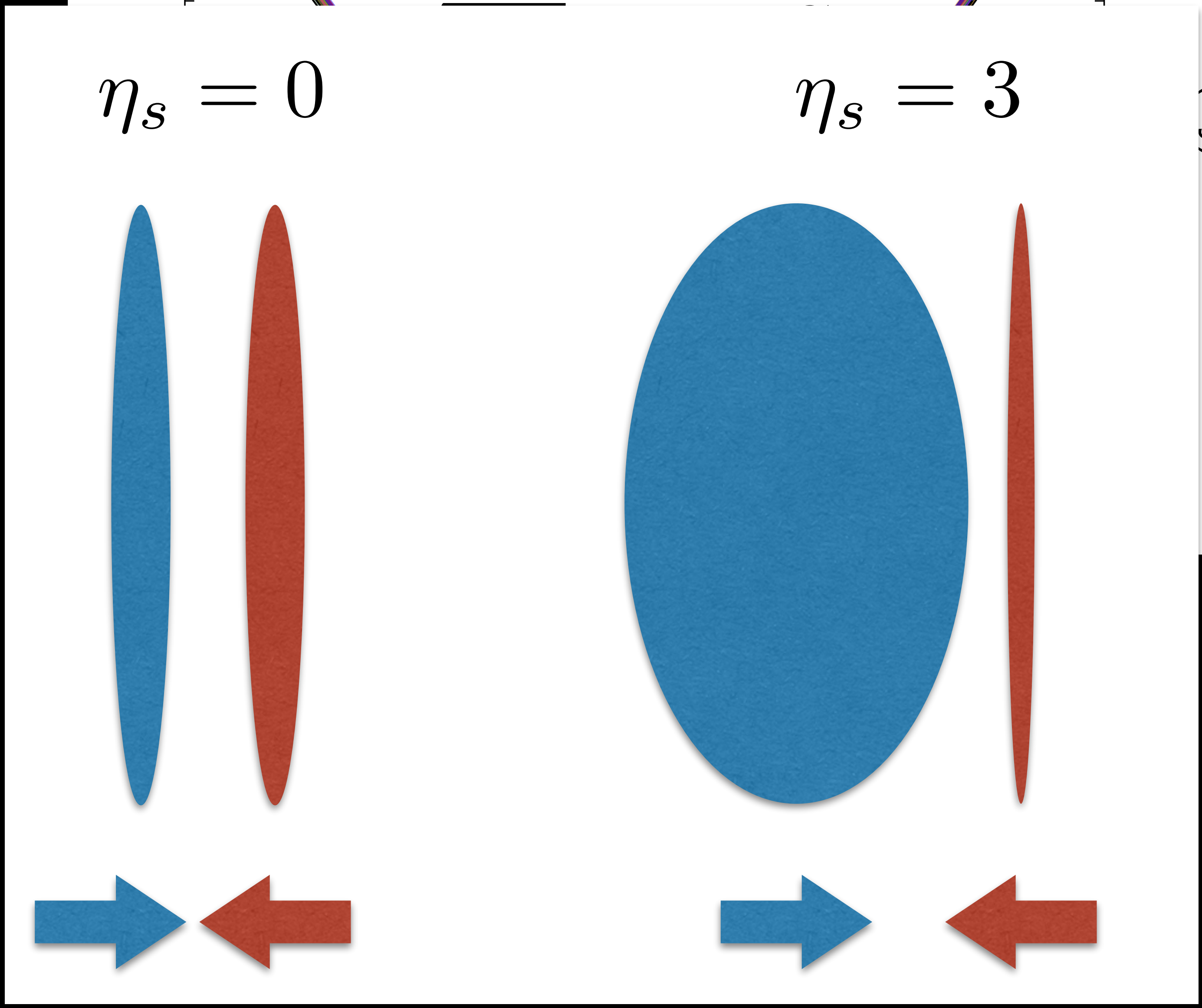
C. Shen and B. Schenke, Phys.Rev. C97 (2018) no.2, 024907

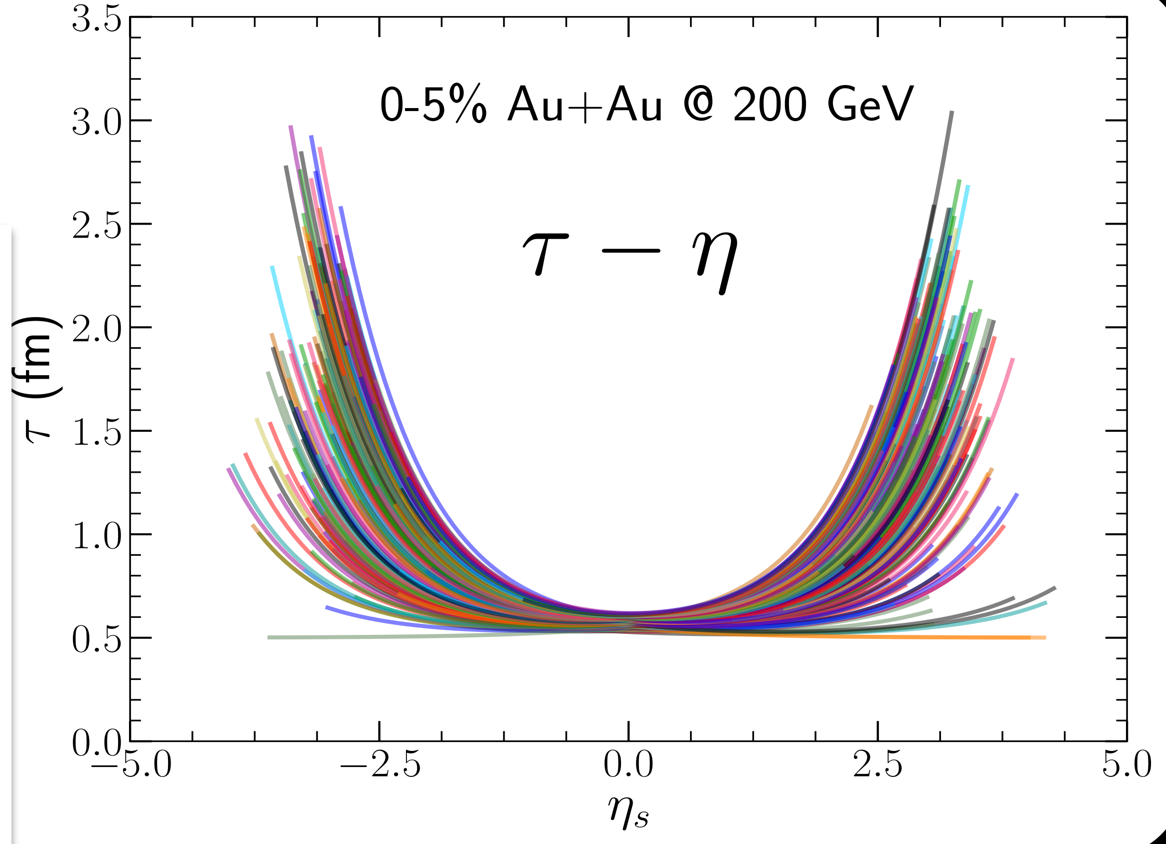
String space-time distribution



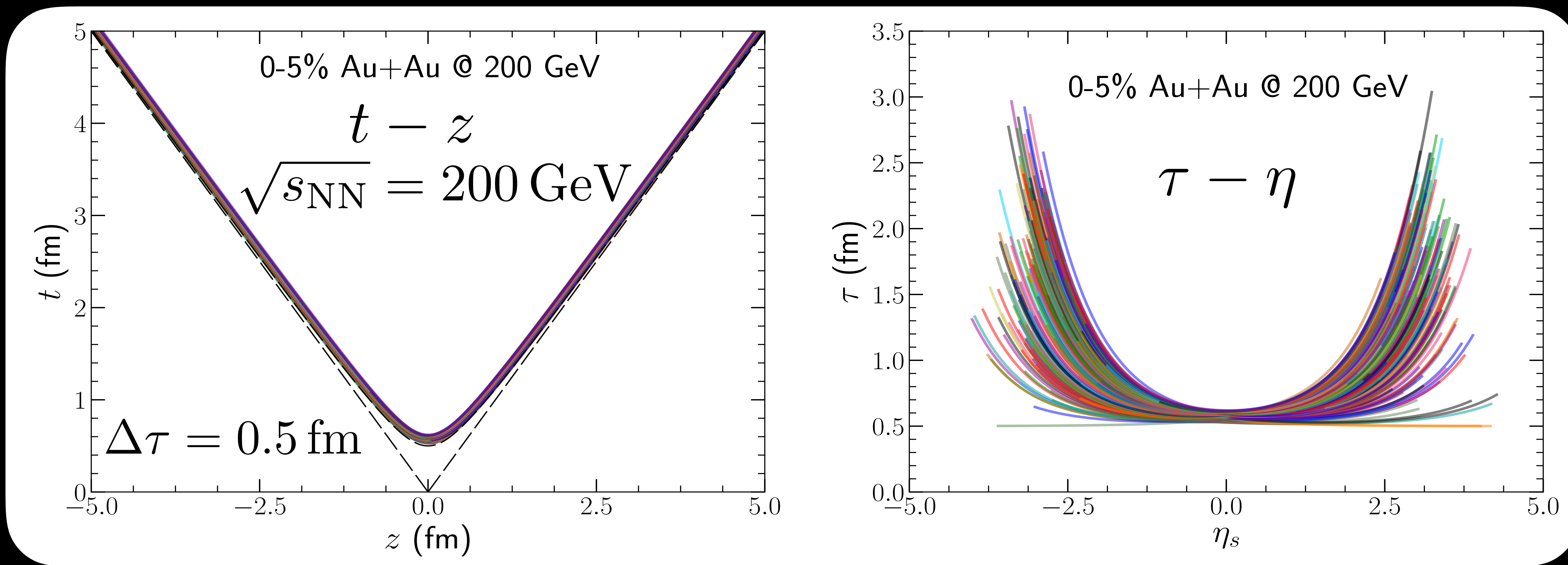
String space-time distribution

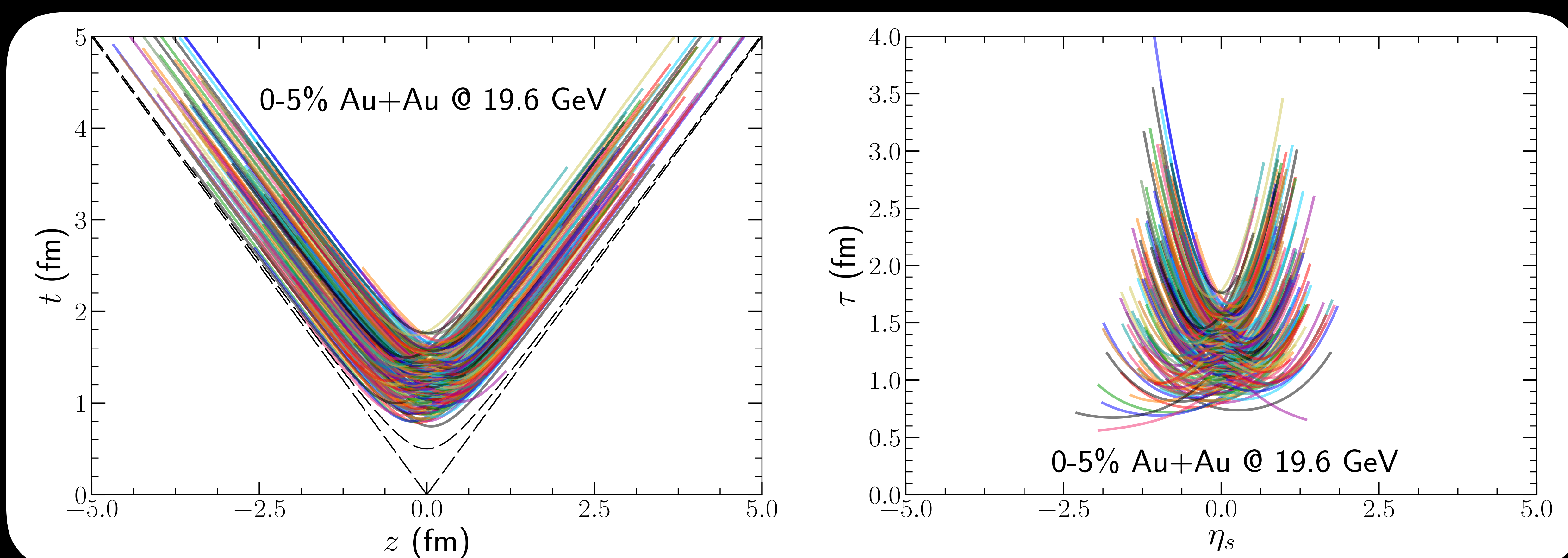






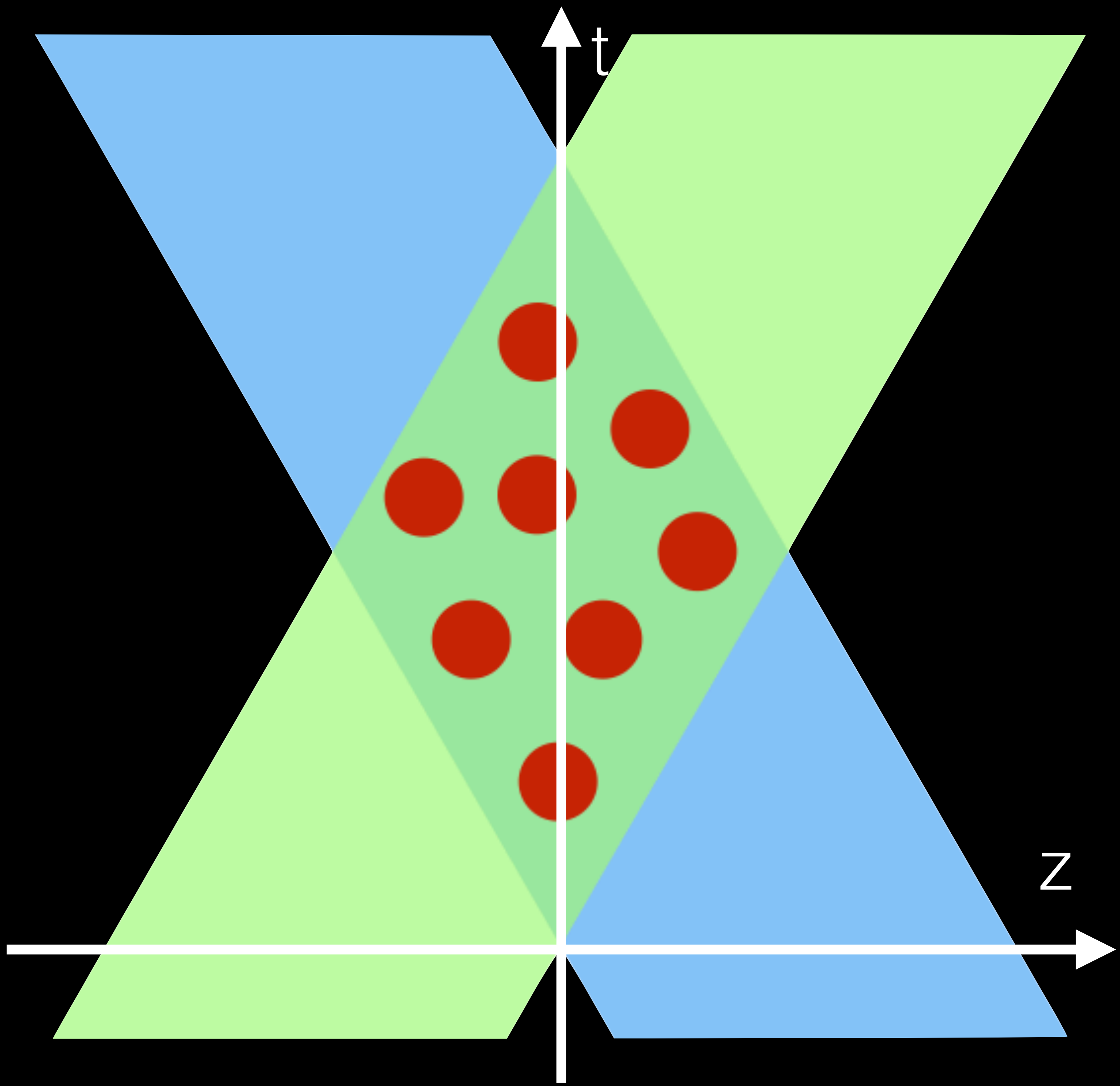
String space-time distribution





Hydrodynamics with sources

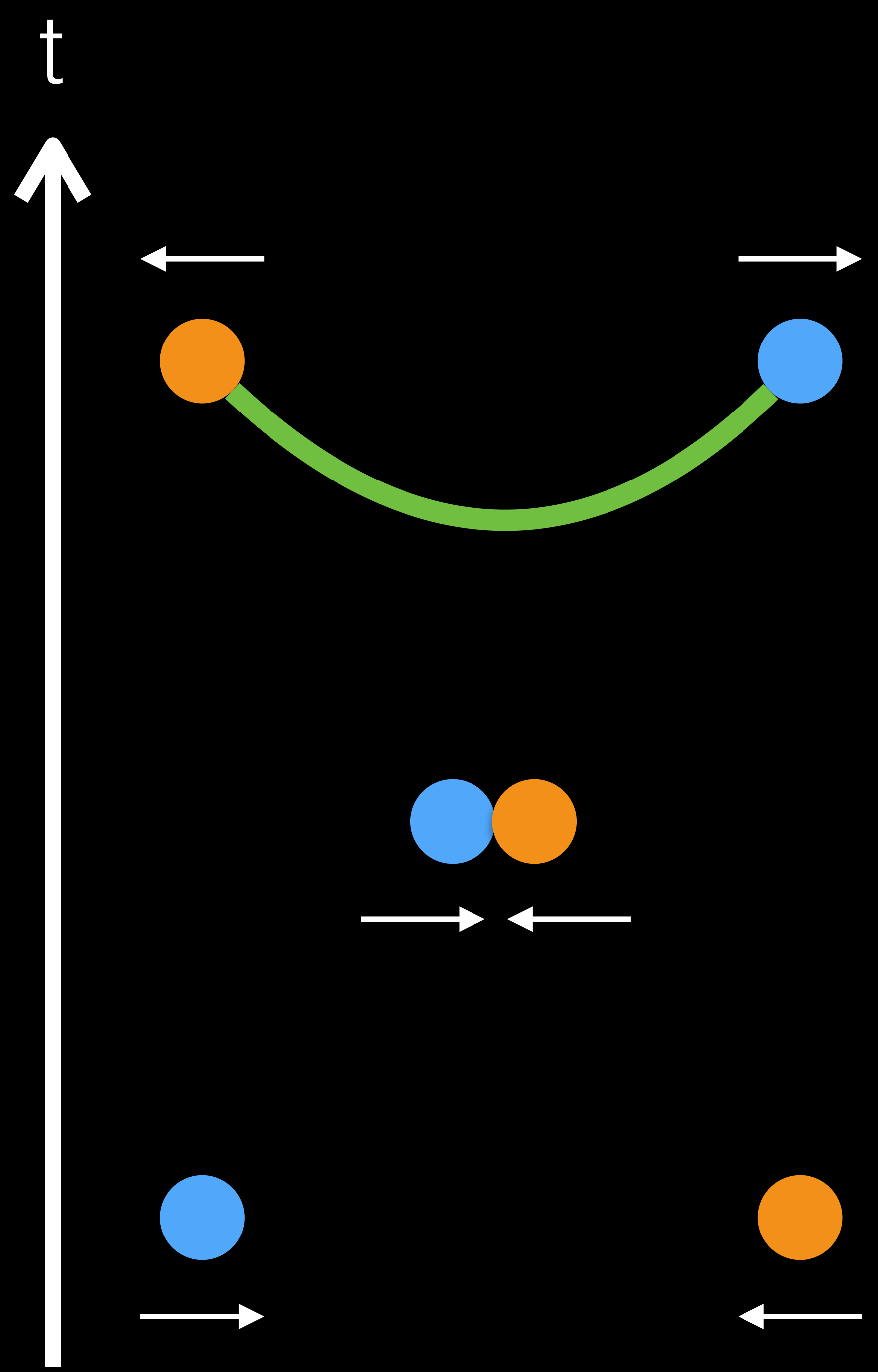
Energy-momentum current and net baryon density are fed into hydrodynamic simulation as source terms



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

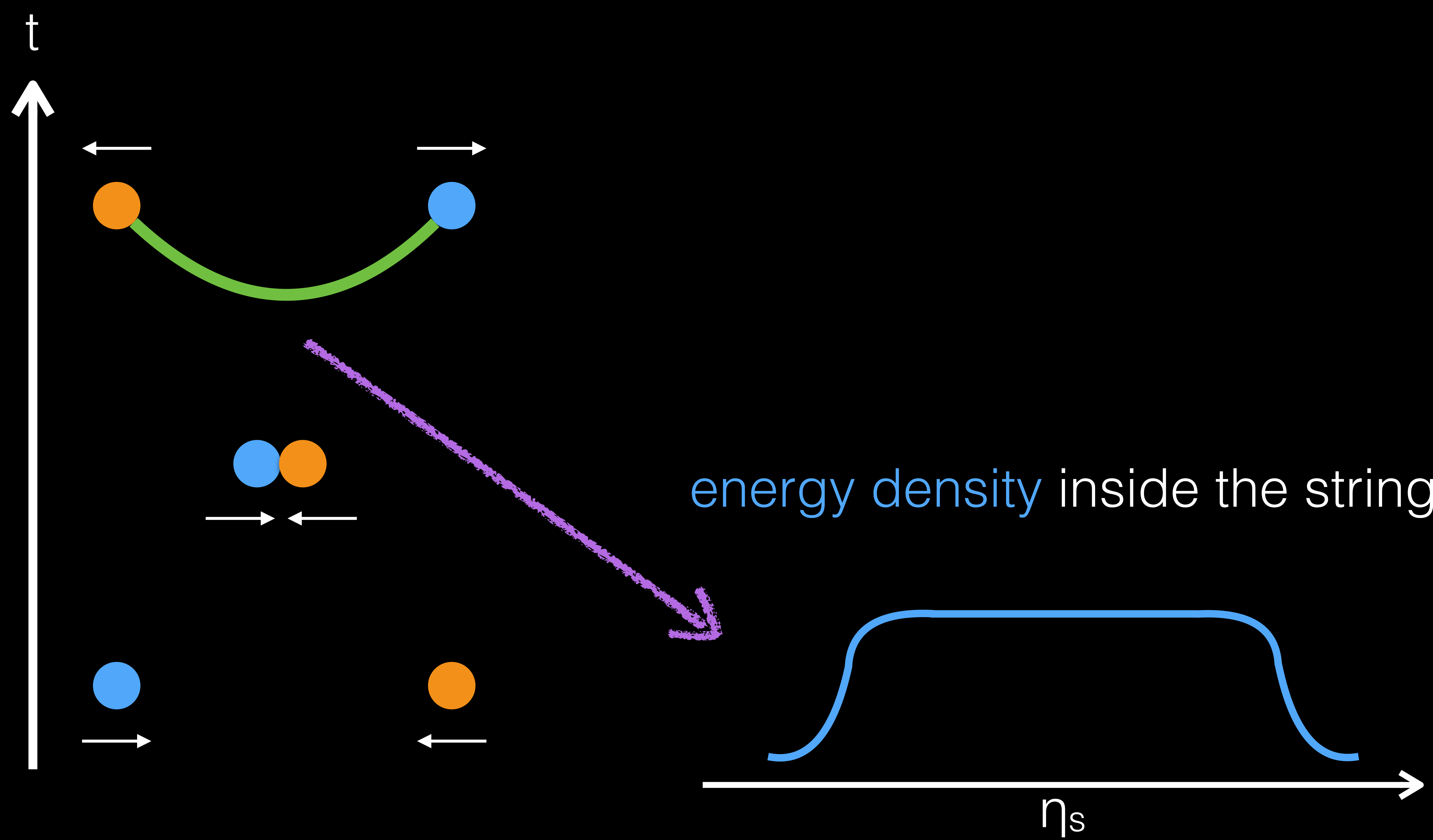
Details about the dynamical initialization

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



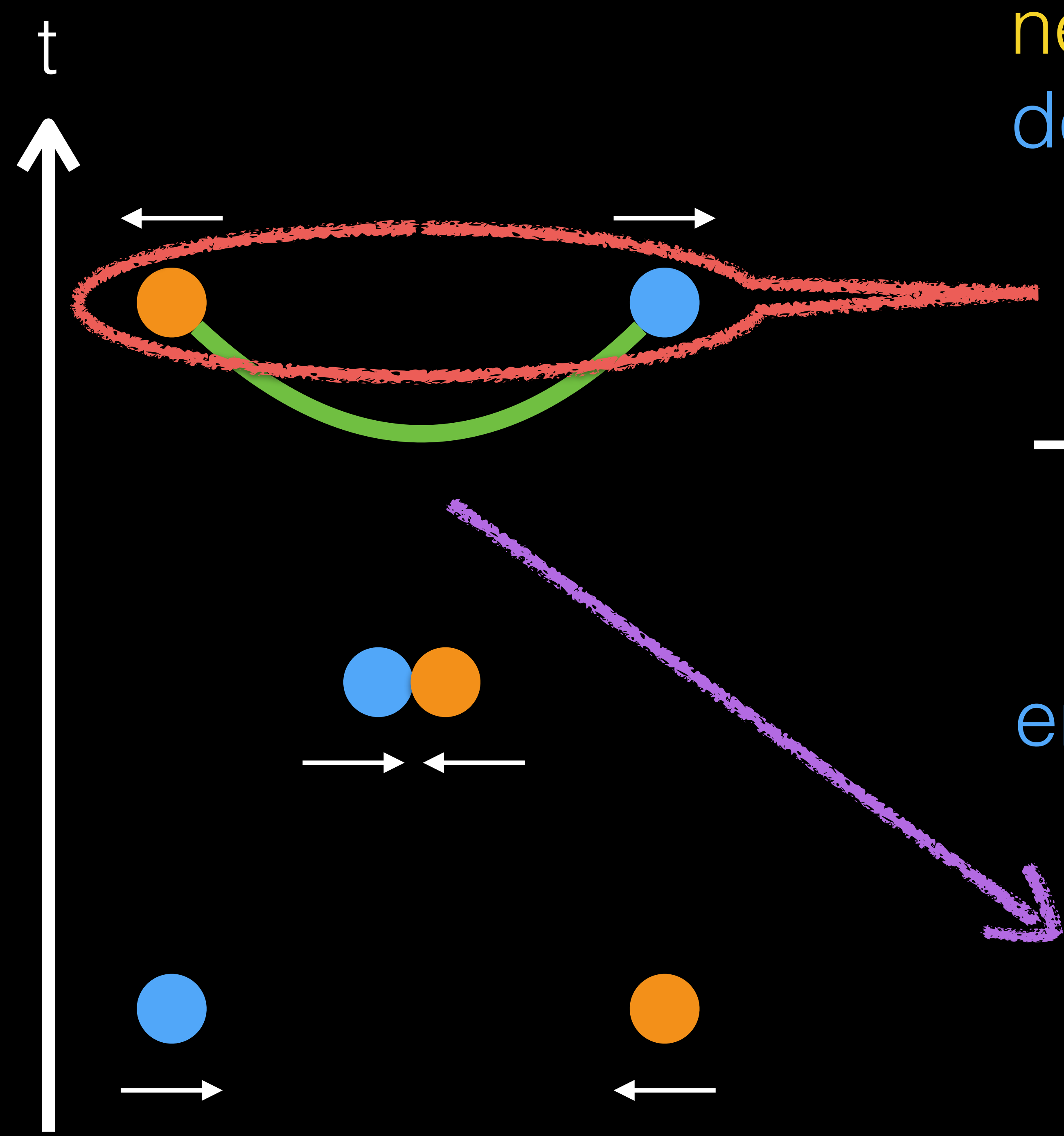
Details about the dynamical initialization

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

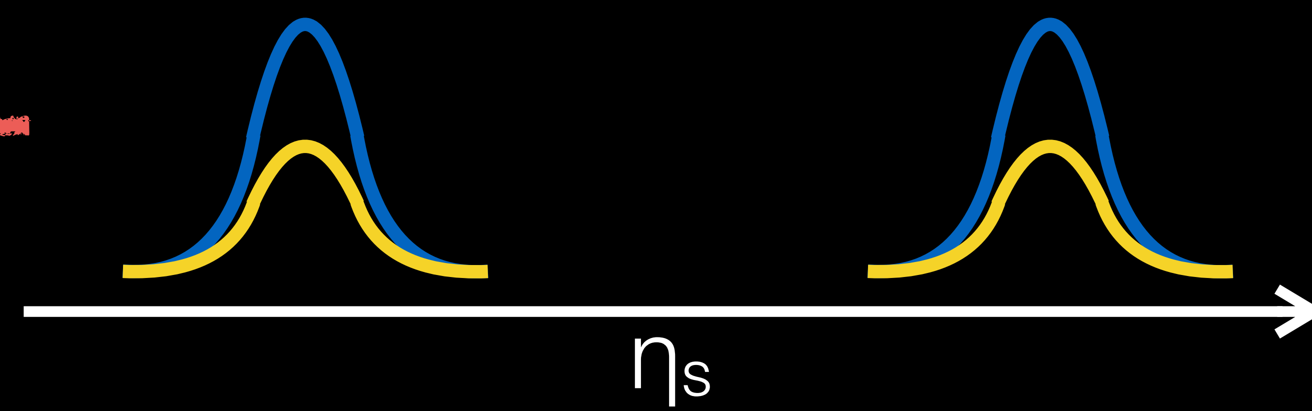


Details about the dynamical initialization

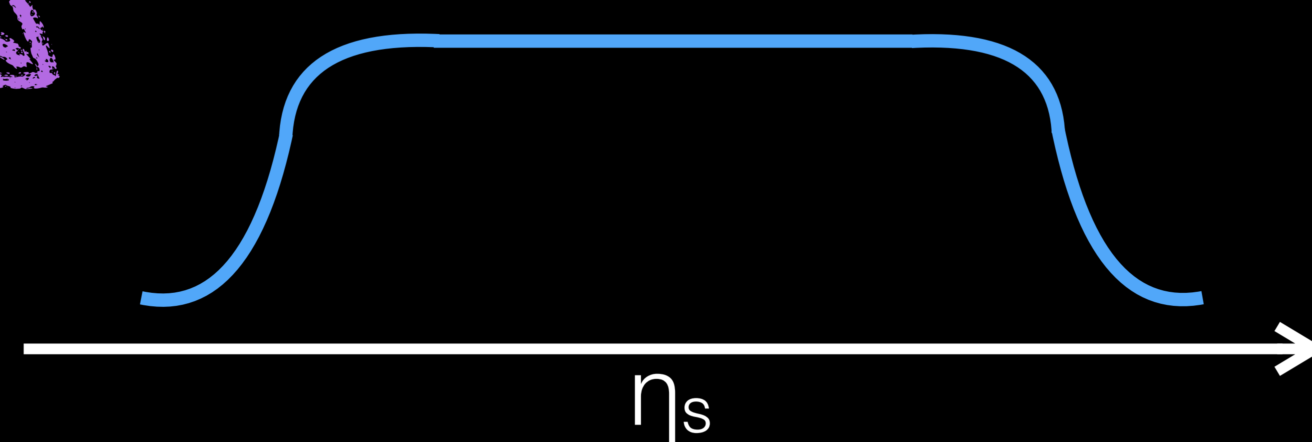
C. Shen and B. Schenke, Phys.Rev. C97 (2018) 024907



net baryon density and energy density at the string ends

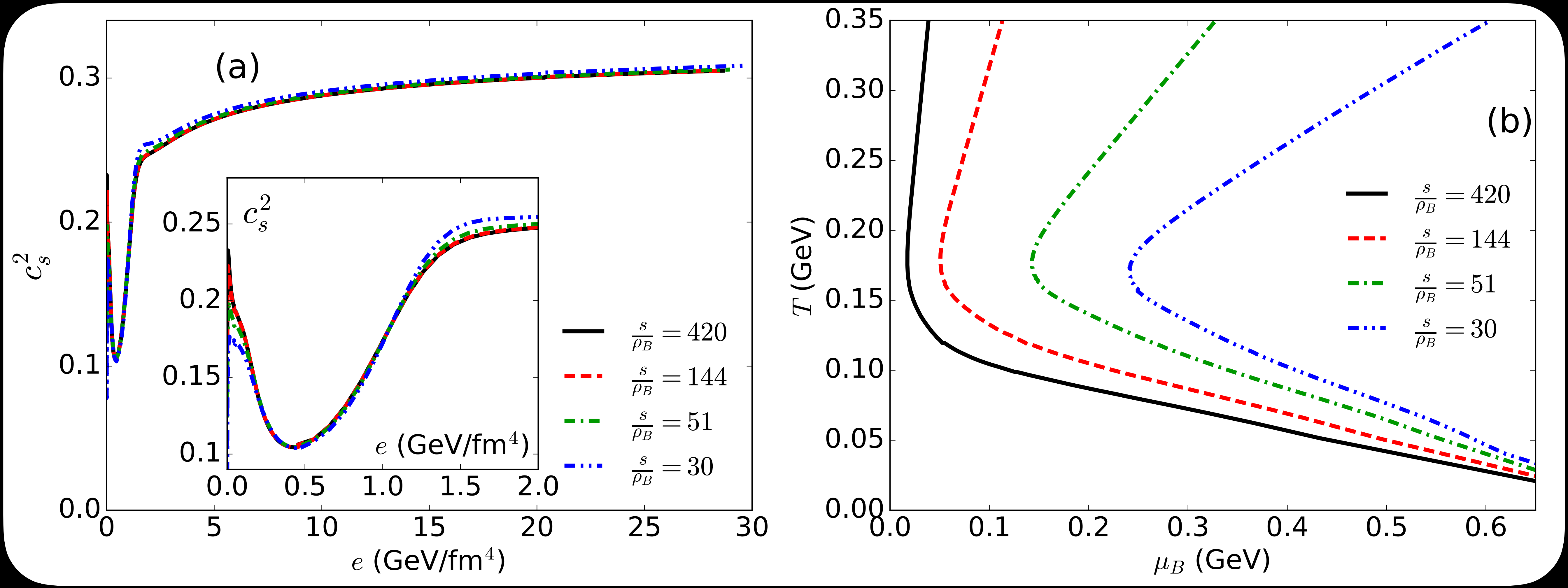


energy density inside the string



Equation of State at finite μ_B

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



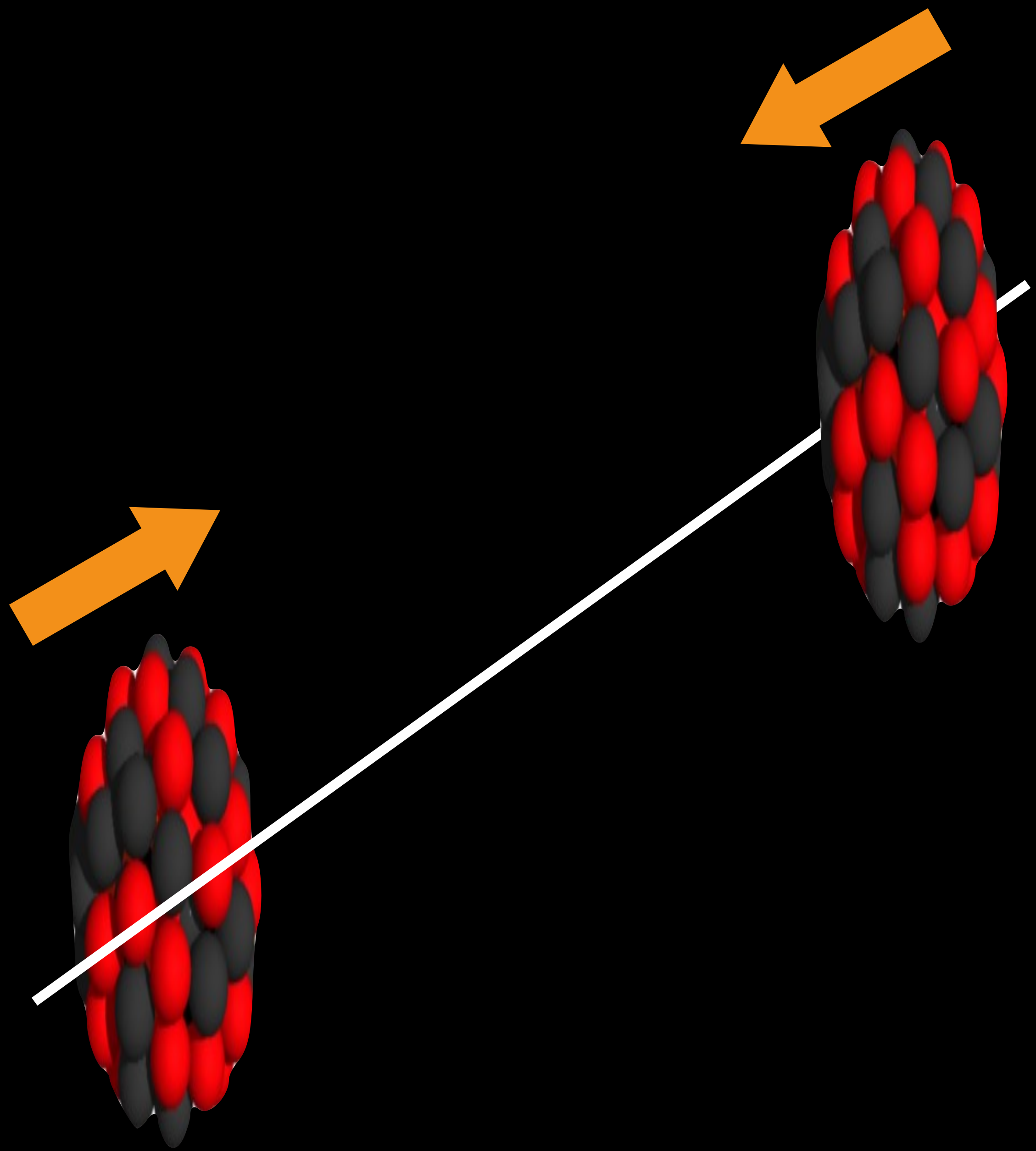
High temperature:

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

Low temperature:

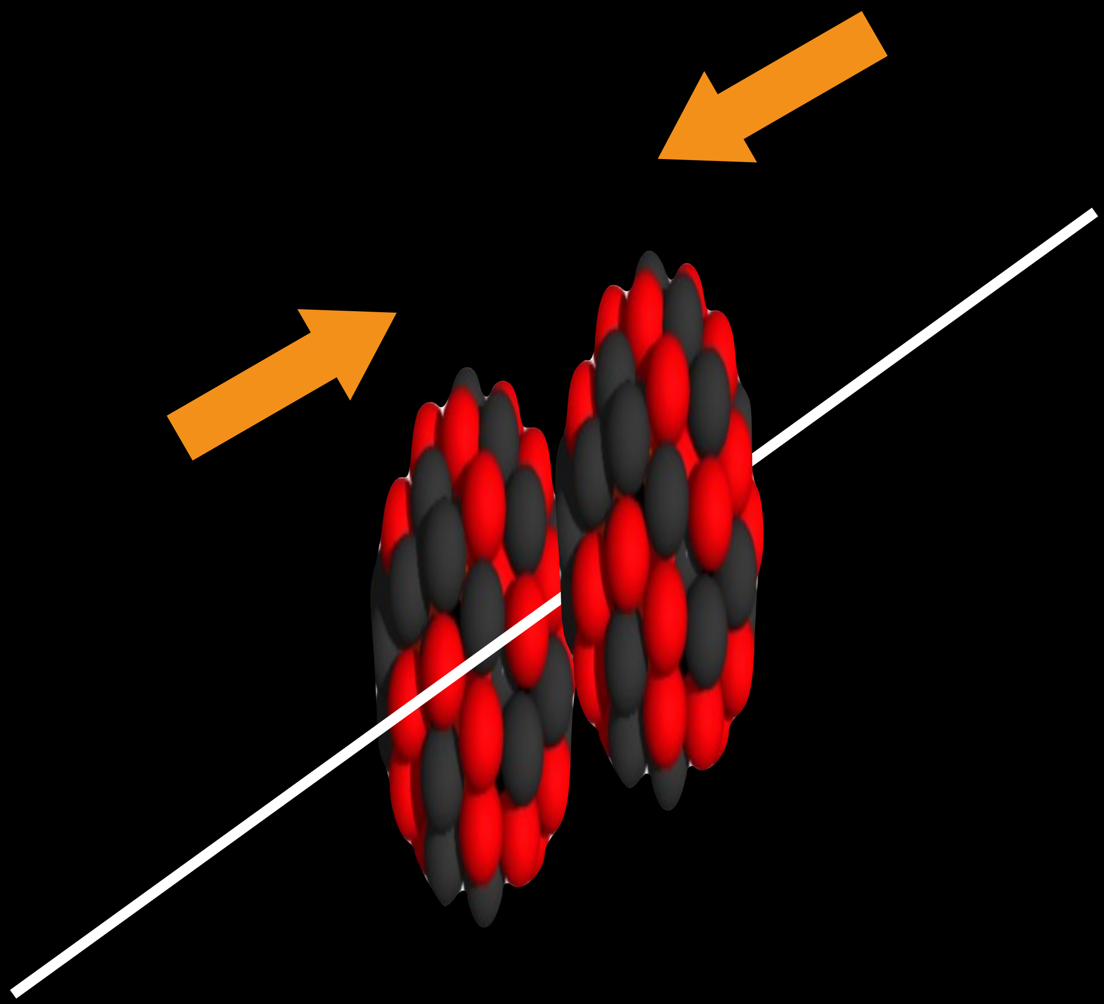
- Glued with hadron resonance gas EoS

Hydrodynamical evolution with sources



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

Hydrodynamical evolution with sources



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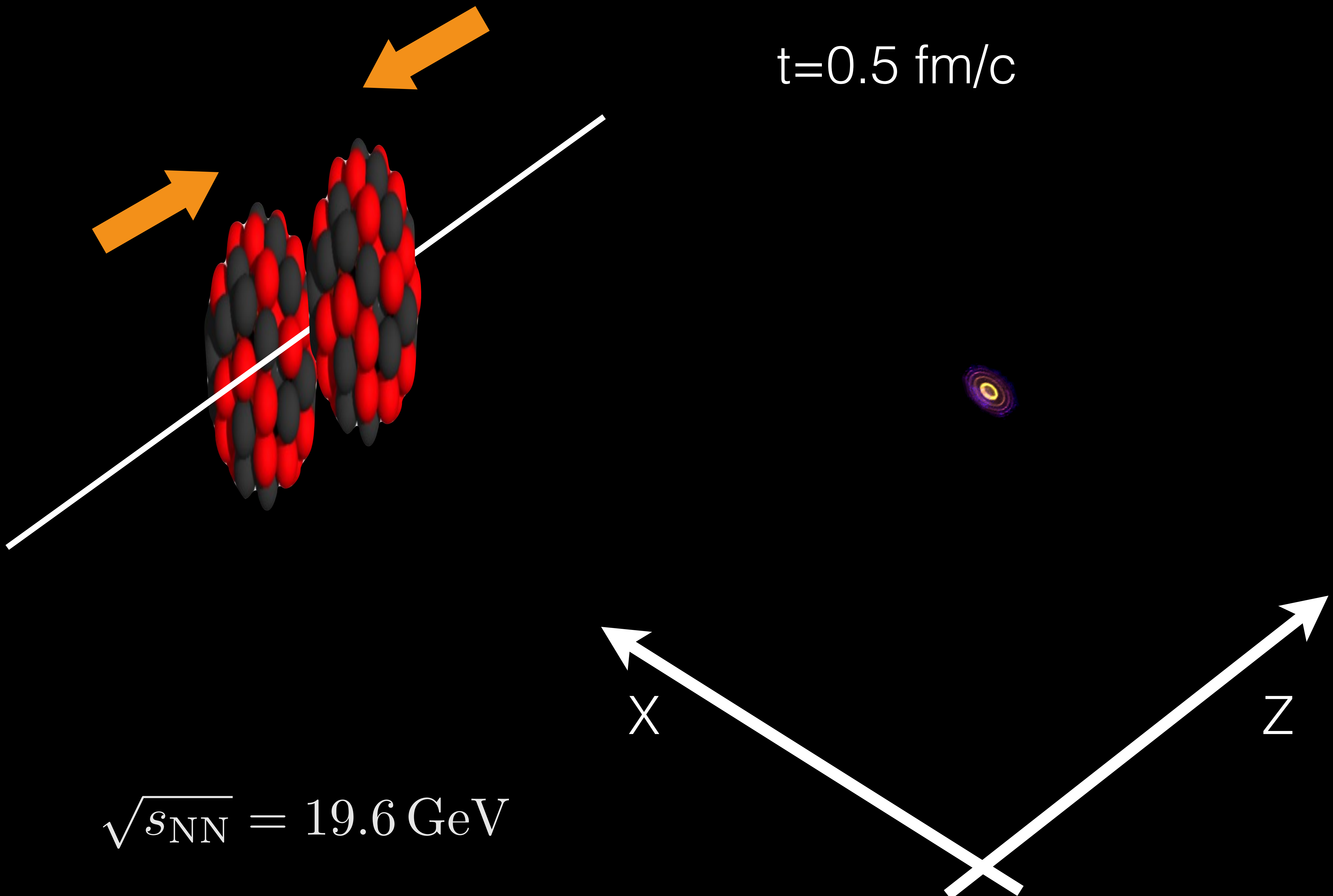
Hydrodynamical evolution with sources



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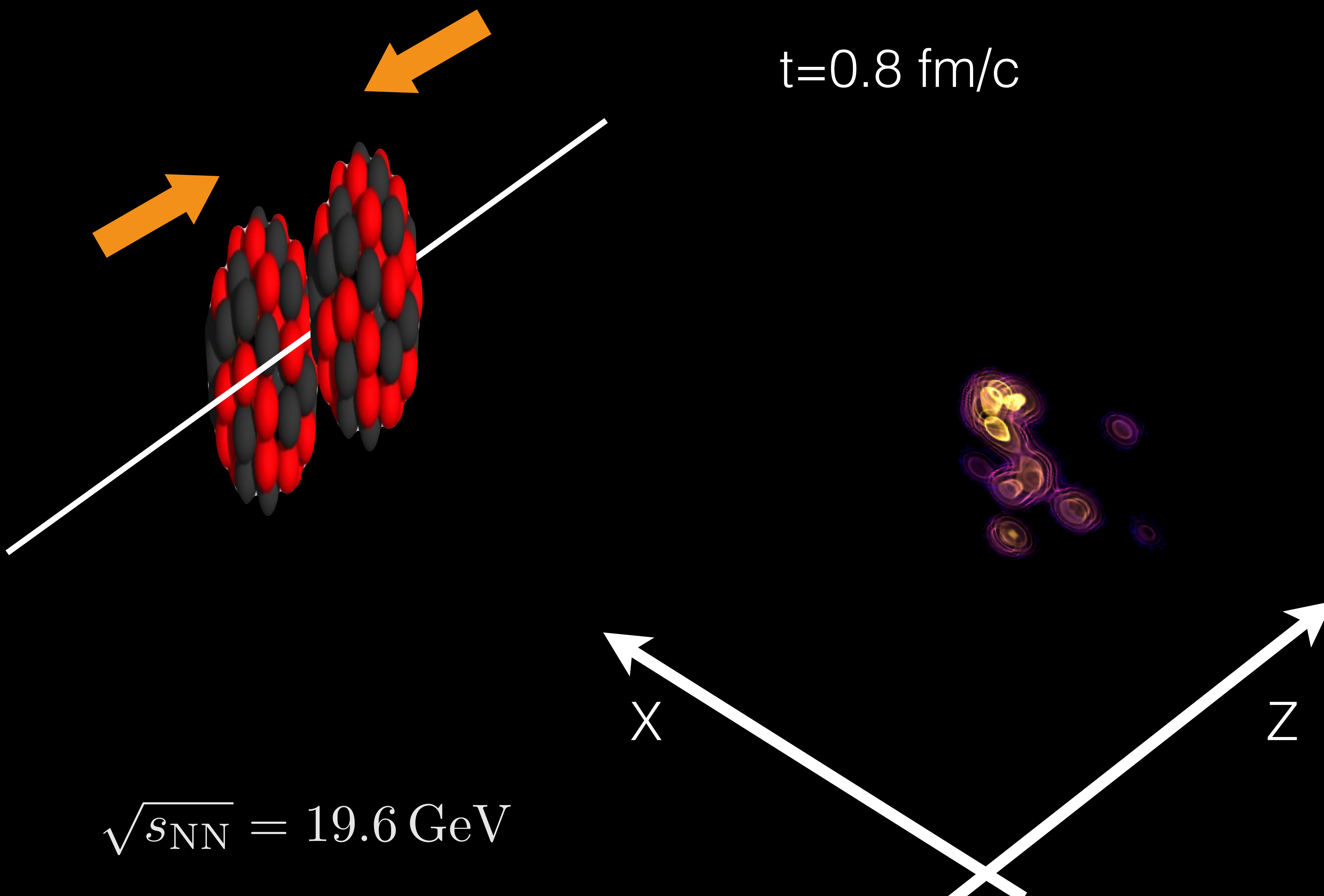
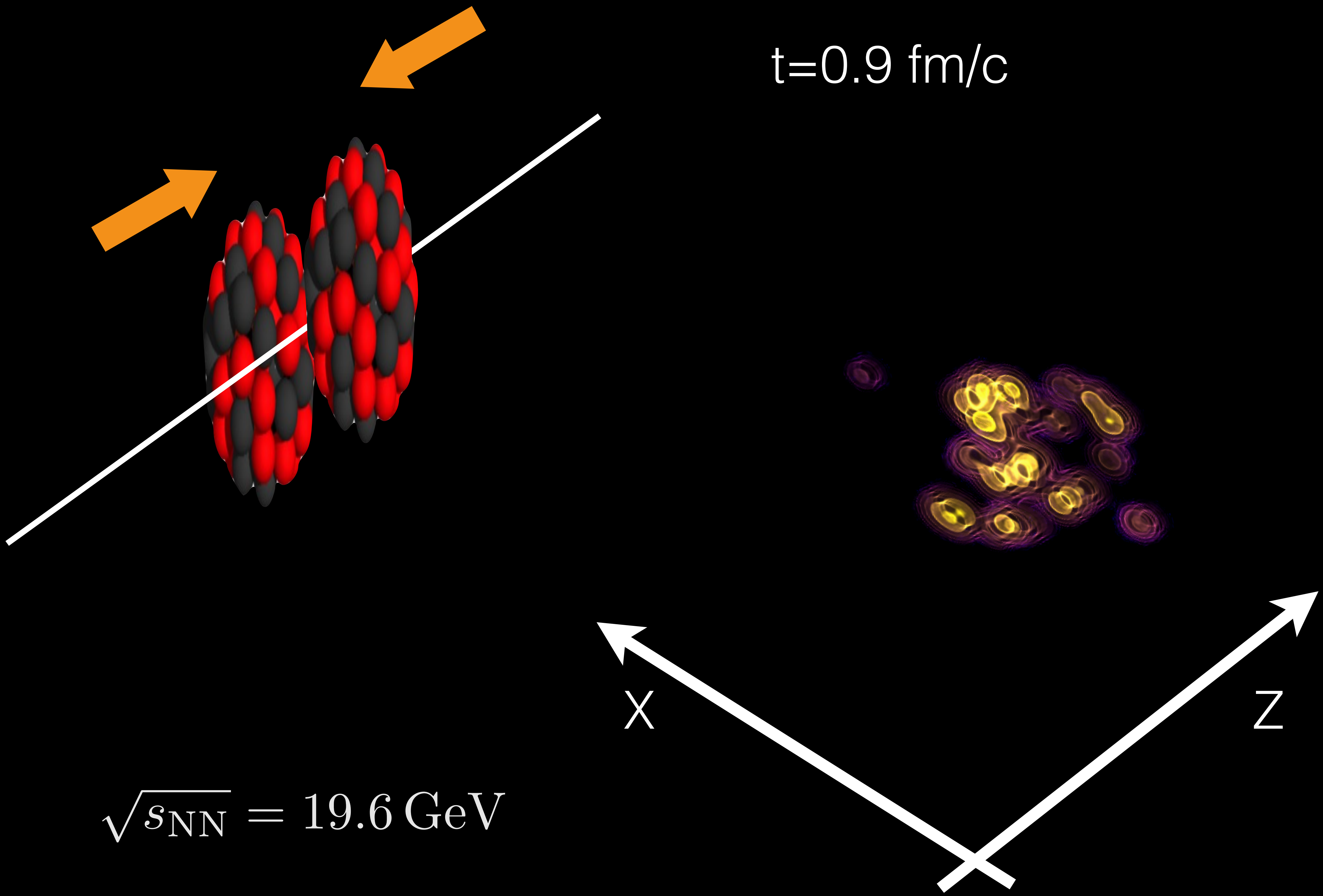
Hydrodynamical evolution with sources



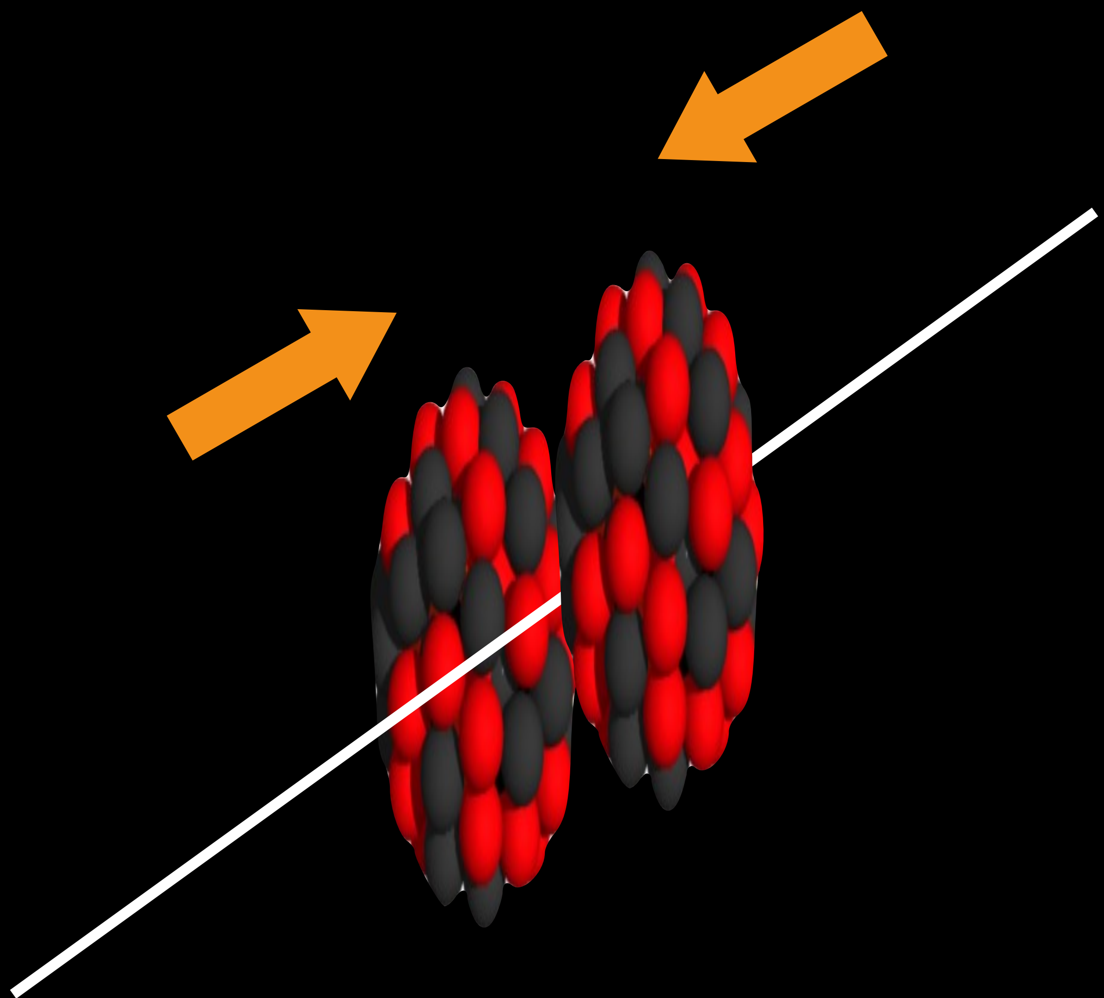
$$\sqrt{s_{\mathrm{NN}}} = 19.6\,\mathrm{GeV}$$

Hydrodynamical evolution with sources

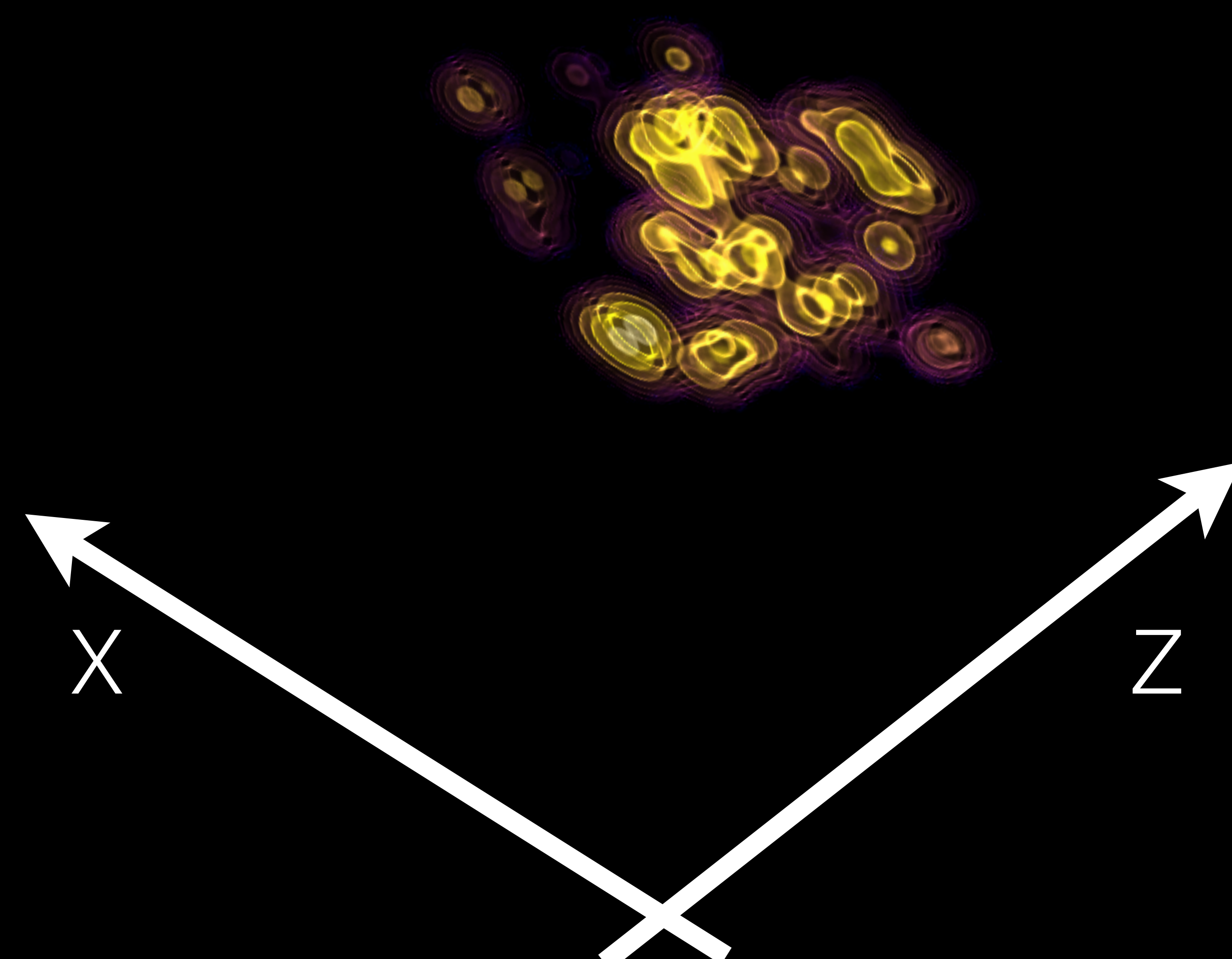


$\sqrt{s_{\rm NN}} = 19.6\,\rm GeV$

Hydrodynamical evolution with sources

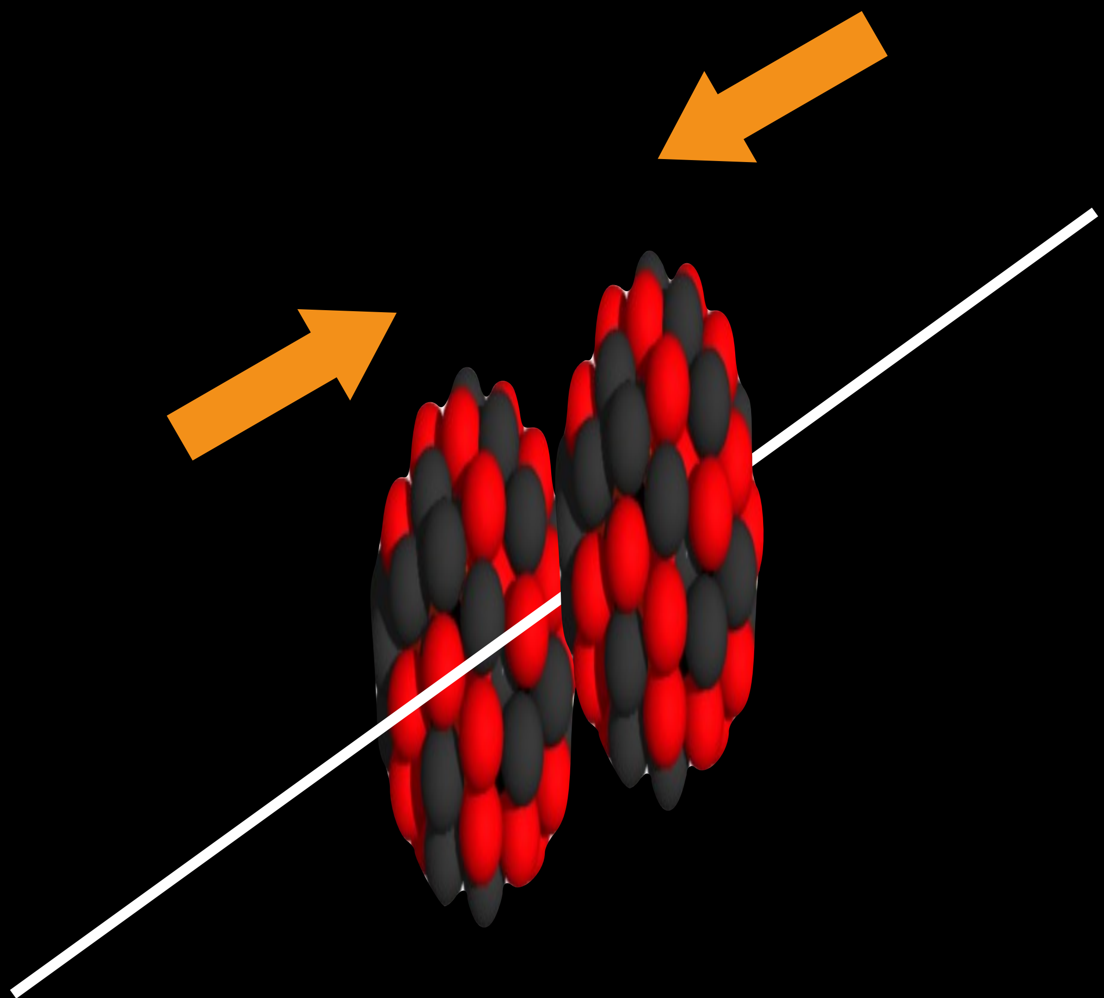


t=1.0 fm/c



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

Hydrodynamical evolution with sources



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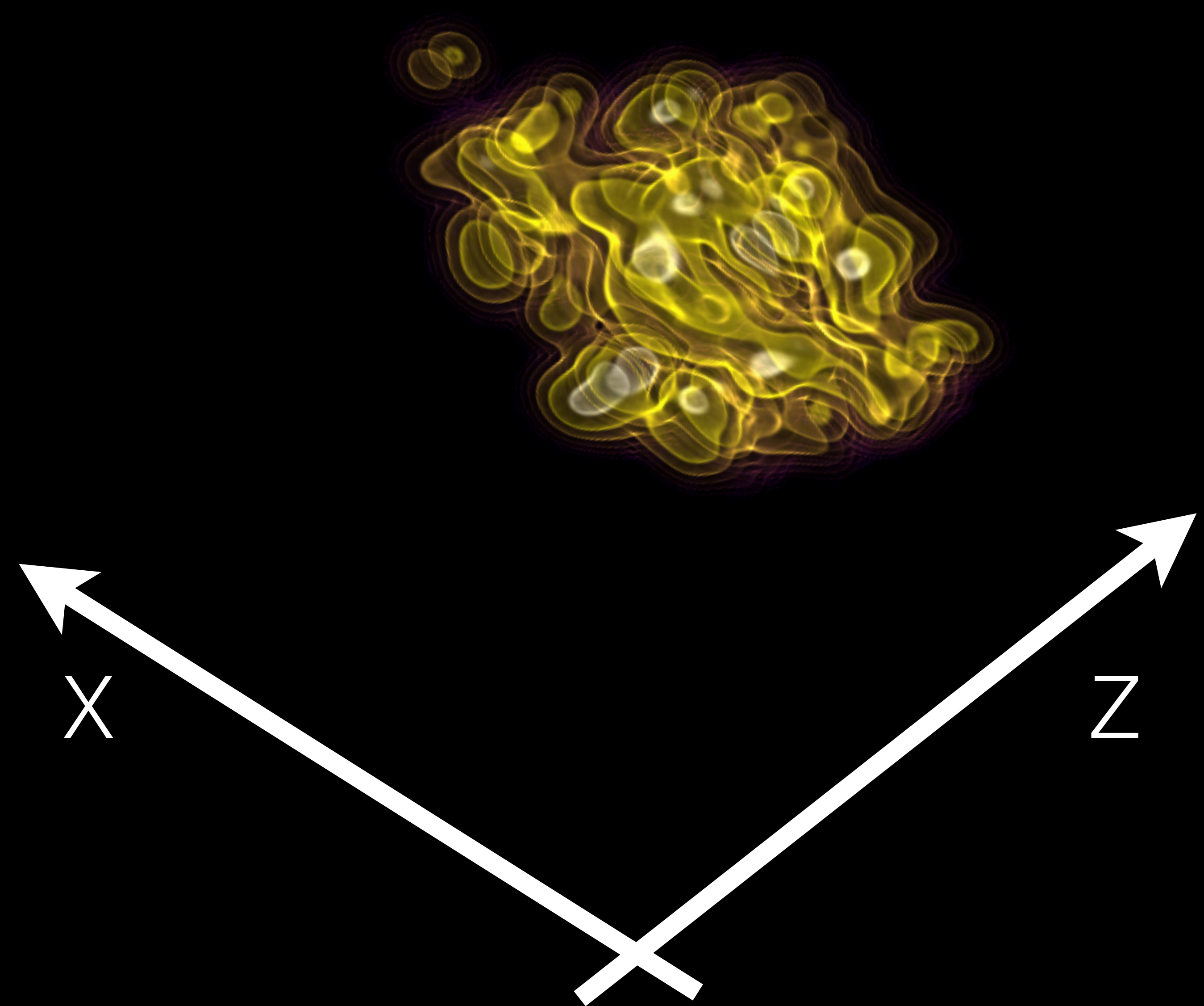
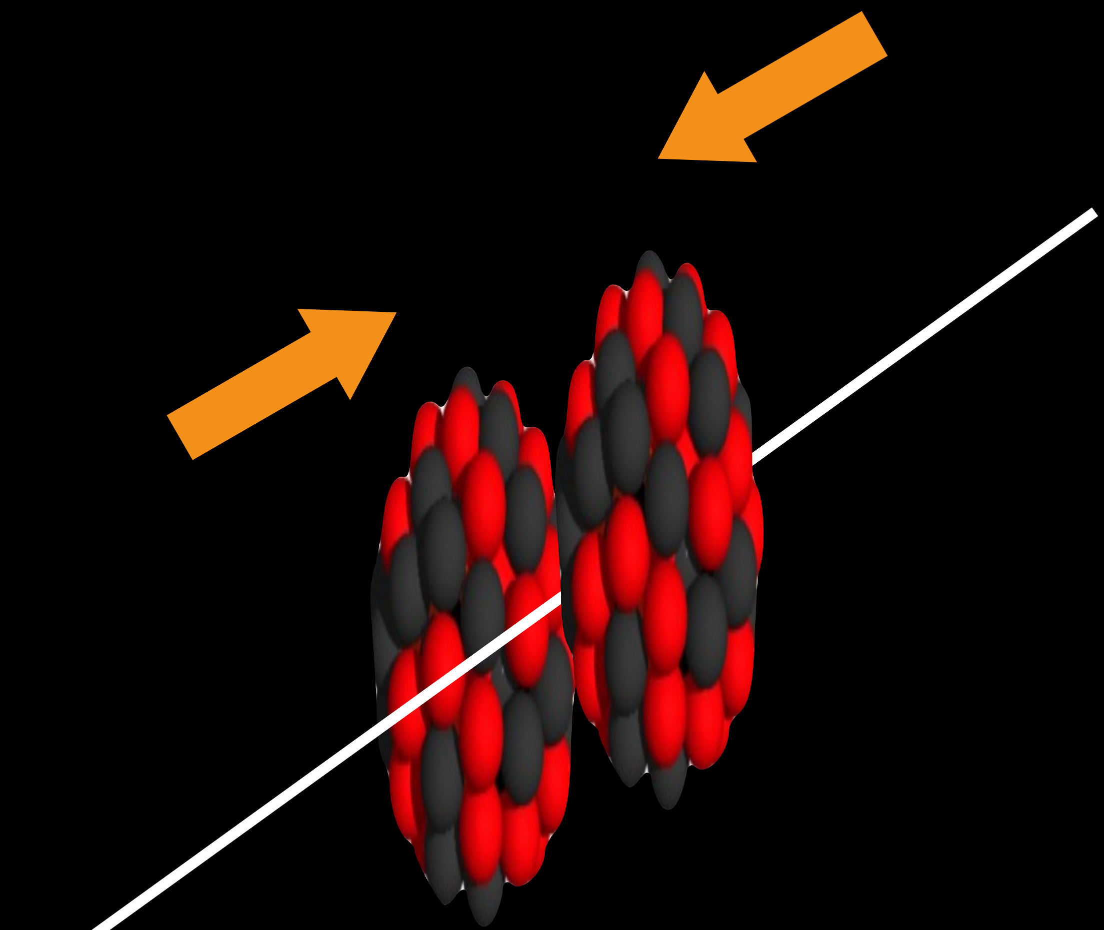
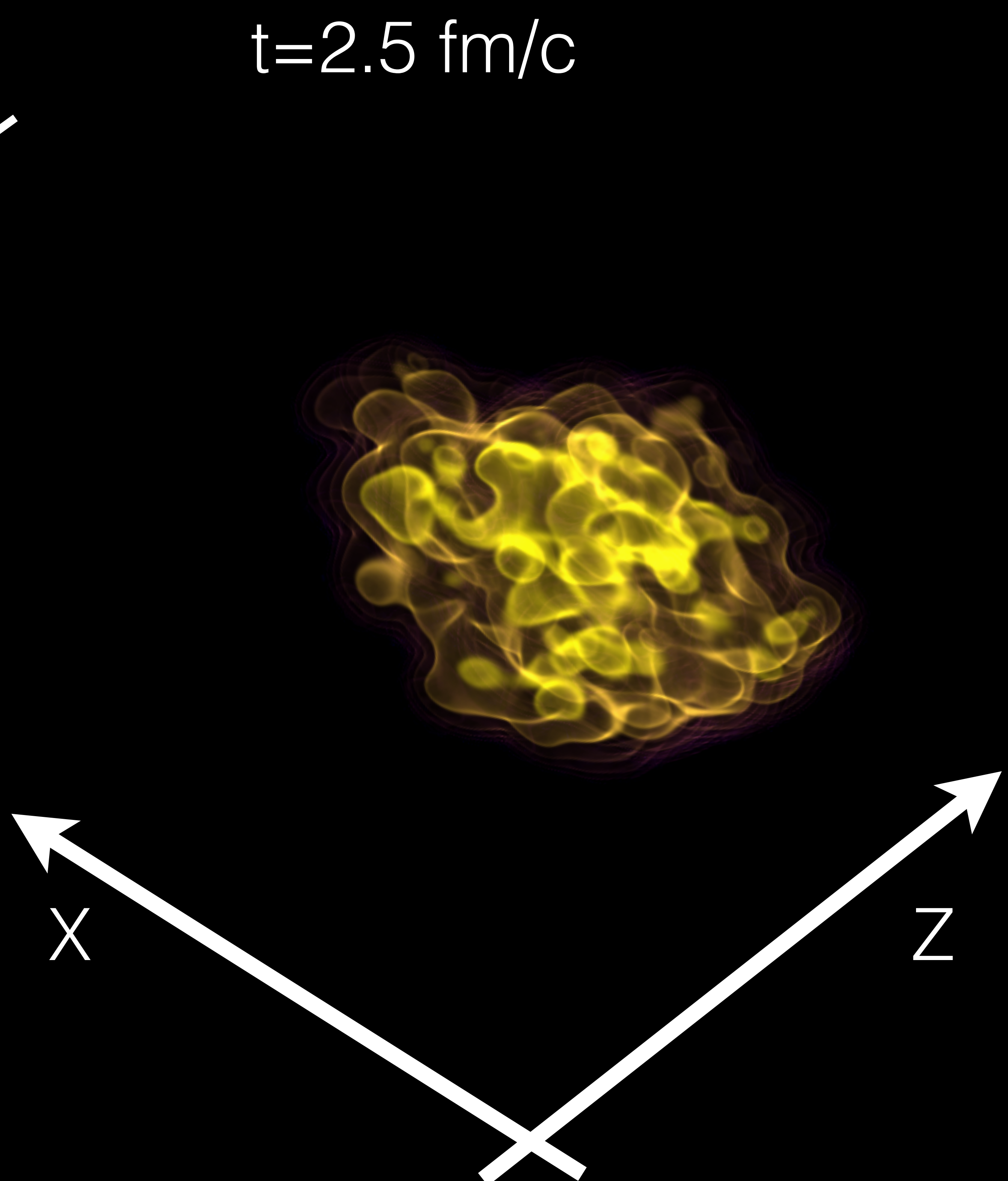


$$\sqrt{s_{\rm NN}} = 19.6\,{\rm GeV}$$

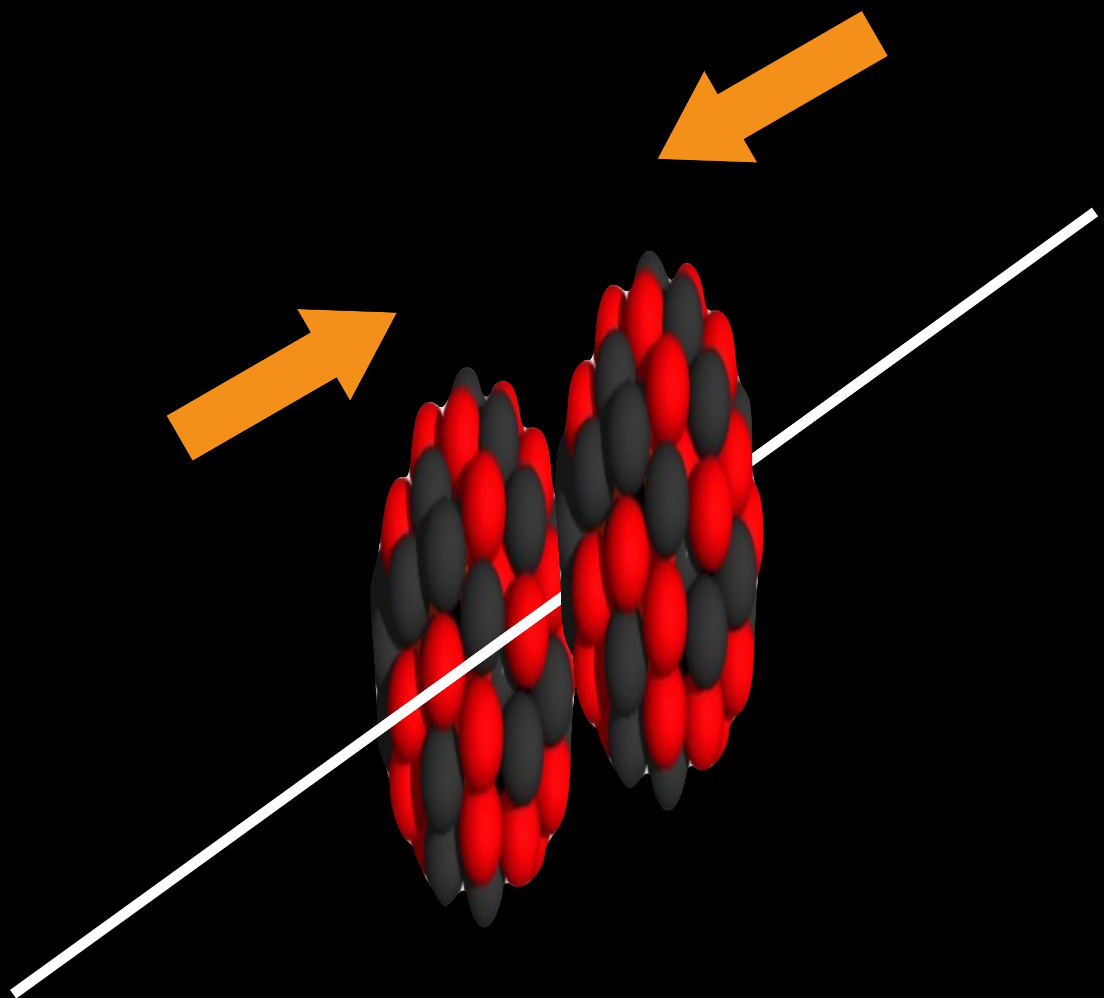
Hydrodynamical evolution with sources



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



Hydrodynamical evolution with sources



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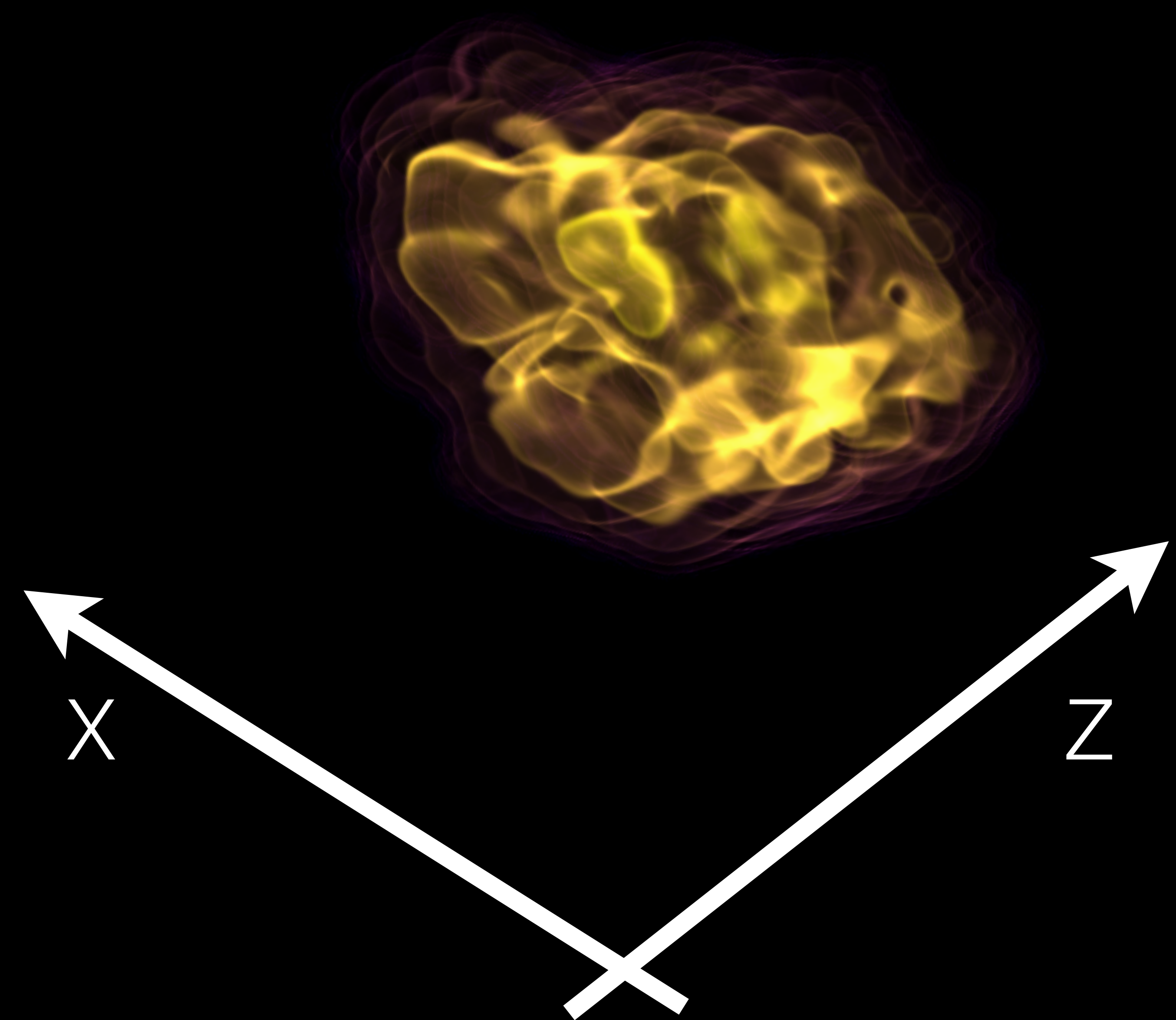
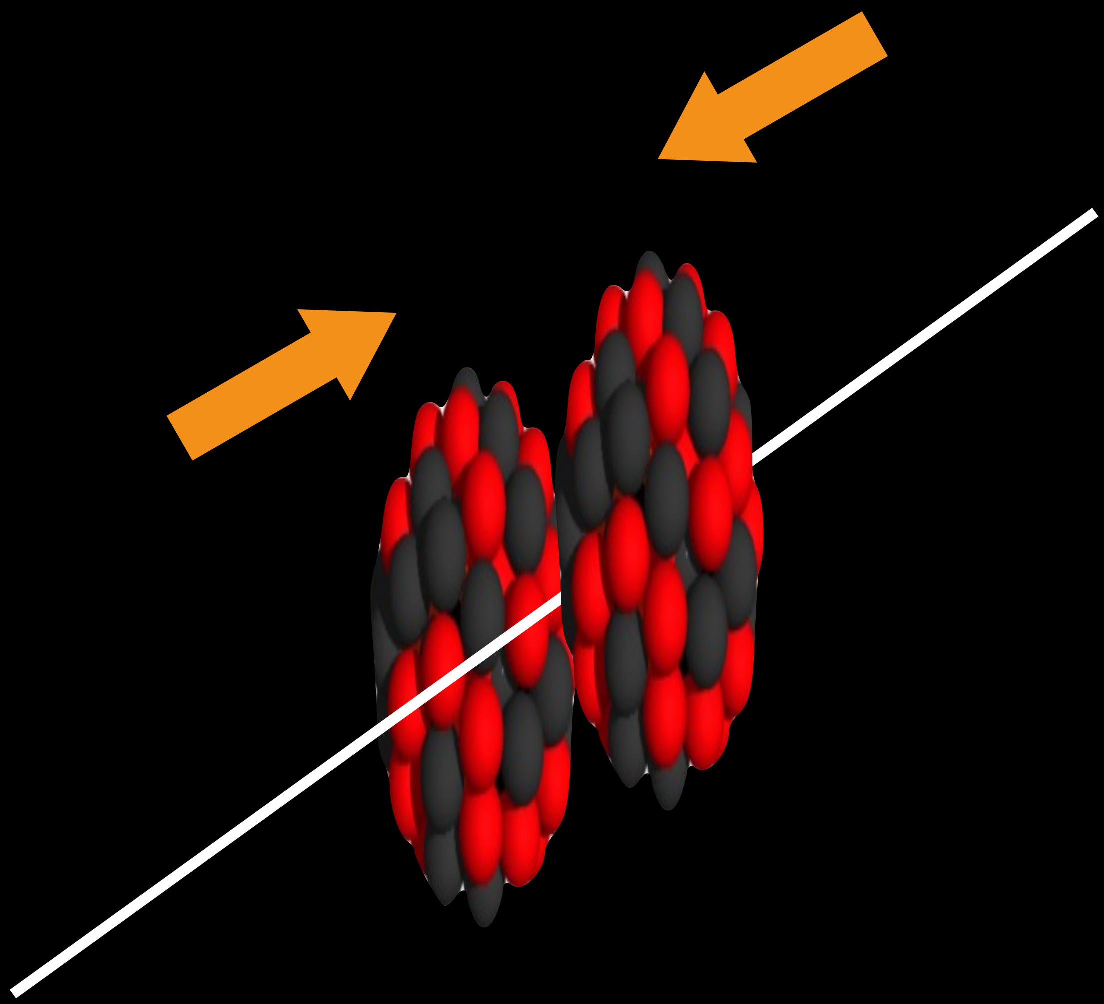
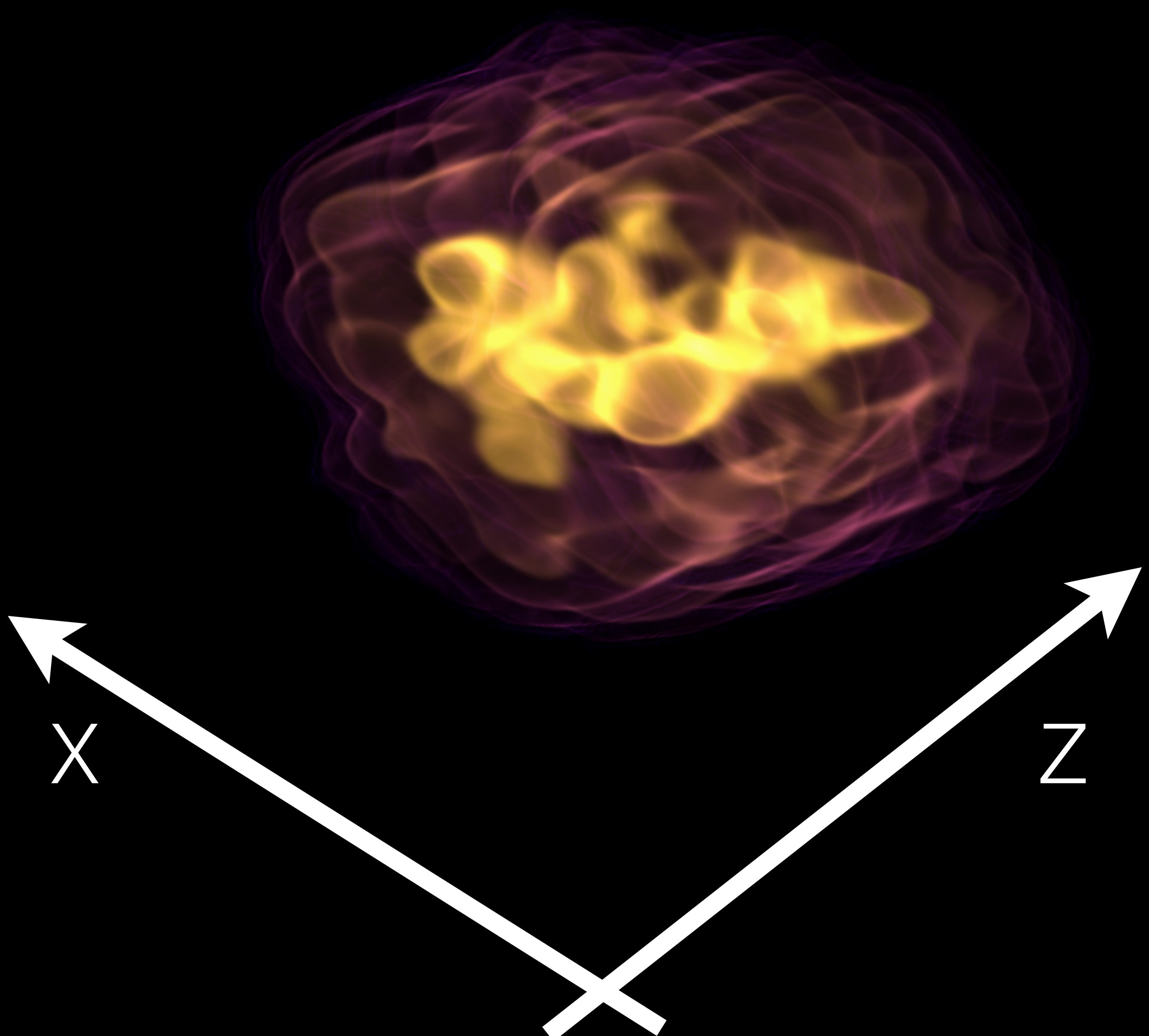


$$\sqrt{s_{\rm NN}} = 19.6\,{\rm GeV}$$

Hydrodynamical evolution with sources





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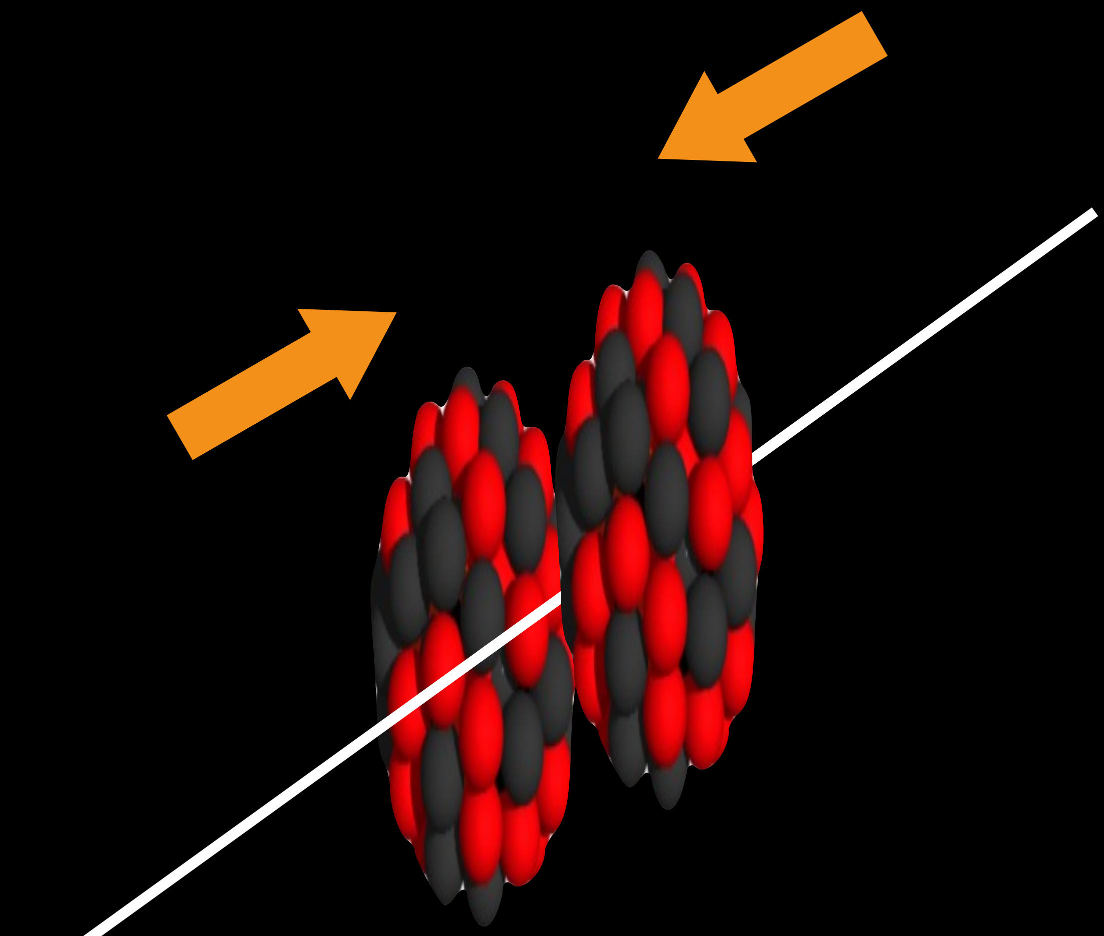
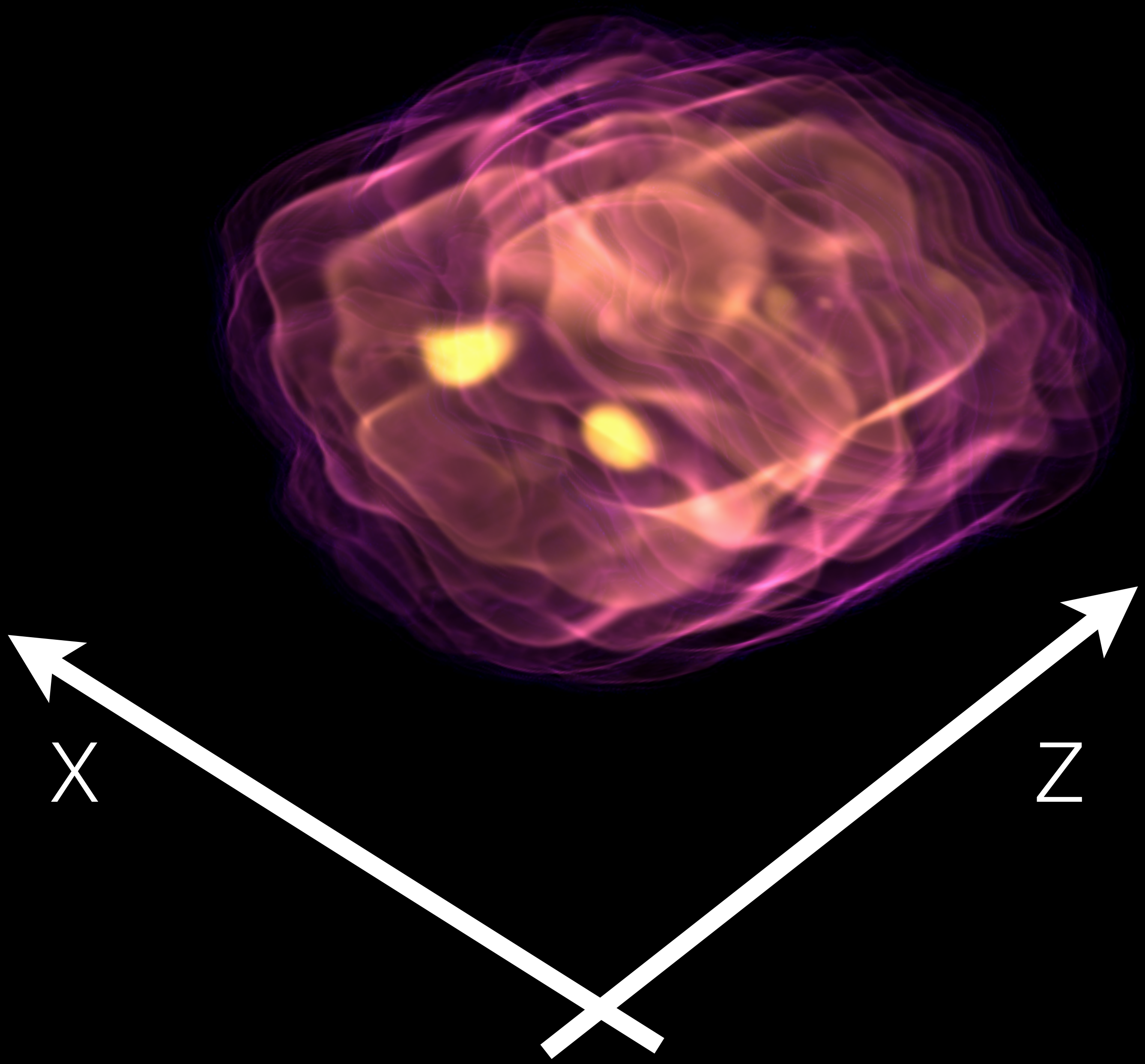
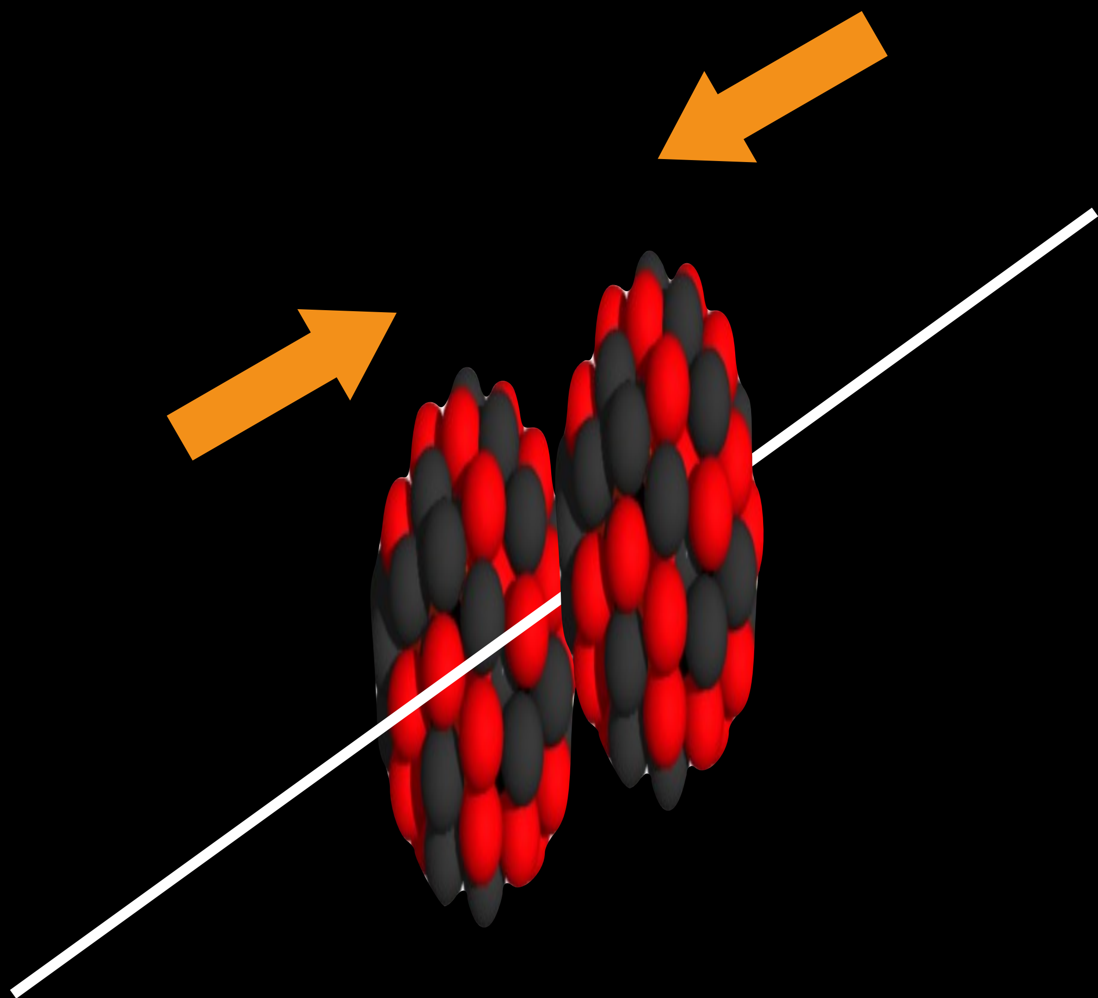
Hydrodynamical evolution with sources





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

Hydrodynamical evolution with sources



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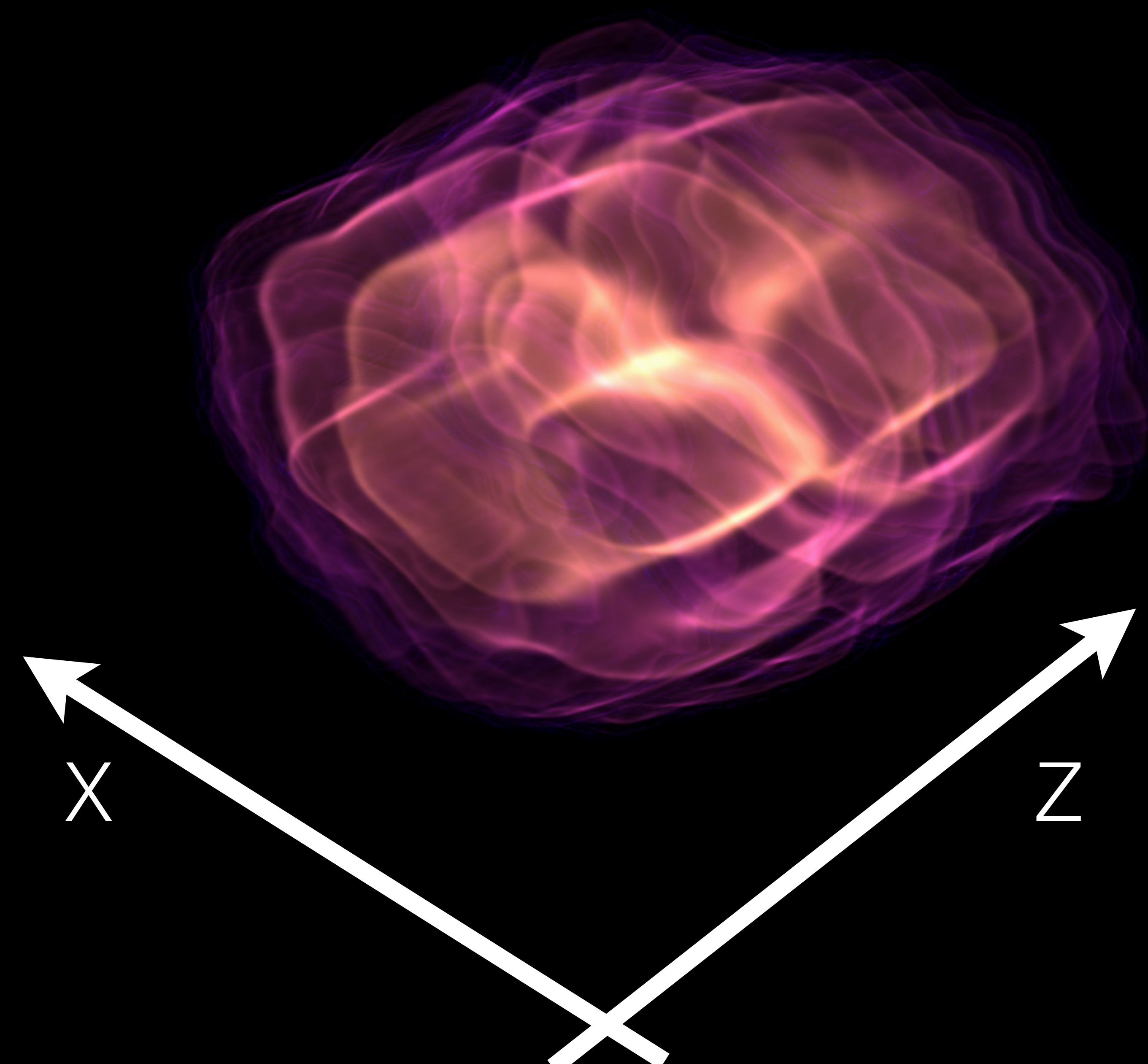
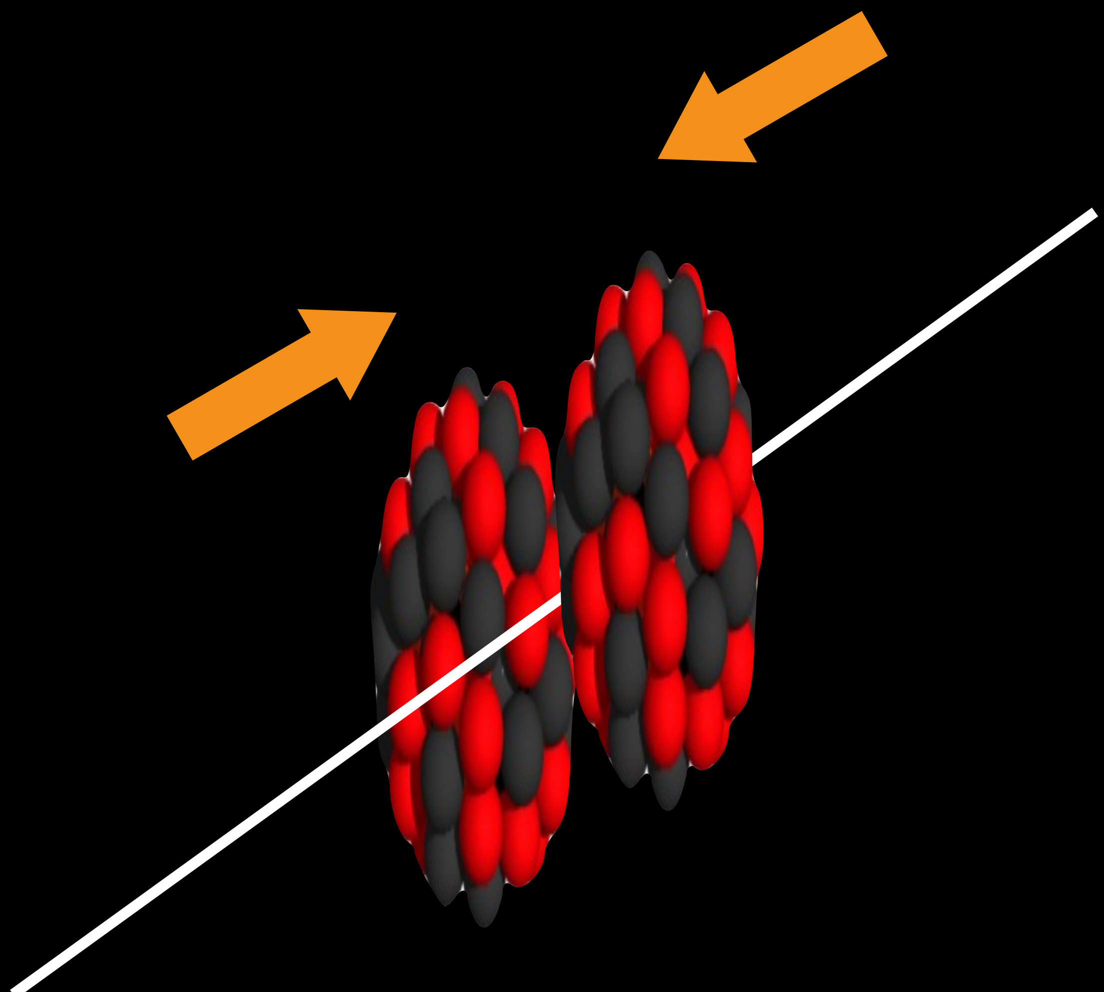
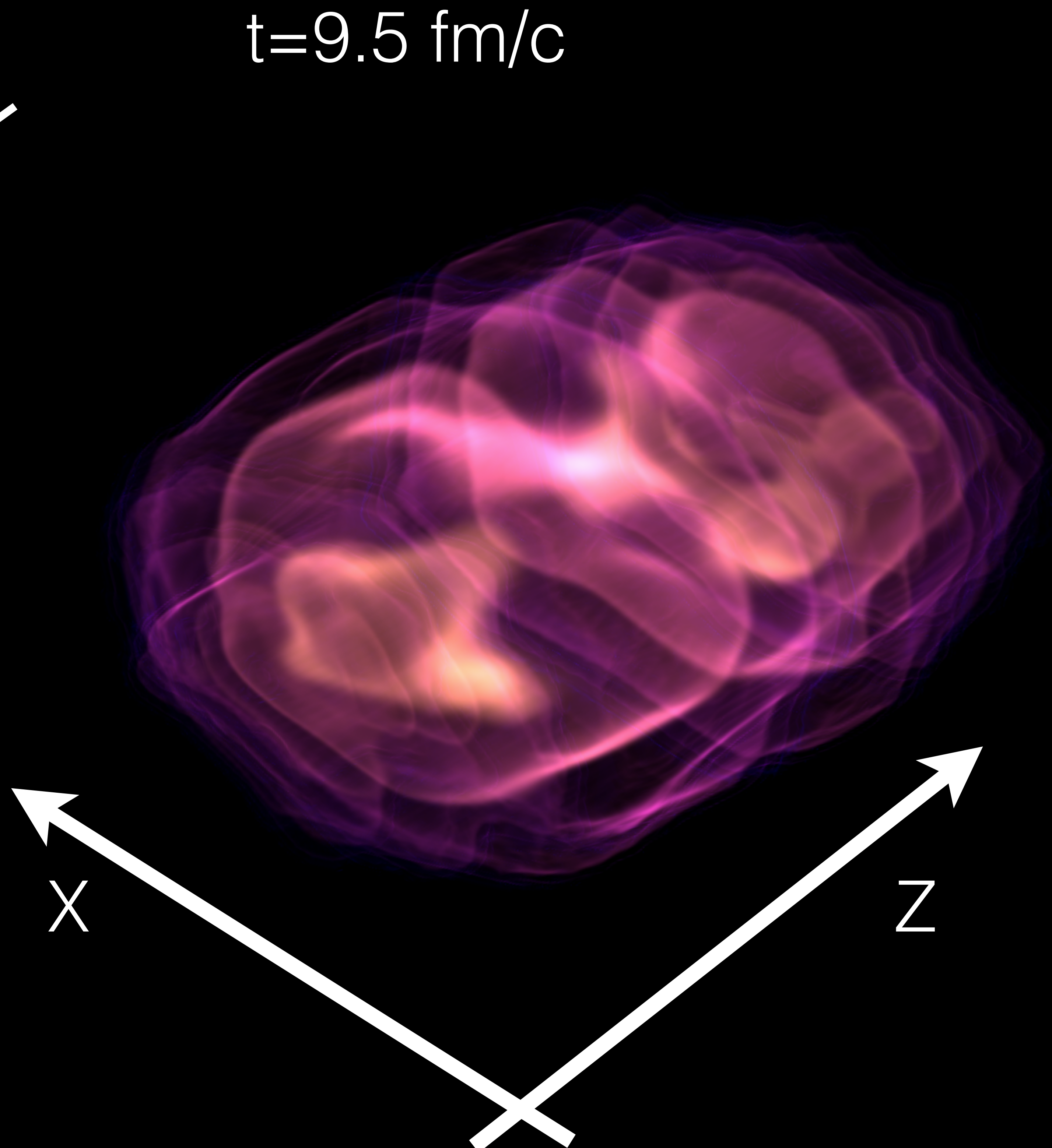


$$\sqrt{s_{\mathrm{NN}}} = 19.6\,\mathrm{GeV}$$

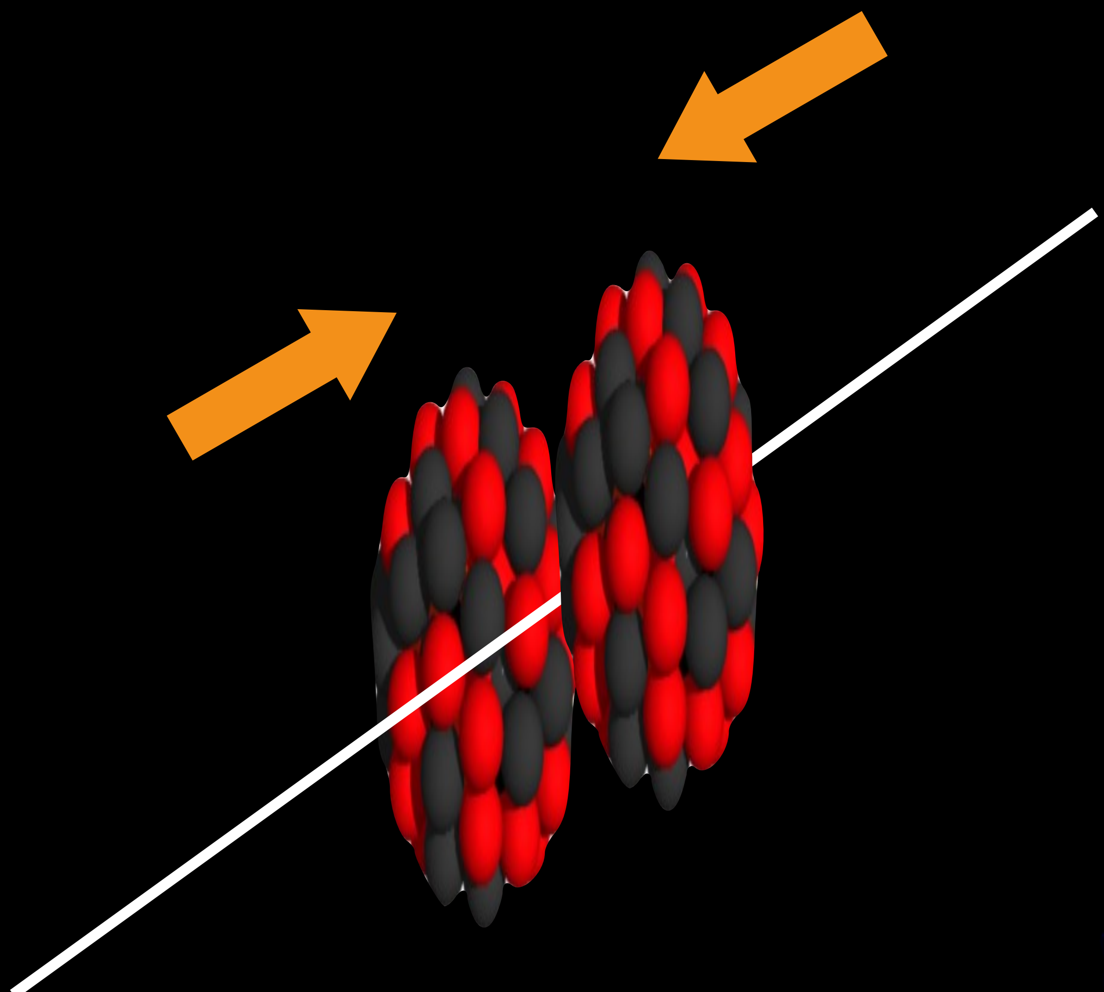
Hydrodynamical evolution with sources





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

Hydrodynamical evolution with sources



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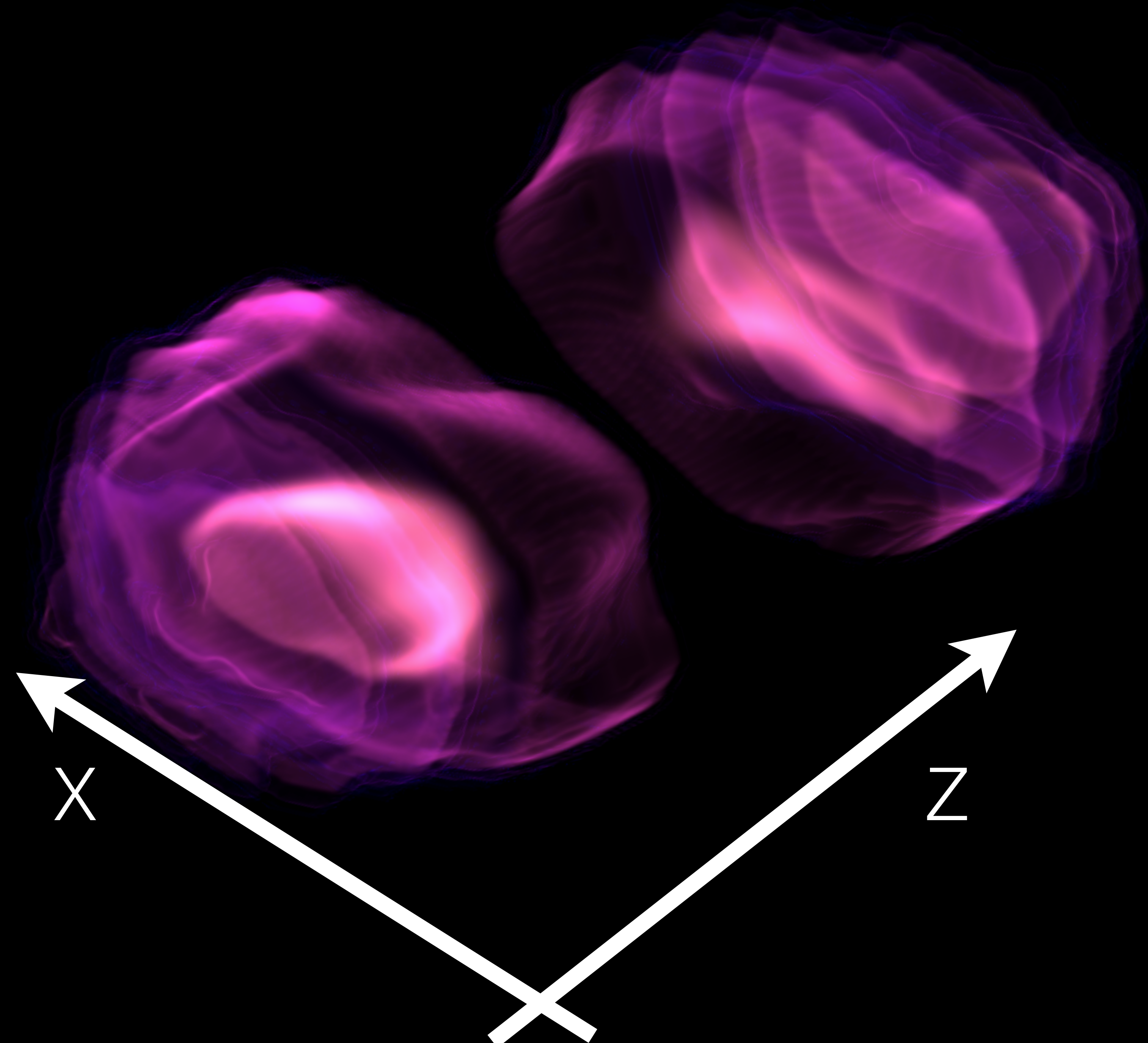
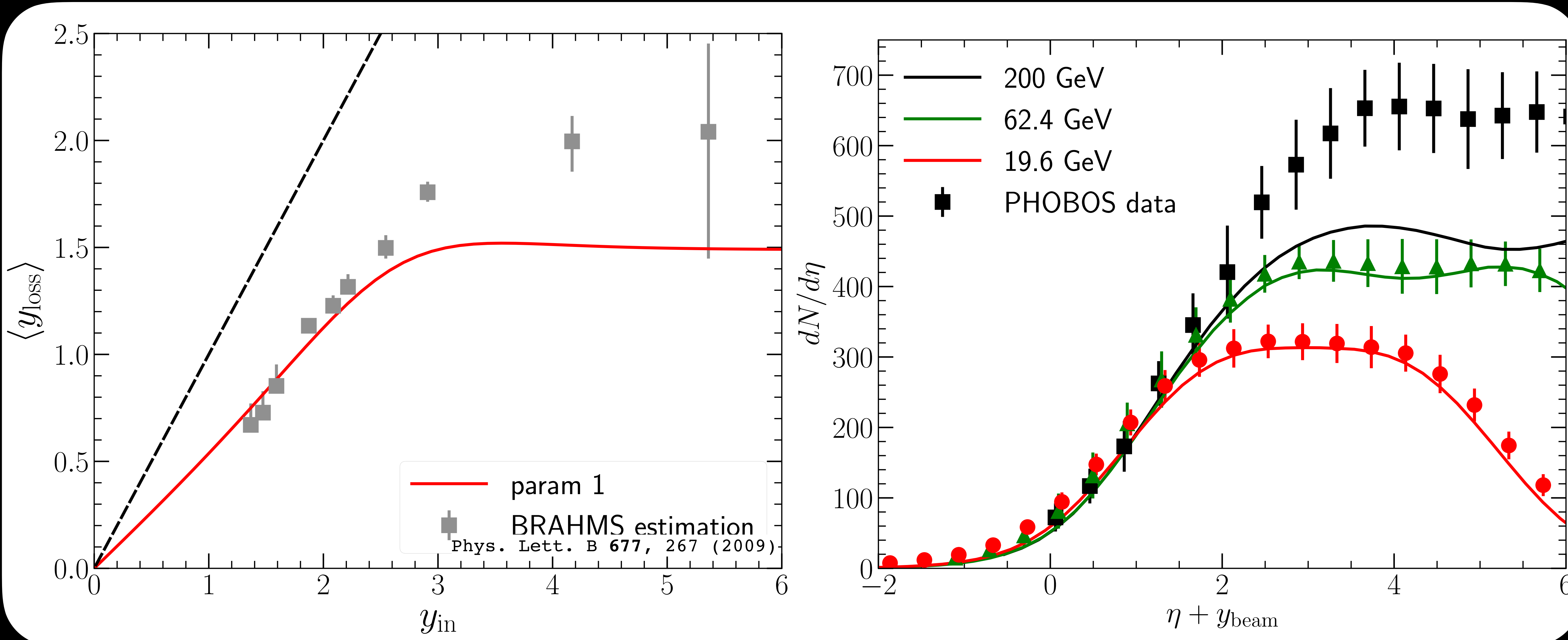


$$\sqrt{s_{\rm NN}} = 19.6\,{\rm GeV}$$

Model the baryon stopping

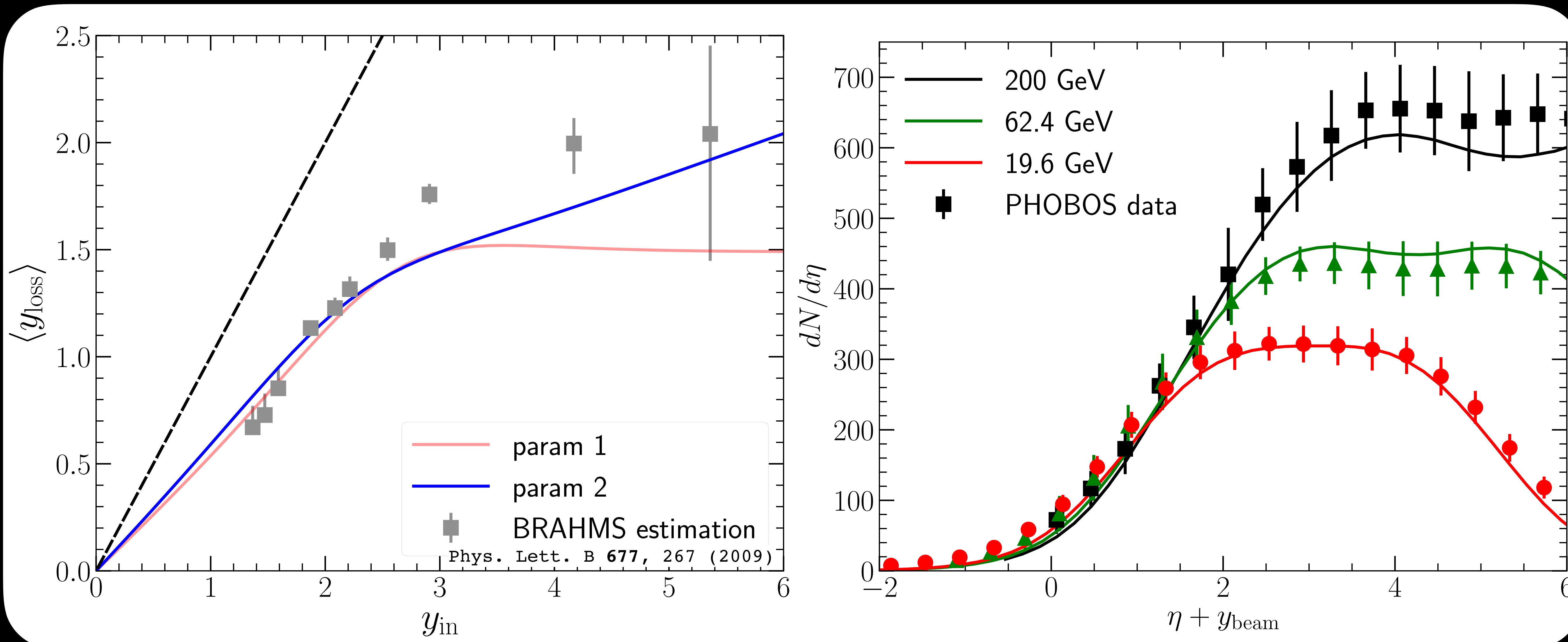
C. Shen and B. Schenke, arXiv:1807.05141



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

Model the baryon stopping

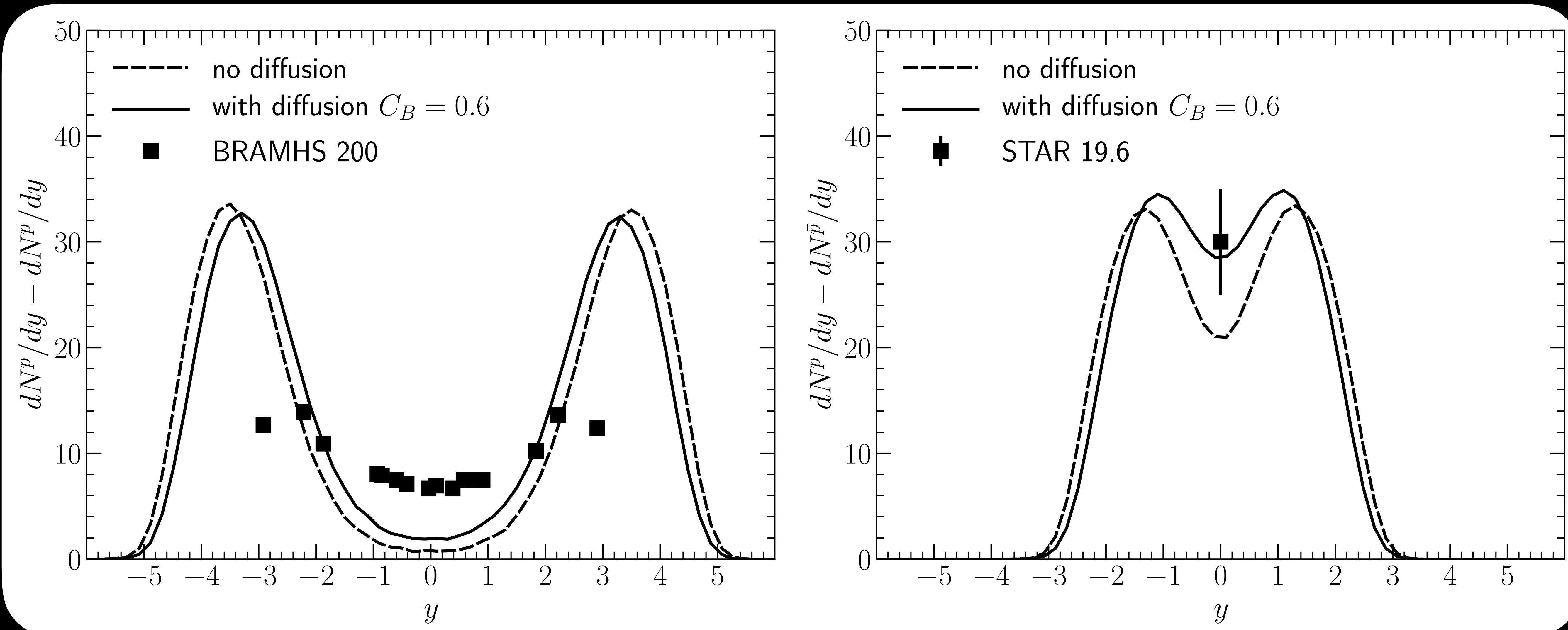
C. Shen and B. Schenke, arXiv:1807.05141



- 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

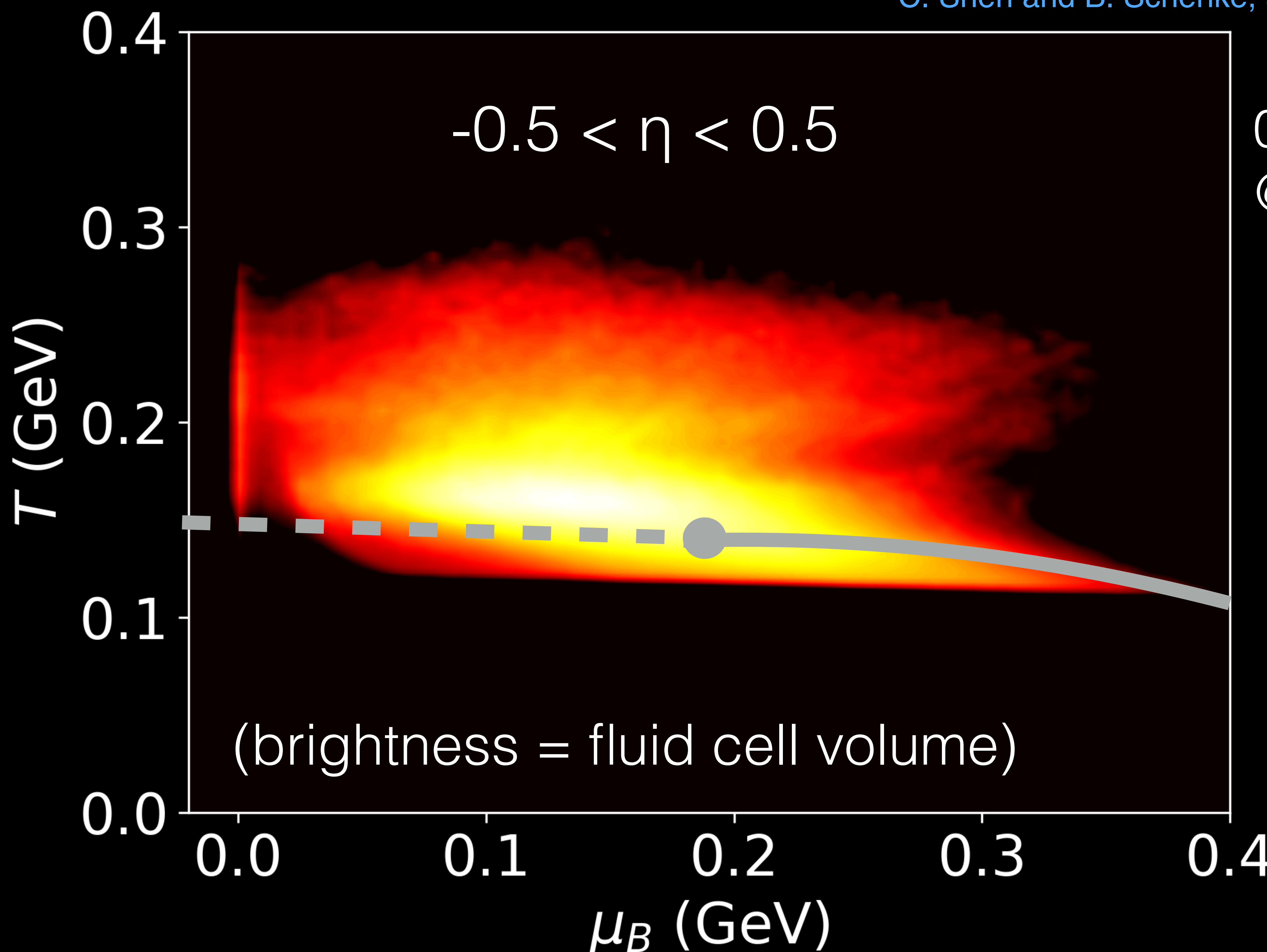
G. Denicol, C. Gale, S. Jeon, A. Monnai, B. Schenke and C. Shen, arXiv:1804.10557 [nucl-th]



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

Sailing in the phase diagram

C. Shen and B. Schenke, arXiv:1807.05141



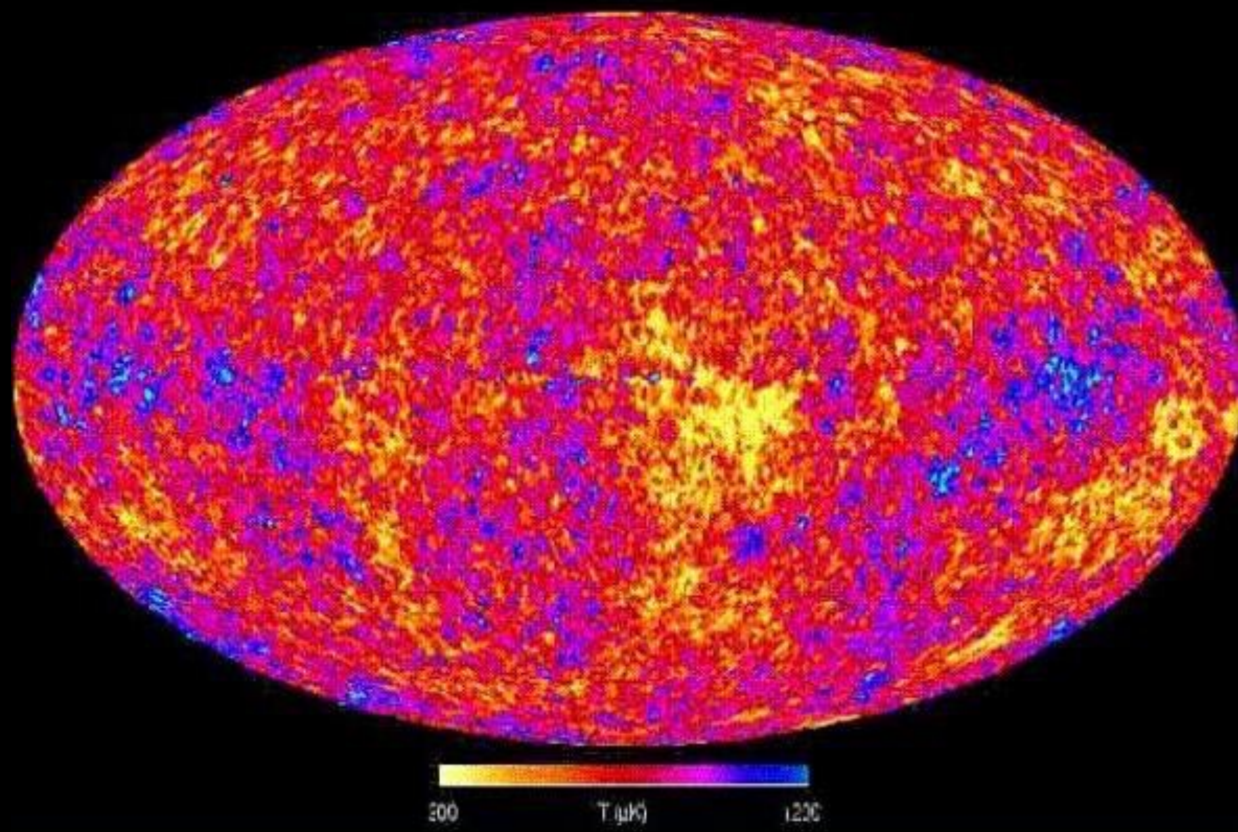
0-5% AuAu
@19.6 GeV

indispensable information for the critical point search

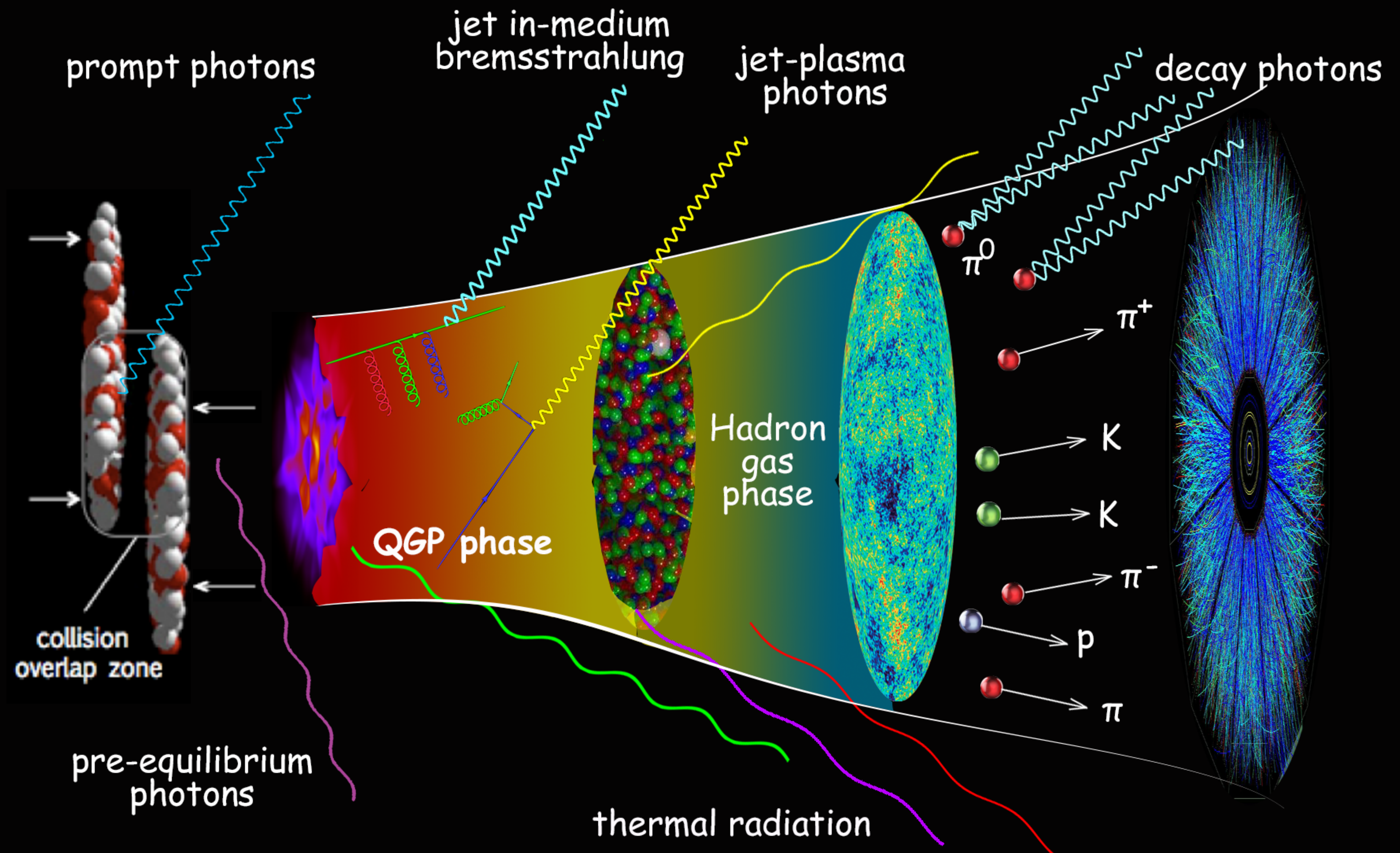
How can we probe it?

Probes for Quark Gluon Plasma

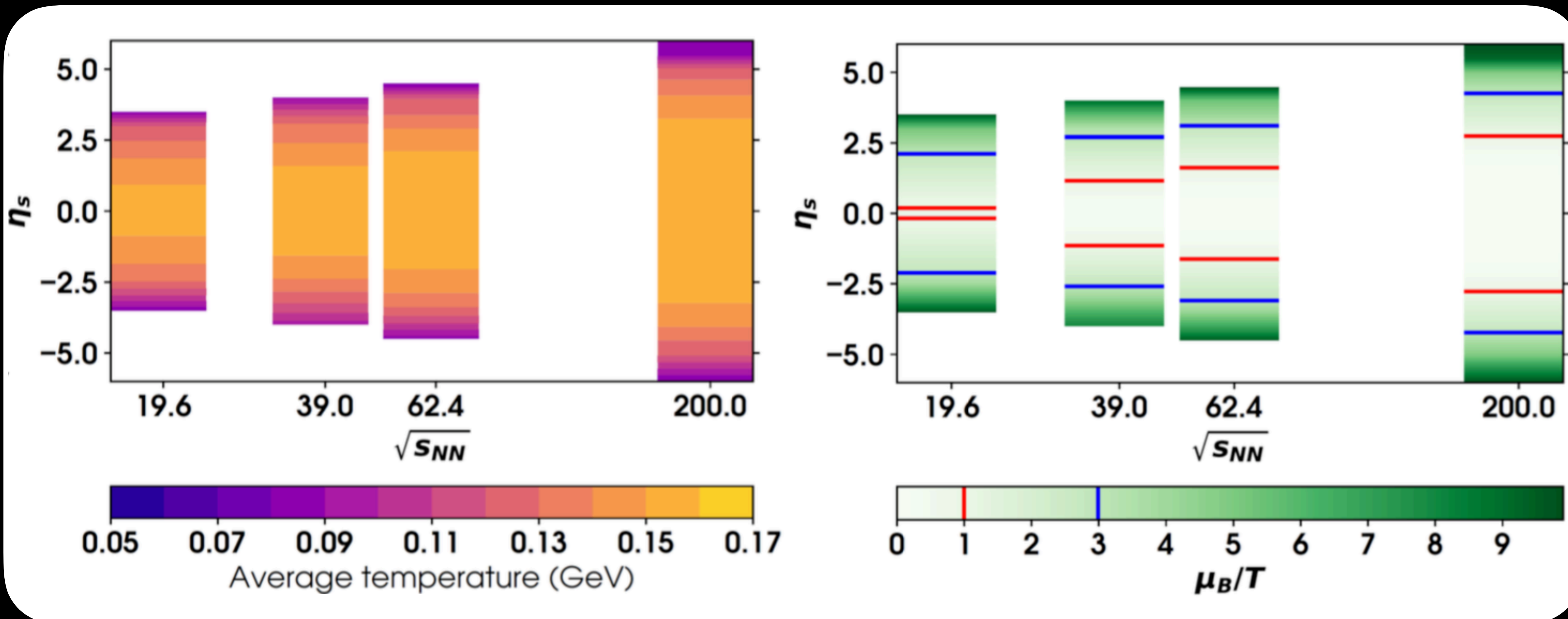
- Electromagnetic radiation



EM radiation in heavy-ion collisions



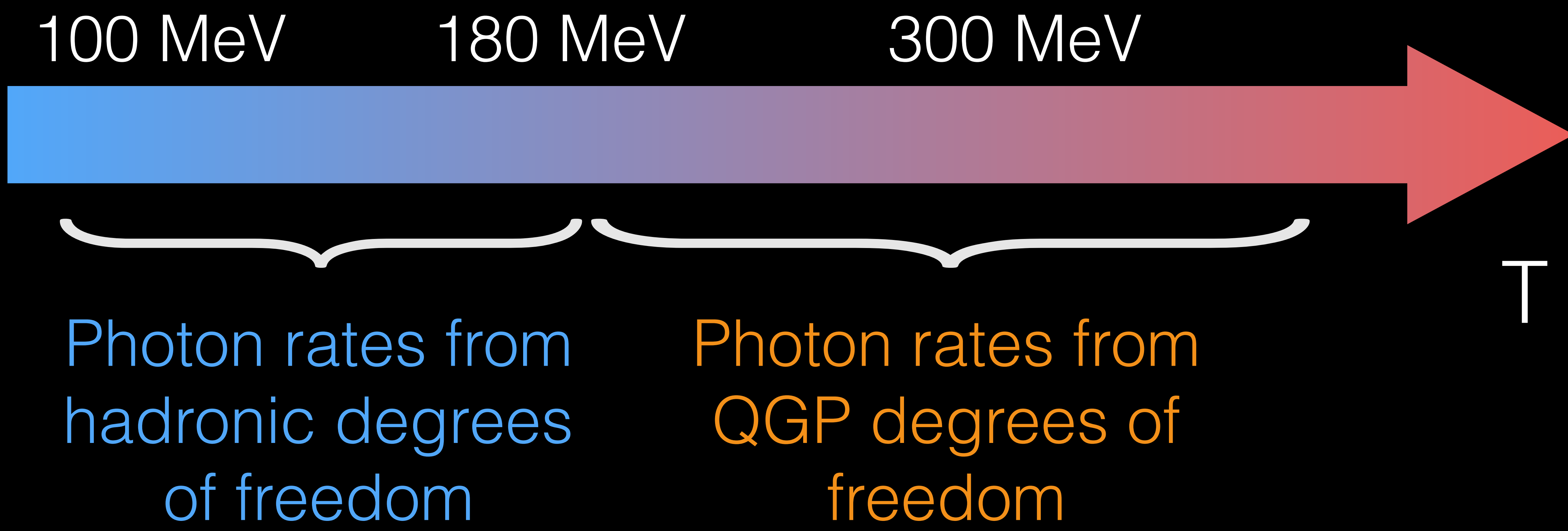
HIC thermodynamics at RHIC BES



Temperature averaged over the plasma's lifetime
(depend on freeze-out energy density)

Baryon chemical potential to temperature ratio
(μ_B/T reaches up to ~3)

Photon rates at finite μ_B



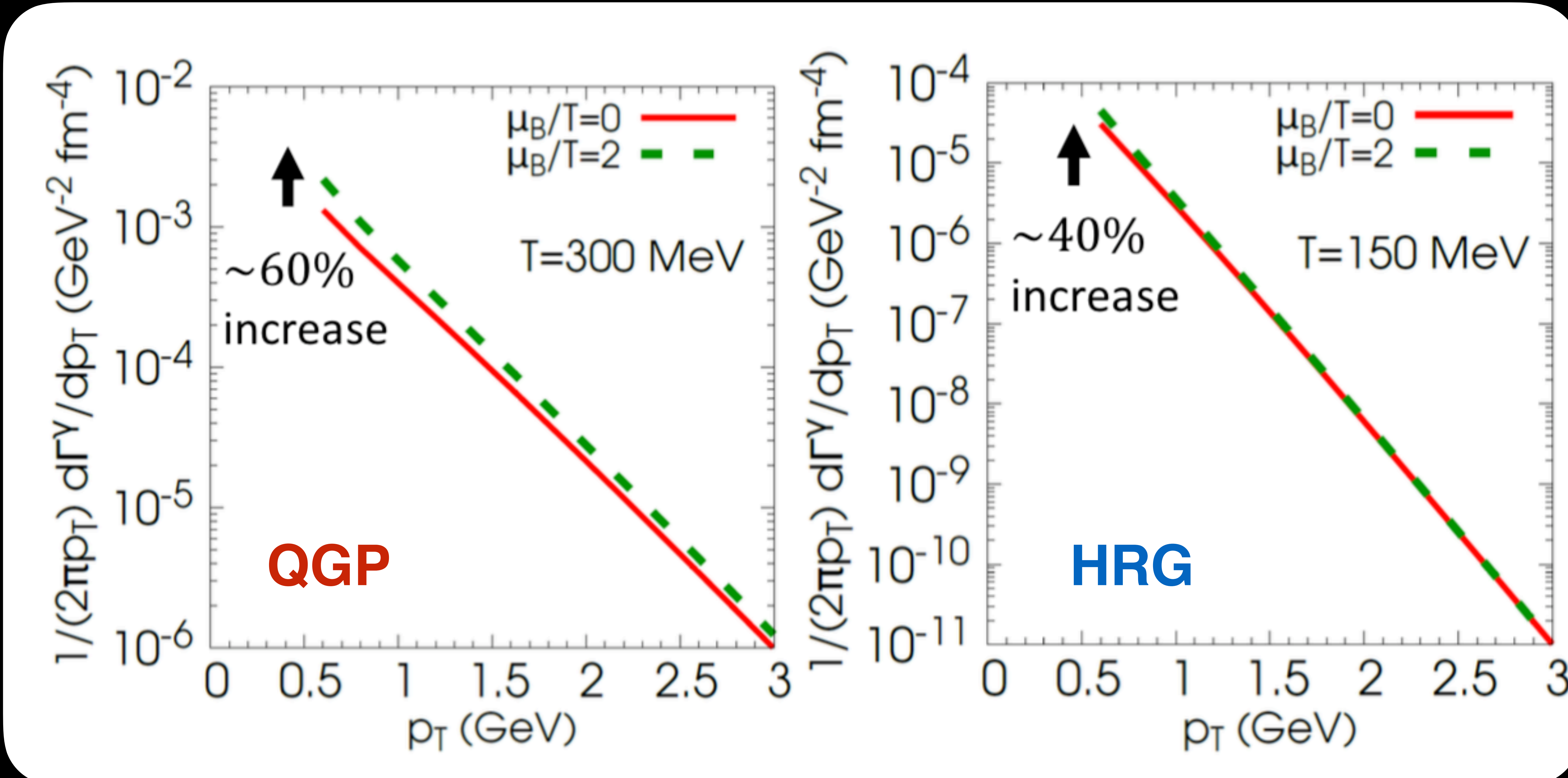
QGP rates: Compton scatterings, $q\bar{q}$ annihilation & bremsstrahlung (with LPM) at finite μ_B

Traxler, Vija, Thoma (1995); Gervais, Jeon (2012);

Hadronic rates: meson scatterings & baryon interactions (at finite μ_B)

Turbide, Rapp, Gale (2004); Heffernan, Hohler, Rapp (2014); Holt, Hohler, Rapp (2016)

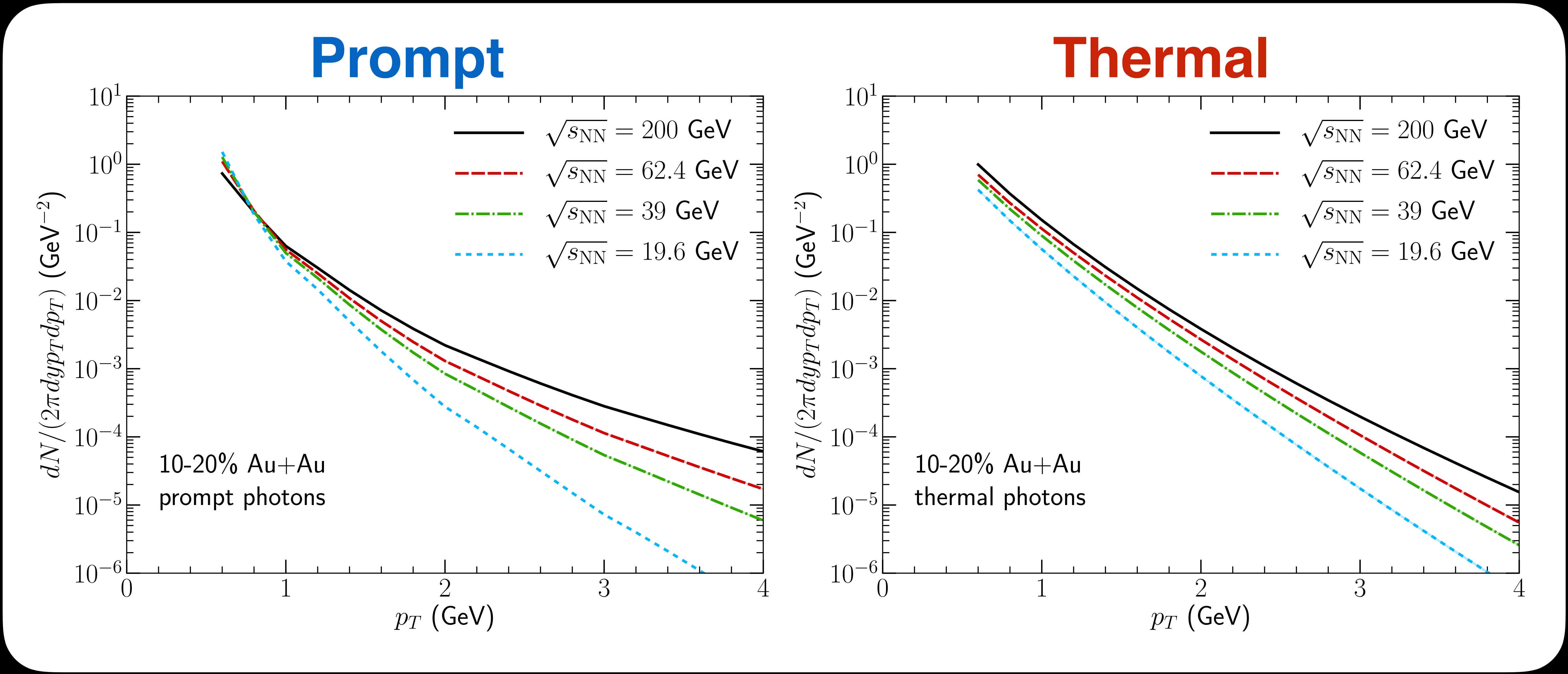
Photon rates at finite μ_B



- Baryon chemical potential increases photon rates at low transverse momentum

Photon production in RHIC BES energies

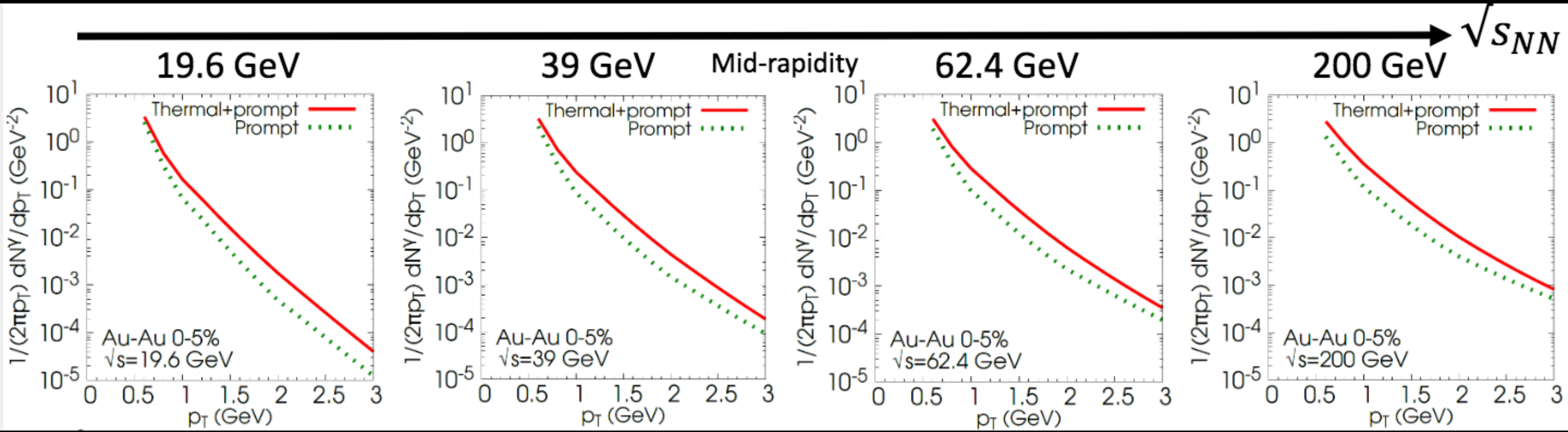
C. Gale, S. Jeon, S. McDonald, J.F. Paquet and C. Shen, arXiv:1807.09326 [nucl-th]



- Prompt photons decreases faster than thermal photons as collision energy goes down

Photon production in RHIC BES energies

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



Thermal photons are visible for all collision energies

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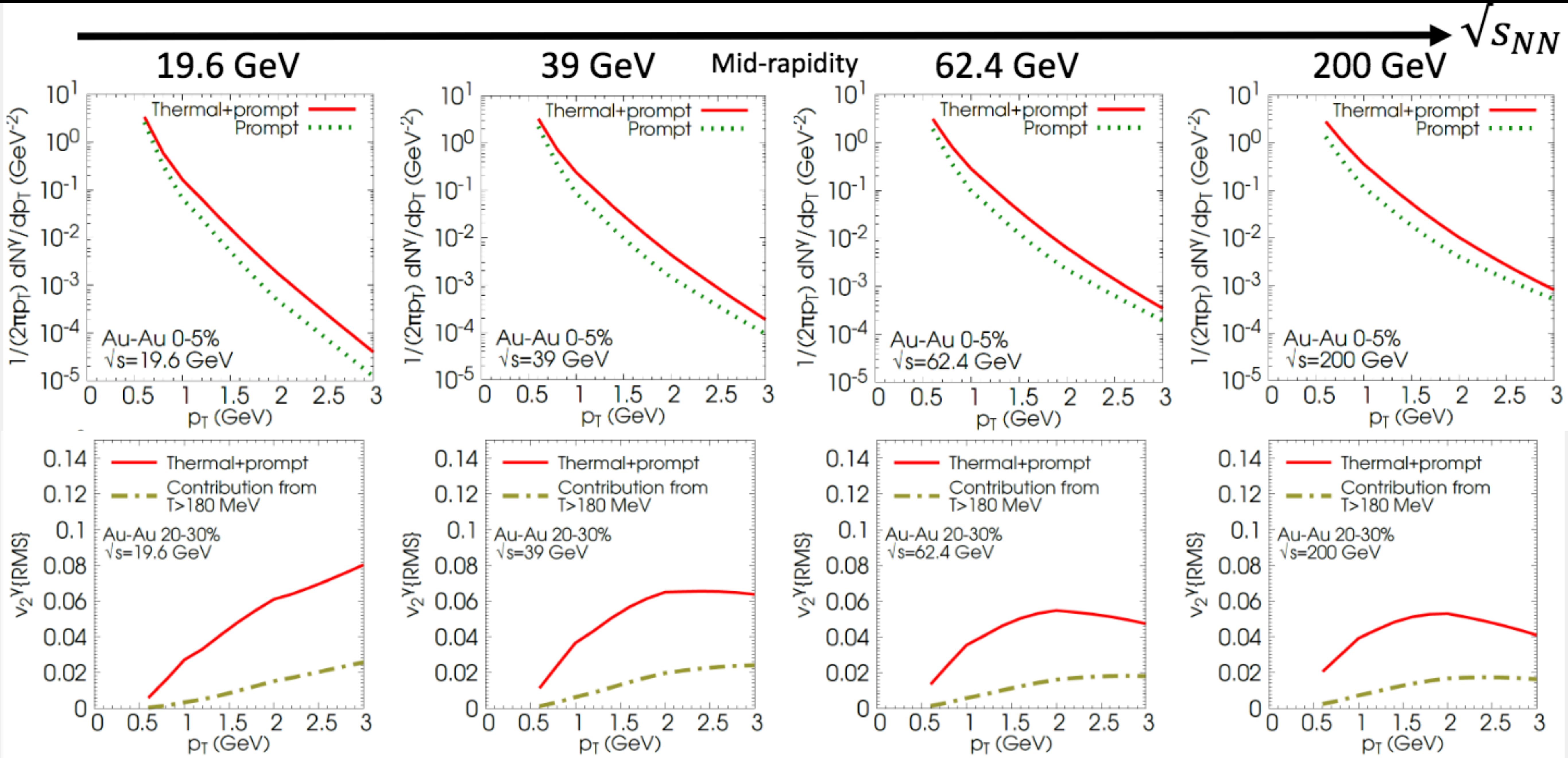
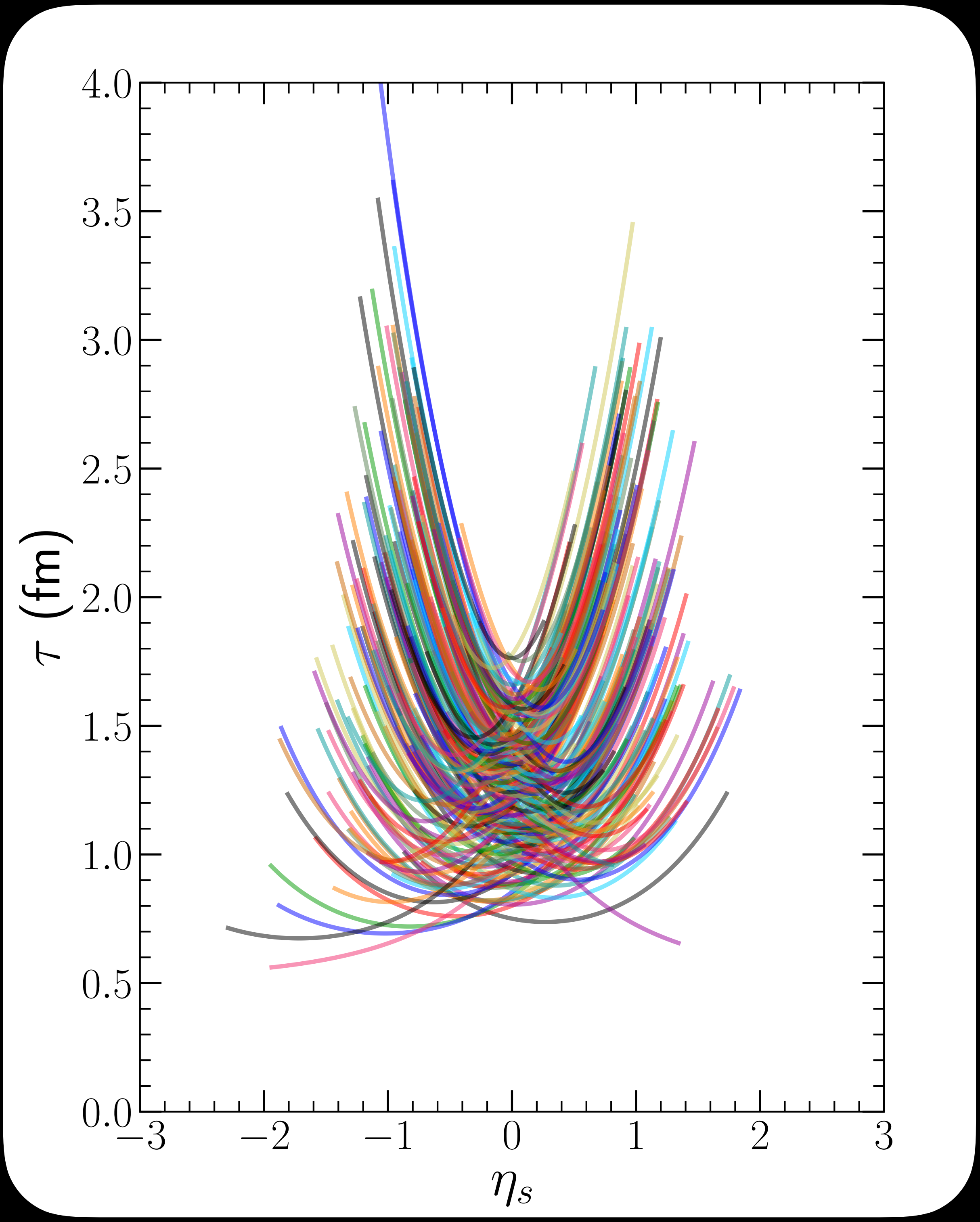
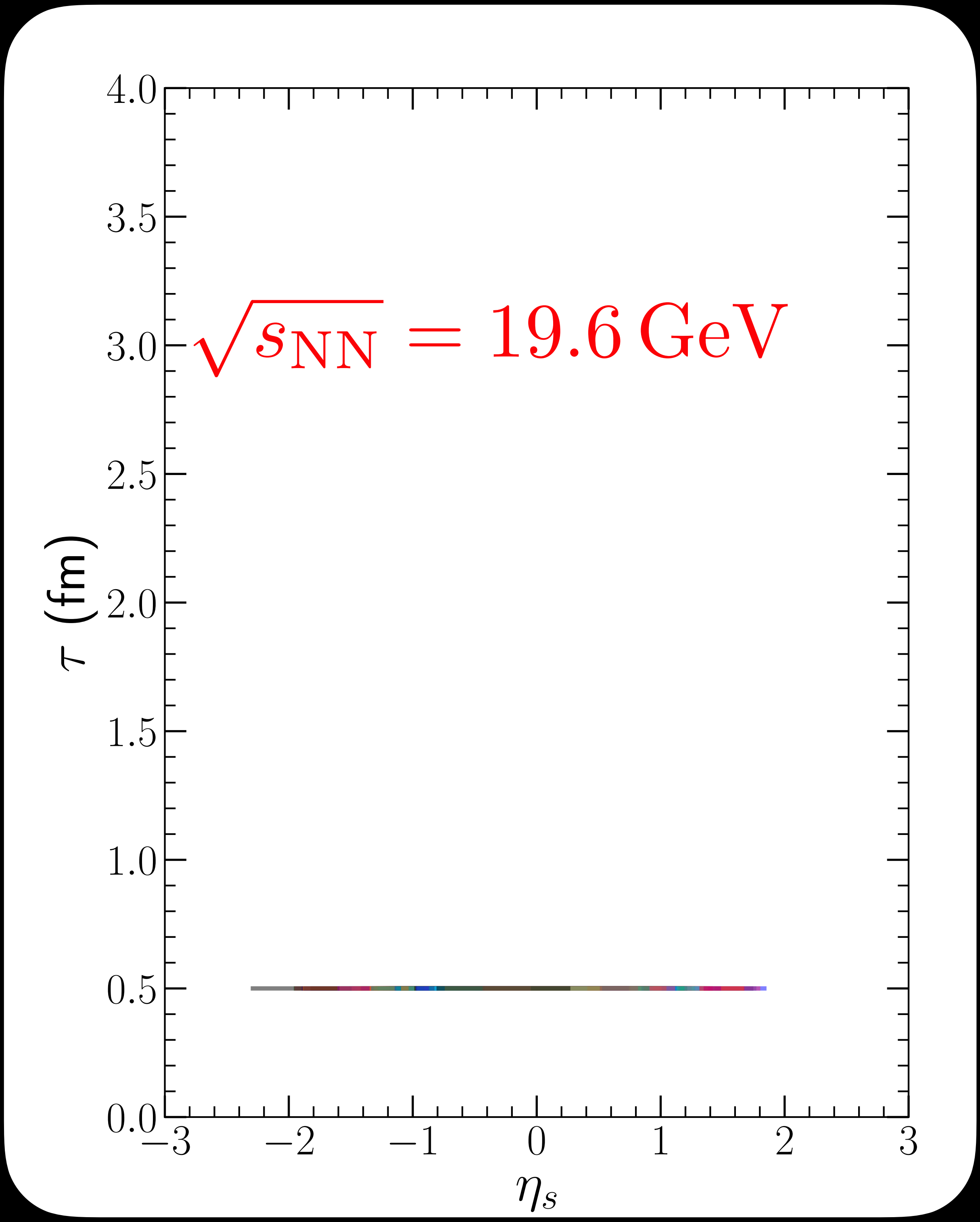


Thermal photons are visible for all collision energies

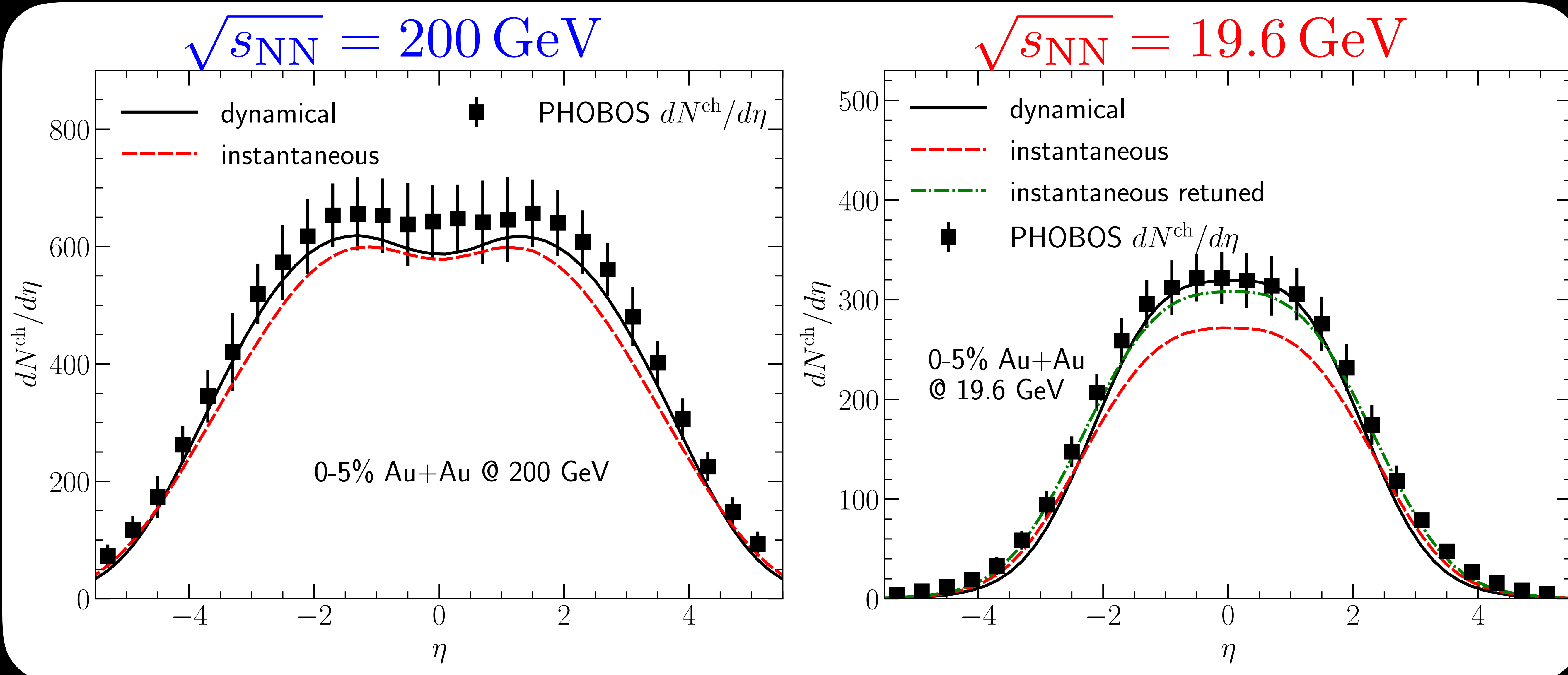
Do we really need dynamical initialization?



vs.

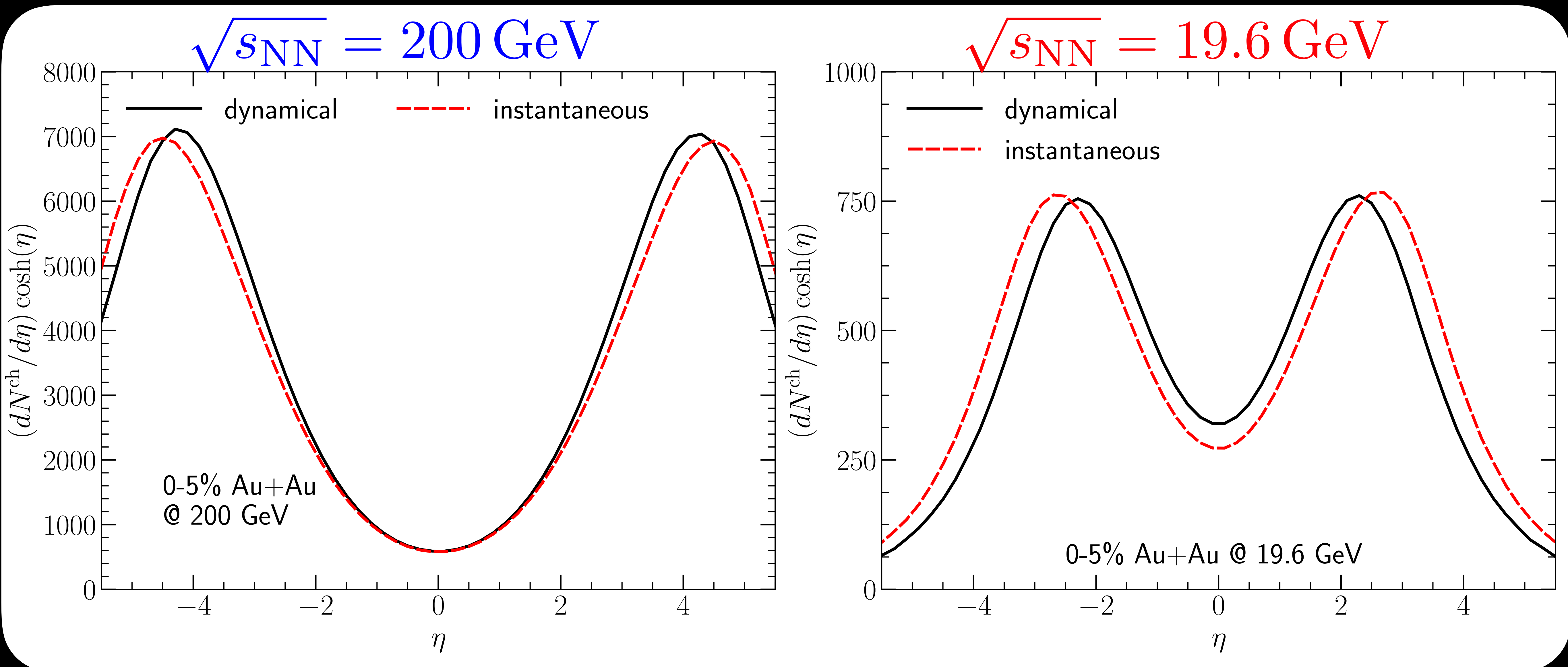


Dynamical vs instantaneous initialization



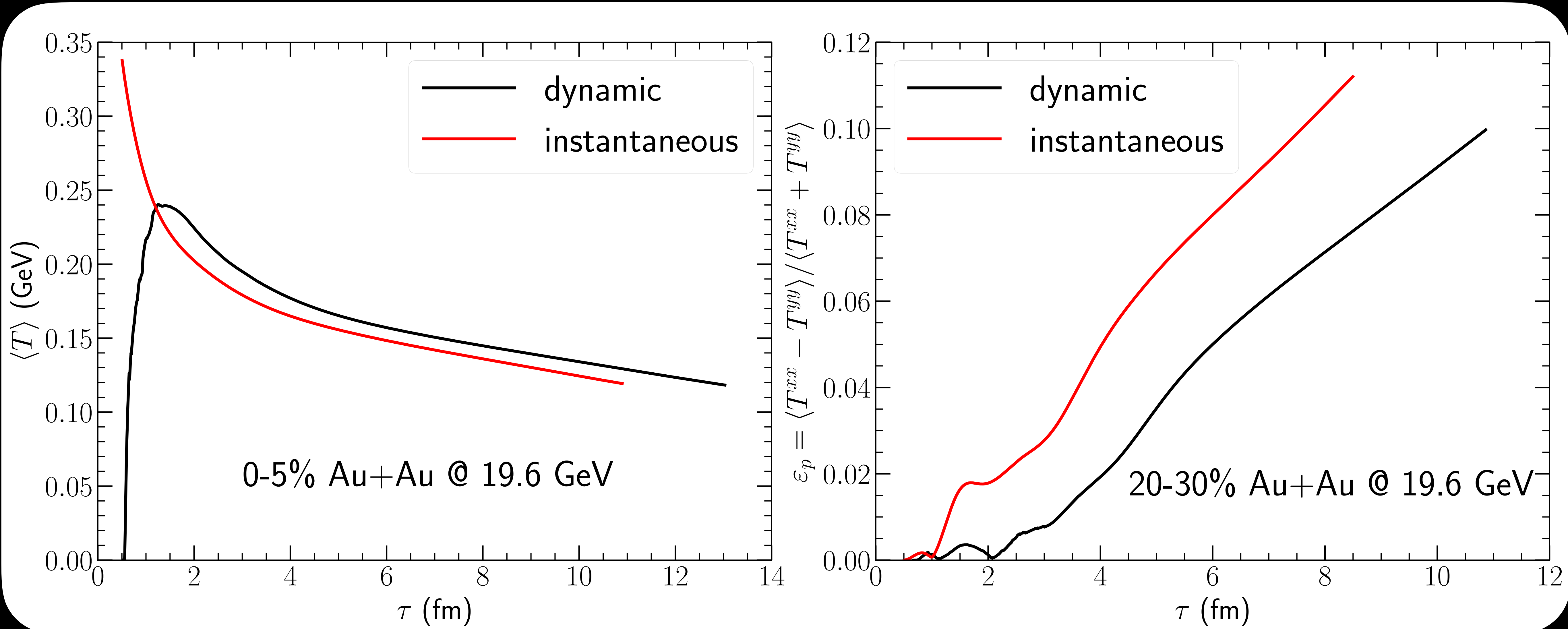
- With the same input collision energy, instantaneous initialization results in 10-15% smaller charged multiplicity at mid-rapidity at 19.6 GeV

Dynamical vs instantaneous initialization



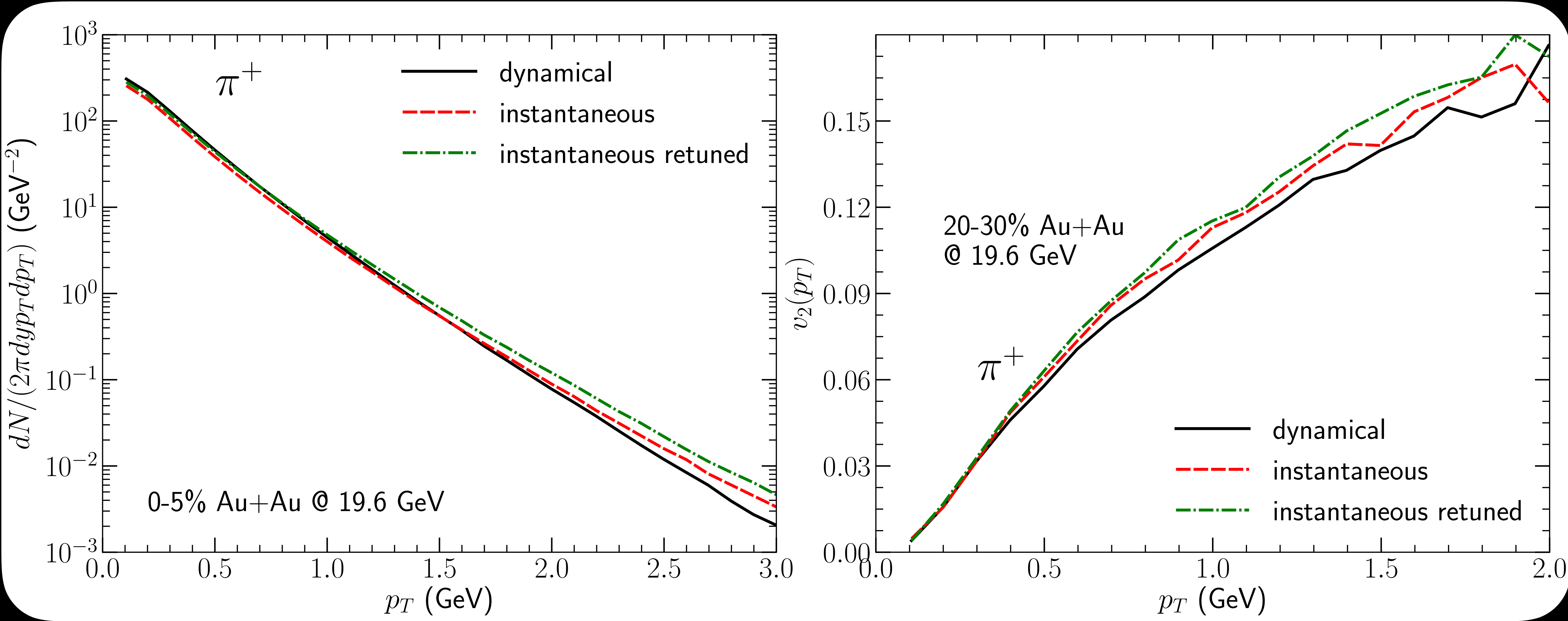
- Instantaneous initialization starts with an earlier longitudinal expansion and pushes more energy to the forward rapidity region

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

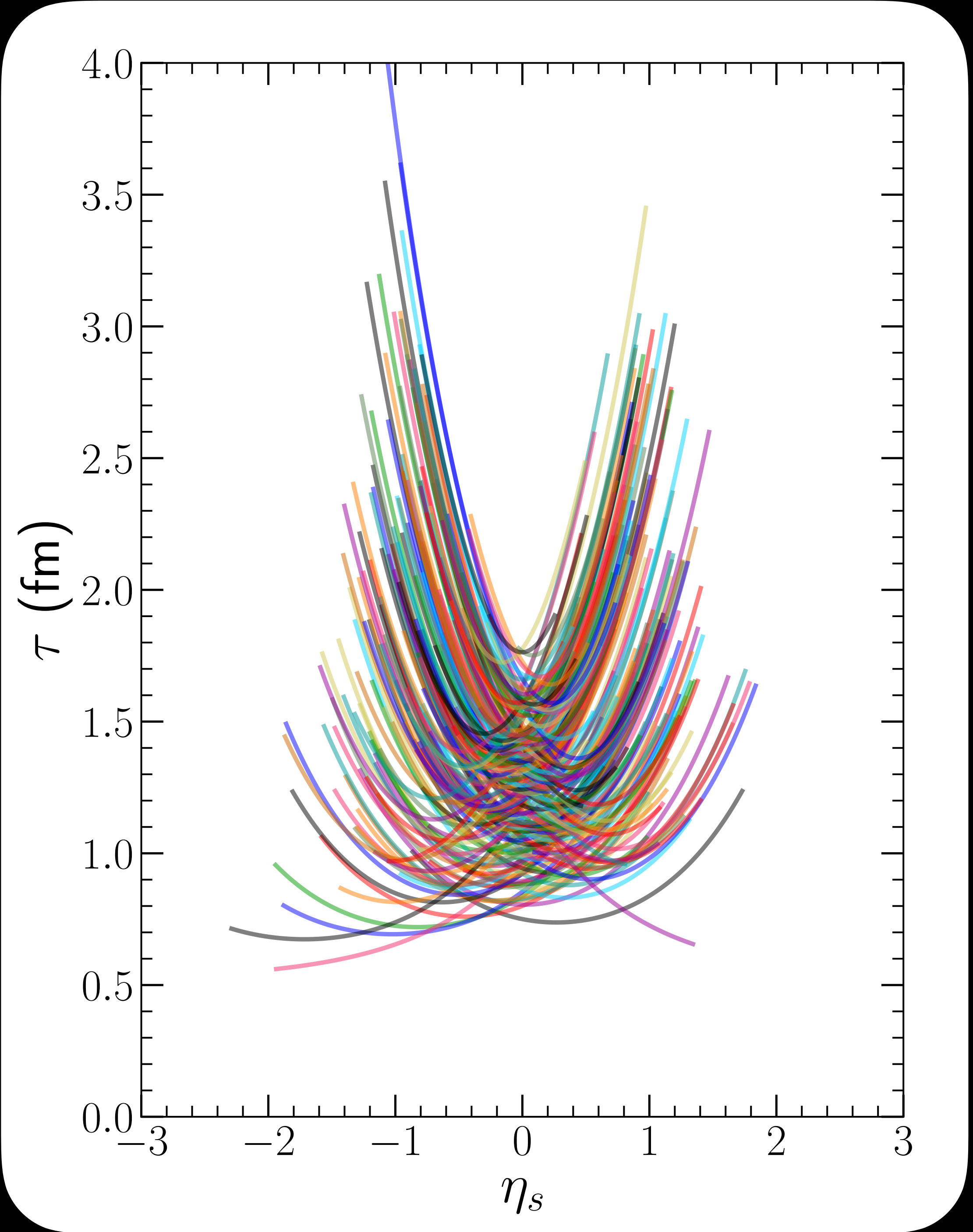


- Dynamical initialization results steeper particle spectra and smaller $v_2(p_T)$

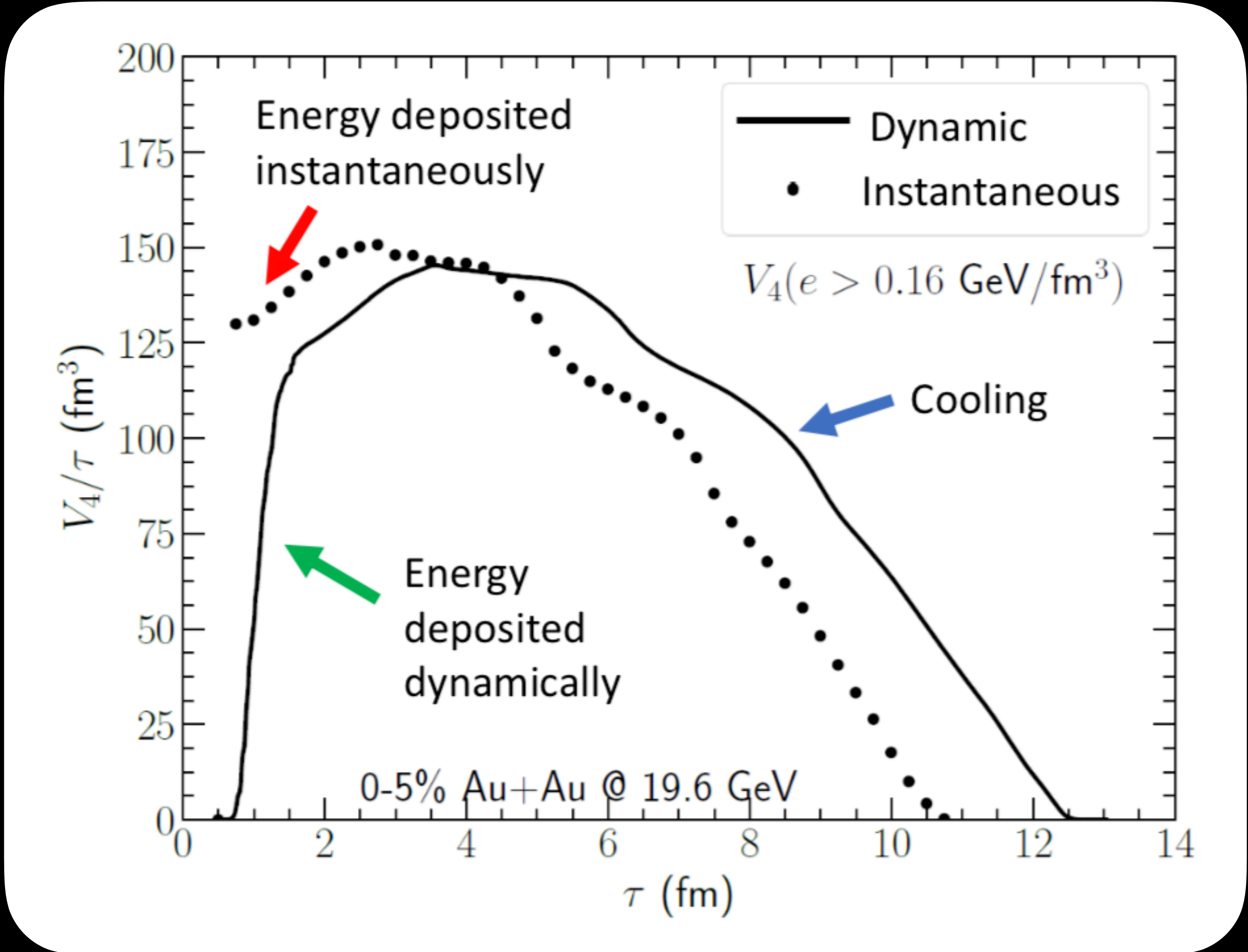
5-10% less radial and elliptic flow

= 20-50% variation on extracted transport coefficients

Probing the early-time dynamics



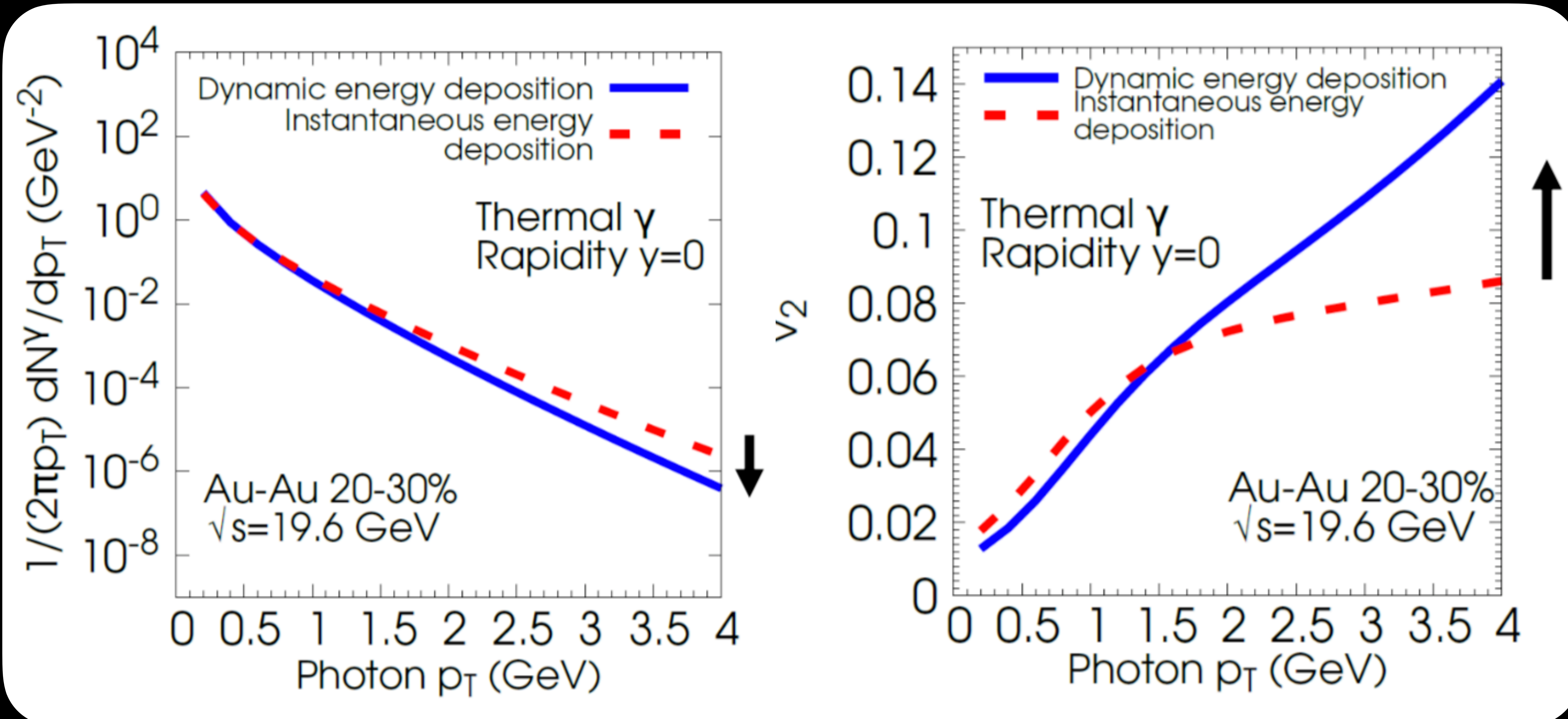
Space-time 4-volume (above freeze-out) versus time



Early photon production will be affected by the reduction of space-time volume

Probing the early-time dynamics

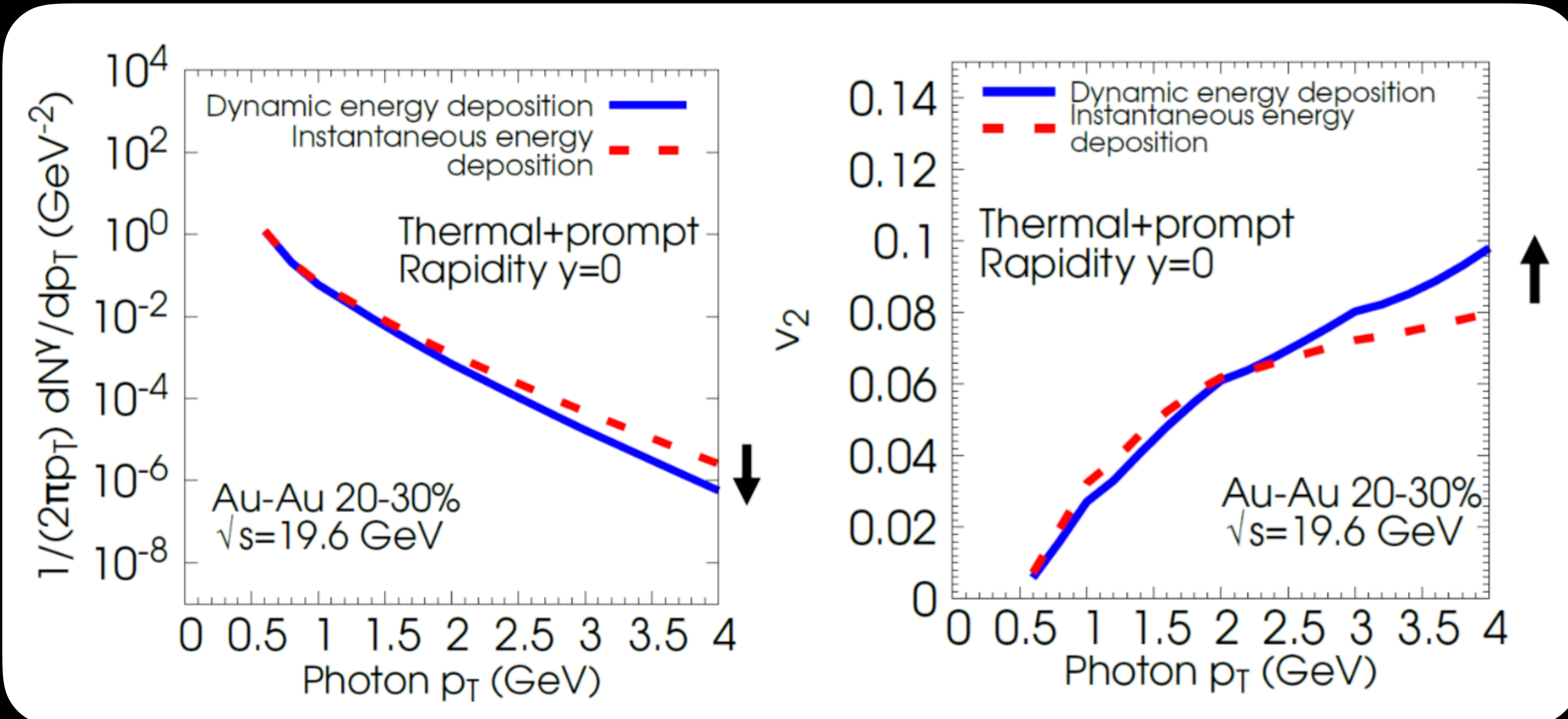
Thermal photons $\sqrt{s_{NN}} = 19.6\,\mathrm{GeV}$



Effect of energy deposition (instantaneous vs dynamic) is visible in photons

Probing the early-time dynamics

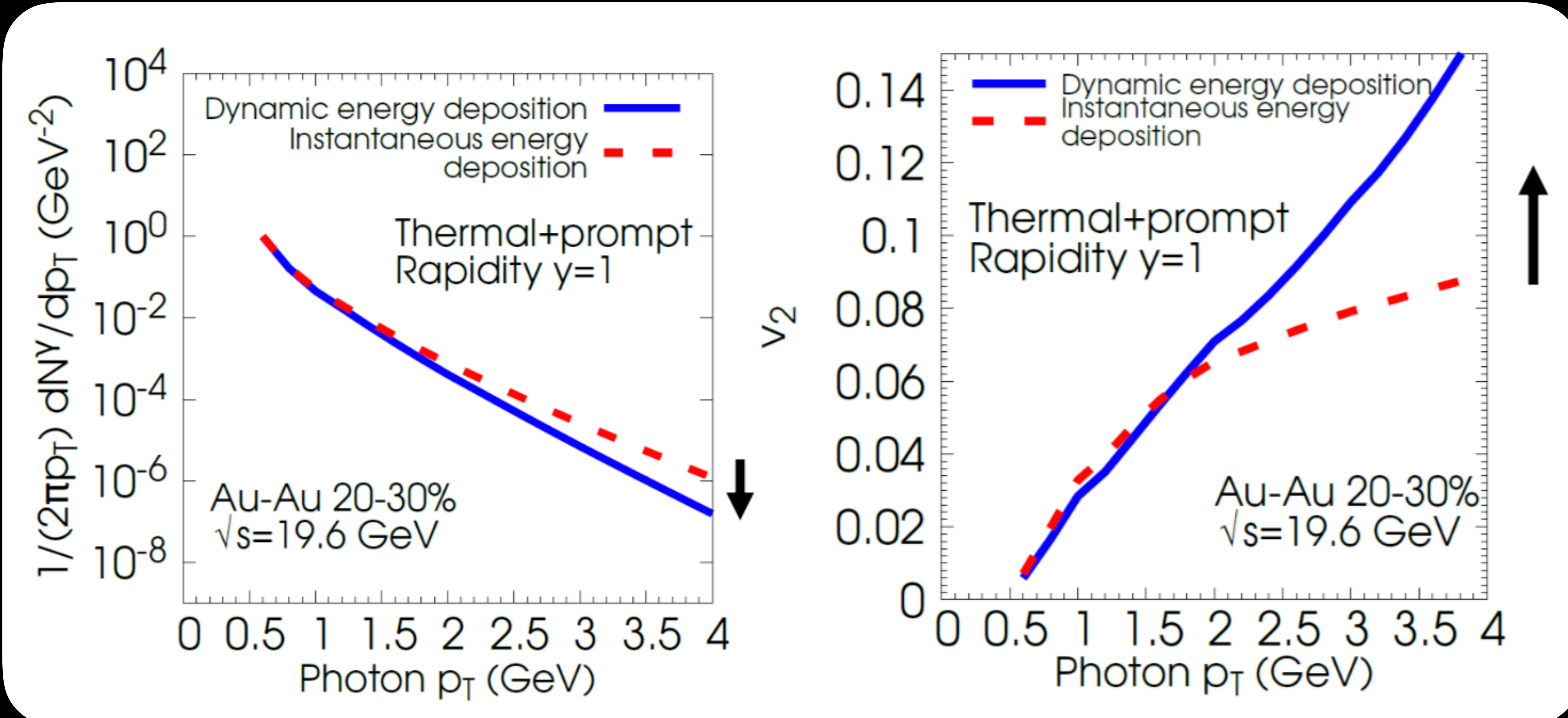
$y = 0$ Thermal + prompt $\sqrt{s_{\rm NN}} = 19.6\,{\rm GeV}$



Effect of energy deposition (instantaneous vs dynamic) is visible in photons

Probing the early-time dynamics

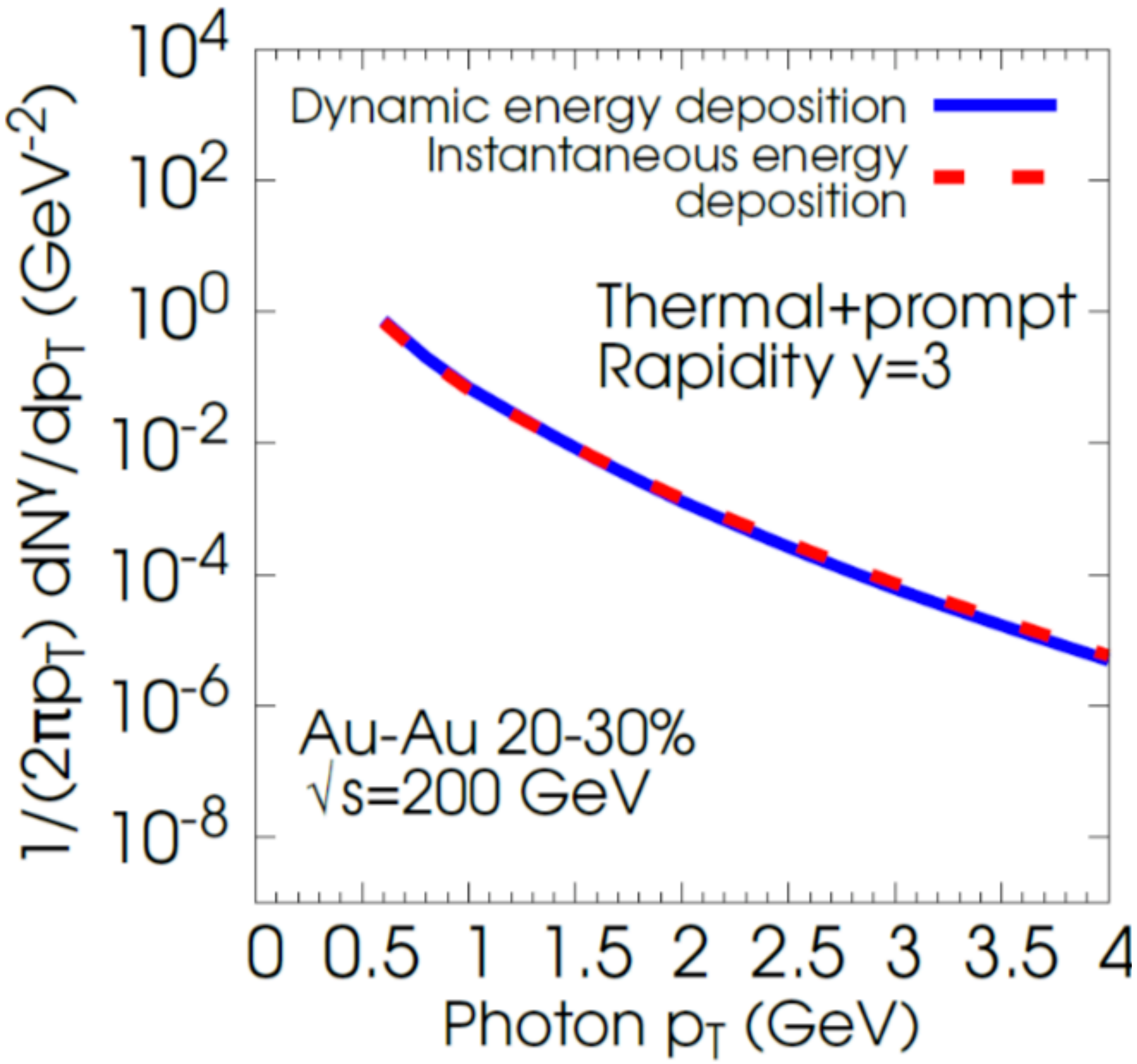
$y = 1$ Thermal + prompt $\sqrt{s_{\rm NN}} = 19.6\,{\rm GeV}$

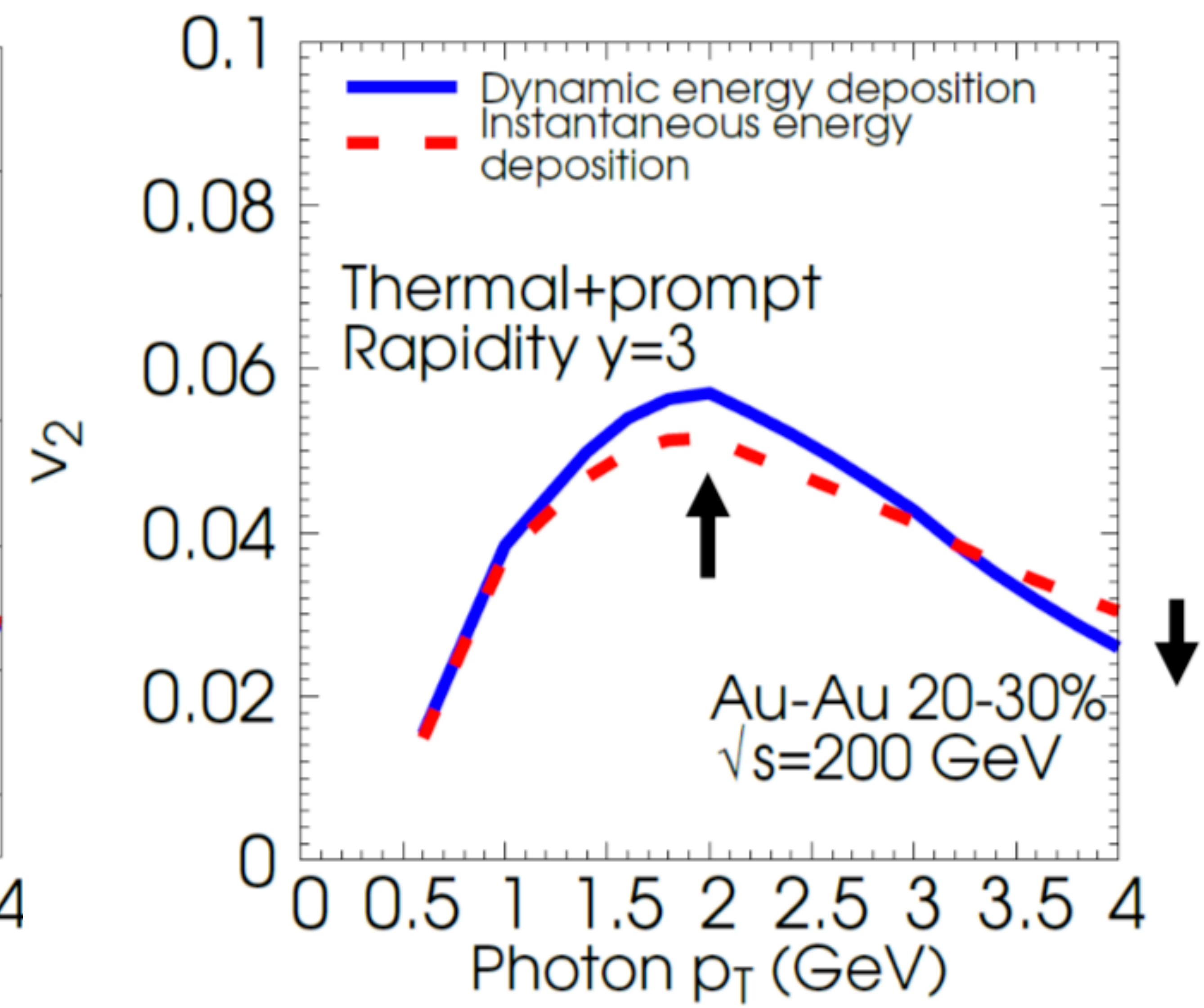


Effect of energy deposition (instantaneous vs dynamic) is visible in photons

Probing the early-time dynamics

$y = 3$ Thermal + prompt $\sqrt{s_{\rm NN}} = 200\,{\rm GeV}$





At high collision energy, the dynamical effect is visible at high rapidity

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

- Photons are **unique** direct probes of this complex dynamics of heavy-ion collisions at RHIC BES

  Significant thermal photon signals

  High sensitivity to the early stage dynamics

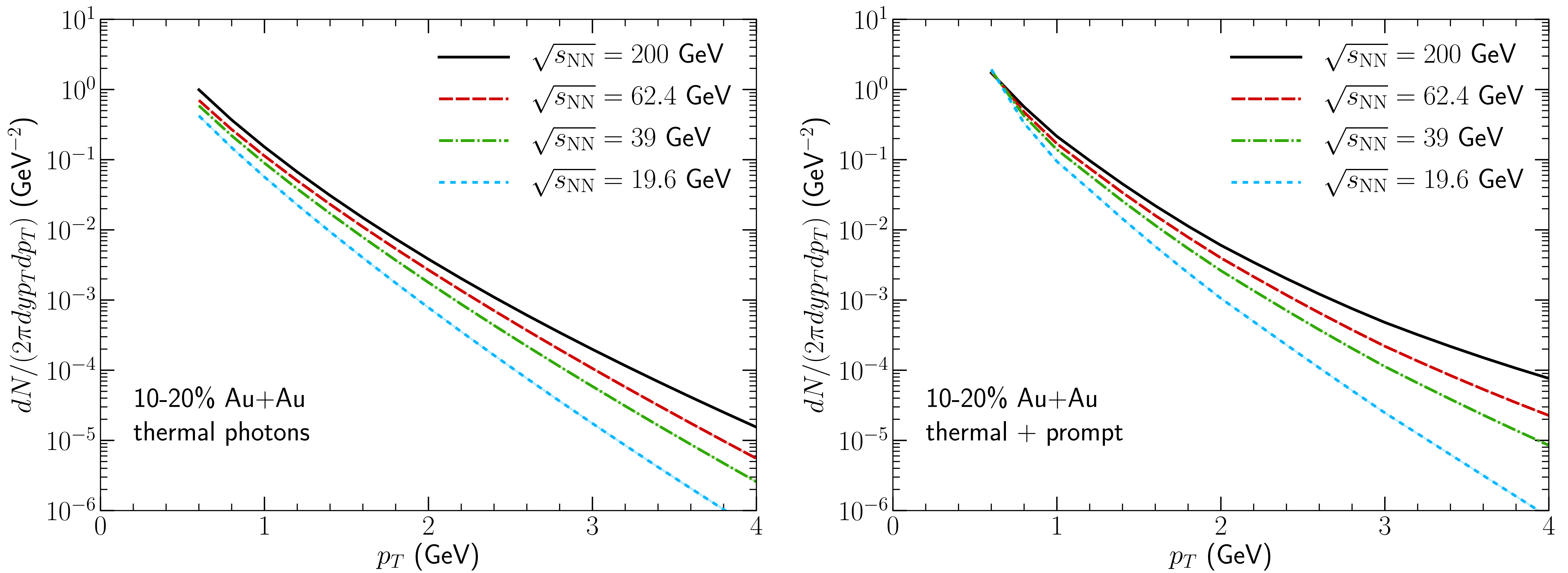
  Prompt photons at low energies are challenging

Dileptons will come soon …


BACKUP

Photon production in RHIC BES energies

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

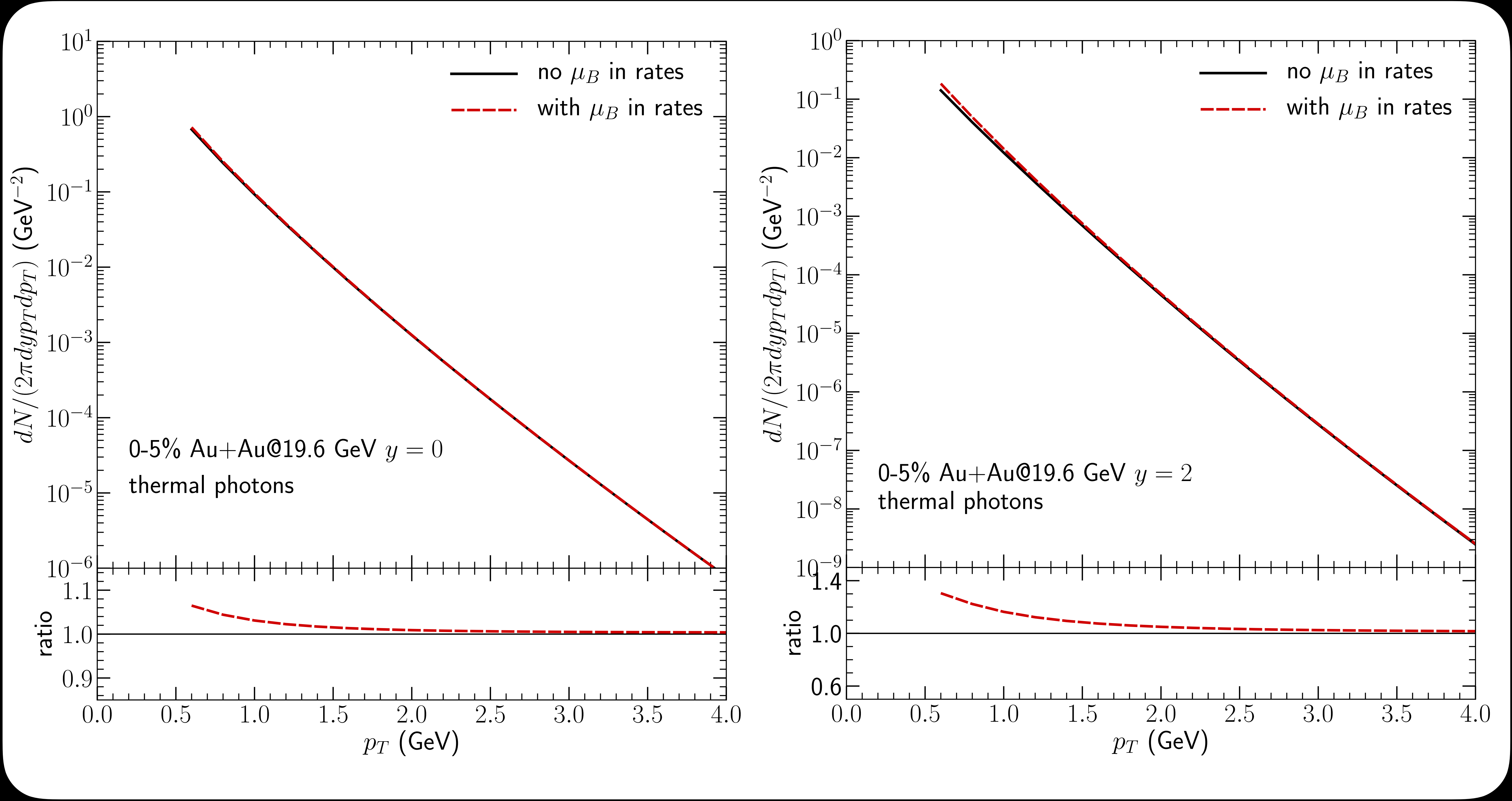


Thermal photons are visible for all collision energies

Chun Shen (WSU)

Photon production in RHIC BES energies

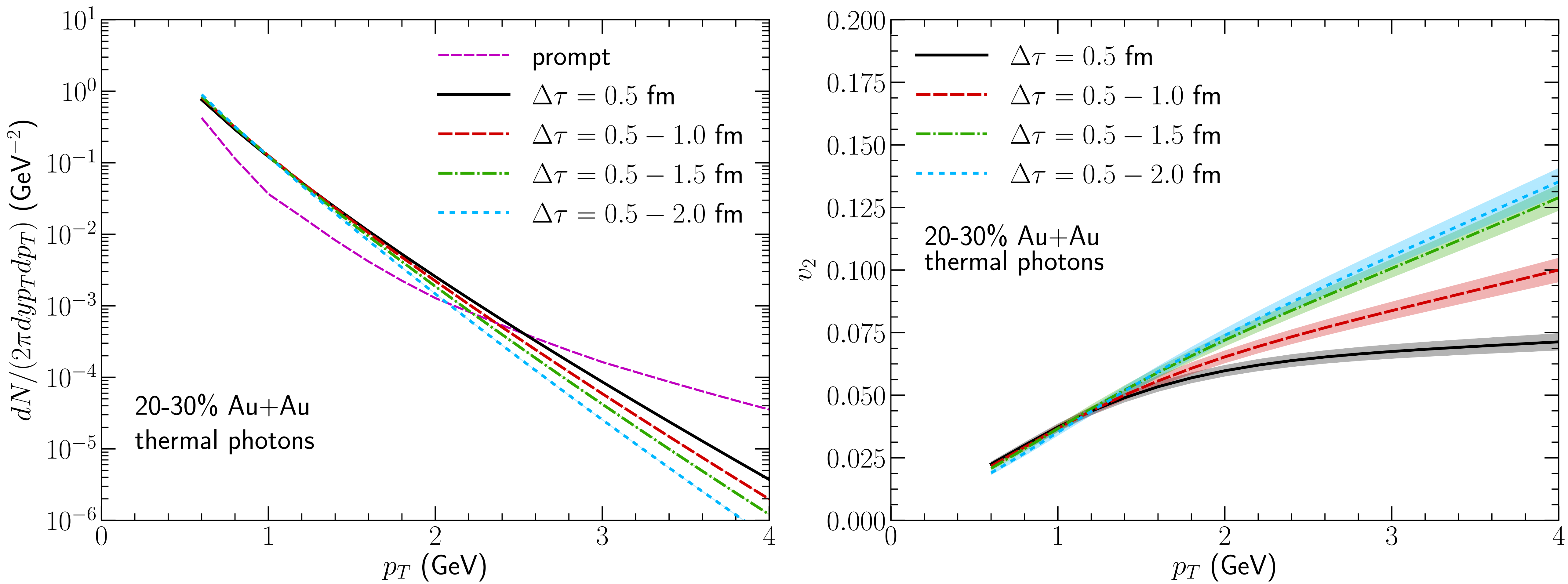
C. Gale, S. Jeon, S. McDonald, J.F. Paquet and C. Shen, arXiv:1807.09326 [nucl-th]



Enhancement from μ_B is small

Will dynamical initialization help photon observables?

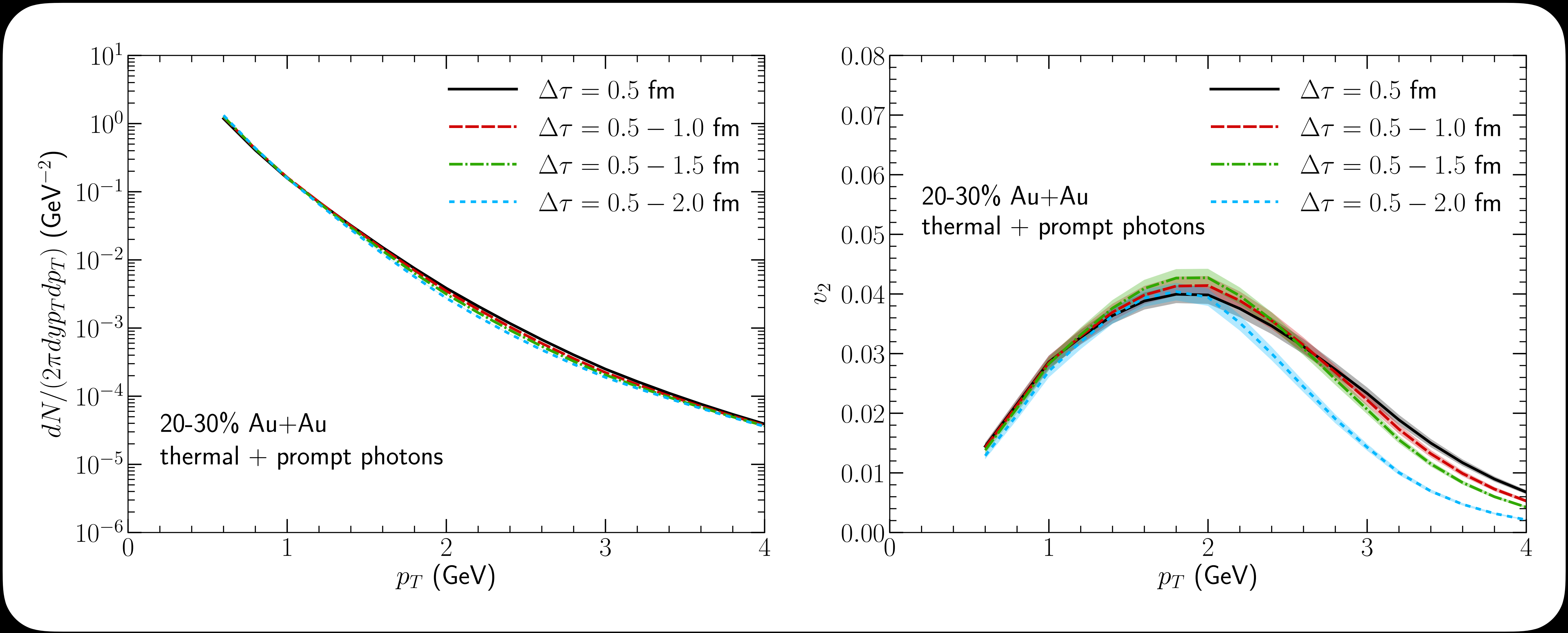
C. Gale, S. Jeon, S. McDonald, J.F. Paquet and C. Shen, arXiv:1807.09326 [nucl-th]



- A finite time interval of energy deposition leads to a reduction of thermal photon production and an increase of thermal photon v_2 at high p_T

Will dynamical initialization help photon observables?

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



- The prompt photons dilute the dynamical initialization effects on direct photon observables

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:

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

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

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

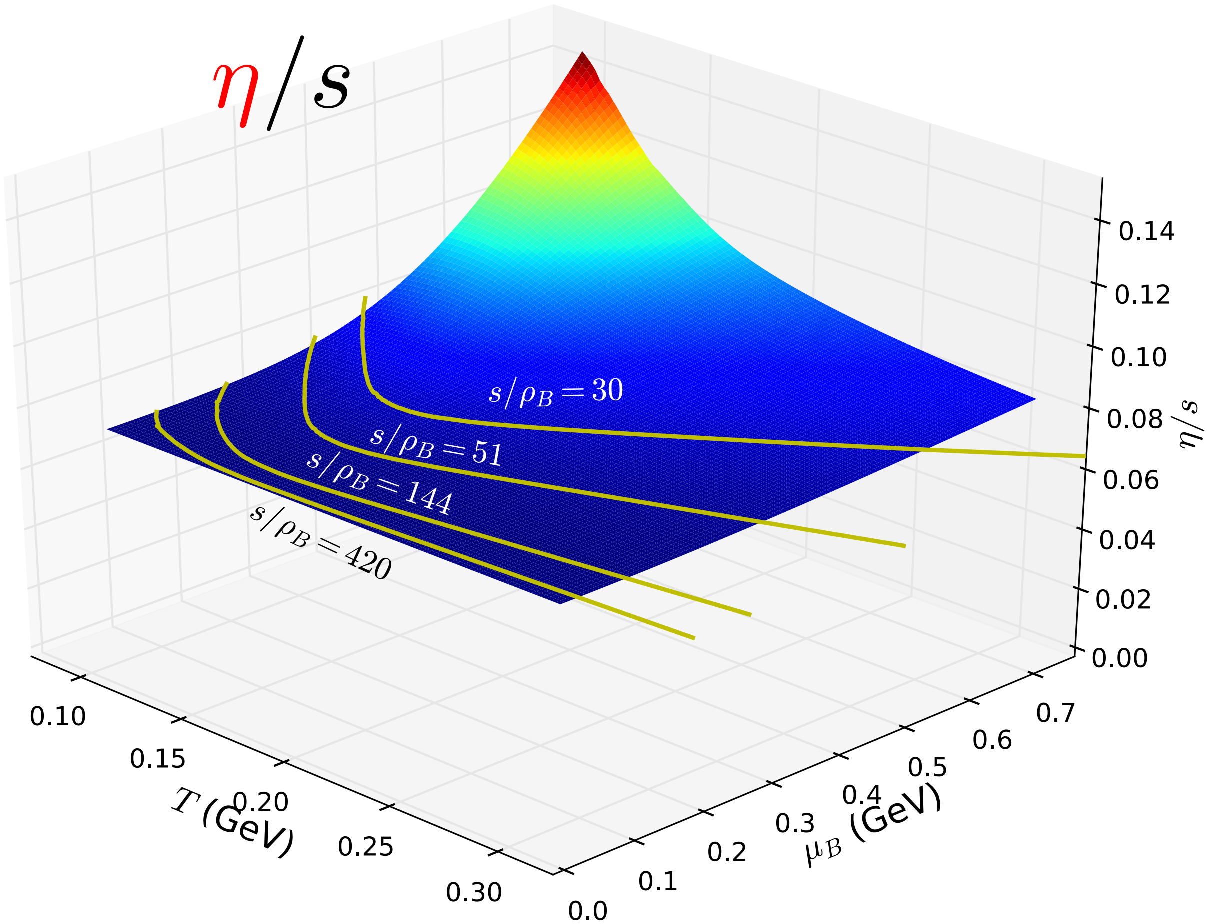
Transport coefficients

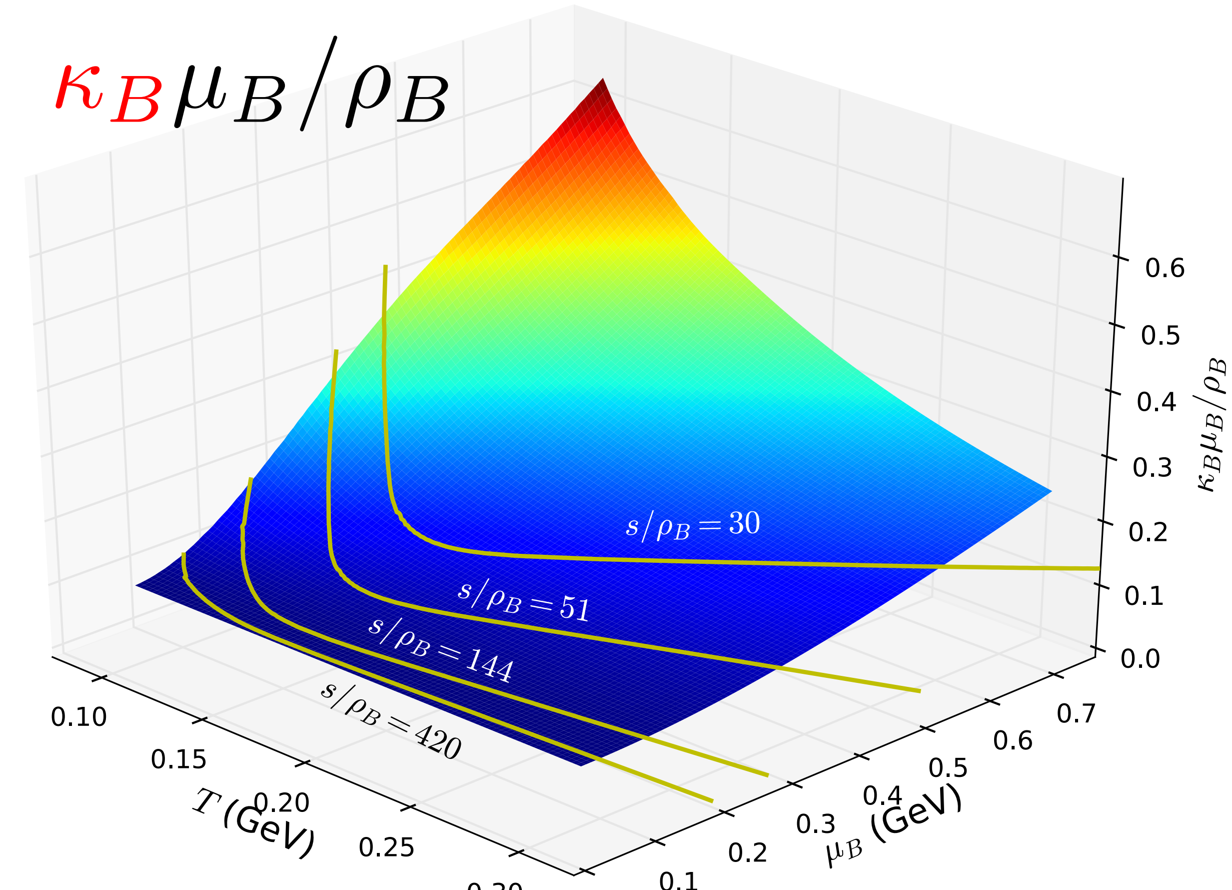
Dissipative part: (relaxation time approximation)

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

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

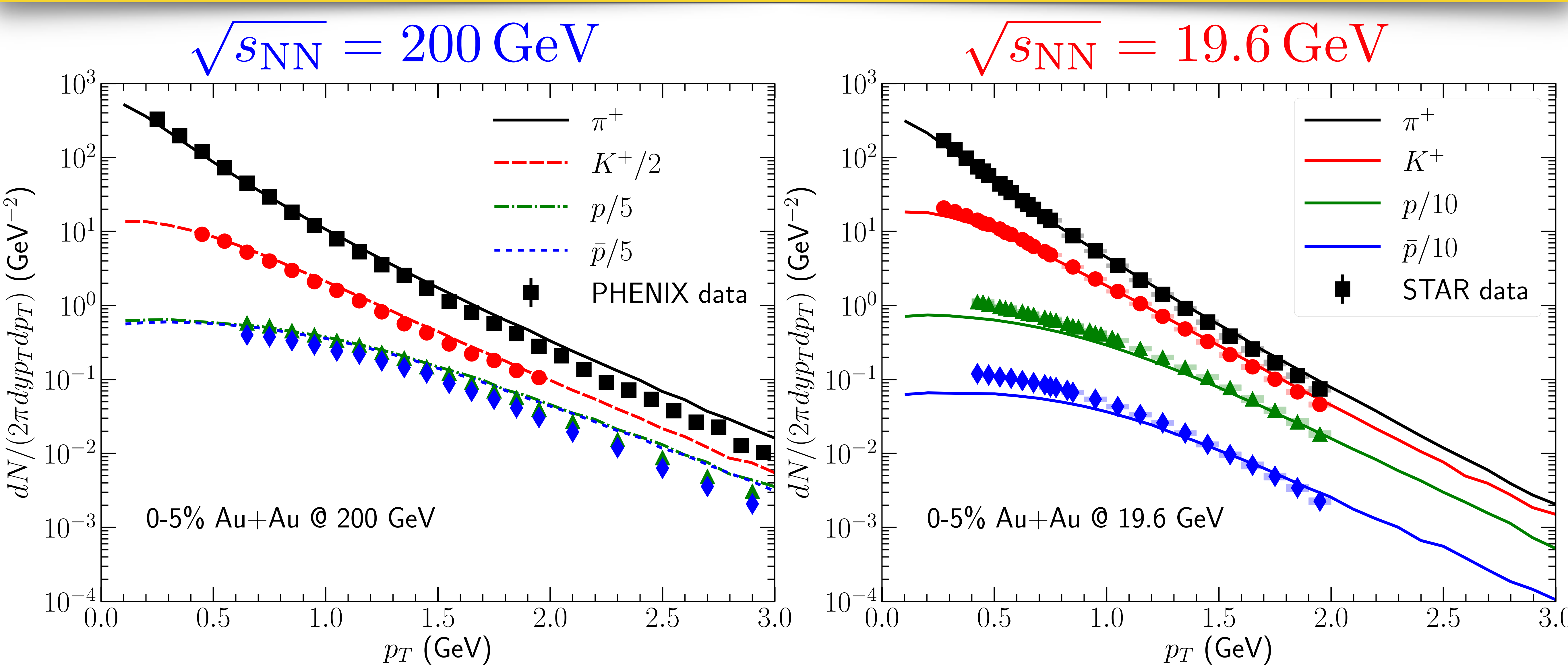
With non-zero μ, we choose $\tau_\pi = \tau_q = \frac{0.4}{T}$ $\quad \frac{\eta T}{e + \mathcal{P}} = 0.08$





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

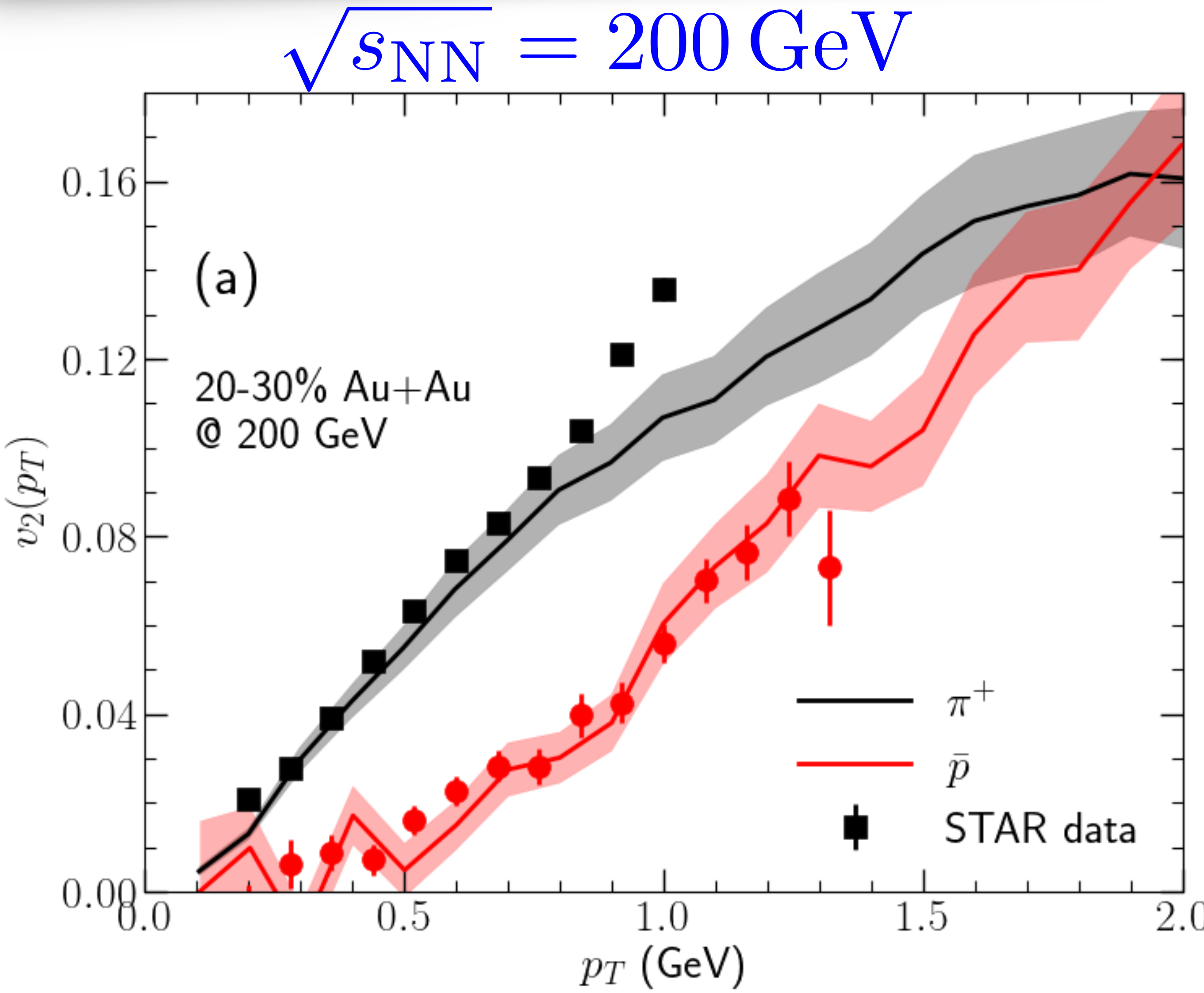
Transverse Dynamics

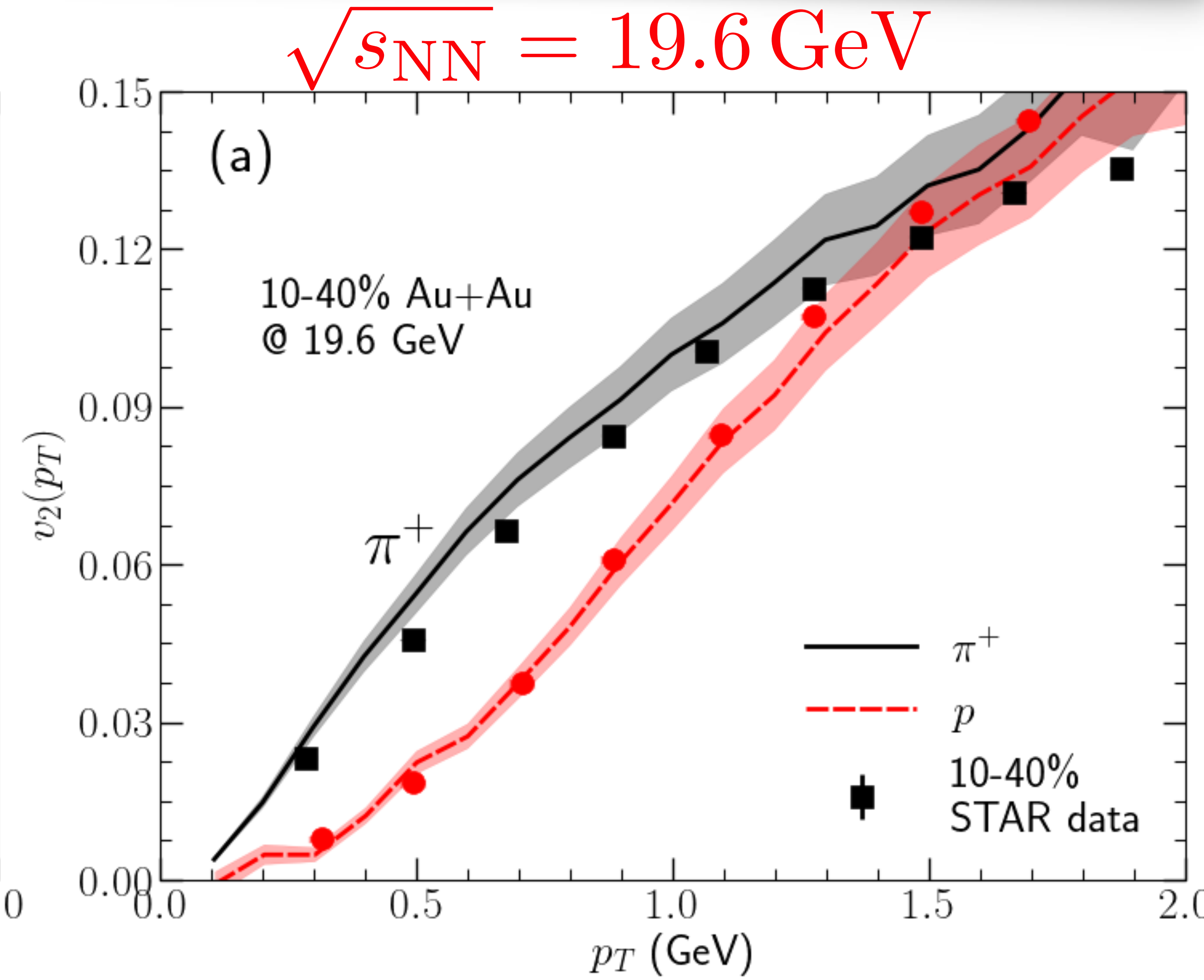


- Particle spectra are slightly flatter than the experimental data

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

Transverse Dynamics

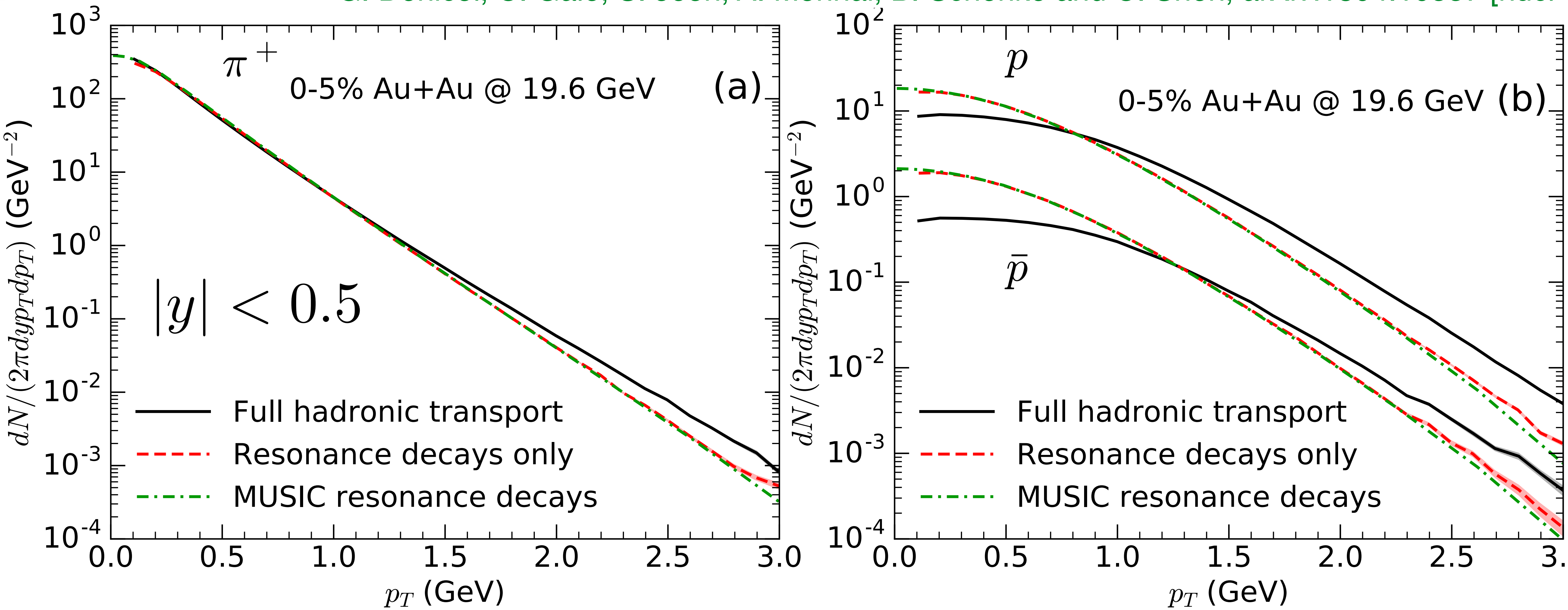




- Fair agreement of identified particle v2(p_T) at mid-rapidity
- Mass splitting is reproduced by the model

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]

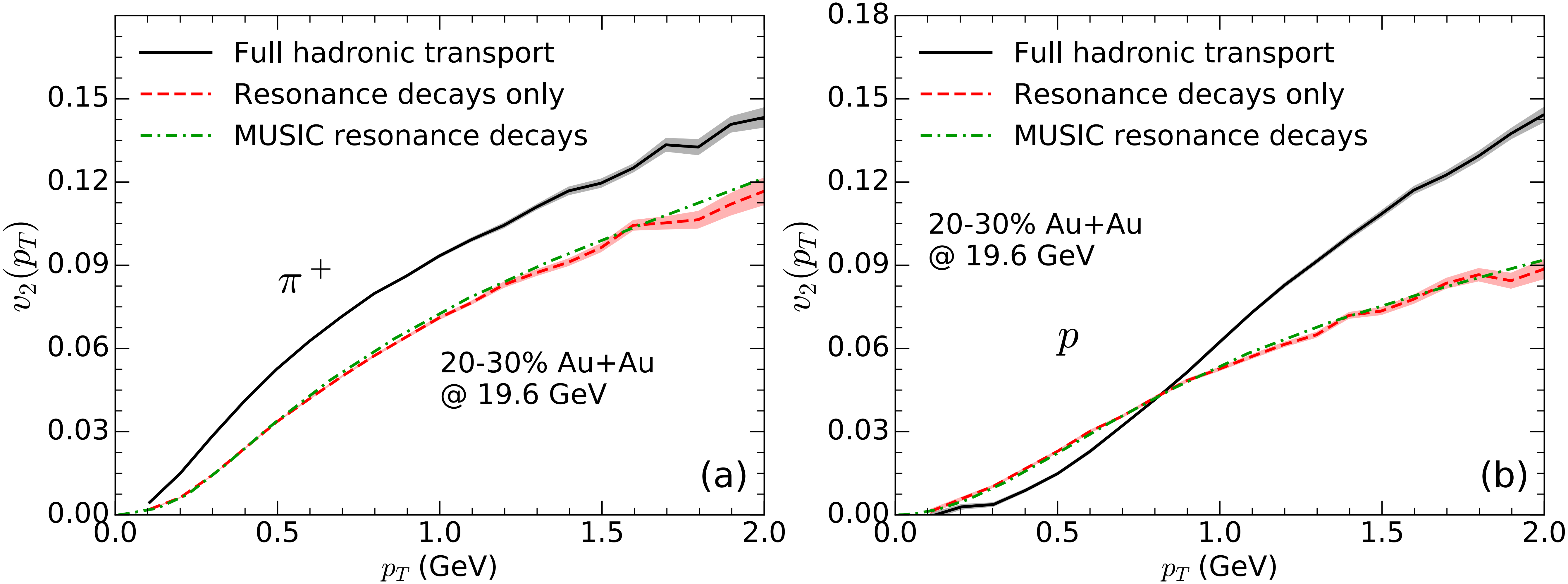


- Hadronic afterburner harden pion spectra at high p_T
- Heavy baryon spectra are largely affected

hadronic afterburner is essential for baryon spectra

Effects of hadronic afterburner on pid 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