Hybrid Model of Heavy-Ion Collisions at BES Energies with Dynamical Sources

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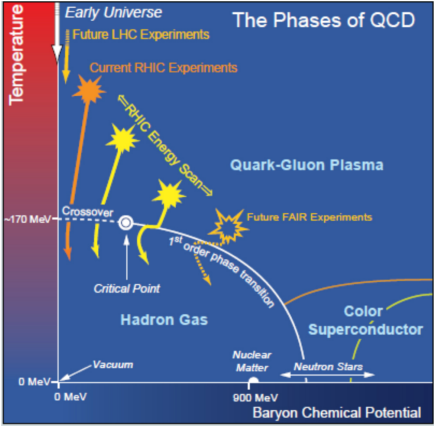
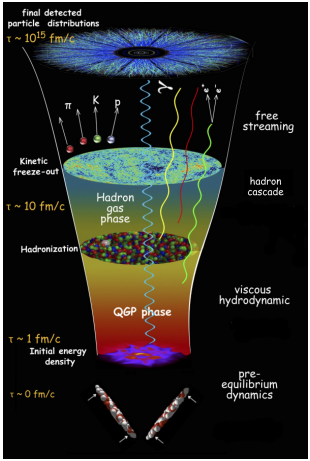
May 14, 2018

QCD phase diagram and heavy-ion collisions



2007 NSAC Long Range Plan



C. Shen *et al*, Comput.Phys.Commun. **199** (2016) 61-85

Hybrid models

Fluidization features in different hybrid approaches [D. Oliinychenko and H. Petersen, Phys.Rev. **C93** (2016) 034905]

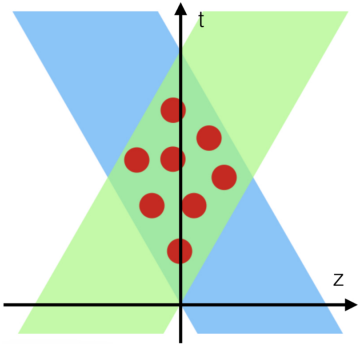
Model	Initial condition	Hydro	Switching criterion
UrQMD hybrid [17]	UrQMD cascade	ideal 3+1D, SHASTA	$t_{CM} = \max(2R\sqrt{\frac{E_{\rm lab}}{2m_N}}, 1.0)$ fm/c
Skokov-Toneev hybrid [18]	Quark-Gluon-String Model	ideal 3+1D, SHASTA	t_{CM} such that $S/Q_B = \text{const}$
EPOS [19]	Strings (Regge- Gribov model)	ideal 3+1D	τ
NeXSPheRIO hybrid [20,27]	Strings (Regge- Gribov model)	ideal 3+1D, SPH	$\tau = 1$ fm [28]
Gale *et al.* [21]	IP glasma	viscous 3+1D, MUSIC	$\tau = 0.2$ fm/c ($\sqrt{s_{NN}} = 2.76$ TeV)
Karpenko hybrid [22]	UrQMD cascade	viscous 3+1D	$\tau_{\rm geom}$
Pang *et al.* hybrid [23]	AMPT	ideal 3+1D, SHASTA	τ
Bhalerao *et al.* hybrid [24]	AMPT	viscous 2+1D, VISH2+1	$\tau = 0.4$ fm/c ($\sqrt{s_{NN}} = 2.76$ TeV)

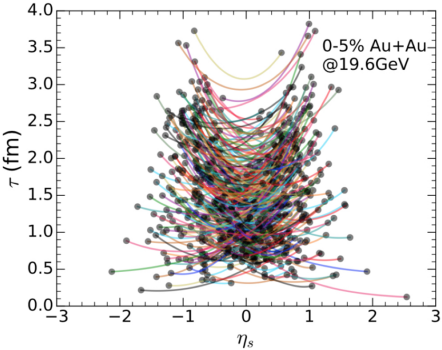
- The switching criteria: either constant proper time τ or constant time in the center-of-mass frame t_{CM}, determined by geometrical criterion.

Dynamical string model (Shen and Schenke, 2016 – 2018)

Chun Shen, Dynamical initialization and hydrodynamic modeling of relativistic heavy-ion collisions

16 May 2018, 11:30





K. Kajantie and L. McLerran, Phys. Lett. **B119**, 203 (1982), Nucl. Phys. **B214**, 261 (1983).
M. Okai *et al*, Phys.Rev. **C95** (2017) 054914.

C. Shen *et al*, Nucl. Phys. **A967** (2017) 796, Phys.Rev. **C97** (2018) 024907.

Conservation laws and source terms

The conservation laws are

$$
\begin{aligned}
d_\mu T^{\mu\nu} &= d_\mu \left[T^{\mu\nu}_{\text{fluid}} + T^{\mu\nu}_{\text{particle}} \right] = 0 \,, \\
d_\mu N^{\mu} &= d_\mu \left[N^{\mu}_{\text{fluid}} + N^{\mu}_{\text{particle}} \right] = 0 \,,
\end{aligned}
$$

from which we can get the source terms for the fluid as

$$
\begin{aligned}
d_\mu T^{\mu\nu}_{\text{fluid}} &= J^{\nu}_{\text{source}}(x) \equiv -d_\mu T^{\mu\nu}_{\text{particle}}(x) \,, \\
d_\mu N^{\mu}_{\text{fluid}} &= \rho_{\text{Bsource}}(x) \equiv -d_\mu N^{\mu}_{\text{particle}}(x) \,.
\end{aligned}
$$

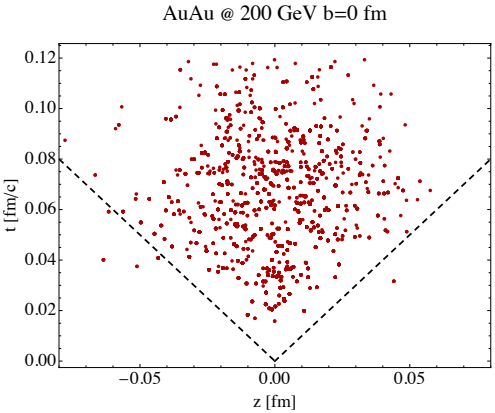
What is needed to get source terms:

- Pre-equilibrium dynamics to give information of particles;
- Energy-momentum tensor and net baryon current constructed from particles.

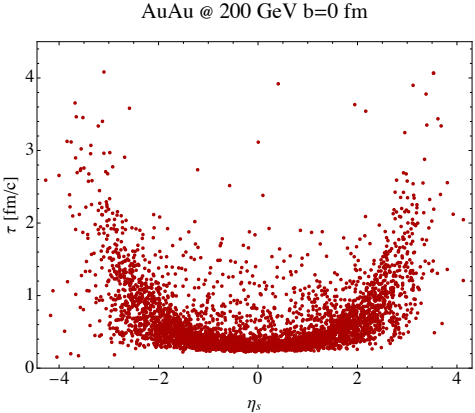
Pre-equilibrium dynamics

Our model: Dynamical initialization based on UrQMD

Instead of rescattering after production, particles get thermalized after formation time.



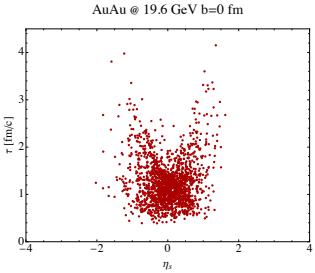
$t - z$ plot of particles at production time

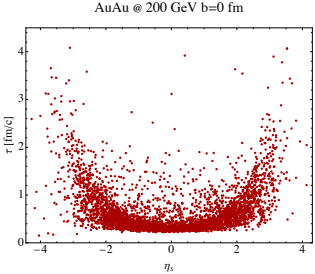


$\tau - \eta_s$ plot of particles at formation time

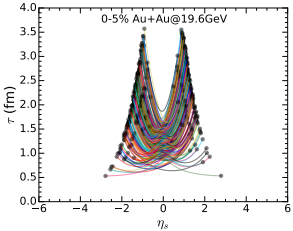
Energy deposition

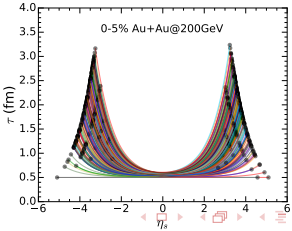
Our model:



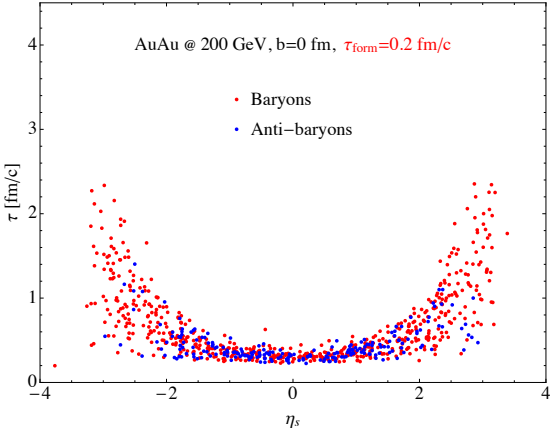


C. Shen and B. Schenke, Phys.Rev. **C97** (2018) 024907:

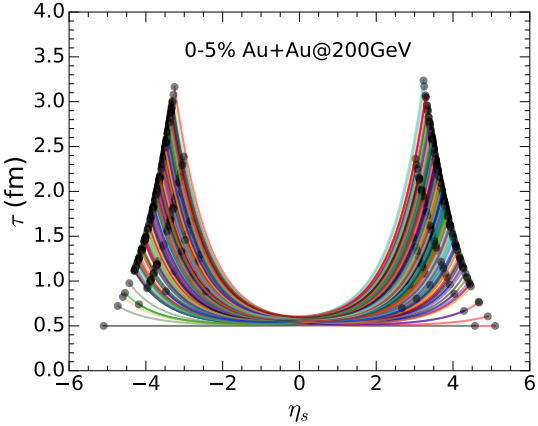




Baryon distribution



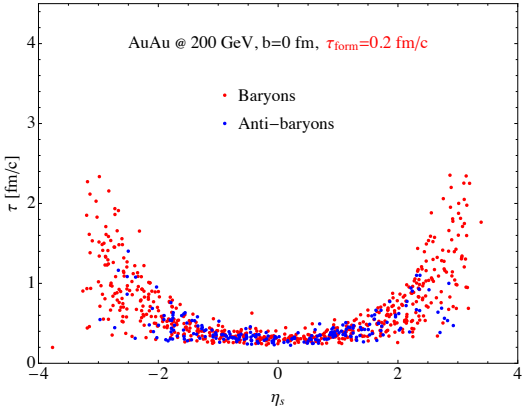
Our model (produced mesons not shown)

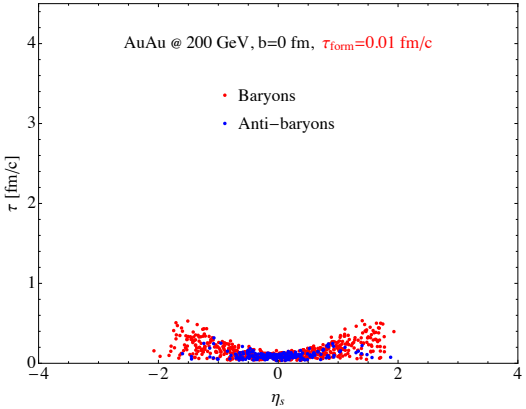


C. Shen and B. Schenke, Phys.Rev. **C97** (2018) 024907

Baryon distribution

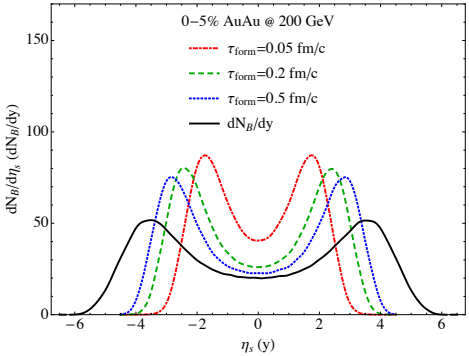
Particle formation time strongly affects the baryon distribution in space-time rapidity



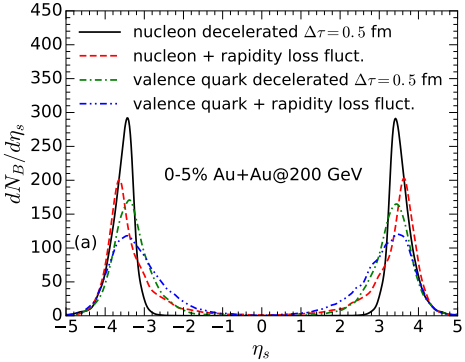


Interesting question: how will this difference affect the final momentum distributions?

Baryon distribution in space-time rapidity (central AuAu @ 200 GeV)



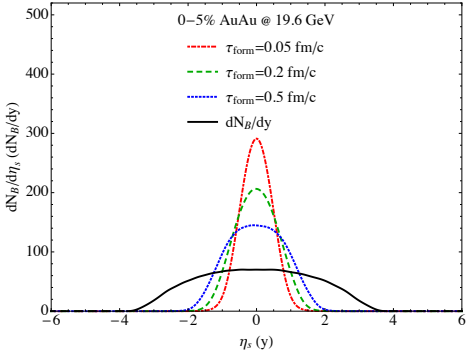
This model



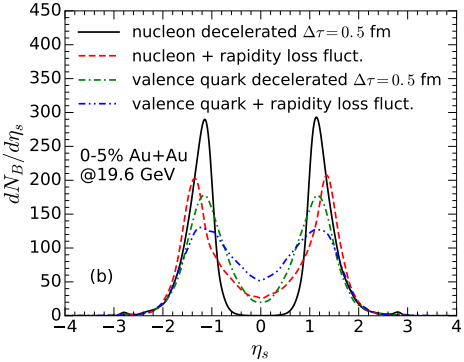
C. Shen and B. Schenke, Phys.Rev. **C97** (2018) 024907

- The initial spacetime distribution of net baryon number can be strongly model dependent, within our model on the value of the formation time.
- Similar rapidity distributions can correspond to very different space-time rapidity distributions, and different space-time rapidity distributions may lead to different hydrodynamic evolution.

Baryon distribution in space-time rapidity (central AuAu @ 19.6 GeV)



This model



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

- The initial spacetime distribution of net baryon number can be strongly model dependent, within our model on the value of the formation time.
- Similar rapidity distributions can correspond to very different space-time rapidity distributions, and different space-time rapidity distributions may lead to different hydrodynamic evolution.

Source terms

Constructing the source terms

Baryon current and energy-momentum tensor of the particles are given by [D. Oliinychenko and H. Petersen, Phys.Rev. **C93** (2016) 034905]

$$T^{\mu\nu}_{\text{particle}}(t,\boldsymbol{r}) = \sum_i \frac{p_i^\mu p_i^\nu}{p_i^0} K(\boldsymbol{r}-\boldsymbol{r}_i(t),\, p_i)\ ,$$

$$N^{\mu}_{\text{particle}}(t,\boldsymbol{r}) = \sum_i b_i \frac{p_i^\mu}{p_i^0} K(\boldsymbol{r}-\boldsymbol{r}_i(t),\, p_i)\ .$$

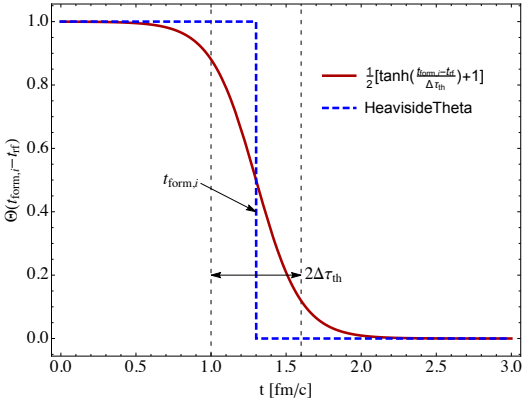
The smearing kernel in the rest frame is given by

$$K_i(t_{\text{rf}},\boldsymbol{x}_{\text{rf}},p_i) = \gamma_i \frac{1}{(2\pi\sigma^2)^{3/2}} \exp\left[\frac{-(\boldsymbol{x}_{\text{rf}}-\boldsymbol{r}_{\text{rf},i})^2}{2\sigma^2}\right] \Theta(t_{\text{form},i}-t_{\text{rf}}),$$

$$\equiv \gamma_i \frac{1}{(2\pi\sigma^2)^{3/2}} \exp\left[\frac{(x-x_i(t))^2-(u_i\cdot(x-x_i(t)))^2}{2\sigma^2}\right] \Theta(t_{\text{form},i}-t_{\text{rf}}).$$

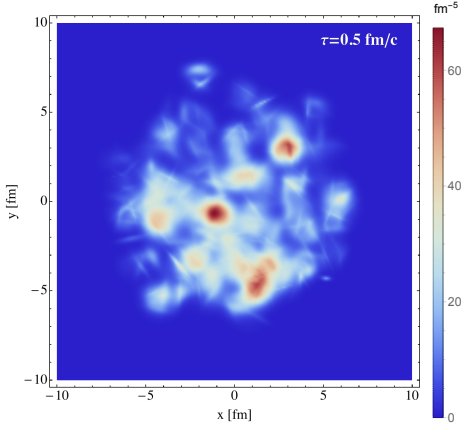
Thermalization of particles

$$\Theta(t_{\rm form}-t)=\frac{1}{2}\left[\tanh\left(\frac{t_{\rm form}-t}{\Delta\tau_{\rm th}}\right)+1\right]\xrightarrow{\Delta\tau_{\rm th}\to 0}\theta(t_{\rm form}-t).$$

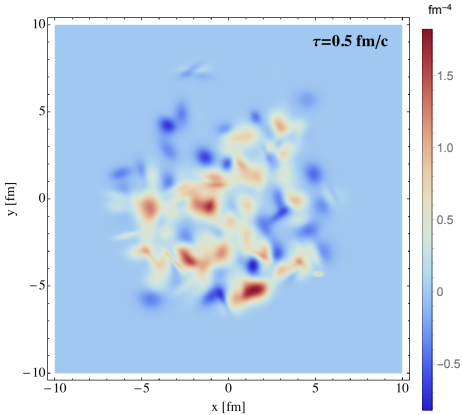


Dynamical sources (central AuAu @ 200 GeV)

Energy-momentum source J^{τ}_{source}



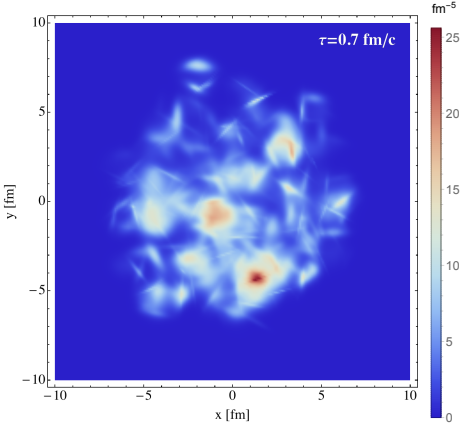
Baryon number source ρ^{B}_{source}



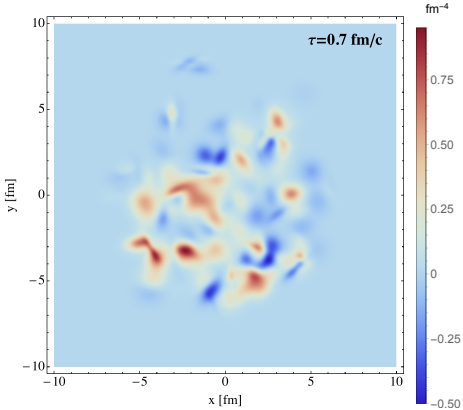
$\tau = 0.5$ fm/c

Dynamical sources (central AuAu @ 200 GeV)

Energy-momentum source J^{τ}_{source}



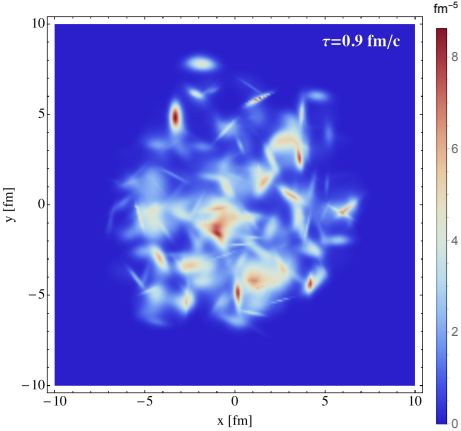
Baryon number source ρ^{B}_{source}



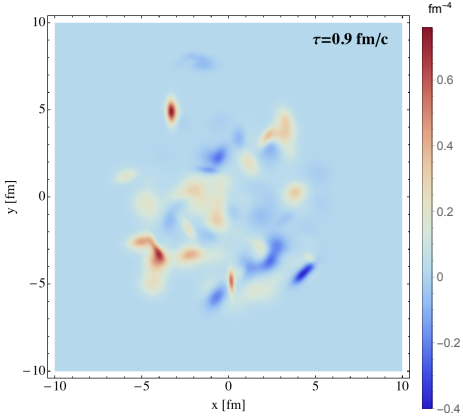
$\tau = 0.7$ fm/c

Dynamical sources (central AuAu @ 200 GeV)

Energy-momentum source J^{τ}_{source}



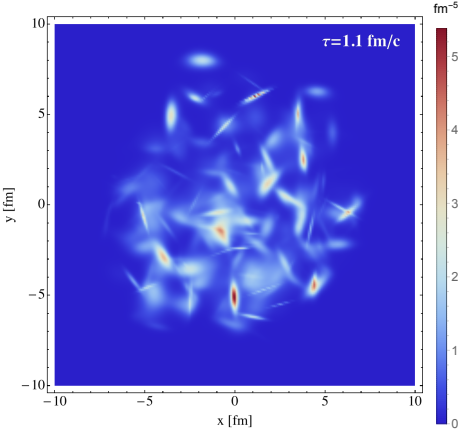
Baryon number source ρ^{B}_{source}



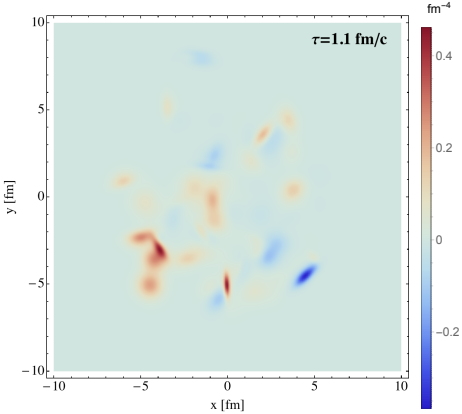
$\tau = 0.9$ fm/c

Dynamical sources (central AuAu @ 200 GeV)

Energy-momentum source J^{τ}_{source}



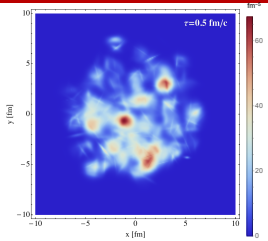
Baryon number source ρ^{B}_{source}

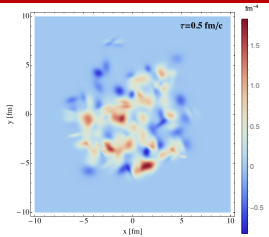


$\tau = 1.1$ fm/c

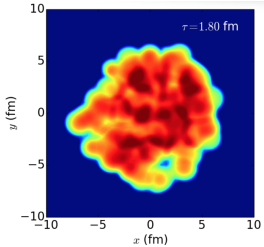
Evolution in the transverse plane (AuAu @ 200 GeV)

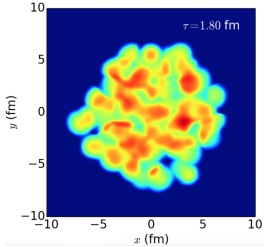
Our model





C. Shen, QM2017





- In our model, bumpiness of ρ_B is not correlated with that of e.

Hydrodynamics with dynamical sources

Dissipative hydrodynamics

The conservation law of energy momentum is

$$d_\mu T^{\mu\nu}_{\text{fluid}} = d_\mu(eu^\mu u^\nu - (p_0 + \Pi)\Delta^{\mu\nu} + \pi^{\mu\nu}) = J^\nu_{\text{source}}.$$

The dissipative transport equations are

$$\tau_\Pi \dot{\Pi} + \Pi = -\zeta\theta - \delta_{\Pi\Pi}\Pi\theta + \lambda_{\Pi\pi}\pi^{\mu\nu}\sigma_{\mu\nu} - \ell_{\Pi n}\nabla\cdot n - \tau_{\Pi n} n\cdot\nabla p_0 - \lambda_{\Pi n} n\cdot\nabla\left(\frac{\mu_B}{T}\right),$$

$$\tau_\pi \dot{\pi}^{\langle\mu\nu\rangle} + \pi^{\mu\nu} = 2\eta\sigma^{\mu\nu} + 2\tau_\pi \pi_\lambda^{\langle\mu}\omega^{\nu\rangle\lambda} - \delta_{\pi\pi}\pi^{\mu\nu}\theta - \tau_{\pi\pi}\pi^{\lambda\langle\mu}\sigma_\lambda^{\nu\rangle} + \lambda_{\pi\Pi}\Pi\sigma^{\mu\nu}$$
$$-\tau_{\pi n} n^{\langle\mu}\nabla^{\nu\rangle} p_0 + \ell_{\pi n}\nabla^{\langle\mu} n^{\nu\rangle} + \lambda_{\pi n} n^{\langle\mu}\nabla^{\nu\rangle}\left(\frac{\mu_B}{T}\right),$$

D. Bazow *et al*, Comput.Phys.Commun. 225 (2018) 92-113.

G. S. Denicol *et al*, Phys. Rev. **D89**, 074005, Phys. Rev. **C90**, 024912.

Baryon evolution

The conservation law of the net baryon number is

$$d_\mu N^\mu_{\text{fluid}} = d_\mu(\rho_B u^\mu + n^\mu) = \rho_{\text{Bsource}} \ .$$

The dissipative transport equation for the baryon diffusion current is

$$\tau_n \dot{n}^{\langle\mu\rangle} + n^\mu = \kappa_B \nabla^\mu \left(\frac{\mu_B}{T}\right) - \tau_n n_\nu \omega^{\nu\mu} - \delta_{nn} n^\mu \theta - \lambda_{nn} n_\nu \sigma^{\mu\nu} \ .$$

In the Navier-Stokes limit, the baryon diffusion current is

$$n^\mu \sim \kappa_B \nabla^\mu \left(\frac{\mu_B}{T}\right) .$$

- $\rho_B u^\mu$ and n^μ together control transportation of the net baryon number when there is no source.

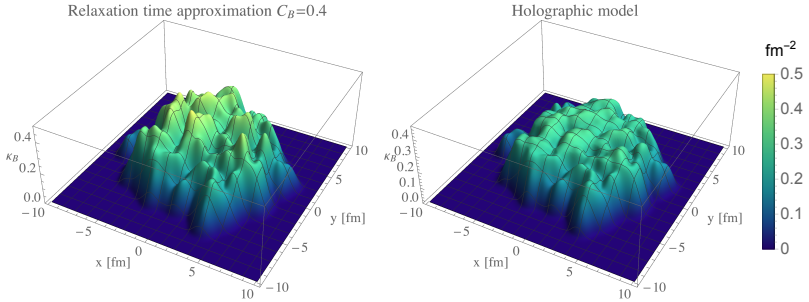
G. S. Denicol *et al*, Phys. Rev. **D89**, 074005, Phys. Rev. **C90**, 024912.

Baryon diffusion coefficient

Relaxation time approximation [G. S. Denicol *et al*, arXiv:1804.10557 [nucl-th]]

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

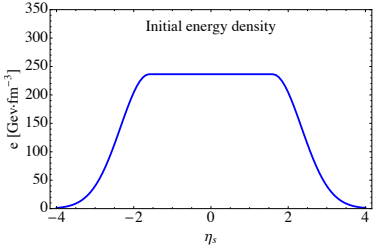
Holographic model [R. Rougemont *et al*, Phys. Rev. Lett. **115**, 202301]

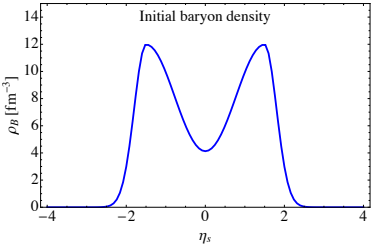


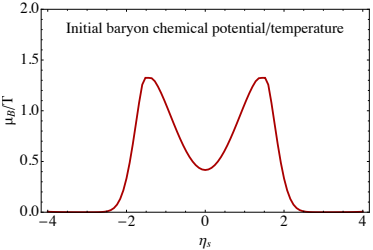
- Holographic model smoothes out spatial fluctuations of κ_B.

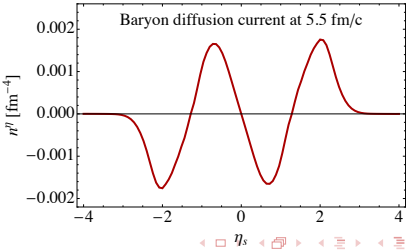
Initial longitudinal profiles and driving forces

Initial longitudinal profiles: P. Bozek, *et al*, Phys. Rev. **C91** (2015) 054912, C. Shen, Quark Matter 2017.

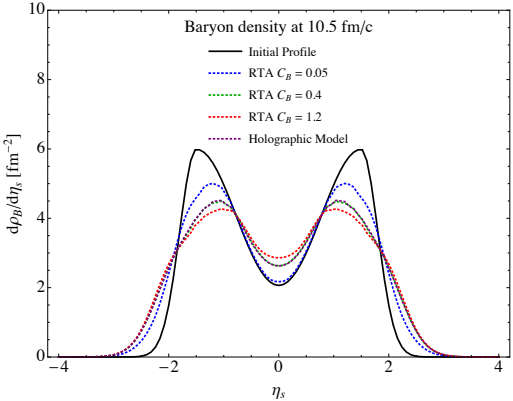


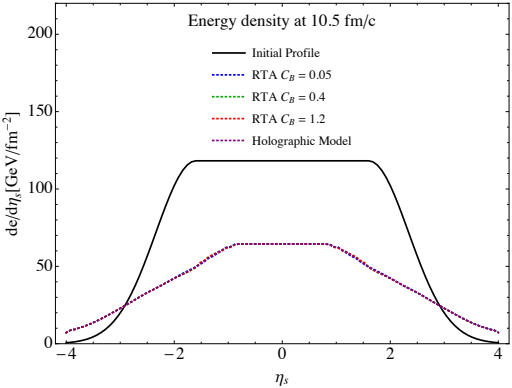






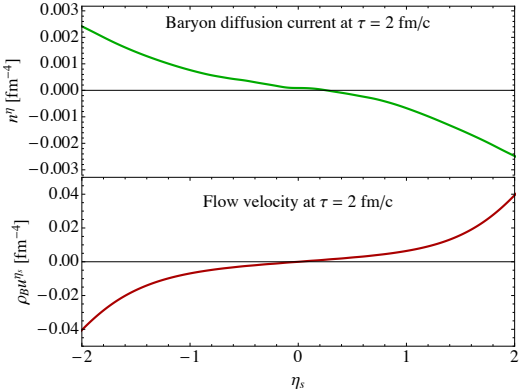
Baryon diffusion coefficient

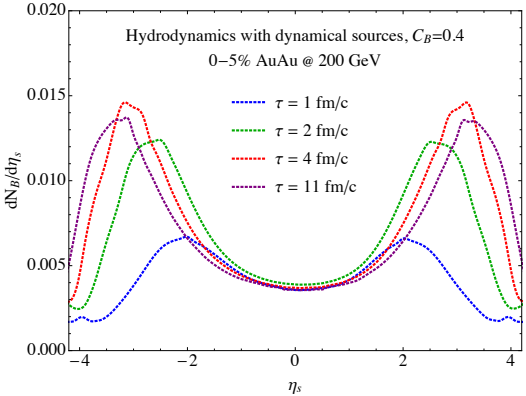




- Net baryon number is transported to midrapidity by diffusion, and to large rapidities by longitudinal expansion; energy density is insensitive to baryon diffusion.
- Consistent with C. Shen *et al*, Nucl. Phys. **A967** (2017) 796-799.

Baryon evolution with dynamical sources





- In spite of the expansion of the fireball, net baryon number at large rapidity increases due to continued feeding by baryon number sources (dynamical sources cease at 4 fm/c).
- Net baryon number doesn't decrease strongly in midrapidity because the baryon diffusion is against the flow velocity.

Conclusions

- Based on modified UrQMD, a dynamical source model for both the energy-momentum and net baryon current is constructed;
- A (3+1)D hydrodynamical code with baryon evolution has been developed which can handle dynamical sources;
- The initial space-time rapidity distribution of net baryon number is strongly model dependent even within a single model, on the value of the formation time in our model; its influence on the final momentum distributions is an interesting question under investigation.
- The baryon evolution in the longitudinal direction is studied and is consistent with previous studies when the same initial condition is used; how the evolution will be changed with the quite different initial conditions got from our dynamical source model needs to be studied.
- Study of final spectra from full (3+1)D hydrodynamics with dynamical sources for both the energy-momentum and net baryon current is upcoming.

Thank you very much!