MUSIC with After-burner

Sangyong Jeon & Sangwook Ryu

Department of Physics
McGill University
Montréal, QC, CANADA

McGill

Current MUSIC Team

- Charles Gale (McGill)
- Sangyong Jeon (McGill)
- Sangwook Ryu (McGill)
- *Björn Schenke* (Formerly McGill, now BNL)
- *Clint Young* (McGill)
- Gojko Vujanovic (McGill)
- Jean-Francois Paquet (McGill)
- Michael Richard (McGill)
- Igor Kozlov (McGill)

What we want to do:

- Run 3+1D E-by-E viscous hydrodynamics (MUSIC)
- At $T_{\mathrm{trans.}}$, switch to hadrons
- Run hadron cascade (UrQMD)

Why we want to do those:

- Closer to reality
- Take into account *both* sources of fluctuation
- η/s not so small in hadronic phase – Automatically taken care of by the cascade

What we want to learn:

- QGP η/s
- E-by-E soft background for Jet identification

MUSIC

MUScl for Ion Collisions

MUSCL: Monotone Upstream-centered Schemes for Conservation Laws

3+1D Event-by-Event Viscous Hydrodynamics

- 3+1D parallel implementation of new *Kurganov-Tadmor Scheme* in (τ, η) with an additional baryon current
  (No need for a Riemann Solver. Semi-discrete method.)
- Ideal *and* Viscous Hydro
- Event-by-Event fluctuating initial condition
- Sophisticated Freeze-out surface construction
- Full resonance decay (3+1D version of Kolb and Heinz)
- Many different equation of states including the newest from Huovinen and Petreczky
- *New Development*: UrQMD after-burner

- Ideal part

$$T^{\mu\nu} = \varepsilon u^{\mu} u^{\nu} + (g^{\mu\nu} + u^{\mu} u^{\nu}) P(\varepsilon)$$

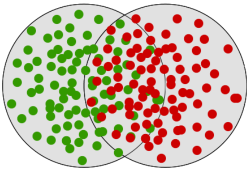
- Viscosity effect implemented following H. Song's thesis (0908.3656)

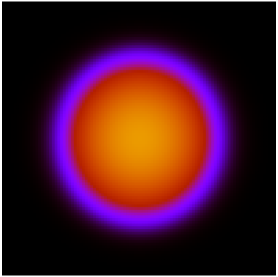
$$\Delta^{\mu\alpha}\Delta^{\nu\beta} D\pi_{\alpha\beta} = -\frac{1}{\tau_\pi}\left(\pi^{\mu\nu} - 2\eta\nabla^{\langle\mu} u^{\mu\rangle} + \frac{4}{3}\tau_\pi \pi^{\mu\nu}(\partial_\alpha u^\alpha)\right)$$

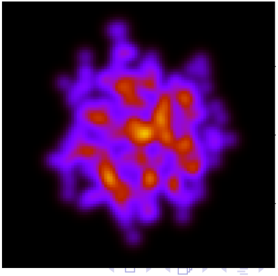
which comes from Baier, Romatschke, Son, Starinets, Stephanov (0712.2451) by setting other transport coefficients to zero.

Fluctuating Initial Condition

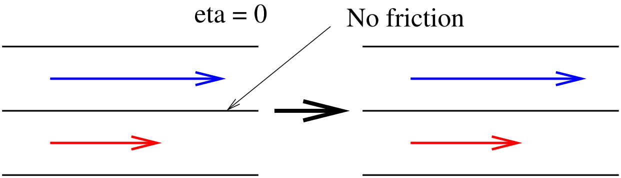
Each event is *not* symmetric: Fluctuating initial condition $\Longrightarrow$ All v_n are non-zero.



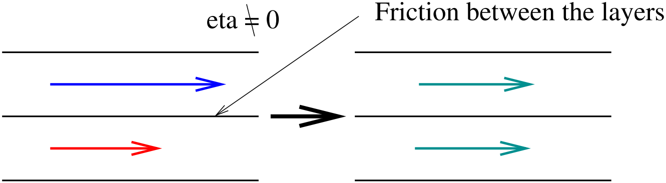




Effect of viscosity

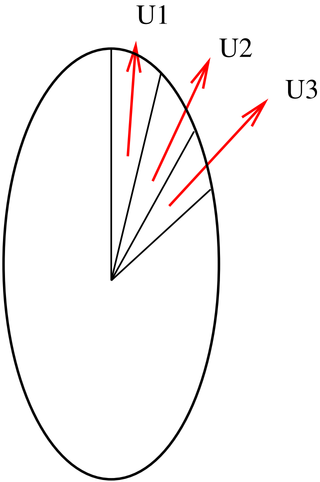


The relative velocity of the two layers does not change.



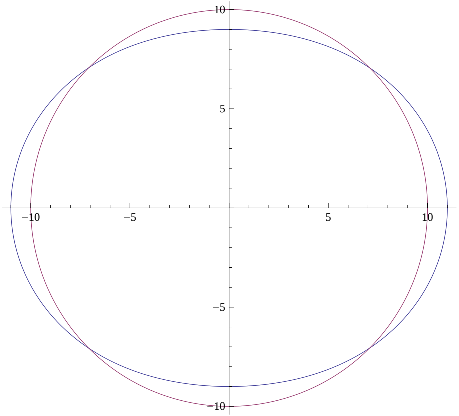
The velocities eventually become the same.

Effect of viscosity



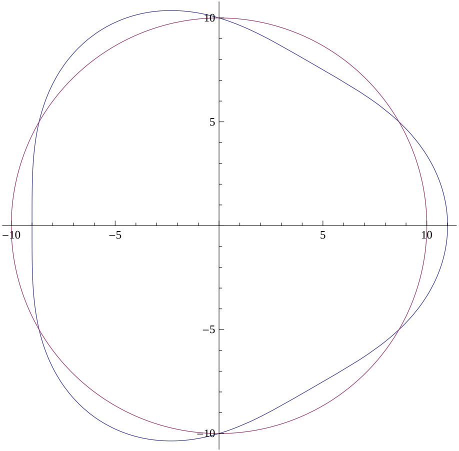
- $\eta = 0$ means $u_1 < u_2 < u_3$ is maintained for a long time
- $\eta \neq 0$ means that $u_1 \simeq u_2 \simeq u_3$ is achieved more quickly
- Shear viscosity smears out flow differences (it's a diffusion)
- Shear Viscosity reduces flow

ϵ_n

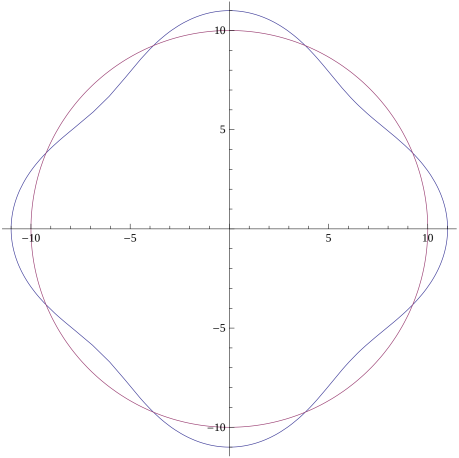


This causes elliptic flow. It is harder to destroy this than ...

ϵ_n

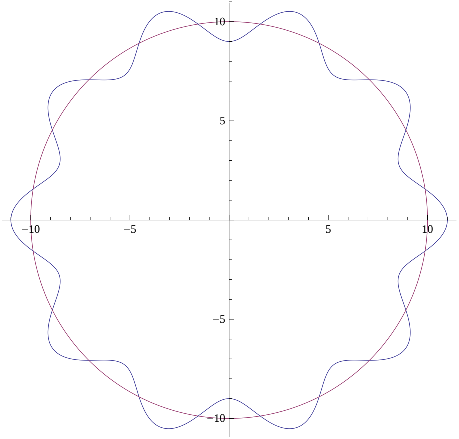


this ...



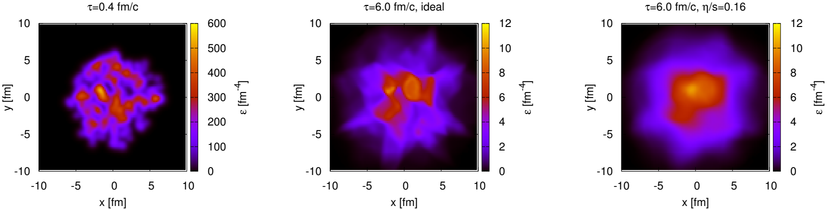
or this ...

ϵ_n



or this.

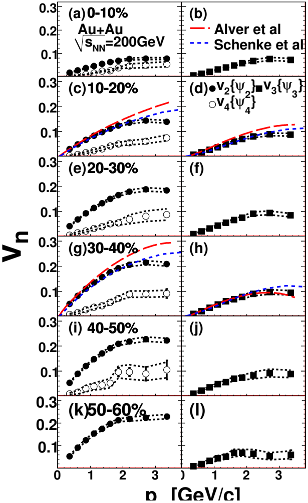
Ideal vs. Viscous



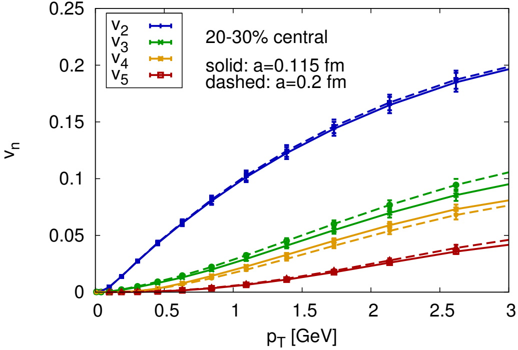
Fluctuations and Viscosity

- Magnitude of higher harmonics, $v_3, v_4, \cdots$, (almost) independent of centrality – Local fluctuations dominate
- Higher harmonics are easier to destroy that v_2 which is a *global* distortion – Viscosity effect.
- To get a good handle on flow: Both fluctuations and viscosity are essential

E-by-E MUSIC vs PHENIX Data

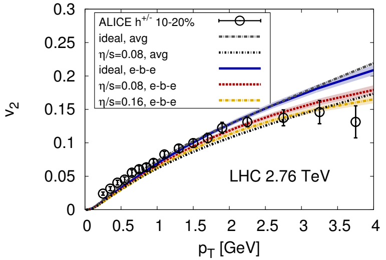


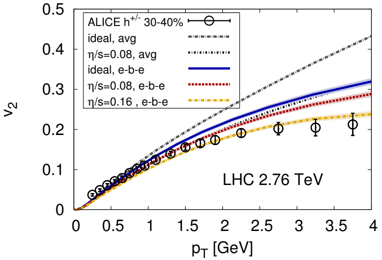
[QM11]

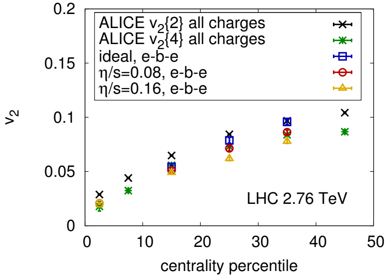


[Phys.Rev. C85 (2012) 024901, Schenke, Jeon and Gale]

E-by-E MUSIC vs LHC Data – v_2

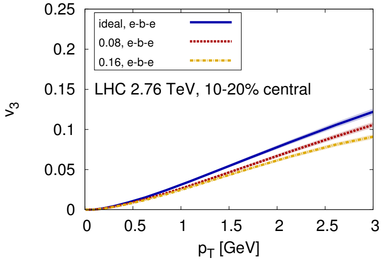


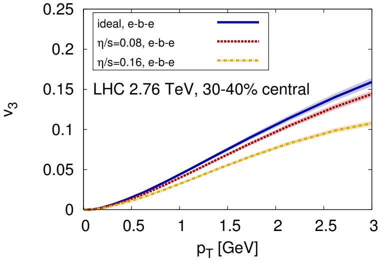


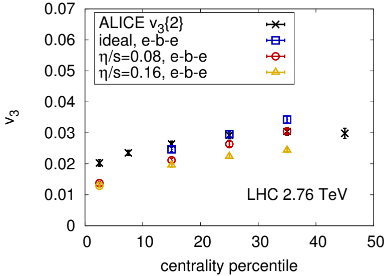


- Slight under-prediction of low p_T and integrated v_2 – After-burner can correct this

E-by-E MUSIC vs LHC Data – v_3







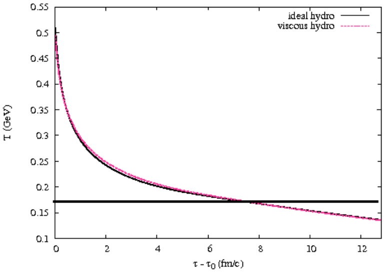
- Slight under-prediction of integrated v_3 – After-burner can correct this

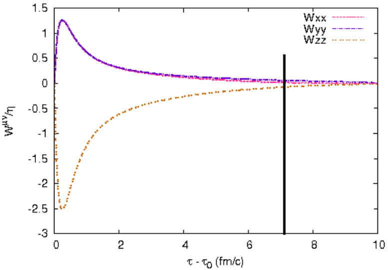
UrQMD After-burner

UrQMD After-burner

- Based on UrQMD v3.3-p1 by H. Petersen et al. (Phys.Rev.C78:044901,2008, Phys.Rev.C81:044906,2010)
- Implemented proper use of transition hyper-surface element $p^\mu d\Sigma_\mu$
- Fluctuations are enhanced – Both the initial state fluctuations as well as the finite number fluctuations are taken into account.
- Viscosity in the QGP phase taken into account
- Results are preliminary.
  - Without re-tuning MUSIC parameters
  - δf not yet taken into account

δf evolution





[Temperature and $W^{\mu\nu} = \pi^{\mu\nu}$ evoution at $x = y = 2.5\,\text{fm}$, $z = 0$. From M. Dion et al. Phys.Rev. C84 (2011) 064901.]

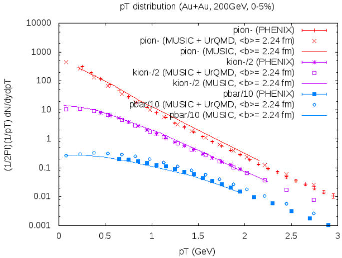
In MUSIC:

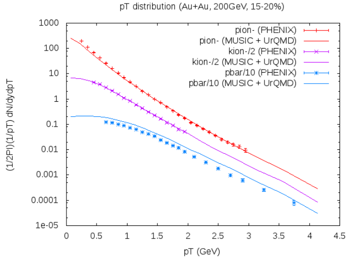
$$\begin{aligned}
\delta f &= f_0(1 \pm f_0)\frac{p^\alpha p^\beta \pi_{\alpha\beta}}{2(\varepsilon + P)T^2} \\
&= f_0(1 \pm f_0)\frac{p^\alpha p^\beta}{T^2}\frac{\eta}{s}(\partial^{\langle i}u^{j\rangle}/T)
\end{aligned}$$

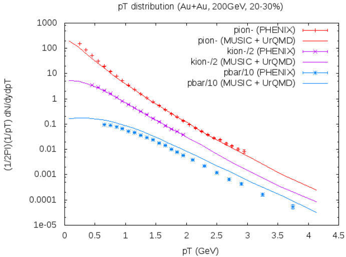
After $T_{\text{trans}} = 170\,\text{MeV}$ (around 7 fm/c), $\pi_{\mu\nu}/s$ is not that big.

Spectra at RHIC (Midrapidity)

In each centrality class: 100 UrQMD events on each of 100 MUSIC events



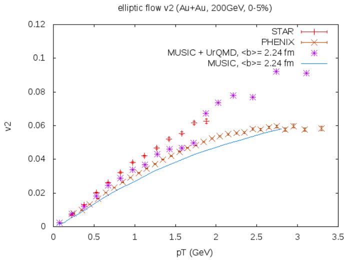


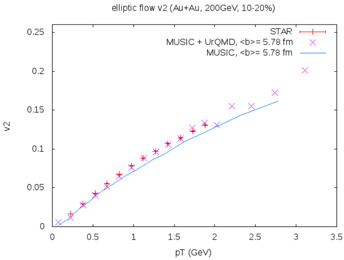


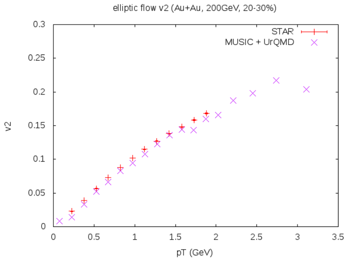
- $\eta/s = 1/4\pi$
- Spectra reasonably reproduced
- $\bar{p}$ spectra enhanced

v_2 at RHIC (Midrapidity)

In each centrality class: 100 UrQMD events on each of 100 MUSIC events



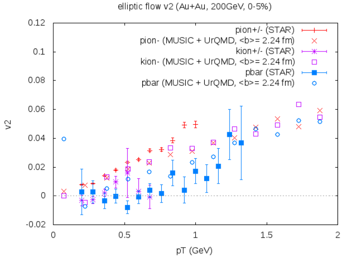


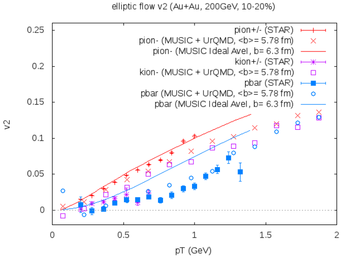


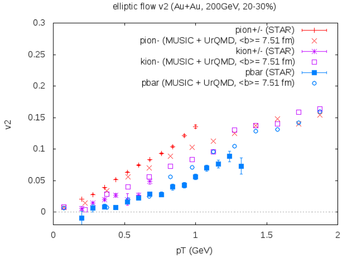
- $\eta/s = 1/4\pi$
- Using previous MUSIC parameters that were tuned to reproduce PHENIX v_n

v_2 at RHIC (Midrapidity)

In each centrality class: 100 UrQMD events on each of 100 MUSIC events



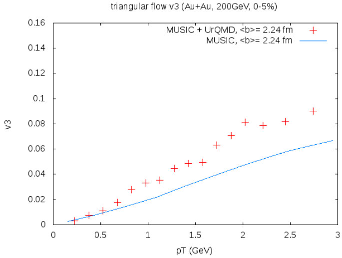


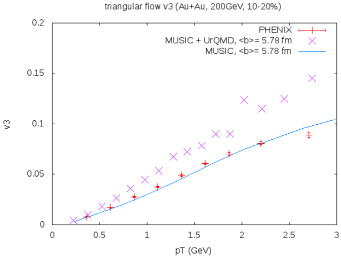


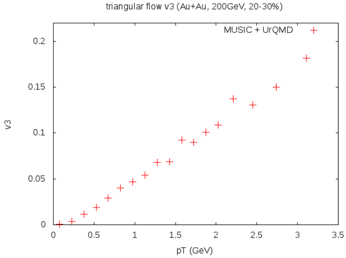
- $\eta/s = 1/4\pi$
- Using previous MUSIC parameters that were tuned to reproduce PHENIX v_n

v_3 at RHIC (Midrapidity)

In each centrality class: 100 UrQMD events on each of 100 MUSIC events



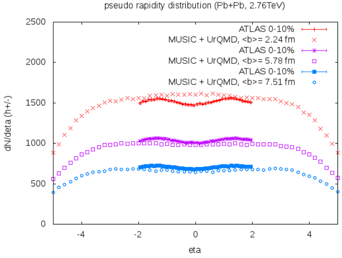


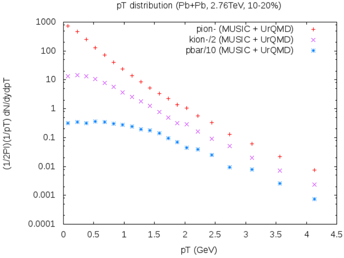


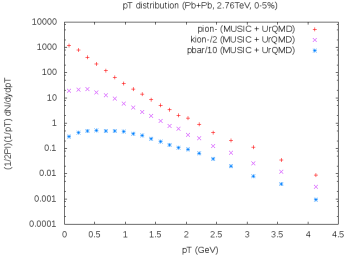
- $\eta/s = 1/4\pi$
- Using previous MUSIC parameters that were tuned to reproduce PHENIX v_n
- After-burner enhances v_3 due to added fluctuations

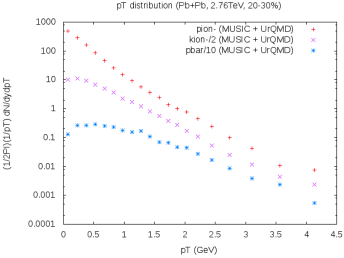
LHC Spectra

In each centrality class: 100 MUSIC + UrQMD events

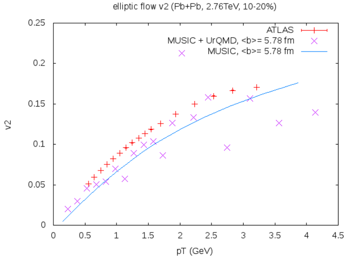


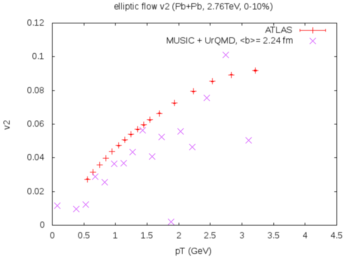


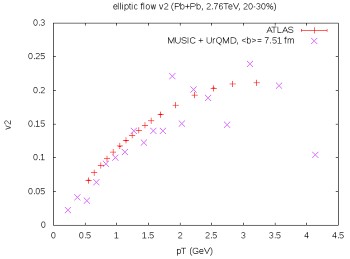


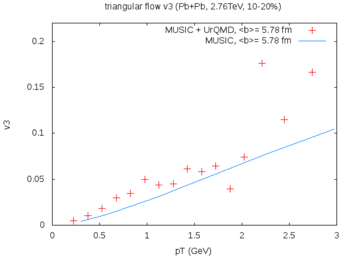


In each centrality class: 100 MUSIC + UrQMD events







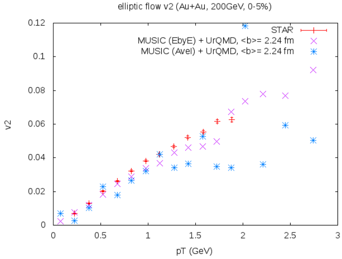


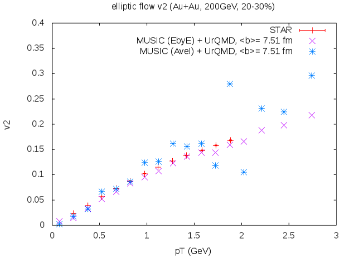
Summary and What's coming

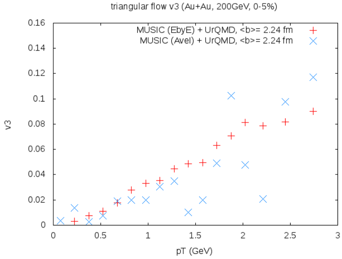
- 3+1D Event-by-event Hydrodynamics + UrQMD
- Obvious: Event-by-event fluctuation is enhanced $\Longrightarrow$ v_3 (also higher harmonics) feels it more
- Better estimate of QGP η/s should be possible: Need detailed study of identified particle v_n spectra
- Need to study
  - $T_{\rm trans}$ dependence
  - MUSIC parameter dependence
  - δf dependence
  - Baryon chemistry
- Immediate goal: MUSIC + UrQMD + MARTINI $\Longrightarrow$ Provides realistic soft background for JET identification
- Ultimate goal: Glasma-IC (Schenke) + MUSIC + UrQMD + MARTINI

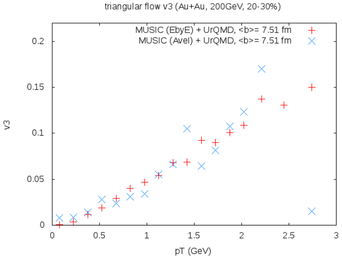
Backup Slides

In each centrality class: 100 UrQMD events









Cooper-Frye

Based on:

$$\langle N \rangle = \int \frac{d^3p}{(2\pi)^3 E_p} \int d^3x\, E_p\, f(E_p)$$

Here $d^3p/E_p = 2d^4p\delta(p^2 - m^2) = dyd^2p_T$ is Lorentz invariant.

$$\frac{dN}{dyd^3p_T} = \frac{1}{(2\pi)^3} \int d^3x\, E_p\, f(E_p)$$
$$= \frac{1}{(2\pi)^3} \int d\Sigma_0 p^0\, f(E_p)$$

In an arbitrary frame,

$$\frac{dN}{dyd^2p_T} = \frac{1}{(2\pi)^3} \int d\Sigma_\mu p^\mu f(u^\mu p_\mu)$$

Cooper-Frye

- How do you get $f_i(u^\mu p_\mu)$ from $T^{\mu\nu} = T^{\mu\nu}_{\rm id.} + W^{\mu\nu}$?
  - Get energy density and the flow velocity from

$$T^{\mu\nu} u_\nu = -\varepsilon u^\mu$$

  - ε is the local energy density

$$\varepsilon = \sum_{i=m_0}^{m_N} g_i \int \frac{d^3p}{(2\pi)^3} E_p^i f_i(E_p^i)$$

where $E_p^i = \sqrt{\mathbf{p}^2 + {m_i}^2}$

  - Get temperature assuming $f_0^i = 1/(e^{E_i/T} \mp 1)$.
- "Ideal fluid" to "Ideal gas"

$$T^{\mu\nu}_{\rm id.}(x) = \sum_i g_i \int \frac{d^3p}{(2\pi)^3 E_p} (p^\mu p^\nu + \delta U(x)\, g^{\mu\nu})\, f_i(x, \mathbf{p})$$

  - Strictly conserved by Boltzmann equation. δU: Takes care of $T(x)$.

Viscous Correction

When $\eta \neq 0$,

$$T^{\mu\nu}_{\rm id.}(x) + \pi^{\mu\nu}(x) = \sum_i g_i \int \frac{d^3p}{(2\pi)^3 E_p} (p^\mu p^\nu + \delta U(x)\, g^{\mu\nu})\,(f_0^i + \delta f^i)(x, \mathbf{p})$$

Kinetic theory requirements (Boltzmann limit):

$$\pi^{ij} = -2\eta \langle \partial^i u^j \rangle = \int \frac{d^3p}{(2\pi)^3} \frac{p^i p^j}{E_p} \delta f$$

$$\eta = \frac{1}{15} \int \frac{d^3p}{(2\pi)^3} \frac{p^2}{E_p} n_p \chi(p)$$

where

$$sT = \varepsilon + P$$

and

$$\delta f = -n_p \chi(\mathbf{p}) \hat{p}^i \hat{p}^j \left\langle \partial_i u_j \right\rangle$$

Viscous Correction

Consistent choice to use in the Cooper-Frye procedure

$$\delta f = f_0(1 \pm f_0)\frac{p^\alpha p^\beta \pi_{\alpha\beta}}{2(\varepsilon + P)T^2}$$

$$= f_0(1 \pm f_0)\frac{p^\alpha p^\beta}{T^2}\frac{\eta}{s}(\partial^{\langle i}u^{j\rangle}/T)$$

Issues to be resolved

- Cooper-Frye:

$$\frac{dN}{dyd^2p_T} = \frac{1}{(2\pi)^3}\int d\Sigma_\mu p^\mu f(u^\mu p_\mu)$$

- Can show:

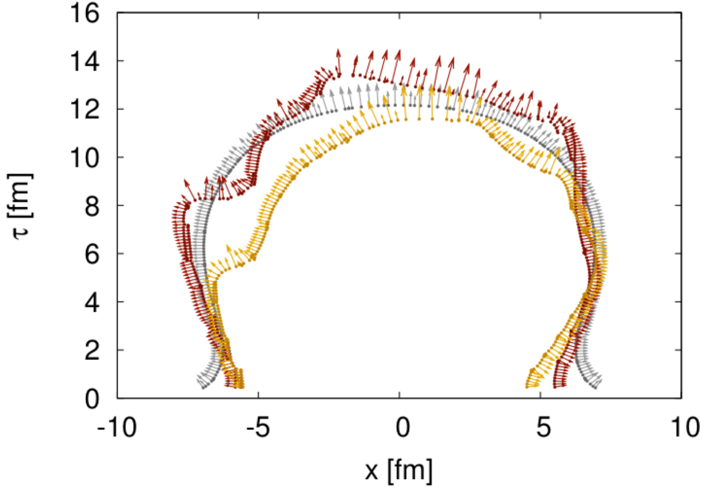
$$p^\mu d\Sigma_\mu = (m_T\partial_\eta(\tau_f \sinh(y-\eta)) - \tau_f \mathbf{p}_T\cdot\nabla_T\tau_f)\, dxdyd\eta$$

  where $\tau_f(x,y,\eta)$ is the freeze-out time (or transition time) at (x,y,η).

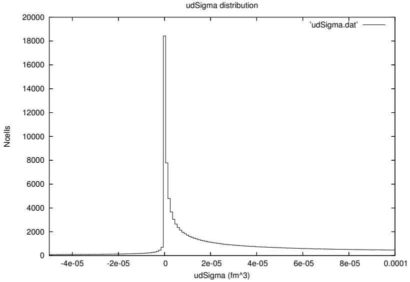
- $p^\mu d\Sigma_\mu$ can be negative when $d\Sigma_\mu$ is spacelike.

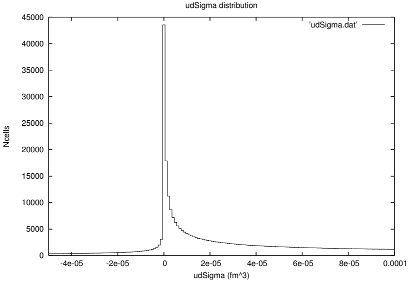
Issues to be resolved

- No guarantee that $d\Sigma_\mu$ is always timelike.



Negative contribution to Cooper-Frye





- Fortunately, not so big.
- For now: $\theta(p^\mu d\Sigma_\mu)$.