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Investigating transition interfaces in hybrid approaches

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Motivation: Transitions in Hybrid Approaches

There are two critical transitions in hybrid approaches: the initial thermalization and final particlization. Both transitions give rise to challenges. For the final transition negative contributions to the Cooper-Frye hypersurface have to be treated and in the initial state the assumption of local thermalization has to be verified. To investigate both of these issues, a coarse-grained microscopic transport approach has been employed.

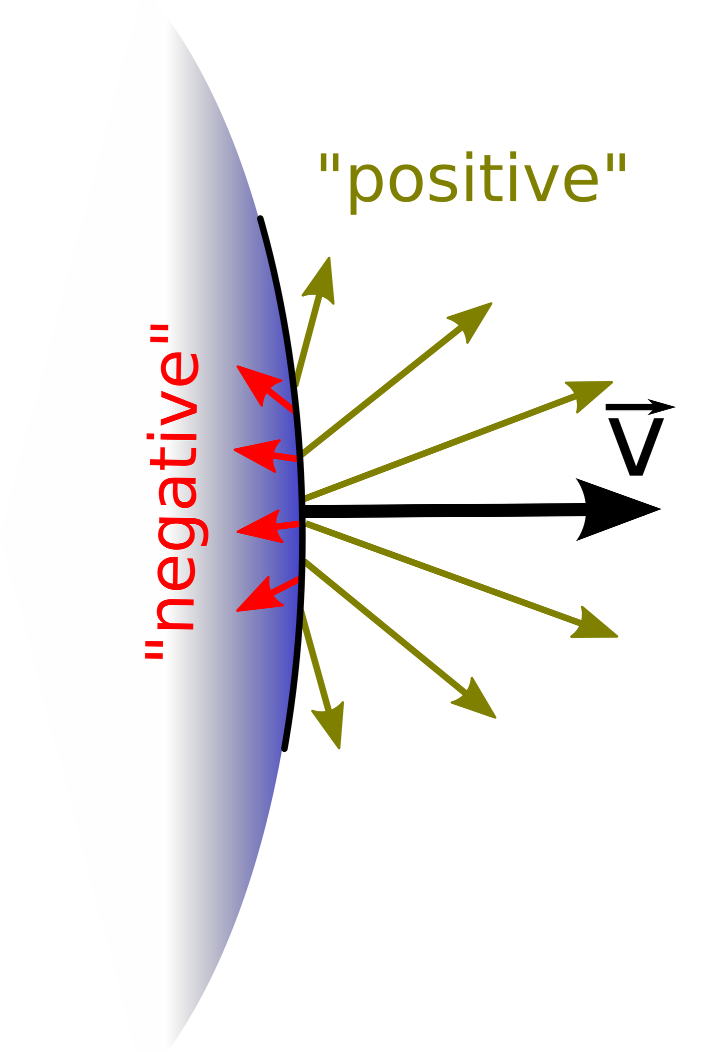
Introduction: The particlization transition

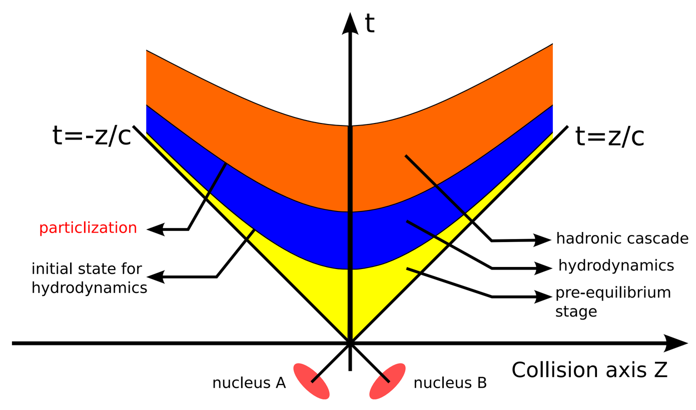
Standard switching from hydro to particles, "Cooper-Frye formula"
[F. Cooper, G. Frye, Phys. Rev. D 10, 186, 1974.]

$$p^0 \frac{d^3N}{d^3p} = f(p) p^\mu d\sigma_\mu$$

$$f(p) = \left(e^{\frac{p^\mu u_\mu - \mu}{T}} \pm 1 \right)^{-1}$$

conserves energy, momentum and charges
$p^\mu d\sigma_\mu$ can be $< 0 \rightarrow$ number of particle can be negative





$d\sigma_\mu$ - normal 4-vector
$u_\mu = (\gamma, \gamma \vec{v})$ - 4-velocity
T - temperature
μ - chemical potential

$p^\mu d\sigma_\mu > 0$: positive contribution, particles fly out
$p^\mu d\sigma_\mu < 0$: negative contribution, particles fly in

Possible solutions to negative contributions:

1) Include feedback to hydro - great increase in complexity
K. Bugaev, Phys Rev Lett. 2003; L.Czernai, Acta Phys. Hung., 2005
2) Artificial corrections
S. Pratt, 2014, nucl- th1401.0136
3) Neglect them and violate conservation laws
nearly all present hybrid models do this
for details see P. Huovinen, H. Petersen, Eur. Phys. J. A48 (2012) 171

When is neglecting negative contributions justified?
What changes if we neglect them and how much?

Methodolody: Hypersurface in coarse-grained UrQMD

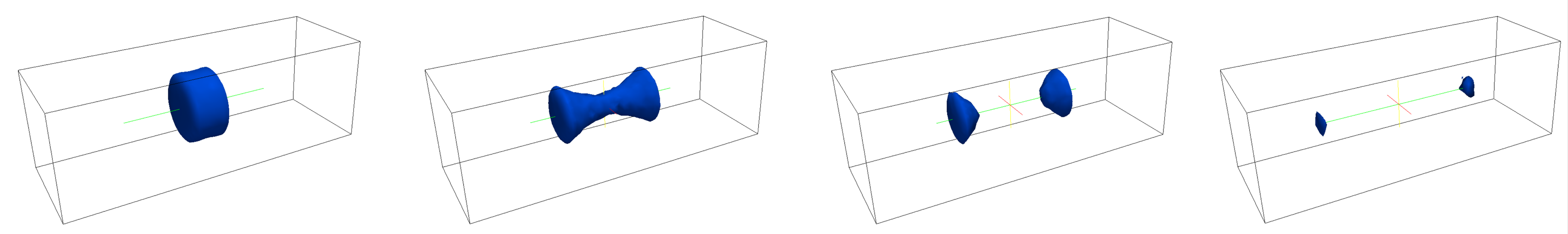
Coarse-grained microscopic transport approach
Hypersurface of constant Landau rest frame energy density that mimics hybrid model transition surface

Generate many UrQMD events
[urqmd.org, Prog. Part. Nucl. Phys. 41 (1998) 225-370, J. Phys. G: Nucl. Part. Phys. 25 (1999) 1859-1896]

On a (t,x,y,z) grid calculate $T^{\mu\nu} = \left\langle \frac{1}{V_{cell}} \sum_{i \in cell} \frac{p_i^\mu p_i^\nu}{p_i^0} \right\rangle$ event average

In each cell go to Landau frame: $T_L^{0\nu} = (\epsilon_L, 0, 0, 0)$
Construct surface $\epsilon_L(t, x, y, z) = \epsilon_0$ using Cornelius [https://karman.physics.purdue.edu/OSCAR]

Example: E = 160 AGeV, Au+Au central collision, ϵ_0 = 0.3 GeV/fm^3



t = 4 fm/c   t = 11 fm/c   t = 13 fm/c   t = 18 fm/c

Two ways to calculate negative contributions
equivalent at thermal equilibrium

A) "Cooper-Frye"

$$p^0 \frac{d^3N^+}{dp^3} = \frac{p^\mu d\sigma_\mu}{exp(p^\nu u_\nu / T) \pm 1} \theta(p^\nu d\sigma_\nu)$$

$$p^0 \frac{d^3N^-}{dp^3} = \frac{p^\mu d\sigma_\mu}{exp(p^\nu u_\nu / T) \pm 1} \theta(-p^\nu d\sigma_\nu)$$

B) "by particles"

count UrQMD particles that cross surface

N^- - from outside to inside
N^+ - from inside to outside

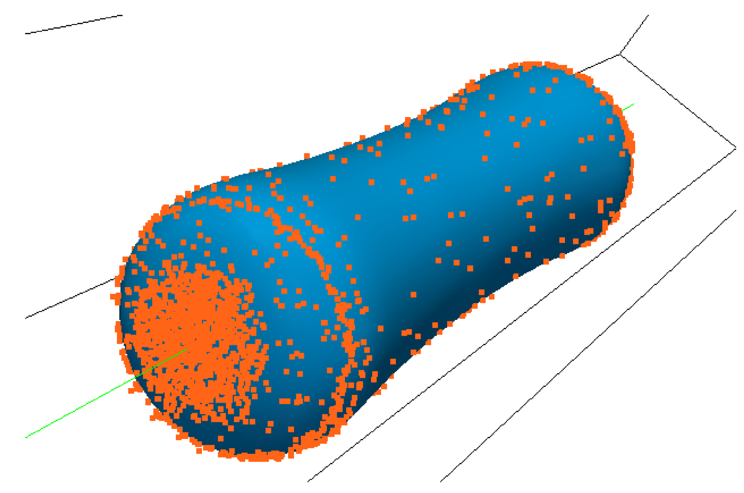
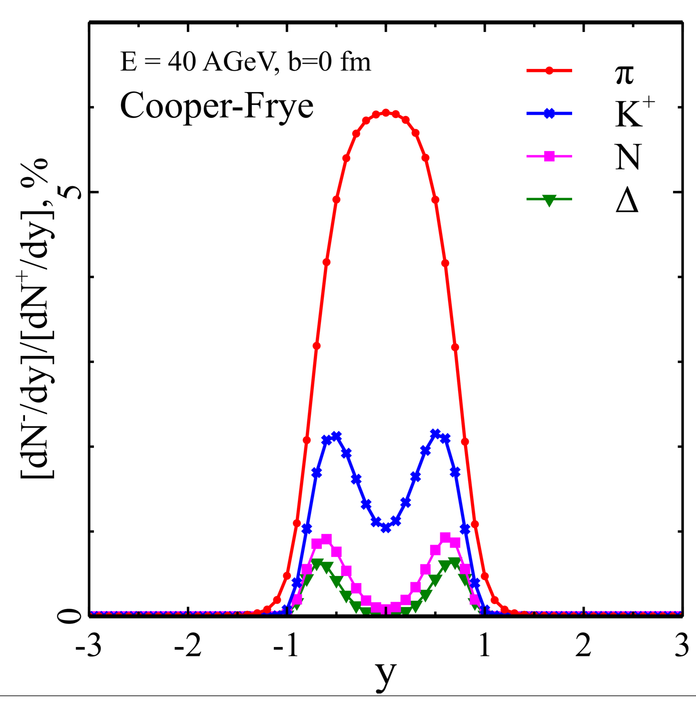


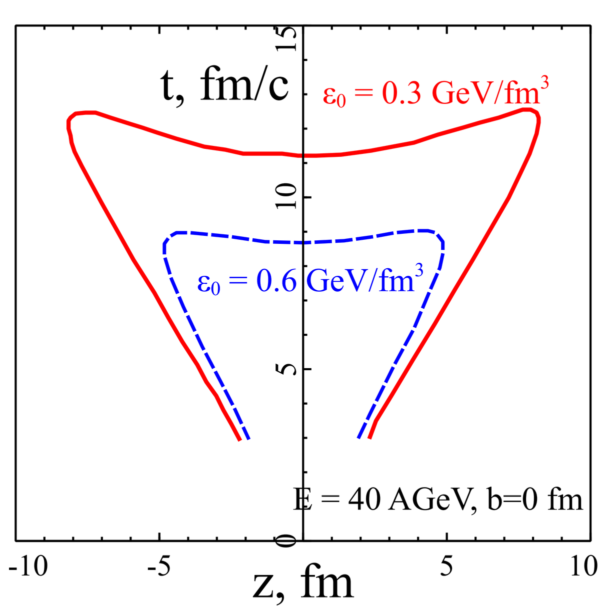
Figure: Snapshot of surface, orange dots are particles crossing surface from outside to inside

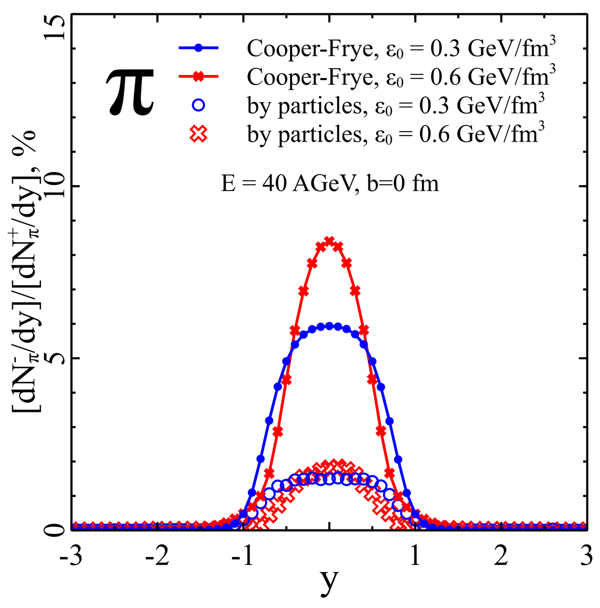
Negative contributions: Results

Larger hadron mass - smaller negative contribution

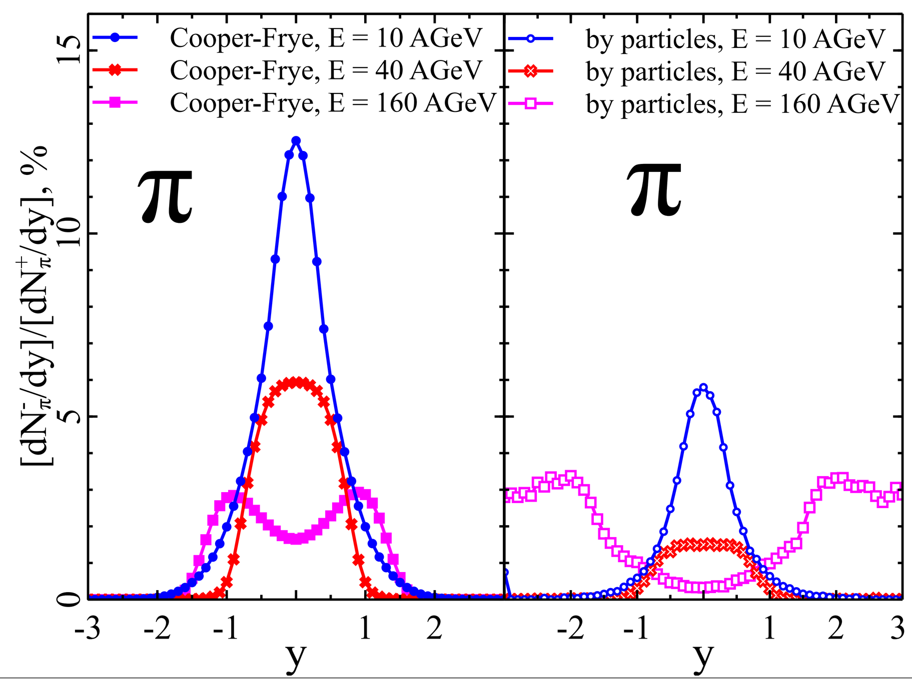


Larger isosurface criterion - larger negative contribution





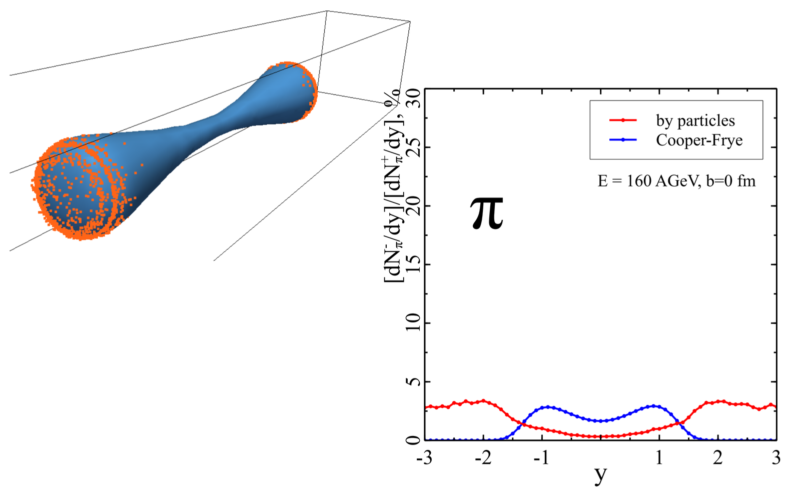
Negative contributions: Results



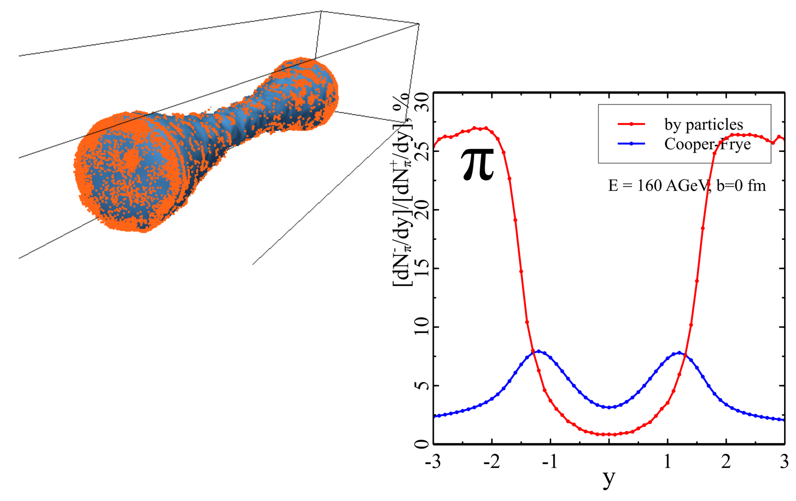
Larger collision energy - smaller negative contribution

Lumpy surface can lead to huge negative contributions
this may happen in event-by-event studies

Smooth surface

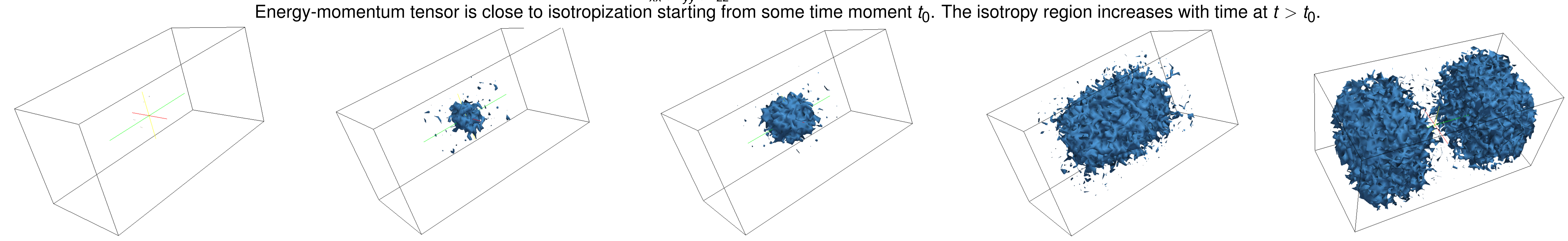


Lumpy surface



Coarse-grained $T^{\mu\nu}$ study: Where and when is isotropization reached in UrQMD?

E = 40 AGeV, Au+Au, b=0. Isotropization variable $x = \frac{|T_{xx} - T_{yy}| + |T_{yy} - T_{zz}| + |T_{zz} - T_{xx}|}{T_{xx} + T_{yy} + T_{zz}}$ = 0.15 isosurface, where $T^{\mu\nu}$ is energy-momentum tensor in Landau rest frame.
Energy-momentum tensor is close to isotropization starting from some time moment t_0. The isotropy region increases with time at $t > t_0$.



$t < t_0$ = 10 fm/c - no isotropization   t = 11 fm/c   t = 13 fm/c   t = 21 fm/c   t = 28 fm/c

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