# Multi-fluid Hydrodynamics for RHIC BES/FAIR, remade

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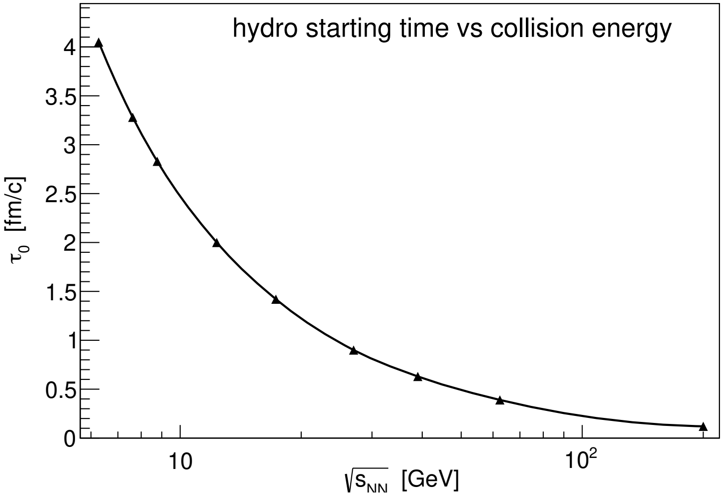
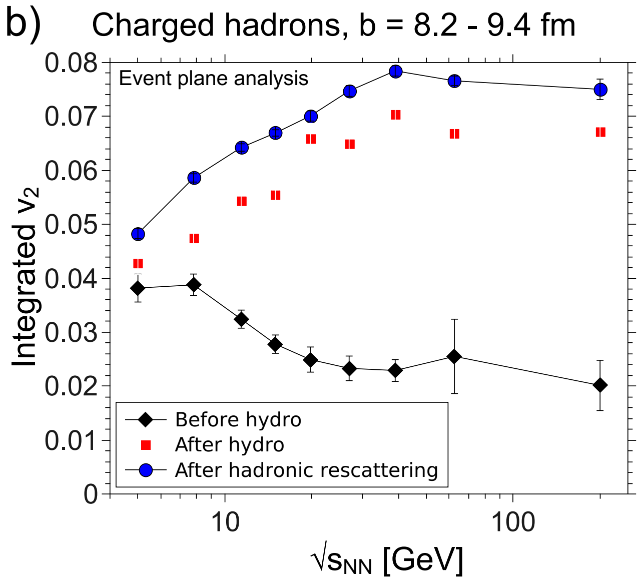
# Motivation

When simulating heavy-ion collisions at lower energies, the paradigm of “thin pancakes” gradually loses its applicability.

In a “classic” hybrid model with initial state→hydro transition at fixed τ, towards low energies:

- starting time increases
- Effect of hydrodynamic stage gets weaker

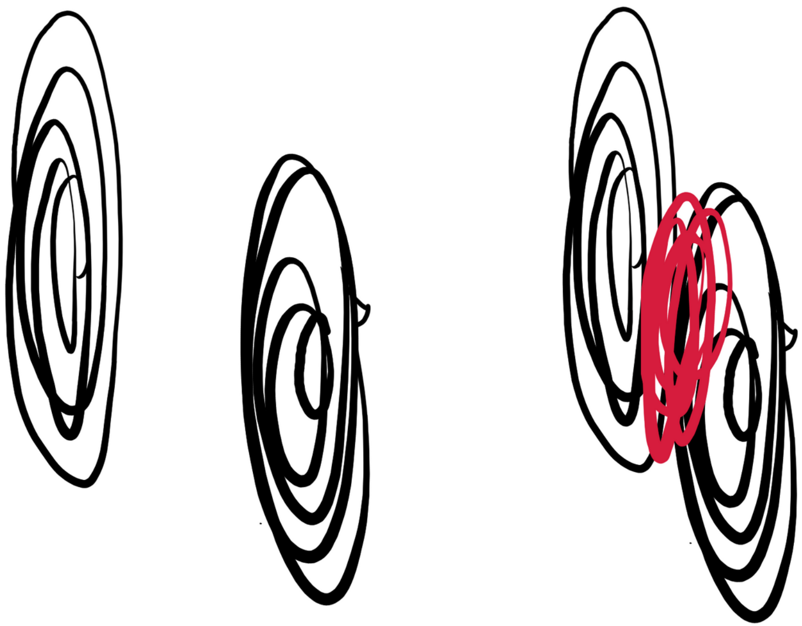



UrQMD 3.4 (UrQMD IC + ideal hydro + UrQMD afterburner) J. Auvinen, H. Petersen, Phys.Rev.C 88:064908,2013

# The hydro description has to start early!

A way to address this challenge: **multi-fluid dynamics**.



- The initial state is two blobs of cold nuclear matter (fluids) colliding.
- The colliding fluids produce 3rd fluid which is called a fireball fluid.
- As such the hydro picture is applied from t=0
- Fluids can (and do) overlap in space

There is an existing 3-fluid hydrodynamics model by Ivanov, Russkikh and Toneev, however it has a very limited flexibility and is numerically unstable for when simulating $\sqrt{s}$>20 GeV HIC.

Yu.B. Ivanov, V.N. Russkikh, V.D. Toneev, Phys.Rev.C 73:044904, 2006 [nucl-th/0503088]

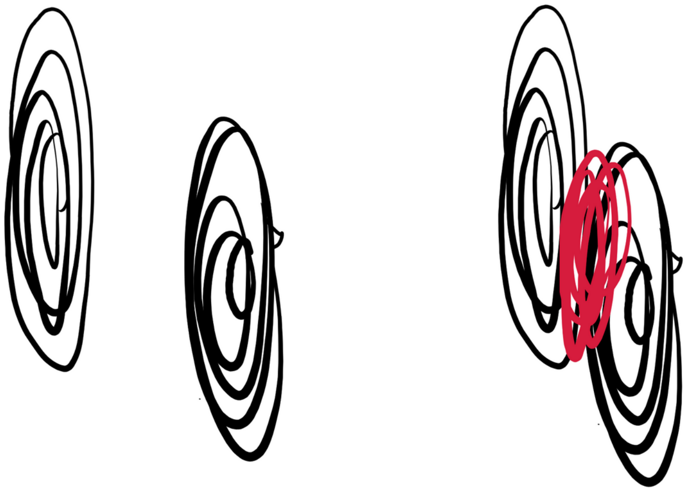
# Multi-fluid hydrodynamics: formalism

Not one but **three** sets of energy-momentum conservation equations, with non-geometrical source terms:

$$\partial_\mu T^{\mu\nu}_{\rm p}(x) = -F^\nu_{\rm p}(x) + F^\nu_{\rm fp}(x)$$

$$\partial_\mu T^{\mu\nu}_{\rm t}(x) = -F^\nu_{\rm t}(x) + F^\nu_{\rm ft}(x)$$

$$\partial_\mu T^{\mu\nu}_{\rm t}(x) = F^\nu_{\rm p}(x) + F^\nu_{\rm t}(x) - F^\nu_{\rm fp}(x) - F^\nu_{\rm ft}(x)$$



All fluids interact with each other via the source terms

The total energy of all fluids is conserved locally:

$$\partial_\mu \left(T^{\mu\nu}_{\rm p} + T^{\mu\nu}_{\rm t} + T^{\mu\nu}_{\rm f}\right) = 0$$

Friction terms:

$$F^\nu_\alpha = \kappa^2 \rho_p \rho_t m_N V^{\rm pt}_{\rm rel} \left[(u^\nu_\alpha - u^\nu_{\bar\alpha})\sigma_P(s_{pt}) + (u^\nu_p + u^\nu_t)\sigma_E(s_{pt})\right]$$ (from original 3FH)

$$F^\nu_\alpha = \frac{(u^*)^\nu_\alpha \sqrt{\varepsilon_p \varepsilon_t}}{\lambda}$$ (simple friction term)

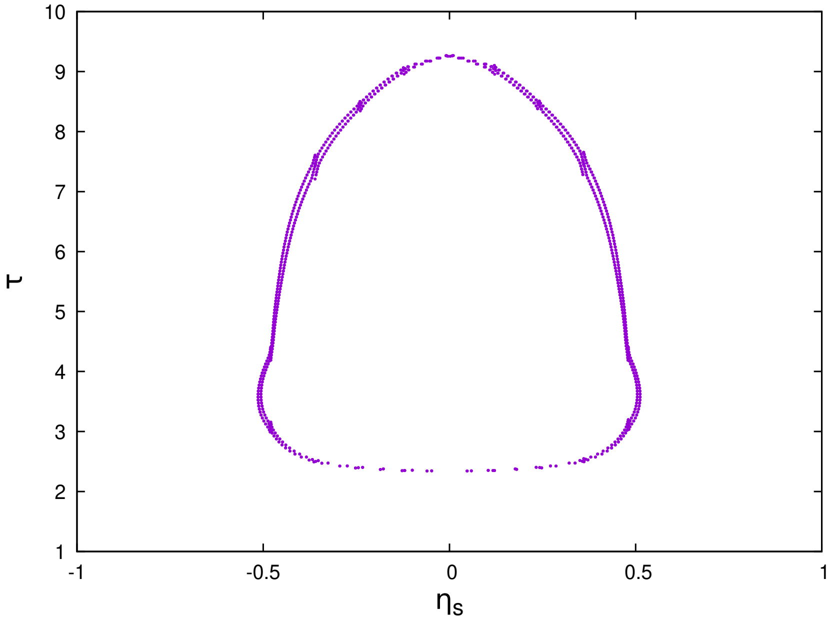
+projectile-fireball, target-fireball friction terms

# Post-hydrodynamic stage

**Particlization procedure:**

- In 1-fluid hydro, there is an industry standard: particlization at fixed energy density or temperature Reasoning: in a static medium, scattering rate ↔ temperature (at mu_b=0)
- In multi-fluid hydro, there is more space for ambiguity: there are densities of 3 fluids, which are generally counter-flowing.
- We adopted particlization at fixed “total” energy density. Total energy density is $T^{00}$ in diagonalized total energy-momentum tensor $T^{\mu\nu}_{\rm tot} = T^{\mu\nu}_{\rm p} + T^{\mu\nu}_{\rm t} + T^{\mu\nu}_{\rm f}$

  - The particlization surface s common for all 3 fluids, and the full distribution function is a sum from the 3 fluids: $f_{\rm tot} = f_{\rm p} + f_{\rm t} + f_{\rm f}$
  - We discard surface elements with:
    time-like normal and $d\Sigma_0 < 0$
    space-like normal and $d\Sigma_\mu u^\mu < 0$
  - Last but not least: **SMASH hadronic cascade** is used to treat post-hydro rescatterings.



# Some results