Directed flow in heavy-ion collisions and its implications for astrophysics

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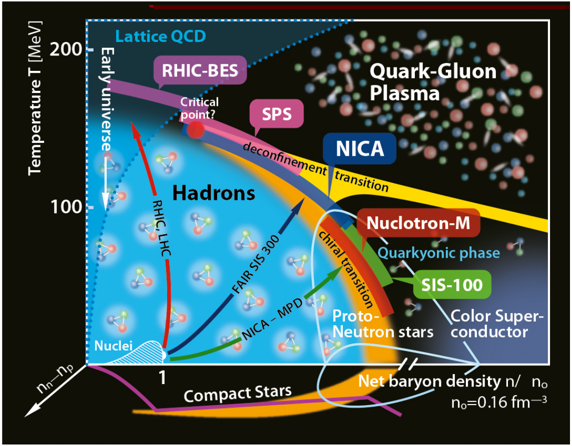
Exploring Nuclear Phase Diagram



What is the order of the deconfinement transition at high baryon densities?
Is there a critical end point in the phase diagram?

Hydrodynamics directly addresses Equation of State

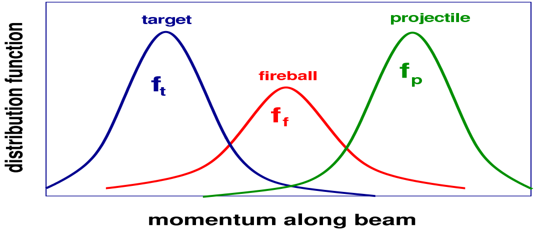
However, nonequilibrium prevents direct application of Hydrodynamics

3-Fluid Approximation

- Distributions are separated in momentum space
  $\Rightarrow$ different fluids
- Leading particles carry baryon charge
  $\Rightarrow$ 2 baryon-rich fluids: **projectile-like** and **target-like**

At high incident energies ($E_{lab} \gtrsim 10A$ GeV)

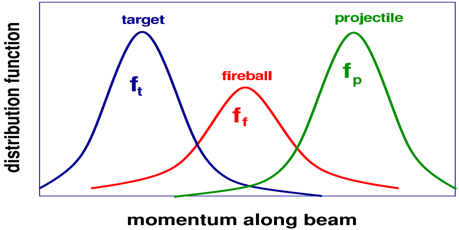
- Produced particles populate mid-rapidity $\Rightarrow$ **fireball fluid**



This a minimal extension of hydrodynamics required by heavy-ion dynamics

3-Fluid Dynamics (3FD)

Produced particles populate mid-rapidity
$\Rightarrow$ fireball fluid



Target-like fluid: $\partial_\mu J^\mu_t = 0$ $\quad$ $\partial_\mu T^{\mu\nu}_t = -F^\nu_{tp} + F^\nu_{ft}$

Leading particles carry bar. charge $\quad$ exchange/emission

Projectile-like fluid: $\partial_\mu J^\mu_p = 0$, $\quad$ $\partial_\mu T^{\mu\nu}_p = -F^\nu_{pt} + F^\nu_{fp}$

Fireball fluid: $J^\mu_f = 0$, $\quad$ $\partial_\mu T^{\mu\nu}_f = F^\nu_{pt} + F^\nu_{tp} - F^\nu_{fp} - F^\nu_{ft}$

Baryon-free fluid $\quad$ Source term $\quad$ Exchange

The source term is delayed due to a formation time τ

Total energy-momentum conservation:

$$\partial_\mu (T^{\mu\nu}_p + T^{\mu\nu}_t + T^{\mu\nu}_f) = 0$$

In-plain evolution of energy density

3FD model

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3FD Model

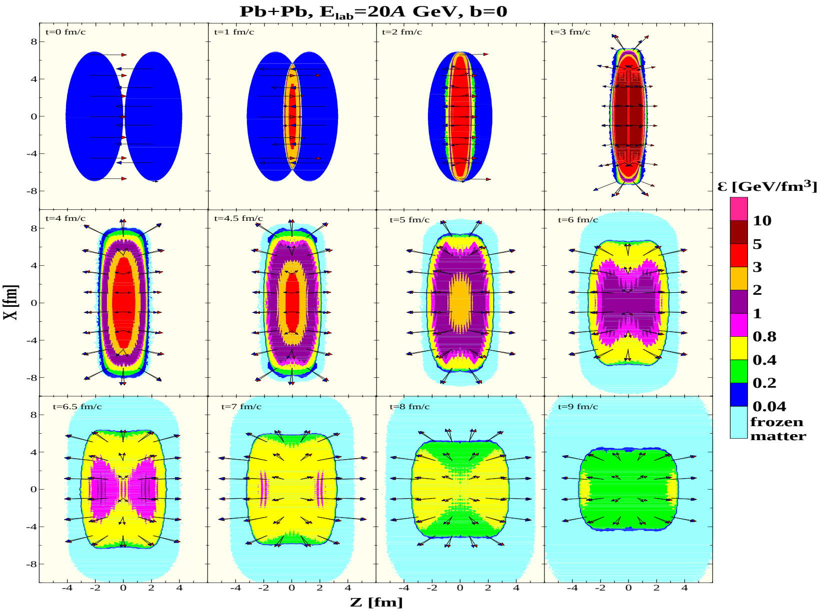
Phys. Input

Results

So far

Directed Flow

Summary

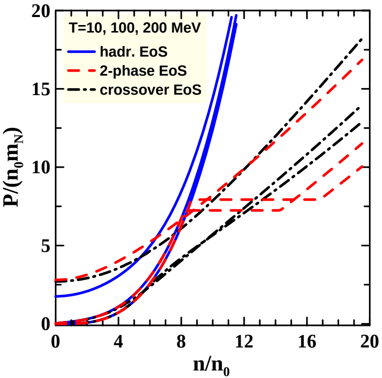


Physical Input I

I. Equation of State

- **Hadronic EoS**
  Galitsky&Mishustin (1979)
- 1st-order transition to QGP **(2-phase EoS*)**
- **crossover EoS***

*[Khvorostukhin, Skokov, Redlich, Toneev, (2006)]



Phase transition $\Longrightarrow$ EoS softening

Physical Input II and III

II. Friction was fitted to reproduce the baryon stopping

- **Hadronic EoS**

  Friction in hadronic phase was estimated by Satarov (SJNP 1990)

  This friction had to be enhanced.

- **2-phase EoS and crossover EoS**

  Phenomenological friction in QGP phase.

  Advantage of deconfinement scenarios:

  Satarov's friction in hadronic phase needs no modification

III. Freeze-out

When system becomes dilute, hydro has to be stopped

Freeze-out energy density ε_{frz} = 0.4 GeV/fm^3

Phase Evolution

3FD model

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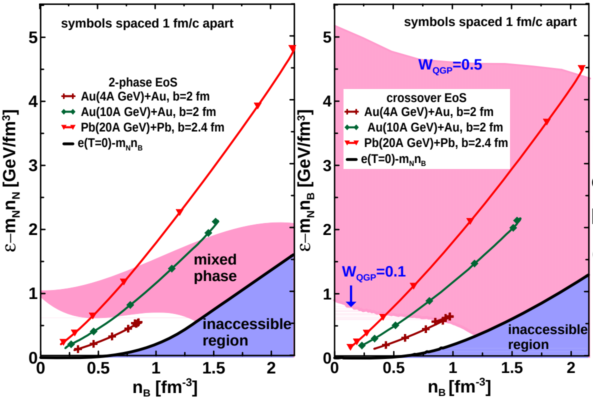

Dynamical trajectories of matter in the central box of colliding nuclei ($4\text{fm}\times 4\text{fm}\times \gamma_{cm}$ 4fm)

Crossover transition by ***Khvorostukhin et al.*** **is too smooth**

Lattice QCD predicts a fast crossover.

Therefore, a true EoS is somewhere in between the *"Khvorostukhin et al."*-crossover and *"Khvorostukhin et al."*-2-phase EoS's.

Onset of deconfinement happens at top-AGS–low-SPS energies.

Results analyzed so far

- **Particle Production:**
  QCP is required at high collision energies
- **Transverse-Momentum Spectra:**
  QCP is required at high collision energies
- **Inverse Slopes and Mean Transverse Masses:**
  QCP is required at high collision energies

Predictions of the crossover and first-order-transition scenarios look very similar.

Transition into QGP takes place.

Only a slight preference of the crossover EoS.

Results analysed so far

3FD model

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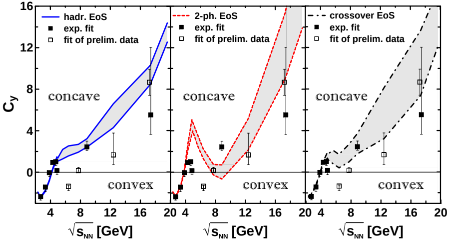
- **Baryon Stopping, i.e. proton rapidity distributions:**

C_y = reduced curvature of net-proton rapidity distribution at midrapidity



a wiggle irregularity of C_y at midrapidity

This irregularity is a signal from hot and dense stage of nuclear collision

Except for the baryon stopping, predictions of the crossover and first-order-transition scenarios looked very similar so far.

Flow

Fourier expansion of a particle distribution, $d^2N/dy\ d\phi$, in azimuthal angle ϕ with respect to the reaction plane

$$\frac{d^2N}{dy\ d\phi} = \frac{dN}{dy}\left(1 + \sum_{n=1}^{\infty} 2\ v_n(y)\cos(n\phi)\right)$$

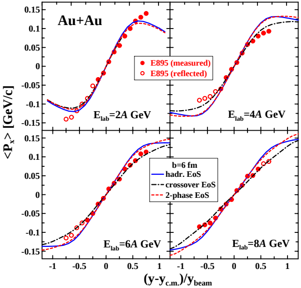
where y is the longitudinal rapidity of a particle.

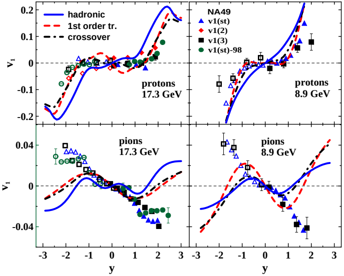
$v_1(y)$ = **directed flow**

$v_2(y)$ = **elliptic flow**

$v_3(y)$ = **triangular flow**

Directed Flow at AGS and SPS





$$\langle P_x \rangle (y) = \frac{\int d^2 p_T \; p_x \; E \; dN/d^3 p}{\int d^2 p_T \; E \; dN/d^3 p},$$

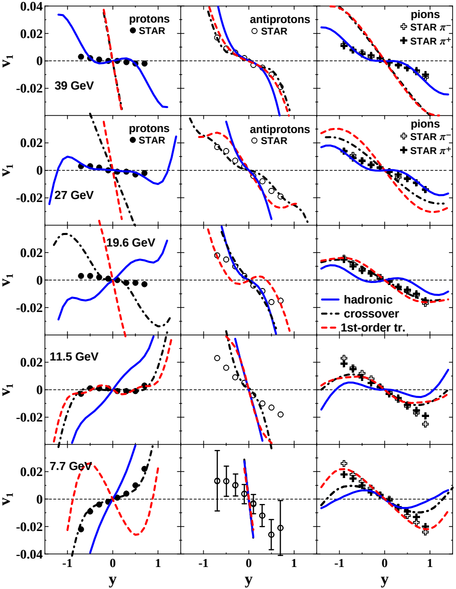
where p_x is the transverse momentum of in the reaction plane.

The crossover $\langle P_x \rangle (y)$ almost perfectly reproduces the data.

The crossover is preferable at AGS and SPS energies.

Y. B. Ivanov and A. A. Soldatov, Phys. Rev. C **91**, no. 2, 024915 (2015)

Directed Flow at RHIC



STAR data: L. Adamczyk *et al.*, Phys. Rev. Lett. 112, 162301 (2014)

High sensitivity of the proton directed flow to the EoS.

The crossover EoS is preferable in the energy range of 7.7 $\lesssim \sqrt{s_{NN}} \lesssim$ 20 GeV.

The deconfinement EoS's in the QGP sector should be stiffer at high baryon densities than those used in the calculation.

V. P. Konchakovski, W. Cassing, Y. B. Ivanov and V. D. Toneev, Phys. Rev. C 90, no. 1, 014903 (2014)

Y. B. Ivanov and A. A. Soldatov, Phys. Rev. C 91, no. 2, 024915 (2015)

Midrapidity slopes of Directed Flow

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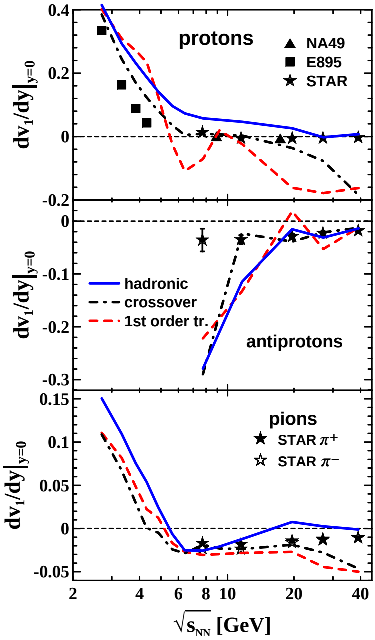


High sensitivity of the proton directed flow to the EoS.

v_1 indicates the crossover deconfinement transition in a wide range of energies $4 \lesssim \sqrt{s_{NN}} \lesssim 20$ GeV.

The crossover EoS is preferable in this energy range.

The deconfinement EoS's in the QGP sector should be stiffer at high baryon densities.

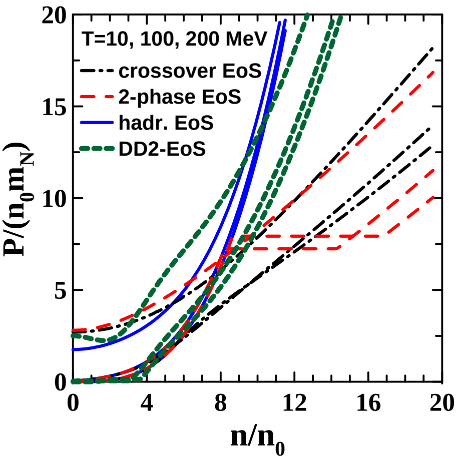
The latter is in agreement with that discussed in astrophysics.

QGP EoS at high baryon densities

- **Hadronic EoS**
  Galitsky&Mishustin (1979)
- 1st-order transition **(2-phase EoS*)**
- **crossover EoS***
- **density-dependent (DD2) EoS****

*[Khvorostukhin, Skokov, Redlich, Toneev, Eur. Phys. J. **C48**, 531 (2006)]

**[S. Typel et al. PRC 81 (2010) 015803]



Phase transition $\Longrightarrow$ EoS softening

however

This softening should be weak at high baryon densities

Danielewicz plot

3FD model

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- **Hadronic EoS**
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- 1st-order transition
  (2-phase EoS*)
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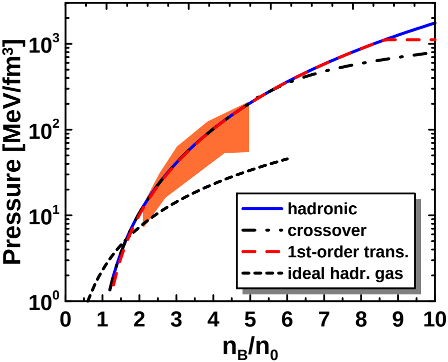

Phase transition $\Longrightarrow$ EoS softening

however

This softening happens at higher baryon densities than those of the exp. constraint

Summary

- Deconfinement scenarios are preferable at $\sqrt{s_{NN}} > 4$ GeV
  So far only a slight preference of the crossover EoS.

- **directed flow:**
  - High sensitivity of the proton directed flow to the EoS
  - v_1 indicates the crossover deconfinement transition in a wide range of energies $4 \lesssim \sqrt{s_{NN}} \lesssim 20$ GeV.
  - QGP EoS's at high baryon densities should be stiffer than those used in the calculation

    Similar conjecture from astrophysics

- Analysis is still in progress:

  DD2 EoS [S. Typel et al. PRC 81 (2010) 015803]

  THESEUS generator [P. Batyuk et al. PRC 94 (2016) 044917]