Directed flow in heavy-ion collisions at high baryon densities

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[PRC **110,** 014907 (2024)]

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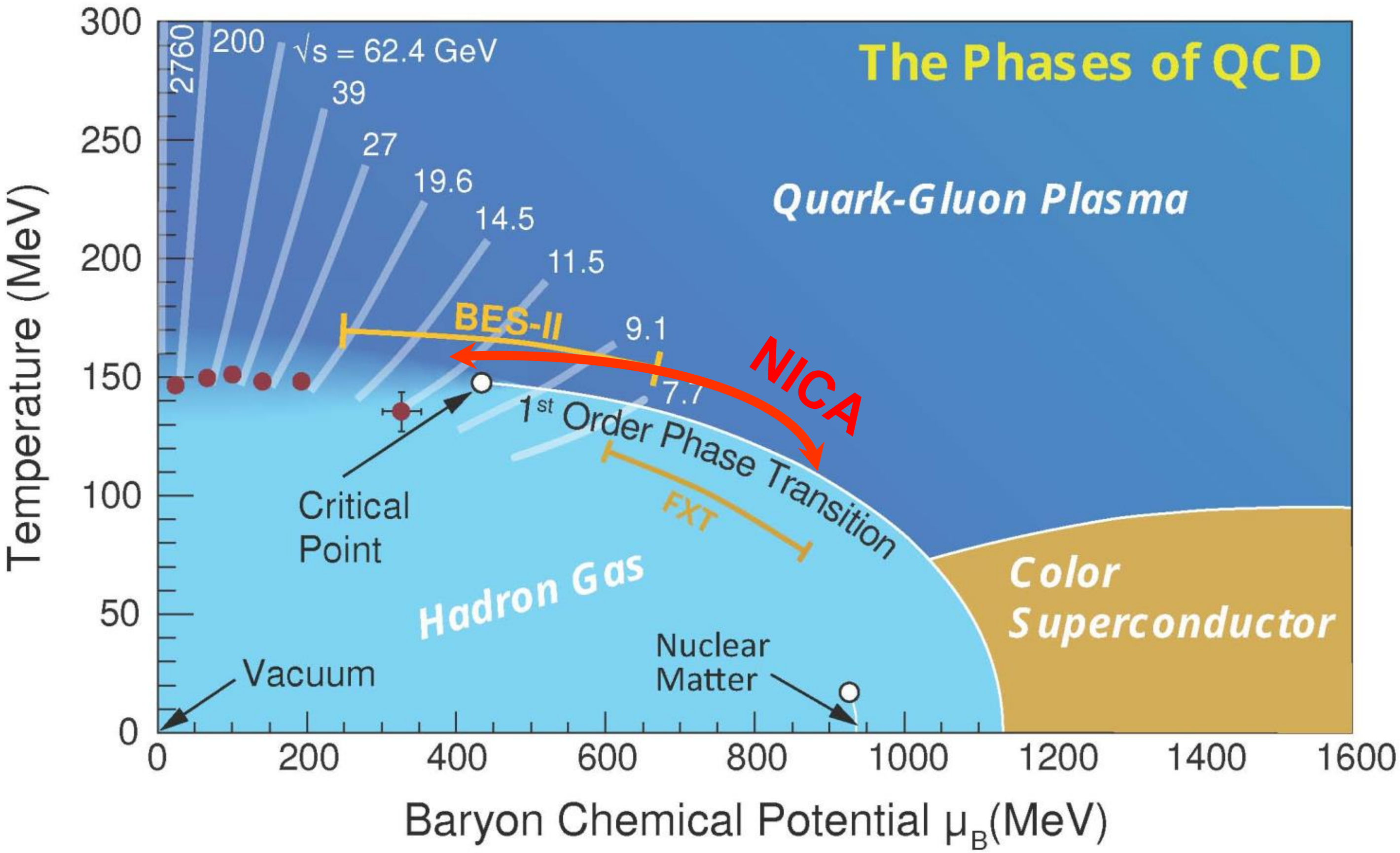
Exploring Nuclear Phase Diagram



From M. Stephanov, EPJ Web Conf. 314, 00042 (2024)

Hydrodynamics directly addresses Equation of State

However, nonequilibrium prevents direct application of Hydrodynamics

Hydrodynamics versus Kinetics

Hydrodynamics

- ✓ directly addresses **Equation of State (EoS)**!
- ✓ **Phase transition in QGP** is accessible through EoS

However, there are certain **problems**

Standard hydrodynamics (e.g.,vHLLE)

- ✓ Requires local equilibrium, therefore
  Pre-equilibrium (kinetic or parametrised) stage is required
- ✓ Is not applicale at very end of collision because of nonequlibrium
  Kinetic afterburner is required
- ✓ At $\sqrt{s_{NN}} \leq 6$ GeV the time for hydro turns out to be very short

- ✓ **Phase transition into QGP is inaccessible in kinetics**
  Exceptions: PHSD, PHQMD, AMPT ➔ only crossover transition

- ✓ **3FD overcomes these problems**

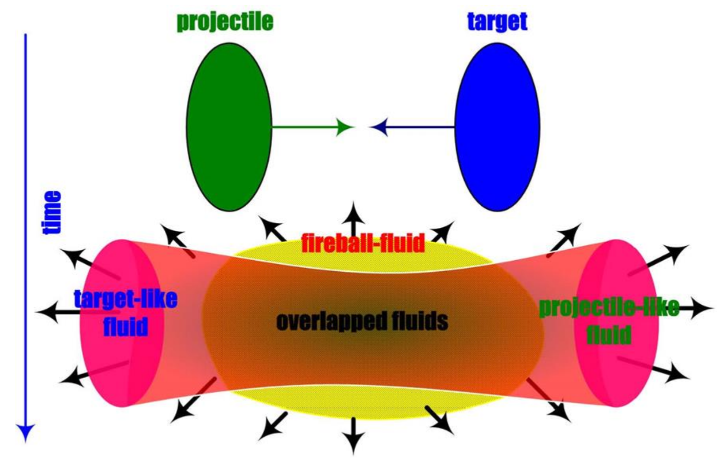
3-fluid dynamics (3FD) model describes initial equilibration

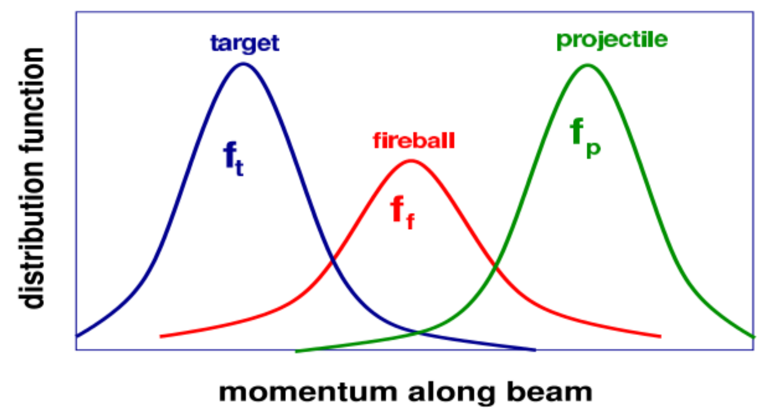
The 3FD approximation simulate the early, nonequilibrium stage of the strongly-interacting matter:

- ✓ **baryon-rich fluids**: nucleons of the projectile (p) and the target (t) nuclei.

  They are separated in momentum space

- ✓ **fireball (f) fluid**: newly produced particles which dominantly populate the midrapidity region.





3FD model

Target-like fluid: $\partial_\mu J_t^\mu = 0$ $\quad \partial_\mu T_t^{\mu\nu} = -F_{tp}^\nu + F_{ft}^\nu$

Leading particles carry bar. charge — exchange/emission

Projectile-like fluid: $\partial_\mu J_p^\mu = 0,$ $\quad \partial_\mu T_p^{\mu\nu} = -F_{pt}^\nu + F_{fp}^\nu$

Fireball fluid: $J_f^\mu = 0,$ $\quad \partial_\mu T_f^{\mu\nu} = F_{pt}^\nu + F_{tp}^\nu - F_{fp}^\nu - F_{ft}^\nu$

Baryon-free fluid — Source term — Exchange

The source term is delayed due to a formation time τ

Total energy-momentum conservation:

$$\partial_\mu (T_p^{\mu\nu} + T_t^{\mu\nu} + T_f^{\mu\nu}) = 0$$

Physical Input

- ✓ Equation of State (**EoS**)
- ✓ Friction
- ✓ Freeze-out energy density ε_{frz} = 0.4 GeV/fm^3

3FD: YI, Russkikh, Toneev, PRC 73, 044904 (2006)

EoS:

- hadronic EoS (no phase transition)

Mishustin, Russkikh and Satarov,

Sov. J. Nucl. Phys. 54, 260 (1991)

- hadronic+QGP with 1st-order Phase Transition (1PT)
- hadronic+QGP with crossover

Khvorostukhin, Skokov, Toneev, Redlich, EPJ C48, 531 (2006)

- Friction in hadronic phase is estimated [Satarov, Yad. Fiz. 52, 412 (1990)].
- Friction in QGP is parametrized [Y.I. PRC 87, 064904 (2013)]

Afterburner (kinetic evolution after hydro)

Afterburner by means of event generator THESEUS

(**T**hree-fluid **H**ydrodynamics-based **E**vent **S**imulator **E**xtended by **U**rQMD final **S**tate interactions)

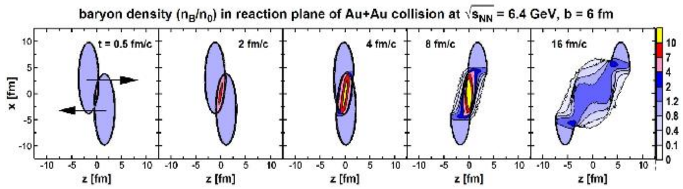
THESEUS-v1, Batyuk, Blaschke, Bleicher, YI, Karpenko, Merts, Nahrgang, Petersen and Rogachevsky, PRC 94, 044917 (2016)

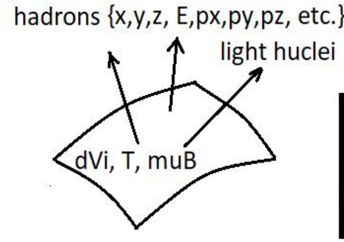
THESEUS-v2 updated, Kozhevnikova, YI, Karpenko, Blaschke and Rogachevsky, PRC 103, 044905 (2021)

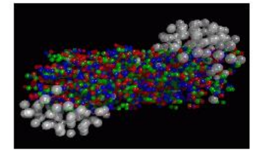
THESEUS:

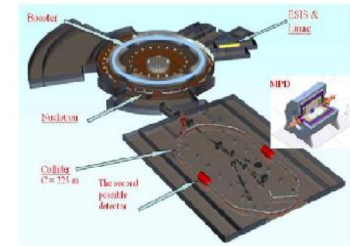
- transformation of 3FD output (fields of T, μ_B and μ_S) into set of particles (**particlization)**
- Post-freeze-out kinetic evolution by means of UrQMD (**afterburner**)

Afterburner is important at moderately relativistic energies









Initial state → hydrodynamic evolution → particlization → afterburner → detector response

3-fluid hydrodynamical model
(Y.Ivanov et al.)

THESEUS generator

(optionally) UrQMD, etc.
(Iu. Karpenko, H.Elfner)

GEANT, MPD,BM@N
(O.Rogachevsky,
P.Batuyk, S.Merts et al.)

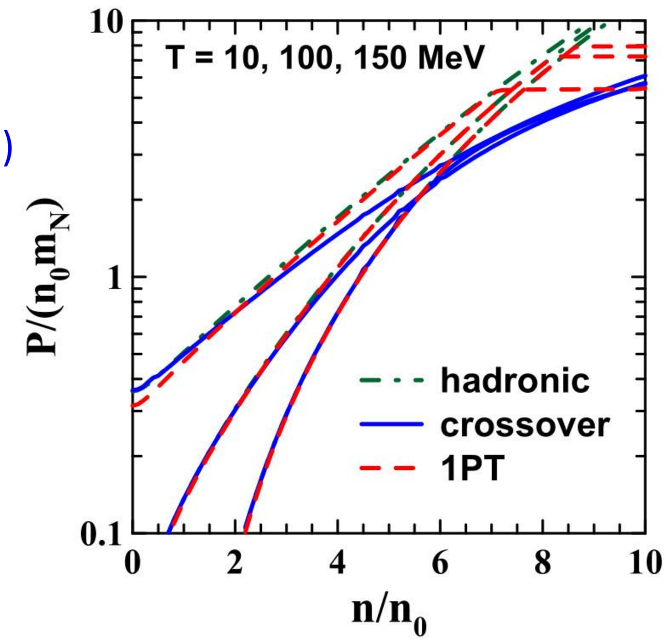
(prepared by M. Kozhevnirjva)

3DF+THESEUS-v2 can predict almost all except for few things:

- ✓ Fluctuations, because there are no fluctuations in the initial state
- ✓ Collisions of light nuclei and very peripheral collisions because hydro is inapplicable to few-particles systems
- ✓ Collisions at $\sqrt{s_{NN}} \geq 40$ GeV because of numerical problems

Equation of State

Pressure vs baryon density



Hadronic EoS (hadr.-EoS)

Mishustin, Russkikh Satarov, Sov. J. Nucl. Phys. 54, 260 (1991)

1st-order transition to QGP (1PT-EoS)

Khvorostukhin, Skokov, Redlich, Toneev, EPJ **C48**, 531 (2006)

crossover transition to QGP

Khvorostukhin, Skokov, Redlich, Toneev, EPJ **C48**, 531 (2006)

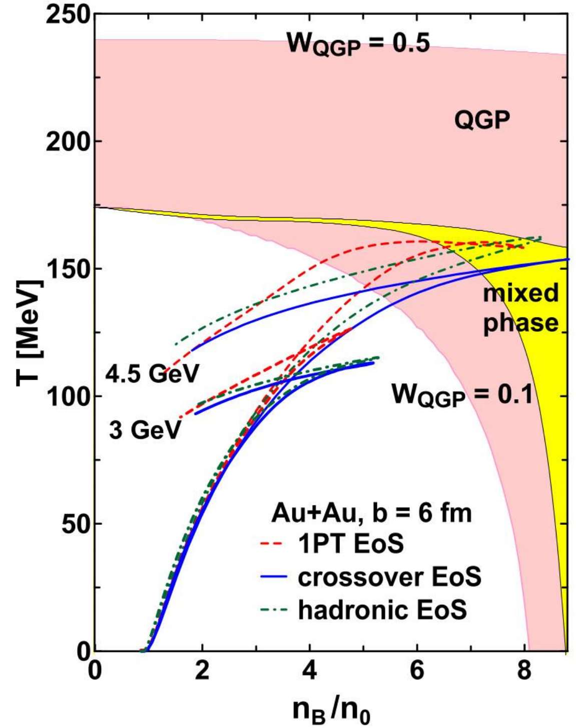
Phase transition ➔ EoS softening (in dense baryon matter)

Hadronic phase: Friction was estimated by Satarov [Sov.J.Nucl.Phys. 52, 264 (1990)]
QGP phase: Phenomenological friction fitted to reproduce baryon stopping [YI, PRC 87 (2013), 064904]

Dynamical trajectories of matter in central region

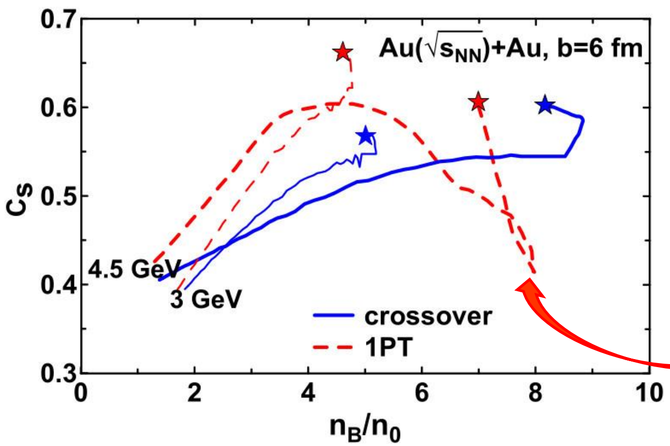
Temperature vs baryon density

- ✓ **Turning points at 3 GeV does not reach the QGP.**
- ✓ **4.5-GeV trajectories fall well into crossover QGP region and even enter the the 1PT mixed phase.**



Speed of sound vs baryon density

Evolution starts from instants (indicated by ★) when matter is equilibrated.



$c_s = (dP/d\varepsilon)$ along trajectory

softest-point region is probed at 4.5 GeV within 1PT scenario.

How are these features manifested in directed flow?

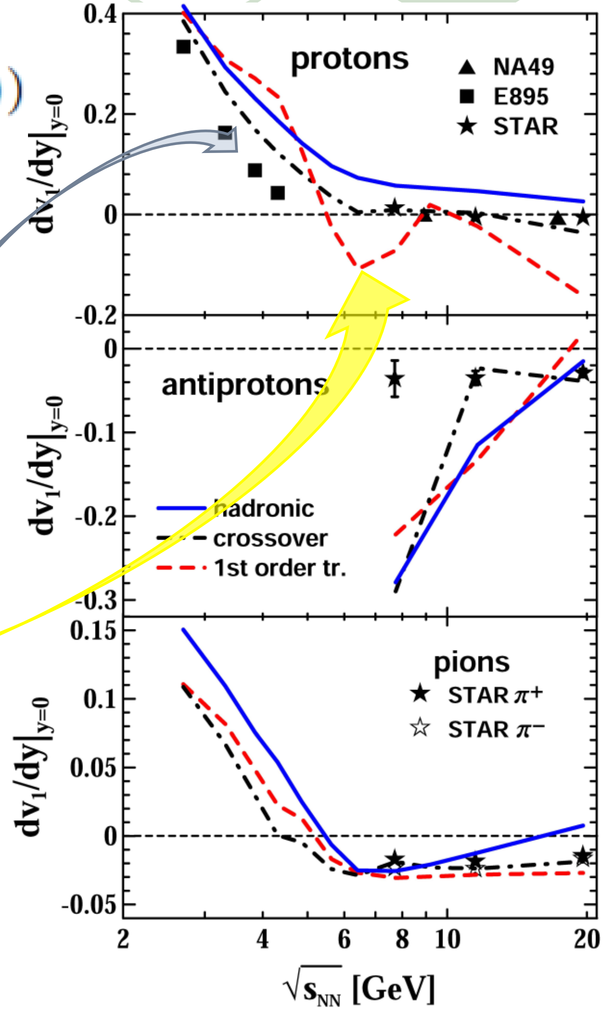
Directed flow (v_1)

YI and Soldatov, PRC 91 (2015) 2, 024915

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1+\sum_{n=1}^{\infty} 2v_n\cos(n(\phi-\Psi_{RP}))\right)$$

φ = azimuthal angle

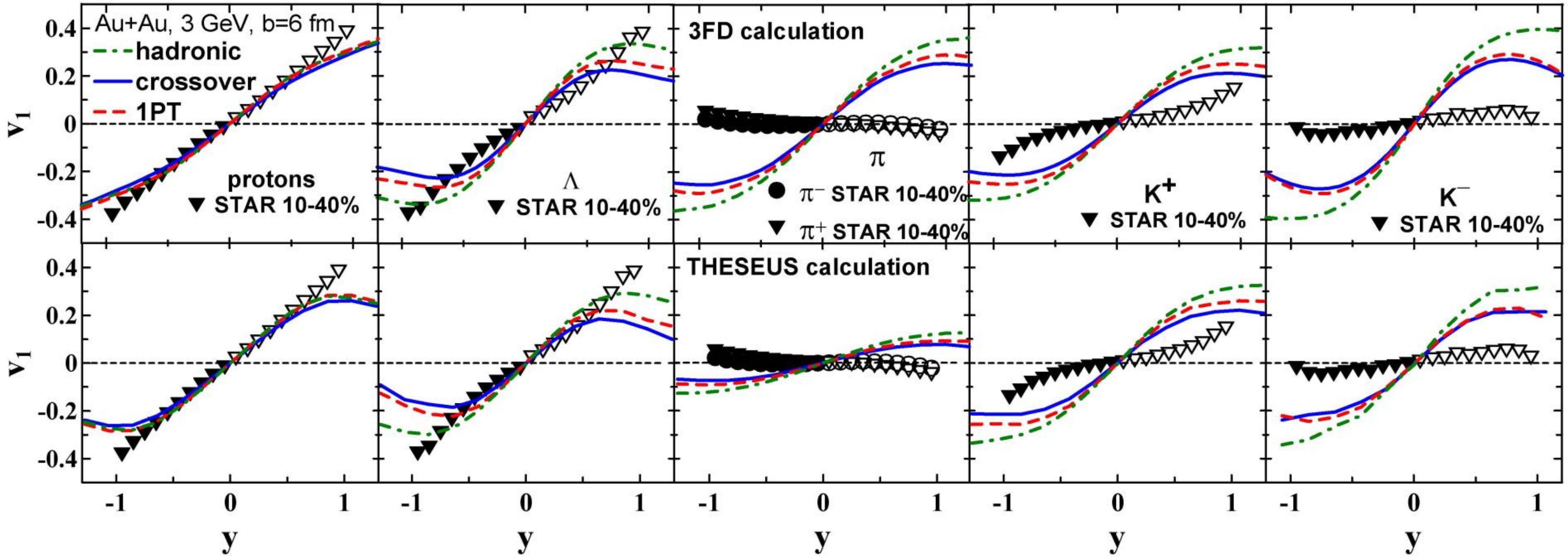
v_1 = directed flow v_2 = elliptic flow



- Proton directed flow at √sNN < 7 GeV is well reproduced in terms of ‹P_x› but not in terms of v_1.

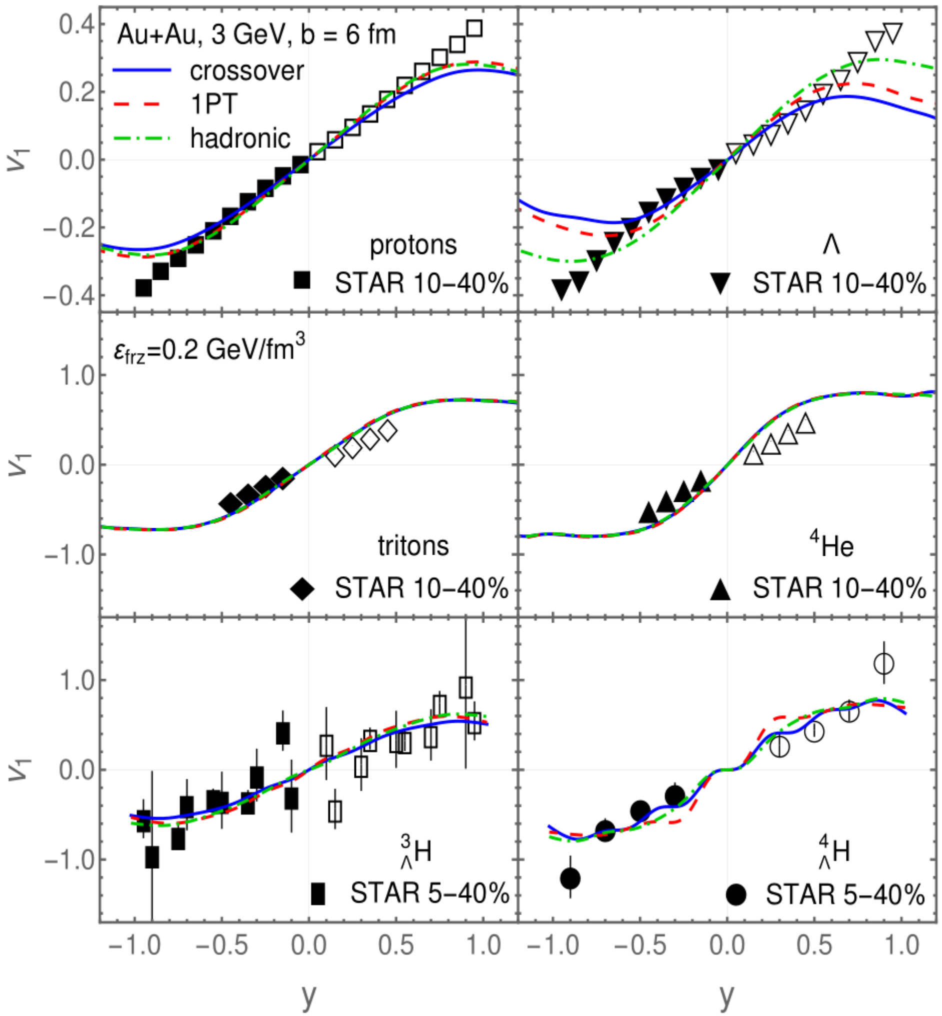
- ✓ v_1 is very sensitive to onset of deconfinement transition and softest point
- ✓ Onset of deconfinement transition happens in the NICA energy range.
- ✓ Crossover EoS is preferable.

Directed flow at 3 GeV



- ✓ v_1 in midrapidity does not depend on EoS → **no QGP transition**
- ✓ *p* and Λ v_1 are well reproduced with all EoS's → **no QGP tr.**
- ✓ **Afterburner is important for *π*, Λ and K^-**:
  shadowing of participants by spectators
- ✓ Description of this shadowing still is not perfect
- ✓ **K^+ is not equilibrated or requires early freeze-out**

v_1 of light nuclei and hypernuclei at 3 GeV



3FD-THESEUS: Kozhevnikova and YI

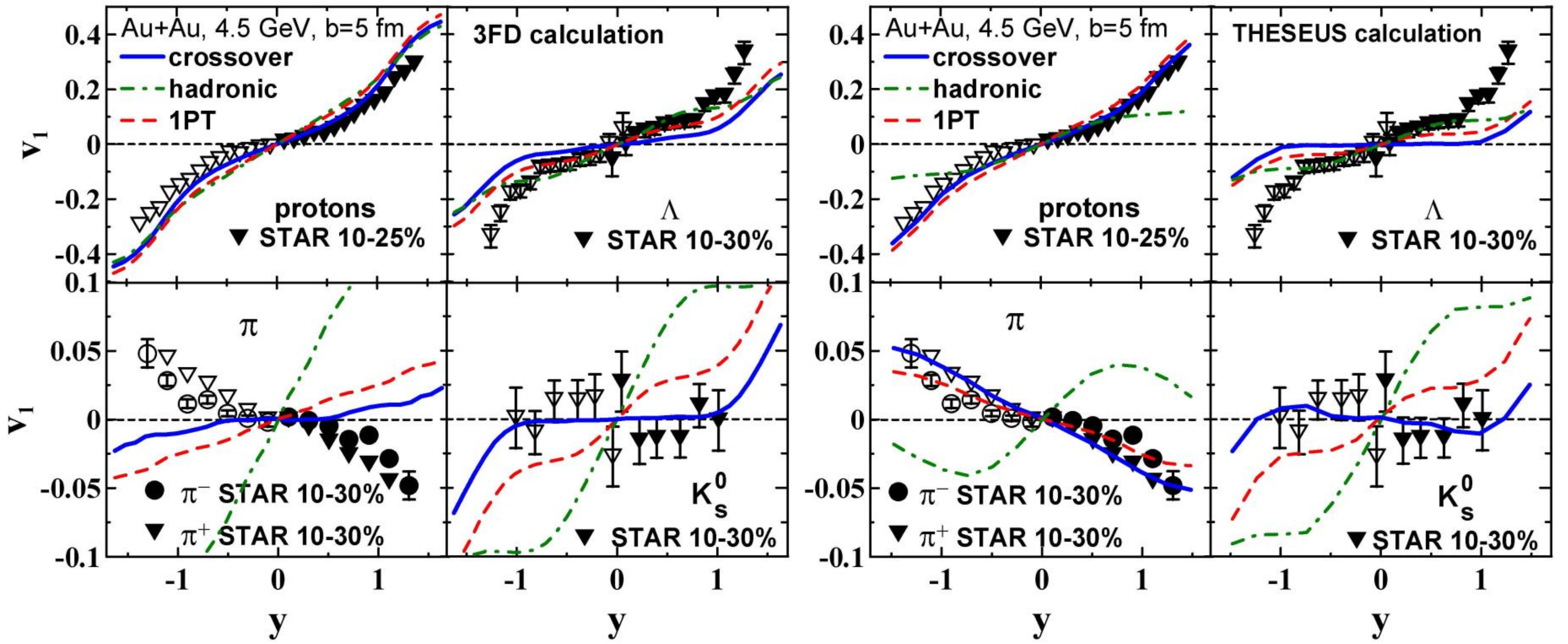
Light nuclei: PRC109 (2024), 014913

Light hypernuclei: PRC 109 (2024), 034901

Hadrons: PRC 110 (2024), 014907

Data: STAR, PRC 110 (2024) 5, 054911; PLB 827, 136941 (2022); PRL 130, 212301 (2023); PRC 103, 034908 (2021); PLB 827, 137003 (2022)

Directed flow at 4.5 GeV

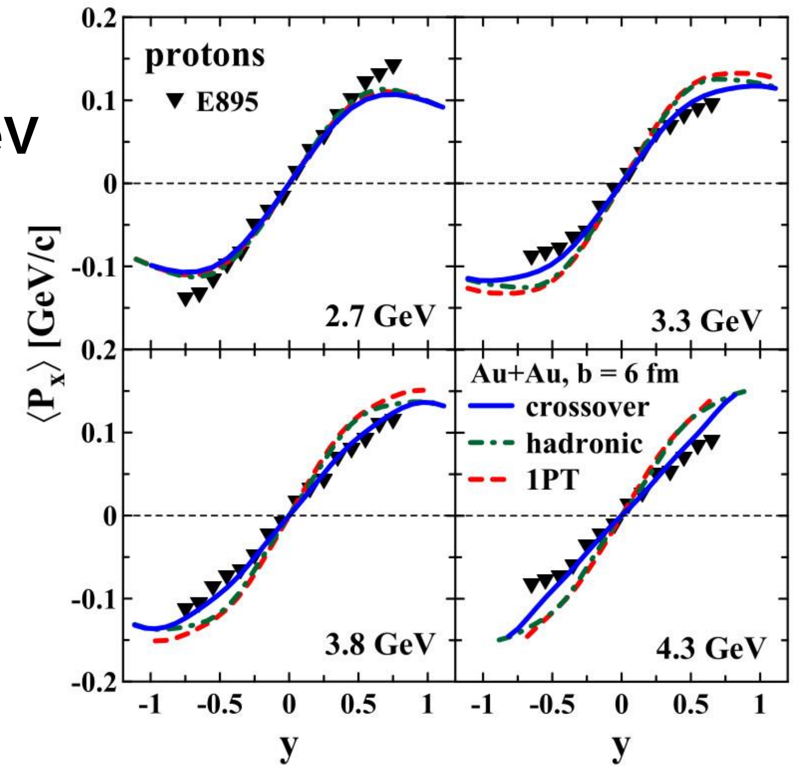


- ✓ **v_1 does depend on EoS → QGP transition**
- ✓ *p*, ***π*** and **K^0** are well reproduced with crossover EoS. **Afterburner is important, especially for *π*,** because of shadowing of participants by spectators
- ✓ **Different particles probe EoS in different parts and at different stages of the colliding system**

Proton v_1 evolution between 2.7 and 4.5 GeV

YI and Soldatov, PRC 91 (2015) 2, 024915

- ✓ Note that $v_1 = \langle p_x/p_T \rangle$
- ✓ v_1 does not depend on EoS **at 2.7 GeV** → **no QGP transition**
- ✓ Crossover EoS gradually becomes preferable at $\sqrt{s_{NN}} > 3$ GeV
- ✓ Hadronic and 1PT scenarios give almost identical v_1



Consensus: QGP onset happens between $\sqrt{s_{NN}}$ = 3 and 4.5 GeV

Model	Potential interaction	QGP phase	Transition to QGP	type
UrQMD	optional	No	Above $4n_0$*	QMD
QGSM	no	No	No	Kin. Eq.
PHSD	Mean-field (optional)	yes	$\varepsilon > 0.5$ GeV/fm^3	Kin. Eq.
PHQMD	2-body potential	yes	$\varepsilon > 0.5$ GeV/fm^3	QMD
AMPT	Mean-field (optional) Various versions	yes	lower than ~ $2.5n_0$ $3\text{--}5n_0$ $4.3\text{--}5.7n_0$	Kin. Eq.
SMASH	Mean-field	no	$3\text{-}4n_0$*	Kin. Eq.
JAM	Mean-field (optional)	no	Above $3\text{--}4n_0$*	Kin. Eq.
3FD (THESEUS)	**Non-gas EoS**	**yes**	**Above $4\text{--}5n_0$**	**hydro**

* "Softenning of EoS" is required

Summary

- **v_1 is one of most sensitive observable to the QGP transition**
- v_1 data indicate **onset of QGP transition at $\sqrt{s_{NN}} \geq 4$ GeV**
- **Onset of QGP transition happens at $n \geq 4$--$5n_0$ and $T \approx 150$ MeV**

- v_1 of various particles provide information on EoS in different parts and at different stages of the colliding system
- information on EoS is not always directly accessible because of strong influence of afterburner stage or insufficient equilibration.

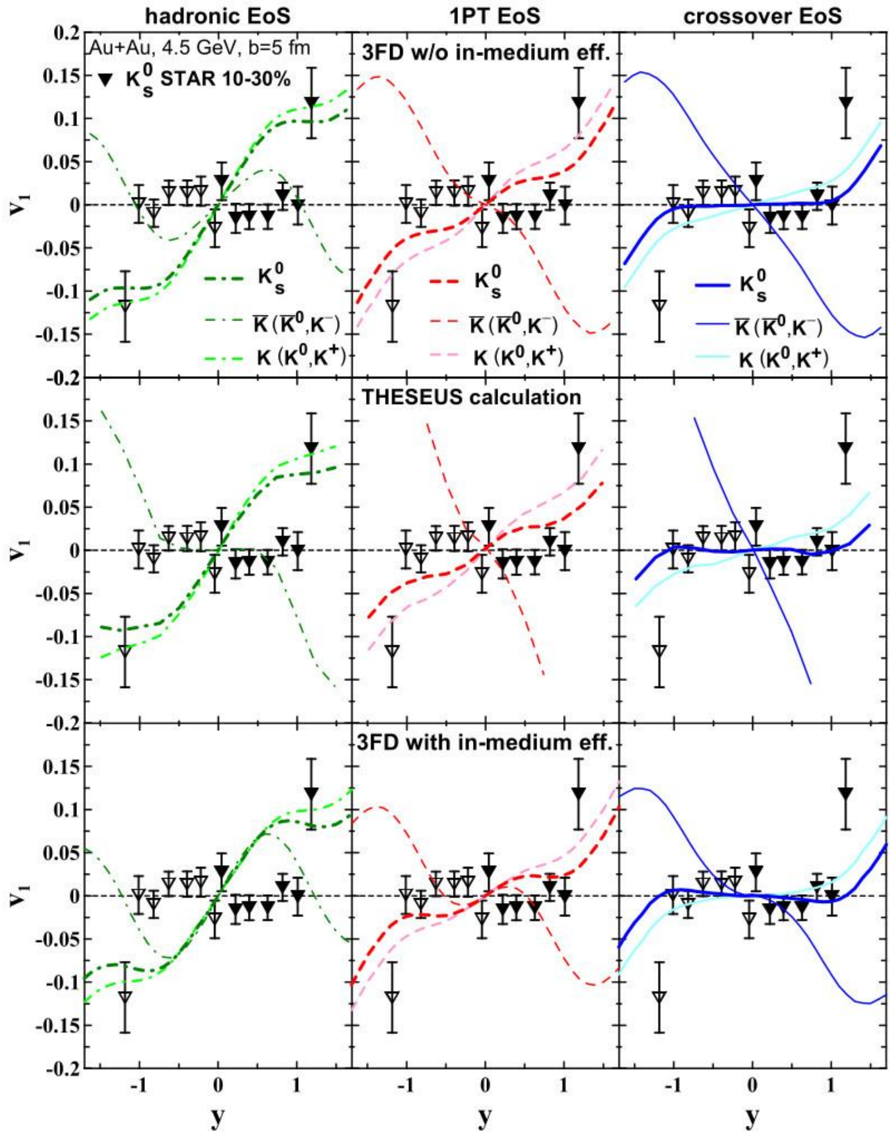
- **Crossover EoS gives the best overall description of the data**
- This EoS crossover may mimic a weak 1PT, as the critical point is likely located in the upper part of NICA energy range [STAR, 2504.00817]
- The used 1PT EoS corresponds to strong 1PT

Thank you

for your attention!

Backup

v_1 of medium modified Kaons



$$E(\mathbf{p}) = \left[m_K^2 + \mathbf{p}^2 - \frac{\Sigma_{KN}}{f_K^2}\rho + \left(\frac{3}{8}\frac{n}{f_K^2}\right)^2 \right]^{1/2} \pm \frac{3}{8}\frac{n}{f_K^2},$$

$$n = \sum_B \langle \bar{B}\gamma^0 B \rangle,$$

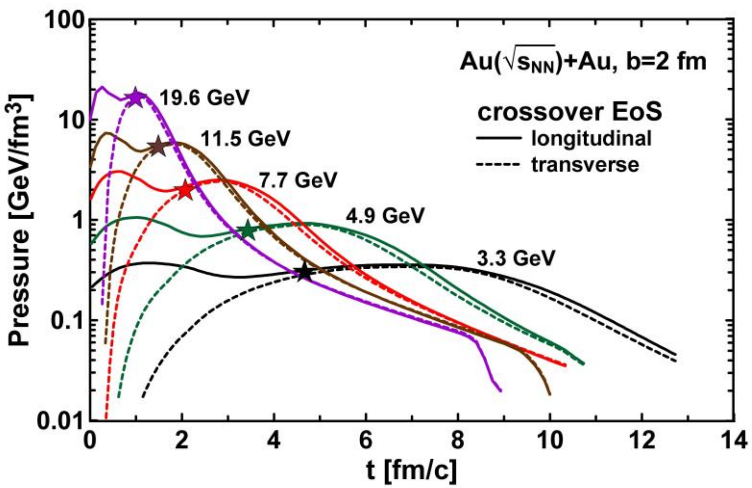
$$\rho = \sum_B \langle \bar{B}B \rangle$$

upper(lower) sign refers to K(anti-K).
n and ρ are proper baryon and scalar baryon densities, respectively.

v_1 of K and anti-K are changed, while v_1 of K^0_s remains almost unchanged

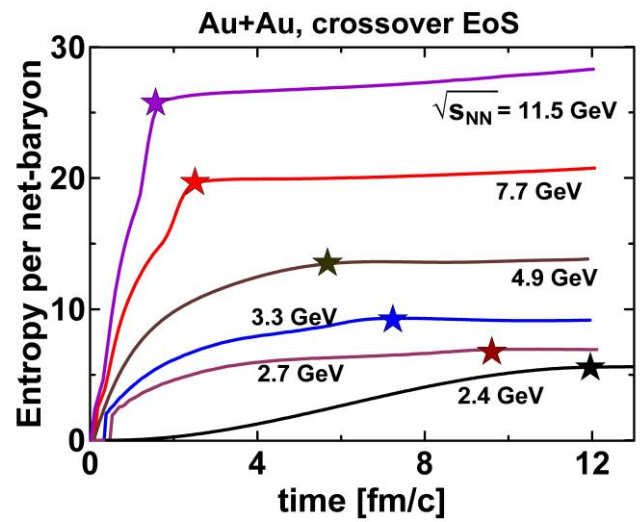
Initial Equilibration

vHLLE: **UrQMD (till the equilibration) → hydro → UrQMD (afterburner)**
This is a typical scheme for any 1-fluid hydro model



3FD
Simulations

Ivanov, Soldatov PRC 101 (2020) 2, 024915



- ✓ Time of initial equilibration is long at lower NICA energies.
- ✓ Therefore, the time for hydro turns out to be short
- ✓ Therefore, vHLLE applicability is $\sqrt{s_{NN}} \geq 6$ GeV
- ✓ Therefore, starts already in the QGP phase because of

Consensus: QGP is present at $\sqrt{s_{NN}}$ = 4.5 GeV and no QGP at $\sqrt{s_{NN}}$ = 3 GeV in Au+Au collisions

Kinetics: advantages and disadvantages

Advantages:

Kinetic and QMD models

✓ directly address nonequilibrium

✓ can treat non-gas systems (mean fields, 2-body potentials)

✓ naturally treat fluctuations (CEP search)

Disadvantages:

➢ Huge amount of input data (**often experimentally unknown**)

➢ In practice, kinetics ⟶ only binary collisions/interactions

Approximation of binary collisions is bad in dense system!

➢ Phase transition into QGP is inaccessible in kinetics, as a rule

Exceptions: PHSD, PHQMD, AMPT ➡ crossover transition

Hydrodynamics versus Kinetics

Hydrodynamics

- ✓ takes into account any multi-particle interactions
- ✓ directly addresses **Equation of State (EoS)**!
- ✓ Phase transition in QGP is accessible through EoS

However, there are certain **problems**

Standard hydrodynamics (vHLLE)

- ✓ Requires local equilibrium, therefore it cannot be applied from the very beginning of the collision

  Pre-hydro (kinetic or parametrised) stage is required

  3FD overcomes this problem (see below)
- ✓ Is not applicale at the very end of the collision because of nonequlibrium

  Kinetic afterburner is required

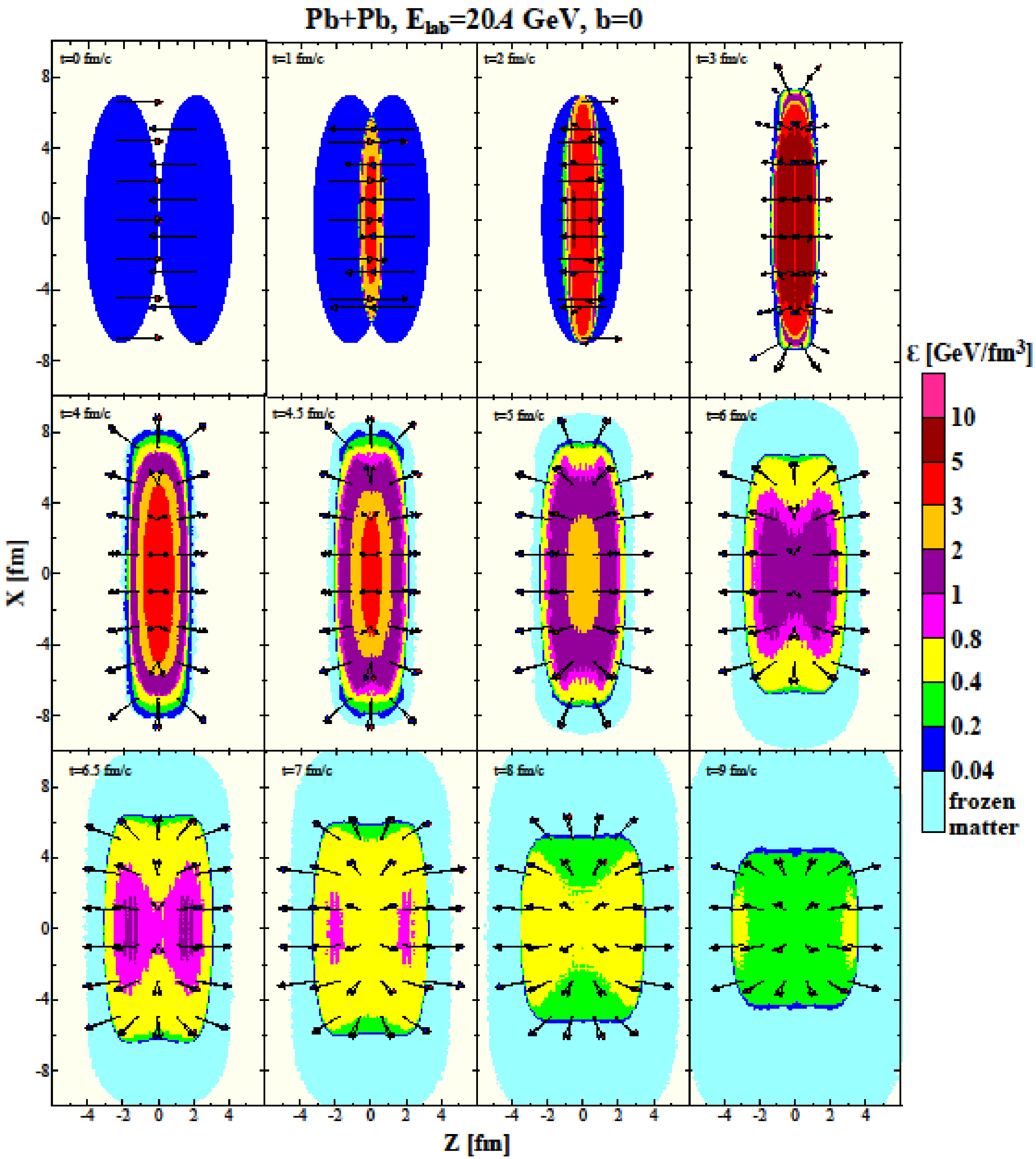


illustration:

Time evolution of energy density in reaction plane