Directed flow of protons in nuclear collisions as a signal of transition to the quark-gluon phase

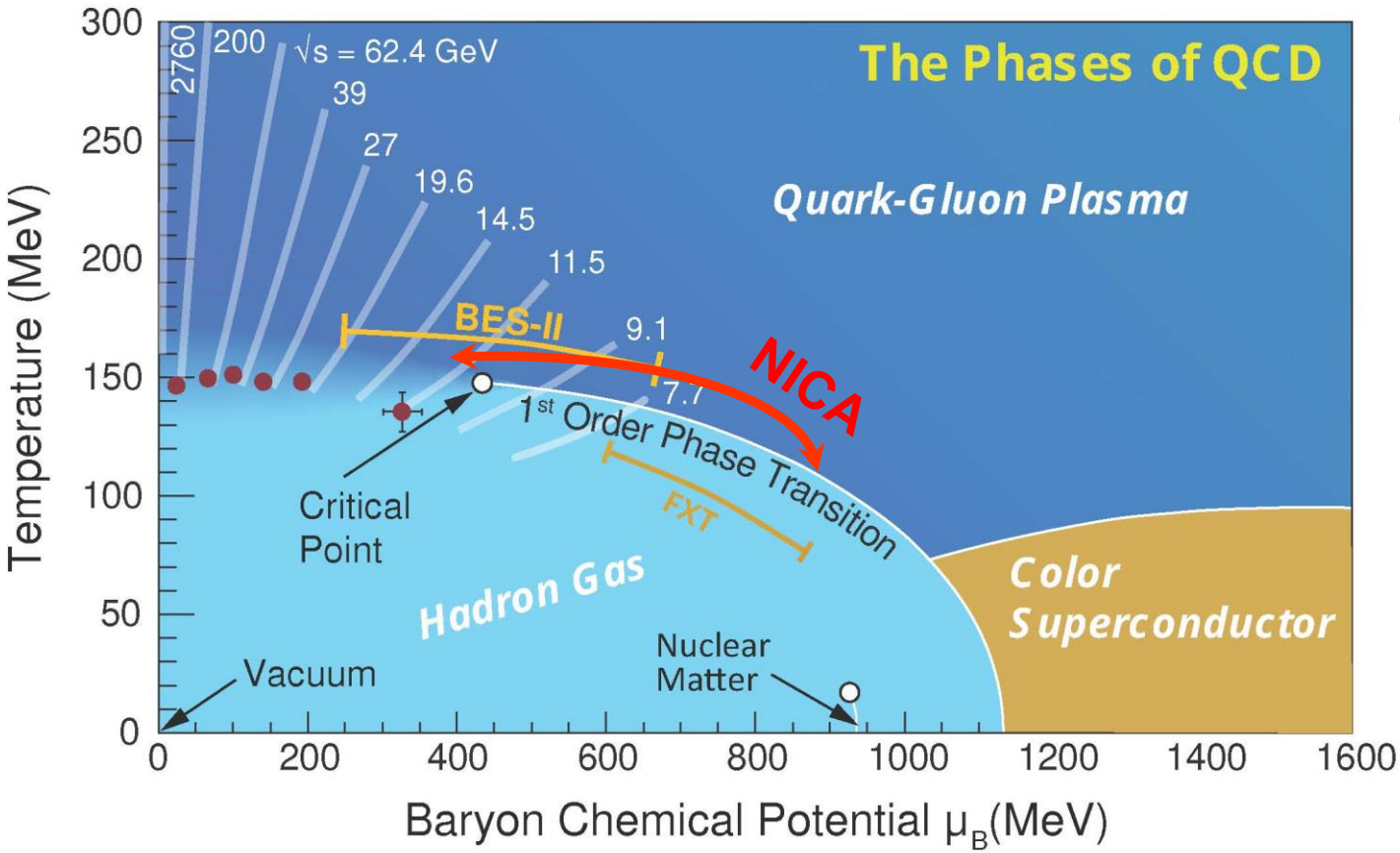
Phys. Rev. C 113, 024914 (2026)

Yuri B. Ivanov

BLTP Bogoliubov Laboratory of Theoretical Physics

LHEP, February 27, 2026

Exploring Nuclear Phase Diagram



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

Onset of transition into QGP and Critical Point are expected in NICA energy range

Directed flow (v_1)

Spectrum is expanded in Fourier series

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

φ - Ψ_{RP}= azimuthal angle relative to Reaction Plane

v_1 = directed flow

v_2 = elliptic flow

v_3 = triangular flow

v_n = higher-order flows

S. Voloshin and Y. Zhang, Z. Phys. C 70, 665 (1996)

S. A. Voloshin, A. M. Poskanzer and R. Snellings, in Landolt-Boernstein New Series, I/23, p. 5-54, edited by R. Stock (Springer-Verlag, 2010) arXiv:0809.2949[nuclex]

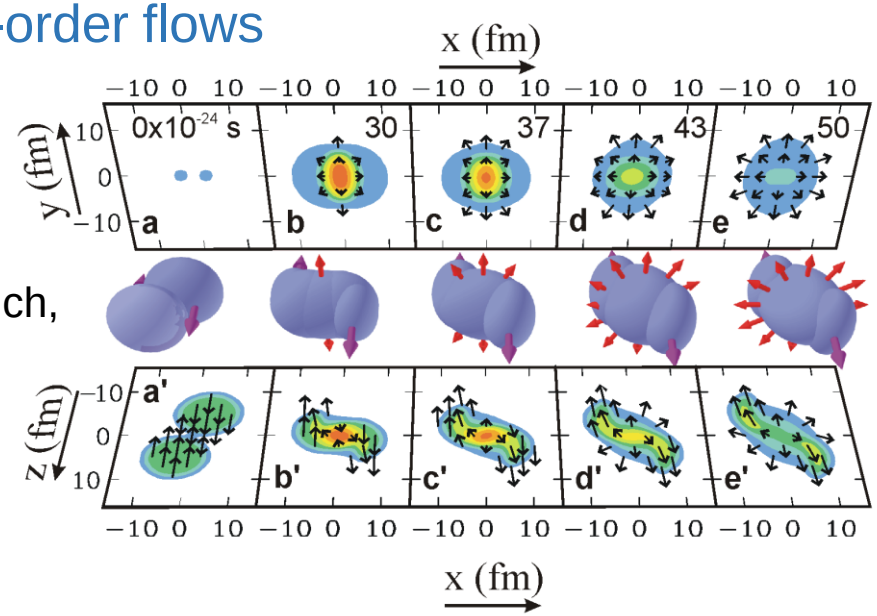
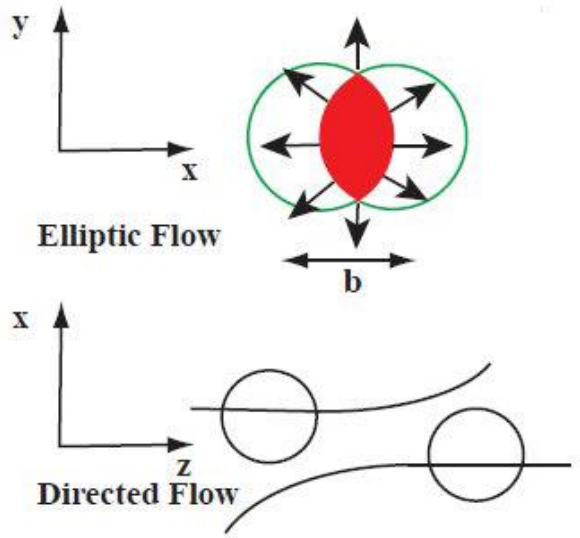


Fig. from Danielewicz, Lacey and Lynch, Science 298, 1592 (2002)



Proton v_1 is very sensitive to EoS

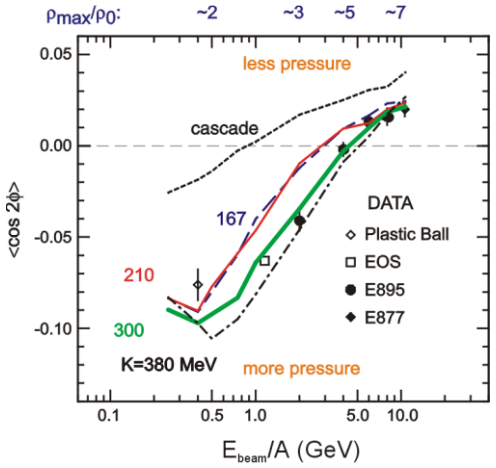
P. Danielewicz, R. Lacey and W. G. Lynch, Science 298, 1592-1596 (2002)

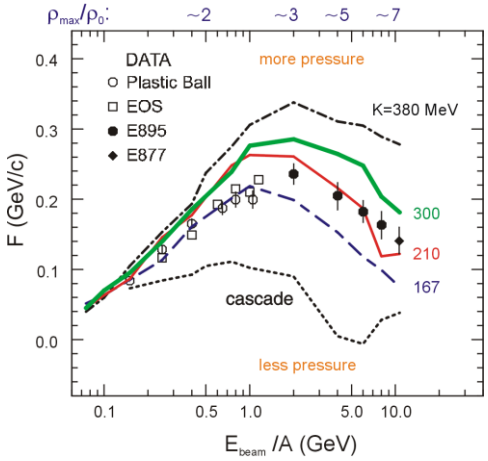
Analysis was done in terms of proton transverse momentum $\langle p_x \rangle$ [P. Danielewicz and G. Odyniec, PLB 157, 146 (1985)]

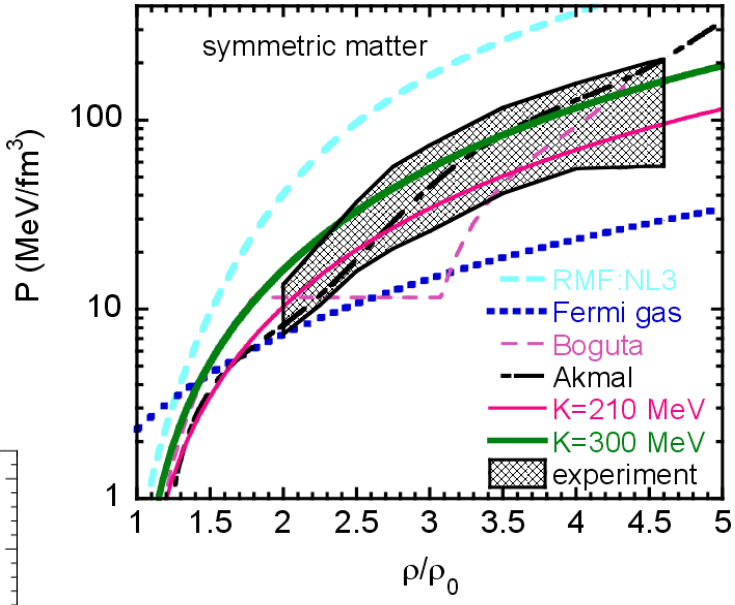
$F = d\langle p_x \rangle / d(y/y_{cm})$ = midrapidity slope of $\langle p_x \rangle(y)$

Incompressibility of EoS:

$K \equiv 9dP/d\rho|_{s/\rho}$ at normal nucl. density and T=0







$\langle p_x \rangle$ requires softer EoS

v_2 requires stiffer EoS

Thus

210 MeV < *K* < 300 MeV

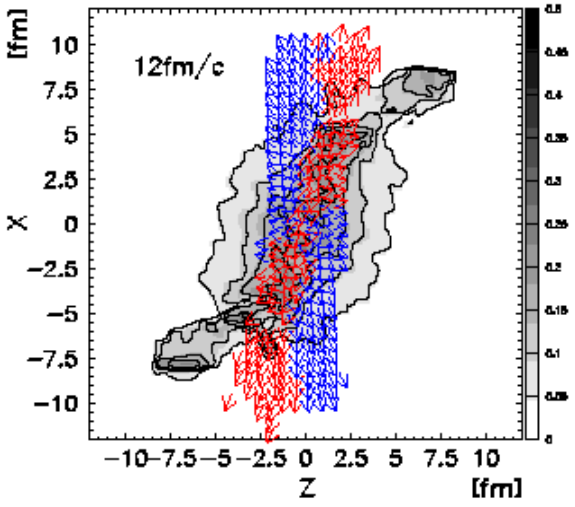
Still unanswered question

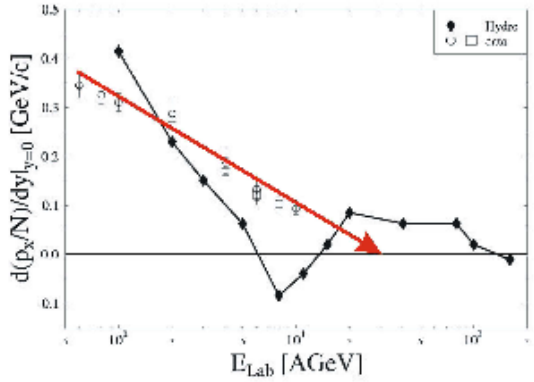
- The models JAM, SMASH, UrQMD, and AMPT model report preference of stiff EoSs (up to K = 380 MeV) for proton v_1 at $\sqrt{s_{NN}}$ = 3, 4.5 GeV, contrary to conclusions of [**P. Danielewicz, R. Lacey and W. G. Lynch, Science 298, 1592-1596 (2002)]**

- **What has happened since 2002?**

- The EoS stiffness and baryon stopping are closely interrelated.
- **Pressure, required for v_1 formation, consists of two parts:**
- **the kinetic pressure, that results from the baryon stopping**
- **and the potential pressure due to the EoS stiffness.**
- If the kinetic pressure is high (strong baryon stopping) the lower potential pressure (a soft EoS) is needed to reproduce v_1

Phase transition to QGP





Normal flow:
In the early compression stage particles are deflected by the pressure in the central hot and dense zone.

Onset of QGP ➔ Softest point in mixed phase ➔ slow dynamics in mixed phase ➔ tilted source ➔ **antiflow** around midrapidity, while normal flow dominates forward/backward rapidities.

When collision energy increases, system quickly passes the softest-point region due to accumulated expansion inertia ➔ **no antiflow**

J. Brachmann et al., Phys. Rev. C 61, 024909 (2000)

L. P. Csernai and D. Rohrich, Phys. Lett. B 458, 454 (1999)

H. Stoecker Nucl.Phys.A 750 (2005) 121

Wiggle
flow-antiflow-flow
Signals
Onset of QGP

Not only phase transition

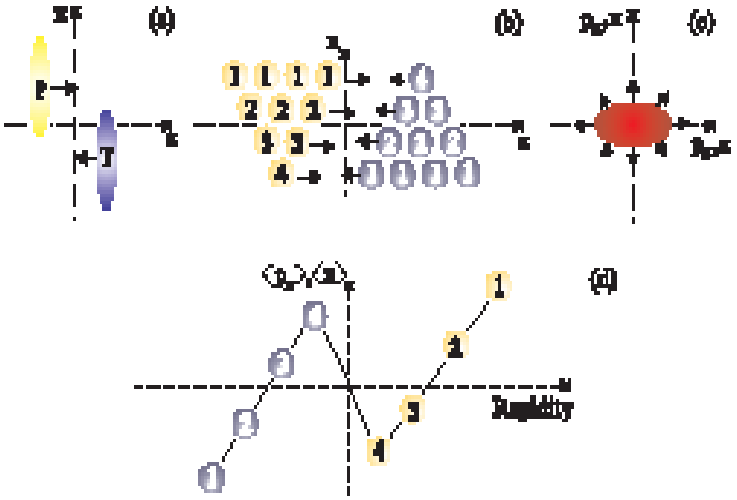
R. J. M. Snellings, H. Sorge, S. A. Voloshin, F. Q. Wang and N. Xu, Phys. Rev. Lett. 84, 2803 (2000)

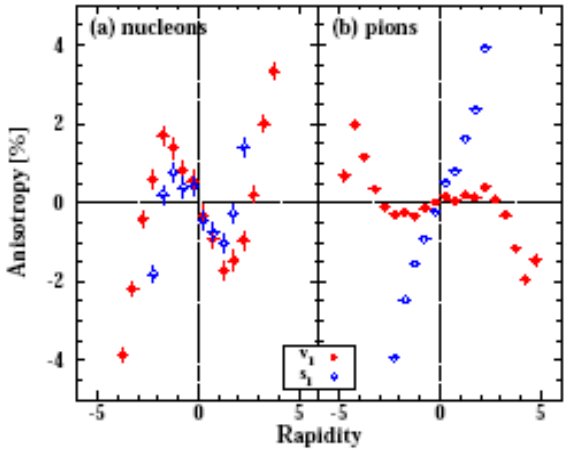
The antiflow can have different physical origin.

Nuclei become partially transparent to each other **at high collision energies.**

This transparency in combination with radial expansion of the system results in antiflow in midrapidity.

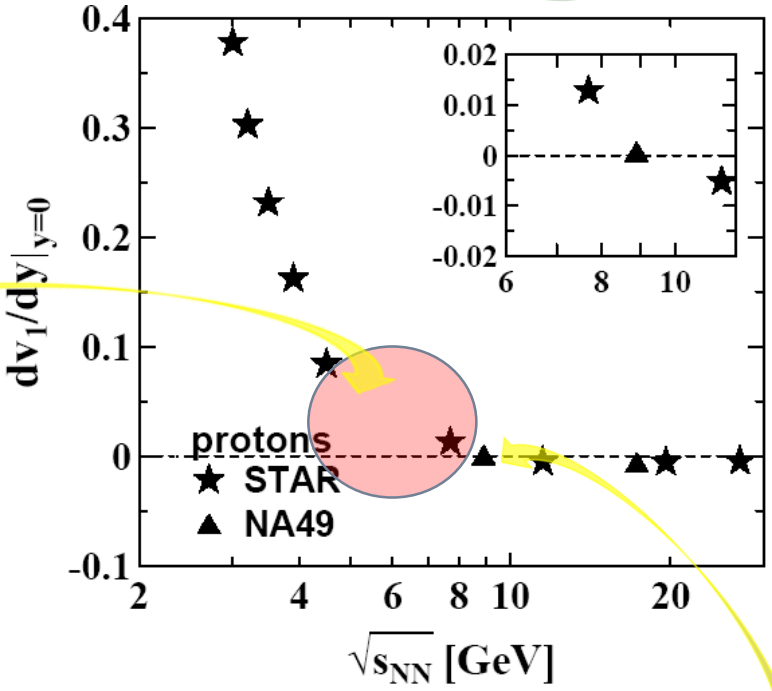
RQMD calculation:
Space-momentum (s_1-v_1) correlation for nucleons, and no correlation for pions.





Current data on proton v_1 slopes

Is there a wiggle indicating onset of QGP transition?



Change of sign **but not an onset of QGP transition**

3FD model

Target-like fluid: $\partial_\mu J_t^\mu = 0$ — Leading particles carry bar. charge; $\partial_\mu T_t^{\mu\nu} = -F_{tp}^\nu + F_{ft}^\nu$ — exchange/emission

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

Fireball fluid: $J_f^\mu = 0,$ — Baryon-free fluid; $\partial_\mu T_f^{\mu\nu} = F_{pt}^\nu + F_{tp}^\nu - F_{fp}^\nu - F_{ft}^\nu$ — 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)]

Equation of State

Hadronic EoS (hadr.-EoS)

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

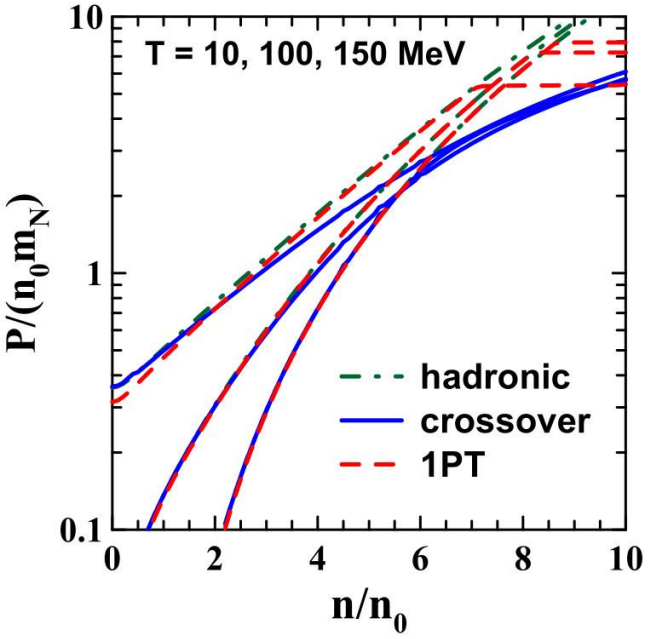
1st-order transition to QGP (1PT-EoS)

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

crossover transition to QGP

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

Pressure vs baryon density

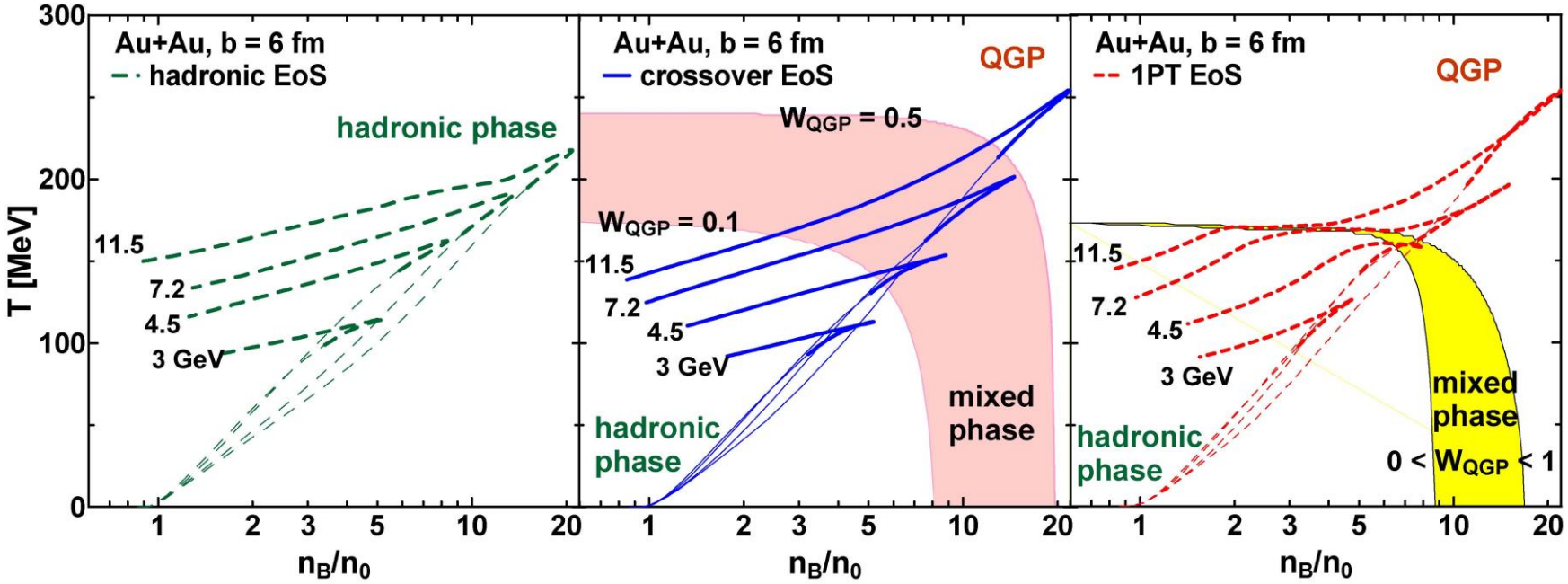


Phase transition ➔ **EoS softening** (in dense baryon matter)

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 QGP region and even enter the 1PT mixed phase.**
- ✓ **At $\sqrt{s_{NN}}$ > 5, the turning points are well within mixed phase (crossover) and QGP (1PT).**

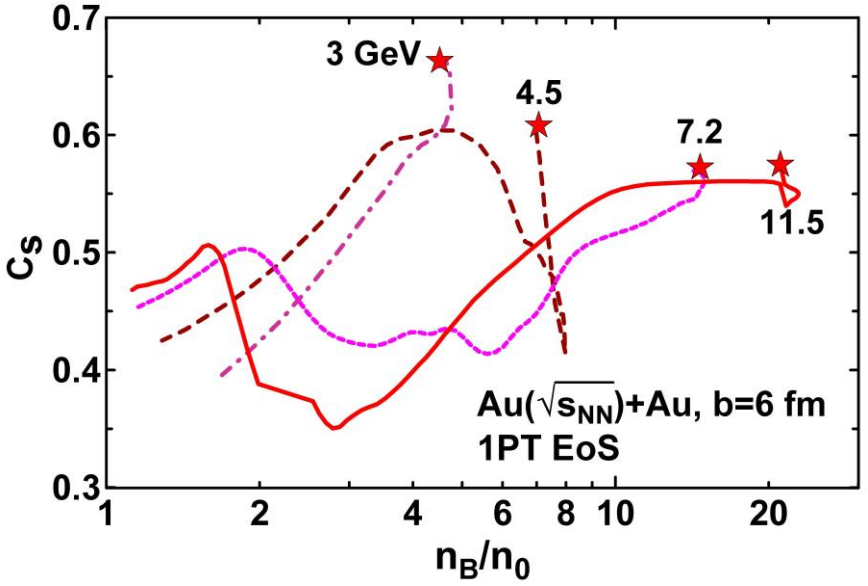
Dynamical trajectories of matter in central region

$c^2_s = (dP/d\varepsilon)$ along trajectory

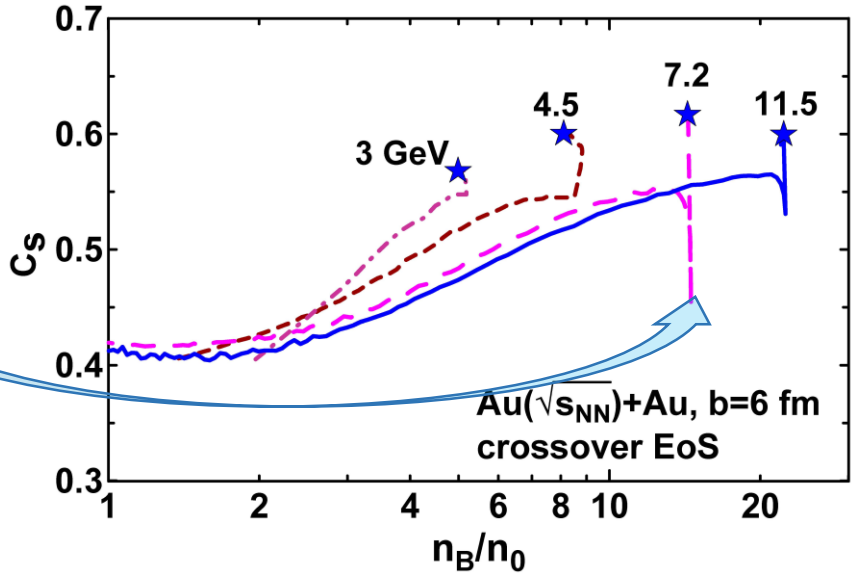
Speed of sound vs baryon density

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

softest-point region is probed at $\sqrt{s_{NN}}$ > 4.5 GeV within 1PT scenario.



Something like softest point at 7.2 GeV within crossover scenario.



How are these features manifested in directed flow?

Why proton v_1 rather than of other hadrons?

- ✓ **v_1 of other hadrons depends not only on EoS**

- ✓ **Afterburner is important for π, Λ and K^-**, i.e. non equilibrium dynamics in final stage of the collision
- ✓ Shadowing of participants by spectators
- ✓ **K^+ is not equilibrated or requires early freeze-out**

- ✓ **Proton v_1 is the most direct probe of the EoS**

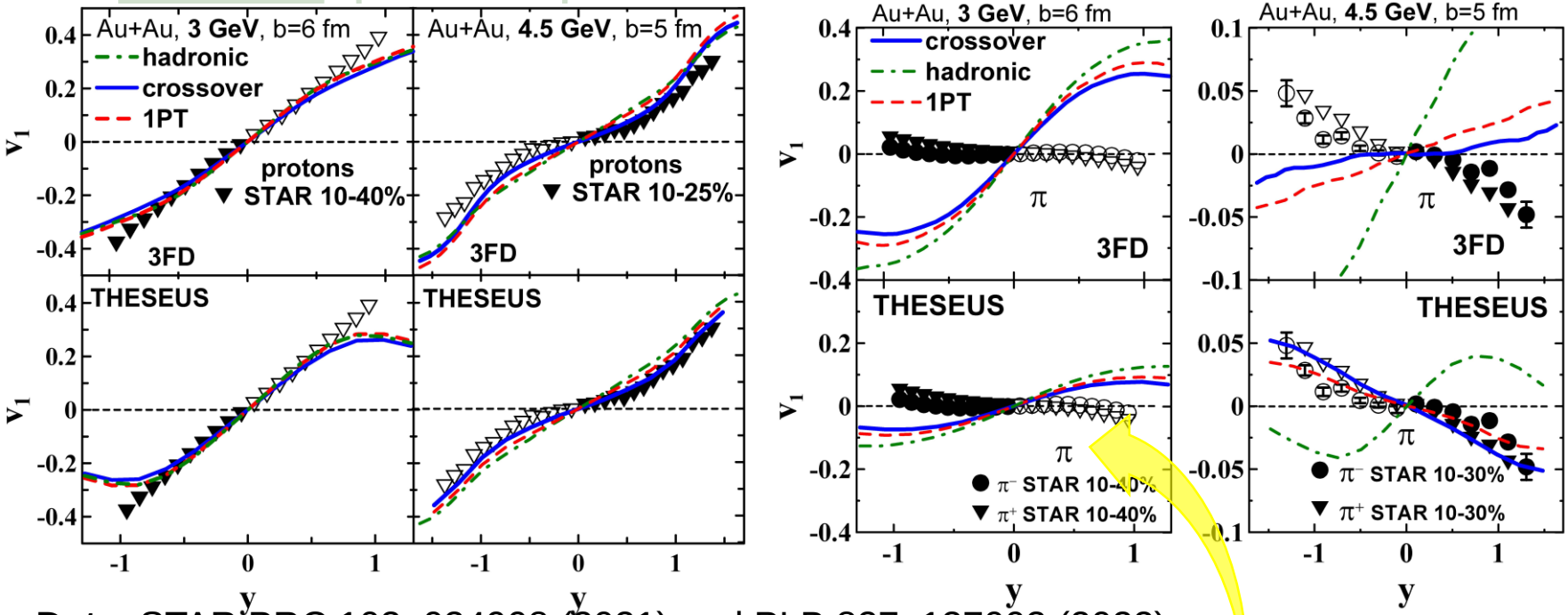
Afterburner by means of event generator THESEUS

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

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

Directed flow at 3 and 4.5 GeV

YI, Kozhevnikova, PRC 110 (2024) 014907

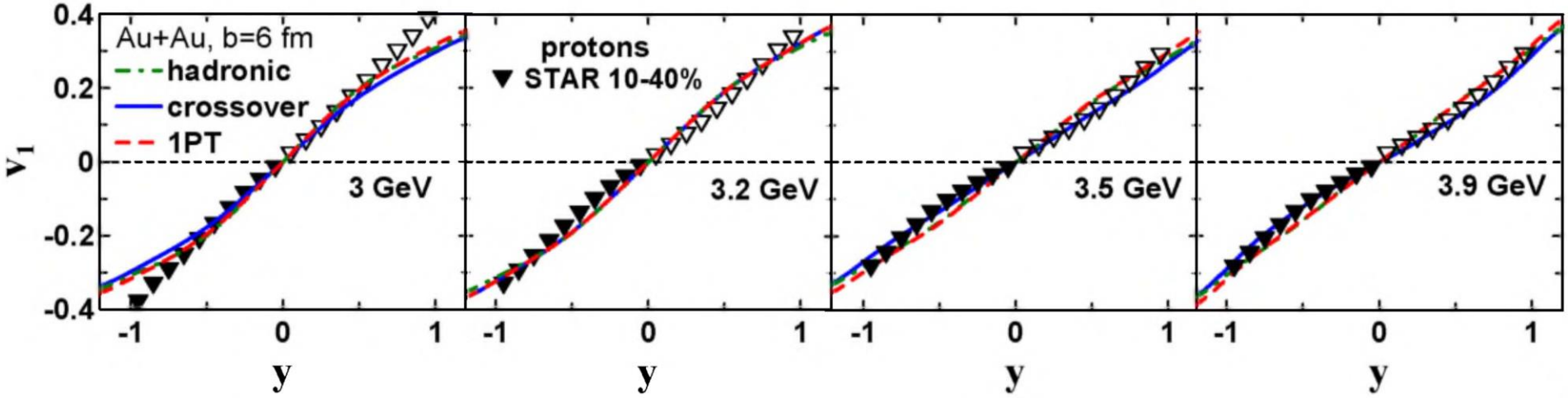


Data: STAR PRC 103, 034908 (2021) and PLB 827, 137003 (2022)

- ✓ Proton v_1 is practically independent of nonequilibrium afterburner
- ✓ **Therefore, proton v_1 is a direct probe of EoS**
- ✓ **Afterburner is important for π, Λ and K^-**:
  shadowing of participants by spectators
- ✓ Description of this shadowing still is not perfect
- ✓ **Therefore, v_1 of π, Λ and K are only indirect probes of EoS**

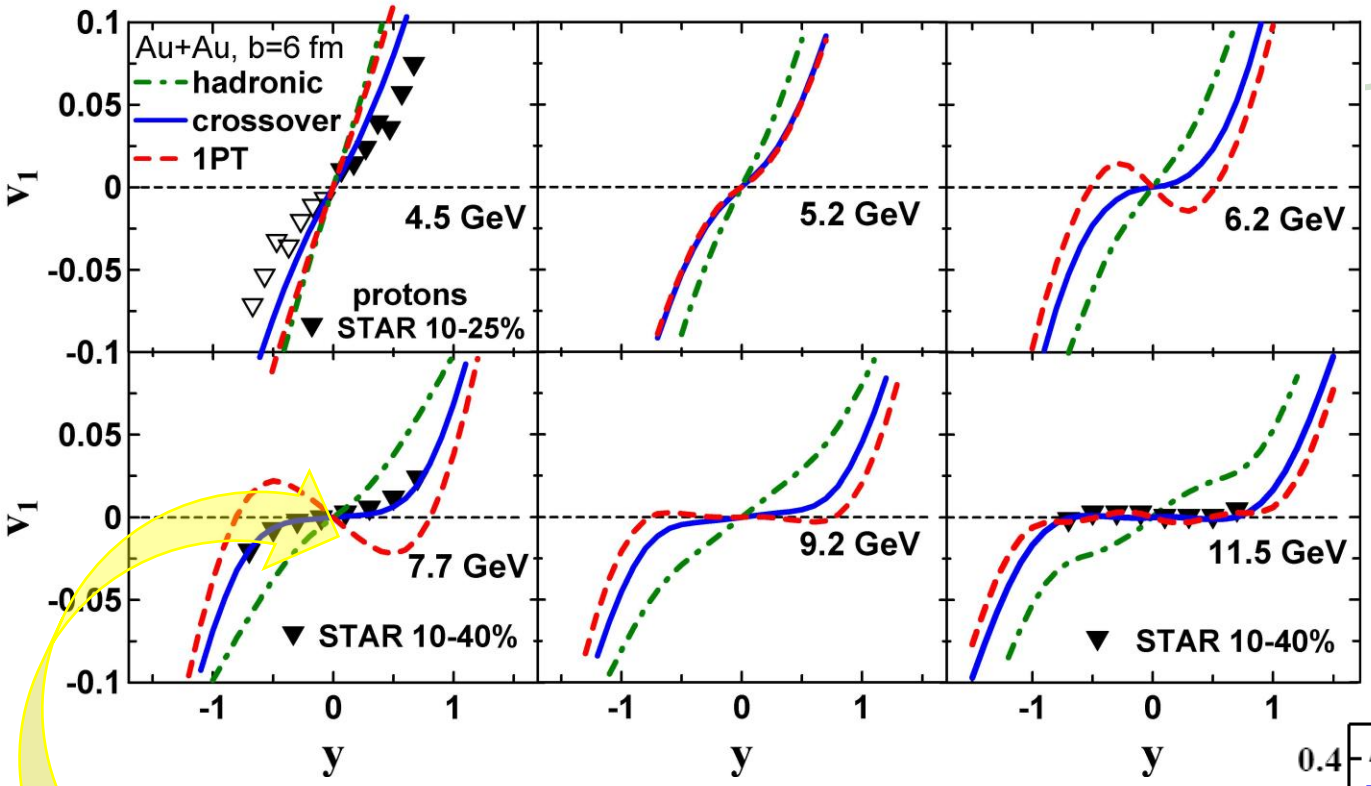
Proton v_1 at 3 – 3.9 GeV

Data: STAR, PLB 827, 137003 (2022), arXiv:2503.23665 [nucl-ex].



- ✓ 3FD well agree with the STAR data, contrary to the old E895 data
- ✓ All EoS's equally well describe data ➔ no transition into QGP
- ✓ At 3.9 GeV, crossover EoS is slightly preferable ➔ QGP transition begins

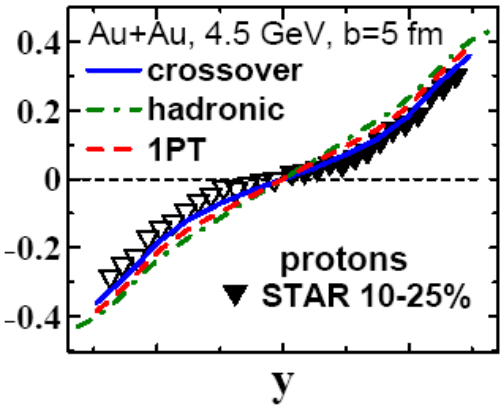
Proton v_1 at 4.5 – 11.5 GeV



Data: STAR, PRC 103, 034908 (2021), PRC 112, no.16, 162301 (2014).

YI, Kozhevnikova, PRC 110 (2024) 014907

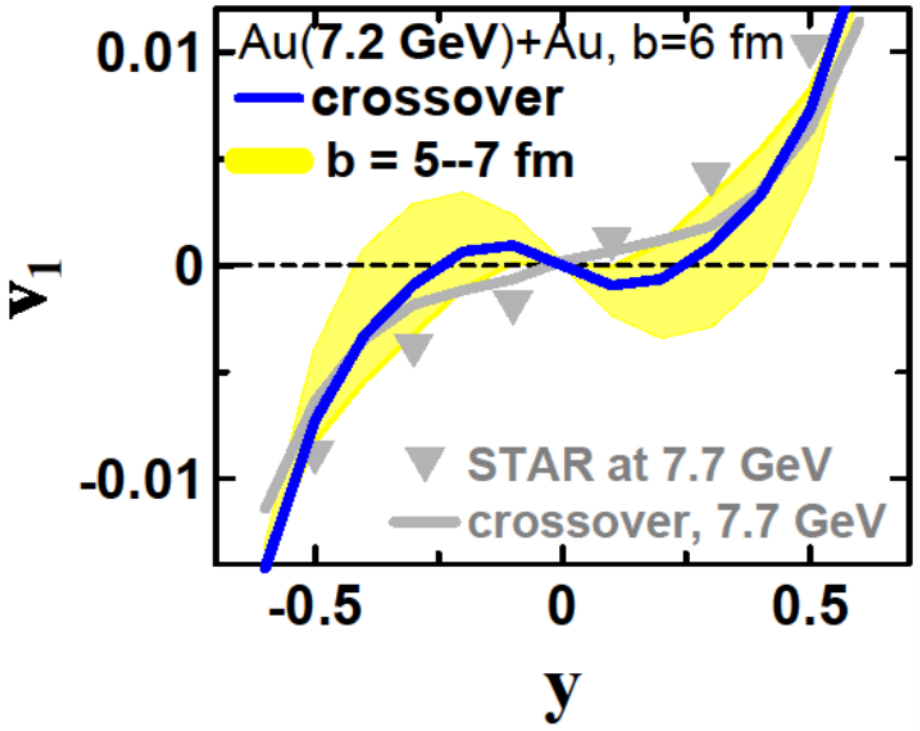
THESEUS calculation



- ✓ At 4.5 GeV, v_1 is presented for b = 6 fm, while b = 5 fm is more relevant
- ✓ **Antiflow in 1PT scenario ➔ transition into QGP**
- ✓ **Crossover EoS looks preferable**
- ✓ It seems, there is no antiflow in crossover scenario

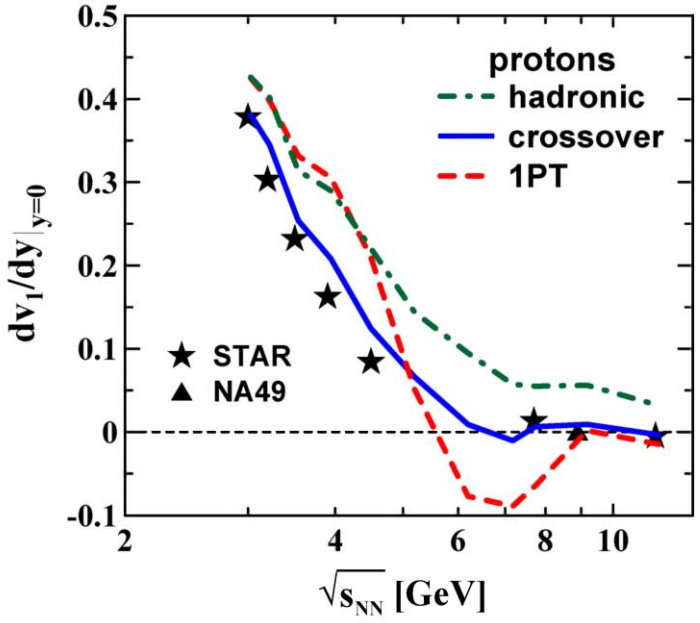
Proton v_1 at 7.2 GeV

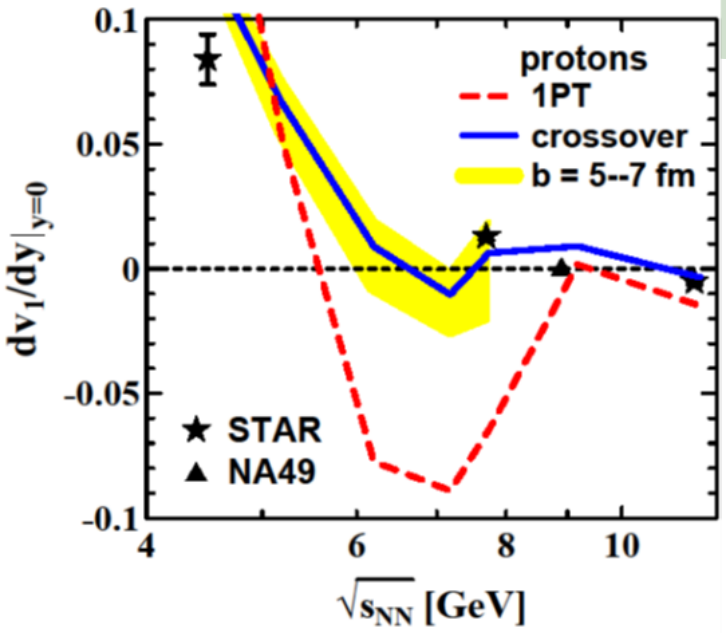
Data: STAR,
PRC 112, no.16, 162301 (2014).



✓ **Antiflow in crossover scenario ➔ onset of transition into QGP**

Midrapidity slopes of proton v_1

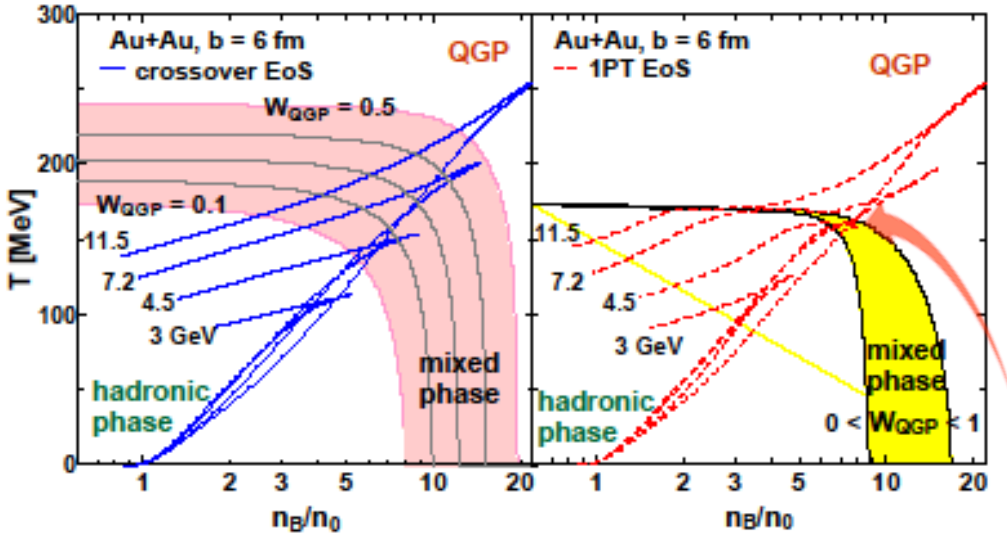


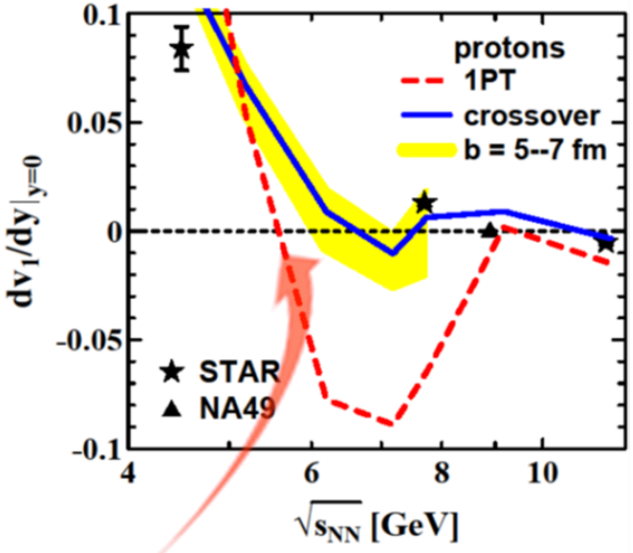


- ✓ **Antiflow at 7.2 GeV in crossover scenario => transition into QGP**
- ✓ **Crossover EoS looks preferable**
- ✓ **crossover antiflow looks very similar to 1PT one but is much weaker**
- ✓ Antiflow at $\sqrt{s_{NN}}$ > 10 GeV results from interplay between incomplete baryon stopping and transverse expansion of the system [Snellings, Sorge, Voloshin, Wang and Xu, PRL 84, 2803 (2000)].

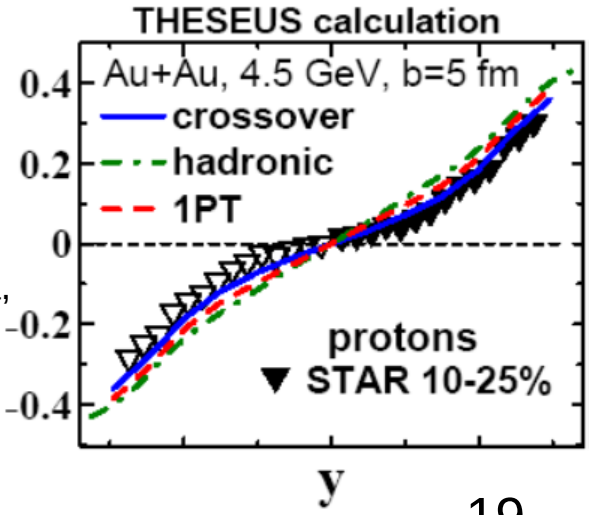
QCD transition starts earlier than antiflow

Temperature vs baryon density





- ✓ **4.5-GeV 1PT trajectory touches mixed-phase region.**
- ✓ **1PT antiflow stars only at $\sqrt{s_{NN}} \approx 6$ GeV**
- ✓ **In crossover scenario, delay between antiflow and mixed-phase onset is even larger.**



YI, Kozhevnikova, PRC 110 (2024) 014907

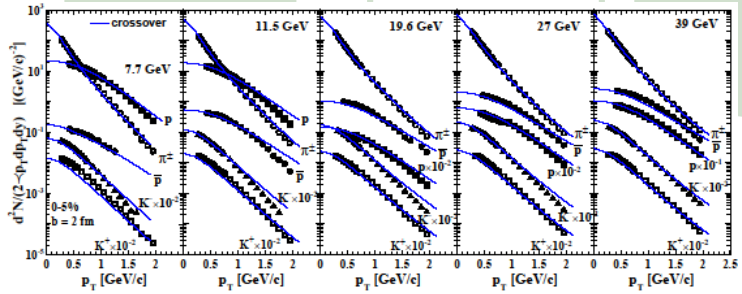
Consensus: QGP onset happens between $\sqrt{s_{NN}}$ = 3 and 4.5 GeV

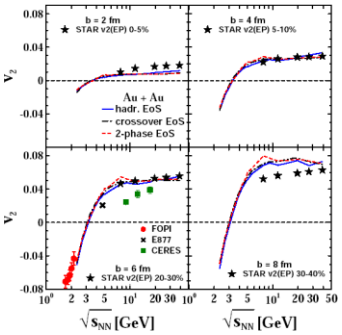
Model	Potential interaction	QGP phase	Transition to QGP	type
UrQMD Steinheimer at al., Eur.Phys.J. C 82, 911 (2022)	optional	no	Above $4n_0$*	QMD
SMASH Oliinychenko at all., PRC 108 (2023) 034908	Mean-field	no	$3\text{-}4n_0$*	Kin. Eq.
JAM Nara at al., PRC 105 (2022) 014911	Mean-field (optional)	no	Above $3\text{--}4n_0$*	QMD
AMPT Various versions	Mean-field (optional)	yes	$3\text{--}5n_0$ $4.3\text{--}5.7n_0$	Kin. Eq.
3FD (THESEUS)	**Non-gas EoS**	**yes**	**Above $4\text{--}5n_0$**	**hydro**

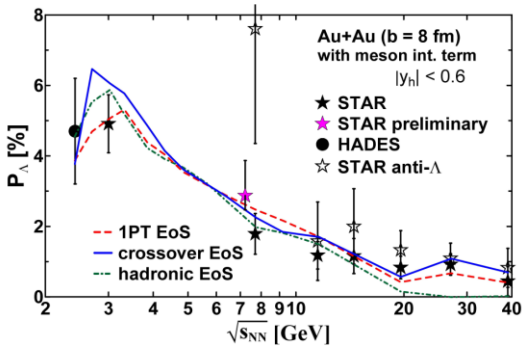
* "Softenning of EoS" is required

Crossover EoS also reproduces other observables

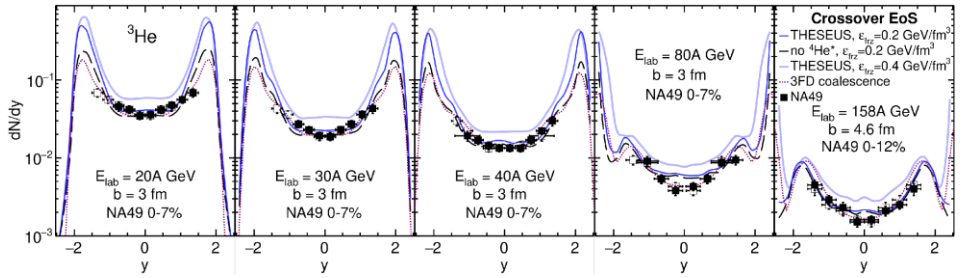
- ✓ Bulk observables
- ✓ Elliptic flow
- ✓ Global Λ polarization
- ✓ Light-nuclei production (with M. Kozhevnikova)







Some examples of calculations



Therefore, Crossover predictions for proton v1 can be trusted

Summary

- ✓ **Proton v_1 is one of most sensitive observable to QGP transition**
- ✓ **Crossover EoS gives the best overall description of available data**
- ✓ The crossover may mimic a weak 1PT
- ✓ **It is predicted that there is antiflow at 7.2 GeV within crossover scenario which indicates onset of QGP transition**
- ✓ Observed antiflow at $\sqrt{s_{NN}}$ > 10 GeV results from interplay between incomplete baryon stopping and transverse expansion of the system [Snellings, Sorge, Voloshin, Wang and Xu, PRL 84, 2803 (2000)].
- ✓ **All above results also apply to NICA MPD with Au replaced by Bi.**

Thank you

for your attention!

Backup

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 $\sim 2.5n_0$ $3\text{--}5n_0$ $4.3\text{--}5.7n_0$	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**

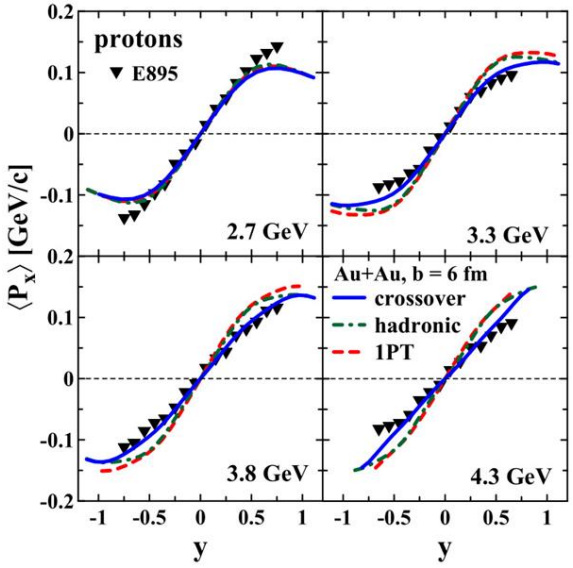
* "Softenning of EoS" is required

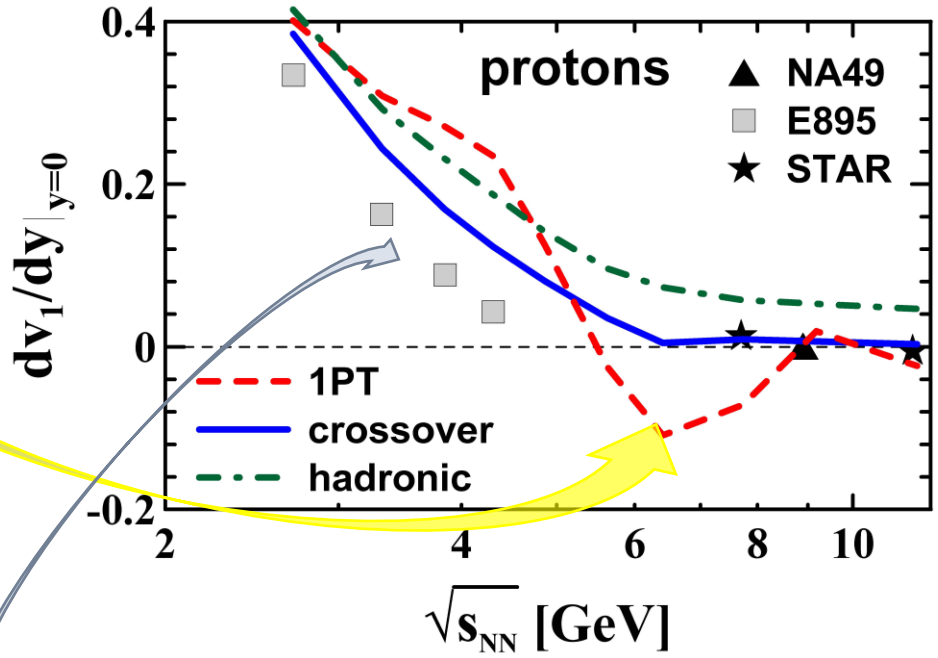
Directed flow (v_1)

$v_1 = \langle p_x/p_T \rangle$

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

- ✓ v_1 is very sensitive to onset of deconfinement transition
- ✓ A gap in data between 4 and 7.7 GeV
- ✓ There are new STAR data at 3--4.5 GeV

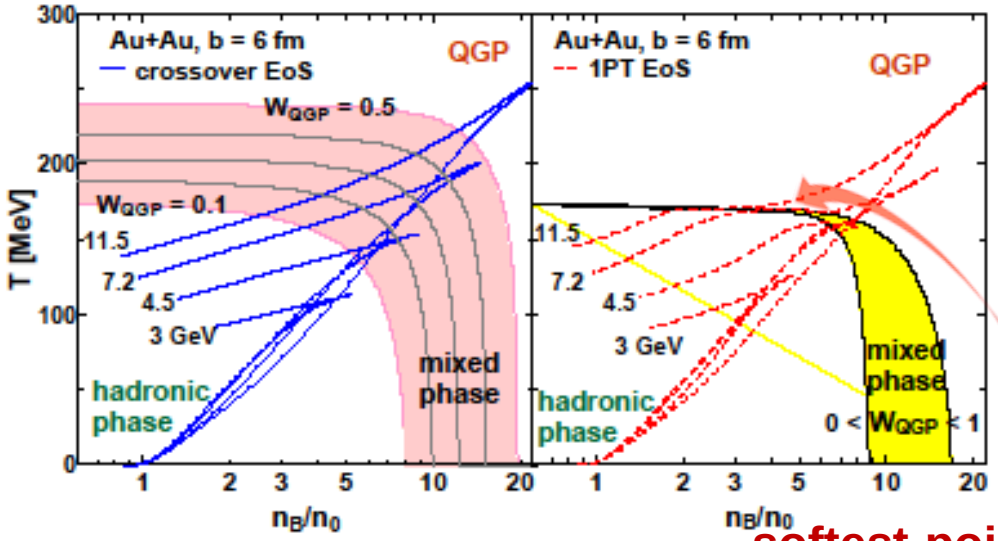




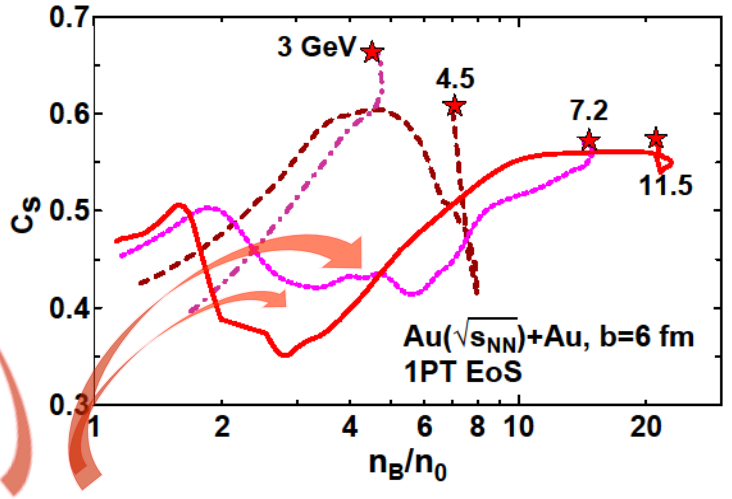
E895 data at √sNN < 5 GeV are well reproduced in terms of $\langle P_x \rangle$ but not in terms of v1.

Dynamical trajectories of matter in central region

Temperature vs baryon density



c^2_s= (dP/dε) along trajectory



softest-point region responsible for antiflow

- ✓ **Turning points at 3 GeV does not reach the QGP.**
- ✓ **4.5-GeV trajectories only touch the mixed-phase region.**
- ✓ **Therefore, no signals of QGP onset at $\sqrt{s_{NN}} \leq 4.5$ GeV**
- ✓ **At $\sqrt{s_{NN}} > 5$ GeV trajectories are captured in mixed-phase region.**

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

The softest-point region manifests itself in directed flow at higher energies

Directed flow (v_1)

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

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

φ = azimuthal angle

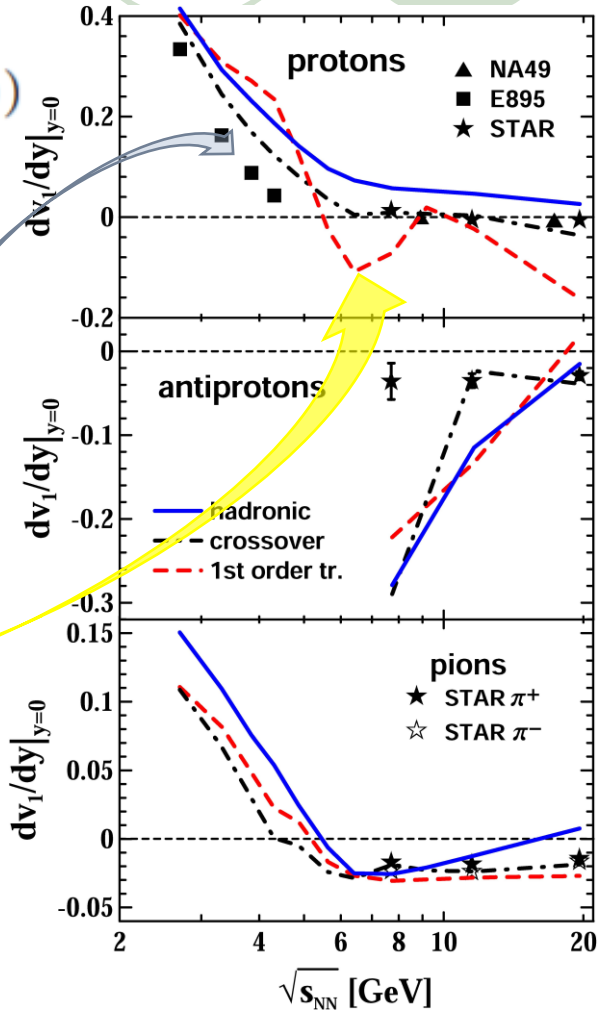
v_1 = directed flow v_2 = elliptic flow

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

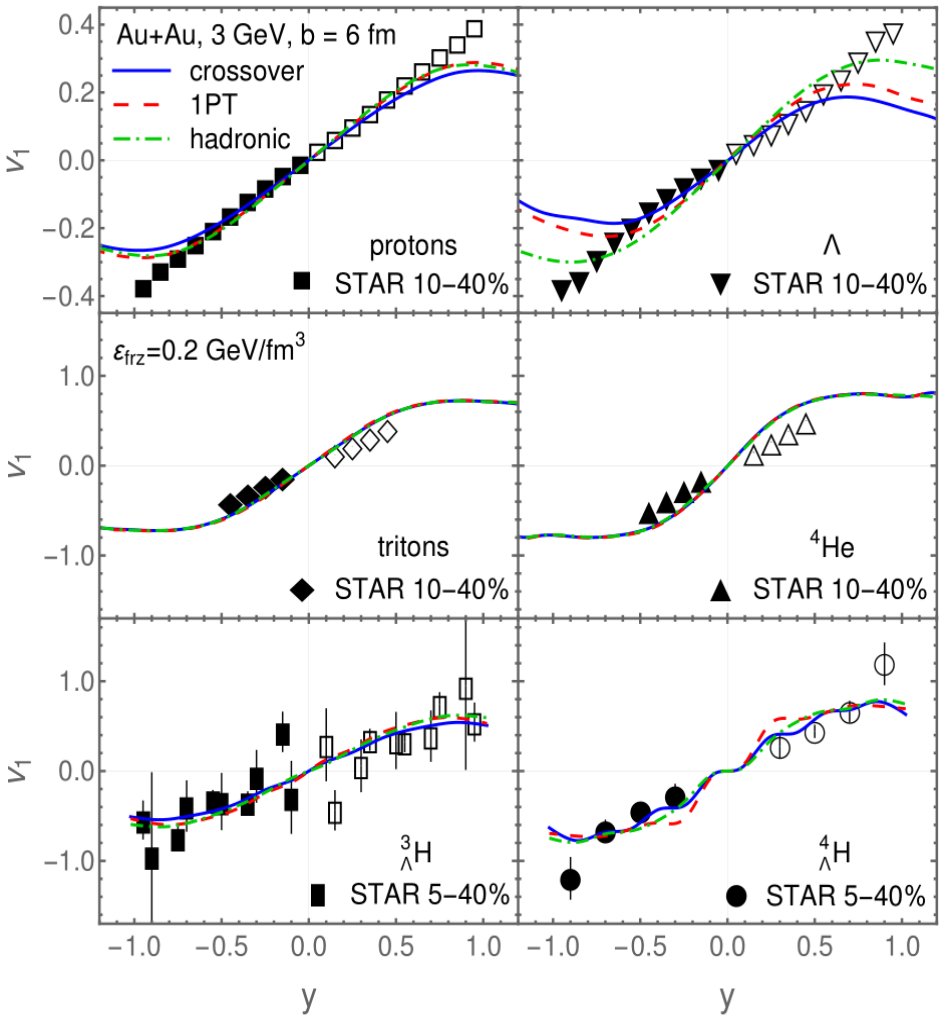
- ✓ v_1 is very sensitive to onset of deconfinement transition and softest point

- ✓ Onset of deconfinement transition happens in the NICA energy range.

- ✓ Crossover EoS is preferable.



v_1 of light nuclei and hypernuclei at 3 GeV



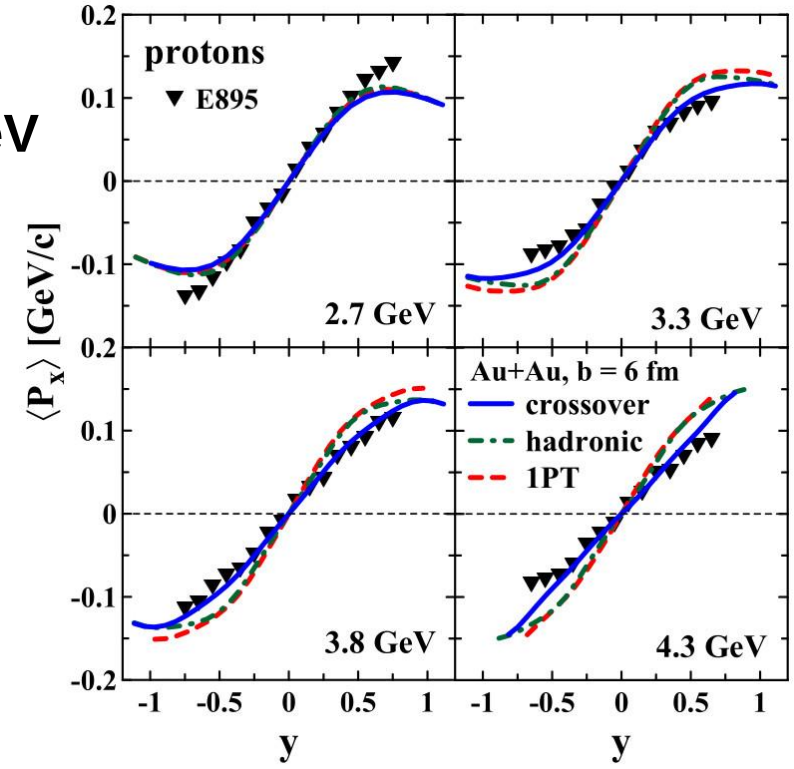
3FD-THESEUS: Kozhevnikova and YI
Light nuclei: PRC109 (2024), 014913
Light hypernuclei: PRC 109 (2024), 034901
Hadrons: PRC 110 (2024), 014907

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

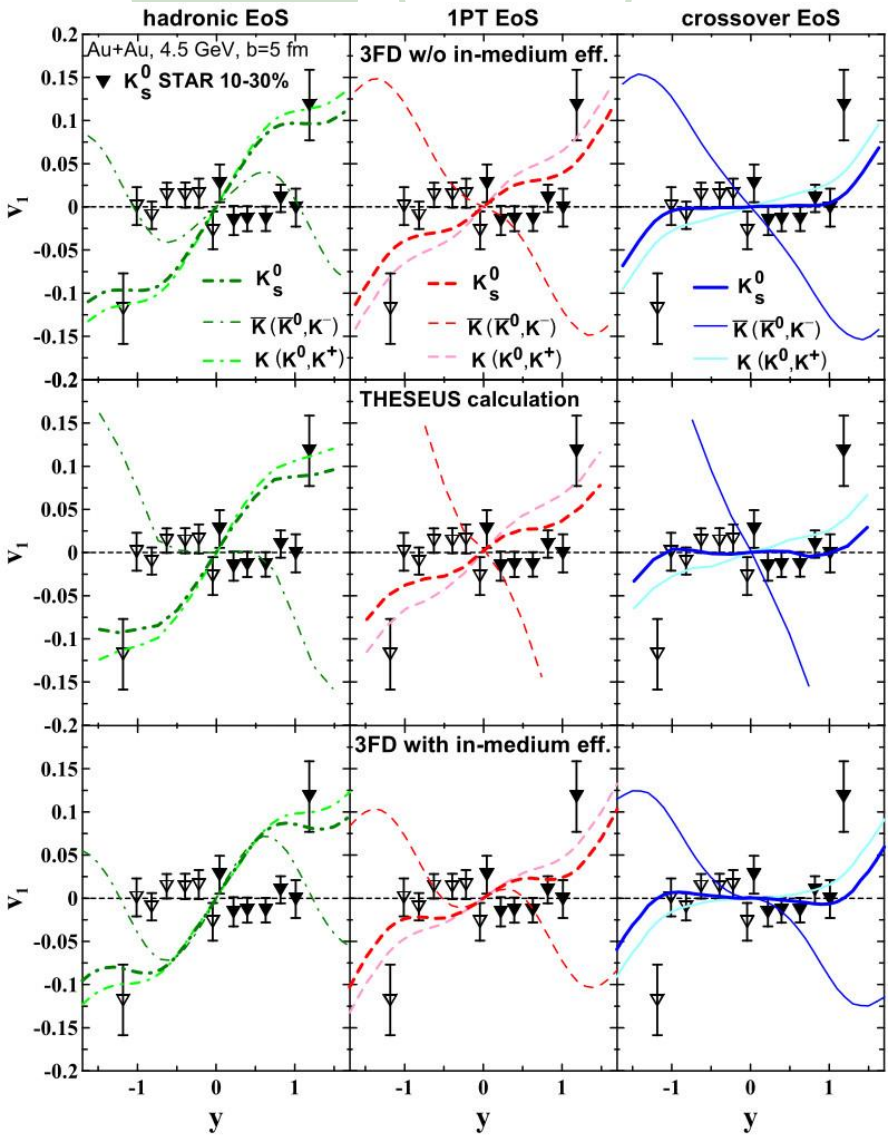
Proton v_1 evolution between 2.7 and 4.5 GeV

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



v_1 of medium modified Kaons



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

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

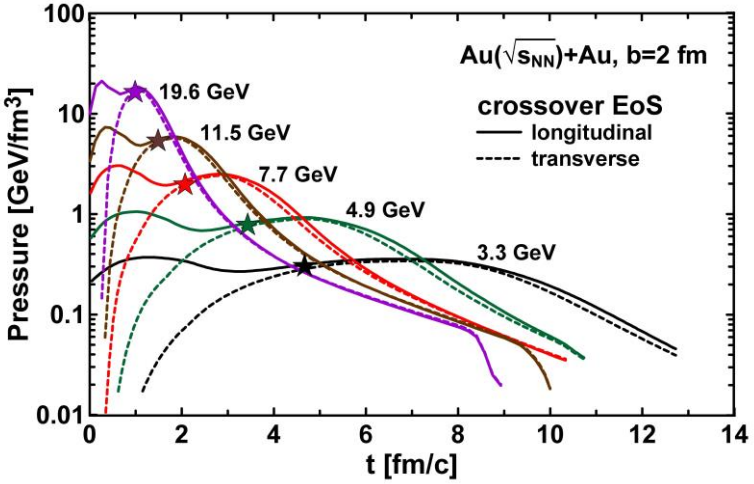
$$\rho = \sum_B \langle \bar{B} B \rangle$$

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

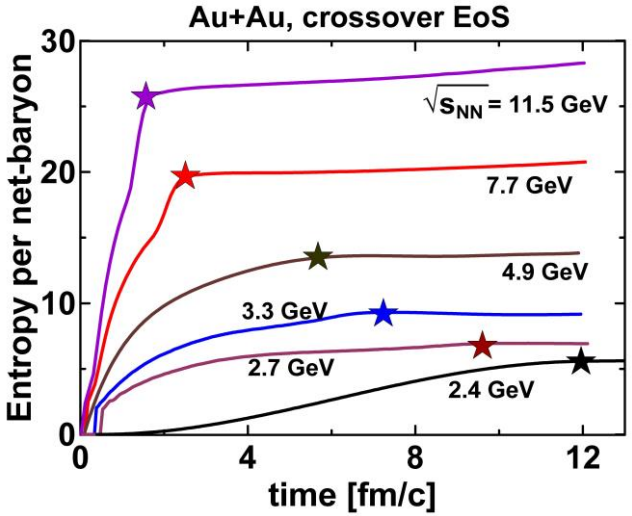
Initial Equilibration

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

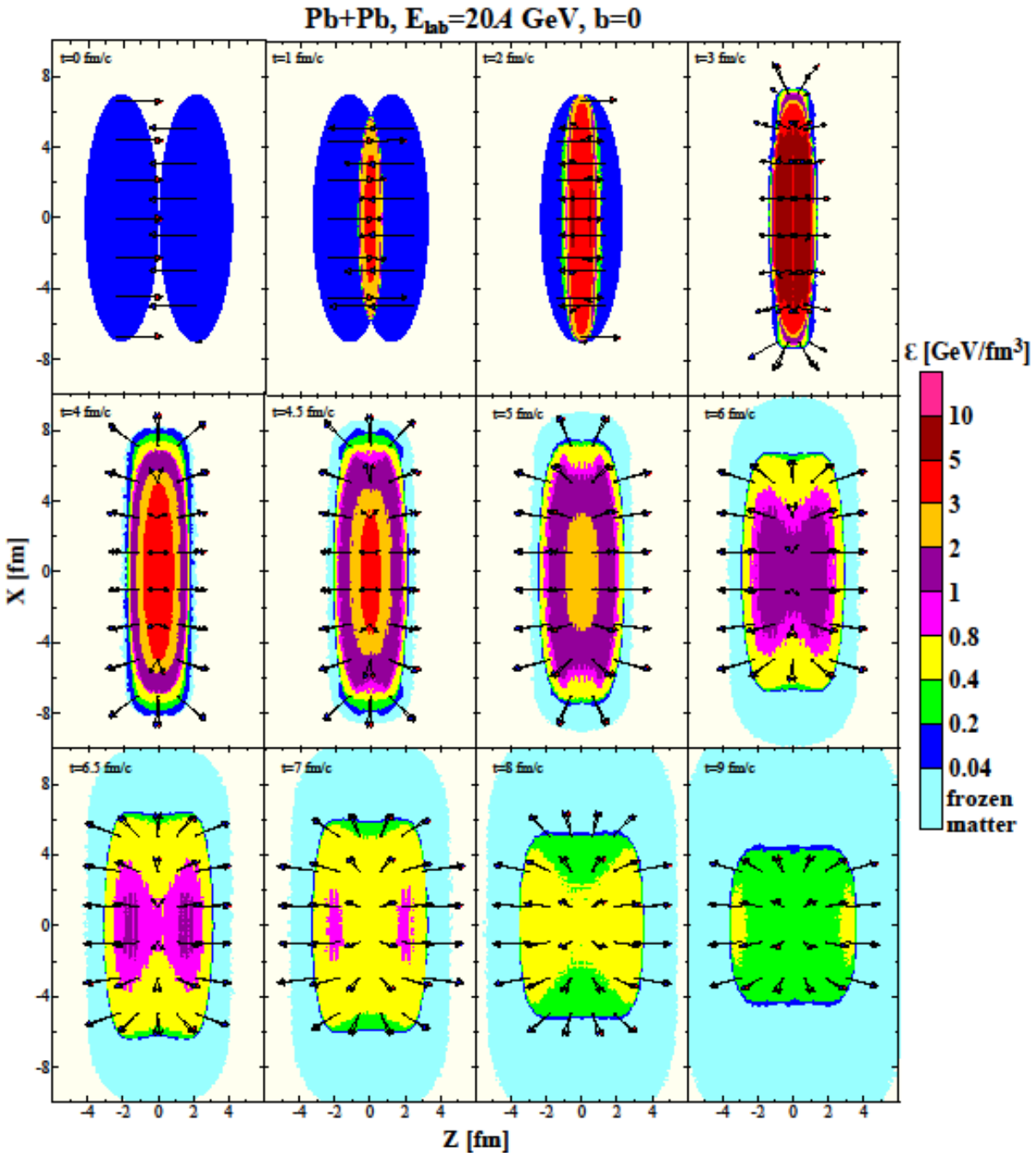


illustration:

Time evolution of energy density in reaction plane

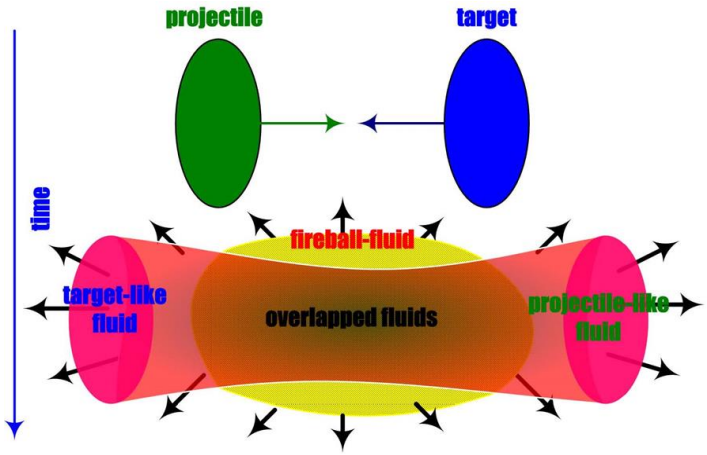
3-fluid dynamics (3FD) model describes initial equilibration

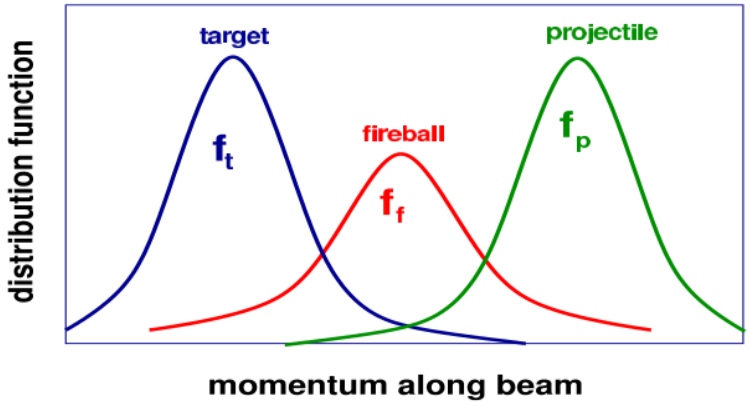
The 3FD approximation simulate the early, nonequilibrium stage of the strongly-interacting matter:

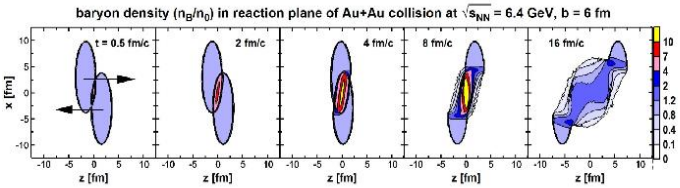
- ✓ **baryon-rich fluids**: nucleons of the projectile (p) and the target (t) nuclei.

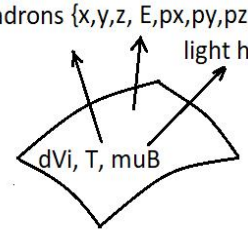
  They are separated in momentum space

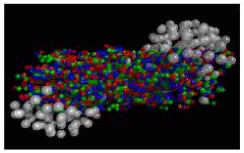
- ✓ **fireball (f) fluid**: newly produced particles which dominantly populate the midrapidity region.

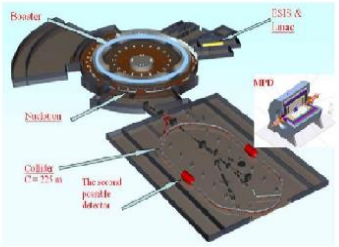


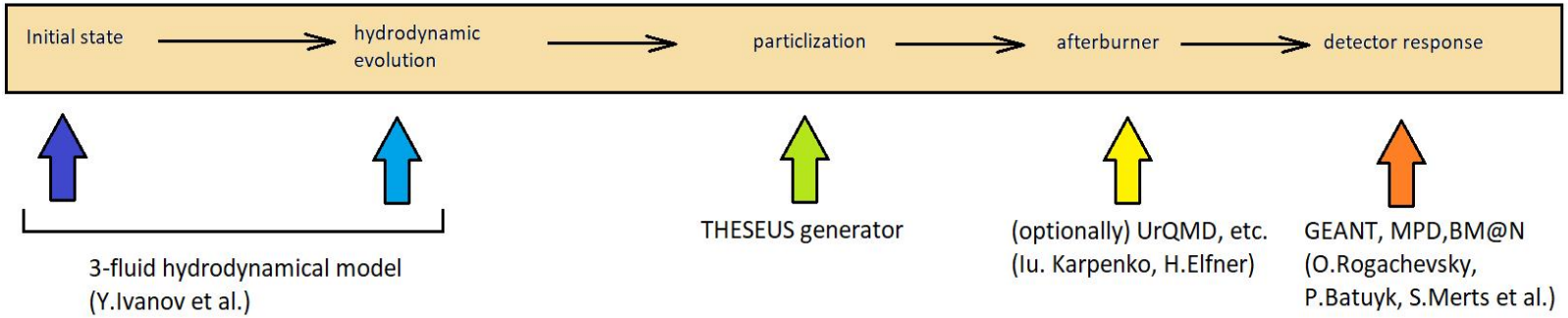












(prepared by M. Kozhevnirjva)

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