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Hydrodynamic Modeling of Deconfinement Phase Transition in and out of Equilibrium

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FIAS Frankfurt Institute for Advanced Studies

HIC for FAIR Helmholtz International Center

RUSSIAN RESEARCH CENTRE KURCHATOV INSTITUTE

Contents

Introduction: hydrodynamic modeling of nuclear collisions

Ideal hydrodynamics assumes solving differential equations

$$\partial_\nu T^{\mu\nu} = 0, \quad \partial_\mu J_B^\mu \equiv \partial_\mu (n u^\mu) = 0, \qquad (\mu, \nu = 0,1,2,3).$$

expressing local energy-momentum and baryon number conservation, where

$$T^{\mu\nu} = (\varepsilon + p) u^\mu u^\nu - p g^{\mu\nu}$$

Is the energy-momentum tensor of the ideal fluid: ε is the nergy density, P-pressure and u-collective 4-velocity.

These equations should be supplemented by

a) **equation of state (EOS)** of the fluid $P = P(\varepsilon, n)$

b) **initial conditions: n present calculations we start from two cold nuclei approaching each other.**

The nuclei are stabilized by the mean field and have realistic (Woods-Saxon) density distributions.

Most famous hydro models

1+1-d models: Landau, 1953 – full stopping of produced fluid in Lorenz-contracted volume; Bjorken, 1983 – partial transparency of colliding nuclei, delayed formation of produced fluid at proper time;

;

2+1-d models (transverse hydro + Bjorken longitudinal expansion)**:**
Kolb, Sollfrank & Heinz, 1999; Teaney, Lauret & Shuryak, 2001; Hirano, 2002;

Full 3+1d models (starting with cold nuclei): Harlow, Amsden & Nix, 1976; Stoecker, Maruhn & Greiner,1979; Rischke et al, 1995; Hama et al. 2005;

Multi-fluid models: Amsden et al, 1978; Clare & Strottman, 1986; Mishustin, Russkikh & Satarov, 1988; Brachmann et al, 2000; Ivanov, Russkikh & Toneev, 2006;

Hydro-kinetic models: Bass&Dumitru, 2000; Teaney et al. 2002001, Petersen, Steinheimer, Bleicher at al. 2008.

EOS1: HG with excluded volume correction

Satarov, Dmitriev&Mishustin: Phys. Atom. Nucl. 72 (2009) 1390

$$P = \sum_{i=\text{hadrons}} P_i^{id}(\mu_i - P v_i, T)$$

P_i^{id} – pressure of ideal gas

$v_i = v \sim (0.5—2)\ \text{fm}^3$ excluded volume

Excluded volume correction following Rischke, Gorenstein, Stöcker, Greiner, Z. Phys. C51 (1991) 485

μ_S is determined from the net strangeness neutrality

$$n_S = 0$$

Chemical potential for species i

$$\mu_i = \mu_B B_i + \mu_S S_i$$

Baryonic charge Strangeness

Hadronic species included: all known hadrons with m ≤ 2 GeV, apart of $f_0(600)$

$$i = \begin{cases} M = \pi, \rho, \omega, \ldots, K, \overline{K}, \ldots (bosons) \rightarrow i \le N_B = 59 \\ B = N, \Delta, \Lambda, \Sigma, \ldots (fermions) \rightarrow i \le N_F = 41 \\ \overline{B} = \overline{N}, \overline{\Delta}, \overline{\Lambda}, \overline{\Sigma}, \ldots (fermions) \rightarrow i \le N_F = 41 \end{cases}$$

This set Is very similar to THERMUS : Wheaton&Cleymans, hep-ph/0407174)

EOS2: Quark-Gluon phase within the Bag model

$$P_Q(\mu,T) = (N_g + \frac{21}{2}N_f)\frac{\pi^2}{90}T^4 + N_f(\frac{T^2\mu^2}{18} + \frac{\mu^4}{324\pi^2}) +$$
$$+\frac{1-\xi}{\pi^2}\int_{m_s}^{\infty} dE(E^2 - m_s^2)^{3/2}\left\{\left[e^{\frac{E-\mu_s}{T}}+1\right]^{-1} + \left[e^{\frac{E+\mu_s}{T}}+1\right]^{-1}\right\} - B$$

$$N_g = 16(1-0.8\xi)$$

$$N_f = 2(1-\xi)$$

perturbative correction $(\xi \sim \alpha_s)$

ξ, B, m_s – parameters of the model

$\xi=0.2$ extracted from lattice data

$m_s = 150$ MeV

$B^{1/4} = 230$ MeV/fm^3

$T_c(n=0) = 165$ MeV

for u,d quarks

$$\mu_q = \frac{\mu}{3}$$

for s quarks

$$\mu_s = \frac{\mu}{3} - \mu_S$$

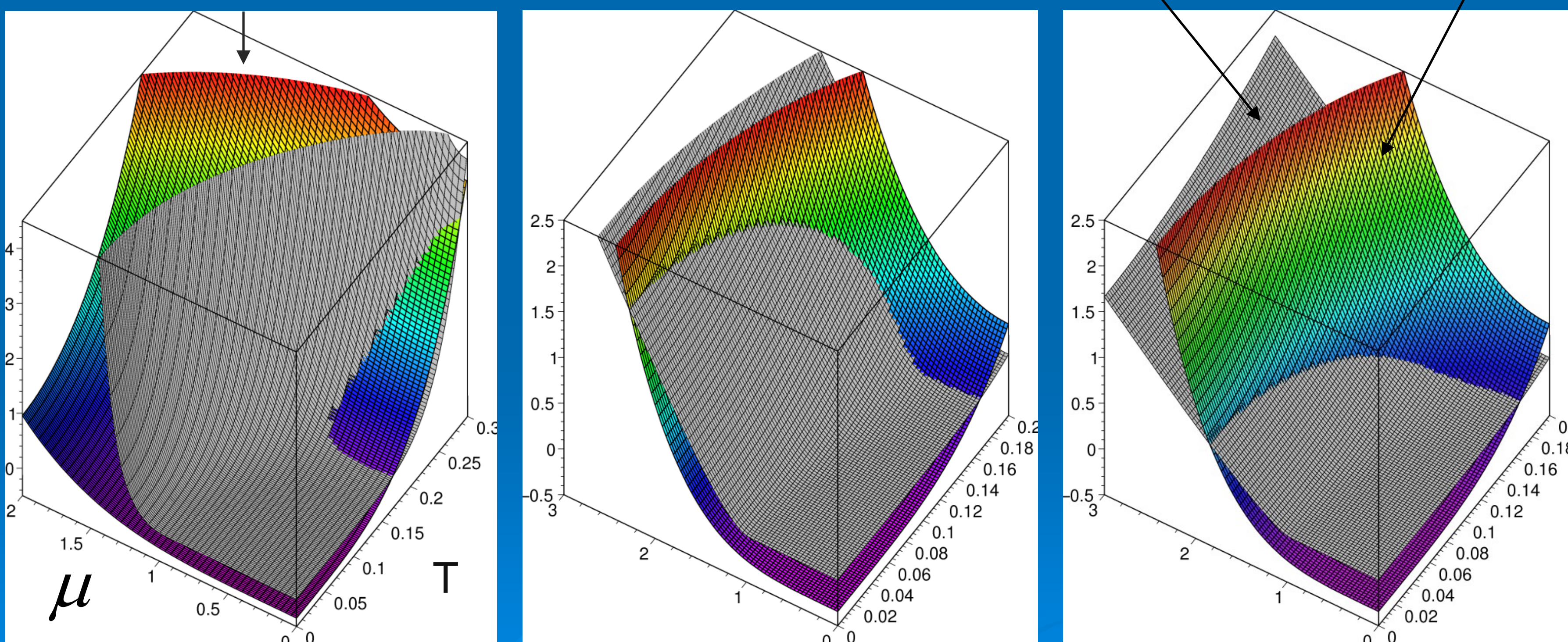
Phase transition HG-QGP

Gibbs criterion for phase transition: $P_H(\mu_B, T) = P_Q(\mu_B, T)$

Compare pressures of two phases as functions of T, μ

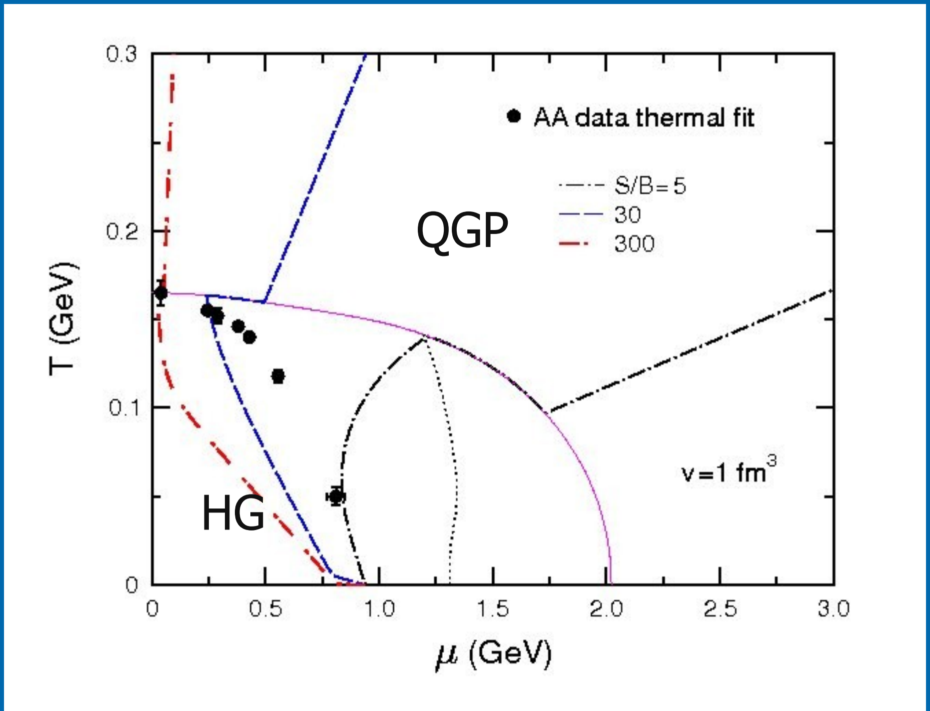
unphysical phase diagram

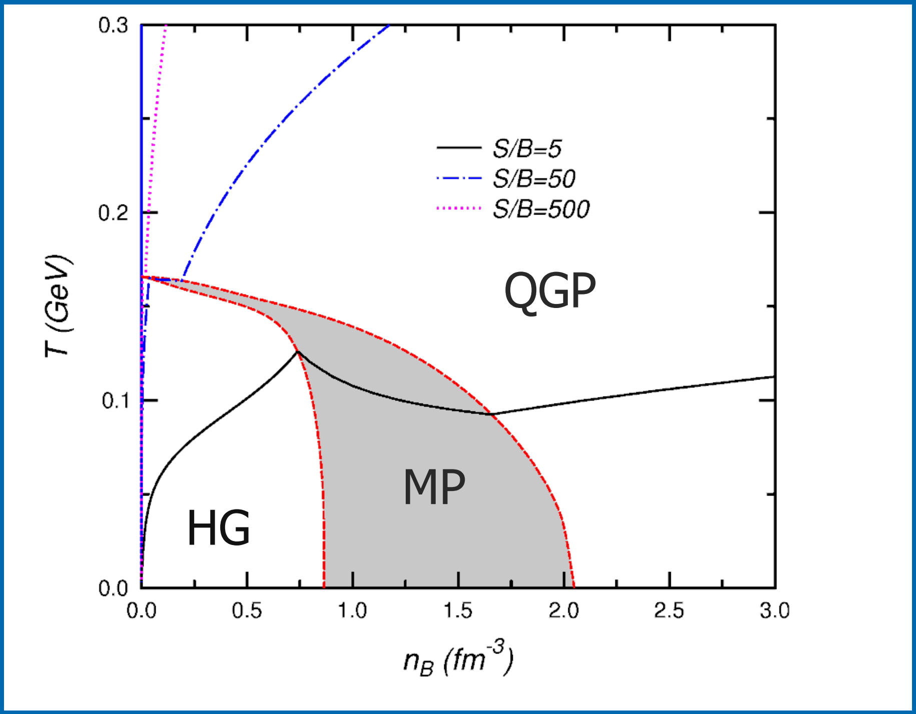
Hadronic phase Quark phase



$v = 0$ $v = 0.5\ \text{fm}^3$ $v = 1\ \text{fm}^3$

Adiabatic trajectories





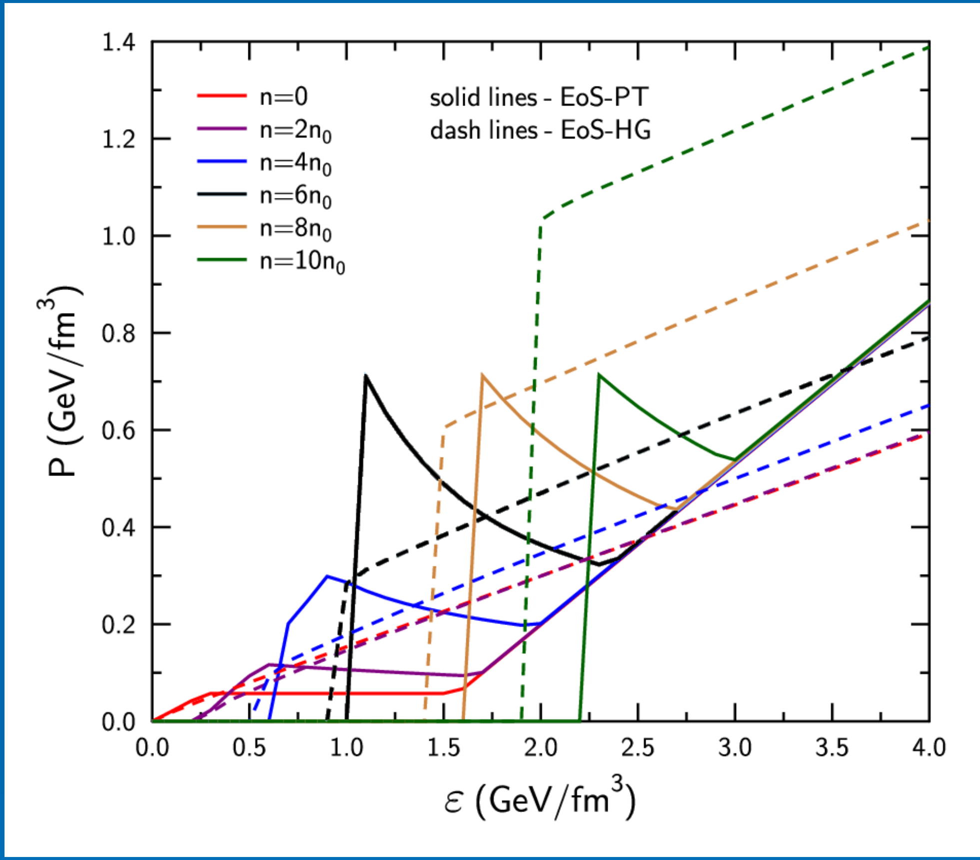
Temperature increases at transition from quarks to hadrons.

(similar to Barz, Schulz, Frieman, Knoll,1983)

This is different compared to chiral models like LσM or NJL

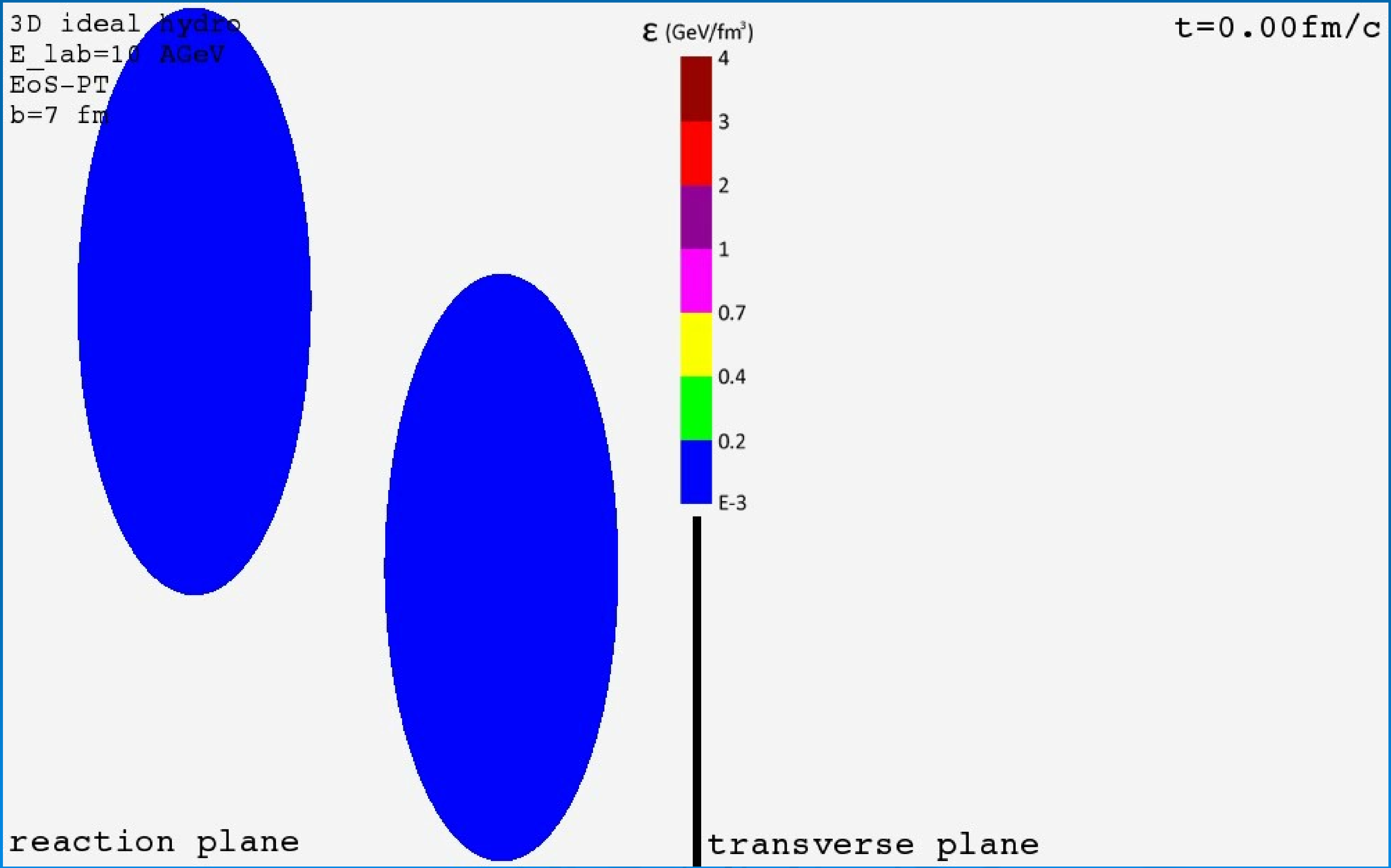
Scavenius, Mocsy, Mishustin, Rischke 2001

Pressure for EoS-HG and EoS-PT

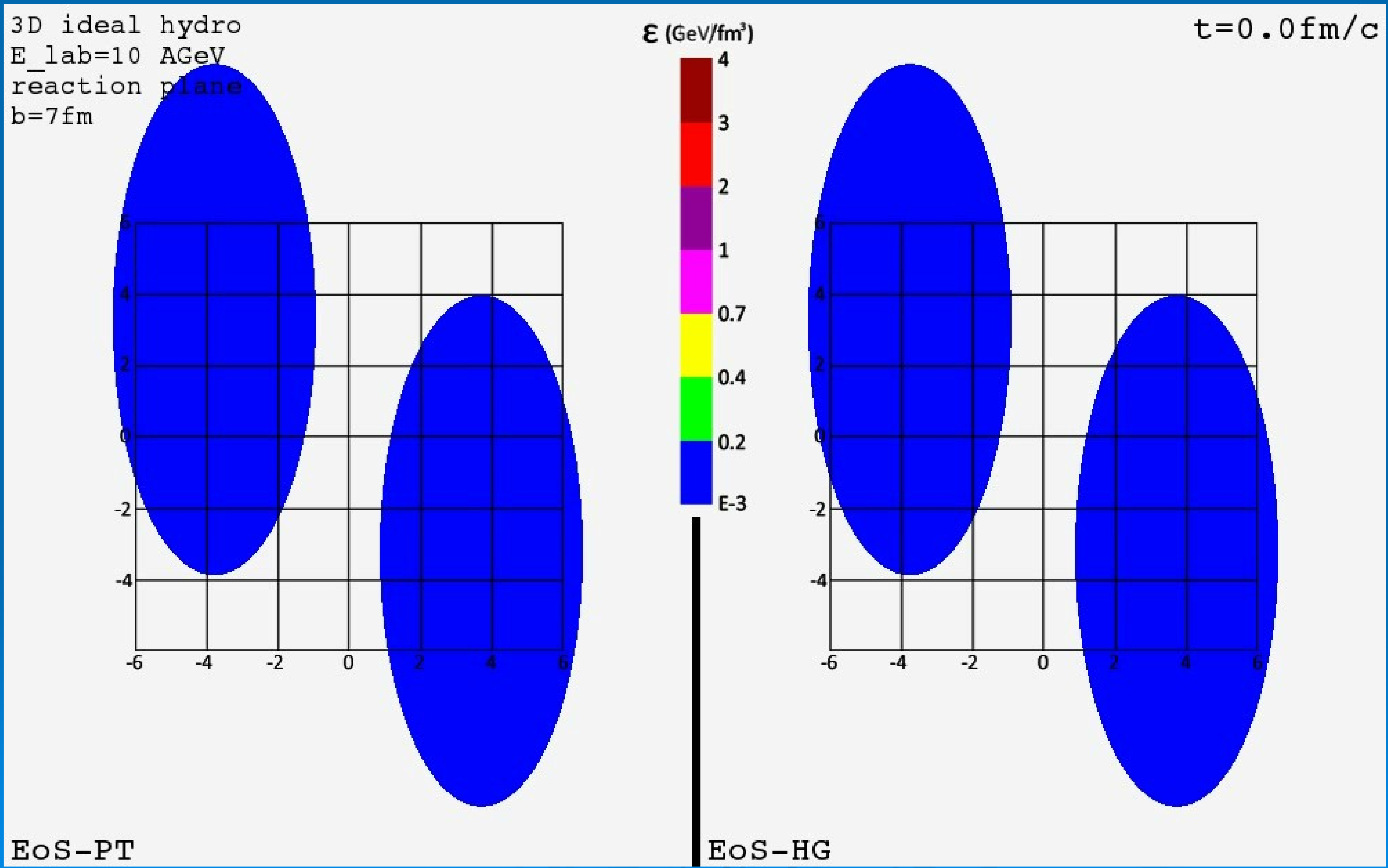


- in principle EoS-PT is "softer " than EoS-HG
- but in some density intervals P_EoS-PT > P_EoS-HG (mixed phase effect)

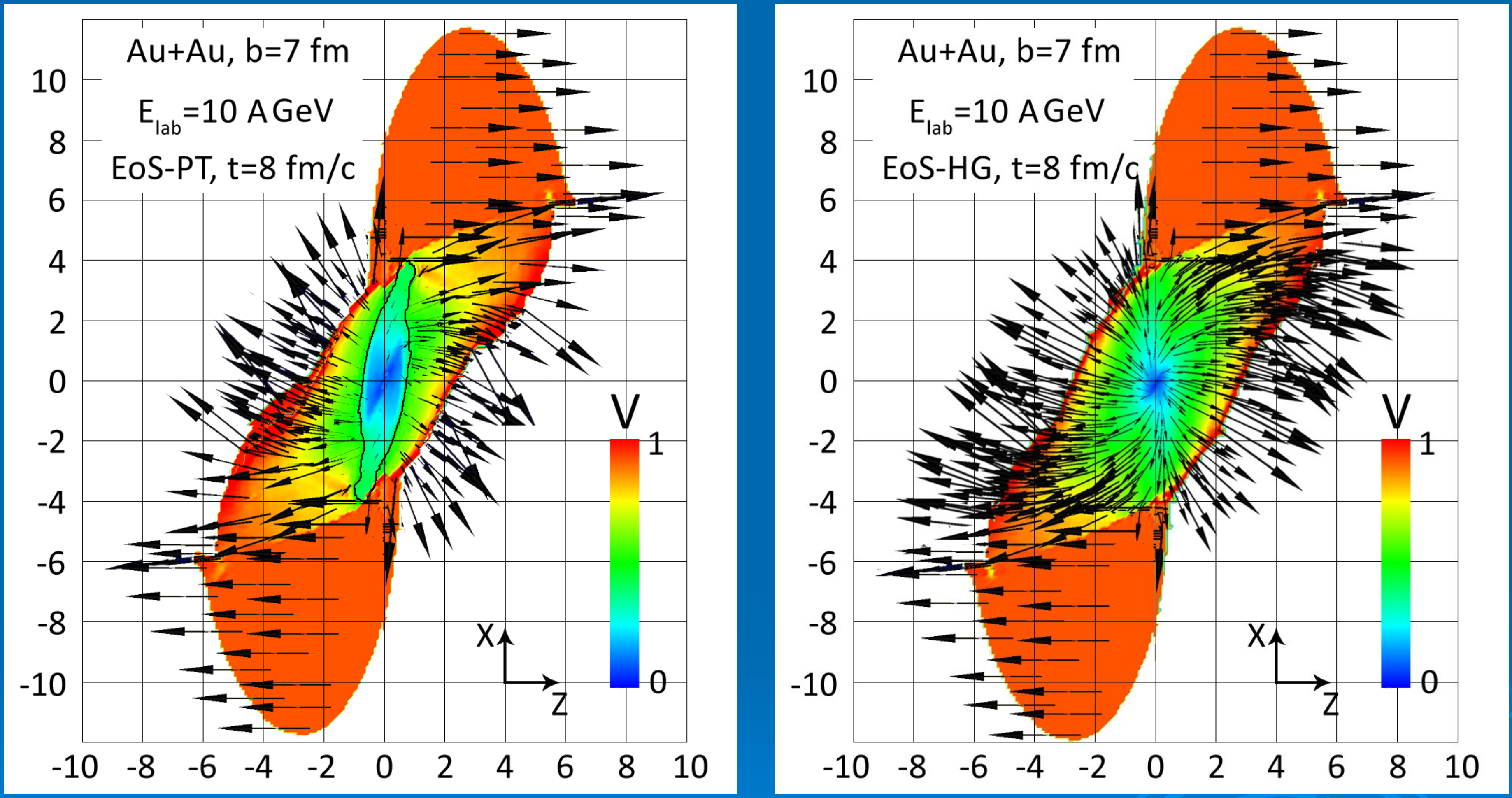
Peripheral Au+Au collision (EoS-PT)



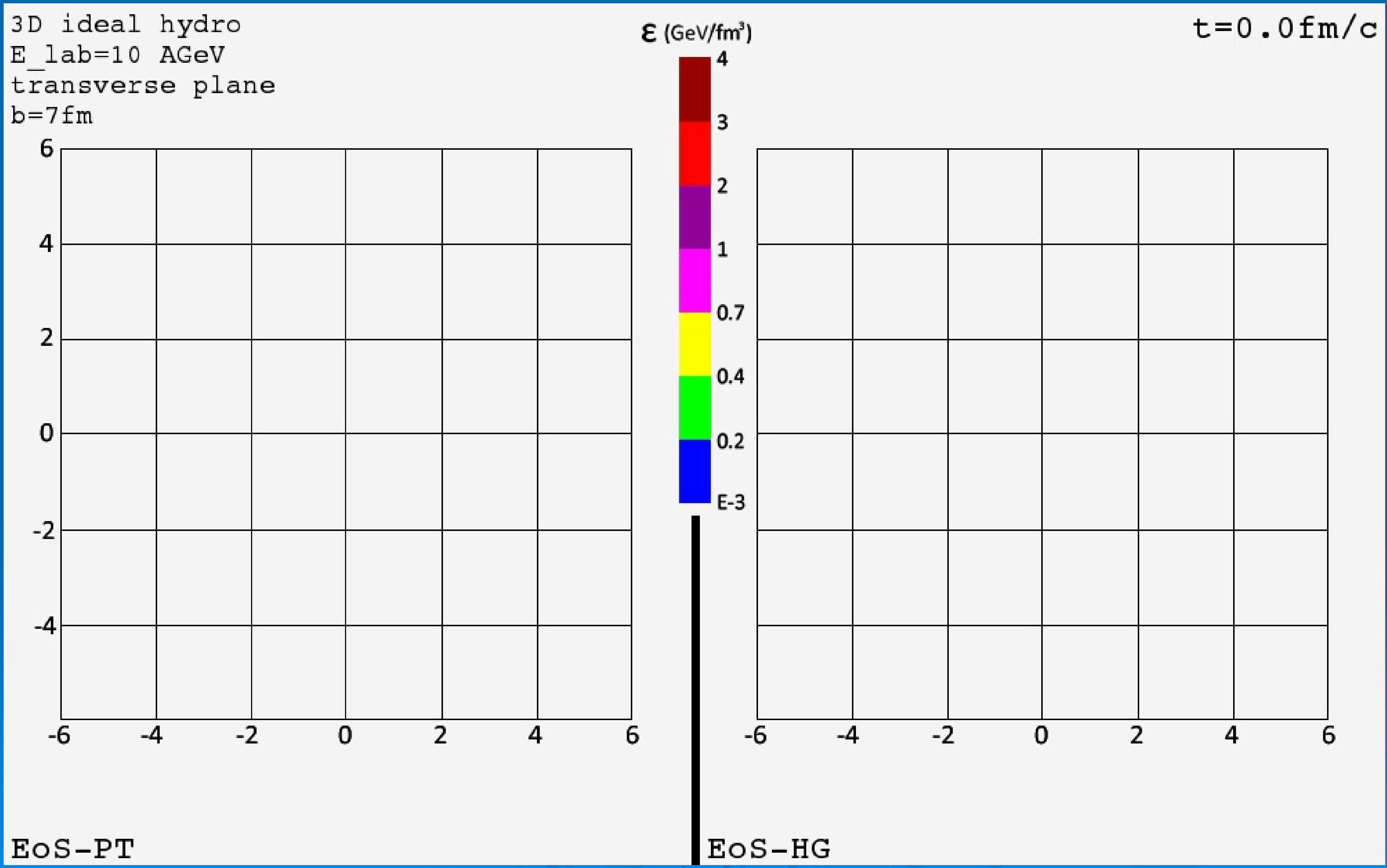
Peripheral Au+Au collision (PT vs HG)



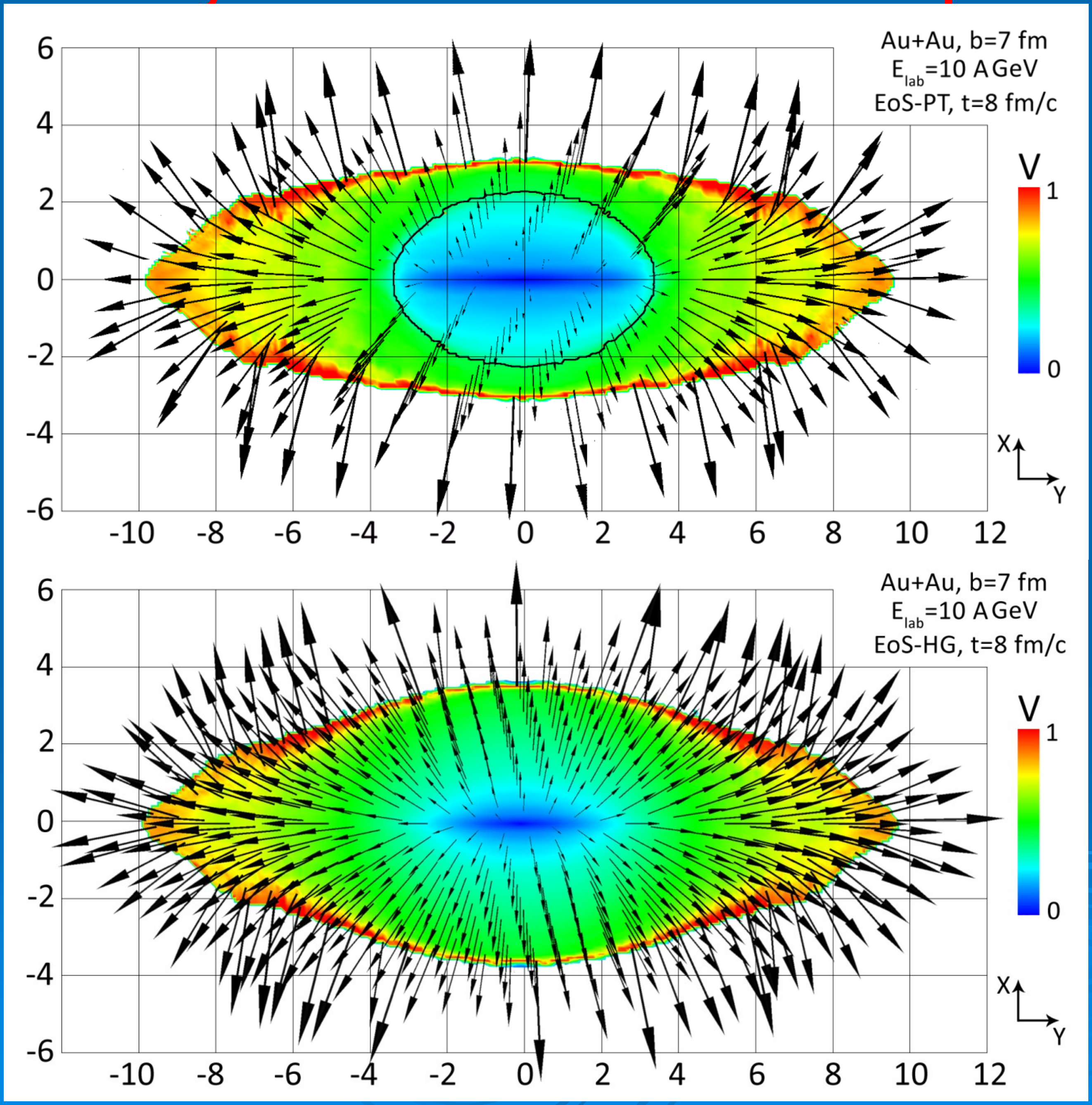
Velocity fields in reaction plane



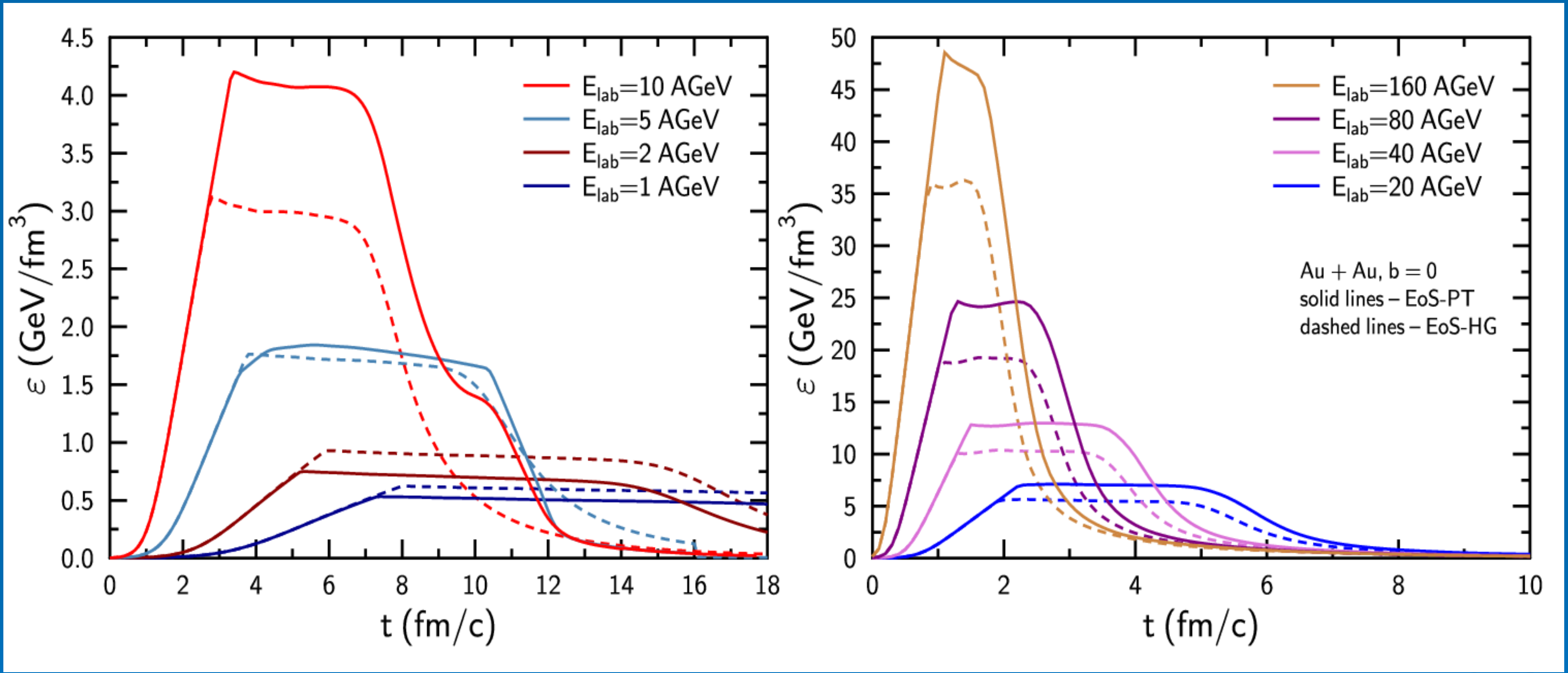
Peripheral Au+Au collision (PT vs HG)



Velocity fields in transverse plane

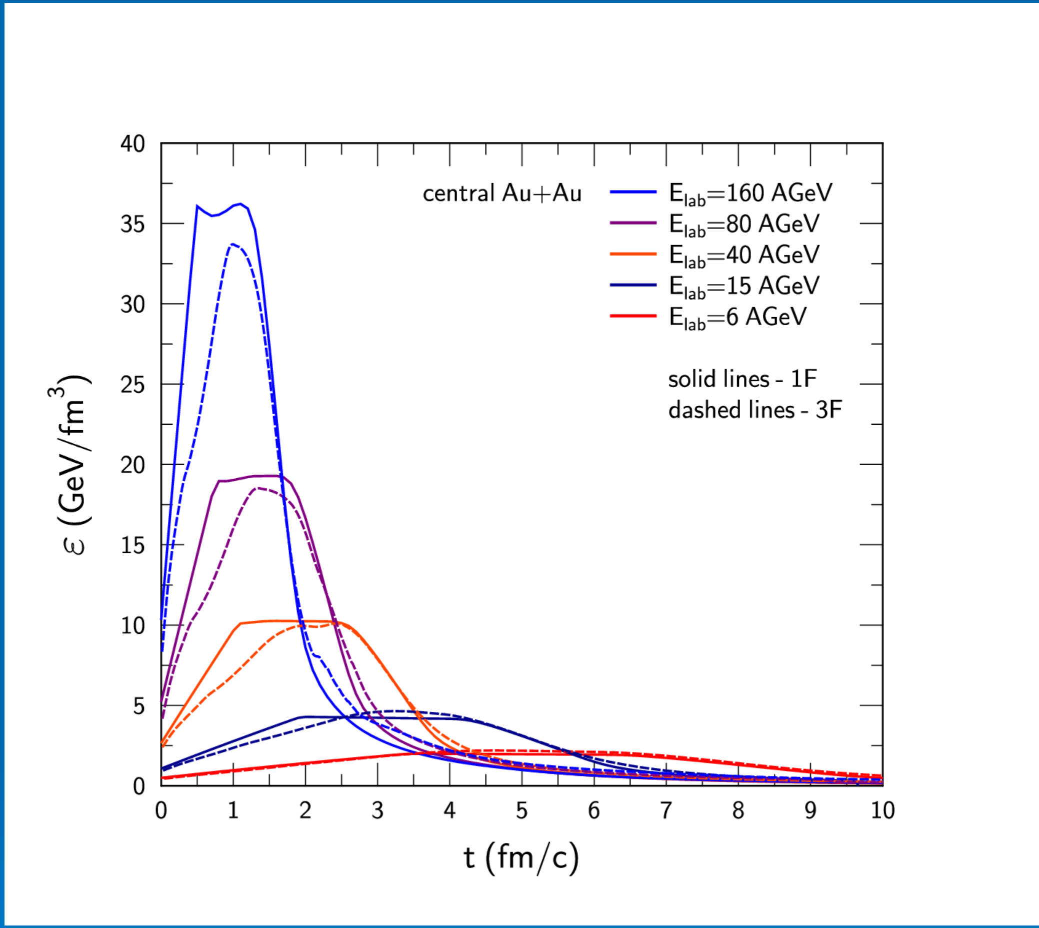


Energy density and baryon density in central box



- Energy densities above 2 GeV/fm^3 appear only at Elab >5 AGeV and exist during the time interval less than 5 fm/c fm/c.
- Baryon densities abiove 10 n_0 can be reached at E_{lab}>10 AGeV!

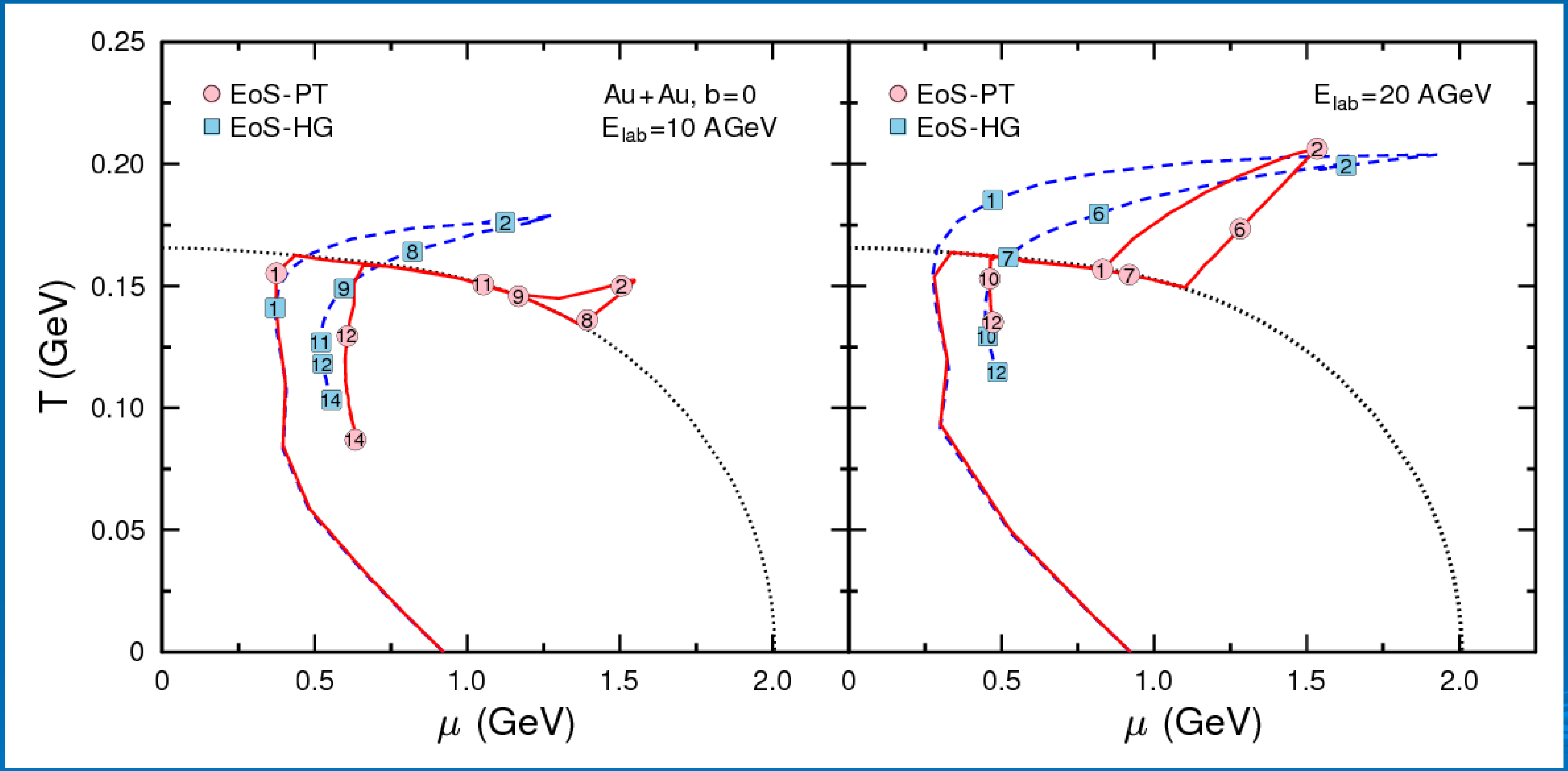
Comparison of 1-fluid and 3-fluid* models



- Transparency effects are rather week at E_{lab}<15 AGeV (in central collisions), at higher energies they are noticeable only at very early times, less than 2 fm/c

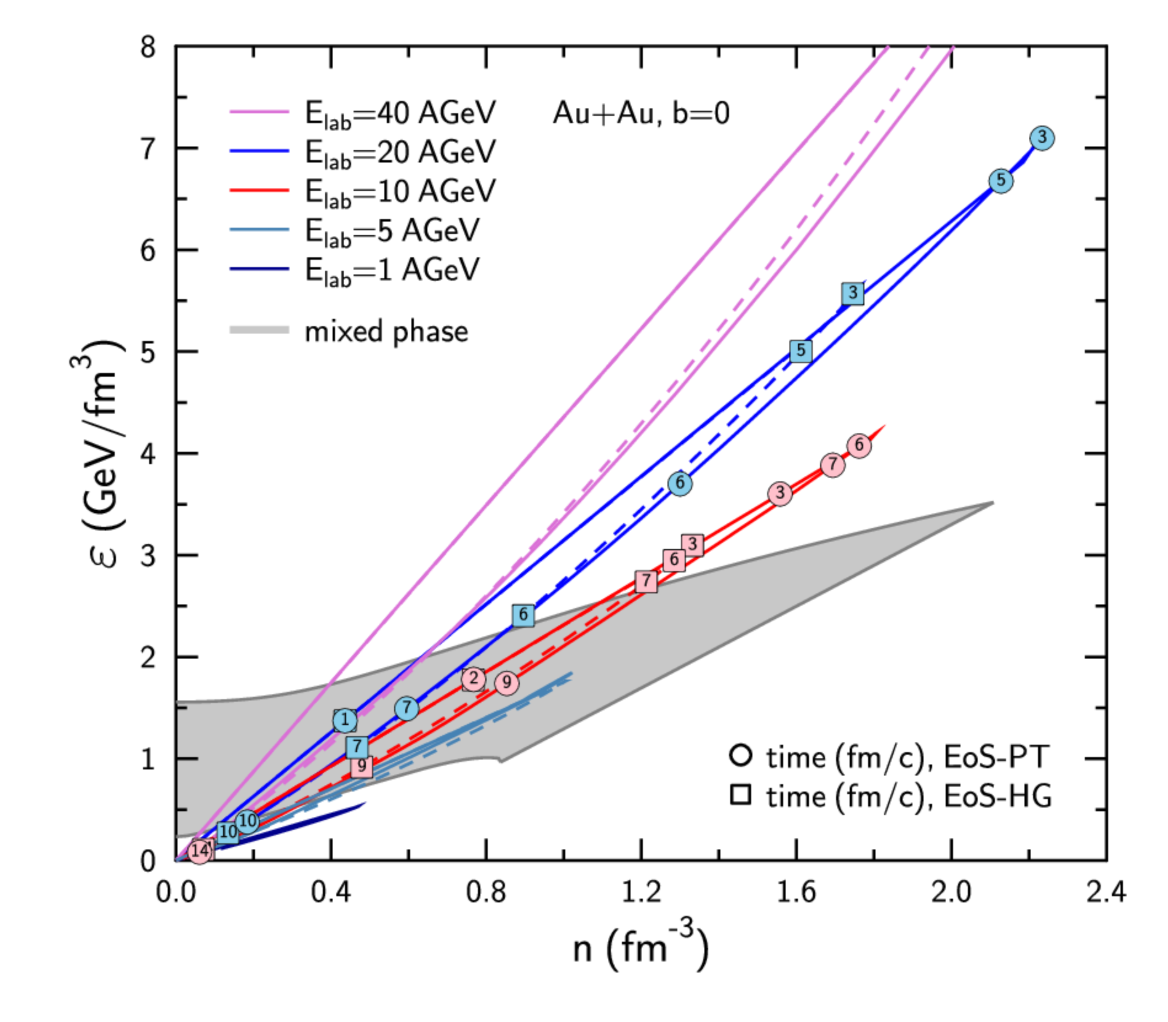
*} we thank Yu.B. Ivanov for providing us with the 3-fluid data

Dynamical trajectories of matter in central cell 1



➡ In the equilibrium scenario the final state is not sensitive to the phase transition. Non-equilibrium effects may help to see it!

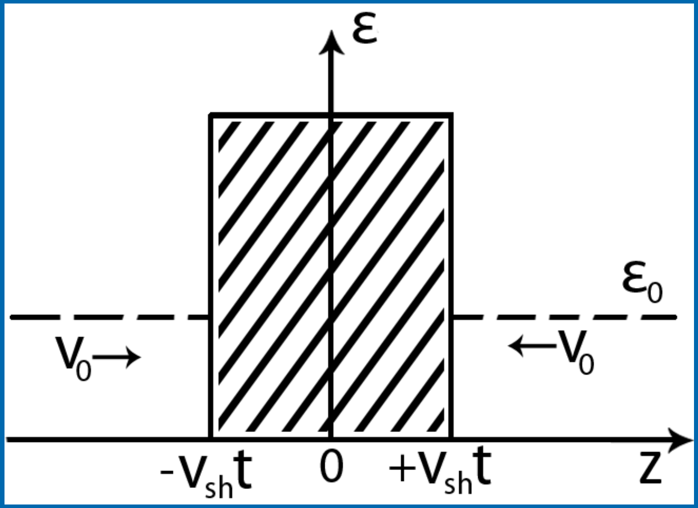
Dynamical trajectories of matter in central cell 2



The passage time through the mixed-phase region is very short, only about 3 fm/c: non-equilibrium effects must be important!

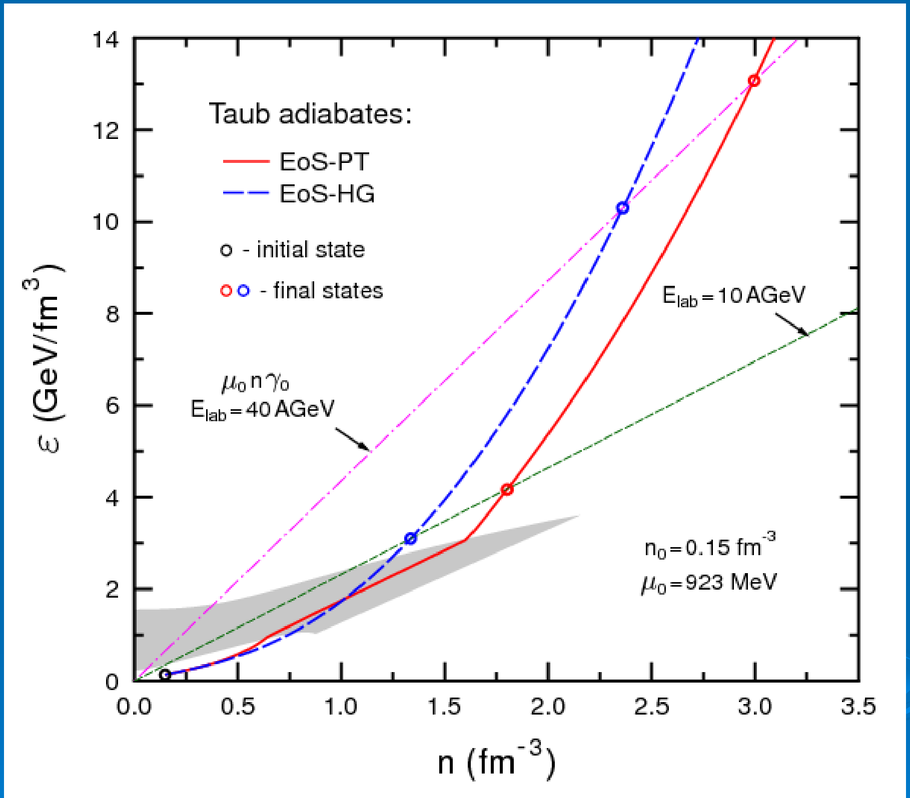
Initial stae:1D shock wave

collision of two slabs



T^{0z}, T^{zz}, nU^z continuous in the shock front rest frame

➡ Taub adiabate

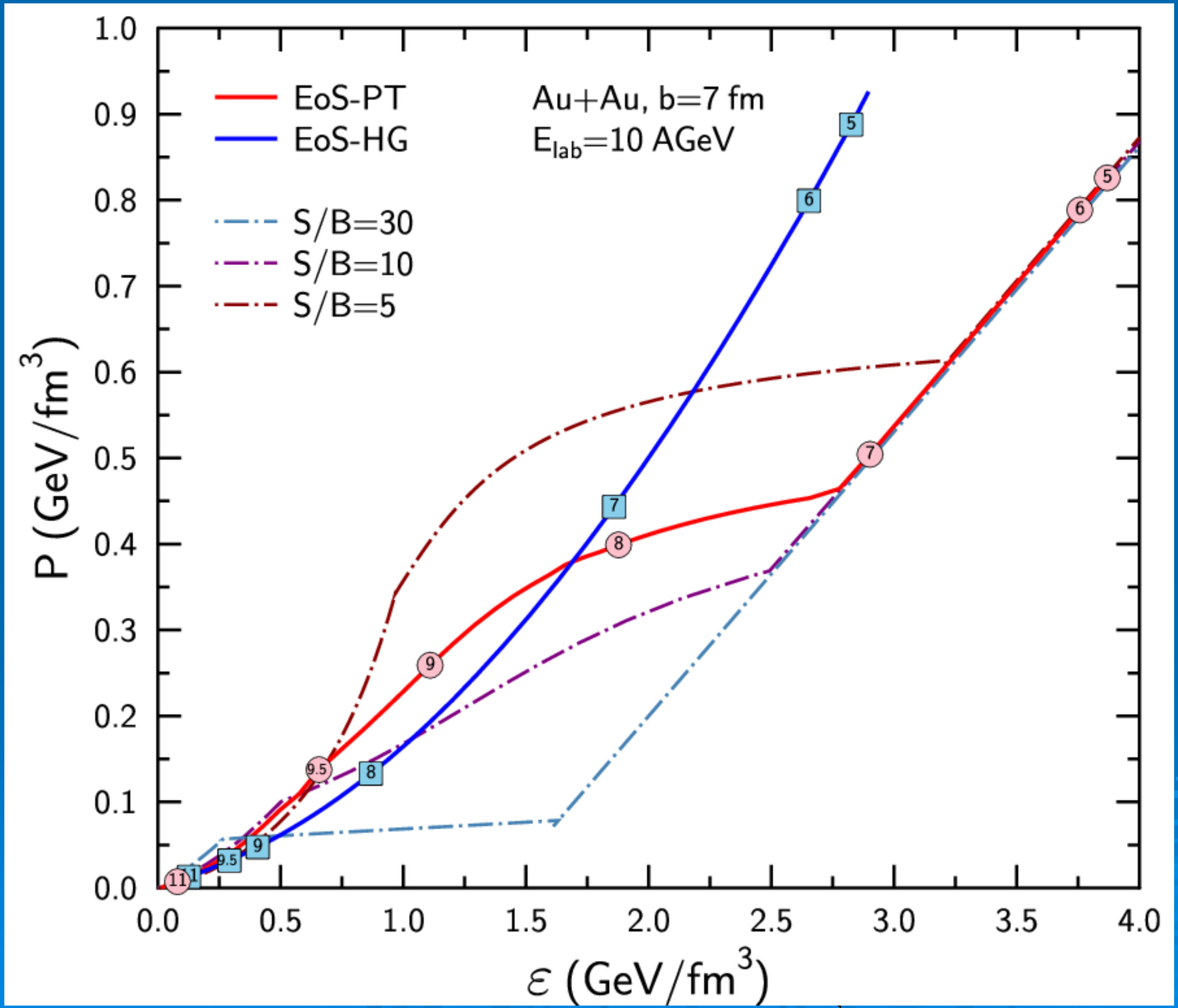


$$\varepsilon_0 (P + \varepsilon_0)\, n^2 = \varepsilon (P + \varepsilon)\, n_0^2$$

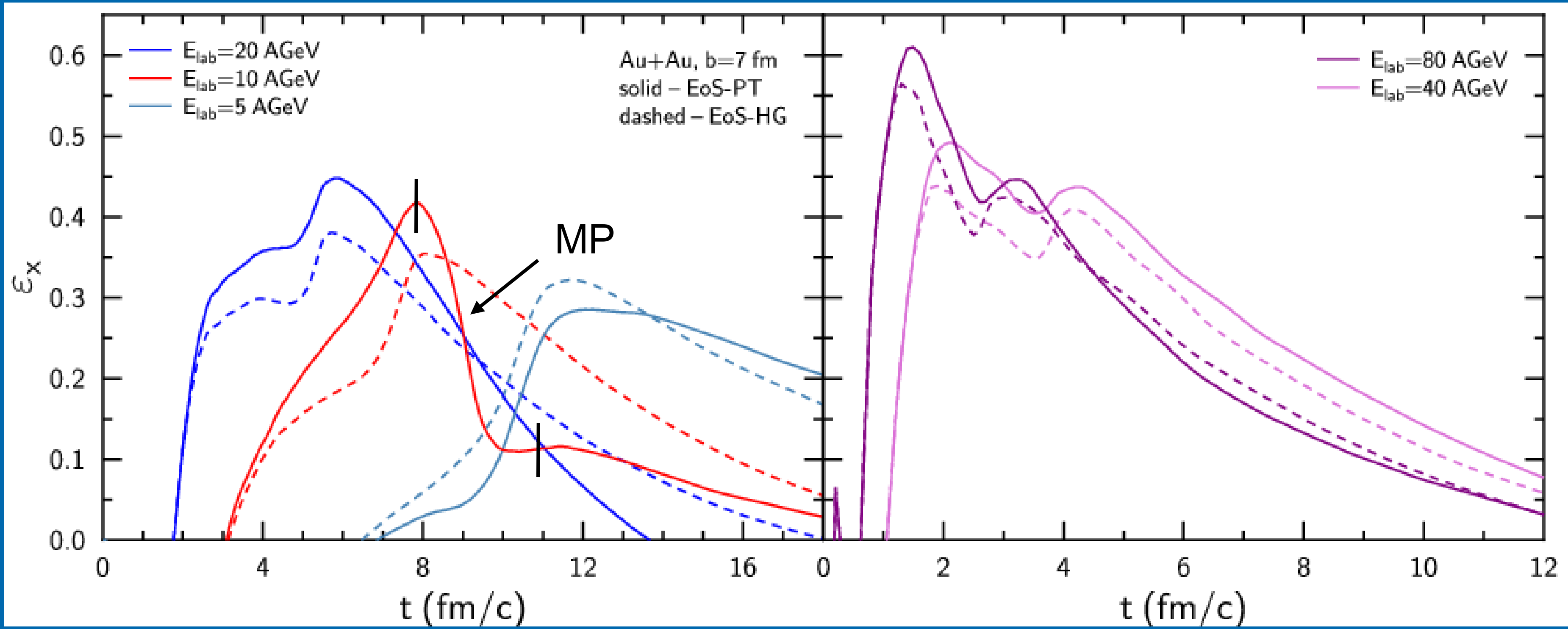
$$P = P(\varepsilon, n) \qquad P_0 = 0 \qquad \varepsilon_0 = \mu_0 n_0$$

$$\frac{\varepsilon(n,T)}{n} = \gamma_0 \frac{\varepsilon_0}{n_0}$$ stopping condition

Final state: isentropic expansion



Spatial anisotropy



- Larger drop of ε_x for EoS-PT (for Elab = 10 AGeV)

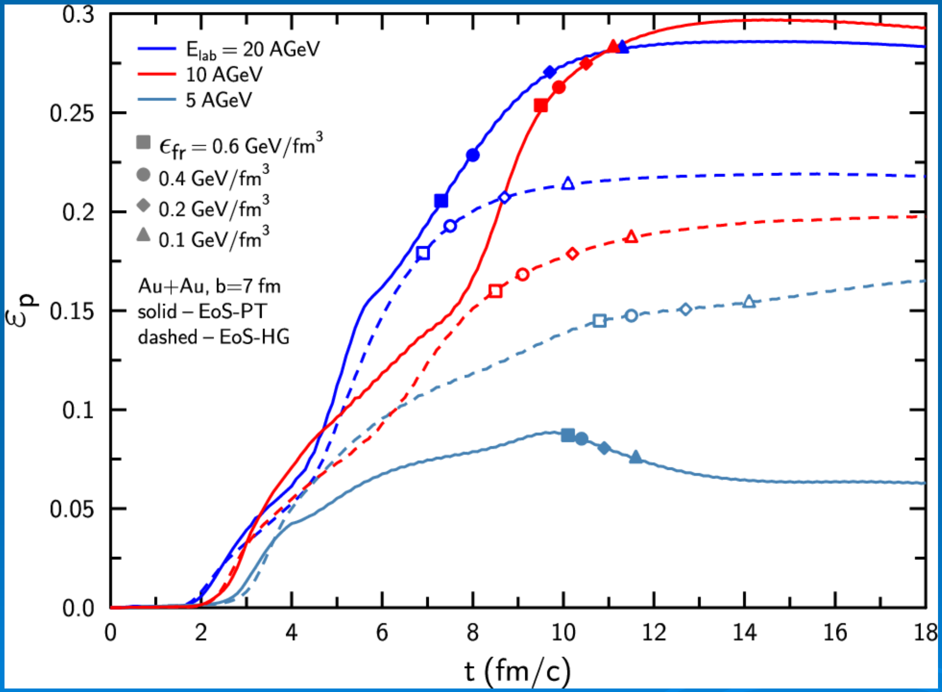
$$\varepsilon_x = \frac{\int dx dy \left(y^2 - x^2\right) \gamma \varepsilon}{\int dx dy \left(y^2 + x^2\right) \gamma \varepsilon}$$

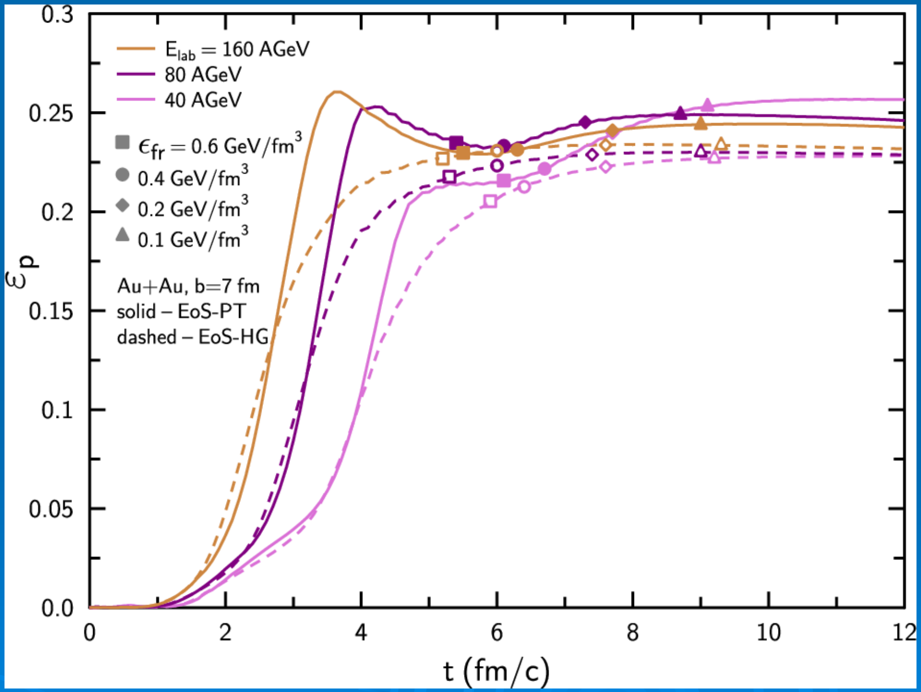
Momentum anisotropy

$$\varepsilon_p = \frac{\int dxdy\,(T^{xx} - T^{yy})}{\int dxdy\,(T^{xx} + T^{yy})}$$

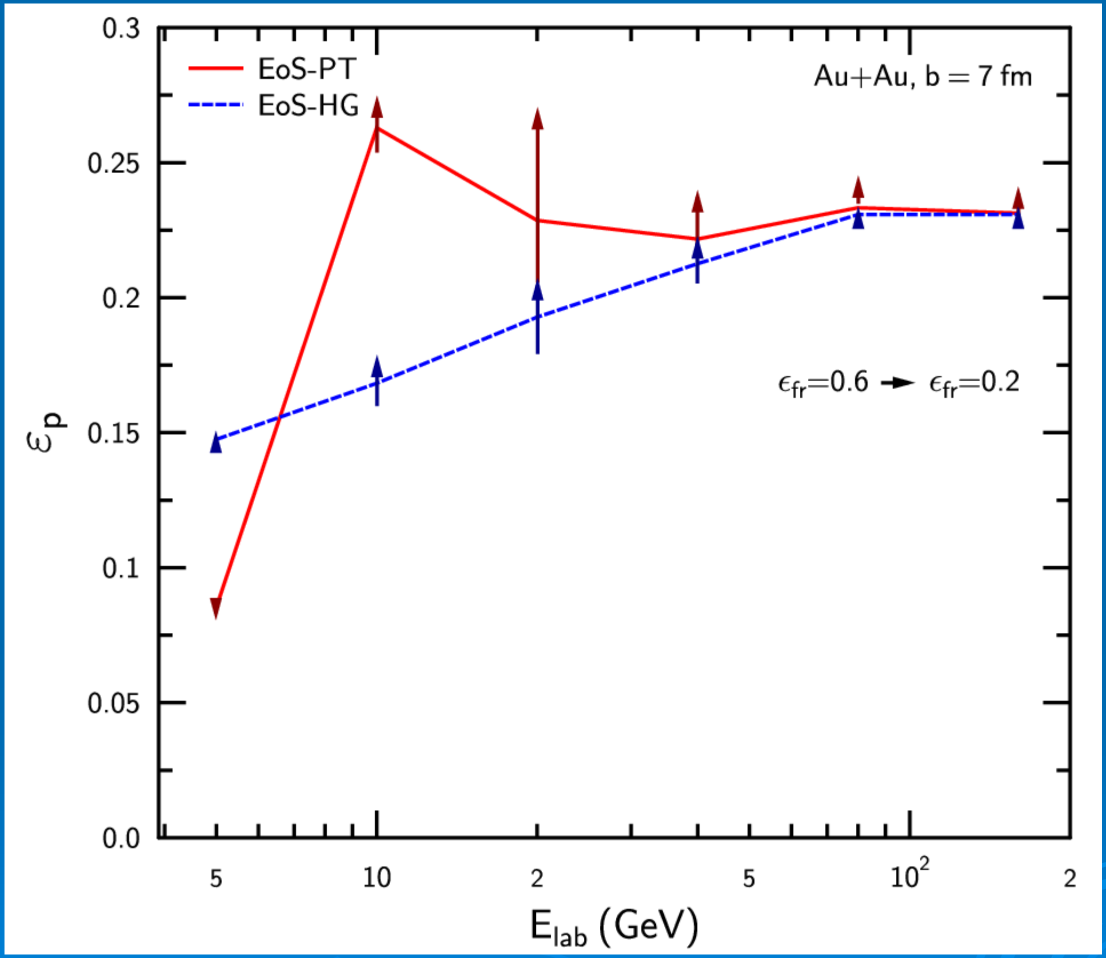
$$T^{xx} = (\varepsilon + P)\gamma^2 v_x^2 + P$$

$$T^{yy} = (\varepsilon + P)\gamma^2 v_y^2 + P$$





Excitation function of elliptic flow



- The peak at Elab=10 AGeV is correlated with the longest time spent in the mixed phase

Hadronic spectra

$$E\frac{d^3N_i}{d^3p} = \frac{d^3N_i}{dy\,d^2p_T} = \frac{g_i}{(2\pi)^3}\int d\sigma_\mu p^\mu \left\{\exp\left(\frac{p_\nu U^\nu - \mu_i}{T}\right) \pm 1\right\}^{-1}$$

instantaneous freeze-out,
Cooper&Frye (1974)

isochronous (t=const) freeze-out surface

$$d\sigma_\mu = d^3x \cdot \delta_{\mu,0}$$

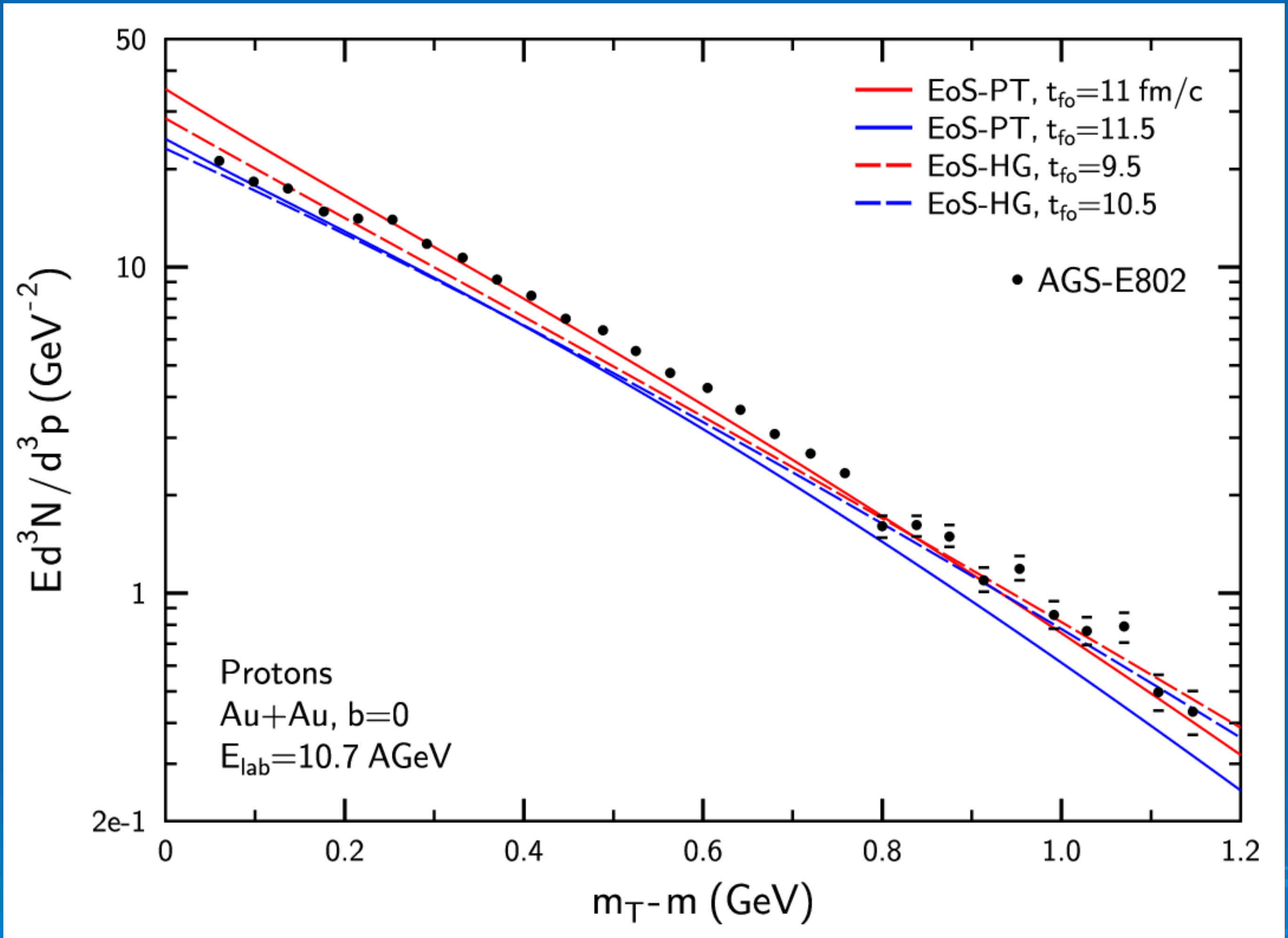
Contribution from resonance decays

$$E\frac{d^3N_{R\to iX}}{d^3p} = \frac{1}{4\pi q_0}\int d^3p_R \frac{d^3N_R}{d^3p_R}\,\delta\left(\frac{pp_R}{m_R} - E_0\right)$$

zero-width approximation

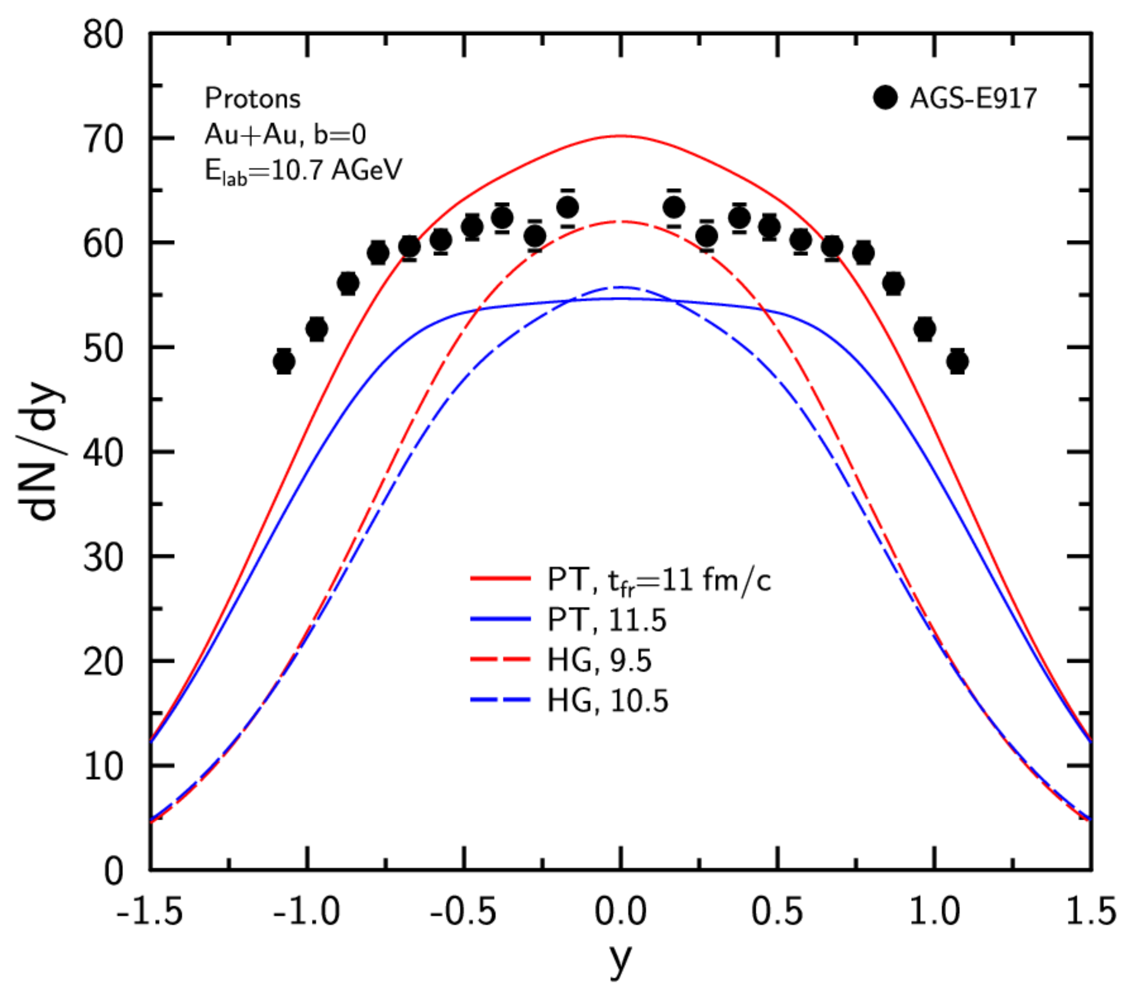
$$E_0 = \sqrt{m_i^2 + q_0^2} = \frac{m_R^2 + m_i^2 - m_X^2}{2m_R}$$

Pt spectra of hadrons



➡ Low sensitivity to the EOS and freeze-out time

Proton rapidity distributions



➡ Strong sensitivity to the EOS: more flat with PT

Summary

- 3D hydro calculations are important for understanding the dynamics of the matter evolution and physical conditions.

- Phase transition changes the intermediate-state dynamics but observables of the final state are not very sensitive to it.

- Calculations with EoS-PT as compared with EoS-HG show:
  - higher momentum anisotropy
  - broader nucleon rapidity distributions

  } at Elab ~ 10-20 AGeV

- Low energy program at RHIC and FAIR/NICA experiments may help to find traces of the deconfinement phase transition

Outlook

- Incorporation of the realistic freeze-out effects: hybrid hydro-cascade approach a la Bleicher&Petersen
- Implementing non-equilibrium hadronization scenarios : explicit dynamics of the order parameter, fluctuations, critical slowing down
- Calculation of HBT radii
- Study of photon and dilepton emission
- Extension to higher energies by using fireball-like initial conditions