Multi-Fluid Dynamics

Transverse Flow in 3-Fluid Dynamics (AGS to SPS)

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Outline

Hadronic EoS (Galitsky&Mishustin 1979)

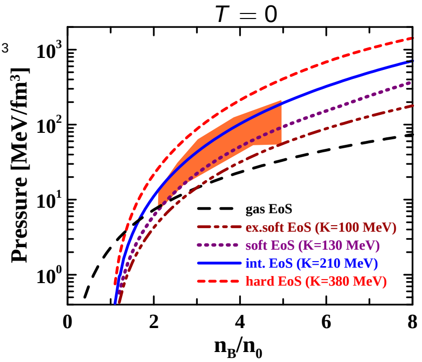
Energy density: $\varepsilon(n_B,T) = \underbrace{\varepsilon_{gas}(n_B,T)}_{\text{hadron gas in mean field}} + \underbrace{W(n_B)}_{\text{mean field}}$

Pressure: $P(n_B,T) = \underbrace{P_{gas}(n_B,T)}_{\text{hadron gas in mean field}} \underbrace{+ n_B \frac{dW(n_B)}{dn_B} - W}_{\text{mean field}}$

$$\frac{\varepsilon(n_B,0)}{m_N n_0} = a\left(\frac{n_B}{n_0}\right)^{5/3} - b\left(\frac{n_B}{n_0}\right)^2 + c\left(\frac{n_B}{n_0}\right)^{7/3}$$

$\varepsilon(n_B,0))$ saturates the cold matter at $n_0 = 0.15$ fm^{-3} and $\varepsilon(n_0, T=0)/n_0 - m_N =$ -16 MeV, and provides incompressibility K.

Astrophysical constraints on EoS
T. Klahn et al., nucl-th/0602038:
hard EoS's are preferable at $T=0$.



Danielewicz, Lacey, Lynch (2002)

Physical Input for Hadronic Scenario

- Hadronic EoS
- Enhanced Friction

  fitted to observed stopping power (i.e. proton rapidity distributions)

  Function of 3 variables, $dN/dy(y, b, E_{lab})$**, is fitted by function of 1 variable,** $\xi_h^2(s)$**!**
- Freeze-out: $\varepsilon_{frz} \approx 0.2$ GeV/fm^3 (≈ 0.1 GeV/fm^3 at $E_{lab} < 3$ A·GeV)

  fitted to observed proton p_T spectra

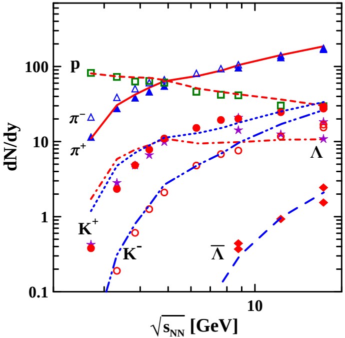
  Funct. of 4 variables, $(1/2\pi m_T)d^2N/dm_T dy(m_T, y, b, E_{lab})$**, is fitted by 1 parameter** ε_{frz}**!**
- Formation Time $\tau = 2$ fm/c $\Rightarrow$ $\tau_{particle} \approx 1$ fm/c

  fitted to observed pion production at $E_{lab} > 30$ A·GeV

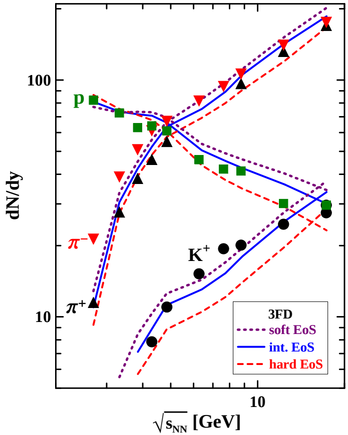
  - $\tau_{particle} < \tau = \int d^3p \; \tau_{particle}\gamma_{particle} f(p) \Big/ \int d^3p \; f(p)$ If $T \approx 100$ MeV, $\tau_{particle} \approx 1$ fm/c.

dN/dy at midrapidity in central Au+Au and Pb+Pb coll.

Int. EoS



soft, **int.** and hard EoS's

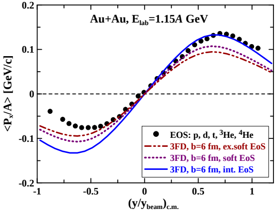


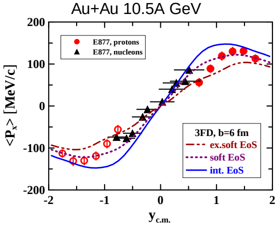
Int. EoS is also good for:

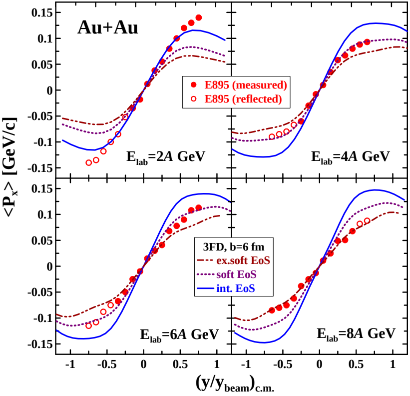
- multiplicities
- m_T spectra

Flow?

Directed Flow at AGS







Data favor: int. EoS (1*A* GeV) ⇒ soft EoS (4*A* GeV) ⇒ extra-soft EoS (8*A* GeV) ⇒ ?(SPS)

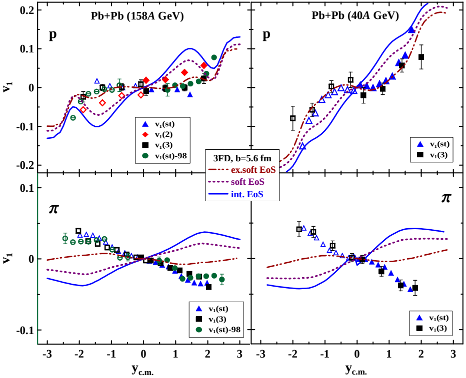
HSD, UrQMD, JAM: **no softening required**

HSD, UrQMD, JAM: *"transition from hadronic to string matter"[1]* ⇒ *effective softening*

[1] P.K. Sahu, W. Cassing, U. Mosel and A. Ohnishi, Nucl. Phys. **A672**, 376 (2000)

Directed Flow at SPS

HSD: Cassing and Bratkovskaya, PR **308**, 65 (1999); **UrQMD**: Bass *et al.*, PPNP **41**, 225 (1998); **JAM**: Isse *et al.*, PRC **72**, 064908 (2005).



Pions: **no shadowing**

⇒ **no anticorrelation**

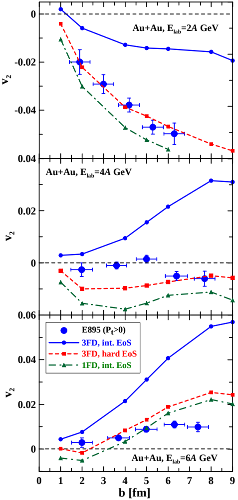
Softening saturates: int. EoS (1*A* GeV)⇒ soft EoS (4*A* GeV)⇒ extra-soft EoS (*E* > 8*A* GeV)

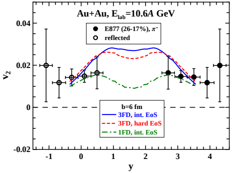
HSD: "transition from hadronic to string matter" saturates *at top AGS energies*

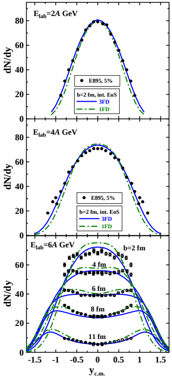
Initial stage is of prime importance for flow!

Int. EoS is good for "late-stage" and "stopping-power" observables.

Elliptic Flow at AGS







Dir. flow requires softer EoS
Elliptic flow — harder EoS

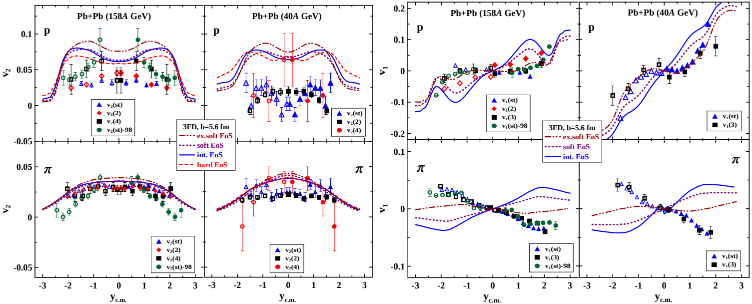
Similar to Danielewicz *et al.*,

Science **298**, 1592 (2002)

1FD is quite good at lower AGS energies ⇒

HSD, JAM: **proper momentum dependence is of prime importance!**

Elliptic Flow at SPS



HSD, JAM: **proper momentum dependence is of prime importance!**

⇓

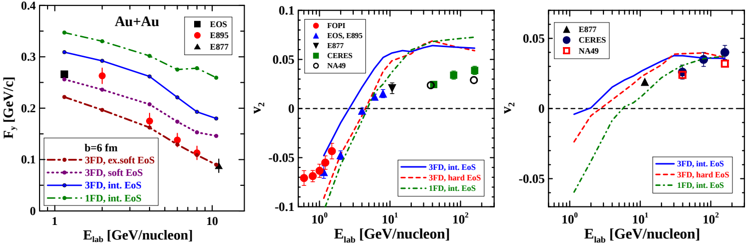
Early-stage nonequilibrium is important for $v_2 = \langle (p_x^2 - p_y^2)/p_T^2 \rangle$

because otherwise this momentum dependence is integrated over in EoS

Excitation Functions of Flow

directed protons

elliptic protons pions

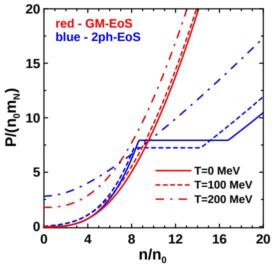


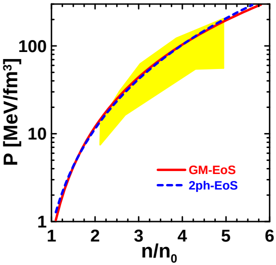
Summary:

- **Effective softening at initial stage is required** by directed flow
  "transition from hadronic to string matter" Sahu et al., Nucl. Phys. **A672**, *376 (2000)*
  Initial stage is of prime importance for flow!
- Proper momentum dependence is of prime importance for elliptic flow which means that
  Early-stage nonequilibrium is important for v_2
- **3FD with int. EoS is good for "late-stage" and "stopping-power" observables**.

EoS with 1st order phase transition

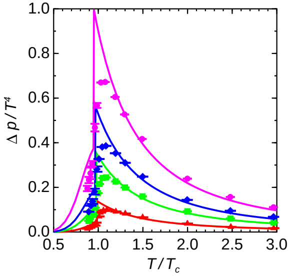
A.S.Khvorostukhin, V.V.Skokov, K.Redlich, V.D.Toneev, nucl-th/0605069

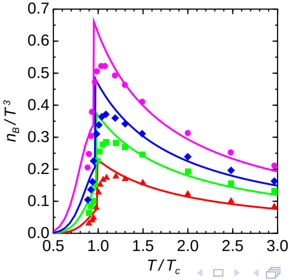




Danielewicz, Lacey, Lynch (2002)

Bag with heavy quarks ($m_{u/d} = 70MeV$, $m_s = 145MeV$) and gluons (700 MeV), to fit lattice data (Fodor et al.)

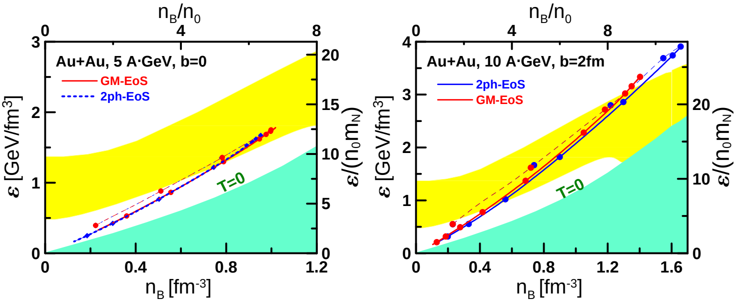




μ_b = 210, 330, 410, 530 MeV

2ph-EoS Preliminarily!!!

Dynamic Trajectories for central box 4 fm $\times$ 4 fm $\times$ 4 fm/γ_{cm} (Preliminary!)

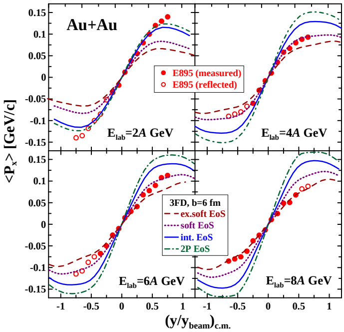


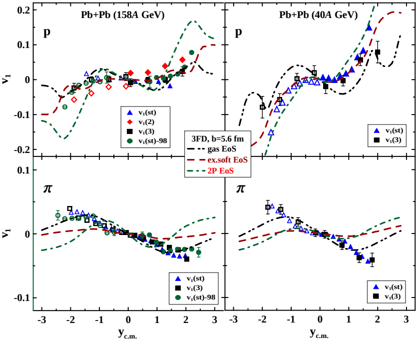
Phase transition starts at 5A GeV

At 10A GeV the matter mostly lives in the phase-coexistence region

2ph-EoS Preliminarily!!!

Directed flow (Preliminary!)





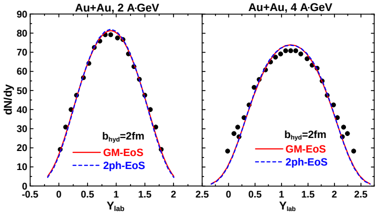
2P-EoS:

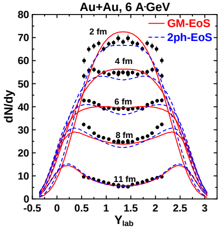
too hard in hadronic phase

too soft in QGP phase

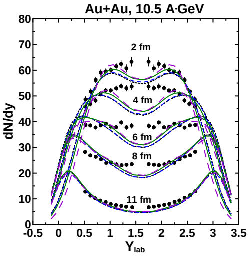
2ph-EoS Preliminarily!!!

Proton Rapidity Distributions (Preliminary!)

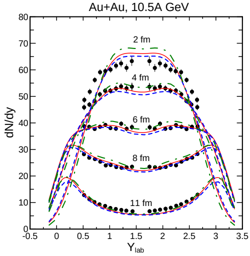




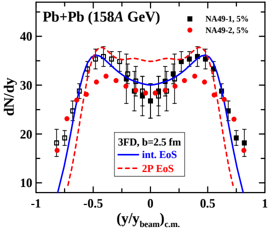
2ph-EoS: variation of friction



Hadr. EoS: variation of friction



2ph-EoS: variation of friction



Phase transition happens too early

Summary

Hydrodynamics addresses **Equation of State**!
Simple hadronic EoS $\Longrightarrow$ Natural reference point

- Simple *hadronic EoS* reasonably reproduces observables (except flows).
  - Flows require a softer EoS and hence leave room for **phase transition to quark-gluon phase**

    or **“transition from hadronic to string matter”** (HSD, UrQMD, JAM)
- EoS with 1st order phase transition:
  - **Phase transition starts too early!** (Au+Au at 5A GeV)
  - **2ph-EoS is too hard in hadronic phase**
  - **2ph-EoS is too soft in QGP phase**