Kinetic transport theory of heavy ion collisions

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Outline

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- What have we learned up to now on the EOS?

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- Kinetic models for HICs

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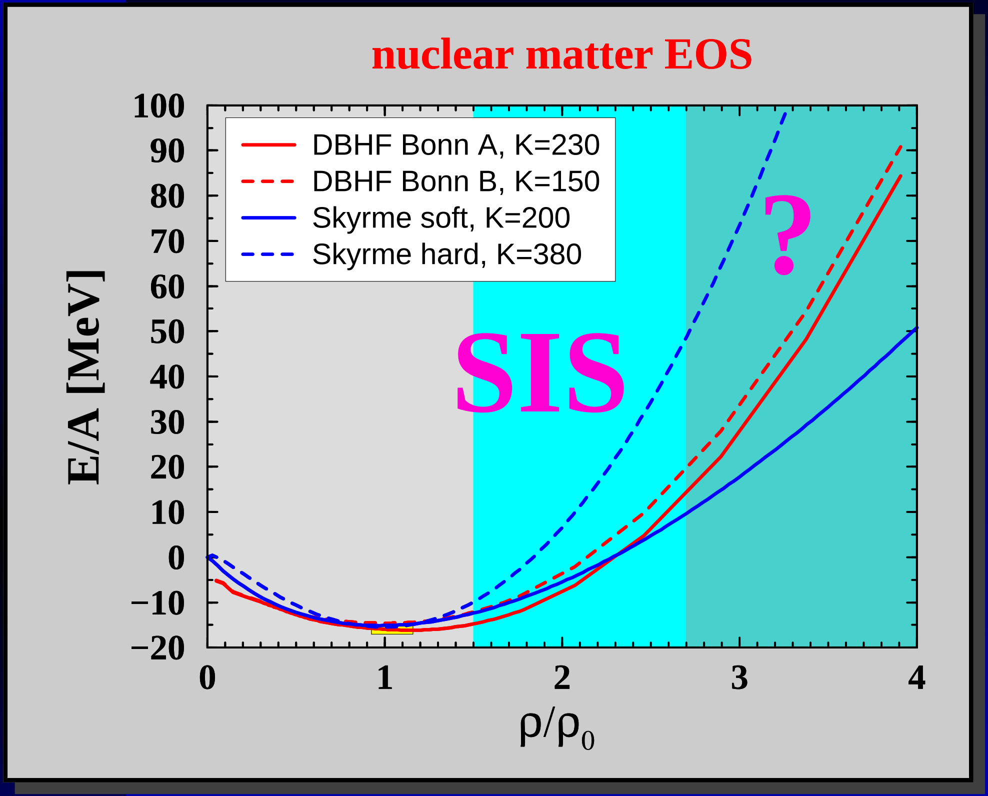
- Status of transport
- Predictions for CBM

Nuclear Equation of State

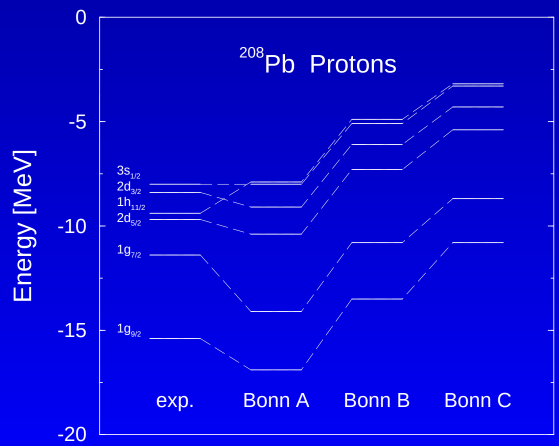


$E(\rho),\ \rho_0$ from ^{208}Pb

finite nuclei: $\rho/\rho_0 \leq 1$

heavy ions: $\rho/\rho_0 \leq 3-?$

neutron stars: $\rho/\rho_0 \leq 10$



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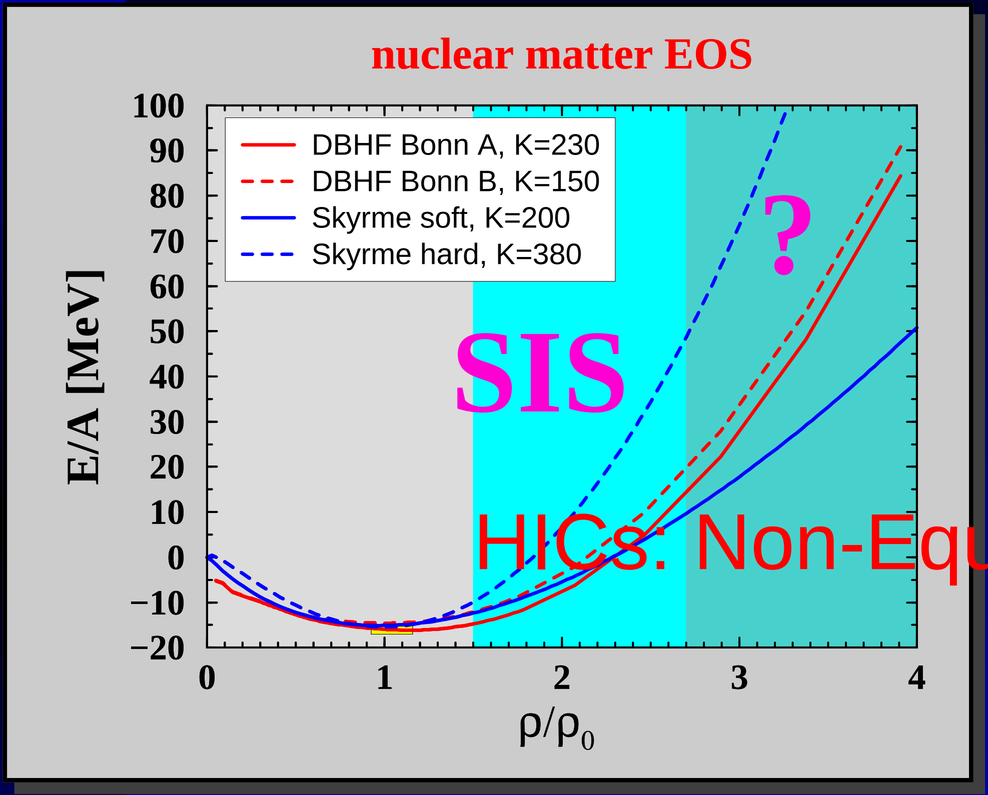

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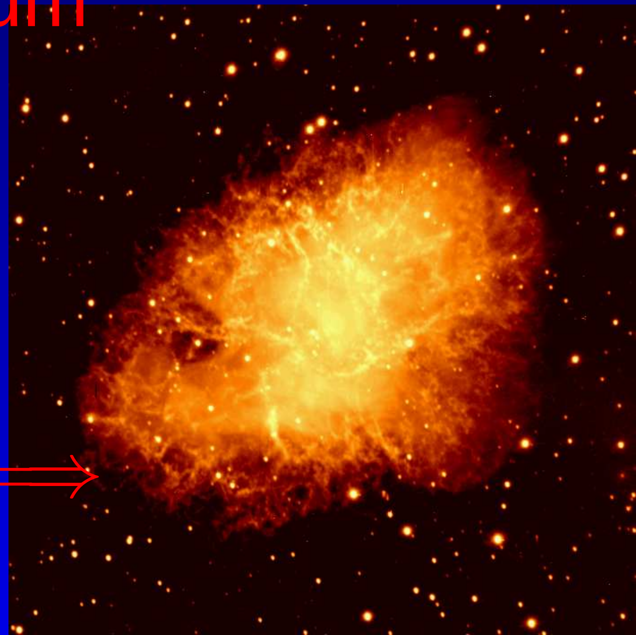
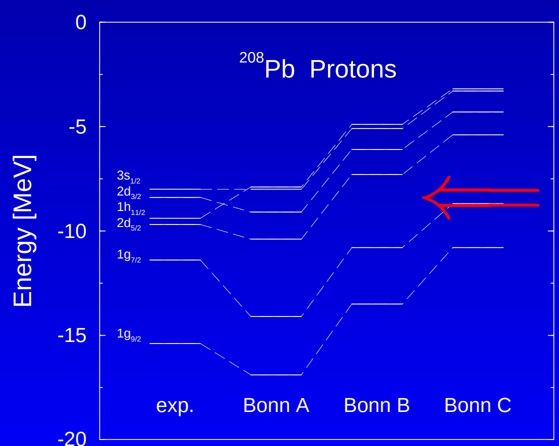
HICs: Non-Equilibrium

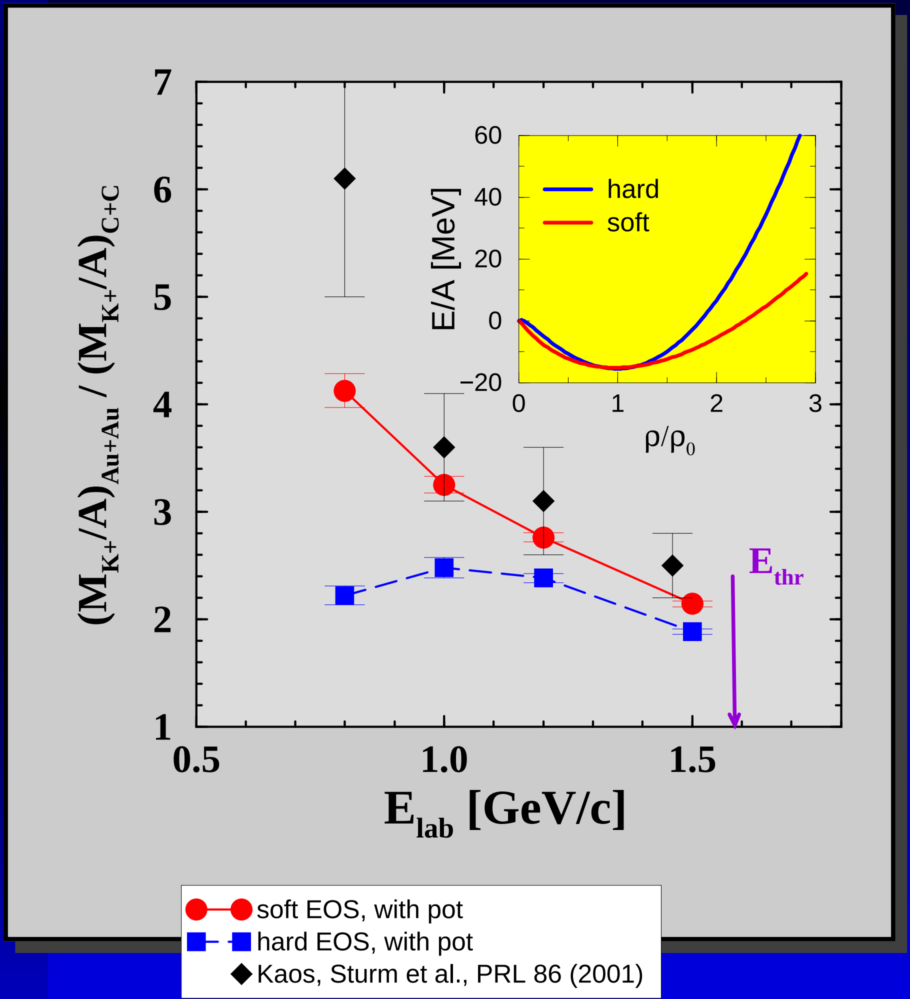


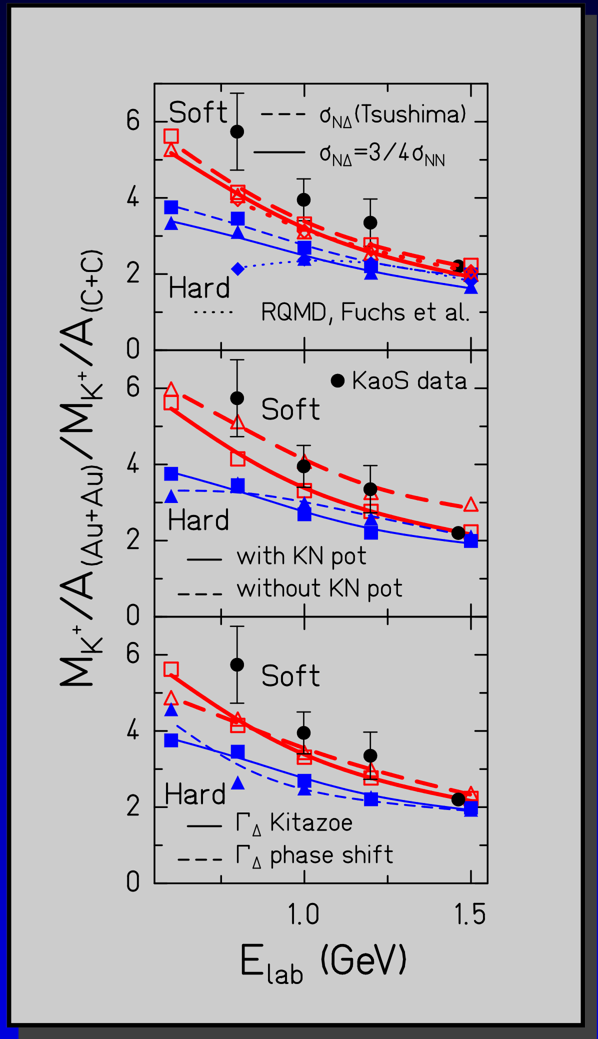


$\Longleftarrow$ Equilibrium $\Longrightarrow$

Constraints on EOS: K^+ @ SIS

SIS: $\rho < 3\rho_0$, subthreshold K^+ is a penetrating probe:



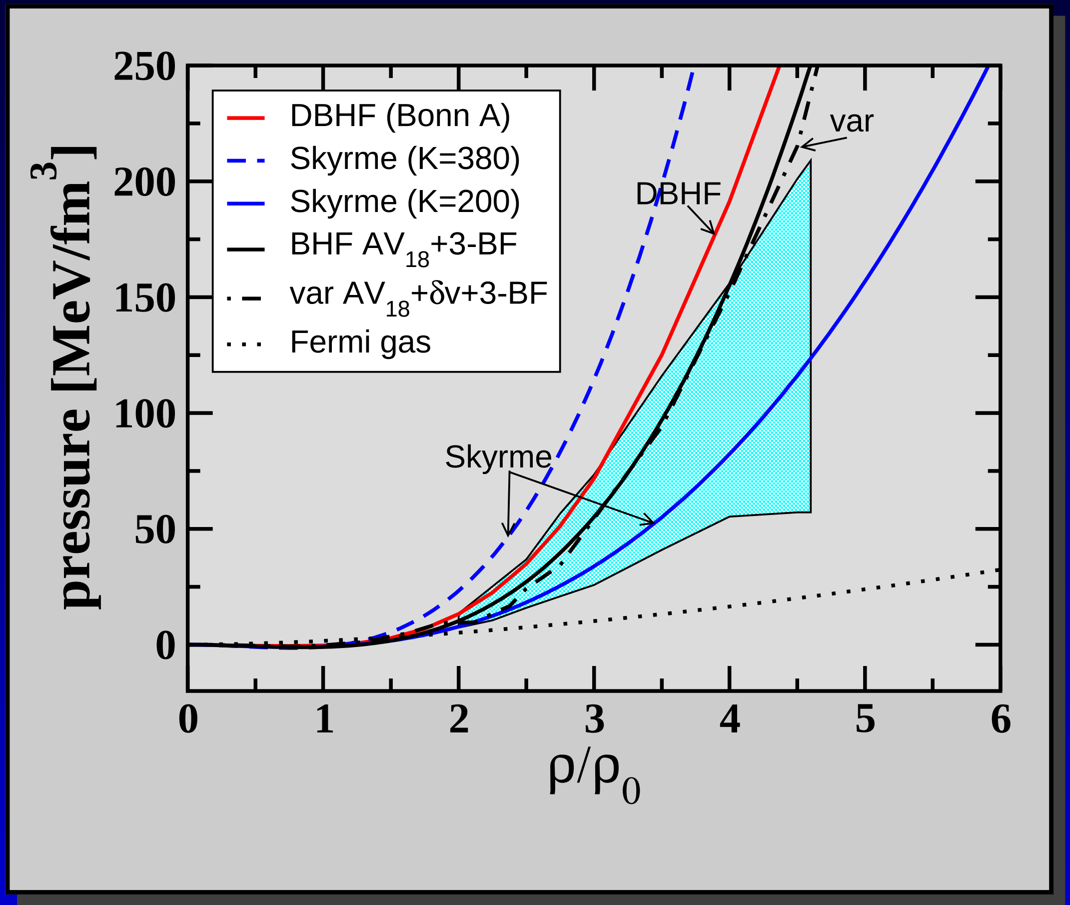


KaoS data $\Longrightarrow$ soft EOS!

C.F. et al., PRL 86 (2001) 1974; Hartnack et al.,nucl-th/0506087

Flow @ SIS-AGS

SIS/AGS: $\rho < 6\rho_0$, compilation of v_1 &v_2



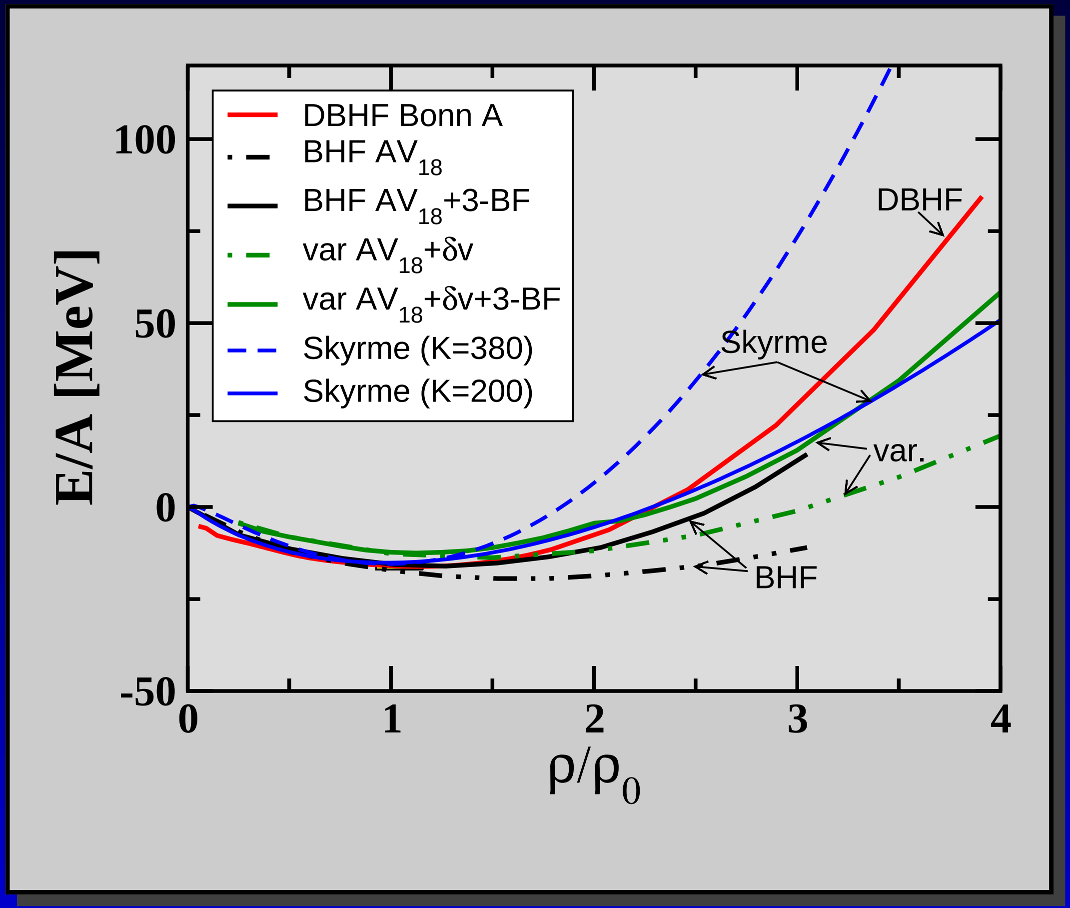
Flow data $\Longrightarrow$ compatible with soft EOSe

space for stiffer EOS at high density (AGS)

Danielewicz at al., Science 298, 1592 (2002)

Predictions for EOS

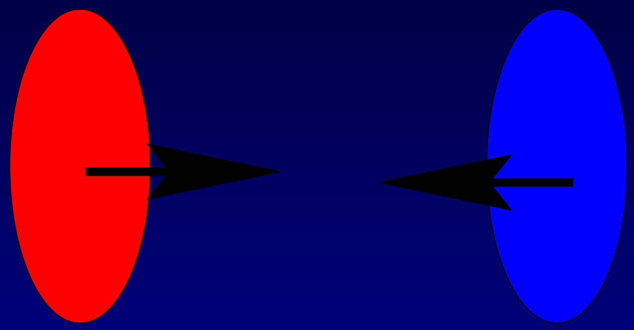
Ab inito many-body theory (Brueckner, variational)

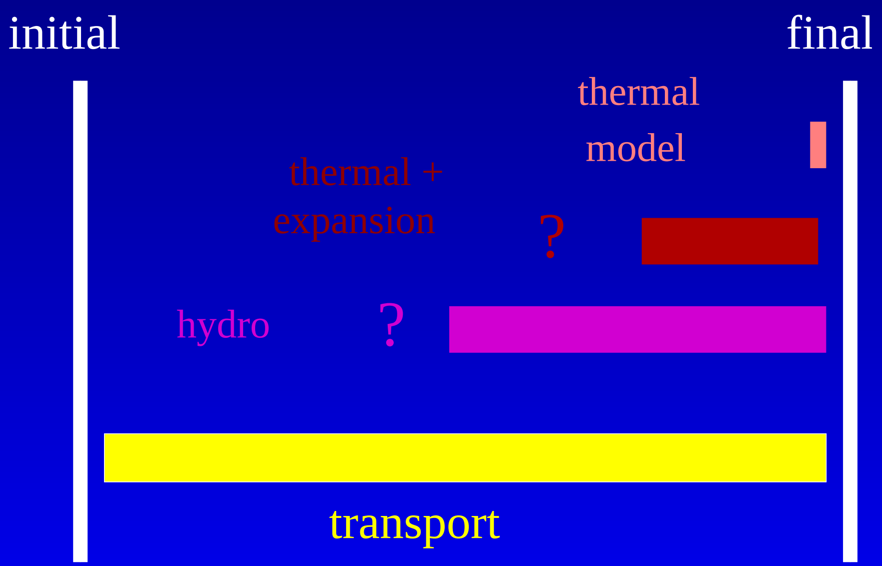


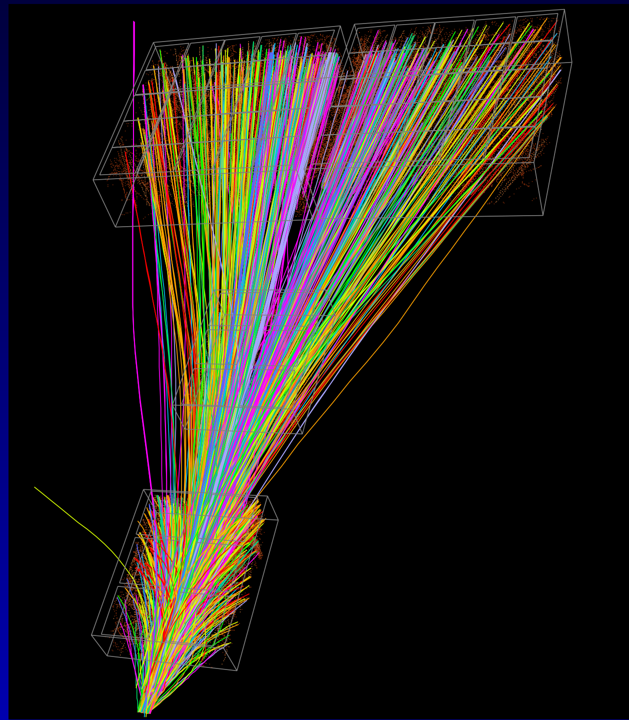
soft in the SIS domain; stiffer EOS at higher densities (AGS)

see e.g. C.F., Prog. Part. Nucl. Phys. 56 (2006) 1

Models for heavy ion collisions





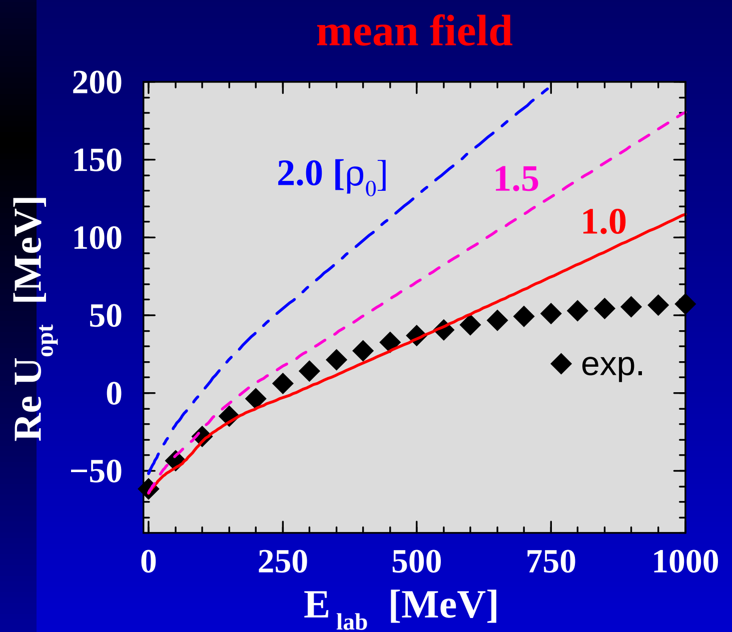


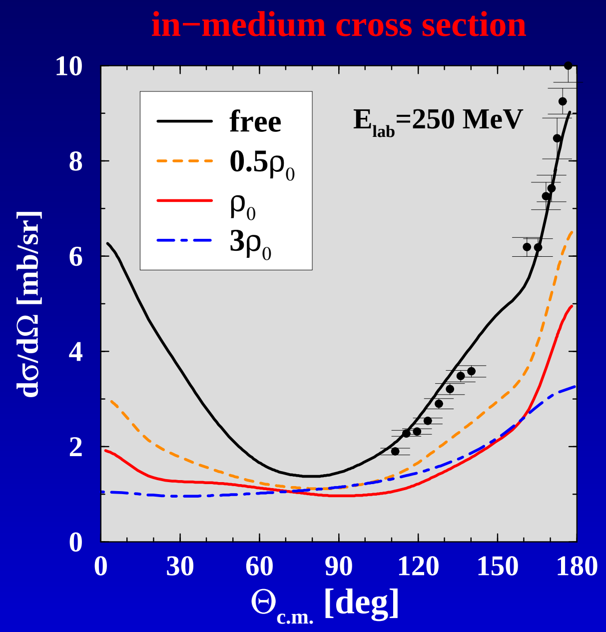
Non-Eq.-QFT: Kinetic Theory

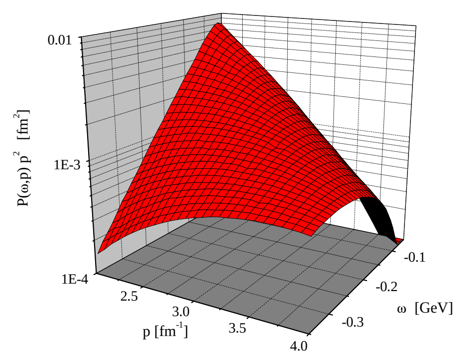
$$(s - s^\dagger)G^< - [Re\Sigma^+, G^<] - [\Sigma^>, G^+] = \frac{1}{2}(\{\Sigma^>, G^<\} - \{\Sigma^<, G^>\})$$

$$[\partial_t + \partial_{\vec{p}} U \partial_{\vec{x}} - \partial_{\vec{x}} U \partial_{\vec{p}}]\, f(\vec{x}, \vec{p}, t) = I_{\text{coll}}[f, \sigma, \Gamma] \quad (\text{BUU})$$

$$T = V + iVQGGT \quad (\text{Bethe} - \text{Salpeter})$$







$$\Gamma \sim \text{Im}\, tr[Tf]$$

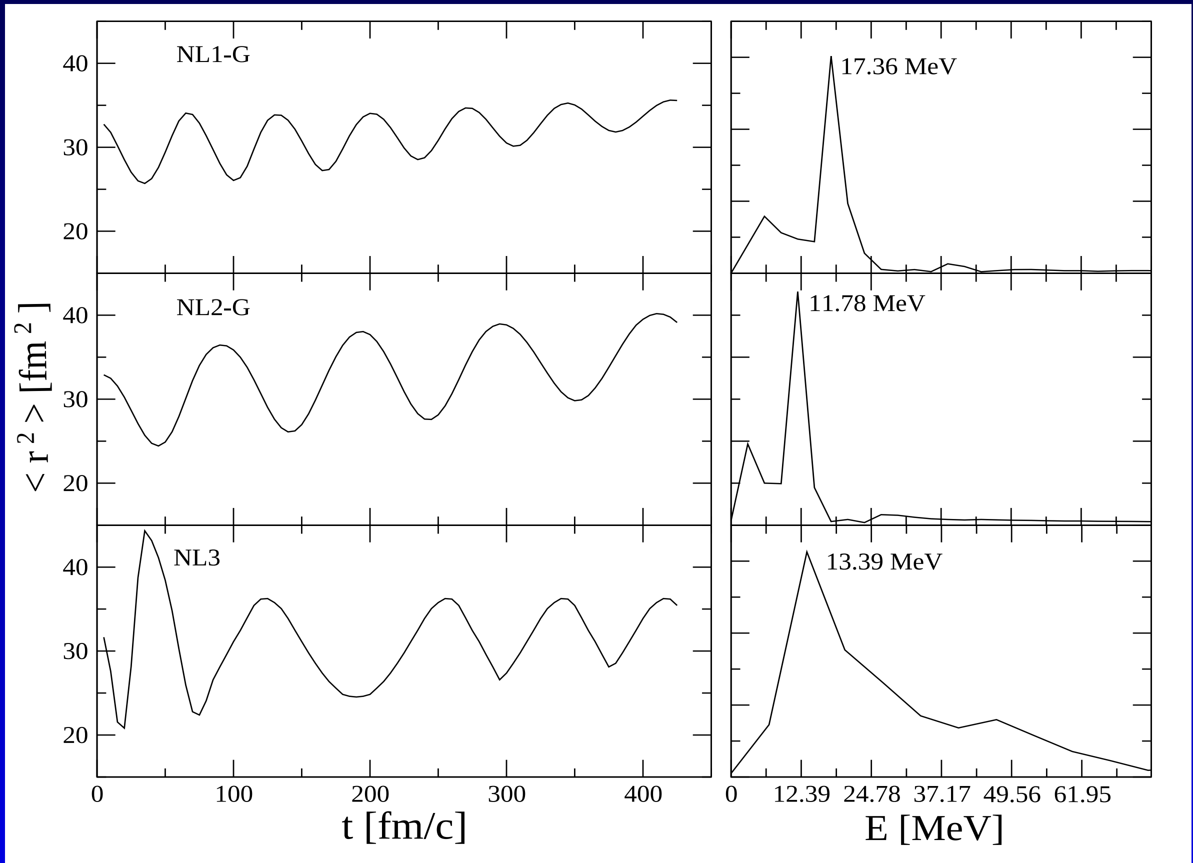
Lehr, Mosel et al. ('99)

$$U \sim \text{Re}\Sigma \sim \text{Re}tr[Tf], \quad d\sigma = |T|^2 d\Omega, \quad \Gamma \sim \text{Im}\Sigma \sim \text{Im}tr[Tf]$$

E.g C.F. et al. PRC 58 ('97) 2022, PRC 64 ('01) 024003

Transport is more than billard

Example: Isoscalar GMR (^{208}Pb) with RBUU (testparticle method) Di Toro, Gaitanos et al., nucl-th/0507014



Exp: $E = 13.7 \pm 0.3$ MeV

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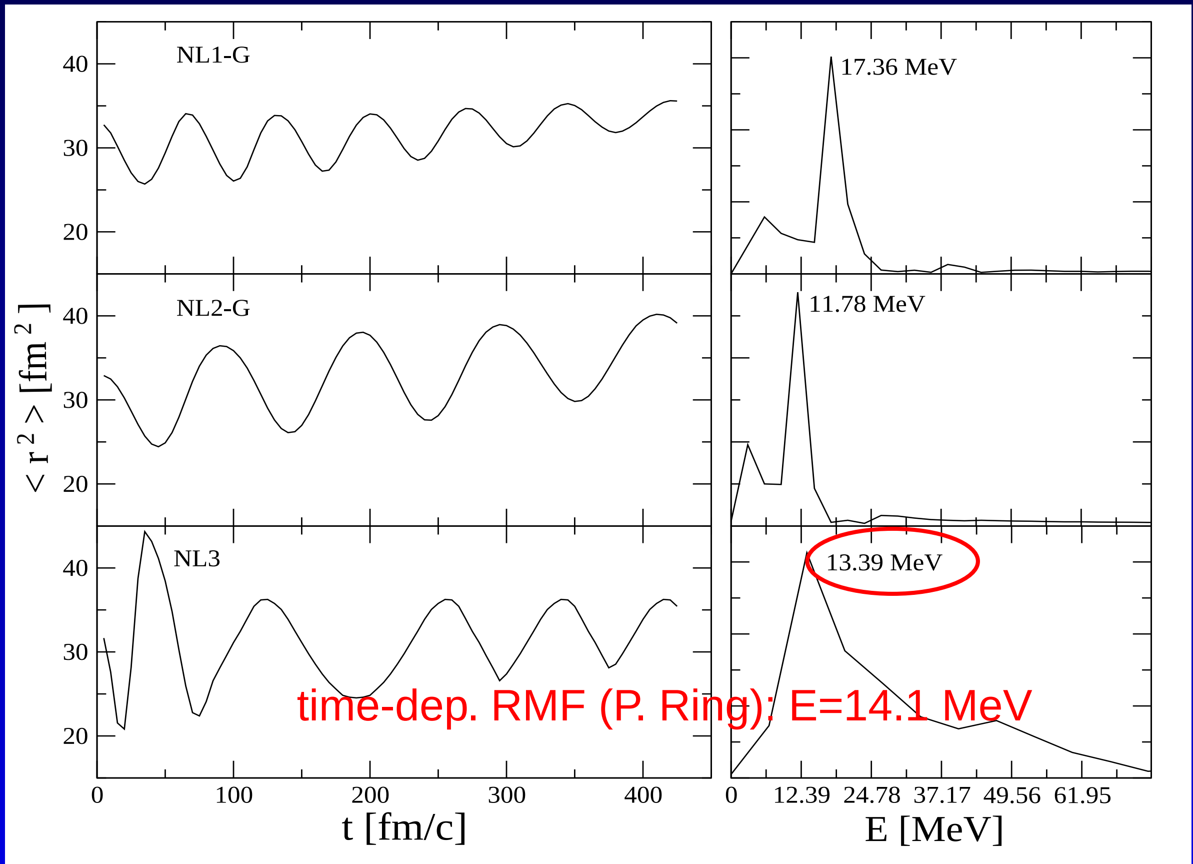

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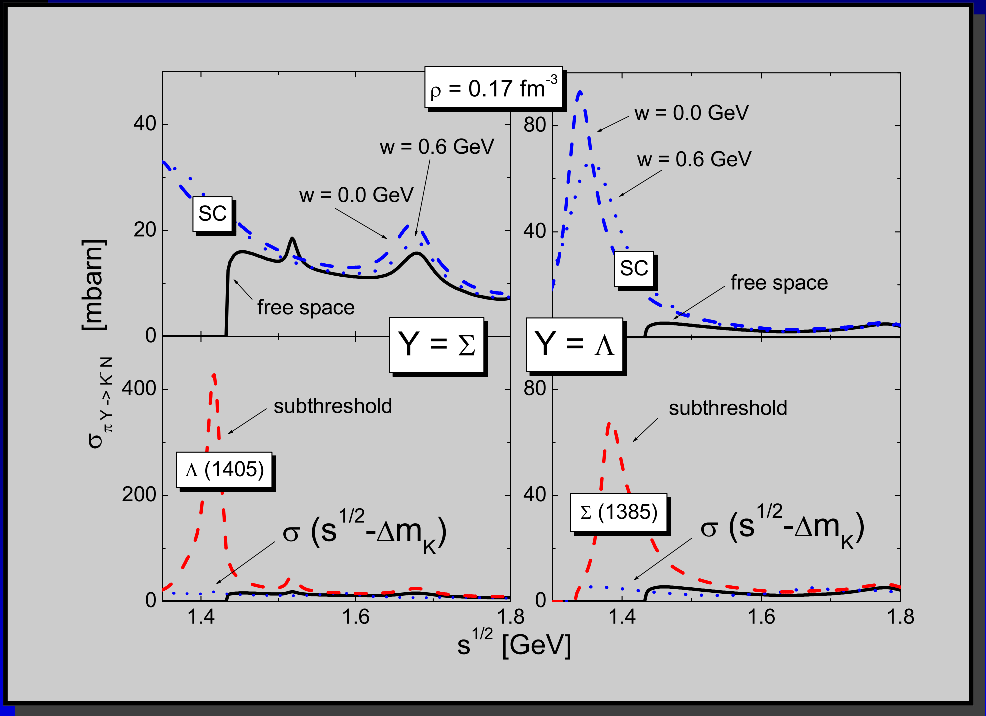
Coupled channel problem

$$[\partial_t + \partial_{\vec{p}} U_N \partial_{\vec{x}} - \partial_{\vec{x}} U_N \partial_{\vec{p}}]\, f_N = I_{\rm coll}[f_N, \sigma_N, \Gamma_N, f_\pi, f_K, \cdots]$$

$$[\partial_t + \partial_{\vec{p}} U_\pi \partial_{\vec{x}} - \partial_{\vec{x}} U_\pi \partial_{\vec{p}}]\, f_\pi = I_{\rm coll}[f_\pi, \sigma_\pi, \Gamma_\pi, f_N, f_K, \cdots]$$

$$[\partial_t + \partial_{\vec{p}} U_K \partial_{\vec{x}} - \partial_{\vec{x}} U_K \partial_{\vec{p}}]\, f_K = I_{\rm coll}[f_K, \sigma_K, \Gamma_K, f_N, f_\pi, \cdots]$$

$$[\cdots] f_{\Lambda,\Sigma} = \cdots, \quad \cdots, \cdots$$



In-medium cross sections:

K^- close to Λ_{1405} resonance

$\Longrightarrow$ strong medium dependence

M. Lutz, NPA700

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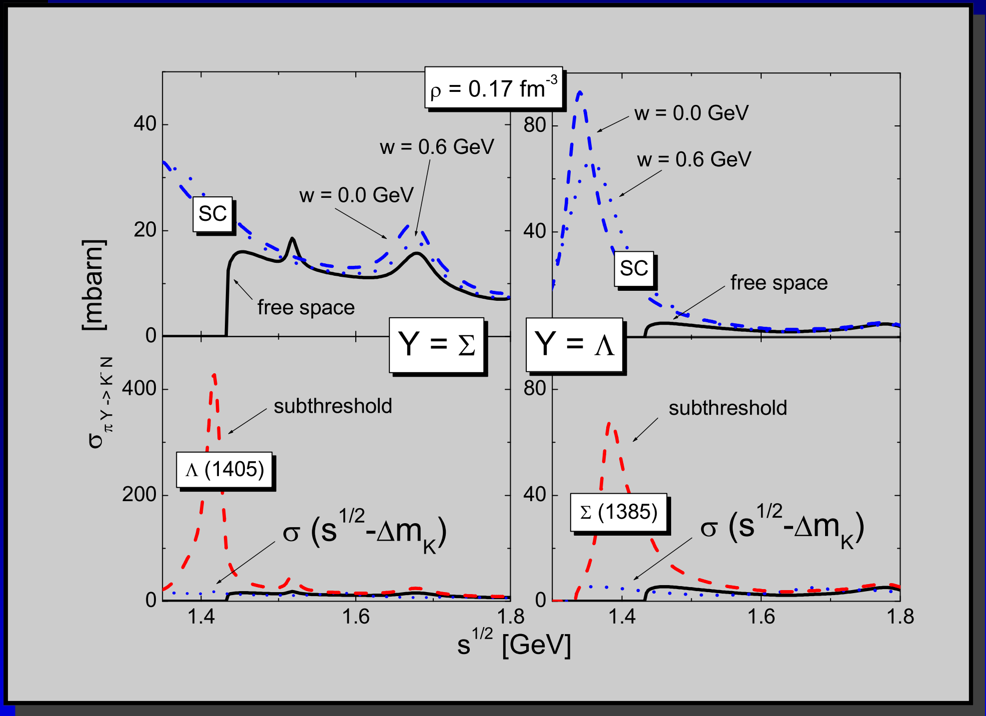

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$\Downarrow$

Use all exp. & theo. hadronic input

Open questions

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- Does it have the right degrees of freedom?
  - $\sqrt{s} < 4$ GeV: nucleons + resonances + mesons
  - $\sqrt{s} > 4$ GeV: hadrons + strings
  - $\sqrt{s} > 130$ GeV: hadrons + strings + partons

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  - $\sqrt{s} < 4$ GeV: nucleons + resonances + mesons
  - $\sqrt{s} > 4$ GeV: hadrons + strings
  - $\sqrt{s} > 130$ GeV: hadrons + strings + partons
- Does it have the right correlations?
  - BUU propagates 1-body distribution, semi-classical Hartree-Fock for 2-body corr., statistical fluctuations
  - QMD propagates N-body distribution, statistical + dynamical fluctuations

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- Mulit-particle scattering ? Usually No!
  detailed balance violated! ($p\bar{p} \rightleftharpoons \pi\pi\pi\pi\pi$ ...)

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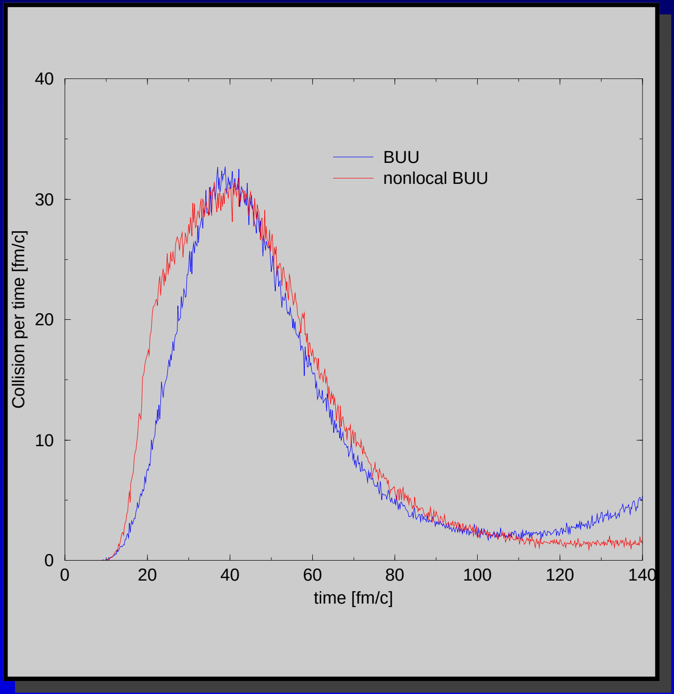
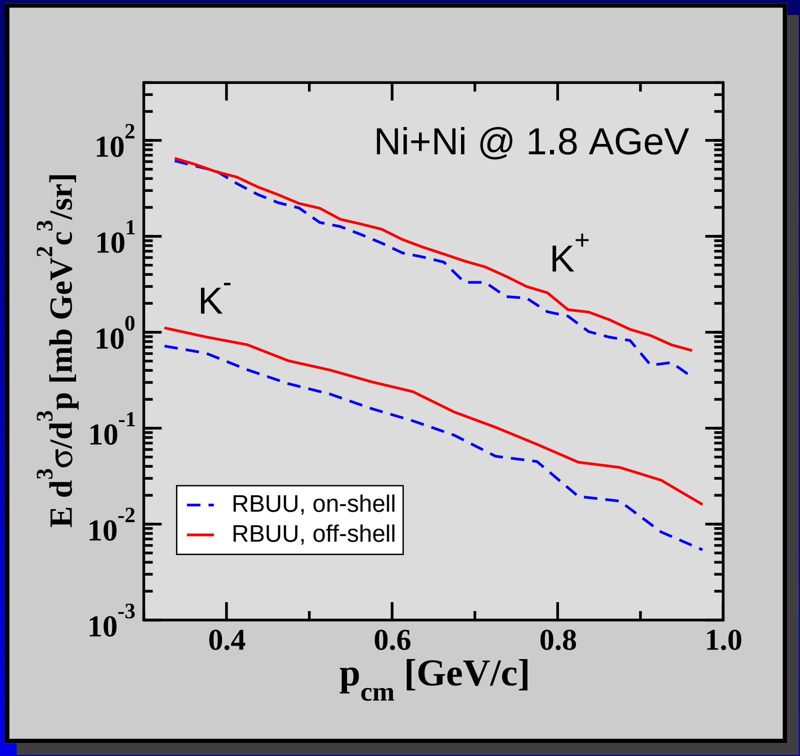
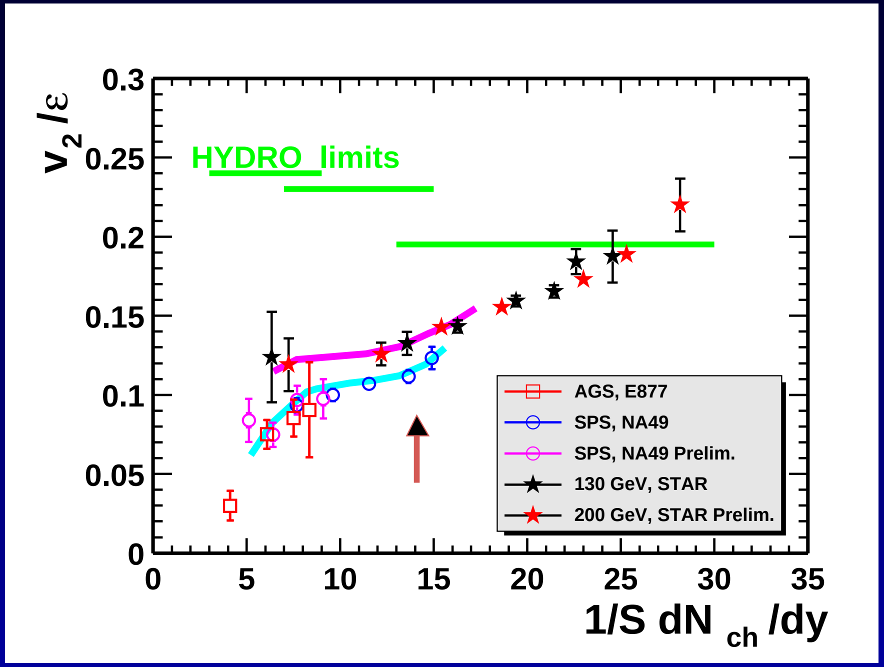




Morawetz et al., PRL 82 (1999) 3767

Cassing et al., NPA 727 (2003) 59.

Does hydro work?



- Hydro limit: $\Longrightarrow v_2 \propto \epsilon$ (= spatial ellipicity of overlapp)
  $\Longrightarrow$ geometry dependence!
- Low density limit: $\Longrightarrow v_2 \propto dN/dy\ S^{-1}$
  $\Longrightarrow$ density dependence!
- multi-fluid hydro?

Comparison of different codes

Workshop on transport models Trento, May 2003:

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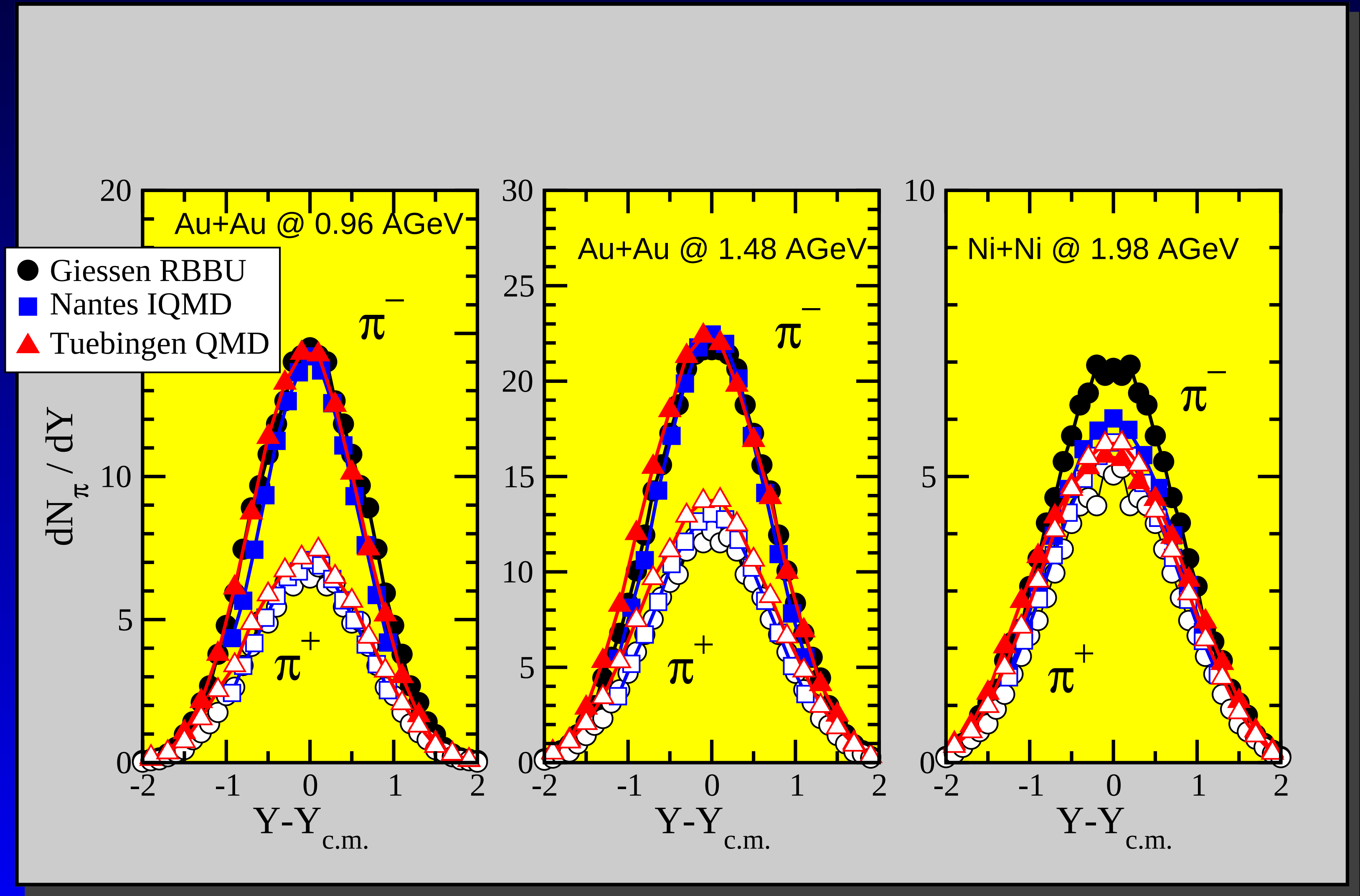

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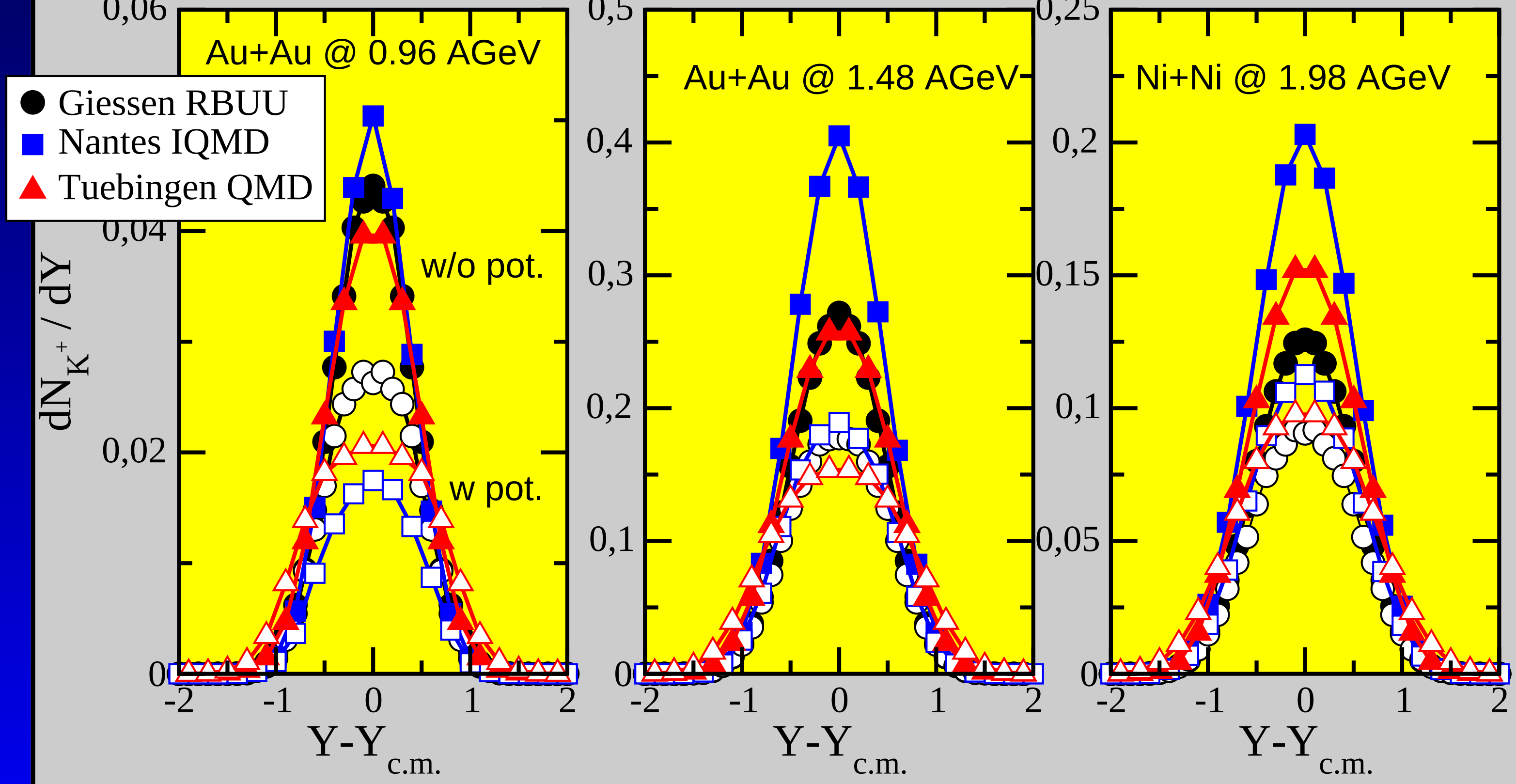
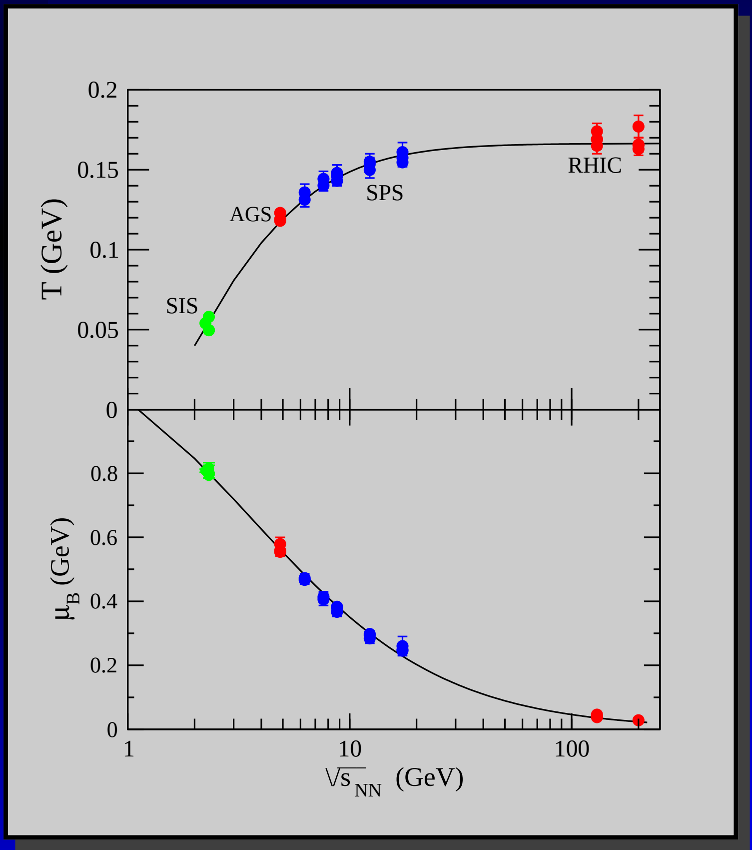


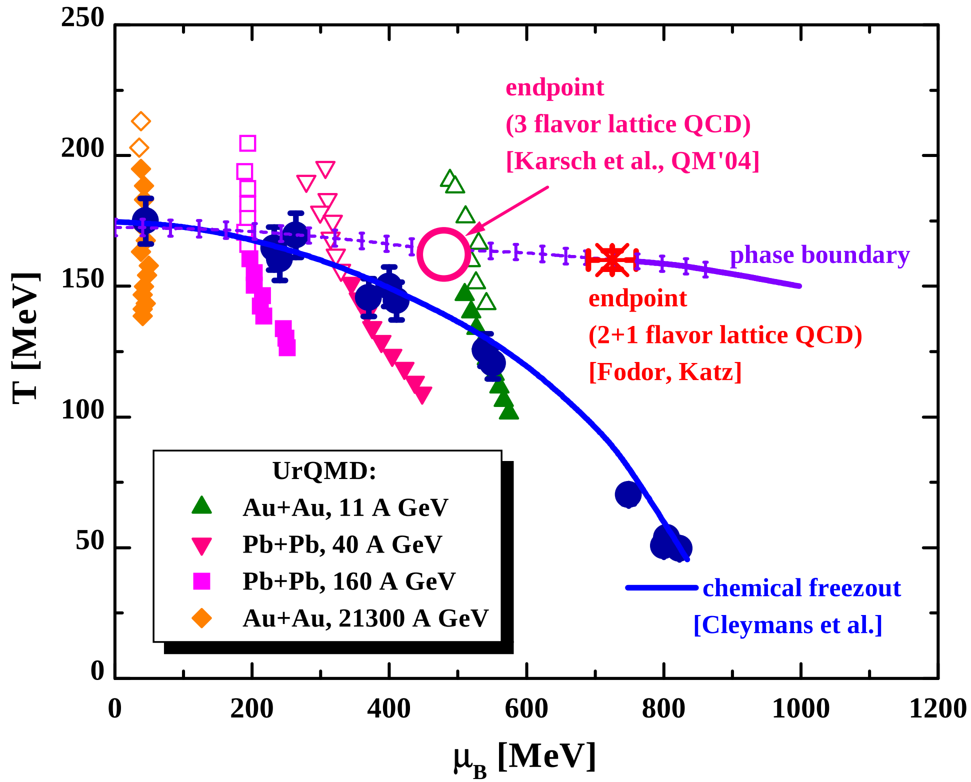
CBM predictions

Statistical model: uniform freeze-out curve at
$E/A \sim 1\ \mathrm{GeVfm}^{-3}$



Cleymans et al.,

hep-ph/0511094



UrQMD: Bratkovskaya et al.,

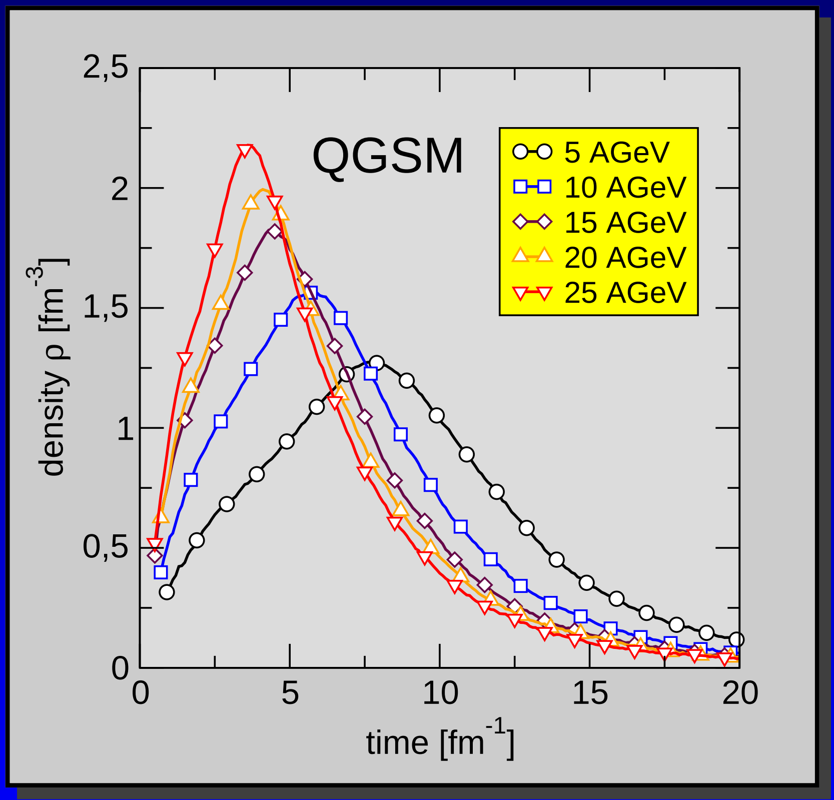
PRC 69 (2004) 054907

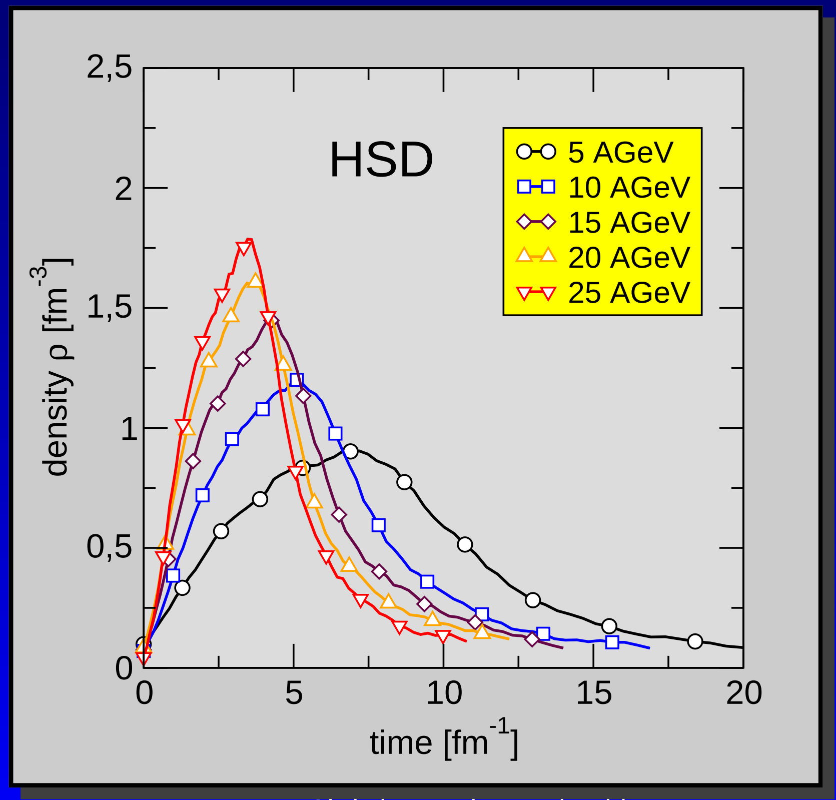
CBM predictions: transport

More by Jorgen Randrup (discussion round)!

Baryon density in central cell (Au+Au, b=0 fm):

- HSD: mean fi eld, hadrons + resonances + strings
- QGSM: Cascade, hadrons + resonances + strings (GRT)

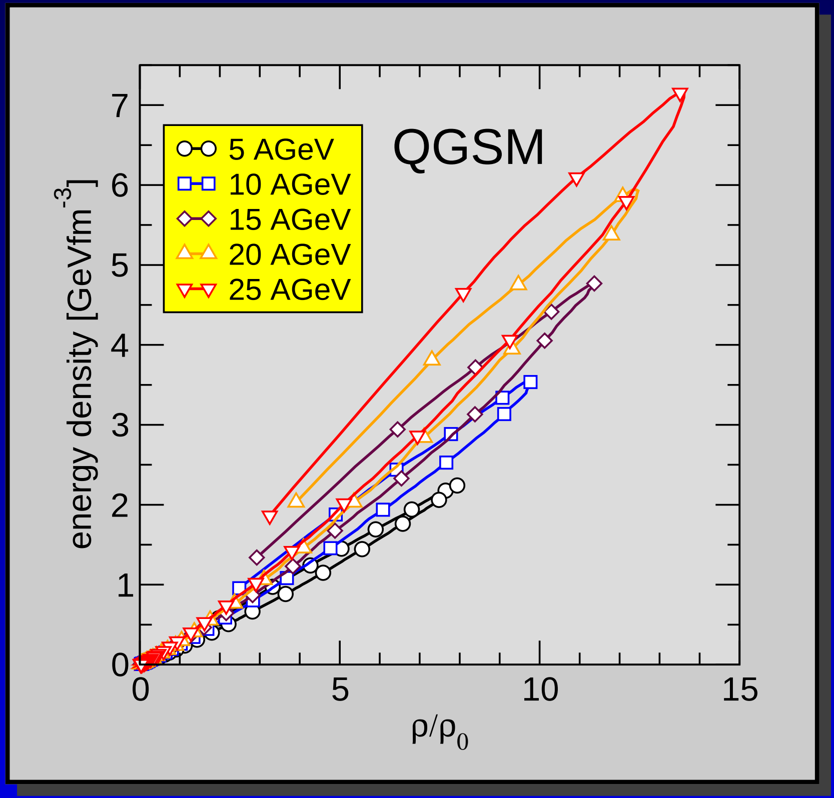


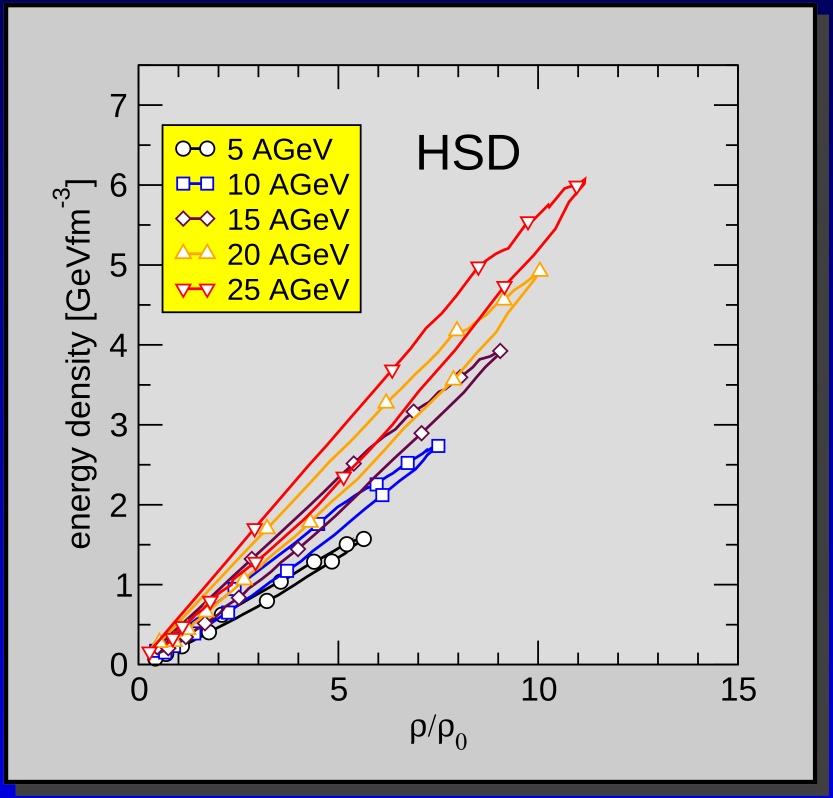


CBM predictions: transport

Trajectories in the $\rho - \epsilon$ plane:

(Au+Au, b=0 fm, central cell)

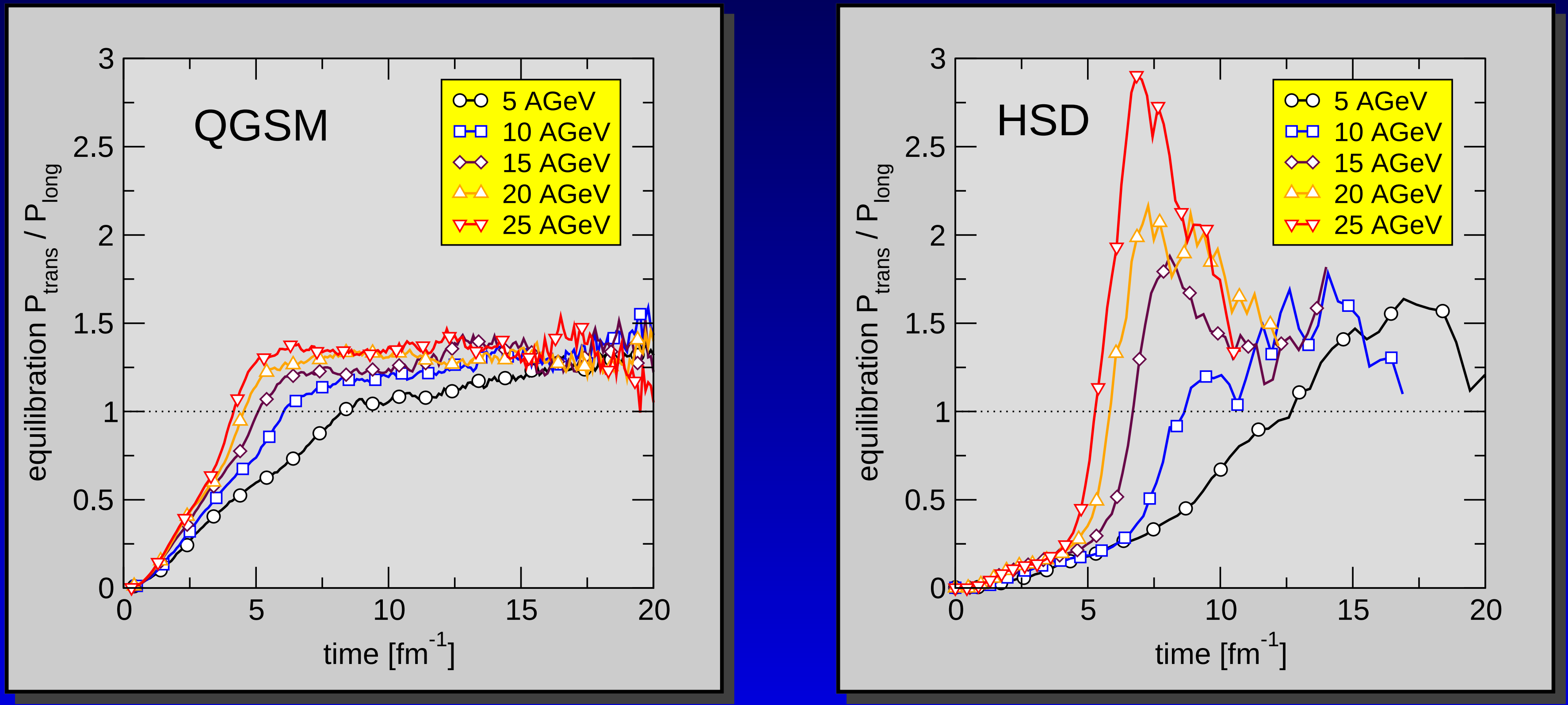




CBM predictions: transport

Equilibration $P_{\mathrm{trans}}/P_{\mathrm{long}}$:

(Au+Au, b=0 fm, central cell)



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- A lot of work to do !!!