Nonequilibrium Green's Functions for Nuclear Physics

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Nonequilibrium Dynamics
in Particle Physics and Cosmology
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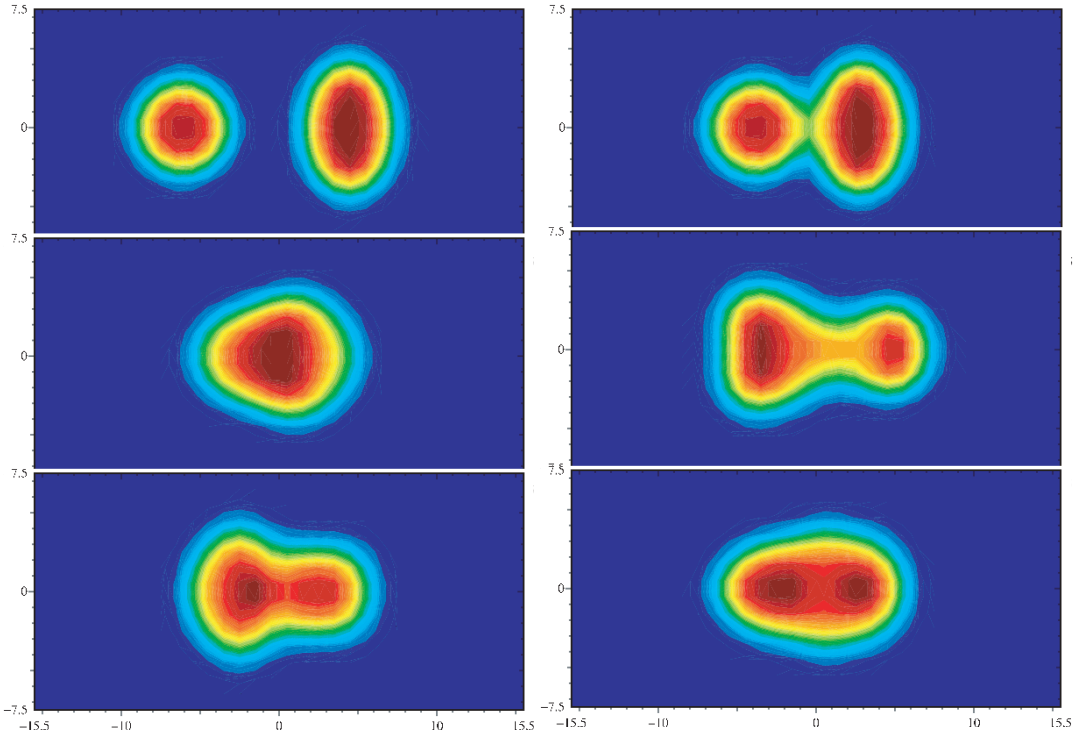
Time-Dependent Hartree-Fock

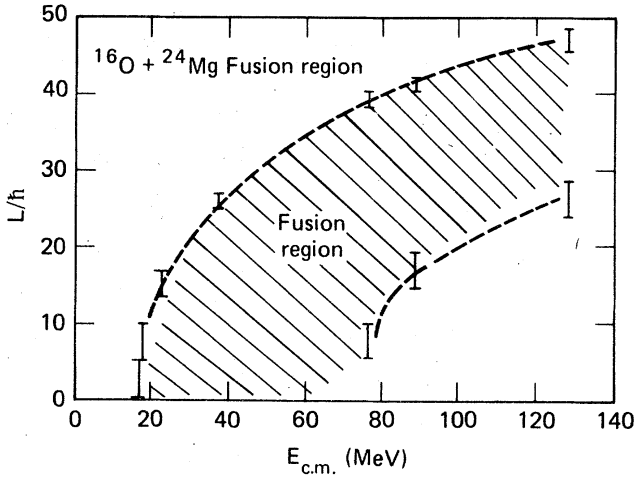
$$i\frac{\partial}{\partial t}\phi_\alpha = -\frac{\nabla^2}{2m}\phi_\alpha + U(\rho(\boldsymbol{r}))\,\phi_\alpha$$

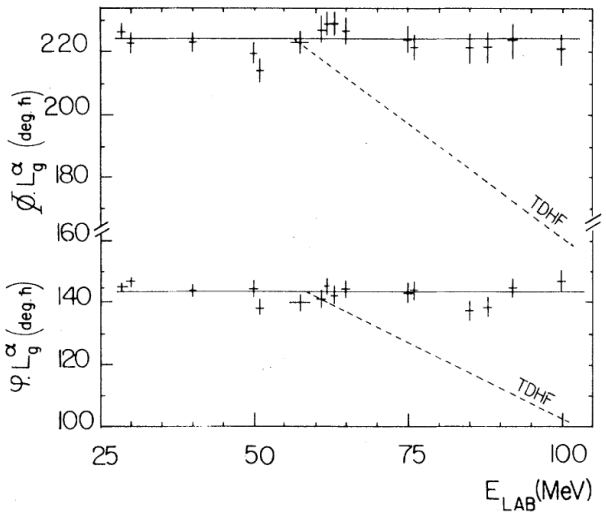


^{16}O+^{22}Ne at 2.5 MeV/nucl

Oberacker&Umar

low-ℓ fusion window as energy increases

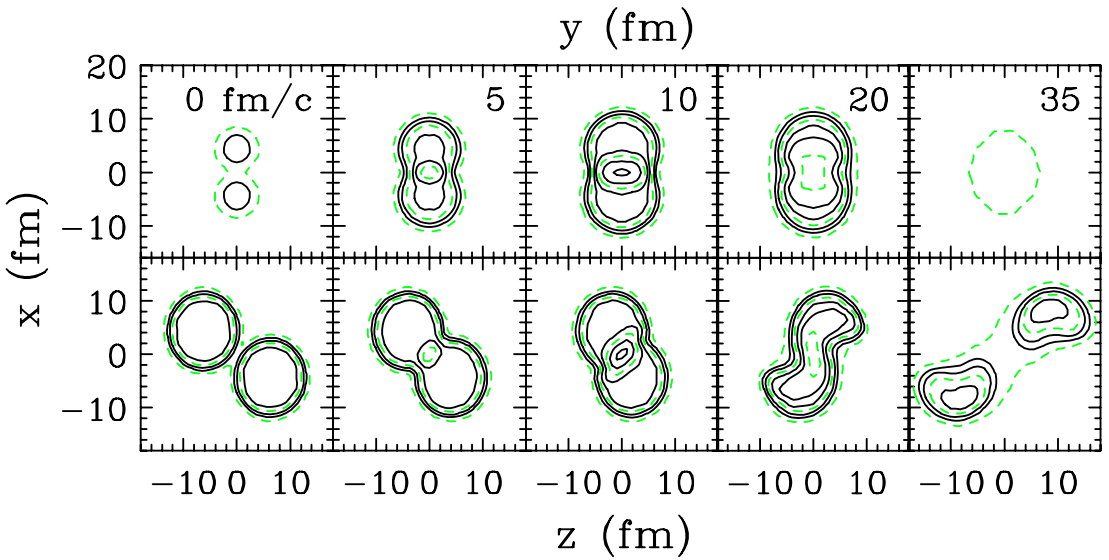




No window in the data!

Boltzmann Equation

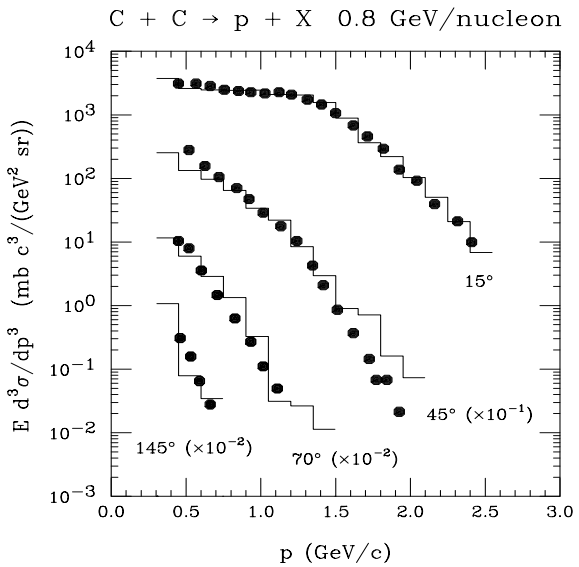
$$\frac{\partial f}{\partial t} + \frac{\partial \omega_{\boldsymbol{p}}}{\partial \boldsymbol{p}} \frac{\partial f}{\partial \boldsymbol{r}} - \frac{\partial \omega_{\boldsymbol{p}}}{\partial \boldsymbol{p}} \frac{\partial f}{\partial \boldsymbol{p}} = I\{f\}$$

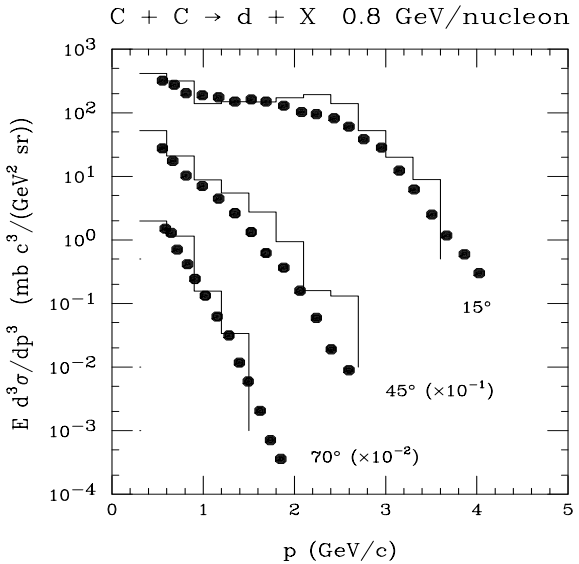


Au+Au at 400 MeV/nucl (PD)

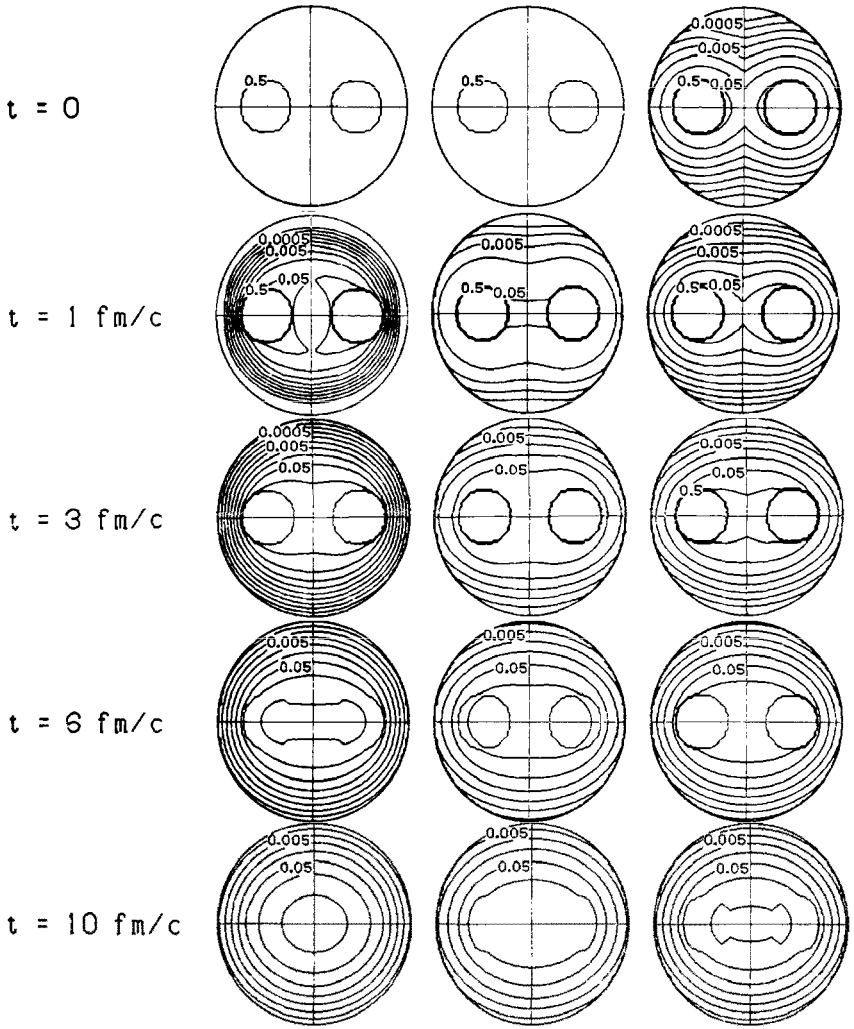
$$f(\boldsymbol{r},\boldsymbol{p},t) \simeq \sum_i \delta(\boldsymbol{r}-\boldsymbol{r}_i(t))\,\delta(\boldsymbol{p}-\boldsymbol{p}_i(t))$$

Test particles: $\dot{\boldsymbol{r}}_i = \frac{\partial \omega_{\boldsymbol{p}}}{\partial \boldsymbol{p}} \qquad \dot{\boldsymbol{p}}_i = -\frac{\partial \omega_{\boldsymbol{p}}}{\partial \boldsymbol{r}}$

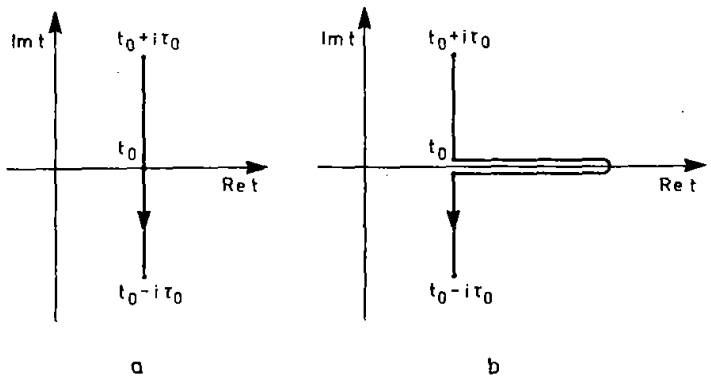




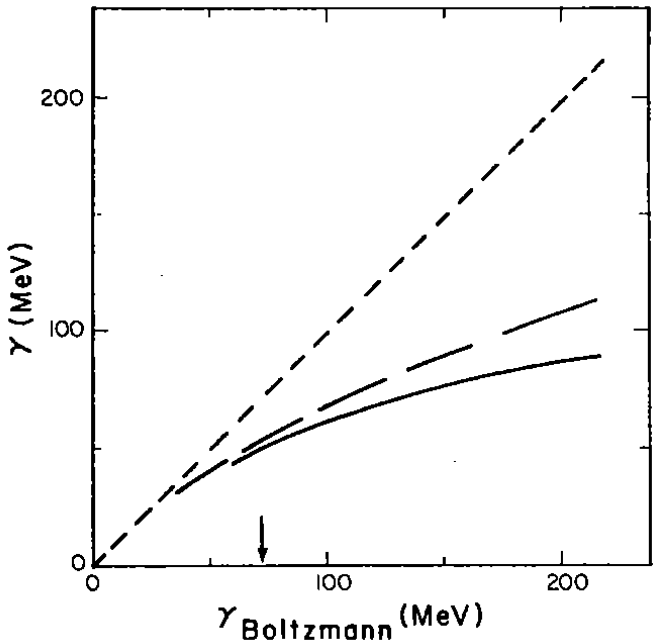
Evolution Comparison



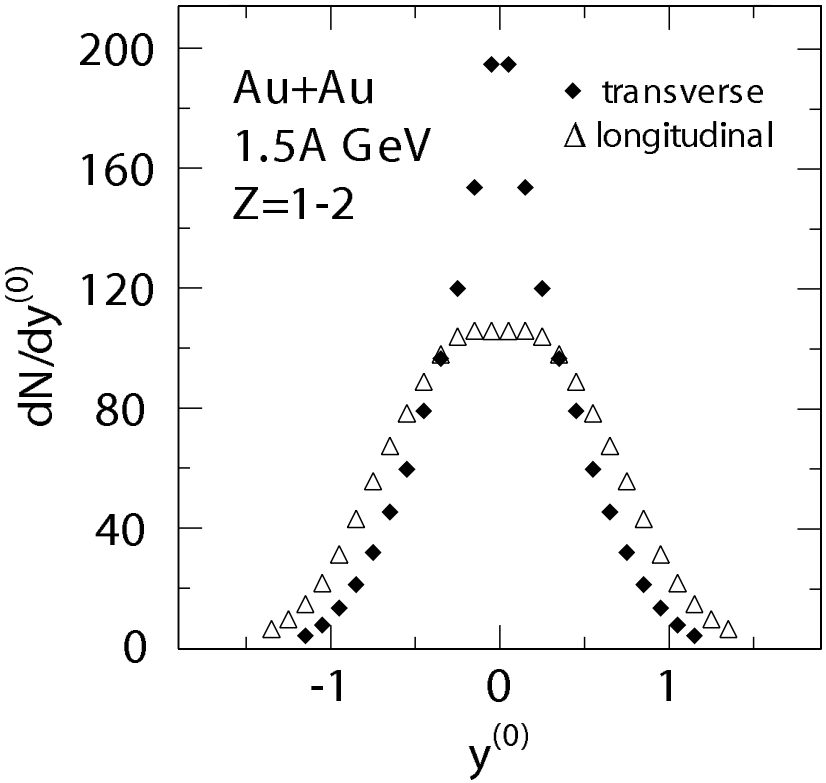
PD



Rate comparison



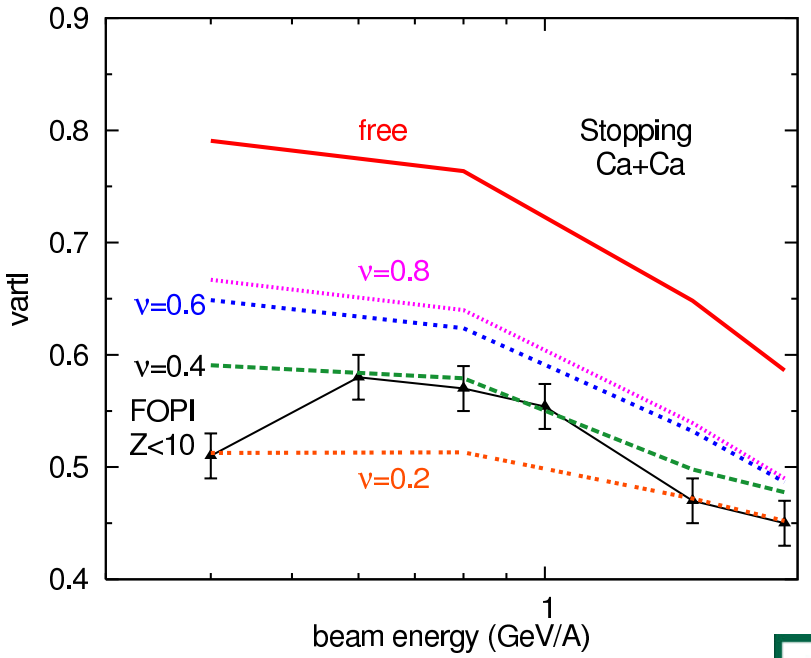
Phenomenology: E.g. Stopping ⇔Viscosity



Rapidity ratio: $vartl = \frac{\Delta y_t}{\Delta y_l}$

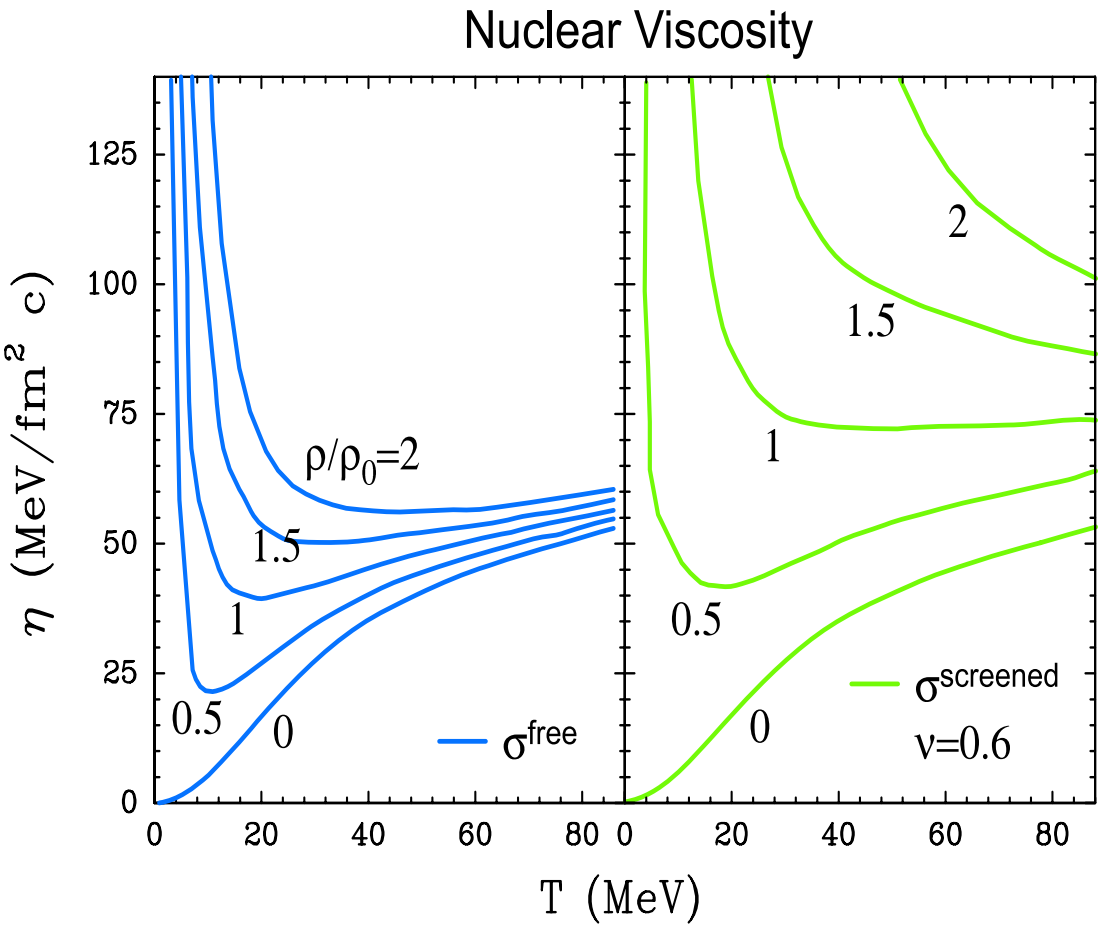
FOPI Reisdorf *et al*

Significant cross-section reduction needed to describe data



Viscosity from Reduced Cross-Sections

PD & Brent Barker: same cross-section $\Leftrightarrow$ same viscosity



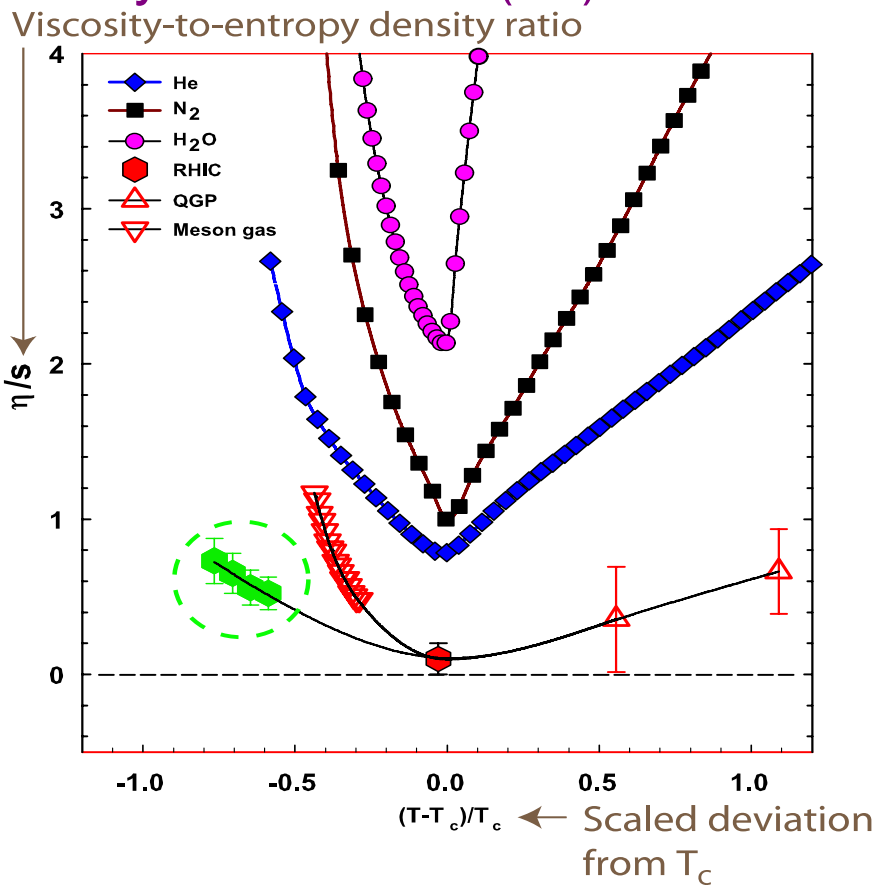
Significant enhancement of the viscosity due to in-medium cross-section reduction.

At $n \sim n_0$,
$\eta \sim 75\,\mathrm{MeV/fm^2}\,c$

Normalized Viscosity

In intermediate-energy reactions, $s/n \equiv S/A =$ (3-4.5), corresponding to $T =$ (40-70) MeV at $n = n_0$, yielding $\eta/s =$ (0.5-0.7)

Lacey *et al* PRL98(07)092301



PD&Gyulassy PRD31(85)53

$$\eta \sim \frac{1}{3} n p \lambda \;\&\; \boxed{p\lambda \geq 1}$$

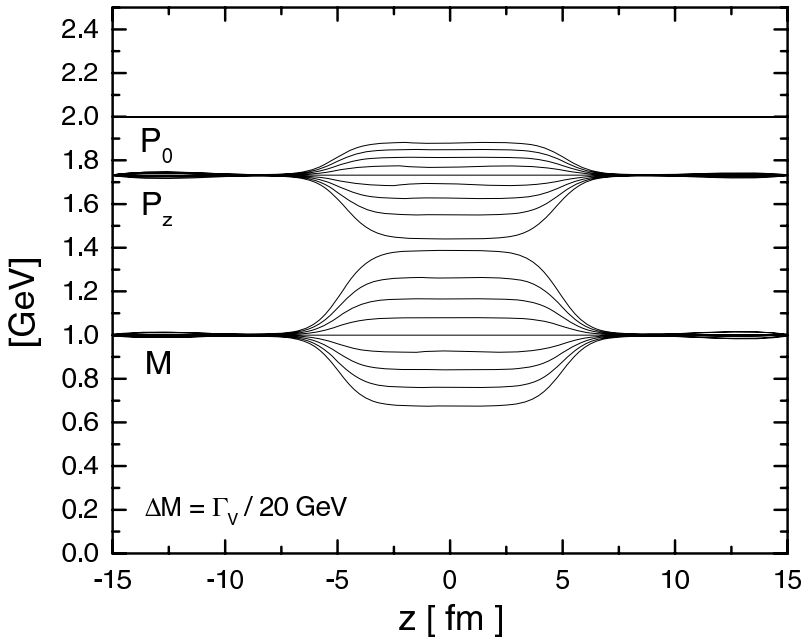
$$\Rightarrow \eta \geq \frac{n}{3} \text{ or } \boxed{\frac{\eta}{s} \geq \frac{1}{12}}$$

with $s = \dfrac{e+P}{T} = 4n$

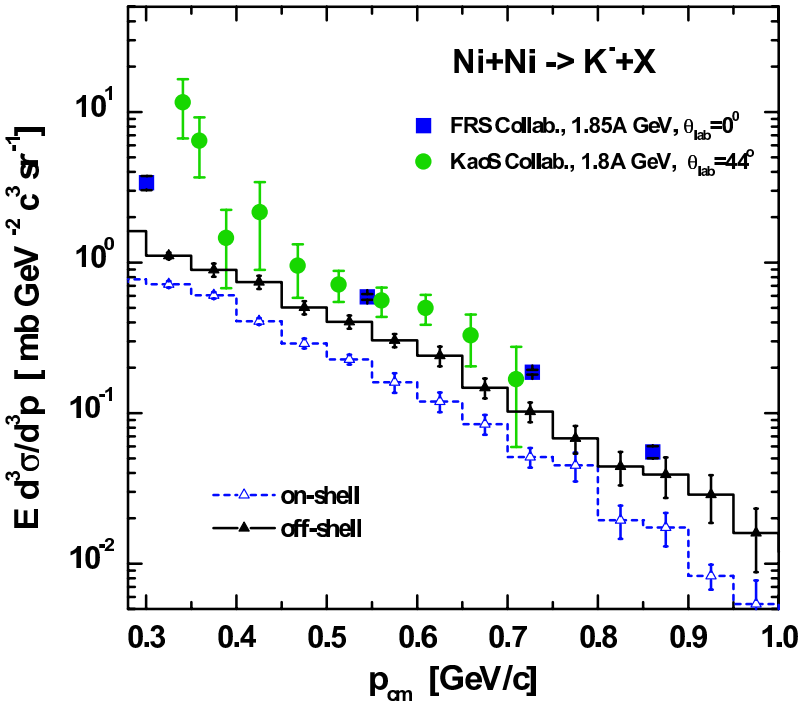
for massless gas

Generalized Boltzmann Equation

Juchem & Cassing

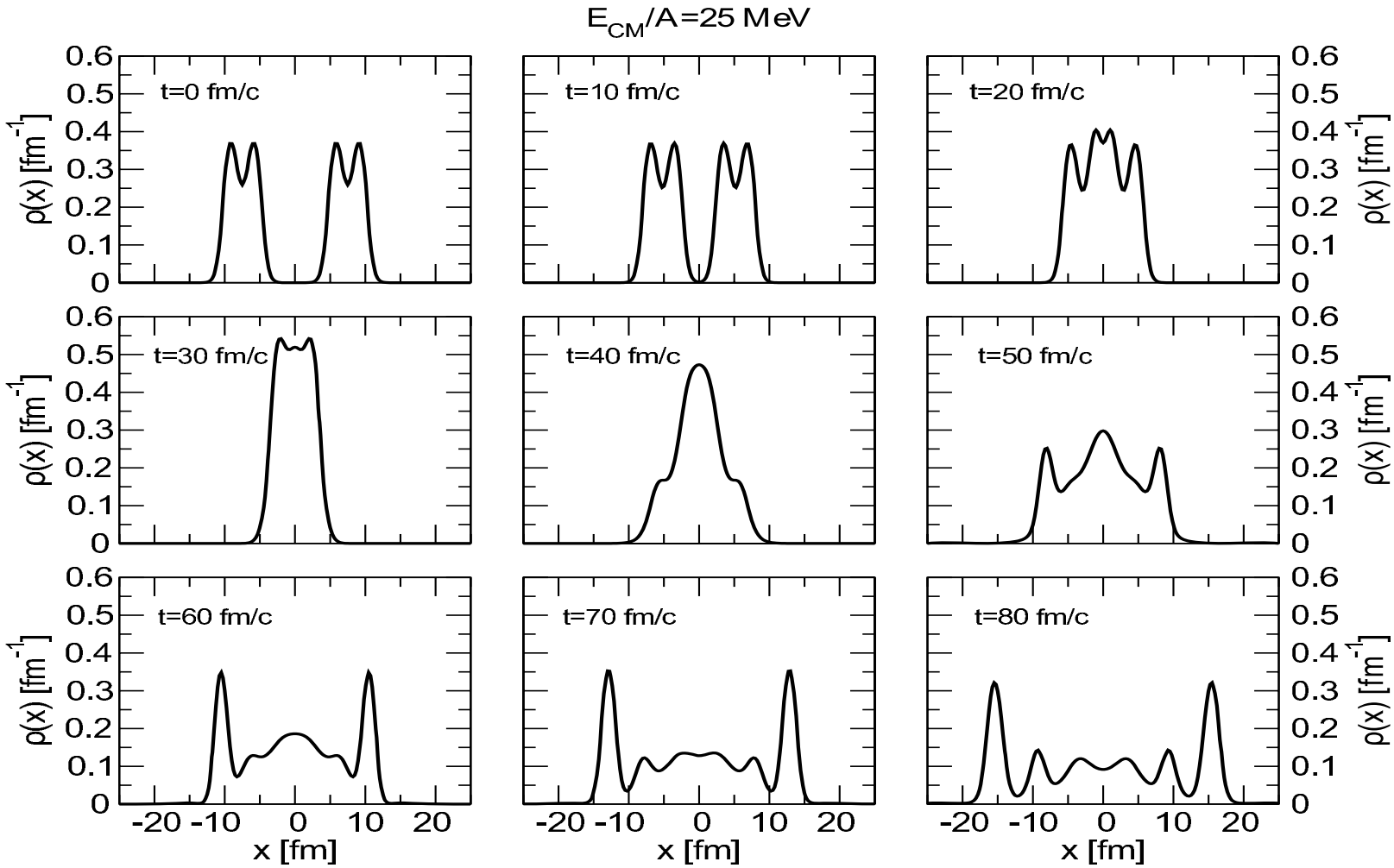


Nucleon incident on complex potential in terms of test-particles



Full-scale reaction-simulation

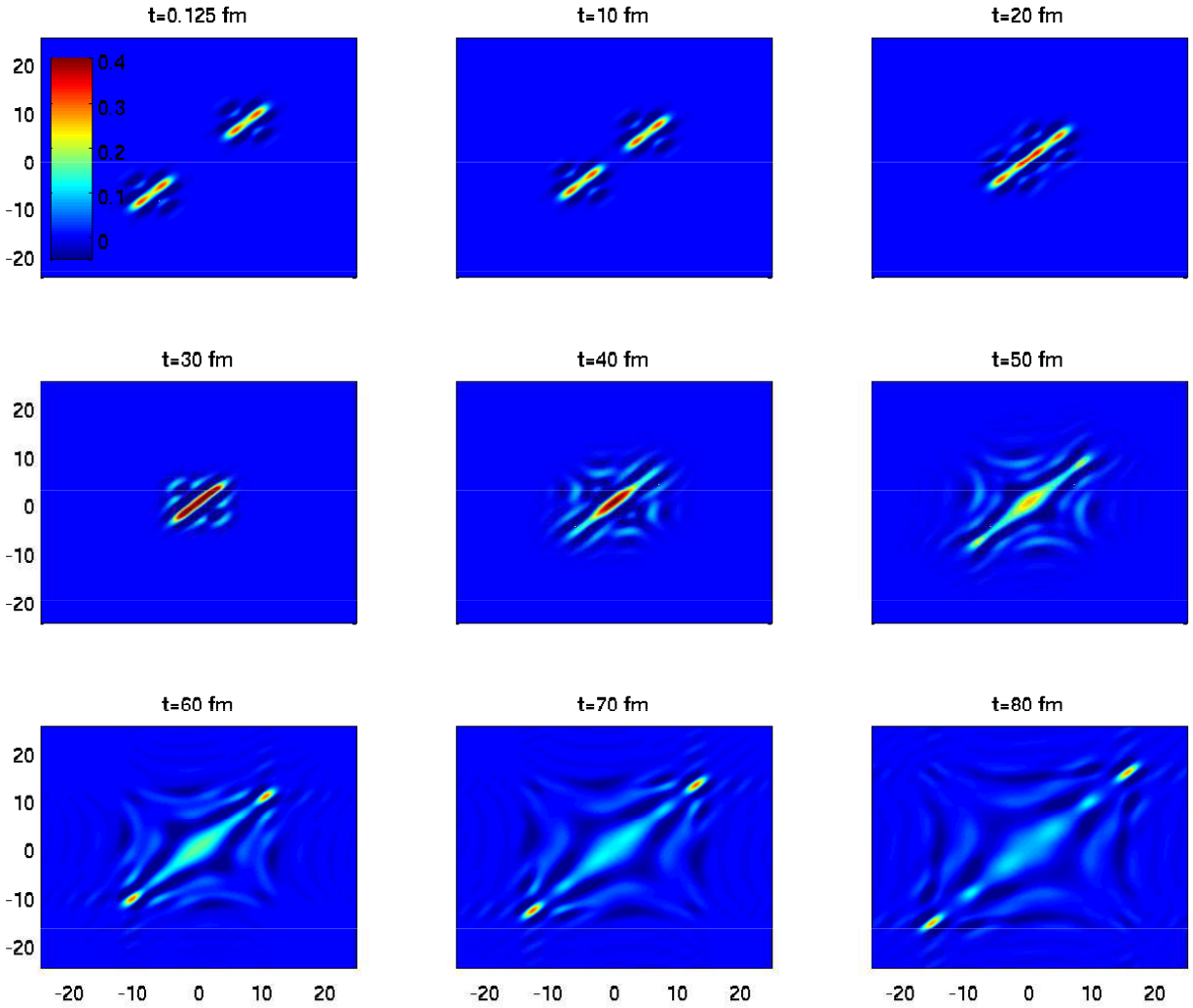
Slab Collisions



density matrix $-iG^<(x, x', t)$ in mean-field dynamics

$\rho(x, t) = -iG^<(x, x, t)$ Rios & PD

$-iG^{<}(x, x', t)$ for Slab Collisions



Diagonal band structure + long-range correlations

Summary

- Low energy: TDHF
- High energy: kinetic *Both Flawed*
- Options:
  - Phenomenology
  - Generalized Boltzmann
  - Nonequilibrium Green's Functions
- Density matrix: short-range + long-range structure
- Otherwise, Green's functions useful as a guidance.