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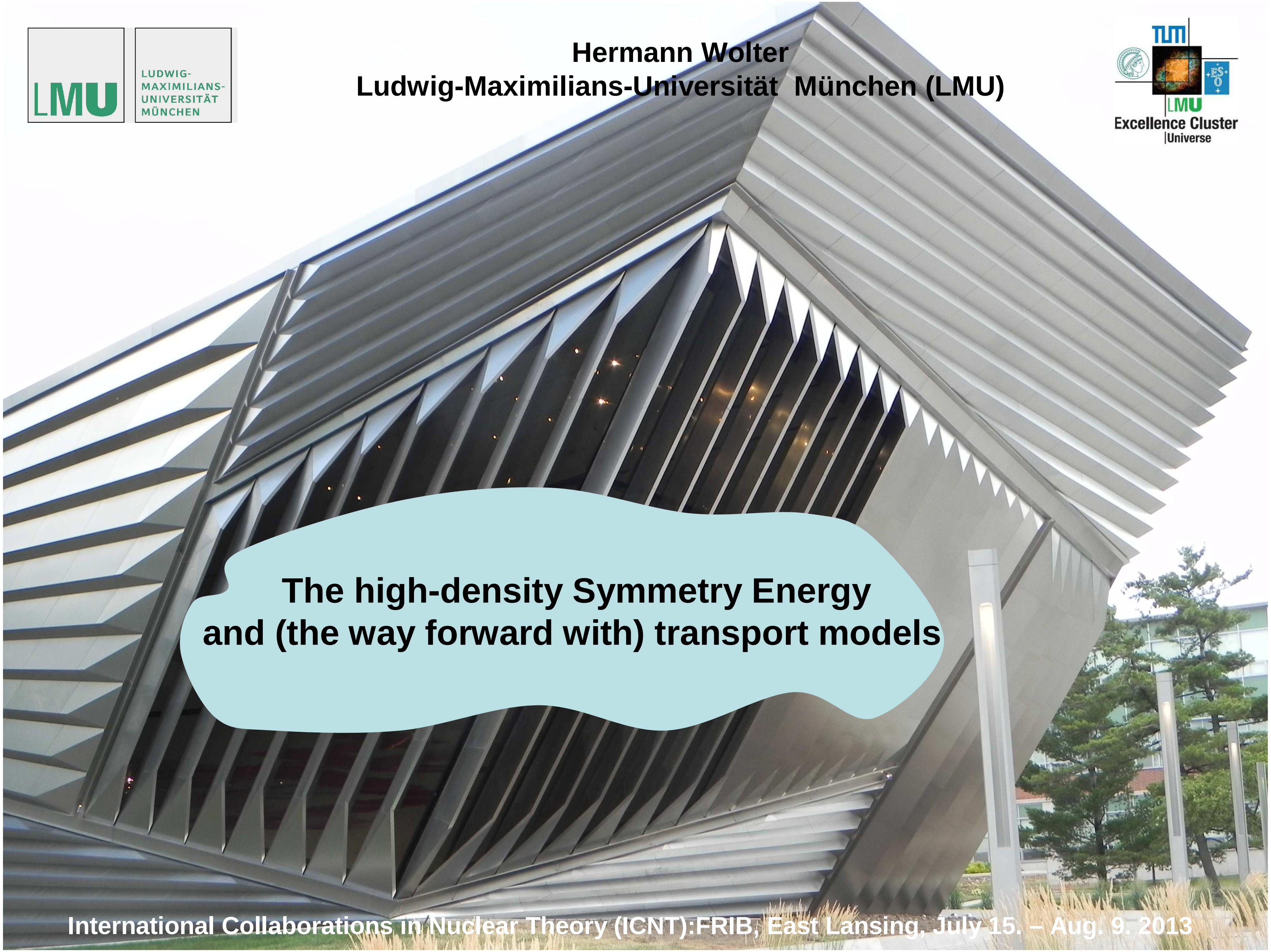


The high-density Symmetry Energy and (the way forward with) transport models

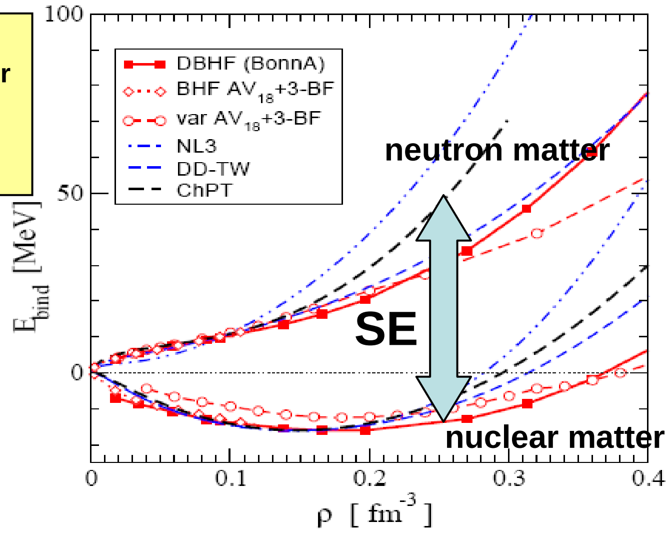
International Collaborations in Nuclear Theory (ICNT):FRIB, East Lansing, July 15. – Aug. 9. 2013

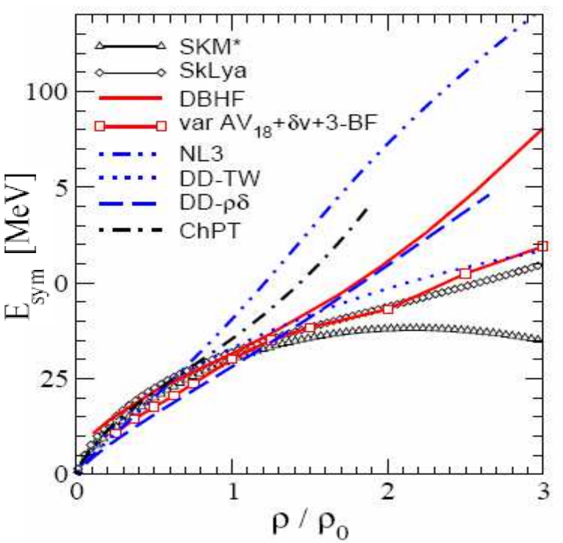
The Nuclear Symmetry Energy (SE) in „realistic“ models

The EOS of symmetric and pure neutron matter in different many-body aproaches

C. Fuchs, H.H. Wolter, EPJA 30 (2006) 5

Rel, Brueckner
Nonrel. Brueckner
Variational
Rel. Mean field
Chiral perturb.





Also momentum dependence of symmetry potential → p/n effective mass splitting

Uncertainity in many-body theory:
→ In-medium ρ mass, and short range isovector tensor correlations (B.A. Li; I. Vidana);

→ Investigate in: - HIC in the laboratory and and interpretation with transport models
- Neutron star observations and modelling of NS structure

Outline:

1. **Probes of the high-density Symmetry energy in HIC:**
   Yvonne Leifels, very extensive overview
   here: Promises and Problems

2. **Transport models**
   Theory and Realizations

3. **Wish list for transport practitioners**

Transport Theory in Heavy Ion Collisions

Transport theory describes the non-equilibrium aspects of the temporal evolution of a collision.

1. **Evolution in coordinate space:**

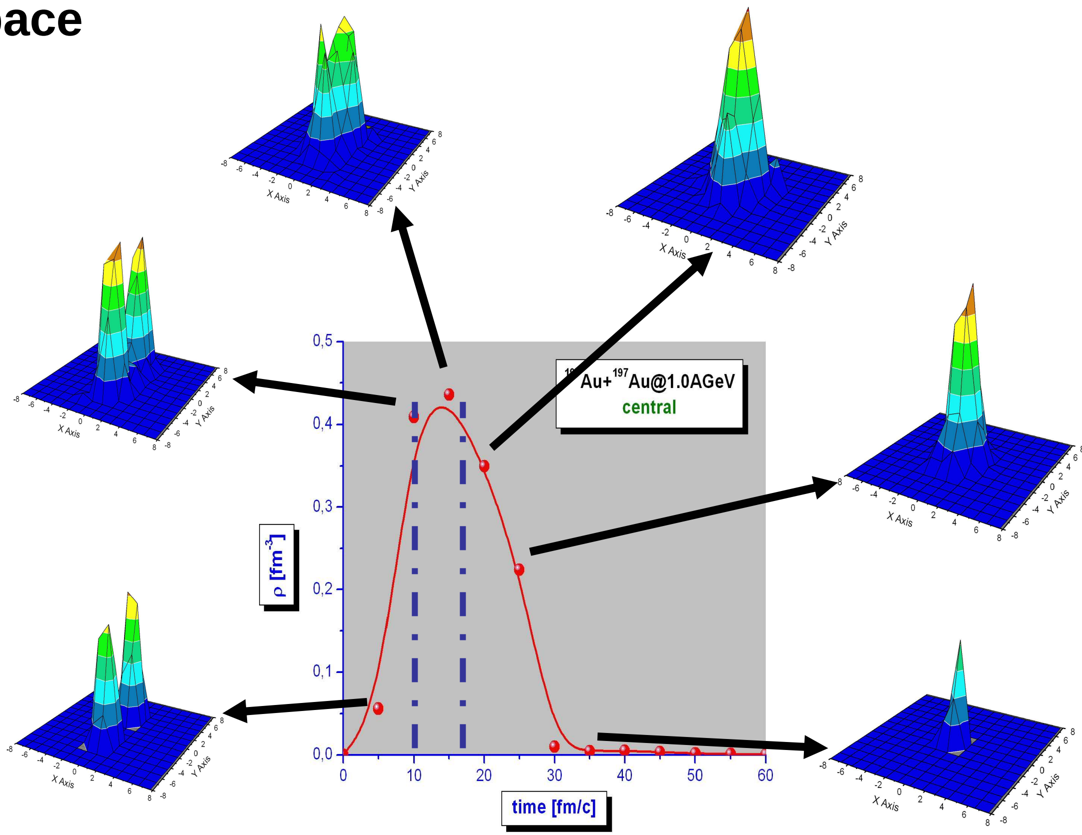
Au+Au, E=1.8AGeV, b=2fm

movie thanks to T. Gaitanos, T.Chossy

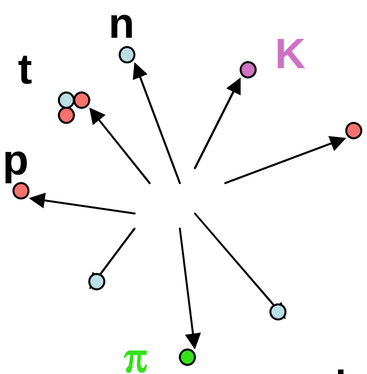
2. **Evolution in momentum space**

Need to go to energies of several 100 AMeV to test high density

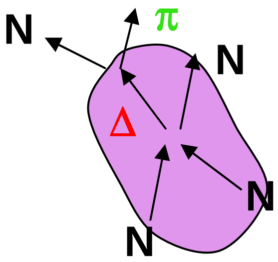
non-equilibrium, non-sphericity of local momentum distributions



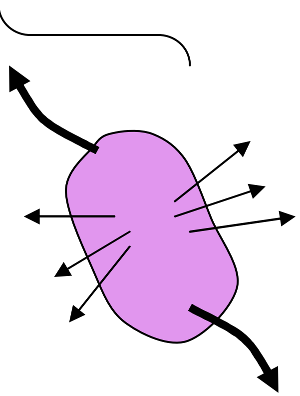
Sketch of reaction mechanism at intermediate energies and observables



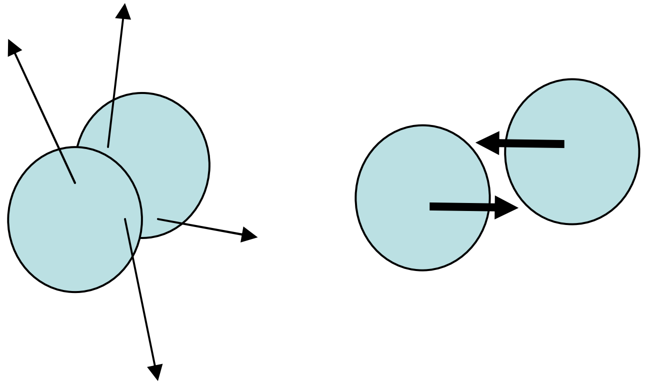
disintegration



Inel.collisions
Particle product.
NN->NΔ–>NΛK
Nπ



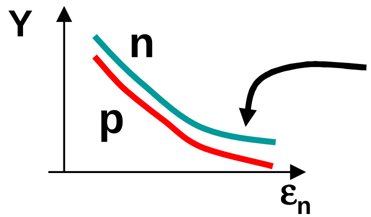
Flow,
In-plane, transverse
Squeeze-out, elliptic



Pre-equilibr emiss.
(first chance,
high momenta)

Yield and spectra of light part.

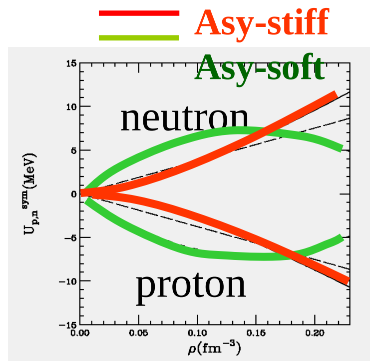
flow



e.g.asy-stiff
n preferential n/p ↑

residual source
more symm. N/Z ↓

Differential p/n
flow (or t/3He)



diff # p,n
(asymmetry of
system)

diff. force on n,p

Pion , kaon production

nn -> Δ^- p
→ $n\pi^-$

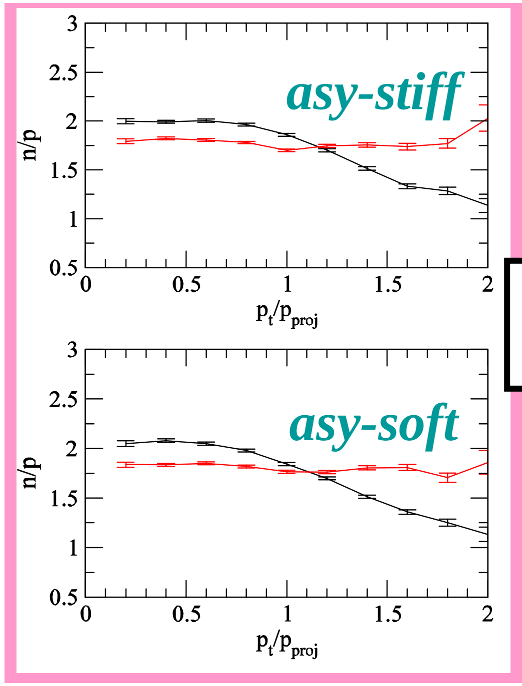
pp -> Δ^{++} n
→ $p\pi^+$

Pre-equilibrium nucleon and light cluster emission

$^{197}Au+^{197}Au$
600 AMeV b=5 fm,
$|y_0|\leq 0.3$

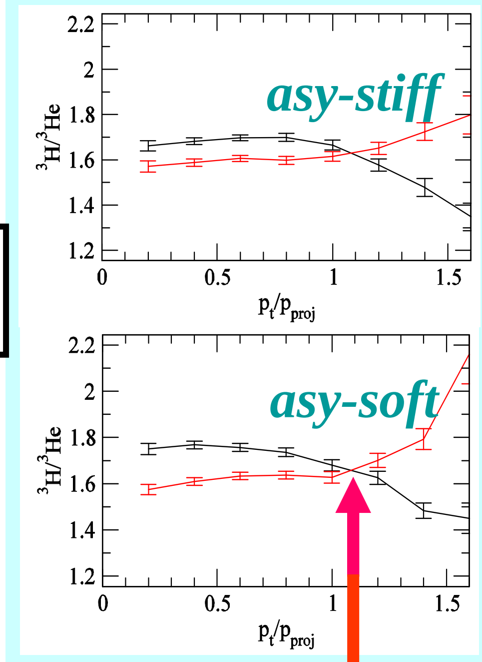
effect of effective mass more prominent than of asy-stiffness

n/p yield ratio



- $m^*_n > m^*_p$
- $m^*_n < m^*_p$

Light isobar $^3H/^3He$ ratio

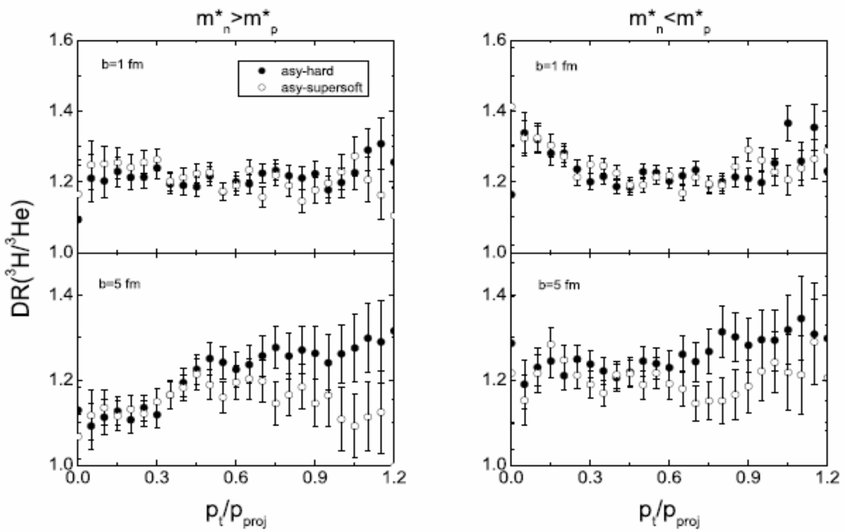


V.Giordano, M.Colonna et al., PRC 81(2010)

Crossing of the symmetry potentials for a matter at $\rho \approx 1.7\,\rho_0$

Double ratios t/3He

197Au+197Au, 400 AMeV



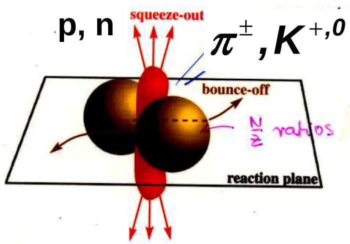
Z.Q. Feng, NPA878, 3 (2012)

Sensitivity more to effective mass than to symmetry energy,

effect of clustering ?

Momentum distributions, "Flow"

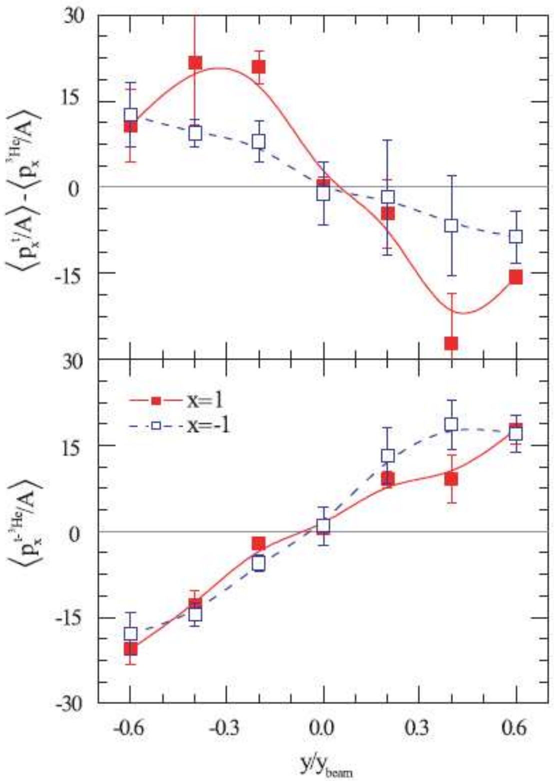
prediction



- **Directed flow** not very sensitive to SE (involves many different densities)

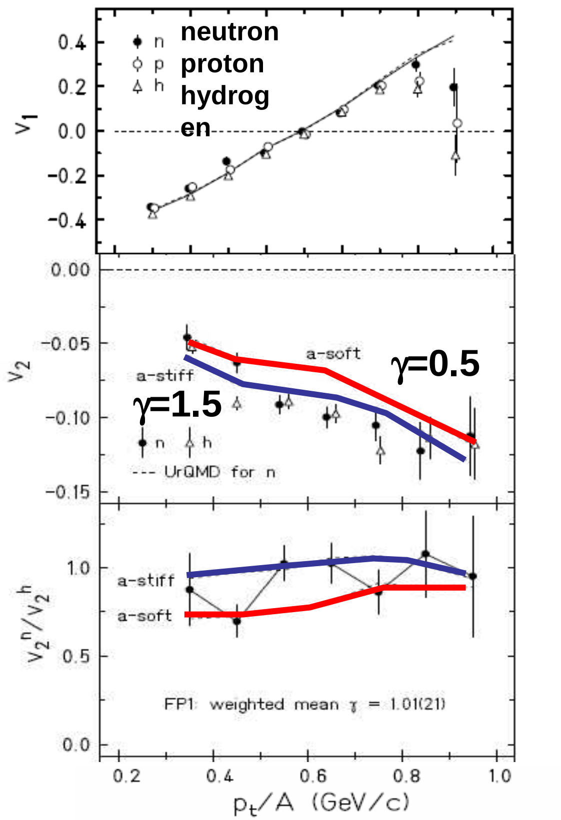
- **Elliptic flow** in this energy region probe of high density

$^{132}Sn+^{124}Sn$, 400 AMeV



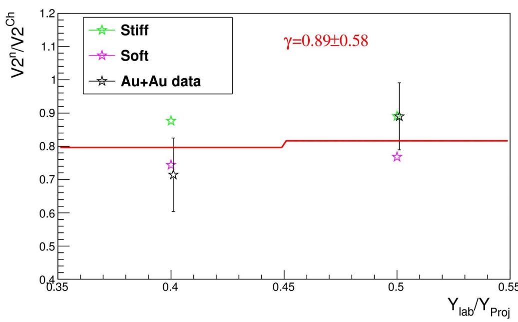
G.C,Yong, et al., PRC80, 044608 (2009)

Au+Au @ 400 AMeV, FOPI-LAND



(Russotto, et al., PLB 697, 471 (11))

preliminary result from new experiment ASY-EOS
(Russotto, Thexo workshop, ECT*, 2013)



not very precise (yet) but indicates rather stiff SE, γ~1

Production of high energy (hard) photons in HIC:

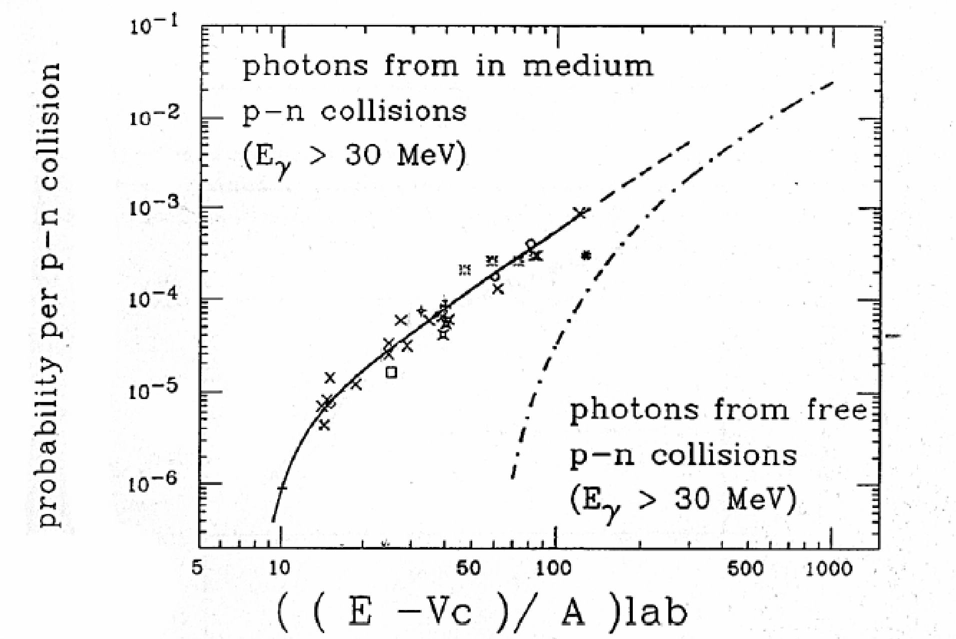


Fig. 8 – Emission probability for photons with E_{γ}>30 MeV per in-medium nucleon-nucleon collisions as a function of the incident energy per nucleon. Vc is the Coulomb barrier [**27**Metag88]

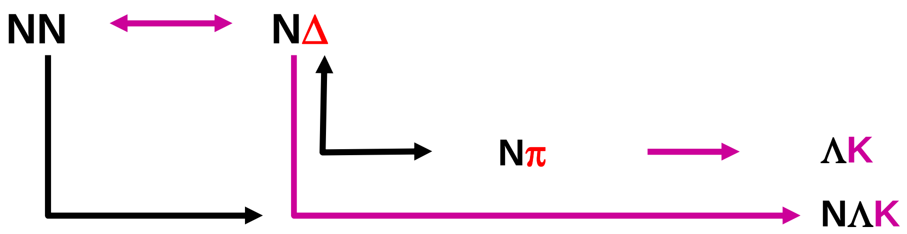
Universal curve, when scaled relative to Coulomb barrier:

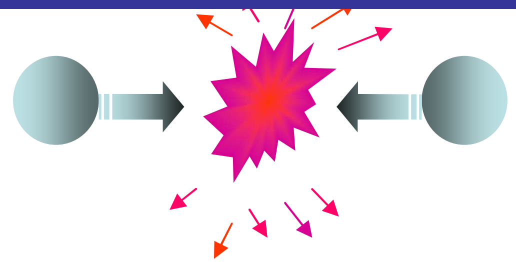
→ First chance pn collisions

→ medium modification of pnγ cross section

Particle Production

„Network“ of reactions, many particles are produced in secondary or ternary reactions.





Inelastic collisions: Production of particles and resonances: Coupled transport equations

e.g. pion and kaon production;

coupling of Δ and strangeness channels via collision term

$$\frac{d}{dt} f_N(x_\mu) = I_{coll}(\sigma_{NN\to NN}, f_N;\ \sigma_{NN\to N\Delta} f_\Delta;....)$$

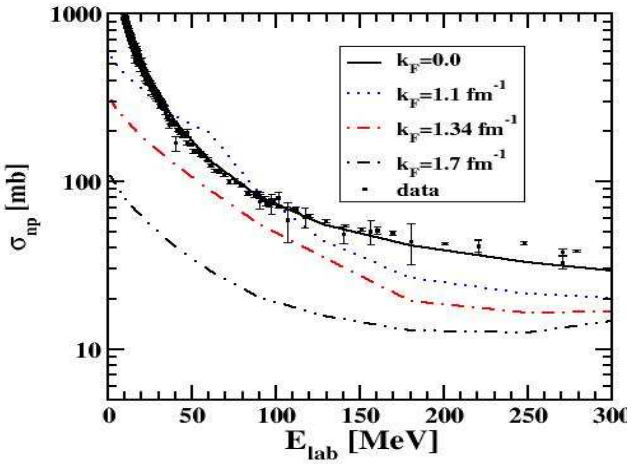
$$\frac{d}{dt} f_\Delta(x_\mu) = I_{coll}(\sigma_{\Delta N\to NYK} f_Y f_K;....)$$

etc.

Elastic baryon-baryon coll.: NN↔NN (in-med. σ_{NN}), NΔ↔NΔ, ΔΔ↔ΔΔ

Inelastic baryon-baryon coll, (*hard* Δ-production): NN↔NΔ, NN↔ΔΔ
Inelastic baryon-meson coll. (*soft* Δ-production): Nπ↔Δ

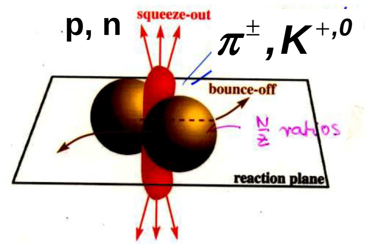
Channels with strangeness (perturbative kaon production):
Baryon-Baryon : BB→BYK (B=N,$\Delta^{\pm,0,++}$, Y=Λ,$\Sigma^{\pm,0}$, K=$K^{0,+}$)
Pion-Baryon : πB→YK (strangeness exchange)
Kaon-Baryon : BK→BK (elastic, isospin exchange)
Different parametrizations

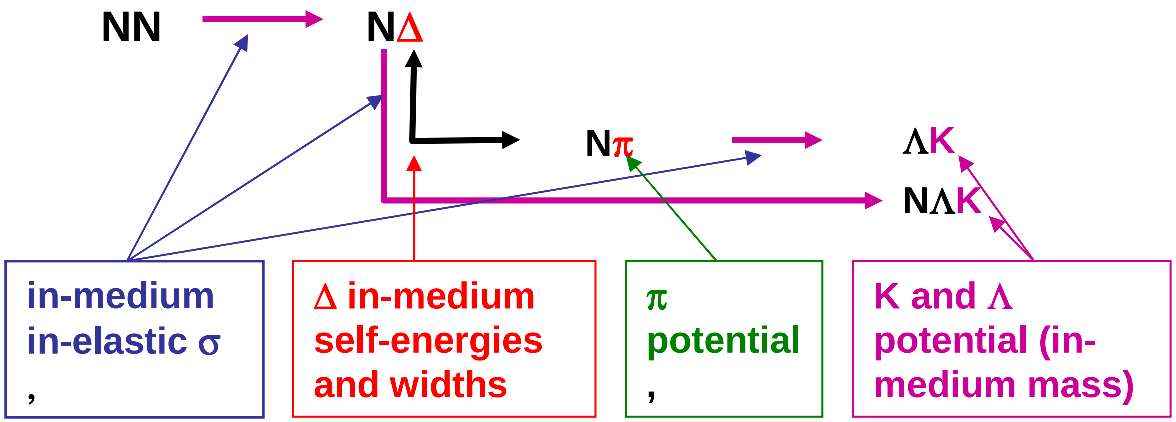


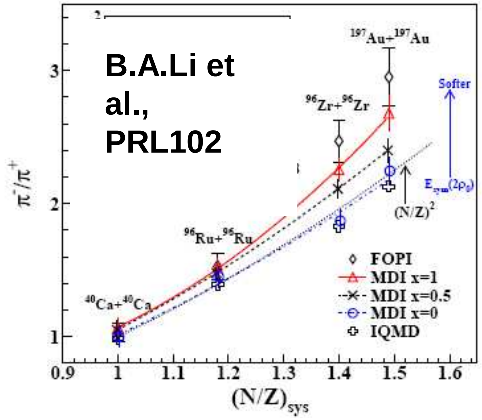
Particle production as probe of symmetry energy

Difference in neutron and proton potentials

1. „direct effects“: difference in proton and neutron (or light cluster) emission and momentum distribution
2. „secondary effects“: production of particles, isospin partners $\pi^{-,+}$, $K^{0,+}$







Two limits:

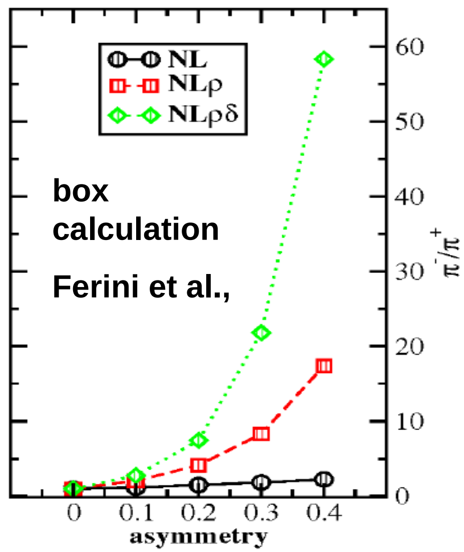
1. isobar model (yield determined by CG-Coeff of Δ->Nπ

$$\pi^- / \pi^+ = \frac{5N^2 + NZ}{5Z^2 + NZ} \approx \left(\frac{N}{Z}\right)^2$$

2. chemical equilibrium

$$\pi^- / \pi^+ \propto exp \frac{2(\mu_n - \mu_p)}{T} = exp \frac{8\delta E_{sym}(\rho)}{T}$$

-> in principle π–/π+ hould be a good probe!



Particle production as probe of symmetry energy

Two effects:

G.Ferini et al.,PRL 97 (2006) 202301

1. Mean field effect: U_{sym} more repulsive for neutrons, and more for asystiff
→ pre-equilibrium emission of neutron, reduction of asymmetry of residue

$$\frac{n}{p}\downarrow \Rightarrow \frac{Y(\Delta^{0,-})}{Y(\Delta^{+,++})}\downarrow \Rightarrow \frac{\pi^-}{\pi^+}\downarrow$$

decrease with asy – stiffness

2. Threshold effect, in medium effective masses:

Canonical momenta have to be conserved. To convert to kinetic momenta, the self energies enter

$$I_{coll} = \int d\vec{v}_2\, d\vec{v}_{1'} d\vec{v}_{2'} v_{12} \sigma_{inel}(\Omega)(2\pi)^3 \delta(p_1 + p_2 - p_{1'} - p_{2'})$$
$$\times \left[f_{1'} f_{2'}(1-f_1)(1-f_2) - f_1 f_2 (1-f_{1'})(1-f_2')\right]$$

In inelastic collisions, like nn->pΔ⁻, the selfenergies may change. Simple assumption about self energies of Δ..

$$\Sigma_i(\Delta^-) = \Sigma_i(n),$$
$$\Sigma_i(\Delta^0) = \frac{2}{3}\Sigma_i(n) + \frac{1}{3}\Sigma_i(p),$$
$$\Sigma_i(\Delta^+) = \frac{1}{3}\Sigma_i(n) + \frac{2}{3}\Sigma_i(p),$$
$$\Sigma_i(\Delta^{++}) = \Sigma_i(p),$$

Yield of pions depends on

$$\sigma = \sigma_{inel}\left(\sqrt{s_{in}} - \sqrt{s_{in}}\right)$$

Detailed analysis gives

$$\frac{\pi^-}{\pi^+}\uparrow \textit{ increase with asy – stiffness}$$

Competing effects!
Not clear, how taken into account in all studies
Assumptions may also be too simple.

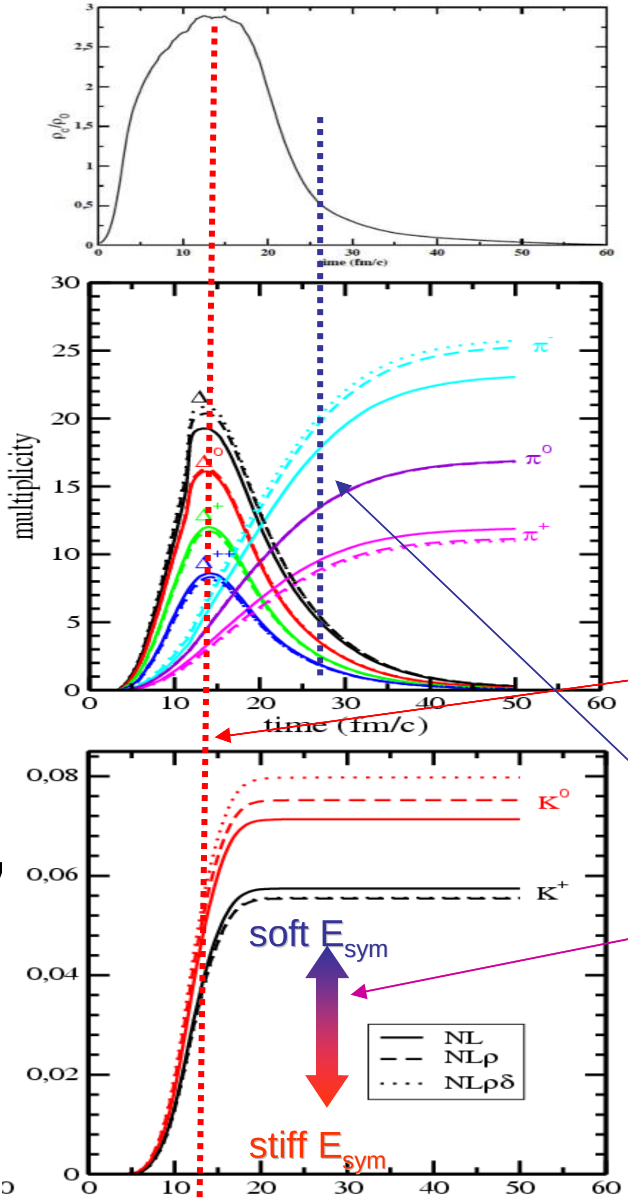
Dynamics of particle production (Δ,π,K) in heavy ion collisions

Au+Au@1AGeV

Central density

π and Δ multiplicity

$K^{0,+}$ multiplicity



→ time [fm/c]

Dependence of ratios on asy-stiffness

n/p

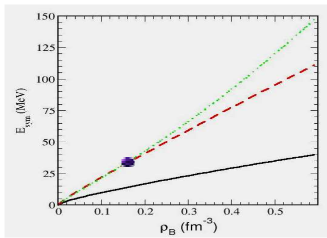
→ $\Delta^{0,-}/\Delta^{+,++}$

→ π^-/π^+

Δ and K: production in high density phase

Pions: low and high density phase

Sensitivity to asy-stiffness

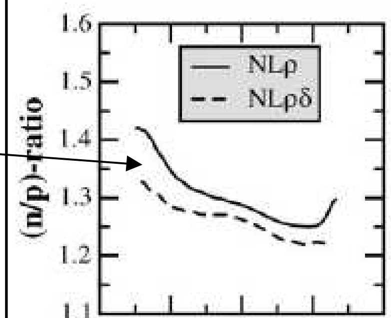


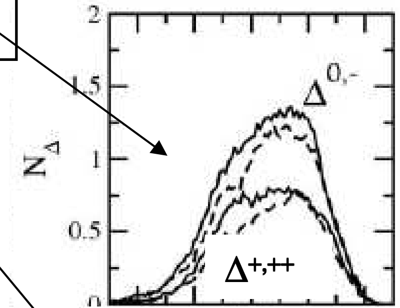
NLρδ

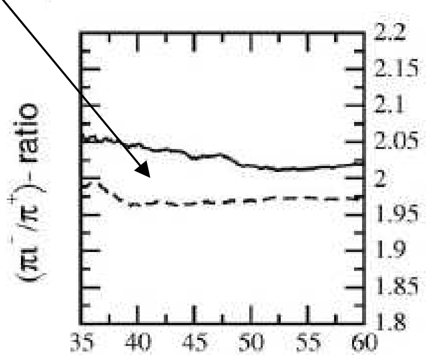
NLρ

NL

Au+Au, 0.6AMeV







time [fm/c]

G.Ferini et al.,PRL 97 (2006) 202301

Pion ratios in comparison to FOPI data

Au+Au, semi-central

- MDI, x=0, mod. soft } Xiao,.. B.A.Li, PRL 102 (09)
- MDI, x=1, very soft }
- NLρδ, stiff } Ferini, Gaitanos,.. NPA 762 (05)
- NLρ, linear }
- γ=2, stiff } Feng,… PLB 683 (10)
- SIII, very soft }
- small dep. on SE — J. Hong, P.Danielewicz
- FOPI exp (NPA 781, 459 (07))

Possible causes:

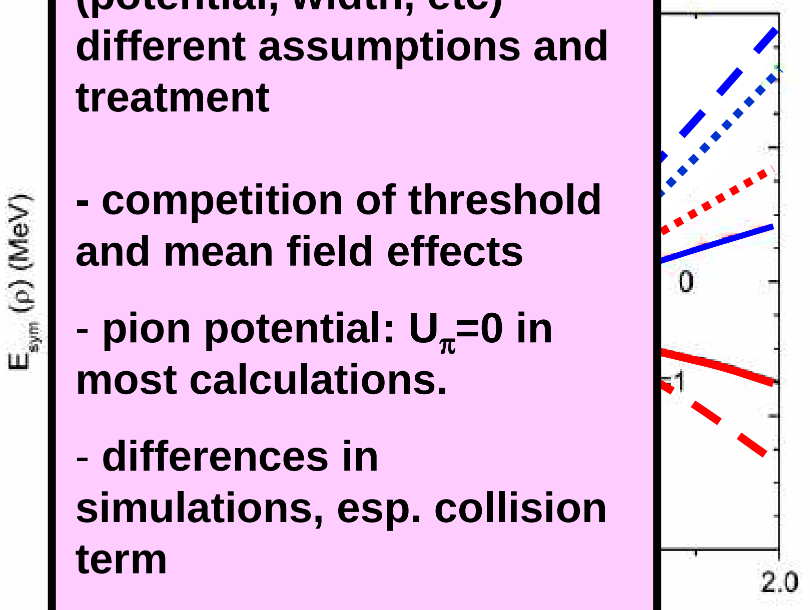
- pion are created via Δ's. Δ dynamics in medium (potential, width, etc) different assumptions and treatment

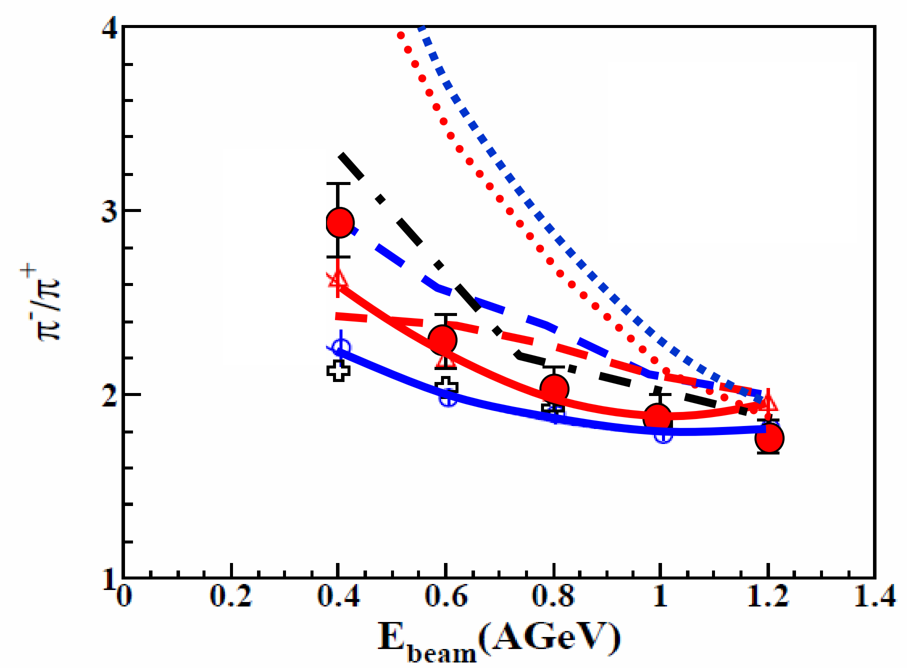
- competition of threshold and mean field effects

- pion potential: $U_\pi=0$ in most calculations.

- differences in simulations, esp. collision term

- Urgent problem to solve!!!

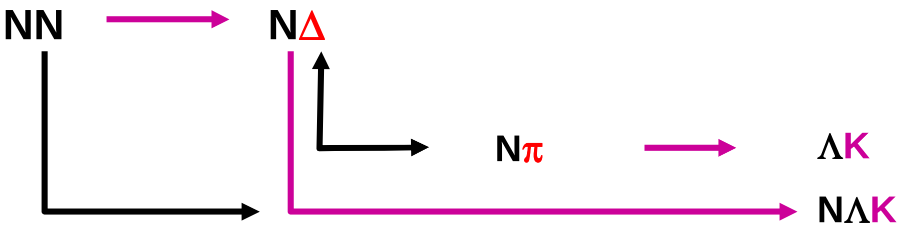




Contradictory results, trend with asy-stiffness differs

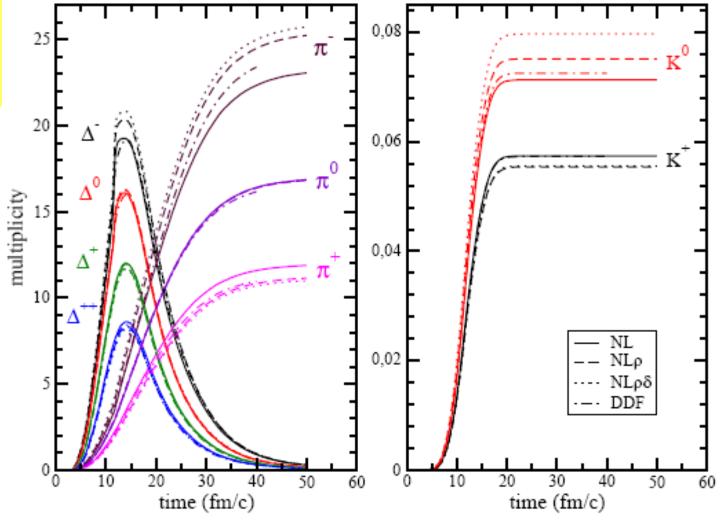
Kaon production as a probe for the EOS

Subthreshold, E_{th}=1.58 MeV

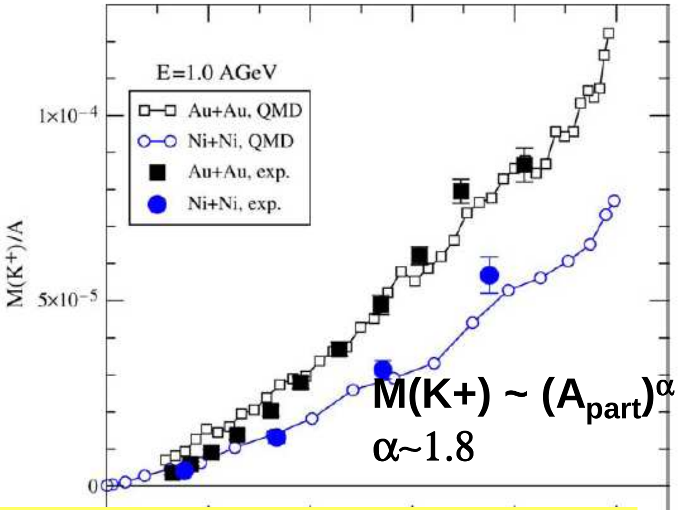


Two-step process dominant

In havier systems. Collective effect



messengers from the high density phase



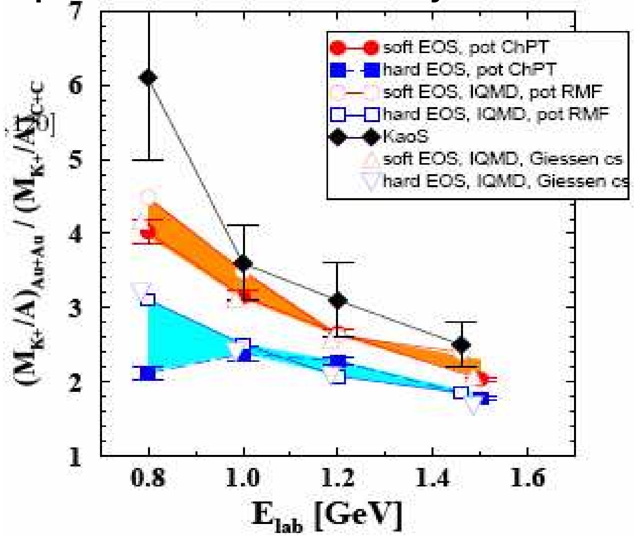
$M(K+) \sim (A_{part})^{\alpha}$

$\alpha \sim 1.8$

$\alpha>1$: evidence of two-step process

C. Fuchs / Progress in Particle and Nuclear Physics 56 (2006) 1–103

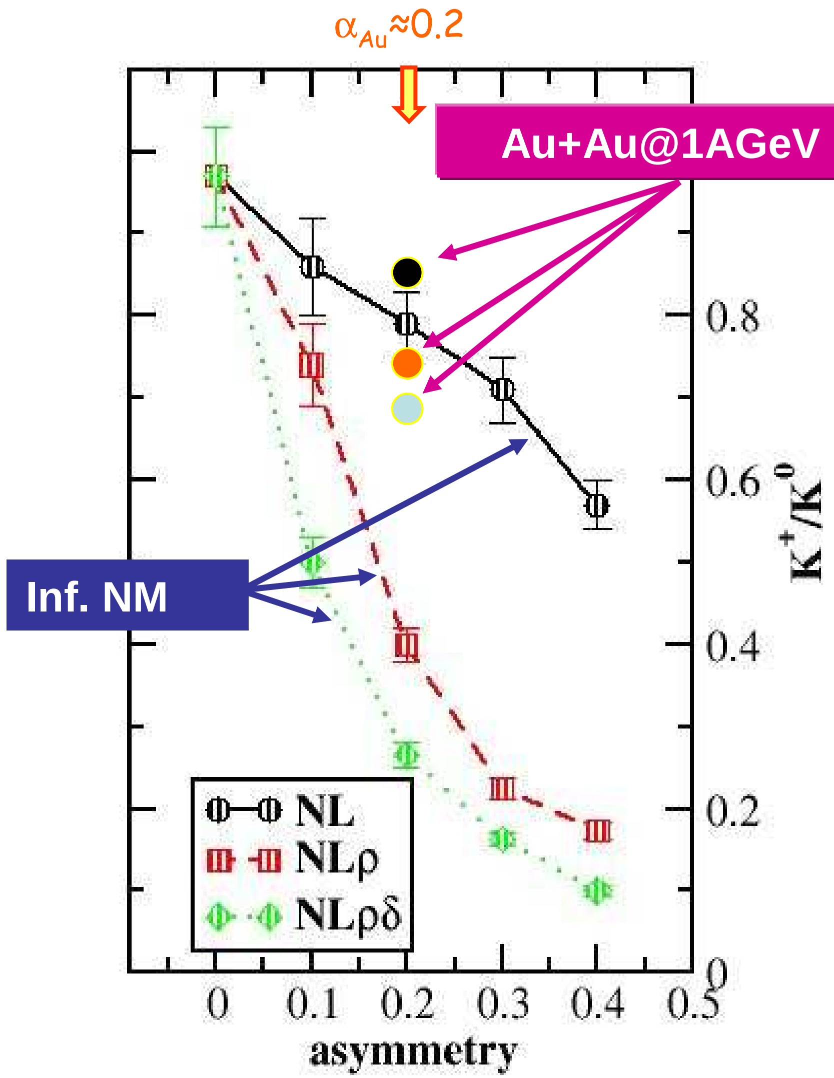
Important to fix the EOS of symm. nucl. matter



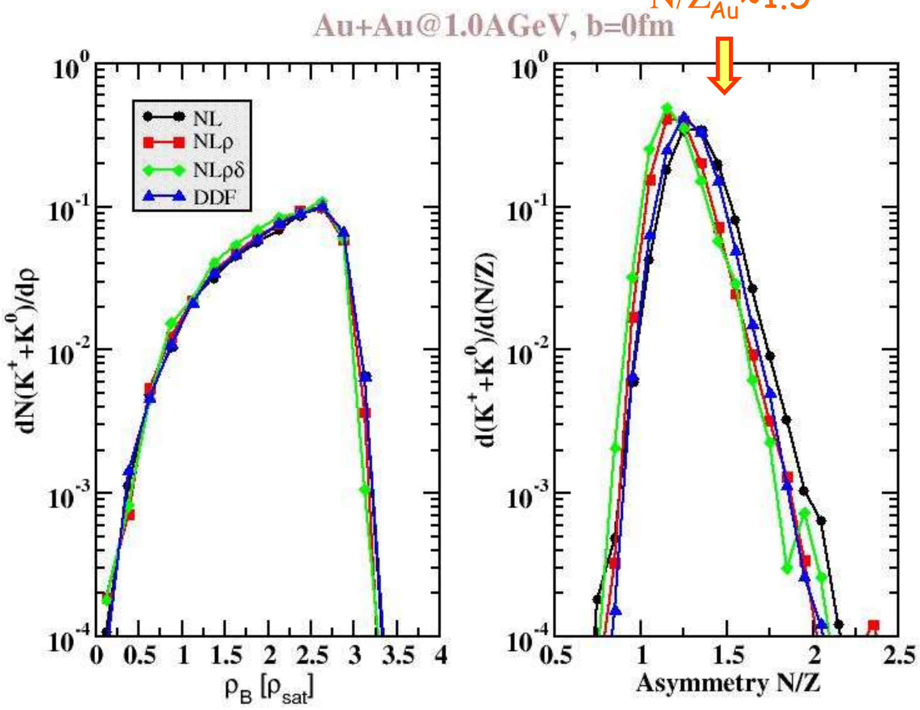
Fuchs, et al., PRL 86 (01)

Strangeness ratio : Infinite Nuclear Matter vs. HIC

G. Ferini, et al., NPA762(2005) 147



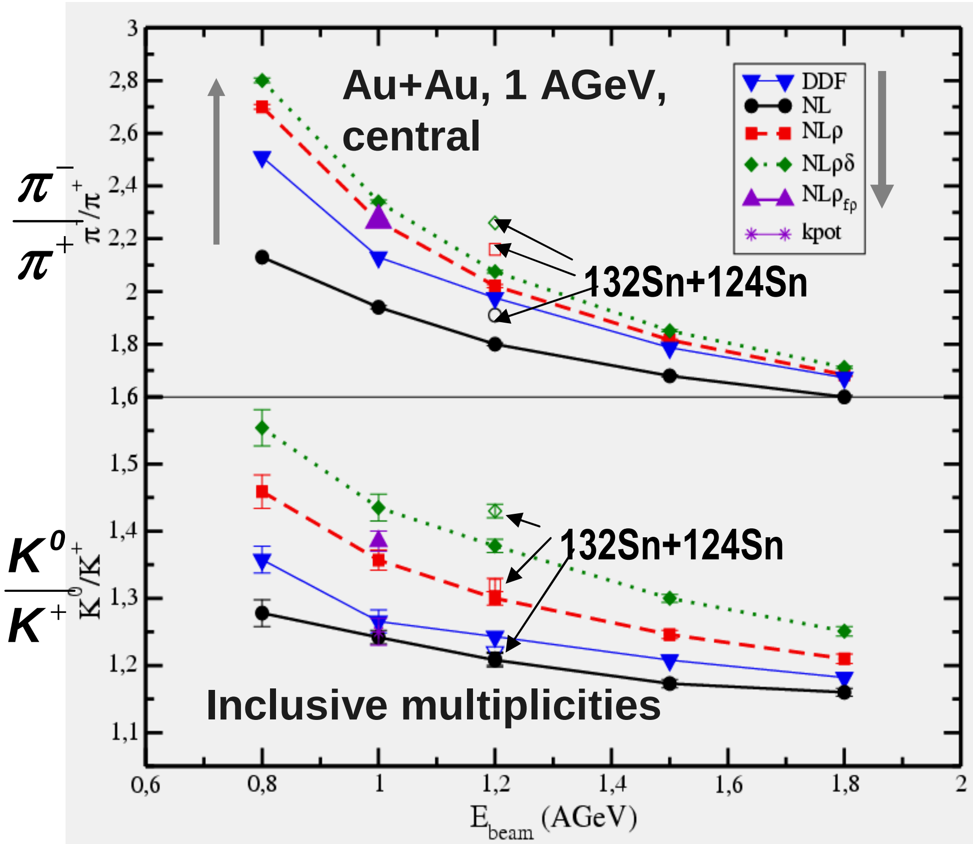
Density & asymmetry of the K-source



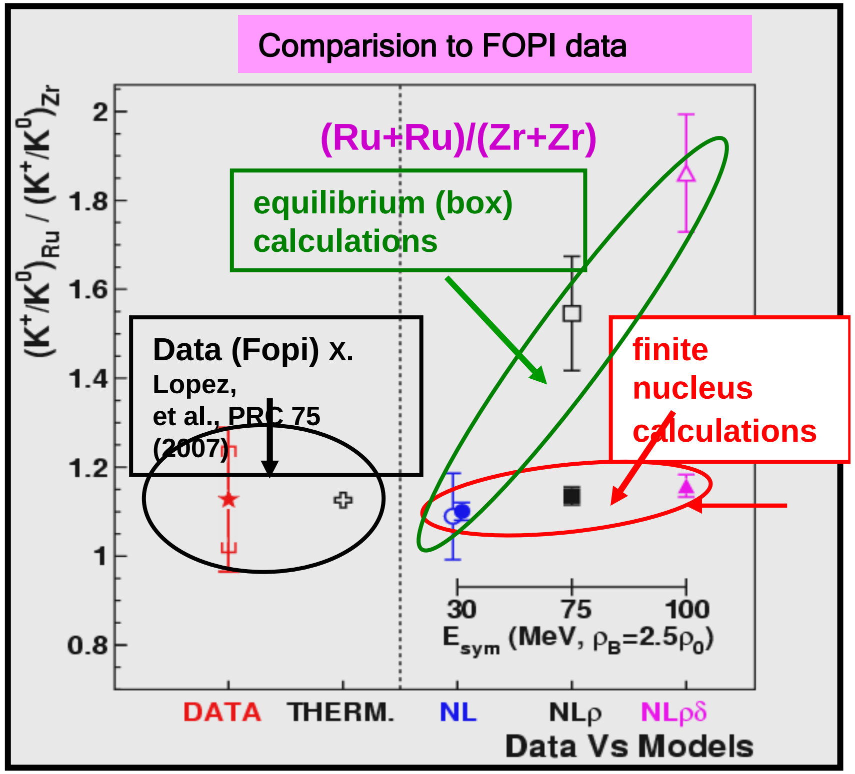
NL→ DDF→NLρ→NLρδ increas. asy-stiffness
more neutron escape and more n→p transformation
(less asymmetry in the source)

Pre-equilibrium emission (mainly of neutrons) reduces asymmetry of source for kaon production → reduces sensitivity relative to equilibrium (box) calculation

Kaon production in HIC



G.Ferini et al.,PRL 97 (2006) 202301



G. Ferini, et al., NPA762(2005) 147

- From asy-soft to stiff from lower to upper curves: Stiffer asy-EOS→larger ratio! Opposite to mean field effect!
- Kaons a somewhat more sensitive than pions
- esp. at low energies, close to threshold

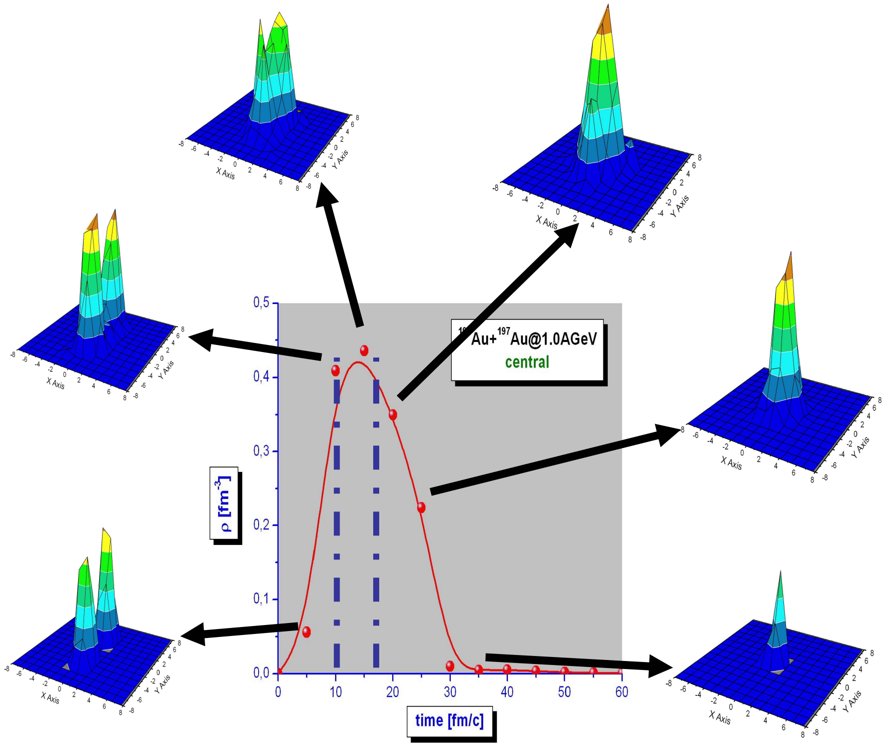
single ratios more sensitive

• enhanced in larger systems

Transport Theory

There are chances and difficulties in the interpretation of HIC experiments
--- but, do we completely master the theoretical description???

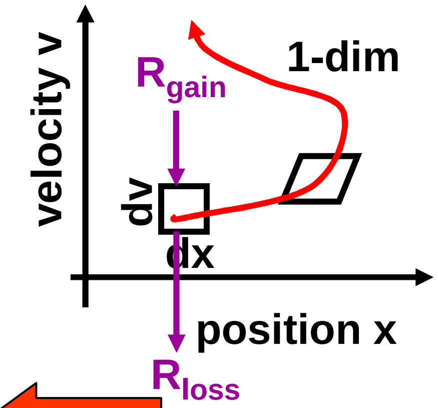
- **Need transport theory to describe non-equilibrium evolution of system**
- **Foundation of transport theory**
- **Molecular dynamic approaches, comparisons**
- **Open problems in transport theory**



Classical derivation of a BUU transport equation

1-body phase space distribution: $f_i(\vec{r},\vec{p};t)$

probability to find at time t a particle if type i at point r with momentum p



phase space density is constant in time (Liouville theorem),

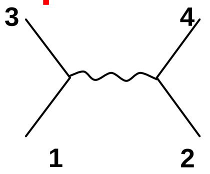
then $$df = \frac{\partial f}{\partial t} + dr\frac{\partial f}{\partial r} + dp\frac{\partial f}{\partial p}$$

or generally in a potential U(r): (Vlasov equ.)

$$\frac{df}{dt} = \frac{\partial f}{\partial t} + \frac{\vec{p}}{m}\vec{\nabla}^{(r)}f - \vec{\nabla}^{(r)}U(r)\,\vec{\nabla}^{(p)}f = 0$$

drift term acceleration by the field

BUU eqn.



Collisions will change the phase space density!

$$R_{loss} = \int d\vec{v}_2\, d\Omega\, v_{21}\, \sigma(\Omega)\, f_1\, f_2$$ correspondingly gain

Pauli principle: blocking factors $(1-f(r,v_i;t)) \equiv (1-f_i) := \bar{f}_i$

energy momentum conservation: $p_1 + p_2 = p_{1'} + p_{2'}$

$$I_{coll} = \int d\vec{v}_2\, d\vec{v}_{1'}\, d\vec{v}_{2'}\, |v_2 - v_1|\, \sigma(\Omega)\,(2\pi)^3\,\delta(p_1+p_2-p_{1'}-p_{2'})\left[f_{1'}f_{2'}\bar{f}_1\bar{f}_2 - f_1 f_2 \bar{f}_{1'}\bar{f}_{2'}\right]$$

Collision term added „by hand"
Relation of mean field U and medium cross section σ not clear.
→ 3 more ways to arrive at the BUU eqn. which clarify its foundations

Quantum Derivation of Vlasov Equation

Start with TDHF $\rho(r_1,r_2)=\langle slat.det|\hat\psi^+(r_1)\,\hat\psi(r_2)|slat.det\rangle$

$$\frac{\partial}{\partial t}\rho=\tfrac{1}{i}[h,\rho]_{1,2} \qquad h(1,2)=T(1,2)+\underbrace{\sum_{3,4}(V_{13,24}-V_{14,23})\,\rho_{3,4}}_{U(1,2)}$$

Wigner transform
Fourier transf wrt
fast variation

$$f(r,p)=\frac{1}{(2\pi)^3}\int ds\, e^{-ips}\ \rho(r+\tfrac{s}{2},r-\tfrac{s}{2})$$

Equation of motion for Wigner transform f.
Use gradient approximation for Wigner transform of products

$$\frac{1}{i}\frac{1}{(2\pi)^3}\int ds\, e^{-ips}\,(U(r+\tfrac{s}{2})-U(r-\tfrac{s}{2}))\,\rho(r+\tfrac{s}{2},r-\tfrac{s}{2})=2\sin\frac{\nabla_r^{(U)}\nabla_p^{(f)}}{2}\,U f\approx\nabla_r U\,\nabla_p f+\dots$$

again Vlasov eq.

$$\frac{\partial f}{\partial t}+\frac{p}{m}\nabla_r f-\nabla_r U(r)\,\nabla_p f(r,p)=0 \qquad \Rightarrow I_{coll}$$

Remarks:

- collision term has to be added „by hand“ as before
- quantum statistics only contained in initial condition, but is preserved by the evolution (Liouville theorem; for coll. term explicitely via blocking terms)

Can also be done in a relativistic formulation (RMF) $L(\psi;\sigma,\omega,\pi,\eta,\delta,\ldots)$

$$\left[p^{*\mu}\,\partial_\mu^{(r)}+(p^*_\nu\,F^{\mu\nu}+m^*\,\partial^\mu_{(r)}m^*)\,\partial_\mu^{(p^*)}\right]f(r,p^*)=I_{coll}$$

$$m^*=m-\Sigma_s;\qquad p^*_\mu=p_\mu-\Sigma_\mu$$

\+ Mass shell constraint: $(p^{*2}-m^{*2})f(r,p)=0$

New Feature: two potentials: scalar-vector → mom.dep. mean field, „Lorentz- like“ forces

Non-equilibrium Transport Theory (Kadanoff-Baym)

To derive a collision term consistently, one has to include the non-equilibrium features of the process

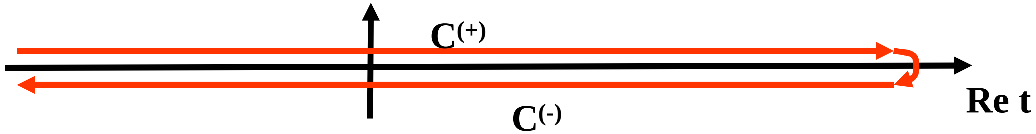
L.P.Kadanoff, G. Baym, Quantum statistical mechanics, 1965
P. Danielewicz, Ann. Phys. 152 (1984) 239
O. Buss, T. Gaitanos, … U. Mosel, Phys. Rep. 512 (2012) 1

Hierarchy of n-body Green functions (Martin-Schwinger hierarchy)

$$(i\gamma^\mu \partial_\mu - m)G^{(1)}(1,2) = \delta(1-1') + (12|V|1'2')G^{(2)}(12,1'2')$$
$$=: \delta(1-1') + \Sigma(1,1')G^{(1)}(1'',2)$$

(Dyson eq.)

decouple formally via the self energy Σ, or by an approximation to it, e.g. BHF



$$G(1,2) = \begin{pmatrix} G^{--}(1,2) & G^{-+}(1,2) \\ G^{+-}(1,2) & G^{++}(1,2) \end{pmatrix}$$

The GF's are defined on a closed time-contour (Schwinger-Keldysh). All quantities become 2x2 matrices. In non-equilibrium there are two independent 1-body Green functions (GF), since the propagation forward and backward in time is different.

$$G^<(1,2) := G^{-+} = i\langle \overline{\psi}(1)\psi(2)\rangle \xrightarrow[\text{Wigner transf}]{} i\,A(r,p)F(x,p)$$

F generalized occupation

$$G^>(1,2) := G^{+-} = i\langle \psi(1)\overline{\psi}(2)\rangle \xrightarrow[\text{Wigner transf}]{} i\,A(r,p)(1-F(x,p))$$

A spectral function

Wigner transform, Lorentz decomposition (scalar, vector, tensor), gradient expansion of products

Kadanoff-Baym equations:

$$(\vec{D}G^< - G^<\overleftarrow{D}^*) - [Re\,\Sigma^+, G^<] - [\Sigma^<, Re\,G^+] = \tfrac{1}{2}\left([\Sigma^>, G^<]_+ - [\Sigma^<, G^>]_+\right)$$

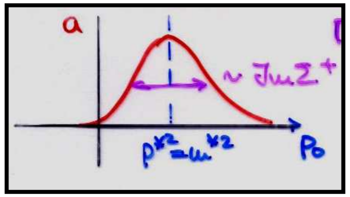
Kinetic term | **mean field term** | **„back-flow" term** | **collision term**

Self Energy Approximation

→ Quasi-particle approximation (QPA) $G^{<} = A(r.p)F(r,p)$ **A spectral function**

$$A(x,p) \propto \frac{2\Gamma(x,p)}{(p^{*2}-m^{*2})+\Gamma^2(x,p)} \quad \xrightarrow{\text{QPA}} \quad \propto \delta(p^{*2}-m^{*2})\,\Theta(p^{*0})$$

$$\Gamma(x,p) = m^* \, Im\, \Sigma_s^+ - p_\mu^* \, Im\, \Sigma^{+\mu}$$



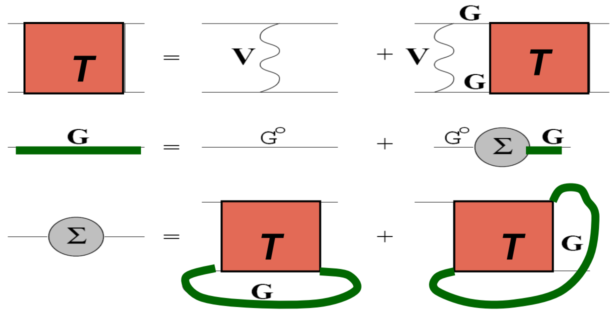
reduces no.of variables from 8 to 7→ particle interpretation possible

$$\left[p^{*\mu}\,\partial_\mu^{(r)} + (p^*_\nu F^{\mu\nu} + m^*\,\partial^\mu_{(r)} m^*)\,\partial_\mu^{(p^*)}\right] f(r,p^*) = I_{coll}[\sigma_{NN}^{(in-med)}]$$

$$m^* = m - \Sigma_s$$
$$p^*_\mu = p_\mu - \Sigma_\mu$$

The self energy can be taken in the T_Matrix approximation, including exchange and two-body correlations: Brueckner HF theory.

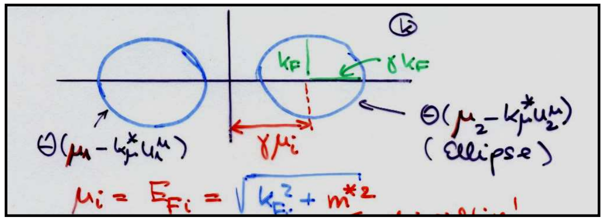
$$\Sigma_{s,\mu} \approx Tr\,(T\,f); \qquad \sigma_{NN}^{(in-med)} \approx \left|T^2\right|$$



→Now the collision term appears consistently and is obtained on the same footing from the Brueckner T-Matrix.

→ without QPA, „off-shell transport" (particles with widths) (Buss et al., Phys. Rep. 512, 1 (2012) has not been investigated in great detail

→ non-equlibrium effects in T-Matrix
(e.g. 2-Fermi sphere approximation; Fuchs, Sehn, HHW)



Testparticle Solutions of BUU Equation

$$\frac{\partial f}{\partial t} + \frac{\vec{p}}{m}\vec{\nabla}^{(r)} f - \vec{\nabla} U(r)\,\vec{\nabla}^{(p)} f(\vec{r},\vec{p};t) = \int d\vec{v}_2\, d\vec{v}_{1'}\, d\vec{v}_{2'}\, v_{21}\,\sigma_{12}(\Omega)\,(2\pi)^3\,\delta(p_1+p_2-p_{1'}-p_{2'})$$
$$\left[f_{1'} f_{2'} (1-f_1)(1-f_2) - f_1 f_2 (1-f_{1'})(1-f_2')\right]$$

non-linear integro-differential equation, no closed solutions

- but deterministic !

a) solution on a lattice: has been used for low-dimensional model systems, but too expensive for realistic cases

b) test particle method (Wong 82)

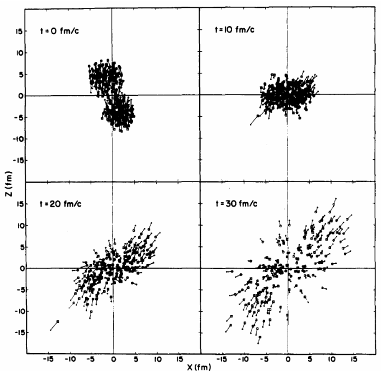
$$f(r,p;t) = \frac{1}{N_{TP}} \sum_{i=1}^{AN_{TP}} \delta(r - r_i(t))\,\delta(p - p_i(t))$$

where $\{r_i(t), p_i(t)\}$ are the positions and momenta of the TP as a funct. of time,
and N_{TP} is the number of TP per nucleon (usually 50 – 200)

→ approximate a (continuous) phase space distribution by a swarm of δ-functions
variant: Gaussian TP: smoother distribution with fewer TP

→ ansatz into Vlasov eq. →Hamiltonian equations of motion:

$$\frac{\partial r_i}{\partial t} = \frac{p_i}{m}; \qquad \frac{\partial p_i}{\partial t} = -\nabla U\big|_{r_i}$$



c) the rhs (collision term) is simulated, stochastically; like cascade

→ describes average effect of collisions (→dissipation), NOT Fluctuation

→ if $N_{TP} \to \infty$, exact solution of BUU eqn. !

d) include fluctuations explicitely Boltzmann-Langevin eq.

$$\frac{\partial f}{\partial t} + \frac{\vec{p}}{m}\vec{\nabla}^{(r)} f - \vec{\nabla} U(r)\,\vec{\nabla}^{(p)} f(\vec{r},\vec{p};t) = I_{coll} + \delta I_{fluct}$$

different approx. treatments
simplest: adjust no. of TP to
most unstable mode

Second family: Molecular Dynamics

Classical solution of the many-body problem with assumptions of 2-body interaction instead of MF depending on density

$$\frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{r}_i = \{\boldsymbol{r}_i, \mathcal{H}\}, \qquad \frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{p}_i = \{\boldsymbol{p}_i, \mathcal{H}\},$$

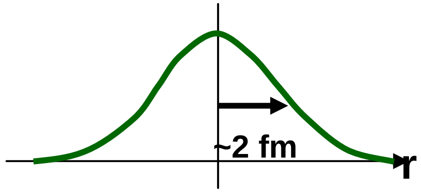
where the many-body Hamiltonian is of the form

$$\mathcal{H}\{\boldsymbol{r}_n, \boldsymbol{p}_n\} = \sum_{i=1}^{A} \frac{\boldsymbol{p}_i^2}{2m_i} + \sum_{i<j} V(|\boldsymbol{r}_i - \boldsymbol{r}_j|).$$

1. **Classical Molecular dynamics CMD**
   point particles, deterministic,
   but possibly chaotic behaviour because
   of short range repulsion

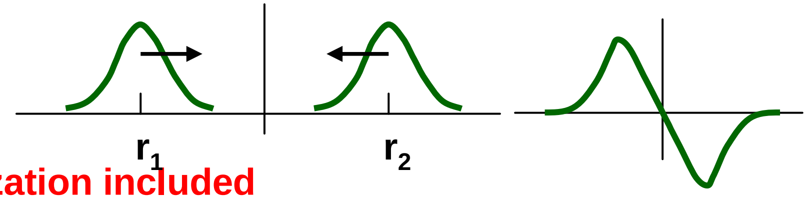
2. **Quantum molecular dynamics QMD**

   Gaussian particles with large width to smooth fluctuations,
   not a wave packet, no antisymmetrization,
   collision term as in BUU, but between nucleons,
   origin not clear, and also not cross section
   (thus similar to BUU with N_{TP}=1) but event generator.



3. **Antisymmetrized MD (AMD), Fermionic MD (FMD),**

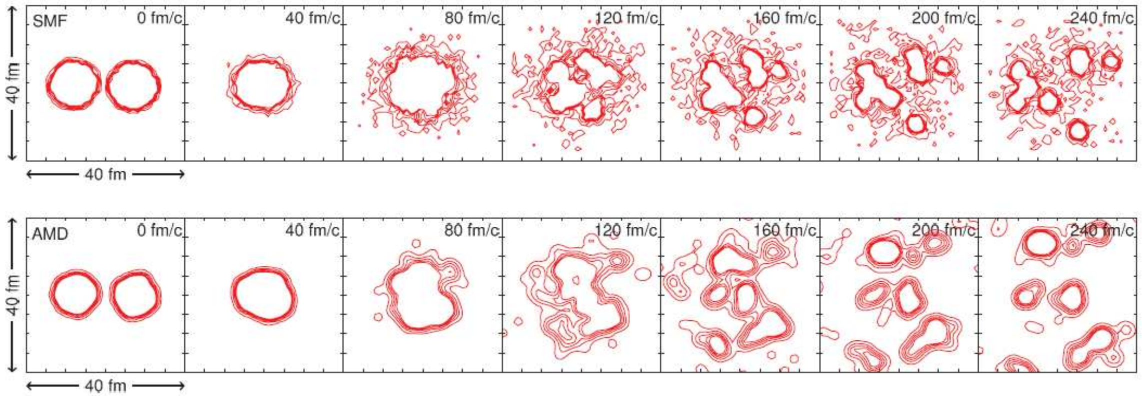
   TDHF with Slaterdeterminant of s.p. wave functions
   in terms of Gaussian wave packets with psition and
   momentum as dynamical variables i.e. antisymmetrization included
   Collision term: „wave packet splitting“, reduction of wp
   (Variant: Constrained MD, CoMD, like QMD but correction for self-interaction term)



4. **fluctuations: larger in MD approaches, since collision moves nucleon (and not TP),**
   parameter for fluctuations: width of „wave packets“.
   clusterization: additional physical source of fluctuations

Comparison of simulations: SMF-AMD: (Rizzo, Colonna,Ono, PRC76(2007); Colonna et al., PRC82 (2010))

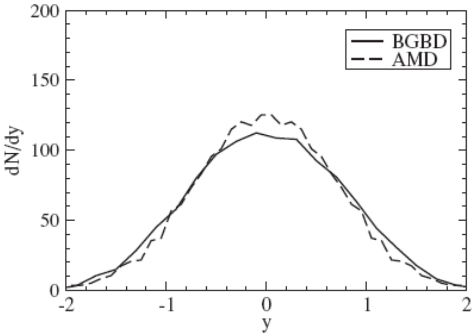
112Sn+112Sn, 50 AMeV



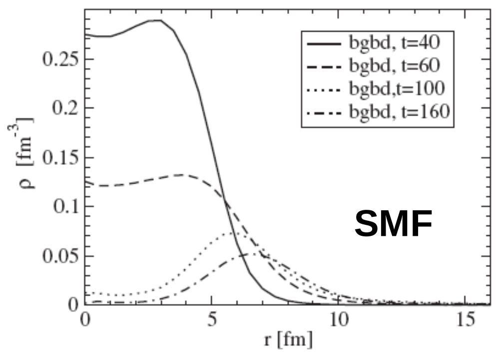
SMF (BGBD)

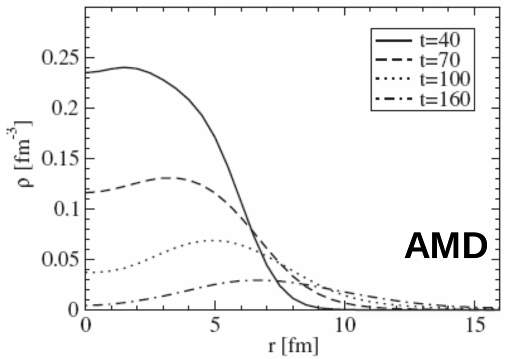
AMD

Stopping: similar



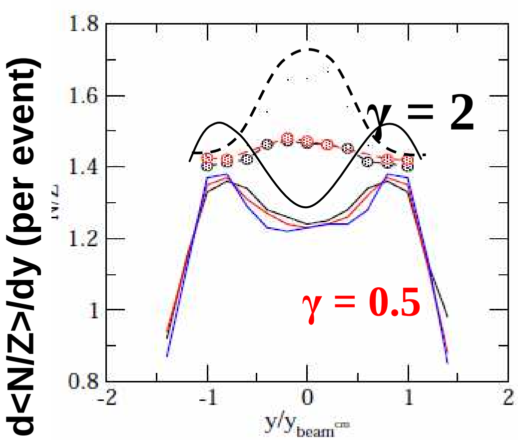
Radial density at different times: SMF more bubble like





Comparison, SMF-ImQMD: more transparency in QMD (M. Colonna, X.Y.Zhang)

SMF = dashed lines
ImQMD = full lines



BUU(BNV)/SMF ←Comparison→ QMD/CoMD/AMD

Mean field evolution →very similar!

BUU(BNV)/SMF	QMD/CoMD/AMD
Semiclass approx to TDHF Solved with inf. no. of TP	TD-Hartree with product wf of sp Gaussians of large width (AMD TDHF)

Collision term and med cross sect→similar in principle, often not implement

BUU(BNV)/SMF	QMD/CoMD/AMD
Consistently derivable from KB approach, good approx. BHF	Not consistently derivable but empirically the same,

collisions →different effect of collisions

Main diff of approaches

BUU(BNV)/SMF	QMD/CoMD/AMD
full ens.: TP coll→ small fluct parall. ens.: average after each timestep, same →Too little fluct by collision, only av. dissip. (improve: Bertsch method (Colonna): move N_{TP} TP)	collide particles →Generates large fluct in phase space depending on width of Gaussian affects also Pauli blocking

Fluctuations →diff mainly by effect of collision term

Inital state correlations, similar, initial wf not realistic

BUU(BNV)/SMF	QMD/CoMD/AMD
BUU eq. should be replaced by Boltzmann-Langevin eq.	higher order corr due to localized (packet) wf but averaged out by smearing AMD: cluster dynamics

Fragment formation and recognition

Fluct as seeds of fragments, amplified by mf, (at least for not too large inc. energy.)
Early/late recognition does not affect dynamics; a-posteriori

BUU(BNV)/SMF	QMD/CoMD/AMD
Can implement TP sampling and thus also MST,SACA,etc methods	MST, SACA/ECRA methods natural, clustering in AMD

Small clusters (d,t,3He,α)

not well described in BUU and QMD (better in AMD)
Best treated explicitely (but include α!)

Open Problems in Transport Theory and Calculations:

1. Ensure that codes are internally consistent (same physical input → same output); resp., determine theoretical systematic error from remaining differences
2. Standardization, logical naming of versions (code numbers, QMD 2.1, etc.)
3. Consistency of mean field (self energy) and in-medium cross sections (e.g. DBHF)
4. Momentum dependence of isoscalar and isovector forces (effective masses)
5. Control and study of role of fluctuations (diff. in BUU and QMD type codes)
6. Relativistic transport codes for higher energy: scalar and vector fields, Lorentz force, no 3-body terms
7. Investigation of „off-shell“ transport, esp. for subthreshold production of particles, development of reliable approximations for propagation of particles with finite width, e.g. Δ, but in principle every particle
8. Treatment of clusters: dynamical generation of clusters with medium modifications, in-medium amplitudes for cluster production
9. Inelastic amplitudes for in-medium production of particles

Thank you

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