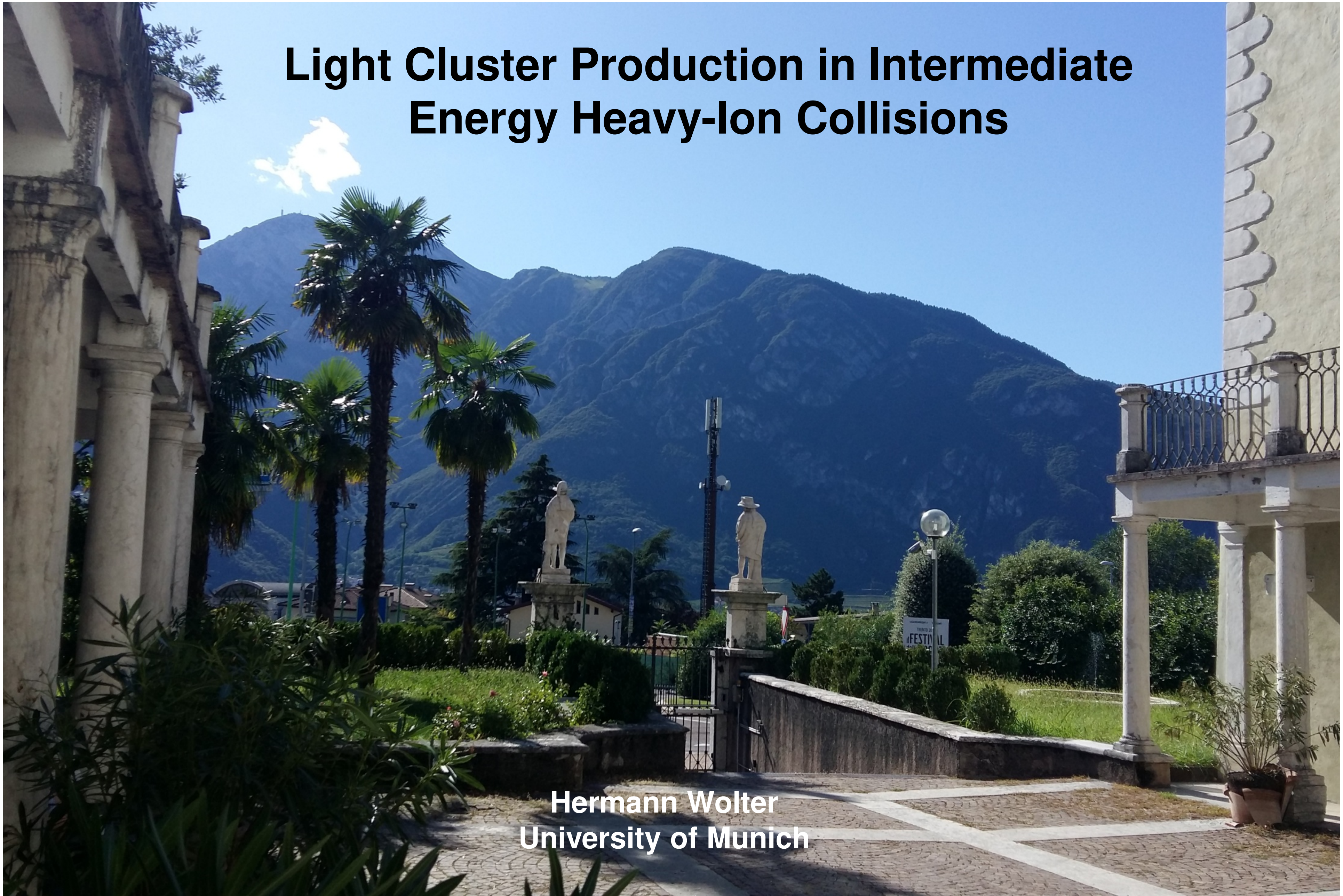
Light Cluster Production in Intermediate Energy Heavy-Ion Collisions



Hermann Wolter
University of Munich

Workshop „Light Clusters in Nuclei and Nuclear Matter: Nuclear Structure and Decay, Heavy-Ion Collisions, and Astrophysics
ECT*, Trento, Italy, Sept. 2-6, 2019

Overview of Treatment of Light Cluster Production in Transport Approaches for Heavy-Ion Collisions (HIC)

- Motivation: Astrophysics
- Phenomenology of light cluster (LC) production in HIC
- Remarks on derivation of transport equations transport description for HIC
- beyond mean field: fluctuations and correlations
- Treatment in BUU and QMD and results
- LC observables and the nuclear symmetry energy
- Summary

I make use formulations and calculations of several people and collaborators, in particular, Workshop „Challenges to transport theory for heavy-ion collisions“. May 20-24, 2019, ECT*, Trento

TUM LMU ORIGINS Excellence Cluster lrz

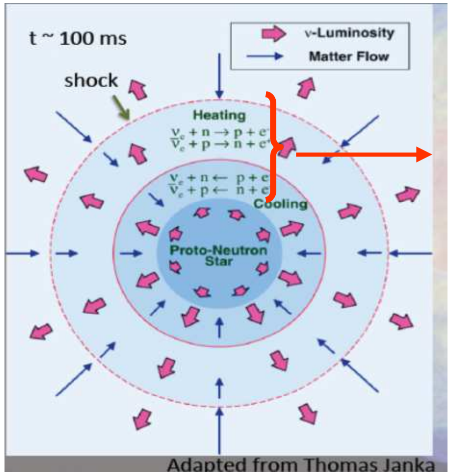
LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

Motivation: Possible role of clusterization of matter in Core Collapse Supernovae

Relevance for neutrino opacity in ν-sphere → workshop in ECT*, Trento, May 2014,

Simulating the supernova neutrinosphere with heavy ion collisions

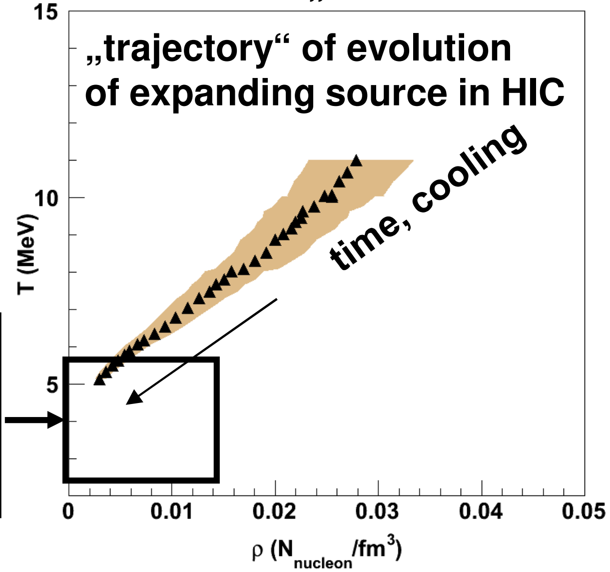
Super-Nova



ν–sphere

conditions of neutrinosphere:
densities 1/1000 to 1/10 ρ_o
temperature T=1-5 MeV
asymmetry Y_e=0.1 – 0.25

„Femto-Nova“



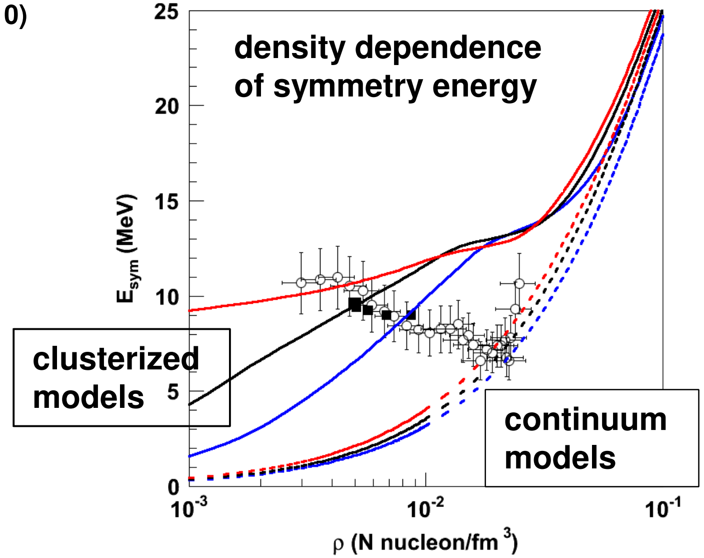
Semi-central heavy ion collisions,
(^{64}Zn+^{92}Mo,^{197}Au at 35MeV/A), talk by J. Natowitz
J. Natowitz, G. Röpke,…, PRL 104, 202501 (2010)

Differential Scattering/Absorption Rate:

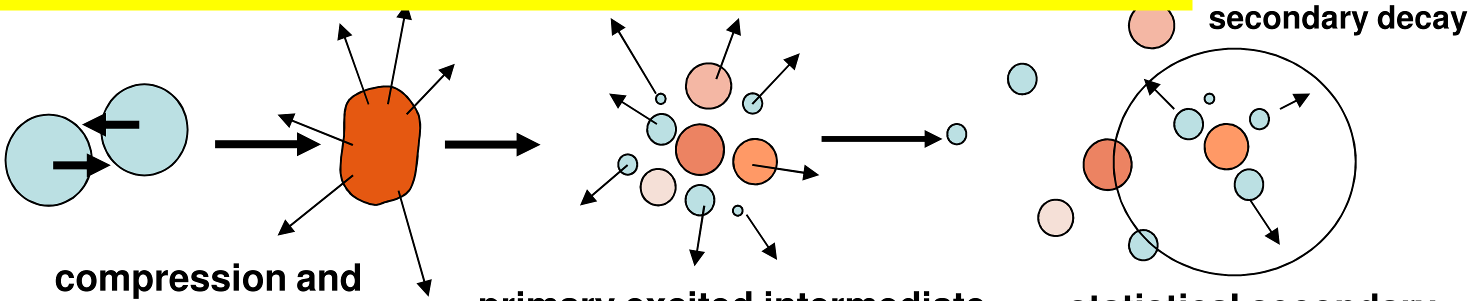
$$\frac{d\Gamma(E_1)}{d\cos\theta\, dq_0} = \frac{G_F^2}{4\pi^2}(E_1-q_0)^2\left[(1+\cos\theta)\, S_V^{\mathrm{RPA}}(q_0,q) + (3-\cos\theta)\, S_A^{\mathrm{RPA}}(q_0,q)\right]$$

spectrum of density fluctuations

spectrum of spin fluctuations



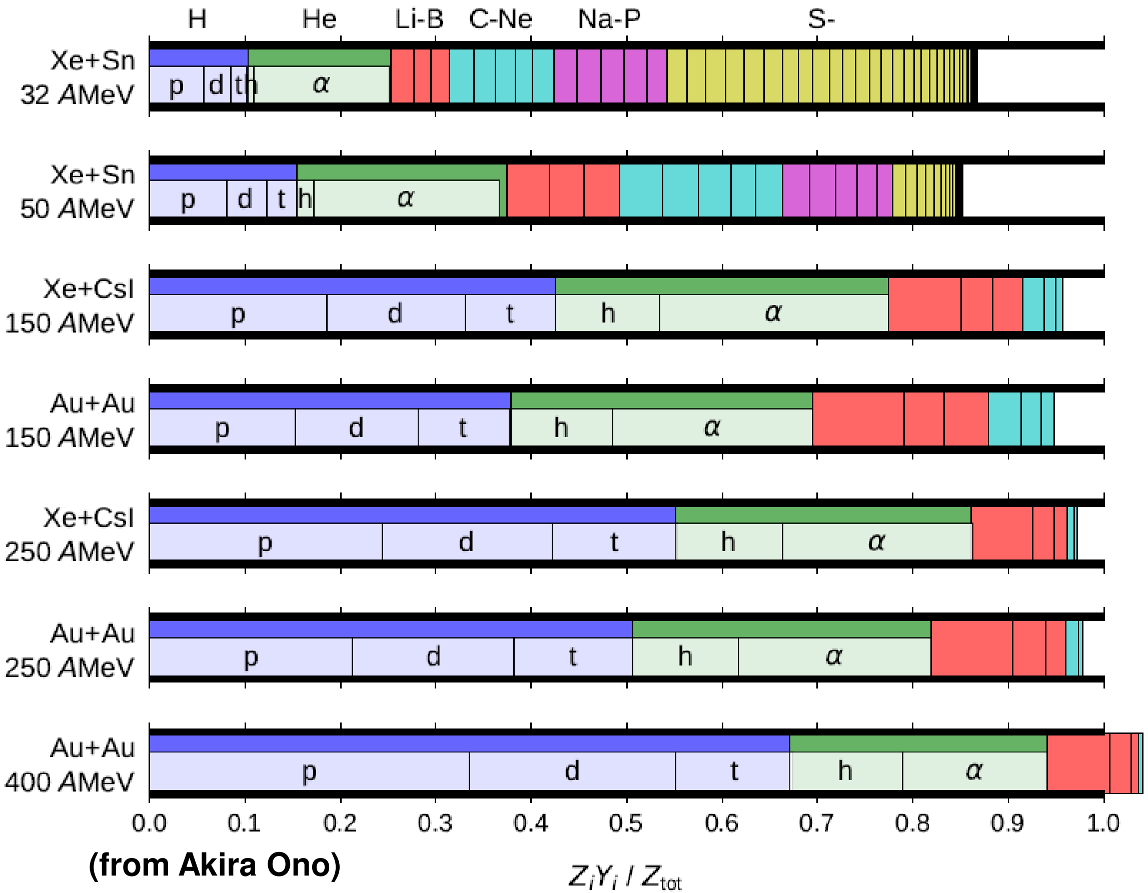
Clusters and fragments in intermediate energy HIC



compression and pre-equil. emission of light clusters (LC) n,p,d,t,3He,α (A≤4)

primary excited intermediate mass fragments (IMF) (5≤A≤≈30)

statistical secondary decay of fragments Emission of nucleons and LC



(from Akira Ono)

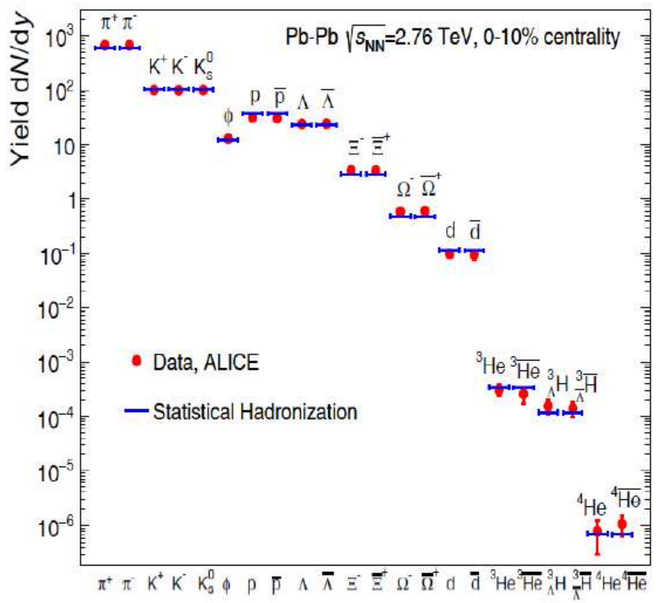
a large part of the final state of a HIC consists of LC and fragments even at higher energy

Correlations and fluctuations are seeds to formation of clusters and fragments

→ but often also treated with statistical models with considerable success

Cluster production at high energies/densities

Alice LHC



baryonless fireball T=156MeV
"snowflakes from hell"

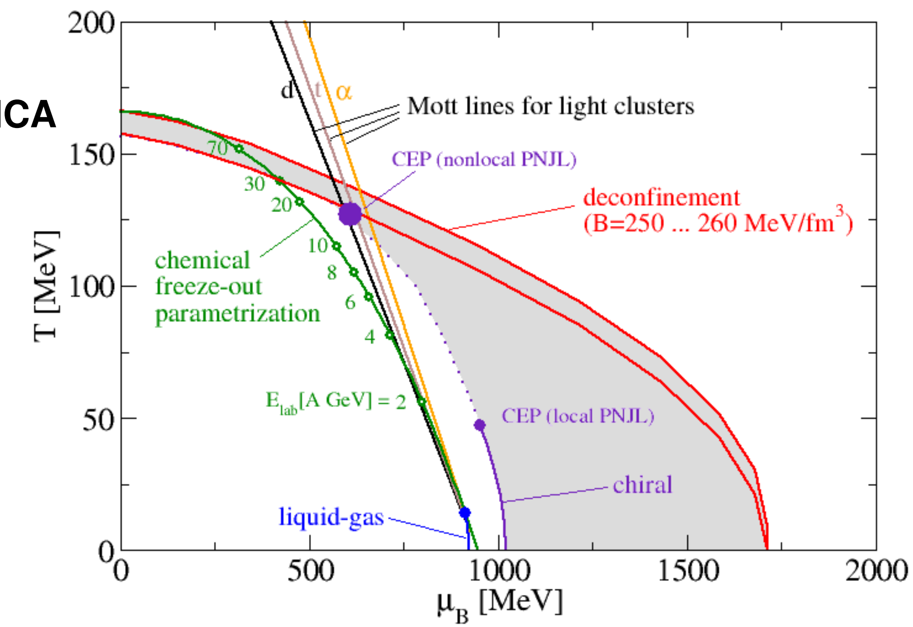
A. Andronic, P. Braun-Munzinger, K. Redlich and J. Stachel, Nature 561, 321 (2018)

-> talk by S. Mrówczyński (Friday)

coalescnence & afterburner
(see also D. Oliinychenko)

3-fluid hydro, Au+Au deuteron flow

NICA

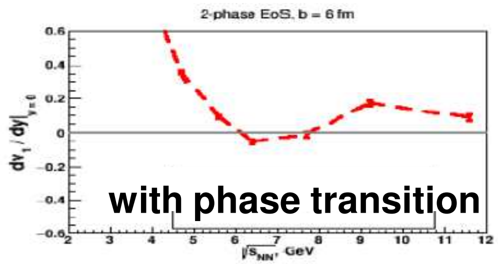


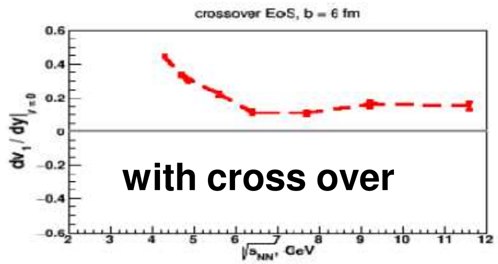
light clusters can be present at high densities near the deconfinement phase transition

N.U. Bastian, et al., EPJ A 52, 244 (2016)

3-fluid hydro flow, Au+Au,

Flow of LC traces eearly pressure distribution, probe of phase transition

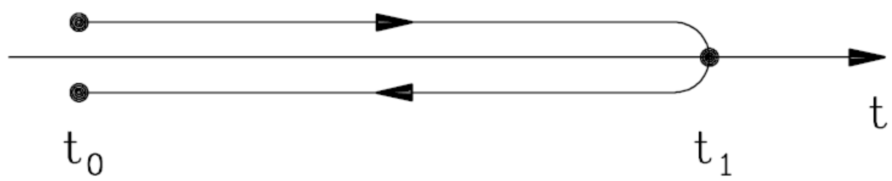




Remarks on derivation of transport theory for HIC
(e.g. P. Danielewicz, Ann. Phys. 152, 239 (1984), and Transport 2019 workshop, ECT*)

Real-time Green function method

$$iG(1,2) = \left\langle T\left[\hat{\psi}(1)\hat{\psi}^{\dagger}(2)\right]\right\rangle = i\begin{pmatrix} G^{c} & G^{<} \\ G^{>} & G^{a} \end{pmatrix}$$



Truncation on **1-body level** and self energy Σ

$$iG_1(1,2) = \int d3\,d4\,d5\,G_1(1,3)\langle 35|V|45\rangle G_2(4,5;2,4)$$
$$\approx \int d3\,d4\,G_1(1,3)\Sigma(3,4)G_1(4,2)$$

Expansion on contour yields Kadanoff-Baym eqs. for different GFs.

This neglects higher order correlation effects,
they have to re-introduced: - in the form of fluctuations (for fragments, IMF)
- explicitely (for light clusters)

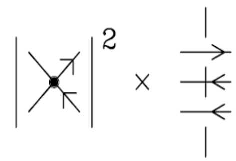
Quasi-particle approx.: under slow spatial and temporal changes of the system the Wigner transform of $G^{<}$ becomes a 1-body phase space densiity

$$f(\mathbf{p};\mathbf{R},T) = \int d\mathbf{r}\,e^{-i\mathbf{p}\mathbf{r}}(\mp i)G^{<}(\mathbf{R}+\mathbf{r}/2,T,\mathbf{R}-\mathbf{r}/2,T)$$

For which we can write an evolution equation of the Boltzmann-Vlasov type
Mean field evolution plus collision term

$$\boxed{\frac{\partial f}{\partial t} + \frac{\partial \epsilon_{\mathbf{p}}}{\partial \mathbf{p}}\frac{\partial f}{\partial \mathbf{r}} - \frac{\partial \epsilon_{\mathbf{p}}}{\partial \mathbf{r}}\frac{\partial f}{\partial \mathbf{p}} = \underbrace{-i\Sigma^{<}(1-f)}_{\text{gain -}}\underbrace{-\,i\Sigma^{>}f}_{\text{loss term}}}$$

$i\Sigma^{<} =$



In practice two main transport approaches

Boltzmann-Vlasov-like (BUU/BL)

$$\left(\frac{\partial}{\partial t}+\frac{\vec{p}}{m}\vec{\nabla}^{(r)}-\vec{\nabla}U(r)\vec{\nabla}^{(p)}\right)f(\vec{r},\vec{p};t) = I_{coll}[\sigma^{in-med}]+\delta I_{fluct}$$

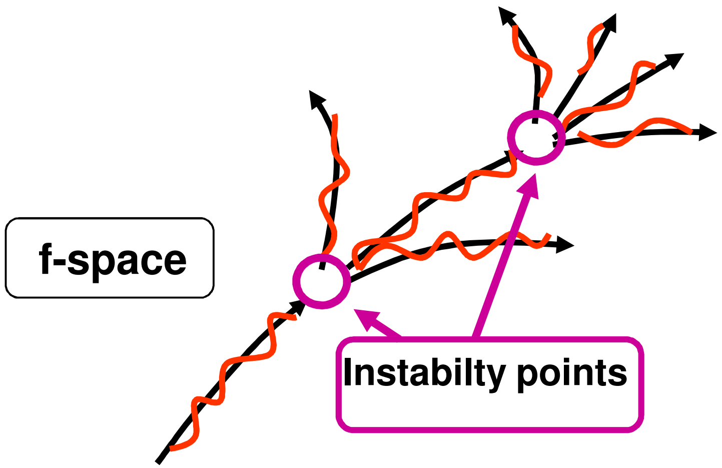
Dynamics of the 1-body phase space distribution function f with 2-body dissipation (deterministic)

fluctuations around diss. solution

$$f(r,p,t)=\bar{f}(r,p,t)+\delta f(r,p,t)$$

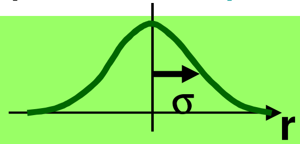
$$\boxed{\frac{df}{dt}=I_{coll}+I_{fluc}}$$

Boltzmann-Langevin eq.



Molecular-Dynamics-like (QMD/AMD)

$$|\Phi\rangle = A\prod_{i=1}^{A}\varphi(r;r_i,p_i)|0\rangle$$



$$\dot{r}_i=\{r_i,H\};\quad \dot{p}_i=\{p_i,H\};\quad H=\sum_i t_i+\sum_{i,j}V(r_i-r_j)$$

TD-Hartree(-Fock)
plus stochastic NN collisions

No quantum correlations,
but classical N-body correlations,
damped by the smoothing.

More fluctuations expected in QMD, since dof are nucleons and not test particles:
→ more fluctuations in representation of phase space distribution
→ more fluctuation gained from collision term
→ amount controlled by width σ of single particle packet

Fluctuations in BUU and QMD

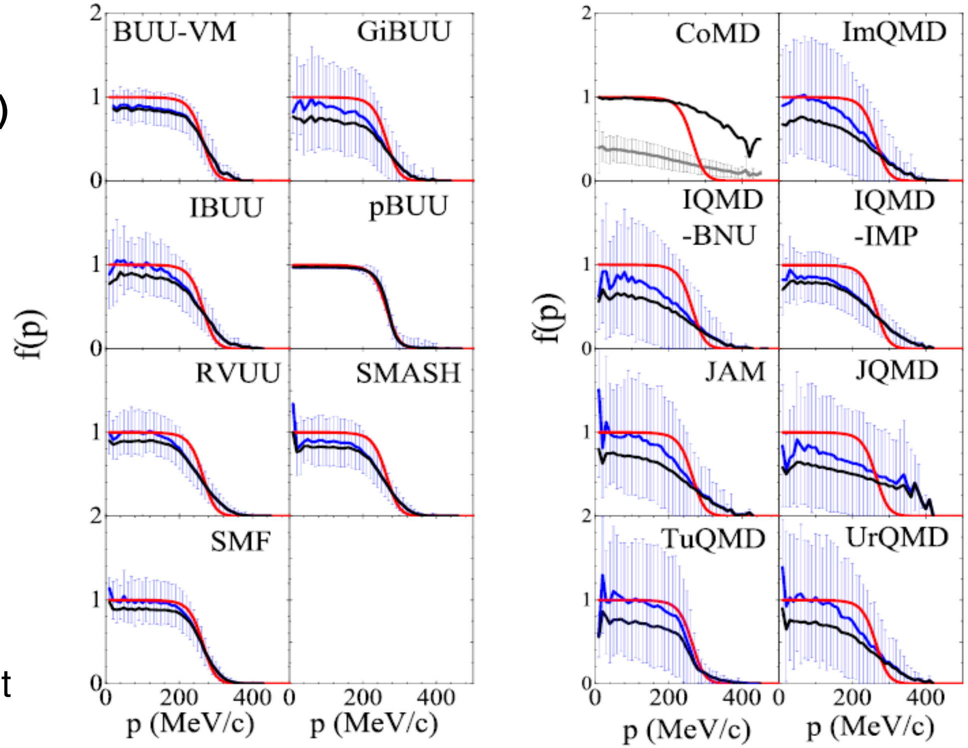
(from code comparison in a periodic box, $\rho=\rho_0$, T=5 MeV)

$$I_{coll} = \int d\vec{p}_2 d\vec{p}_{1'} d\vec{p}_{2'}\, v_{21}\, \sigma_{12}^{in-med}(\Omega)\,(2\pi)^3 \delta(p_1 + p_2 - p_{1'} - p_{2'}) \left[f_{1'} f_{2'} (1-f_1)(1-f_2) - f_1 f_2 (1-f_{1'})(1-f_{2'}) \right]$$

Sampling of occupation prob.
in comp. to prescribed FD distribution (red)

width and averages of calculated occupation numbers in different codes

- prescribed occupation
- average calculated occupation
- average of f<1 occupation (used for the blocking)



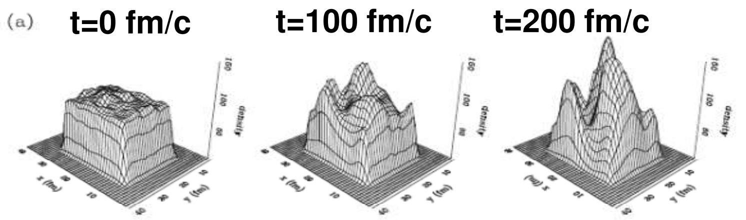
- fluctuation in BUU controlled by TP number, can be made arbitrarily small
- fluctuation in QMD given by width of wave packet

Fluctuations influence blocking and thus dynamics of transport calculations. However the proper treatment of fluctuations in transport is under debate.

Intermediate conclusion:
Both BUU and QMD do not naturally have the correct fluctuations and no quantum correlations (except Pauli correlations in AMD))

way out???
answer is different
for LCs (A≤4) and IMFs (5≤A≤≈30)

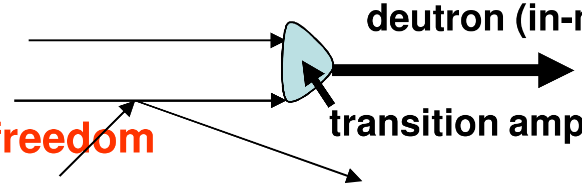
BUU calculation in a box (i.e. periodic boundary conditions) with initial conditions inside the instability region: $\rho=\rho_0/3$, T=5 MeV, $\delta=0$



→ Formation of „clusters (fragments)“, from small (physical) fluctuations in the density. (V.Baran, et al., Phys.Rep.410,335(05))

⇨ **IMF: develop from fluctuation as seeds which are amplified by the mean field**
issue: correct amplitude and spectrum of fluctuations

⇨ **LC: correlation dominated**
(common density functionals are not sophisticated enough to describe LC properly)
Issue: Introduce LCs as explicit degrees of freedom formed in 3-body colisions

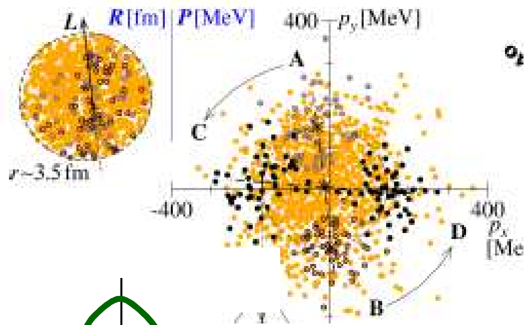


discuss next, how this is done in BUU and QMD

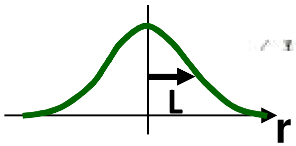
Methods to introduce fluctuations (brief, not main issue here)

BUU: statistical fluctuation of the mean field distribution function f in a Fermi system is $\sigma_f^2(r,p) = \bar{f}(r,p)(1 - f(r,p))$

SMF (stochastic mean field): project on density fluctuations and introduce these „by hand"
BLOB (Boltzmann-Langevin One-Body dynamics) Move N_{TP} testparticles simultaneously (in p-space) to simulate fluctuation connected to NN collisions



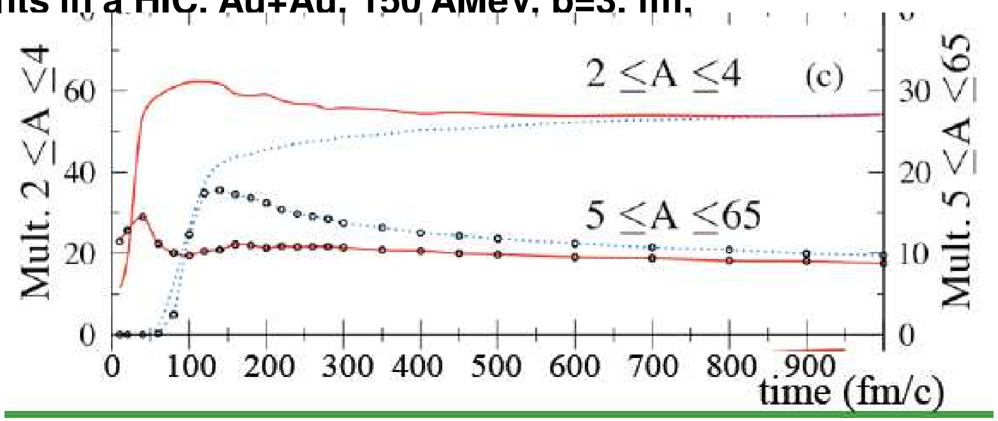
QMD: fluctuations controlled by wave packet width L:
limits: L→ 0 classical point partucles, nuclei not bound
L→ ∞ complete smoothing, no fluctuations



Fragment Recognition

Formation history of clusters and fragments in a HIC. Au+Au, 150 AMeV, b=3. fm,

MST (minimum spanning tree), i.e. coalescence
SACA (simulated annealing and cooling algorithm) i.e. additional energy minimization



SACA recognizes clusters and fragments earlier, but does not influence dynamics, but suggests that they are dynamical

Vermani,..Aichelin, J.Phys.G 37 (2010), Le Fevre Transport 2019

Treatment of Light Cluster dynamics in HIC: BUU

solution different in BUU and Mol.Dyn.(MD) models:
here: P. Danielewicz , Q. Pan, Phys. Rev. C 46, 2002 (1992), and Transport 2019, ECT*

Transport eq. for deuterons (A = 2) from the eq. for 2-ptcle Green's function?

$$iG_2^< = \langle \hat\psi^\dagger(\mathbf{x}_1'\, t')\, \hat\psi^\dagger(\mathbf{x}_2'\, t')\, \hat\psi(\mathbf{x}_2\, t)\, \hat\psi(\mathbf{x}_1\, t)\rangle$$

$$iG_2^< = (1 + G_2^+ v)\; i\mathcal{G}^< \;(1 + v\, G_2^-) \qquad \mathcal{G} \text{ -- irreducible part of } G_2$$

$$\simeq \int d\mathbf{p}\, f_d(\mathbf{p}\,\mathbf{R}\,T)\, \phi_d^*(r')\, \phi_d(r)\, e^{i\mathbf{p}\left(\frac{\mathbf{x}_1+\mathbf{x}_2}{2} - \frac{\mathbf{x}_1'+\mathbf{x}_2'}{2}\right)}\, e^{-i\epsilon_d(t-t')}$$

limit of slow spatial and temporal changes

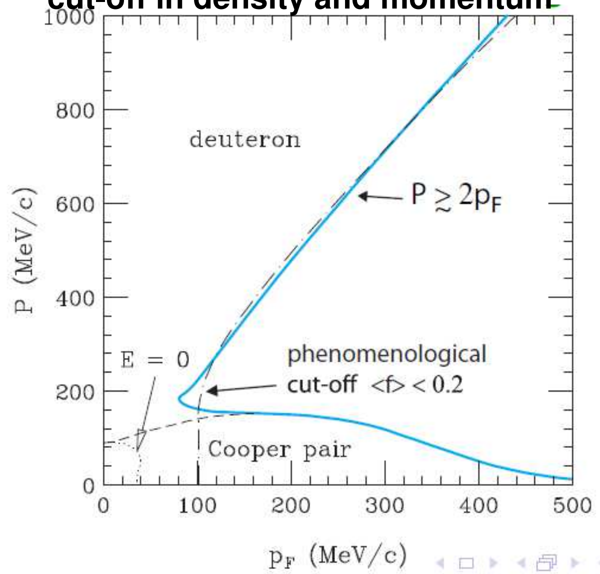
ϕ_d and f_d – internal wave function and cm Wigner function

$$(\epsilon_d(\mathbf{P}) - \epsilon_N(\mathbf{P}/2 + \mathbf{p}) - \epsilon_N(\mathbf{P}/2 - \mathbf{p}))\,\phi_d(\mathbf{p})$$
$$- (1 - f_N(\mathbf{P}/2 + \mathbf{p}) - f_N(\mathbf{P}/2 - \mathbf{p})) \int d\mathbf{p}'\, v(\mathbf{p} - \mathbf{p}')\,\phi_d(\mathbf{p}') = 0$$

transport eq. for deuteron distribution fct $f_d(p,R;t)$

$$\frac{\partial f_d}{\partial T} + \frac{\partial \epsilon_d}{\partial \mathbf{p}}\frac{\partial f_d}{\partial \mathbf{R}} - \frac{\partial \epsilon_d}{\partial \mathbf{R}}\frac{\partial f_d}{\partial \mathbf{p}} = \mathcal{K}^<(1 + f_d) - \mathcal{K}^> f_d$$

medium modification of deuteron :
cut-off in density and momentum



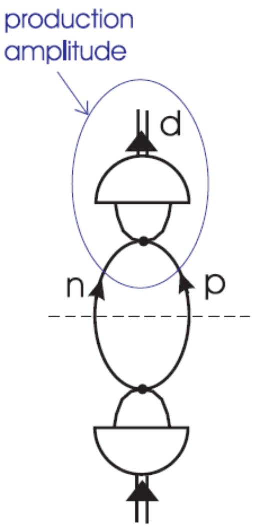
Transport eq. for deuteron distribution fct (cont'd)

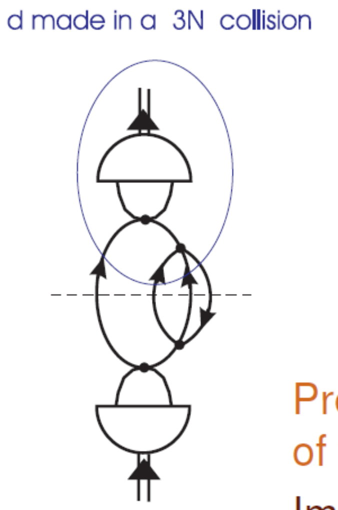
$$\frac{\partial f_d}{\partial T} + \frac{\partial \epsilon_d}{\partial \mathbf{p}}\frac{\partial f_d}{\partial \mathbf{R}} - \frac{\partial \epsilon_d}{\partial \mathbf{R}}\frac{\partial f_d}{\partial \mathbf{p}} = \mathcal{K}^{<}(1+f_d) - \mathcal{K}^{>} f_d$$

collision terms include production of deuteron in NN-collision,
leading contribution

$$\mathcal{K}^{<} = \int d\mathbf{r}\, d\mathbf{r}'\, \phi_d^*\, v\, \langle \hat{\psi}^\dagger(\mathbf{x}_1'\, t')\, \hat{\psi}(\mathbf{x}_1\, t)\rangle\, \langle \hat{\psi}^\dagger(\mathbf{x}_2'\, t')\, \hat{\psi}(\mathbf{x}_2\, t)\rangle\, v\, \phi_d$$

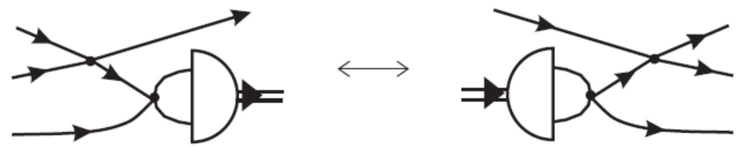
however, if system is approximately uniform and stationary, not allowed by energy-momentum conservation





Detailed balance:

$$\overline{|\mathcal{M}^{npN\to Nd}|^2} = \overline{|\mathcal{M}^{Nd\to Nnp}|^2} \propto \mathrm{d}\sigma^{Nd\to Nnp}$$



Thus, production can be described in terms of breakup.

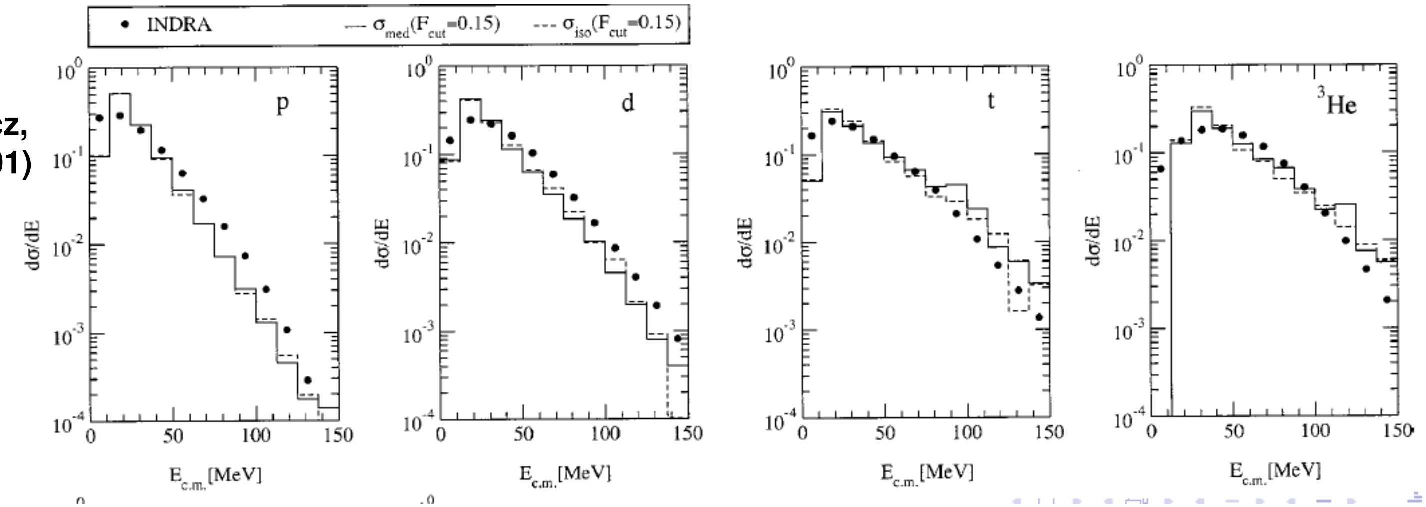
Problem: Breakup cross section only known over limited range of final states - Interpolation/extrapolation needed

Impulse approximation works at high incident energy

Continue for heavier clusters, like t, ^{3}He, α
--> coupled transport eqs. but increasingly complicated collision terms and unknown amplitudes
not (yet) included α partilcle

Results with clusters as explicit degrees of freedom

Energy spectra of LC in
$^{129}Xe+^{119}Sn$ at 50 MeV/A
C. Kuhrts, Beyer, Danielewicz, Röpke, PRC 63, 034605 (2001)

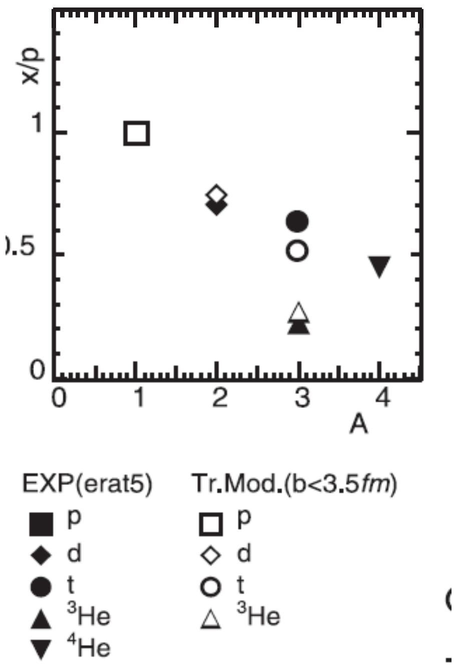


Yield ratio relative to p

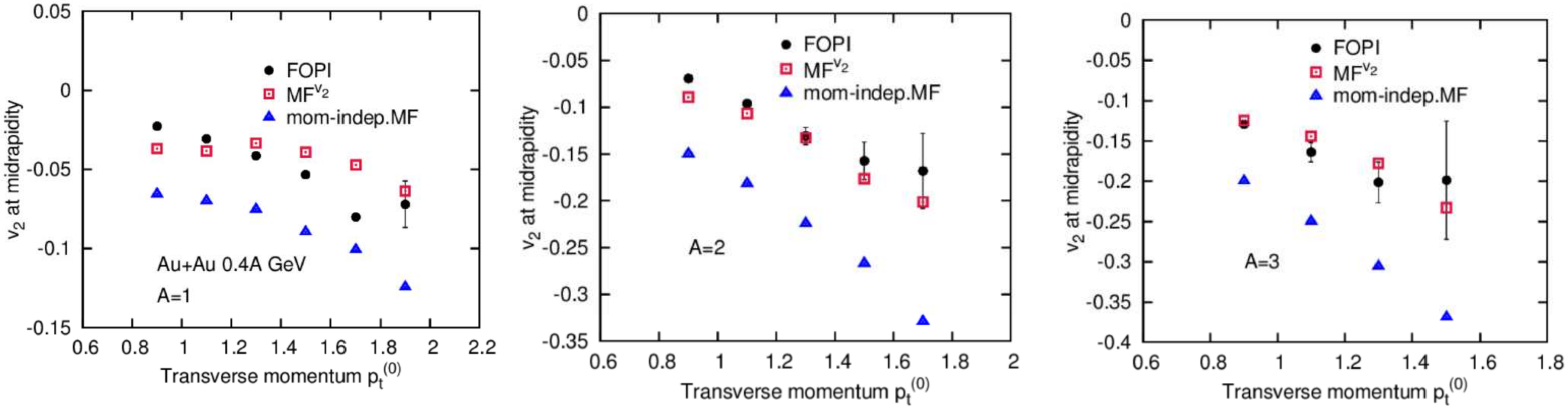
Au+Au 250AMeV $60^{\circ}<\theta_{cm}<90^{\circ}$

filled symbols
-- data, Poggi et al

open symbols
-- calculation



Elliptic flow: Au+Au, 400 MeV/A

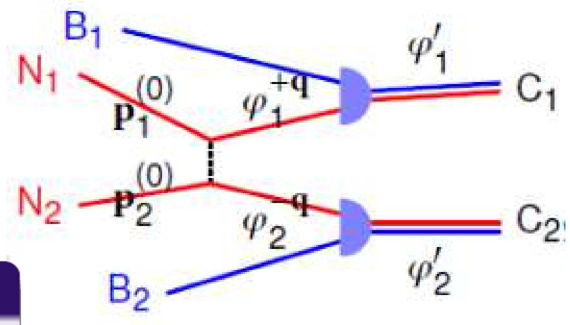


clusters enhance collective motion

Treatment of Light Cluster dynamics in HIC: Mol. Dynamics

QMD: no light cluster correlations
AMD, NN collisions with cluster formation, A. Ono. N. Ikeno, NuSYM2017, Transport 2019

- N_1, N_2 : Colliding nucleons
- B_1, B_2 : Spectator nucleons/clusters
- C_1, C_2 : N, $(2N)$, $(3N)$, $(4N)$ (up to α cluster)



Transition probability

$$W(\mathrm{NBNB} \to \mathrm{CC}) = \frac{2\pi}{\hbar}|\langle \mathrm{CC}|V|\mathrm{NBNB}\rangle|^2 \delta(E_f - E_i)$$

procedure: if decided that cluster is formed, then
- put nucleons into cluster wave function (in momentum space), conserving energy-momentum
- propagate constituent nucleons like any nucleon
- cluster may be desgtroyed , when one or both nucleons collide with another nucleon

to take into account approx. the medium dependence of the cluster:

condition to switch on clusters

$$\rho' < \rho_\mathrm{c}, \qquad \rho_\mathrm{c} = 0.125\ \mathrm{fm}^{-3} \text{ or } 0.060\ \mathrm{fm}^{-3} \text{ etc.}$$

ρ' momentum dependent density $\rho_i'^{(\mathrm{ini})} = \left(\frac{2\nu}{\pi}\right)^{\frac{3}{2}} \sum_{k(\neq i)} \theta(p_\mathrm{cut} > |\mathbf{P}_i - \mathbf{P}_k|)\, e^{-2\nu(\mathbf{R}_i - \mathbf{R}_k)^2}$, etc.

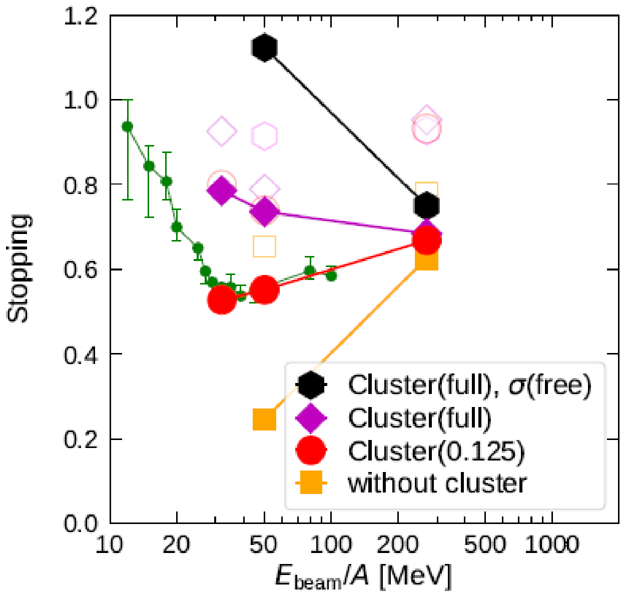
$\rho' = (\rho_1'^{(\mathrm{ini})} \rho_1'^{(\mathrm{fin})} \rho_2'^{(\mathrm{ini})} \rho_2'^{(\mathrm{fin})})^{\frac{1}{4}}$ $\quad p_\mathrm{cut} = (375\ \mathrm{MeV}/c)\, e^{-\epsilon/(225\ \mathrm{MeV})}$, ε collision energy in NN cn

AMD: effect of clustering and influence of parameters

Central collisions ($b < 1$–2 fm)

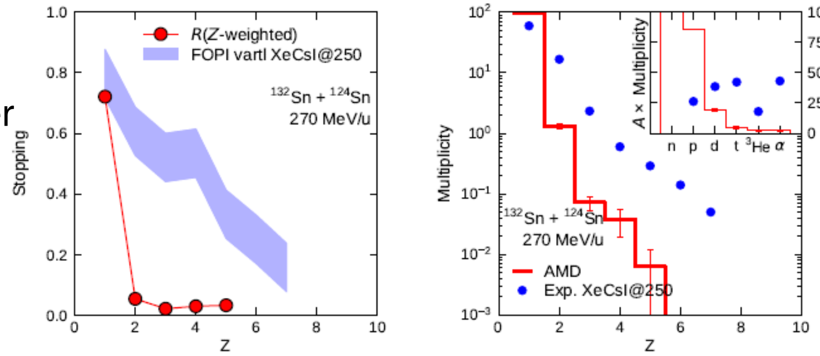
- Xe + Sn for $E \leq 50A$ MeV (INDRA)
- ^{132}Sn + ^{124}Sn at $270A$ MeV (FOPI)

stopping observable $R_E = \dfrac{\sum(E_x + E_y)}{2\sum E_z}$

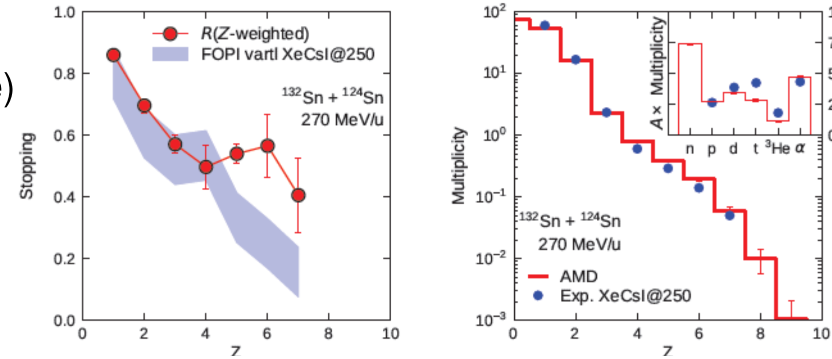


influence on collision dynamics:
- clusterization
- medium efects of cluster
- medium effect of NN cross sect.

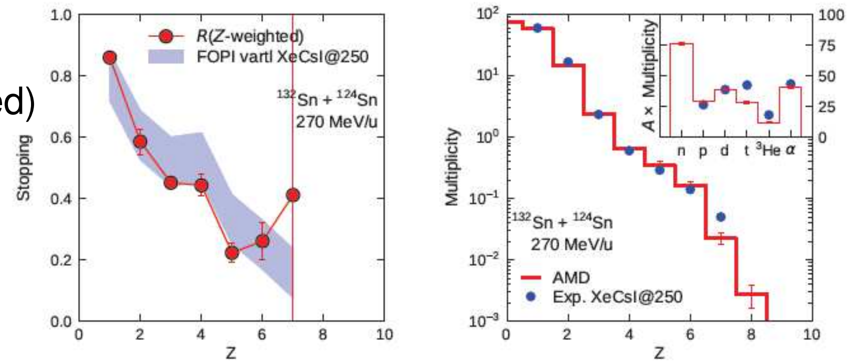
without cluster



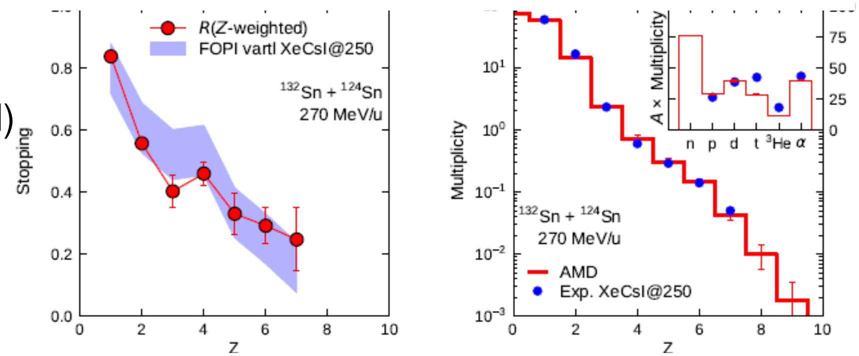
full cluster and $d\sigma_{NN}$(free)



full cluster and $d\sigma_{NN}$(in-med)



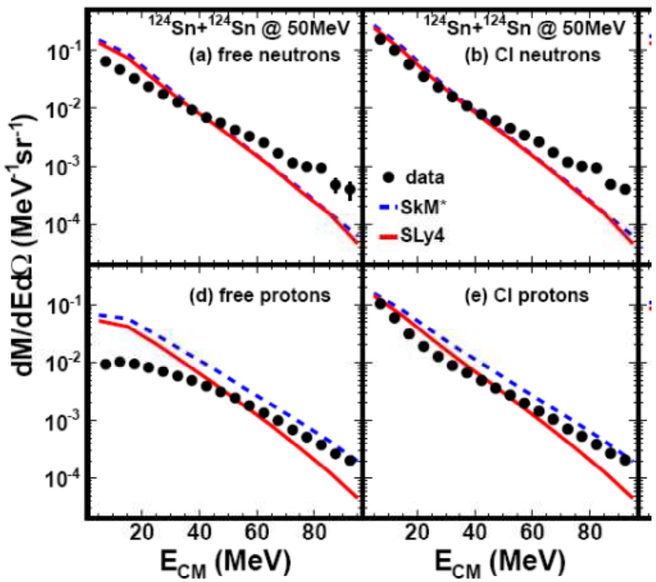
full cluster, cut-off ρ_c=0.125 and $d\sigma_{NN}$(in-med)



Light cluster yields to determine the symmetry energy

$$E^{nm}(\rho,\delta) = E_0(\rho) + E_{sym}(\rho)\delta^2 + \dots$$

p,n spectra: free coalescence invariant (CI)

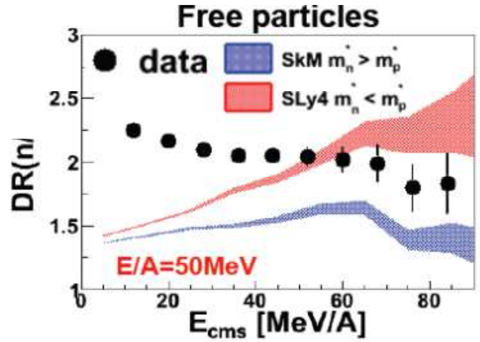


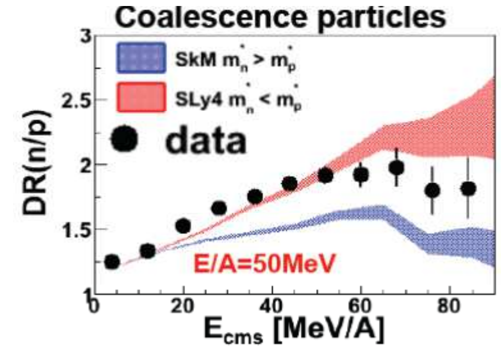
SkM $m_n^*>m_p^*$
SLy4 $m_n^*<m_p^*$

Double Ratios

$$\frac{{}^{124}Sn + {}^{124}Sn}{{}^{112}Sn + {}^{112}Sn}$$

agree only for CI spectra

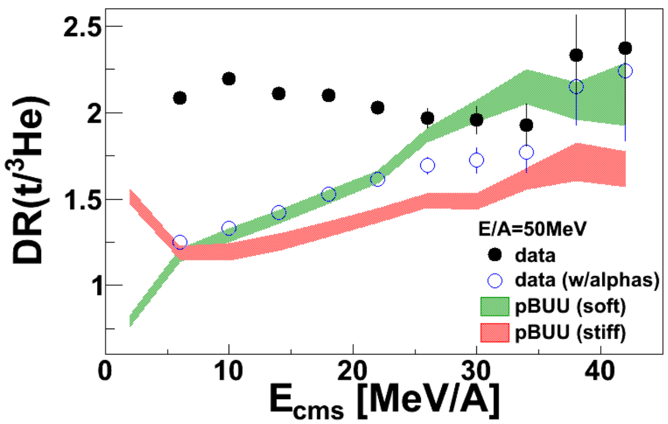




Y.X. Zhang, M.B.Tsang,et al., PLB 732, 186 (2014)
D.D.S.Coupland, et al., PRC 94, 011601(R) (2016)

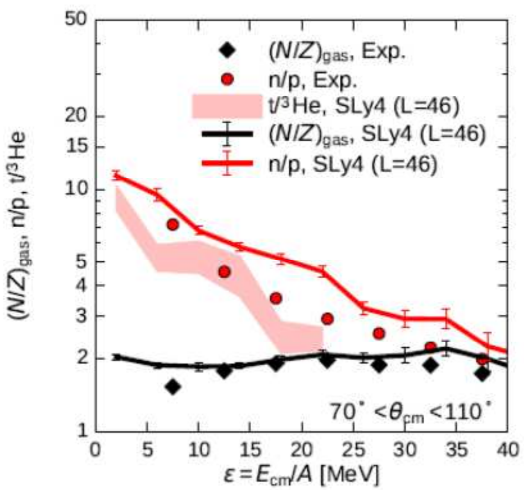
..or with calculation, where clusters are included explicitely

1. pBUU, when exp. α-particles are counted as t and 3He
(Z. Chajecki, NuSYM 13)



2. AMD with clusters
(A. Ono, NuSYM2015):
n/p (and t/h) ratios only reproduced if α-clusters included

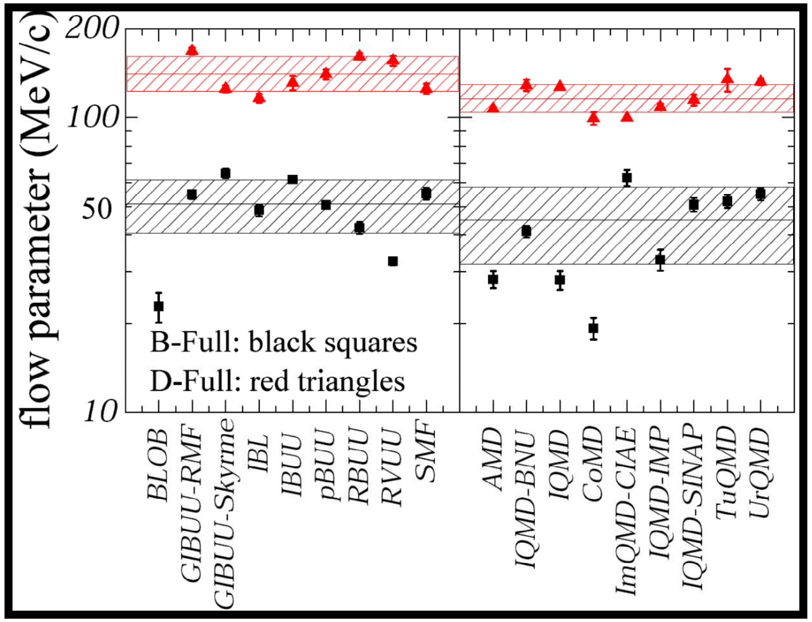
Ratios: n/p, t/3He, $(N/Z)_{gas}$



How much can one trust results of transport calculations, esp. when clusters and fragments are the issue?
--> Code Comparison Project (some brief remarks)

Comparison of all major transport codes under controlled and as far as possible identical conditions.
several stages:

1. full HIC, Au+Au, 100 and 400 MeV/A, semicentral
(J. Xu et al., Phys. Rev. C 93, 064609 (2016)



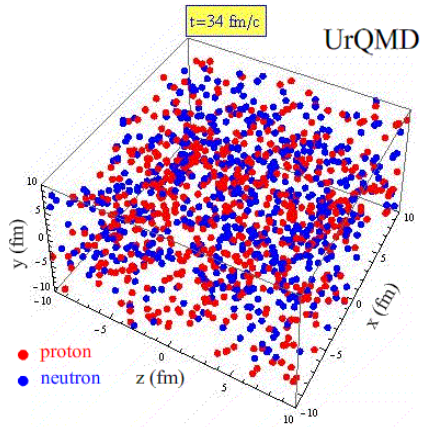
quantify spread of simulations by value of flow parameter =slope of transverse flow at midrapidity
BUU and QMD approx. consistent

uncertainity

100 AMeV: ~30%
400 AMeV: ~13%

rather large differences, esp. at lower energy
reason not easy to isolate: initializations, blocking, ?

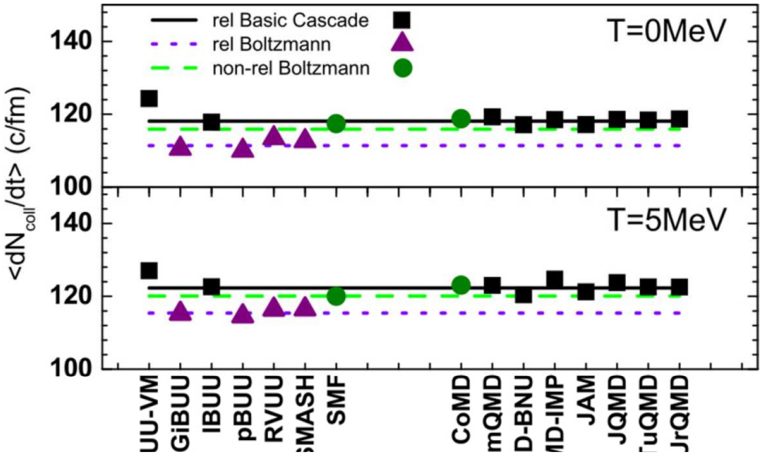
--> easier system: box calculations, evolution in a periodic box
test ingredients separately
compare to exact results

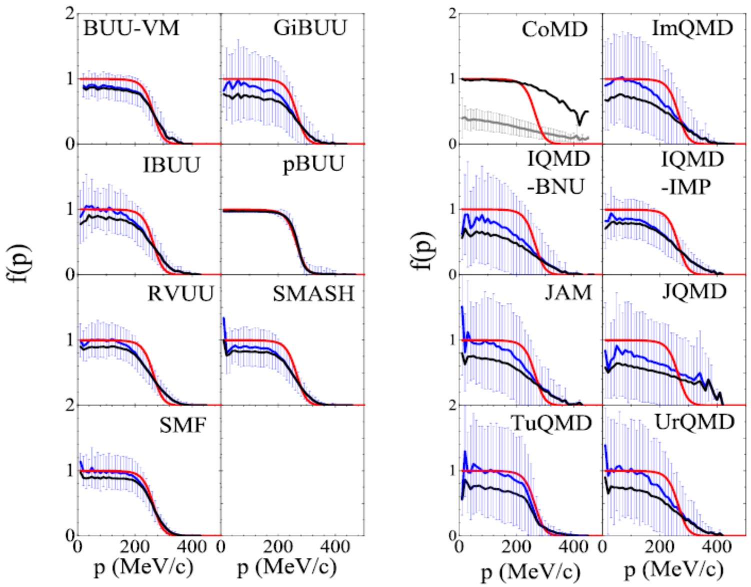


Code Comparison (cont'd):

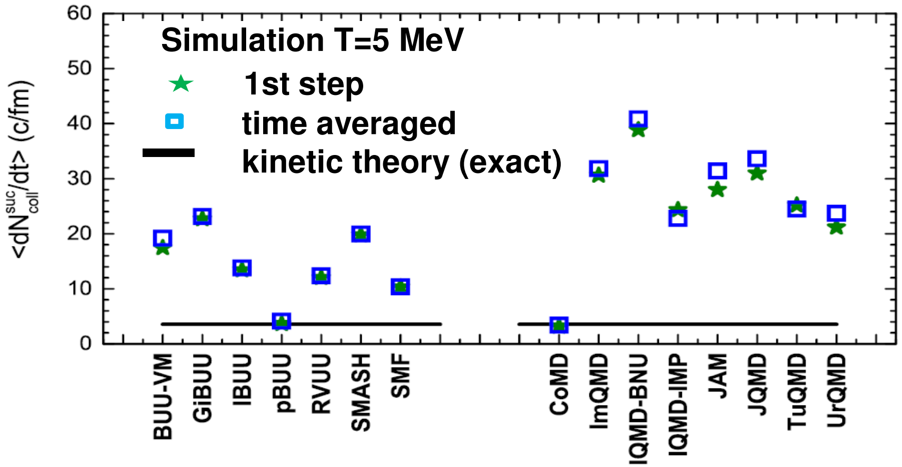
2. Box Cascade calculation (only collisions)
(Y.X. Zhang, et al., Phys. Rev. C 97, 034625 (2018)

without blocking
Comparison to exact limit





with blocking

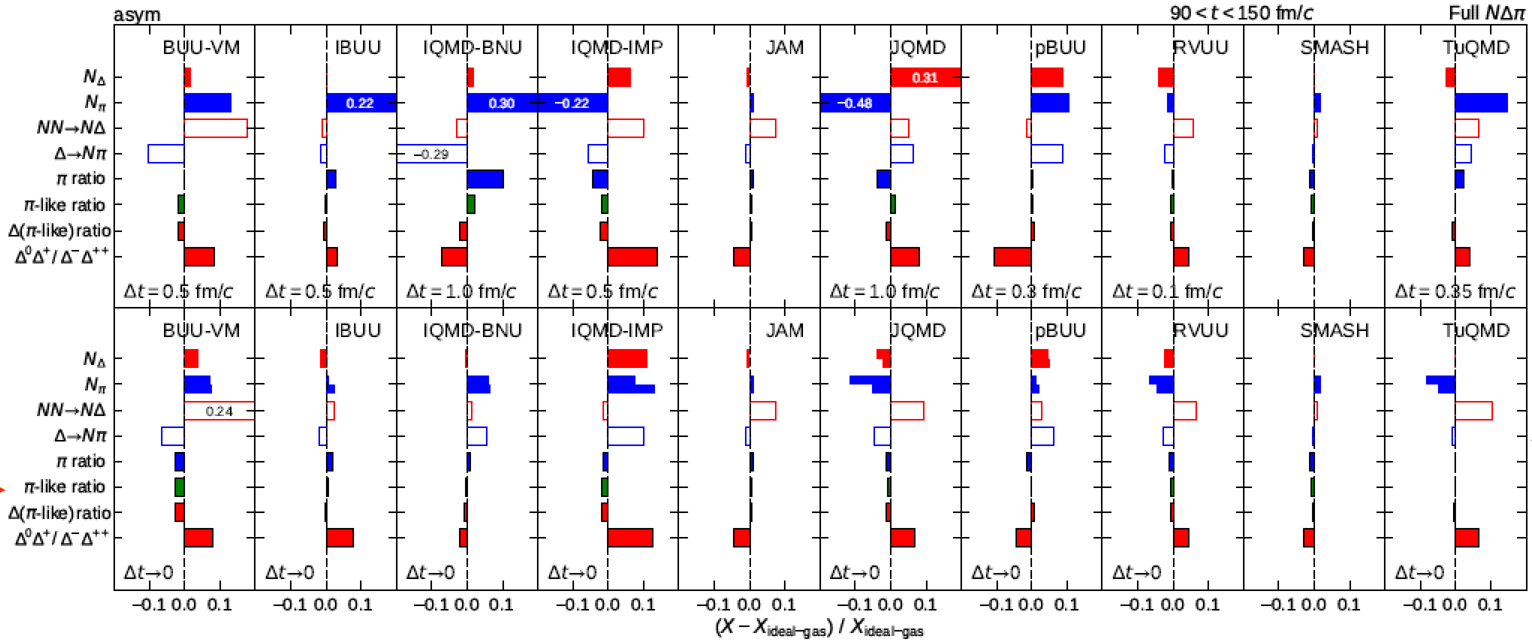


systematic difference between BUU and QMD type
reason: fluctuations of sampled distribution fct
and blocking

Code Comparison (cont'd):

3. Pion production in Cascade (w/o mean field and blocking)
(A.Ono et al., arXiv1904.02888 (2019))

deviations of calculated quantities from exact values (depending on time step Δt



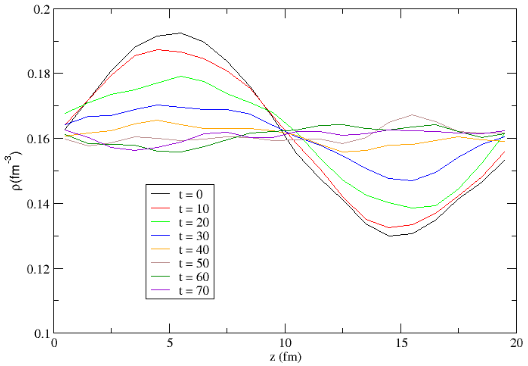
Δt finite

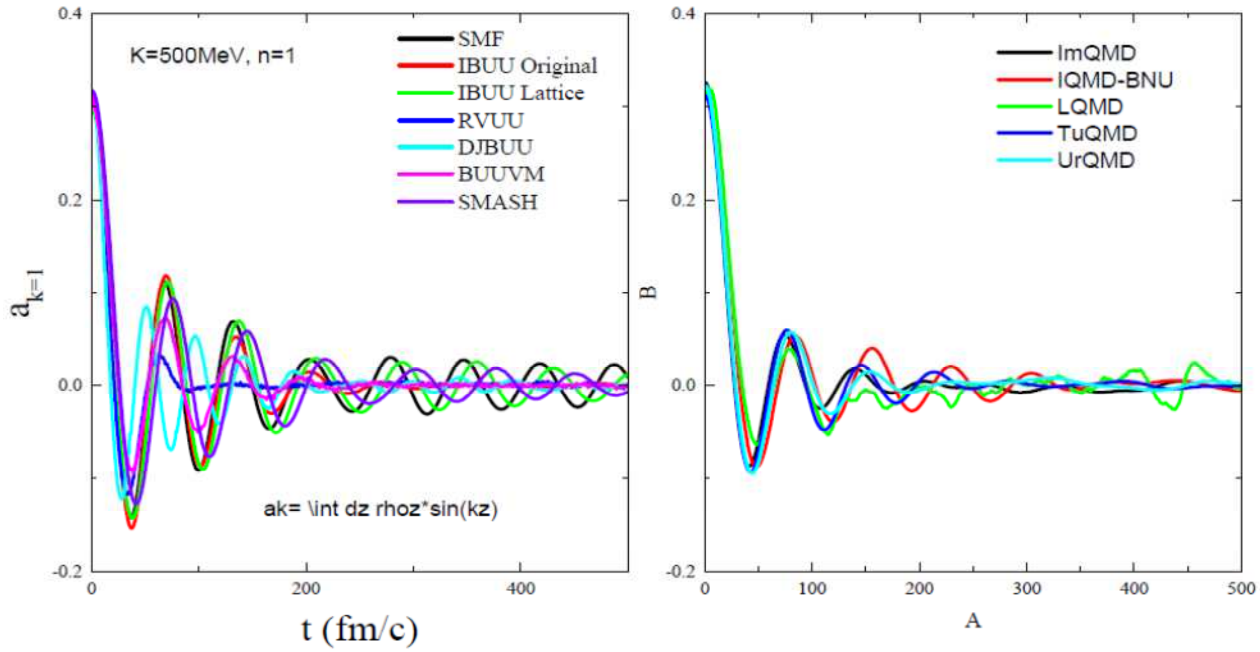
extrapolation
Δt -> 0

π–like ratio corresponds to the measured π–/π+ ratio, which is a probe of the symmetry energy
agrees to within 5% between codes, even though larger differences for other quantities (understood)

Code Comparison (cont'd):

4. box-Vlasov calculation, only mean field propagation,(in progress, preliminary)
   evolution of standing wave and time dependence of Fourier components





differences in damping and in frequency
-->related to fluctuations and smoothing of forces due to finite width particles

Code Comparison (cont'd):

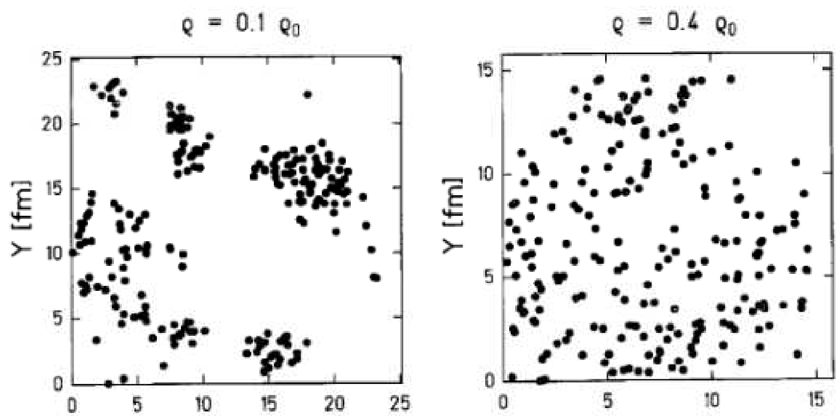
5. Further plans

a. Pion production in HIC (in progress)

b. Clustering and fragmentation in a box

initialize system in instability region

and test rise time and amount of cluster and fragment formation



Summary: Clusters and Fragments in Heavy Ion Collisions:

→ Clusters are ubiquitous in HIC (at low and intermediate energies)
important for analysis (observables depend on treatment of clustering)

→ contain important information on the state of the system
(e.g. equilibration, temperature, density, symmetry energy, etc)

cluster production in HIC

statistical

secondary decay: canonical ensemble
isotopic scaling: grand canonical ensemble

well developed and often successful
but always justified?

dynamical

influence evolution of the reaction
medium modified clusters

light clusters

few body correlations,
beyond mf, treat as explicit
degrees of freedom

IMF

fluctuations and mean
field
+coalescence

area of development, different ways BUU, QMD (AMD)

possible tests in Code Comparison

Thank you