Fragment and Cluster Formation in Heavy Ion Collisions

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FUSTIPEN Topical Meeting on
Dynamical cluster formation and correlations in heavy-ion collisions,
within transport models and in experiments
May 17-19, 2016, GANIL, Caen, France

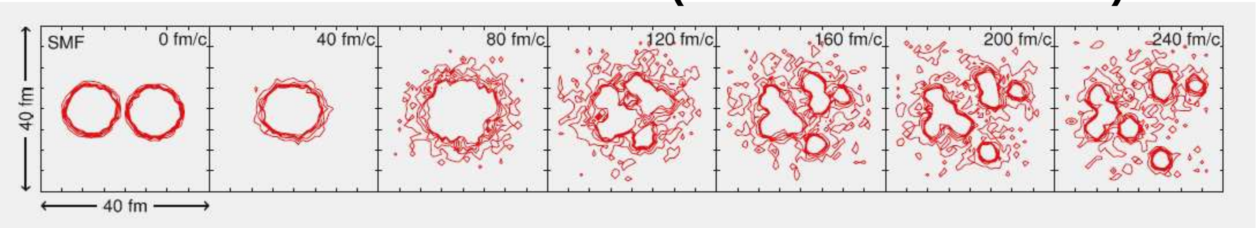
Fragment and Cluster Formation in Heavy Ion Collisions

very wide subject: Essentially the subject of the meeting
introductory remarks and overview,
subjects discussed in much more detail in later talks
P. Danielewicz, J. Natowitz, P. Napolitani, G. Verde, R. Bougault, et al.

Aim of this talk:

- → **emphasize the importance of correlations and clustering in the study of the EoS in HIC, in particular the symmetry energy**
- → **discuss what is involved in a proper treatment**
- → **stress simple concepts, and open problems**

Clusters (A≤4)
(correlation stabilized)



Fragments (Int. Mass Fragm. IMF, A>4)
(mean field stabilized)

large fractions of particles in clusters, e.g.

Partitioning of protons

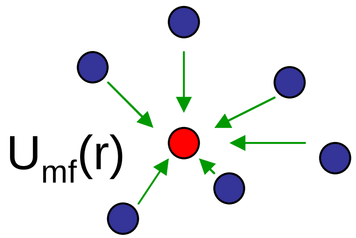
	Xe + Sn 50 MeV/u	Au + Au 250 MeV/u
p	≈10%	21%
α	≈20%	20%
d, t, ^{3}He	≈10%	40%
$A > 4$	≈60%	18%

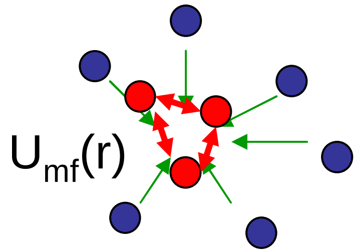
INDRA data, Hudan et al., PRC67 (2003) 064613.
FOPI data, Reisdorf et a **from A. Ono**

My Collaborators:
M. Colonna, M. Di Toro, J. Rizzo (Catania), M. Zielinska-Pfabe (Smith College, USA)
Theo Gaitanos (Univ. Thessaloniki) ; T. Mikhailova (JINR, Dubna)
Stefan Typel (GSI), Gerd Röpke (Rostock), David Blaschke (Wroclav)
- but use material from many other workers in the field

the two
main players:

mean field (mf) ⟺ clustering



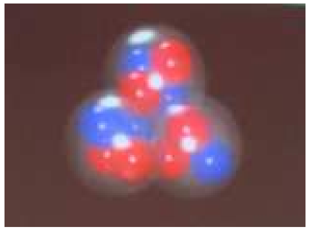


particle in a mean field,
one-body approach

few-body correlation
in a medium
(medium-modification of cluster)

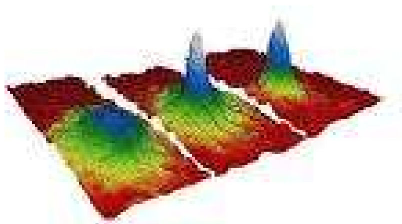
Examples:

1.) e.g. pairing. can be converted into a one-quasi-particle picture.
→ well studied

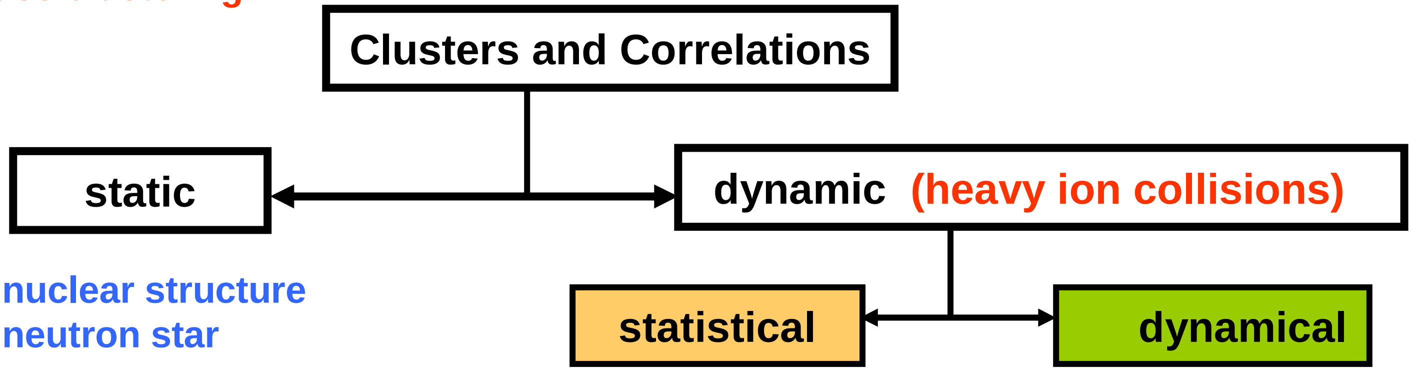


2.) quartetting, α-correlations

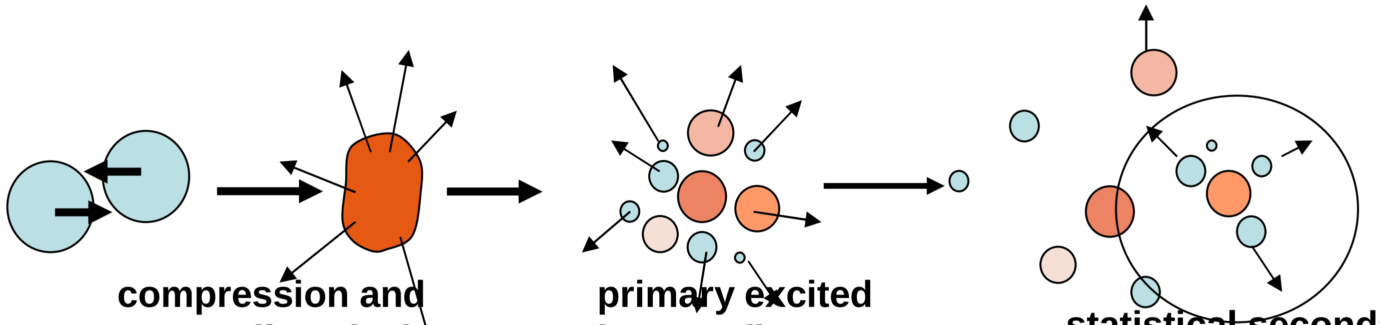
3.) BEC, other fields,..



… correlations: the seeds to clustering and cluster production scheme to discuss clustering



nuclear structure
neutron star
supenovae
(other talks)

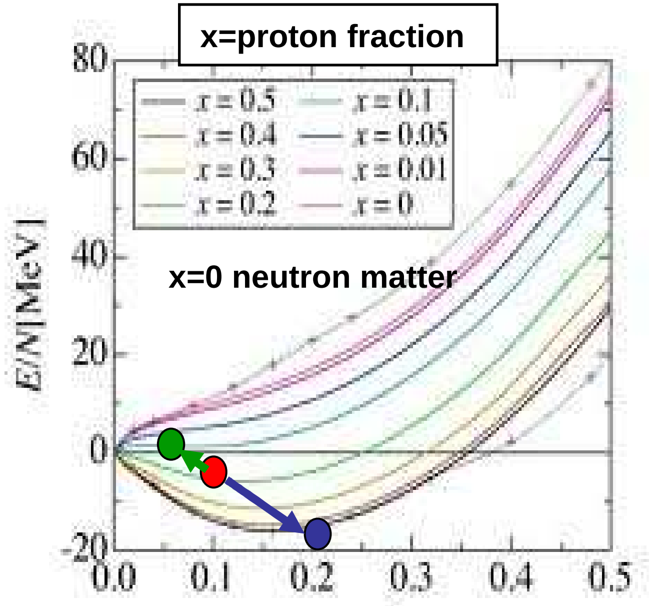


statistical or dynamical?

Freeze-out approximation: assume:
A, Z, volume, excitation energy E*/A
statistical decay code: SMM, Gemini++, SIMON, etc. („afterburner“)
canonical ensemble: E,ρ

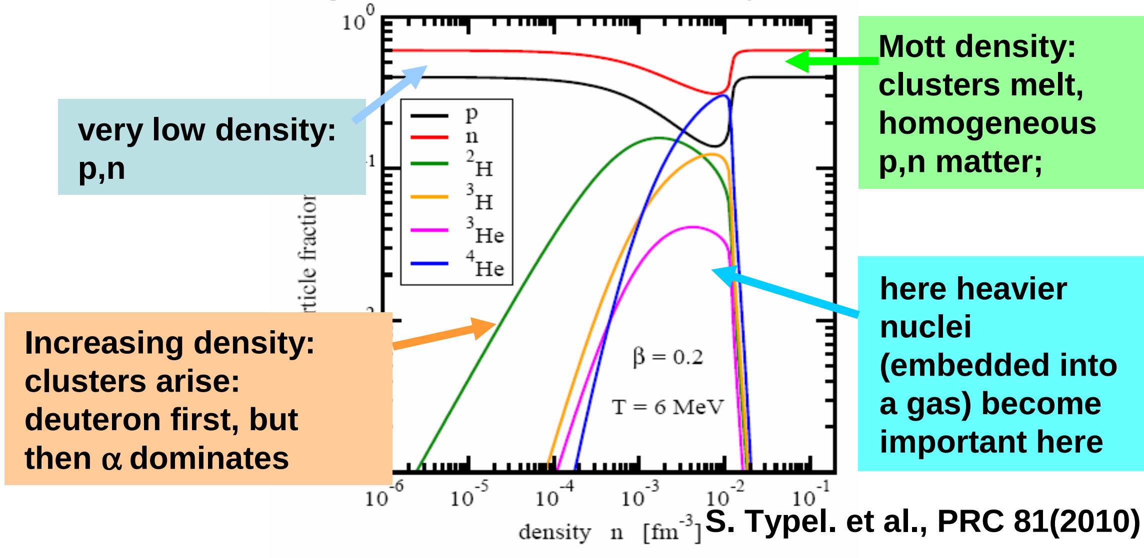
in statistical treatment often use
grand canonical ensemble: T,μ
„unreasonable successfull“, examples

Remark about statistical application: Clustering of very dilute nuclear matter



decrease energy by inhomogeneity
→ fractionation into clusters of higher density
and neutron gas

composition as fct of density; x=0.2, T=6 MeV



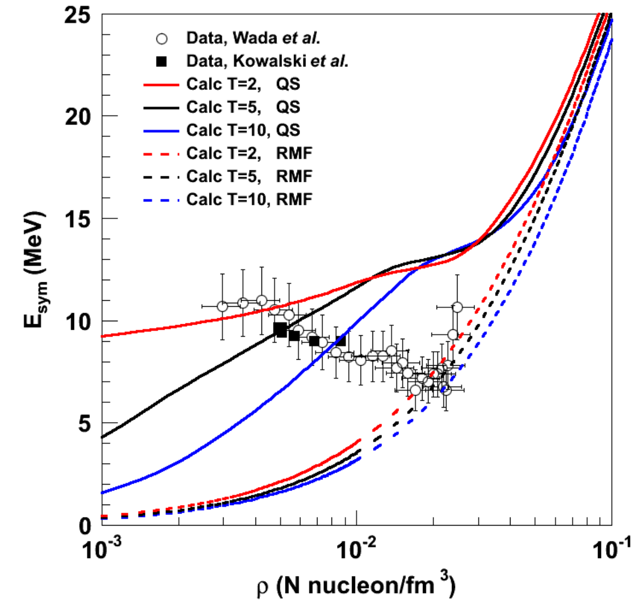
S. Typel. et al., PRC 81(2010)

Can be checked in heavy ion collisions
under the assumption of statistical decay

Semi-central heavy ion collisions,
(^{64}Zn+^{92}Mo,^{197}Au at 35MeV/A)
and time-resolved measurement of light fragments from decay of fireball:

S. Kowalski, J. Natowitz, et al., PRC75 014601 (2007)
J. Natowitz, G. Röpke,…, PRL 104, 202501 (2010)

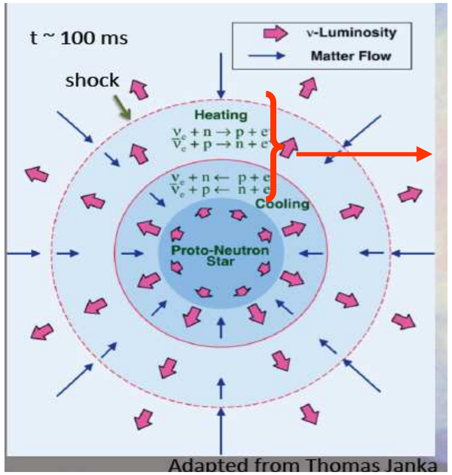
extract symmetry energy and compare with quantumstat. calculation of clustered matt



Relevance for Supernovae physics?

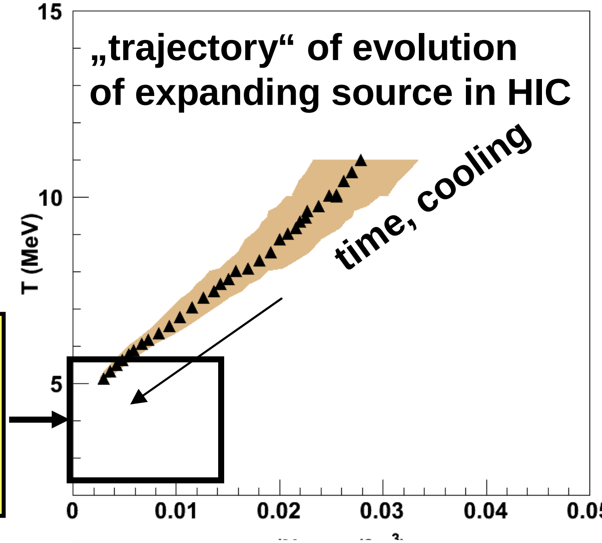
Results relevant for neutrino opacity in ν-sphere in Core Collapse Supernovae
→ workshop in ECT*, Trento, 2014

Simulating the supernova neutrinosphere with heavy ion collisions
7-11 April, 2014



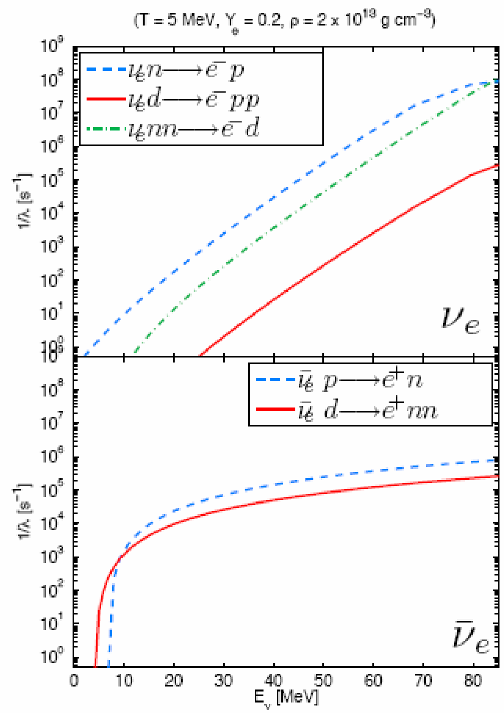
ν–sphere

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



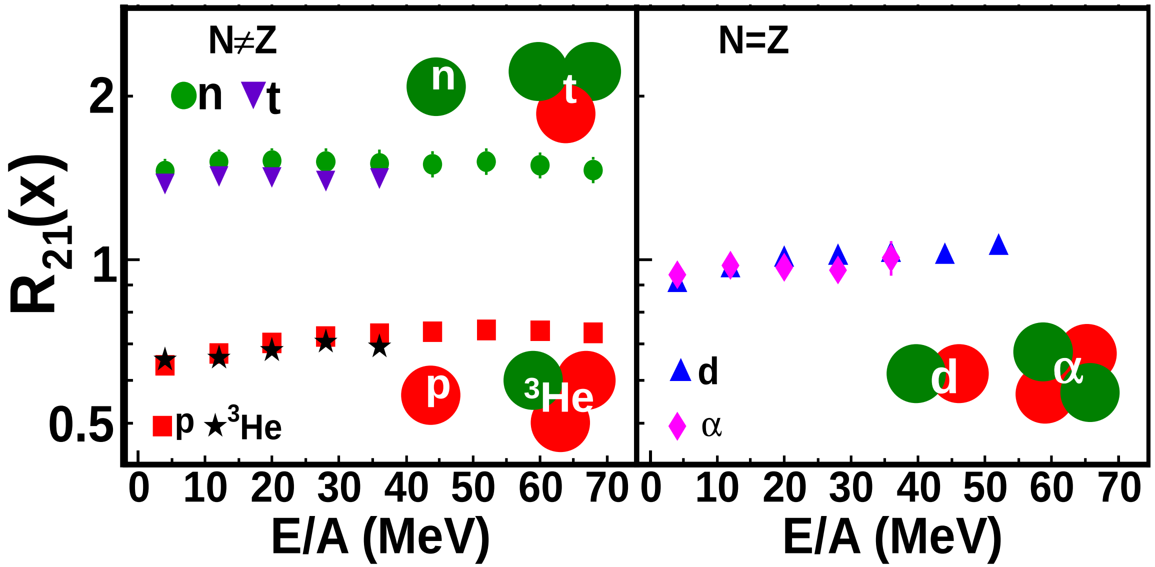
Super-Nova ⟺ Femto-Nova (heavy ion collision)

calculation by T. Fischer (Wroclaw),
ν and anti–ν absorption on nucleons and light clusters,
effect of clustering does not seem to be large



but see also talk of S. Burrello at IWM-EC15 on influence of pairing correlations

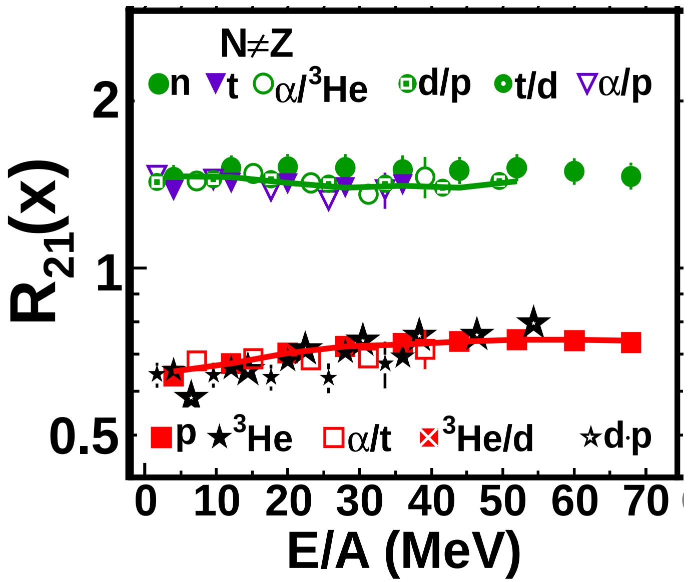
„Chemical potential scaling“ Z.Chajecki, et al., arXiv 1402.5216

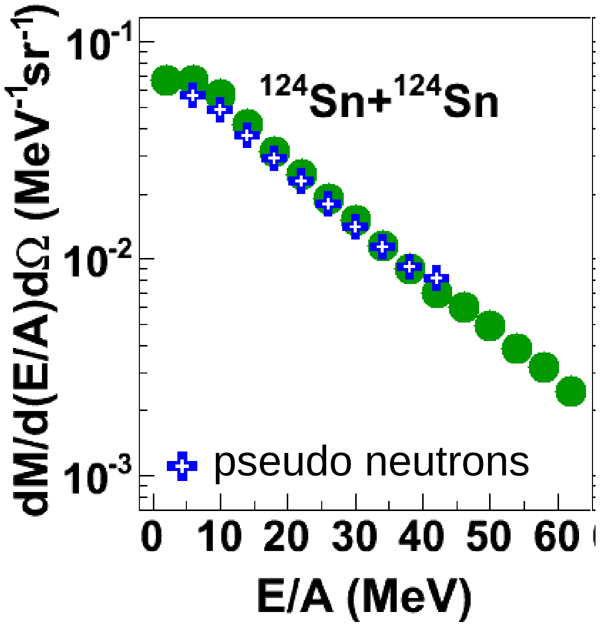


$$R_{21}(N,Z) = \frac{dM_2(N,Z)}{dM_1(N,Z)}$$

expect from chemical potential dependence without correlation contributions

$$R_{21}(N,Z) = \exp\left[\left(N\Delta\mu_n + Z\Delta\mu_p\right)/T\right]$$





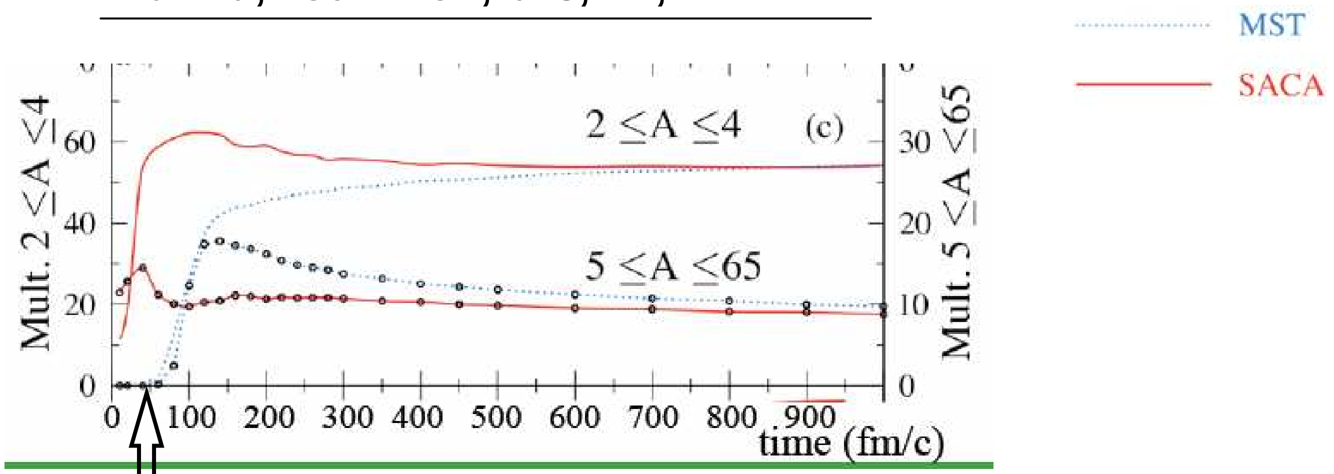
$$\Rightarrow Y(n) = \frac{Y(t)}{Y(^3He)} Y(p)$$

“Pseudo neutron yields”

correlation effects seem to be small for light cluster yields (?)

Dynamical cluster and fragment formation in HIC

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



SACA (simulat. Annealing and Cooling Algorithm):
clusters identified earlier than in coalescence methods (MST minimal spanning tree algorithm) (Vermani,..Aichelin, J.Phys.G 37 (2010)),

→ **early identification in SACA method does not influence dynamics,**

→ **but indicates that fragments are dynamical**
→ **what determines the formation of clusters and fragments?**

correlations ⟺ **fluctuations**

The crucial issue in Fragment and Cluster formation in HIC collisions:

correlations $\Leftrightarrow$ fluctuations

How correlations got lost:
BBGKY hierarchy of coupled
Green fcts. is truncated (formally)
by introduction of self energy Σ

$$D(1)G^{(1)}(1,2) = \delta(1-1') + (12\,|\,V\,|\,1'2')\,G^{(2)}(12,1'2')$$
$$=: \delta(1-1') + \Sigma(1,1'')\,G^{(1)}(1'',2)$$

This neglects higher order correlation effects

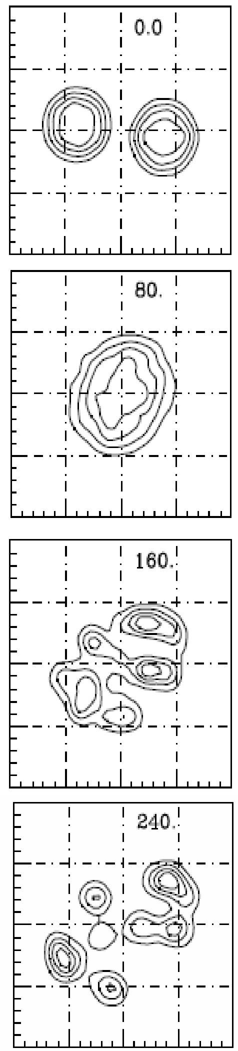
They have to reintroduced
- in the form of fluctuations (for fragments, IMF)
- explicitely (for light clusters, LC)

discuss next , how this is handled in BUU and QMD approaches

1. Boltzmann-Uehling-Uhlenbeck (BUU) $f(\vec{r},\vec{p};t)$ 1-body phase space distribution fct.

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

Derived: → From non-equilibrium theory (Kadanoff-Baym); collision term included,
→ quasi-particle approx., i.e. spectral function on-shell
→ deterministic, no fluctuations
→ test particle method, exact for NTP→∞



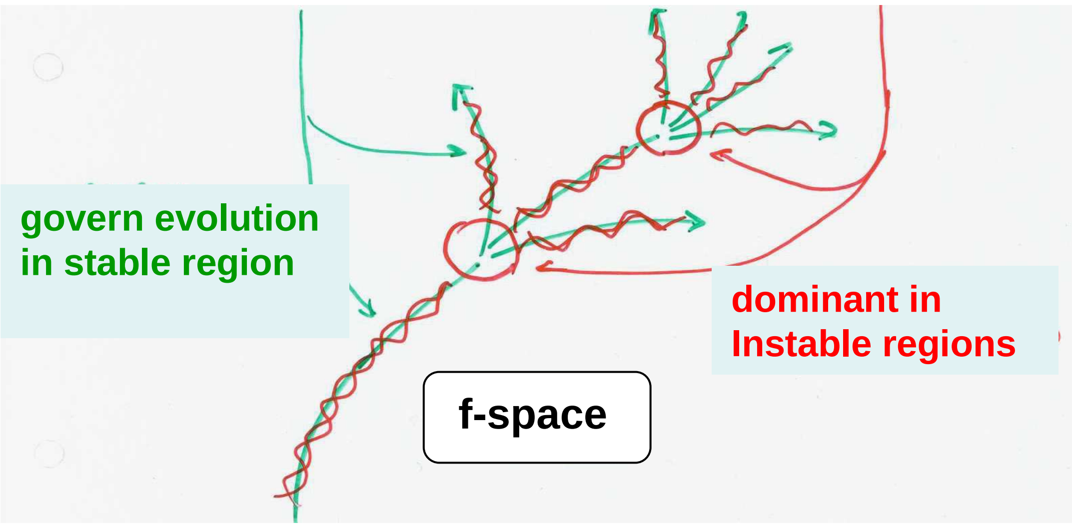
include fuctuations around dissipative solution

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

Mean field evolution (dissipative) fluctuations

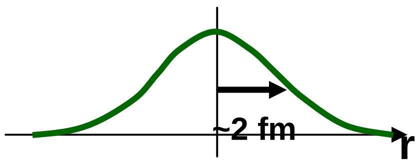
$$\frac{df}{dt} = I_{coll} + I_{fluc}$$

Boltzmann-Langevin eq.



2. Molecular Dynamics (QMD)

can be derived in two ways (two parents)



a) Classical Molecular Dynamics with Gaussian particles to reduce fluctuations

b) from Time-Dependent Hartree , using a product wave function

$$\Psi(\vec{r}_1,\cdots,\vec{r}_N;t)=\prod_i \phi_i(\vec{r}_i;t)$$

$$\phi_i(\vec{r}_i;t)=\frac{1}{(2\pi L)^{3/4}}\exp\left(-\frac{(\vec{r}_i-\vec{R}_i(t))^2}{4L}+i\vec{r}_i\vec{P}_i(t)\right)$$

both lead to the same equations of motion of wave packets centers

$$\frac{dr_i}{dt}=\{r_i,\mathcal{H}\};\quad \frac{dp_i}{dt}=\{p_i,\mathcal{H}\};\quad H=\sum_i t_i+\sum_{i<j}V_{ij}$$

c) Antisymmetrized MD (AMD,FMD):
Slater determinant wave function, antisymmetrization, eom are more complicated
also approximatively CoMD (constrained MD)

d) in all cases add a phenomenological collision term

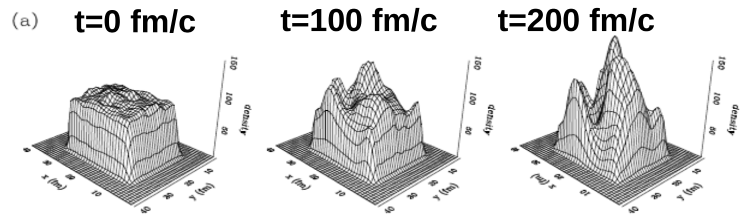
Thus QMD has no quantum correlations,
but classical N-body correlations, damped by the smoothing.

However, more fluctuations, 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 of single particle packet L

Intermediate conclusion:
Both BUU and QMD do not naturally have the correct fluctuations (except AMD)

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

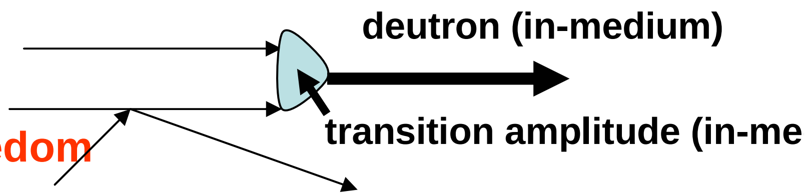
BUU calculation in a box (i.e. periodic boundary conditions) with initial conditions inside the instability region: $\rho=\rho_0/3$, T=5 MeV, $\delta=0$



→ 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
(P. Danielewicz and Q. Pan, PRC 46 (1992)) (d,t,3He, but no α!)

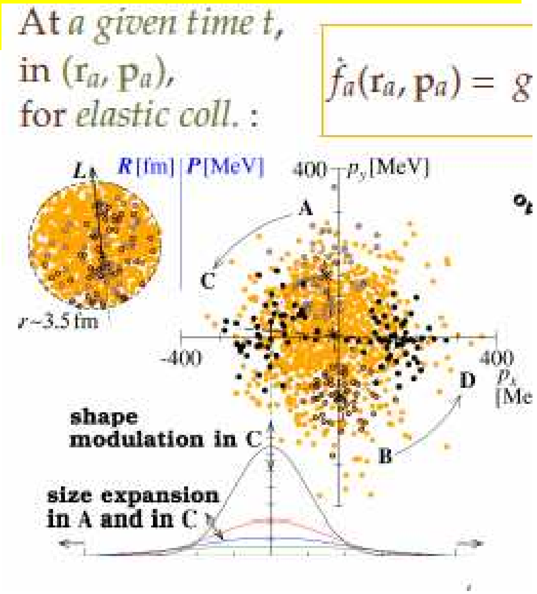


discuss next, how this is done in BUU and QMD

	LC	IMF
BUU	pBUU	BLOB
QMD	clustAMD	wp width

Methods to introduce fluctuations

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

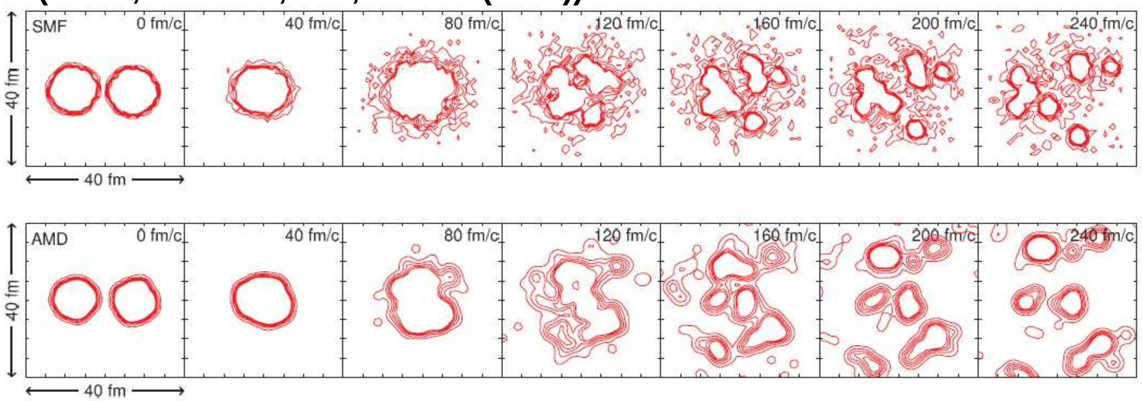


SMF (stochastic mean field): project on density fluctuations and introduce these „by hand“
BLOB (Boltzmann-Langevin One-Body dynamics) Move N_{TP} testparticles simultaneously (in p-space) to simulate fluctuation connected to NN collisions

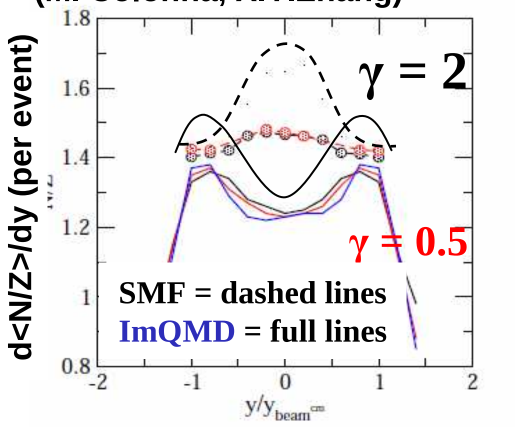
QMD: fluctuations controlled by wave packet width L:
L→ 0 classical point partucles, nuclei not bound
L→ ∞ complete smoothing, no fluctuations

Comparison of fluctuations:

Comparison of simulations: BUU(SMF)-AMD:
(Rizzo, Colonna,Ono, PRC82 (2010))



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



Check fluctuations in the context of the Code Comparison Project
see talk at IWM-EC 2016

check consistency of transport codes in calculations with same system (Au+Au), E=100,400 AMeV, and identical (simple) physical input (mean field (EOS) and cross sections)

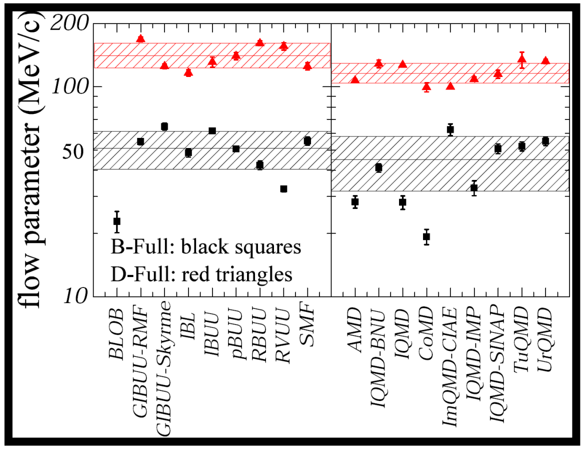
idea: establish sort of theoretical systematic error of transport predictions (and hopefully to reduce it)

quantify spread of simulations by value of „flow“=slope at midrapidity

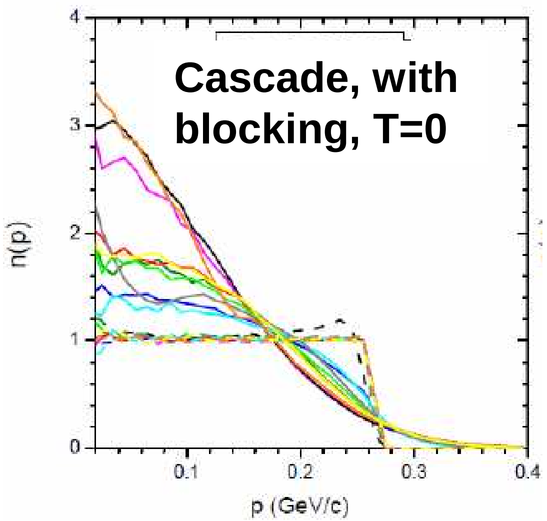
BUU and QMD approx. consistent

uncertainity

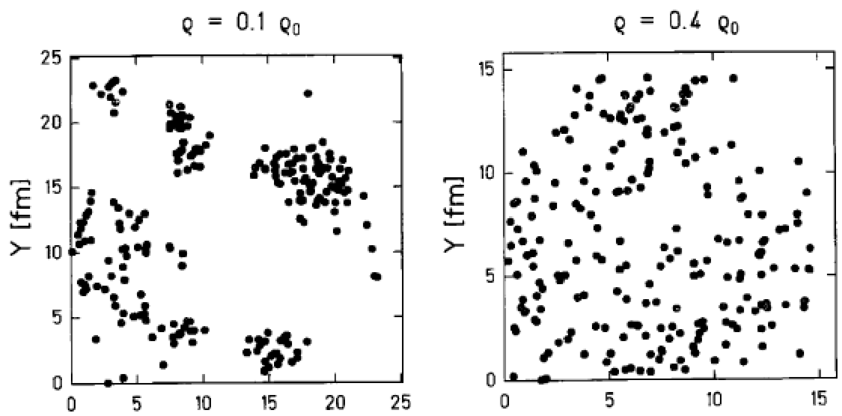
100 AMeV: ~30%
400 AMeV: ~13%



further development: box calculations
test collision routine and Pauli blocking under controlled conditions;



test also fluctuations and fragmentation

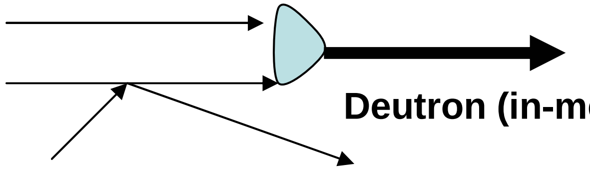


Treatment of Light Cluster dynamics in HIC: BUU

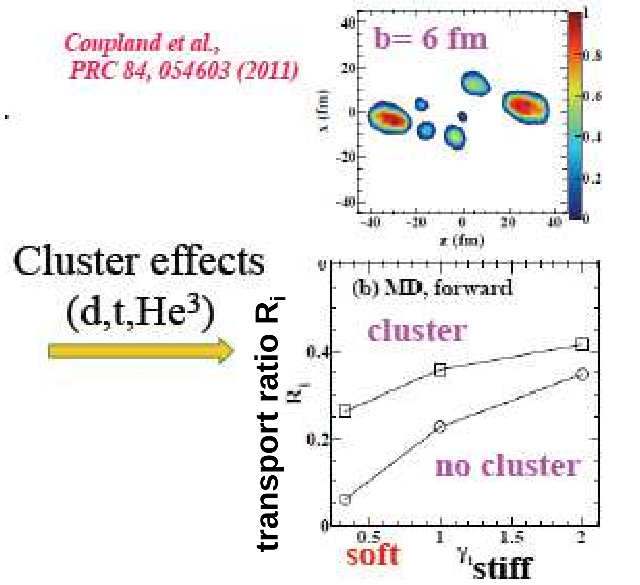
circumvent: compare to „coalescent invariant“ cross sections
only justified if clusters play no dynamical role

solutions: different in BUU and Mol.Dyn.(MD) models:

Solution for BUU models:
LC distribution functions as explicit degrees of freedom of type NNN→NΔ
(P. Danielewicz and Q. Pan, PRC 46 (1992))
(d,t,3He, but no α!)
→ coupled transport equations



pBUU calculations (Danielewicz)



Caveat: Medium properties of LC:

Medium modification of properties and transition amplitudes of light clusters in heavy ion reactions
C. Kuhrts, Beyer, Danielewicz,..PRC63 (2001) 034605

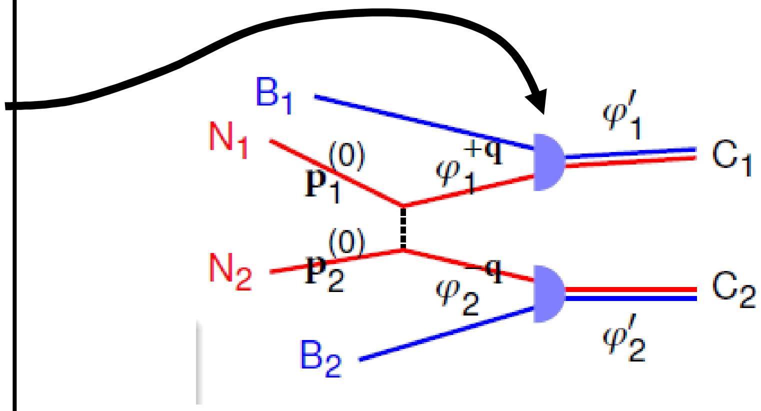
Calculated in nuclear matter and static nuclei in Generalized RMF approach by Typel, Röpke,et al., PRC81 (2010)
→ see talk by S. Typel

R_i: isospin transport ratio for charge equilibration in HIC between nuclei with different isospin content e.g. ^{112,124}Sn+^{112,124}Sn (MSU experiment)

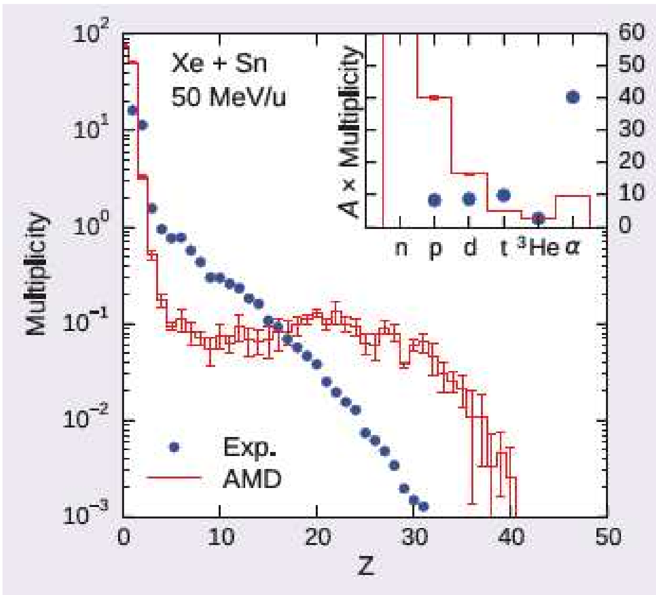
Treatment of Light Cluster dynamics in HIC: QMD

Solution für **AMD**

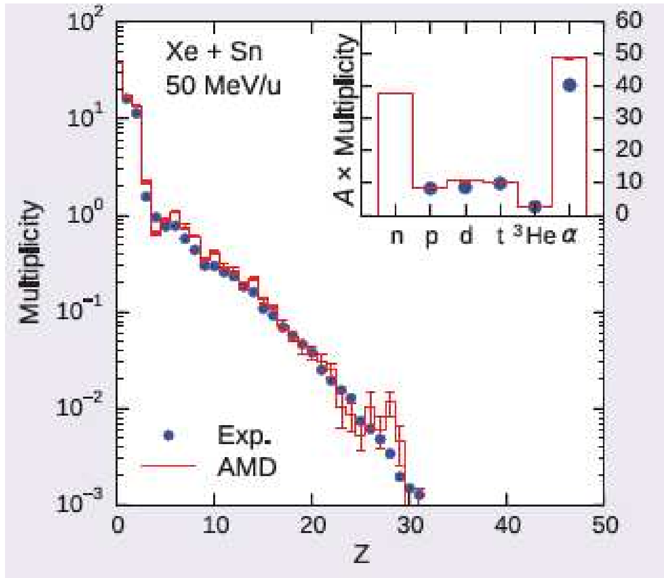
1. in collision term consider formation of clusters in terms of overlap with cluster wave function
2. manipulate phase space: put wave packets of cluster constituent in one place (conservation laws?)
3. consider Pauli principle fully
4. include also cluster-cluster collisions to form bigger clusters



multiplicity distribution w/o clusters



with clusters and cluster-cluster collisions



(A. Ono, NuSYM2015)

Clustering ⟺ Symmetry Energy.   Relevance to workshop?

nucleons come in two flavors: n, p

→   nn,pp interactions different from pn interaction (stronger)

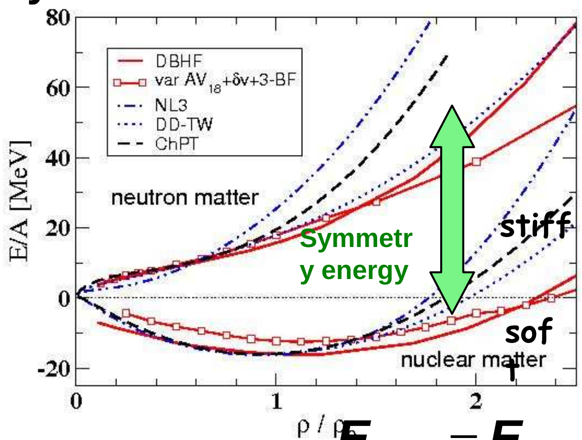
→ in asymmetric system: → U_p and U_n different→ symmetry energy

density-asymmetry dep. of nucl.matt.

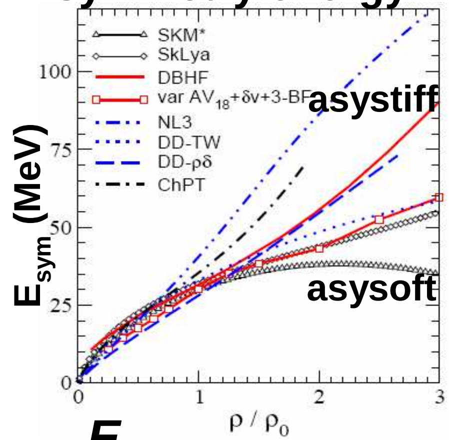
$$\varepsilon(\rho_B,\delta)=\varepsilon_{nm}(\rho_B)+E_{sym}(\rho_B)\delta^2+O(\delta^4)+\dots \qquad \delta=\frac{\rho_n-\rho_p}{\rho_n+\rho_p}$$

$$U(\rho,k;\delta)=\frac{\partial\varepsilon(\rho,\delta)}{\partial f(\rho,k)}=\underbrace{U_0(\rho,k)+U_{sym}(\rho,k)(\tau\delta)}_{U_\tau(\rho,k)}+\dots$$

symmetric and neutron matter

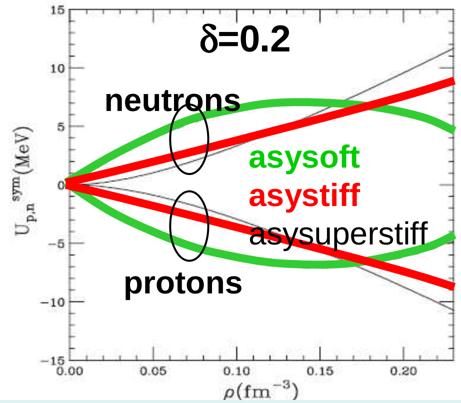


symmetry energy



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

symmetry potential



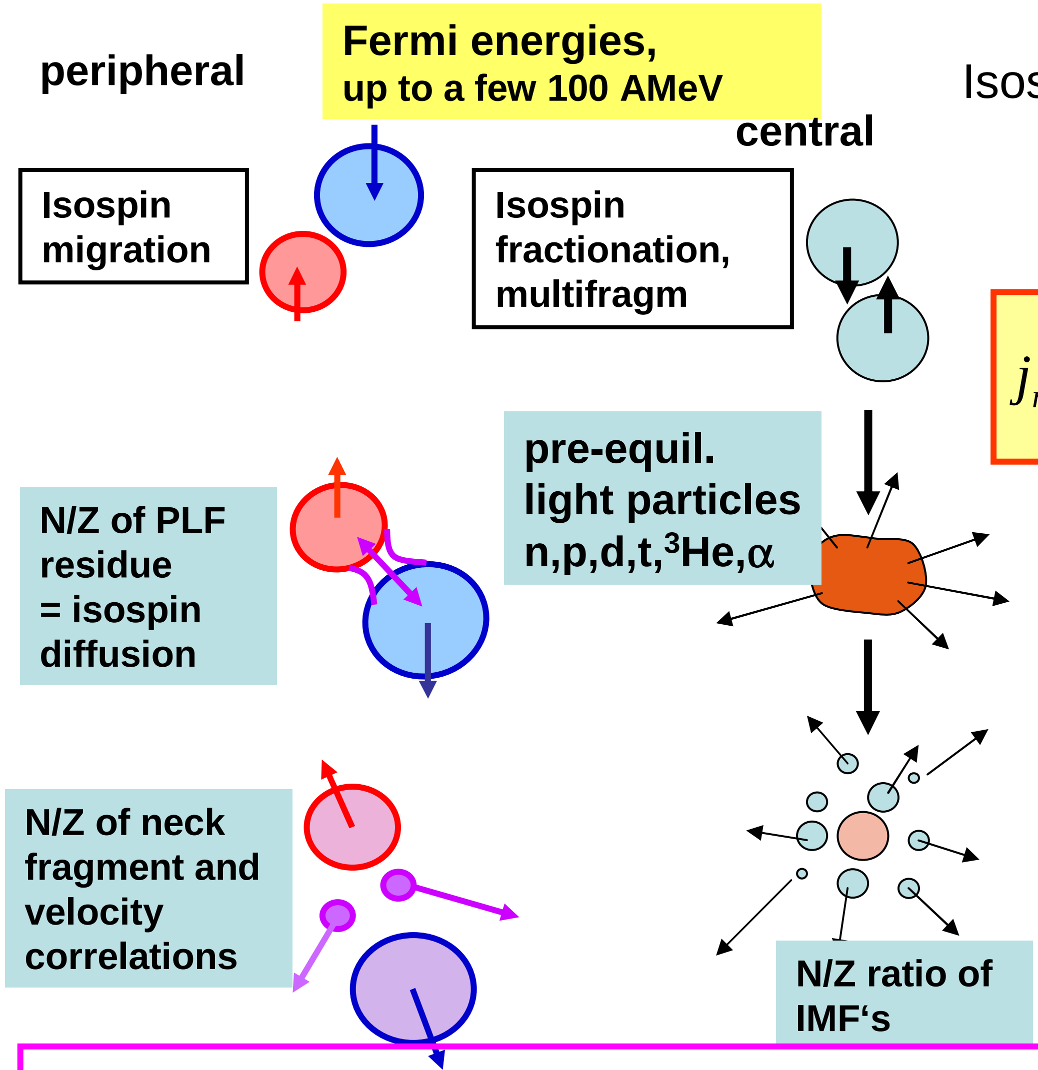
$$E_{sym}=E_{neutr.matt}-E_{nucl.matt}$$

..also momentum dependence
→ effective mass splitting

where does the symmetry energy come in?

1. **clusters properties are driven by the symmetry energy, i.e. the N/Z ratio**
2. **isospin fractionation between clusters and gas**
3. **clusterization gives a direct contribution to the symmetry energy: correlation depends on asymmetry of system; stronger in symmetric system**

Isospin sensitive Observables in Heavy Ion Collisions



Isospin transport:

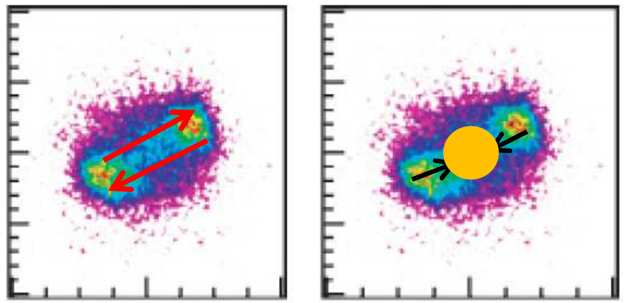
$$j_n = D_n^{\rho}\nabla\rho + D_n^{I}\nabla I$$

$$j_p = D_p^{\rho}\nabla\rho + D_p^{I}\nabla I$$

"drift" "diffusion"

$$j_n - j_p \propto E_{sym}(\rho)\nabla I + \frac{\partial E_{sym}(\rho)}{\partial\rho} I\nabla\rho$$

Diffusion Drift



depend on symmetry energy in different ways

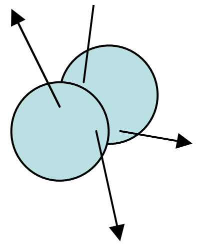
Symmetry energy effects are small absolutely (about 10%)

→ use differences or ratios, to eliminate uncertainties in the isoscalar sector.

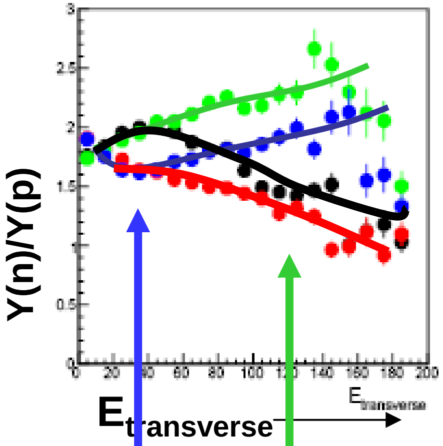
→ successful applications for many observables:

e.g. isospin transport and diffusion, liquid-gas phase transition, etc.

Pre-Equilibrium Emission of Nucleons or Light Clusters

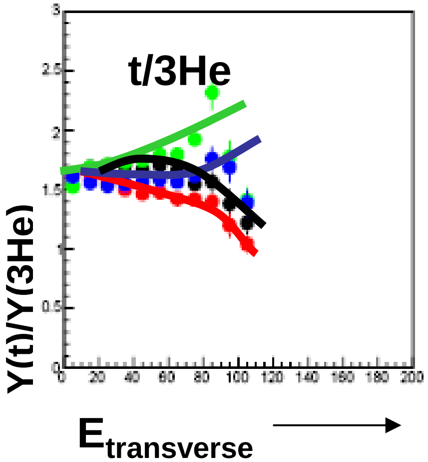


136Xe+124Sn, 150 MeV



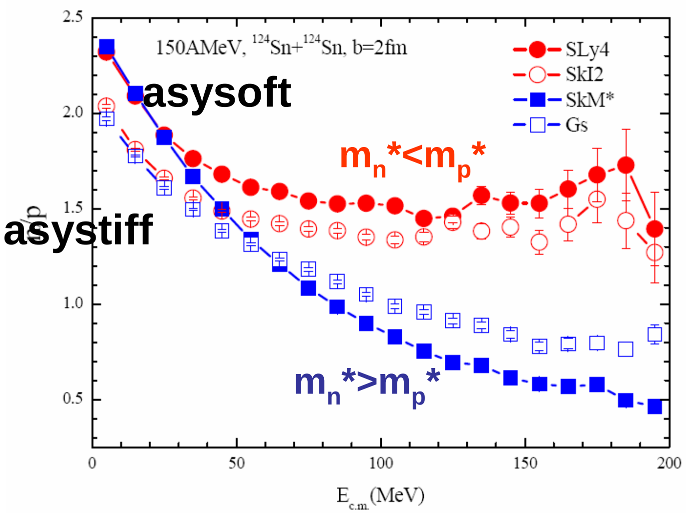
son: asysoft, $m_n^* > m_p^*$
stn: asystiff, $m_n^* > m_p^*$
sop: asysoft, $m_n^* < m_p^*$
stp: asystiff, $m_n^* < m_p^*$

density dep. dominates for slow particles;
mom.dep. (effective mass) for fast particles,
→separate density and momentum dependence



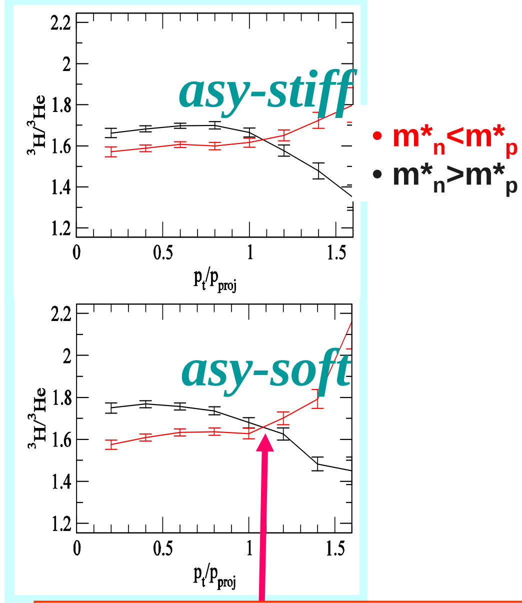
similar findings for Sn+Sn collisions (MSU)

^{124}Sn+^{124}Sn, 150 MeV



Y. Zhang,et al., PLB 732, 186 (2014)

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



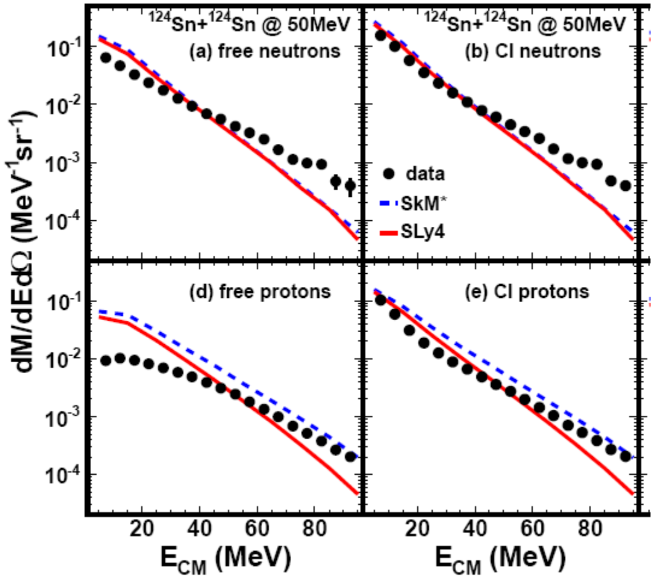
crossing connected to crossing of Lane potentials

effect of effective mass more prominent than that of asystiffness

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

Comparison with data:
problem of light cluster description in transport approaches

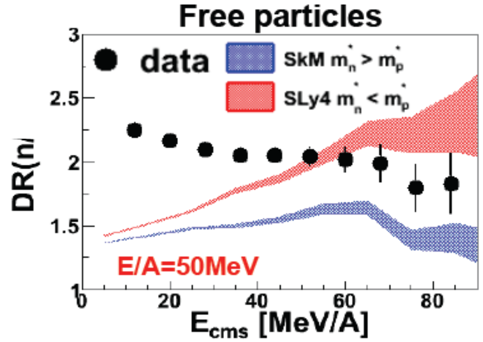
p,n spectra: free coalescence invariant (CI)

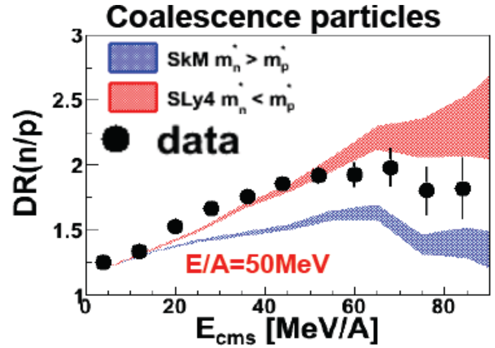


Double Ratios

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

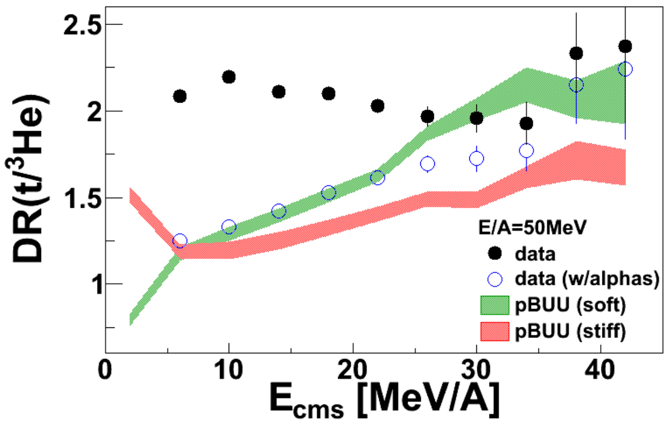
agree only for CI spectra



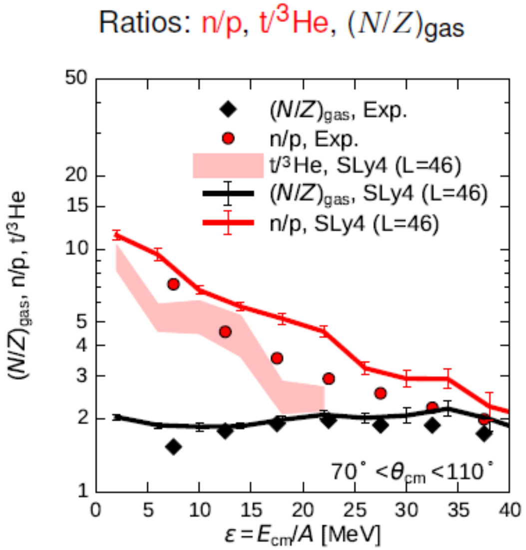


Y.X. Zhang, M.B.Tsang,et al., PLB 732, 186 (2014)
D.D.S.Coupland, arXiv 1406.4546

..or with calculation, where clusters are included explicitely
1. pBUU, when exp. α-particles are counted as t and 3He
(Z. Chajecki, NuSYM 13)

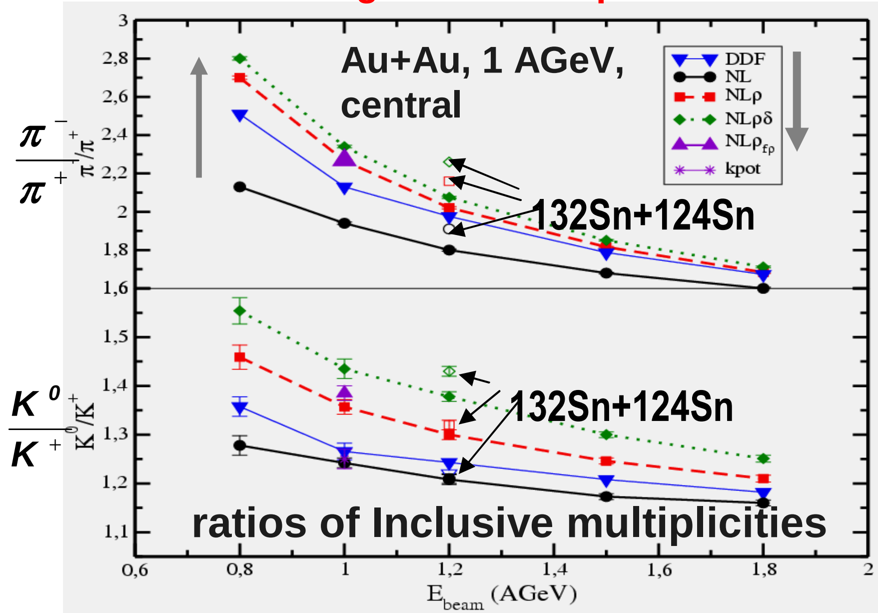


2. AMD with clusters
(A. Ono, NuSYM2015):
n/p (and t/h) ratios only reproduced if α-clusters included



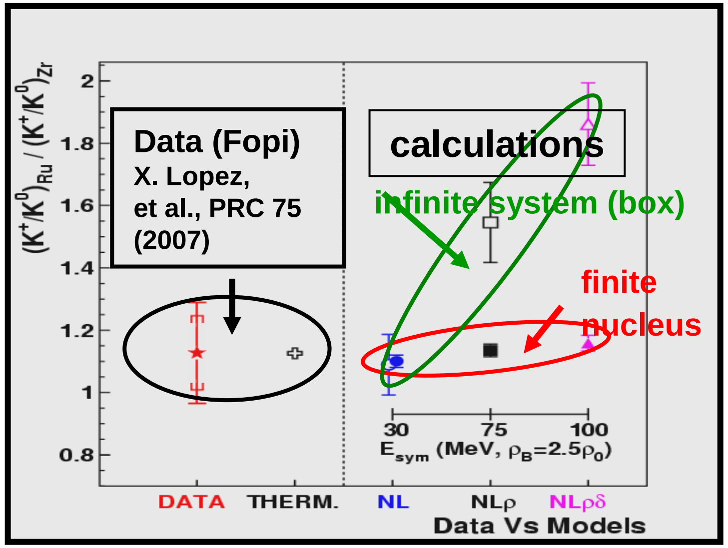
Strangeness in HIC: Kaons

Kaons ratios are (perhaps more) sensitive:
closer to threshold, come from high density,
K^0 and K^+ have large mean free path



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

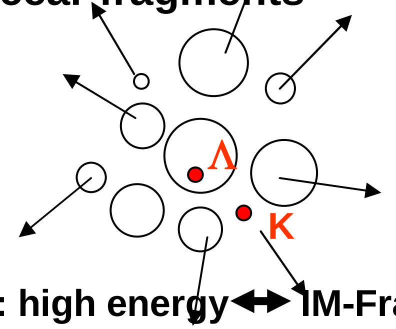
Comp. to FOPI data: Douple ratios (Ru+Ru)/(Zr+Zr)
Single ratios are more sensitive!



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

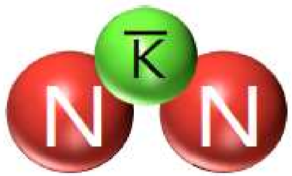
Strange clusters in HIC?

Hypernucear fragments



competion: high energy ↔ IM-Fragments

Kaonic clusters?



$p + p \longrightarrow \Lambda(1405) + p + K^+$

$ppK^- + K^+$

correlations important,
like for normal light clusters

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

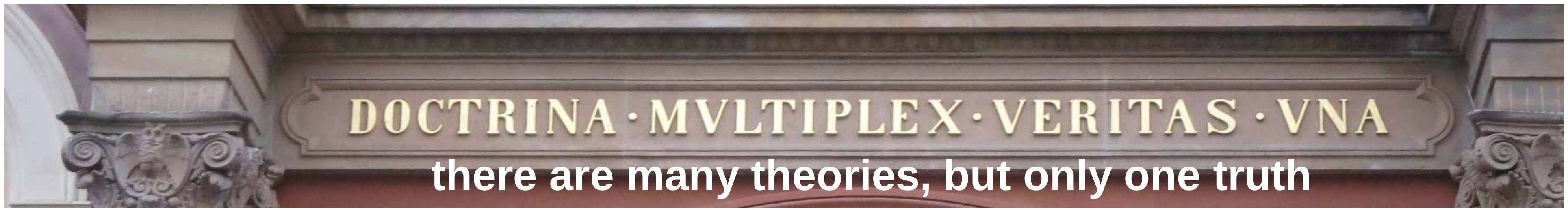
light clusters

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

IMF

fluctuations and mean
field
+coalescence

area of development, differences BUU, QMD (AMD,CoMD)




Thank you for attention
and fruitful discussion on the workshop
basse Normandie
our excursion on the weekend