Correlations and clustering in nuclear matter and heavy ion collisions

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LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

Excellence Cluster Universe

5th Int. Symposium on the Nuclear Symmetry Energy (NuSYM15)
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Correlations and clustering in nuclear matter and heavy ion collisions

very wide subject: introductory remarks and overview,
subjects discussed in much more detail in later talks

Aim of this talk:

→ emphasize the importance of correlations and clustering in the study of the symmetry energy

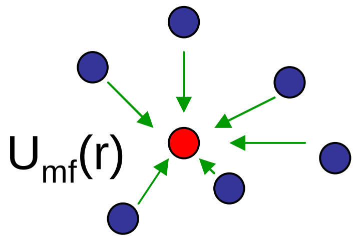
→ discuss what is involved in a proper treatment

→ stress simple concepts (more detail in later talks)

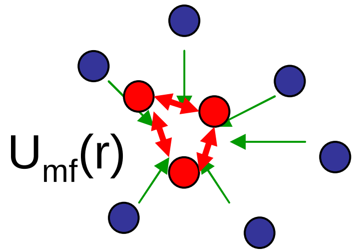
I will use the results and graphs of many workers in the field
(and apologize, if not always cited properly).

the two
main players:

mean field (mf) ⟺ clustering



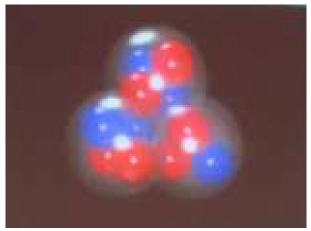
particle in a mean field,
one-body approach



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

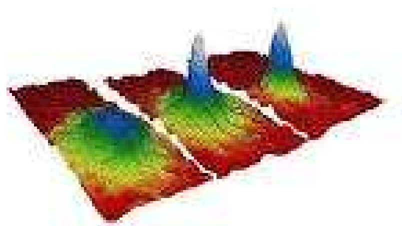
Examples:

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

Clustering ⟺ Symmetry Energy.   Relevance to NuSYM15??

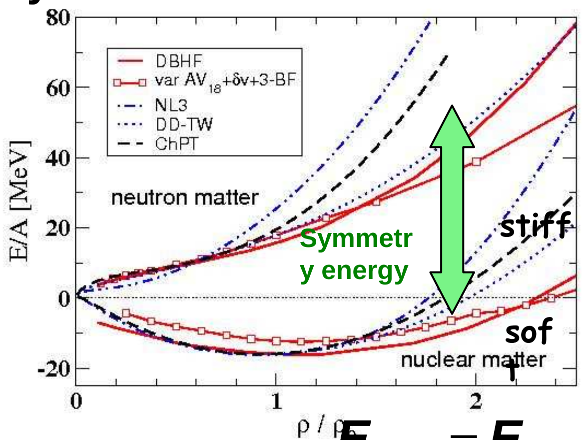
nucleons come in two flavors: n, p
→ nn,pp interactions different from pn interaction (stronger)
→ in asymmetric system: → U_p and U_n different → symmetry energy

density-asymmetry dep. of nucl.matt.

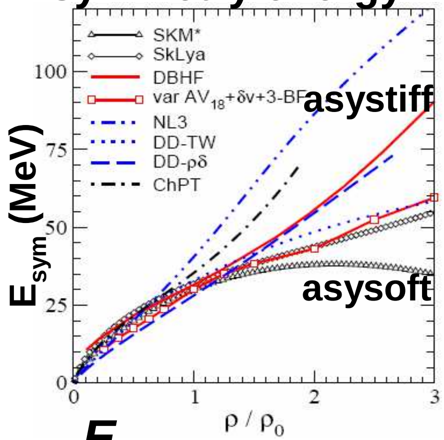
$$\varepsilon(\rho_B,\delta) = \varepsilon_{nm}(\rho_B) + E_{sym}(\rho_B)\delta^2 + O(\delta^4) + \ldots \qquad \delta = \frac{\rho_n - \rho_p}{\rho_n + \rho_p}$$

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

symmetric and neutron matter

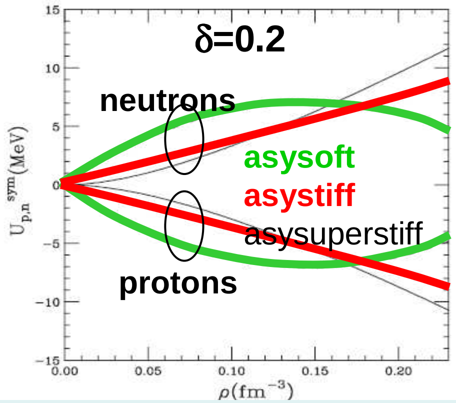


symmetry energy



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 do clusters 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**

Attempt to Cluster Systematics in Nuclear Systems

static

dynamic

nuclear matter

stellar matter

nuclear structure

heavy ion coll, HIC

composition of low density nm,

liquid-gas phase transition

Supernova EOS, ν–sphere, neutron star crust

cluster states, (e.g.Hoyle state) cluster dynamics in excitation

final states heavily clustered

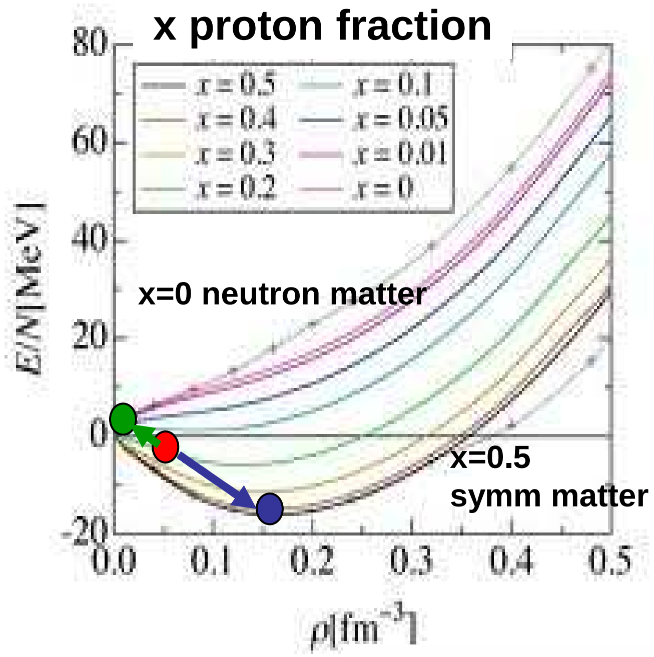
equilibr. and non-eq. emission of light and intermediate mass clusters

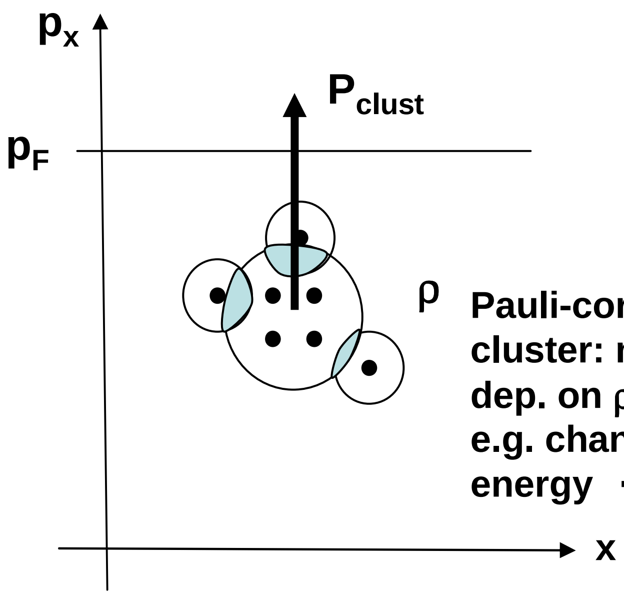
treatment in transport approaches

→ This is a kind of outline of this talk

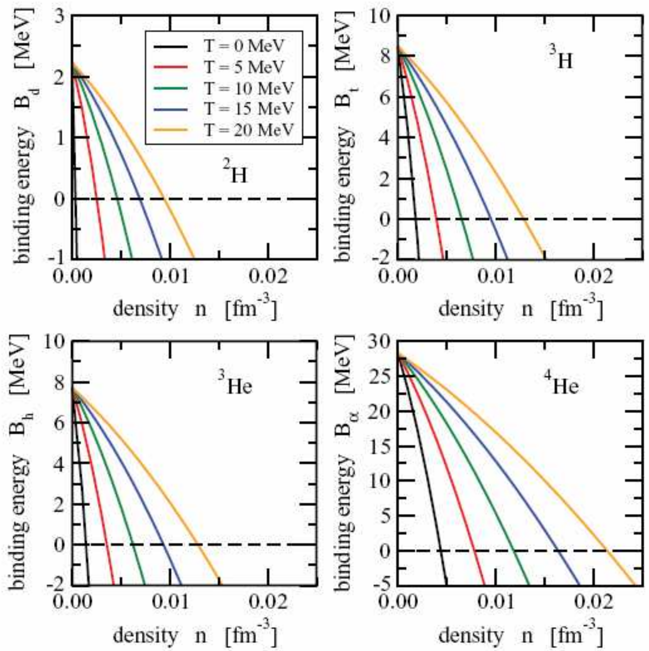
Composition of dilute matter

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





Pauli-correlations weakens cluster: medium effects dep. on ρ, T, P_{clust}, e.g. change of binding energy



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

clusterization increases with ρ↘ ,T ↗, P_{cm} ↗

Treatment of clusters in the medium

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

1. Few-body Schrödinger eq. equation including blocking and in-medium (quasi-)particle energies (Röpke)

$$\left[E^{\mathrm{qu}}(1)+\cdots+E^{\mathrm{qu}}(A)-E^{\mathrm{qu}}_{A,\nu}(K)\right]\psi_{A\nu K}(1\ldots A) + \sum_{1'\ldots A'}\sum_{i<j}[1-\tilde f(i)-\tilde f(j)]V(ij,i'j')\prod_{k\neq i,j}\delta_{kk'}\psi_{A\nu K}(1'\ldots A')=0.$$

EoS in grand canonical picture: density as fct of chem. pot. and temperature

$$n_p^{\mathrm{tot}}(T,\tilde\mu_p,\tilde\mu_n)=\frac{1}{\Omega}\sum_{A,\nu,K} Z f_{A,Z}\left[E^{\mathrm{qu}}_{A,\nu}(K;T,\tilde\mu_p,\tilde\mu_n)\right],$$ corresp. for neutrons

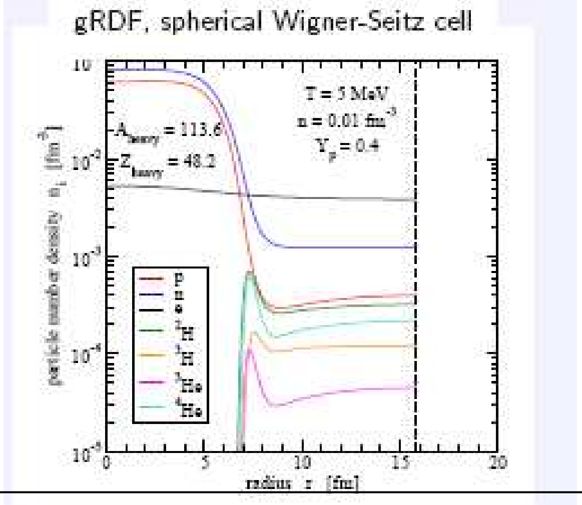
2. Nucl. statistical Equilibrium (NSE) (Hempel): energies of isolated A-nucleon clusters
→ incorrect high density limit, since clusters never disapppear
→ remedy: excluded volume with increasing density. no space for clusters

3. Generalized rel mf (RMF) approach mit cluster degrees of freedom (Typel)

$$\mathcal{L}(\psi;\underbrace{\rho,\omega,\rho,\delta}_{\text{meson with DD coupling}};\underbrace{d,\alpha,t,{}^3He}_{\text{light cluster with DD masses}})$$

interpolate correctly from zero to high density

treatment difficult for heavier clusters:
→ Thomas-Fermi calculation in Wigner-Seitz cell (periodic space)

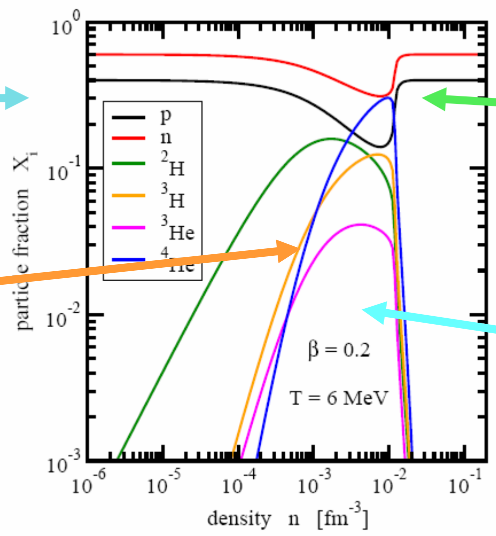


Particle Fractions

very low density: p,n

Increasing density: clusters arise: deuteron first, but then α dominates

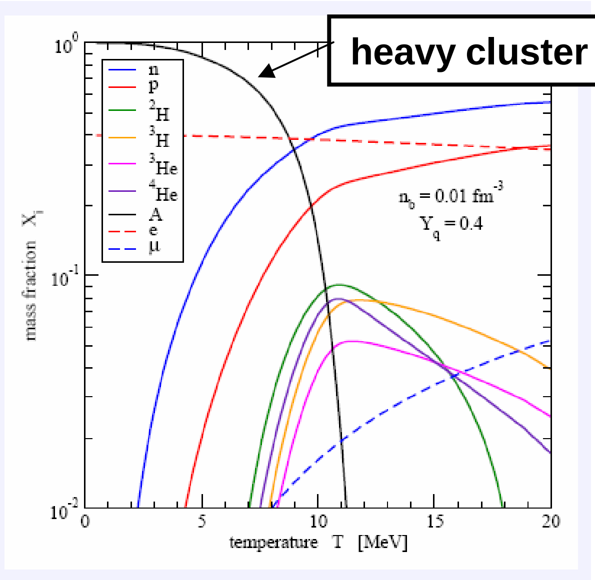
S.Typel, G. Röpke, et al., PRC 81 (2010)



Mott density: clusters melt, homogeneous p,n matter;

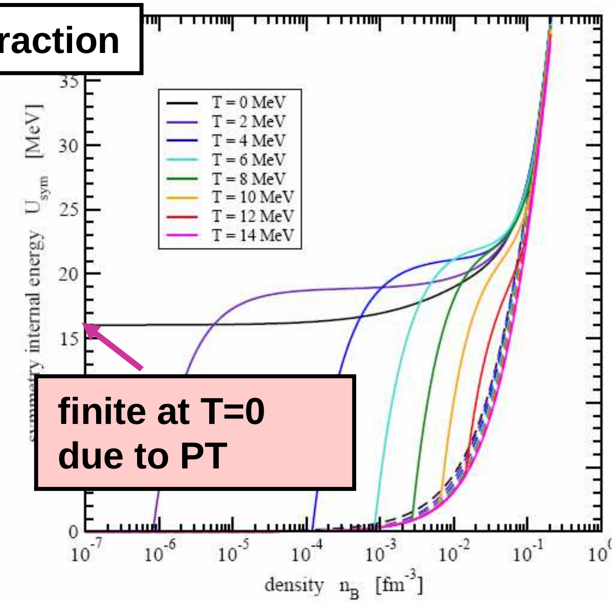
here heavier nuclei (embedded into a gas) become important here

composition as fct of Temp.



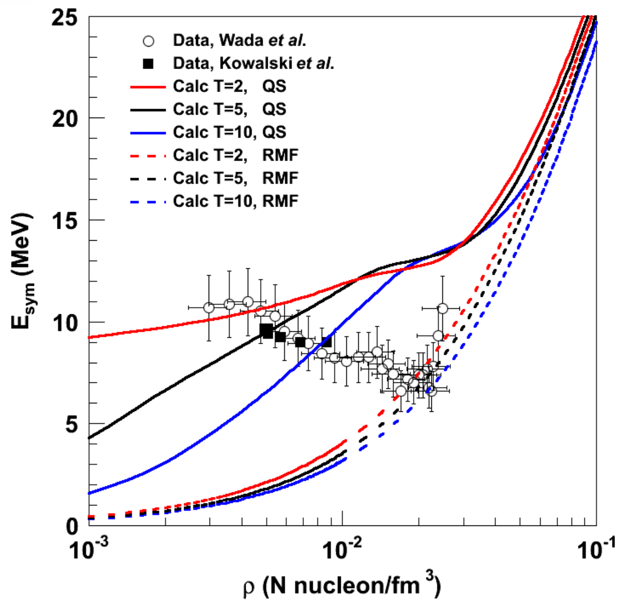
heavy cluster fraction

Symmetry Energy



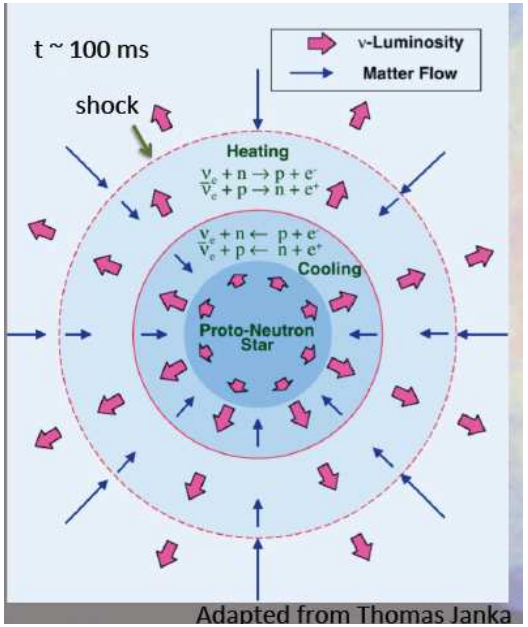
finite at T=0 due to PT

comparison to data from heavy ion collisions



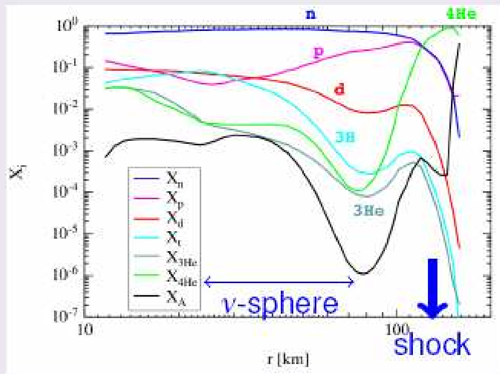
J. Natowitz, G. Röpke,, … HHW, PRL 104, 202501 (2010)

Core Collapse Supernovae and the Neutrinosphere



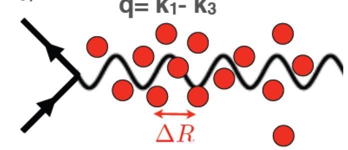
Mass fraction of light clusters in the post-bounce supernova core, based on nuclear statistical equilibrium.

Sumiyoshi and Röpke, PRC77 (2008) 055804.



Correlations & Neutrino Scattering

- Neutrinos "see" more than one particle in the medium.
- Nature of spatial and temporal correlations between nuclei, nucleons and electrons affect the scattering rate.



At small q_0 and $\mathbf{q}$ the neutrino cannot resolve single particles.

Sawyer (1975, 1989)
Iwamoto & Pethick (1982)
Horowitz & Wherberger (1991)
Raffelt & Seckel (1995)

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

direct interface with heavy ion physics, simulate in a box calculation!

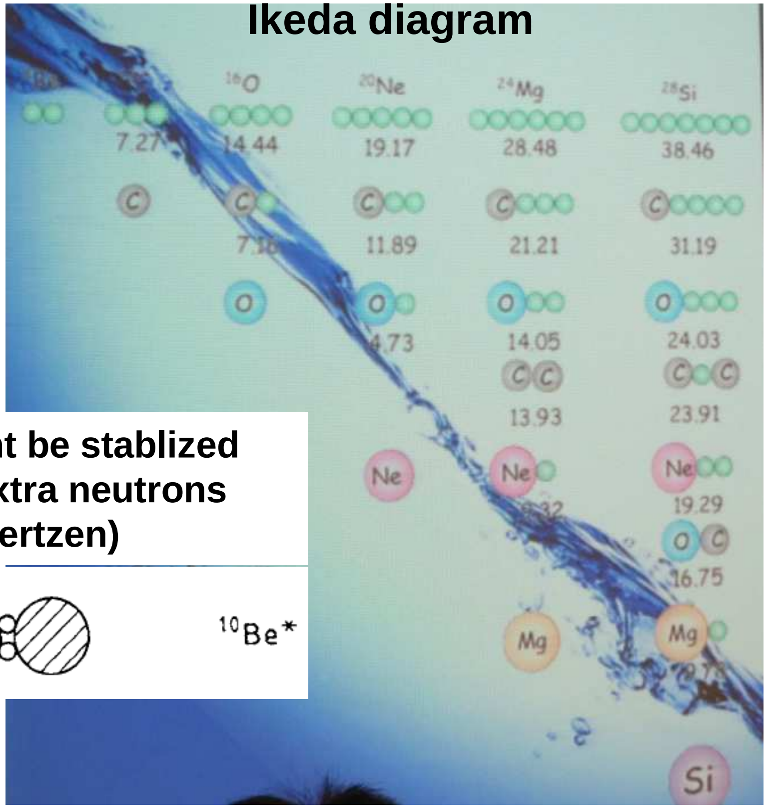
supernova ⟺ femtonova

S. Reddy, workshop simmulating the ν-sphere in heavy ion collisions, ECT*, 2014

Clusters in nuclear structure

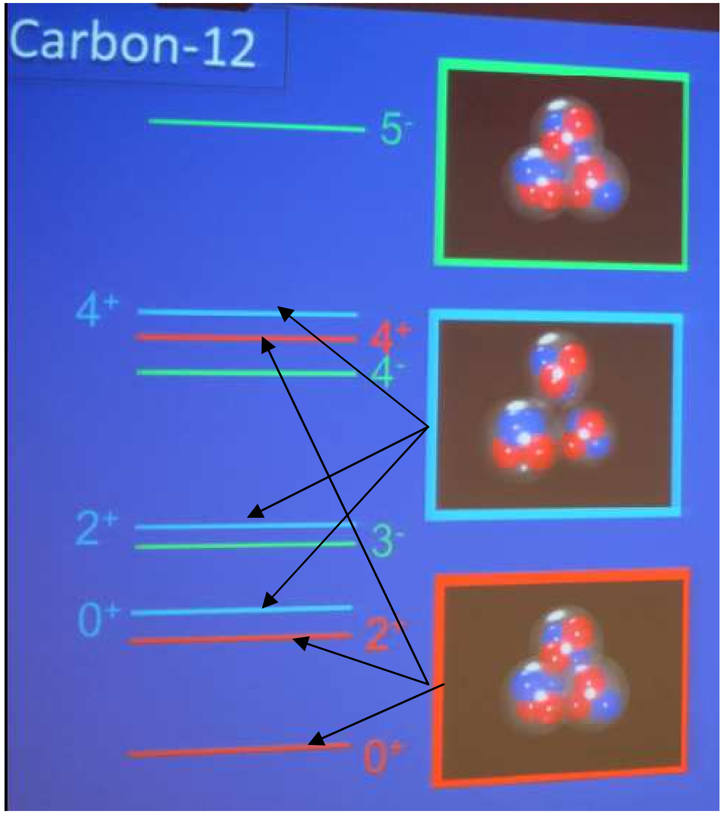
M. Freer, NN2015

Ikeda diagram



might be stablized
by extra neutrons
(v. Oertzen)

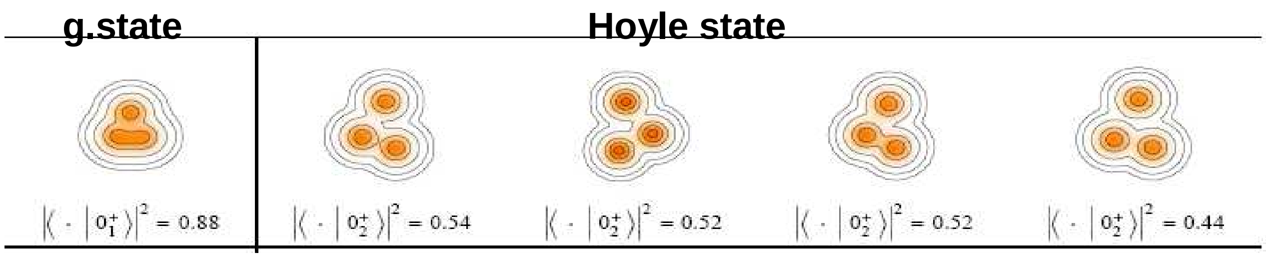
^{10}Be*



octupole
band

Hoyle state
(dilute)

g.s.
(compact)

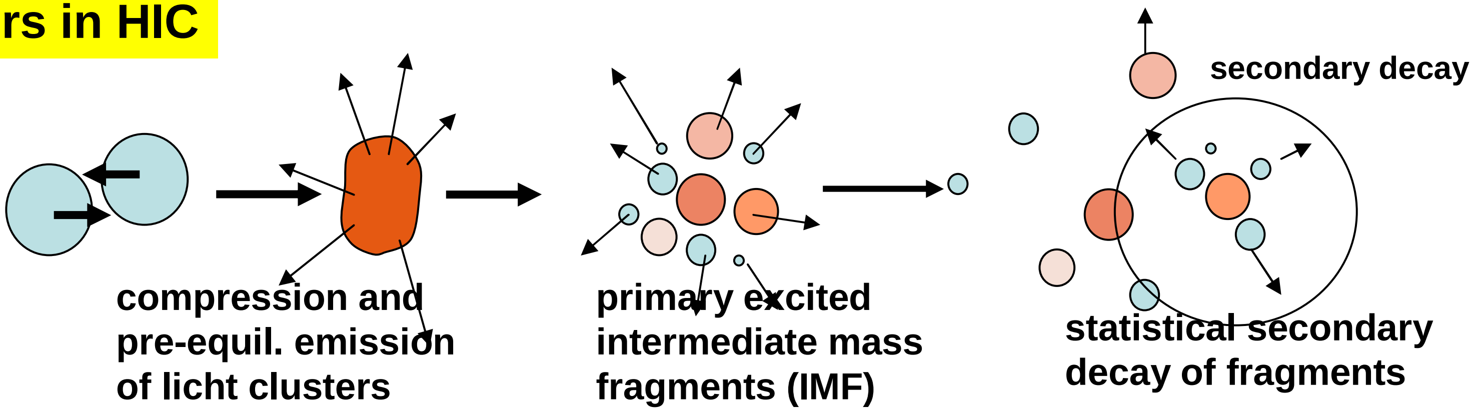


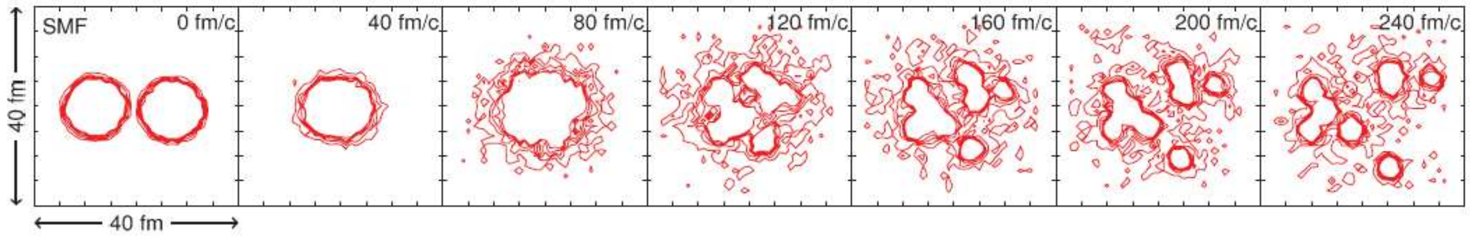
main FMD components (not orthogonal) (T. Neff (NN2015))

surface clustering (→ Typel): change of relation neutron skin ↔ slope of symmetry energy

S. Typel, PRC 89, 064321 (2014)

Clusters in HIC





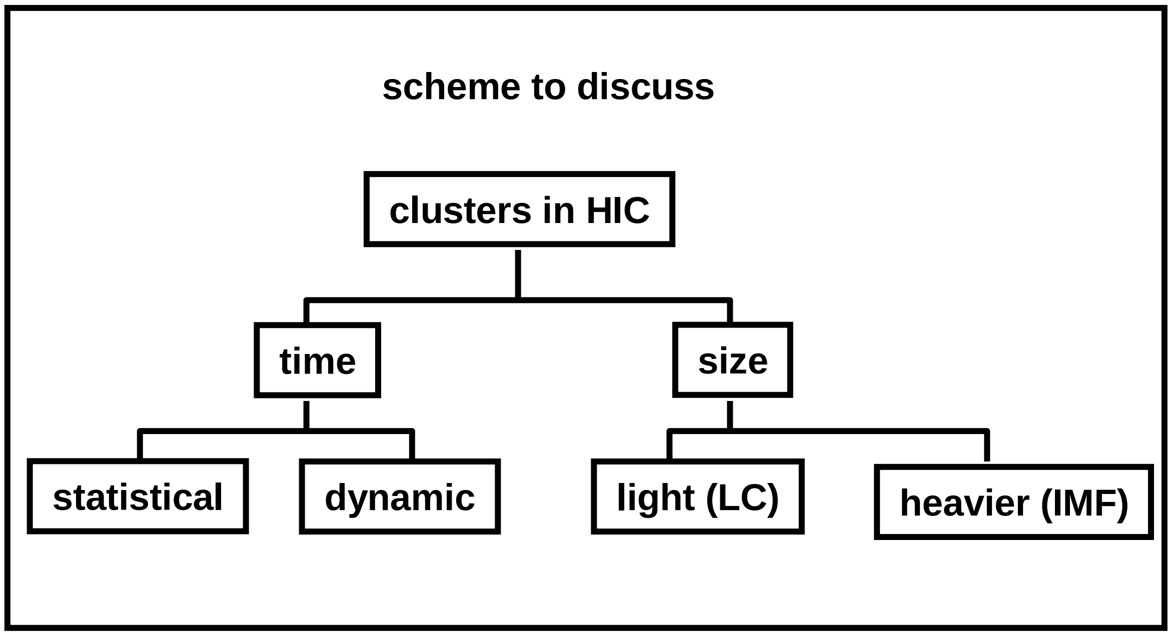
large fractions of particles in clusters, e.g.

Partitioning of protons

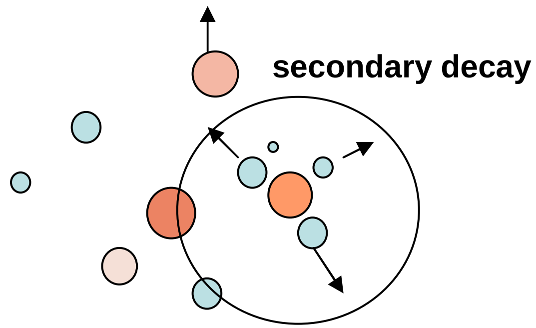
	Xe + Sn 50 MeV/u	Au + Au 250 MeV/u
p	≈10%	21%
α	≈20%	20%
d, t, ^{3}He	≈10%	40%
$A > 4$	≈60%	18%

INDRA data, Hudan et al., PRC67 (2003) 064613.

FOPI data, Reisdorf et al., NPA 848 (2010) 366.

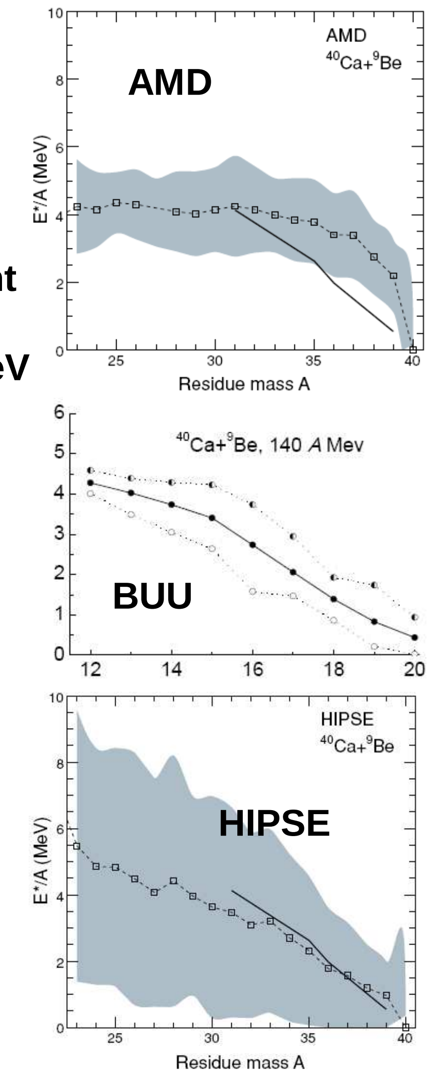


- clusters in HIC
  - time
    - statistical
    - dynamic
  - size
    - light (LC)
    - heavier (IMF)



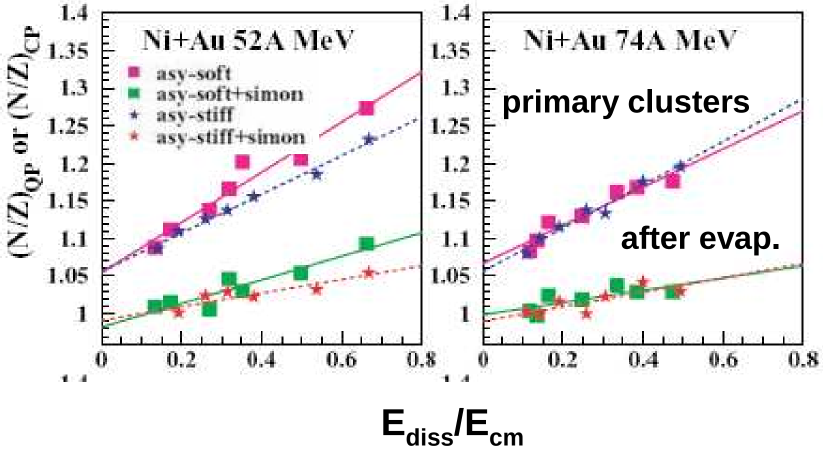
Freeze-out approximation: assume: A, Z, volume, excitation energy/A
statistical decay code: SMM, Gemini++, SIMON, etc
„afterburner“

excitation energy calculated in different approaches for $^{40}Ca+^{9}Be$, at 140 AMeV



M.Mocko, et al., PRC78,024612(08), T. Mikhailova, et al., Peterhof conf. 2015

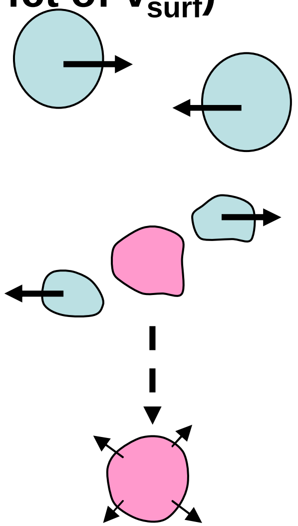
large influence on observables!
hope that „isospin blind“?



Galichet et al., Phys. Rev. C79, 064615 (2009)

Freeze-out and the Supernova (SN) ν-sphere in HI collisions?

Coalescence analysis (as fct of v_{surf})



Experiment and interpret. ^{64}Zn+(^{92}Mo,^{197}Au) at 35 AMeV
S. Kowalski, J. Natowitz, et al.,PRC75 014601 (2007)
J. Natowitz, G. Röpke, S. Typel, et al., PRL 104, 202501 (2010),
R. Wada, et al., PRC 85, 064618 (2013)

albergo thermometer

$$T_{HHe} = \frac{14.3}{\ln\left(\sqrt{9/8}\,(1.59\,\frac{Y(^2H)Y(^4He)}{Y(^3H)Y(^3He)}\right)}$$

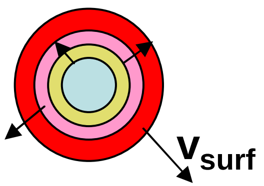
density: momentum space coalescence model (Mekjian, PRC 17 (78))

Symmetry free energy from isoscaling

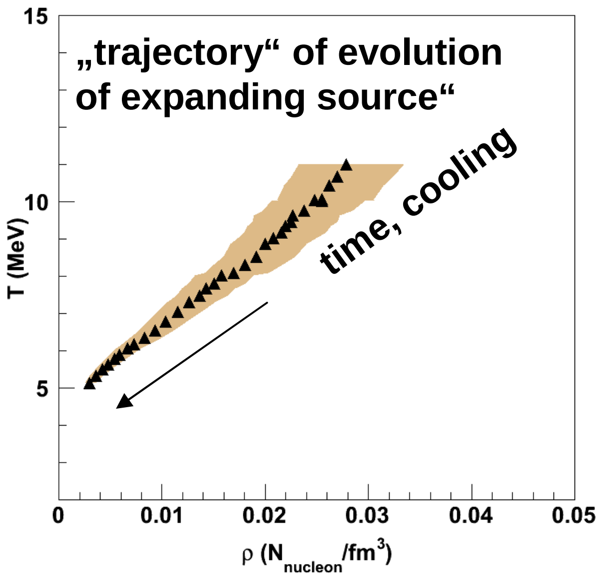
$$\frac{Y_2}{Y_1} = Ce^{\{[\mu_2(n)-\mu_1(n)]N+[\mu_2(p)-\mu_1(p)]Z\}/T} = Ce^{\alpha N+\beta Z}.$$

$$\alpha = 4F_{\rm sym}[(Z_1/A_1)^2-(Z_2/A_2)^2]/T$$

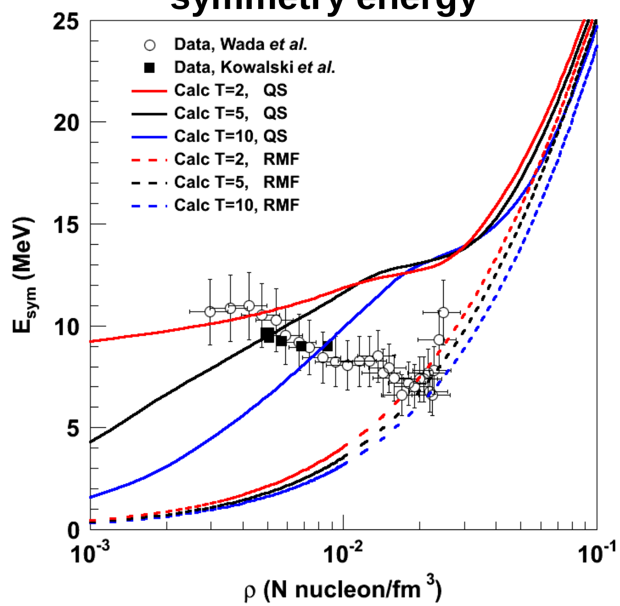
$$\beta = 4F_{\rm sym}[(N_1/A_1)^2-(N_2/A_2)^2]/T,$$



„differential“ freeze-out analysis:
→ source reconstruction,
→ analysis as fct of v_{surf}~time of emission
→ determination of thermodyn. properties and symmetry energy as fct of v_{surf}



symmetry energy



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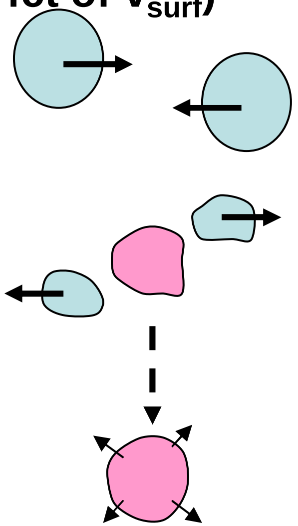

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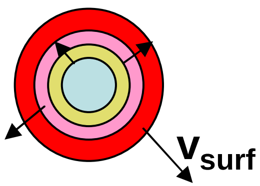
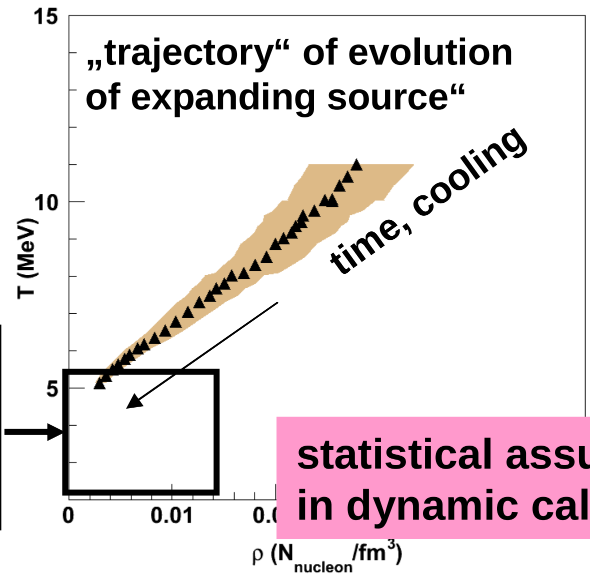
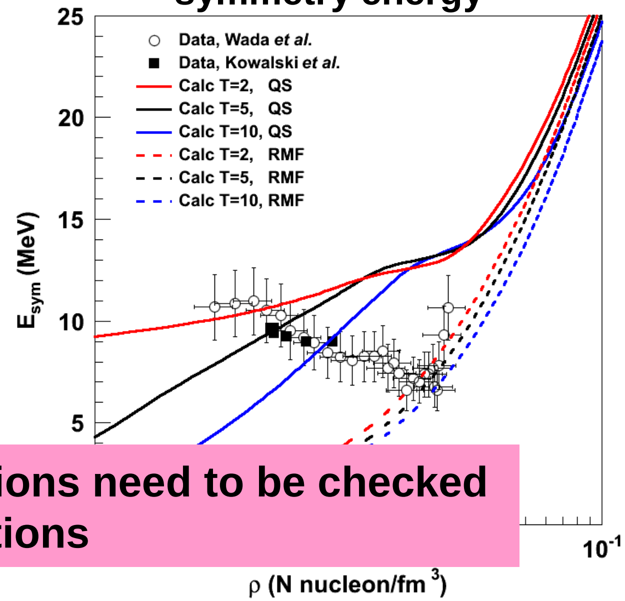
$$\alpha = 4F_{\rm sym}[(Z_1/A_1)^2-(Z_2/A_2)^2]/T$$
$$\beta = 4F_{\rm sym}[(N_1/A_1)^2-(N_2/A_2)^2]/T,$$



„differential" freeze-out analysis:
→ source reconstruction,
→ analysis as fct of v_{surf}

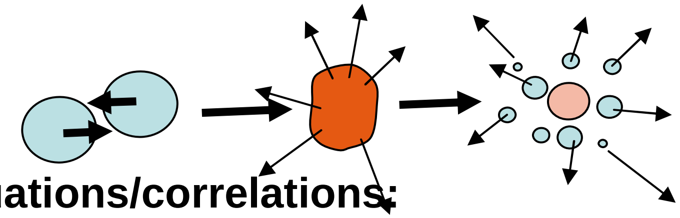
conditions of neutrinosphere:
densities 1/1000 to 1/10 ρ_o
temperature T=4-5 MeV
asymmetry Y_e=0.1 – 0.25





statistical assumptions need to be checked in dynamic calculations

Dynamical cluster formation in HIC



„dynamical clusters“: transport approach with fluctuations/correlations:
seeds of fragment/light cluster formation

BUU/BLE/BLOB

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

deterministic, dissipative 1-body equation + fluctuation

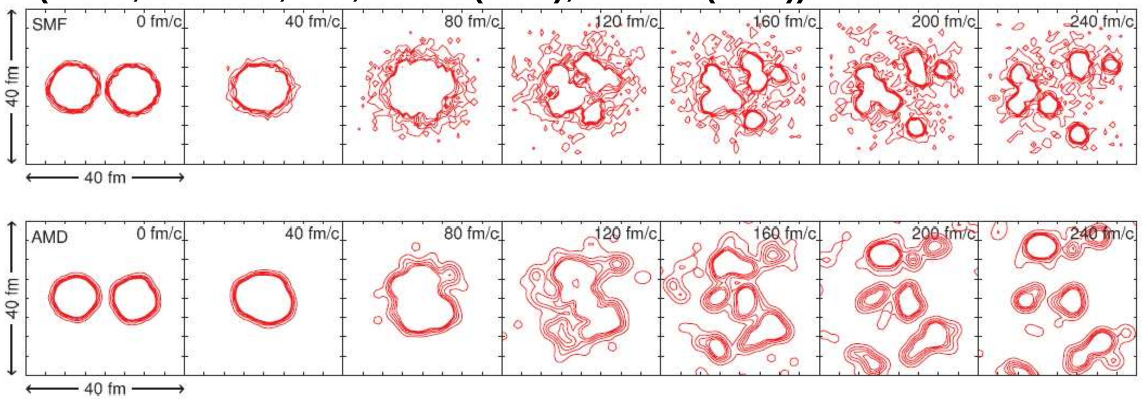
QMD/AMD

$$|\Phi\rangle = A\prod_{i=1}^{A}\varphi(r;r_i,p_i)|0\rangle$$
$$\dot{r}_i=\{r_i,H\};\quad \dot{p}_i=\{p_i,H\};\quad H=\sum_i t_i+\sum_{i,j}V(r_i-r_j)$$

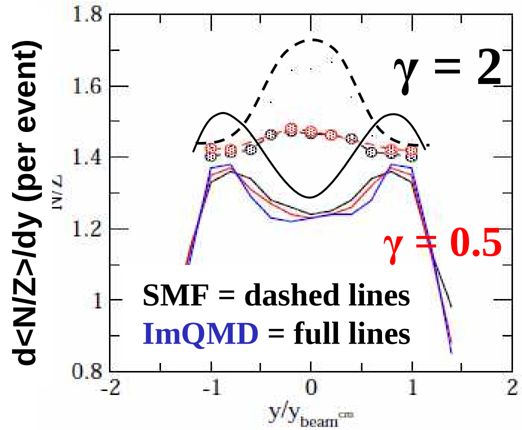
TDHF + stochastic NN collisions

difference in spectrum of fluctuations
→can be adjusted for IMF (intermediate mass fragments) formation, since IMF formation stabilized by mean field

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



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



Interlude:

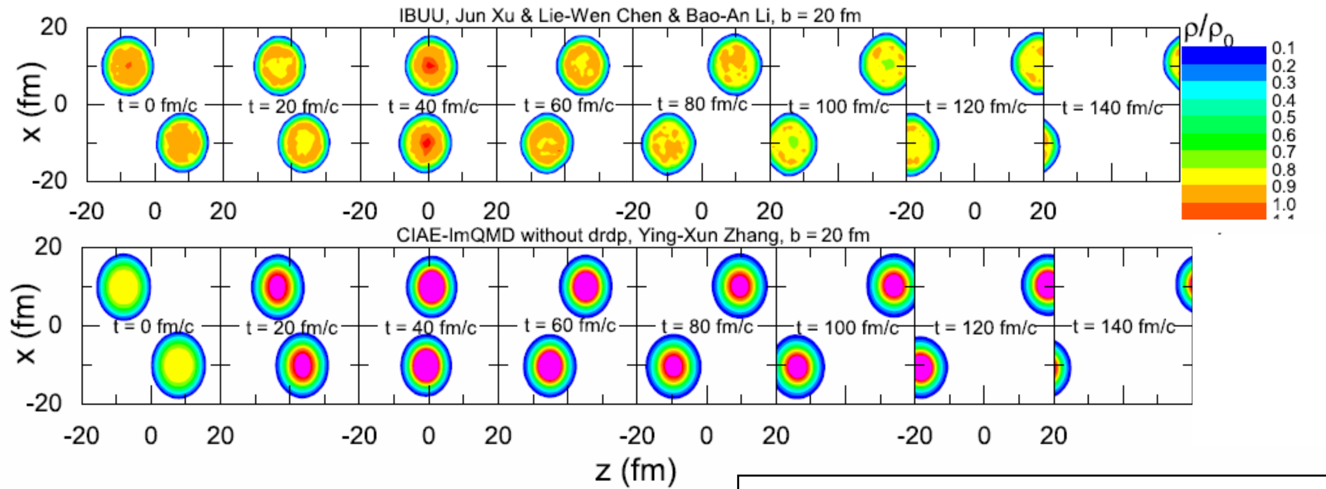
Code Comparison Project: Trento, ECT*, 2006 and 2009
Shanghai, Jan. 2014, Lanzhou 2014

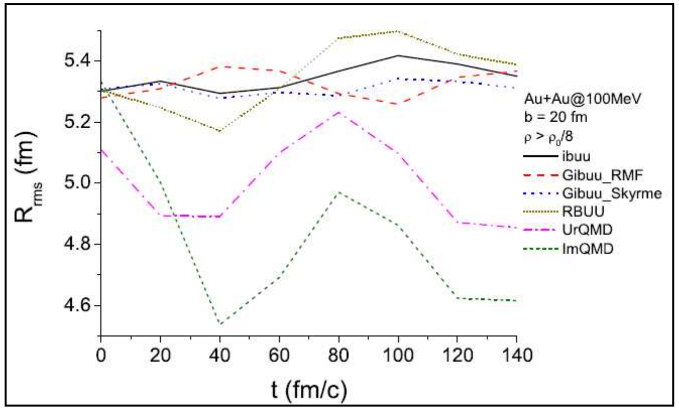
check consistency of transport codes in calculations with same system (Au+Au), E=100,400 AMeV, identical (simple) physical input (mean field (EOS) and cross sections)

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

1. step: Initialize colliding nuclei. usually not exact ground states

free propagation (large impact parameter)





→ nuclei oscillate, influences dynamical evolution in collision, part. at lower incident energies

→ construct better gs, e.g. Thomas-Fermi

Examples of results: Au+Au, PRELIMINARY

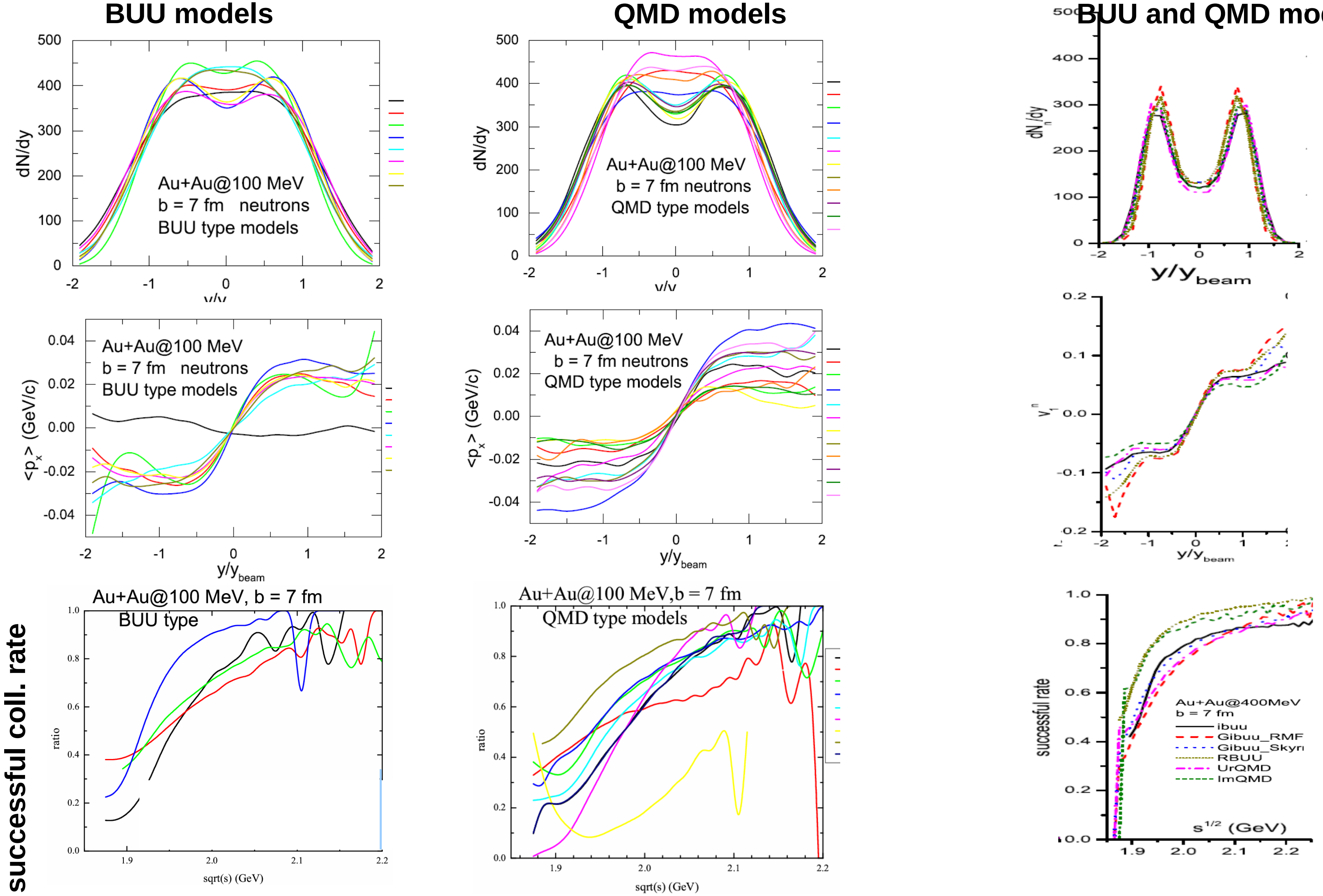
E/A=100 MeV

BUU models

QMD models

E/A=400 MeV

BUU and QMD models

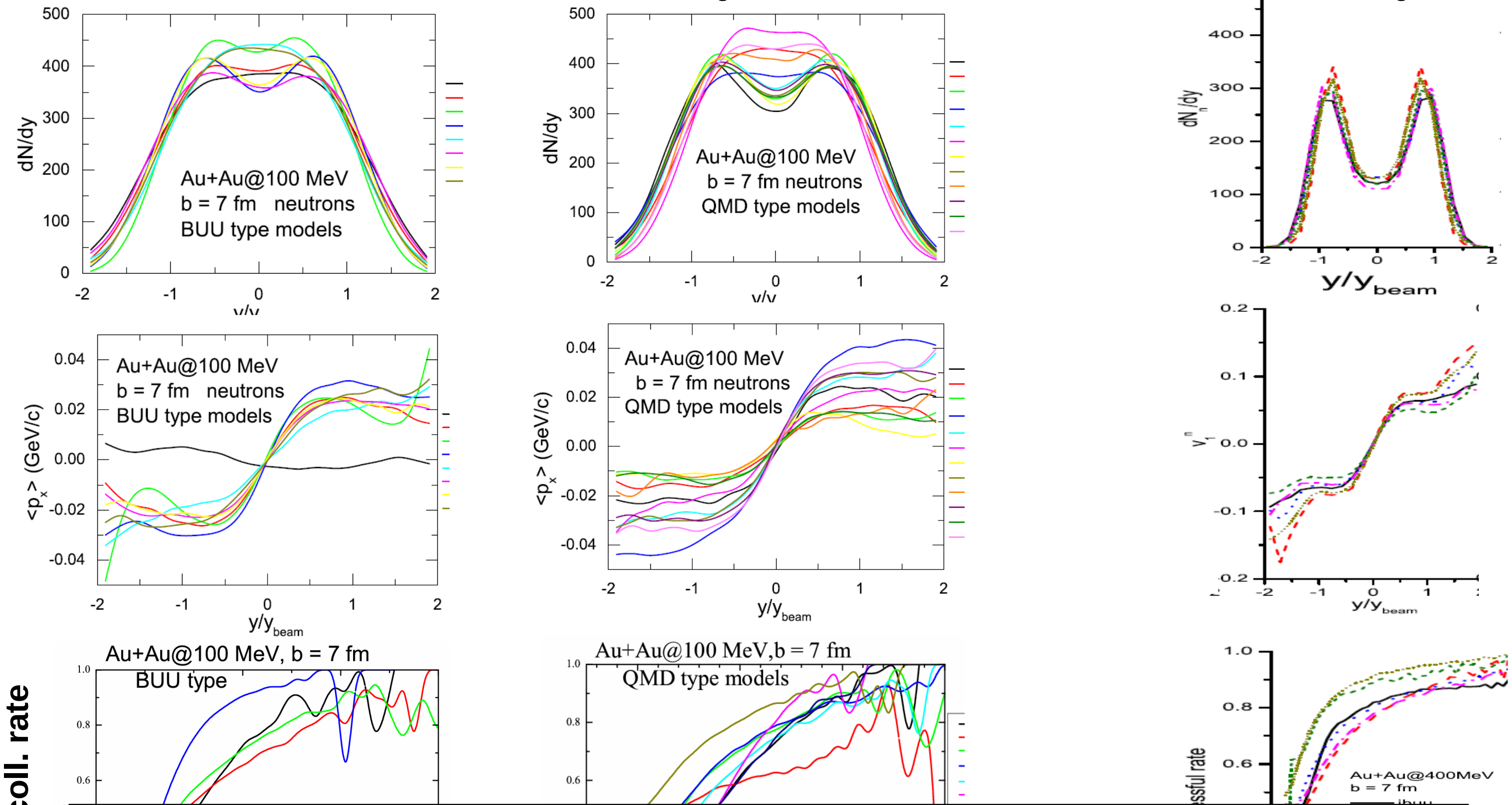


Examples of results: Au+Au, PRELIMINARY

E/A=100 MeV

BUU models | QMD models

E/A=400 MeV
BUU and QMD models



→ considerable differences

→ partly due to initialization, but most likely mainly to collision term

→ no essential difference between BUU and QMD models

→ 100 MeV sensitive region for flow because of competition between mf and collisions, comparison better at higher energy

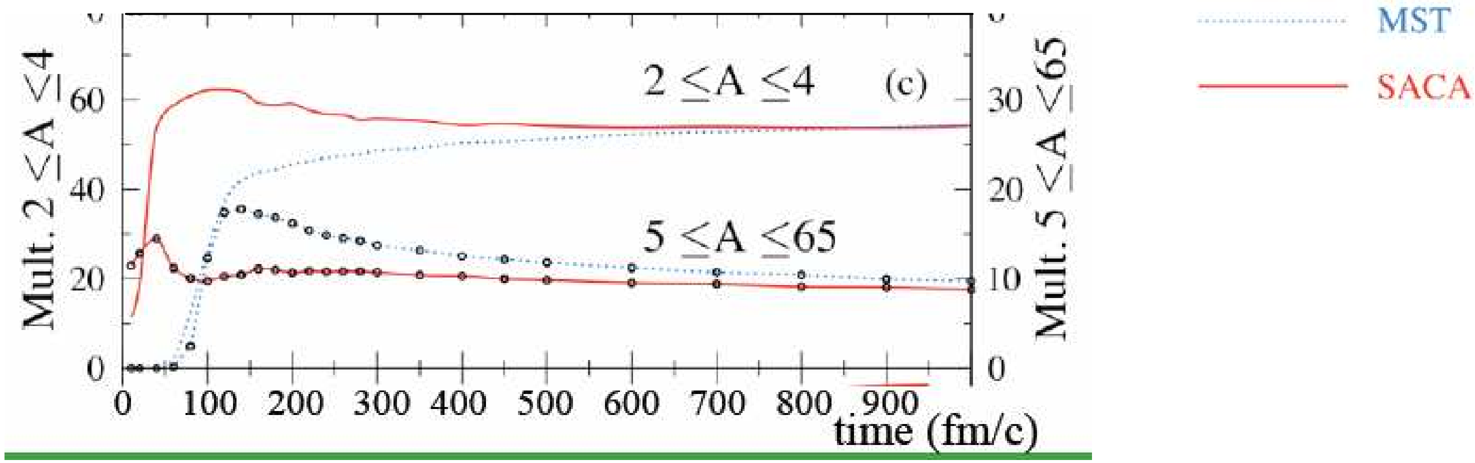
End of Interlude on code comparison

Cluster recognition algorithms:

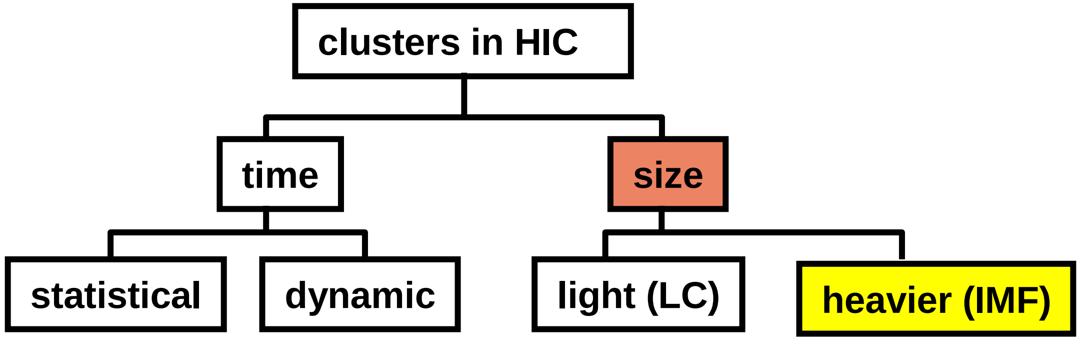
MD: phase space connection: MST, SACA
BUU: a) coalescence: find contours of density ρ_c ~1/10 ρ_0
b) Test particle distribution sampling:
choose A out of N_{TP}*A test particles with correct global properties.
Treat these as nucleons and do coalescence or MST algorithm or SACA (as in QMD)
and do this many times (~1000) to generate a distribution

→ **similar in both approaches, but a-posteriori**
→ **not the same as dynamical clusters**

clusters identified earlier, but converge asymtoticaly and do not influence dynmaics



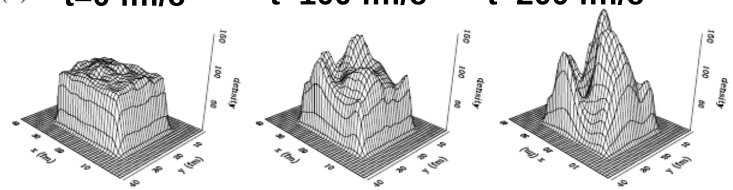
Y, Vermani, et al., J. Phys. G 37, 015105 (2010)



IMF's: formation dominated by mean field, which favors matter at normal density

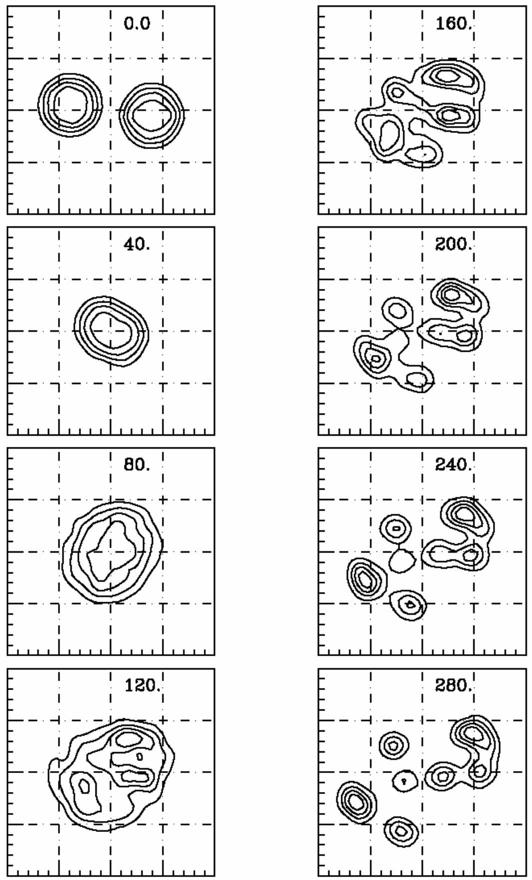
BUU calculation in a box (i.e. periodic boundary conditions) with initial conditions inside the instability region: $\rho=\rho_0/3$, T=5 MeV, $\delta=0$

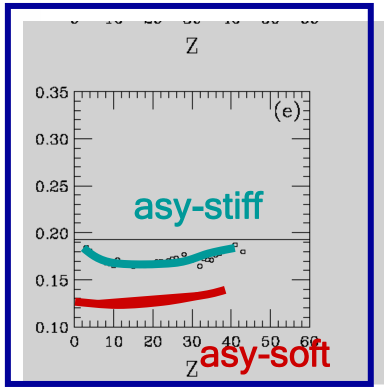
(a) **t=0 fm/c** **t=100 fm/c** **t=200 fm/c**



→ Formation of „clusters (fragments)", from small (numerical) fluctuations in the density. Time scale = growth time of the instable modes (V.Baran, et al., Phys.Rep.410,335(05))

^{124}Sn+^{124}Sn, 50 AMeV,central





Multifragmentation: Isospin fractionation at low densities

successful applications for several observables:
isospin transport and diffusion, liquid-gas phase transition, etc.

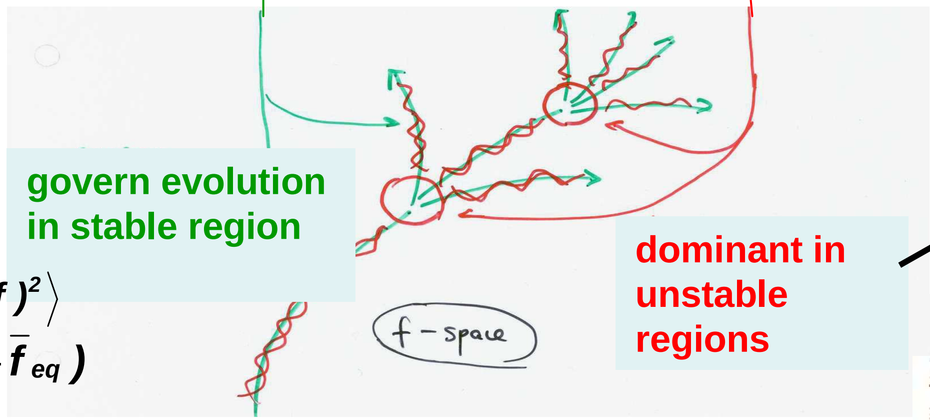
Treatment of Fluctuations (esp. in BUU)

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

Mean field evolution (dissipative)

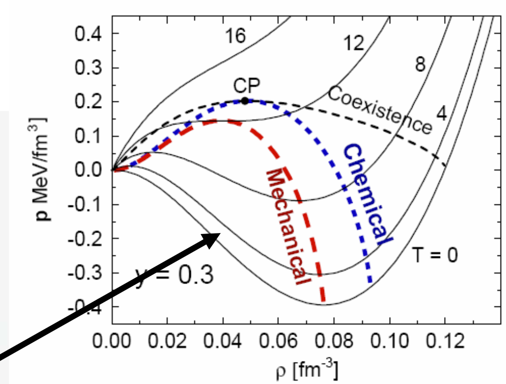
Fluctuations (higher orger correlations)

Boltzmann-Langevin eqn. $\boxed{\frac{df}{dt} = I_{coll} + I_{fluc}}$



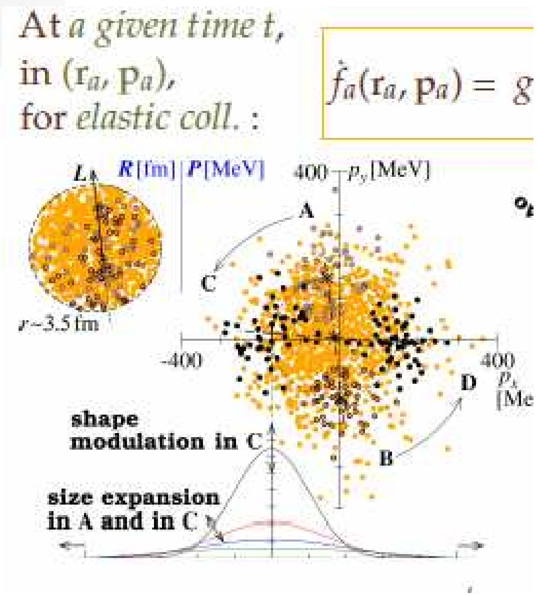
govern evolution in stable region

dominant in unstable regions



$$f = \bar{f} + \delta f; \quad \sigma^2 \equiv \langle (\delta f)^2 \rangle$$

$$\sigma^2 \rightarrow \sigma^2_{eq} = \bar{f}_{eq}(1 - \bar{f}_{eq})$$



approaches:

BOB (One-Body-Brownian): replace fluctuation term by fluctuating force, gauged to most unstable mode: Colonna, Guarnera

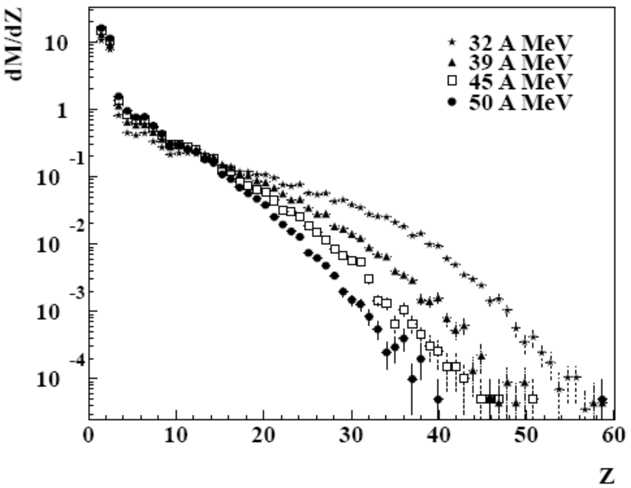
Stochastic MF dynamics (SMF): introduce locally statistical fluctuations into the phase space distribution at certain times accoording to $\sigma^2=f(1-f)$ projected on density fluctuations: Colonna, DiToro,HW

BLOB (Boltzmann-Langevin One-Body)
Bertsch method, developed by M. Colonna, P. Napolitano (see talk later), fluctuation in full phase space
One TP collision moves N_{TP} TP nearby in phase space, to simulate collisions of nucleons (P. Napolitani, this meeting).

- **clusters in HIC**
  - **time**
    - **statistical**
    - **dynamic**
  - **size**
    - **light (LC)**
    - **heavier (IMF)**

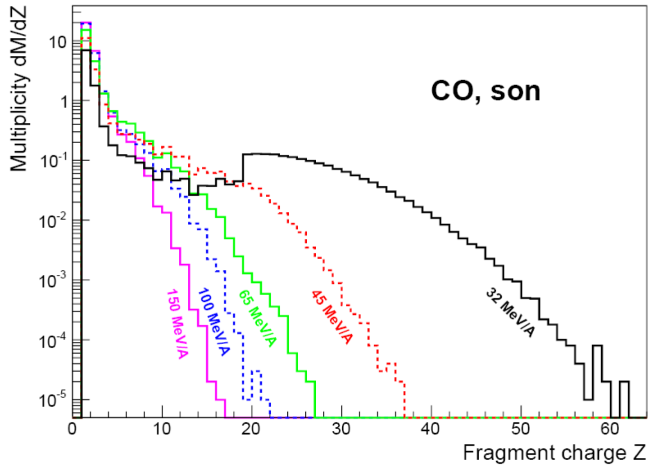
indication: overprediction of :nucleons and light clusters

^{136}Xe+^{124}Sn, E = 32,.,150 AMeV



S. Hudan, et al., PRC67, 064613

^{136}Xe + ^{124}Sn, b = 2 fm



H.H. Wolter, et al.,
EPJ Web of Conf. &&, 03097 (2014)

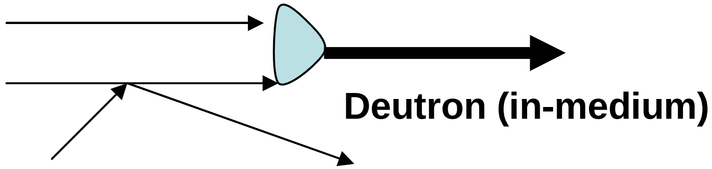
→ **LC are correlation dominated (esp.Pauli-correlation).**
→ **Not well described in BUU and MD models, since simple interactions and classical phase space distribution give bad eigenstates for LC**
→ **need special treatment**

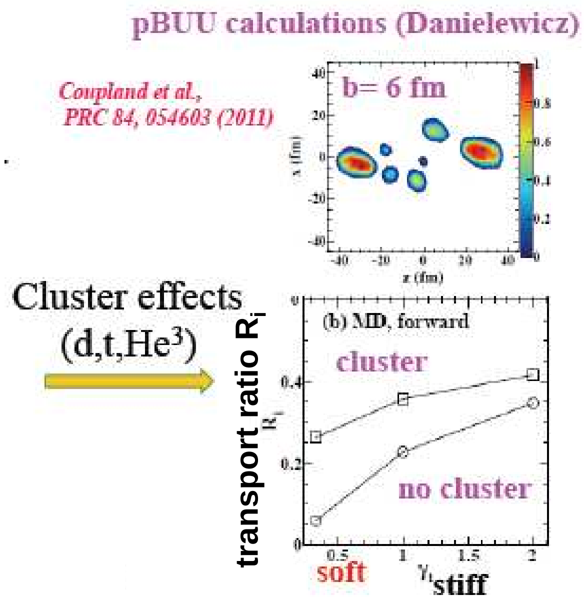
Treatment of Light Cluster dynamics in HIC:

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

solutions different in BUU and 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 a!)
→ coupled transport equations





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)

Caveat: Medium properties of LC:

Medium corrections in the formation of light charged particles 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)

similar: transitions amplitudes in medium

Treatment of Light Cluster dynamics in HIC:

Solution für AMD (see talk of Ono)

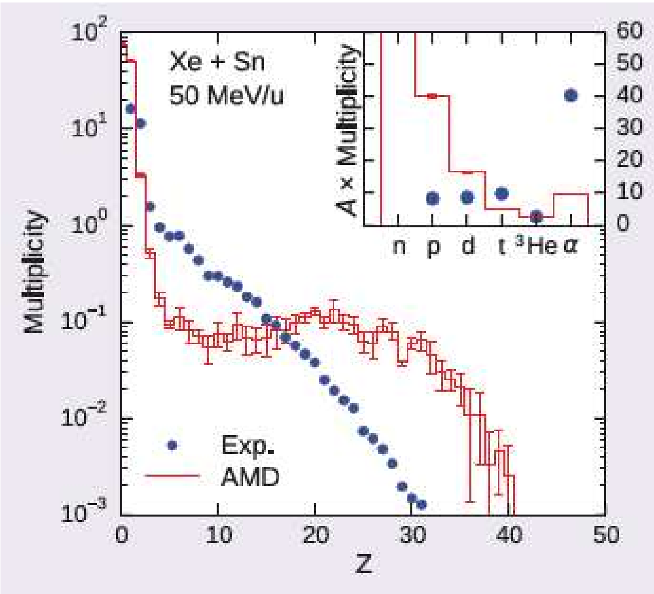
1. in collision term consider formation of clusters in terms of overlap with cluster wave function (detailed balance?)

2. Manipulate phase space: put wave packets of cluster constituent in one place (conservation laws?)

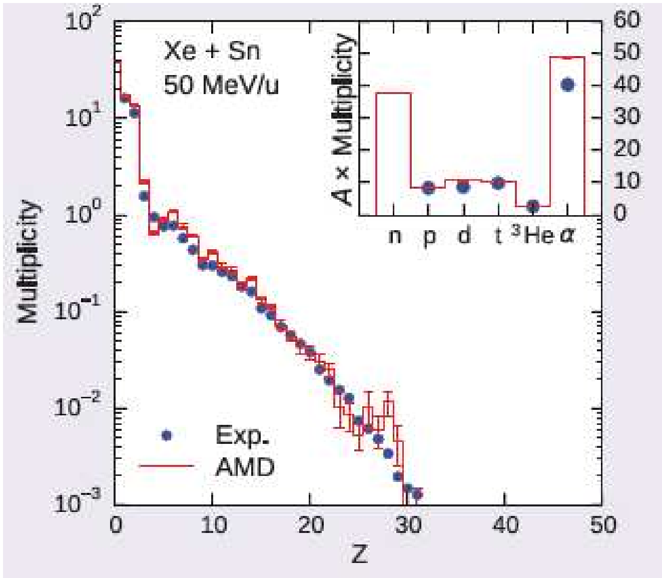
3. consider Pauli correlation fully

4. include also cluster-cluster collisions

multiplicity distribution w/o clusters



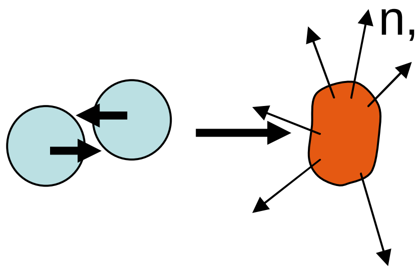
with clusters and cluster-cluster collisions



(A. Ono, this meeting)

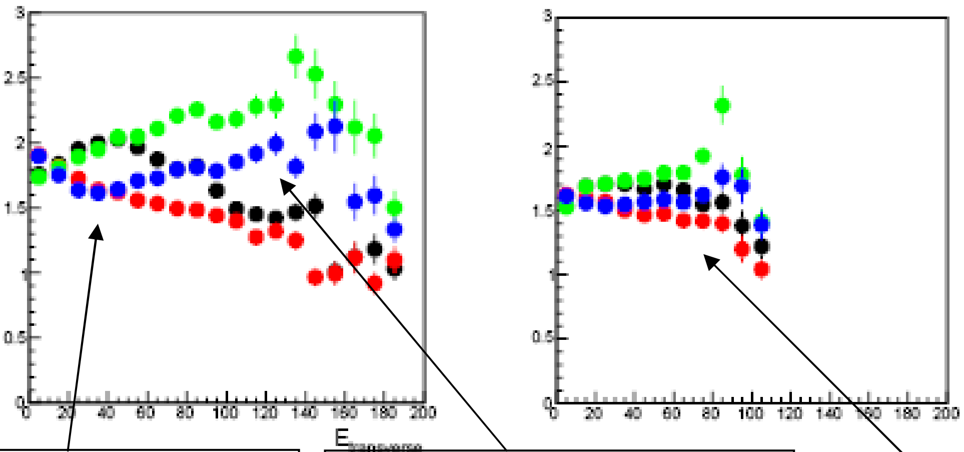
Example: Ratios of emitted pre-equilibrium particles in central collisions

n,p,t,^{3}He,α

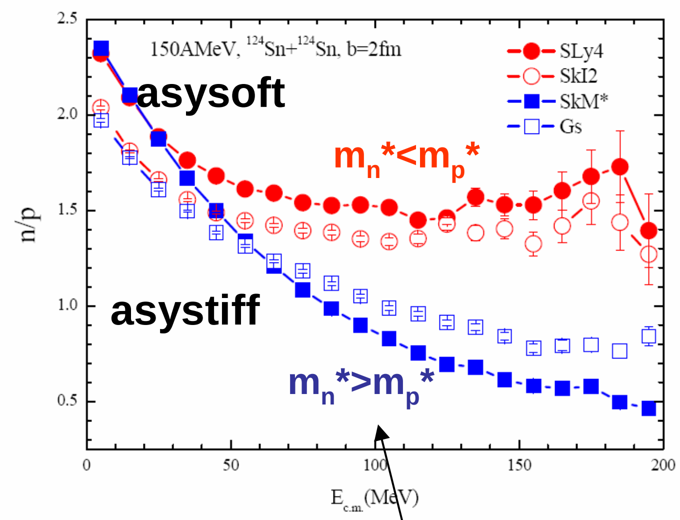


Early emitted Light Clusters reflect difference in potentials in expanded source, e.g. ratio Y(n)/Y(p).

Y(n)/Y(p) **^{136}Xe+^{124}Sn, 150 MeV** **Y(t)/Y(^{3}He)**



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



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

Asy-EOS dominates for slow particles; asysoft has larger repulsion at lower densities

Effective mass dominates for fast particles; smaller eff. mass favors emission

Effect also exists for light clusters (easier to measure) but somewhat reduced

similar findings for Sn+Sn collisions (MSU)

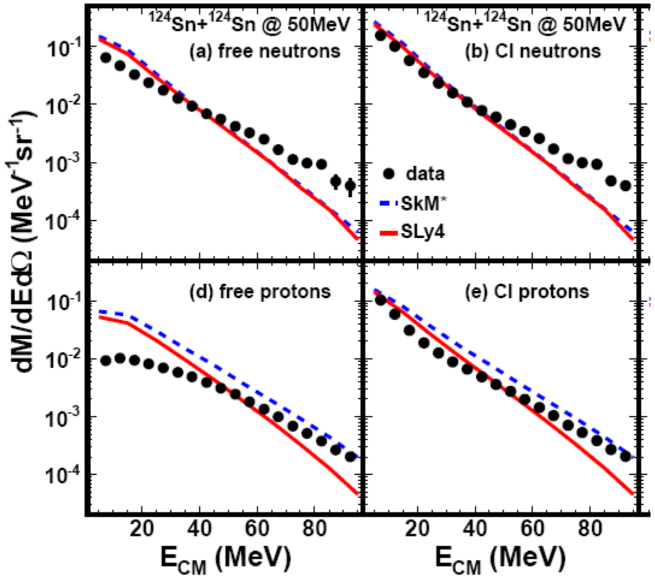
son: asysoft, $m_n^*>m_p^*$
stn: asystiff, $m_n^*>m_p^*$
sop: asysoft, $m_n^*<m_p^*$
stp: asystiff, $m_n^*<m_p^*$

H.H. Wolter, et al.,
EPJ Web of Conf. &&, 03097 (2014)

role of clusters?

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

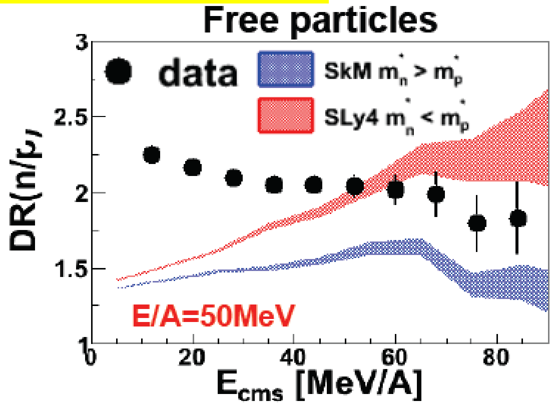
free and coalescence invariant (CI) spectra

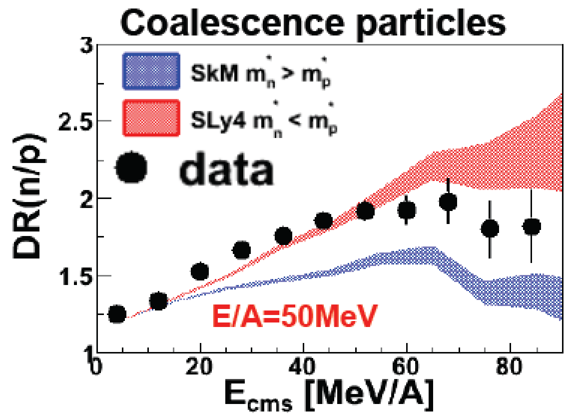


Double Ratios

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

agree only for CI spectra

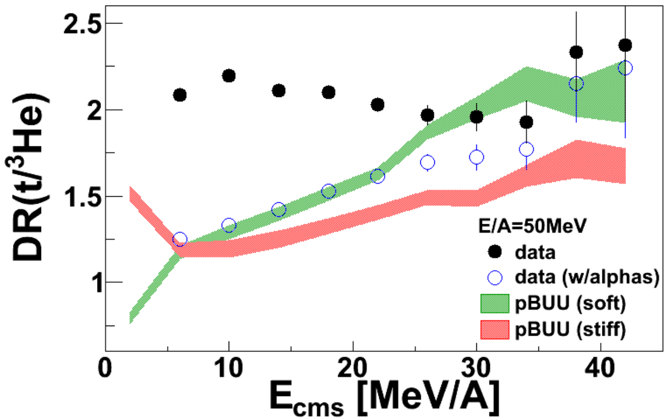




Y.X. Zhang, M.B.Tsang,et al., PLB 732, 186 (2014)
D.D.S.Coupland, arXiv 1406.4546

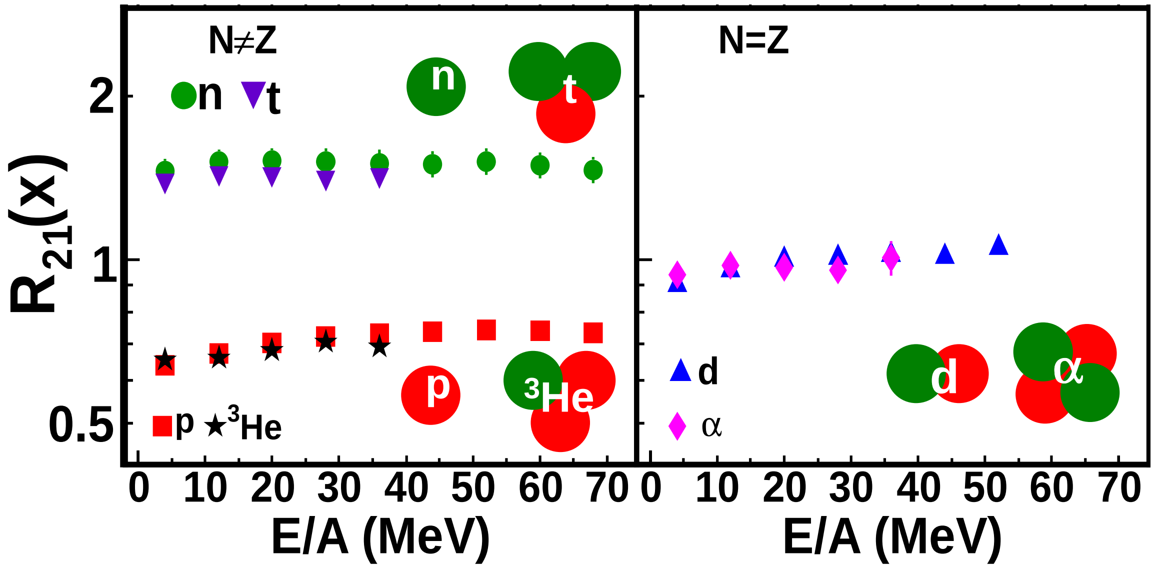
CI spectra
agree better with experiment: A poor man's substitute for not treating light clusters properly in the simulation

.. or with pBUU calc,
if exp. α-particles are counted as t and ^{3}He,
→ importance of dynamical LC treatment



W.Lynch, INPC, Florence, 2013:
^{124,112}Sn+^{124,112}Sn, 50 AMeV;
Z. Chajecki, NuSYM13

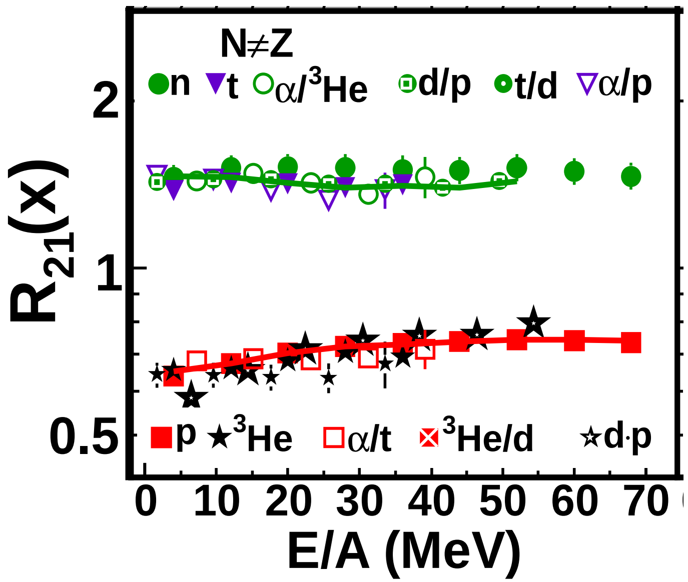
„Chemical potential scaling“ Z.Chajecki, et al., arXiv 1402.5216

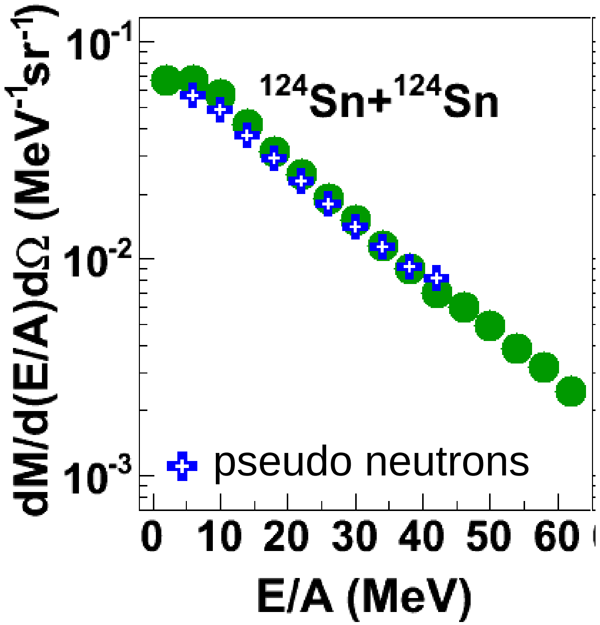


$$R_{21}(N,Z)=\frac{dM_2(N,Z)}{dM_1(N,Z)}$$

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 (?)

Cluster Aspects in Nuclear Systems

static
- nuclear matter
- stellar matter
- nuclear structure

dynamic
- nuclear structure
- heavy ion coll, HIC

nuclear matter

composition of
low density nm,

liquid-gas phase
transition

stellar matter

Supernova EOS,
ν–sphere,
neutron star crust

nuclear structure

cluster states,
(e.g.Hoyle state)
cluster dynamics
in excitation

heavy ion coll, HIC

final states heavily
clustered

equilibr. and non-eq.
emission of light and
intermediate mass clusters

methods well developed for 2-body
more work in heavier cluster expansions
Supernova EOS with clusters

treatment of clusters in transport

IMF → fluctuations, BLOB

LC→ explicitly, AMD, pBUU

comparison of
approaches:
new code comp
project
box calculations

exp. study and verification of properties
of dilute warm matter
ν-sphere,
supernova→femtonova

medium modifications of
clusters and transition
amplitudes

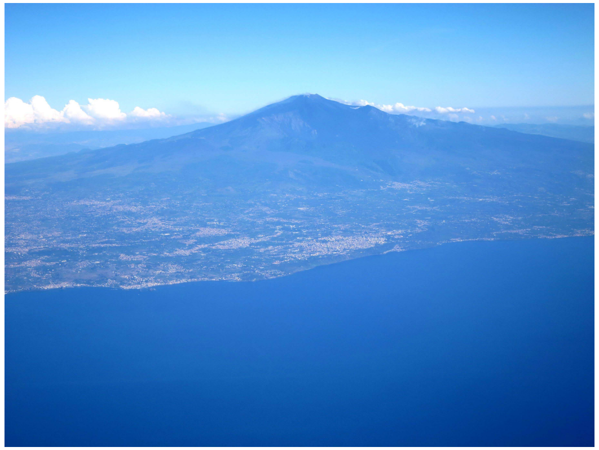
Clustering enters in many aspects of the investigation of nuclear matter, and esp. the symmetry energy.
Here only possible to sketch many ideas, wait for more in-depth talks in this conference!

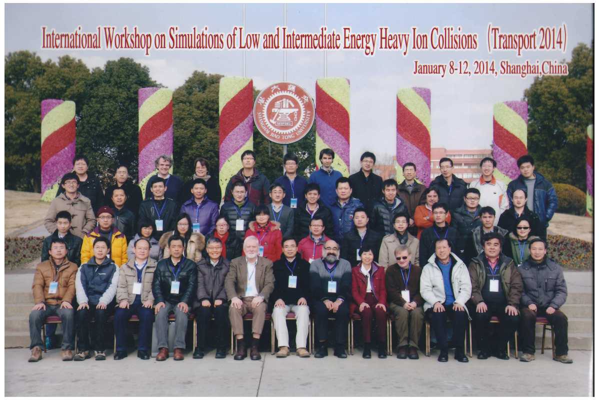
I would like to thank the groups, which whom I have collaborated
:

Catania-Smith connection: M. Colonna, Massimo Di Toro, Enzo Greco, M. Zielinska-Pfabe, and many others

Rostock-Wroclaw-GSI connection: Stefan Typel, Gerd Röpke, David Blaschke, Thomas Klähn, the Texas A&M group,…

MSU-China connection: Pawel Danielewicz, Betty Tsang, W. Lynch, L.W. Chen,
BaoAn Li, YingXun Zhang, Jun Xu, …





…and you for your attention