NN2015

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# Clusters in Heavy Ion Collisions and the Symmetry Energy

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**Aim of this short report:**

**→ observation of yield and isotopic content of clusters in heavy ion collisions is a way to study the nuclear symmetry energy**

**→ light clusters (n,p,d,t,$^{3}$He,$\alpha$) and heavier clusters (intermediate mass fragments, IMF, (3≤Z≤≈20) have to be treated differently and carry different information**

**→ characteristic examples for both cases**

**connected to talks by: Y.X. Zhang (Monday), P. Napolitani (earlier today)**
**S. Yenello and A. Ono (plenary session tomorrow)**

**with**
**Malgorzata Zielinska-Pfabe, Piotr Decowski† (Smith Coll., USA),**
**Maria Colonna (LNS Catania),**
**and support from Remi Bougault (LPC Caen), Abdou Chbihi (GANIL, Caen)**

LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

TUM LMU Excellence Cluster Universe

# Equation-of-State and Symmetry Energy

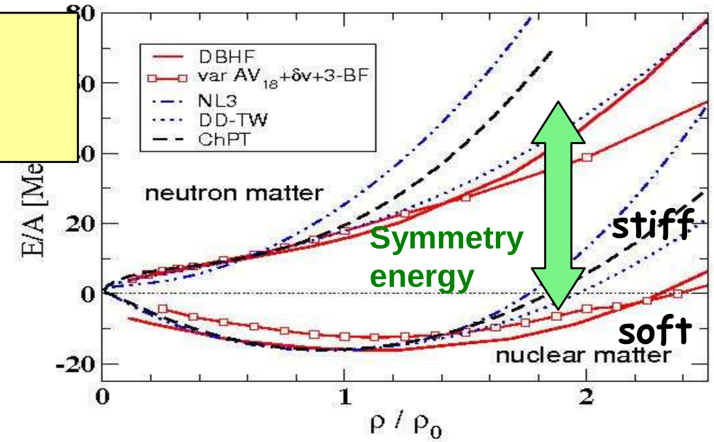
density-asymmetry dep. of nucl.matt.

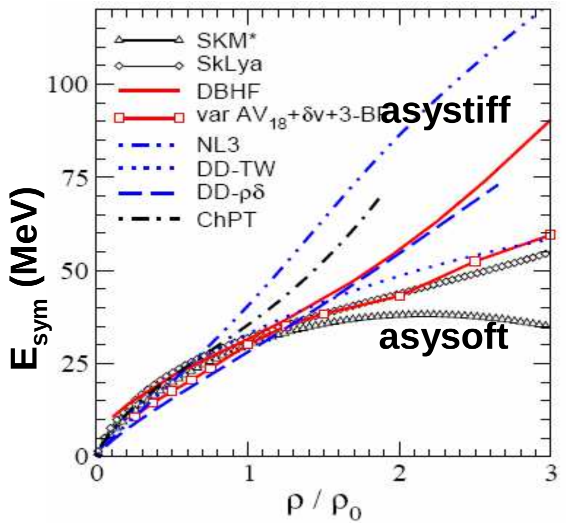
$$E(\rho_B,\delta)/A = E_{nm}(\rho_B) + E_{sym}(\rho_B)\delta^2 + O(\delta^4) + \ldots$$

$$\delta = \frac{\rho_n - \rho_p}{\rho_n + \rho_p}$$

$$a_S \approx E_{sym}(\rho_0)$$

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




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

**Why is symmetry energy so uncertain??**
**→ In-medium ρ mass, and short range isovector tensor correlations (e.g. B.A. Li, PRC81 (2010));**
**→ use heavy ion collisions to investigate in the laboratory**

# Symmetry potentials and effective masses

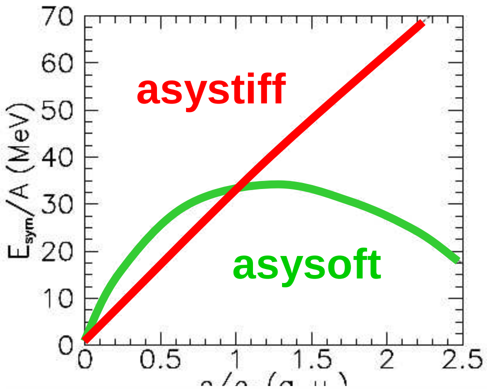
**Momentum dependence of symmetry potential (isoscalar and isovector)**

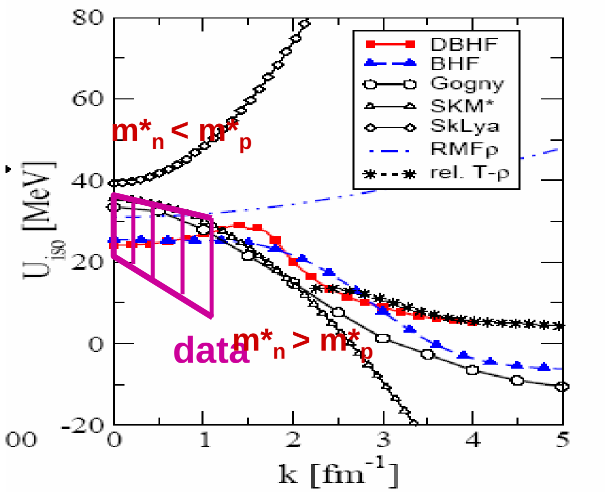
$$\varepsilon(\rho[f(\rho,k)];\delta) \rightarrow U(\rho,k;\delta) = \frac{\partial \varepsilon(\rho,\delta)}{\partial f(\rho,k)} = \underbrace{U_0(\rho,k) + U_{sym}(\rho,k)(\tau\delta)}_{U_\tau(\rho,k)} + \dots$$

**Proton-Neutron effective mass splitting**

$$\frac{m^*_\tau}{m} = \left(1 + \frac{m}{\hbar^2 k}\frac{\partial U_\tau}{\partial k}\right)^{-1}$$

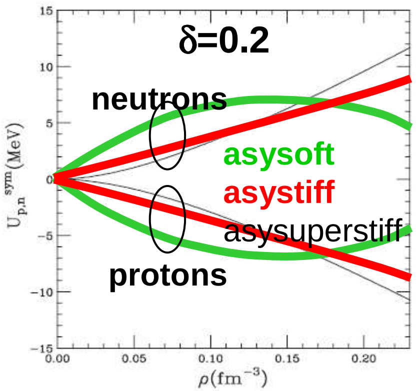
**Symmetry energy (BGBD)**

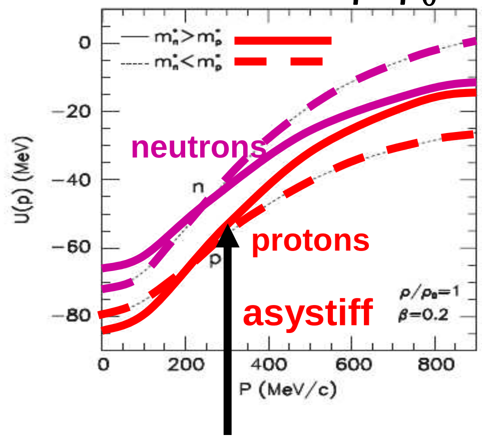



**Neutron/proton potentials as a fct of**

**density for $p=p_F$** **momentum for $\rho=\rho_0$**



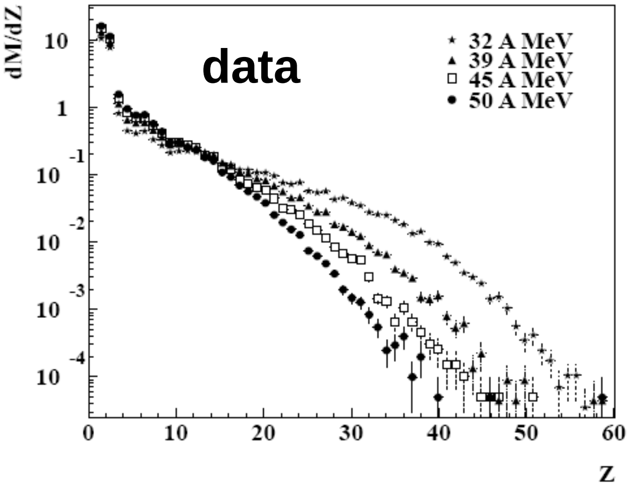

**crossing of potentials**

**→ leads to crossing of emission spectra**

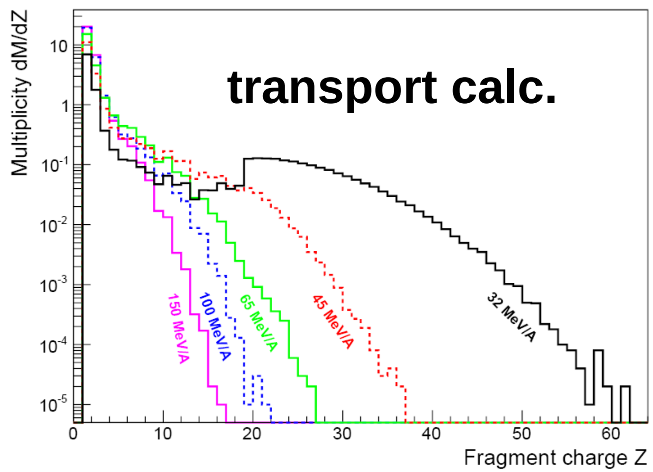
**No agreement on behavior and even ordering of n/p effective masses between Skyrme, RMF, BHF, DBHF**

# Clusters in heavy ion collisions

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




S. Hudan, et al., PRC67, 064613

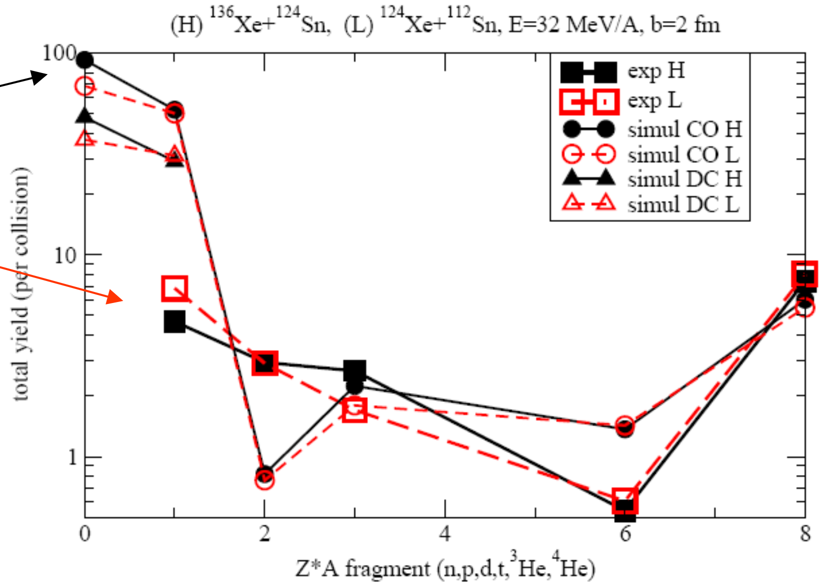



H.H. Wolter, et al., EPJ Web of Conf. &&, 03097 (2014)

a closer look at light clusters (LC)

overpredict nucleons

data R. Bougault, A. Chbihi (Ganil, prelim, IWM11)




H: $^{136}Xe+^{124}Sn$

L: $^{124}Xe+^{112}Sn$

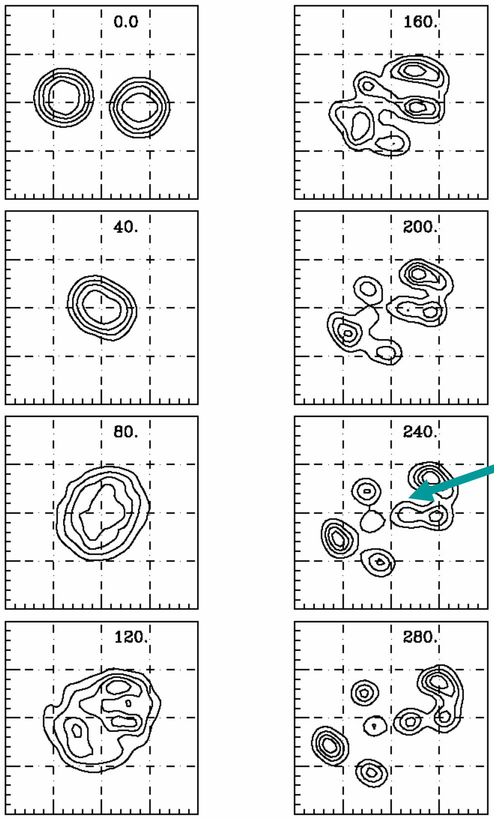
general pattern ok, but differences in detail, difficulty to descibe LC in transport

# Symmetry energy drives isospin content of clusters (Isospin dynamics)

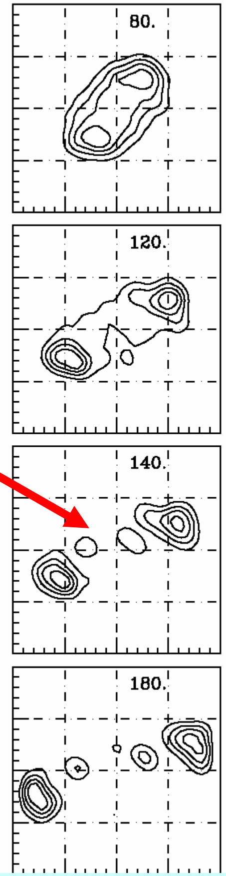
V.Baran et al.,
NPA703(2002)603
NPA730(2004)329

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

Central collision, b=2 fm

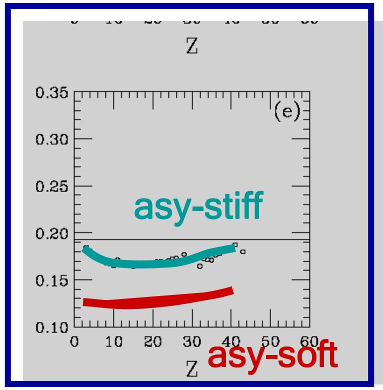


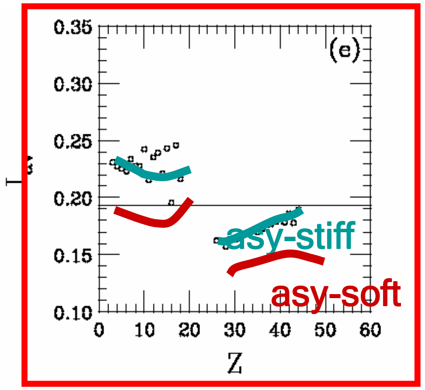

Peripheral collision, b=6 fm




bulk fragmentation

neck fragmentation




**Multifragmentation: Isospin fractionation at low densities**

**Neck-fragmentation: Isospin migration at interface with normal density**

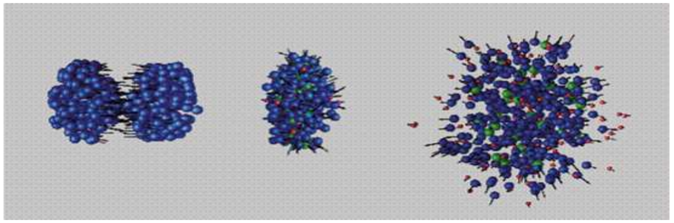
# Isospin sensitive Observables in Heavy Ion Collisions

peripheral

Coulomb barrier to Fermi energies

central

Relativistic energies



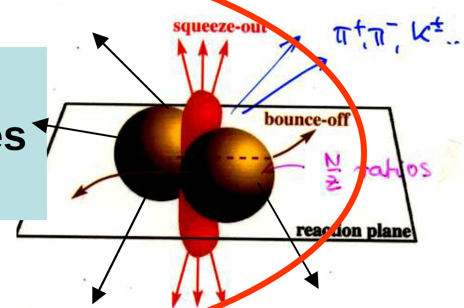
Isospin migration

Isospin fractionation, multifragm

deep-inelastic

pre-equil. dipole

pre-equil. light particles n,p,d,t,$^3$He,$\alpha$




N/Z of PLF residue = isospin diffusion

N/Z ratio of IMF's

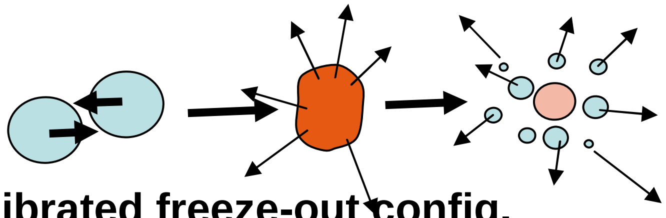
Flow: directed and elliptic

Production of particles, $\pi$,K

N/Z of neck fragment and velocity correlations

Symmetry energy effects are small absolutely (about 10%)
→ use differences or ratios of isospin dependent observables,
to eliminate uncertainties in the isoscalar sector.

# Approaches to cluster formation in HIC



1. freeze-out approx.: statistical decay of excited, equilibrated freeze-out config.
„statistical clusters“

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

**BUU/BLE/BLOB**

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

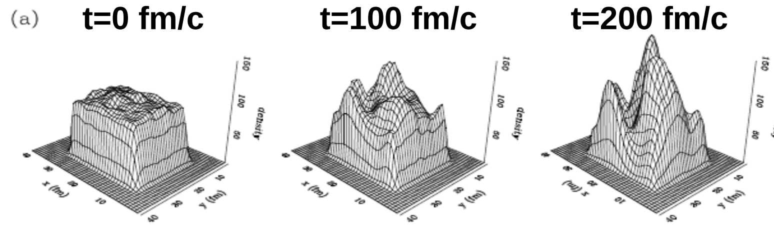
deterministic, dissipative 1-body equation + fluctuation

**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




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 (numerical) fluctuations in the density.
Time scale = growth time of the instable modes

**But LC (light cluster) formation dominated by correlations: not well described in mean field**

# Fragment formation II

## Light clusters (LC:d,t,$^3$He,$\alpha$)

Correlation dominated (esp.Pauli-correlation). not good in BUU and MD models, since simple interactions and classical phase space distribution give bad eigenstates for LC

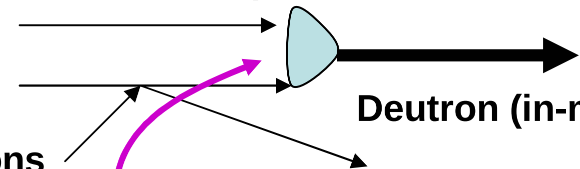
except(!) for AMD: can define realistic wave functions for LC with reasonable BE;

## Solution for BV models:

LC distribution functions as explicit degrees of freedom coupled to nucleon distribution functions by 3-body collisions of type NNN→ND

→ P. Danielewicz and Q. Pan, PRC 46 (1992)

(d,t,$^3$He, but no $\alpha$!) coupled transport equations



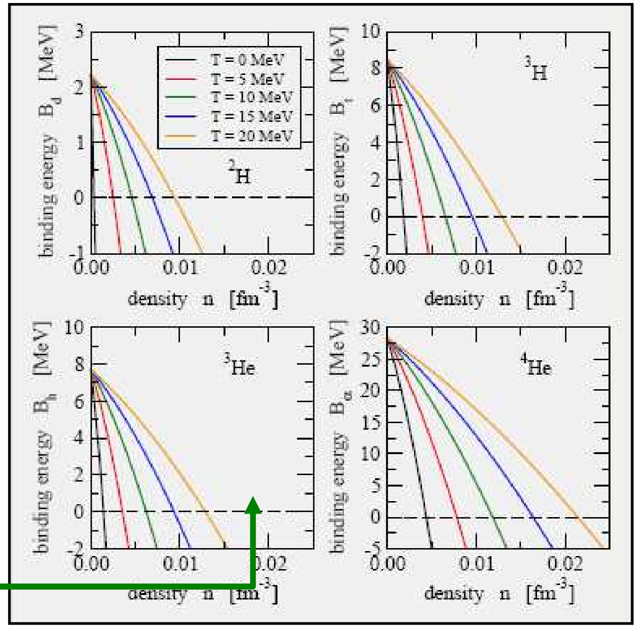
Deutron (in-medium)

## 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,…,HW, PRC81 (2010)

similar: transitions amplitudes in medium

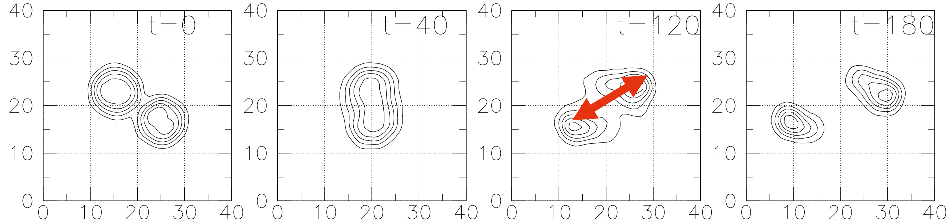



**Mott density:**
**Cluster dissolves**

# Isopin diffusion

**isospin transport through „neck“ in peripheral collisions**

$^{124}Sn(H)+^{112}Sn(L)$




**Isospin transport ratio R :**

$$R = \frac{2X_{AB} - X_{AA} - X_{BB}}{X_{AA} - X_{BB}}$$

*B. Tsang et al., PRL 102 (2009)*

**A dominance** → **+1**

**mixing** → **0**

**B dominance** → **-1**

**Simple equil. model**

$$\beta^{M}_{P,T} = \beta^{eq} + (\beta^{H,L} - \beta^{eq})\ e^{-t/\tau},$$

$$\Rightarrow R^{\rho}_{P,T} = \pm e^{-t/\tau}$$

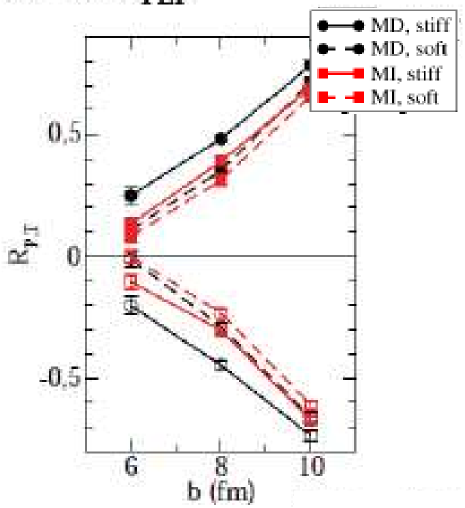
**Ratio det. by interact. and relax. times**

**$^{124}Sn + ^{112}Sn$, 50 AMeV**

**SMF calculations**

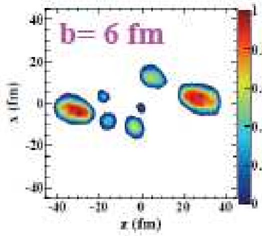
*J. Rizzo et al., NPA(2008)*

**X = N/Z$_{PLF}$**

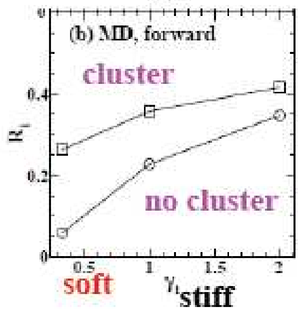



**pBUU calculations (Danielewicz)**

*Coupland et al., PRC 84, 054603 (2011)*

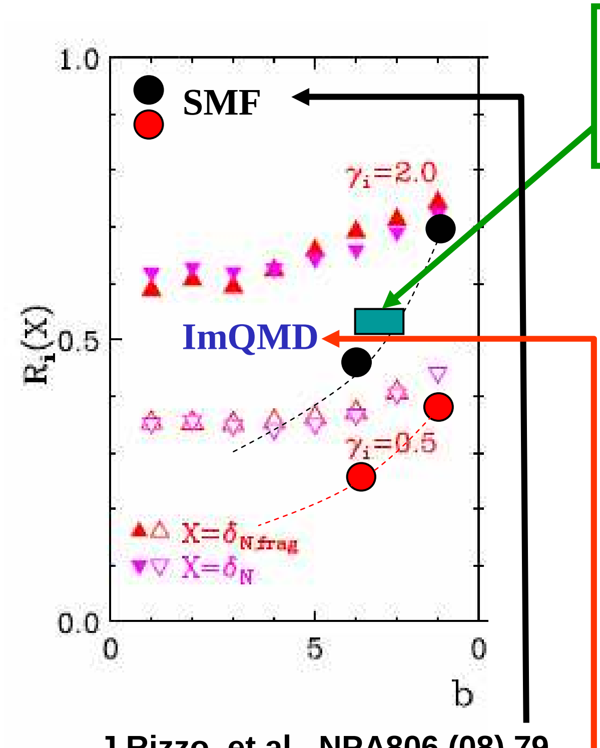



Cluster effects (d,t,He$^3$)

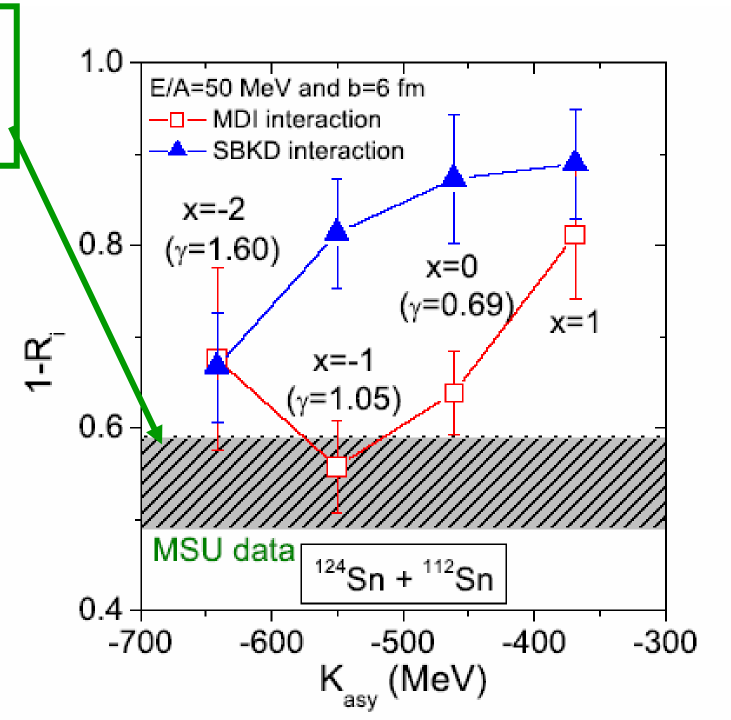


## Transport Ratios for Projectile/Target Residues: $^{112,124}$Sn + $^{112,124}$Sn, 50 MeV

## Comparison of models:




experimental data (B. Tsang et al. PRL 92 (2004) )



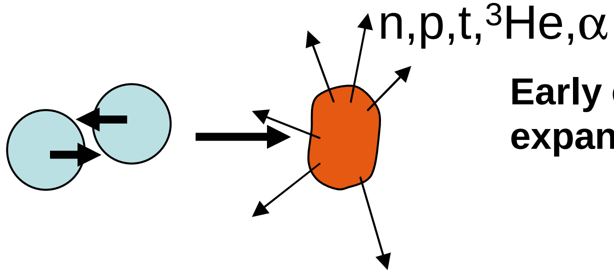

**J.Rizzo, et al., NPA806 (08) 79**

**M.B. Tsang, et al., PRL 102 (08)**

**L.W.Chen, C.M.Ko, B.A.Li, PRL 94, 032701 (2005)**

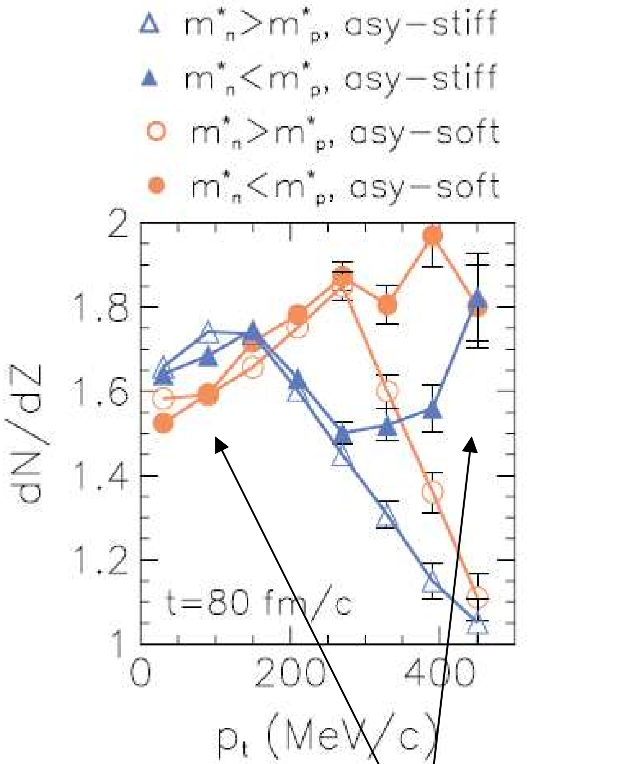
1. **Qualitative agreement, but not quantitative**
2. **different impact parameter dependence; to be understood**

# Ratios of emitted pre-equilibrium particles in central collisions




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

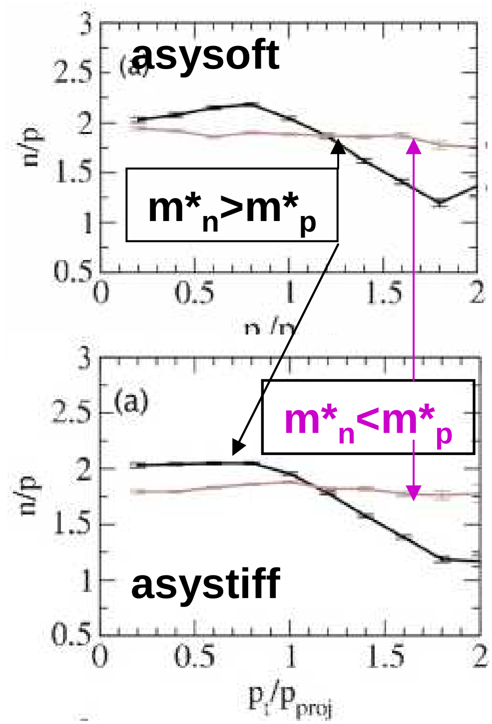
**$^{132}Sn+^{124}Sn$, 100 AMeV**




**splitting dep. on stiffness of symm energy resp. effect, mass**

**(J. Rizzo et al., PRC72,064609 (2005))**

**$^{197}Au+^{197}Au$. 600 AMeV**

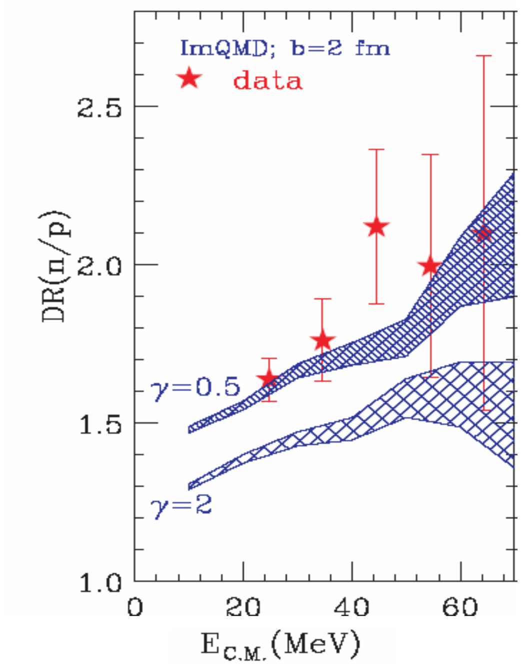



**essentially only dep. on eff. mass**

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

**Double Ratios** $\frac{^{124}Sn + ^{124}Sn}{^{112}Sn + ^{112}Sn}$

**50 AMeV**




**no effective mass depend.**

**M. Famiano, et al., PRL 97,052701 (06)**
**M.B.Tsang, et al., PRL 102, 122701 (09)**

# Light Cluster Emission: $^{136,124}Xe+^{124,112}Sn$, E = 32,..,150 AMeV ,

**Single ratios**

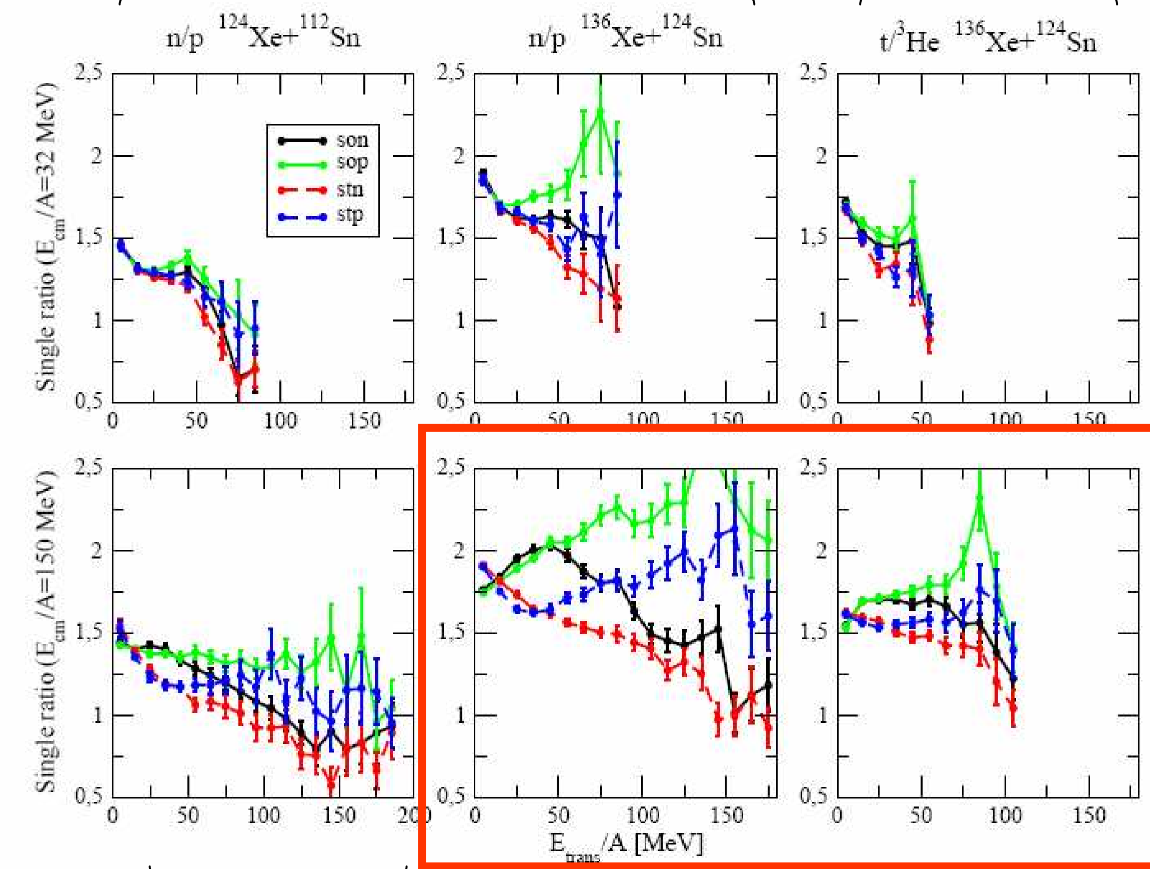
effects smaller for heavier clusters,
but have to improve statistics

**n/p** **t/3He**

Variation
of density dep. and
effective mass splitting
with isoscalar potential
held fixed
(Bombaci-Gale-
Bertsch-DasGupta
type)

E=32 AMeV

E=150 AMeV




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

look in more detail

neutron poor
$^{124}Xe+^{112}Sn$

neutron rich
$^{136}Xe+^{124}Sn$

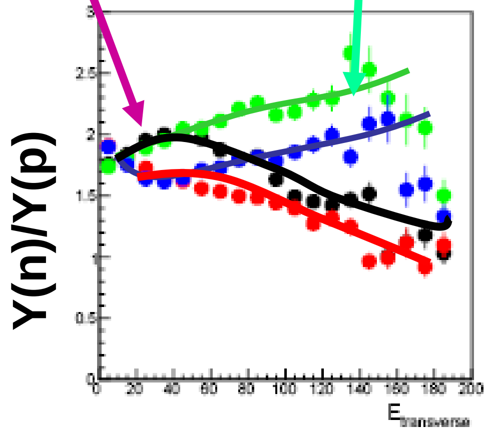
effects larger for higher energy and neutron rich system

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

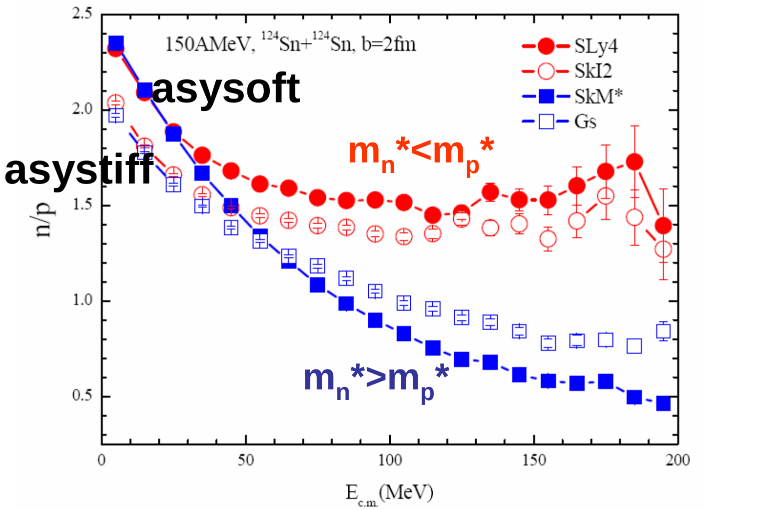
**Asy-EOS dominates for slow particles; asysoft has larger repulsion at lower densities**

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

**E=150 AMeV**

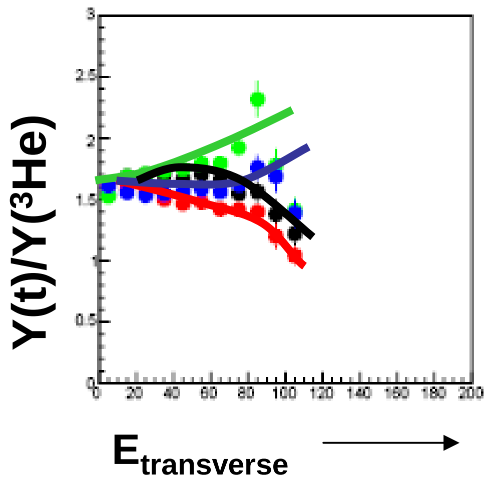



**similar conclusions for Sn+Sn collisions (MSU)**




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

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



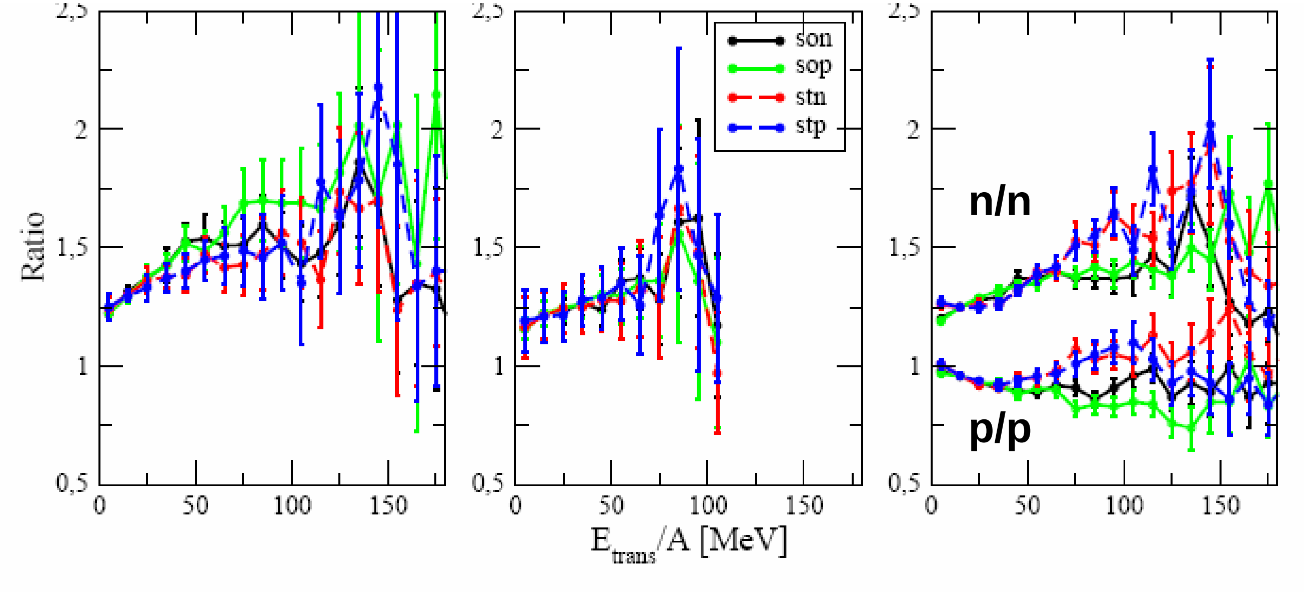

son: asysoft, $m_n^* > m_p^*$
stn: asystiff, $m_n^* > m_p^*$
sop: asysoft, $m_n^* < m_p^*$
stp: asystiff, $m_n^* < m_p^*$

**Possibility to separate density and momentum dependence of symmetry energy**

**Double Ratios**

**Singe Ratios**

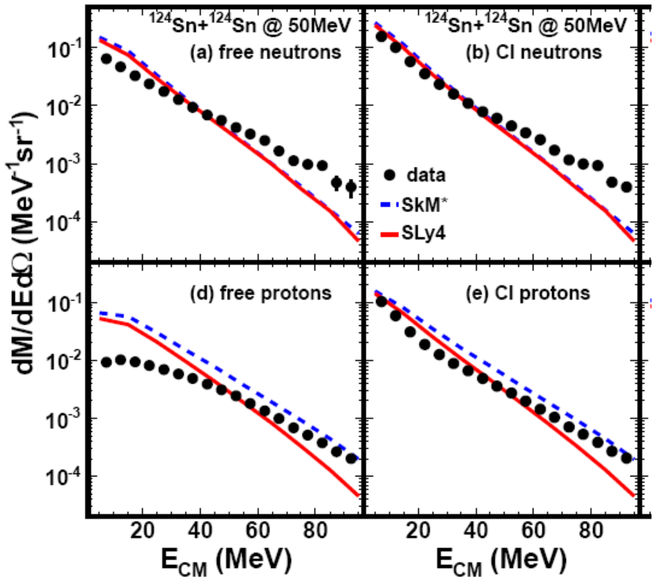
$$\frac{n/p_{\,^{136}Xe+^{124}Sn}}{n/p_{\,^{124}Xe+^{112}Sn}} \qquad \frac{t/{}^{3}He_{\,^{136}Xe+^{124}Sn}}{t/{}^{3}He_{\,^{124}Xe+^{112}Sn}} \qquad \frac{n_{\,^{136}Xe+^{124}Sn}}{n_{\,^{124}Xe+^{112}Sn}},\ resp.,\ \frac{p_{\,^{136}Xe+^{124}Sn}}{p_{\,^{124}Xe+^{112}Sn}}$$



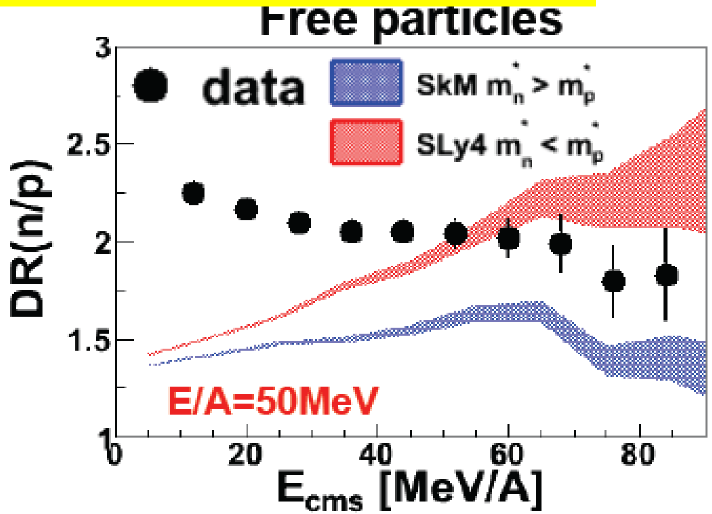

**sensitivity much smaller**

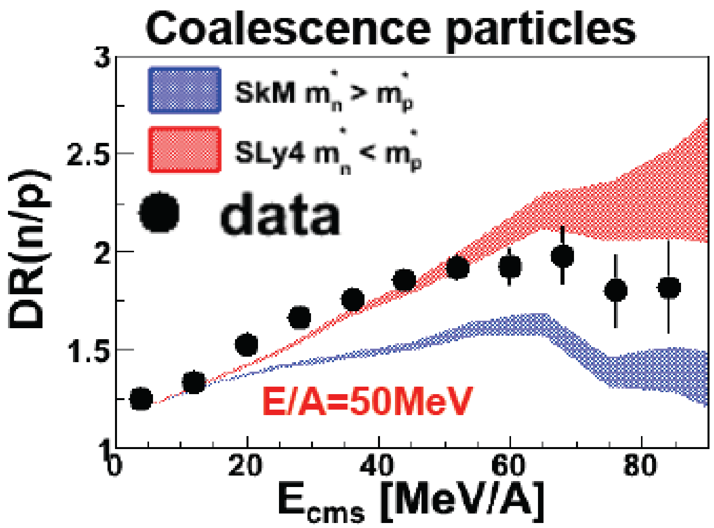
**sensitivity only to asy-stiffness**

# Comparison with data:
# problem of light cluster description in transport approaches
# → „coalescence invariant“ (CI) spectra




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



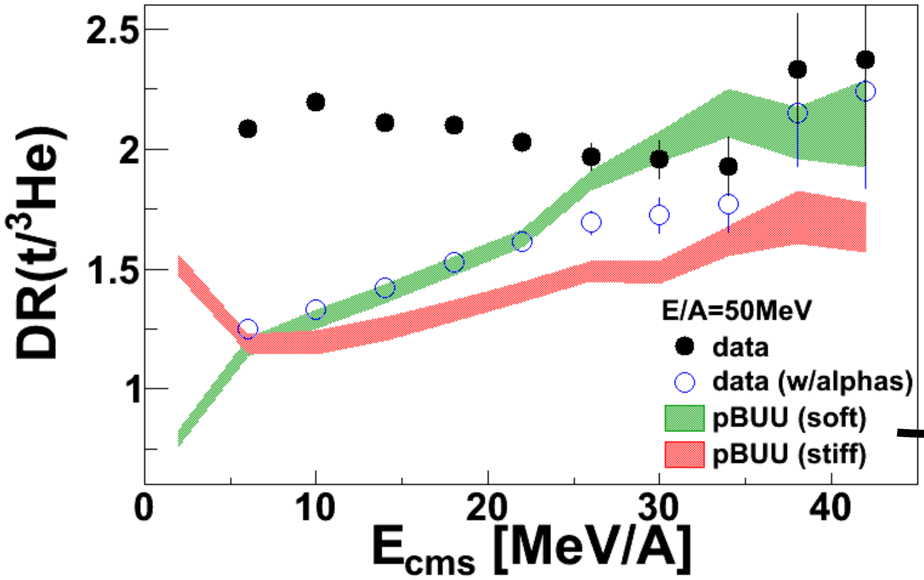




favors $m_n^*<m_p^*$ (in contrast to optical model analyses)
→ more work required!

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

# Interdependence of light cluster (LC) yields

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




Cluster yields depend on dynamic treatment of LC production in HIC

## Conclusions:

- cluster production in heavy ion collisions is an important source of information on the symmetry energy

- the information is different in bigger fragments (IMF, mean field dominated) and light clusters (LC, mf and effective masses)

- the single ratio spectra of LC may allow to separate the density and momentum dependence.
- more asymmetric systems and the n/p ratio are most sensitive. The t/3He ratio carries a similar information

- more precise data recently available, but not yet precise enough to determine effective masses (at stress with other determinations)

- strongly connected with the question to descibe dynamical cluster formation in HIC

**Grazie!**