Isospin Effects in Heavy Ion Reactions :
results from transport theories

IWM-EC 2014

May 6-9, 2014
Catania - Italy

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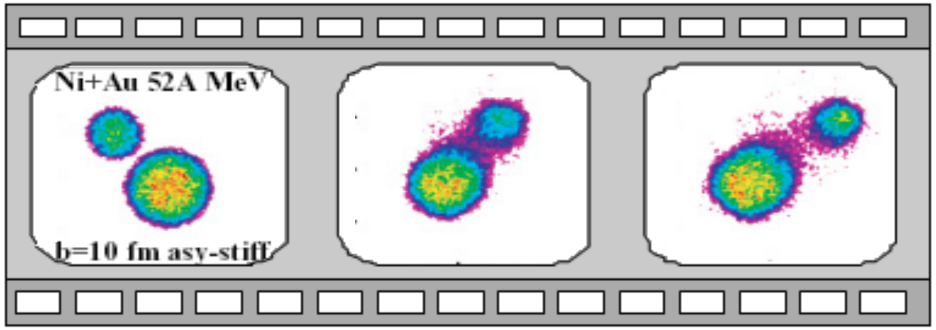
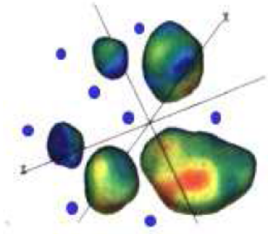
Content

- Brief introduction to transport theories
- Fragmentation mechanisms at low and Fermi energies
- Charge equilibration at Fermi energies

Microscopic dynamical approach



- Mean-field (one-body) dynamics
- Two-body correlations
- Fluctuations



two-body density matrix — *one-body density matrix*

$$\rho_2(12,1'2') = \rho_1(1,1')\rho_1(2,2') + \delta\sigma(12,1'2')$$

one-body

$$H = H_0 + v_{1,2}$$

Mean-field (H_0) — ***Residual interaction*** ($v_{1,2}$)

$$i\hbar\frac{\partial}{\partial t}\rho_1(1,1',t) = \langle 1|[H_0,\rho_1(t)]|1'\rangle + K[\rho_1] + \delta K[\rho_1,\delta\sigma]$$

TDHF

$K = F(\rho_1, |v|^2)$ — *Average effect of the residual interaction*

$\delta K = F(v, \delta\sigma)$ $\quad < \delta K >= 0 \quad$ $< \delta K \delta K >$ → *Fluctuations*

1. *Semi-classical approximation*

Chomaz,Colonna, Randrup
Phys. Rep. 389 (2004)
Baran,Colonna,Greco, Di Toro
Phys. Rep. 410, 335 (2005)

Transport equation for the one-body distribution function f

(semi-classical analog of Wigner function)

$$\frac{df(r,p,t)}{dt} = \underbrace{\frac{\partial f(r,p,t)}{\partial t} + \{f,h\}}_{\text{Vlasov}} = k[f] + \delta k$$

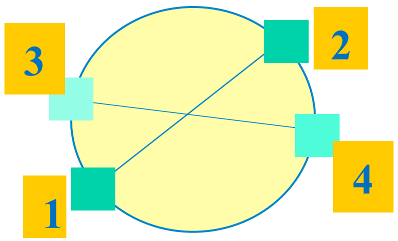
Residual interaction:
Correlations, Fluctuations

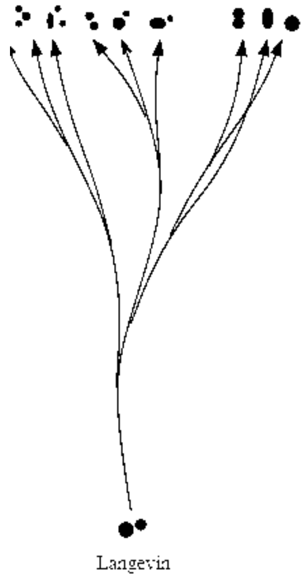
- *Two-body Collision Integral* **(BUU)**

$$\bar{K}(\boldsymbol{r},\boldsymbol{p}_1) = g\sum_{234} W(12;34)\left[\bar{f}_1\bar{f}_2 f_3 f_4 - f_1 f_2 \bar{f}_3 \bar{f}_4\right]$$

$$W(12;34) = v_{rel}\left(\frac{d\sigma}{d\Omega}\right)_{12\to 34}\delta(\boldsymbol{p}_1+\boldsymbol{p}_2-\boldsymbol{p}_3-\boldsymbol{p}_4) \qquad \bar{f} = 1-f$$

(1,2) ⟶ (3,4)





Boltzmann-Langevin (BL) equation

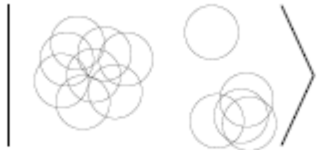
- *Fluctuations in collision integral* ⟶ ● *Stochastic Mean-Field* **(SMF)** *model*

Fluctuations are projected in coordinate space (density profile)

$$\prec \delta K(\boldsymbol{r},\boldsymbol{p},t)\,\delta K(\boldsymbol{r}',\boldsymbol{p}',t') \succ = C(\boldsymbol{p},\boldsymbol{p}',\boldsymbol{r},t)\,\delta(\boldsymbol{r}-\boldsymbol{r}')\,\delta(t-t')$$

2. *Molecular Dynamics approaches (AMD, ImQMD, CoMD,…)*

$$|\Phi(Z)\rangle = \det_{ij}\left[\exp\left\{-\nu\left(\mathbf{r}_j - \frac{\mathbf{Z}_i}{\sqrt{\nu}}\right)^2\right\}\chi_{\alpha_i}(j)\right]$$



A.Ono, ***Phys.Rev.C59,853(1999)***
Zhang and Li, ***PRC74,014602(2006)***
J.Aichelin, ***Phys.Rep.202,233(1991)***
M. Papa et al., ***PRC64, 024612 (2001),***
……

χ_{α_i} : Spin-isospin states = $p\uparrow, p\downarrow, n\uparrow, n\downarrow$

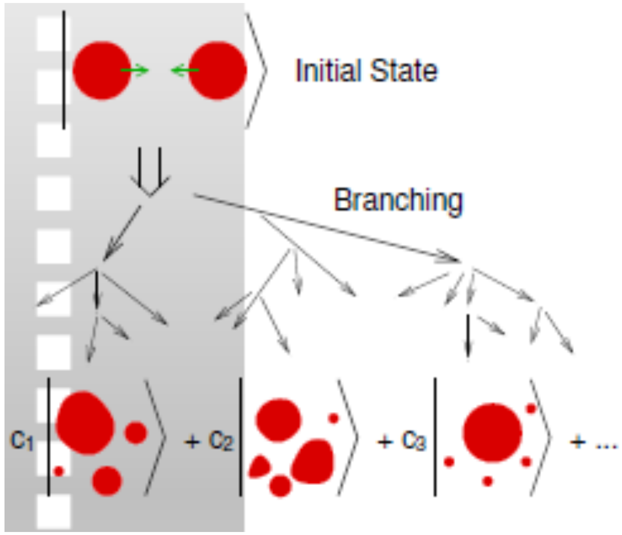
$$\mathbf{Z}_i = \sqrt{\nu}\mathbf{D}_i + \frac{i}{2\hbar\sqrt{\nu}}\mathbf{K}_i$$

ν : Width parameter = $(2.5\text{ fm})^{-2}$

Stochastic equation of motion for the wave packet centroids Z:

$$\frac{d}{dt}\mathbf{Z}_i = \{\mathbf{Z}_i, \mathcal{H}\}_{\text{PB}} + \quad \text{stochastic NN collisions}$$

- Mean field (Time evolution of single-particle wave functions)
- Nucleon-nucleon collisions (as the residual interaction)



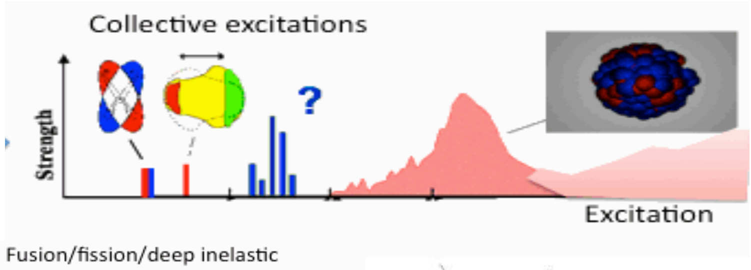
Collision integral fully stochastic, but approx. description of mean-field effects…

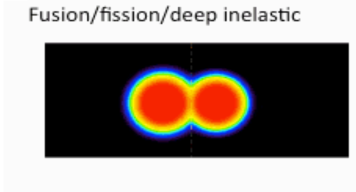
A. Ono, IWM *2011*

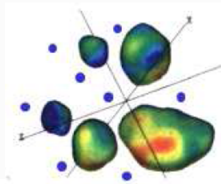
Colonna, Ono, Rizzo, *Phys. Rev..C82,054613 (2010)*

Isospin effects in Heavy Ion Reactions

- New collective excitations
- *Competition between reaction mechanisms*
- Isospin diffusion and drift
- *Charge equilibration*
- Isotopic features of light particles and IMFs







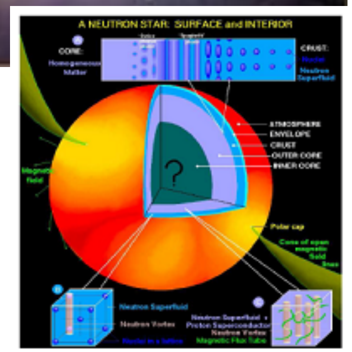
What can we access by transport theories?

➢ Test the mean-field potential (nuclear effective interaction)

⟶ *Nuclear Equation of State* ***EOS***

(Energy or Pressure as a function of density, temperature …)

⟶ Astrophysical implications …



➢ *The interplay between mean-field and correlation effects (clusters) in nuclear reaction mechanisms*

⟶ The **EOS** of clustered matter

Symmetry energy and effective mass splitting

$$E/A(\rho) = E(\rho) + E_{sym}(\rho)\,\beta^2$$

β=(N-Z)/A

Often used parametrization:

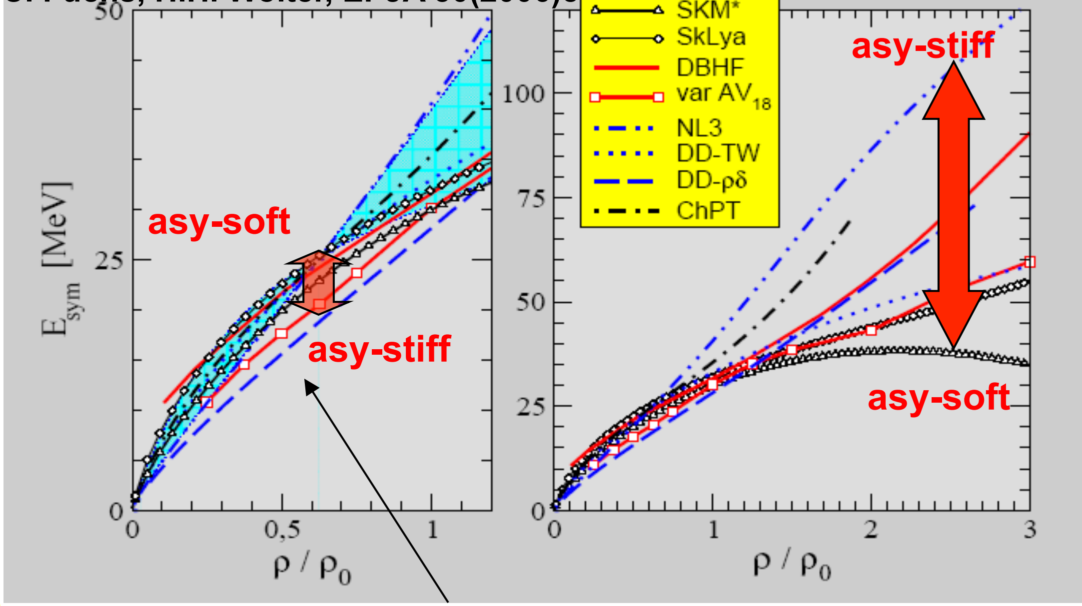
$$E_{sym}^{pot} \approx (\rho/\rho_0)^{\gamma}$$

γ<1 asy-soft, γ>1 asy-stiff

$$E_{sym}(\rho) = \underset{or\ J}{S_0} + L\,\frac{\rho-\rho_0}{3\rho_0} + \ldots$$

$\gamma = L/(3S_0)$

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

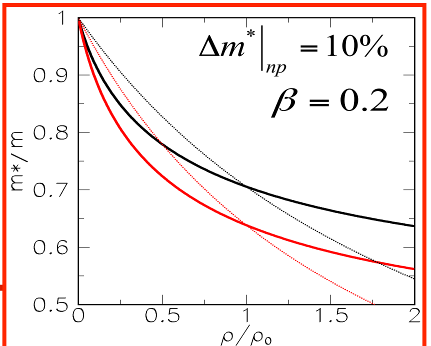


zoom at low density

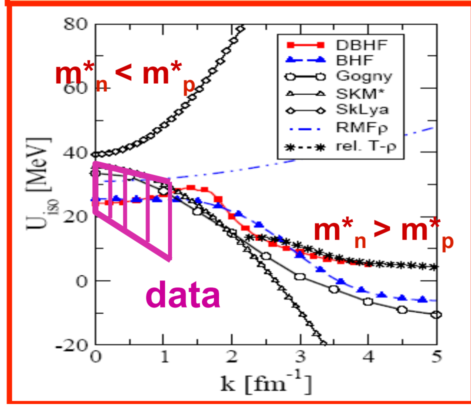
Momentum dependence (MD)

effective mass different for protons and neutrons

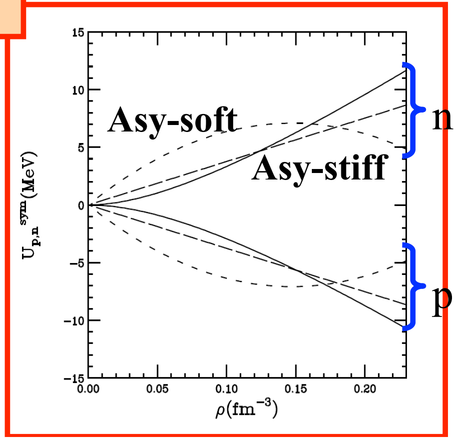
$$\frac{m_q^*}{m} = \left[1 + \frac{m}{\hbar^2 k}\frac{\partial U_q}{\partial k}\right]^{-1}$$



Lane potential $U_{Lane} = \frac{U_n - U_p}{2\beta}$



Symmetry potential

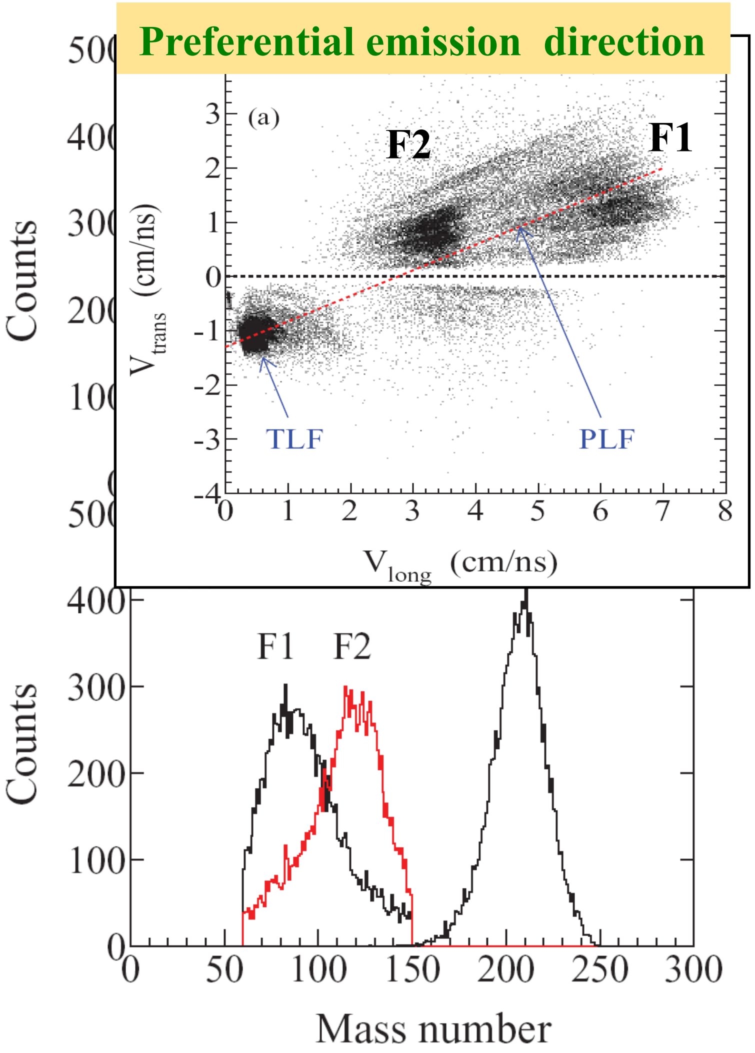


Fragmentation and flows

➢ Ternary break-up

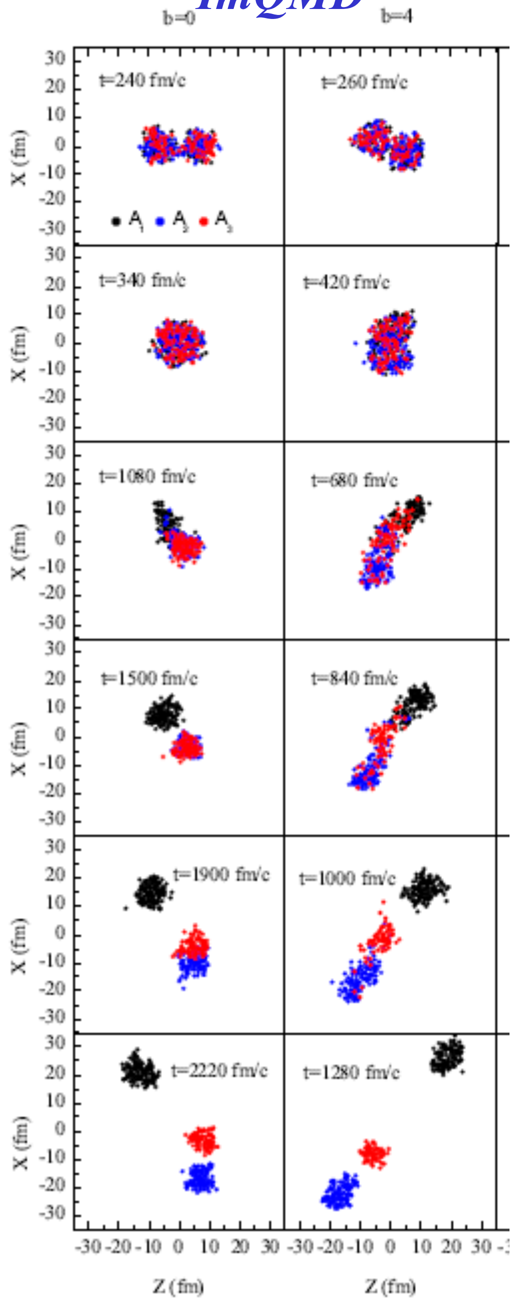
^{197}Au + ^{197}Au collisions - 15 MeV/A
(Chimera@LNS data) ***PRC 81, 024605 (2010)***

Preferential emission direction

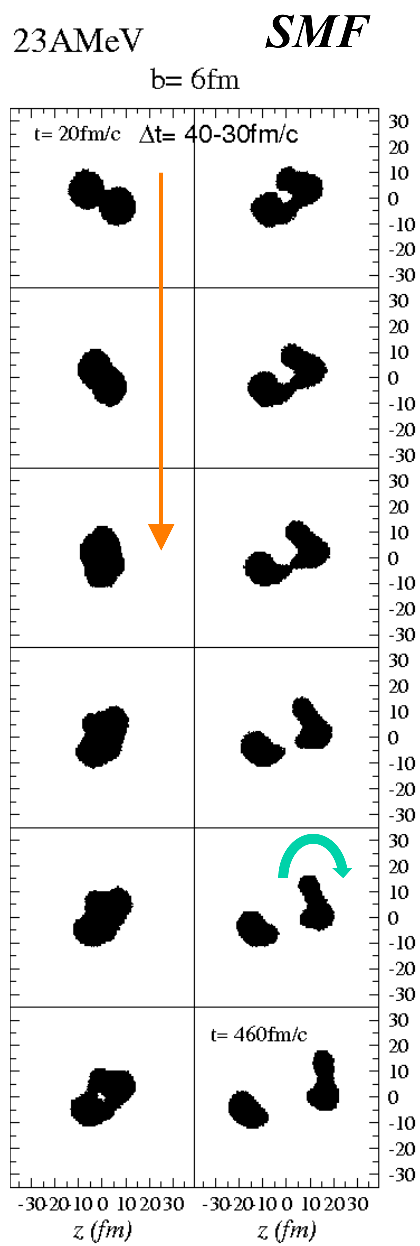


Y.Li et al., NPA (2013)

ImQMD

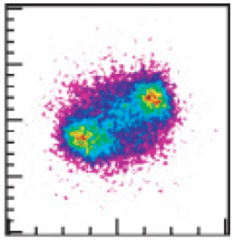


C.Rizzo et al. (2014)

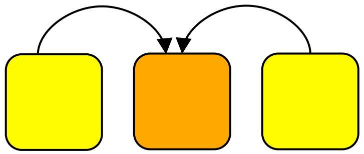


see P. Cammarata talk

➢ Isospin migration in neck fragmentation



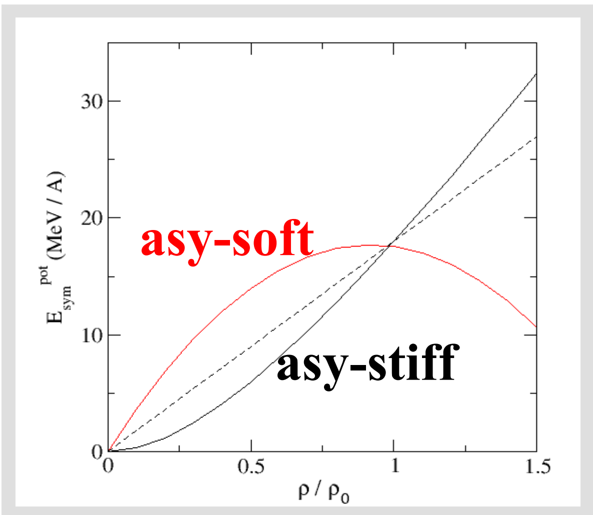
Asymmetry flux



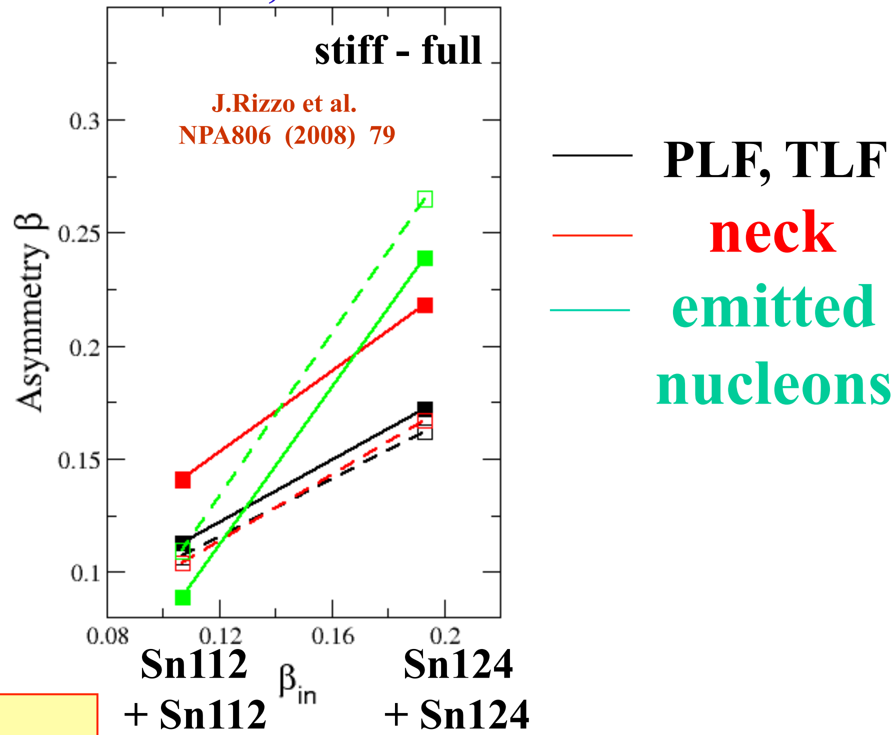
- Transfer of asymmetry from PLF and TLF to the low density neck region: **neutron enrichment of the neck region**
- Effect related to the derivative of the symmetry energy with respect to density

$\rho_{IMF} < \rho_{PLF(TLF)}$

Density gradients ⟶ derivative of E_{sym}



b = 6 fm, 50 AMeV



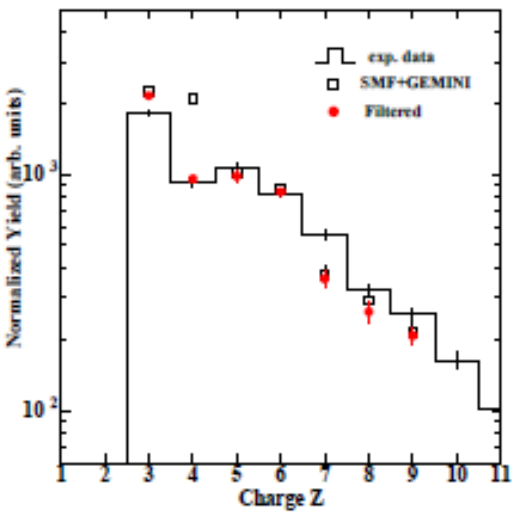
Larger derivative with asy-stiff ⟶ larger isospin migration effects

The asymmetry of the neck is larger than the asymmetry of PLF (TLF) in the stiff case

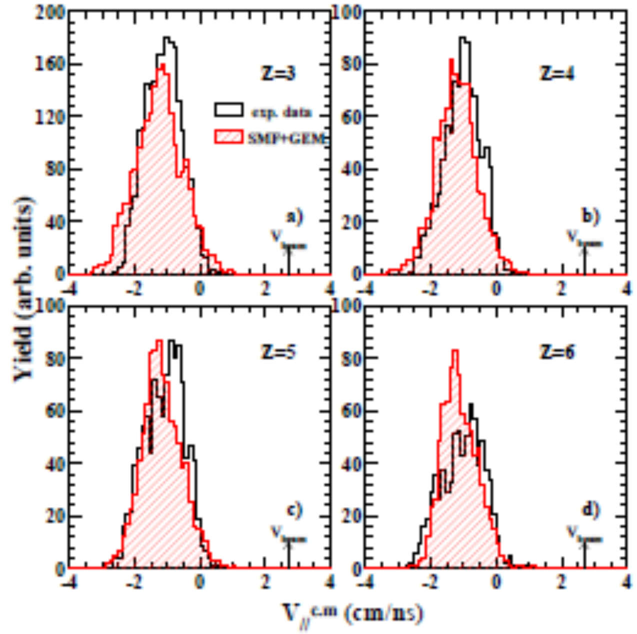
Comparison with Chimera data

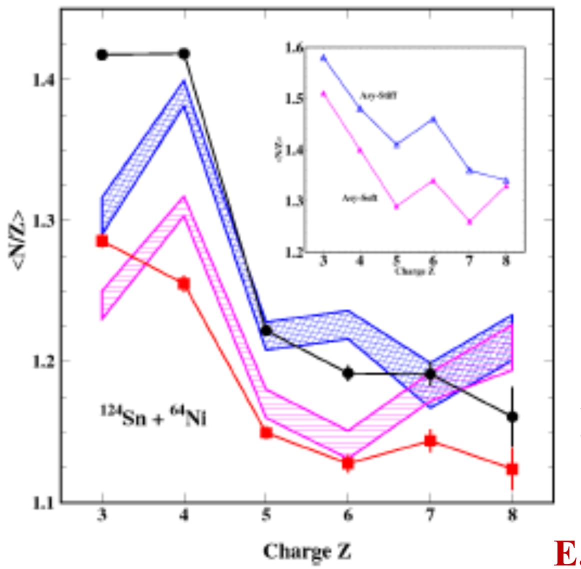
Properties of 'dynamically emitted' (DE) fragments

Charge distribution



Parallel velocity distribution





DE

SE

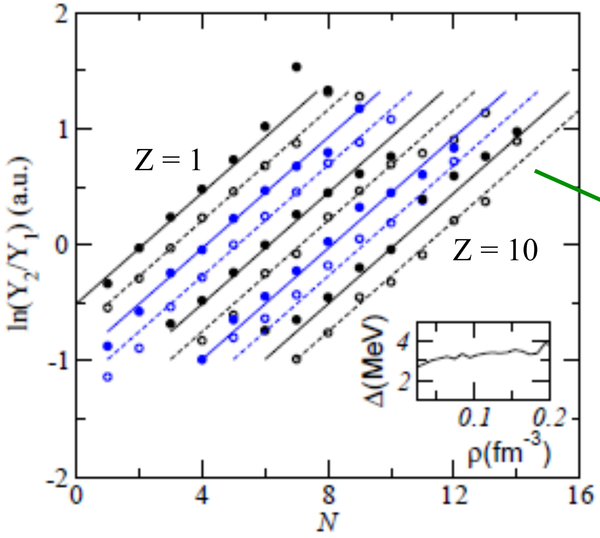
- Good reproduction of overall dynamics
- The N/Z content of IMF's in better reproduced by asystiff (L =75 MeV)

^{124}Sn + ^{64}Ni 35 AMeV

E. De Filippo et al., PRC(2012)

see also Brown et al, PRC87,061601(2013)

➢ Fragment production and isoscaling



M.Colonna, *PRL 110, 042701 (2013)*

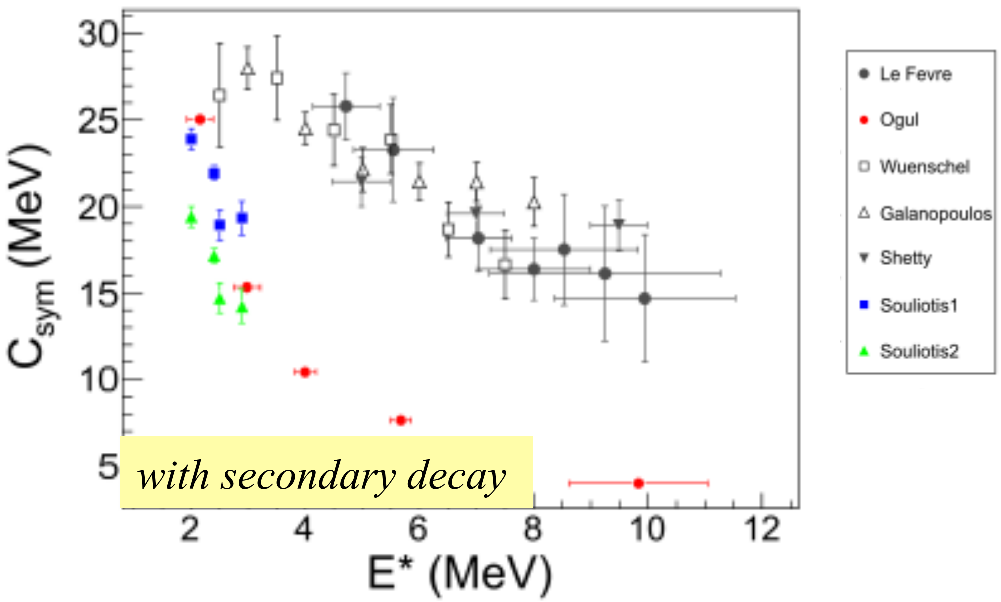
H. S. Xu et al., *PRL 85, 716 (2000)*

$$\frac{Y(neutron-rich)}{Y(neutron-poor)}$$

The fragment yield ratio is sensitive to the symmetry energy

$$\alpha = \frac{4C_{sym}}{T}\left[\left(\frac{Z_1}{A_1}\right)^2 - \left(\frac{Z_2}{A_2}\right)^2\right] = \frac{4C_{sym}}{T}\Delta(Z/A)^2$$

(at equilibrium)

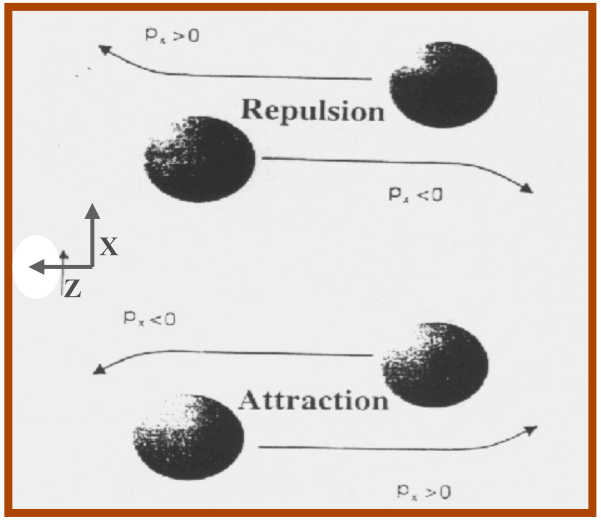


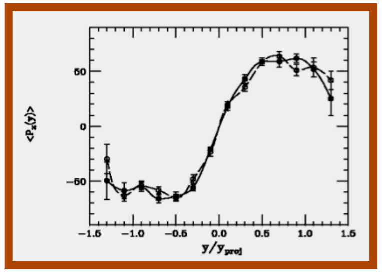
- Extraction of C_{sym} from exp. isoscaling analyses

Kohley and Yennello, *EPJA 2014*

- Secondary decay generally reduces the isotopic width
  → Large apparent C_{sym}

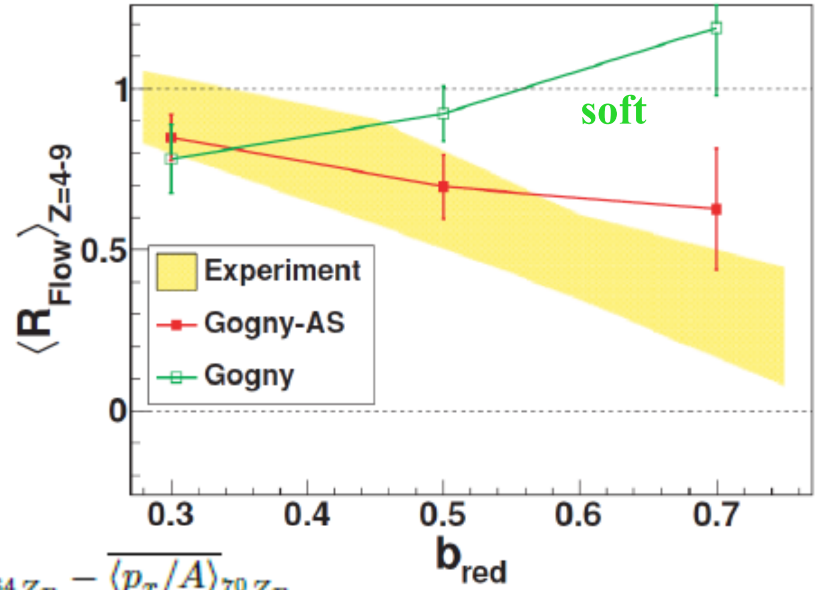
➢ IMF transverse flow





$$F = \frac{\partial \langle p_x \rangle}{\partial Y_r}\Big|_{Y_r=0}$$

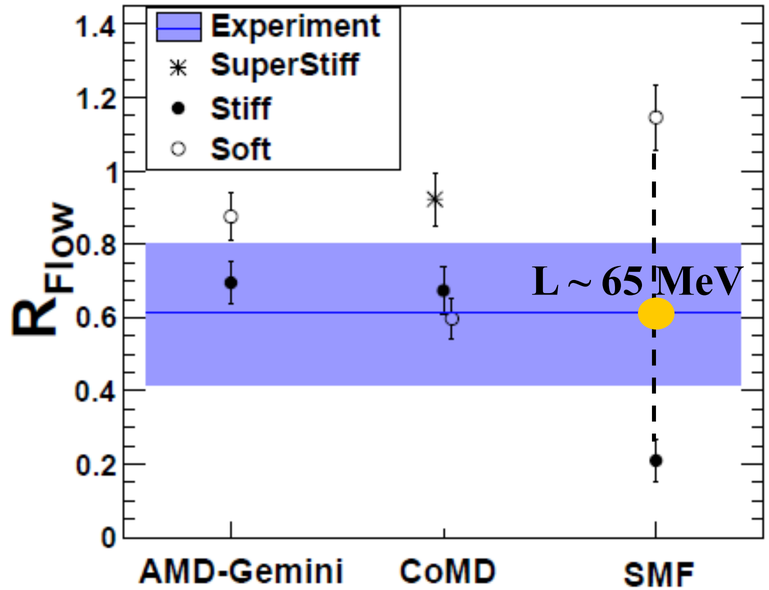
$$R_{Flow} = \frac{\overline{\langle p_x/A\rangle}_{^{64}Zn} - \overline{\langle p_x/A\rangle}_{^{70}Zn}}{\overline{\langle p_x/A\rangle}_{^{64}Ni} - \overline{\langle p_x/A\rangle}_{^{70}Zn}}$$



Z. Kohley et al., PRC 82, 064601 (2010)

Simulation	Form	$E_{sym}(\rho_0)$	L (MeV)	K_{sym} (MeV)
AMD	Stiff	30.5	65	-96
	Soft	30.5	21	-277
SMF	Stiff	33	95	-72
	Soft	33	19	-249
CoMD	Super-Stiff	30	105	93
	Stiff	30	78	-24
	Soft	30	51	-65

35 MeV/A



Z. Kohley et al., PRC 85, 064605 (2012)

Charge equilibration at Fermi energies

➢ Charge Equilibration in “mean-field” models

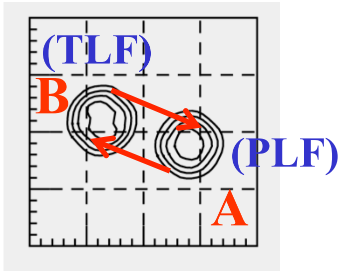
Isospin transport ratio R :

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

A dominance → +1

mixing → 0

B dominance → -1



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

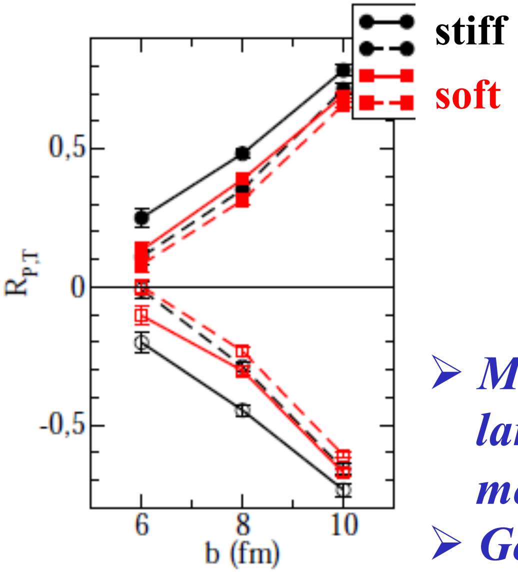
-- AA and BB refer to two symmetric reactions between n-rich and n-poor nuclei

AB to the mixed reaction -- X is an observable related to the N/Z of PLF (or TLF)

Mass(A) ~ Mass(B) ; N/Z(A) ≠ N/Z(B)

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

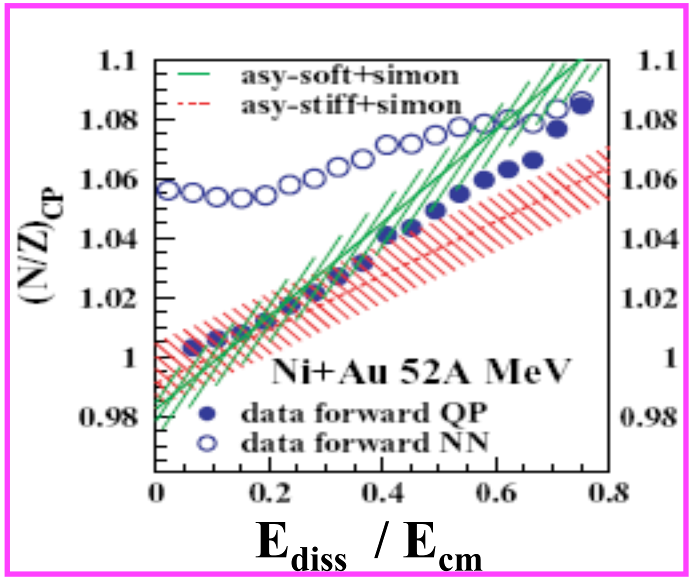
X = N/Z$_{PLF}$



SMF calculations

- ***More central collisions:***
  larger contact time
  more dissipation, smaller R
- ***Good sensitivity to Asy-EoS***

INDRA data, *Galichet et al., PRC (2010)*



Observable:

$(N/Z)_{CP}$ = N/Z of light charge particles emitted by PLF

➢ Charge Equilibration: Mean-field vs. correlation effects

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
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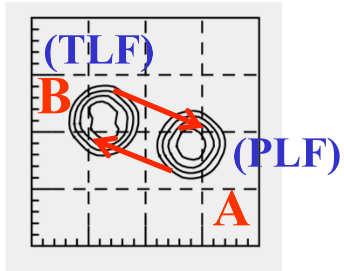
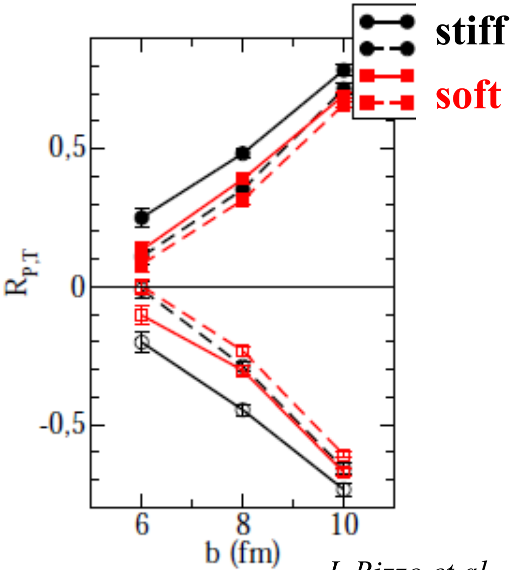


$^{124}Sn + ^{112}Sn$, 50 AMeV

SMF calculations

X = N/Z$_{PLF}$

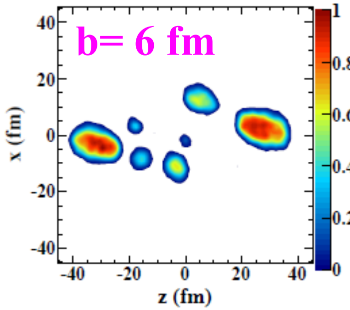


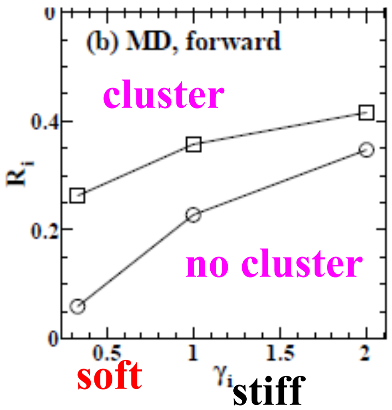
J. Rizzo et al., NPA(2008)

Cluster effects (d,t,He^3)

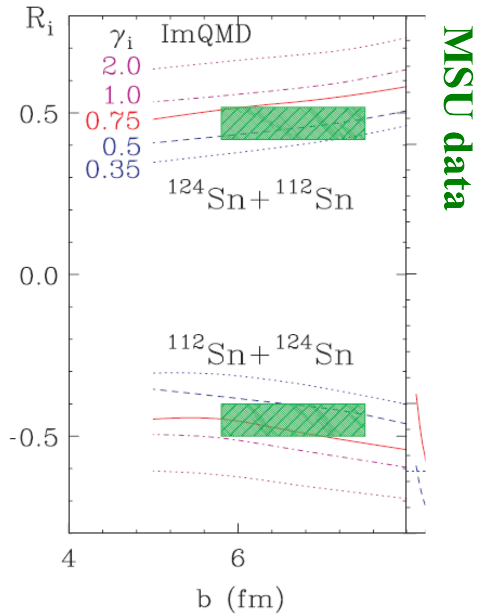
pBUU calculations (Danielewicz)

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





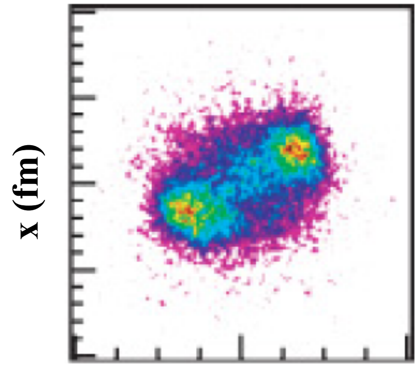
ImQMD (Y.Zhang)

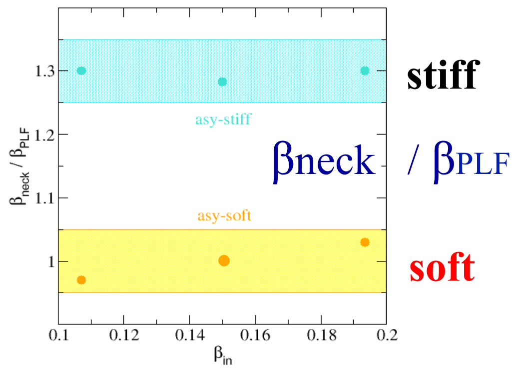


B. Tsang et al., PRL 102 (2009)

➢ Open problem: Impact on IMF isotopic properties

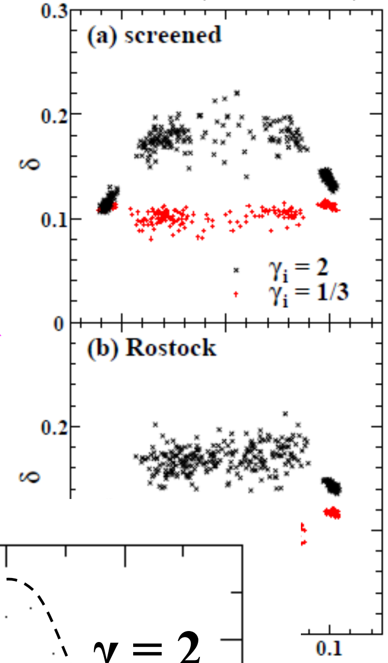
Neck dynamics in **SMF***: Isospin migration*



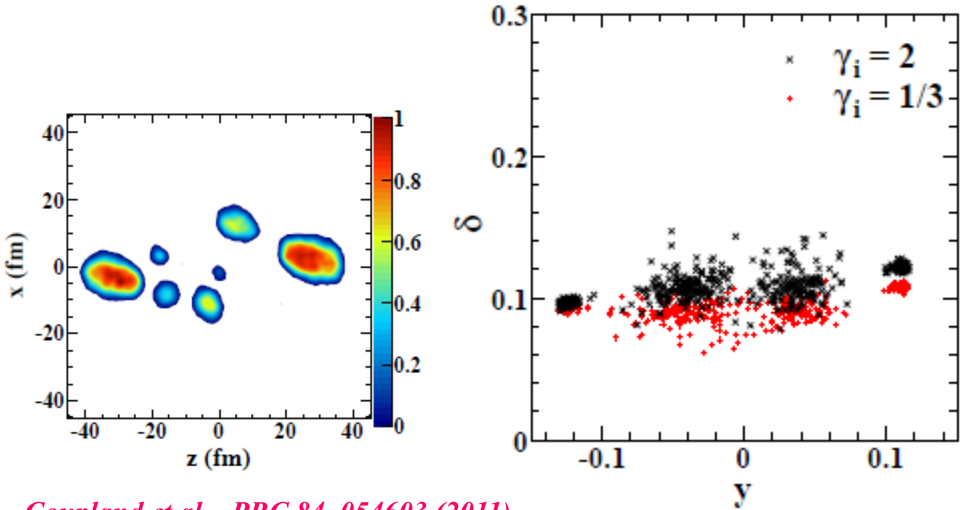


IMF asymmetry

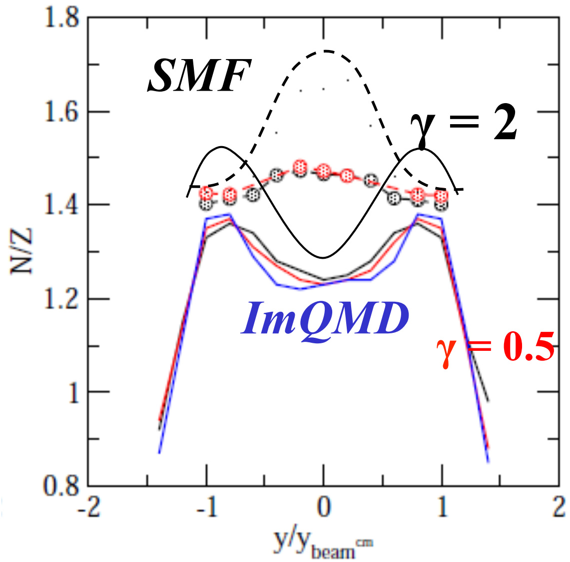
also seen in **pBUU** *(without clusters)*



pBUU *(with clusters): No isospin migration !*



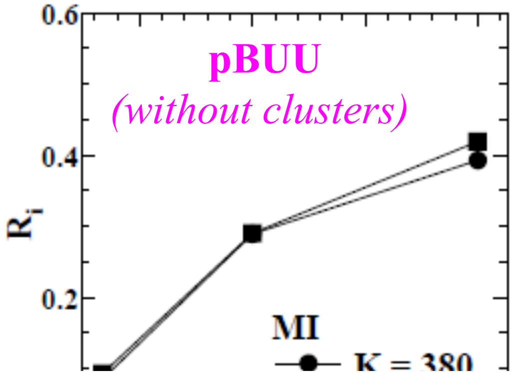
Coupland et al., PRC 84, 054603 (2011)

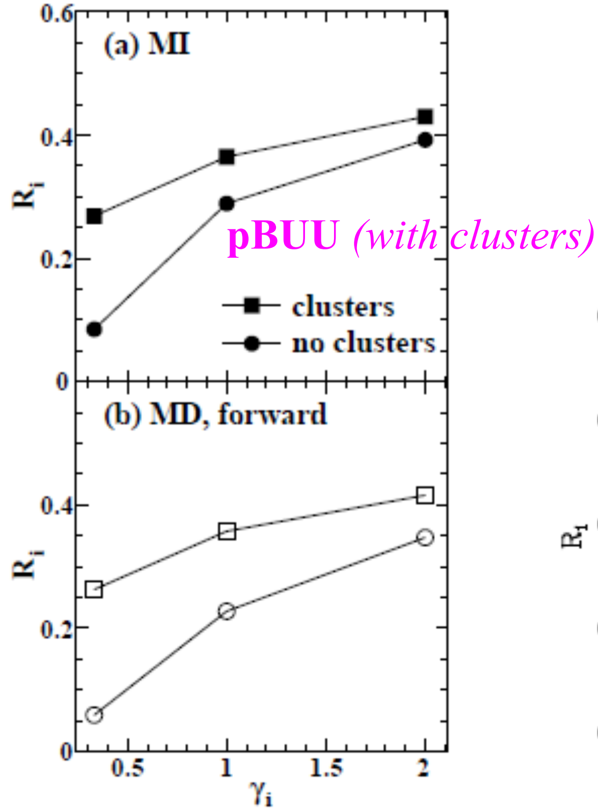


ImQMD: *no isospin migration*

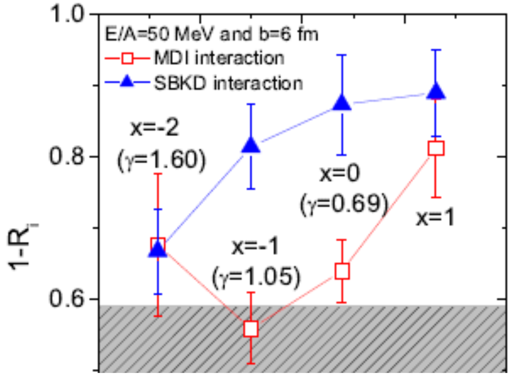
➢ Sensitivity of isospin transport R to other ingredients

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



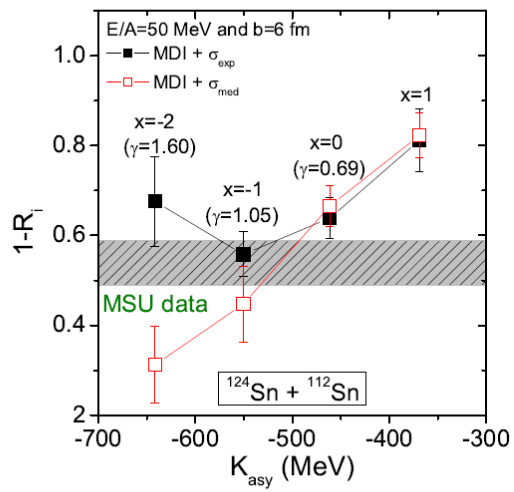


LW Chen et al., PRL 94,032701 (2005)

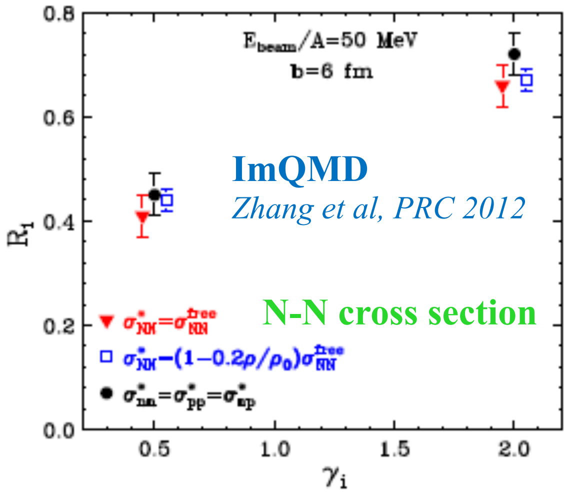


Li and Chen., PRC 72, 064611 (2005)

BUU *calculations*



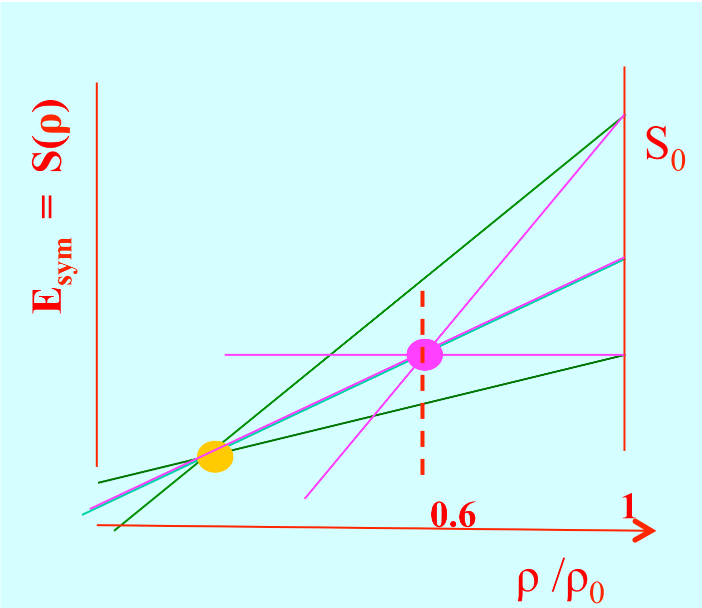
- N-N cross section



--- In models including cluster production:

- Sensitivity to other ingredients quite reduced !

Constraining E_{sym} : a bidimensional analysis

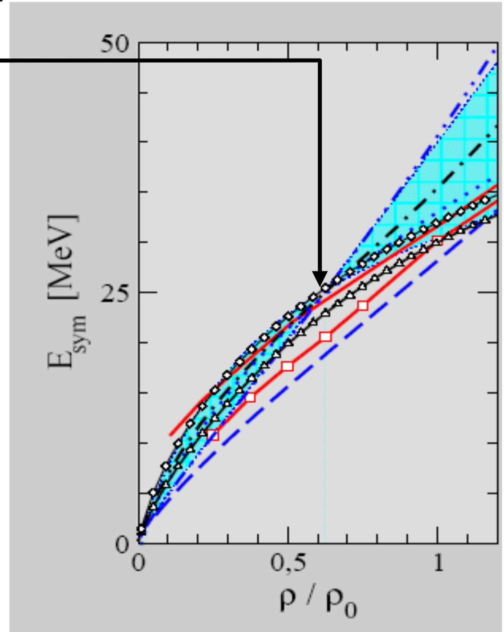


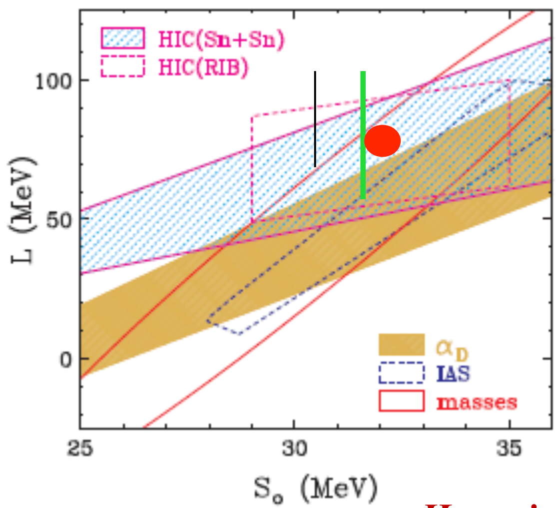
empirical asy-EOS's cross at about

$$\rho \approx 0.6\,\rho_0$$

The fit of nuclear masses imposes a ($S_0 - L$) correlation

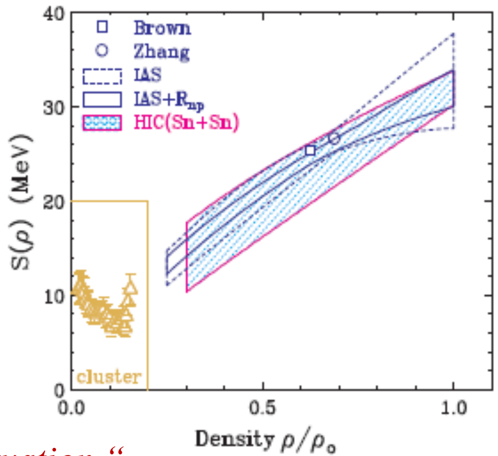
C. Fuchs, H.H. Wolter, EPJA 30(2006)5





-- PDR and polarizability
--charge equilibration (MSU)
--isospin drift (neck) +
charge equil. (INDRA)
--isoscaling
--IMF flow

Symmetry Energy



Horowitz et al, arXiv:1401.5839

"A way forward in the study of the symmetry energy: experiment, theory, and observation "

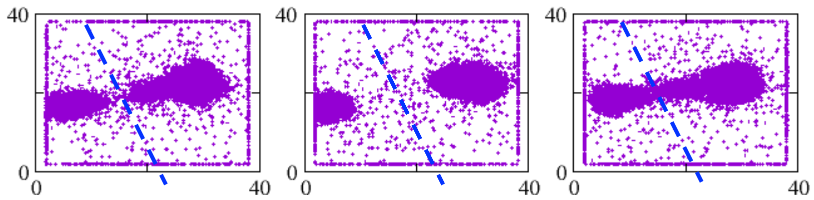
Conclusions and outlook

➢ **Exp-theo analyses**:
- *Multidimensional analysis: several ingredients → several observables*
- *Selective observables, sensitive to a particular ingredient*
- Comparison of transport models

➢ **Improve theoretical models** :
- Mean-field
- Fluctuations (see P.Napolitani, BLOB)
- Cluster production (A.Ono, AMD update)

S.Burrello, M. Di Prima, C.Rizzo, M.Di Toro (LNS, Catania)
V.Baran (NIPNE HH,Bucharest), F.Matera (Firenze)
P.Napolitani (IPN, Orsay), H.H.Wolter (Munich)

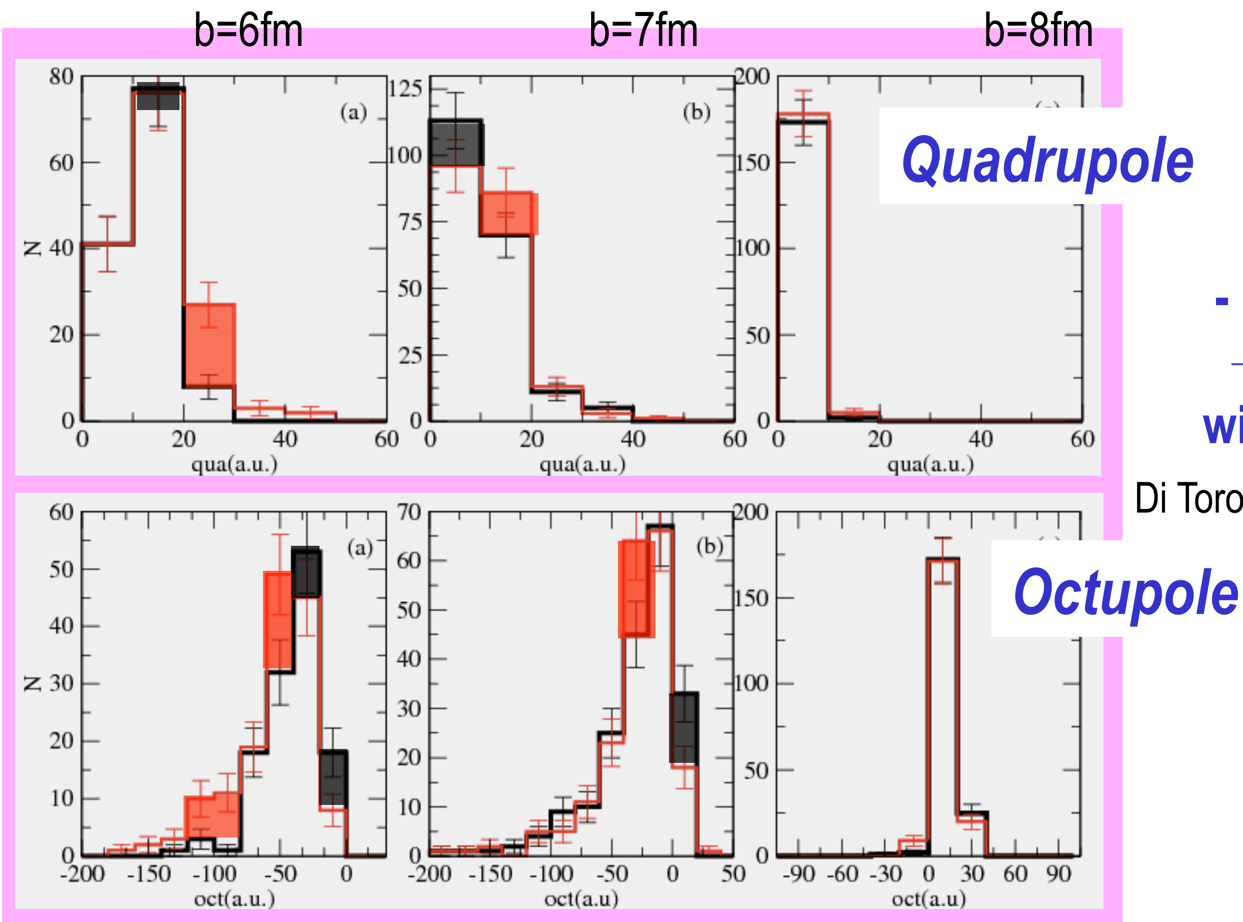
Ternary breakup in n-rich systems: Sensitivity to Esym



^{132}Sn + ^{64}Ni , E/A = 10 MeV, b = 7 fm

3 events, t = 500 fm/c

- Analysis of the deformation of the residues



200 runs each
per impact parameter

— *Asysoft*
— *Asystiff*

- Larger residue deformations
→ more ternary events
with Asystiff

Di Toro et al., NPA 787 (2007) 585c

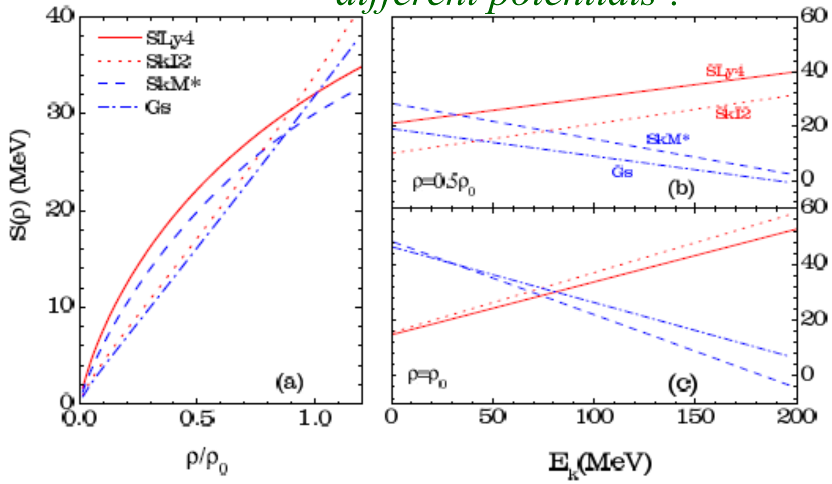
↓

- Perform a more complete analysis

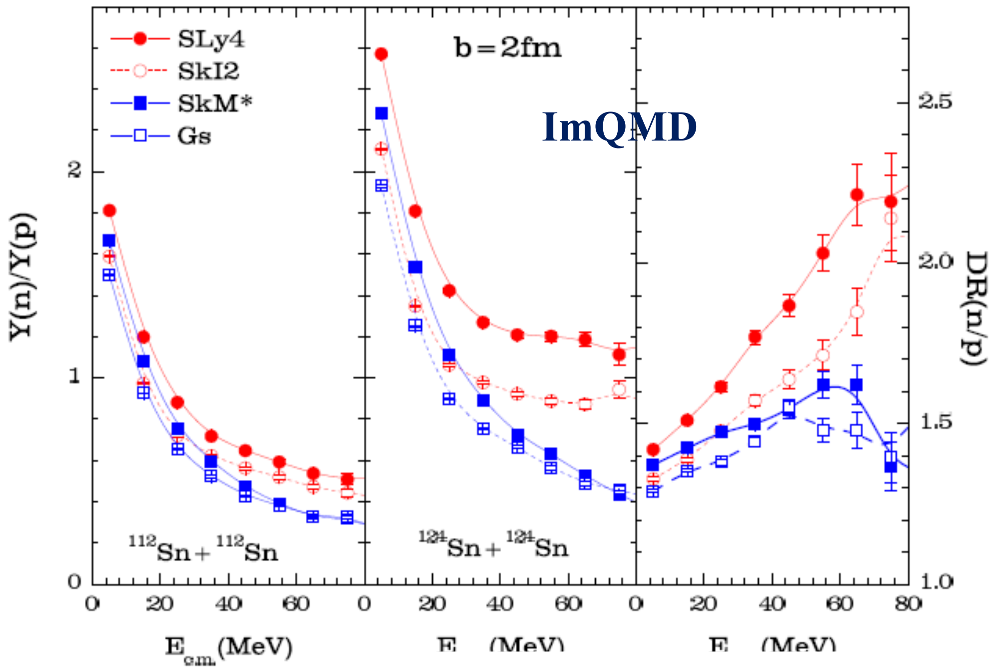
See LoI by Casini et al.

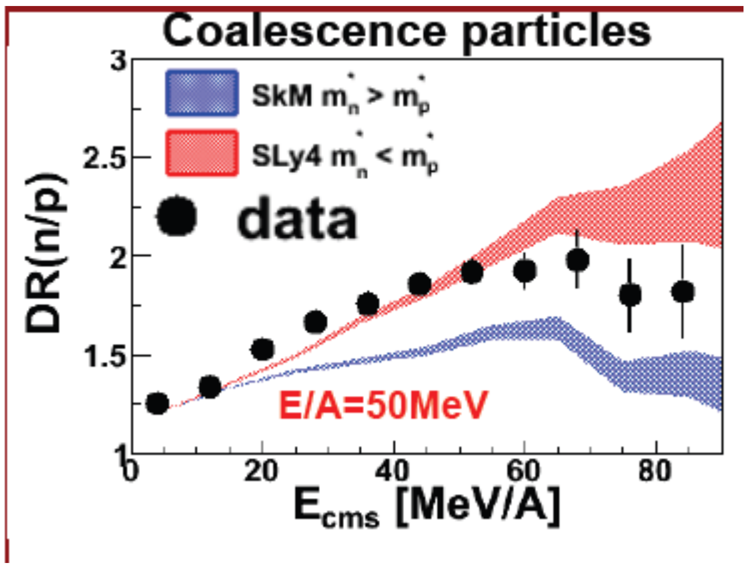
Ratios of pre-equilibrium emitted particles (n,p,t, 3He,…)

Sly4, SKM: same symmetry energy, but …*
different potentials !

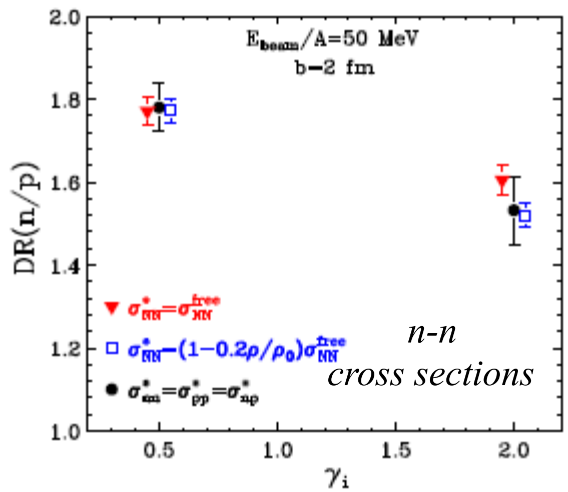


Transport simulations: $^{132}Sn+^{124}Sn$





Recent attempts to fit MSU data



n-n cross sections

Dynamics of many-body systems

$$\rightarrow \quad i\hbar \frac{\partial}{\partial t} \rho_1(1,1',t) = \sum_2 \langle 12 | [H, \rho_2(t)] | 1'2 \rangle$$

$$\rightarrow \quad i\hbar \frac{\partial}{\partial t} \rho_2(12,1'2',t) = \langle 12 | [H, \rho_2(t)] | 1'2' \rangle + O(\rho_3)$$

$$\rho_2(12,1'2') = \rho_1(1,1')\rho_1(2,2') + \delta\sigma(12,1'2')$$

one-body

$$H = H_0 + v_{1,2}$$

Mean-field ← H_0; $v_{1,2}$ → ***Residual interaction***

$$i\hbar \frac{\partial}{\partial t} \rho_1(1,1',t) = \langle 1 | [H_0, \rho_1(t)] | 1' \rangle + K[\rho_1] + \delta K[\rho_1, \delta\sigma]$$

TDHF

$K = F(\rho_1, |v|^2)$ *Average effect of the residual interaction*

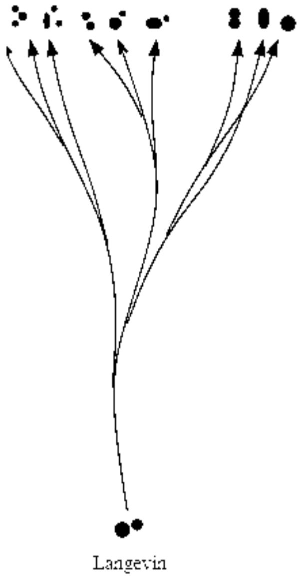
$\delta K = F(v, \delta\sigma)$ $\quad < \delta K > = 0 \quad < \delta K \delta K > \rightarrow$ *Fluctuations*

Dynamics of many-body systems

$$K = g \sum_{234} W(12;34) \left[\bar{f}_1 \bar{f}_2 f_3 f_4 - f_1 f_2 \bar{f}_3 \bar{f}_4 \right]$$

$$\bar{f} = 1 - f$$

Transition rate W
Interpreted in terms of
NN cross section



-- If statistical fluctuations larger than quantum ones

$$< \delta K(p,t) \delta K(p',t') >= C \delta(t - t')$$

$$C(\boldsymbol{p}_a, \boldsymbol{p}_b, \boldsymbol{r}, t) = \delta_{ab} \sum_{234} W(a2;34) F(a2;34)$$

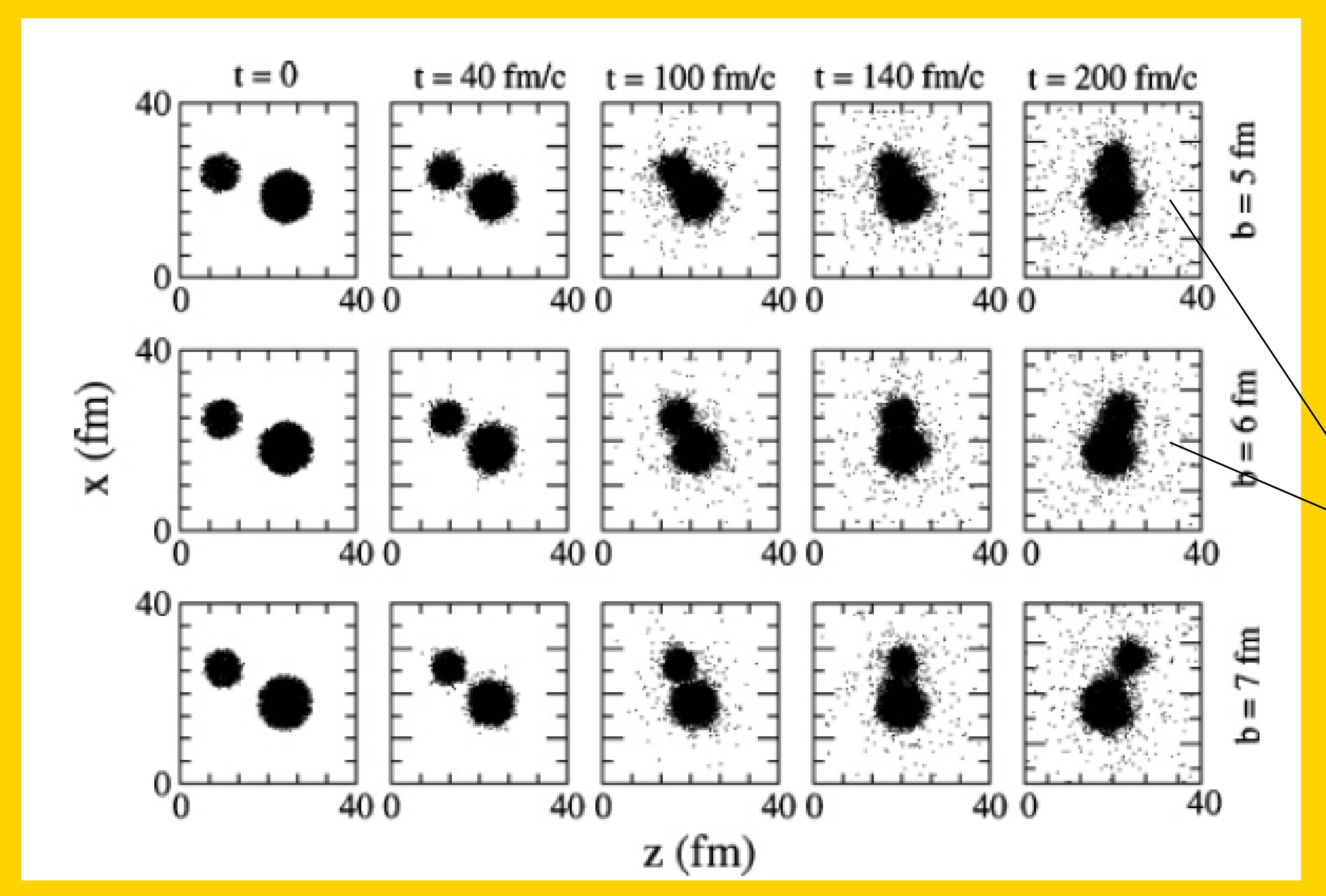
$$F(12;34) \equiv f_1 f_2 \bar{f}_3 \bar{f}_4 + \bar{f}_1 \bar{f}_2 f_3 f_4 .$$

Main ingredients:

- **Residual interaction (2-body correlations and fluctuations)**
  In-medium nucleon cross section
- **Effective interaction**
  (self consistent mean-field)

see BHF

Competition between reaction mechanisms: fusion vs deep-inelastic



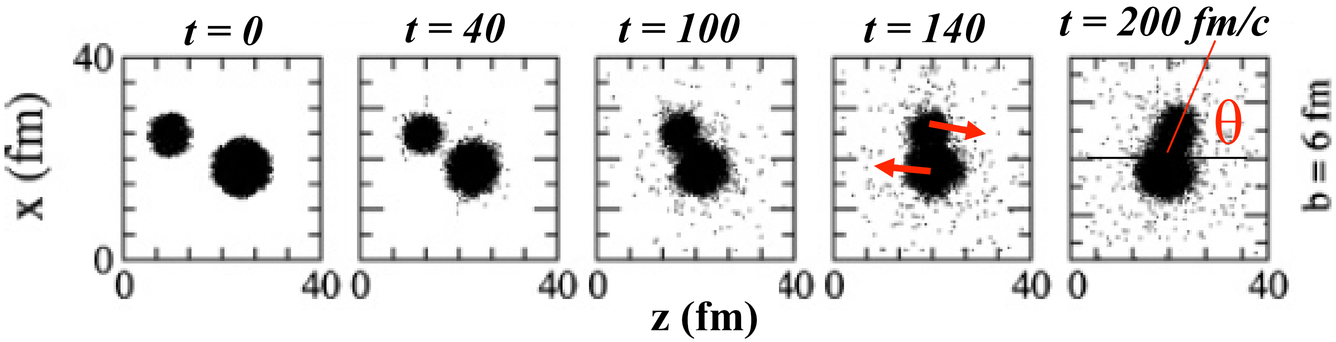
^{36}Ar + ^{96}Zr ,
E/A = 9 MeV

Fusion or
break-up ?

- **Fusion probabilities may depend on the N/Z of the reaction partners:**
  - *A mechanism to test the isovector part of the nuclear interaction*
- **Important role of fluctuations**

C.Rizzo et al., PRC83, 014604 (2011)

Competition between reaction mechanisms

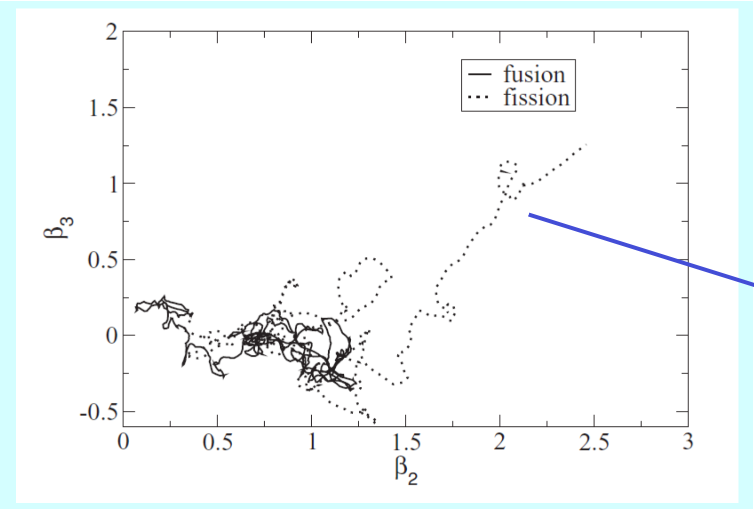


$^{36}Ar + ^{96}Zr$,
E/A = 9 MeV,
b = 6 fm

β_2 , β_3,
E*~250 MeV, J ~70ħ

✓ Starting from t = 200-300 fm/c, solve the **Langevin Equation (LE)** for selected degrees of freedom: **Q** (quadrupole), β_3 (octupole), **θ,** and related velocities

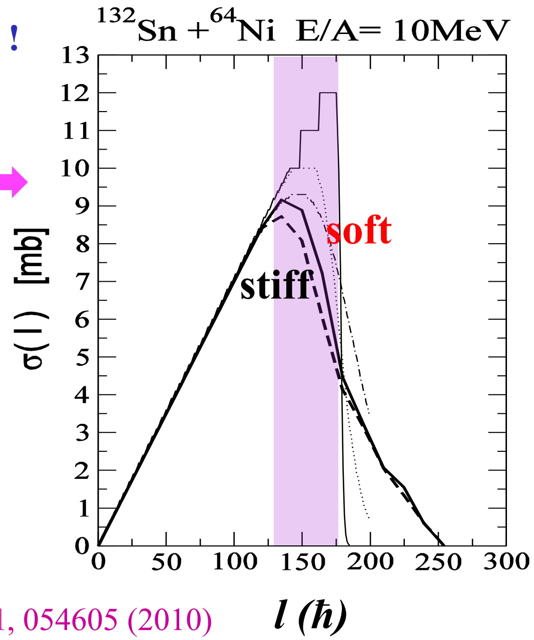
Examples of trajectories



Break-up times of the order of 500-1000 fm/c !

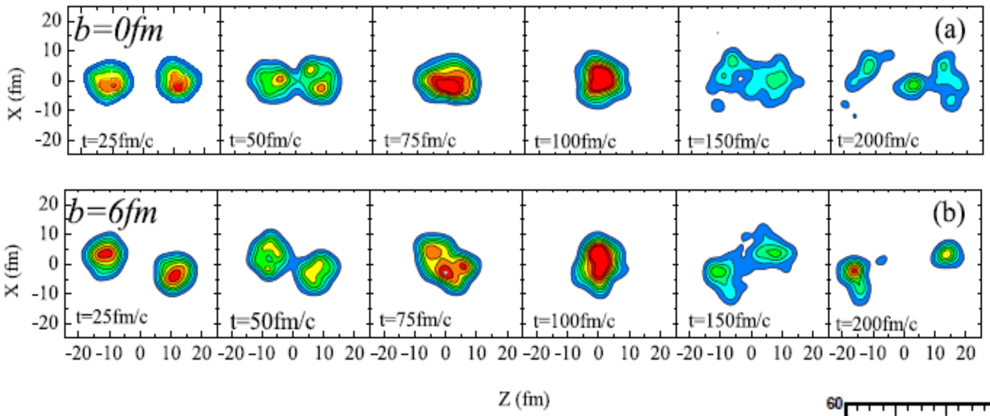
Break-up configurations

Extract the fusion cross section

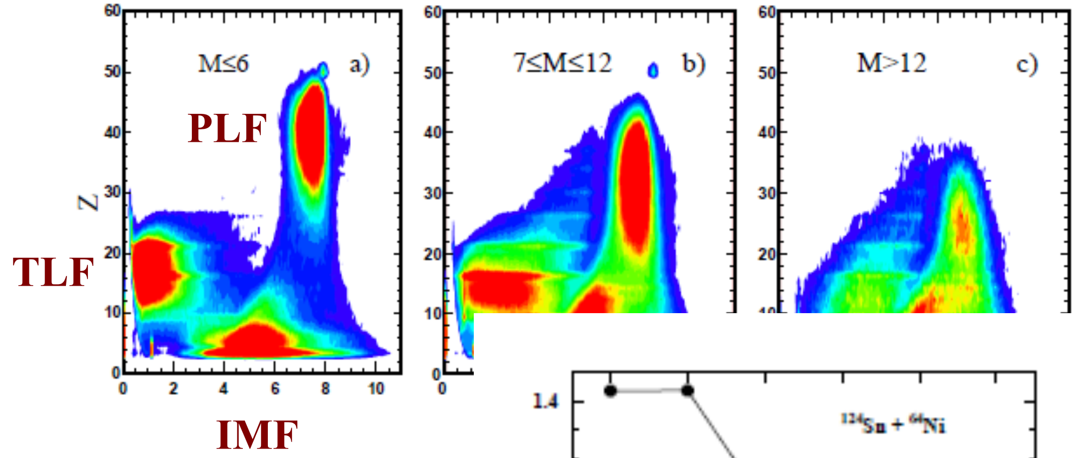


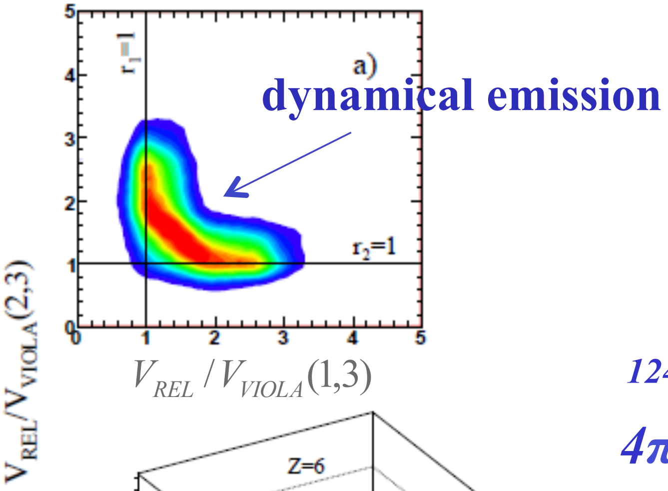
Shvedov, Colonna, Di Toro, PRC **81**, 054605 (2010)

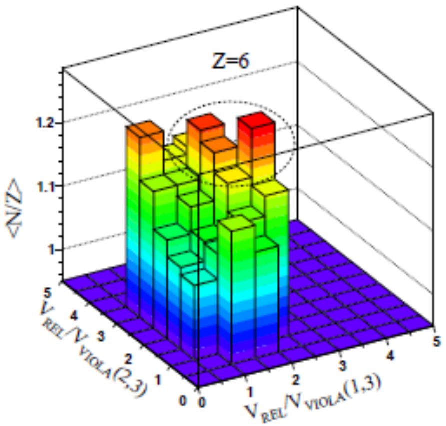
Fragmentation mechanisms at Fermi energies



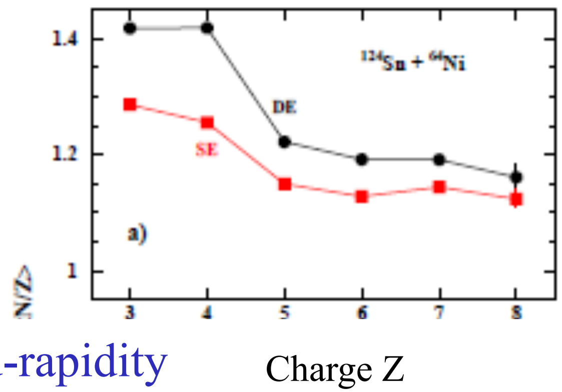
Y.Zhang et al., PRC(2011)





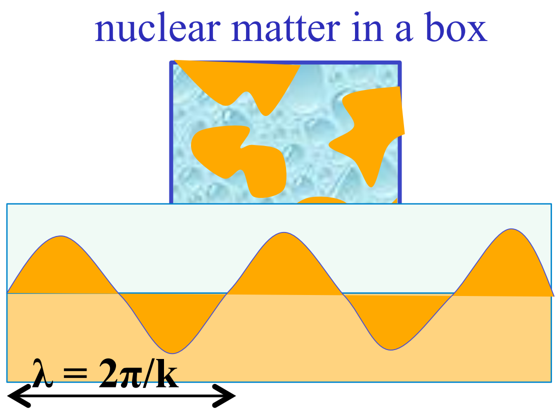


$^{124}Sn + ^{64}Ni$ 35 AMeV:
4π CHIMERA detector



- Fragment emission at mid-rapidity (neck emission)
- neutron-enrichment of the neck region

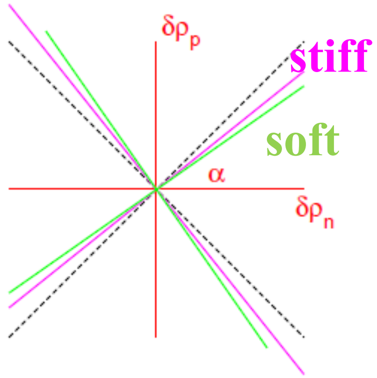
E. De Filippo et al., PRC(2012)



Fragment isotopic distribution and symmetry energy

Fragmentation can be associated with mean-field instabilities
(growth of unstable collective modes)

Oscillations of the total (isoscalar-like density) ⟶ fragment formation
and average Z/A (see $\delta\rho_n / \delta\rho_p$)



Oscillations of the isovector density (ρ_n - ρ_p) ⟶ isotopic variance
and distributions (Y_2 / Y_1 , isoscaling)

- Study of isovector fluctuations, link with symmetry energy in fragmentation

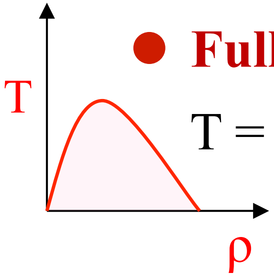
⟶ At equilibrium, according to the fluctuation-dissipation theorem

$$\sigma_k^i = \frac{T}{F^i(k)}$$

Isovector density $\rho^v = \rho_n - \rho_p$ ⟶ F^v coincides with the free symmetry energy
at the considered density

What does really happen in fragmentation ?

Nuclear matter in a box

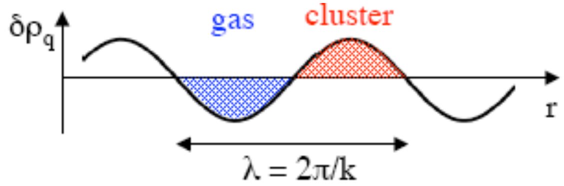


- **Full SMF simulations**

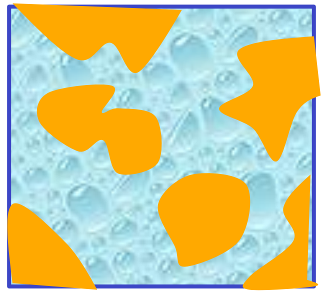
T = 3 MeV, Density: $\rho_1 = 0.025\ fm^{-3}$, $2\rho_1$, $3\rho_1$

I = 0.14

M.Colonna, PRL,110(2013)



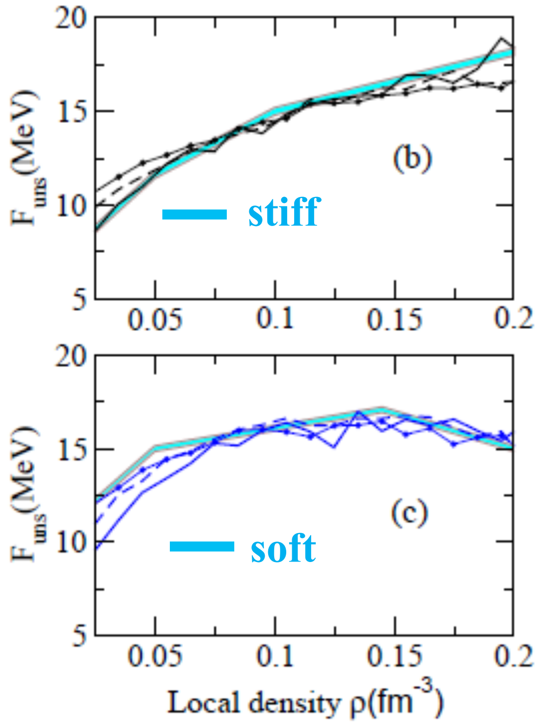
freeze-out



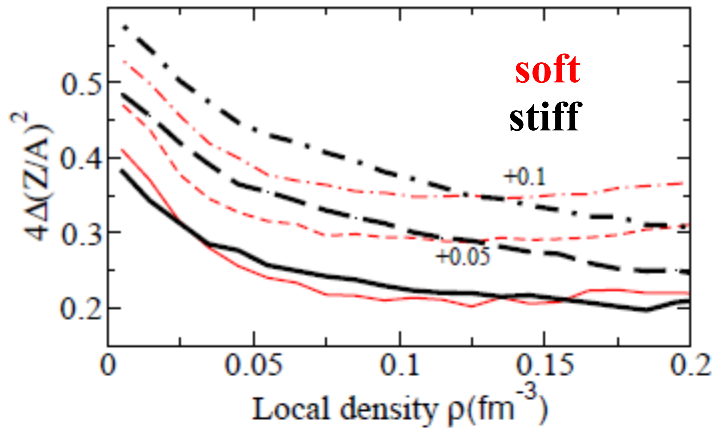
$$\sigma_{\rho^v} = < (\delta\rho_n(\boldsymbol{r}) - \delta\rho_p(\boldsymbol{r}))^2 >\Big|_\rho$$

F' ~ T / σ

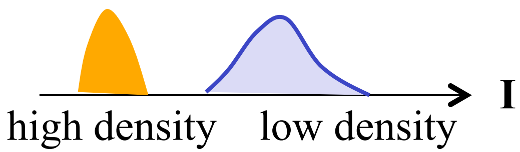
Average Z/A and isovector fluctuations
as a function of local density ρ



F' follows the local equilibrium value !

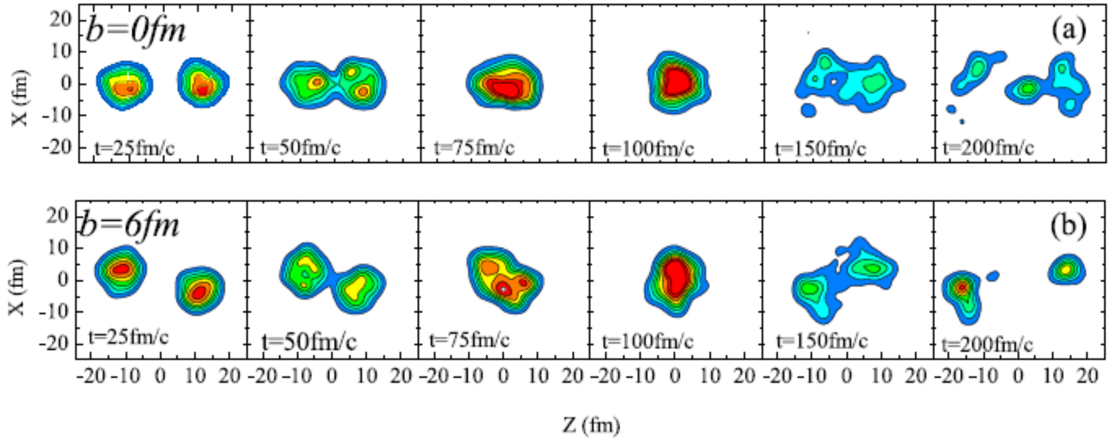


The isospin distillation effect goes together with the isovector variance

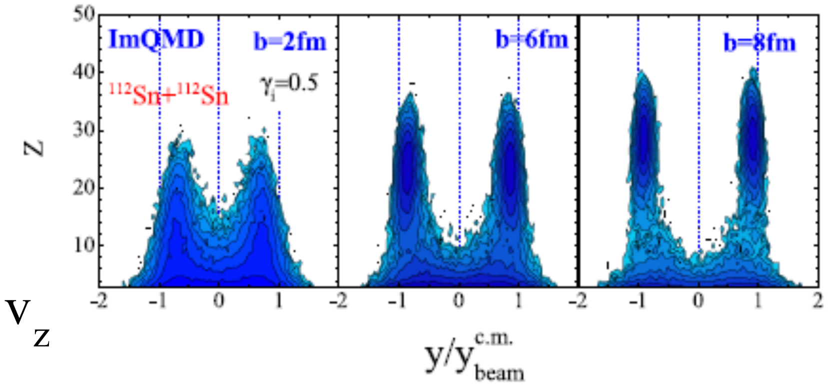


Dissipation and fragmentation in "MD" models

ImQMD calculations, $^{112}Sn + ^{112}Sn$, 50 AMeV



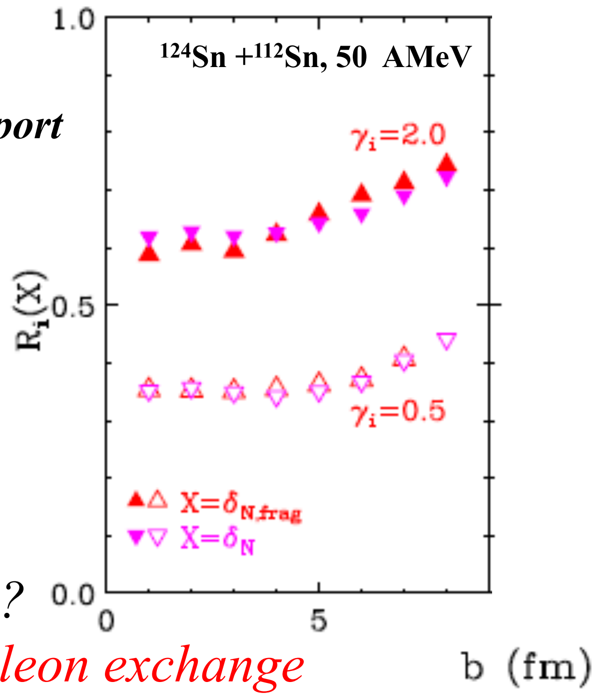
- ***More 'explosive' dynamics:***
  - *more fragments and light clusters emitted*
  - *more 'transparency'*



$y \approx v_z$

Y.Zhang et al., PRC(2011)

Isospin transport ratio R



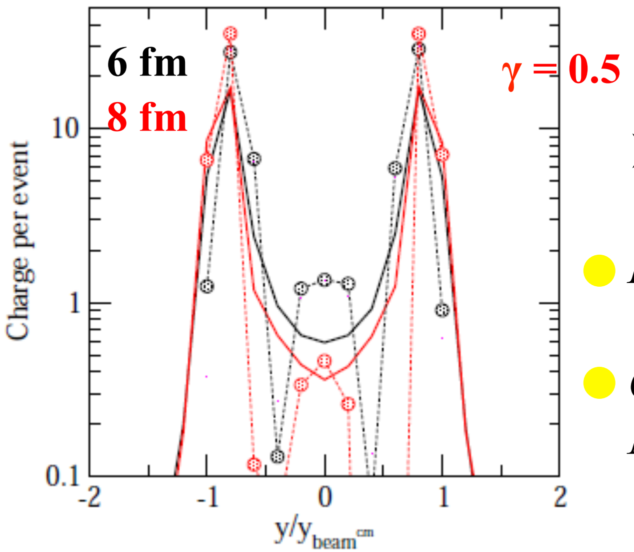
What happens to charge equilibration ?

Rather flat behavior with impact parameter b:

- *Weak dependence on **b** of reaction dynamics ?*
- *Other dissipation sources (not nucleon exchange) ?*

fluctuations, cluster emission *weak nucleon exchange*

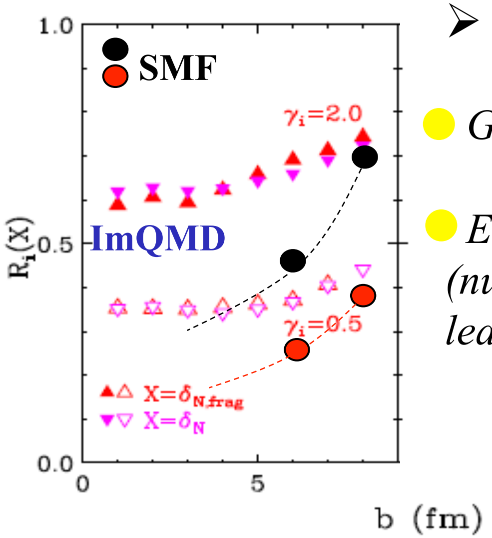
Comparison SMF-ImQMD



SMF = dashed lines
ImQMD = full lines

➤ For semi-central impact parameters:

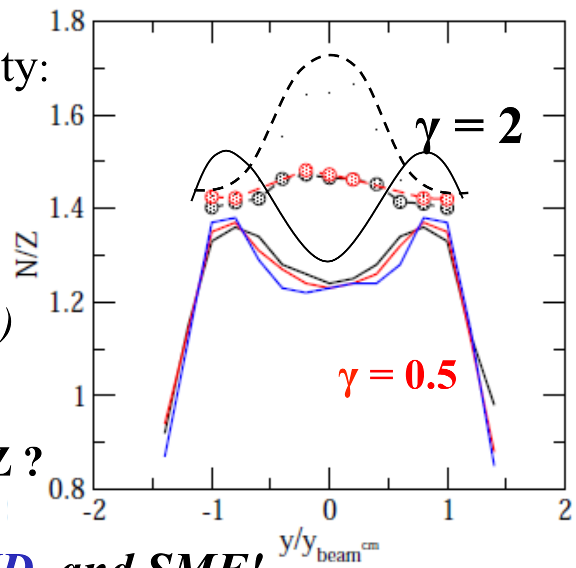
- ***Larger transparency** in **ImQMD** (but not so a drastic effect)*
- ***Other sources of dissipation** (in addition to nucleon exchange)*
  More cluster emission



➤ Isospin transport R around PLF rapidity:

- *Good agreement in peripheral reactions*
- *Elsewhere the different dynamics*
  *(nucleon exchange less important in **ImQMD**)*
  leads to less iso-equilibration

What about fragment N/Z ?

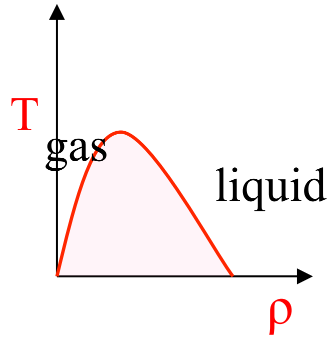


Different trends in ImQMD and SMF!

Details of SMF model

- Correlations are introduced in the time evolution of the one-body density: $\rho \longrightarrow \rho + \delta\rho$ as corrections of the mean-field trajectory
- Correlated density domains appear due to the occurrence of mean-field (spinodal) instabilities at low density

Fragmentation Mechanism: spinodal decomposition



Is it possible to reconstruct fragments and calculate their properties only from *f* ?

Fragment Recognition

Extract random A nucleons among test particle distribution Coalescence procedure
Check energy and momentum conservation
A.Bonasera et al, PLB244, 169 (1990)

Liquid phase: $\rho > 1/5\ \rho_0$
Neighbouring cells are connected (coalescence procedure)

Fragment excitation energy evaluated by subtracting Fermi motion (local density approx) from Kinetic energy

❖ Several aspects of multifragmentation in central and semi-peripheral collisions well reproduced by the model

Chomaz,Colonna, Randrup Phys. Rep. 389 (2004)
Baran,Colonna,Greco, Di Toro Phys. Rep. 410, 335 (2005)
Tabacaru et al., NPA764, 371 (2006)

❖ Statistical analysis of the fragmentation path

A.H. Raduta, Colonna, Baran, Di Toro, PRC 74,034604(2006)
PRC76, 024602 (2007)

❖ Comparison with AMD results

Rizzo, Colonna, Ono, PRC 76, 024611 (2007)