Stochastic transport theories as a tool to investigate nuclear dynamics

Fluctuations and Temporal Evolution
in Heavy Ion Collisions
Workshop of the *Espace de Structure Nucléaire Théorique*
May 9-10, 2012
CEA/SPhN, Orme des Merisiers (Gif-sur-Yvette)

Maria Colonna
INFN - Laboratori Nazionali del Sud (Catania)

- Outline

- *Overview of stochastic transport theories BL,BOB,SMF,BLOB --- MD, AMD*
- *Study of HI central collisions (multifragmentation) and comparison between results of different models*
- *Charge equilibration and fragmentation mechanisms in semi-peripheral collisions*

➢ *What can we learn about the nuclear effective interaction ?*

Dynamics of many-body systems

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

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

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

one-body

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

Mean-field ***Residual interaction***

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

TDHF

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

$$\delta K = F'(v,\delta\sigma)$$ $$<\delta K \delta K> = F'(|v|^2, <\delta\sigma\delta\sigma>) \rightarrow F'(\rho_1,|v|^2)$$ *Fluctuations*

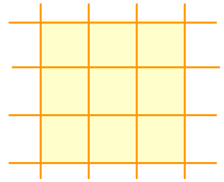
➢1. *Semi-classical approximation to Nuclear Dynamics*

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 the Wigner transform of the one-body density matrix

Density $f = f(\mathbf{r},\mathbf{p},t)$



Phase space (r,p)

➢ $$\frac{df(r,p,t)}{dt} = \frac{\partial f(r,p,t)}{\partial t} + \{f, H_0\} = 0$$

$$H_0 = \mathrm{T} + \mathrm{U}$$

Vlasov Equation,
like Liouville equation:
The phase-space density is constant in time

➢ **Mean-field approximation**:

The potential U is self-consistent: **U = U(ρ)**

Nucleons move in the field created by all other nucleons

● **Effective interactions**

Energy Density Functional theories: The exact density functional is approximated with powers and gradients of one-body nucleon densities and currents.

$$E = \langle \Psi | \hat{H} | \Psi \rangle$$
$$\approx \langle \Phi | \hat{H}_{eff} | \Phi \rangle = E[\hat{\rho}]$$

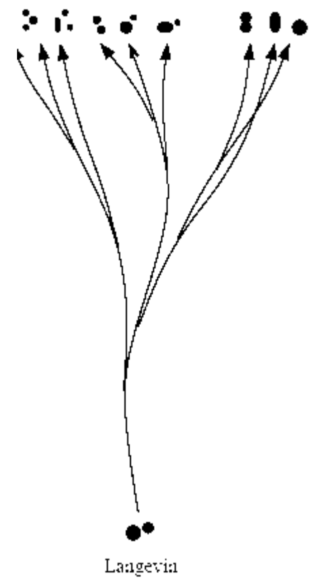
1.1 *Semi-classical approximation*

Transport equation for the one-body distribution function f

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

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

Residual interaction: Correlations, Fluctuations

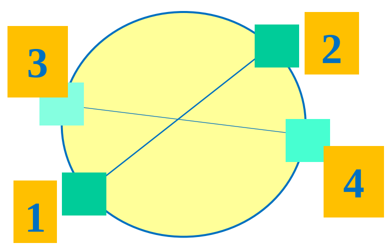


- *Two-body Collision Integral*

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

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

(1,2) $\longrightarrow$ **(3,4)**



- Fluctuations in collision integral

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

$$\longrightarrow C = F(K)$$

1.2 Collision integral and Fluctuations

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

Boltzmann collision integral + Pauli blocking (fermions)

(1,2) ⟶ (3,4)

(1-f)

(Sums over momentum)

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

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

Boltzmann-Langevin

$$C(\boldsymbol{p}_a,\boldsymbol{p}_b,\boldsymbol{r},t) = \delta_{ab}\sum_{234} W(a2;34)F(a2;34) + \sum_{34}\left[W(ab;34)F(ab;34) - 2W(a3;b4)F(a3;b4)\right]$$

$\delta_{ab} \equiv h^3\delta(\boldsymbol{p}_a - \boldsymbol{p}_b)$ and $F(12;34) \equiv f_1 f_2 \bar{f}_3\bar{f}_4 + \bar{f}_1\bar{f}_2 f_3 f_4$.

N_{coll} = collision number $\qquad \sigma_N = N_{coll}$

- ***Approximate treatment of fluctuations*:**
  Replace the stochastic collision integral by a stochastic force ⟶ density fluctuations **Stochastic mean-field (BOB,SMF) approaches**

1.3 Stochastic mean-field models (BOB, SMF)

$$\frac{\partial f}{\partial t} + \boldsymbol{v} \cdot \frac{\partial f}{\partial \boldsymbol{r}} - \frac{\partial U}{\partial \boldsymbol{r}} \cdot \frac{\partial f}{\partial \boldsymbol{p}} = \bar{I}_{coll}[f] + \frac{\partial U_{ext}}{\partial \boldsymbol{r}} \cdot \frac{\partial f}{\partial \boldsymbol{p}}$$

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

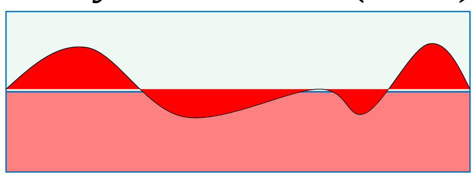
- $U[\rho]$: self-consistent mean-field potential

Nuclear EoS, *Energy Density Functional (EDF) theories*

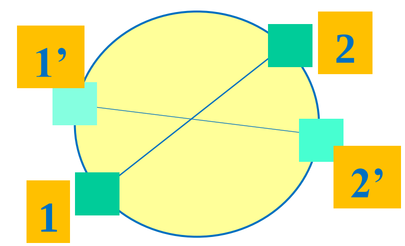
$$E = \langle \Psi | \hat{H} | \Psi \rangle$$

$$\approx \langle \Phi | \hat{H}_{eff} | \Phi \rangle = E[\hat{\rho}]$$

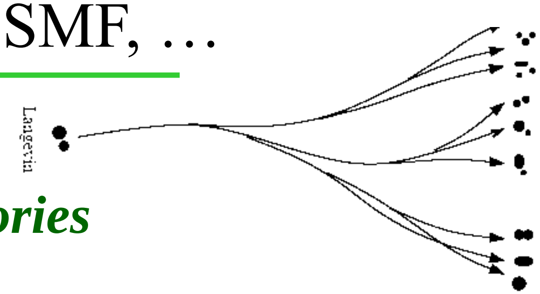
Mean-field



- Collision Integral I_{coll}: residual part of the nuclear interaction



- U_{ext} : external, stochastic field ⟶ BOB, SMF, …



Amplification of instabilities, bifurcations of trajectories

-- ***Brownian-One-Body (BOB)*** *method:* replace δI by a stochastic force

Chomaz et al., PRL73, 3512 (1994)

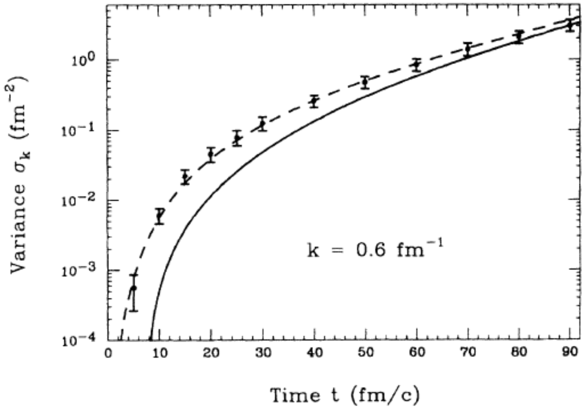
$$\delta I[f] \rightarrow \delta \tilde{I}[f] = -\delta \boldsymbol{F}[f] \cdot \frac{\partial f}{\partial \boldsymbol{p}}$$

$$2D = \prec \delta K(\boldsymbol{r},\boldsymbol{p},t)\, \delta K(\boldsymbol{r}',\boldsymbol{p}',t') \succ = C(\boldsymbol{p},\boldsymbol{p}',\boldsymbol{r},t)\, \delta(\boldsymbol{r}-\boldsymbol{r}')\, \delta(t-t')$$

$$2\tilde{D}(\mathrm{s}_1;\mathrm{s}_2) = 2\tilde{D}_0 \frac{\partial f(\mathrm{s}_1)}{\partial \boldsymbol{p}_1} \cdot \frac{\partial f(\mathrm{s}_2)}{\partial \boldsymbol{p}_2} \delta(\boldsymbol{r}_{12})$$ *(BOB)*

- *Tune D_0 to reproduce the projection on the* ***most unstable mode***

$$\mathcal{D}_k^{\nu\nu'} = \int \frac{d\boldsymbol{p}_1}{h^D} \frac{d\boldsymbol{p}_2}{h^D} \hat{f}_{\mathbf{k}}^{\nu}(\boldsymbol{p}_1)^* D(\boldsymbol{p}_1,\boldsymbol{p}_2) \hat{f}_{\mathbf{k}}^{\nu'}(\boldsymbol{p}_2)$$



(method based on local instability concept)

-- ***SMF*** *method:* agitating the radial density profile

Colonna et al., NPA642, 449(1998)

(method based on local equilibrium concept)

$$\sigma_f^2 = \overline{(f-\bar{f})^2} = \bar{f}(1-\bar{f})$$

In actual calculations of SMF, only the density variance is considered,

$$\sigma_\rho^2 = \sum_{\text{p-cell}} \sigma_f^2$$

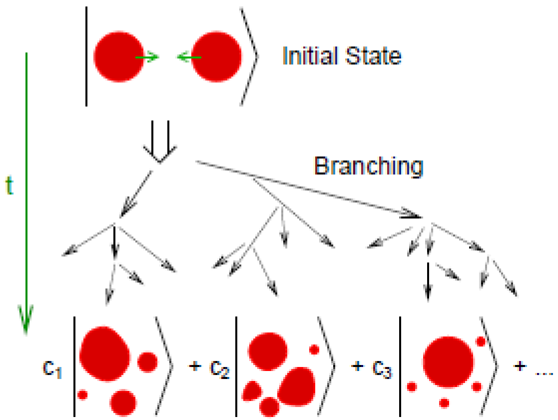
- *Fluctuations are injected in* ***coordinate space*** *, to reproduce the* ***analytical variance***

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

Zhang and Li, *PRC74,014602(2006)*
J.Aichelin, *Phys.Rep.202,233(1991)*

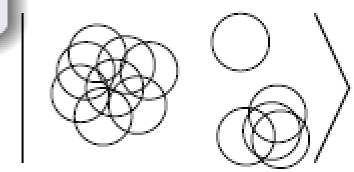
Antisymmetrized Molecular Dynamics

A.Ono, *Phys.Rev.C59,853(1999)*



AMD wave function

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



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

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

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

Stochastic equation of motion for the wave packet centroids Z

$$\frac{d}{dt}\mathbf{Z}_i = \{\mathbf{Z}_i, \mathcal{H}\}_{\mathrm{PB}} + (\text{NN collisions}) + \Delta\mathbf{Z}_i(t)$$

- Mean field (Time evolution of single-particle wave functions)
- Nucleon-nucleon collisions (as the residual interaction)
- Wave packet splitting (Mean filed + Quantum branching)

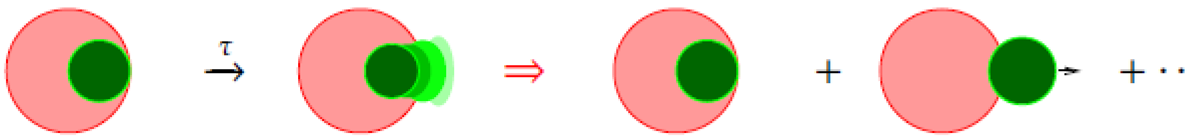
A.Ono, IWM2011

2.1 Mean field + Quantum branching

At each time step t_0, for each wave packet k,...

$$t = t_0 \qquad\qquad t = t_0 + \tau$$

$$|\mathbf{Z}_k\rangle\langle\mathbf{Z}_k| \xrightarrow[\text{Mean field}]{} |\psi_k\rangle\langle\psi_k| \xrightarrow[\text{Branching/Decoherence}]{} \int |\mathbf{z}\rangle\langle\mathbf{z}|\, w_k(\mathbf{z})d\mathbf{z} \qquad \text{for } k = 1,\ldots,A$$



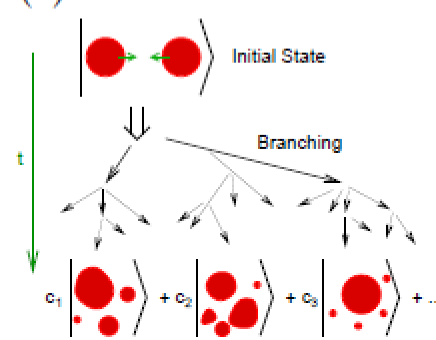
$$i\hbar\frac{d}{dt}|\psi_k(t)\rangle = h^{\mathrm{HF}}|\psi_k(t)\rangle$$

$$\frac{\partial f_k}{\partial t} = -\frac{\partial h^{\mathrm{HF}}}{\partial \mathbf{p}}\cdot\frac{\partial f_k}{\partial \mathbf{r}} + \frac{\partial h^{\mathrm{HF}}}{\partial \mathbf{r}}\cdot\frac{\partial f_k}{\partial \mathbf{p}}$$

$$|\Phi(Z)\rangle\langle\Phi(Z)| \qquad |\Psi\rangle\langle\Psi| \xrightarrow[\text{Branching/Decoherence}]{} \int |\Phi(z)\rangle\langle\Phi(z)|\, w(z)dz$$

Coherence time τ

- $\tau \to 0$ (Strongest branching)
- $\tau = \tau(\rho)$ (Density-dependent)
- $\tau = \tau_{\text{NN-coll}}$ (Decoherence at NN collisions) :default



Fluctuation in Mean Field Models

Different trajectories $f(\mathbf{r},\mathbf{p},t)$ for different events. (Boltzmann-Langevin Eq.)

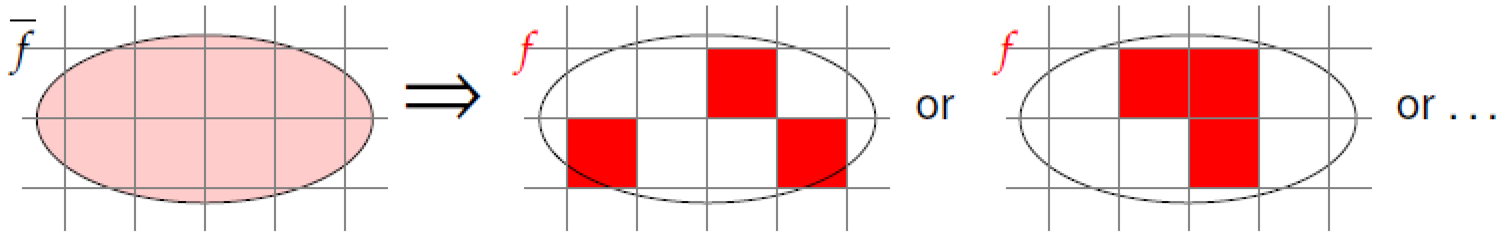
$$\frac{\partial f}{\partial t} = \frac{\partial h}{\partial \mathbf{r}} \cdot \frac{\partial f}{\partial \mathbf{p}} - \frac{\partial h}{\partial \mathbf{p}} \cdot \frac{\partial f}{\partial \mathbf{r}} + I_{\text{coll}}(\mathbf{r},\mathbf{p},t) + \delta I(\mathbf{r},\mathbf{p},t)$$

$$\overline{\delta I(\mathbf{r},\mathbf{p},t)} = 0, \quad \overline{\delta I(\mathbf{r},\mathbf{p},t)\,\delta I(\mathbf{r}',\mathbf{p}',t')} = \cdots$$

$\Rightarrow$ Variance of f in each phase-space cell of $(2\pi\hbar)^d$

[Stochastic Mean Field: Colonna et al., NPA 642 (1998) 449.]

$$\sigma_f^2 = \overline{(f-\bar{f})^2} = \bar{f}(1-\bar{f}) \qquad = (1-\bar{f})^2 \times \bar{f} + (0-\bar{f})^2 \times (1-\bar{f})$$



an occupied cell $\approx$ a wave packet in AMD $(\Delta x \Delta p = \frac{1}{2}\hbar)$

In actual calculations of SMF, only the density variance is considered,

$$\sigma_\rho^2 = \sum_{\text{p-cell}} \sigma_f^2 \longrightarrow \textit{BLOB}$$

Boltzmann-Langevin One Body (BLOB) dynamics

Chomaz, Colonna Rizzo, NPA (2008)

P.Napolitani

Space $\mathcal{R}$: *collision sites*

- Random candidates of radius $R_{\mathcal{R}} = \sqrt{\bar{\sigma}_{\text{N-N}}/\pi} + 2r_{\text{nucl}} \sim 3.5\text{fm}$

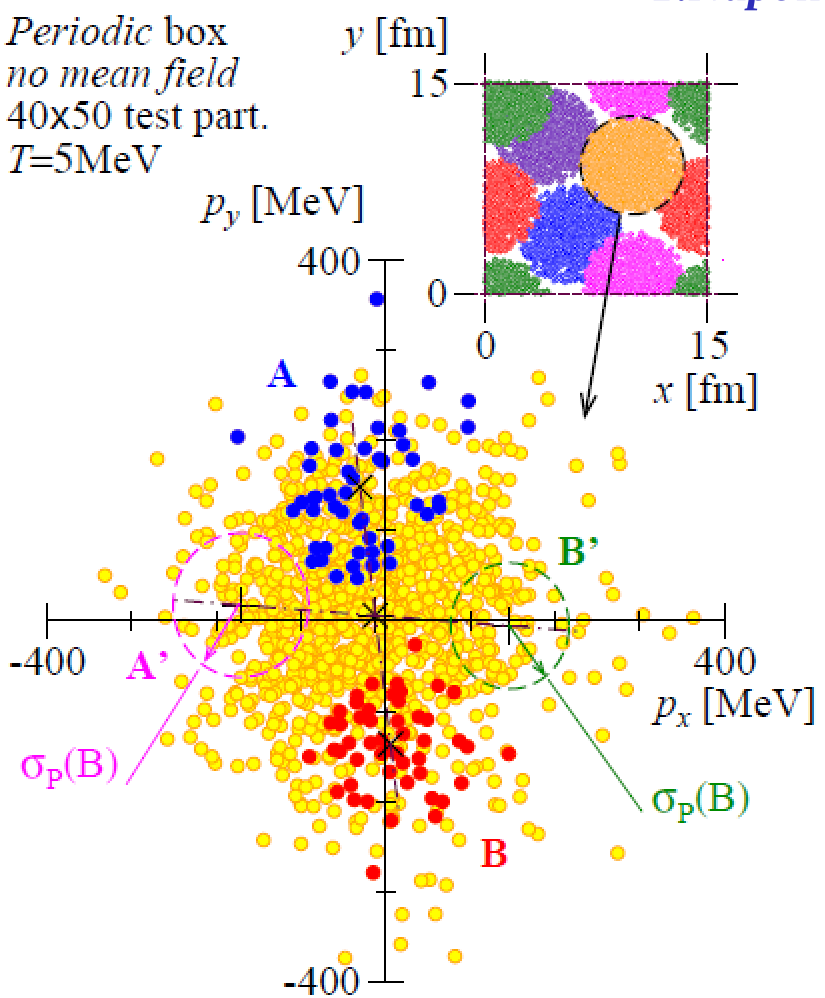
Space $\mathcal{P}$: two colliding "nucleons"

- Random agglomerates of N_t t.-particles having not previously collided in the same dt

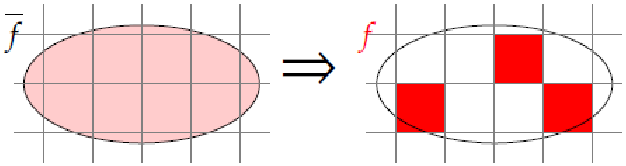
Sizes from : $\frac{E}{N_t} = \frac{3}{5}\frac{R_{\mathcal{P}}{}^2}{2m} =$

$$= \int_0^\infty \frac{\mathrm{r}^2}{2m} e^{-\mathrm{r}^2/(2\sigma_{\mathcal{P}}{}^2)} \mathrm{d}\mathrm{r} \Big/ \int_0^\infty e^{-\mathrm{r}^2/(2\sigma_{\mathcal{P}}{}^2)} \mathrm{d}\mathrm{r}$$

- if mean free path condition satisfied → good candidates
- given θ, probability to collide weighted on final occupations



Closest particles in phase space ⟶ nucleon wave packet



…. but the wave packet can have any shape

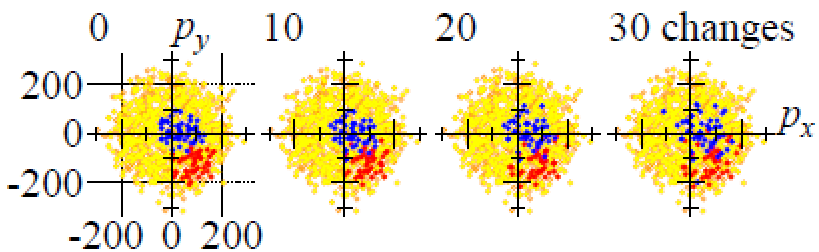
➢ The nucleon 'cloud' is enlarged if the final states are not empty

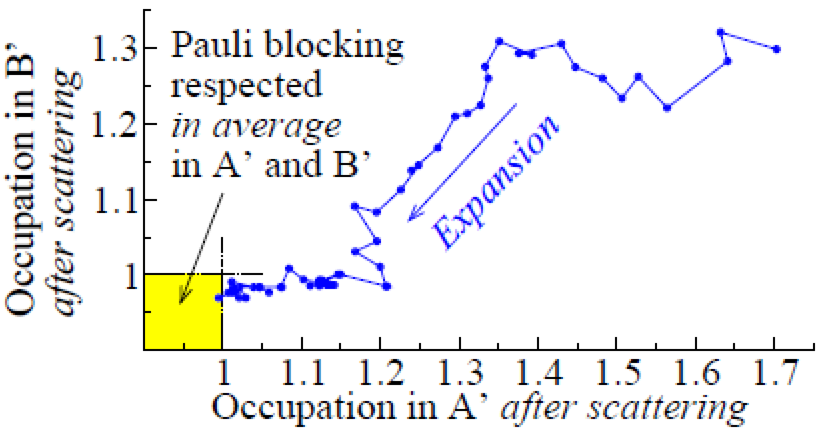
➢ This is done trying to optimize the compactness of the nucleon wave packet

Expansion in $\mathcal{P}$ of A,B :

- If final occupation > 1 in A′,B′

⇒ test larger A,B configurations (redefine c.m., keep θ)





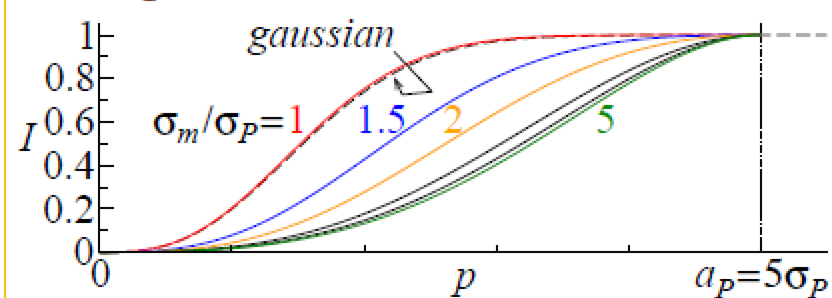
Modulation in $\mathcal{P}$ of A′,B′ :

- define gaussian-like distributions : $F_{a_P,\sigma_P} = M_{a_P} G_{\sigma_P}$

$$\int_0^{a_P} F_{a_P,\sigma_P} \mathrm{d}^3p = 1,$$

$$\lim(a_P \to \infty) = G_{\sigma_P}$$

example of F for $a_P = 5\sigma_P$:



P.Napolitani, IWM2011

Test on the collision number

Pauli disregarded :
number of attempted collisions

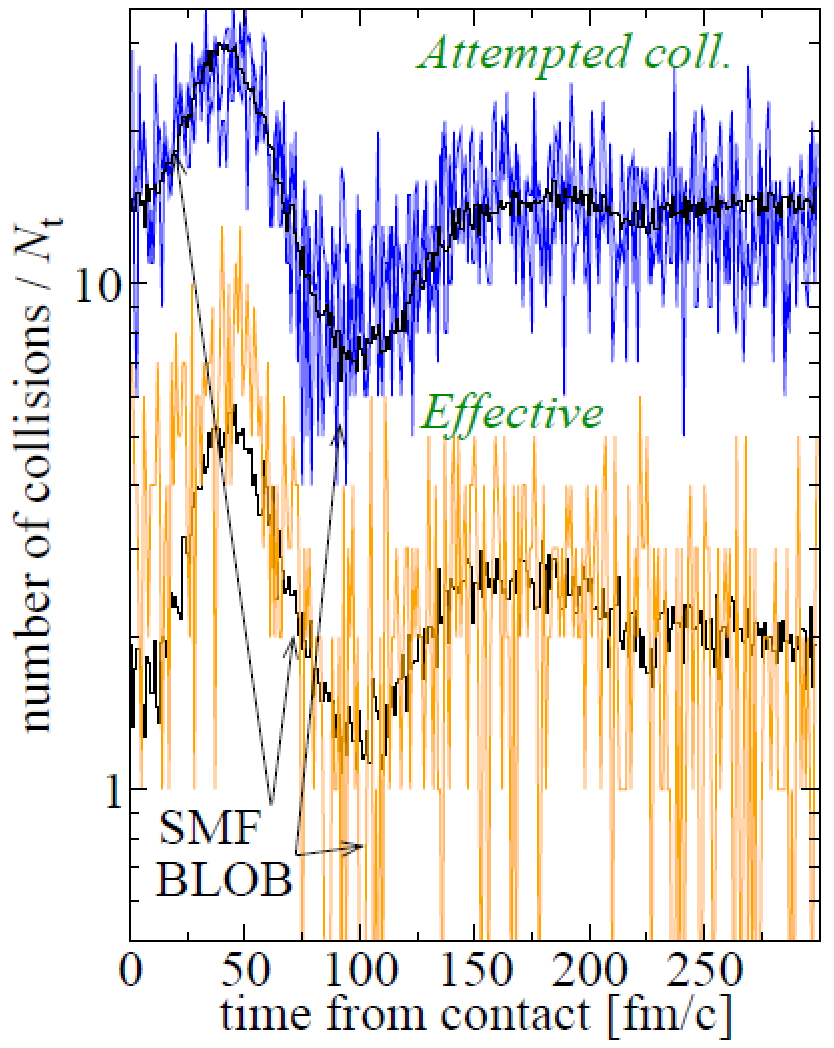
• Statistics based on *mean-free path* selection only

⇒ *SMF* and *BLOB* should have the same mean trajectory

• *BLOB* present fluctuations with nucleon-size amplitude

Pauli accounted for :
number of effective collisions

^{181}Ta+^{58}Ni 39*A*MeV *b*=0 one event

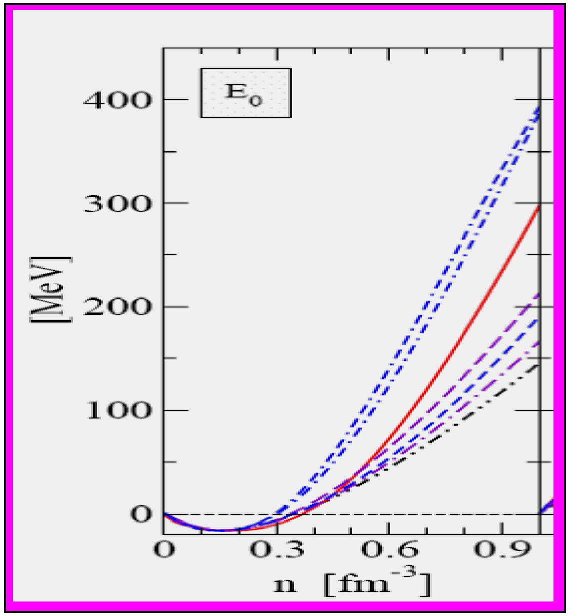


Heavy Ion Collisions (HIC) allow one to explore the behavior of nuclear matter under several conditions of density, temperature, spin, isospin, …

HIC from low to Fermi energies (~10-60 MeV/A) are a way to probe the density domain just around and below normal density. The reaction dynamics is largely affected by surface effects, at the borderline with nuclear structure.

Varying the N/Z of the colliding nuclei (up to exotic systems) , it becomes possible to test the isovector part of the nuclear interaction (symmetry energy) around and below normal density.

Effective interactions and symmetry energy



The nuclear interaction, contained in the Hamiltonian ***H**eff*,
is represented by effective interactions (Skyrme, Gogny,…)

Equation of State (EoS)

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

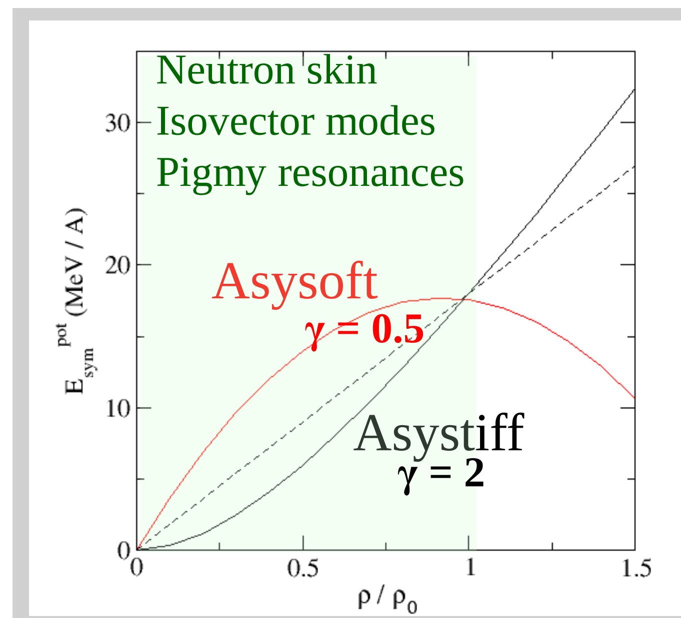
Asymmetry $\beta=(\rho_n-\rho_p)/\rho$

Symmetry energy E_{sym}

The density dependence of E_{sym} is rather controversial, since there exist effective interactions leading to a variety of shapes for E_{sym}:

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

$\gamma<1$ **Asysoft**, $\gamma>1$ **Asystiff**



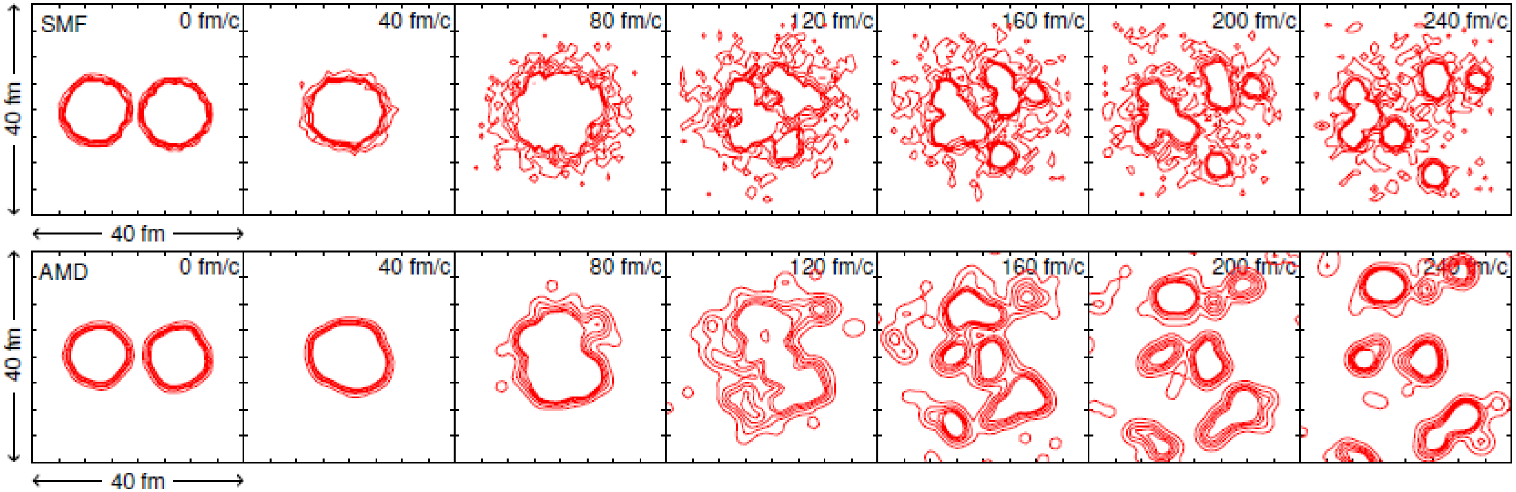
Central collisions: Comparison AMD – SMF for multifragmentation

Mean-field effects vs. many-body correlations

Expansion followed by fragmentation

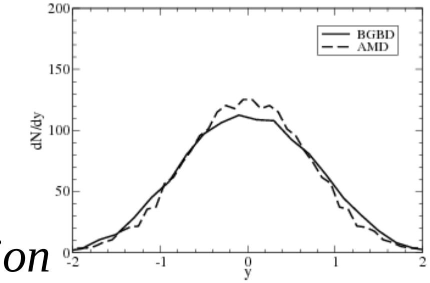
Rizzo, Colonna, Ono, PRC76 (2007) 024611.
Colonna, Ono, Rizzo, PRC82 (2010) 054613.

- SMF = Stochastic Mean Field model
- AMD = Antisymmetrized Molecular Dynamics



Central Collisions of ^{112}Sn + ^{112}Sn at 50 MeV/nucleon

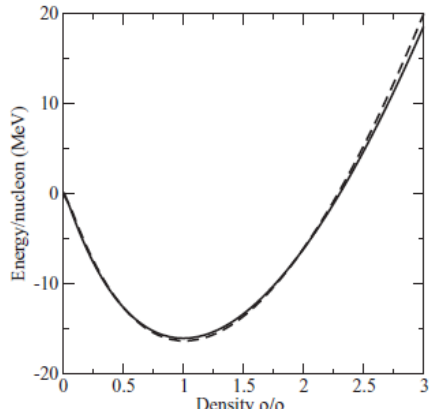
Used the same σ_{NN} and very similar effective interactions in both models.



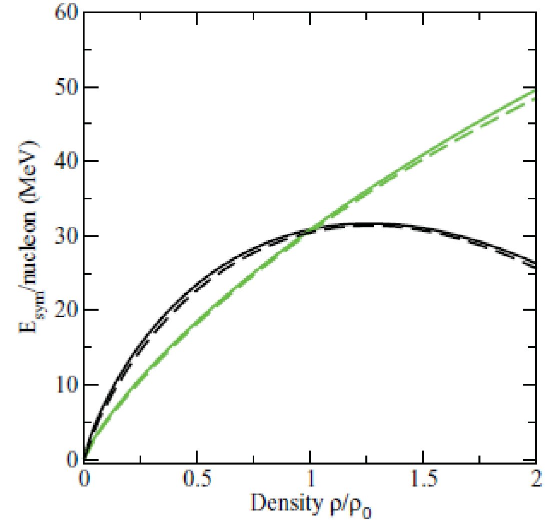
Rapidity distribution

A.Ono, IWM2011

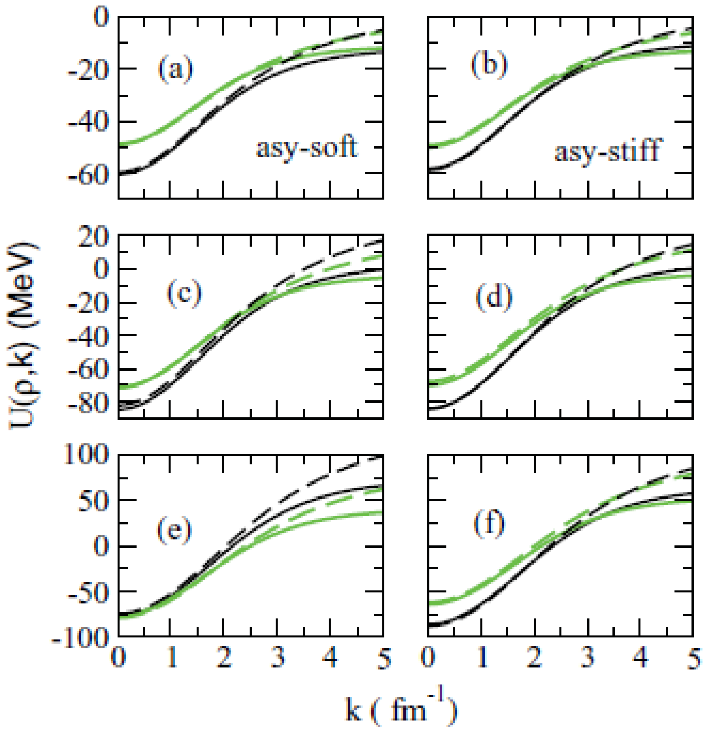
Details of the interaction employed in AMD (Gogny) and SMF (Skyrme)



EoS at T=0



Symmetry energy at T=0



$\rho_0/2$

ρ_0

$2\rho_0$

Neutron (green) *and* **proton (black)** *potential*

- - - **SMF**

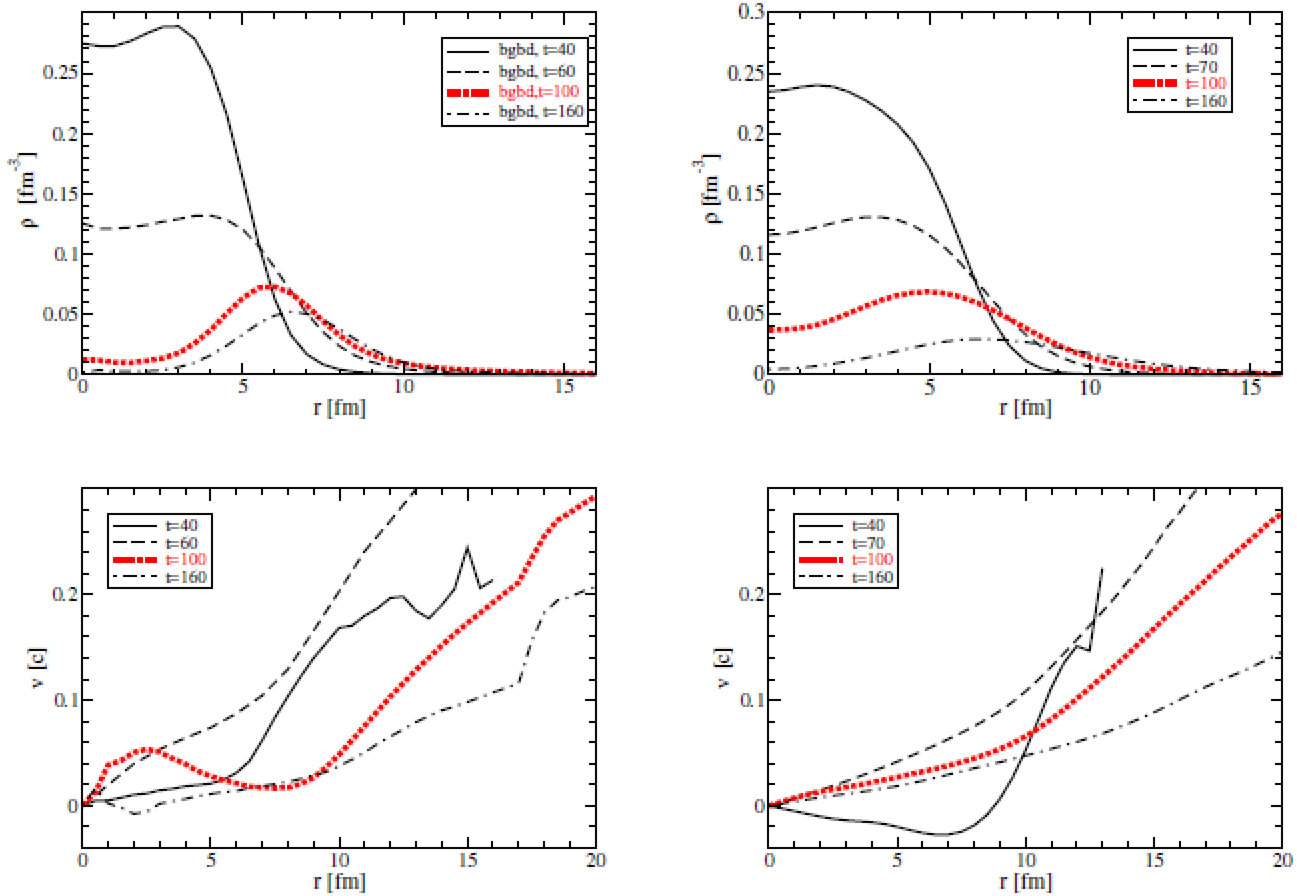
____ **AMD**

Comparison of collective expansion

SMF AMD

Density distribution $\langle \rho \rangle (r)$

Collective momentum $\left\langle \frac{\mathbf{r}}{|\mathbf{r}|} \cdot \mathbf{p} \right\rangle (r)$



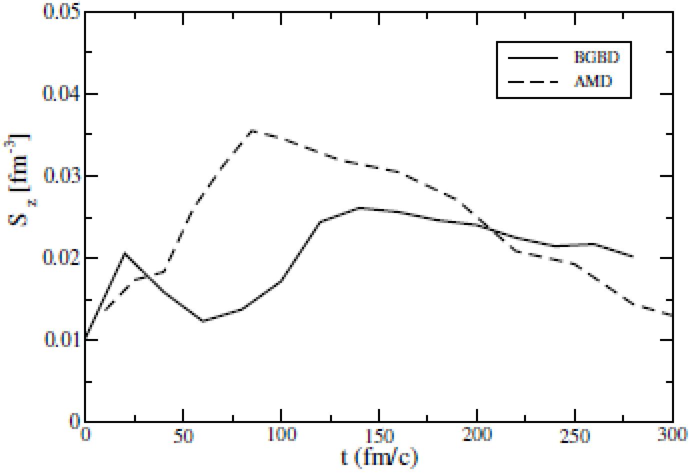
r = distance from the center of the system

A.Ono, IWM2011

Comparison of density fluctuation

Density fluctuation $\sim \left\langle \left(\rho(\mathbf{r},t) - \langle\rho\rangle(\mathbf{r},t) \right)^2 \right\rangle$ (on the z-axis)

- $\rho(\mathbf{r},t)$: Density in each event
- $\langle\rho\rangle(\mathbf{r},t)$: Density averaged over events



Different mechanisms of fragmentation

- SMF: Spinodal decomposition
- AMD: Earlier prefragments

⇓

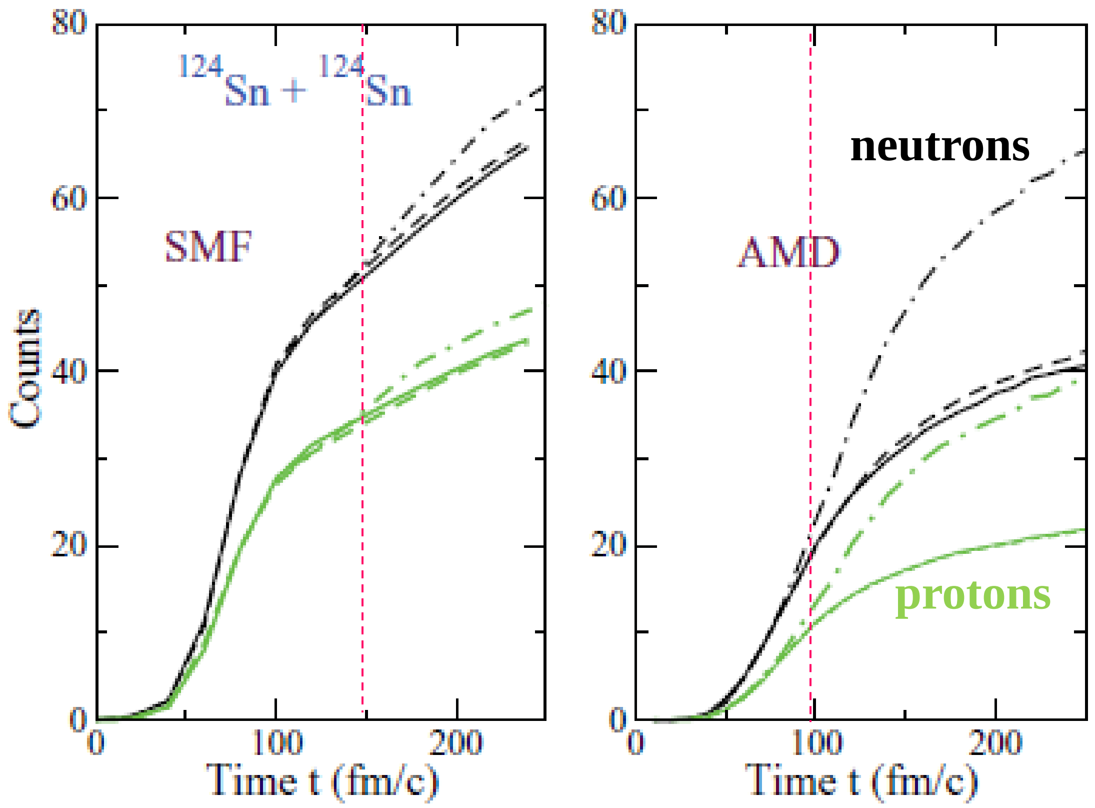
Different collective expansions

Slow or rapid expansion

Bubble-like or broader density distribution

A.Ono, IWM2011

Comparison AMD – SMF pre-equilibrium emission

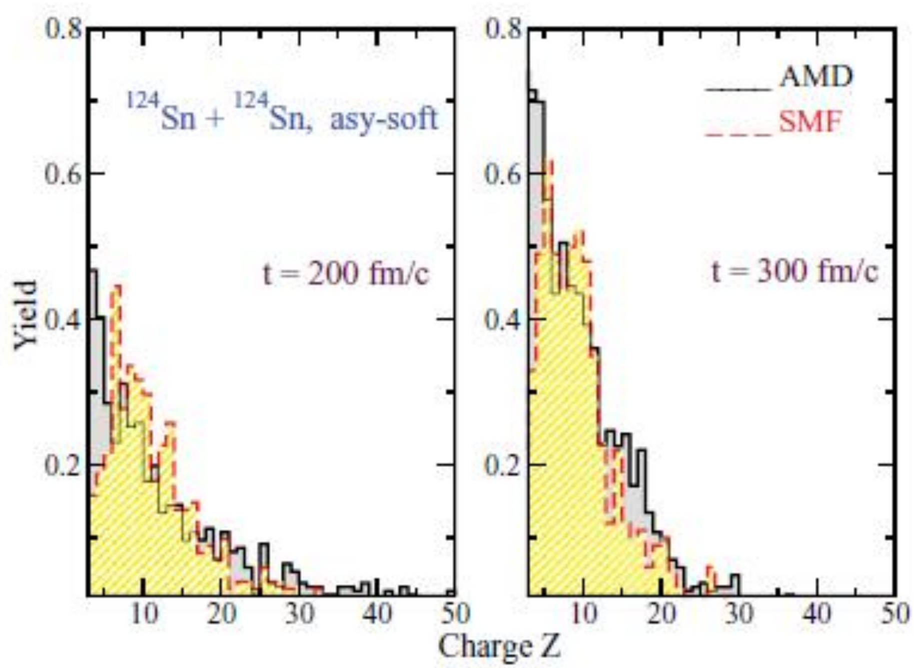


➢ *More particles (A<5) emitted in SMF ,*
and more energy dissipated
(see Lacroix, Chomaz, **NPA 636 (1998)** *)*

➢ *More light clusters 4<A<16 emitted in AMD*

- **Larger expansion velocity in AMD**
- **Earlier cluster and fragment formation in AMD**

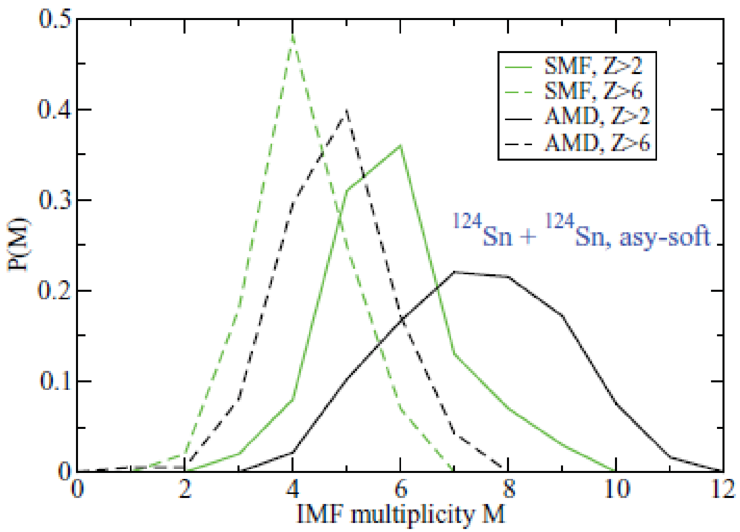
Comparison AMD – SMF fragment emission



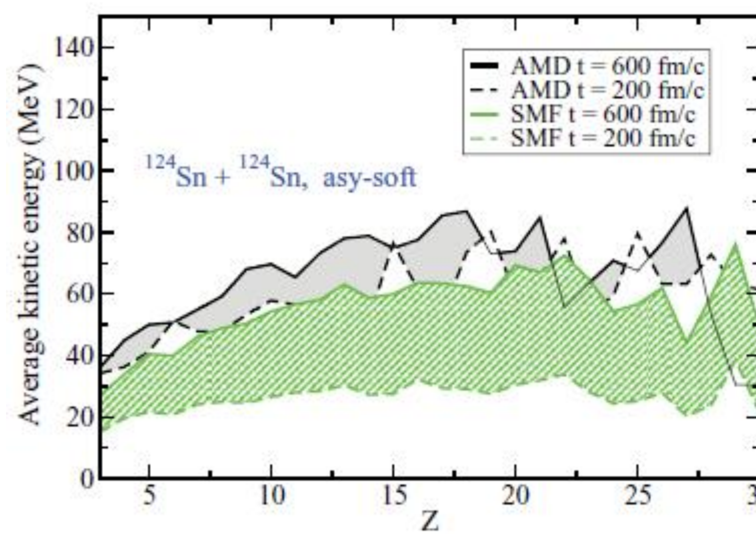
Charge distribution of primary fragments

- **Mean-field mechanism in SMF:**
  Spinodal instabilities

but both models fit exp. data

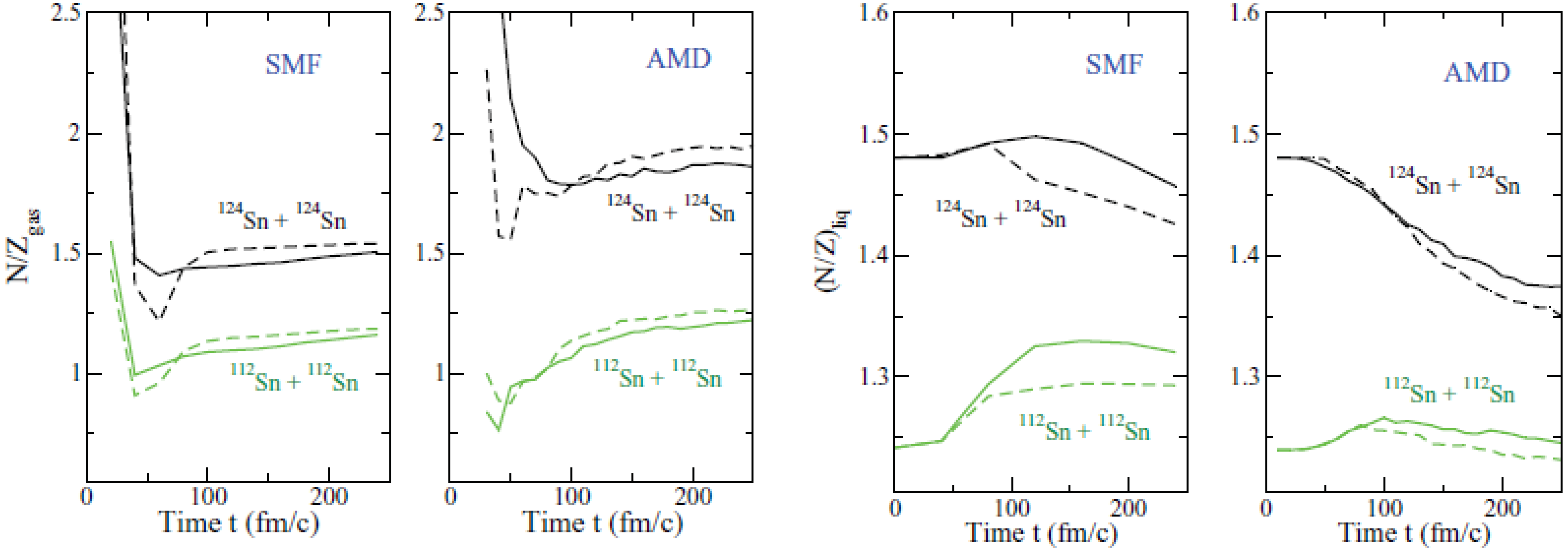


Primary IMF multiplicity



IMF kinetic energy

Comparison AMD – SMF isotopic properties



The reaction dynamics influences fragment isotopic properties:

➢*More abundant, but less neutron-rich emission in SMF*

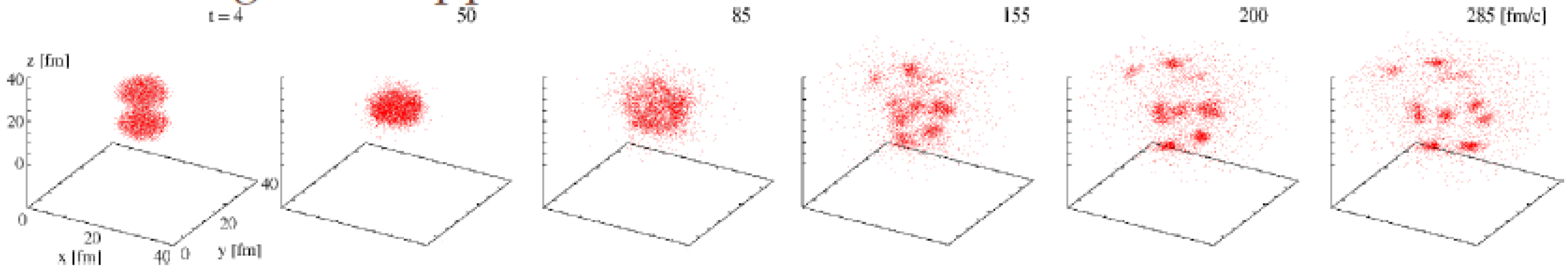
➢*More effective clustering in AMD, with protons trapped in light clusters*

--- too much pre-equilibrium emission in SMF

BLOB. *Kinematics*

BLOB, $^{124}Sn+^{124}Sn$, 50AMeV, $b = 0$:

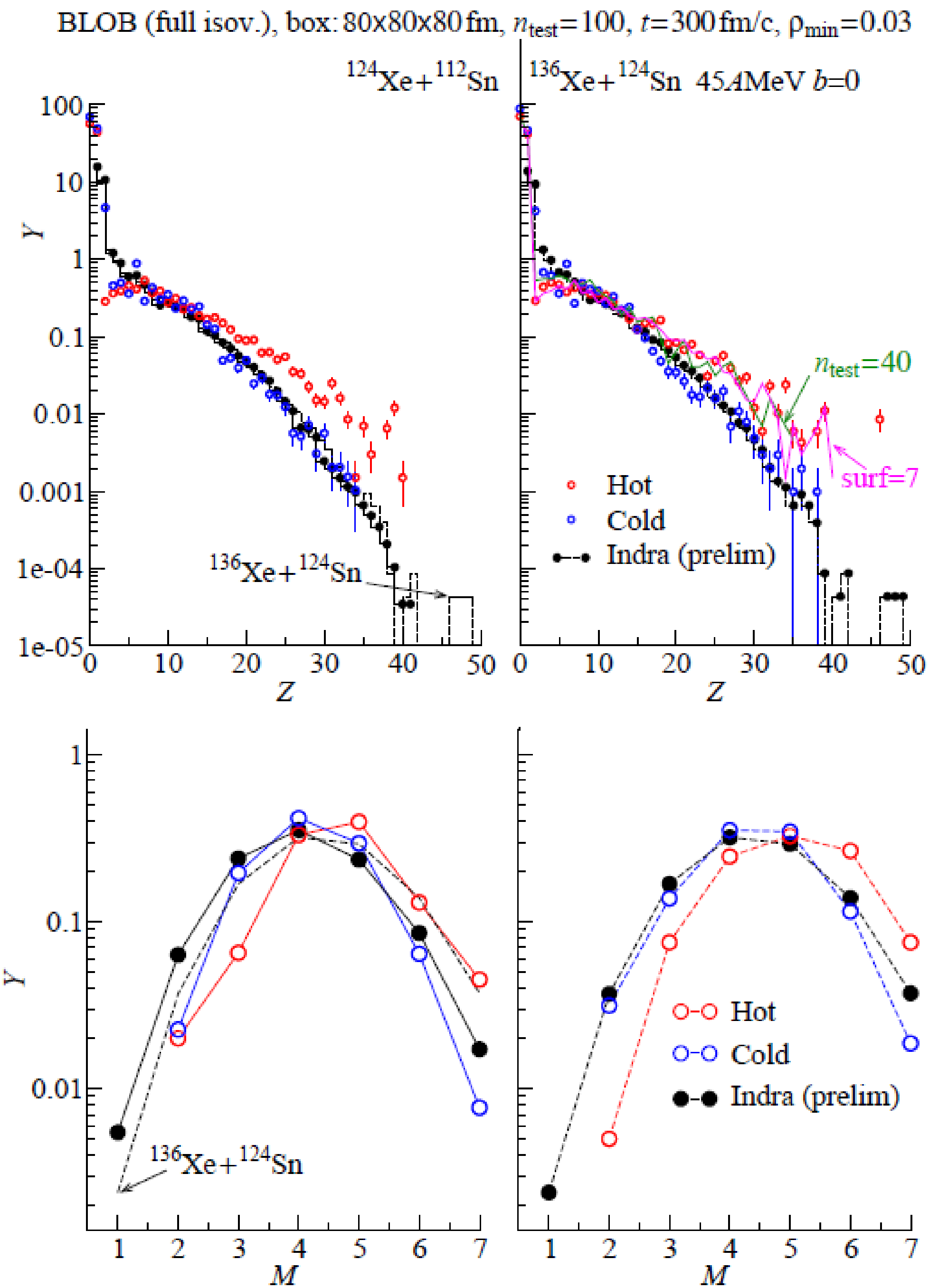
- t 50 Maximum compression
- t 85 Hollow appear, with instabilities (seeds for fragment formation)
- t 155 Fragments appear



→ *Some comparison with INDRA data*

P.Napolitani

BLOB results

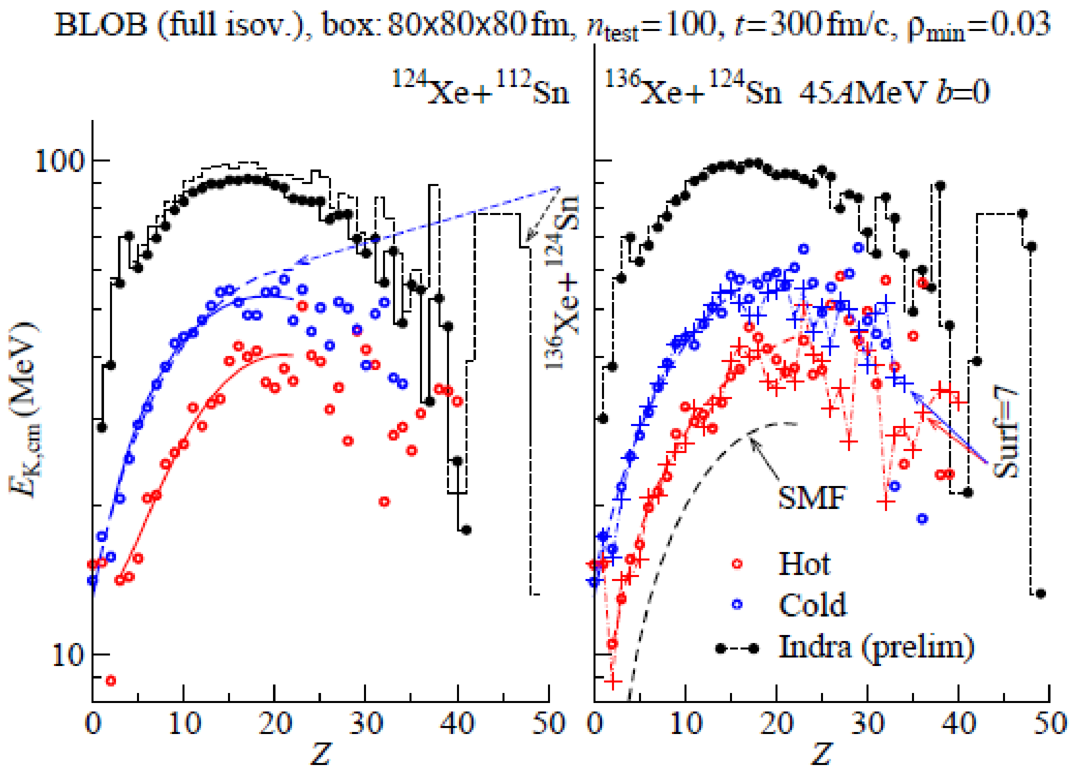


Charge distribution

Multiplicity distribution

P.Napolitani

Fragment kinetic energies



BLOB results

➢ Fragments are faster in the BLOB model (with respect to SMF)

➢ Experimental energies still underestimated

Too much pre-equilibrium emission ?

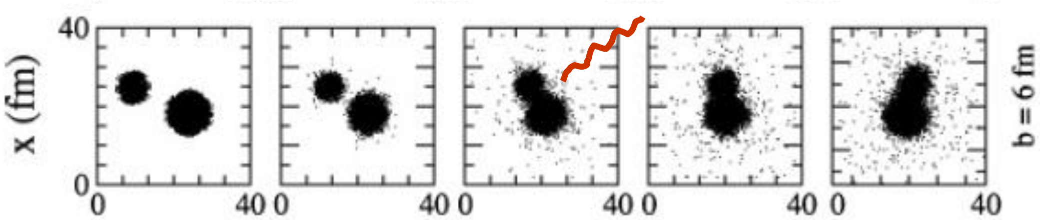
P.Napolitani

Dissipation and fragmentation in Heavy Ion Collisions: (semi-peripheral)

→ ***Low energies (~ 10 MeV/A)***

- Competition between reaction mechanisms: fusion, deep-inelastic, neck rupture
- Charge equilibration mechanism has a **collective** character (dynamical dipole resonance)

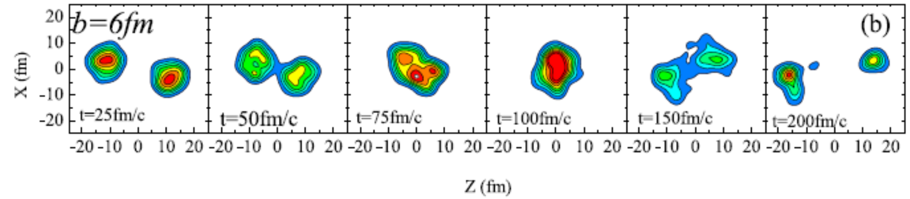
"Mean-field " picture



→ ***Fermi energies (30-60 MeV/A)***

- Neck rupture, fragmentation
- Charge equilibration mechanism has a **diffusive** character

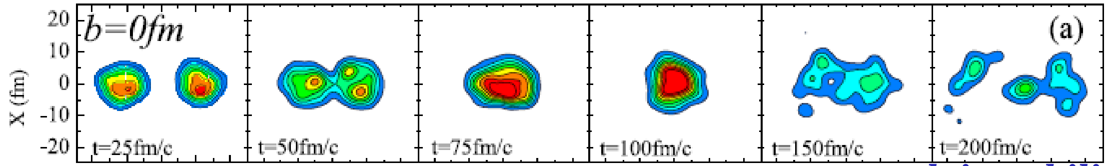
Two-body correlations essential !



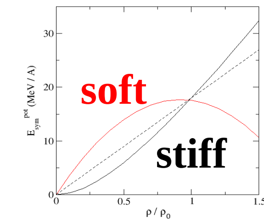
➡ Focus on charge equilibration mechanism and its connection to the isovector part of the nuclear interaction at Fermi energies.

Fermi energy mechanisms:
Dissipation and fragmentation

Isospin transport and fragmentation mechanisms in semi-central collisions



neck instabilities



Simple hydro picture

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

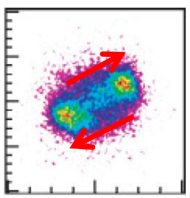
$$j_p = D_p^{\rho}\nabla\rho + D_p^{I}\nabla I$$

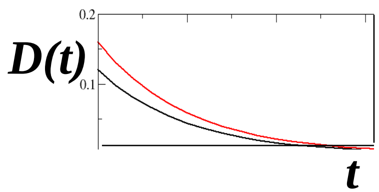
drift **diffusion**

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

Diffusion **Drift**

-- Diffusion: charge equilibration





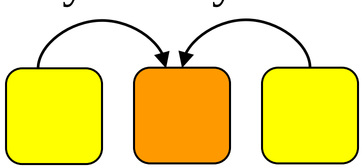
Overdamped dipole oscillation

$$D(t) = D(0)\ e^{-t/\tau_d}$$

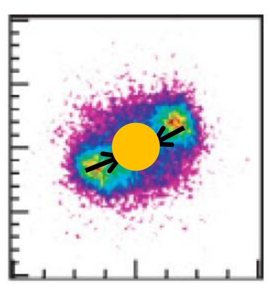
$$\tau_d \longrightarrow E_{sym}$$

-- Drift: Isospin migration

Asymmetry flux

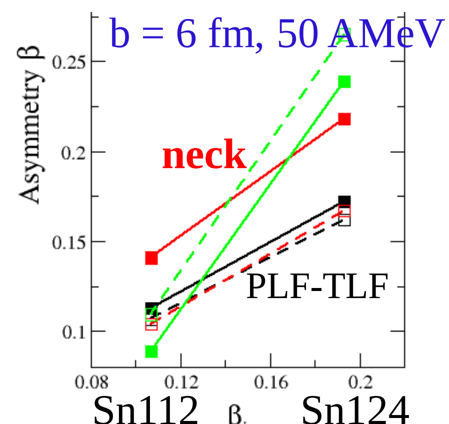


$\rho_{neck} < \rho_{PLF(TLF)}$



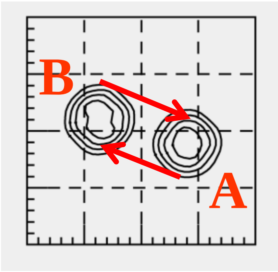
$\beta = (\rho_n - \rho_p)/\rho$

Neck fragments are neutron-richer than PLF-TLF



Tools to study charge equilibration between A and B

$$\mathrm{Mass(A)} \sim \mathrm{Mass(B)} \quad ; \mathrm{N/Z(A)} \neq \mathrm{N/Z(B)}$$



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

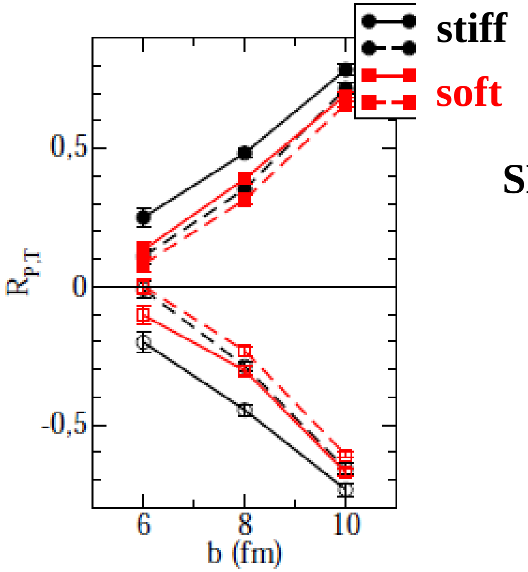
-- X is an observable related to the N/Z of the projectile-like fragments (PLF)

$$R(t) = 2(x_{AB}(t) - x_m) / (x_A - x_B)$$

$$R_{AB} = e^{-t/\tau_d} \qquad \tau_d \longrightarrow E_{sym}$$

$x_m = (x_A + x_B)/2$ $\quad$ t = contact time

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



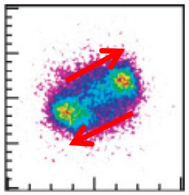
SMF calculations

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

$X = N/Z_{PLF}$

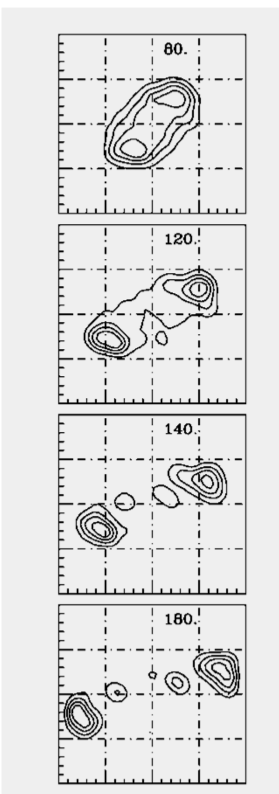
Dissipation and fragmentation in "MF" models

➢ ***Diffusion: mass exchange, charge equilibration, energy dissipation***



$$R_{AB}(t) = e^{-t/\tau_d} \qquad E^{kin}_{AB}(t) = E^{kin}(t=0)\, e^{-t/\tau_{ex}}$$

$$\longrightarrow \quad R_{AB} = [E^{kin}_{AB} / E^{kin}(t=0)]^{\tau_d/\tau_{ex}}$$

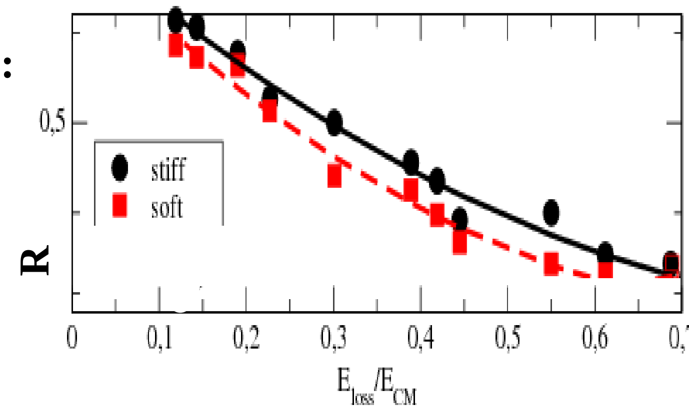


J. Rizzo et al., NPA(2008)

Relative weight of Is and Iv dissipation:

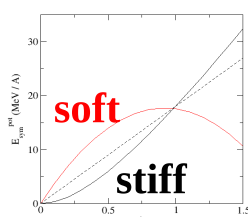
- ***Isovector modes faster than isoscalar modes: $\tau_d/\tau_{ex} < 1$***

- ***Larger symmetry energy at low density: Faster equilibration with soft***

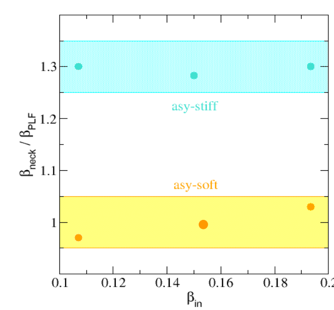


SMF calculations, $^{124}Sn + ^{112}Sn$, 50 AMeV

➢ Neck instabilities: important role of *fluctuations*….
but still '**mean-field**' dominated mechanism:
isospin migration

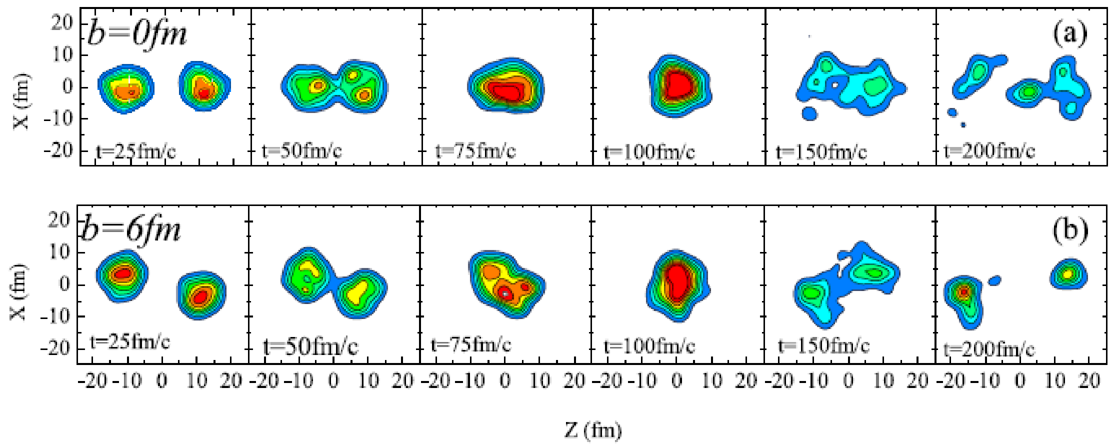


$$\frac{\beta_{IMF}}{\beta_{res}} = \frac{E_{sym}\ (PLF)}{E_{sym}\ (neck)}$$

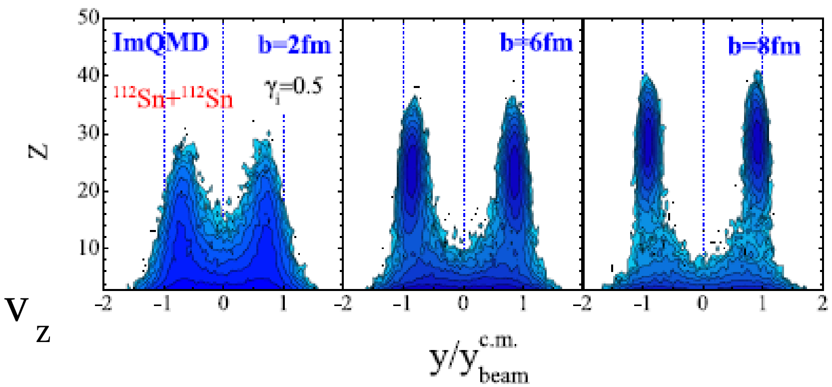


Dissipation and fragmentation in "MD" models

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



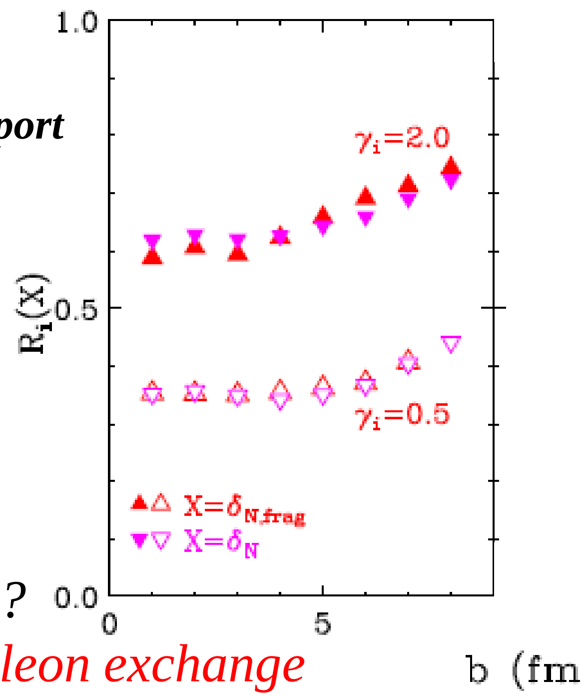
- ***More 'explosive' dynamics:***
  - *more fragments and light clusters emitted*
  - *more 'transparency'*



$y \approx v_z$

Y.Zhang et al., PRC(2011)

Isospin transport ratio R



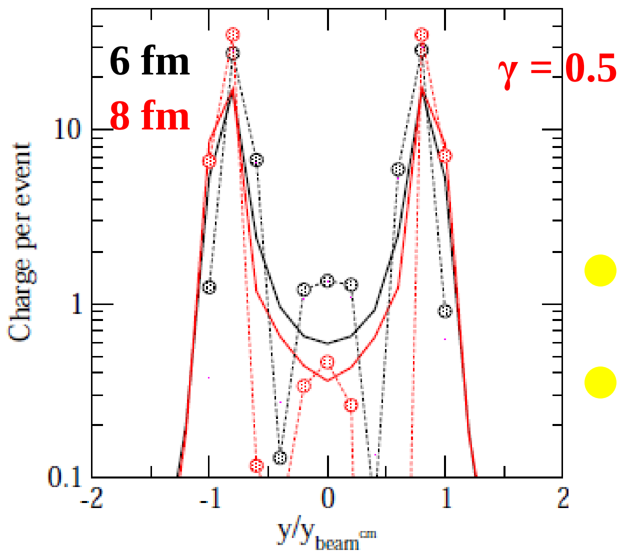
What happens to charge equilibration ?

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*

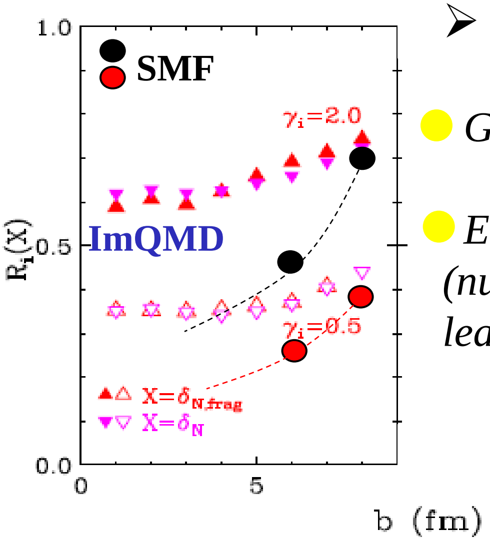
Comparison SMF-ImQMD



SMF = dashed lines
ImQMD = full lines

➢ For semi-central impact parameters:

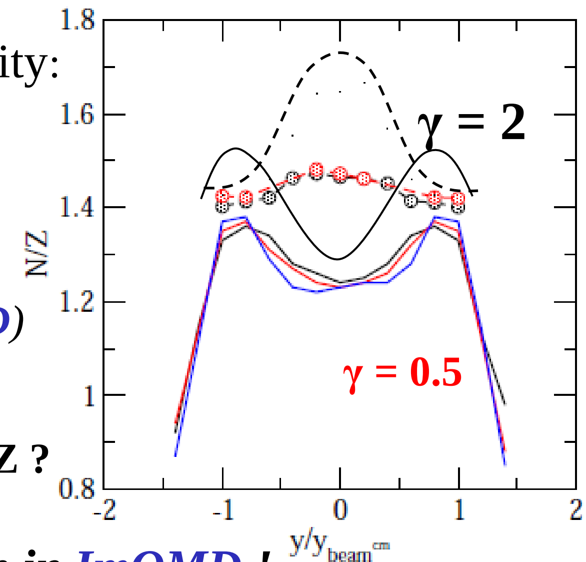
- ***Larger transparency** in **ImQMD** (but not so a drastic effect)*
- ***Other sources of dissipation** (in addition to nucleon exchange)*
  More cluster emission



➢ 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 ?



No isospin migration in ImQMD !

Summary

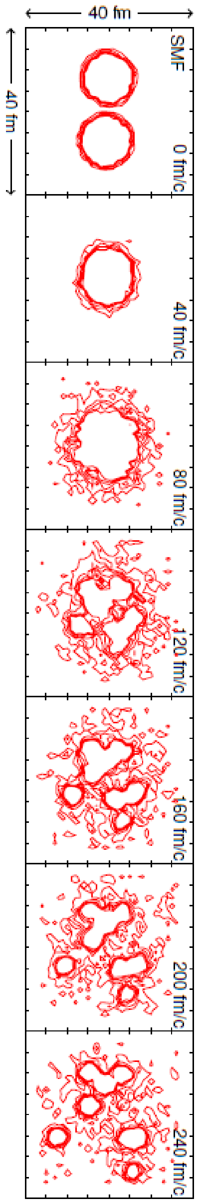
- The relative role of "mean-field" and "correlations" is different in the different transport theories

- A given description may be better than others only in a given energy range (and for given reaction mechanims)

➢ *Central collisions*

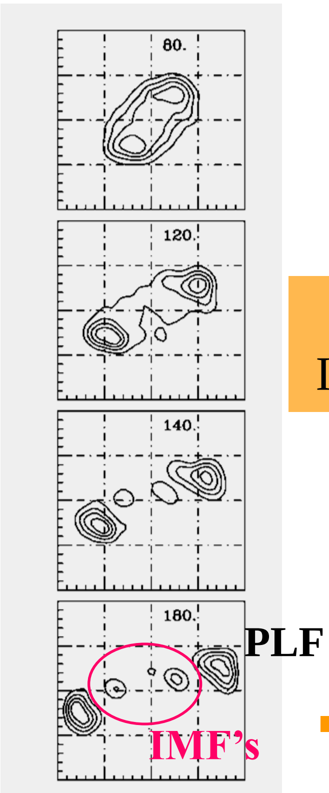
- *Nucleon emission is overestimated in* **semi-classical transport theories**.
- *As a consequence, radial flow is inderestimated*
- *Lack of primary light cluster (2<Z<7) production with respect to* **MD** *models*

The reaction dynamics influences also isotopic properties



Summary

➢ *Semi-peripheral collisions*



➢ **Fermi energies**: *from full to partial isospin equilibration*

• Mid-peripheral impact parameters: *Results are model-dependent*
Important to check the **reaction dynamics** (dissipation and nature of dissipation)

→ Look at the correlation between charge and velocity of **PLF** residues and IMF's (2<Z<9) multiplicity

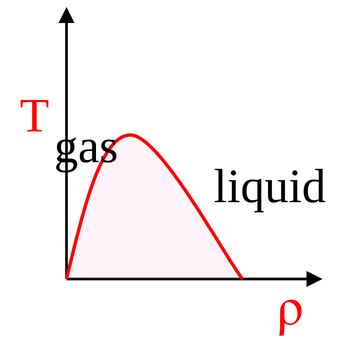
→ **N/Z** of neck fragments can help to check the reaction dynamics
⟶ Isospin as a tracer

In collaboration with

Y.Zhang (ImQMD)
A.Ono (AMD)
P.Napolitani (BLOB)

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* ?

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

Fragment Recognition

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)