Symmetry Energy and Reaction Mechanisms at SPIRAL/SPES beam energy

Asy-EoS 2015

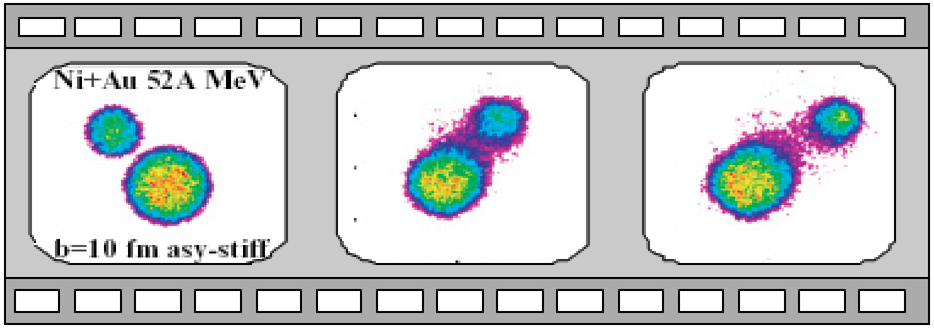
3^{rd}-6^{th} March, 2015
Piazza Armerina (Italy)

Maria Colonna
INFN - Laboratori Nazionali del Sud (Catania)

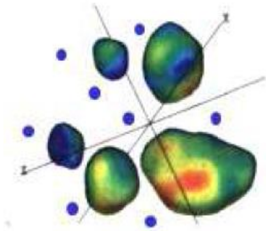
Content

- Brief introduction to transport theories
- Low-energy fragmentation mechanisms
- Charge equilibration: Collective mechanisms

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

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

$$\delta K = F(v, \delta\sigma)$$

$$<\delta K> = 0$$

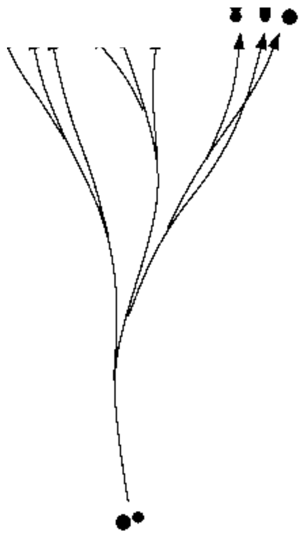
$$<\delta K \delta K> \longrightarrow$$ <u>*Fluctuations*</u>

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) ***Skyrme forces***

Semi-classical approximation $\longrightarrow$ **transport theories**

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

Vlasov

Correlations, Fluctuations

…MD

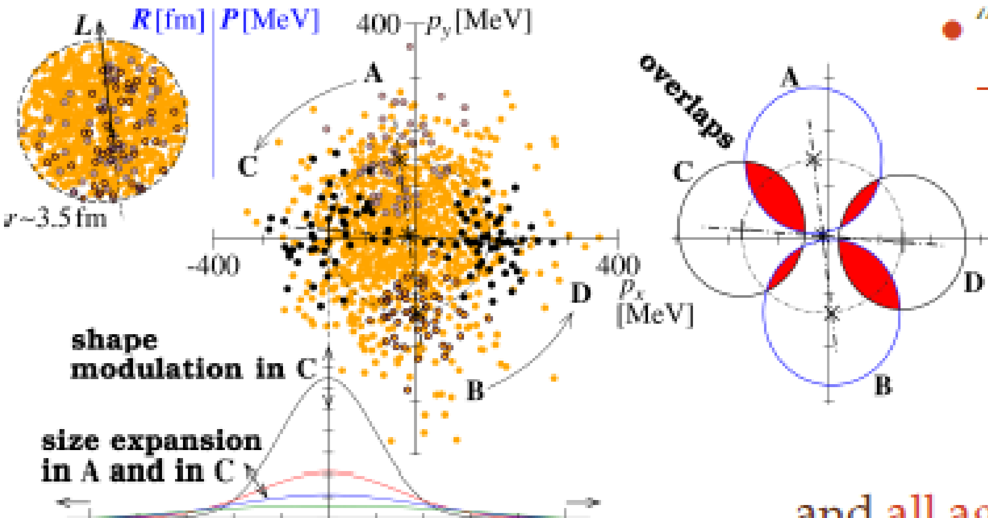
BUU, SMF

- Stochastic Mean-Field (SMF) model :
  Fluctuations are projected on the coordinate space

- Boltzmann-Langevin One Body (**BLOB**) model :
  fluctuations implemented in full phase space

At *a given time t*,
in $(\mathbf{r}_a, \mathbf{p}_a)$,
for *elastic coll.* :

$$\dot{f}_a(\mathbf{r}_a, \mathbf{p}_a) = g \int \frac{\mathrm{d}\mathbf{p}_b}{h^3} \int \mathrm{d}\Omega \, W(AB \leftrightarrow CD) \, F(AB \rightarrow CD)$$



- *"nucleon wave packets"* → → *phase-space agglomerates* of N_{test} test-particles of equal isospin $(a \in A, b \in B \ldots)$
- at each Δt : all phase space is scanned for collisions and all agglomerates are redefined

- Clouds of test particles (nucleons) are moved once a collision happens
- Shape modulation of the packet ensures Pauli blocking is respected

Napolitani and Colonna, PLB 2013

Effective interaction and Symmetry Energy

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

$\beta = (N-Z)/A$

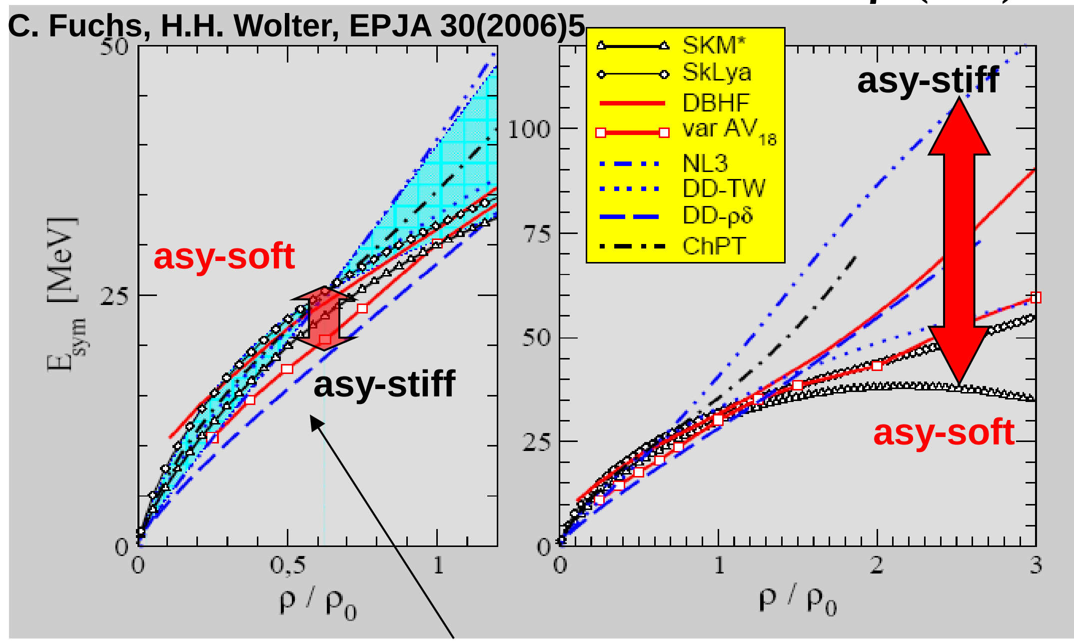
Often used parametrization:

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

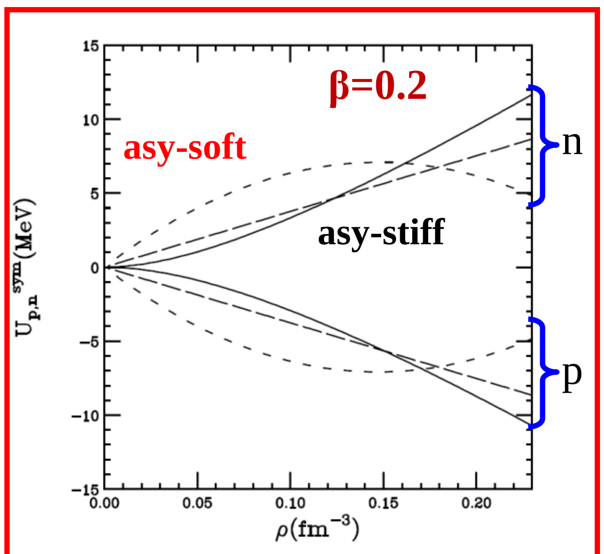
$\gamma<1$ **asy-soft**, $\gamma>1$ **asy-stiff**

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

$\gamma = L/(3S_0)$

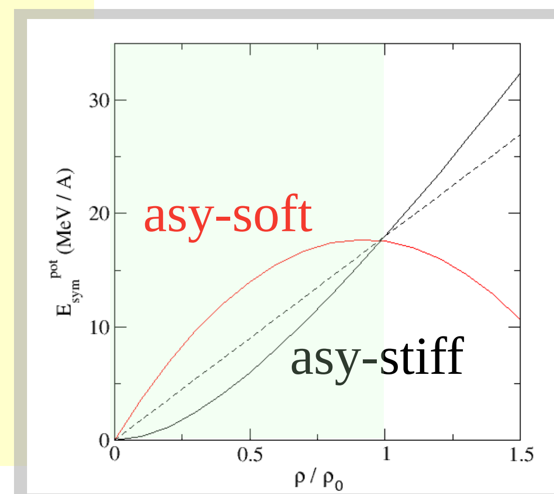


zoom at low density



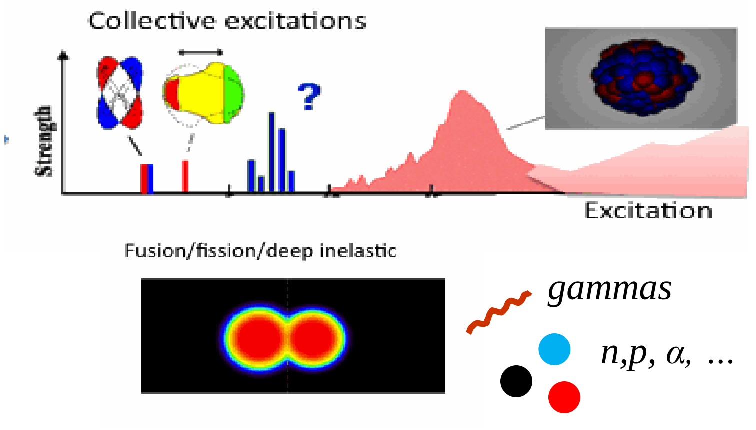
Symmetry potential :

- *Below normal density :* larger per **asy-soft**
- *Above normal density:* larger for **asy-stiff**

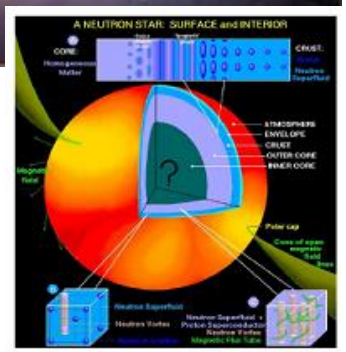


Isospin effects in Low-energy Heavy Ion Reactions

- New collective excitations
- *Competition between reaction mechanisms*
- Charge equilibration
- *Isotopic features of emitted particles*



What can we access by transport theories?



➢ Test the mean-field potential

(nuclear effective interaction)

⟶ *EDF (Nuclear Structure)*

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

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

Astrophysical implications …

Low-energy fragmentation mechanisms

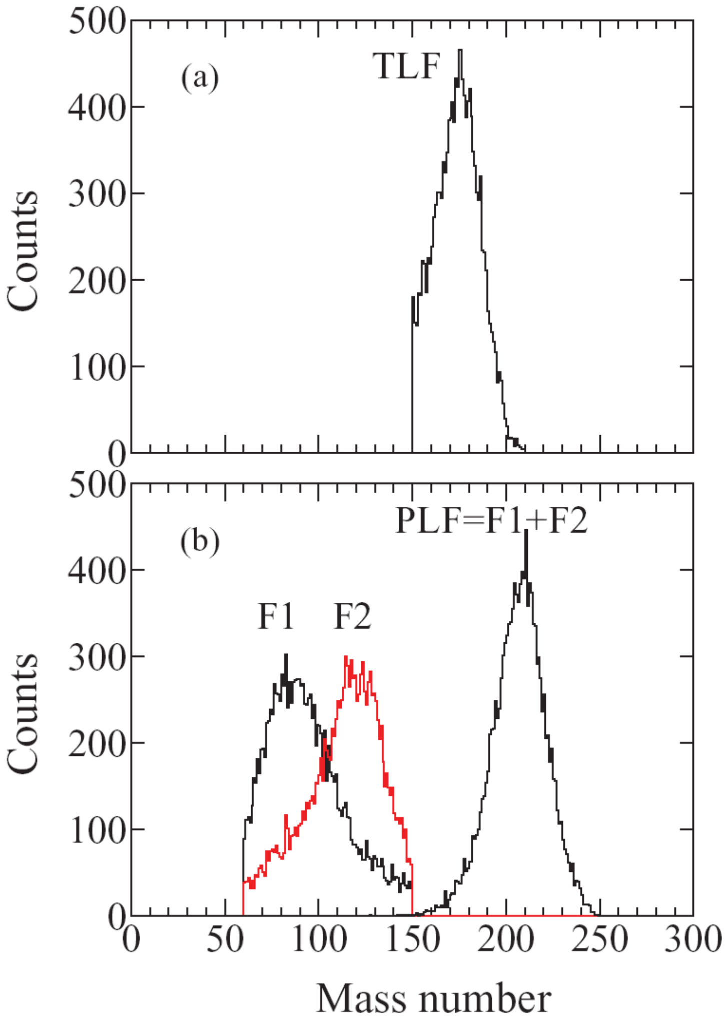
➢ Ternary break-up

Y.Li et al., NPA 902 (2013)

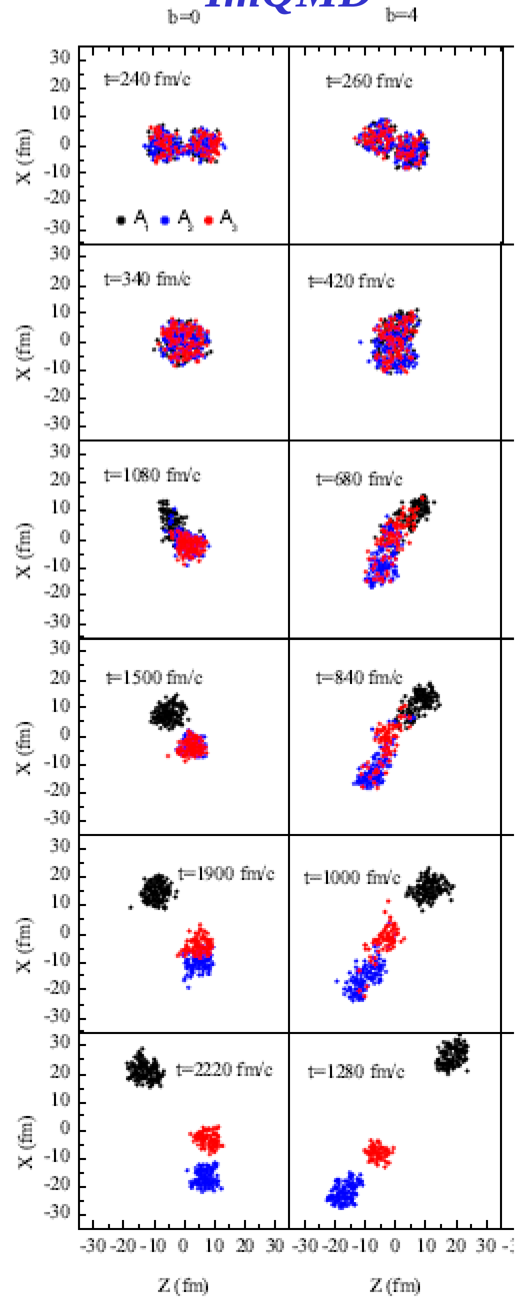
C.Rizzo et al., PRC (2014)

^{197}Au + ^{197}Au collisions - 15 MeV/A

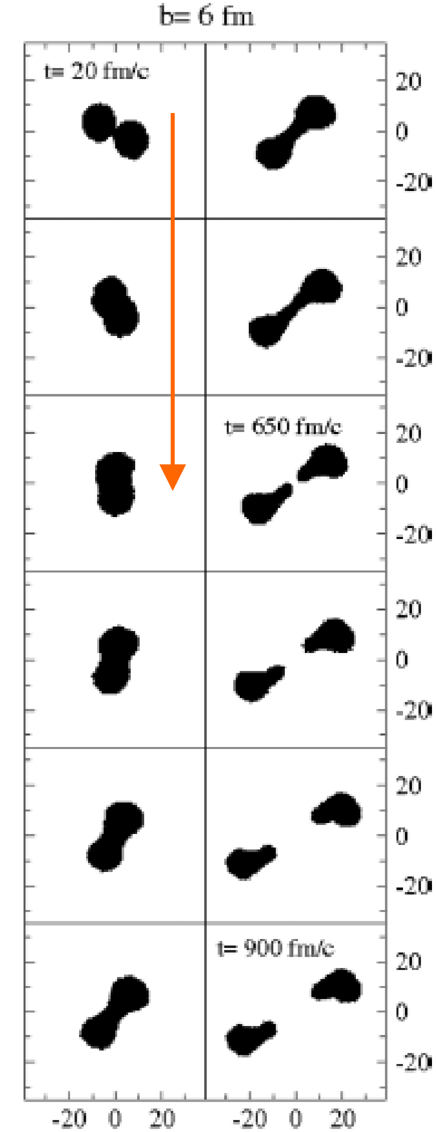
(Chimera@LNS data) ***PRC 81, 024605 (2010)***



ImQMD

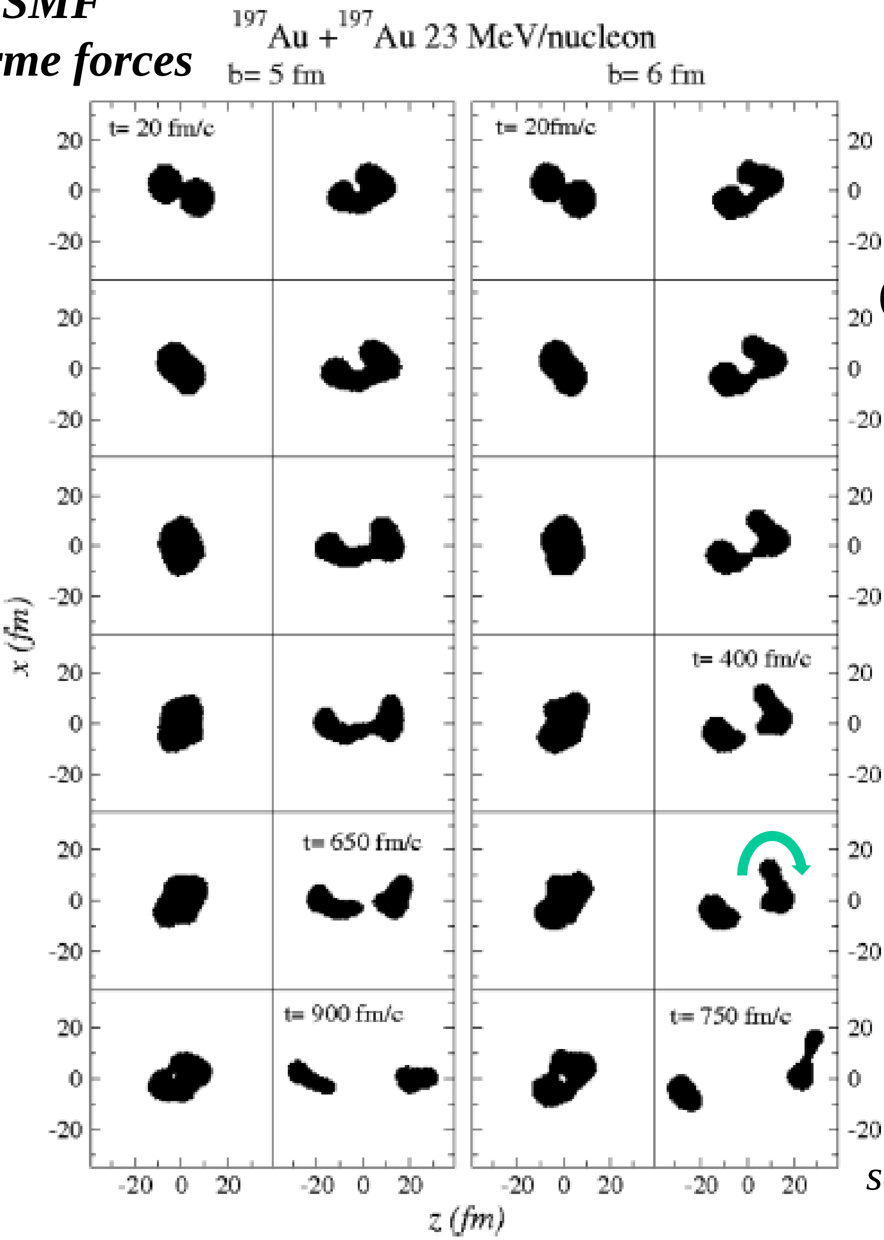


SMF



➢ PLF-TLF properties

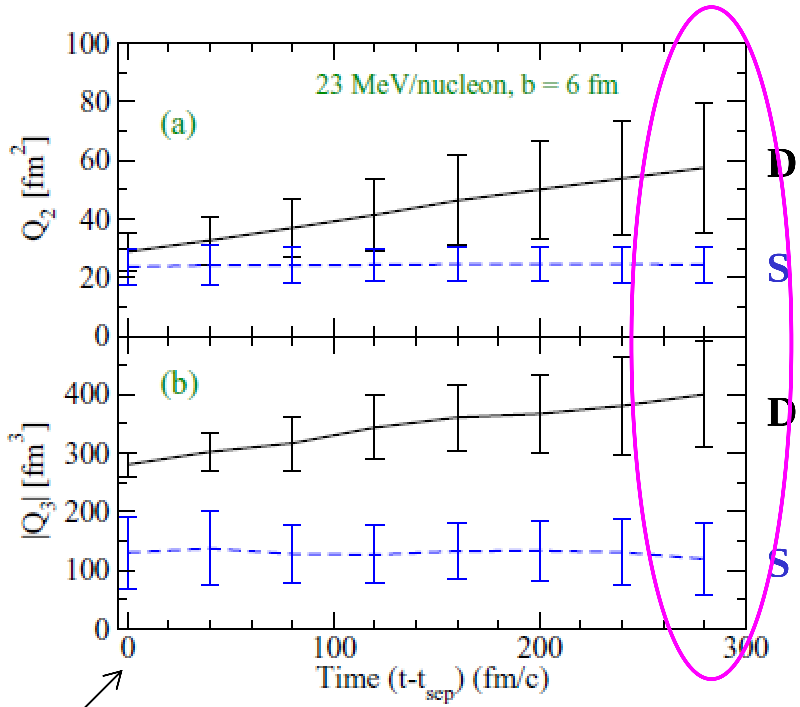
SMF
Skyrme forces



^{197}Au + ^{197}Au collisions - 23 MeV/A

- Shape Observables:

Quadrupole and Octupole moments



"PLF-TLF separation time"

D F: deformed fragment

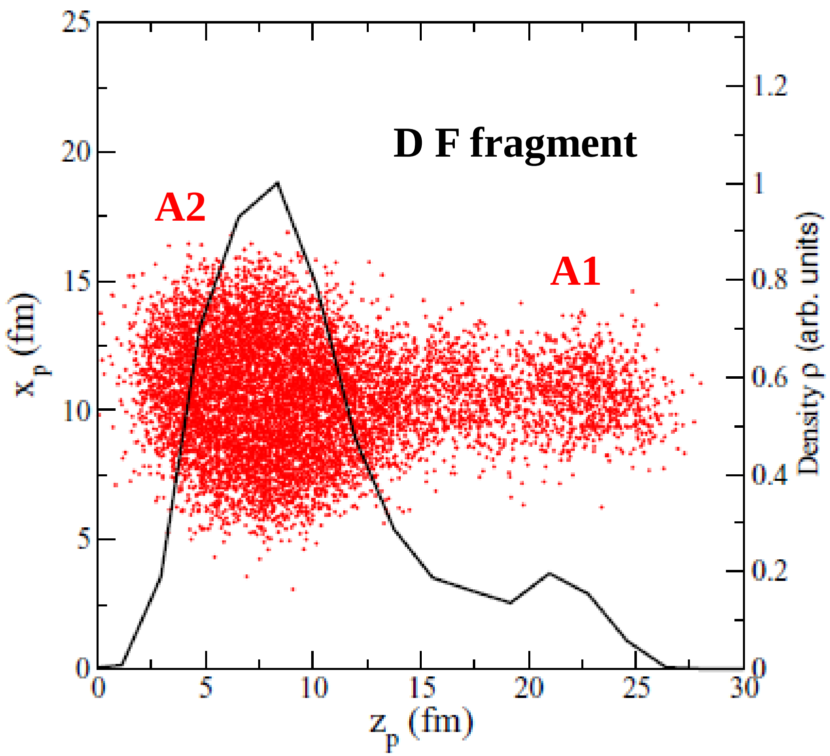
S F: "spherical" fragment

C.Rizzo et al., PRC 90 (2014)

➢ PLF(or TLF) break-up

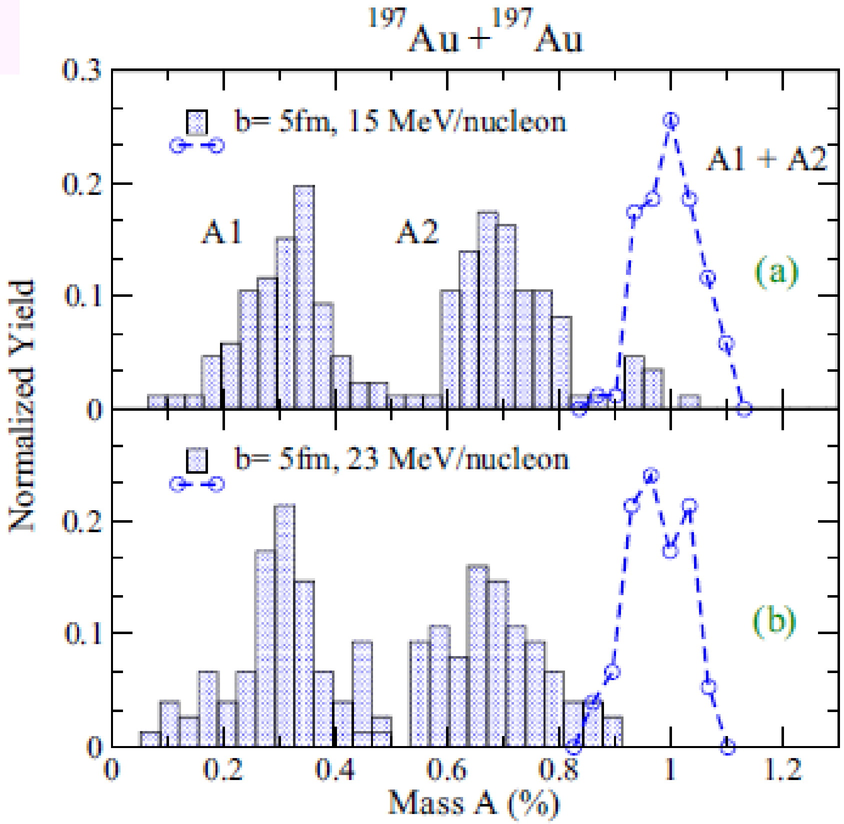
- Fragment recognition procedure:

✓ *Determine the most suitable two fragment configuration that fits the DF density profile at final time*



maximum elongation axis

- Mass distribution of fragments emitted by DF fragment



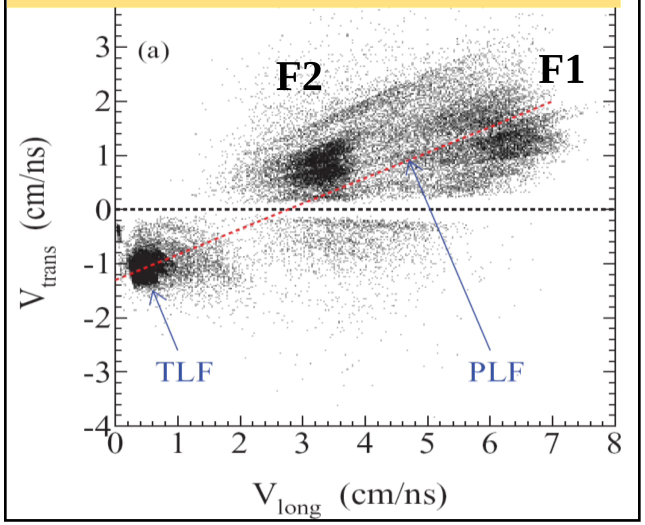
A1: lightest fragment
A2: heaviest fragment

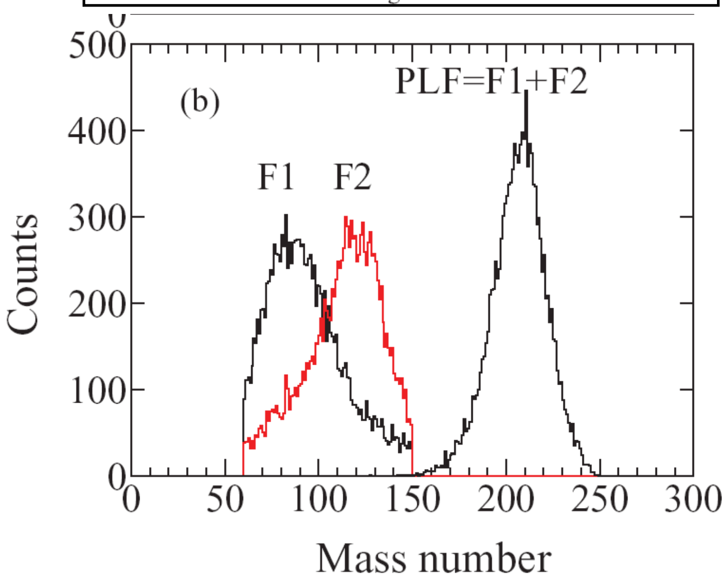
➢ Ternary break-up: emission direction

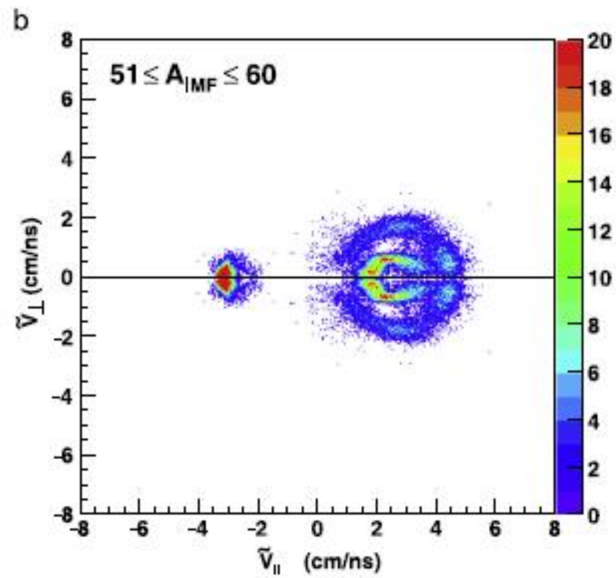
15 MeV/A - PRC 81, 024605 (2010)

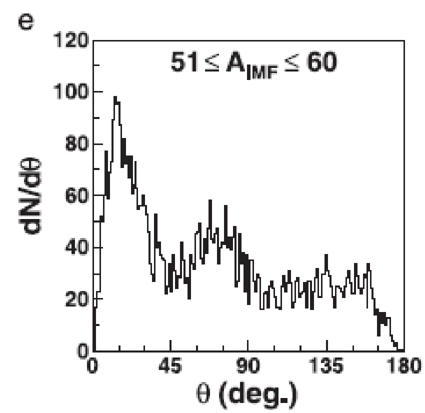
23 MeV/A - T. Cap et al., Phys. Scr. 89 (2014) 054005

Preferential emission direction



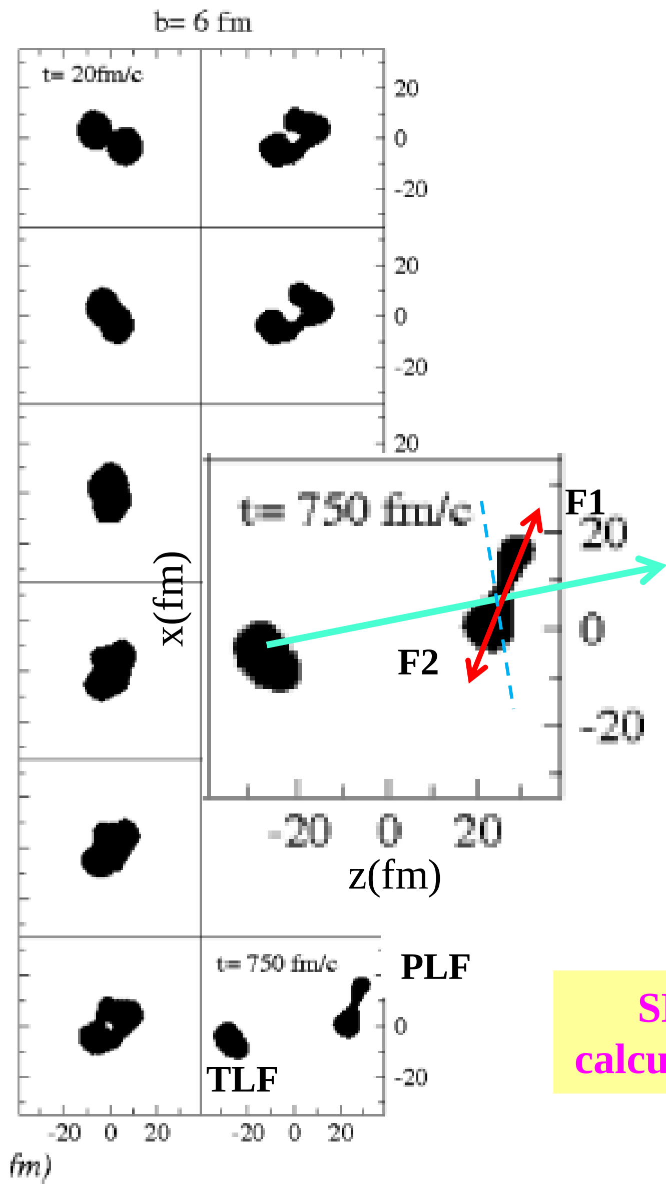


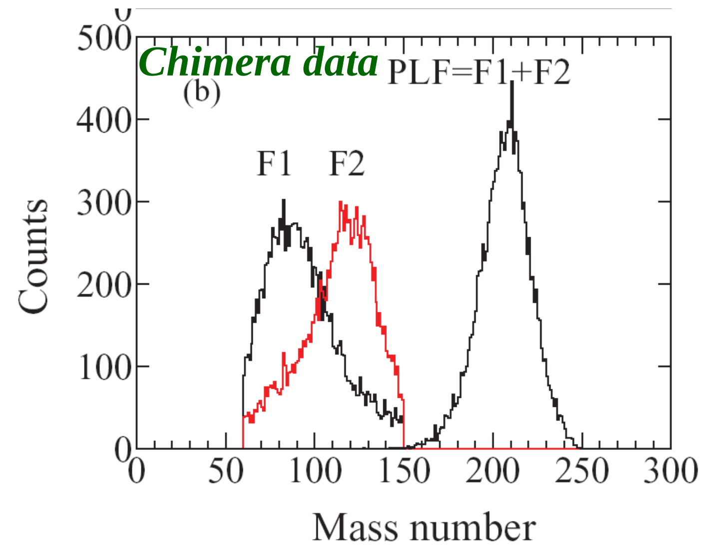


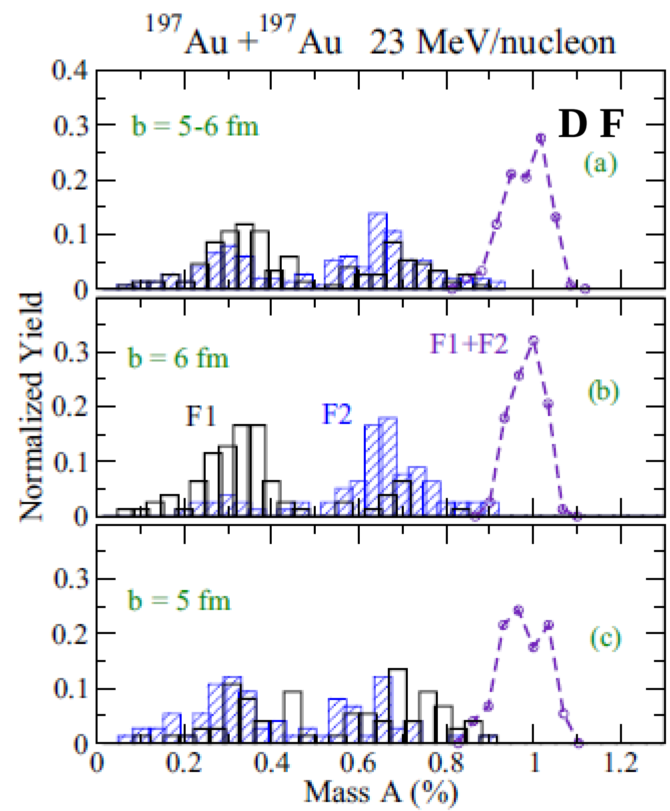


➢ Mass-velocity correlations

^{197}Au + ^{197}Au - 23 MeV/A *b = 6 fm*



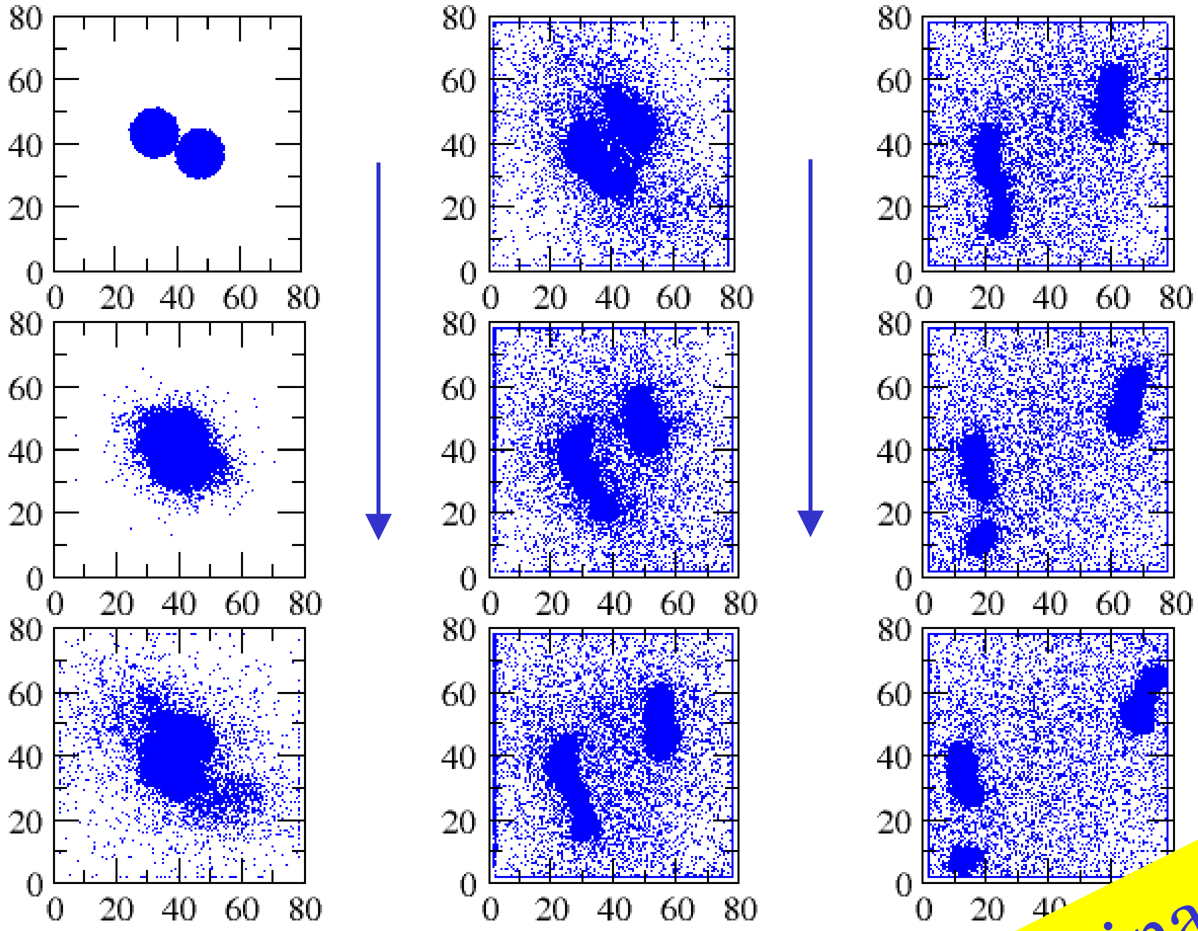




SMF calculations

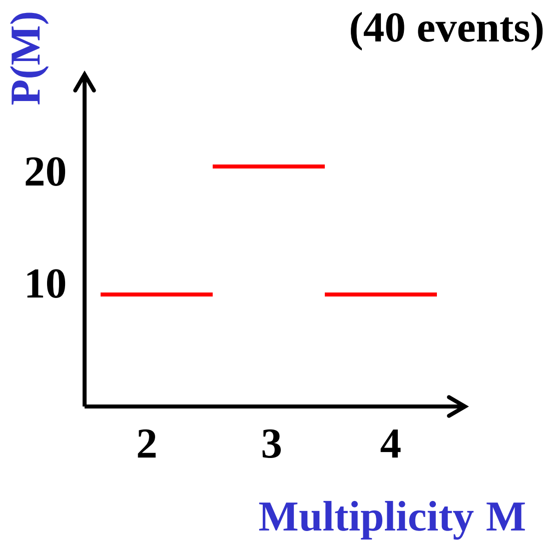
BLOB calculations

$^{197}Au + ^{197}Au$ - 23 MeV/A ***SMF calculations, b = 6 fm***



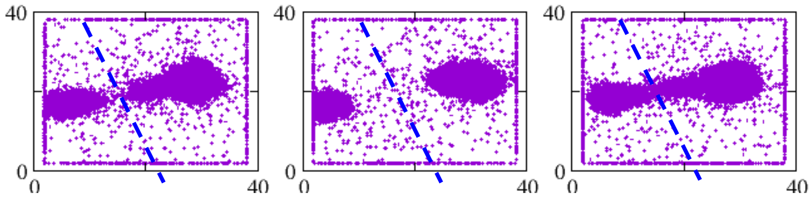
Final fragment multiplicity distribution

(40 events)



Preliminary results

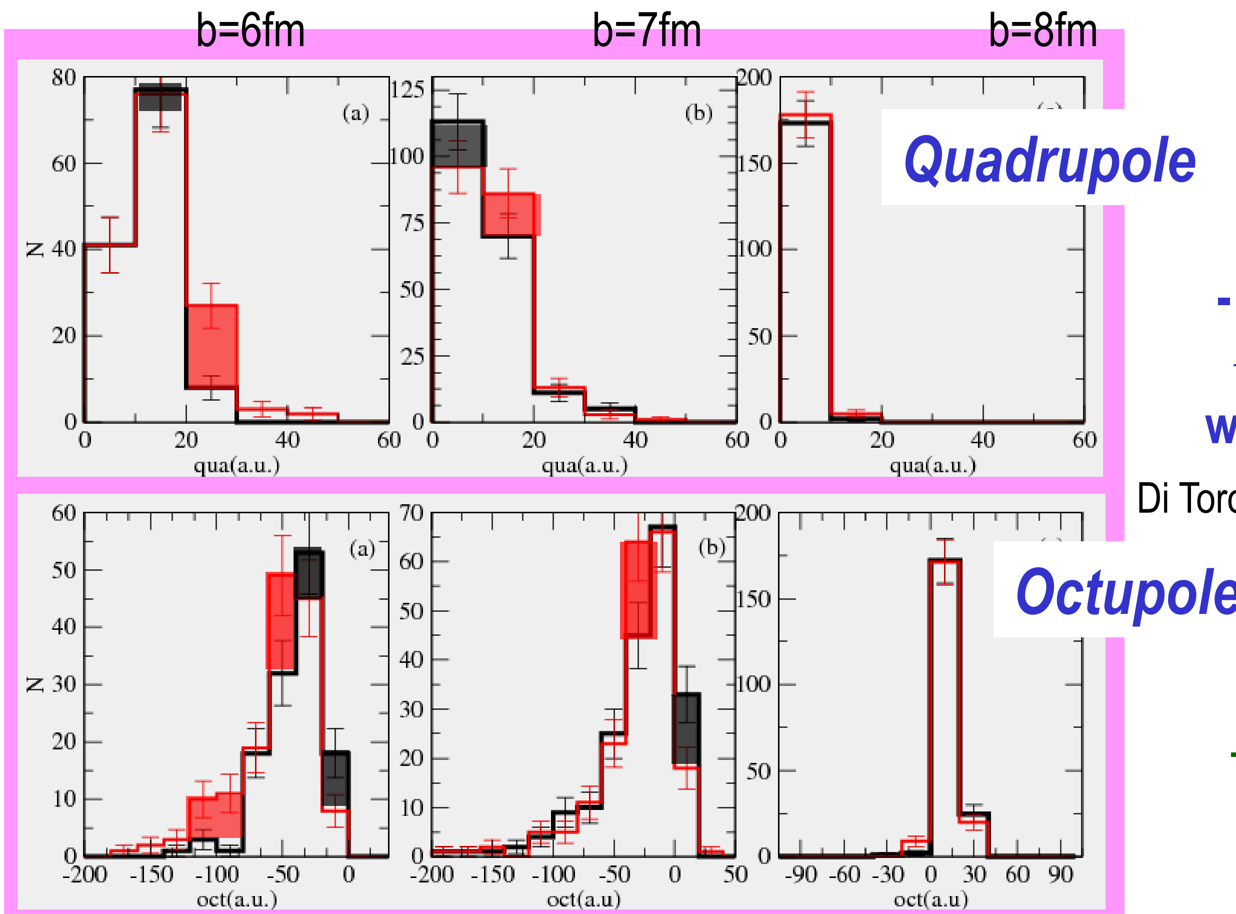
Ternary breakup in n-rich systems: Sensitivity to Esym



^{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

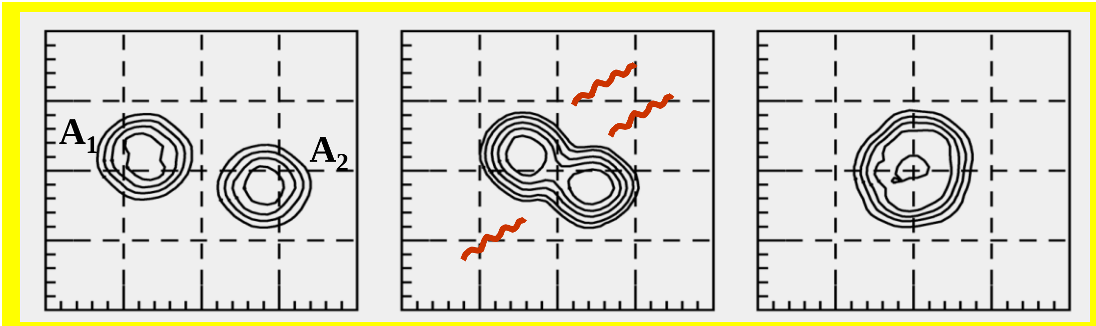
- Larger residue deformations → more ternary events with Asystiff

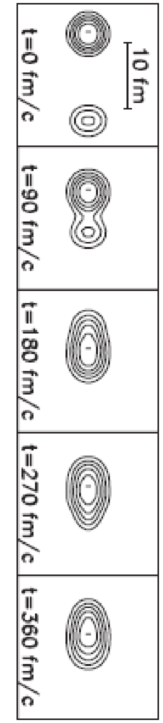
Di Toro et al., NPA 787 (2007) 585c

- A more complete analysis is in progress

Charge equilibration

➢ *Charge equilibration in fusion and D.I. collisions*





Initial Dipole **D(t) : bremss. dipole radiation** **CN: stat. GDR**

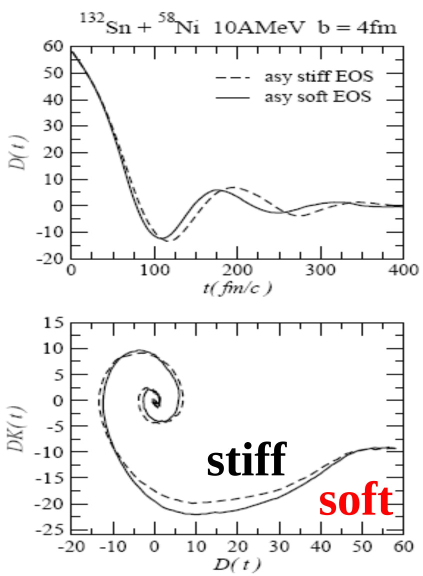
If $N_1/Z_1 \neq N_2/Z_2$

TDHF calculations

→ **Relative motion of neutron and proton centers of mass**

Simenel et al, PRC 76, 024609 (2007)

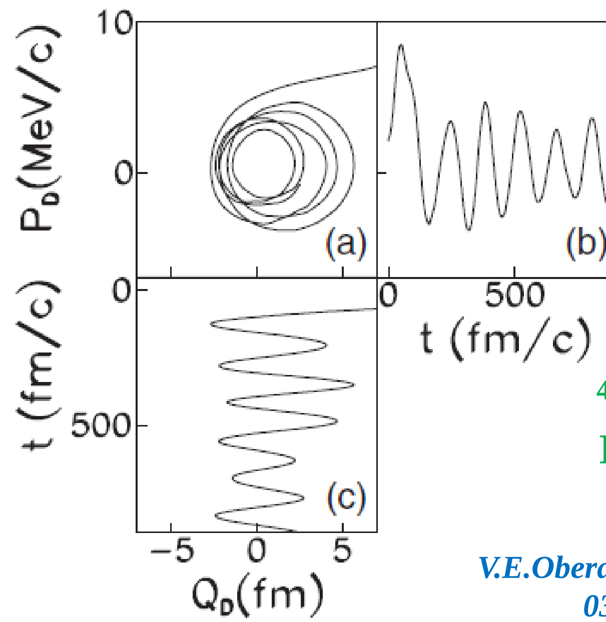
$$D(t) \equiv \frac{NZ}{A}\left[X_p(t) - X_n(t)\right] \rightarrow X_{p,n} \equiv \frac{1}{Z,N}\Sigma x_i^{p,n}$$



SMF simulations

^{132}Sn + ^{58}Ni , D_0 = 45 fm
E/A = 10 MeV

C.Rizzo et al., PRC 83, 014604 (2011)

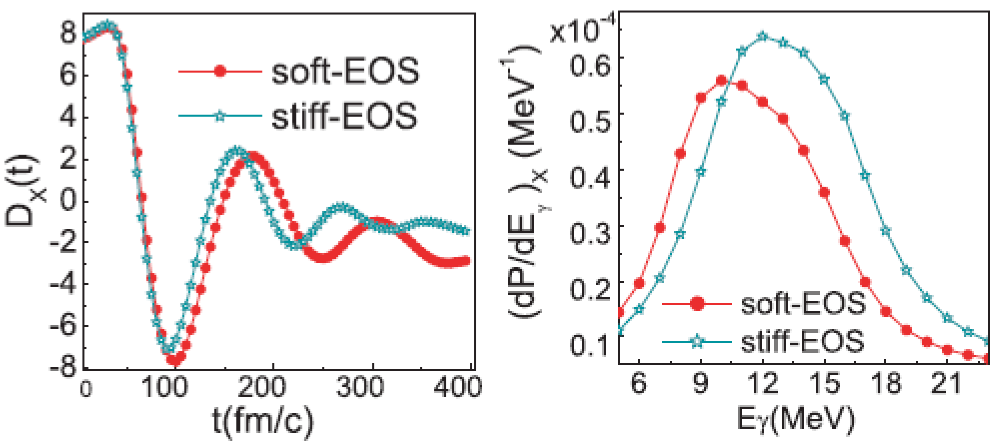


^{40}Ca + ^{100}Mo
E/A = 4 MeV

V.E.Oberacker et al., PRC 85, 034609 (2012)

Dynamical dipole (DD) emission: a 'robust' collective mechanism

PHYSICAL REVIEW C **81**, 047602 (2010)



Bremsstrahlung: Quantitative estimation

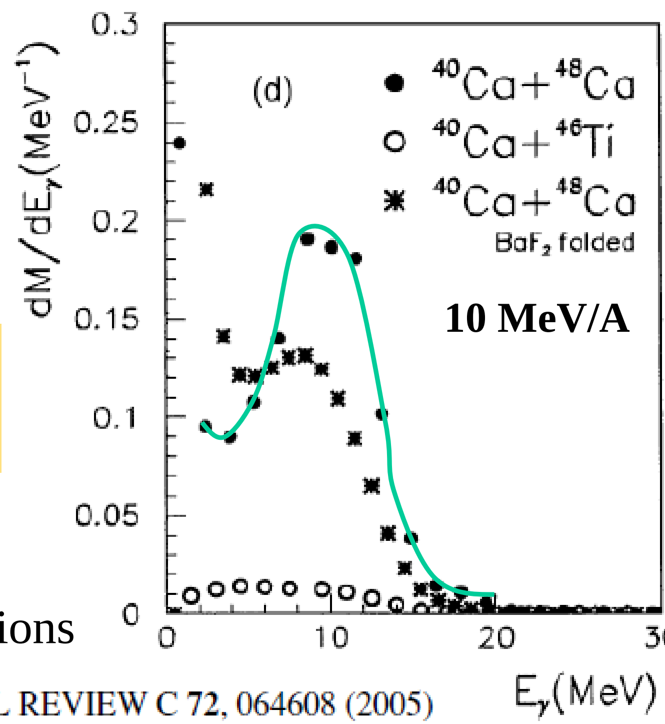
V.Baran, D.M.Brink, M.Colonna, M.Di Toro, PRL.87 (2001)

$$\frac{dP}{dE_\gamma} = \frac{2e^2}{3\pi\hbar c^3 E_\gamma}\left(\frac{NZ}{A}\right)^2 \left|X''(\omega)\right|^2$$

H.L.Wu et al. , **Isospin dependent (ID) QMD model**

$^{40}Ca + {}^{48}Ca$, E_{beam} = 10 MeV/A, b = 4 fm

➢ The dipole mechanism is clearly observed also In Molecular Dynamics calculations



M. Papa et al., **CoMD model**

LNS experiment - binary collisions

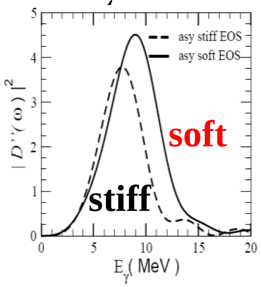
PHYSICAL REVIEW C **72**, 064608 (2005)

Dynamical dipole (DD) emission and symmetry energy

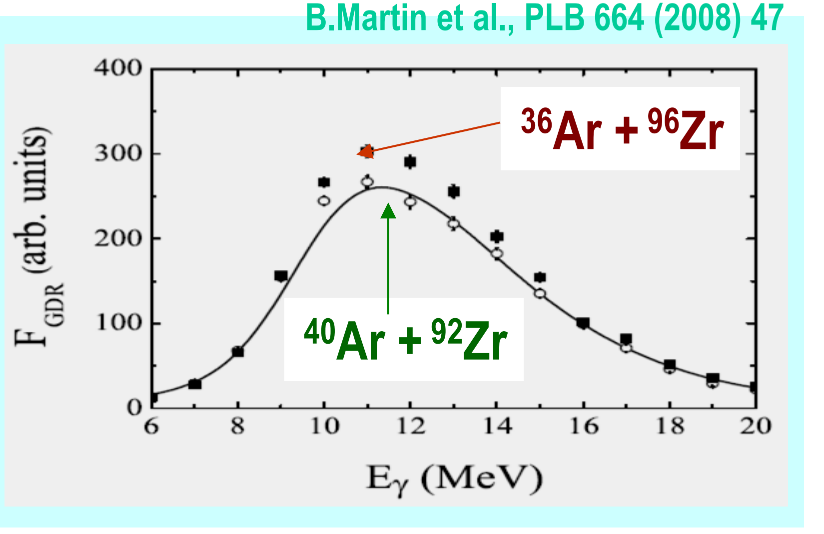
Bremsstrahlung: Quantitative estimation

V.Baran, D.M.Brink, M.Colonna, M.Di Toro, PRL.87 (2001)

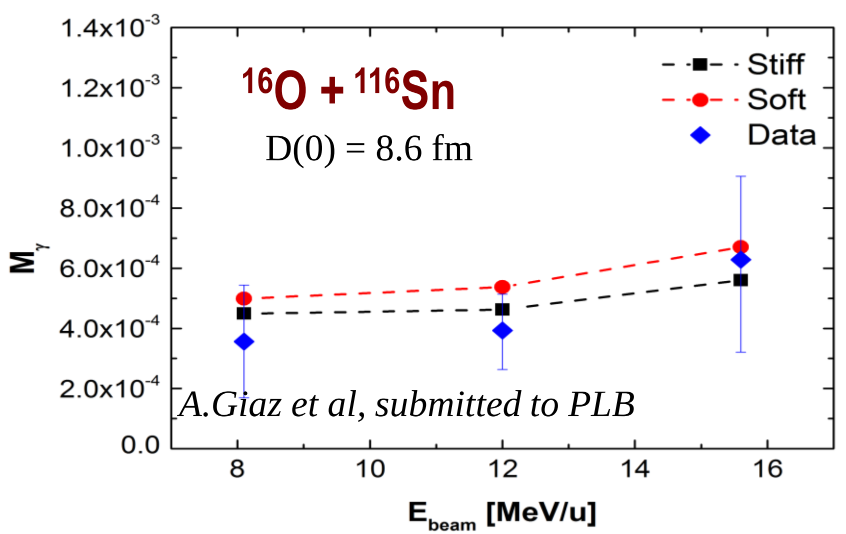
$$\frac{dP}{dE_\gamma} = \frac{2e^2}{3\pi\hbar c^3 E_\gamma}\left(\frac{NZ}{A}\right)^2 \left|X''(\omega)\right|^2$$



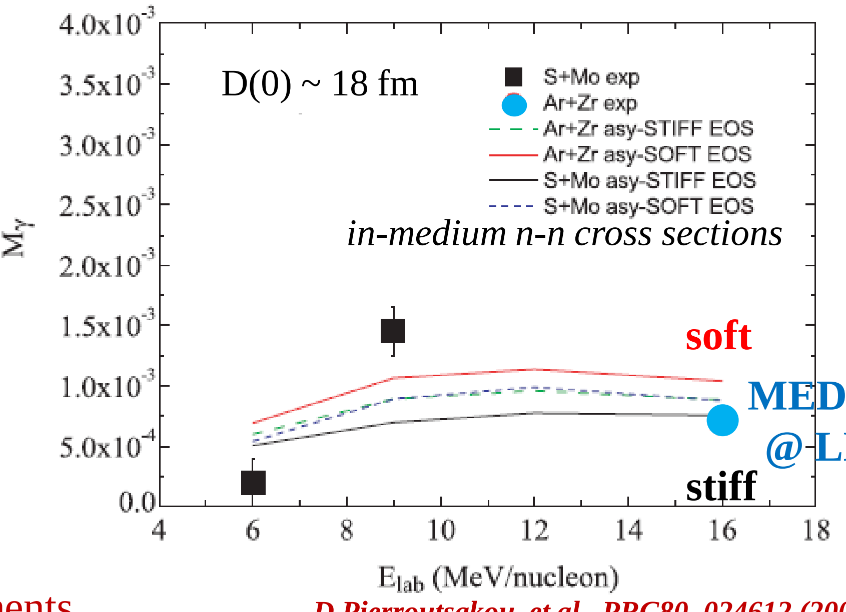
B.Martin et al., PLB 664 (2008) 47



Experimental evidence of the extra-yield (LNL & LNS data)



A.Corsi et al., PLB 679, 197 (2009), LNL experiments

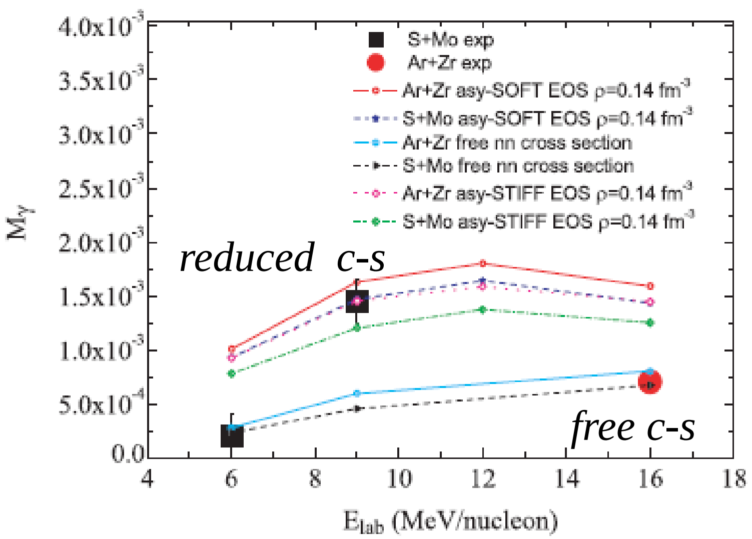


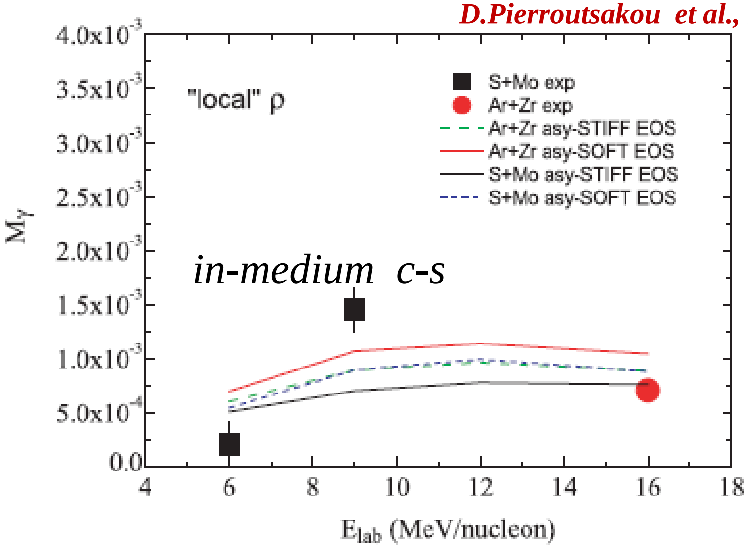
MEDEA @LNS

D.Pierroutsakou et al., PRC80, 024612 (2009)

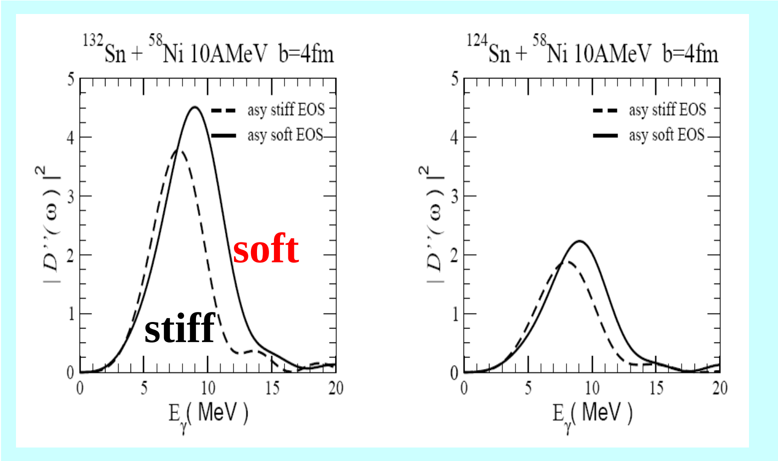
Dynamical dipole (DD) emission: sensitivity to n-n cross-section (c-s)

D.Pierroutsakou et al., PRC80, 024612 (2009)





- *1) Important to check and fix the n-n cross section* ⟶ **pre-equilibrium particle emission**
- *2) Enhance the sensitivity to symmetry potential (S_0,L)* ⟶ **reactions with large D(0)**



asy-soft ⟶
larger symmetry energy,
Bigger DD (30 % larger than asy-stiff !)

$5.7\ 10^{-3}$ vs. $4.4\ 10^{-3}$ for Mγ

Sensitivity to *EOS* may become larger than exp. error bars

$^{132}Sn + ^{58}Ni$, D_0 = 45 fm **$^{124}Sn + ^{58}Ni$, D_0 = 33 fm**

V. Baran et al., PRC79, 021603(R) (2009)

❑ Conclusions

Reactions with n-rich systems open the opportunity to learn about fundamental properties of the nuclear effective interaction, of interest also in the astrophysical context

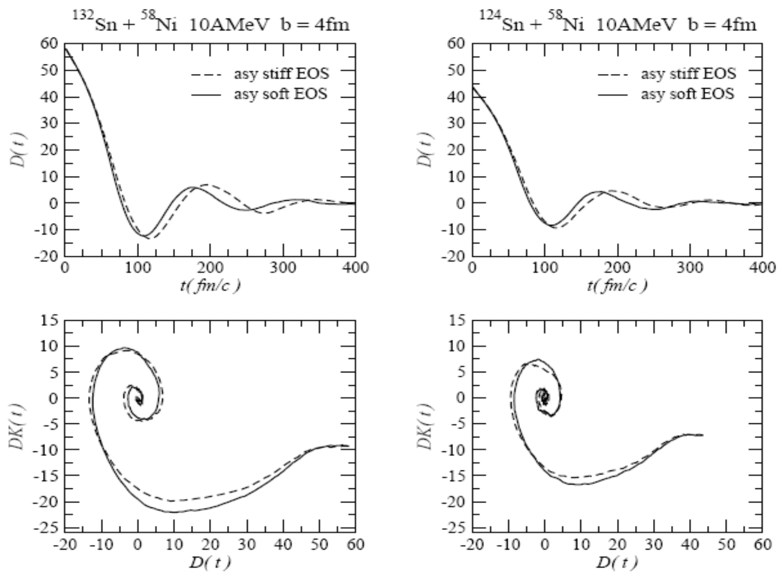
➢ Low energy collisions:
Reaction mechanisms at the borderline with nuclear structure

-Pre-equilibrium dipole oscillations (role of symmetry energy)
-Competition between reaction mechanisms (n-rich neck dynamics)

Collaborators: V.Baran (NIPNE HH,Bucharest)
M.Di Toro, **C.Rizzo** (LNS, Catania)
P.Napolitani (IPN, Orsay)

Abstract. The dynamical dipole mode was investigated in the mass region of the ^{192}Pb compound nucleus, by using the ^{40}Ca + ^{152}Sm and ^{48}Ca + ^{144}Sm reactions at E_{lab}=11 and 10.1 MeV/nucleon, respectively. Both fusion–evaporation and fission events were studied simultaneously for the first time. Our results show that the dynamical dipole mode survives in reactions involving heavier nuclei than those studied previously, however, its yield is lower than that expected within BNV calculations.

Dynamical dipole emission in very n-rich systems



^{132}Sn + ^{58}Ni , D_0 = 45 fm

^{124}Sn + ^{58}Ni, D_0 = 33 fm

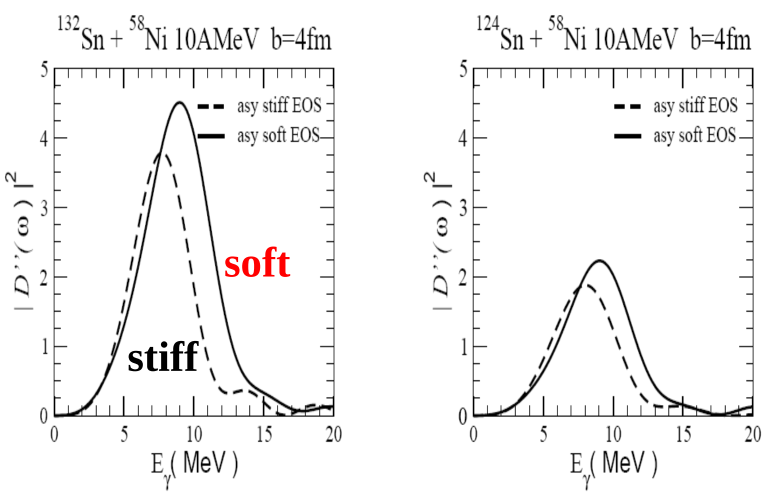
See LoI's by Pierroutsakou and Casini

$$D(t) \equiv \frac{NZ}{A}\left[X_p(t) - X_n(t)\right] \rightarrow X_{p,n} \equiv \frac{1}{Z,N}\Sigma x_i^{p,n}$$

$$DK(t) \equiv P_p - P_n \rightarrow P_{p,n} \equiv \frac{1}{Z,N}\Sigma p_i^{p,n}$$

$$[D, DK] = i\hbar$$

$$\frac{dP}{dE_\gamma} = \frac{2e^2}{3\pi\hbar c^3 E_\gamma}\left(\frac{NZ}{A}\right)^2 \left|X''(\omega)\right|^2$$



Asysoft →
larger symmetry energy,
Bigger DD (30 % larger than Asystiff !)

5.7 10^{-3} vs. 4.4 10^{-3} for Mγ

→ Sensitivity to EOS may become larger than exp. error bars

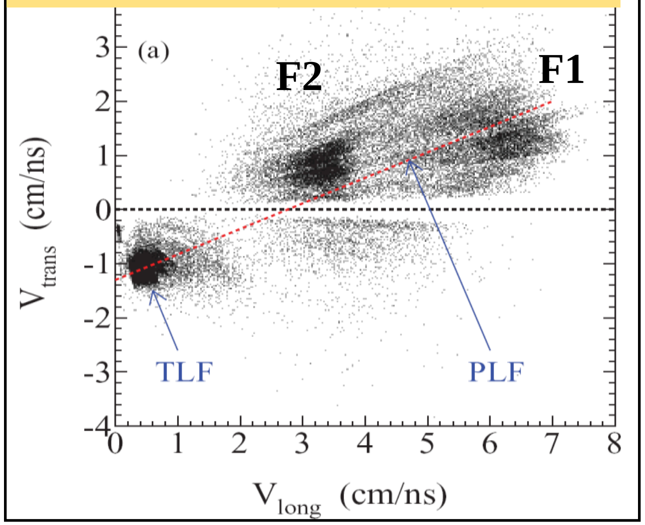
V. Baran et al., PRC79, 021603(R) (2009)

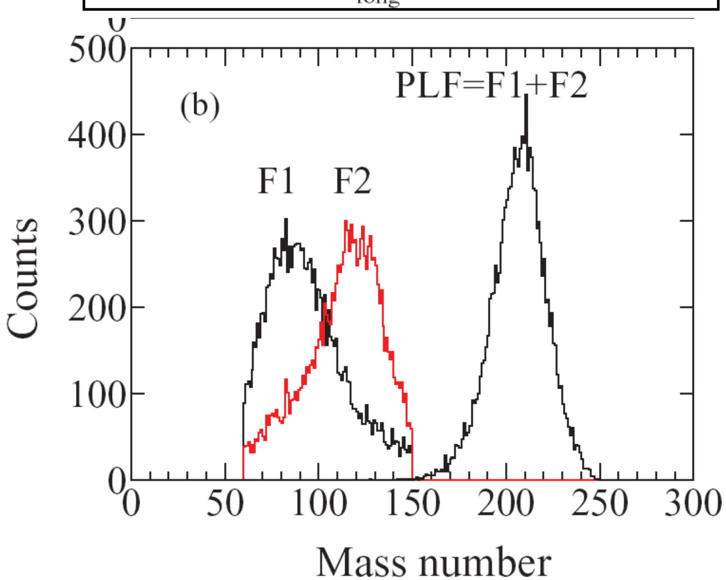
➢ Ternary break-up: emission direction

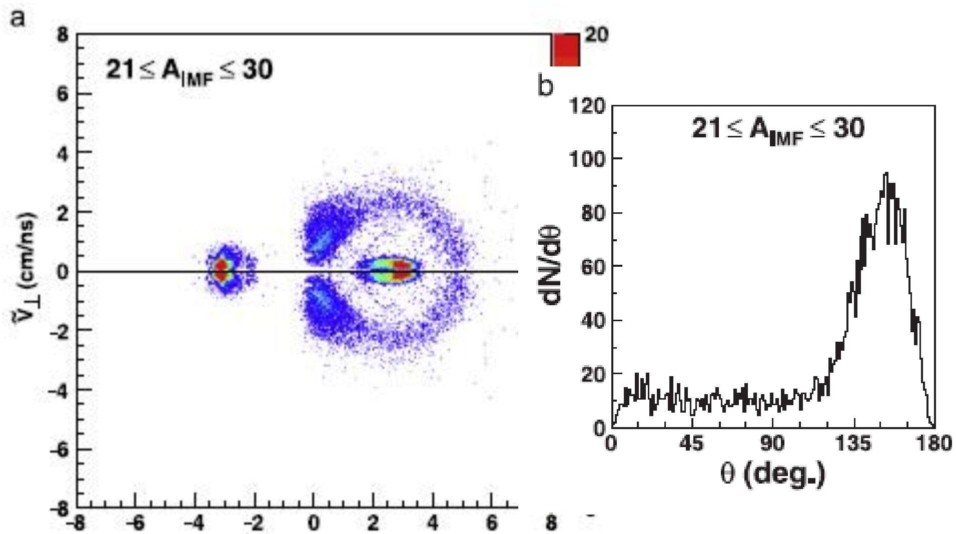
15 MeV/A - PRC 81, 024605 (2010)

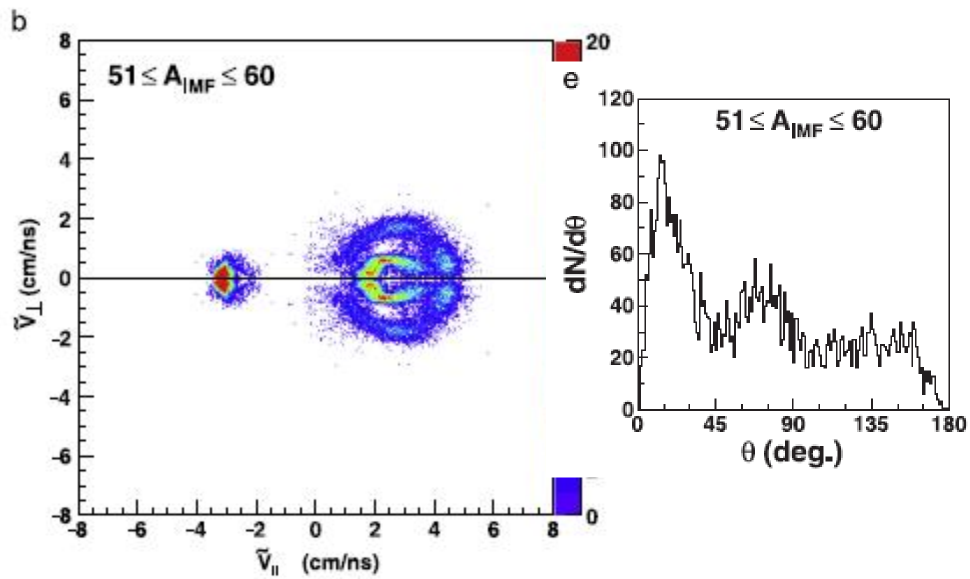
23 MeV/A - T. Cap et al., Phys. Scr. 89 (2014) 054005

Preferential emission direction



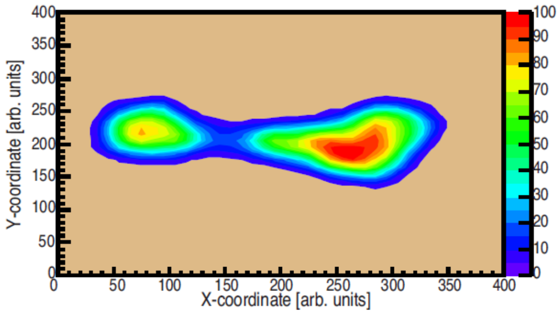


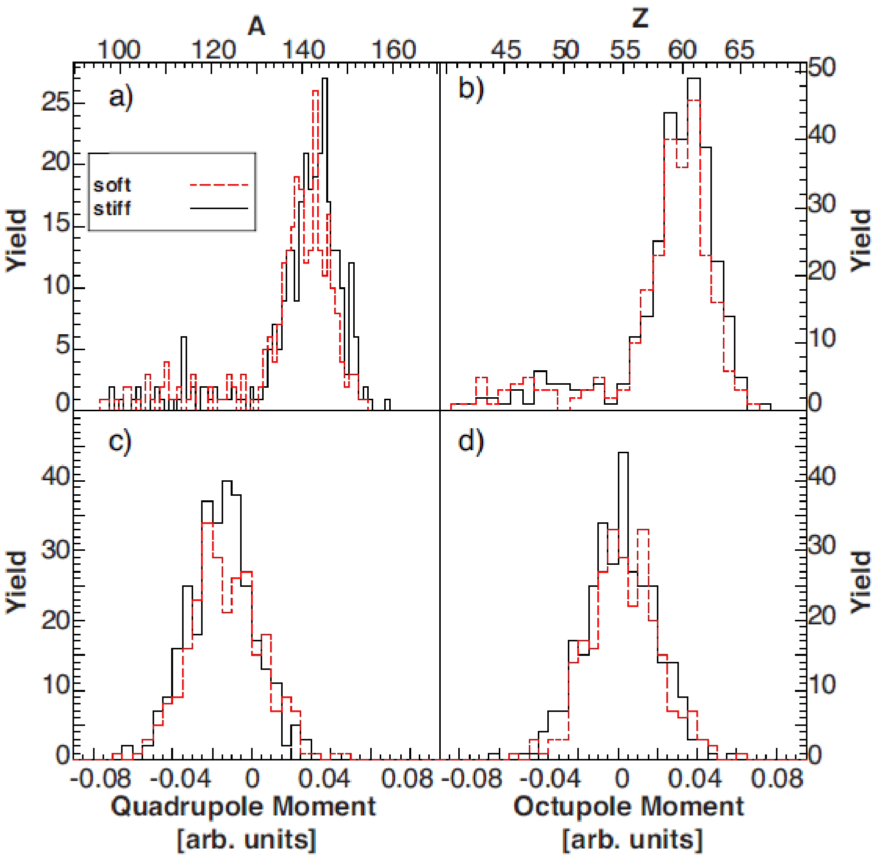


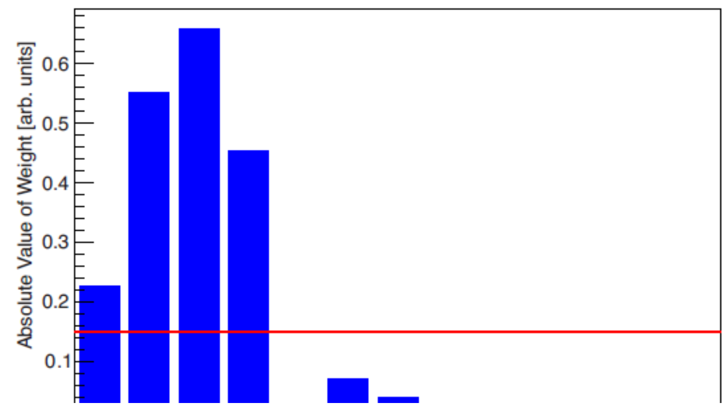


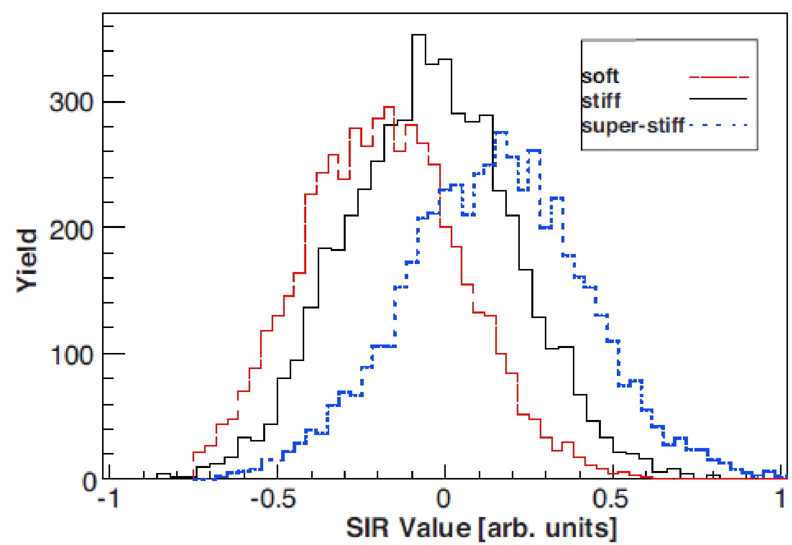
➢ Ternary breakup in n-rich systems: Sensitivity to Esym & Multidimensional Analysis

^{124}Sn + ^{64}Ni , E/A = 15 MeV, b = 6-8 fm









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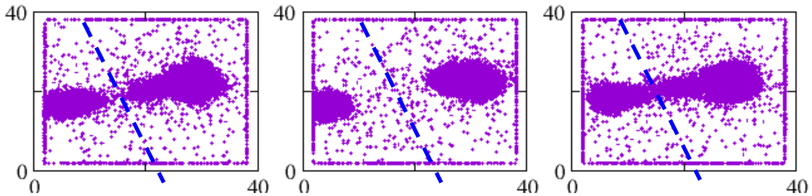
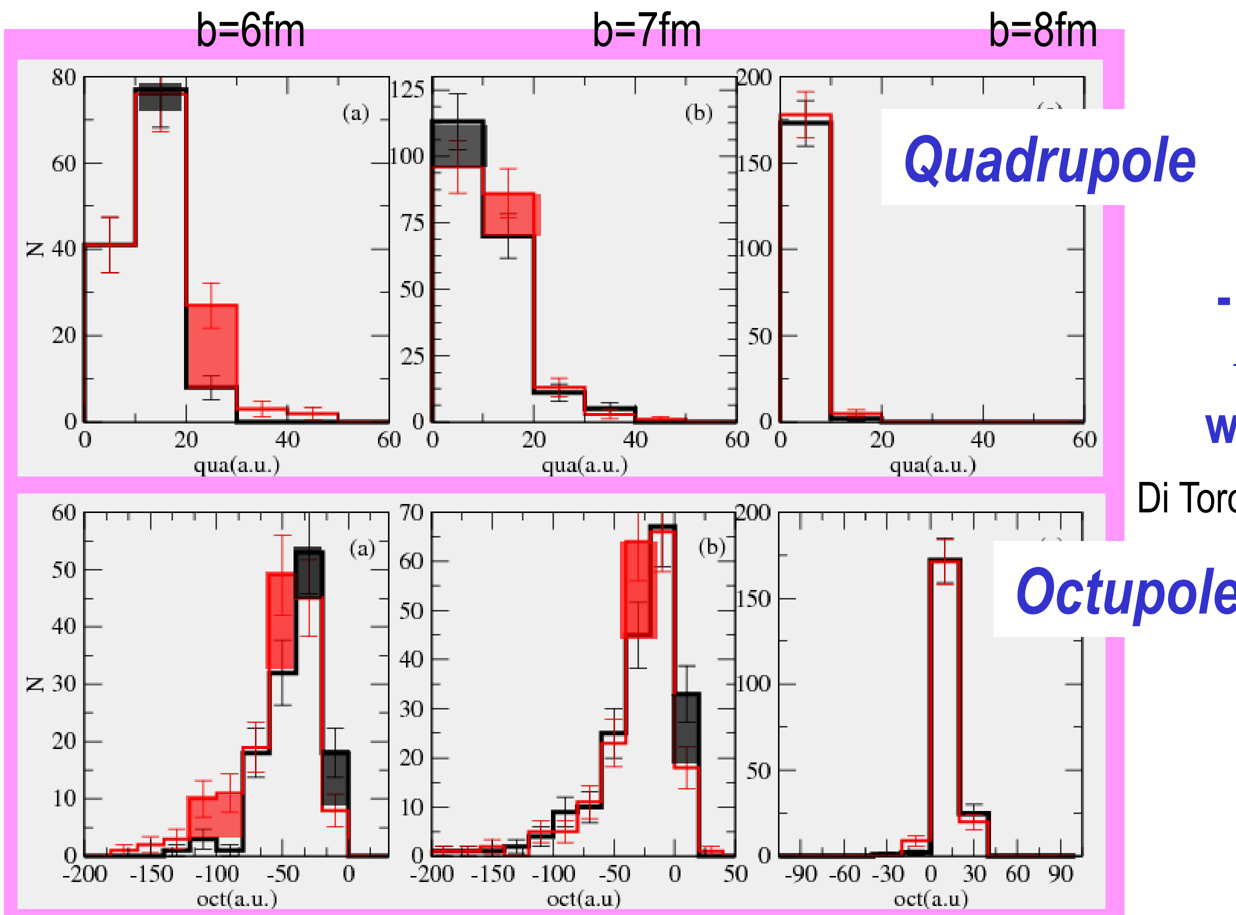
P.Cammarata et al., Texas A&M, to appear in NIMA

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.

Dynamics of many-body systems

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

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

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

one-body

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

Mean-field ***Residual interaction***

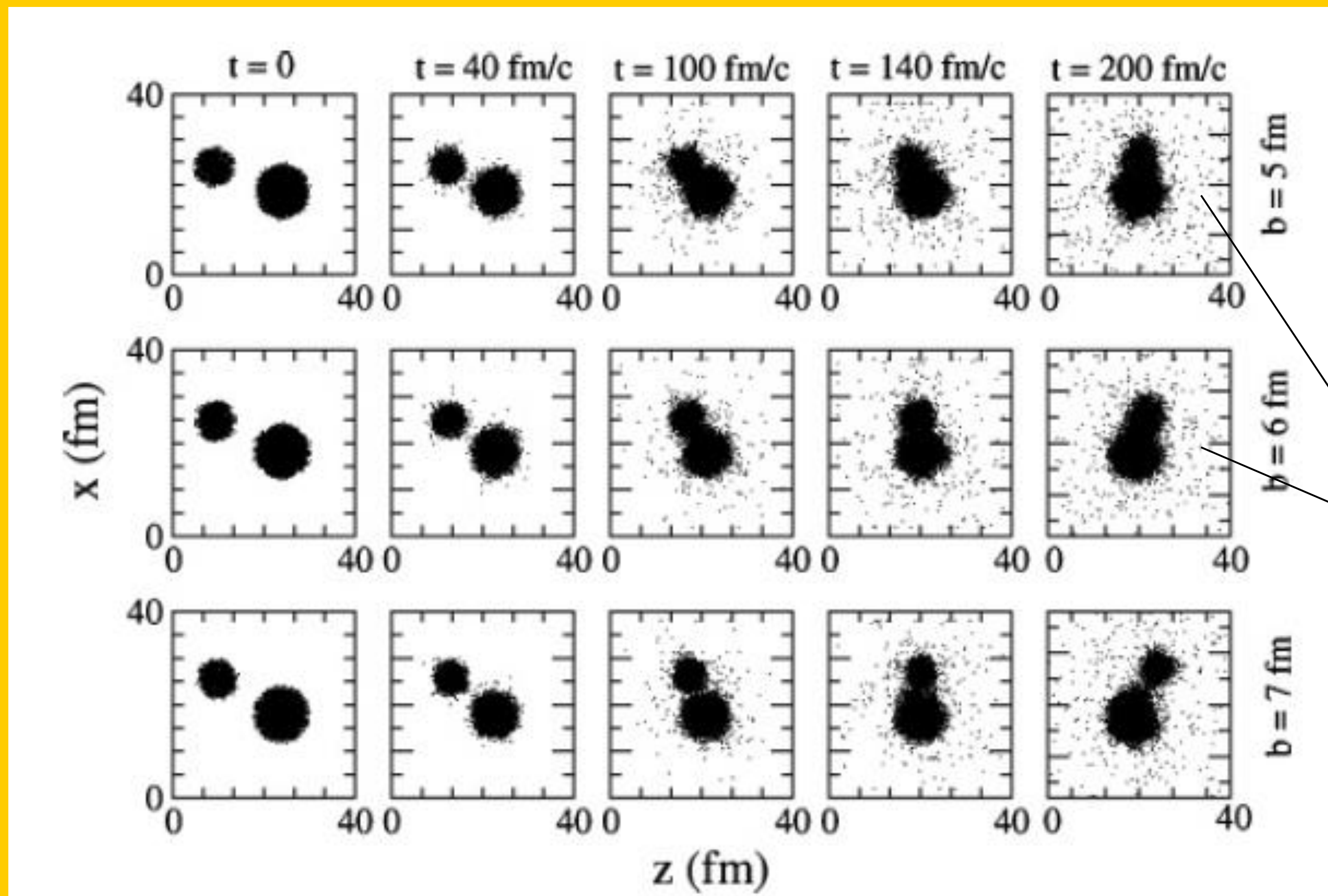
$$i\hbar \frac{\partial}{\partial t}\rho_1(1,1',t) = \langle 1 | [H_0, \rho_1(t)] | 1' \rangle + K[\rho_1] + \delta K[\rho_1, \delta\sigma]$$

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*

Competition between reaction mechanisms: fusion vs deep-inelastic



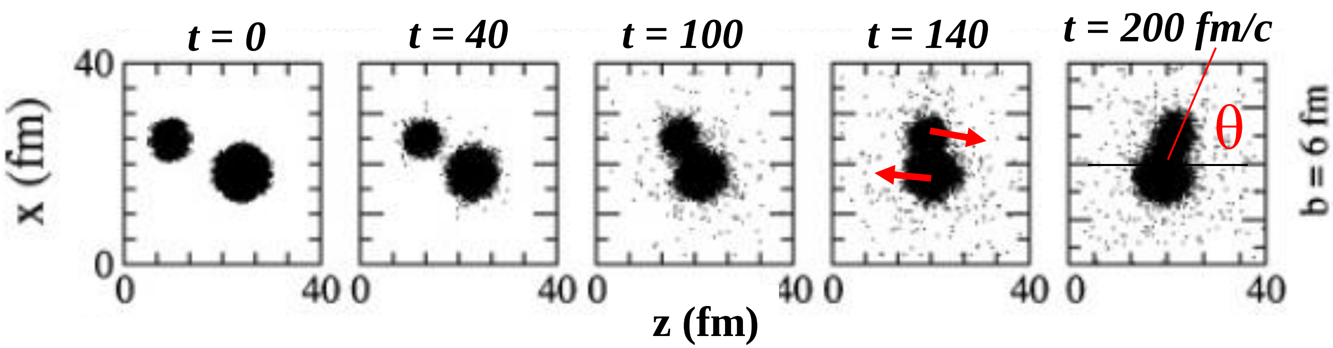
^{36}Ar + ^{96}Zr ,
E/A = 9 MeV

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



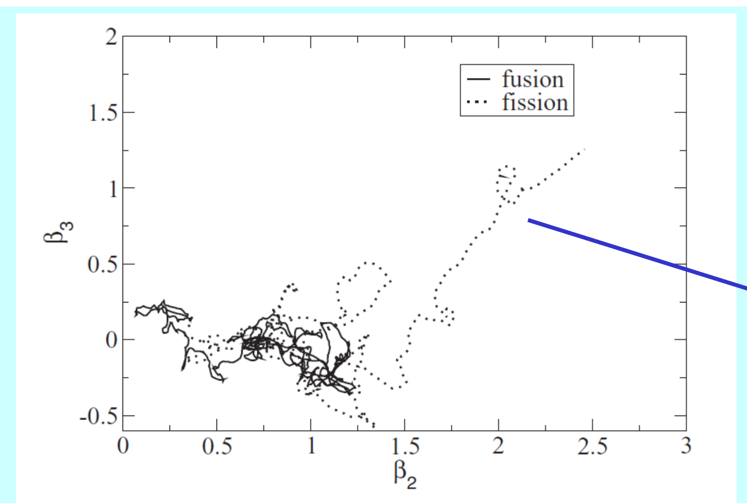
$^{36}Ar + ^{96}Zr$,
E/A = 9 MeV,
b = 6 fm

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**

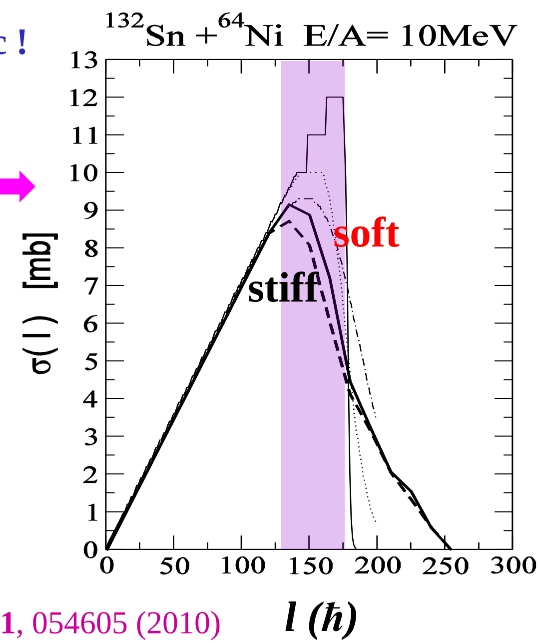
Break-up times of the order of 500-1000 fm/c !

Examples of trajectories



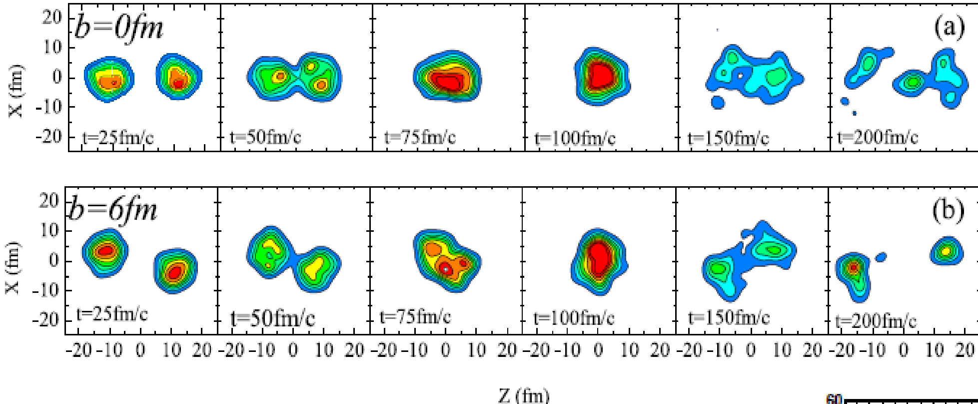
Break-up configurations

Extract the fusion cross section

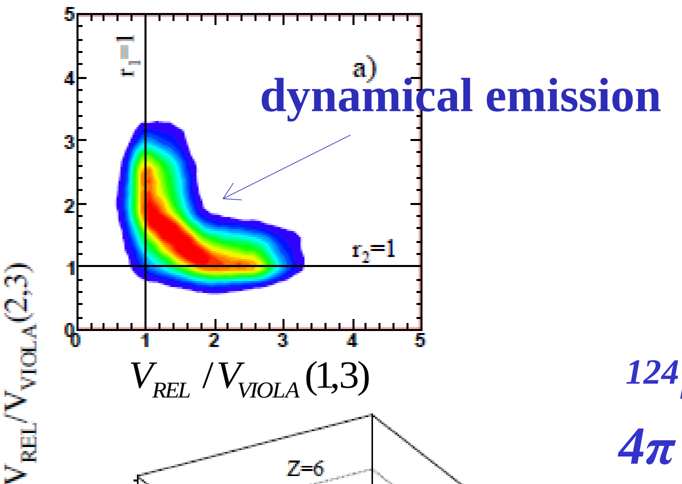


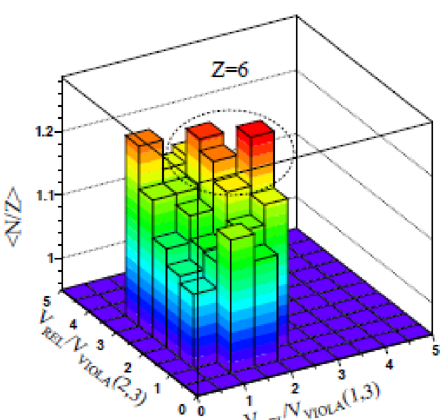
Shvedov, Colonna, Di Toro, PRC **81**, 054605 (2010)

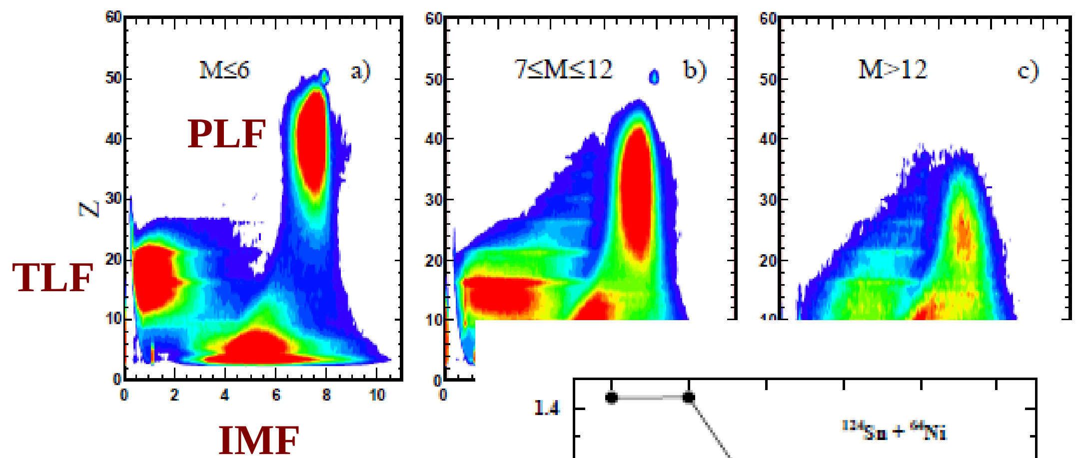
Fragmentation mechanisms at Fermi energies



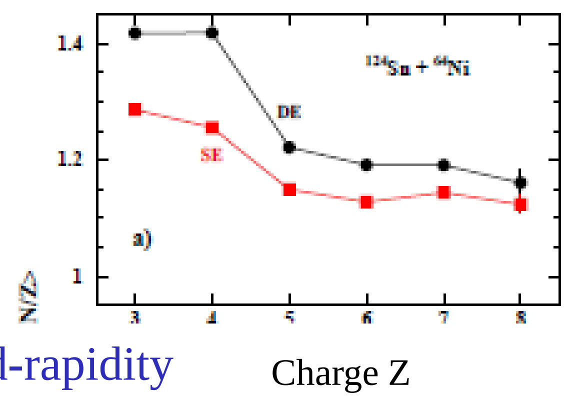
Y.Zhang et al., PRC(2011)







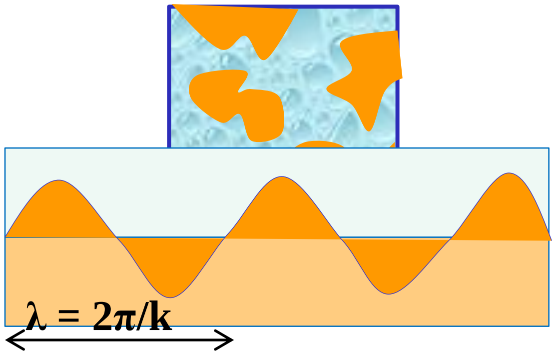
^{124}Sn + ^{64}Ni 35 AMeV:
4π CHIMERA detector



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

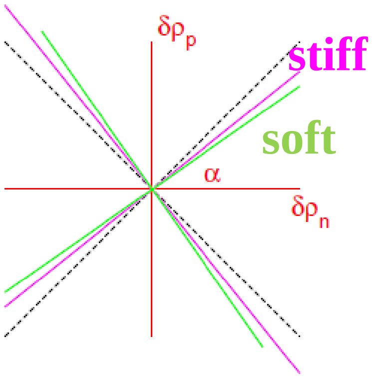
E. De Filippo et al., PRC(2012)

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

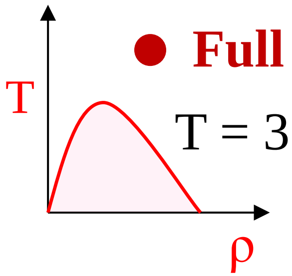
⟶ At equilibrium, according to the fluctuation-dissipation theorem

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

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

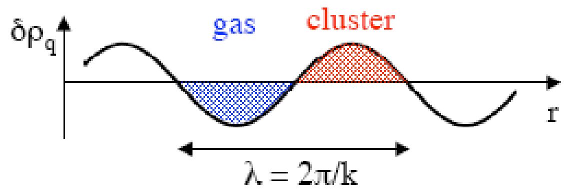


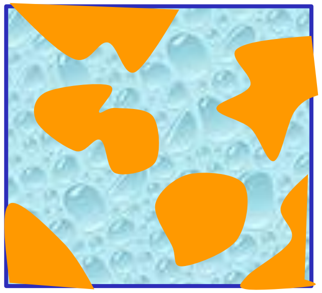
- **Full SMF simulations**

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

I = 0.14

M.Colonna, PRL,110(2013)



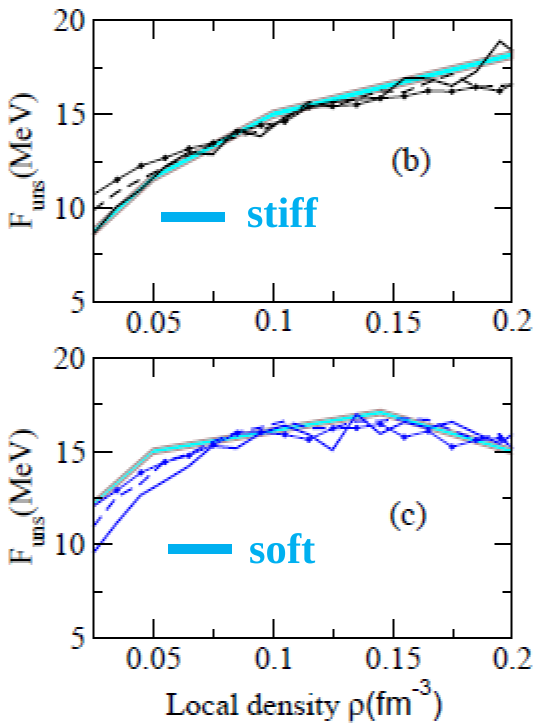


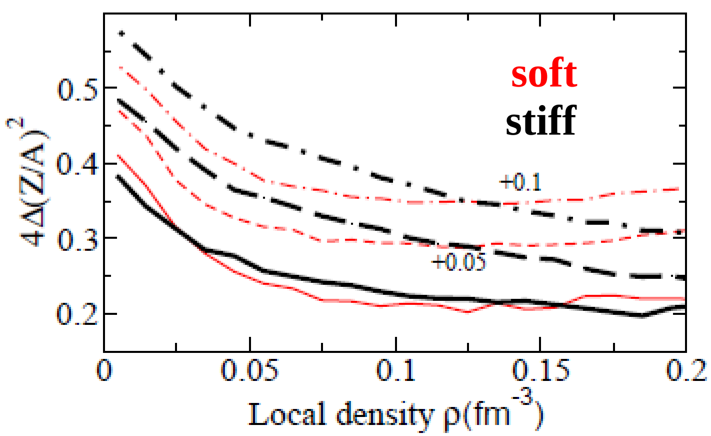
freeze-out

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

F' ~ T / σ

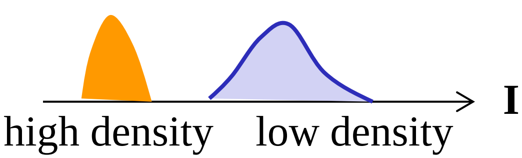
Average Z/A and isovector fluctuations
as a function of local density ρ





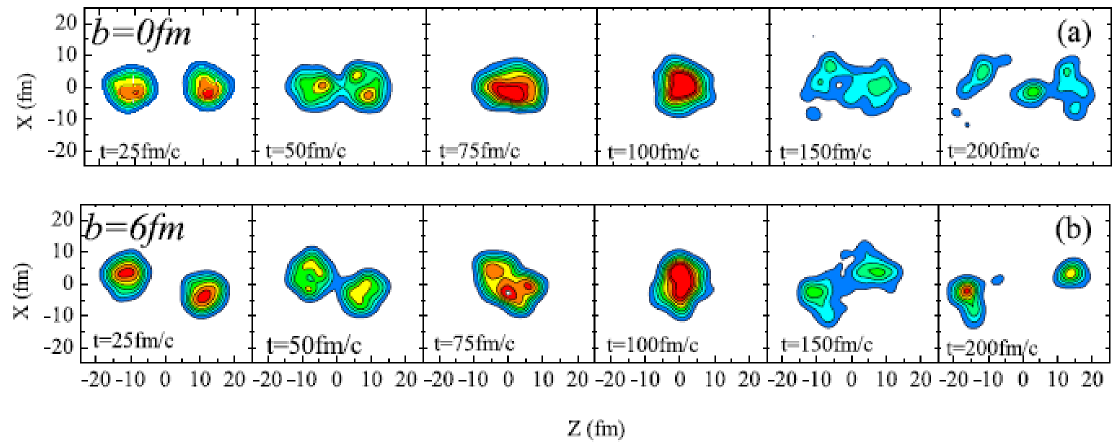
The isospin distillation effect goes together with the isovector variance

F' follows the local equilibrium value !

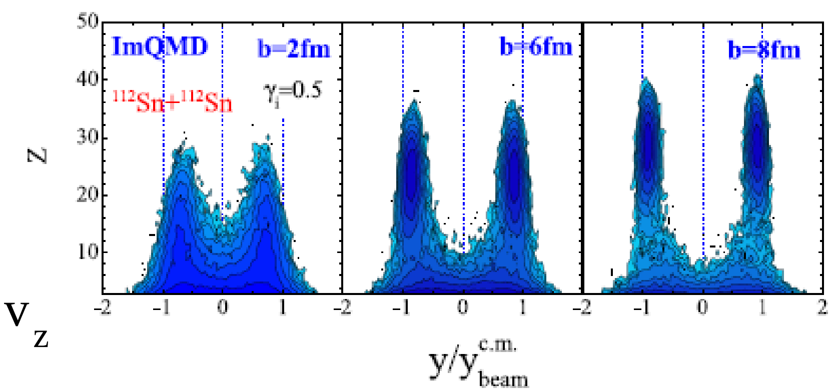


Dissipation and fragmentation in "MD" models

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



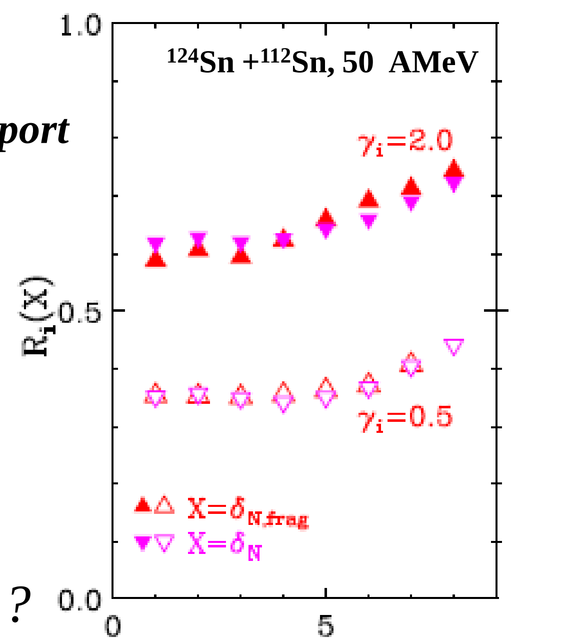
- ***More 'explosive' dynamics:***
  - *more fragments and light clusters emitted*
  - *more 'transparency'*



$y \approx v_z$

Y.Zhang et al., PRC(2011)

Isospin transport ratio R



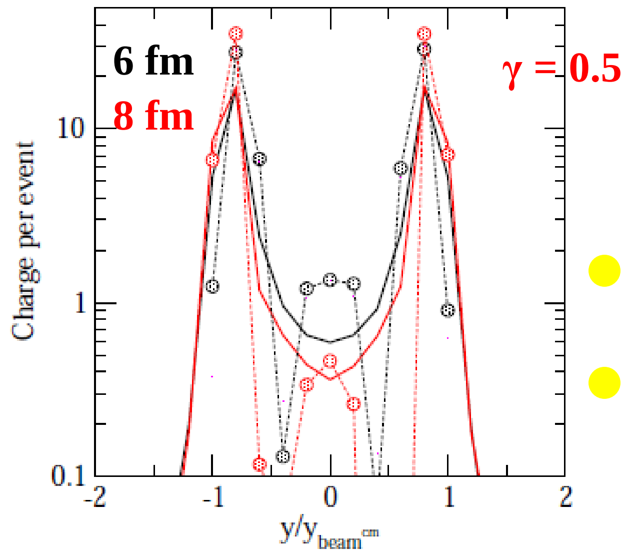
What happens to charge equilibration ?

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

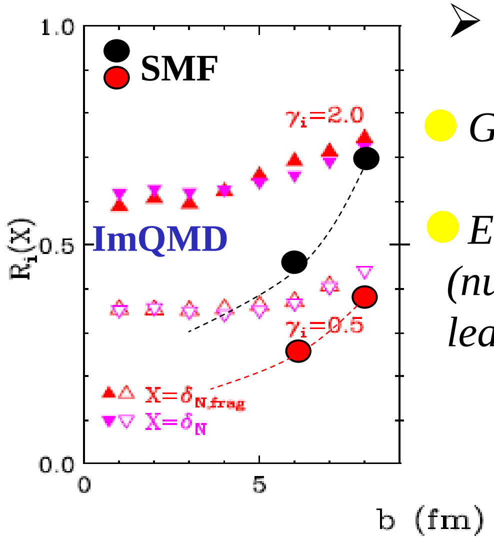


SMF = dashed lines
ImQMD = full lines

- 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

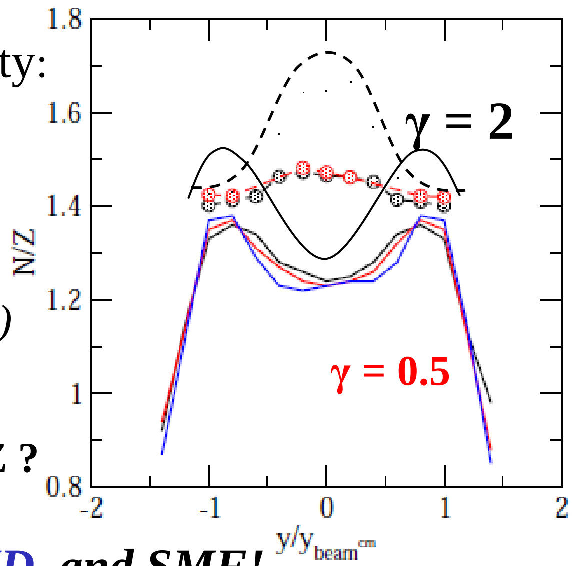


- Isospin transport R around PLF rapidity:

● *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 ?

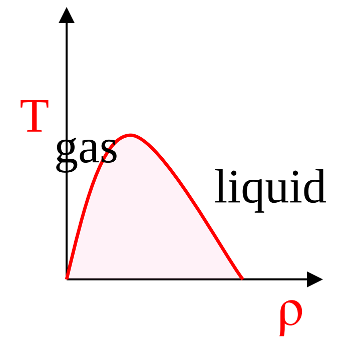


Different trends in ImQMD and SMF!

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 ?

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)

Conclusions and outlook

- **Exp-theo analyses**:
 - *Multidimensional analysis: several ingredients $\longrightarrow$ 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)