Symmetry Energy Effects in Heavy Ion Collisions at Low Energies

SPES 2010 Workshop
&
IV LEA-COLLIGA Meeting

15-19 November 2010 INFN-LNL

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

HIC at low energies (~10 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.

Transport equation for the one-body distribution function f,
Stochastic Mean Field (SMF) approach

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

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

Residual interaction: Correlations, Fluctuations

The nuclear interaction, contained in the Hamiltonian ***h***, is represented by effective interactions (Skyrme)

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

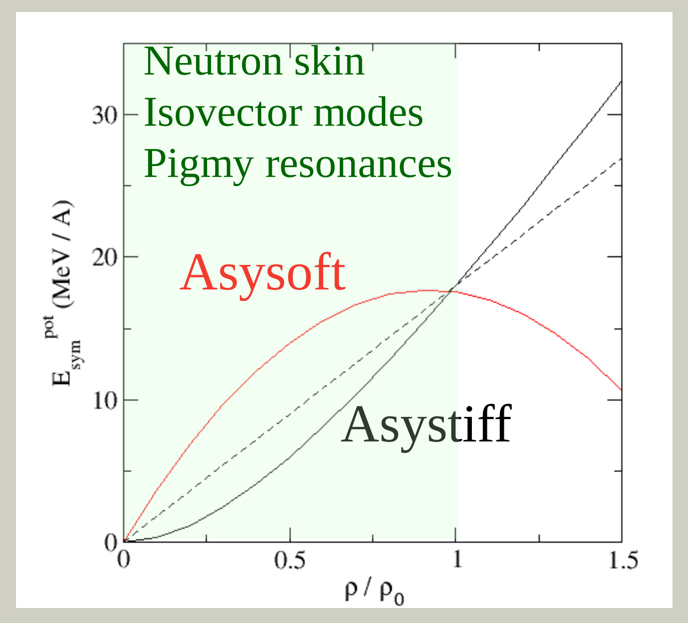
$\beta=(N-Z)/A$

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**

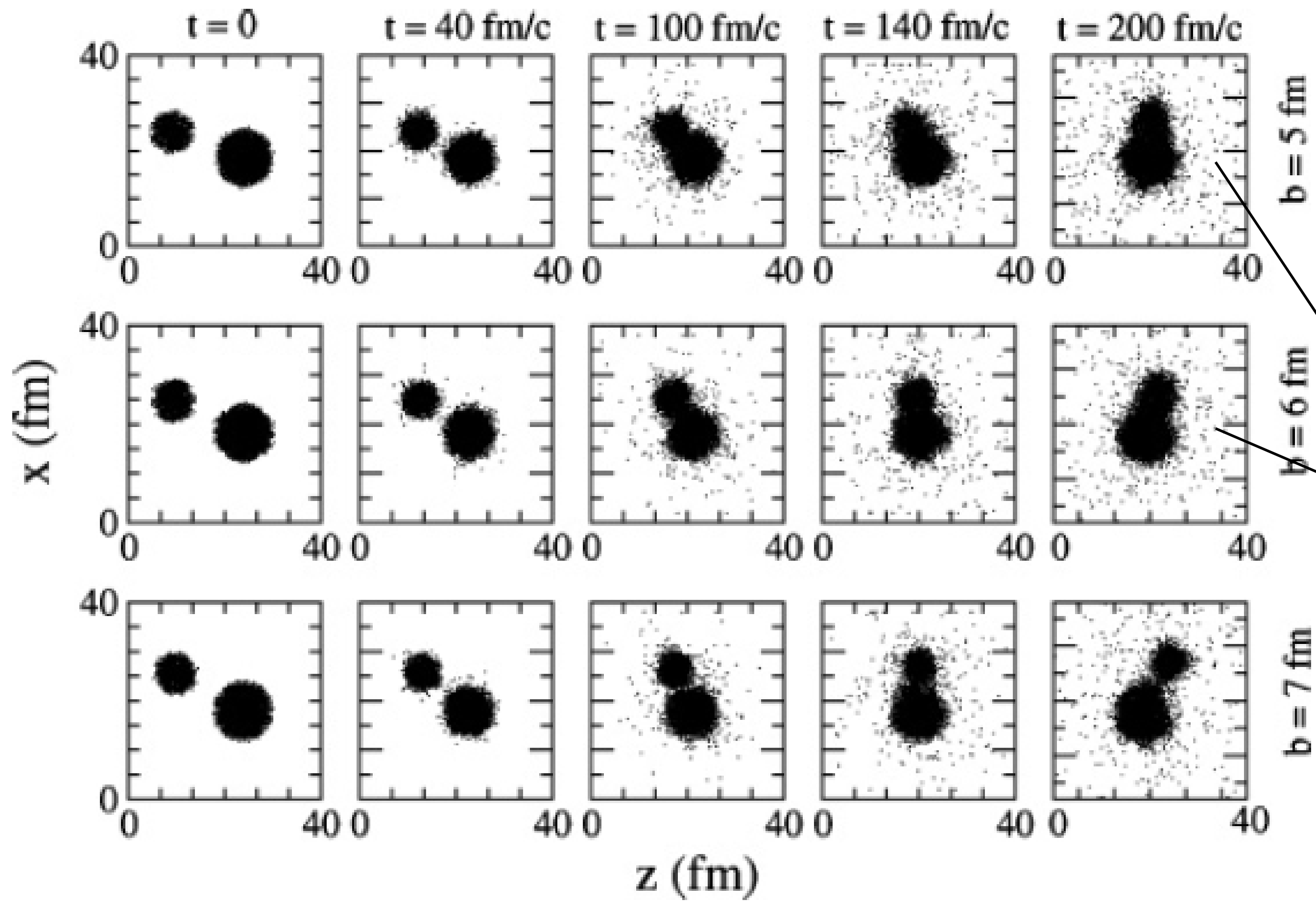
Symmetry energy



- ✓ **Investigate the sensitivity of the reaction dynamics to this ingredient**
- ✓ **Put some constraints on the effective interactions**

Competition between reaction mechanisms

Competition between reaction mechanisms: fusion vs deep-inelastic



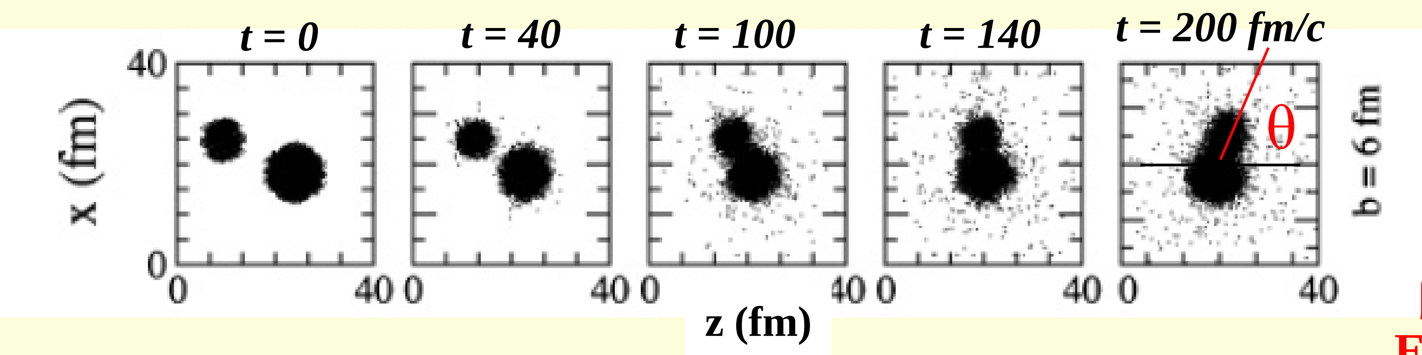
$^{36}Ar + ^{96}Zr$,
E/A = 9 MeV

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

F.Amorini et al., PRL 2009, P. Marini et al., IWM09

Competition between reaction mechanisms



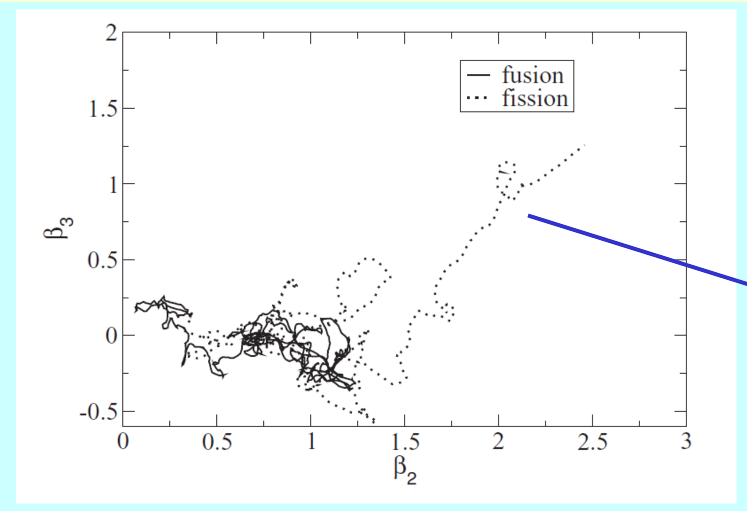
^{36}Ar + ^{96}Zr ,
E/A = 9 MeV,
b = 6 fm

β_2, β_3,
E*~250 MeV, J ~70ħ

Low energy: time scales for break-up not compatible with SMF treatment →

✓ **Starting from t = 200-300 fm/c, solve the Langevin Equation (LE) for selected degrees of freedom: β_2 (quadrupole), β_3 (octupole), θ, and related velocities**

Examples of trajectories



Break-up configurations

Break-up times are rather long, of the order of 500-1000 fm/c !

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

From the Langevin dynamics, leading parameters are quadrupole moment and angular momentum (and fluctuations)

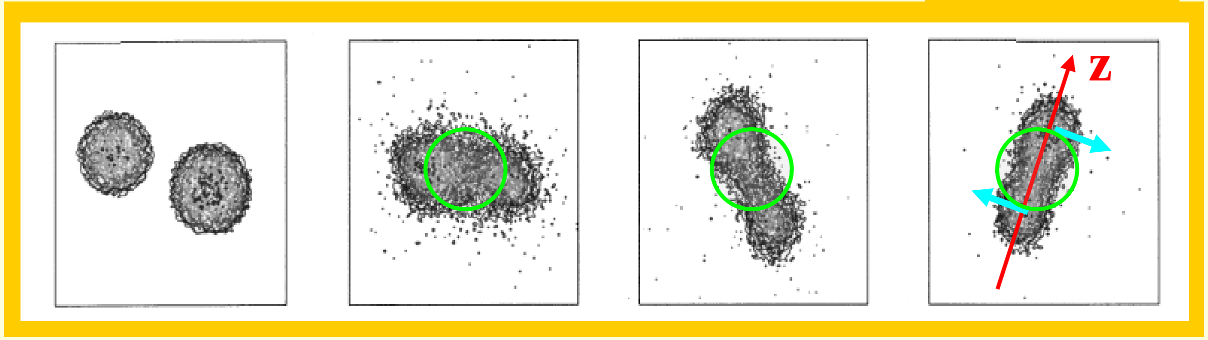
✓ We make an attempt to describe, by a new method, the reaction mechanism through a phase space shape analysis at the early stage (t ~ 300 fm/c)

Time evolution of Quadrupole moment in coordinate space:

$$Q(t) = < 2z^2(t) - x^2(t) - y^2(t) >$$

SMF calculations

t = 300 fm/c



and in momentum space in a region around the center of mass:

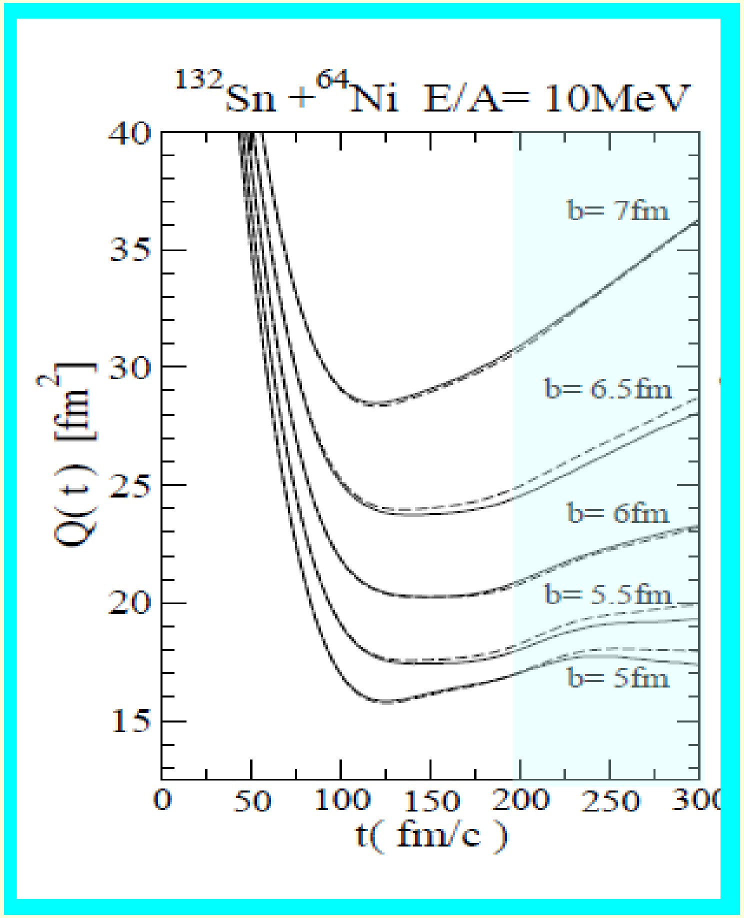
$$QK(t) = < 2p_z^2(t) - p_x^2(t) - p_y^2(t) >$$

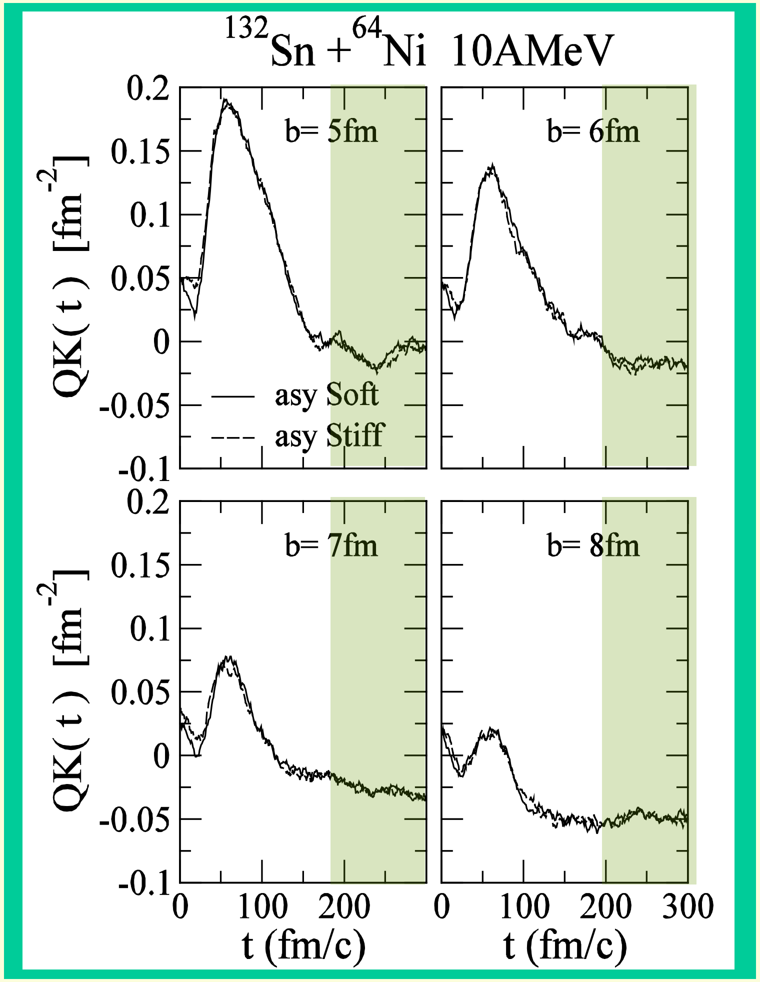
Negative QK values denote the presence of velocity components orthogonal to symmetry axis (angular momentum effect)

C.Rizzo et al., arXiv:1010.2927

There is a window of impact parameters (5-6 fm) where QK and the derivative of Q (→Q') are both close to zero, on average.

→ Fluctuations determine the fate of the reaction

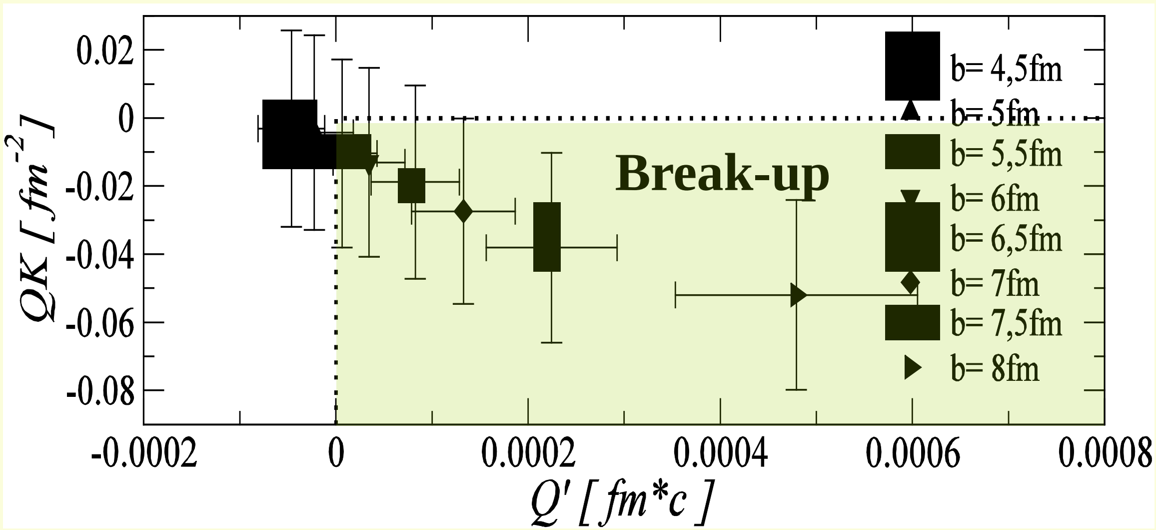




How to extract the fusion probability from the shape analysis at early times ?

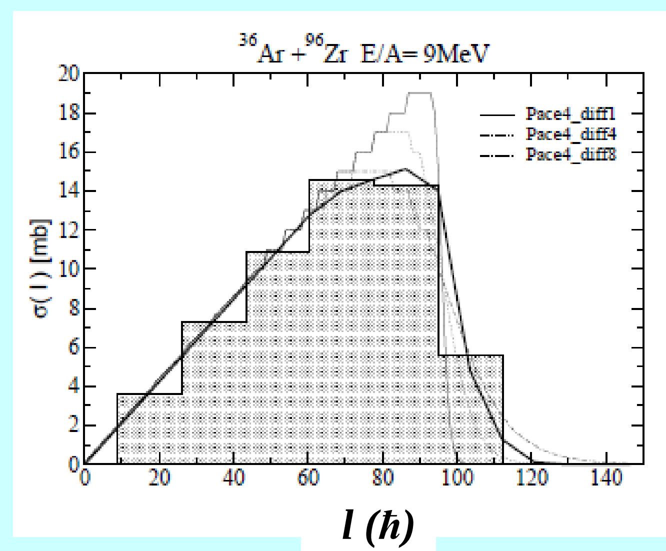
Combine the information from the two observables (Q' and QK) and select

positive Q' and negative QK for break-up.



200 runs each
per impact parameter

Extract the fusion cross section



Results for ^{36}Ar + ^{96}Zr @ 9 MeV/A

- Full line: this analysis

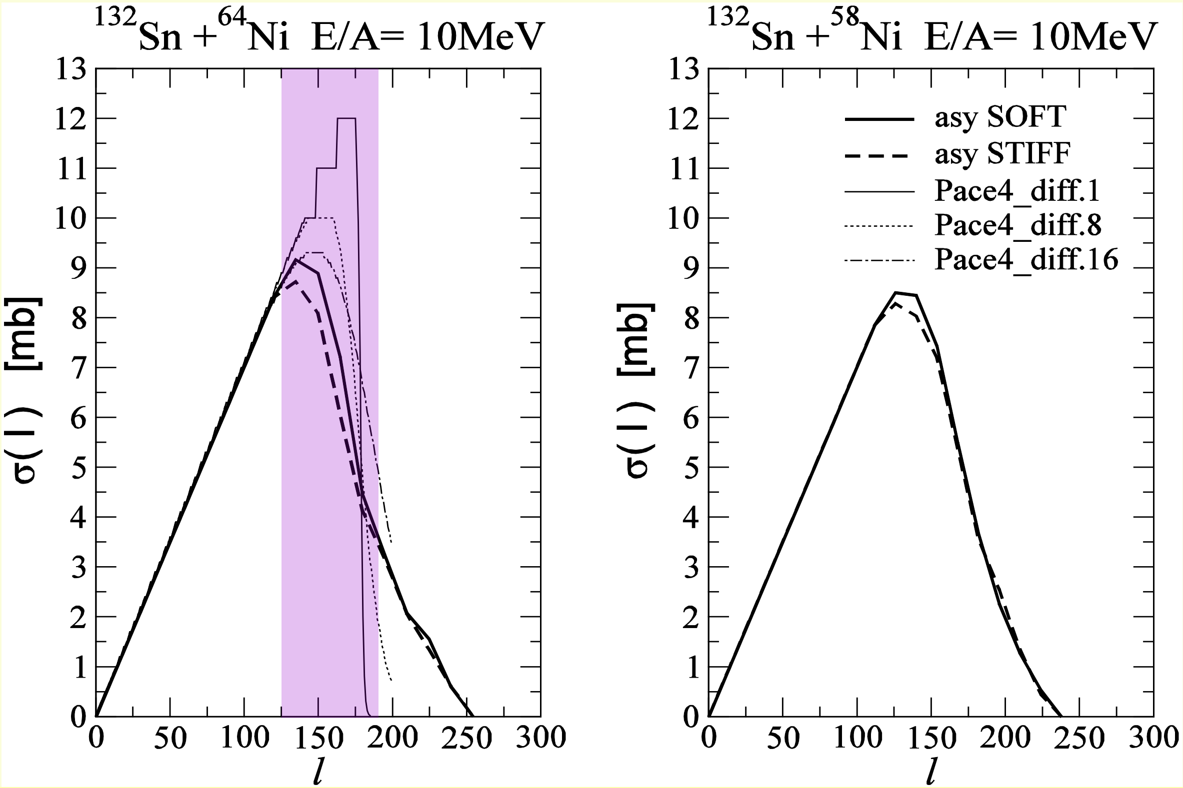
Histogram: results of the procedure based on LE

Good agreement between the two procedures !

C.Rizzo et al., arXiv:1010.2927

Isospin effects on fusion cross section:

Asysoft vs. Asystiff



- Larger fusion cross section in ^{132}Sn + ^{64}Ni (1100 mb vs. 1000 mb)

- Larger fusion cross section in the Asysoft case (10% effect in the transition region)

- Good agreement with recent data taken at ORNL (lower energy)

Pace4 calculations (fixing total cross section and max. angular momentum):

Rather large diffuseness value , $\Delta l = 16$, needed to reproduce our calculations

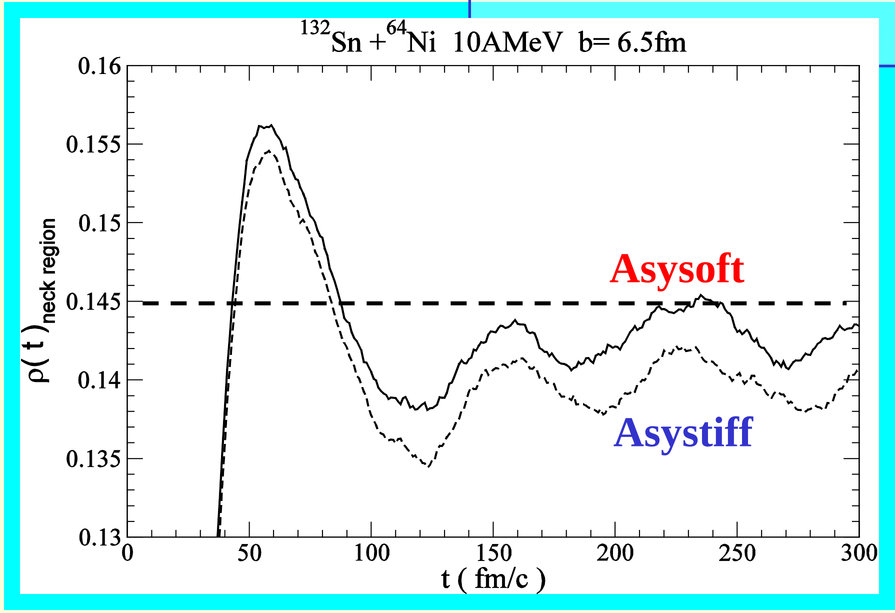
(Standard value: $\Delta l = 4$)

⟶ Evidence of neutron-skin effects

see also F.Amorini et al., PRL 2009

Analysis of symmetry energy effects:

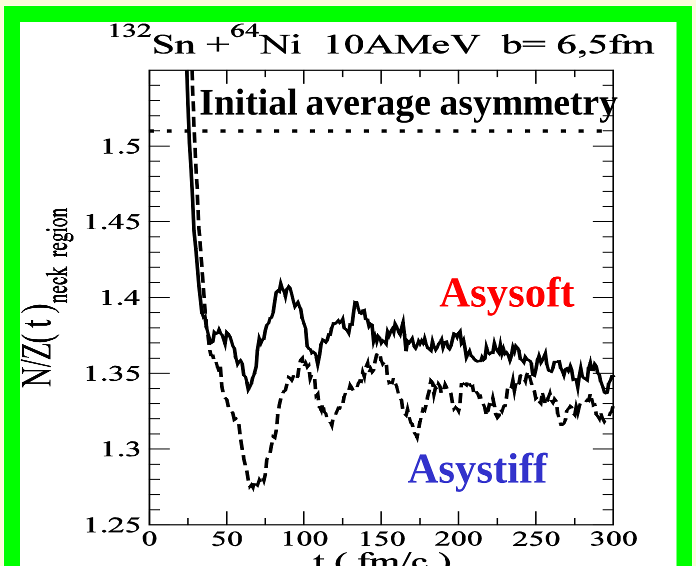
Asysoft vs. **Asystiff**



← *Density in the neck region*

Density domain just above normal density
→ Smaller repulsion with Asysoft:
Larger fusion cross section

The density keeps larger with Asysoft



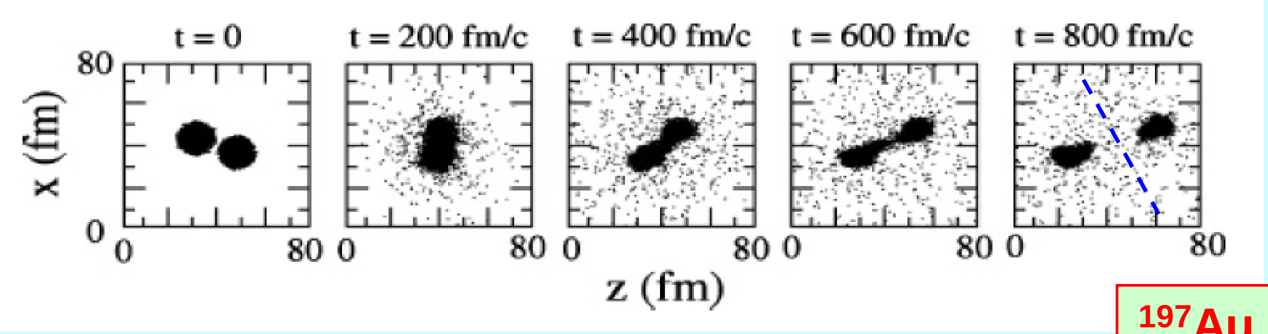
The N/Z of the neck region is systematically larger with Asysoft

N/Z oscillations are observed after 100 fm/c:
→ Excitation of isovector modes along the path to fusion or break-up.

Neck dynamics in break-up events

See LoI by Casini et al.

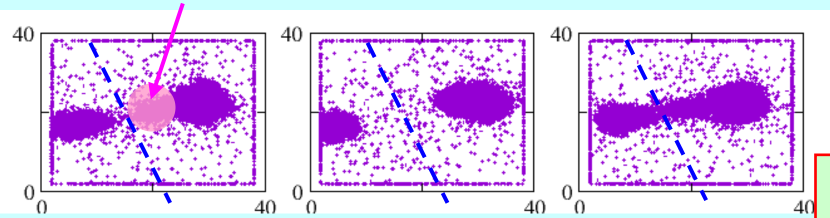
- Dynamics of residues (PLF and/or TLF):
Shape analysis at the break-up stage (low density)



$^{197}Au + {}^{197}Au$ Elab = 10 MeV/A
b = 7 fm

J. Wilczynski *et al.*, PRC **81**, 024605 (2010)

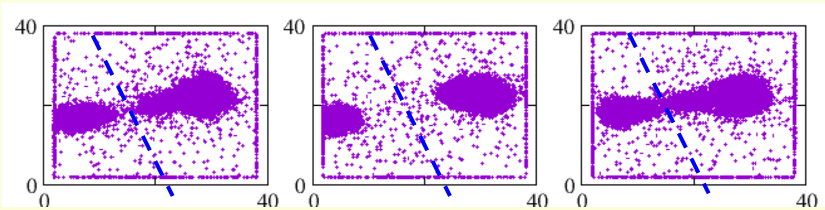
Low-density neck region



$^{132}Sn + {}^{64}Ni$ Elab = 10 MeV/A
b = 7 fm, 3 events at t = 500 fm/c

Observables: Ternary (quaternary) breaking, i.e. fragment production
Isospin effects on fragment production, fragment N/Z

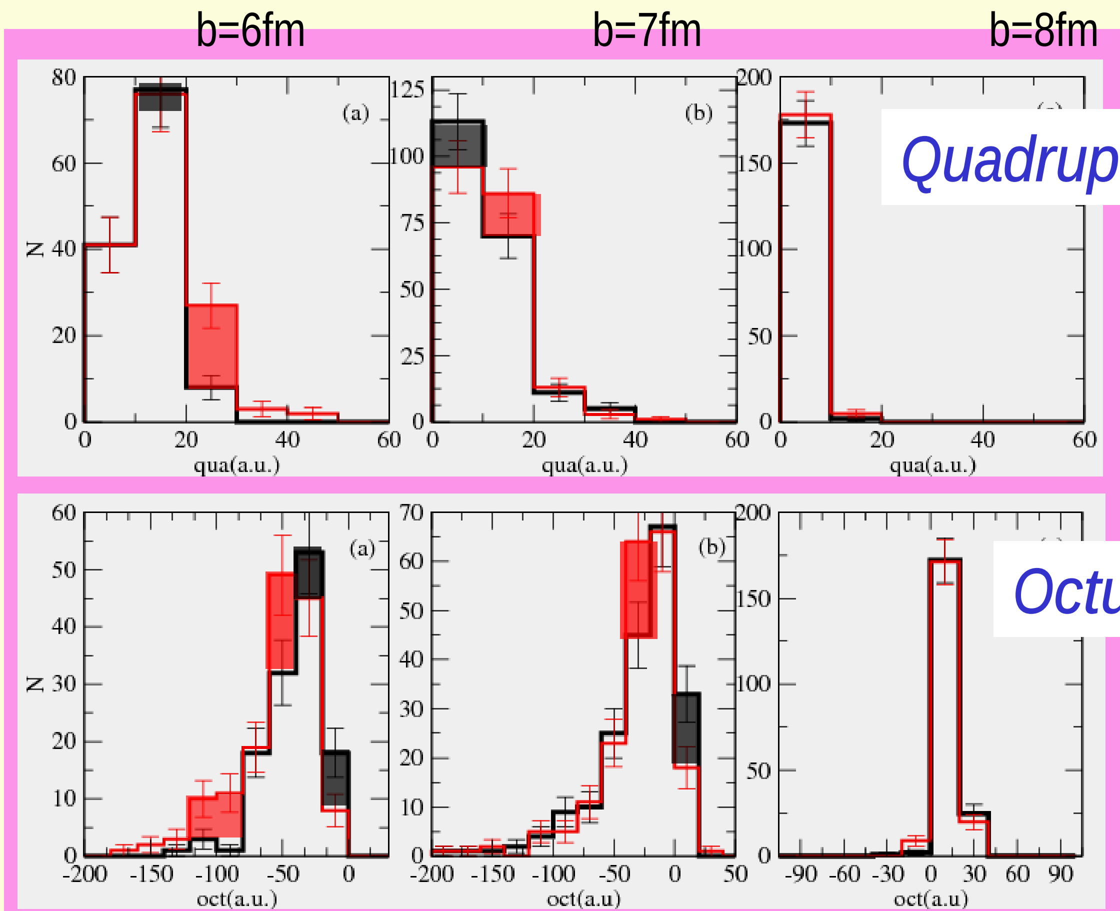
Shape analysis of residues (PLF and/or TLF)



$^{132}Sn + ^{64}Ni$, E/A = 10 MeV, b = 7 fm
3 events, t = 500 fm/c

- Analysis of the largest deformation of the residues

200 runs each
per impact parameter



— *Asysoft*
— *Asystiff*

- Larger residue deformations
→ more ternary events
with Asystiff

- Try the analysis in terms of Q' and QK

NN06, Rio de Janeiro, NPA 787 (2007) 585c

See LoI by Casini et al.

Collective excitations in exotic systems

Pre-equilibrium Dipole Radiation

Collective Dipole Oscillations of the Di-nuclear System

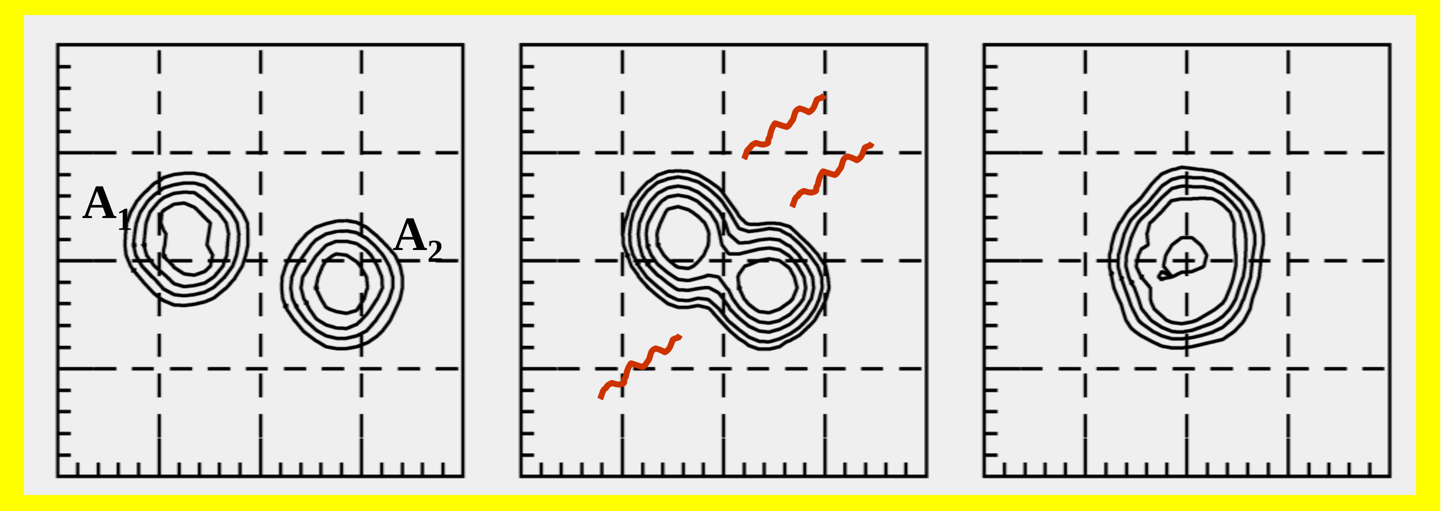
→ **Relative motion of neutron and proton centers of mass**

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

If $N_1/Z_1 \neq N_2/Z_2$

$$\boxed{D_0 = \frac{Z_1 Z_2}{A}\left(\frac{N_1}{Z_1} - \frac{N_2}{Z_2}\right)(R_1 + R_2)}$$

Dipole oscillations are excited in the initial conditions



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

Pre-equilibrium Dipole Radiation

See LoI's by Pierroutsakou and Casini

- A way to explore the fusion path

- A possible cooling mechanism in the formation of super-heavy elements

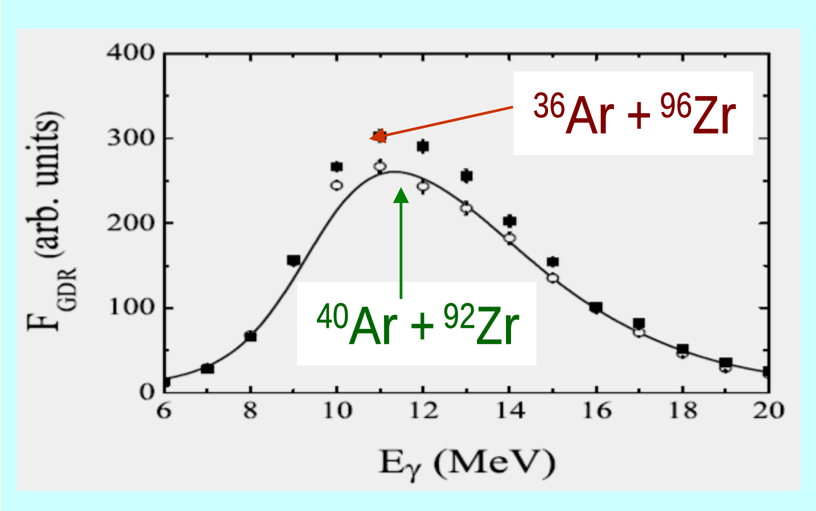
- Test of the isovector part of the nuclear interaction (the restoring force):
  density behavior of the symmetry energy

B.Martin et al., PLB 664 (2008) 47,
A.Corsi et al., PLB 679 (2009) 197

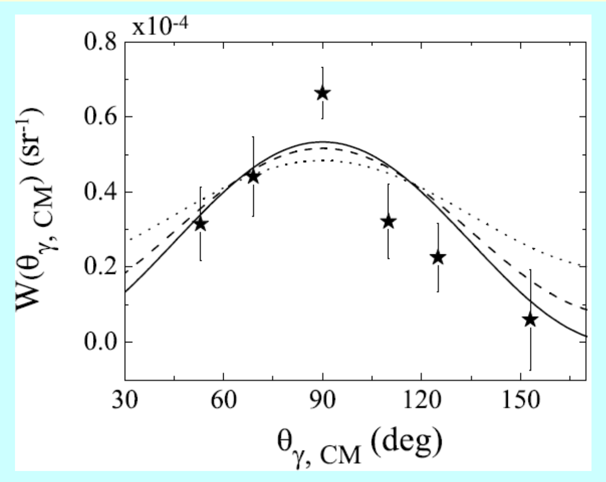
$^{36}Ar + ^{96}Zr$: $D_0 = 20.6$ fm

$^{40}Ar + ^{92}Zr$: $D_0 = 4.0$ fm

Experimental evidence of the extra-yield LNS data

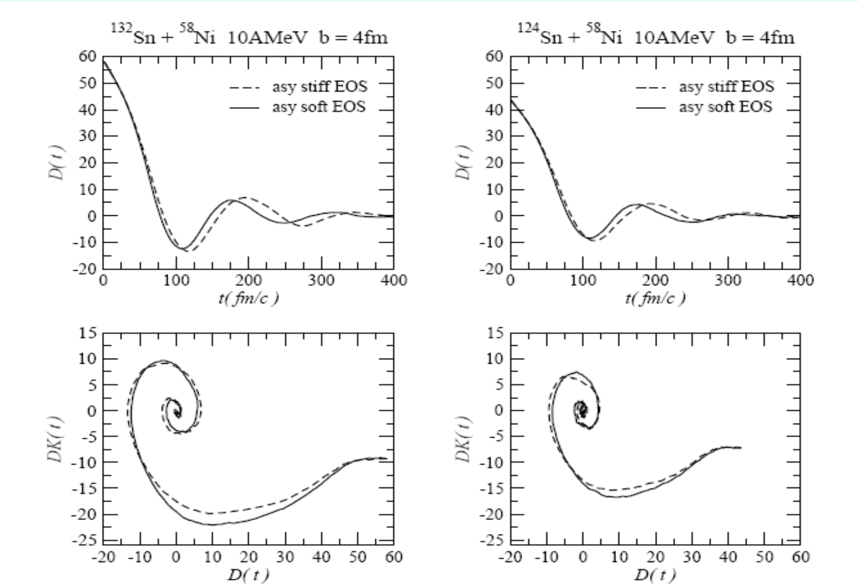


B.Martin et al., PLB 664 (2008) 47



Angular distribution: Anisotropy

Pre-equilibrium dipole emission in transport approaches



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

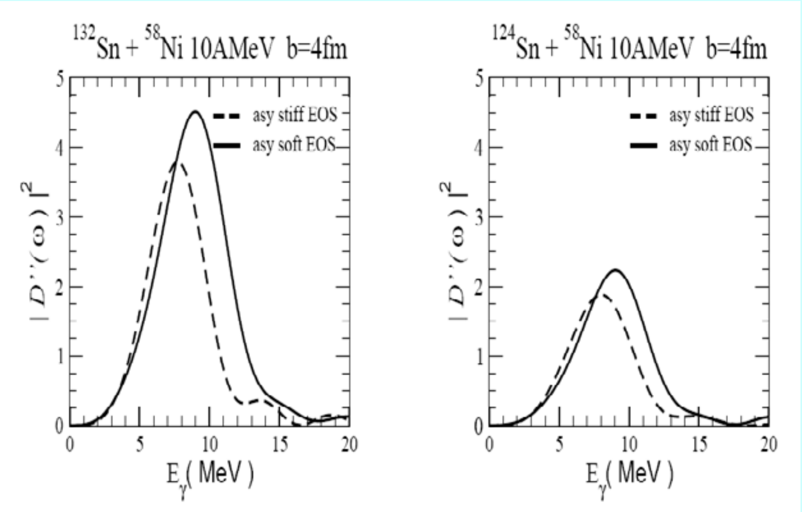
$$D(t) \equiv \frac{NZ}{A}\left[X_p(t) - X_n(t)\right] \rightarrow X_{p,n} \equiv \frac{1}{Z,N}\Sigma x_i^{p,n}$$

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

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

$\longrightarrow$ SPIRALS → **Collective Oscillations!**

also seen in TDHF calculations :
C.Simenel, Ph.Chomaz, G.de France



Bremsstrahlung:
Quantitative estimation

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

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

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

Damped oscillator model :

$$D(t) = D(t_0)e^{i(\omega_0 + i/\tau)t}$$

ω_0 = frequency of the dipole oscillation

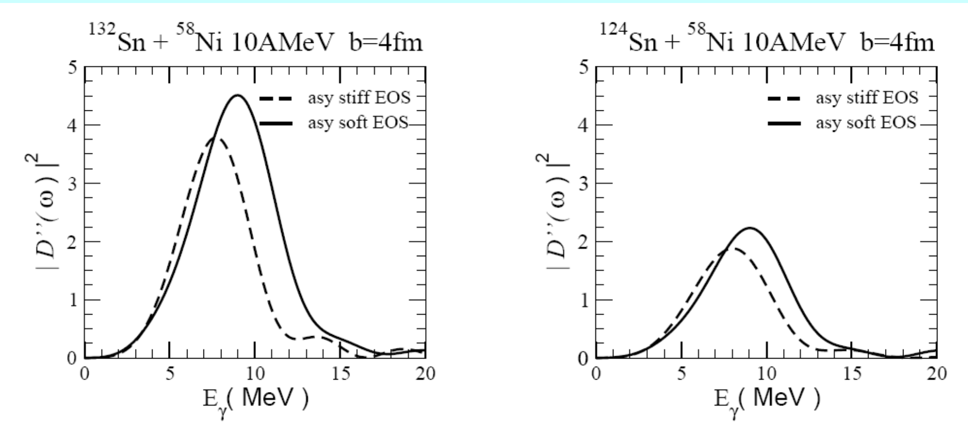
$\longrightarrow E_{sym}$

$$|D''(\omega)|^2 = \frac{(\omega_0^2 + 1/\tau^2)^2 D(t_0)^2}{(\omega - \omega_0)^2 + 1/\tau^2}$$

τ = damping time
(width of the spectrum)

Larger frequency $\longrightarrow$ Larger response amplitude

Larger $D(t_0)$ $\longrightarrow$ Larger response amplitude



Larger restoring force for Asysoft, corresponding to mean densities below saturation (low-density surface contributions)

Central collisions: 5.7 10^{-3} vs. 4.4 10^{-3} (30%)

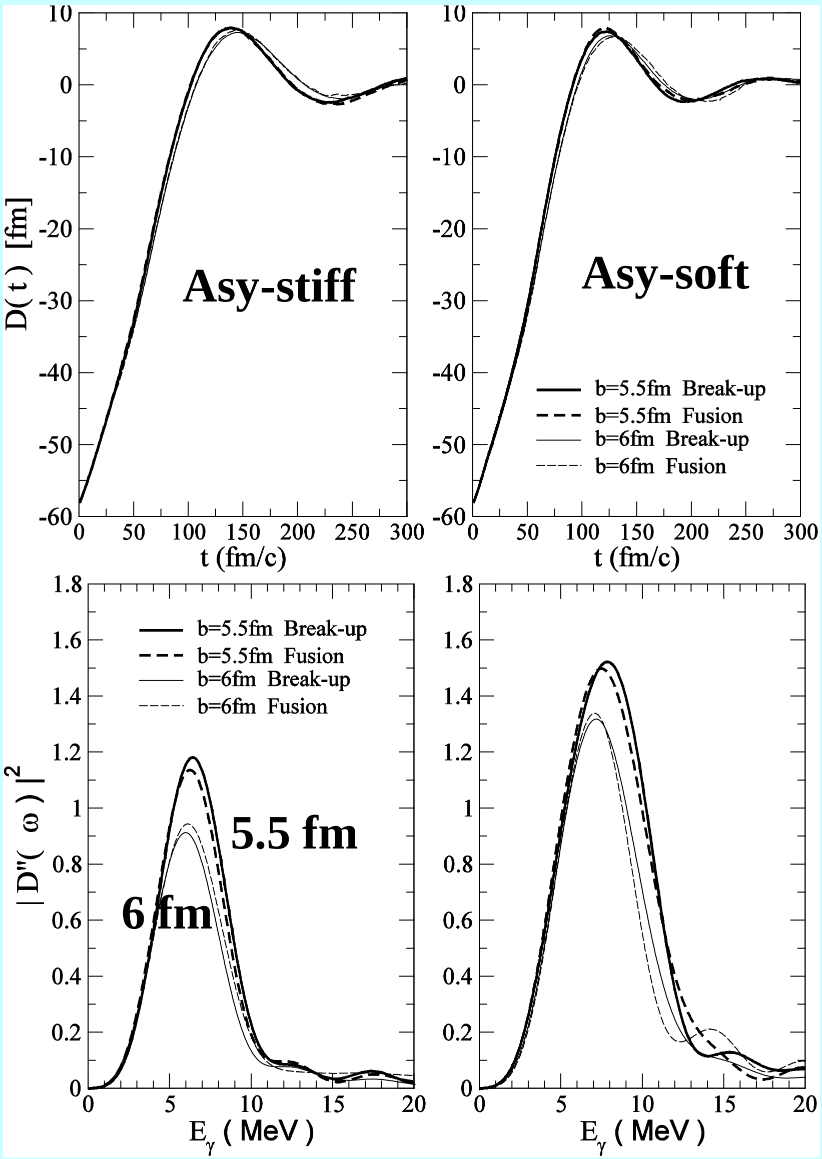
Energy-integrated Yield

$$P_\gamma \sim \omega_0^3 \tau D(t_0)^2$$

The dipole extra-yield increases with D_0^2 :
large effects expected in exotic systems

Pre-equilibrium dipole mode in deep-inelastic channels

C.Rizzo et al., arXiv:1010.2927



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

In the fusion or deep-inelastic channels, the Dipole mode is present almost with the same strength (semi-central collisions)

- **Smaller strength in less central collisions**

- **Centroid shifted to lower values, corresponding to more deformed shapes of the di-nuclear system**

For b = 5.5 fm:
P_γ = 2.3 10^{-3} (soft) and 1.6 10^{-3} (stiff)
difference: 44%
Central collisions: 5.7 10^{-3} vs. 4.4 10^{-3} 30%

Conclusions

Dissipative dynamics at low energies may allow to access new, complementary information on the density behavior of E_{sym}
from just above to below normal density

Isospin effects are revealed just selecting into "exotic"experiments the impact parameter window corresponding to semi- peripheral reactions.

Some promising observables:

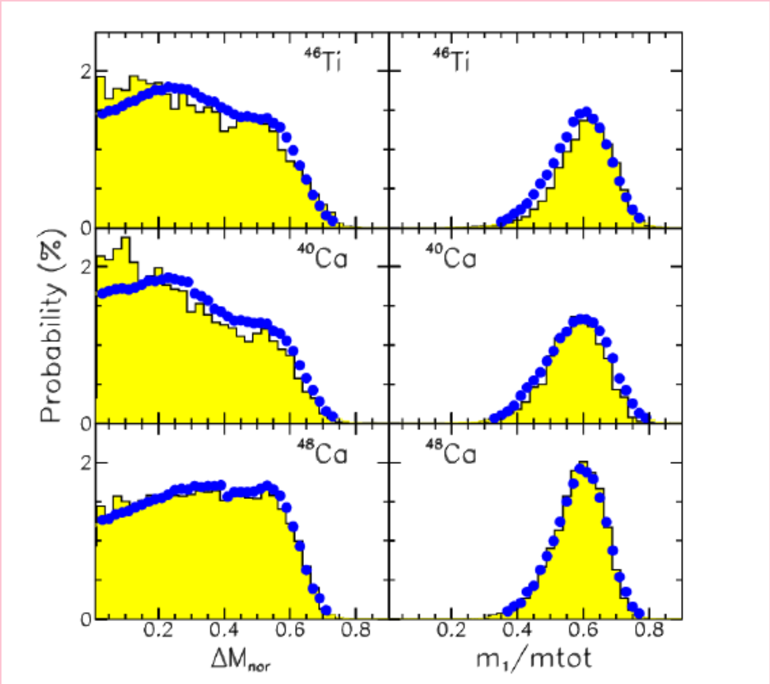
1. Fusion vs. Break-up probabilities in the centrality transition region;

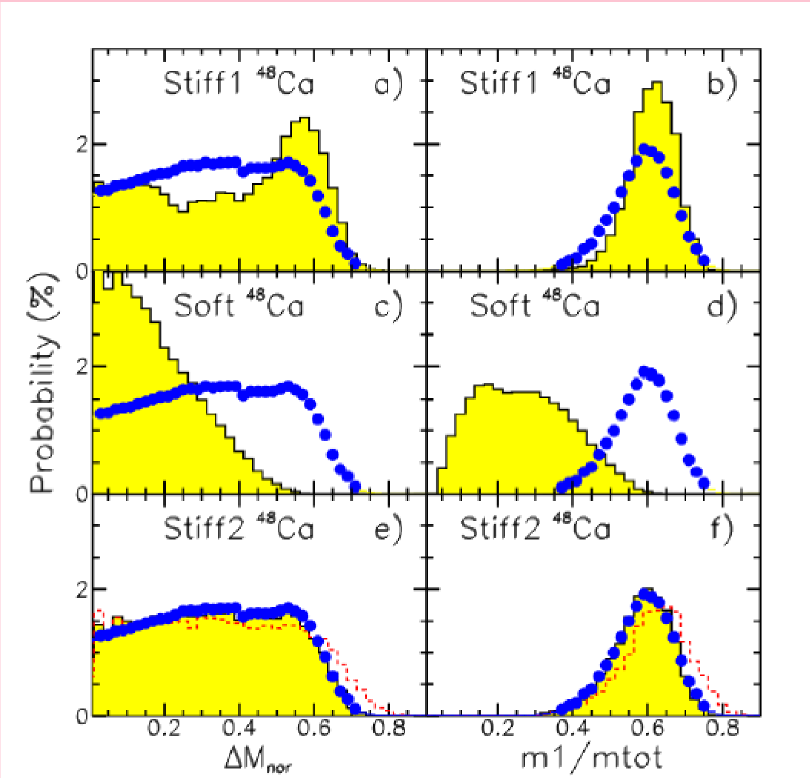
2. Fragment deformations in break-up processes and probability of ternary/quaternary events;

3. γ-multiplicity and anisotropy of the Prompt Dipole Radiation, for dissipative collisions in charge asymmetric entrance channels.

V.Baran (NIPNE HH,Bucharest)
M.Di Toro, C.Rizzo (LNS, Catania)
Odsuren Myagmarjav (University of Mongolia)

Incomplete fusion cross section at 25 MeV/A with ^{40}Ca projectile (LNS data)





$\Delta M = M1 - M2$ (two largest fragments)

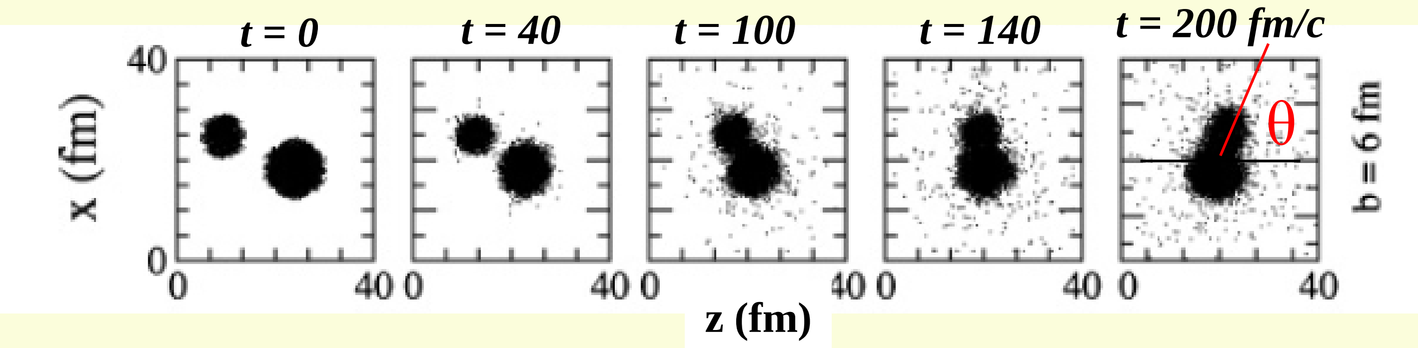
Isospin effects on fusion cross section

In fact the neutron excess of the ^{40}Ca+^{48}Ca system pushes the formed hot compound nucleus closer to the stability valley. On the contrary, the intermediate systems formed with the other two N≈Z targets are much closer to the proton drip line.

Very sensitive to the asy-EOS
CoMD calculations

F.Amorini et al., PRL 2009

Competition between reaction mechanisms

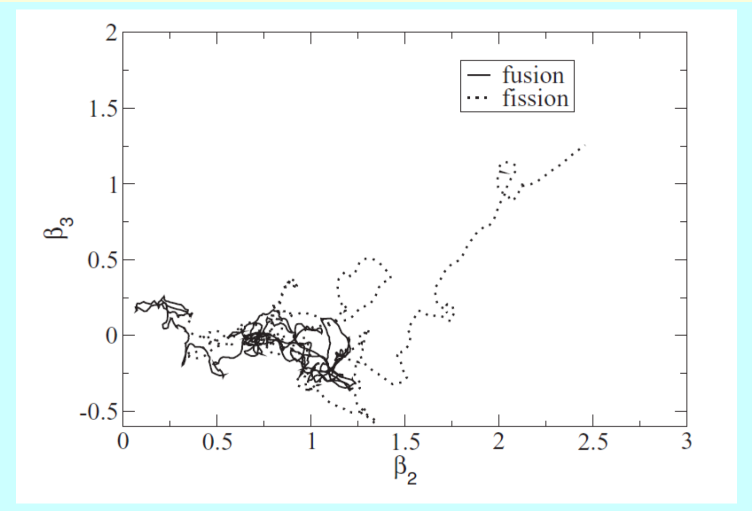


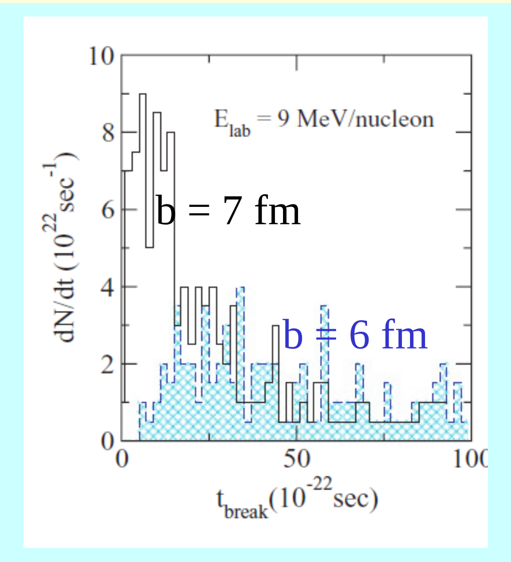
$^{36}Ar + ^{96}Zr$,
E/A = 9 MeV,
b = 6 fm

Low energy: time scales for break-up not compatible with SMF treatment →

✓ **Starting from t = 200 fm/c, solve the Langevin Equation (LE) for selected degrees of freedom: β_2 (quadrupole), β_3 (octupole), θ, and related velocities**

Examples of trajectories

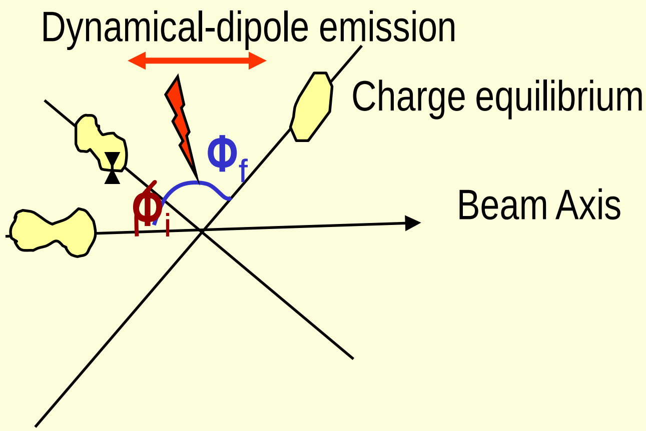




Break-up time distribution for break-up events

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

Angular distribution and anisotropy

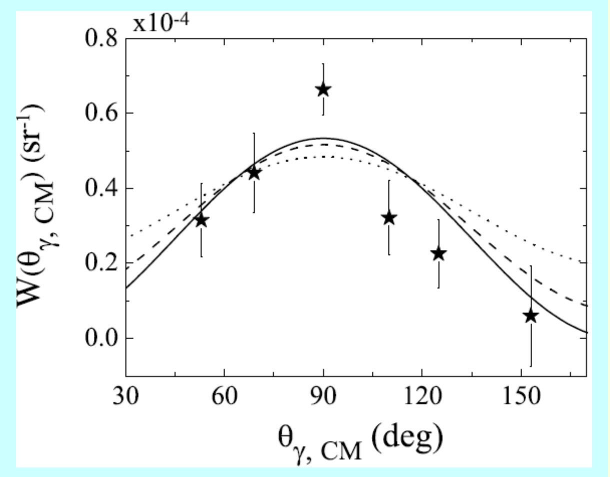


- **Emission from a deformed system, along the beam axis (no rotation)**

$$W(\theta) \sim \sin^2\theta \sim 1 + a_2 P_2(cos\theta)$$

(a_2 = -1)

Data ⟶



- For an emitting system rotating from φ_i to φ_f

$$W(\theta) \sim 1 - (\frac{1}{4} + \frac{3}{4}x)P_2(cos\theta)$$

$$x = cos(\phi_f + \phi_i)\frac{sin(\phi_f - \phi_i)}{\phi_f - \phi_i} \quad .$$

For $\varphi_i = \varphi_f = 0$, $x = 1$, $a_2 = -1$

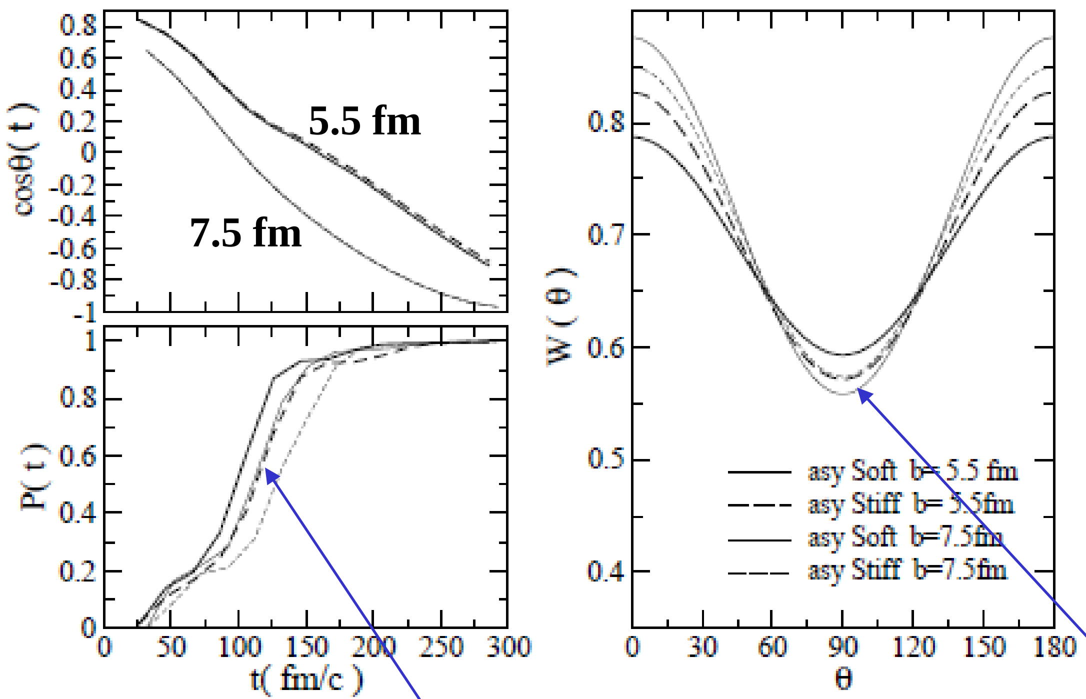
For $\varphi_f = \varphi_i + 2\pi$, $x = 0$, $a_2 = 1/4$

⟶ Statistical emission

But the emission probability is changing while the system rotates $\longrightarrow$

$$W(\theta) = \sum_{i=1}^{t_{max}} \beta_i W(\theta, \Phi_i)$$

$\beta_i = P(t) / P_{tot}$
is the probability to emit γ's at the time t



- **Angular distribution as a clock of dipole emission**

- **(Small) sensitivity to symmetry energy**

Delay of dipole response for asy-stiff (dashed) $\longrightarrow$ larger rotation and more pronounced min at 90º

Low energy: time scales for break-up not compatible with SMF treatment →

Simplified approach for macroscopic observables: quadrupole (β_2) and octupole (β_3) moments

Rayleigh-Lagrange equations of motion:

$$\frac{\mathrm{d}}{\mathrm{d}t}\frac{\partial L}{\partial \dot{q}_i} + \frac{\partial F}{\partial \dot{q}_i} = \frac{\partial L}{\partial q_i} \tag{1}$$

where $L(q_i, \dot{q}_i) = E_{kin}(q_i, \dot{q}_i) + E_{rot}(q_i, \dot{q}_i) - E_{pot}(q_i)$ is the Lagrangian of the system and

$$F(q_i, \dot{q}_i) = \frac{1}{2}\frac{\mathrm{d}E}{\mathrm{d}t} = \frac{1}{2}\sum_{i,j=1}^{2} R_{ij}\dot{q}_i\dot{q}_j \tag{2}$$

is the Rayleigh's dissipation function.

$q_i = \beta_2(t), \beta_3(t), \omega(t)$ are our general coordinates (β_2 and β_3 describe shape and ω is a rotation angle).

$$R(\theta, \phi) = R_0(\beta_2, \beta_3)\left\{1 + \beta_1(\beta_2, \beta_3)Y_{10}(\theta) + \beta_2 Y_{20}(\theta) + \beta_3 Y_{30}(\theta)\right\} \tag{3}$$

$Y_{10}(\theta)$, $Y_{20}(\theta)$ and $Y_{30}(\theta)$ are spherical harmonics

Stochastic extension $\longrightarrow$ the Langevin equation

Langevin equation:

$$\frac{\mathrm{d}}{\mathrm{d}t}\frac{\partial L}{\partial \dot{q}_i}+\frac{\partial F}{\partial \dot{q}_i}=\frac{\partial L}{\partial q_i}+F_{fluc}(t)$$

The difference with the classical Rayleigh-Lagrange equations is in adding the F_{fluc} – a rapidly fluctuating stochastic force determining fluctuations in momentum according to the value of the diffusion coefficient D. We assume that

$$\langle F_{fluc}(t)F_{fluc}(t+s)\rangle = D\delta(s)$$

The force F_{fluc} may be simulated numerically by repeatedly producing a random kick δP in the collective momentum. The value of δP is chosen randomly from a Gaussian distribution with a mean value and variance given by:

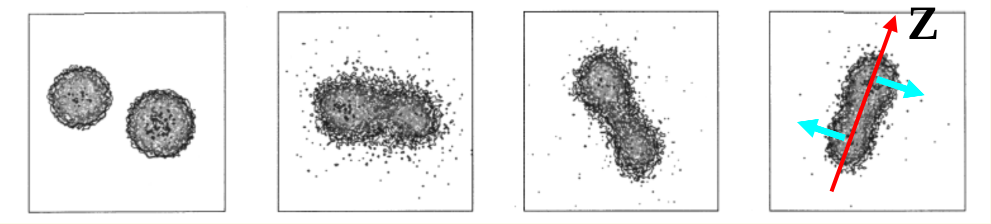
$$\overline{\delta P}=0$$

$$\overline{(\delta P)^2}=D\delta t$$

D = 2Tγ, where γ is related to the dissipation tensor

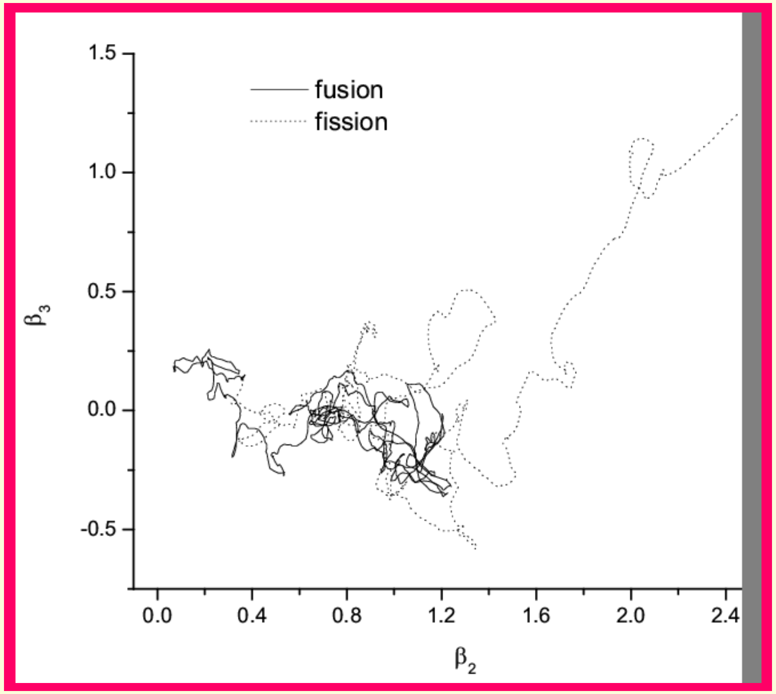
Competition between reaction mechanisms: fusion vs deep-inelastic at lower energy ⟶ Langevin treatment of shape observables

$^{36}Ar + ^{96}Zr$, E/A = 9,16 MeV/A,
b= 4-7 fm

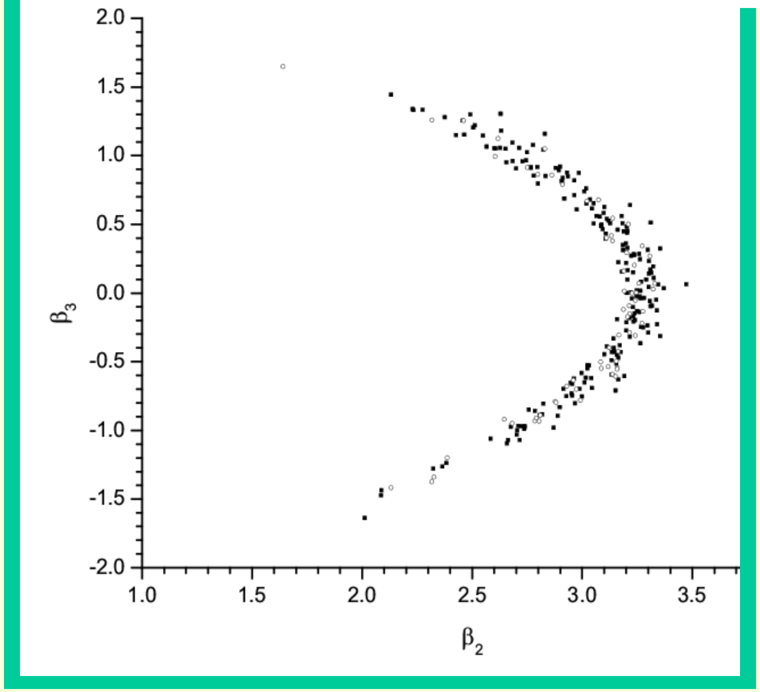


Initial conditions (b= 5 fm) :
A = 118, Z=52, J= 77 ħ, E* = 250 MeV,
β_2= 0.63, β_3= 0.40
time of branching: 200 fm/c

Trajectories in the β_2 β_3 plane according to the Langevin treatment

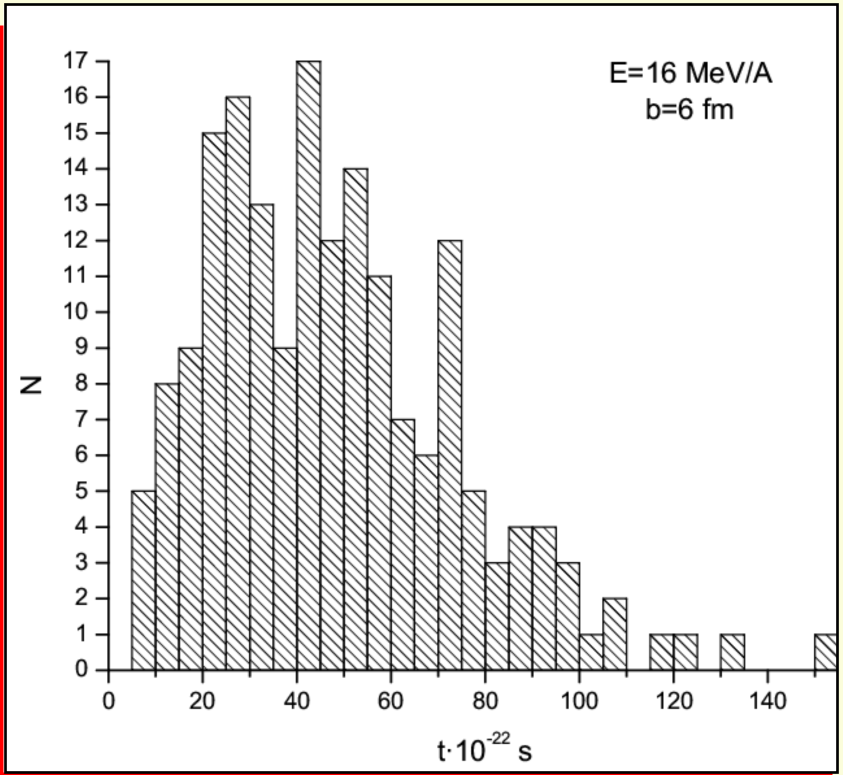


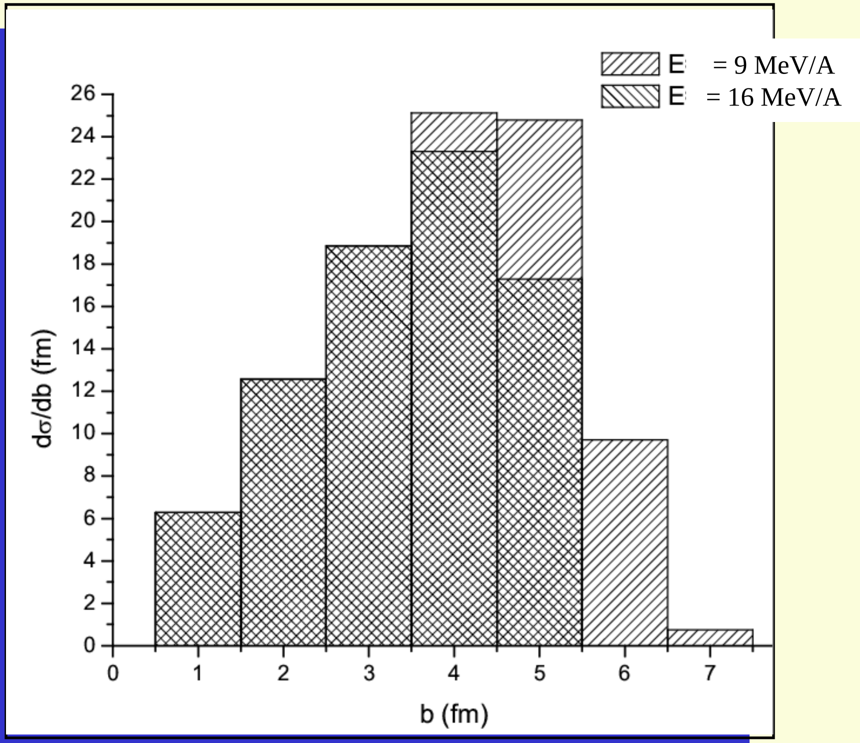
Configurations at break-up:
Lost of memory of initial conditions !



Competition break-up -- nucleon emission:
The excitation energy is dissipated through nucleon emission. Typical life time : 1000 fm/c

✓ Predict fusion cross section



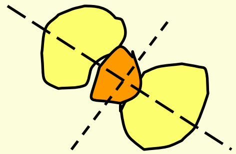


Time distribution of break-up probability

✓ **Extend to charge asymmetric systems and test different asy-EOS**

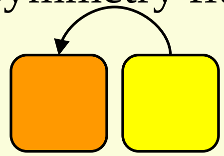
L.Shvedov et al, in preparation

Isospin migration in neck fragmentation



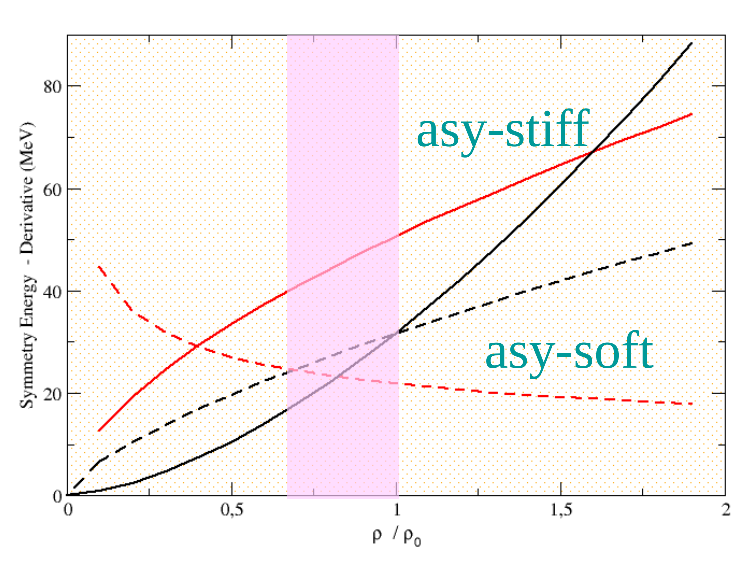
- Transfer of asymmetry from PLF and TLF to the low density neck region
- Effect related to the derivative of the symmetry energy with respect to density

Asymmetry flux

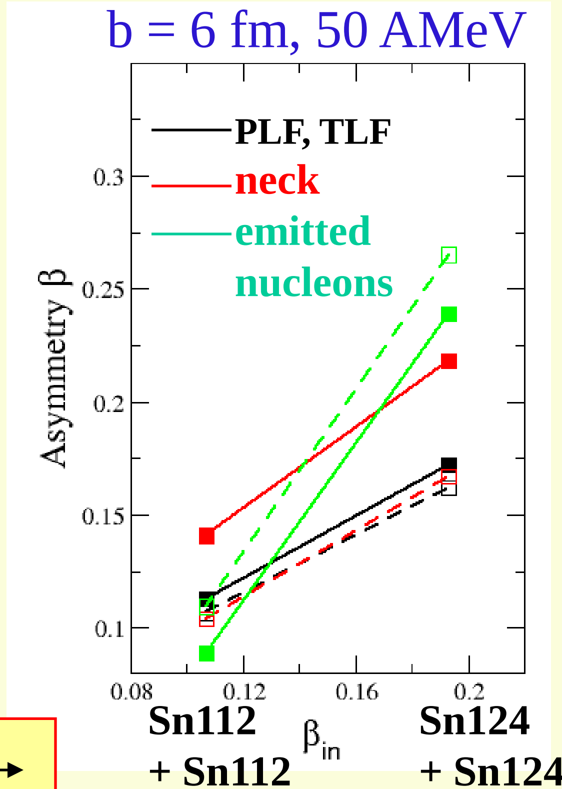


$\rho 1 < \rho 2$

Density gradients ⟶ derivative of Esym

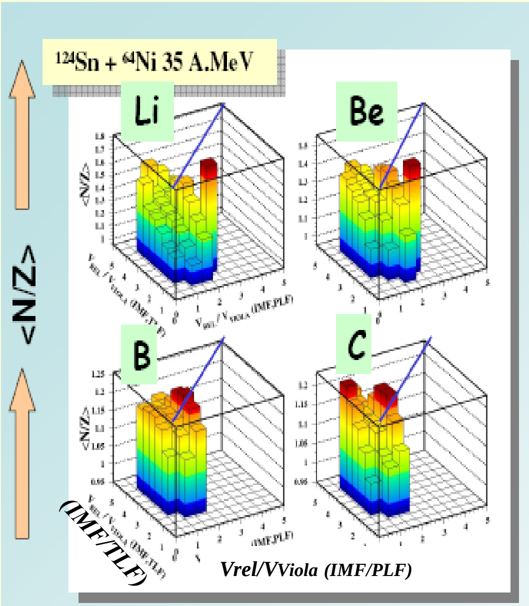


Larger derivative with asy-stiff ⟶ larger isospin migration effects



J.Rizzo et al. NPA806 (2008) 79

LNS data – CHIMERA coll.



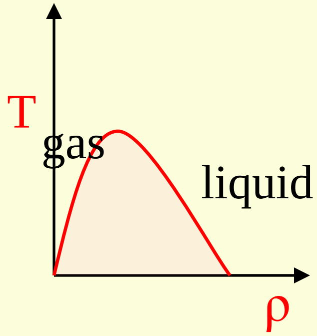
Experimental evidence of n-enrichment of the neck: Correlations between N/Z and deviation from Viola systematics

E.De Filippo et al., PRC71,044602 (2005)

E.De Filippo et al. NUFRA 2007

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)