Hints on the effective interaction from low energy reaction dynamics (EOS studies with SPES)

3rd International SPES Workshop

October 10-12, 2016

LNL, Legnaro

Maria Colonna

INFN - Laboratori Nazionali del Sud (Catania)

Dissipative reaction mechanisms, involving heavy ions, can probe several aspects of the nuclear effective interaction and nuclear EOS

Outline

- The tool: mean-field models (TDHF, Vlasov, SMF) and effective interactions

- Some examples of suitable low-energy (E/A ~ 5-10 MeV/A) reaction mechanisms

- Covariance analysis:
  Sensitivity of selected observables to specific ingredients of the effective interaction

Mean-field models and effective interactions

One-body description

ρ_1 : one-body density

$$i\hbar \frac{\partial}{\partial t}\rho_1(t) = [H_{eff}, \rho_1(t)] + K(\rho_1) + \delta K(\rho_1, \delta\sigma)$$

TDHF **ETDHF**

semi-classical approximation

$$\frac{\partial f(r,p,t)}{\partial t} + \{f, H_{eff}\} = k_l[f] + \delta k$$

Vlasov **BUU, SMF**

Residual interaction:
in-medium NN cross section $\boldsymbol{\sigma_{NN}}$
2-body correlations, Fluctuations

H_{eff} : **effective Hamiltonian**

- Expectation value of physical quantities :

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

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

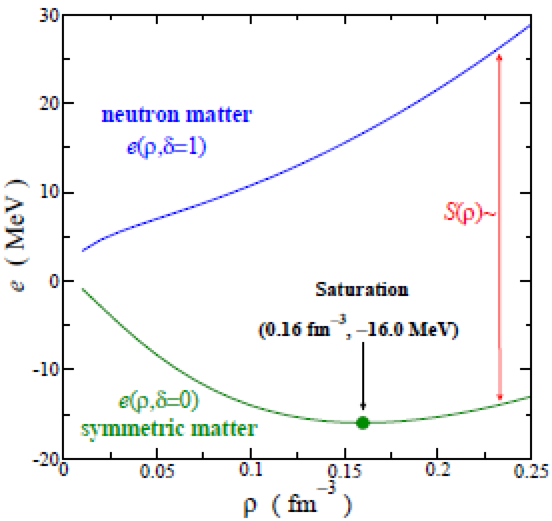
functions of isoscalar, spin, isospin densities, currents … → **DTF, Nuclear matter EOS**

- Effective interactions are phenomenological (ex: **Skyrme** interactions, …)

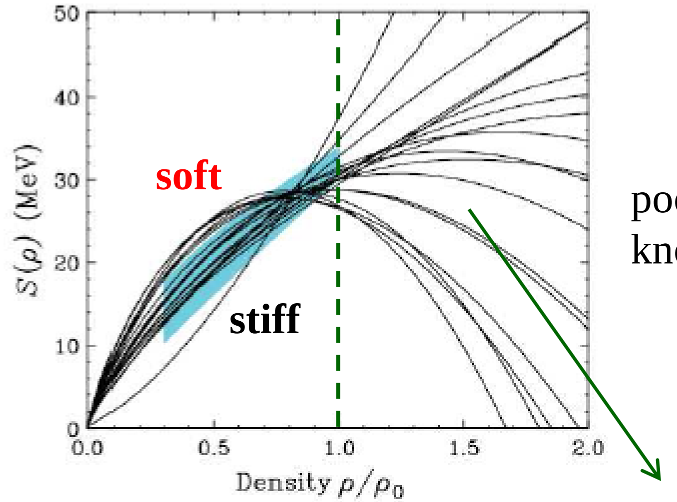
- Fitted parameters incorporate the effects of correlations beyond mean-field

The nuclear **Equation of State (T = 0)**

Energy per nucleon E/A (MeV)



Symmetry energy E_{sym} (MeV)



poorly known …

predictions of several effective interactions

$$\frac{E}{A}(\rho,\beta) = \frac{E}{A}(\rho,\beta=0) + E_{sym}(\rho)\beta^2 + O(\beta^4)$$

symm. matter ***symm. energy***

expansion around normal density

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

or J

$25 \leq J \leq 35$ MeV $20 \leq L \leq 120$ MeV

β = asymmetry parameter = $(\rho_n - \rho_p)/\rho$

➢ analogy with **Weizsacker mass formula** for nuclei (symmetry term) !

Low-energy reaction mechanisms: a study within mean-field models

- Fusion vs Quasi fission or Deep Inelastic
- Ternary breaking
- Charge equilibration

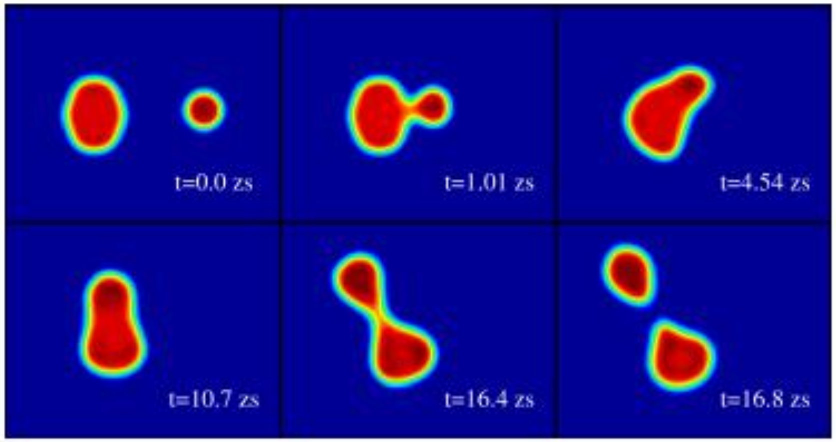
➡

- Fragmentation
- Isospin diffusion

(Fermi energies)

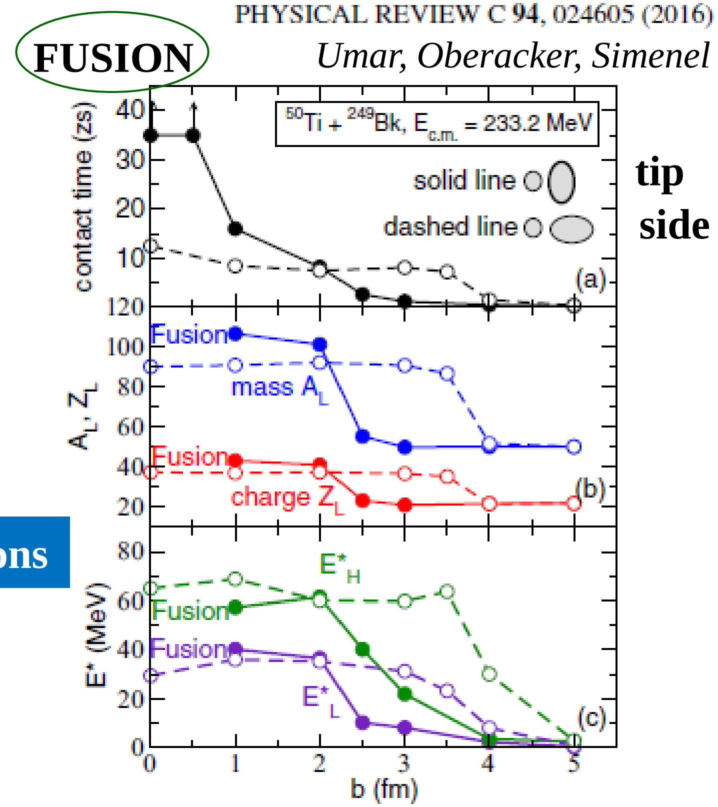
Fusion vs. Quasi Fission: towards the synthesis of SHE

^{50}Ti +^{249}Bk 233 MeV

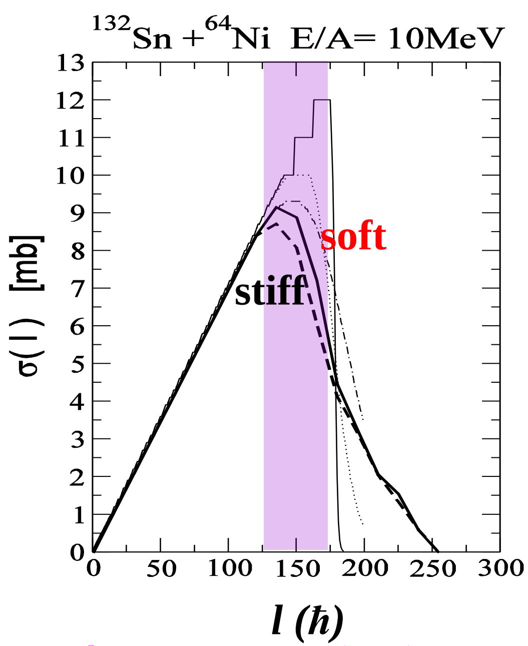


PHYSICAL REVIEW C 94, 024605 (2016)

Umar, Oberacker, Simenel



TDHF calculations



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

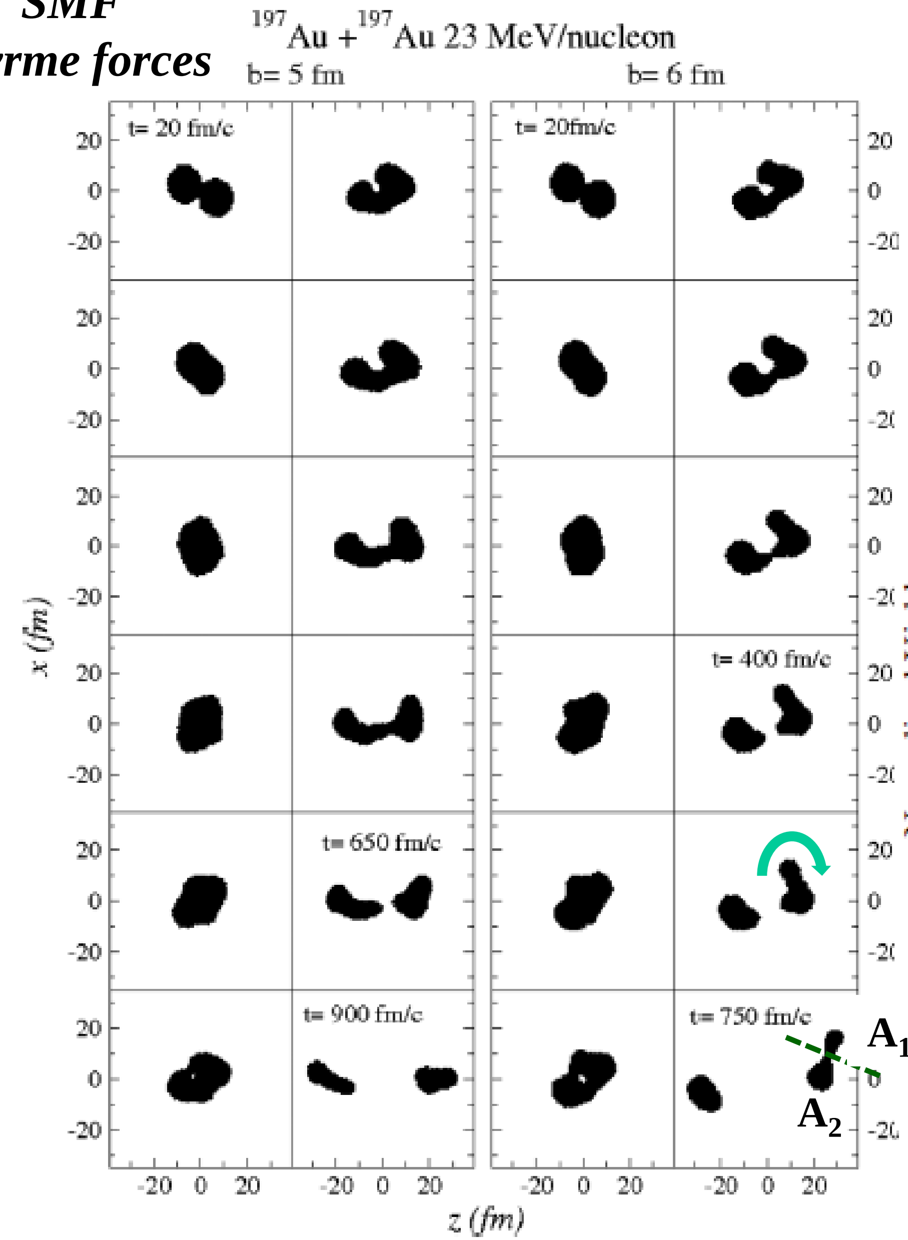
• Fusion probability depends on the deformation/orientation of colliding nuclei

➢ Possible summetry energy effects ??

SMF calculations with neutron rich systems

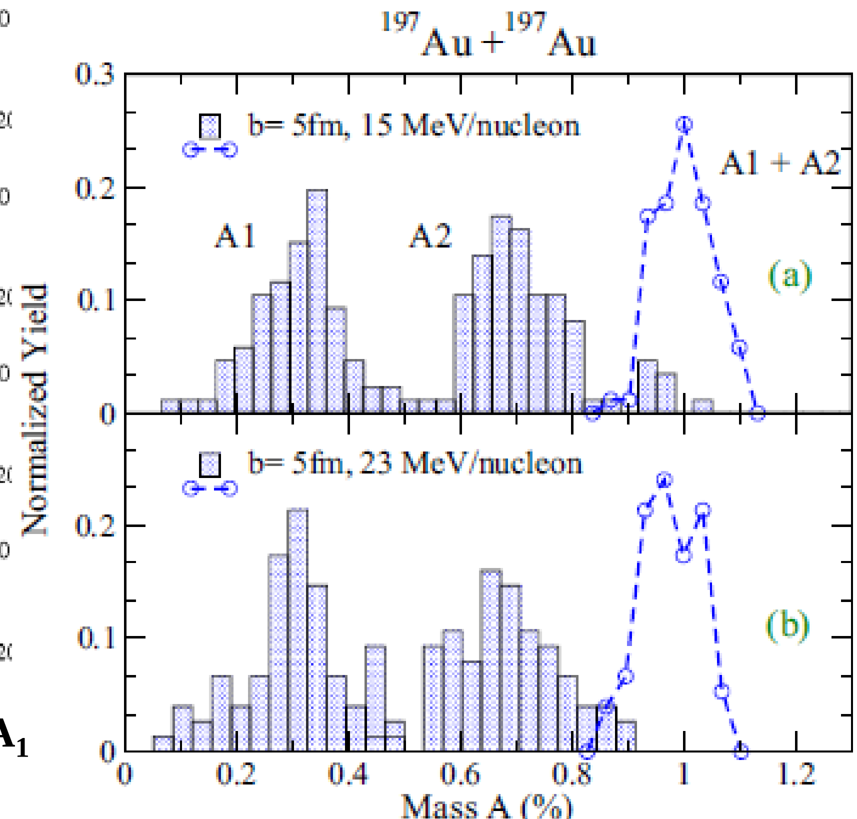
➢ A recent investigation: Ternary Quasi Fission

SMF
Skyrme forces



^{197}Au + ^{197}Au collisions - 15 and 23 MeV/A

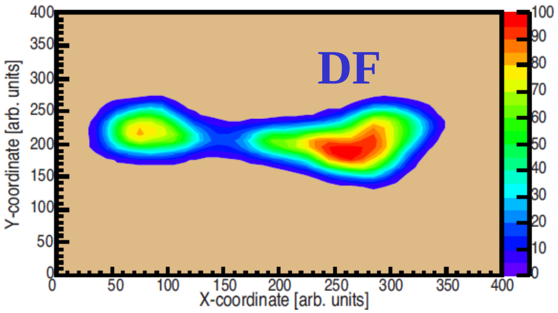
- Mass distribution of fragments emitted by DF fragment



A1: lightest fragment
A2: heaviest fragment

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

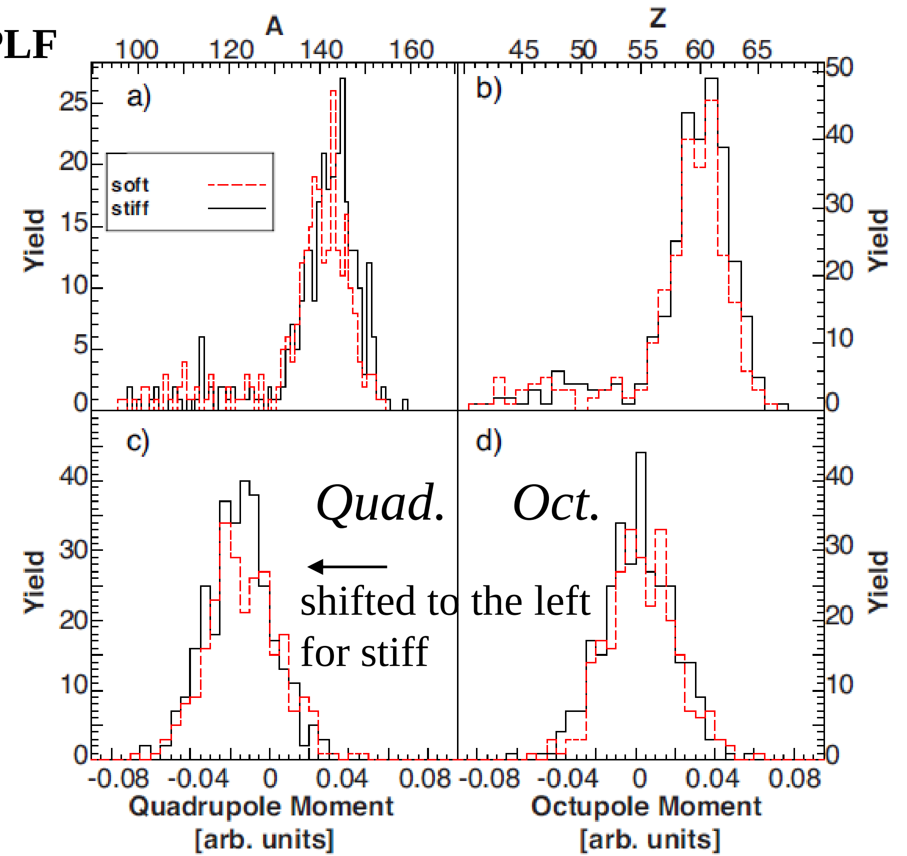
Ternary breakup in n-rich systems: Sensitivity to E_{sym} & Multidimensional Analysis

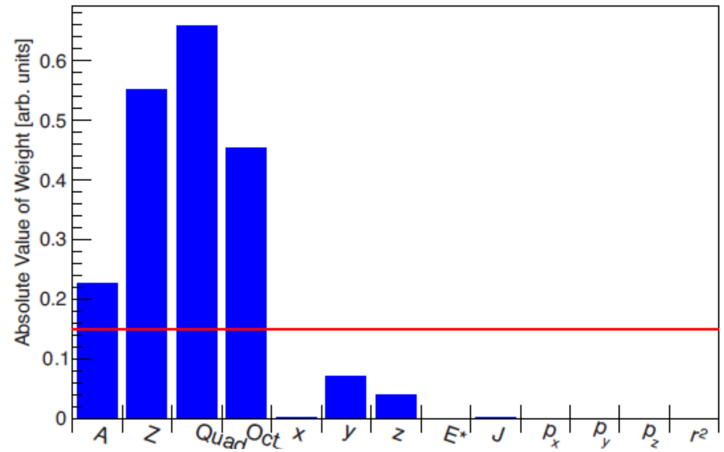


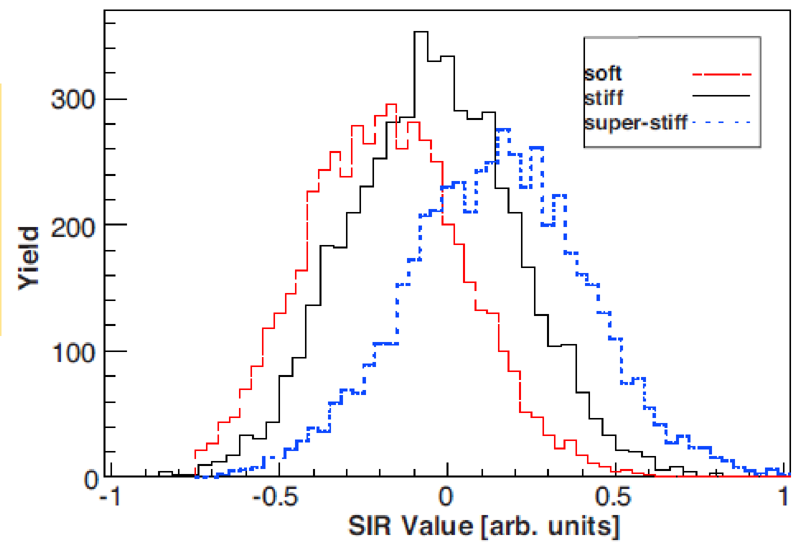
$^{124}Sn + ^{64}Ni$, E/A = 10 MeV, b = 6-8 fm

PLF-TLF configuration at separation time

PLF

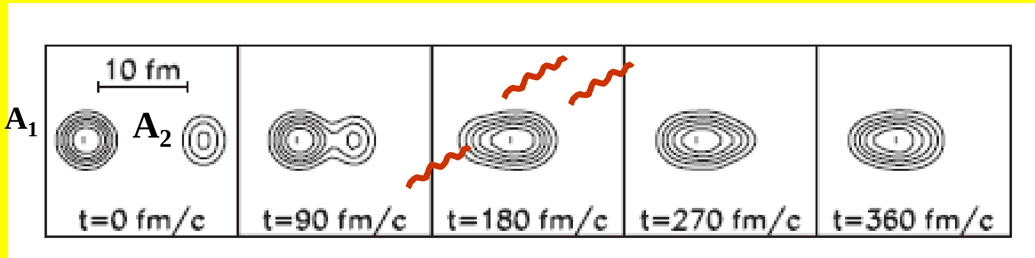






P.Cammarata et al., NIM A761, 1-6 (2014)

➢ Dipole excitations in heavy ion reactions (Dyn. Dipole)



TDHF calculations

Simenel et al, PRC 76, 024609 (2007)

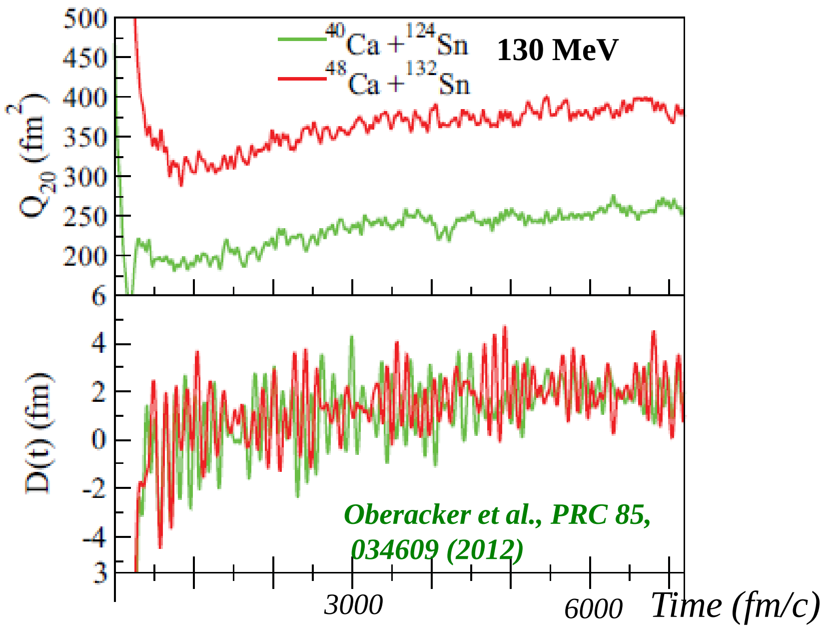
Initial Dipole **D(t) : bremss. dipole radiation** **Compound: stat. GDR**

If $N_1/Z_1 \neq N_2/Z_2$

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

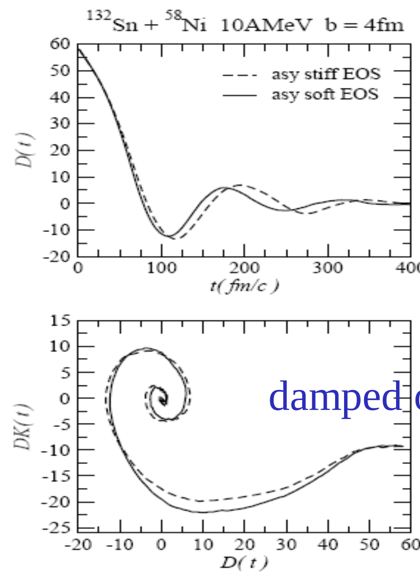
+ 2-body collisional damping

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



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

SMF simulations



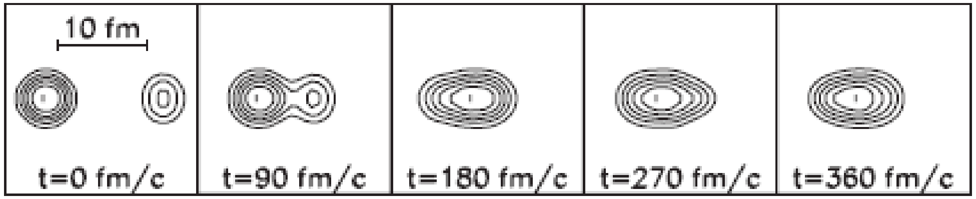
$^{132}Sn + ^{58}Ni$, D_0 = 45 fm
E/A = 10 MeV

damped oscillations

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

Dynamical Dipole in heavy ion reactions (DD)

- The restoring force is provided by the symmetry term (as in the standard GDR) probe the symmetry energy in the density conditions and configurations reached along the reaction path



- Cooling mechanism in the formation of SHE

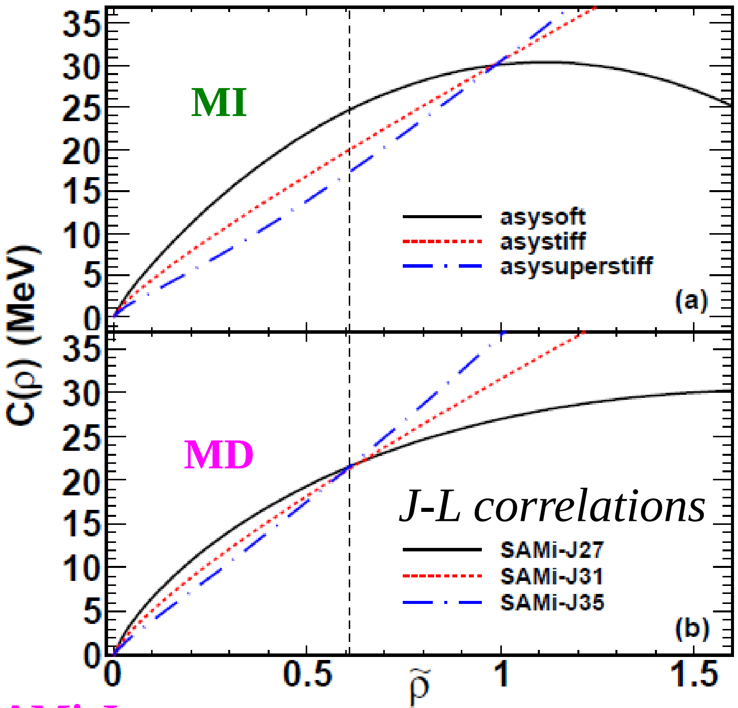
➢ **Few experimental data: more systematic analysis needed**

➢ **Theory**:   a more systematic study of the sensitivity of this mechanism to the ingredients of of the effective interaction and two-body dissipation needed

Ground state deformation important ???

→ DD in the fusion-evaporation of the ^{40}**Ca** + ^{152}**Sm** heavy system, C.Parascandolo et al., PRC 93, 044619(2016)

DD oscillations: dependence on the effective interaction



SAMi-J:

X. Roca-Maza, G. Colò, H. Sagawa, Phys. Rev. C **86**, 031306(R) (2012); X. Roca-Maza *et al.*, Phys. Rev. C **87**, 034301 (2013).

Skyrme (MI) : *H.Zheng et al.,*

PHYSICAL REVIEW C **94**, 014313 (2016)

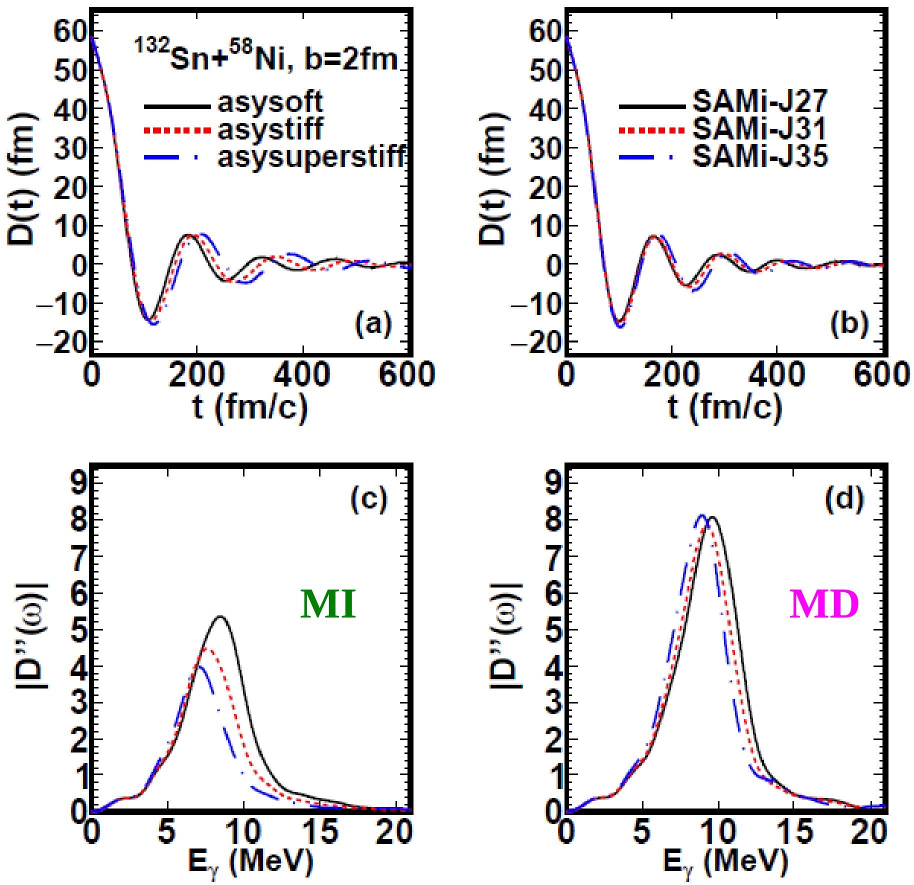
- **free n-n cross section**

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

$$P_\gamma \approx D_0^2 E_{centr}^3 \tau_{coll}$$

(damped harmonic oscillator)

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

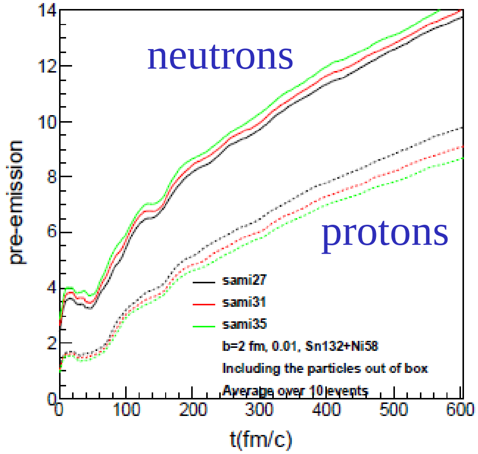


- The DD emission looks sensitive to E_{sym} at $\rho = 0.6\ \rho_{sat}$
- Larger strength seen in the MD case: similar to the enhancement factor in the GDR sum rule

Correlations: observables vs. parameters

A set of 8 parameterizations in SMF simulations:
Skyrme (MI) and SAMi-J31
+ σ_{NN} = 40 mb, *2, /2

Observables (A):
DD centroid, D"(ω) **integral** and **N/Z** of **pre-equilibrium nucleon emission**



Parameters (B):
Symmetry energy slope **L**, effective mass **m***
and NN cross section (**cs**)
τ_{coll} : collisional damping time

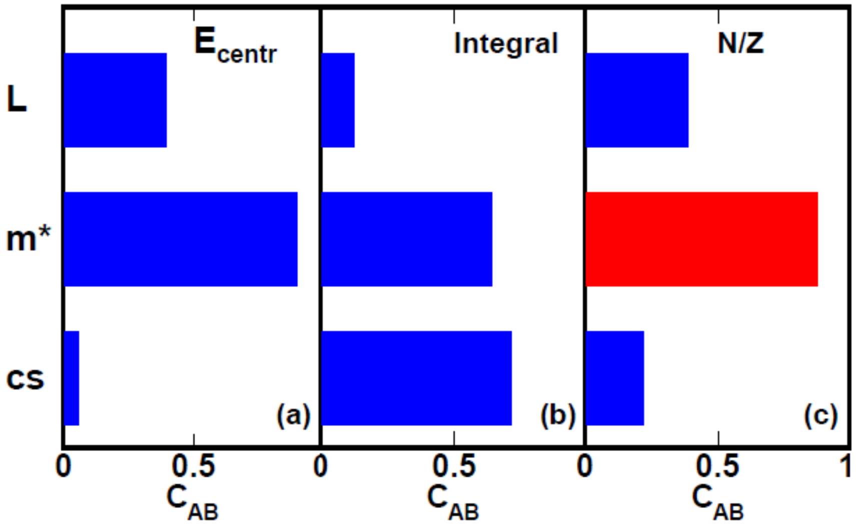
Covariance analysis

see also Zhang et al, PLB 749, 262 (2015)

$$C_{AB} = \overline{(A_{(n)} - \overline{A})(B_{(n)} - \overline{B})}$$

$$c_{AB} \equiv \frac{C_{AB}}{\sqrt{C_{AA} C_{BB}}}$$

Blue: negative **Red: positive**



compare with $P_\gamma \approx D_0^2 E_{centr}^3 \tau_{coll}$

(energy-integrated yield)

❑ Conclusions

Reactions with RIB's 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:
- role of effective interaction, 2-body dissipation
- n-skin, g.s. deformation

-Competition between reaction mechanisms (n-rich neck dynamics)
-Pre-equilibrium γ and particle emission

Collaborators: **Hua Zheng** (LNS), **Stefano Burrello** (LNS), V.Baran (University of Bucharest, Romania)