Competition between fusion and quasi-fission processes in heavy ion collisions close to the Coulomb barrier

IWM-EC 2018

International Workshop on Multi facets of Eos and Clustering

22nd - 25th May 2018
Catania, Italy

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

- Low-energy (E/A ~ 5-10 MeV/A)
  reaction mechanisms:
  from fusion to quasi-fission and deep-inelastic

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

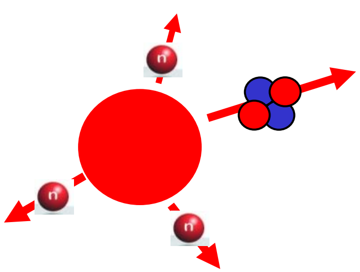
- Sensitivity of selected observables to specific ingredients
  of the effective interaction

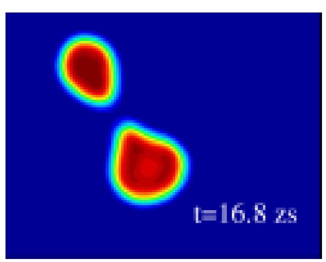
Low-energy reaction mechanisms: a study within mean-field models

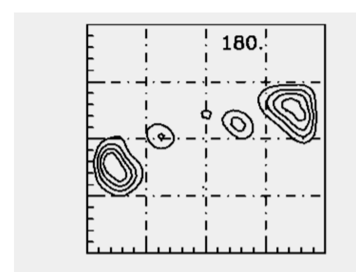
(Fermi energies)

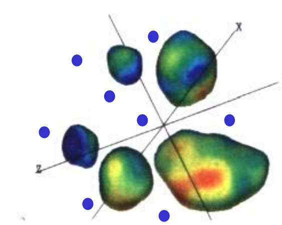
- Charge equilibration
- Fusion vs Quasi fission or Deep Inelastic

- Fragmentation
- Fragment isotopic composition









(Beyond) Mean-field models and effective interactions

One-body description ➡

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

TDHF   ETDHF

ρ_1 : one-body density

semi-classical approximation

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

Vlasov   BUU, Boltzmann-Langevin

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

H_{eff} : **effective Hamiltonian**

- Expectation value of physical quantities :

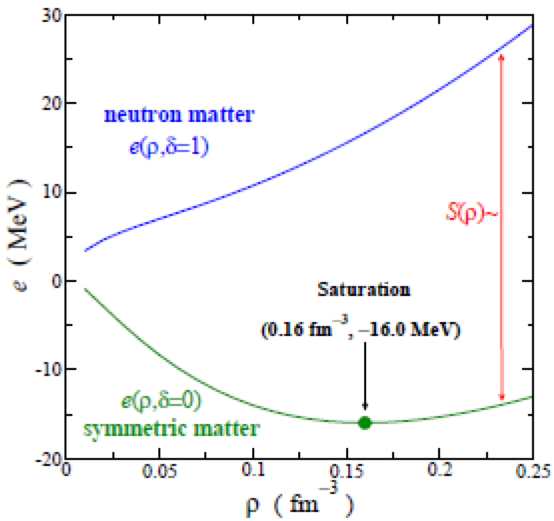
$$E = \langle \Psi | \hat{H} | \Psi \rangle$$
$$\approx \langle \Phi | \hat{H}_{eff} | \Phi \rangle = E[\hat{\rho}]$$

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

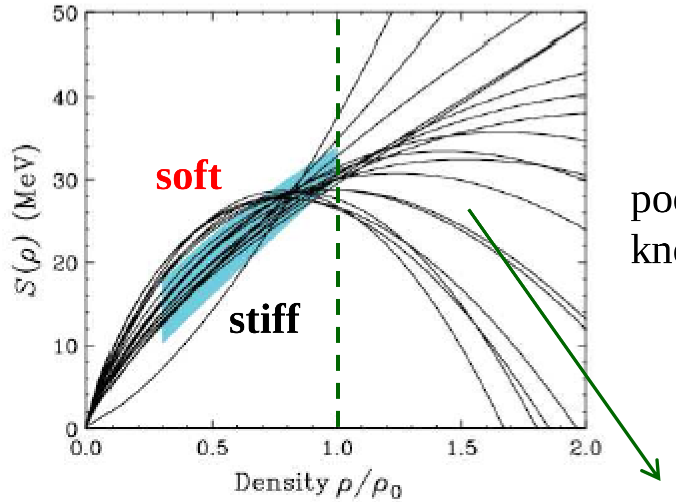
functions of isoscalar, spin, isospin densities, currents … ➡ **EDF, Nuclear matter EOS**

The nuclear **Equation of State (T = 0)** and the **symmetry energy**

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

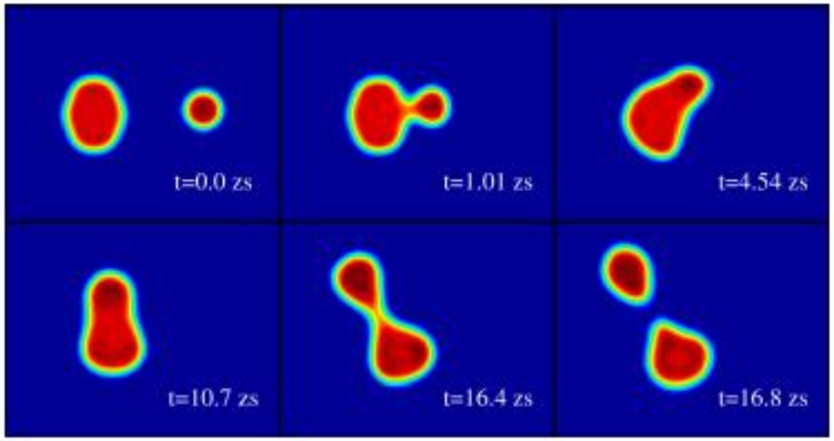
$25 \le J \le 35$ MeV $20 \le L \le 120$ MeV

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

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

Fusion vs. Quasi Fission: towards the synthesis of SHE

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

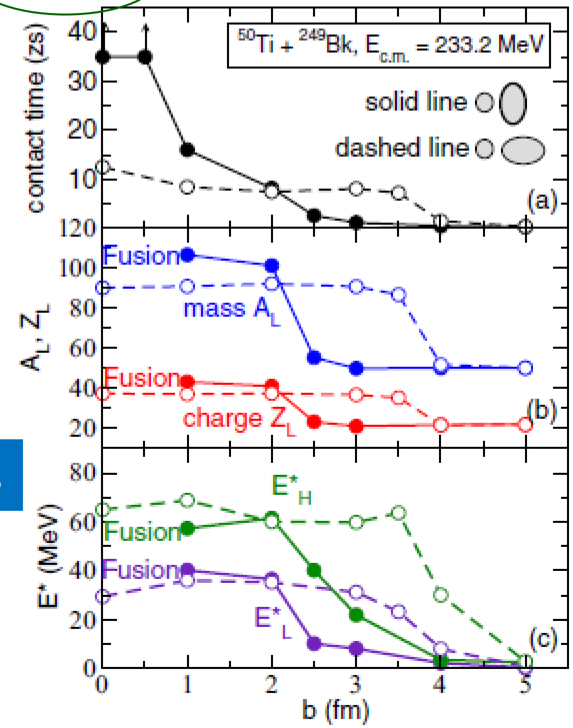


TDHF calculations

PHYSICAL REVIEW C **94**, 024605 (2016)

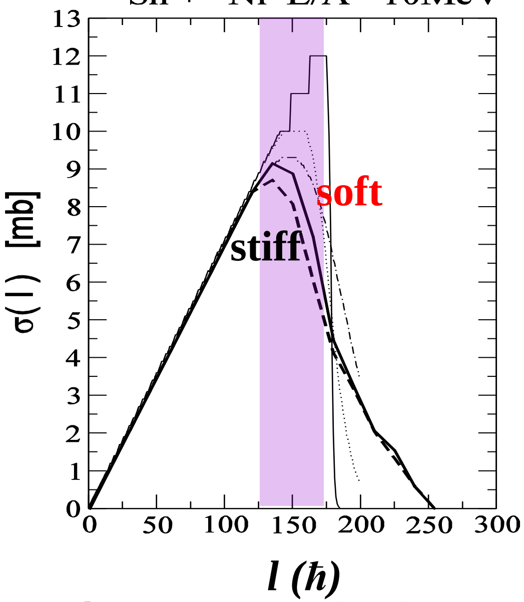
Umar, Oberacker, Simenel

FUSION



side
tip

^{132}Sn +^{64}Ni E/A= 10MeV



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

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

➢ Symmetry energy effects

Semi-class. calculations with neutron rich systems

TDHF and effective interactions

D.Lacroix
IPN-Orsay

$$i\hbar\partial_t \rho'(t) = [h[\rho'], \rho'(t)],$$

TDHF equation

Energy density functional with Skyrme *interactions*

$$\mathcal{E}(\rho) = \frac{\hbar^2}{2m}\tau + C_0\rho^2 + D_0\rho_3^2 + C_3\rho^{\sigma+2} + D_3\rho^\sigma\rho_3^2 + C_{eff}\rho\tau + D_{eff}\rho_3\tau_3 + C_{surf}(\bigtriangledown\rho)^2 + D_{surf}(\bigtriangledown\rho_3)^2, \quad (2)$$

isoscalar $\rho = \rho_n + \rho_p$, and isovector, $\rho_3 = \rho_n - \rho_p$

kinetic energy densities $(\tau = \tau_n + \tau_p, \tau_3 = \tau_n - \tau_p)$

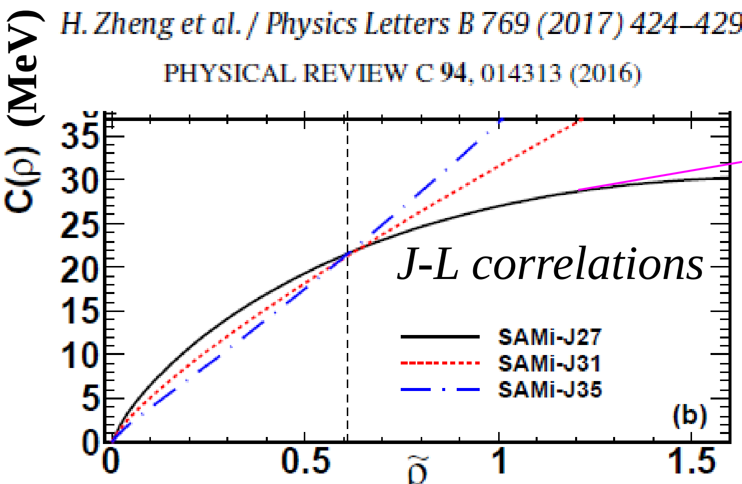
9 parameters → 9 nuclear properties can be fixed

Connecting the reaction dynamics to nuclear properties

No	EoS	ρ_0 (fm^{-3})	E_0 (MeV)	K_0 (MeV)	J (MeV)	L (MeV)	m_s^*/m	m_v^*/m	f_I	G_S	G_V
	SAMi-J27	0.160	-15.93	245	27	30	0.675	0.664	-0.0251	149.2	-8.6
S1	SAMi-J31	0.156	-15.83	245	31	74	0.675	0.664	-0.0251	140.9	3.1
	SAMi-J35	0.154	-15.69	245	35	115	0.675	0.664	-0.0251	131.1	15.4

H. Zheng et al. / Physics Letters B 769 (2017) 424–429

PHYSICAL REVIEW C 94, 014313 (2016)



SAMi-J:

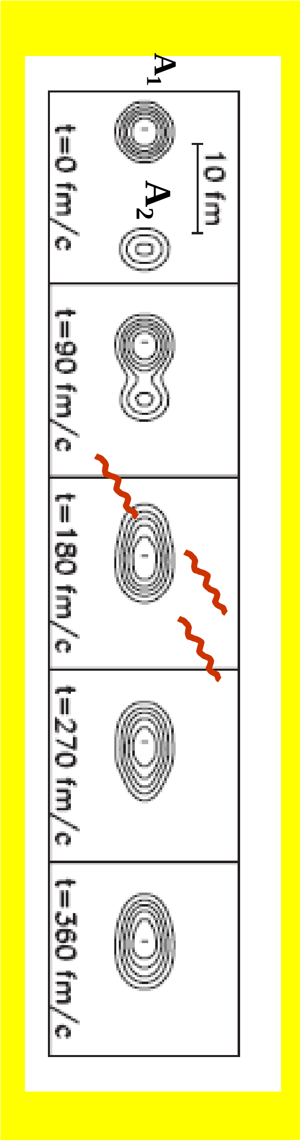
X. Roca-Maza, G. Colò, H. Sagawa, Phys. Rev. C **86**, 031306(R) (2012); X. Roca-Maza *et al.*, Phys. Rev. C **87**, 034301 (2013).

SAMi-J:
changing the symmetry energy slope

Taking SAMi-J31 as a reference:
consider interactions with different
- compressibility
- effective mass
- n/p effective mass splitting
- surface terms

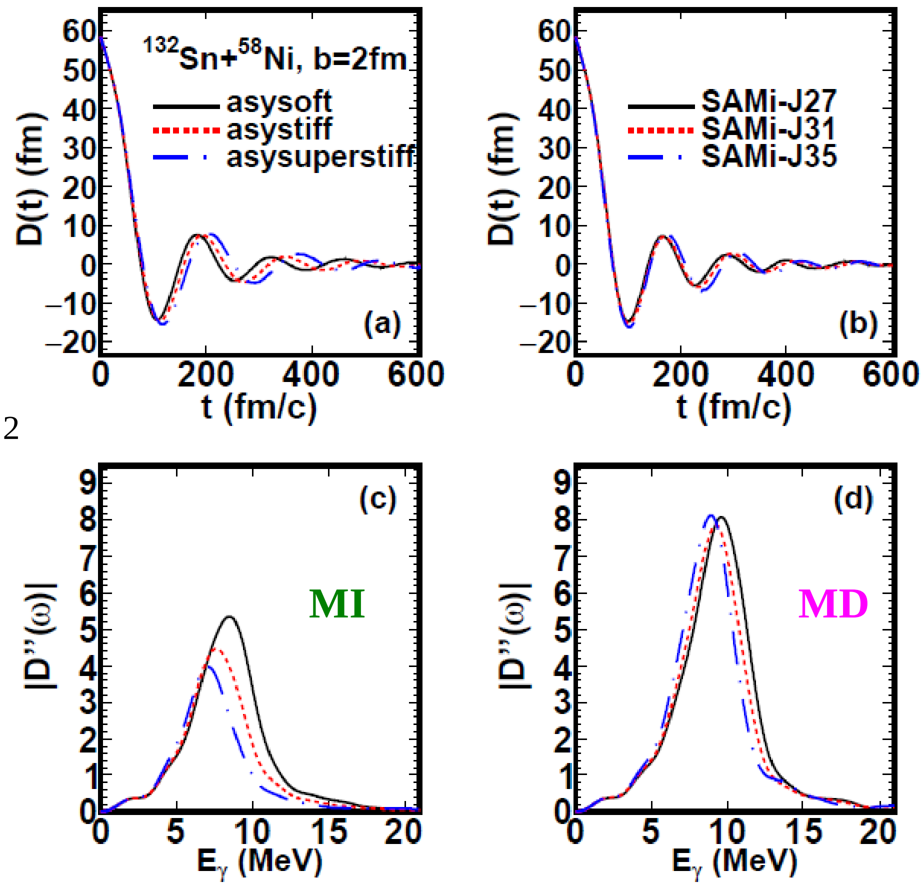
(ground state properties are affected by less than 5%)

Charge equilibration and dipole oscillations: dependence on the effective interaction



Vlasov calculations

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



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

H. Zheng et al. / Physics Letters B 769 (2017) 424–429

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

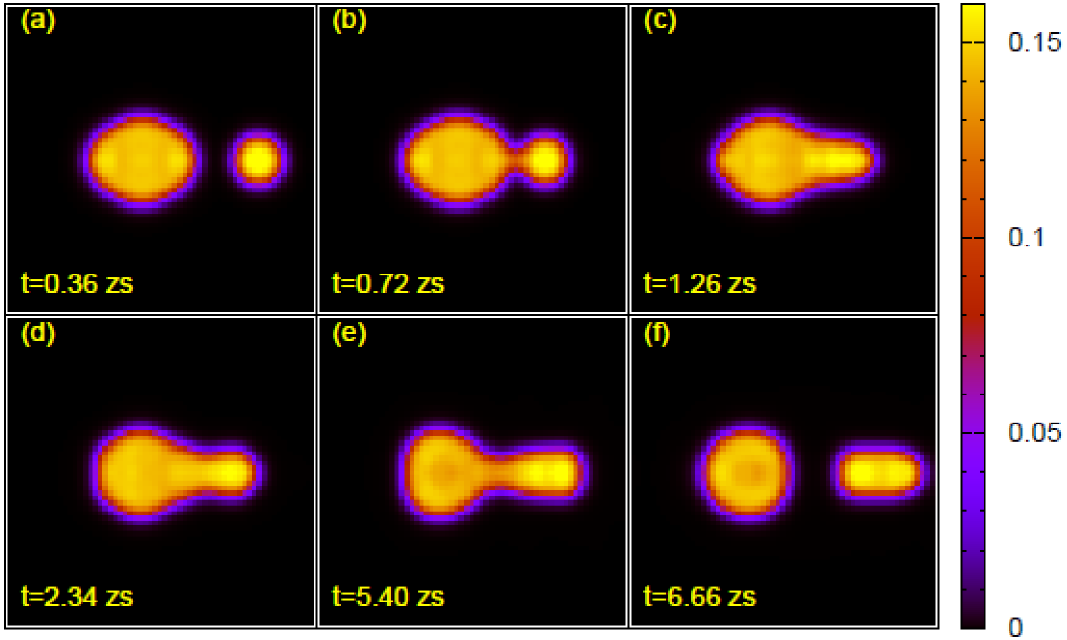
(damped harmonic oscillator)

- The DD emission looks sensitive to E_{sym} at ρ = 0.6 ρ_{sat}
- Larger strength seen in the MD case
- damping connected to n-n collision time (τ_{coll})

Fusion vs quasi-fission: TDHF simulations

$^{238}\mathrm{U}+^{40}\mathrm{Ca}$ at $E_{cm} = 203$ MeV

at the threshold between fusion and quasi-fission



- Sensitivity of sub-barrier fusion cross section to EOS ingredients

→ *P-G Reinhard et al.* PHYSICAL REVIEW C **93**, 044618 (2016)

tip collisions

^{238}U is deformed:

→ sensitivity to projectile-target orientation (side or tip)

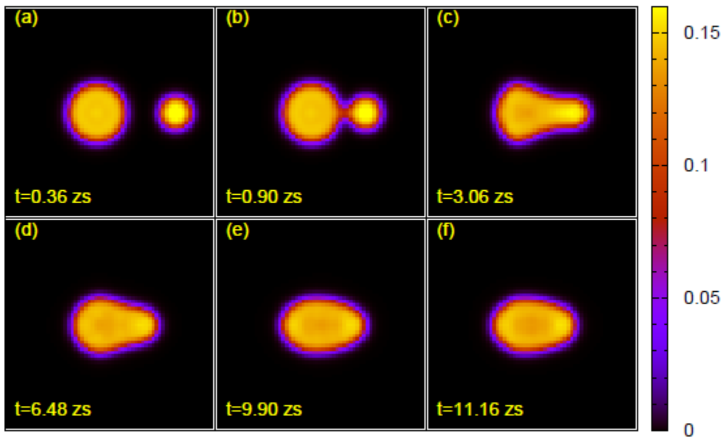
→ quasi-fission observed for the tip configuration

V. E. Oberacker, A. S. Umar and C. Simenel, Phys. Rev. C **90**, 054605 (2014).

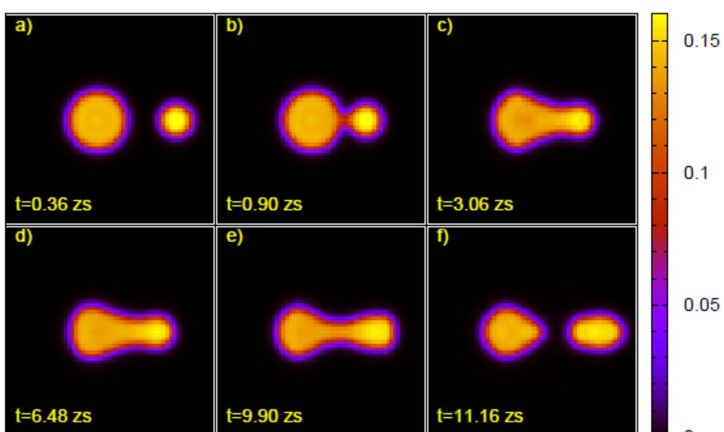
TDHF simulations

$^{238}\mathrm{U}+^{40}\mathrm{Ca}$ at $E_{cm} = 203$ MeV

side collisions



SAMi-J31

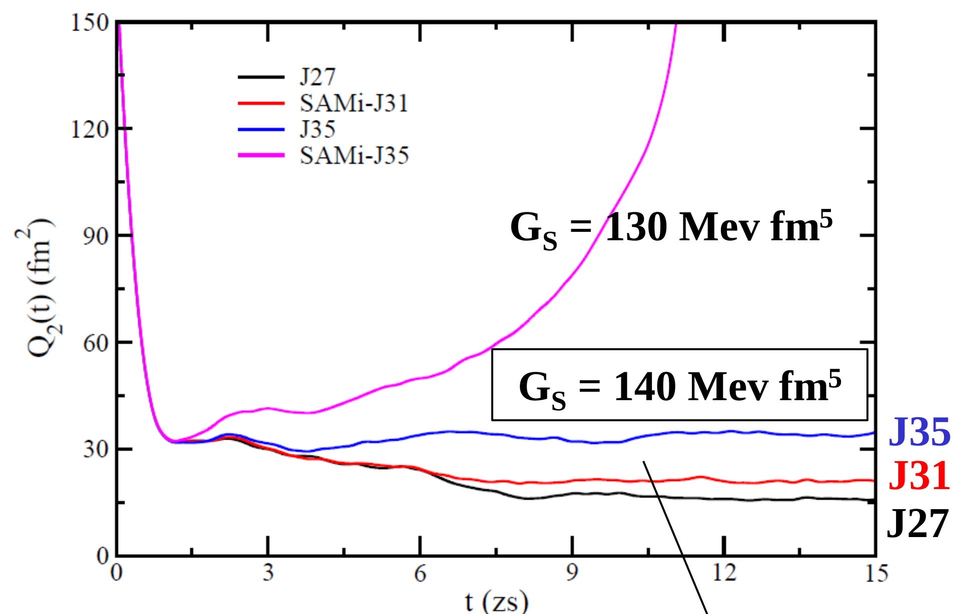


SAMi-J35

quadrupole moment evolution

$$Q_2(t) = \langle 2x^2 - y^2 - z^2 \rangle$$

x
beam axis



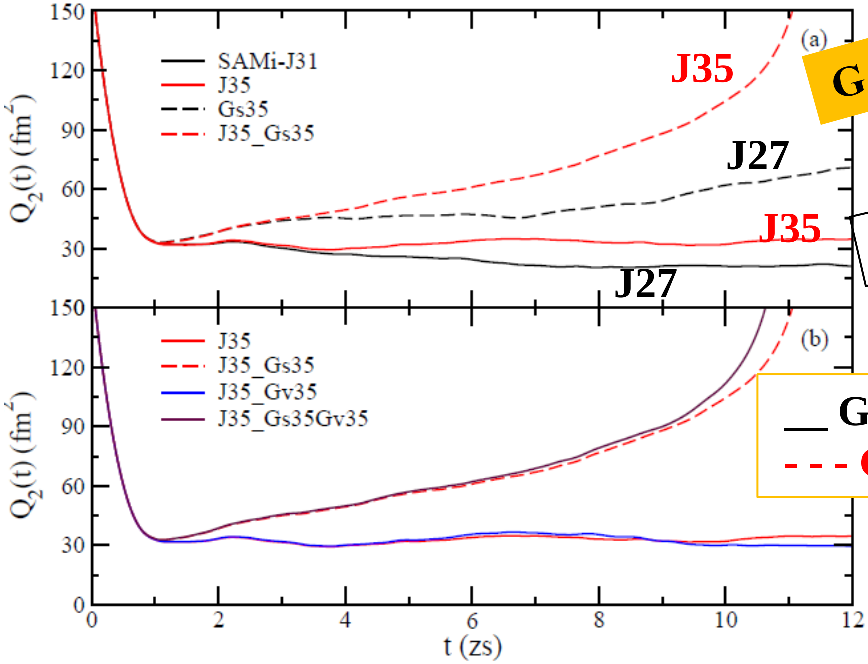
➢ **symmetry energy effects**

Larger effects are due to the surface term !

TDHF simulations

$^{238}U + ^{40}Ca$ at $E_{cm} = 203$ MeV

side collisions



$G_S = 130$ Mev fm^5

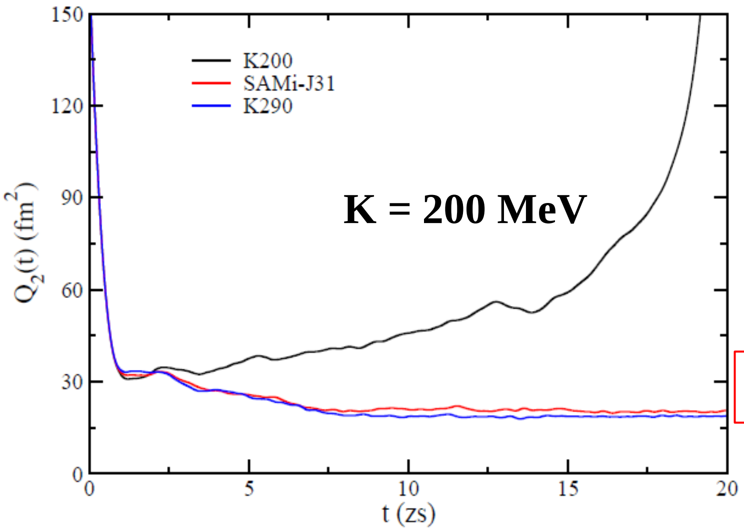
$G_S = 140$ Mev fm^5

— $G_S = 130$ Mev fm^5, $G_V = 15$ MeV fm^5

- - - $G_S = 130$ Mev fm^5, $G_V = 3$ MeV fm^5

➢ **Surface effects**

Isoscalar surface term → large effects



K = 240 MeV

K = 290 MeV

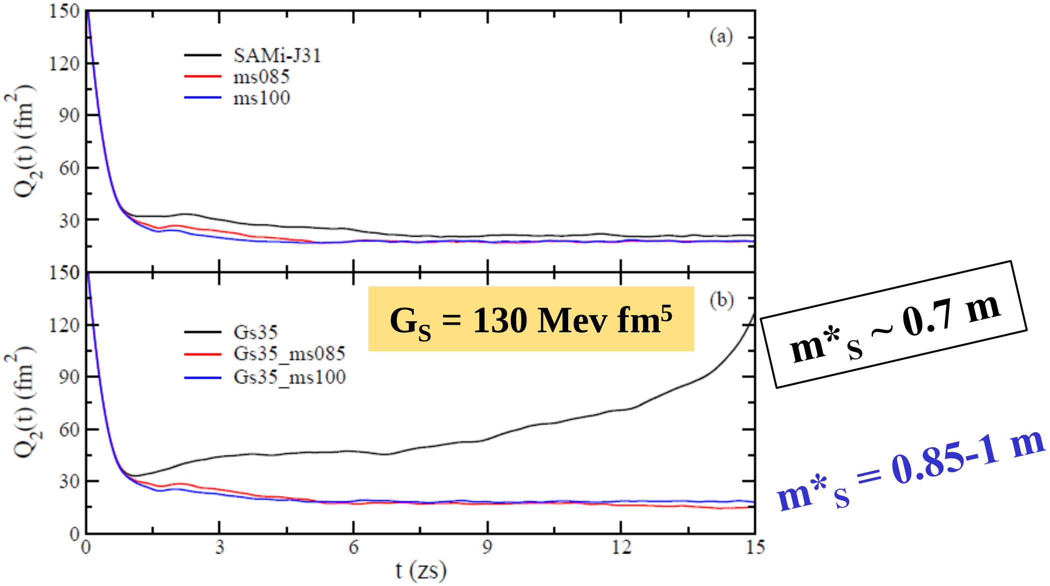
➢ **Compressibility effects**

Nuclear compressibility →
large effects

TDHF simulations

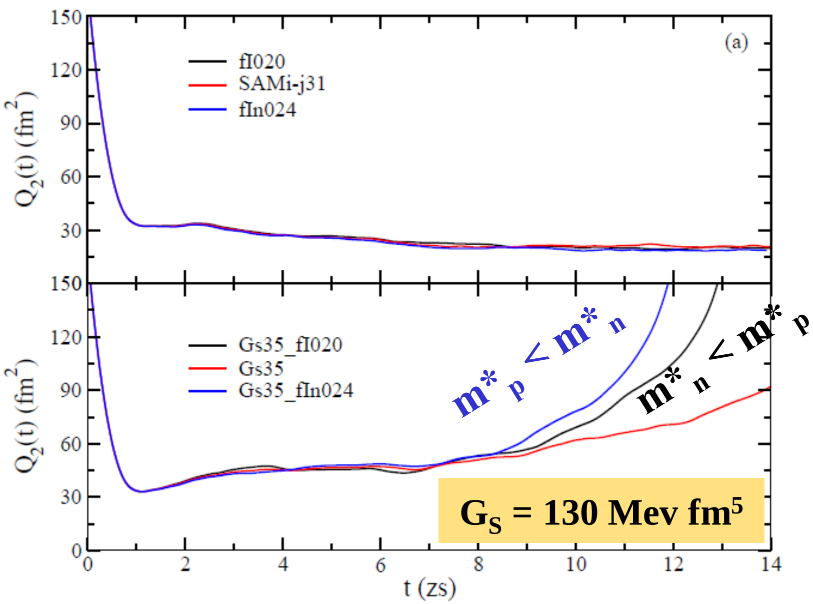
$^{238}U+^{40}Ca$ at $E_{cm} = 203$ MeV

side collisions



➢ Isoscalar effective mass

With increased **effective mass** :
→ jump from quasi-fission to fusion



➢ Isovector effective mass

With increased **effective mass splitting**:
→ faster quasi-fission

❑ Conclusions

Dissipative reactions at low energies open the opportunity to learn about fundamental properties of the nuclear effective interaction, of interest also in the astrophysical context

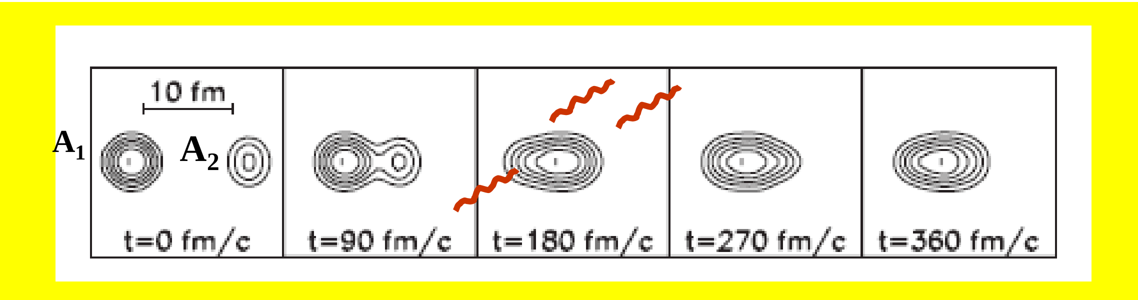
➢ Competition between fusion and quasi-fission

Reaction mechanisms at the borderline with nuclear structure:

- In ^{40}Ca + ^{238}U reactions at energies close to the Coulomb barrier an important sensitivity is observed to nuclear EoS properties: surface - compressibility – effective mass – symmetry energy

Collaborators: **Hua Zheng** (LNS), S. Burrello (LNS & Seville), D. Lacroix (IPN-Orsay), G. Scamps (Tsukuba Univ.)

➢ Charge equilibration 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**

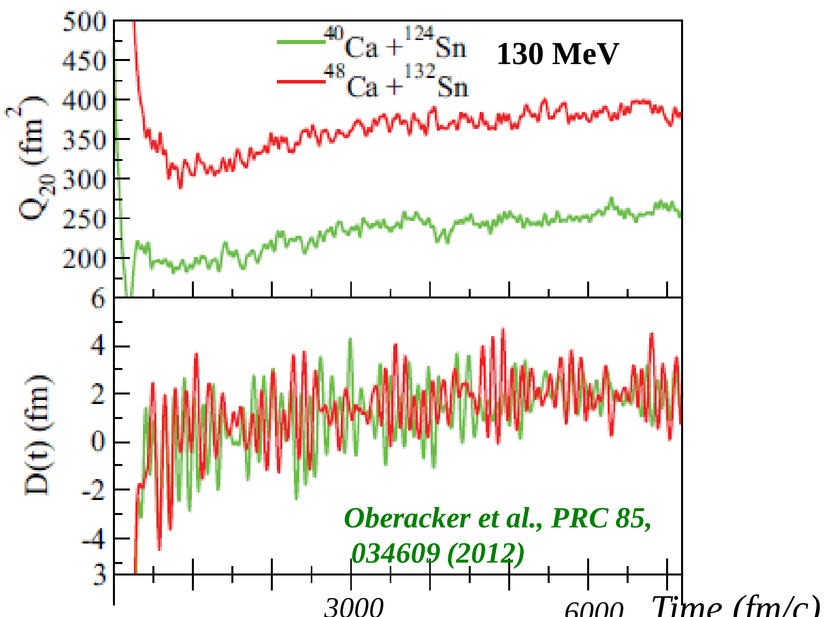
If $N_1/Z_1 \neq N_2/Z_2$

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

+ 2-body collisional damping

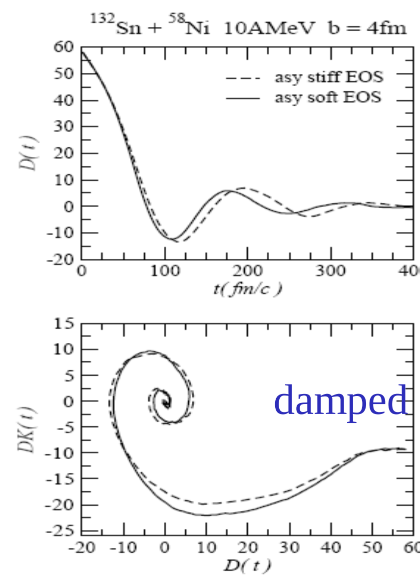
$$D(t) \equiv \frac{NZ}{A}\left[X_p(t) - X_n(t)\right] \rightarrow X_{p,n} \equiv \frac{1}{Z,N}\Sigma x_i^{p,n}$$

TDHF calculations



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

Semi-classical simulations



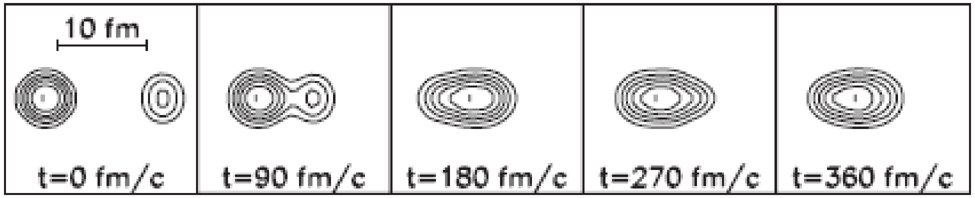
^{132}Sn + ^{58}Ni , D_0 = 45 fm
E/A = 10 MeV

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 (low density)



- Cooling mechanism in the formation of Super Heavy Elements (SHE)

➢ **Theory**: a more systematic study of the sensitivity of this mechanism to the ingredients 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)