Description of reaction dynamics
-from low to Fermi energies-
with stochastic semi-classical approaches

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Nuclear Structure Physics, Reactions, Astrophysics and Superheavy Elements Network

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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, BLOB) and effective interactions

- Some examples of suitable low- and Fermi-energy (E/A ~ 10-50 MeV/A) reaction mechanisms: from deep-inelastic to fragmentation

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

(Beyond) 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, 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**

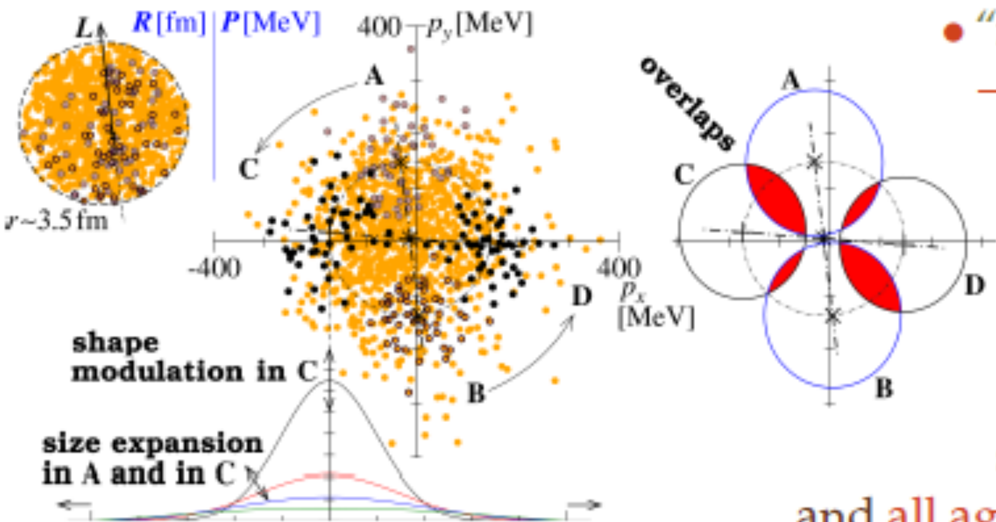
Boltzmann-Langevin One Body (**BLOB**) model :
*fluctuations implemented in full phase space – full **BL** approach*

W.Bauer,G.F.Bertsch,S.DasGupta,PRL58,863(1987)

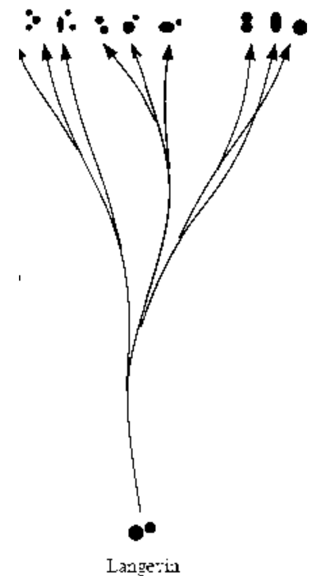
Rizzo,Chomaz,Colonna, NPA 806,40(2008)
Napolitani and Colonna, PLB 726,382(2013)

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

test particles



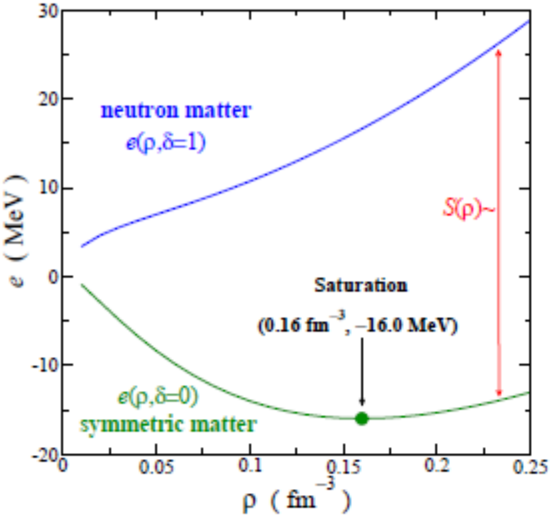
- *"nucleon wave packets"* → → *phase-space agglomerates* of N_{test} test-particles of equal isospin ($a \in A, b \in B \ldots$)
- at each Δt : all phase space is scanned for collisions and all agglomerates are redefined



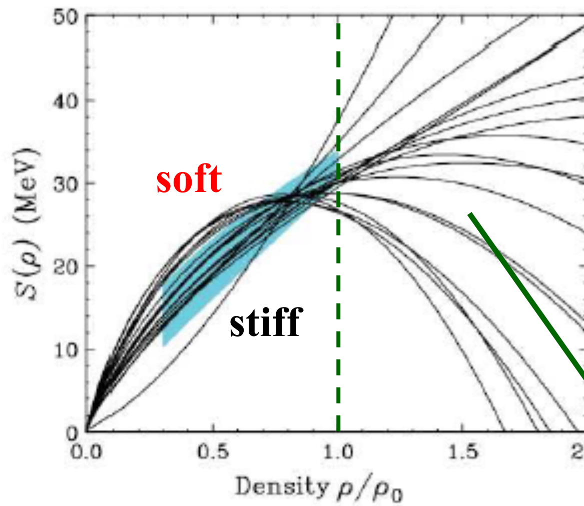
- Nucleons packets are moved once a collision happens
- Shape modulation of the packet ensures Pauli blocking is respected

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

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

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

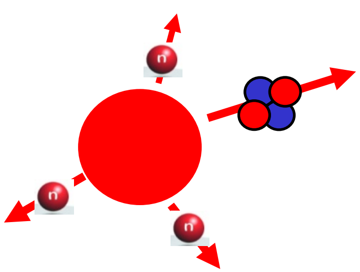
- analogy with **Weizsacker mass formula** for nuclei (symmetry term) !

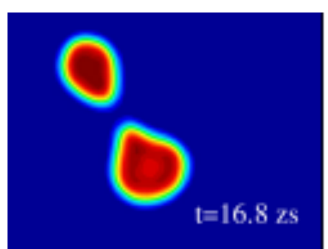
Low-energy reaction mechanisms: a study within mean-field models

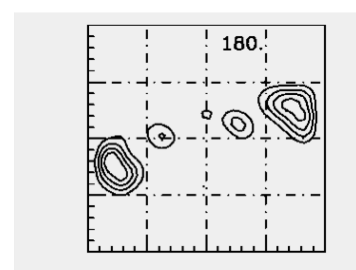
(Fermi energies)

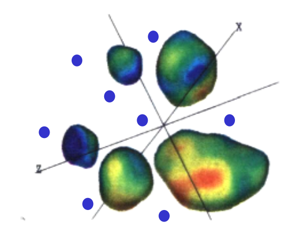
- **Charge equilibration**
- **Fusion vs Quasi fission or Deep Inelastic**

- **Fragmentation**
- **Fragment isotopic composition**

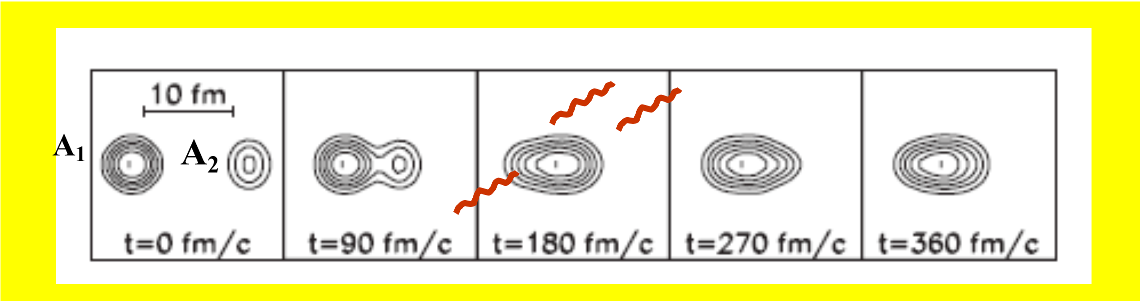








➢ *Charge equilibration in heavy ion reactions (Dyn. Dipole)*



TDHF calculations

Simenel et al, PRC 76, 024609 (2007)

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

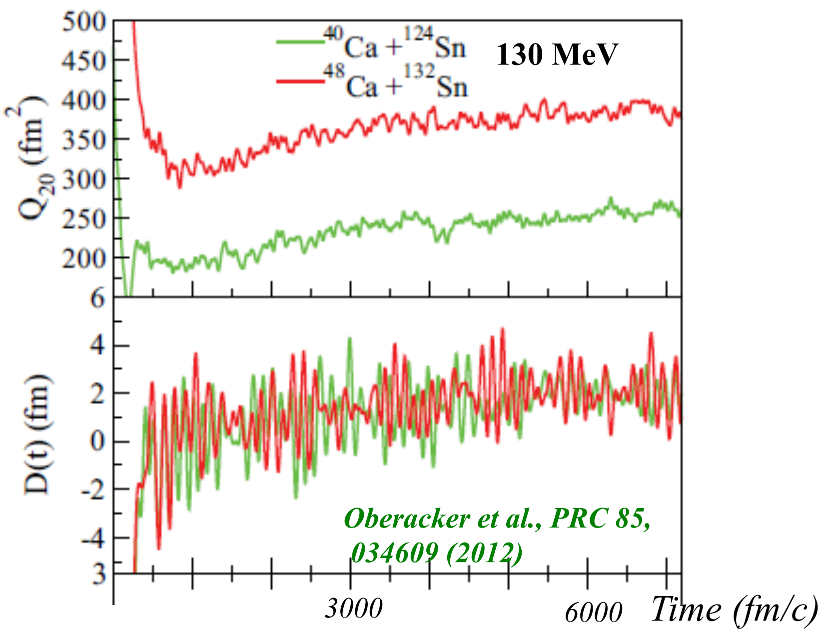
If $N_1/Z_1 \neq N_2/Z_2$

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

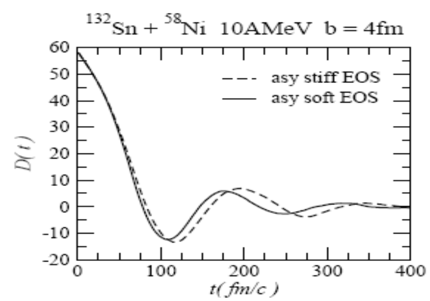
+ 2-body collisional damping

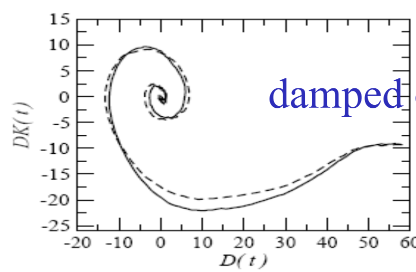
$$D(t) \equiv \frac{NZ}{A}\left[X_p(t) - X_n(t)\right] \rightarrow X_{p,n} \equiv \frac{1}{Z,N}\Sigma x_i^{p,n}$$

Semi-classical simulations



TDHF calculations





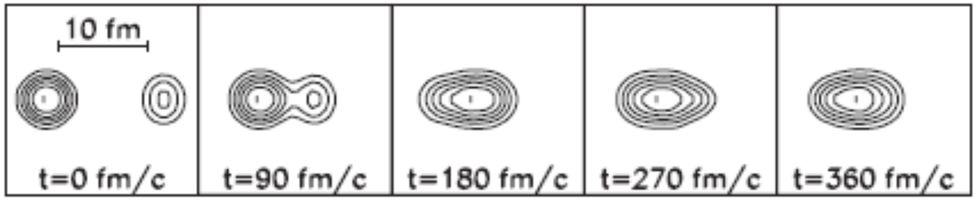
damped oscillations

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

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)



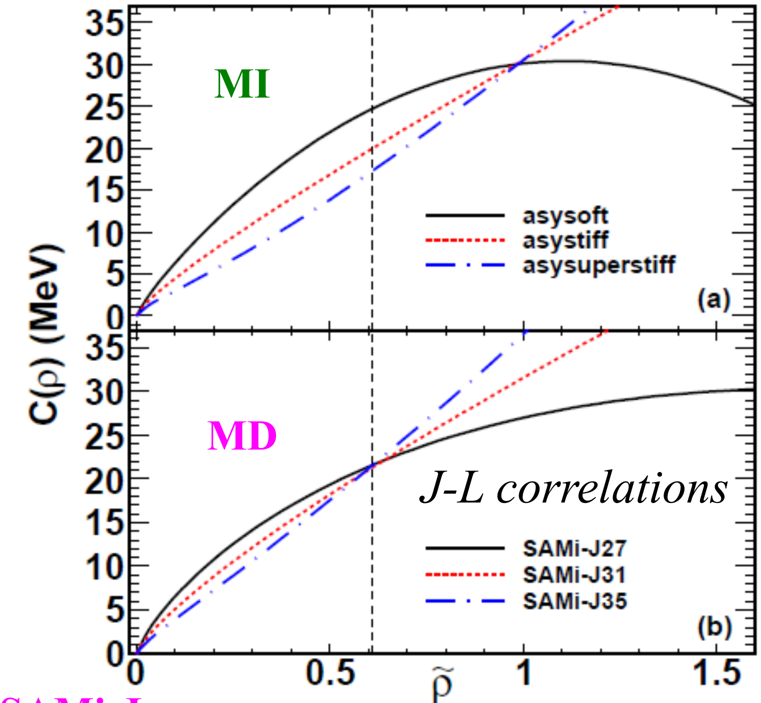
- Cooling mechanism in the formation of Super Heavy Elements (SHE)

➢ **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 ???

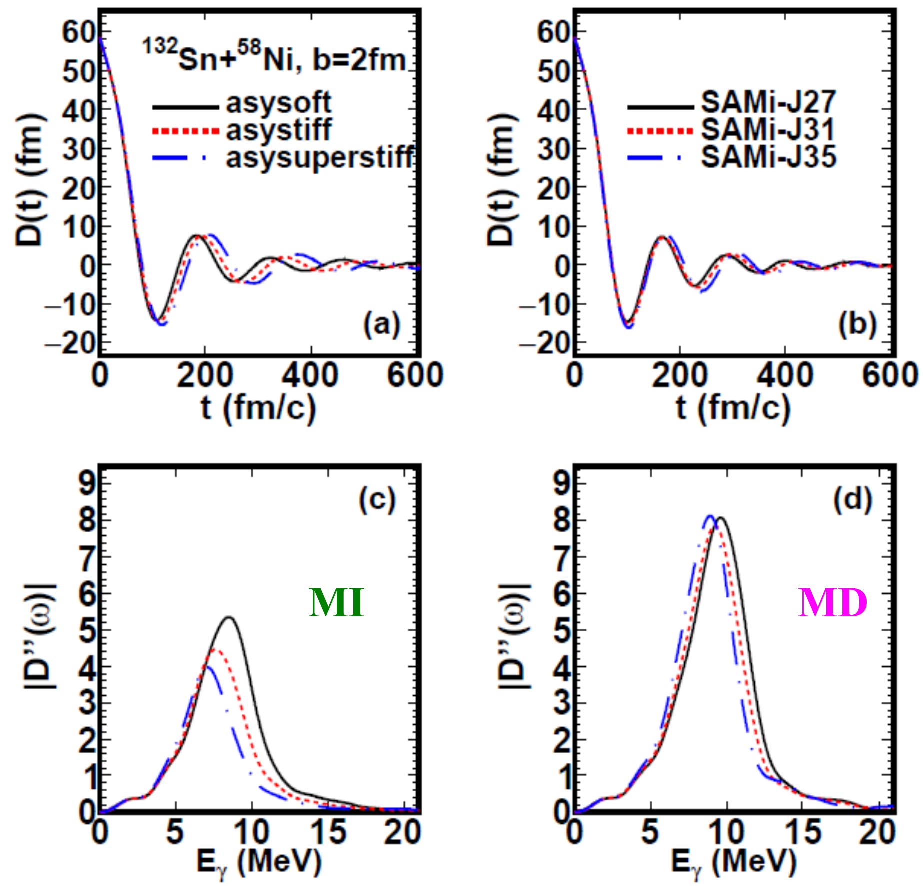
→ DD in the fusion-evaporation of the ^{40}**Ca** + ^{152}**Sm** heavy system, C.Parascandolo et al., PRC 93, 044619(2016)

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



DD oscillations: dependence on the effective interaction

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



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

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

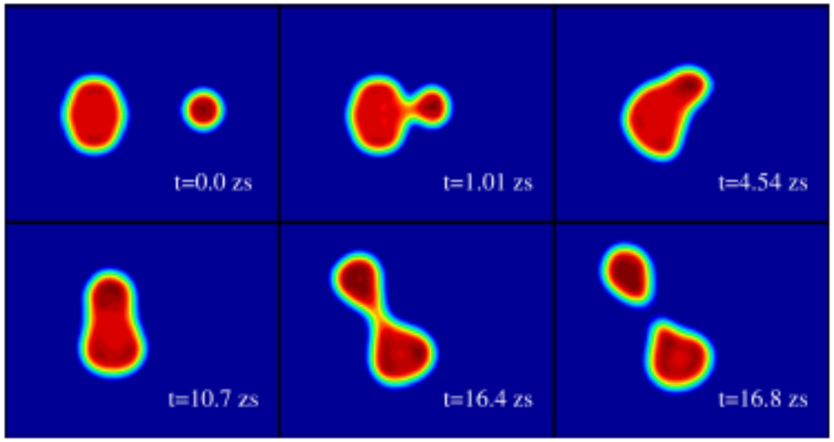
$$P_\gamma \approx D_0^2 E_{centr}^3 \tau_{coll}$$

(damped harmonic oscillator)

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

Fusion vs. Quasi Fission: towards the synthesis of SHE

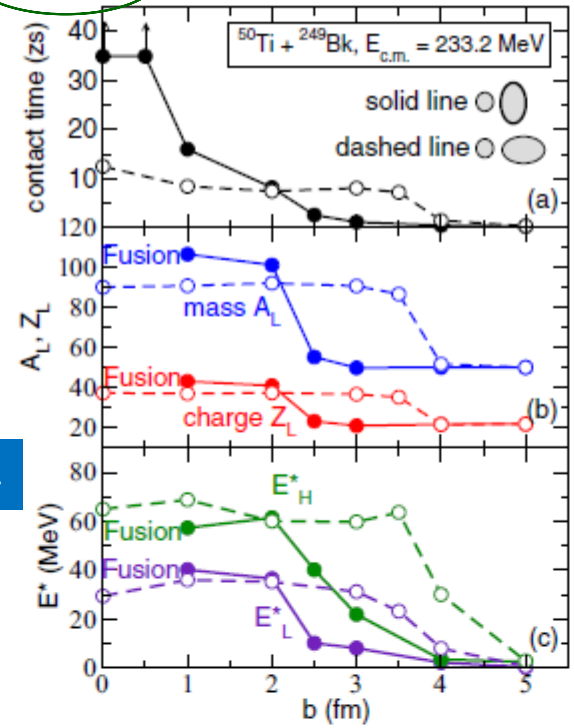
$^{50}Ti + ^{249}Bk$ 233 MeV



PHYSICAL REVIEW C 94, 024605 (2016)

Umar, Oberacker, Simenel

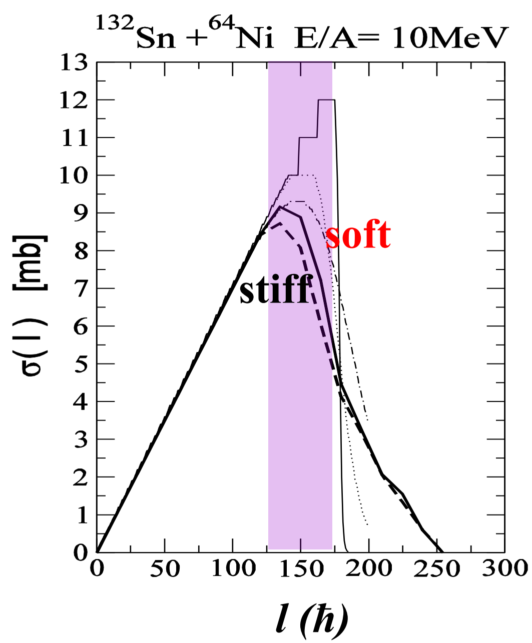
FUSION



tip

side

TDHF calculations



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

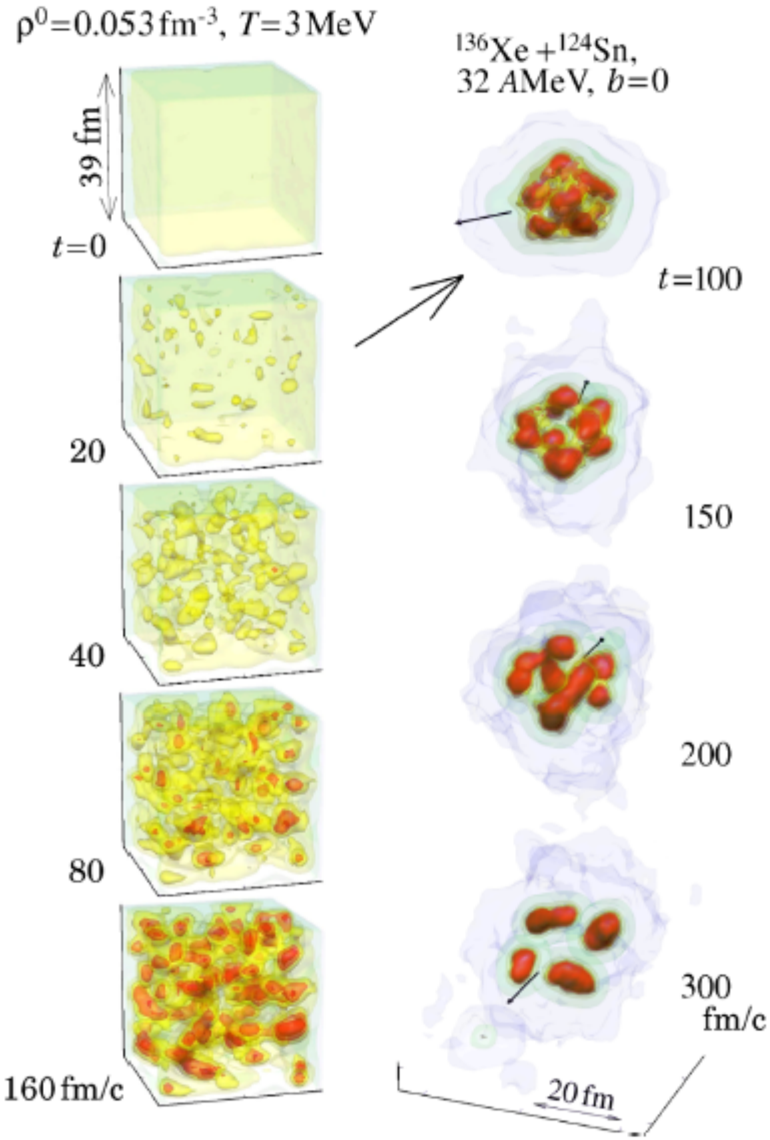
- Fusion probability depends on the deformation/orientation of colliding nuclei

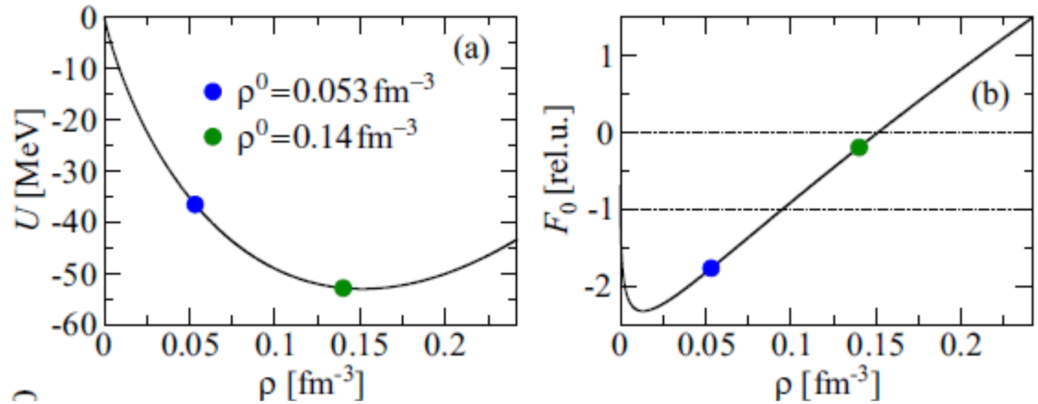
➢ Possible symmetry energy effects ??

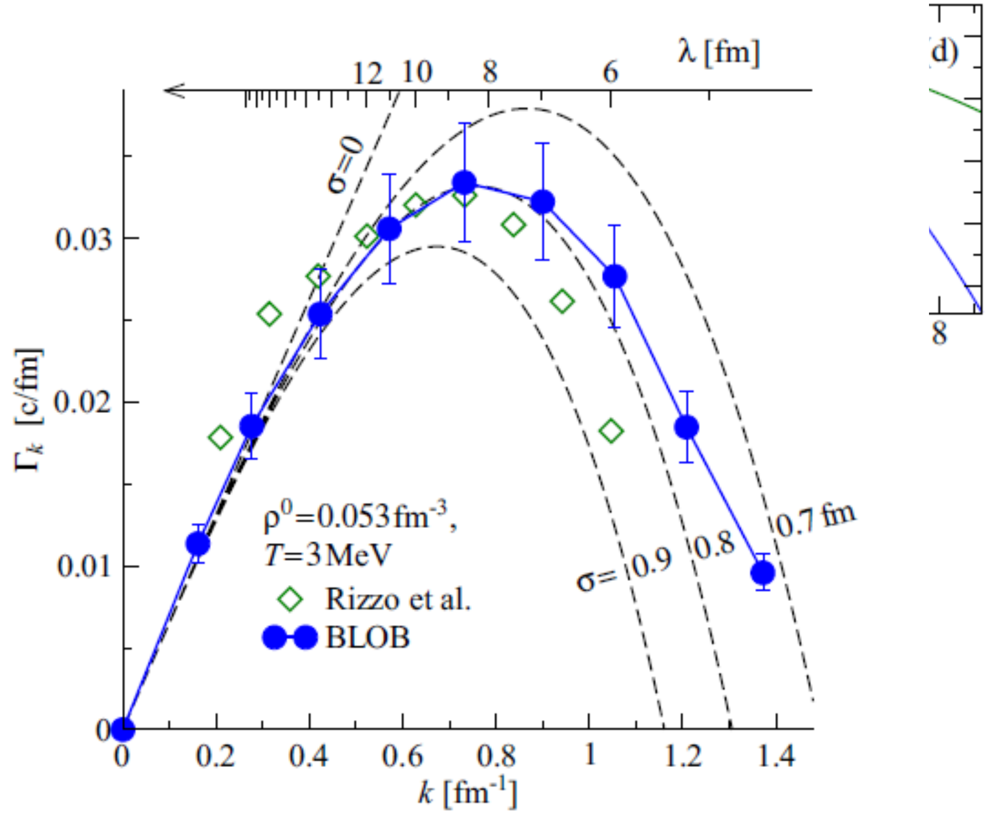
Semi-class. calculations with neutron rich systems

Fragmentation: the onset of instabilities in nuclear matter

Napolitani and Colonna, PHYS REV C 96, 054609 (2017)



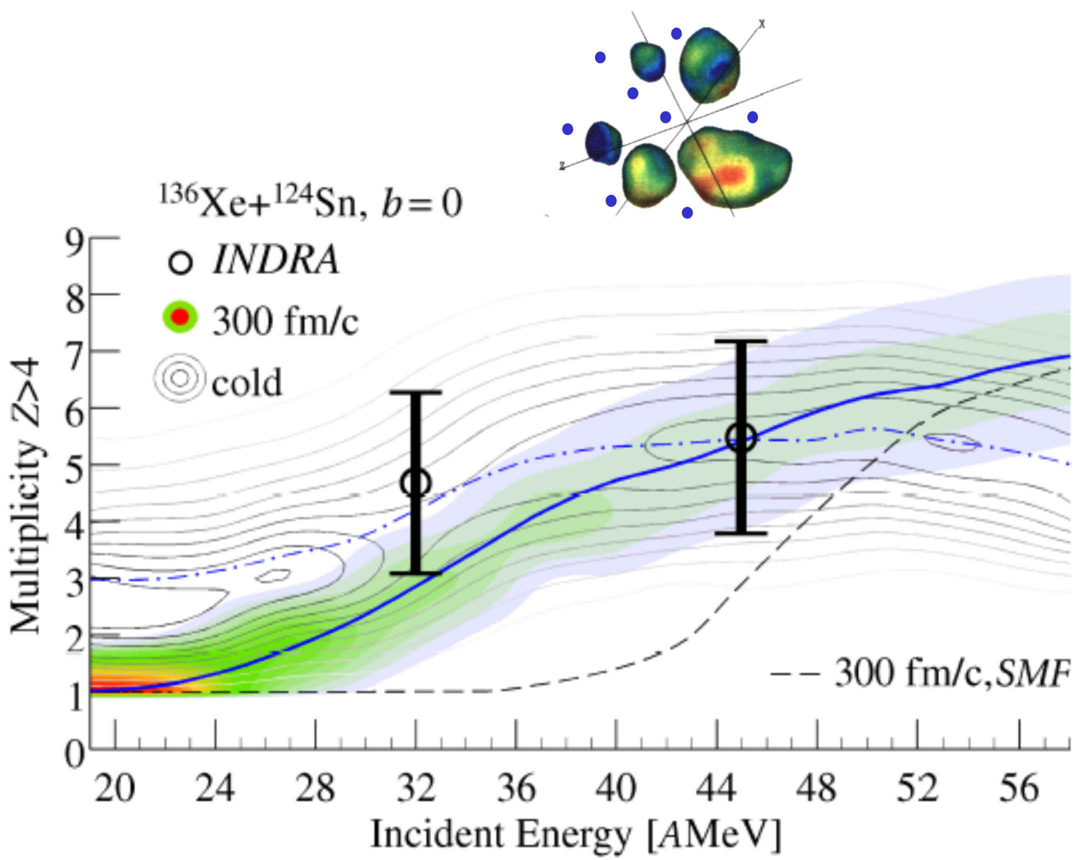




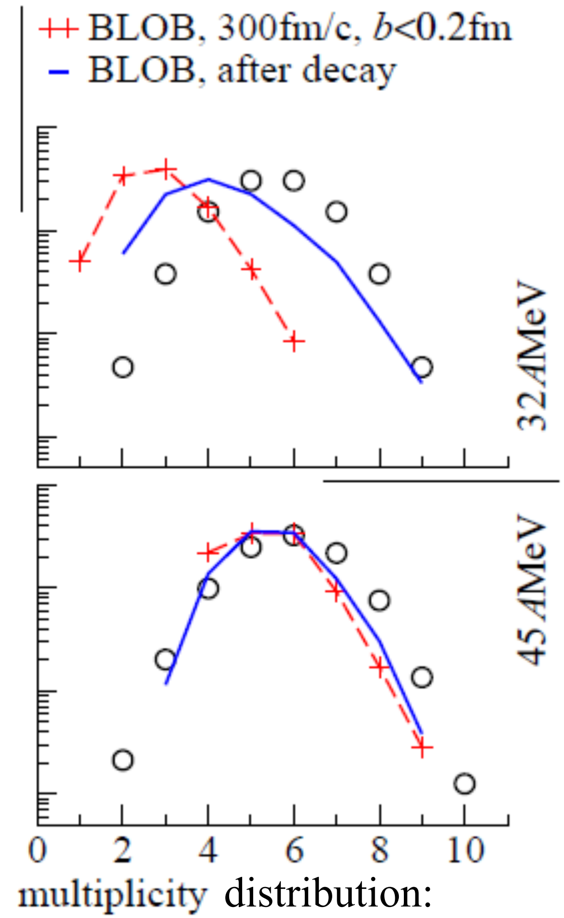
BLOB results: Dispersion relation

Colonna, Napolitani, Baran, IJMP E (2018)

BLOB simulations:
Fragment multiplicity in central heavy ion reactions at Fermi energies



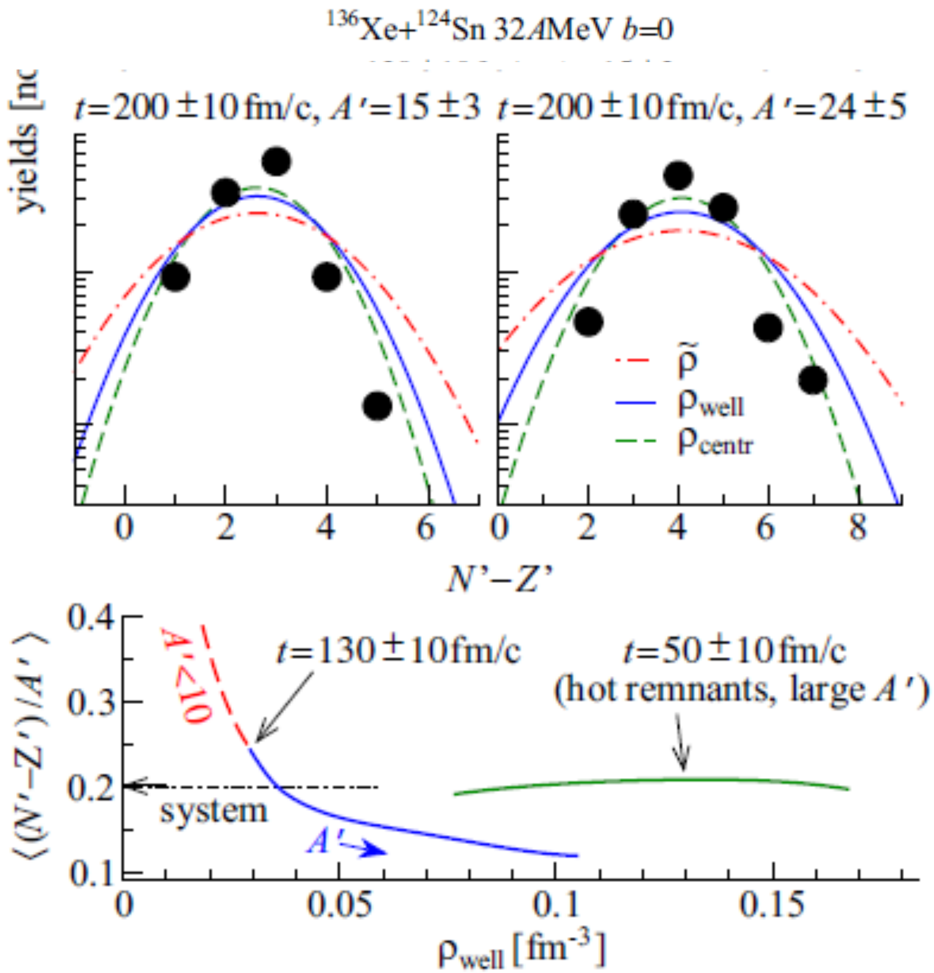
G. Ademard et al. (INDRA Collaboration), Eur. Phys. J. A **50**, 33 (2014).



Comparison with INDRA data (dots)

Napolitani and Colonna, PHYS REV C 96, 054609 (2017)

BLOB simulations: Fragment isotopic features in central heavy ion reactions at Fermi energies



→ The width of isotopic distributions (dots) is related to the symmetry energy at low density (in agreement with analytical expectations – lines)

$$Y \approx \exp[-(\delta^2/A')C_{sym}(\rho)/T].$$

M.B. Tsang et al., Phys. Rev. Lett. **102**, 122701 (2009).

→ Isospin "distillation": The gas phase is neutron richer than the liquid phase

❑ Conclusions

Dissipative reactions (at low and Fermi energies) 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 on pre-equilibrium gamma ray emission and competition between reaction mechanisms

-Perspective: n-skin, g.s. deformation effects

(Coll. IPN-Orsay – LNS – Milano Univ. *within* Theos *of* ENSAR2*)*

➢ Fermi energies:

Fluctuation dynamics well reproduced by the BLOB model:

-link between fragment properties and ingredients of eff. interaction.

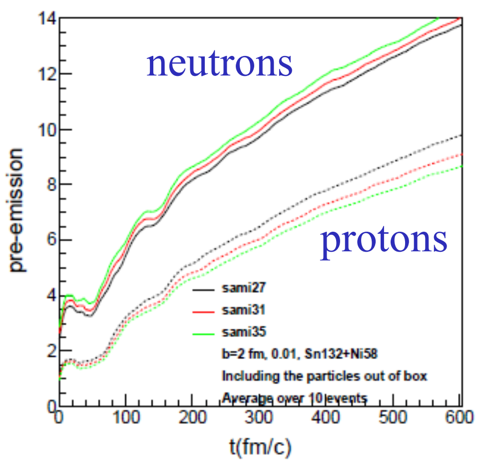
Collaborators: **Hua Zheng** (LNS), **Stefano Burrello** (LNS),
V.Baran (University of Bucharest, Romania),
P.Napolitani (IPN-Orsay, France)

Correlations: observables vs. parameters

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

A set of 8 parameterizations
in SMF simulations:
Skyrme (MI) and SAMi-J31
+ σ_{NN} = 40 mb, *0.5 or zero (no coll.)

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

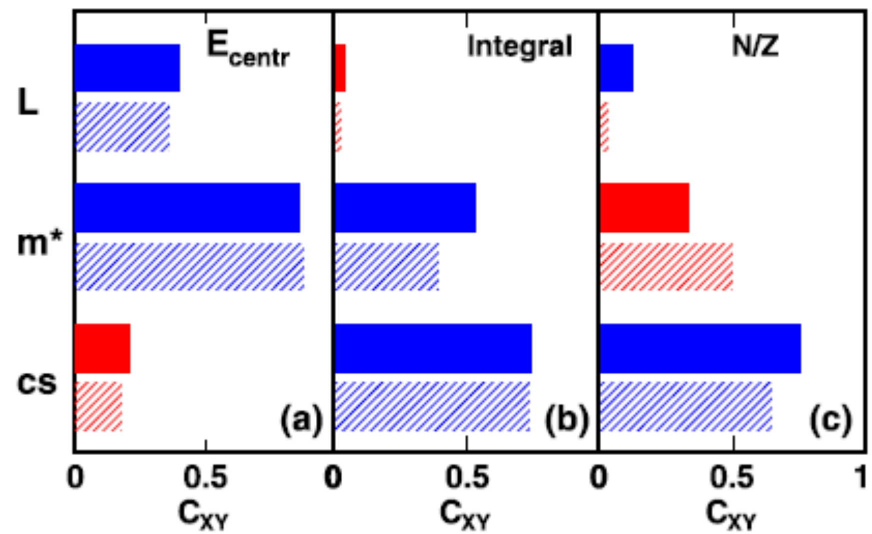
Covariance analysis

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)