Symmetry Energy Effects in low-energy Reaction Dynamics with Improved Transport Codes

NUSYM16

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Content

- Brief introduction to transport theories

- Low-energy reaction dynamics:

  Charge equilibration as a collective mechanism

Dynamics of many-body systems

Main ingredients:

- **Residual interaction (2-body correlations (2p-2h) 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

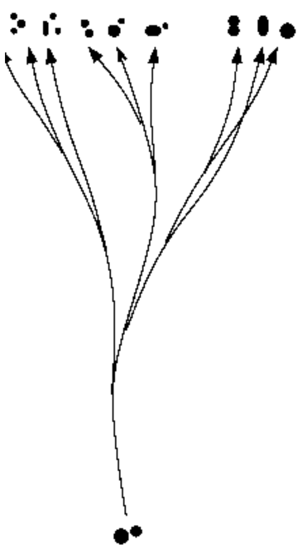
…MD

BUU, SMF

$$K = g \sum_{234} W(12;34) \left[\bar{f}_1 \bar{f}_2 f_3 f_4 - f_1 f_2 \bar{f}_3 \bar{f}_4 \right]$$

$$\bar{f} = 1 - f$$

Transition rate W interpreted in terms of NN cross section


Langevin

-- If statistical fluctuations larger than quantum ones

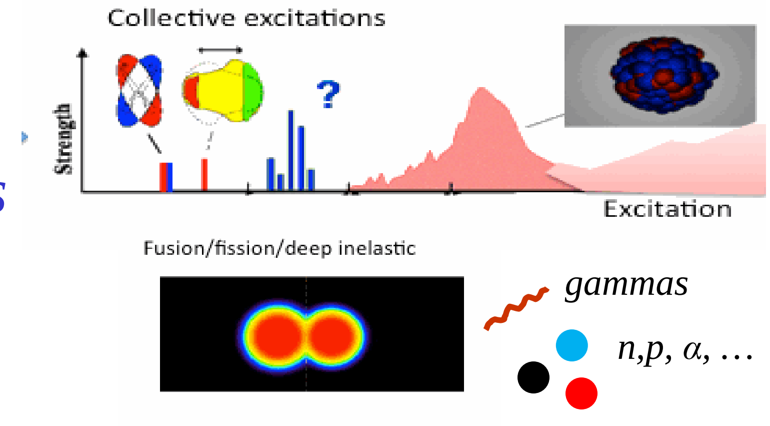
$$< \delta K(p,t) \delta K(p',t') >= C \delta(t - t')$$

$$C(\boldsymbol{p}_a, \boldsymbol{p}_b, \boldsymbol{r}, t) = \delta_{ab} \sum_{234} W(a2;34) F(a2;34)$$

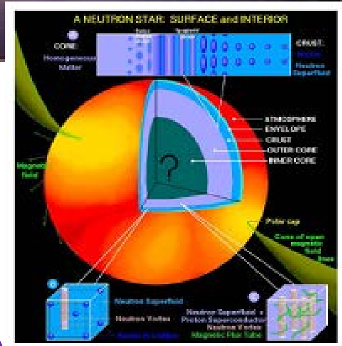
$$F(12;34) \equiv f_1 f_2 \bar{f}_3 \bar{f}_4 + \bar{f}_1 \bar{f}_2 f_3 f_4 .$$

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)*

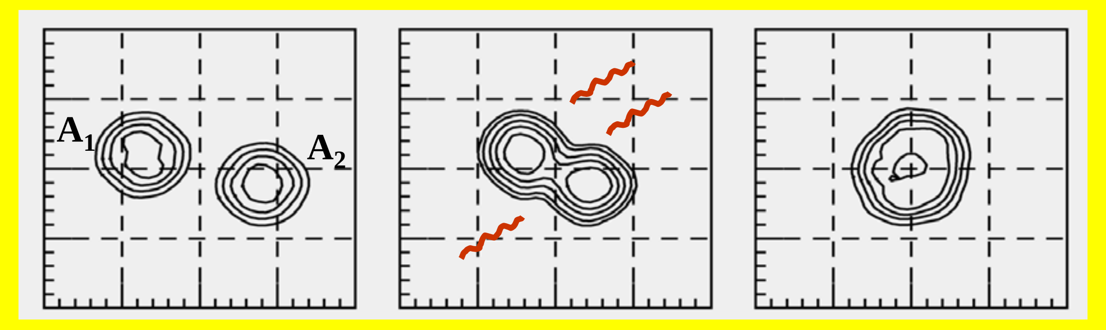
⟶ *Nuclear Equation of State* ***EOS***

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

Astrophysical implications …

Charge equilibration in low-energy reactions (E = 5-10 MeV/u)

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

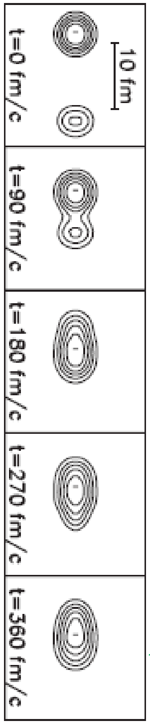


Initial Dipole **D(t) : bremss. dipole radiation** **CN: stat. GDR**

If $N_1/Z_1 \neq N_2/Z_2$

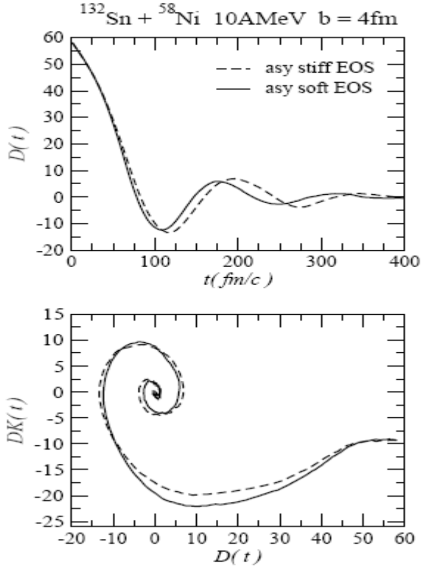
→ **Relative motion of neutron and proton centers of mass**

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



TDHF calculations

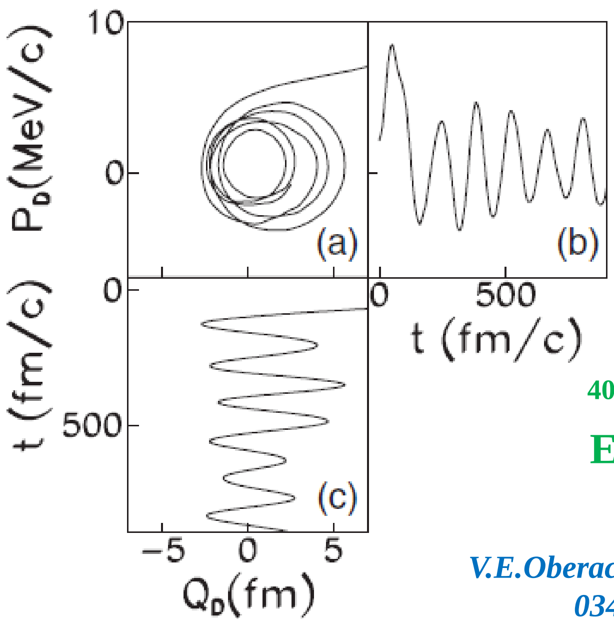
Simenel et al, PRC 76, 024609 (2007)



SMF simulations

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

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

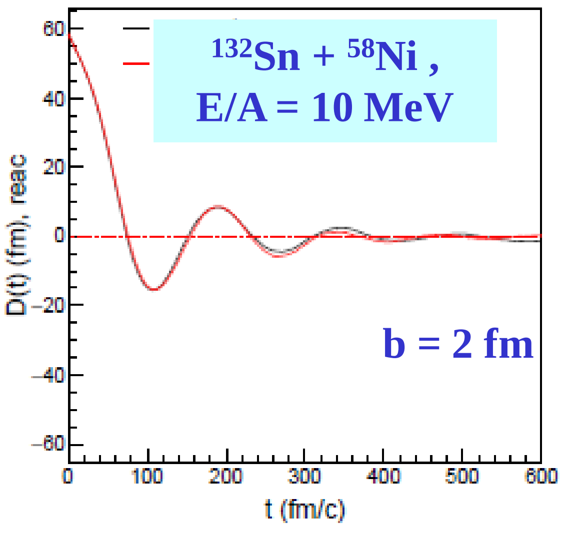


^{40}Ca + ^{100}Mo
E/A = 4 MeV

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

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

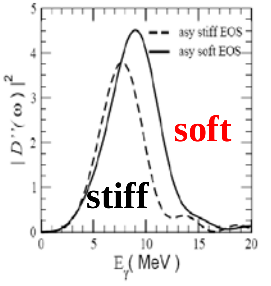
Dipole moment D



Bremsstrahlung: Quantitative estimation

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

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

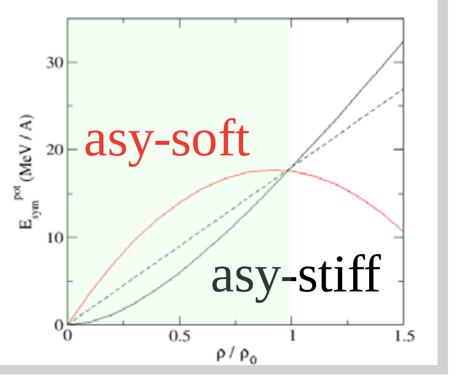


Damped harmonic oscillator:

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

→ *Energy-integrated yield* $P_\gamma \sim \omega_0^3 \tau D(t_0)^2$

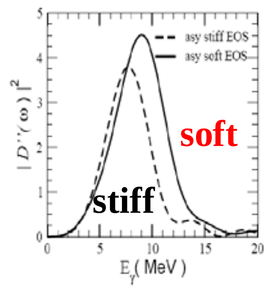
- Restoring force given by the **symmetry potential** → ω_0
- *Oscillations are inside an elongated system: smaller frequency with respect to GDR*
- γ emission probability sensitive to the damping τ → **n-n cross section**
- *Signal is enhanced in systems with a large initial dipole moment* **$D(t_0)$**



Dynamical dipole (DD) emission and symmetry energy

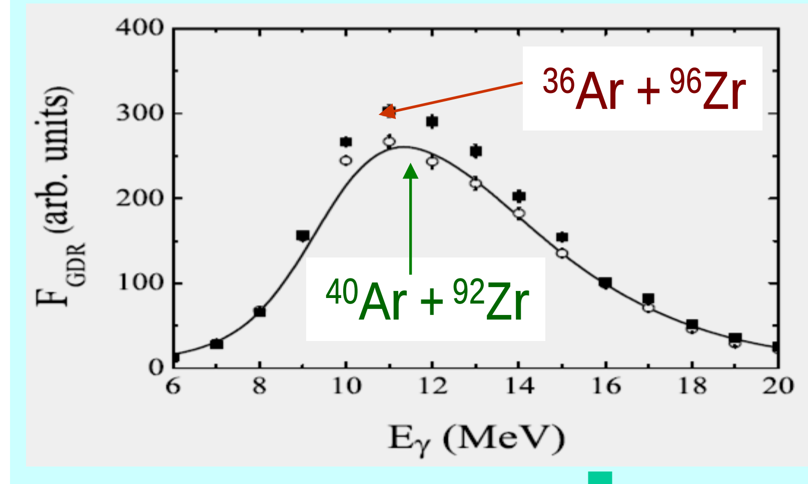
Bremsstrahlung:
Quantitative estimation

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

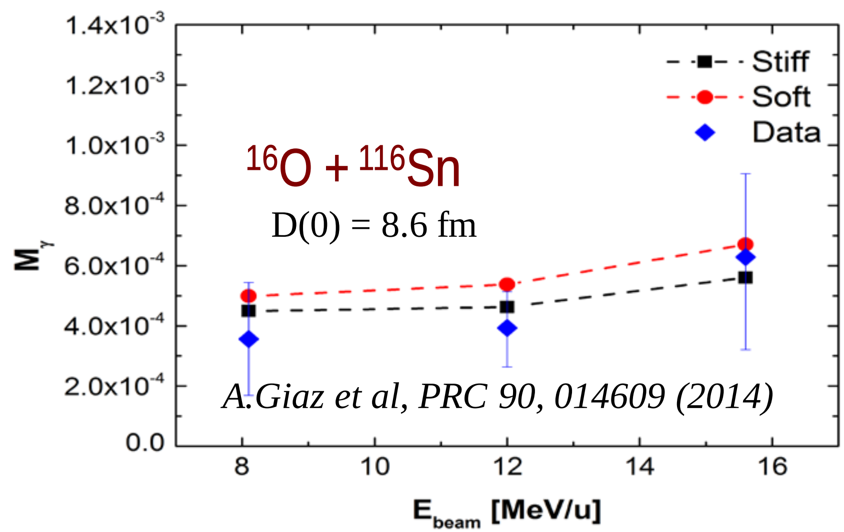


$$\frac{dP}{dE_\gamma} = \frac{2e^2}{3\pi\hbar c^3 E_\gamma}\left(\frac{NZ}{A}\right)^2 \left|X''(\omega)\right|^2$$

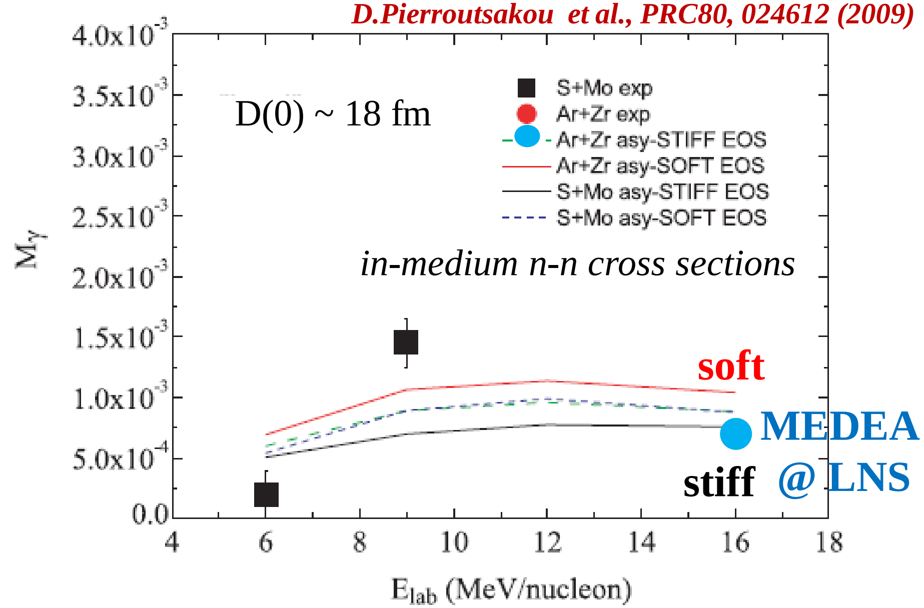
B.Martin et al., PLB 664 (2008) 47



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



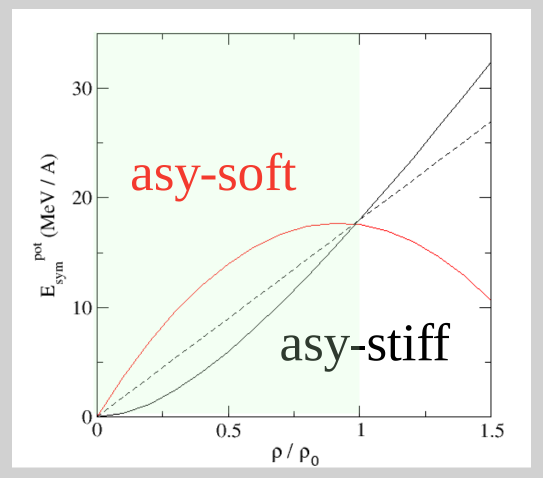
D.Pierroutsakou et al., PRC80, 024612 (2009)



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

→ DD in the fusion-evaporation of the **40Ca + 152Sm** heavy system, PRC 93, 044619(2016)

More refined calculations: a multi-dimensional analysis



Only symm. energy parametrizations which cross at normal density were considered in our previous calculations (fixed J)

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

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

or J

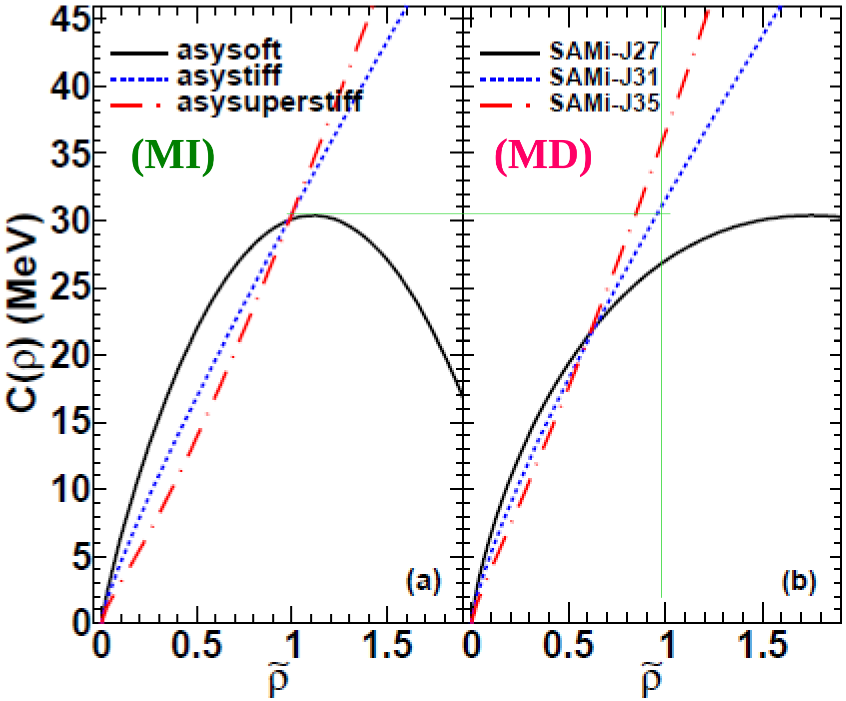
around normal density

o Explore the sensitivity to both J and L

o Explore the sensitivity to Nucleon.-Nucleon cross section

Look at:
- Dynamical Dipole (DD)
- pre-equilibrium particle emission

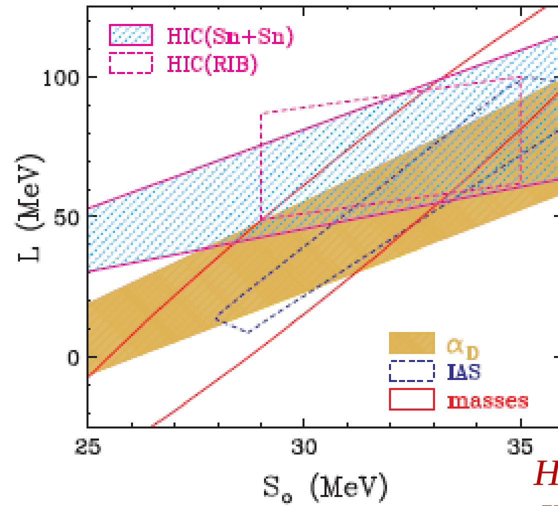
More refined calculations: a bidimensional E_{sym} analysis



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

or J

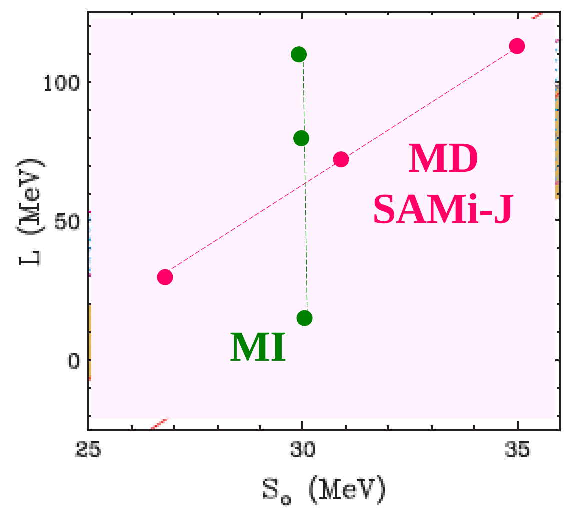
around normal density



Horowitz et al,
JPG 41,093001 (2014)

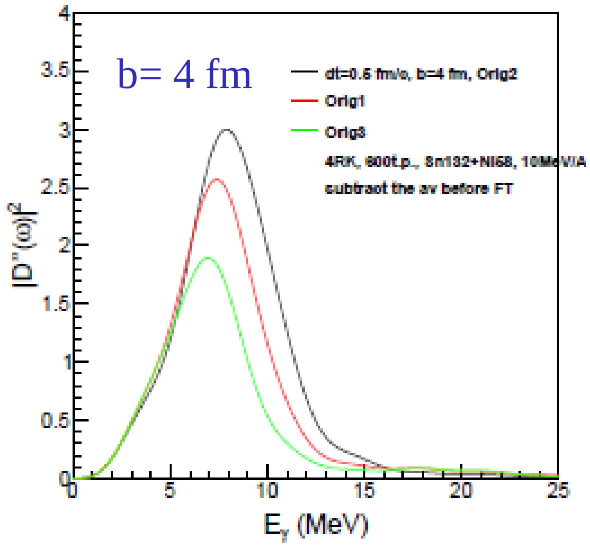
SAMi-J interactions:
Skyrme interactions
especially devised to improve the spin-isospin properties of nuclei

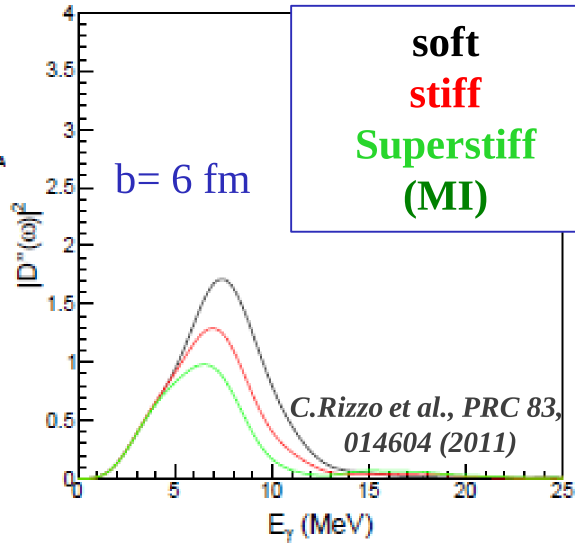
X. Roca-Maza, G. Colò, H. Sagawa, Phys. Rev. C **86**, 031306(R) (2012); X. Roca-Maza *et al.*, Phys. Rev. C **87**, 034301 (2013).



S_0 – L correlation

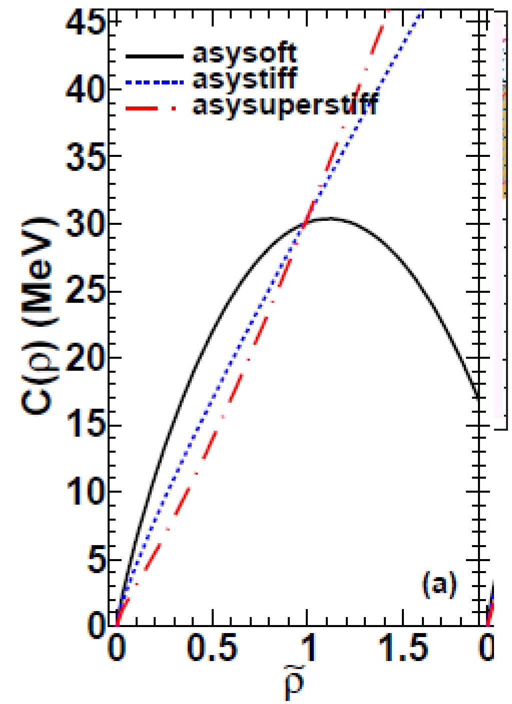
The pre-equilibrium dipole strength ^{132}Sn + ^{58}Ni, 10 MeV/A



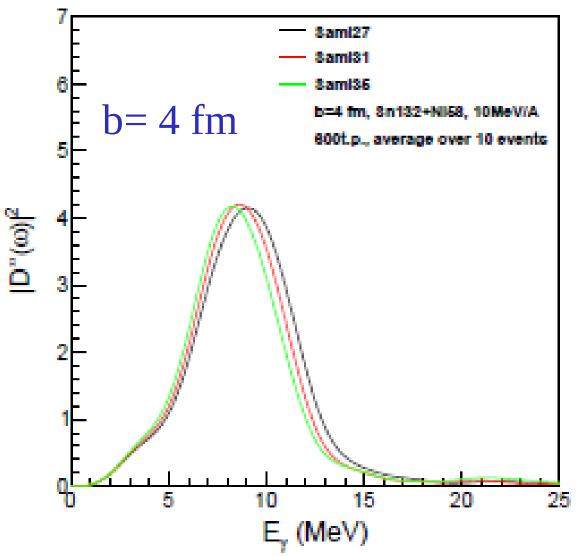


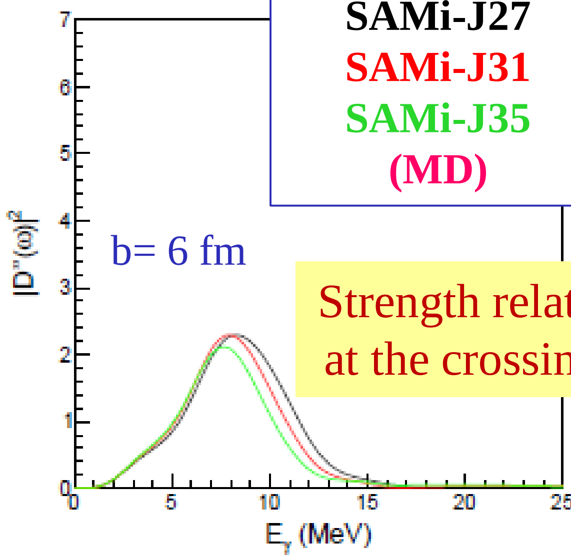
soft
stiff
Superstiff
(MI)

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



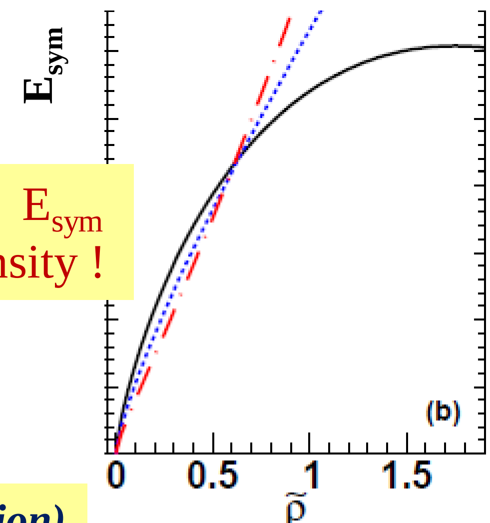
➤ *DD sensitive to E_{sym} below normal density*





SAMi-J27
SAMi-J31
SAMi-J35
(MD)

Strength related to E_{sym} at the crossing density !

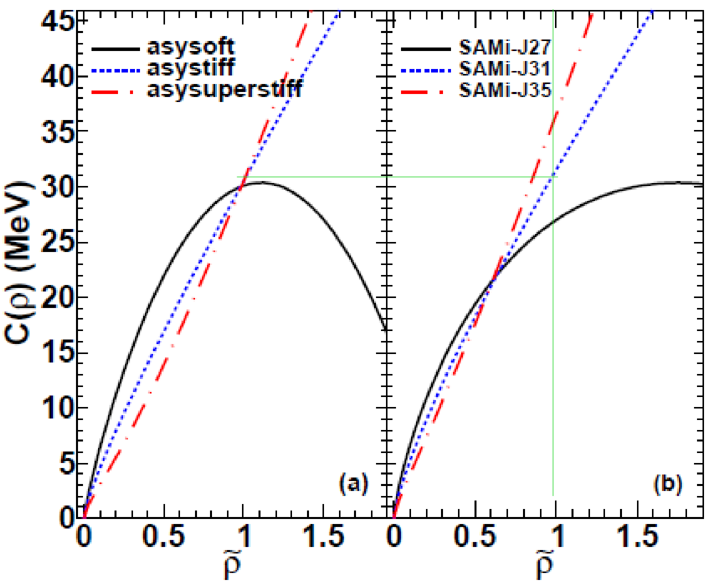


^{132}Sn + ^{58}Ni , E/A = 10 MeV/u

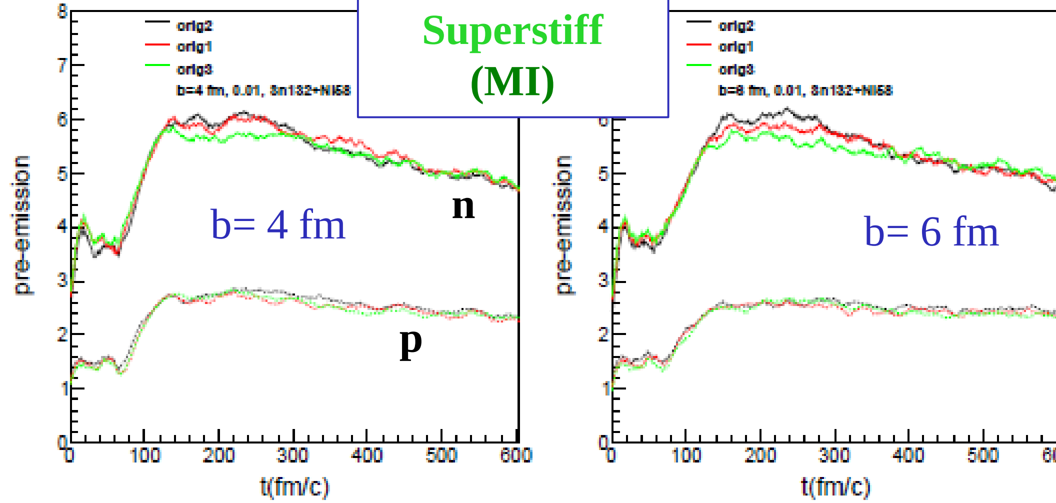
(free n-n cross section)

E_{sym} effects on pre-equilibrium particle emission

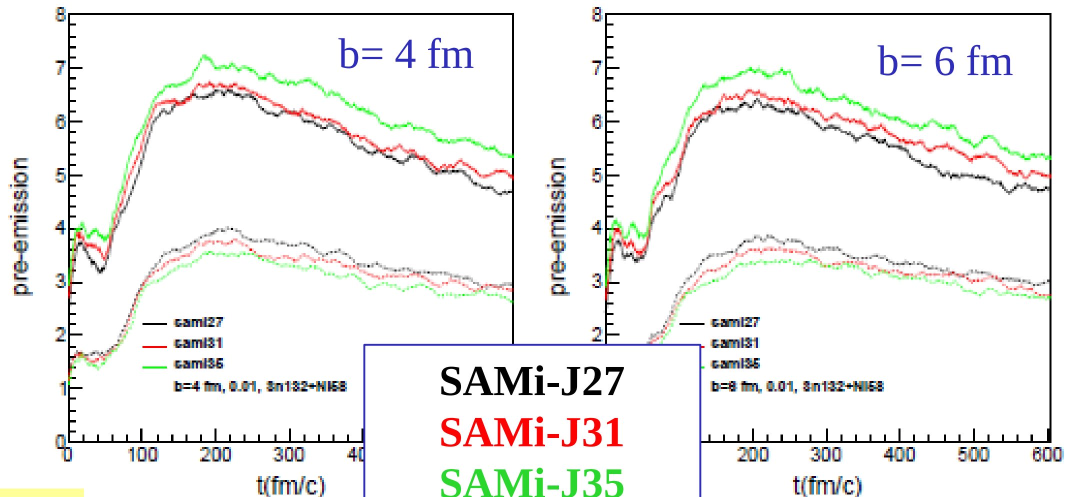
$^{132}Sn + ^{58}Ni$, E/A = 10 MeV/u



soft
stiff
Superstiff
(MI)



Number of nucleons in regions with density $\rho < 0.01\ fm^{-3}$



SAMi-J27
SAMi-J31
SAMi-J35
(MD)

- Particle emission looks sensitive to E_{sym} close to normal density:

N/Z = 2.1 SAMi-J35

N/Z = 1.6 SAMi-J27

(at t = 200 fm/c)

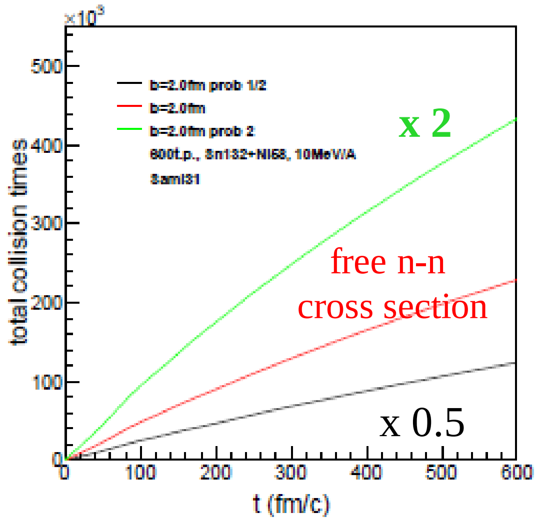
600 test particles (t.p.) , free n-n cross section

Sensitivity of pre-equilibrium effects to n-n cross sections

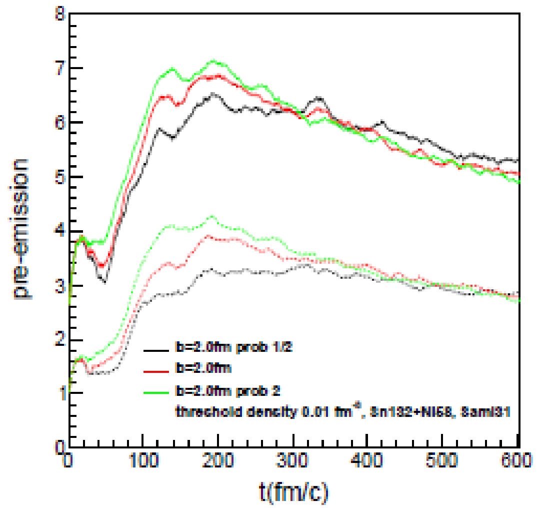
^{132}Sn + ^{58}Ni , E/A = 10 MeV/u
b= 2 fm

SAMi-J31 interaction

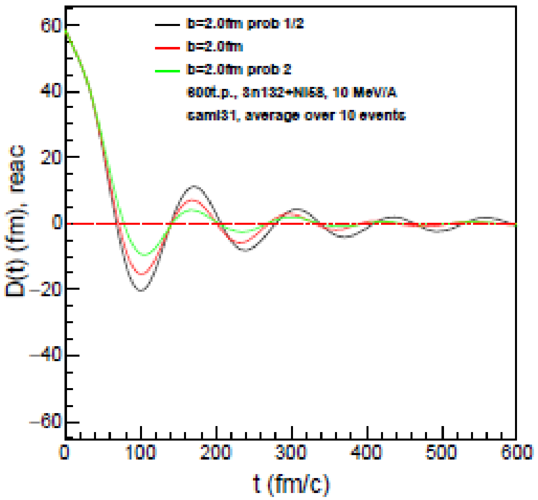
total t.p. collision number



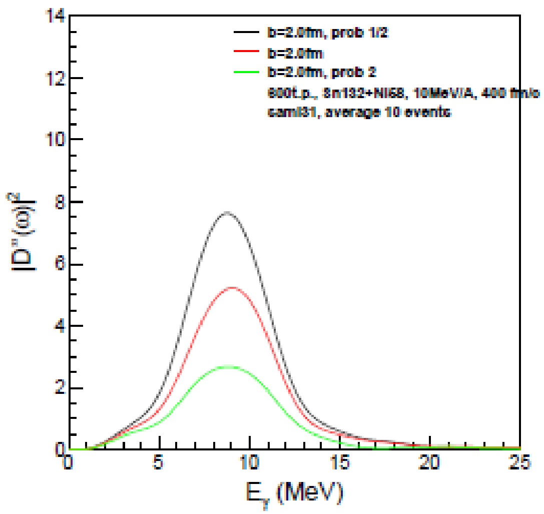
nucleons emitted



- enhanced nucleon emission for larger cross section, but the N/Z is not so sensitive !



dipole oscillations



DD strength

- small n-n cross section
  ⟶ larger damping time τ
  ⟶ larger DD strength

see energy-integrated yield

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

❑ Conclusions

➢ Low energy collisions involving n-rich systems:
-Pre-equilibrium dipole oscillations and particle emission
A way to constrain symmetry energy and two-body correlation effects

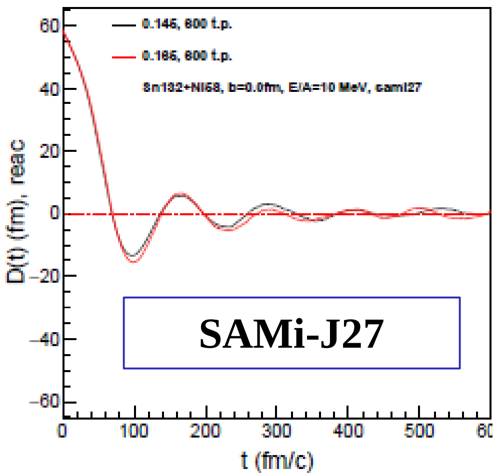
- the DD strength reflects the symmetry energy at the crossing density of the SAMi-J interactions (as also observed for the GDR)

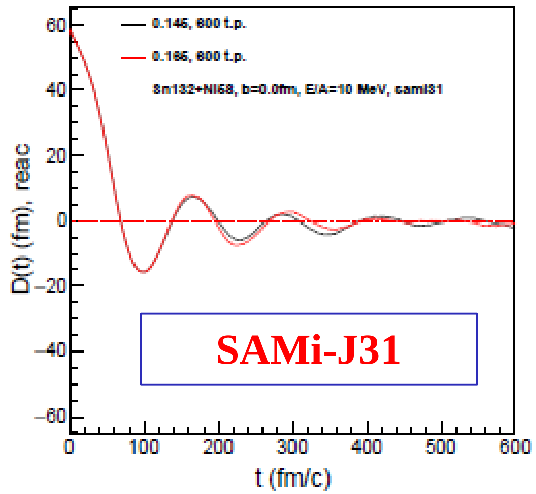
- the N/Z of pre-equilibrium nucleon emission is sensitive to symmetry energy closer to normal density

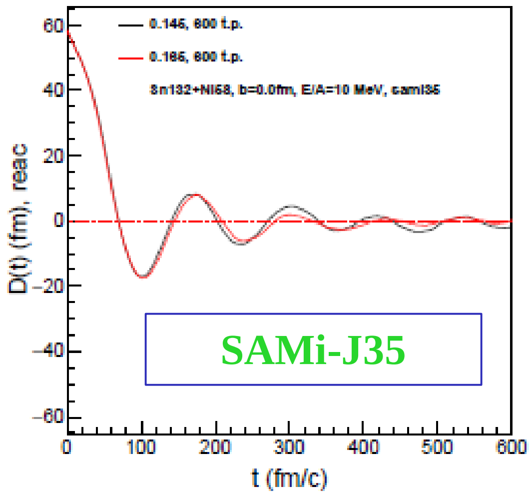
- the DD strength is sensitive to the n-n cross section

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

Looking at dipole oscillations



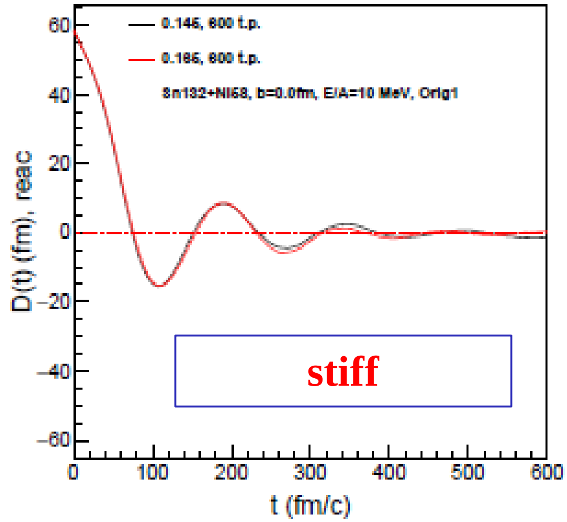




Energy-integrated yield

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

Is ω_0 just sensitive to E_{sym} ?



➢ Stiff and SAMi-J31: same symmetry energy, but different oscillation frequency: momentum dependence (MD) effects ! (also seen in the GDR case)