Classical vs quantal effects in equilibrium and non-equilibrium dynamics

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Outline

- ✧ **Introduction**

- ✧ **Dynamical dipole (DD) in $^{132}Sn+^{58}Ni$ at 10 MeV/A, BNV**

- ✧ **Dynamical dipole in $^{152}Sm+^{40}Ca$ at 11 MeV/A (experimental case), TDHF, Vlasov, BNV**

- ✧ **Conclusions**

Dynamics of many-body systems

Main ingredients:

- Residual interaction
- Effective interaction: **Skyrme interaction**
  (self-consistent mean-field)

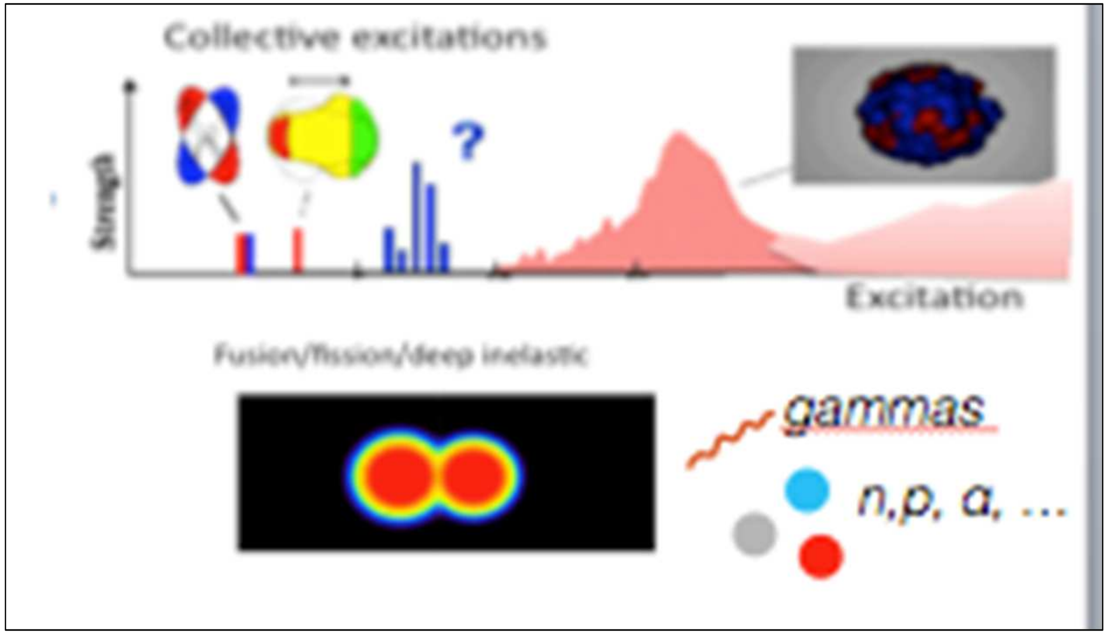
Study approaches:

- Semi-classical approach: **Vlasov, BNV**, MD, SMF…
- Quantal approach: **TDHF**, HF+RPA …

Isospin effects in the Low-energy Heavy-Ion reactions

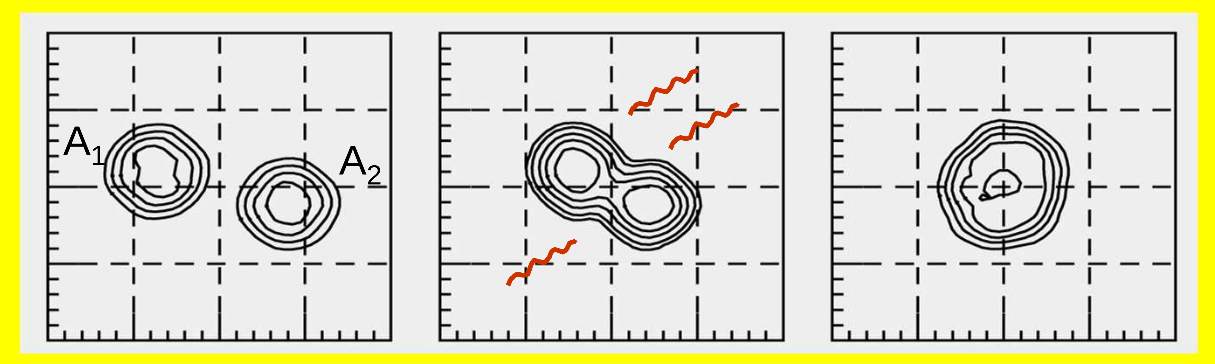
Experiment:

- New collective excitations
- Competition between reaction mechanisms
- Charge equilibration
- Isotopic features of emitted particles



Objects

Charge equilibration in fusion and D.I. collisions

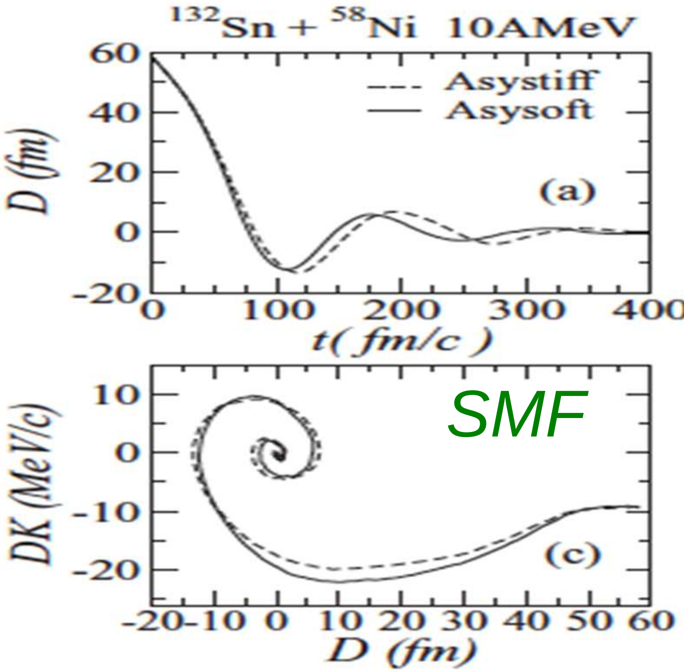


Initial Dipole D(t) : bremss. dipole radiation CN: stat. GDR

If $N_1/Z_1 \neq N_2/Z_2$

→ Relative motion of neutron and proton centers of mass

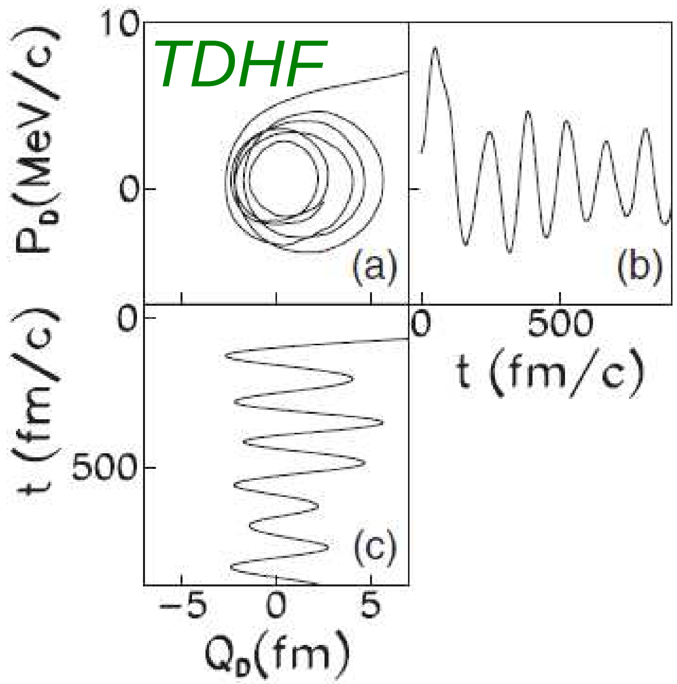
$$D(t) \equiv \frac{NZ}{A}\left[X_p(t) - X_n(t)\right] \rightarrow X_{p,n} \equiv \frac{1}{Z,N}\Sigma x_i^{p,n}$$



$^{132}Sn + ^{58}Ni$

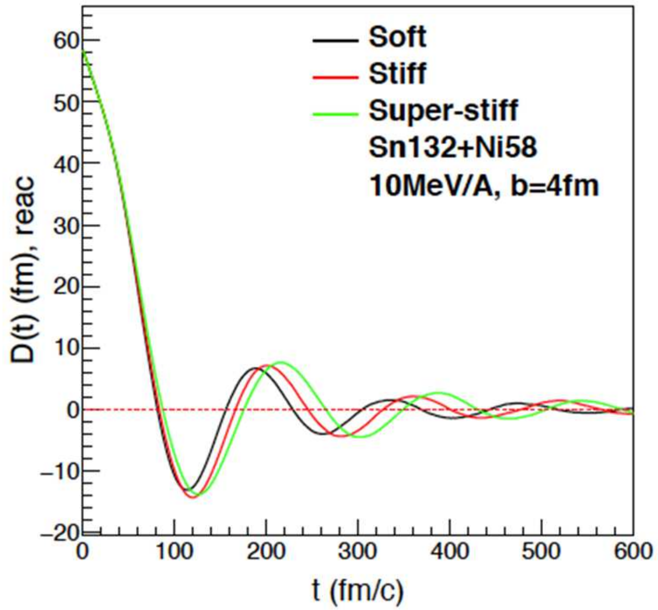
C.Rizzo et al., PRC 83, 014604 (2011)

Simenel et al, PRC 76, 024609 (2007)



$^{40}Ca + ^{100}Mo$

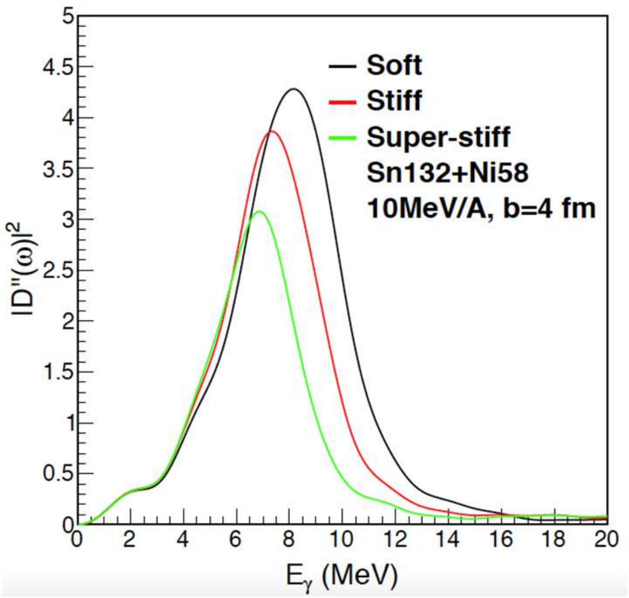
Dynamical dipole (DD) emission



Bremsstrahlung: Quantitative estimation

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

Damped harmonic oscillator:



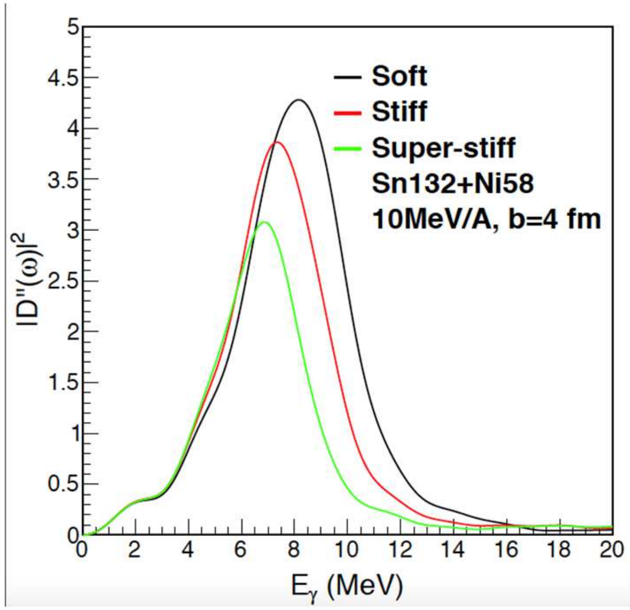
$$|D''(\omega)|^2 = \frac{(\omega_0^2 + 1/\tau^2)^2 D(t_0)^2}{(\omega - \omega_0)^2 + 1/\tau^2}$$

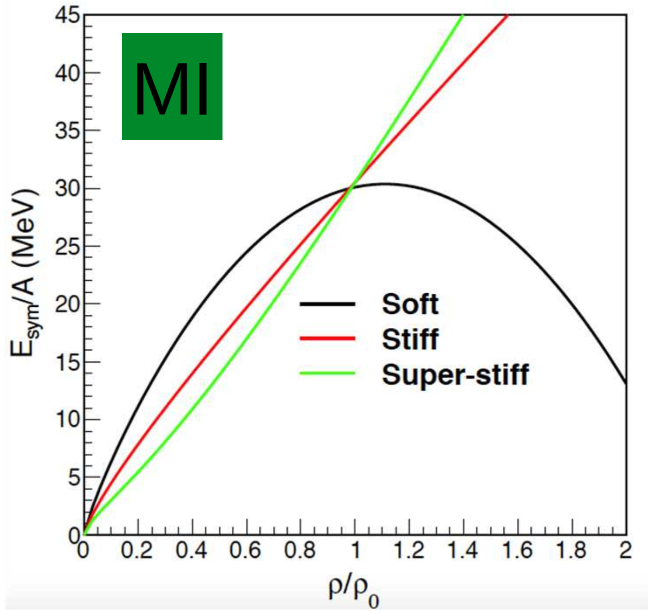
Energy-integrated yield

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

V.Baran, D.M.Brink, M.Colonna, M.Di Toro, PRL.87 (2001)
V. Baran et al., PRC 79, 021603®, (2009)

Dynamical dipole emission





- **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**

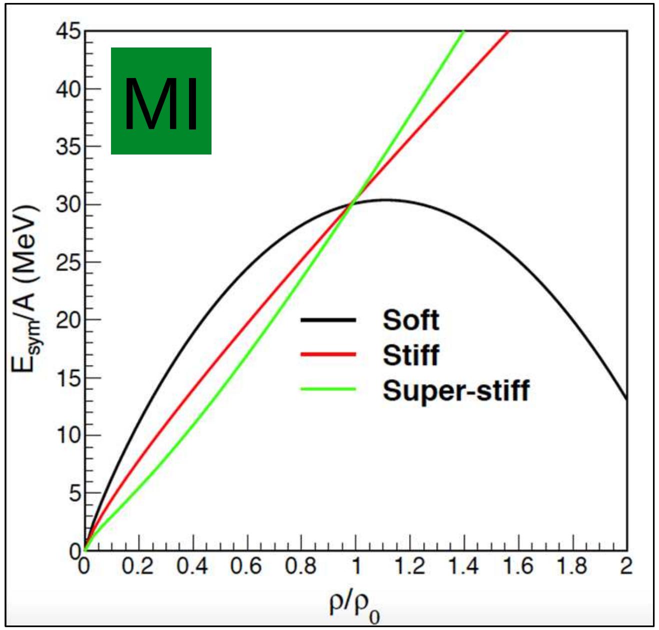
  n-n cross section

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

- **Signal is enhanced in system with a large initial dipole moment $D(t_0)$**

V.Baran et al., PRC.79, 021603® (2009)

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

o Explore the sensitivity to both J and L

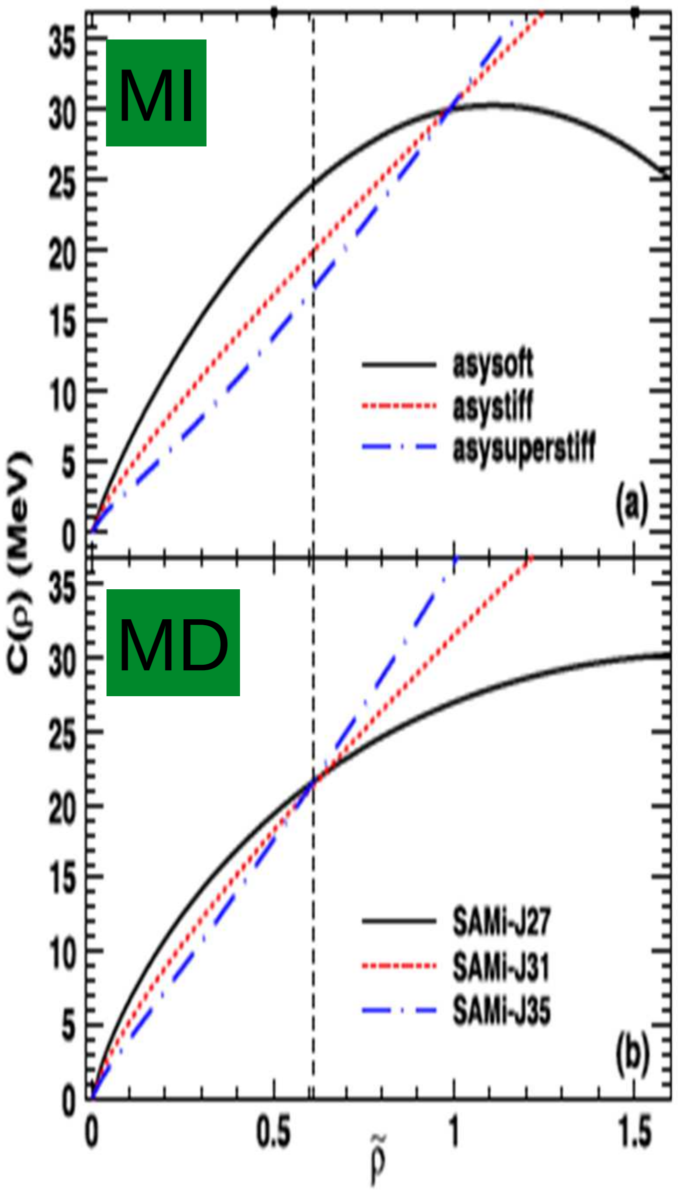
o Explore the sensitivity to Nucleon-Nucleon cross section

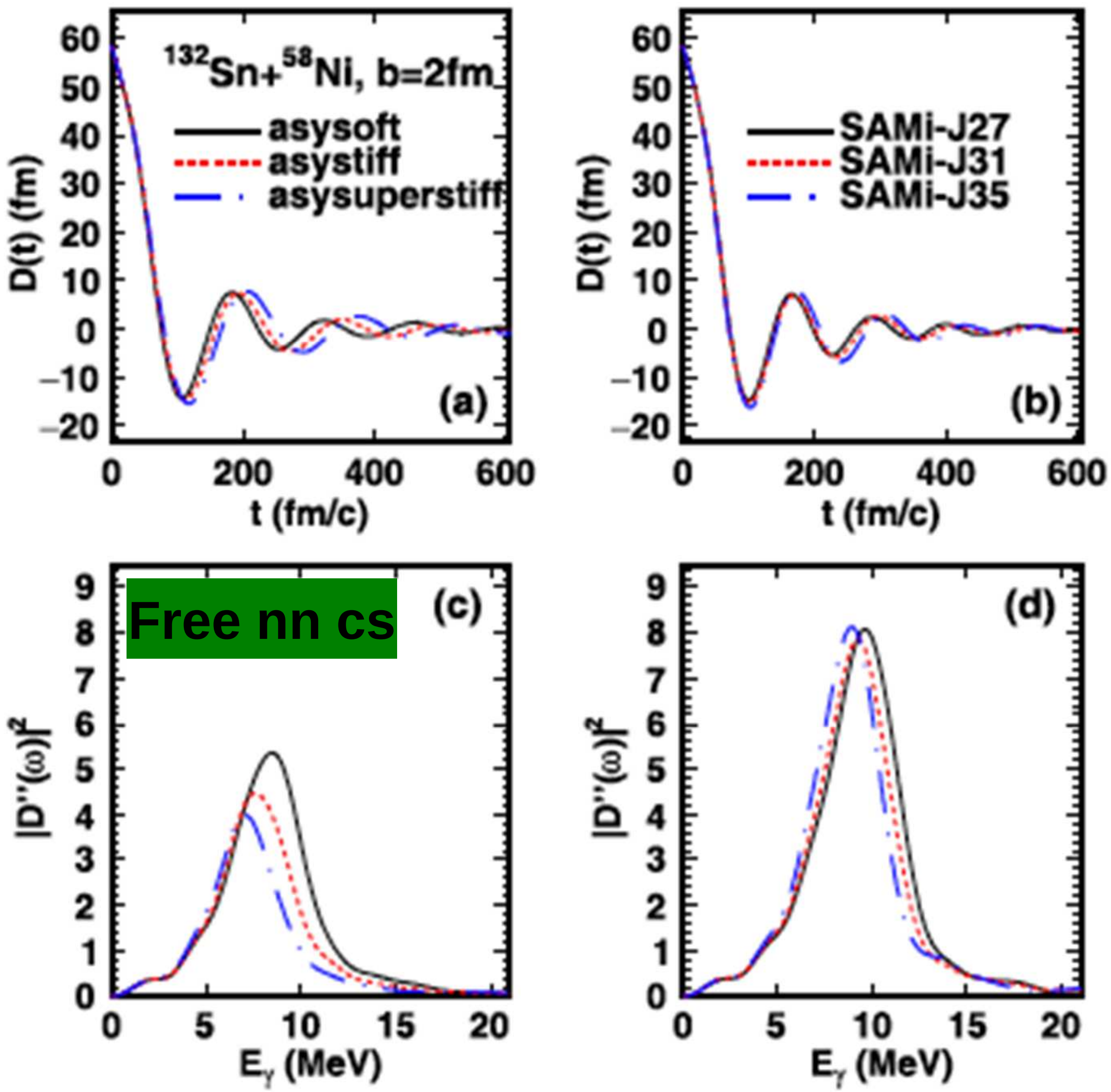
Look at:

- Dynamical Dipole
- pre-equilibrium particle emission

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

H. Zheng et al. PLB 769, 424, 2017

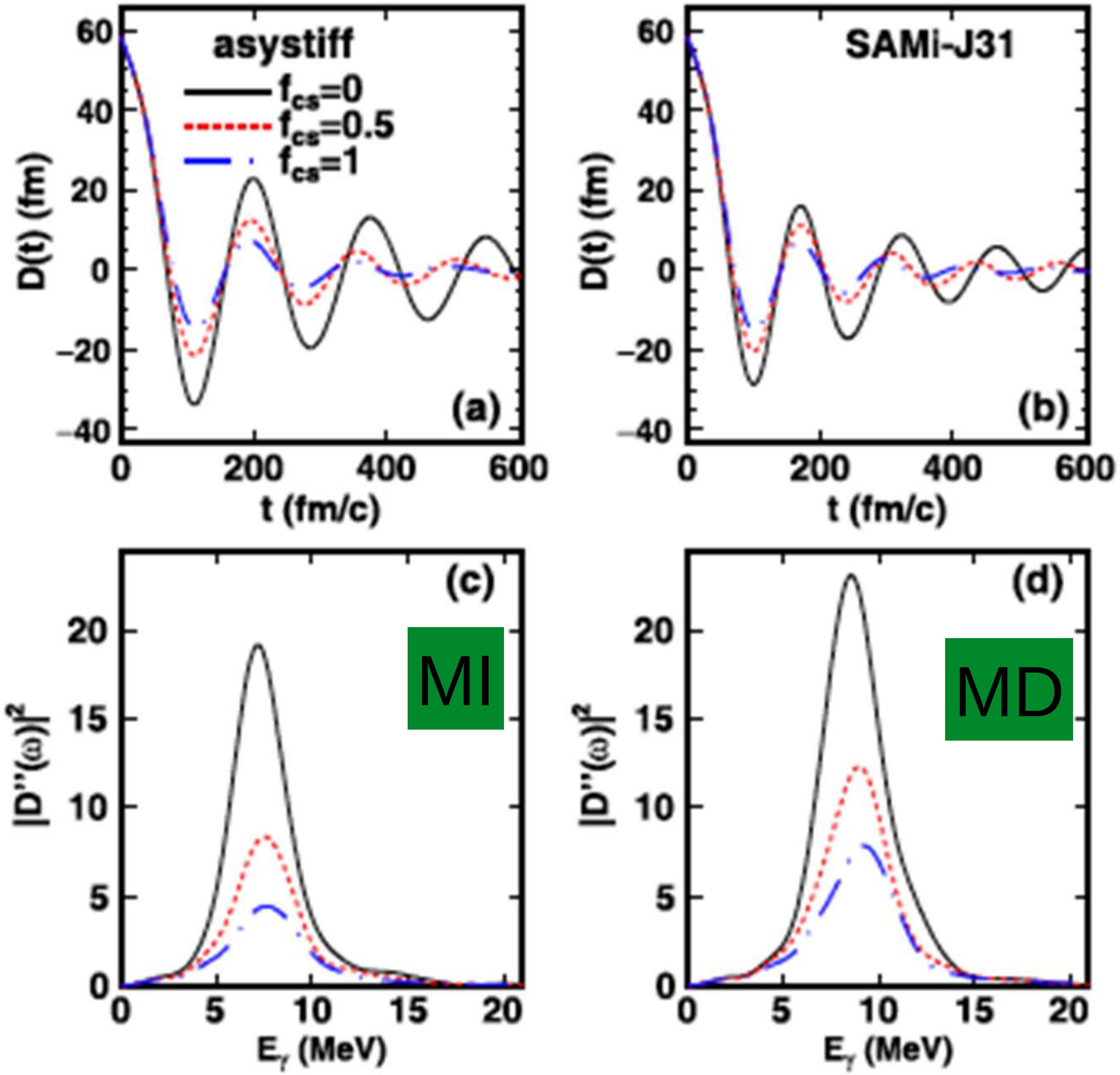




DD is sensitive to the E_{sym} below the normal density and m*

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

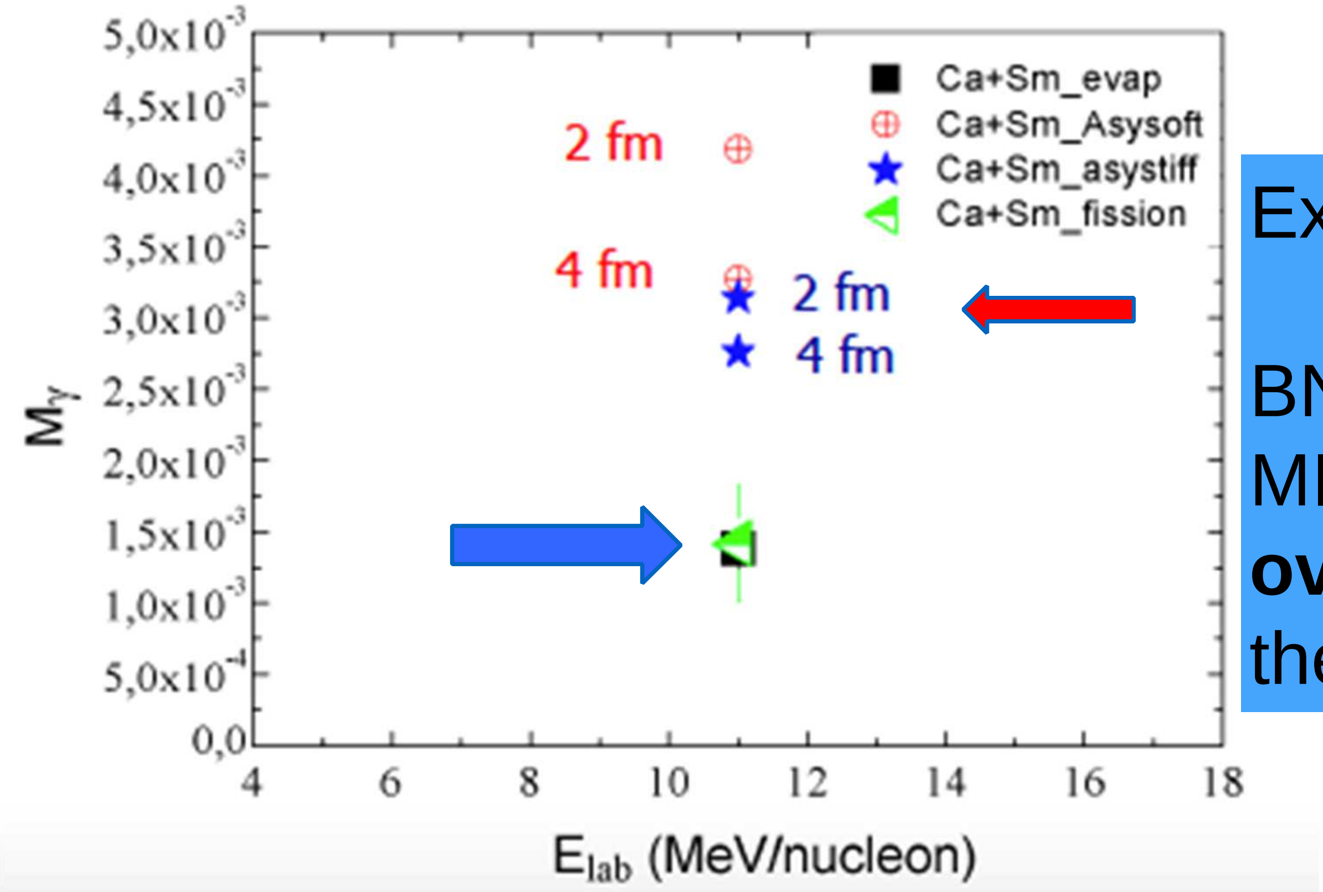
H. Zheng et al. PLB 769, 424, 2017



An addition collision probability f_{cs} to the free nn cross section

The gamma multiplicity in $^{152}Sm+^{40}Ca$, 11 MeV/A

$E_{DD,exp}$ (MeV)	$\Gamma_{DD,exp}$ (MeV)	$M_{\gamma,DD,exp}$	$E_{DD,th}$ (MeV)	$\Gamma_{DD,th}$ (MeV)	$M_{\gamma,DD,th}$	b_{max} (fm)
11.0 ± 0.3	3.5 ± 0.5	$[1.2 \pm 0.2] \times 10^{-3}$	8.3(9.8)	~4(4)	$3.15(4.20) \times 10^{-3}$	2
					$3.08(4.04) \times 10^{-3}$	3
					$2.86(3.50) \times 10^{-3}$	4
					$2.23(2.81) \times 10^{-3}$	6



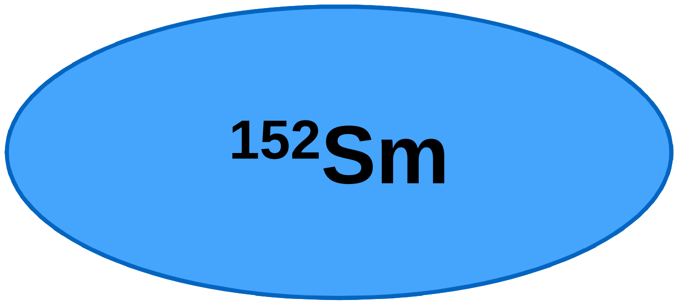
Experiment: LNS, Catania

BNV model with
MI EoS and spherical gs
overpredicts
the multiplicity of gamma

C. Parascandolo et al., PRC.93, 044619 (2016), D. Pierroutsakou's talk

^{152}Sm is prolate

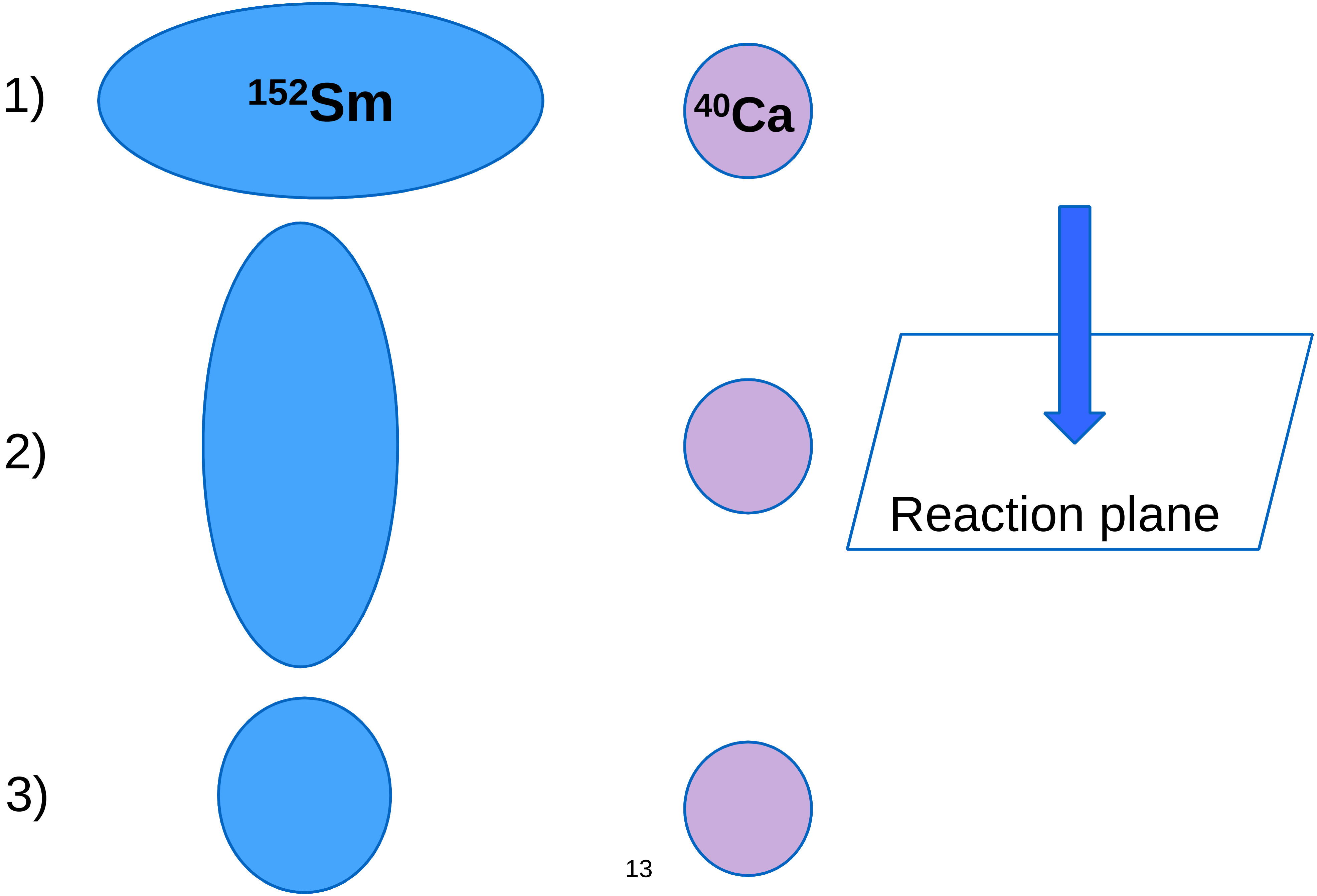
No.	β_2	β_4	reference
1	0.287±0.003	0.070±0.003	PRL 28, 1711 (1972) PRC 13, 1083 (1976)
2	0.286±0.002	0.092±0.002	PRL 38, 584 (1977)
3	0.276±0.004	0.089±0.014	PRC 15, 921 (1977)
4	0.252±0.004	0.072±0.013	PRC 15, 921 (1977)
5	0.250, 0.261, 0.260, 0.232, 0.22 (different methods)		PLB 61, 29 (1976)



I am deformed and prolate

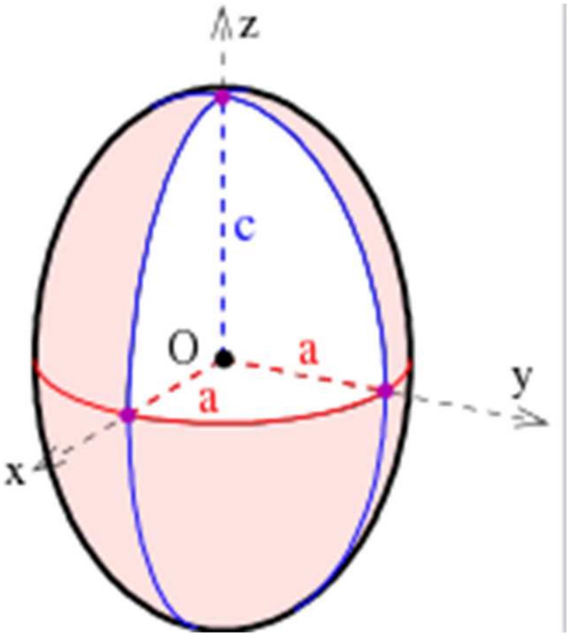
HF, the deformation of the gs is automatically obtained

The collision configurations in $^{152}Sm+^{40}Ca$



Introduce the deformed configuration in semi-classical model

Spheroid



$$\frac{x^2+y^2}{a^2}+\frac{z^2}{c^2}=1$$

$$a=R(1-s)$$

$$c=R(1+s)$$

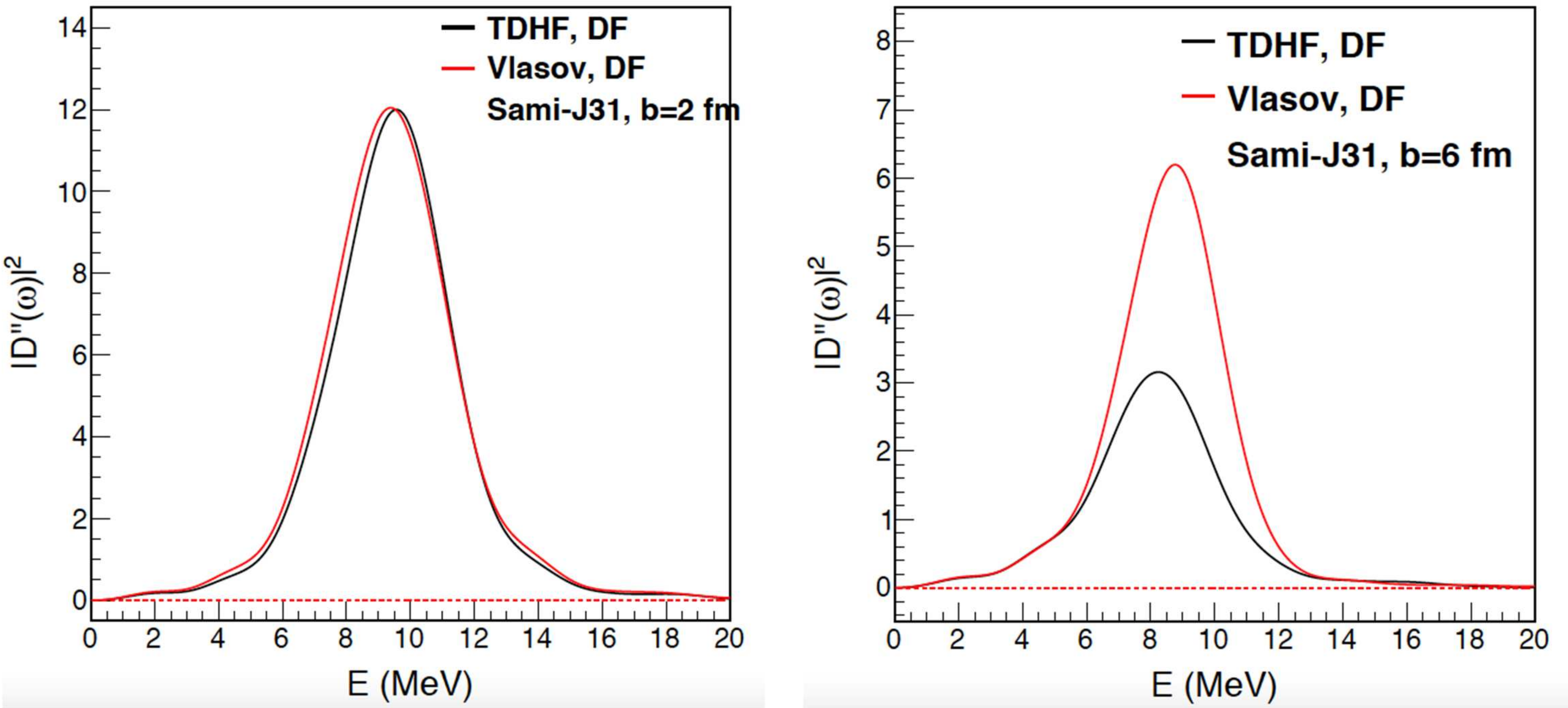
Comparing the quadruple moment: $\beta_2 \approx 2.11s$

R.W. Hasse, W.D. Myers, Geometrical Relationships of Macroscopic Nuclear Physics, 1988

To do list

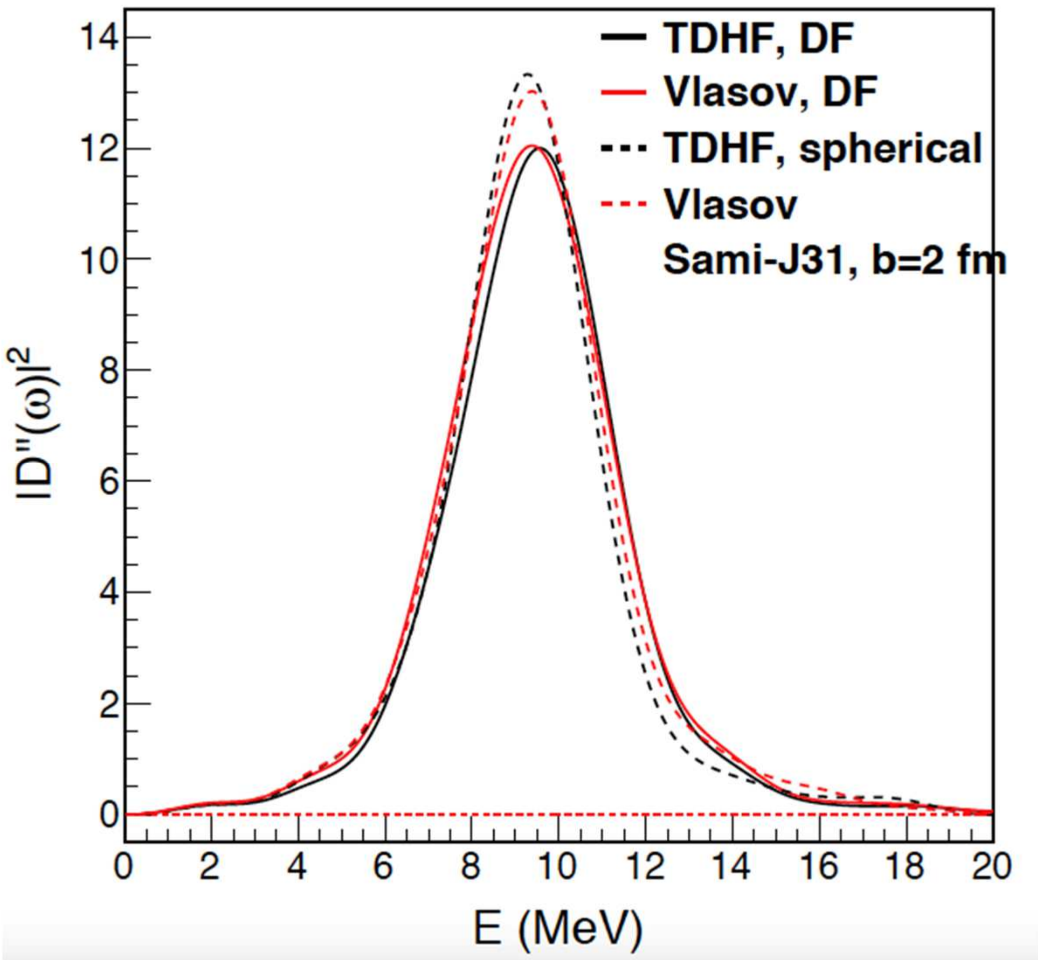
Model	collision	Quantum effect	^{152}Sm shape
TDHF	X	✓	spherical
TDHF	X	✓	prolate
Vlasov	X	X	spherical
Vlasov	X	X	prolate
BNV	✓	X	spherical
BNV	✓	X	prolate

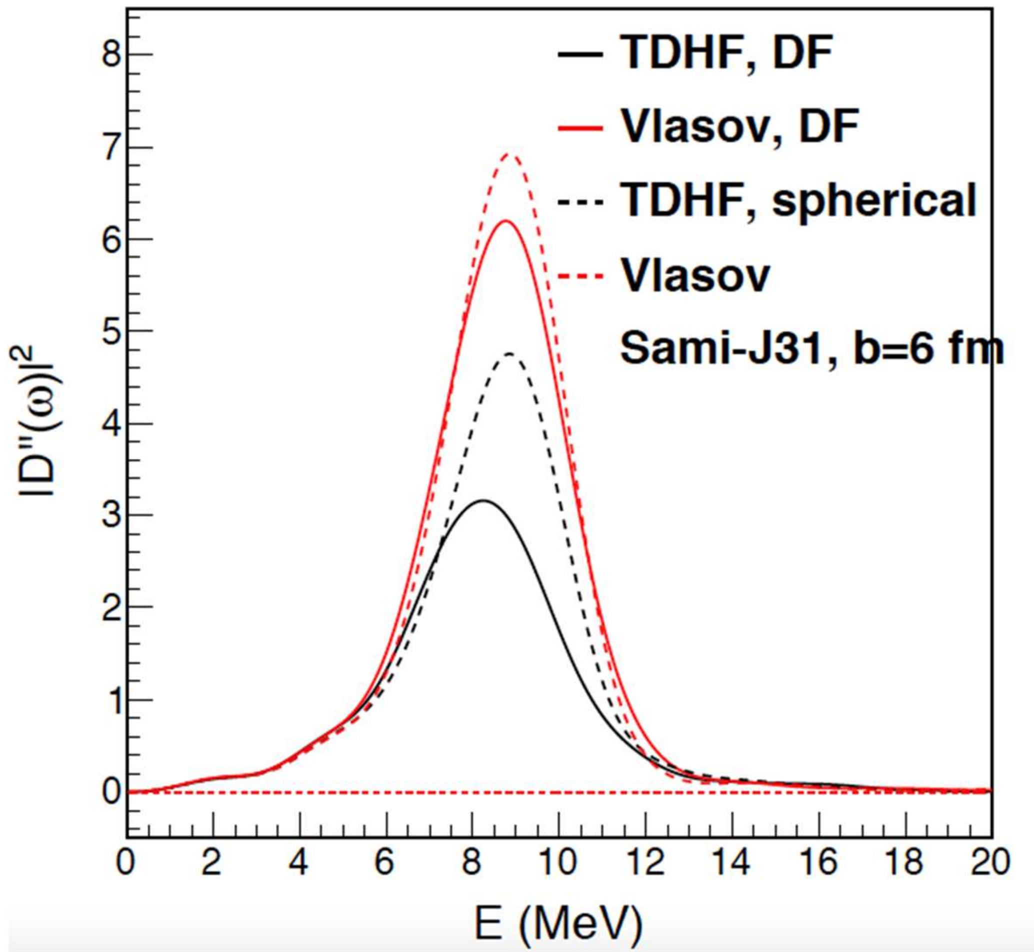
Comparison between TDHF and Vlasov



1) Central collisions, volume involved, energy level structure is not important
2) Peripheral collisions, surface involved, energy level structur e becomes important

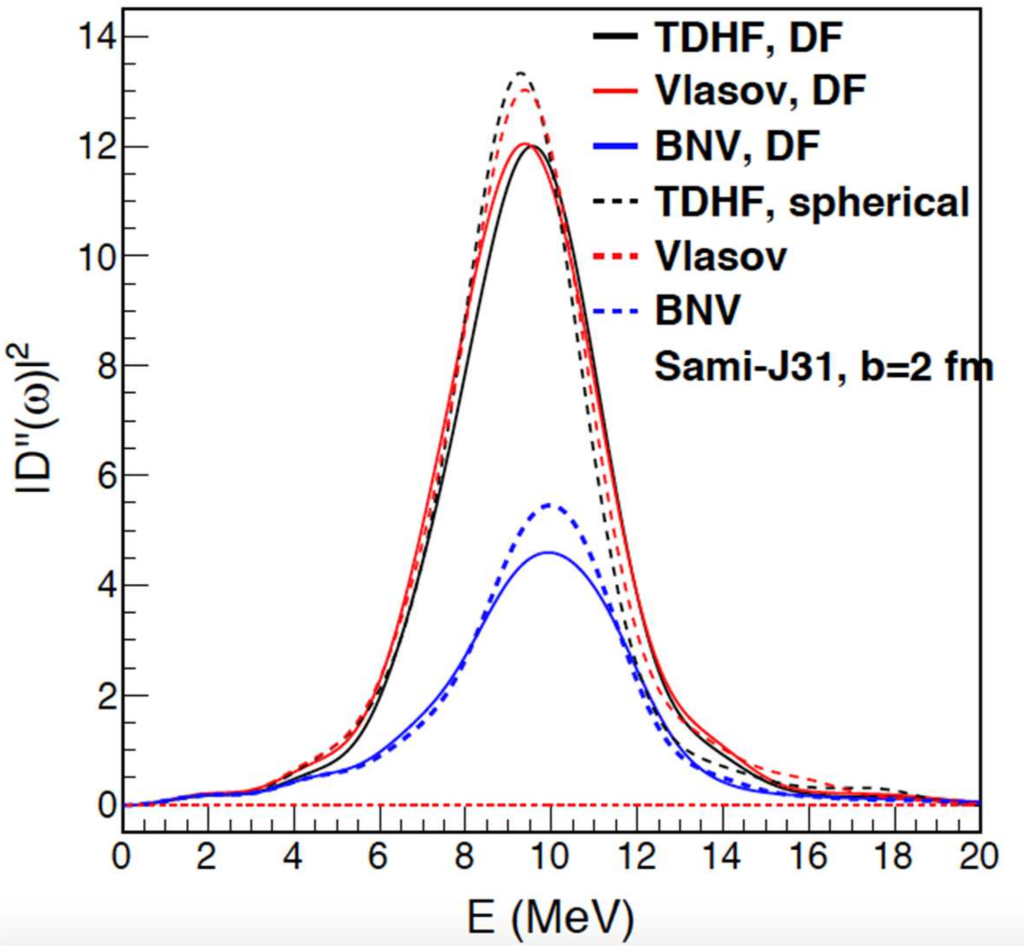
Comparison between TDHF and Vlasov

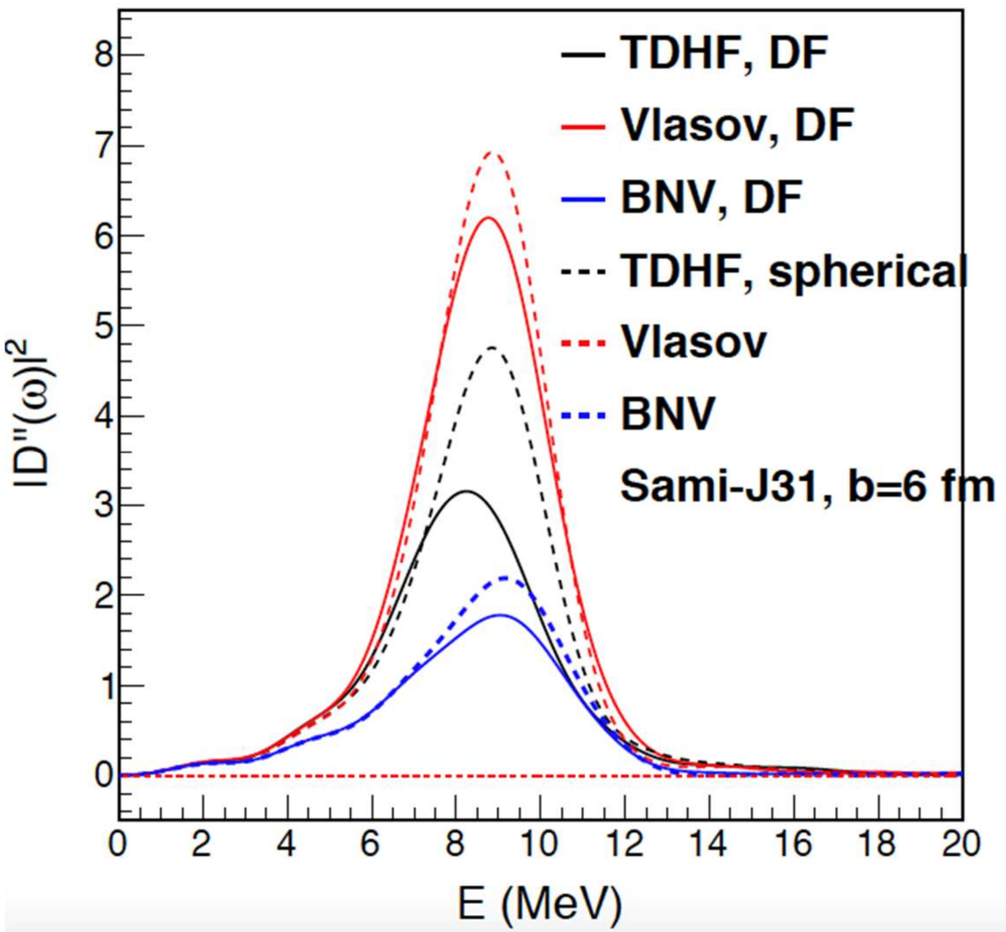




1) Central collisions, volume involved, deformation and energy level structure are not important
2) Peripheral collisions, surface involved, deformation and ene rgy level structure become important

Comparison between TDHF and Vlasov





1) Collisions are needed (BNV)
2) Deformation is needed
3) The energy level structure contribution should be taken into account (normalize VLASOV to TDHF)

Conclusions

➢ Low energy collisions involving n-rich systems:
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 DD strength is sensitive to the n-n cross section
- The deformation of the nuclei plays an important role in the DD
- A possible way to take into account the quantum effects and collisions in the DD is proposed as the preliminary results