Collective motion in nuclei: a journey across Italy between theory and experiments

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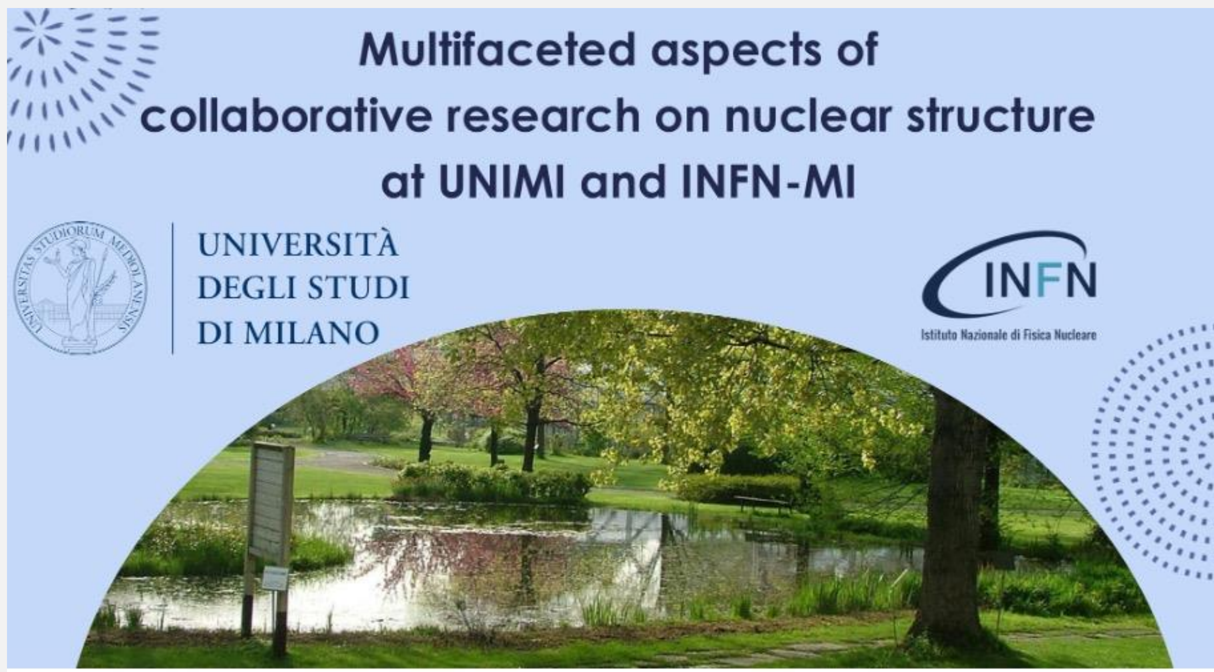
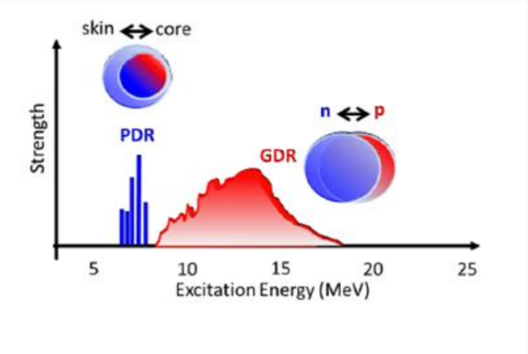
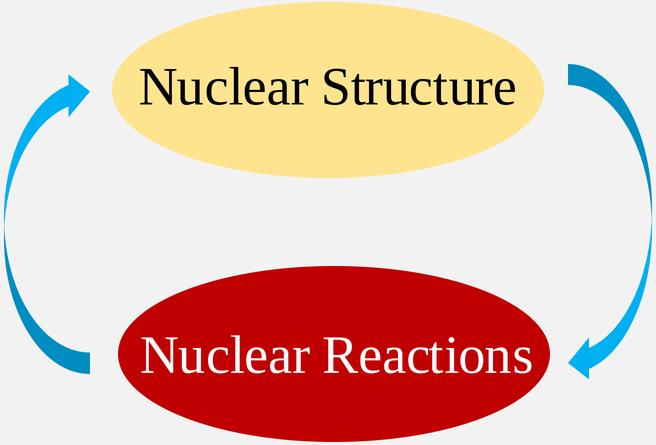
Physics Department



Celebrating Franco's, Gianluca's and Silvia's 60th birthday

- The nuclear many-body problem: a challenging interplay between single-particle and collective effects





Structure models
Ex: HF, HFB, RPA, QRPA,…

↕

Corresponding **time-dependent approaches**
Ex: TDHF, TDHFB,…

↕

Semi-classical methods
Ex: Vlasov, BUU, BNV,…

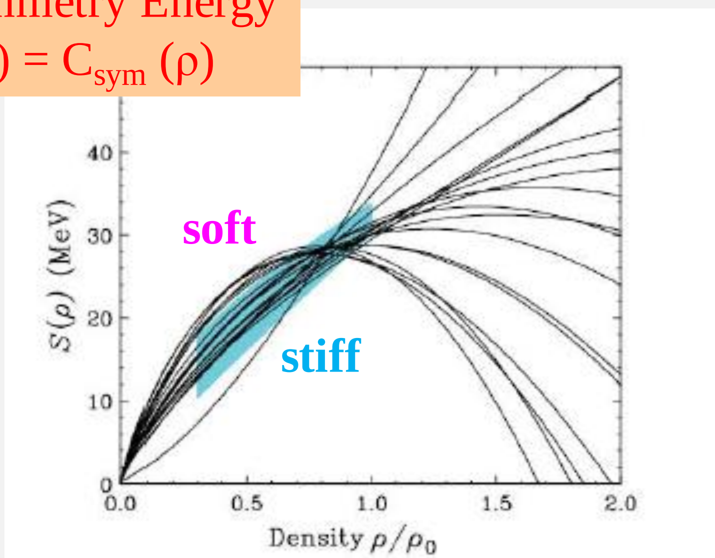
➡ (beyond) mean-field approaches based on the use of **effective interactions** → **Energy Density Functionals** → **EOS**

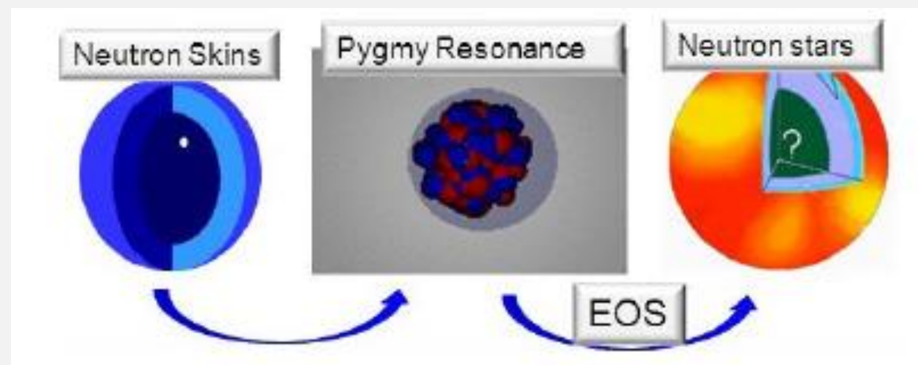
- The nuclear matter EOS: a *crucial ingredient* for
  - nuclear structure
  - Heavy Ion Collisions dynamics
  - modeling of compact stellar objects and GW emission signals

$$E/A(\rho, \delta) = E/A(\rho, \delta=0) + S(\rho)\delta^2 + O(\delta^4)$$

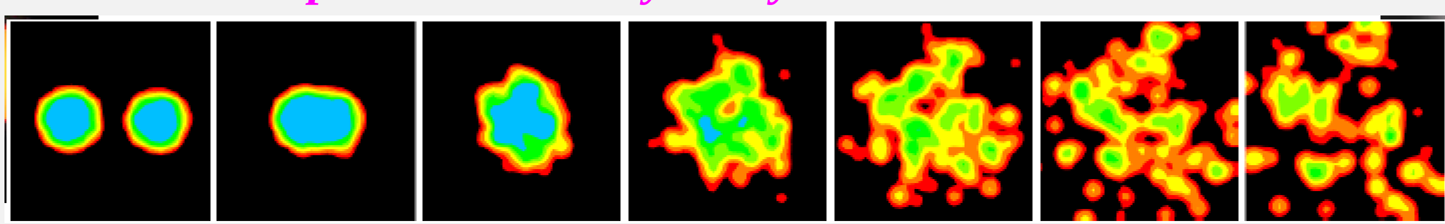
$$\delta = \frac{\rho_n - \rho_p}{\rho}$$

Symmetry Energy
$S(\rho) = C_{sym}(\rho)$





Femto-nova explosion created by heavy ion collisions !



from A. Ono

- Interesting connections between Milano and Catania groups !

➡ **Collective motion** in nuclei:

- a fascinating phenomenon at the borderline between *nuclear structure* and *reaction dynamics*

- direct link with global features of the *nuclear effective interaction* and **EOS** (→ symmetry energy)

Joint **INFN** *Theory Project*

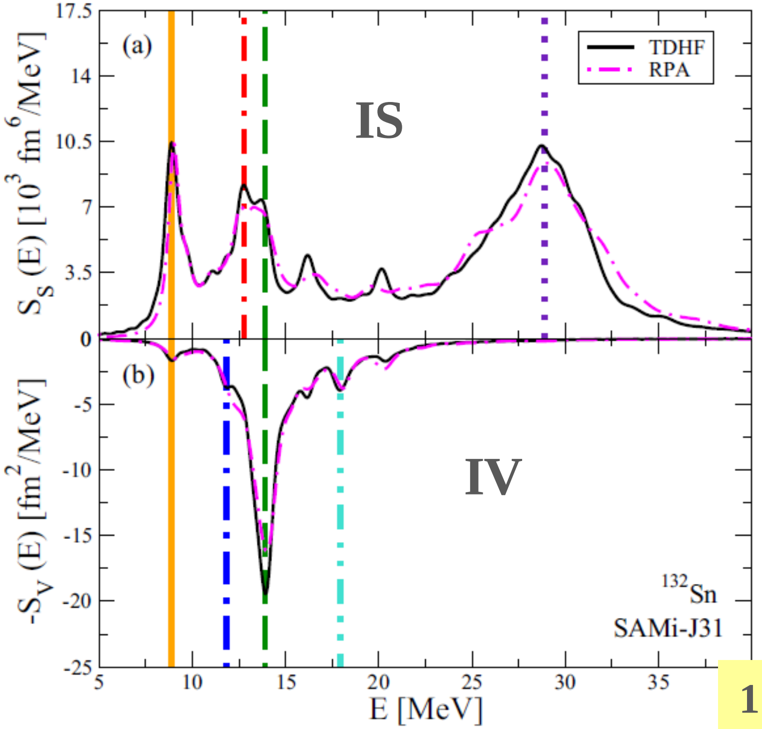
MOdeling **N**uclear **ST**ructure and **RE**actions

- **Collaboration with Milano's experimental group**

→ experiments performed at LNL

…but also in **ENSAR2** and **EURO-LABS** !

https://institucional.us.es/theo4exp/



- Strength function of the dipole response

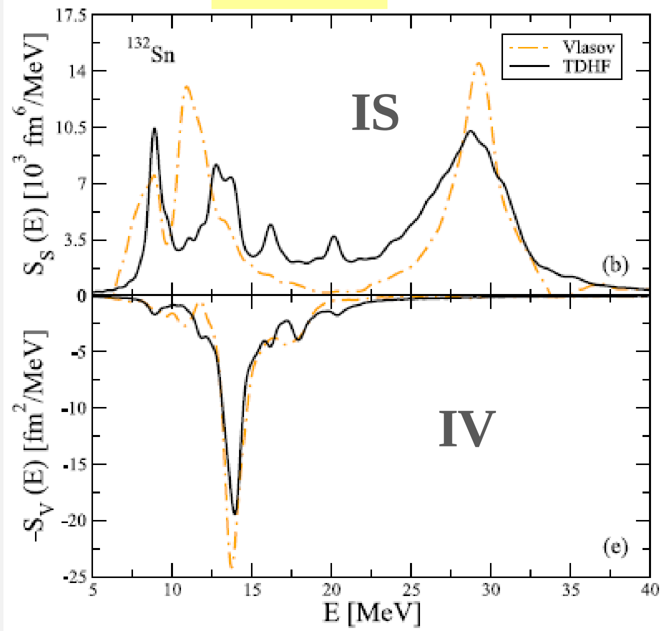
PHYSICAL REVIEW C **99**, 054314 (2019)

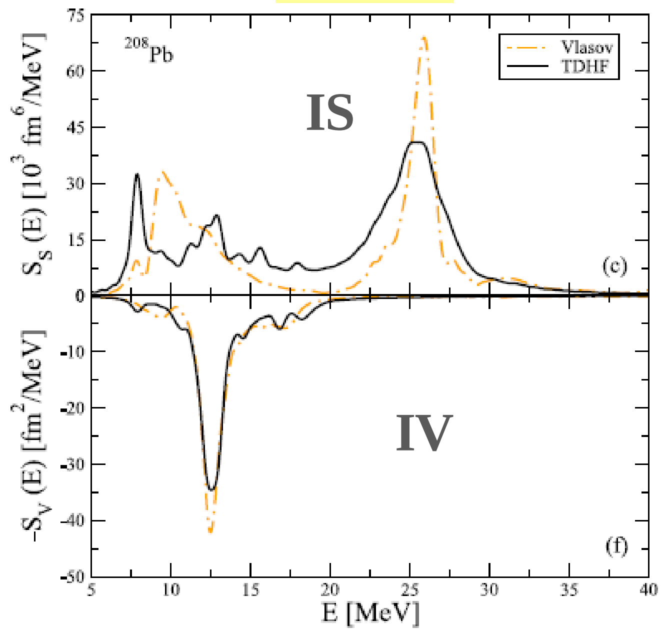
Interplay between low-lying isoscalar and isovector dipole modes: A comparative analysis between semiclassical and quantum approaches

S. Burrello,[1] M. Colonna,[1] G. Colò,[2,3] D. Lacroix,[4] X. Roca-Maza,[2,3] G. Scamps,[5,6] and H. Zheng[1,7]

^{132}Sn

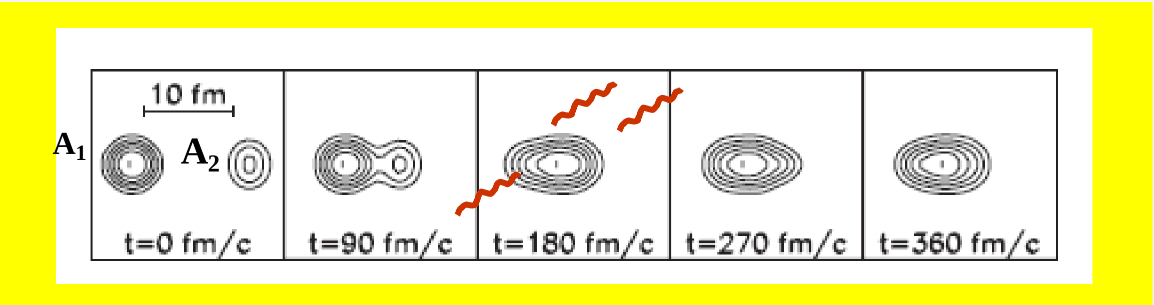
^{208}Pb





Semi-classical (Vlasov) approaches capture the main features of **ISGDR** and **IVGDR**

More than giant..'*dipolone*' → Dipole excitations in heavy ion reactions



TDHF calculations

Simenel et al, PRC 76, 024609 (2007)

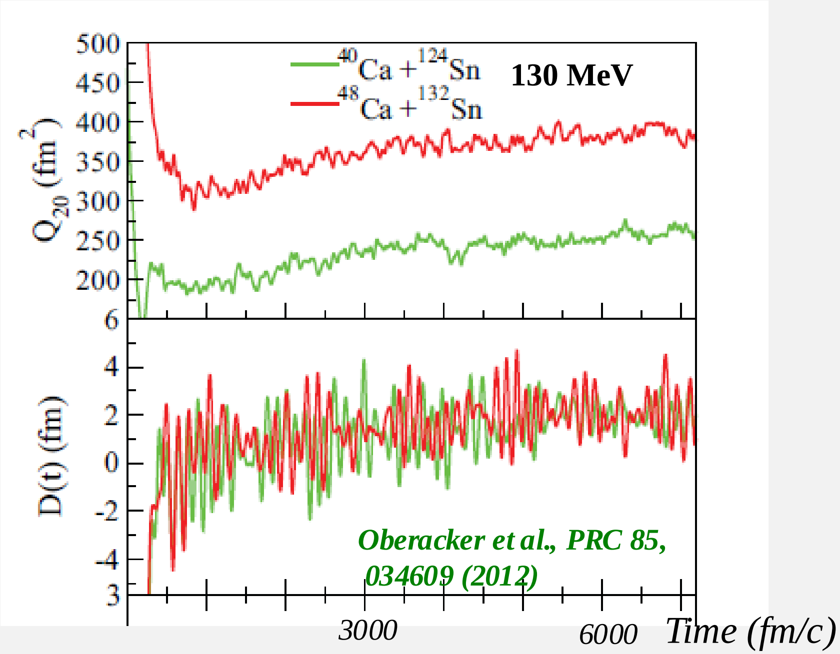
Initial Dipole **D(t) : bremss. dipole radiation** **Compound: stat. GDR**

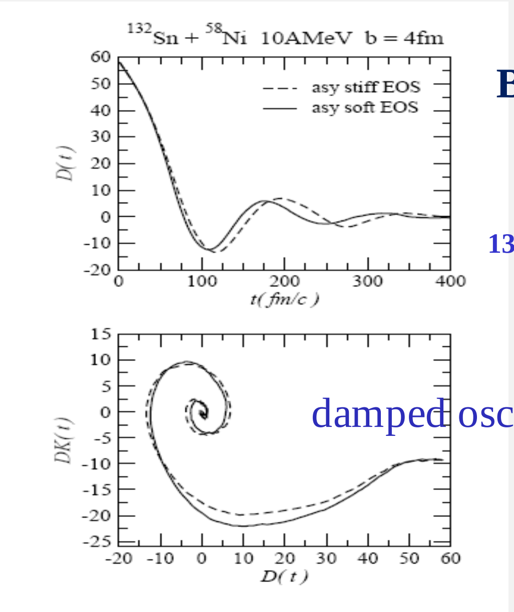
If $N_1/Z_1 \neq N_2/Z_2$

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

+ 2-body collisional damping

→ Relative motion of neutron and proton centers of mass





damped oscillations

BNV calculations

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

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

Physics Letters B 679 (2009) 197–202

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Physics Letters B

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- LNL experiment

with **GARFIELD + HECTOR**

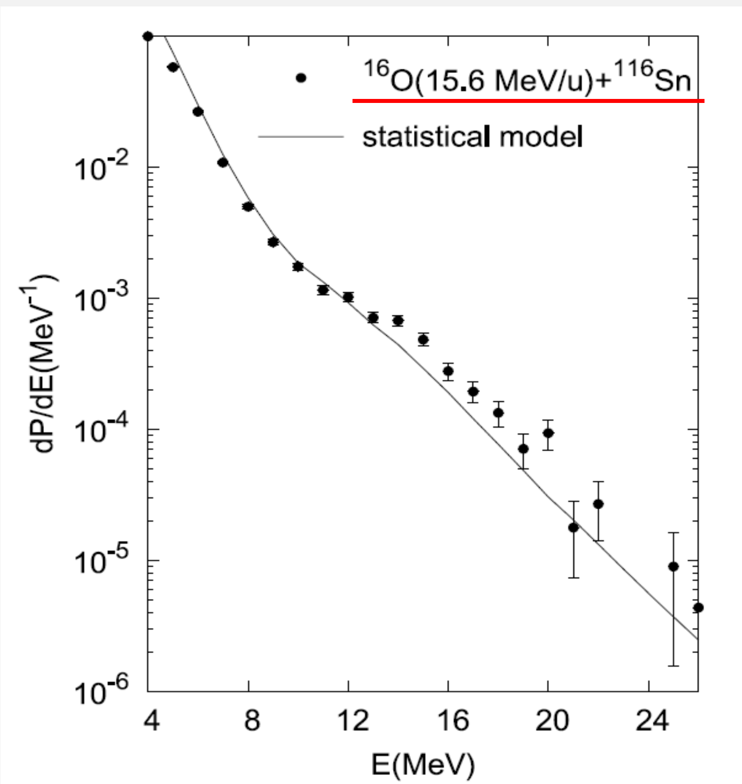
(DD)

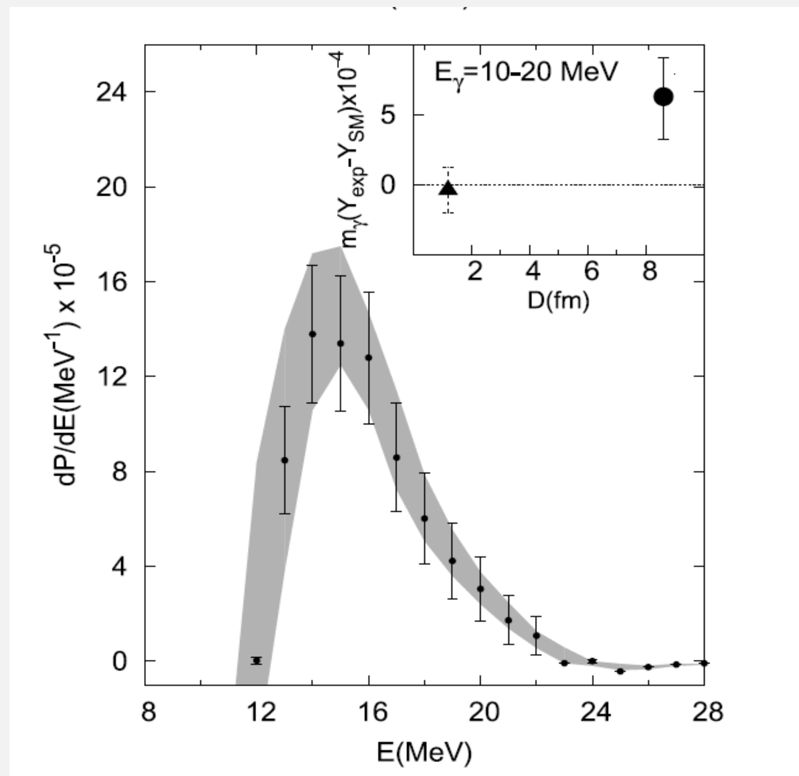
Excitation of the dynamical dipole in the charge asymmetric reaction $^{16}O + ^{116}Sn$

A. Corsi [a,b], O. Wieland [b], V.L. Kravchuk [c], A. Bracco [a,b], F. Camera [a,b,*], G. Benzoni [b], N. Blasi [b], S. Brambilla [b], F.C.L. Crespi [a,b], A. Giussani [a,b], S. Leoni [a,b], B. Million [b], D. Montanari [a,b], A. Moroni [a,b], F. Gramegna [c], A. Lanchais [c], P. Mastinu [c], M. Brekiesz [d], M. Kmiecik [d], A. Maj [d], M. Bruno [e,f], M. D'Agostino [e,f], E. Geraci [i,j], G. Vannini [e,f], S. Barlini [g], G. Casini [g], M. Chiari [g], A. Nannini [g], A. Ordine [h], M. Di Toro [i,j], C. Rizzo [i,j], M. Colonna [i,j], V. Baran [k]

$^{16}O + ^{116}Sn$ ($D_0 = 8.6$ fm)

E/A = 8.1, 15.6 MeV/u

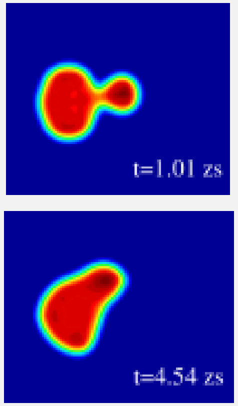




PHYSICAL REVIEW C **90**, 014609 (2014)

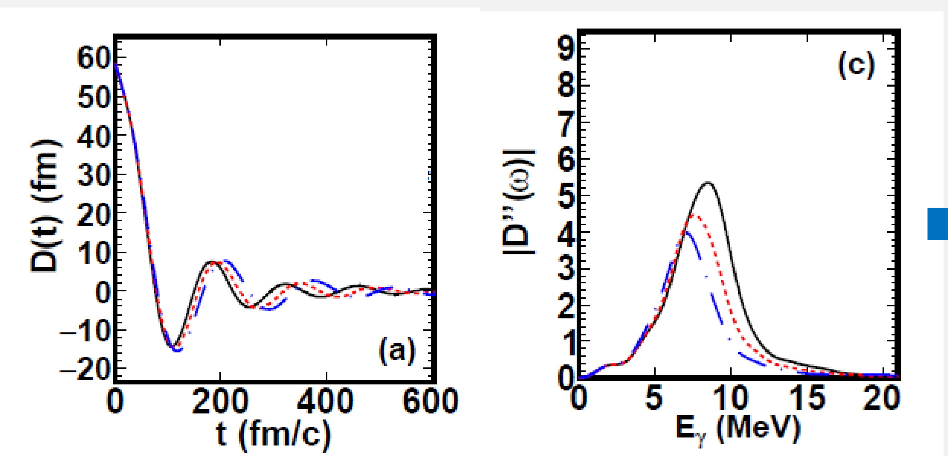
Measurement of dynamical dipole γ-ray emission in the N/Z-asymmetric fusion reaction $^{16}O + ^{116}Sn$ at 12 MeV/nucleon

A. Giaz,[1,*] A. Corsi,[1,†] S. Barlini,[6] V. L. Kravchuk,[3,‡] O. Wieland,[2] M. Colonna,[8] F. Camera,[1] A. Bracco,[1] R. Alba,[8] G. Baiocco,[5,§] L. Bardelli,[6] G. Benzoni,[2] M. Bini,[6] N. Blasi,[2] S. Brambilla,[2] M. Bruno,[5] G. Casini,[10] M. Ciemala,[4] M. Cinausero,[3] F. C. L. Crespi,[1] M. D'Agostino,[5] M. Degerlier,[3,‖] M. Di Toro,[9] F. Gramegna,[3] M. Kmiecik,[4] S. Leoni,[1] C. Maiolino,[8] A. Maj,[4] T. Marchi,[3] K. Mazurek,[4] S. Myalski,[4] B. Million,[2] D. Montanari,[1,¶] L. Morelli,[5] R. Nicolini,[1] G. Pasquali,[6] S. Piantelli,[10] A. Ordine,[7] G. Poggi,[6] V. Rizzi,[3] C. Rizzo,[8] S. Sambi,[5,**] D. Santonocito,[8] and V. Vandone[1]

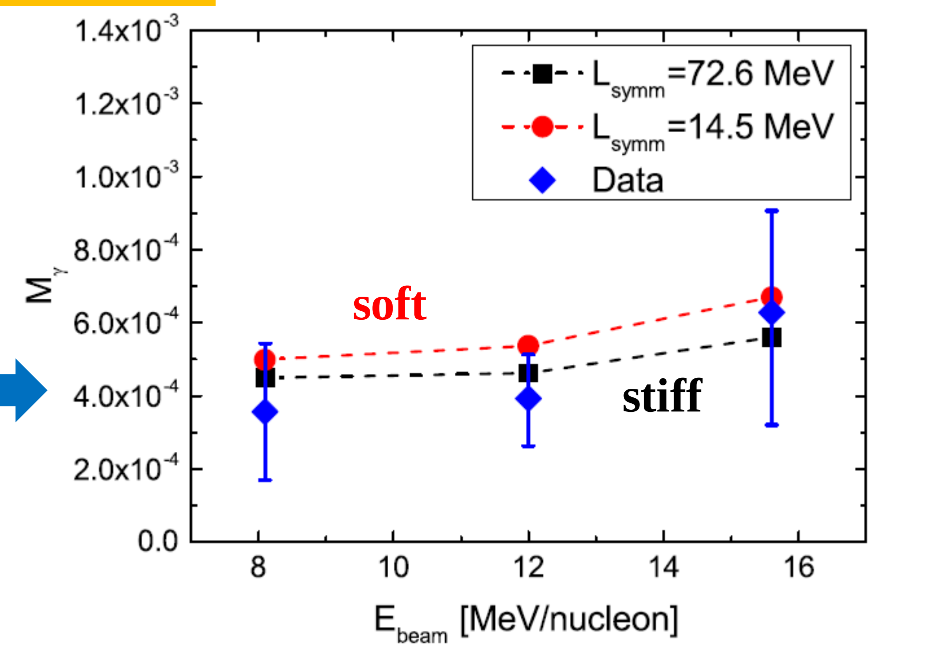


The restoring force is provided by the symmetry term (as in the standard GDR) → probe the symmetry energy in the density conditions and configurations reached along the reaction path

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

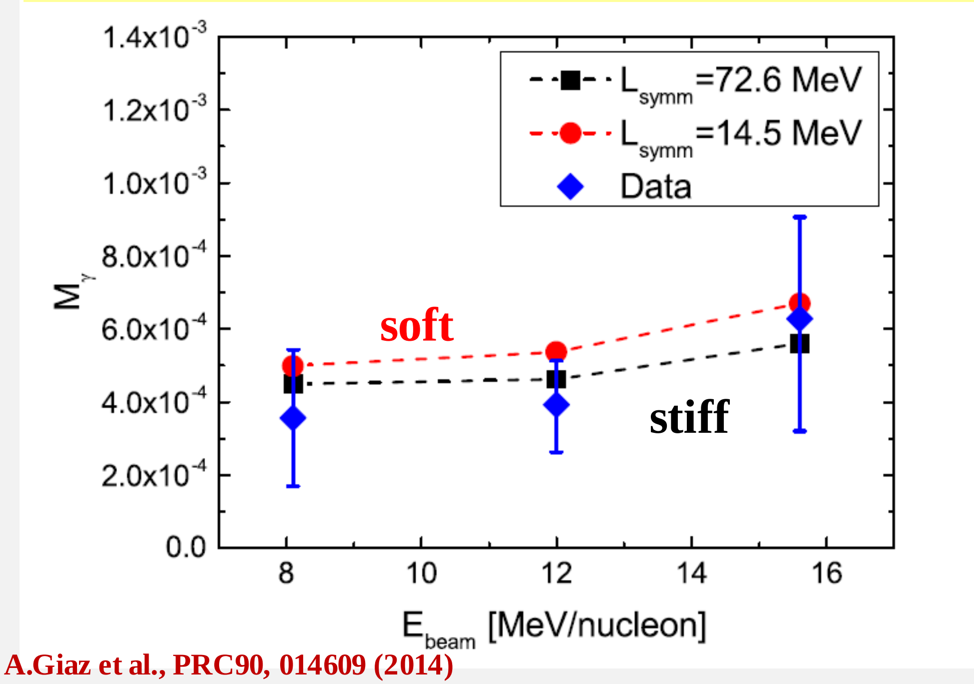


BNV calculations



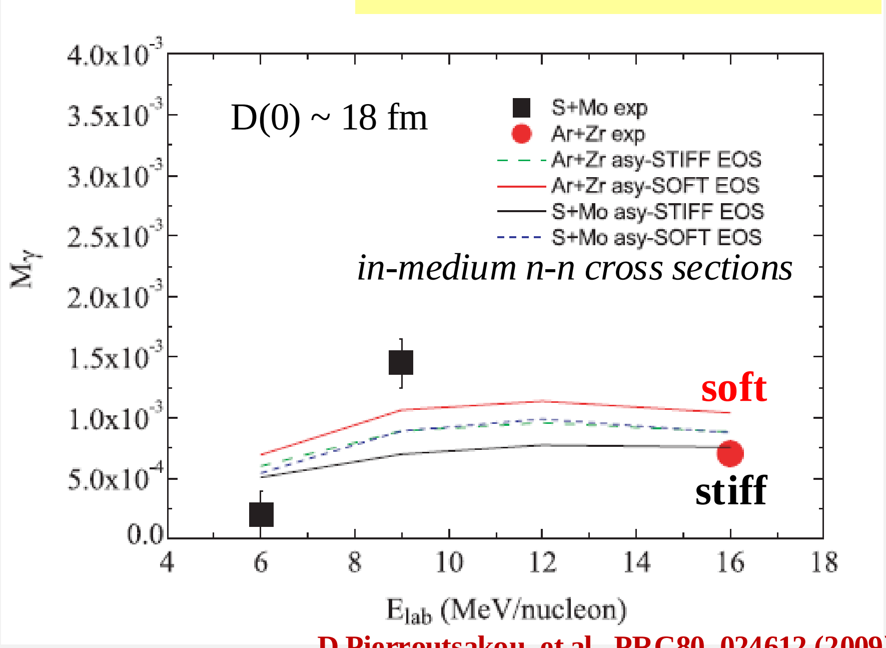
- Dedicated experiments at LNL and LNS

$^{16}O + ^{116}Sn$ (D_0 = 8.6 fm), E/A = 8.1, 12, 15.6 MeV/u



A.Giaz et al., PRC90, 014609 (2014)

$^{36}Ar + ^{96}Zr$ (D_0 = 18 fm)
E/A = 16 MeV/u



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

$^{40}Ca + ^{48}Ca$ (D_0 = 15.4 fm)
E/A = 10 MeV/u

M.Papa et al., PRC72, 064608 (2005)

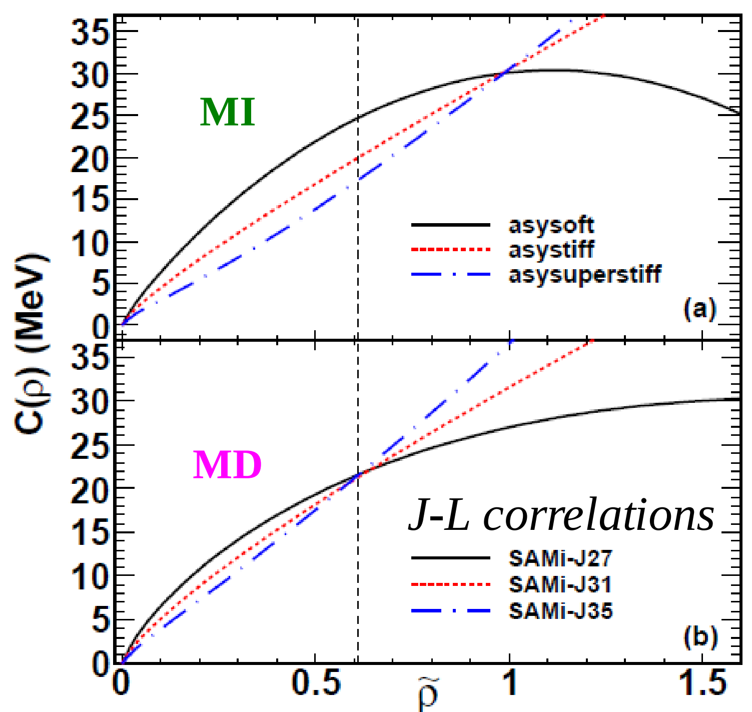
$^{40}Ca + ^{152}Sm$ (D_0 = 30.6 fm)
E/A = 11 MeV/u

C.Parascandolo et al., PRC105, 064611 (2022)

Few experimental data: more systematic analysis needed !

Exotic systems?

DD oscillations in ^{132}Sn + ^{58}Ni : dependence on the effective interaction



SAMi-J:

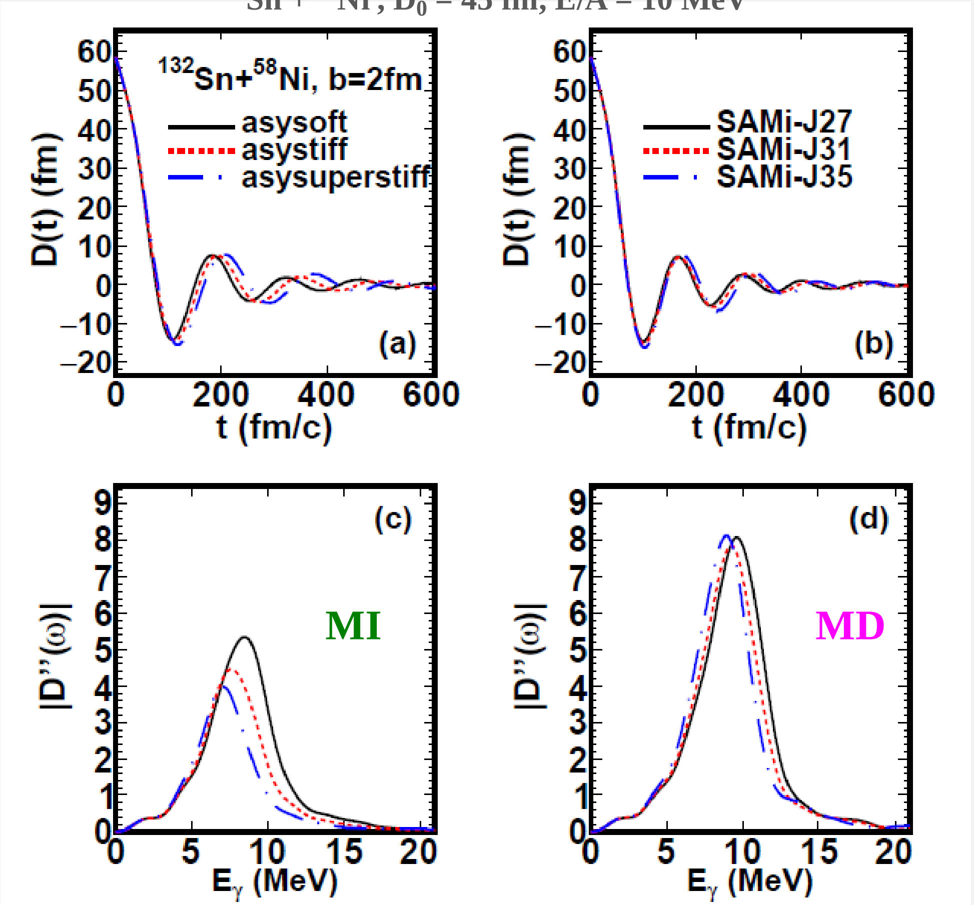
X. Roca-Maza, G. Colò, H. Sagawa, Phys. Rev. C **86**, 031306(R) (2012); X. Roca-Maza *et al.*, Phys. Rev. C **87**, 034301 (2013).

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

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

- **free n-n cross section**

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



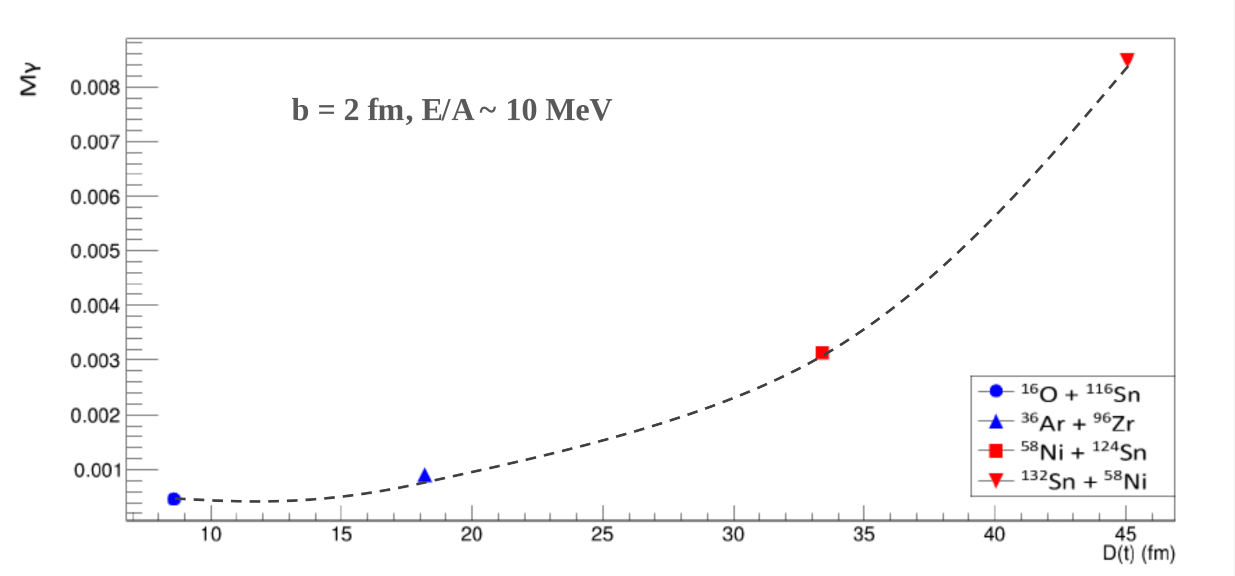
$$|D''(\omega)|^2 = \frac{(\omega_0^2 + 1/\tau^2)^2 D_0^2}{(\omega - \omega_0)^2 + 1/\tau^2}$$

(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

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

- …DD is back!

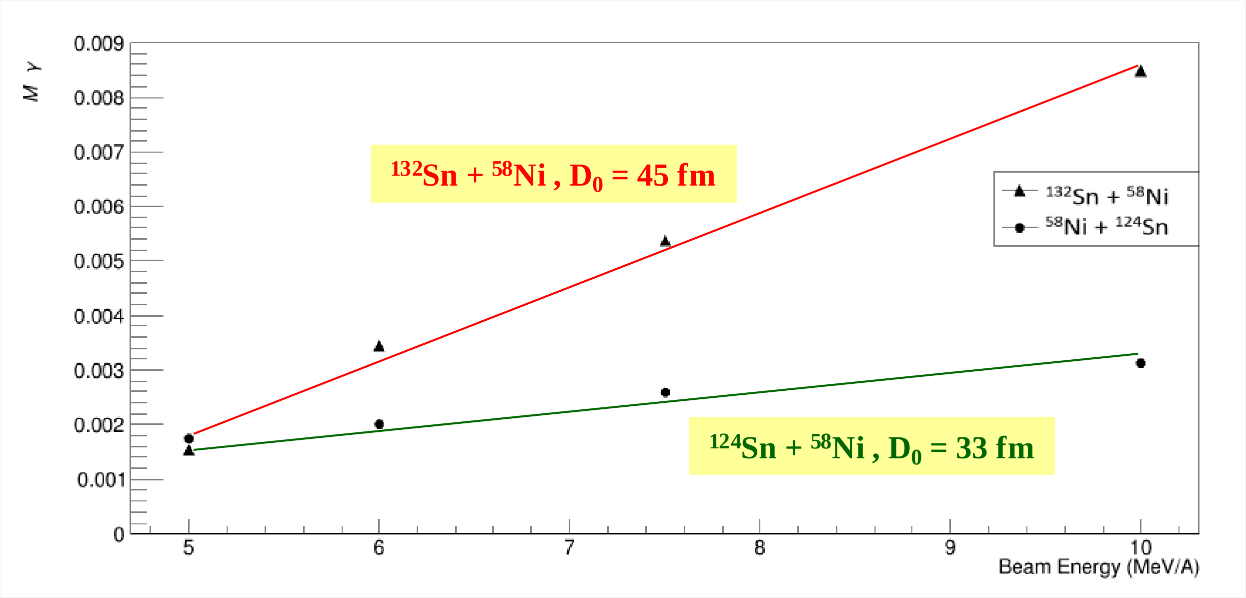


BNV calculations

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

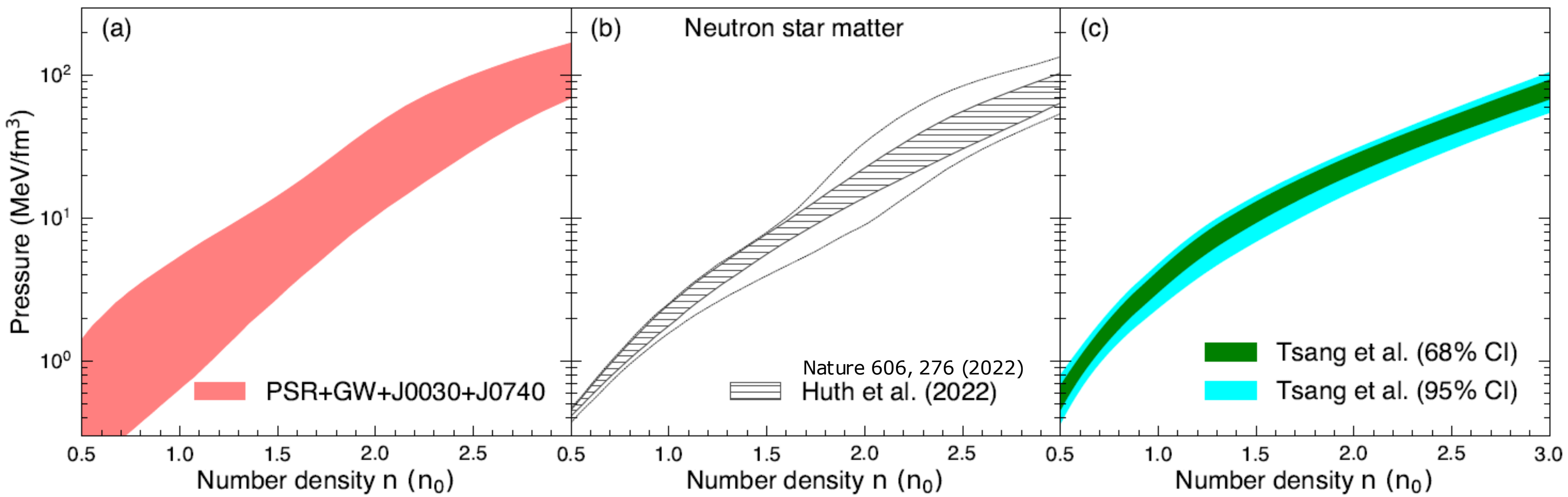
$$|D''(\omega)|^2 = \frac{(\omega_0^2 + 1/\tau^2)^2 D_0^2}{(\omega - \omega_0)^2 + 1/\tau^2}$$

damped oscillator



Master Thesis
Giulia Spina
University of Milano,
April 2024

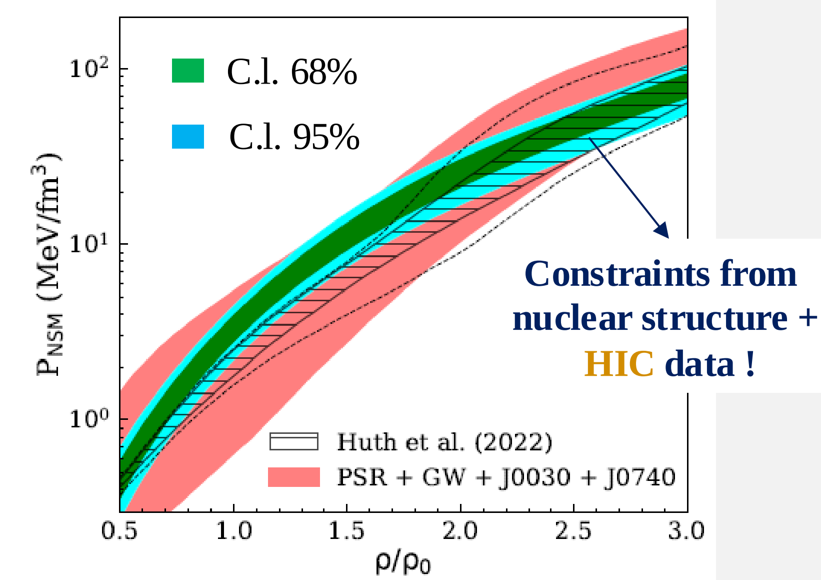
Symm. Energy from structure, nuclear reactions and astrophysics



C.Y. Tsang et al., Nature Astron. 8 (2024) 328

● The pressure of neutron star matter from a Bayesian analysis with:

- only astro observations (**red**)
- astro + structure + HIC data (**green** and **light blue**)



➡ Contribution from dissipative heavy ion reactions!

Dear Franco, Gianluca and Silvia,

many congratulations on your achievements !

and

Happy Birthday !