Challenges in theory in connection to GANIL experiments

XXIst Colloque GANIL 2019
- GUEC Session -

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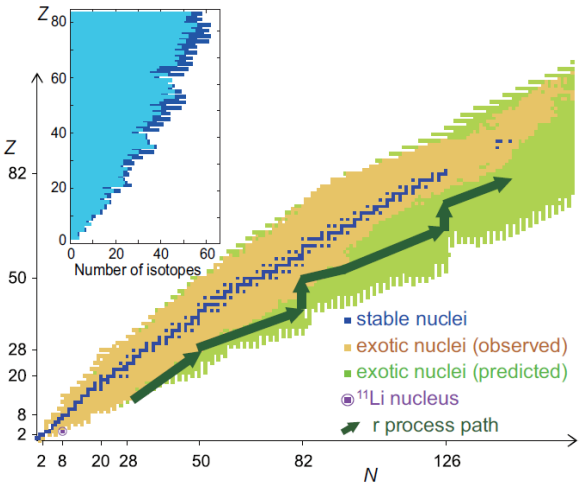
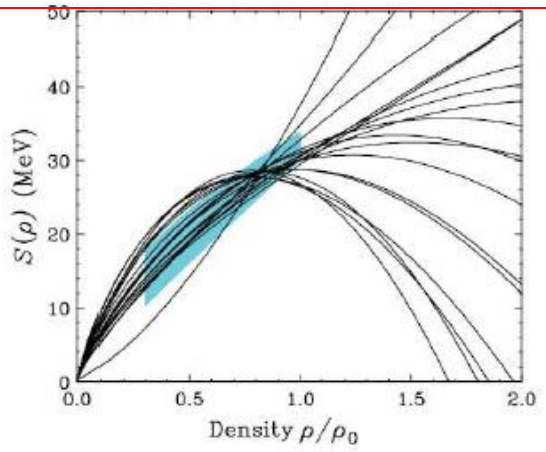
Physics @ GANIL

- Structure and reaction dynamics of exotic nuclei



[*Otsuka* et al, arXiv:1805.06501v4]

The symmetry energy of the nuclear EoS



- Nuclear collisions under various conditions. Nuclear matter dynamics and thermodynamics Equation of State

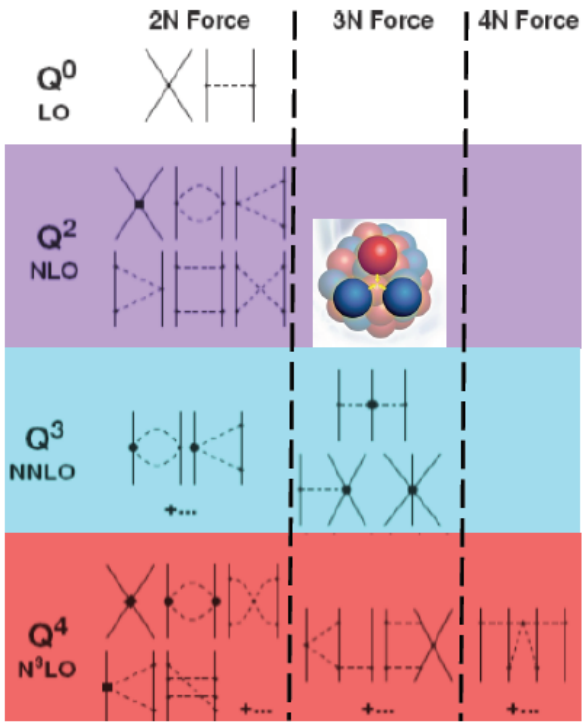
- Fundamental interactions, atomic, condensed matter physics, radiobiology, medical applications, …

The **ab-initio** breakthrough: a challenge for **nuclear theory**

Starting point : Chiral Lagrangian

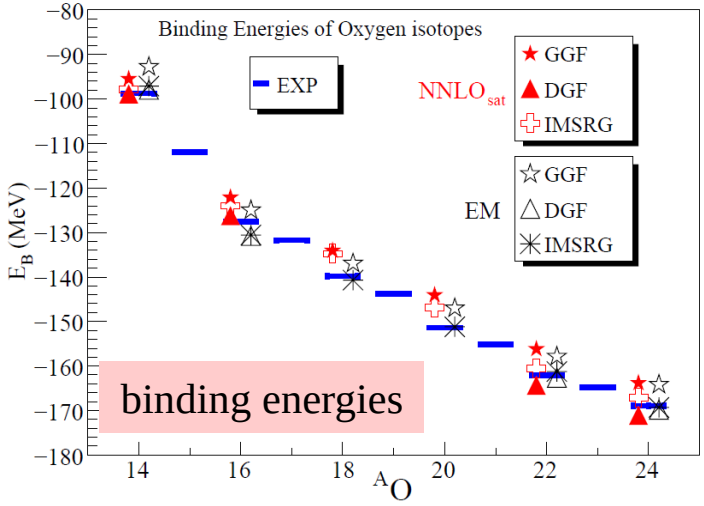
$$\mathcal{L}_{QCD} \longrightarrow \mathcal{L}_{EFT} = \mathcal{L}_{\pi\pi} + \mathcal{L}_{\pi N} + \mathcal{L}_{NN} + \cdots$$

Feynman diagrams

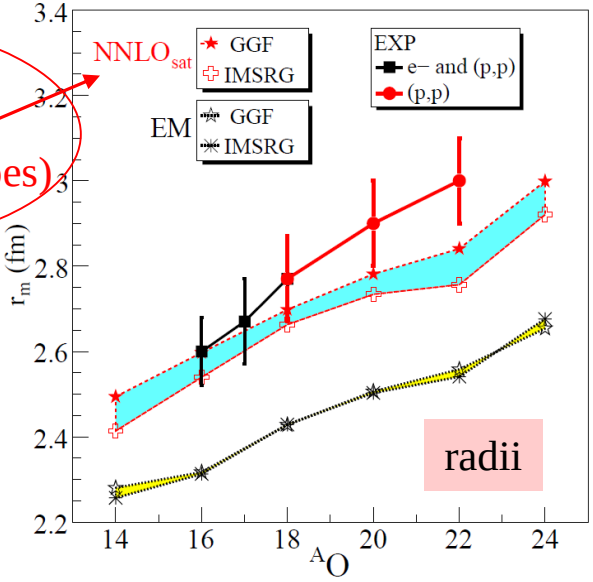


- **Direct link to QCD (chiral)**
- **Systematic constructive method**
- **Consistent NN, 3N, 4N**

Lapoux et al., PRL 117 (2016)



with exp. constraints
also from light nuclei
(selected C and O isotopes)

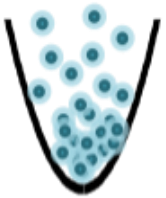


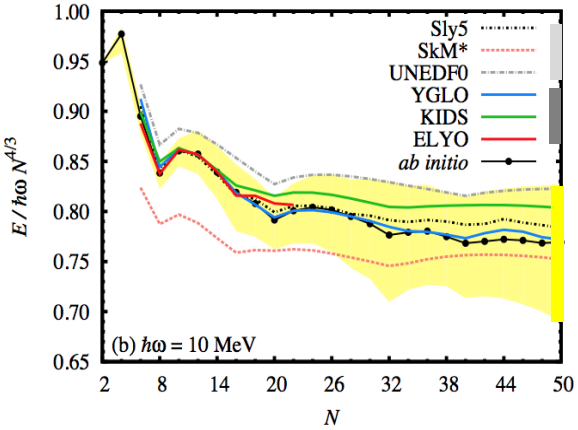
fundamental role of
3-body forces !

New **effective interactions** (DFT): spin-isospin channels

- New EFT-guided nuclear density functionals (DFT): cold neutrons in a trap (inclusion of spin-orbit and pairing)

YGLO: *Yang, Grasso, Lacroix*, PRC94 (2016)
ELYO: PRC95 (2017)
Bonnard et al., PRC98 (2018)

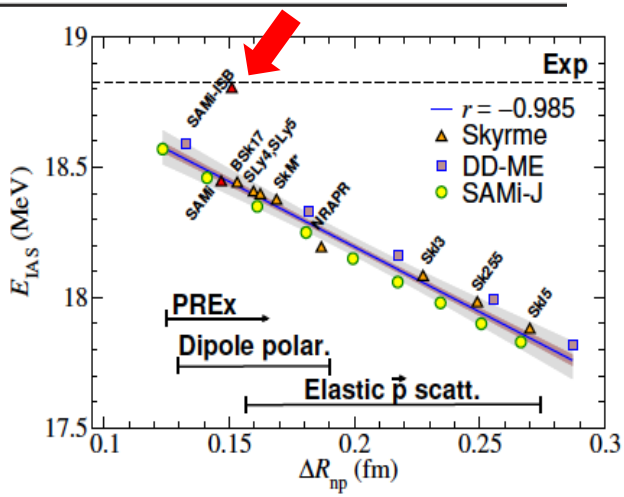




- New Skyrme functionals: **SAMi-ISB**, **SAMi-T**

Roca-Maza, Colò, Sagawa

PHYSICAL REVIEW LETTERS **120,** 202501 (2018)



IAS energy in ^{208}Pb

-- New functional SAMi-T ⟶ Fit of:

- Masses and charge radii, Spin-orbit splitting of selected nuclei
- Spin-orbit splittings in **neutron drops**
- Total energy of **neutron drops**

Neutron drops are calculated using RBHF.

S. Shen et al., PRC99 (2019)

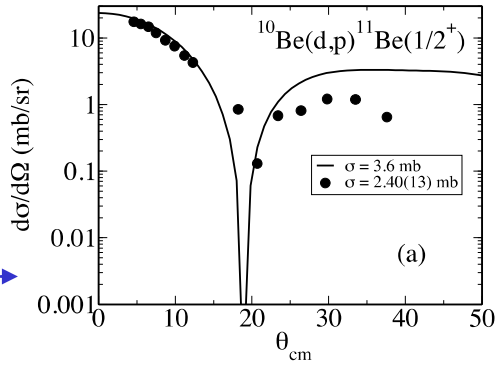
Merging structure and reaction dynamics (light systems)

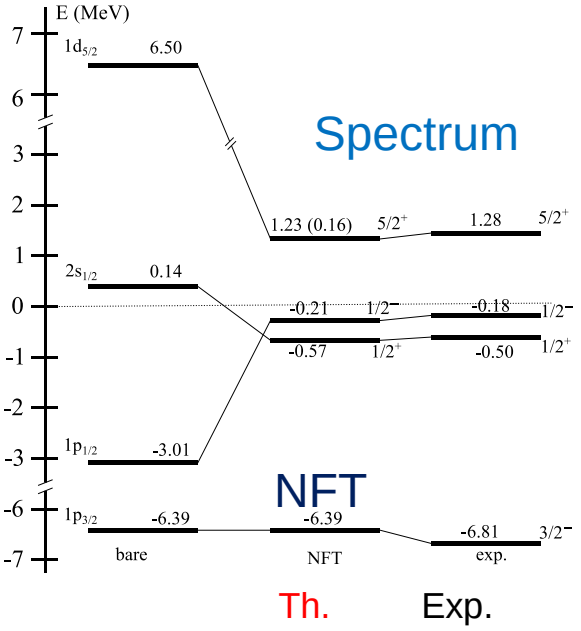
- quantitative description of structure and reactions of ***^{11}Be***

F. Barranco et al., PRL119 (2017) 082501

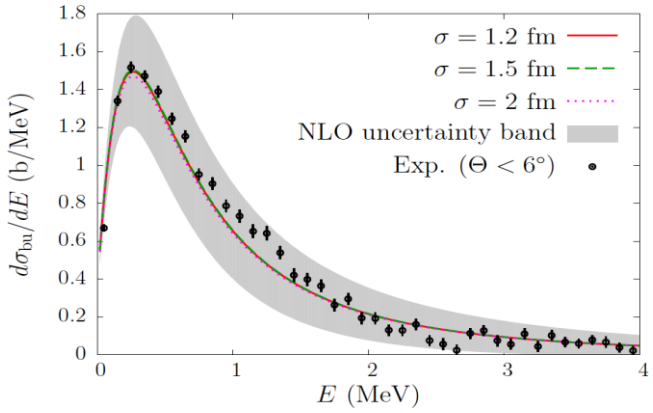
- Beyond Mean Field: Particle – vibration coupling (**Nuclear FT** model)

transfer reactions →

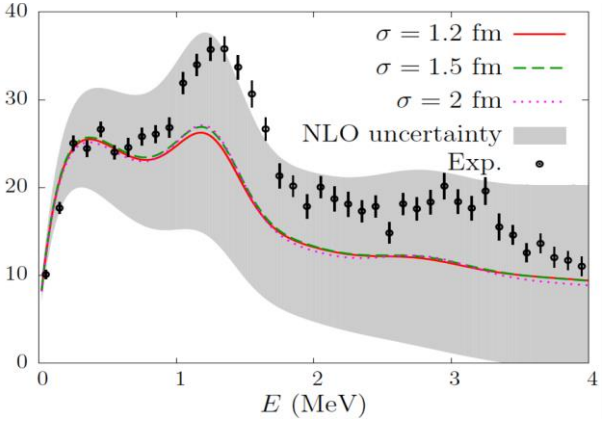




^{11}Be+Pb→^{10}Be+n+Pb @ 70*A*MeV



^{11}Be+C→^{10}Be+n+C @ 70*A*MeV

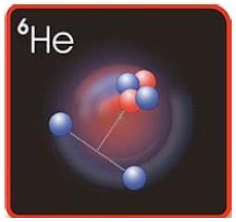


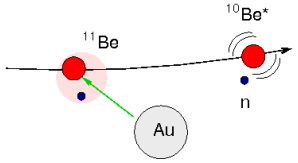
P. Capel et al. PRC 98, 034610 (2018)

- **Breakup reactions** with Halo EFT description of **^{11}Be**

- adjusted on ***ab initio*** calculations (*Calci* et al., PRL 2016)

halo nuclei …

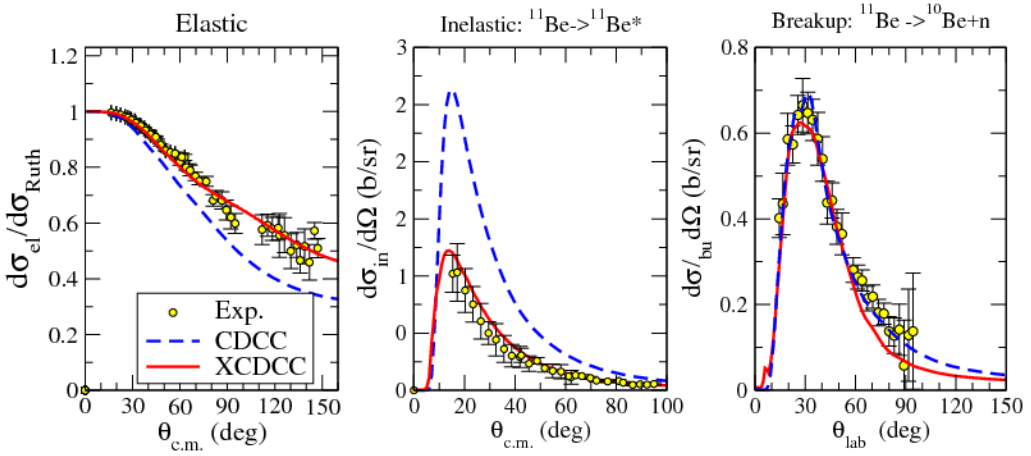




- **New reaction models**:

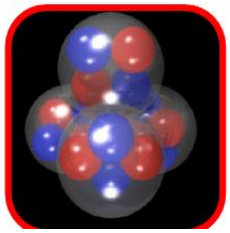
New CDCC code with **core excitations** for breakup in weakly bound nuclei.

Study of ^{11}Be+^{197}Au at 3-4 MeV/u



V.Pesudo et al, PRL118, 152502 (2017)

… and clustered systems, exotic structure…

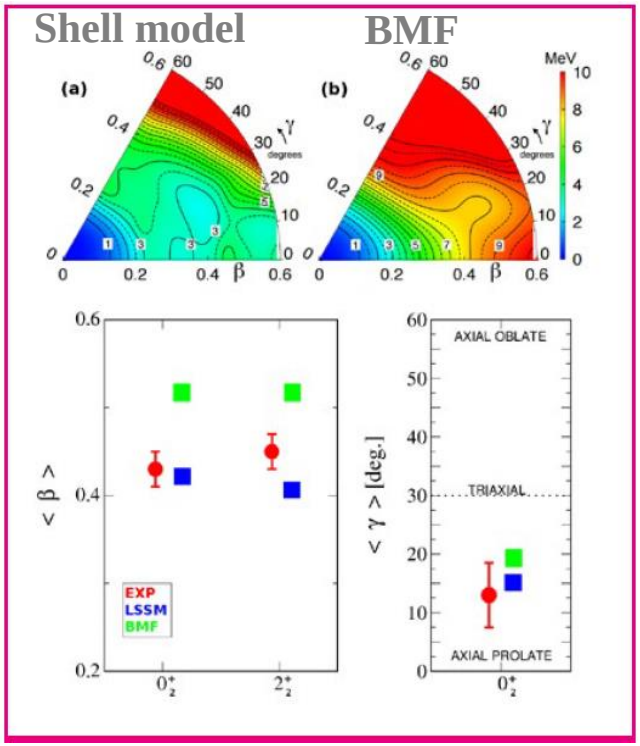


✓ Experiments proposed at GANIL (last PAC meetings): a few examples…

- ***Study of ^{20}O***: ^{19}O(d,p)^{20}O reactions (**AGATA + MUGAST + VAMOS**), ^{19}O by **SPIRAL1**
- ***Study of resonant clustered structure of ^{12}Be***: ^{4}He(^{8}He, ^{8}He)^{4}He reactions (**SPIRAL1**, **ACTAR TPC**)
- ***Proton (or two-proton) halo***: ^{17}Ne + ^{208}Pb (elastic and ^{15}O detection),^{14}O, ^{8}B, ^{9,10}C, ^{15}O radiative capture rate (**SPIRAL1**), ^{34}Ca bubble nucleus, …

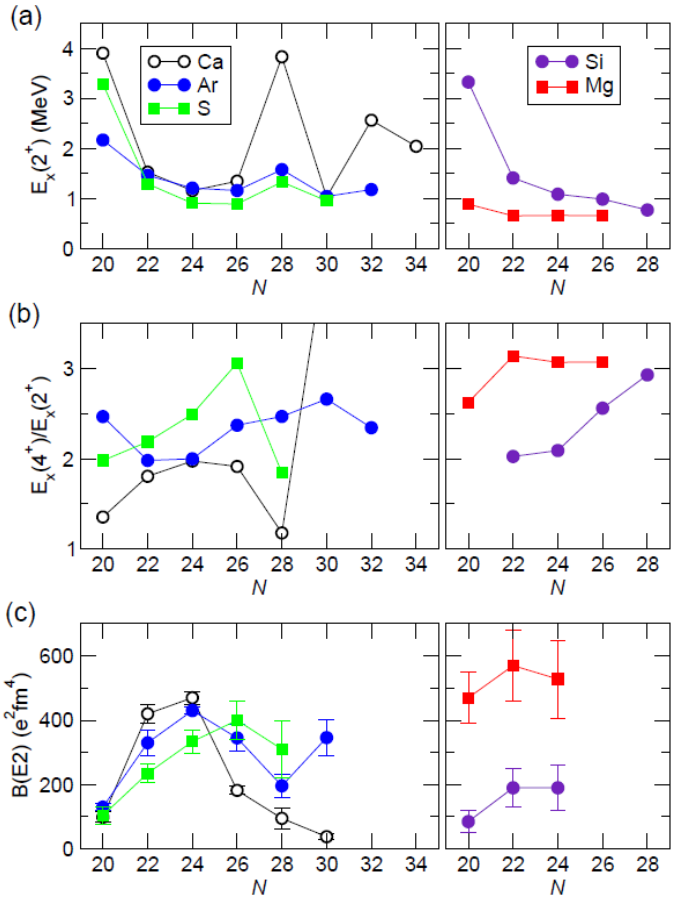
Understanding shell evolution, configuration mixing and shape co-existence

- **N = 20, 28** shell closure
- Nuclei with **N = Z** ⟶ role of **n-p pairing** (^{100}Sn region)
- Ni isotopes beyond **N=50**, Sn isotopes near and beyond **N=82** **(new generation ISOL)**



From NuPECC LRP 2017

-- *Co-existence of spherical and super-deformed structure in ^{42}Ca*

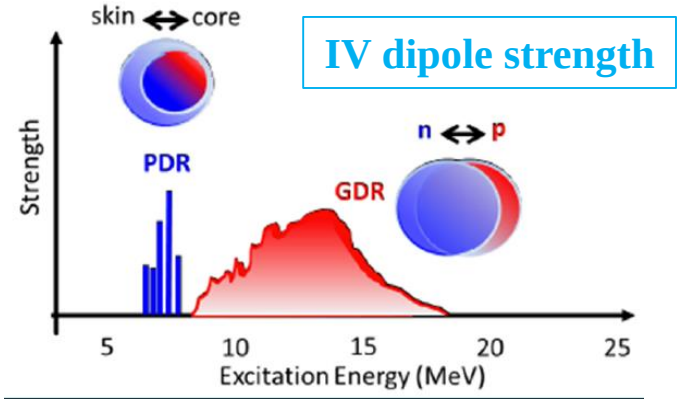


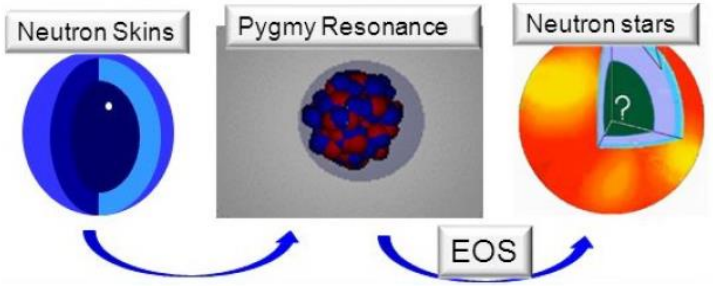
[*Otsuka* et al, arXiv:1805.06501v4]

-- *Disappearance of N=28 closed shell structure (exp. data)*

→ GANIL experiments (VAMOS + AGATA + MUGAST) (ex. ^{46}Ar(^{3}He,d)^{47}K)

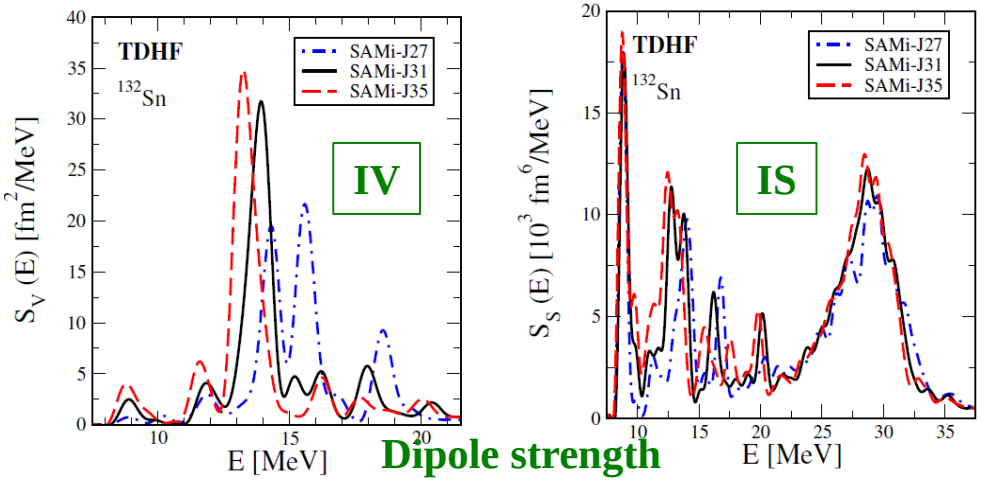
Collective motion in nuclei





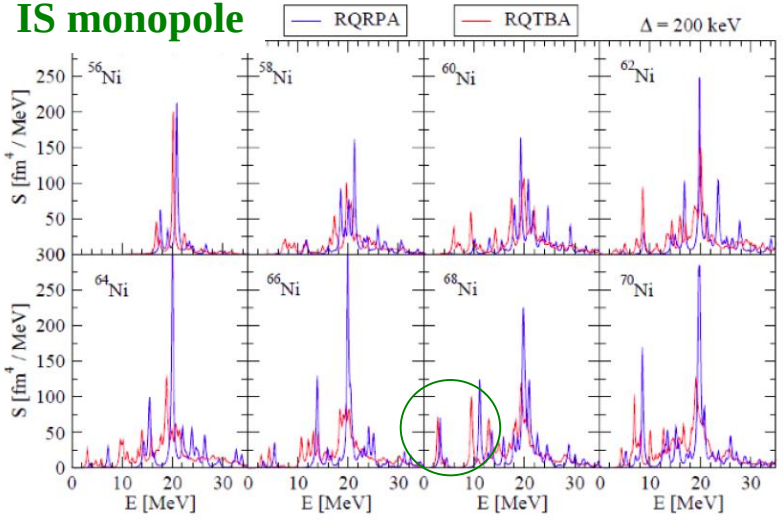
- Collective motion ⟶ 'macroscopic' features (NM compressibility, symm. energy..) ⟶ **EOS**

[*S.Burrello* et al, PRC99, 054314 (2019)]



Dipole strength

IS monopole



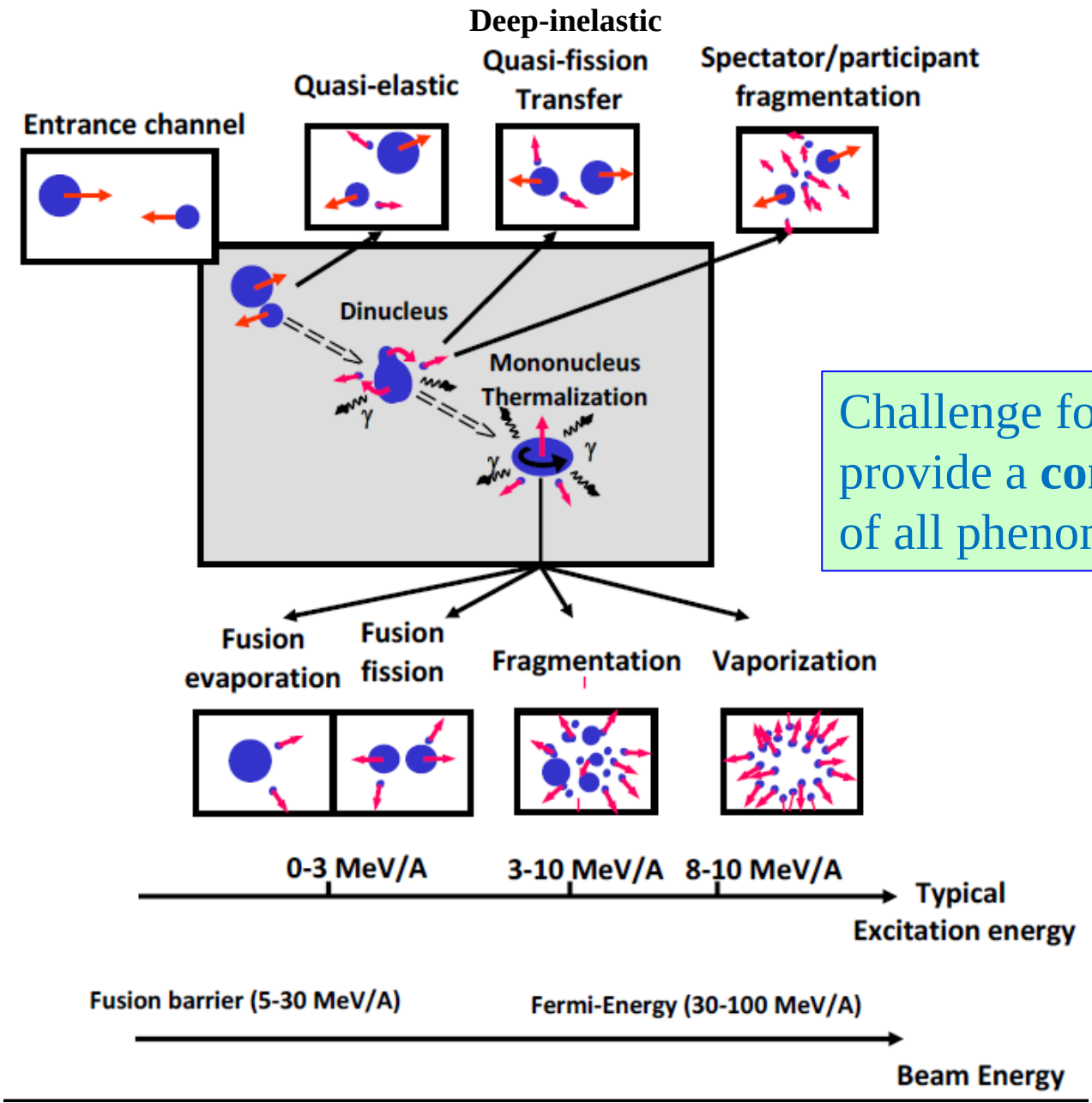
[*E.Litvinova* et al, PRC 78, 014312 (2008)]

[*Gambacurta,Grasso,Sorlin*, PRC 100 (2019)]

→ exp. with active targets

- **ISGMR**: Extraction of symm. matter **K** and symmetry energy compressibility $\mathbf{K_s}$
- **IS/IV Dipole response**: neutron skin, symmetry energy slope **L**

Challenges for reactions: from direct reactions to dissipative collisions



Challenge for **reaction theory**: provide a **consistent** decription of all phenomena !

from D.Lacroix
NUSPRASEN 2018

Fusion/fission and Quasi-fission: shell effects & EOS

Ex: Inverse kinematics at VAMOS/GANIL

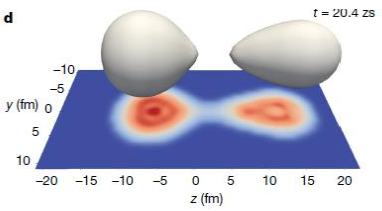
$^{238}U + ^{12}C$ at 6 MeV/u

- Fission from fusion and multi-nucleon transfer
- Quasi-fission

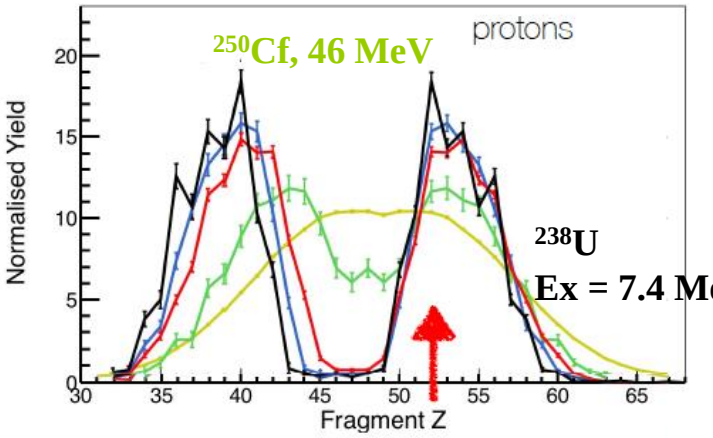
→ Shell effects, isospin effects, potential surface…

Quadrupolar or Octupolar ?

[*Scamps & Simenel*, Nature 564 (2018)]

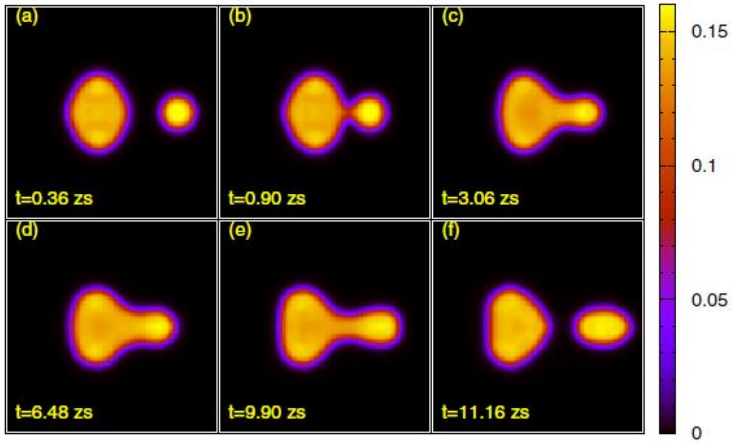


[*D.Ramos* et al, PRC97, 054612 (2018)]

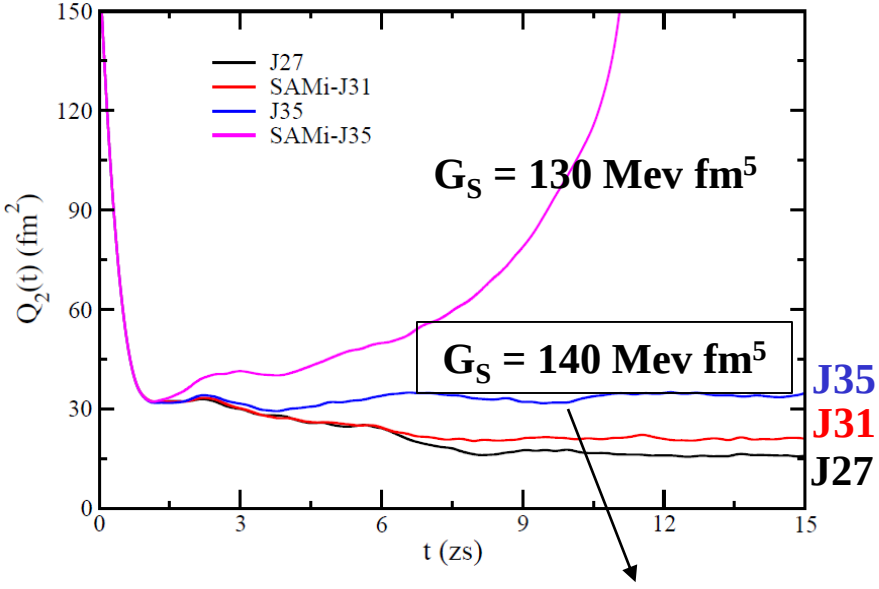


→ Fusion vs. quasi-fission

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



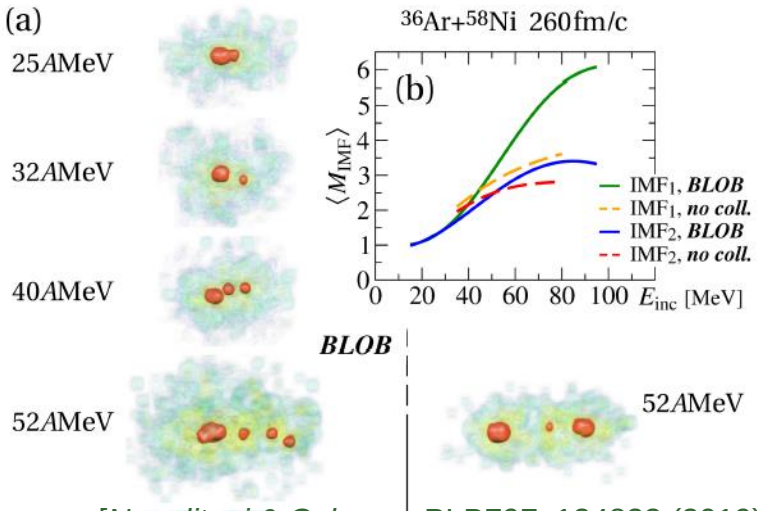
Quadrupole moment evolution



SAMi-J35 symm.energy [*H.Zheng* et al, PRC98, 024622 (2018)]

➢ **symmetry energy effects**

Fragmentation at Fermi energies & the nuclear EOS



[*Napolitani & Colonna*, PLB797, 134833 (2019)]

- Characterization of reaction dynamics:

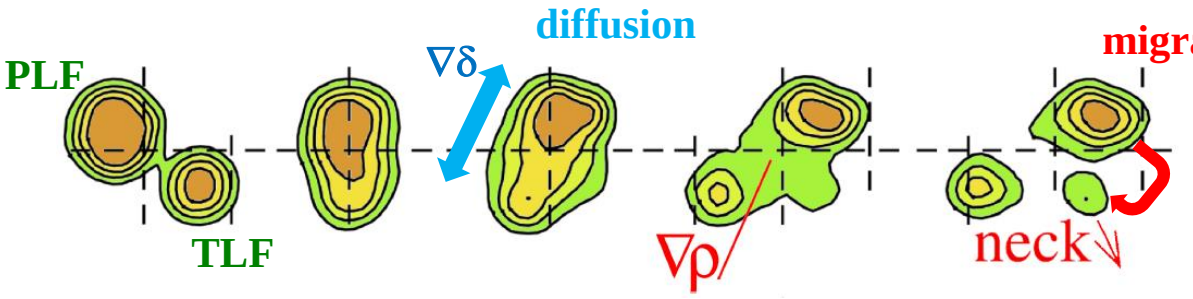
Treatment of the dynamics of a many-body system !
→ reach consistent transport model description

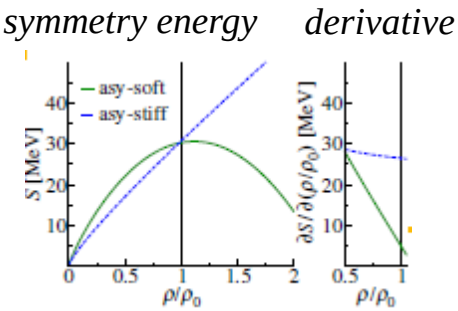
- Dynamics and thermodyn. of Nuclear Matter:

low-density clustering, isospin effects..

- Isospin dynamics and symmetry energy

→ Diffusion and migration within the same experiment:
Indra + Vamos @ GANIL
Indra + FAZIA @ GANIL



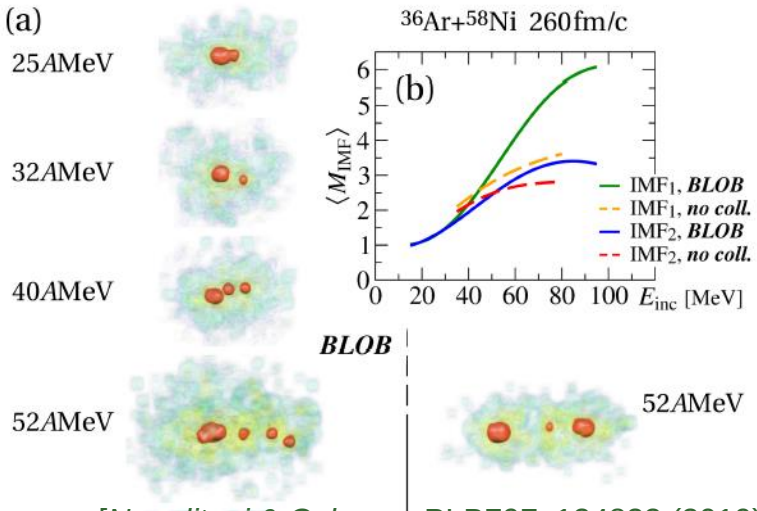


Difference between neutron and proton flow:

$$j_n - j_p \propto \delta\left(\frac{\partial E_{sym}}{\partial \rho}\right)\nabla\rho - \rho E_{sym}\nabla\delta$$

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

Fragmentation at Fermi energies & the nuclear EOS



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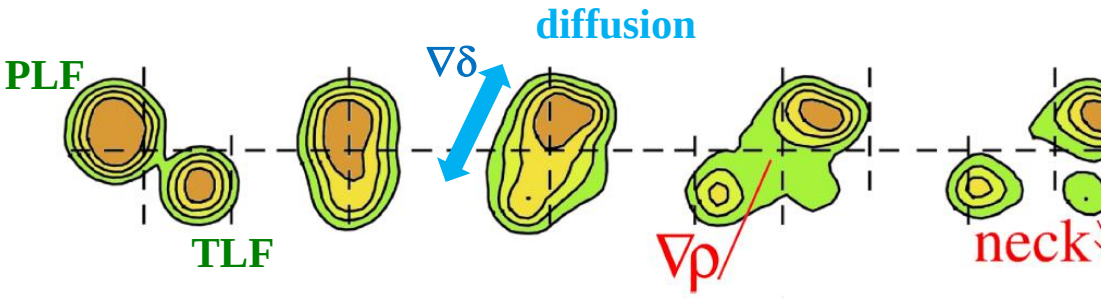
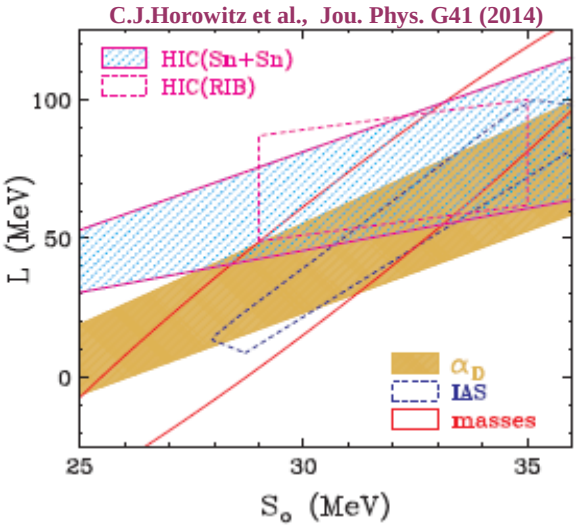


Difference between neutron and proton flow:

$$j_n - j_p \propto \delta(\frac{\partial E_{sy}}{\partial \rho}$$



$-\rho_p$

❑ Summary

➢ Reach a consistent description (through models and associated eff. interactions) of the structure of nuclei along the nuclear chart.

➢ Reach a consistent description of reaction dynamics, from low to intermediate energy.

➢ Describe the behavior of nuclear matter under several conditions of density, temperature, charge asymmetry, ..

The synergy between theory and experiments is essential to progress !!

Thanks to Denis Lacroix !