New properties of exotic nuclei, drip line and open quantum systems

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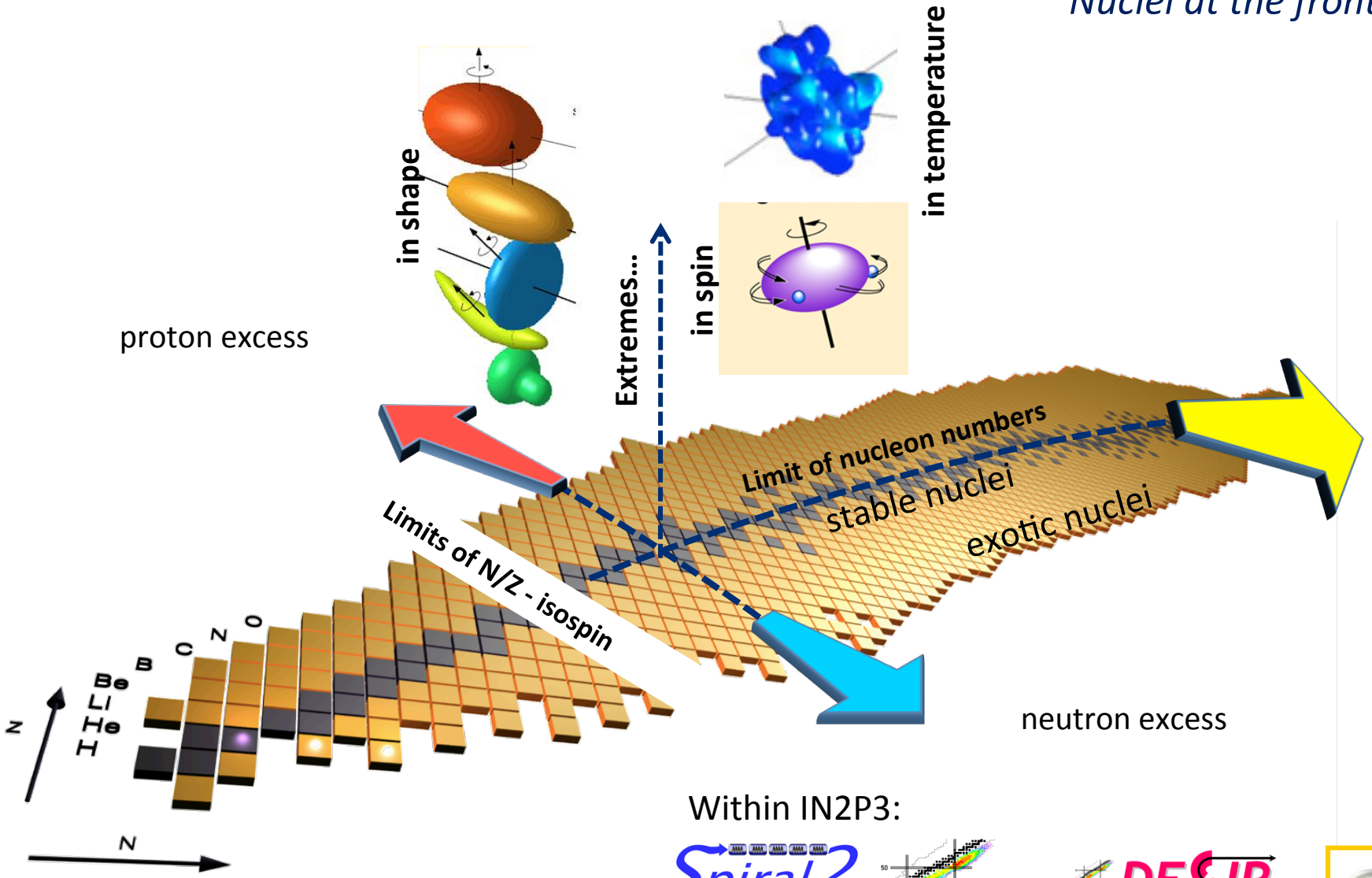
INSTITUT DE PHYSIQUE NUCLÉAIRE ORSAY

Outline:

- Generalities
- Already known new phenomena in exotic nuclei
- Emergent aspects in weakly bound systems
- Open questions and future of low energy nuclear physics.

Nuclear Physics today

Nuclei at the frontiers



Within IN2P3:

Spiral2 EURISOL

Spiral2 DESIR ALTO Accélérateur Linéaire et Tandem à Orsay

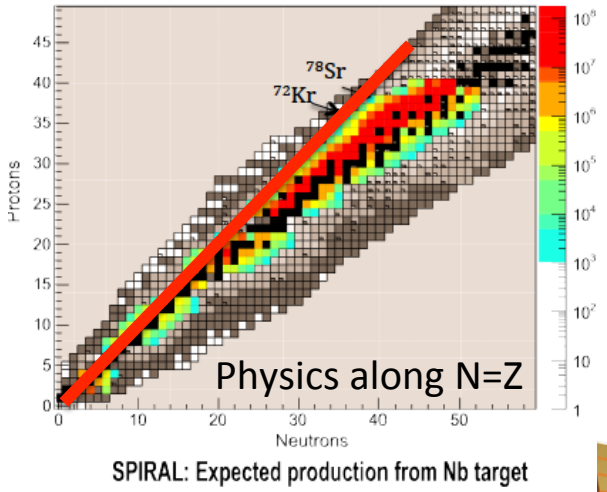
S3

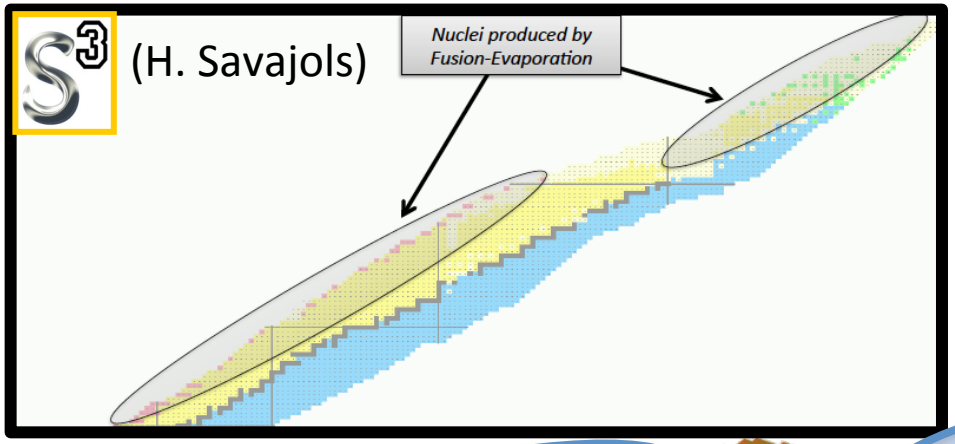
Taken from Irfu/IN2P3 perspectives-2012
(D. Lacroix)

From Dream to reality

Nuclei at the frontiers

Spiral 1 upgrade (P. Delahaye)

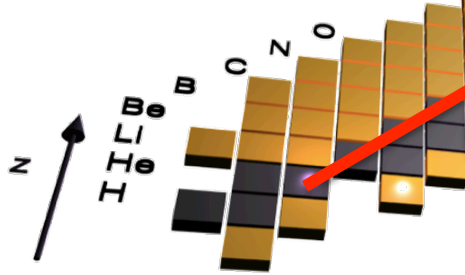


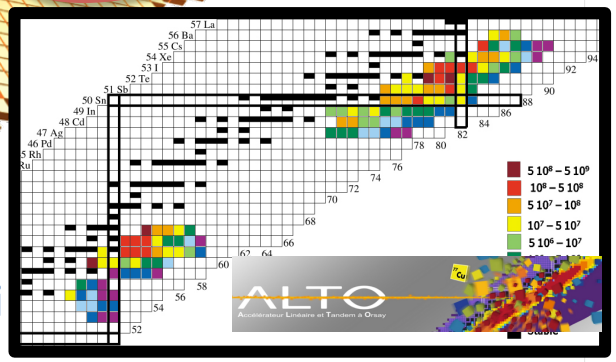


Nuclei at the extreme of mass

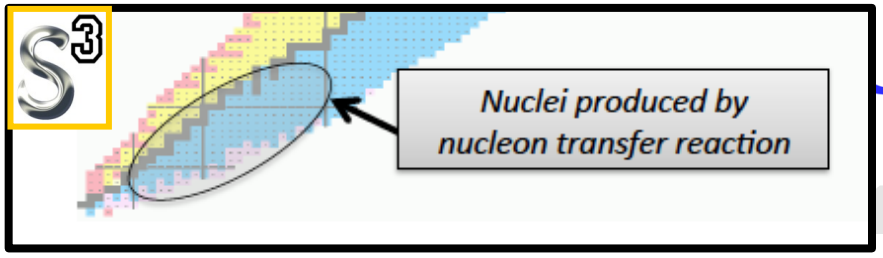
Proton rich nuclei

So what?





Neutron rich nuclei

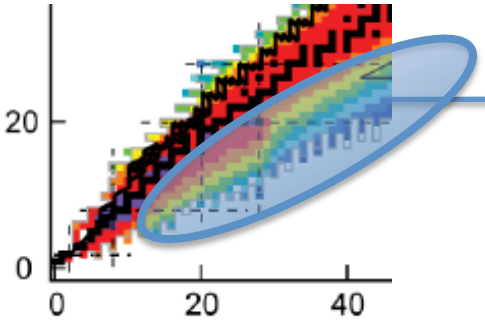


Spiral2

EURISOL

Spiral2 DESIR

ALTO
Accélérateur Linéaire et Tandem à Orsay

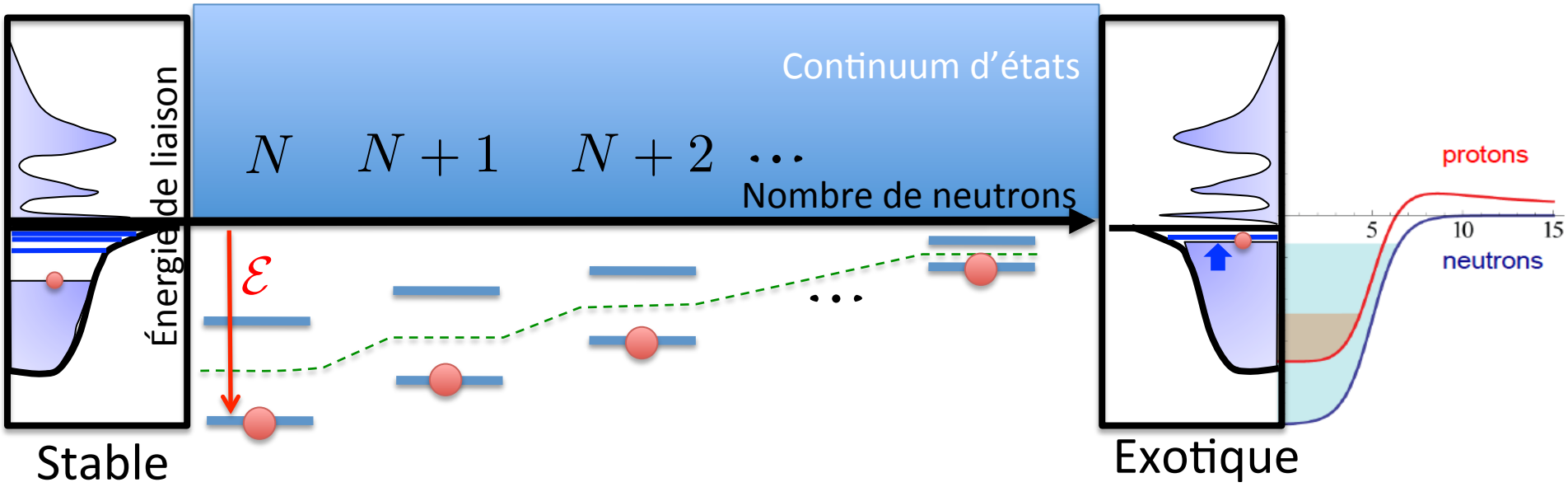


The physics of exotic nuclei

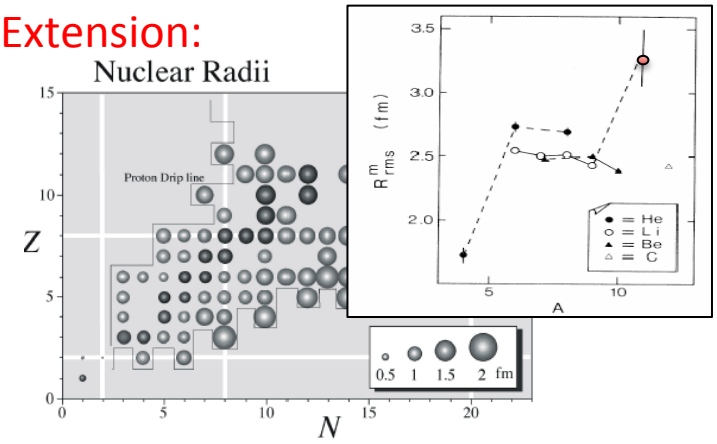
Weakly bound neutron rich nuclei

How organizes neutron and proton matter in neutron rich systems?

What we know/expected:

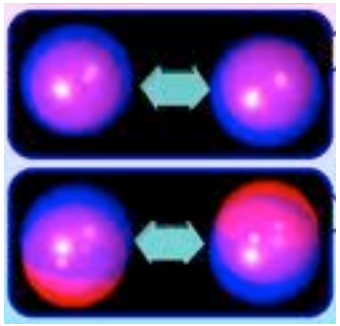


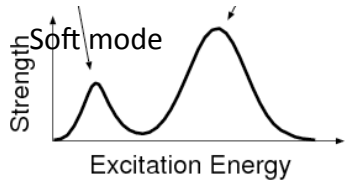
Nuclei can have anomalous Extension:

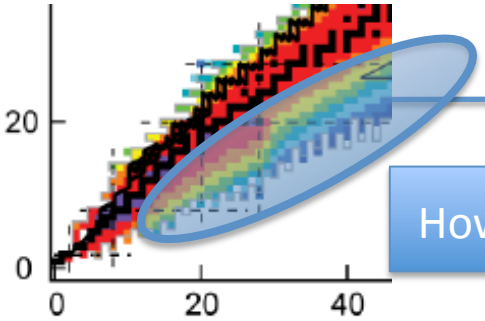


New excitation modes can emerge (?)

New excitation modes





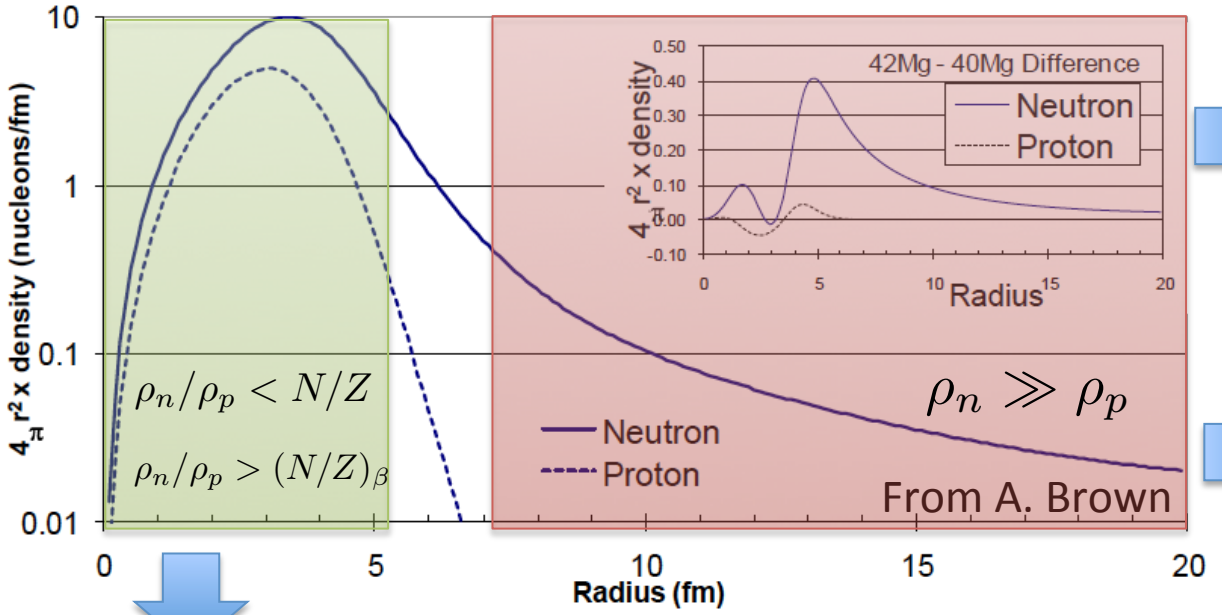


The physics of exotic nuclei

Weakly bound neutron rich nuclei

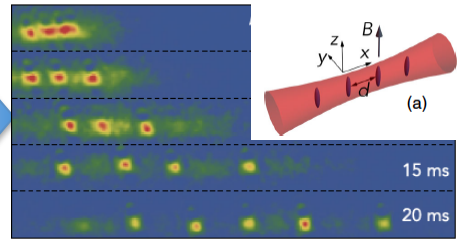
How organizes neutron and proton matter in neutron/proton rich systems?

What if we directly access the neutron density?



Gives direct information on the isospin properties of nuclei

Quantum droplet physics



PRL 2016

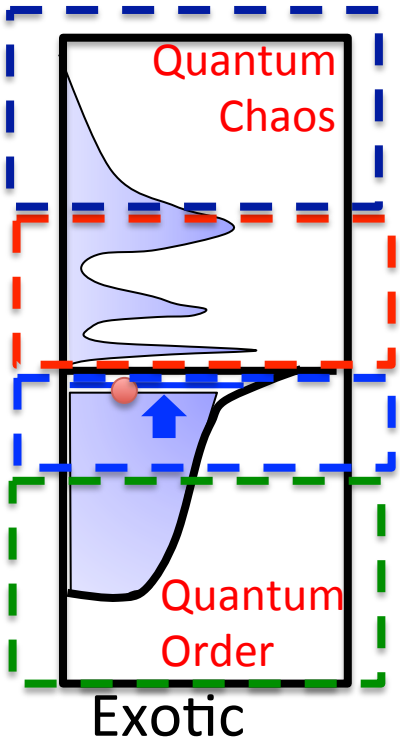
Neutron star physics

- Physics of systems at anomalously large scattering length (close to unitary regime)
- Systems at very low density
- Pairing effects, continuum and other correlations

The physics of exotic nuclei

Resonantly interacting systems and new radioactivity?

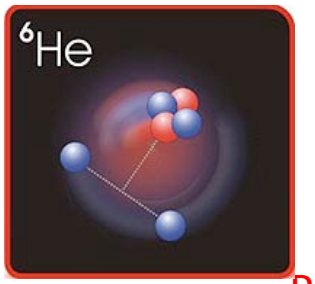
From bound to unbound systems (passing the emission threshold)
Correlation effect



Statistical mechanics and level density in stable and unstable nuclei

Resonance and correlations

Minimal Cooper pair

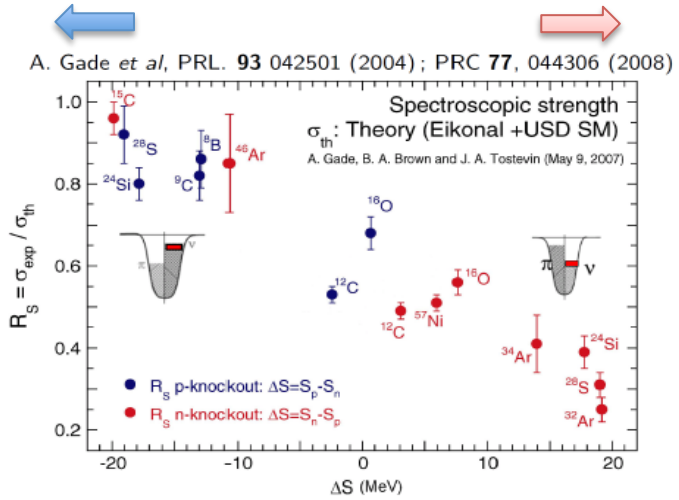


Physics at or below the Particle emission threshold

Physics of deeply bound state at very large asymmetry

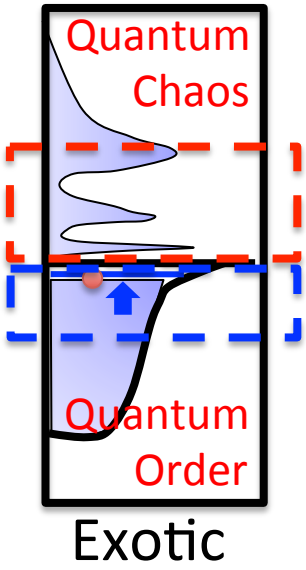
Neutron rich

Proton rich



The physics of exotic nuclei

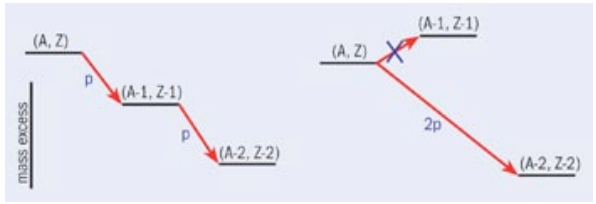
Resonantly interacting systems and new radioactivity?



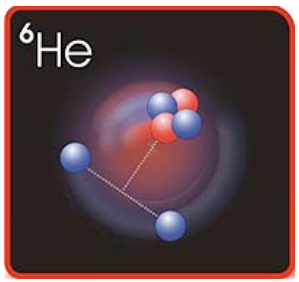
➡ From bound to unbound systems (passing the emission threshold)
Correlation effect

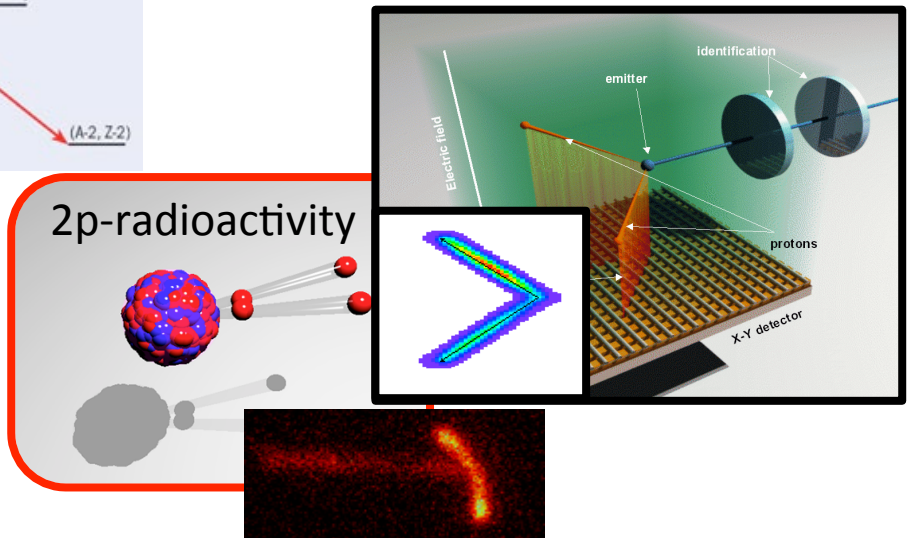
➡ Can new radioactivity exists?

-Yes-



Minimal Cooper pair



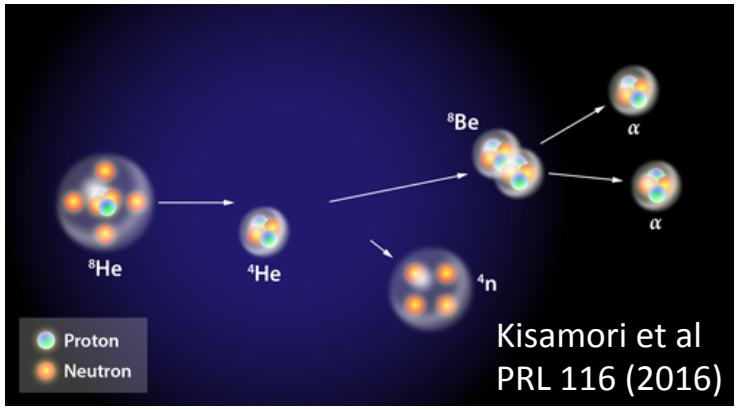


Search for the existence of new radioactivity?

➡ 2 neutron radioactivity?

➡ Multi-neutron radioactivity?

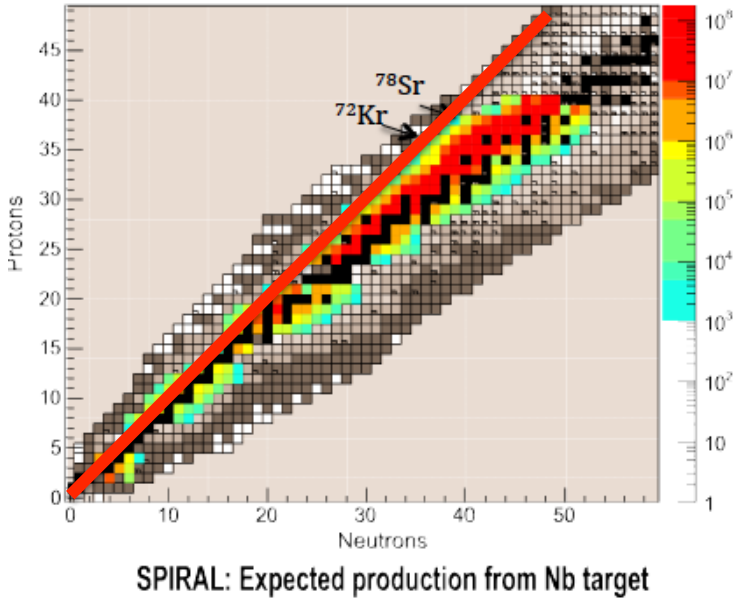
➡ Others?



The physics of exotic nuclei

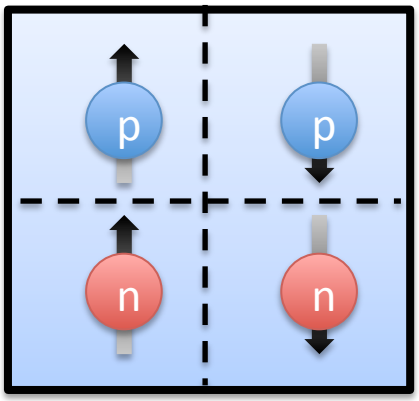
Proton rich side

$N = Z$



SPIRAL: Expected production from Nb target

Resistance of spin-isospin symmetry in nuclei SU(4)



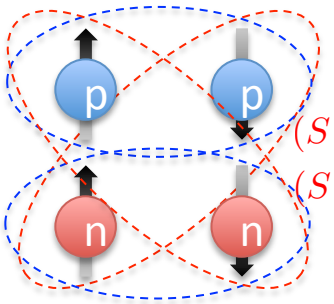
Symmetry destroyed by

- Coulomb
- Spin-orbit And tensor

Competition with quarteting?

Coexistence of particle like and neutron-proton pairing in nuclei?

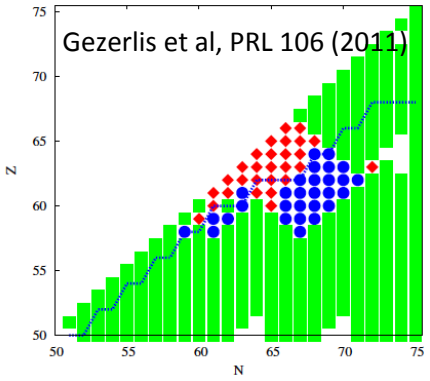
$(S = 0, T = 1)$

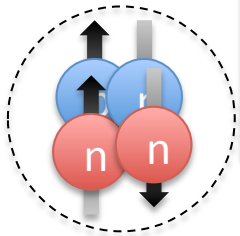


$(S = 1, T = 0)$

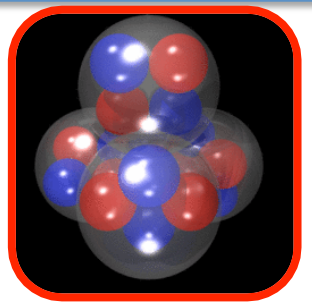
$(S = 0, T = 1)$

$(S = 0, T = 1)$





Origin of clustering in nuclei?

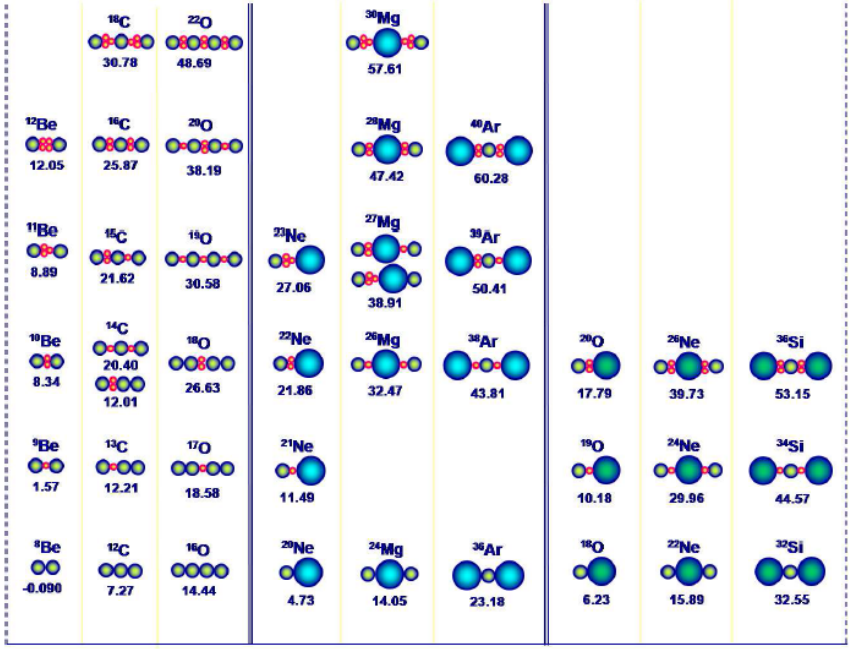


The physics of exotic nuclei

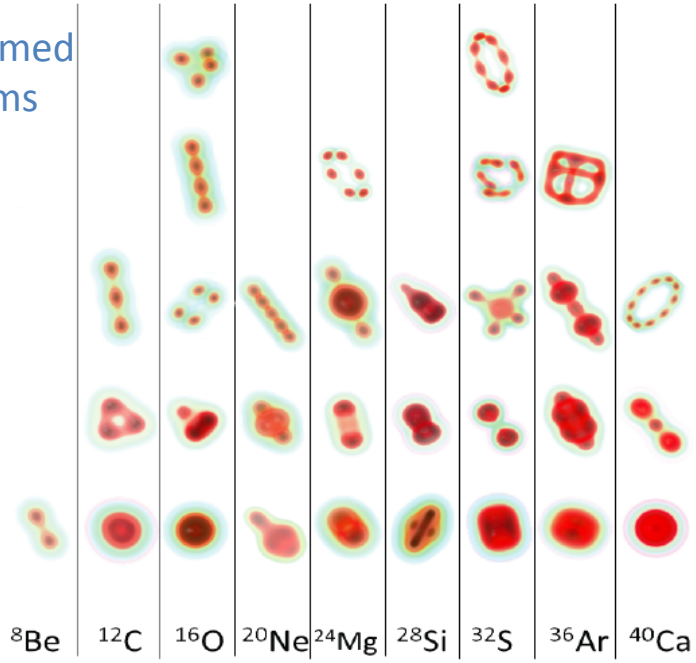
Exploring the transition from liquid nuclei to quasi-molecular states

Extended Ikeda diagram

W. von Oertzen, EPJA (2001)

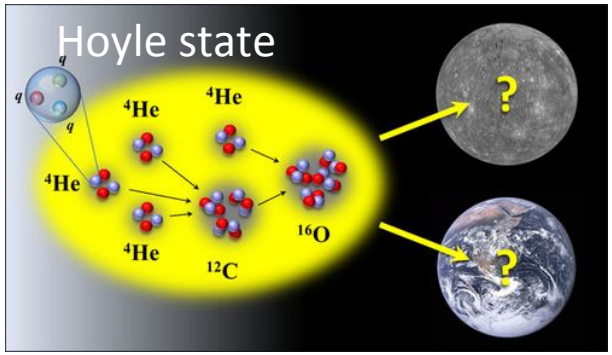


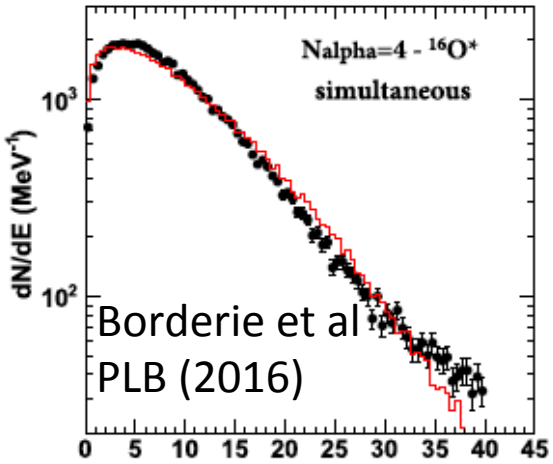
Deformed systems



J.-P. Ebran et al, Nature 487 (2012)

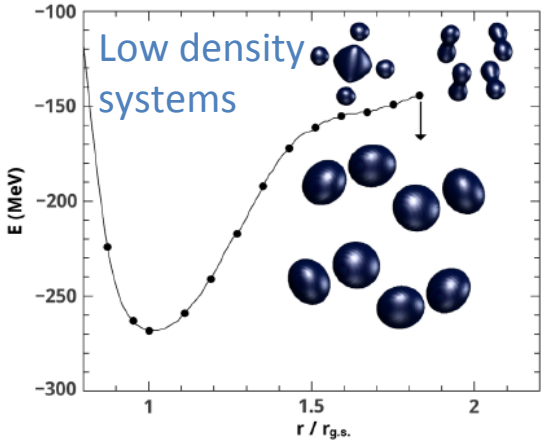
Experiments





Borderie et al PLB (2016)

Low density systems



Girod, Schuck, PRL111 (2013)

The physics of exotic nuclei

Fermi liquid versus quasi-molecular states: some present and future questions

Clustering versus shape coexistence

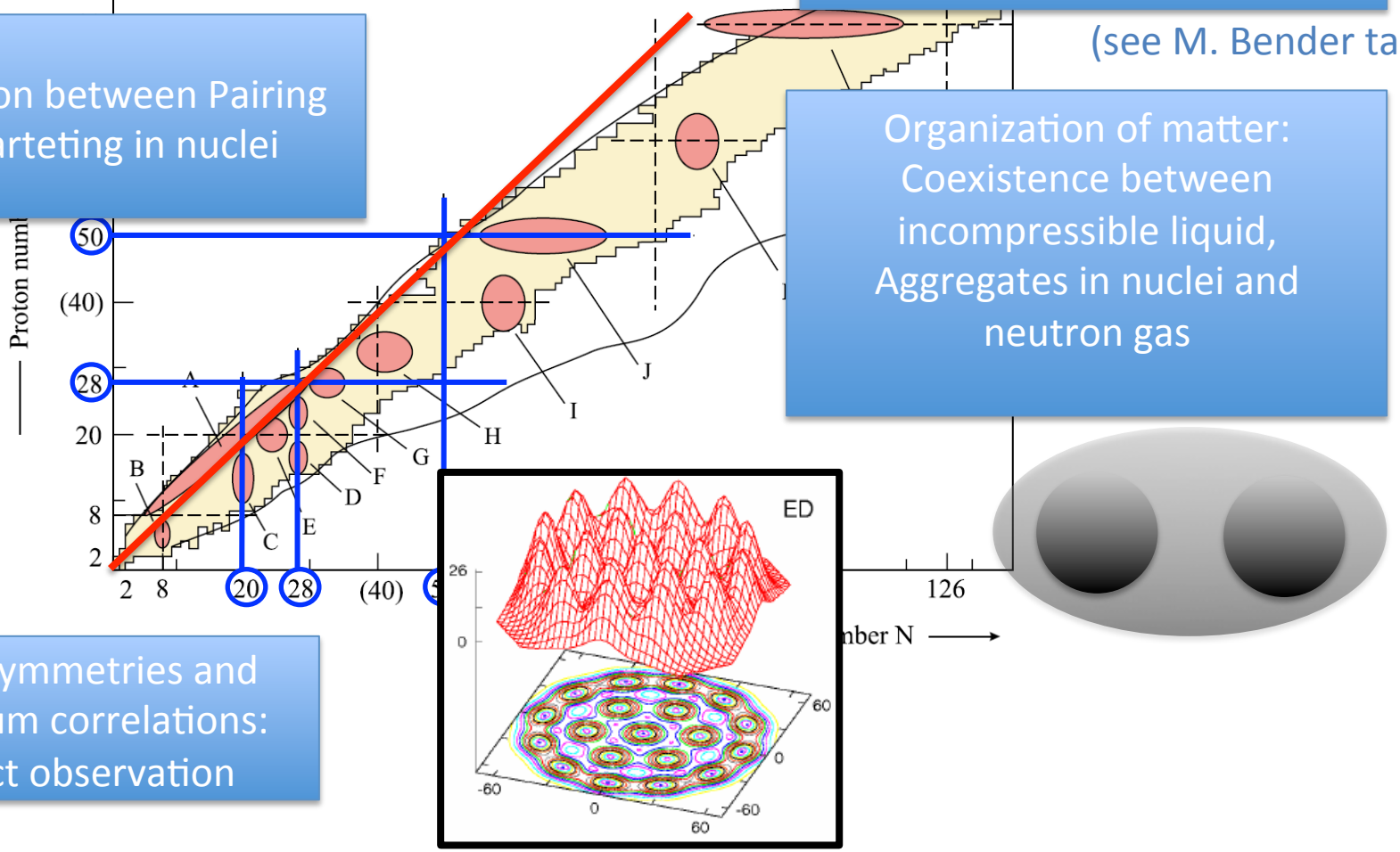
Heyde & Wood Rev. Mod. Phys. 83 (2011) 1467

Clarify the link between clusters and shape coexistence

(see M. Bender talk)

Competition between Pairing and quarteting in nuclei

Organization of matter: Coexistence between incompressible liquid, Aggregates in nuclei and neutron gas



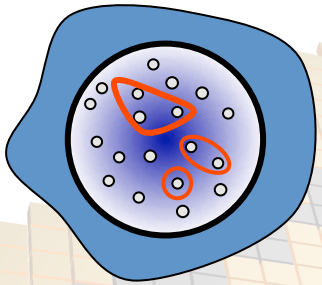
New symmetries and quantum correlations: Direct observation

Yannouleas et Lanzman, Rep. Prog. Phys. (2007)

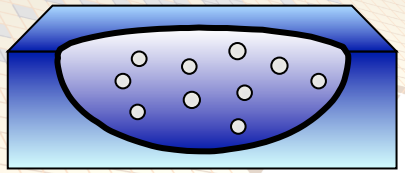
Nuclear physics today

Emerging phenomena and theoretical challenges

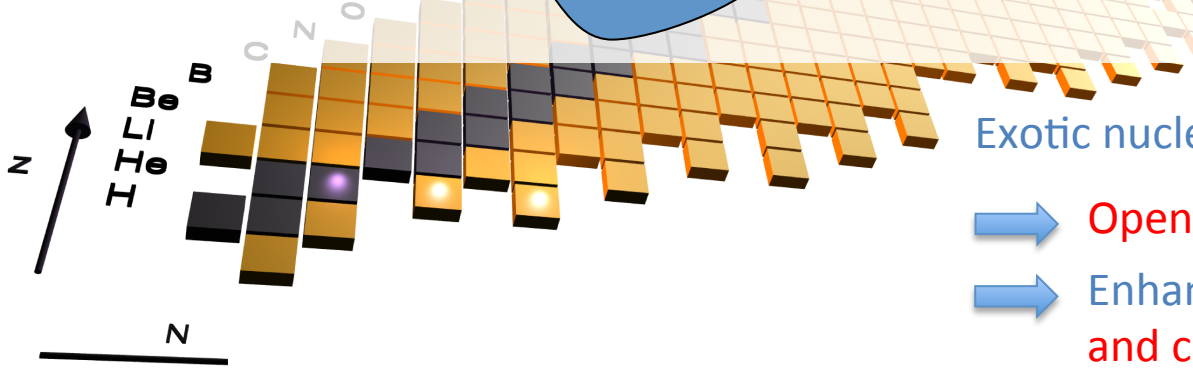
Correlated system



VS

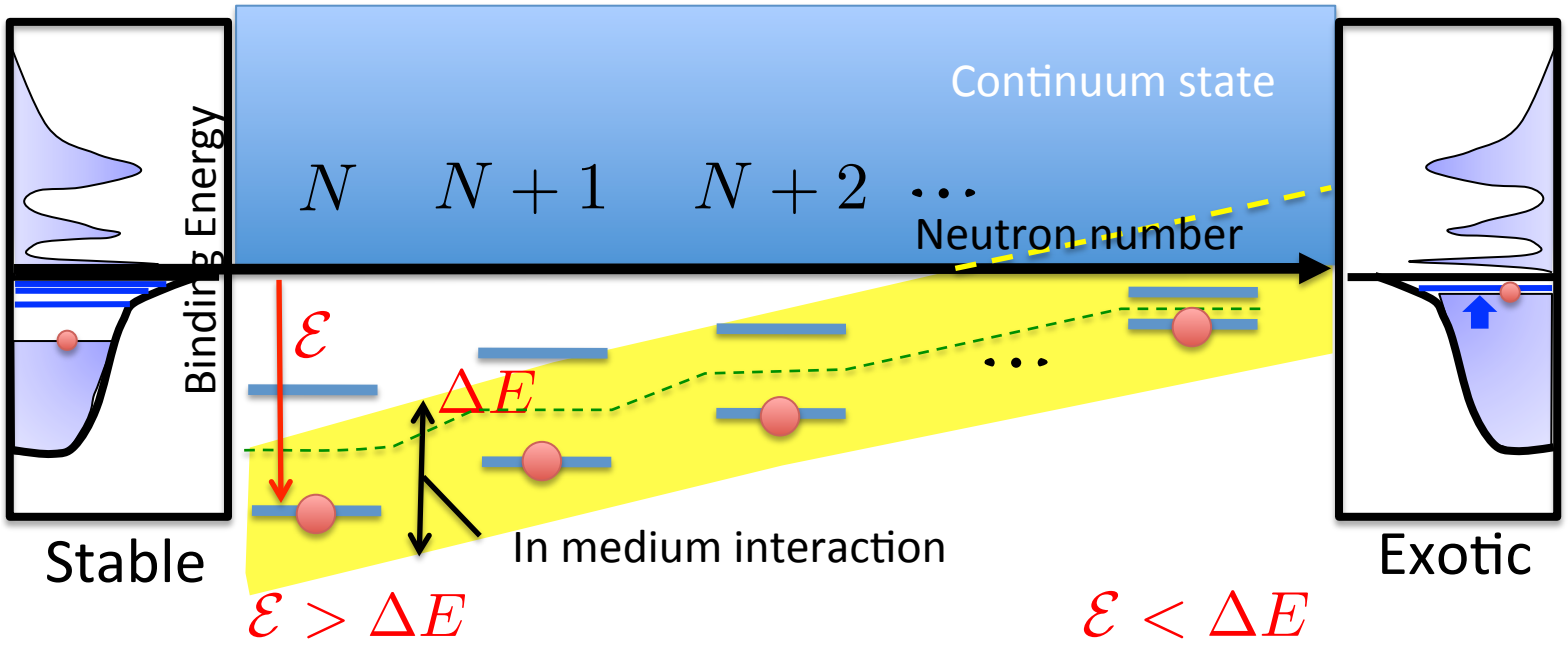


Independent Particles system



Exotic nuclei challenging theoretical physics

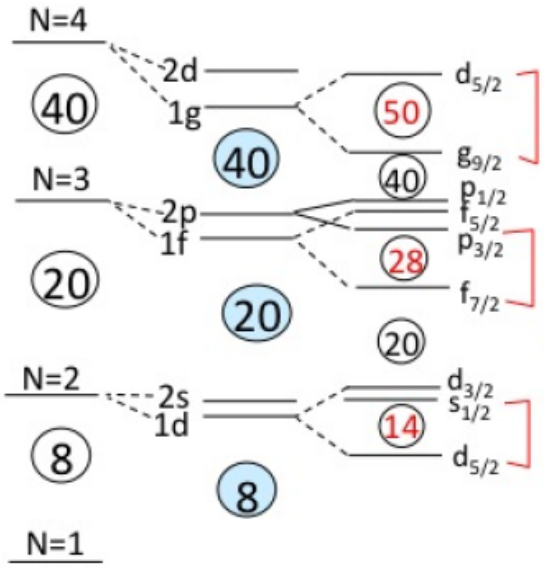
- Open mesoscopic systems
- Enhanced effect of correlations and continuum



Nuclear physics today

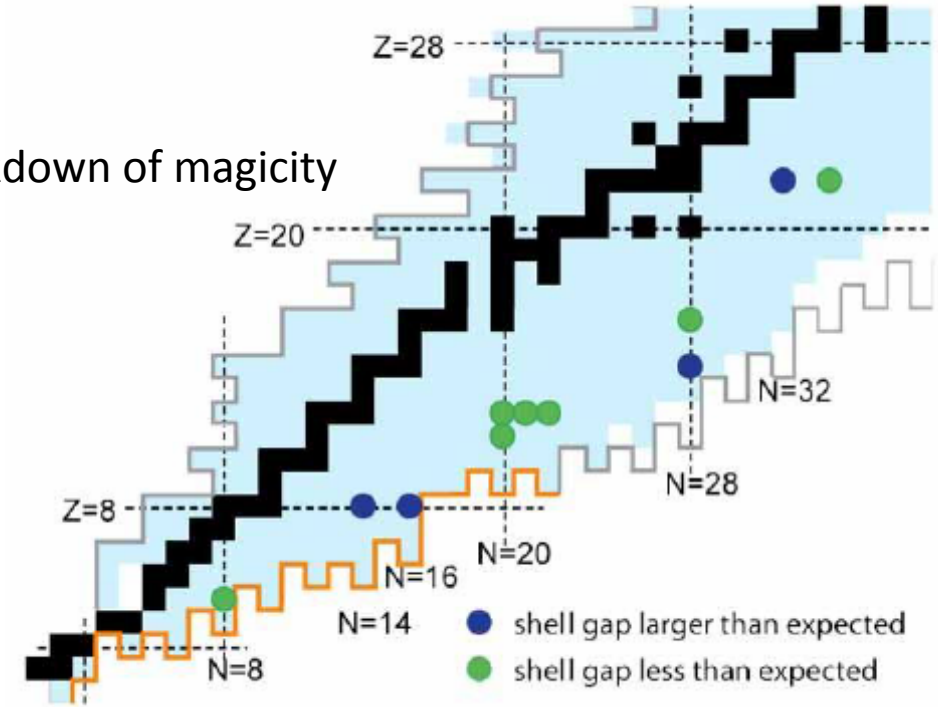
Shell structure and Nuclear interactions

Traditional single-particle Shell picture



$H.O. + L^2 + \vec{L}.\vec{S}$

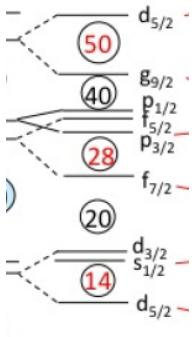
Breakdown of magicity



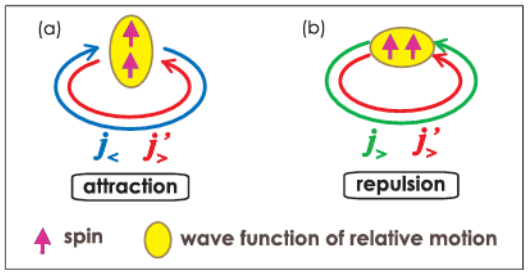
(B. Sherrill, Ecole Joliot Curie 2011)

Competing effects close to drip-line

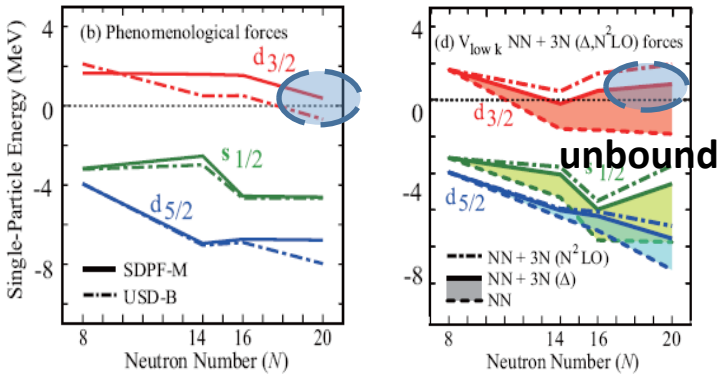
Spin-orbit

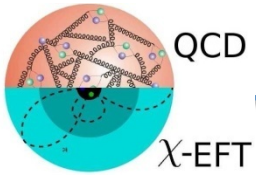


Tensor interaction



Role of 3-body interaction





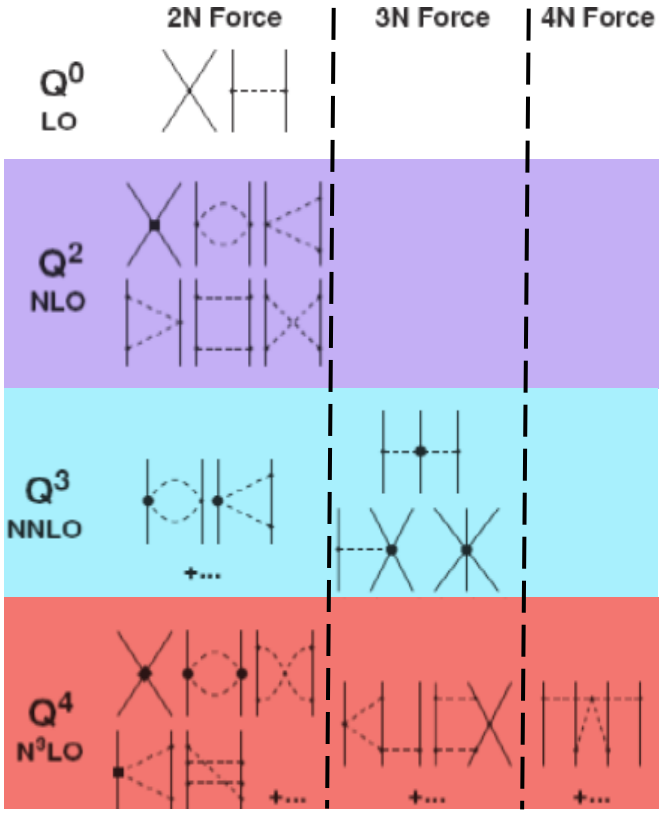
Nuclear physics today

Towards less-empirical approach to low energy nuclear physics

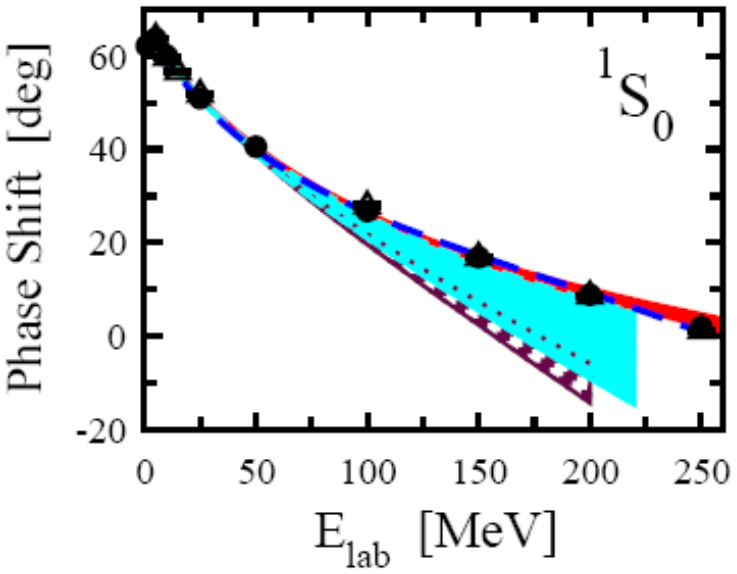
Starting point : Chiral Lagrangian

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

Feynman diagrams



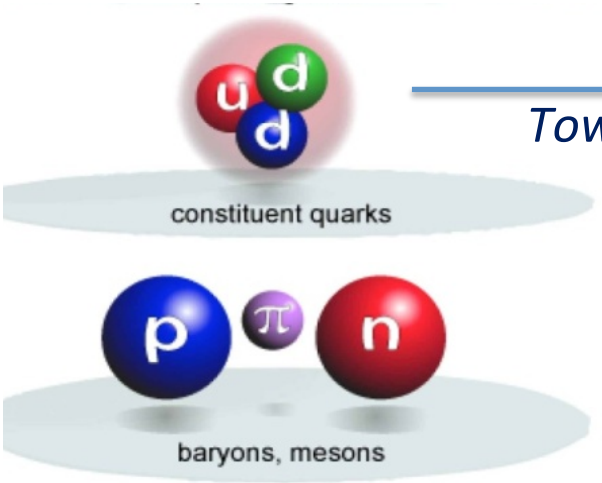
Epelbaum et al, arXiv:0811.1338



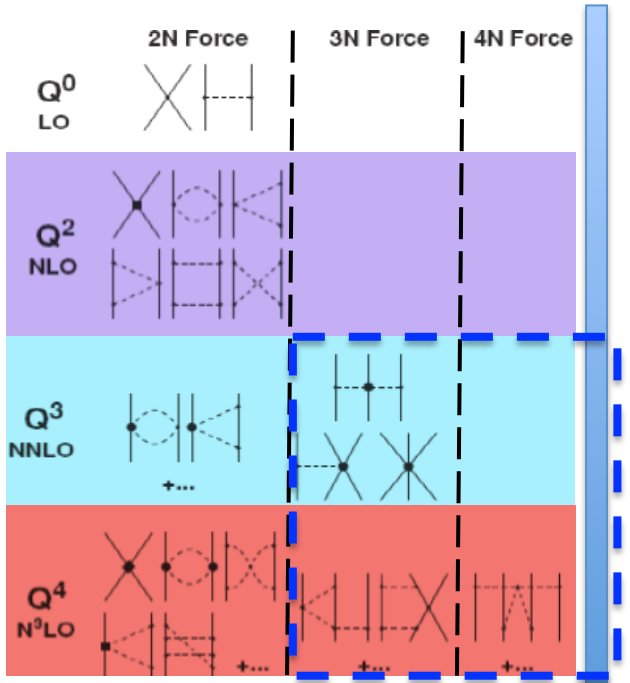
- Direct link to QCD (chiral)
- Systematic Constructive method
- Consistent NN, 3N, 4N …

Nuclear physics today

Towards less-empirical approach to low energy nuclear physics



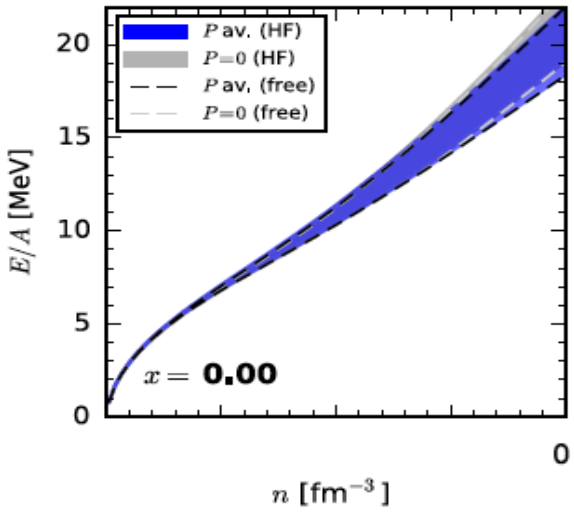
Can we probe sub-nucleonic degrees of freedom with low energy nuclear data?



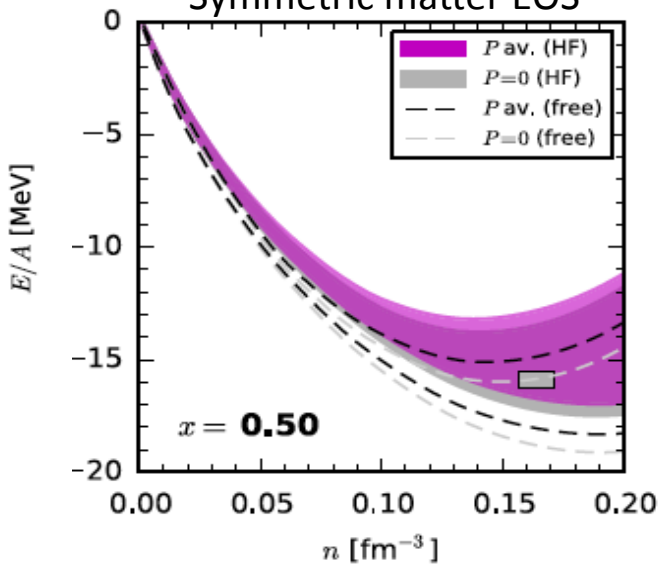
Increased complexity
Low energy constant ?
Fit on nuclei

Convergence
And power counting

Neutron matter EOS



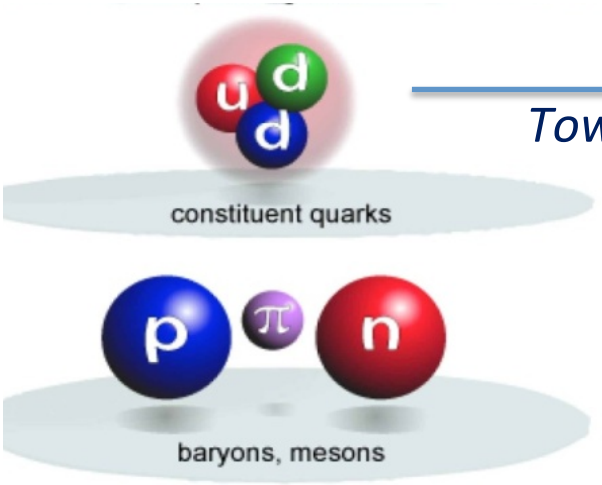
Symmetric matter EOS



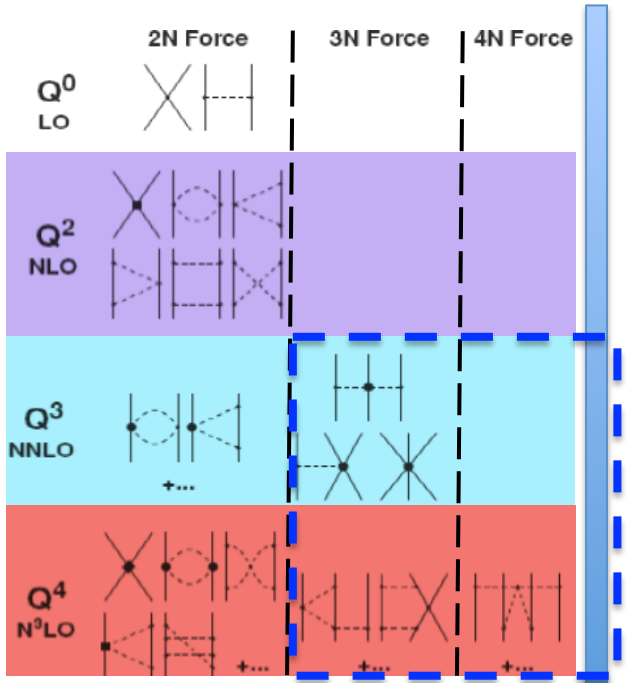
Drischler, Hebeler, and Schwenk Phys. Rev. C 93 (2016)

Nuclear physics today

Towards less-empirical approach to low energy nuclear physics

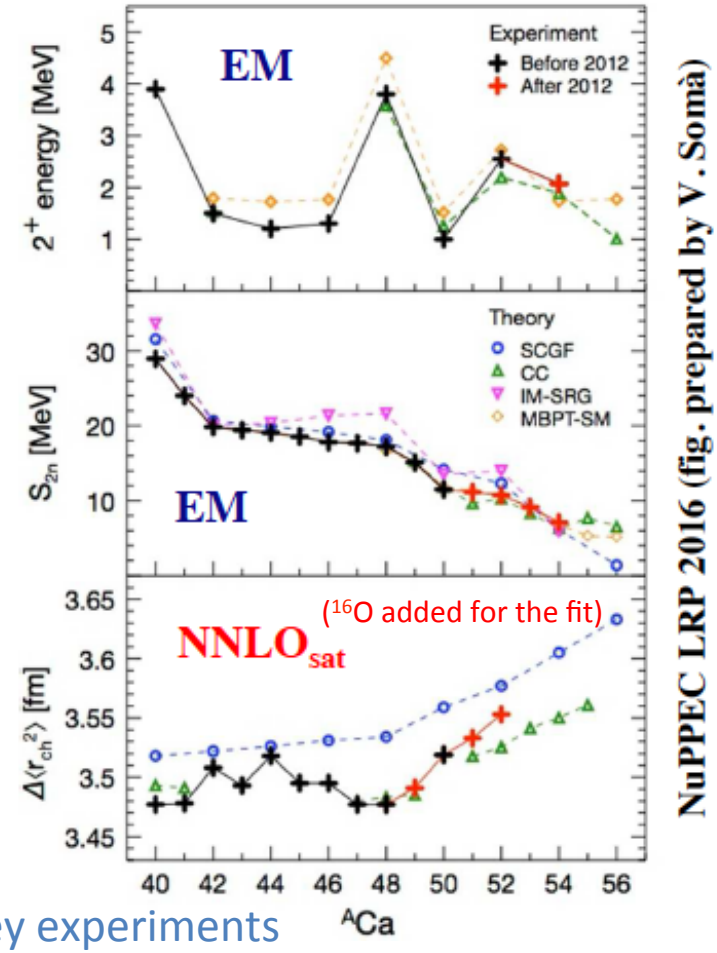


Can we probe sub-nucleonic degrees of freedom with low energy nuclear data?



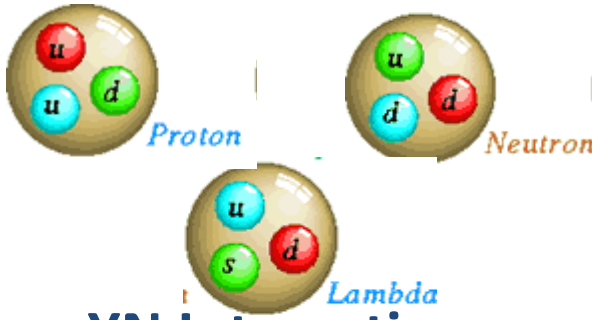
Increased complexity
Low energy constant
Fit on nuclei

Convergence
And power counting



Identify key experiments

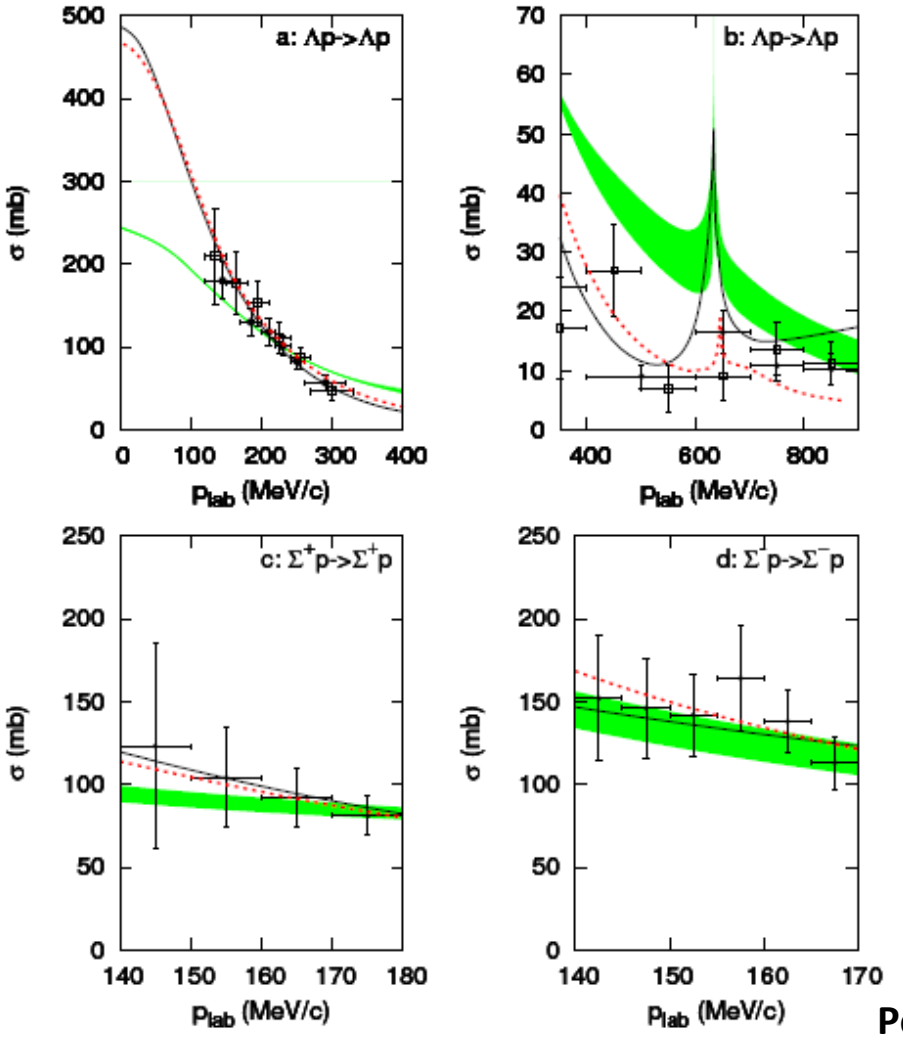
What about the unification of theory for nuclei?



Ab-initio vs experiments

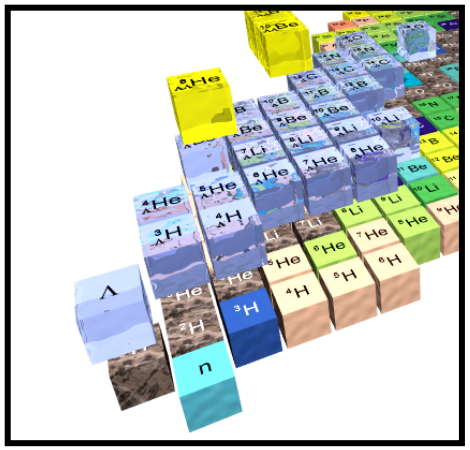
From nuclei to hypernuclei (see E. Khan discussion)

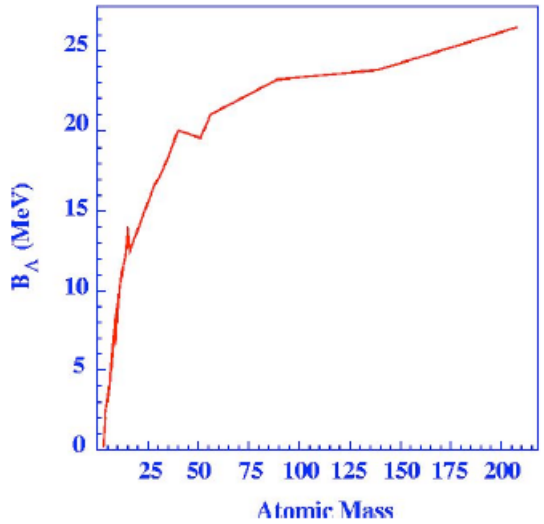
YN Interaction



LO EFT
Jülich 04
Nijm 97f

35 data only
(for comparison nn, np… between 2000/3000 data)



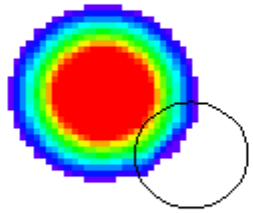


Polinder et al, NPA (2006) (see E. Khan talk)

Reactions with exotic nuclei: just some remarks

We know that reactions are more complex with exotic nuclei

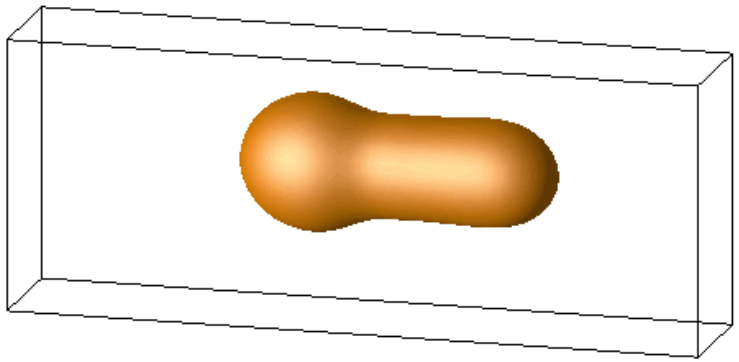
- Enhanced effect of continuum and break-up



- Need for precise and dedicated improvement of understanding and description of spectroscopic tools: Transfer reactions, break-up and knock out
- Onset of new collective excitations (especially in isovector channels)

Large amplitude collective motion is also modified

- Competition between transfer and fusion deep below the Coulomb barrier
- Competition between break-up and neutron rich assisted fusion
- Isospin and pairing effect on fission ?



Some collected research orientation

Probing sub-nucleonic degrees of freedom with low energy nuclear data?
Understanding the interaction between nucleons from first principle

How organizes neutron and proton matter in neutron rich systems?

- Physics of systems at anomalously large scattering length (close to unitary regime)
- Systems at very low density
- Pairing effects, continuum and other correlations

Coexistence of particle like and neutron-proton pairing in nuclei, quarteting and origin of clustering in nuclei?

Search for the existence of new radioactivity?