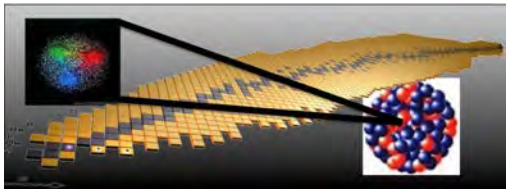
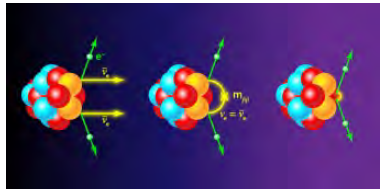
Réactions et structure nucléaire
-Nuclear structure and nuclear reactions-

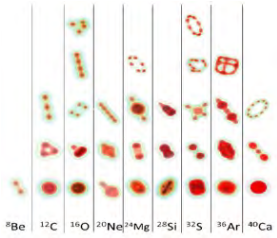
Denis Lacroix - IJCLab-Orsay

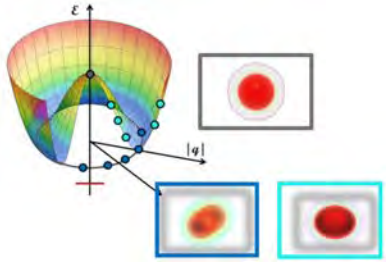
Strong interaction and decays

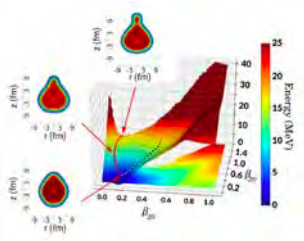


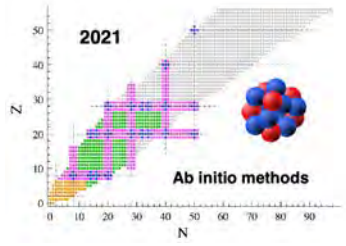


Nuclear structure and shapes

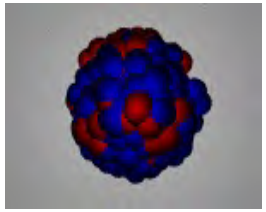


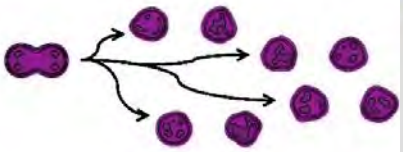




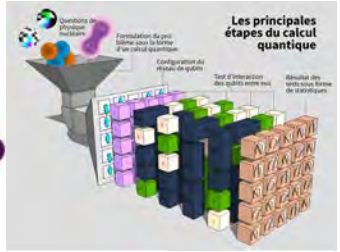


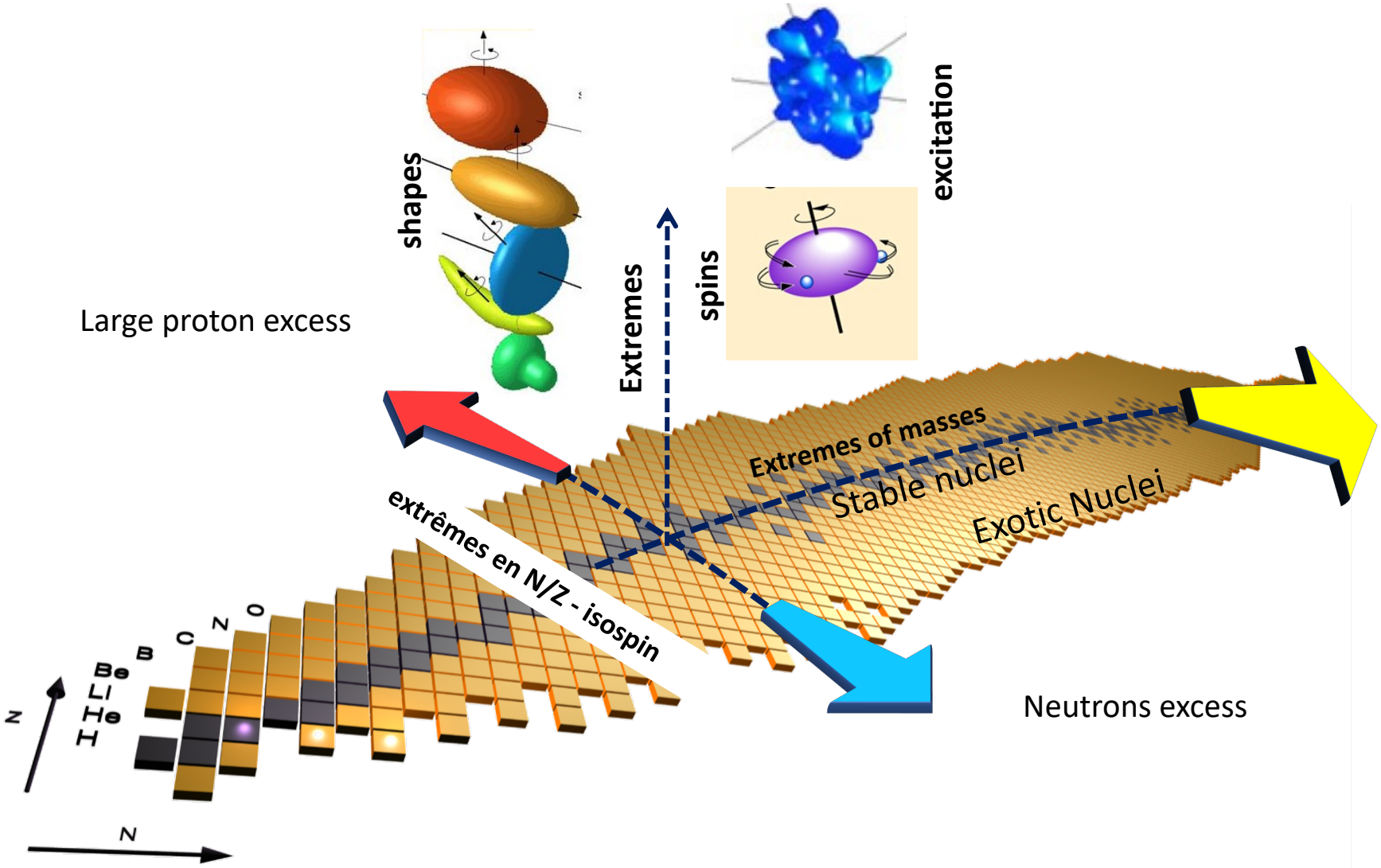
Dynamics



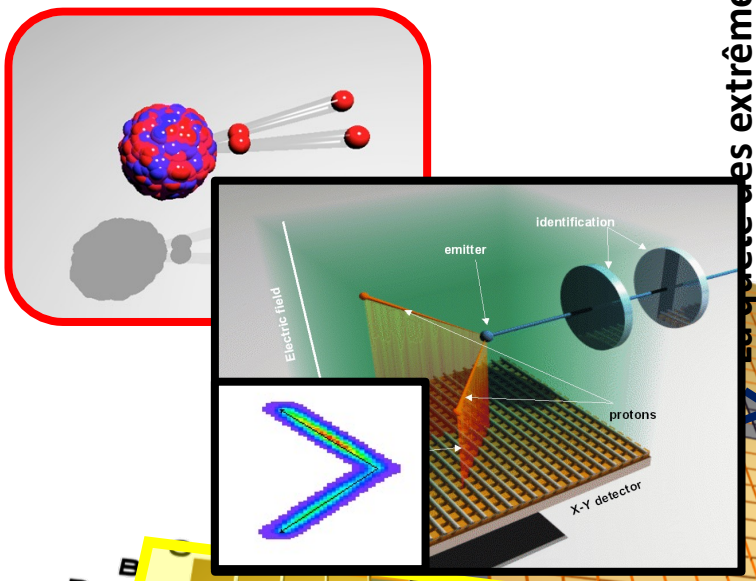


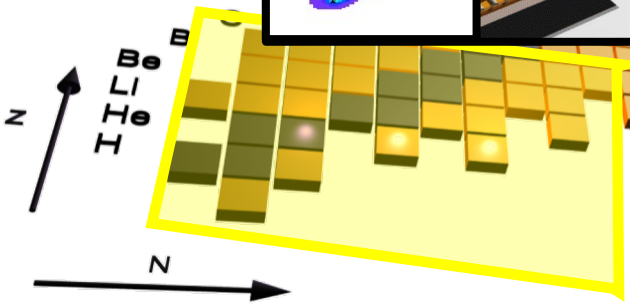
New technologies




shapes
excitation
spins
Extremes
Large proton excess
Extremes of masses
Stable nuclei
Exotic Nuclei
extrêmes en N/Z - isospin
Neutrons excess
Z
N
H
He
Li
Be
B
C
N
O

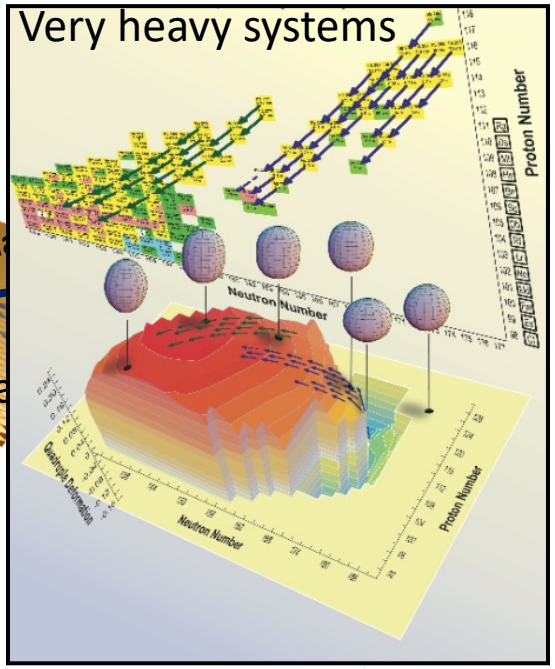
New radioactivity



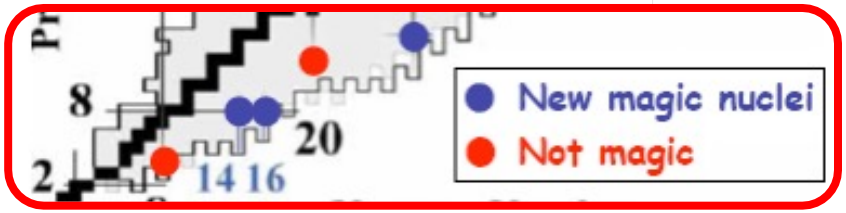


Light « molecules »

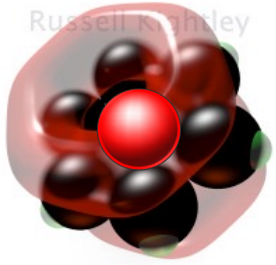
Very heavy systems

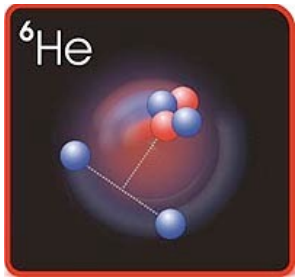


Shell effects, New magicity

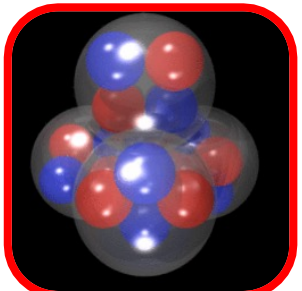


Halos

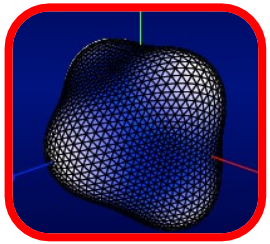




Clustering

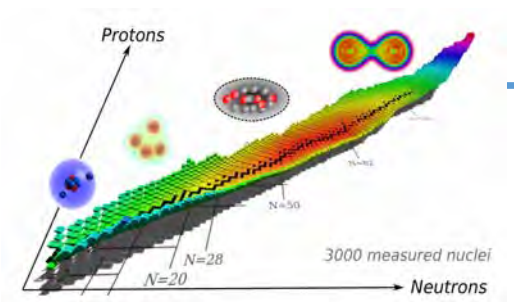


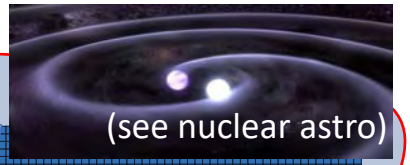
New shapes



Nuclear Theory in France

A short guide tour to nuclear physics theory @ IN2P3





Proton number Z (up to 118)

82
50
126
28
20
8
2
50
28
20

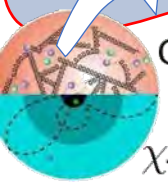
Nuclear Density Functional theory
(Effective interaction, EDF,
static and time-dependent,
configurations mixing…)

Configuration Interaction methods
(Shell model, …)

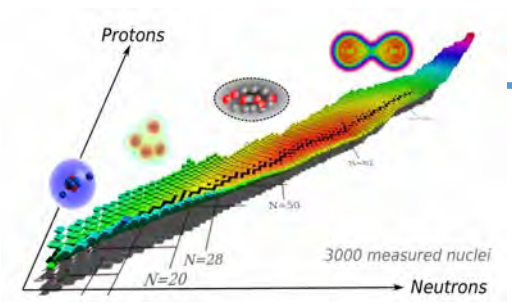
- Stable
- Atomic mass evaluation 2020
- *Ab initio* 2020
- Energy density functional (Gogny D1M)

Data taken from:
S. Hilaire and M. Girod, EPJA 33, 237 (2007)
M. Wang et *al.*, Chin. Phys. C 45, 030003 (2021)
H. Hergert (private communications)

Neutron number N (up to 258)



Modern bare NN Interaction and ab-initio methods
(Few-Body theory, No-Core Shell model, Monte-Carlo, …)



Who's who in France

A short guide tour to nuclear physics theory @ IN2P3

Shell Model in the Continuum
Algebraic models
Fission model

EDF, statistical model
Reaction models

Reaction models

Shell model, EDF
New interaction
Fission model

Nuclear interaction
Few-body systems and Ab-initio methods,
Effective interaction new EDF, reaction models

Shell Model, Ab-initio and few-body, EDF

EDF methods

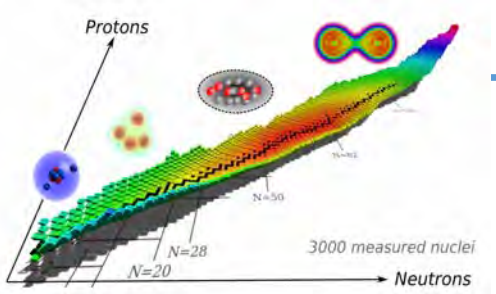
EDF methods,
New effective interaction
Configuration mixing

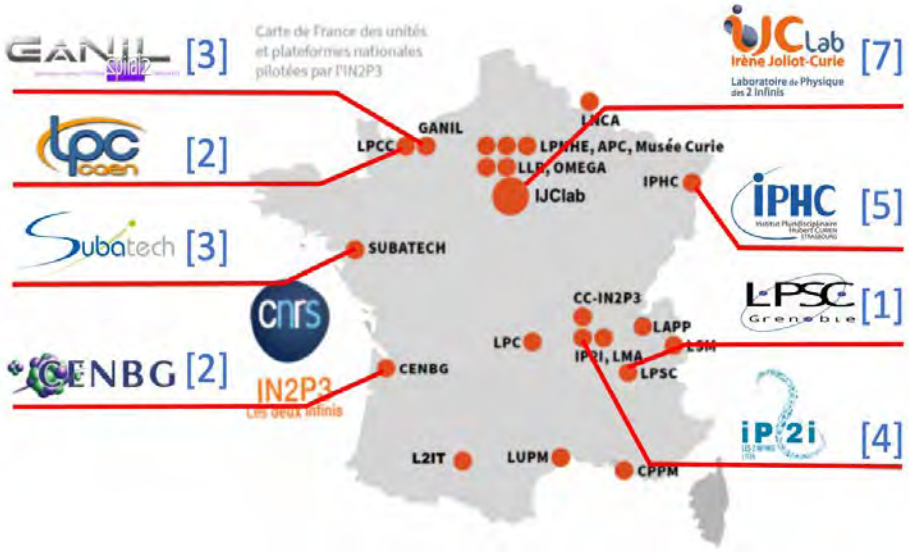
➡ Around 27 persons in nuclear theory @ IN2P3
(some working partially in nuclear astrophysics or being also experimentalists)

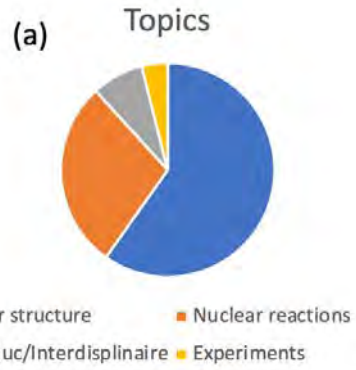
* Number of permanents scientists working in nuclear theory

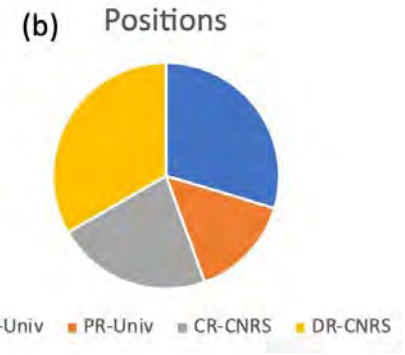
Who's who in France

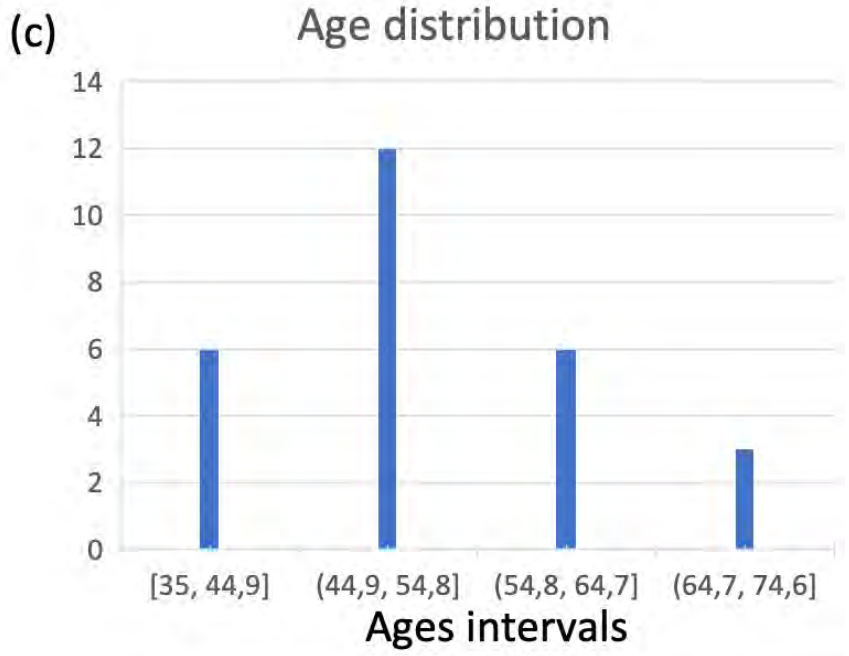
A short guide tour to nuclear physics theory @ IN2P3



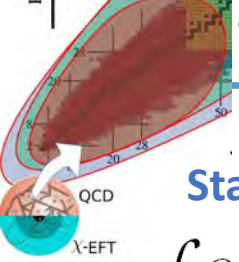








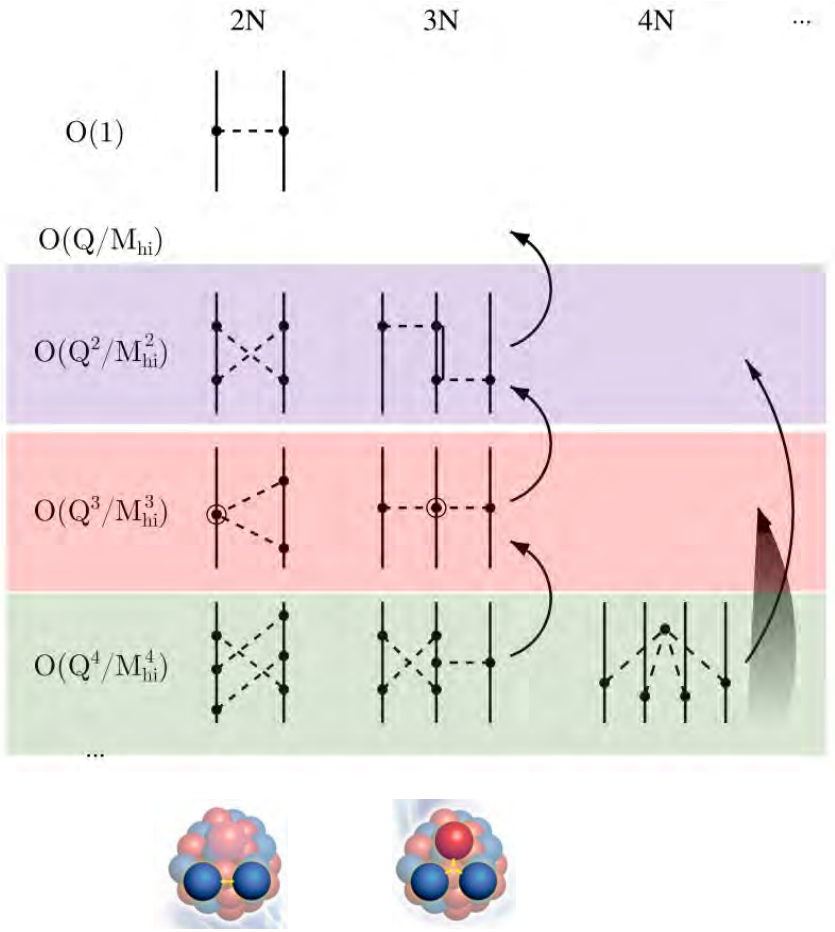
Nuclear interaction and ab-initio methods



Starting point : Chiral Lagrangian

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

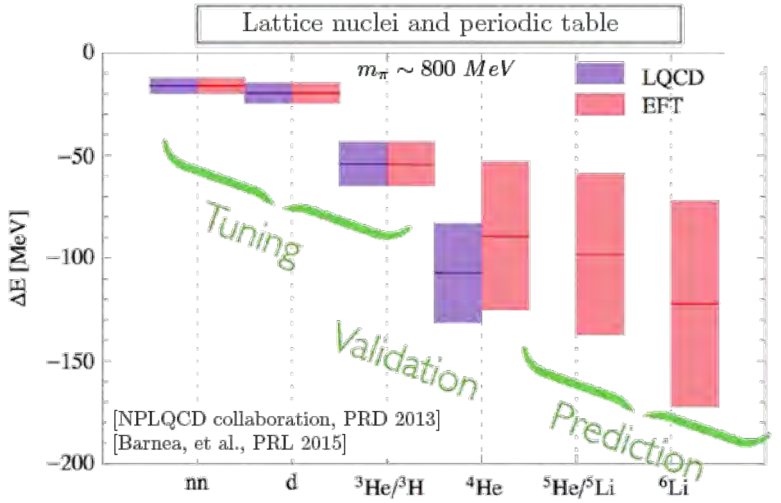
Chiral EFT based interaction



One main goal is to develop NN interaction:

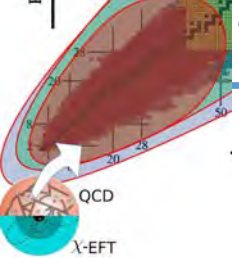
- With high accuracy
- Systematically improvable
- With improved power counting
- Applicable in state-of-the art ab-initio methods

From LQCD to nuclear *pionless*EFT



Impact on other areas of nuclear theory (3-body interaction, towards non-empirical EDFs, universal behavior, …)

H.-W. Hammer, S. König, and U. van Kolck, Rev. Mod. Phys. 92, 025004 (2020)

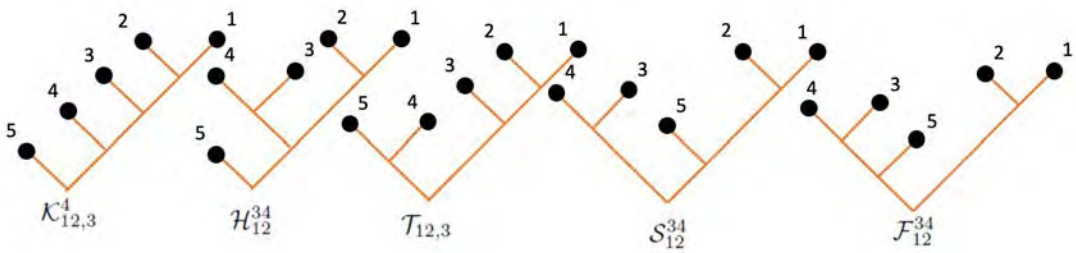


Some scientific highlights of nuclear physics theory @IN2P3

Nuclear interaction and ab-initio methods

Ab-inito methods gives a strong validation of the NN interaction

Few-body sector



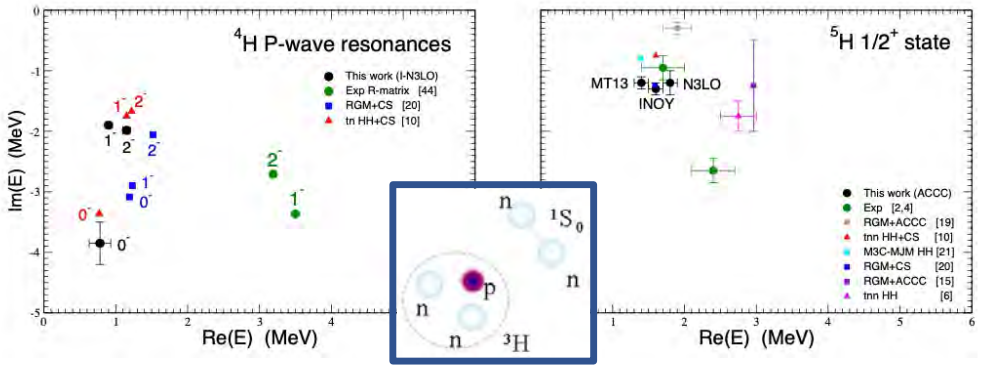
R. Lazauskas and J. Carbonell Few-Body Syst. **60**, 62 (2019)

System	Number eq. (= particles)	Number eq. (≠ particles)
$A=2$	1	1
$A=3$	1	3
$A=4$	2	18
$A=5$	5	180
$A=6$	15	2700
$A=N$	$\mathrm{nint}\left(\frac{2(N-1)!}{\left(\frac{\pi}{2}\right)^N}\right)$	$\frac{N!\,(N-1)!}{2^{(N-1)}}$

Applications

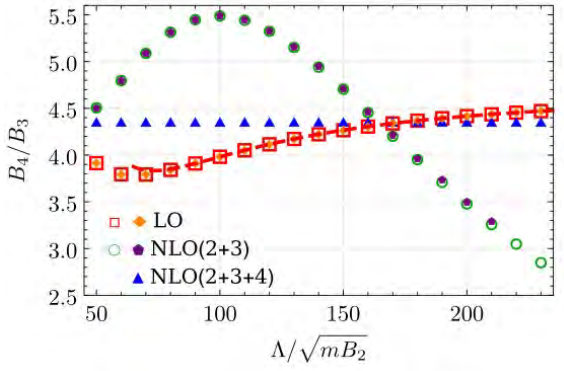
- Usually very accurate
- Define references for other theories

^{5}H resonance



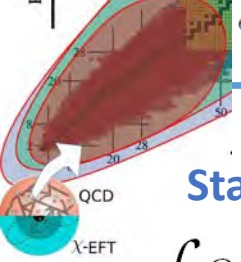
Lazauskas, Carbonell, Phys. Lett. B (2019)

Universality in boson systems



B. Bazak et al, Phys. Rev. Lett. (2019)

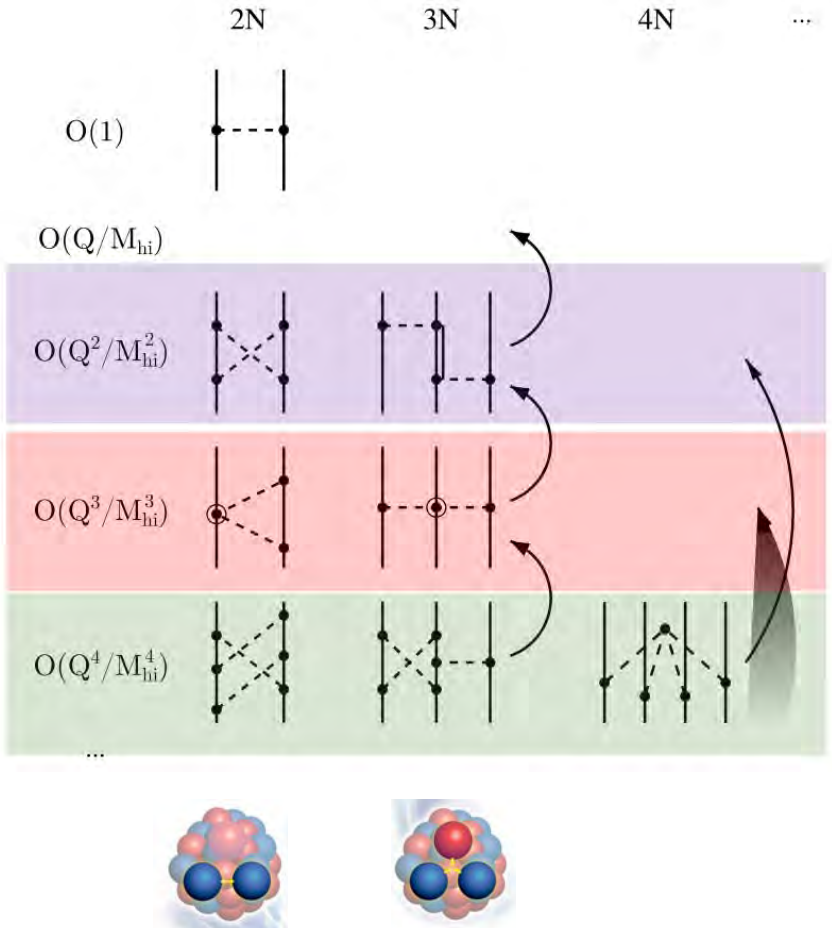
Nuclear interaction and ab-initio methods



Starting point : Chiral Lagrangian

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

Chiral EFT based interaction



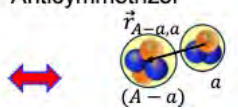
Reaction with ab initio methods

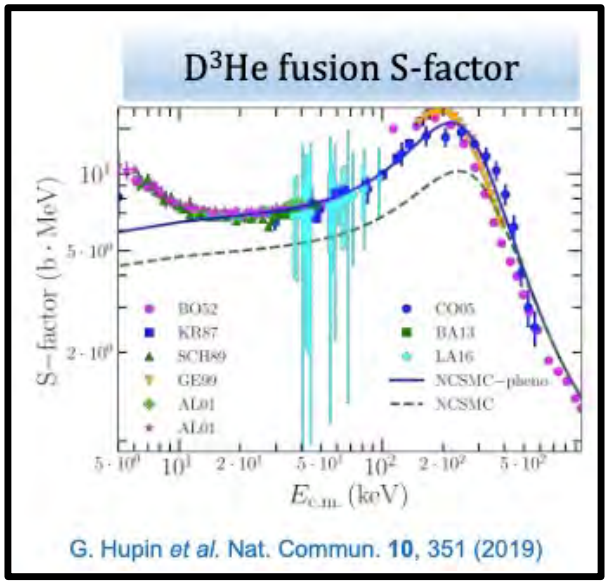
$$\Psi^{(A)}_{NCSM} = |A\lambda J^\pi T\rangle = \sum_\alpha c_\alpha \; |A\alpha j_z{}^\pi t_z\rangle \quad \Leftrightarrow \quad |A\lambda J^\pi T\rangle_{SD}\,\phi_{00}(\vec{R}^A_{c.m.})$$

Mixing coefficients (unknown) — A-body harmonic oscillator states — Second quantization

$$= \sum_v \int d\vec{r}\; g_v(\vec{r})\, \hat{A}_v \left| \Phi^{(A-a,a)}_{v\vec{r}} \right\rangle$$

tive wave inction (unknown) — Antisymmetrizer — Channel basis

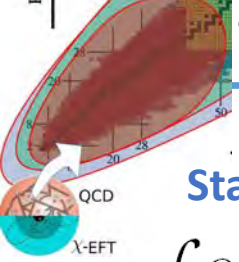




G. Hupin *et al.* Nat. Commun. **10**, 351 (2019)

H.-W. Hammer, S. König, and U. van Kolck, Rev. Mod. Phys. 92, 025004 (2020)

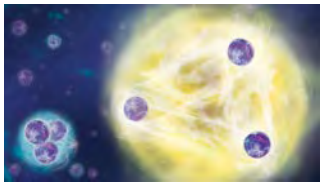
Nuclear interaction and ab-initio methods



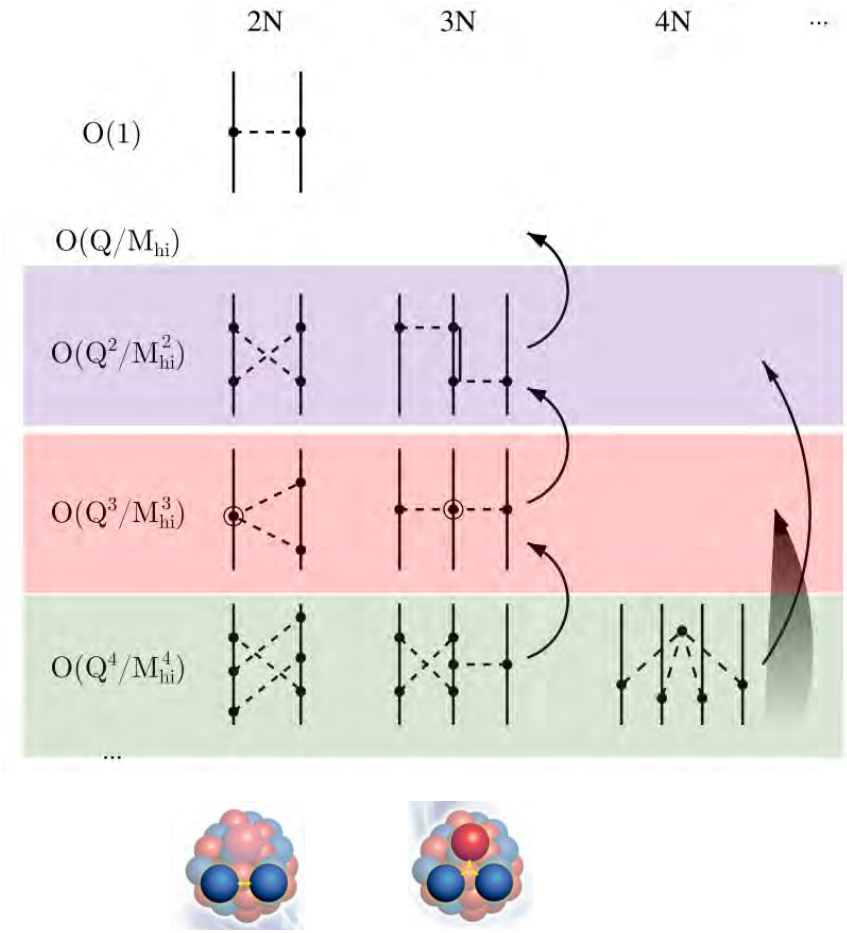
Starting point : Chiral Lagrangian

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

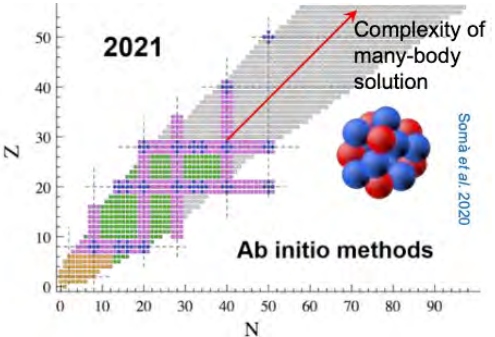
Future developments



Chiral EFT based interaction

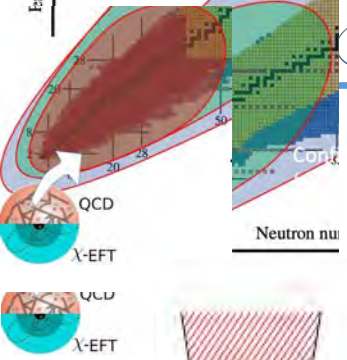


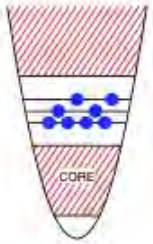
- Search for universal physics (discrete Scale invariance, Efimov)
- Search of new physics (Beyond standard model)
- Impact of 3-body int. on nuclear structure and reactions
- Description of the nuclear resonances in light, very neutron rich systems (ex ^{7}H)
- Bridges ab-initio with other theories (Shell model and EDF)



H.-W. Hammer, S. König, and U. van Kolck, Rev. Mod. Phys. 92, 025004 (2020)

Configuration interaction methods for nuclear structure and reactions





- define effective interaction
- $\mathscr{H}_{\text{eff}}\Psi_{\text{eff}} = E\Psi_{\text{eff}}$
- build and diagonalize energy matrix

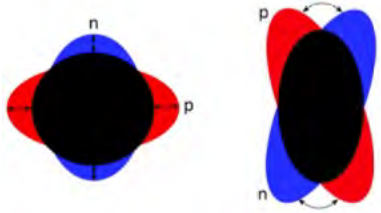
Computational aspect

- Exponential growth of basis dimensions: $D \sim \begin{pmatrix} d_\pi \\ p \end{pmatrix} \cdot \begin{pmatrix} d_\nu \\ n \end{pmatrix}$

  In *pf* shell :
  ^{56}Ni **1,087,455,228**
  In *pf-sdg* space :
  ^{78}Ni **210,046,691,518**
- Actual limits in giant diagonalizations: **0.2 10^{12}** (^{114}Sn)
- Largest matrices up to now: **$\sim 10^{14}$** non-zero matrix elements
- Strasbourg LSSM codes: **ANTOINE** and **NATHAN**

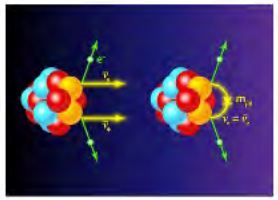
Nuclear forces and nuclear structure

- Shell evolution: from stability to dripline
- Isospin symmetry breaking
- Emergence of quadrupole collectivity, superdeformation
- Vibrational modes
- Dipole resonances
- Symmetries



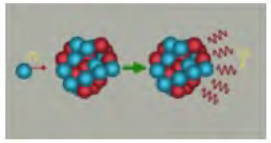
Weak processes

- β decay $\iff$ fundamental interactions
  $\iff$ nucleosynthesis
- $\beta\beta$ decay $\iff$ nature of neutrino
- *e* capture $\iff$ supernovae

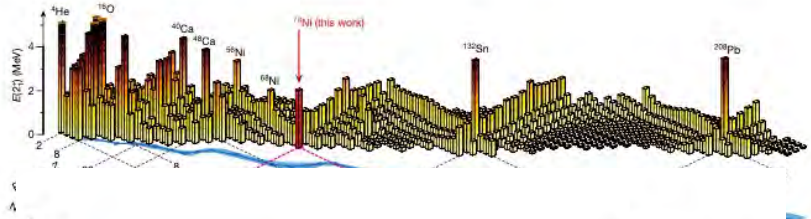


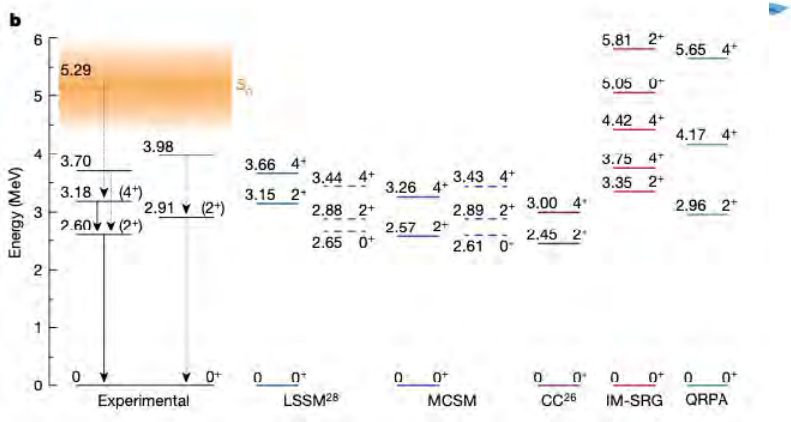
Particle capture reactions

- Neutron-capture rates $\iff$ r-process
- Proton-capture rates $\iff$ rp-process
  $\iff$ novae



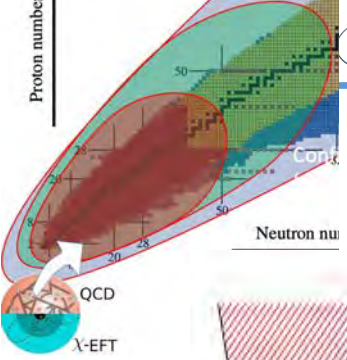
^{78}Ni revealed as a doubly magic stronghold against nuclear deformation

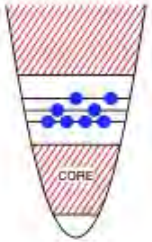




R. Taniuchi et al., NATURE **569**, 53-58 (2019)

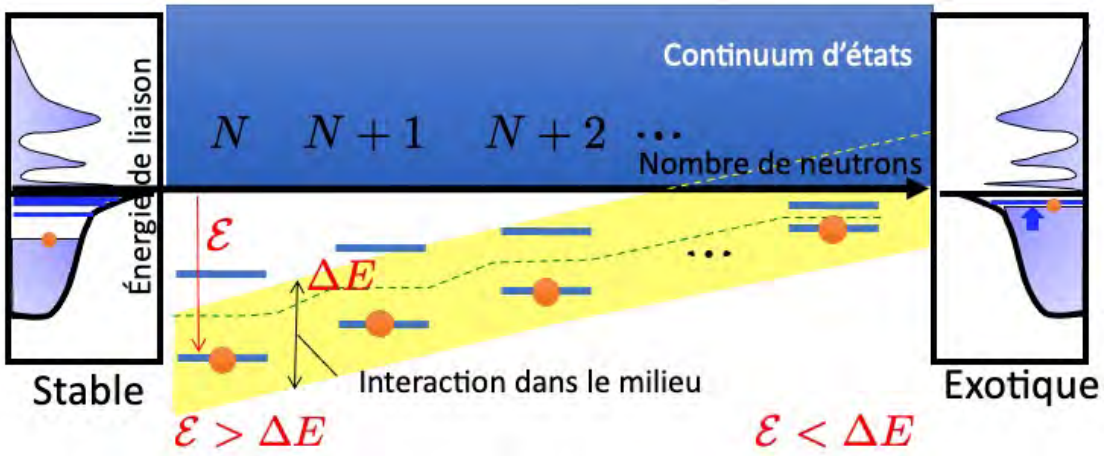
Configuration interaction methods for nuclear structure and reactions





- define effective interaction
- $\mathscr{H}_{\text{eff}}\Psi_{\text{eff}} = E\Psi_{\text{eff}}$
- build and diagonalize energy matrix

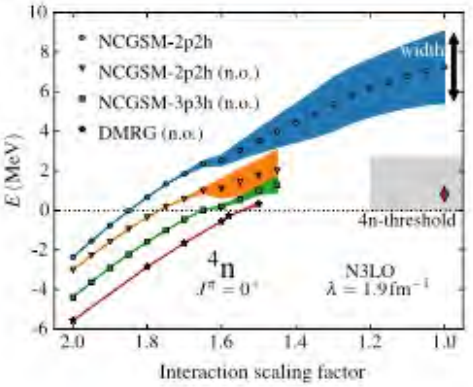
Shell model close with continuum



PRL 119, 032501 (2017) PHYSICAL REVIEW LETTERS week ending 21 JULY 2017

Can Tetraneutron be a Narrow Resonance?

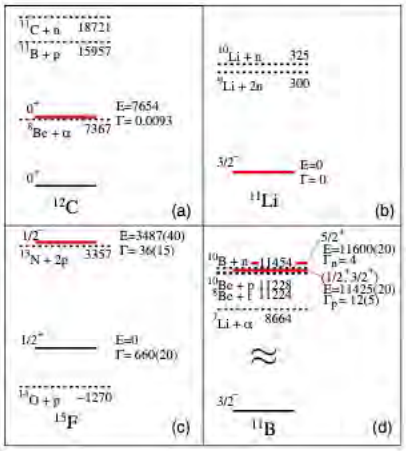
K. Fossez,[1] J. Rotureau,[1,2] N. Michel,[1] and M. Płoszajczak[3]



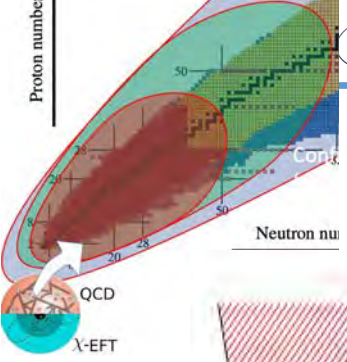
PHYSICAL REVIEW LETTERS 124, 042502 (2020)

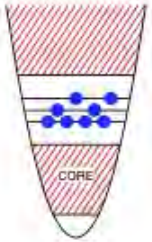
Convenient Location of a Near-Threshold Proton-Emitting Resonance in ^{11}B

J. Okołowicz,[1] M. Płoszajczak,[2] and W. Nazarewicz[3]



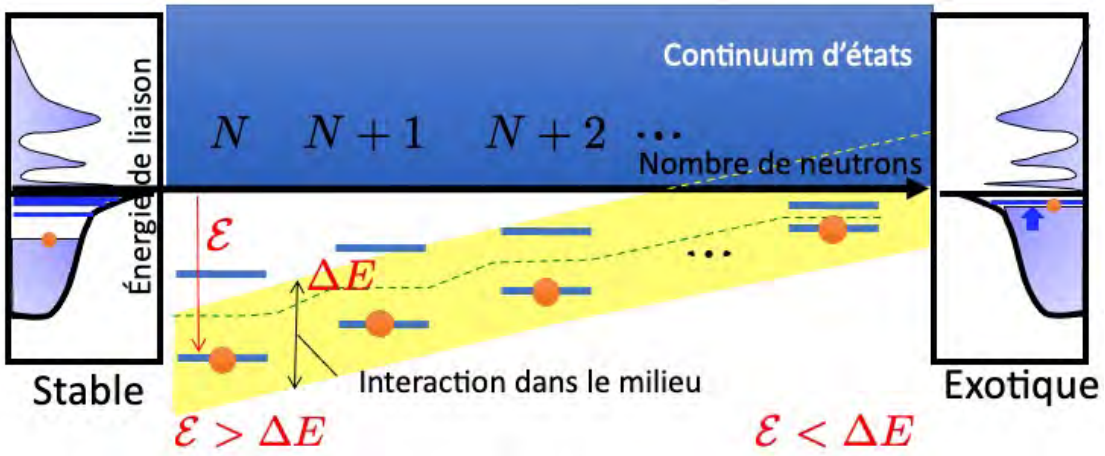
Configuration interaction methods for nuclear structure and reactions





- define effective interaction
- $\mathscr{H}_{\text{eff}}\Psi_{\text{eff}} = E\Psi_{\text{eff}}$
- build and diagonalize energy matrix

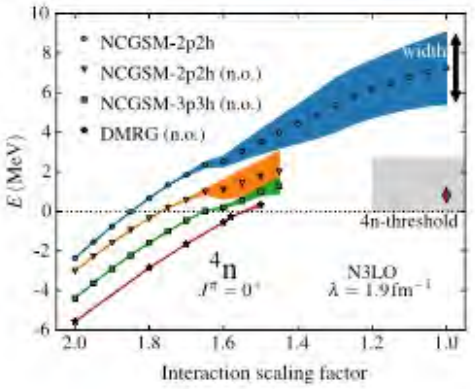
Shell model close with continuum



PRL 119, 032501 (2017) PHYSICAL REVIEW LETTERS week ending 21 JULY 2017

Can Tetraneutron be a Narrow Resonance?

K. Fossez,[1] J. Rotureau,[1,2] N. Michel,[1] and M. Płoszajczak[3]

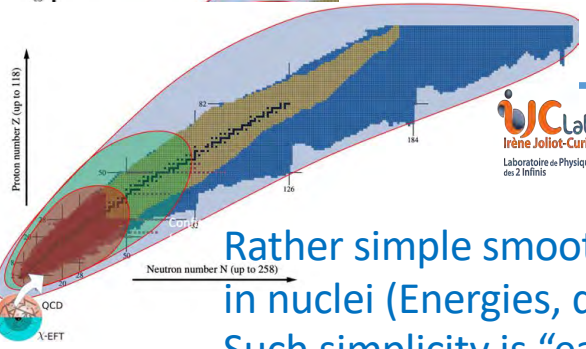


Discussion

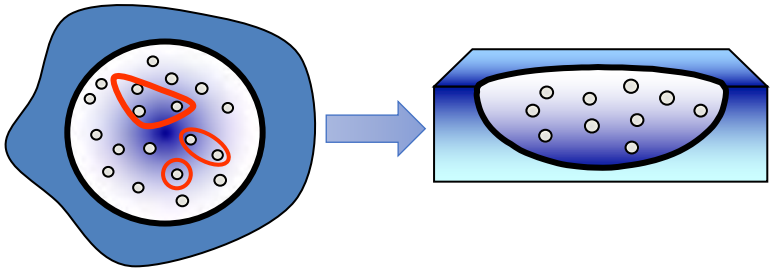
- Intense support for future experimental programs and developments
- Existing cross fertilizing collaborations in several domains: ab-initio studies, isospin symmetry breaking, astrophysics, β β decay ...
- Bridges between CI and ab-initio studies are being made

Some scientific highlights of nuclear physics theory @IN2P3

Energy Density Functional methods



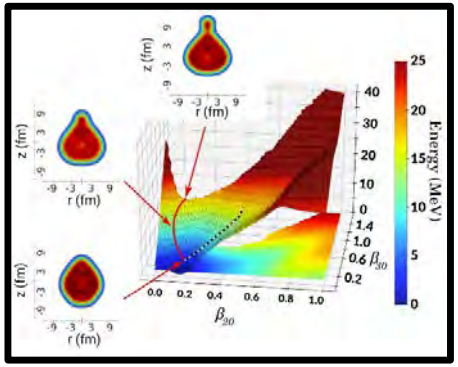
Rather simple smooth properties emerge in nuclei (Energies, density, shell effects …)
Such simplicity is “easily” grasp by DFT



The nuclear DFT is a simple highly accurate and versatile approach

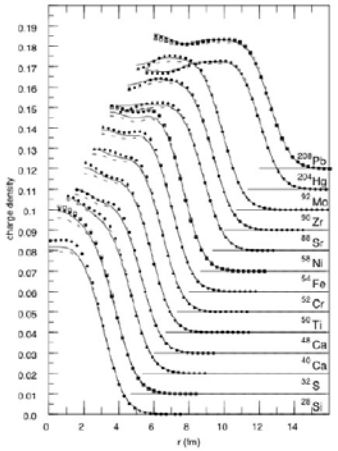
Static properties

Shapes



F. Mercier et al, Phys. Rev. C 102 (rapid com.) (2020)

densities

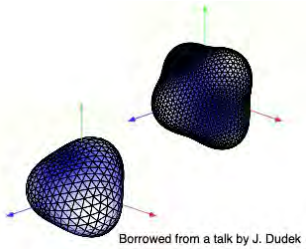


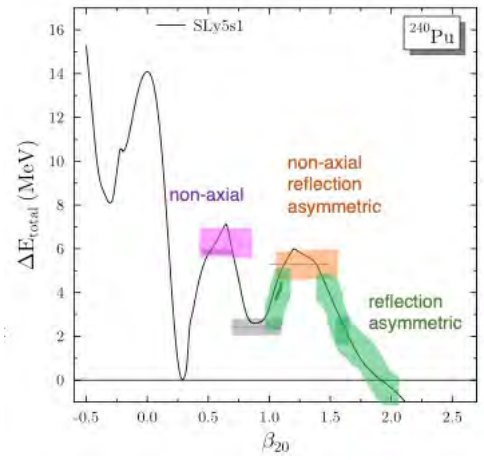
Dynamics

Time (fm/c)

Current tendency in EDF: mean-field level

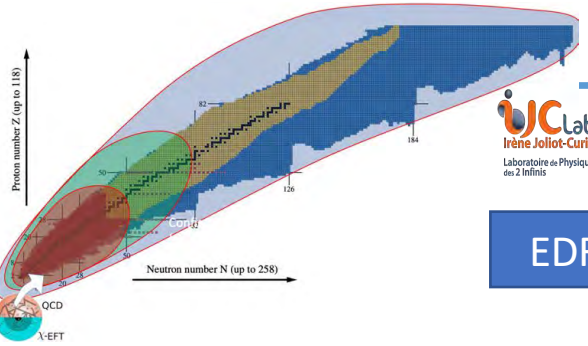
Construction of standard symmetry unrestricted codes with state of the art Effective interaction





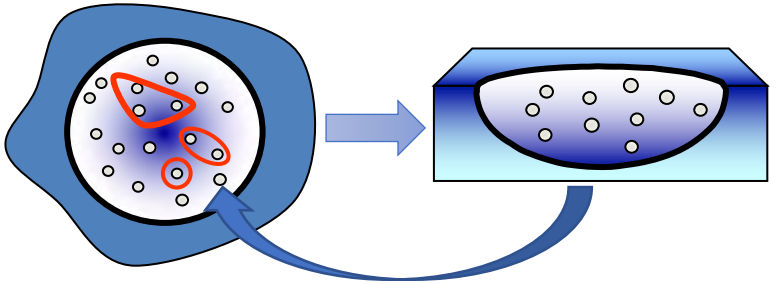
W. Ruyssen, M. Bender, K. Bennaceur et al, Phys. Rev. C99 (2019)

Some scientific highlights of nuclear physics theory @IN2P3

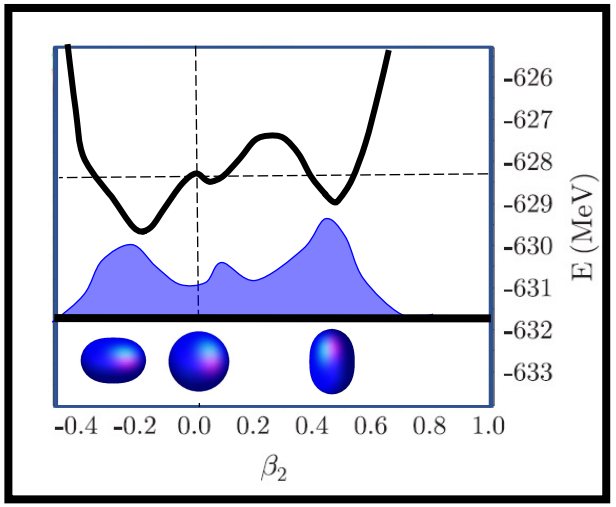


Energy Density Functional methods

EDF: beyond-mean-field level



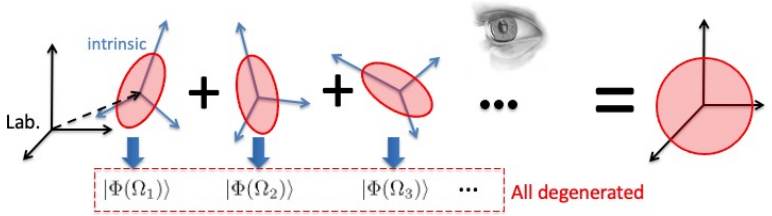
Shape coexistence and nuclear spectroscopy

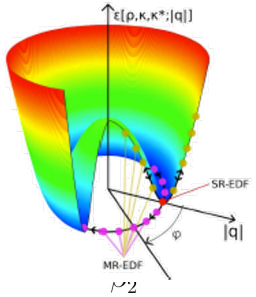


Generator Coordinate method

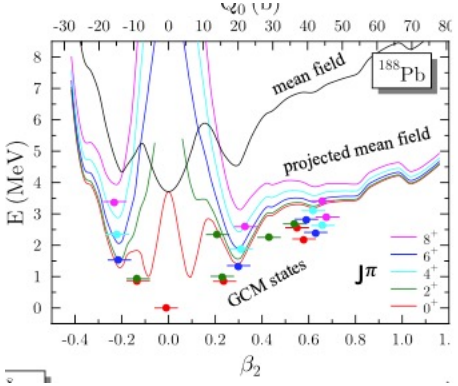
$$\left|\Psi_{\epsilon}^{\lambda i}\right\rangle = \sum_{j=1}^{d_\lambda} f_{\epsilon}^{\lambda j} \hat{P}_{ij}^{\lambda} \left|\Theta\right\rangle,$$

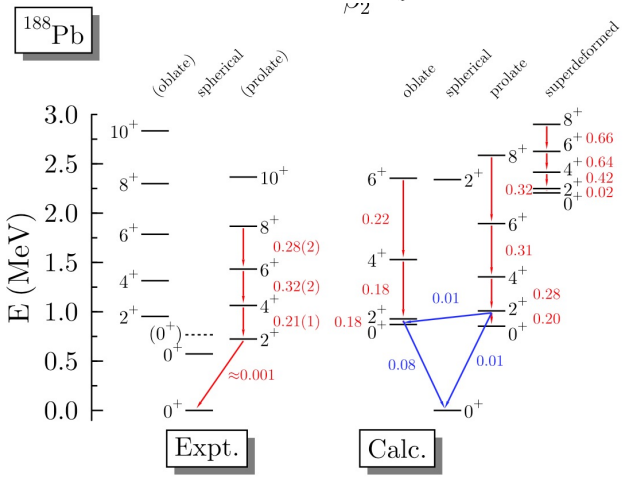
➡ Used nowadays for symmetry restoration
(crucial for comparison with experiments)





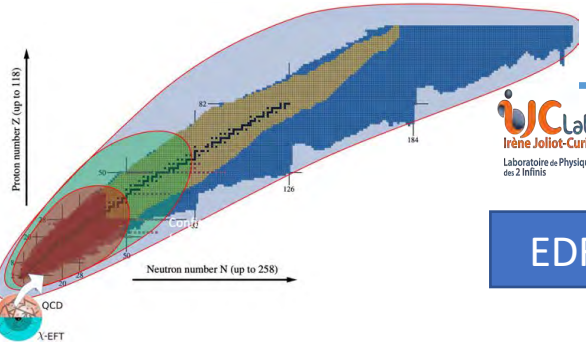
➡ Used for shape coexistence



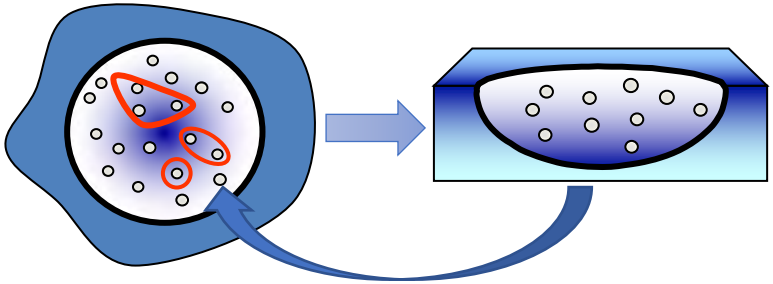


(from M. Bender, atelier theory 7-8th June talk)

Some scientific highlights of nuclear physics theory @IN2P3

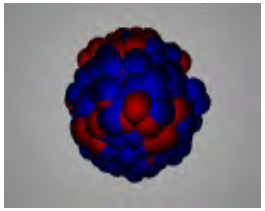


Energy Density Functional methods



EDF: beyond-mean-field level

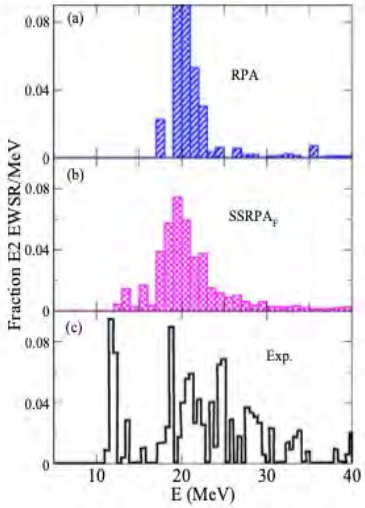
The subtracted Second-RPA method (SSRPA)



$$\begin{pmatrix} H_{PP} & H_{PQ} \\ H_{QP} & H_{QQ} \end{pmatrix}$$

Recent applications

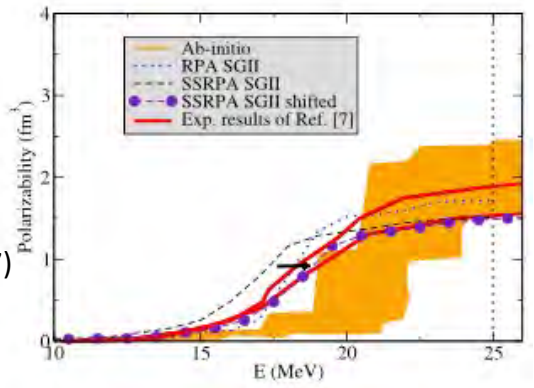
➡ Spreading width of the quadrupole excitation



Gambacurta, Grasso, Engel, Phys. Rev. C92 (2015)

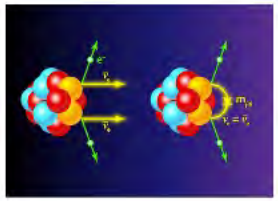
➡ Electric dipole polarizability in 48Ca

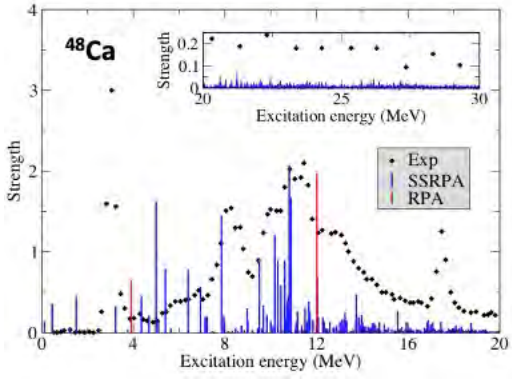
Gambacurta, Grasso, Vasseur, Phys. Lett. B777 (2017)



➡ Solving the mystery Of missing Gamow-Teller strength

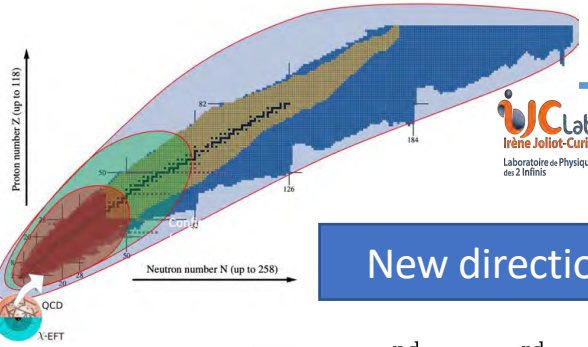
Gambacurta, Grasso, Engel, Phys. Rev. Lett. (2020)





Some scientific highlights of nuclear physics theory @IN2P3

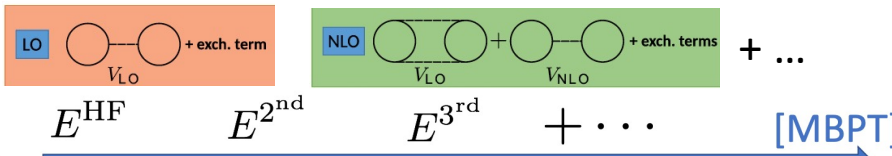
Energy Density Functional methods



New directions in the construction of EDF

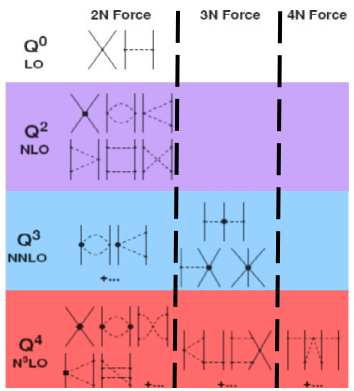
- Difficulties in beyond-mean-field applications
- Needs for a systematic improvable framework "à la EFT"

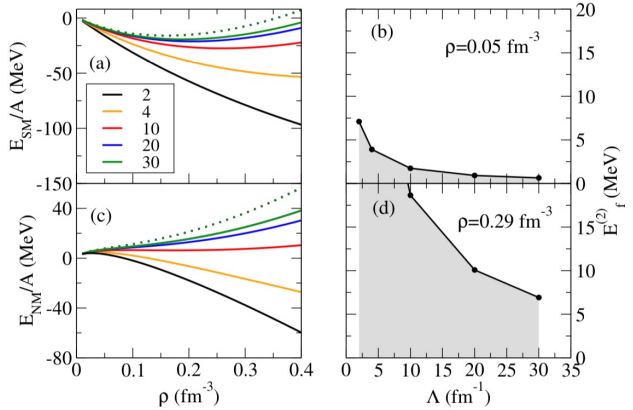
$$E = E^{\mathrm{HF}} + E^{2^{\mathrm{nd}}} + E^{3^{\mathrm{rd}}} + \ldots$$



$E^{\mathrm{HF}} \quad E^{2^{\mathrm{nd}}} \quad E^{3^{\mathrm{rd}}} \quad + \cdots$ [MBPT]

$(a_s k_F) \quad (r_e k_F) \quad \ldots$





Burrello, Grasso, Yang, PLB 811 (2020)

Tailoring functionals for BMF approach

(defining power counting as in EFT …)

$a_s = -18.9 \text{ fm} \quad r_e = 2.7 \text{ fm}$

Bridging EDF with EFT-ab-initio

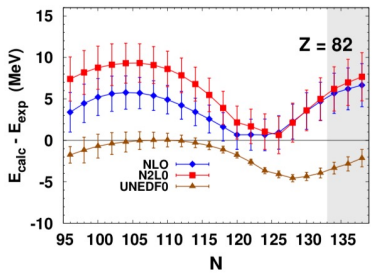
(description of low density regime, unitarity gas…)

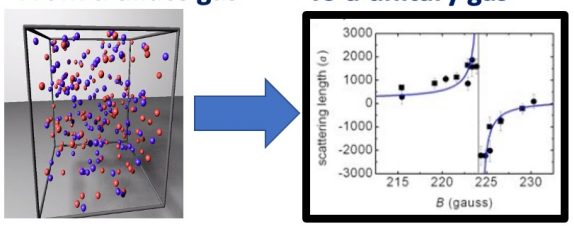
Grasso, Prog. Part. Nucl. Phys. 106, 256 (2019)

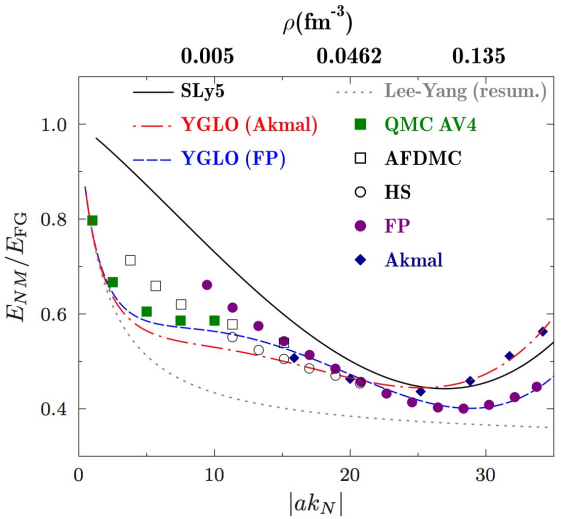
$$\langle \mathbf{k}|V_{\mathrm{eft}}|\mathbf{k}'\rangle = C_0 + \frac{1}{2}C_2(\mathbf{k}^2 + \mathbf{k}'^2) + C_2' \mathbf{k}\cdot\mathbf{k}' + \cdots$$

Bennaceur et al, J. Phys. G (2017)

Enriching functional at the MF level

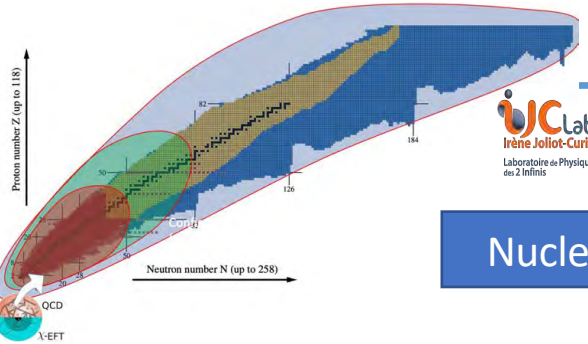






(new terms, new 3-body int.,New fit protocol, handling finite size effects, …)

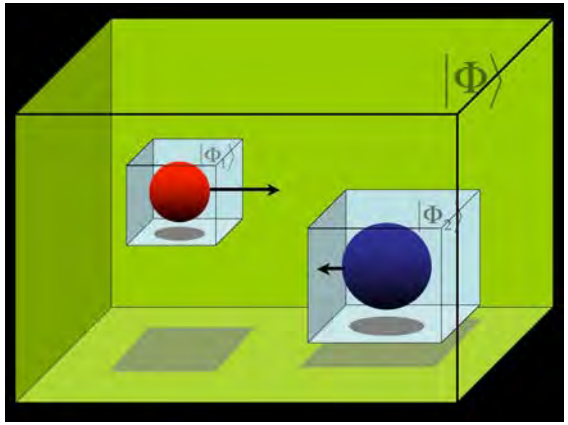
Yang, Grasso, Lacroix PRC94 (2016)



Some scientific highlights of nuclear physics theory @IN2P3

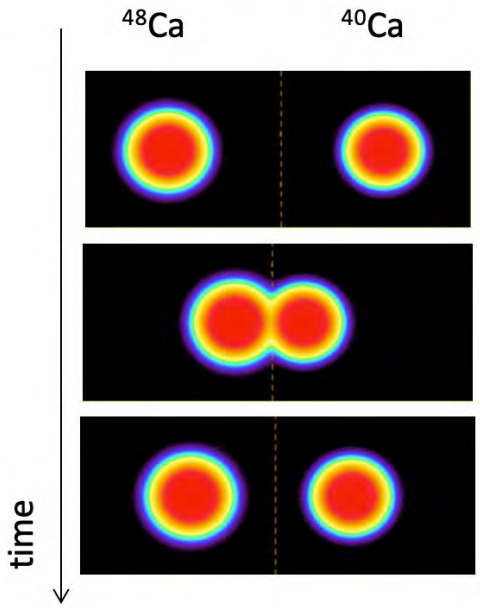
Energy Density Functional methods

Nuclear dynamics: time-dependent mean-field

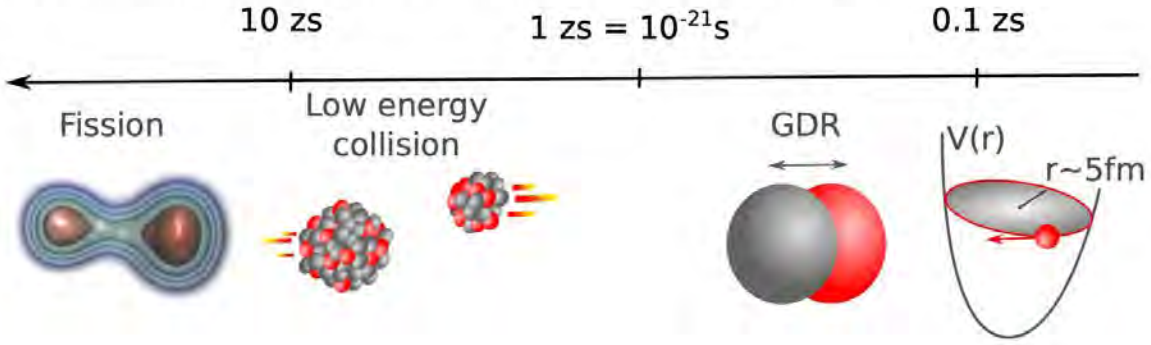


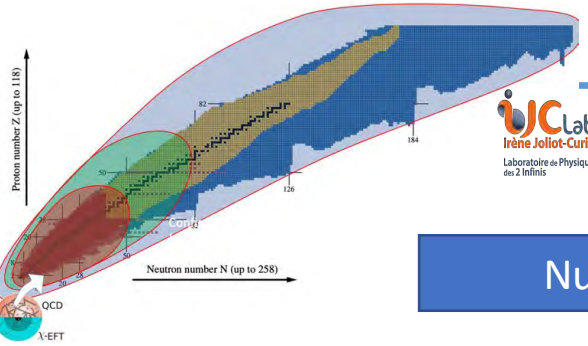
- Full 3D time-dependent solvers with superfluidity
- With effective interaction consistent with static mean-field

Current applications



- **Collective vibrations**:
  Gamma strength function
- **Heavy ion collision**:
  Fusion cross sections, nucleon transfer, nuclear matter properties
- **Induced fission**:
  Mass and charge yields, sharing of the energy and spin



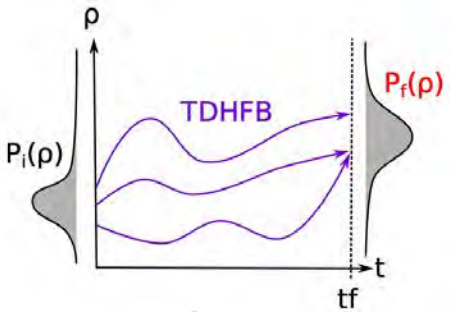


Some scientific highlights of nuclear physics theory @IN2P3

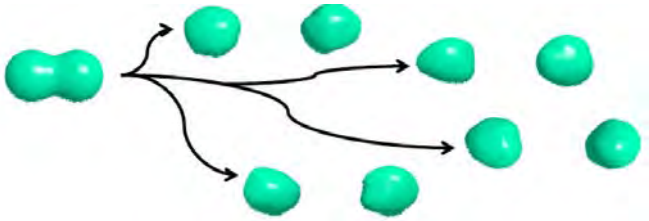
Energy Density Functional methods

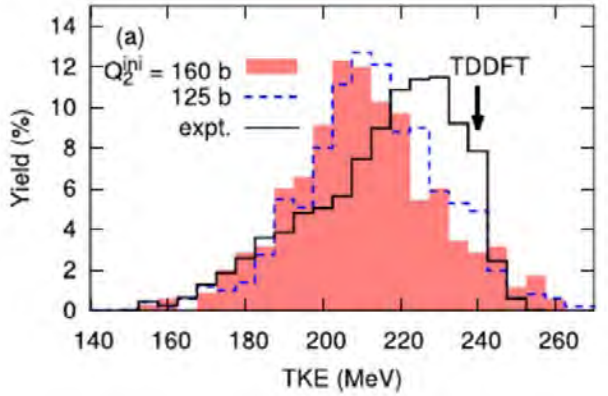
Nuclear dynamics: beyond mean-field

➡ Phase-space approach to quantum fluctuations



Application to the Fission process

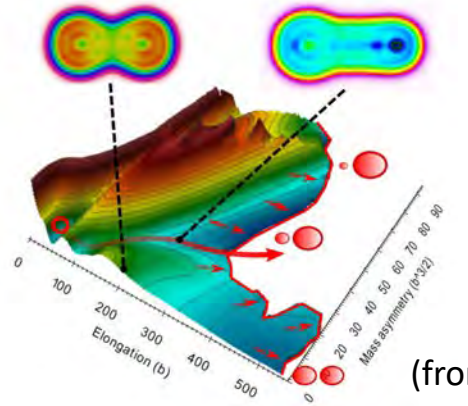




Tanimura, Lacroix, Ayik, PRL 118 (2017)

Towards path integrals

$$|\psi(t)\rangle = f_1(t)\left|\;\right\rangle + f_2(t)\left|\;\right\rangle + \cdots$$

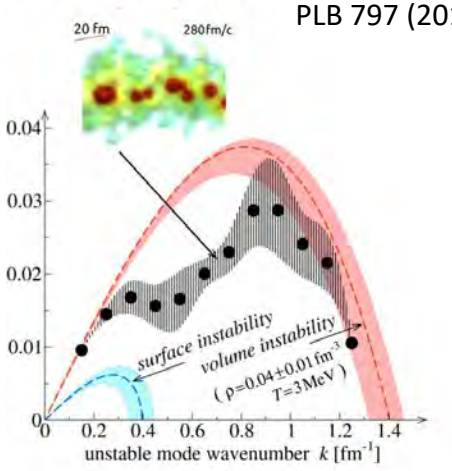


(from D. Regnier, Atelier theory 7-8 June)

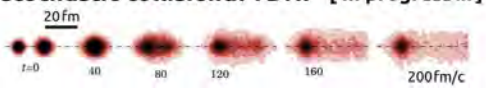
Beyond MF for Fermi energy collisions

stream of clusters (jet) in ^{36}Ar+^{58}Ni 74*A*MeV

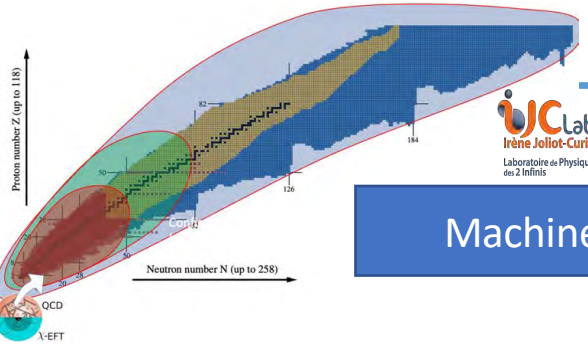
Boltzmann-Langevin Napolitani, Colonna, PLB 797 (2019)



***stochastic collisional* TDHF [in progress...]**



➡ Generalization of the TD-GCM to non-adiabatic motion



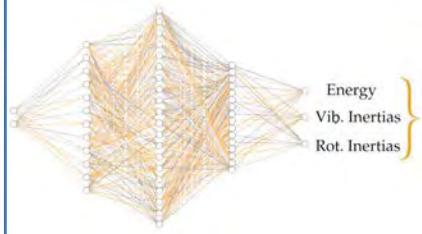
Some scientific highlights of nuclear physics theory @IN2P3

Using New technologies: quantum computing and machine learning

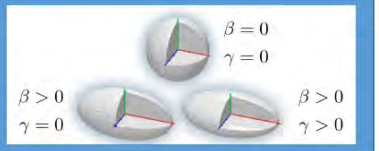
Machine learning

Select nucleus (N,Z)

Compute its HFB energy landscape



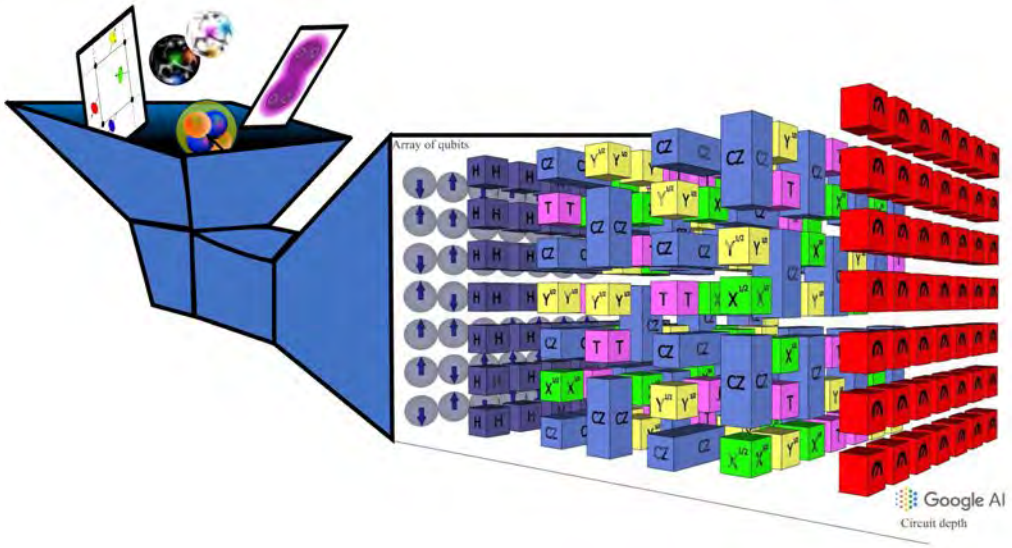
Map the energy Landscape onto a 5D Collective Hamiltonian

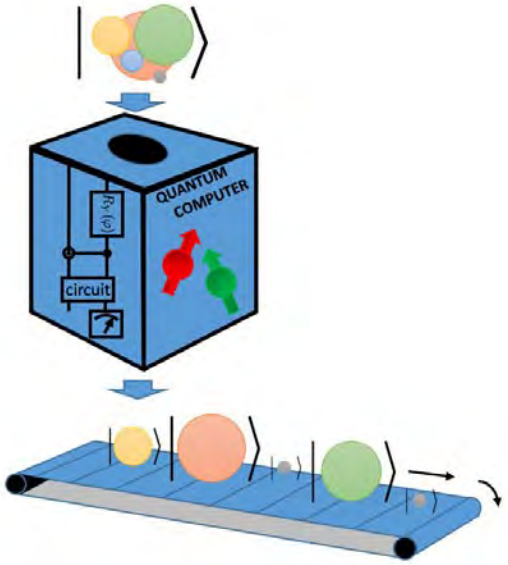


Deformations, Energy Spectrums, Transition amplitudes, …

Lasseri et al, PRL 124, (2020).

Quantum computing





Lacroix, PRL 125, 230502 (2020).

Some More statistics on nuclear theory @ IN2P3

Publications, Talks (2016-2020)

Regular articles published in international journals with review: 370
Article published as Letters/Natures: 65
Review articles: 14
Including ~100 articles with experimentalists

Number of other publications (including proceedings): 78
Number of invited talks: 244
Other talks: 102

Thesis, postdocs (2016-2020)

PhD thesis: 23, Postdocs: 16

Research Managements

Members of many national and international committees (full list in the document)

Selected items:
-members of different CS
-IN2P3 collaboration agreements (Russia, Italy, Poland, …)
-Members of PAC (GANIL, ALTO, JYFL)+strong support to exp. Proposals (RIKEN, MSU,CERN-Isolde, …)
-ECT*Board, ENSAR2 TheoS JRA

Some short summary of the Atelier physique théorique des 2 infinis

Ab-initio methods and progress in bare interactions	*Guillaume Hupin*	11:15 - 11:33
Configuration Interaction methods for nuclear structure and reactions	*Kamila Sieja*	11:33 - 11:51
Modern energy-density functionals and effective interactions	*Marcella Grasso*	11:51 - 12:09
Mean-Field and Beyond Mean-Field approaches for nuclear structure	*Michael Bender*	12:09 - 12:27
Nuclear dynamics with nuclear density functional theory	*David Regnier*	12:27 - 12:45
Towards description of light antiprotonic atoms (in relation with PUMA experiment)	*Rimantas Lazauskas*	12:45 - 12:50
Nuclear physics for neutrinoless double beta decay	*Frederic NOWACKI*	12:50 - 12:55
The Unitarity Limit and Universality	*Ubirajara van Kolck*	12:55 - 13:00
Quantum computing of atomic nuclei	*Denis LACROIX*	13:00 - 13:05
Final Discussion of the session		13:05 - 13:15

- 11 contributions were submitted
  (~ 30 contributors [CNRS, CEA and INP])
- Representative of the French nuclear Physics community
- 5 long talks (18') and 4 short (5') highlights
  Criteria for highlights: current discussion, Interdisciplinarity.
- Several interesting discussions:
  -standardization of models/theories
  -inputs of Lattice QCD for nuclear physics studies.
  -probe of short-range correlations
  -nuclear inputs for reliable predictions in unexplored areas and its use for nuclear astrophysics.

Thank you !