# Topics addressed in GT1 (physics at the drip line***S***)

1) Shell evolution towards the continuum (respective role of 3body, continuum effects)
2) Evolution of pairing towards the drip line / proton neutron forces close to continuum
3) Clustering towards the drip line (di-proton, di-neutron, quasi-molecular states)
4) Study of in-medium clustering
5) Emergence of halo & Borromean states and related properties
6) Broken mirror symmetries
7) Quenching of SF towards drip line or between systems involving haloes & cluster nuclei
8) Giant and pigmy modes in exotic nuclei
9) Synergy with other quantum systems.

First meeting organized at IPN Orsay in about 2 days in different session (≈ 32 participants each)

22 Talks presented + about 3 hours of discussion

A lot of enthusiasm, many ideas presented !

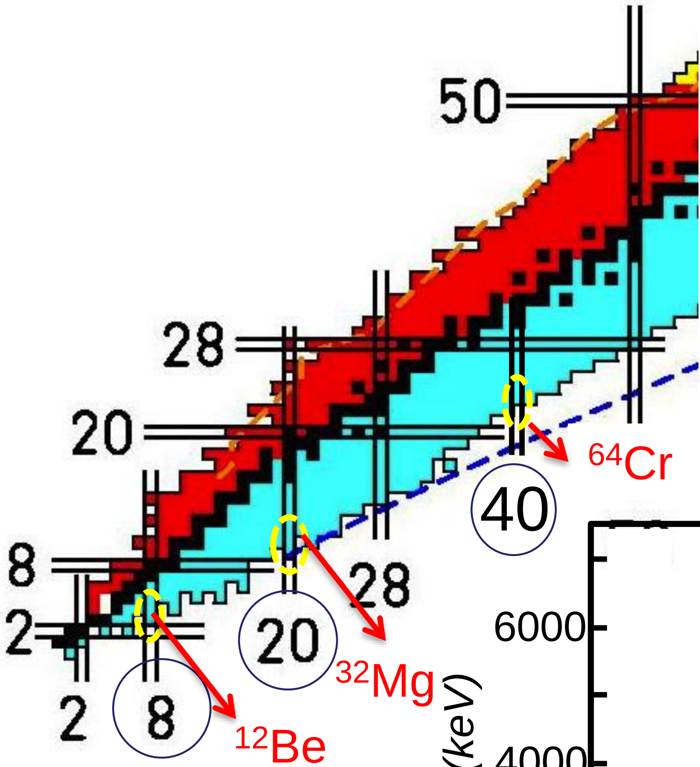
In general very well perceived

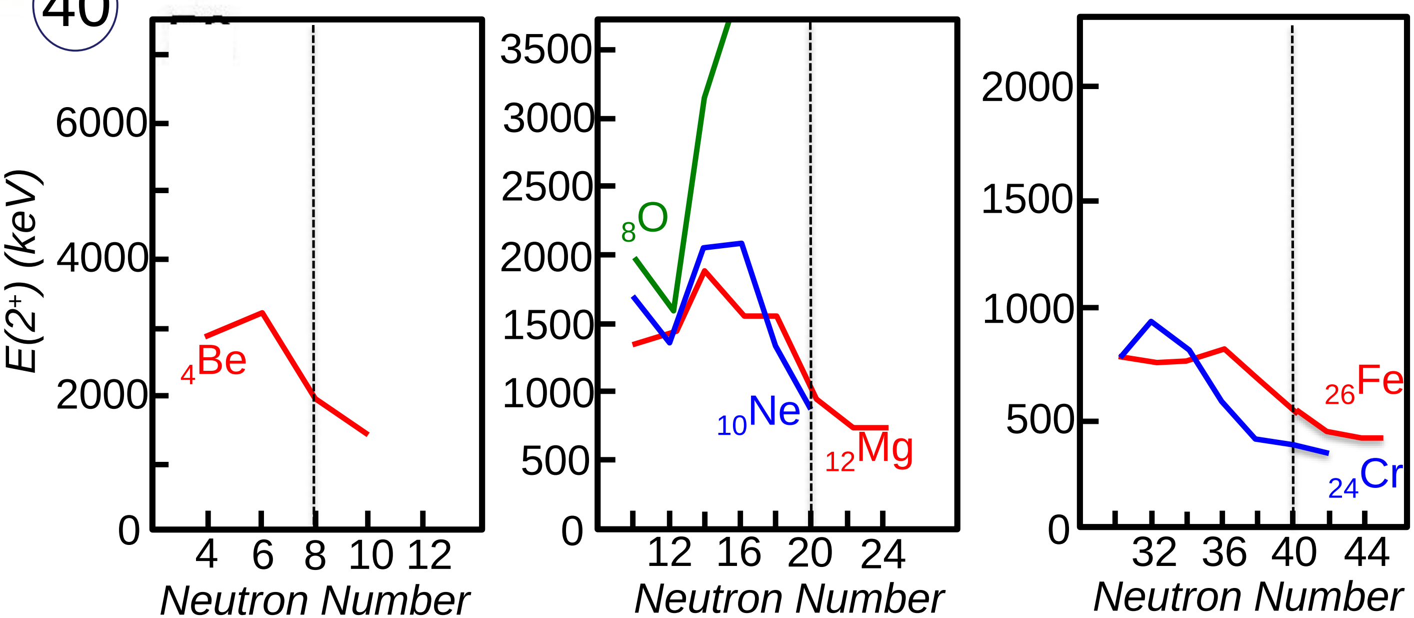
.

# Assuming our world was more neutron-rich

-> There is sign of shell closure and magic nuclei (no increase of $2^+$ energy at N=8, 20, 40)

While adding protons toward stability, central and tensor forces create magic numbers




N=40

↳ Hannawald PRL 82 (1999), Sorlin, EPJA16 (2003), Aoi, PRL 102 (2009), Gade PRC 81 (2010)
W. Rother PRL106 (2011), Lenzi PRC82 (2010), Santamaria PRL 115 (2015), …

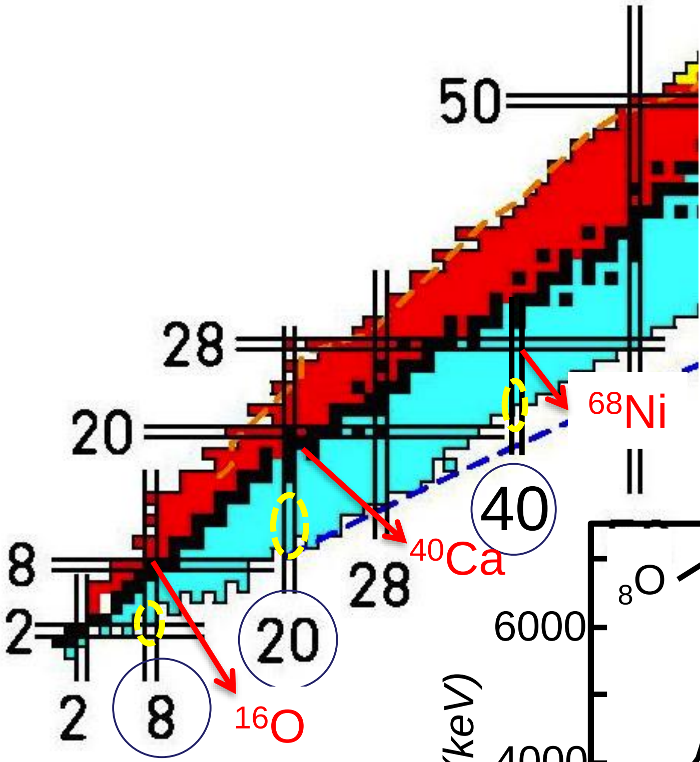
# Back to stability: magic numbers

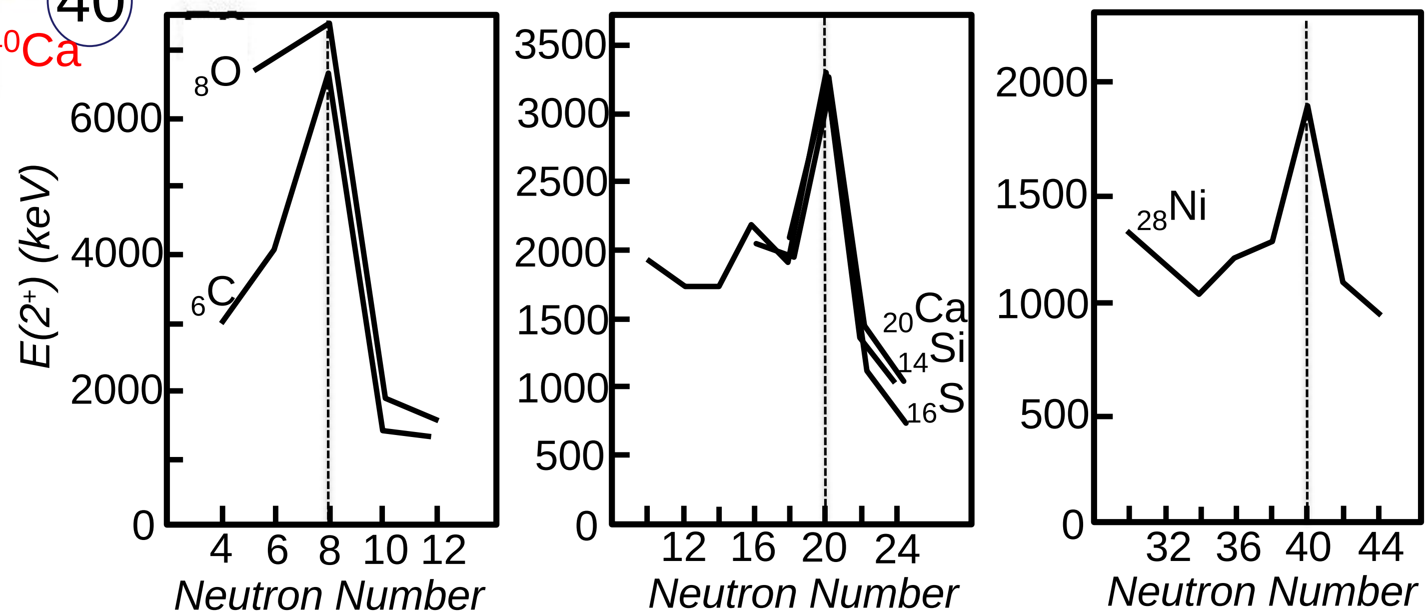
Increase of $2^+$ energy at N=8, 20, 40

Creation of shell gaps expected with HO

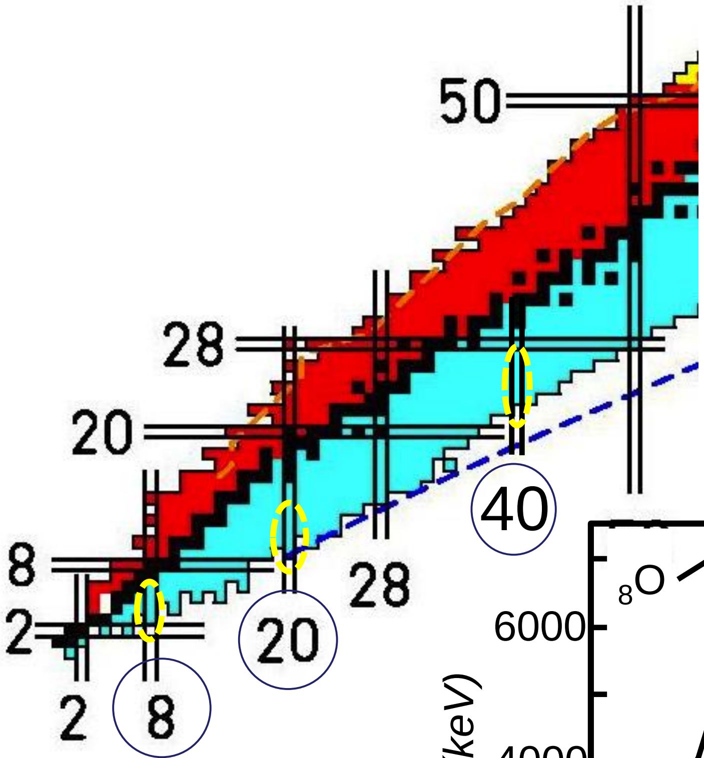
-> Likely a universal mechanism

-> Hierachy of NN forces (central and tensor)



# A universal mechanism ….

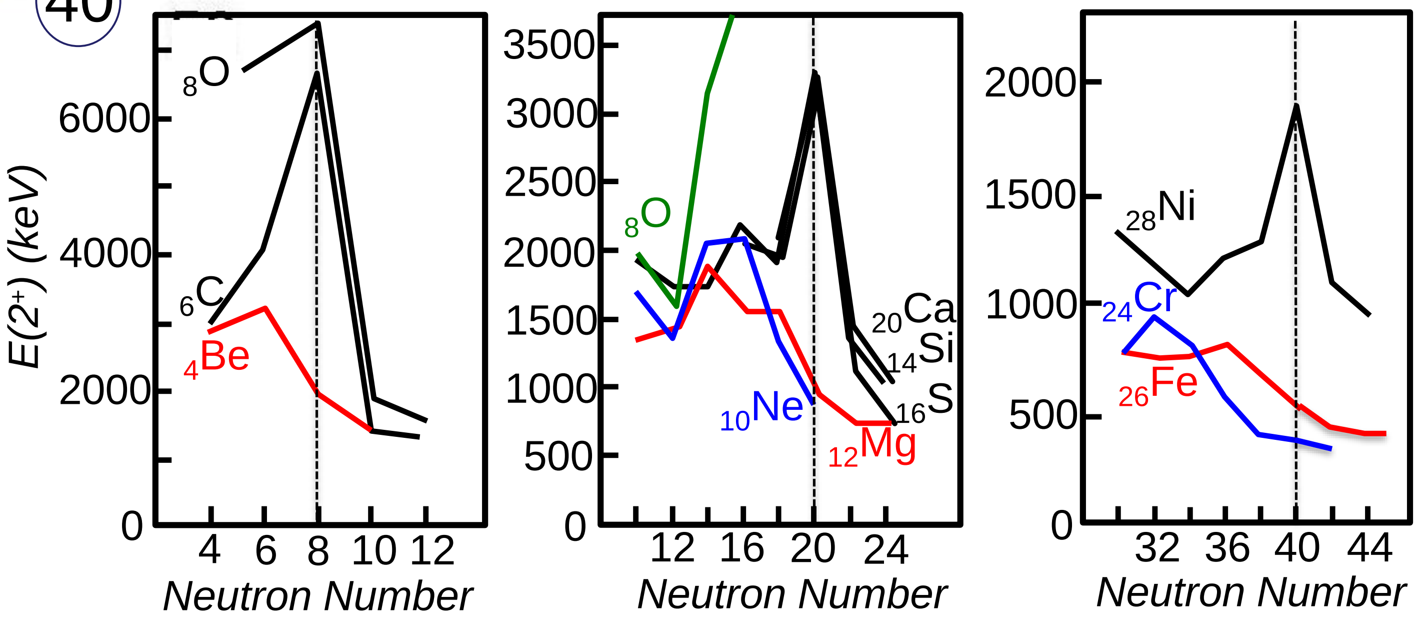



Increase of $2^+$ energy at N=8, 20, 40

Creation of shell gaps expected with HO

-> Likely a universal mechanism

-> Hierachy of NN forces (central and tensor)



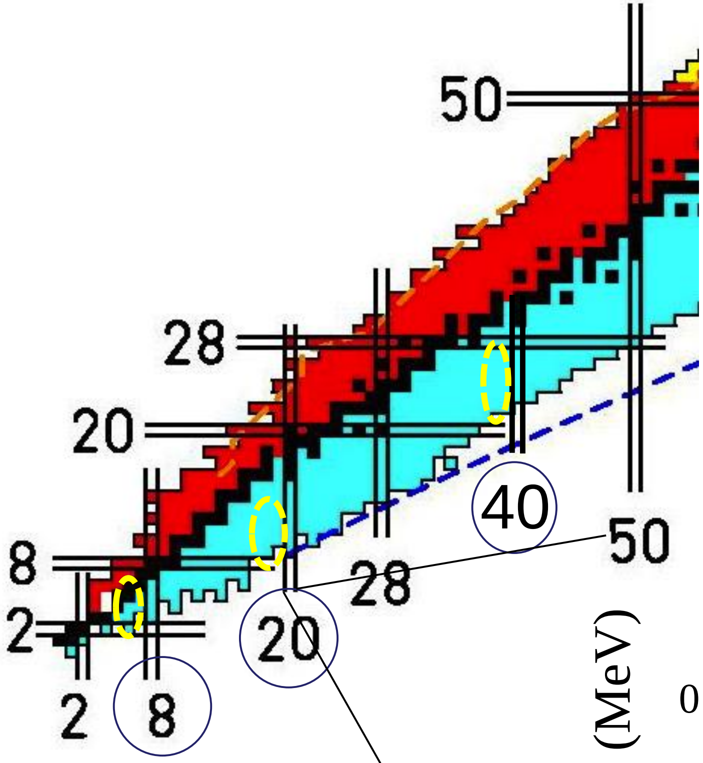
# A universal mechanism ….

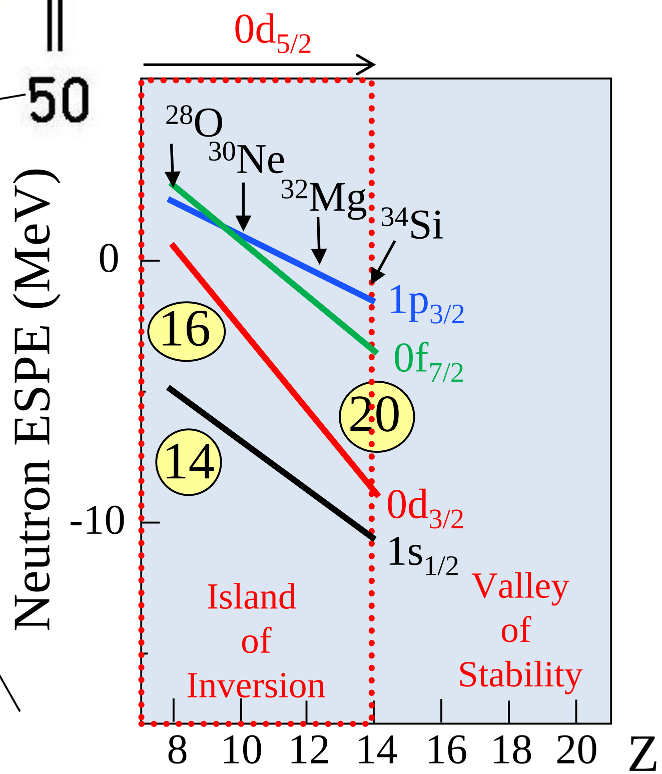
Increase of $2^+$ energy at N=8, 20, 40

Creation of shell gaps expected with HO

-> Likely a universal mechanism

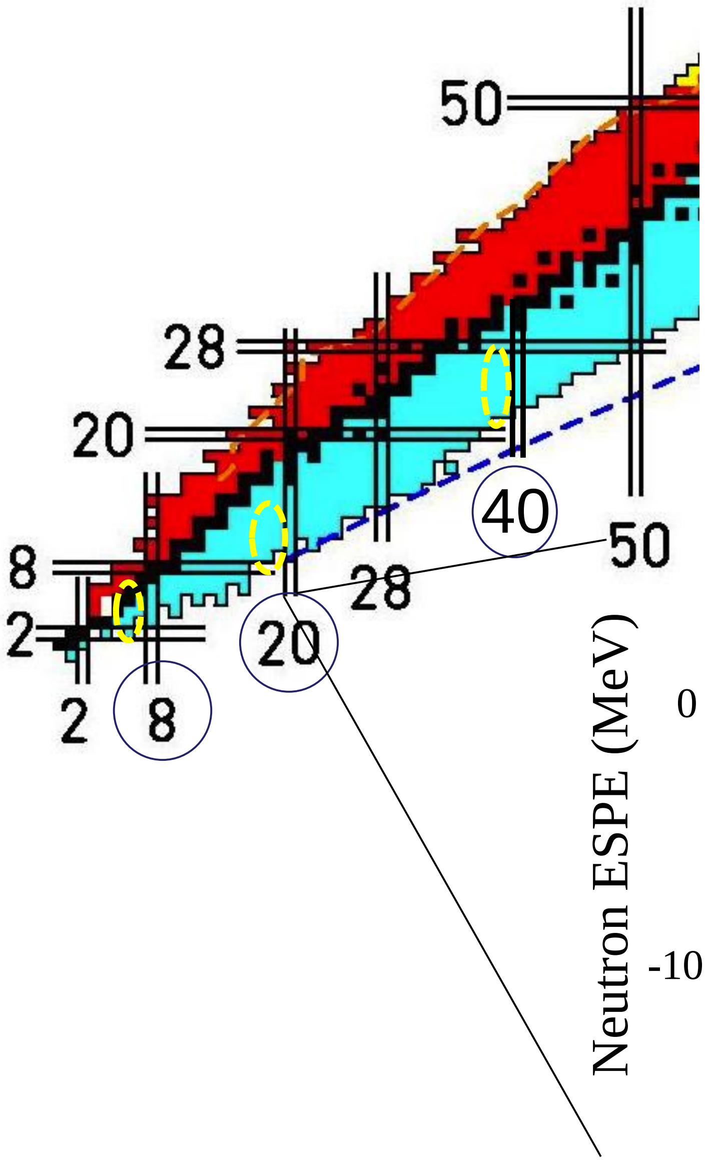
-> Hierachy of NN forces (central and tensor)




*Y. Utsuno et al. PRC 60 (1999) 054315*

# A universal mechanism ….

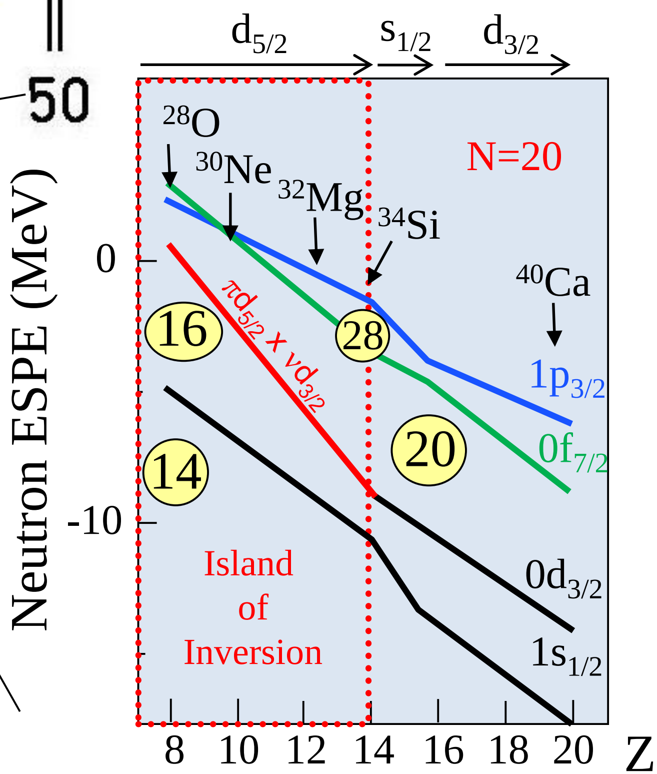



Increase of $2^+$ energy at N=8, 20, 40

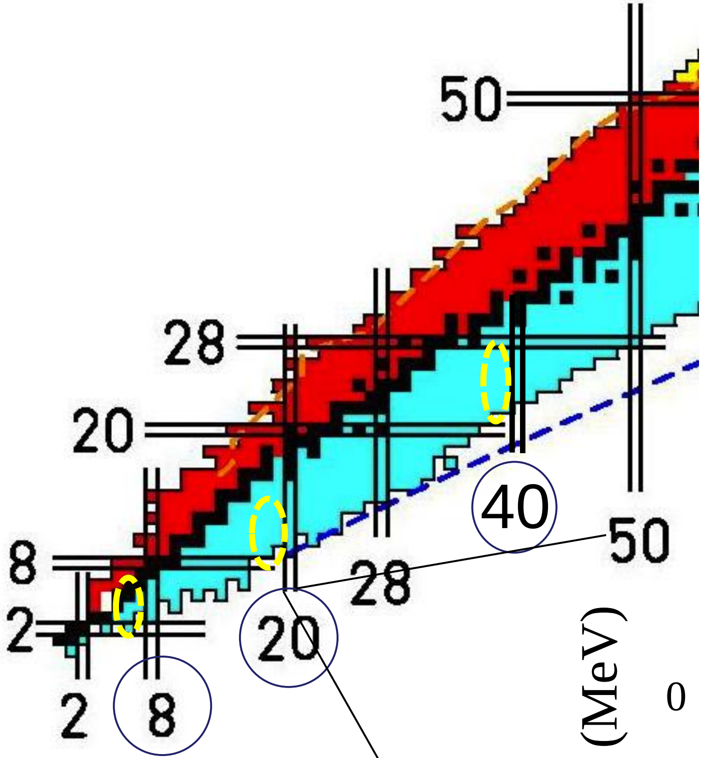
Creation of shell gaps expected with HO

-> Likely a universal mechanism

-> Hierachy of NN forces (central and tensor)



# Shell evolution: the rôle of the proximity to the continuum

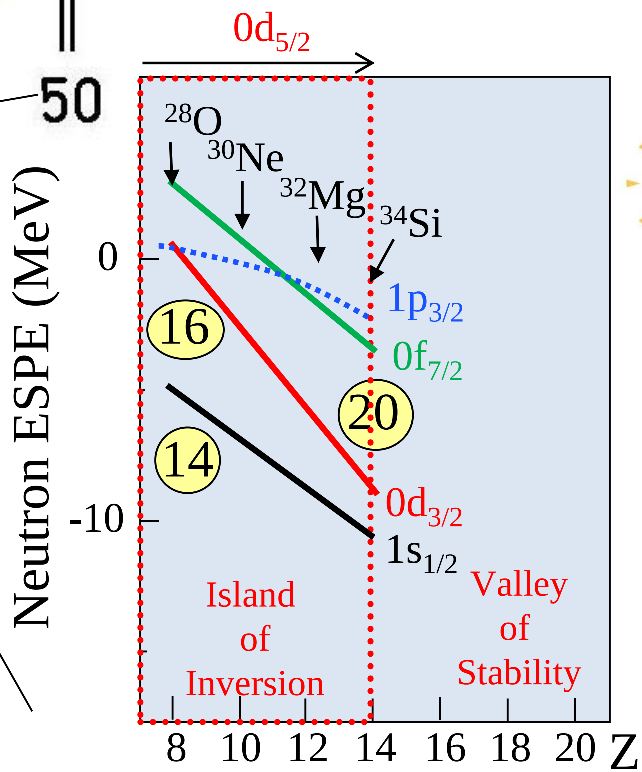



Increase of $2^+$ energy at N=8, 20, 40

Creation of shell gaps expected with HO

-> Likely a universal mechanism

-> Hierachy of NN forces or/and drip line effect?



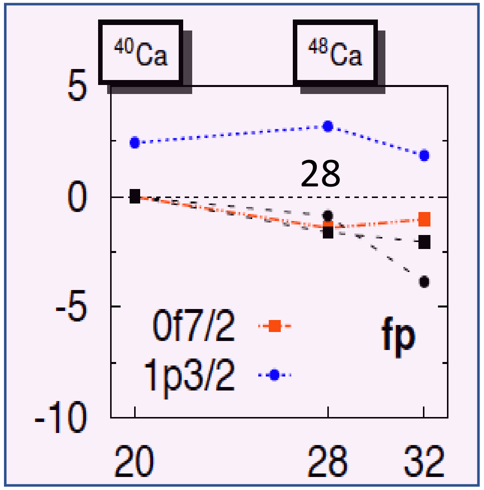

Prove the inversion between $3/2^-$ , $3/2^+$ and $7/2^-$ states in the $^{23,25}O$ isotopes

charge exchange

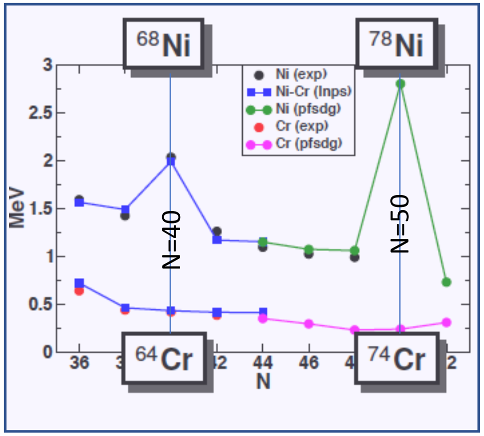
ACTAR-TPC @ RIKEN

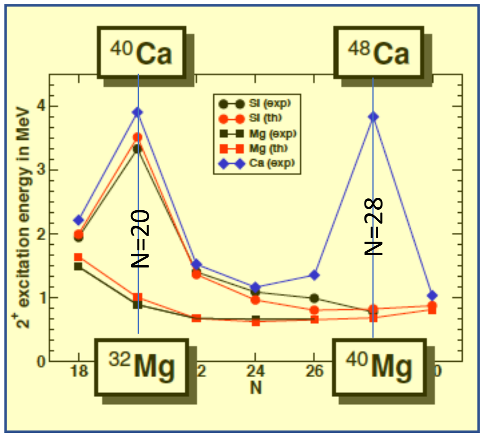
# Change of paradigm far from stability

Increase of N=28 gap by 3 MeV with 3N forces

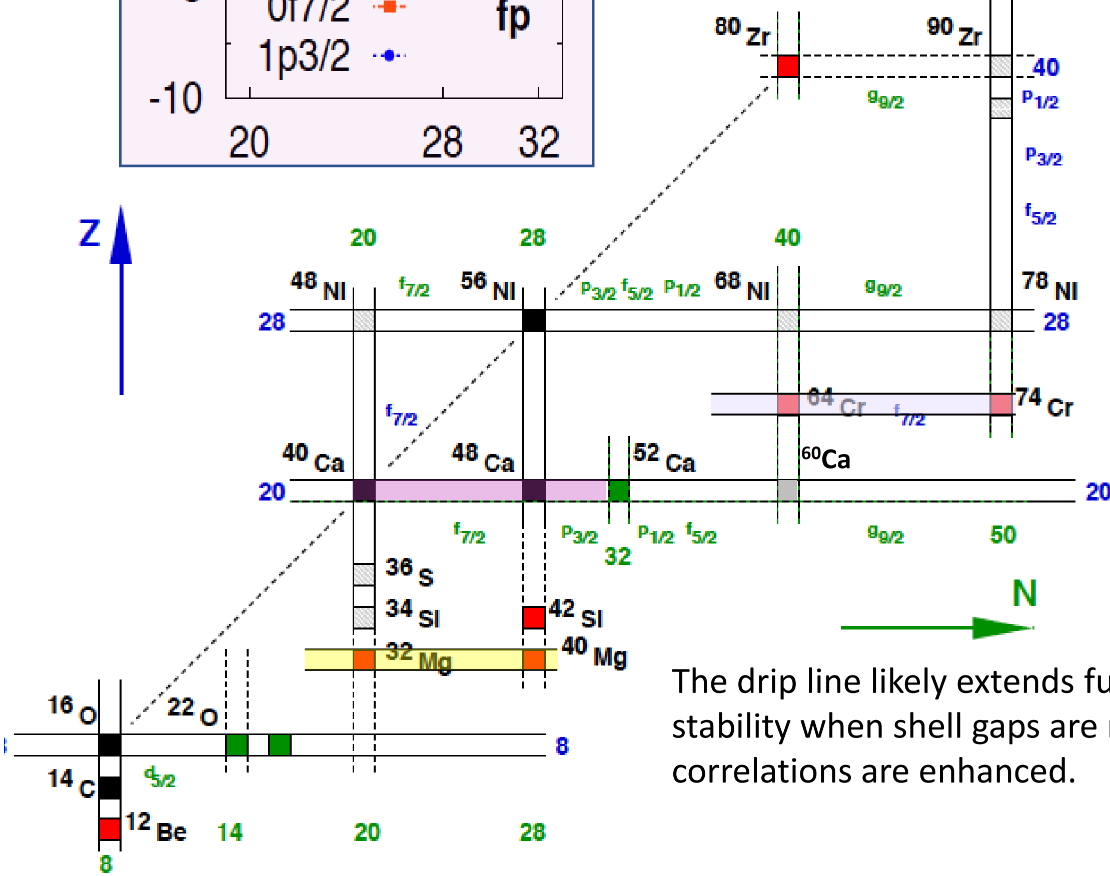


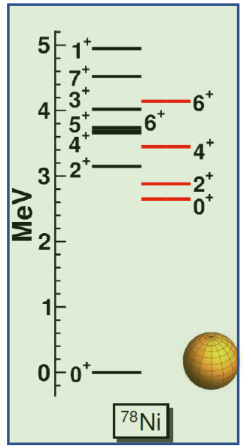

Merging of island of inversions?



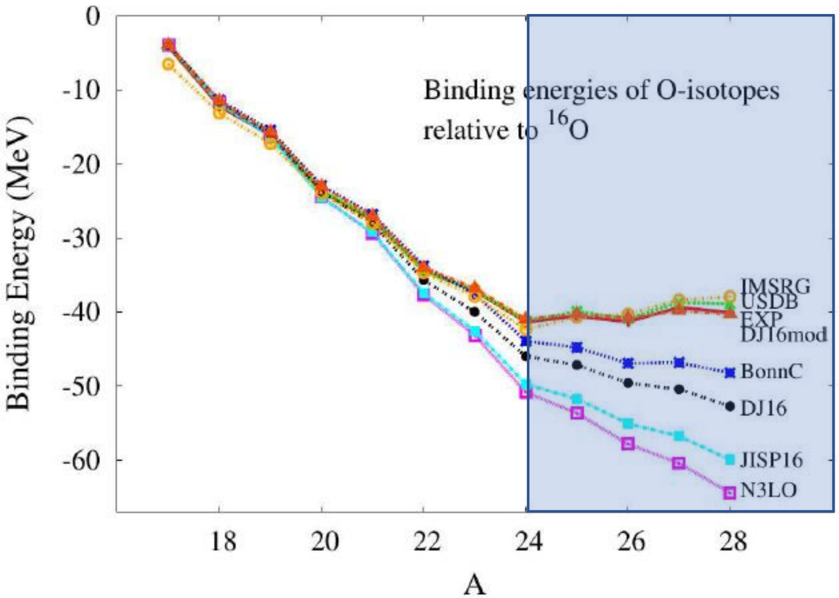

*(F. Nowacki)*

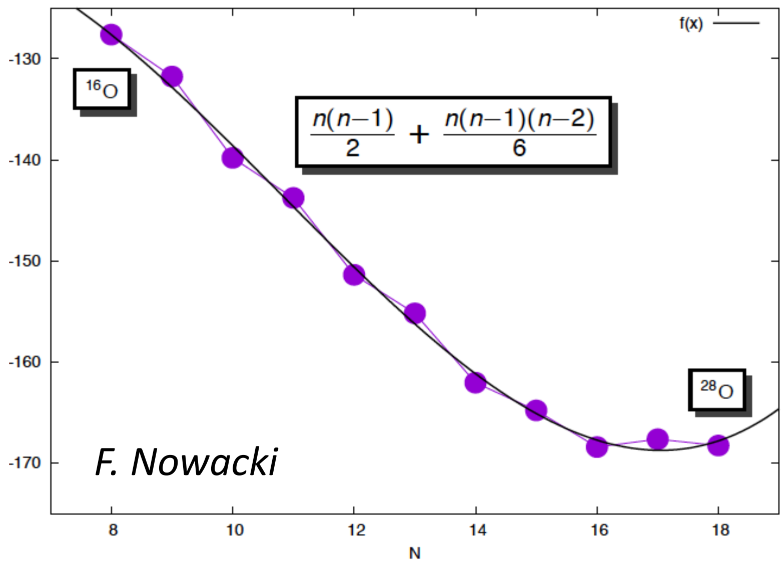



The drip line likely extends further from stability when shell gaps are reduced and correlations are enhanced.

# Shell evolution in the O chain: 3N forces viz continuum ?




Curvature of BE in O chain accounted for by effective 2-body or 'realistic' 3-body forces.

But the proximity of the continuum is expected to produce non-linear effects as well.

-> These two contributions have to be calculated and their effect should be disentangled

# Evolution of nuclear pairing close and beyond the drip line

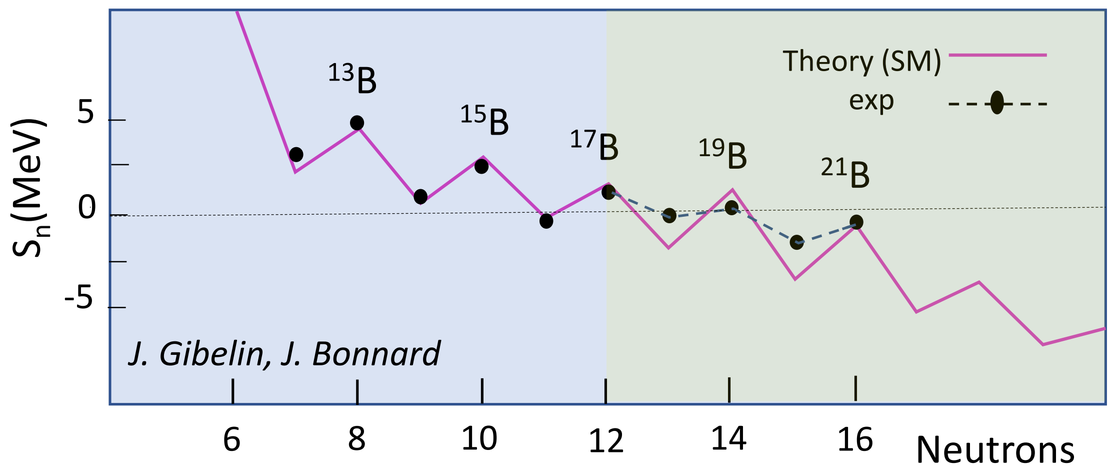
Study of 1n and 2n decays of unbound B nuclei at RIKEN allows rather accurate determinations of $S_n$ values beyond the drip line

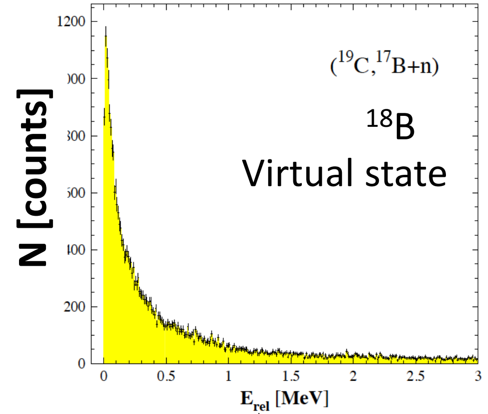
-> reduced odd-even effects as compared to SM calculations

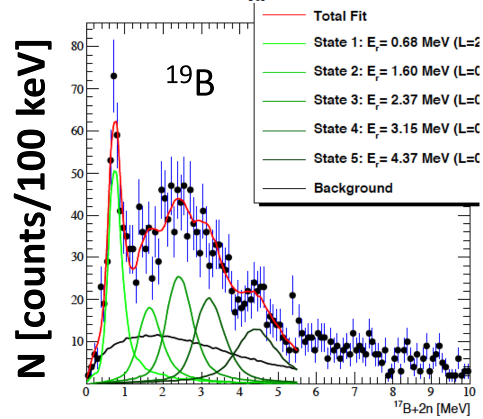
Anti-pairing effect due to pn interaction *(M. Ploszajczak)*
or reduced pairing strength ?

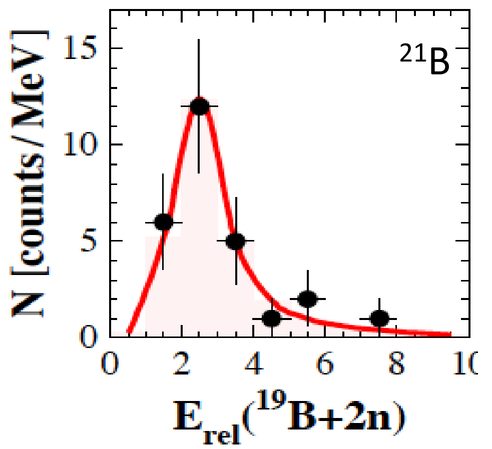
Gapless superconductivity?

Study C, N, O chains (*J. Gibelin work in progress)*



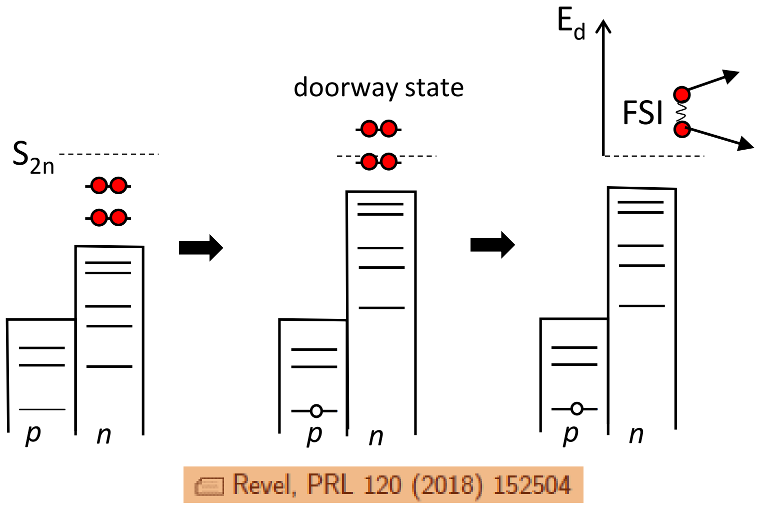



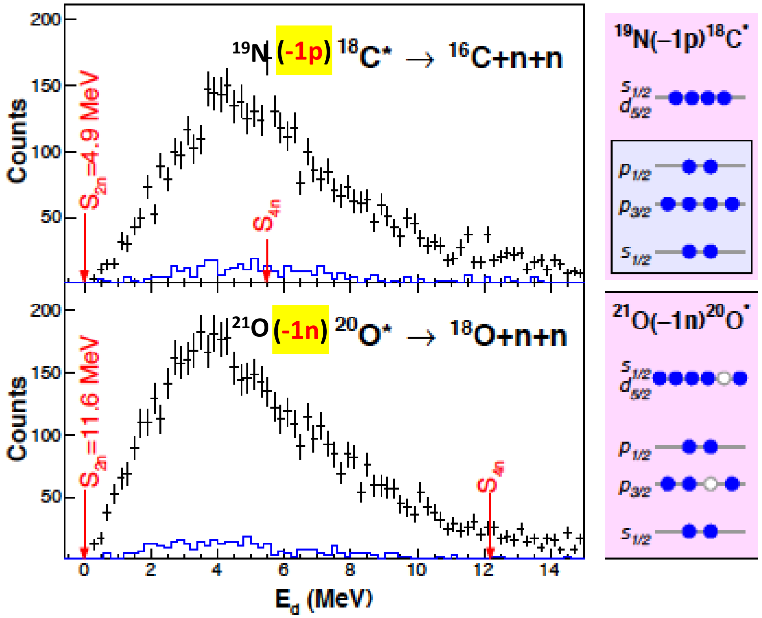




RIKEN / SAMURAI

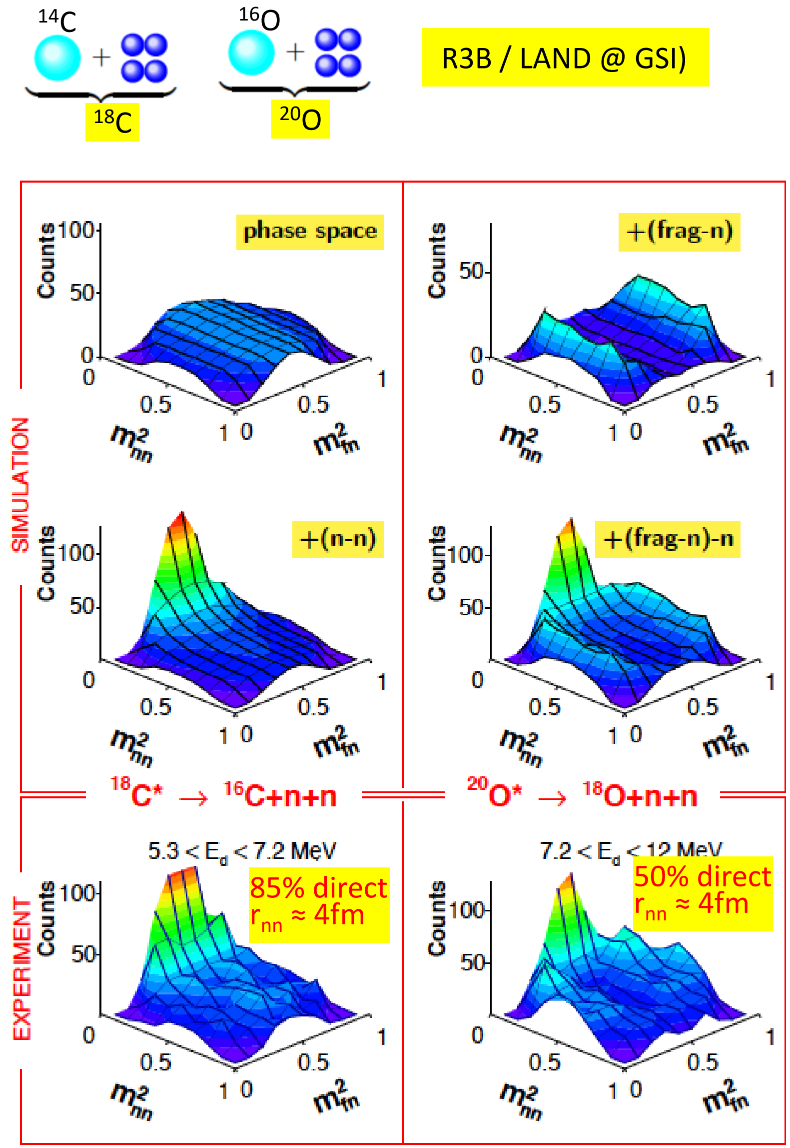
*S. Leblond et al. Accepted in PRL (2018)*

# Strong neutron pairing correlations in (core +4n) nuclei



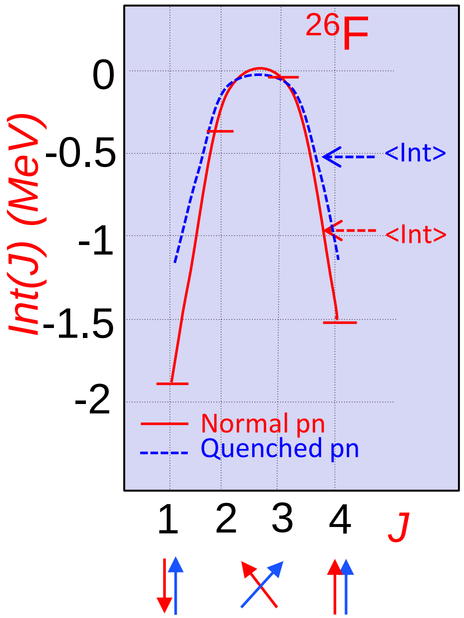

N=12 isotones ($^{18}C$ & $^{20}O$) above $S_{2n}$

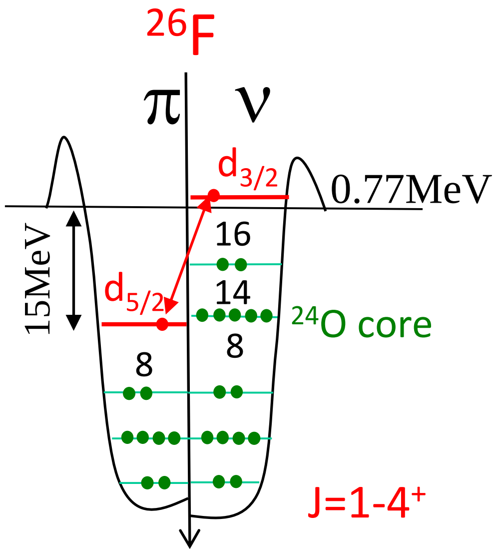


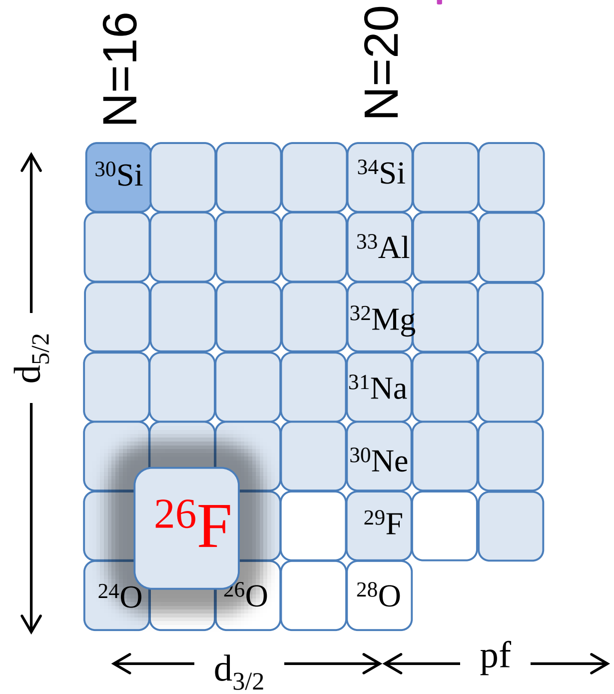

Analogy with photoemission of Cooper pairs? (*R. Wehlitz PRL 109 (2012)*)

# Evolution of effective proton-neutron interaction at the drip line

(pp) $\pi d_{5/2}$-$\nu d_{3/2}$ coupling in $^{26}F$



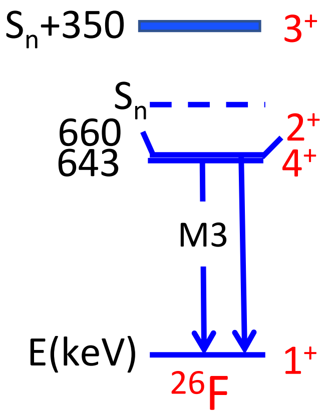



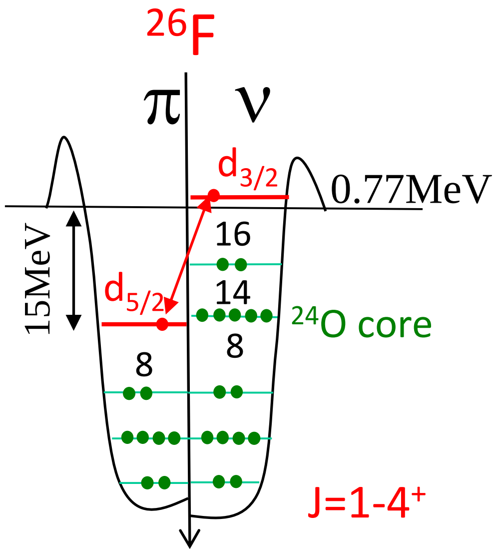

Study of pn interaction in a system with very asymmetric p and n binding energies

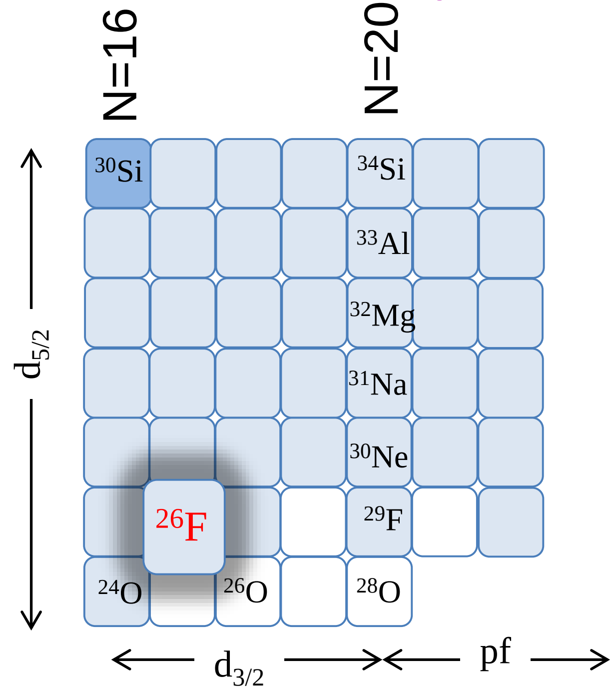
Three experiments needed to determine the energies of the J=2,3,4$^{+}$ states in $^{26}F$

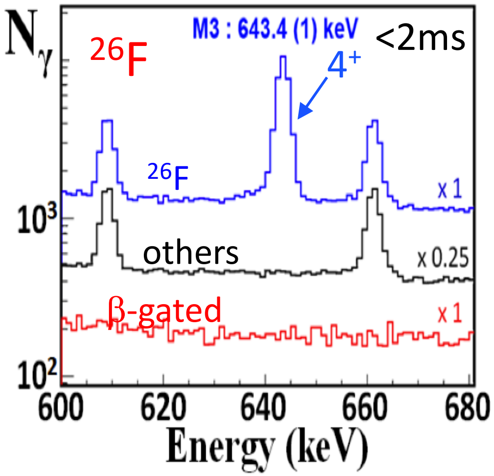
# Evolution of effective proton-neutron interaction at the drip line

(pp) $\pi d_{5/2}$-$\nu d_{3/2}$ coupling in $^{26}$F



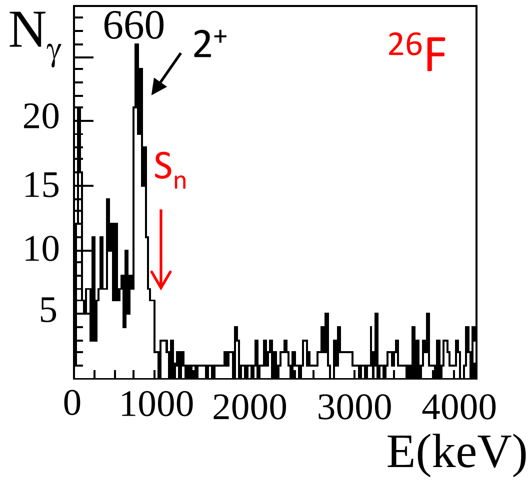



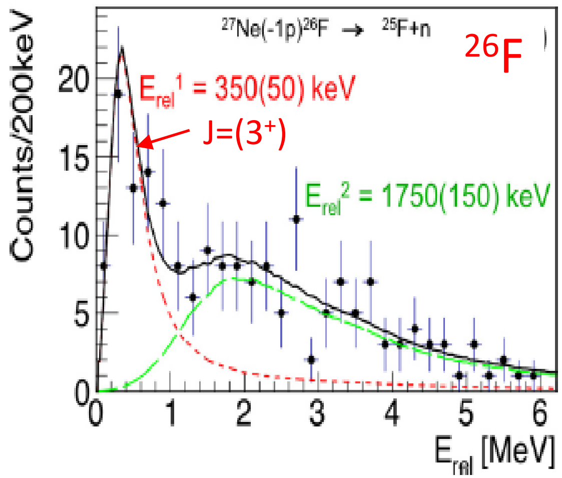

*A. Lepailleur et al. PRL (2013)*

GANIL/LISE




*M. Stanoiu et al. PRC (2012)*

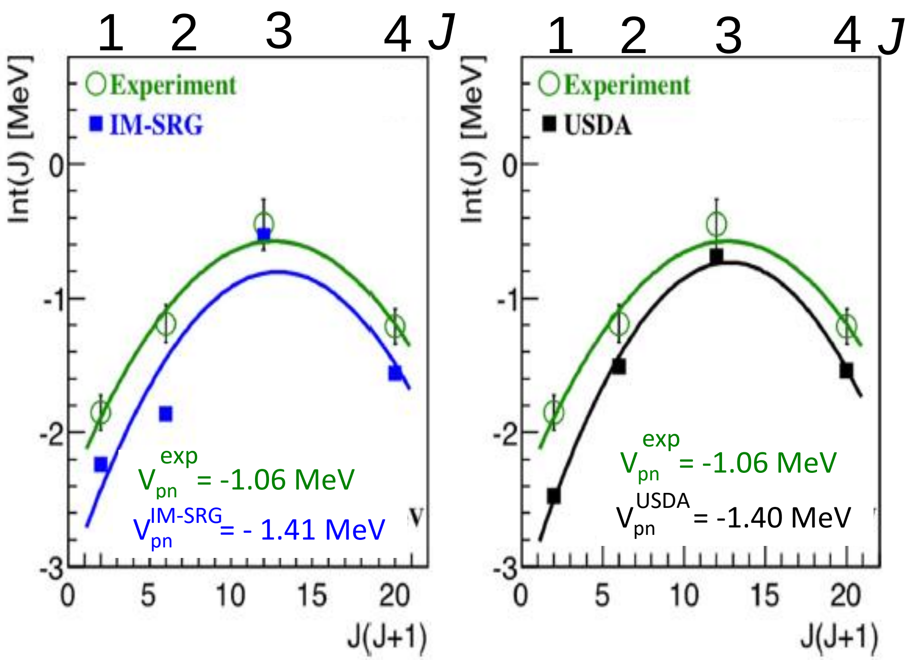
GANIL/SISSI

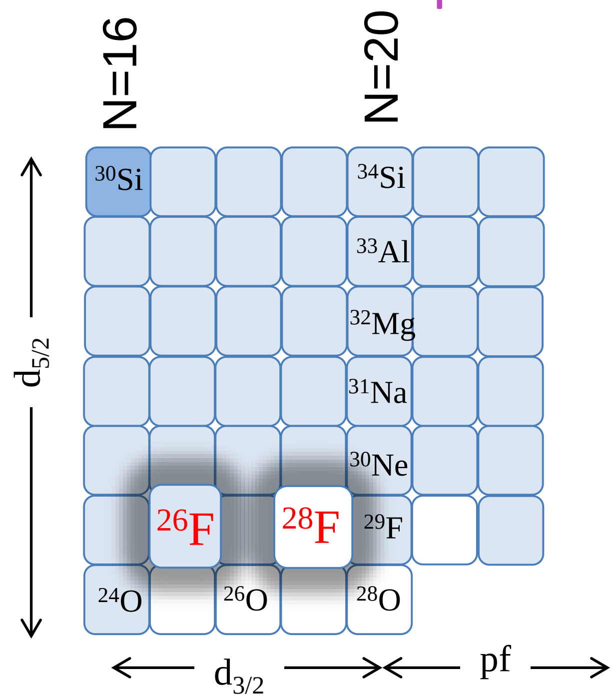



*M. Vandebrouck et al., PRC (2017)*

GSI/R3B

# Evolution of effective proton-neutron interaction at the drip line




Reduced monopole and residual effective interactions as compared to theories

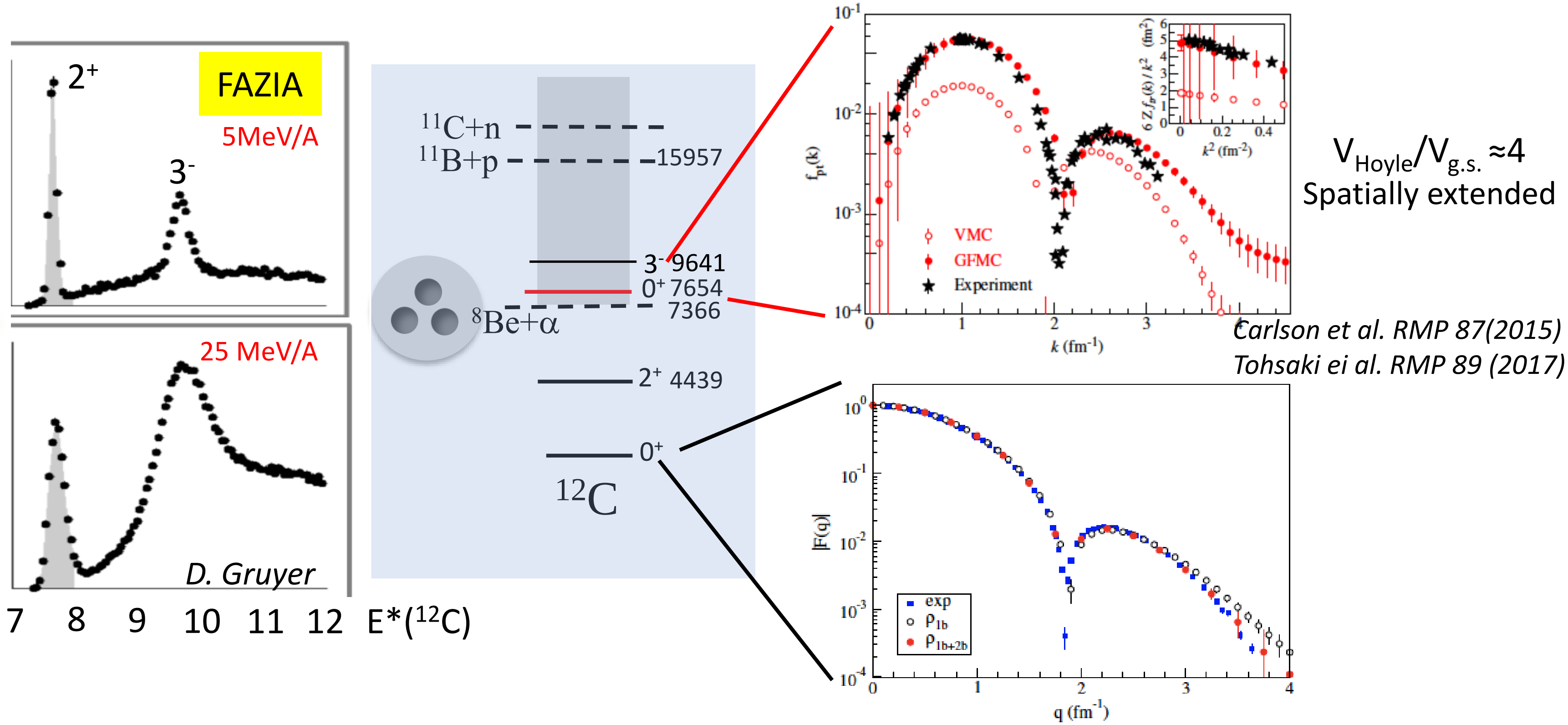
Reduction of spatial overlap between p and n (as for $^{16}F$)?

Would the (ph) coupling scheme work for $^{28}F$?
Is $^{28}F$ out of the island of inversion ?

*-> A. Revel - RIKEN*

What is the role of the imaginary part of the pn interaction ? -> M. Ploszajczak

# Nuclear clustering – the Hoyle state



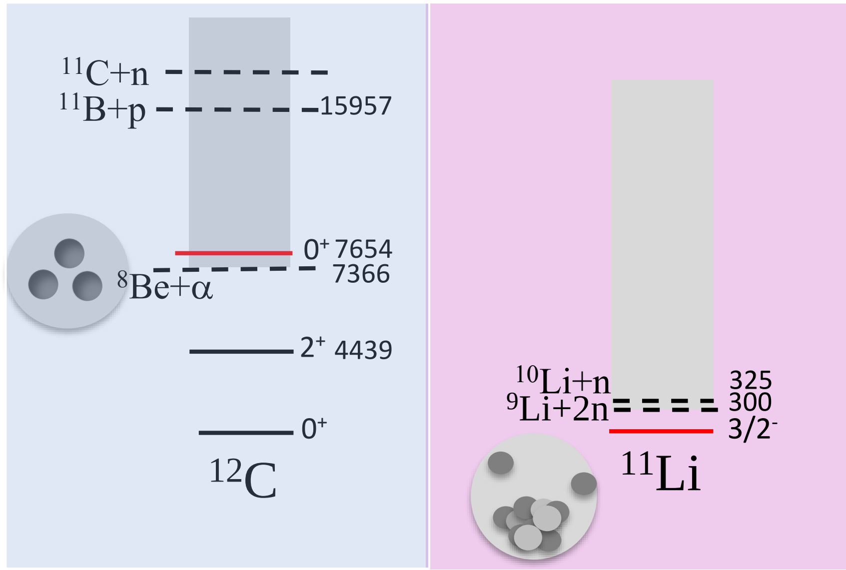

The Hoyle state has been characterized by its inelastic form factor and decay pattern.

It decays by < 0.043 % directly *(R. Smith PRL 119 (2017), Dell'Aquila PRL 119 (2017))*
In medium, it has be found to decay by 17% ! *(Raduta PLB 705 (2011))*

This in-medium effect needs to be confirmed (D. Gruyer, G. Verde...)
Decay mode and Γ width may be modified by the medium in which it is formed?
Other cases to be studied?

# Does the Ikeda conjecture apply to di- or tetra- nucleon configurations?

(*J. Okolowicz, et al. Prog. Th. Phys. Supp. 196 (2012)*)

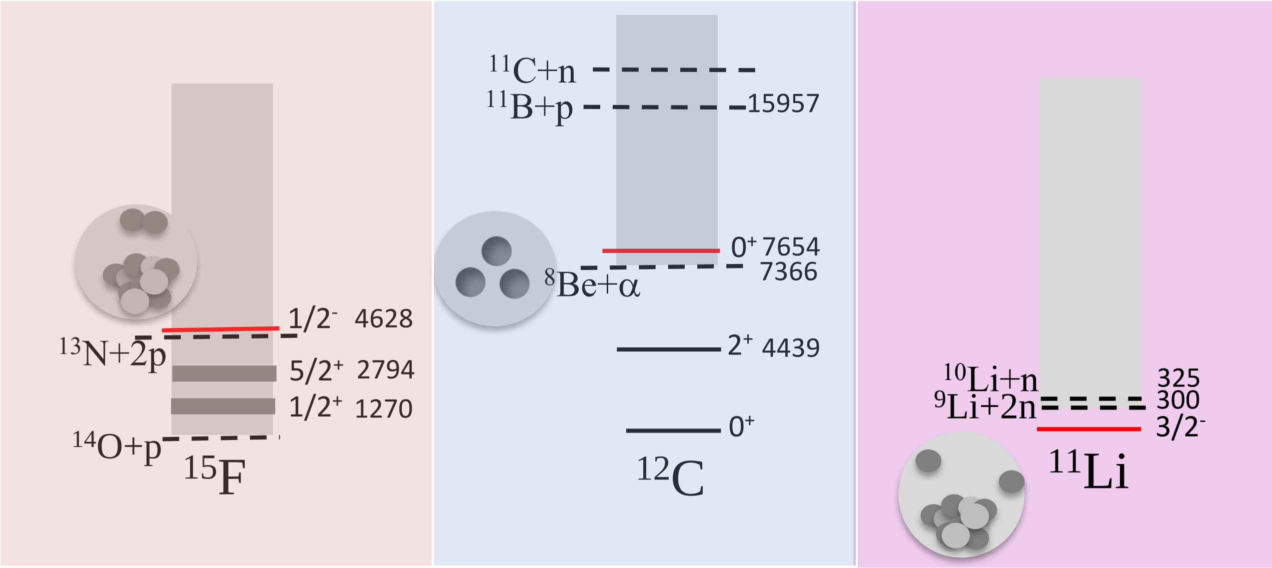



Ikeda conjecture :

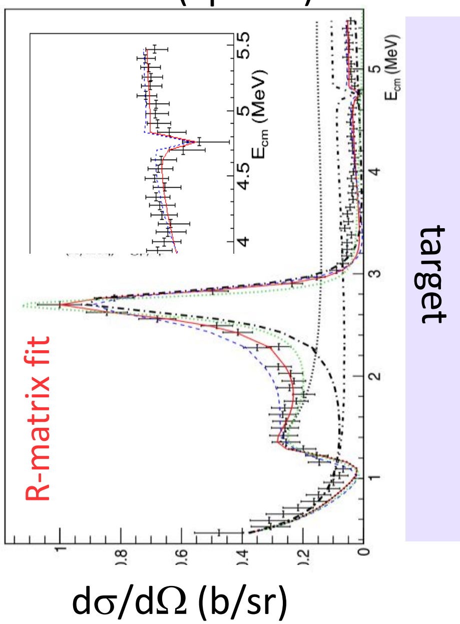
Existence of narrow resonances (cluster states) at the corresponding energy thresholds

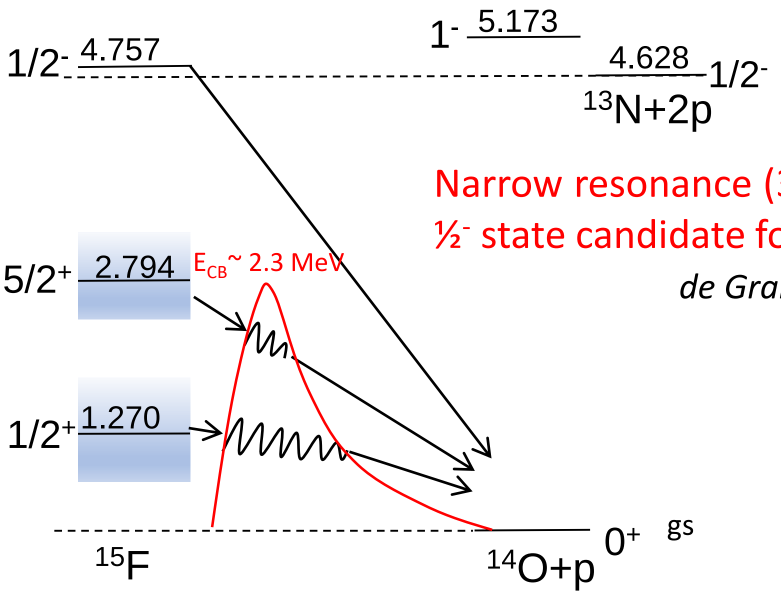
# Search for 2p cluster configurations around $S_{2p}$ threshold

*(J. Okolowicz, et al. Prog. Th. Phys. Supp. 196 (2012))*




14O beam (Spiral1)



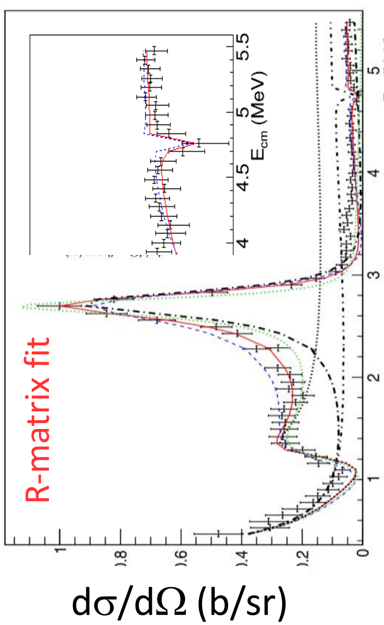



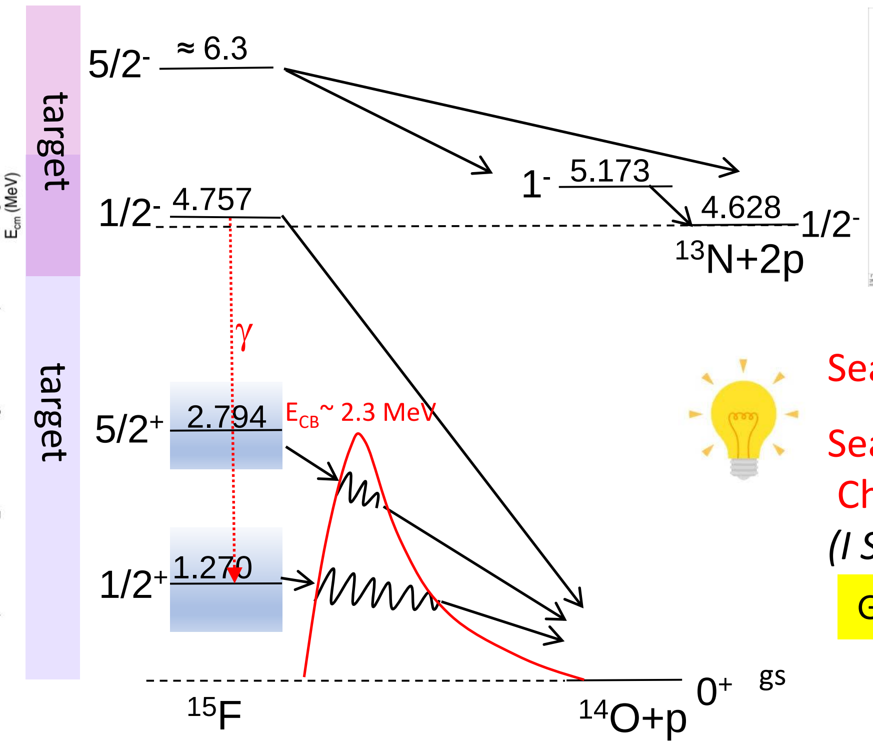

Narrow resonance (35 keV) just above $S_{2p}$

½⁻ state candidate for a 2p cluster

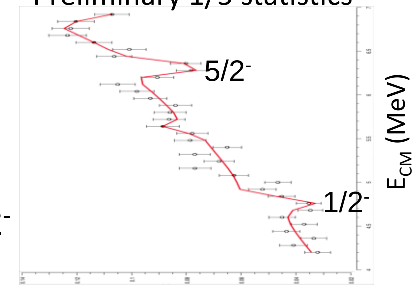
*de Grancey et al. PLB (2016)*

# Search for 2p cluster configurations around $S_{2p}$ threshold




*V. Alcindor PhD IPNO /GANIL*
Preliminary 1/5 statistics




Search for E1 fast γ decay

Search for other 2p states
Characterize their decays
*(I Stefan, F. De Oliveira)*

GANIL/MUGAST

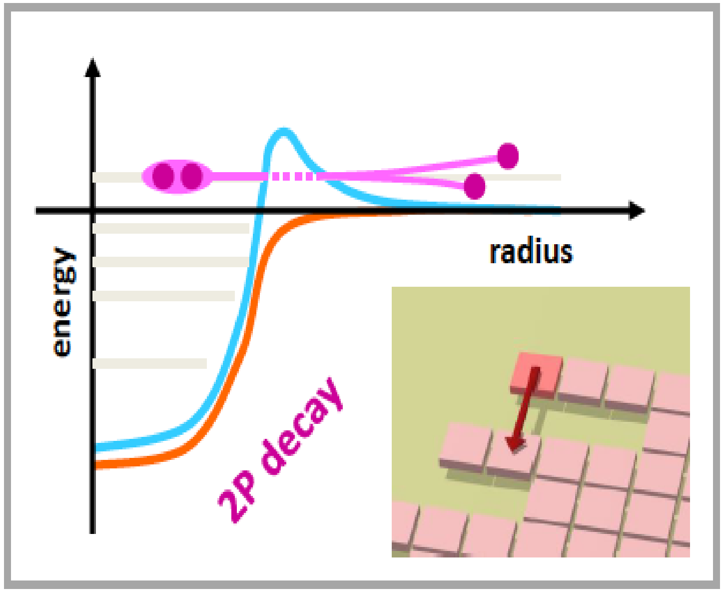
# 2p decay radioactivity

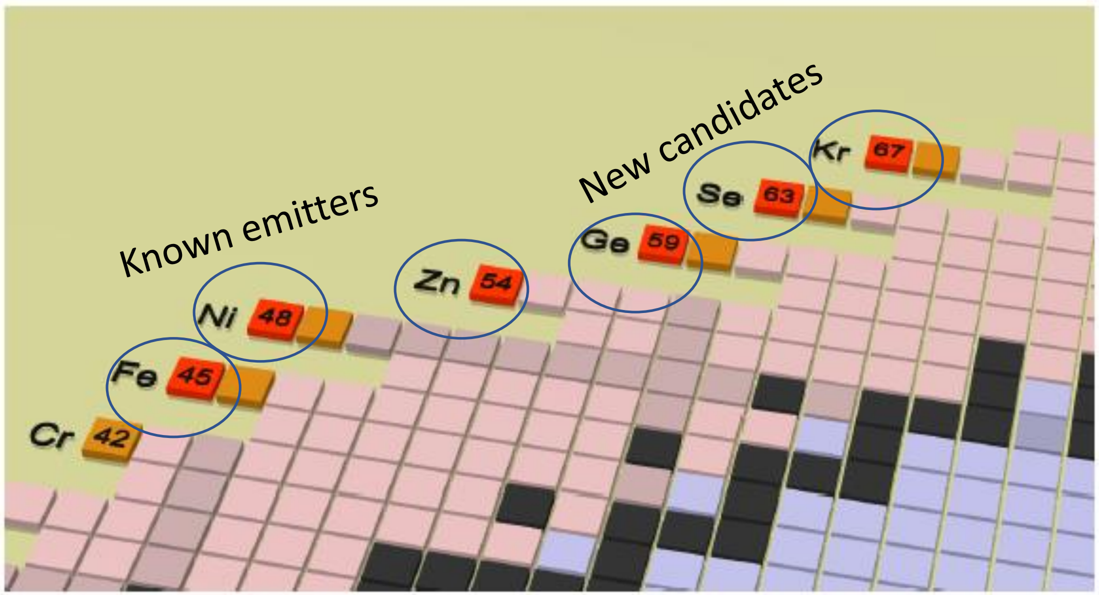
The 2p radioactivity is a rare process.

It is found when the 1p daughter is unbound and when the 2p are trapped inside a barrier

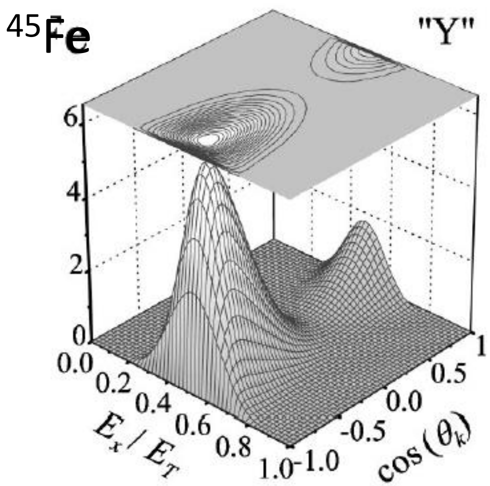
The lifetime of the nucleus should be long enough to call it ‘radioactivity’.

Understanding the 2p radioactivity process requires proper modeling of the nuclear structure and the dynamics



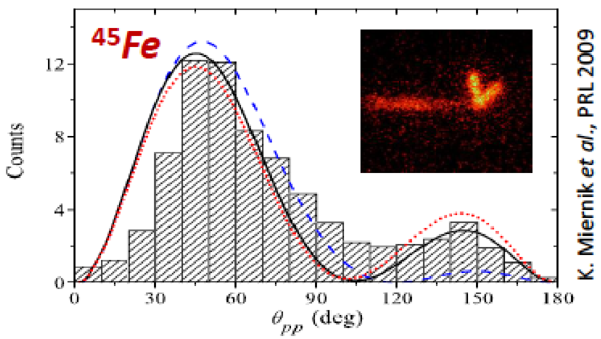
# 2p decay radioactivity

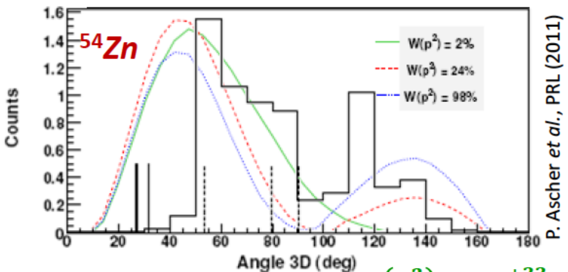



**"Shell model corrected half-lives"**

A = A(f²) + A (p²) ⟹ $T_{1/2}$(2P)

| | calculation | experiment(s) | |
|---|---|---|---|
| $^{45}Fe$ | $2.7\ ms$ | $3,76 \pm 0,26\ ms$ | OK |
| $^{54}Zn$ | $1.6\ ms$ | $1.98^{+0.73}_{-0.41}\ ms$ | OK |
| | | *Goigoux PRL (2016)* | |
| $^{67}Kr$ | ~~$660\ ms$~~ | $21 \pm 12\ ms$ | NOT OK ! |
| | → 24±10 ms | *Nazarewicz PRL 120 (2018)* | |



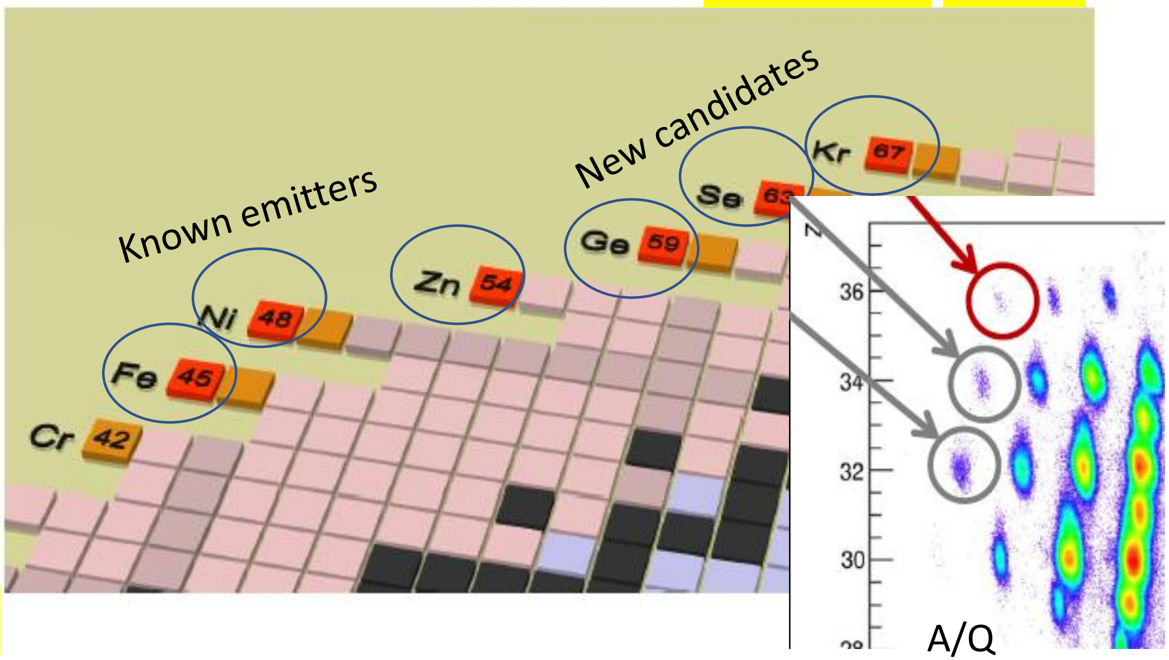

$W(p^2) = 30^{+33}_{-21}\%$

$^{48}$***Ni*** Spherical case

ACTAR-TPC GANIL?

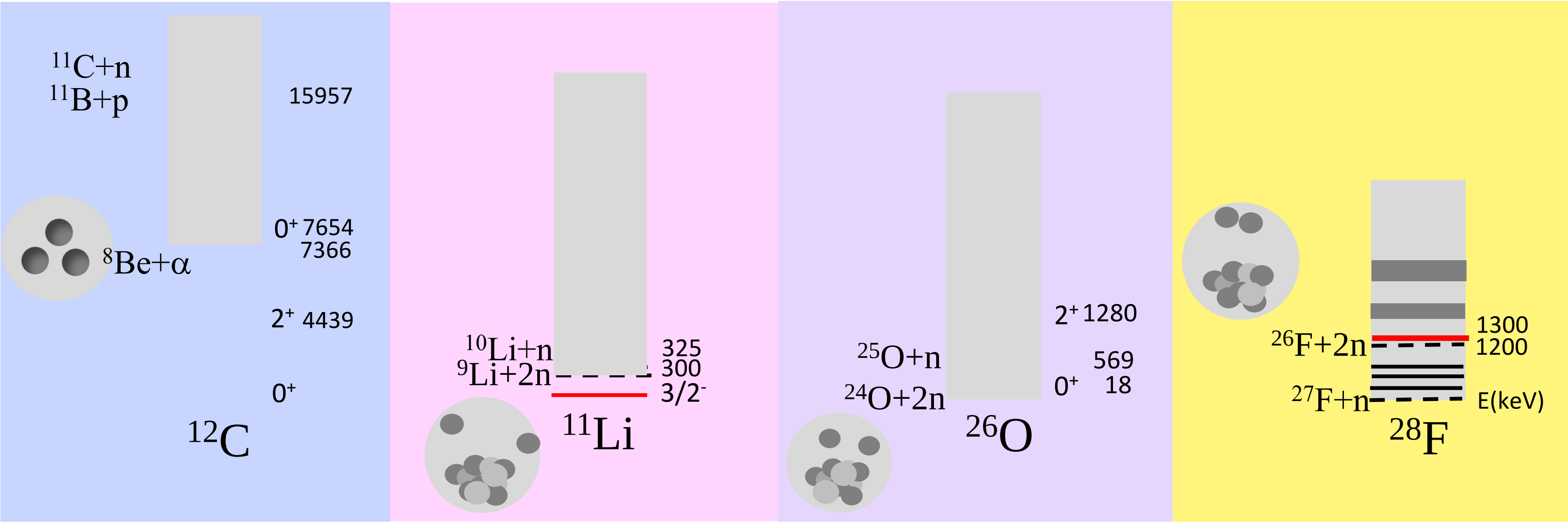
First deformed 2p emitter or sequential decay

Study its 2p decay (Giovinazzo) ACTAR-TPC RIKEN

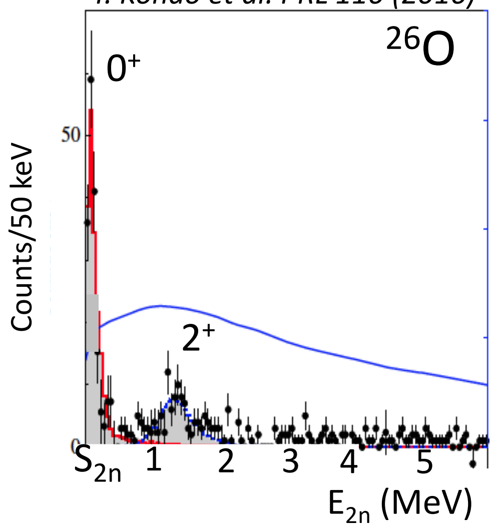


# Search for 2n cluster configurations around $S_{2n}$ threshold

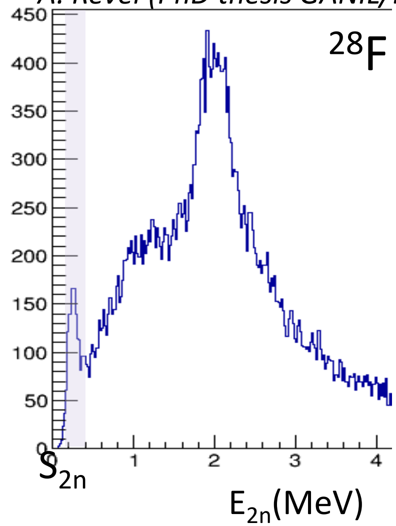
(*adapted from J. Okolowicz, et al. Prog. Th. Phys. Supp. 196 (2012)*)




*Y. Kondo et al. PRL 116 (2016)*




*A. Revel (PhD thesis GANIL/LPC)*



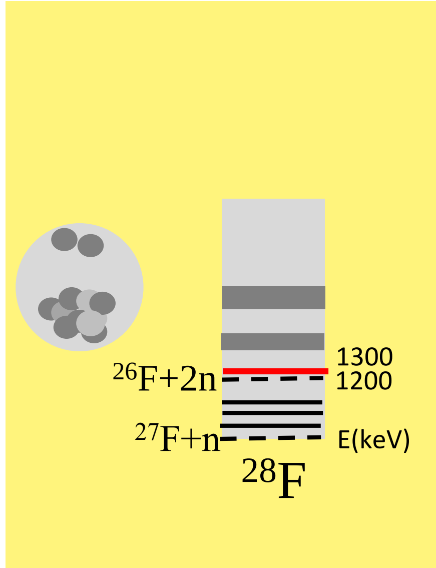

Narrow resonances around $S_{2n}$ in $^{26}$O and $^{28}$

-> Do they correspond to cluster states ?

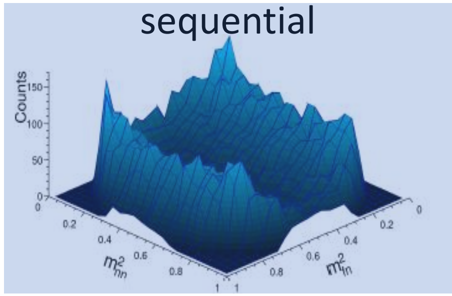
-> Characterize their decay pattern

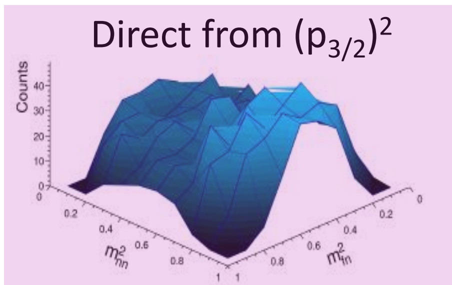
RIKEN

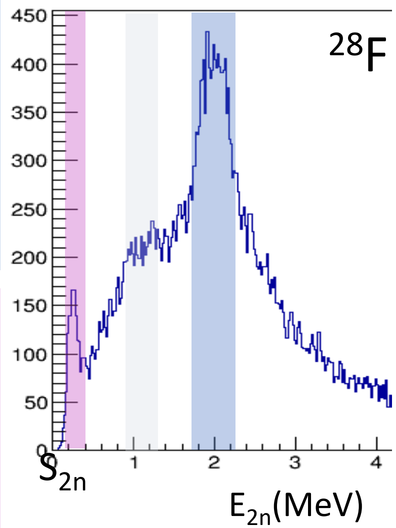
# Search for 2n cluster configurations around $S_{2n}$ threshold




Almost exclusive sequential decay through $^{27}F^*$



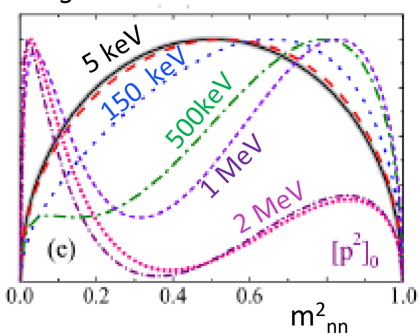




Narrow resonance in $^{28}$F:

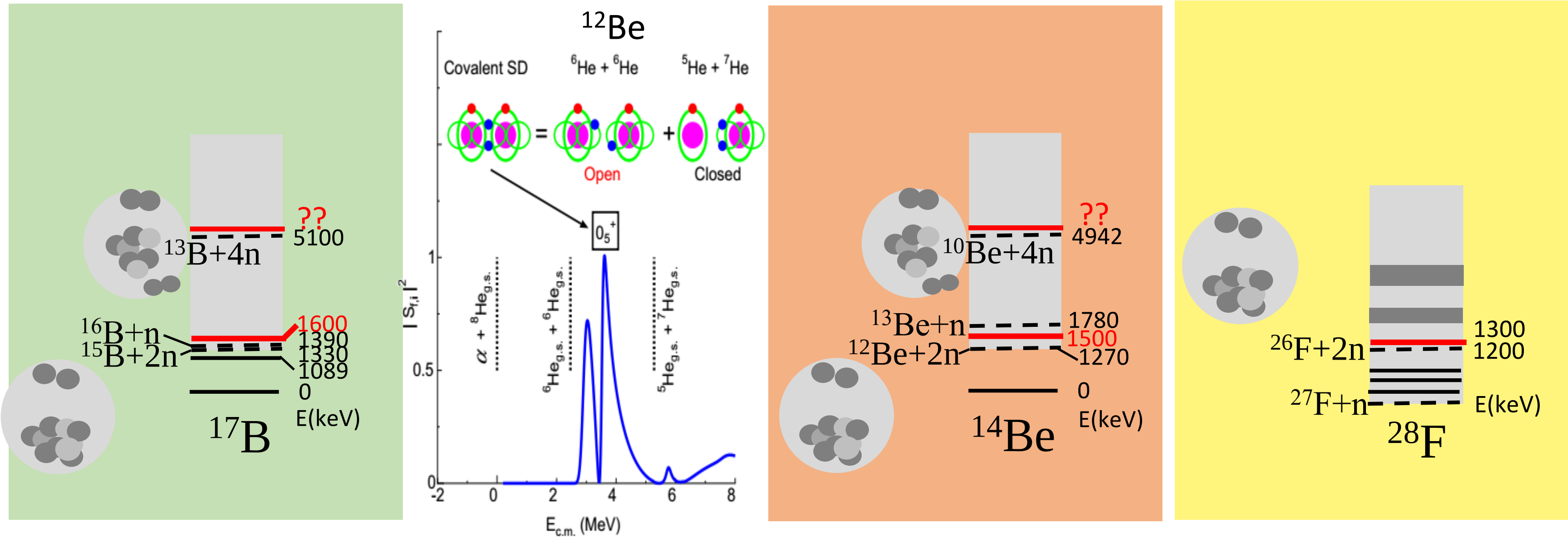
$(\nu 2p_{3/2})^2$ above $^{26}$F?

*Grigorenko et al. PRC 2018*




*A. Revel (PhD GANIL/LPC work in progress)* RIKEN

# Search for 2n and 4n cluster configurations around $S_{2n}$ and $S_{4n}$ thresholds




RIKEN +GSI R3B | GANIL / ACTAR | GSI/ R3B | RIKEN

Syst. appearence of narrow states close to $S_{2n}$ ? In which condition ? -> other cases, e.g. $^{17}$B

What is the nature of these states?

Search for enhanced E1 $\gamma$-strength

2n decay correlation pattern with Dalitz plots.

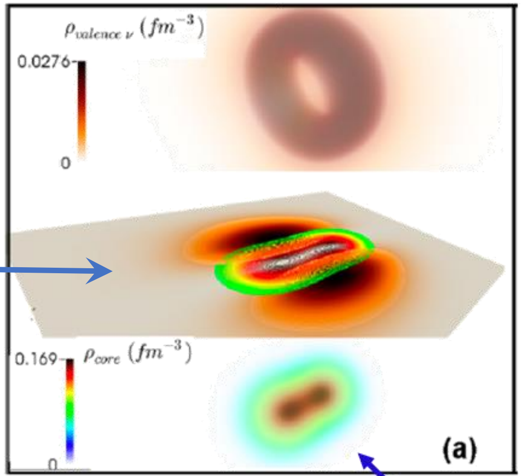
Does 2n radioactivity exist ? -> high-L orbits -> $^{31}$F good candidate ? *(S. Grévy)*

Are there narrow resonances around $S_{4n}$ -> 4n clustering ?

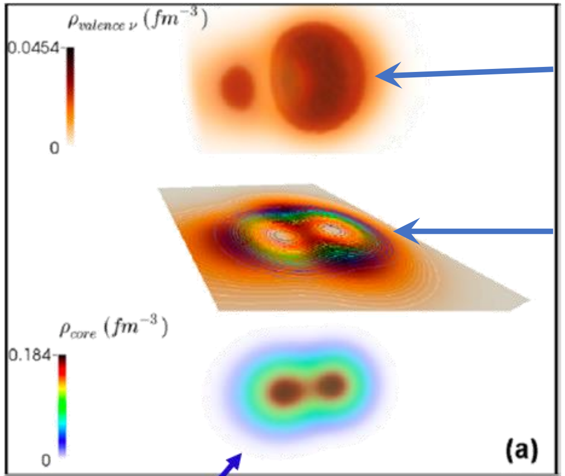
How would 4n correlations contribute to nuclear superfluidity ? *(O.S, P. Ujic)*

# Evolution of nuclear a clustering in neutron-rich nuclei

**$^{10}$Be**




**$^{14}$Be**




π molecular configuration

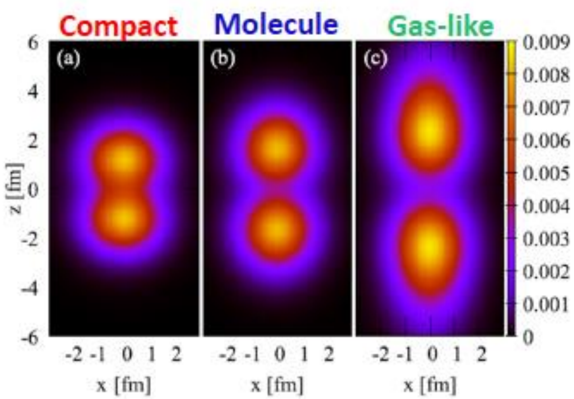
Neutron spatial Distribution (halo)

σ molecular configuration

*J. P. Ebran PRC 90 (2014)*

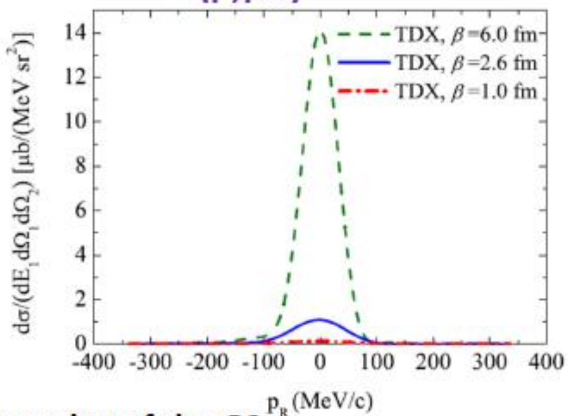
**Density of α+α core**

**$^{10}$Be GS wave function**




DWIA calc.

**$^{10}$Be(p,pα) cross-section**



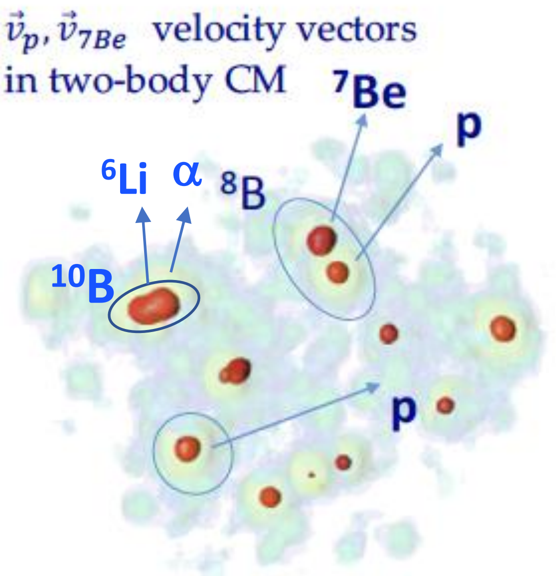

**High sensitivity of X-sect to the extent of clustering of the GS**

*M.Lyu et al., PRC 97 (2018)*

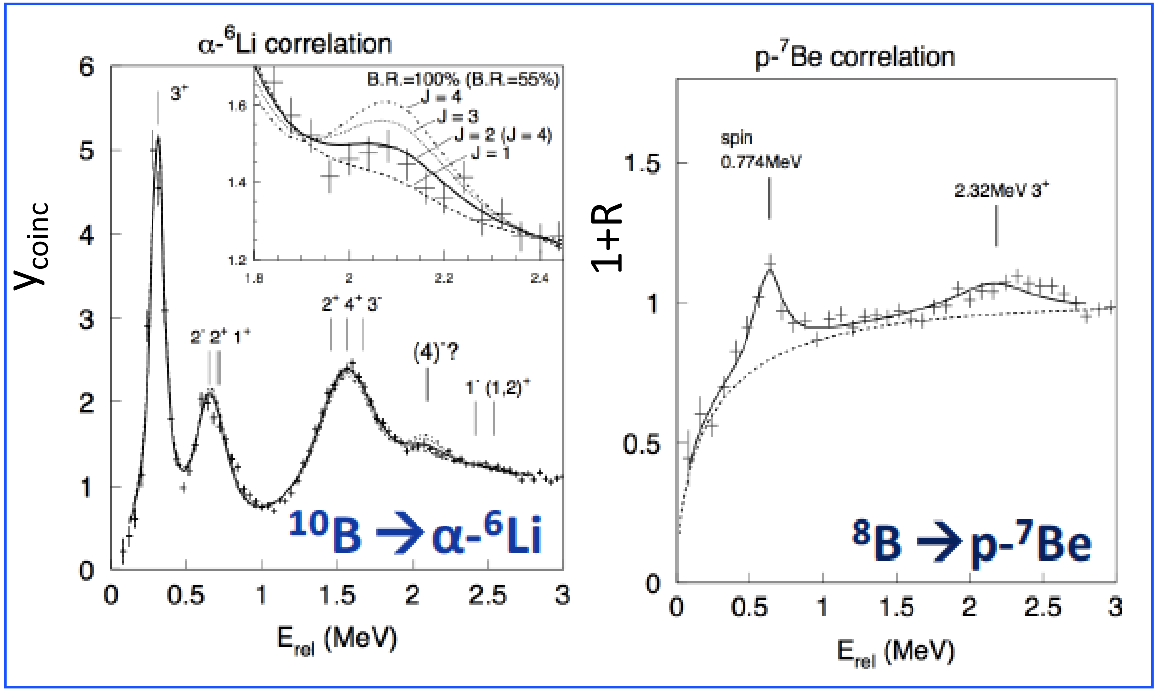
$^{10,12,14}$Be (pp,α) at 250 MeV/A *(D. Beaumel)* RIKEN

Cluster in neutron-rich C isotopes planned to be studied as well in the future.

# In-medium cluster formation and resonance decay spectroscopy




Particle emitting sources extended in phase-space




Determine the $Y_{coinc}$ and $1+R(q_{rel})$ in different reactions with FAZIA

**Coincidence yields**

$$Y_{coinc}(a,b)$$

→ Temperature, branching ratios

**Correlation function**

$$1 + R(q_{rel}) = \frac{Y_{coinc}(a,b)}{Y_{evt\ mixing}(a,b)}$$

→ Volume, Density, Spin

Modification of the widths of the resonances by the medium?

Analogy with K, Σ, Λ, Ξ resonance production in heavy collisions

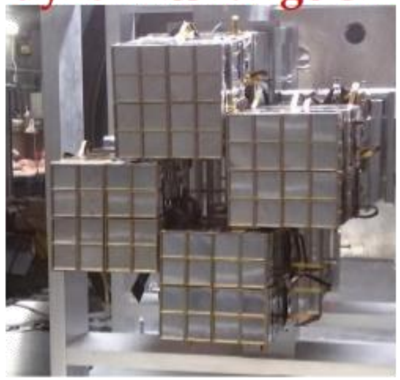
# Some preliminary Nα-X correlations

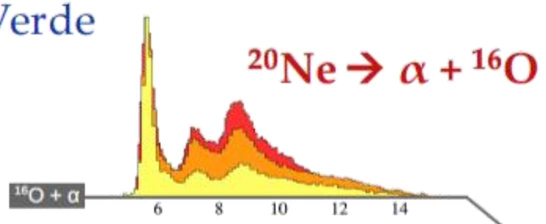
**FAZIACOR Exp @ LNS**

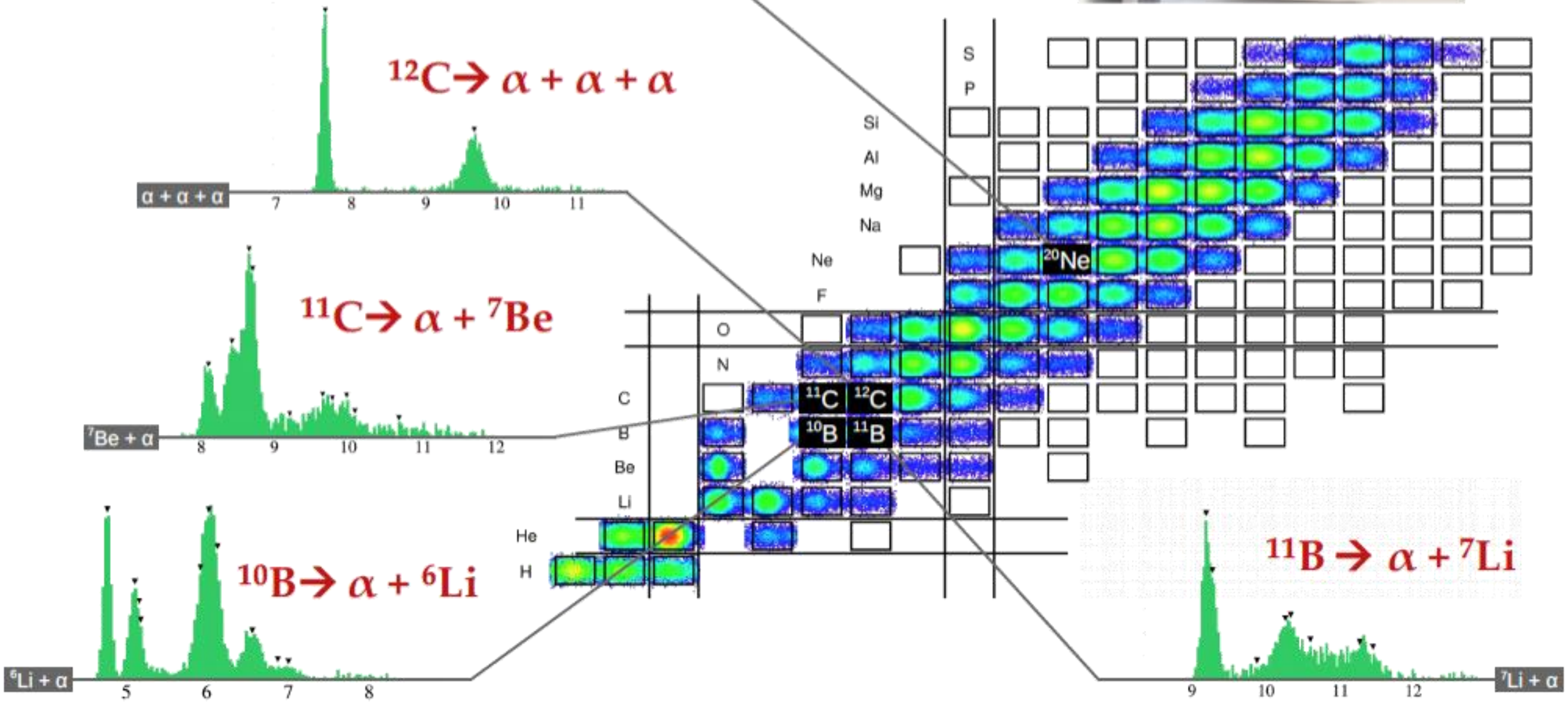
$^{20}$Ne+$^{12}$C, $^{32}$S+$^{12}$C E/A=25, 50 MeV

D. Gruyer, G. Verde

**Wide dynamics range of FEE**





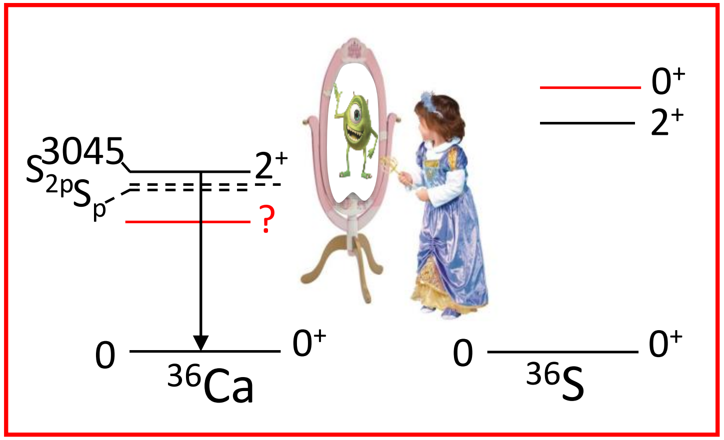




Study the profiles of resonances in different medium

FAZIA

# Study of broken mirror symmetries

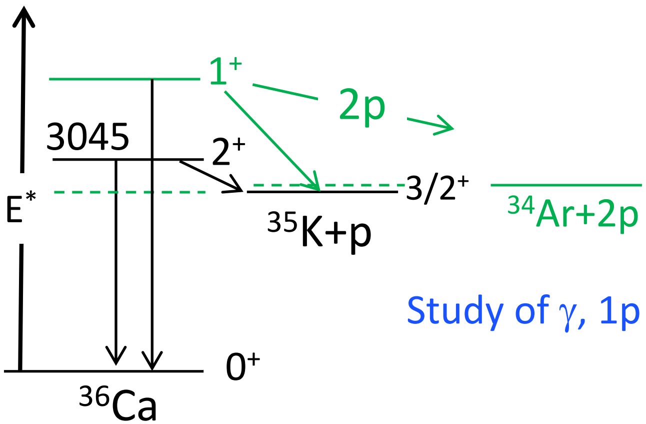
Massive shift of $0^+_2$ between A=36 mirror nuclei?
*Valiente Dobon et al. PRC 98, 011302(R) (2018)*



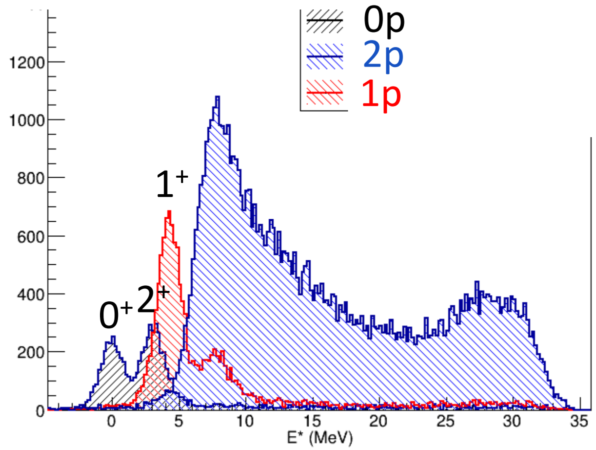

Preservation of the N=16 gap?

$^{37}$Ca(p,d) $^{36}$Ca and $^{38}$Ca(p,t) $^{36}$Ca
*(L. Lalanne PhD IPNO / GANIL)*

GANIL/MUST2




Study of γ, 1p and 2p decays




Change of reduced transition probabilities between mirror nuclei (e.g. B(E2))?

How does the 2p decay proceeds?

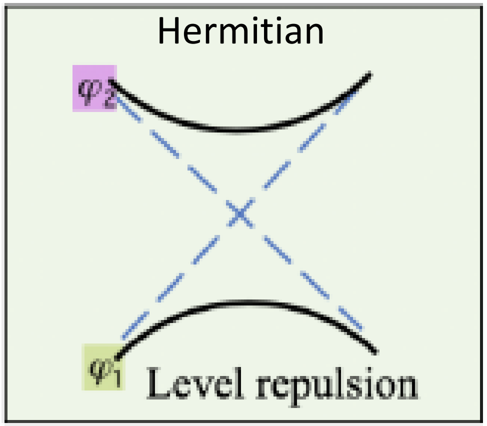
Change from spherical to deformed structures between mirror nuclei?

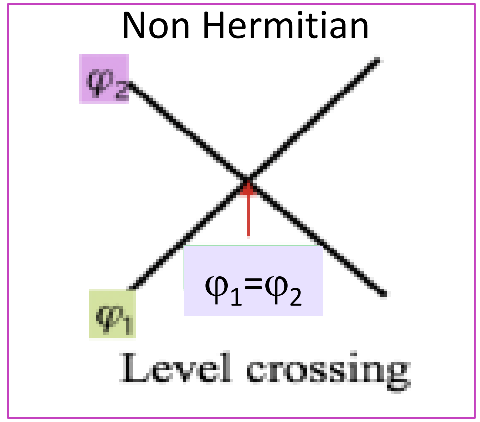
*Possible continuation of experimental program* GANIL

*Accepted experiments (A. Gillibet, A. Corsi)* RIKEN

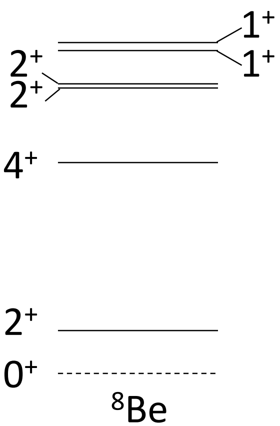
# Search for exceptional points in the continuum

Consequences of these exceptional points on the decay pattern of neighboring states?
*(M. Ploszajczak)*



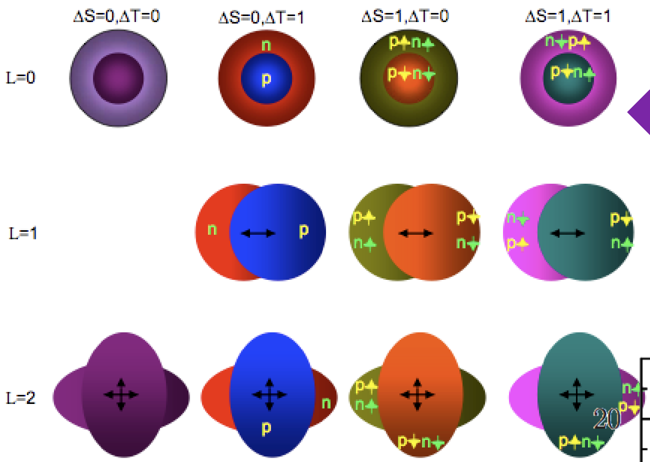




Microwave cavities



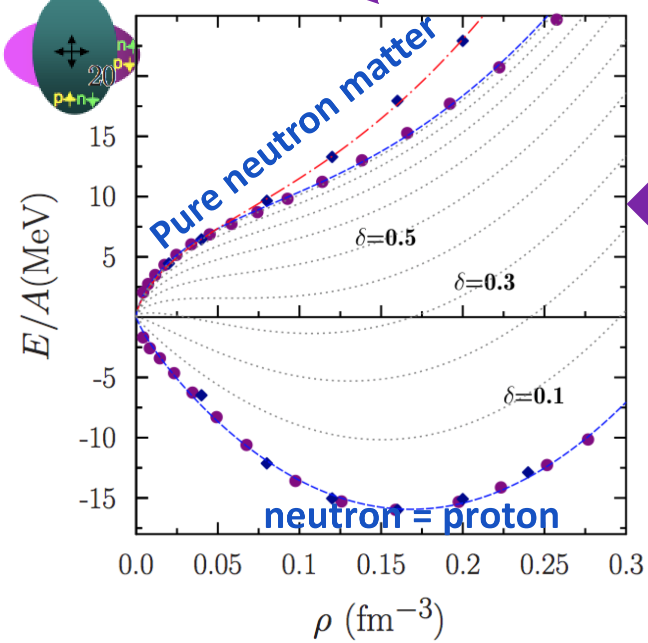

In $^8$Be two $2^+$ states lie at very close energy and can attract a large fraction of the $\gamma$ strength and influence significantly the decay of the $1^+$ state to the $0^+$ ground state.

# Measurements and calculations of nuclear excitation spectra

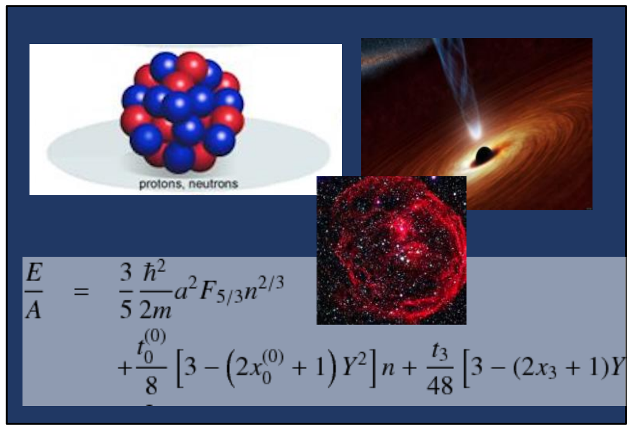



may constrain

i.e. excitation modes are sensitive to properties of the equation of state of infinite matter




constrains/guides to construct

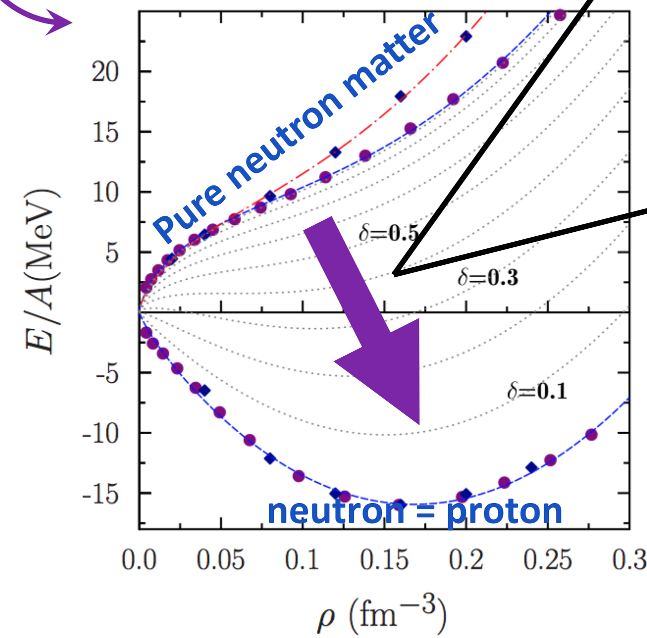


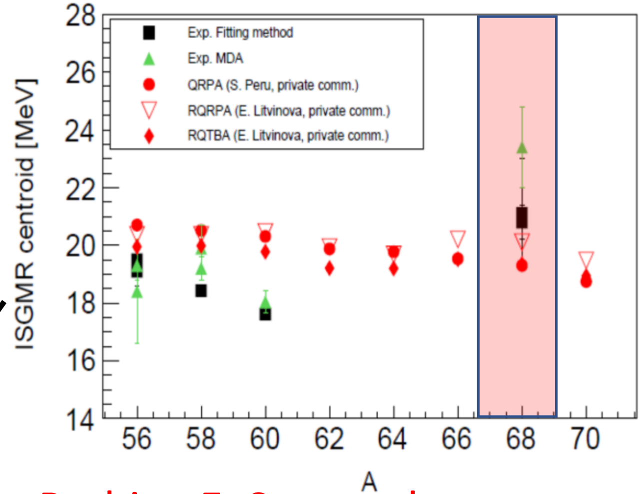
# Measurements and calculations of nuclear excitation spectra

Giant Monopole Resonance: $E_{GMR} \sim \sqrt{K_A}$

$$K_A \equiv K_V + K_S A^{-1/3} + K_\tau I^2 + K_C \frac{Z^2}{A^{4/3}}$$

$$\lim_{A \to \infty} K_A$$

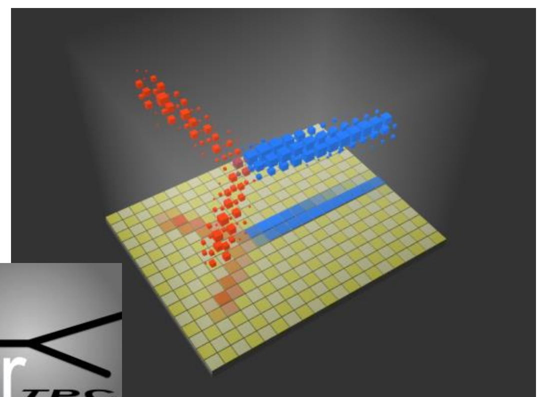



Probing EoS towards neutron rich: unexpected result

*M. Vandebrouck et al., Phys. Rev. Lett. 113, 032504 (2014)*

Better $\theta = 0^\circ$ resolution



actar TPC

# Measurements and calculations of nuclear excitation spectra

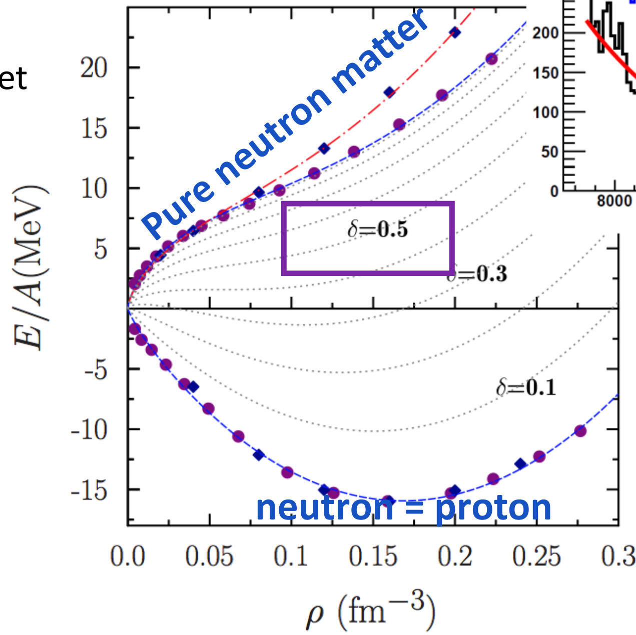
***PRL 102, 2009: Wieland et al.***
- Ni68@600 MeV/nucl, Coulex on Au
- EWSR = 5.0(15)%;
- $E_{PDR}$ = 11.0(5) MeV;
- B(E1)=1.2 e2fm2;

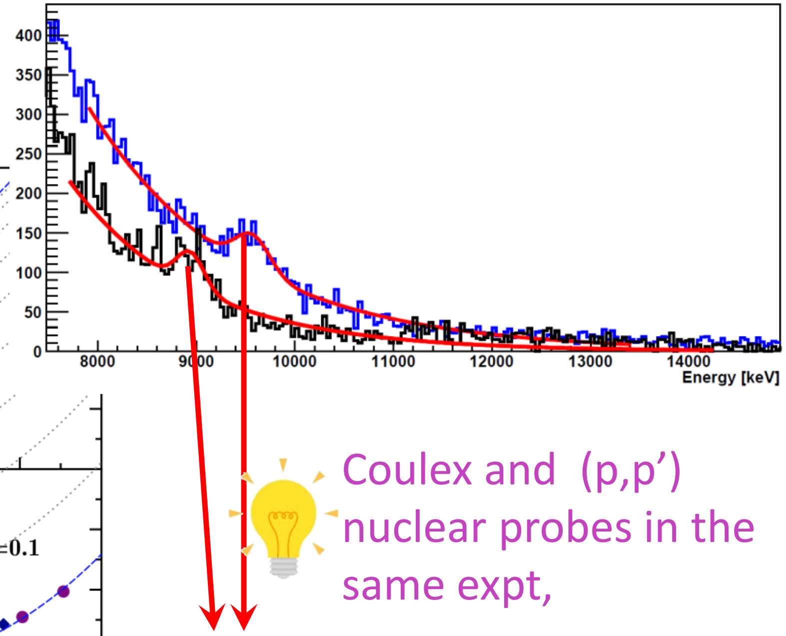
***PRL 111, 2013: Rossi et al.***
- Ni68@502.7 MeV/u, Coulex on Pb
- EWSR = 2.8(5)%;
- $E_{PDR}$ = 9.55(17) MeV;

***PLB782, 2018: Martorana***
- Ni68@30 MeV/nucl on Carbon target
- EWSR = 9(2) %;
- $E_{PDR}$ ~10 MeV;
- $\sigma_{PDR}$ = 0.32 mb with 18% stat error

Pigmy dipole resonnance, probe dependant ?

GANIL Experiment (E611)



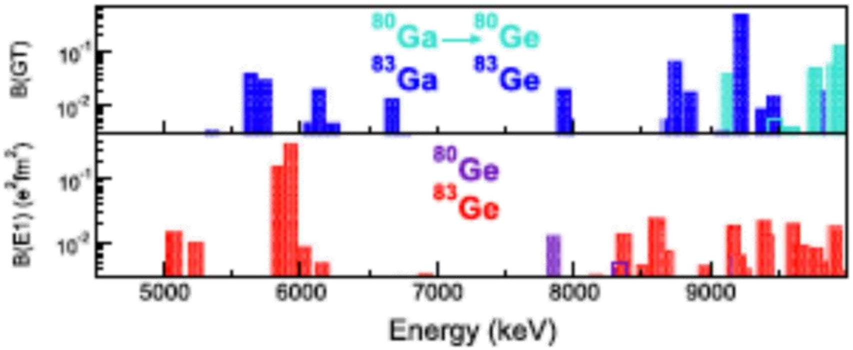

Coulex and (p,p') nuclear probes in the same expt,

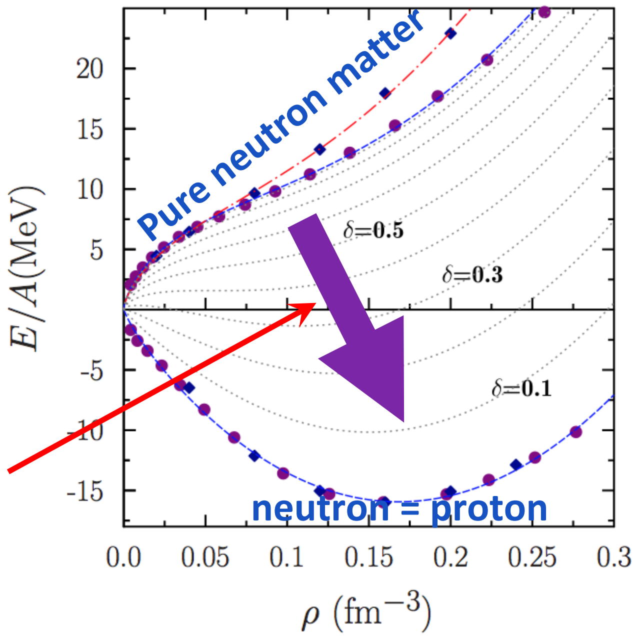
(γ,γ'):
$E_{PDR}$ = 9.40(27) MeV
$\sigma_{PDR}$= 26(4) mb
(C,C'), (p,p'):
$E_{PDR}$ = 10.00(25) MeV
$\sigma_{PDR}$(p,p')= 7.1(15) mb

# Measurements and calculations of nuclear excitation spectra

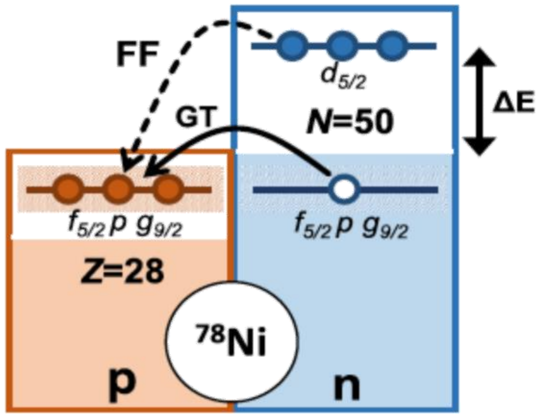
Collective mode populated through beta decay

Few experimental hints available




- High-energy γ transition from beta-decay observed
- Hints of beta-decay feeding pygmy mode



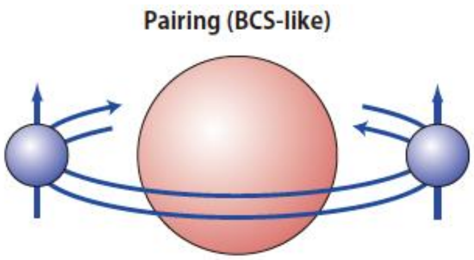

Studying collective modes in exotic nuclei is a challenge

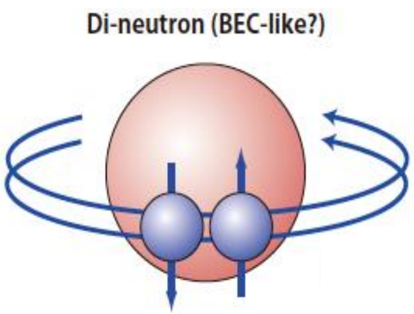
Propose to use beta-decay to populate pygmy resonances in exotic nuclei (In -> Sn)

*A. Gottardo et al., PLB772 (2017)*
*M. Madurga et al., PRL117 (2016)*

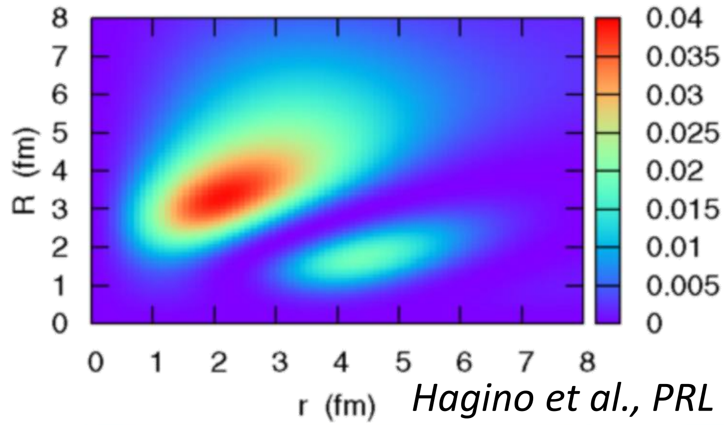
# Probing the structure of Borromean halo nuclei

Where the neutrons are likely to be ?



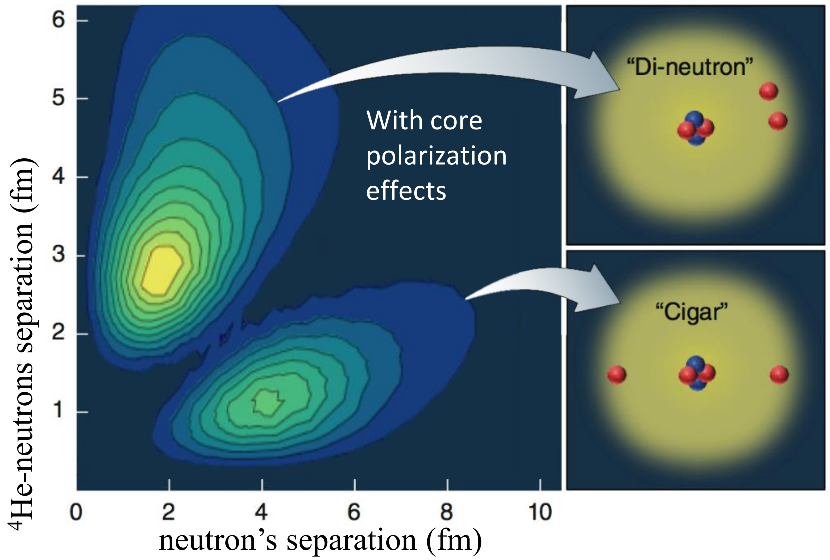




$^{11}Li$




*Hagino et al., PRL 99 (2007)*

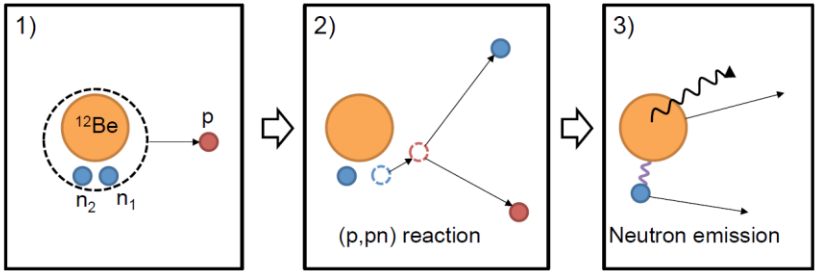
$^{6}He$

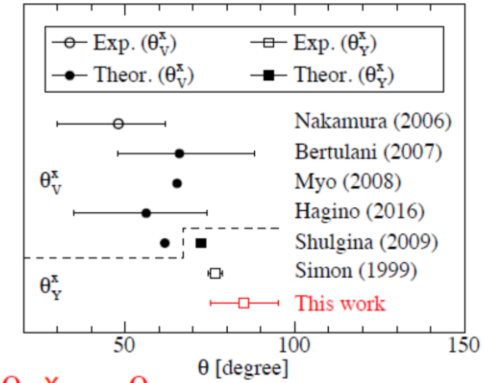



*Romero-Redondo et al., PRL 117 (2016)*

# Probing the structure of Borromean halo nuclei

## QFS on Hydrogen target at high momentum transfer (minimize FSI)



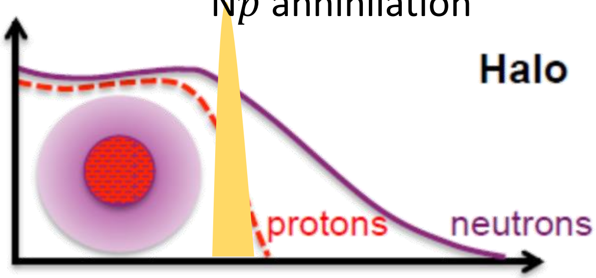



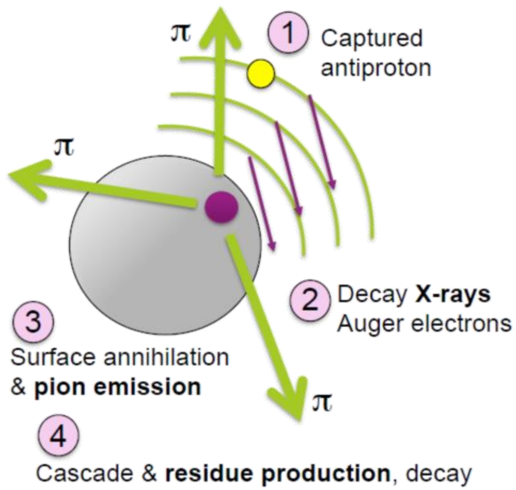

$\theta_Y^x = \pi - \theta_Y$

Correlation weaker than prev. experiments

*A.Corsi et al, in preparation*

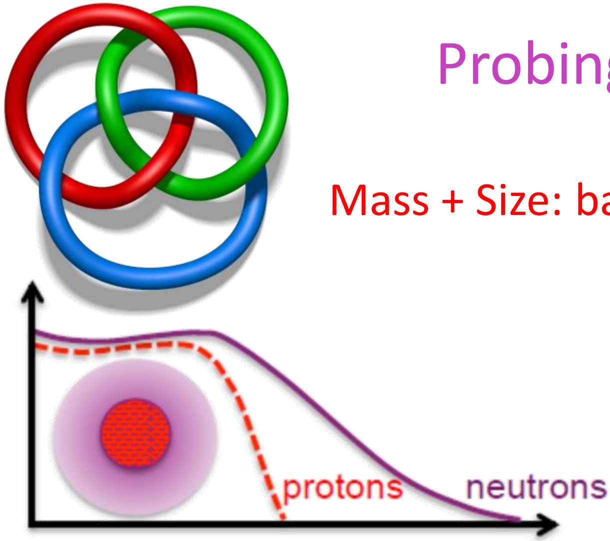
## Anti-proton annihilation to probe the nuclear surface




*A. Obertelli, ERC CoG 2016, TUD*

# Probing the size of neutron-rich nuclei



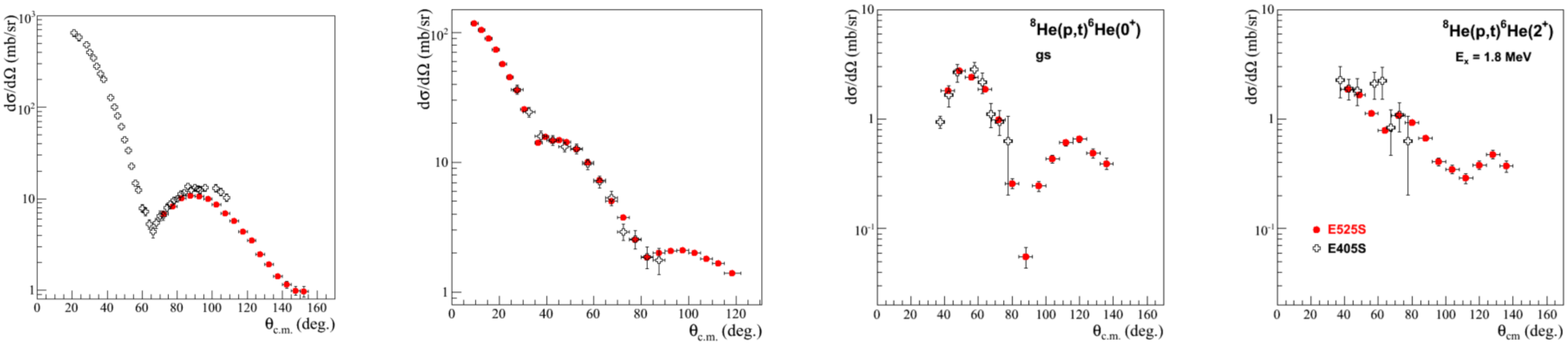

Mass + Size: basic understanding of an object

- (e,e): new machine for RI-electron collisions, yet challenging for low-Z nuclei
- Neutron-rich RI beams + (p,p) scattering = $\rho_m$
- If (e,e) and (p,p) = $\rho_p$ and $\rho_m$ then $\rho_n$

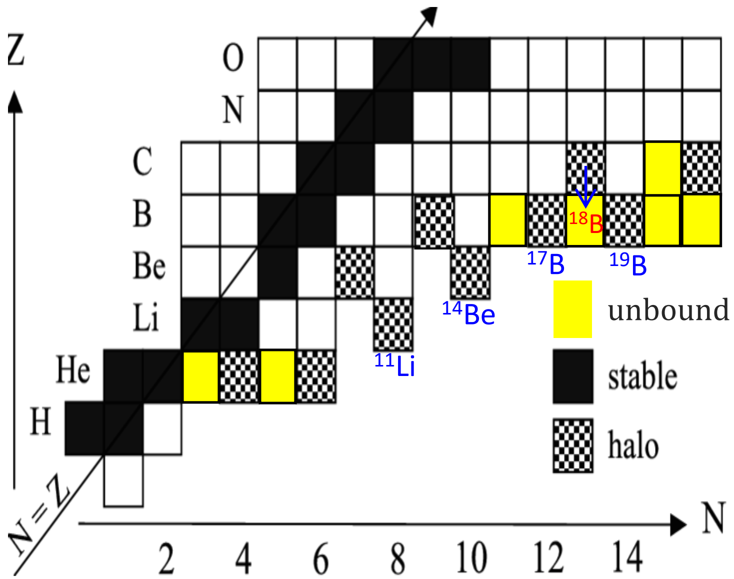
Model depend: NEED microscopic optical model potential analysis to extract nuclear matter densities

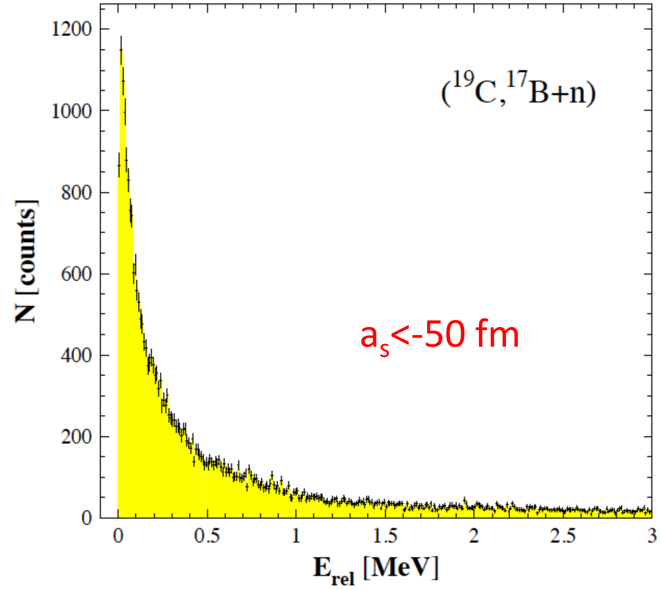
Complete parametrization of OMP using various reaction channel

15.4 A.MeV E525S MUST2 data PLB **718**, 441 (2012)



# Exotic decay of Borromean systems: the $^{19}B$ case

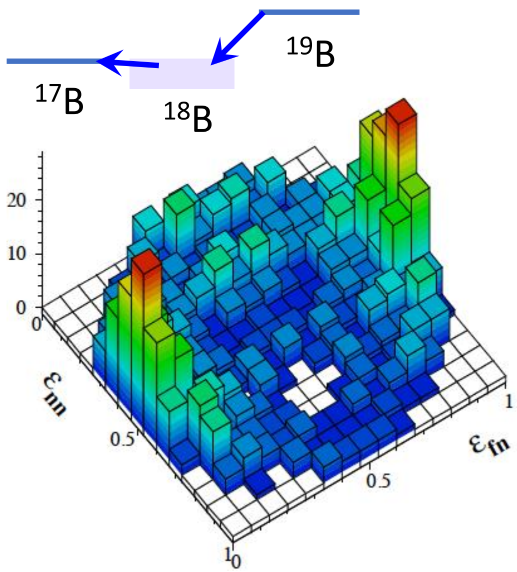


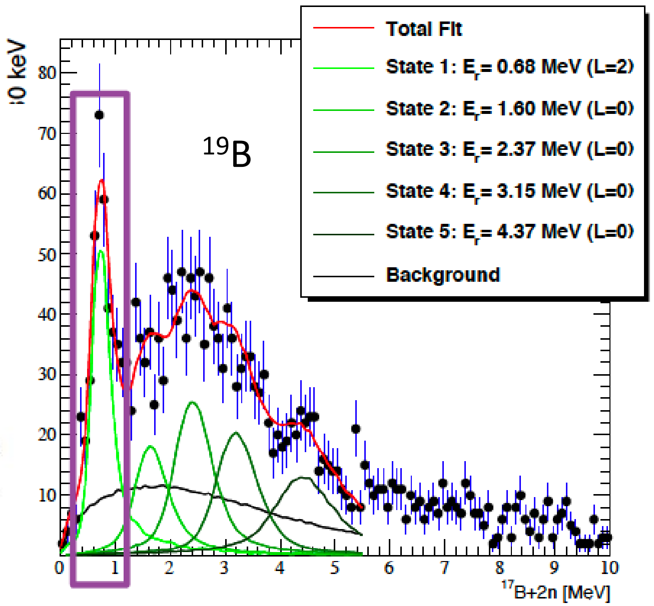




Sequential decay of $^{19}B$
through the virtual state in $^{18}B$

*J. Gibelin, M. Marques et al.* *RIKEN*

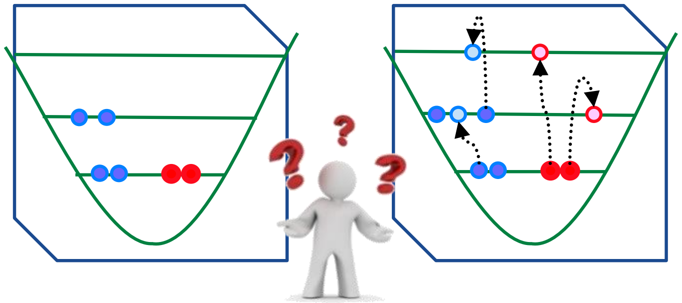
Other systems, e.g. $^{16}Be$ decay
*B. Monteagudo, M. Marques*

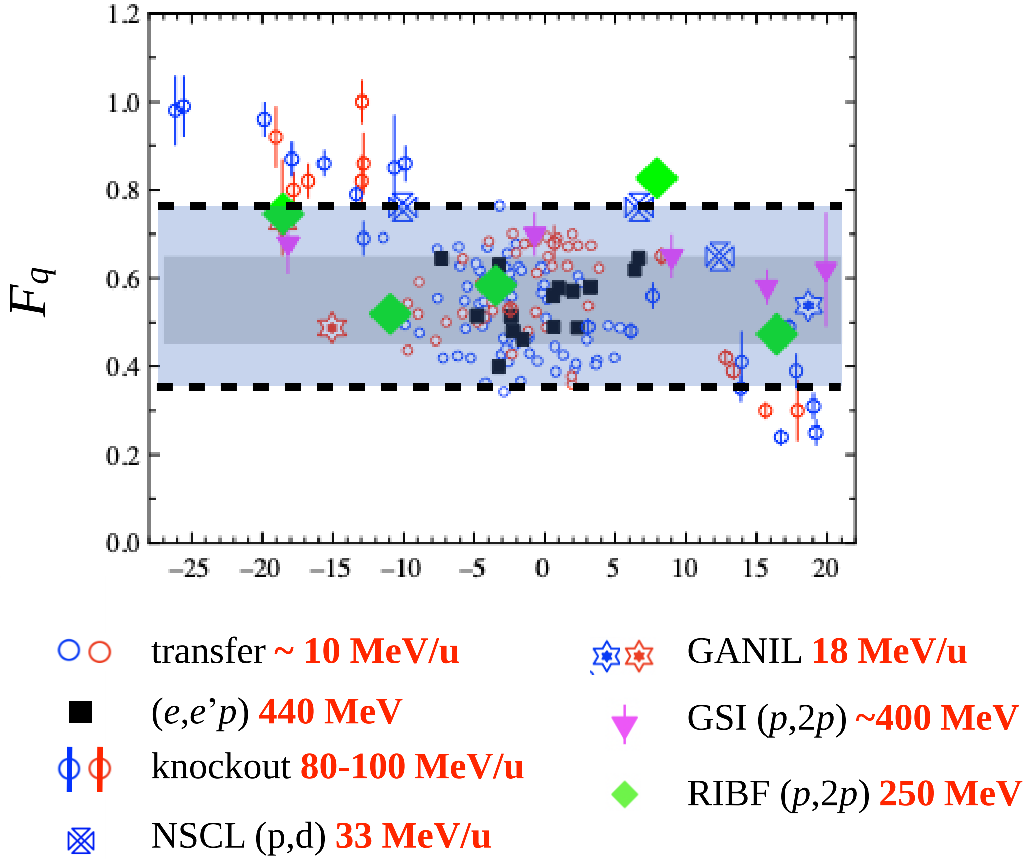


# (n,p,d,t,α…)Spectroscopic factors

Natural orbital feeling… more complicated debate






- Inconsistency between knockout and any other reaction mechanism more or less understood
- Small slope along N/Z

*S. Kawase et al., PTEP2018, 021D01 (2018)*

# SUMMARY - PERSPECTIVES

French community has a  strong visibility and leadership in many experimental programs
*(high impact in publications, many spokespersons, training several PhD students)*

Experiments carried out at different facilities, e.g. GANIL/LISE, RIKEN/SAMURAI and GSI/R3B

Make use of state-of-the-art instrumentations, e.g. MUST2, ACTAR-TPC, neutron walls...

Mostly physics group of modest size who know each other's work and often collaborate
-> GDR can serve to strengthen links between these groups & encourage newcomers

Physics of the continuum at the interface of nuclear structure, nuclear reaction, and physics of open quantum systems, with  many synergies with other disciplines
-> It is worth to exploit this synergy e.g. communicate more, meetings / theory in common?

A few theoreticians work in good and close connection with experimentalists
Some pioneers of the field are close to retirement
Clear lack of manpower and absence of long-term visibility
-> The GDR can express needs & recommendations
-> The GDR can encourage new collaborative projects between theory and experiments
-> 1-day meetings with limited participants to exchange ideas on given topics
-> Benefit from mutual expertise in a new field, emergence of new ideas