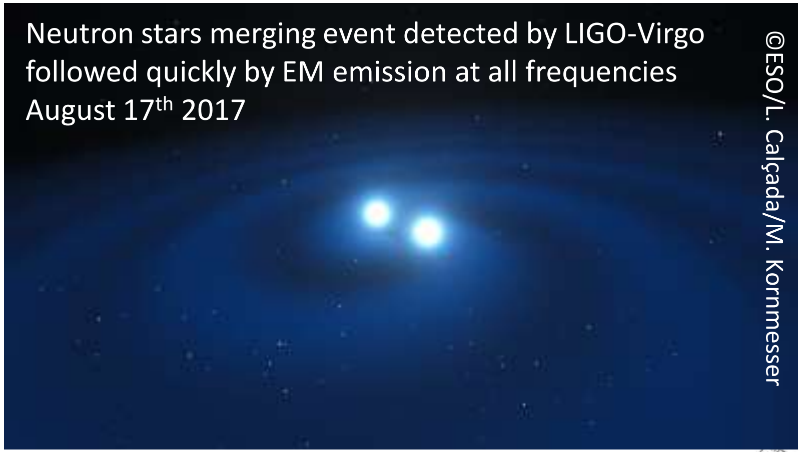
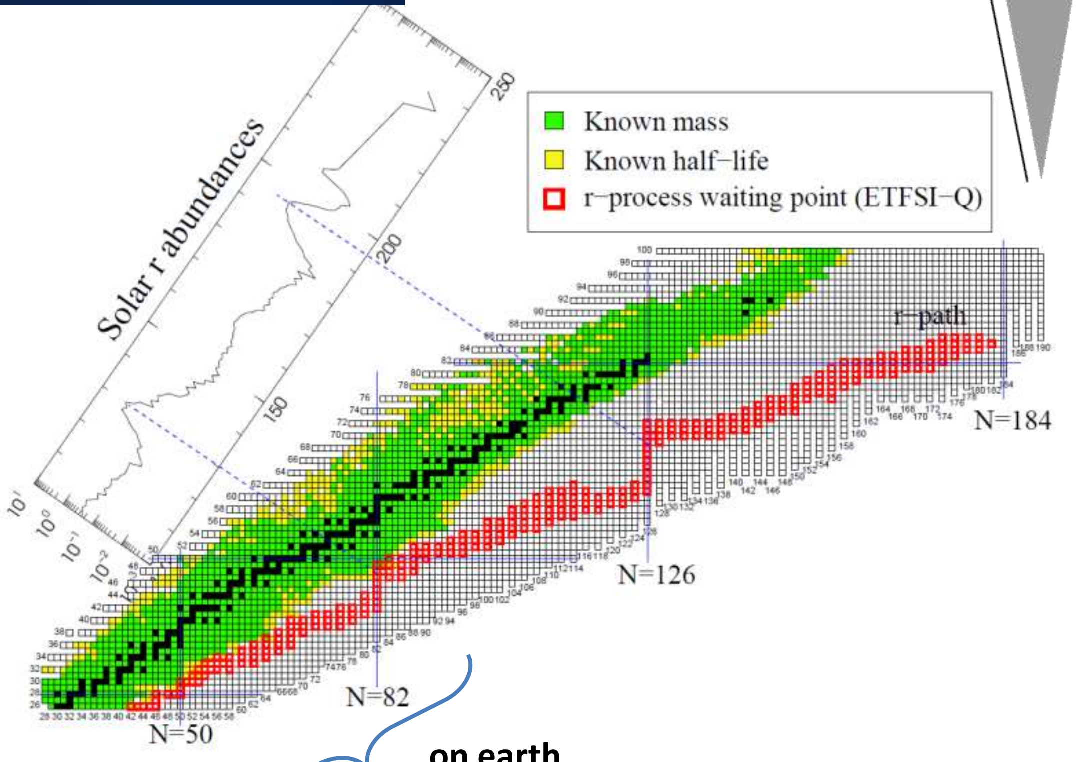
Spectroscopy investigation of the ^{78}Ni region: Potential avenues for a joint effort within EURISOL-DF

David Verney, IPN Orsay

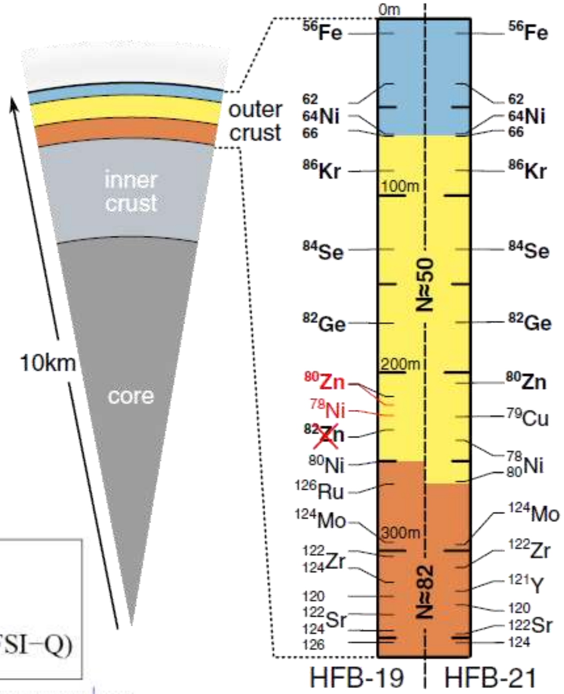
- Physics motivations: the N=50 shell effect/evolution towards ^{78}Ni
- What did we learn ?
- Special role of ISOL-based results
- What remains to be done ?
- Towards a “distributed” venture ?

SO magic numbers in nature





on earth
fission of actinides



Wolf et al. PRL 110 (2013)

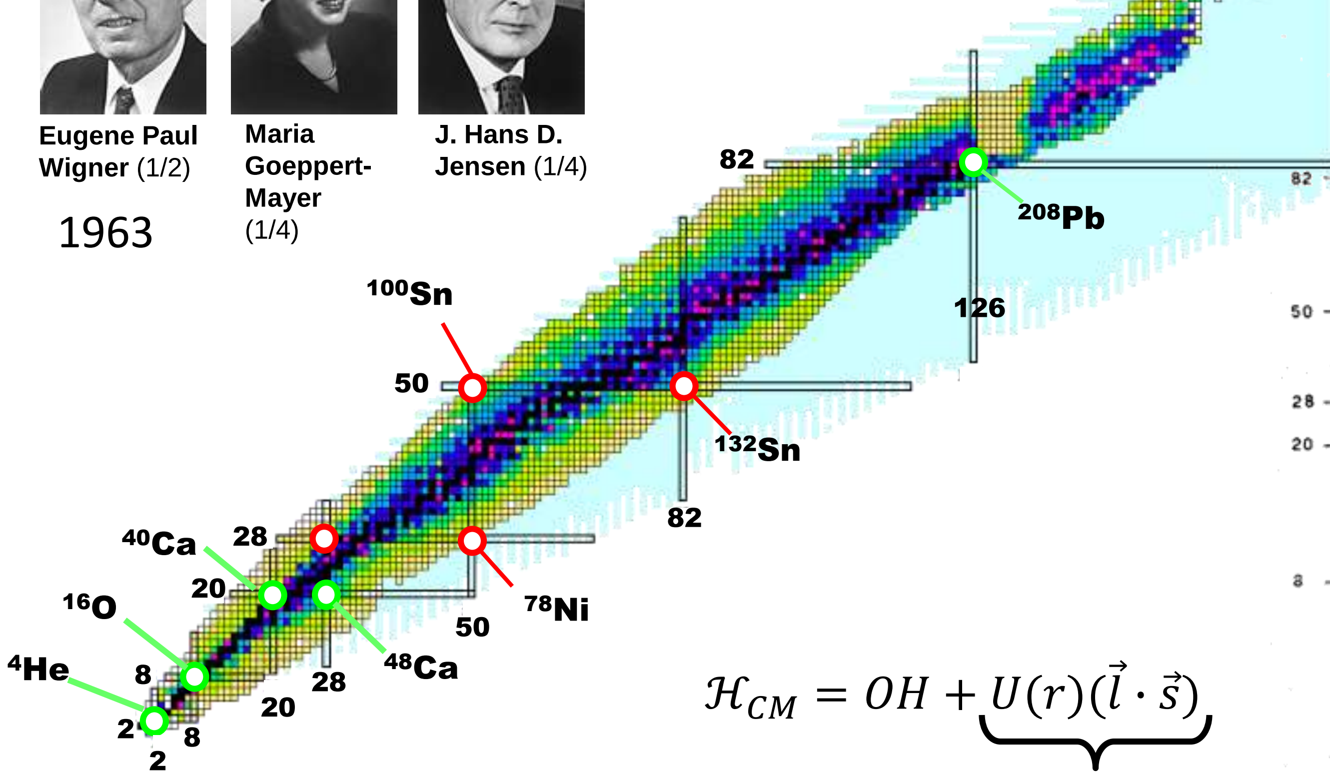
SO magic numbers in historical nuclear physics

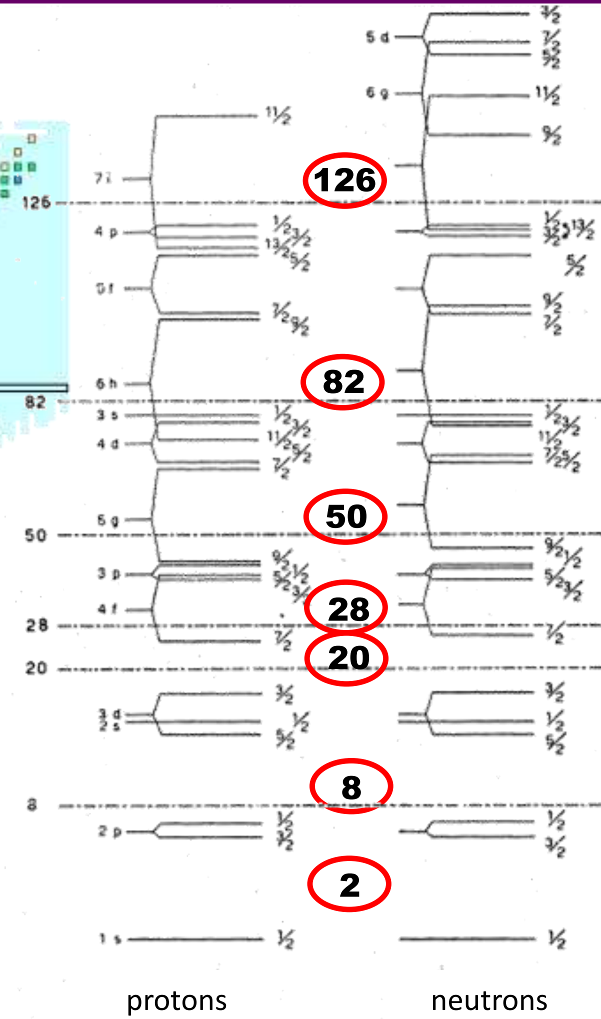
Eugene Paul Wigner (1/2)

Maria Goeppert-Mayer (1/4)

J. Hans D. Jensen (1/4)

1963

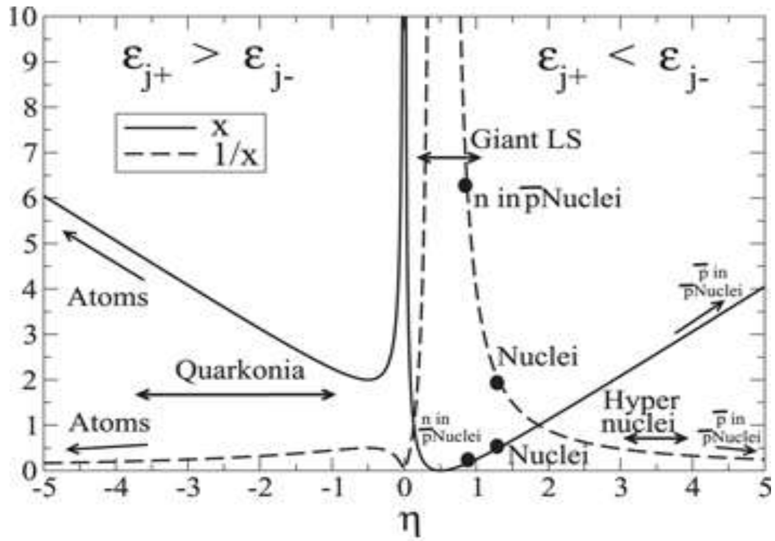




$$\mathcal{H}_{CM} = OH + \underbrace{U(r)(\vec{l}\cdot\vec{s})}_{V^{LS}}$$

the great surprise: $x \equiv \frac{\hbar\omega_0}{|\Delta\langle V^{SL}\rangle|} \approx 1$

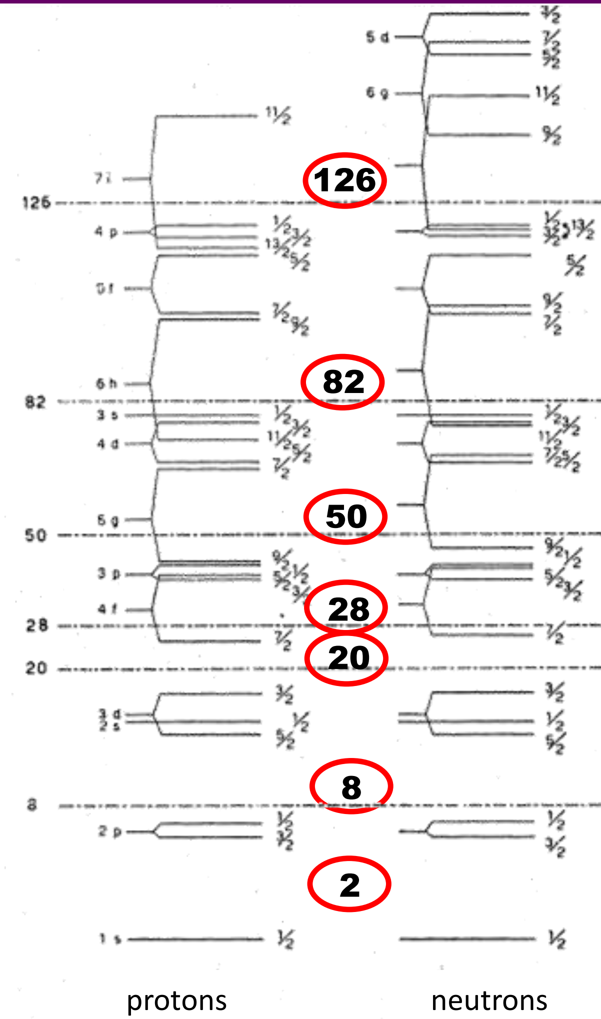
spin-orbit : universal effect for quantum systems made of particles having spin : atoms, nuclei, hyper-nuclei, quarkonia…
important role in condensed matter : cold atoms, spintronics, topological insulators...



J-P Ebran et al 2016 J. Phys. G: Nucl. Part. Phys. 43 085101

$$\eta \equiv \frac{m}{V-S}$$

$$x \equiv \frac{\hbar\omega_0}{|\Delta\langle V^{SL}\rangle|}$$



Dirac equation gouverning the single particle motion dynamics →

$$V^{LS} = \frac{1}{2M^2(r)}\frac{1}{r}\frac{d}{dr}(V(r)-S(r))\vec{l}\cdot\vec{s}$$

vector potential (short range repulsion) $\approx +350$ MeV

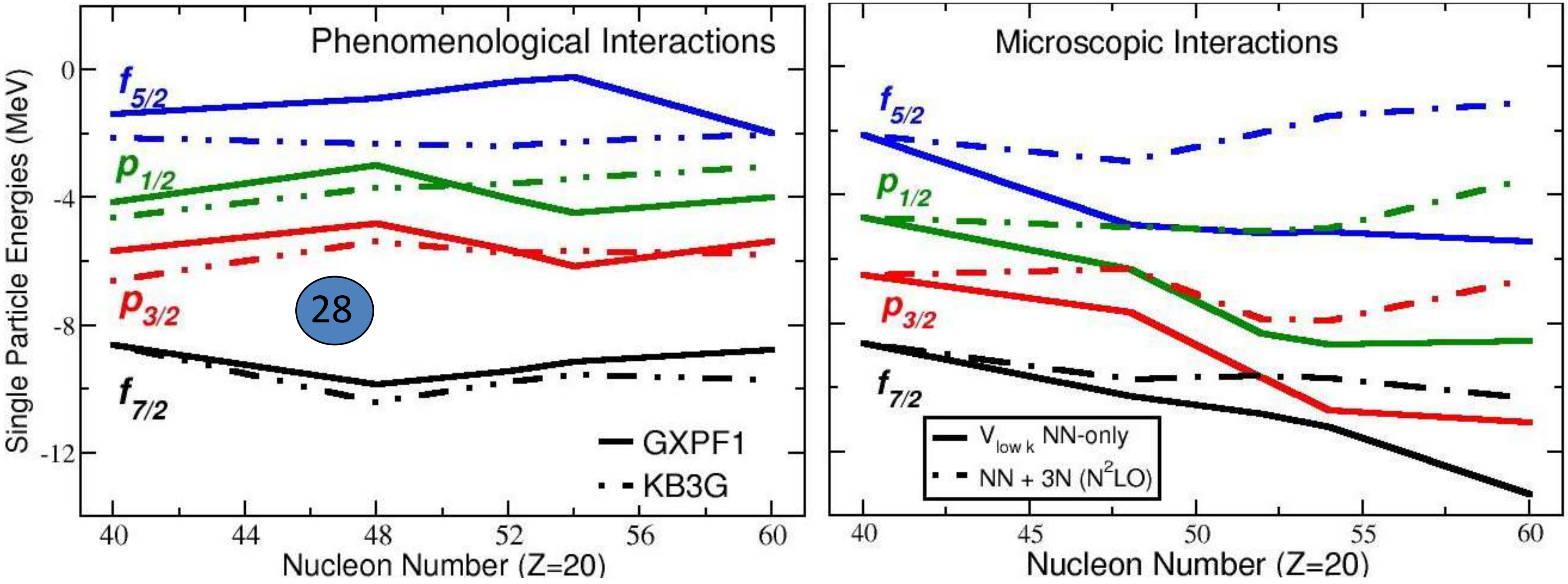
scalar potential (medium range attraction) ≈ -400 MeV

nucleon mass ≈ 940 MeV

in atomic system:

$$x \sim \frac{1}{\alpha^2} \approx 10^4$$

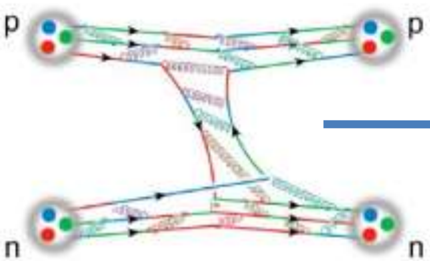
SO magic numbers : an emerging phenomenon



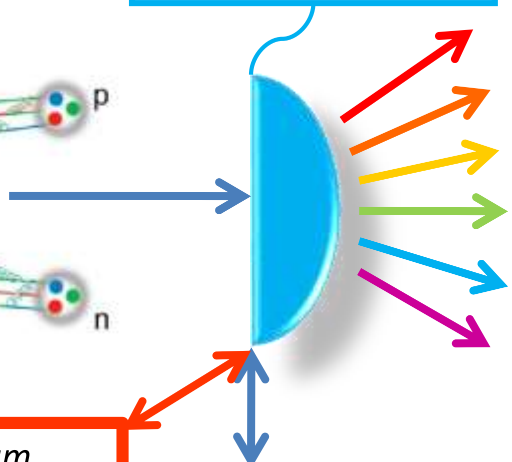
Holt, Otsuka, Schwenk, Suzuki

SO magic numbers : an emerging phenomenon

nucleon-nucleon interaction

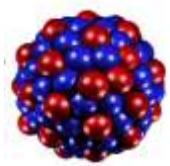


many body problem

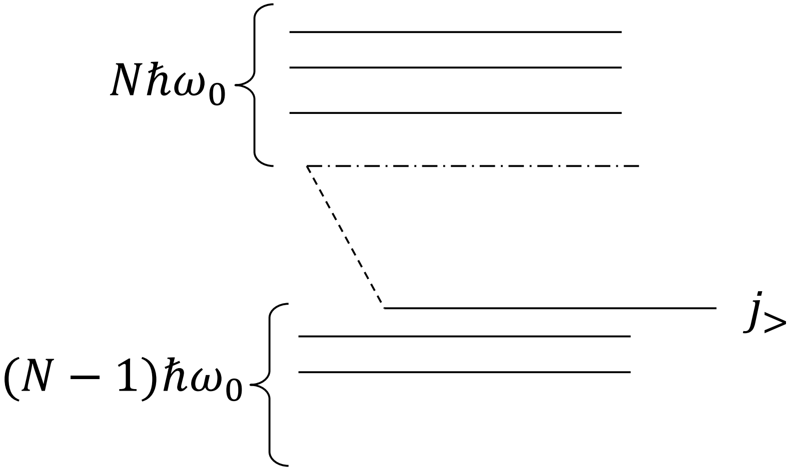


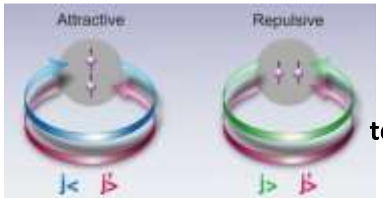
varying *in-medium conditions*
≡ explore exoticity

in medium

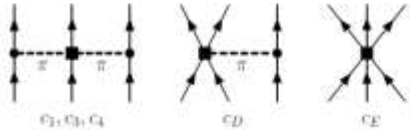


"effective" nuclear spin-orbit





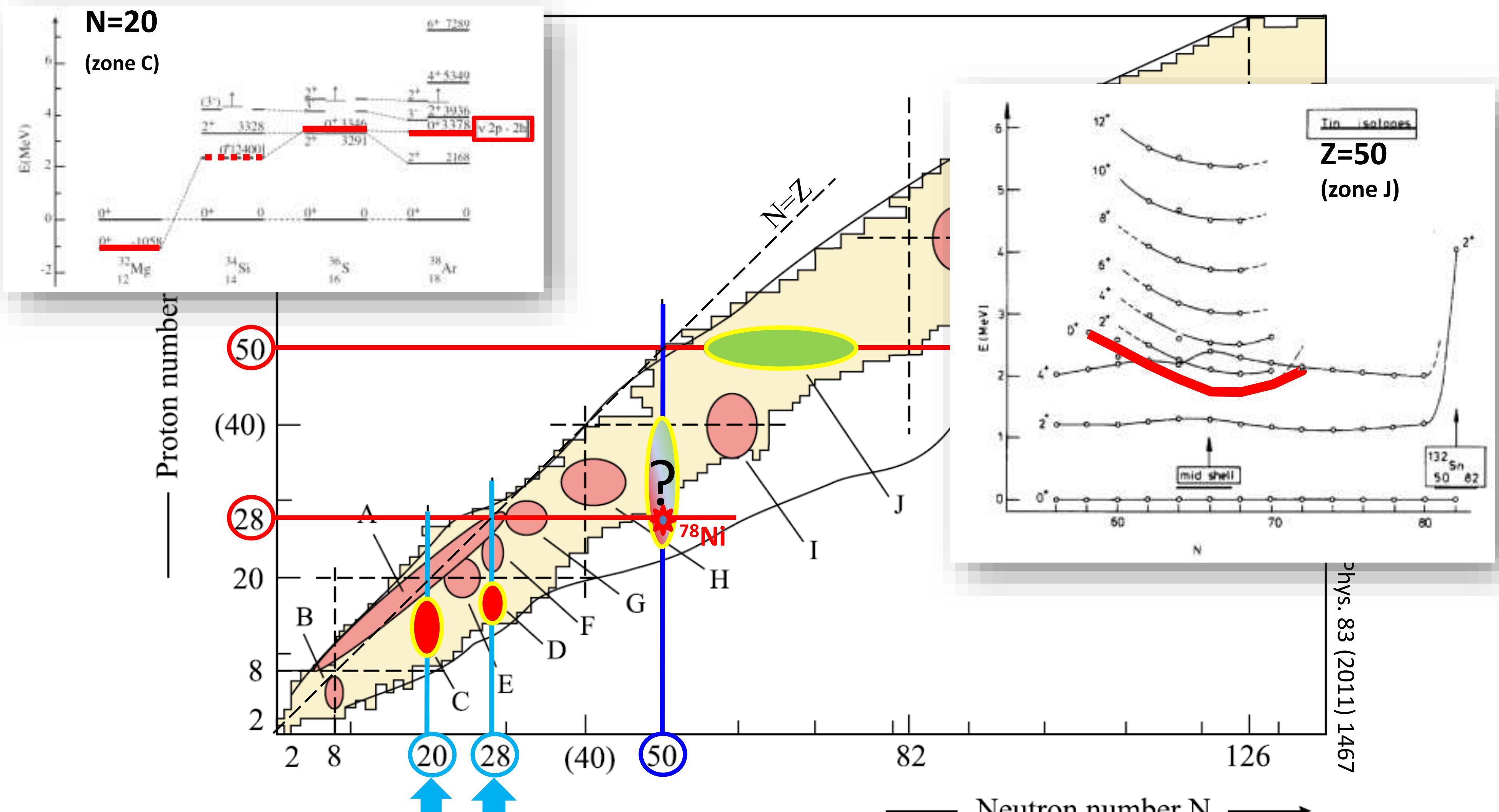
tensor



3-body

diffusivity, orbit size etc

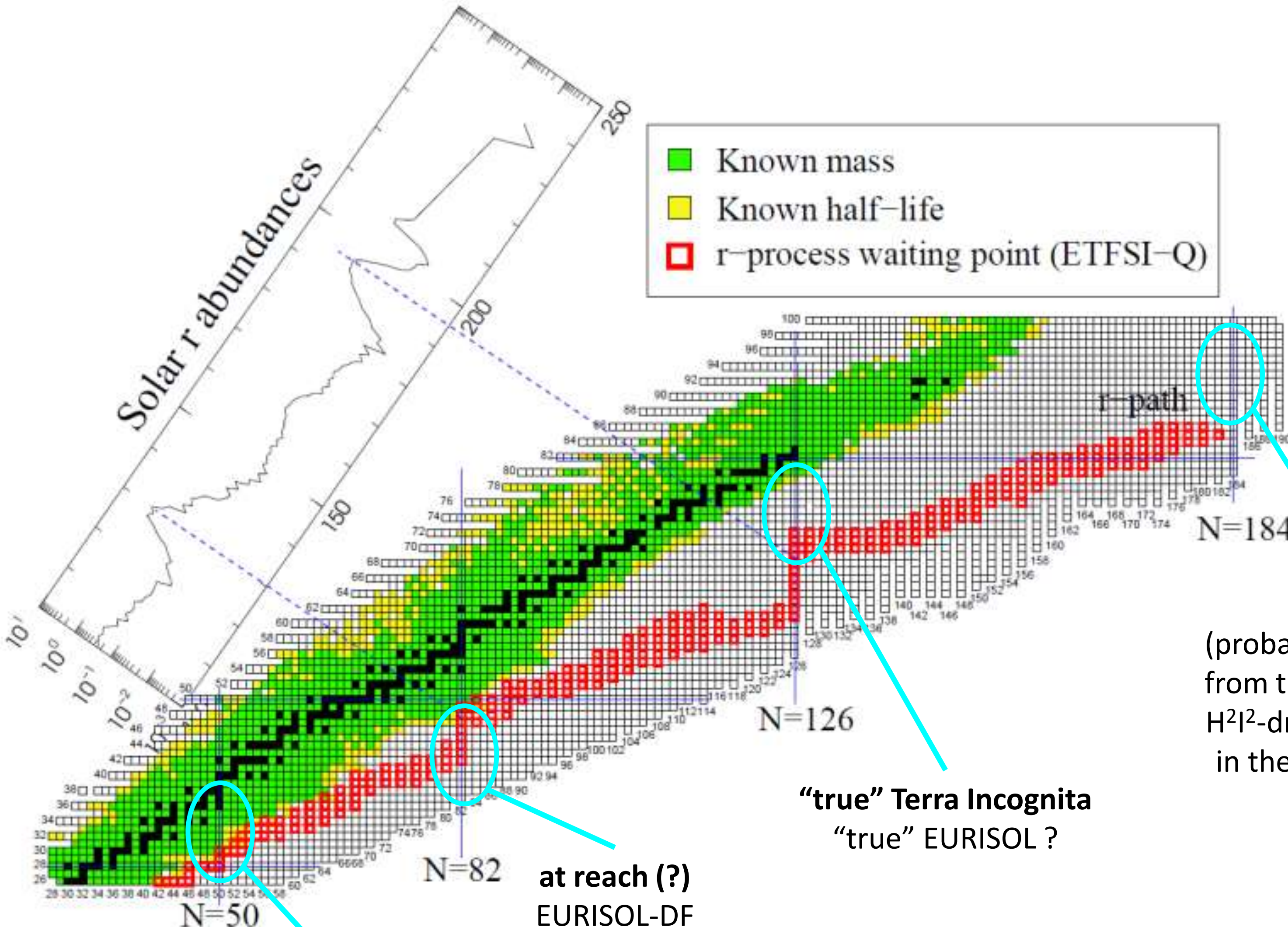
SO magic numbers from a shape-coexistence point of view



historical case N=20 (^{32}Mg region)
Klapisch PRL 31 118 (1973)
Thibault PRC 12 644 (1975)
Détraz PRC 19 164 (1979)

N=28 (^{42}Si region)
Bastin PRL 99 022503 (2007)
GANIL

SO magic numbers : a long-term roadmap (on earth)



at reach
EURISOL-DF

at reach (?)
EURISOL-DF

“true” Terra Incognita
“true” EURISOL ?

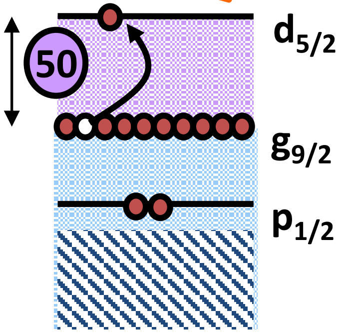
?????
(probably a lot to learn from the future unique H^2I^2-driven ISOL device in the world : S3-LEB)

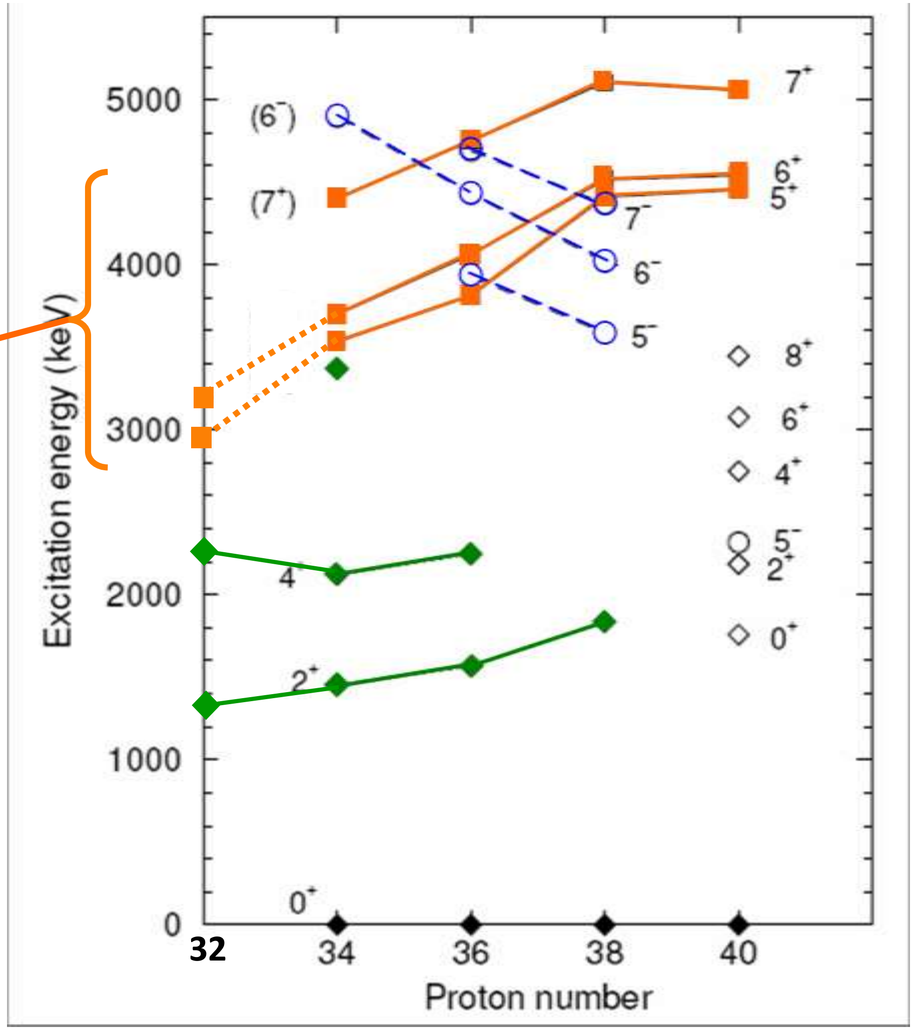
N=50 shell effect in the ^{78}Ni region : what we have learned

- gap size $\rightarrow$ Z=32 "singularity"
- shape coexistence
- neutron valence space above ^{78}Ni
- neutron threshold effects and the question of ff transitions in the ^{78}Ni region

Yrast spectroscopy

Zr: H.Fann et. al
Phys. Lett. B 44, 19 (1973)
Sr: P.C.Li et. al.
Nucl. Phys. A 462, 26 (1987)
Kr: G.Winter et. al.
Phys. Rev. C48, 1010 (1993)
Se: Prevost et. al.
Eur. Phys. J. A 22,391-395 (2004)
Ge: T.Rzaca-Urban et. al.
PRC 76, 027302 (2007)





some “shell quenching”

O. Sorlin, M.G. Porquet
Prog. Part. Nucl. Phys. 61 (2008) 602

N=50 gap extrapolation
→ ^{78}Ni =3.0(5) MeV

High-precision mass spectrometry (JYFLTRAP and ISOLTRAP)

Hakala et al PRL 101, 052502 (2008); S. Baruah et al PRL 101, 262501 (2008)

later on : up to ^{82}Zn ISOLTRAP [Wolf et al. PRL 110, 041101 (2013)]

$\Delta = S_{2n}(52) - S_{2n}(50)$

(Quantity usually used to extract shell gaps from mass data)

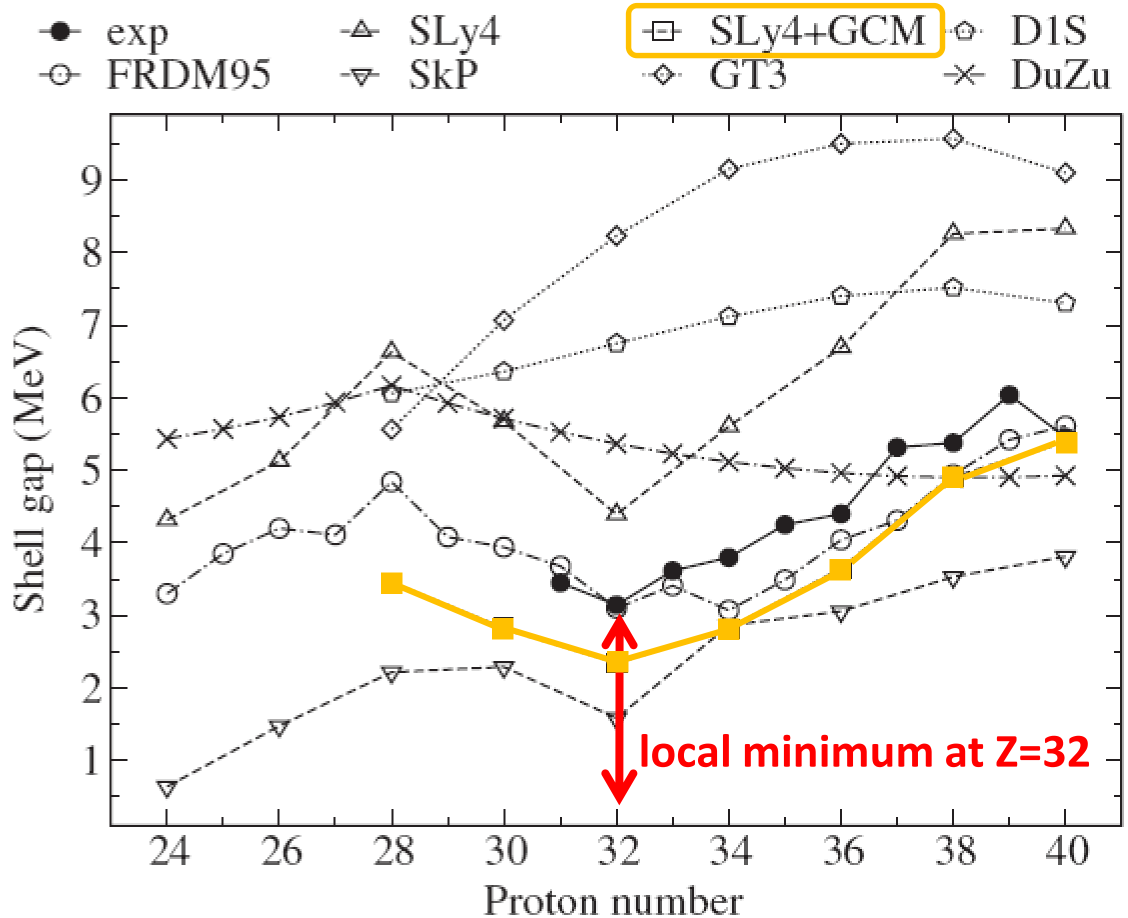
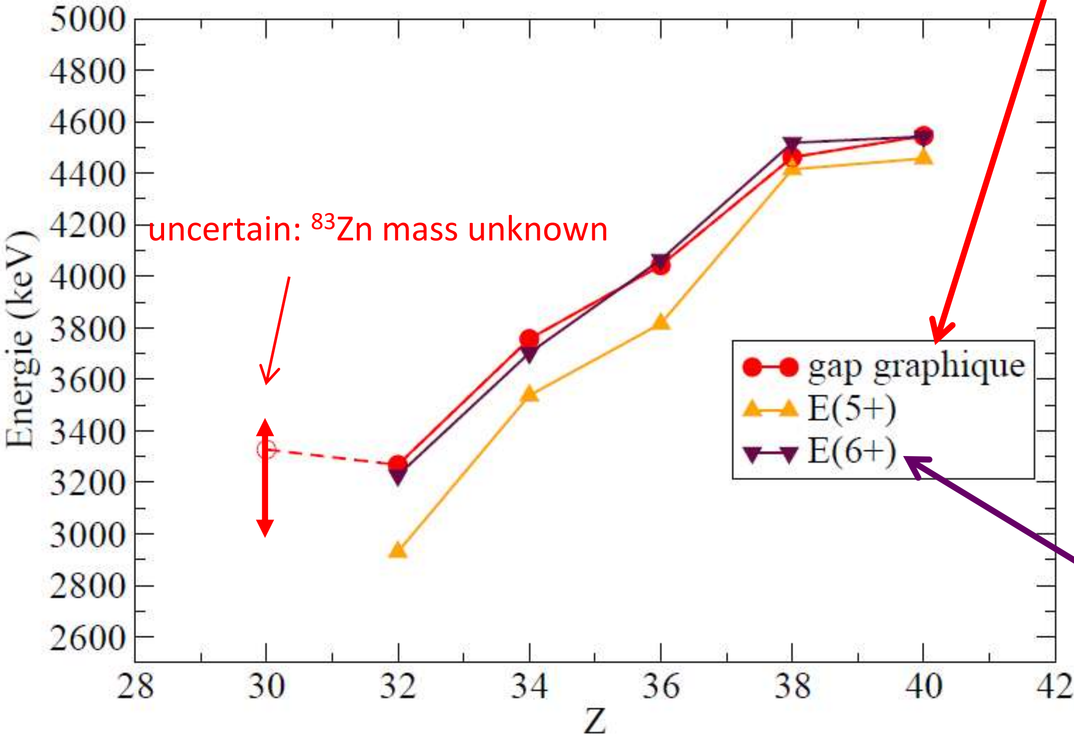
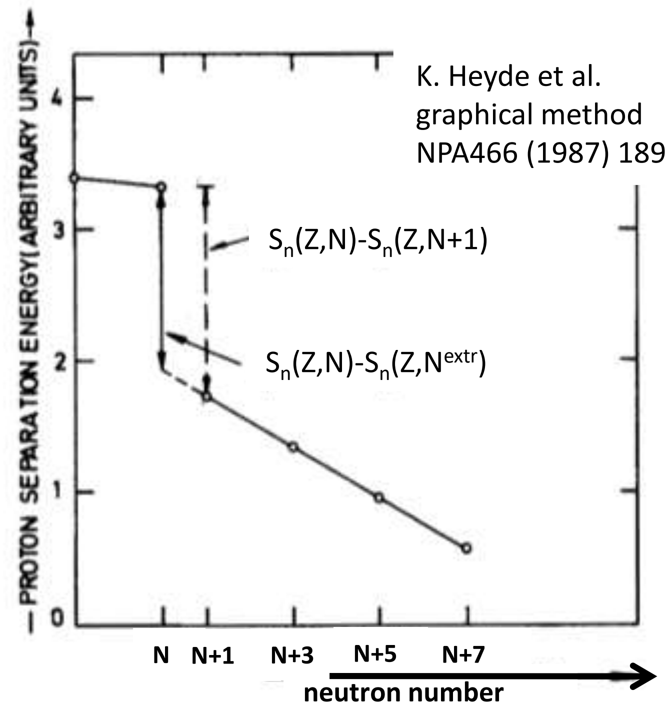


FIG. 4. Evolution of the $N = 50$ shell gap and comparison to theoretical models.

Striking similitude

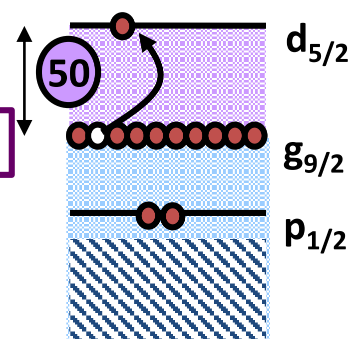
from mass measurement (after correction of upper shell effects)





K. Heyde et al. graphical method NPA466 (1987) 189

from γ-spectroscopy



neutrons

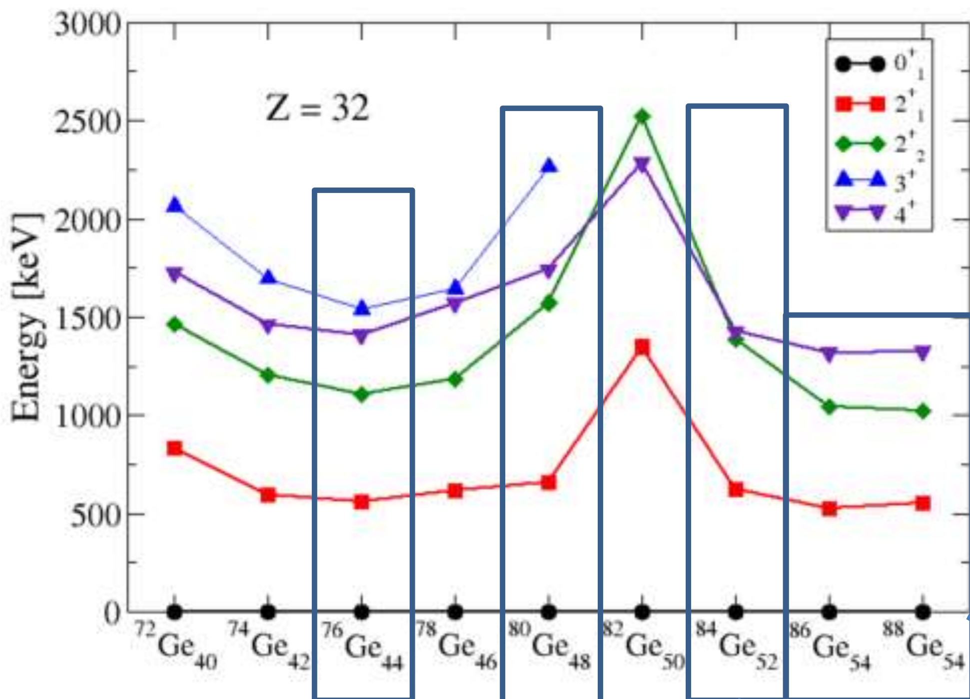
→ pure monopole effect ?

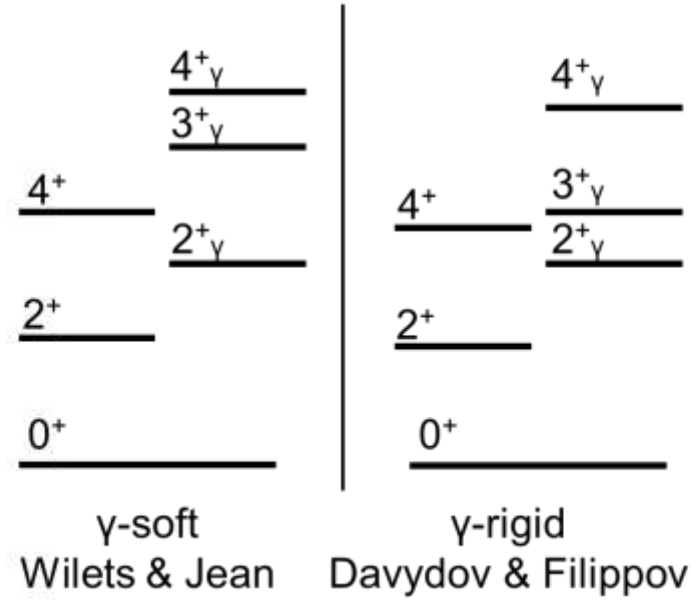
→ how to disentangle spherical mean field from correlation effects ?

→ what correlations ?

The Z=32 "singularity"

Z=32 : a triaxiality "corridor" ?





M. Lettman et al. PRC 96, 011301(R) (2017)

$E(4^+)/E(2^+)$ ratio + shell model

stable

Y. Toh et al. PRC 87, 041304(R) (2013)
(multistep-coulex)

S. Mukhopadhay et al. PRC 95, 014327 (2017)
(n,n'γ)

→ clearly triaxial

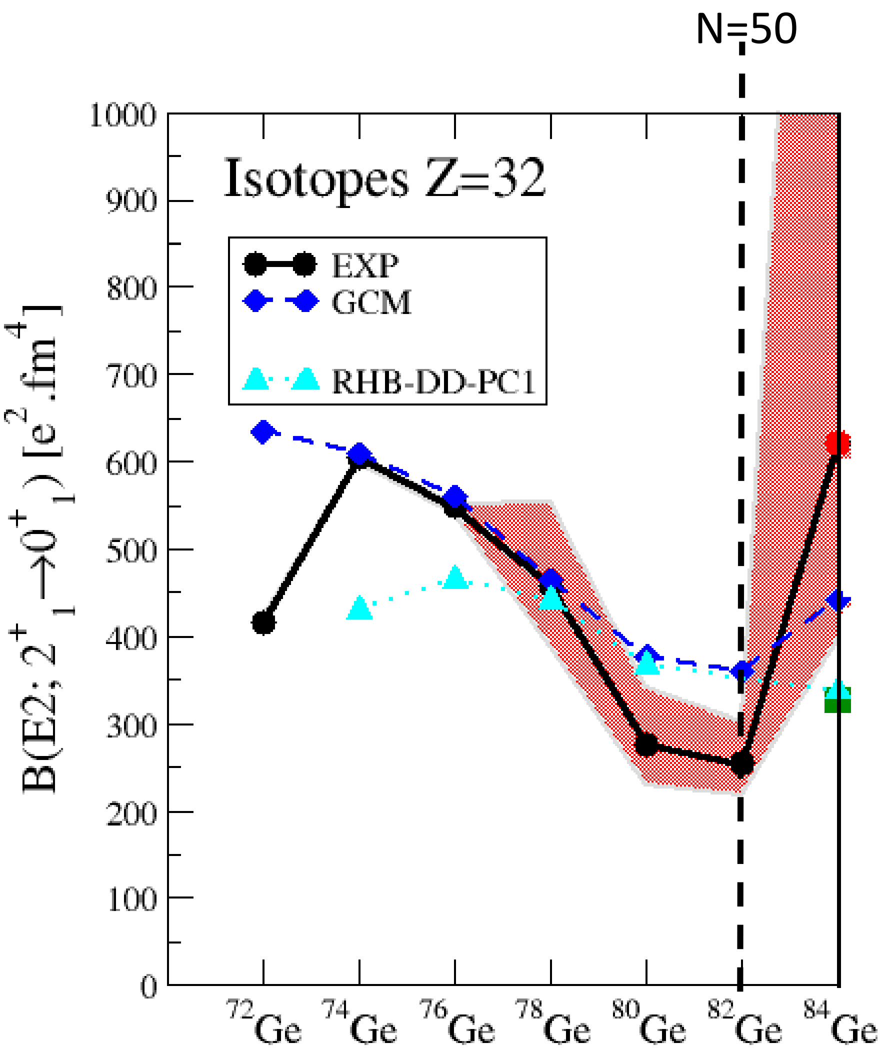
M. Lebois et al. PRC 80, 044308 (2009)

$E(4^+)/E(2^+)$ ratio + beyond mean field

D. Verney et al. PRC 87, 054307 (2013)

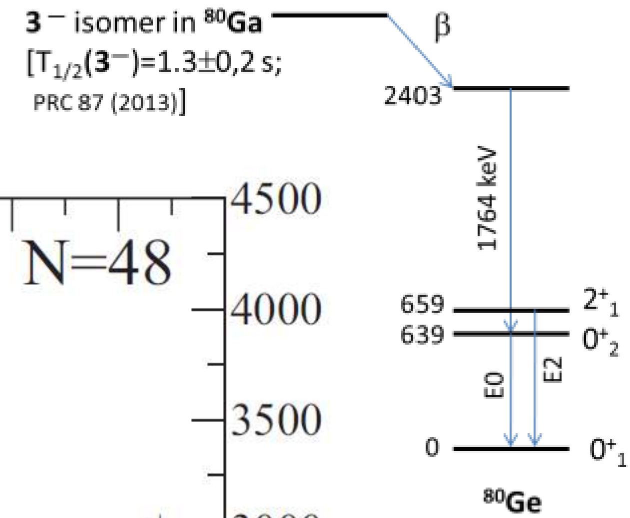
Level scheme and spin assignment (2^+,(3^+),4^+ states)
+ shell model

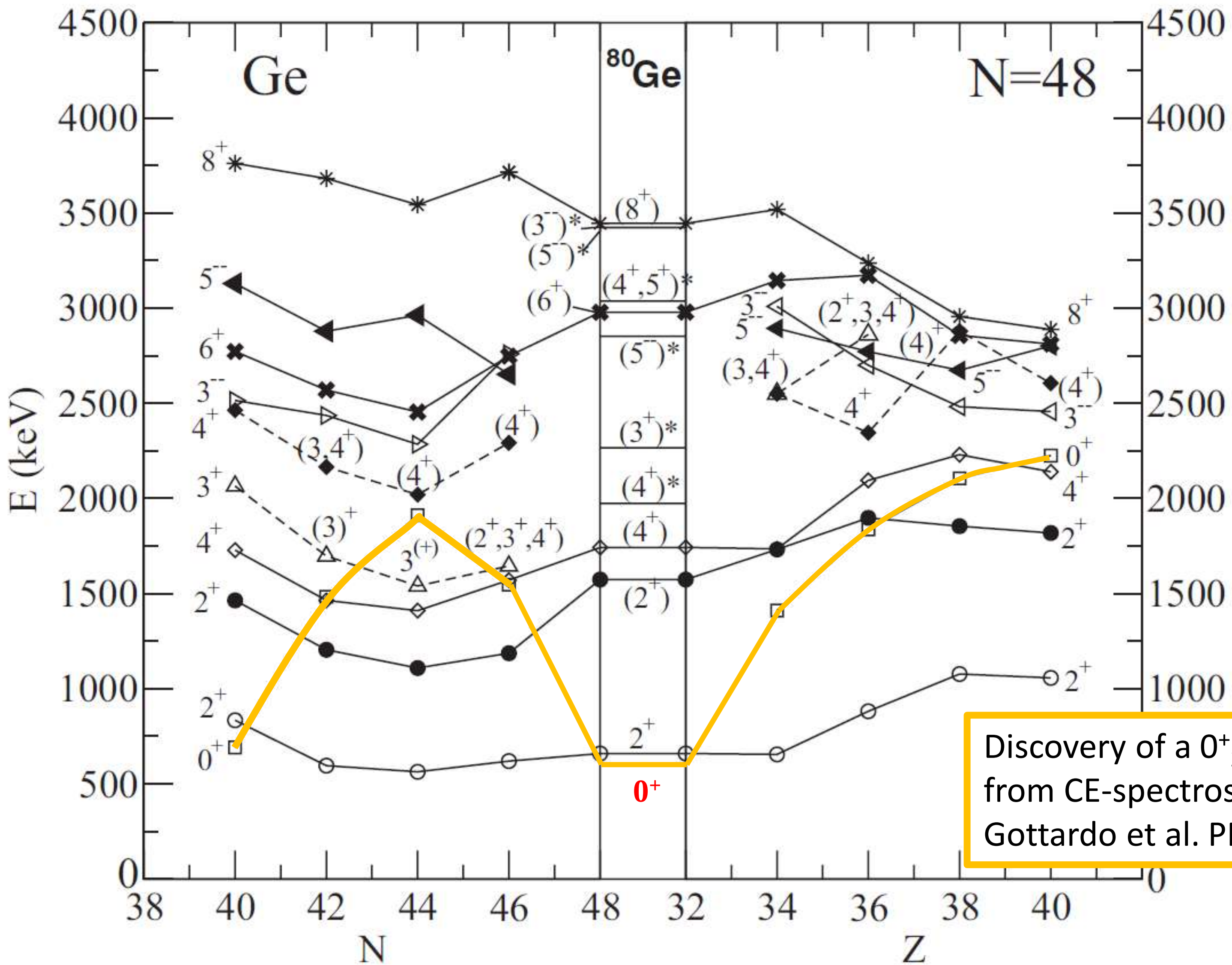
^{84}Ge 2^+ lifetime measurement : plunger AGATA + VAMOS – Exp. E669 GANIL (C. Delafosse et al. to be published)



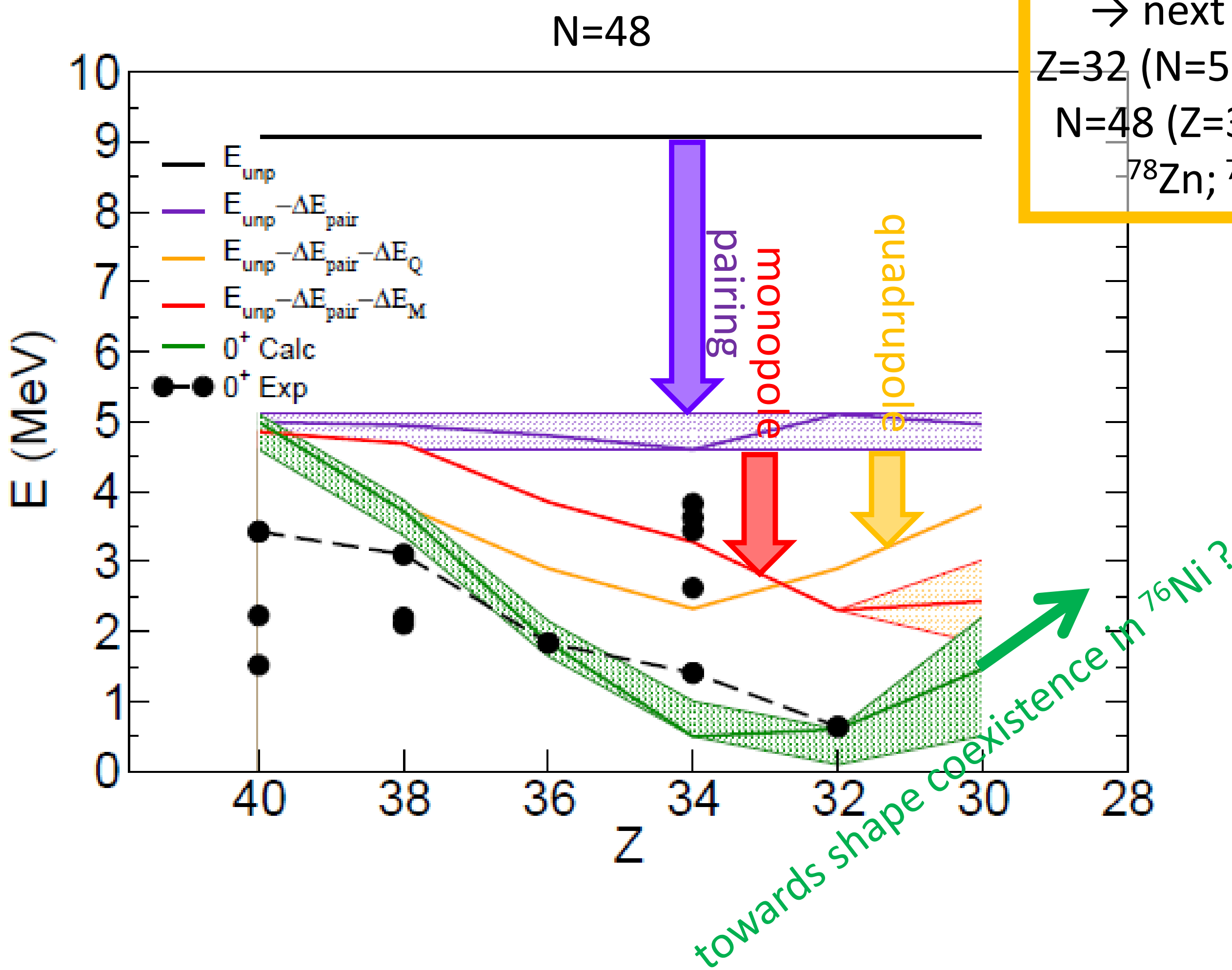
→ what triggers quadrupole correlation / triaxiality at Z=32 ?

Z=32 : definitely a “special” proton number

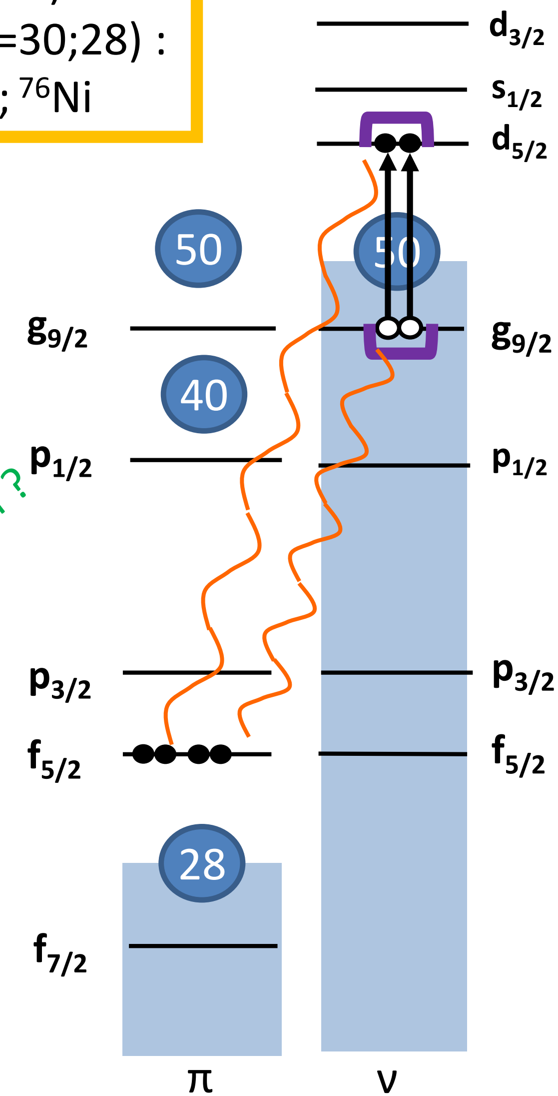




Discovery of a 0^+_2 state in ^{80}Ge from CE-spectroscopy at ALTO Gottardo et al. PRL 116 (2016)



→ next steps
Z=32 (N=50) : ^{82}Ge
N=48 (Z=30;28) :
^{78}Zn; ^{76}Ni



all quantities deduced from most recent **mass data**
(except quadrupole correlation : IBM estimate)

PRL 117, 272501 (2016) PHYSICAL REVIEW LETTERS week ending 30 DECEMBER 2016

Shape Coexistence in ^{78}Ni as the Portal to the Fifth Island of Inversion

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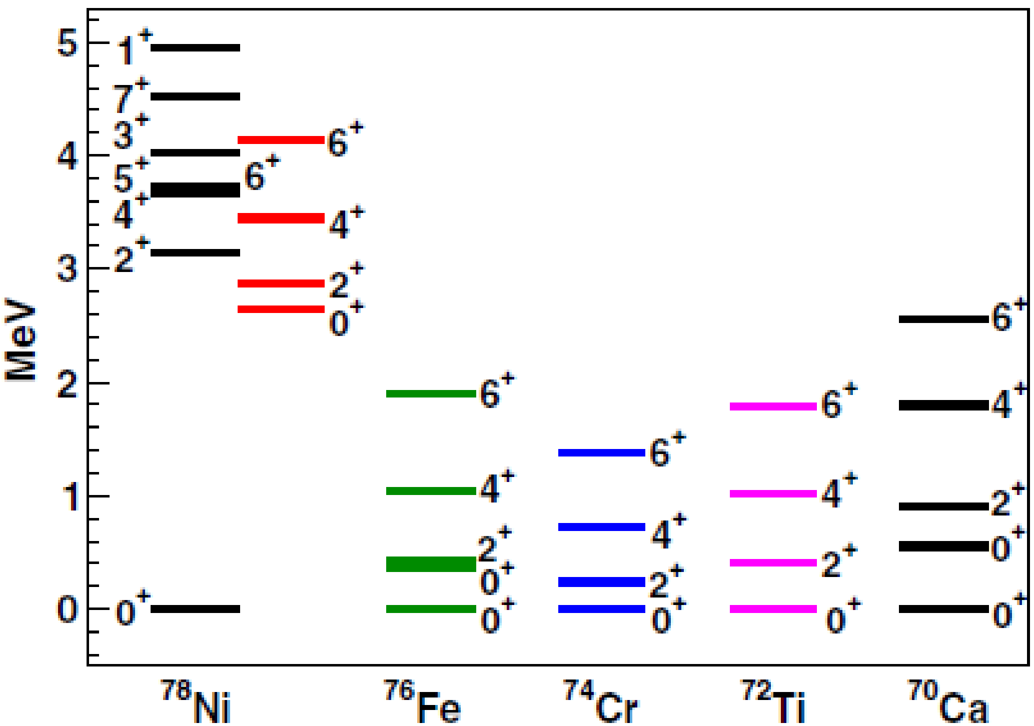
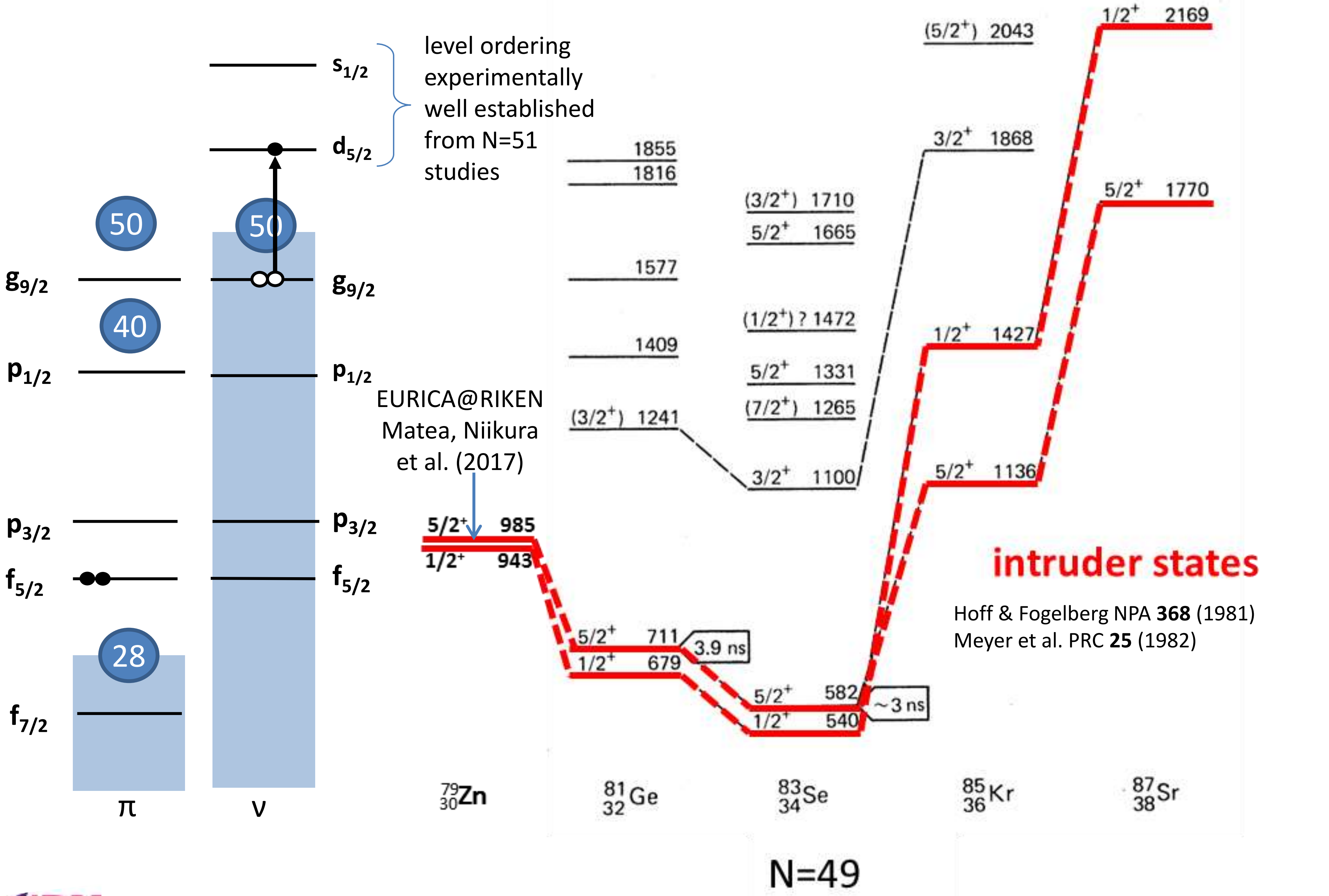
[1]*Université de Strasbourg, IPHC, 23 rue du Loess 67037 Strasbourg, France*
[2]*CNRS, UMR7178, 67037 Strasbourg, France*
[3]*Departamento de Física Teórica e IFT-UAM/CSIC, Universidad Autónoma de Madrid, E-28049 Madrid, Spain and Institute for Advanced Study, Université de Strasbourg, France*
(Received 30 May 2016; revised manuscript received 14 July 2016; published 27 December 2016)



PFSDG-U shell-model calculations reproduce correctly the recently measured mass of ^{79}Cu PRL 119, 192502 (2017)

… but not the intruder 0^+_2 state in ^{80}Ge

Shape coexistence (N=49)

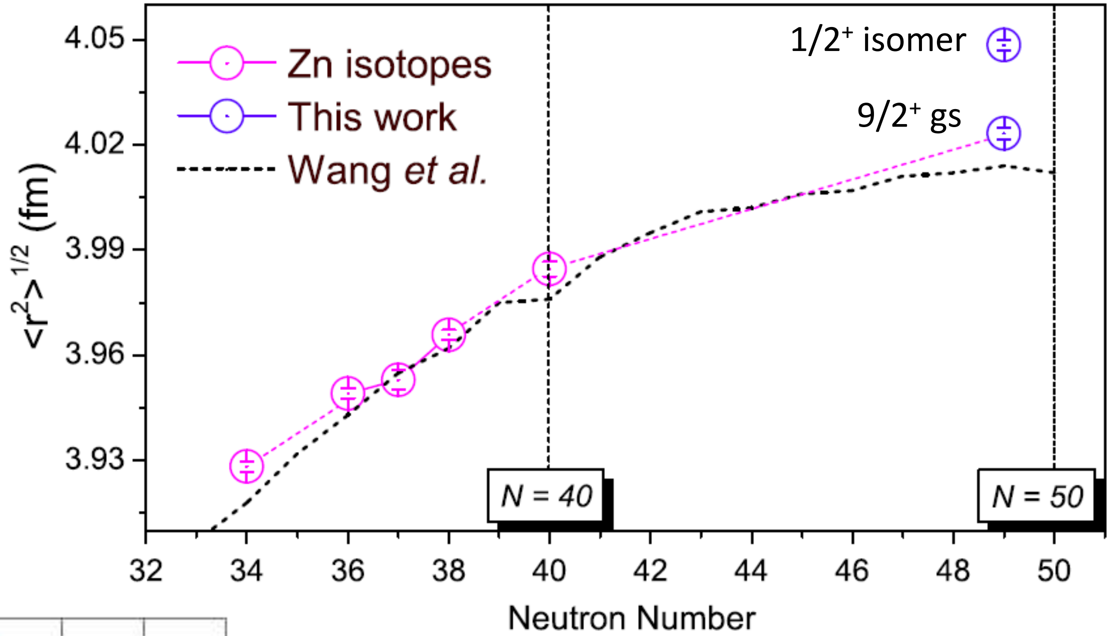


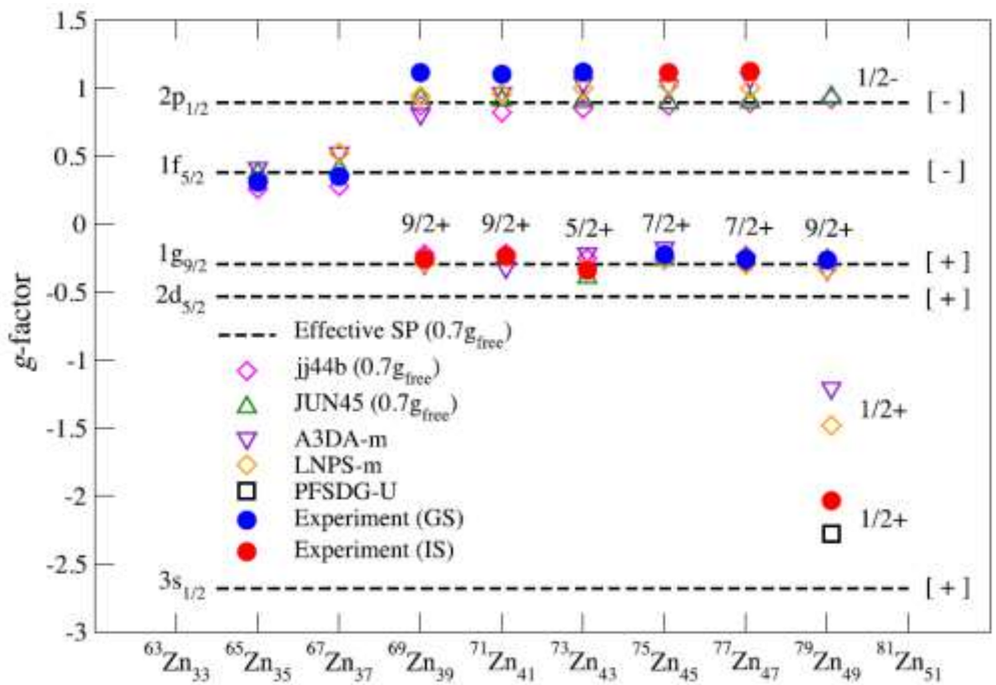
X. Yang et al. PRL 116 (2016)

^{79}Zn : isomer shift measured

COLLAPS collaboration

$$\langle r_c^2\rangle(^{79m}\mathrm{Zn}) - \langle r_c^2\rangle(^{79g}\mathrm{Zn}) = 0.204(6)[36]\ \mathrm{fm}^2$$

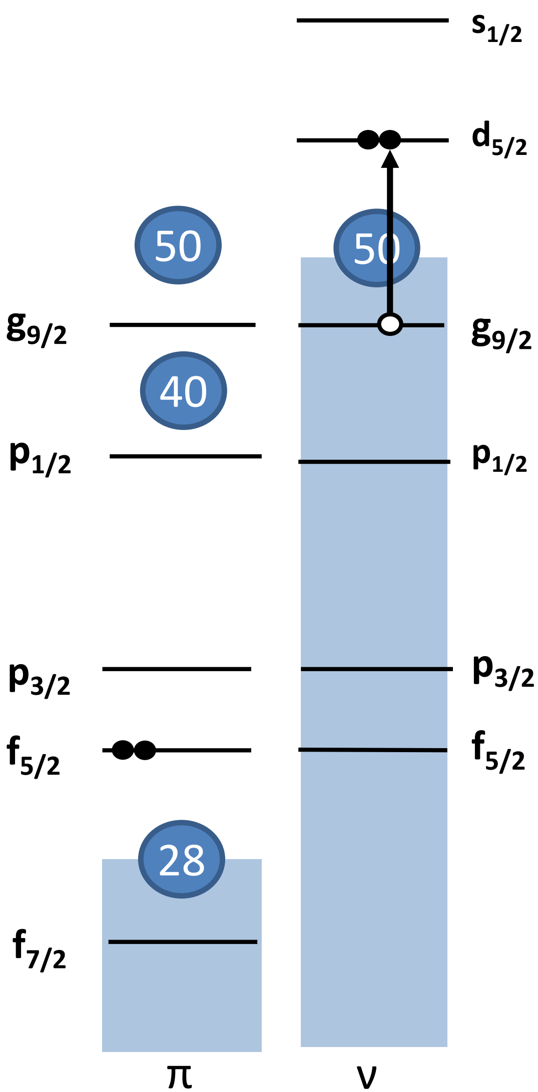




C. Wraith et al. PLB 771 385 (2017)

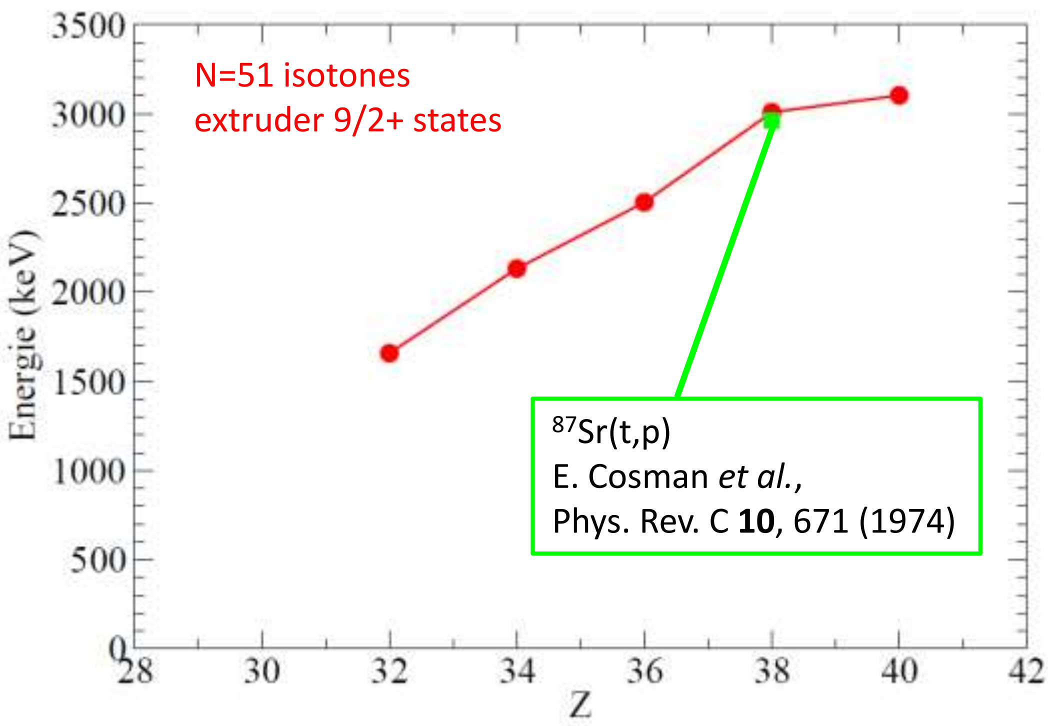
PFSDG-U based shell model calculations
→ $\mathbf{s_{1/2}}\ d_{5/2}\ (d_{3/2}\ g_{7/2})$ composition
of the $1/2^+$ intruder state seems under control (?)

Extruder counterparts identified at N=51 : none identified so far



using the same mass ingredients as for the evaluation of the 0^+_2 intruder energy in ^{80}Ge →

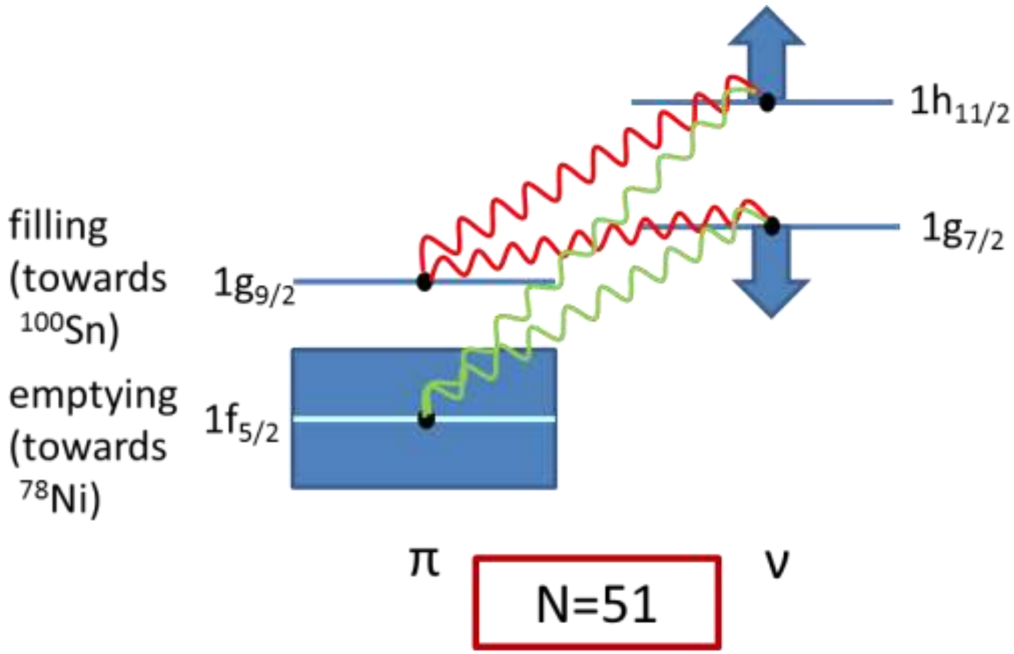
$$E^{\text{unp}}_{d^2_{5/2}g^{-1}_{9/2}} = \tilde{\epsilon}_{d_{5/2}} - \tilde{\epsilon}_{g_{9/2}} + \Delta E_{\text{pairing}}(p)$$



Energy location of high-ℓ orbitals

Tensor (Otsuka) mechanism: a robust feature of the physics of the ^{100}**Sn** region which brings the $\nu 1g_{7/2}$ close to the g.s.

should be true also for the ^{78}**Ni** region
⇒ the 7/2+ state stemming from $\nu g_{7/2}$ should become Yrast along the N=51 line towards ^{79}Ni



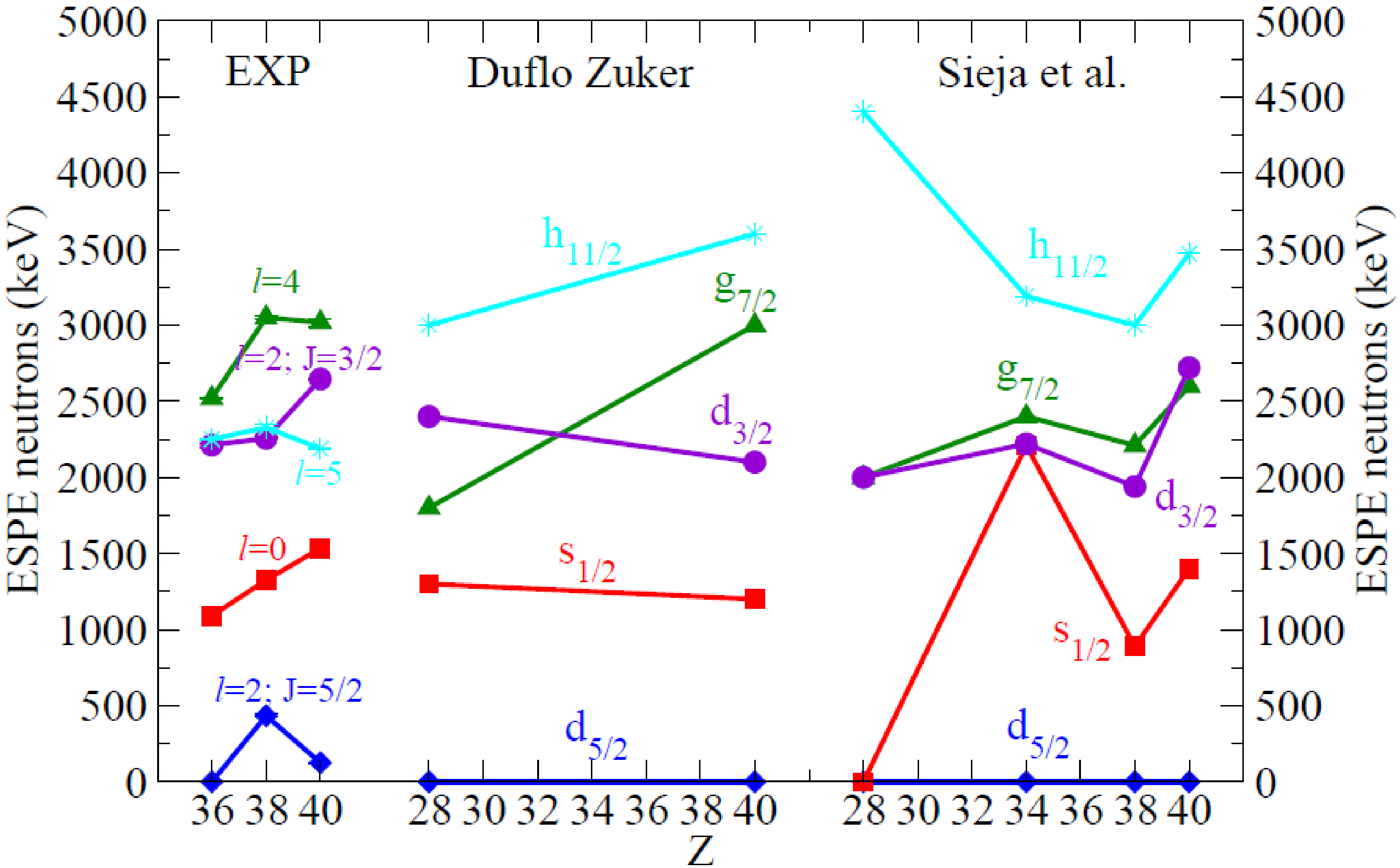
*D. K. Sharp et al., PRC **87**, 014312 (2013)*

From Duflo Zuker

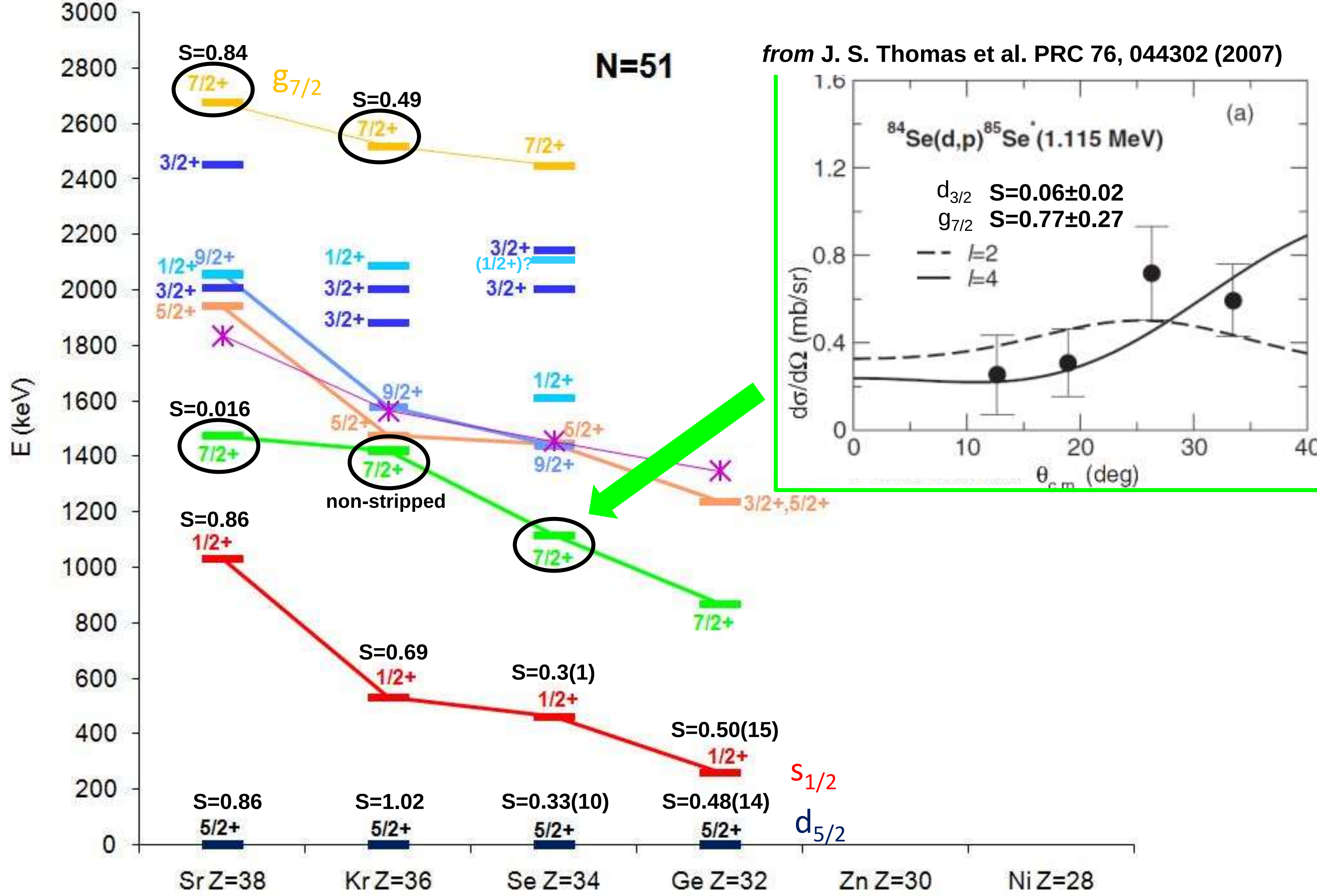
*PRC **59**, R2347 (1999)*

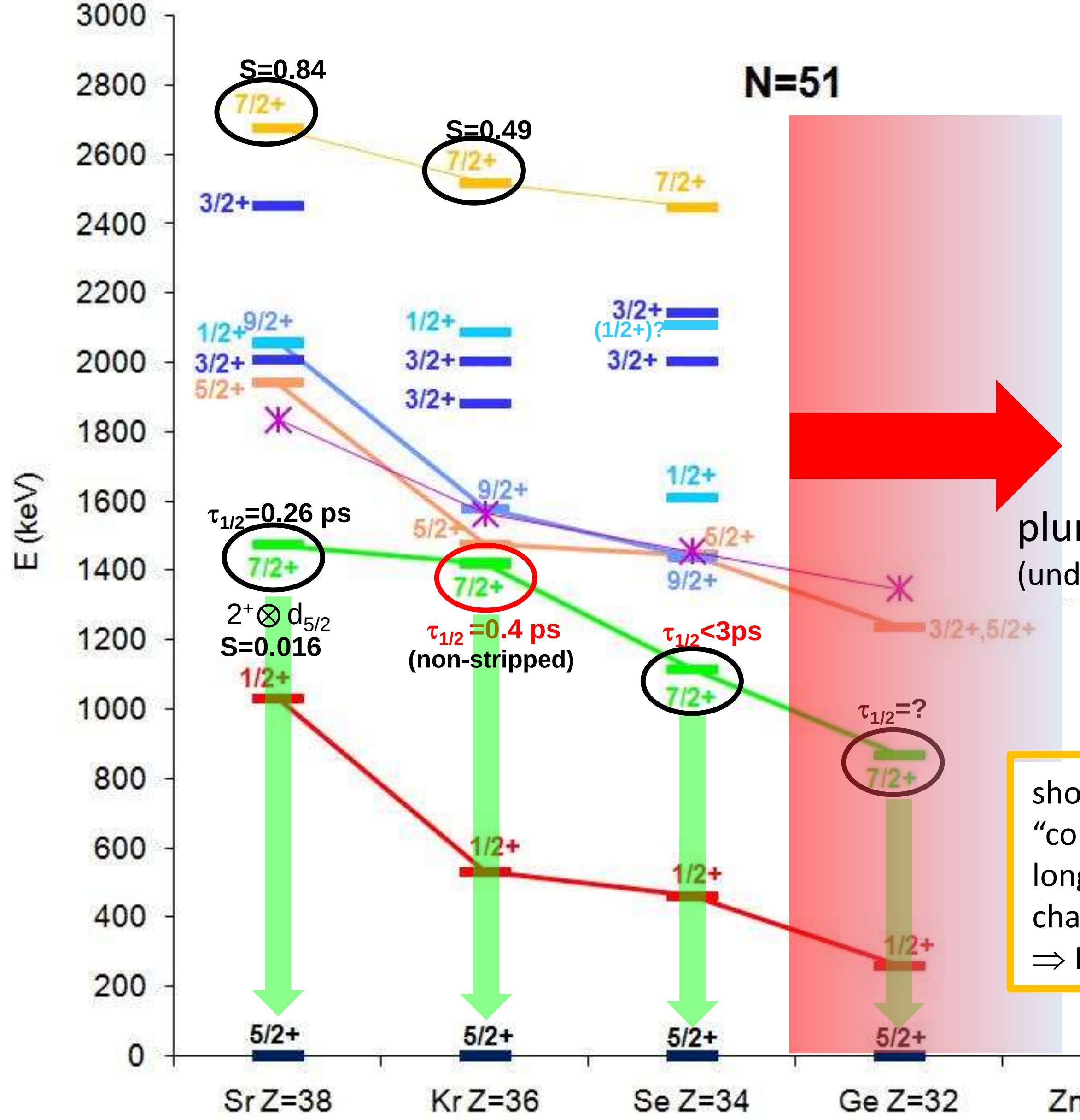
SM calculations in valence space above ^{78}Ni

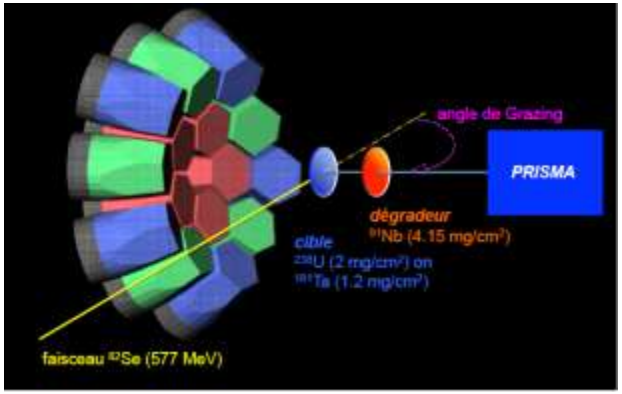
*K. Sieja et al. PRC **79**, 064310 (2009)*



neutron valence space above ^{78}Ni ?



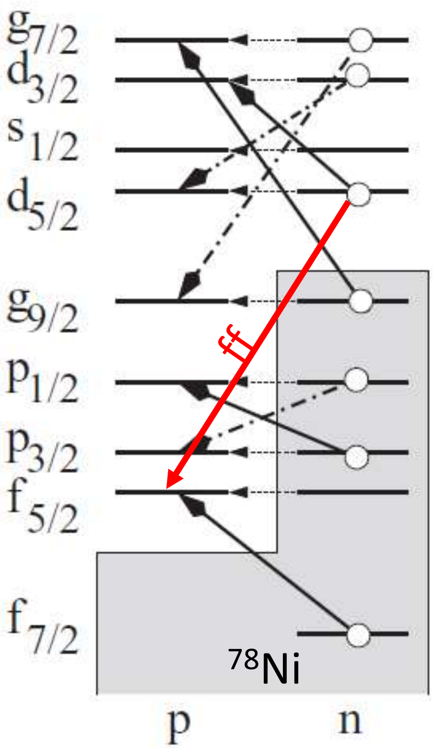




LNL results : Didierjean et al
PRC **96**, 044320 (2017)

plunger AGATA+VAMOS E669
(under analysis C. Delafosse IPN Orsay)

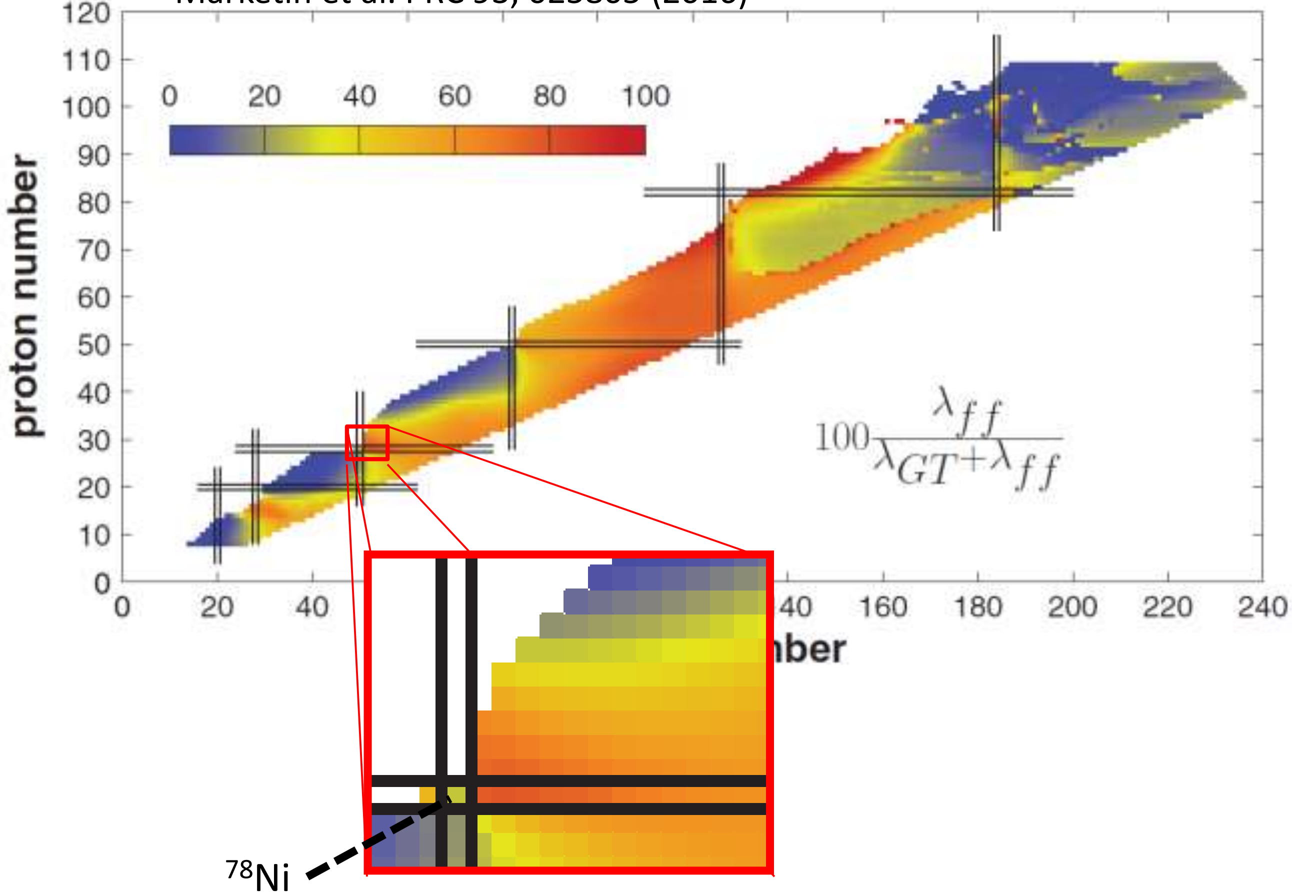
short-lived state (~0.1 ps)↔ core-coupled "collective" state
long-lived state (10 ps) ↔ "single particle" character
⇒ RDDS measurement



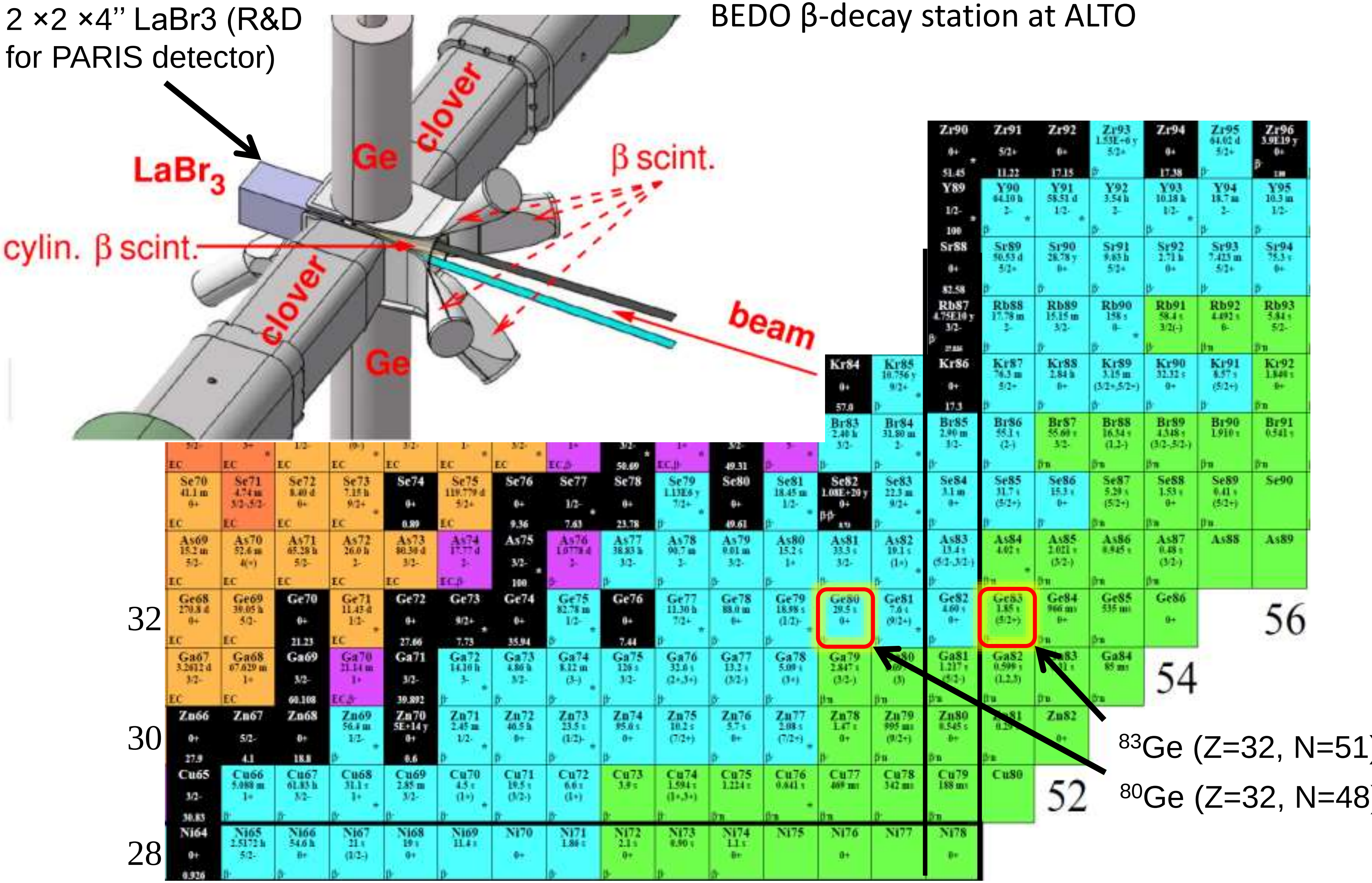
Because of the structure of the valence space in very N/Z asymmetric nuclei first-forbidden transition are believed to play a major role just after closed neutron shell

→ consequences for r-process modeling

Marketin et al. PRC 93, 025805 (2016)



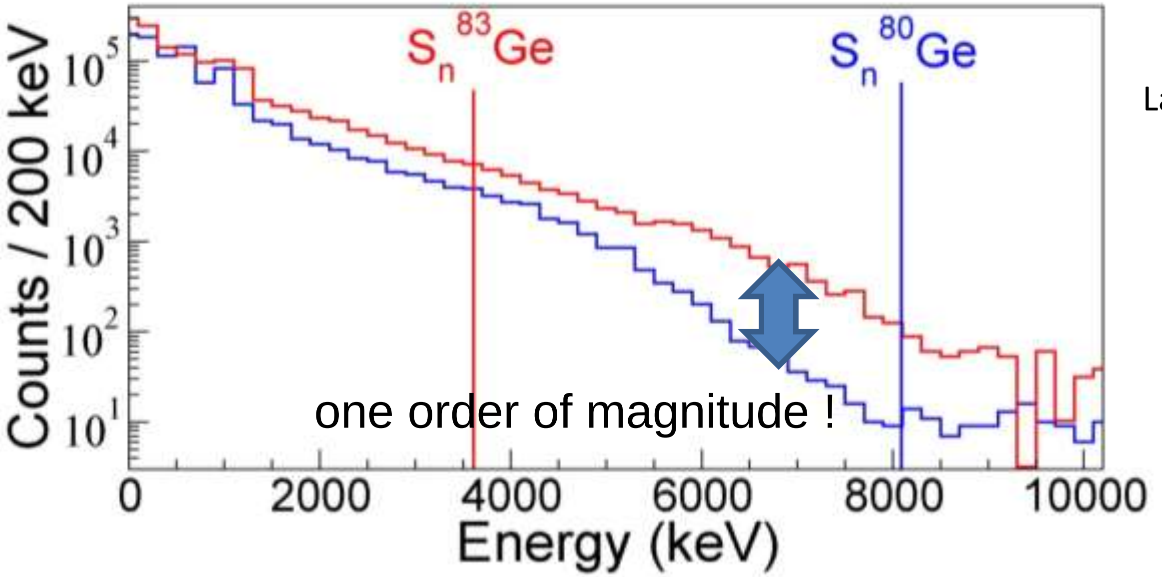
The question of ff-transitions in the ^{78}Ni region



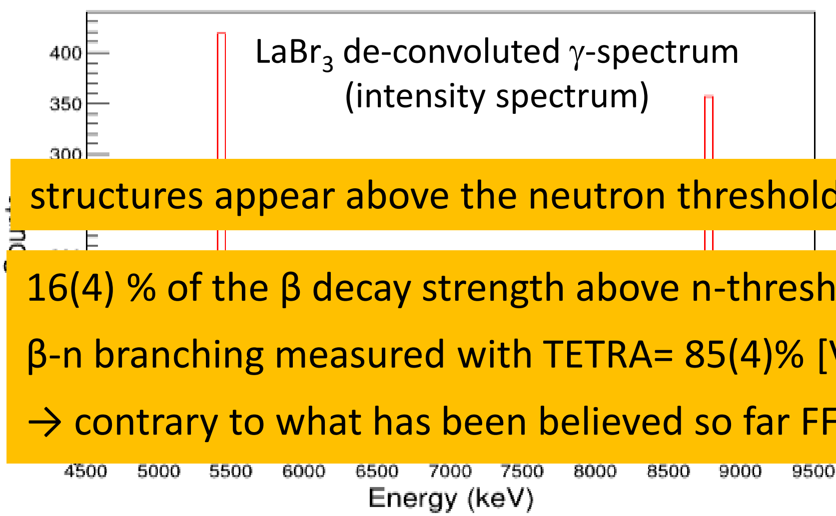
Gottardo et al. Phys. Lett. B 772 359 (2017)

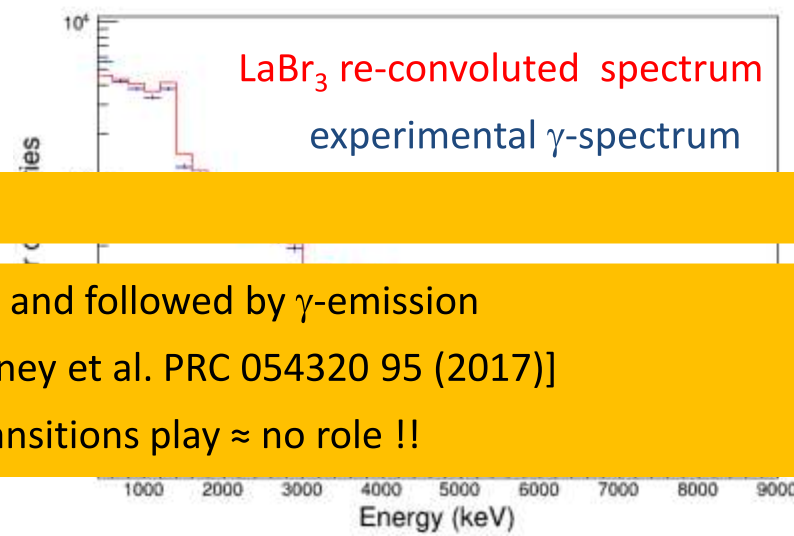
The question of ff-transitions in the ^{78}Ni region

comparison of ^{80}Ge vs ^{83}Ge spectra (below vs above N=50) up to $\approx Q_\beta$



Response function + energy linearity of LaBr3 detector fully characterized up to 11 MeV using ^{27}Al(p,γ)^{28}Si reaction at the ARAMIS accelerator (CSNSM in Orsay)





structures appear above the neutron threshold

16(4) % of the β decay strength above n-threshold and followed by γ-emission

β-n branching measured with TETRA= 85(4)% [Verney et al. PRC 054320 95 (2017)]

→ contrary to what has been believed so far FF transitions play ≈ no role !!

Gottardo et al. Phys. Lett. B 772 359 (2017)

N=50 shell effect in the ^{78}Ni region : open questions

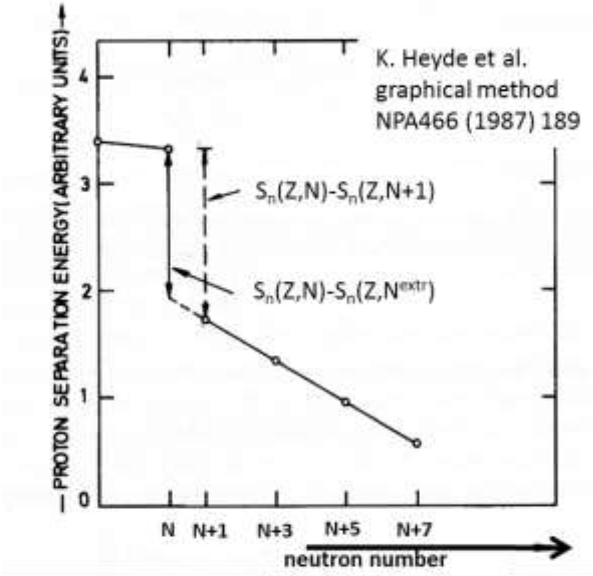
- gap size → Z=32 "singularity"
  - monopole effect ? (quadratic ??) ⟶ mass measurements
  - dynamical effect ? (triaxiality corridor ??) ⟶ (multi-step) coulex
- shape coexistence
  - 0^+_2 states ⟶ β-delayed e- spectroscopy
  - extruder states at N=51 ⟶ direct nucleon exchange (t,p)
- neutron valence space above ^{78}Ni : high ℓ ⟶ direct nucleon exchange (d,p) and (α,^{3}He)
- first-forbidden transitions in the ^{78}Ni region ⟶ β-delayed neutron and high-energy γ spectroscopy

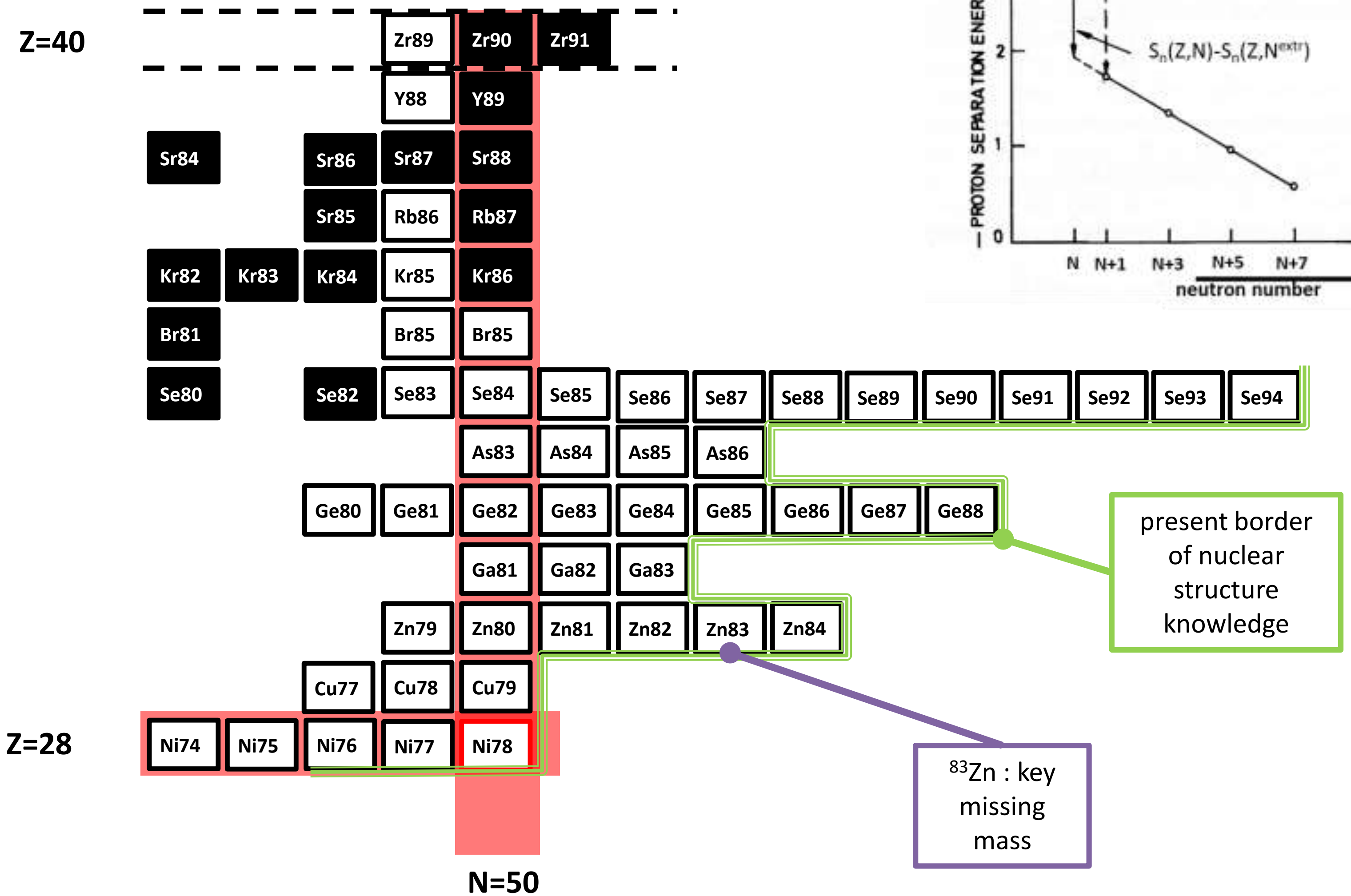
conclusions and outlook:

some suggestions for a possible joint N=50/^{78}Ni program within EURISOL-DF

• gap size → Z=32 “singularity” **mass measurements**

monopole effect ? (quadratic ??)

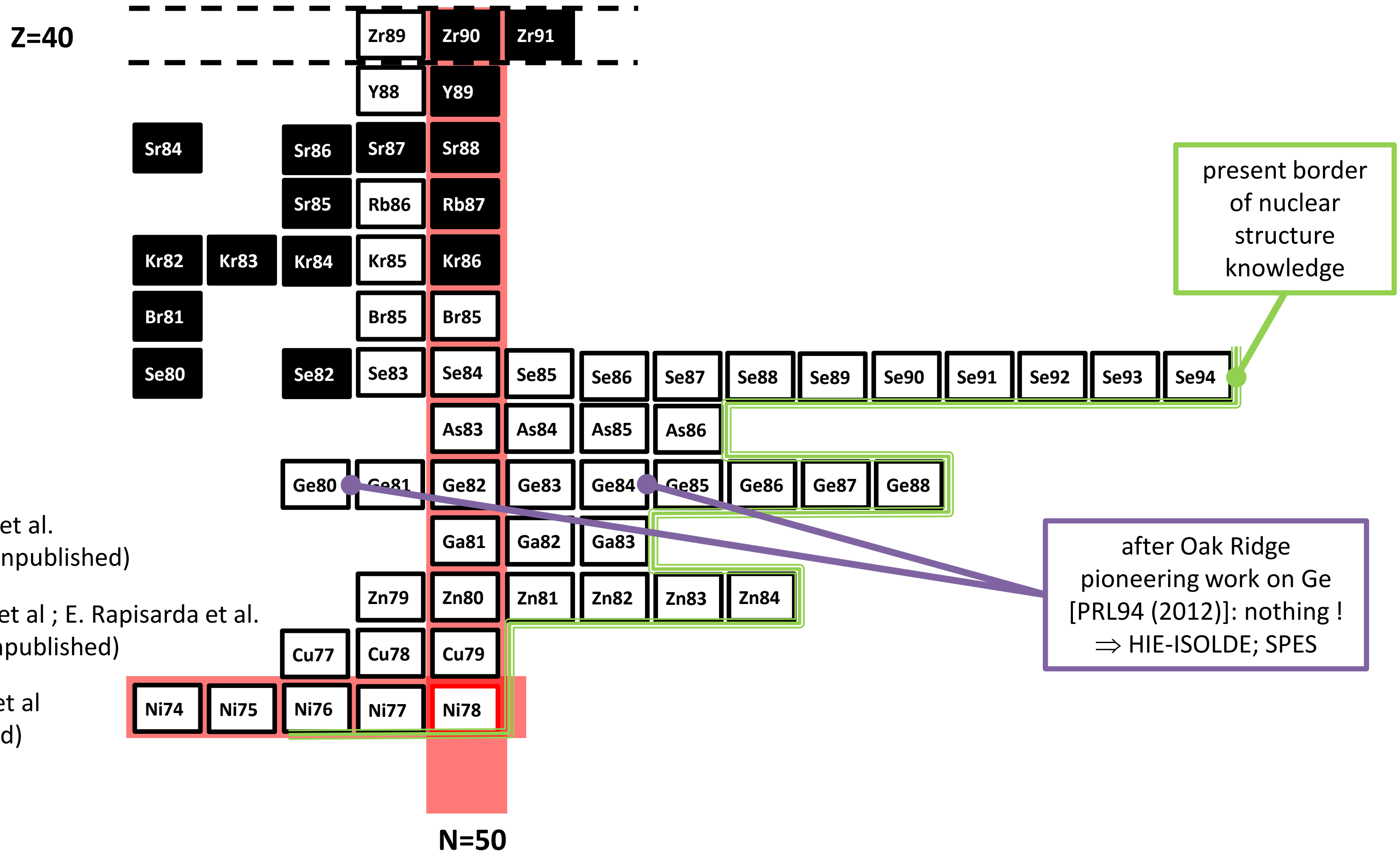




Some suggestions for a "EURISOL-DF joint N=50 program"

- gap size → Z=32 "singularity" **(multistep) coulex**

  dynamical effect ? (triaxiality ??)



→^{78}Zn Zielinska et al.
data available (unpublished)

Cu: I. Stefanescu et al ; E. Rapisarda et al.
data available (unpublished)

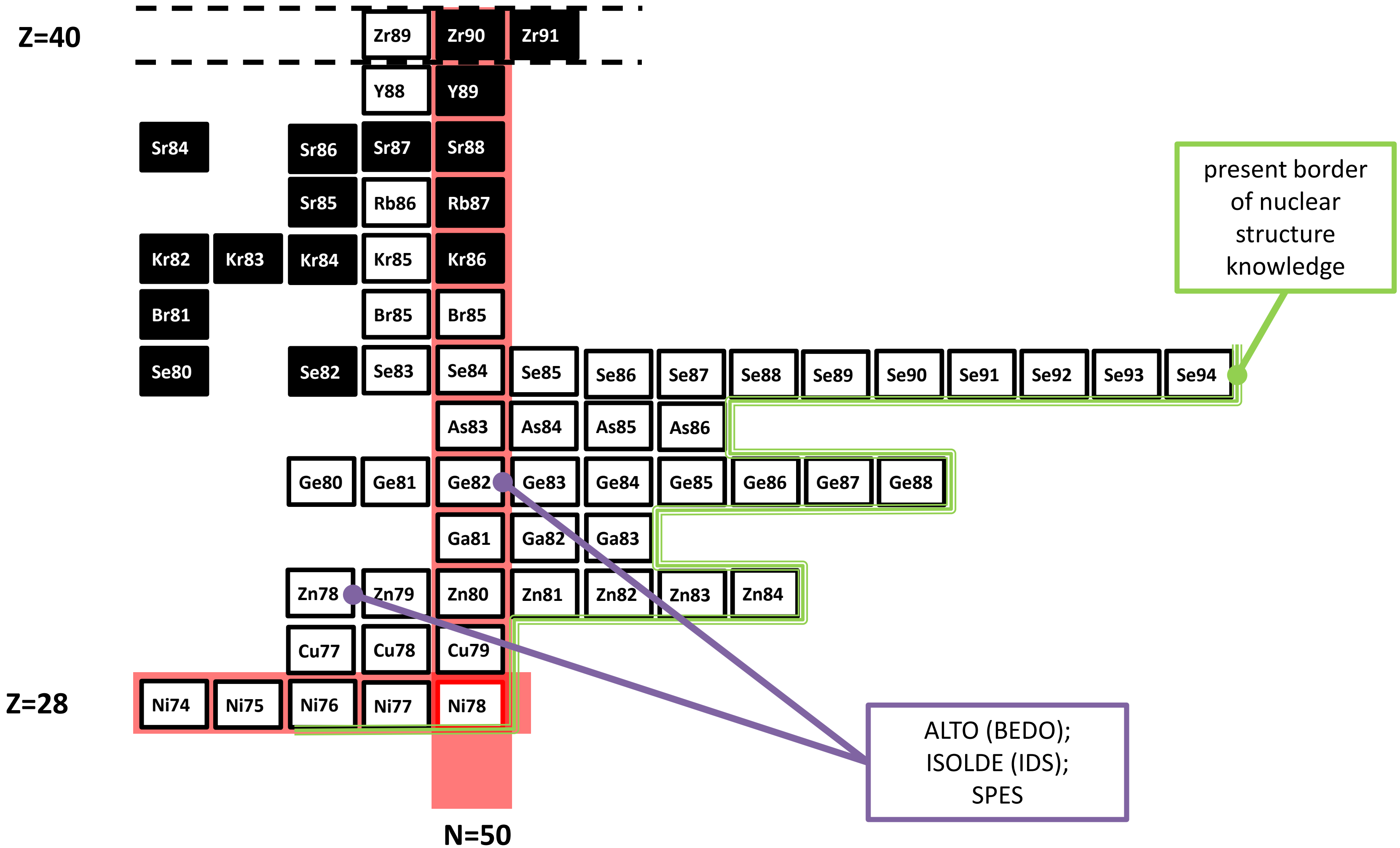
→^{68}Ni Zielinska et al
ISOLDE (approved)

Some suggestions for a "EURISOL-DF joint N=50 program"

- shape coexistence

β-delayed e- spectroscopy

0^+_2 states



Some suggestions for a "EURISOL-DF joint N=50 program"

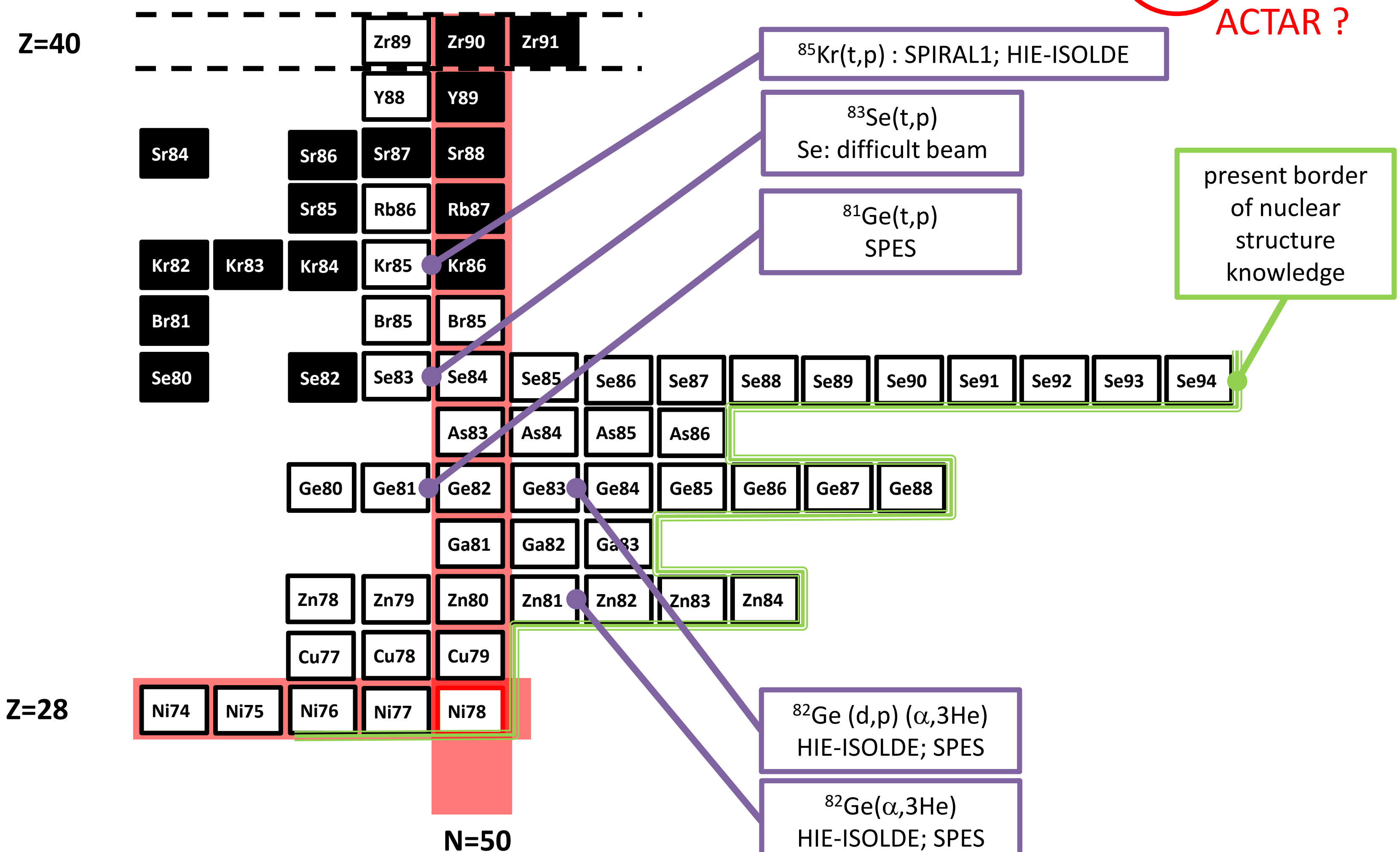
direct nucleon exchange

- shape coexistence

extruder states at N=51 : (t,p) reaction

- neutron valence space above ^{78}Ni : **high ℓ**

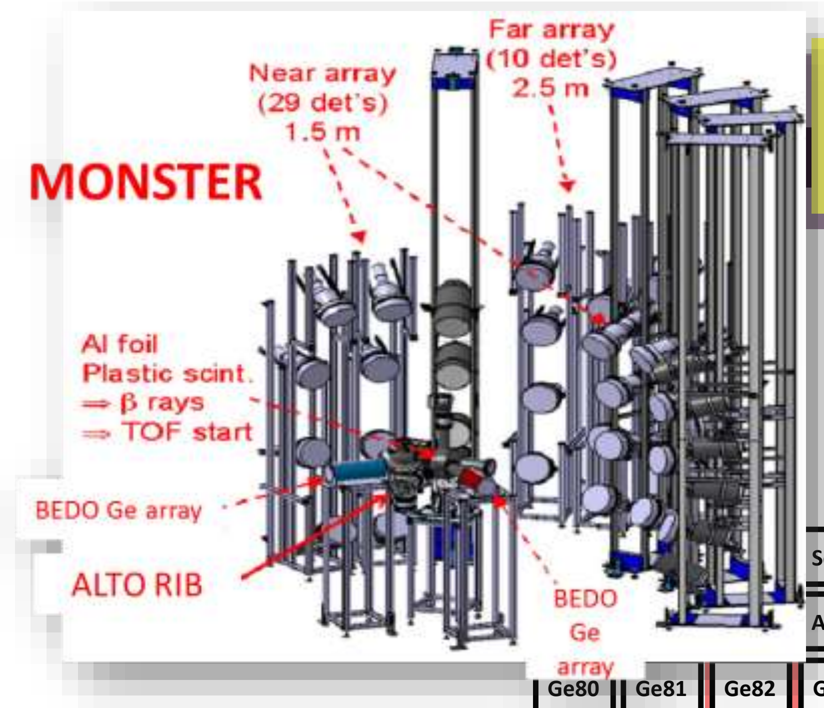
direct nucleon exchange (d,p) and (α,^{3}He)



Some suggestions for a "EURISOL-DF joint N=50 program"

- first-forbidden transitions in the ^{78}Ni region

β-delayed neutron and high-energy γ spectroscopy

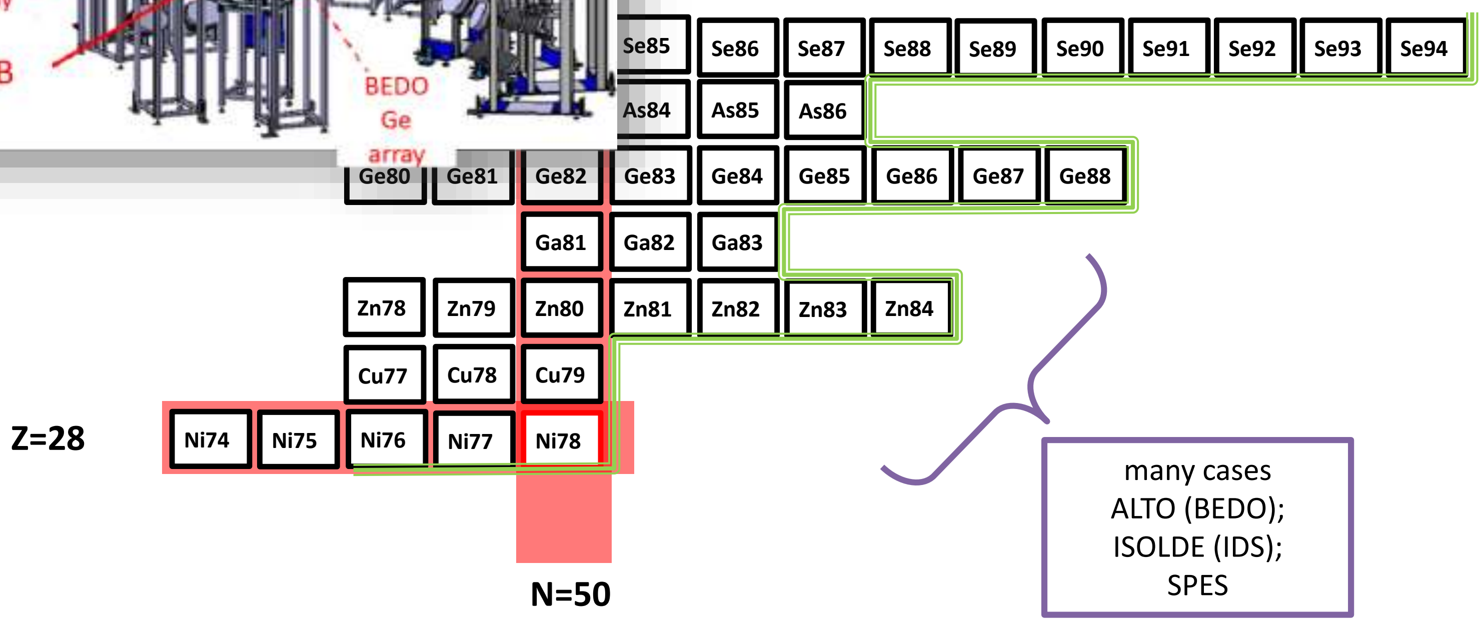


Example : coupling BEDO with

- a TOF neutron detector (MONSTER) for neutron energy spectroscopy
- a high efficiency high-energy γ-array : PARIS ??

MONSTER campaign at ALTO in 2018-19

in collaboration with:
D. Cano Ott (CIEMAT Madrid)



many cases
ALTO (BEDO);
ISOLDE (IDS);
SPES

Thank you !