Lect III. A walk on the wild side: physics towards drip lines

I. Introduction

II. Hierarchy of nuclear forces: consequences on shell evolution

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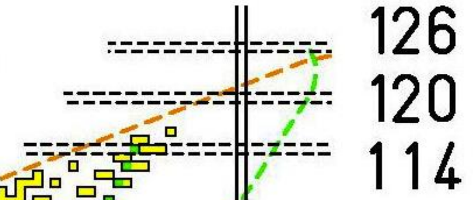
Shell evolution far from the valley of stability

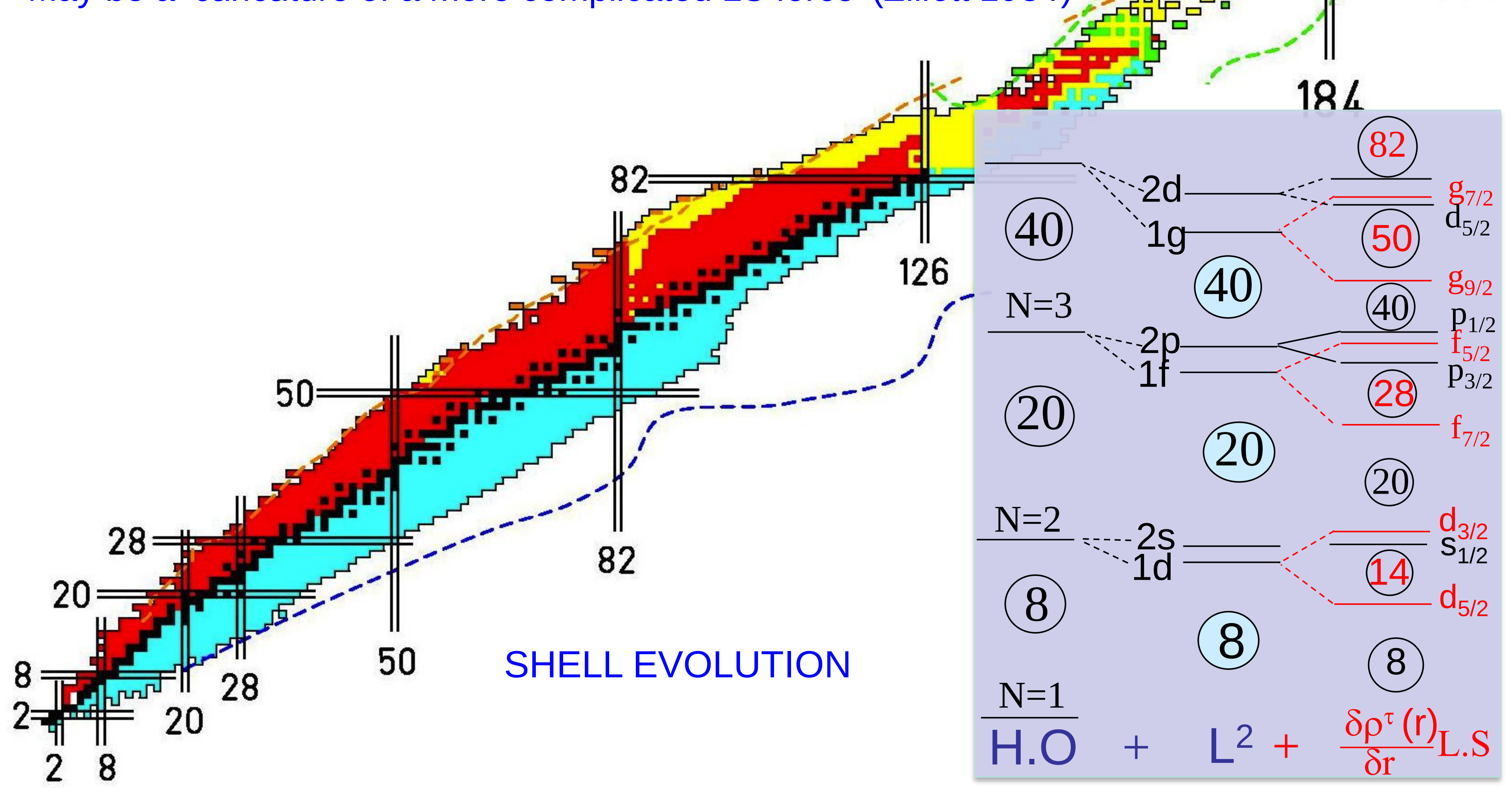
Nucleons generate their own Mean Field (MF) potential

-> Shell gaps, magic numbers (drop in S_n, increase in $E(2^+)$ …)

Early version V= HO + L^2 + LS (*Haxel, Goppert Mayer 1949*)

- May be a ‘caricature of a more complicated LS force’ (*Elliott 1954*)





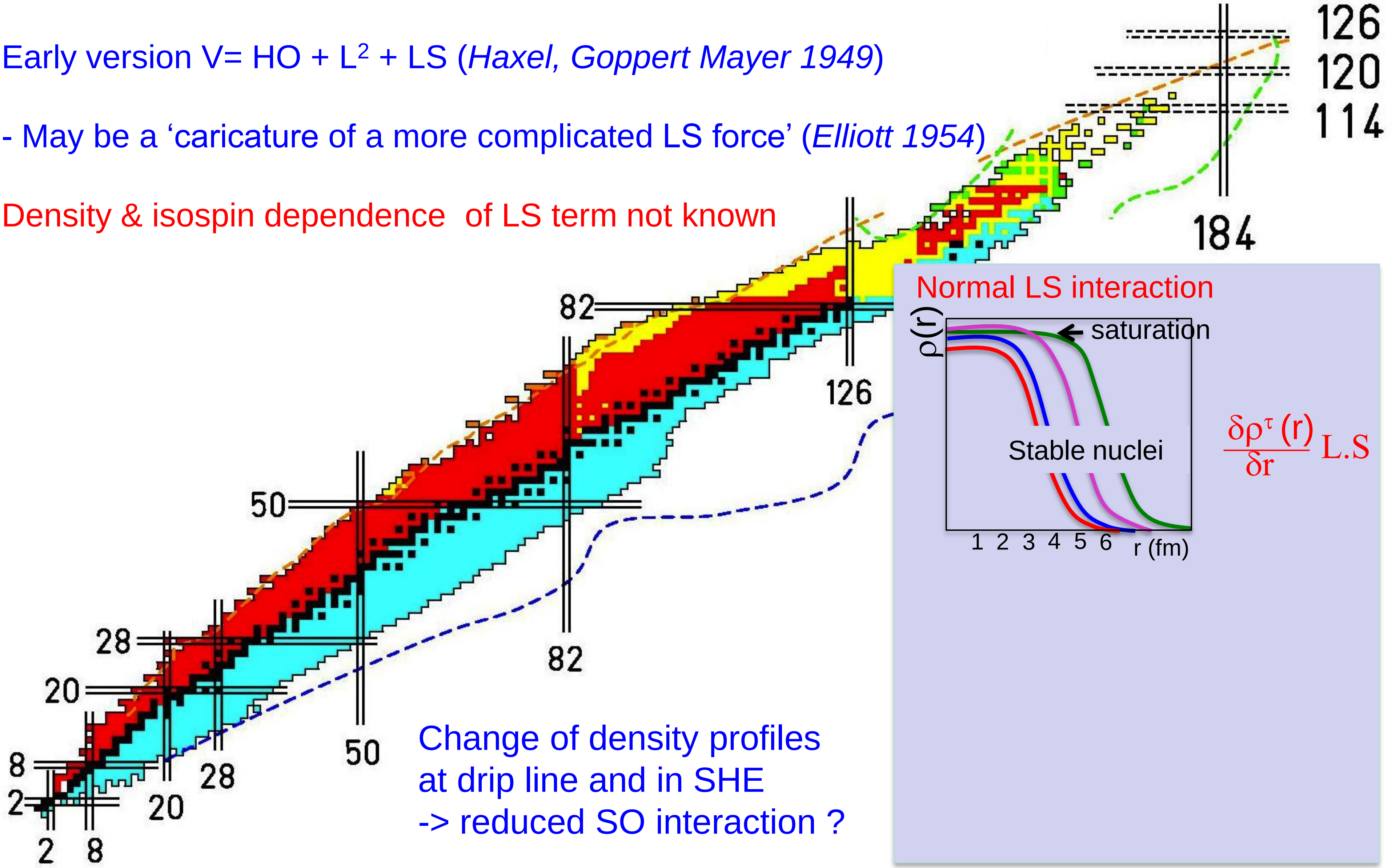
Shell evolution far from the valley of stability

Nucleons generate their own Mean Field (MF) potential, two fluids (n,p)
-> Shell gaps, magic numbers disappear -> universal ? -> Which forces ?

Early version V= HO + L^2 + LS (*Haxel, Goppert Mayer 1949*)

- May be a ‘caricature of a more complicated LS force’ (*Elliott 1954*)

Density & isospin dependence of LS term not known



$$\frac{\delta\rho^{\tau}(r)}{\delta r}\, L.S$$

Change of density profiles
at drip line and in SHE
-> reduced SO interaction ?

Shell evolution far from the valley of stability

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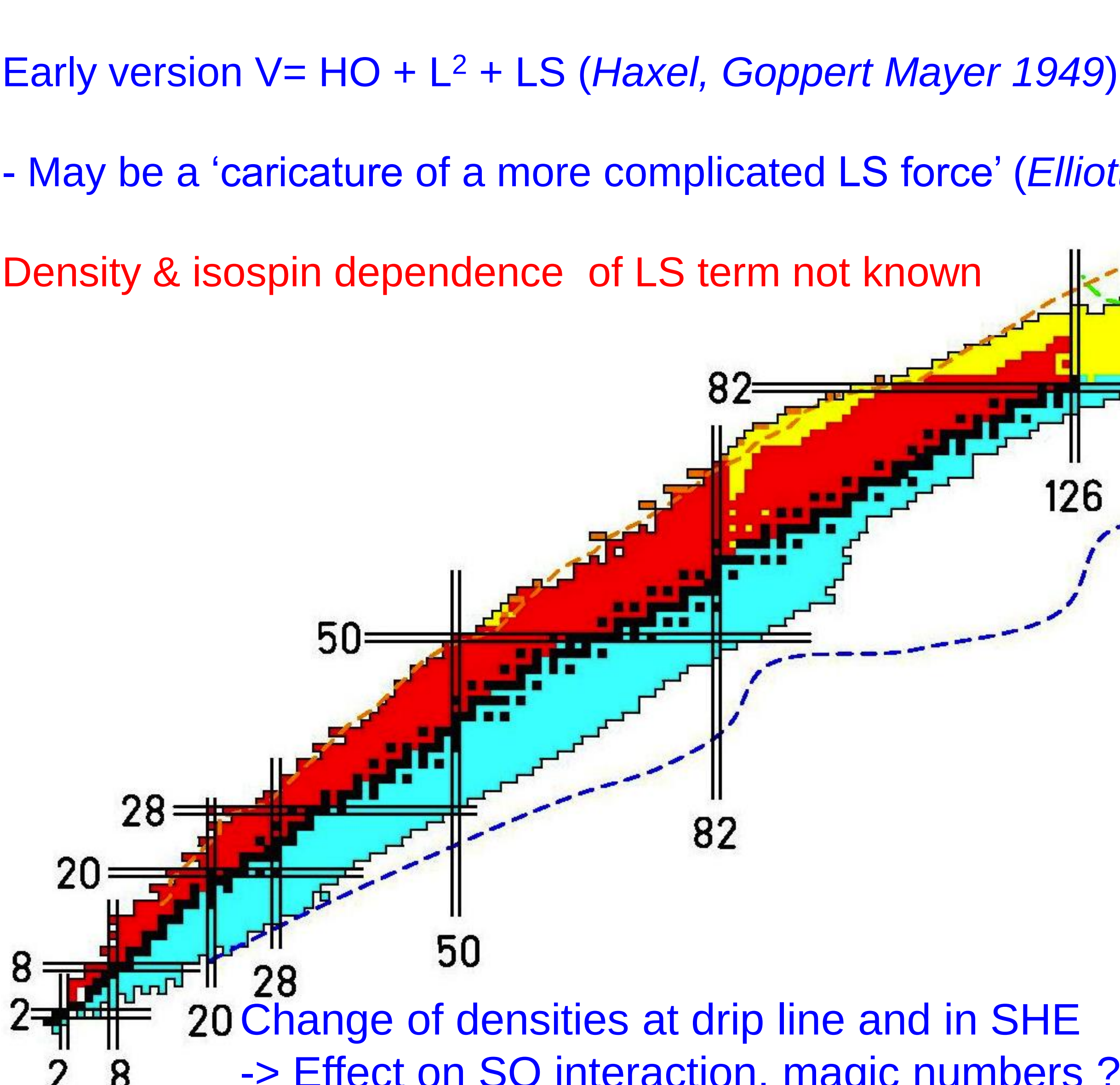

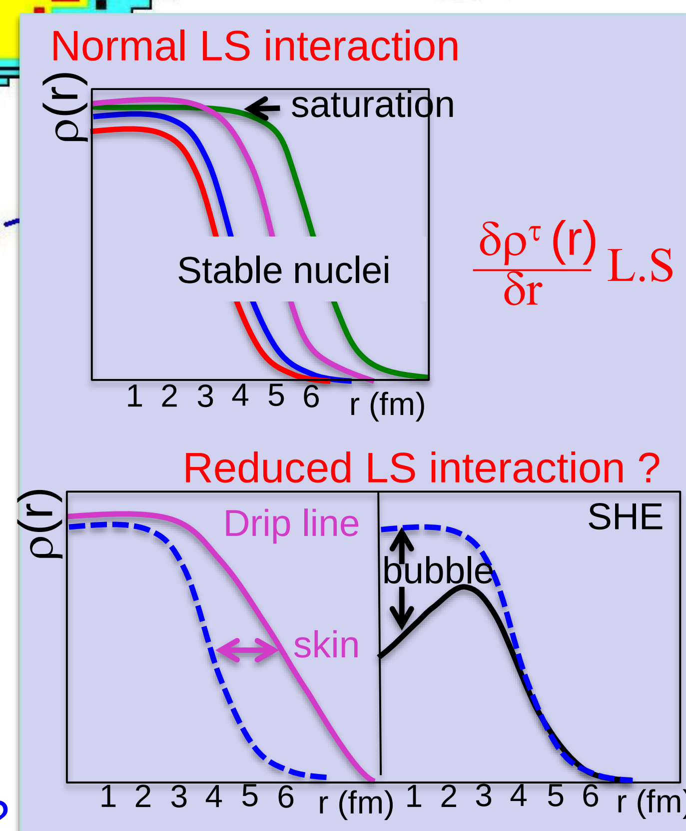

Change of densities at drip line and in SHE
-> Effect on SO interaction, magic numbers ?

Shell evolution far from the valley of stability

Nucleons generate their own Mean Field (MF) potential, two fluids (n,p)
-> Shell gaps, magic numbers disappear -> universal ? -> Which forces ?

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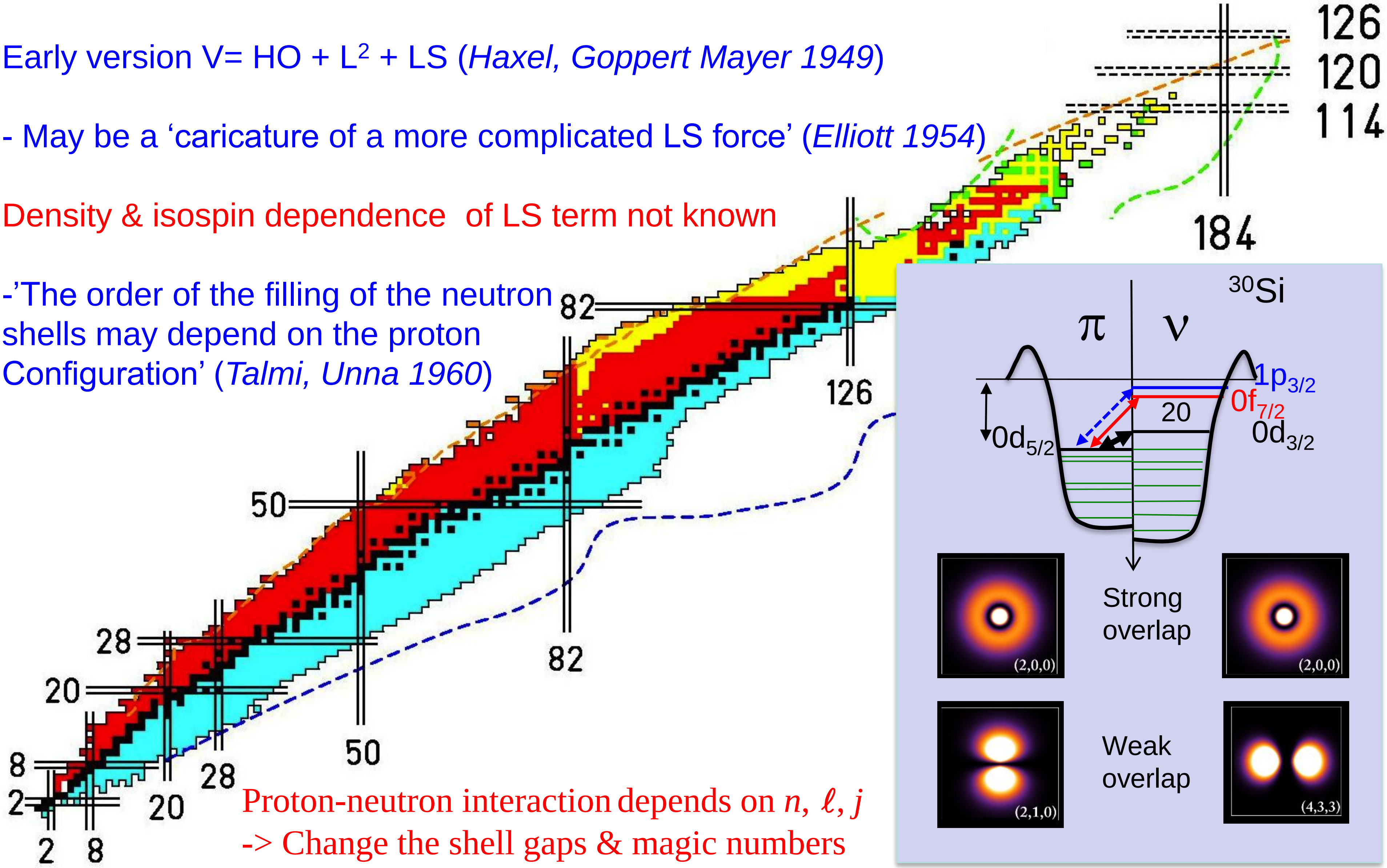
-'The order of the filling of the neutron shells may depend on the proton Configuration' (*Talmi, Unna 1960*)



Proton-neutron interaction depends on n, ℓ, j
-> Change the shell gaps & magic numbers

Shell evolution far from the valley of stability

Nucleons generate their own Mean Field (MF) potential, two fluids (n,p)
-> Shell gaps, magic numbers disappear -> universal ? -> Which forces ?

Early version V= HO + L^2 + LS (*Haxel, Goppert Mayer 1949*)

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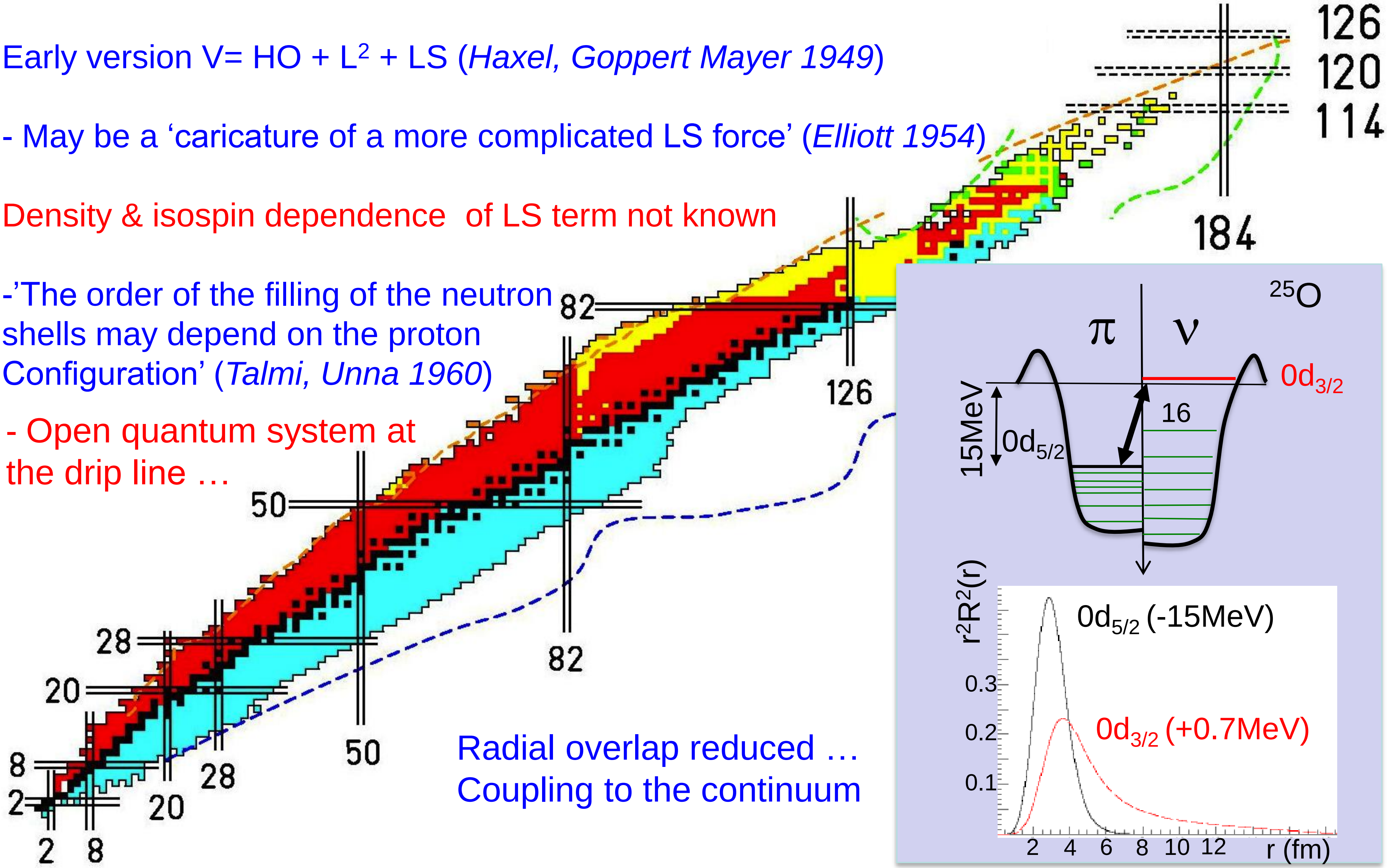
Density & isospin dependence of LS term not known

-'The order of the filling of the neutron shells may depend on the proton Configuration' (*Talmi, Unna 1960*)

- Open quantum system at the drip line …

Radial overlap reduced …
Coupling to the continuum



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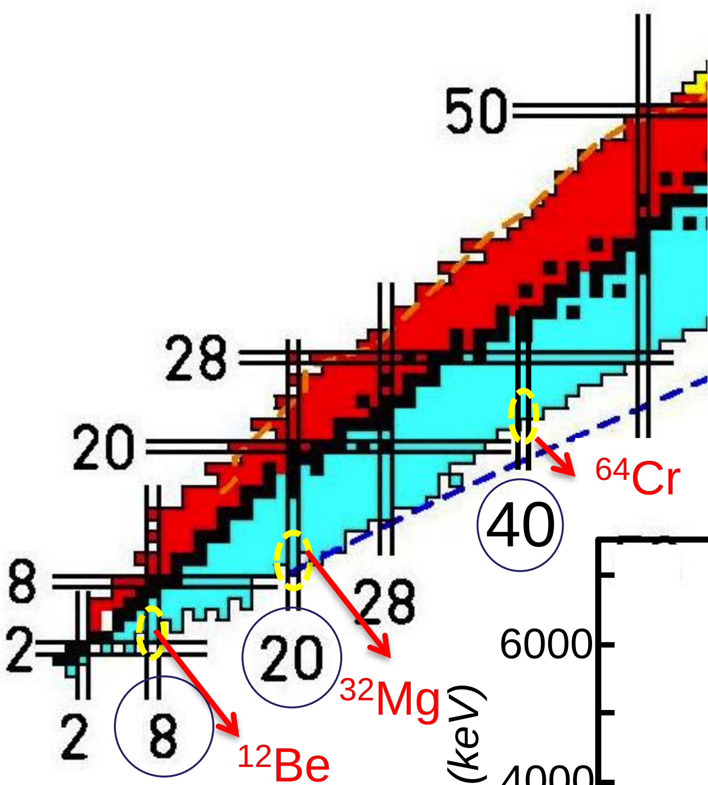
The Jedi instructed their members to the Force following a well-defined hierarchy…

Obi-Wan Kenobi 'Star Wars'

If our world were more neutron-rich ….

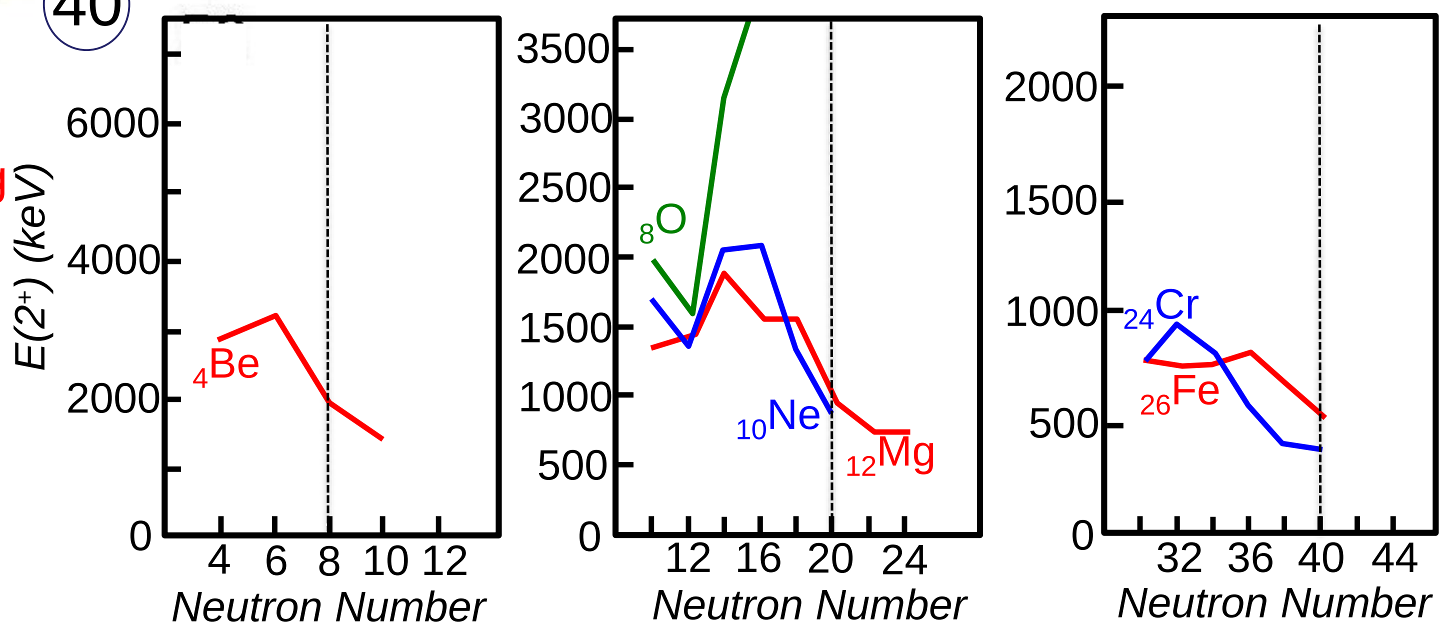


Assume our world was more neutron-rich

-> No increase of 2^+ energy at N=8, 20, 40

-> No magic number from HO -> change paradigm

What has happened while reaching stability ?



N=40

↳ Hannawald PRL 82 (1999), Sorlin, EPJA16 (2003), Aoi, PRL 102 (2009)
Gade PRC 81 (2010), Ljungvall PRC81 (2010), Lenzi PRC82 (2010), W. Rother PRL106 (2011)

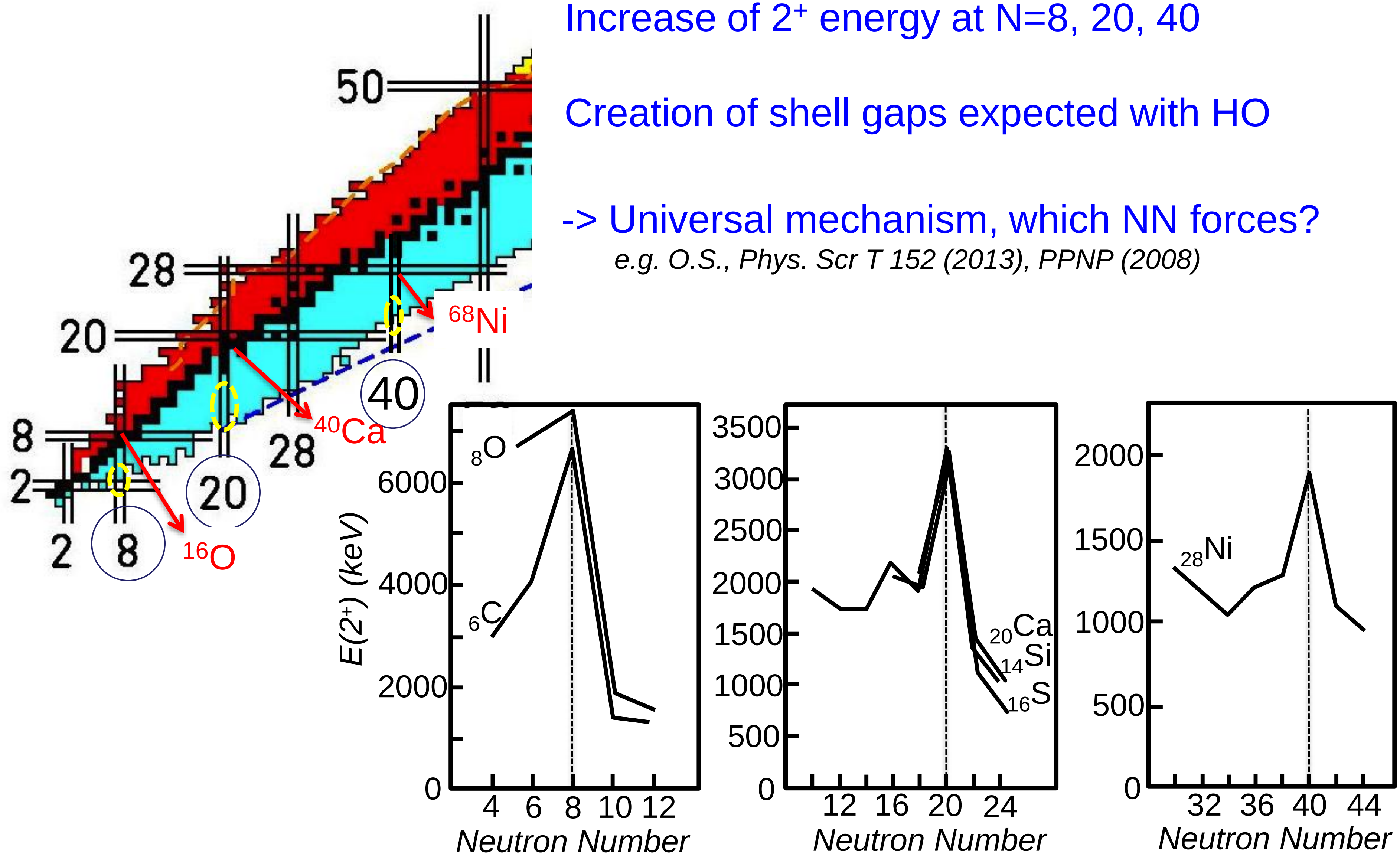
Back to stability ….

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

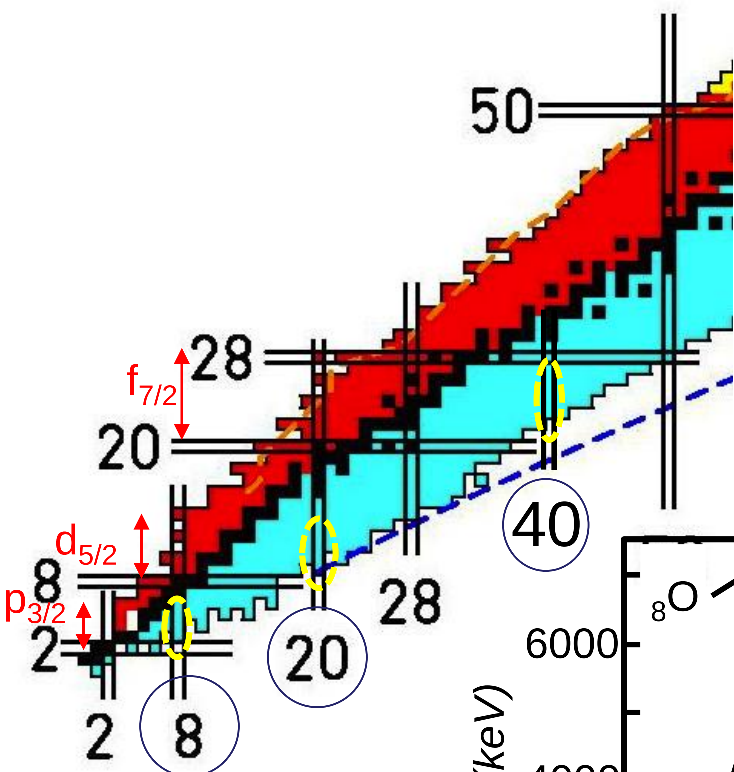
Creation of shell gaps expected with HO

-> Universal mechanism, which NN forces?

e.g. O.S., Phys. Scr T 152 (2013), PPNP (2008)



Summary ….



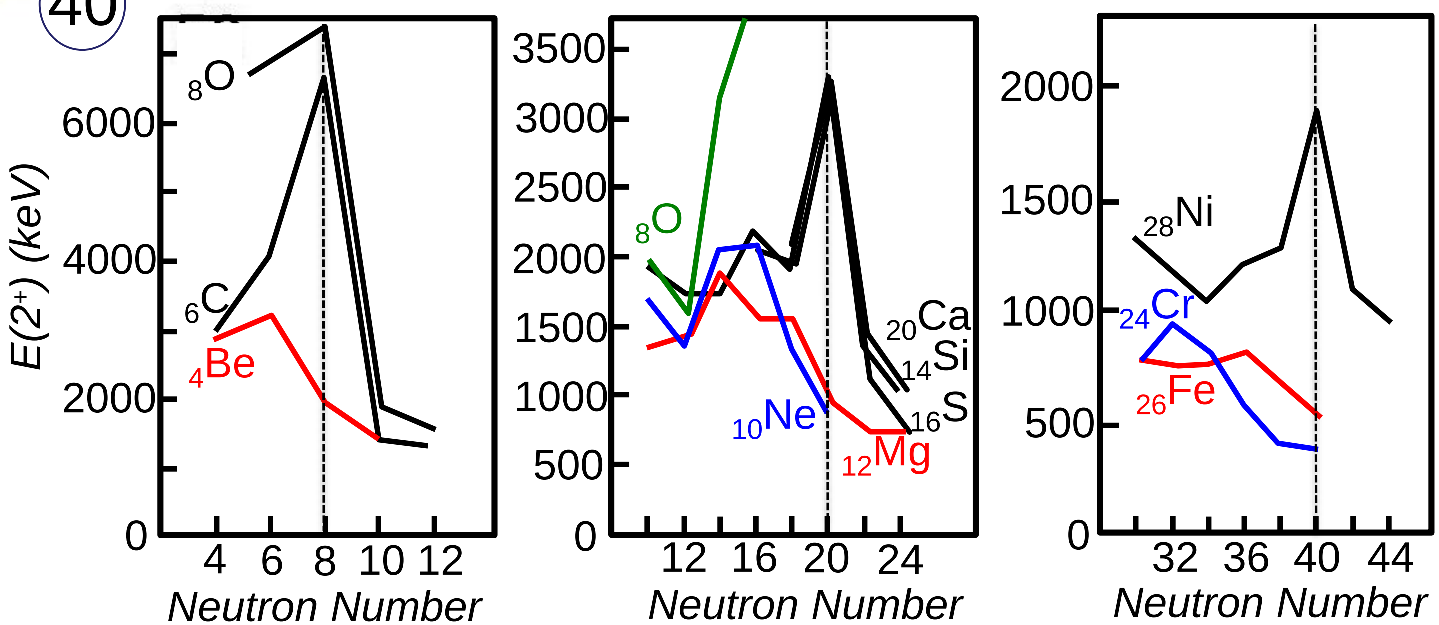
Increase of 2^+ energy at N=8, 20, 40 shell gaps

But failure far from stability for all HO shell gaps

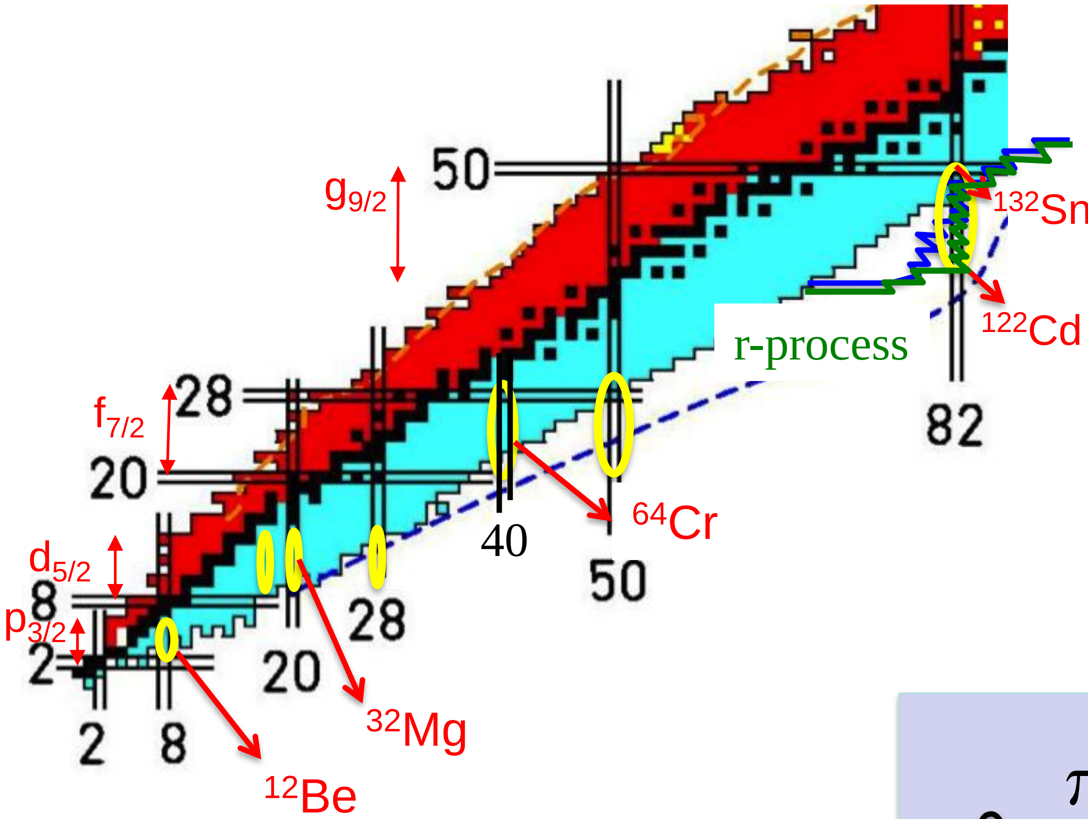
-> Universal mechanism

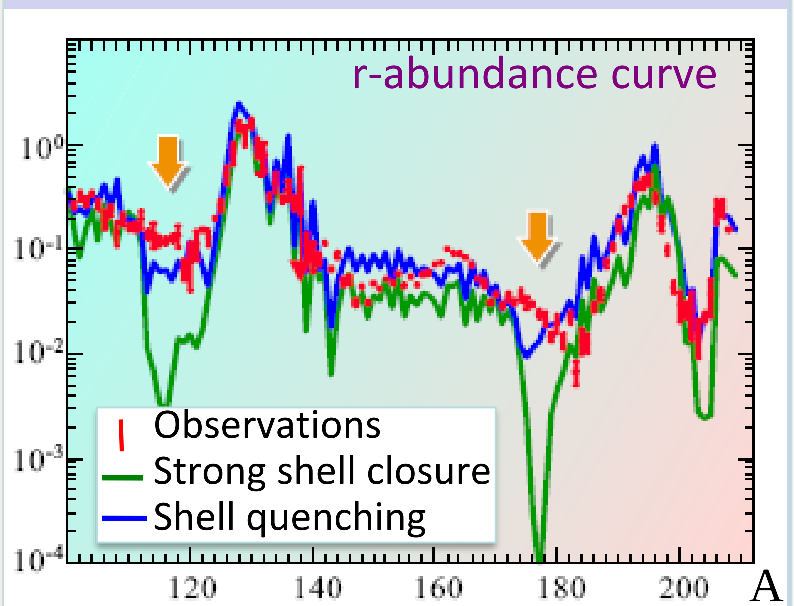
-> Hierarchy of nuclear forces …

e.g. Sorlin, Porquet PPNP 61 (2008)
Otsuka Phys. Scr T152 (2013)

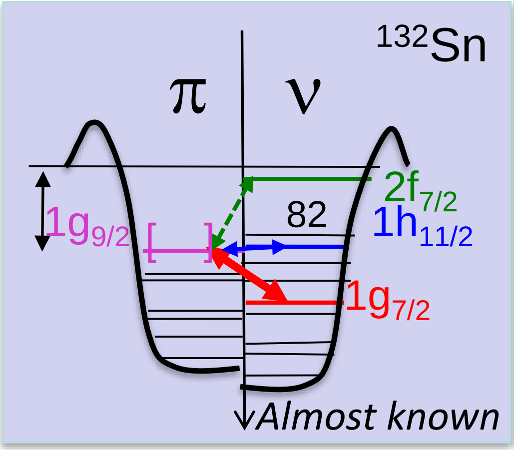


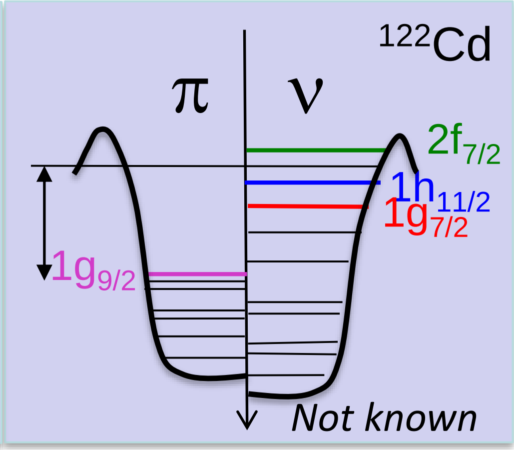
Hierarchy of nuclear forces





B. Pfeiffer, et al., NPA 693 (2001) 282





Same hierachy of nuclear forces

Shell re-ordering-> change lifetimes, σ_n

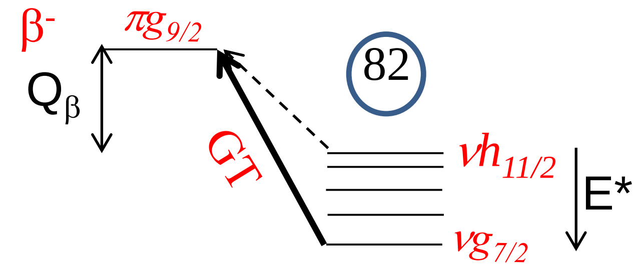
Takes more time to occur in heavy nuclei

Sorlin, Web of Conf. 66 (2014) 01016

Models must consider this hierarchy

$$\text{Around N=82:} \left|V^{pn}1g_{9/2}1g_{7/2}\right| >> \left|V^{pn}1g_{9/2}1h_{11/2}\right| > \left|V^{pn}1g_{9/2}2f_{7/2}\right|$$

Influence of pn interactions on beta-decay half-lives

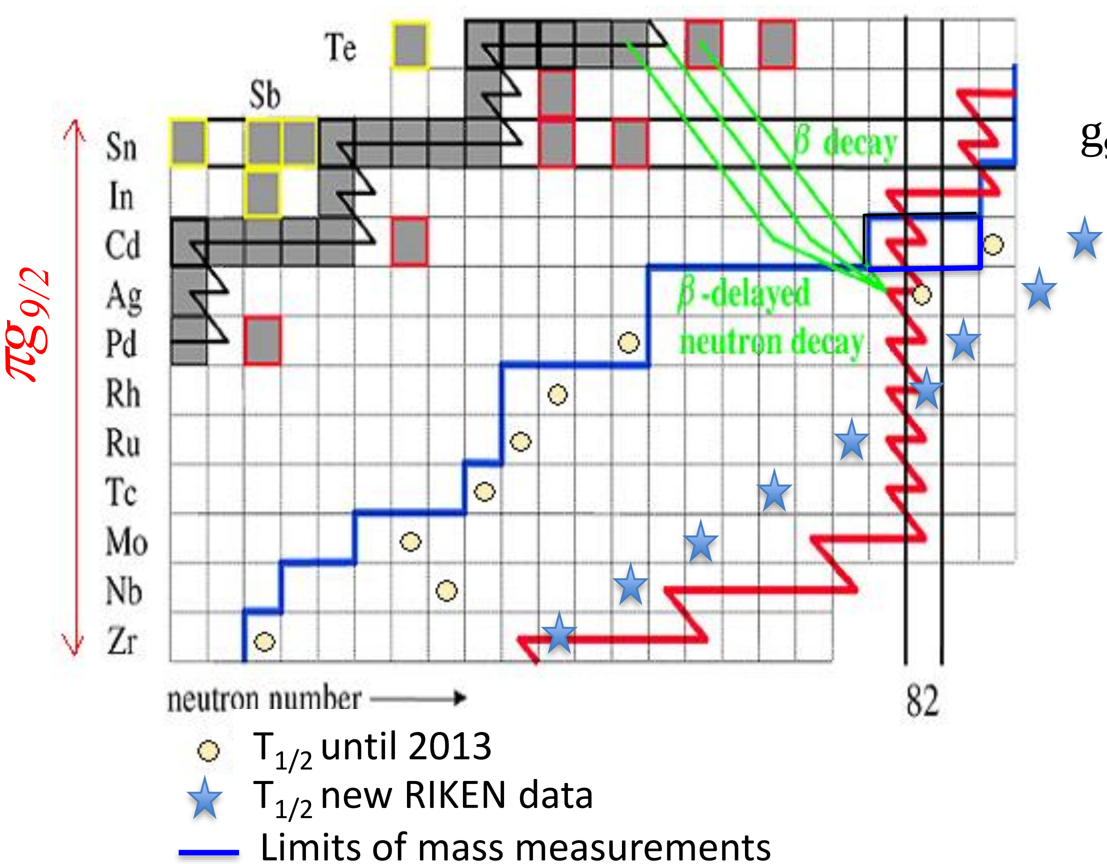


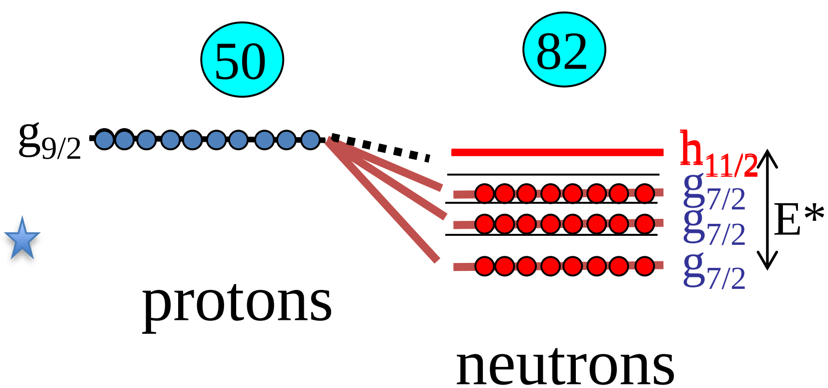
Gamow Teller transition $\Delta J=0, \pm 1, \Delta L=0$

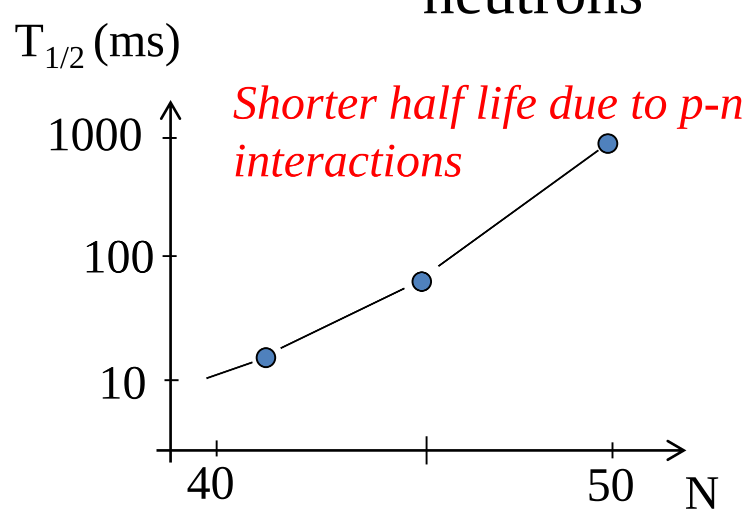
$1/T_{1/2} \approx S_{GT}(Q_\beta - E^*)^5$, E^* energy of the state

$T_{1/2}$ scales with energy of the transition, and strength of force

See also Cuenca-Garcia EPJA (2007)







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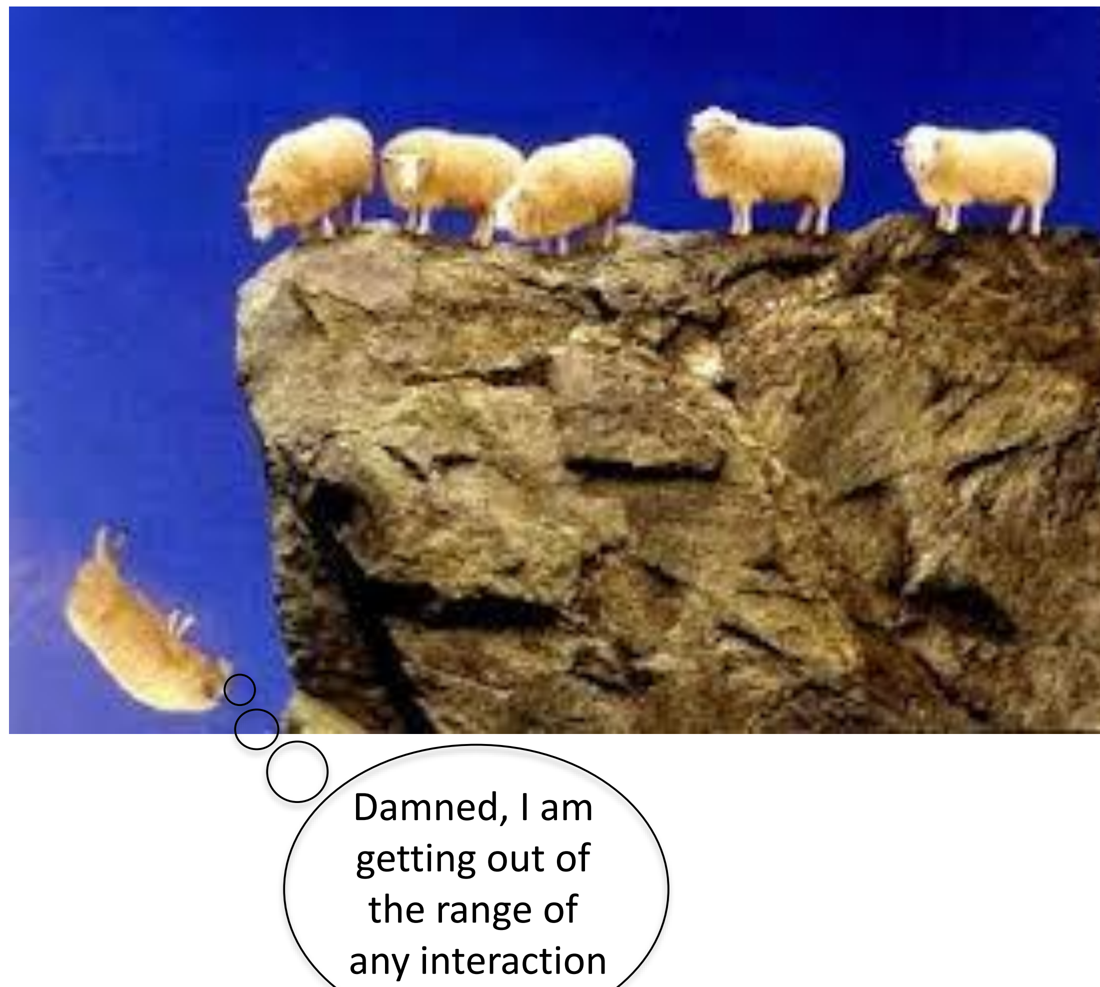
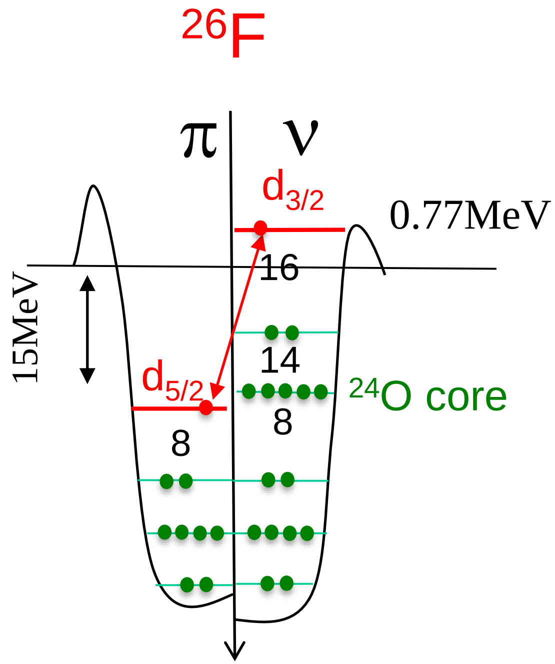
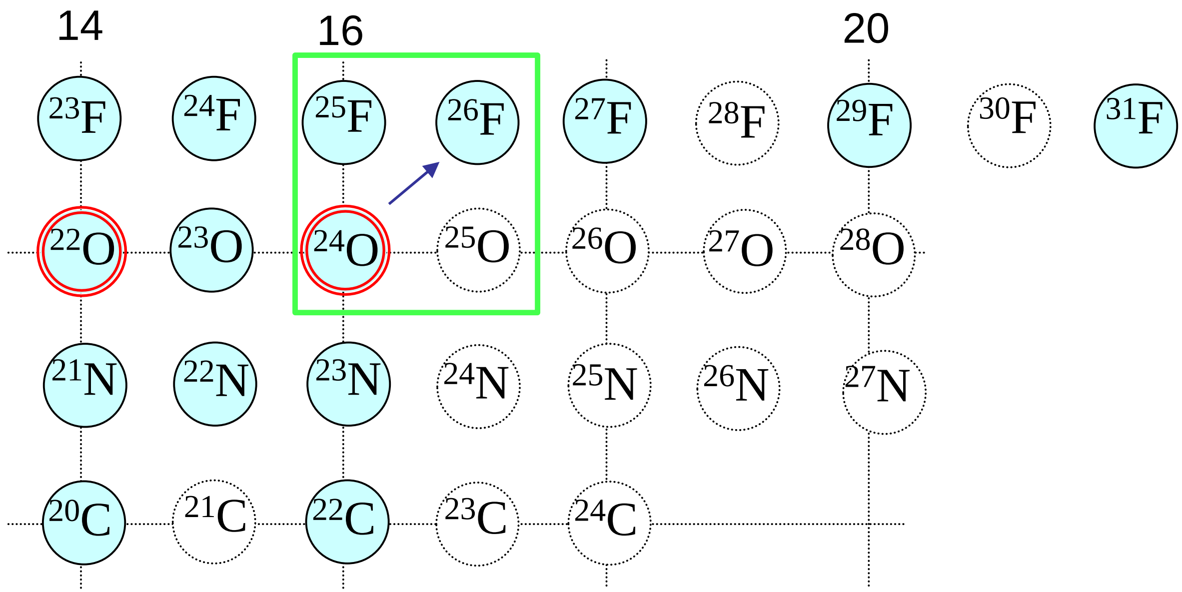


Nuclear forces in ^{26}F



C. R. Hofmann PRL 100 (2008)



Probe proton neutron forces with large binding energy asymmtery

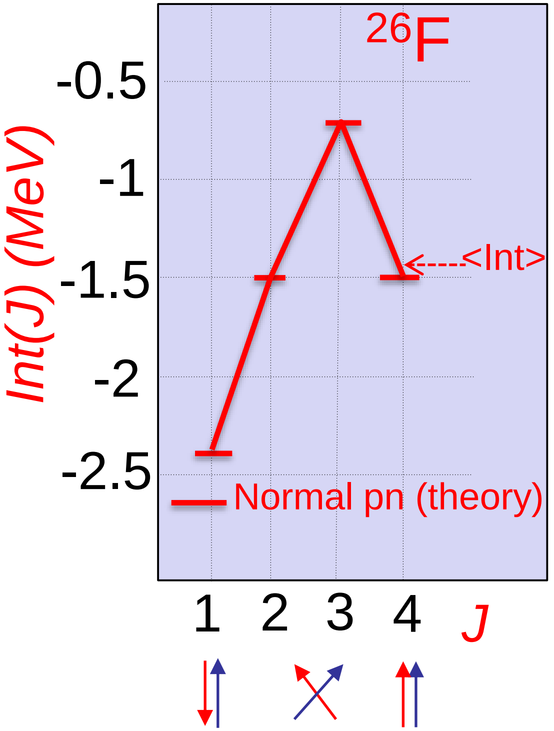
r process nucleosynthesis, shell evolution towards the drip-line

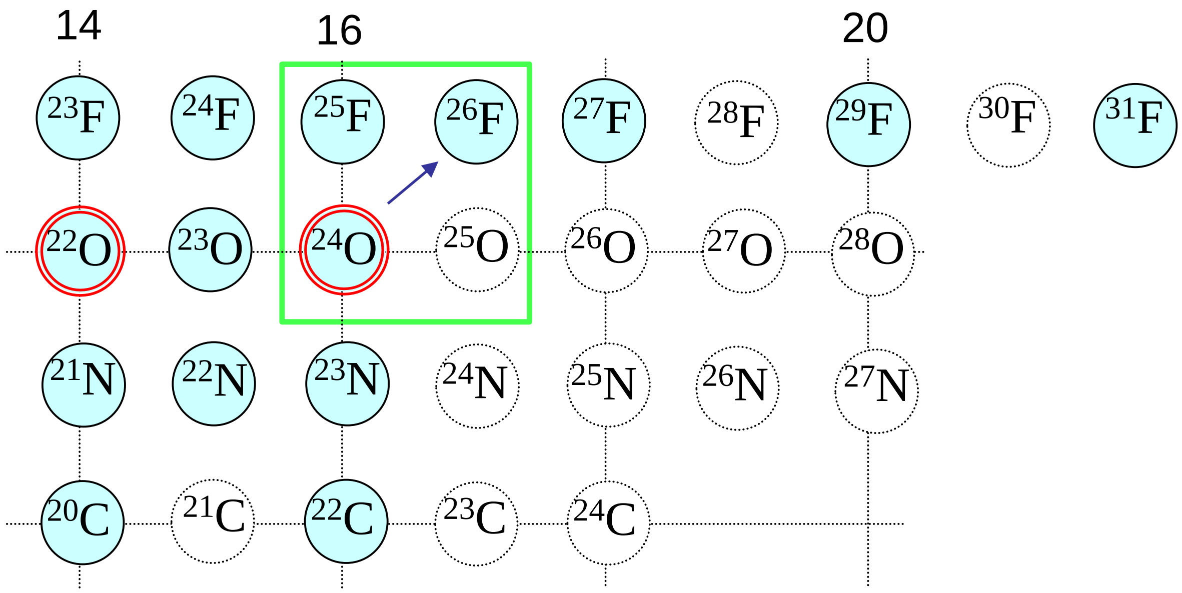
Extension of drip line in F, as compared to O

-> One single proton binds 6 more neutrons !

Coupling of proton $d_{5/2}$ and neutron $d_{3/2}$ -> $J=1,2,3,4^+$

Nuclear forces in ^{26}F





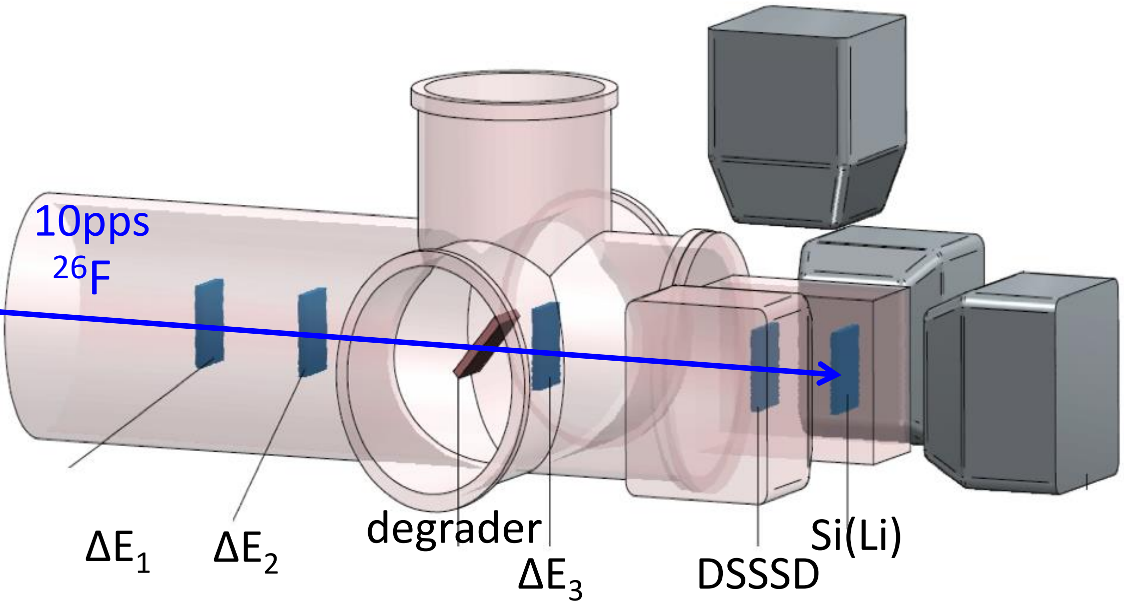
Calculated states of multiplet arranged in a parabolic shape (stable nucleus)

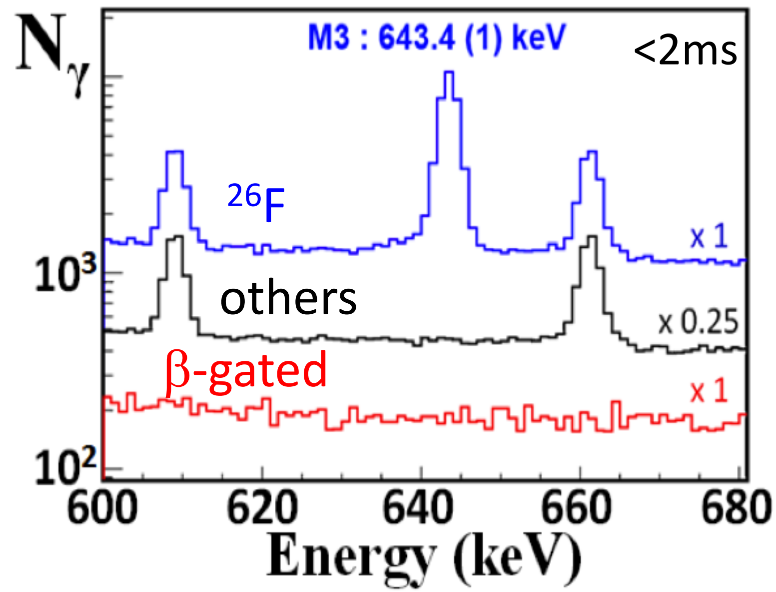
Determine the experimental energies of:

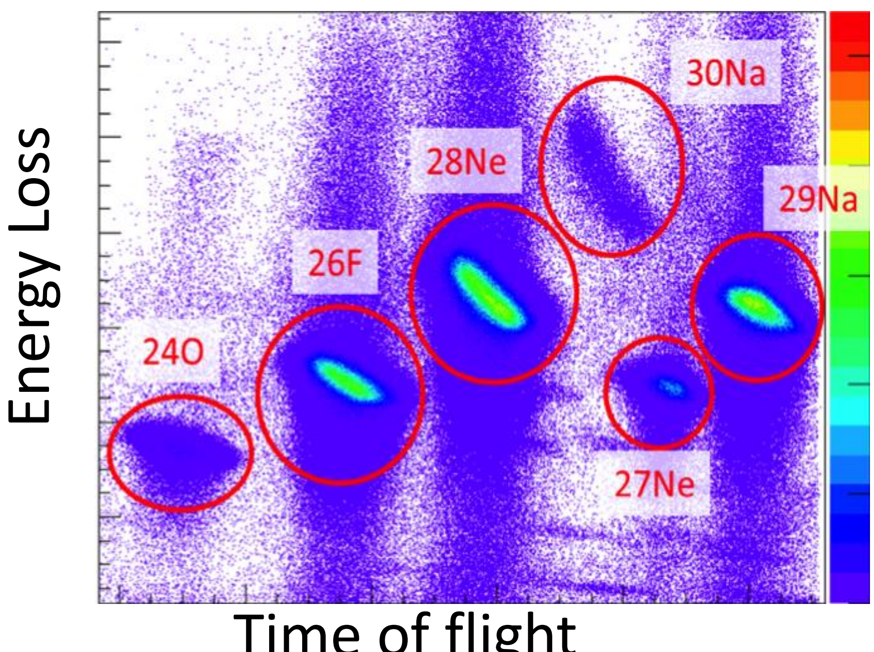
^{26}F g.s.: J=1$^+$ / J=4$^+$ isomer / J=2$^+$ prompt γ-decay / J=3$^+$ neutron unbound

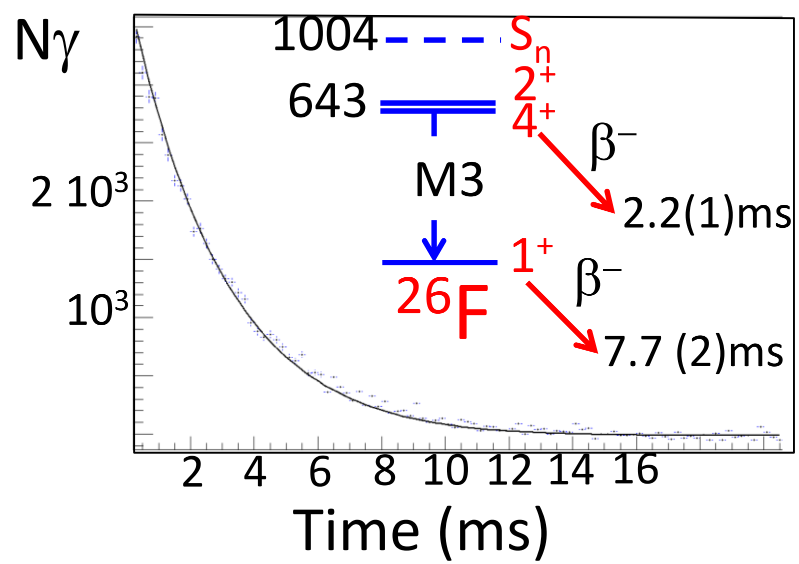
->Compare to calculated mean energy and amplitude of multiplet
-> Effect of the drip line ?
-> Requires different experimental techniques

Discovery of a 4^+ isomer in ^{26}F



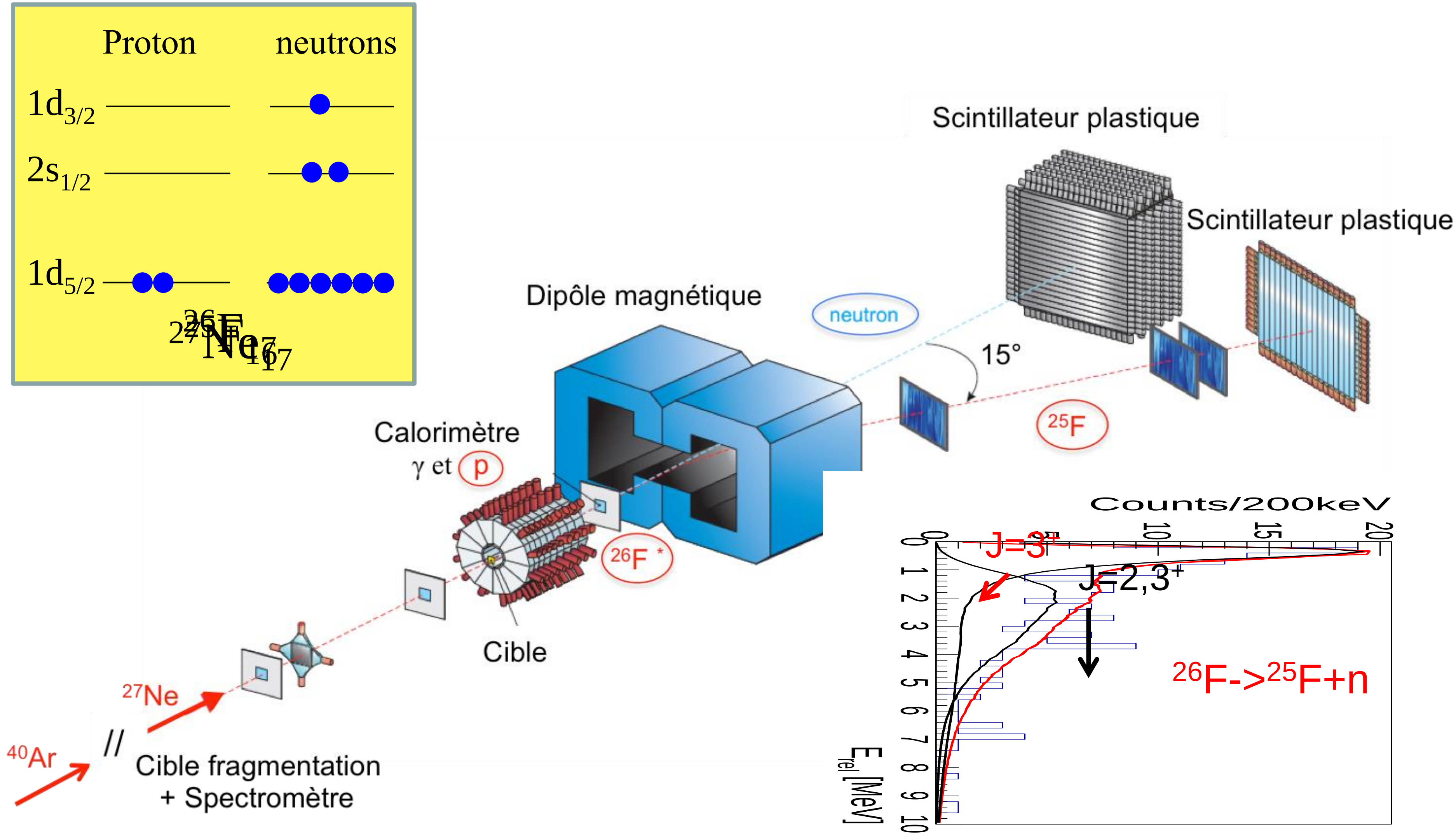






A. Lepailleur et al. Phys. Rev. Lett. 110 (2013

J=3$^+$ unbound states in ^{26}F studied at GSI/LAND

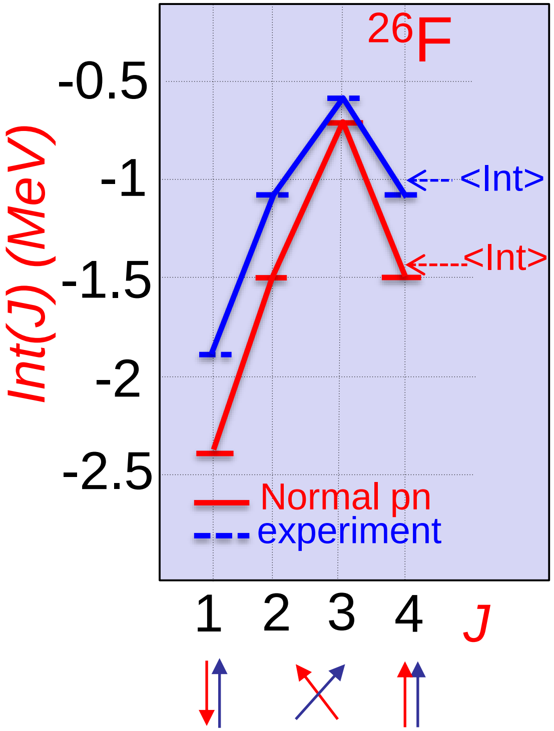


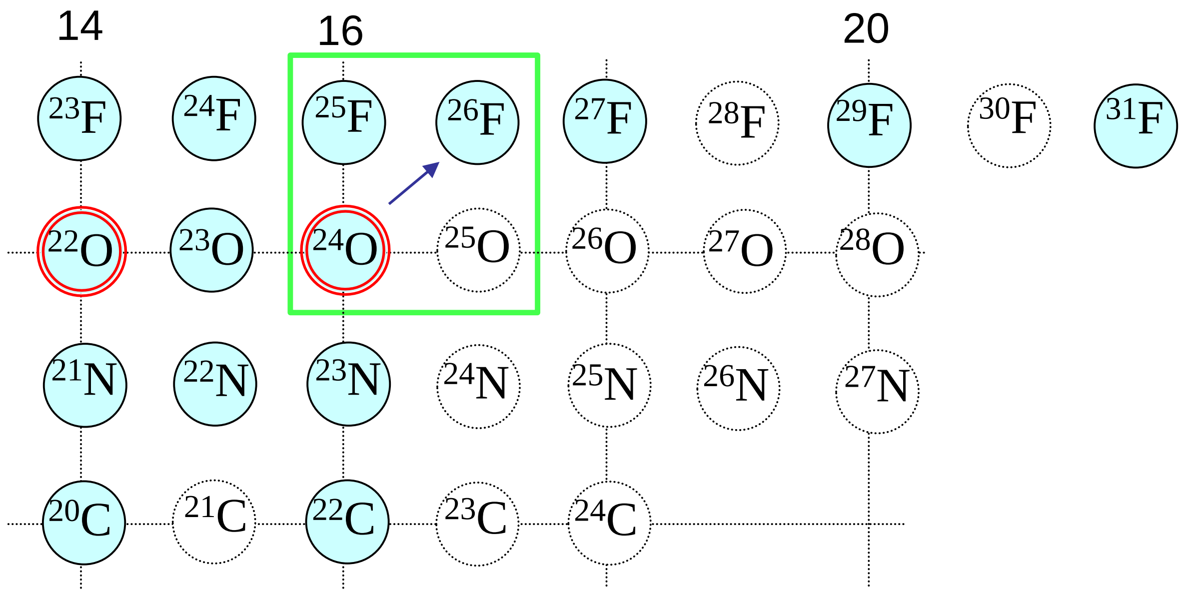
Excellent J=3$^+$ candidate at 350 keV

M. Vandebrouck, to be submitted to PRC

Agrees with work of Franck et al. PRC 84 (2011)

Nuclear forces in ^{26}F





Probe proton neutron forces with large binding energy asymmtery

r process nucleosynthesis, shell evolution towards the drip-line

At drip line -> Mean interaction and correlations reduced by about 30 %

Not yet considered in theoretical models ….

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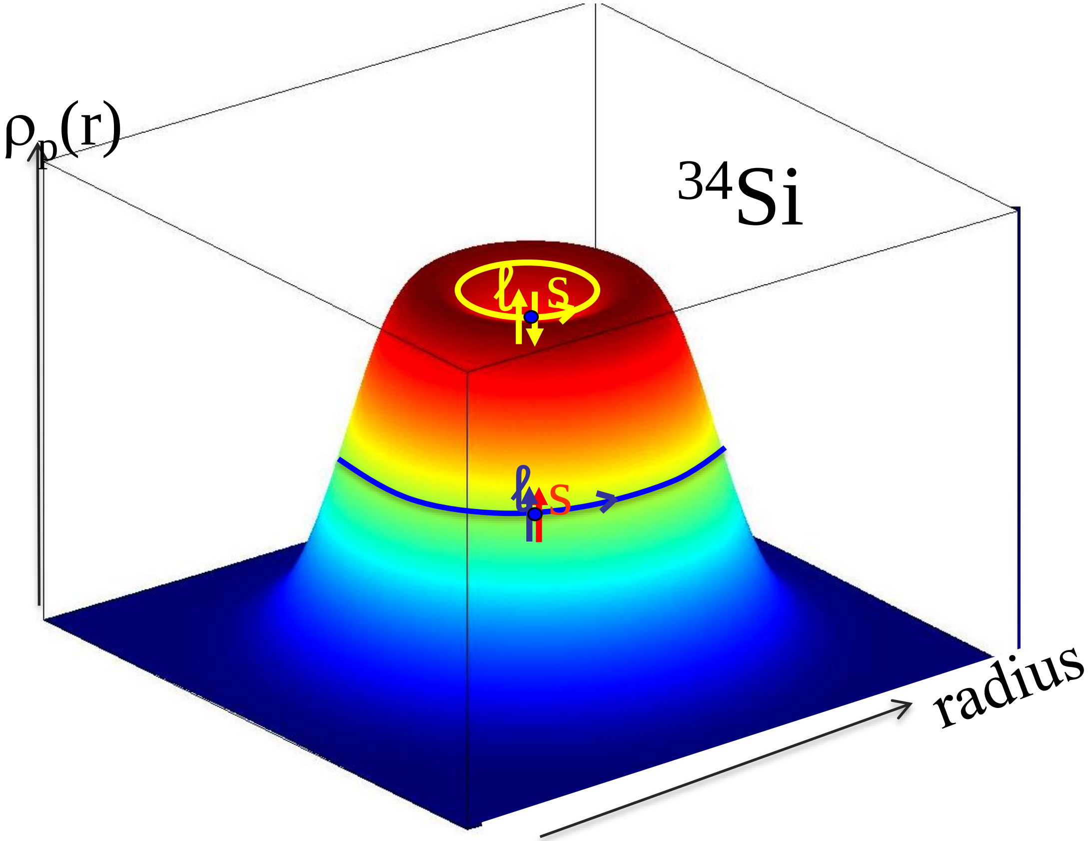


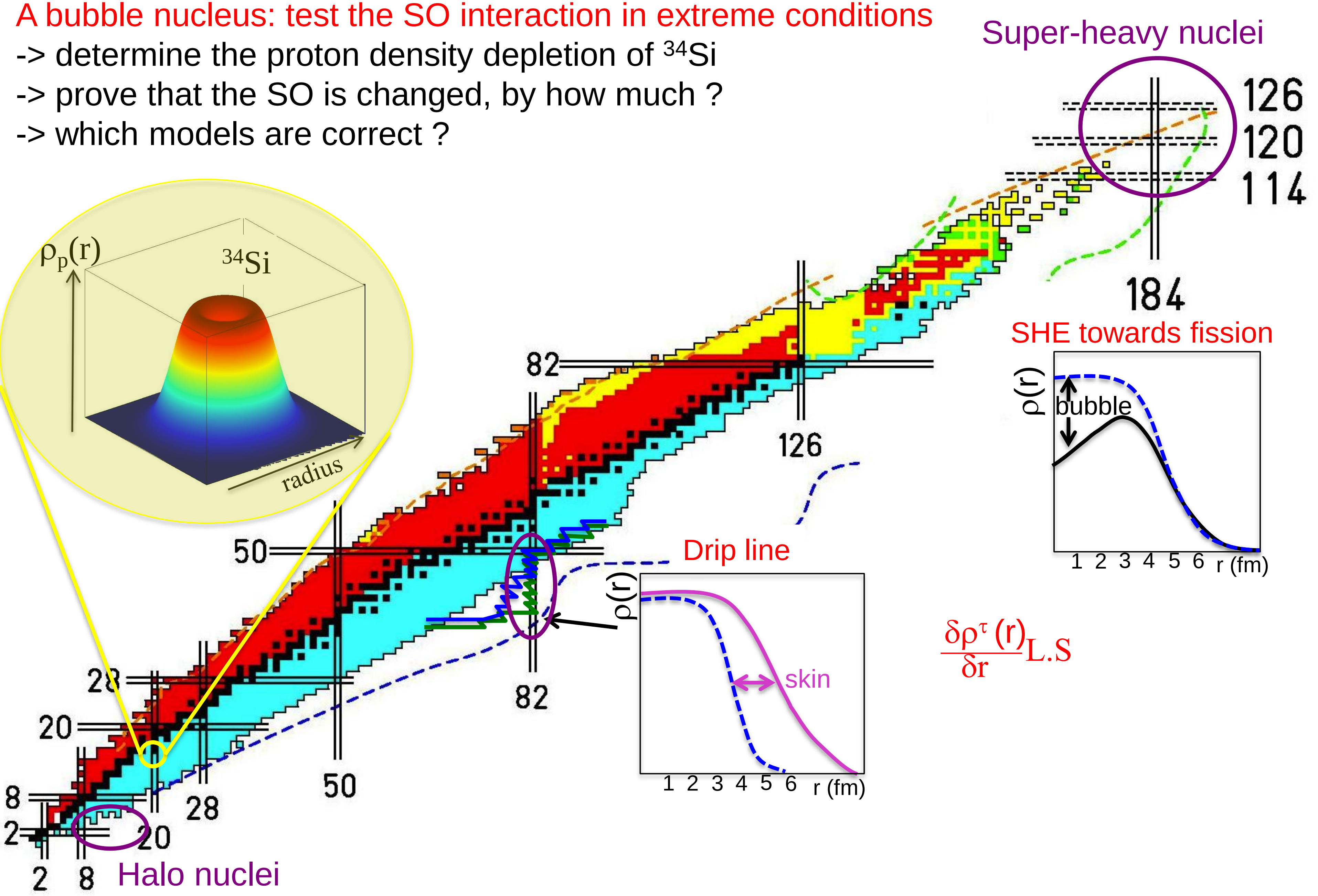
Spin Orbit interaction towards the extremes

A bubble nucleus: test the SO interaction in extreme conditions

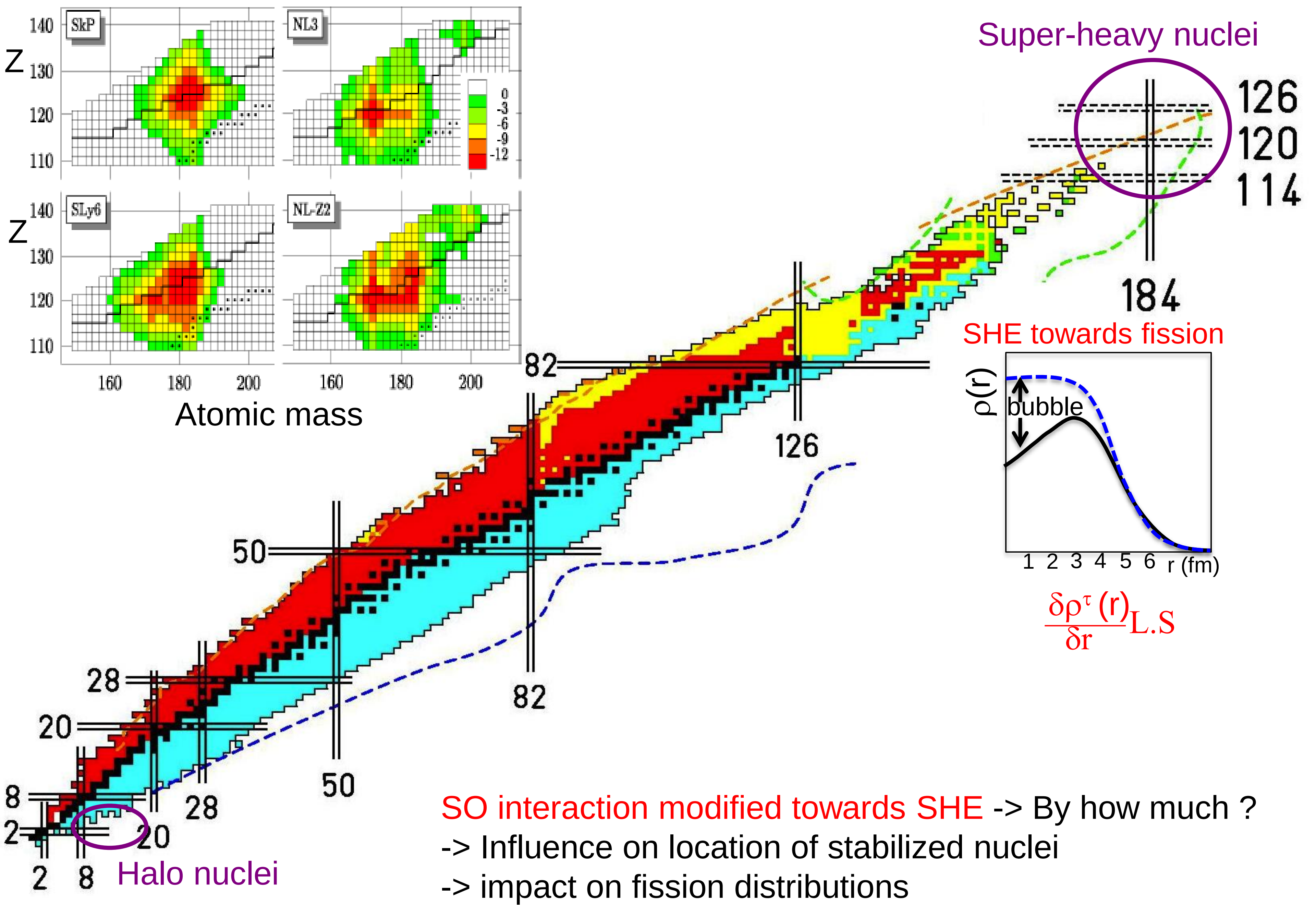
-> determine the proton density depletion of ^{34}Si

-> prove that the SO is changed, by how much ?

-> which models are correct ?



Spin Orbit interaction towards the extremes



SO interaction modified towards SHE -> By how much ?

-> Influence on location of stabilized nuclei

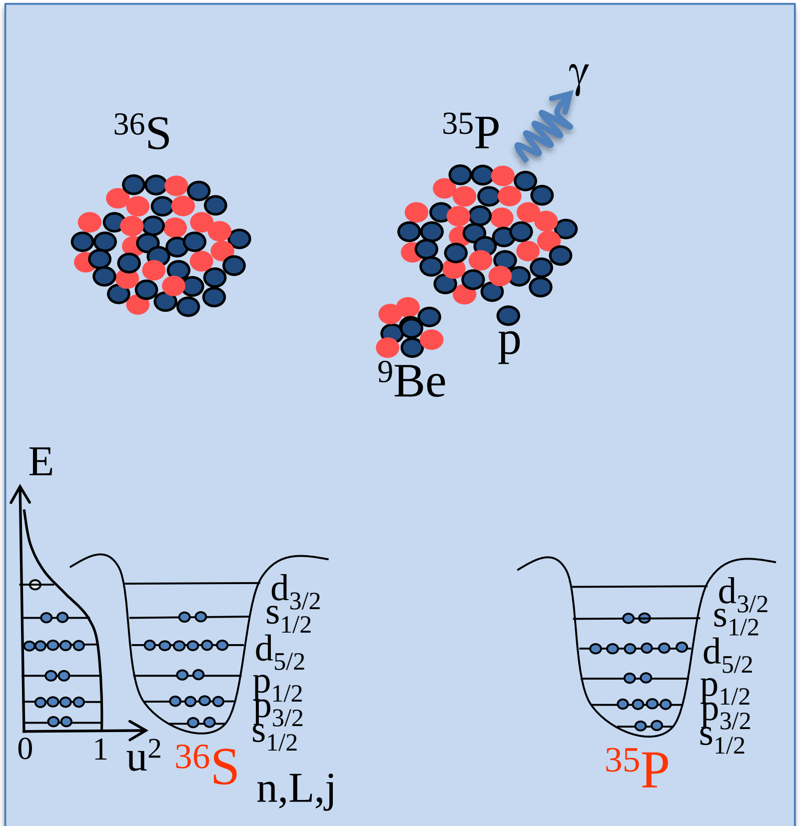
-> impact on fission distributions

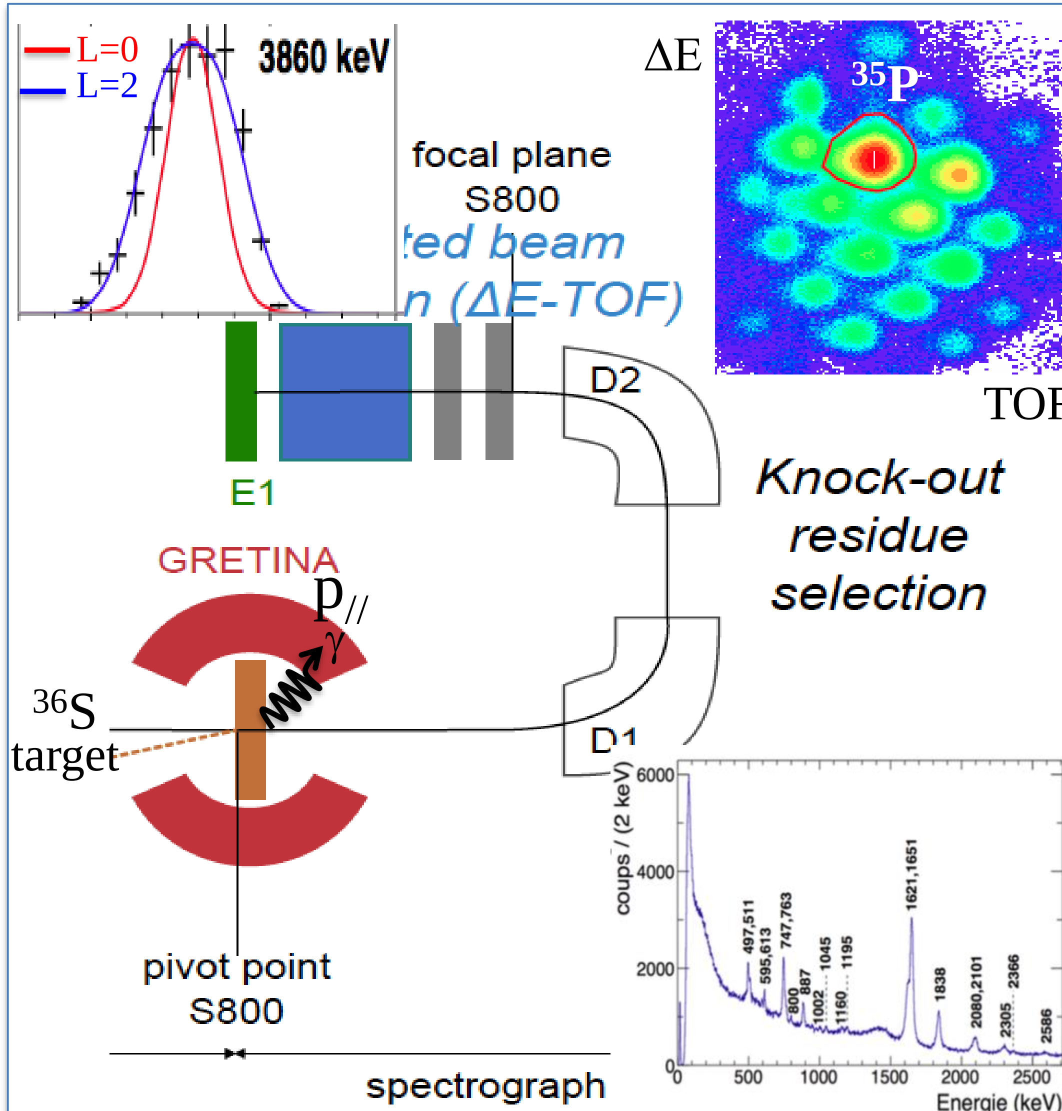
Probing proton densities in ^{36}S and ^{34}Si

Knock-out reactions at $\beta \approx 0.4$

$$\sigma(n,L) = C^2 S\,(j,n,L) \quad \sigma_{sp}(j,S_p)\,R_S$$

normalized occupancy — *reaction theory*





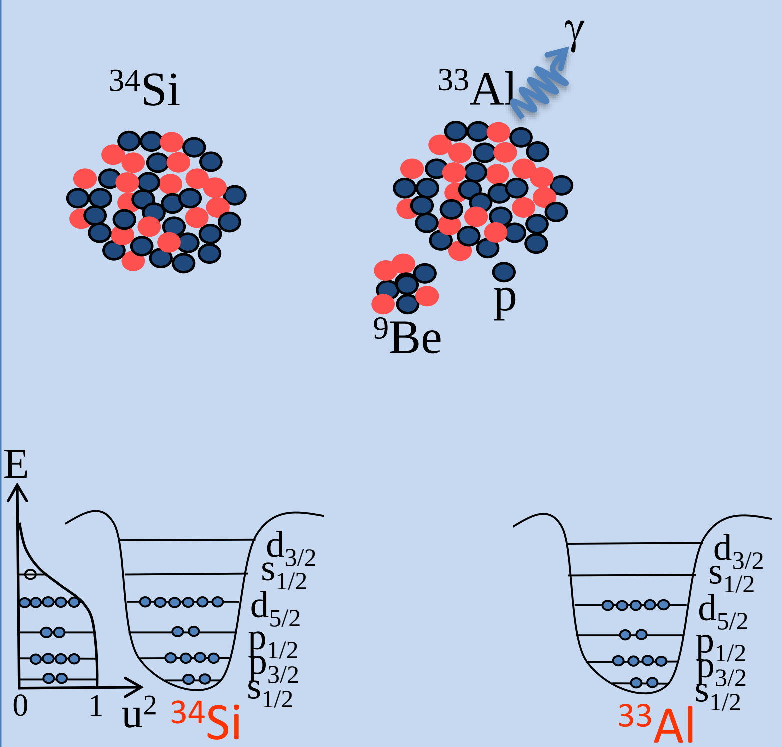
Large ^{36}S(-1p) cross section for L=0 knock out -> $s_{1/2}$ orbit is almost fully occupied in ^{36}S

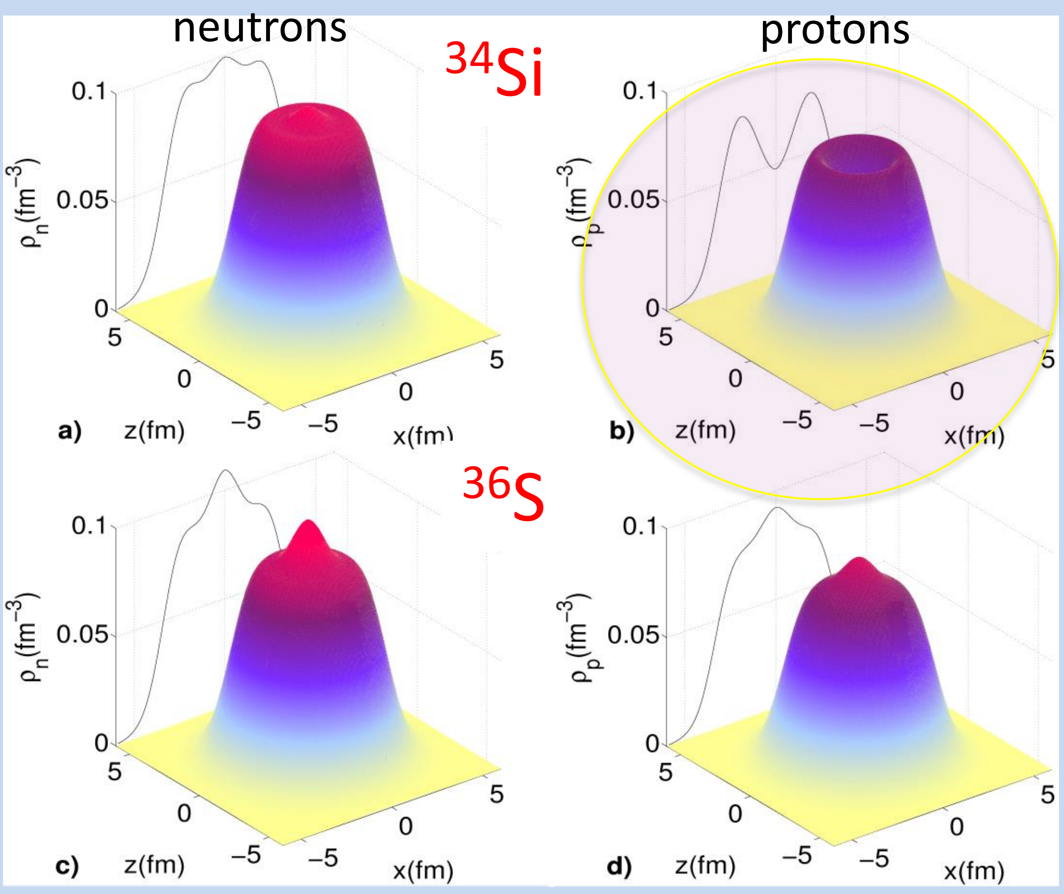
Probing proton densities in ^{34}Si

Knock-out reactions at $\beta \approx 0.4$

$$\sigma(n,L) = C^2 S(j,n,L) \quad \sigma_{sp}(j,S_p)\, R_S$$

occupancy *reaction theory*





In ^{34}Si, the proton $s_{1/2}$ is occupied by less than 10% -> central depeletion

Neutron density distributions of ^{34}Si and ^{36}S look similar

A. Mutschler, submitted to Nature Physics

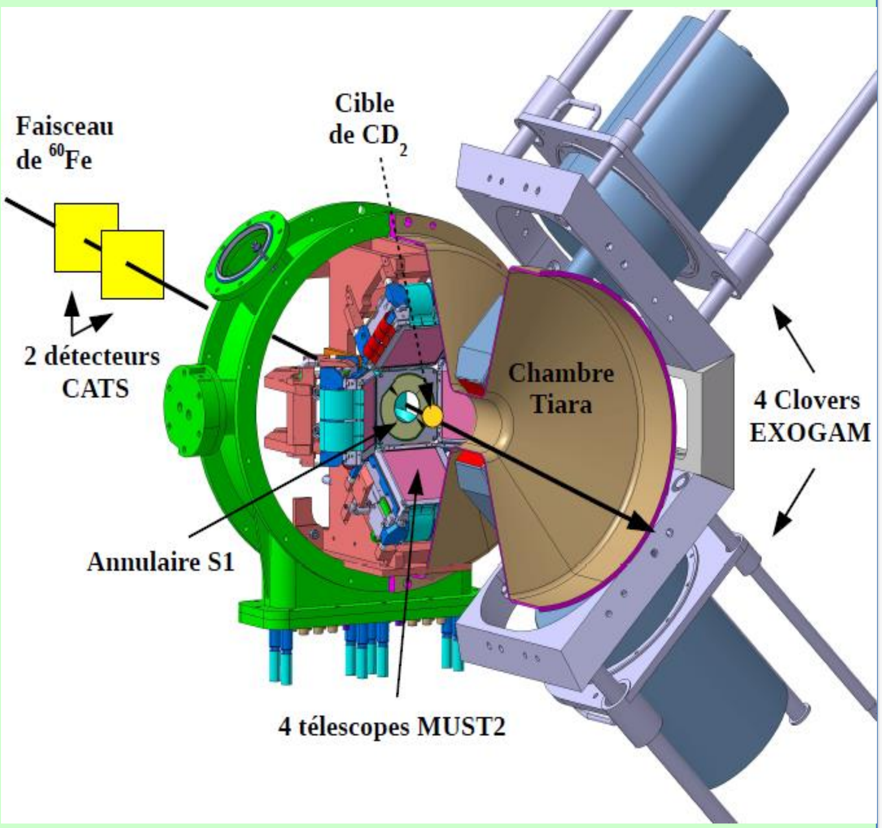
^{34}Si(d,p) reaction in inverse kinematics

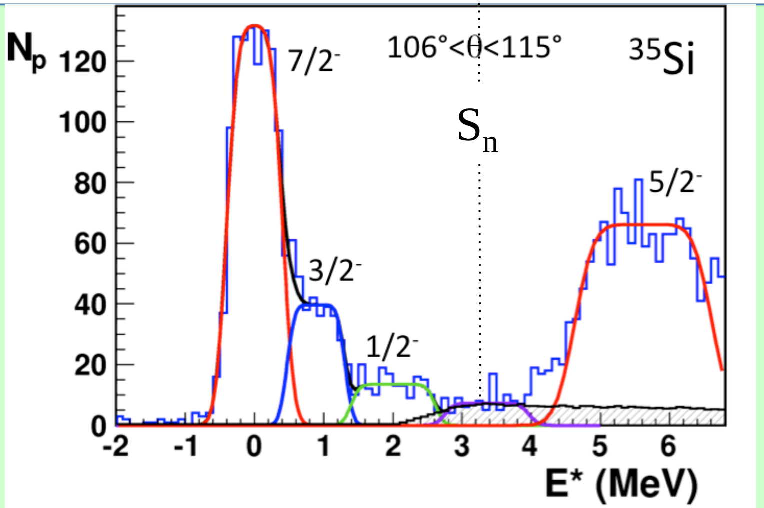
Transfer reaction (d,p) at $\beta \approx 0.15$

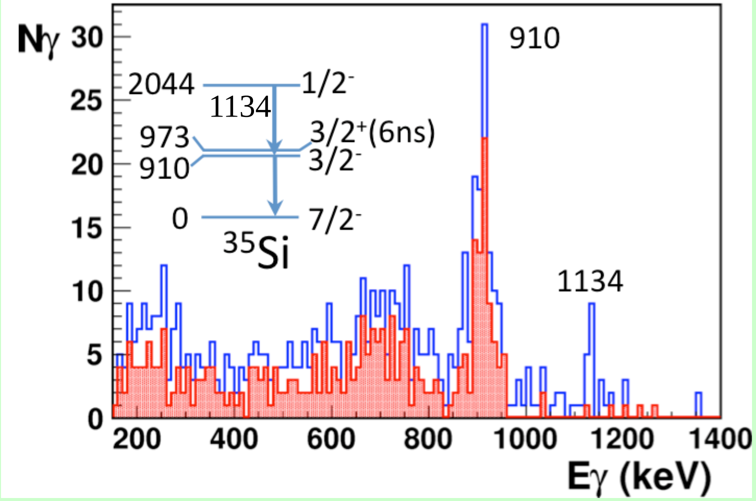
$$\frac{d\sigma(n,L,\theta)}{d\Omega} = (2j+1)\, C^2S^+ \frac{d\sigma_{AWBA}(n,L,\theta)}{d\Omega}$$

vacancy *reaction theory*

Proton energy -> (binding) energy of orbit
Proton angle -> orbital momentum L
Cross section -> vacancy of the orbit
Appropriate momentum matching required



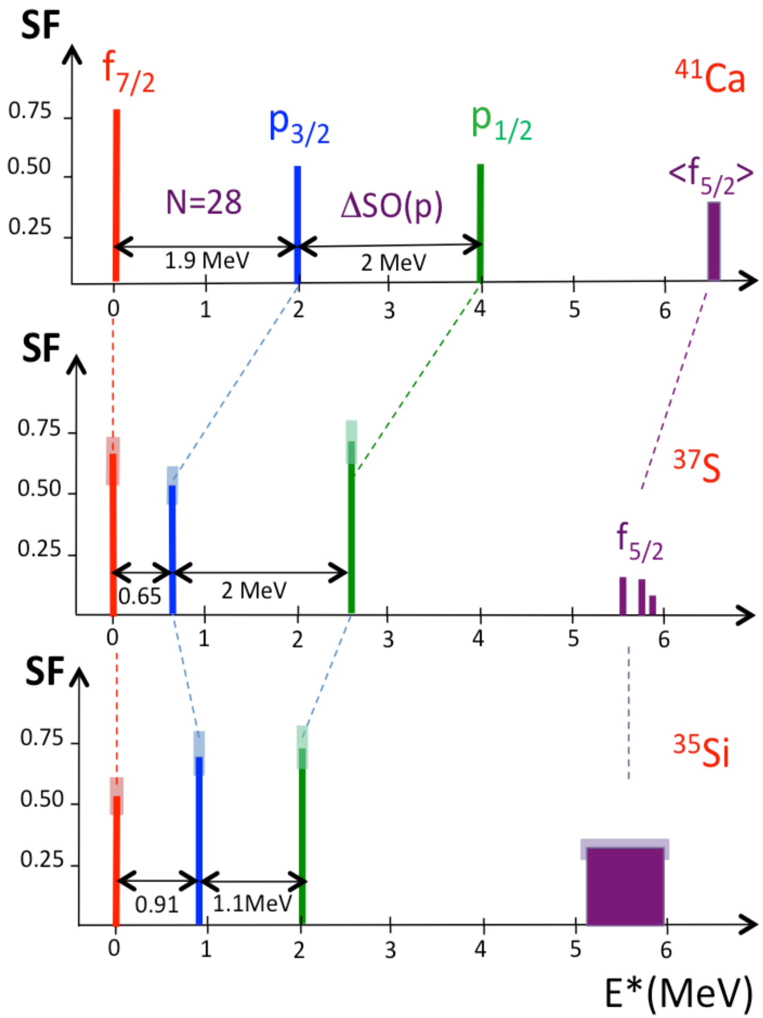


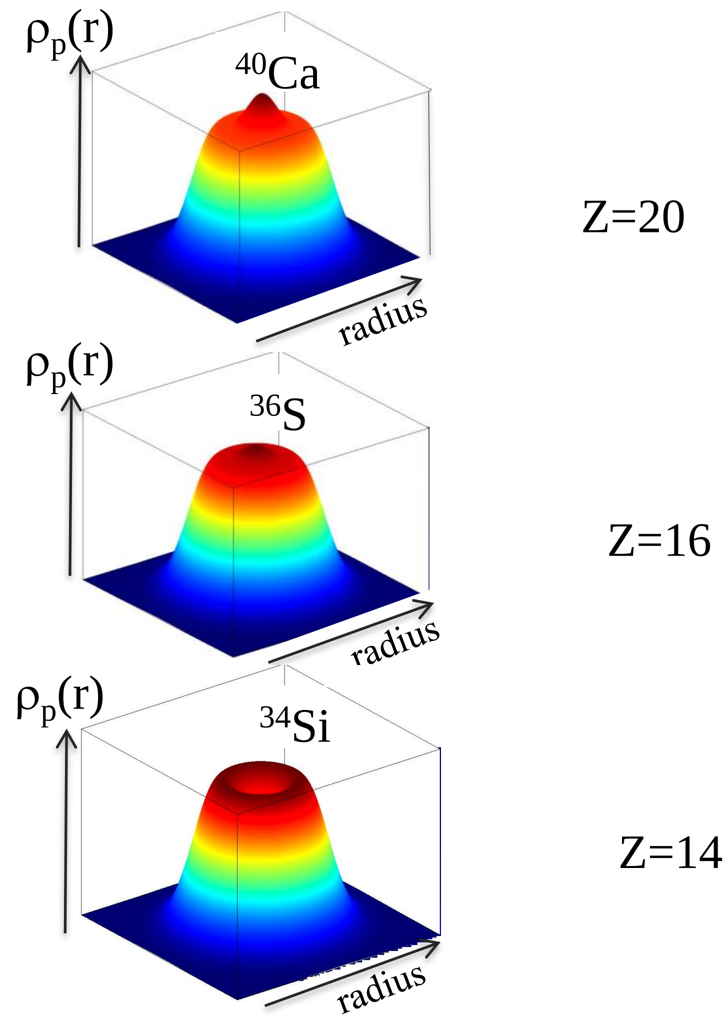


Evolution of the $p_{3/2}$-$p_{1/2}$ SO splitting

Use of (d,p) reaction to determine the change in SO interaction in the N=20 nuclei

G. Burgunder, Phys. Rev. Lett. 112 (2014)

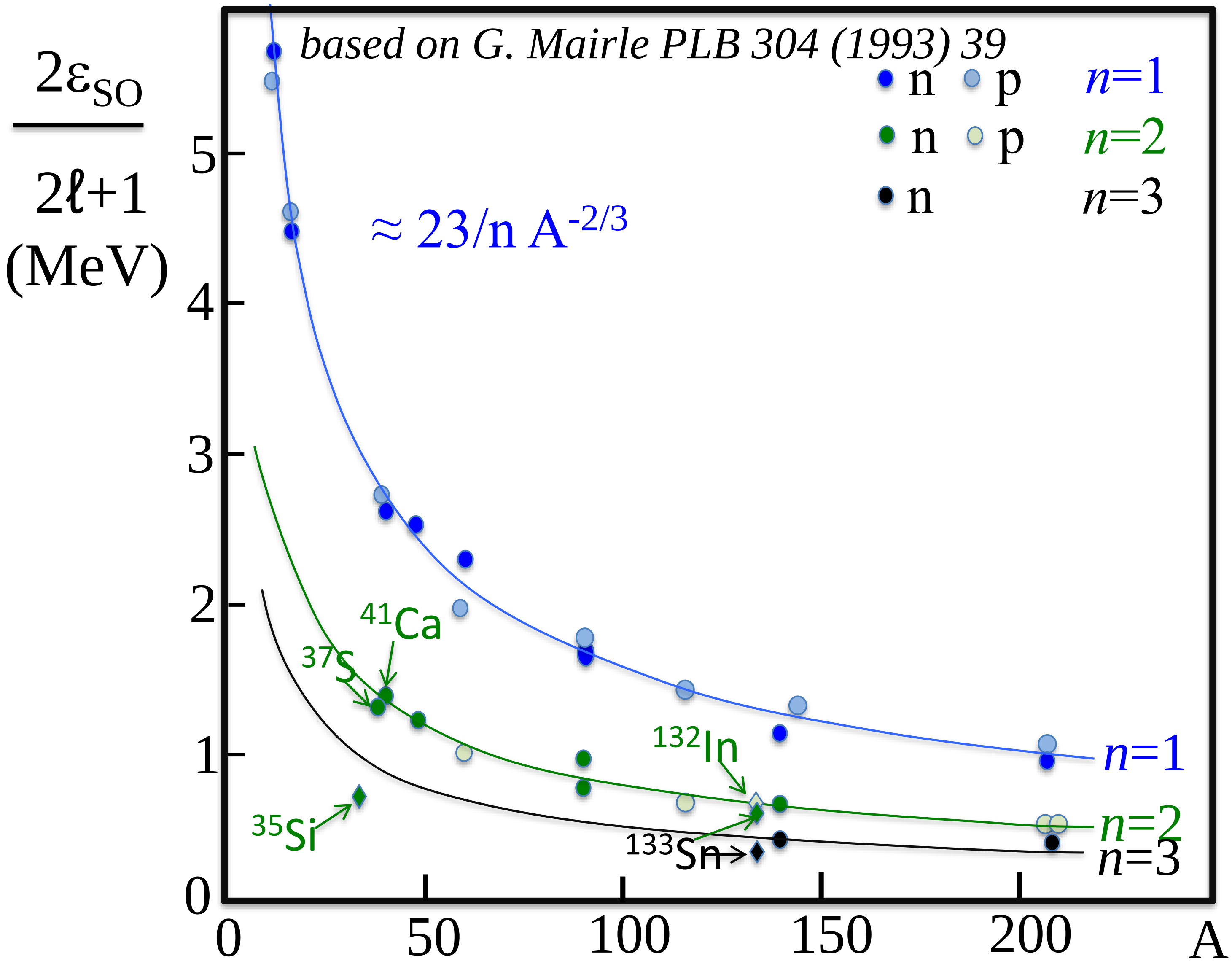




The $p_{3/2}$-$p_{1/2}$ splitting changes by almost a factor of 2 between ^{37}S and ^{35}Si

Density dependence of the SO interaction proven – Isospin dependance constrained

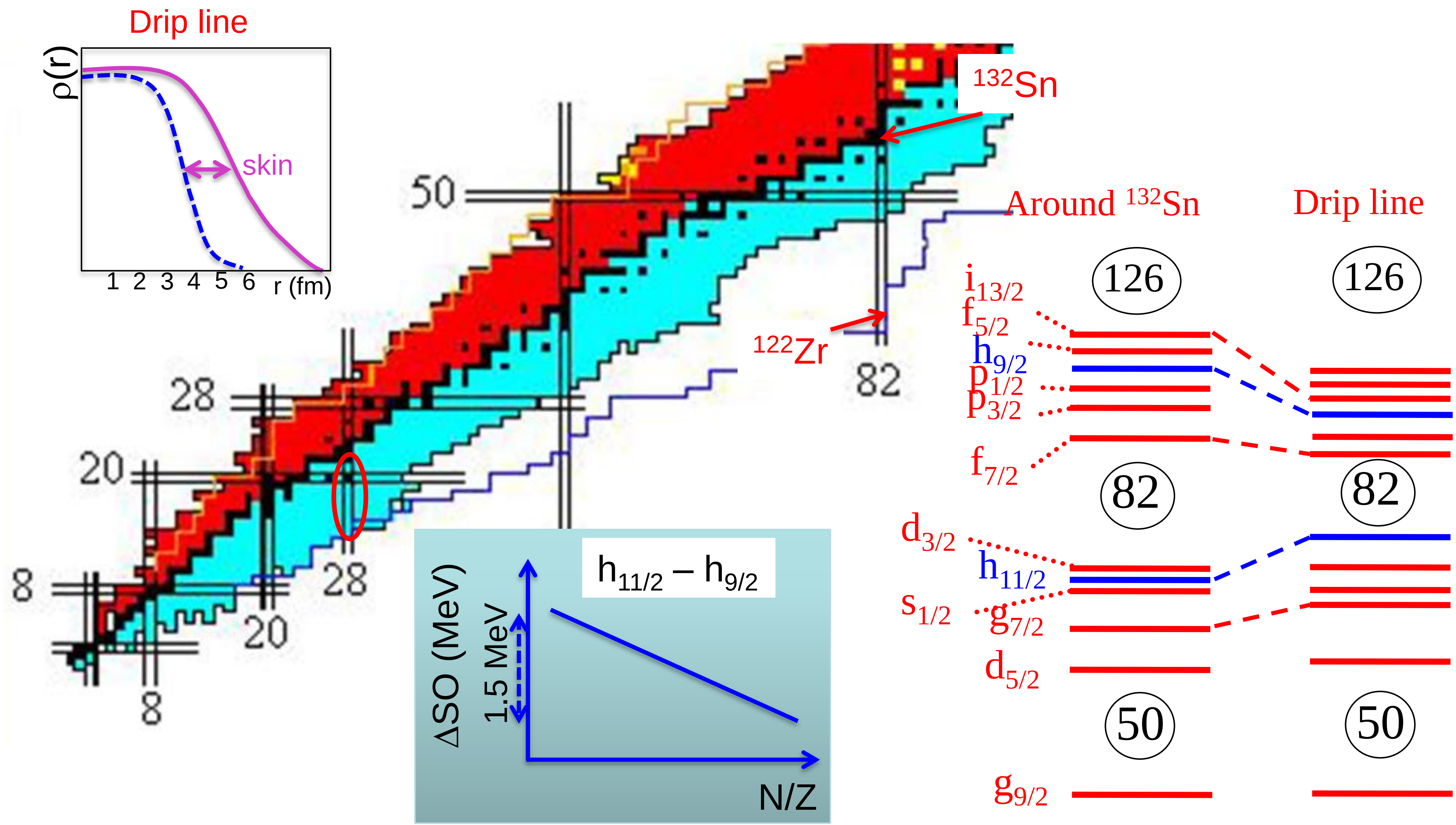
Systematics of SO splittings



The result of ^{35}Si strongly deviates as compared to all other systems

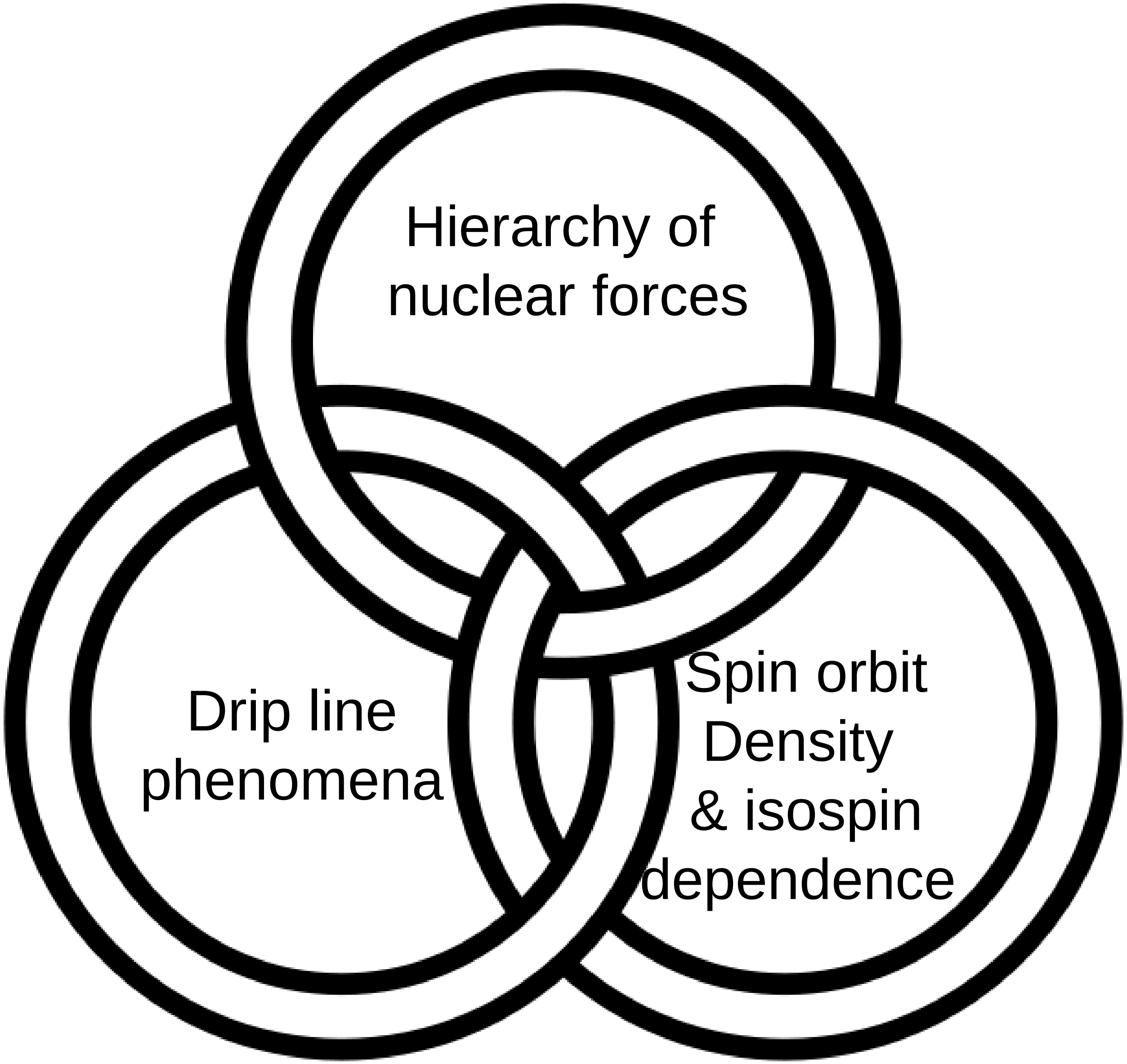
Shell evolution far from stability

Combined actions of different forces SO, tensor …

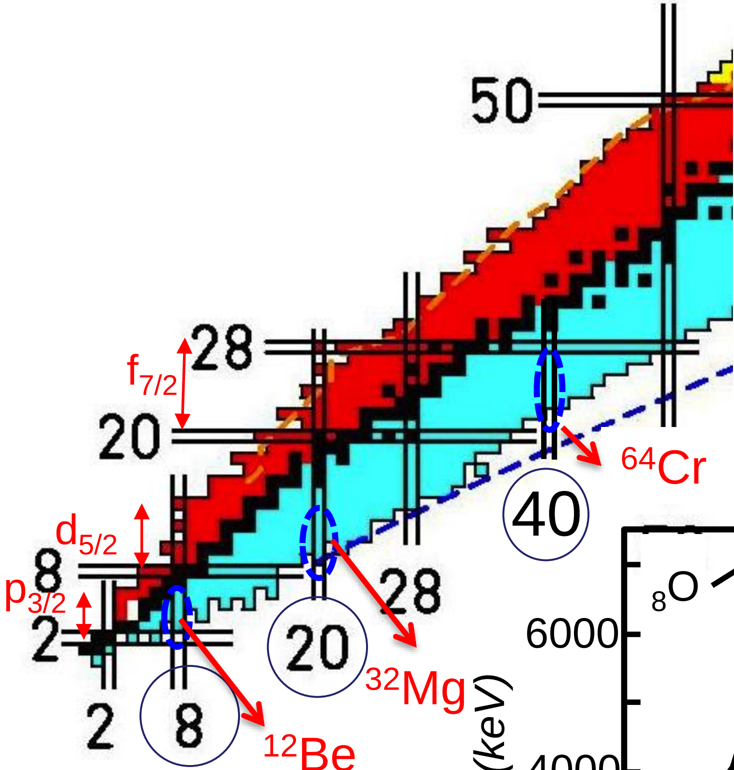


How does the SO interaction changes with surface diffuseness ? -> depends on model …

Shell evolutions far from stability



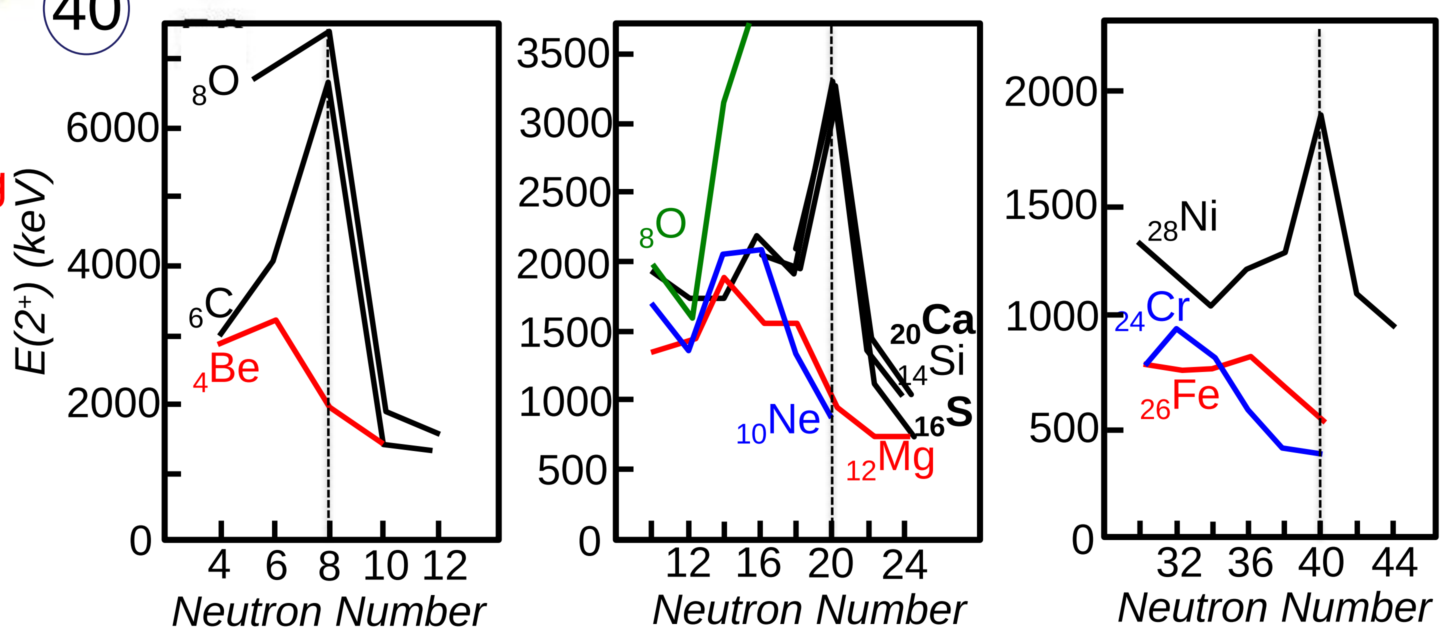
Harmonic oscillator magic numbers



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

If our universe was more neutron-rich
HO magic numbers would have not been present
N=14, 16 new local closed shells
e.g. Stanoiu PRC 69 (2004), Hoffmann PLB 672(2009)

Which mechanisms -> dramatic changes ?
e.g. Sorlin, Porquet PPNP 61 (2008), Phys. Scr T 152 (2013)
Otsuka Phys. Scr T152 (2013)



N=40
↳ Hannawald PRL 82 (1999), Sorlin, EPJA16 (2003), Aoi, PRL 102 (2009)
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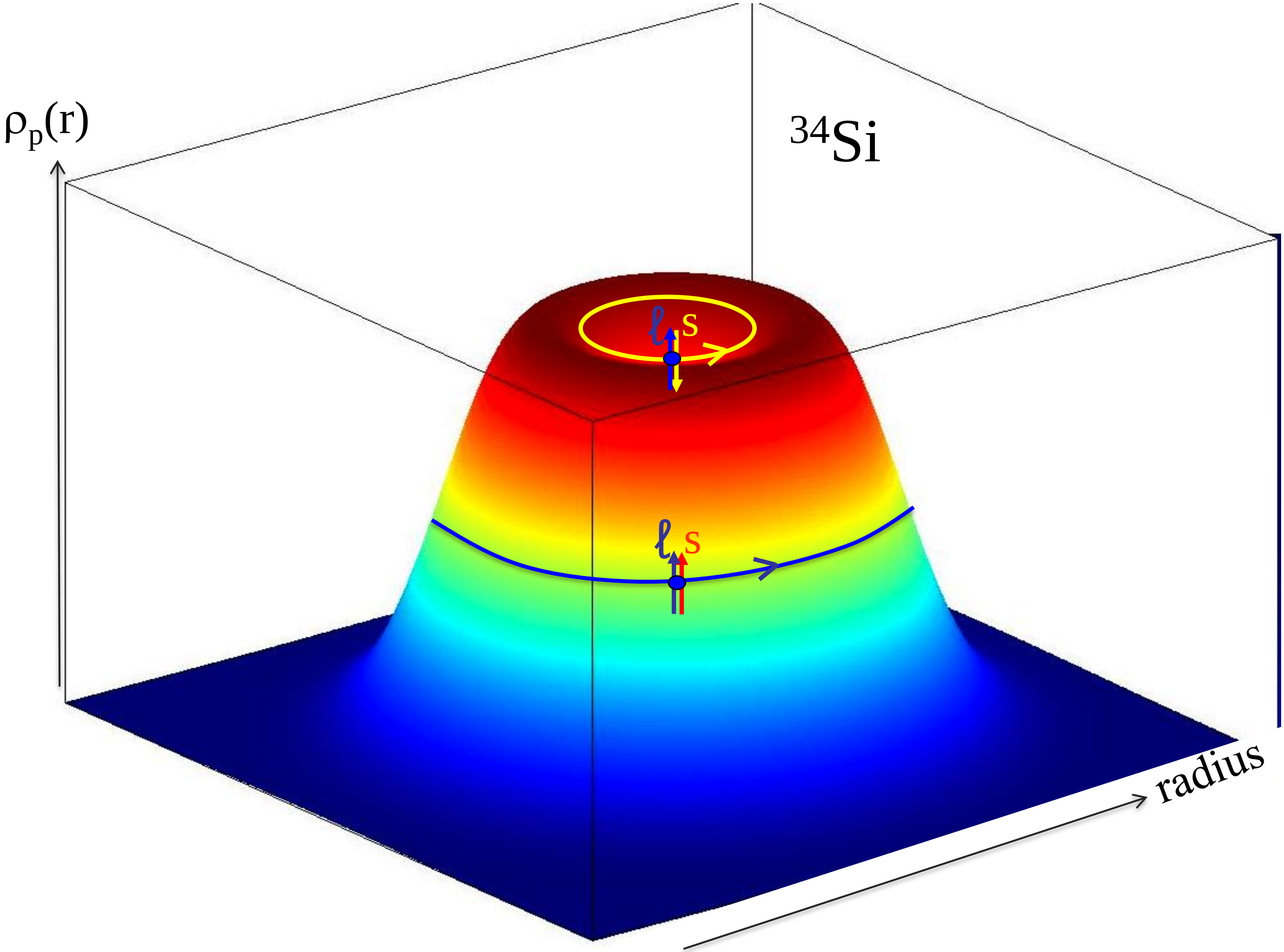
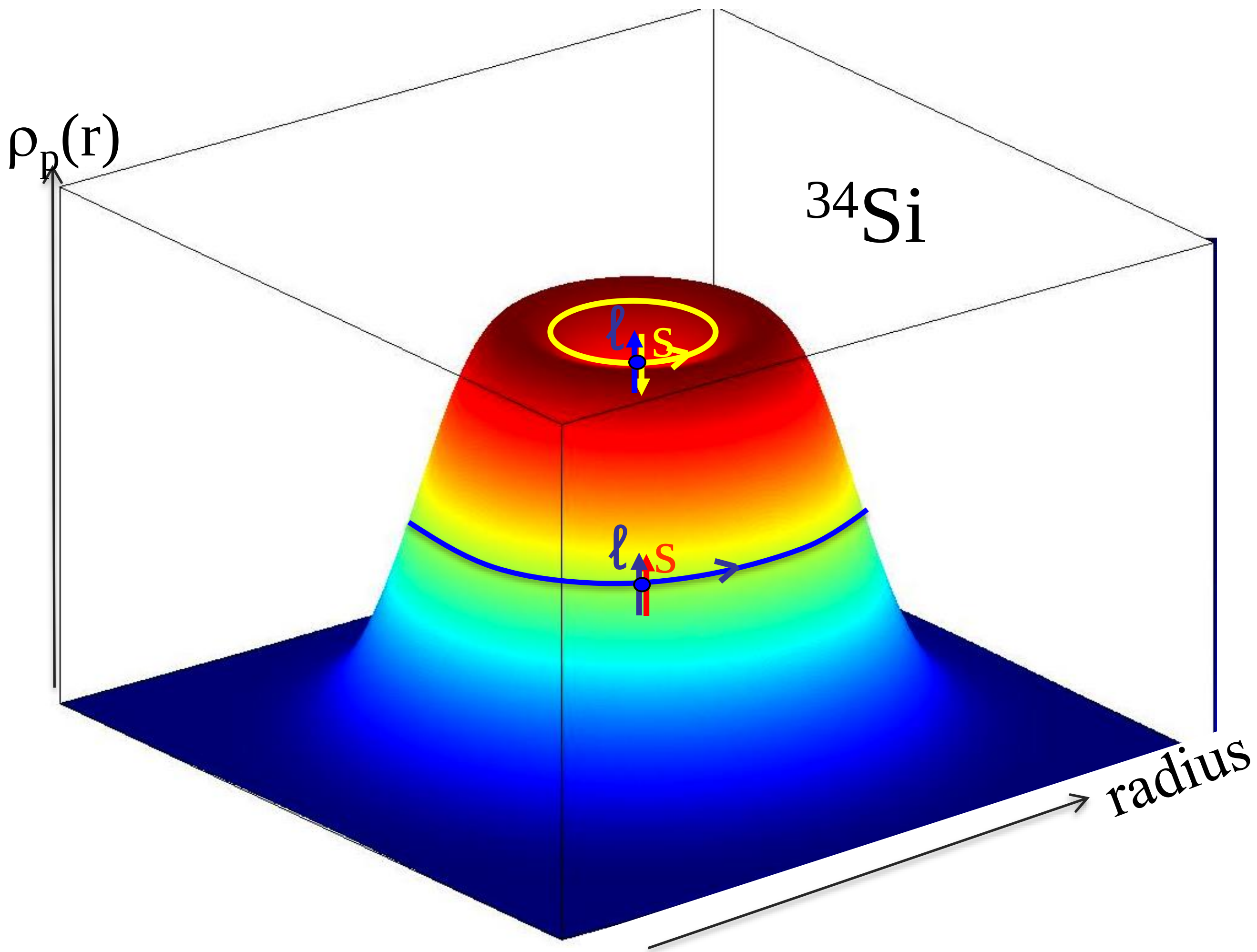
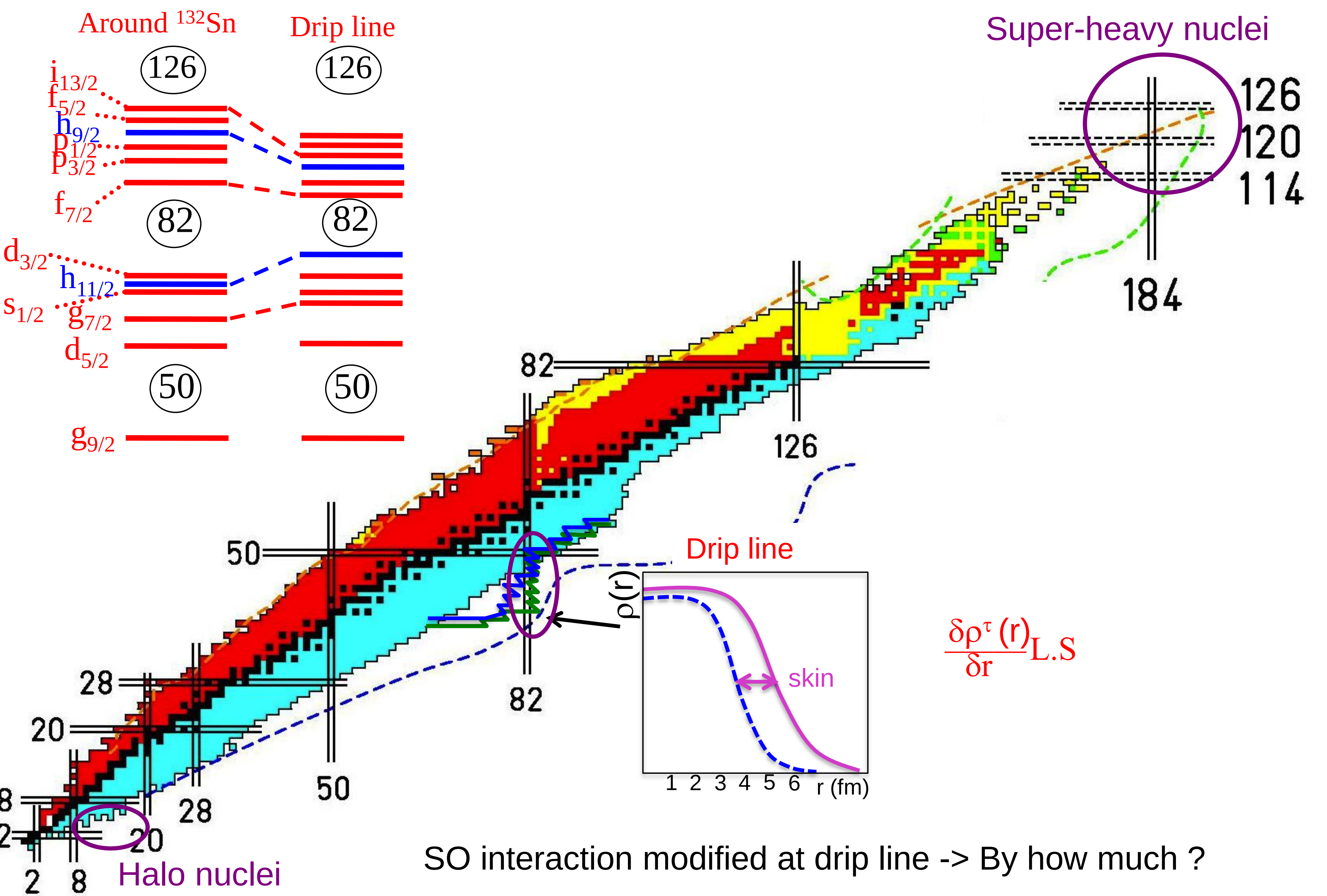
Density dependence of the spin orbit interaction



Density dependence of the spin orbit interaction

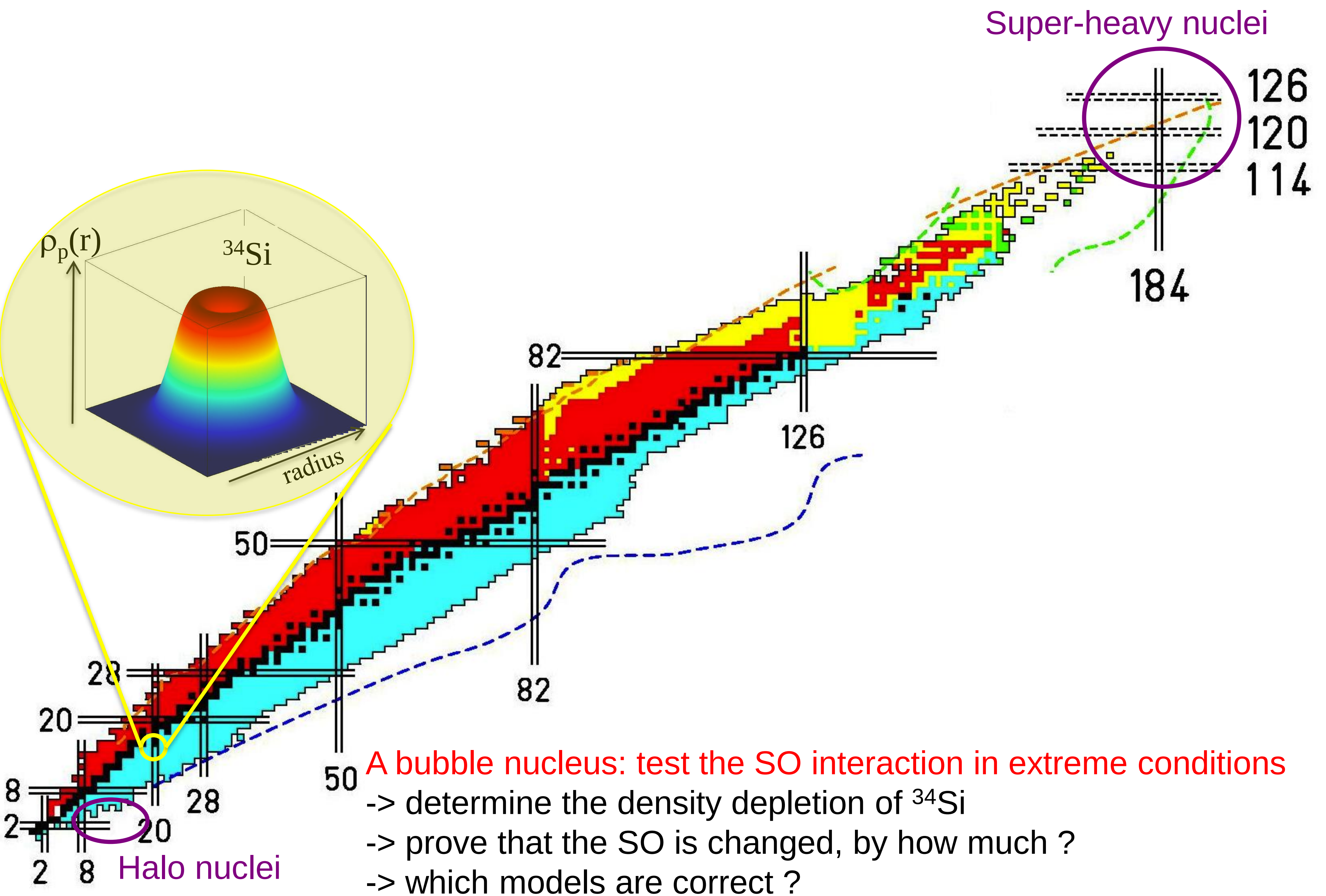


Spin Orbit interaction towards the extremes



SO interaction modified at drip line -> By how much ?

Spin Orbit interaction towards the extremes



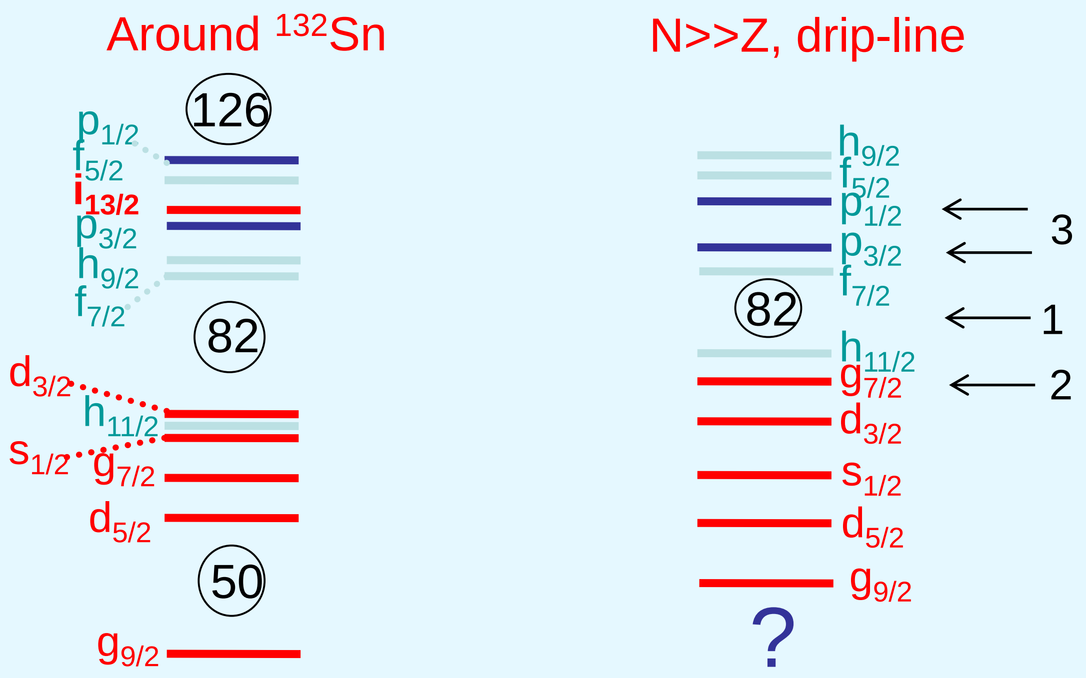
A bubble nucleus: test the SO interaction in extreme conditions

-> determine the density depletion of ^{34}Si

-> prove that the SO is changed, by how much ?

-> which models are correct ?

Nuclear Shell Structure Evolution



Mean field near stability
Strong spin-orbit interaction

Reduced spin-orbit
Tensor forces
Mean field for N>>Z ?
Effect of continuum ?

Adapted from J Dobaczewski

Major consequences :

1 : Reduction/disappearence of shell gaps -> modify the shape of r abundance peaks
2 : Change of $g_{7/2}$ energy, increase the $g_{7/2} \rightarrow g_{9/2}$ GT transition, shorten β-decay lifetim
3 : The valence p states appear at weak excitation energy, favor neutron capure with ℓ_n