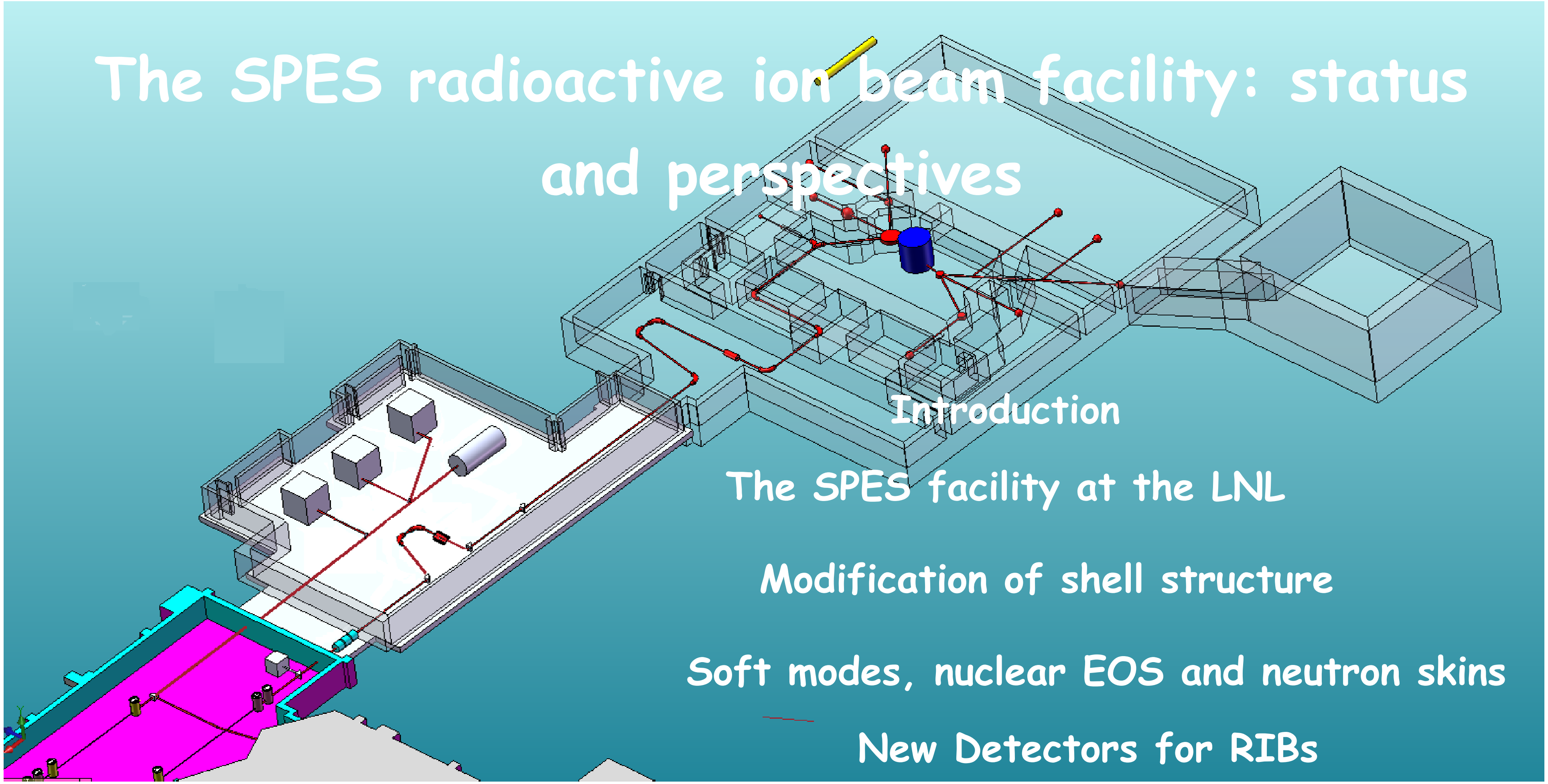
The SPES radioactive ion beam facility: status and perspectives



Introduction

The SPES facility at the LNL

Modification of shell structure

Soft modes, nuclear EOS and neutron skins

New Detectors for RIBs

Giacomo de Angelis

INFN Laboratori Nazionali di Legnaro

for The SPES collaboration

The goal of SPES

- **S**elective **P**roduction of **E**xotic **S**pecies

production of re-accelerated neutron-rich exotic beams
10^{13} fission/s in-target production, and re-acceleration at 10*A MeV (A=132)

- Optimized use of the two exits high current proton driver

Radioisotope production & Medical applications
innovative radiopharmaceuticals (e.g. Sr-82, Cu- 64, Cu-67)

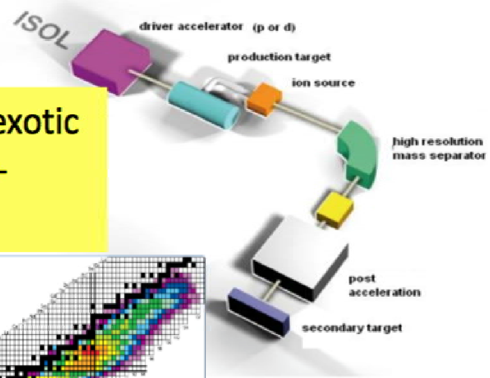
Fast neutron production & material applications: Atmospheric neutron spectra, QMN
Single Event Effect, neutron capture cross sections

SPES Strategy

BEST Cyclotron installation & commissioning:
- 70 MeV proton beam
- 750 μA

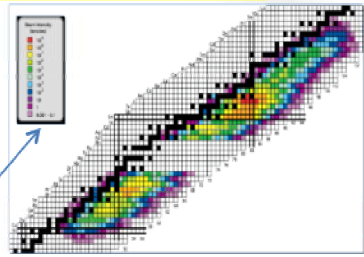
Funded

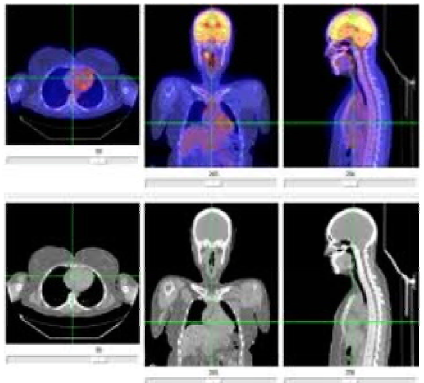
Second generation ISOL facility
Toward EURISOL



Production & re-acceleration of exotic beams. Neutron–rich ions from p-induced Fission on UCx (10^{13} f/s)

Funded





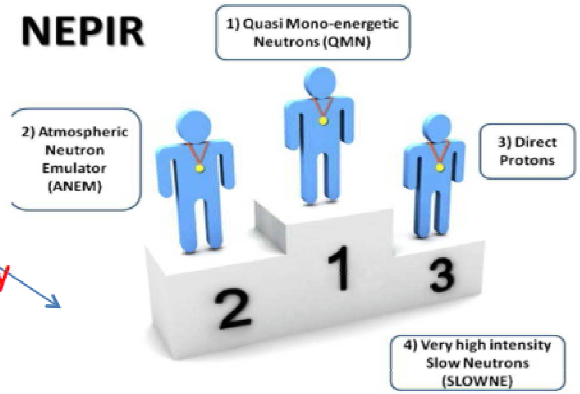
LARAMED

Partially funded 6.8 M€

Research and Production of Radio-Isotopes for Nuclear Medicine

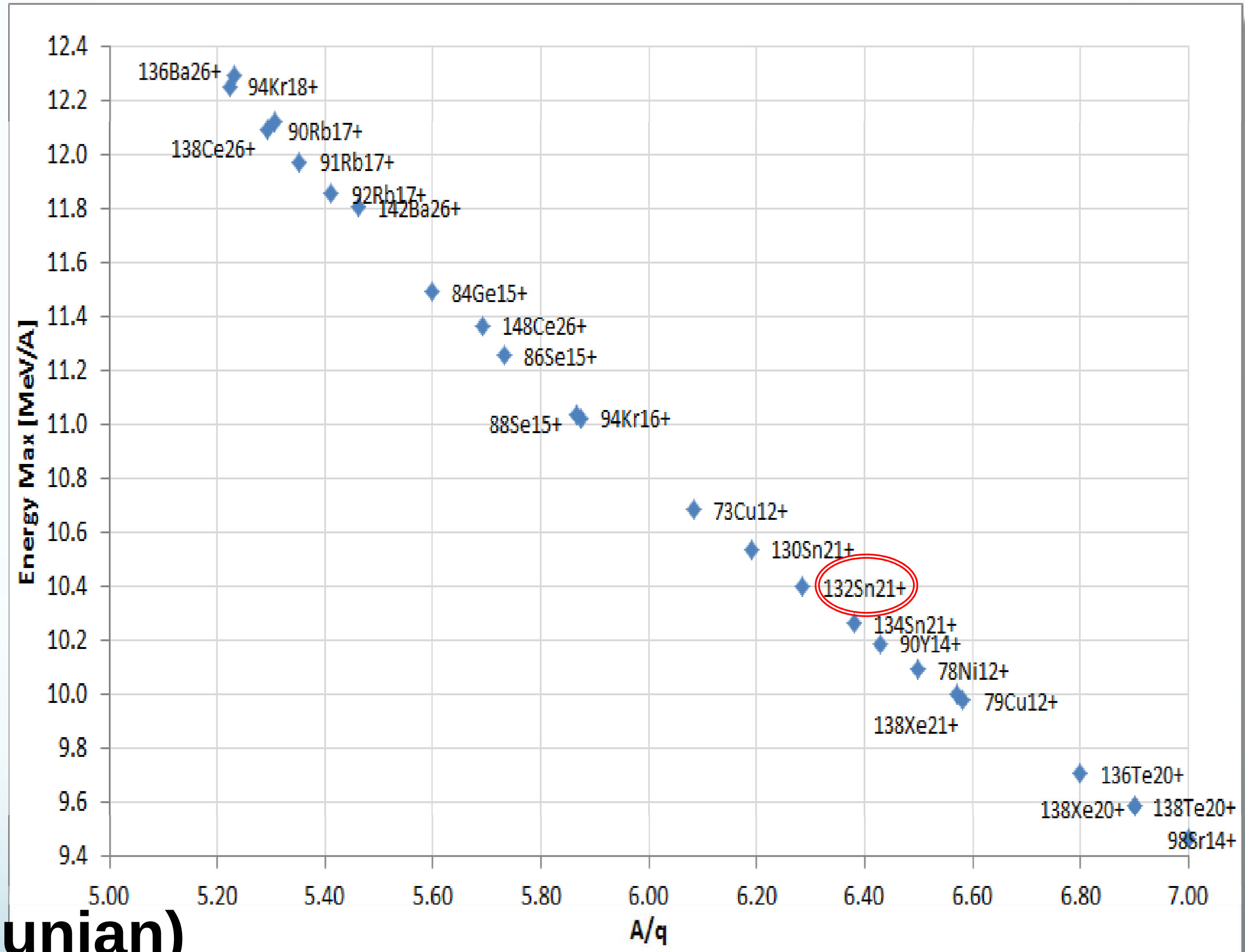
Design study

NEPIR



Accelerator based neutron source (Proton and Neutron Facility for Applied Physics)

Energy from SPES Post-Accelerator as function of A/q

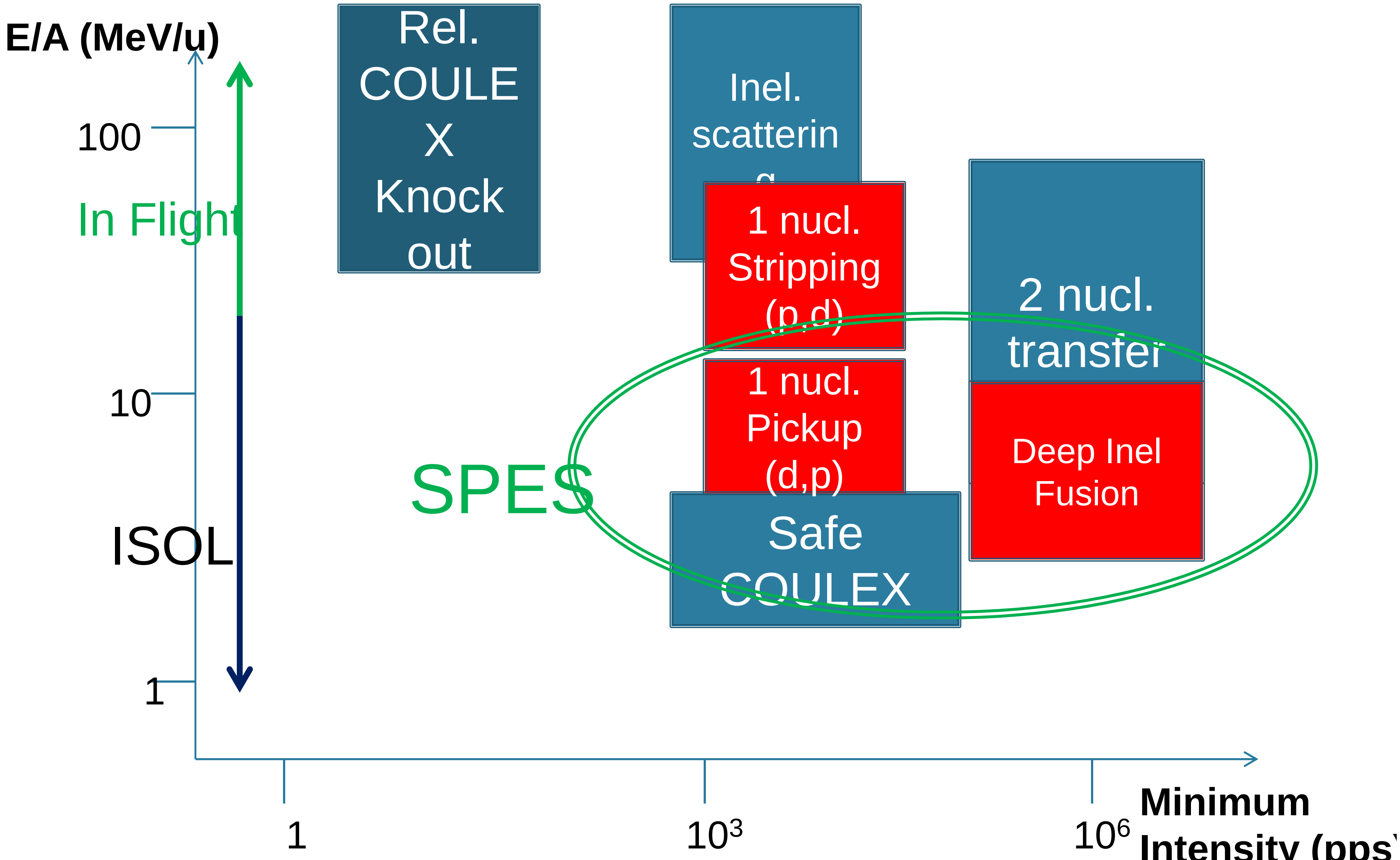


(M. Comunian)

Preliminary results from alpi performances with 2 cavities as margin, Low Beta=5 MV/m, Medium Beta=4.3 MV/m, High Beta=5.5 MV/m

Giacomo de Angelis

Reaction domains



Giacomo de Angelis

SPES Scientific Program

Scientific Advisory Committee

T.	Aumann	GSI
G.	de France	GANIL
B.	Fornal	Poland
K.	Gelbke	MSU
T.	Motobayashi	Riken
A.	Olmi	Firenze
P.	Van Duppen	Loeven
A.	Vitturi	Padova
A.	Cuttone	LNS
G.	Fiorentini	LNS
G.	Prete	LNL
G.	de Angelis	LNL

Project evaluation,
Evaluation of the LOI
and of the new instrumentation

Study group

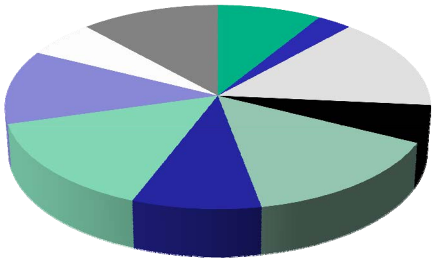
A.	Bonaccorso	INFN Pisa
G.	Casini	INFN Firenze
G.	Colò	Università di Milano
G.	de Angelis	INFN LNL
A.	Di Pietro	INFN LNS
A.	Gargano	INFN Napoli
S.	Lenzi	Università di Padova
S.	Pirrone	INFN Catania
G.	Pollarolo	Università di Torino

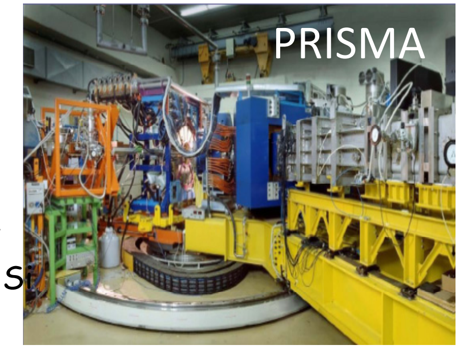
Organization of workshops
On dedicated aspects of the
Project (one-day workshops: Ex.
Transfer Reactions Napoli, Coulex
Firenze, Collective modes Milano
Ground state properties and β-decay
Milano May 2015
Preparing the SAC evaluation phase

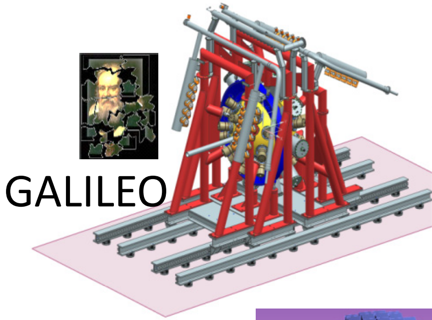
Presented 37 Letters of Intents

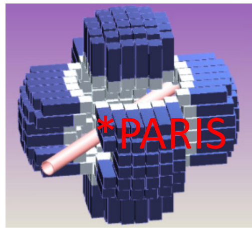
SPES2010 Workshop
(LNL- November 15th-17th, 2010)
24 LoI's for reaccelerated exotic beams

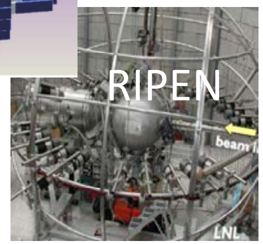
SPES LOIs Topics



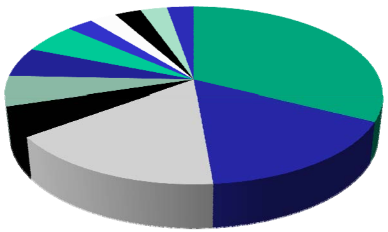


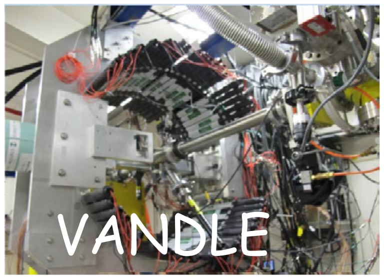


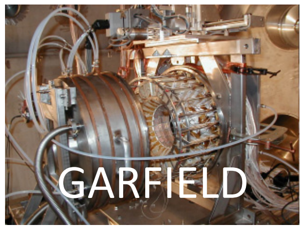




SPES LOIs Spokespersons







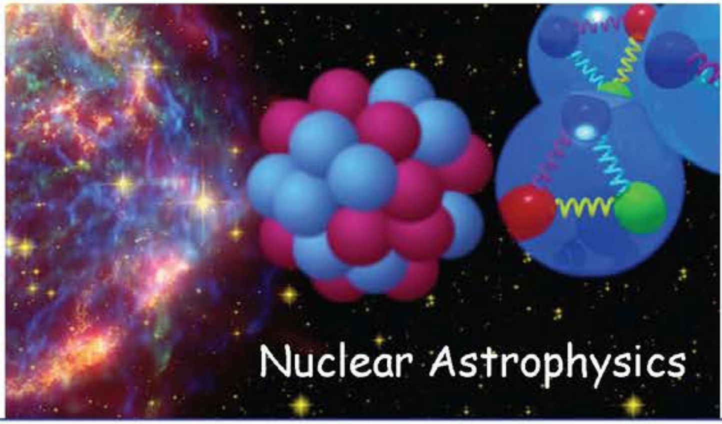
3° international SPES workshop 10-12 October 2016

Update the previous letters of intent, and add new scientific cases.
Define and organize the structure of the experimental halls according to the requirements of the scientific community.
Identify and estimate the major experimental setups and equipment that are necessary to carry on the proposed experiments.
Start the development of collaborations and research groups of users having common scientific interests.
Create the basis for defining priorities for the SPES day-1 experiments
deadline of July 8th, 2016

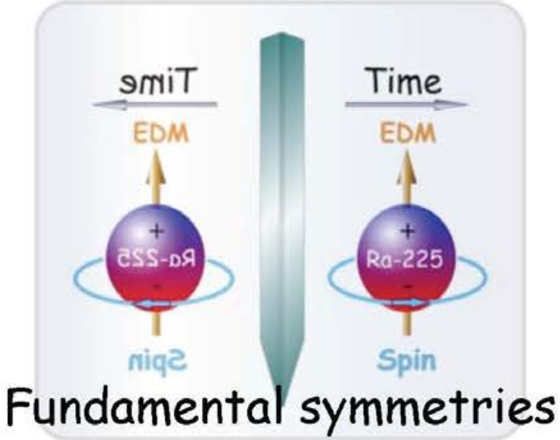
LOIs at ISOL Facilities

	SPES	SPIRAL2 Phase 2	HIE-ISOLDE
Decay Studies	4	20	Not Applicable
Elastic /Inelastic	2	4	3
COULEX	7	2	13
Transfer	8 (3HI)	7	16
Deep Inelastic/ MNTR	5	1	0
Fusion/Fission	11	3	2
New instrumentation	4	NA	5
Astrophysics	3	6	4

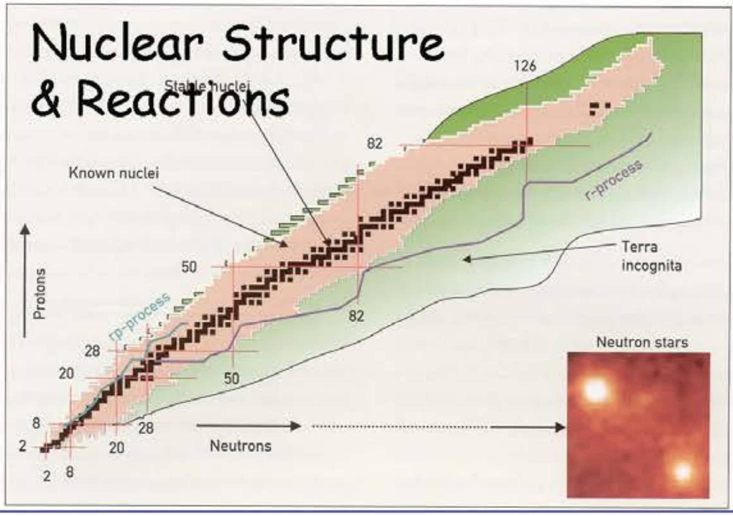
Which science drives physics with rare isotopes?



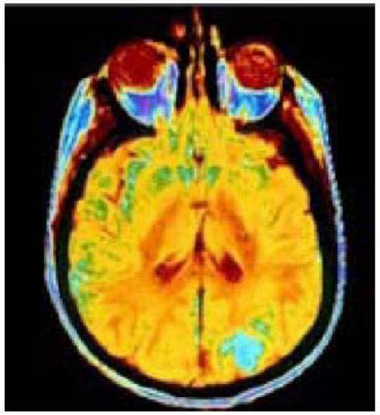
Origin of new elements, rare isotopes powering stellar explosions, neutron star crust

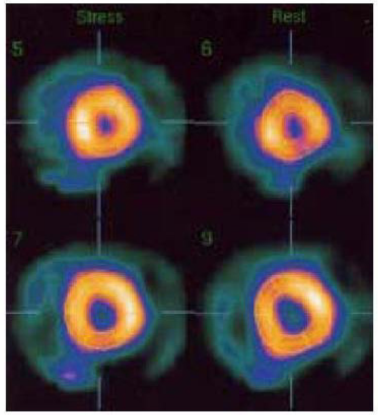


Use of rare isotopes as laboratories where symmetry violations are amplified.



Limits of existence: what makes nuclei stable? New shapes, new collective behavior.





Materials, medical physics, reactors,..

SPES exotic beams for science

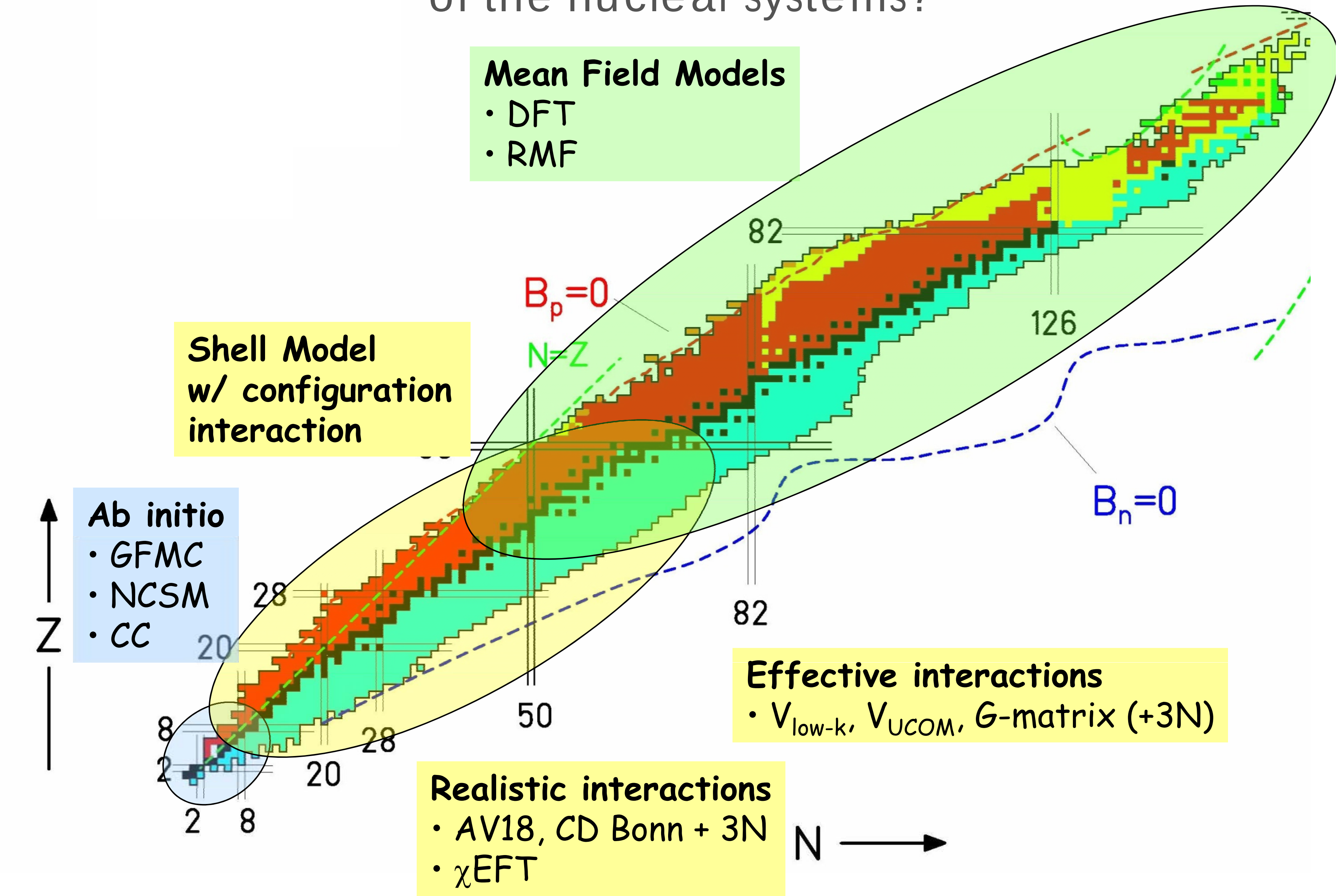
EFFECTIVE INTERACTIONS IN MEDIA

- When going from free space to medium the Interactions are modified (density dependent forces)
- When going from infinite to finite Hilbert space the Interactions are further modified (truncation schemes)

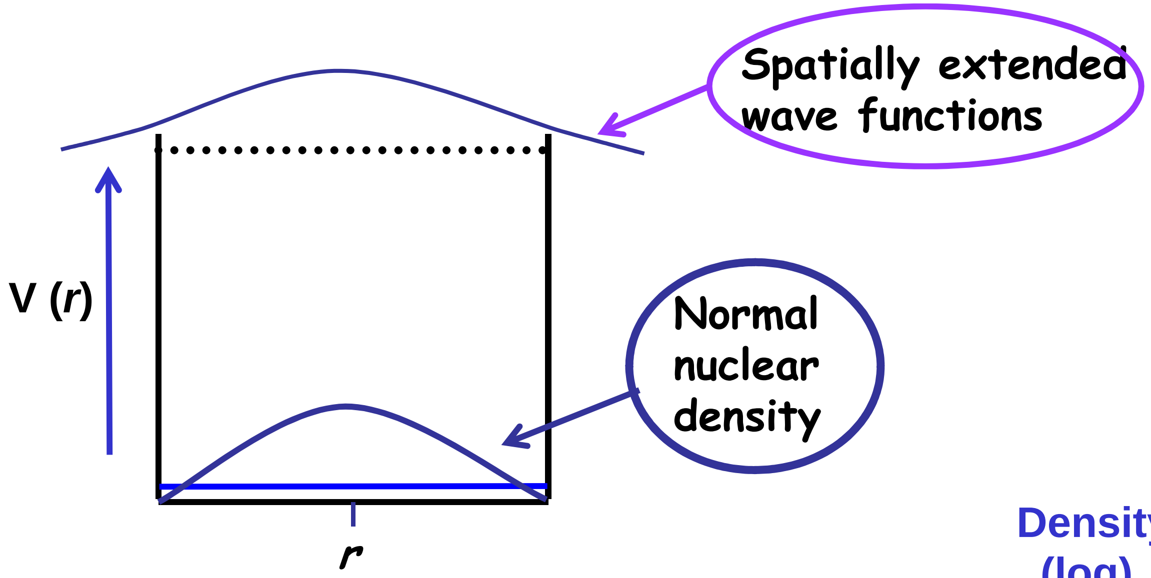
NUCLEAR STRUCTURE OF EXOTIC NUCLEI

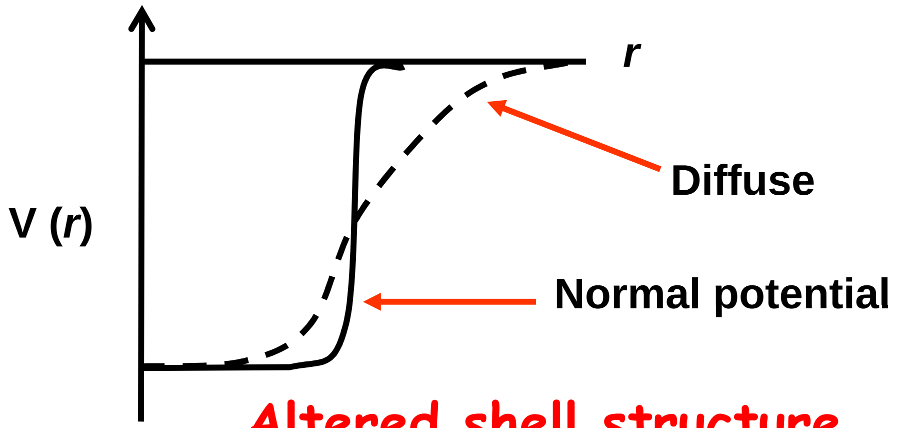
Nuclei close to the dripline are important since they are correlations dominated

One of the challanges: Do we understand the structure of the nuclear systems?



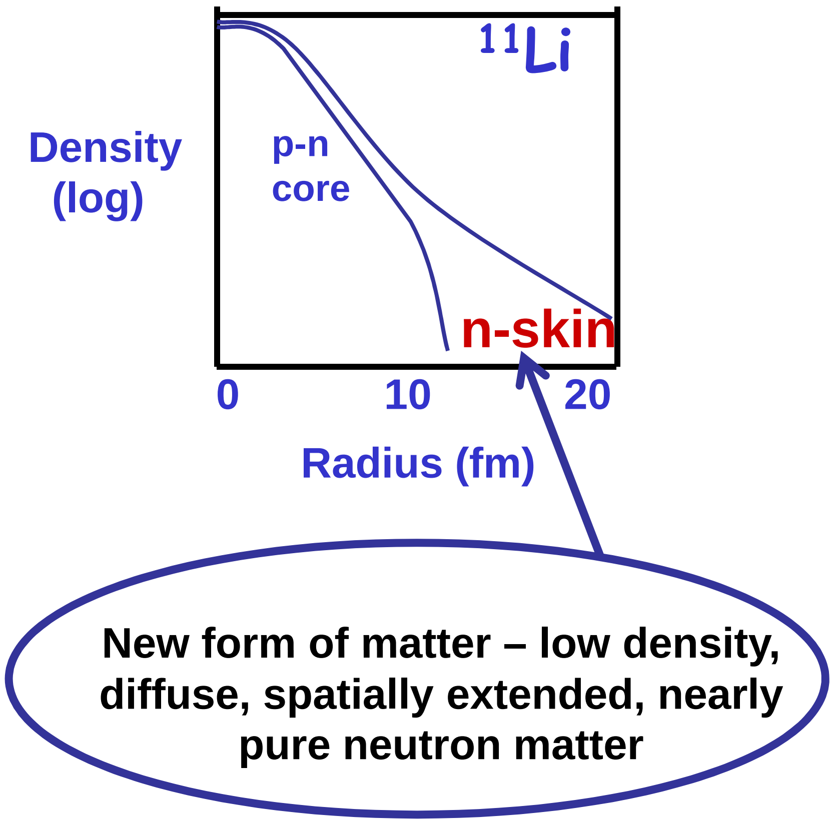
New Features in Weakly Bound Nuclei





Altered shell structure

Halo Nuclei



EFFECTIVE INTERACTIONS IN MEDIA

When going from free space to medium the
Interactions are modified (density dependent forces)
When going from infinite to finete Hilbert space the
Interactions are further modified (truncation schemes)

Type 1 shell evolution

Shells do evolve, ... due to the tensor force (Type 1 evolution).

[Otsuka et al., *PRL* **95** (05) 232502]

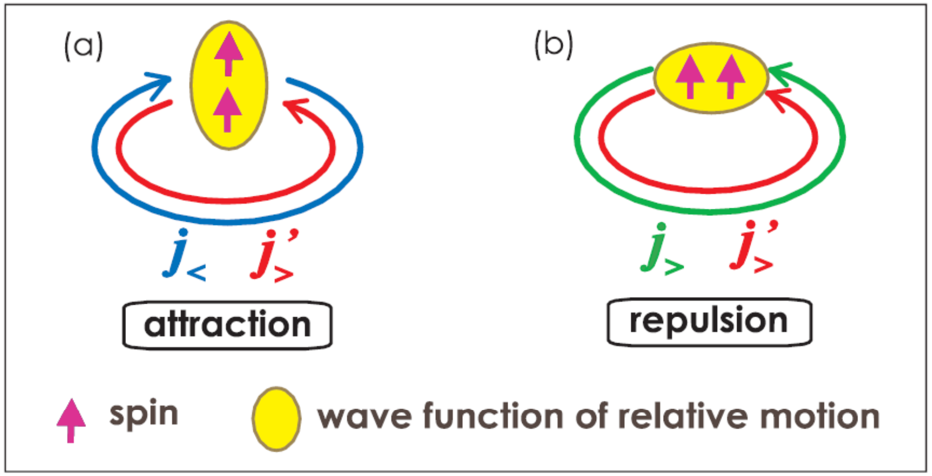
[Otsuka et al., *PRL* **97** (06) 162501]

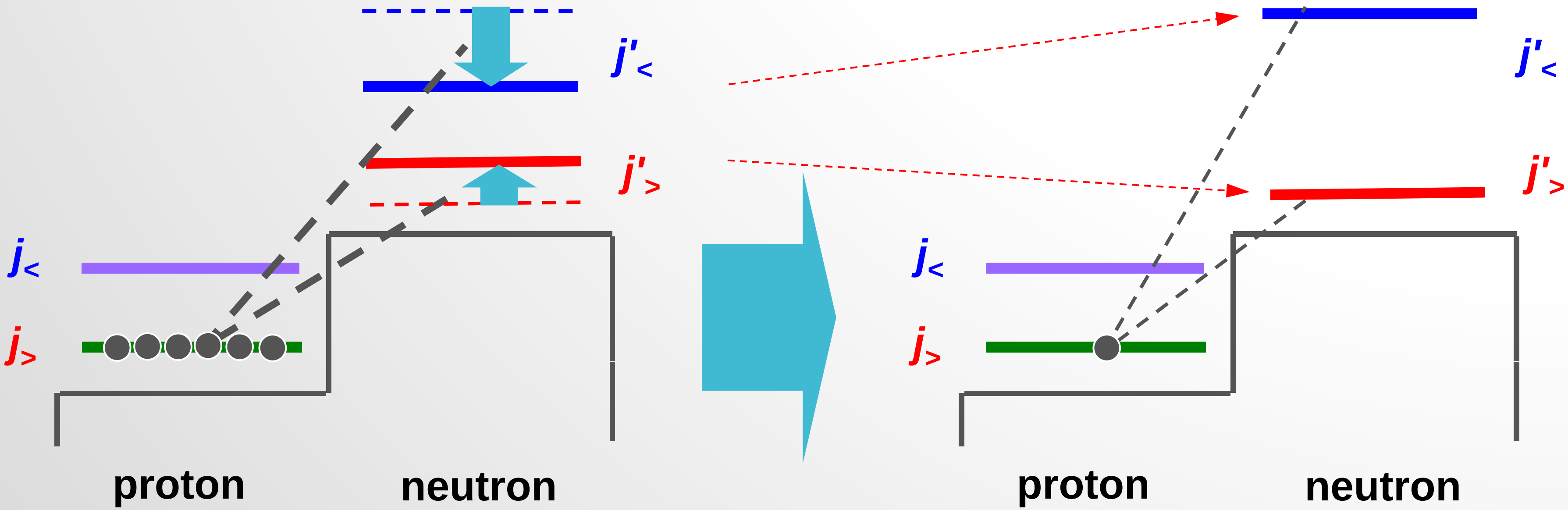
- Monopole energy of the tensor interaction

$$V^{\mathrm{T}}_{j,j'} = \frac{\sum_J (2J+1)\langle jj'|V|jj'\rangle_{JT}}{\sum_J (2J+1)}$$

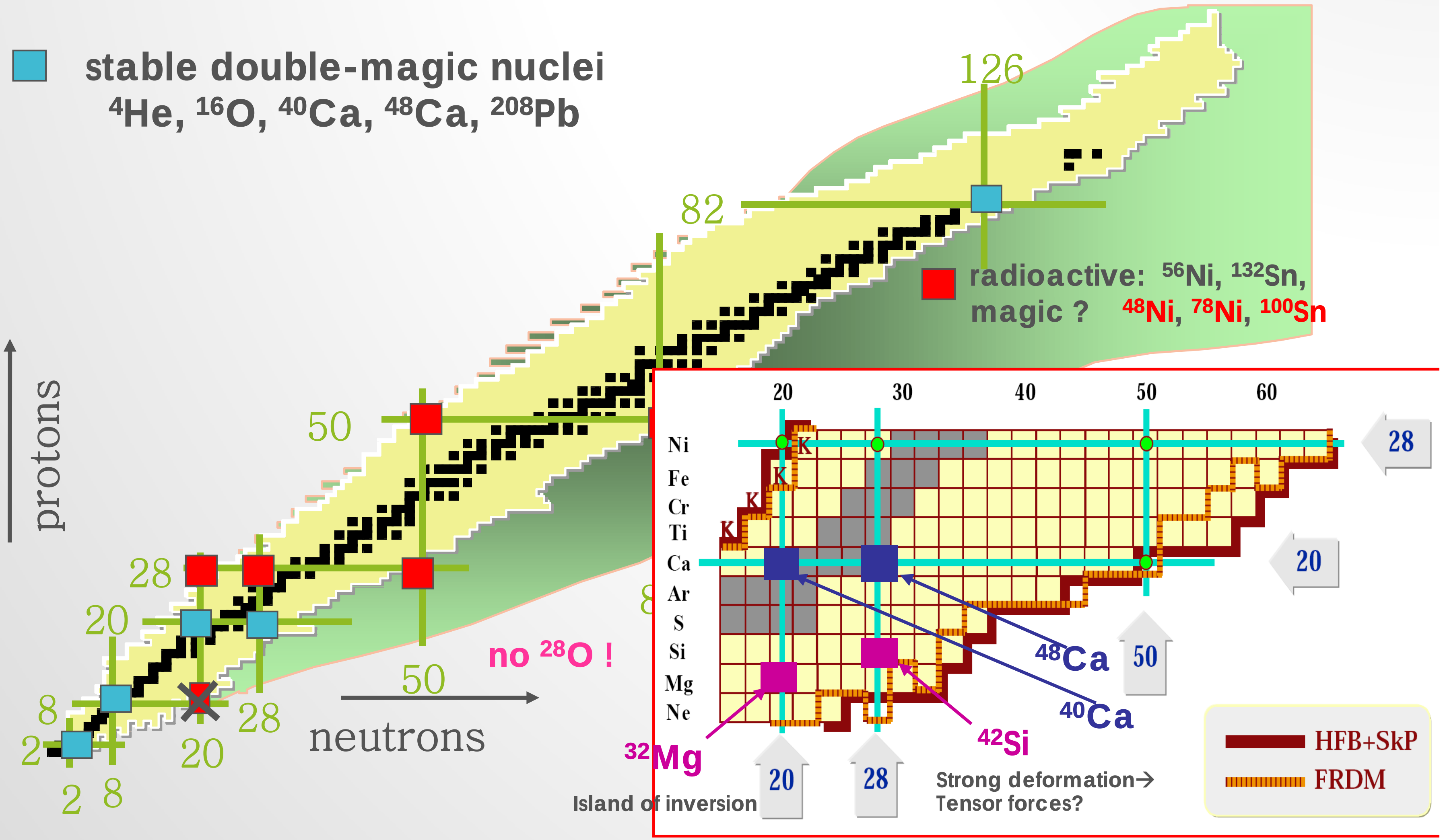
is

- attractive for $j_> - j_<'$, $j_< - j_>'$
- repulsive for $j_> - j_>'$, $j_< - j_<'$





One of the challanges: New magic numbers?



LETTER

doi:10.1038/nature12522

Evidence for a new nuclear 'magic number' from the level structure of ^{54}Ca

D. Steppenbeck[1], S. Takeuchi[2], N. Aoi[3], P. Doornenbal[2], M. Matsushita[1], H. Wang[2], H. Baba[2], N. Fukuda[2], S. Go[1], M. Honma[4], J. Lee[2], K. Matsui[5], S. Michimasa[1], T. Motobayashi[2], D. Nishimura[6], T. Otsuka[1,5], H. Sakurai[2,5], Y. Shiga[7], P.-A. Söderström[2], T. Sumikama[8], H. Suzuki[2], R. Taniuchi[5], Y. Utsuno[9], J. J. Valiente-Dobón[10] & K. Yoneda[2]

Atomic nuclei are finite quantum systems composed of two distinct types of fermion—protons and neutrons. In a manner similar to that of electrons orbiting in an atom, protons and neutrons in a nucleus form shell structures. In the case of stable, naturally occurring nuclei, large energy gaps exist between shells that fill completely when the proton or neutron number is equal to 2, 8, 20, 28, 50, 82 or 126 (ref. 1). Away from stability, however, these so-called 'magic numbers' are known to evolve in systems with a large imbalance of protons and neutrons. Although some of the standard shell closures can disappear, new ones are known to appear[2,3]. Studies aiming to identify and understand such behaviour are of major importance in the field of experimental and theoretical nuclear physics. Here we report a spectroscopic study of the neutron-rich nucleus ^{54}Ca (a bound system composed of 20 protons and 34 neutrons) using proton knockout reactions involving fast radioactive projectiles. The results highlight the doubly magic nature of ^{54}Ca and provide direct experimental evidence for the onset of a sizable subshell closure at neutron number 34 in isotopes far from stability.

The shell structure of the atomic nucleus was first successfully described more than 60 years ago[1]. However, the question of how robust the standard magic numbers are in unstable nuclei with a large excess of neutrons—often referred to as 'exotic' nuclei—has been one of the main driving forces behind recent nuclear structure studies that focus on changes in the shell structure, called 'shell evolution'. A noteworthy example is the disappearance of the $N = 28$ (neutron number 28) standard magic number in ^{42}Si (ref. 4), a nucleus that lies far from the stable isotopes on the Segrè chart. On the contrary, exotic oxygen isotopes[3] provide evidence for the onset of a new shell closure at $N = 16$, one that is not observed in stable nuclei. In both cases, the tensor force, a non-central component of the nuclear force, has a key role in describing the experimental spectra[5].

The region of the Segrè chart around exotic calcium isotopes has also contributed valuable input to the understanding of nuclear shell evolution over recent years owing to experimental advances. Enhanced excitation energies of first $J^{\Pi} = 2^+$ states (spin, J; parity, Π) and reduced γ-ray transition probabilities, which are good indicators of nuclear shell gaps, for ^{52}Ca (refs 6, 7), ^{54}Ti (refs 8, 9) and ^{56}Cr (refs 10, 11) provide substantial evidence for the onset of a sizable energy gap at $N = 32$. This result was recently confirmed by high-precision mass measurements on neutron-rich Ca isotopes[12]. In the framework of tensor-force-driven shell evolution[5], the $N = 32$ subshell closure is a direct consequence of the weakening of the attractive nucleon–nucleon interaction between protons (π) and neutrons (ν) in the $\pi f_{7/2}$ and $\nu f_{5/2}$ single-particle orbitals (SPOs) as the number of protons in the $\pi f_{7/2}$ SPO is reduced and the magnitude of the $\pi f_{7/2}$–$\nu f_{5/2}$ energy gap increases (Fig. 1a–c).

A question that has been asked frequently over recent years is whether or not the onset of another subshell gap occurs in exotic $N = 34$ isotones, which was suggested qualitatively more than a decade ago[13] on the basis of the general properties of nuclear forces. The onset of an appreciable subshell closure at $N = 34$ is illustrated in Fig. 1d, indicating an energy gap between the $\nu p_{1/2}$ and $\nu f_{5/2}$ SPOs in ^{54}Ca that is comparable to the separation of the $\nu p_{3/2}$ and $\nu p_{1/2}$ spin–orbit partners, which is also implied by recent theoretical results; see, for example, ref. 14. We stress, however, that no $N = 34$ subshell closure was reported in the experimental investigations of ^{56}Ti (refs 9, 15) or ^{58}Cr (refs 11, 16), and notable doubt on this magic number for Ca isotopes has been raised[17,18]. Indeed, as indicated in Fig. 2a, theoretical predictions of the energy of the first $J^{\Pi} = 2^+$ state for ^{54}Ca vary considerably, ranging from ~1 MeV in some cases to as high as ~4 MeV in others[14–16,19–24], despite exhibiting close agreement for lighter isotopes; for example, the predictions of the same theories lie within only 0.4 MeV of the empirical result for ^{52}Ca. Such stark discrepancies at $N = 34$ reflect the need for direct experimental input on the matter.

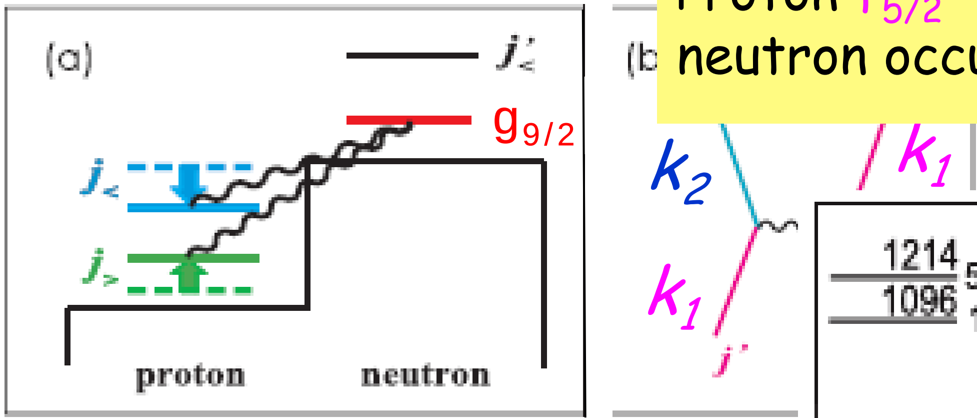
To address this issue, we report on an experimental study of ^{54}Ca to clarify the strength of the $N = 34$ subshell gap in nuclei farther from stability. The energies of nuclear excited states were investigated using proton knockout reactions involving ^{55}Sc and ^{56}Ti projectiles on a Be target at the Radioactive Isotope Beam Factory, Japan, operated by the RIKEN Nishina Center and the Center for Nuclear Study, University of Tokyo. Experimental details are provided in Methods Summary. Particle identification plots indicating the radioactive species transported through the BigRIPS separator and ZeroDegree spectrometer[25], which were used to select and tag radioactive beam projectiles and reaction products, are presented in Fig. 3a and Fig. 3b, respectively. We emphasize that the intensity of the radioactive beam reported here, which was critical to the success of the experiment, is unique to the Radioactive Isotope Beam Factory. Excited-state energies were deduced using the technique of in-beam γ-ray spectroscopy.

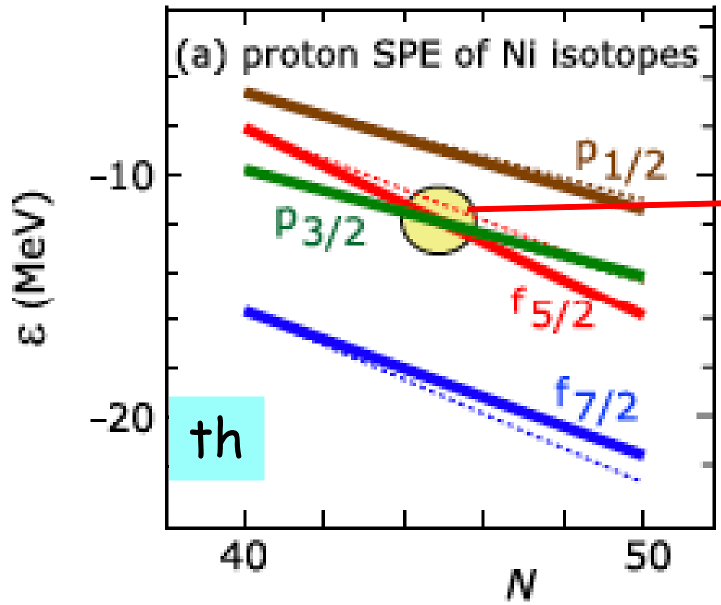
The γ-rays measured in coincidence with ^{54}Ca projectiles produced through the one- and two-proton knockout reaction channels are presented in Fig. 4a. The γ-ray energies measured in the laboratory frame of reference have been corrected for Doppler shifts, and so the transitions appear at the energies they would in the rest frame of the nucleus. The most intense γ-ray line in the ^{54}Ca spectrum, the peak at 2,043(19) keV (error, 1 s.d.) in Fig. 4a, is assigned as the transition from the first 2^+ state (2^+_1) to the 0^+ ground state. In addition, two weaker transitions are located at 1,656(20) and, respectively, 1,184(24) keV. Figure 4b shows a γ-ray spectrum obtained with the condition of a prompt coincidence ($\leq$10 ns) with the 2,043-keV γ-ray, indicating that the weaker transitions were emitted in decay sequences involving the $2^+_1 \rightarrow 0^+$ ground-state transition. On the basis of the γ-ray relative intensities, the 1,656-keV transition is proposed to depopulate a level at 3,699(28) keV, as presented in the ^{54}Ca level scheme in the lower-right section of Fig. 4a. Placement of the 1,184-keV transition in the

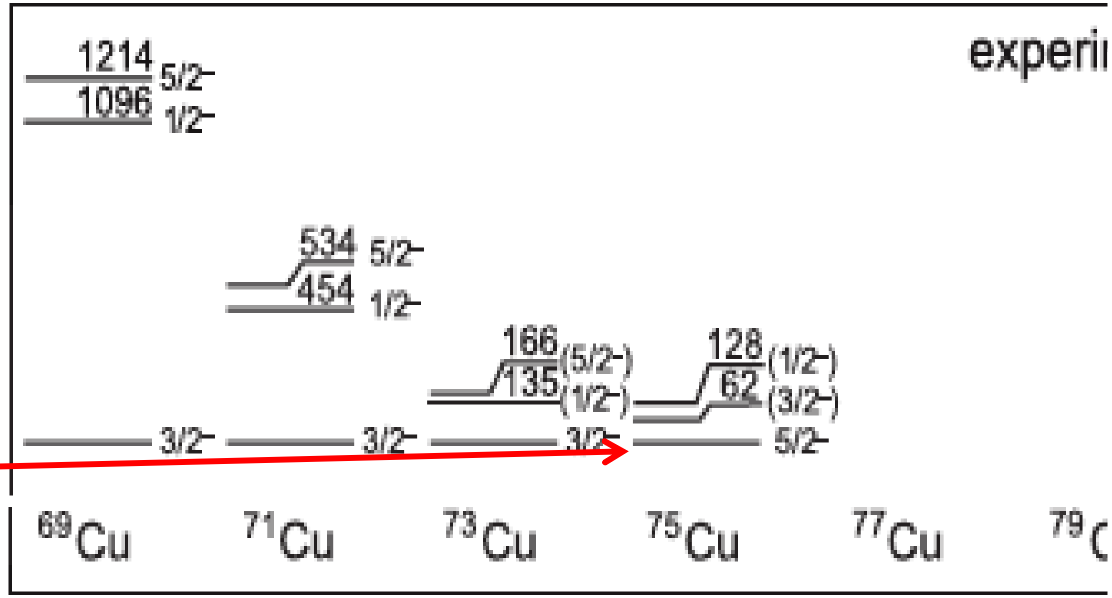
[1]Center for Nuclear Study, University of Tokyo, Hongo, Bunkyo, Tokyo 113-0033, Japan. [2]RIKEN Nishina Center, 2-1, Hirosawa, Wako, Saitama 351-0198, Japan. [3]Research Center for Nuclear Physics, University of Osaka, Ibaraki, Osaka 567-0047, Japan. [4]Center for Mathematical Sciences, Aizu University, Aizu-Wakamatsu, Fukushima 965-8580, Japan. [5]Department of Physics, University of Tokyo, Hongo, Bunkyo, Tokyo 113-0033, Japan. [6]Department of Physics, Tokyo University of Science, Noda, Chiba 278-8510, Japan. [7]Department of Physics, Rikkyo University, Toshima, Tokyo 171-8501, Japan. [8]Department of Physics, Tohoku University, Sendai, Miyagi 980-8578, Japan. [9]Japan Atomic Energy Agency, Tokai, Ibaraki 319-1195, Japan. [10]Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali di Legnaro, Legnaro 35020, Italy.

The Ni region

Proton $f_{5/2}$ - $p_{3/2}$ inversion in Cu due to neutron occupancy of $g_{9/2}$







Franchoo *et al.*, PRC 64, 054308 (2001)

"level scheme … newly established for ^{71,73}Cu"

"… unexpected and sharp lowering of the $\pi f_{5/2}$ orbital"

"… ascribed to the monopole term of the residual int. .."

→ a clean example of tensor-force driven shell evolution

TO, Suzuki, *et al.*
PRL 104, 012501 (2010)

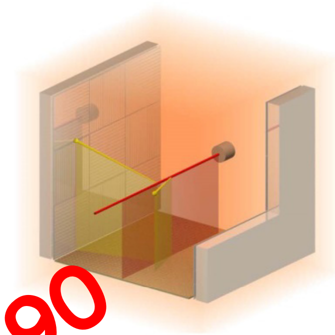
LOI from KU Leuven (Be)

Beyond ^{132}Sn:
a new magic number at N=90?

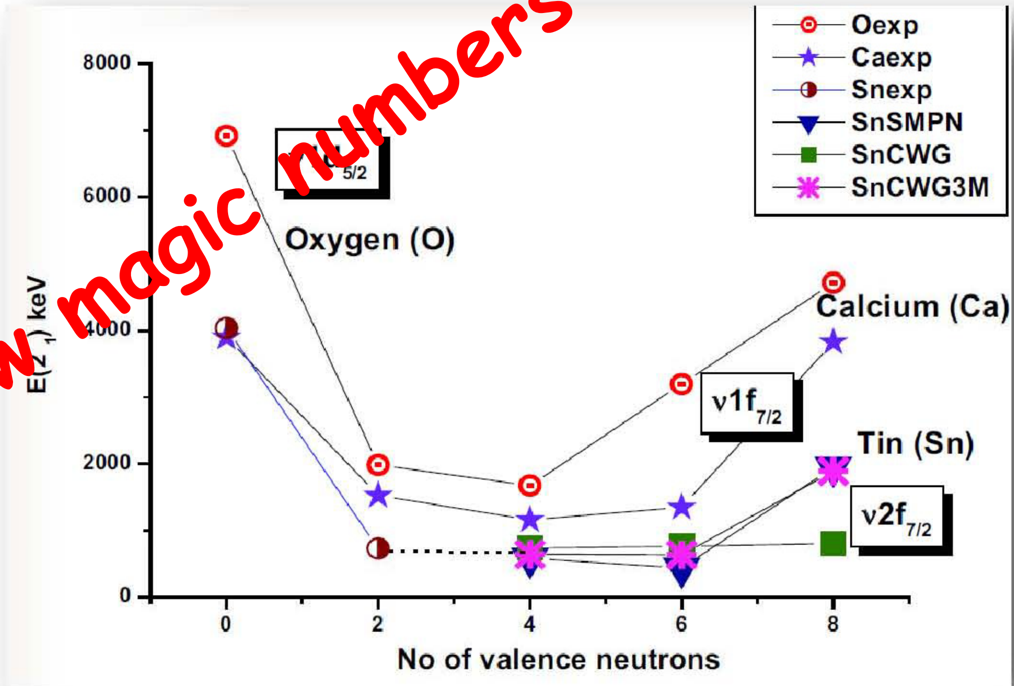
- ^{133}Sn well described by doubly-magic ^{132}Sn+n
- Beyond?
  Behaviour of $\nu f_{7/2}$ similar to that beyond ^{40}Ca
- Empirical or realistic interactions
  Role of n-n interaction and 3-body forces

(d,p) and (p,p') in an active target

- Large luminosity without loss in energy resolution
  → measurement feasible with weak intensities
- (d,p): protons at backward angles stopped in the gas or in auxiliary detectors
- (p,p'): protons in forward direction
- γ-ray detection possible



Sarkar and Saha Sarkar, JoP CS 267 (2011) 012040



Search for new magic numbers: N=90

KU LEUVEN
NUCLEAR AND RADIATION PHYSICS

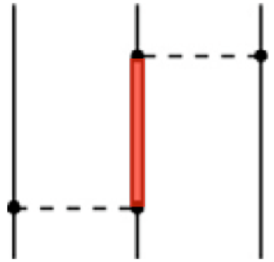
Shells do evolve ….due to 3 body interactions

N=34 subshell closure due to the effects of three body forces driving the monopole part of the nuclear Hamiltonian

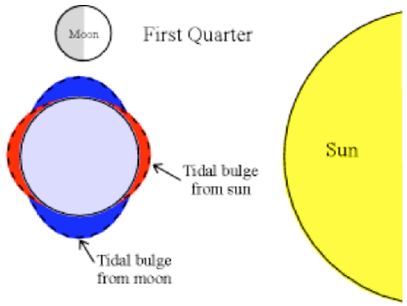
Why are there three-nucleon (3N) forces?

Nucleons are finite-mass composite particles, can be excited to resonances

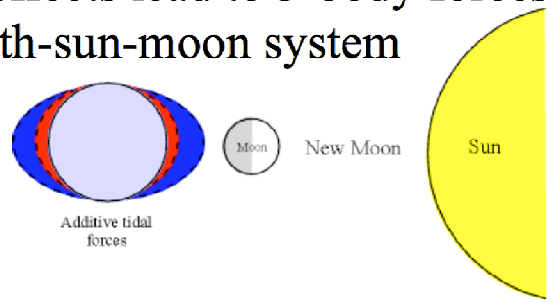
dominant contribution from Δ(1232 MeV)



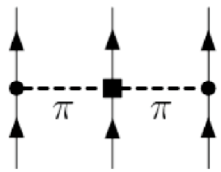
+ many shorter-range parts



tidal effects lead to 3-body forces in earth-sun-moon system



in chiral EFT (Delta-less):



+ shorter-range parts

Shell model calculations with effective interaction based on chiral Effective field theory and three body forces (G. Hagen PRL 109 2012)

Three-body interactions and normal Fermi systems

3N forces important, but why residual 3-body contributions small?

no 3-body Fermi liquid parameters needed in liquid ^{3}He

no evidence of residual 3-body forces in the shell model (I. Talmi)

can be understood in Fermi liquid theory Friman, AS, arXiv:1101.4858.

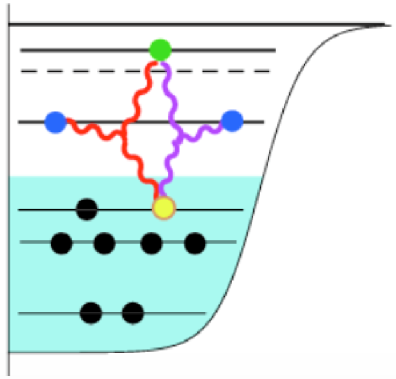
$$\delta E = \sum_1 \varepsilon_1^0 \, \delta n_1 + \frac{1}{2V} \sum_{1,2} f^{(2)}_{1,2} \, \delta n_1 \, \delta n_2 + \frac{1}{6V^2} \sum_{1,2,3} f^{(3)}_{1,2,3} \, \delta n_1 \, \delta n_2 \, \delta n_3$$

contributions from residual 3-body interactions suppressed by E_{ex}/E_F

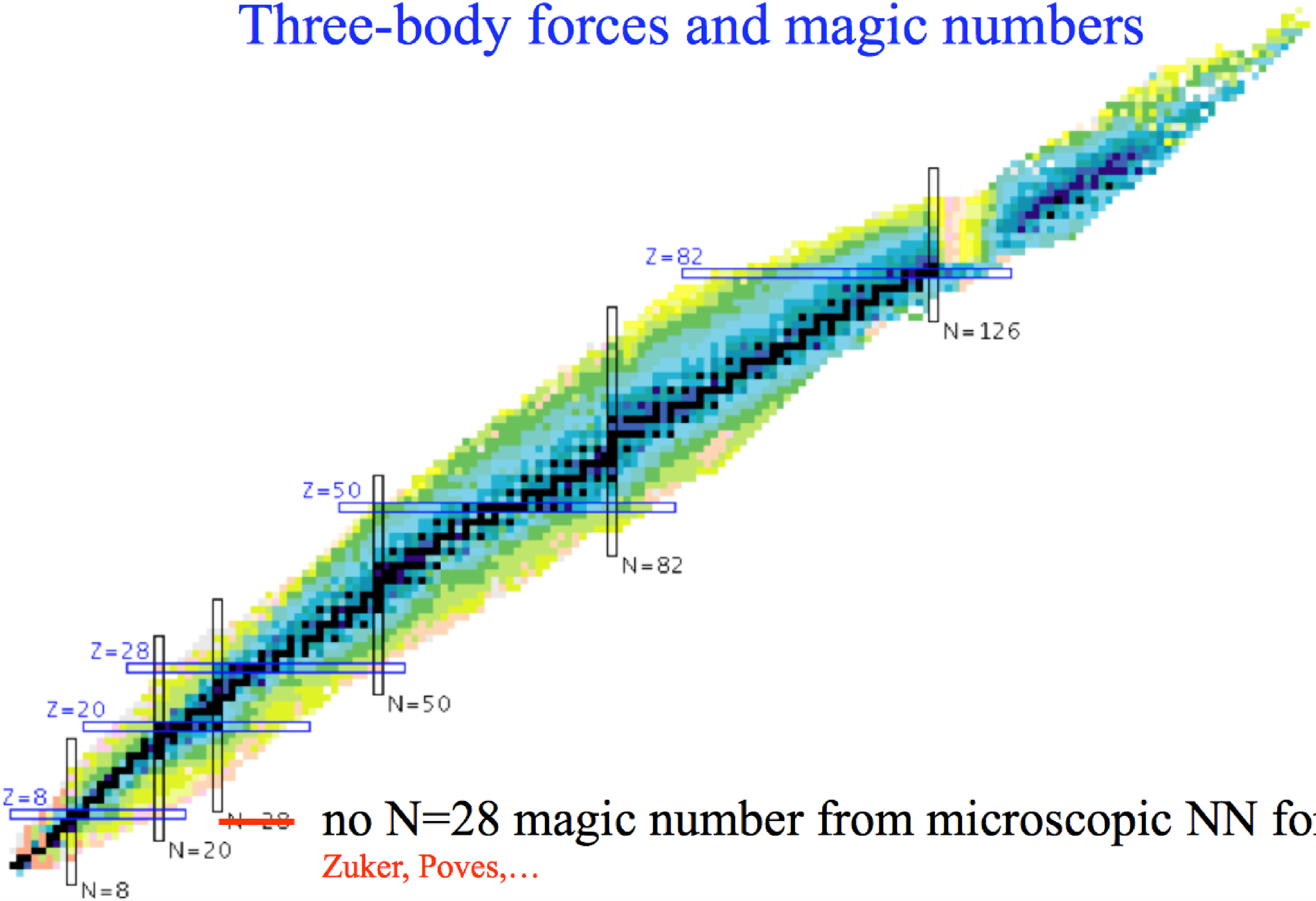
$$\frac{1}{2V} \sum_{1,2} f^{(2)}_{1,2} \, \delta n_1 \, \delta n_2 \sim \frac{1}{V} \langle f^{(2)} \rangle \left(\frac{N\Delta}{\mu} \right)^2 \sim \langle F^{(2)} \rangle \, \frac{N\Delta^2}{\mu}$$

$$\frac{1}{6V^2} \sum_{1,2,3} f^{(3)}_{1,2,3} \, \delta n_1 \, \delta n_2 \, \delta n_3 \sim \frac{n^2}{\mu} \langle f^{(3)} \rangle \, \frac{N\Delta^3}{\mu^2} \sim \langle F^{(3)} \rangle \, \frac{N\Delta^3}{\mu^2}$$

very helpful guiding principle for nuclei



Three-body forces and magic numbers



no N=28 magic number from microscopic NN forces

Zuker, Poves,…

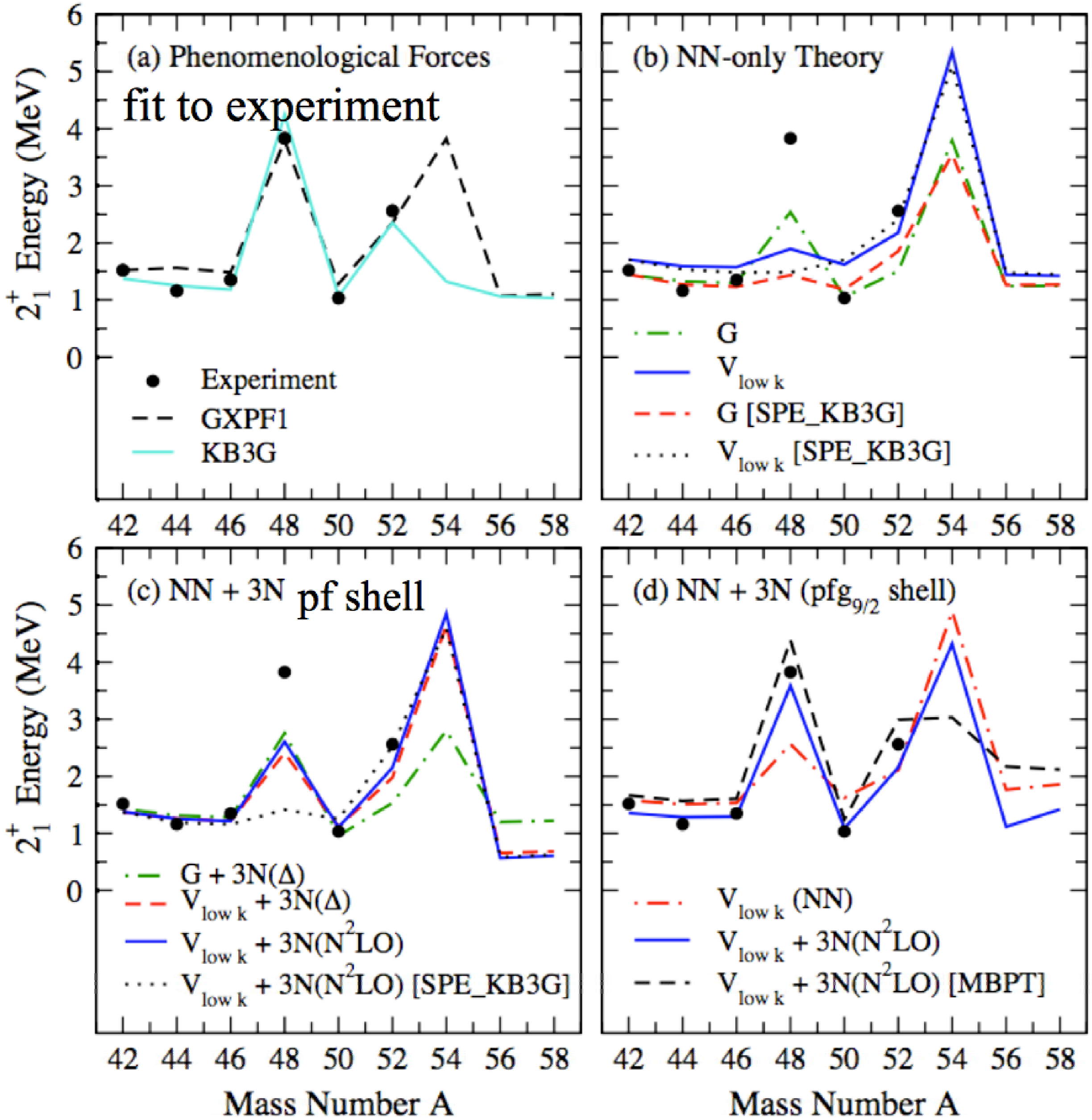
Three-body forces and magic numbers

3N mechanism important for shell structure

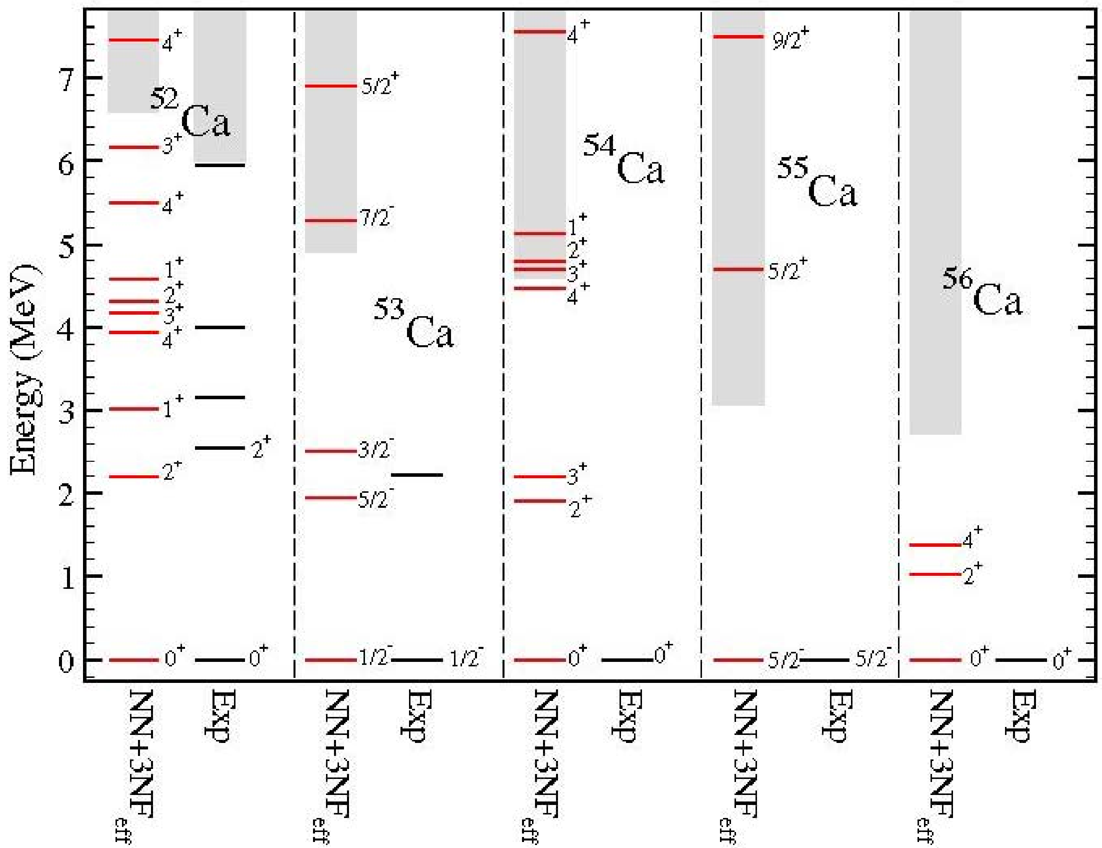
Holt et al., arXiv:1009:5984

N=28 shell closure due to 3N forces and single-particle effects (^{41}Ca)

N=34: predict high 2^+ excitation energy in ^{54}Ca at 3-5 MeV



N=34 subshell closure due to the effects of three body forces driving the monopole part of the nuclear Hamiltonian



Beta delayed
n spectroscopy
n-γ coincidences

LOI SPES A. Gottardo IPN Orsay

Shell model calculations with effective interaction based on chiral Effective field theory and three body forces (G. Hagen PRL 109 2012)

QUANTUM PHASE TRANSITIONS

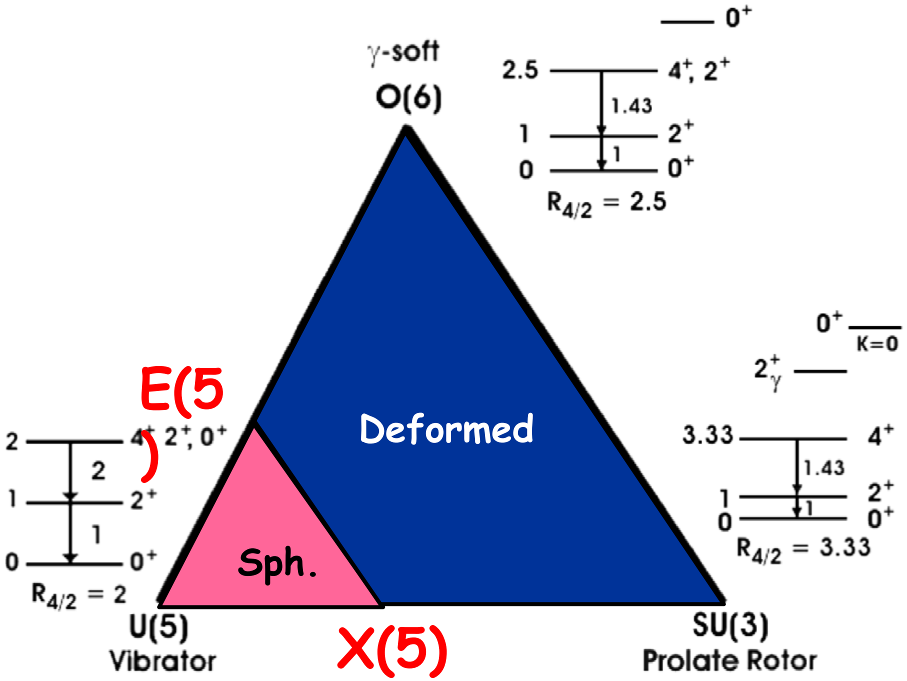
New shape phase transition regions?
Approach to criticality (critical symmetries) E5…

………..

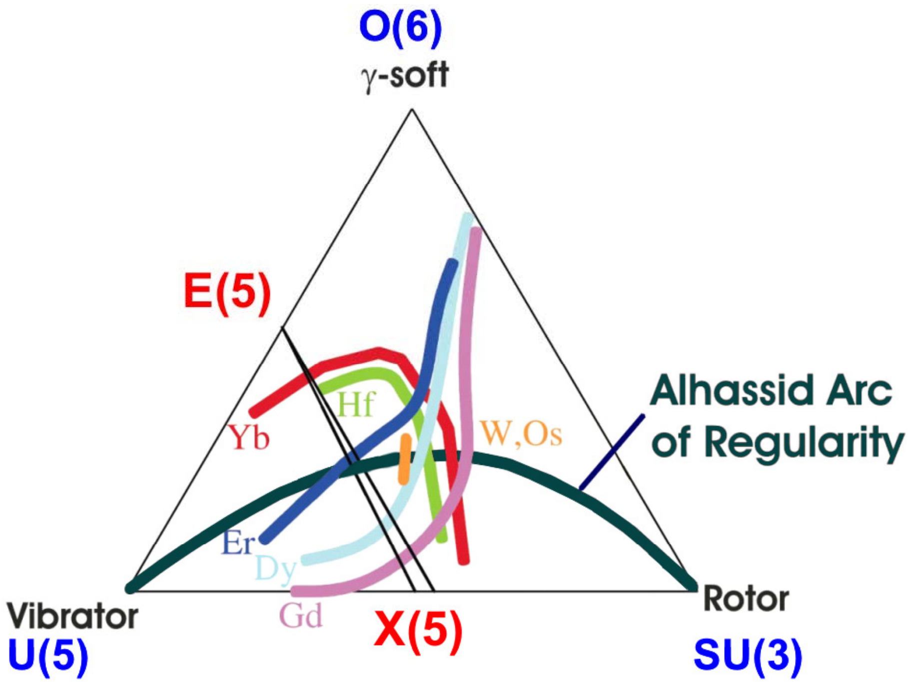
Type 2 shell evolution

Classifying Structure -- The Symmetry Triangle of Collective Behavior

Dynamical Symmetries, Phase Transitions, Critical Point Symmetries, Order and Chaos

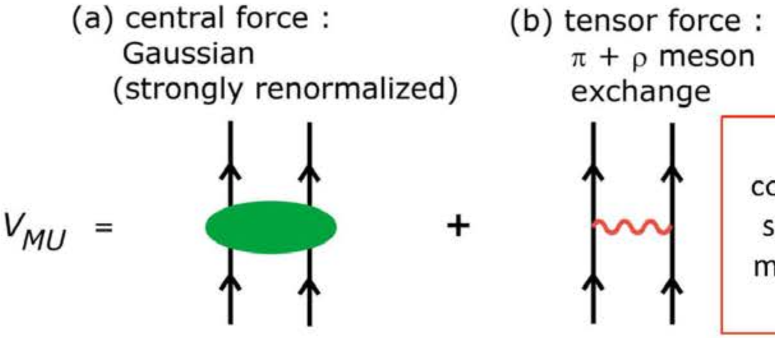


Landau Theory

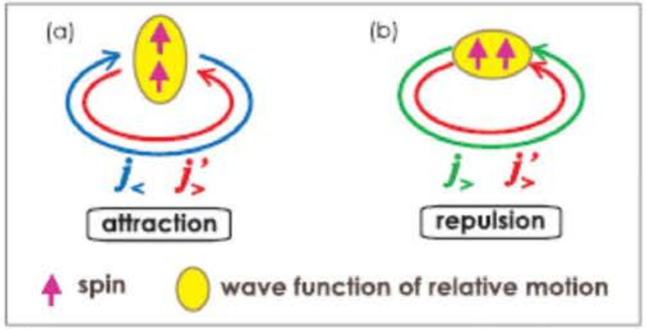


Complementarity of macroscopic and microscopic approaches.
Why do certain nuclei exhibit specific symmetries and not others?
Why these specific evolutionary trajectories? What unknown regularities appear along the Arc? *What will happen far from stability?*

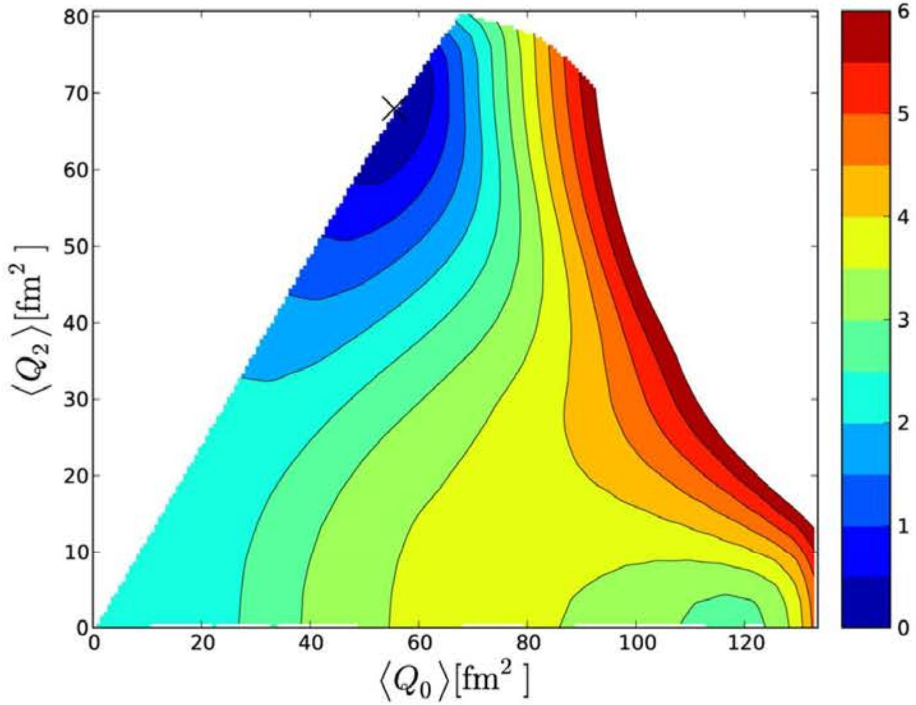
Shells do evolve..for increasing spin: Type II evolution

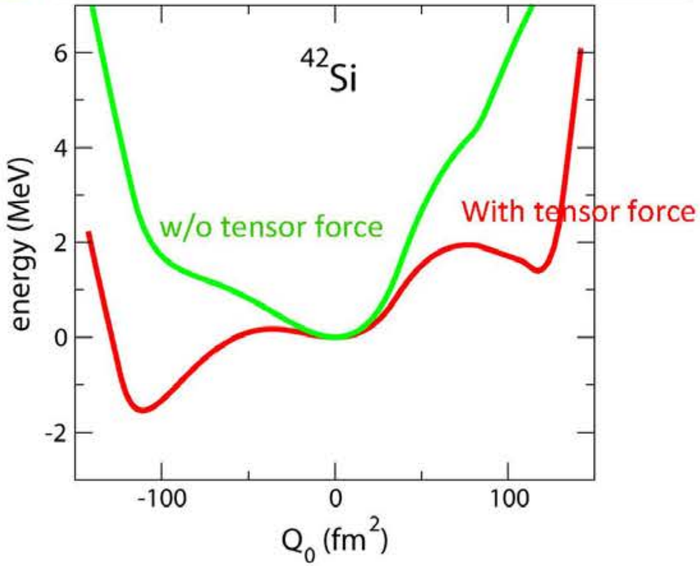


Monopole component is the same in nuclear medium and free space

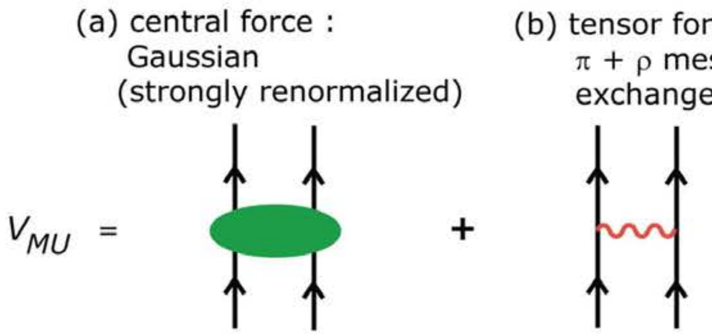


Tensor force

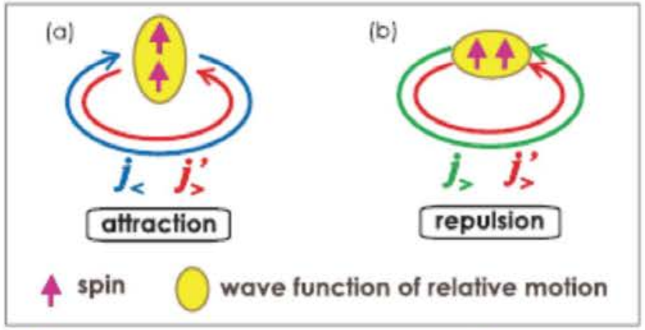




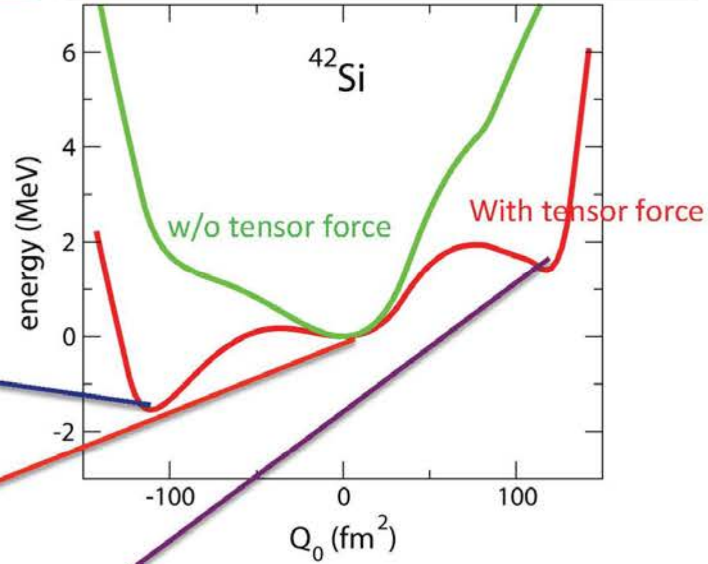
Otsuka, *et al.*

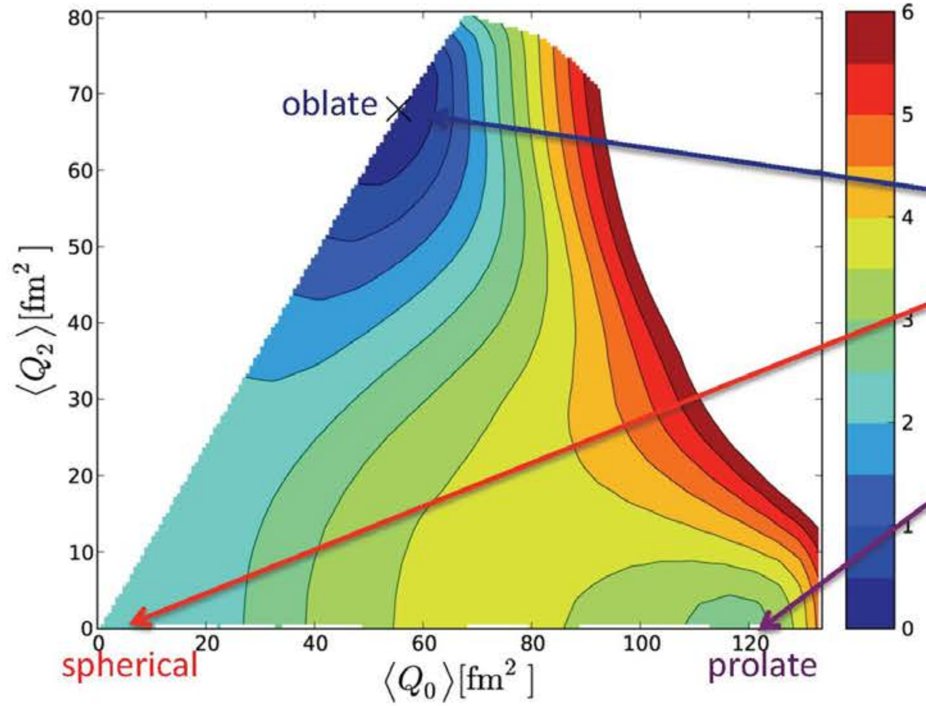


Monopole component is the same in nuclear medium and free space

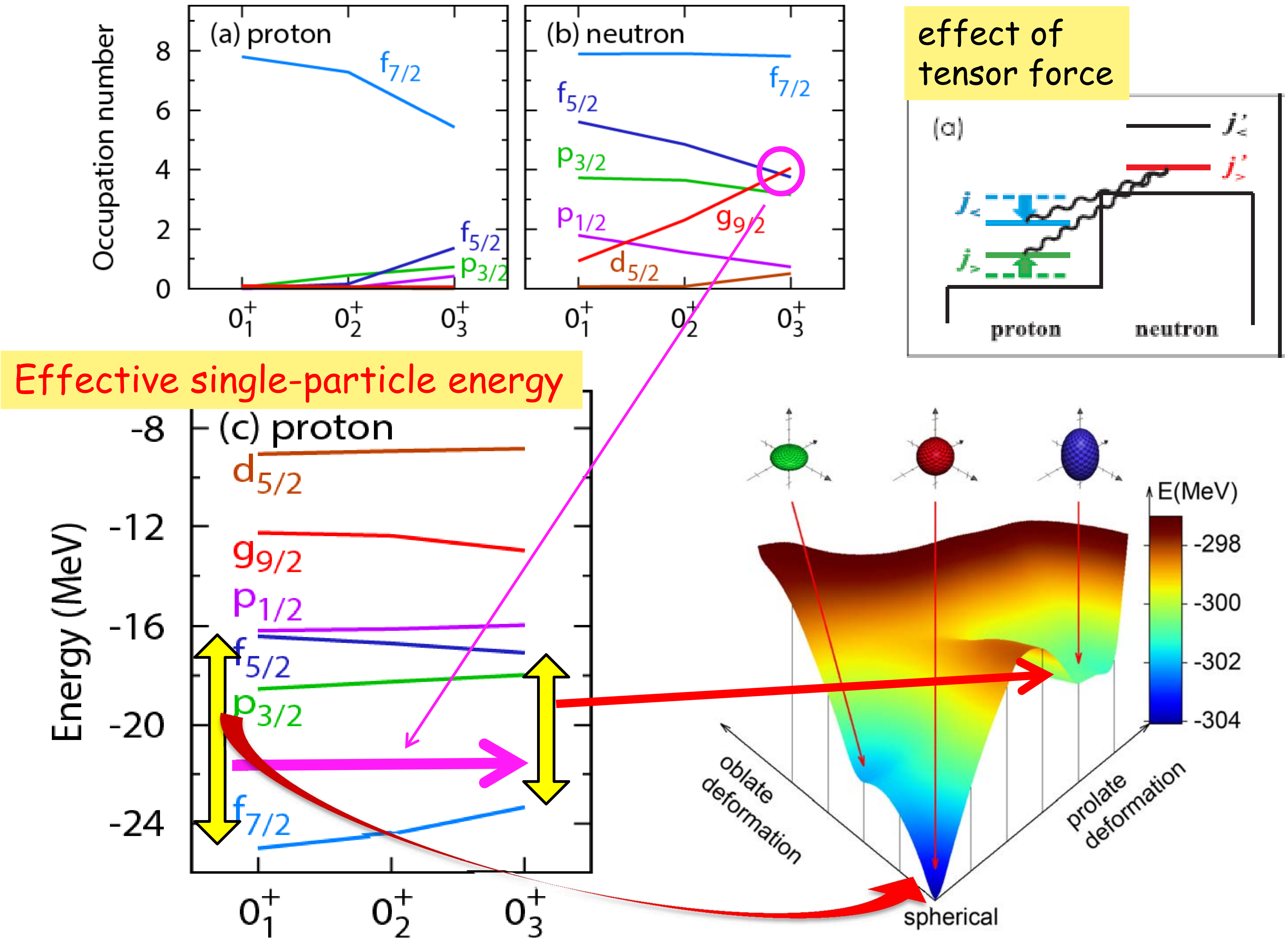


Tensor force





Otsuka, *et al.*


effect of tensor force
Effective single-particle energy
(a) proton
(b) neutron
(c) proton
Occupation number
Energy (MeV)
$f_{7/2}$
$f_{5/2}$
$p_{3/2}$
$p_{1/2}$
$g_{9/2}$
$d_{5/2}$
0_1^+
0_2^+
0_3^+
(a)
$j'_<$
$j'_>$
$j_<$
$j_>$
proton
neutron
E(MeV)
-298
-300
-302
-304
oblate deformation
prolate deformation
spherical

SUMMARY OF SYMMETRIES AND PHASE TRANSITIONS IN NUCLEI

Nuclei show some of the best example of QPT.
The phases are between different shapes
(spherical, axially deformed…)
Also signature of critical behaviour
Have been suggested:
Critical symmetries

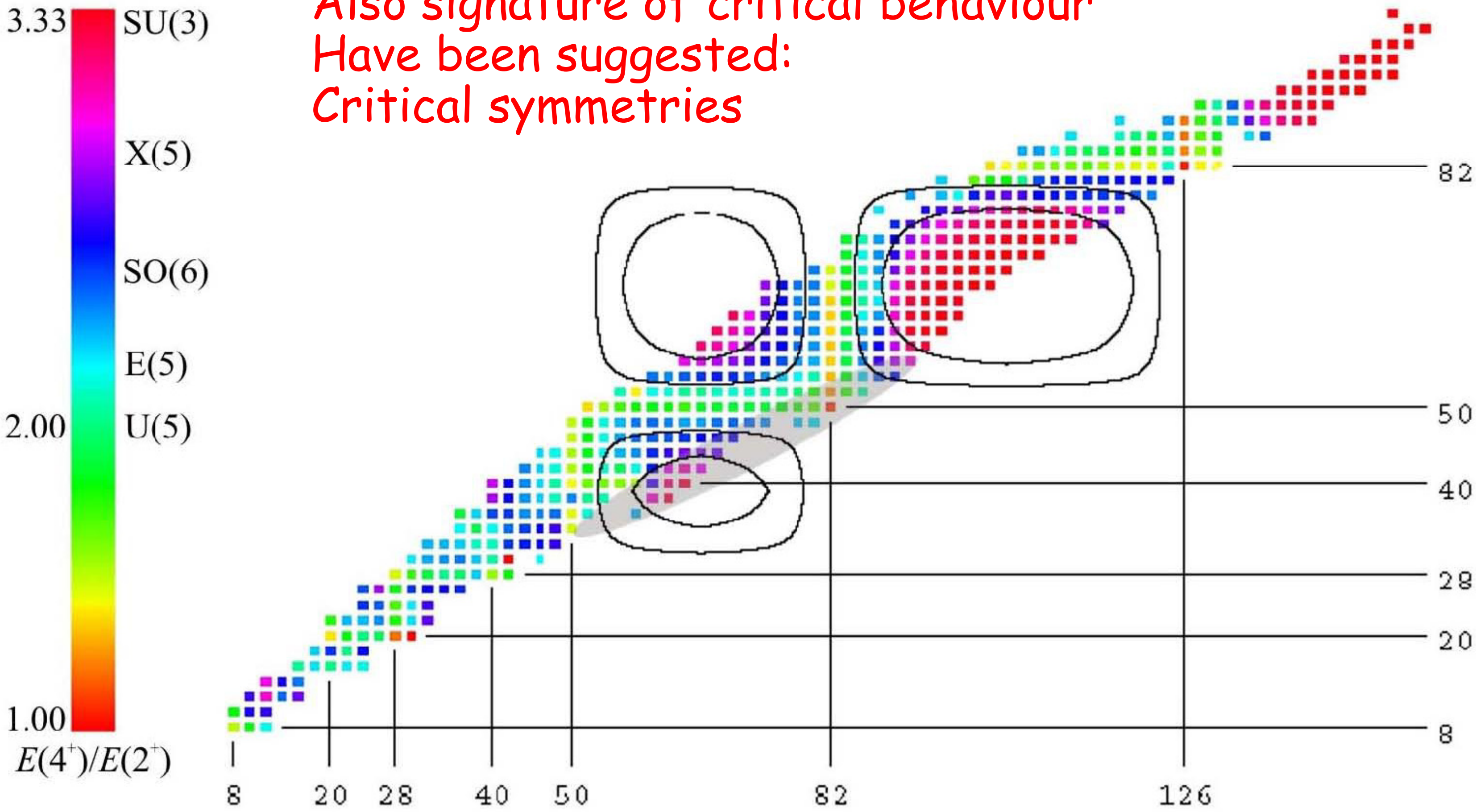
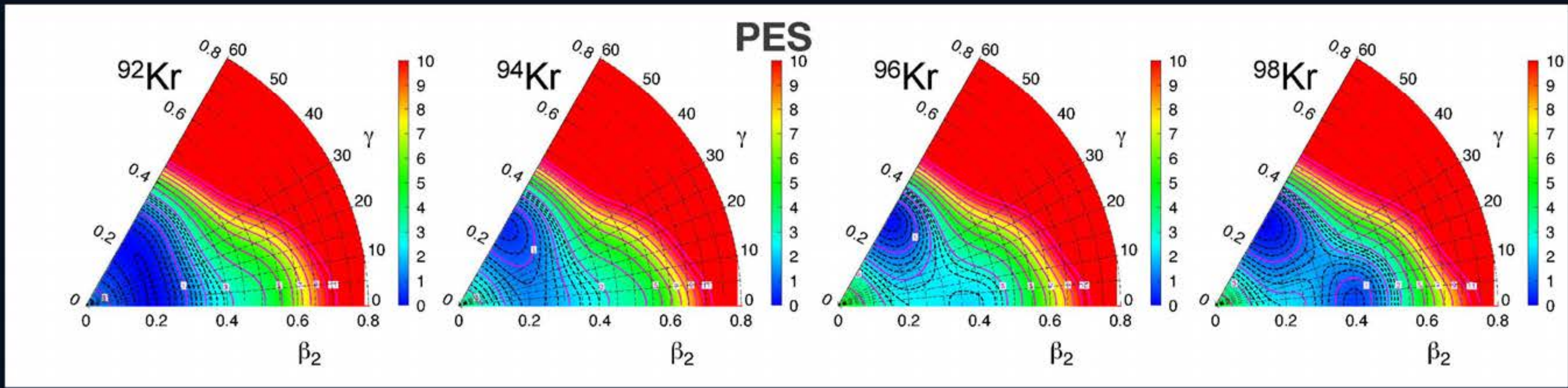


Figure courtesy of P. van Isacker

Giacomo de Angelis

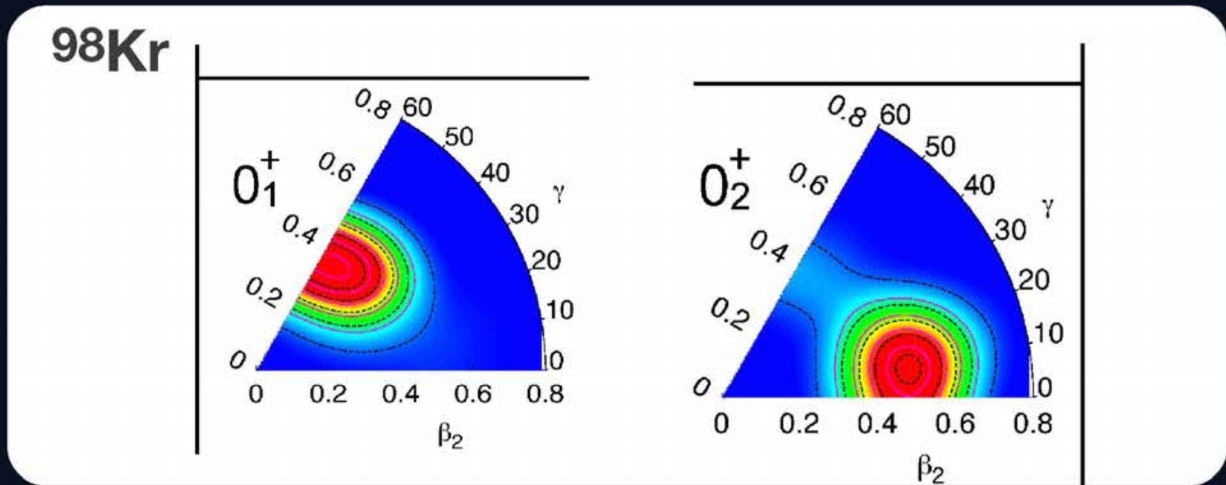
LOI LNL (I)....

Shapes in Kr

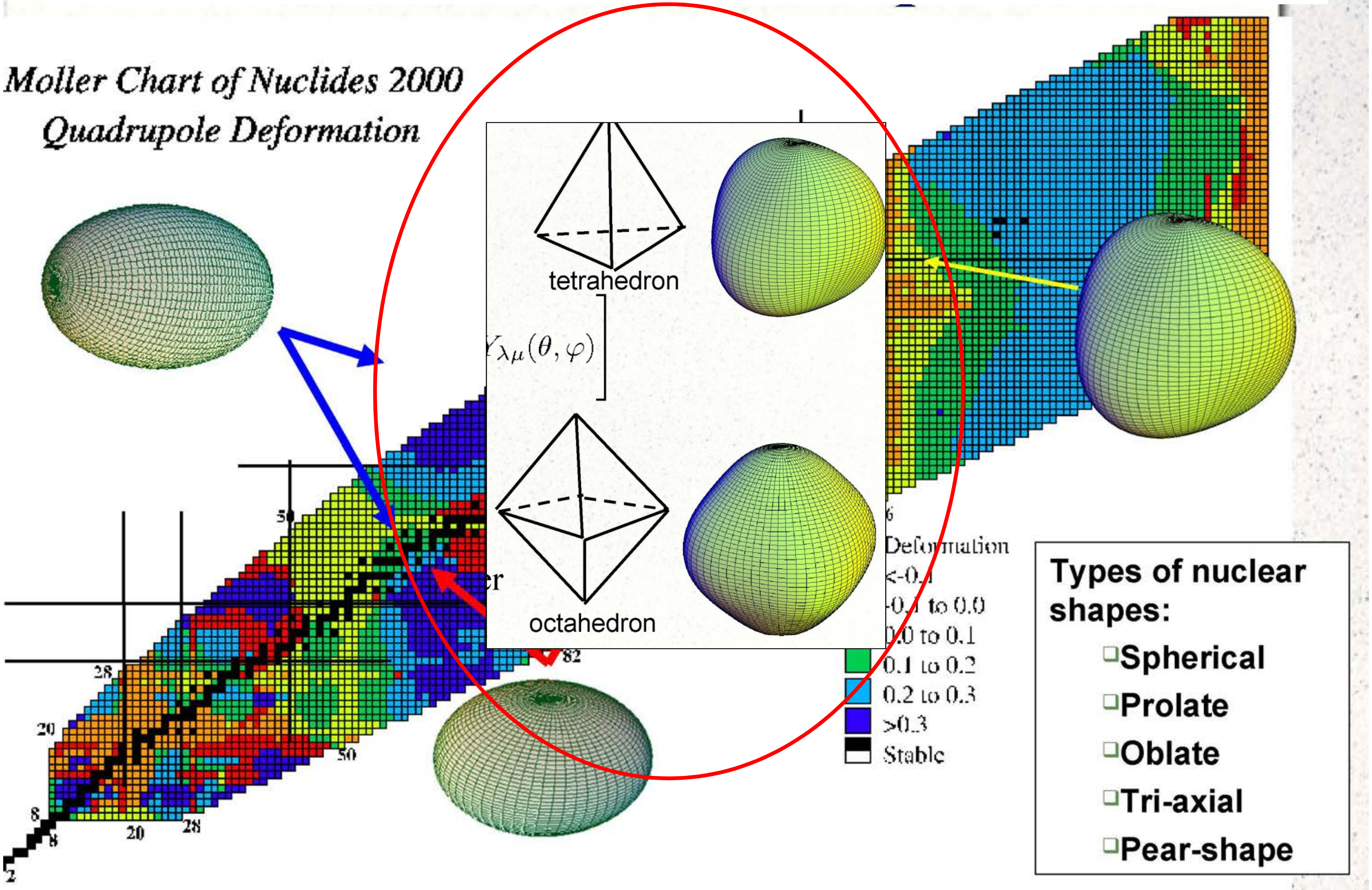


Oblate-Prolate shape coexistence in Kr at N=60: LNL

Shape transition to prolate shape on the second 0+, at N=62



High order Exotic deformations



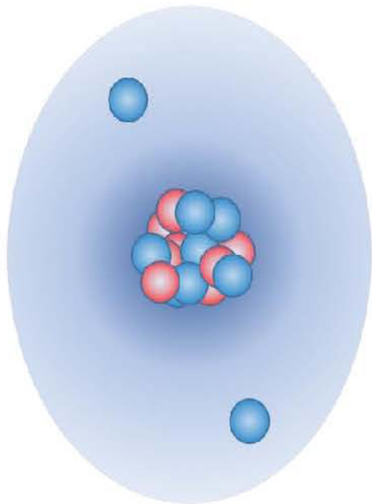
EFFECTIVE INTERACTIONS IN MEDIA

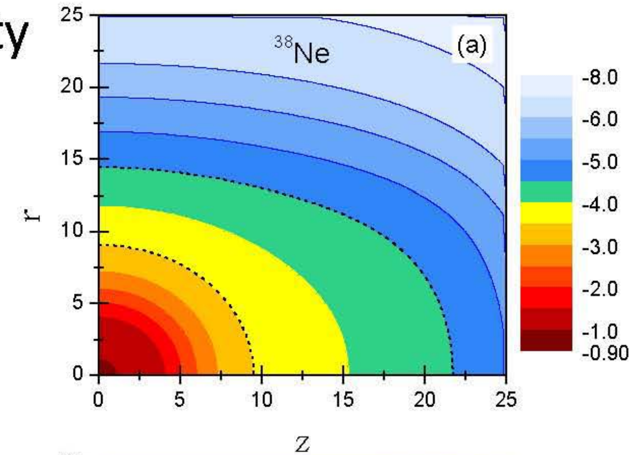
When going from free space to medium the
Interactions are modified (density dependent forces)
When going from infinite to finete Hilbert space the
Interactions are further modified (truncation schemes)

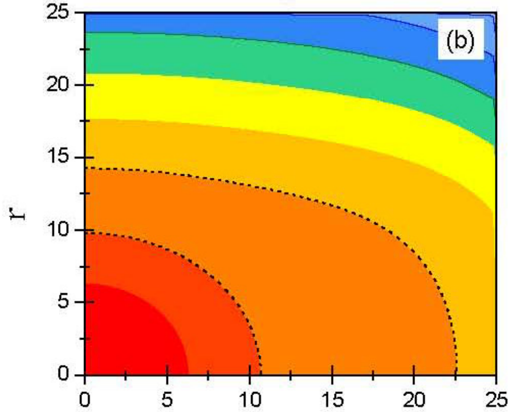
Configurational Isospin Polarization

Exotic egg-like halo structure

- Self-consistent calculations: SLy4 force + density dependent pairing
- 38Ne, (a) neutron density; (b) n pairing density
- About 2 neutrons in the halo
- Deformations: beta2 = 0.24, beta2_pair=0.48
- Mainly contributed by near-threshold continuum







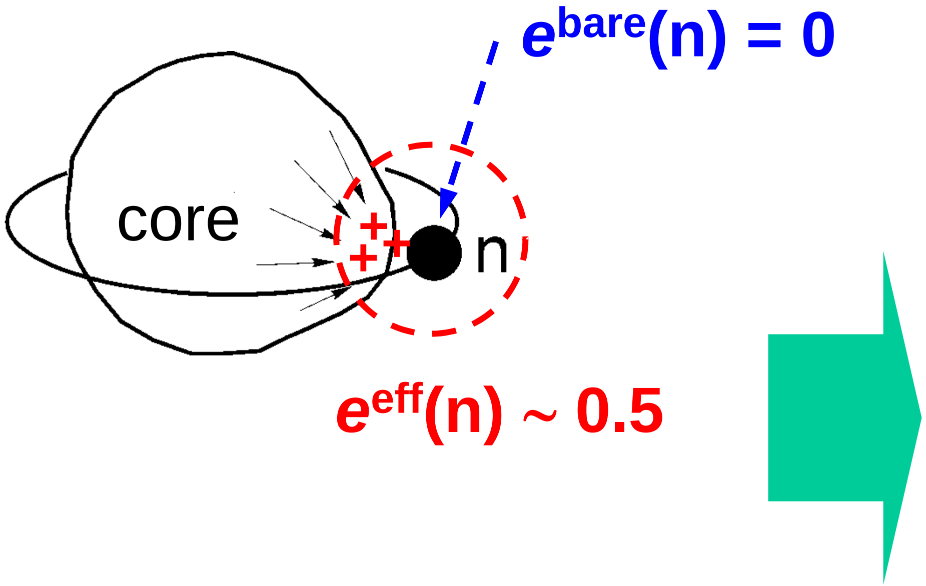
Isovector deformation: pygmy quadrupole resonances

New exotic "egg"-like halo structure obtained; accurate approach is essential

J.P., Y.N. Zhang, F.R. Xu, PRC (R) 87, 051302(2013)

Also,

<u>decoupling of neutron from the core</u>



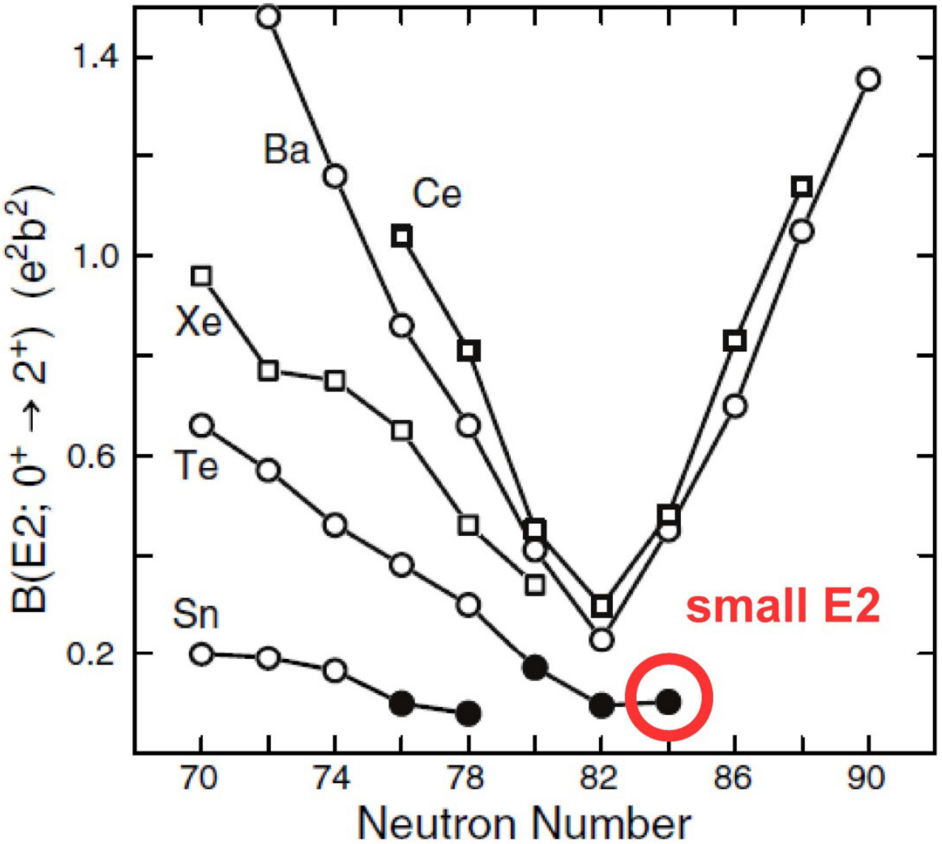
$e_{eff}(n) \sim 0$??

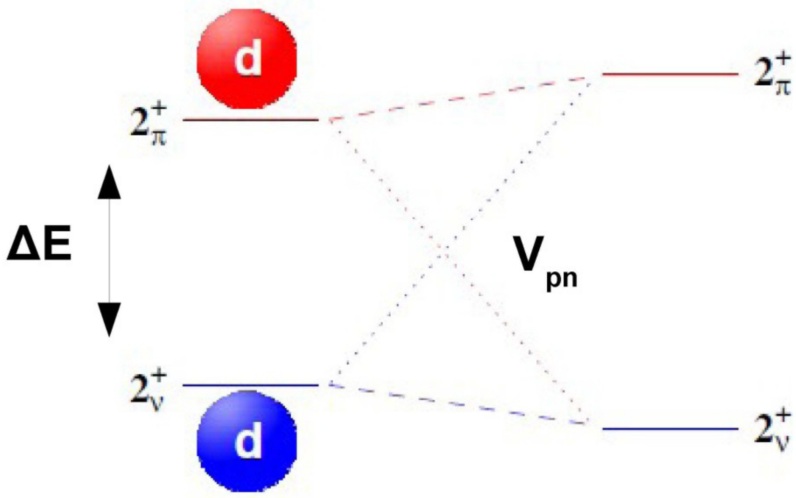
(in a normal nucleus)

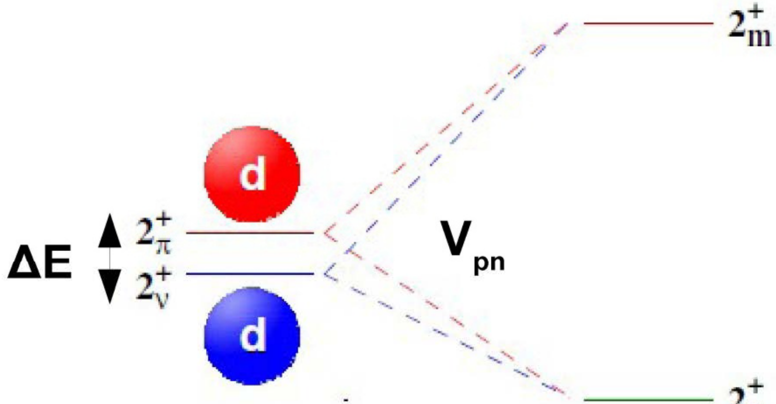
(in a n-rich nucleus)

Such an effect can be detected through measurement of electric quadrupole moments *Q* associated with nuclear spin.

Configurational Isospin Polarization: B(E2)s for nuclei with n-excess







Shell Model:
N. Shimizu, T. Otsuka, T. Mizusaki, M. Honma, PRC 70, 054313 (2004)

QRPA:
J. Terasaki et al., PRC 66, 054313 (2002)

π-ν balance of Q-coll. states of even-even n-rich Te, Xe and Ba

New CIP case predicted: 136Te

TECHNISCHE UNIVERSITÄT DARMSTADT

2+1 and 2+2 have significant E2 -> 1-phonon states

Strong M1 between them -> 2+2 = 2+1,MS

2+1 neutron dominated, 2+2 large proton amplitudes

-> CoulEx at SPES !

The neutron rich Sn region

	$\lambda_i^\pi = 2_i^+$	Energy (MeV) Expt.	Energy (MeV) Theory	Structure	$B(E2; 0_{gs}^+ \to 2_i^+)$ (e^2fm^4) Expt.	$B(E2; 0_{gs}^+ \to 2_i^+)$ (e^2fm^4) Theory	$B(E2; 2_i^+ \to 2_1^+)$ (e^2fm^4) Expt.	$B(E2; 2_i^+ \to 2_1^+)$ (e^2fm^4) Theory	$B(M1; 2_i^+ \to 2_1^+)$ (μ_N^2) Expt.	$B(M1; 2_i^+ \to 2_1^+)$ (μ_N^2) Theory
^{136}Te	2_1^+	0.606	0.92	$97\%[2_1^+]_{QRPA}$	1030±150	1120				
	2_2^+	1.568	2.01	$94\%[2_2^+]_{QRPA}$		740		20		0.51

	State	Energy (MeV)	$B(M1; 2_i^+ \to 2_1^+)$ (μ_N^2)	$B(E2; 0_{gs}^+ \to 2_i^+)$ (e^2fm^4)	$\{n_1l_1j_1, n_2l_2j_2\}_\tau$	X	Y	%
^{136}Te	$[2_1^+]_{QRPA}$	1.05		1010	$\{2f_{7/2}, 2f_{7/2}\}_\nu$	1.32	0.14	86
					$\{2d_{5/2}, 2d_{5/2}\}_\pi$	0.32	0.13	4
					$\{1g_{7/2}, 1g_{7/2}\}_\pi$	0.30	0.12	4
	$[2_2^+]_{QRPA}$	2.20	0.44	920	$\{2f_{7/2}, 2f_{7/2}\}_\nu$	-0.52	0.13	13
					$\{2d_{5/2}, 2d_{5/2}\}_\pi$	0.82	0.04	34
					$\{1g_{7/2}, 1g_{7/2}\}_\pi$	0.83	0.04	34

QPM: A. Severyukhin *et al.*, submitted to PRC

➔ probe bulk properties of nuclei

➔ in-medium modification of NN interaction

➔ symmetry energy

➔ compressibility

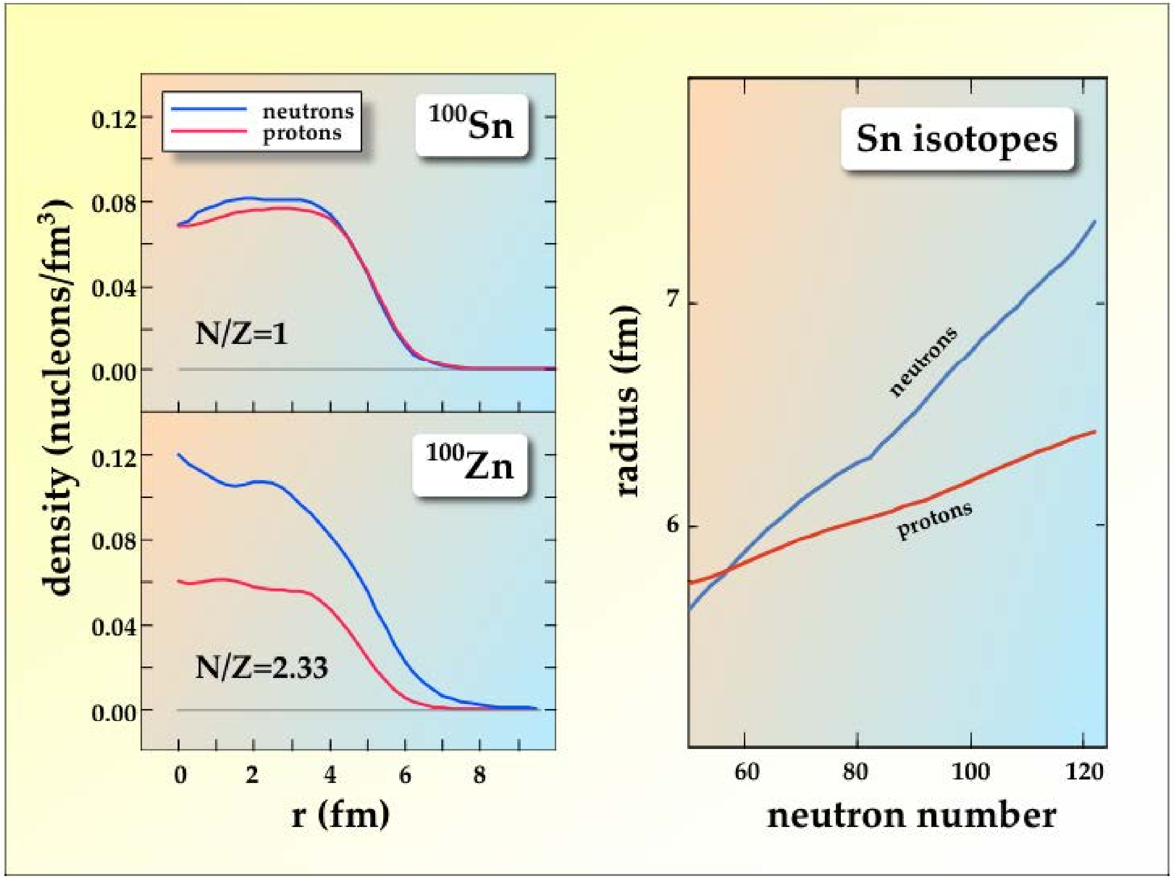
➔ New soft modes

Collective Modes

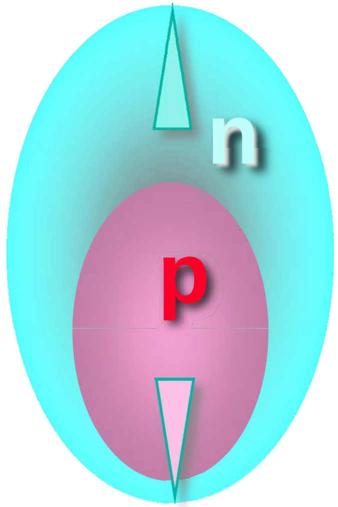
Radioactive beams allow study of isospin dependence

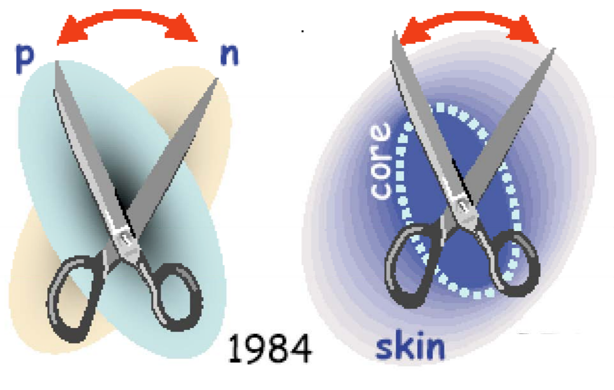
Neutron "skins" near the neutron drip line

Outer regions of low density nearly pure neutron matter

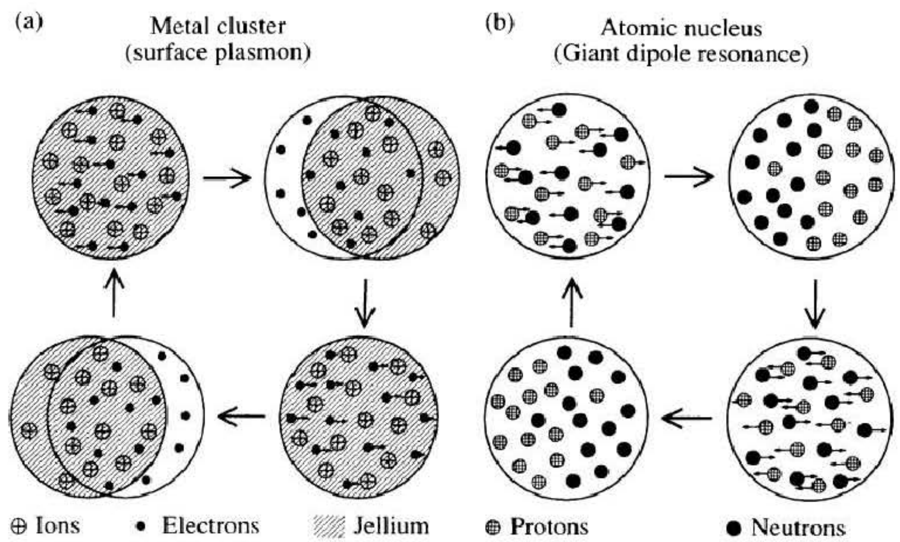


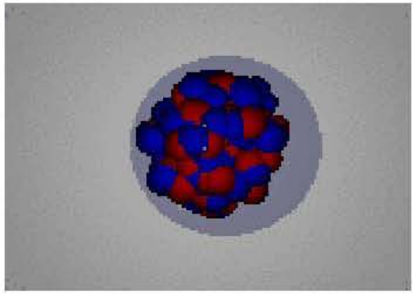
Skins and Skin Modes





Low-lying dipole excitation via nuclear probes in exotic nuclei: INFN Ct and Uni Pd

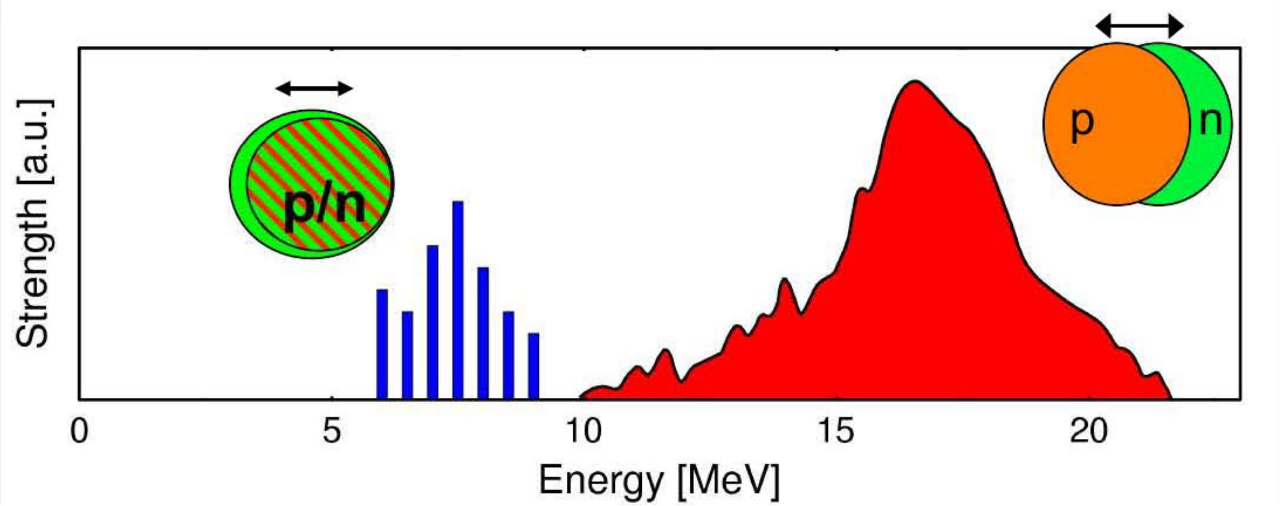




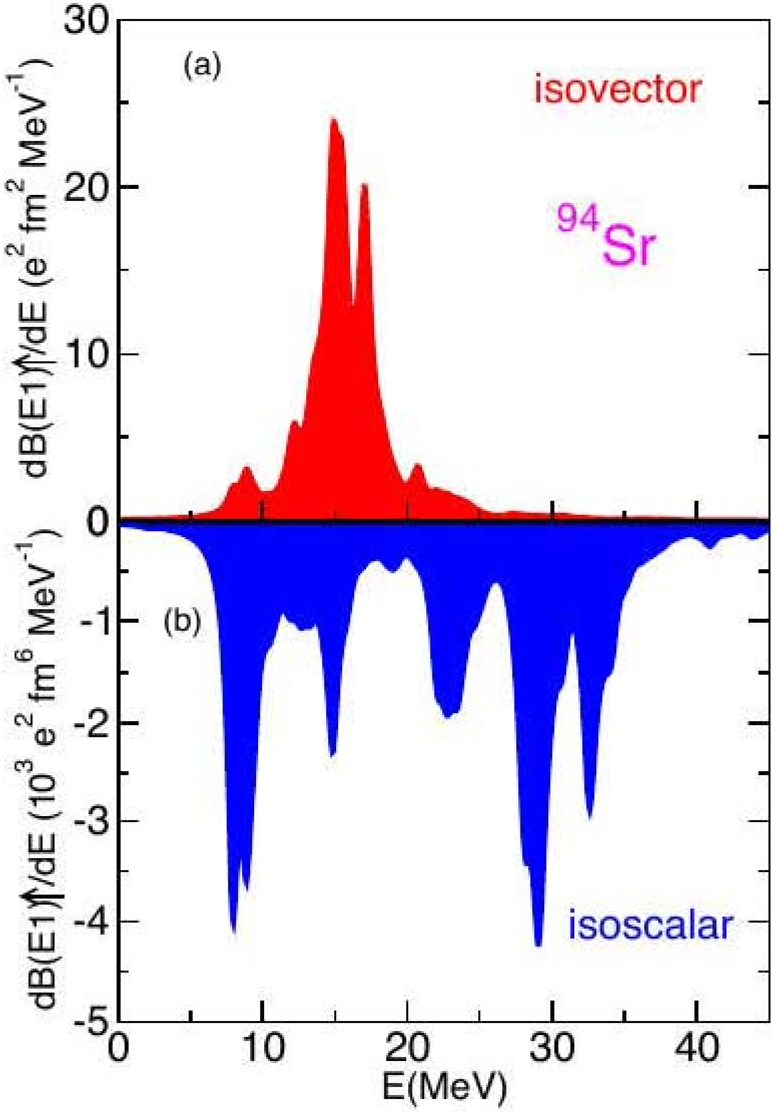
GDR
Universal phenomenon

Accumulation of strength at lower energy: *pygmy*

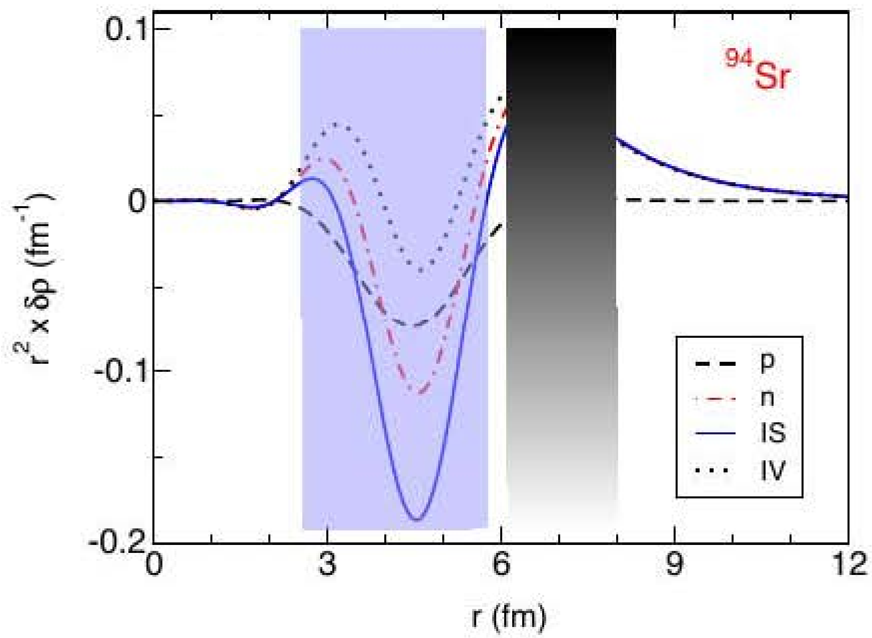
D. Savran , T. Aumann , A. Zilges
Progr.Part. Nuc.Phys 70 (2013) 210–245



RPA structure calculations

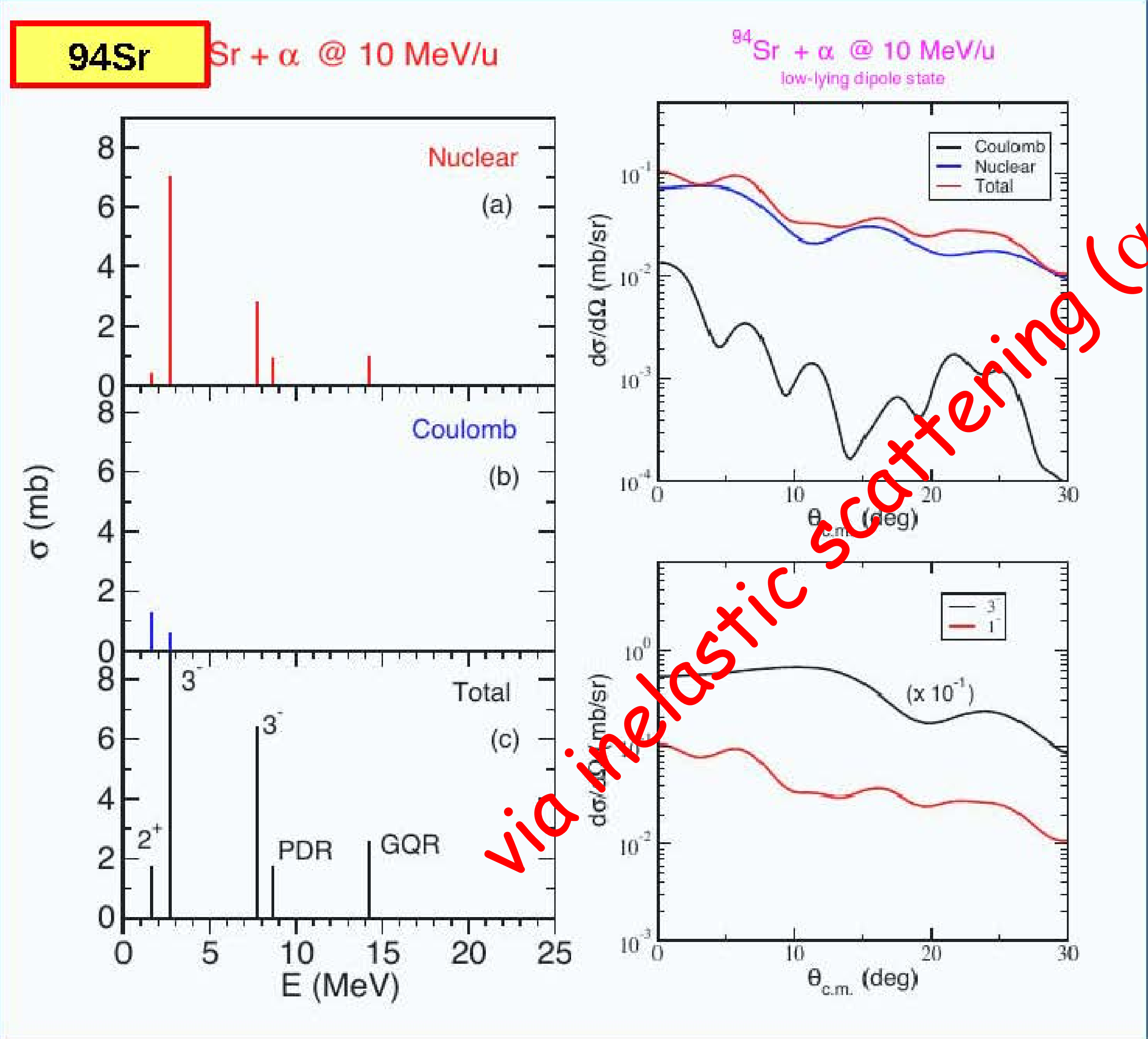


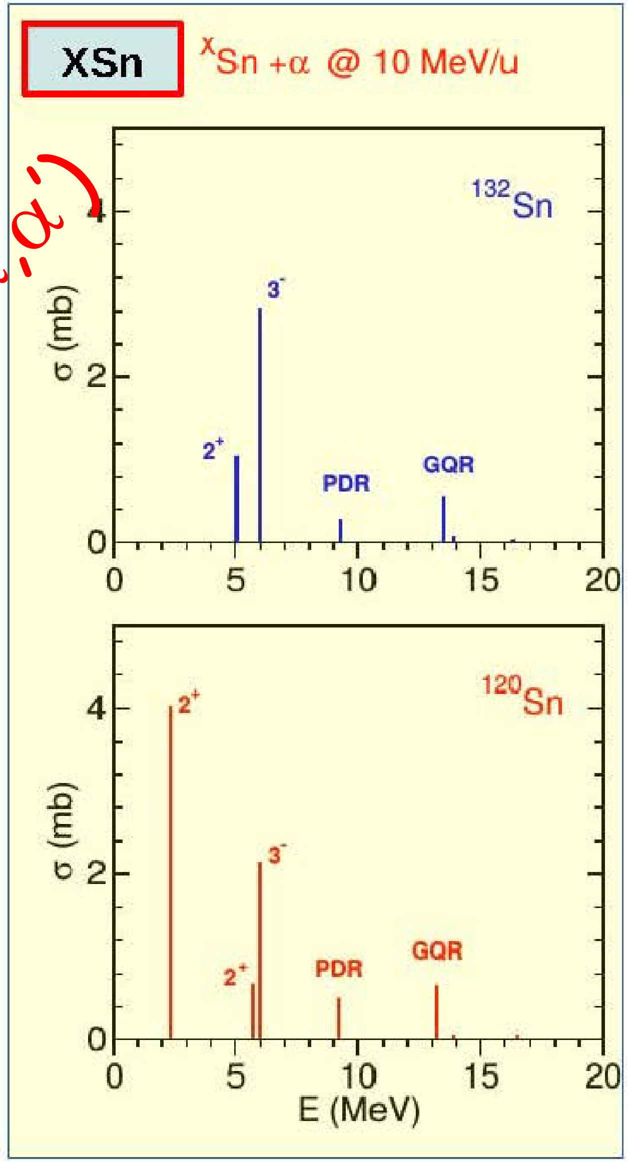
- IS effect CORE
- IS~IV surface



Cross section calculations: semiclassical model

LOI Ct, LNL





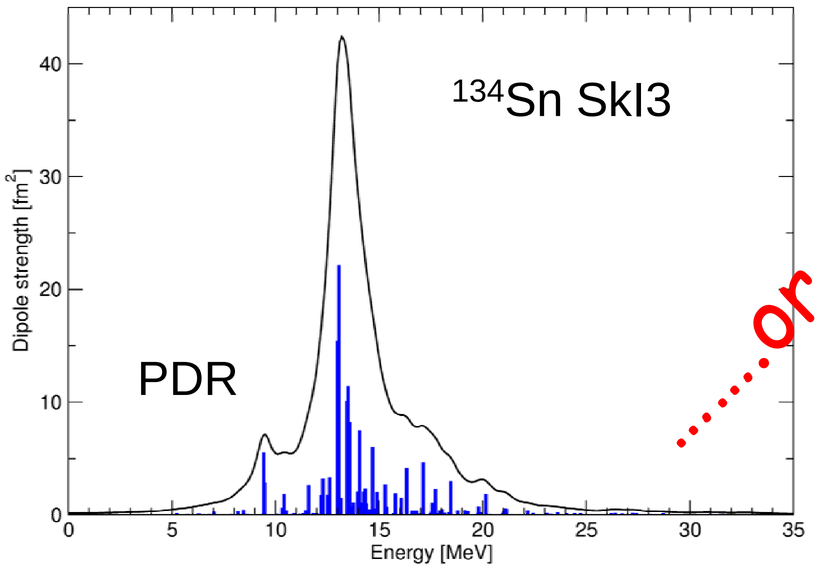
The large Q_β-value window (> 12 MeV) allows populating at least the PDR

The β decay could populate states which are the PDR on the IAS(R) of the mother nucleus

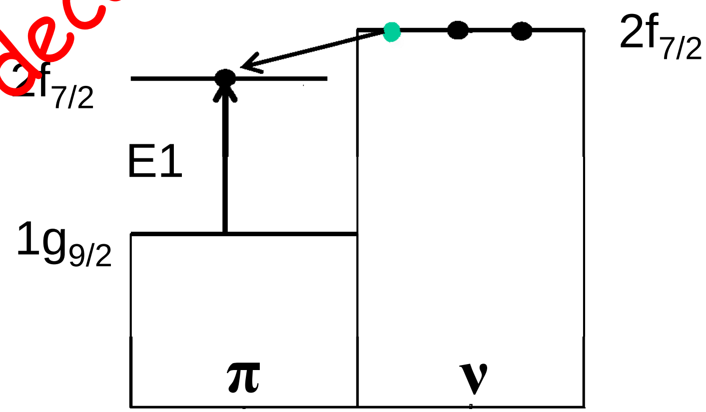
Example: $^{134}In \rightarrow {}^{134}Sn$ (Q_β= 14.7 MeV)

$\nu f_{7/2} \rightarrow \pi g_{9/2}$

β decay: $\nu 2f_{7/2} \rightarrow \pi 2f_{7/2}, \pi 2f_{5/2}$;



……or via β-decay



QRPA calculations with the SkI3 interaction: PDR at 10 MeV

^{133,134}In rates @ ALTO: 1000 pps ; 25 pps (100 times higher at SPES)