Recent developments and perspectives in NUCLEAR STRUCTURE by gamma and particle spectroscopy

Silvia Leoni

UNIMI/INFN: **A. Bracco, F. Camera, F.C.L. Crespi, S. Bottoni, S. Leoni, A. Mentana, A. Pullia, S. Capra, S. Riboldi, P.F. Bortignon, G. Colò**
INFN: **G. Benzoni, B. Blasi, C. Boiano, S. Brambilla, B. Million, O. Wieland, E. Vigezzi**

INFN-CNS3-GAMMA: MI, PD, LNL, FI, PG
International collaborations within EUROPE, JAPAN, USA

Milano, 28-29 June 2017

INTRODUCTION

Challenges in Nuclear Physics

- The Physics – more than 7000 Nuclei !
- Interdisciplinarity *- Astrophysics*
- Dedicated Facility/Detection Setups *– γ spectroscopy*

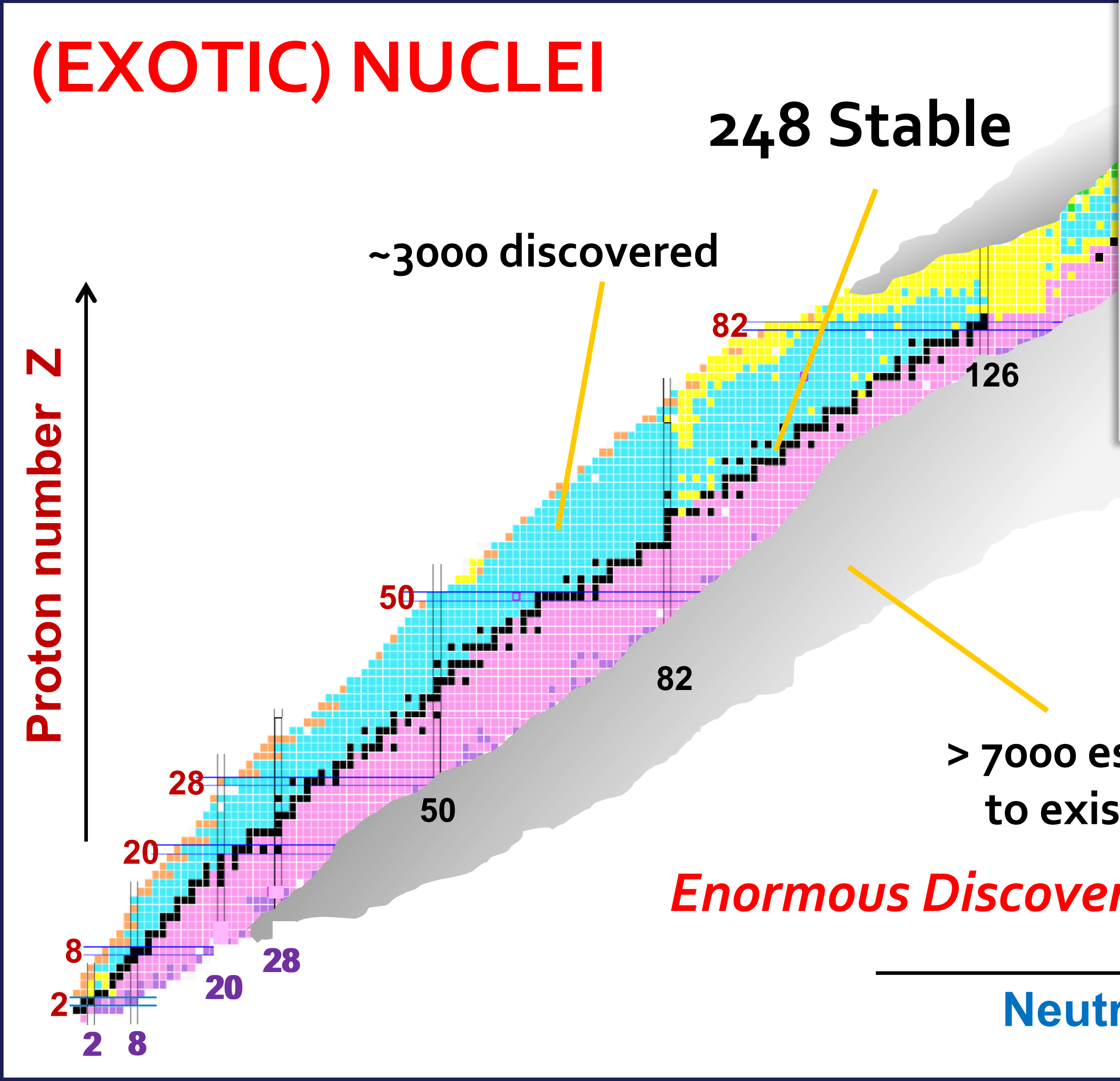
FOCUS on NUCLEAR STRUCTURE

Selected Recent Highlights

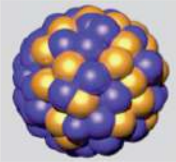
- Shape Coexistence
- Collective Excitations *– Resonances*
- Complex Excitations *– Coupling Particles and Phonons*

- OUTLOOK *– how to pin down the nuclear force …*

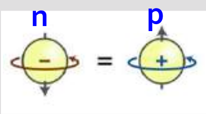
Our Challenge: UNIFIED Description of ALL Nuclei in the Universe



BASIC SCIENCE



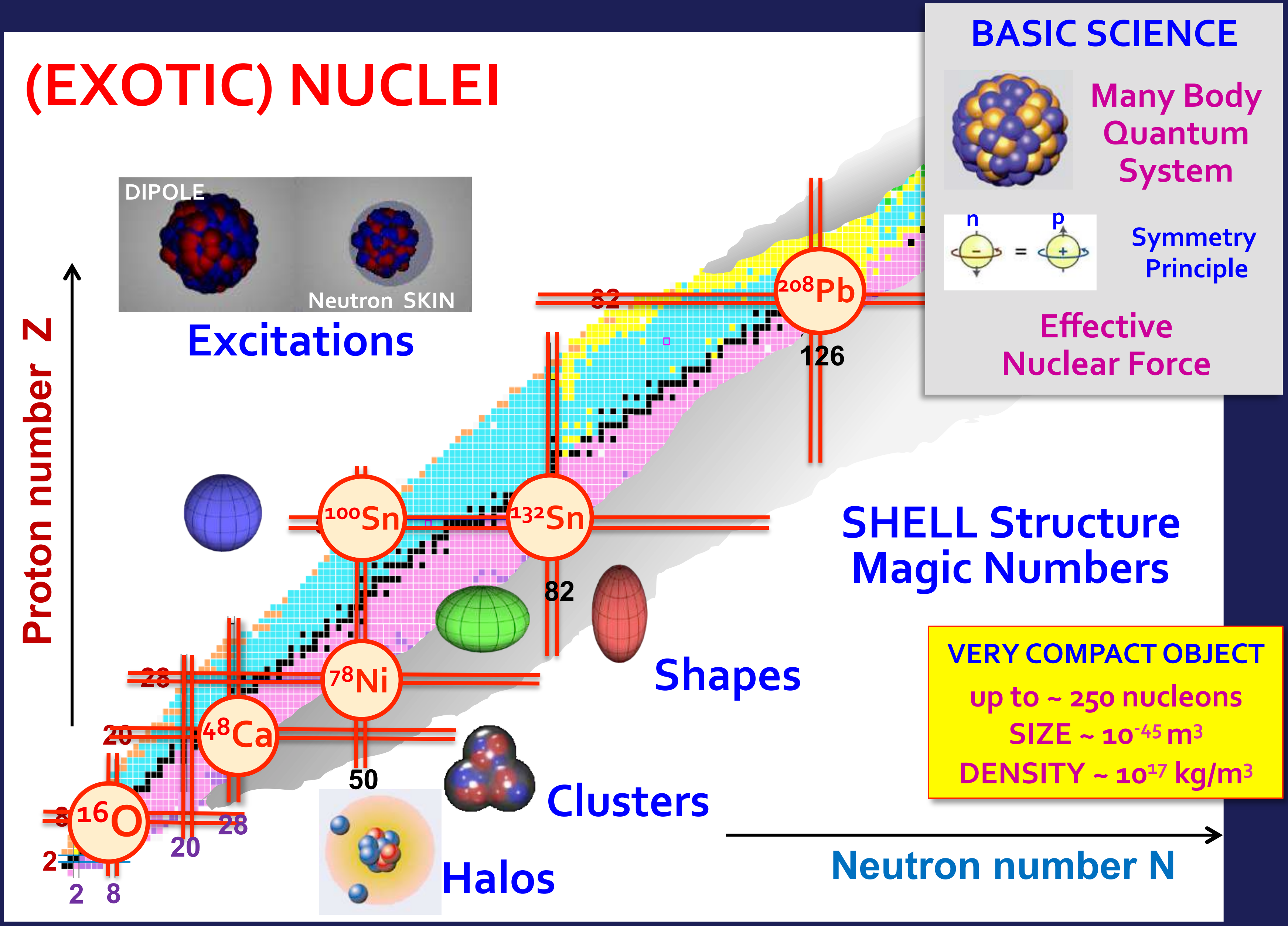
Many Body Quantum System



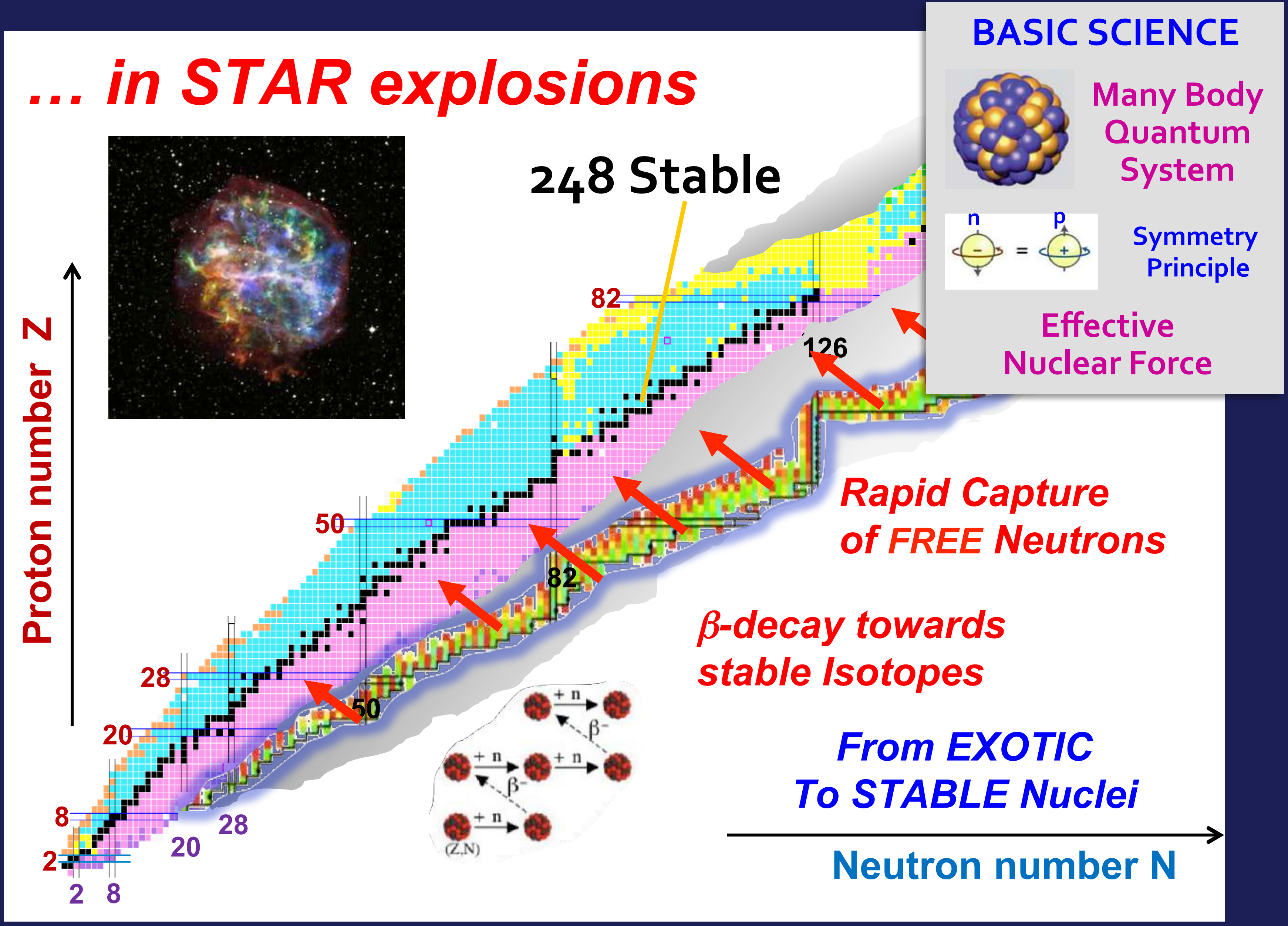
Symmetry Principle

Effective Nuclear Force

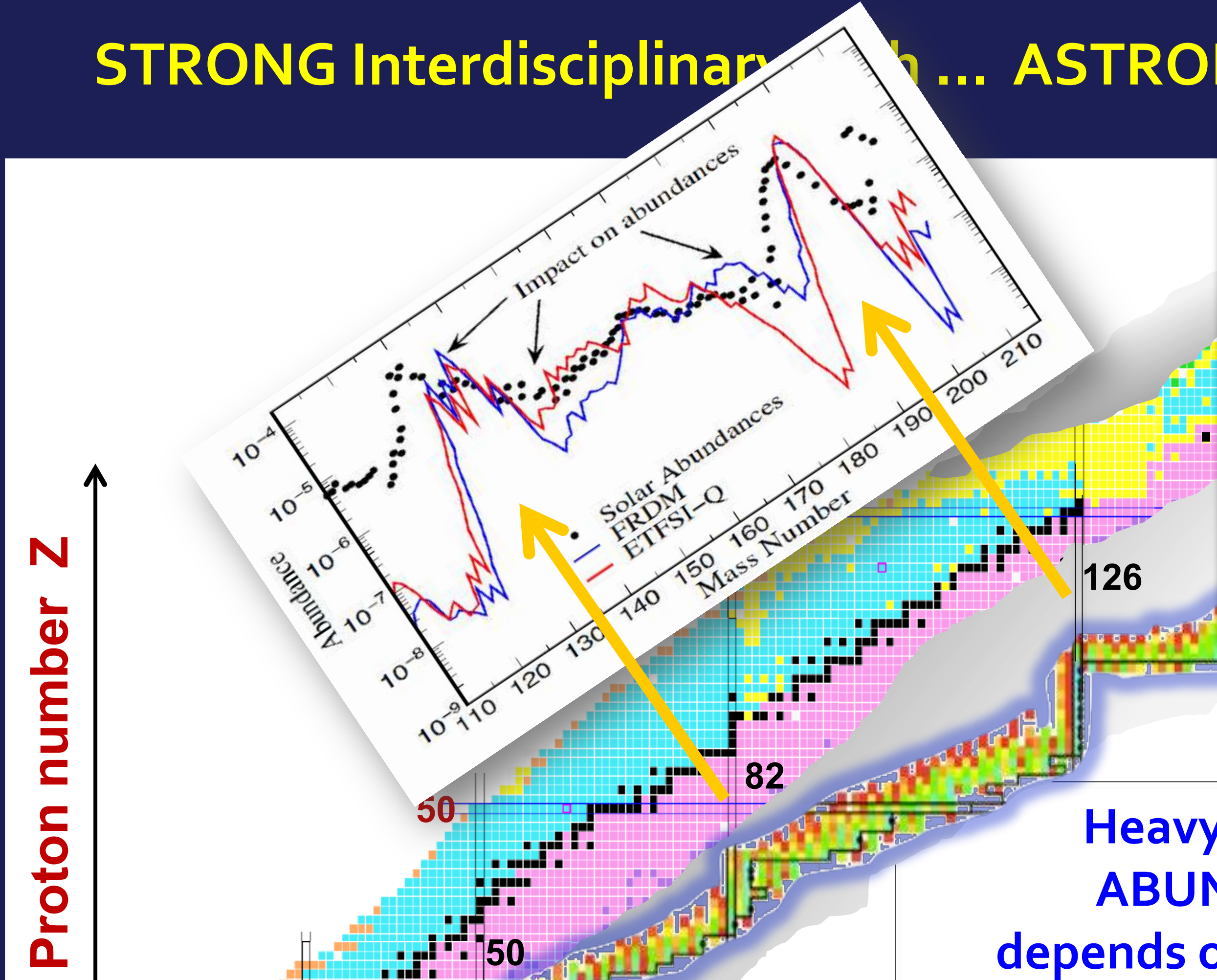
Our Challenge: UNIFIED Description of ALL Nuclei in the Universe



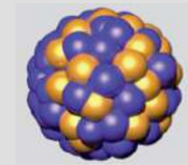
STRONG Interdisciplinary with … ASTROPHYSICS



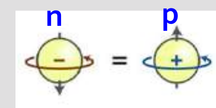
STRONG Interdisciplinar… …h … ASTROPHYSICS



BASIC SCIENCE



Many Body Quantum System

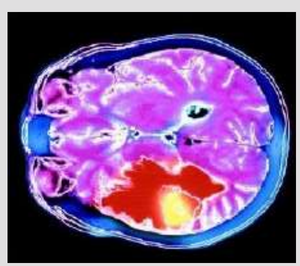


Symmetry Principle

Effective Nuclear Force

APPLICATIONS

Radio isotopes,
Reactors, …



Heavy Elements ABUNDANCES depends on Structure of *UNKNOWN EXOTIC Nuclei*

Magic Numbers, Shapes

$\tau_{\beta\ \mathrm{Spherical}} \sim 10 \times \tau_{\beta\ \mathrm{Deformed}}$

$P_{n\ \mathrm{Spherical}} \sim 0.5 \times P_{n\ \mathrm{Deformed}}$

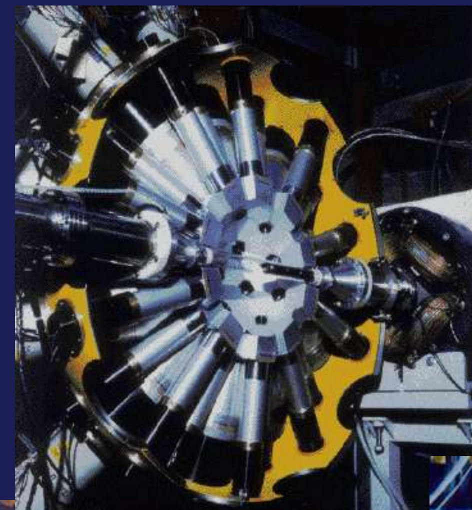
A World Wide Effort to Expand the Nuclear Chart …

- **PRODUCTION**: **stable** and **radioactive ion beams**, **neutron** beams, …
- **INVESTIGATION of Nuclear Structure**: **gamma** and **particle** spectroscopy

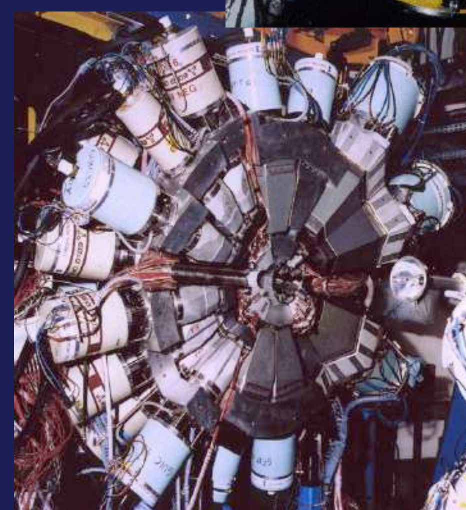
LONG TRADITION OF γ-SPECTROSCOPY
Arrays based on Compton suppressed Ge detectors

Starting from the 80's:

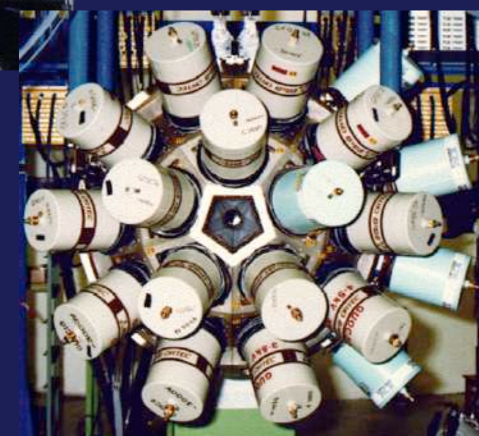
TESSA (Daresbury)
OSIRIS (Berlin)
ARGONNE-ND ARRAY (Argonne)
NORDBALL (Copenhagen)
JUROSPHERE (Jyvaskyla)
EUROGAM (Strasbourg)
CLARION (Oak Ridge)
GASP/GALILEO (Legnaro)
EUROBALL (Legnaro, Strasbourg)
GAMMASPHERE



GASP
Legnaro



EUROBALL
Legnaro, Strasbourg

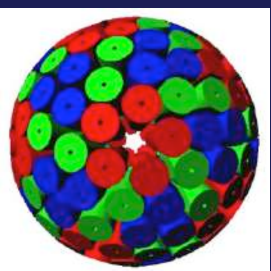


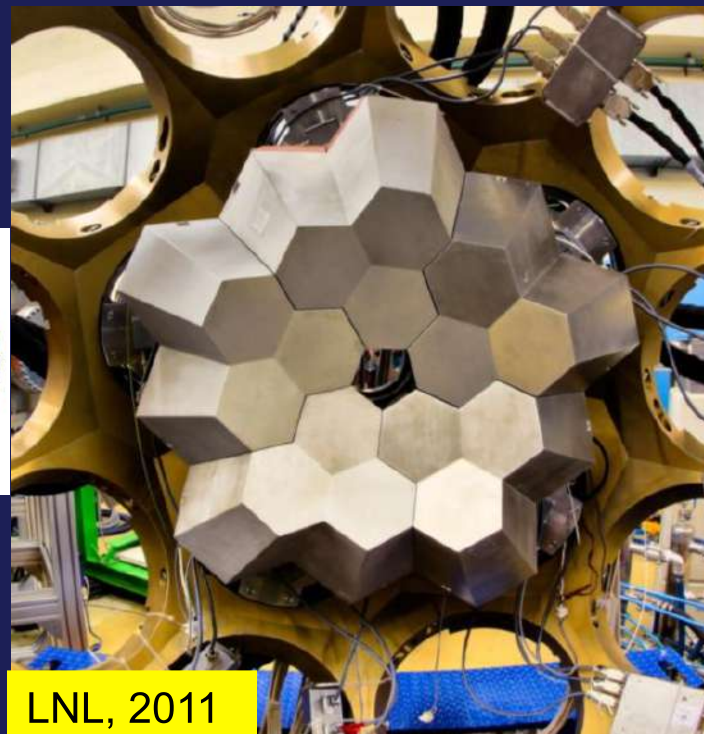
EUROGAM
Daresbury

STATE of the ART Ge ARRAYS

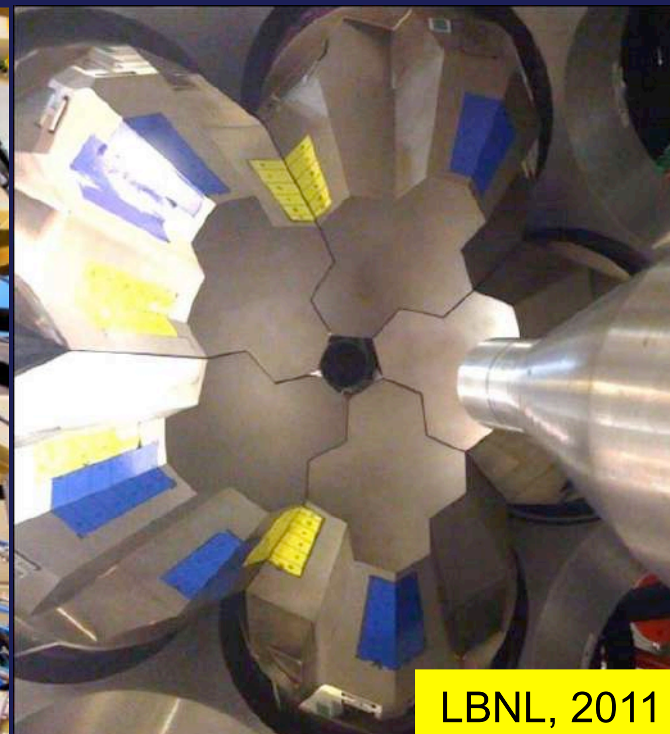
AGATA
(Advanced-GAmma-Tracking-Array)

GRETA
(Gamma-Ray Energy Tracking Array)

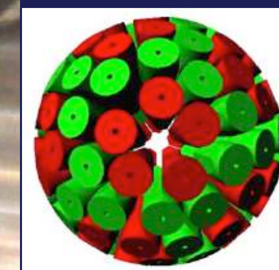




S. Akkoyun et al, NIMA 668 (2012) 26-58



S. Paschalis et al, NIMA 709 (2013) 44-55



The "Ultimate" Ge Arrays

- **EFFICIENCY:** 43% M_γ = 1 and 28% $M\gamma$ = 30 (@ 1 MeV, FULL BALL)
- **COUNT RATE** capabilities (100s KHz)
- **ANGULAR RESOLUTION** of the γ interaction point (θ~1°)
- **"PERFECT" DOPPLER CORRECTION** (6 keV @ 1 MeV, β=50%)

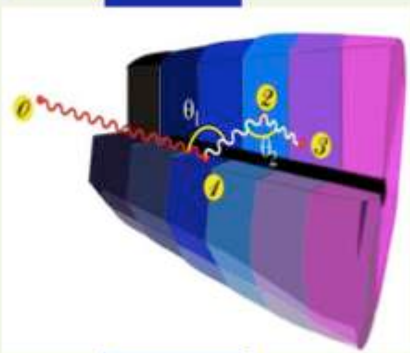
The Gamma Tracking Array Concept

HARDWARE

SOFTWARE

1

Highly segmented HPGe detectors



2

Digital electronics to record and process segment signals

14 bit, 100 MS/s

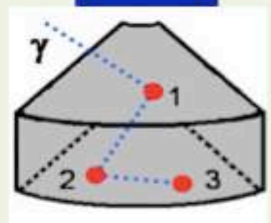
37 signals/crystals

Raw Data Read Out:

10 kB/evt/crystal

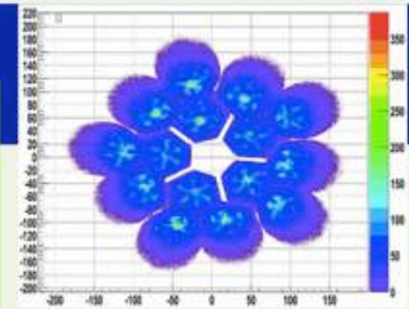
3

Pulse Shape Analysis to decompose recorded waves



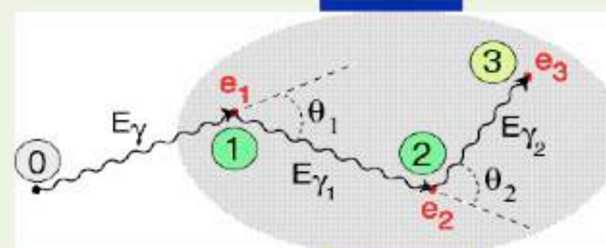
Identified interaction points

$(x,y,z,E,t)_i$



4

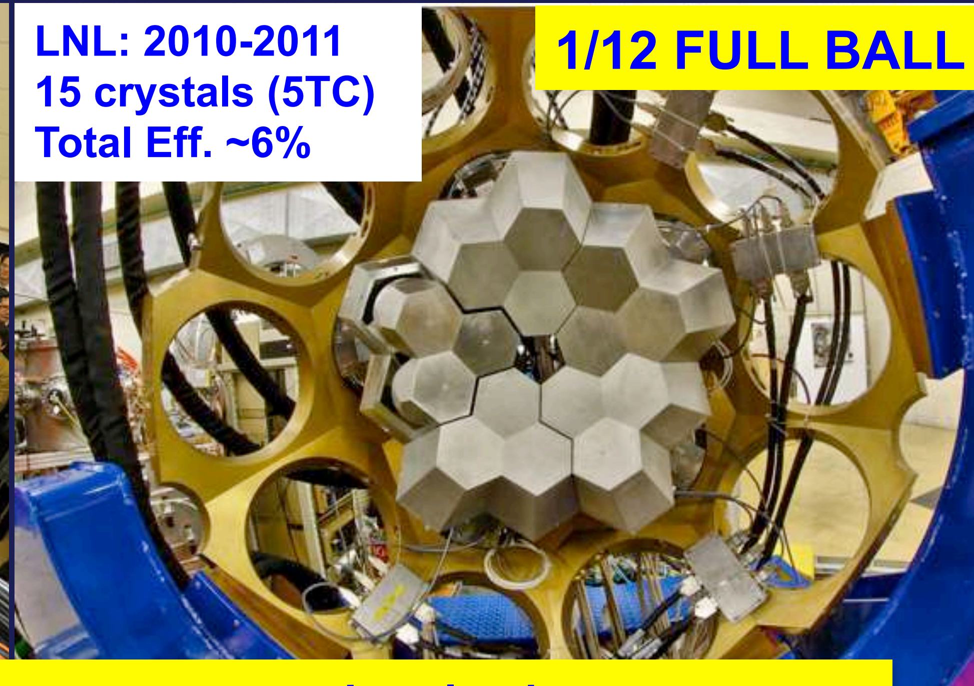
Reconstruction of tracks evaluating permutations of interaction points



Reconstructed gamma-rays

+

Correlation with other detectors



LNL: 2010-2011
15 crystals (5TC)
Total Eff. ~6%

1/12 FULL BALL

AGATA Inauguration: 9th April 2010 – Legnaro National Laboratory INFN

Physics Campaign @ LNL
(2010-2011)

Most Relevant Results from Milano
2 Phys. Rev. Lett.
1 Review Paper
Several Phys. Rev. C

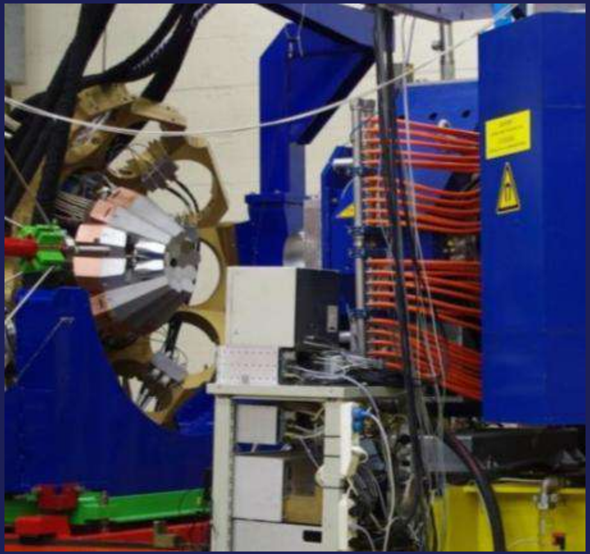
INFN
Legnaro

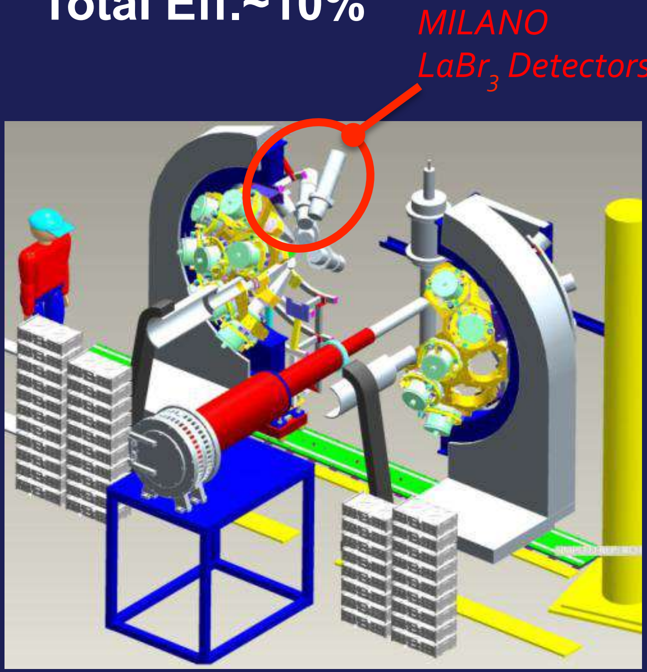
The AGATA Evolution Towards 1π

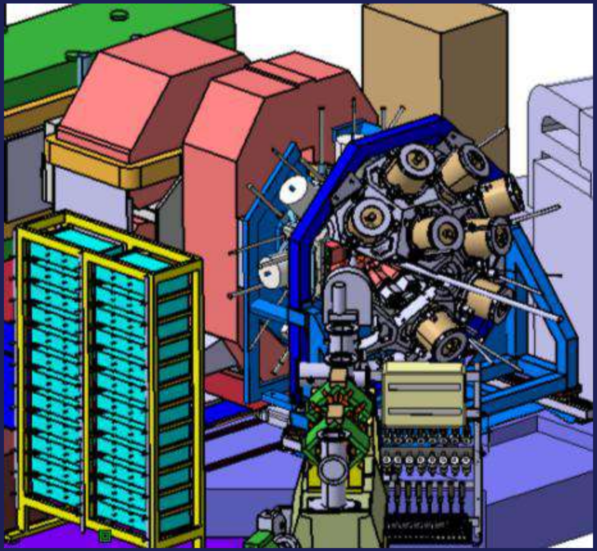
LNL: 2010-2011
15 crystals
Total Eff. ~6%

GSI: 2012-2014
22 crystals
Total Eff.~10%

GANIL: 2015-2019
up to 45 crystals
Total Eff. ~22%







Demonstrator + PRISMA
"backward"
STABLE BEAMS
20 experiments

AGATA + FRS
"forward"
RELATIVISTIC
EXOTIC BEAMS
7 experiments

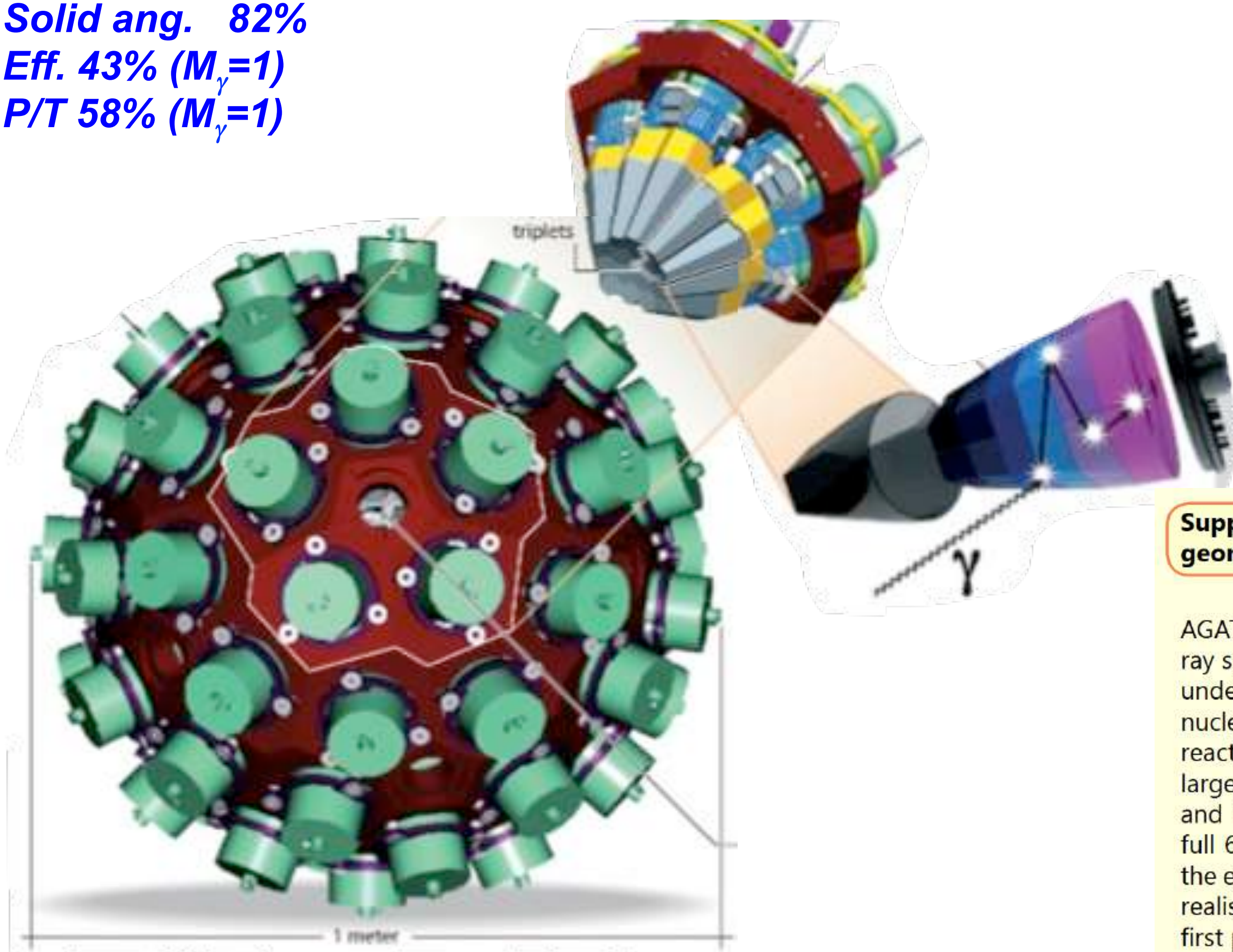
AGATA+VAMOS+ …
"backward"
EXOTIC (ISOL)
& STABLE BEAMS
6 experiments in 2015

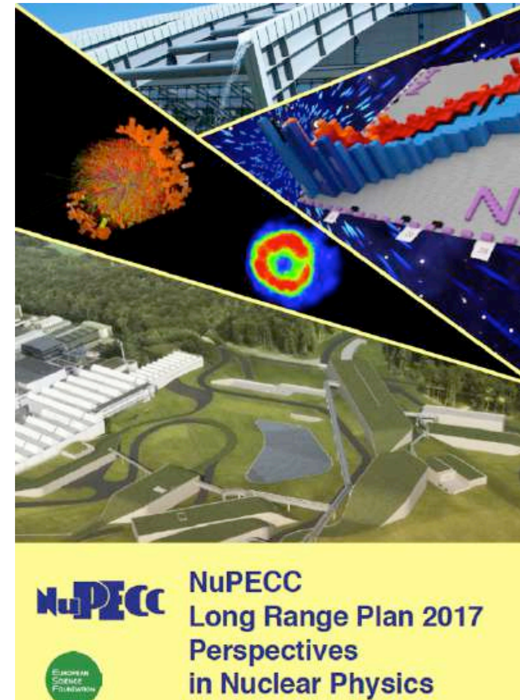
→ From 2020 at Legnaro-INFN (SPES Radioactive ISOL Beams)

AGATA - FULL Detector

180 crystals segmented (6480 segments)
60 triple clusters
2.5 tons
FULLY DIGITAL electronics

Solid ang. 82%
Eff. 43% (M_γ=1)
P/T 58% (M_γ=1)





A. Bracco, Chair

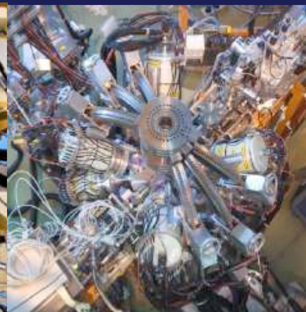
Support to the completion of AGATA in full geometry

AGATA represents the state-of-the-art in gamma-ray spectroscopy and is an essential precision tool underpinning a broad programme of studies in nuclear structure, nuclear astrophysics and nuclear reactions. AGATA will be exploited at all of the large-scale radioactive and stable beam facilities and in the long-term must be fully completed in full 60 detector unit geometry in order to realise the envisaged scientific programme. AGATA will be realised in phases with the goal of completing the first phase with 20 units by 2020.

Detection Systems (State of the Art)

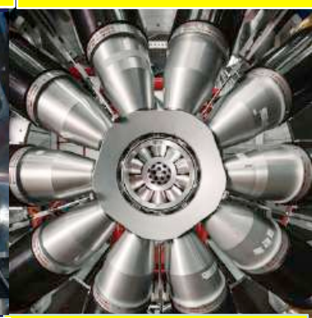
Very Powerful and Complete Experimental Setups ...

AGATA



MINIBALL

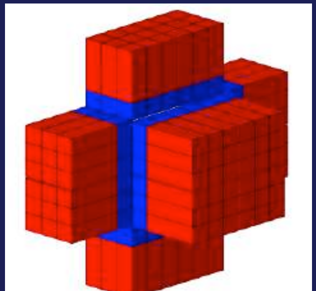
EXOGAM



GALILEO – LNL

Gamma spectroscopy

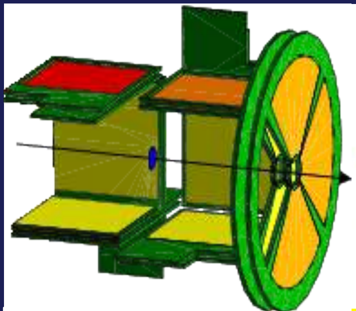
HPGe, scintillators



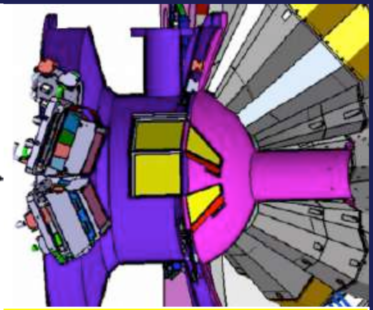
PARIS
Labr3+NaI

charged-particle Spectroscopy

Si stripped/pixel detectors

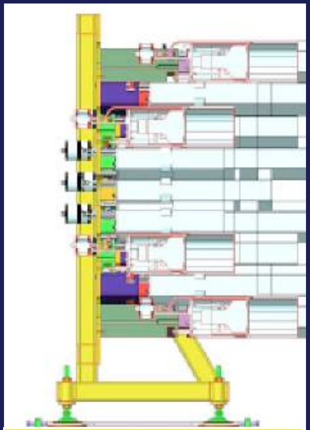


TREX



MUGAST

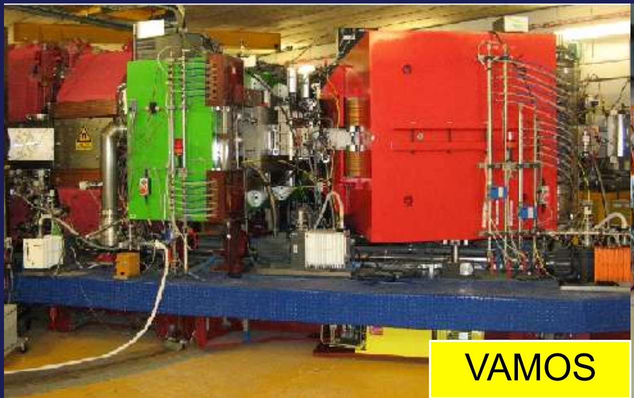
neutron identification



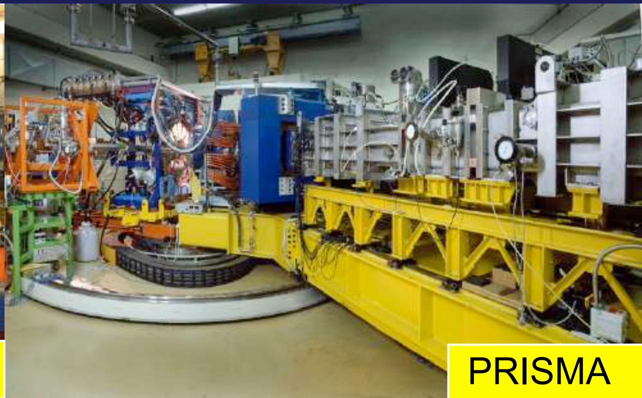
NEDA/NWALL

Magnetic Spectrometer

Large Acceptance

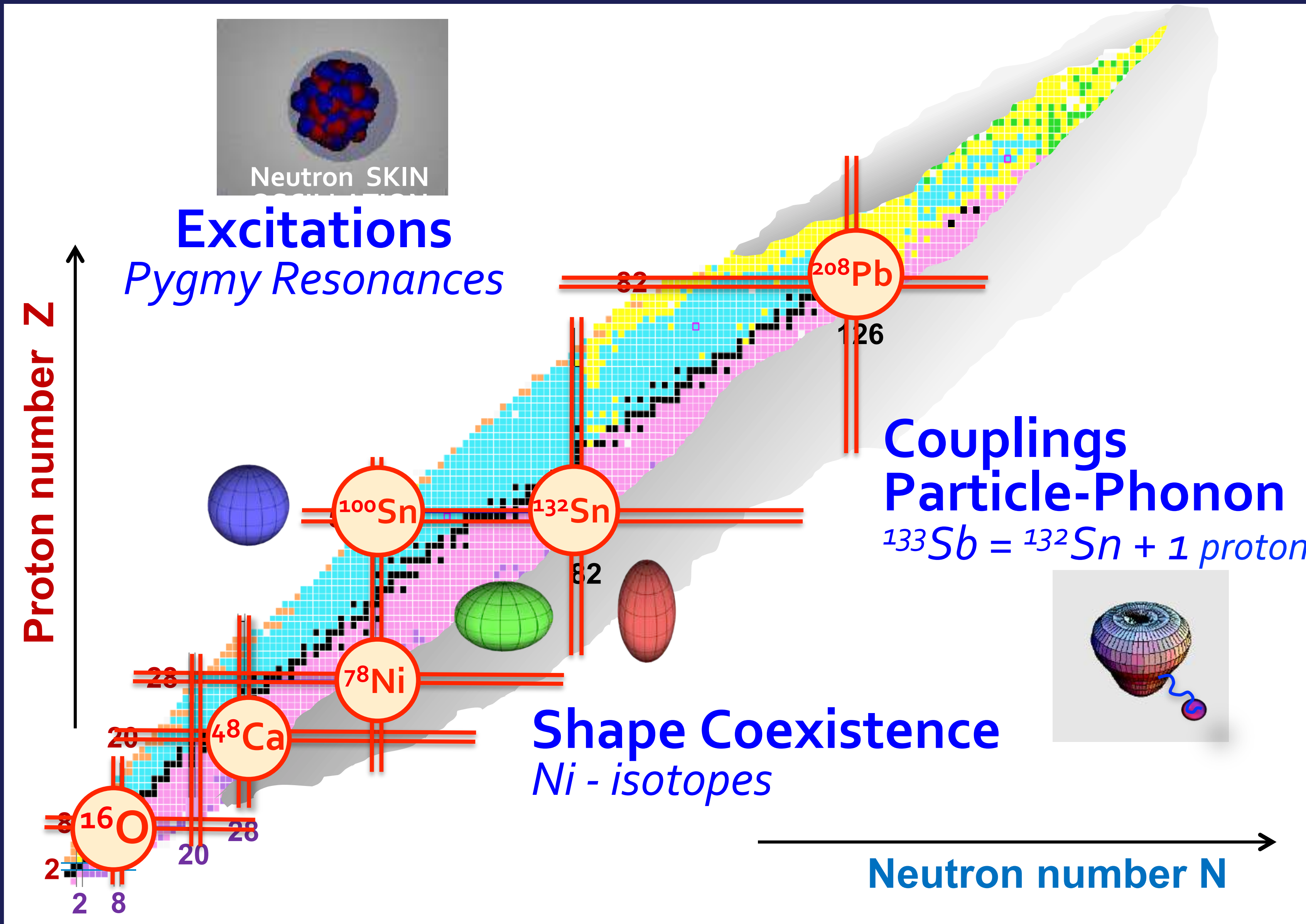


VAMOS

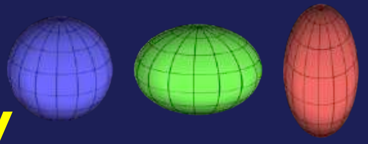


PRISMA

Selected Recent Highlights of γ spectroscopy

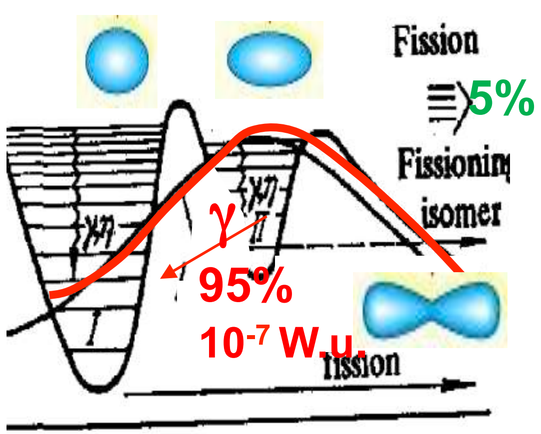


Appearence of DIFFERENT SHAPES in the SAME NUCLEUS at low excitation energy

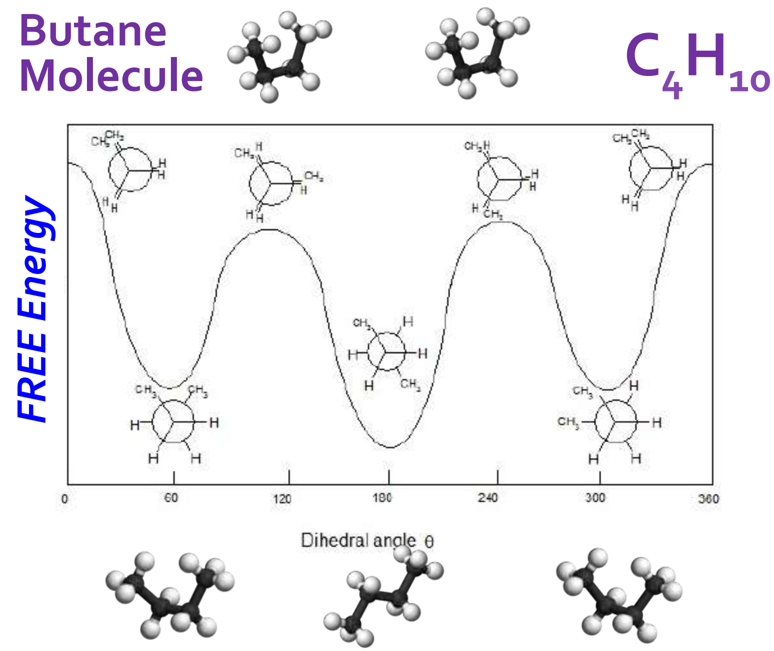


Secondary Minima in the Potential Energy Surface – PES
METASTABLE Configurations

SHAPE ISOMERS in actinide
A=240 Polikanov – 1973
TWO SEPARATE WORLDS



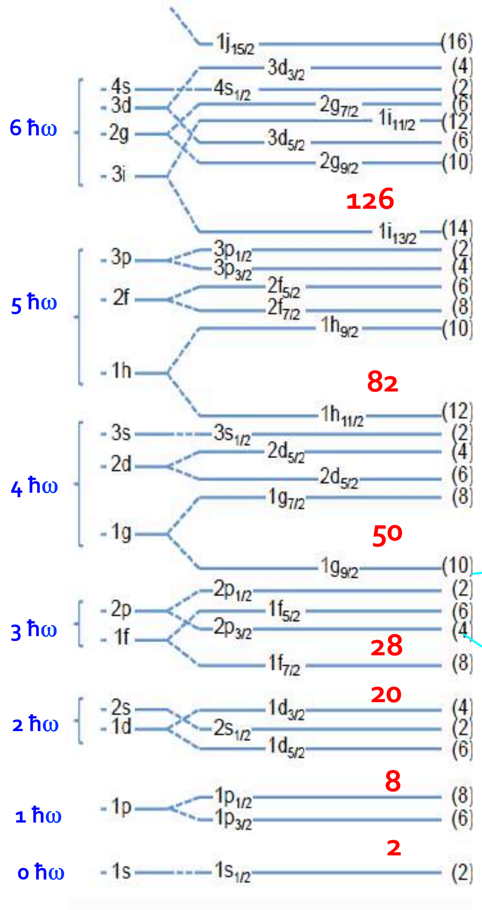
Conformational ISOMER



Present Challenge in Nuclear Physics: MICROSCOPIC description
Emergence of SHAPES and DEFORMATION
in a pure SHELL Model framework (individual nucleons + interaction)

MICROSCOPIC Structure of Nuclei:
a computational challenge …

Shell Structure
for p and n



Divergent Dimension of Configuration Space

$$\binom{K}{A} = \frac{K!}{(K-A)!\,A!}$$

Number of ways to distribute A nucleons over K orbitals

N=Z		Number of configurations
44	^{88}Ru	$\approx 10^{28}$
28	^{56}Ni	$\approx 10^{10}$
24	^{48}Cr	$\approx 10^{7}$
22	^{44}Ti	$\approx 10^{4}$

State-of-the-art SHELL Model possible for A< 100

new calculations scheme

Monte Carlo Approach

Effective N-N interaction

very powerfull computer

10^6 parallel processors

K-Computer

Tokio University

(Prof. Taka Otsuka's group)

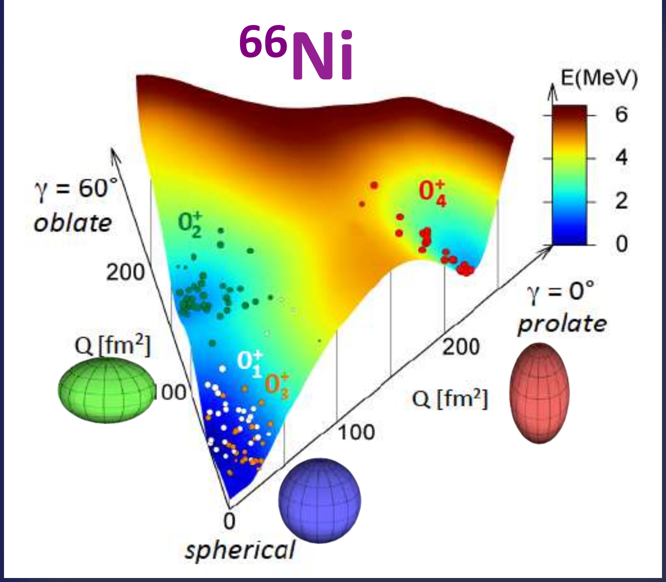
Monte Carlo SHELL Model (T. Otsuka's Group)

^{66}Ni – ^{70}Ni: COEXISTENCE of spherical, oblate and prolate SHAPES

Best Candidate for SHAPE isomerism

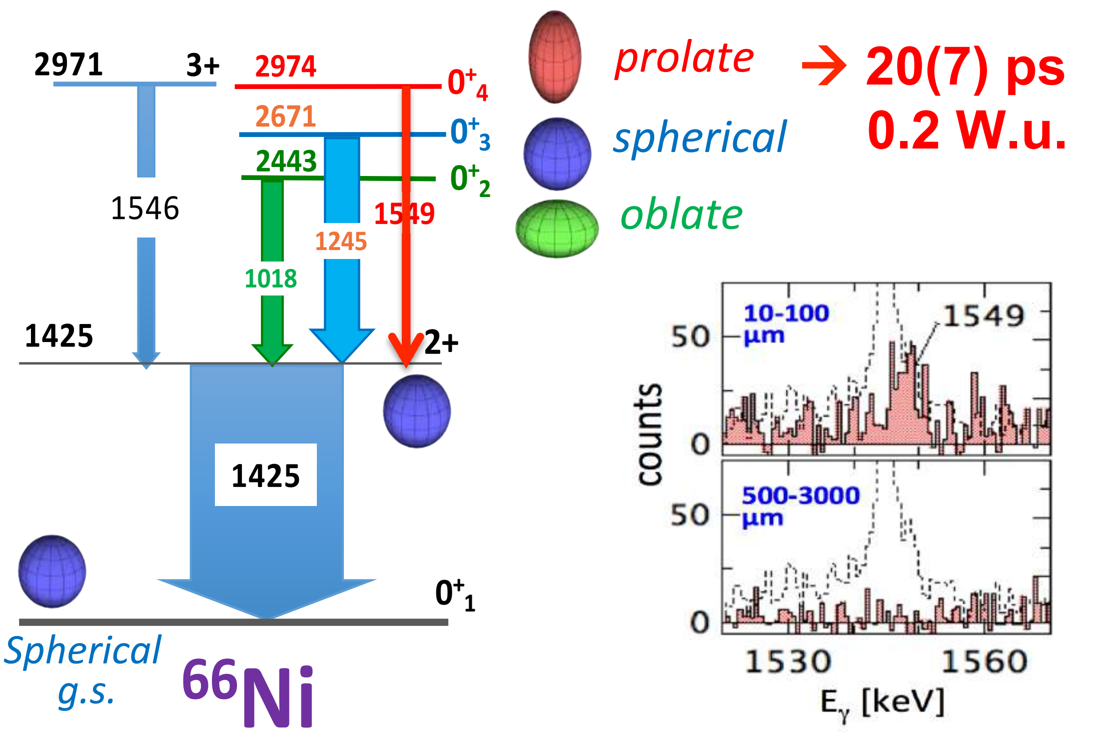
HINDERED γ-decay

PROLATE → SPHERICAL



Confirmed by Experiment !!!

^{18}O + ^{64}Ni → ^{16}O + ^{66}Ni, below Coulomb barrier



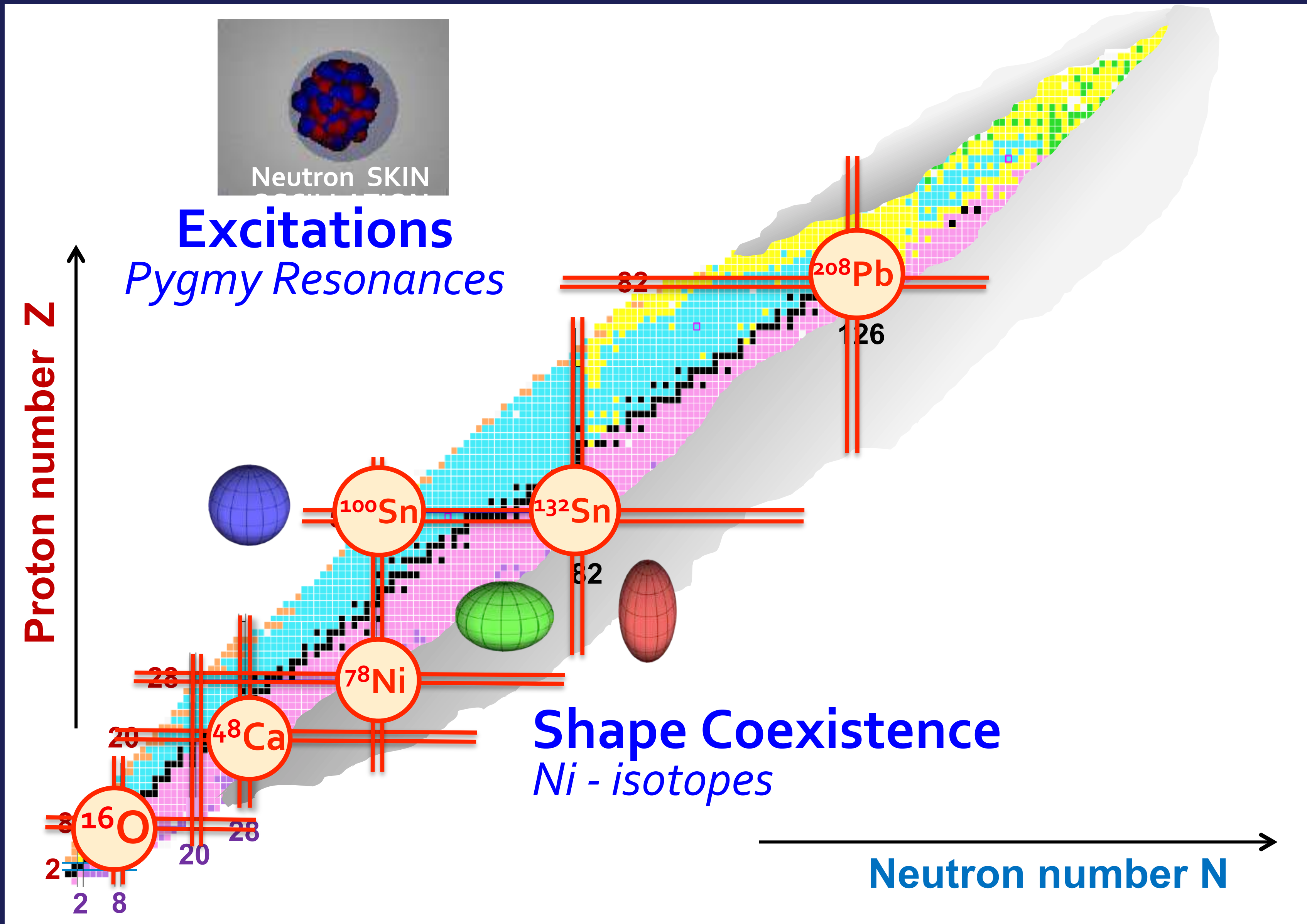
STEP FORWARD in understanding MICROSCOPIC origin of deformation

→ VALIDATION of PREDICTIVE POWER of Most Advanced SHELL Model predictions

S.Leoni, B. Fornal et al., Phys. Rev. Lett. 118, 162502 (2017) – Editor's Suggestion

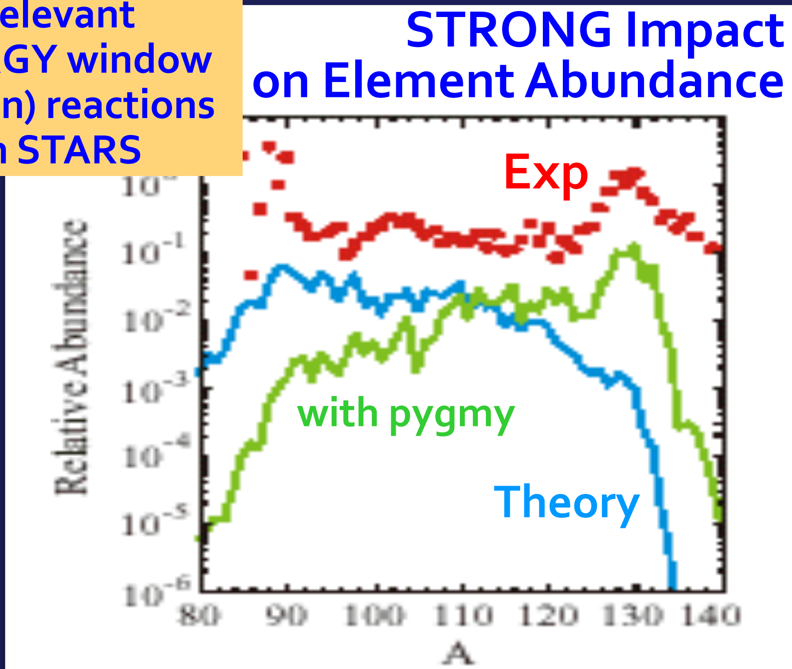
Complementary studies in Ni chain by β-decay: G. Benzoni et al., …

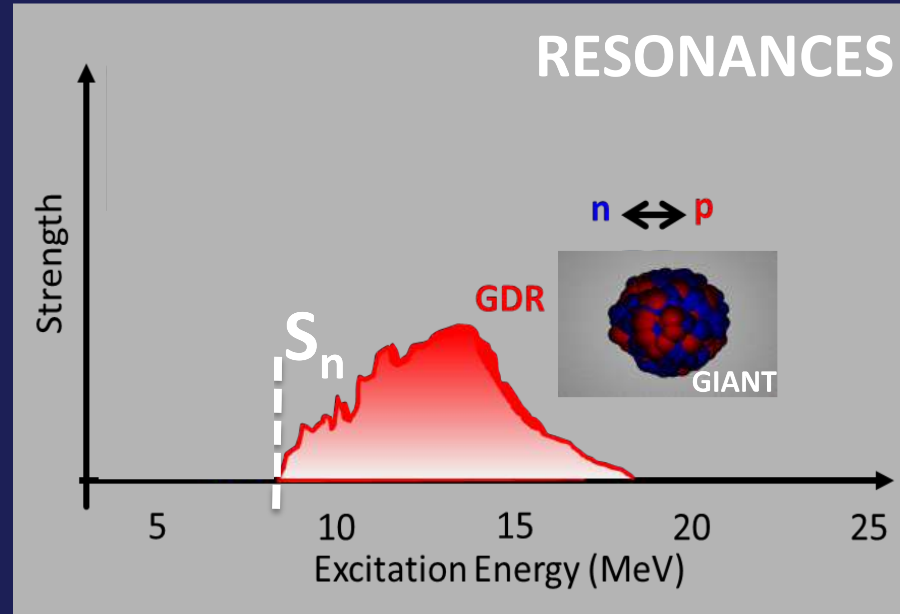
Selected Recent Highlights of γ spectroscopy

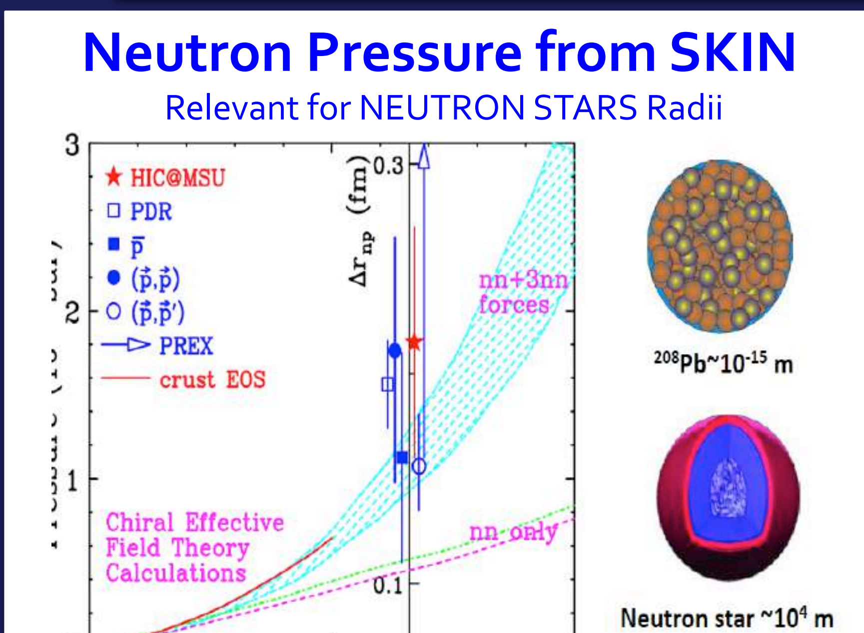


The DIPOLE Response In Nuclei

Relevant ENERGY window for (γ,n) reactions in STARS







ASTROPHYSICS Implications

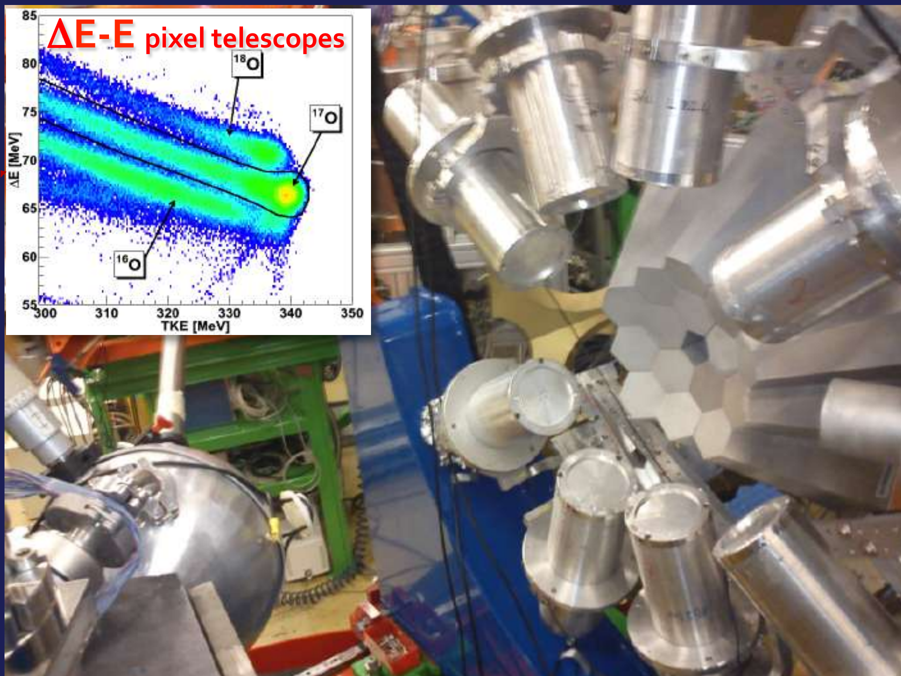
- Nucleosynthesis
- Neutron Stars

Relevance in Nuclear Structure

- Complex Microscopic Nature

Pygmy Resonances in STABLE NUCLEI

Heavy-Ion Inelastic Scattering: a probe sensitive to the **surface**



LNL Campaign

AGATA +

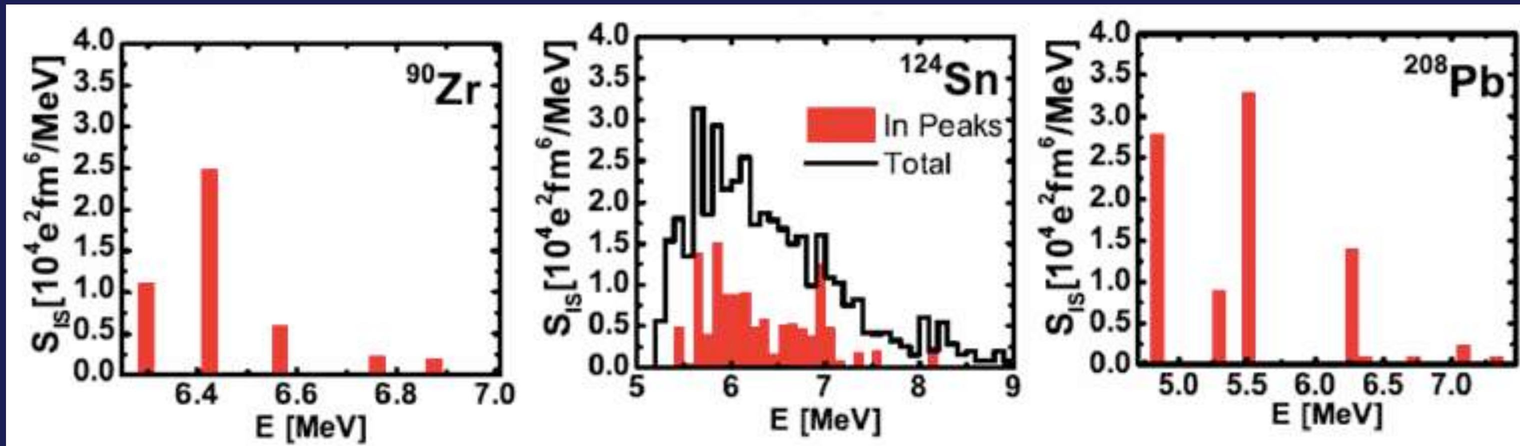
Si Telescopes +

Scintillators (LaBr3)

^{17}O @ 20 MeV/A

on ^{208}Pb, ^{124}Sn, ^{90}Zr, ^{140}Ce

STABLE targets



Pygmy Strength (E1)

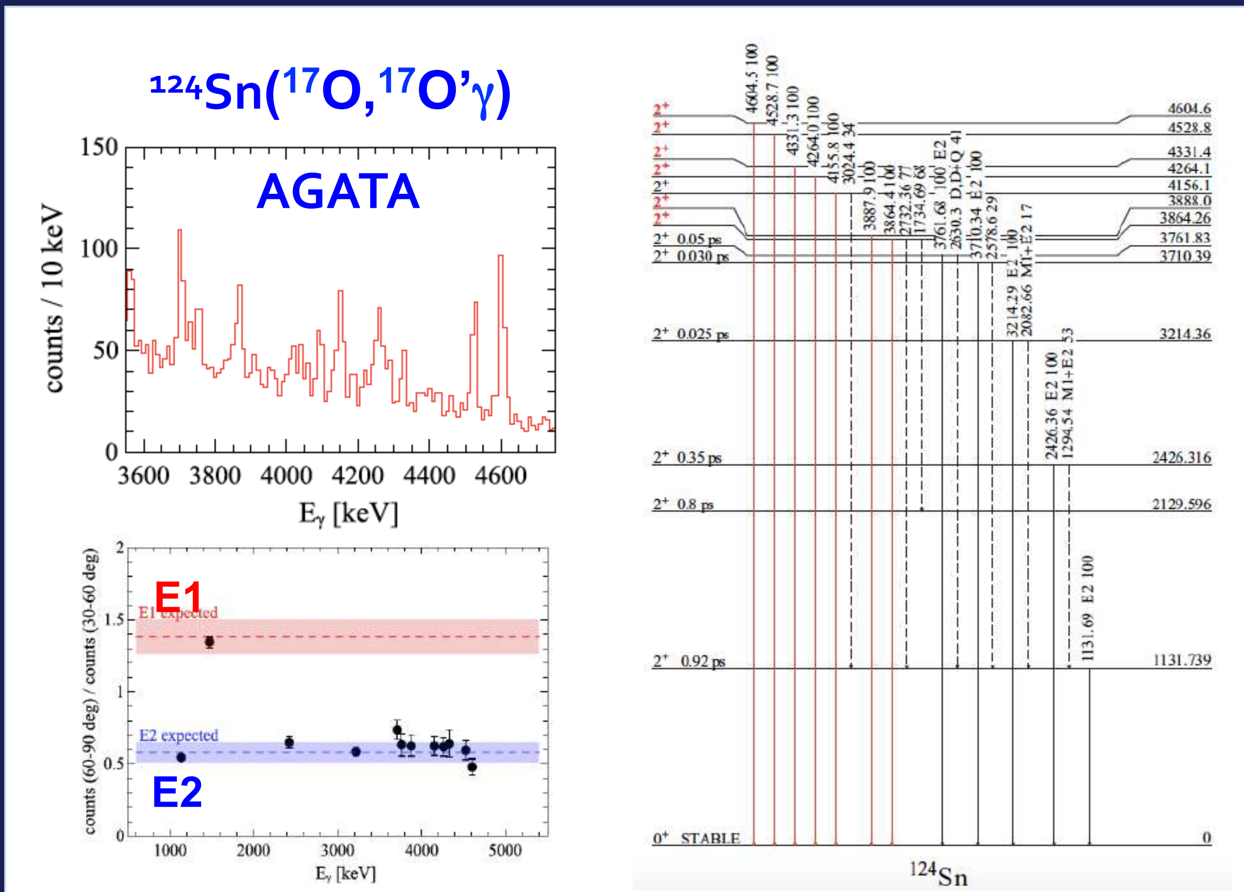
1-3% EWSR

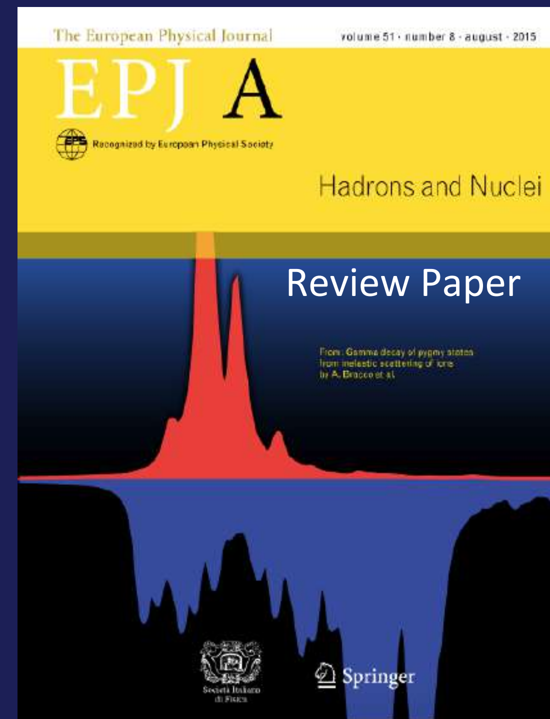
isoscalar E1

See POSTER F. Crespi

A NEW OBSERVATION: ^{124}Sn – QUADRUPOLE PYGMY

Multitude of **2^{+}** discrete states



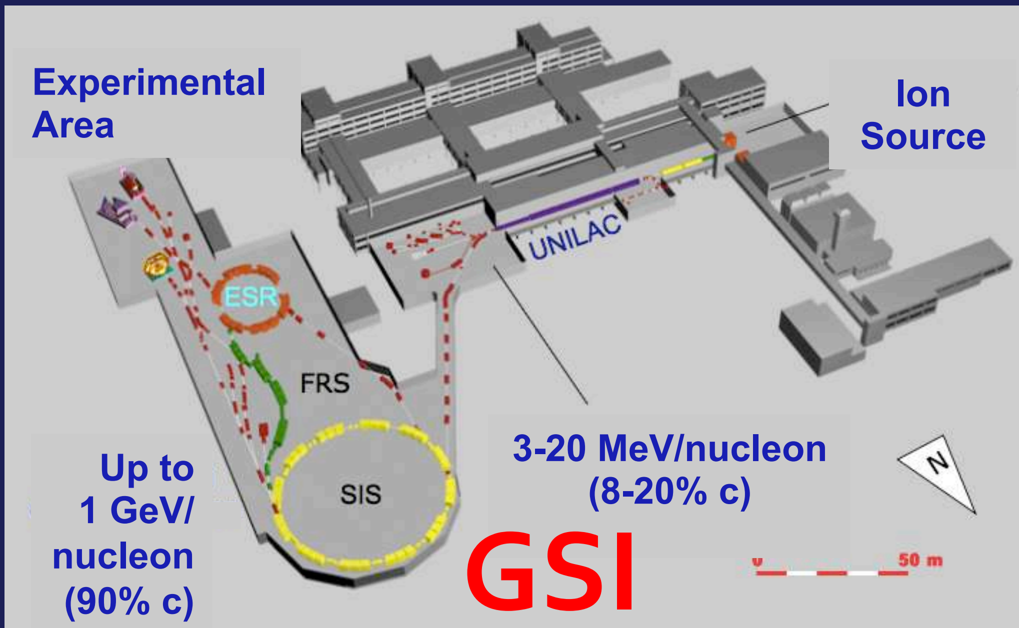


A. Bracco, F. Crespi, E.Lanza,
Eur. Phys. J. A51 (2015) 99

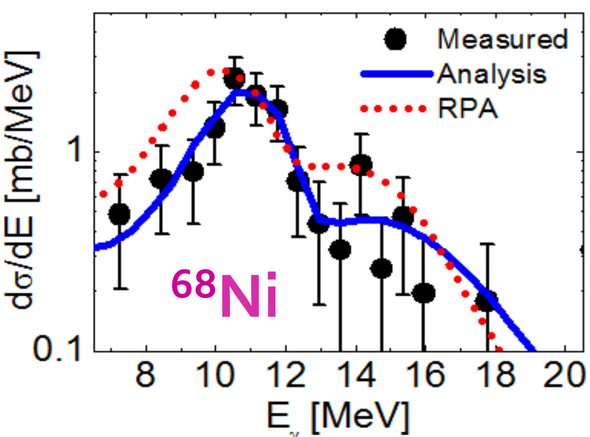
Concentration of E2 Strength
much below the GIANT QUADRUPOLE resonance
- In agreement with Quasi-phonon Model predictions -

Pygmy Resonances in EXOTIC NUCLEI

Relativistic Coulomb Excitation: high selectivity for E1 excitation



FIRST Case: EUROBALL + BaF2 Setup

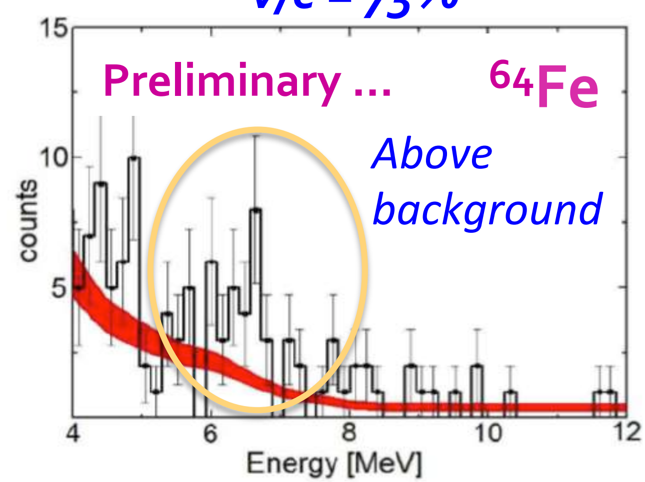


PYGMY Strength: 5-9 % EWSR

O.Wieland, A. Bracco *et al.*, PRL 102, 092502 (2009)

AGATA + $LaBr_3$ Setup

v/c = 73%



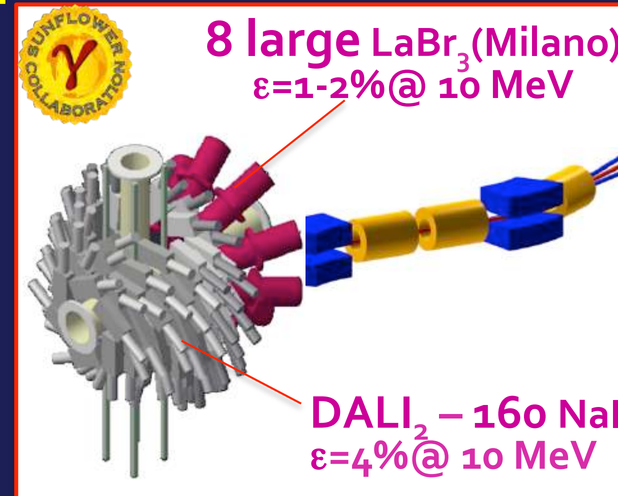
R. Avigo, O.Wieland, … in preparation

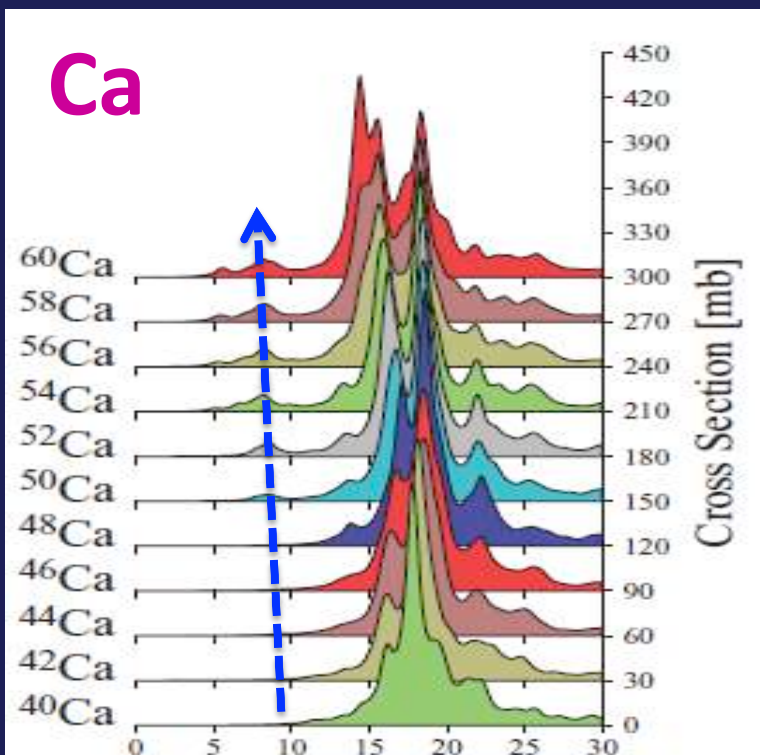
Complementary program at RIKEN-Japan

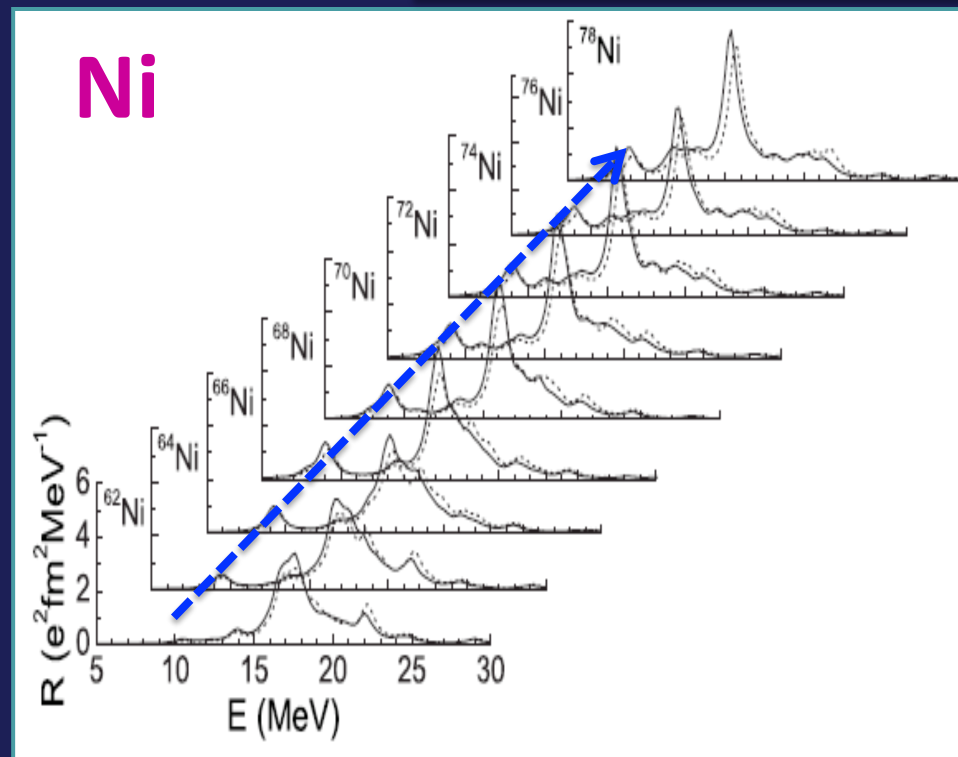
PYGMY studies in the **MOST EXOTIC** Nuclei:

^{20,22,24}O, ^{50,52}Ca, ^{70,72}Ni, ^{128,132}Sn

Evolution of PYGMY strength along isotopic chains

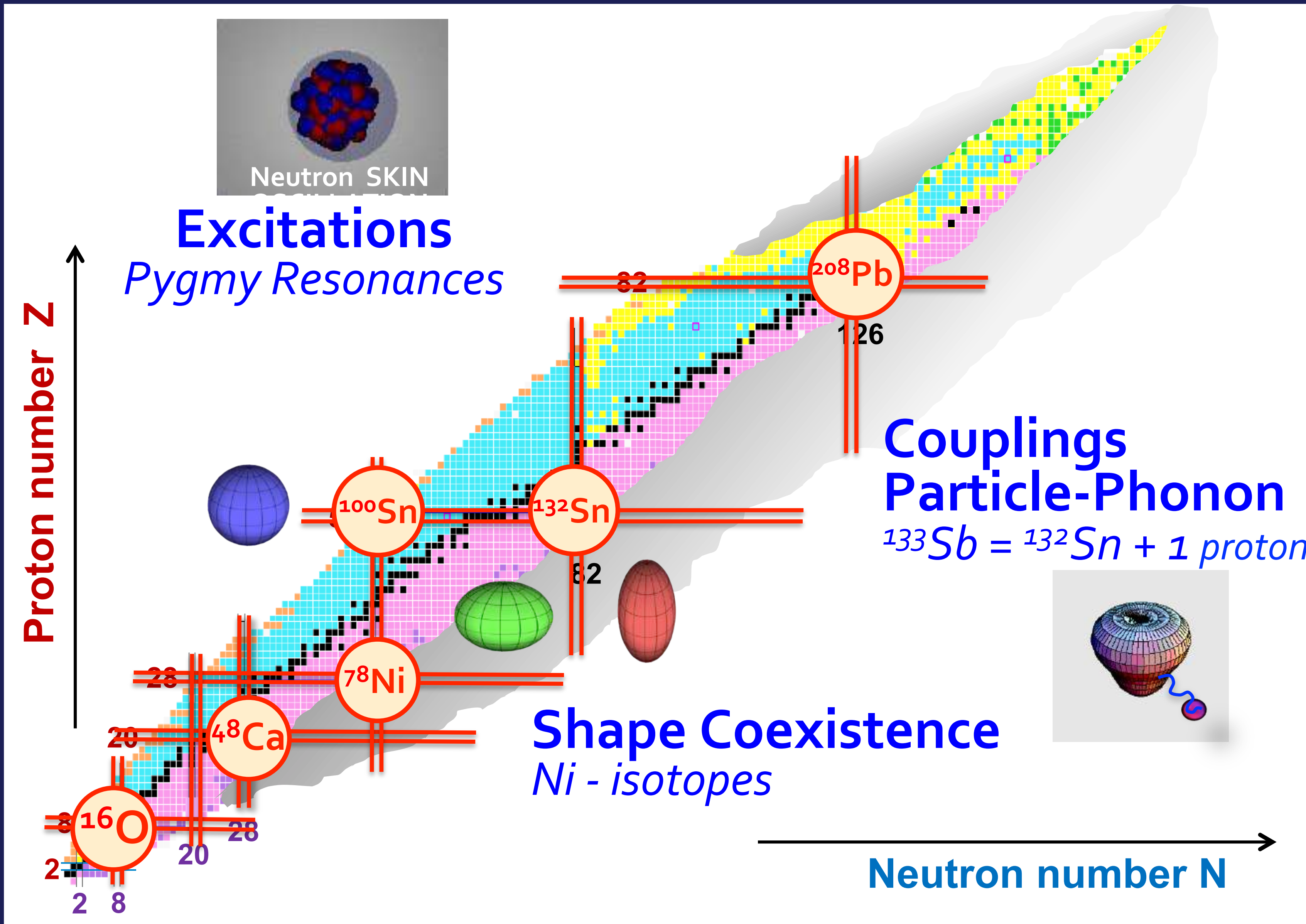






Ongoing Experimental Campaign … *(A. Bracco, F. Camera, F. Crespi, O. Wieland, …)*

Selected Recent Highlights of γ spectroscopy



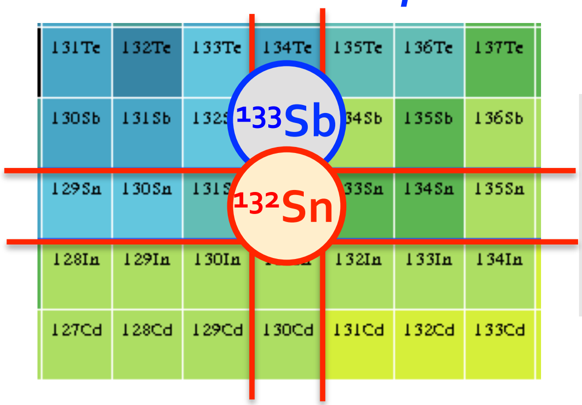
Couplings between Particle and Collective Degrees of Freedom

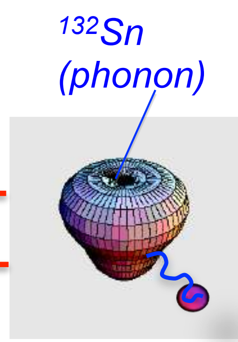
In NUCLEI

Particle-Phonon Couplings

PHONONS = Vibrations of MAGIC Core

$^{133}Sb = {}^{132}Sn + 1$ *proton*





Key Ingredient for:

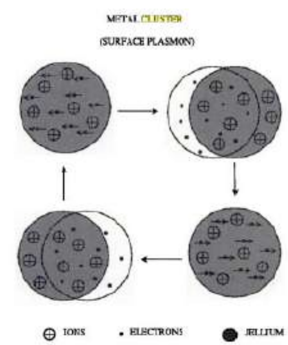
- Anharmonicity of vibrational spectra
- Damping of Giant Resonances

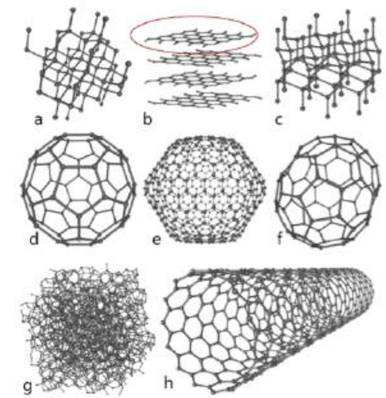
→ *emergence of COMPLEX excitations*

In CONDENSED MATTER

Electron-Phonon Couplings

Phonons and Plasmons





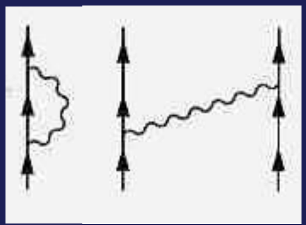
Key Ingredient for:

- Electromagnetic Response
- Superconductivity

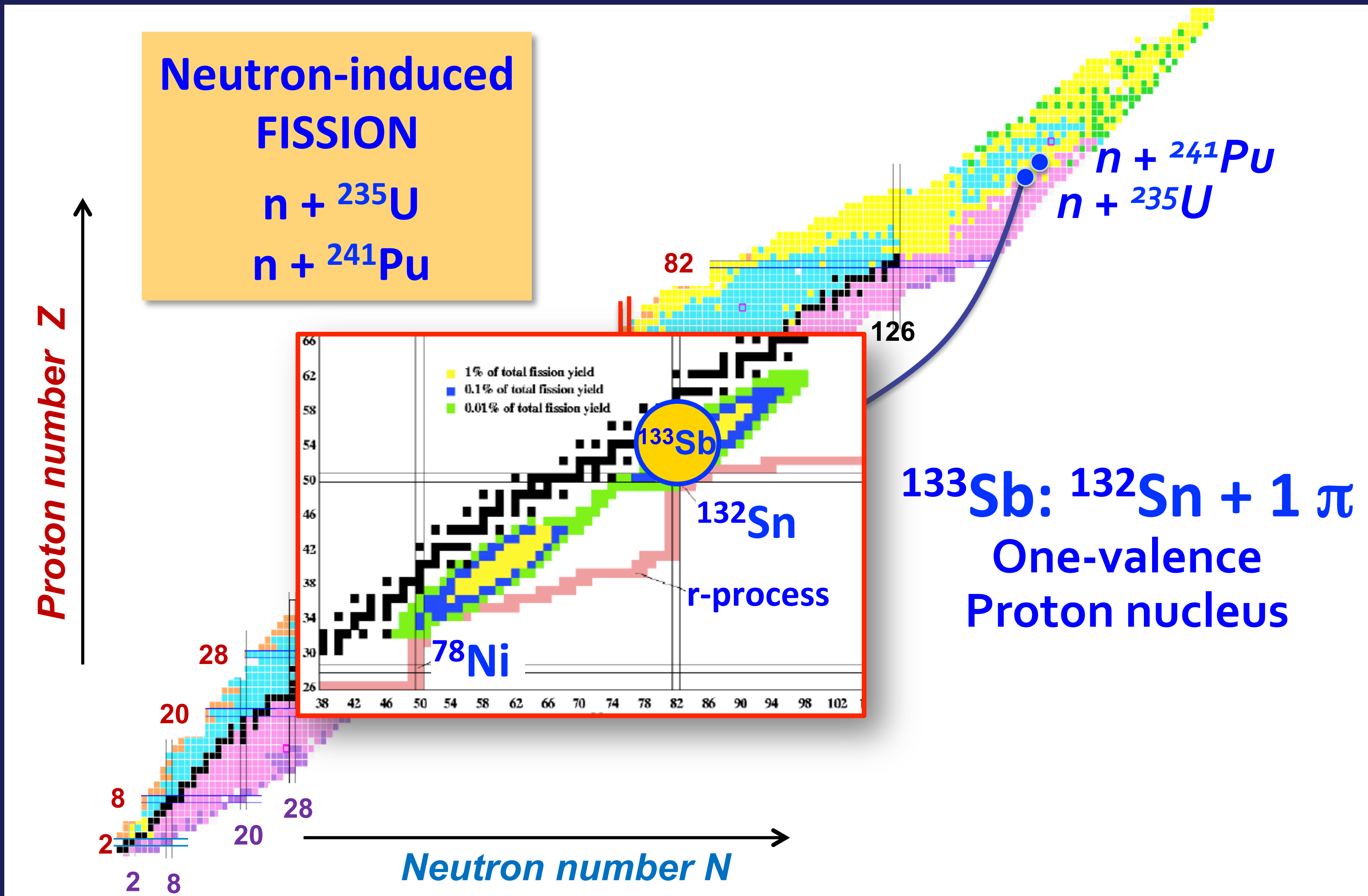
in Metal Clusters, Fullerenes, …

Common many-body diagrammatic techniques

Different energy scales …

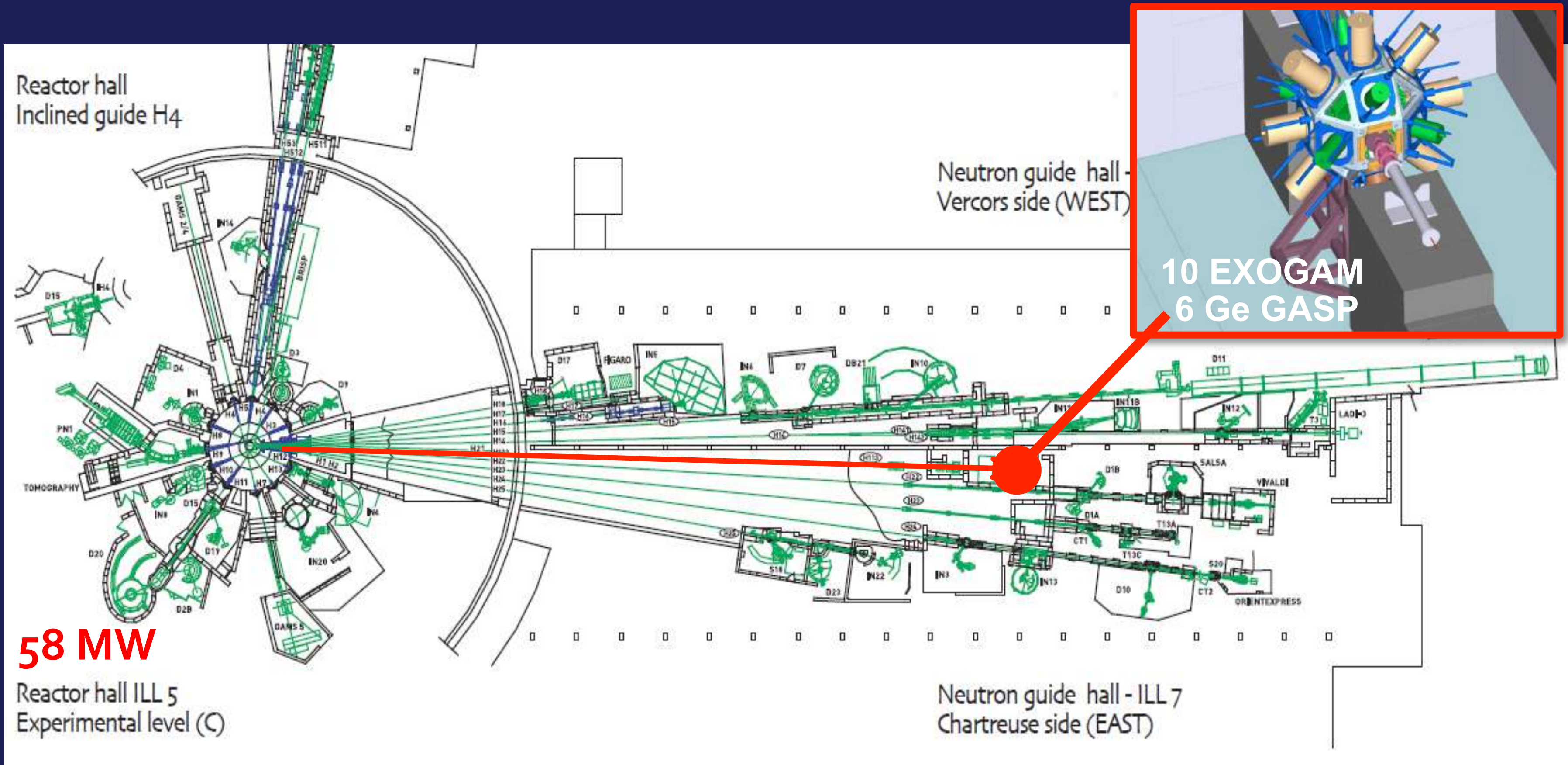


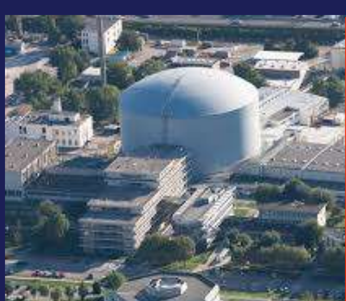
Particle-Phonon Couplings around EXOTIC and Doubly Magic ^{132}Sn



The γ-spectroscopy campaign @ ILL-Reactor (Grenoble)

2012-2013: 100 days, 95% DATA taking





MOST INTENSE
Continuum neutron source

In pile

$\Phi_n = 5\times10^{14}$ n cm^{-2} s^{-1}

Dedicated ballistic neutron guide
highly collimated beam (1 cm^2)
cold neutrons (meV)

$\Phi_n = 2\times10^{8}$ n cm^{-2} s^{-1}

Fission Data

^{133}Sb = ^{132}Sn + 1 proton

Lifetime measurements
with fast scintilltors

	B(M1) [W.u.]
15/2^{+} → 13/2^{+}	0.24
13/2^{+} → 11/2^{+}	0.004

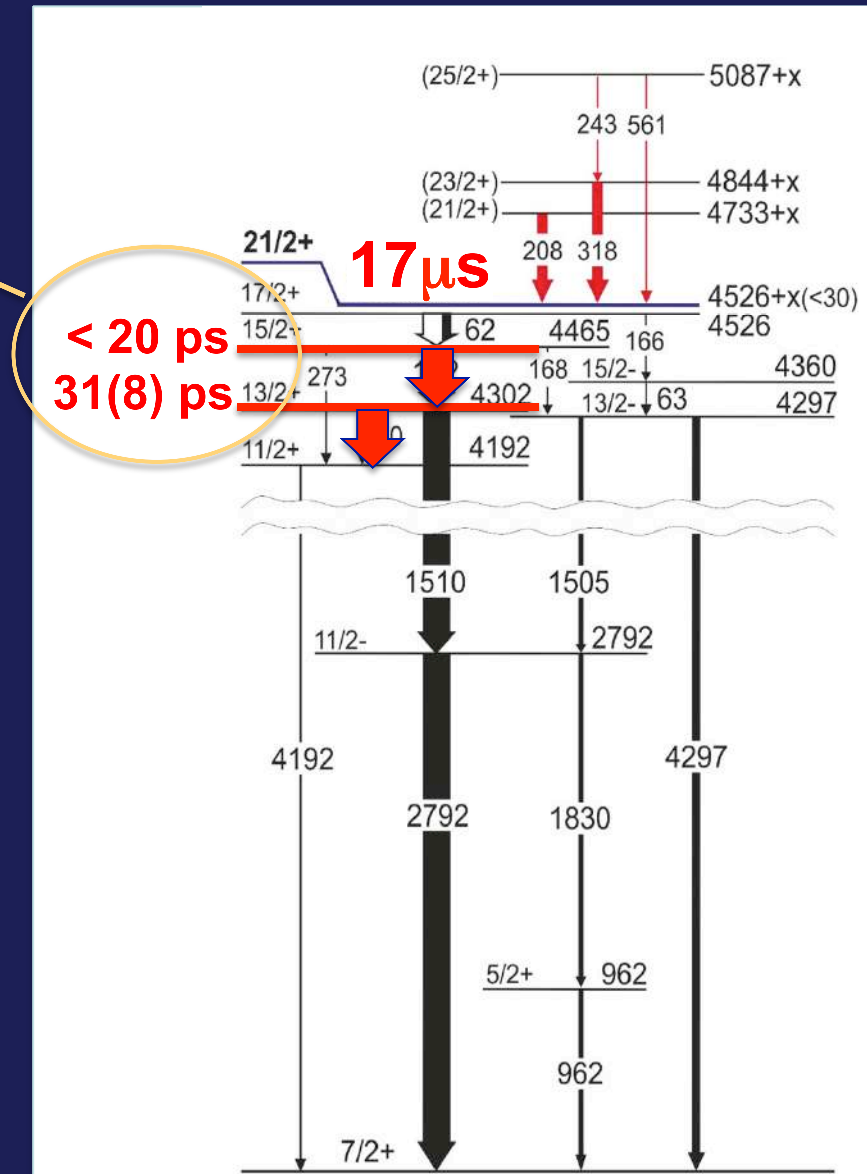
!!

Nature of the States is
COMPLEX and DIVERSE

Interpretation NOT Doable by SHELL Model:

Too LARGE space

→ Alternative Approach



The New "HYBRID" Model (G. Colò, P.F. Bortignon - Milano)

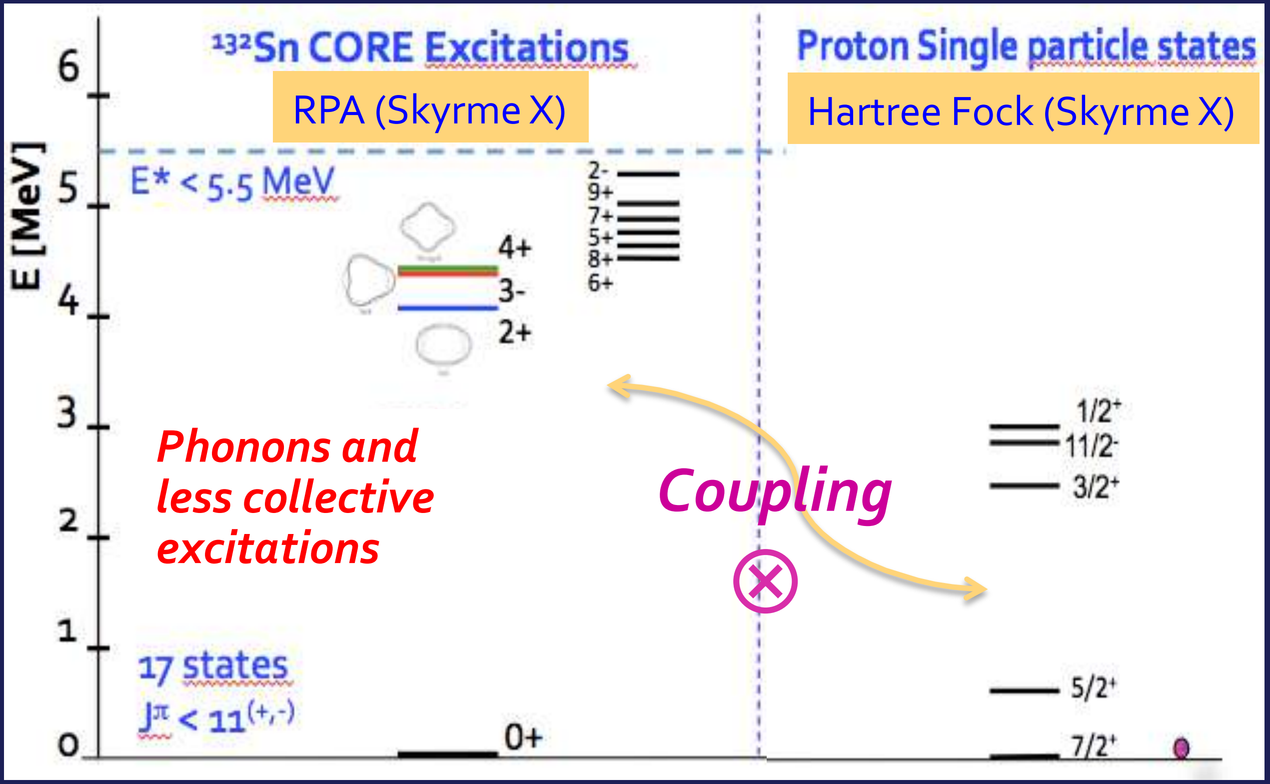
CORE Excitations (Phonons-RPA) + single particle (Hartree Fock)

^{133}Sb: ^{132}Sn + 1π

Coupling
Matrix Elements
between

SINGLE PARTICLE
and
CORE excitations

consistently
calculated



NO FREE PARAMETERS - Same SkX Interaction

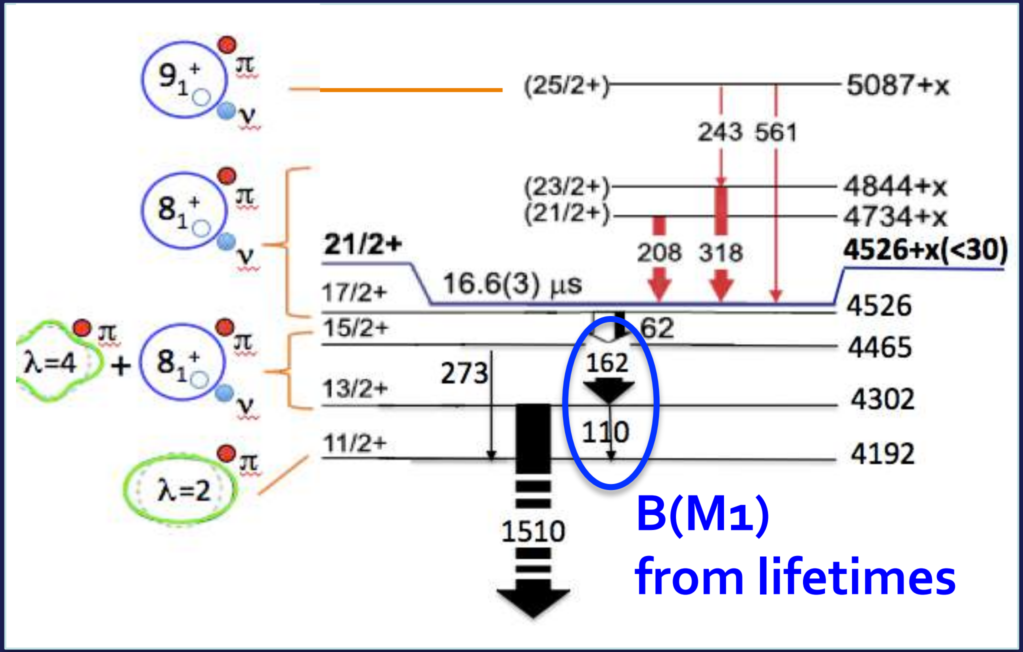
G. Colò, P.F. Bortignon, G. Bocchi, Phys. Rev. C 95, 034303 (2017)

The New "HYBRID" Model (G. Colò, P.F. Bortignon - Milano)

CORE Excitations (Phonons-RPA) + single particle (Hartree Fock)

^{133}Sb: ^{132}Sn + 1π

- ***GOOD Reproduction of Exp.***
- ***MIXED*** States based on *Collective and Non-Collective* Excitations of ^{132}Sn CORE



STARTING POINT for extended investigation in MEDIUM/HEAVY Nuclei NOT possible with SHELL MODEL !!!

G. Bocchi, S. Leoni, B. Fornal et al., ...Phys. Lett. B 760, 273 (2016)

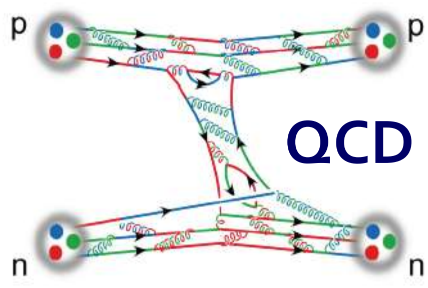
See POSTER S. Bottoni

2016 HIGHLIGHT Institut Laue-Langevin (ILL)

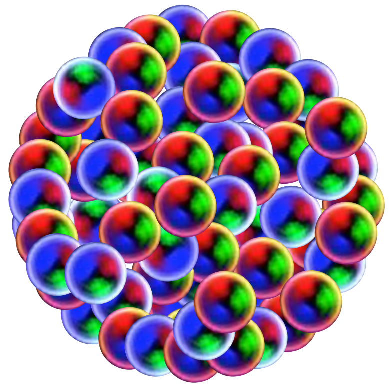
OUTLOOK: pinning down the NATURE of the nuclear force

Major problem in Nuclear Physics:
detail composition of the nuclear force is NOT known !!!

Bare N-N interaction can be derived from QCD



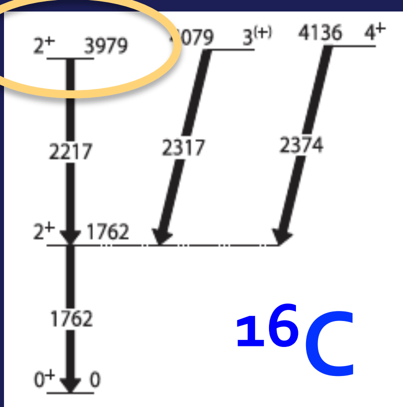
In HEAVY-Systems:
Effective N-N Interaction
Corrections are needed due to the presence of other Nucleons



LIGHT systems ONLY (up to C, O, Ne, …) can be computed by *ab-initio calculations:*
→ they are sensitive to details of the N-N interaction (2 body and 3 body terms)

τ (2+)

0.25 ps	0.08 ps
2 body	**3 body**



AGATA exp. in GANIL - in 10 days:
^{18}O (141 MeV) + ^{238}U (10 mg/cm²)
γ-spectroscopy of n-rich B-C-O-F nuclei
High Precision Lifetimes measurements
τ = 100 fs – 10’s ps

Conclusions

- **NUCLEAR STRUCTURE PHYSICS aims at a unified description of > 7000 Nuclei in the Universe**
  less than half are known … very high discovery potential !!!

- **Several BASIC questions to be answered**

  Microscopic Origin of shapes and deformations

  Nature of Resonance Excitations – *neutron skins …*

  Emergence of complex excitations – *particle-phonon couplings …*

  Outlook: sensitivity to details of nuclear force

- **Strong Interdiciplinarity – Astrophysics**
- **State-of-the-Art SETUP:** **AGATA, large volume scintillators,** …
- **A Major Challenge for THEORY** …

*** Thank You for the Attention ***