UNIVERSITÀ DEGLI STUDI DI MILANO

INFN

"Advances in nuclear structure with modern γ spectrometers"

Silvia Leoni

Università degli Studi di Milano and INFN sez. Milano

Groningen, September 1st 2015

EuNPC 2015 European Nuclear Physics Conference

European Physical Society

university of groningen

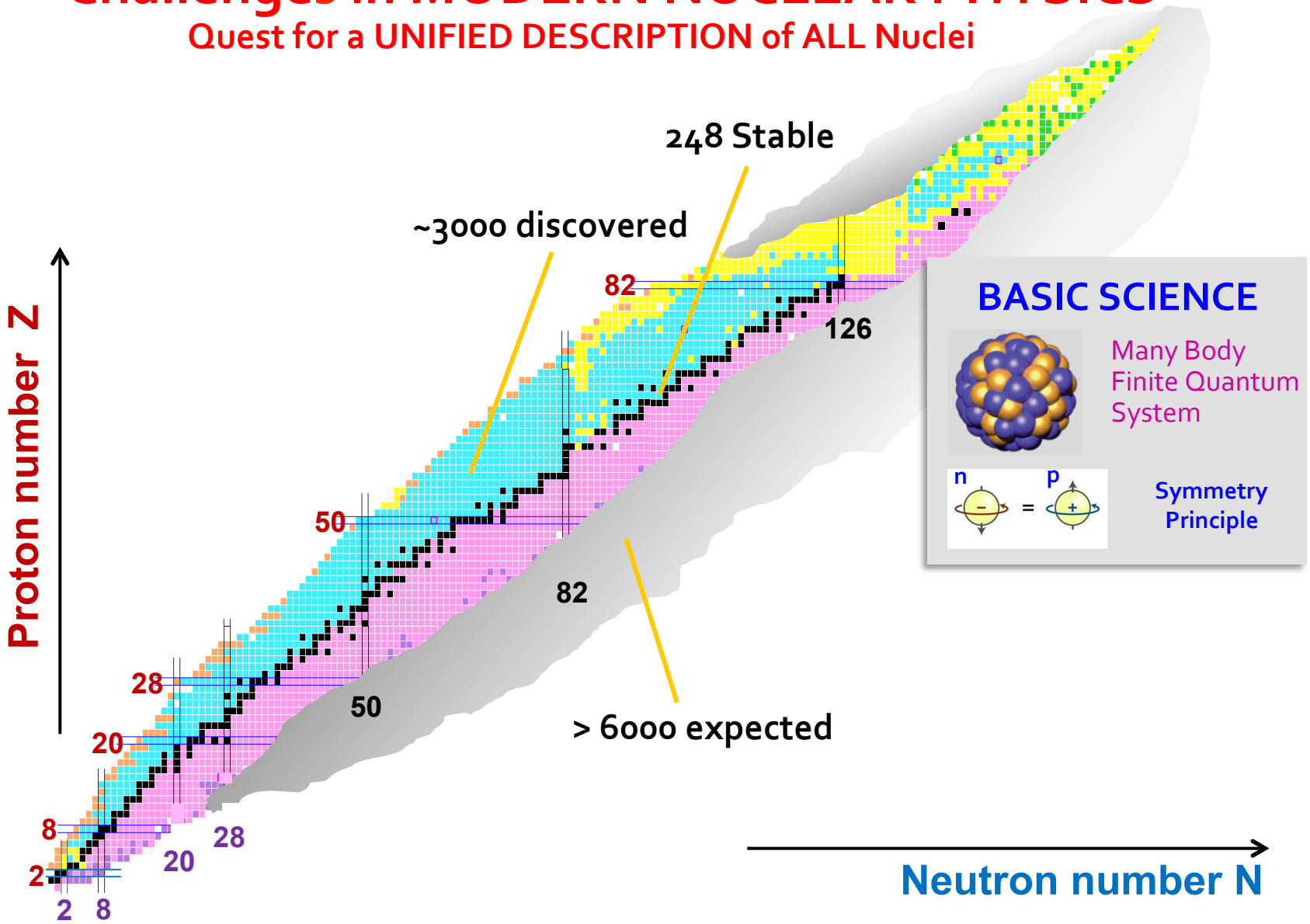
kvi - center for advanced radiation technology

Groningen | 31 August - 4 September 2015 | www.EuNCP2015.org

EuNPC2015

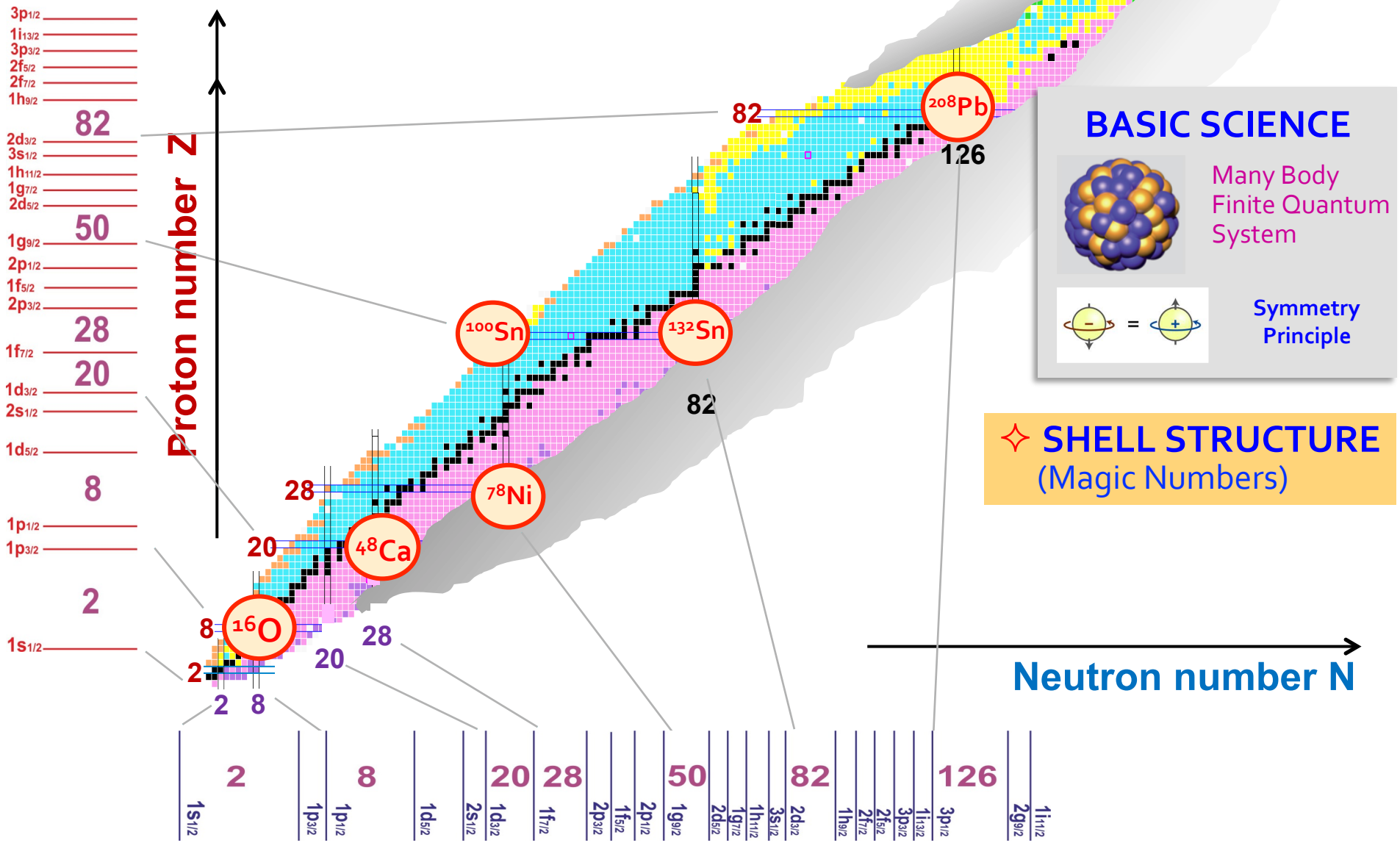
Challenges in MODERN NUCLEAR PHYSICS

Quest for a UNIFIED DESCRIPTION of ALL Nuclei



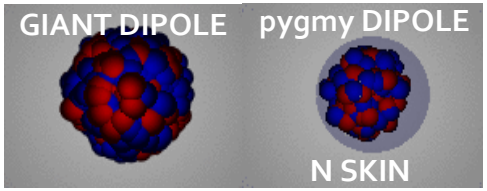
Challenges in MODERN NUCLEAR PHYSICS

Quest for a UNIFIED DESCRIPTION of ALL Nuclei

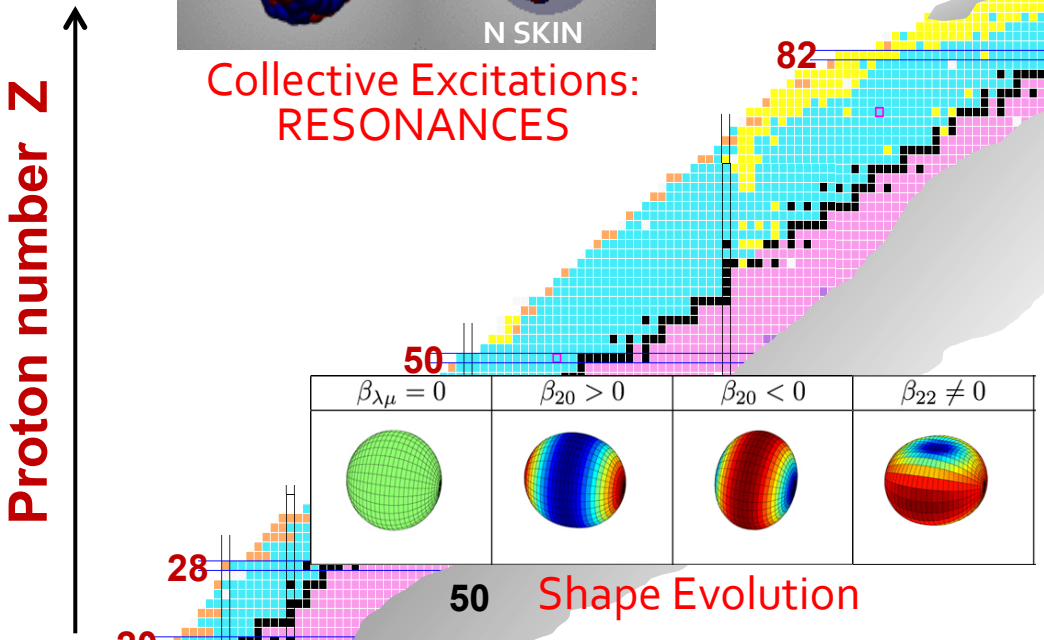


Challenges in MODERN NUCLEAR PHYSICS

Quest for a UNIFIED DESCRIPTION of ALL Nuclei

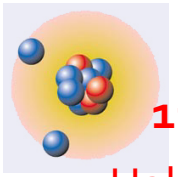


Collective Excitations: RESONANCES



Shape Evolution

^{224}Ra
Stable octupole

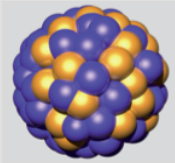


^{11}Li
Halos

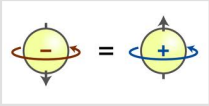
^{12}C
Clusters

Neutron number N

BASIC SCIENCE



Many Body Finite Quantum System



Symmetry Principle

- ✧ **SHELL STRUCTURE** (Magic Numbers)
- ✧ **SHAPES**
- ✧ **EXCITATIONS**

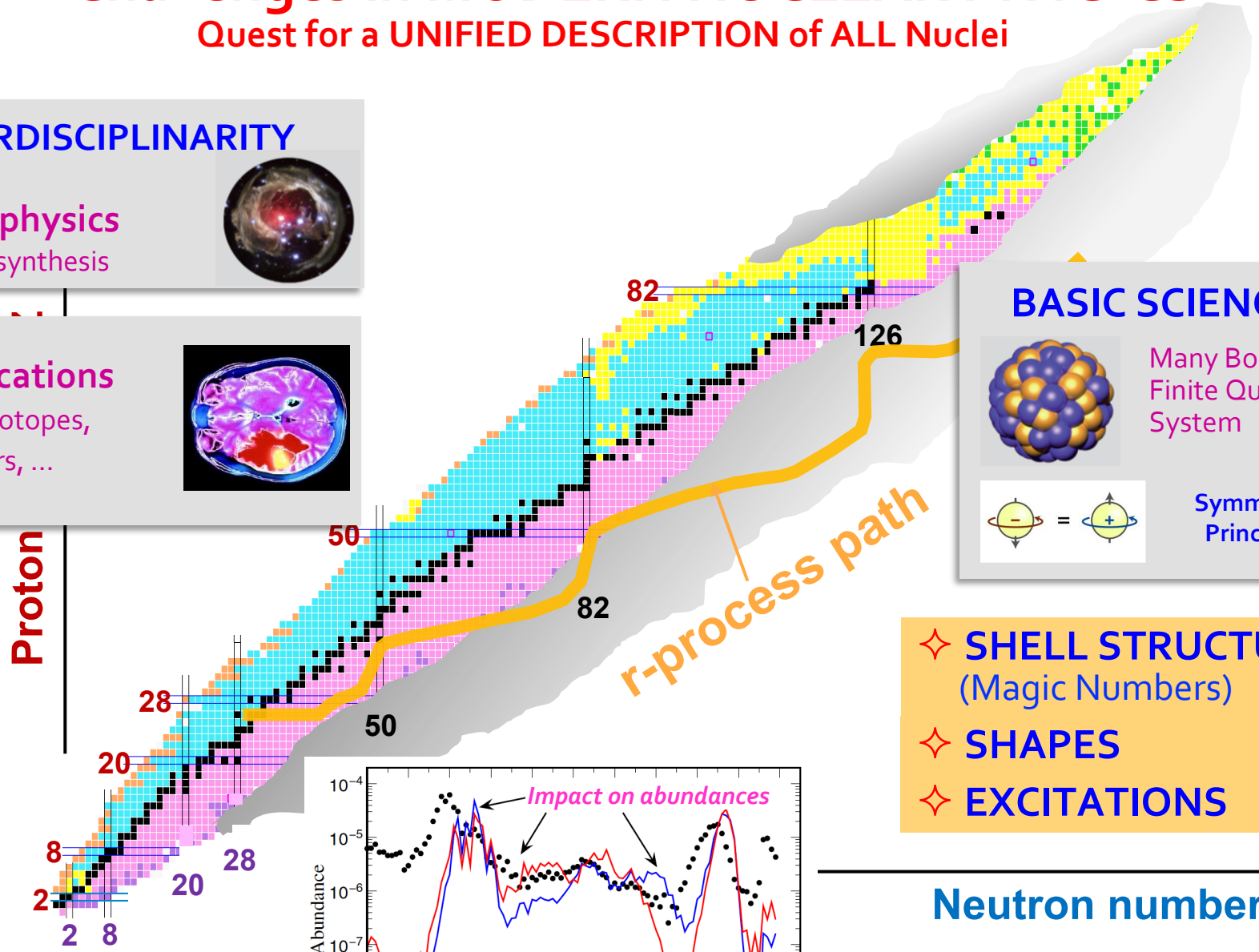
Challenges in MODERN NUCLEAR PHYSICS

Quest for a UNIFIED DESCRIPTION of ALL Nuclei

INTERDISCIPLINARITY

Astrophysics
Nucleosynthesis

Applications
Radioisotopes,
Reactors, ...



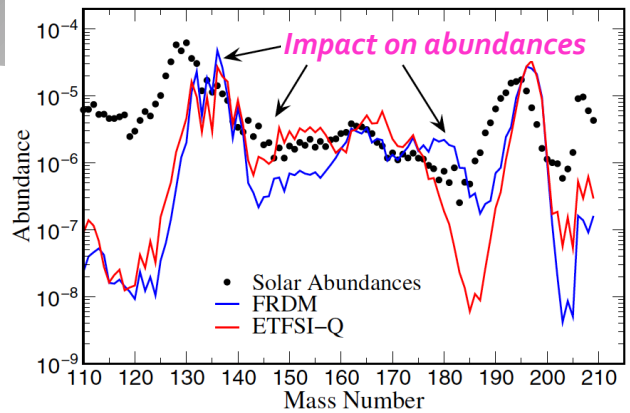
BASIC SCIENCE

Many Body
Finite Quantum
System

Symmetry
Principle

- ✧ **SHELL STRUCTURE** (Magic Numbers)
- ✧ **SHAPES**
- ✧ **EXCITATIONS**

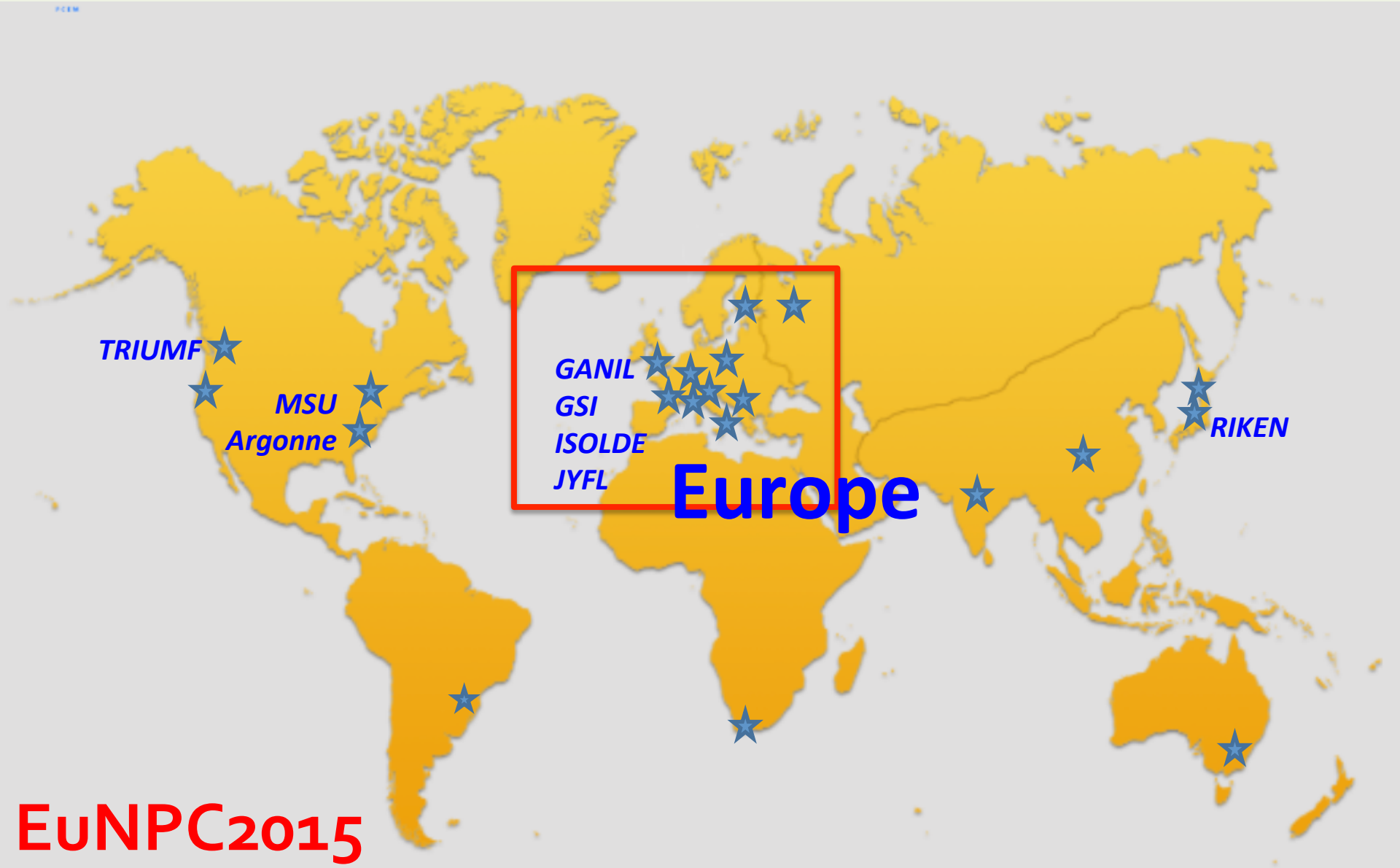
Element ABUNDANCES



Neutron number N

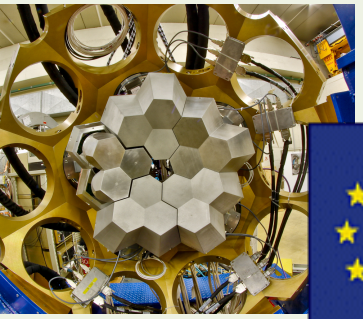
A World Wide Effort to Understand/Expand the Nuclear Chart …

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



EuNPC2015

Selected Examples of EUROPEAN γ-Spectroscopy Activities



AGATA
ADVANCED GAMMA TRACKING ARRAY

JYFL

R. Herzberg
PLENARY

DUBNA

EURICA

Warsaw

GANIL

GSI

Orsay

Legnaro

ILL

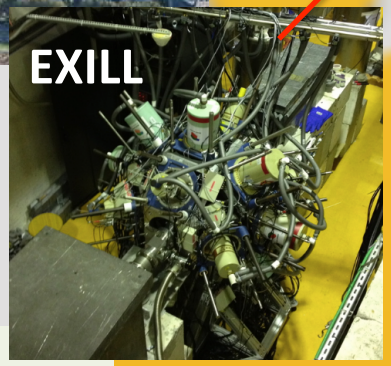
ISOLDE
CERN

Bucharest

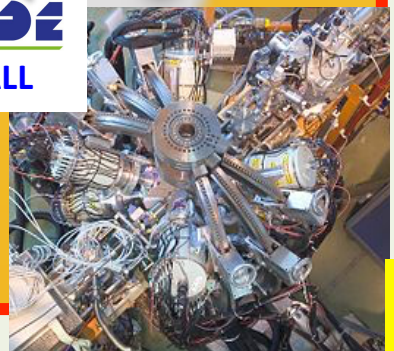
RIKEN

LNS

NEUTRONS FOR SCIENCE



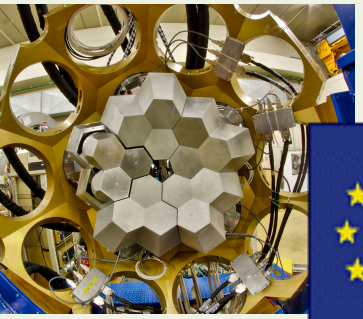
ISOLDE
MINIBALL



L. Gaffney
PLENARY

EuNPC2015

Selected Examples of EUROPEAN γ-Spectroscopy Activities



ADDITIONAL TALKS

A. Gengelbach (@LNL, around A=170), TUESDAY 14:30
A. Gottardo (@GANIL, ^{78}Ni region), THURSDAY 14:45

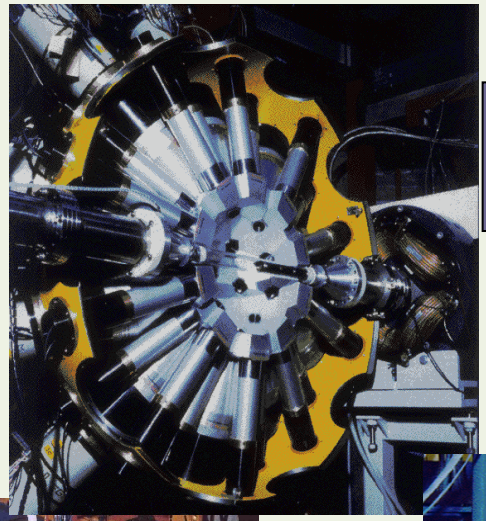
EuNPC2015

LONG TRADITION OF γ-SPECTROSCOPY

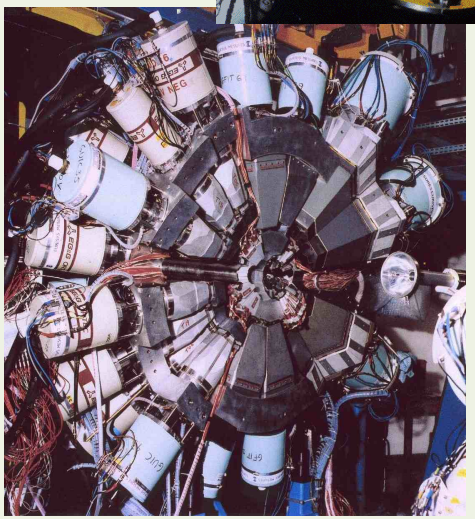
Arrays based on Compton suppressed Ge detectors

Starting from the 80's:

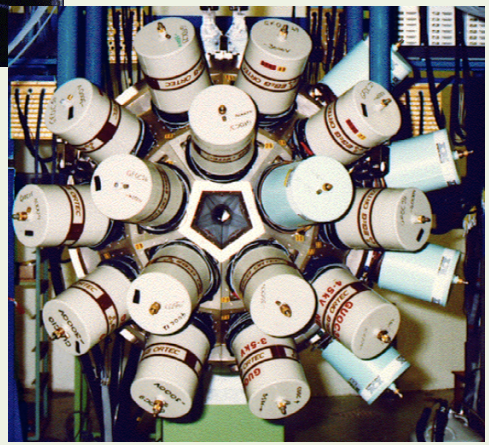
TESSA (Daresbury),
OSIRIS (Berlin),
ARGONNE-ND ARRAY (Argonne)
NORDBALL (Copenhagen),
JUROSPHERE (Jyvaskyla),
EUROGAM (Strasbourg),
CLARION (Oak Ridge)
GASP (Legnaro-Padova)
EUROBALL
GAMMASPHERE



GASP
Legnaro



EUROBALL
Legnaro, Strasbourg

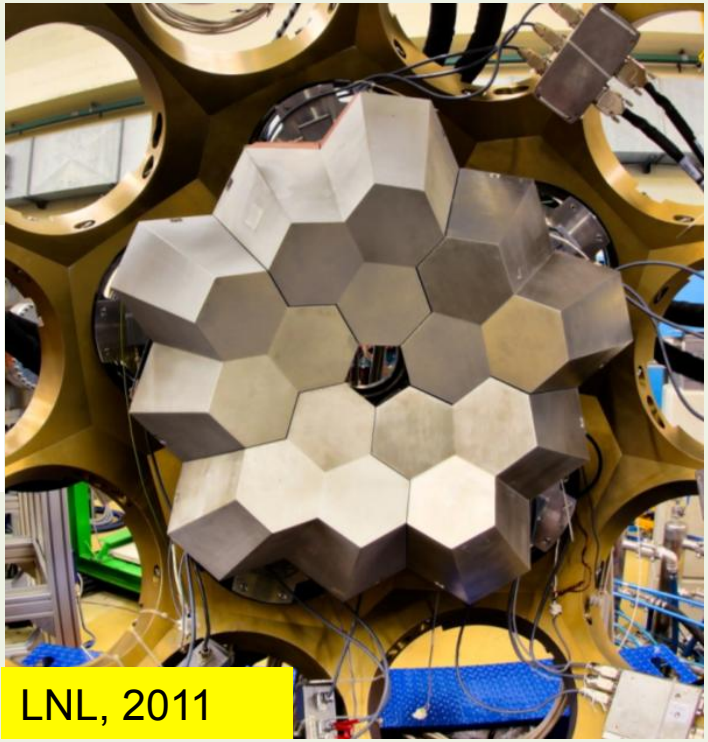


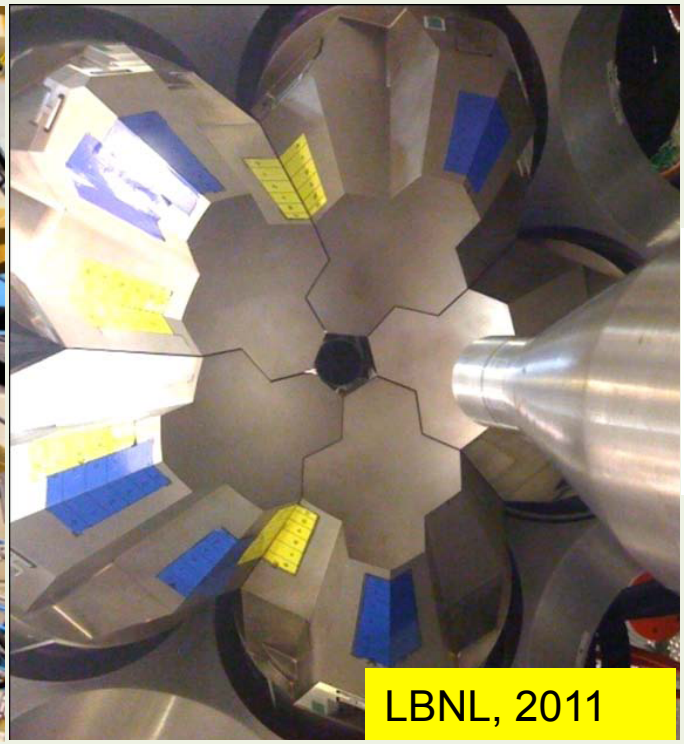
EUROGAM
Daresbury

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

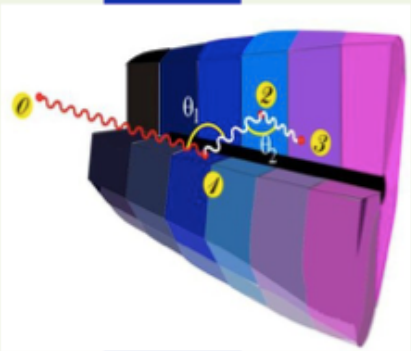
- **EFFICIENCY:** 43% $M_\gamma = 1$ and 28% $M\gamma = 30$ (@ 1 MeV, FULL BALL)
- **COUNT RATE** capabilities (100s KHz)
- **ANGULAR RESOLUTION** of the γ interaction point (θ~1°)
- **"PERFECT" DOPPLER CORRECTION** (6 keV @ 1 MeV, β=50%)

The Gamma Tracking Array Concept

HARDWARE

1

Highly segmented HPGe detectors



2

Digital electronics to record and process segment signals

14 bit, 100 MS/s

37 signals/crystals

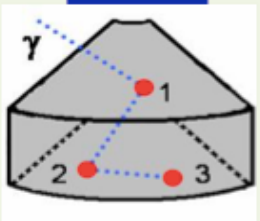
Raw Data Read Out:

10 kB/evt/crystal

SOFTWARE

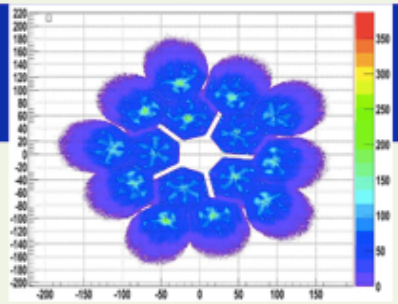
3

Pulse Shape Analysis to decompose recorded waves



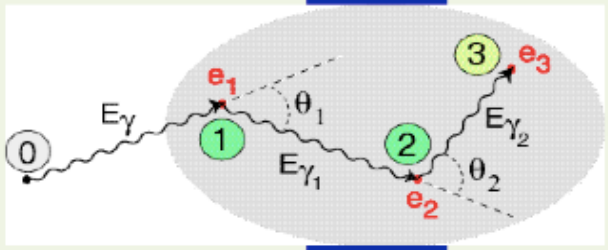
Identified interaction points

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

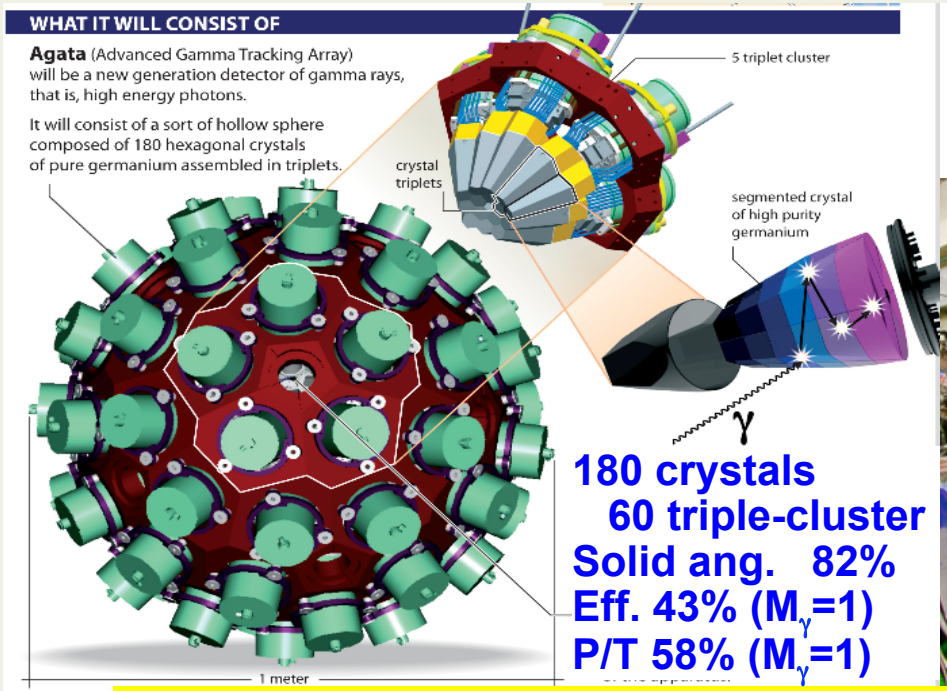


4

Reconstruction of tracks evaluating permutations of interaction points

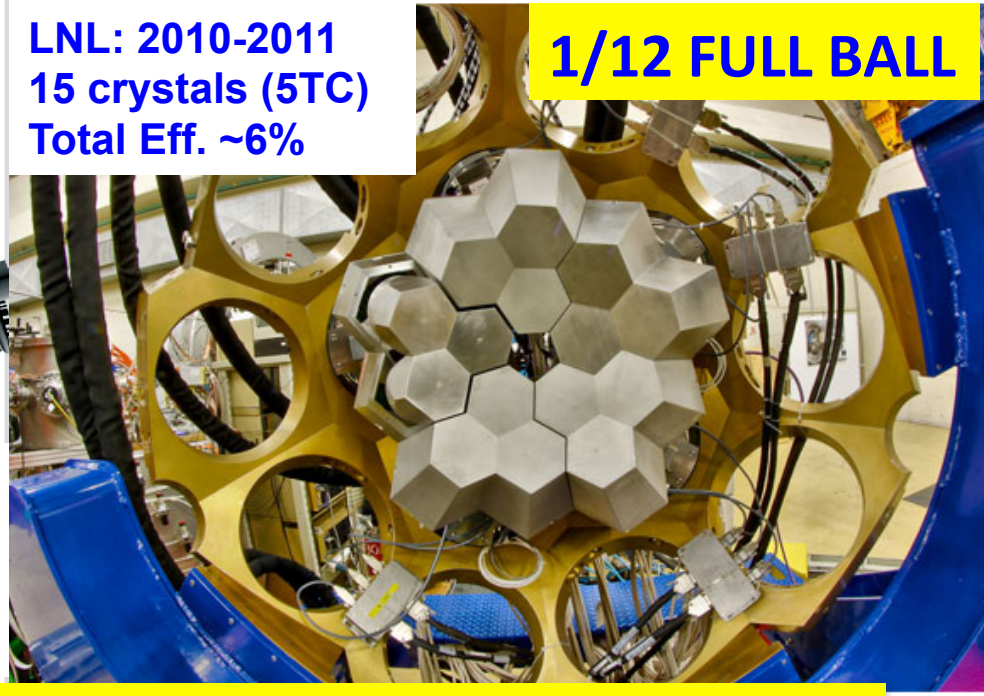


Reconstructed gamma-rays + Correlation with other detectors



180 crystals
60 triple-cluster
Solid ang. 82%
Eff. 43% (M_γ=1)
P/T 58% (M_γ=1)

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



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

Enrico Farnea (1970-2013)
AGATA Project Manager@LNL

The AGATA Evolution Towards 1π

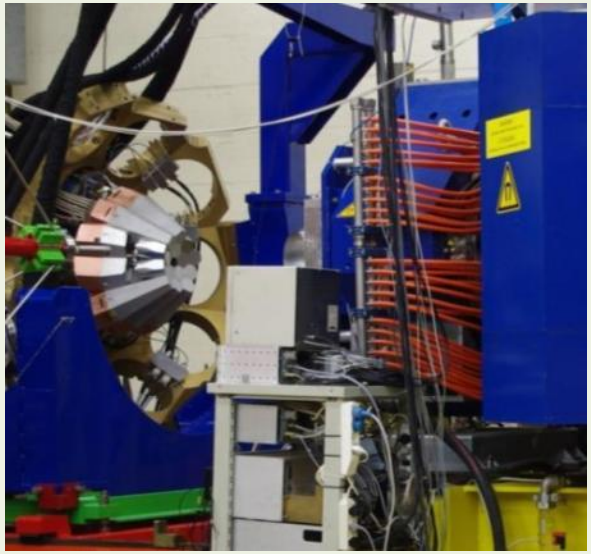
LNL: 2010-2011
15 crystals
Total Eff. ~6%

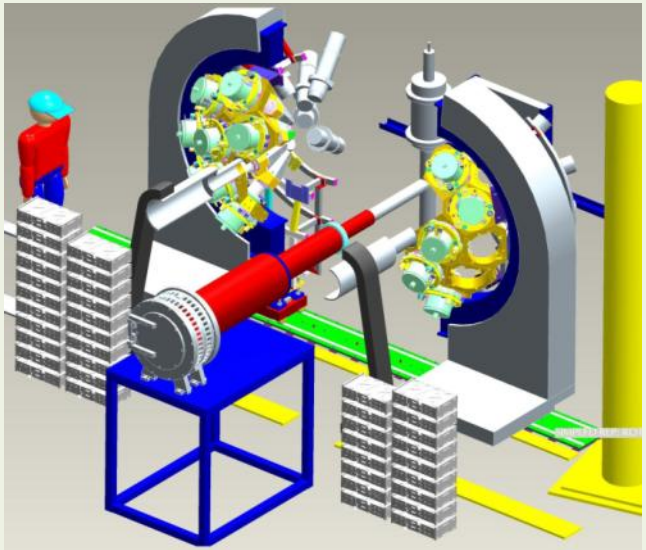
→

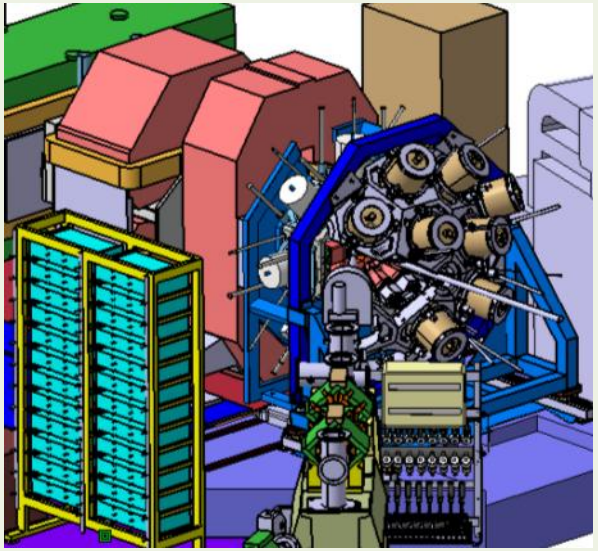
GSI: 2012-2014
22 crystals
Total Eff.~10%

→

GANIL: 2015-2018
up to 39 crystals
Total Eff. ~15%







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 2018 at LNL at SPES (ISOL Beams)

HIGHLIGHTS from AGATA
from LNL and GSI

AGATA
ADVANCED GAMMA TRACKING ARRAY

NUCLEAR STRUCTURE & ASTROPHYSICS APPLICATIONS

Proton number Z

Neutron number N

82
126
0
82
28
50
20
8
2
28
20
2 8

^{15}O

LIFETIMES

C. Michelagnoli,
C. Ur
Padua

^{52,54}Fe, ^{124}Sn

PYGMY RESONANCES

O, Wieland, F. Crespi,
A. Bracco
Milano

^{196}Os

SHAPE TRANSITIONS

P.R. John
Valiente-Dobon, …
Padua

^{238}U

SPECTROSCOPY WITH TRANSFER

A. Vogt
P. Reiter, …
Koeln

HIGHLIGHTS from AGATA
from LNL and GSI

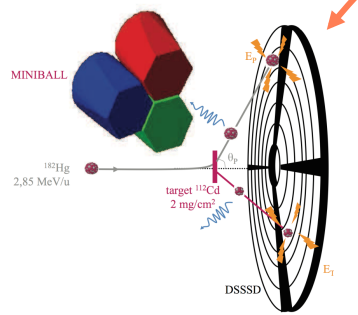
AGATA ADVANCED GAMMA TRACKING ARRAY

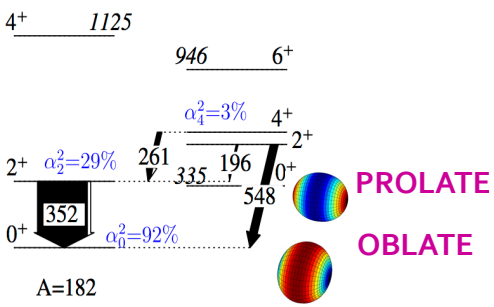
SHAPES and DEFORMATIONS in Heavy Systems

ISOLDE

MINIBALL at REX-ISOLDE COULOMB Excitation

Neutron deficient
$^{182\text{-}188}$Hg
Deformation of Ground and first excited 0+

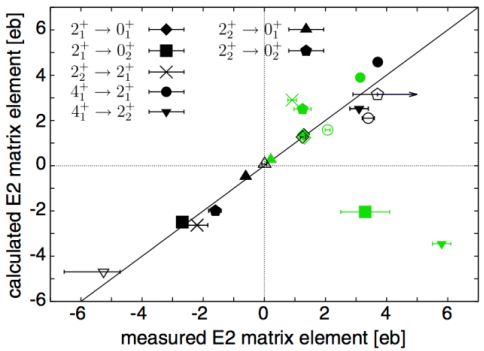


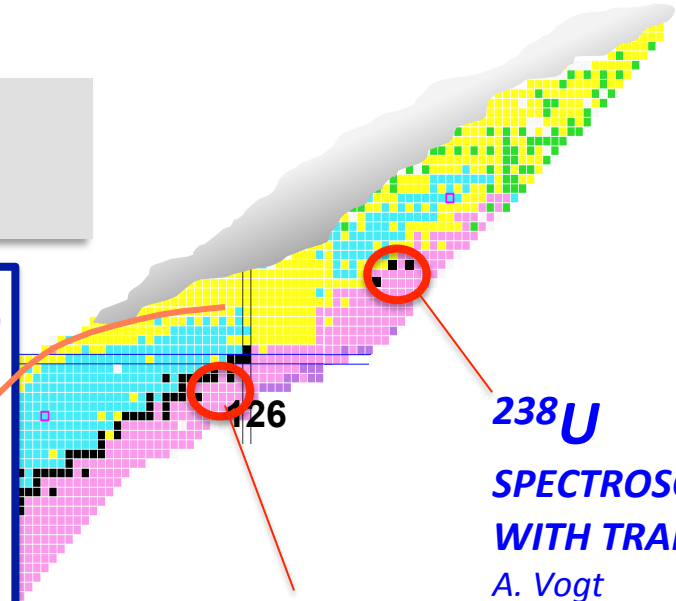


Two different structures
Coexist at low excitation
Partial explanation by theory

N. Bree, PRL 112, 162701 (2014)

Matrix Elements





^{238}U
SPECTROSCOPY WITH TRANSFER
A. Vogt
P. Reiter, …
Koeln

^{196}Os
SHAPE TRANSITIONS
P.R. John
Valiente-Dobon, …
Padua

Neutron number N

HIGHLIGHTS from AGATA
from LNL and GSI

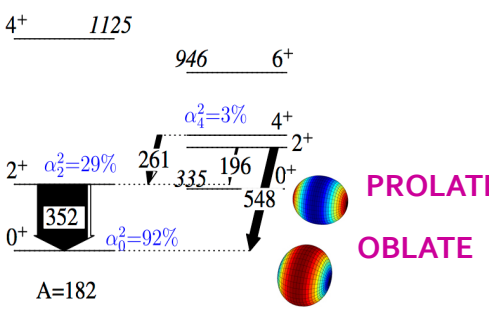
AGATA
ADVANCED GAMMA TRACKING ARRAY

SHAPES and DEFORMATIONS in Heavy Systems

ISOLDE

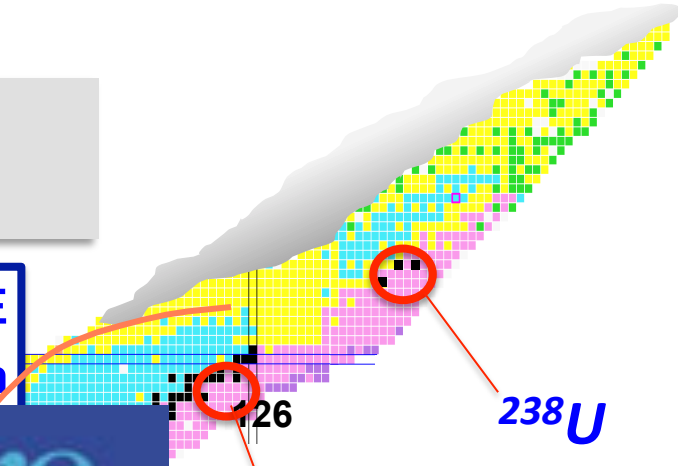
MINIBALL at REX-ISOLDE
COULOMB Excitation

Neutron deficient
$^{182\text{-}188}$Hg
Deformation of
Ground and first excited 0+



Two different structures
Coexist at low excitation
Partial explanation by theory

N. Bree, PRL 112, 162701 (2014)



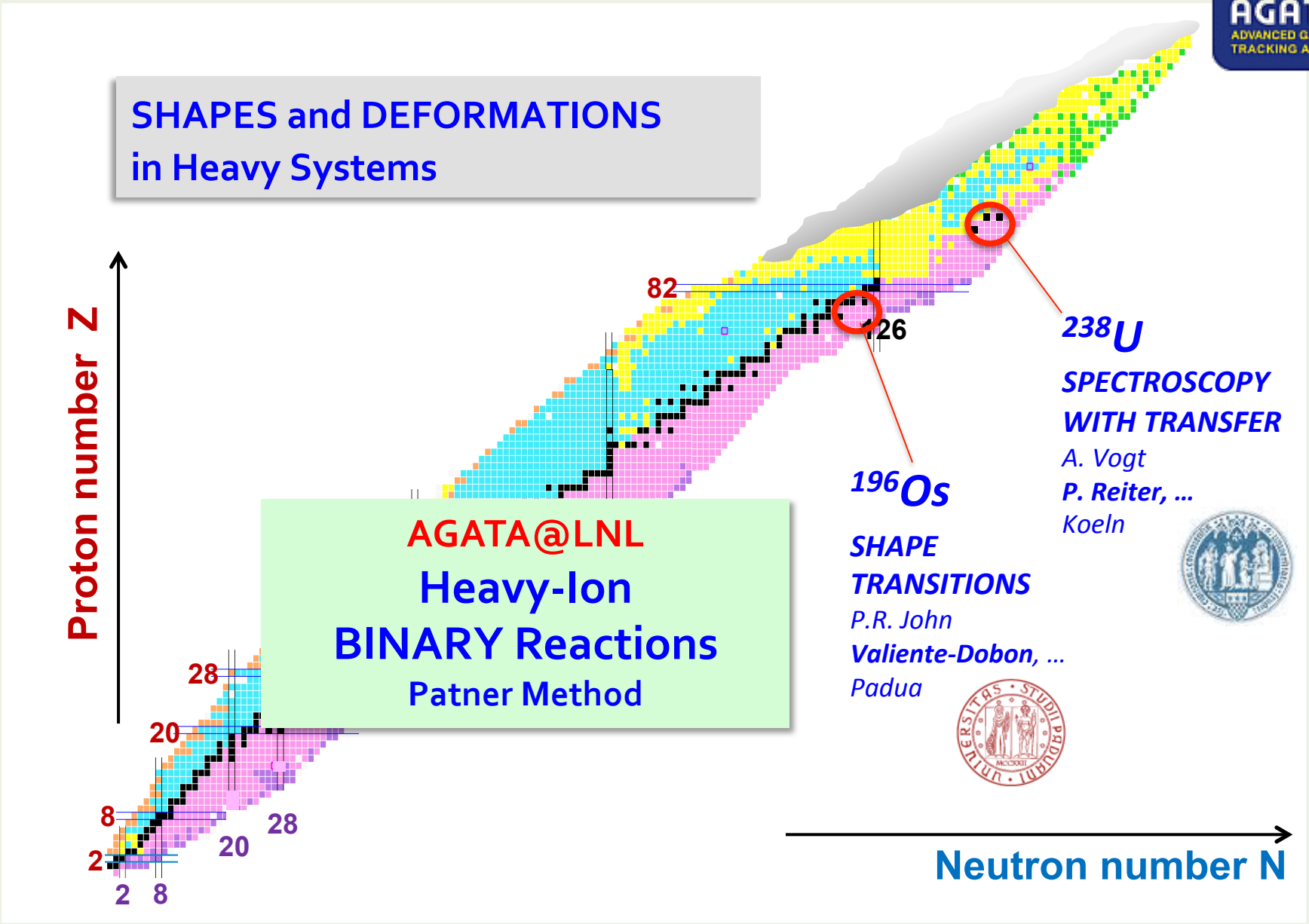
^{238}U
SPECTROSCOPY WITH TRANSFER
A. Vogt
P. Reiter, …
Koeln

^{196}Os
SHAPE TRANSITIONS
P.R. John
Valiente-Dobon, …
Padua

Neutron number N

See Plenary L. Gaffney

HIGHLIGHTS from AGATA
from LNL and GSI

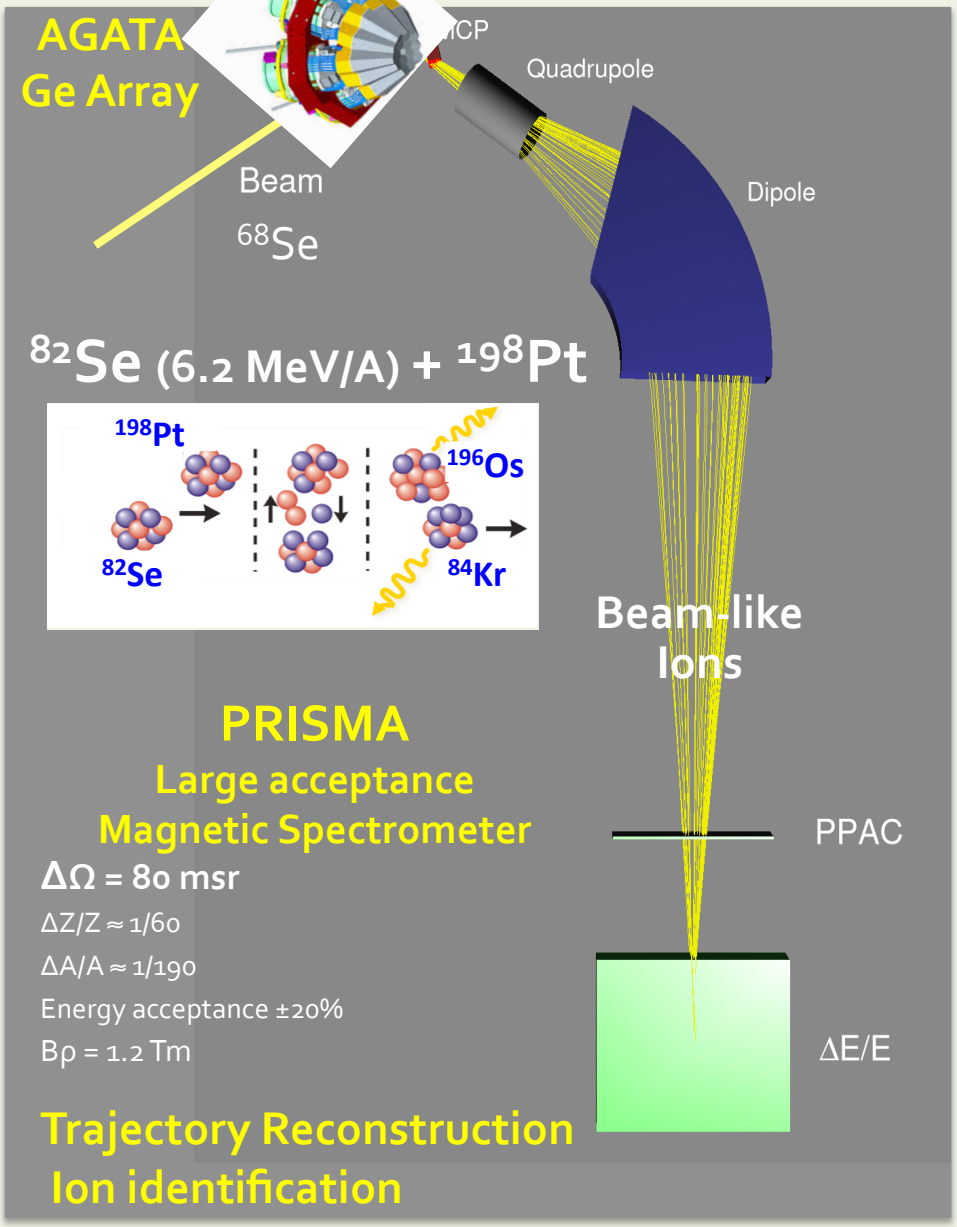


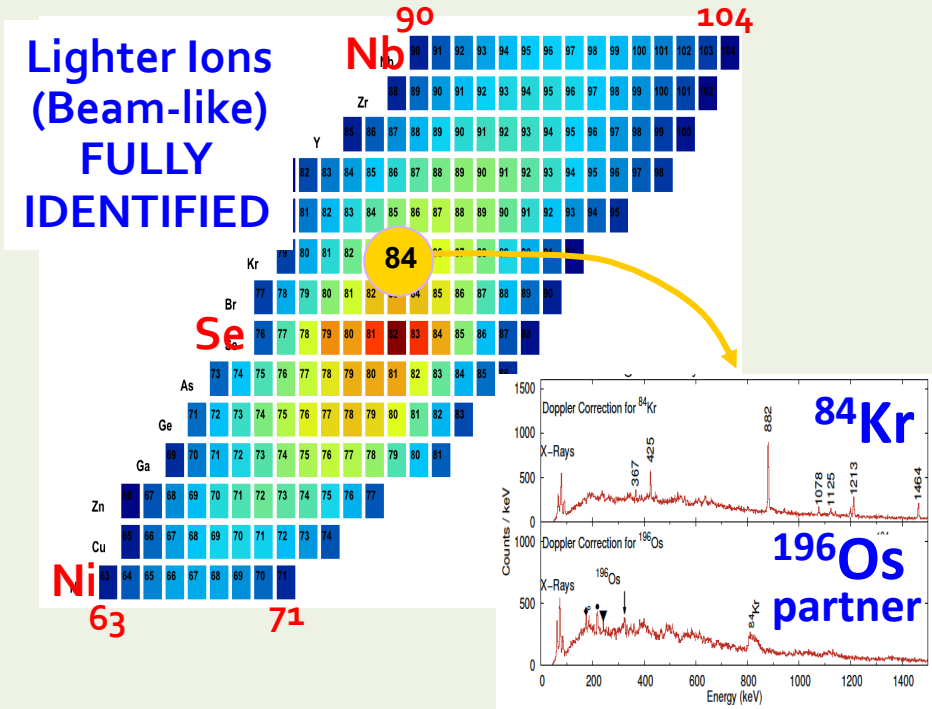
Spectroscopy with Heavy-Ion Binary Reactions

Ge Array coupled to Magnetic Spectrometer

LNL

AGATA
ADVANCED GAMMA TRACKING ARRAY





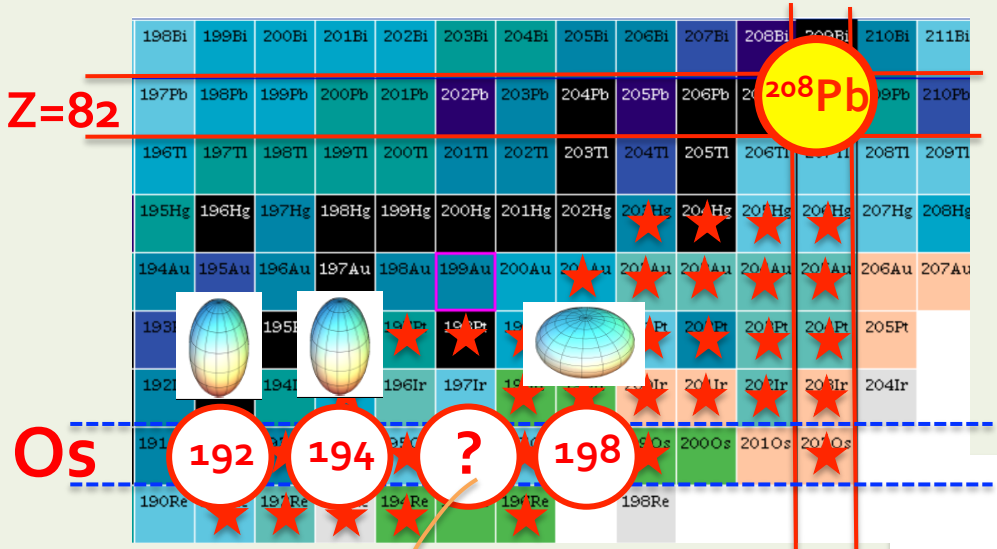
Particle – γ coincidences

Kinematic Reconstruction

SHAPE evolution in Os

LNL

South-West of ^{208}Pb (r-process far out)

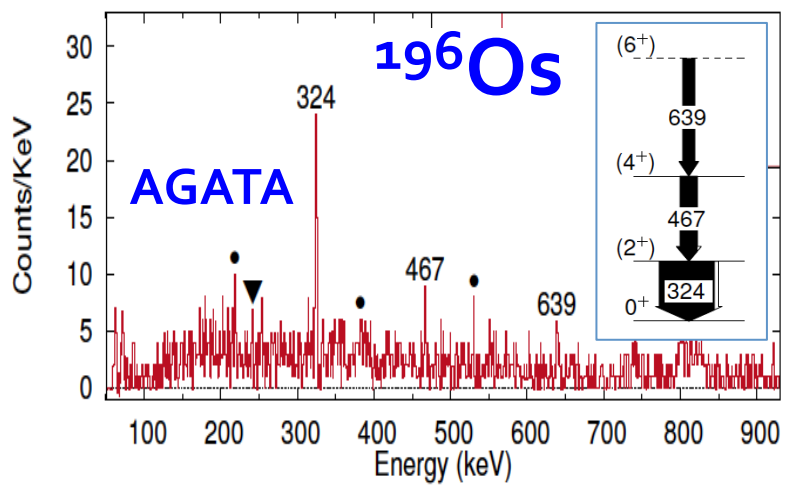


- **ISOMERS** (longed-lived) ★
- **Different SHAPES** (Prolate, oblate, triaxial)

Tuning of Theory
(For Extrapolations)

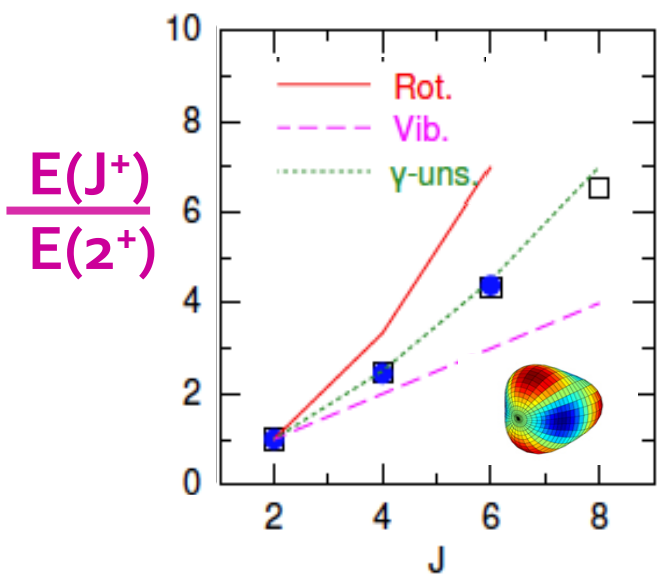
^{82}Se (6.2 MeV/A) + ^{198}Pt

First Observation of Excited States



P.R. John et al, PRC 90 (2014) 021301 R

State-of-the-art **beyond mean-field** calculations describe entire **Os chain** (A=188-198)



^{196}Os is γ-soft

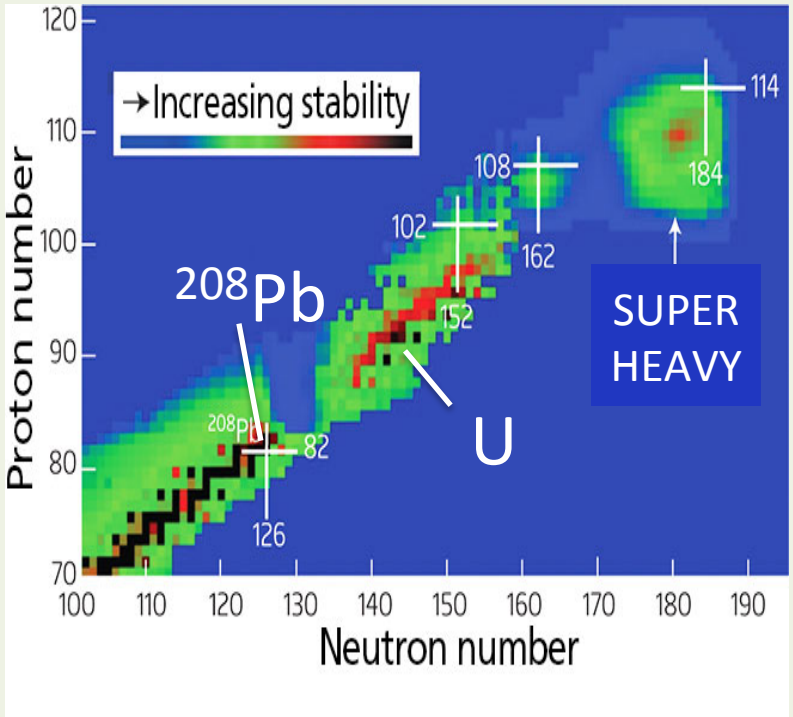
BINARY PARTNER Method
Spectroscopy around Uranium Nuclei

LNL

AGATA ADVANCED GAMMA TRACKING ARRAY

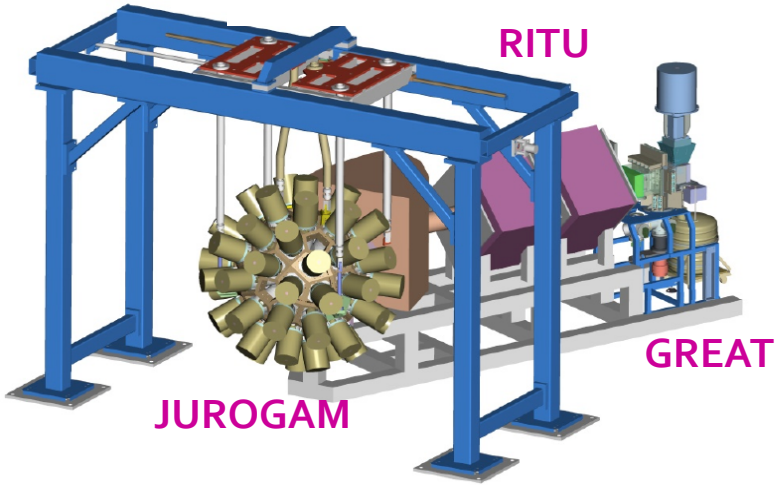
See Plenary R. Herzberg

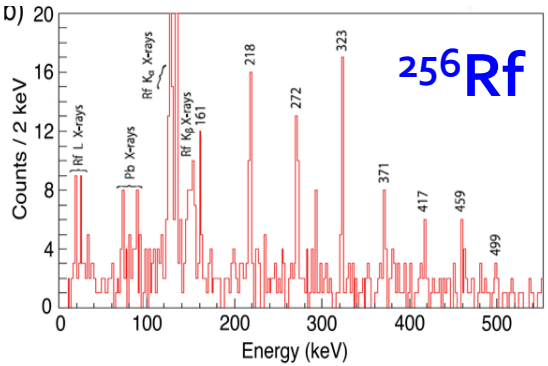
Gateway to Super Heavy



Super Heavy In-Beam Spectroscopy

JYVASKYLA: Recoil-Decay-Tagging





heaviest nucleus
ever probed in-beam
(up to 20 $\hbar$!)

FUSION
$^{50}Ti + ^{208}Pb$

Viewpoint Physics

P. T. Greenlees et al., PRL109, 012501 (2012)

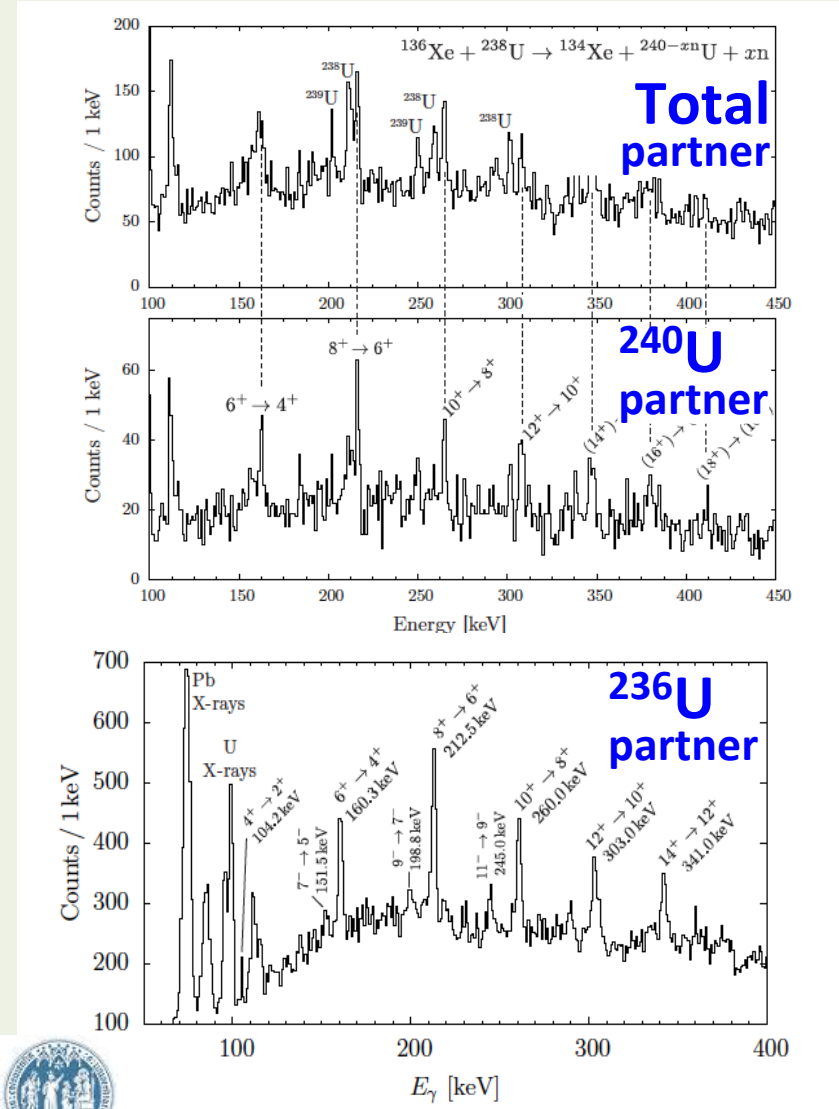
Tuning of Theory
(For Extrapolations)

Koeln

BINARY PARTNER Method

Spectroscopy around Uranium Nuclei

LNL



A. Vogt et al, PRC92, 024619 (2015)

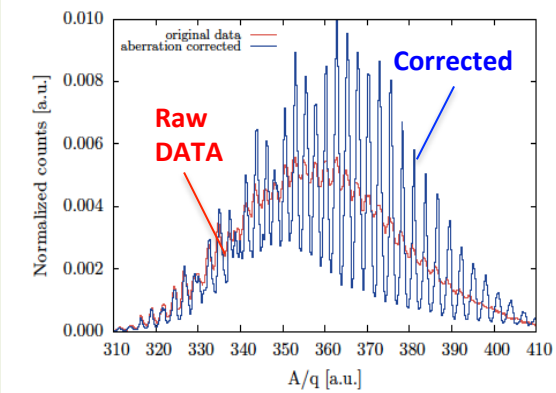
Koeln

AGATA + PRISMA

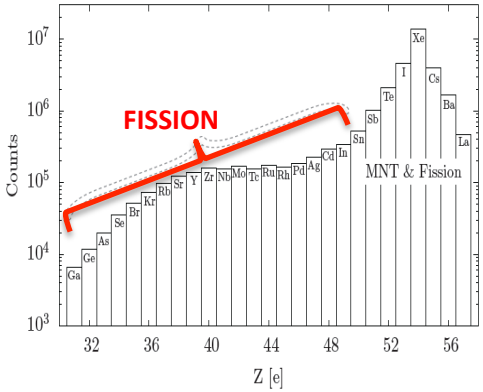
^{136}Xe (1 GeV) + ^{238}U

VERY Harsh Conditions

Mass Reconstruction (Rather Heavy Beam)

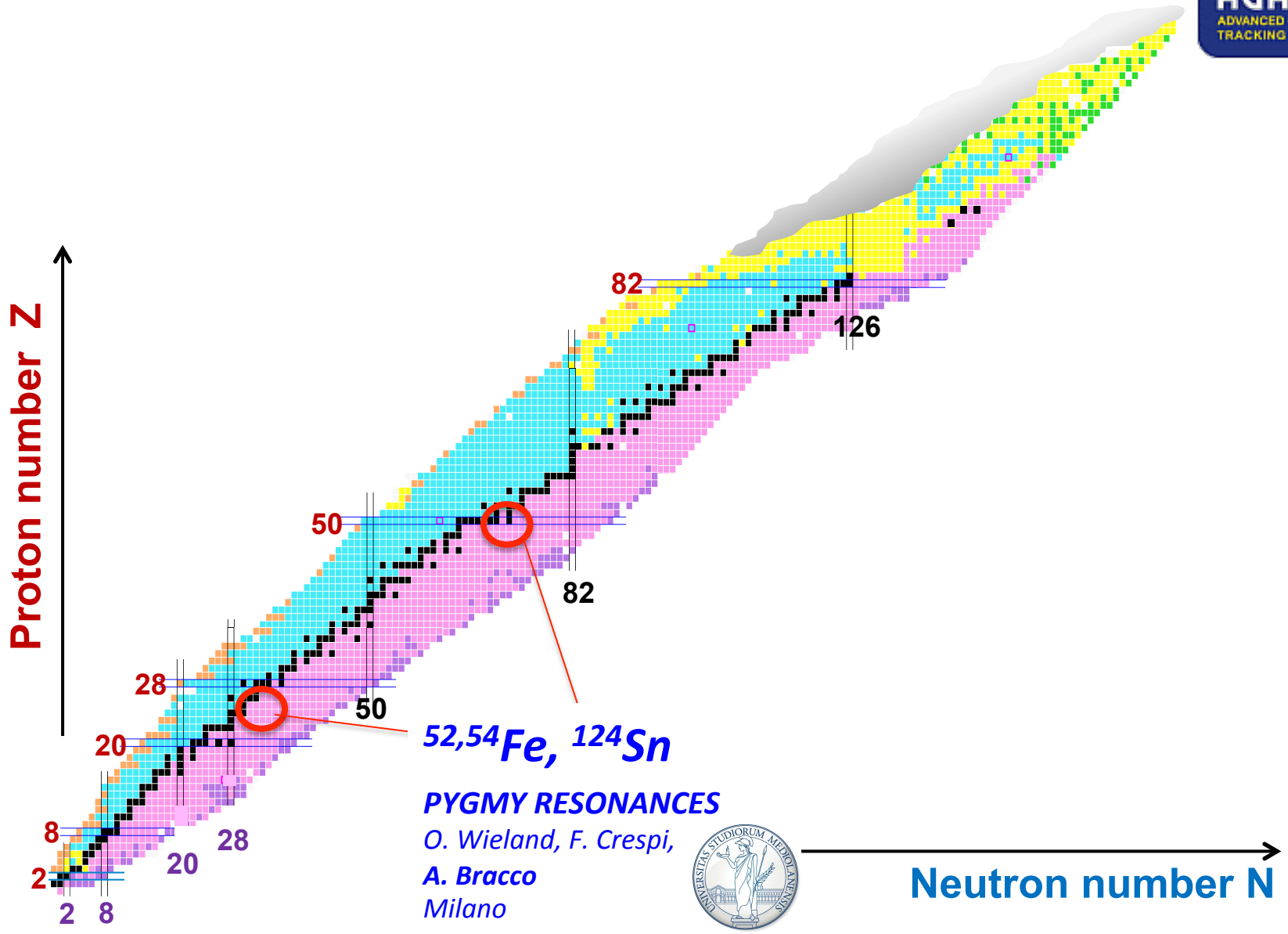


Huge Background (Fission)



Powerful Technique for Spectroscopy of VERY Heavy Systems

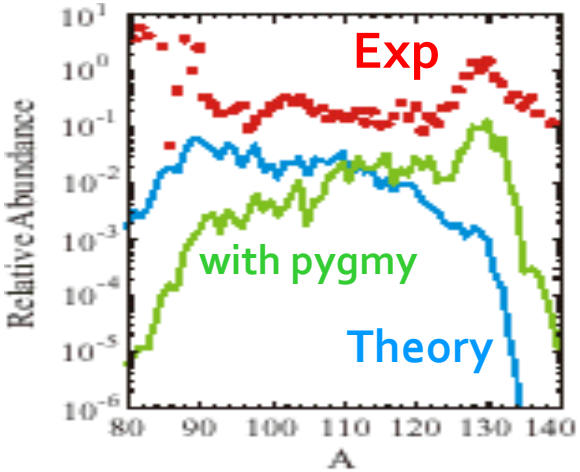
HIGHLIGHTS from AGATA
from LNL and GSI



The DIPOLE Response In Nuclei

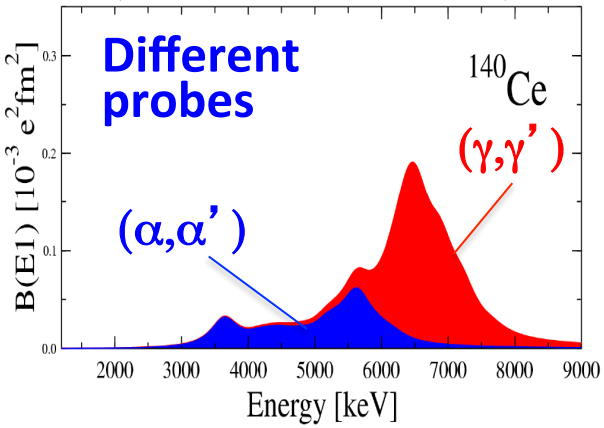
Element Abundance

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

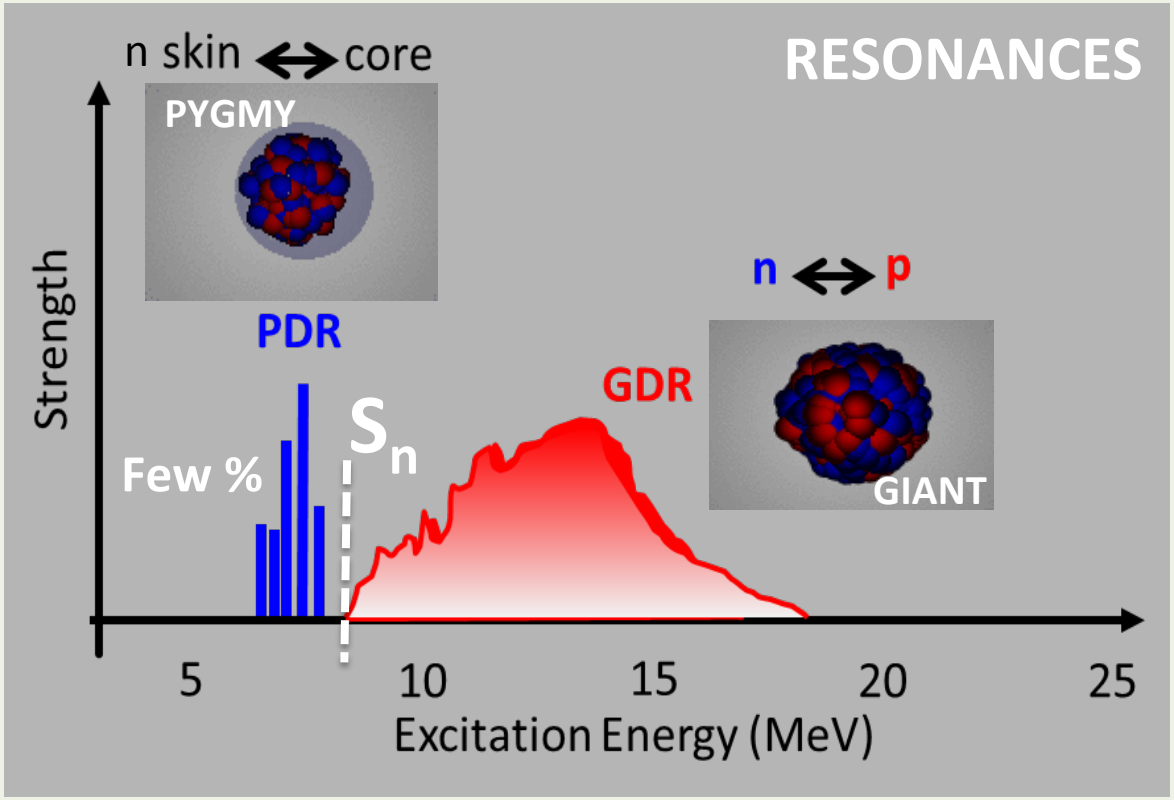


UNDERLYING Structure

(KVI and Darmstadt)



D. Savran et al. PRL97,172502(2006)
J. Endres et al., PRL105, 212503 (2010)



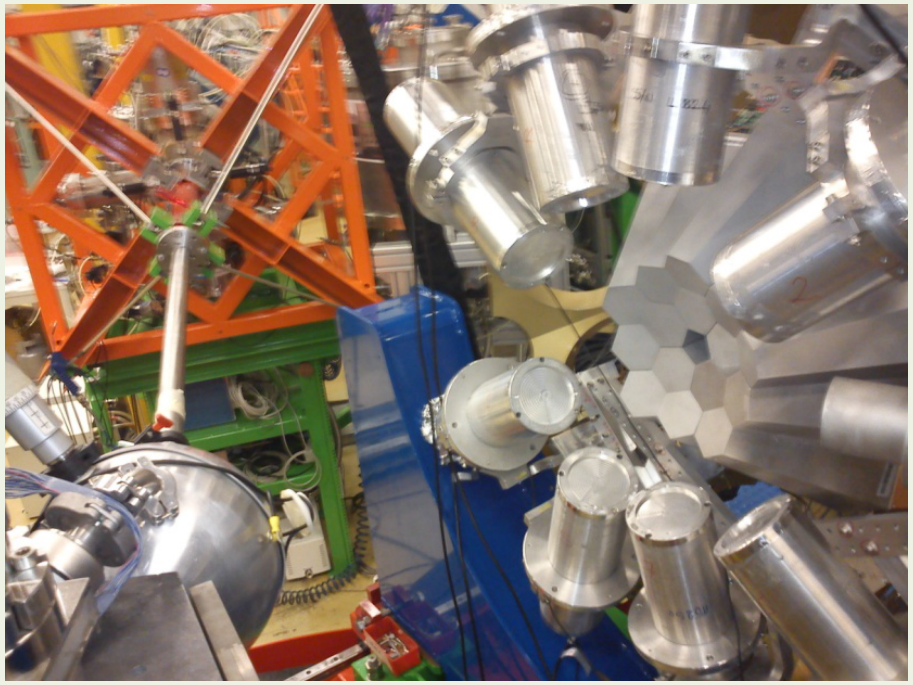
→ Important for ASTROPHYSICS (Nucleosynthesis, Neutron Stars)

→ Relevant in NUCLEAR STRUCTURE (Microscopic Nature…)

Pygmy Resonances in STABLE NUCLEI

LNL

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



LNL Campaign

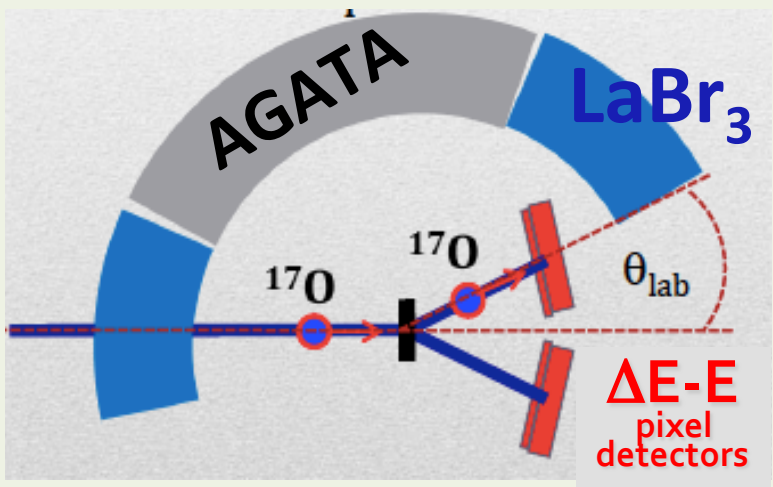
AGATA +

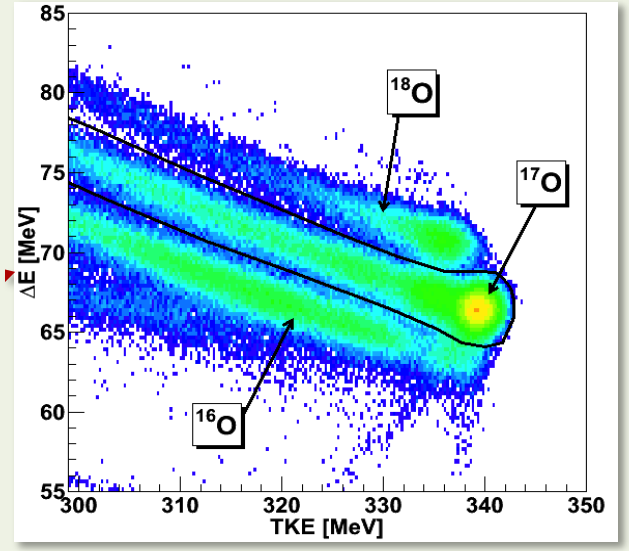
Si Telescopes +

Scintillators (LaBr3)

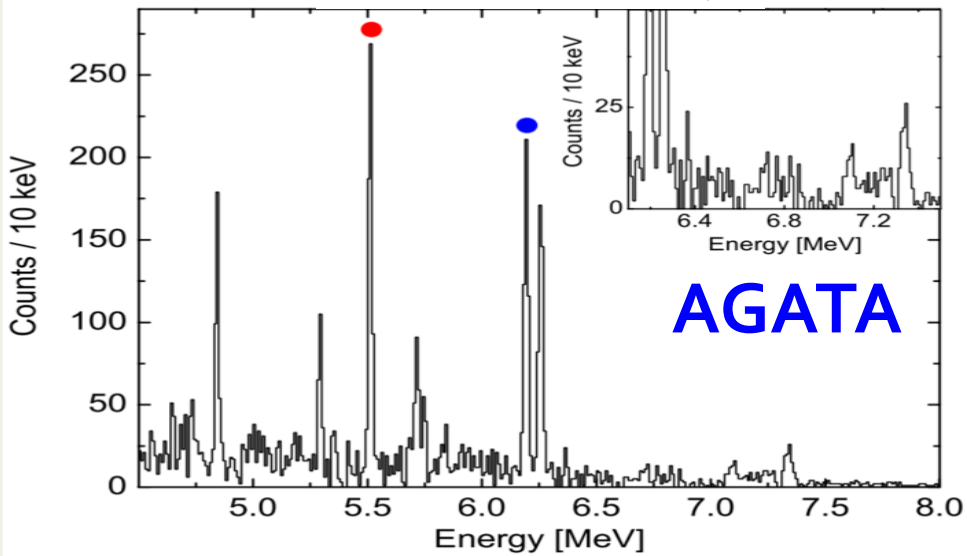
^{17}O @ 20 MeV/A

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

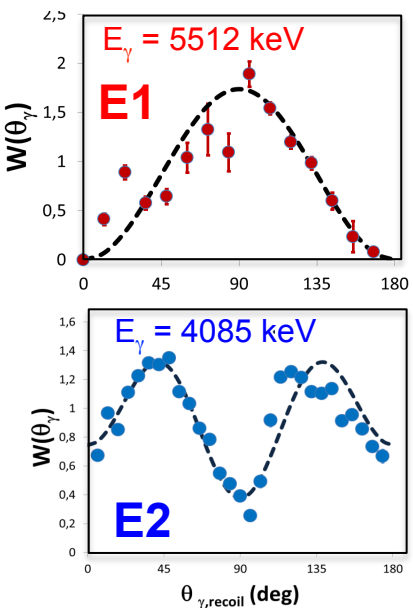




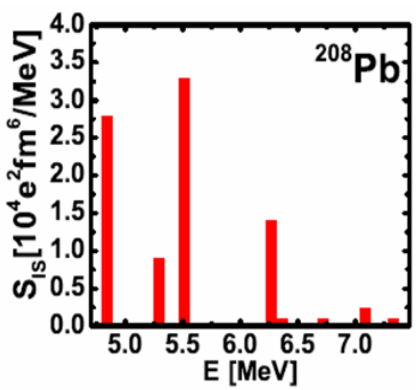
$^{208}Pb(^{17}O,^{17}O'\gamma)$



CONTINUOUS Angular Ditributions

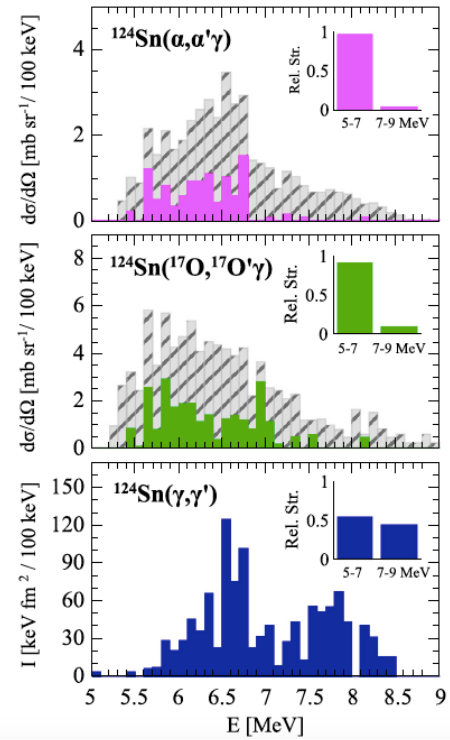


Pygmy Strength: 1-3% EWSR isoscalar E1



LNL

^{124}Sn – 3 different probes



(α,α') KVI

$(^{17}O,^{17}O')$ AGATA-LNL

(γ,γ') Darmstadt

5< E <7 MeV: E1 Isoscalar **(n SKIN)**

7< E <9 MeV: E1 isovector **(GDR Tail)**

^{208}Pb: F.C.L. Crespi, A. Bracco et al., PRL113 (2014) 012501

^{124}Sn: L. Pellegri, A. Bracco et al., PLB738 (2014)519

^{90}Zr: F.C.L. Crespi et al, PRC 91 (2015) 024323

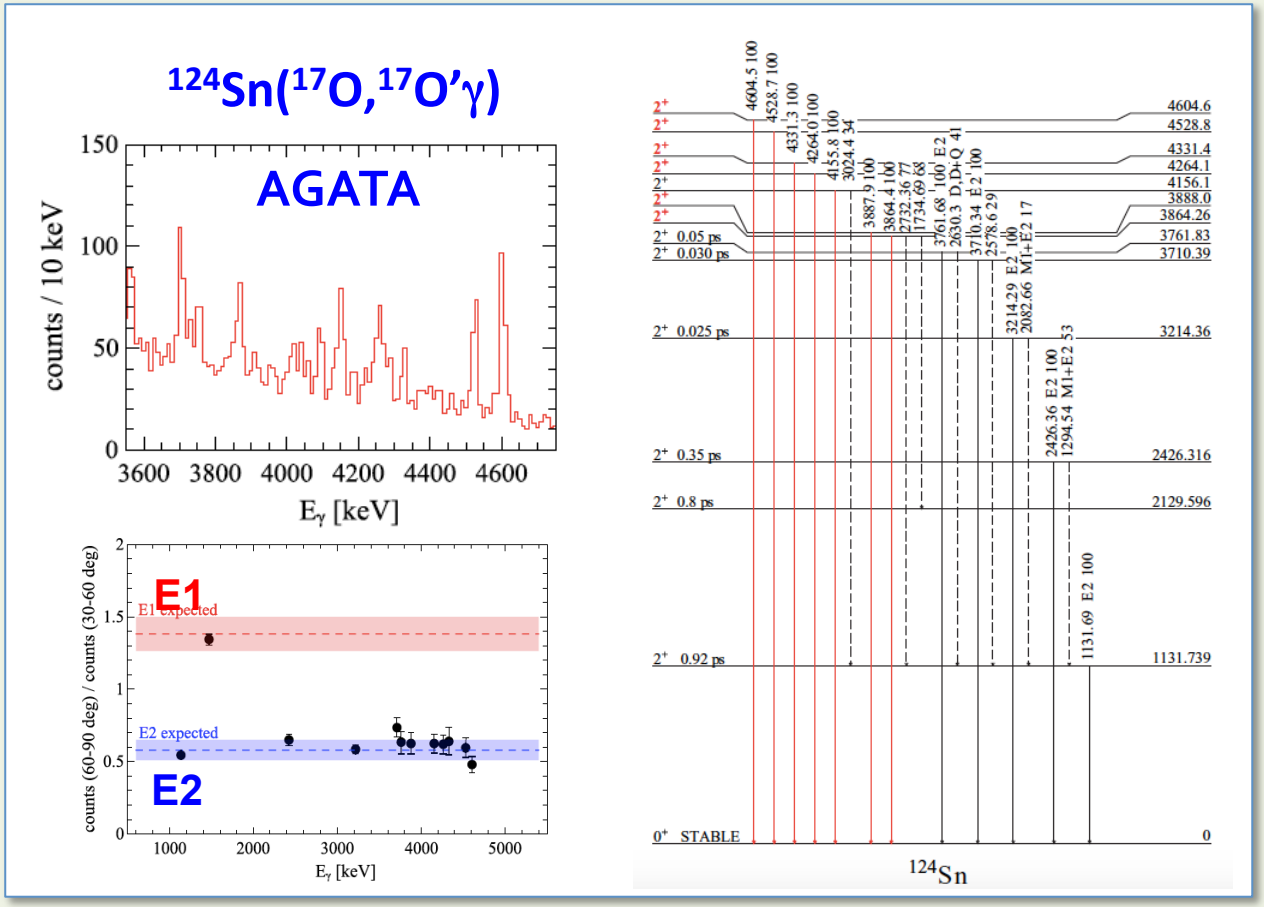
^{140}Ce: Krakow Group (A. Maj et al.)

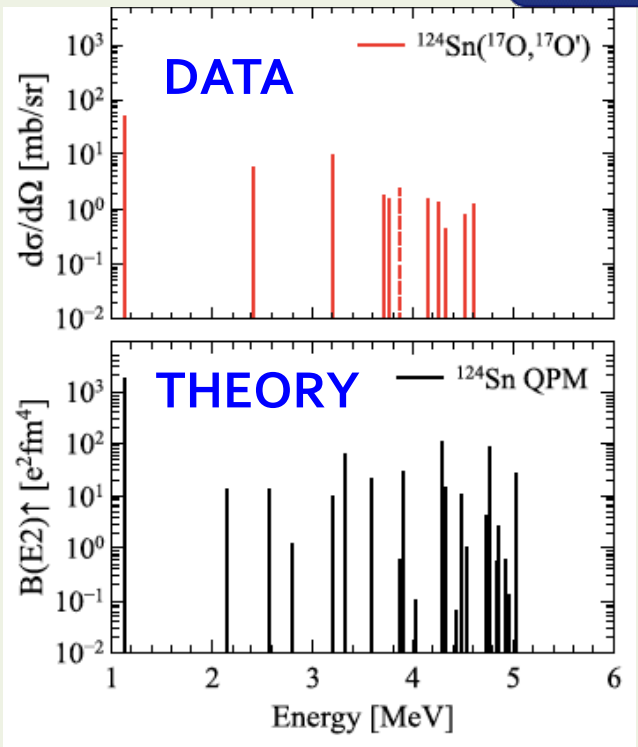
MILANO-KRAKOW LNL Collaboration

^{124}Sn – QUADRUPOLE PYGMY: NEW !

LNL

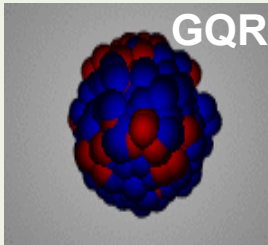
Multitude of 2^+ discrete states





Quasi-Phonon Models
with multiphonon degrees of freedom
(N. Tsoneva, H. Lenske)

Concentration of E2 Strength
much below the GIANT QUADRUPOLE RESONANCE

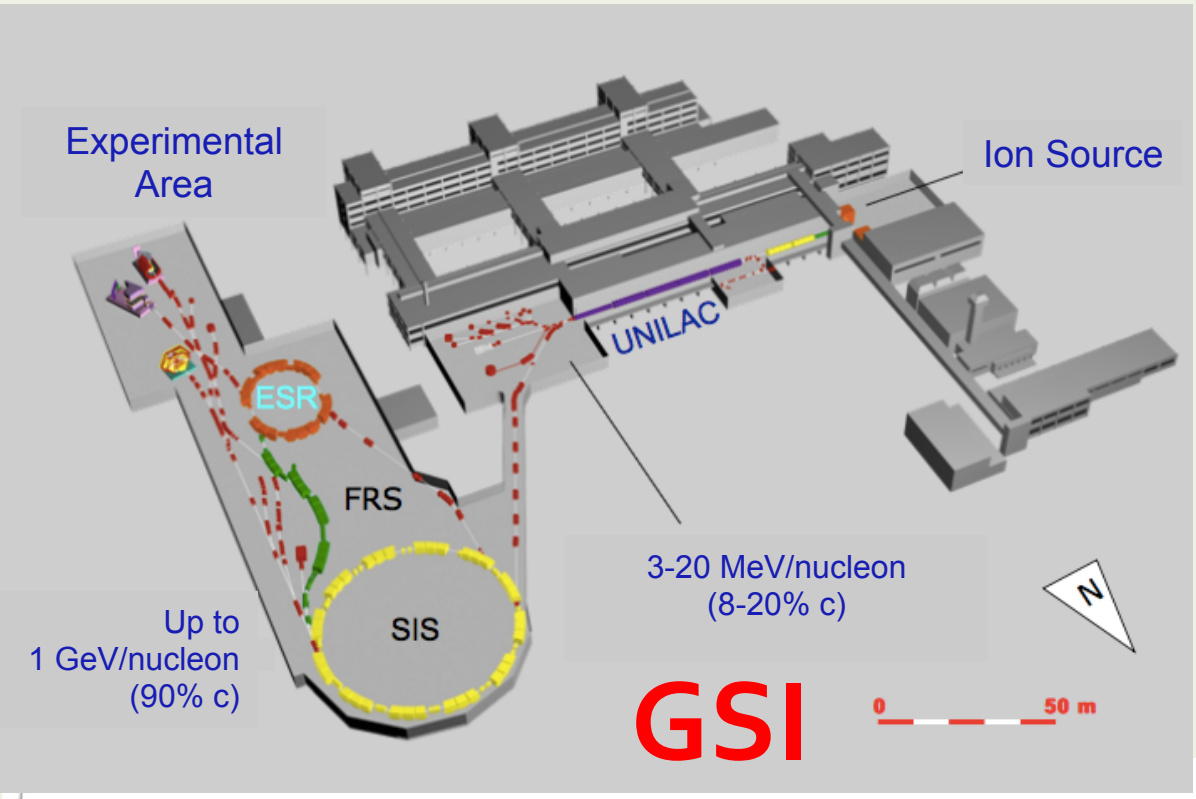


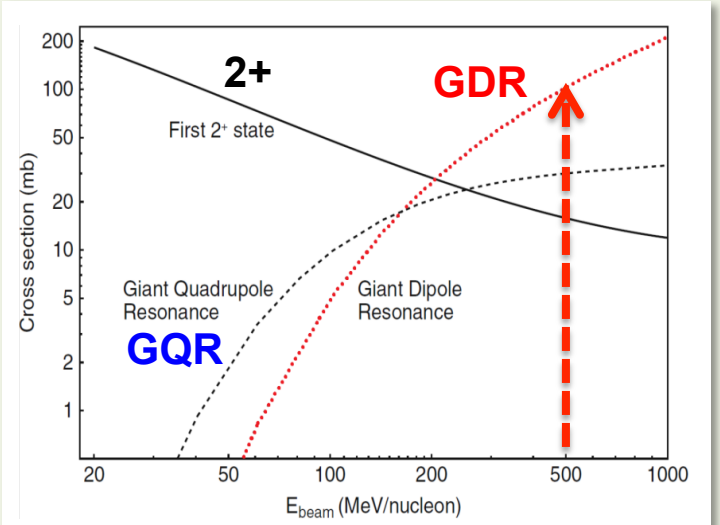
L. Pellegri, A. Bracco et al., PRC92, 014330 (2015)
Recent Review: A. Bracco, F. Crespi, E. Lanza, Eur. Phys. J. A51 (2015) 99

Pygmy Resonances in EXOTIC NUCLEI

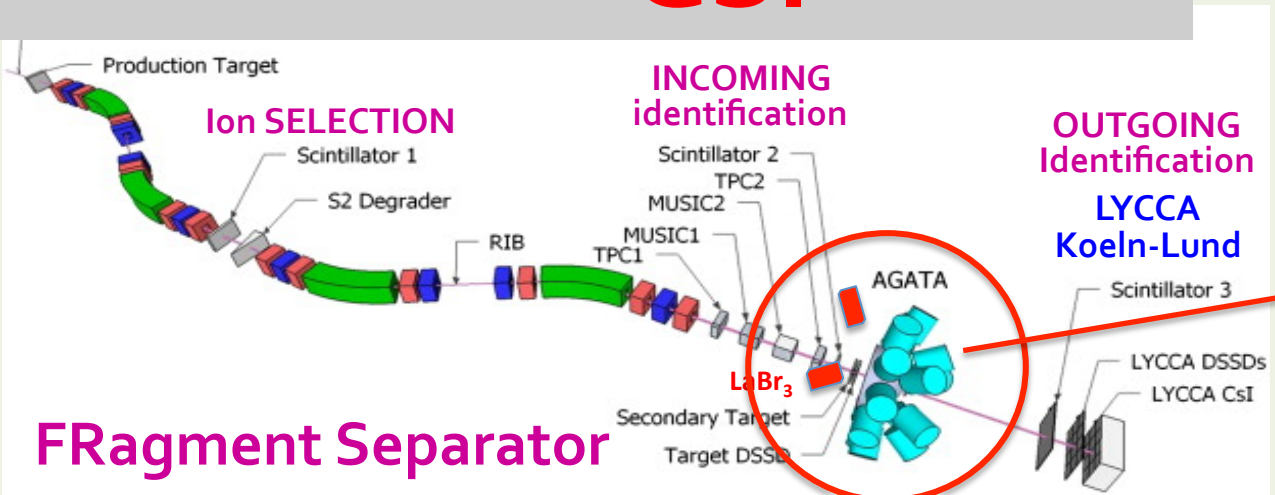
GSI

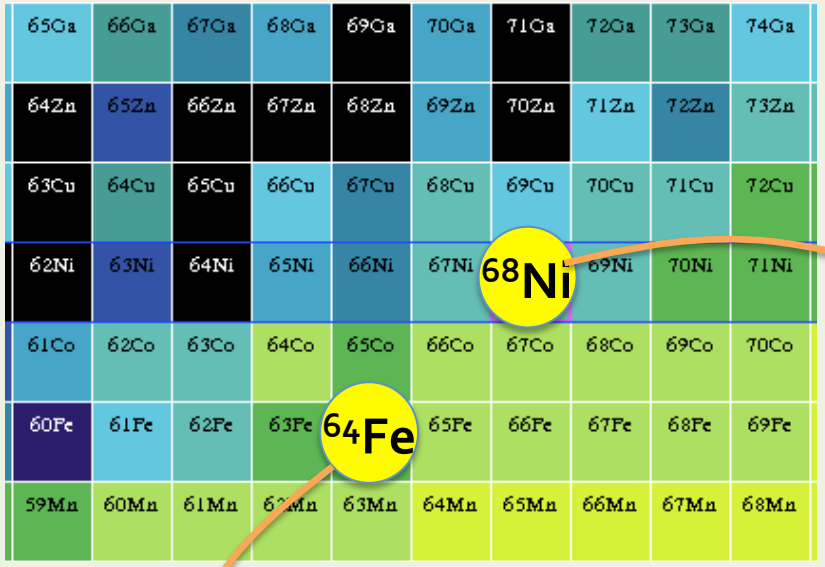
Relativistic Coulomb Excitation: high selectivity for E1 excitation





T.Aumann et al EPJ 26(2005)441



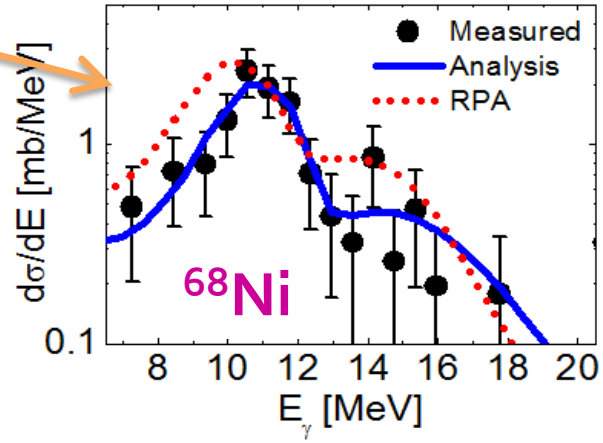


GSI

AGATA ADVANCED GAMMA TRACKING ARRAY

2005 FIRST Case: RISING Setup

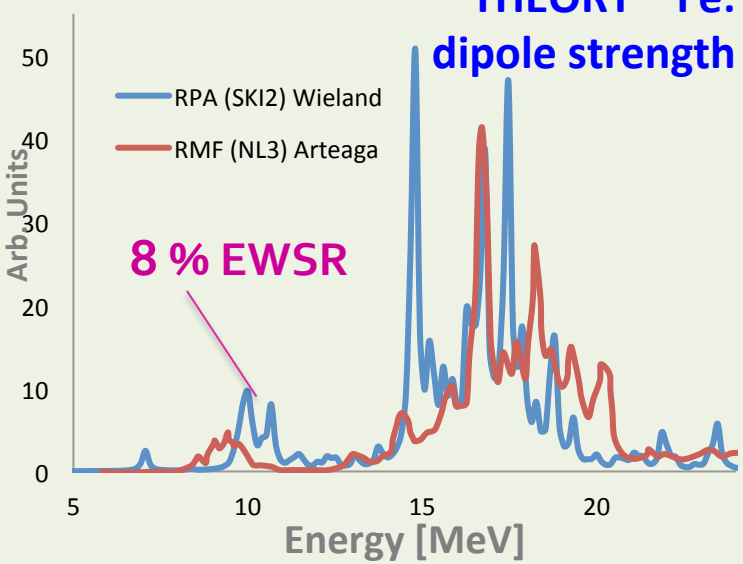
(EUROBALL Clusters + BaF2)



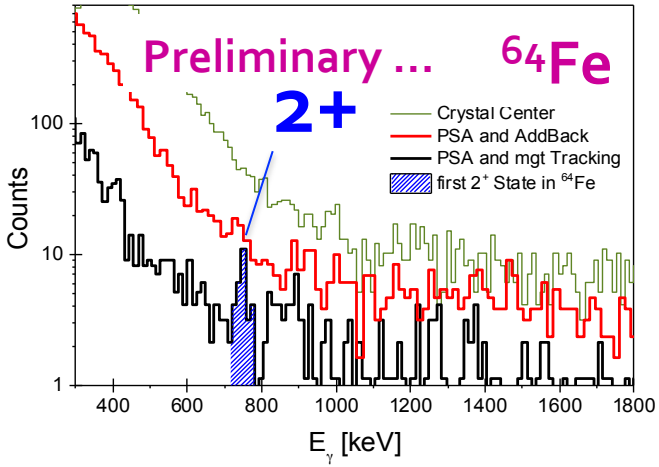
PYGMY Strength: 5-9 % EWSR

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

THEORY ^{64}Fe: dipole strength

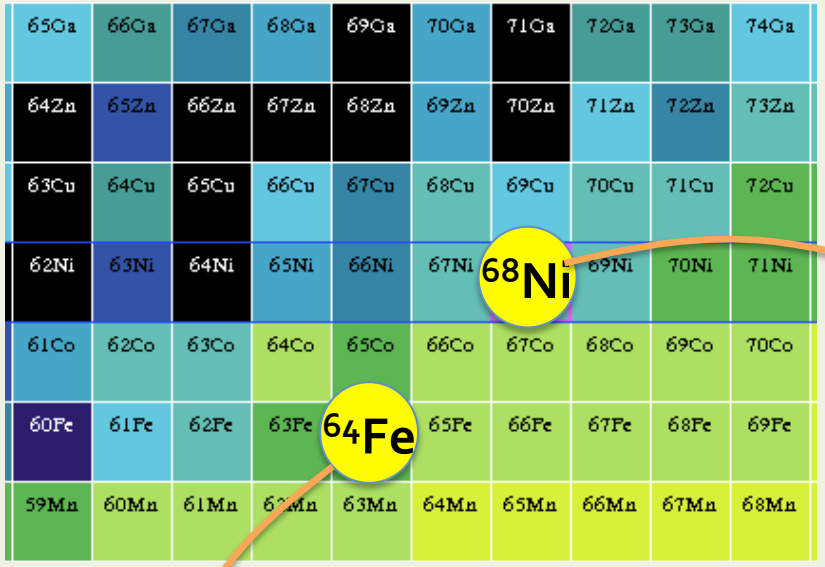


AGATA + LaBr3 Setup



Doppler correction v/c = 73%

R. Avigo, O.Wieland, ... MILANO

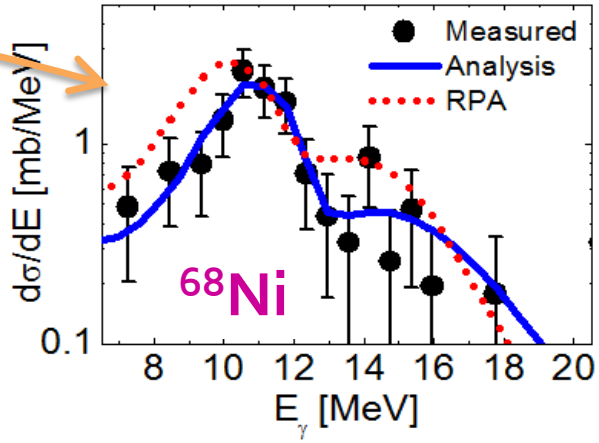


GSI

AGATA ADVANCED GAMMA TRACKING ARRAY

2005 FIRST Case: RISING Setup

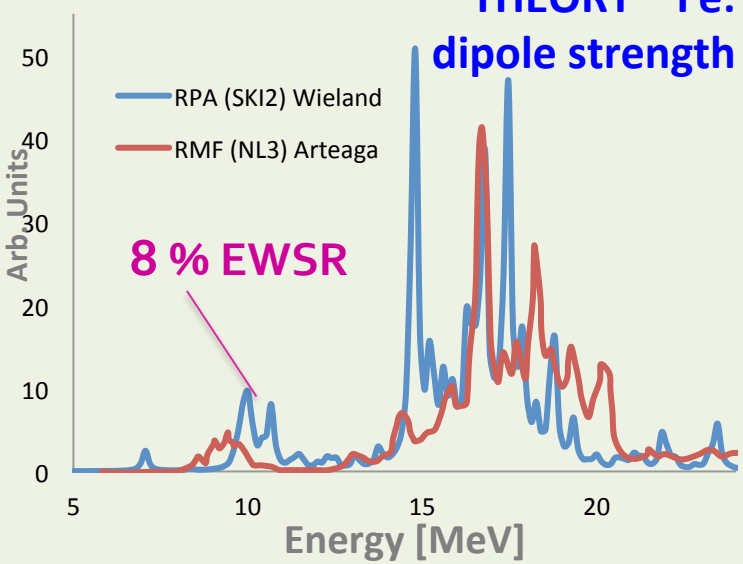
(EUROBALL Clusters + BaF2)



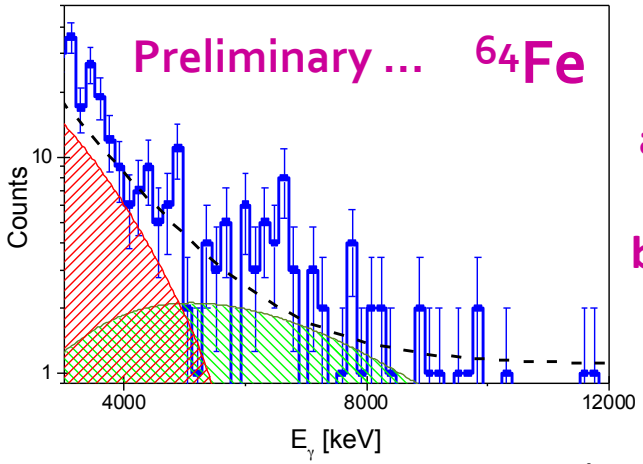
PYGMY Strength: 5-9 % EWSR

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

THEORY ^{64}Fe: dipole strength



AGATA + LaBr3 Setup

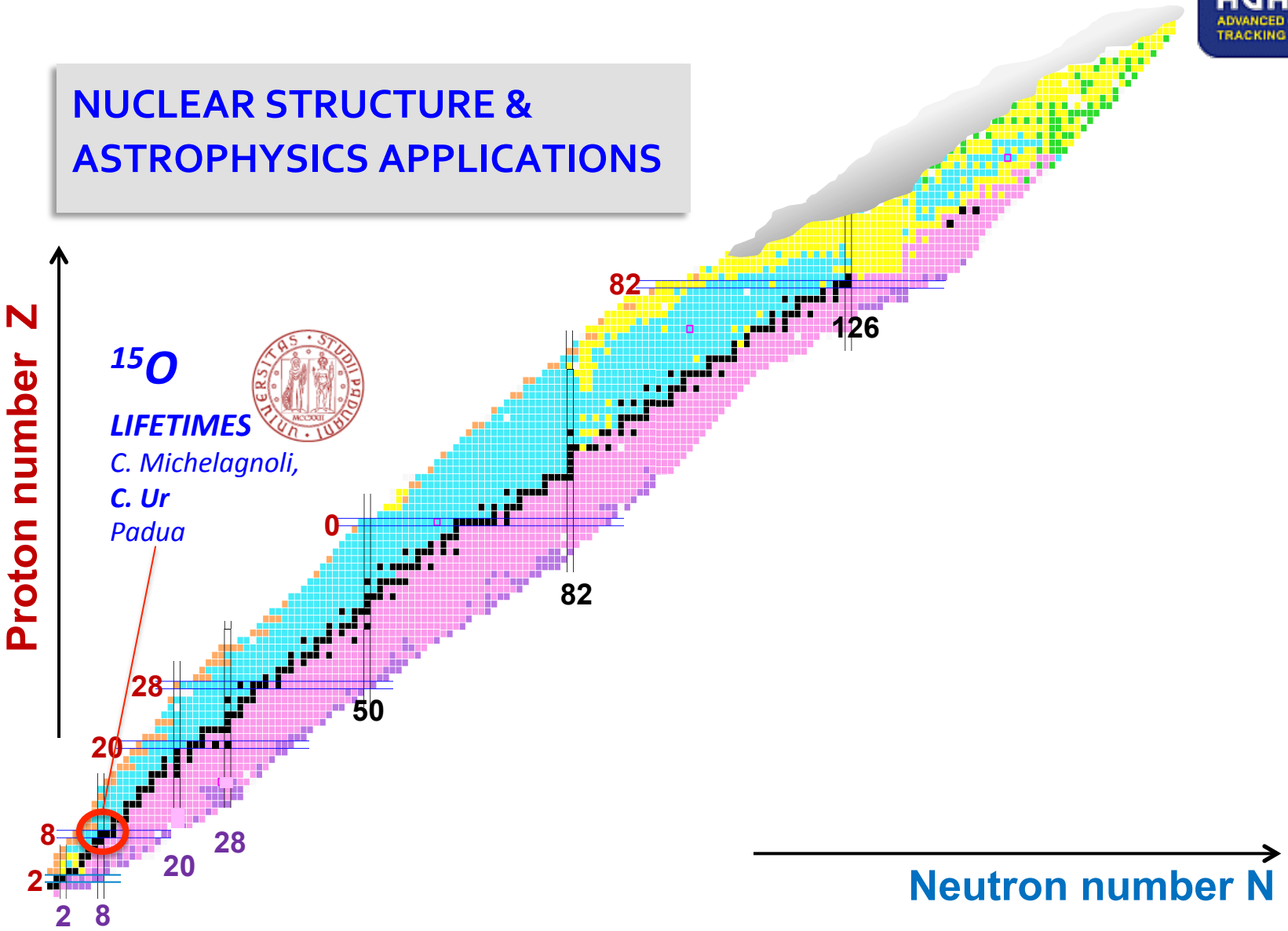


Structures at 6-7 MeV Above background

R. Avigo, O.Wieland, ... MILANO

HIGHLIGHTS from AGATA
from LNL and GSI

NUCLEAR STRUCTURE & ASTROPHYSICS APPLICATIONS



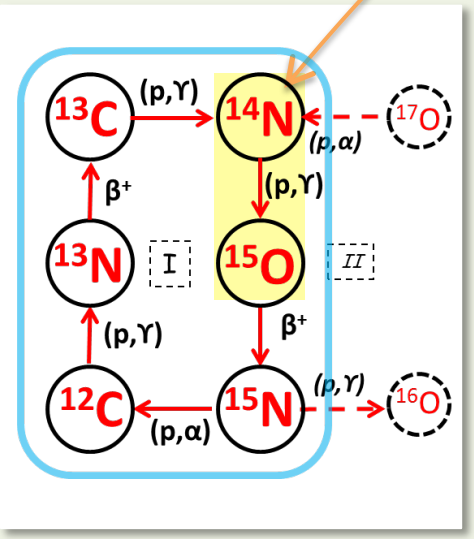
Sub-femtosecond LIFETIME measurement of astrophysical interest

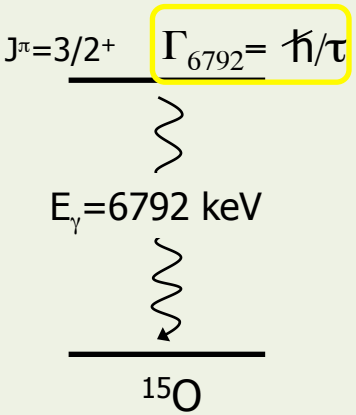
LNL

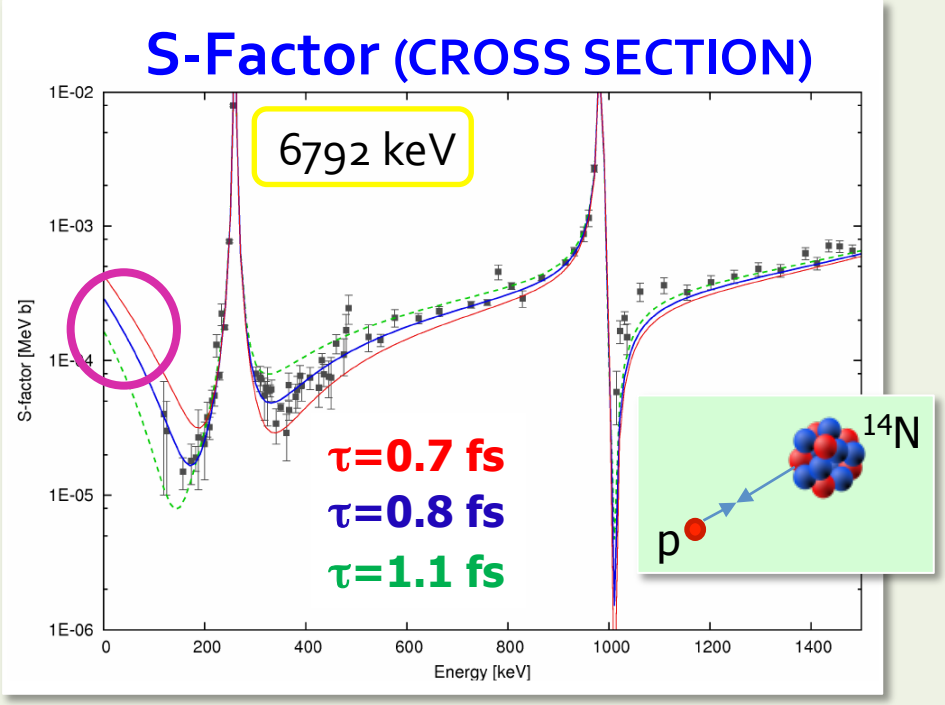
The $^{14}N(p,\gamma)^{15}O$ reaction:

BOTTLENECK of the Carbon-Nitrogen-Oxygen (CNO) cycle

Crucial for stellar burning rate





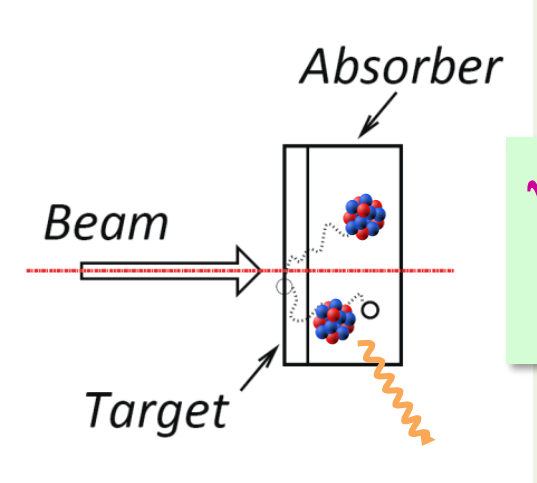


$\Gamma_{6792} = \hbar/\tau_{6792}$ dominates extrapolation of cross-section at STELLAR ENERGIES

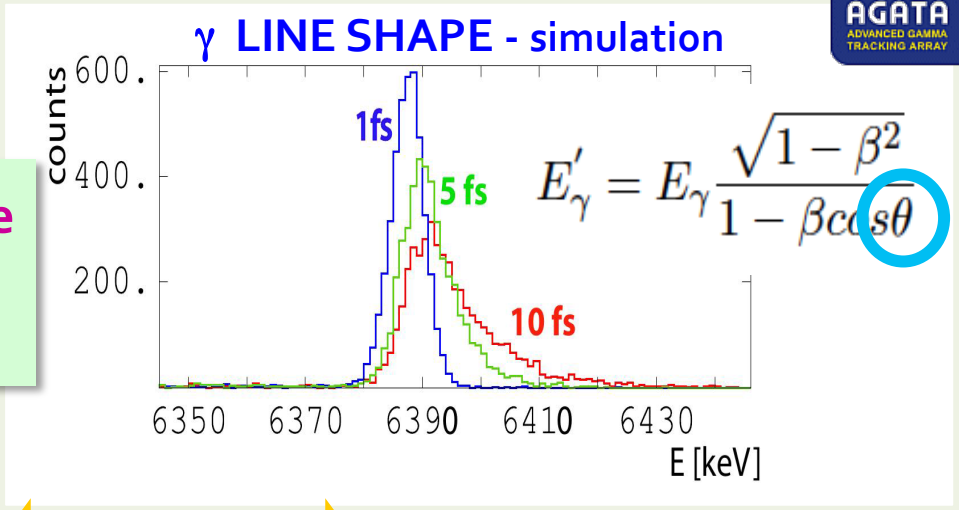
→ need for precise τ at < 1 fs level ....

Doppler Shift Attenuation Method (DSAM)

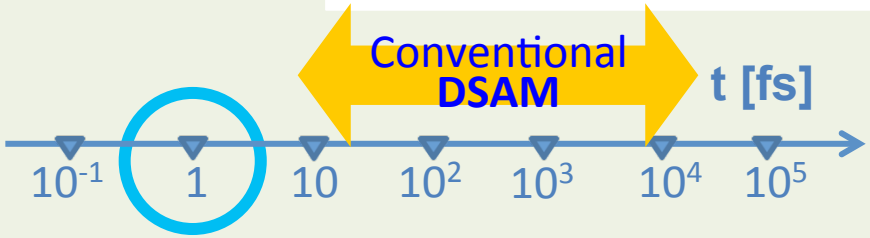
LNL



γ EMISSION while slowing down in ABSORBER



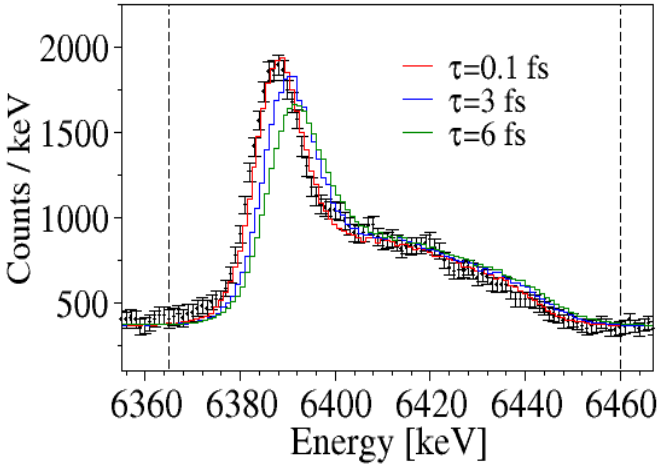
$$E'_\gamma = E_\gamma \frac{\sqrt{1-\beta^2}}{1-\beta\cos\theta}$$



AGATA

position sensitivity (θ~1°)
→ DSAM at the limit

"CONTINUOUS" angular distribution



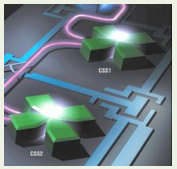
τ < 0.5 fs (99% C.L.)

Γ_{6792} > 1.32 eV (99% C.L.)

$S_{GS}(0)$ > 0.05 keV b (99% C.L.)

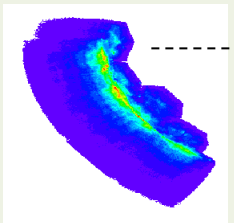
C. Michelagnoli, PhD Thesi - Padua and submitted to PRL

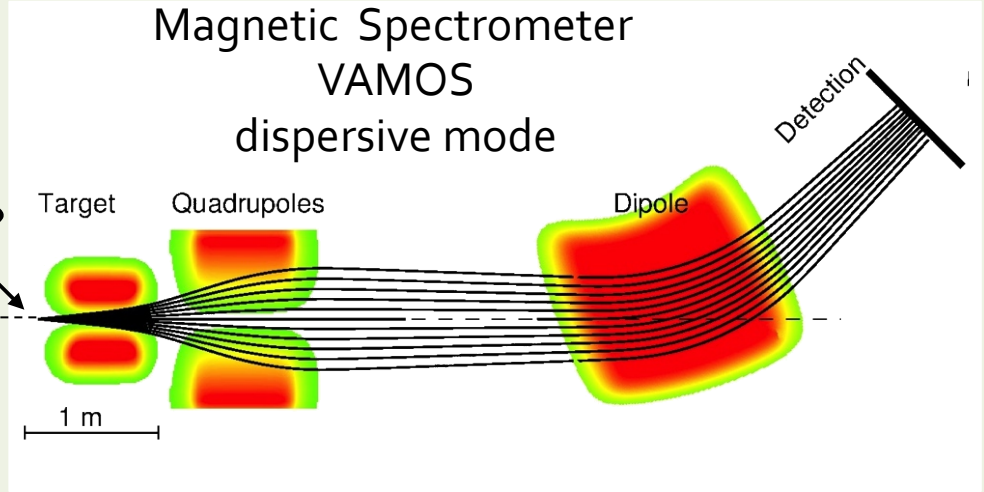
AGATA + VAMOS @ GANIL (2014-2018)



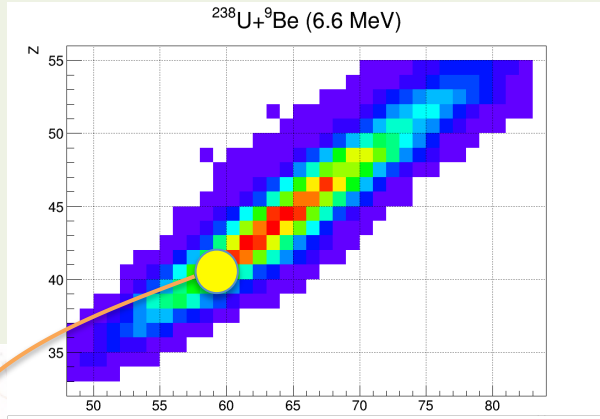
beam

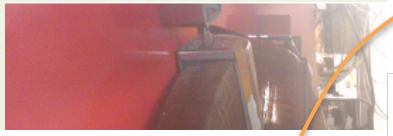
AGATA



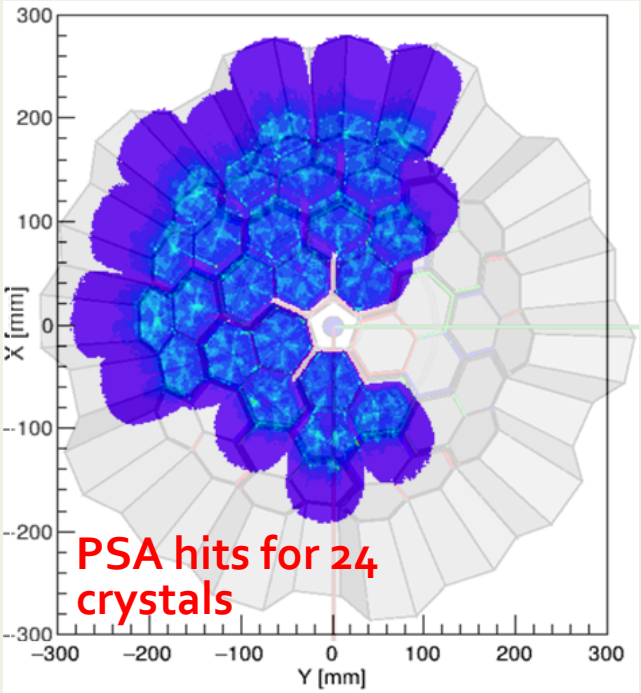


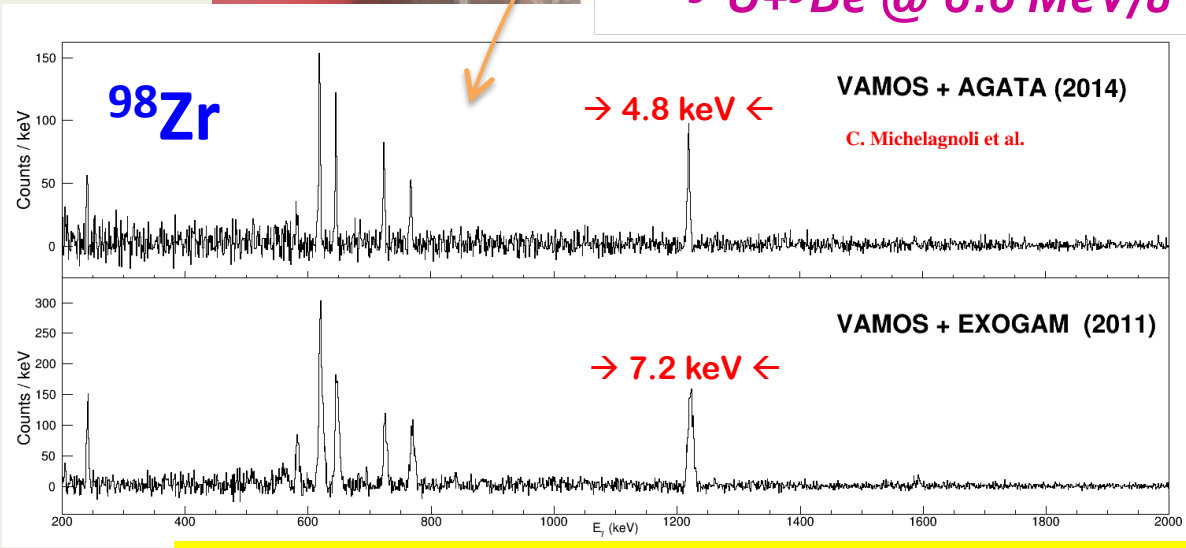
Commissioning in December 2014





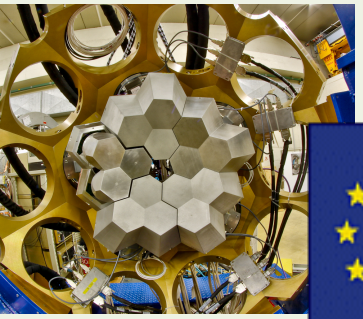
^{238}U+^{9}Be @ 6.6 MeV/u

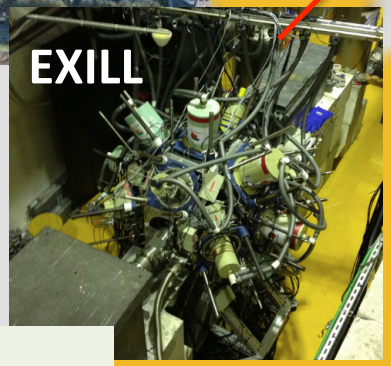




See A. Gottardo: Preliminary from AGATA@GANIL

Selected Examples of EUROPEAN γ-Spectroscopy Activities





AGATA
ADVANCED GAMMA TRACKING ARRAY

NEUTRONS FOR SCIENCE

EXILL

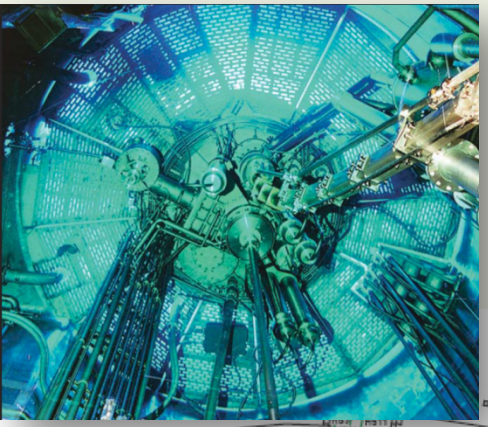
Oslo
JYFL
DUBNA
Warsaw
GANIL
GSI
Orsay
Legnaro
ILL
ISOLDE CERN
Bucharest
LNS

EuNPC2015

The γ-Spectroscopy Campaign @ ILL-reactor (Grenoble)

2012-2013: 100 days, 95% DATA Taking

58 MW REACTOR



World Brightest Continuum neutron source

In pile

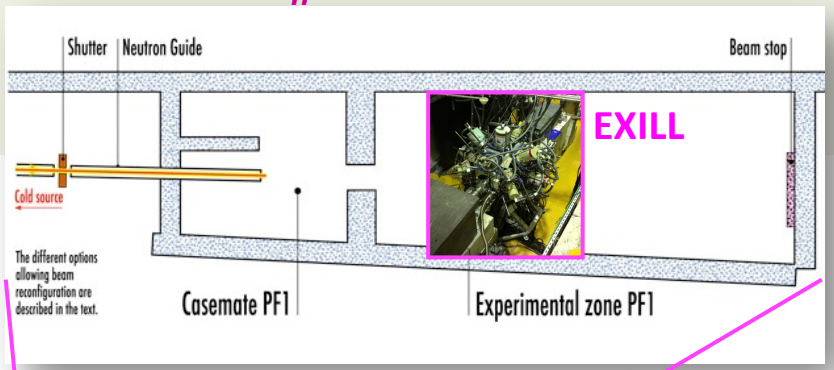
$\Phi_n = 5\times10^{14}\ n\ cm^{-2}\ s^{-1}$

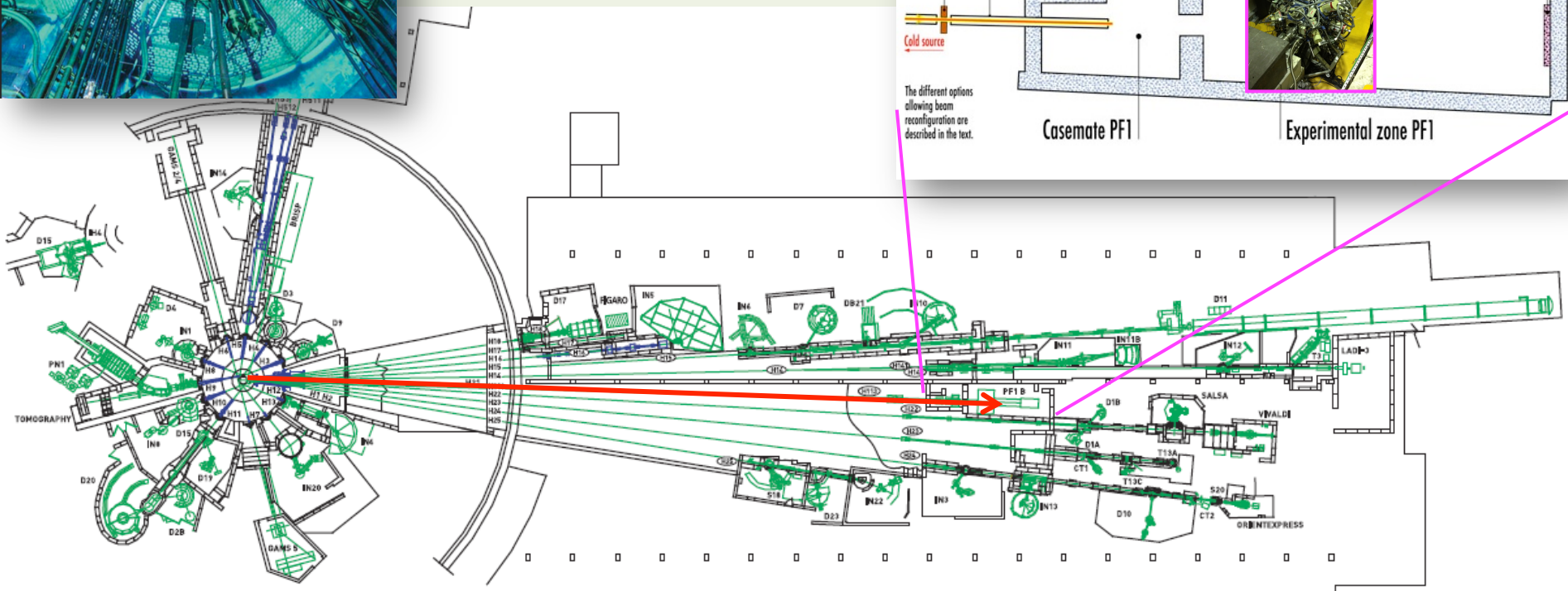
Dedicated ballistic neutron guide

Highly collimated beam (1 cm²)

Cold neutrons (meV)

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





Reactor hall ILL 5
Experimental level (C)

Neutron guide hall - ILL 7
Chartreuse side (EAST)

H. Abele et al., Nucl. Instr. Meth. Phys. Res. A 562, 407 (2006)

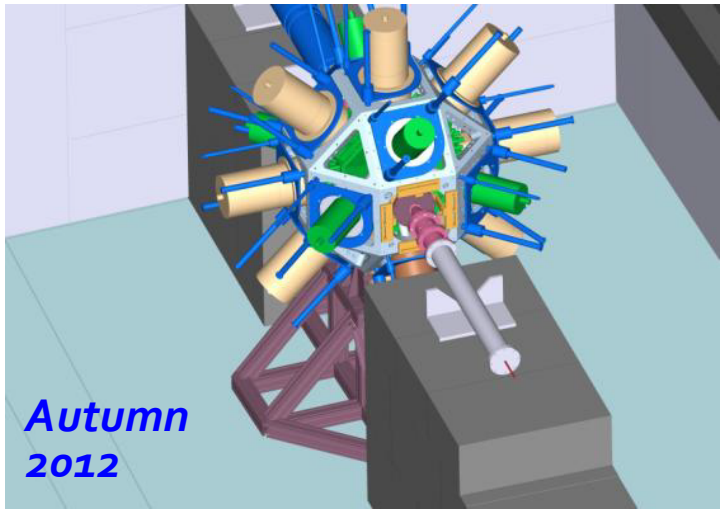
First time a **large HPGe array** (up to 52 Ge crystals) installed around a **highly collimated cold-neutron beam**

NEUTRONS FOR SCIENCE

SETUP 1

γ – spectroscopy

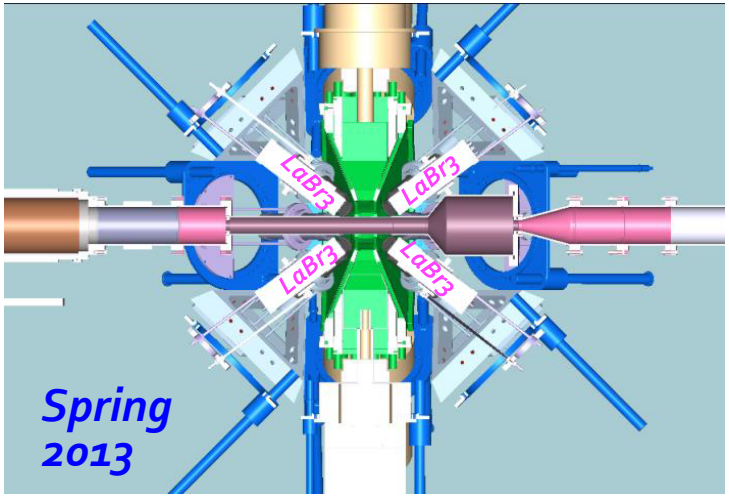
10 EXOGAM – Clovers + 6 Ge GASP
6% efficiency



SETUP 2

Lifetime Measurement

8 EXOGAM – Clovers + 16 LaBr3
FATIMA ARRAY: Fast Timing



The ACQUISITION SYSTEM

A Fully Digital Approach, TRIGGERLESS

>10 kHz/crystal, **>600 kHz total, 10 ns clock**

*Unique opportunity for **γ-coincidences** over **several μs** time window*

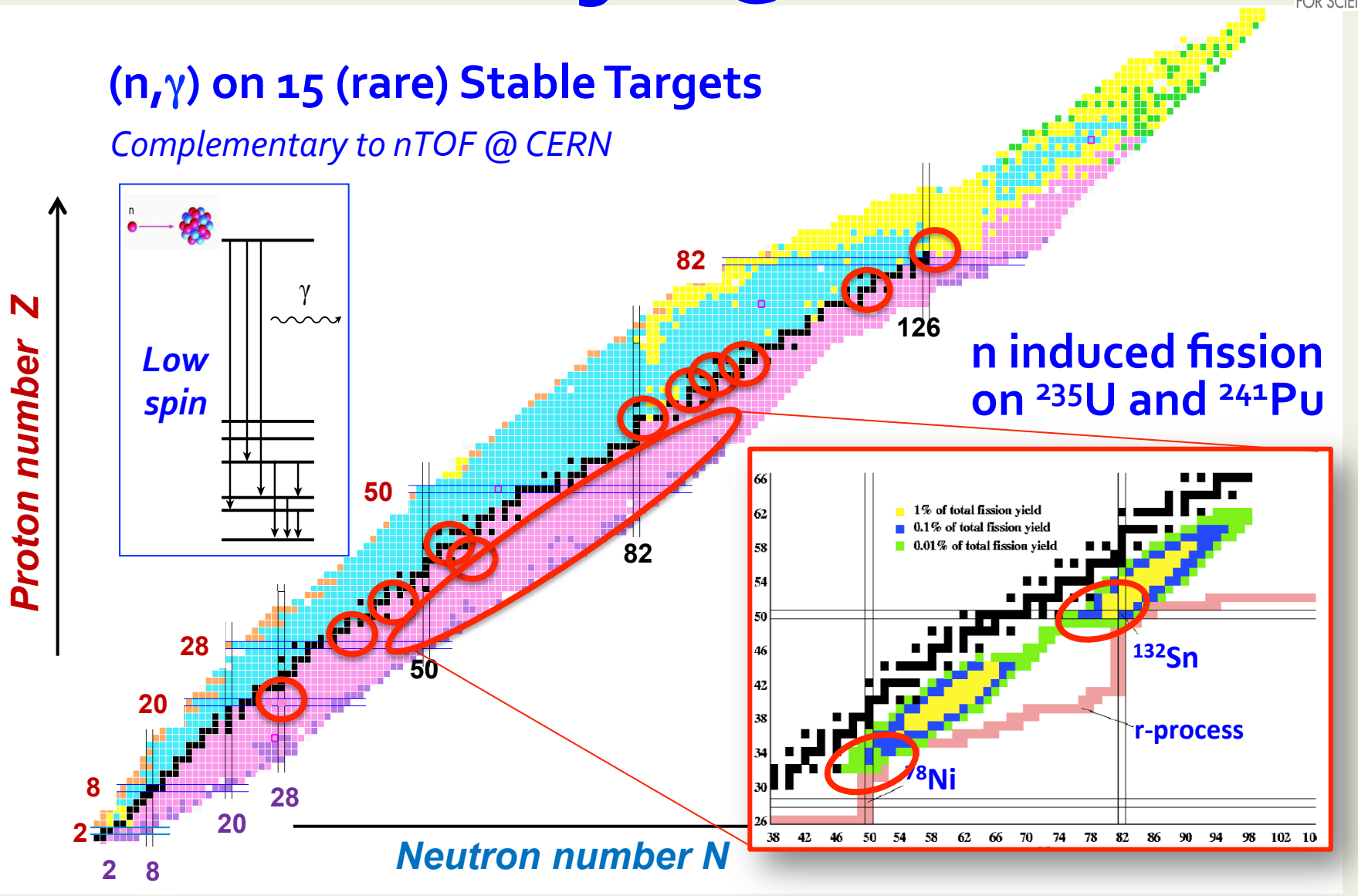
G. DeFrance, A. Blanc, U. Koster, M. Jentschel, P. Mutti, G. Simpson, J.M. Regis, C. Ur et al.

EXogam@ILL

EXILL NEUTRONS FOR SCIENCE

(n,γ) on 15 (rare) Stable Targets

Complementary to nTOF @ CERN

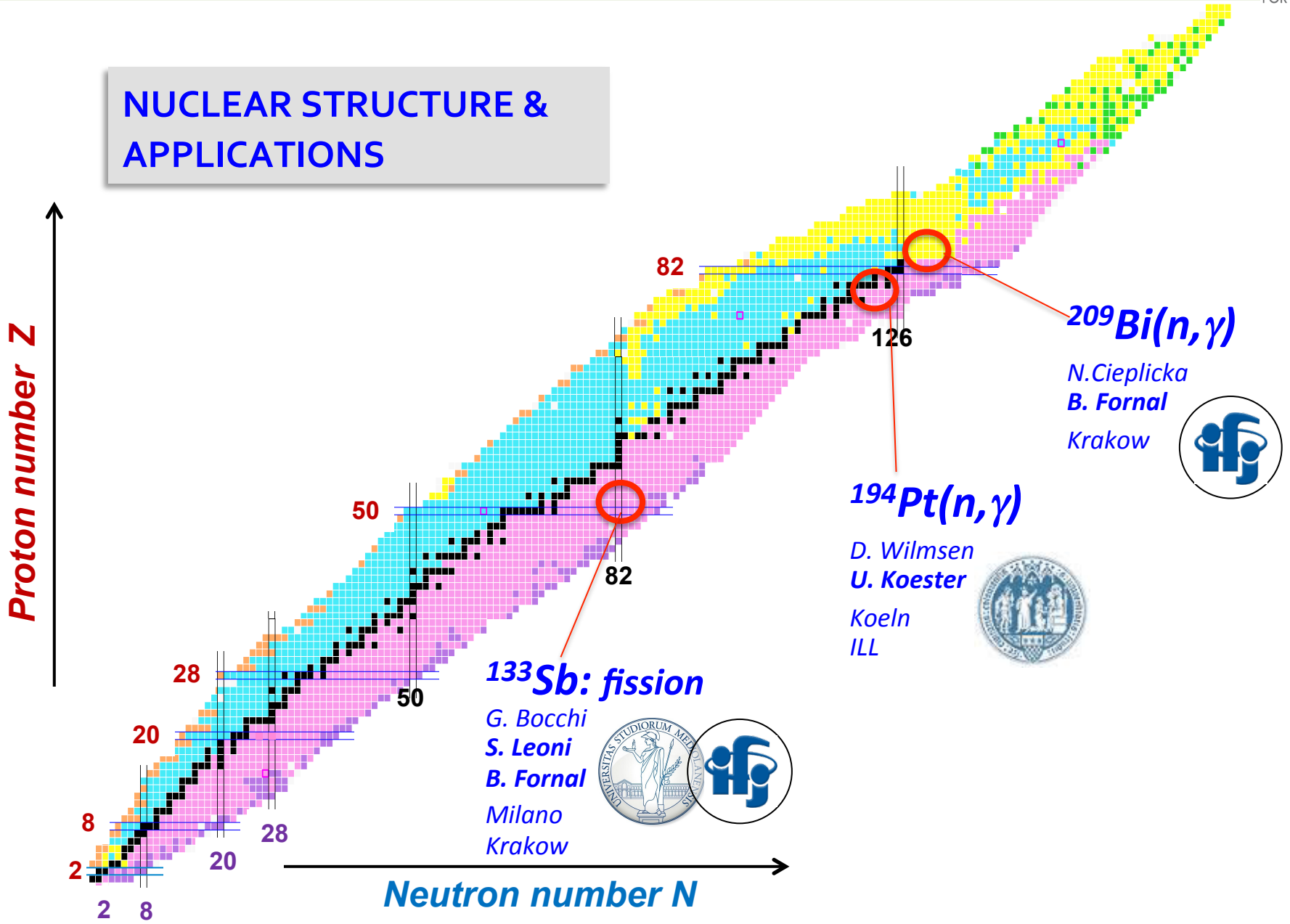


Complementary to existing data sets on Spontaneus Fission ^{248}Cm, ^{252}Cf

HIGHLIGHTS from EXILL

EXILL NEUTRONS FOR SCIENCE

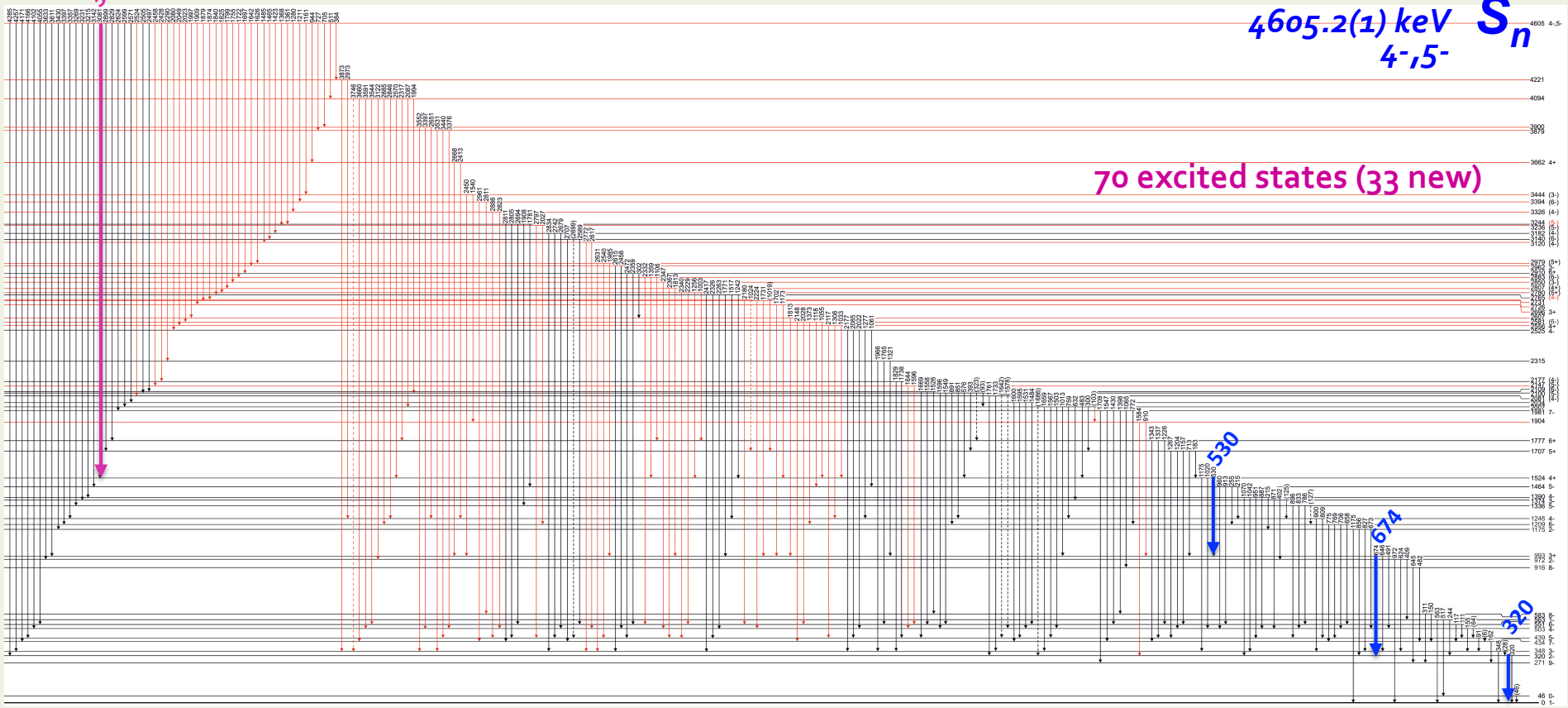
NUCLEAR STRUCTURE & APPLICATIONS

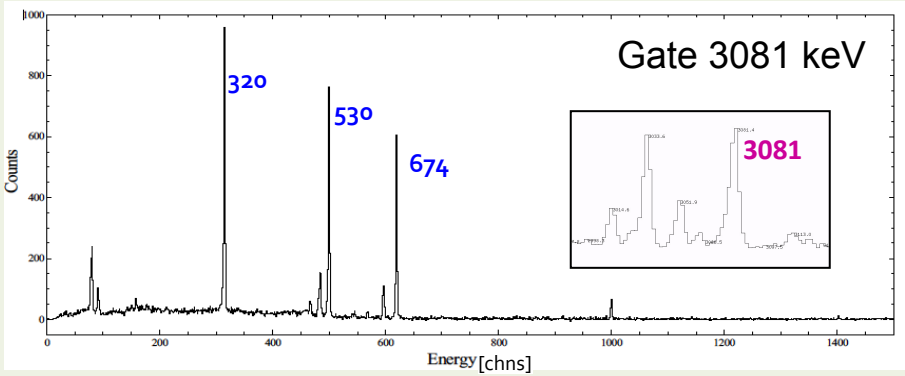


$^{209}Bi(n,\gamma)^{210}Bi$ – ILL Grenoble

EXILL NEUTRONS FOR SCIENCE

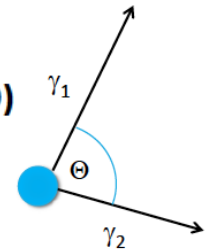
64 primary transitions (40 new)





Angular Correlations

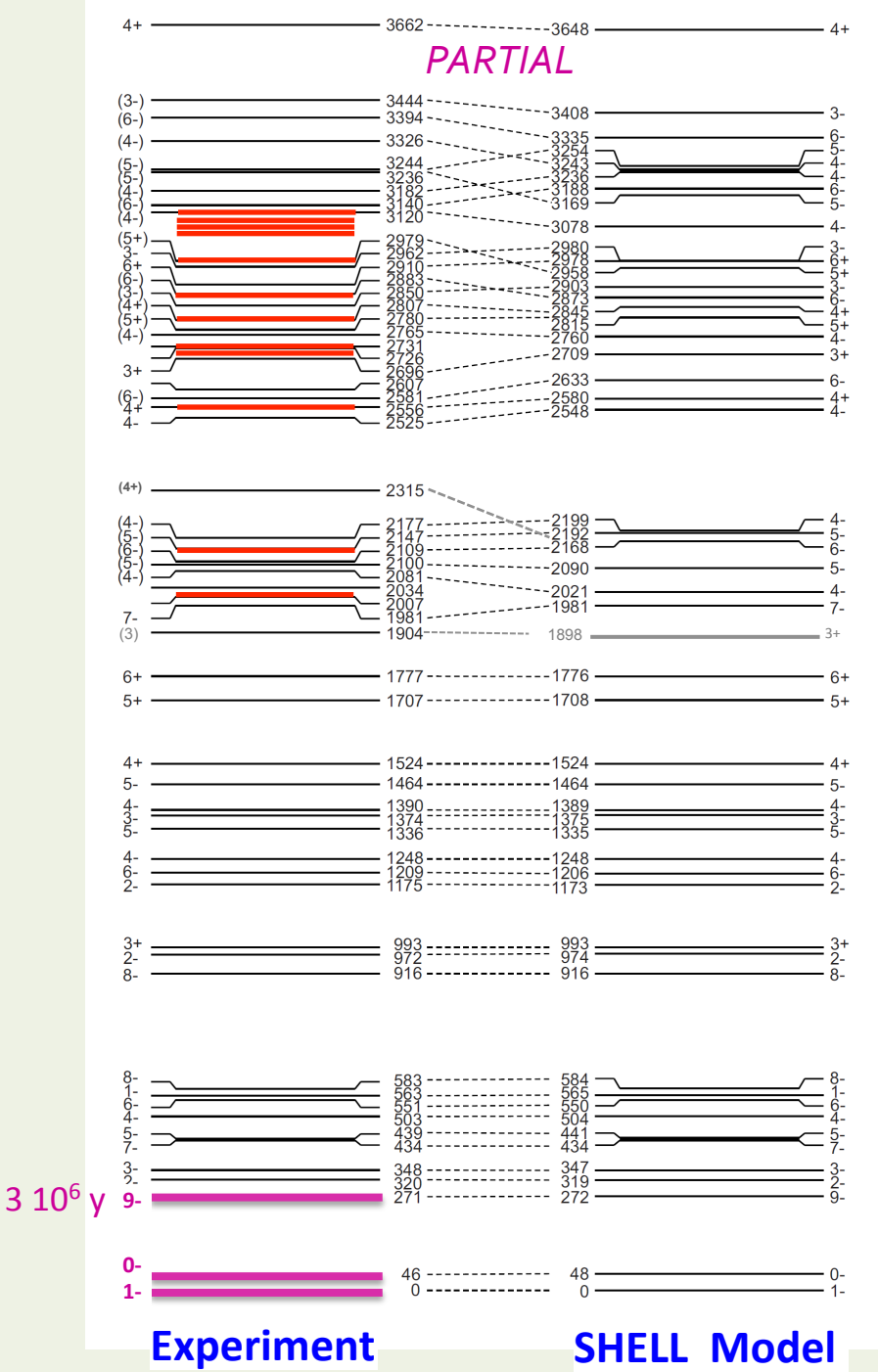
$$W(\Theta) = 1 + A_2 P_2(\cos\Theta) + A_4 P_4(\cos\Theta)$$



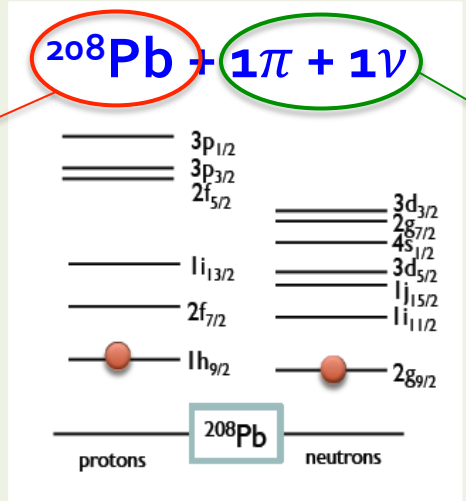
Multipolarities of γ-decay
Spin (Parity) of States

N.Cieplicka, PhD-Thesis, Krakow

Complete Low Spin Spectroscopy of ^{210}Bi



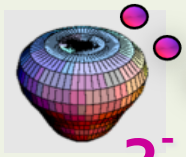
Comparison with SHELL Model



12 Low-Spin States

2 < E < 3 MeV

NOT described by **SHELL Model**

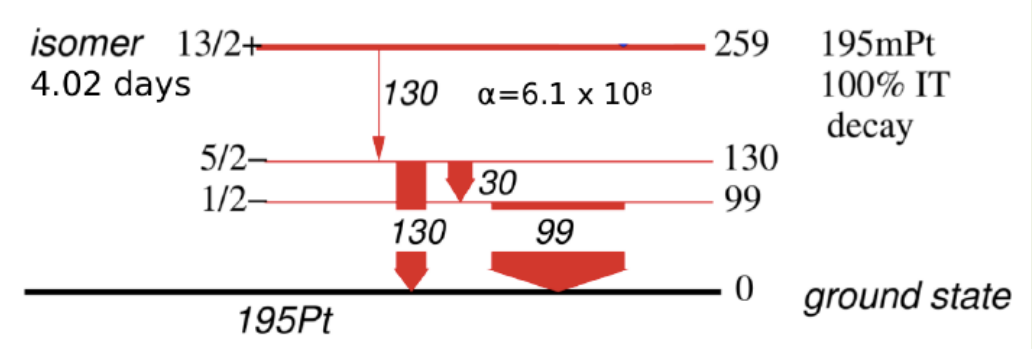


3^-

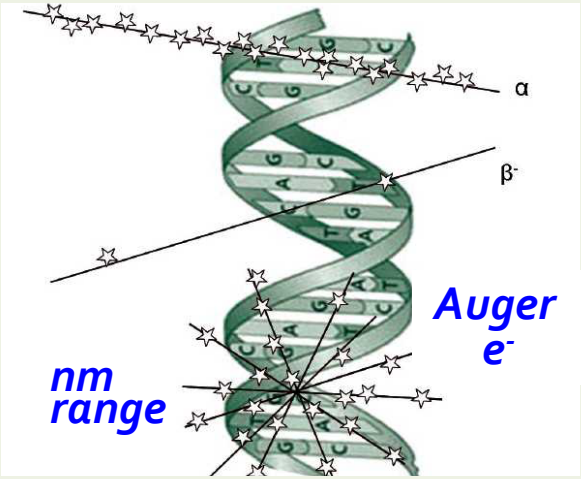
Couplings with **CORE Excitations ?**

$E_x(3^-)$ = 2.6 MeV, B(E3) = 34 W.u.

$^{194}Pt(n,\gamma)^{195}Pt$



High Spin Isomer (13/2+)
Strong population from low spin capture state



IDEAL Properties for Medical Application:

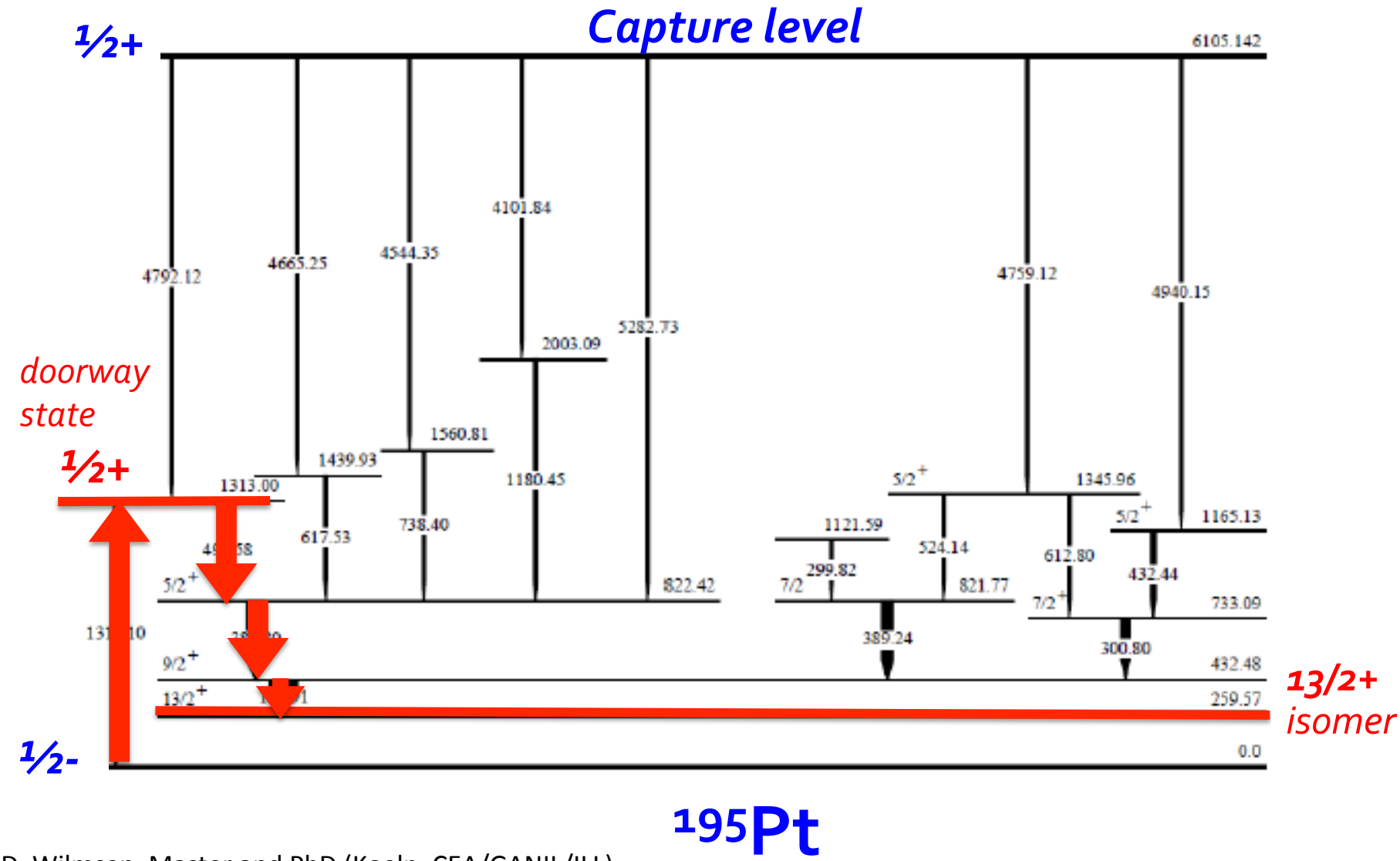
- **4 days half-life** (nuclear medicine in-vivo)
- **IMAGING with 99 keV γ-ray and X-rays** (similar to ^{99m}Tc and ^{201}Tl)
- **Conversion and Auger electron used in RADIO-CHEMOTHERAPY**
- **Chemical similarities with cytotoxic chemotherapeutic compounds**

→ ***Search for low-spin "doorway states" feeding the isomer***

See Plenary
U. Koester

$^{194}Pt(n,\gamma)^{195}Pt$

EXILL NEUTRONS FOR SCIENCE



D. Wilmsen, Master and PhD (Koeln, CEA/GANIL/ILL)

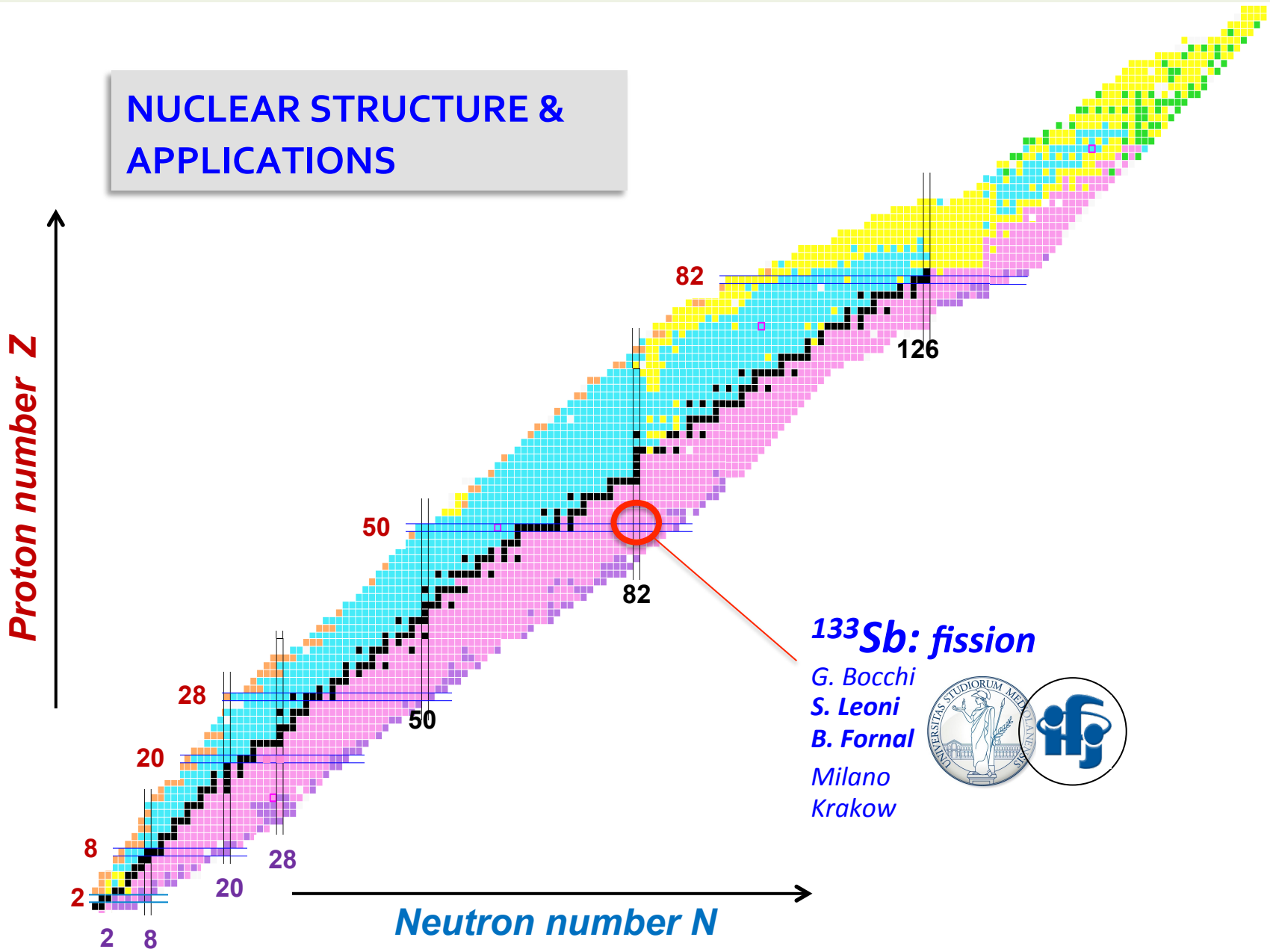
→ *photoproduction (ELI like GAMMA Beam Facility ?)*

See Plenary C. Ur

HIGHLIGHTS from EXILL

EXILL NEUTRONS FOR SCIENCE

NUCLEAR STRUCTURE & APPLICATIONS

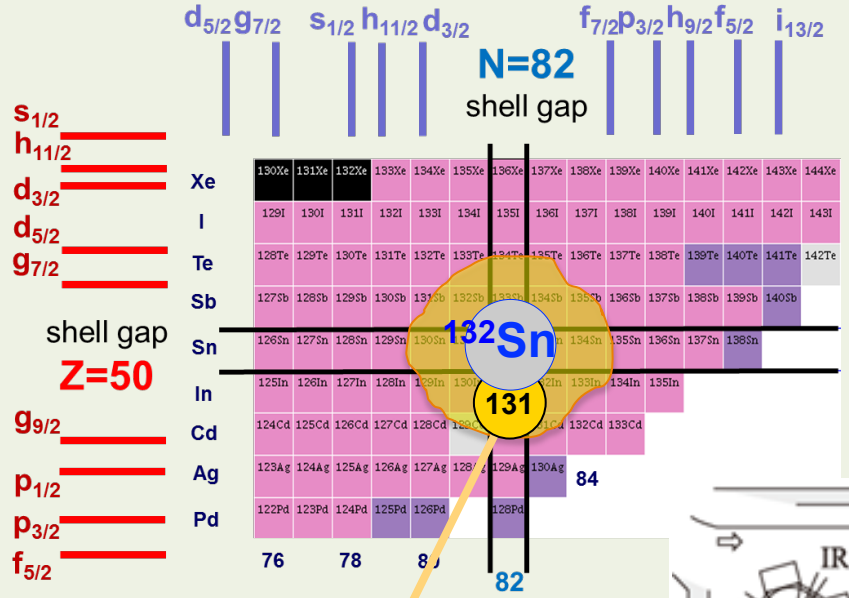


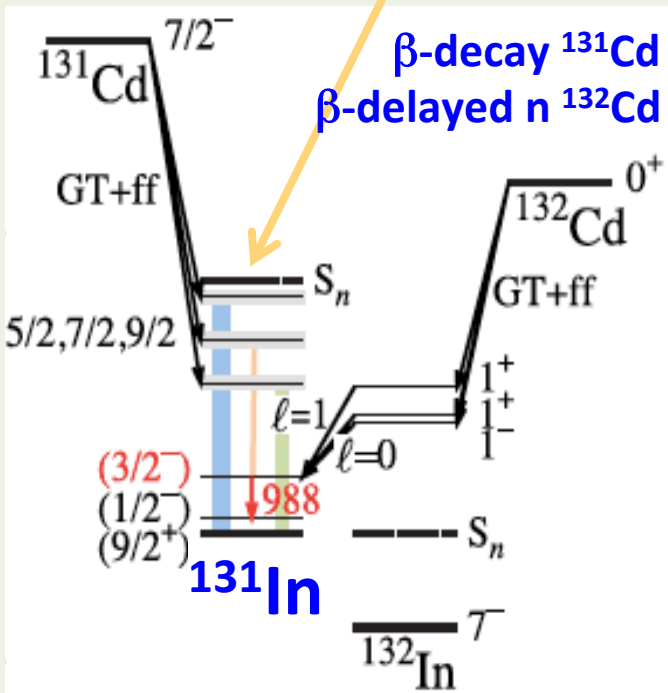
^{133}Sb: fission

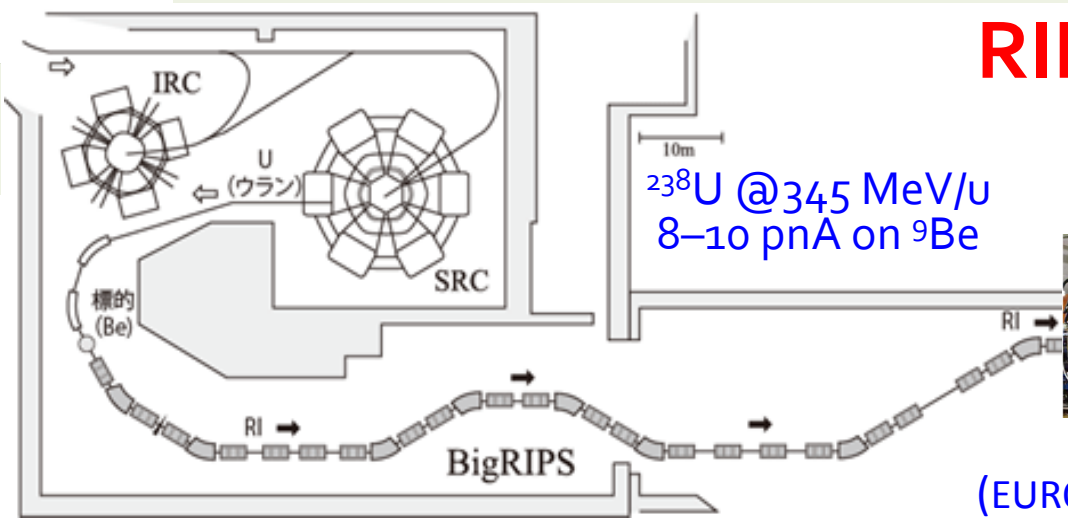
G. Bocchi
S. Leoni
B. Fornal
Milano
Krakow

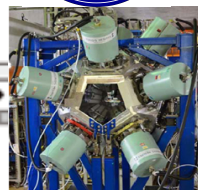
Limited YRAST Spectroscopy

✧ Difficult population (SOUTH)









EURICA'
(EUROBALL Ge)
and
Segmented
Si Strips

$\pi p_{3/2}$ single-hole state at 1353 keV

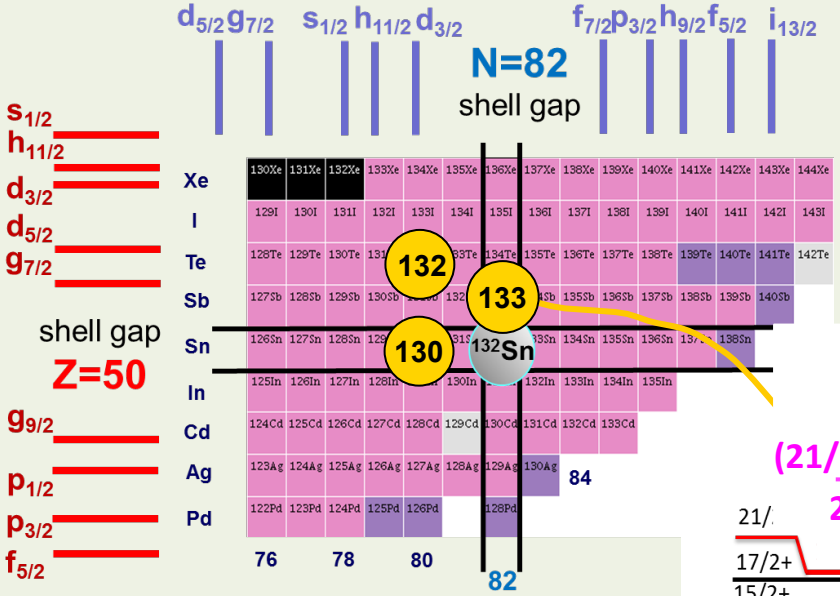
Absence of N=82 shell closure below ^{132}Sn
→ Consequences on r-process

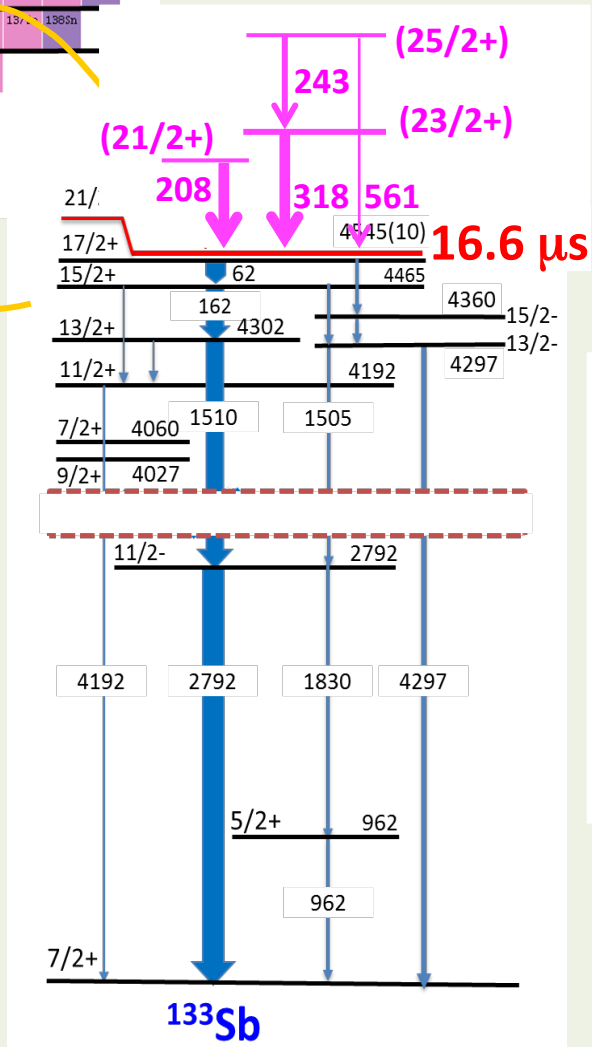
J. Taprogge, A. Jungclaus et al., Phys. Rev. Lett. 112, 132501 (2014)

Limited YRAST Spectroscopy

EXILL NEUTRONS FOR SCIENCE

✧ long-lived microsecond isomers





Prompt-Delayed Coincidences

over μs time range

PROBLEM:

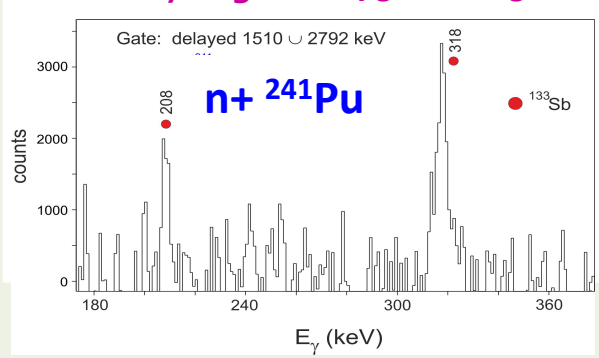
SHELL Model Calculations **are NOT possible:**

Too Large Space !!

Not Simple Configurations !

FEEDING of the ISOMER up to 25/2+

delayed gates: 2792 and 1510



W. Urban et al., PRC79(2009)037304

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

Extended Microscopic Particle-Vibration Coupling Model

NO FREE PARAMETERS

same SkX interaction in coupling matrix elements

^{132}Sn CORE Excitations < 5.5 MeV

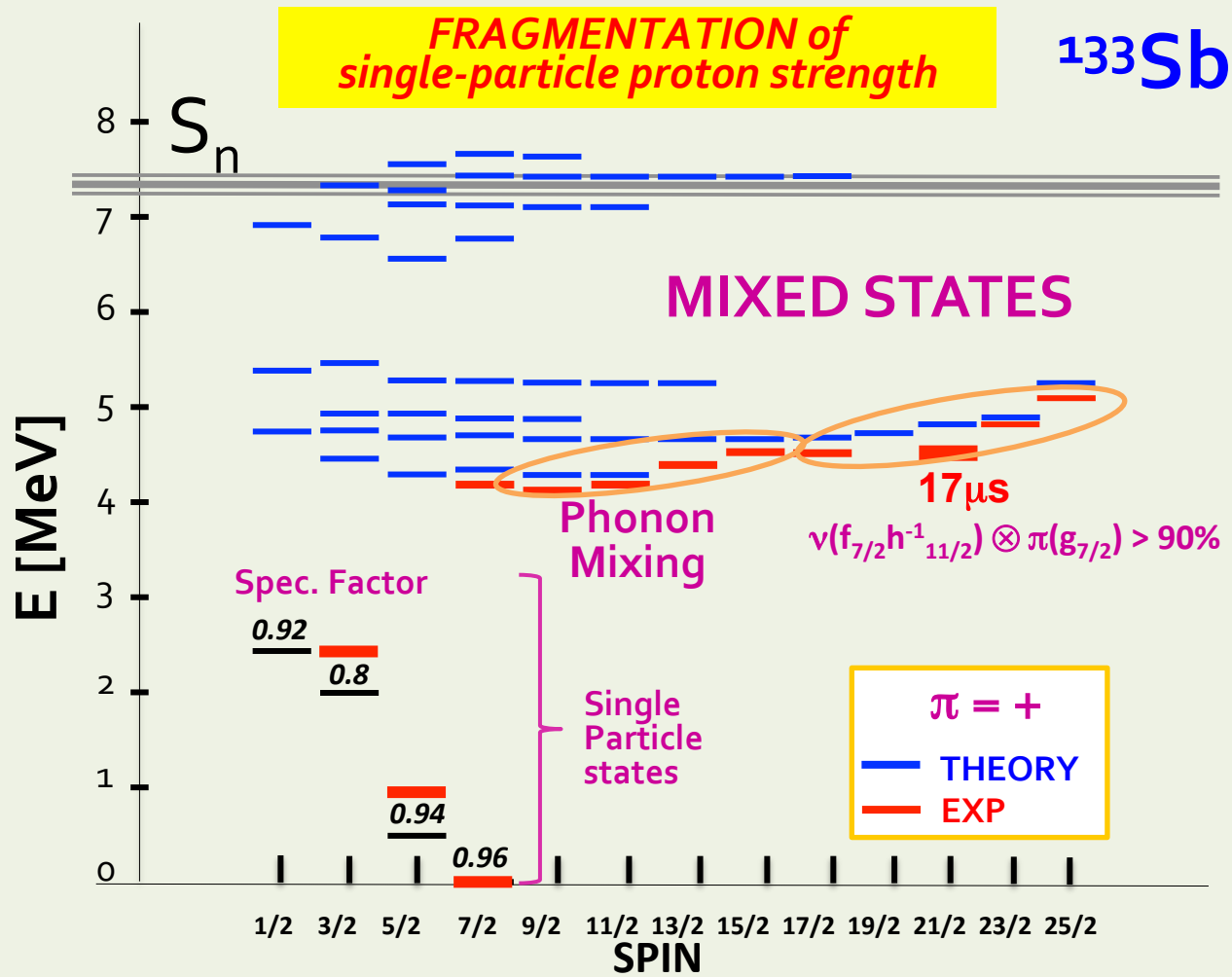
(phonons and non-collective):

RPA - Skyrme X

⊗

Proton Single particle states

Hartree-Fock Skyrme X



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

Extended Microscopic Particle-Vibration Coupling Model

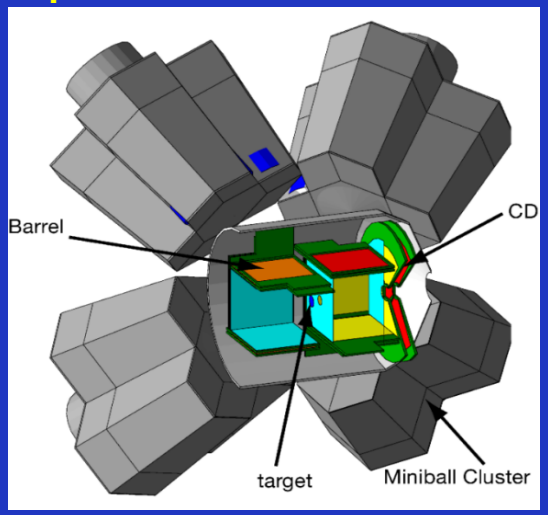
NO FREE PARAMETERS

same SkX interaction in coupling matrix elements

COMING SOON:
^{133}Sb Off Yrast States

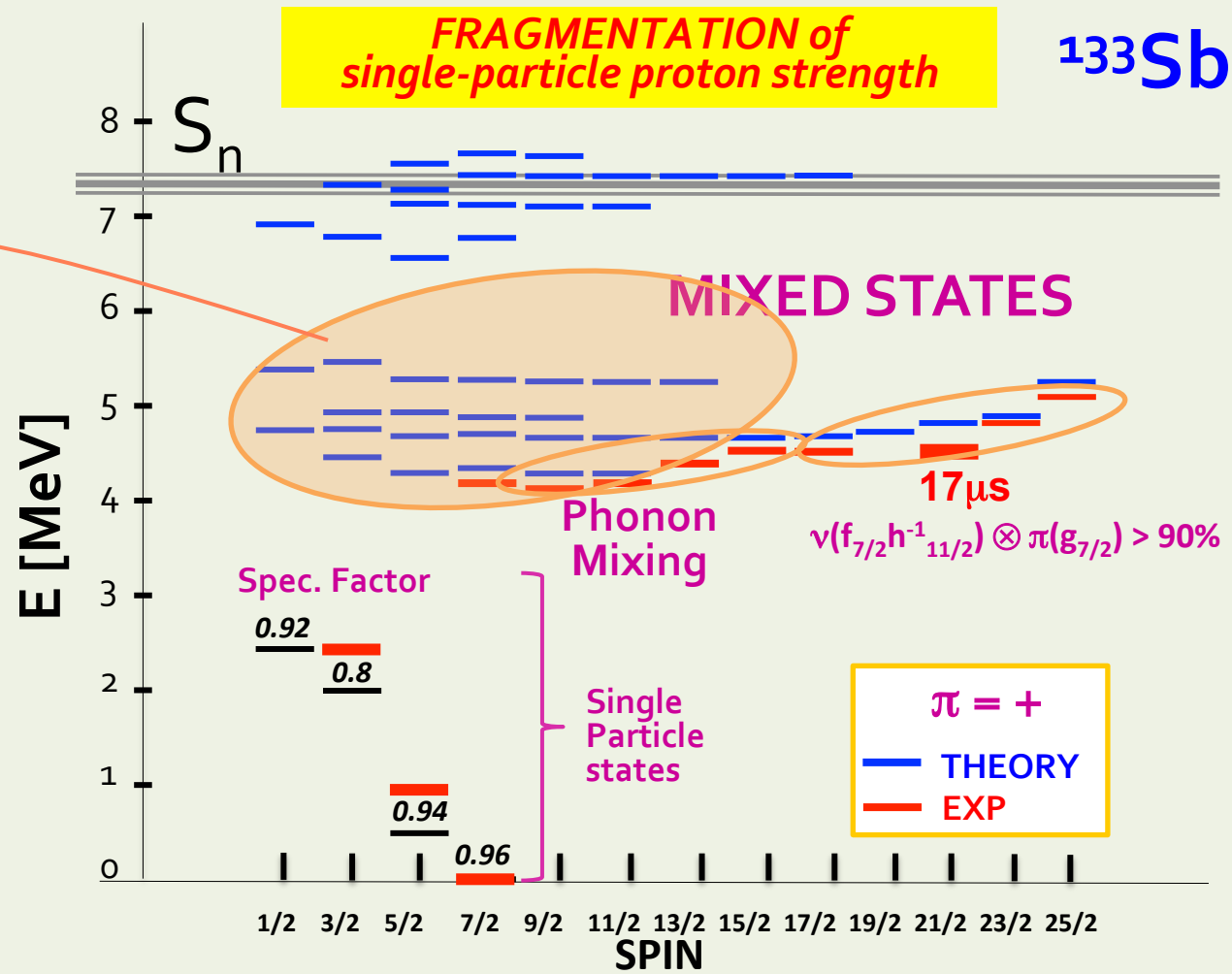
^{132}Sn + ^{7}Li → $^{135-x}$Sb + α+xn

4 MeV/A – HIE-ISOLDE



Tested reaction
(Cluster-Transfer)
@ REX-ISOLDE

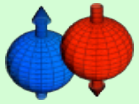
S.Bottoni *et al.*, PRC92(2015)024322

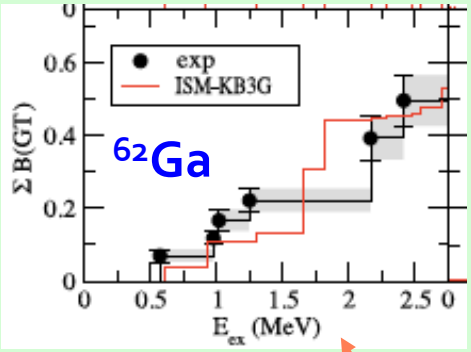


IT WAS A SMALL SELECTION ONLY …

PAIRING (GSI, RISING)

No T= 0 Pairing
from Gamow Teller Strength





E. Grodner et al., PRL113(2014) 092501

Coulomb Excitations (Warsaw,OSIRIS/ EAGLE)

Shapes and deformations in heavy Mo

K. Wrzosek-Lipska et al., PRC86,(2012)064305

Cluster Transfer Reactions (Bucharest,ROSPHERE)

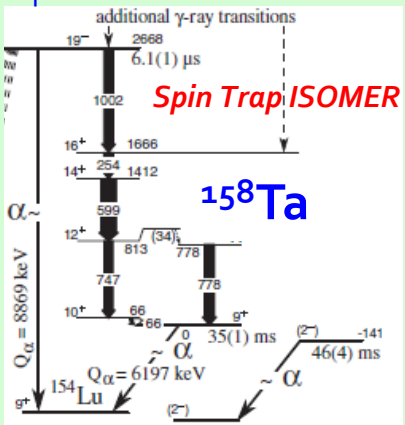
Particle-CORE coulpings in Cu chain and ^{209}Bi

C. Nita et al., PRC89(2014) 064314
G. Bocchi et al., PRC89(2014) 054302
O. Roberts et al., sub. to PRC

P DRIPLINE (Jyvaskyla, JUROGAM)

γ-decay from proton-unbound nucleus

p dripline is blurred

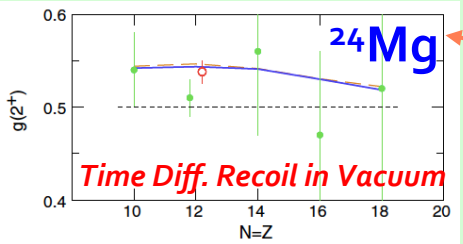


R.J. Carrol et al., PRL 112 2014) 092501

G-FACTOR (ALTO-Orsay, ORGAM)

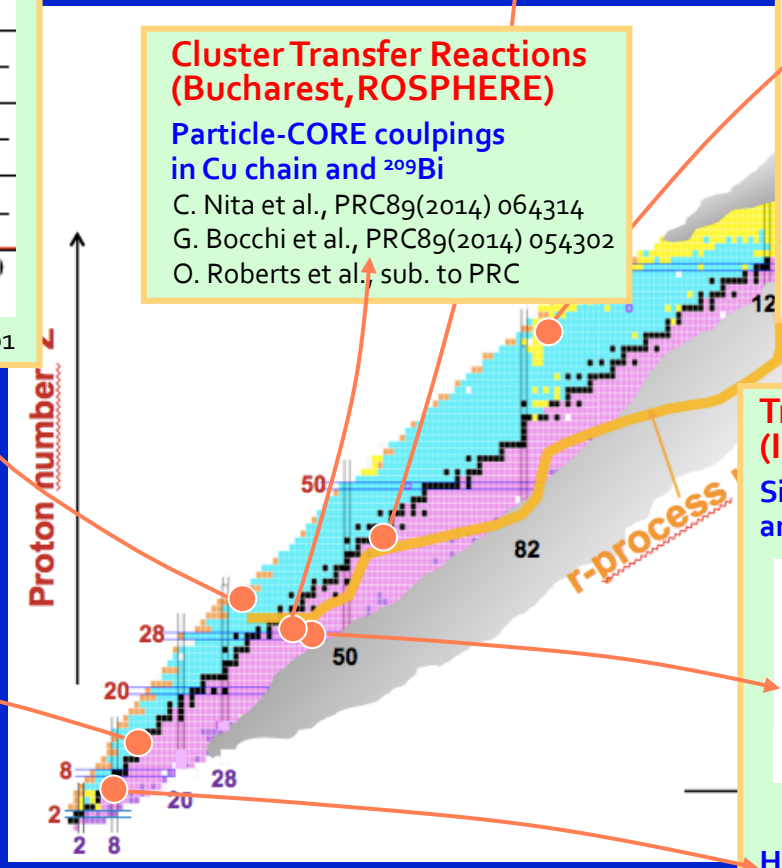
High Precision

First PRECISE TEST of THEORY
New technique for Exotic systems



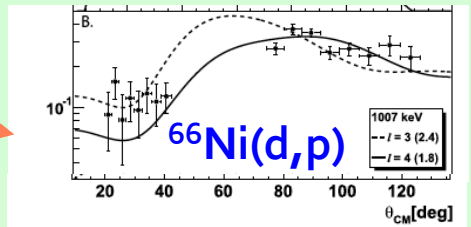
A. Kusoglu et al., PRL114(2015) 062501

See Talk G. Georgiev, THURSDAY



Transfer Reactions (ISOLDE, MINIBALL+TREX)

Single Particle Levels around ^{68}Ni, exotic Zn and Ar



J. Diriken et al., PLB736 (2014)533

HALOS and CLUSTERS in Light Nuclei
d(^{8}Li,p)^{9}Li*, d(^{11}Be,p)^{12}Be

J. C. Johansen et al., PRC88, 044619 (2013)

… a Many FACETS Panorama with a HUGE Discovery Potential …

… the effort of a large collaboration

Milano University and INFN

A. Bracco, G. Benzoni, N. Blasi, F. Camera, F. Crespi, S. Leoni, B. Million, O. Wieland, R. Avigo, S. Bottoni, G. Bocchi, S. Ceruti, A. Giaz, R. Nicolini, L. Pellegri, P.F. Bortignon, G.Colò, et al.

Legnaro INFN Laboratory

G. DeAngelis, D. Montanari, D. Napoli, J.J. Valiente-Dobon, L. Corradi, E. Fioretto, A. Stefanini et al.

Padova University and INFN

D. Bazzacco, E. Farnea, S. Lenzi, S.Lunardi, D. Mengoni, G. Montagnoli, F. Recchia, F. Scarlassara, C.Ur, et al.

IFJ-PAN, Krakow, Poland

A. Maj, B. Fornal, P. Bednarczyk,, M. Ciemala, N. Cieplicka, M. Kmiecik, M. Krzysiek, B. Szpak et al.,

KU Leuven

R. Raabe et al.,

IFIN-HH Bucharest

N. Marginean, D. Bucurescu, C. Mihai, C. Nita et al.

CSIC-University of Valencia

A. Gadea

EXILL

G. DeFrance, A. Blanc, U. Koster, M. Jentschel, **C. Michelagnoli**, P. Mutti, G. Simpson, J.M. Regis et al.

AGATA

Thank You for the Attention