

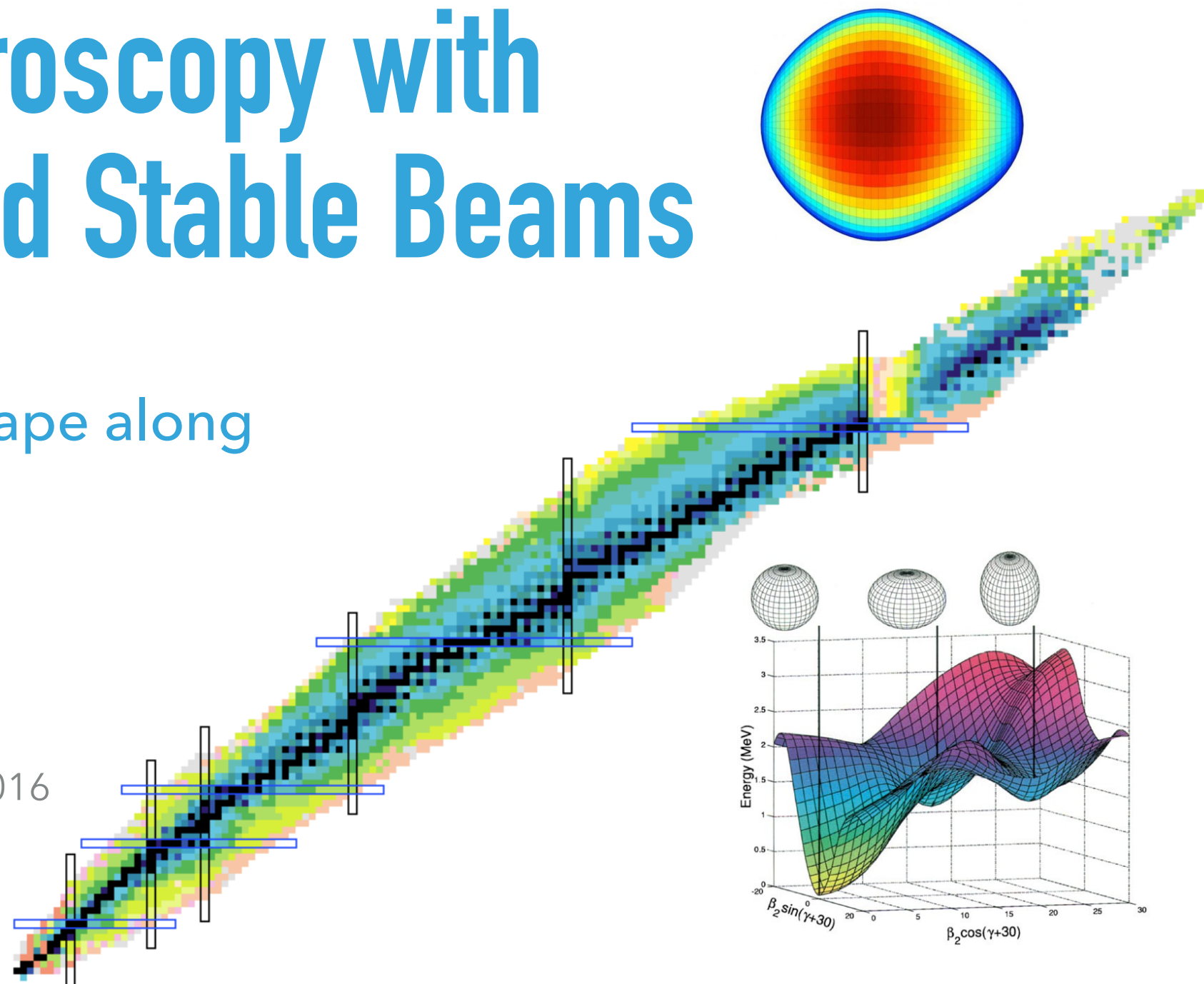
Marco Rocchini

Università degli Studi di Firenze and INFN Sezione di Firenze

Nuclear Spectroscopy with Radioactive and Stable Beams

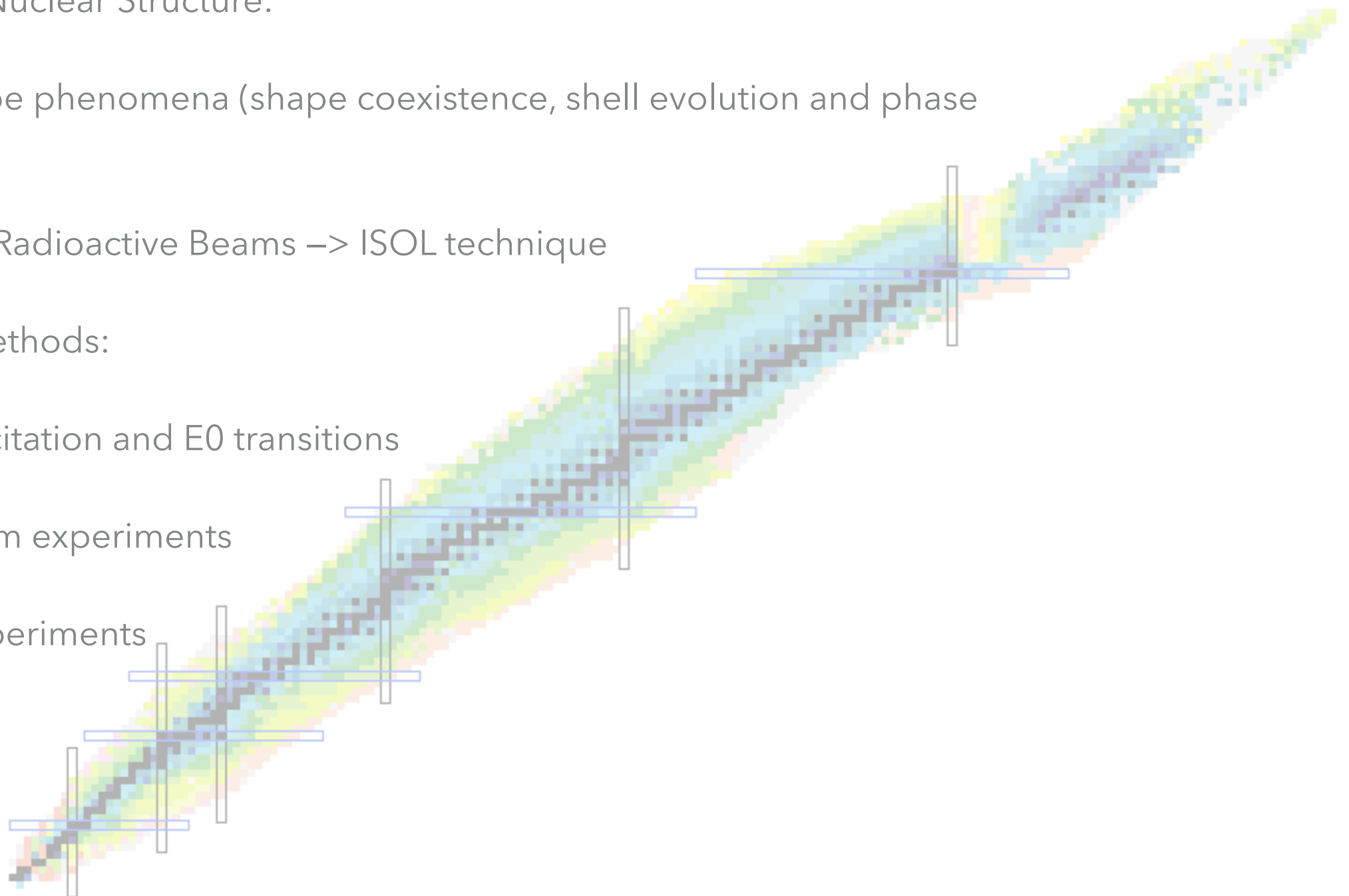
Exploring the Nuclear Shape along
the Nuclide Chart

Consiglio di Sezione, Firenze 06/09/2016



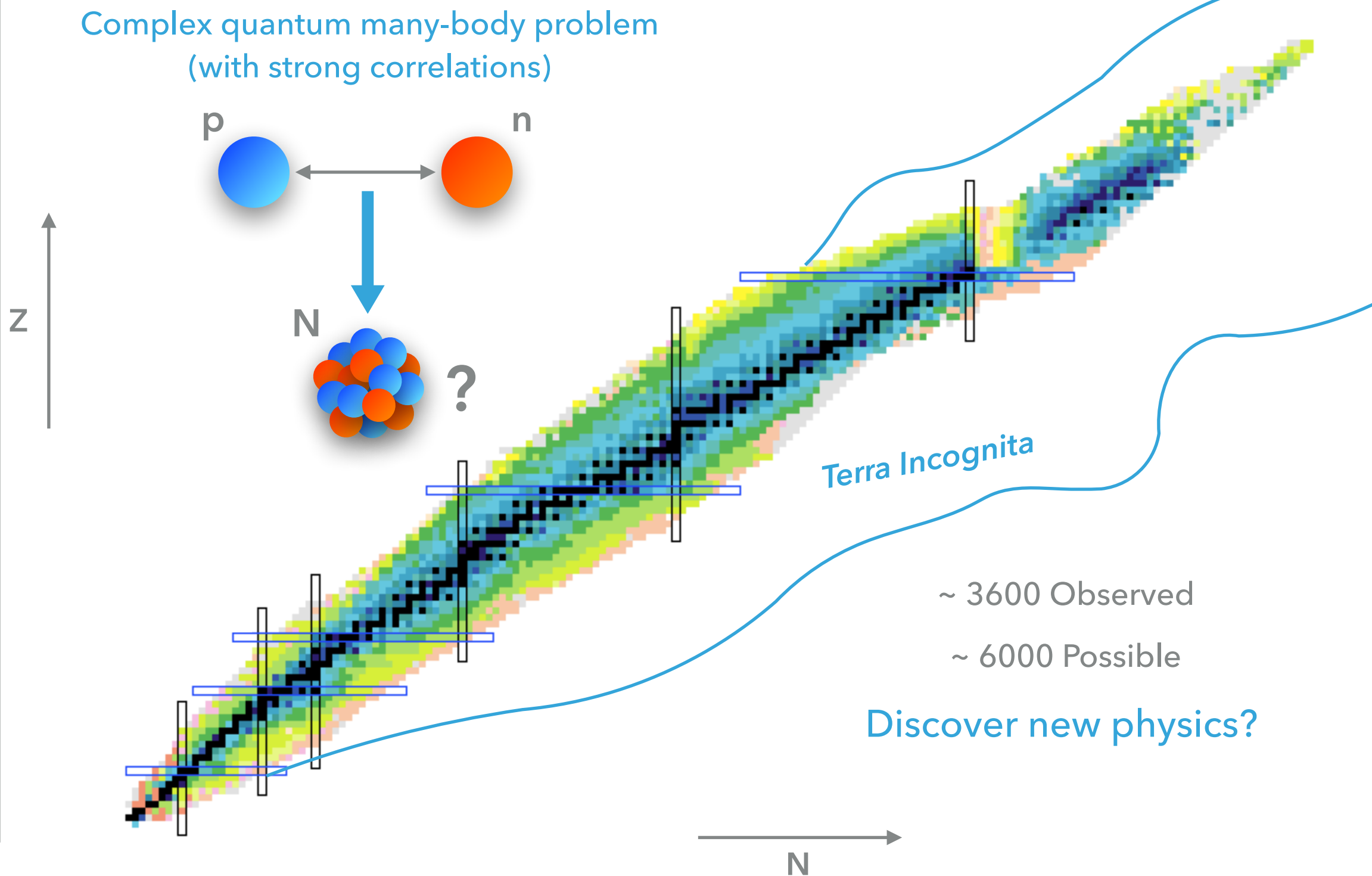
Outline

- ▶ Perspectives in Nuclear Structure:
 - ▶ Nuclear Shape phenomena (shape coexistence, shell evolution and phase transitions)
- ▶ Introduction on Radioactive Beams → ISOL technique
- ▶ Experimental methods:
 - ▶ Coulomb excitation and E0 transitions
- ▶ Radioactive beam experiments
- ▶ Stable beam experiments



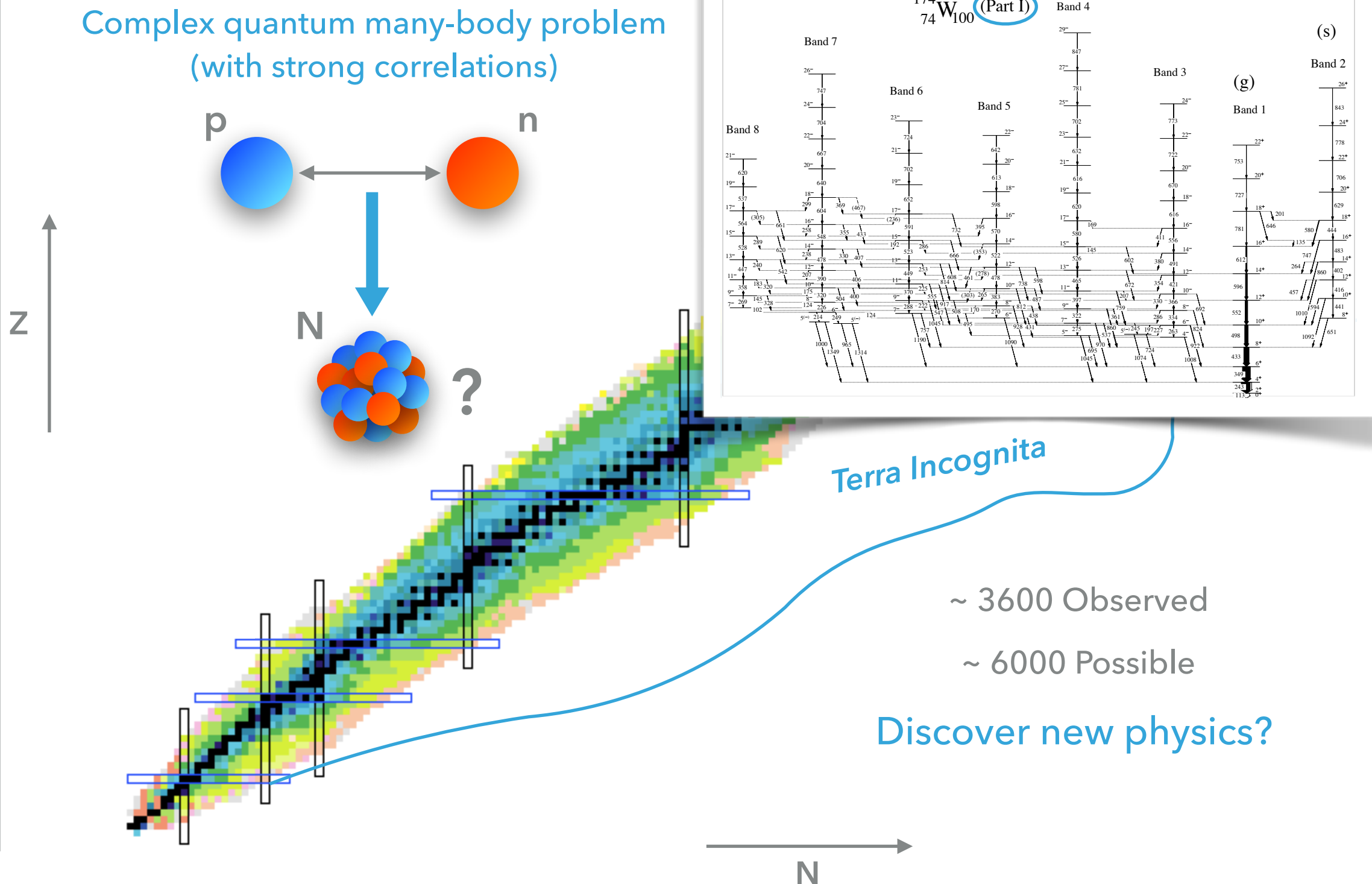
Perspectives in Nuclear Structure

- ▶ Perspective in Nuclear Structure
- ▶ Radioactive Beams
- ▶ Experimental Methods
- ▶ ISOL Facilities
- ▶ Radioactive Beams Experiments
- ▶ Stable Beams Experiments



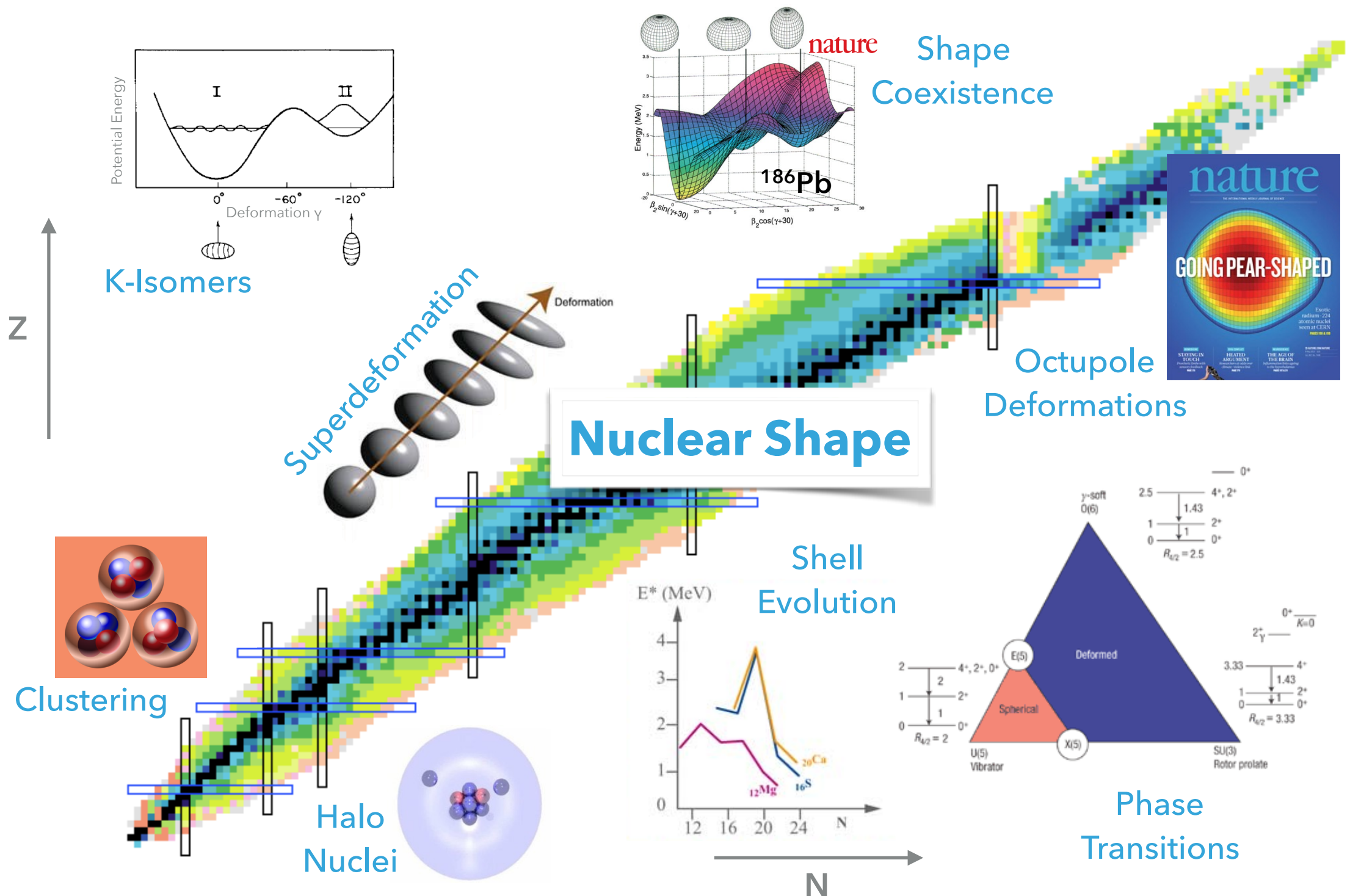
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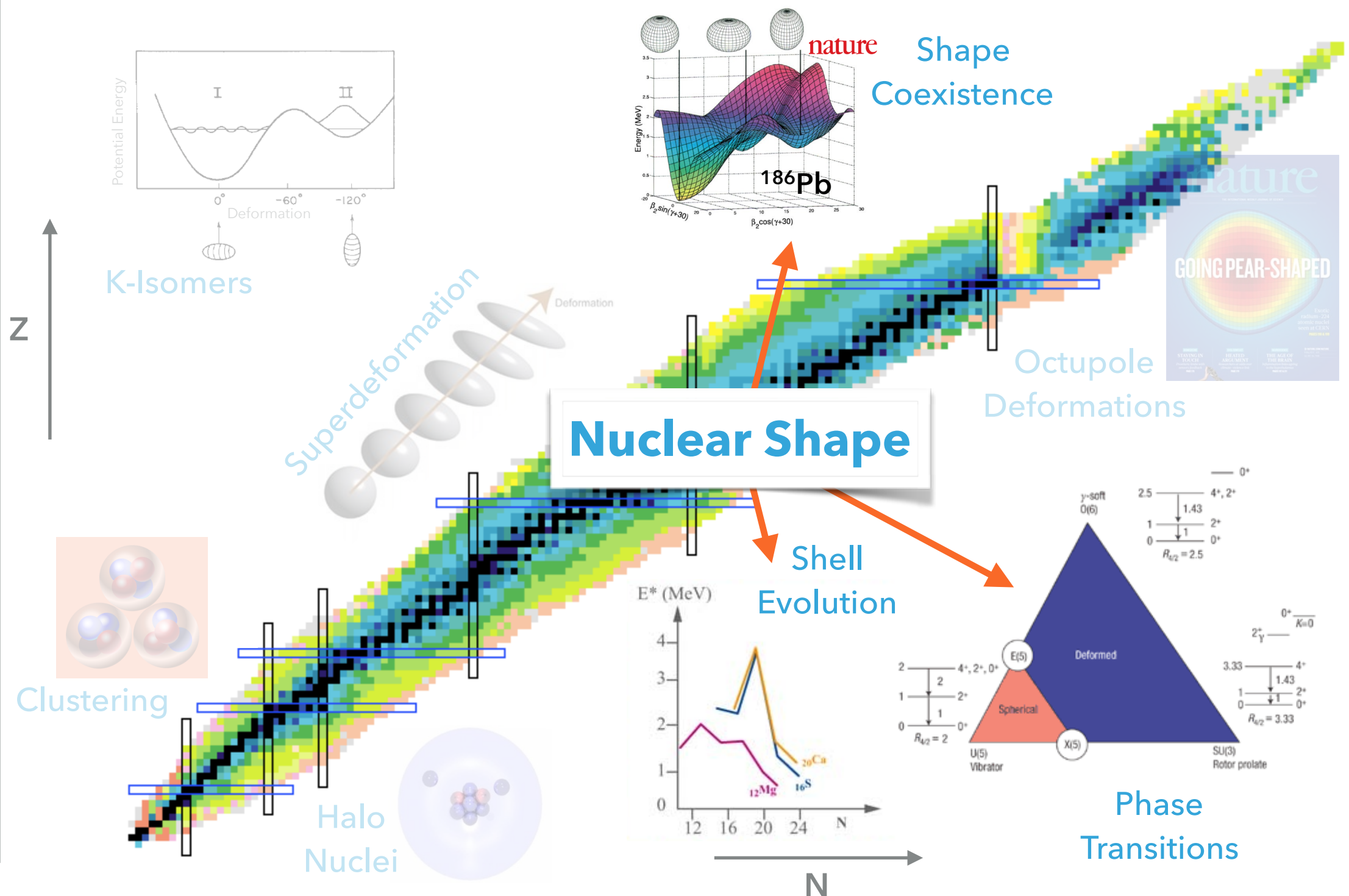


Perspectives in Nuclear Structure

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- ▶ **Perspective in Nuclear Structure**
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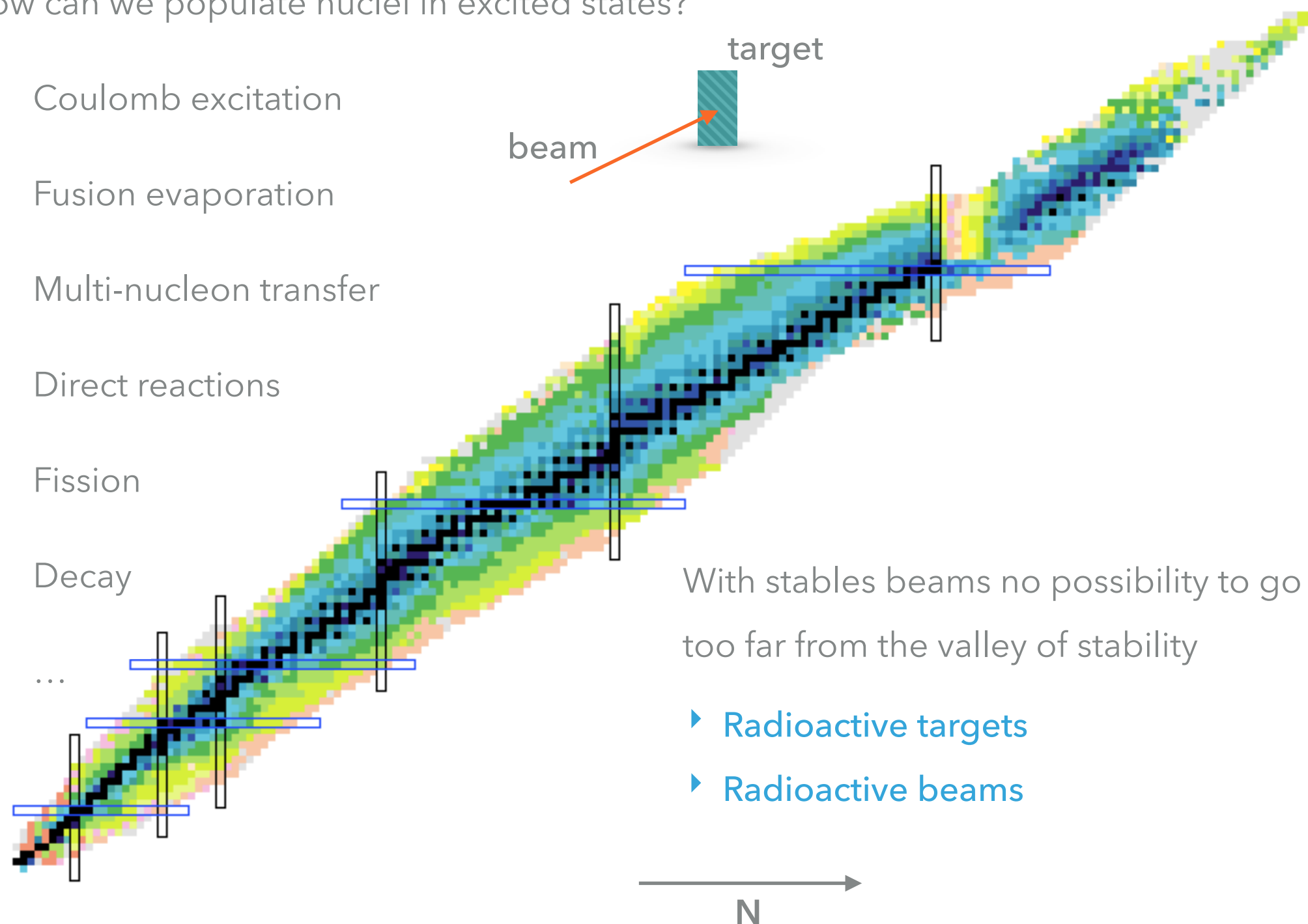


Why Radioactive Beams?

- ▶ Perspective in Nuclear Structure
- ▶ **Radioactive Beams**
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- ▶ How can we populate nuclei in excited states?

- ▶ Coulomb excitation
- ▶ Fusion evaporation
- ▶ Multi-nucleon transfer
- ▶ Direct reactions
- ▶ Fission
- ▶ Decay
- ▶ ...

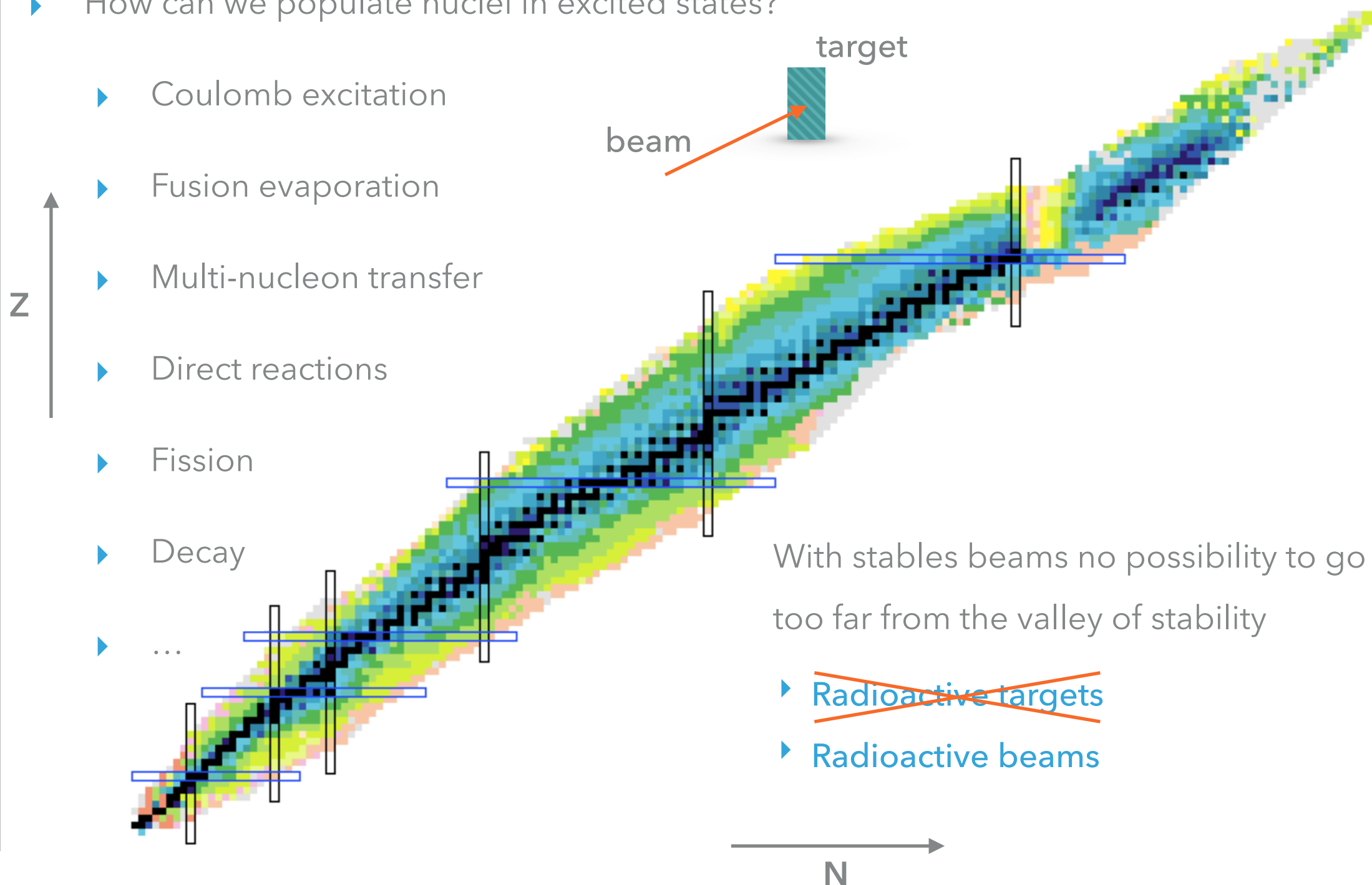


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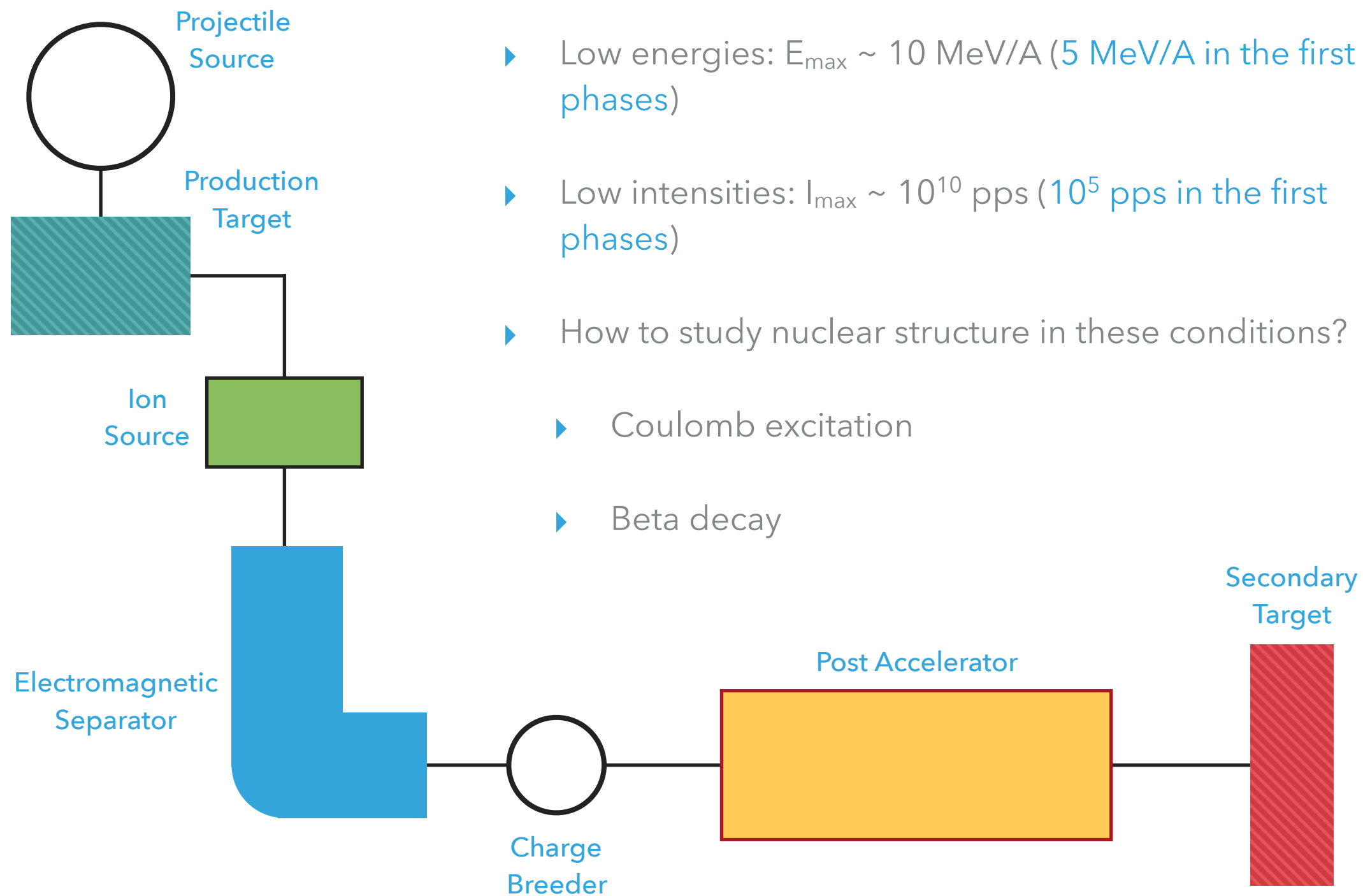


Radioactive Beams around the World

- ▶ Perspective in Nuclear Structure
- ▶ **Radioactive Beams**
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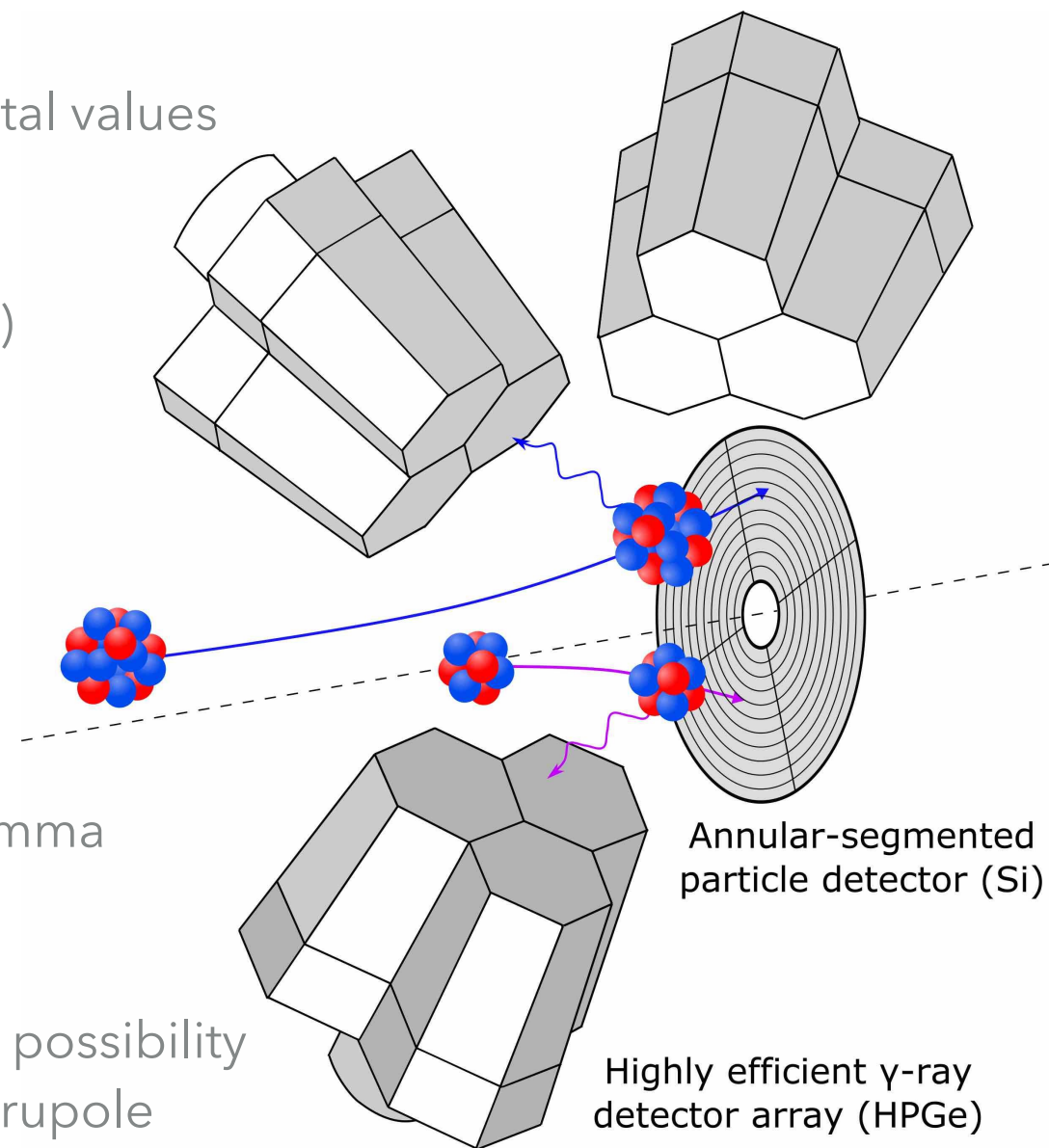
ISOL Radioactive Beams and Limitations



Coulomb Excitation

- ▶ Perspective in Nuclear Structure
- ▶ Radioactive Beams
- ▶ **Experimental Methods**
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- ▶ Collision below the "Safe energy" ($\sim 5 \text{ MeV/A}$)
- ▶ Electromagnetic interaction $\rightarrow$ experimental values in a model-independent way
- ▶ **High cross sections** ($\sim$ barns for the first 2^+)
- ▶ Cross section measurement
$$d\sigma_{\text{coulex}} \sim d\sigma_{\text{Ruth}} \cdot P(i \rightarrow f)$$
- ▶ Necessity to reconstruct the kinematic: gamma detector and heavy ions detector
- ▶ Direct access to all the matrix elements $\rightarrow$ possibility to obtain transition probabilities and quadrupole moments (**deformation**)



E0 Transitions

- ▶ Perspective in Nuclear Structure
- ▶ Radioactive Beams
- ▶ **Experimental Methods**
- ▶ ISOL Facilities
- ▶ Radioactive Beams Experiments
- ▶ Stable Beams Experiments

- ▶ Only electron conversion and pair production, **sensitive to nuclear shape**

E0 operator

$$T(E0) = \sum_k e_k r_k^2$$

E0 transition strength

$$\rho^2(E0) = \left| \frac{\langle f | T(E0) | i \rangle}{eR^2} \right|^2$$

Nuclear observable

$$\rho^2(E0) = C \frac{I_K(E0; J_i \rightarrow J_f)}{I_K(E2; J_i \rightarrow J_j)} \cdot (\tau_i)^{-1}$$

C = tabulated and calculated values

- ▶ Sensitive to level mixing:

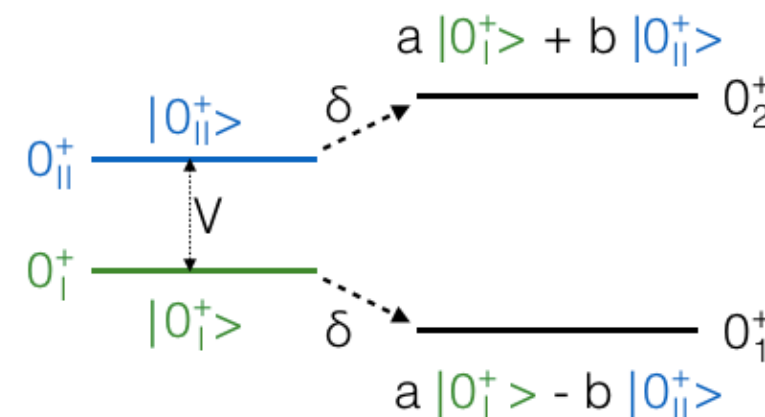
$$\rho^2(E0) = \frac{Z^2}{R^4} a^2 b^2 (\Delta \langle r^2 \rangle)^2$$

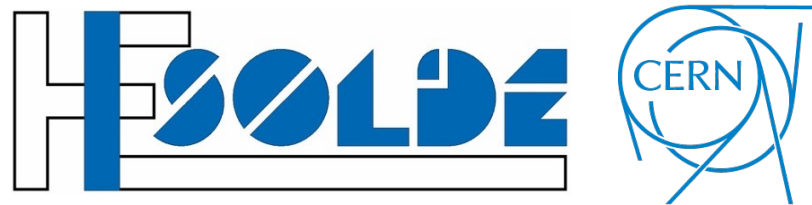
Wave function mixing

Difference in mean square radii

- ▶ Complementary with Coulomb excitation:

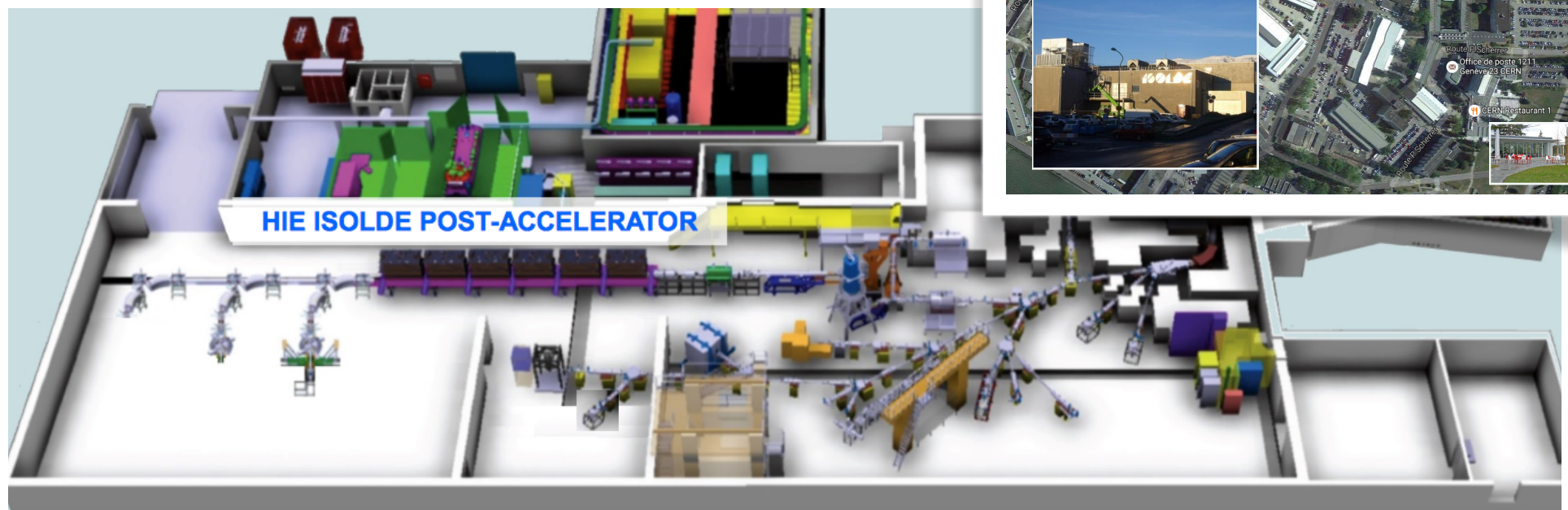
- ▶ E0 measurements: needs information about lifetime and shape from Coulex
- ▶ Coulex: needs information about E0 contribution to be included in the analysis from electron conversion measurements
- ▶ Usually off-line measurements via beta decay → **radioactive beams**





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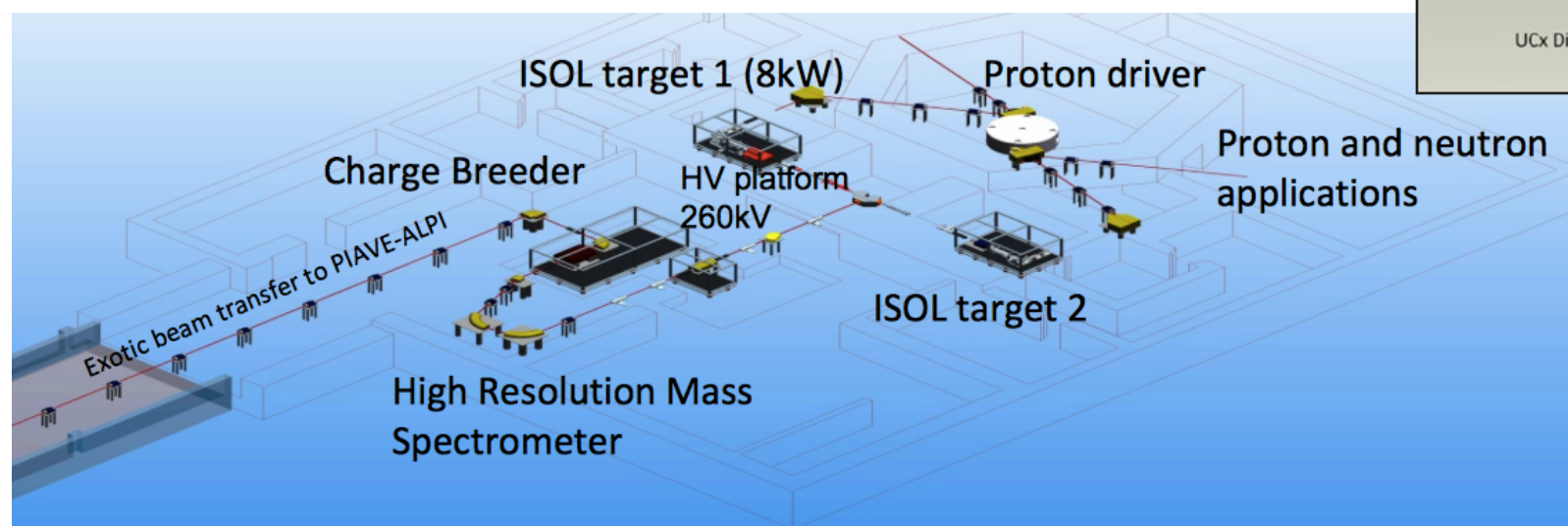
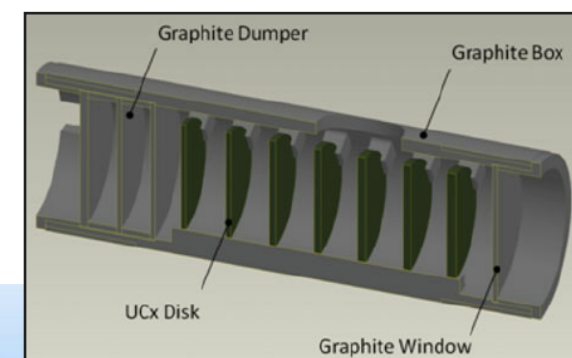
- ▶ 1967: ISOLDE (no post-acc.) → 2001: REX-ISOLDE ($E_{\max} = 3 \text{ MeV/A}$) → 2015: HIE-ISOLDE ($E_{\max} = 10 \text{ MeV/A}$, at the moment 5 MeV/A)
- ▶ Primary reaction: proton beam from PBS (1.4 GeV, 2 uA) on a thick target
- ▶ Surface, plasma and laser ion sources (60 different elements)
- ▶ Mass separators: GPS, HRS, off-line separator
- ▶ Post acceleration: SC linear accelerator





- ▶ Perspective in Nuclear Structure
- ▶ Radioactive Beams
- ▶ Experimental Methods
- ▶ **ISOL Facilities**
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- ▶ Completely founded (dedicated cyclotron)
- ▶ Innovative UCx target
- ▶ Advanced instrumentation
- ▶ High performing mass spectrometer
- ▶ Post-acceleration: PIAVE-ALPI
- ▶ First 10 MeV/A beams: before HIE-ISOLDE?

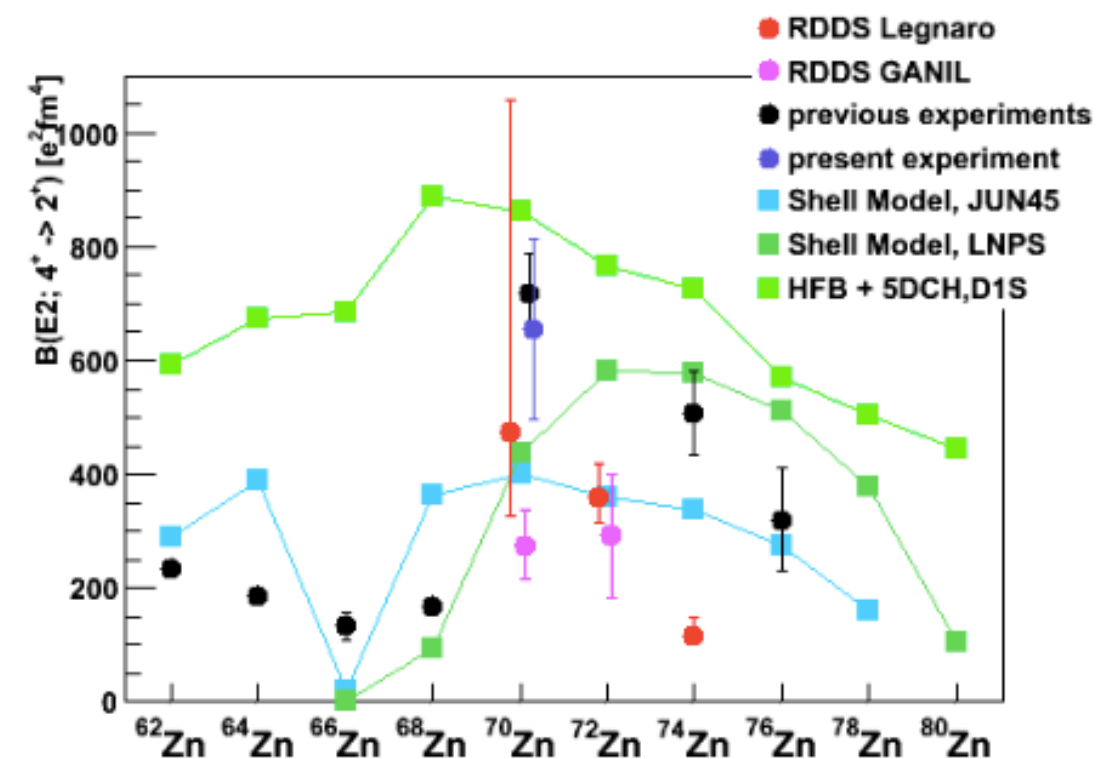
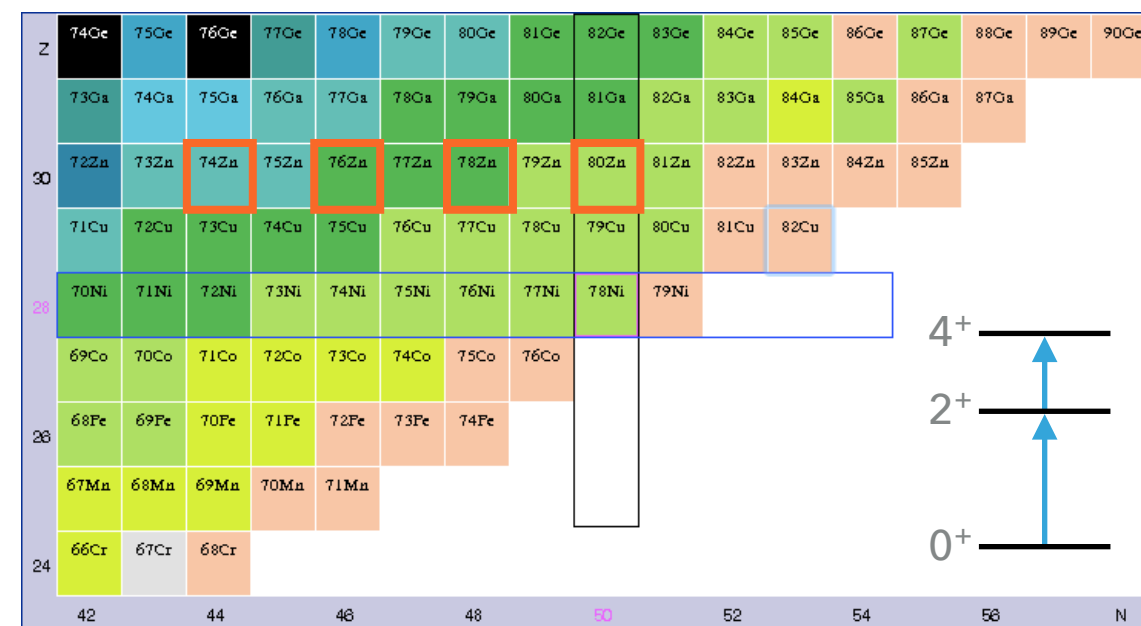


Coulomb Excitation of ^{74}Zn – ^{80}Zn ($N=50$): probing the validity of Shell-Model descriptions around ^{78}Ni (SP: E. Rapisarda, P. Van Duppen, M. Zielinska)

- ▶ Perspective in Nuclear Structure
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- ▶ Evolution of the shell gap for $N = 50$
- ▶ Contribution of three body forces
- ▶ Different effective interactions
- ▶ $B(E2; 4^+ \rightarrow 2^+)$: different values using different techniques
- ▶ $B(E2; 4^+ \rightarrow 2^+) / B(E2; 2^+ \rightarrow 0^+)$: key parameter to understand nuclei
- ▶ Same experiment already performed with REX-ISOLDE (no possibility to have multi-step, only $B(E2; 2^+ \rightarrow 0^+)$ values)

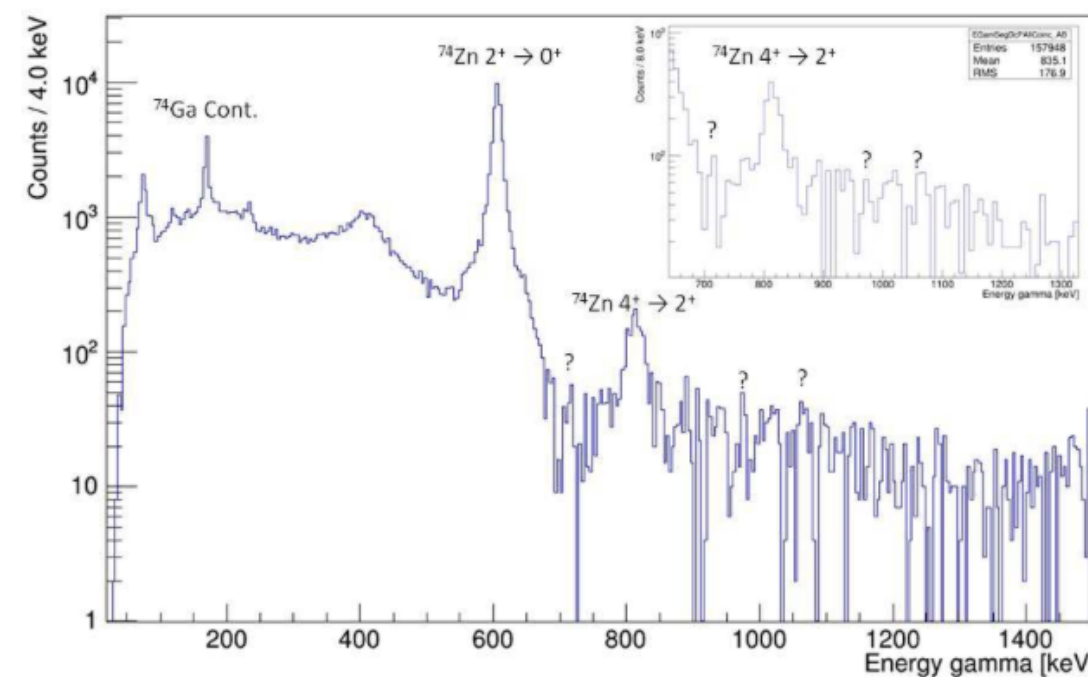
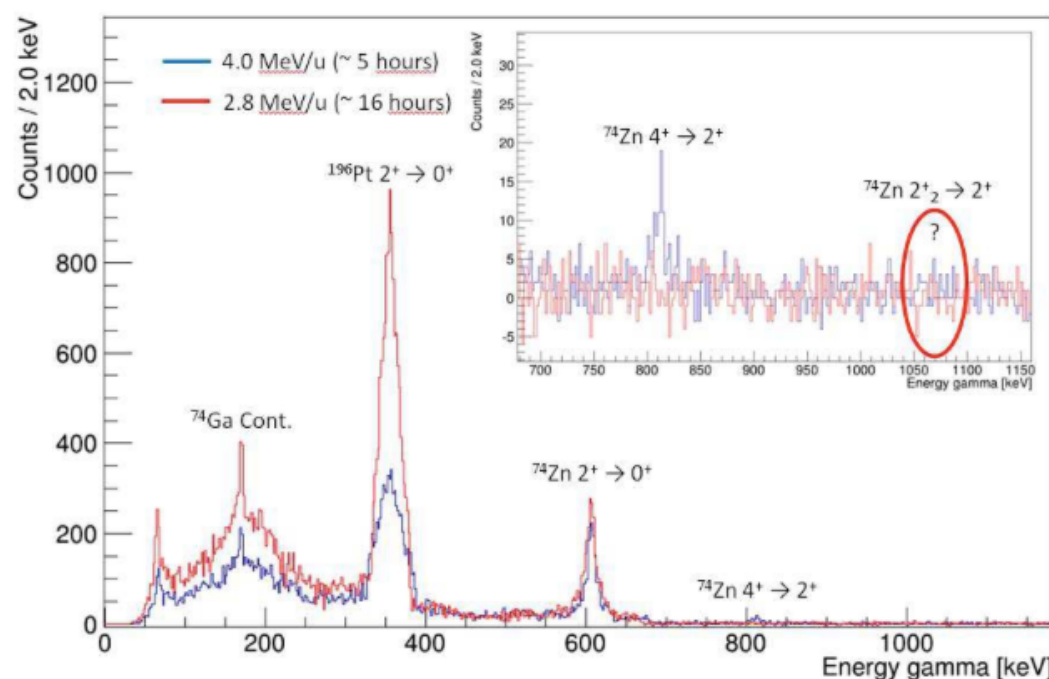
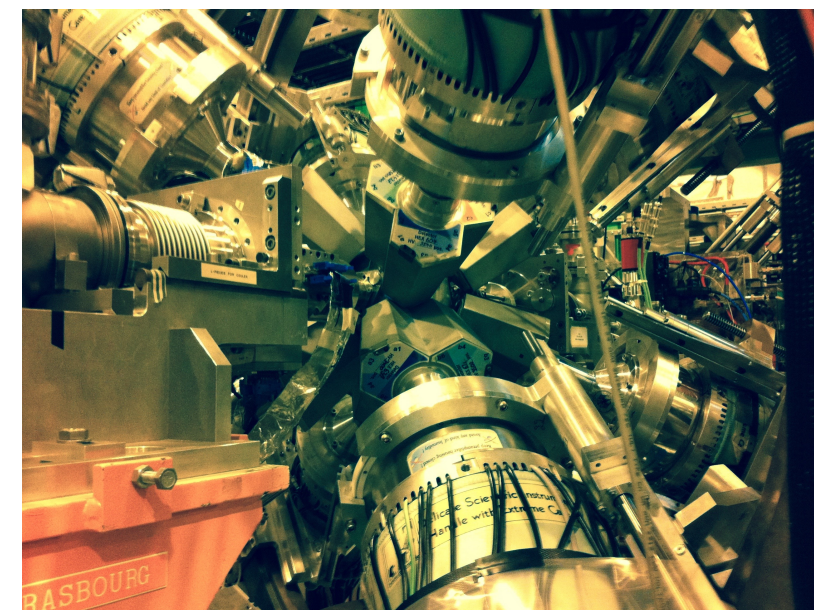
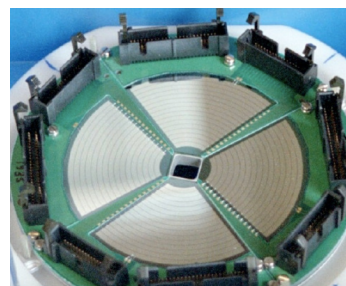
↓
Perfect as a first experiment



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- ▶ $^{74,76}\text{Zn}$: performed in October 2015
- ▶ Energy = 4 MeV/A, Intensity = $10^4 - 10^5$ pps
- ▶ ^{196}Pt target (5 mg/cm²)
- ▶ $B(E2; 4^+ \rightarrow 2^+)$ achievable
- ▶ $^{78,80}\text{Zn}$: October 2016



Analysis by A. Illana

Future Experiments At Isolde

- ▶ Perspective in Nuclear Structure
- ▶ Radioactive Beams
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▶ Probing Shape Coexistence in neutron-deficient ^{72}Se via Low-Energy Coulomb Excitation (SP: D. T. Doherty)

- ▶ Complicate shape coexistence $\rightarrow$ strong mixing
- ▶ Theory: discrepancies using different approaches, for some of them oblate ground state (unusual)



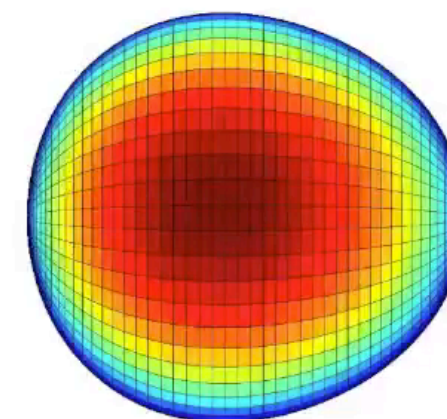
Prolate

Spherical



▶ Two-phonon octupole collectivity in the doubly-magic nucleus ^{146}Gd (SP: G. De Angelis)

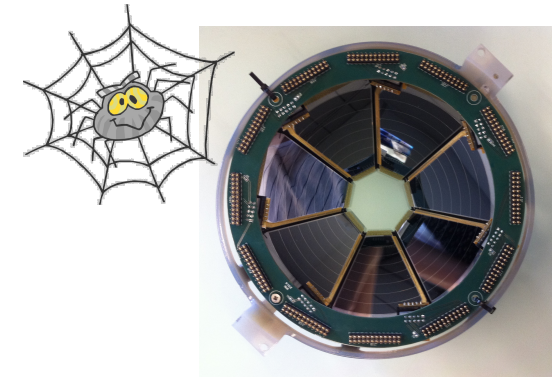
- ▶ First excited state: 3^- (only in ^{208}Pb)
- ▶ Multi-phonon excitation states very rare
- ▶ Large discrepancies with models



LoI SPES

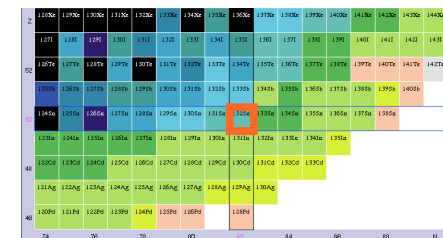
► Set-up for Coulomb excitation measurements of radioactive ions (SP: A. Nannini)

- Experimental set-up for Coulomb excitation at SPES using SPIDER + AGATA (or GALILEO)
- Several Coulomb excitation LoI for SPES



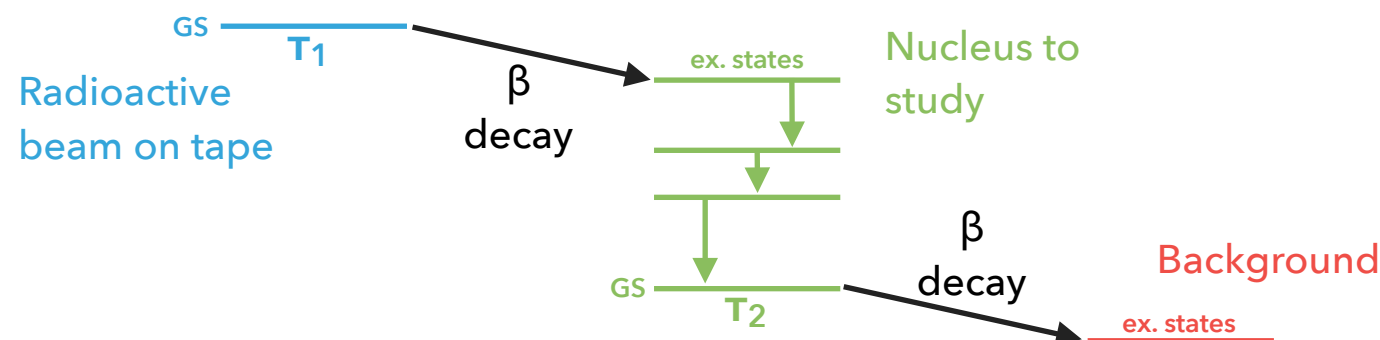
► Coulomb excitation measurements in nuclei around ^{132}Sn (SP: B. Melon)

- Shell evolution around doubly magic ^{132}Sn
- Nuclei to study: $^{134,135}\text{Sb}$, $^{126,127,128}\text{Cd}$



► Electron conversion measurements at SPES 1+ beam line (SP: A. Nannini)

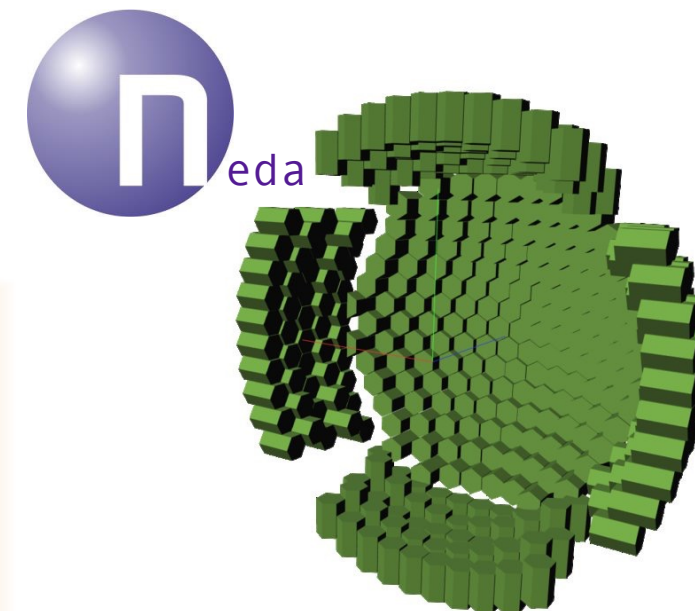
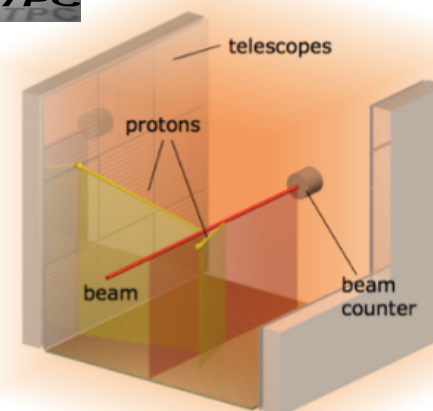
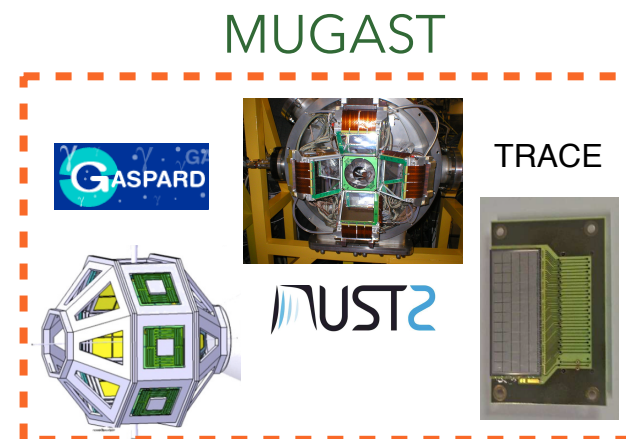
- Shape coexistence in ^{96}Sr → mini-orange, scintillator and HPGe



Nuclear Structure with Stable Beams

- ▶ Perspective in Nuclear Structure
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- ▶ Radioactive Beams Experiments
- ▶ **Stable Beams Experiments**

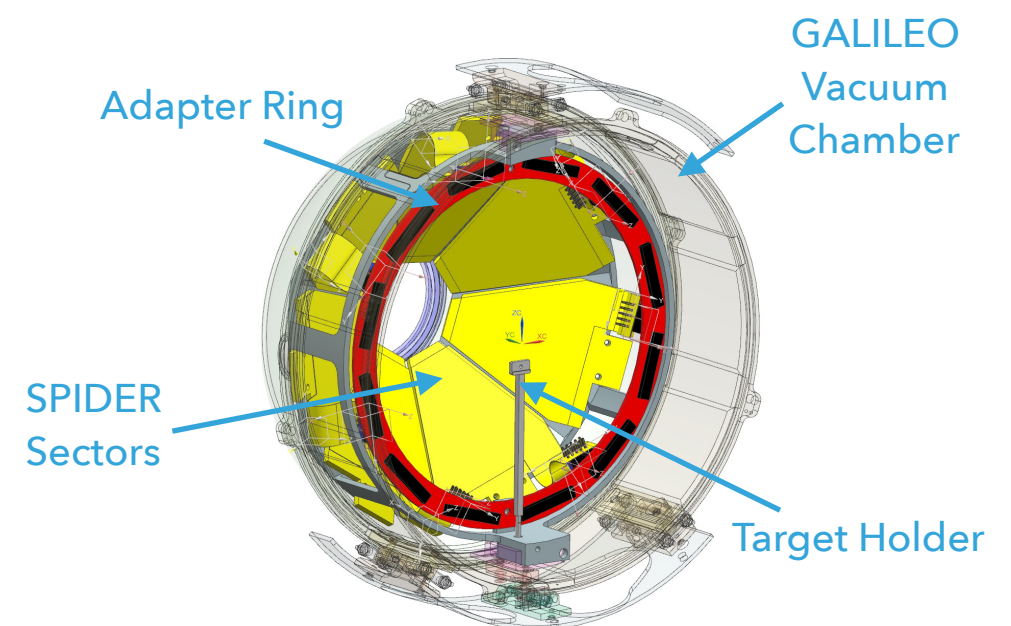
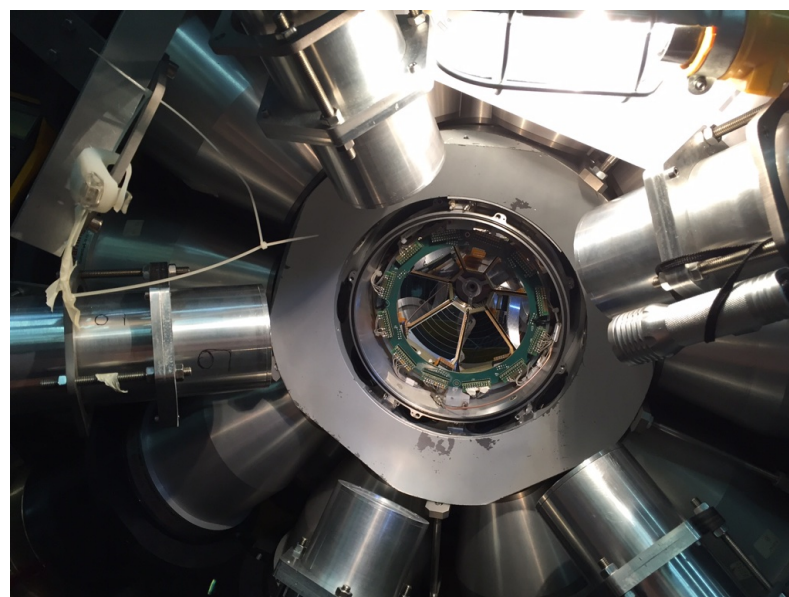
- ▶ Developments in the stable beam accelerators → ex.: PIAVE - ALPI @LNL
- ▶ Instrumentation developments:



Commissioning of a new charge particle detector SPIDER for the Coulomb Excitation studies with GALILEO (SP: M. Rocchini, K. Hadynska-Klek)

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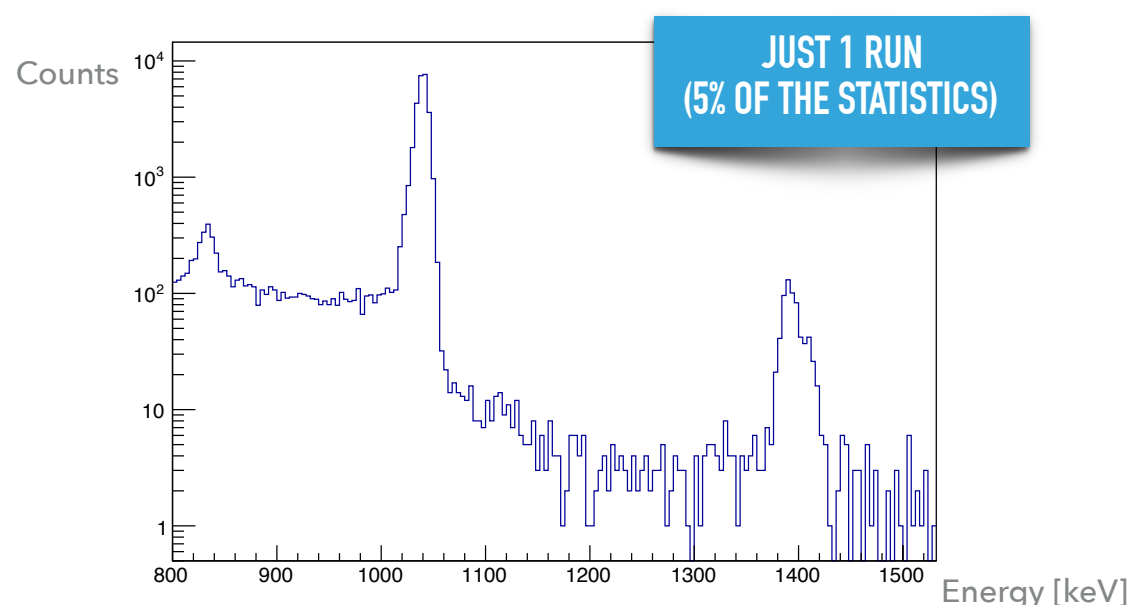
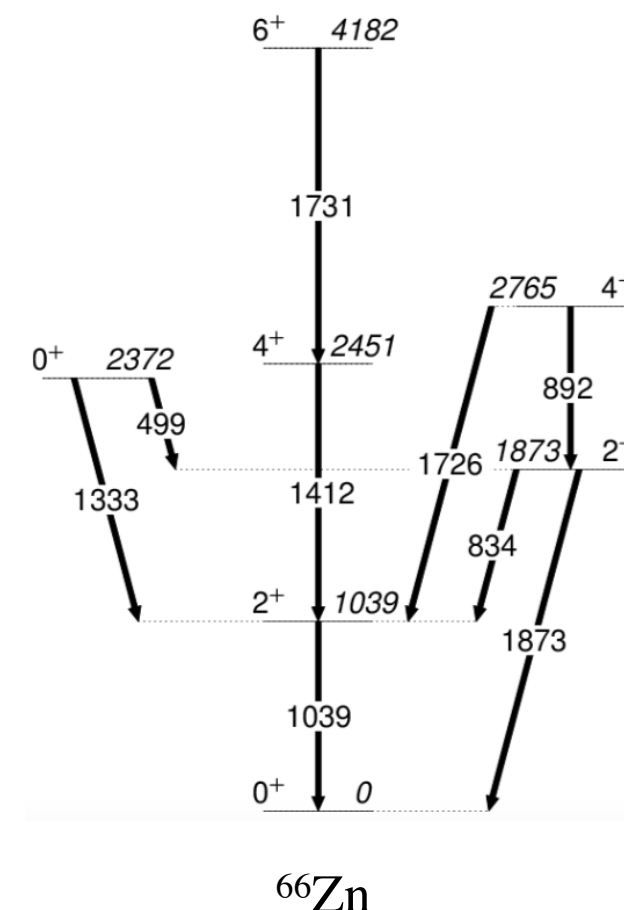
- ▶ Developing Coulomb excitation technique at LNL: new possibilities with GALILEO and stable beams, priority for SPES
- ▶ Cone configuration to fit the GALILEO vacuum chamber
- ▶ Same acquisition system of EUCLIDES: 56 electronic channels can be used as trigger signals -> 56 needed for SPIDER (8 strips for 7 sectors)
- ▶ New mechanical frame and electronic adapter to connect SPIDER



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- ▶ First commissioning with GALILEO: ^{66}Zn @ 240 MeV on 1 mg/cm^2 ^{208}Pb target, 4 days obtained from the LNL PAC (4 days of measurements performed)
- ▶ Commissioning experiment, but with some physics behind:
 - ▶ B(E2) and Q known with high precision
 - ▶ 0_2 oblate? $\rightarrow$ no B(E2) value known
 - ▶ 2_2 high-collective or not? $\rightarrow$ different values for the lifetime
 - ▶ 4_1 ground state band collective or not? $\rightarrow$ different values for the B(E2)

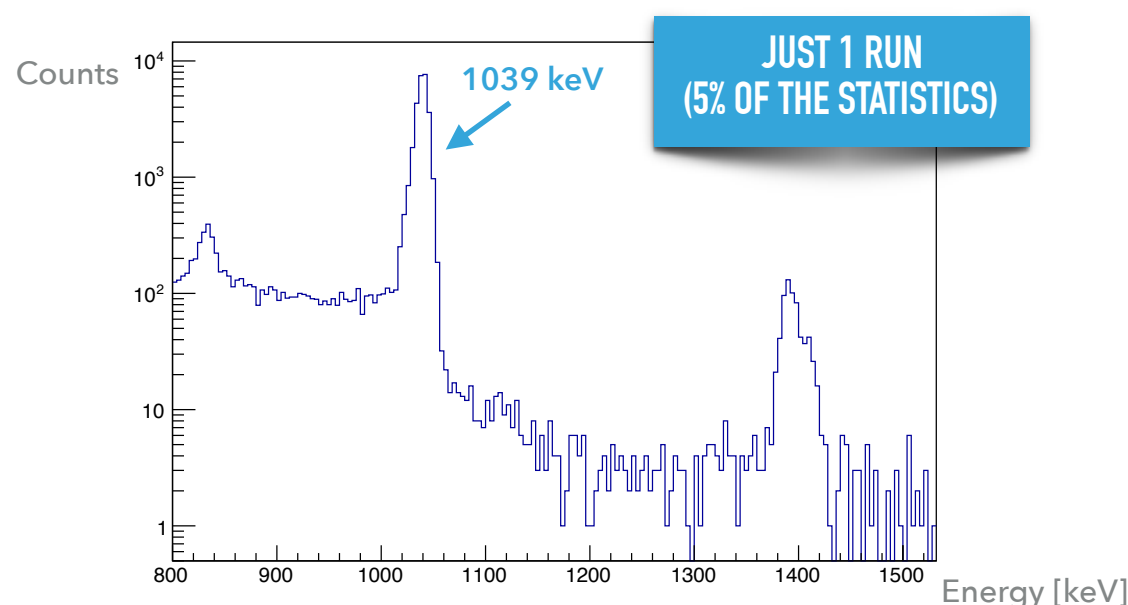
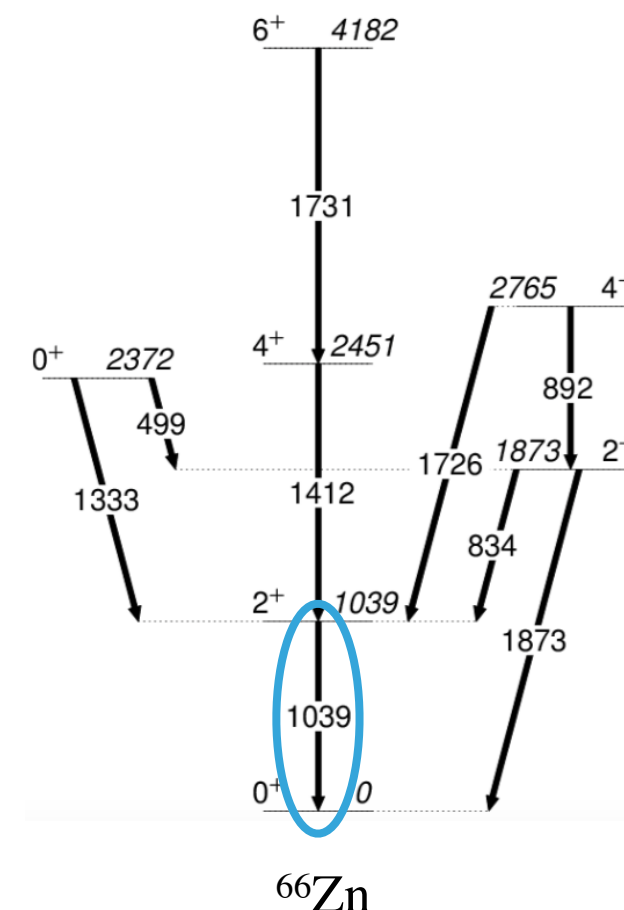


- ▶ Possibility to study the radiation damage on silicon detectors induced by heavy ions (few works in the literature)

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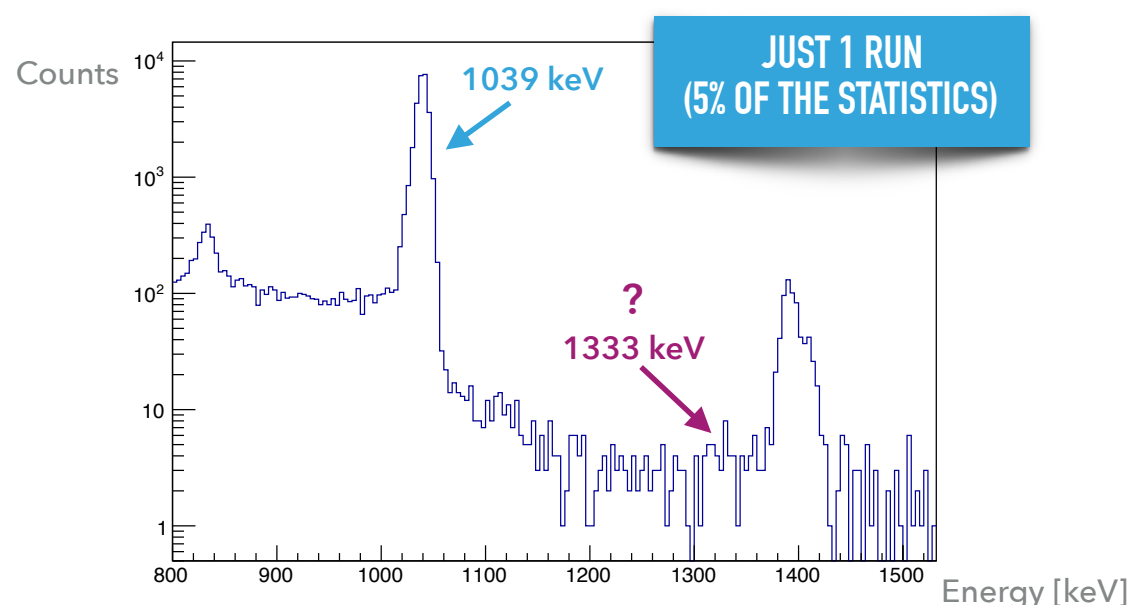
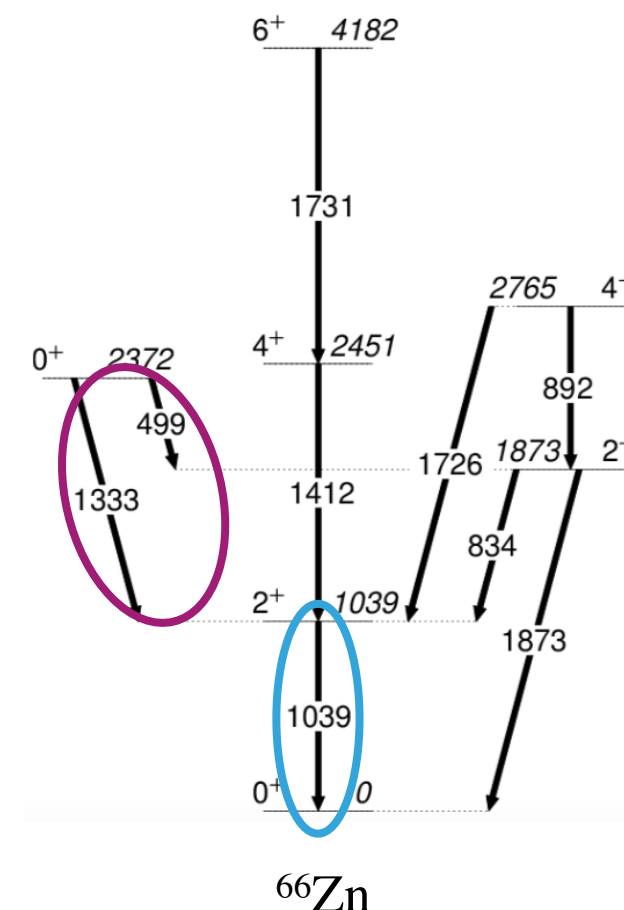


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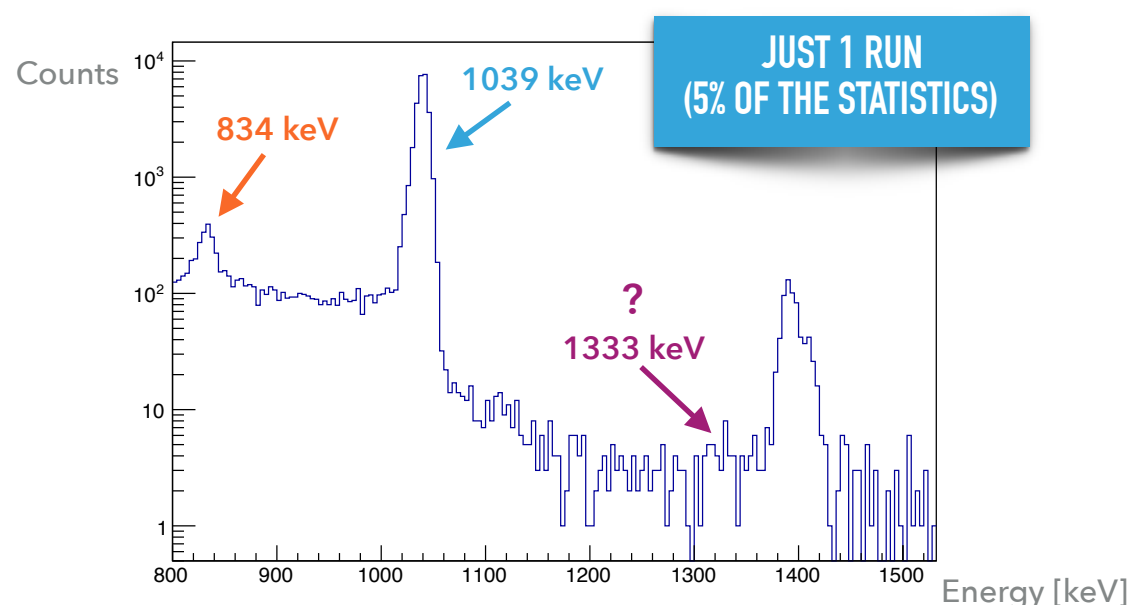
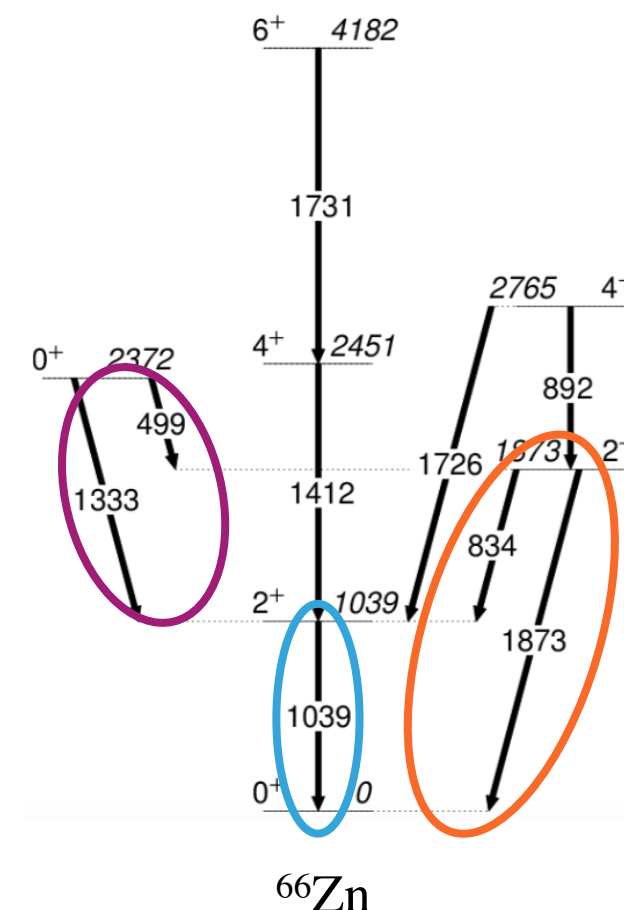


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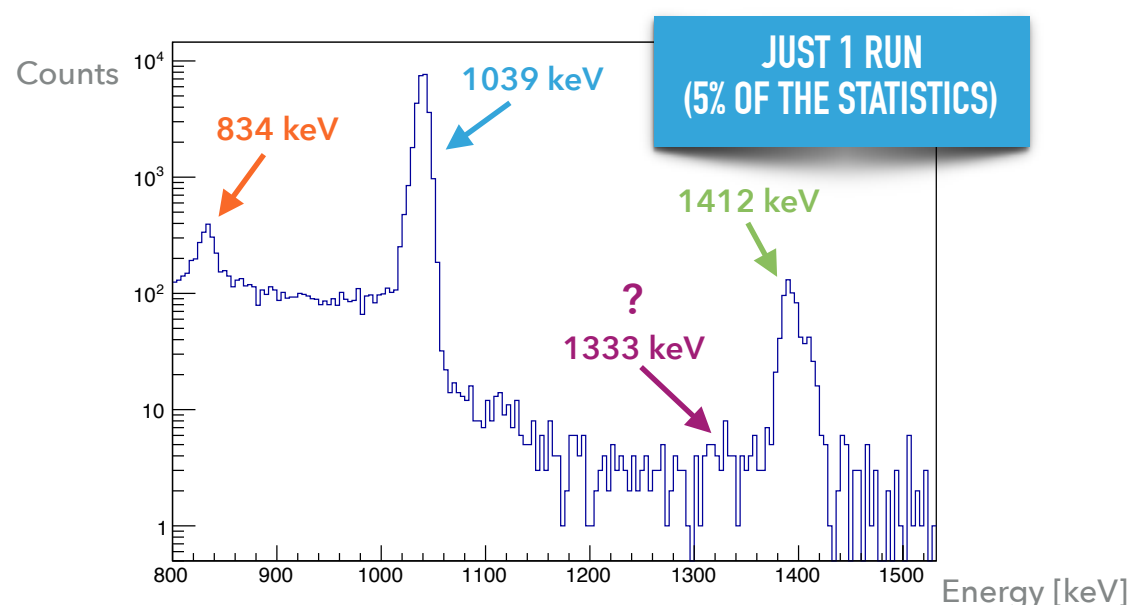
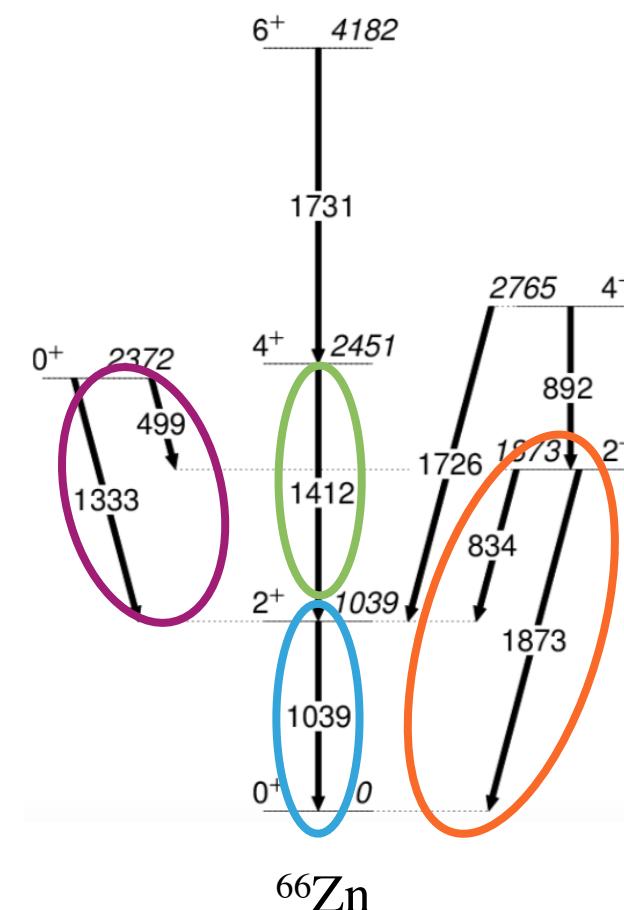


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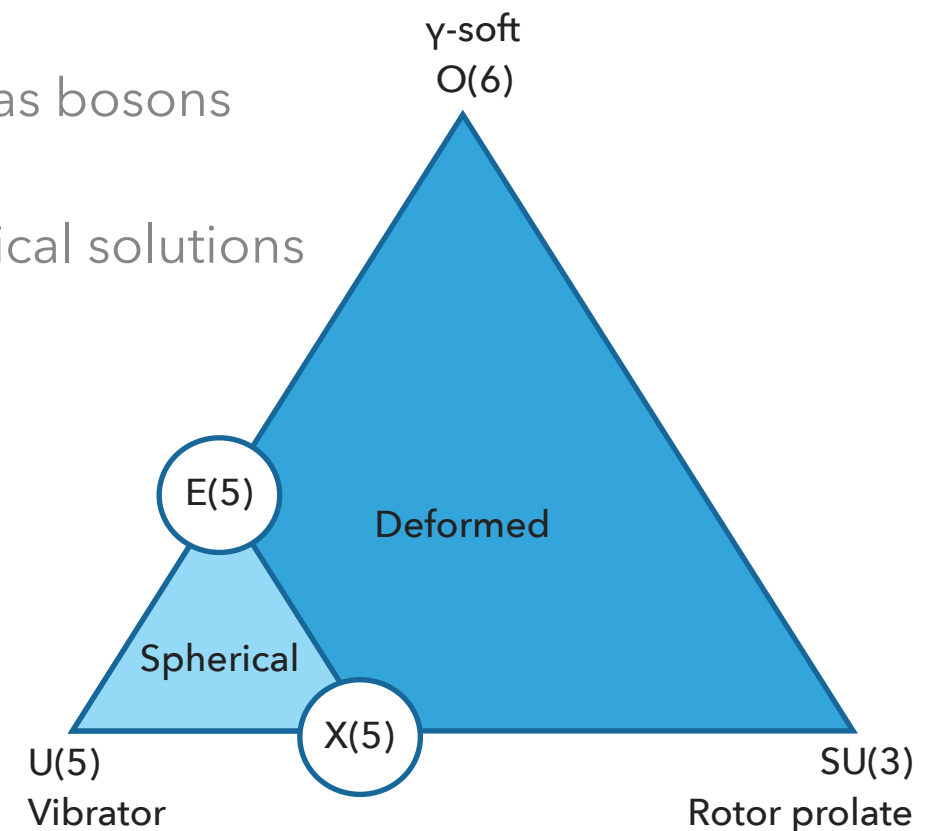
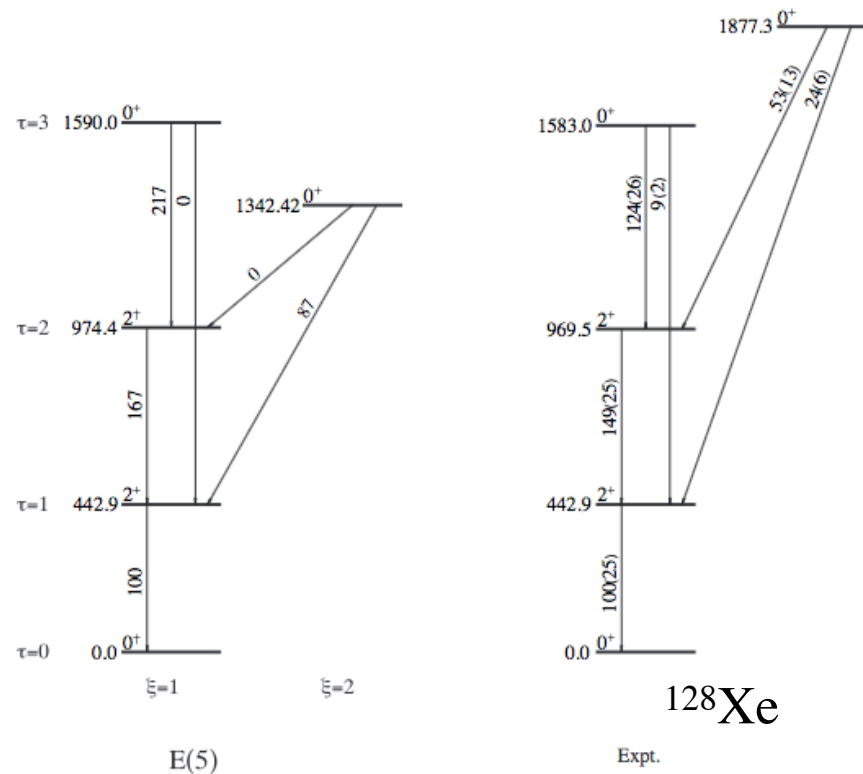


- ▶ Possibility to study the radiation damage on silicon detectors induced by heavy ions (few works in the literature)

E0 Transitions In $^{126,128}\text{Xe}$ (SP: A. Nannini, B. Melon)

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- IBA models: pairs of identical nucleons treated as bosons
- Nuclei in the Casten triangle vertexes $\rightarrow$ Analytical solutions
- Selection rules for different symmetries
 - $^{126}\text{Xe} \rightarrow$ O(6) symmetry breaking
 - $^{128}\text{Xe} \rightarrow$ E(5) candidate



Z	122Ce	123Ce	124Ce	125Ce	126Ce	127Ce	128Ce	129Ce	130Ce	131Ce	132Ce	133Ce	134Ce	135Ce	136Ce	137Ce	138Ce
	121La	122La	123La	124La	125La	126La	127La	128La	129La	130La	131La	132La	133La	134La	135La	136La	137La
56	120Ba	121Ba	122Ba	123Ba	124Ba	125Ba	126Ba	127Ba	128Ba	129Ba	130Ba	131Ba	132Ba	133Ba	134Ba	135Ba	136Ba
	119Cs	120Cs	121Cs	122Cs	123Cs	124Cs	125Cs	126Cs	127Cs	128Cs	129Cs	130Cs	131Cs	132Cs	133Cs	134Cs	135Cs
54	118Xe	119Xe	120Xe	121Xe	122Xe	123Xe	124Xe	125Xe	126Xe	127Xe	128Xe	129Xe	130Xe	131Xe	132Xe	133Xe	134Xe
	117I	118I	119I	120I	121I	122I	123I	124I	125I	126I	127I	128I	129I	130I	131I	132I	133I
52	116Te	117Te	118Te	119Te	120Te	121Te	122Te	123Te	124Te	125Te	126Te	127Te	128Te	129Te	130Te	131Te	132Te
	115Sb	116Sb	117Sb	118Sb	119Sb	120Sb	121Sb	122Sb	123Sb	124Sb	125Sb	126Sb	127Sb	128Sb	129Sb	130Sb	131Sb
50	114Sn	115Sn	116Sn	117Sn	118Sn	119Sn	120Sn	121Sn	122Sn	123Sn	124Sn	125Sn	126Sn	127Sn	128Sn	129Sn	130Sn
	64	66	68	70	72	74	76	78	80	82	84	86	88	90	92	94	96
																	N

E0 Transitions In $^{126,128}\text{Xe}$ (SP: A. Nannini, B. Melon)

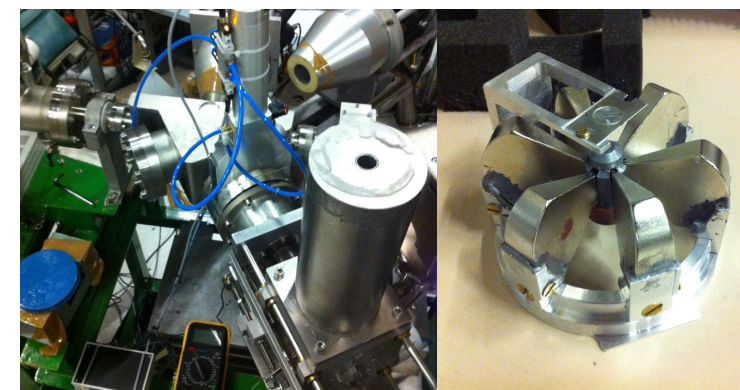
- ▶ Perspective in Nuclear Structure
- ▶ Radioactive Beams
- ▶ Experimental Methods
- ▶ ISOL Facilities
- ▶ Radioactive Beams Experiments
- ▶ Stable Beams Experiments

- ▶ Two different experiments: $^{126}\text{Xe} \rightarrow$ LNL Legnaro, $^{128}\text{Xe} \rightarrow$ LNS Catania
- ▶ Similar apparatuses $\rightarrow$ off-line beta decay experiments:

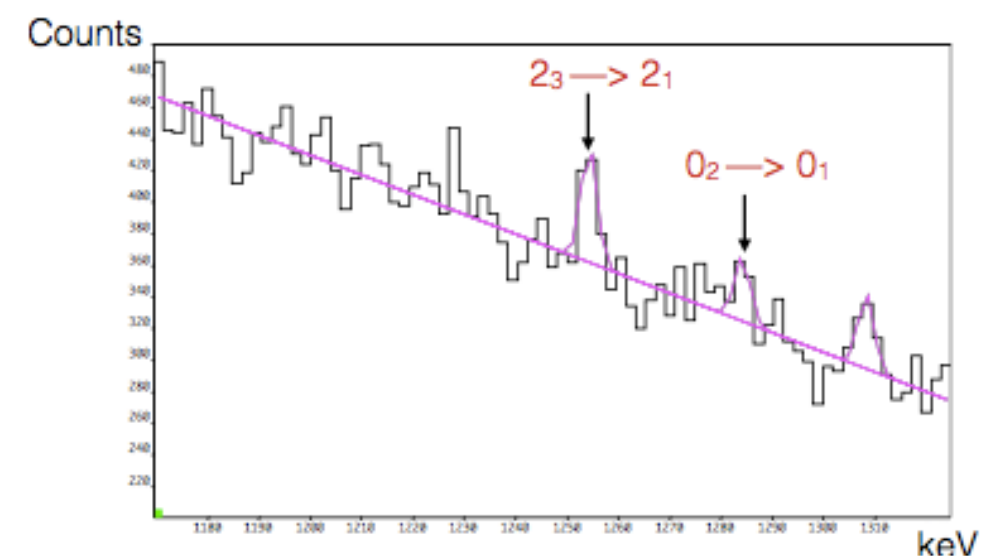
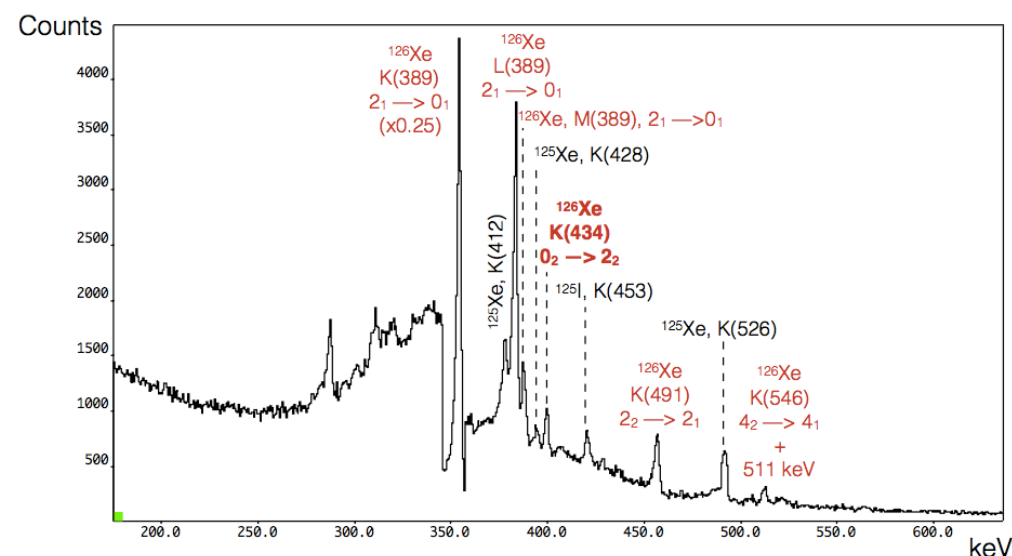
LNL:
Florence Magnetic
Electron
Spectrometer



LNS:
Mini-Orange



- ▶ ^{126}Xe preliminary results:



Conclusions

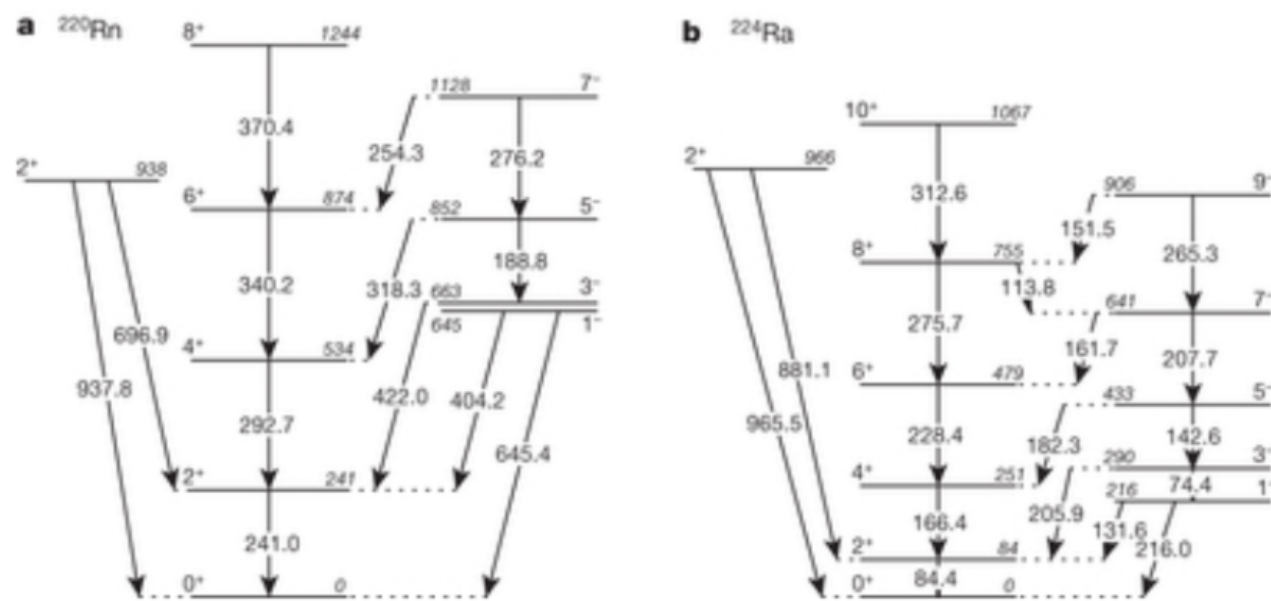
- ▶ Discover of the nucleus in 1909 → still under investigation (complicate quantum many-body problem)
- ▶ Shape as a key characteristics in nuclei
- ▶ Experimental work necessary → need for radioactive beams development
- ▶ Coulomb excitation and E0 transition measurements suitable with radioactive beams
- ▶ Instrumentation developments → possibility to study nuclear structure with stable beams



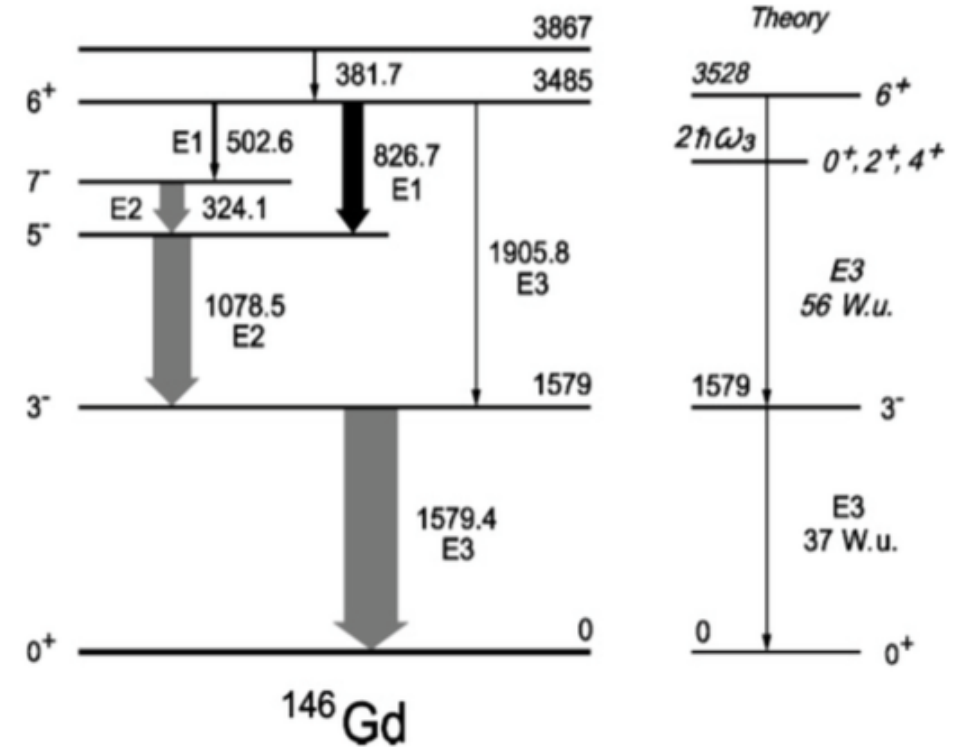
THANK YOU FOR THE ATTENTION

Octupole Excitations

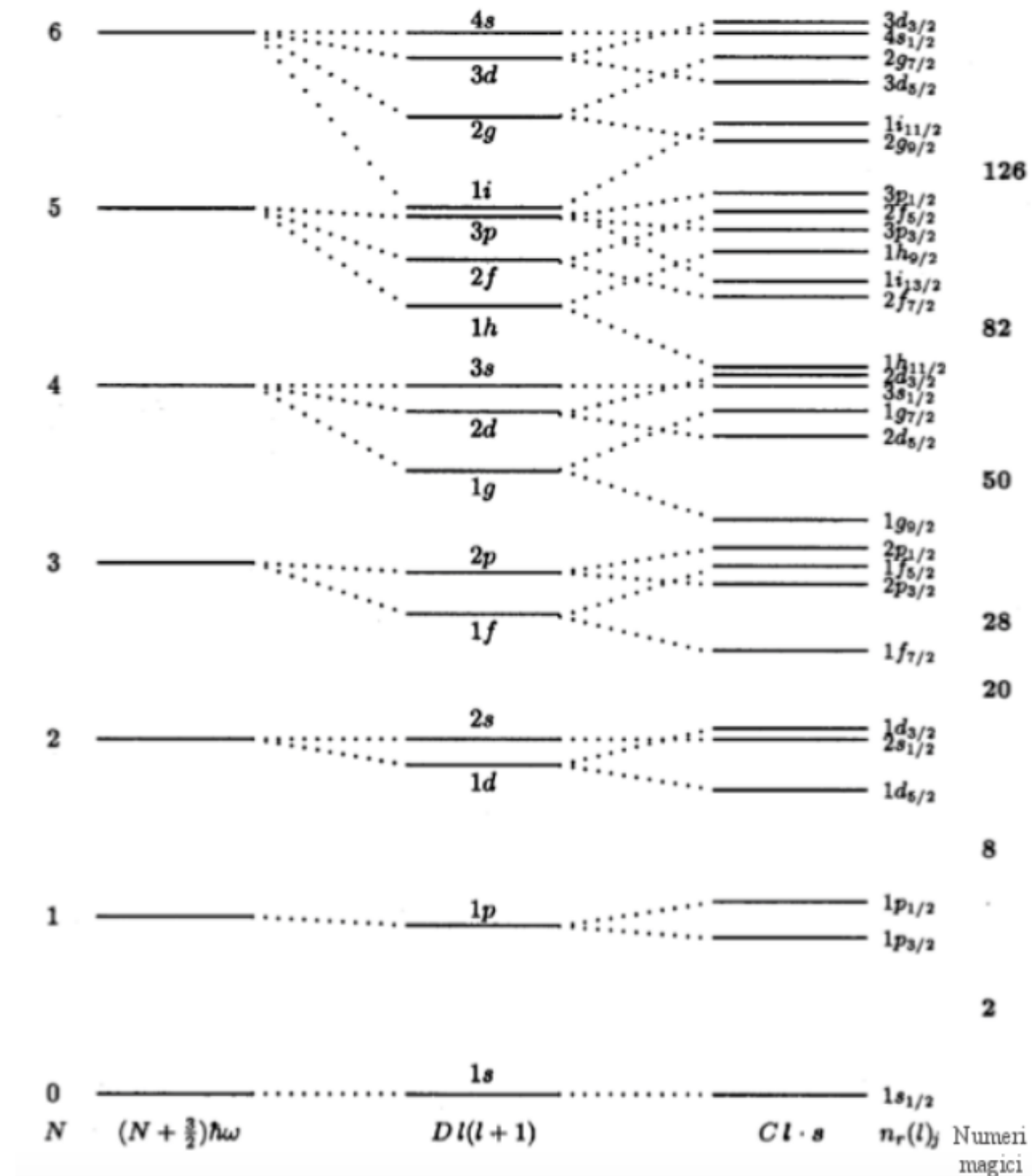
Rotation



Vibration



Shell Model



IBA Models

$$H = \varepsilon n_d + \kappa Q \cdot Q \quad \text{parametri: } \kappa/\varepsilon, \chi \text{ (in } Q\text{)}$$

