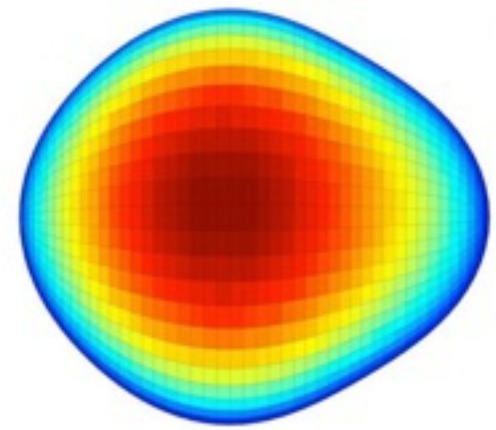
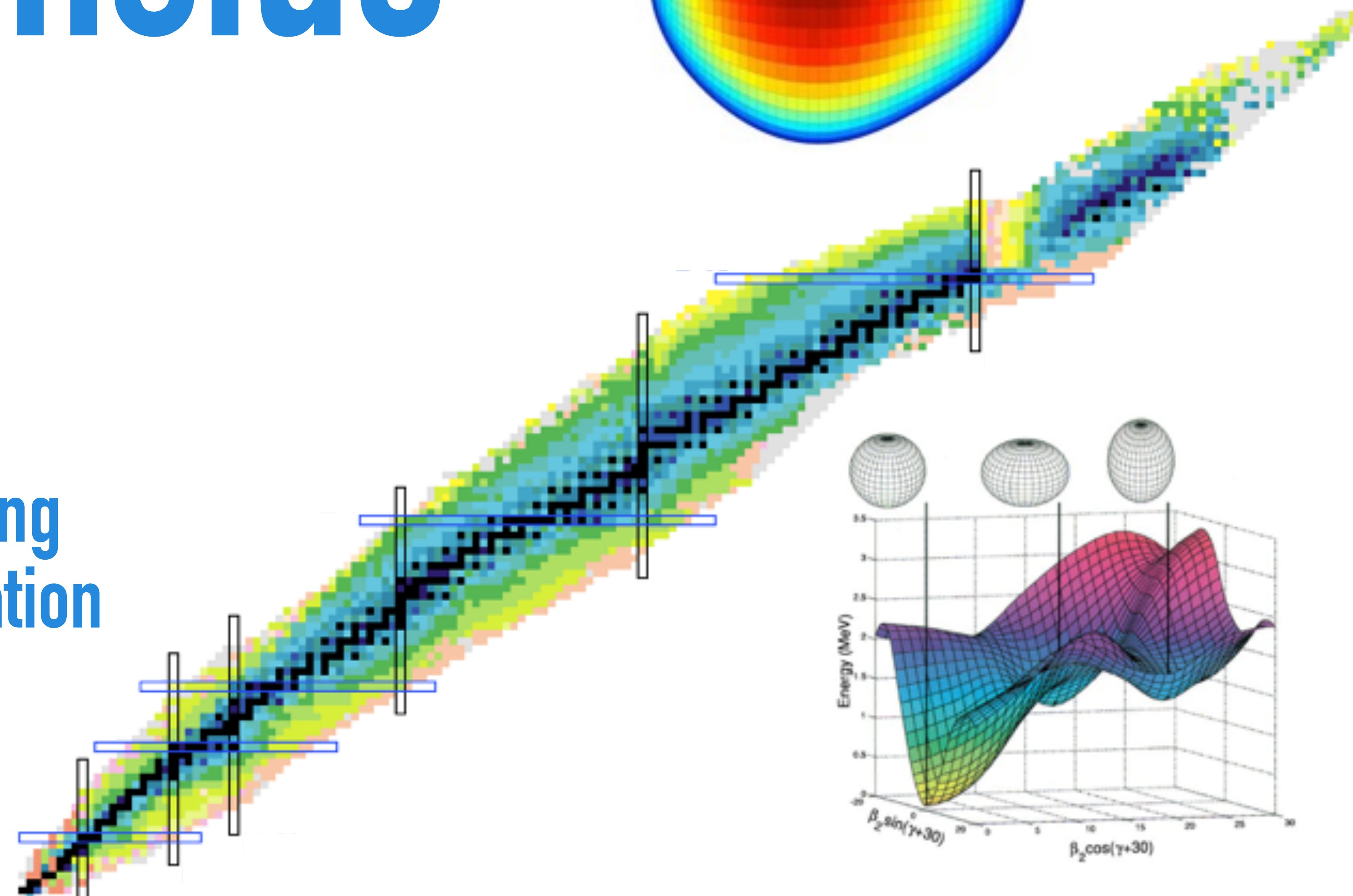
PhD Diessertation

Marco Rocchini

Università degli Studi di Firenze and INFN Sezione di Firenze

Looking Inside Atoms

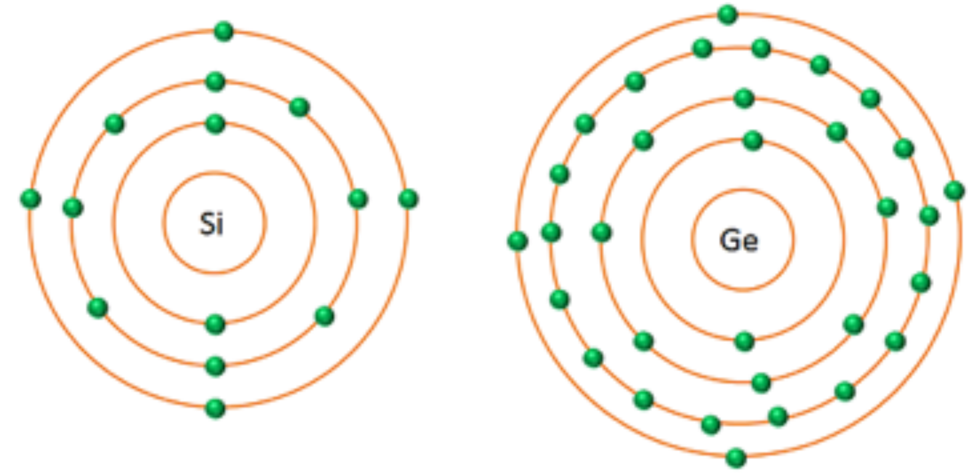


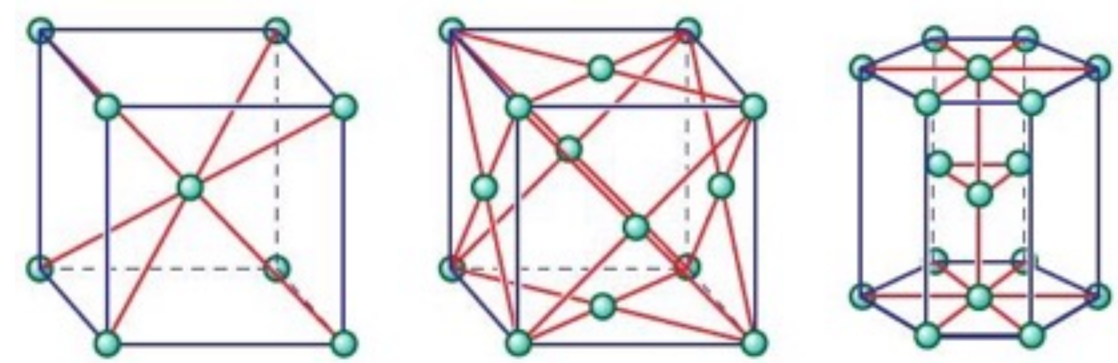


Shapes of Atomic Nuclei using Low-Energy Coulomb excitation

Outline

- Introduction about Nuclear Structure:
    - Theoretical and Experimental challenges
- Basics idea about Future Radioactive Beams facilities
- Shape Related Phenomena
- Cross-Disciplinary Phenomena
- How to look inside atoms?
    - An example, the Low-Energy Coulomb-Excitation technique



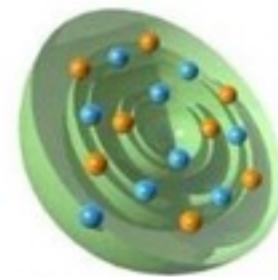


- Nuclear Models
- Gamma Spectroscopy
- Radioactive Beams
- Shape Phenomena
- Cross-Disciplinary Phenomena
- Coulex

Nuclear Models: History

Maria Goeppert Mayer

Nobel Prize in Physics 1963

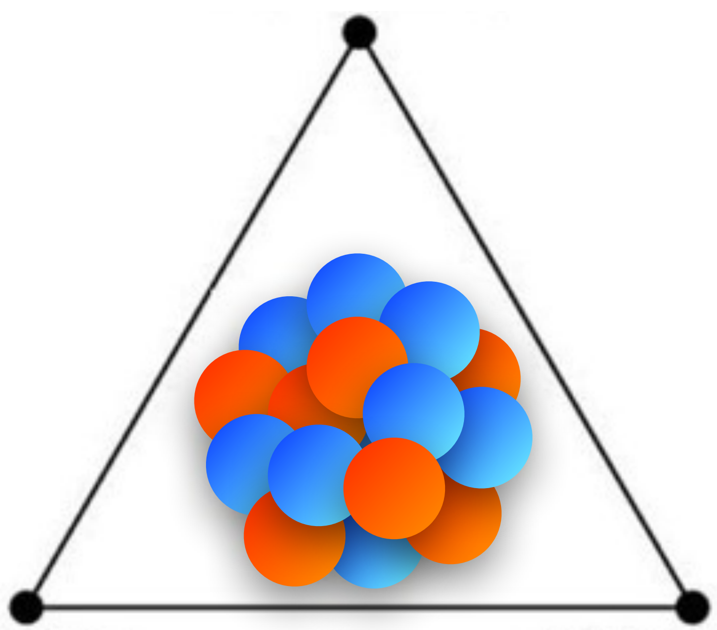


Shell Model

Aage Niels Bohr & Ben Roy Mottelson & Leo James Rainwater

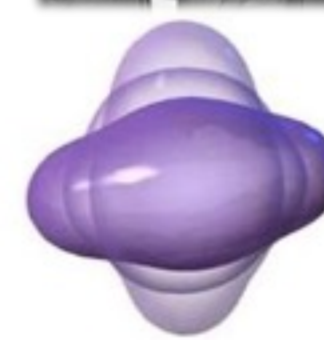
Nobel Prize in Physics 1975

Francesco Iachello & Akito Arima

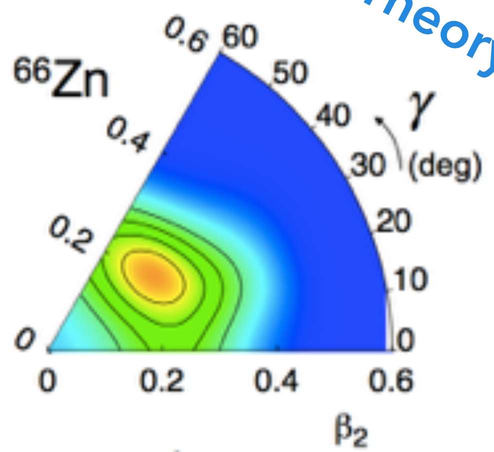


Interacting Bosons Models

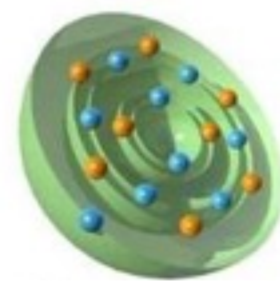
Collective Models



Nuclear Models: Modern Approaches

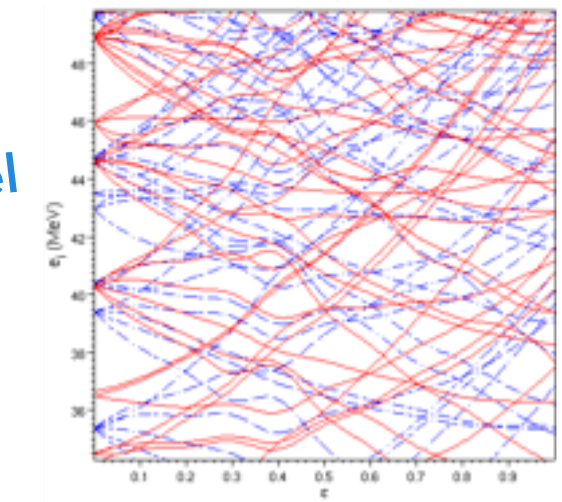


Density Functional Theory



Shell Model

Nilsson Model



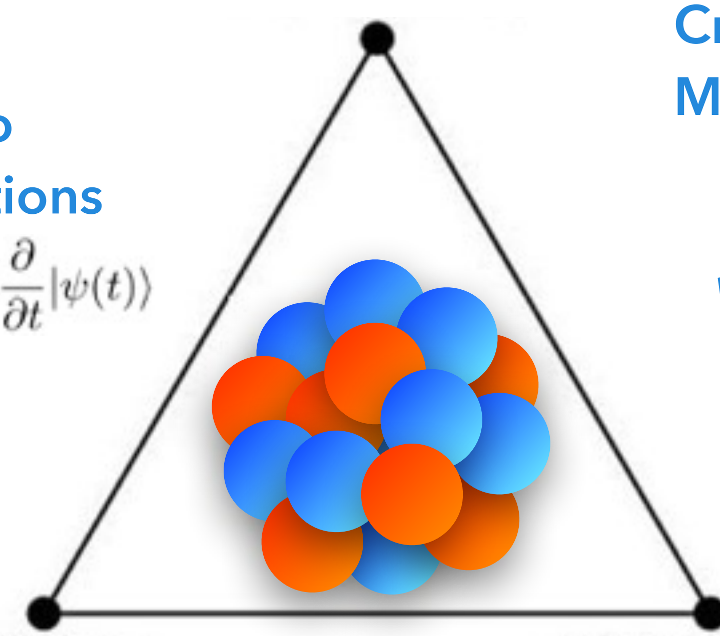
Cranking Models

Cluster Models

Ab Initio Calculations

$$H(t)|\psi(t)\rangle = i\hbar\frac{\partial}{\partial t}|\psi(t)\rangle$$

Monte Carlo Shell Model Calculations

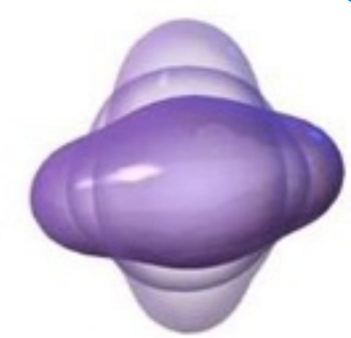


Random Phase Approximation

Beyond Mean Field Models

Interacting Bosons Models

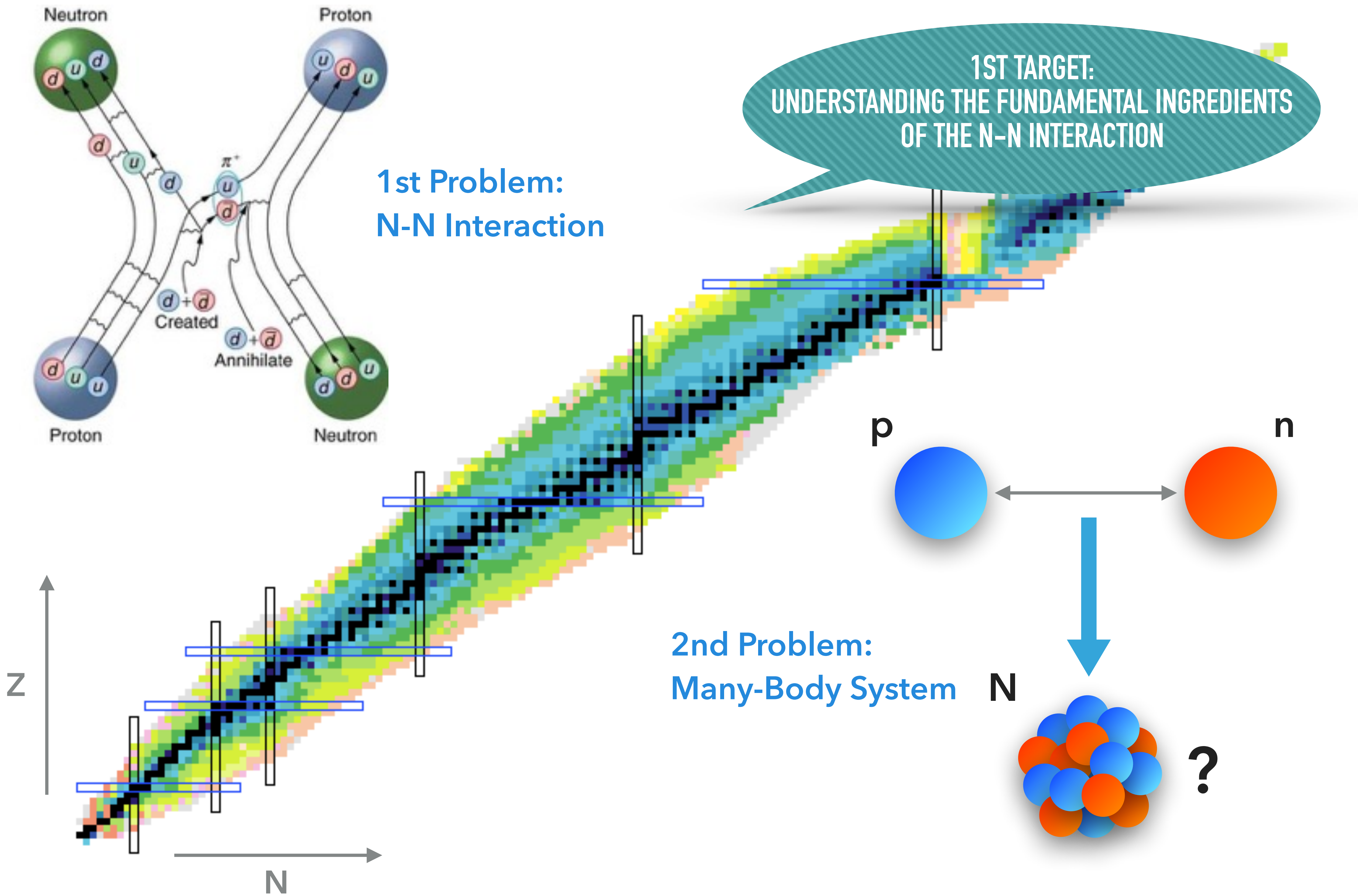
Collective Models



No Nuclear Structure Standard Model

Nuclear Structure Challenges

- **Nuclear Models**
- Gamma Spectroscopy
- Radioactive Beams
- Shape Phenomena
- Cross-Disciplinary Phenomena
- Coulex



1st Problem:
N-N Interaction

1ST TARGET:
UNDERSTANDING THE FUNDAMENTAL INGREDIENTS
OF THE N-N INTERACTION

2nd Problem:
Many-Body System

Nuclear Structure & Gamma Spectroscopy

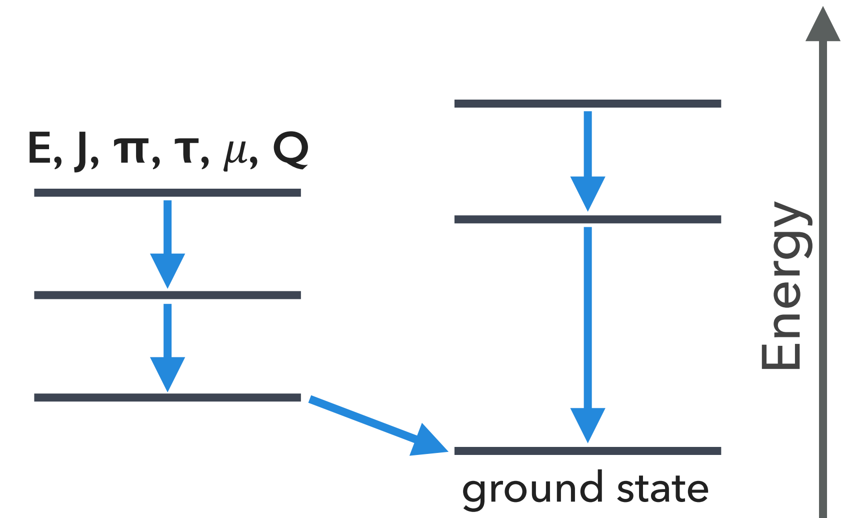
- Nuclear Models
- **Gamma Spectroscopy**
- Radioactive Beams
- Shape Phenomena
- Cross-Disciplinary Phenomena
- Coulex

Observables

- Energy E
- Spin J
- Parity π
- Lifetime τ
- Nuclear Moments μ, Q

γ Spectroscopy

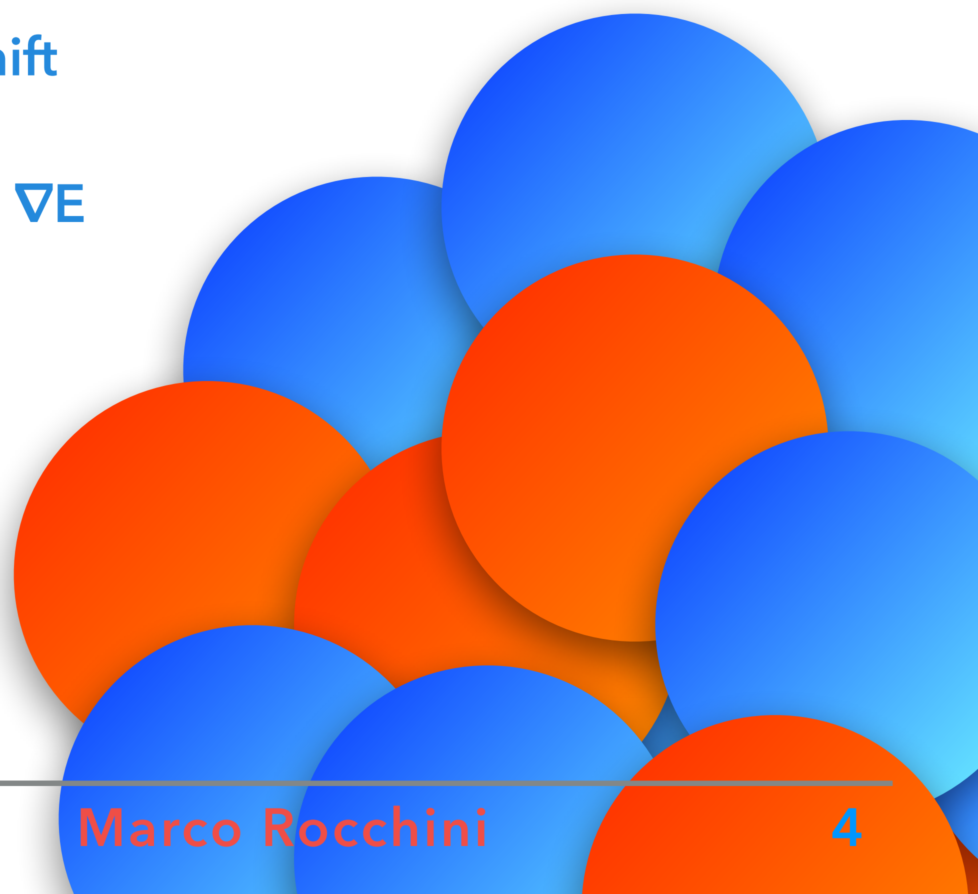
- γ Energy
- Angular Distribution
- Linear Polarization
- Timing, Doppler Shift
- Interactions with B, ∇E

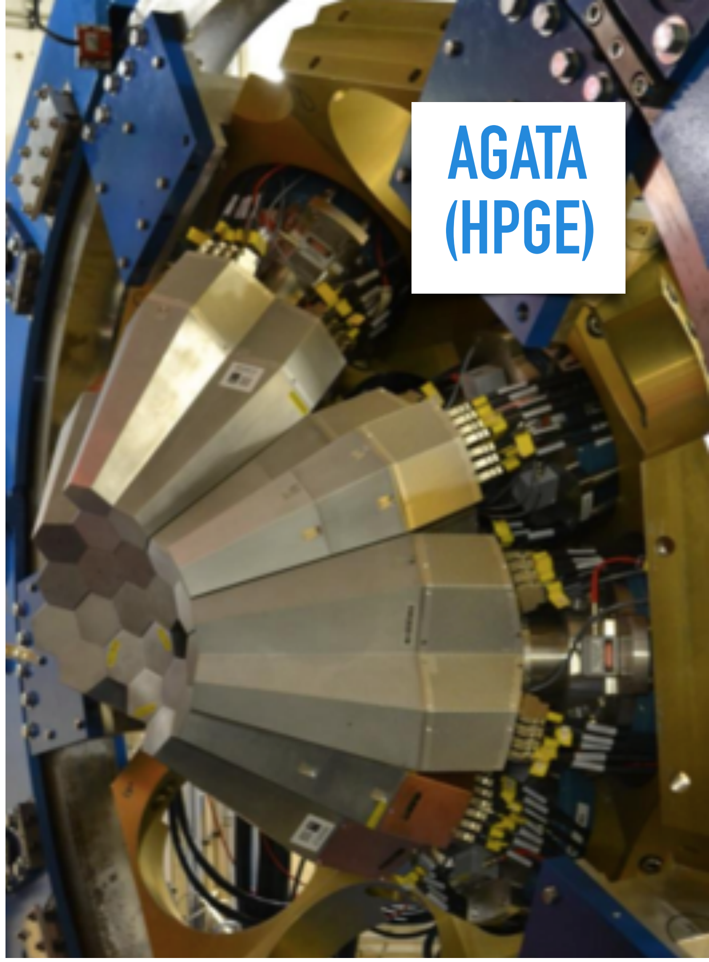


Q –> Collective Property

Prolate Q>0 | Spherical Q=0 | Oblate Q<0

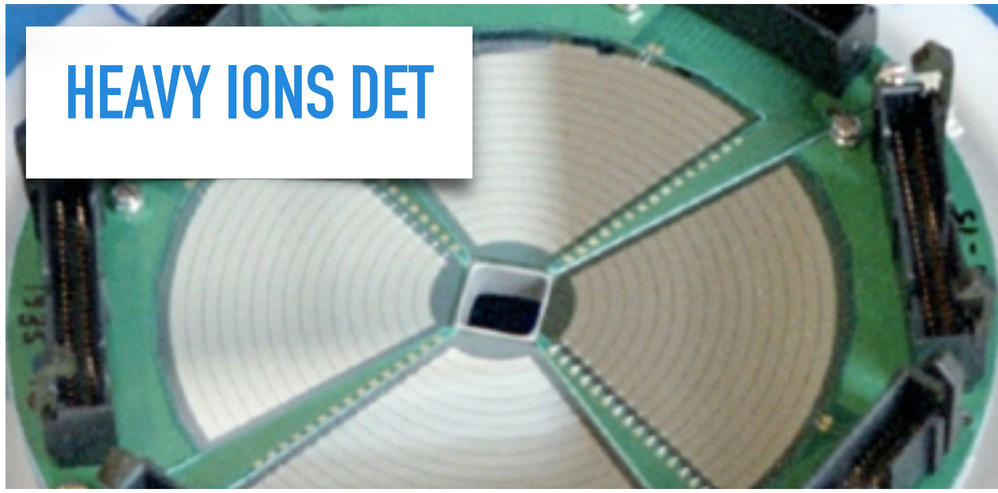


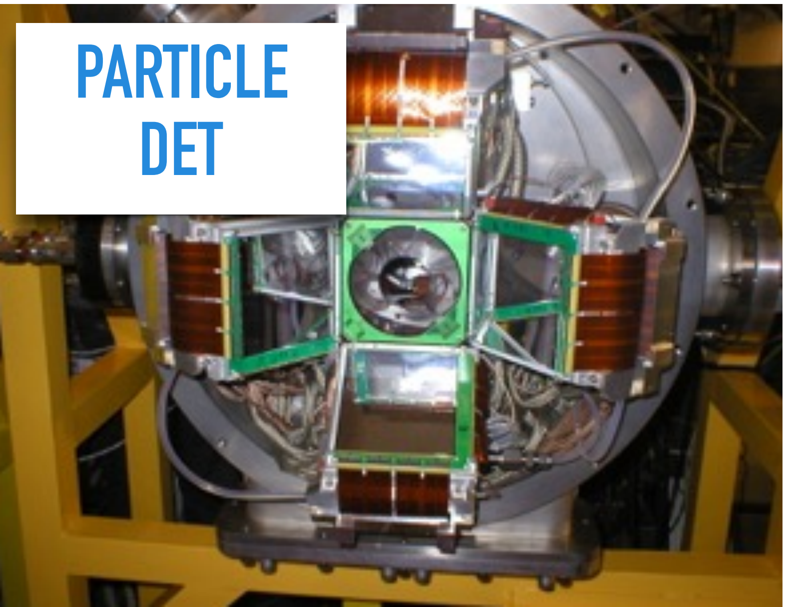


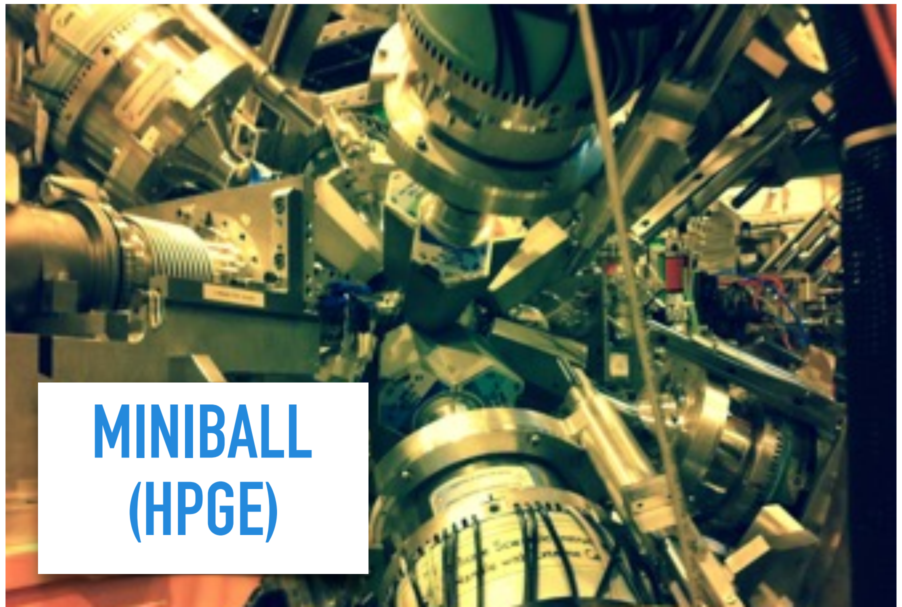


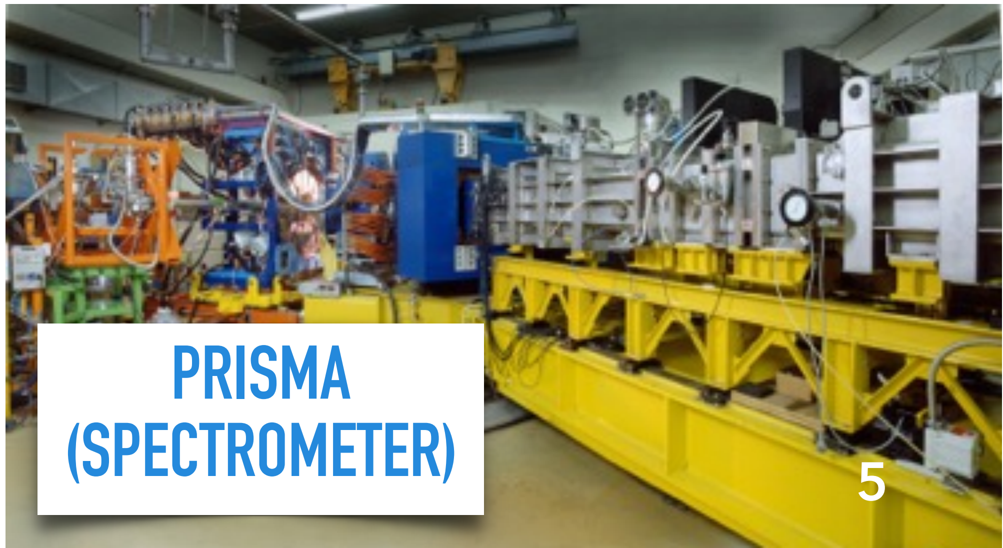
2ND TARGET

Development of Detectors and New Techniques



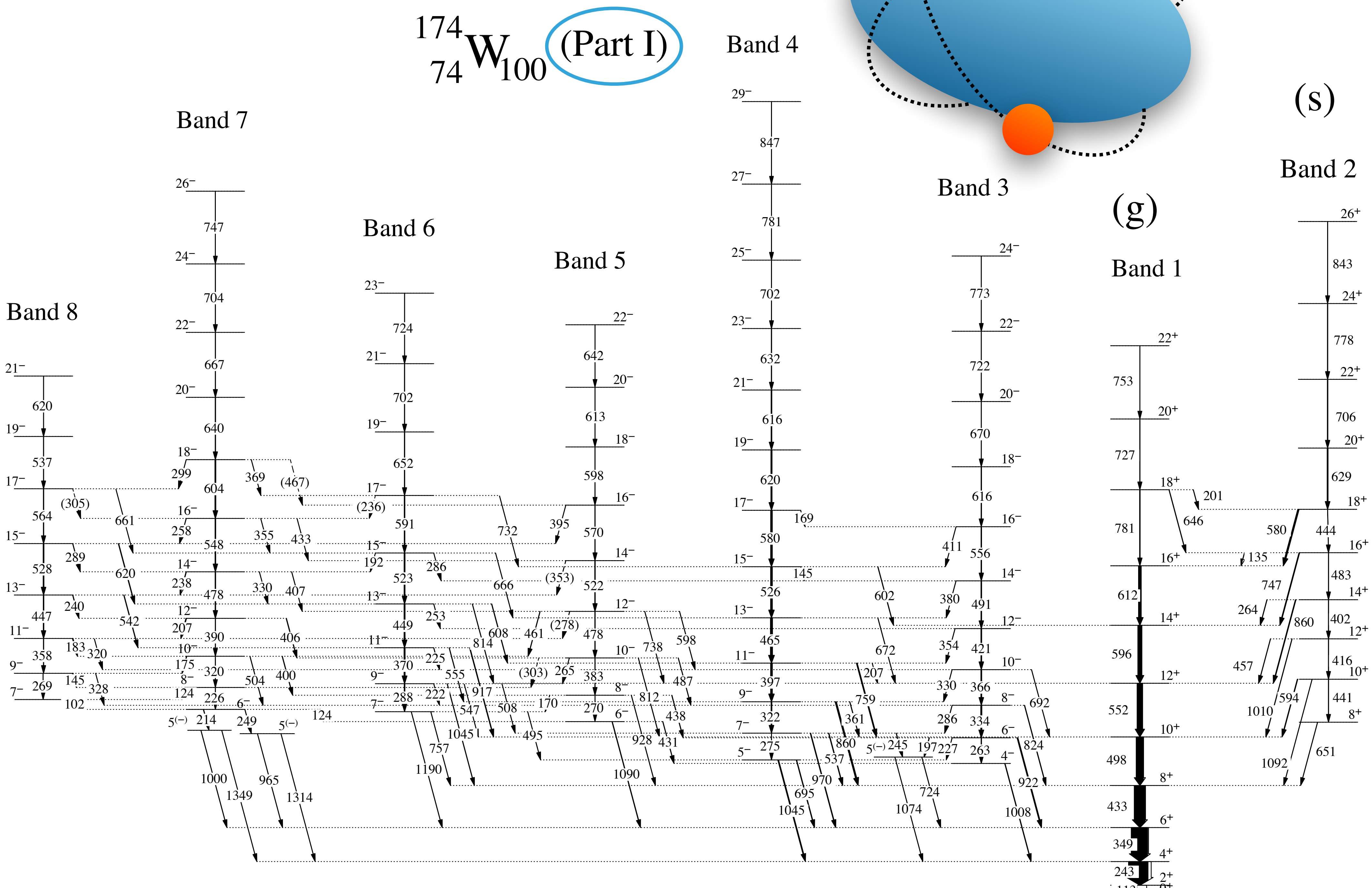






A Level Scheme

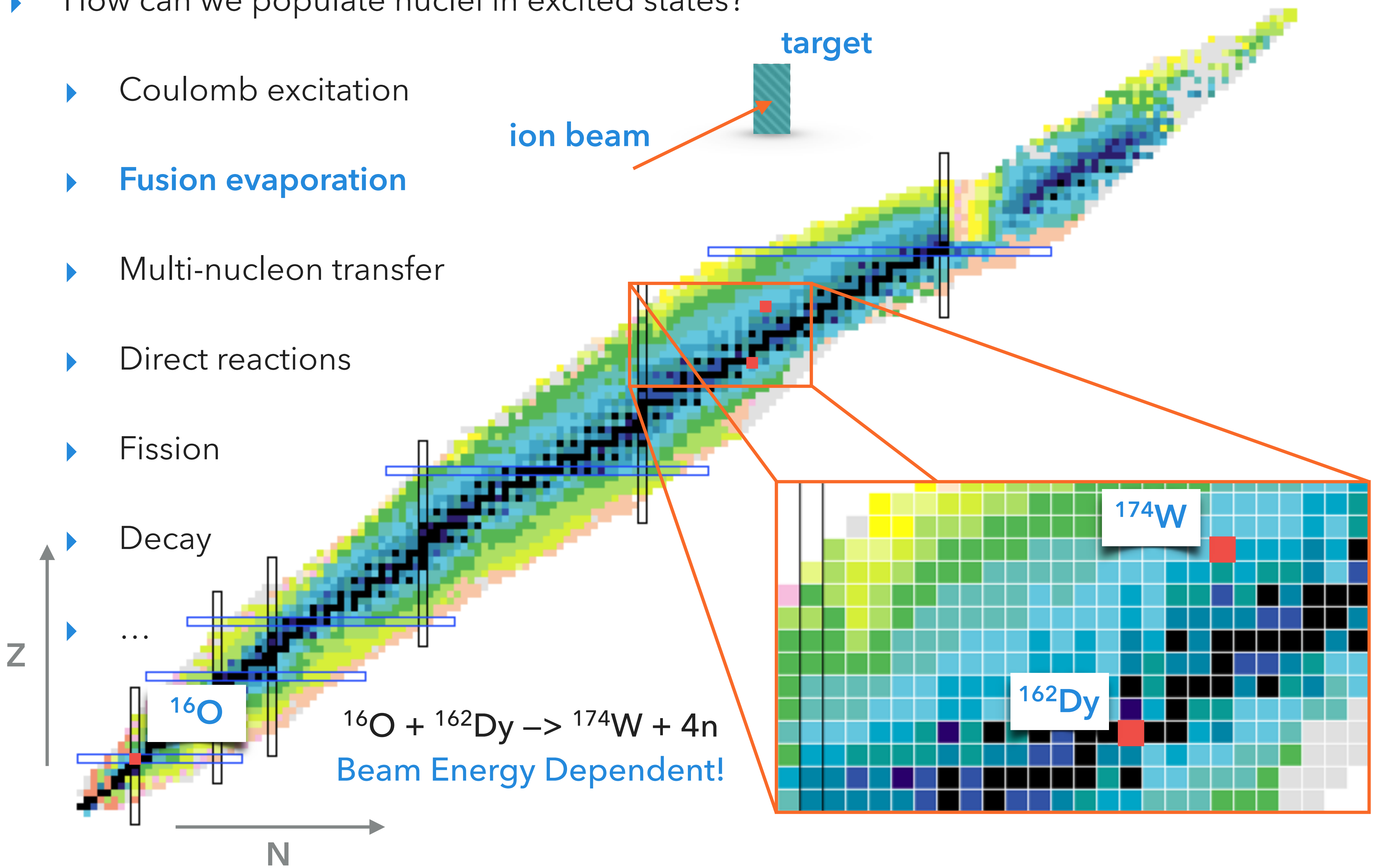
- Nuclear Models
- **Gamma Spectroscopy**
- Radioactive Beams
- Shape Phenomena
- Cross-Disciplinary Phenomena
- Coulex



Tandel et al., *Phys. Rev. C*, 73 (2006) 044306

Terra Incognita & Radioactive Beams

- How can we populate nuclei in excited states?
  - Coulomb excitation
  - **Fusion evaporation**
  - Multi-nucleon transfer
  - Direct reactions
  - Fission
  - Decay
  - ...

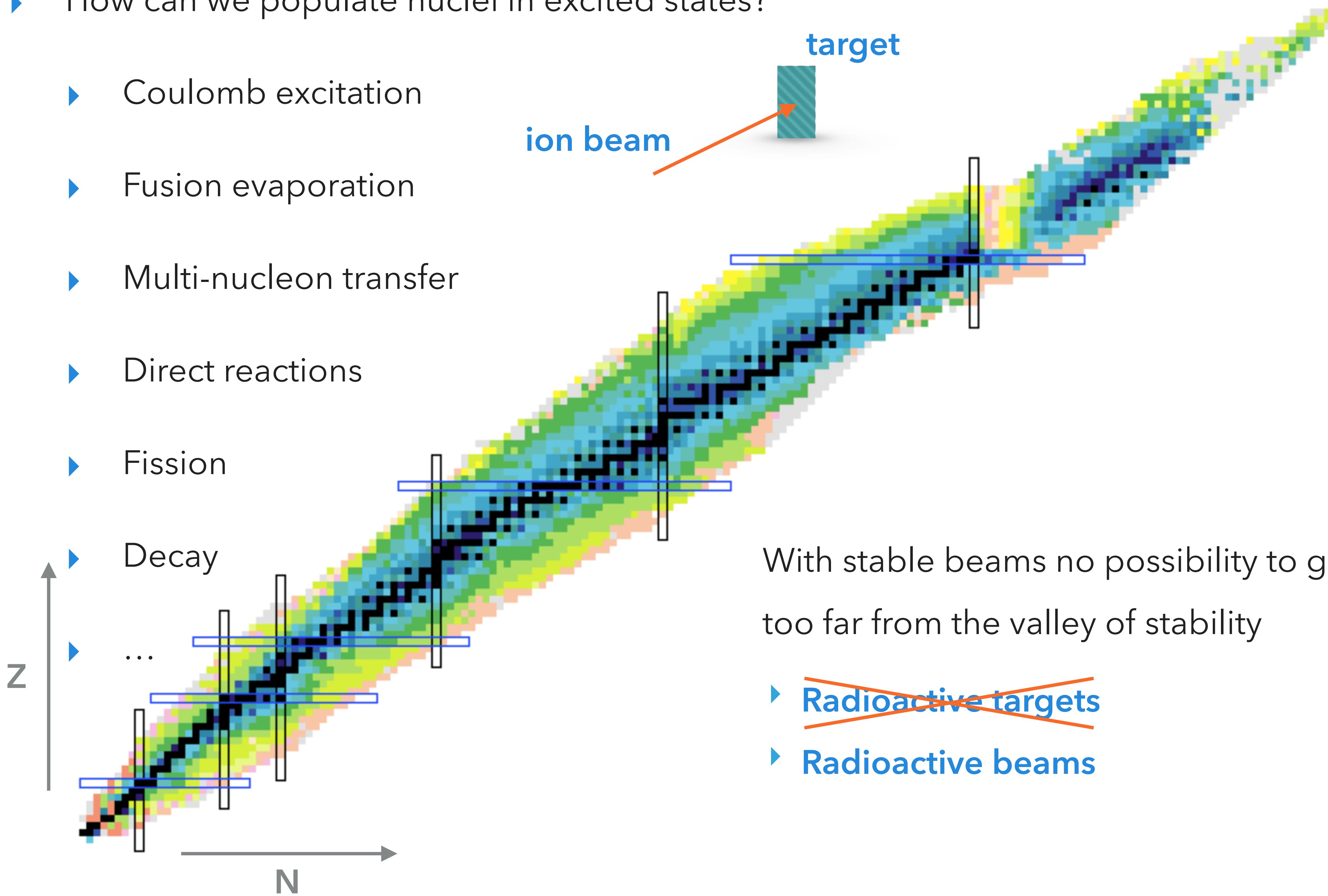


$^{16}O + ^{162}Dy \rightarrow ^{174}W + 4n$

Beam Energy Dependent!

Terra Incognita & Radioactive Beams

- How can we populate nuclei in excited states?
  - Coulomb excitation
  - Fusion evaporation
  - Multi-nucleon transfer
  - Direct reactions
  - Fission
  - Decay
  - …



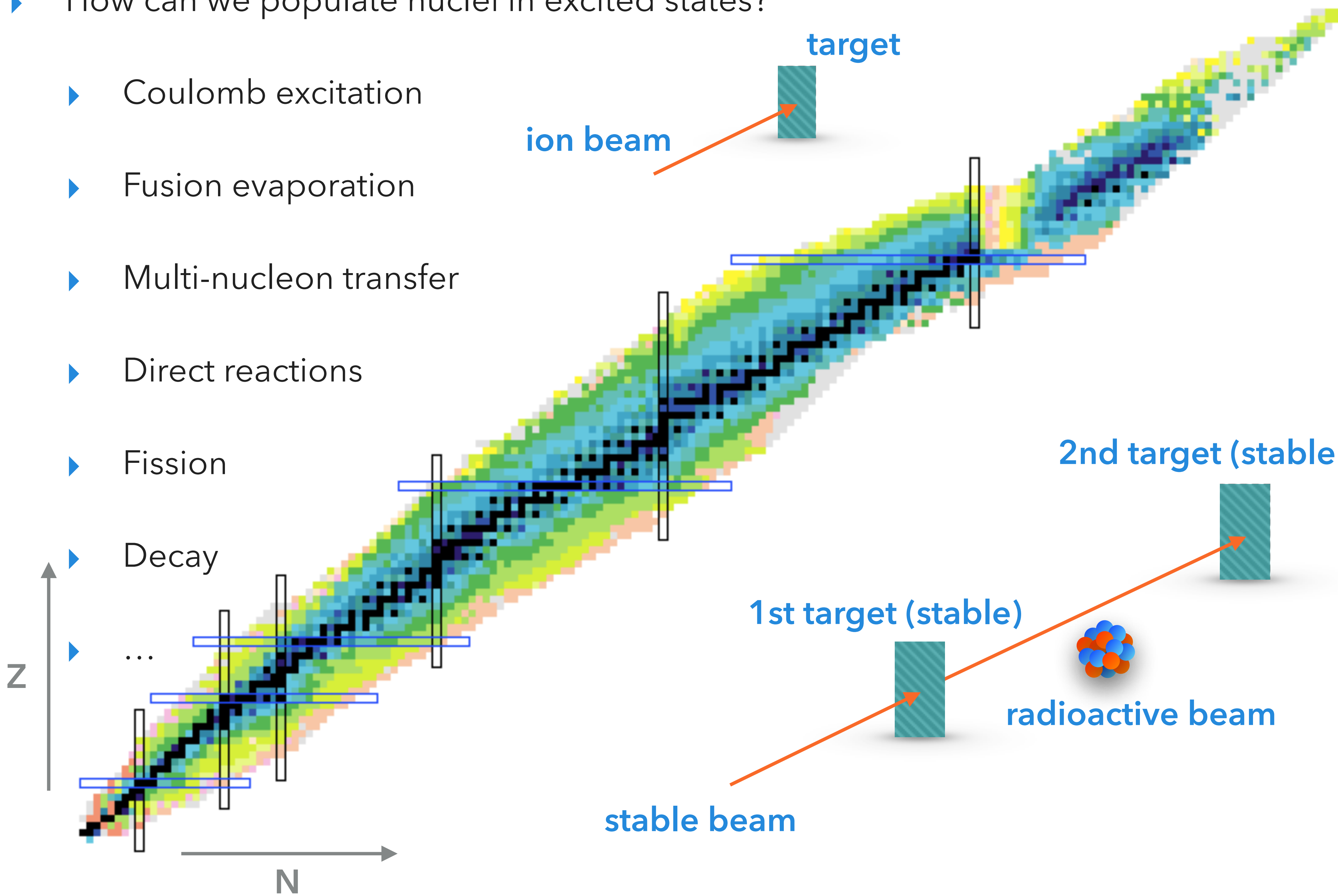
With stable beams no possibility to go too far from the valley of stability

- ~~Radioactive targets~~
- Radioactive beams

Terra Incognita & Radioactive Beams

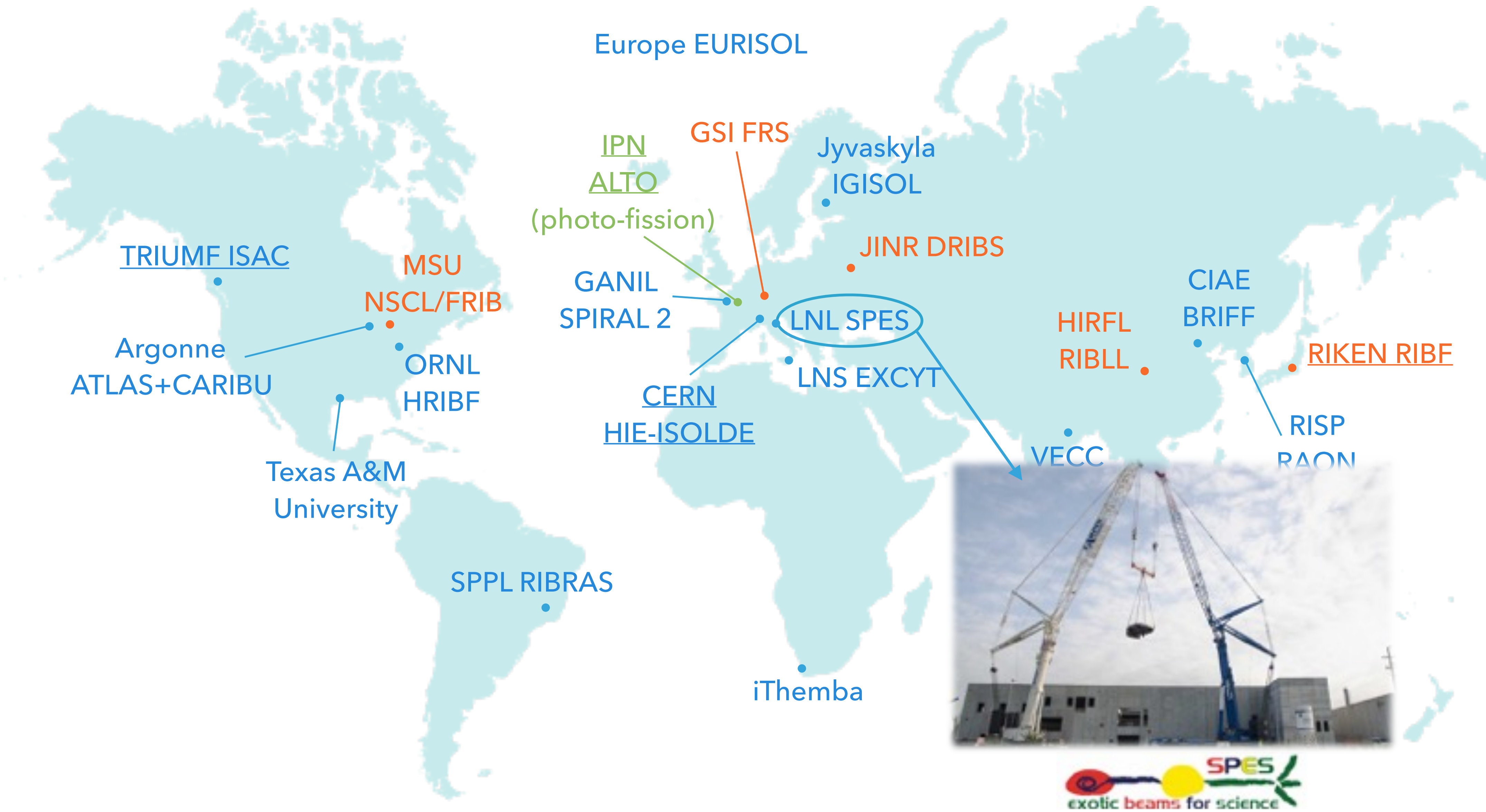
- Nuclear Models
- Gamma Spectroscopy
- **Radioactive Beams**
- Shape Phenomena
- Cross-Disciplinary Phenomena
- Coulex

- How can we populate nuclei in excited states?
  - Coulomb excitation
  - Fusion evaporation
  - Multi-nucleon transfer
  - Direct reactions
  - Fission
  - Decay
  - …



Radioactive Beams Around The World

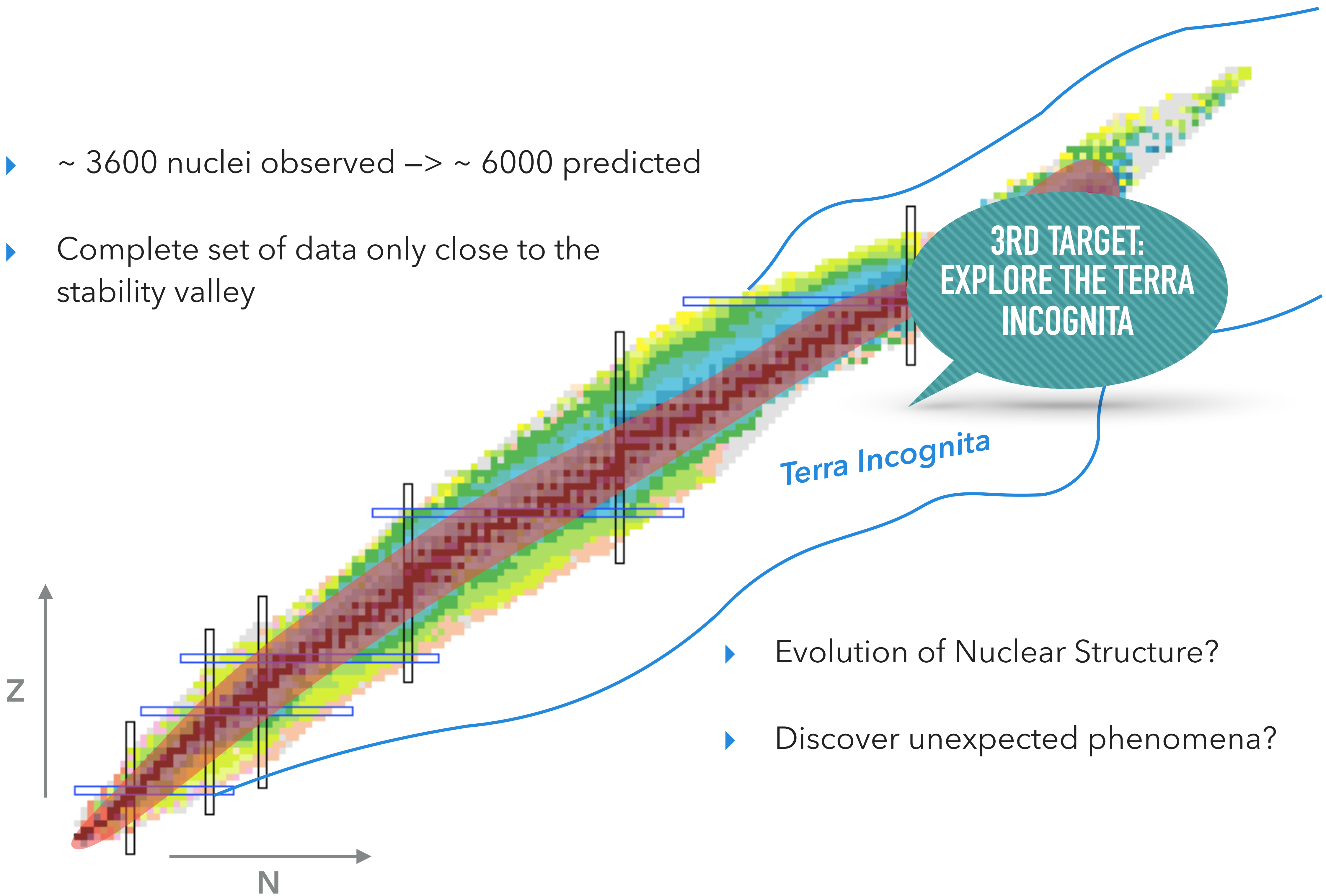
- Nuclear Models
- Gamma Spectroscopy
- **Radioactive Beams**
- Shape Phenomena
- Cross-Disciplinary Phenomena
- Coulex



ISOL In-Flight Operational

Terra Incognita & Radioactive Beams

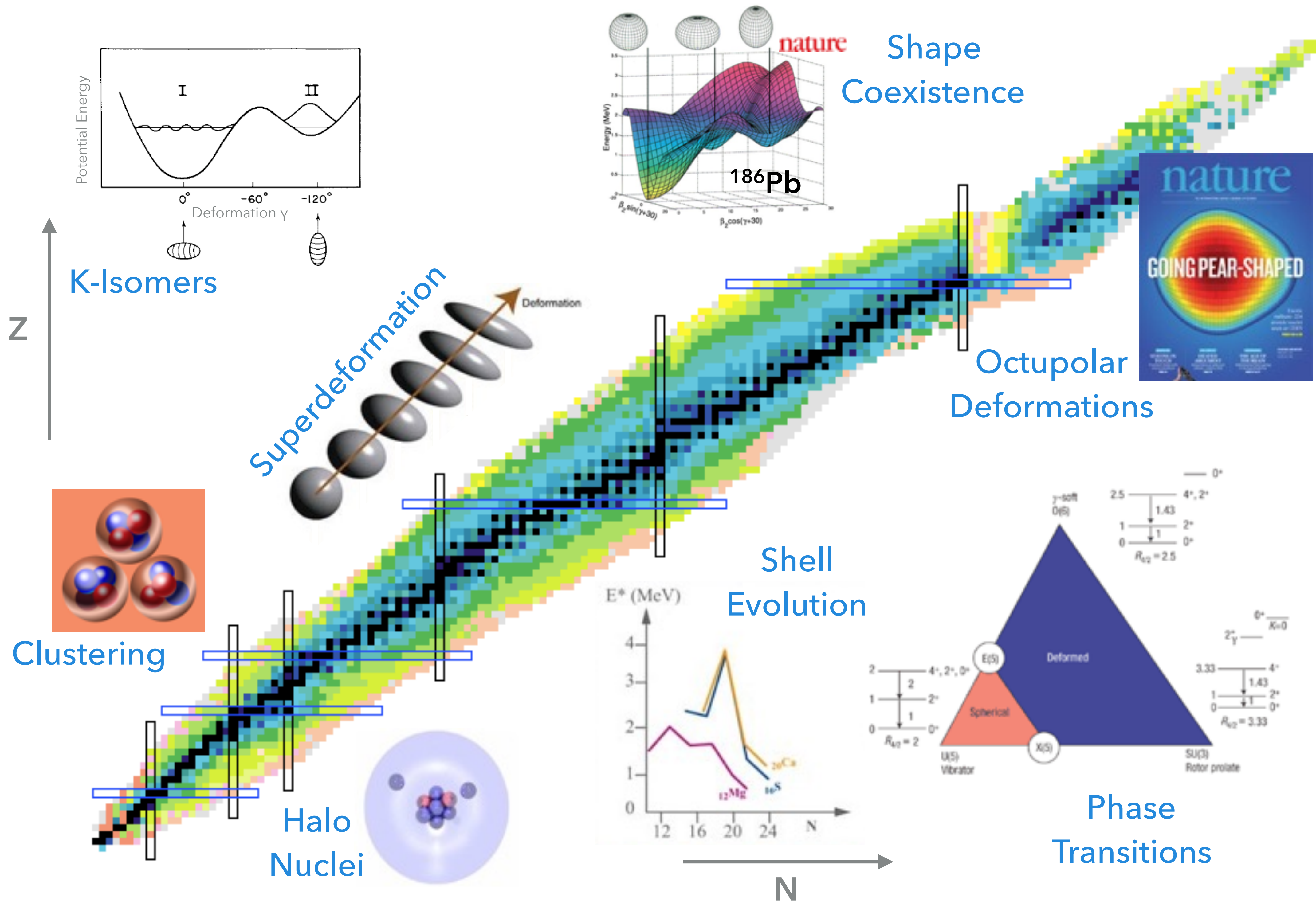
- ~ 3600 nuclei observed –> ~ 6000 predicted
- Complete set of data only close to the stability valley



- Evolution of Nuclear Structure?
- Discover unexpected phenomena?

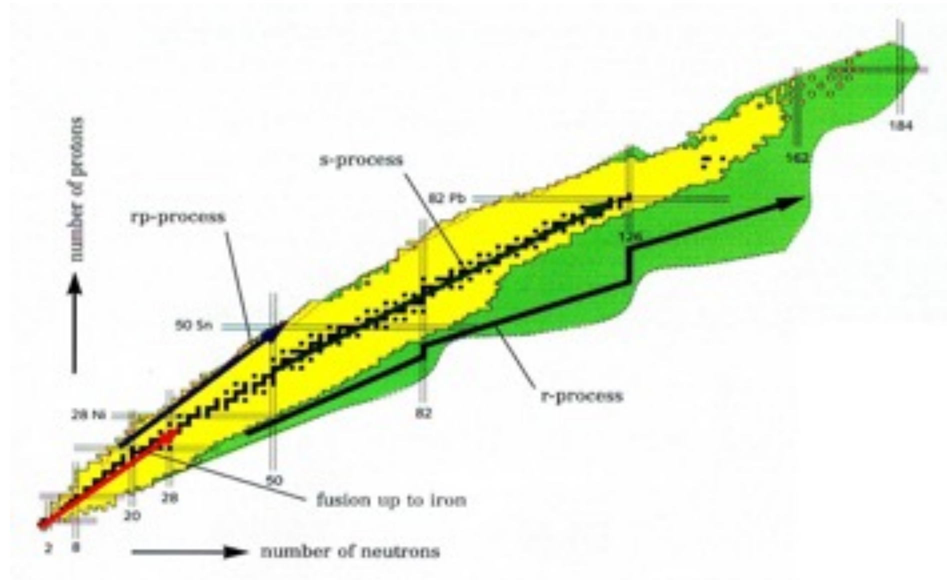
Shape Related Phenomena

- Nuclear Models
- Gamma Spectroscopy
- Radioactive Beams
- **Shape Phenomena**
- Cross-Disciplinary Phenomena
- Coulex

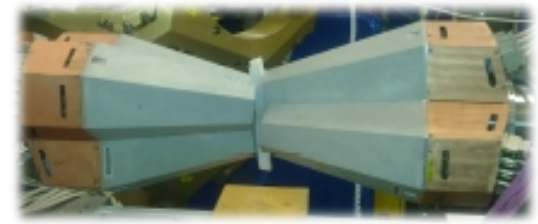


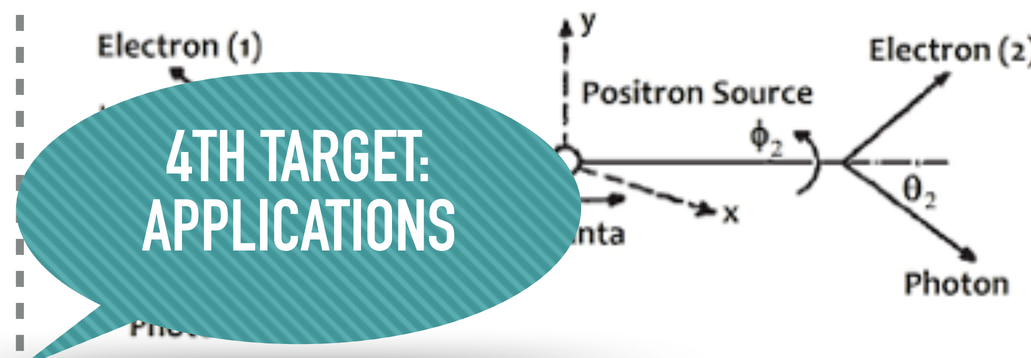
Cross-Disciplinary Phenomena

- r-Process

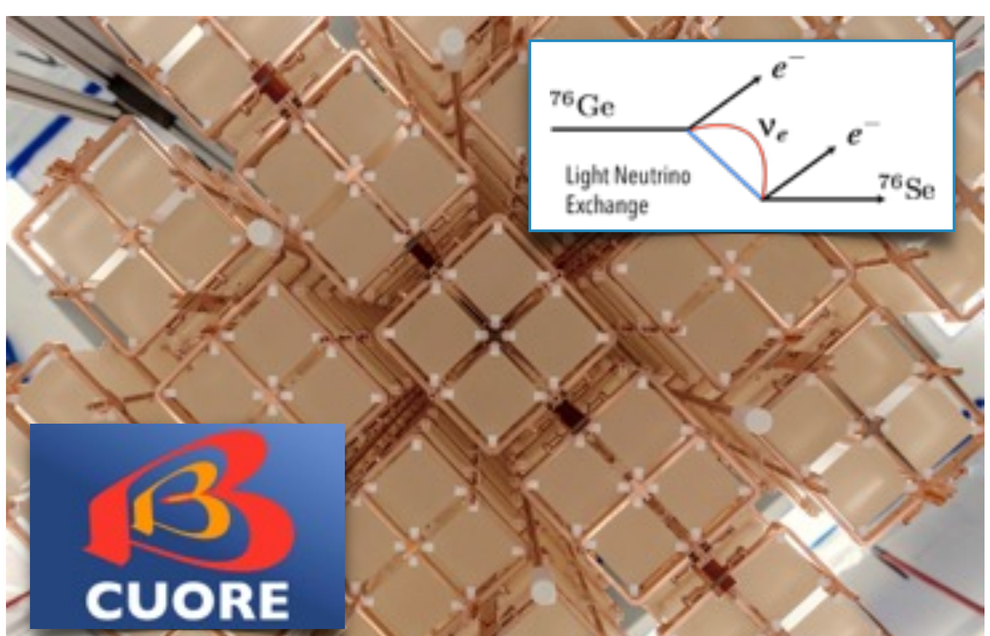


- Entanglement

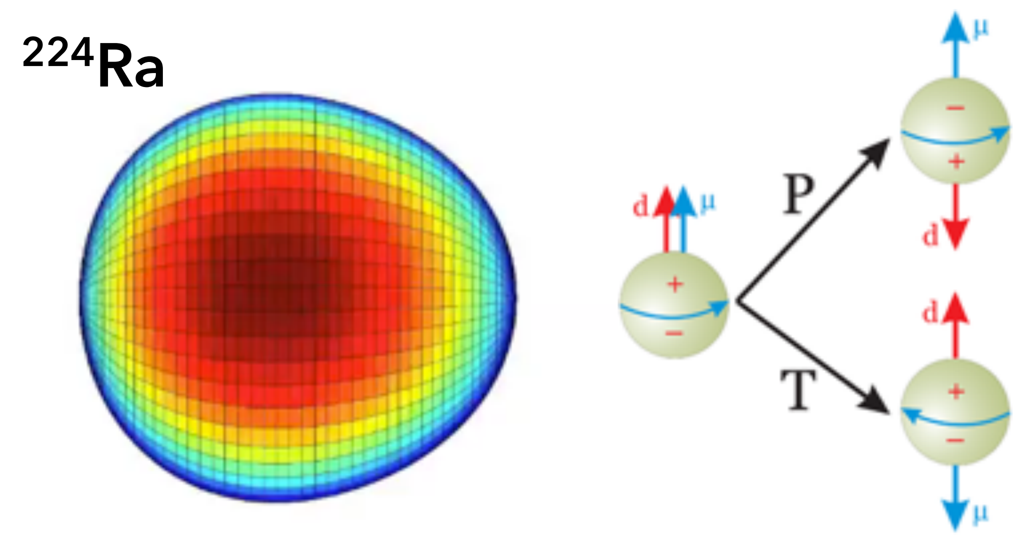




- Double beta decay



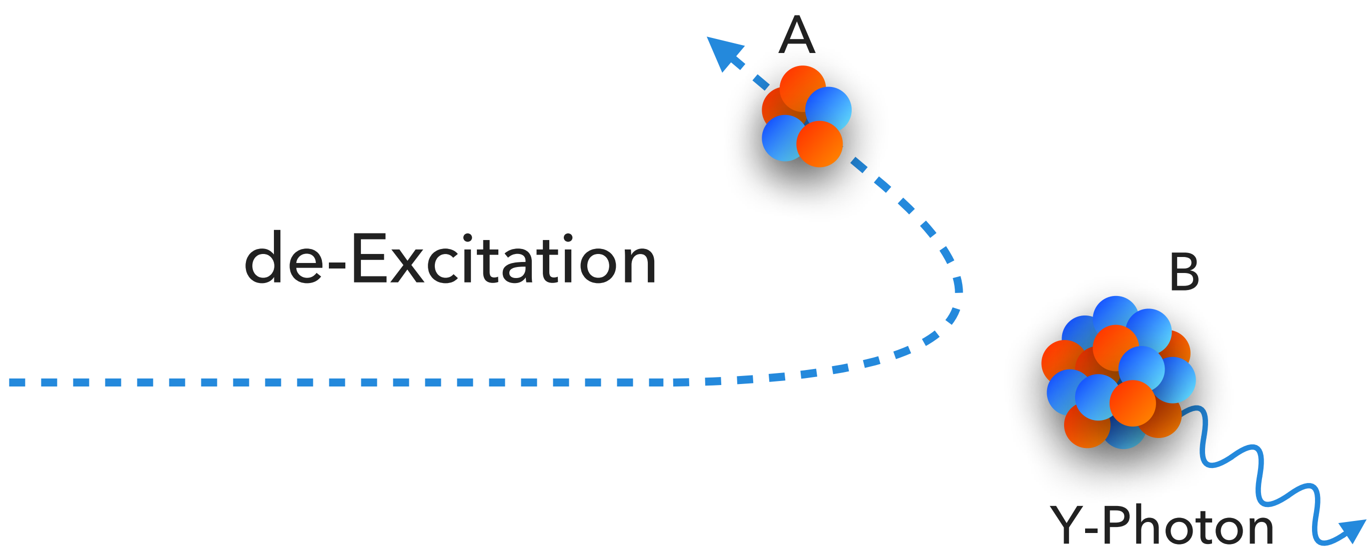
- Pear-Shaped Nuclei

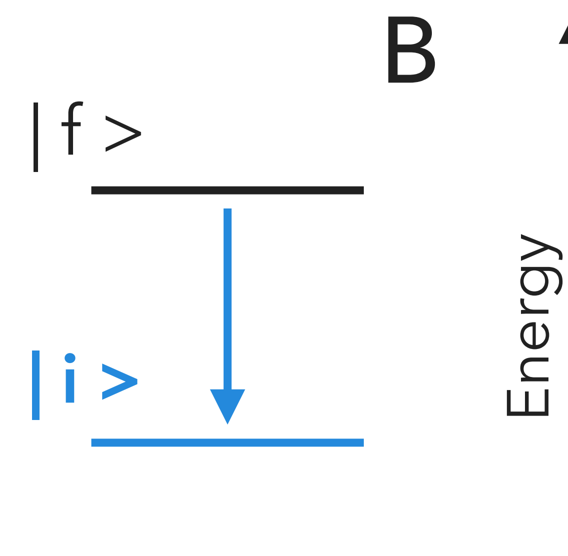


L. P. Gaffney et al., *Nature, 497* (2013) 199-204

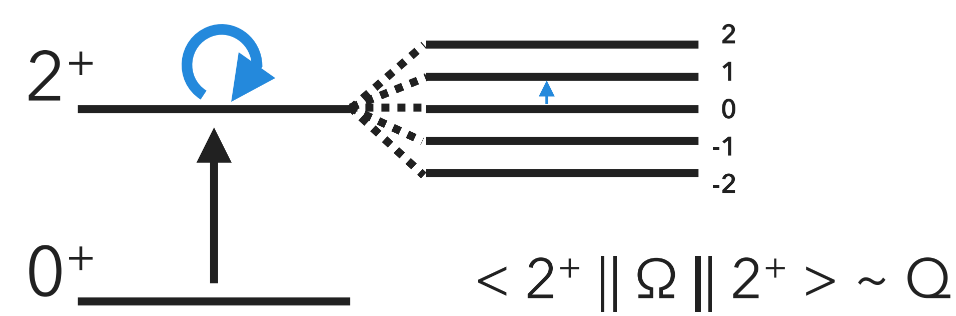
Low-Energy Coulomb Excitation

- Beam energy < Safe energy (~ 5 MeV/u)





- Excitation and de-excitation processes can be described using the electromagnetic operator
  - ME(non-diagonal) ~ 1 / τ
  - ME(diagonal) ~ Q



Low-Energy Coulomb Excitation

- Purely electromagnetic interaction –> Model independent analysis

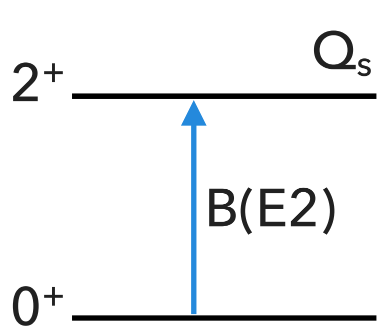
- Cross sections as a direct measure of electromagnetic matrix elements

$$\frac{d\sigma_{clx}}{d\Omega} = \frac{d\sigma_{Ruth}}{d\Omega} \cdot P\left(i \longrightarrow f\right)$$

  - Example: first 2^+ state in an even-even target nucleus

$\sim|\langle 2^+||E2||0^+\rangle|^2$ $\sim\langle 2^+||E2||2^+\rangle$

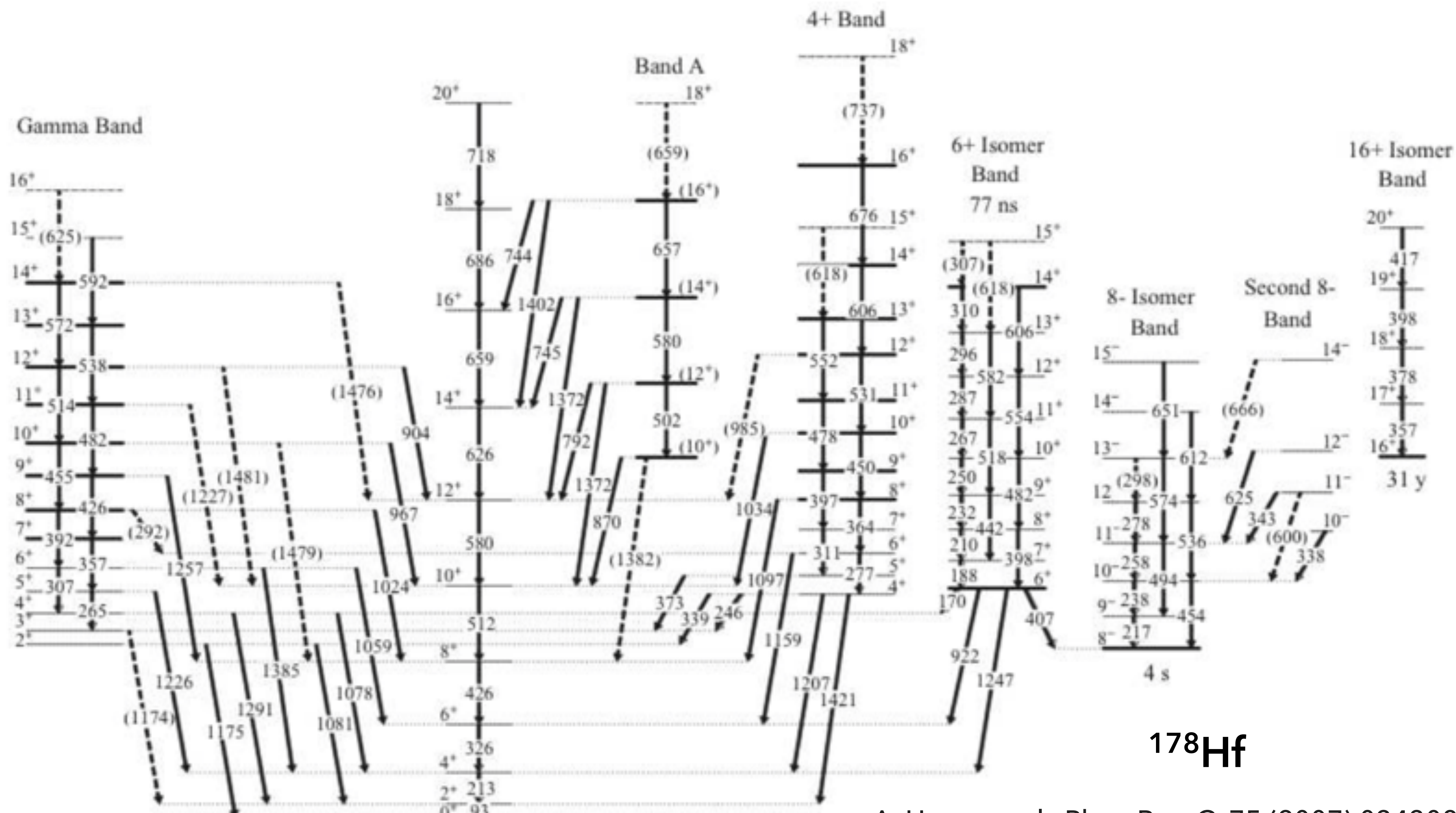
$$P\left(0_1^+ \longrightarrow 2_1^+\right) = F\left(\theta, E_P\right) B(E2) \left[1 + 1.32 \frac{A_P}{Z_T} \frac{\Delta E}{\left(1 + \frac{A_P}{A_T}\right)} Q_s\left(2^+\right) K\left(\theta, E_P\right)\right]$$



Access to: lifetimes, quadrupole moments

Low-Energy Coulomb Excitation

- Nuclear Models
- Gamma Spectroscopy
- Radioactive Beams
- Shape Phenomena
- Cross-Disciplinary Phenomena
- **Coulex**



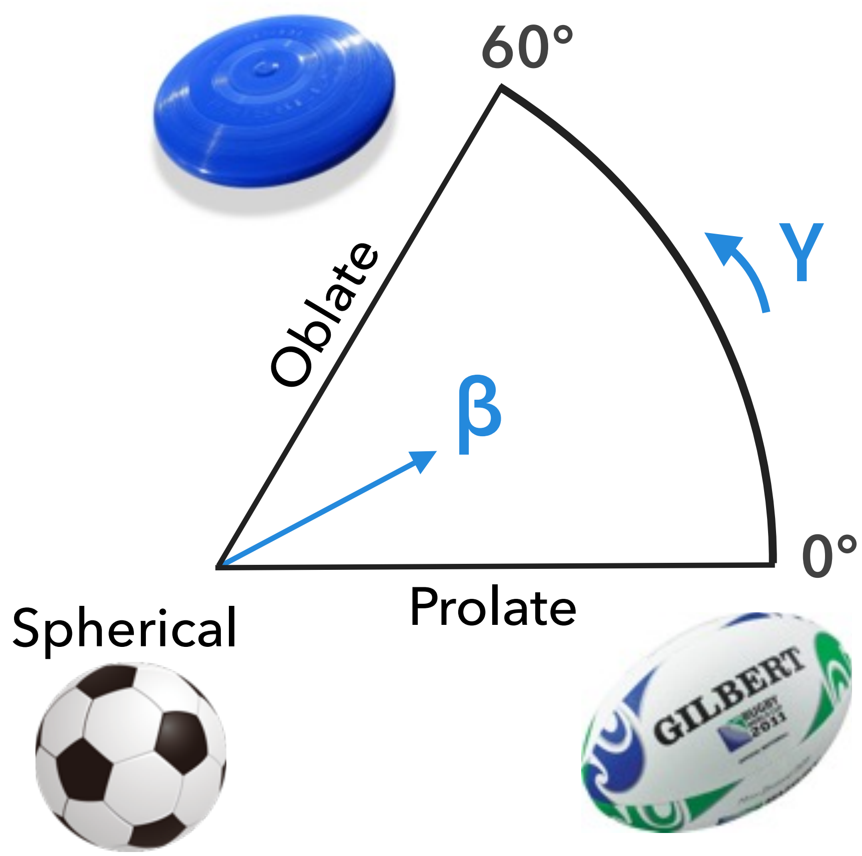
A. Hayes et al., Phys. Rev. C, 75 (2007) 034308

- Theory of the electromagnetic interaction well-known –> quantum Coulomb excitation cross section calculation possible, but complicate –> semiclassical approach

Low-Energy Coulomb Excitation

- Nuclear Shape (only quadrupole deformations):

$$R(\theta,\phi) = R_0 \left[1 + \beta \sqrt{\frac{5}{16\pi}} \left(\cos\gamma (3\cos^2\theta - 1) + \sqrt{3}\sin\gamma \sin^2\theta \cos 2\phi \right) \right]$$



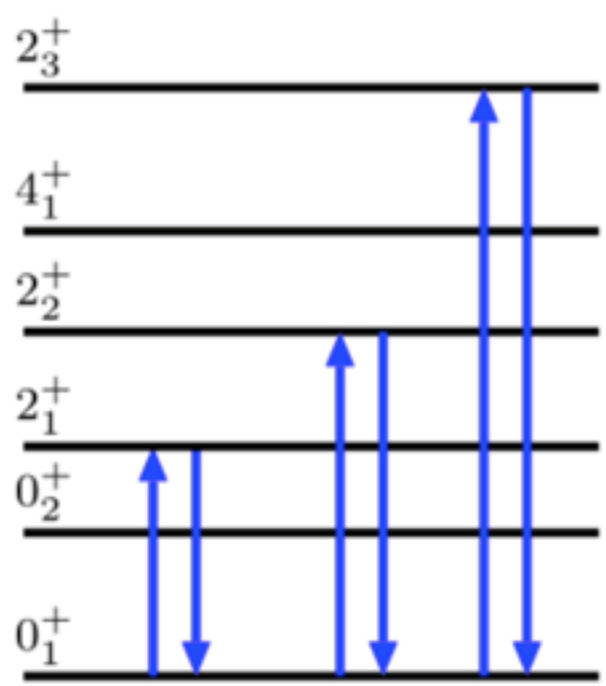
- Hill-Weeler parameters:
  - β –> amount of deformation
  - γ –> axial symmetry

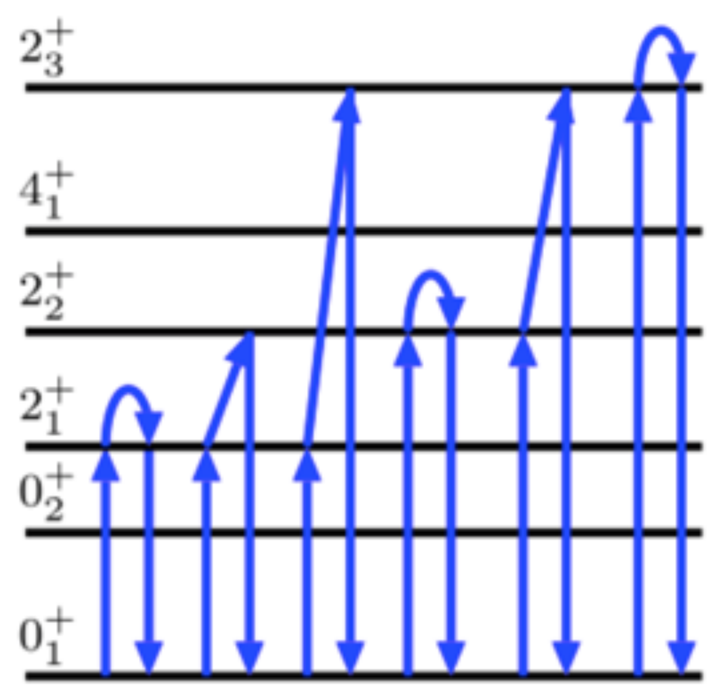
Low-Energy Coulomb Excitation

- Rotational invariant (only quadrupole deformations):

$$\langle \beta^2 \rangle = \frac{\sqrt{5}}{\sqrt{2I_i+1}} \sum_t \langle i \,||E2||\, t\rangle \langle t \,||E2||\, i\rangle \begin{Bmatrix} 2 & 2 & 0 \\ I_i & I_i & I_t \end{Bmatrix}$$

$$\langle \beta^{2/3} \cos(\gamma) \rangle = \frac{\sqrt{35}}{\sqrt{2}} \frac{1}{\sqrt{2I_i+1}} \sum_{tu} \langle i \,||E2||\, t\rangle \langle t \,||E2||\, u\rangle \langle u \,||E2||\, i\rangle \begin{Bmatrix} 2 & 2 & 2 \\ I_i & I_t & I_u \end{Bmatrix}$$





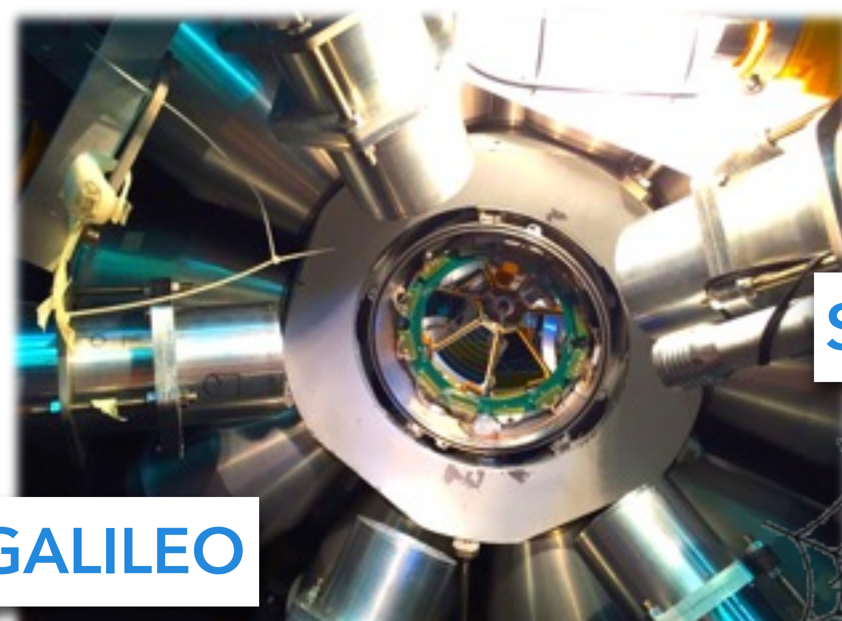
Experimental Set-Up

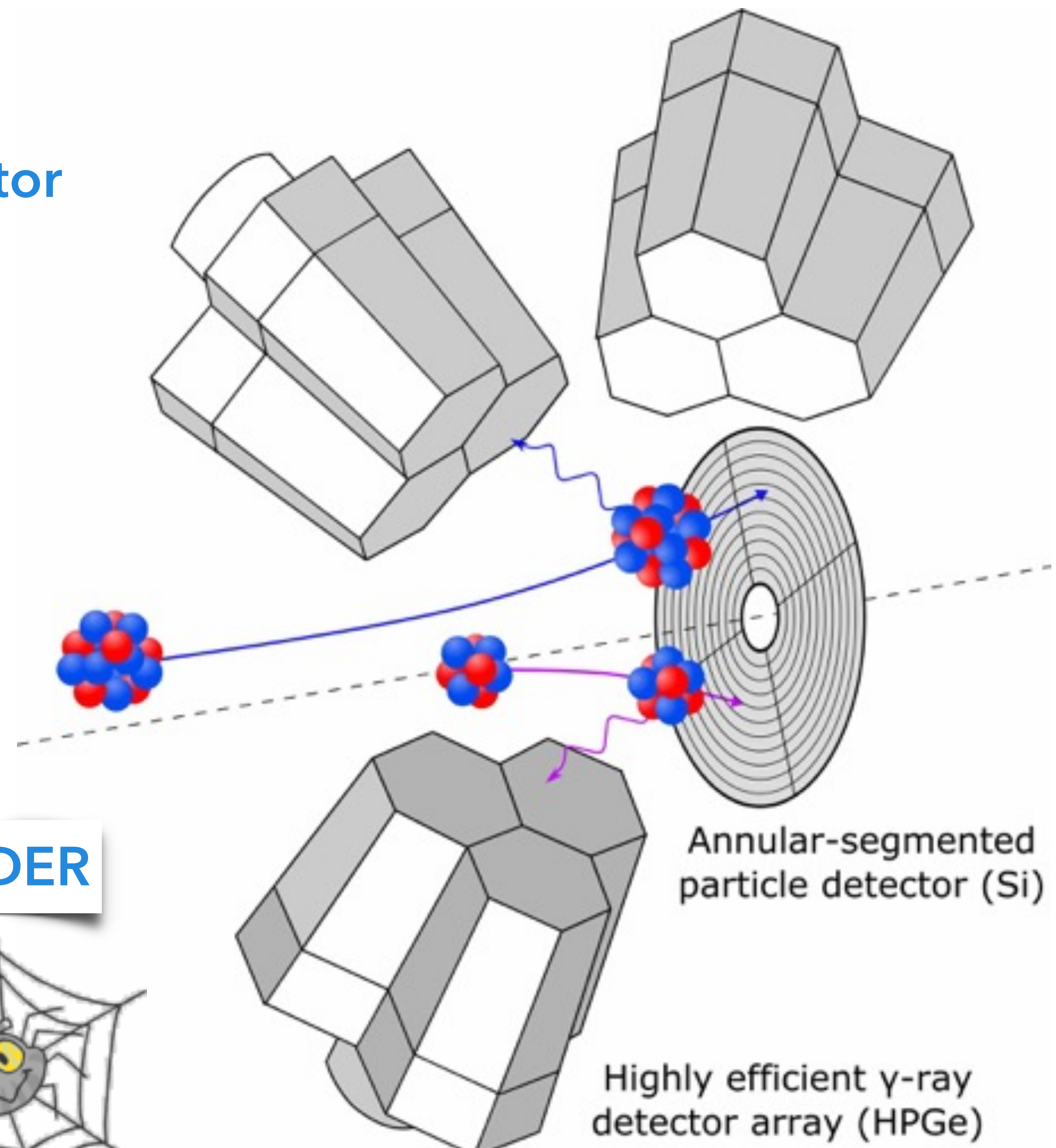
- Nuclear Models
- Gamma Spectroscopy
- Radioactive Beams
- Shape Phenomena
- Cross-Disciplinary Phenomena
- **Coulex**

Particle detector

Gamma detector

$$\frac{d\sigma_{clx}}{d\Omega} = \frac{d\sigma_{Ruth}}{d\Omega} \cdot P\,(i \longrightarrow f)$$

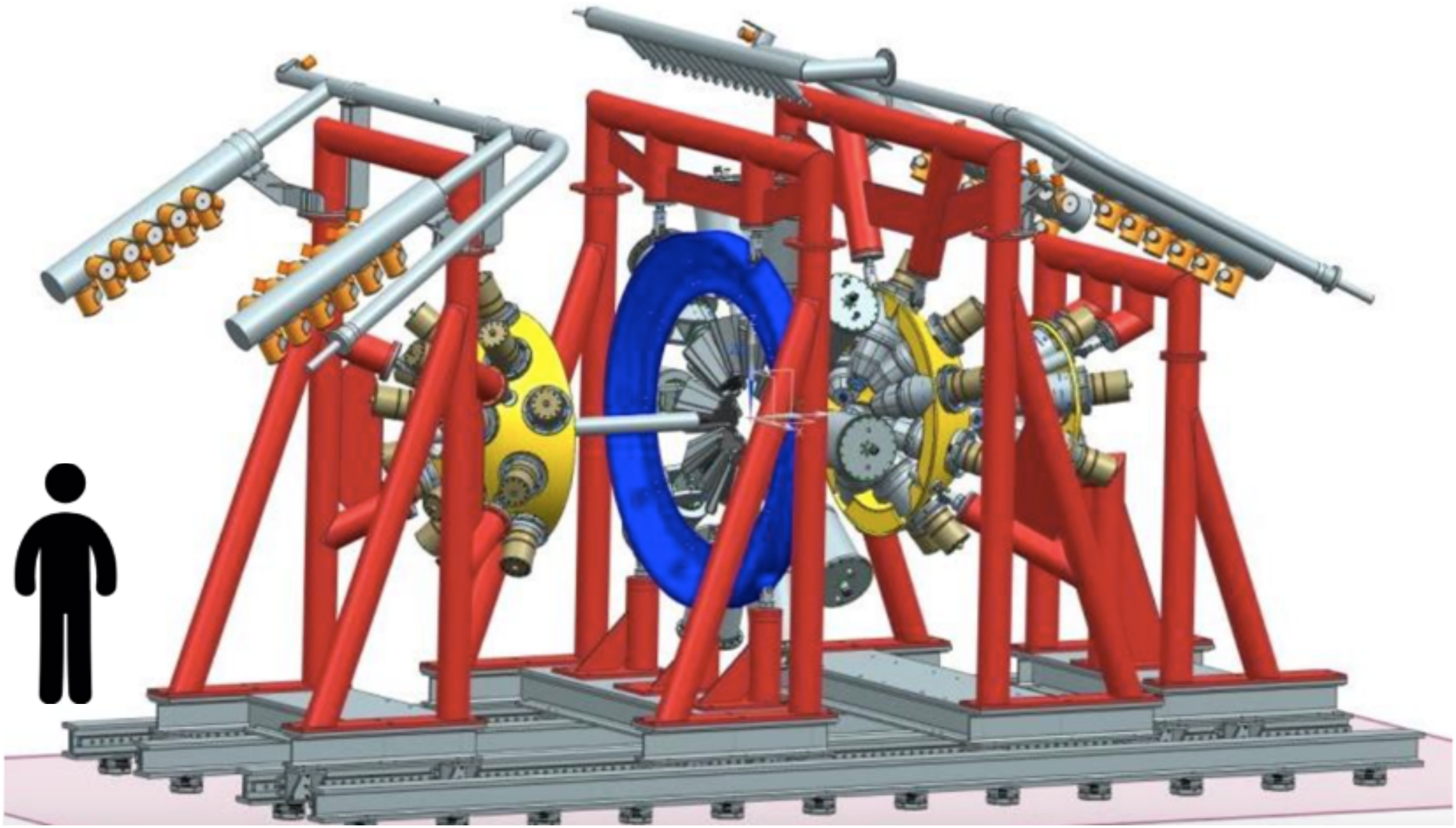




Courtesy of L. Gaffney

GALILEO@LNL (from July 2015)

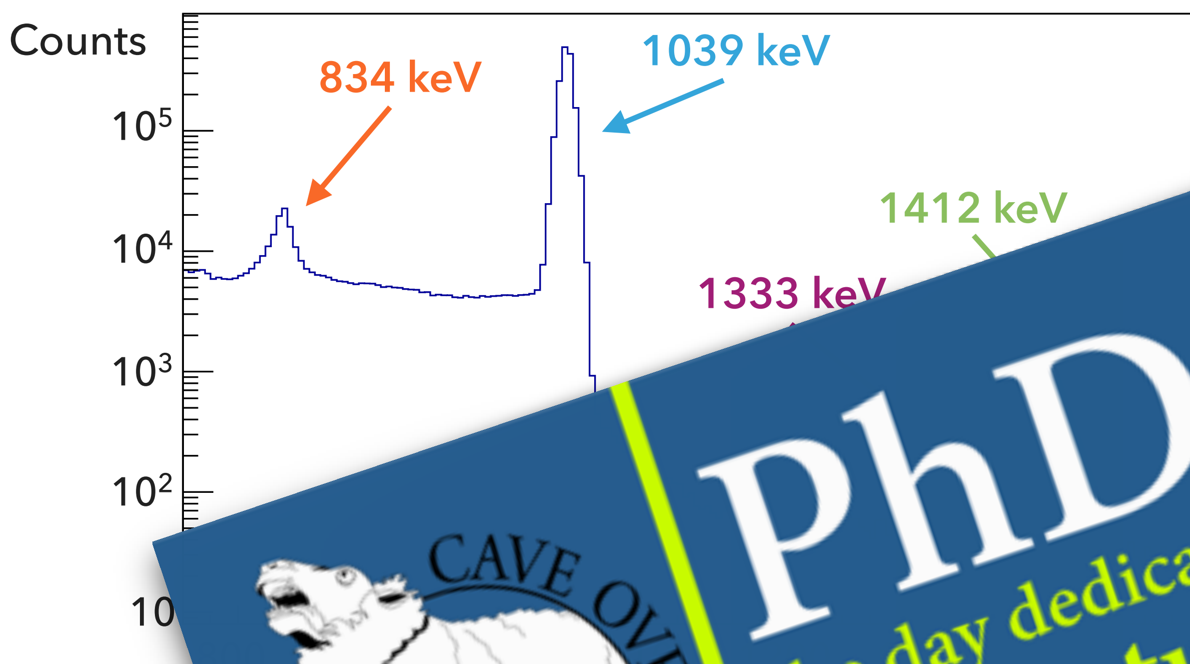
- Nuclear Models
- Gamma Spectroscopy
- Radioactive Beams
- Shape Phenomena
- Cross-Disciplinary Phenomena
- **Coulex**



Coulomb Excitation of ^{66}Zn

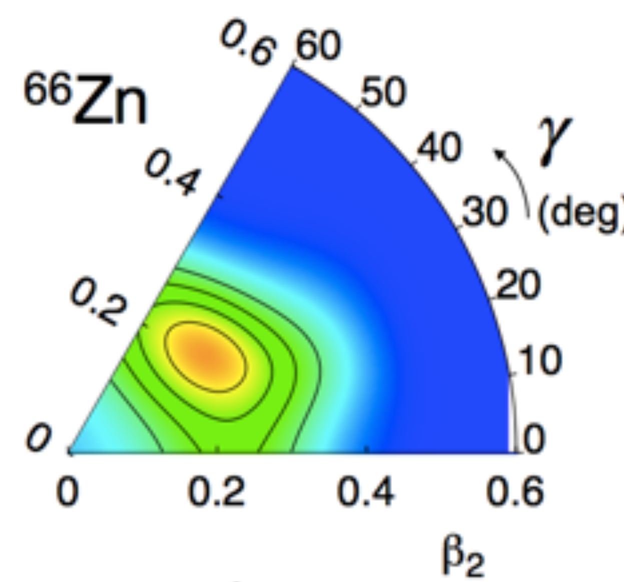
Spokespersons: M. Rocchini, K. Hadynska-Klek

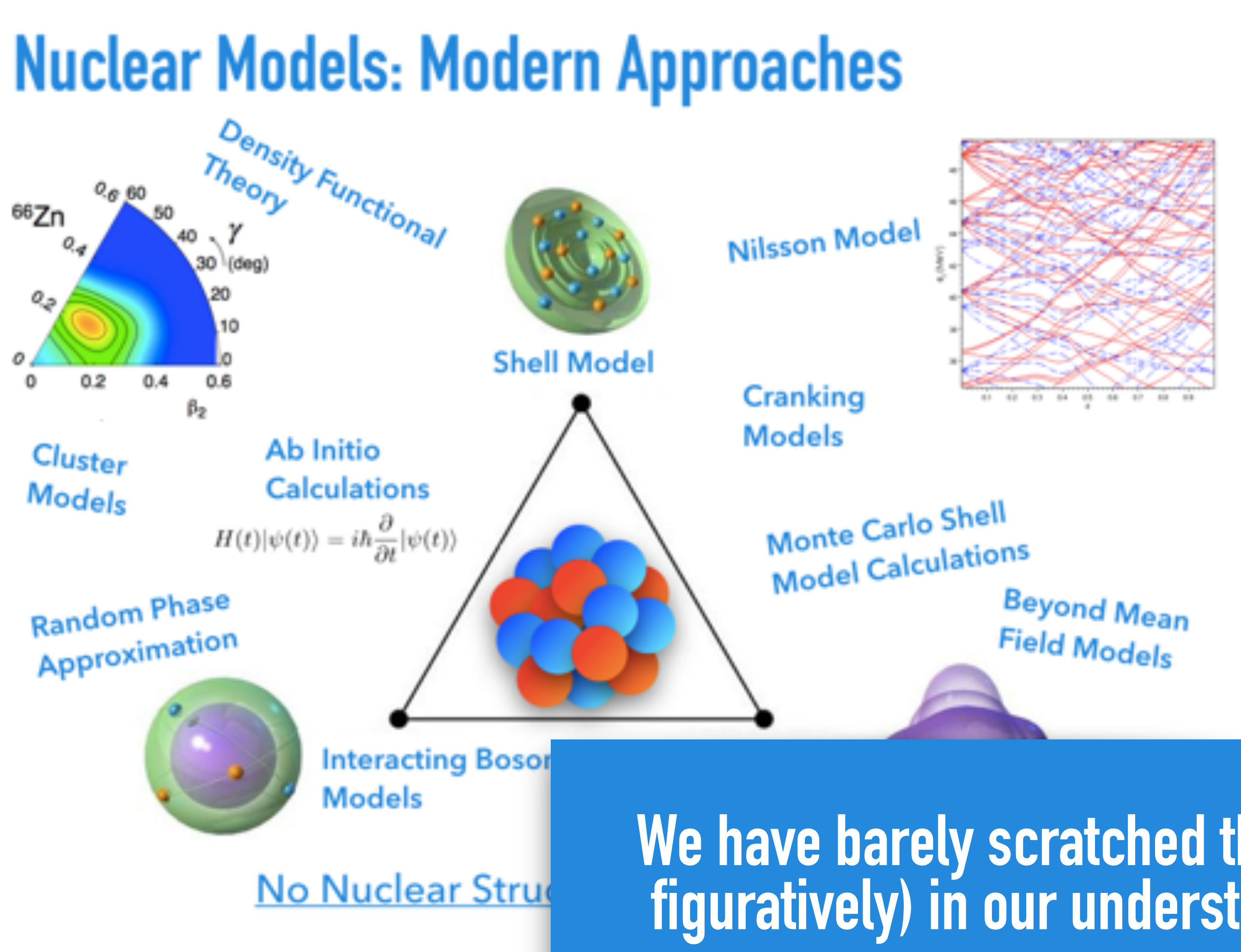
- Nuclear Models
- Gamma Spectroscopy
- Radioactive Beams
- Shape Phenomena
- Cross-Disciplinary Phenomena
- **Coulex**



Matrix E... ...ents)

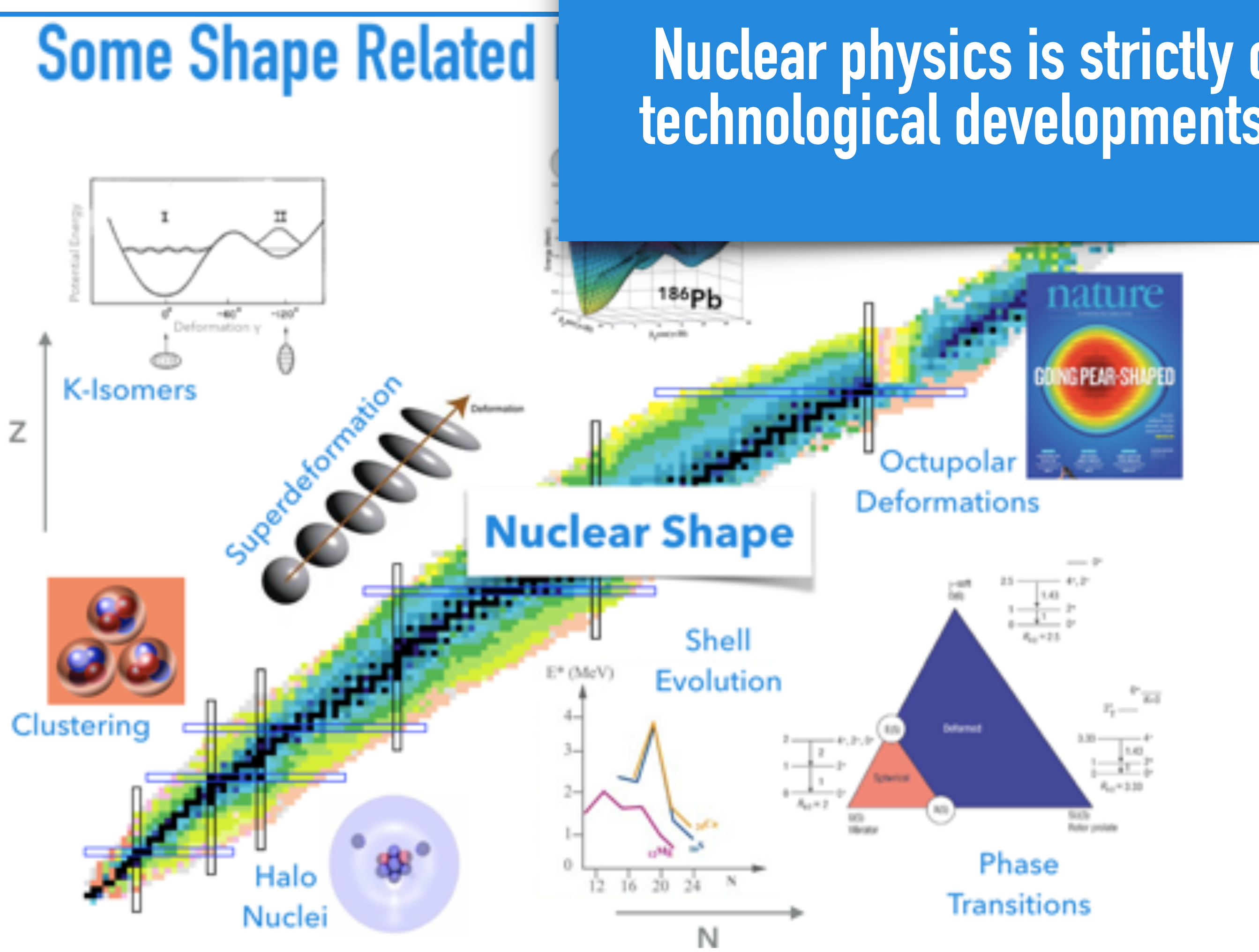
1	1					-4.6 ,	5.3 PC
2	1					-15.2 ,	8.0 PC
3	2				16563)......	-44.9 ,	49.1 PC
4	2				0.01236)......	-9.9 ,	3.7 PC
5	2			02460 ,	0.05938)......	-4.6 ,	11.0 PC
6	2			(-0.00468 ,	0.00408)......	-11.2 ,	9.8 PC
7	2		00015	(-0.00015 ,	0.02752)......	-0.2 ,	45.7 PC
8	3		0.55894	(-0.35786 ,	0.17071)......	-64.0 ,	30.5 PC
9	3	4	-0.34562	(-0.57513 ,	0.05223)......	-166.4 ,	15.1 PC
10	3	5	-0.02949	(-0.15448 ,	0.13641)......	-523.9 ,	462.6 PC
11	3	6	-1.75533	(-0.21725 ,	0.23537)......	-12.4 ,	13.4 PC
12	4	4	0.33748	(-3.96751 ,	3.34237)......	-1175.6 ,	990.4 PC
13	5	5	-0.36536	(-0.04751 ,	0.12229)......	-13.0 ,	33.5 PC
14	5	6	0.23265	(-0.03493 ,	0.01998)......	-15.0 ,	8.6 PC
15	5	7	0.04449	(-0.06472 ,	0.03224)......	-145.5 ,	72.5 PC
16	7	8	-0.26855	(-0.23476 ,	0.96819)......	-87.4 ,	360.5 PC
17	2	5	-0.21918	(-0.34817 ,	0.13816)......	-158.9 ,	63.0 PC

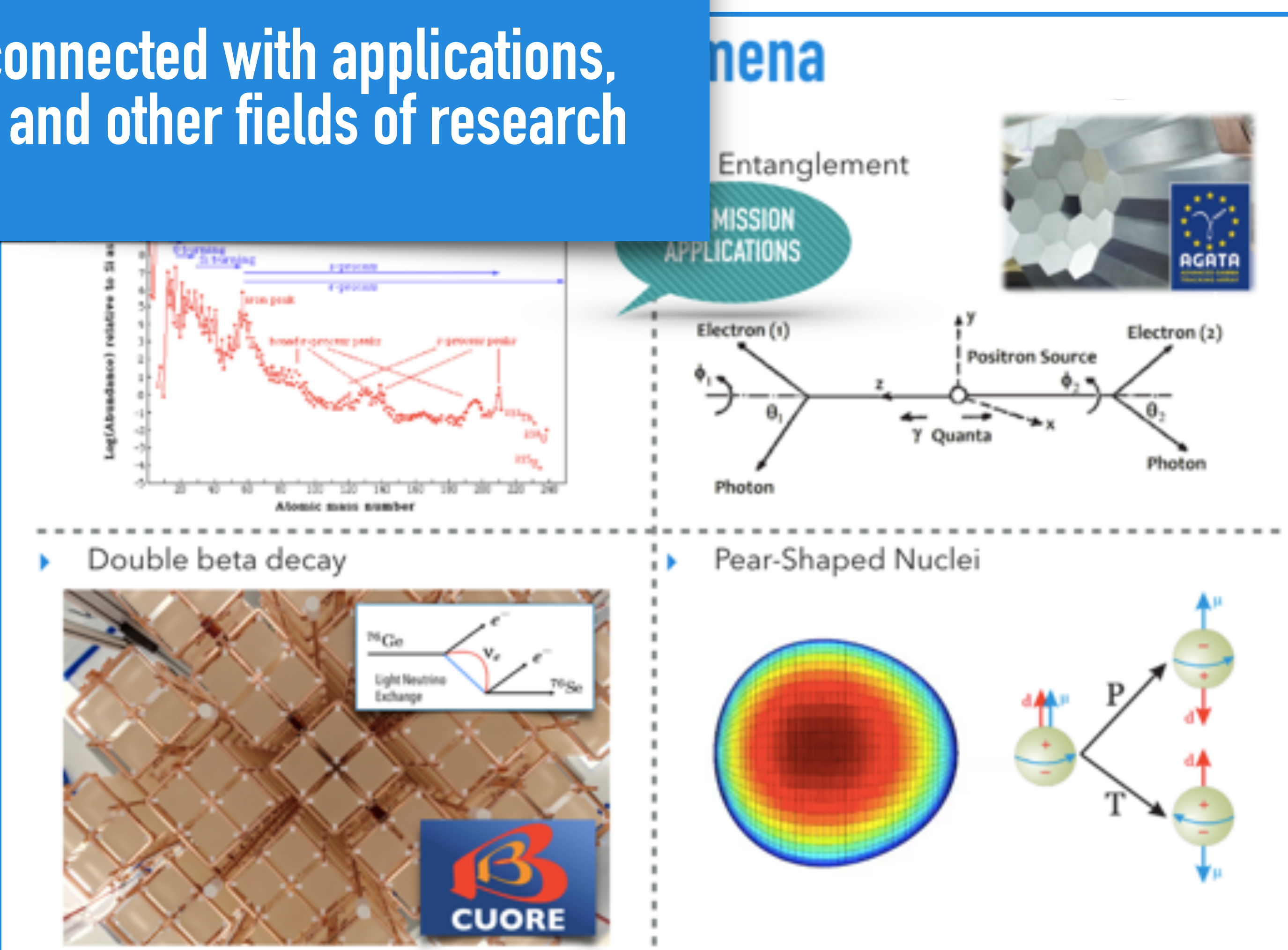




We have barely scratched the surface (both literally and figuratively) in our understanding of nuclear structure.

Nuclear physics is strictly connected with applications, technological developments and other fields of research





THANK YOU FOR THE ATTENTION

Hulk VS GAMMASPHERE

Florence Future Experiments (2017)

Spokespersons	Subject	Where
D. T. Doherty, M. Rocchini, M. Zielinska	Probing collectivity and configuration coexistence in ^{94}Zr with low-energy Coulomb excitation	LNL, Italy
B. Melon, A. Nannini	Conversion electron measurements in light Se isotopes: shape coexistence in ^{74}Se	LNL, Italy
D. T. Doherty, J. Ljungvall	Probing shape coexistence in neutron-deficient ^{72}Se via low-energy Coulomb excitation	ISOLDE, CERN
M. Saxena, R. Kumar	Coulomb excitation of ^{118}Sn	HIL, Poland
W. Korten, J. Smallcombe	Search for low-lying 0^+ states in ^{70}Se	TRIUMF, Canada

Possible Thesis: marco.rocchini@fi.infn.it, nannini@fi.infn.it