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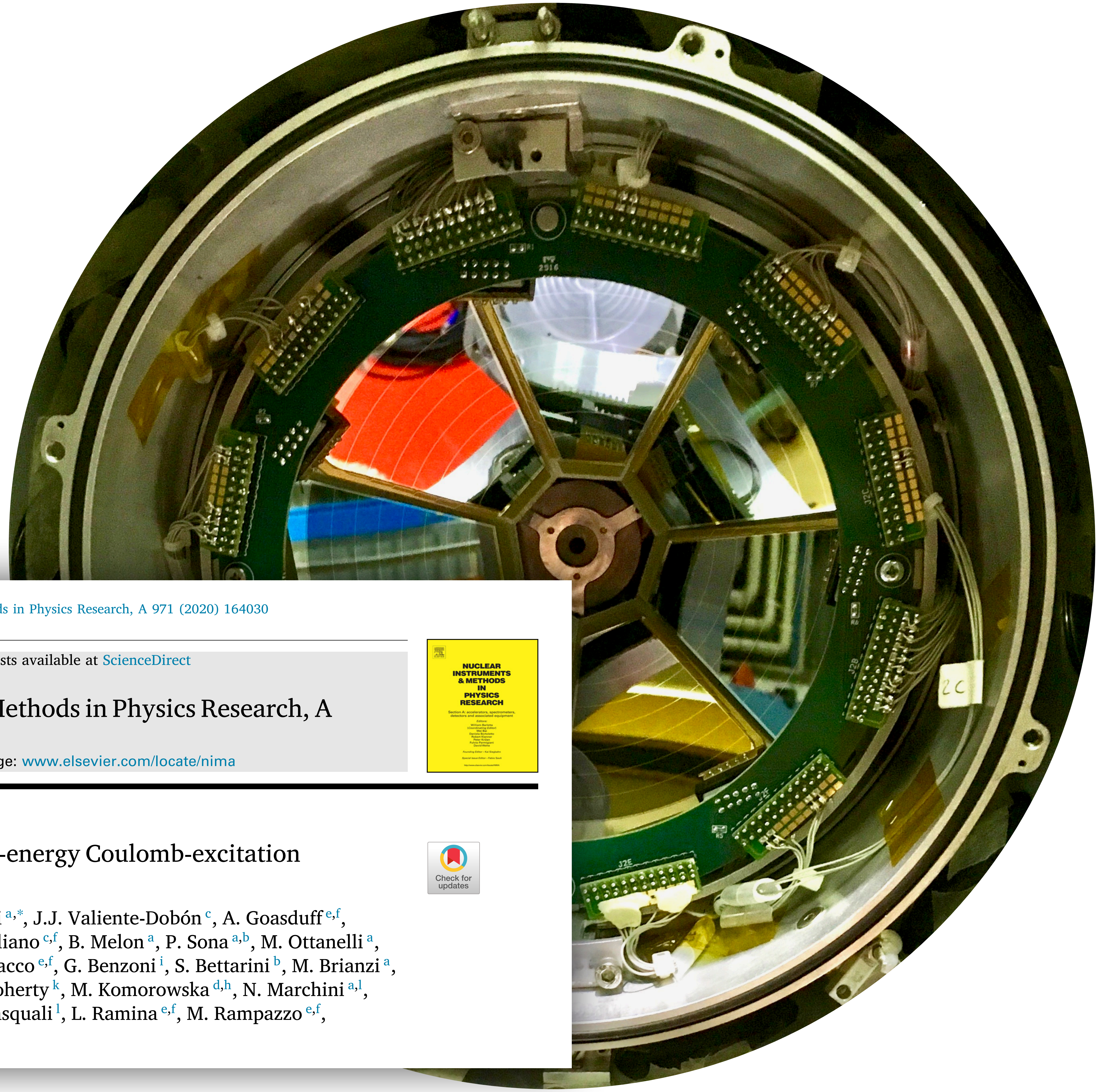
FIRENZE DIVISION

SPIDER:
the Silicon PIe DEtectoR

Outline

- Low-energy Coulomb excitation
- Shape of ground and excited states via Coulomb excitation
- What is SPIDER?
  - Energy resolution, modularity, simulations
- Pulse height correlations
- Radiation damage
- Online RBS analysis with SPIDER
- The GALILEO campaign
- The AGATA campaign



Nuclear Inst. and Methods in Physics Research, A 971 (2020) 164030

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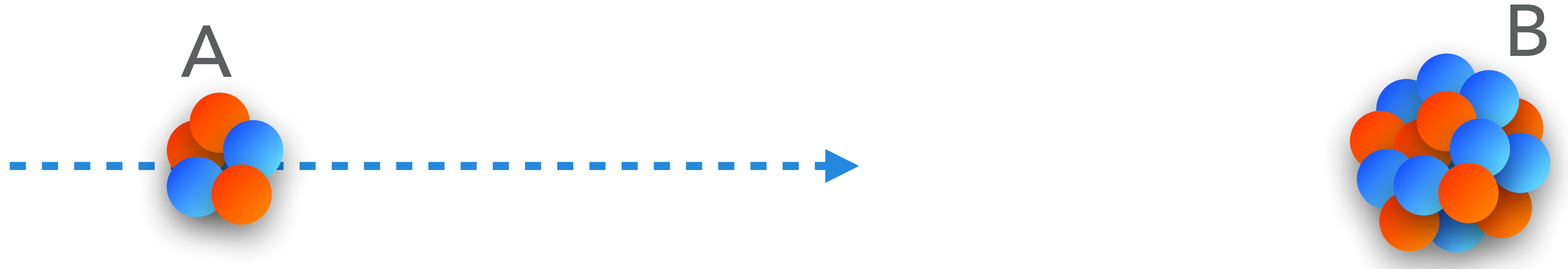
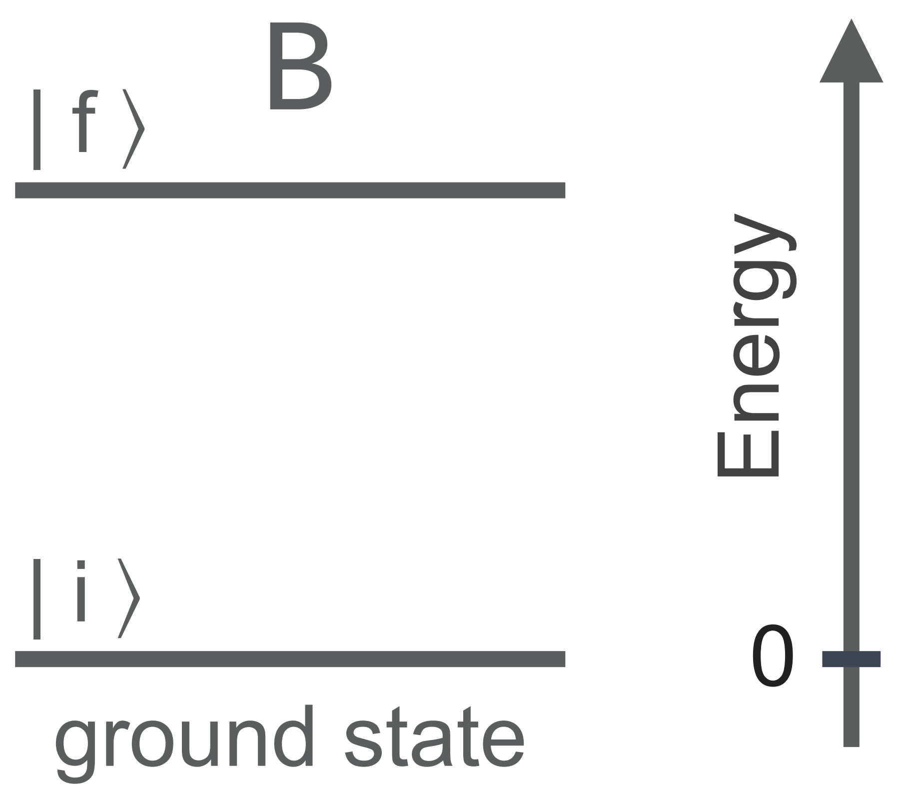
SPIDER: A Silicon PIe DEtectoR for low-energy Coulomb-excitation measurements

M. Rocchini[a,b,1], K. Hadyńska-Klęk[c,d], A. Nannini[a,*], J.J. Valiente-Dobón[c], A. Goasduff[e,f], D. Testov[e,f], D. Mengoni[e,f], P.R. John[e,f,g], M. Siciliano[c,f], B. Melon[a], P. Sona[a,b], M. Ottanelli[a], A. Perego[a,b], M. Chiari[a,b], M. Zielińska[h], D. Bazzacco[e,f], G. Benzoni[i], S. Bettarini[b], M. Brianzi[a], F. Camera[i,j], P. Cocconi[c], C. Czelusniak[a], D.T. Doherty[k], M. Komorowska[d,h], N. Marchini[a,l], M. Matejska-Minda[d,m], P.J. Napiorkowski[d], E. Pasquali[l], L. Ramina[e,f], M. Rampazzo[e,f], F. Recchia[e,f], D. Rosso[c], L. Sottili[b], A. Tredici[b]

Low-Energy Coulomb Excitation

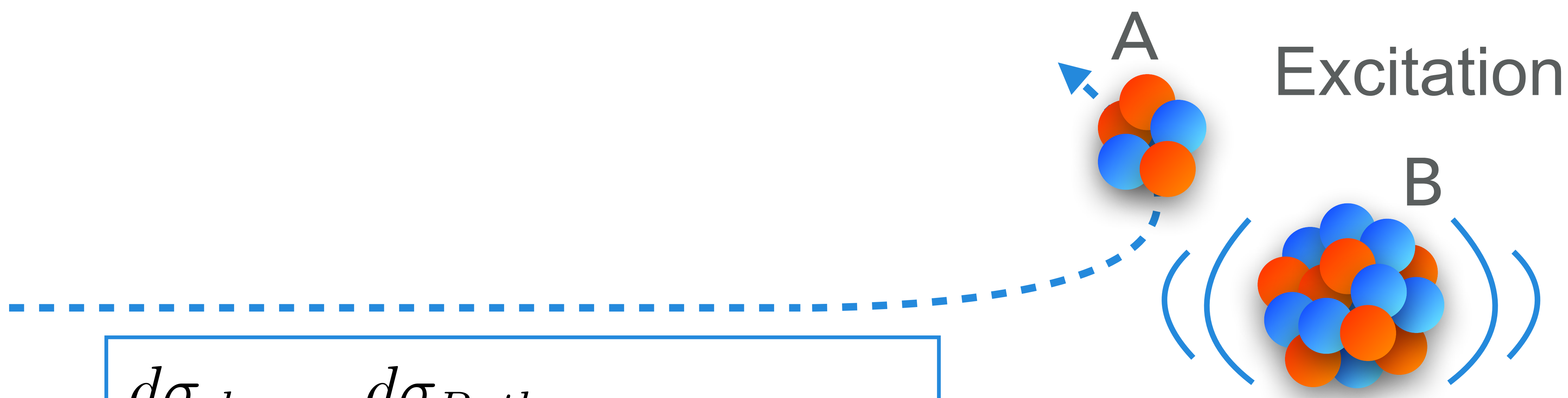
- Inelastic scattering between two interacting nuclei, in the “purely” electromagnetic regime



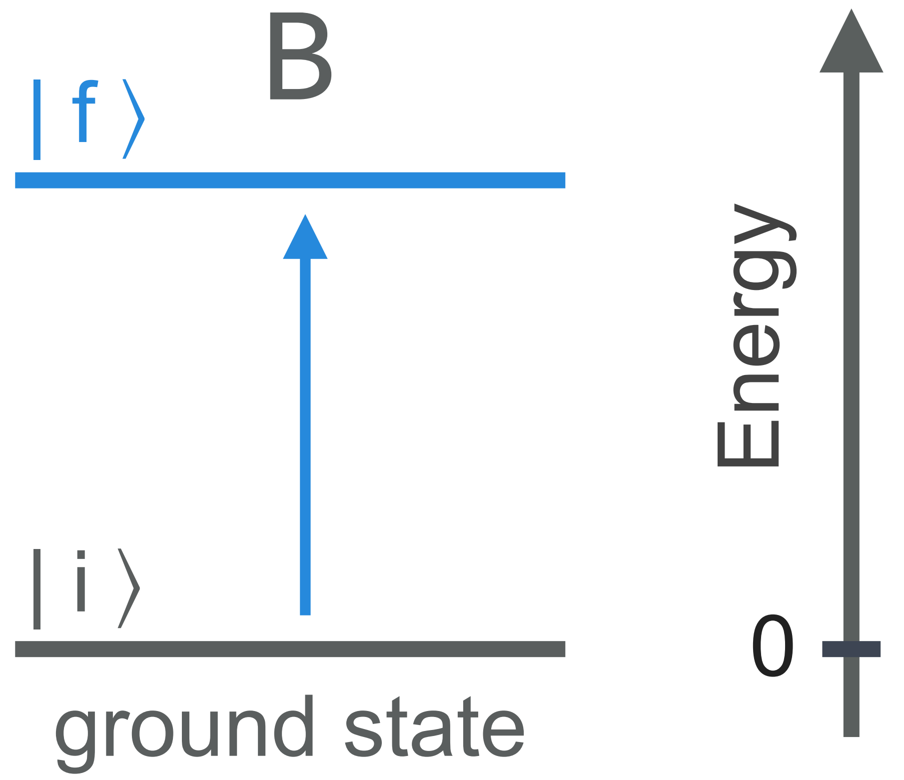


Low-Energy Coulomb Excitation

- Inelastic scattering between two interacting nuclei, in the "purely" electromagnetic regime
- The time-dependent electromagnetic field between the two nuclei can induce excitations



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



Low-Energy Coulomb Excitation

Low-Energy Coulomb Excitation
SPIDER
Pulse Height Correlations
Radiation Damage
Online Target Analysis
The GALILEO Campaign
The AGATA Campaign

- Inelastic scattering between two interacting nuclei, in the "purely" electromagnetic regime
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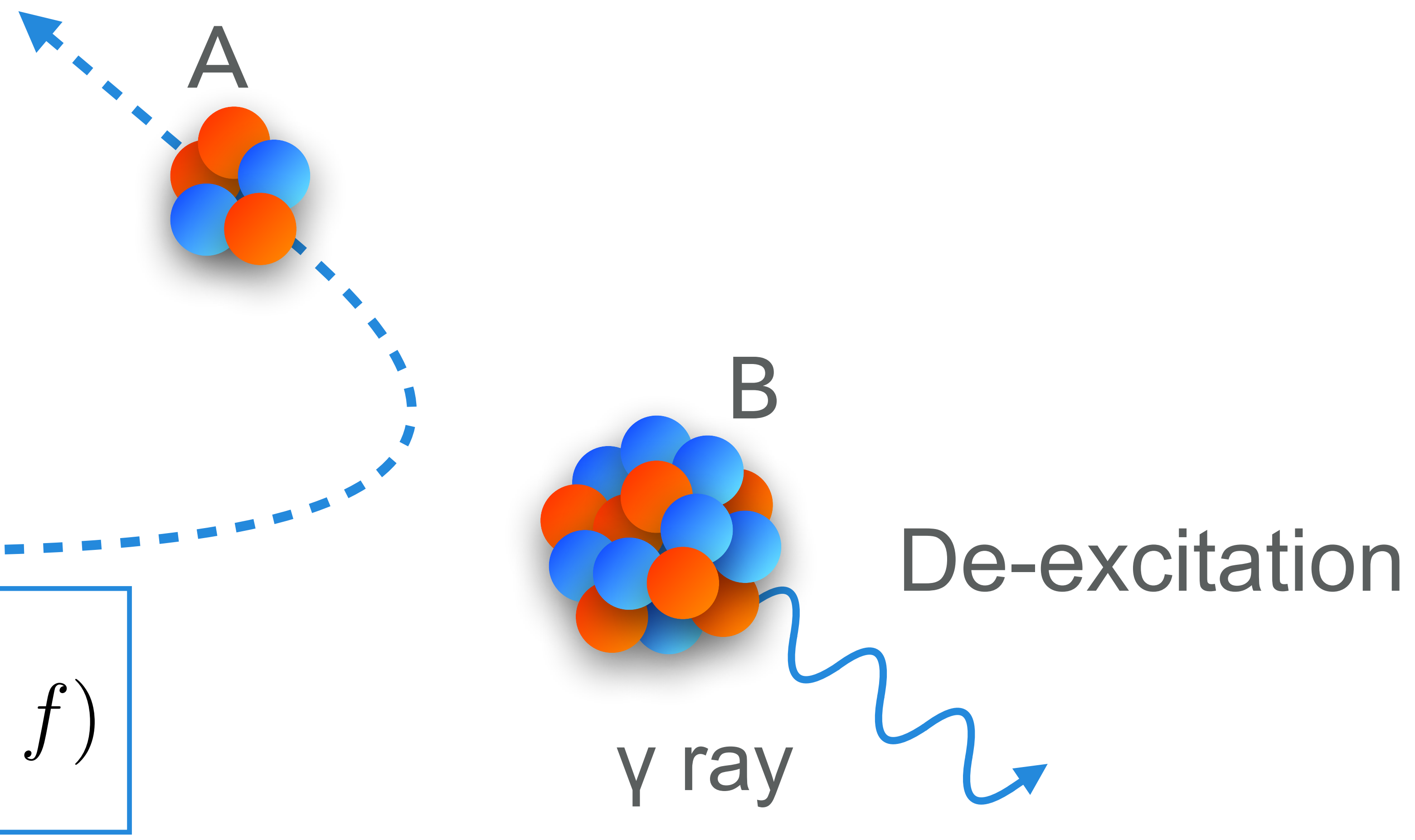
- The nuclei then de-excite; in Coulex we are mostly interested in γ-ray emission



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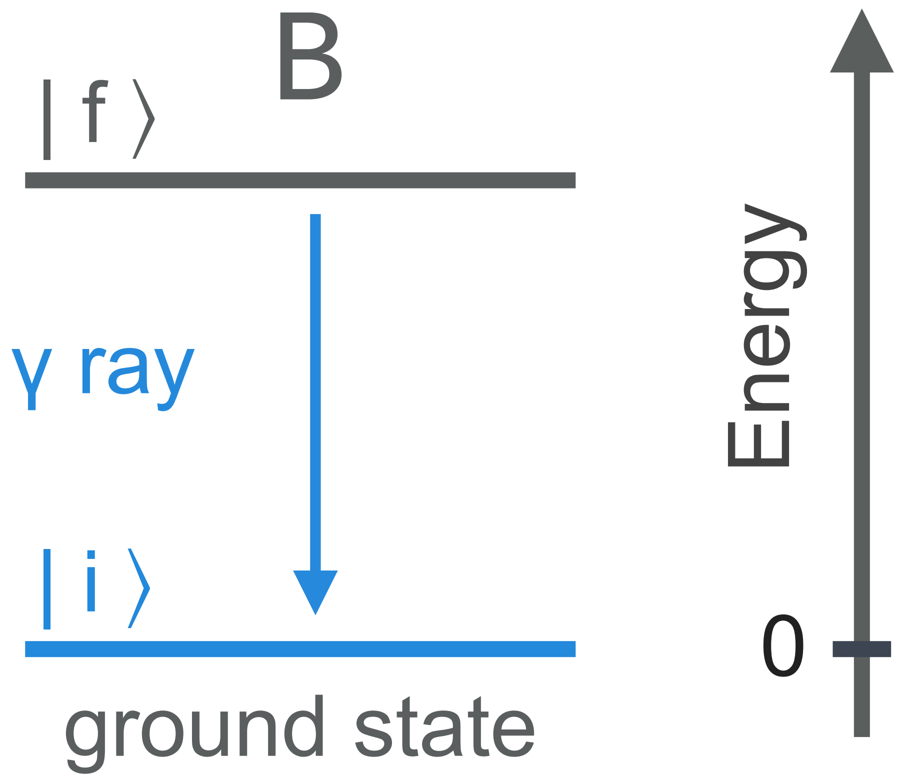

- Example: first 2+ state in an even-even target nucleus

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

Low-Energy Coulomb Excitation

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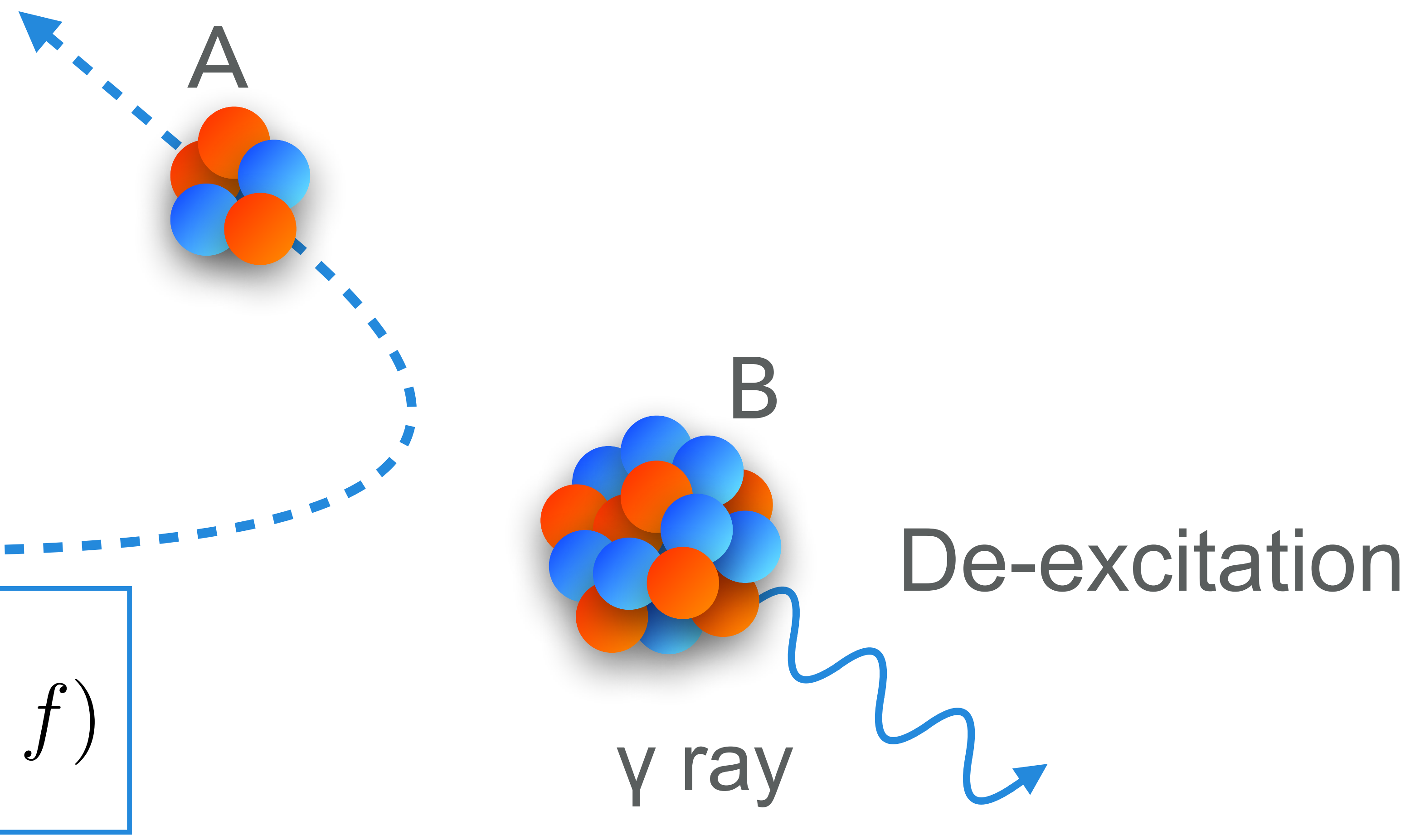
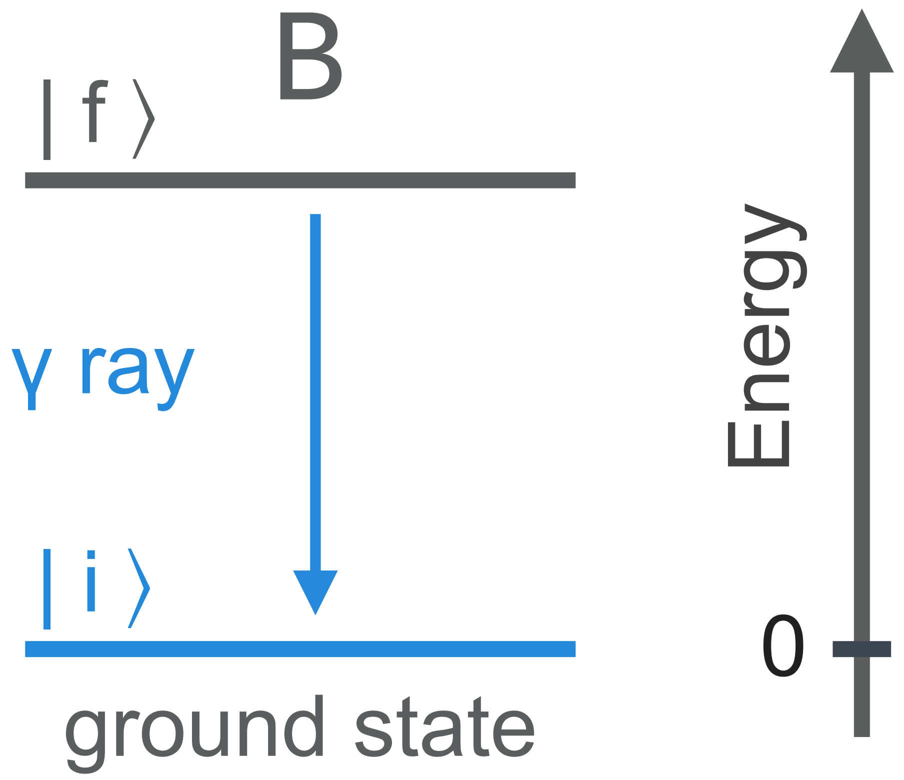




$$\frac{d\sigma_{clx}}{d\Omega} = \frac{d\sigma_{Ruth}}{d\Omega} \cdot P\left(i \longrightarrow f\right)$$

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

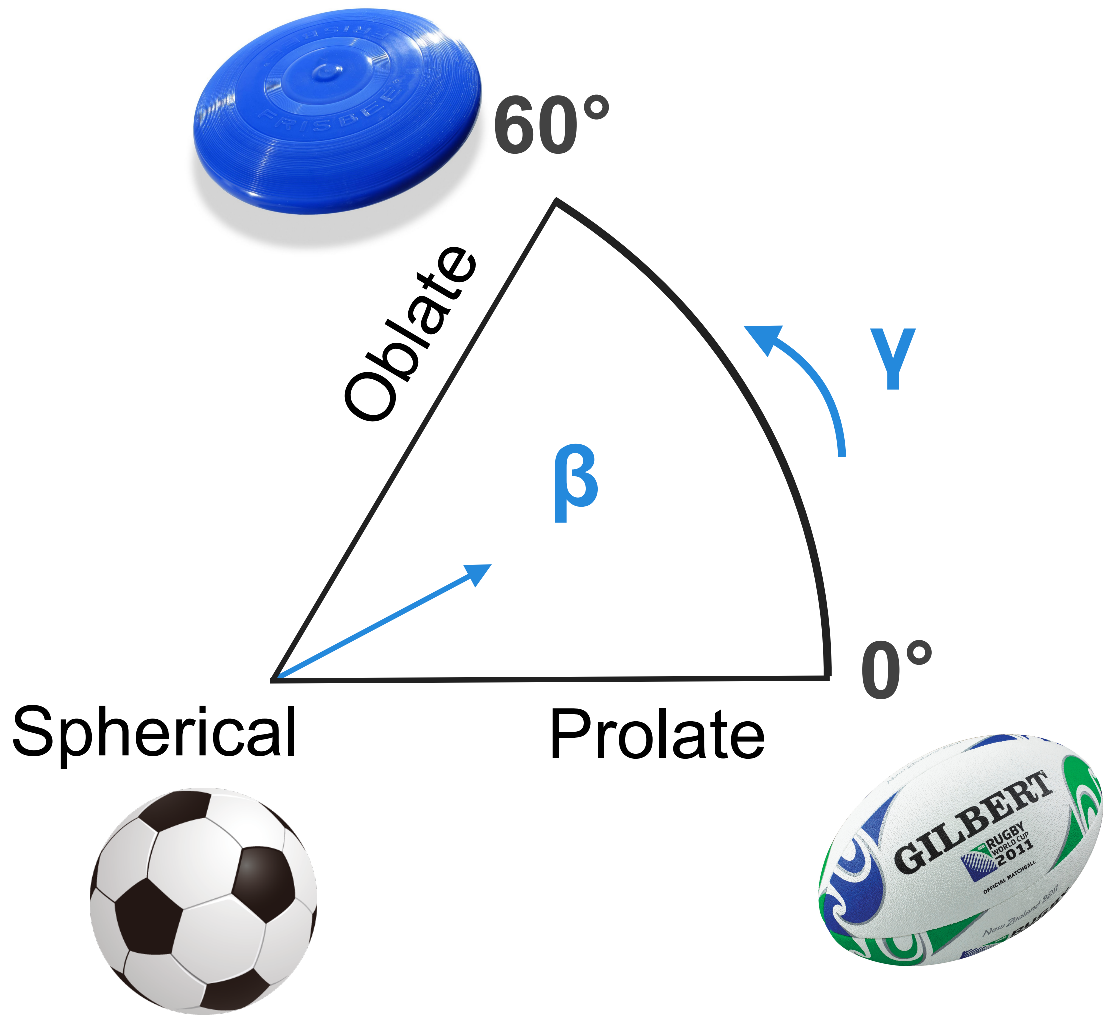
~|⟨2+||E2||0+⟩|²   ~⟨2+||E2||2+⟩

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

Access to: transition probabilities, spectroscopic quadrupole moments

Quadrupole Sum Rules

- Unique feature of low-energy Coulomb excitation ⟹ Possible to get relative signs of transitional matrix elements, and spectroscopic quadrupole moments of excited states with their sign
- Quadrupole Sum Rules ⟹ (β, γ) deformation parameters for g.s. and excited states in a model-independent way



K. Kumar, Phys. Rev. Lett. 28 (1972) 249 & D. Cline, Annu. Rev. Nucl. Part. Sci. 36 (1986) 683

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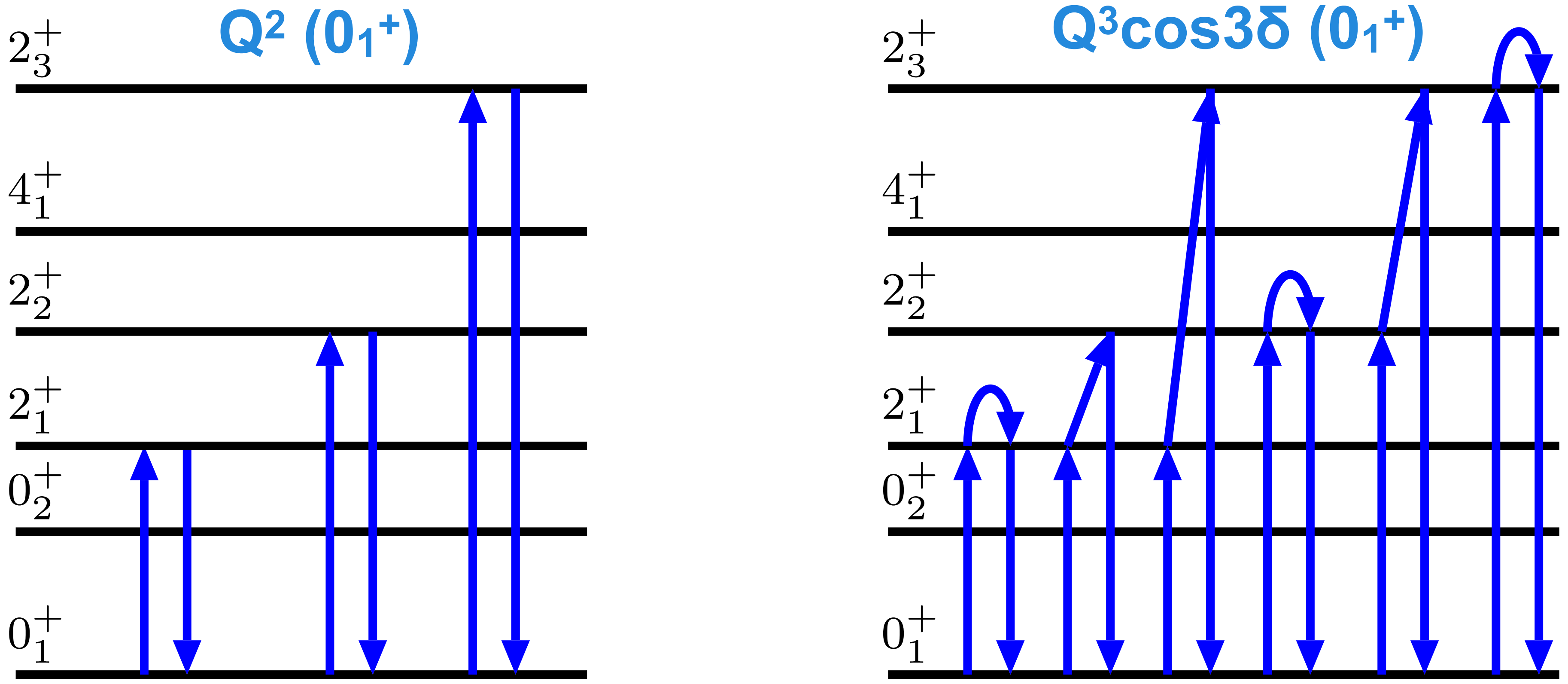
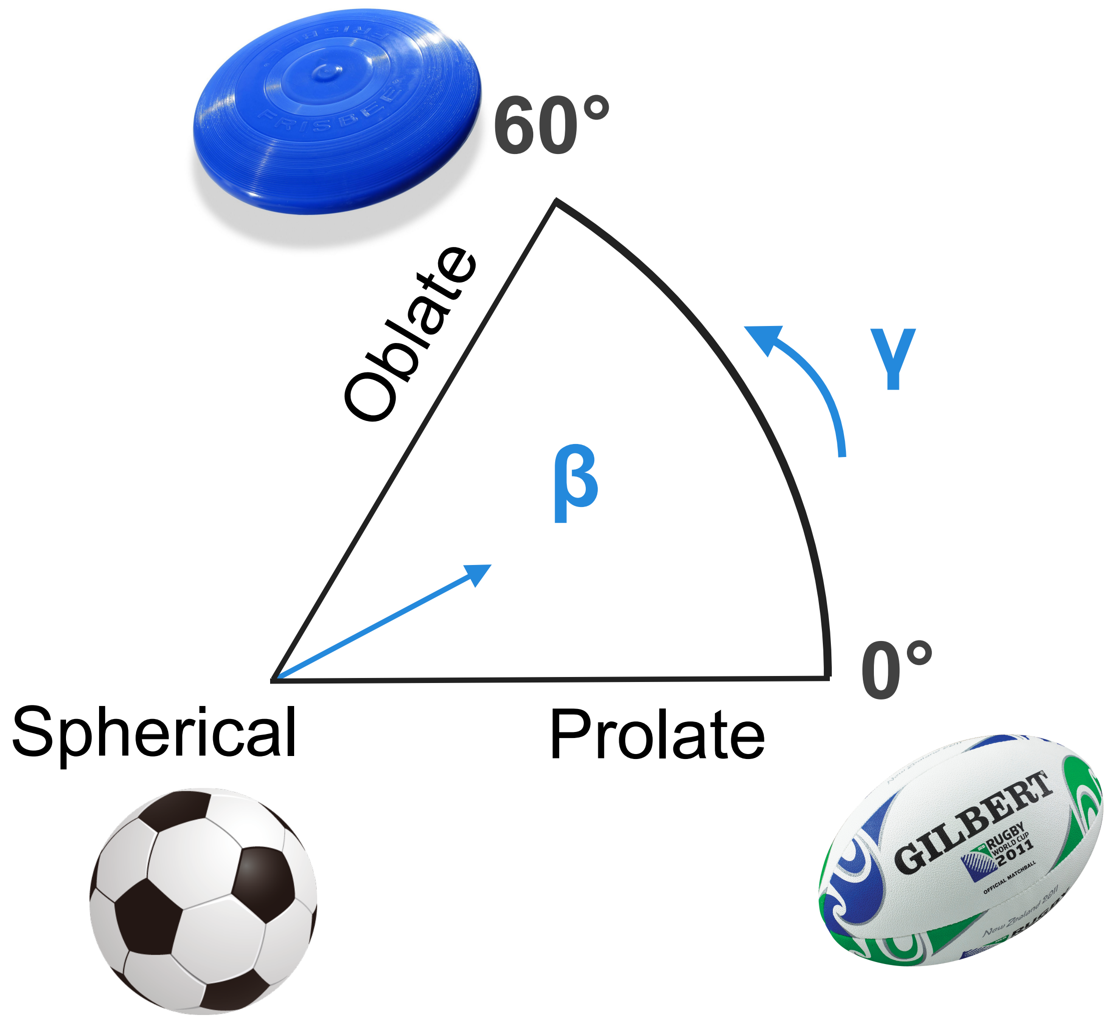
- Quadrupole Sum Rules ⟹ (β, γ) deformation parameters for g.s. and excited states in a model-independent way

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

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

(Q, δ) equivalent to (β, γ)





K. Kumar, Phys. Rev. Lett. 28 (1972) 249 & D. Cline, Annu. Rev. Nucl. Part. Sci. 36 (1986) 683

Excited 0+ States in Mid-Mass Nuclei

Low-Energy Coulomb Excitation

SPIDER

Pulse Height Correlations

Radiation Damage

Online Target Analysis

The GALILEO Campaign

The AGATA Campaign

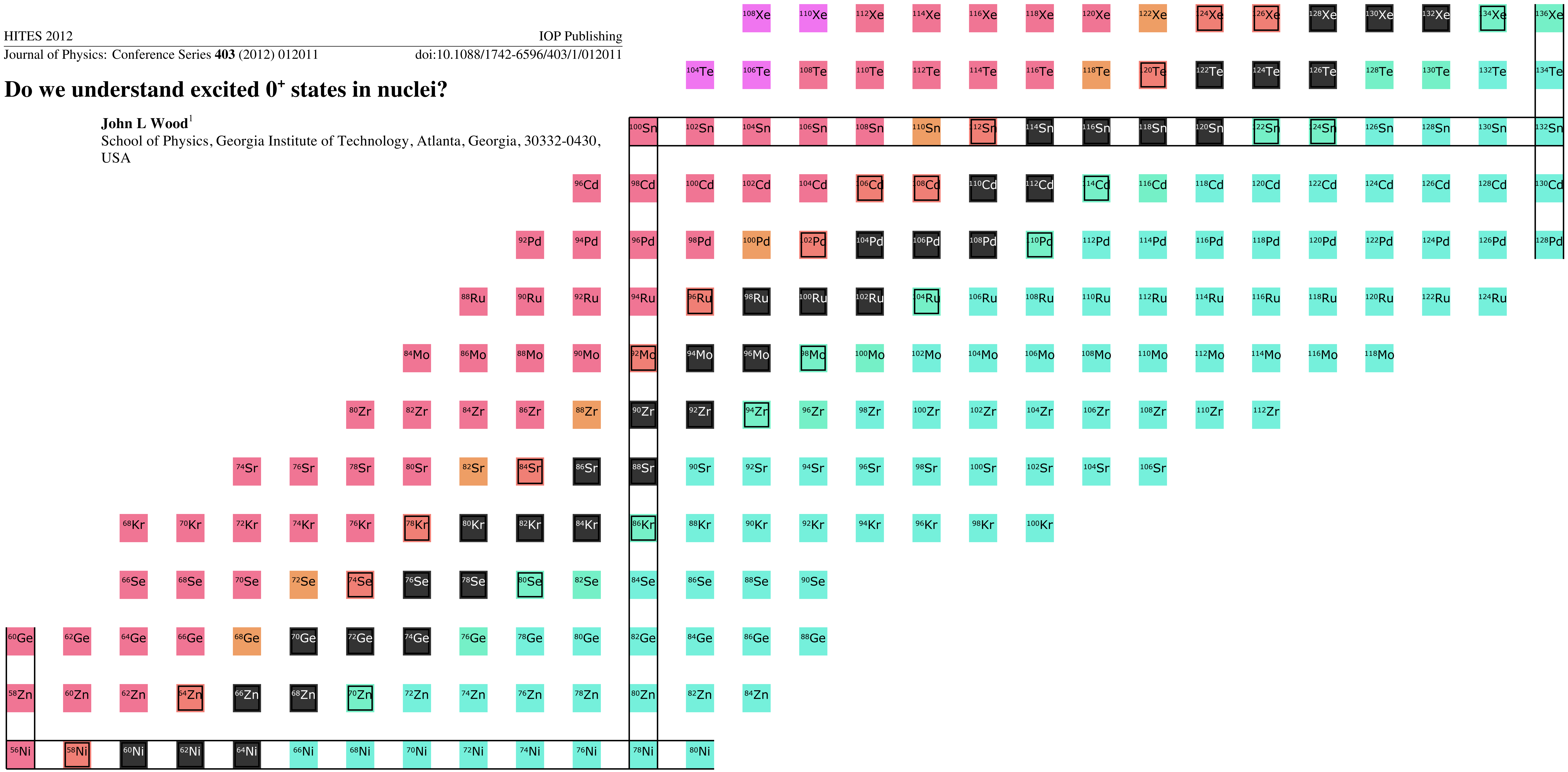
HITES 2012 IOP Publishing

Journal of Physics: Conference Series **403** (2012) 012011 doi:10.1088/1742-6596/403/1/012011

Do we understand excited 0^+ states in nuclei?

John L Wood[1]

School of Physics, Georgia Institute of Technology, Atlanta, Georgia, 30332-0430, USA



Excited 0+ States in Mid-Mass Nuclei

- Low-Energy Coulomb Excitation
- SPIDER
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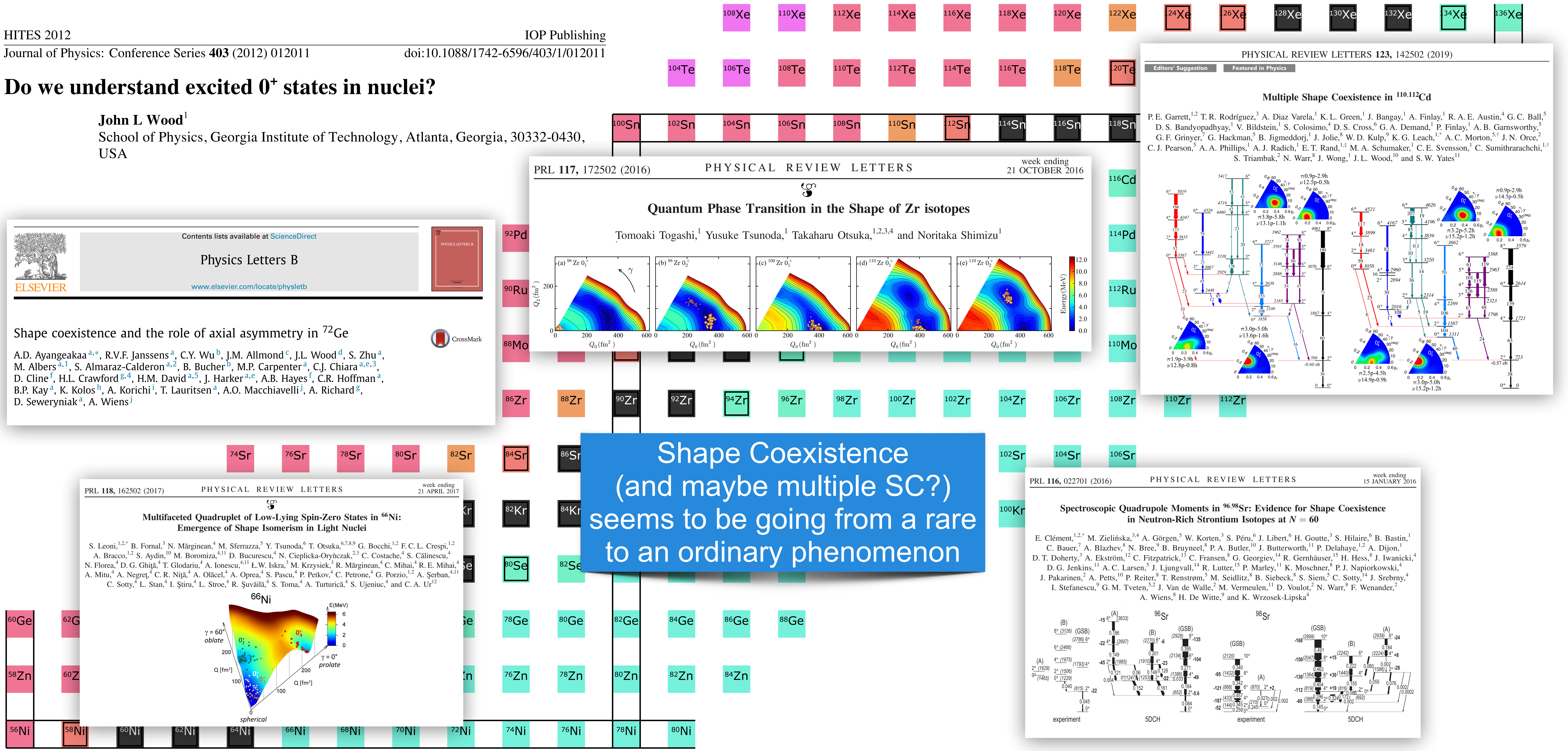
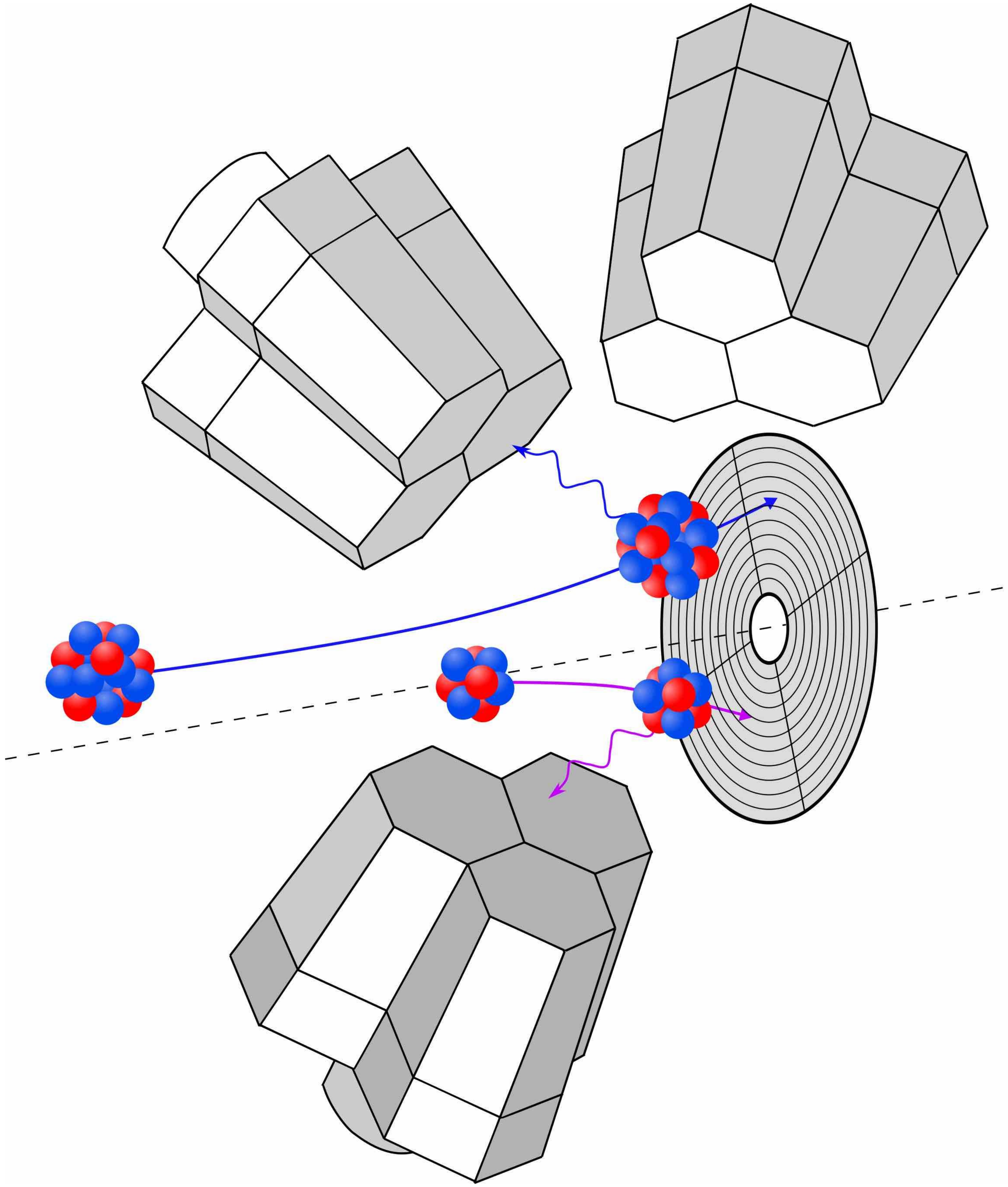


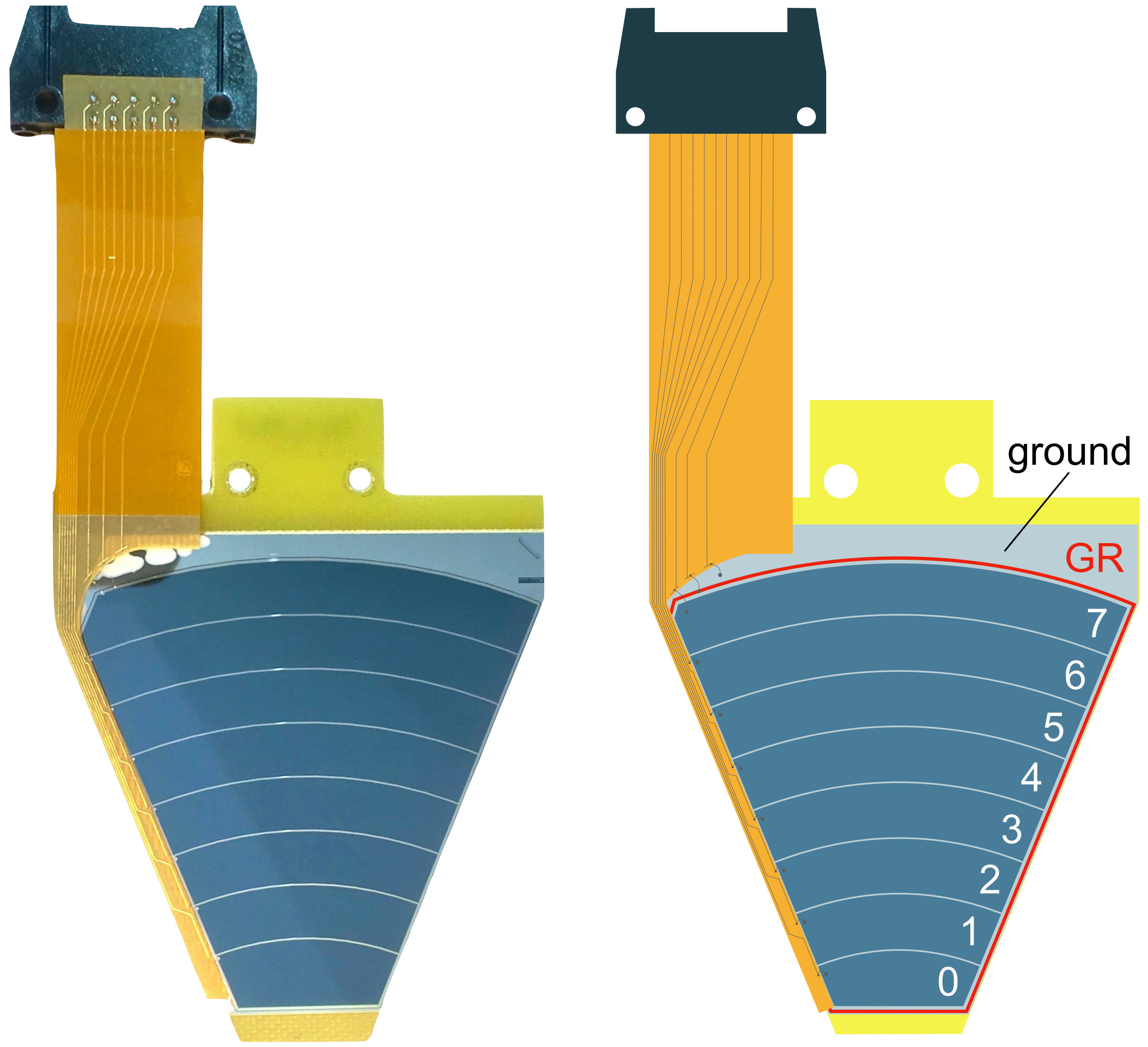
Experimental Setup

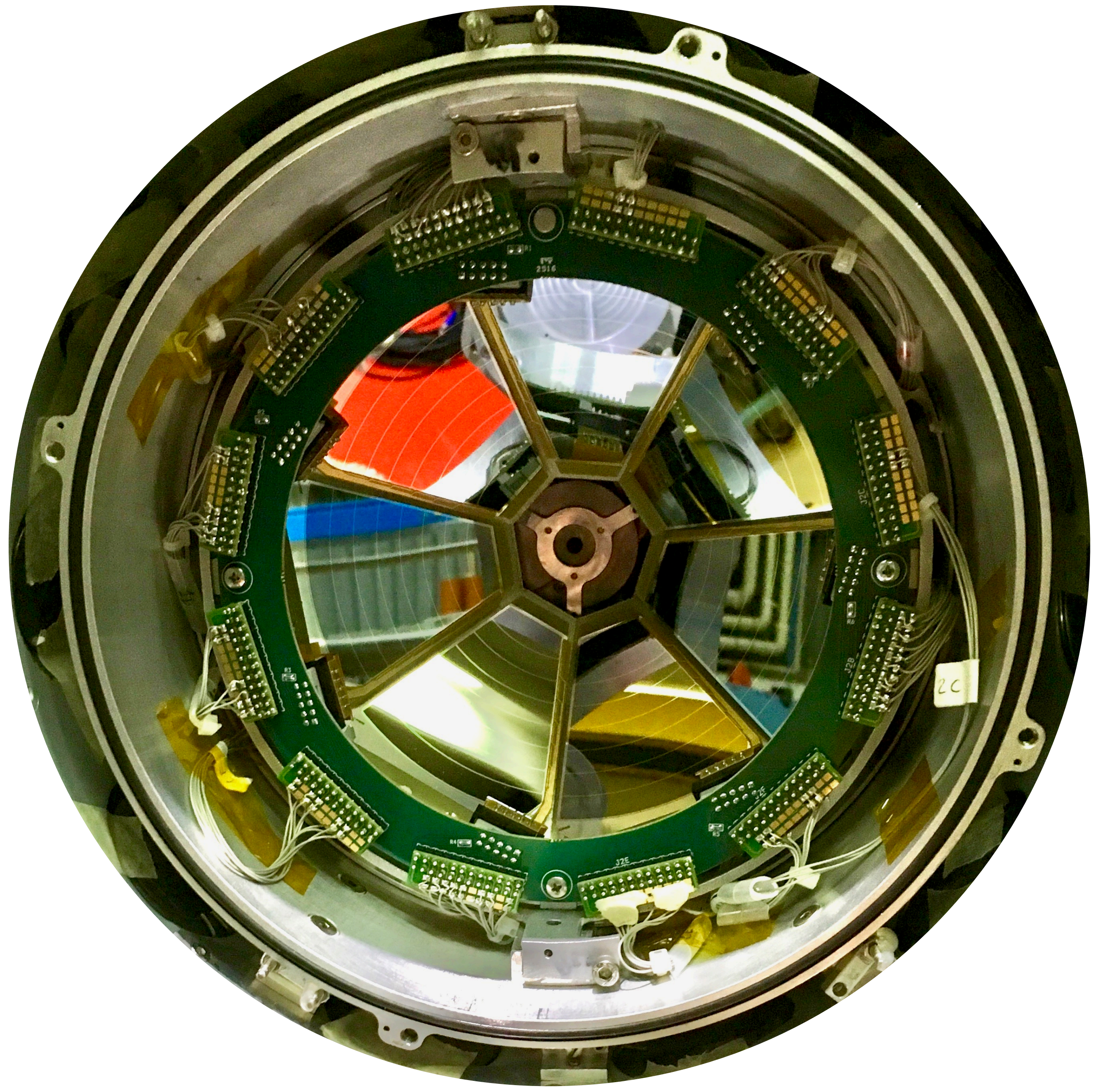
- γ-ray detector:
  - To measure γ-ray yields for the different transitions
- Particle detector:
  - To select the events of interest
  - To distinguish between projectile and target nuclei
  - To perform the Doppler correction
  - To select the scattering angle
  - To monitor the experiment



SPIDER: the Silicon PIe DEtectoR

- Modular segmented silicon detector, originally designed for low-energy Coulomb-excitation measurements
- Independent sectors, 8 strips + guard ring
- Detector thickness ~ 300 μm, dead layers ~ 50 nm in the junction (front) side and ~ 350 nm in the ohmic (rear) side
- Cone configuration (7 sectors) at backward angles: 8.5 cm from the target ⟹ $\Delta\Theta = 37.4°$, $\Omega/4\pi = 17.3\%$

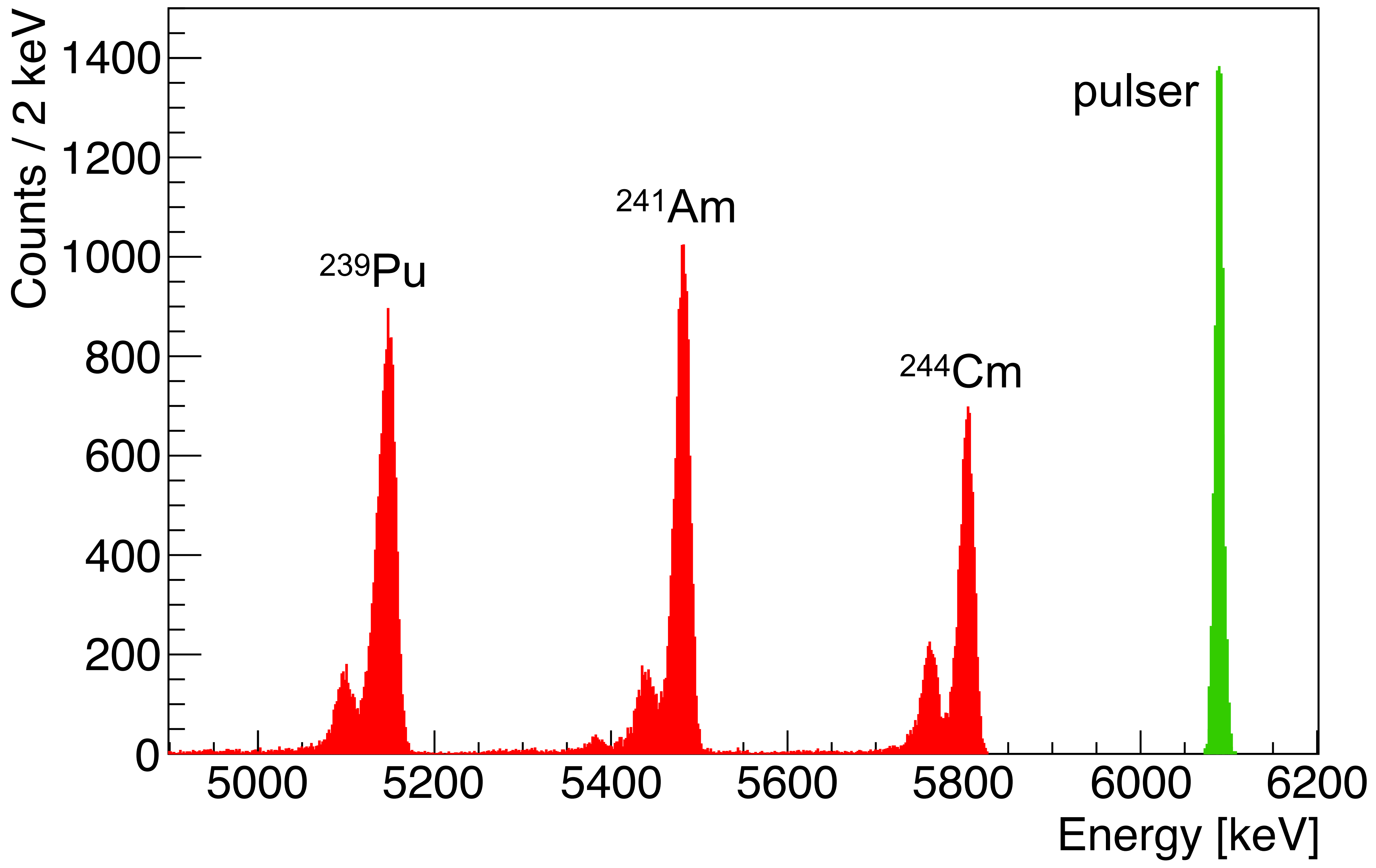


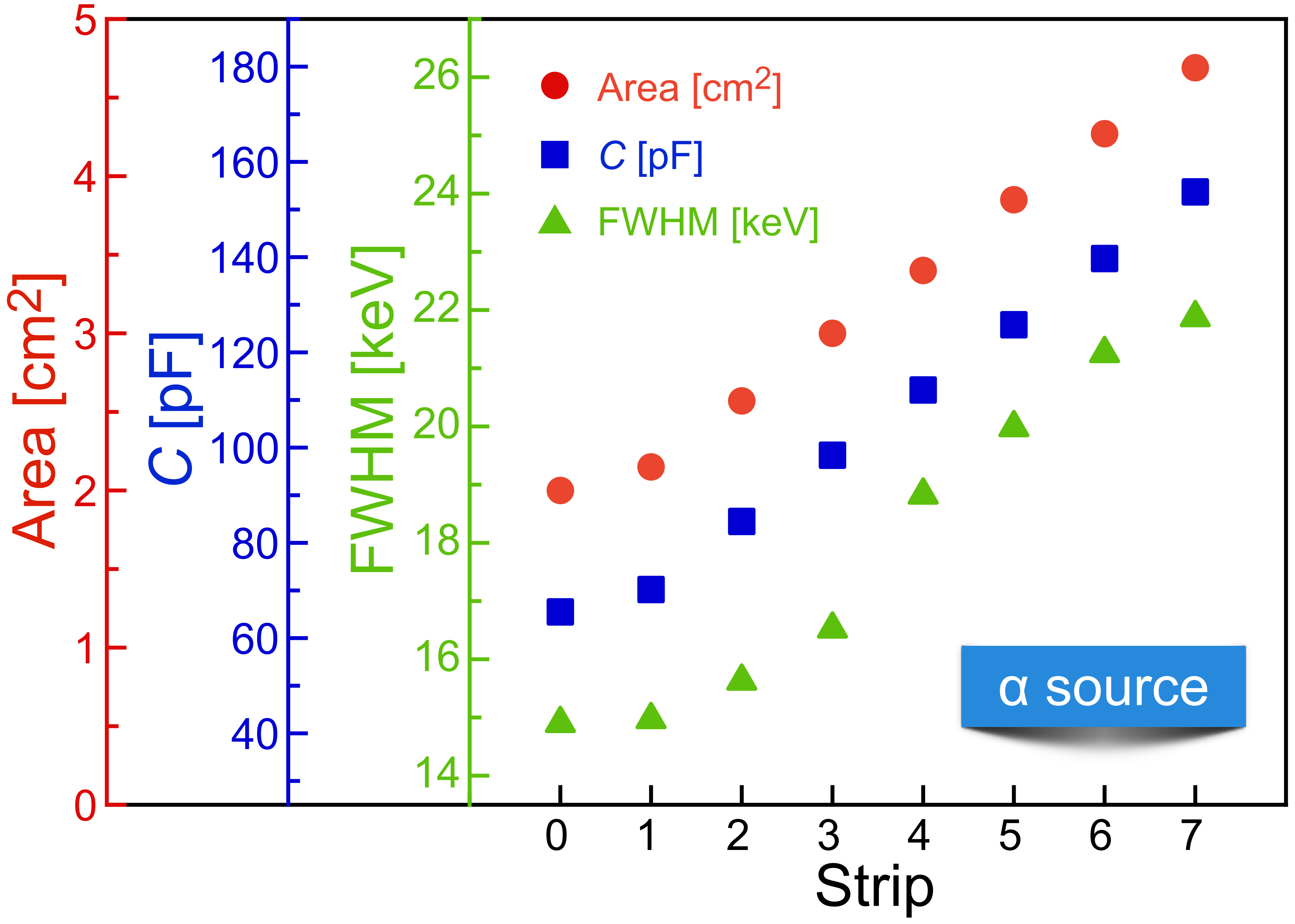


M. Rocchini, K. Hadyńska-Klęk, A. Nannini et al., NIMA 971 (2020) 164030

Energy Resolution

- nTD silicon detectors, high quality, high energy resolution (less than ~ 1% for 5.5-MeV α particles)





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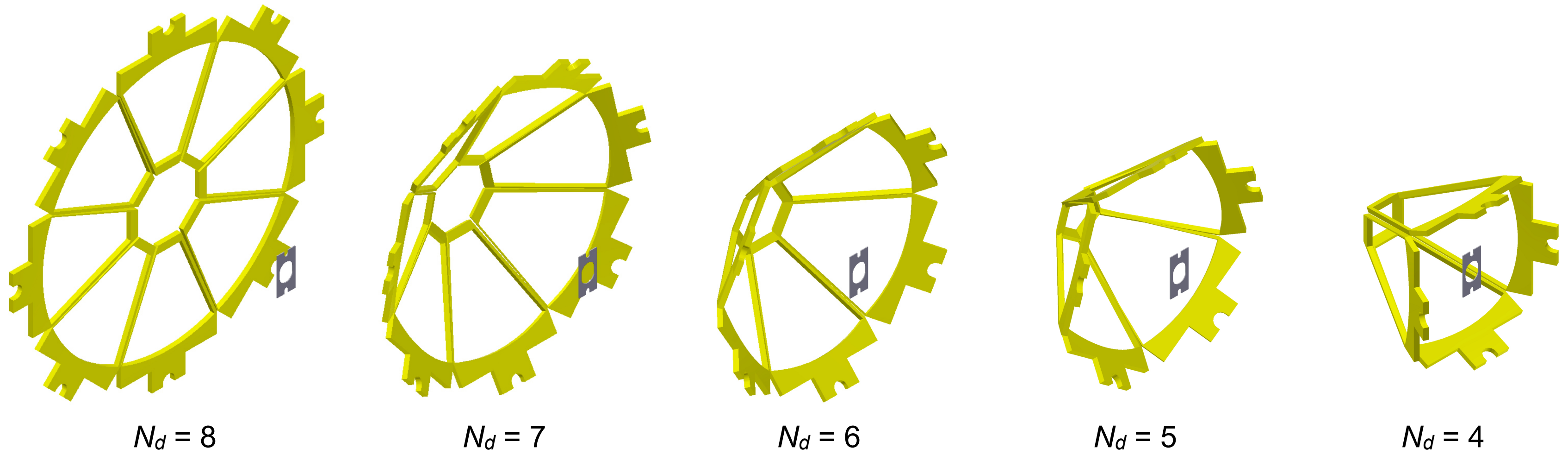
Modularity

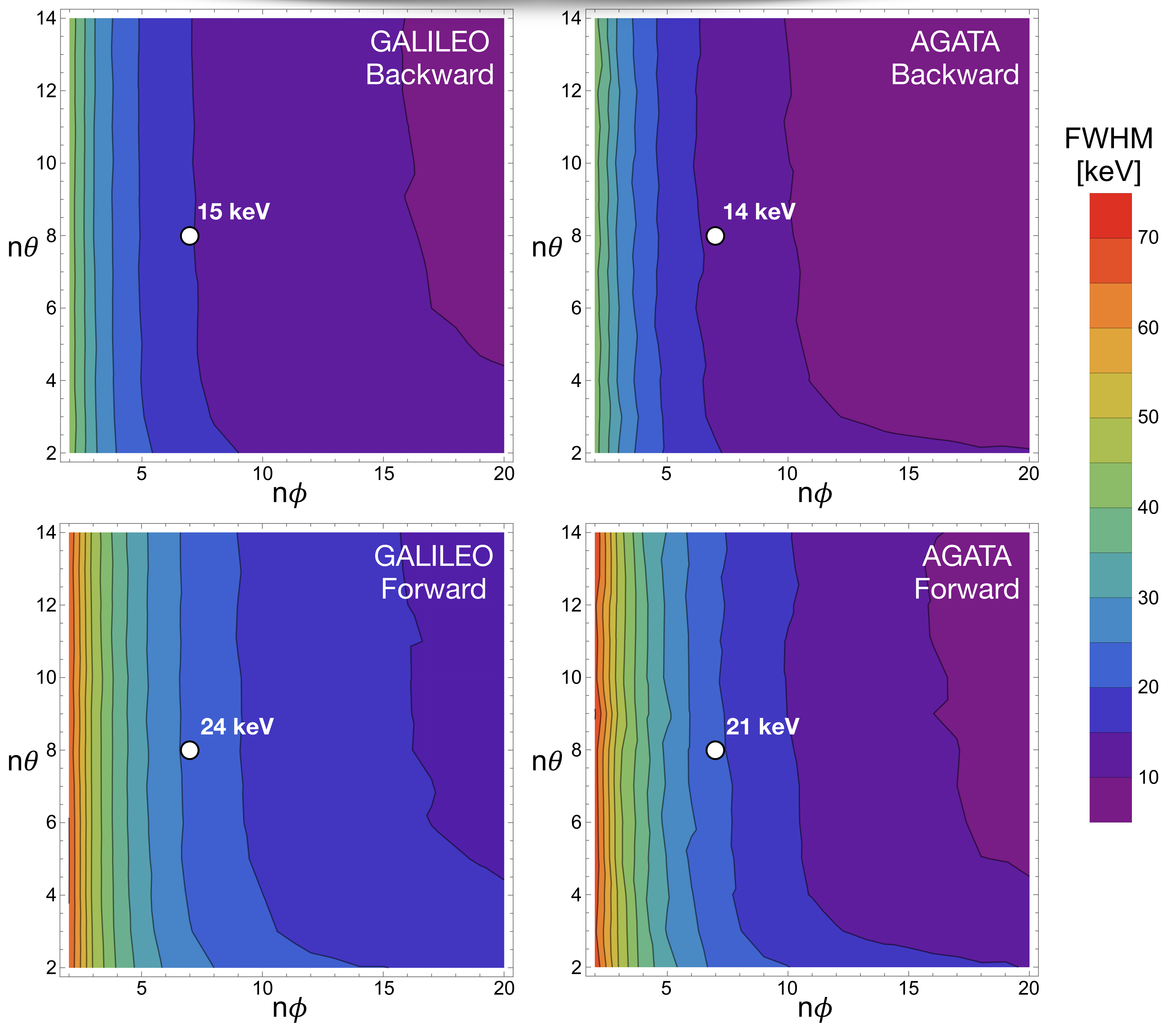
- The detector can be mounted in different arrangements, using from 1 to 8 sectors, giving different Doppler-correction capabilities and angular coverages



- Polar and solid angles with an 8.5-cm distance from the target:

Strip	θ_{min} [deg]	θ_{mean} [deg]	θ_{max} [deg]	$\Delta\theta$ [deg]	Ω [srad]
7	123.5	125.4	127.5	4.0	0.046
6	127.5	129.6	131.8	4.3	0.046
5	131.8	134.0	136.4	4.6	0.045
4	136.4	138.7	141.2	4.8	0.043
3	141.2	143.6	146.1	5.0	0.040
2	146.1	148.6	151.2	5.1	0.035
1	151.2	153.7	156.3	5.1	0.030
0	156.3	158.8	161.3	5.1	0.028

Simulated ^{60}Ni on ^{208}Pb at the safe energy



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Geant4 Simulations

Low-Energy Coulomb Excitation

SPIDER

Pulse Height Correlations

Radiation Damage

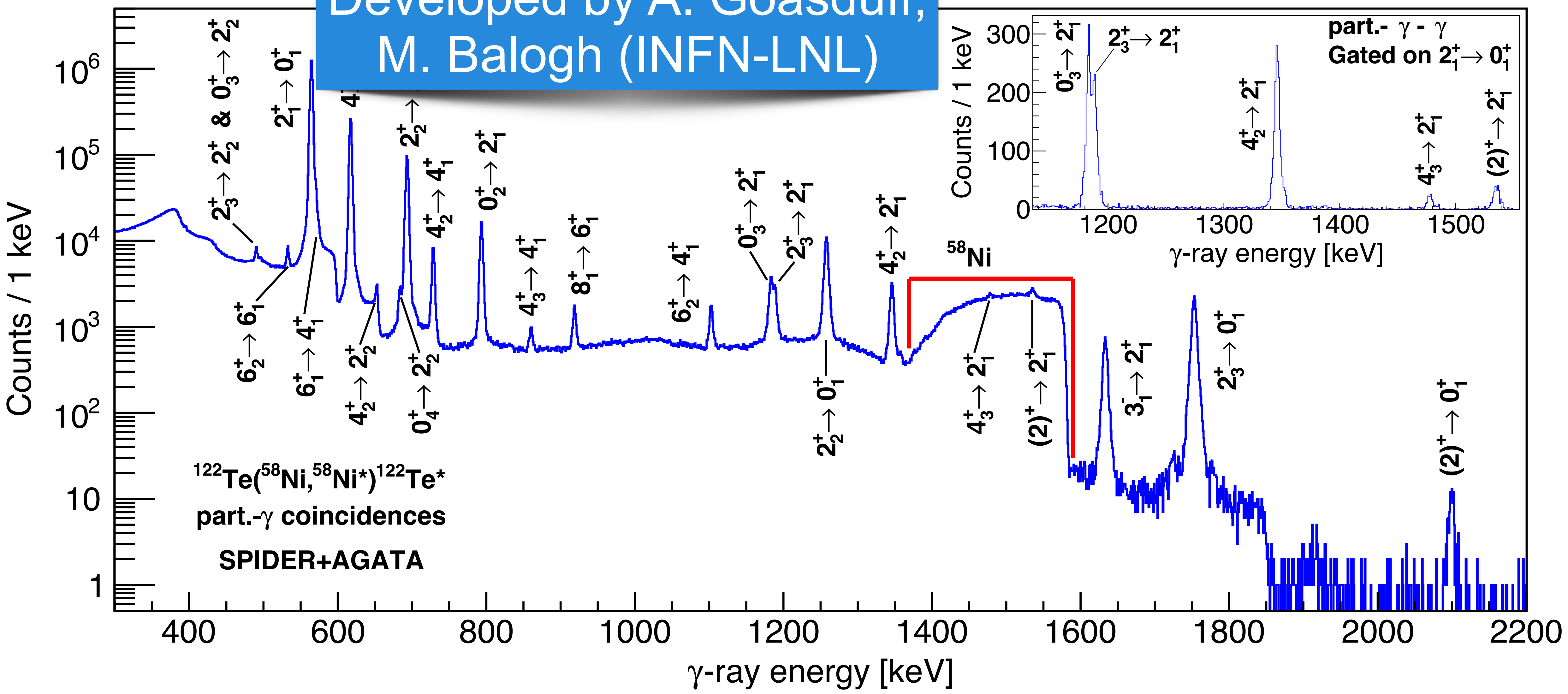
Online Target Analysis

The GALILEO Campaign

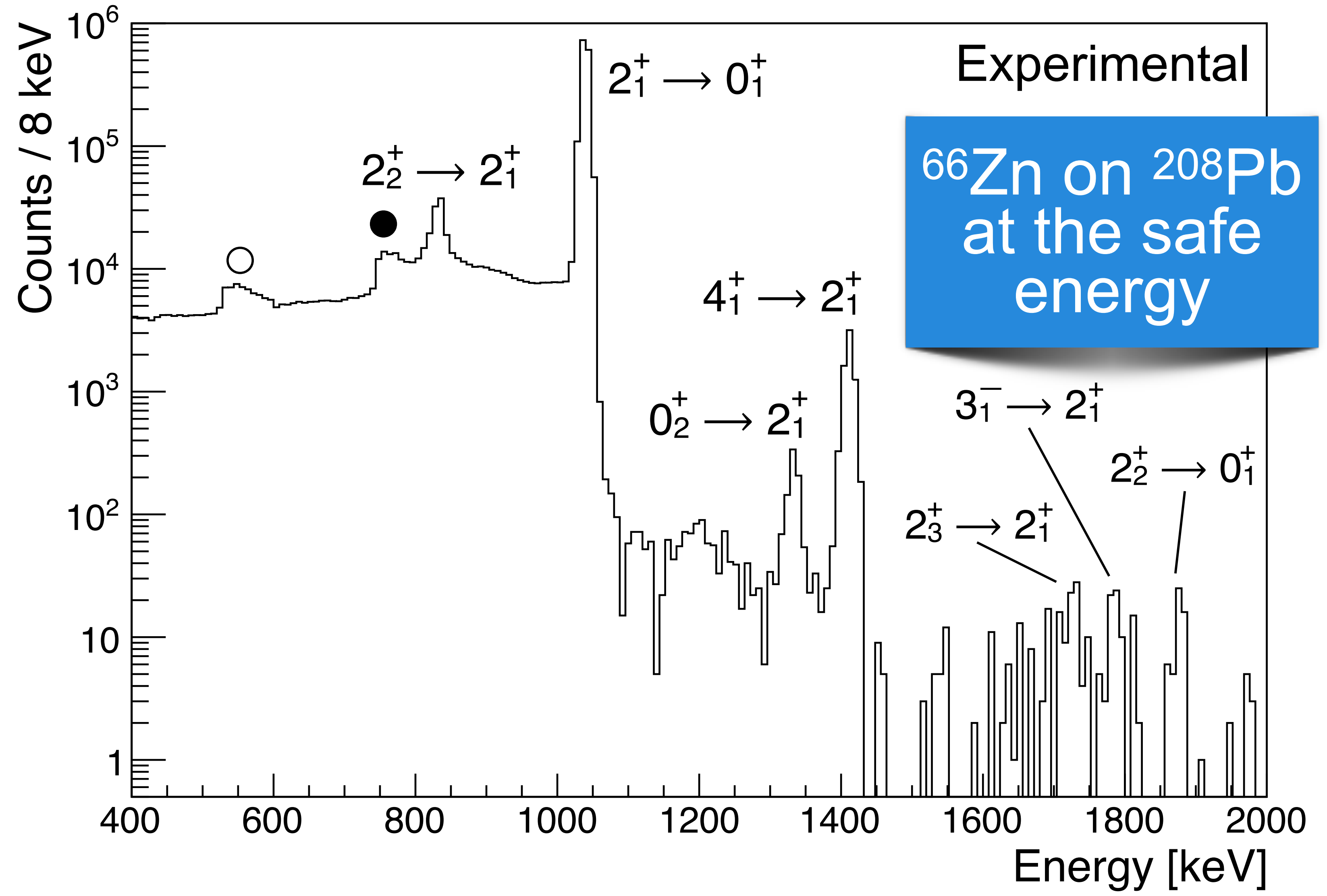
The AGATA Campaign

- Geant4 package available to simulate in detail each experiment
- Input from GOSIA (reference code for Coulomb-excitation cross-section calculations)
- Possibility to include both the beam and the target excitations

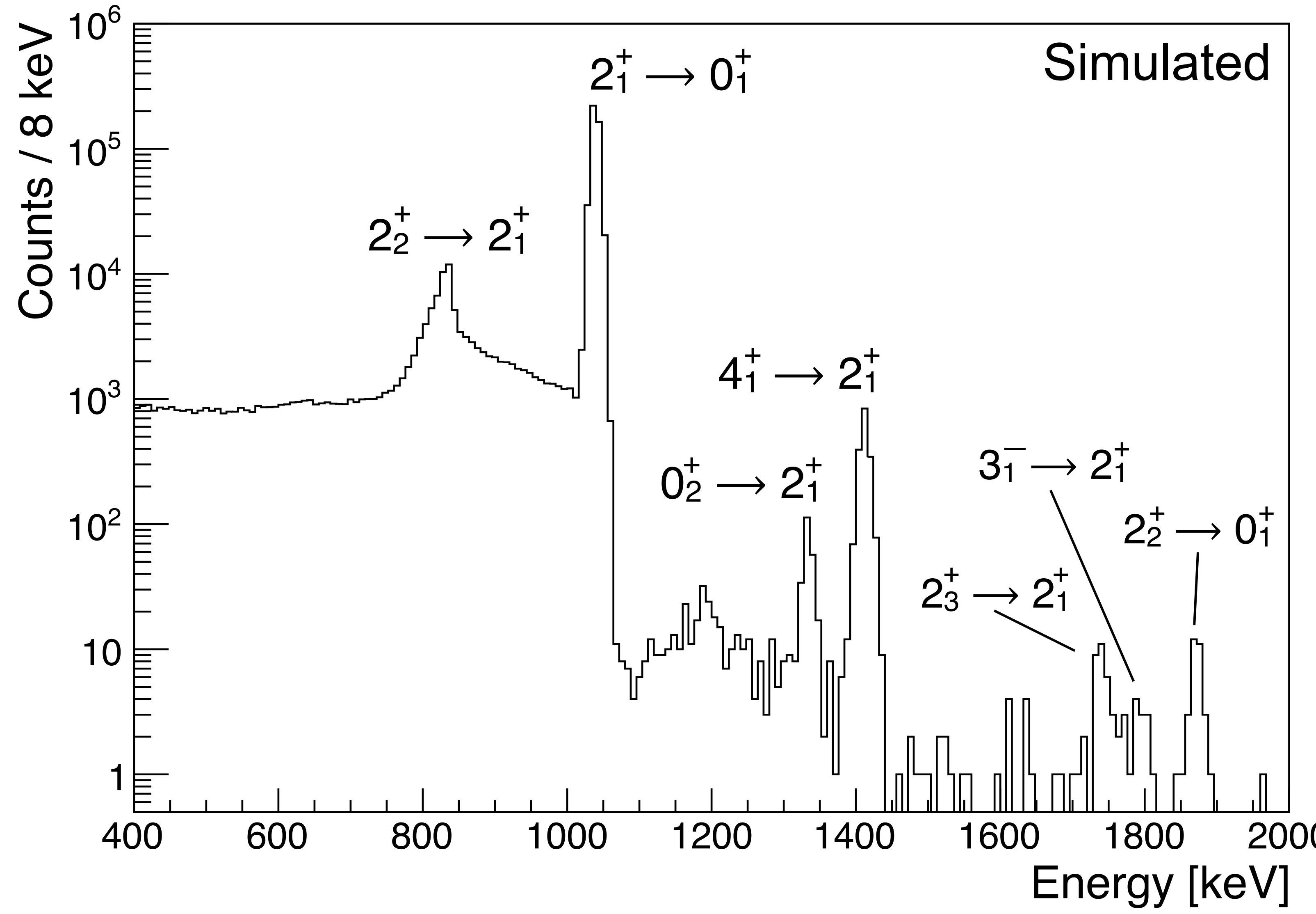
Developed by A. Goasduff, M. Balogh (INFN-LNL)



M. Rocchini, K. Hadyńska-Klęk, A. Nannini et al., NIMA 971 (2020) 164030

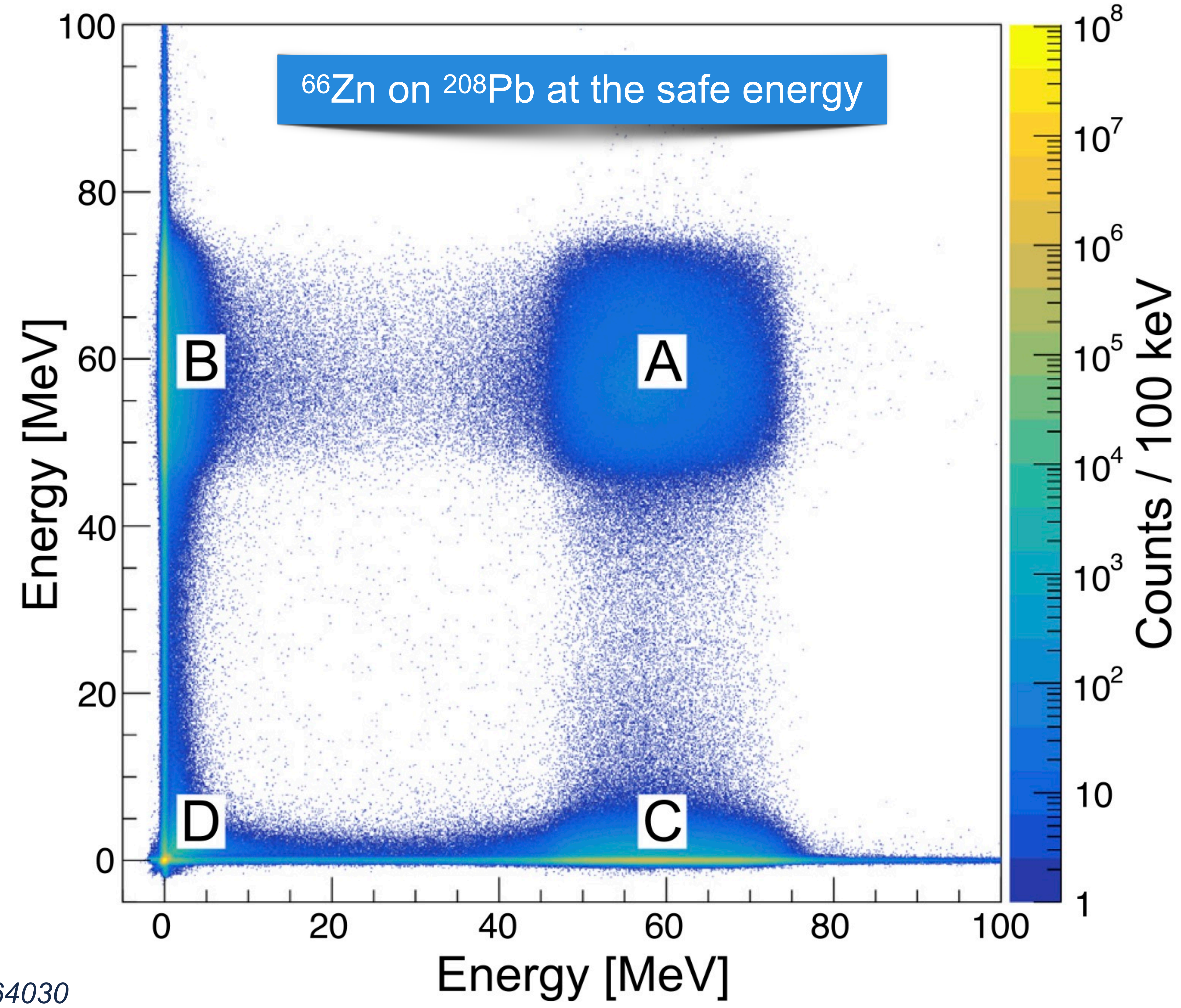


^{66}Zn on ^{208}Pb at the safe energy



Pulse Height Correlations

- Time coincidences between SPIDER signals (rejected in the analysis)
  - A = double hits (~ 0.2‰ of the total statistics)
  - B,C = real signals in coinc. with noise and low-amplitude signals
  - D = noise coincidences



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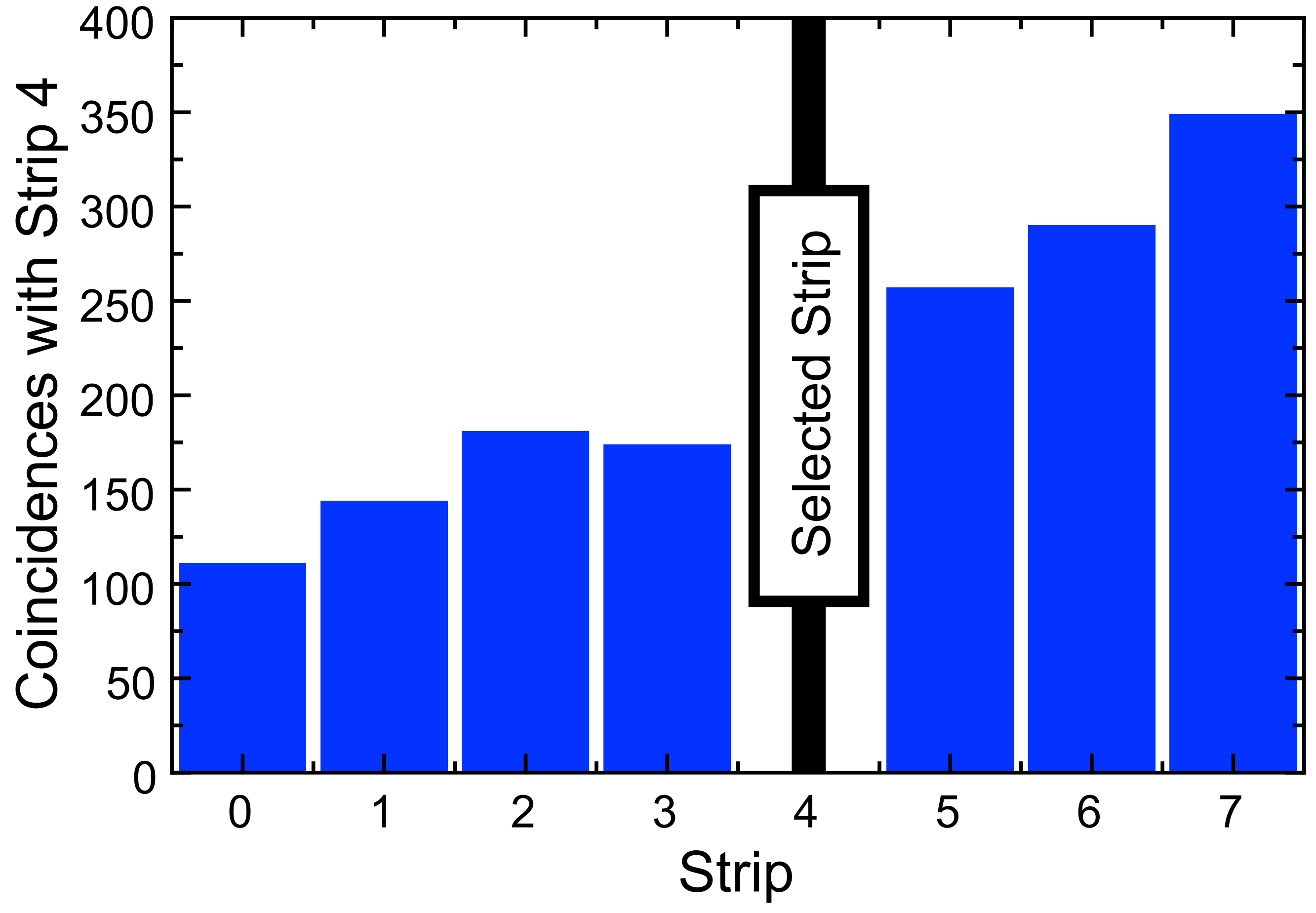
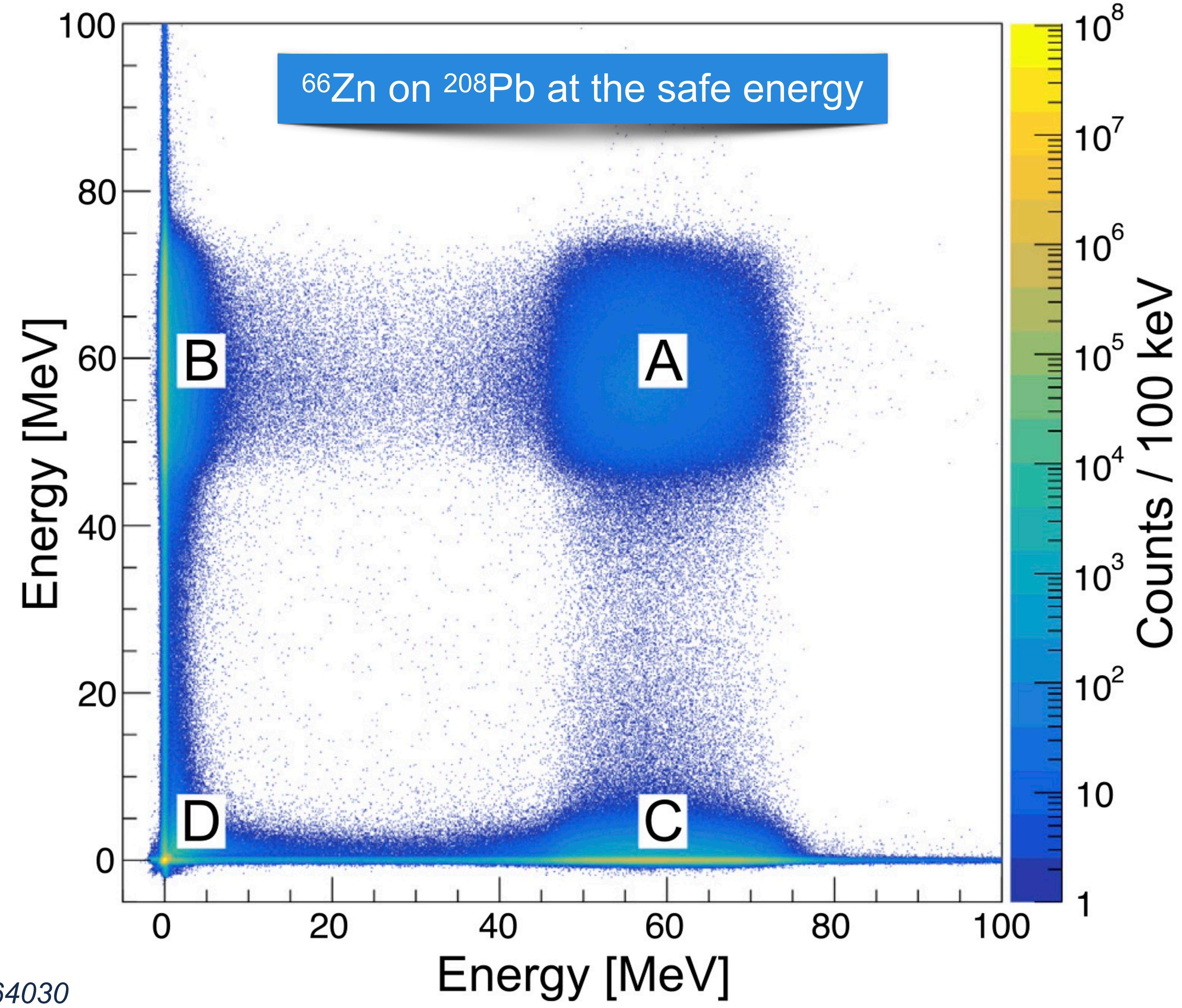
- Negative polarity signals





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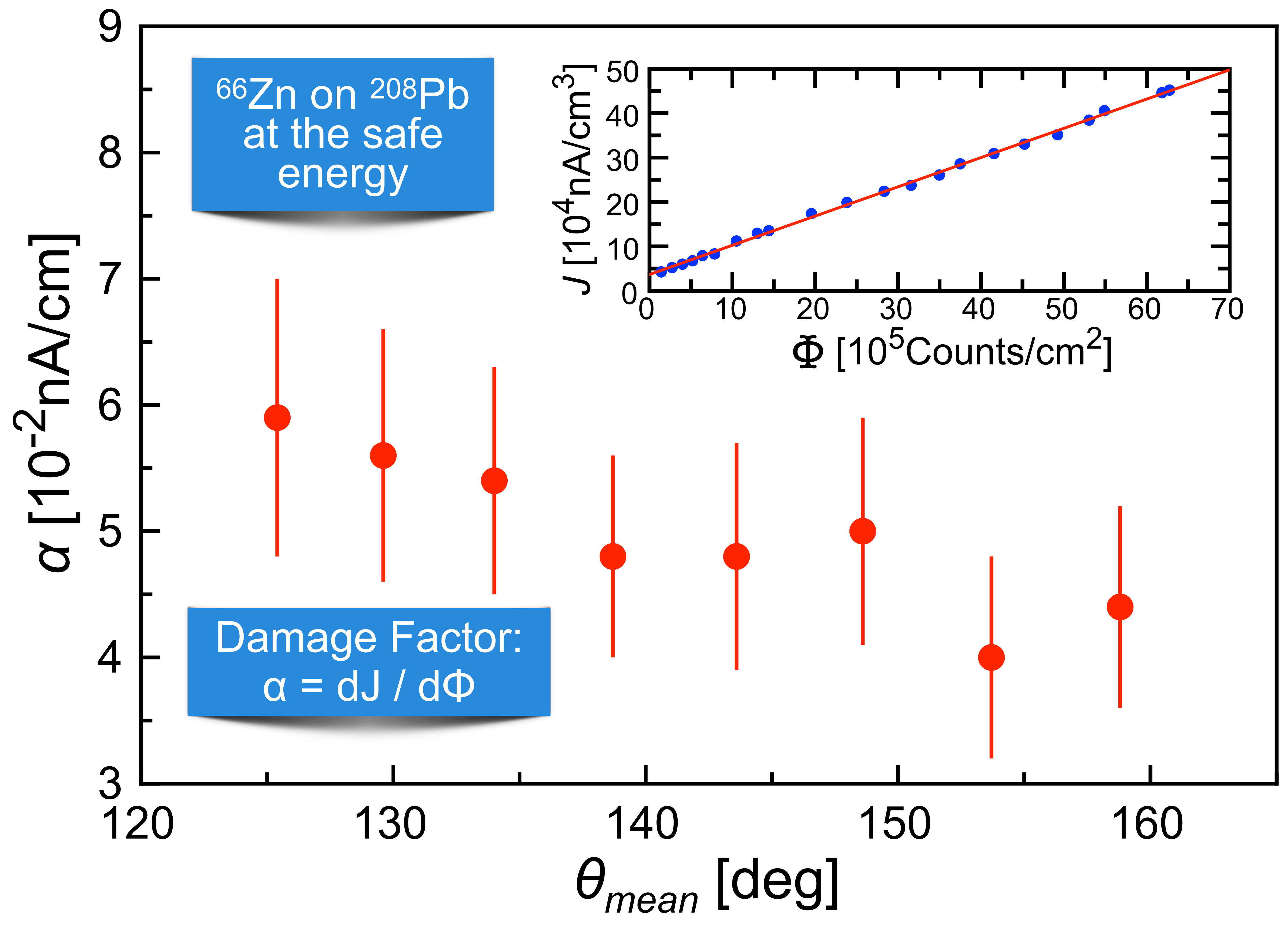
Radiation Damage

- Permanent lattice defects or temporary effects (temperature, auto-recovered displacements …)



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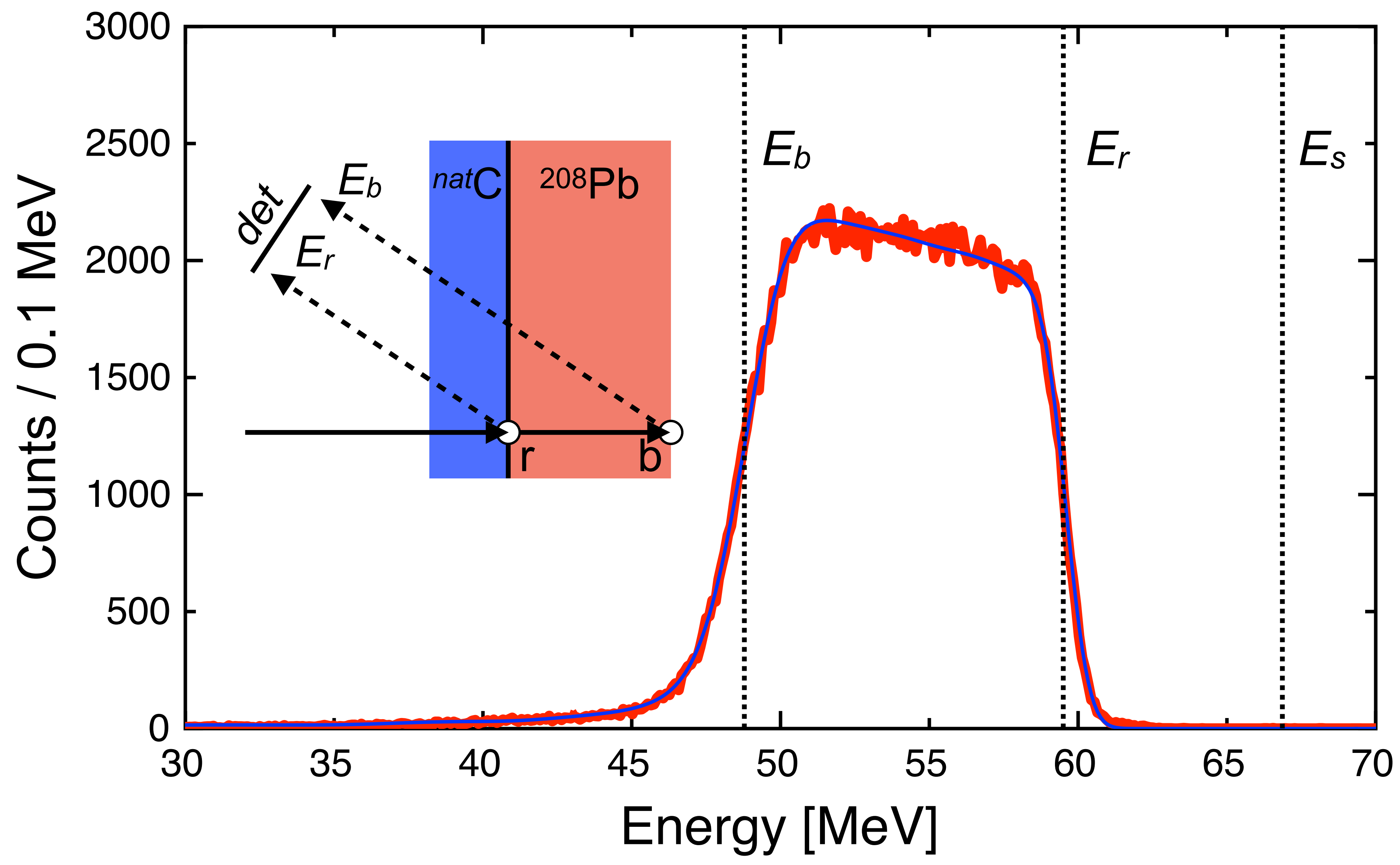
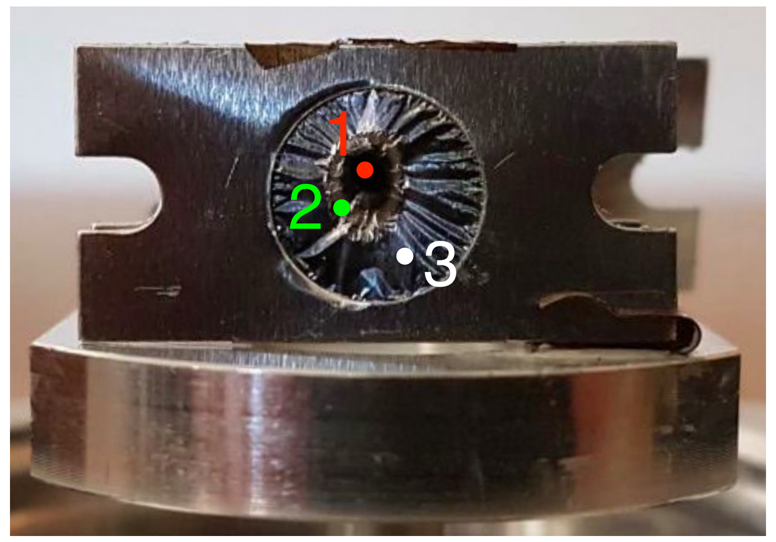
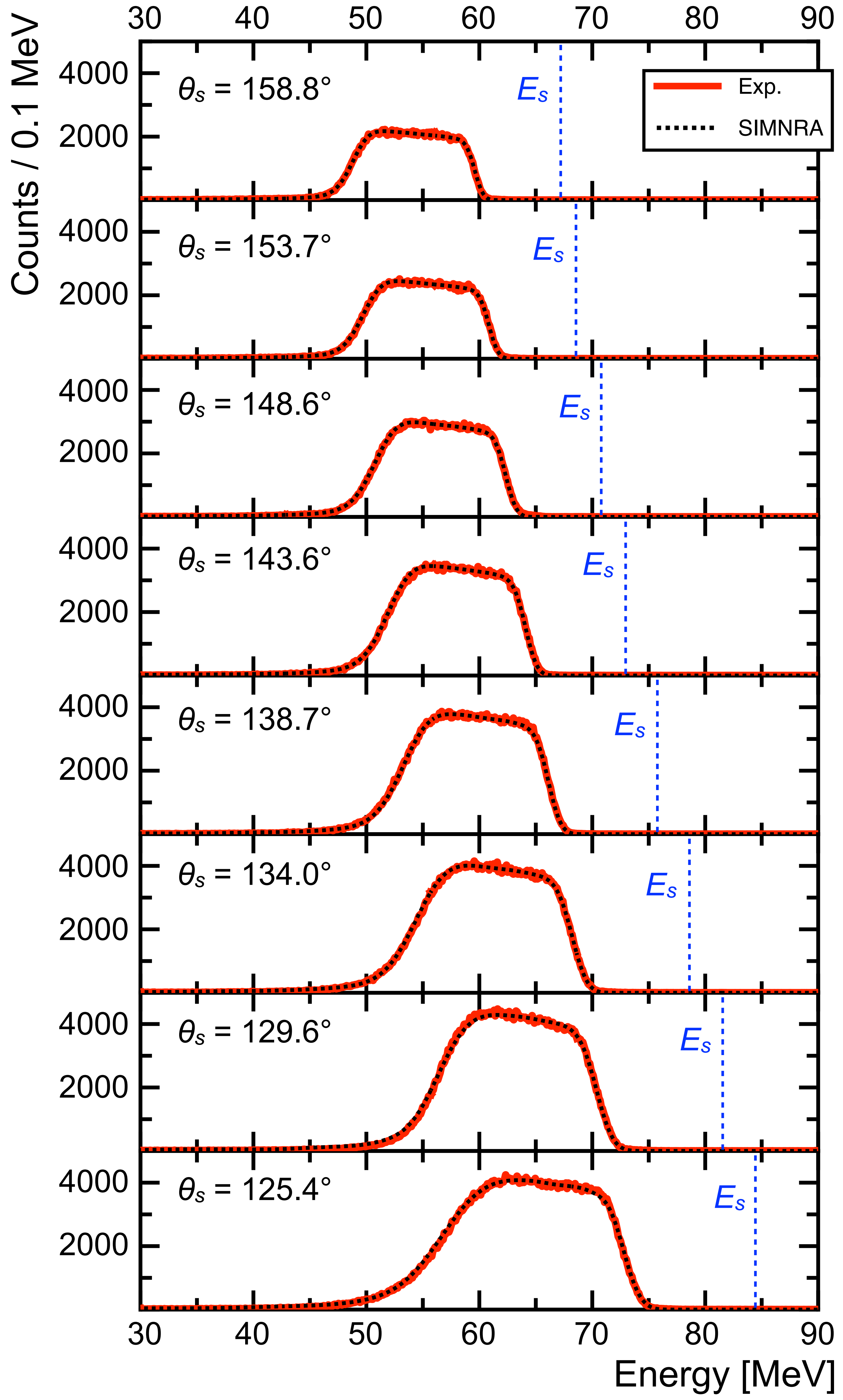
Online Target Analysis

- The high energy resolution of SPIDER allows for the online application of the Rutherford-backscattering technique (e.g., using the SIMNRA code)
- Target thickness, contaminants, carbon-built-up layer, etc…
- Example in ^{66}Zn on ^{208}Pb with GALILEO:
  - ^{208}Pb thickness = 616(11) mg/cm^2, ^{12}C built-up = 114(12) mg/cm^2





M. Rocchini, M. Chiari, E. Pasquali et al., NIMB 486 (2021) 68



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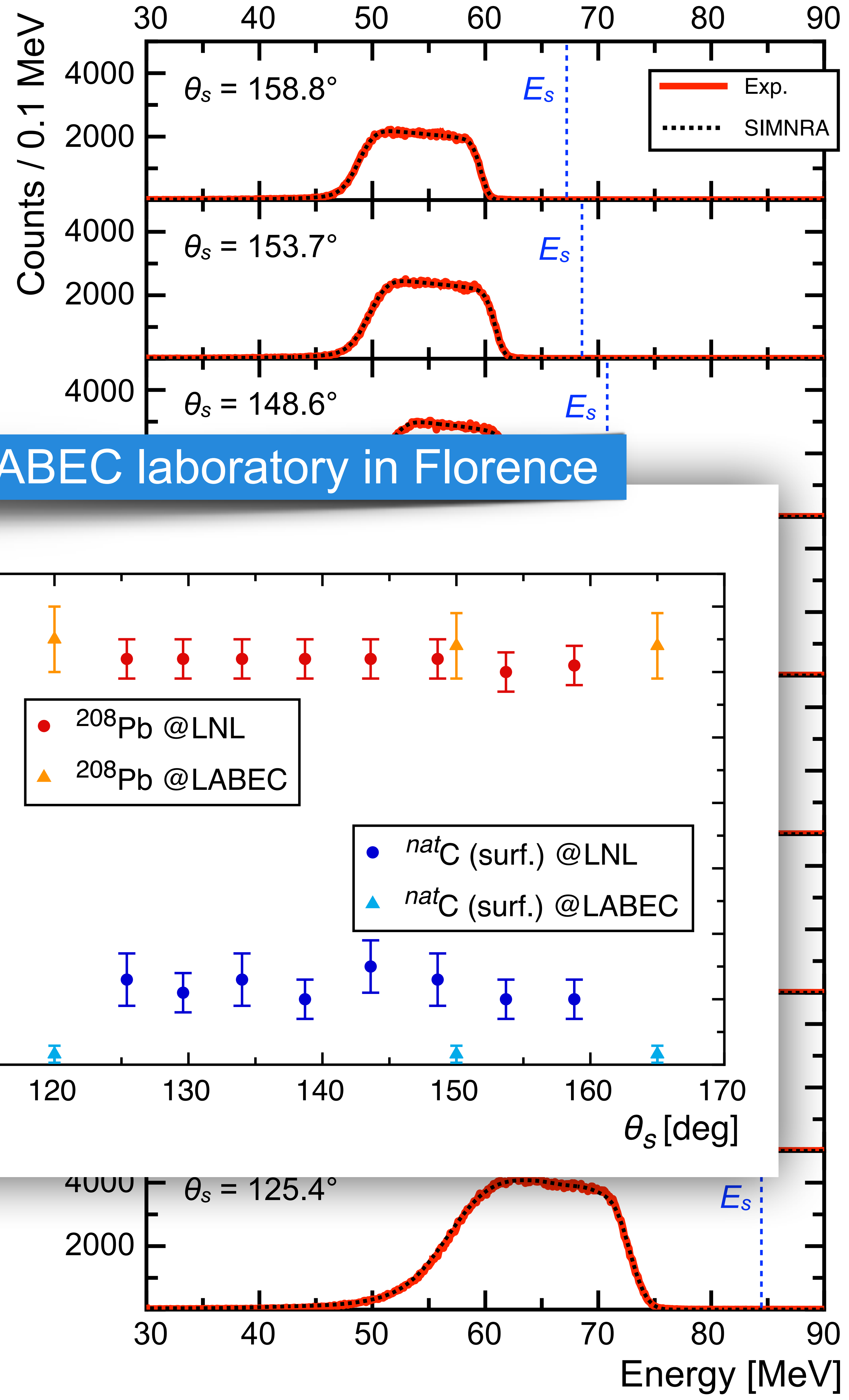
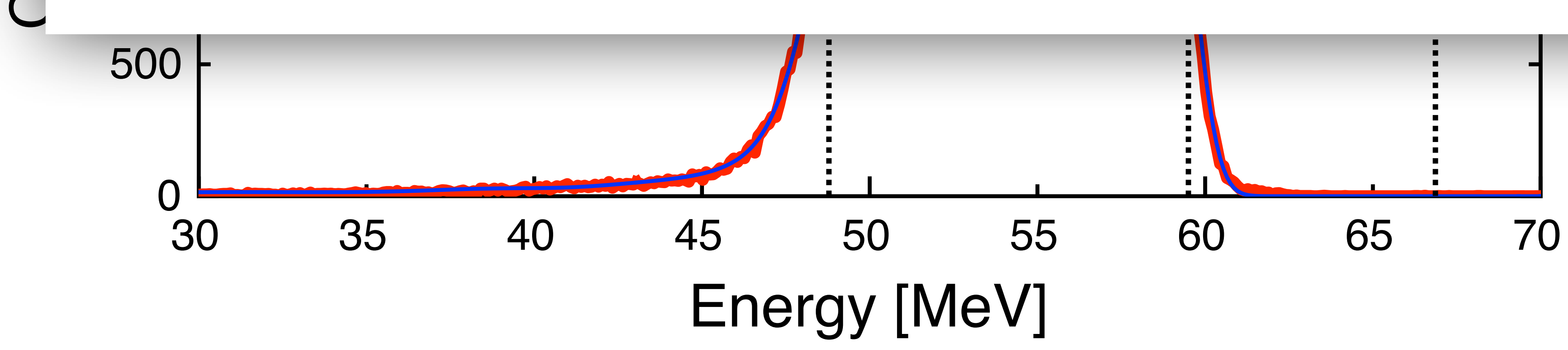
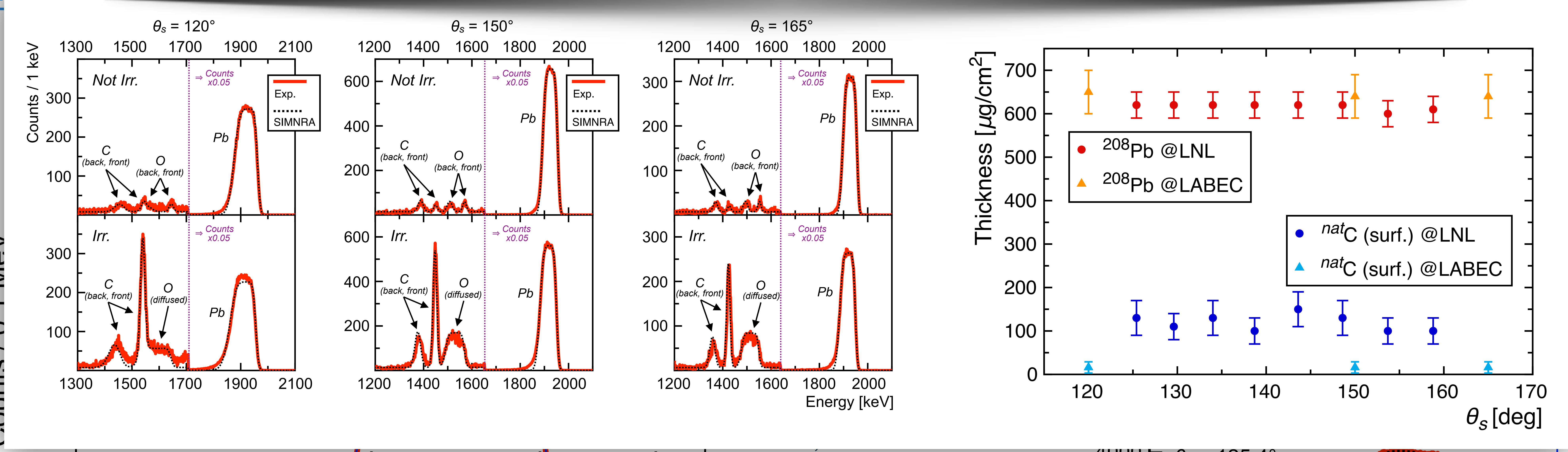
- E





E. Pasquali et al., NIMB 486 (2021) 68

Results validated with an independent RBS measurement at the LABEC laboratory in Florence



GALILEO

- 25 HPGe Compton-suppressed detectors (GASP type)
- FWHM (@1332.5 keV) < 2.4 keV
- Efficiency (@1332.5 keV) = 2.1%
- Full digital electronics (takes advantage of the developments made for AGATA):
  - Trigger-less mode
  - Typical operational rate ~ 20 kHz/det
  - Common clock synchronization
  - Local data processing

A. Goasduff, D. Mengoni, F. Recchia, J.J. Valiente-Dobón et al., NIMA 1015 (2021) 165753

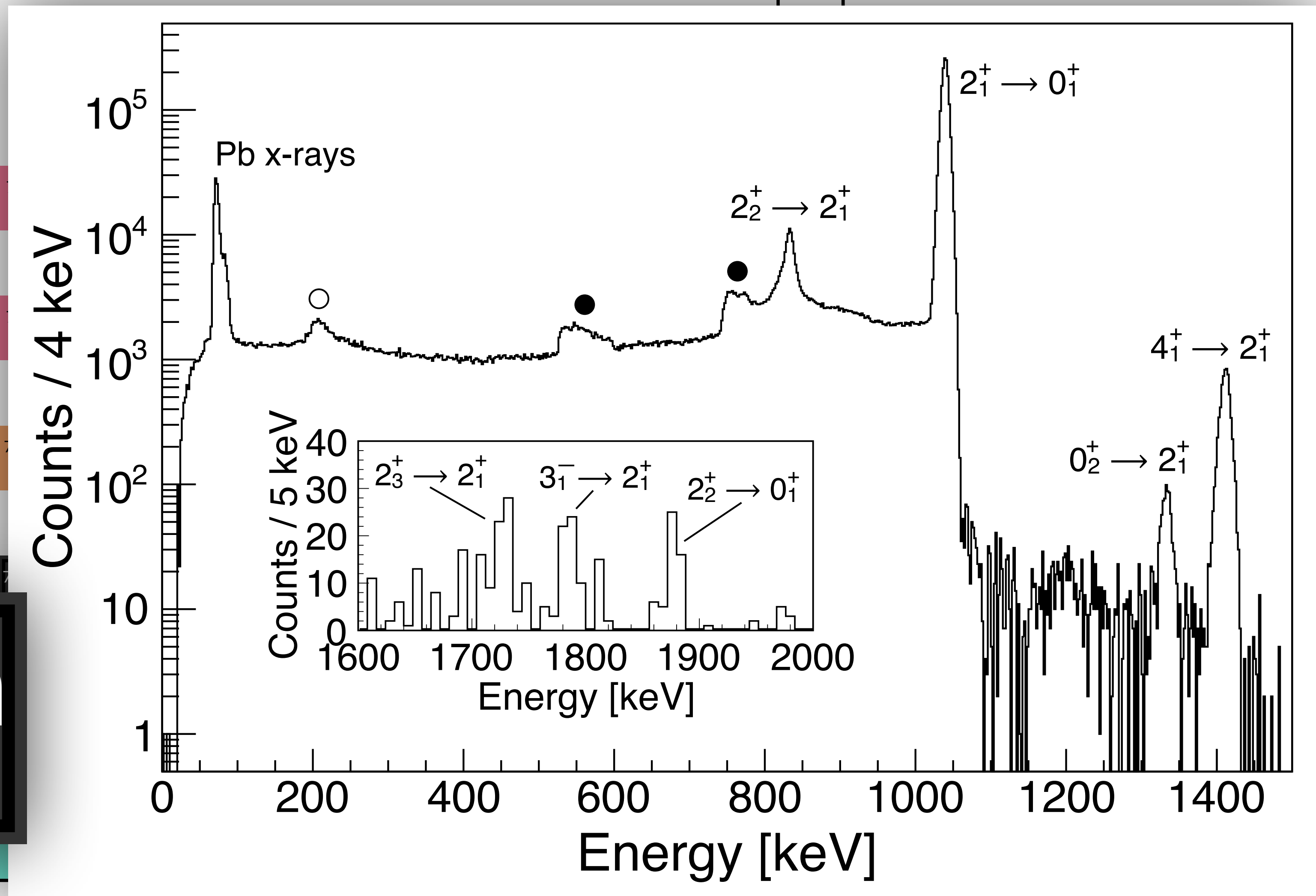
GALILEO with SPIDER (2016 - 2019)

Triaxiality and an “Isolated” 0_2^+ State in ^{66}Zn

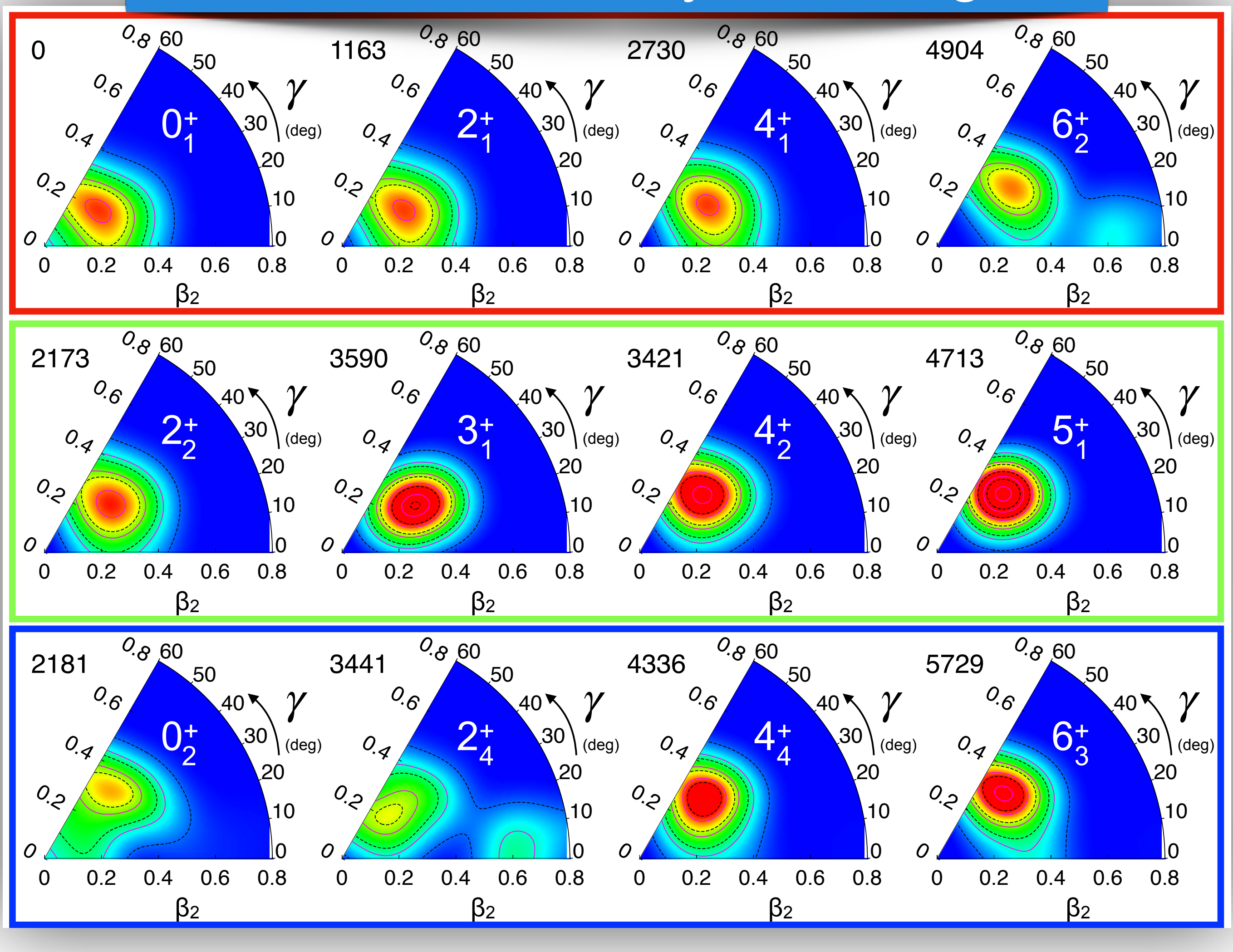
^{66}Zn on ^{208}Pb | SPs: K. Hadyńska-Klęk, M. Rocchini

- GALILEO+SPIDER commissioning
- New results:
  - $B(E2; 0_2^+ \rightarrow 2_1^+) = 3.0(10)$ W.u.
    $B(E2; 0_2^+ \rightarrow 2_2^+) = 1.6(6)$ W.u.
  - $\rho^2(E0; 0_2^+ \rightarrow 0_1^+) = 4.0(15)$
  - 0_1^+: $\beta = 0.224(6)$, $\gamma = 44°(8°)$
  - 0_2^+: $\beta \geq 0.051(7)$

Triaxial ground state and a 0_2^+ state that seems to possess a different and isolated structure



BMF calculations by T. Rodríguez



M. Rocchini, K. Hadyńska-Klęk, A. Nannini et al., PRC 103 (2021) 014311

Type-II Shell Evolution in ^{94}Zr

- Low-Energy Coulomb Excitation
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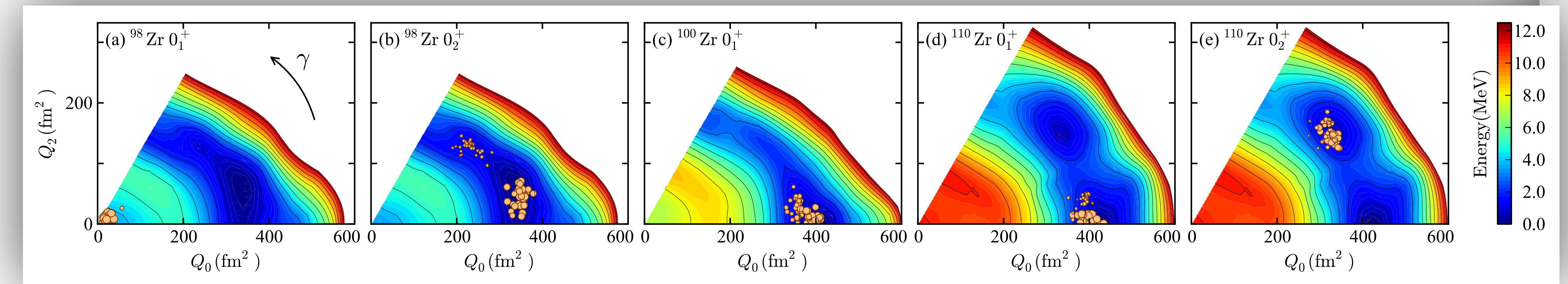
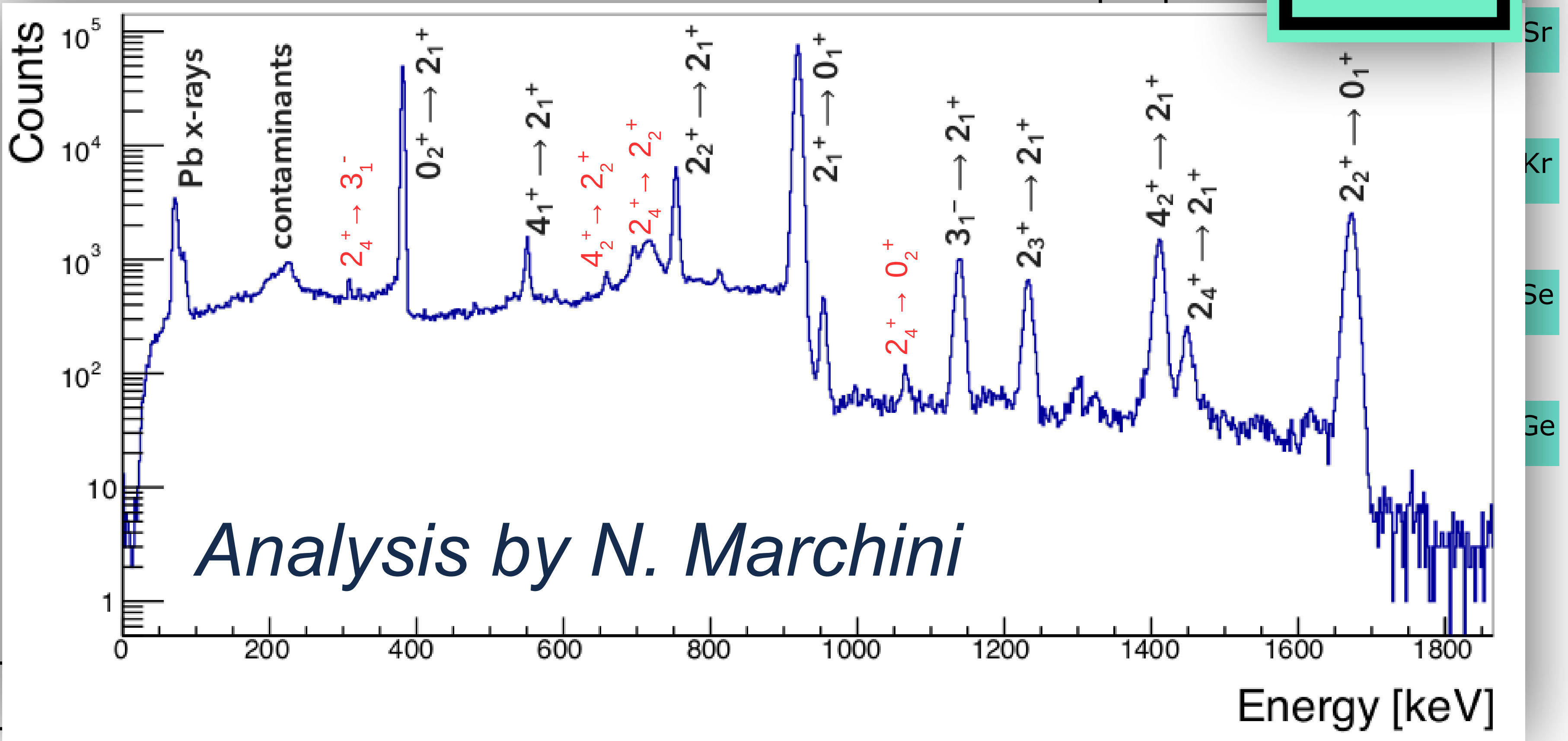
^{94}Zr on ^{208}Pb | SPs: D.T. Dohery, M. Zielińska, M. Rocchini

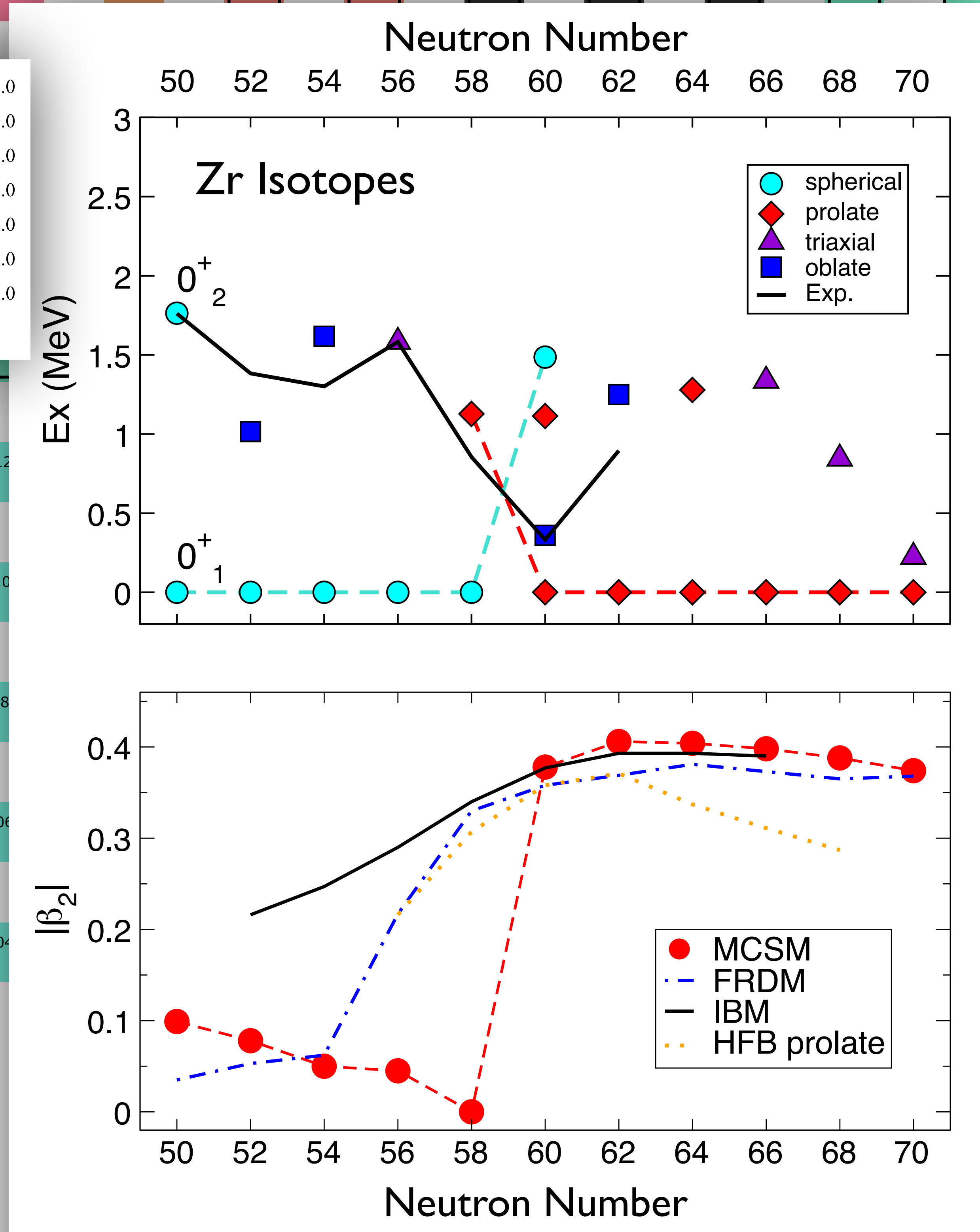
- New results:
  - 0_1^+:
    $\beta = 0.118(2)$
    $v(\beta; 0) = 0.151(3)$
    $\gamma = 37.2^{+1.5}_{-1.4}$
  - 0_2^+:
    $\beta = 0.194(2)$
    $v(\beta; 0) = 0.091(2)$
    $\gamma = 48^{+12}_{-5}$



First application of quadruple sum rules in the Zr isotopic chain:
"Spherical" g.s. coexisting with a deformed, oblate 0_2^+ state

^{94}Zr





T. Togashi, Y. Tsunoda, T. Otsuka et al., PRL 117 (2016) 172502

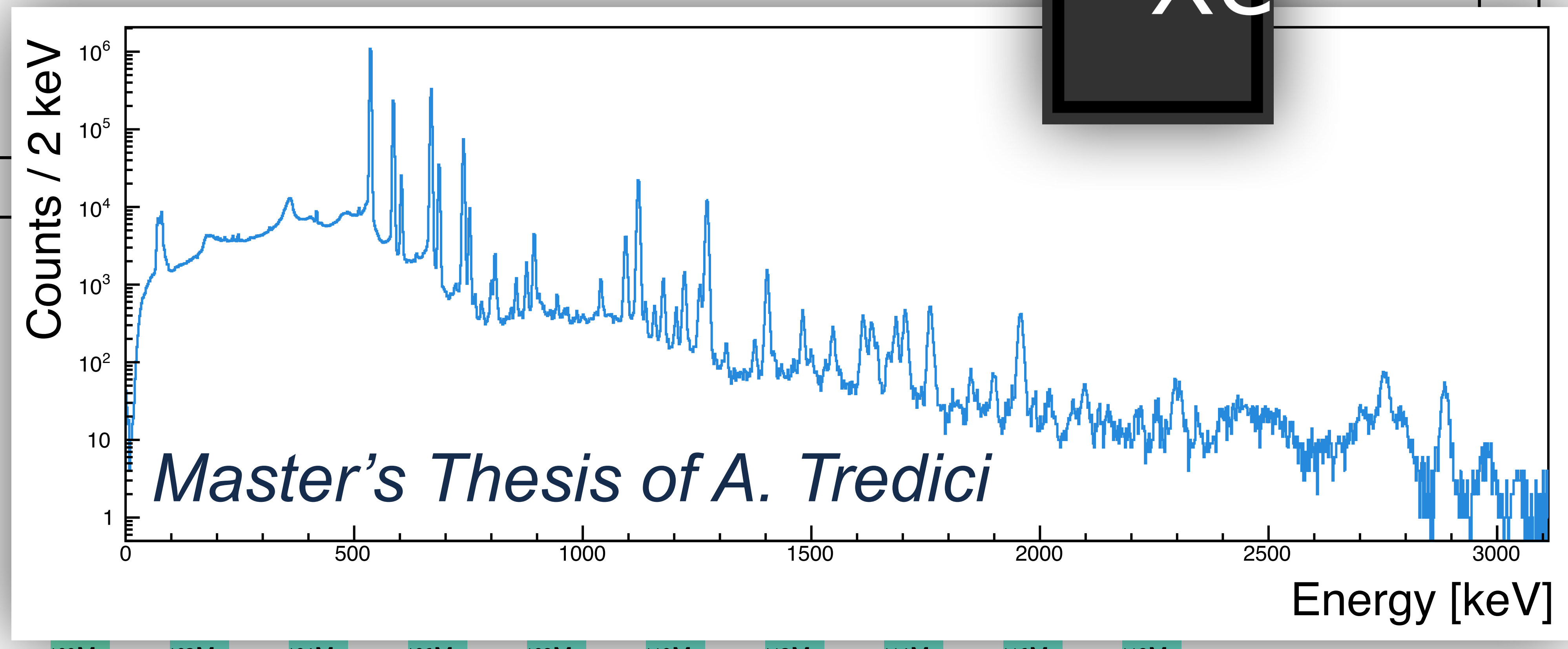
N. Marchini, M. Rocchini, A. Nannini, D.T. Doherty, Zielińska et al., EPJ Web of Conferences 223 (2019) 01038

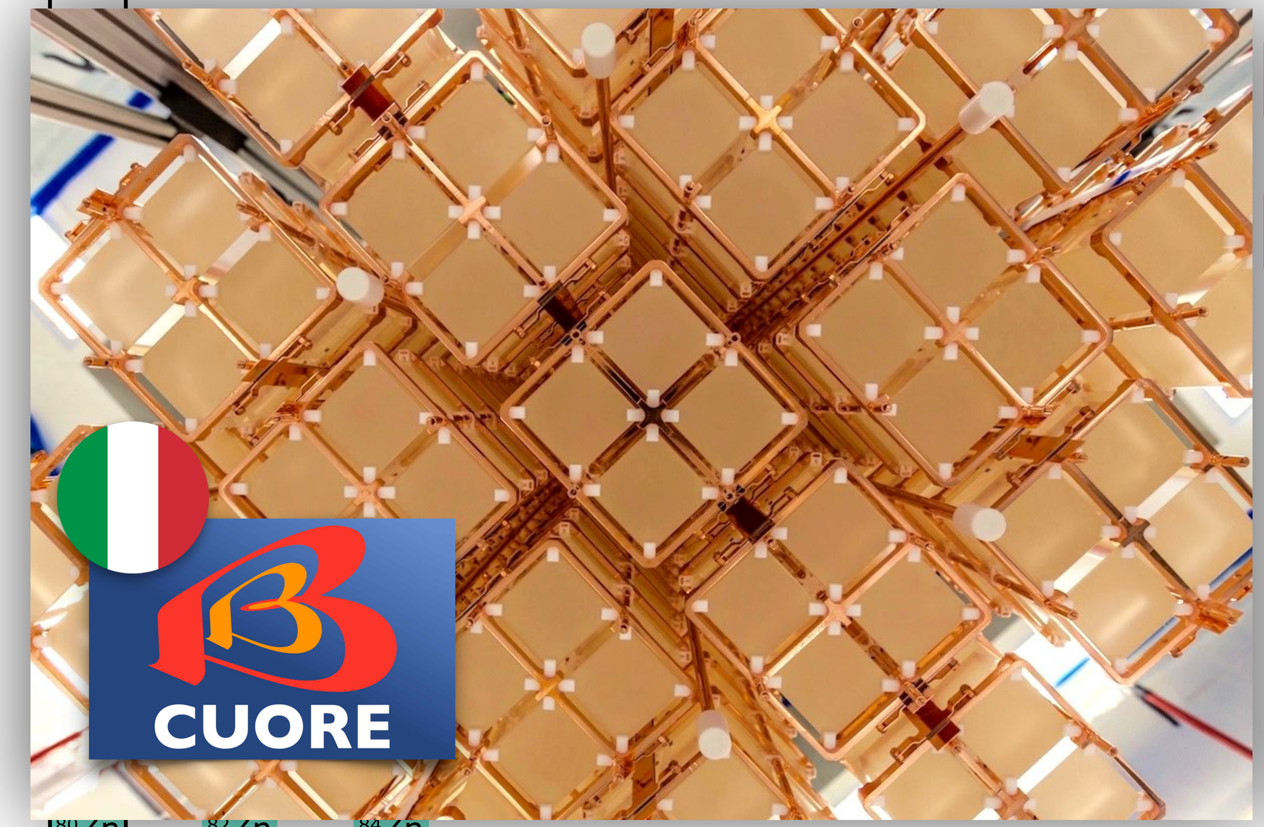
Shapes in ^{130}Xe for ^{130}Te 0νββ Decay

^{130}Xe on ^{208}Pb | SPs: A. Nannini, M. Rocchini, P. Napiorkowski

- On-going analysis:
  - More than 30 states populated
  - 5 excited 0^+ candidates populated
  - More than 50 transitions observed, 10 new

Deformation parameters and their dispersions for the g.s. should be accessible from GOSIA analysis





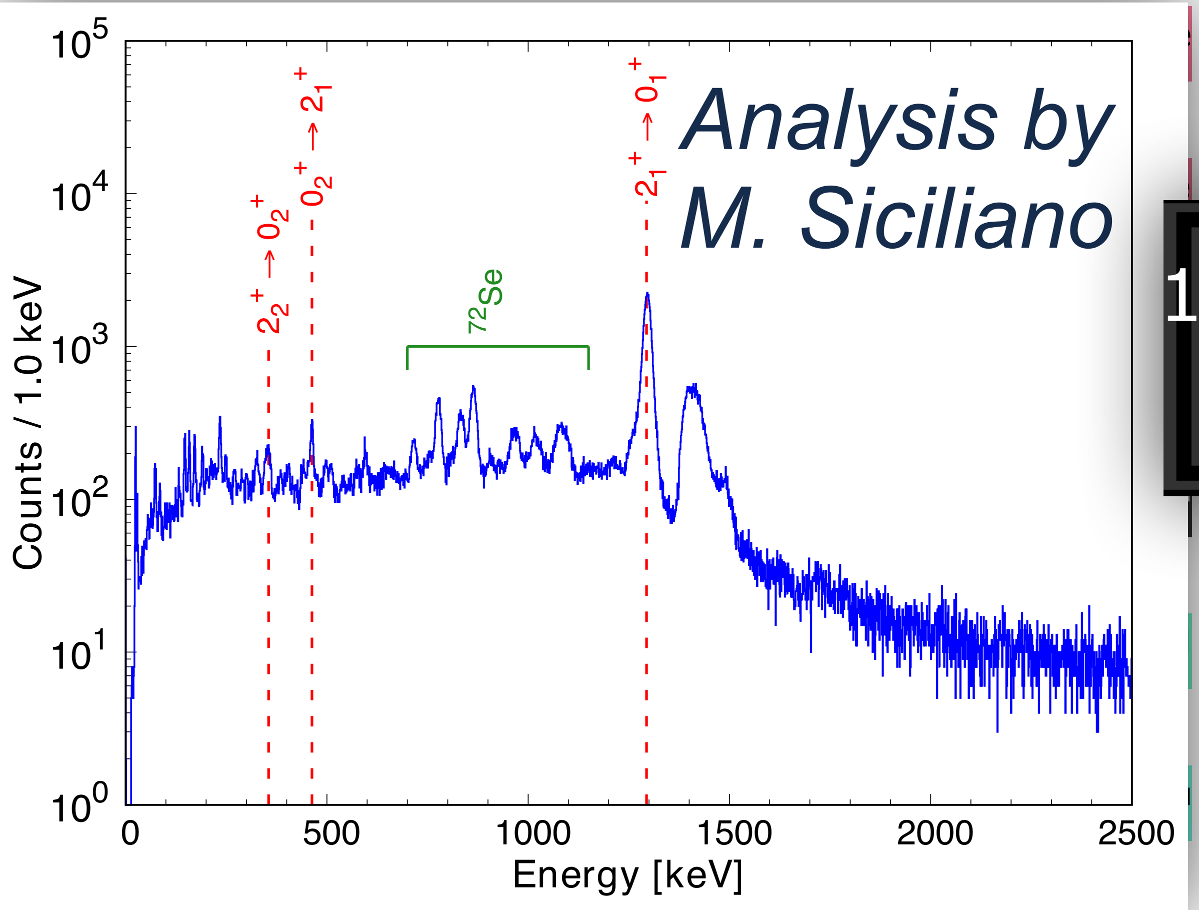
A. Tredici, A. Nannini, M. Rocchini, P. Napiórkowski et al., LNL Annual Report 2019 (2020) 59

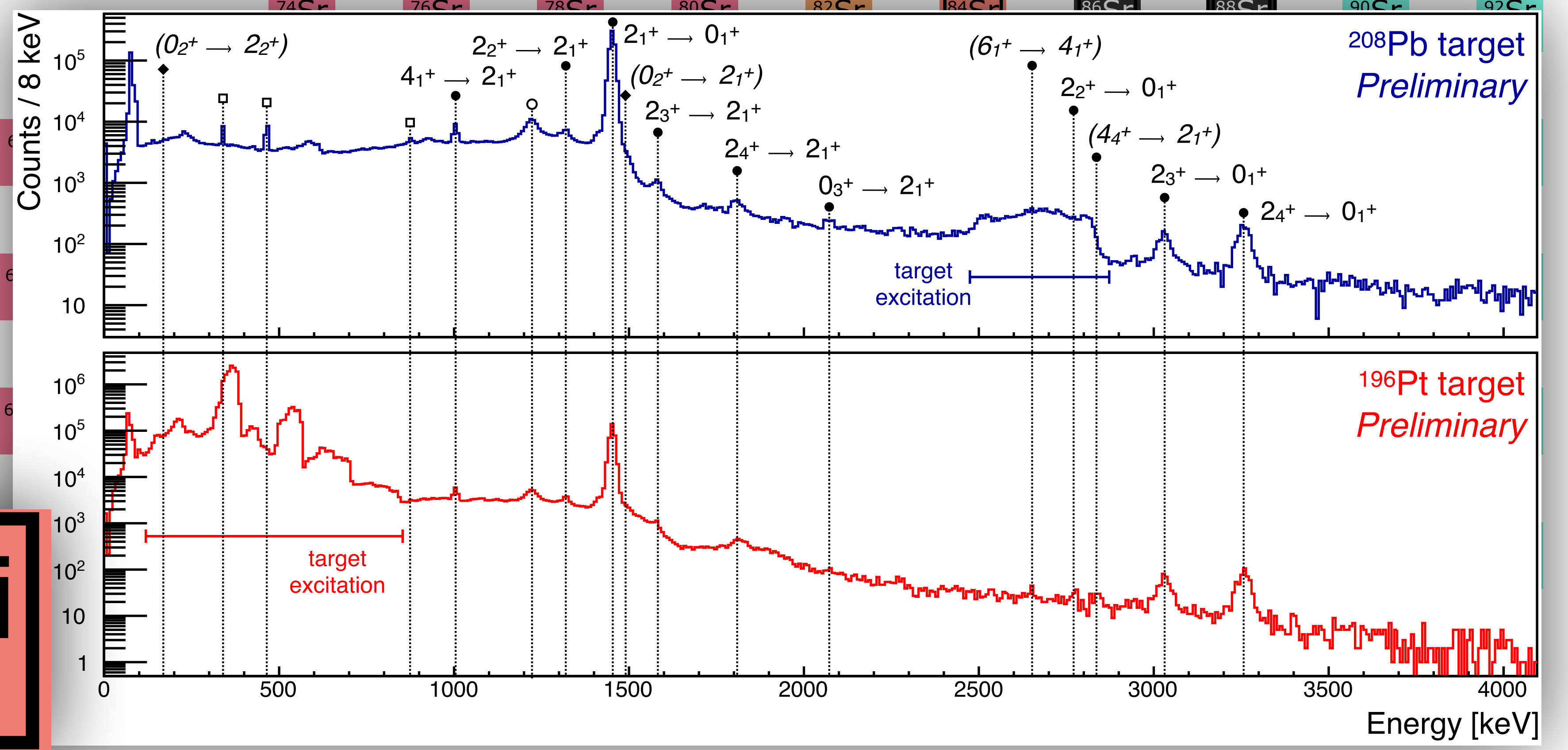
Coulex of ^{58}Ni and ^{116}Sn

^{58}Ni on ^{116}Sn | SPs: M. Siciliano, A. Illana, M. Saxena

M. Siciliano, A. Goasduff, M. Rocchini et al., LNL Annual Report 2019 (2020) 52

- ^{116}Sn (analysis ongoing):
  - Population of 2^+ states above the $0_{2,3}^+$ states achieved
  - Cut on the fusion evaporation background





Analysis by K. Hadyńska-Klęk

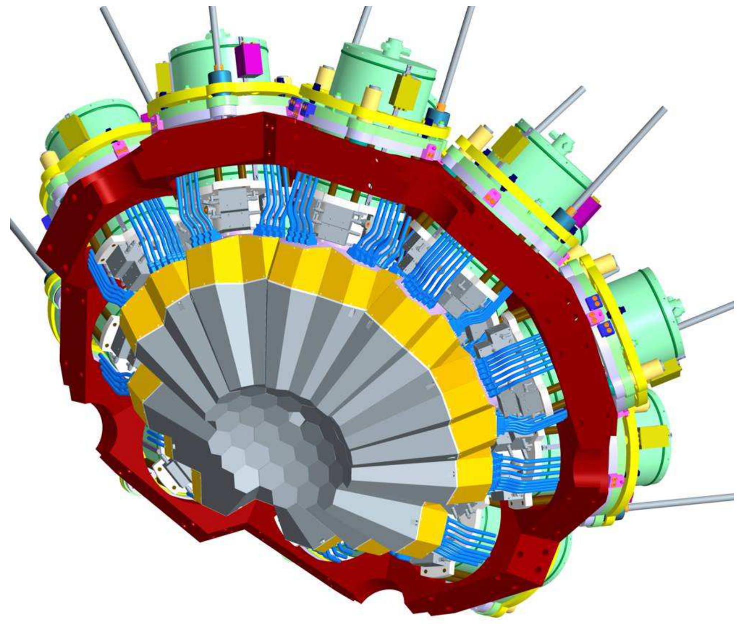
- ^{58}Ni (analysis ongoing):
  - 0_3^+ state populated
  - States above the 2_2^+ state ⟹ Qs(2_2^+) achievable

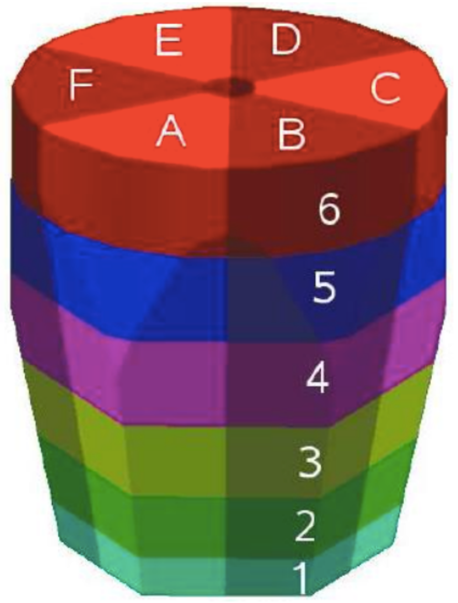
^{58}Ni on ^{208}Pb,^{196}Pt | SPs: M. Rocchini, A. Nannini, K. Hadyńska-Klęk

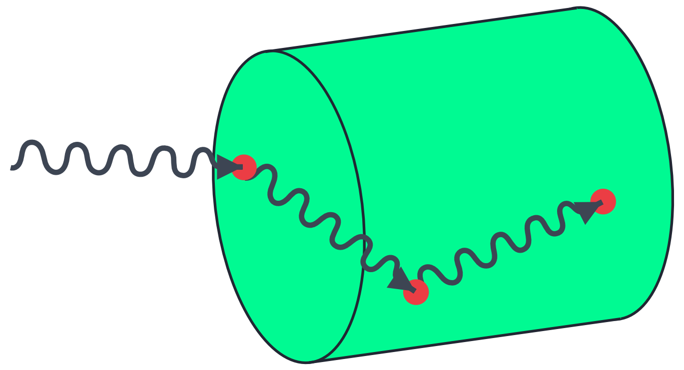
M. Rocchini, A. Nannini, K. Hadyńska-Klęk et al., LNL Annual Report 2020 (2021) 39

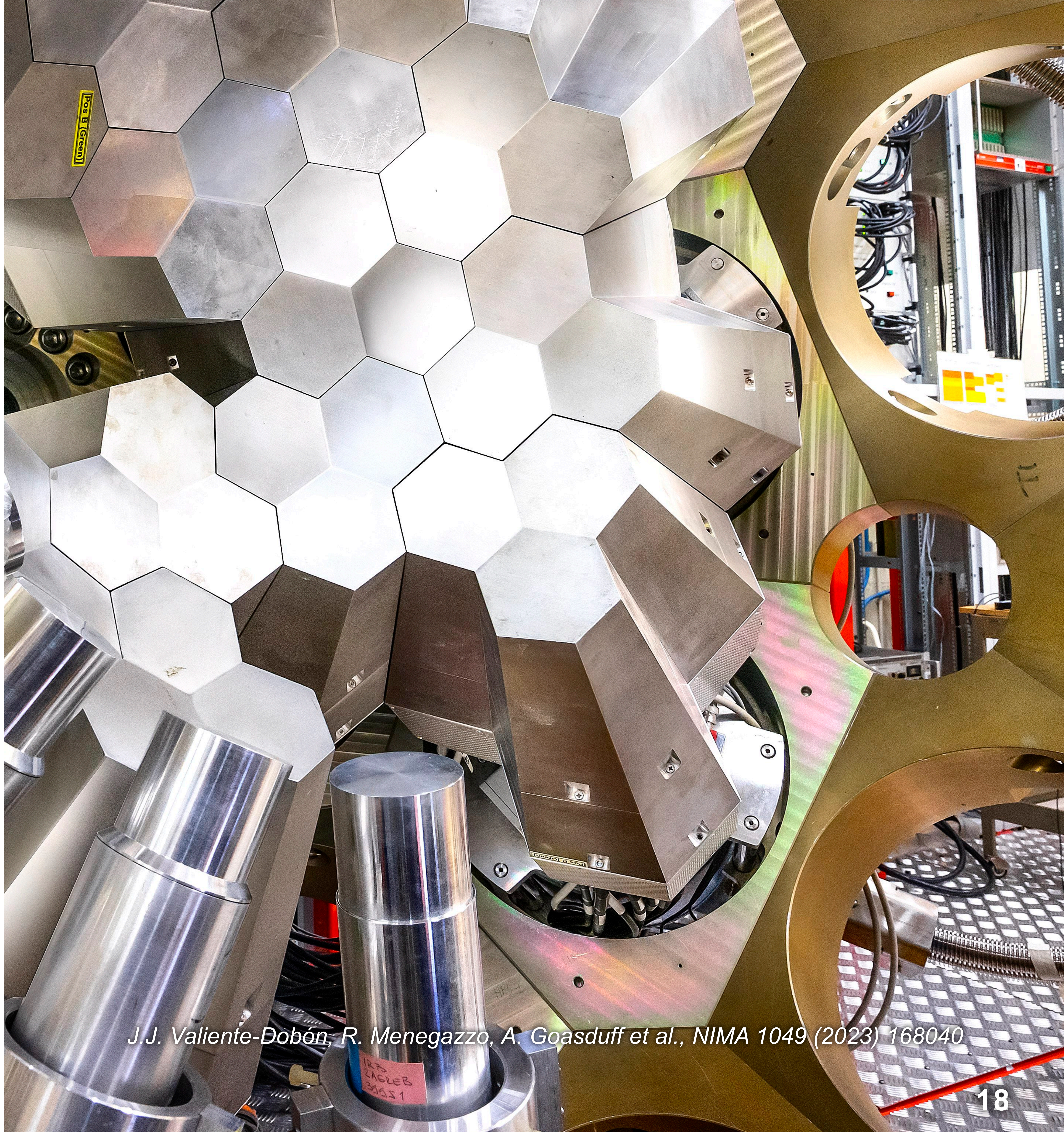
AGATA

- Last generation γ-ray spectrometer composed of higly-segmented HPGe detectors
- Employs advanced PSA and γ-ray tracking methods to avoid Compton-suppressors and garantee high efficiency









J.J. Valiente-Dobón, R. Menegazzo, A. Goasduff et al., NIMA 1049 (2023) 168040

AGATA with SPIDER (2022 - ongoing)

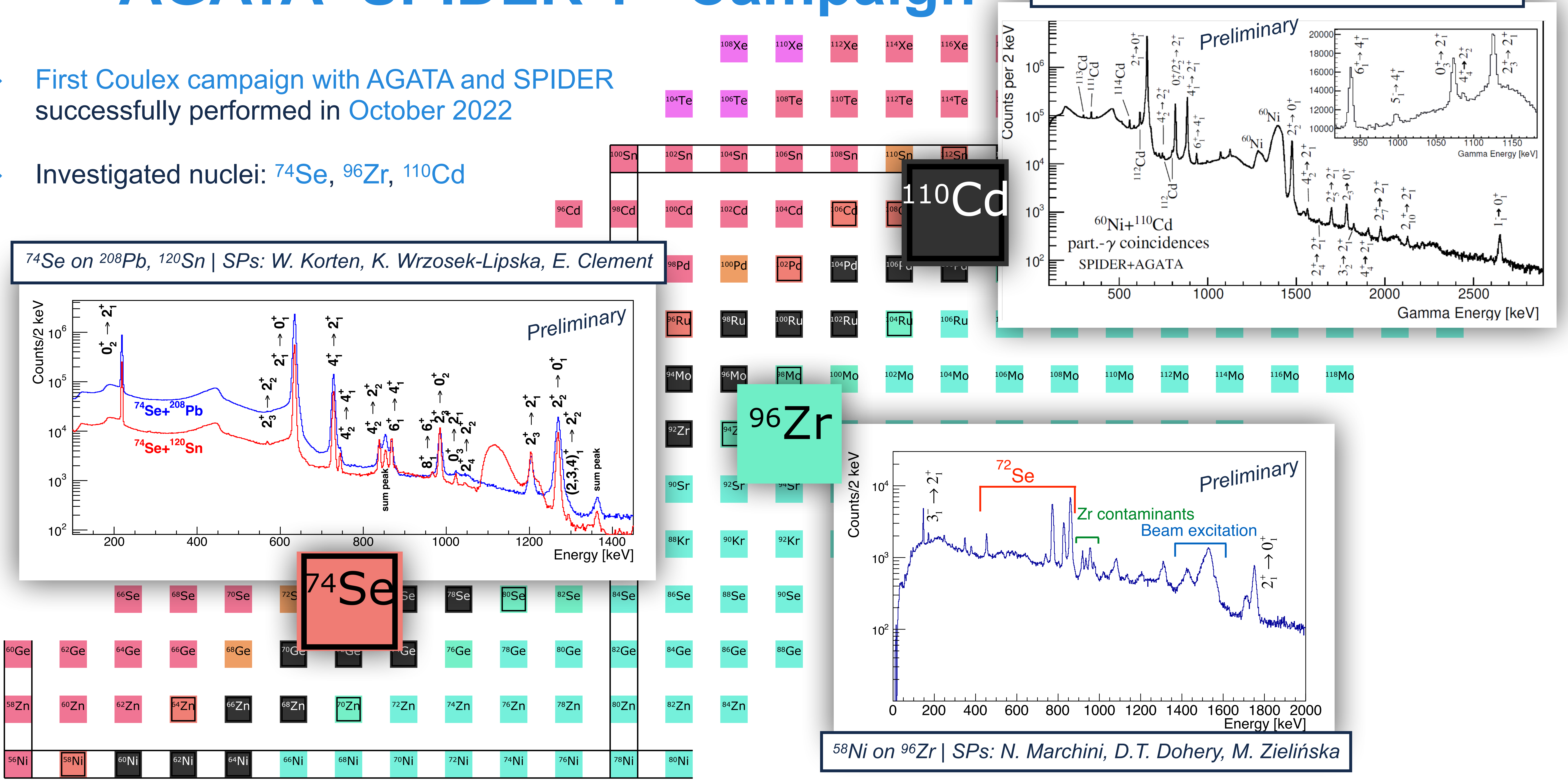
AGATA with SPIDER (2022 - ongoing)

AGATA+SPIDER 1st Campaign

- First Coulex campaign with AGATA and SPIDER successfully performed in October 2022
- Investigated nuclei: ^{74}Se, ^{96}Zr, ^{110}Cd

^{60}Ni on ^{110}Cd | SPs: K. Wrzosek-Lipska, P.E. Garrett, A.Nannini, M. Rocchini, M. Zielińska

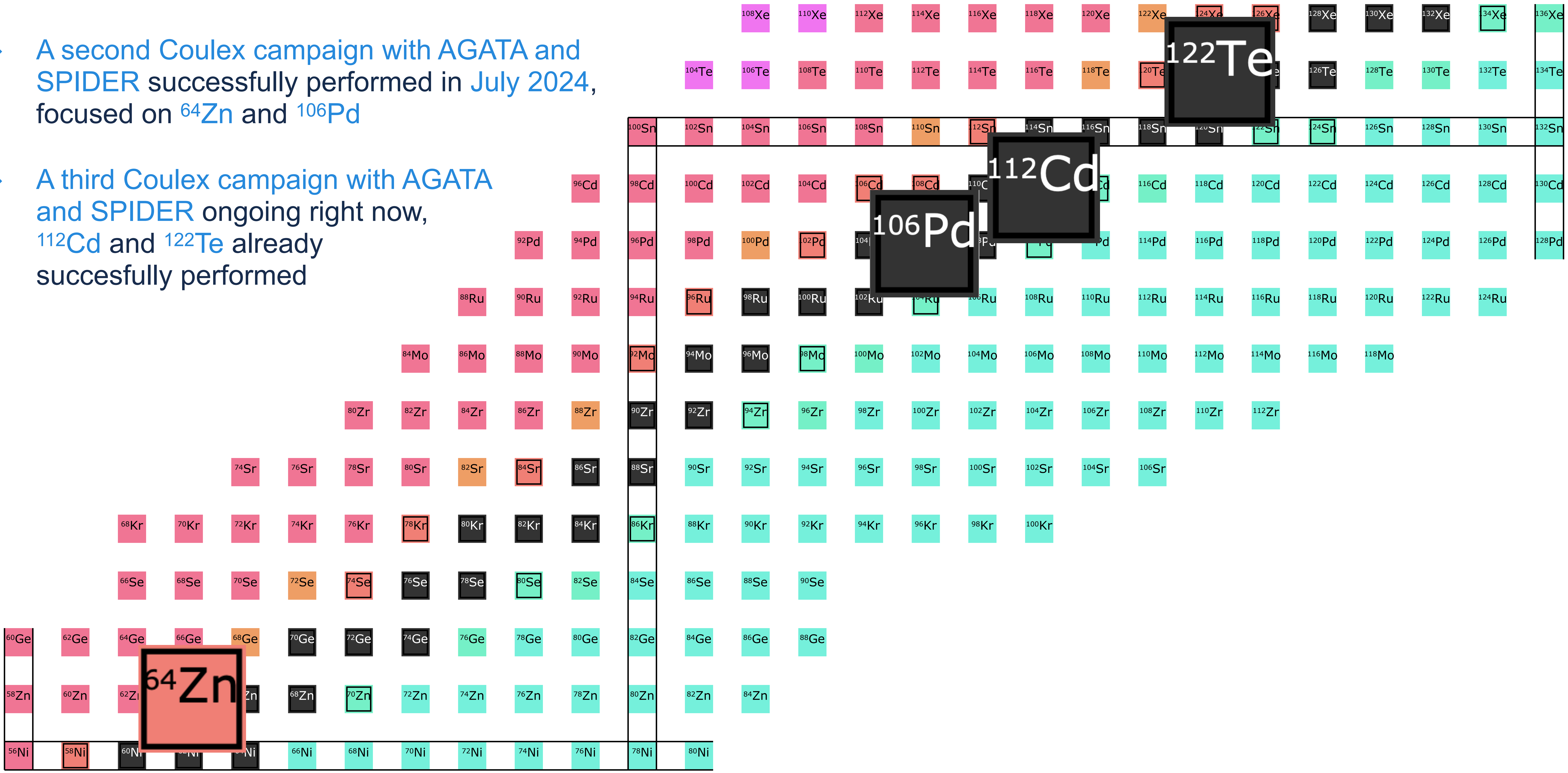
^{74}Se on ^{208}Pb, ^{120}Sn | SPs: W. Korten, K. Wrzosek-Lipska, E. Clement



^{58}Ni on ^{96}Zr | SPs: N. Marchini, D.T. Dohery, M. Zielińska

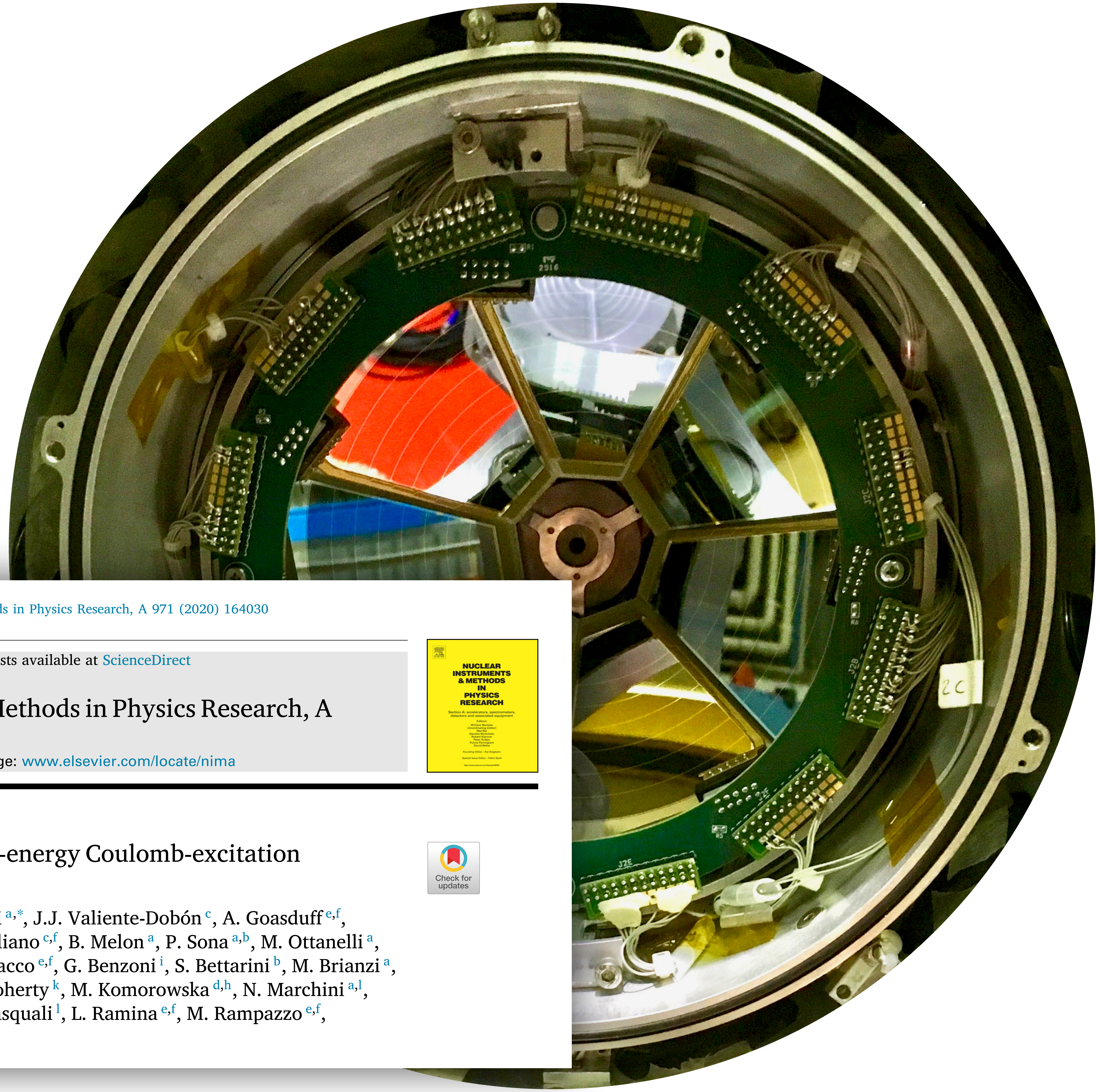
AGATA+SPIDER 2nd and 3rd Campaign

- A second Coulex campaign with AGATA and SPIDER successfully performed in July 2024, focused on ^{64}Zn and ^{106}Pd
- A third Coulex campaign with AGATA and SPIDER ongoing right now, ^{112}Cd and ^{122}Te already succesfully performed



Summary

- SPIDER is a segment, modular silicon detector designed for low-energy Coulomb excitation measurements with modern γ-ray spectrometers
- The detector is characterized by an excellent energy resolution, which makes it possible to take into account the target thickness in the Doppler correction of the γ-ray energy
- We studied radiation damage and pulse height correlations for our applications
- The detector is "as simple as possible", making it a very reliable instrument (100% success rate)



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SPIDER: A Silicon PIe DEtectoR for low-energy Coulomb-excitation measurements

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THANK YOU FOR THE ATTENTION