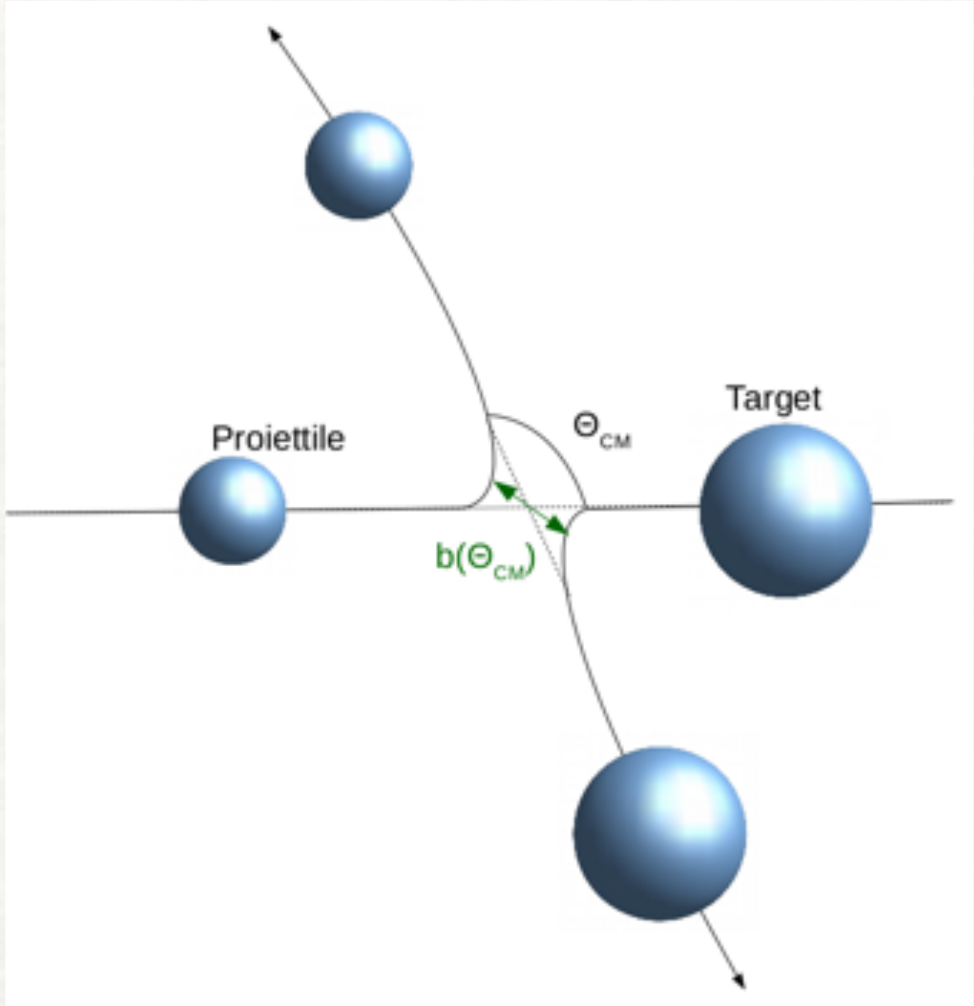
Istituto Nazionale di Fisica Nucleare

ADRIANA NANNINI
INFN — FIRENZE

COULOMB EXCITATION AT LNL WITH THE SPIDER ARRAY

COULOMB EXCITATION

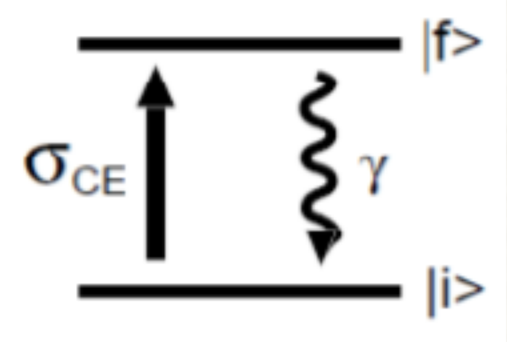
Low-energy Coulomb excitation is a simple and precise tool to measure excitation probabilities and provide insight on the collectivity of nuclear excitations and in particular on nuclear shapes.



COULOMB EXCITATION

- cross-sections give a measure of the matrix elements of the e.m. operators

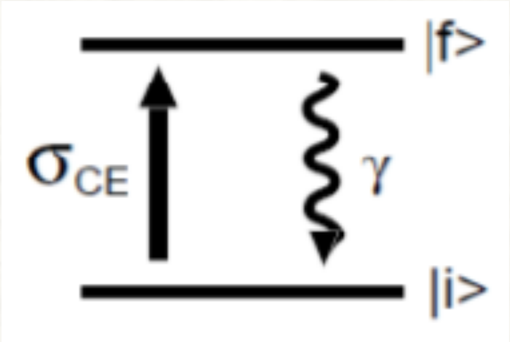
$$\frac{d\sigma_{clx}}{d\Omega} = \frac{d\sigma_{Ruth}}{d\Omega} \cdot P\left(i \longrightarrow f\right)$$



COULOMB EXCITATION

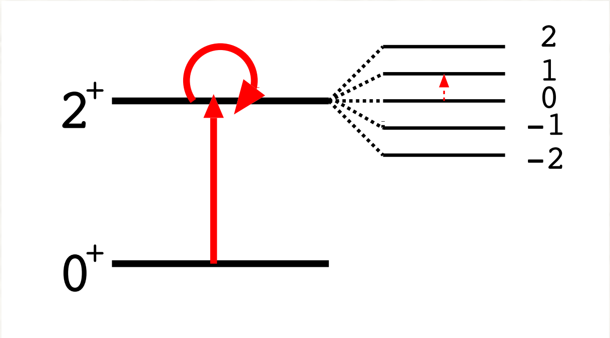
- cross-sections give a measure of the matrix elements of the e.m. operators

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



- diagonal matrix elements (spectroscopic quadrupole moments) give a measure of charge distribution

$$Q_s\left(J\right) = \sqrt{\frac{16\pi}{5}} \frac{\langle JJ20|JJ\rangle}{\sqrt{2J+1}} \langle J\,||E2||\,J\rangle$$

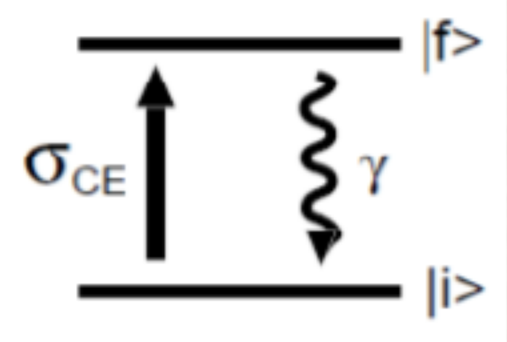


INFN FIRENZE
Istituto Nazionale di Fisica Nucleare
Sezione di Firenze

COULOMB EXCITATION

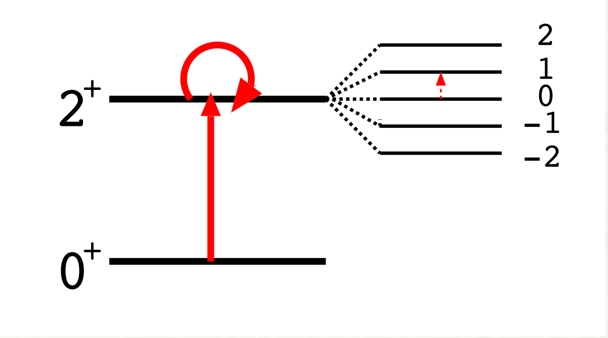
- cross-sections give a measure of the matrix elements of the e.m. operators

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

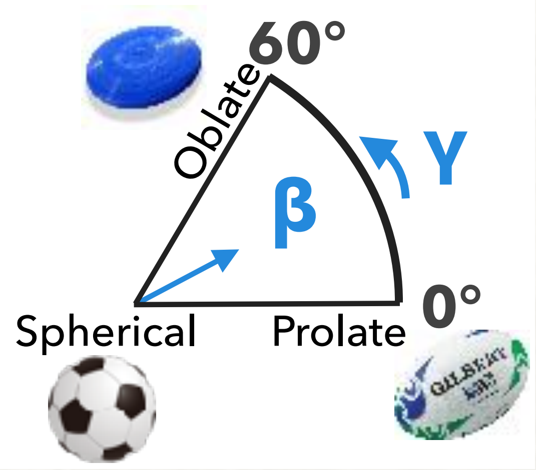


- diagonal matrix elements (spectroscopic quadrupole moments) give a measure of charge distribution

$$Q_s\left(J\right) = \sqrt{\frac{16\pi}{5}}\frac{\langle JJ20|JJ\rangle}{\sqrt{2J+1}}\langle J\left|\right|E2\left|\right|J\rangle$$

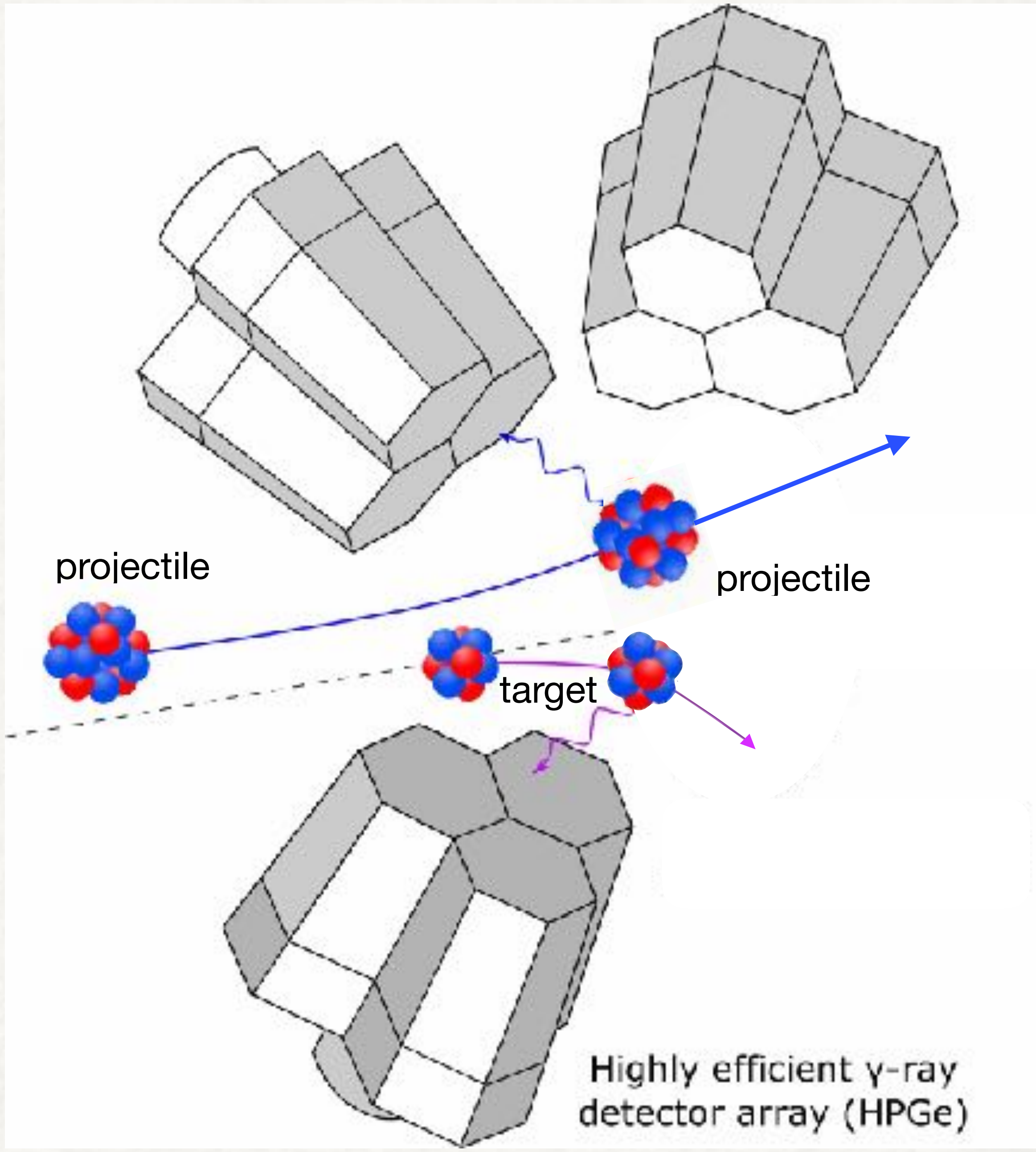


- complete set of E2 matrix elements brings information on shape parameters via the quadrupole sum rules



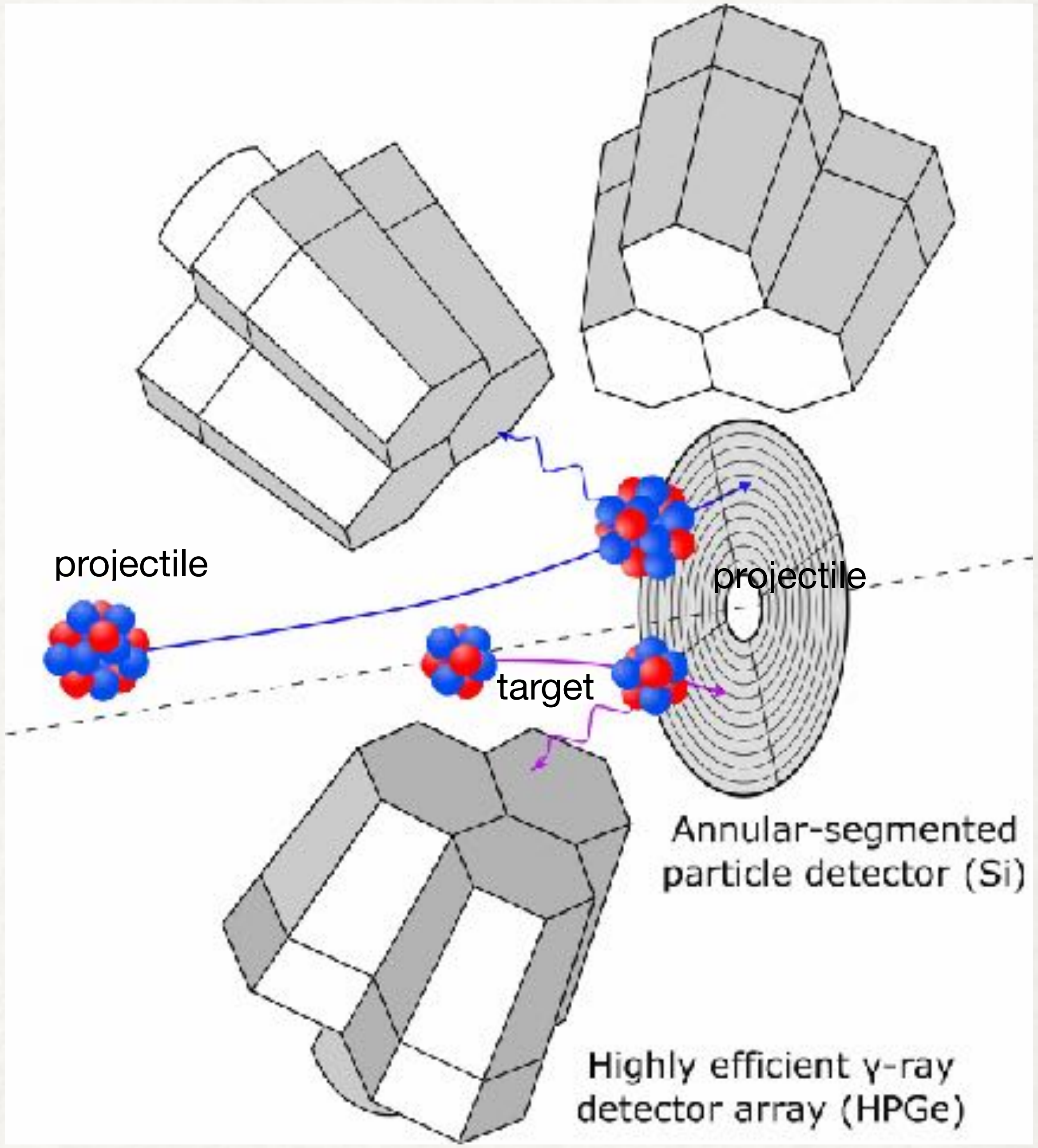
COULOMB EXCITATION MEASUREMENTS

- germanium detectors to detect γ-rays
  - Doppler correction of γ-ray spectra
  - inverse kinematics: excitation of a heavy projectile on a light target (typically ^{12}C)



COULOMB EXCITATION MEASUREMENTS

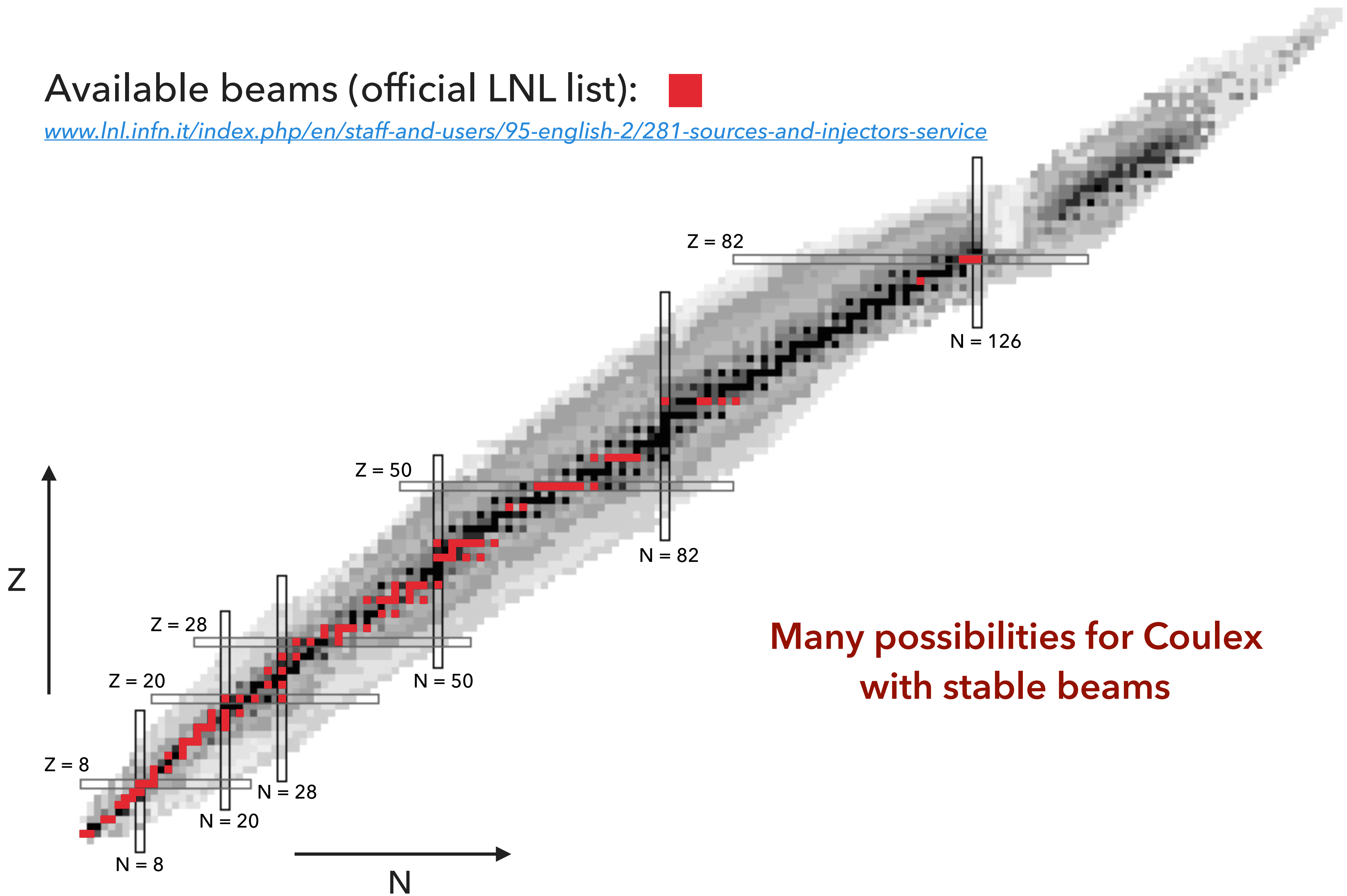
- germanium detectors to detect γ-rays
- segmented particle detector to detect the scattered projectiles and/or recoiling target nuclei
  - to select Coulomb Excitation events
  - to determine scattering angle and reconstruct the kinematics of the reaction
  - to perform Doppler correction



COULEX @ LNL WITH STABLE BEAMS

Available beams (official LNL list):

www.lnl.infn.it/index.php/en/staff-and-users/95-english-2/281-sources-and-injectors-service

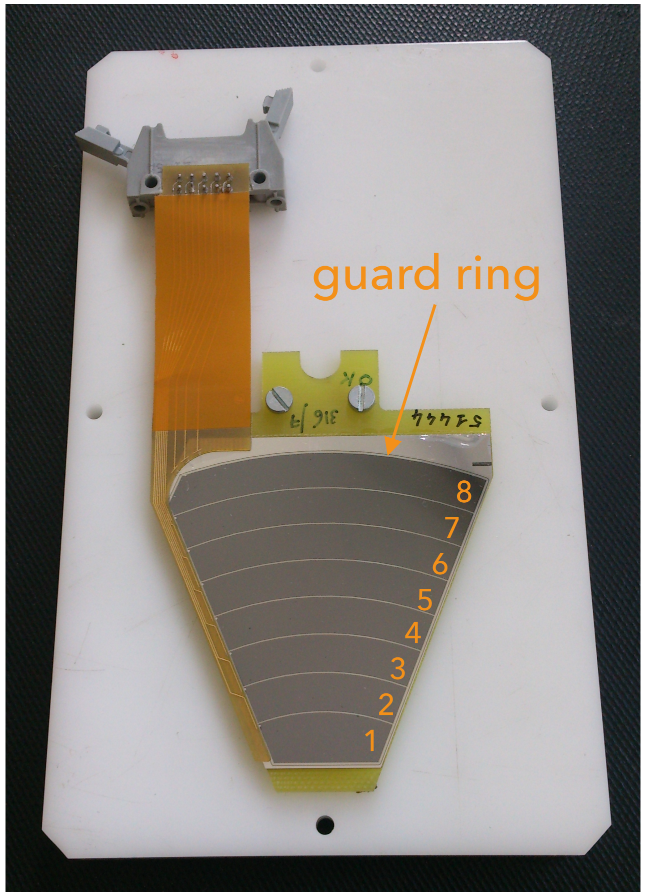


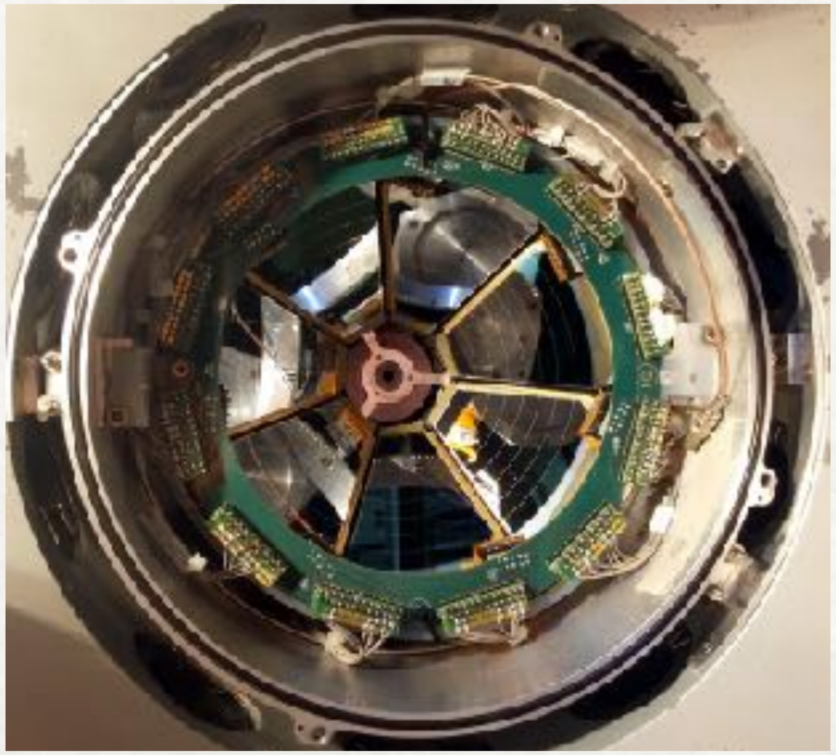
Many possibilities for Coulex with stable beams

THE SPIDER ARRAY

SPIDER Silicon PIe DEtectoR

- 8 independent **sectors**, 8 **strips** + guard ring
- Detector **thickness** ~ 300 μm
- **FWHM** ~21 keV for **α**-particles @ ~5.5 MeV
- modularity: with GALILEO **cone configuration** (7 sectors) at **backward angles** ⟹ ΔΘ ~ 38°, Ω/4π ~ 17%



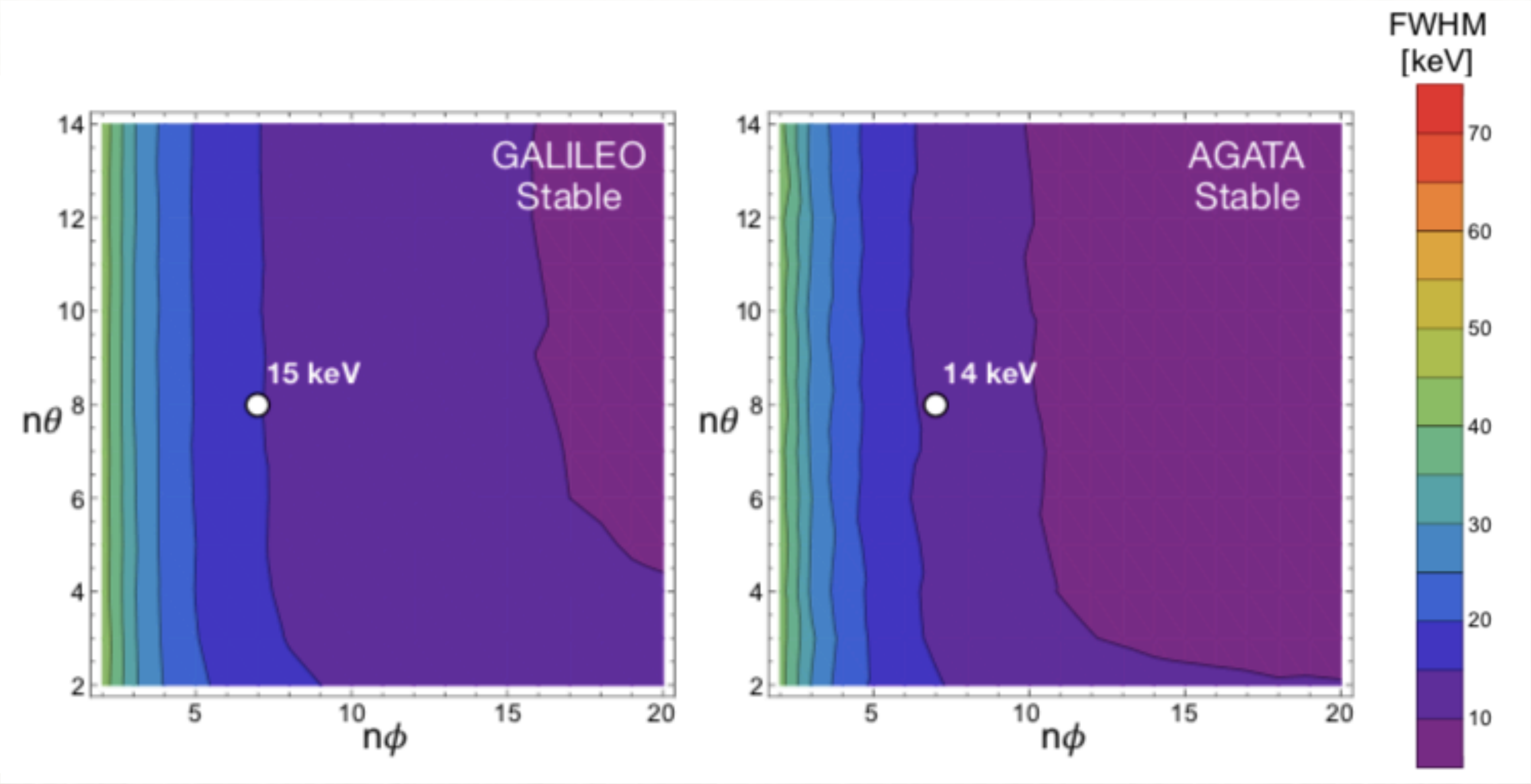


Strip	θ_{min} [deg]	θ_{mean} [deg]	θ_{max} [deg]	$\Delta\theta$ [deg]	Ω [srad]
7	123.5	125.4	127.5	4.0	0.046
6	127.5	129.6	131.8	4.3	0.046
5	131.8	134.0	136.4	4.6	0.045
4	136.4	138.7	141.2	4.8	0.043
3	141.2	143.6	146.1	5.0	0.040
2	146.1	148.6	151.2	5.1	0.035
1	151.2	153.7	156.3	5.1	0.030
0	156.3	158.8	161.3	5.1	0.028
Tot	123.5	142.4	161.3	37.8	2.2

DOPPLER CORRECTION OF GAMMA SPECTRA

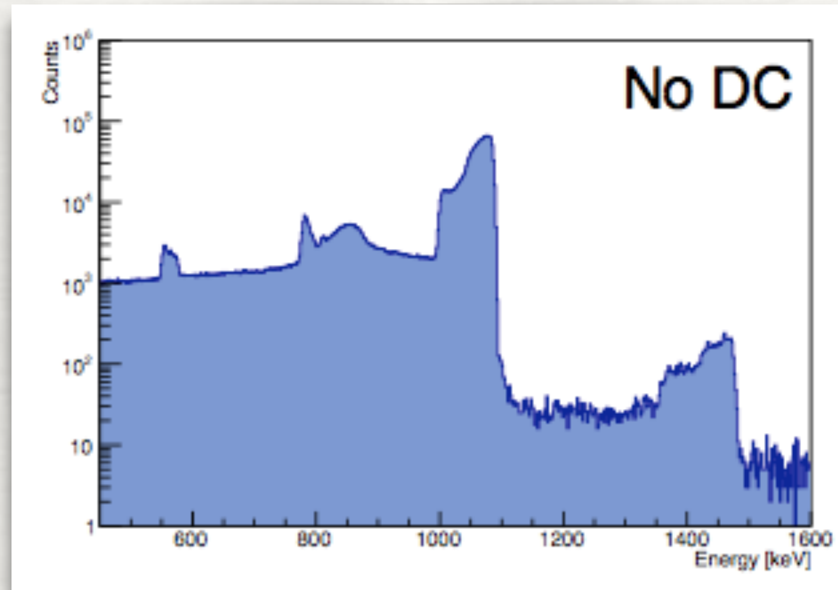
Simulated FWHM @ 1332 keV as a function of the polar (nθ) and azimuthal (nφ) segmentation

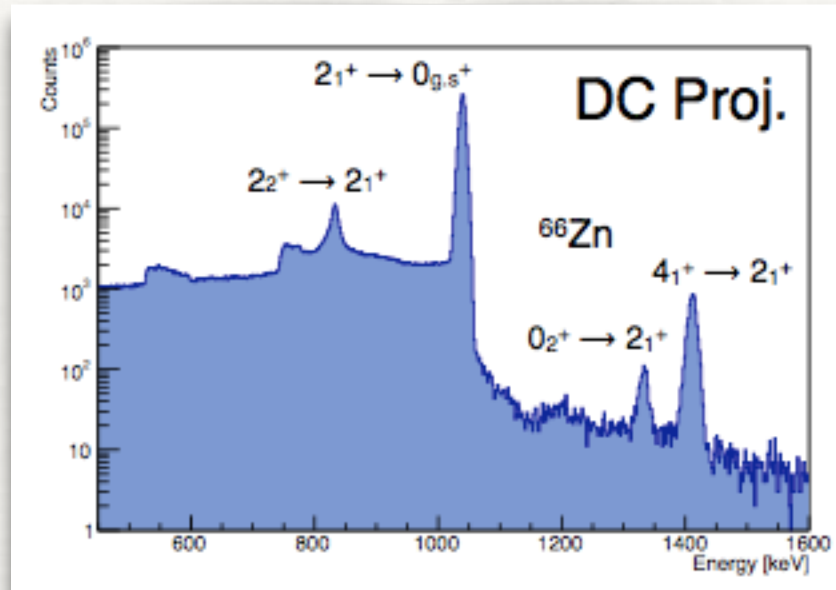
- annular particle detector at 8.5 cm from the target with ΔΘ = 35°
- ^{60}Ni nuclei scattered on a 1 mg/cm2 ^{208}Pb target

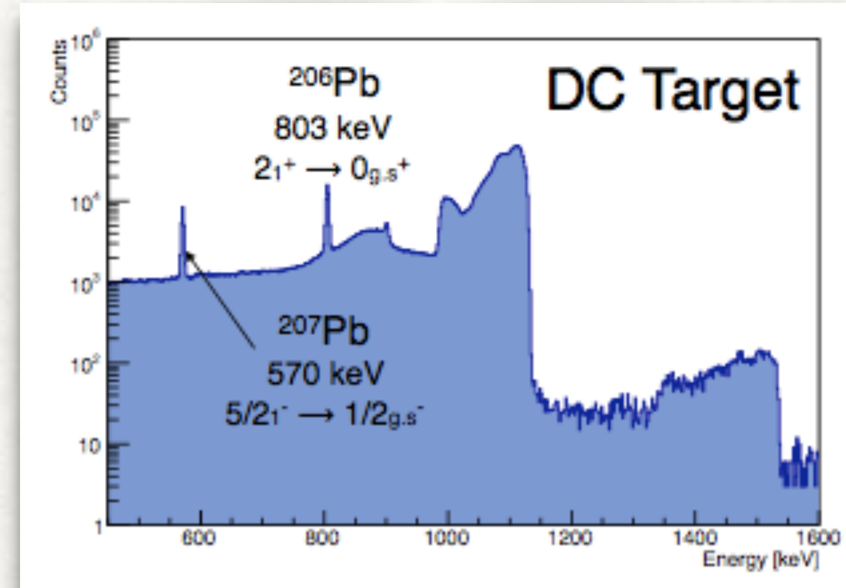


DOPPLER CORRECTION OF GAMMA SPECTRA

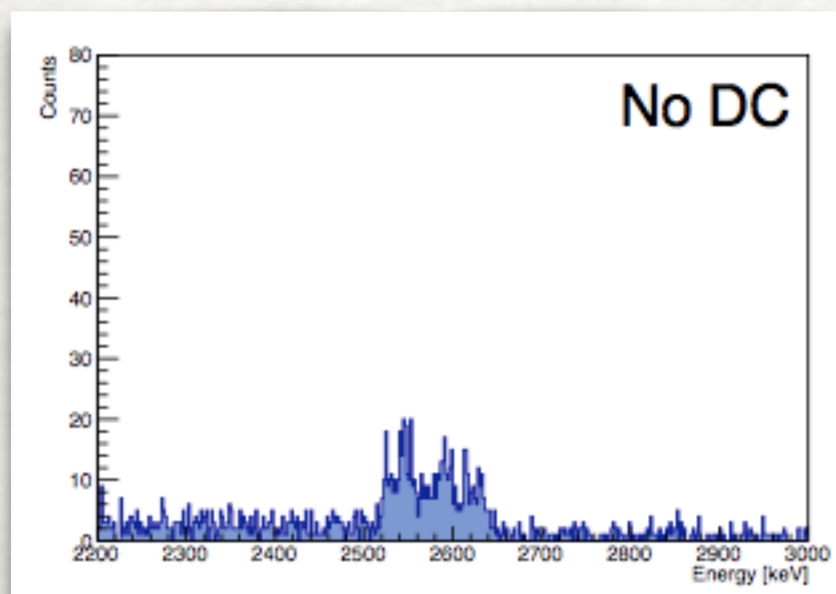
INFN FIRENZE
Istituto Nazionale di Fisica Nucleare
Sezione di Firenze

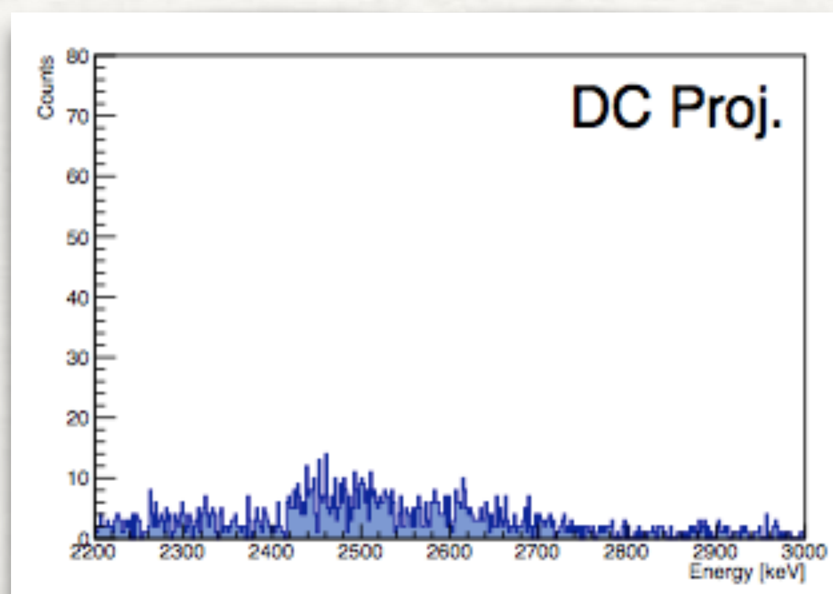


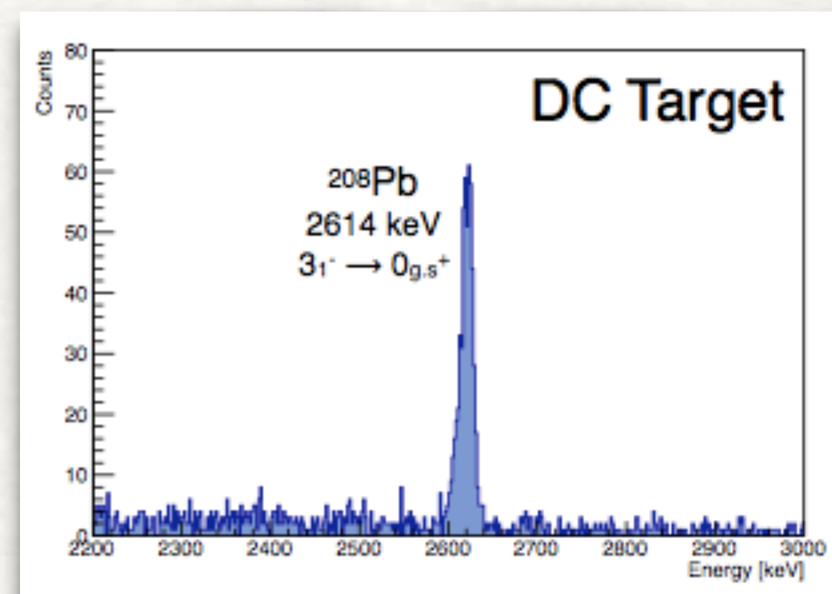




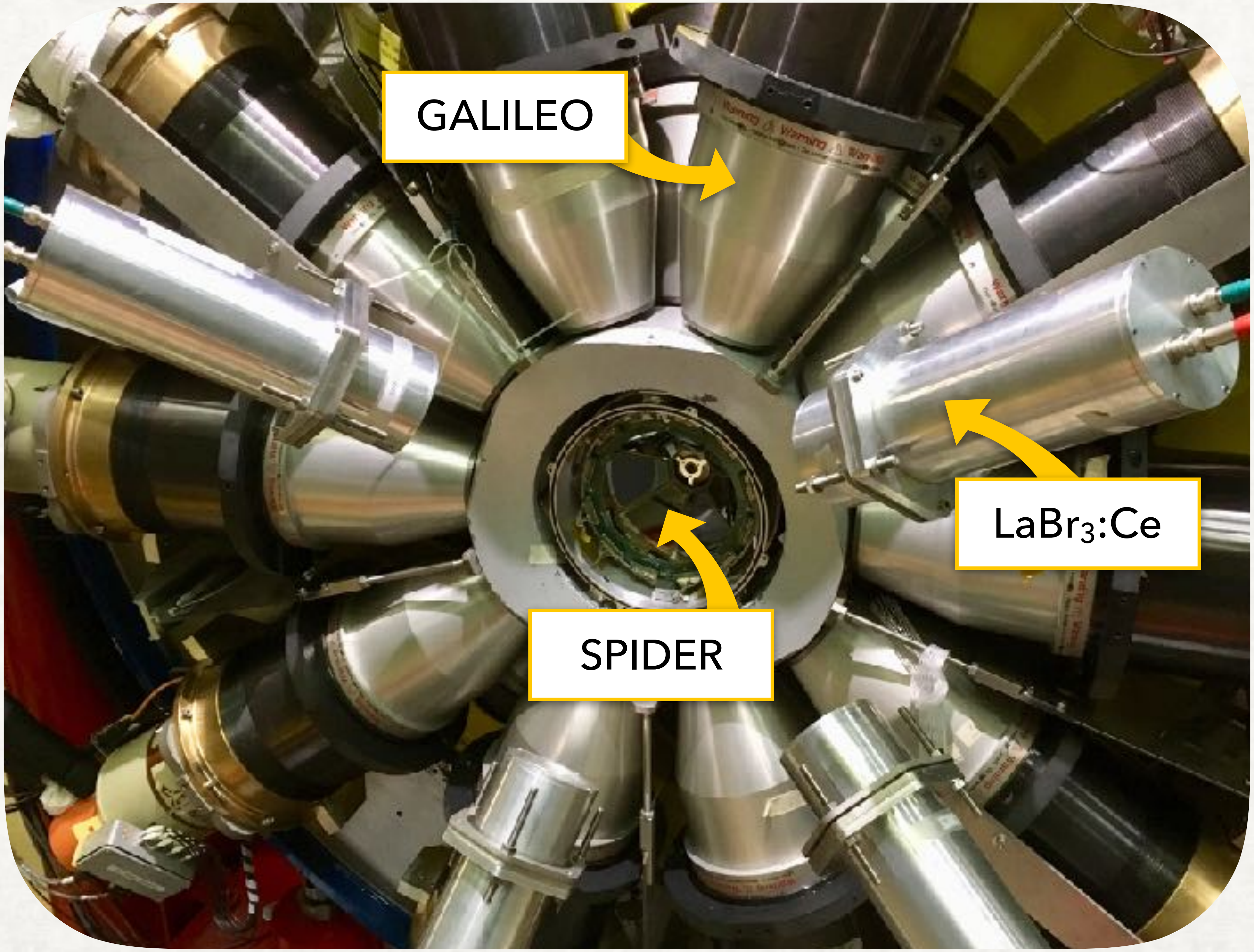
FWHM@1200 ~11 keV





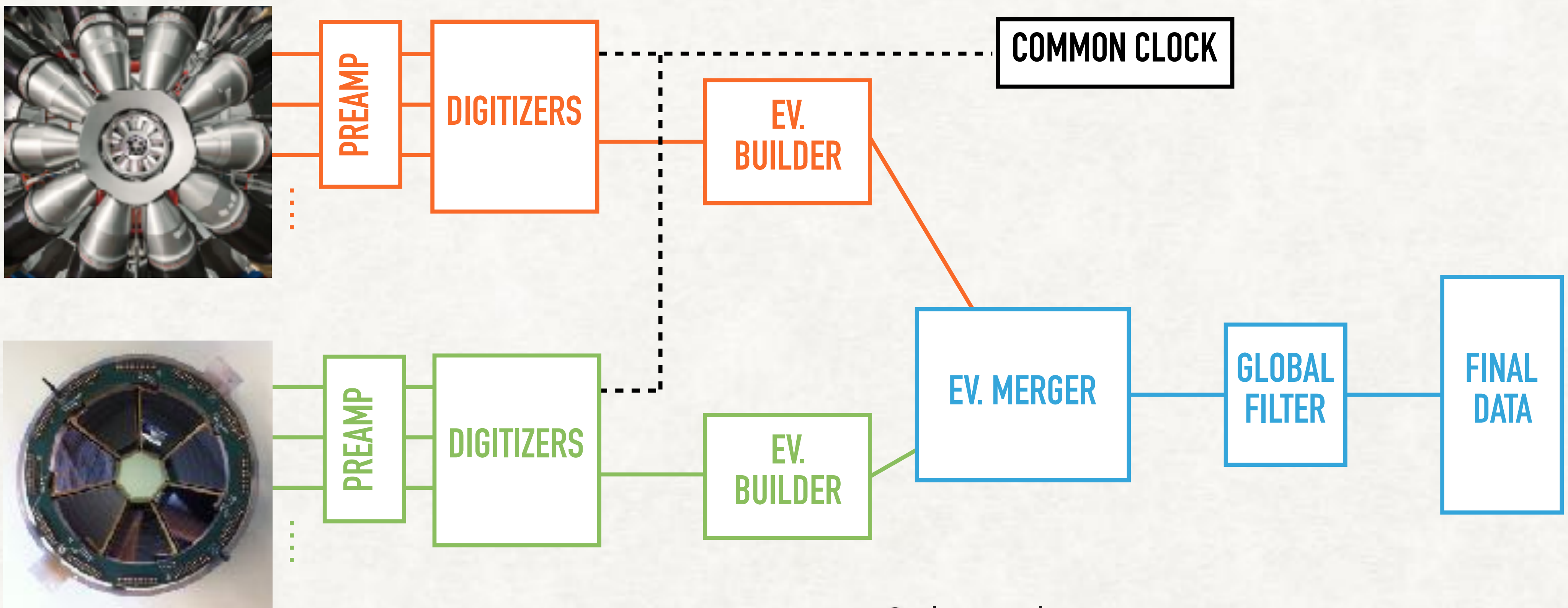


THE SPIDER - GALILEO SETUP



INFN
FIRENZE
Istituto Nazionale di Fisica Nucleare
Sezione di Firenze

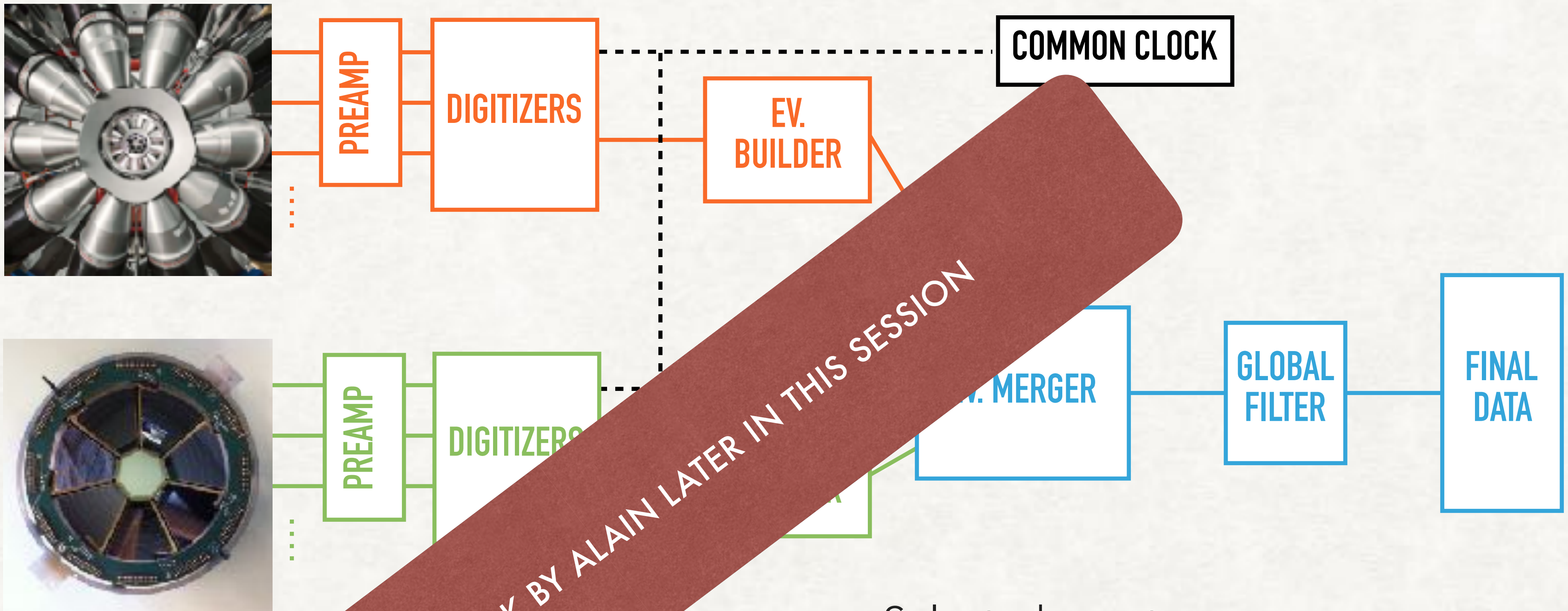
ACQUISITION SYSTEM



- Event structure:
  - Detector id 1
    - Energy
    - Timestamp
    - Time
  - Detector id 2
    - …

- Selected events:
  - One or more particles
  - One or more gammas
  - Particles gammas coincidences
- Data analysis:
  - Particle and gamma singles spectra
  - Gamma-Gamma
  - Particle-Gamma
  - Particles-Gamma-Gamma

ACQUISITION SYSTEM

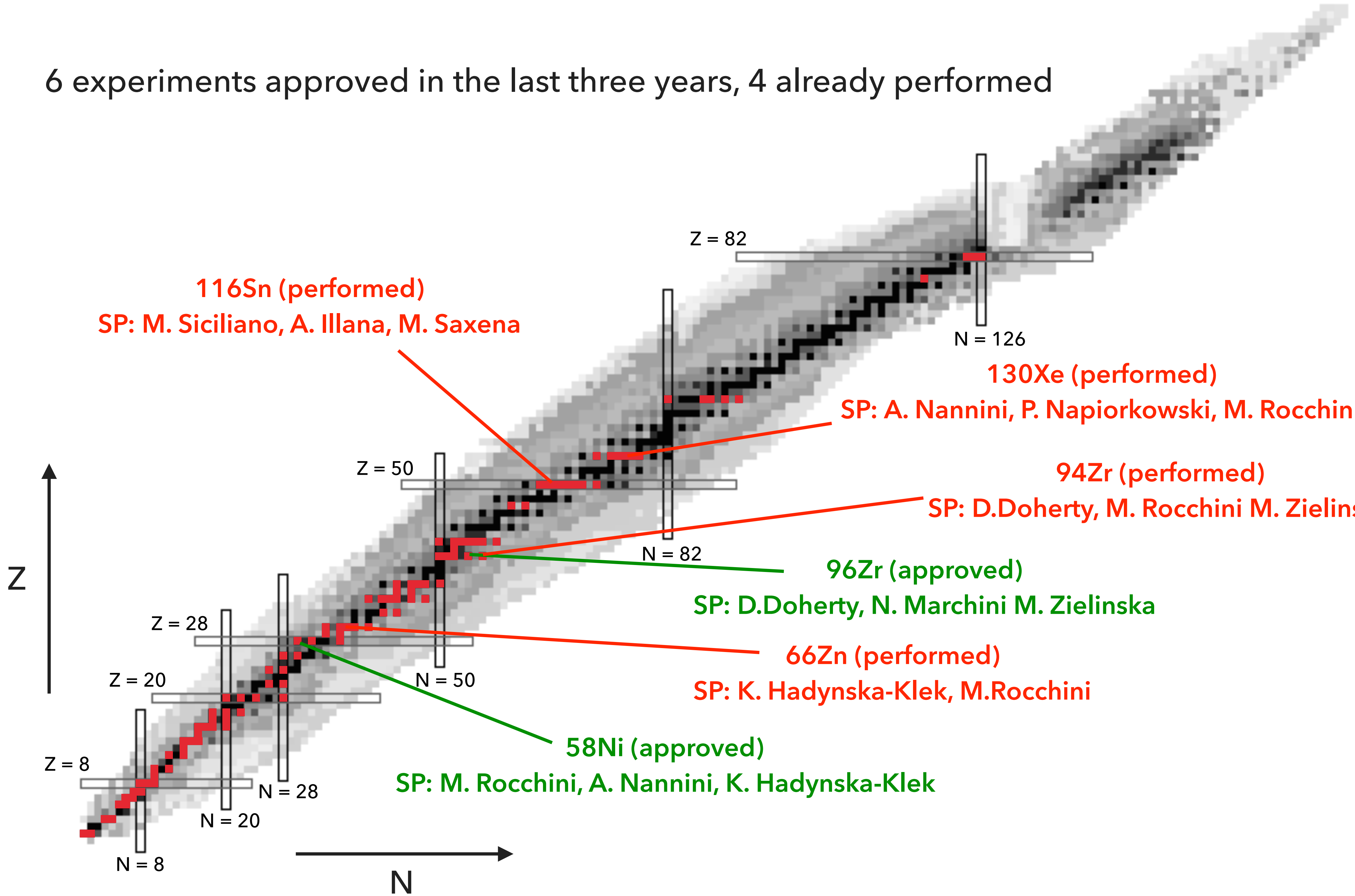


- Event structu
  - Detector id
    - Energy
    - Timestamp
    - Time
  - Detector id 2
    - …

- Selected events:
  - One or more particles
  - One or more gammas
  - Particles gammas coincidences
- Data analysis:
  - Particle and gamma singles spectra
  - Gamma-Gamma
  - Particle-Gamma
  - Particles-Gamma-Gamma

COULEX @ LNL SPIDER&GALILEO

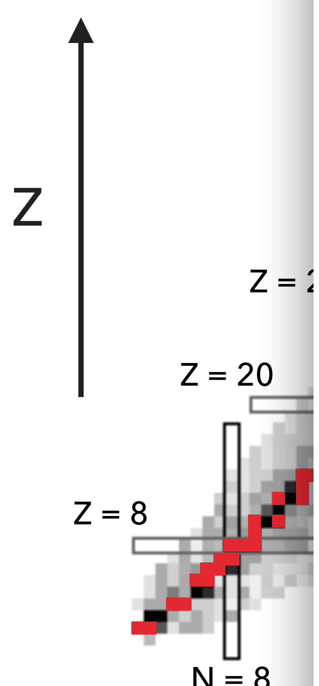
6 experiments approved in the last three years, 4 already performed



COULEX @ LNL SPIDER&GALILEO

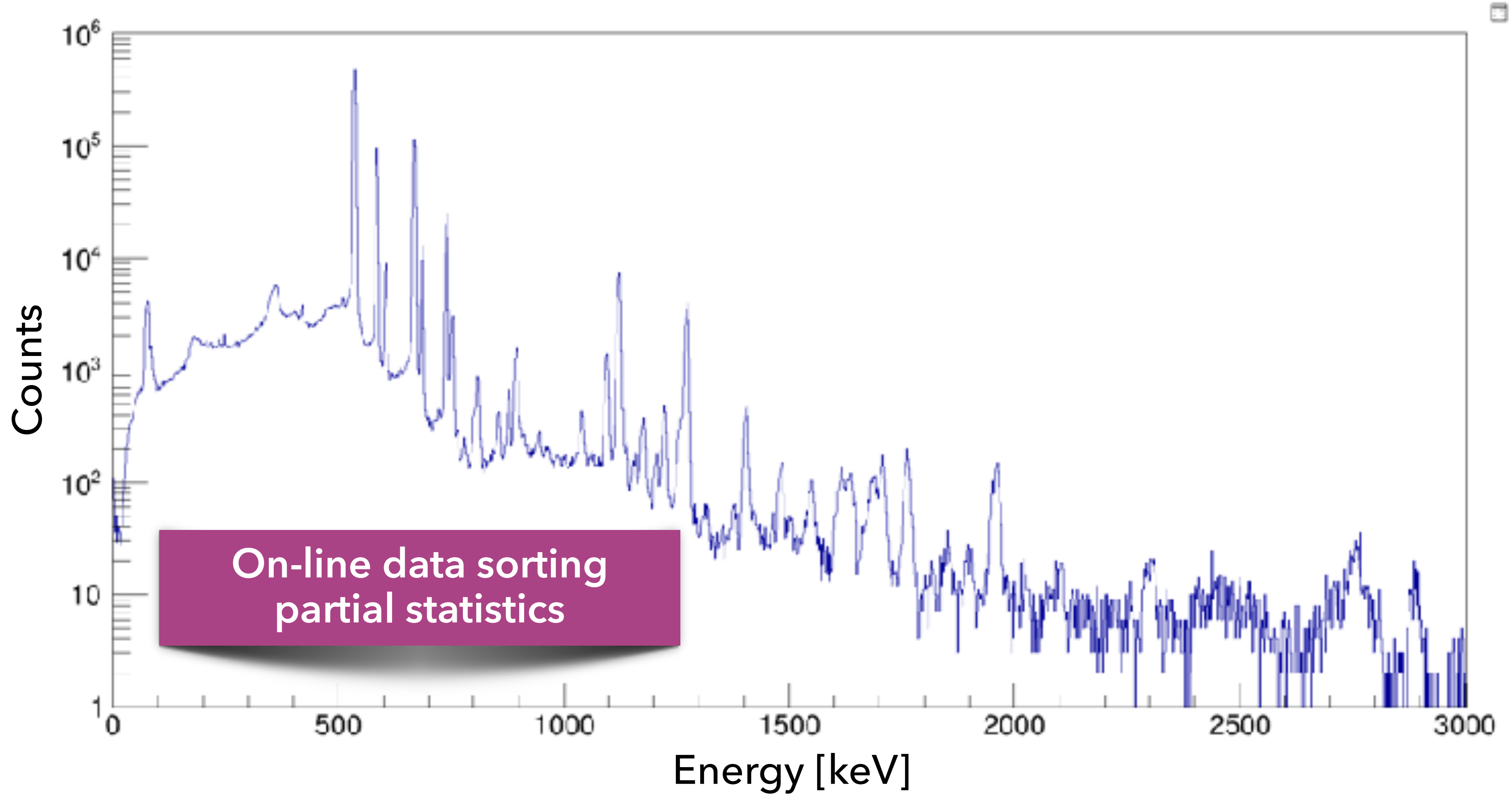
6 experiments approved in the last three years, 4 already performed

SP: M. S



Shapes of 0^+ States and Collectivity in ^{130}Xe for Studies of ^{130}Te ββ-decay

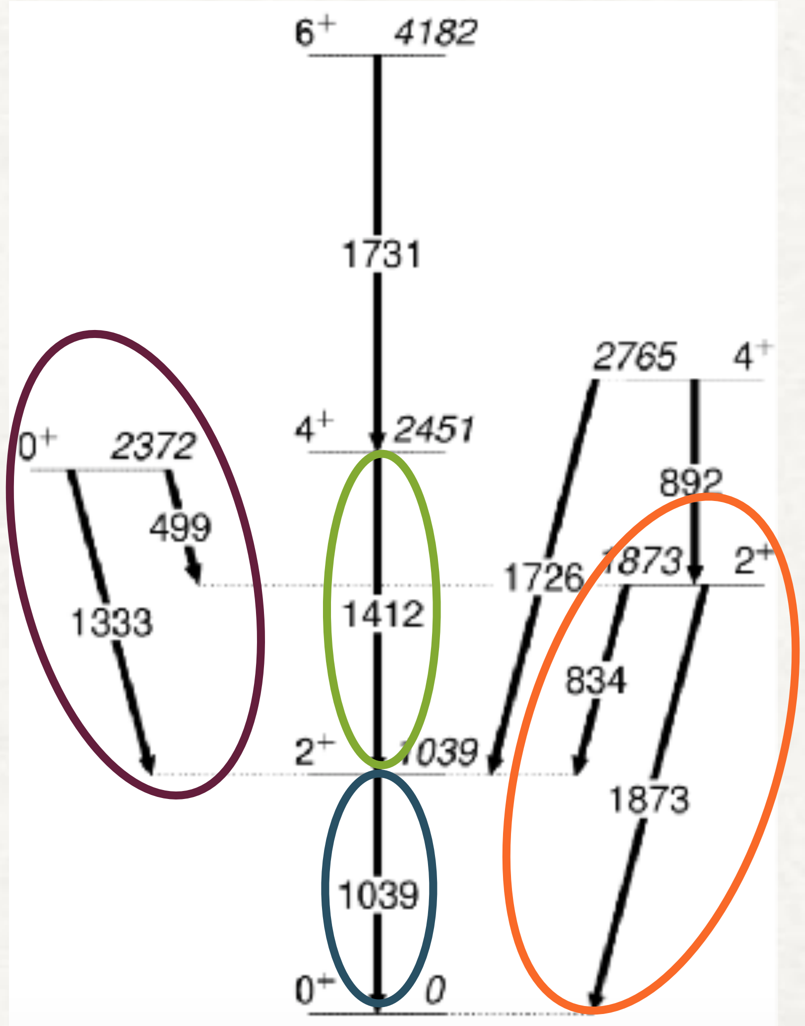
Spokesperson(s): A. Nannini, P. Napiorkowski, M. Rocchini



First Experiment: Collectivity of ^{66}Zn

Spokespersons: M. Rocchini, K. Hadynska-Klek

- Commissioning: B(E2; 2_1^+ —> 0_1^+) and Q(2_1^+) known with high precision.
- New physics:
  - Shape of 0_2^+ ? B(E2) value unknown
  - Is the 2_2^+ high-collective or not? Discrepant values for its lifetime
  - Is the 4_1^+ collective or not? Discrepant values for the B(E2; 4_1^+ —> 2_1^+)



- Beam: ^{66}Zn (240 MeV, 1 — 1.5 pnA)
- Target: 1 mg/cm^2 of ^{208}Pb

First Experiment: Collectivity of ^{66}Zn

Spokespersons: M. Rocchini, K. Hadynska-Klek

- Data already available in the literature confirmed, sufficient precision to distinguish between discrepant values achieved

	Present	NDS	M. Koizumi *et al.*, 2003	K. Moschner *et al.*, 2010
B(E2; $2_1^+ \longrightarrow 0_1^+$) [W.u.]	**17.5(10)**	17.5(4)	18.2(11)	17.4(3)
$Q_s(2_1^+)$ [efm^2]	**+24(9)**	+24(8)	+24(8)	
B(E2; $4_1^+ \longrightarrow 2_1^+$) [W.u.]	**8.1(12)**	18(3)	17.5(7)	8.4(15)
B(E2; $2_2^+ \longrightarrow 2_1^+$) [W.u.]	**35(13)**	330(130)	41(14)	

- First measurement of B(E2) values from 0_2^+: B(E2; $0_2^+ \longrightarrow 2_1^+$) = 3.1(11) W.u., B(E2; $0_2^+ \longrightarrow 2_2^+$) = 1.6(6) W.u. ($\tau$ = 3.9(13) ps)

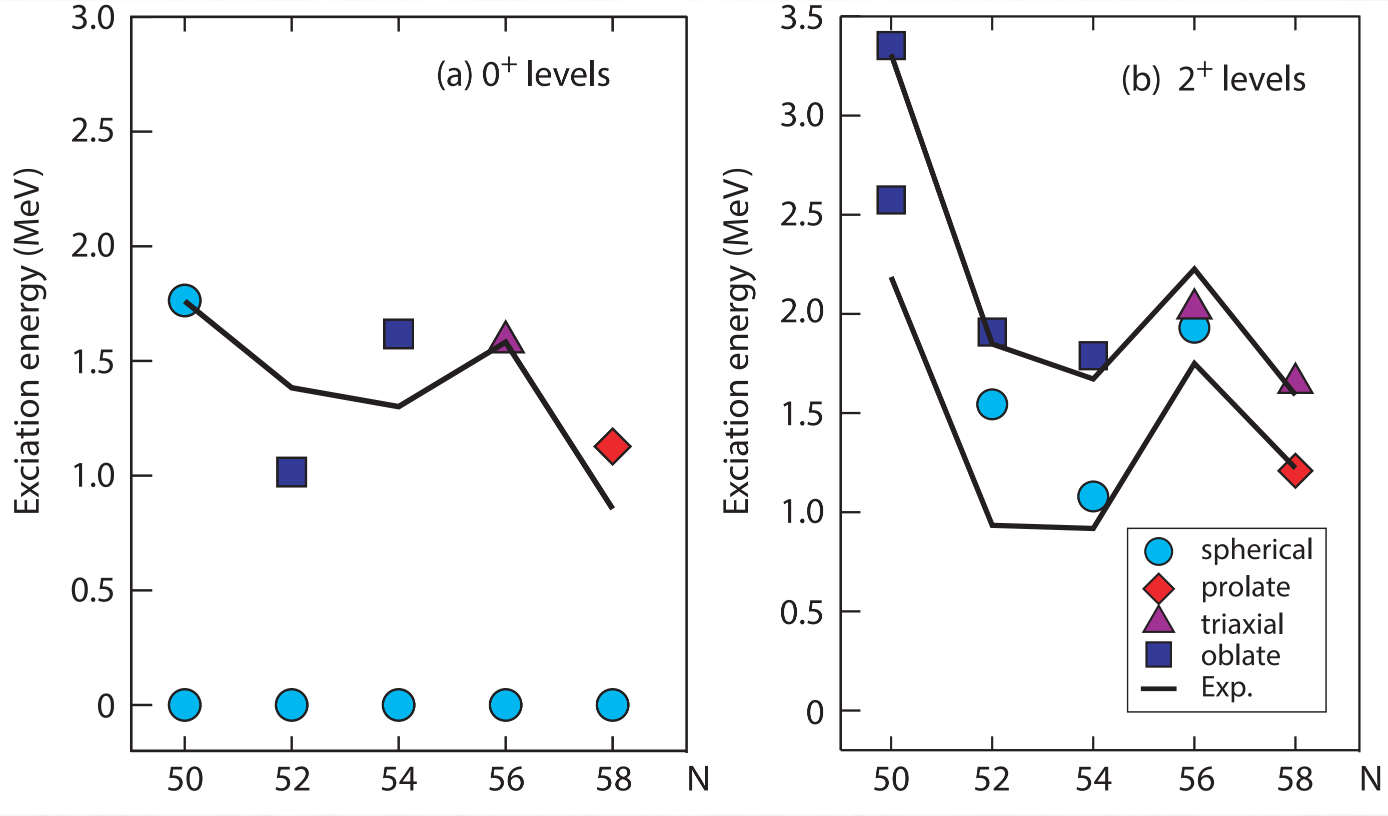
- First measurement of shape parameters for the $\mathbf{0_1^+}$: $\langle\beta\rangle$ = 0.224(6), $\langle\gamma\rangle$ = 45°(5°)

Probing collectivity and configuration coexistence in ^{94}Zr

Spokespersons: D. Doherty, M. Rocchini, M. Zielinska

- Recent state-of-the-art Monte Carlo shell model calculations* predict shape coexistence in Zr isotopes.

  ** T. Togashi et al., PRL 117, 17252 (2016).*



- Observation* of a strong $2^+_2 \rightarrow 0^+_2$ transition (19 W.u.) suggests a deformed band built on 0^+_2 ** A. Chakraborty et al., PRL 110, 022504 (2013).*

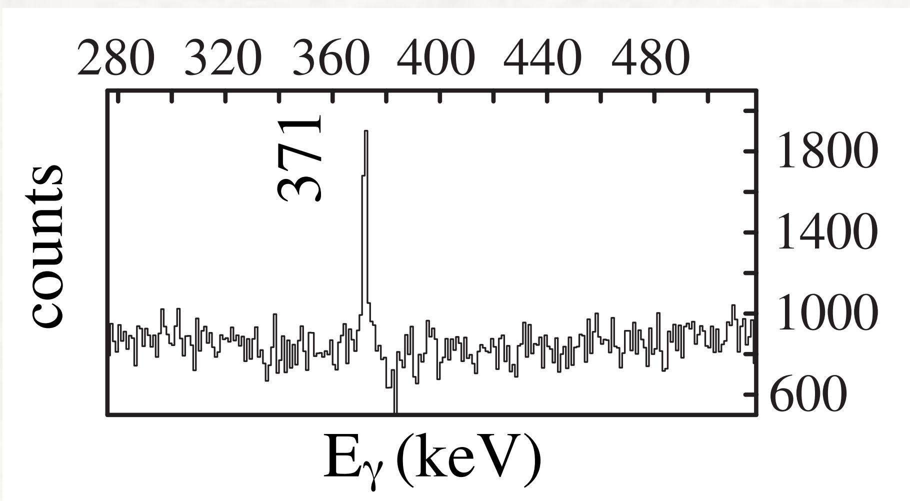
  - Beam: ^{94}Zr (370 MeV, 1 — 1.5 pnA)
  - Target: 1 mg/cm^2 of ^{208}Pb
  - Six 3"X3" $LaBr_3$:Ce used for the first time in COULEX @LNL

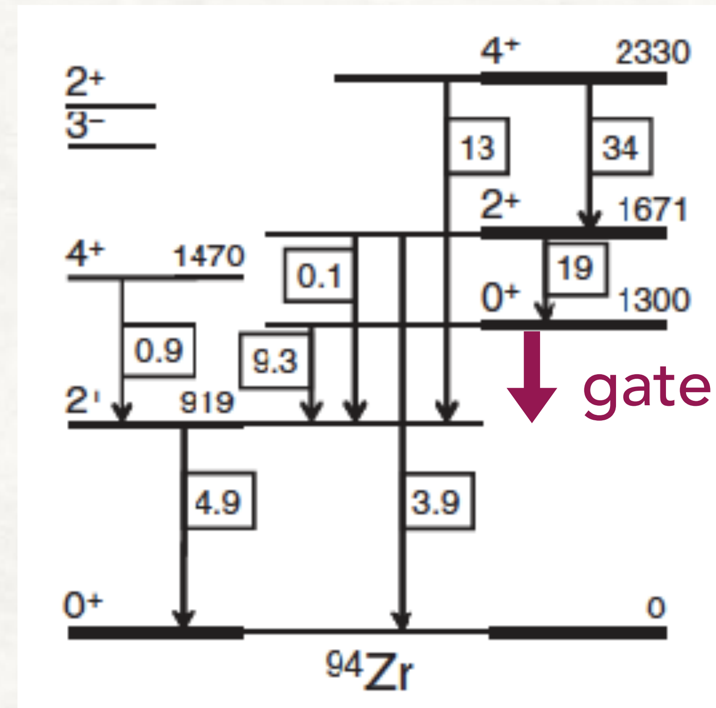
Probing collectivity and configuration coexistence in ^{94}Zr

Spokespersons: D. Doherty, M. Rocchini, M. Zielinska

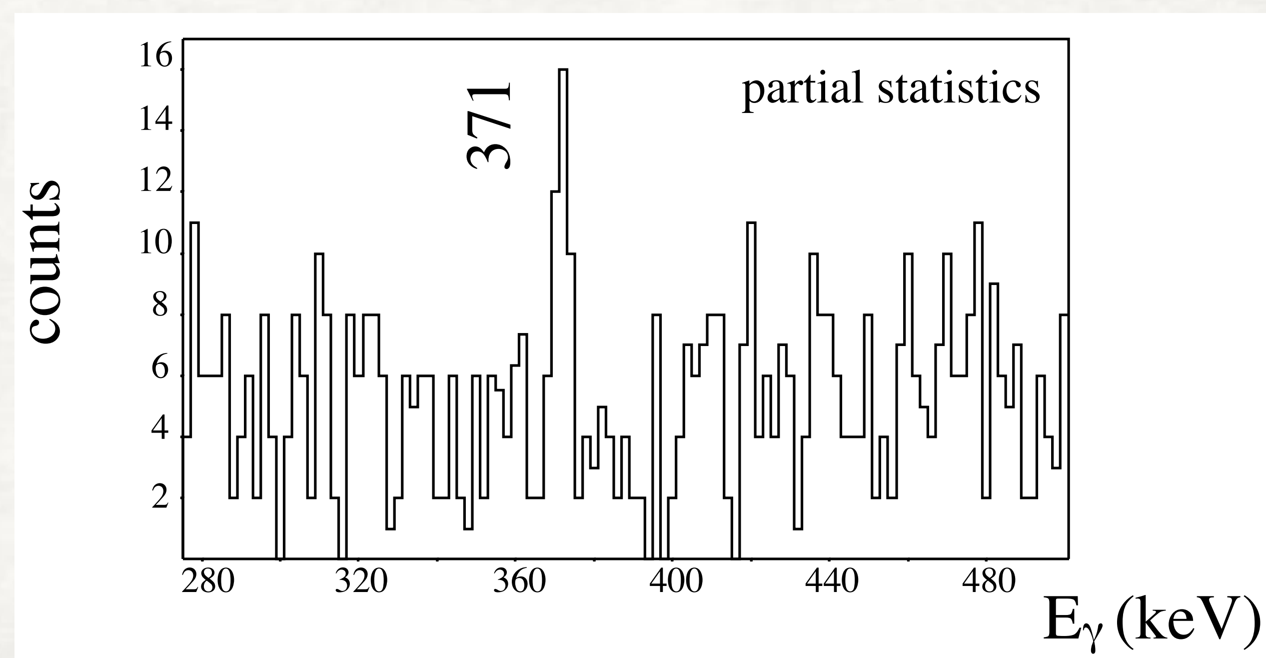
- Random-background-subtracted **γ-γ** coincidence spectrum gated on the 382 keV

  * *A. Chakraborty et al., PRL 110, 022504 (2013).*





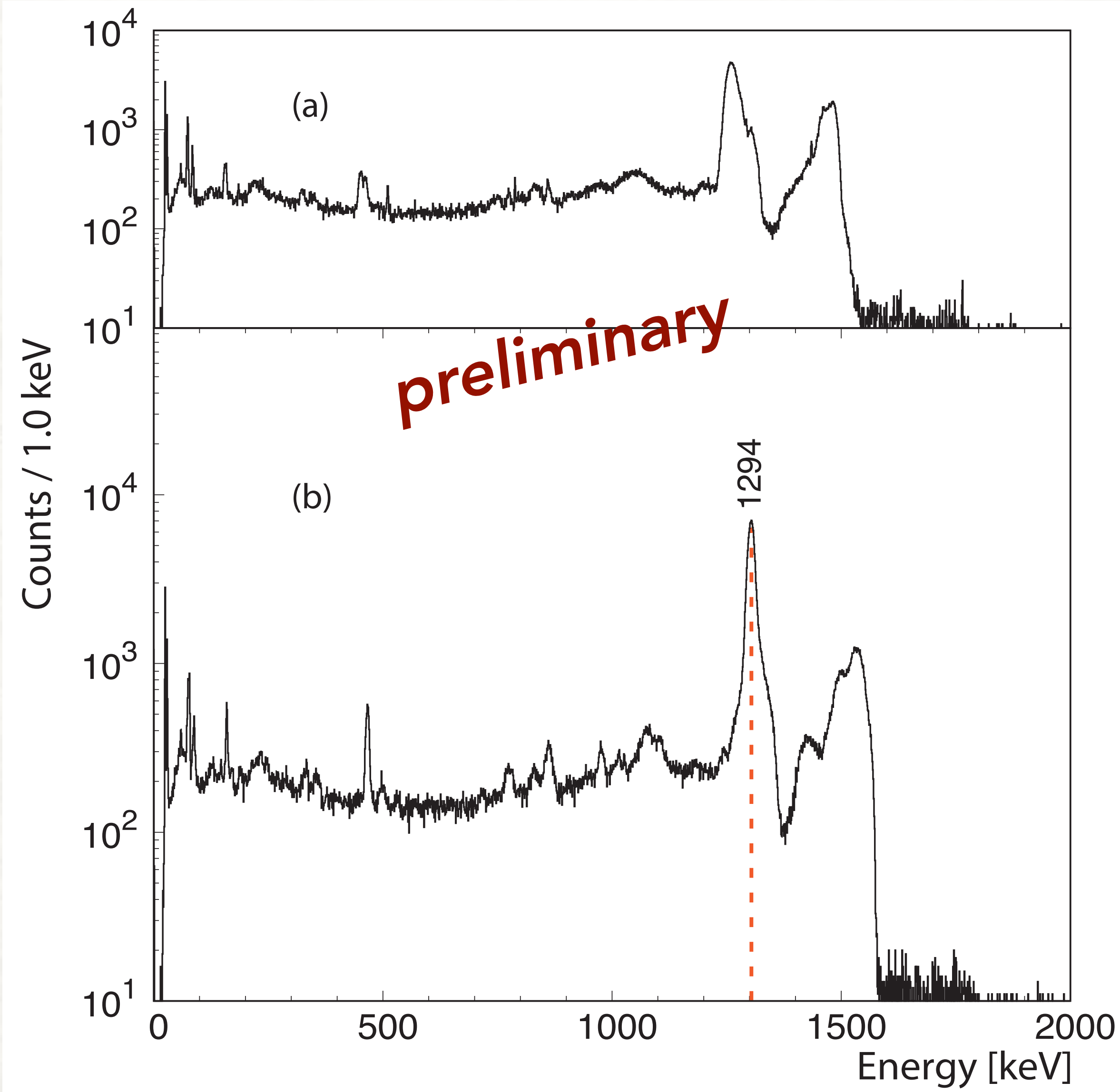
- Random-background-subtracted **γ-γ-particle coincidence** spectrum gated on the 382 keV



Shape Coexistence in the Tin isotopic chain: Coulomb Excitation measurement of ^{116}Sn

Spokespersons: M. Saxena, M. Siciliano, A. Illana

- The semi-magic Sn isotopes represent a good case to study shape coexistence
- Within Sn isotopes ^{116}Sn intriguing position Z=50, N=66
- Discrepant values for the 2_1^+ quadrupole moments in the literature

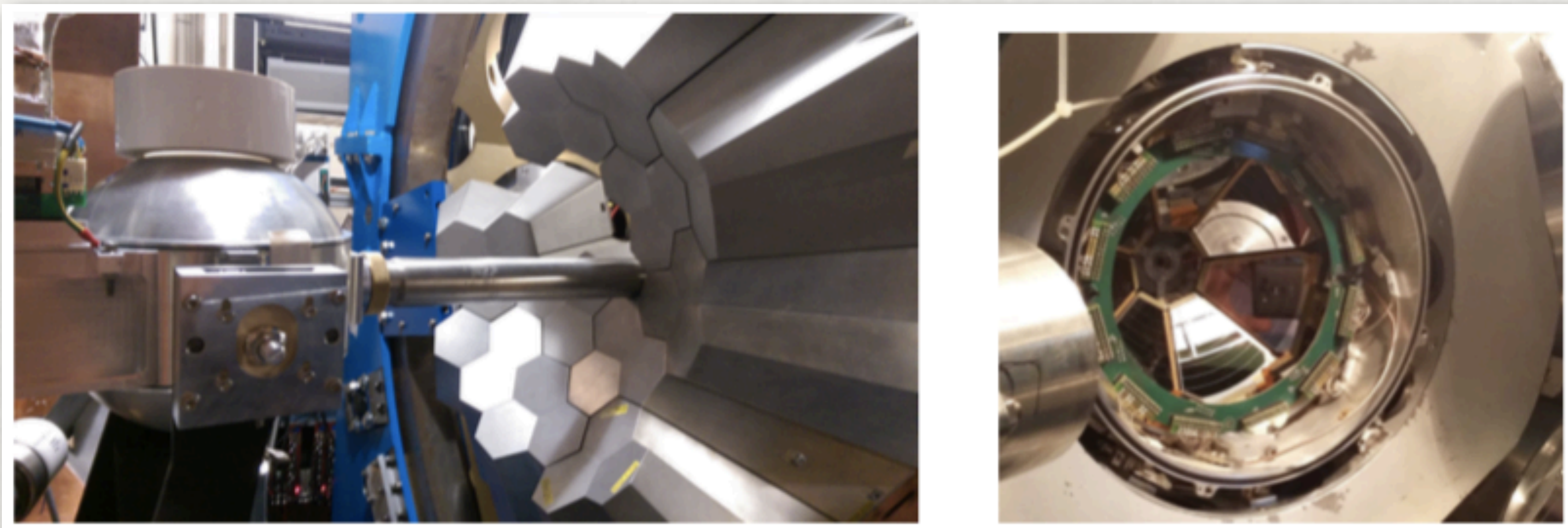


- Beam: ^{58}Ni @ 180 MeV 4 pnA, continuous
- Target: ^{116}Sn 1 mg/cm^2 ^{12}C backing
- Setup: GALILEO (25 HPGe) 6 $LaBr_3$ SPIDER

- **Target excitation**: kinematics reconstruction needed

COULEX @ LNL SPIDER&AGATA

- **Workshop** at the INFN Legnaro National Laboratories (25-26 March 2019)
- **Five LoI** for Coulex with AGATA - SPIDER presented

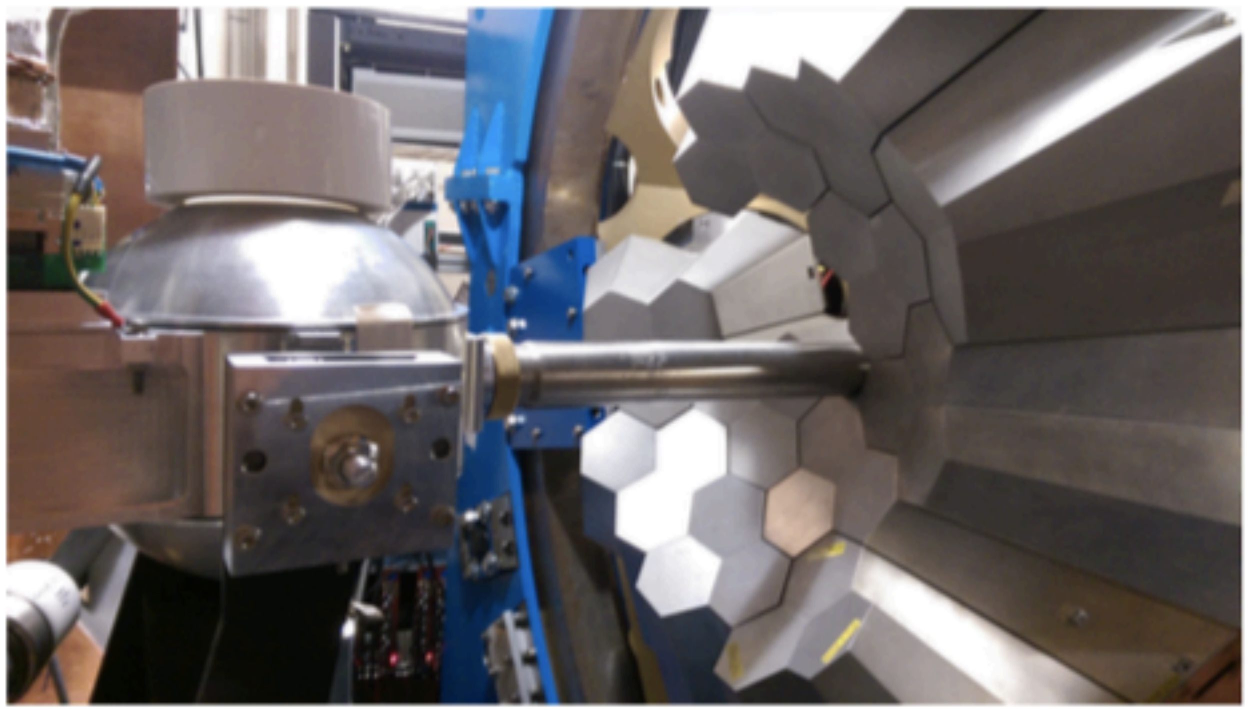


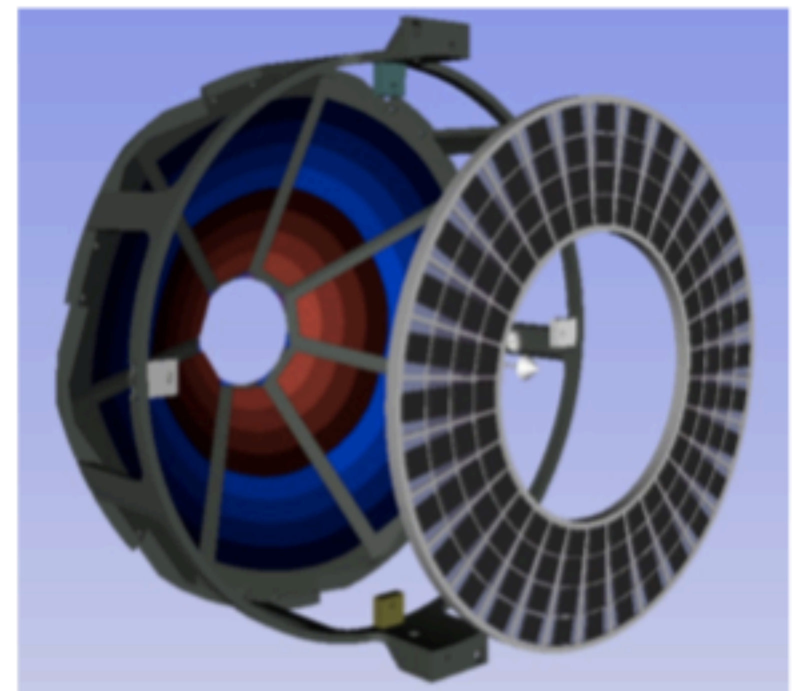
- **Why AGATA?**
  - Better Energy resolution
  - Better Efficiency
  - Higher granularity

→ better Doppler correction for peak identification

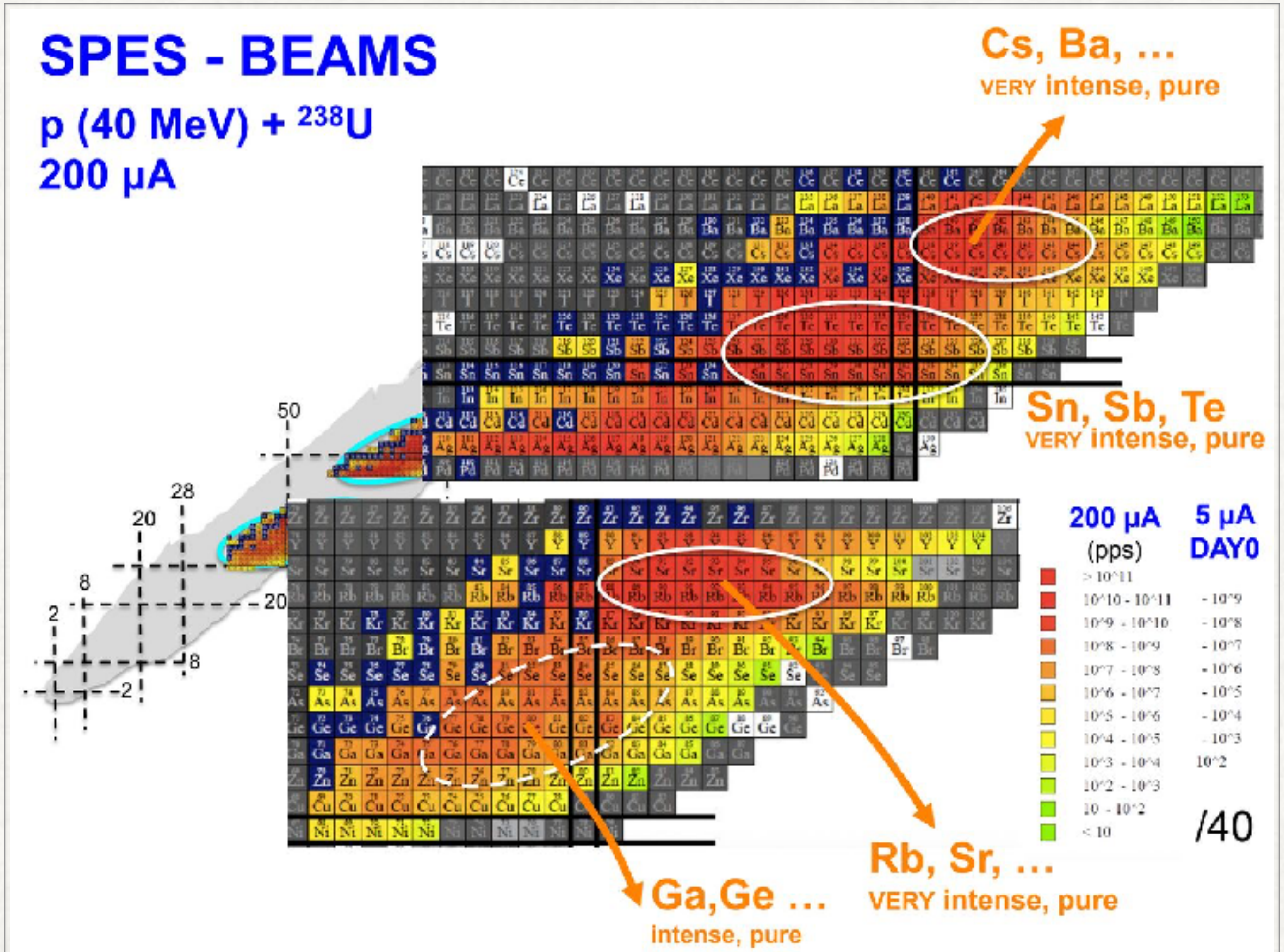
COULEX @ LNL SPIDER&AGATA

- To increase sensitivity to Qs and EM signs $\Longrightarrow$ Use of an additional forward angles particle detector f.i. four ring of SiPM

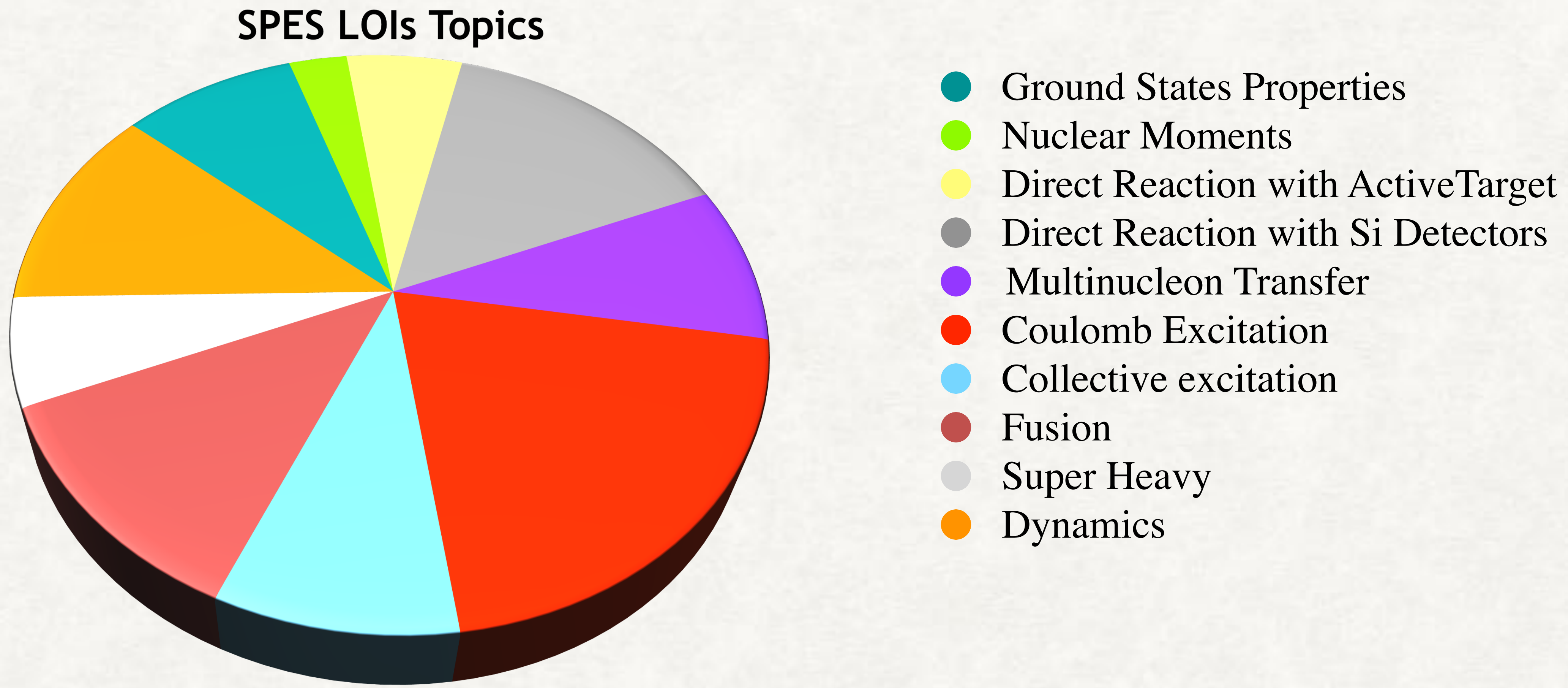




RADIOACTIVE BEAMS @LNL



SPES International Workshop: 47 Letter of Intents



SUMMARY AND OUTLOOK

- Coulomb Excitation @LNL with stable beams is on-going
- Near future 2nd phase GALILEO 30 GASP detectors + 10 triple cluster
- Future: AGATA
- Far future: Coulex @LNL with SPES radioactive beams

THANK YOU FOR THE ATTENTION

A. N[1], M. Rocchini[1], K. Hadynska-Klek[2], N. Marchini[1,3], D.T. Doherty[4], M. Zielinska[5], M. Siciliano[5], A. Illana[6], M. Saxena[2], D. Bazzacco[7,8], G. Benzoni[9], F. Camera[9,10], A. Goasduff[7,8], P.R. John[11], M. Komorowska[2], M. Matejska-Minda[2,12], D. Mengoni[7,8], P. Napiorkowski[2], D.R. Napoli[6], M. Ottanelli[1], F. Recchia[7,8], P. Sona[1], D. Testov[7,8] and J.J. Valiente-Dobon[6],

1 INFN, Sezione di Firenze, Firenze, Italy 2 Heavy Ion Laboratory, University of Warsaw, Warsaw, Poland 3 Division of Physics, School of Science and Technology, Universit`a di Camerino, Camerino (Macerata), Italy 4 University of Surrey, Guildford, UK 5 CEA Saclay, IRFU/SPhN, France 6 INFN, Laboratori Nazionali di Legnaro, Legnaro (Padova), Italy 7 Dipartimento di Fisica e Astronomia, Universit`a degli Studi di Padova, Padova, Italy 8 INFN, Sezione di Padova, Padova, Italy 9 INFN, Sezione di Milano, Milano, Italy 10 Dipartimento di Fisica, Universit`a degli Studi di Milano, Milano, Italy 11 Institut fu¨r Kernphysik, Technische Universit¨at Darmstadt, Darmstadt, Germany 12 Institute of Nuclear Physics Polish Academy of Sciences, Cracow, Poland.

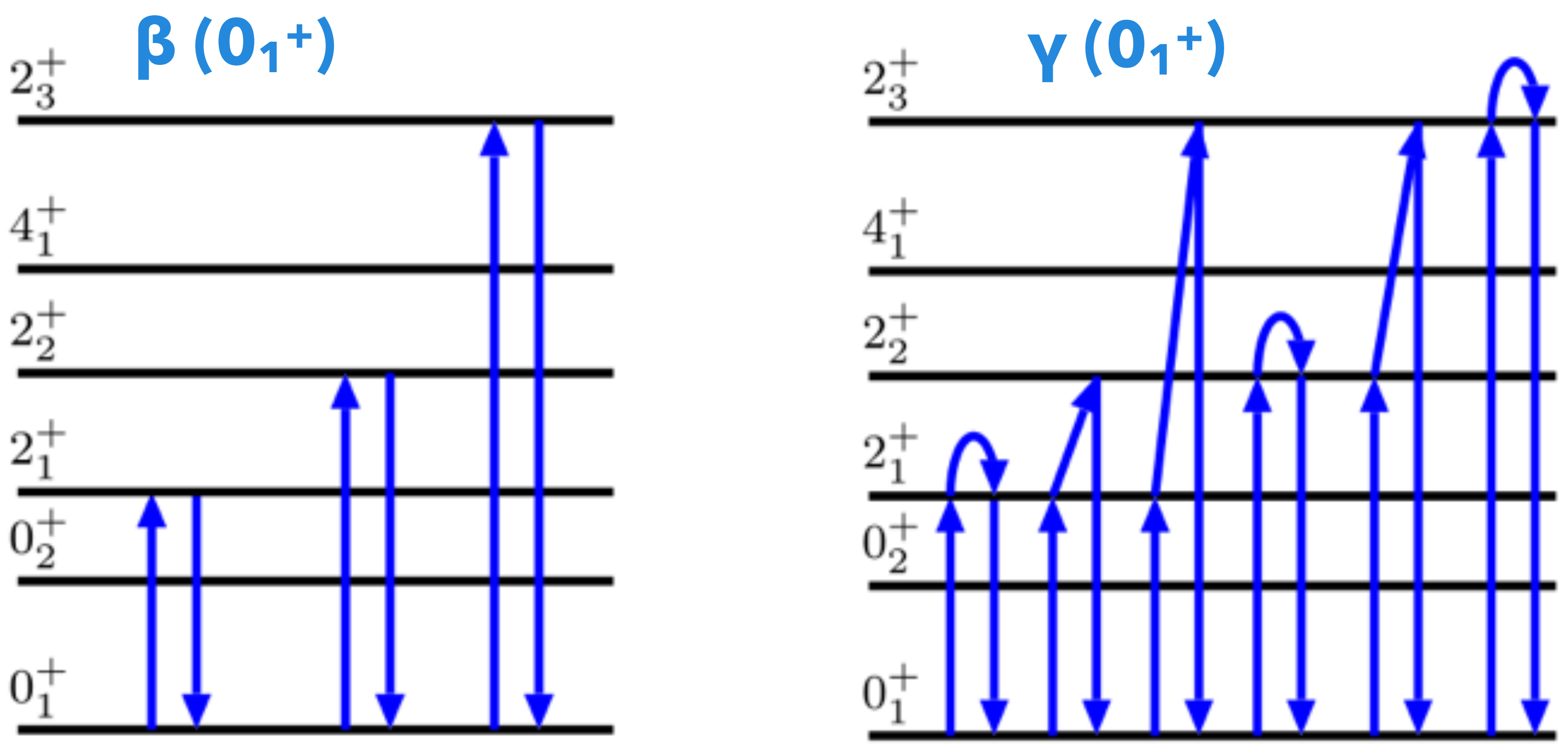
THE SPIDER - GALILEO SETUP

GALILEO 1st Phase

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

$$\langle \beta^2 \rangle = \frac{\sqrt{5}}{q_0^2\sqrt{2I_i+1}} \sum_t \langle i \,||E2||\, t \rangle \langle t \,||E2||\, i \rangle \begin{Bmatrix} 2 & 2 & 0 \\ I_i & I_i & I_t \end{Bmatrix}$$

$$\langle \beta^3 \cos(\gamma) \rangle = \frac{\sqrt{35}}{q_0^3\sqrt{2}} \frac{1}{\sqrt{2I_i+1}} \sum_{tu} \langle i \,||E2||\, t \rangle \langle t \,||E2||\, u \rangle \langle u \,||E2||\, i \rangle \begin{Bmatrix} 2 & 2 & 2 \\ I_i & I_t & I_u \end{Bmatrix}$$



$\langle 2_1^+ \,||E2||\, 0_{g.s}^+ \rangle$

$\langle 2_1^+ \,||E2||\, 0_{g.s}^+ \rangle \langle 2_i^+ \,||E2||\, 2_1^+ \rangle$ e $\langle 2_i^+ \,||E2||\, 2_i^+ \rangle$

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

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

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

Access to: transition probabilities and spectroscopic quadrupole moments in a model independent way