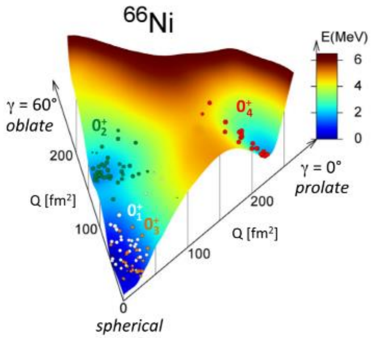
Nuclear Structure studies using high-resolution techniques

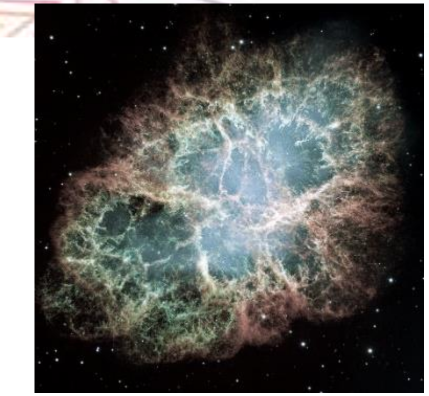
Caterina Michelagnoli

Introducing myself…

Structure of Atomic Nuclei



Nuclear Astrophysics

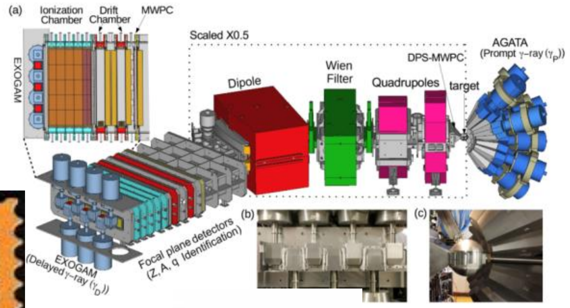


"t_0" = **2009**
undergraduate research grant
Legnaro National Laboratories (LNL, IT)
Diploma Thesis, University of Florence, IT

2013
PhD
University of Padova
and LNL, IT

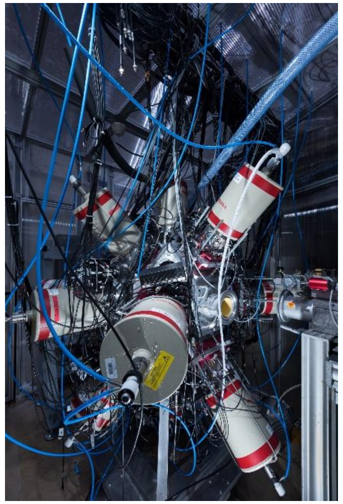
2013-2016
CNRS PostDoc
Grand Accélérateur
National d'Ions
Lourds, FR

2016-present
Research Scientist
ILL
FIPPS instrument responsible



AGATA
ADVANCED GAMMA
TRACKING ARRAY

Nuclear Instrumentation



Introducing my lectures…

Scope : showing you (main) challenges and technologies in high-resolution Nuclear Structure, from and **experimentalist** point of view...

… through a “personal taste and experience”-biased **selection** of examples

Table of contents

- Introduction: main challenges in Nuclear Physics, why γ spectroscopy
  - → Nuclear Structure and Astrophysics
- Why high resolution and how
  - → HPGe detectors and related technologies
  - → Array of HPGe detectors, facilities (in-beam γ-ray spectroscopy)
    - → Performance, back-ground reduction and selectivity
    - → Angular correlations, polarization and lifetimes
- Advanced γ-ray tracking
  - → Basics
  - → The AGATA project

(Main) bibliography

G.F. Knoll "Radiation Detection and Measurement"
F. Recchia and C. Michelagnoli, in Lec. Notes in Phys. (Euroschool Vol. VI)
C. Michelagnoli, PhD Thesis, Univ. of Padova (2013) (and refs therein ☺)

(Detectors working principles, performance, signal treatment)

P. Ring and P. Schuck "The Nuclear Many Body problem"

R.F. Casten "Nuclear Structure from a Simple Perspective"

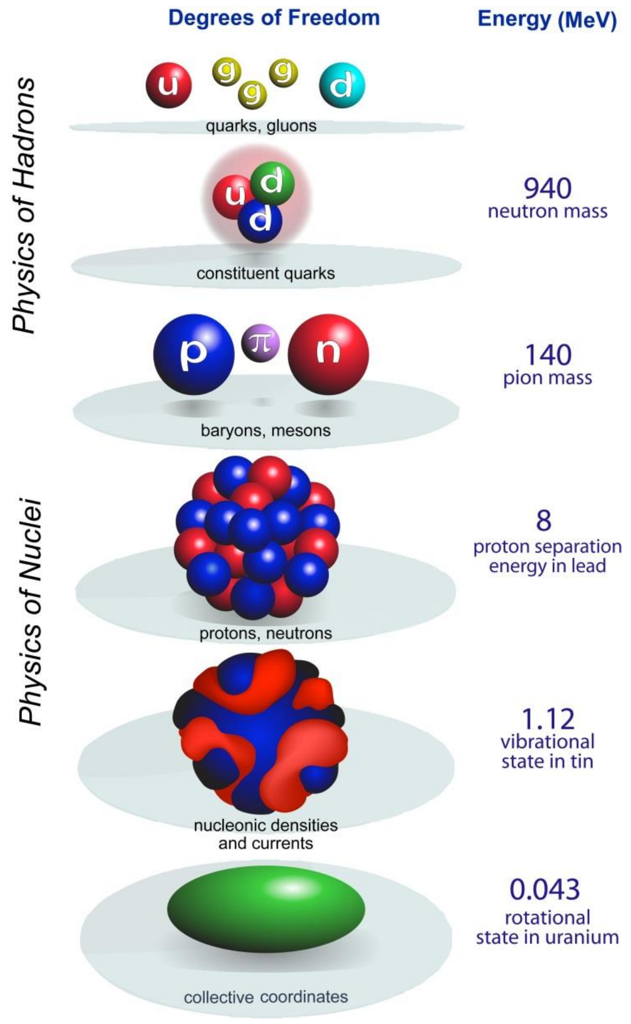
(Nuclear observables and systematics)

Many thanks for material/discussions:

D. Bazzacco, P.G. Bizzeti, J. Dudouet, M. Jentschel, U. Köster, S. Lenzi, …

Nuclear vs Particle and Atomic Physics

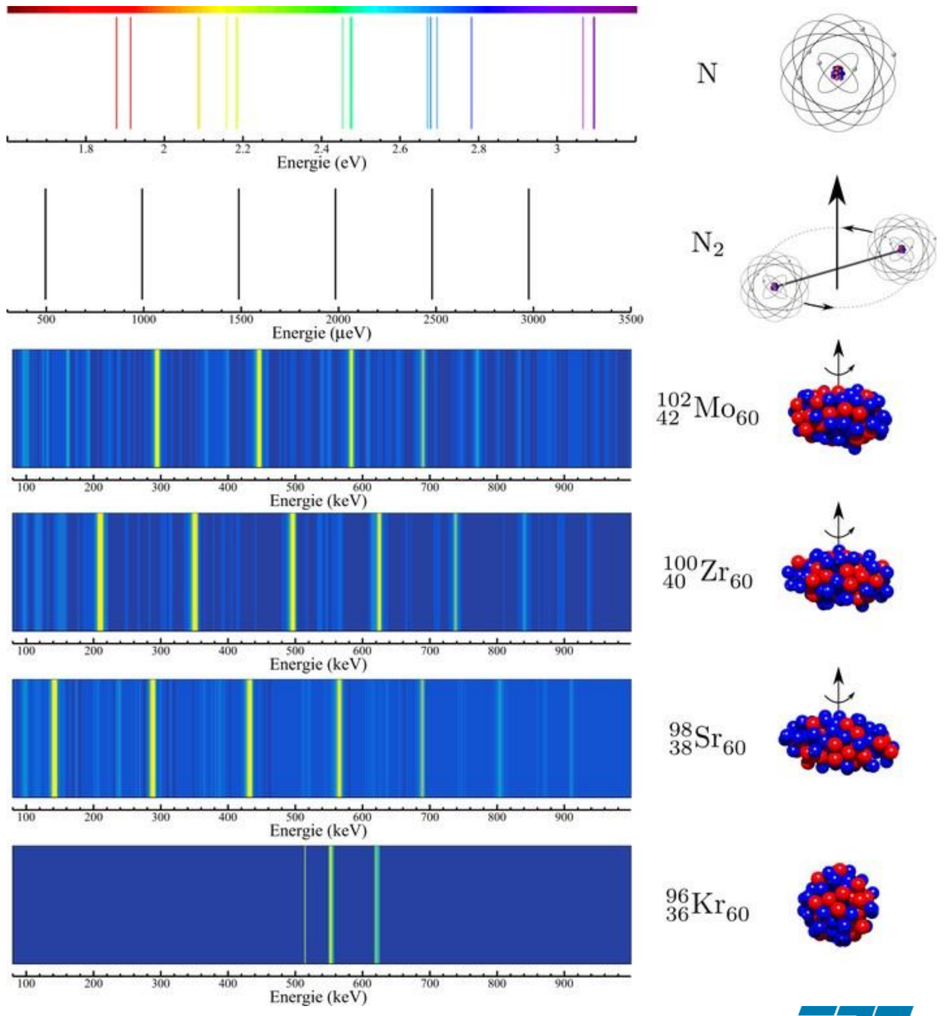
Energy scales: particles and nuclei



Particle Physics

Nuclear Physics
- ❖ Nuclear structure
- ❖ Reaction mechanisms
- ❖ Fission studies
- ❖ …

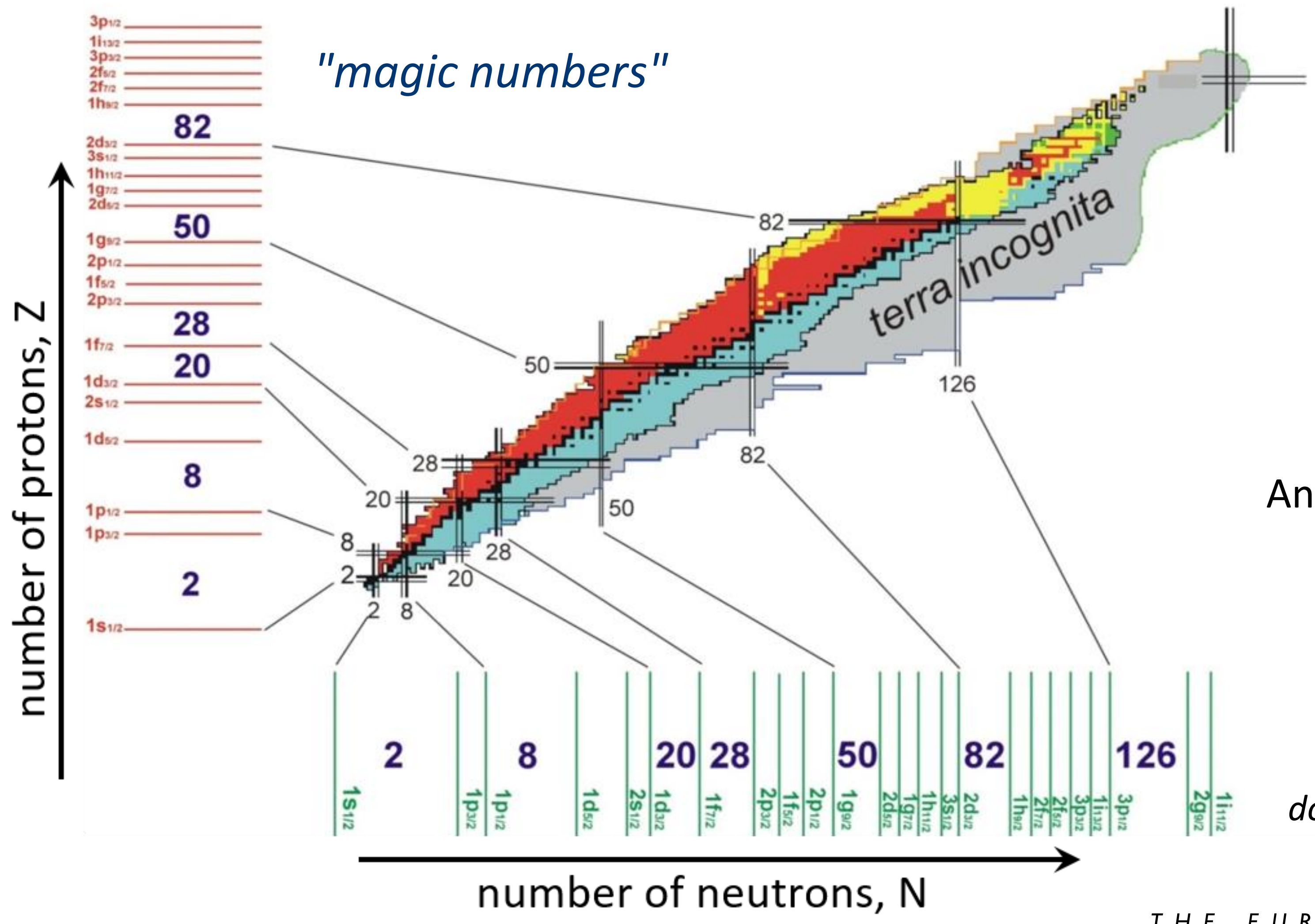
Energy scales: nuclear excitations



http://www.ganil-spiral2.eu/science/actualites/la-forme-du-noyau-comme-reflet-de-l2019interaction-entre-ses-composants

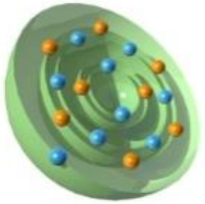
Is there a model describing ALL nuclei?

The first microscopic attempt: the *nuclear Shell Model*



Modified from JJ Valiente-Dobon, LNL

Mayer & Jensen,
Nobel prize 1963
PR75, 1969 (1949)

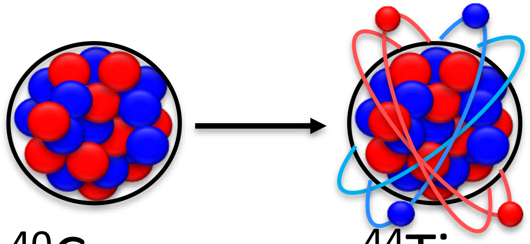


$$H\psi = E\psi$$

$$H = \sum_i e_i n_i + \sum_{ijkl} v_{ijkl} a_i^+ a_j^+ a_l a_k$$

effective nucleon-nucleon interaction

An example:



$^{40}_{20}\mathrm{Ca}_{20}$

doubly "magic" inert core

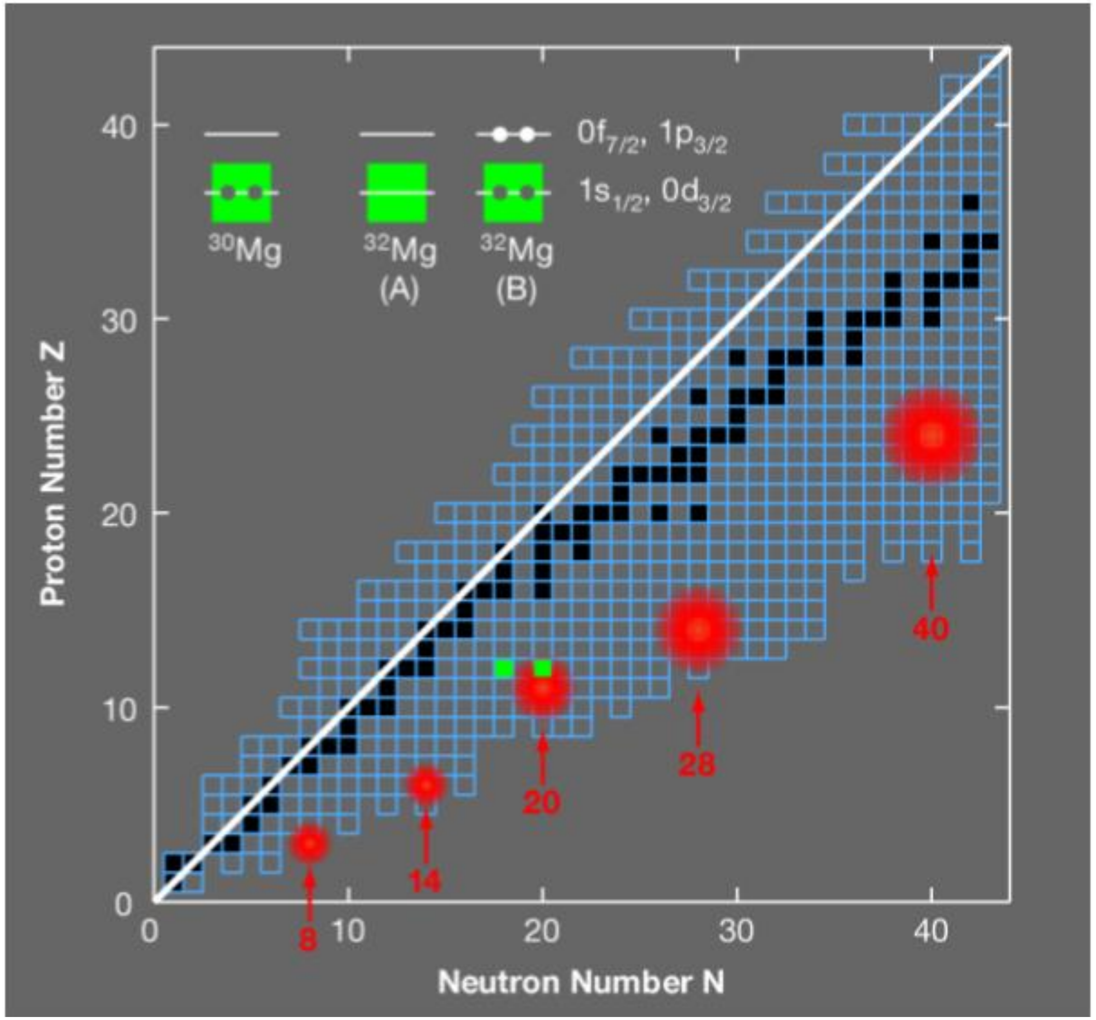
$^{44}_{22}\mathrm{Ti}_{22}$

$\approx 10^4$ configurations

($\approx 10^{28}$ for ^{88}Ru !)

Is there a model describing ALL nuclei?

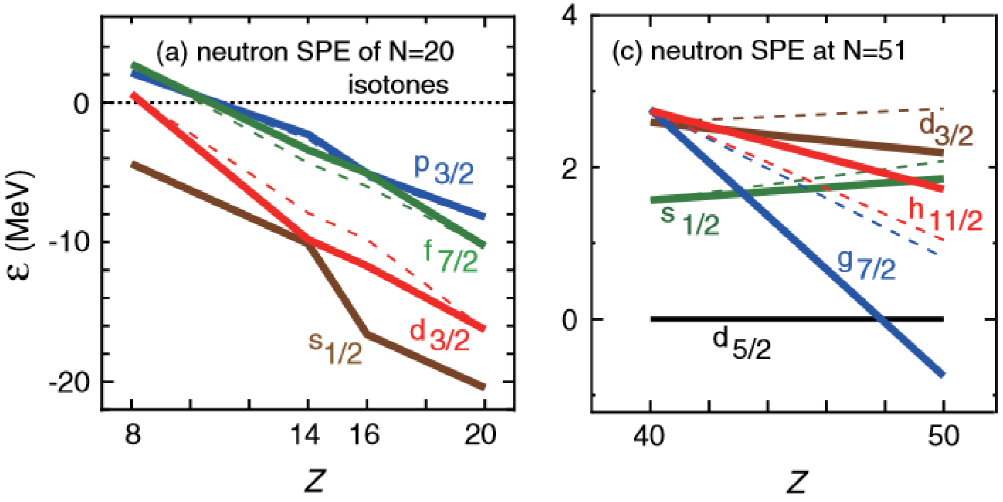
Nuclear magicity and nucleon-nucleon effective interactions



B. Alex Brown, Physics 3 (2010) 104; K. Wimmer et al., Phys. Rev. Lett. 105 (2010) 252501

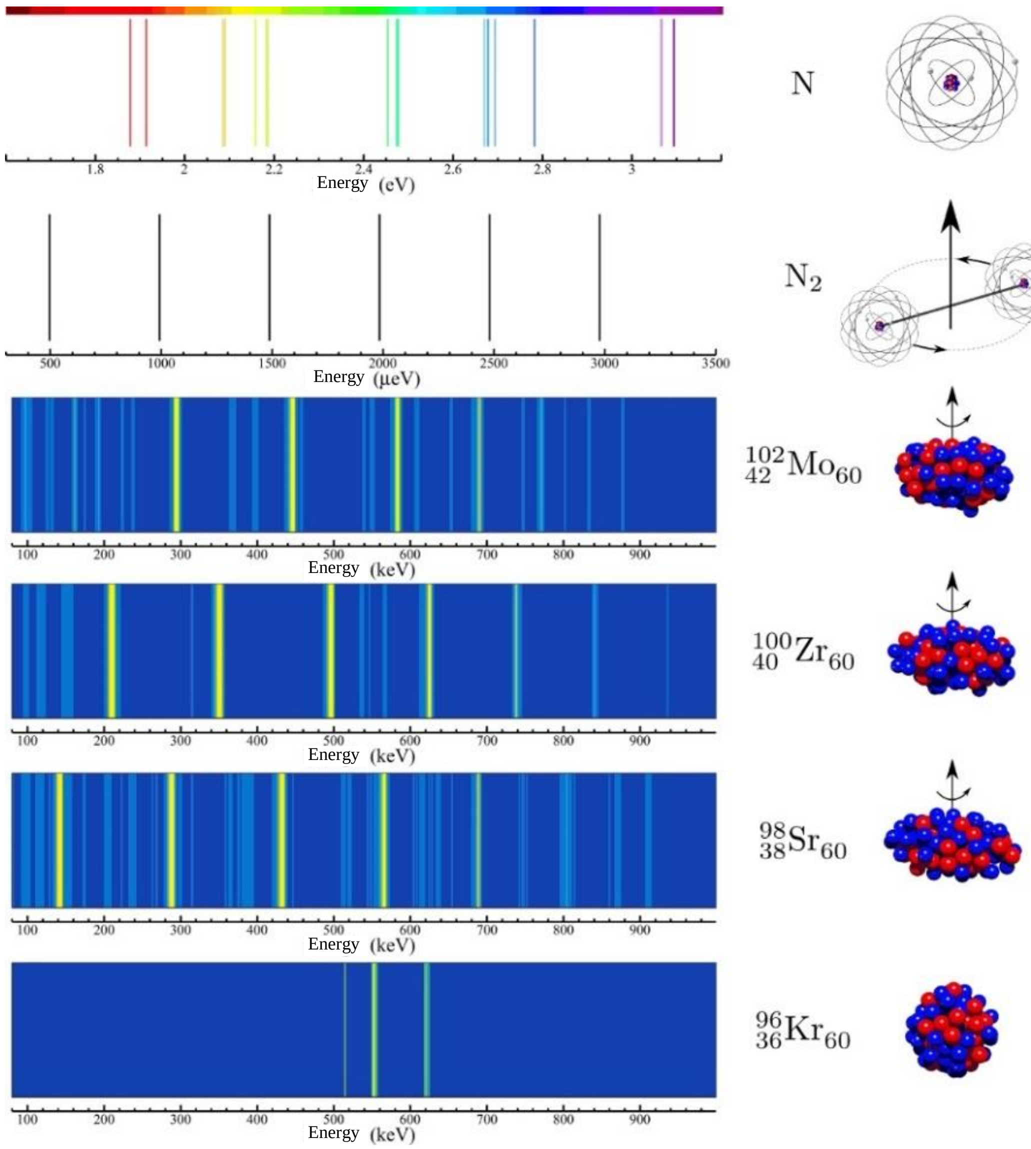
Does nuclear magicity persist far from stability ("islands of inversion")?

What is the effective nucleon-nucleon interaction?

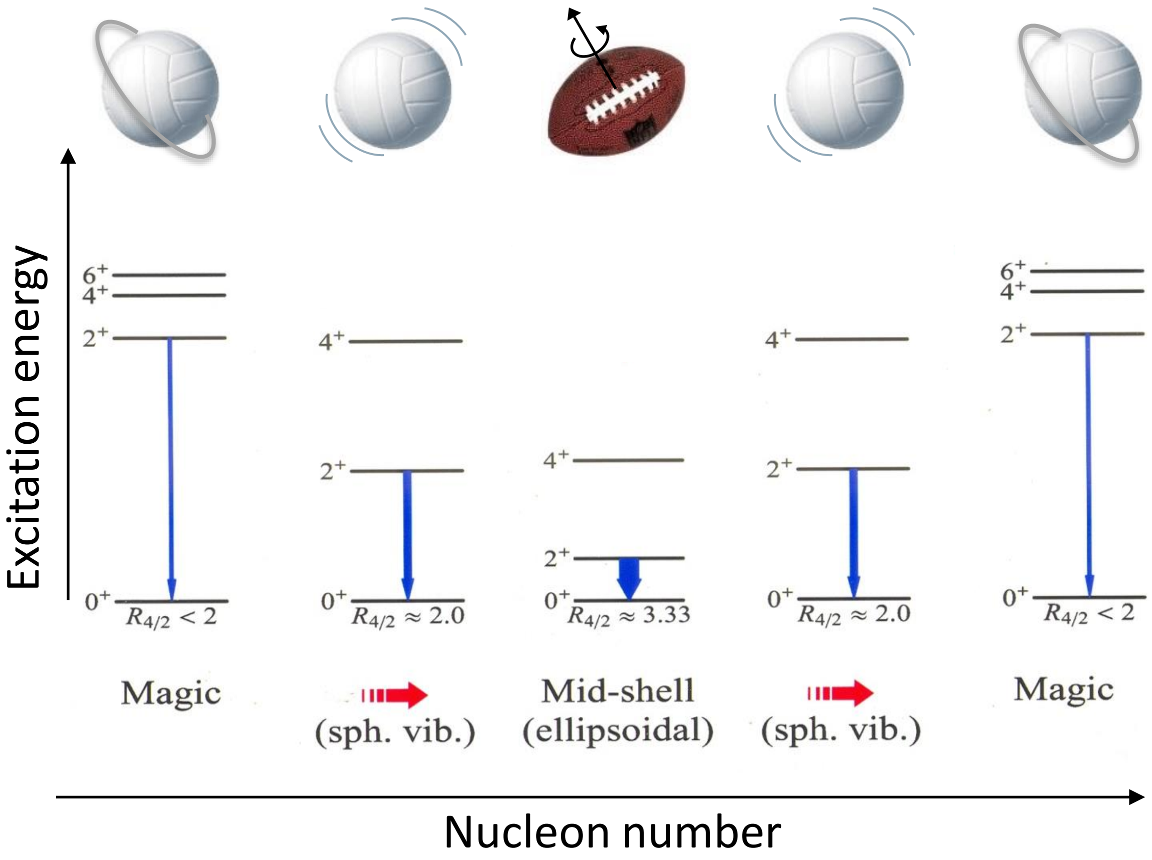


T. Otsuka et al., PRL 104 (2010) 012501

Collective excitations and nuclear shapes



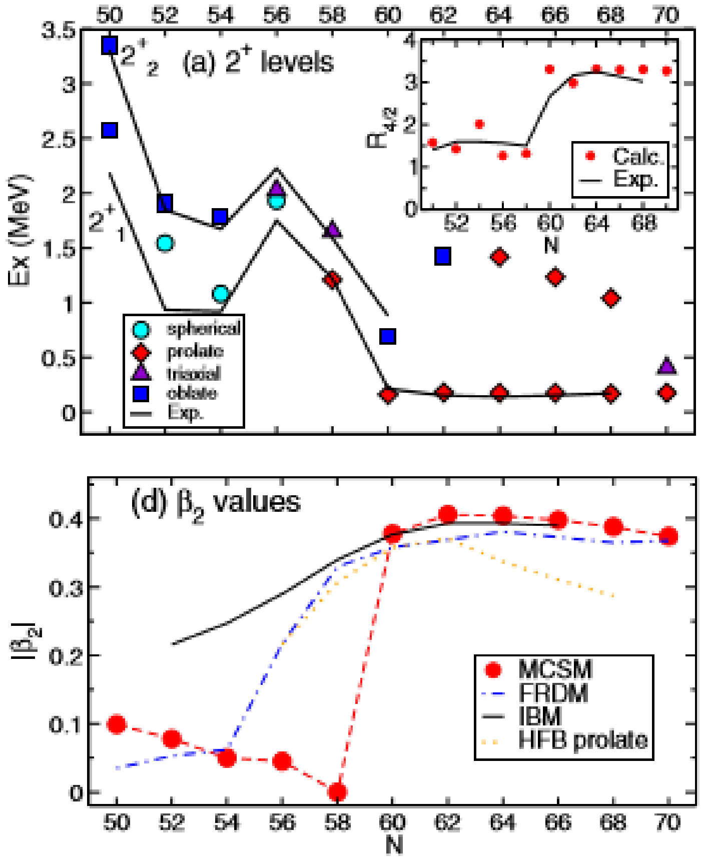
J. Dudouet et al., Phys. Rev. Lett. 118 (2017) 162501



How those shapes evolve
all along the nuclear chart?

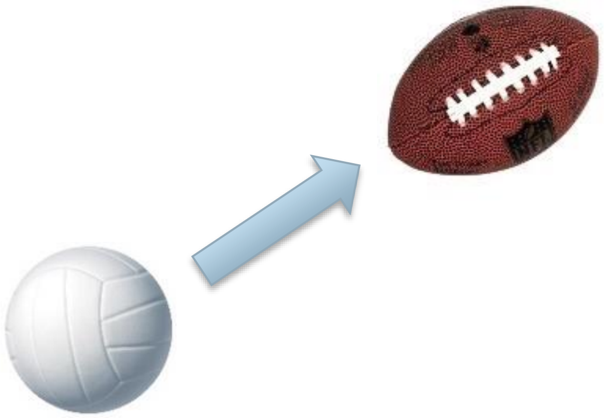
Nuclear shape transitions

Towards the microscopic description of collective phenomena

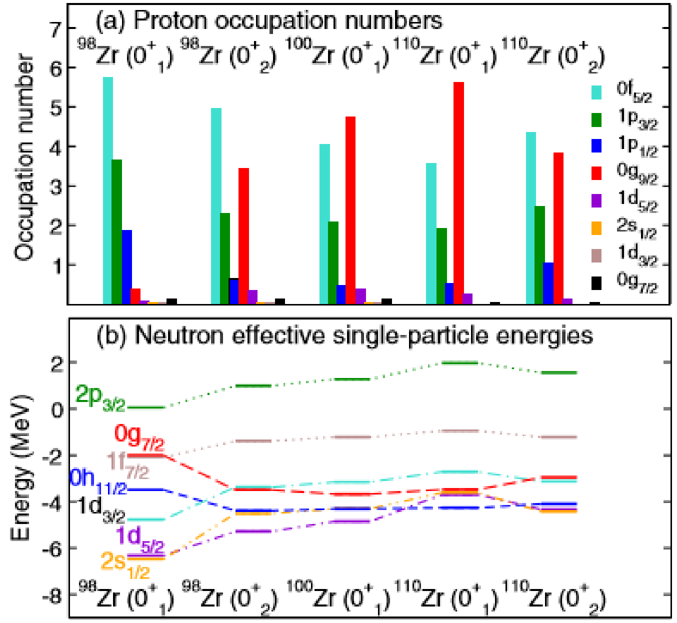


T. Togashi et al., Phys. Rev. Lett. 117 (2016) 172502
T. Otsuka, accepted in Physics (2022)

The example of the Zr nuclei



Recently interpreted microscopically

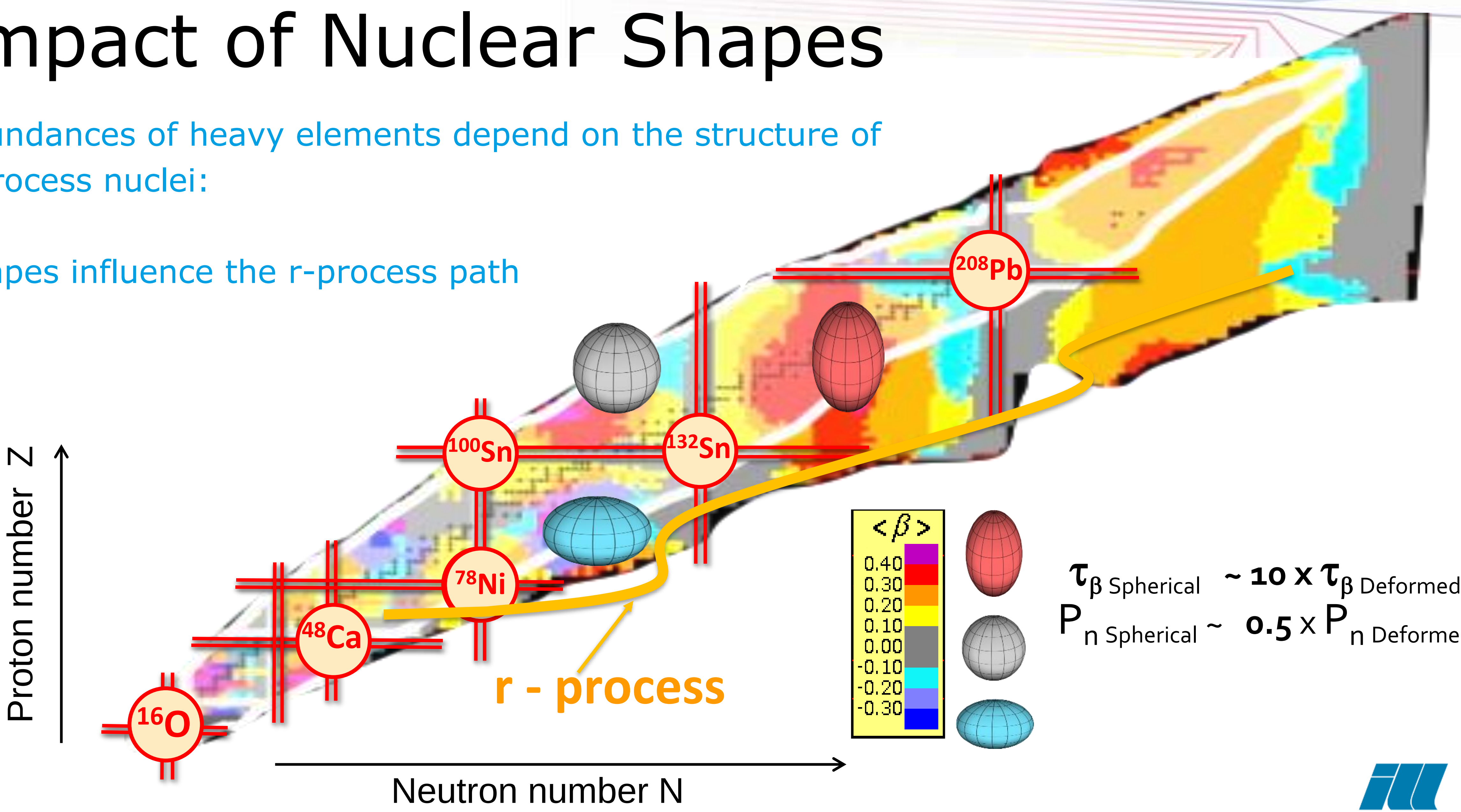


Is it valid for other nuclei, for other shapes?

Impact of Nuclear Shapes

Abundances of heavy elements depend on the structure of r-process nuclei:

Shapes influence the r-process path



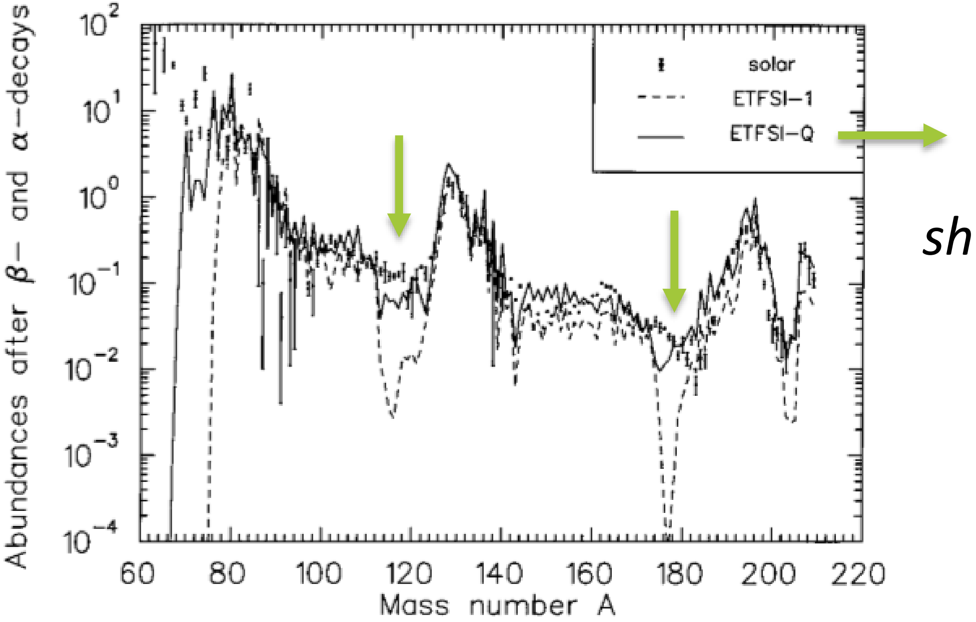
$\tau_{\beta\ \text{Spherical}} \sim 10 \times \tau_{\beta\ \text{Deformed}}$

$P_{n\ \text{Spherical}} \sim 0.5 \times P_{n\ \text{Deformed}}$

MEAN FIELD Calculations, S.Hilaire, M.Girod, Eur. Phys. J. A 33, 237–241 (2007)

Which are the astrophysical sites of the r-process nucleosynthesis?

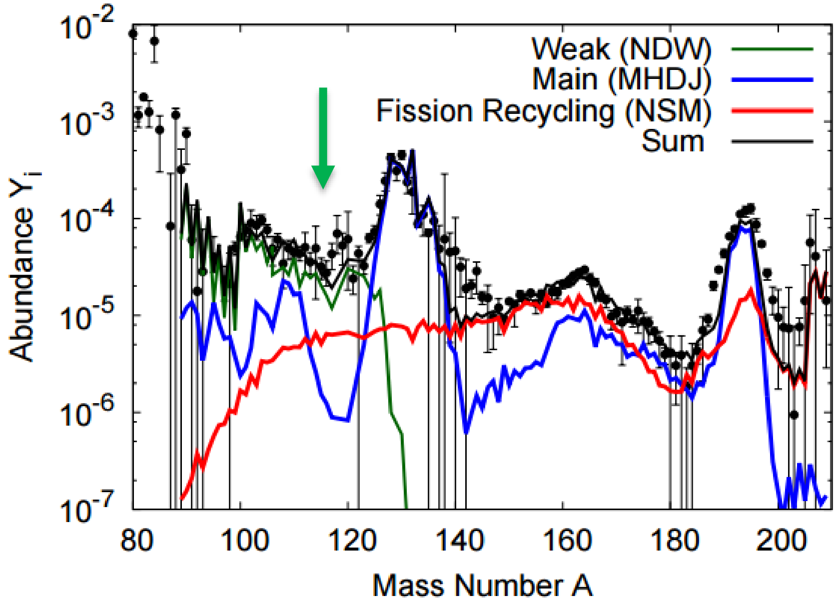
Solid nuclear structure input is needed
to understand the abundances



assuming
N=50, 82
shell quenching

C. Freiburghaus et al., Astrophys. J. 516 (1999) 381

Is fission recycling contributing
to r-process abundances?



S. Shibagaki et al., Astrophys. J. 816 (2016) 79

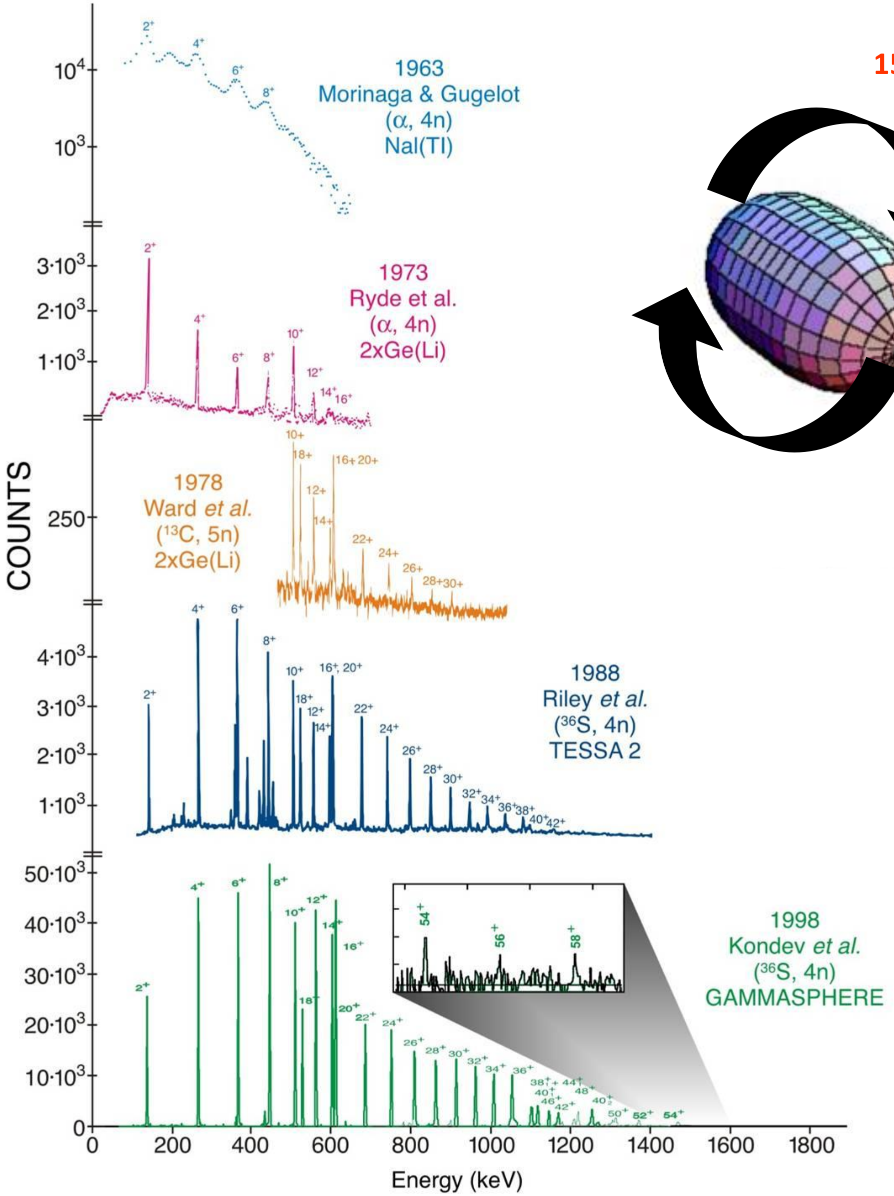
Understanding of nuclear structure and
fission mechanism are crucial

© marketoonist.com

There’s not a nuclear model that explains everything!

A challenge for both theory and nuclear instrumentation

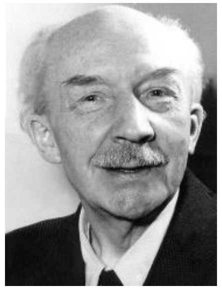
"Spectroscopic history" of ^{156}Dy



progress with the acceleration and detection techniques

better insight on the nuclear structure

Complex gamma-ray spectra: a challenge

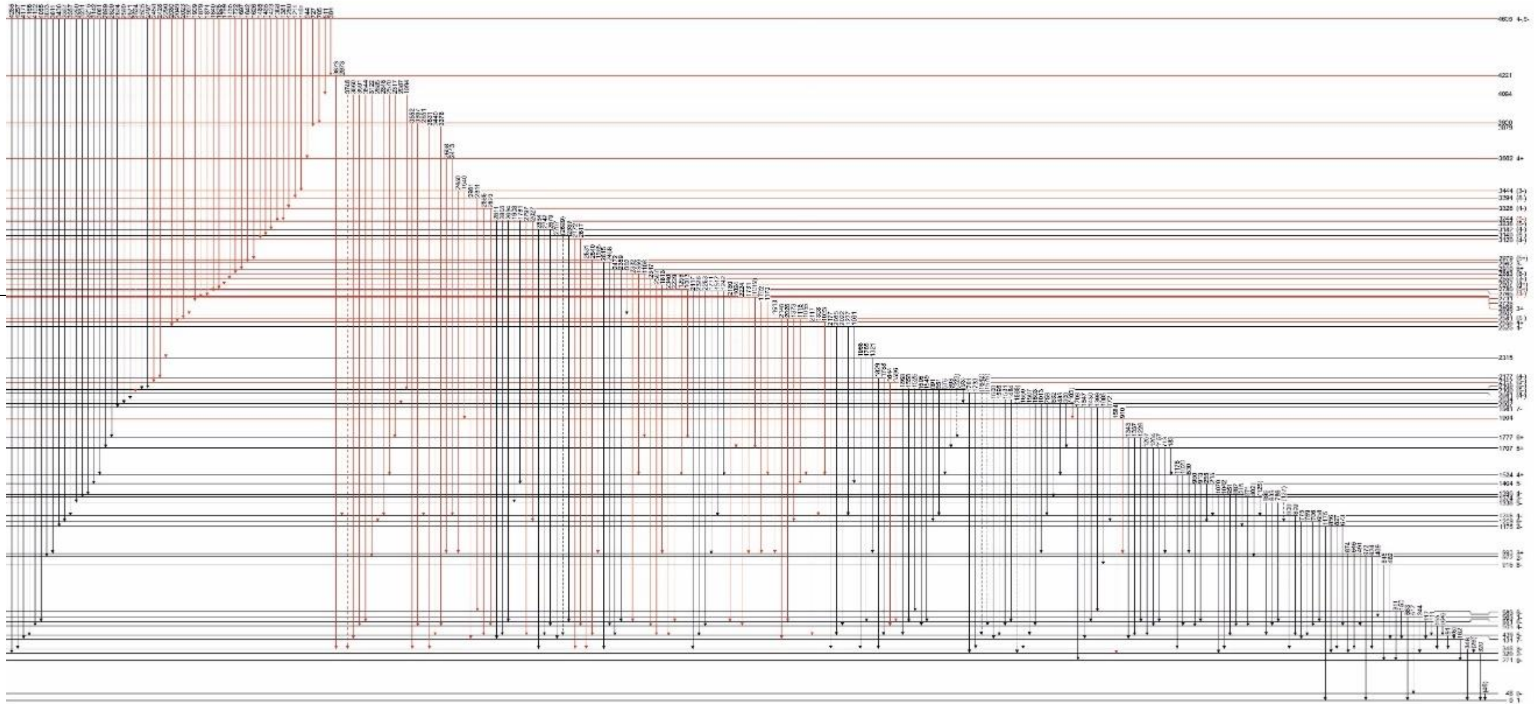


Coincidence method

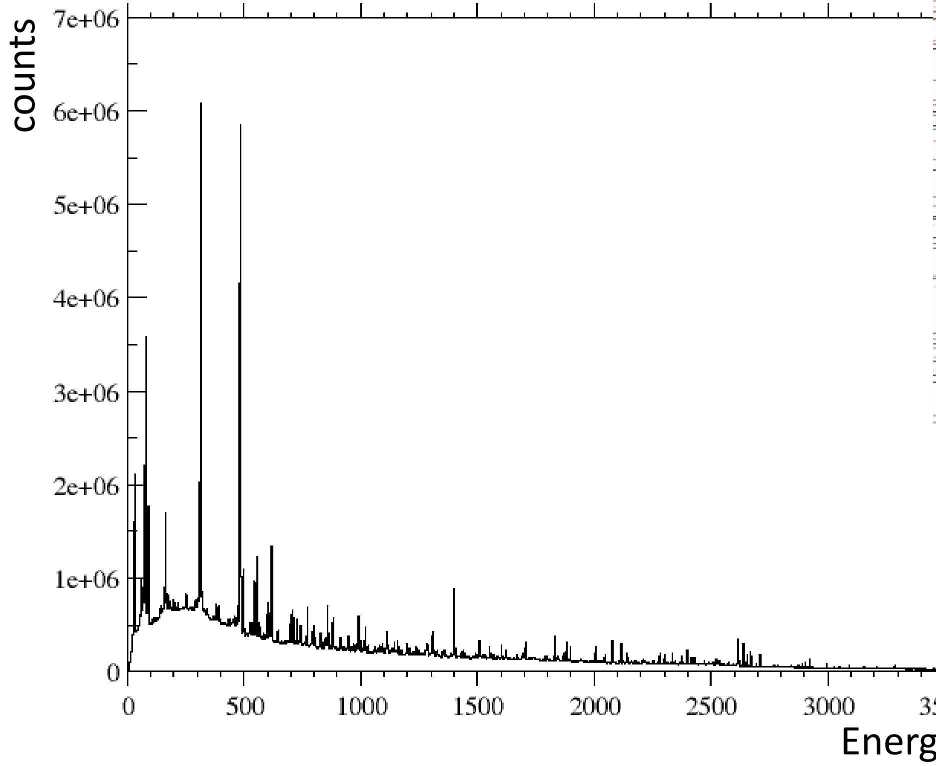
Walter Bothe Nobel prize 1954

What we want to know

^{210}Bi level scheme



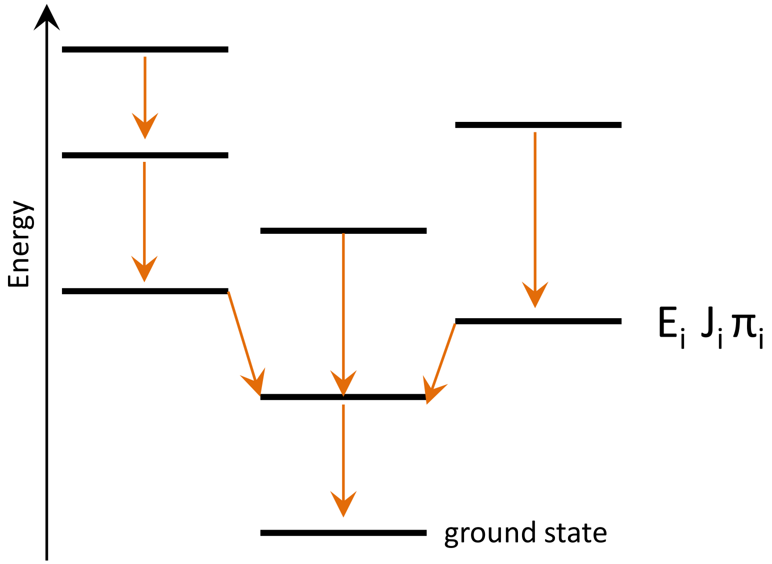
What we measure



A very good detector response function is needed!!!

The structure of the nucleus

Low-energy (<~10-15MeV) nuclear states



Observables:	Measuring γ-ray:
✓energy levels (E_i)	✓energy
✓spin (J_i)	✓angular distribution
✓parity (π_i)	✓linear polarization
✓lifetime (transition probabilities) (τ_i)	✓energy Doppler shift (for example)
✓nuclear moments (g-factors)	✓angular distribution vs t

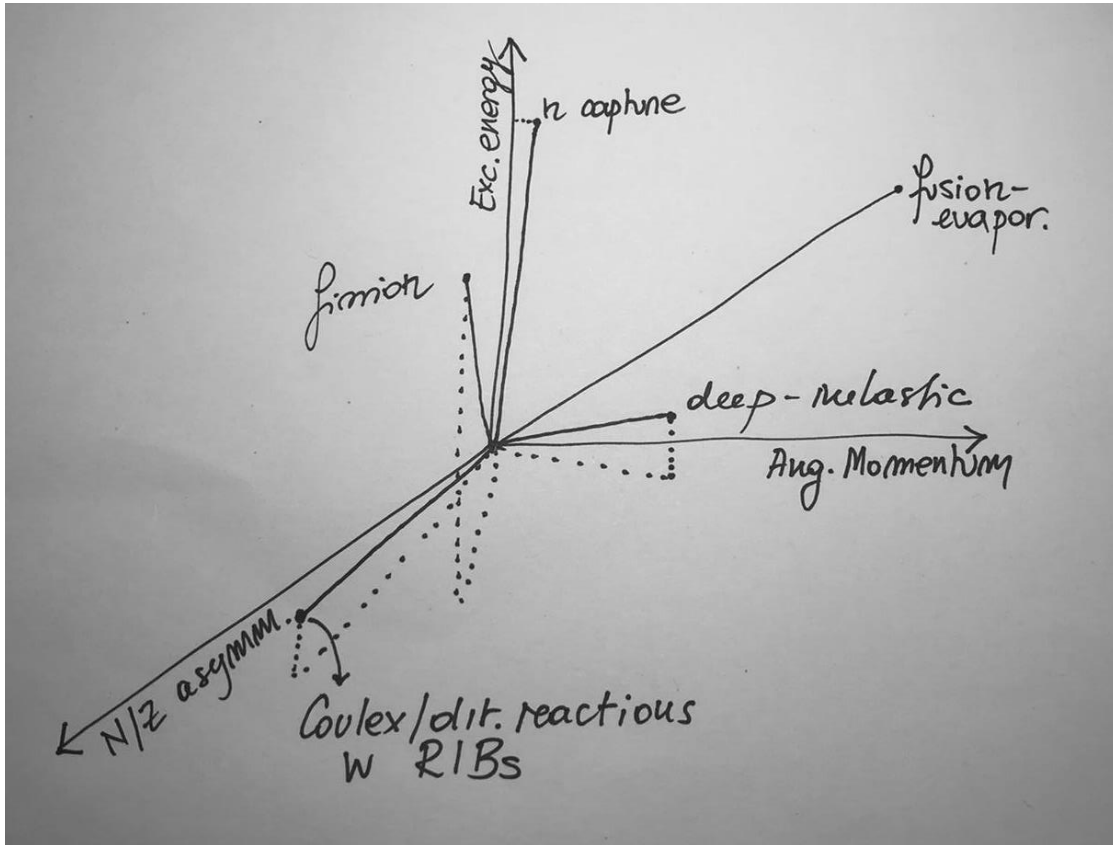
populate in excited state(s) and
observe γ ray de-excitation radiation

γ ray spectroscopy is an approach
for the study of nuclear structure

- ✓ systematics (e.g. shape transitions)
- ✓ benchmarks for nuclear models
  (e.g. Nuclear Shell Model)

Three main “research axes”

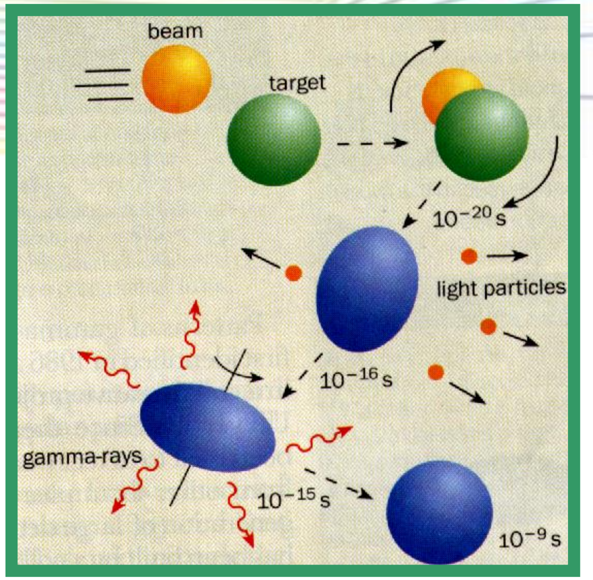
To study nuclear structure under “extreme conditions”



Each production mechanism is characterised by :

- (max) angular momentum, excitation energy and N/Z asymmetry
- Different cross sections (few mbarn for fusion-evaporation, up to 10^5 barn for neutron capture)
- Different recoil velocities (β~0 for n capture reactions, up to 50% for RIBs from fragmentation)
- Different needs for channel selectivity (ancillary detectors –charged particle detectors, mass separators…)

In-beam γ-ray spectroscopy



The "check-list" of detection requirements, Eg ~ 10keV – 10MeV

Energy resolution,
to disentangle complex spectra → germanium detectors

Peak-to-Total ratio,
to maximize "good events" → Compton background suppression

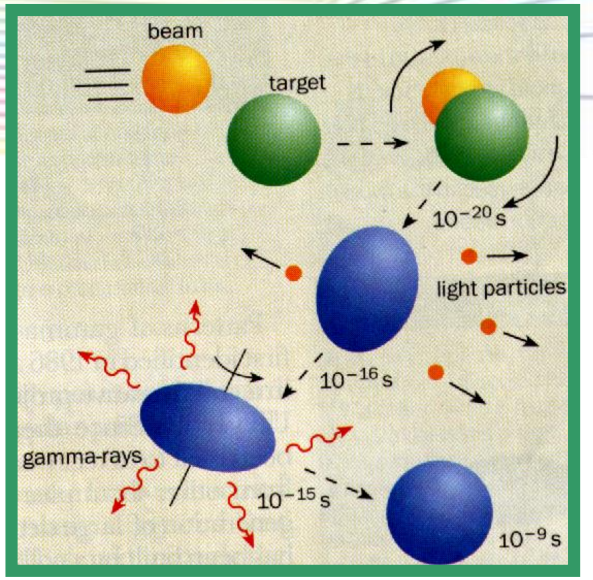
Doppler-correction capabilities,
to compensate the Doppler broadening (emitting nucleus in motion)

Good solid angle coverage,
to maximize the efficiency

Good granularity,
to reduce multiple hits on the detectors, measure angular distributions/correlations

In-beam γ-ray spectroscopy

The “check-list” of detection requirements, Eg ~ 10keV – 10MeV



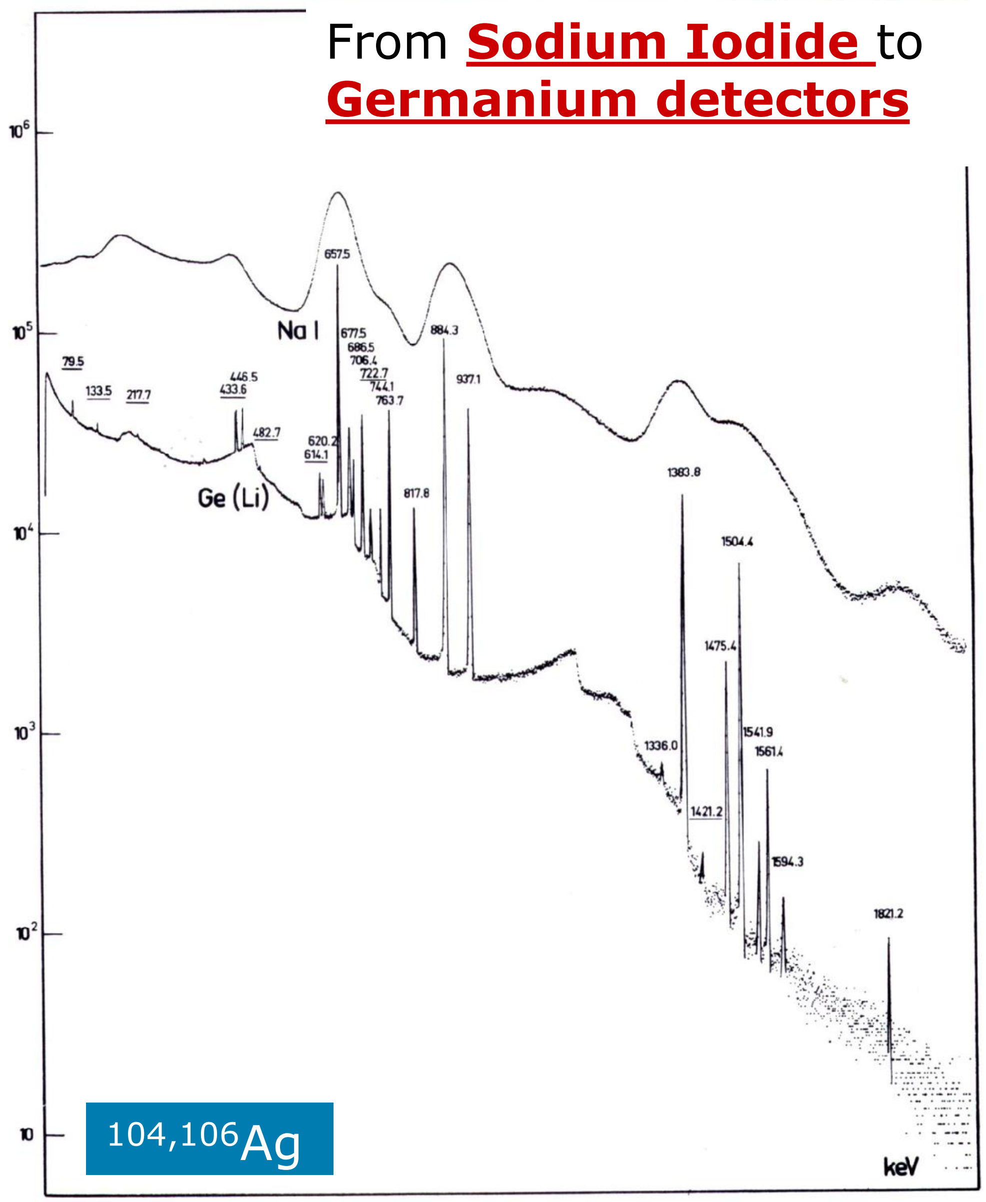
Avoid dead materials,
to avoid radiation absorbtion and preserve low energies

High counting rate capability,
often the channel of interest is (much!) less strong than the bakground

Time resolution,
for prompt events selection, lifetime measurements

Possibility to couple with ancillary devices,
to improve selectivity, determine velocity vector, …

Energy Resolution



From **Sodium Iodide** to **Germanium detectors**

^{104,106}Ag

Response function = differential spectrum obtained with a detector when hit by monochromatic radiation

60’s → Use of Ge(Li) detectors marks the beginning of high-resolution in-beam γ-ray spectroscopy

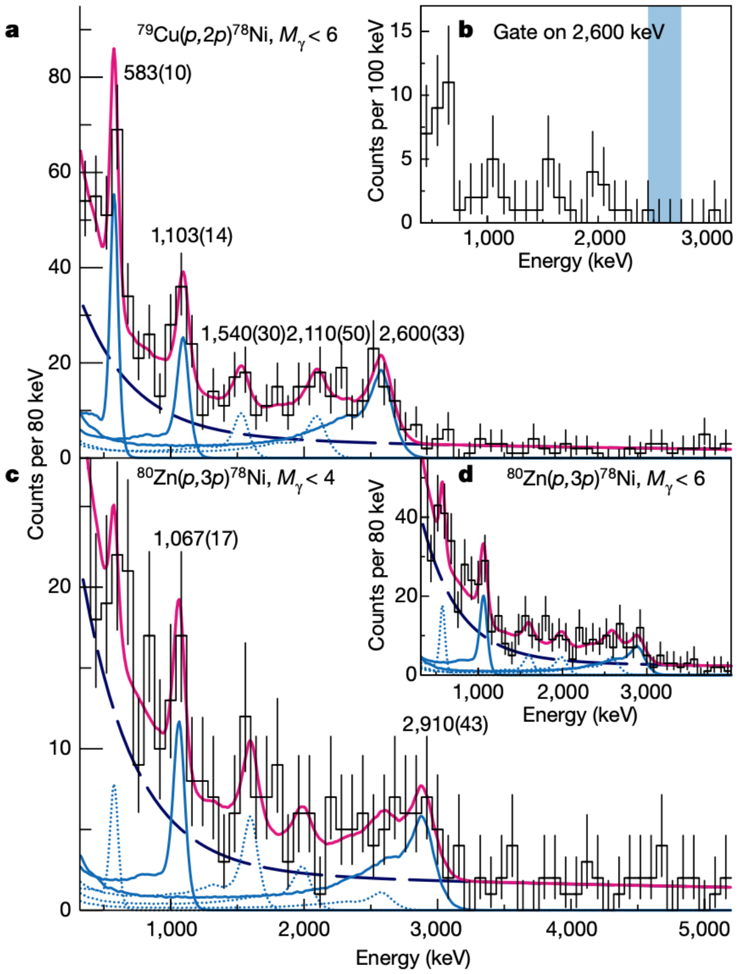
70’s → Only few detectors , operated in γ−γ coincidence. Development of the HP-Ge detector.

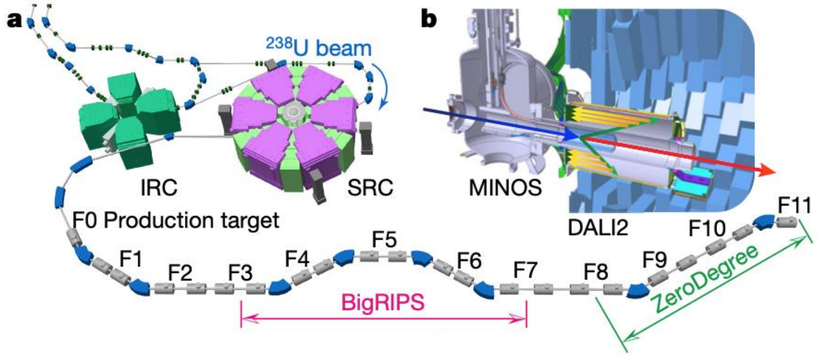
Use of Germanium detectors = breakthrough in nuclear structure

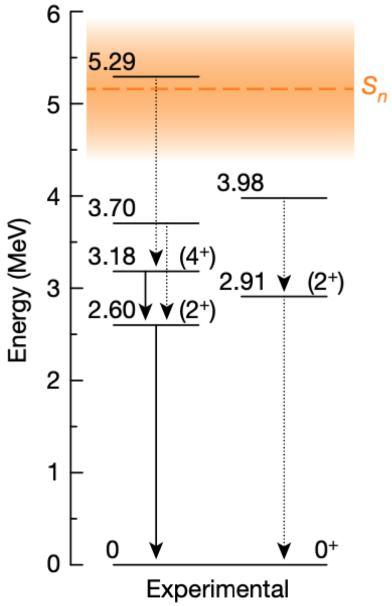
FWHM ~2 keV at 1.3 MeV

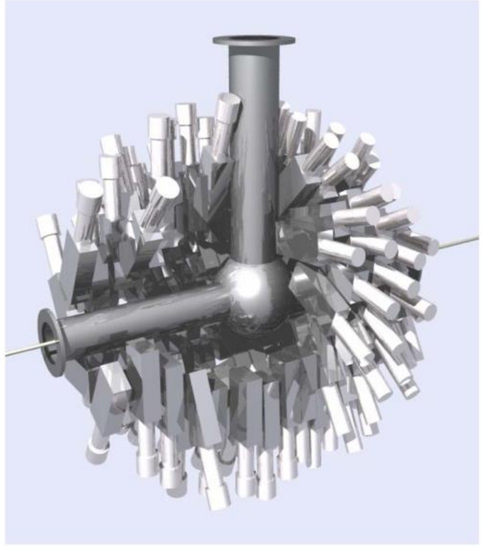
"Low-resolution" γ spectroscopy

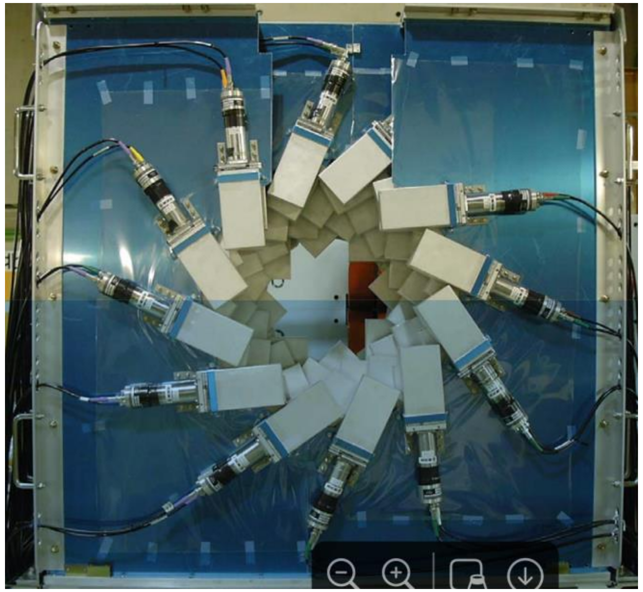
BUT high efficiency and high granularity – DALI2 @ RIKEN, the first γ spectrum of ^{78}Ni











160 NaI(Tl) detectors

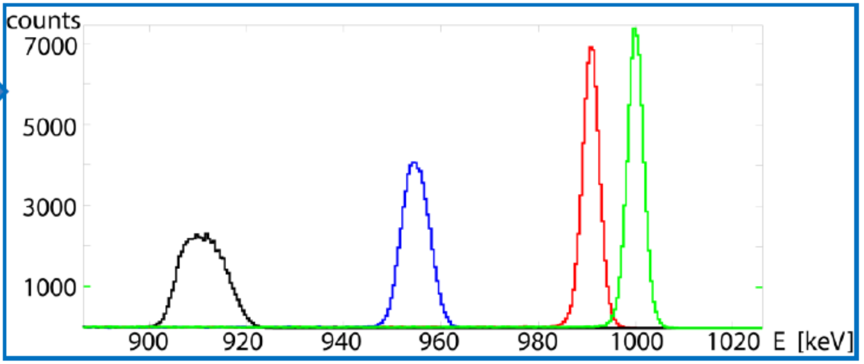
- 4.5*8*16 (cm^3)
- resol. 9% @ 662keV

16 layers, 6-14 dets per layer

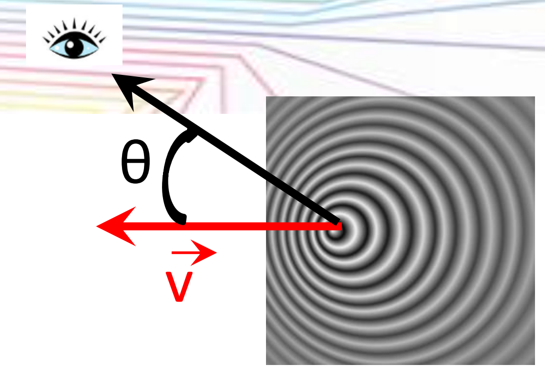
R. Taniuchi et al., Nature, 569 (2019) 53–58 S. Takeuchi et al., NIMA 763 (2014) 596

Doppler effect on γ rays

E_0=1MeV
β=0, 0.01, 0.05, 0.10
(fixed direction)
$\theta = 158\ deg$

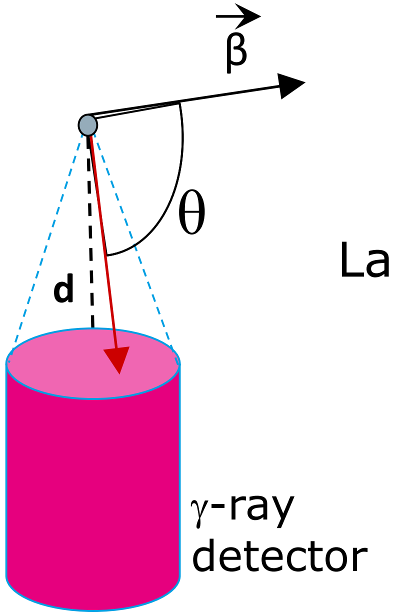


Source at rest → intrinsic energy resolution



$\vec{\beta}$ is a key info.

$$E_\gamma^{Lab}(\theta) = E_\gamma^{CM} \frac{\sqrt{1-\beta^2}}{1-\beta\cdot\cos\theta}$$



Large Ω → Good efficiency

Large Ω → Bad detector position resolution

$$\left(\Delta E_\gamma^{lab}\right)^2 = \left(\frac{\partial E_\gamma^{cm}}{\partial\theta}\right)^2 (\Delta\theta)^2 + \left(\frac{\partial E_\gamma^{cm}}{\partial\beta}\right)^2 (\Delta\beta)^2 + \left(\frac{\partial E_\gamma^{cm}}{\partial E_\gamma}\right)^2 (\Delta E_\gamma)^2.$$

Doppler broadening

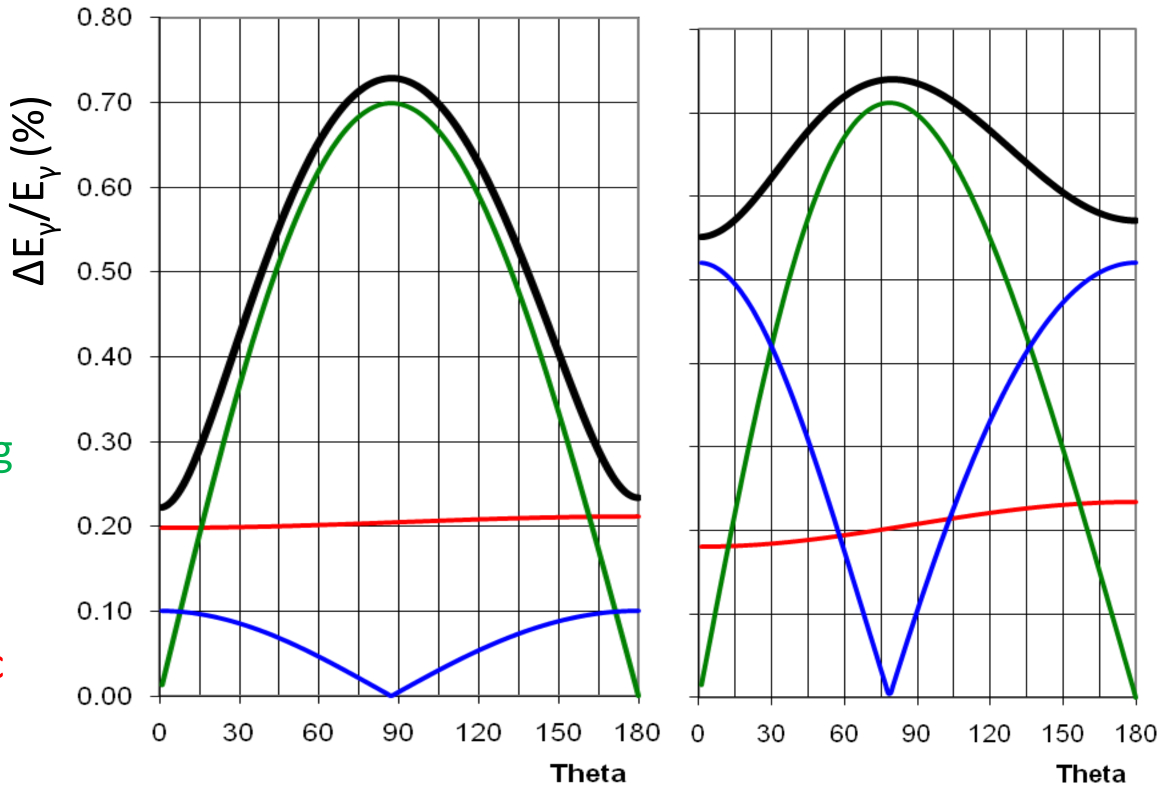
E_γ = 1MeV

β(%)	5±0.01	20±0.005
ΔΘ(deg)	8	2

Opening

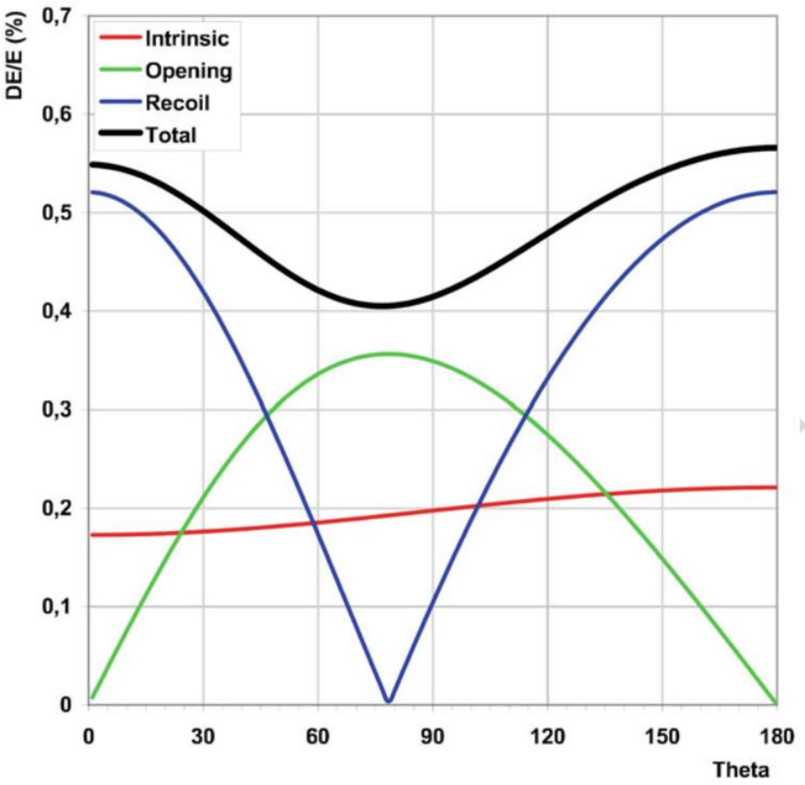
Recoil

Intrinsic



β = 20% $\Delta\beta$ = 0.5%

$\Delta\theta$ = 1%



Photon interaction with matter

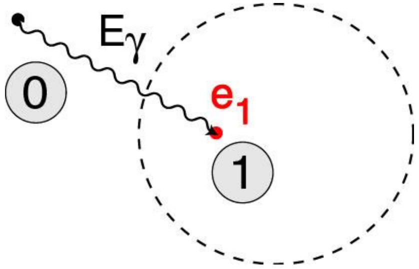
~ 100 keV

~1 MeV

~ 10 MeV

γ ray energy

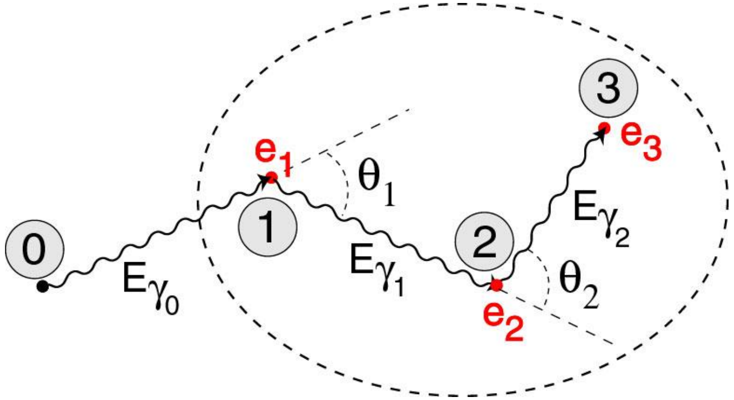
Photoelectric



$$E_{e1}=E_\gamma-E_b$$

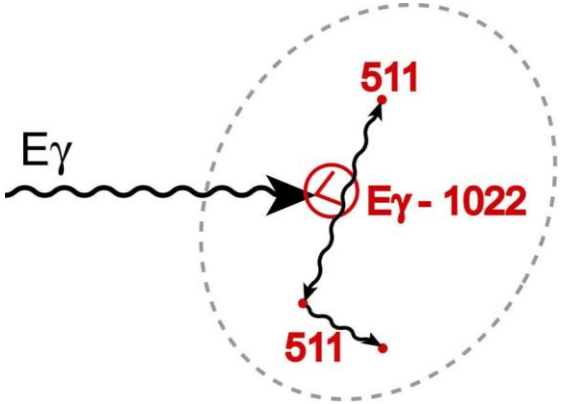
$$\sigma \propto \frac{z^n}{E_\gamma^{3.5}}, \quad n \approx 4 \div 5$$

Compton Scattering



$$E_{\gamma'} = \frac{E_\gamma}{1+\frac{E_\gamma}{m_0c^2}(1-\cos\theta)}$$

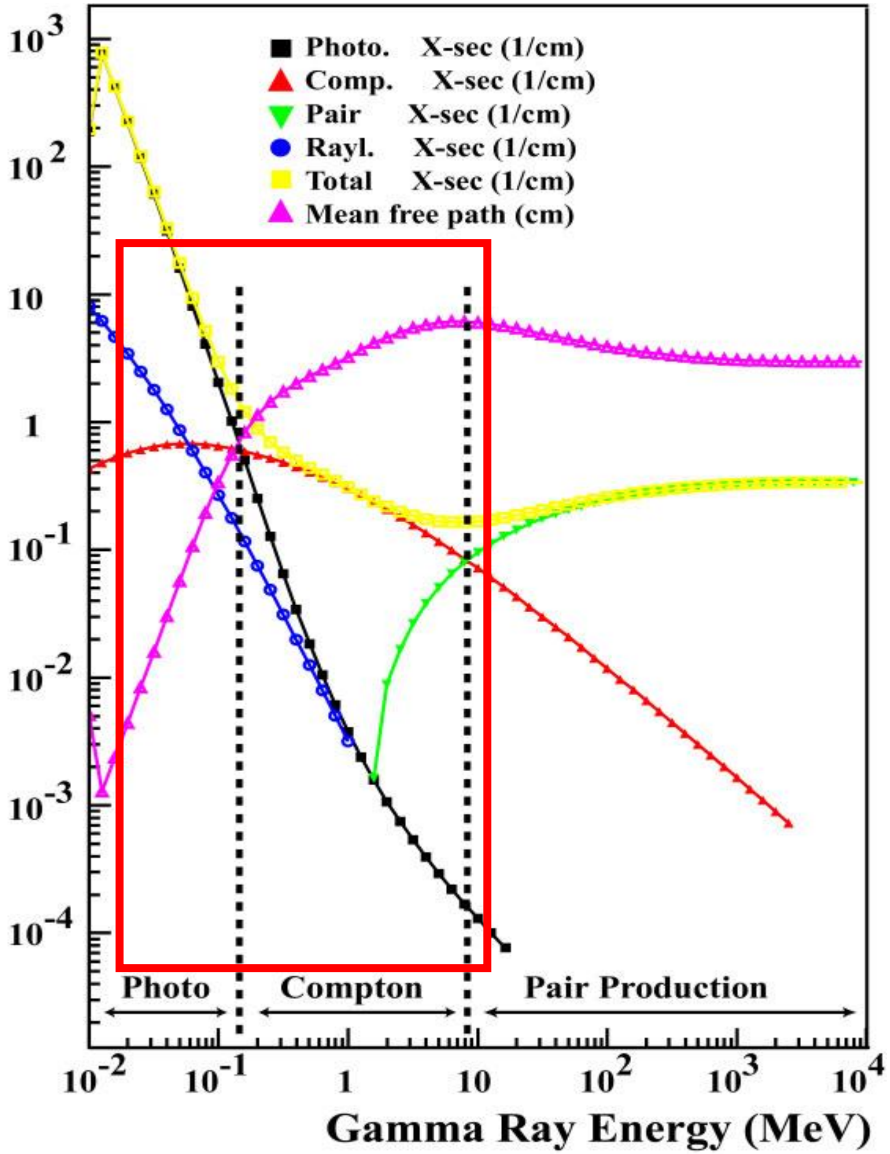
Pair Production



$$(E_\gamma > 2m_ec^2)$$

$$\sigma \propto Z^2$$

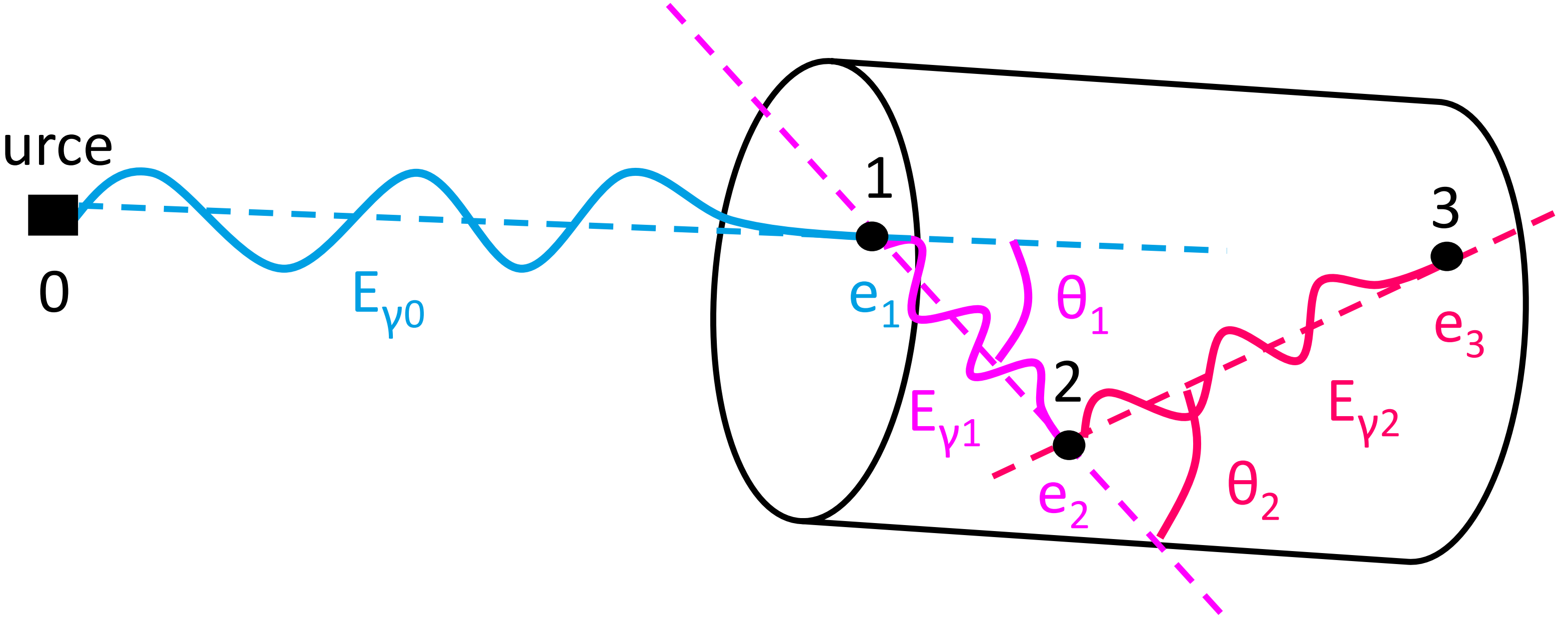
Interaction of photons in germanium



Mean free path determines size of detectors:

λ(10 keV)	~ 55 μm
λ(100 keV)	~ 0.3 cm
λ(200 keV)	~ 1.1 cm
λ(500 keV)	~ 2.3 cm
λ(1 MeV)	~ 3.3 cm
λ(2 MeV)	~ 4.5 cm
λ(5 MeV)	~ 5.9 cm
λ(10 MeV)	~ 5.9 cm

Compton scattering (1)



assuming that the e^- is at rest,
from conservation of energy and momentum:

$$\boxed{E_{\gamma i} = \frac{E_{\gamma\, i-1}}{1 + \frac{E_{\gamma\, i-1}}{m_0 c^2}\left(1 - \cos\theta_i\right)}}$$

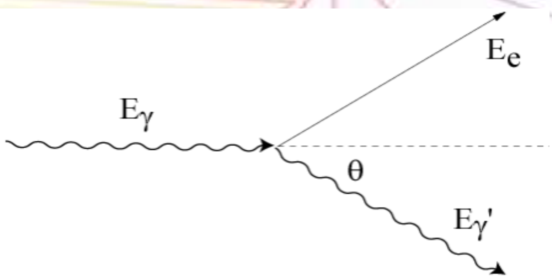
Energy of scattered γ

$$\boxed{e_i = E_{\gamma\, i-1} - E_{\gamma\, i}}$$

Energy of scattered e^-

Arthur Holly Compton
Nobel prize 1927

Compton scattering (2)



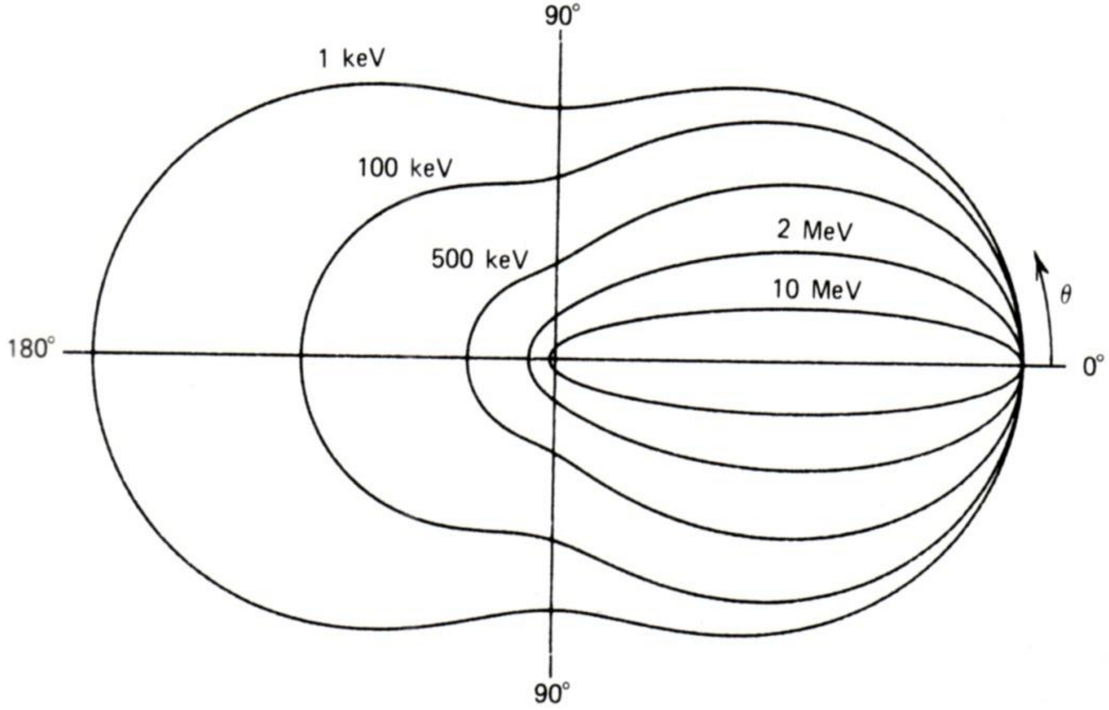
The angular distribution of the scattered photon is described by the Klein-Nishina formula:

$$\frac{d\sigma}{d\Omega} = z r_e^2 \left(\frac{1}{1+\alpha(1-\cos\theta)} \right)^2 \left(\frac{1+\cos^2\theta}{2} \right) \left(1 + \frac{\alpha^2 (1-\cos\theta)^2}{(1+\cos^2\theta)[1+\alpha(1-\cos\theta)]} \right)$$

$\alpha = E_\gamma / m_e c^2$

and r_e is the classical electron radius

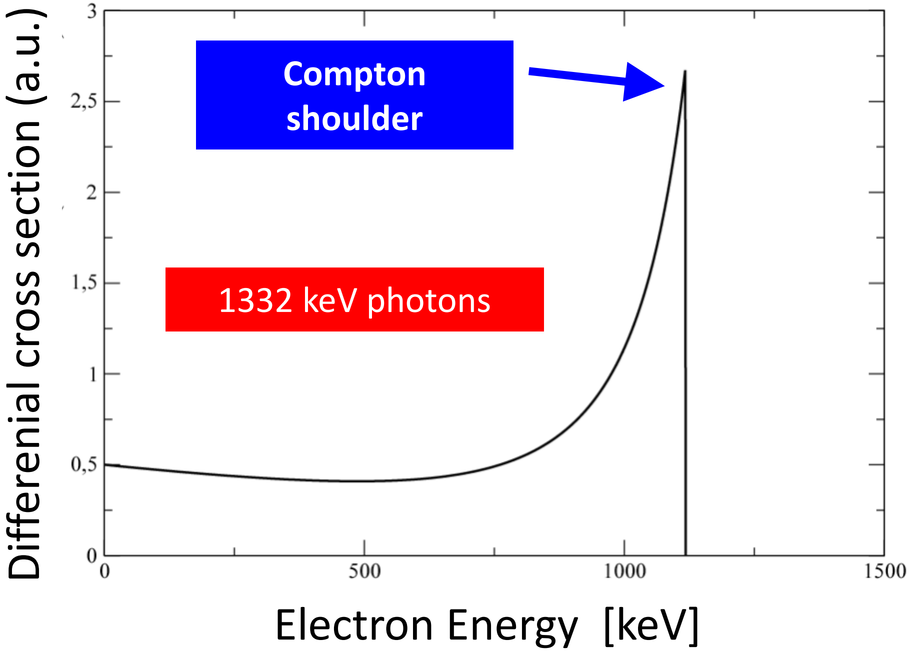
For E_γ >~ few 100 keVs the angular distribution is highly anisotropical and peaked to small <u>forward angles</u>. It strongly ``focuses’’ with the increasing photon energy.



Continuum Compton scattering (2)

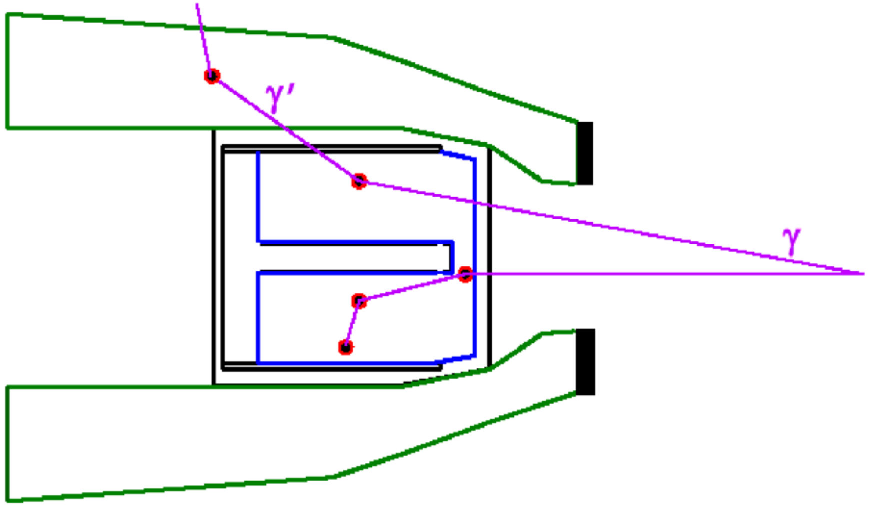
The spectrum of the scattered electrons can be deduced from the Klein-Nishina formula:

$$\frac{dN}{dE_e} \propto \left(\frac{1+f^2(E_e)}{2}\right)\left[1+\frac{1}{1+f^2(E_e)}\frac{E_e^2}{E_\gamma(E_\gamma-E_e)}\right] \qquad f(E_e)=1-\frac{m_e c^2}{E_\gamma}\frac{E_e}{E_\gamma-E_e}$$



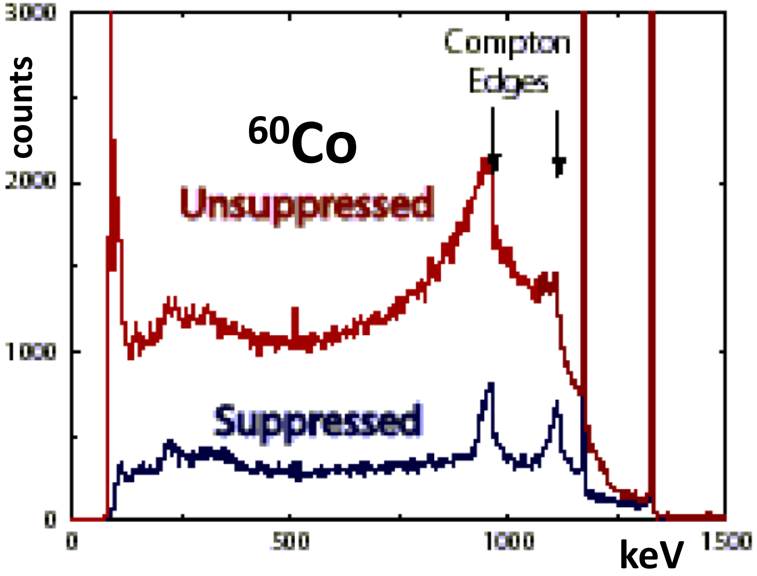
Since <u>the actual energy deposition is performed by the electrons</u>, photons interacting via Compton scattering will produce a continuum.

Compton-suppressed HPGe detectors



For large-volume Ge crystals the Anticompton shield (AC) improves the PeakToTotal ratio (P/T) from ~20% to ~60%

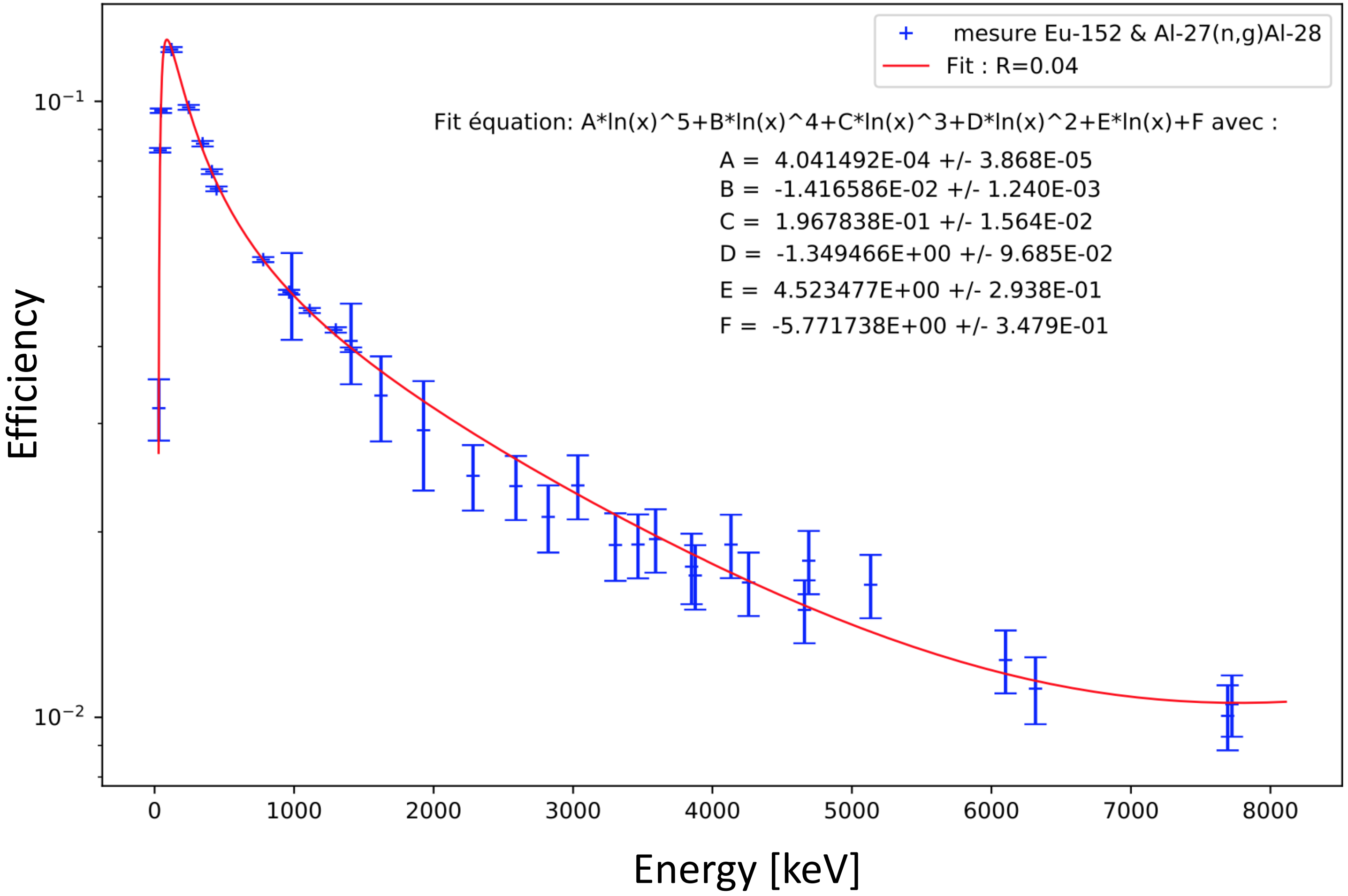
γ1 \ γ2	P	B
P	PP	PB
B	BP	BB



In a g-g measurement, the fraction of useful peak-peak coincidence events grows from 4 % to 36%

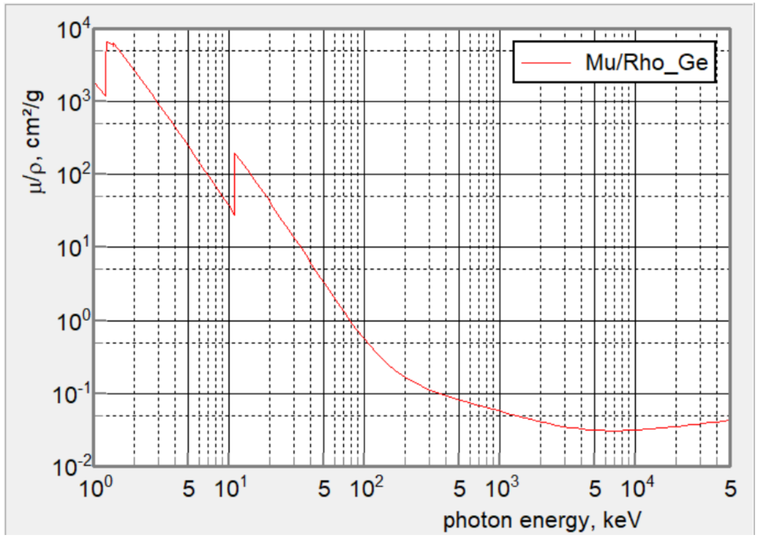
For high fold (F) coincidences the fraction of useful coincidences is P/T^{F}

Efficiency calibration: an exemple



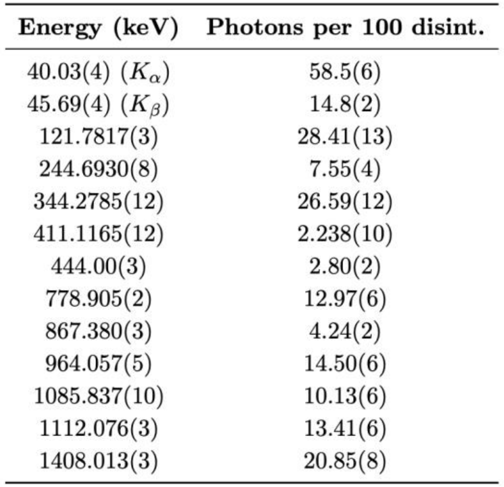
Fit équation: A*ln(x)^5+B*ln(x)^4+C*ln(x)^3+D*ln(x)^2+E*ln(x)+F avec :

A = 4.041492E-04 +/- 3.868E-05
B = -1.416586E-02 +/- 1.240E-03
C = 1.967838E-01 +/- 1.564E-02
D = -1.349466E+00 +/- 9.685E-02
E = 4.523477E+00 +/- 2.938E-01
F = -5.771738E+00 +/- 3.479E-01



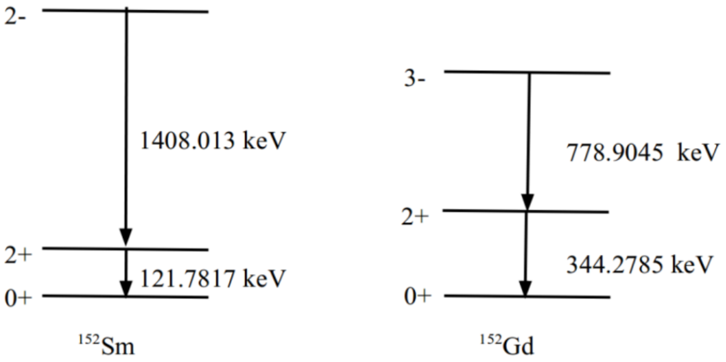
When no data available: extrapolation at high energy with Monte Carlo simulations

Efficiency calibration: singles vs $\gamma\gamma$



Energy (keV)	Photons per 100 disint.
40.03(4) (K_α)	58.5(6)
45.69(4) (K_β)	14.8(2)
121.7817(3)	28.41(13)
244.6930(8)	7.55(4)
344.2785(12)	26.59(12)
411.1165(12)	2.238(10)
444.00(3)	2.80(2)
778.905(2)	12.97(6)
867.380(3)	4.24(2)
964.057(5)	14.50(6)
1085.837(10)	10.13(6)
1112.076(3)	13.41(6)
1408.013(3)	20.85(8)

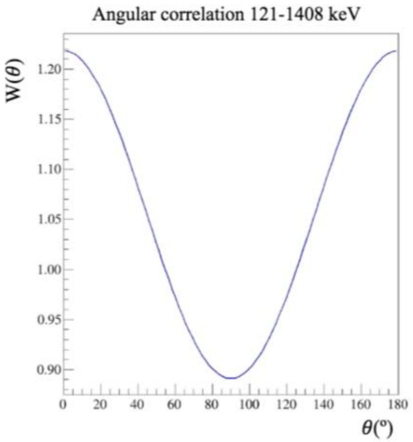
^{152}Eu calibration source

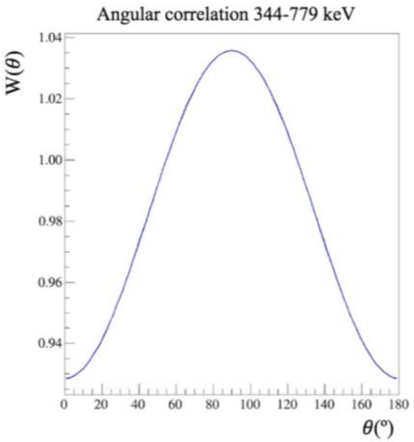


$$N^m_{\gamma\gamma}(121.7817, 1408.013) = N_\gamma(1408.013)P_\gamma(121.7817)\left(\frac{N-1}{N}\right)\epsilon_{abs}(121.7817)\epsilon_{abs}(1408.013)$$

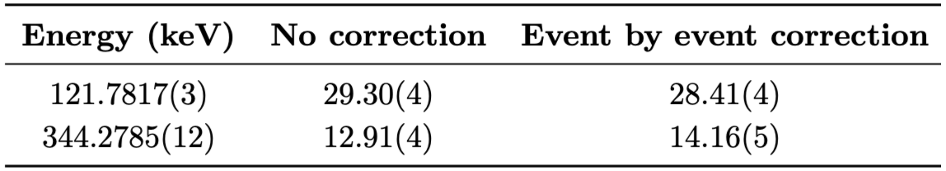
$$\epsilon_{abs}(E_\gamma) = \frac{N^m(E_\gamma)}{I_\gamma A \Delta t}$$

In order to have a "dead-time free" efficiency evaluation





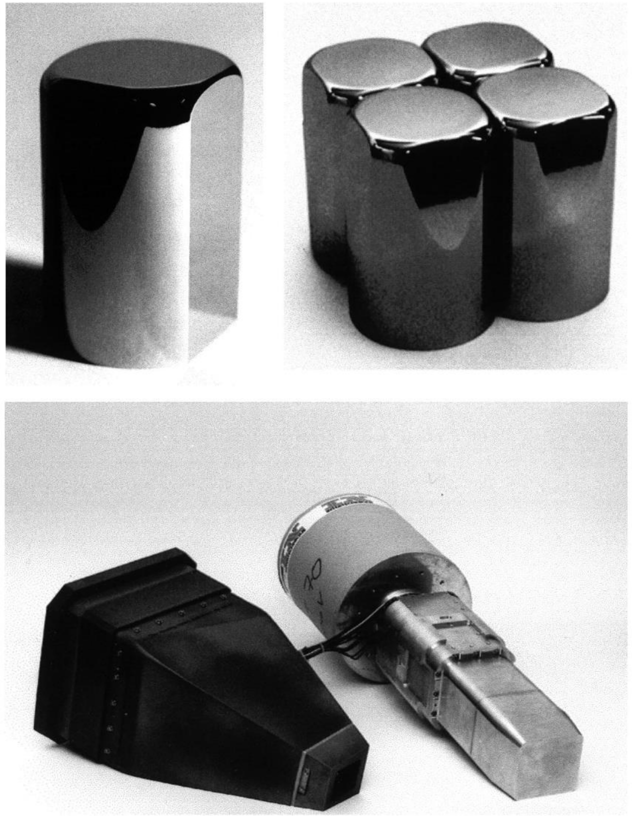
Correction for angular correlations:

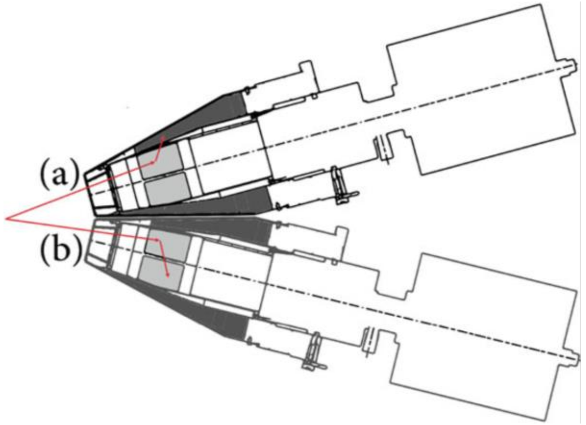


Energy (keV)	No correction	Event by event correction
121.7817(3)	29.30(4)	28.41(4)
344.2785(12)	12.91(4)	14.16(5)

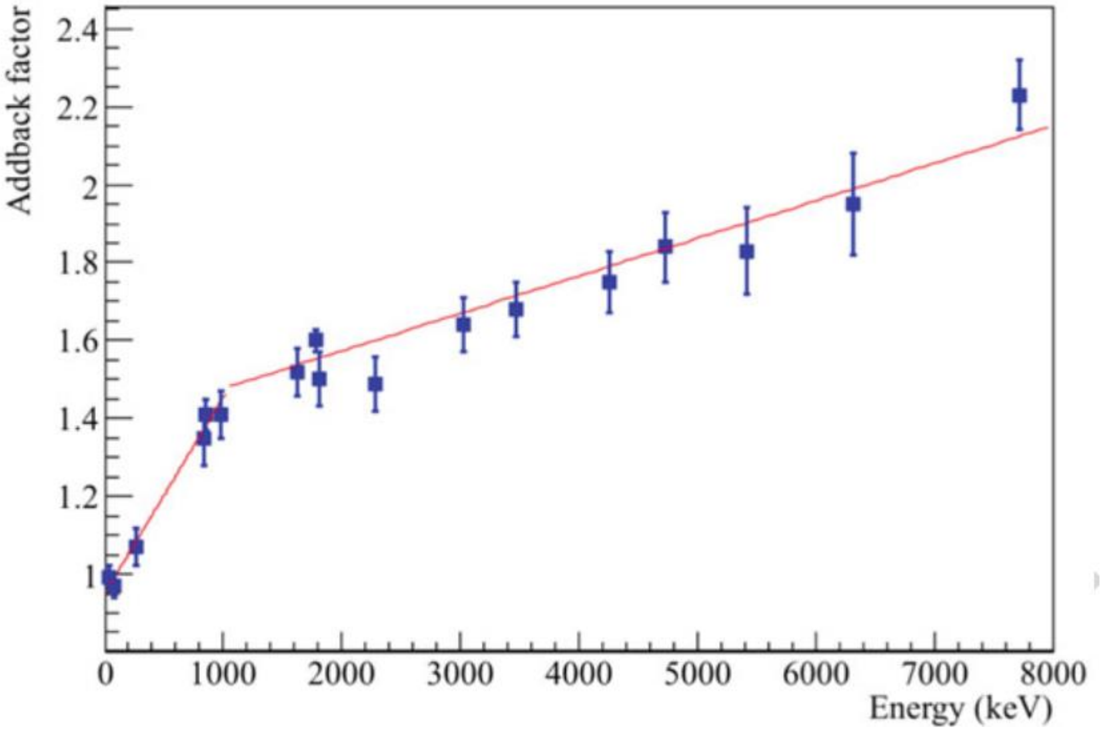
D. Reygadas, PhD Thesis, UGA 2021

Clover detectors





(a) Reject
(b) Add-Back



G. Duchene et al., NIMA 432 (1999) 90

Cross-talk correction for clover detectors

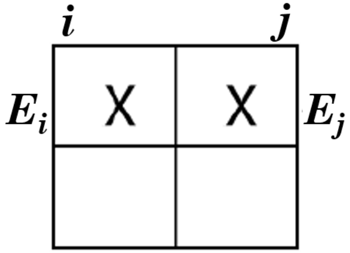
The **magnitude** of the effect of the crosstalk on the energy detected by a crystal:

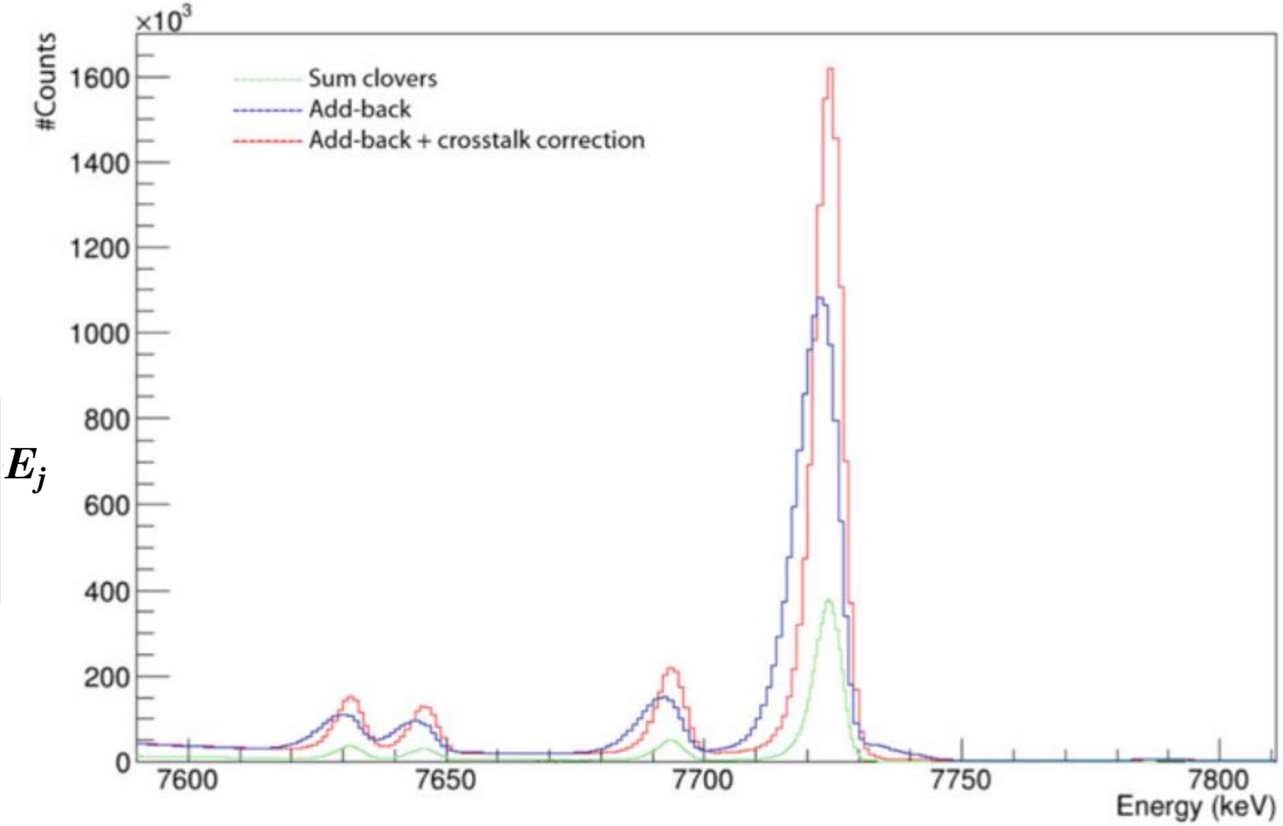
- is linearly proportional to the energy detected by the neighbouring crystal,
- is independent from the energy detected in the crystal itself.

E_j affects E_i → ΔE_{ji}

E_i affects E_j → ΔE_{ij}

⚠ $ij \neq ji$





M = Multiplicity (number of crystals of the same clover that detect an energy in the same time window)

$$\Delta E_{ji}[ch] = E_i^{M=1}[ch] - E_{ji}[ch] = m_{ji} \times E_j[ch]$$

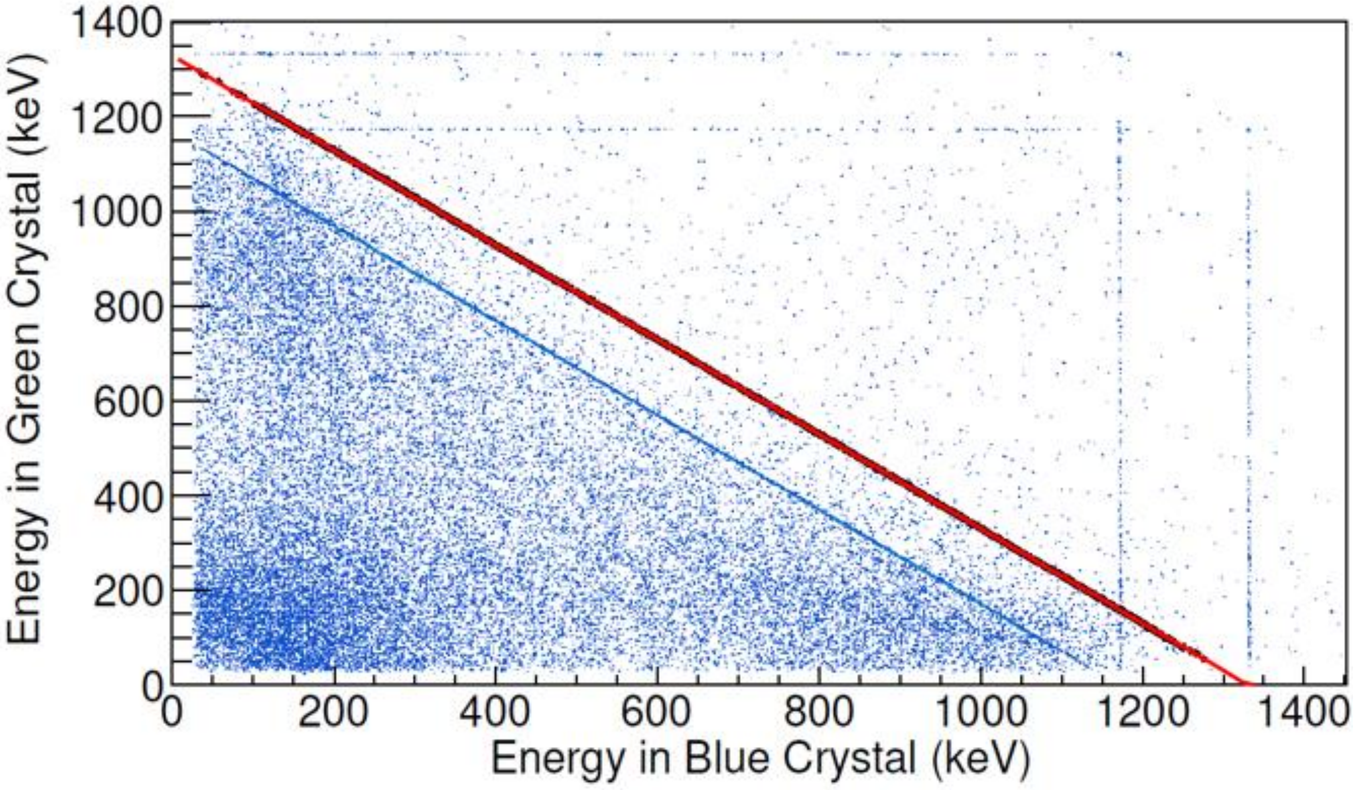
A. B. Garnsworthy et al., NIMA 918 (2019) 9-29

G. Colombi at al., in preparation

Cross-talk correction for clover detectors

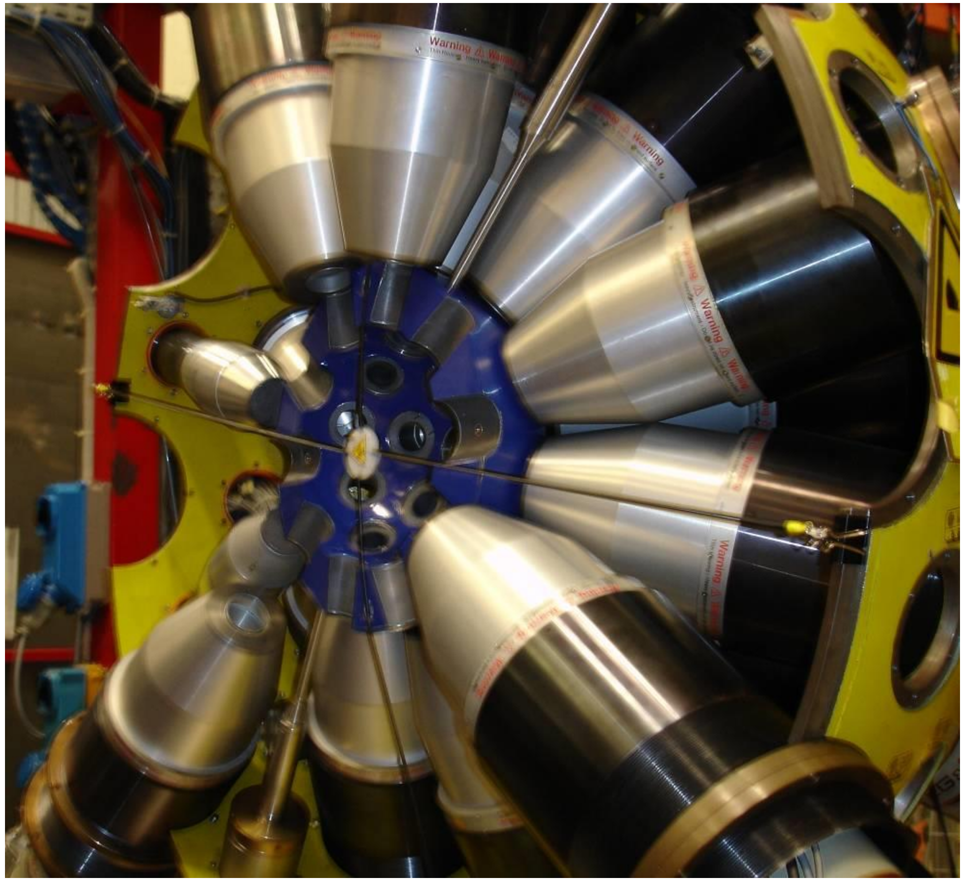
In GRIFFIN facility, the crosstalk is corrected exploiting the Compton scattering line of ^{60}Co in the gamma-gamma matrix.

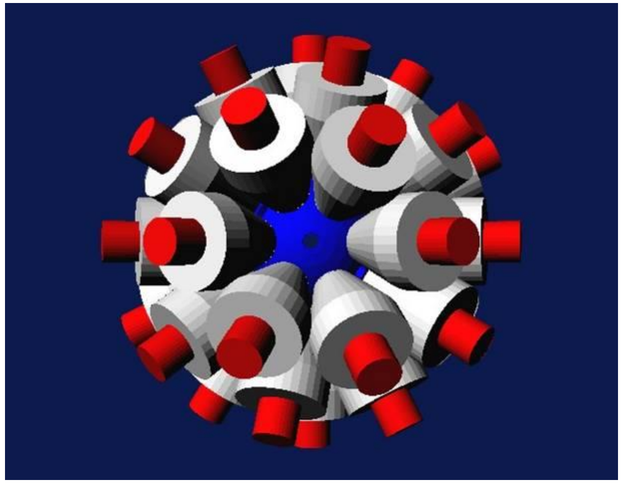
The effect in the FIPPS clovers is too small to be corrected with this method.



A. B. Garnsworthy et al., NIMA 918 (2019) 9-29

GASP @ Legnaro Nat. Lab.





- 40 HPGe + AC (config. II)
  - $d_{\text{target-det.}} = 22$ cm
  - $\varepsilon_{ph} \sim 5.8\%$ @ 1332.5 keV
- Pb collimator (6 cm thick)
  - inner space $R_{int} = 15$ cm

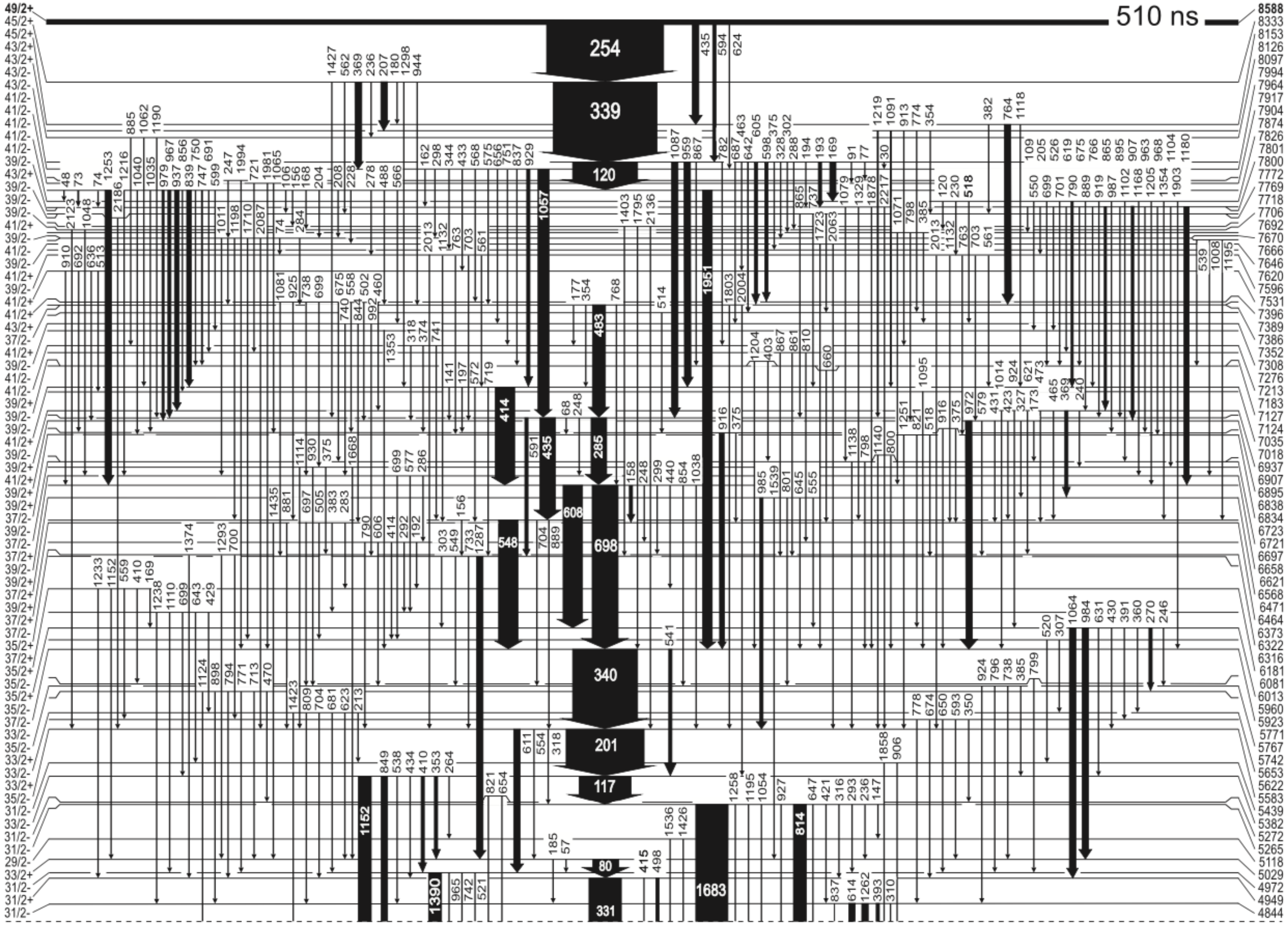
Lifetime measurements with Doppler Shift Techniques

7 rings @	35°,	60°,	72°,	90°,	108°,	120°,	145°
	6	6	4	8	4	6	6

C. Rossi-Alvarez, Nucl. Phys. News Europe 2 (1993) 10

D. Bazzacco, in: Proc. Conf. On Physics from Large γ-ray detector arrays, 1992, p. 376

Shower of γ rays in ^{147}Gd



Upper part of the decay of the isomer (populated in ^{76}Ge(^{76}Ge,5n))

400 new gamma transitions found

Discovery of octupole correlations « among » SM states

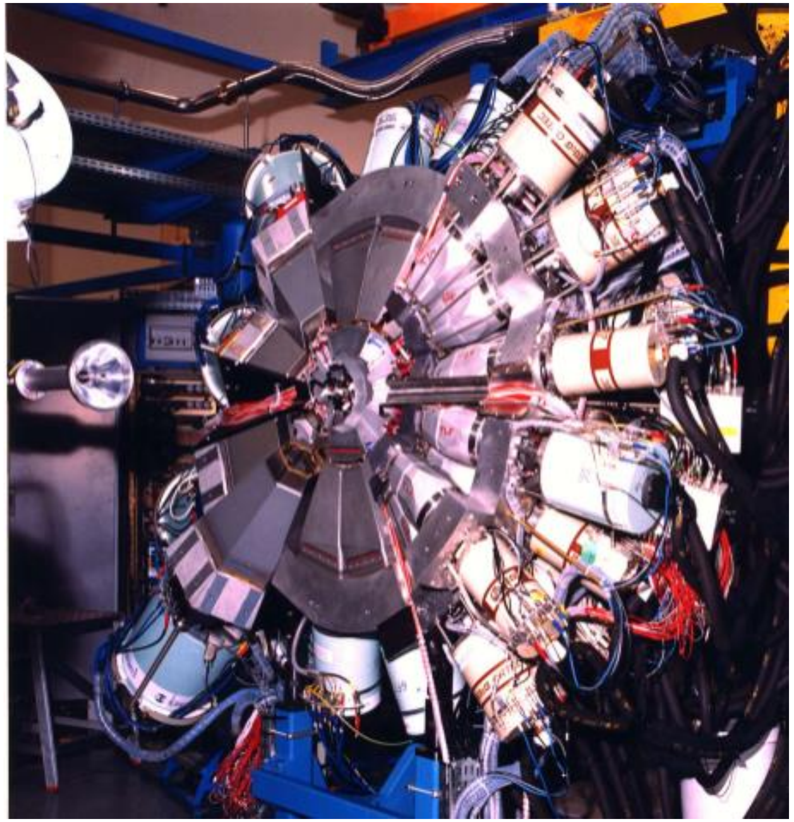
R. Broda et al., PRC 101 (2020) 064320

GAMMASPHERE

up to 110 Compton-Suppressed Ge detectors

I.Y. Lee, NPA 520 (1990) 641

EUROBALL



15 Clusters (7-Ge); 26 Clovers (4-Ge); 30 single Ge
71 CS-systems
239 Ge crystals

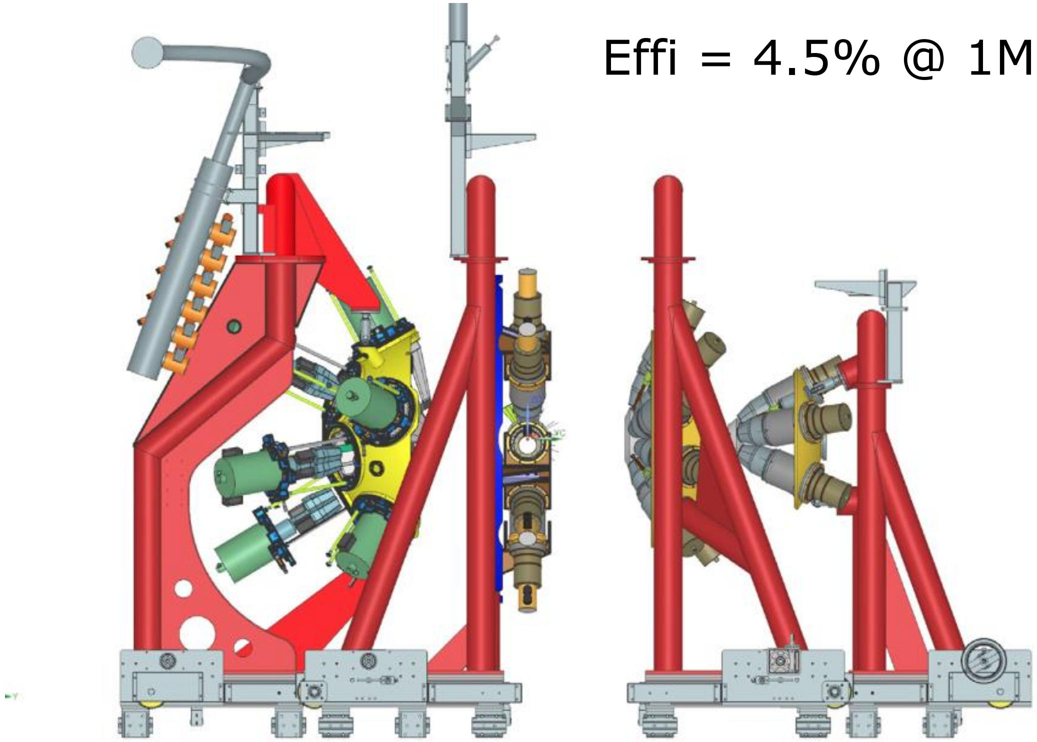
Efficiency ε_p ~ 10 — 5 %
Peak/Total PT ~ 55 — 40 %
(M_γ=1 — M_γ=30)

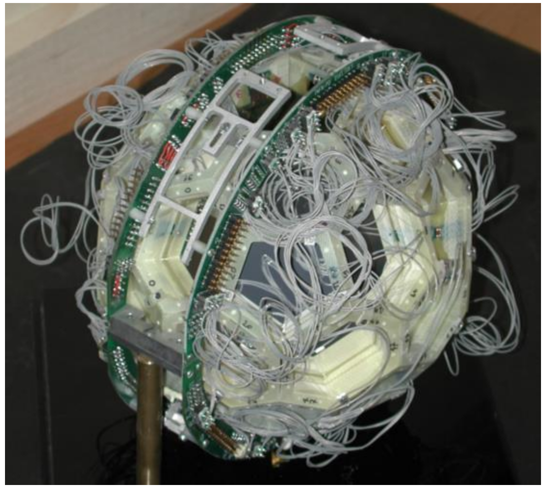
Solid angle covered by Ge ➔ 40-50 %

The GALILEO array at LNL

25 Compton-suppressed HPGe tapered detectors
+ 10 triple clusters+ACs

Effi = 4.5% @ 1MeV





EUCLIDES Si ball for particle detection

A. Goasduff et al., NIMA 1015 (2021) 165753

The nucleus is always full of surprises

Instrumentation advances ⇔ New Science