Decay Spectroscopy at GSI and FAIR - I

J. Gerl

GSI Darmstadt, Germany

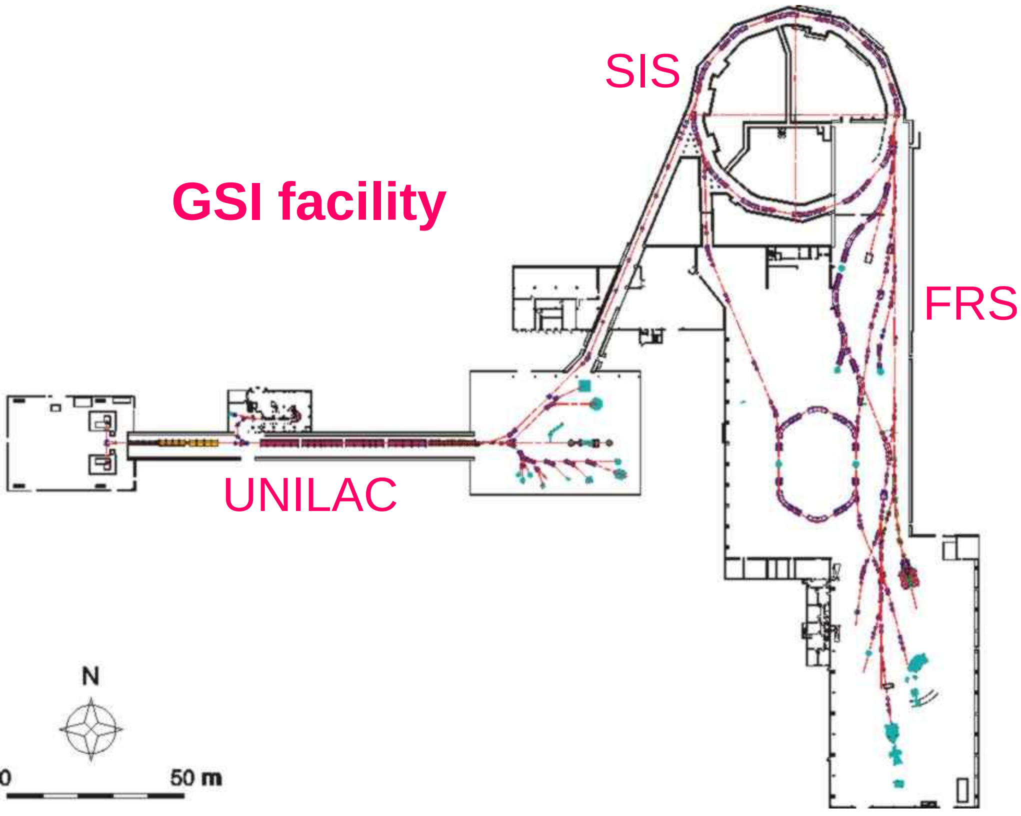
presented at

INUP 2011

Goa, India,

NOVEMBER 9 – 11, 2011

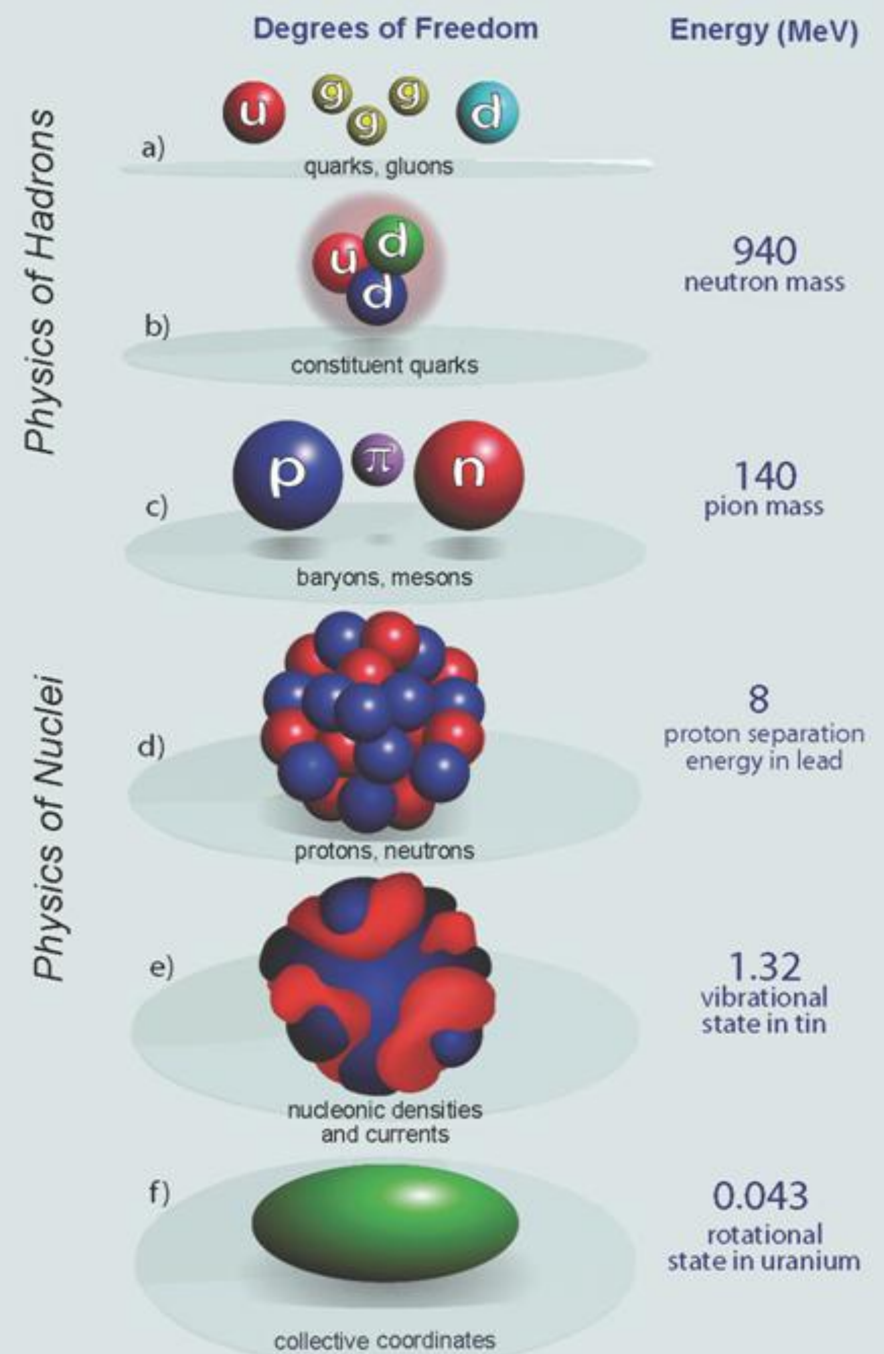
Physics of Hadrons and Nuclei



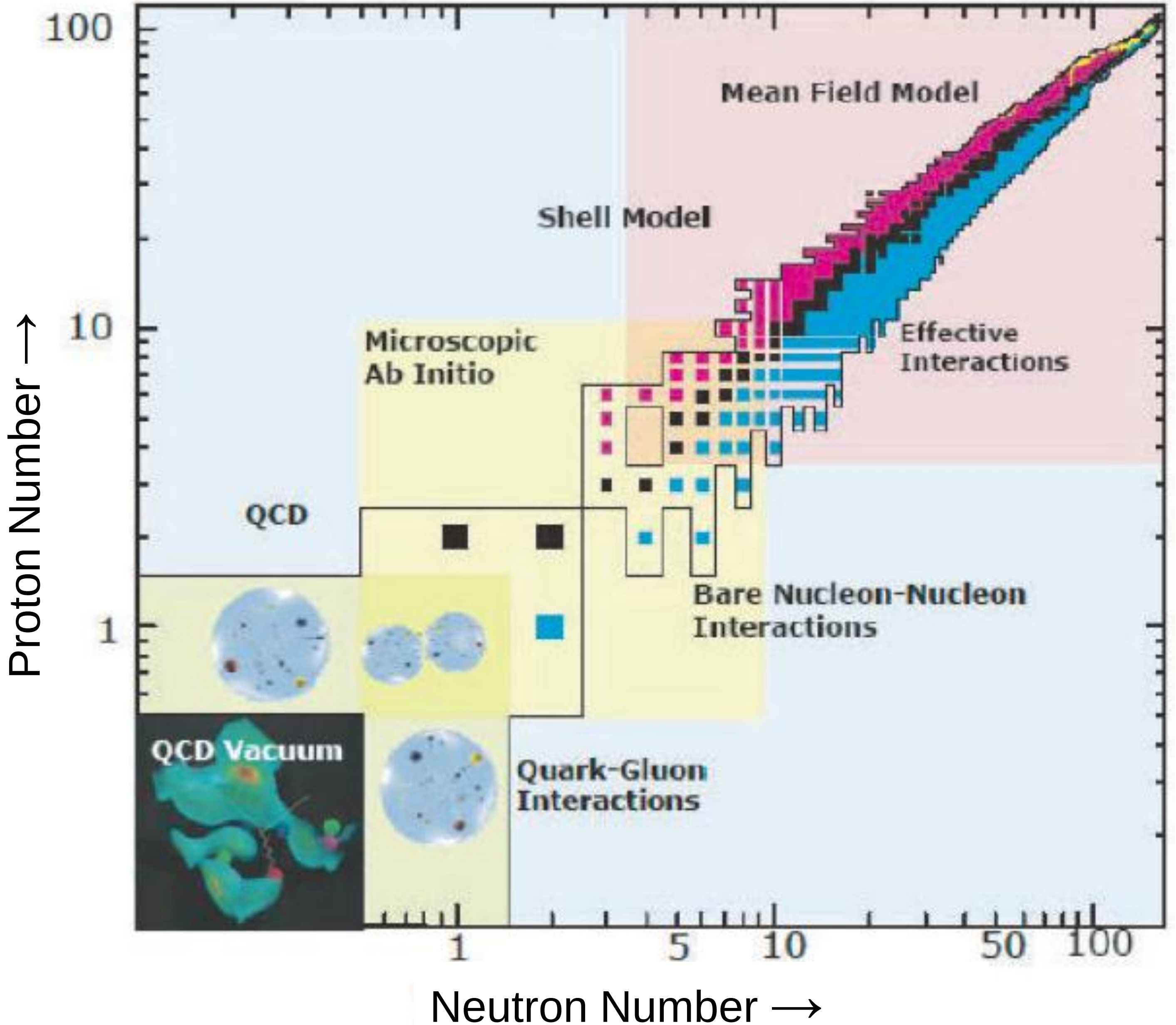
UNILAC: p .... U, E_{max} = 14 A·MeV

SIS: p .... U, E_{max} = 2.0 A·GeV ... 1.4 A·GeV
$I_{max} = 10^{11}$ /s ... 10^{9} /s

FRS: universal RIBs, E < 1 A·GeV
I = 0.01 /s .... 10^{5} /s

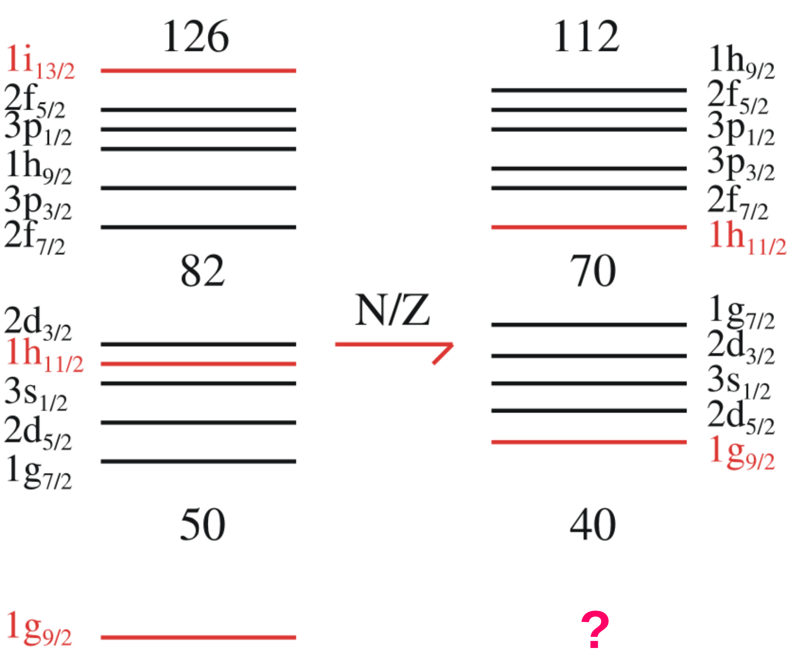


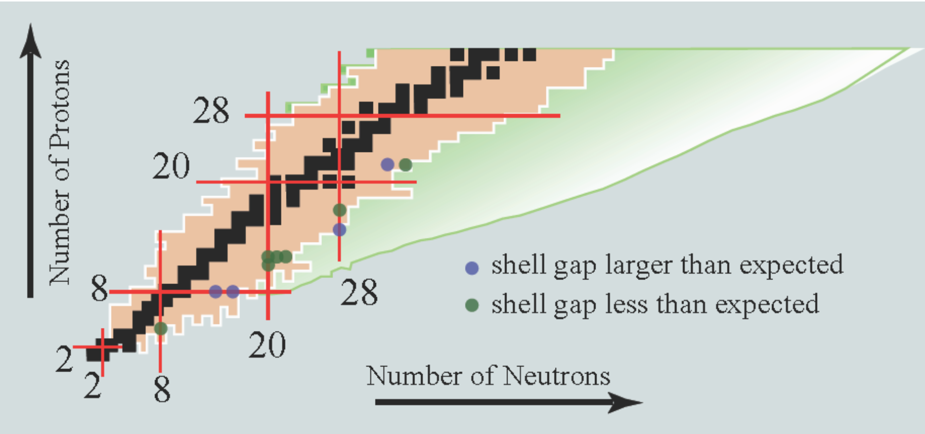
Towards a predictive (and unified) description of nuclei

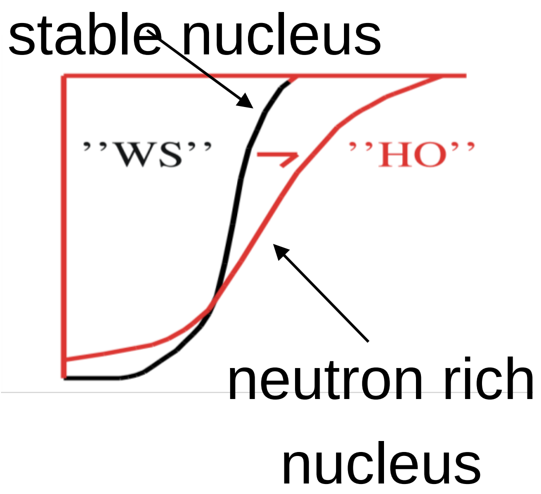


Nuclear shell structure

Shell structure of exotic nuclei changes !!!







around the valley of nuclear stability

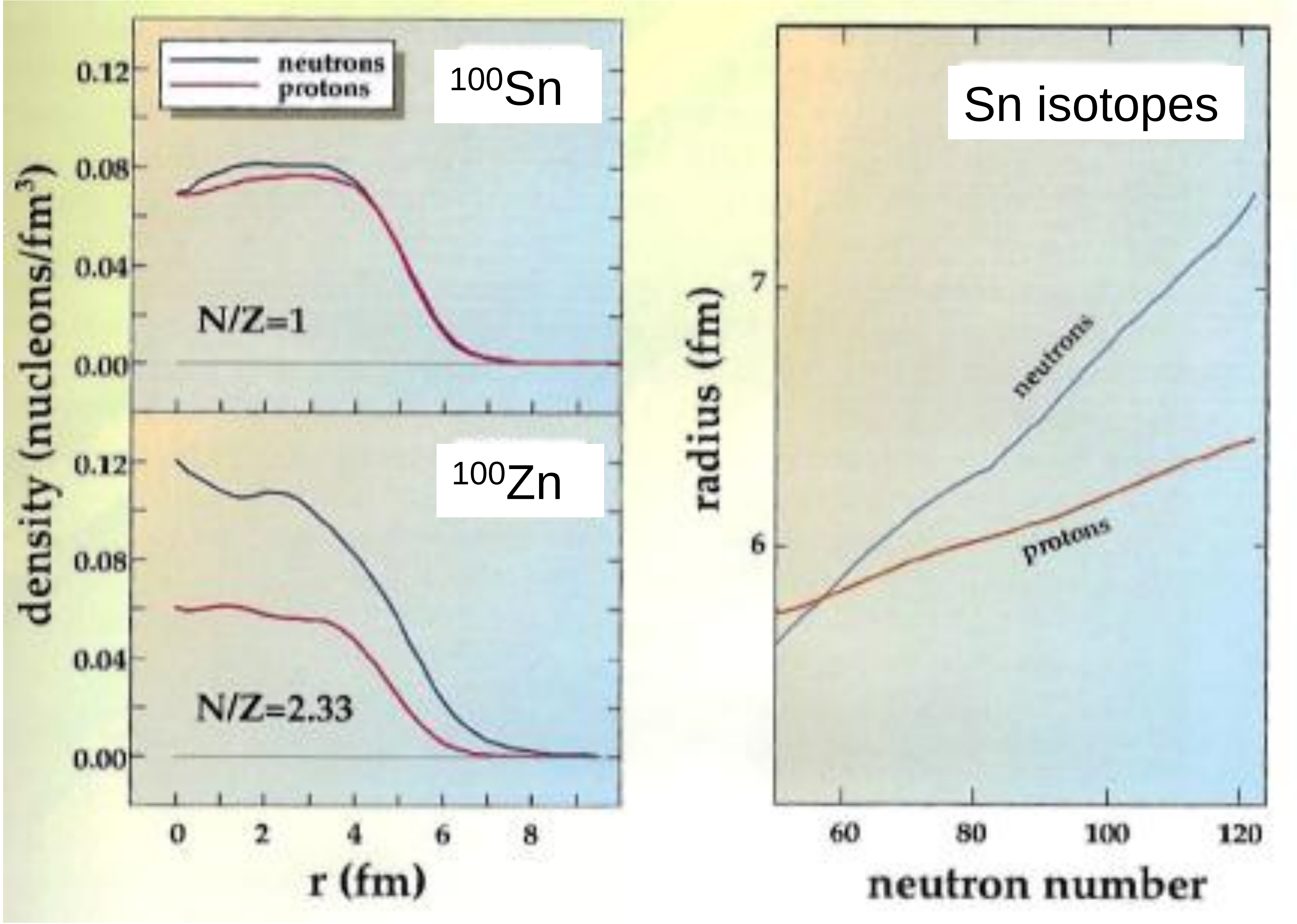
N/Z ≈ 1...1.6

neutron-rich nuclei

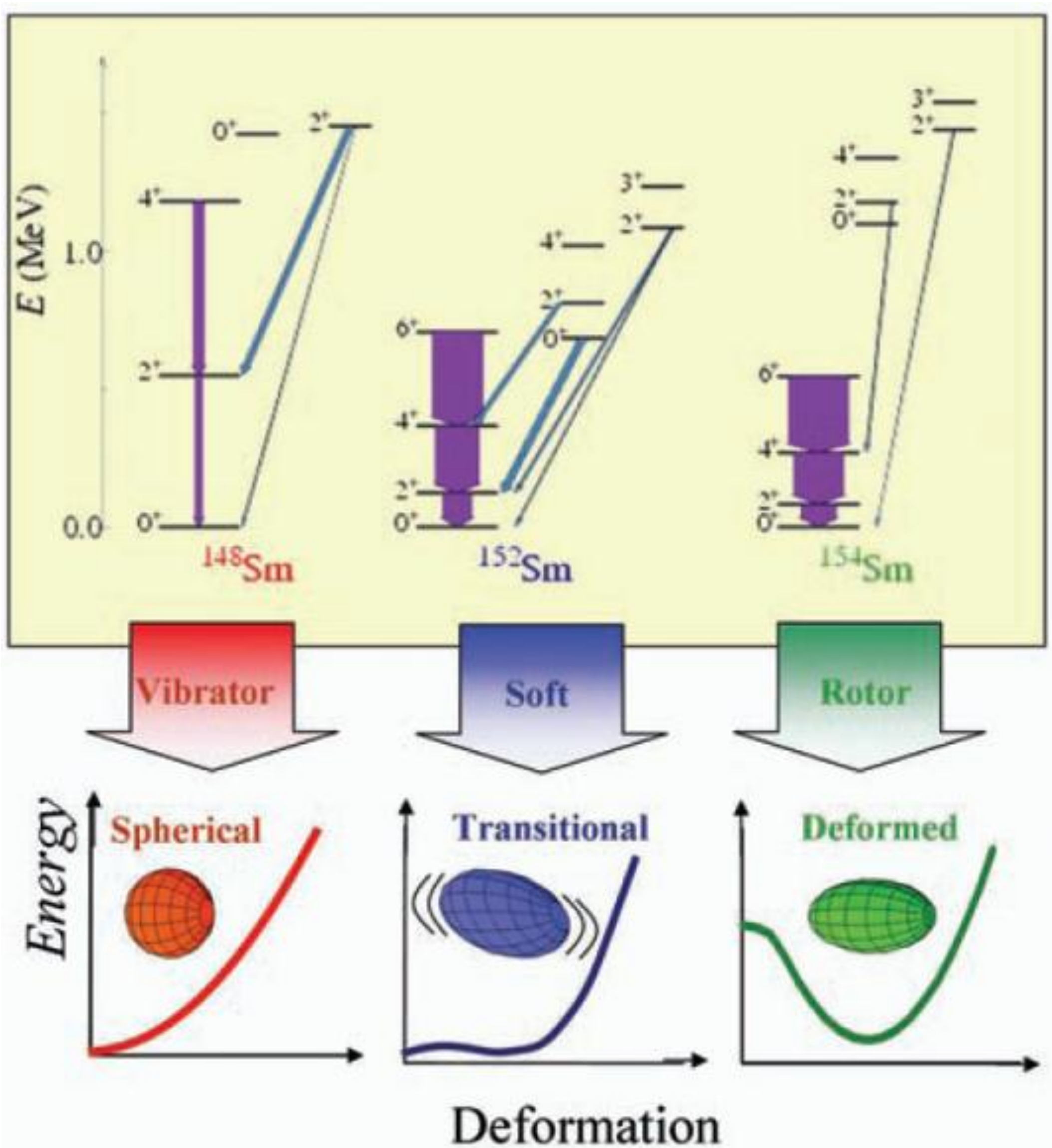
N/Z ≈ 3

Woods-Saxon potential (WS) ⟶ harmonic oscillator (HO)

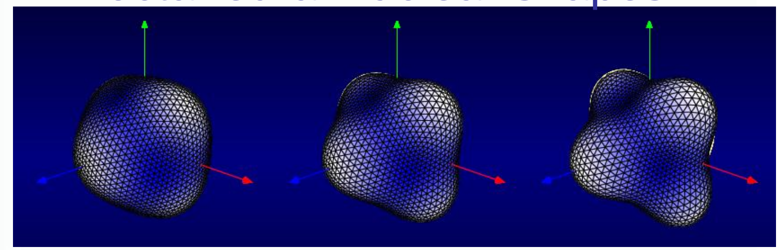
Nuclear density distribition

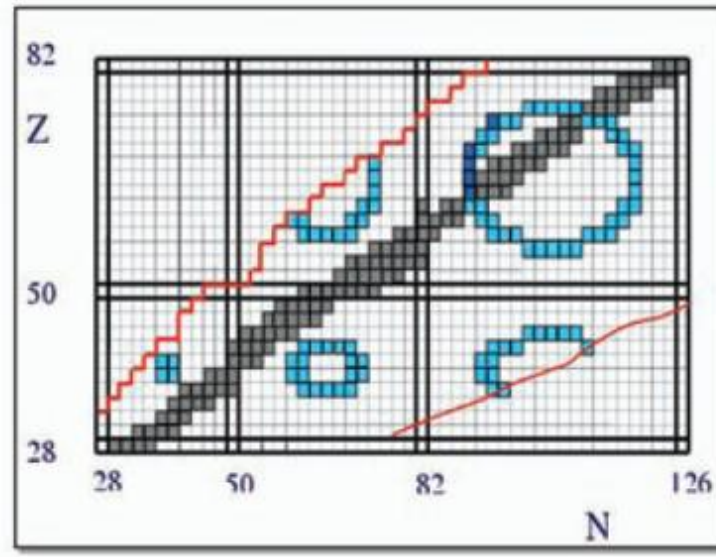


Nuclear shapes



octahedral nuclear shapes

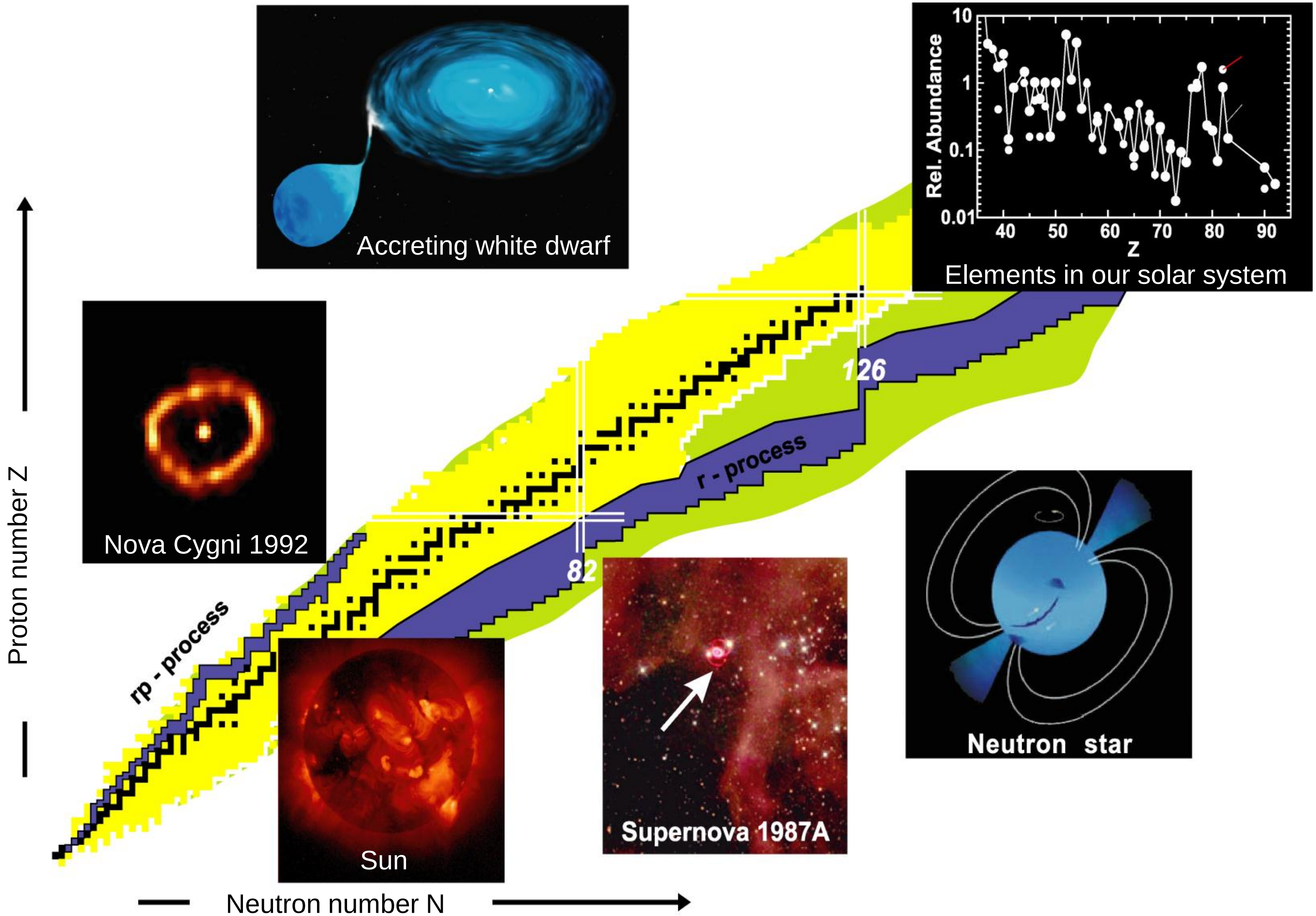




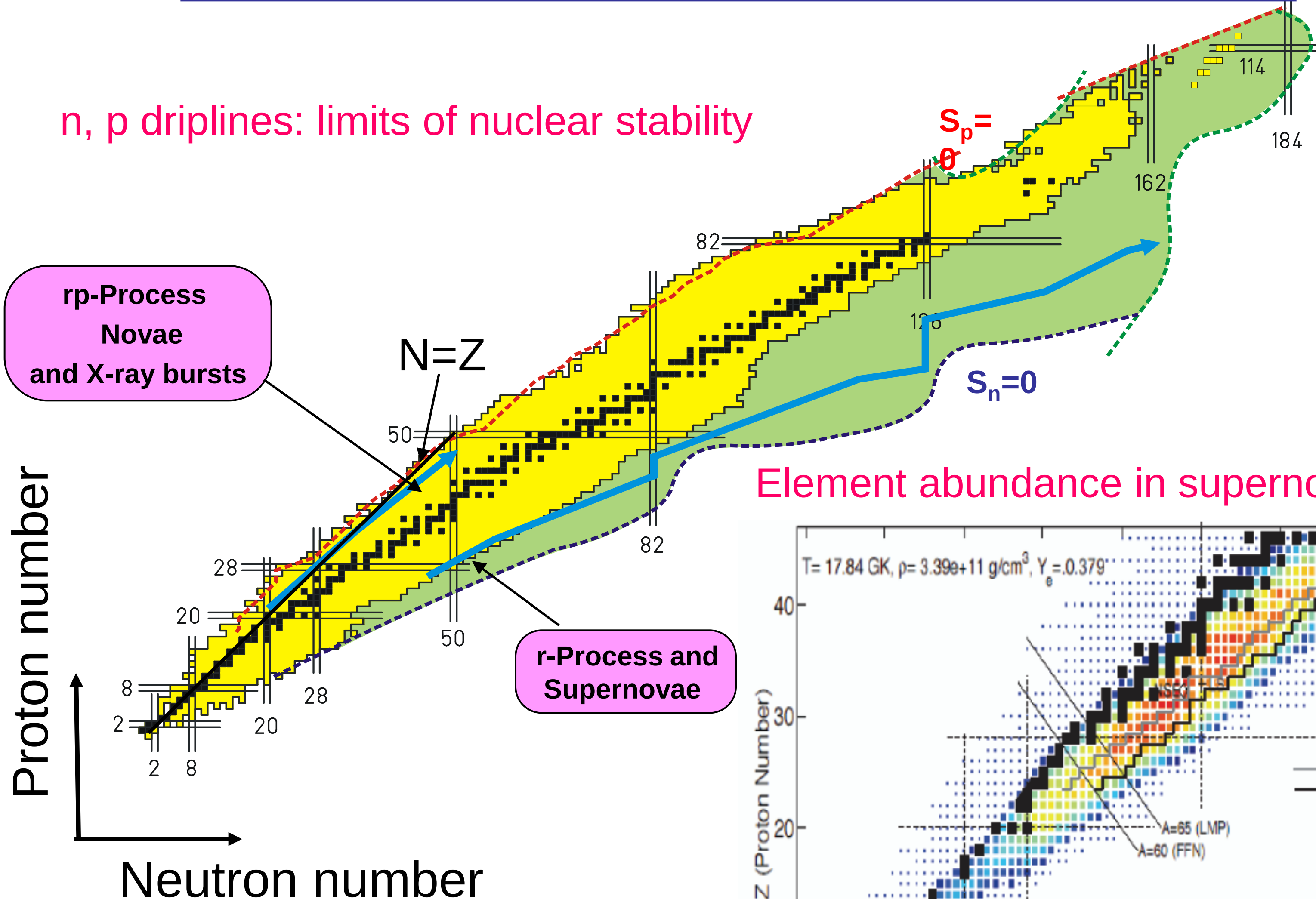
Phase transitions of the equilibrium shapes predicted for exotic nuclei

Nuclear Physics in the Universe

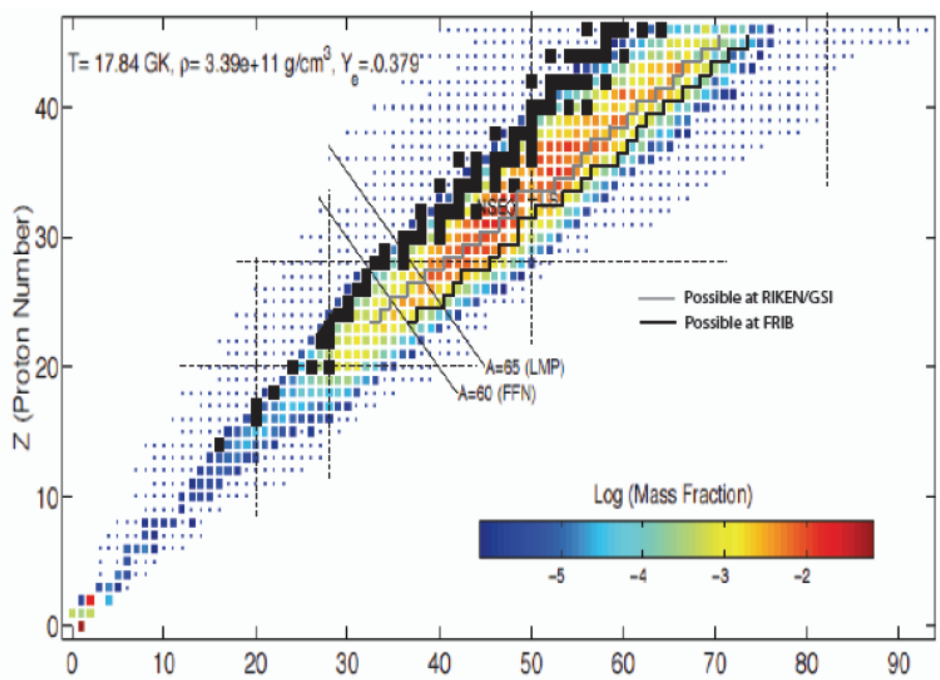
For the understanding of nucleosynthesis and stellar dynamics we need to know properties of many exotic nuclei.



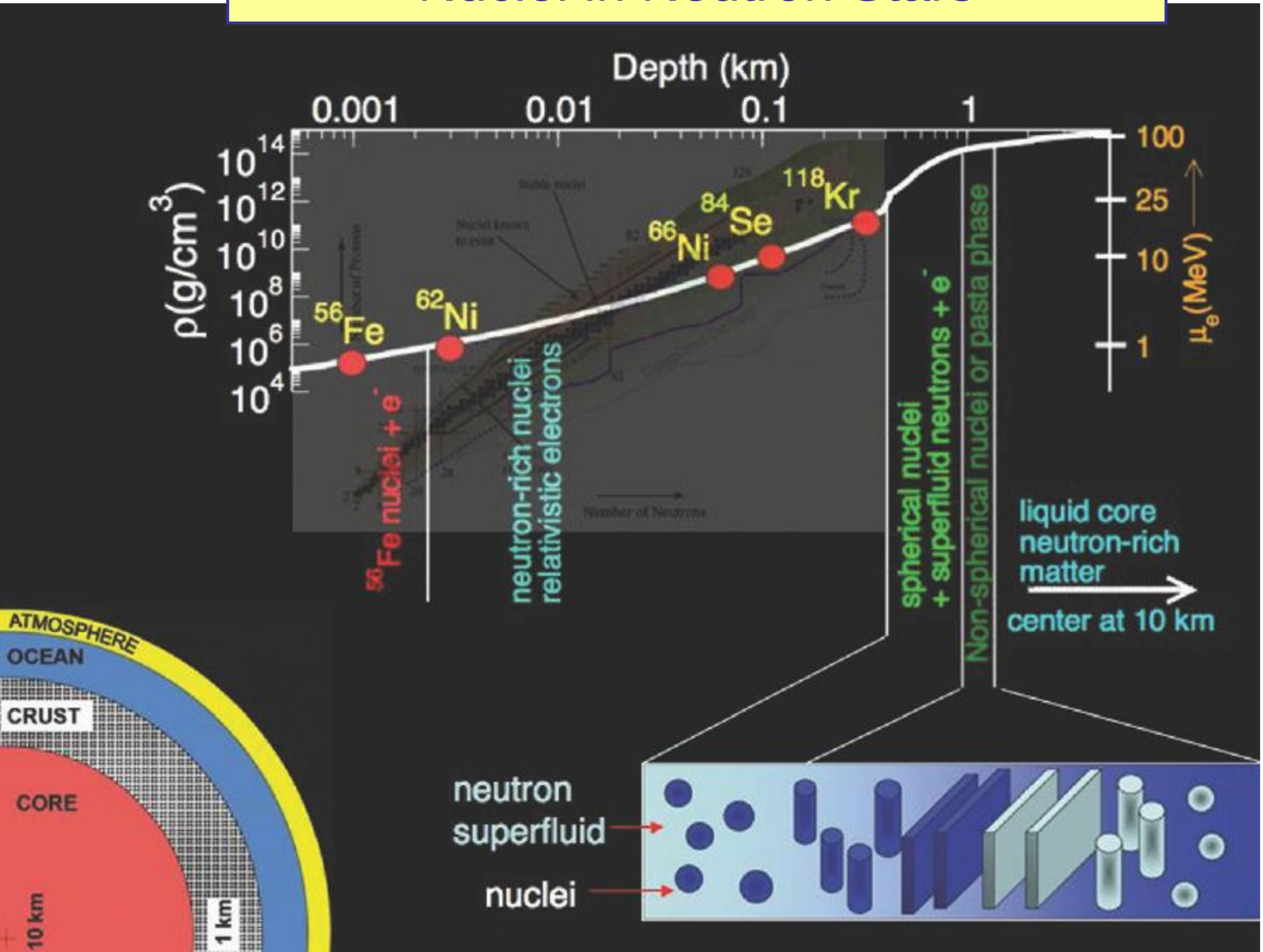
Formation of Elements



Element abundance in supernova collapse



Nuclei in Neutron Stars



NUclear STructure Astrophysics and Reactions

What are the limits for existence of nuclei?

Where are the proton and neutron drip lines situated?

Where does the nuclear chart end?

How does the nuclear force depend on varying proton-to-neutron ratios?

What is the isospin dependence of the spin-orbit force?

How does shell structure change far away from stability?

How to explain collective phenomena from individual motion?

What are the phases, relevant degrees of freedom, and symmetries of the nuclear many-body system?

How are complex nuclei built from their basic constituents?

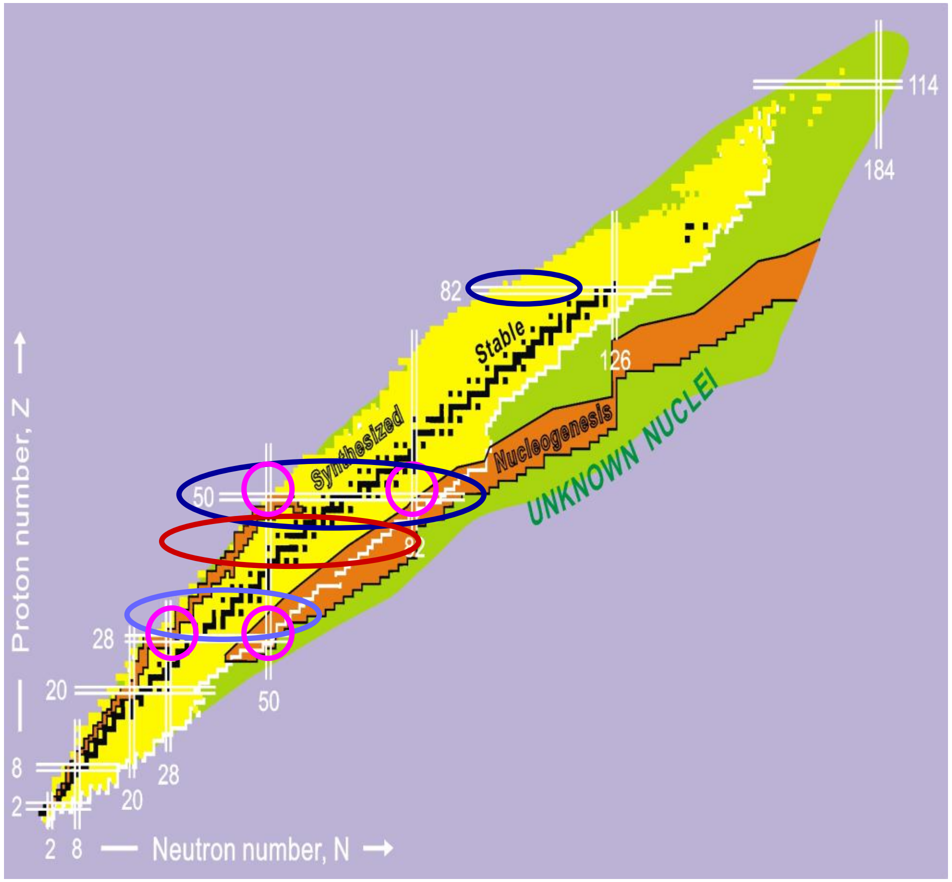
What is the effective nucleon-nucleon interaction?

How does QCD constrain its parameters?

Which are the nuclei relevant for astrophysical processes and what are their properties?

What is the origin of the heavy elements?

Nuclear spectroscopy at GSI



Decay studies using
Rare Isotope Beams and
high-resolution γ Spectroscopy

Nuclear Shell structure :

- N = Z : ^{56}Ni and ^{100}Sn
- N>>Z : ^{78}Ni, ^{132}Sn

Nuclear shapes :

- Quadrupole, Octupole, Triaxiality
- High K-isomers

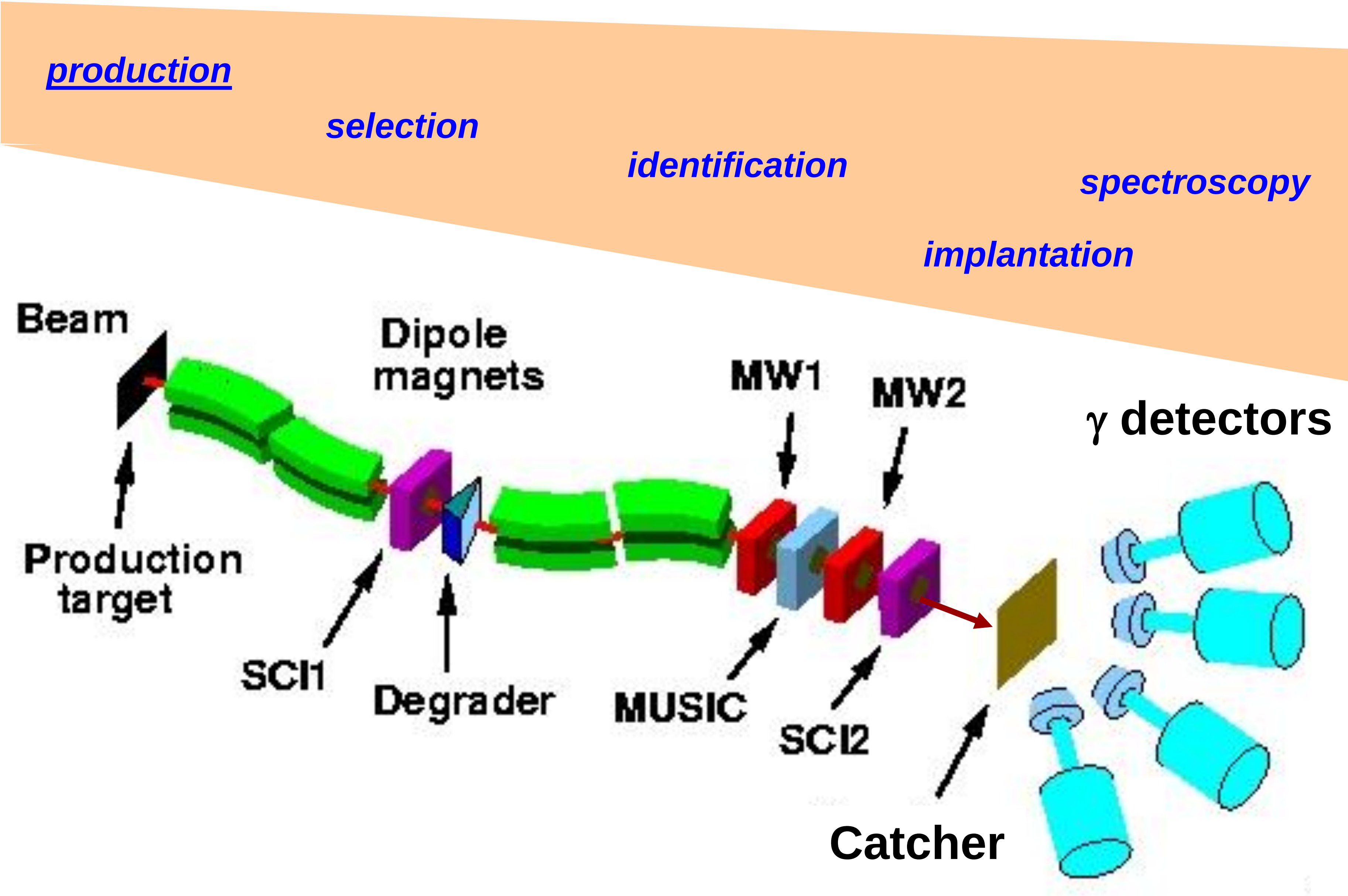
Collective modes:

- N>>Z : GDR soft mode

Nuclear Symmetries :

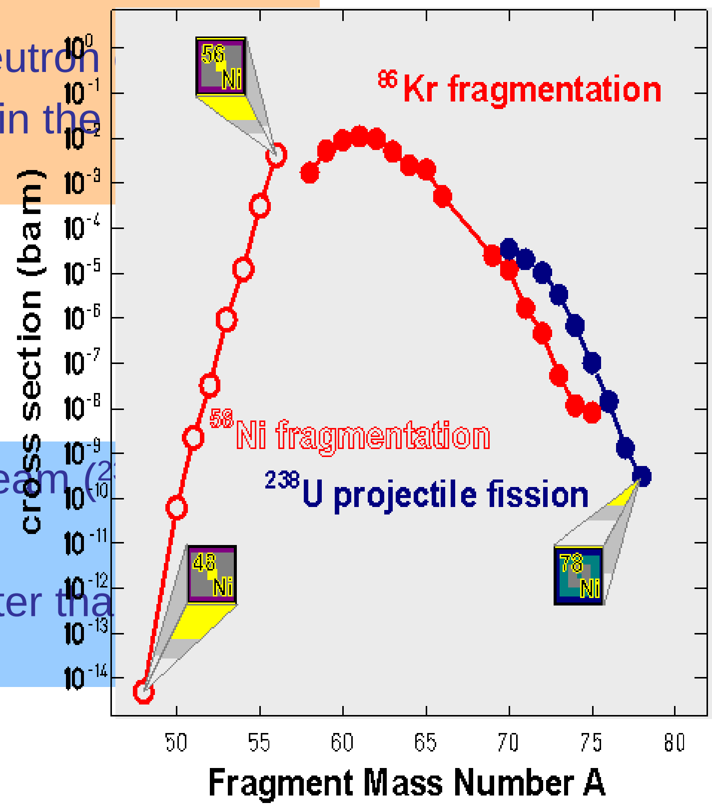
- mirror-isospin, pn-pair correlation

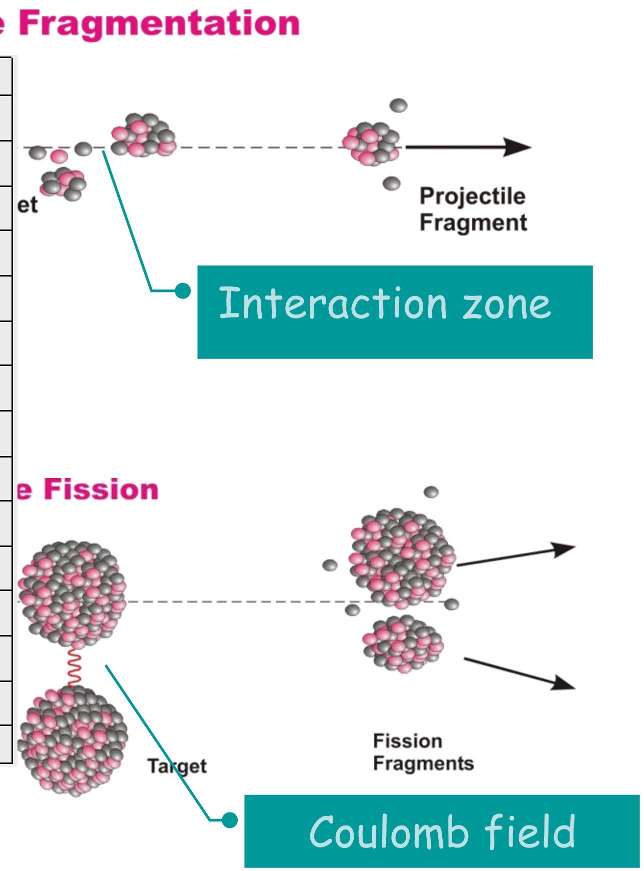
Decay Spectroscopy: Production



Projectile fragmentation or fission in radioactive isotopes production ?

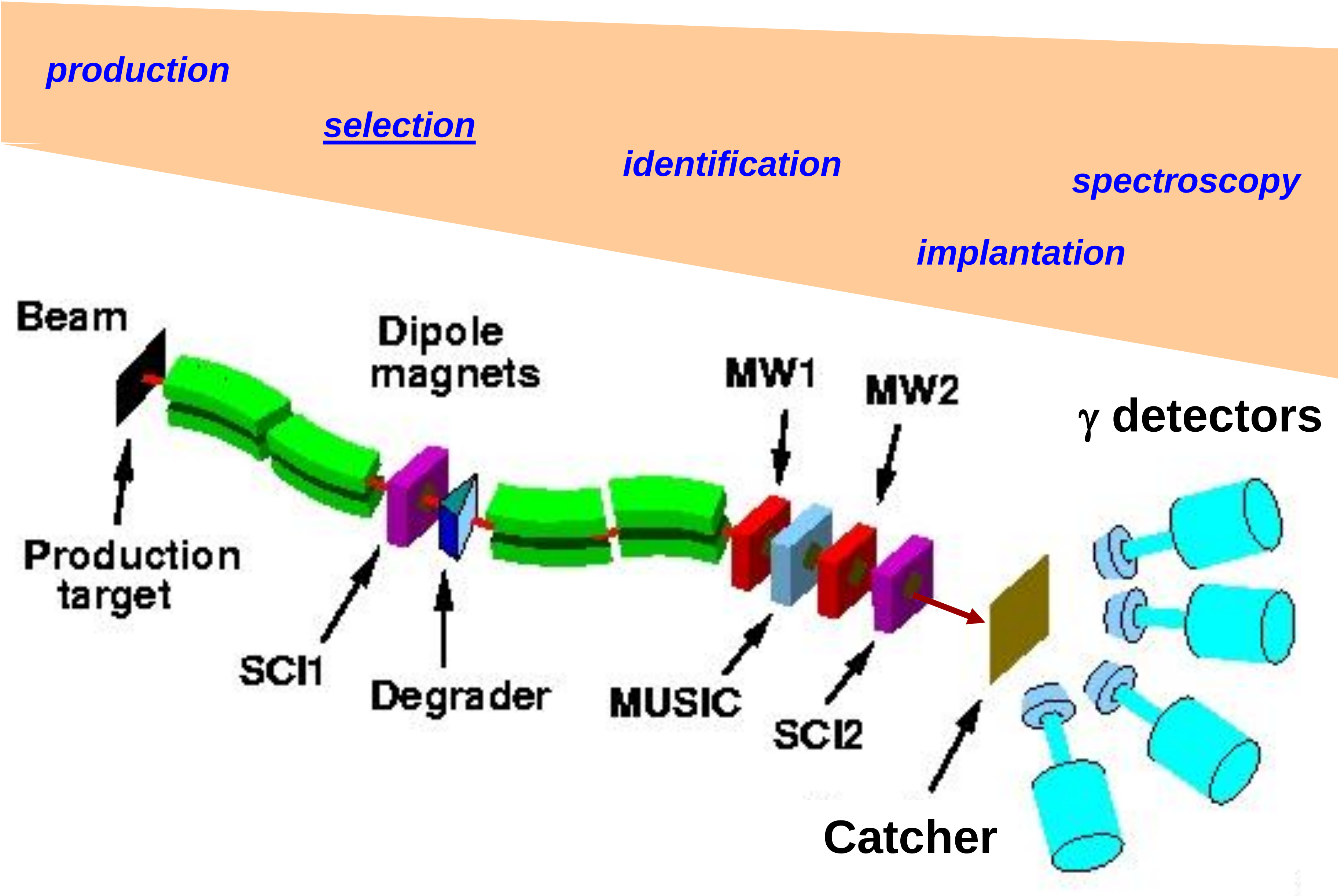
- ^{9}Be target
- exotic nuclei (also neutron
- fragments nearly retain the direction and velocity



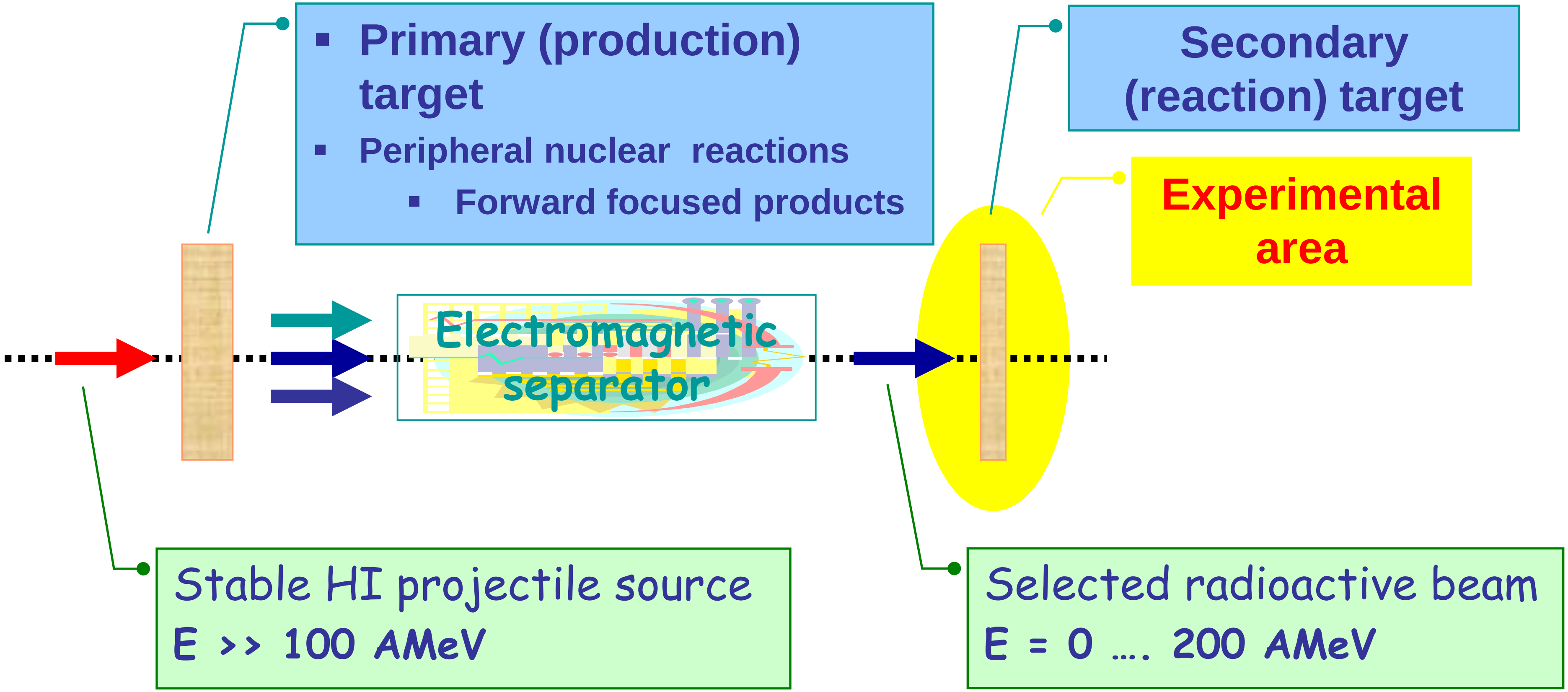


- ^{208}Pb target, heavy beam (2
- neutron rich nuclei
- fragments can be faster tha projectile

Decay Spectroscopy: Selection



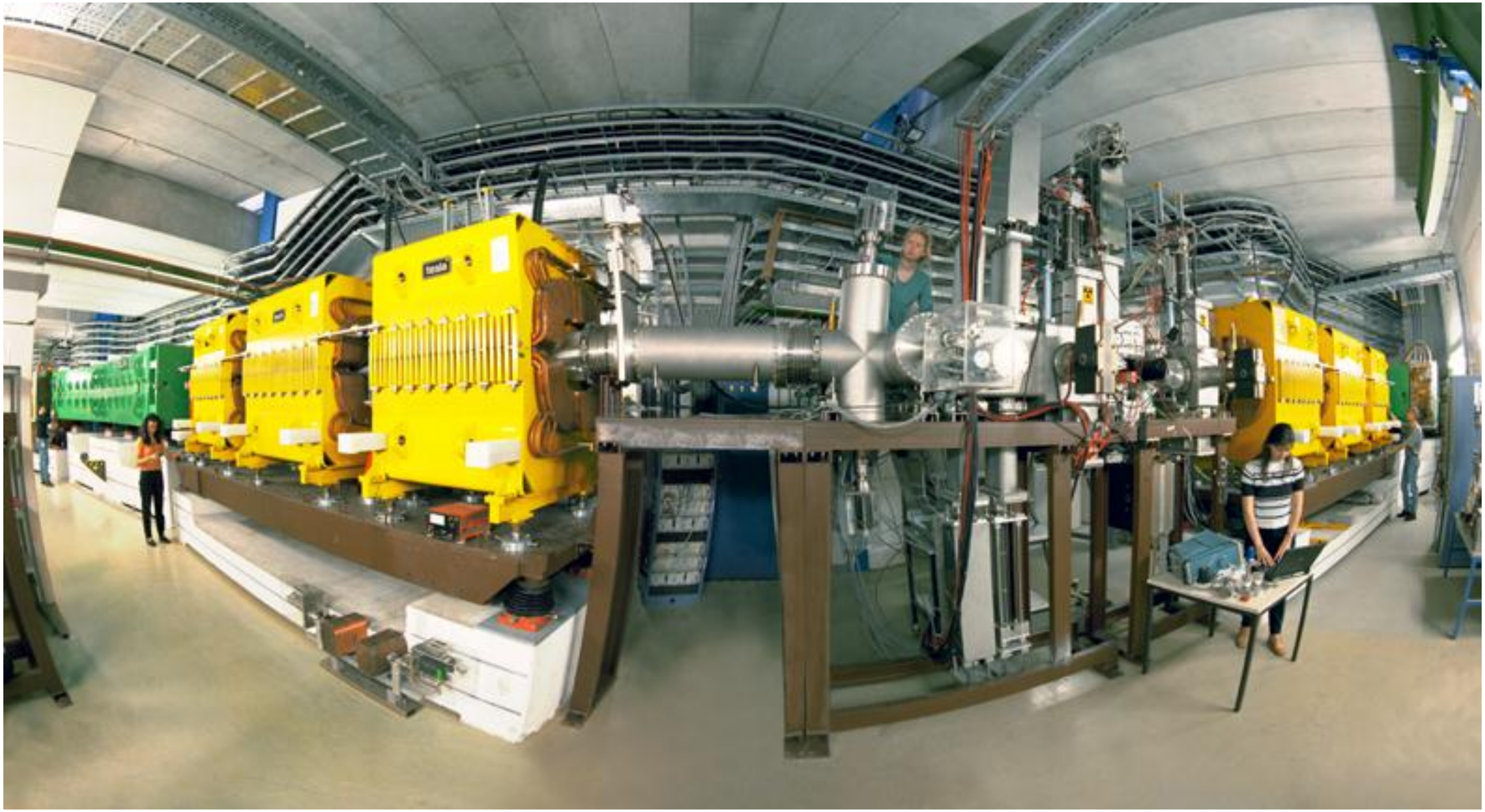
In-flight separation of Rare Isotope Beams



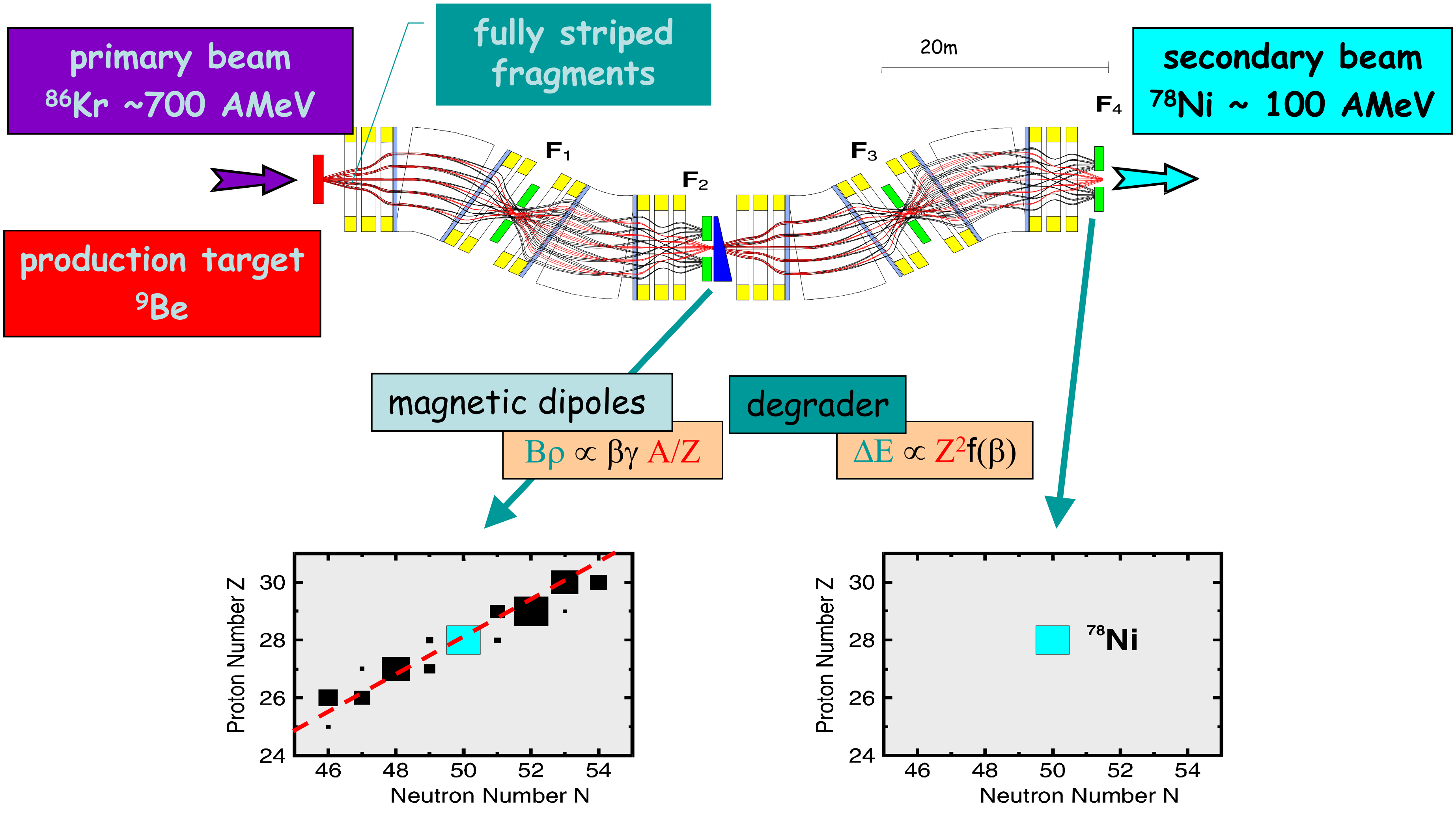
Advantages of In-flight Separation using Projectile Fragmentation and - Fission

High luminosity	Secondary reactions in thick targets ~ g/cm^2
In-flight separation	**Short half-lives** (Lower time limitation by ToF , 200 ns) **High selectivity and sensitivity** Single-atom spectroscopy **Universal separation** Mono-isotopic beams of all elements Cocktail beams optional
Kinematic focusing	**Experiments with high-energy stored nuclei** Effective injection into storage rings Full solid angle coverage, complete kinematics
Favorable Reaction Mechanism	Sudden appoximation, Glauber model

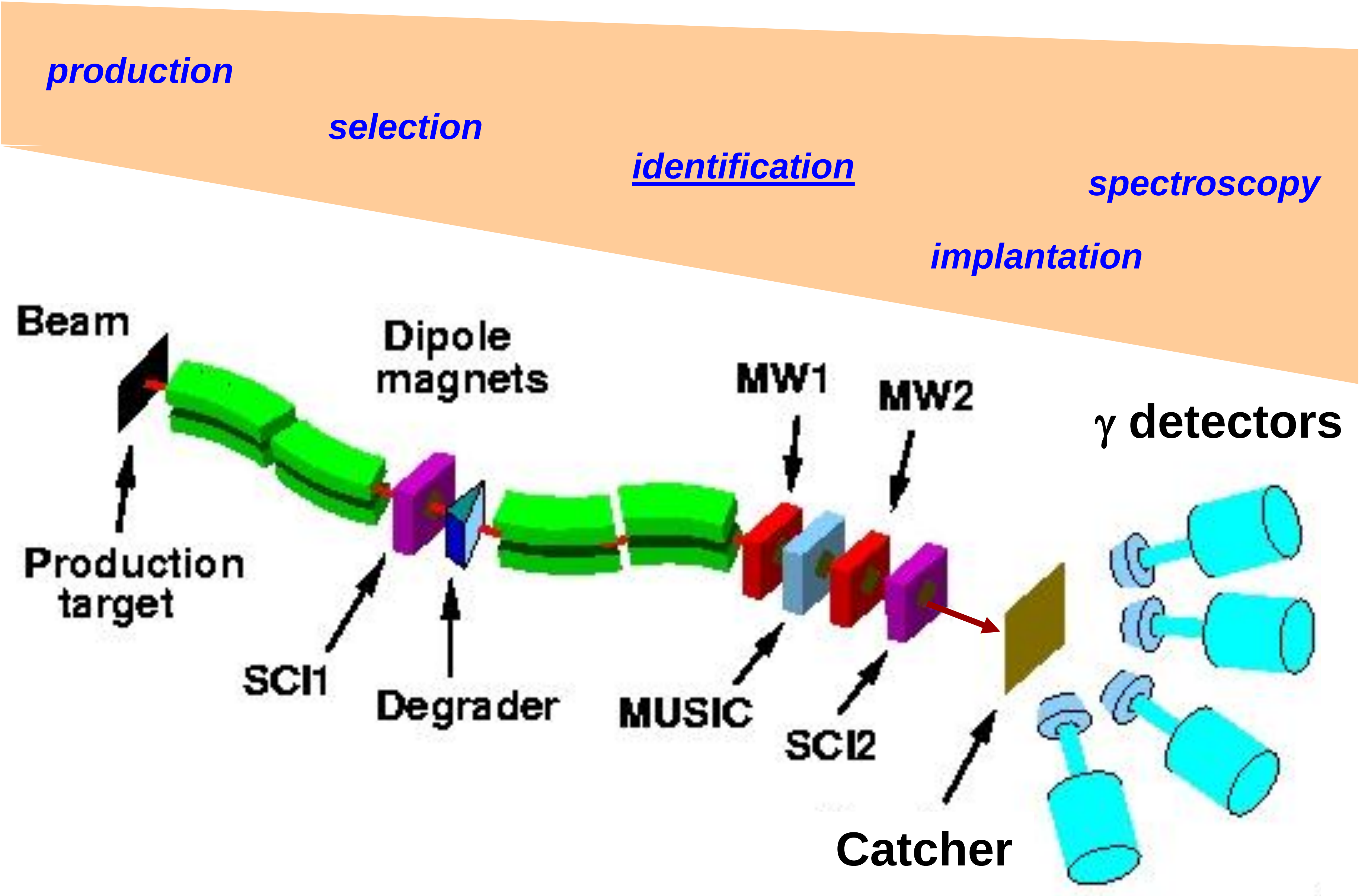
The fragment separator FRS



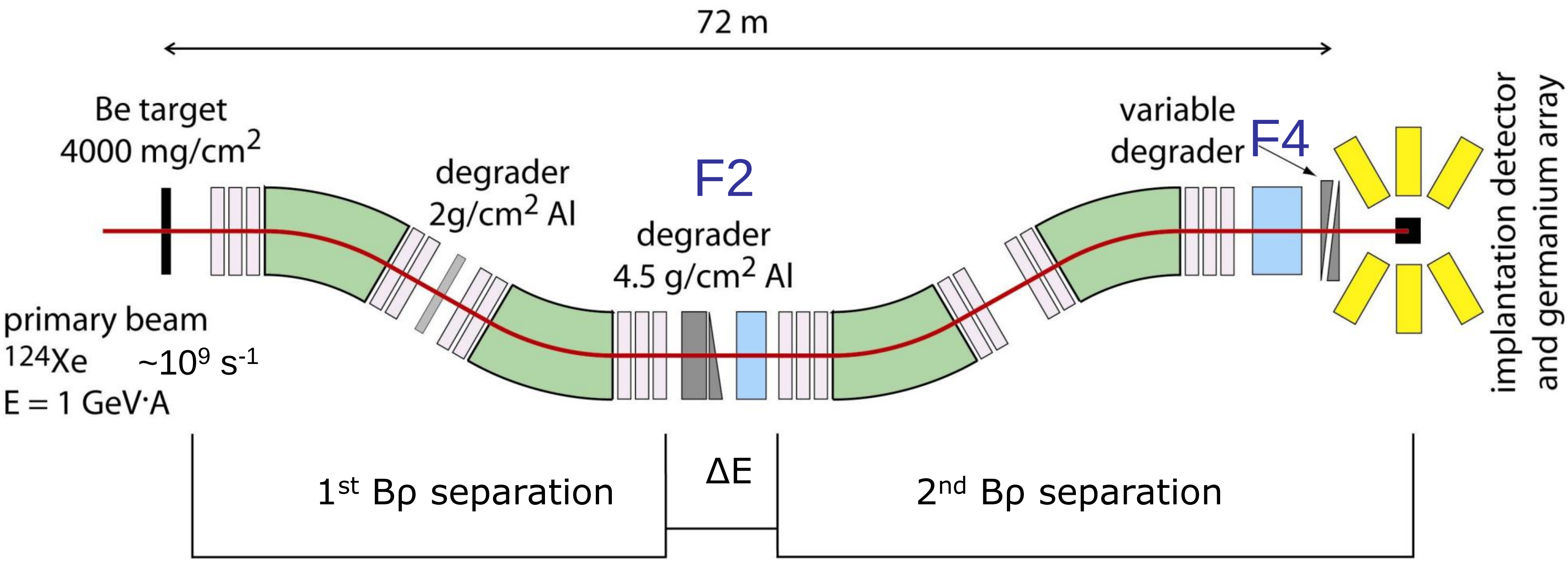
Radioactive isotope selection at FRS
(Bρ–ΔE–Bρ technique)



Decay Spectroscopy: Identification



FRS Identification



identification F2-F4:

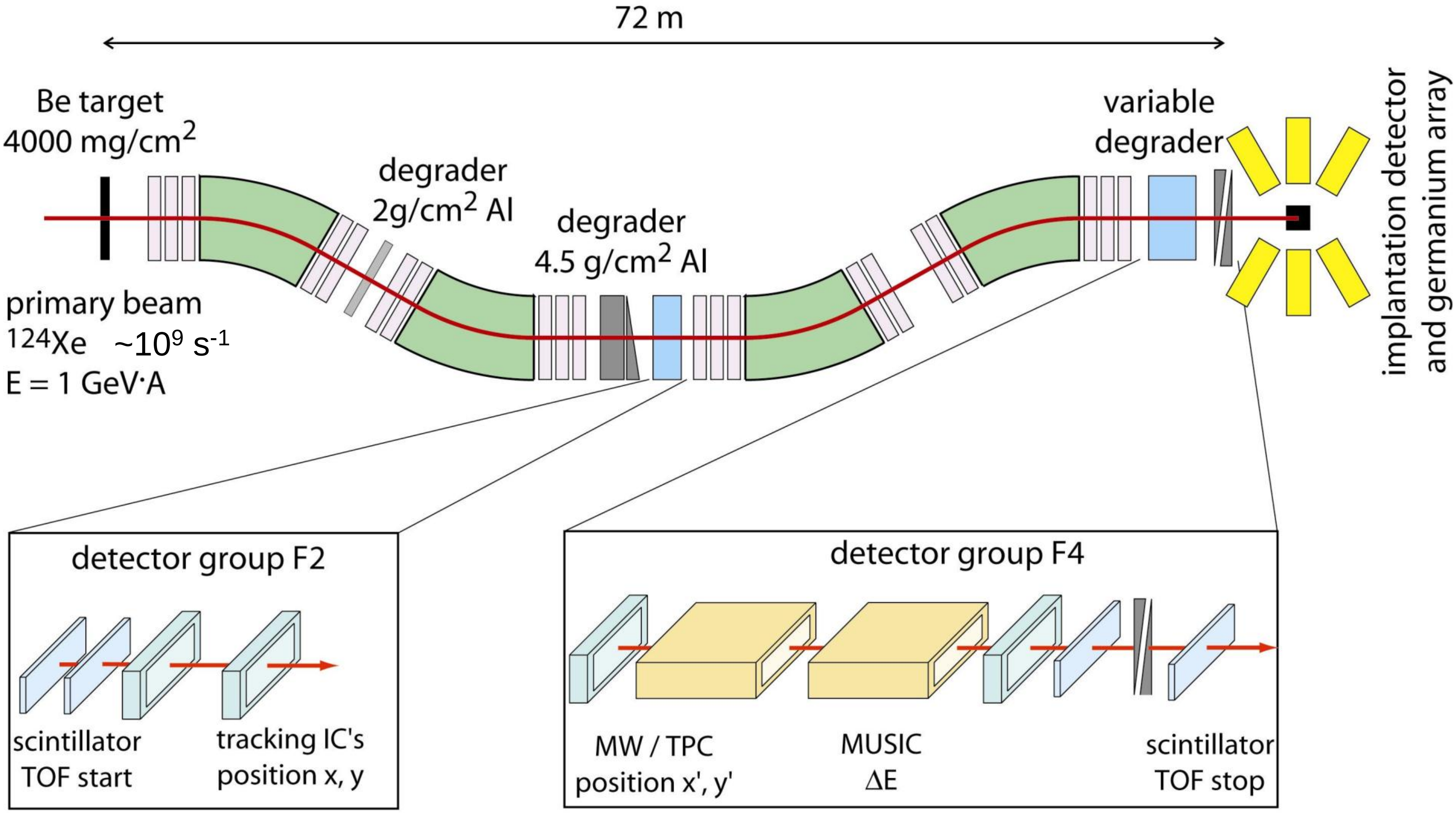
$\Delta E \Rightarrow Z$

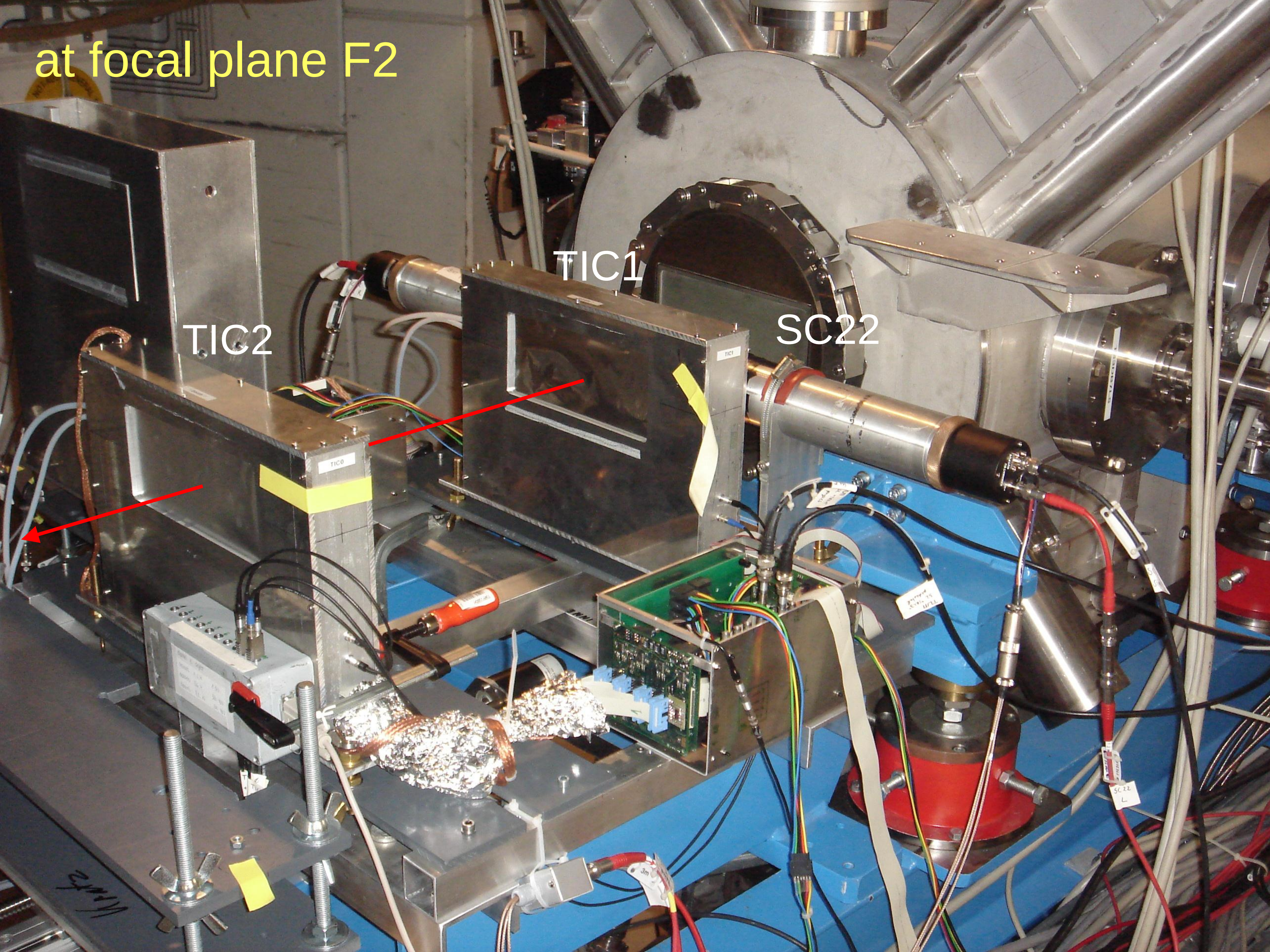
$B\rho(x, x', \alpha') = \beta \gamma A/q \, m_0 c$

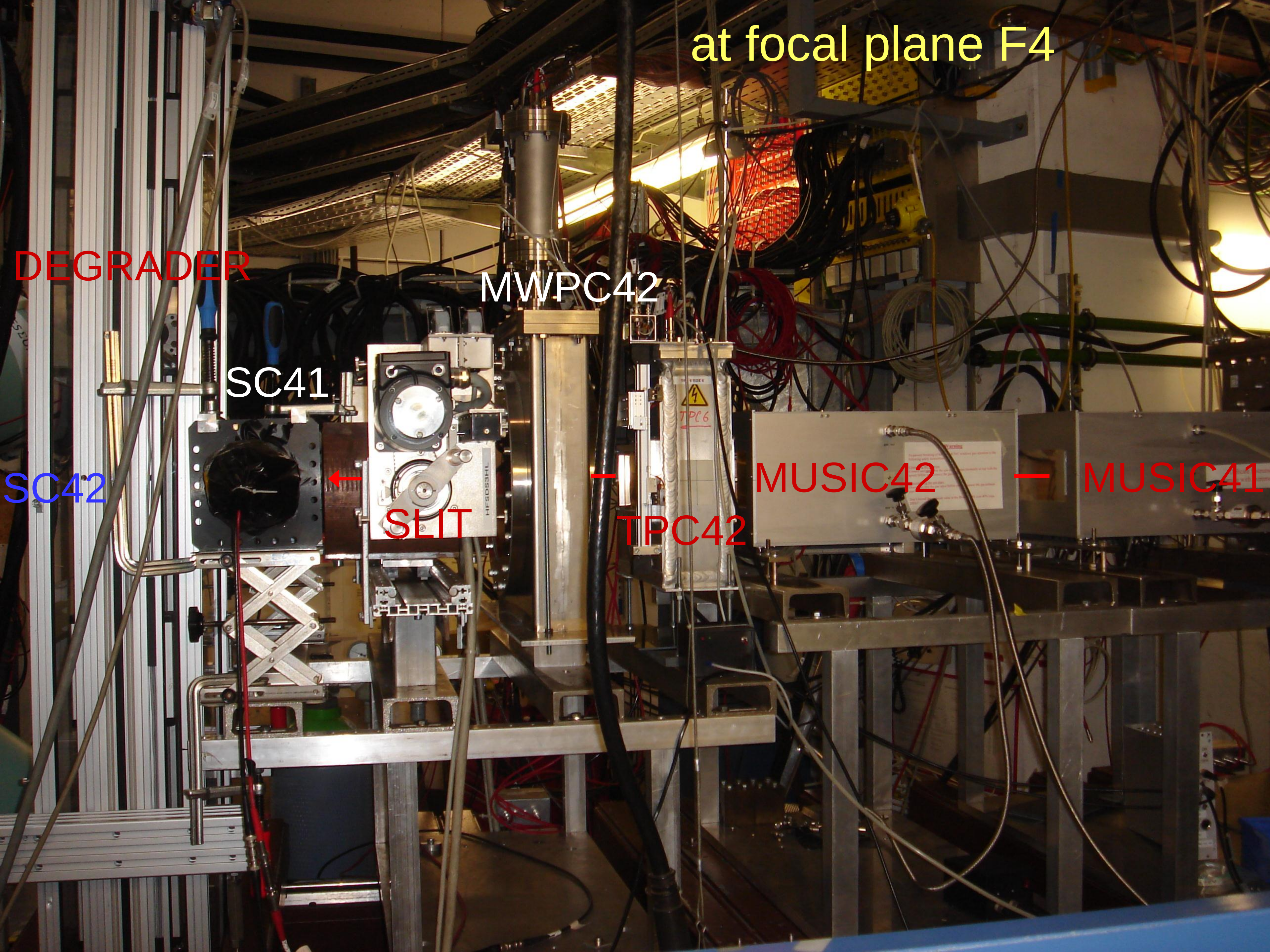
$q = Z$

$TOF \Rightarrow \beta$

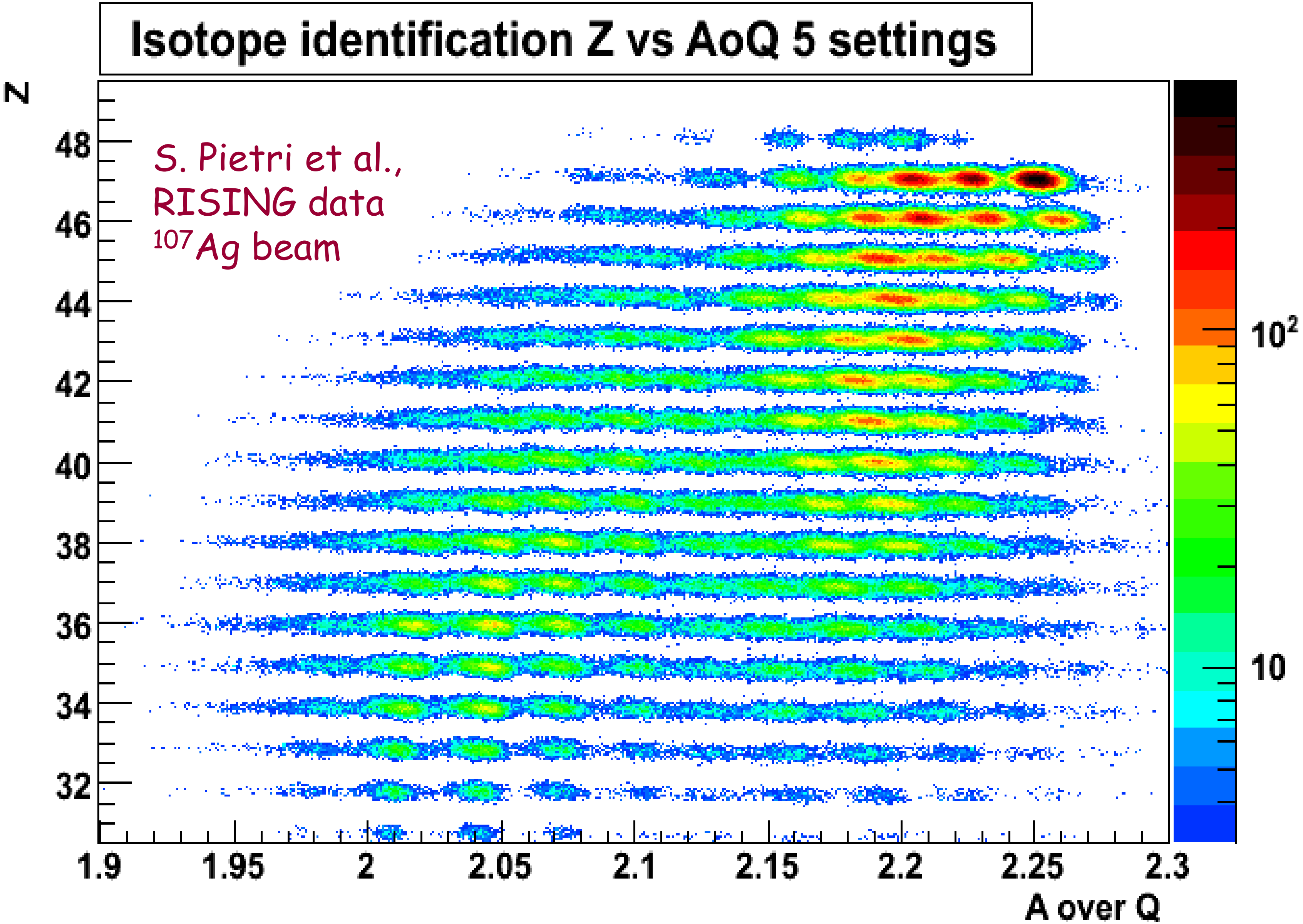
FRS Identification



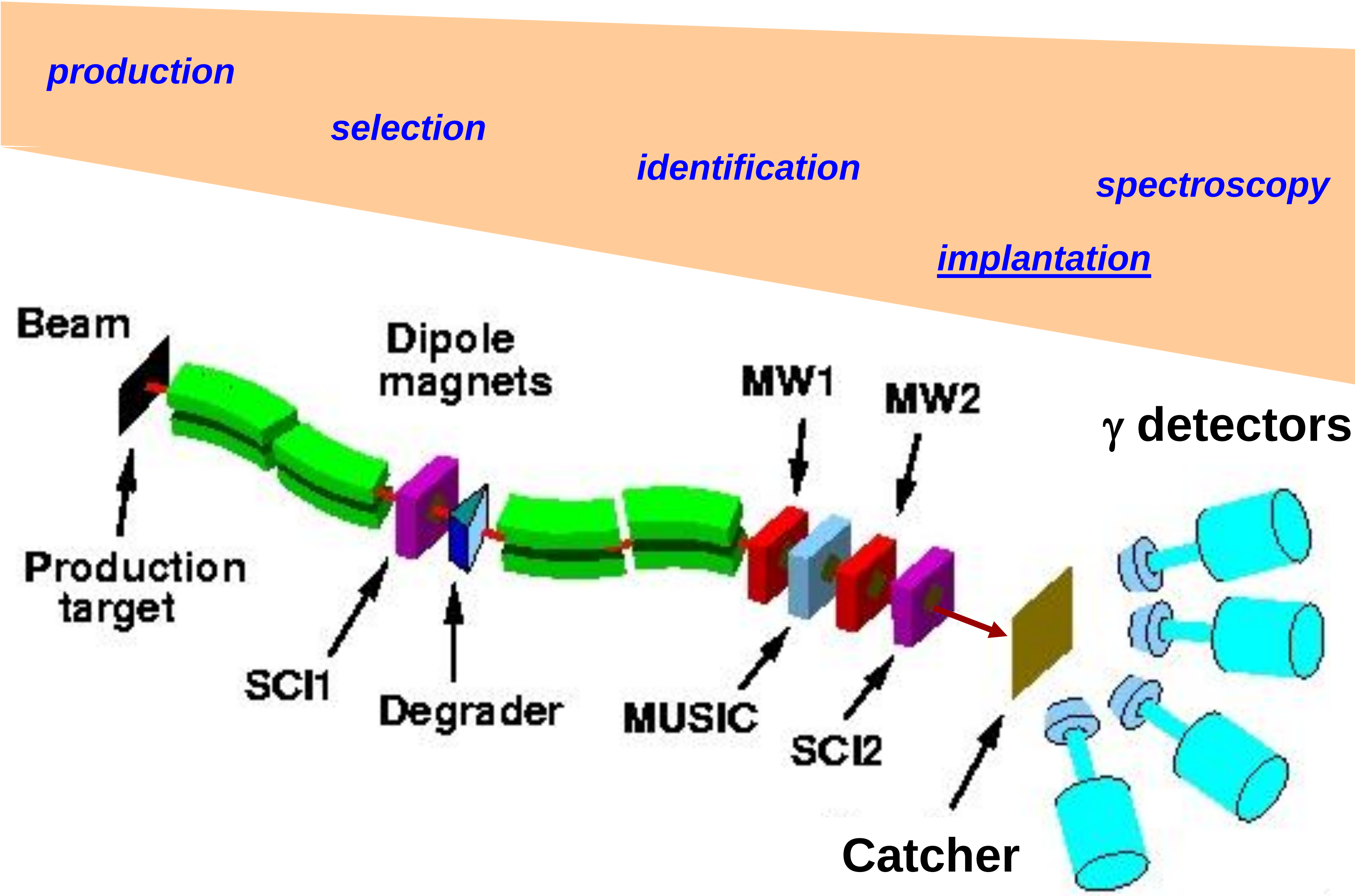

at focal plane F2
TIC1
TIC2
SC22


at focal plane F4
DEGRADER
MWPC42
SC41
SC42
SLIT
TPC42
MUSIC42
MUSIC41

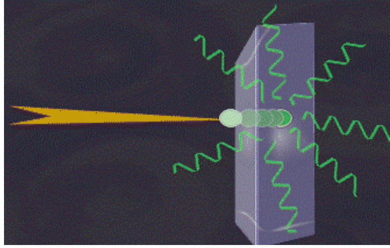
Isotope identification

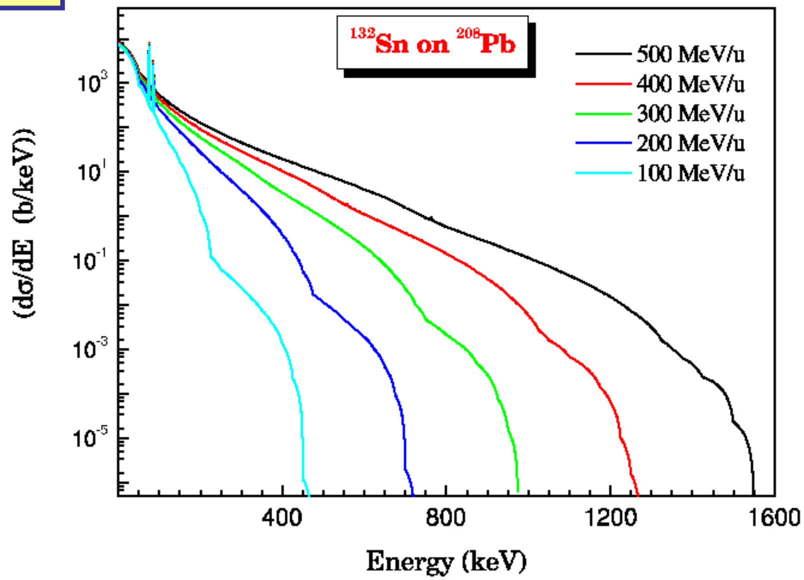


Decay Spectroscopy: Implantation

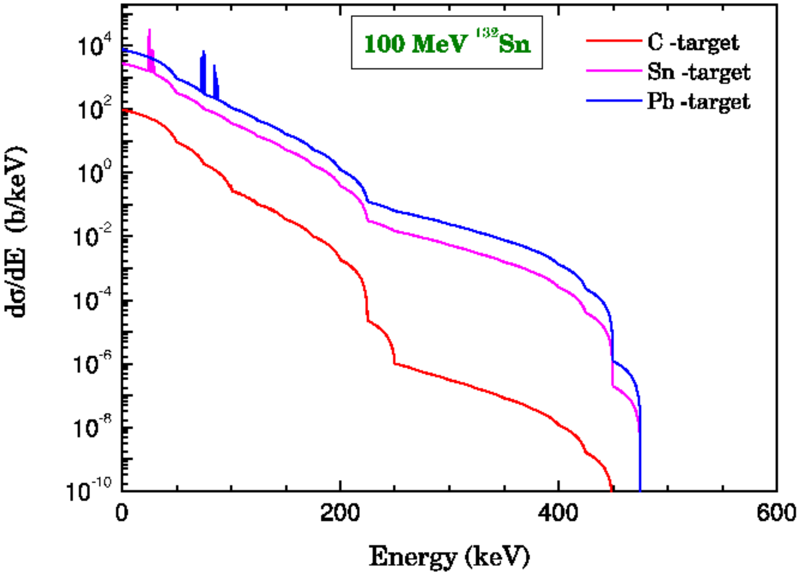


Atomic Background Radiation Bremsstrahlung



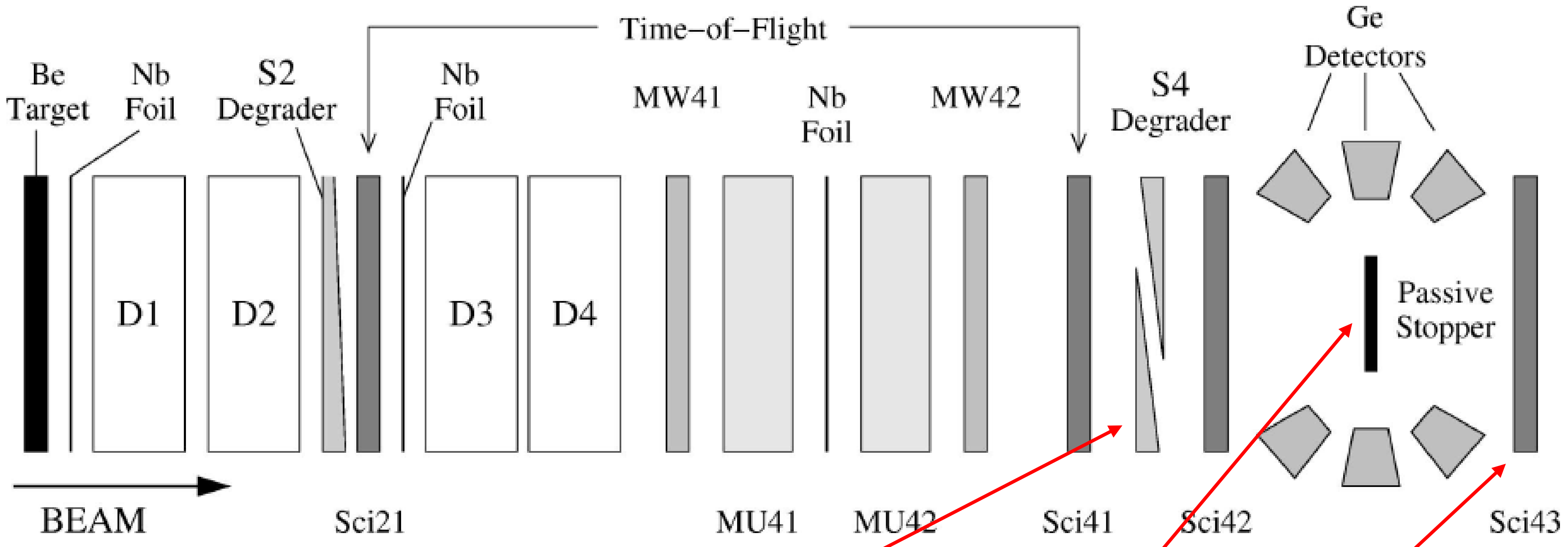


- **Radiative electron capture (REC)**
  capture of target electrons into bound states of the projectile:
  $$\sigma \sim Z_p^2 \cdot Z_t$$
- **Primary Bremsstrahlung (PB)**
  capture of target electrons into continuum states of the projectile:
  $$\sigma \sim Z_p^2 \cdot Z_t$$
- **Secondary Bremsstrahlung (SB)**
  Stopping of high energy electrons in the target: $\sigma \sim Z_p^2 \cdot Z_t^2$



→ **Low Z catcher**
High granularity γ detector

Passive Stopper

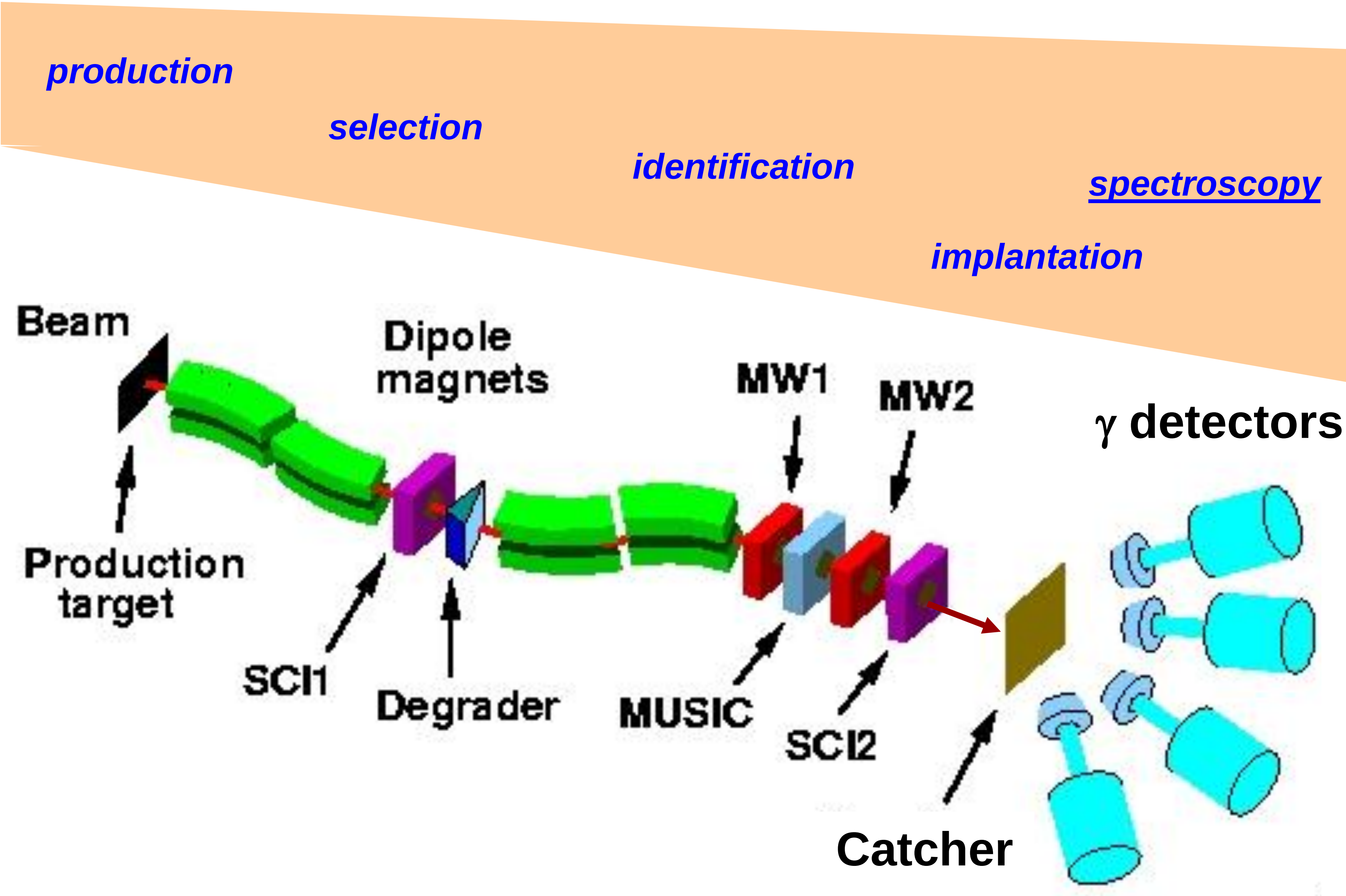


Beam particle energy reduction

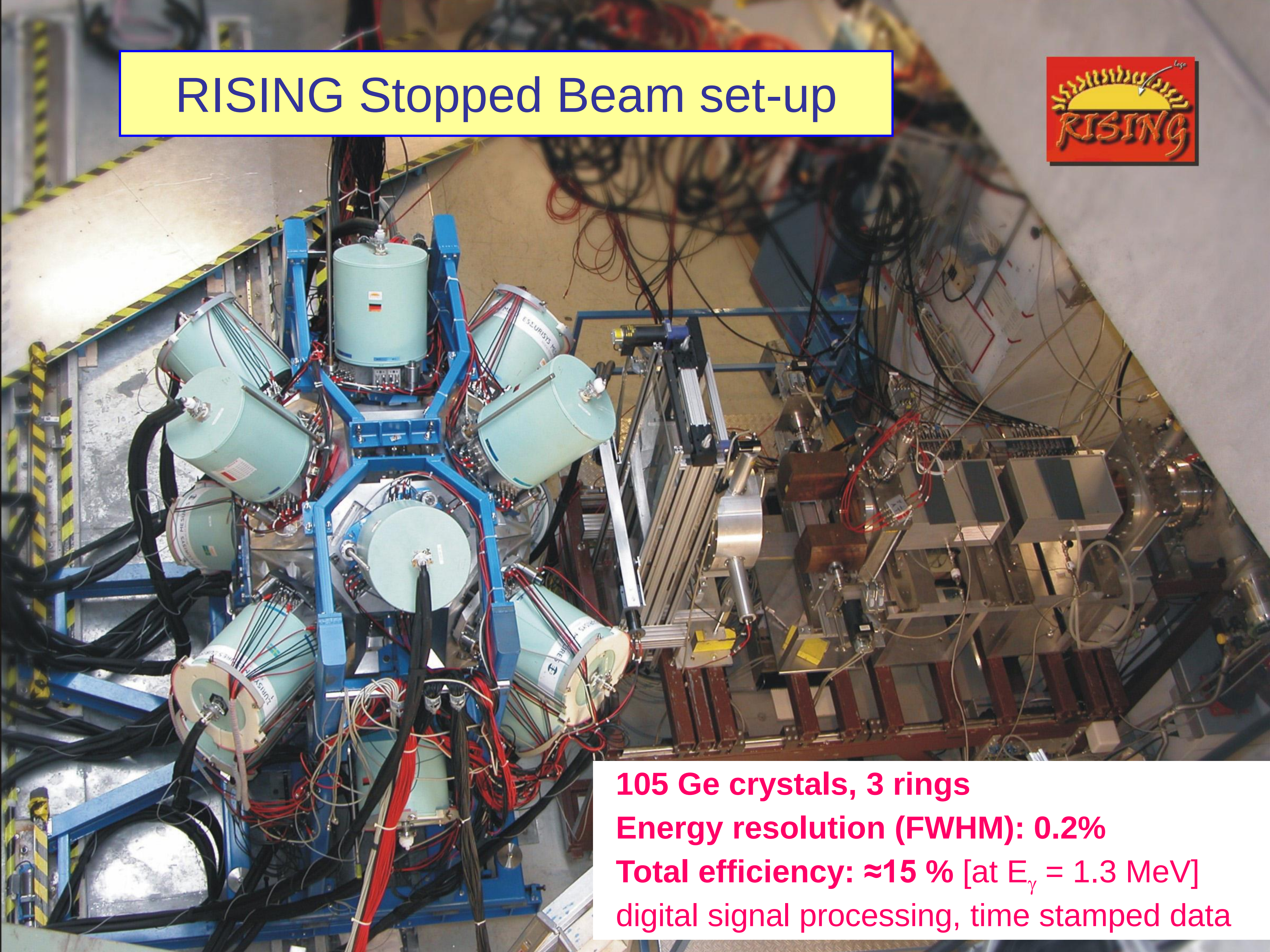
5 mm plastic or 2 mm aluminum catcher

Veto detector for secondary reactions

Decay Spectroscopy: γ detection

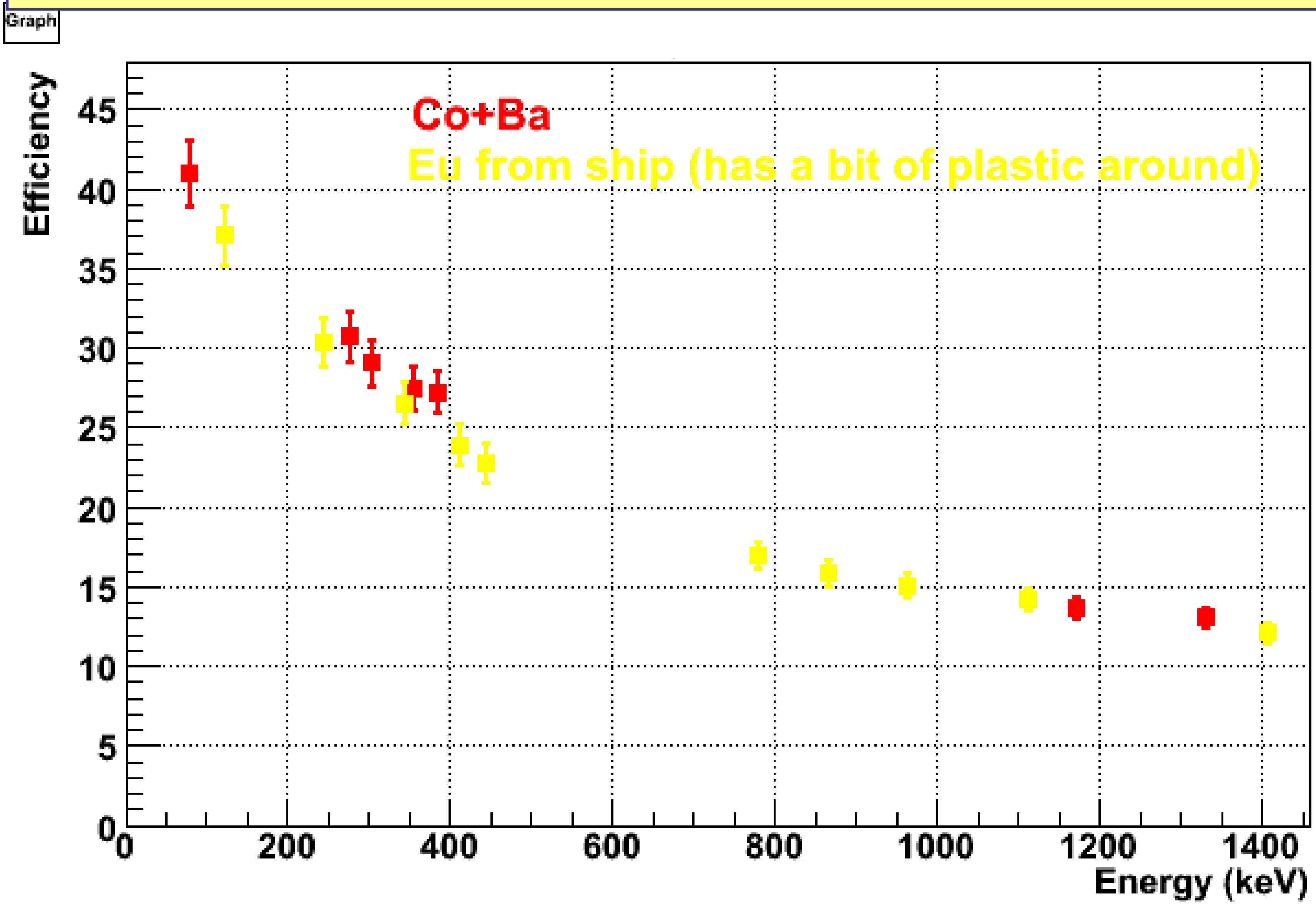


RISING Stopped Beam set-up

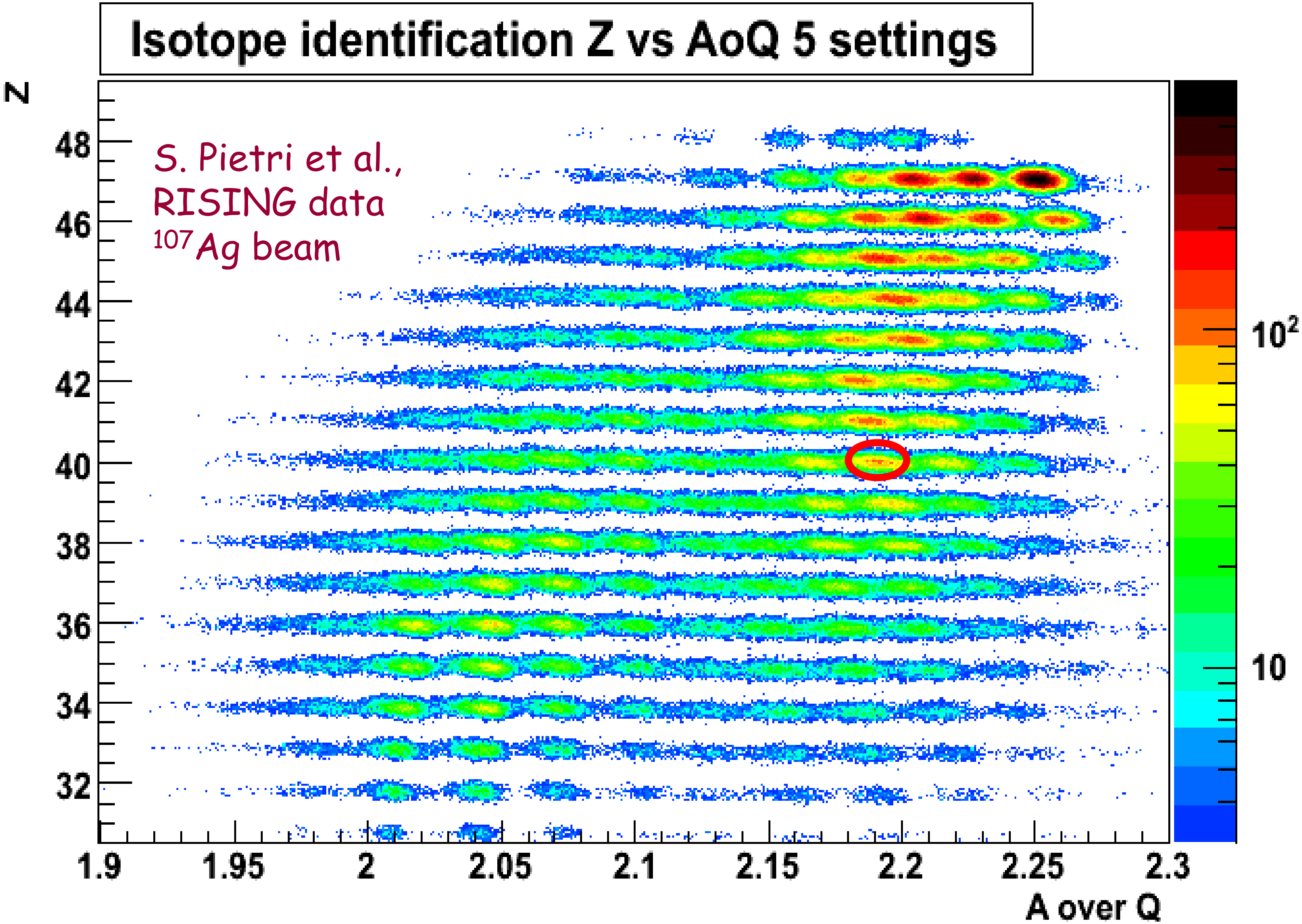


105 Ge crystals, 3 rings
Energy resolution (FWHM): 0.2%
Total efficiency: ≈15 % [at E_γ = 1.3 MeV]
digital signal processing, time stamped data

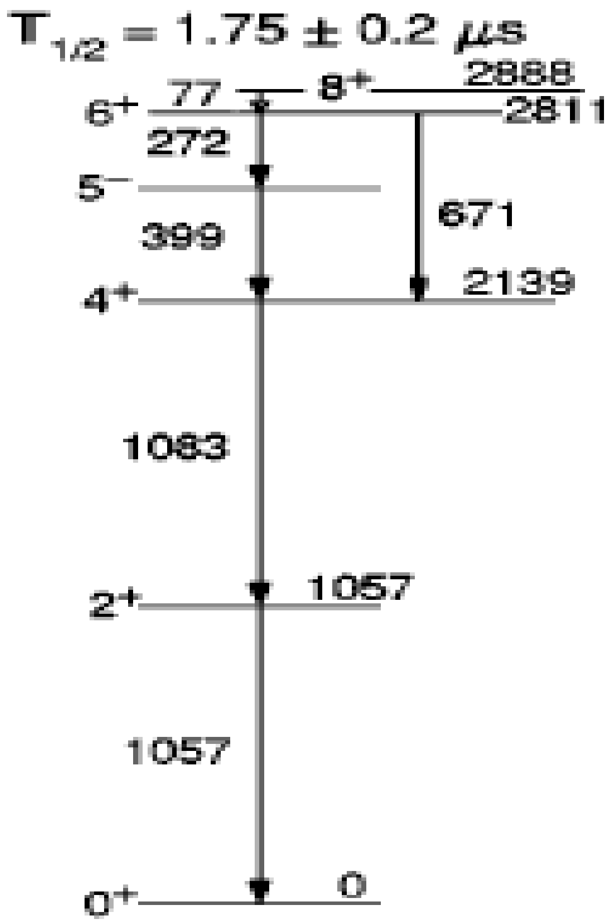
RISING full energy gamma Efficiency



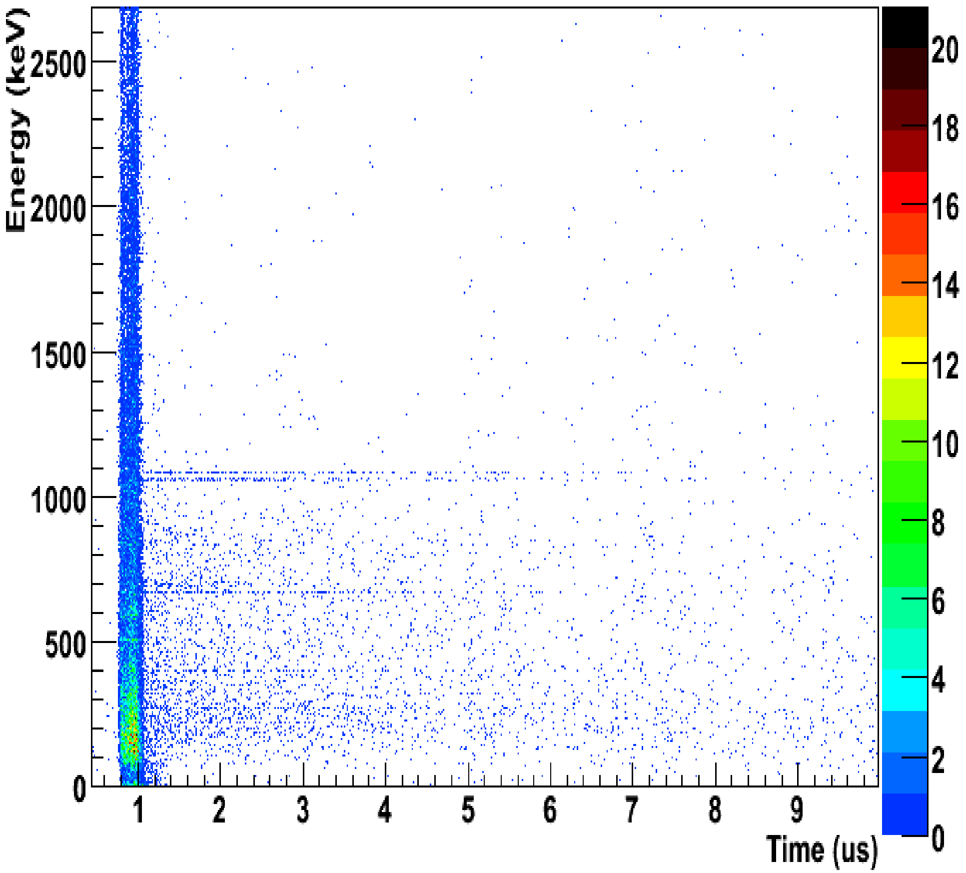
Isotope selection: ^{88}Zr



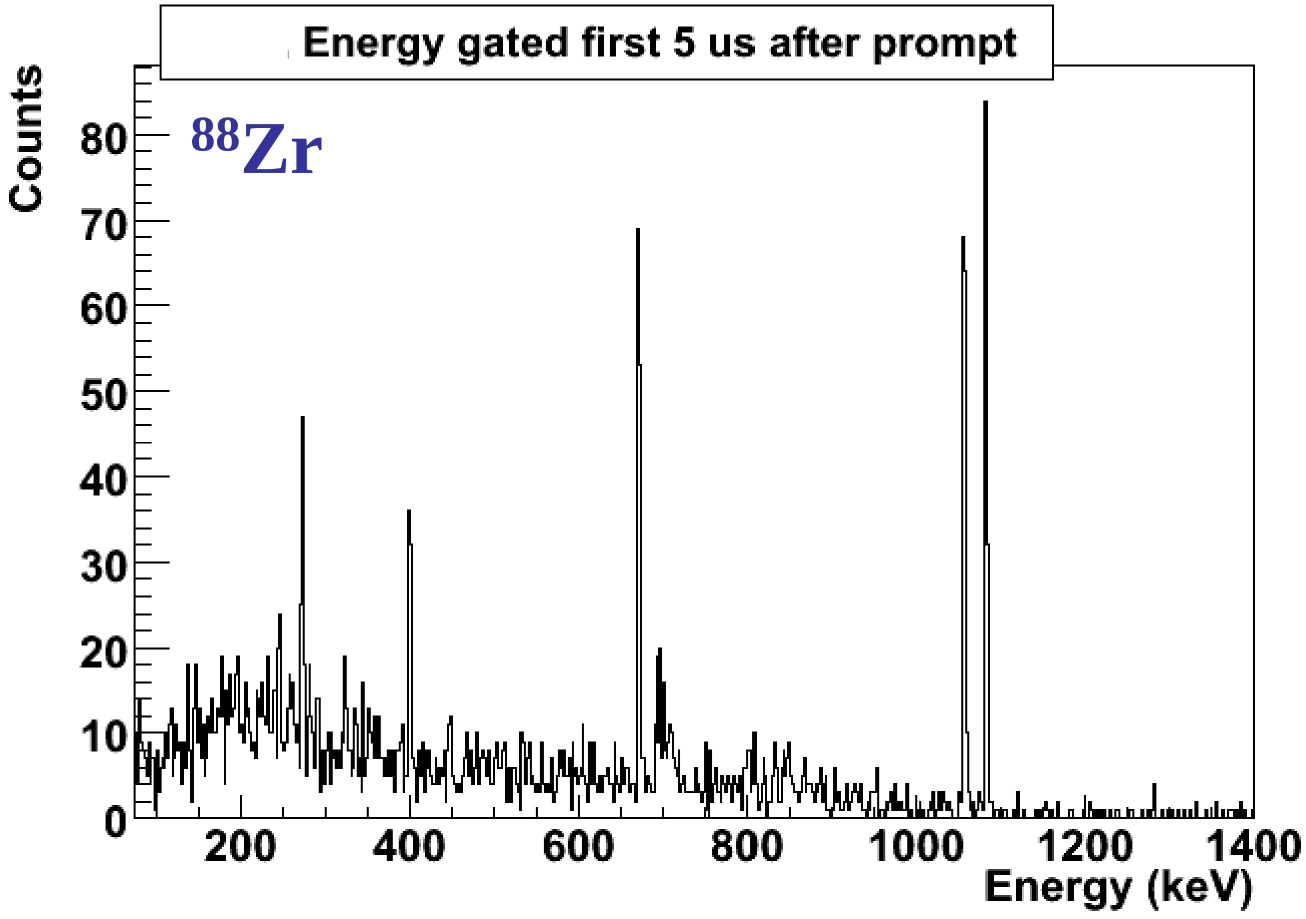
^{88}Zr E_γ - t_γ correlation



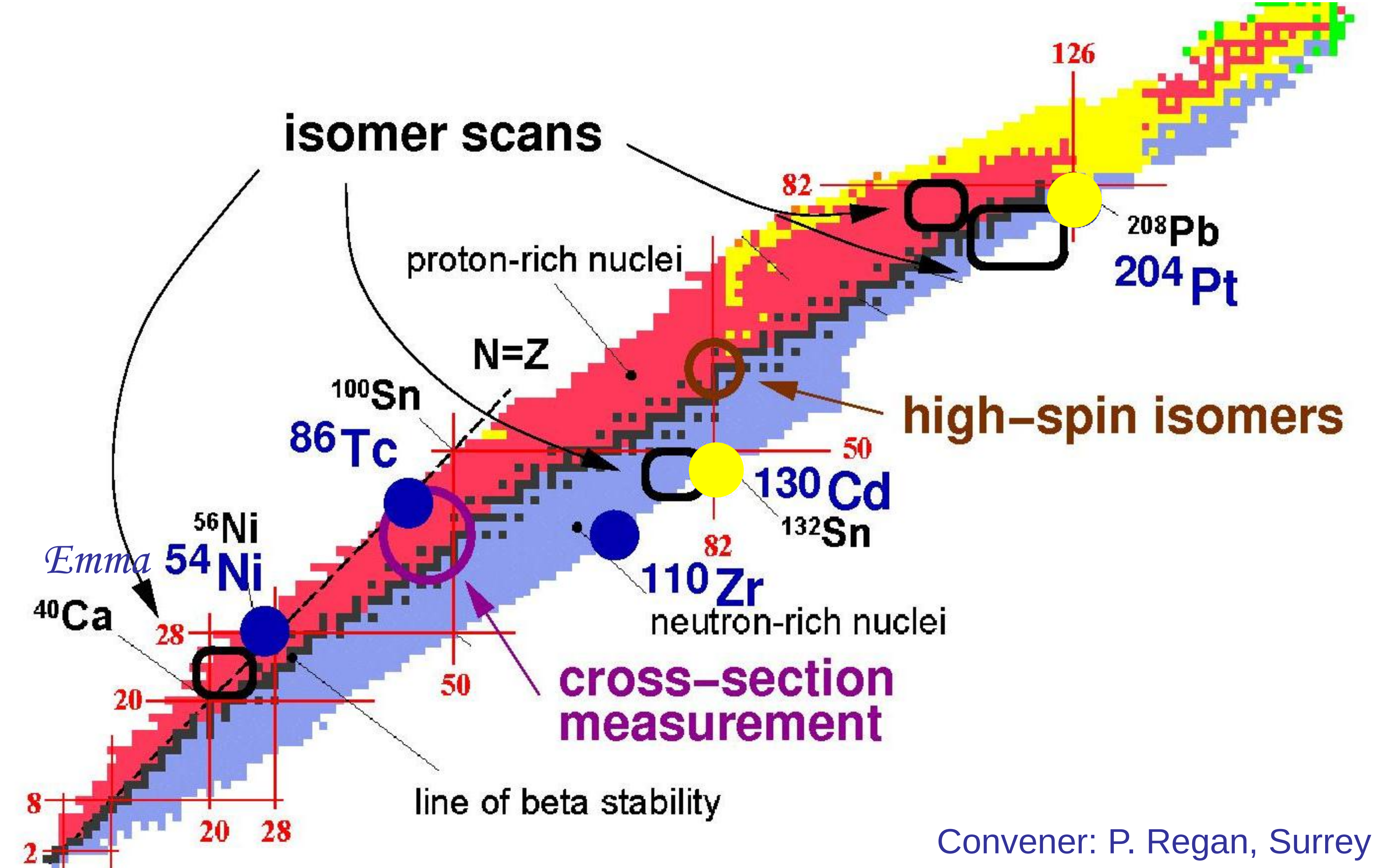
^{88}Zr



$^{88}Zr\ E_\gamma$ after prompt flash

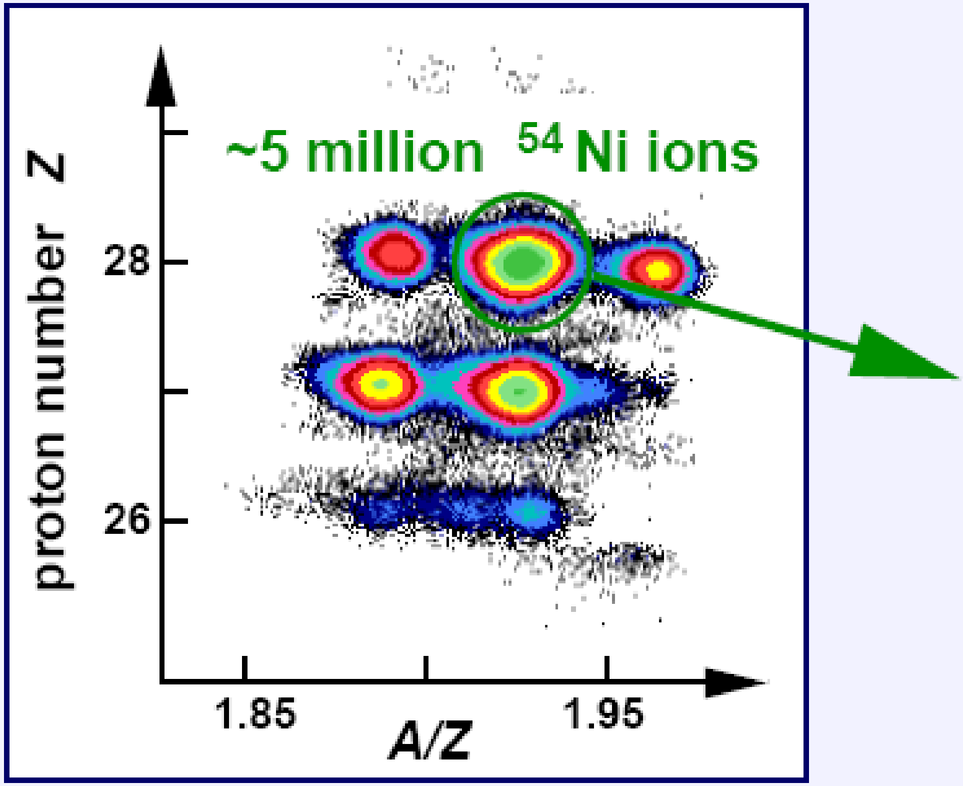


RISING: Stopped beam – physics focus 2006

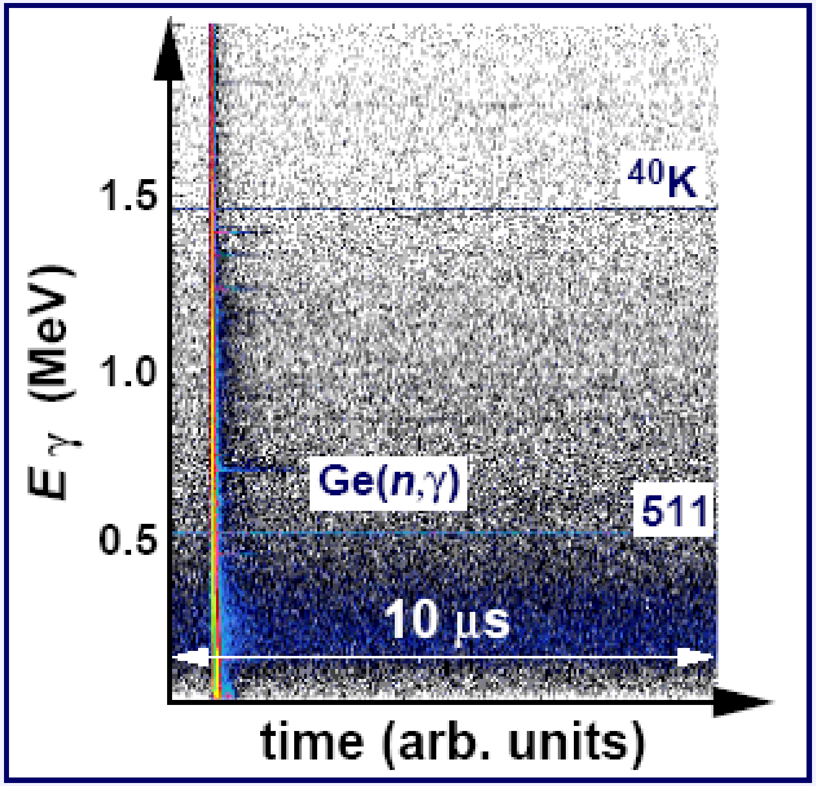


Convener: P. Regan, Surrey

Gamma Energy-Time Correlations



^{54}Ni: DGF–timing

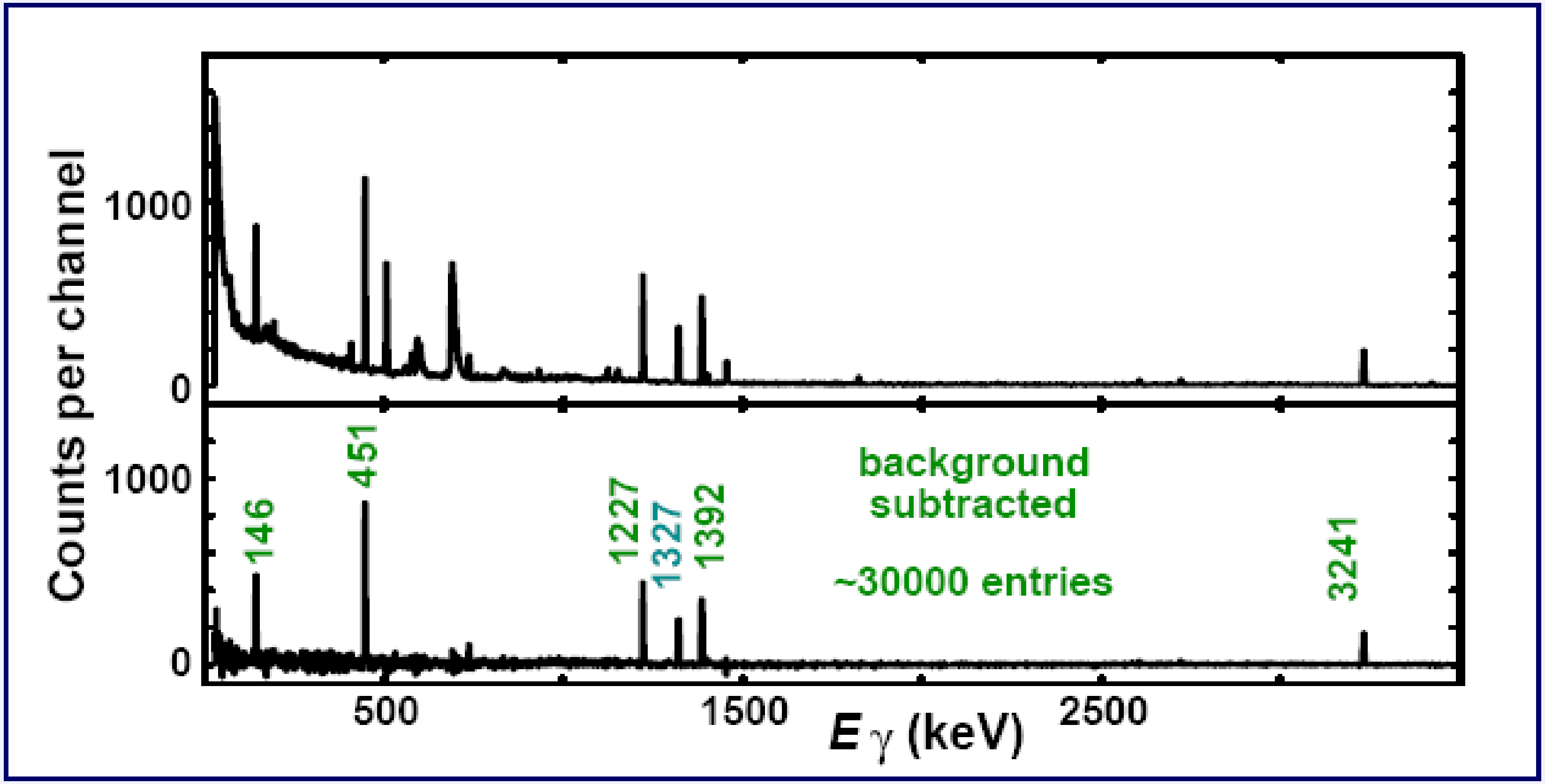


~ 0.9 million entries

D. Rudolph, Lund University

Ge Single Spectra

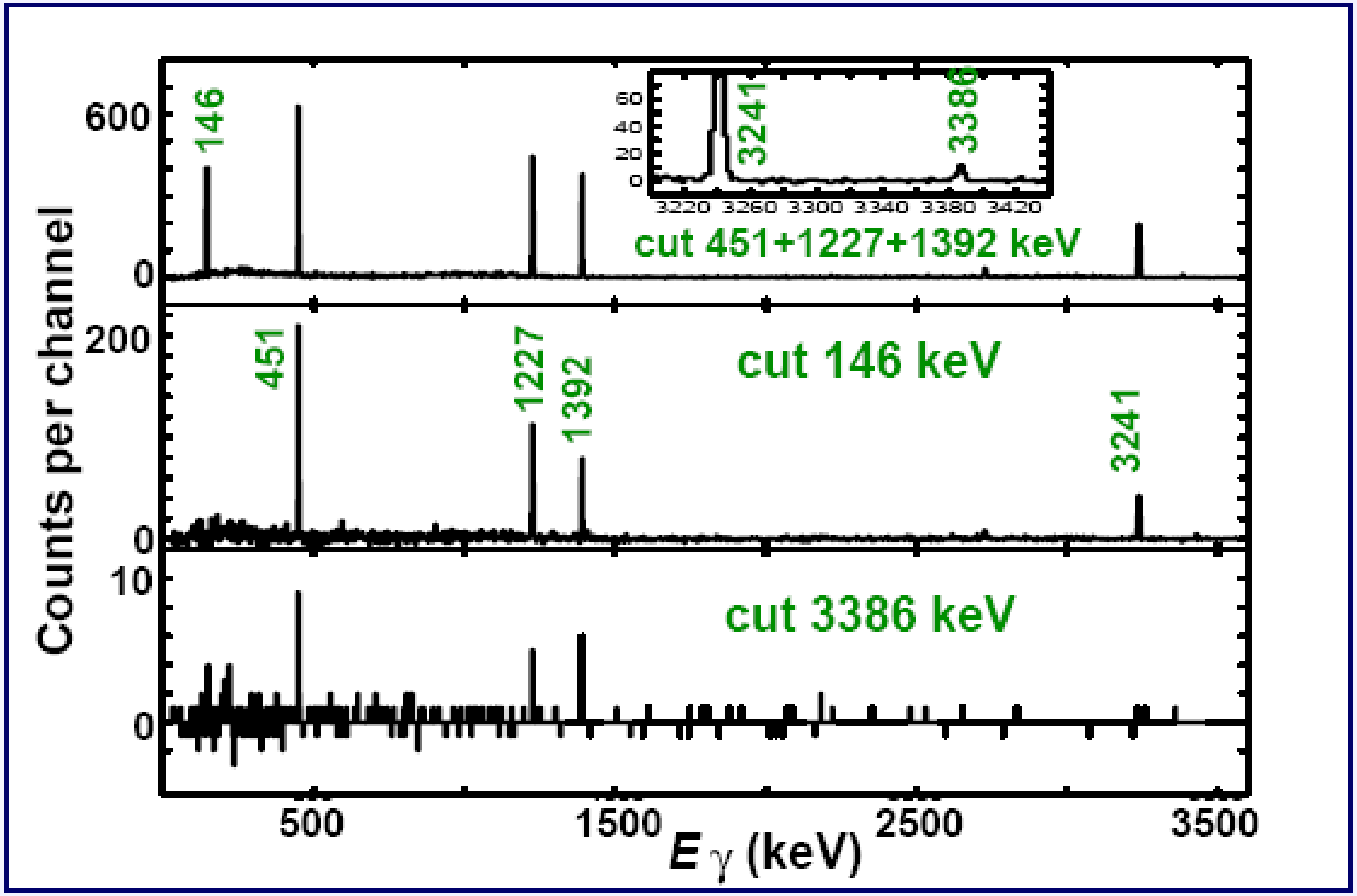
^{54}Ni gated, time range 0.05 – 1.00 μs after implantation



D. Rudolph

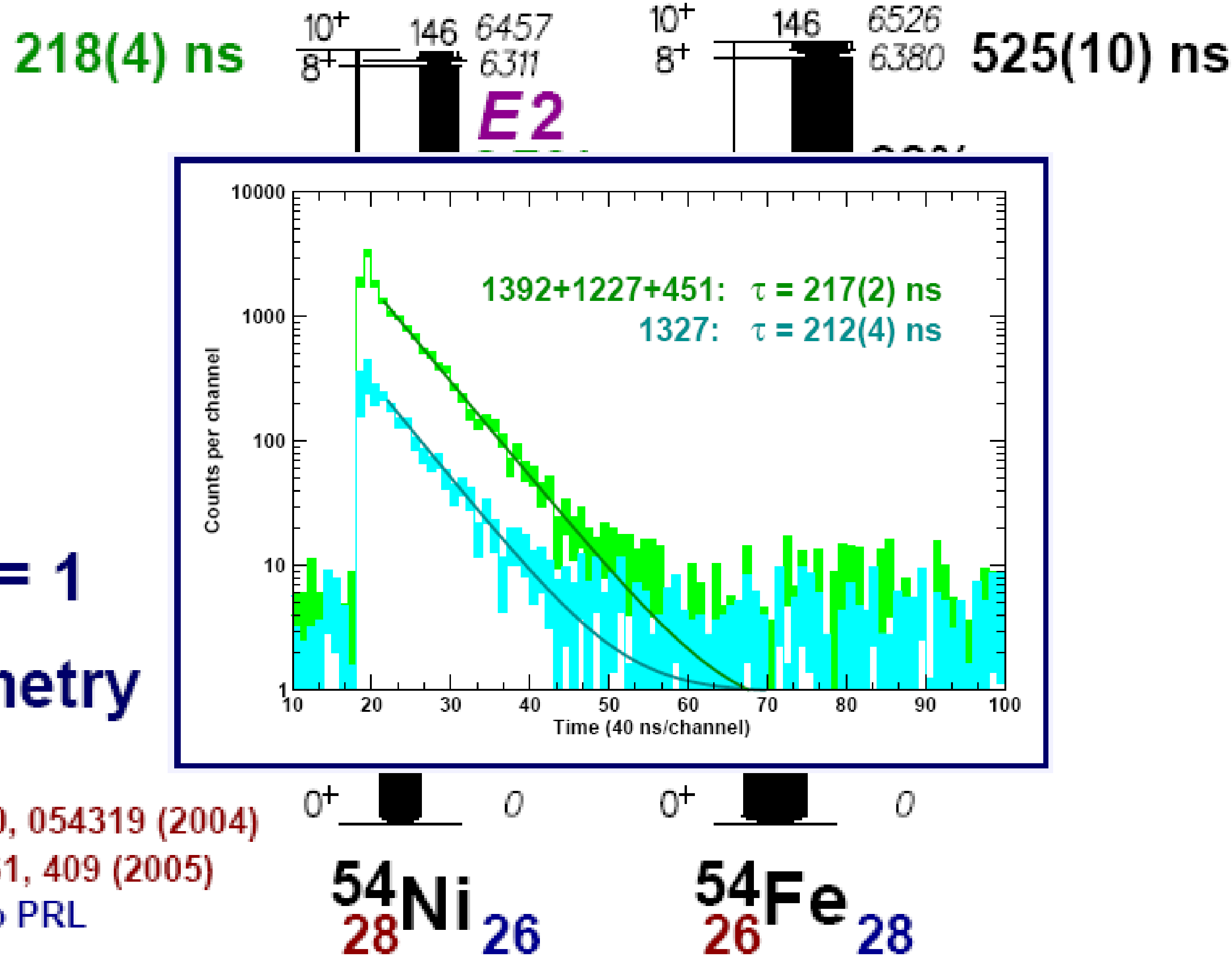
γγ Coincidence Spectra

Ni gated
0.05 – 1.00μs



D. Rudolph

Decay Scheme of ^{54}Ni



***A* = 54, *T* = 1**

Isospin Symmetry

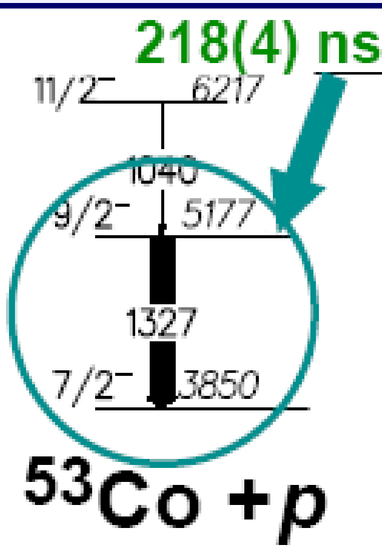
K.L. Yurkewicz *et al.*, PRC70, 054319 (2004)

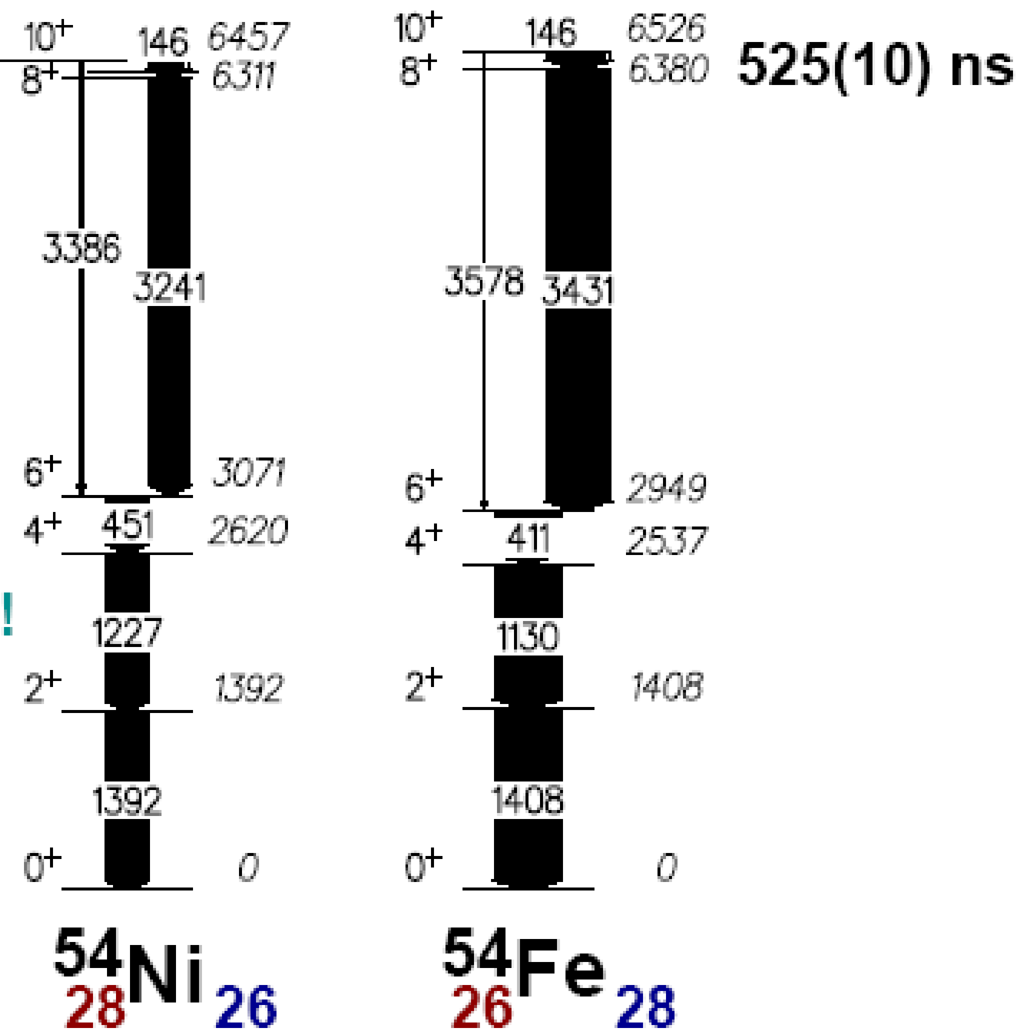
K. Yamada *et al.*, EPJA 25 S1, 409 (2005)

A. Gadea *et al.*, submitted to PRL

D. Rudolph

Decay Scheme of ^{54}Ni



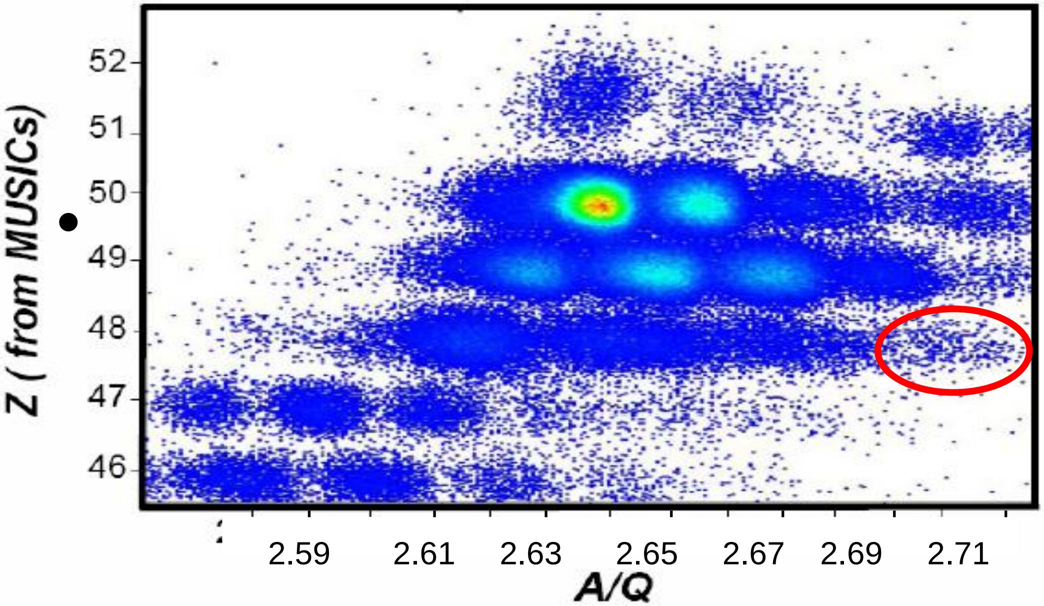


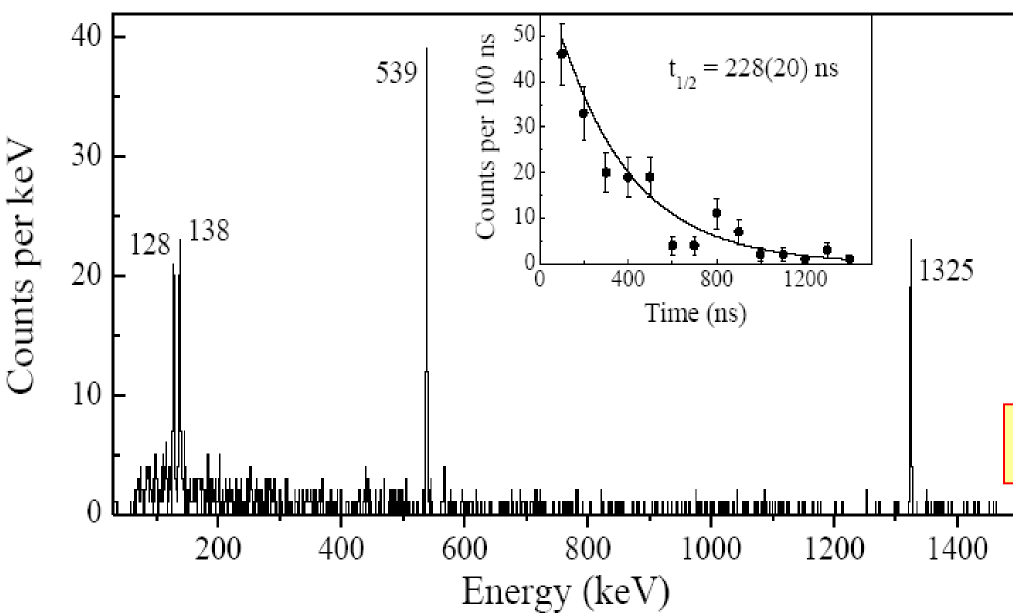
Proton decay is coming home!
^{53}Co

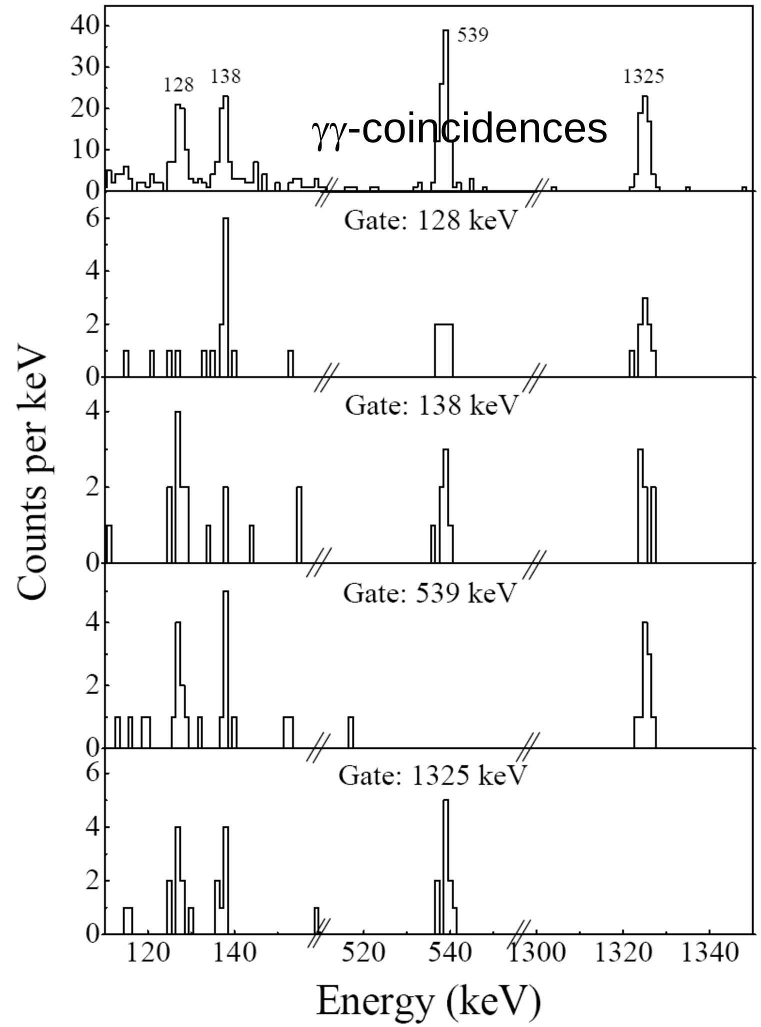
K.P. Jackson *et al.*, PLB 33, 281 (1970)
J. Cerny *et al.*, PLB 33, 284 (1970)

D. Rudolph, Lund University

^{130}Cd from fission and fragmentation





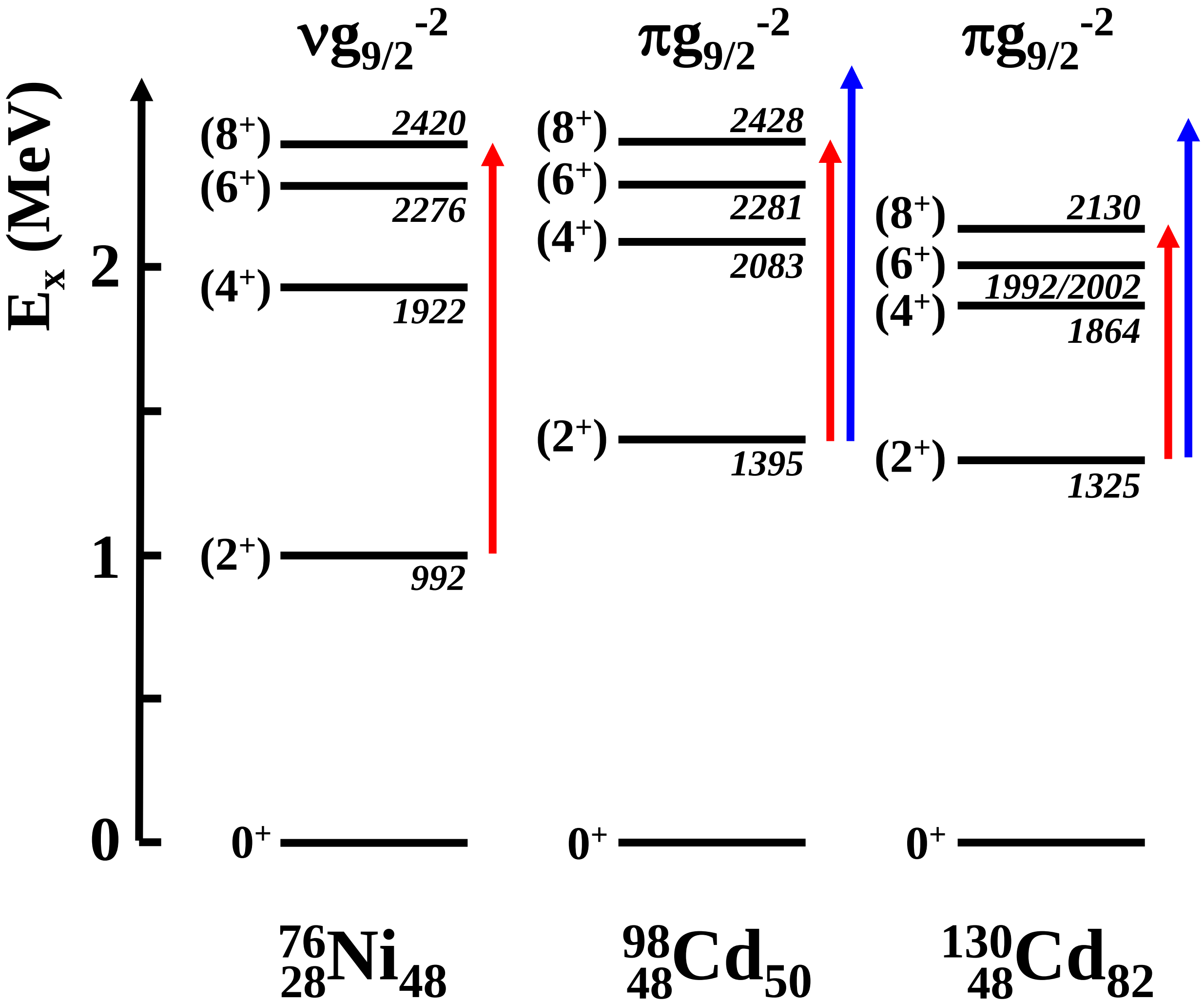


No evidence for shell quenching

Andrea Jungclaus, Madrid

Lucia Caceres, PhD thesis

Unexpected scaling of $(g_{9/2})^{-2}$ two-body interaction



*C. Mazzocchi et al., PLB **622** (2005) 45*

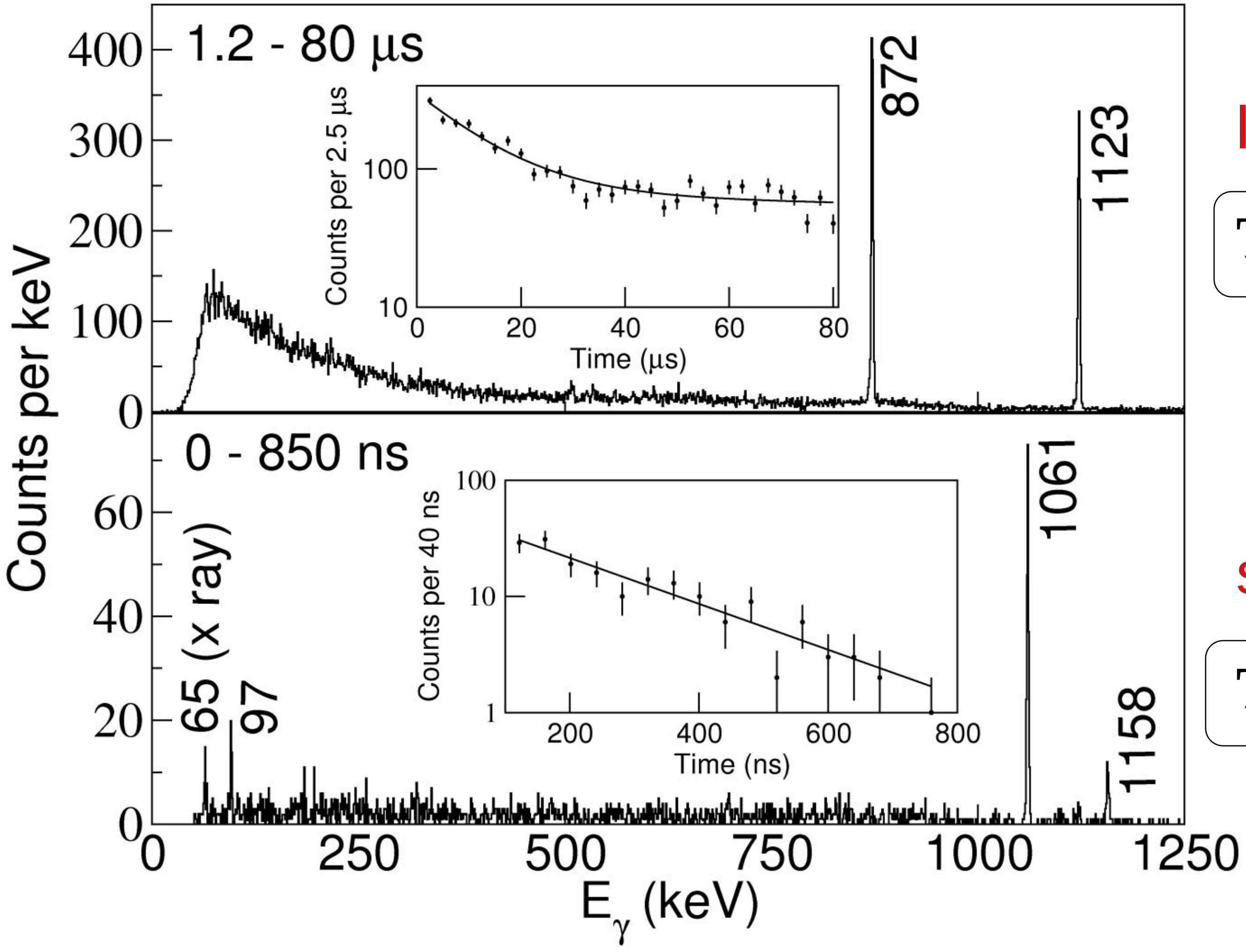
2^+-8^+ levels are pure $(g_{9/2})^{-2}$ states

2^+-8^+ energy spread scales with A^{-1}

not with $\hbar\omega = 41 \cdot A^{-1/3}$ as commonly assumed

idea of H. Grawe

^{204}Pt populated via 4-proton-knockout from ^{208}Pb



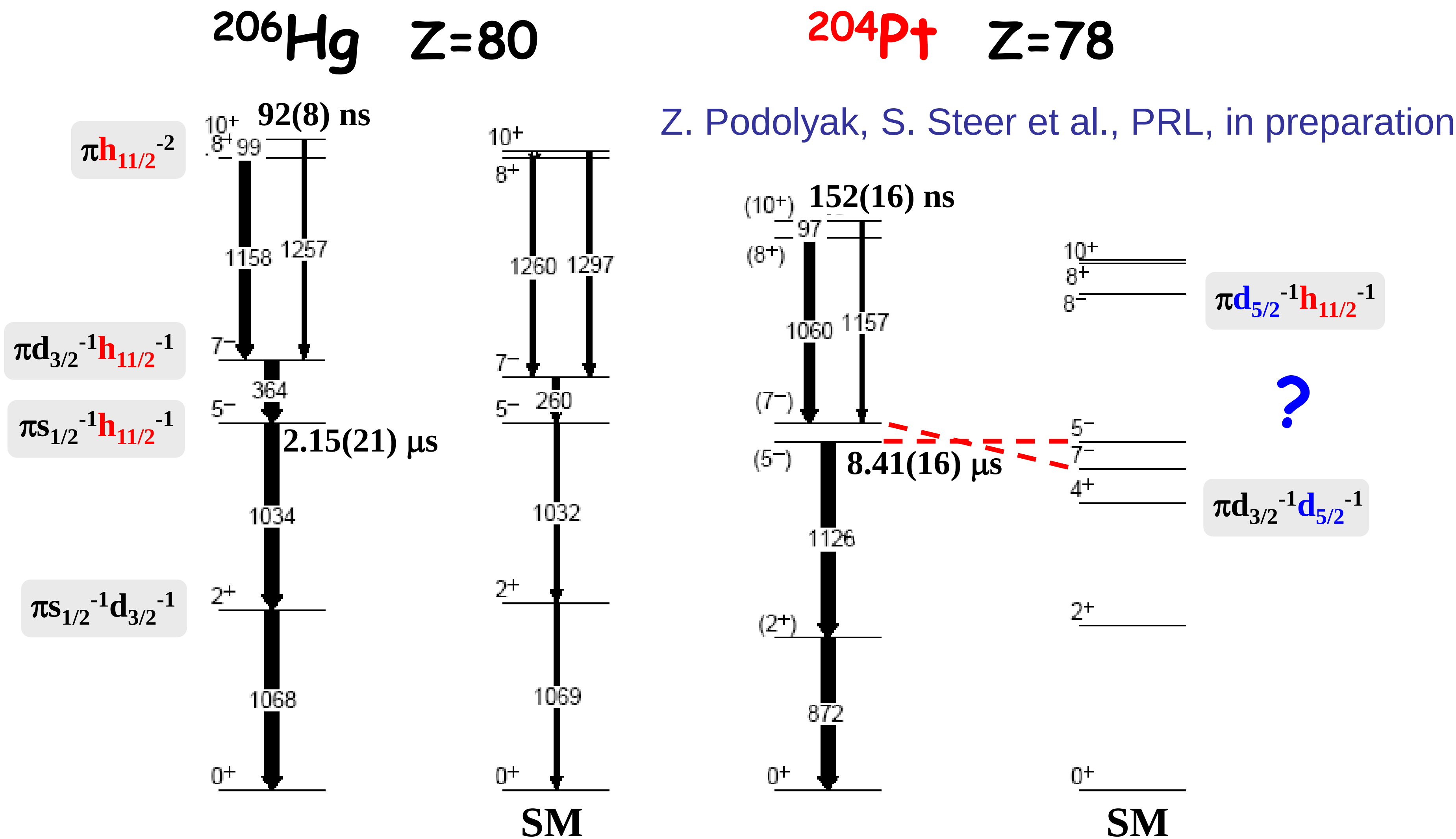
long isomer:

$T_{1/2}$=8.41(16) μs

short isomer:

$T_{1/2}$=152(16) ns

N=126 isotones: $(\pi h_{11/2})^{-2,4}$ $I^{\pi}=10^{+}$ isomers

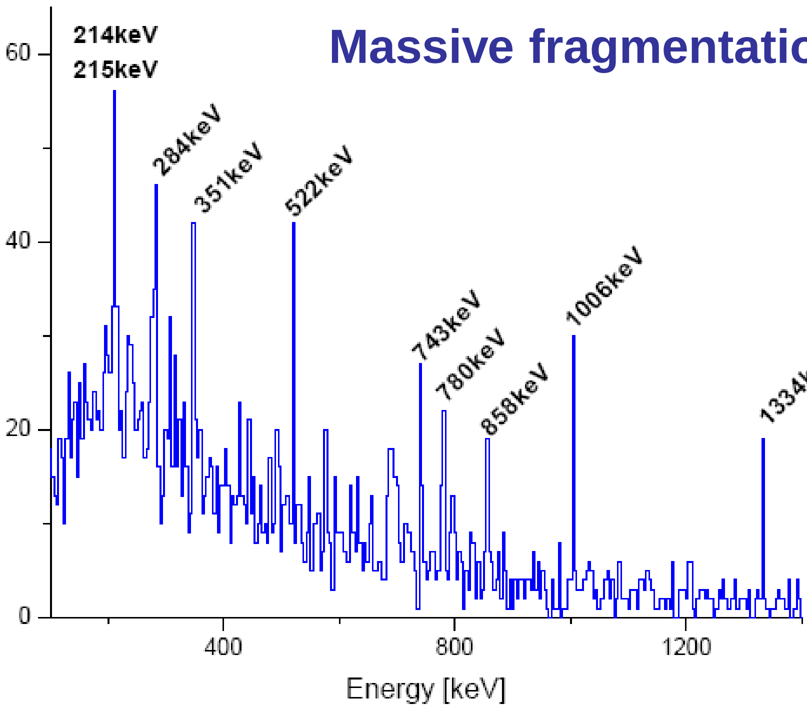


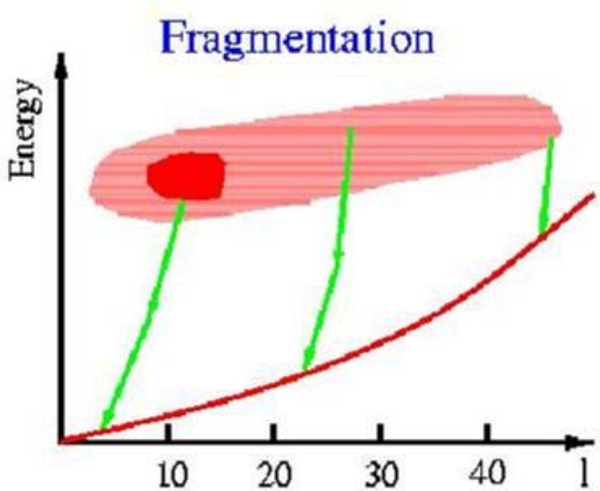
B. Fornal et al.
PRL 87 (2001)212501

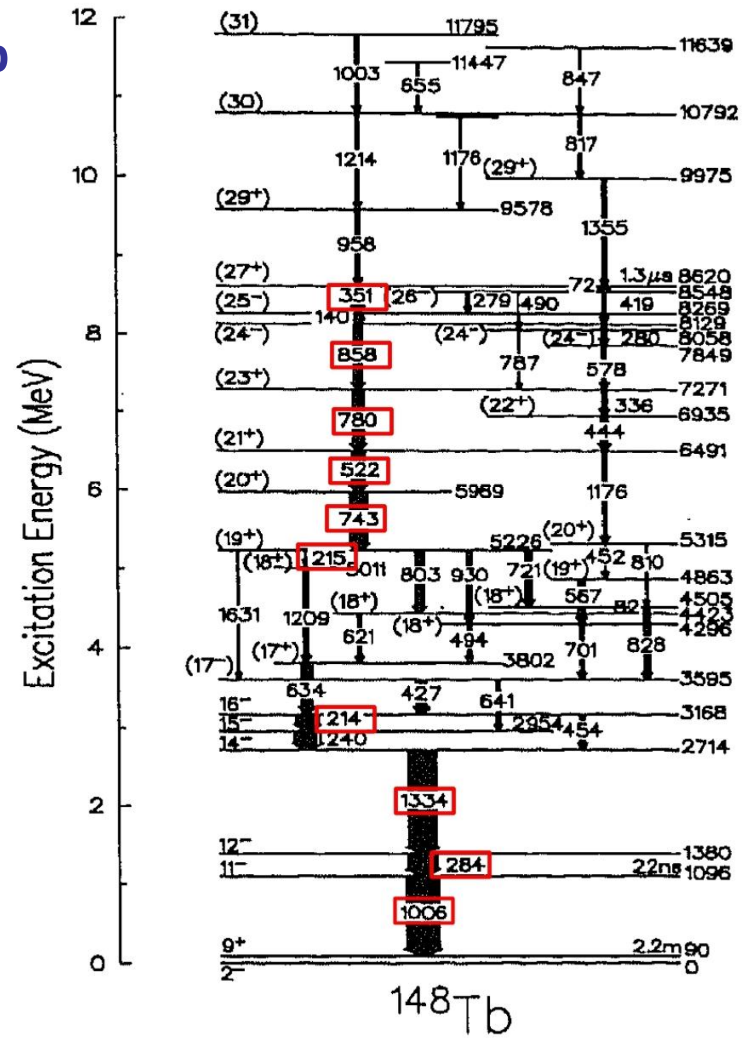
➡ Results require modification of SPE and/or interactions !

27^+ state populated in ^{148}Tb

Massive fragmentation of ^{208}Pb

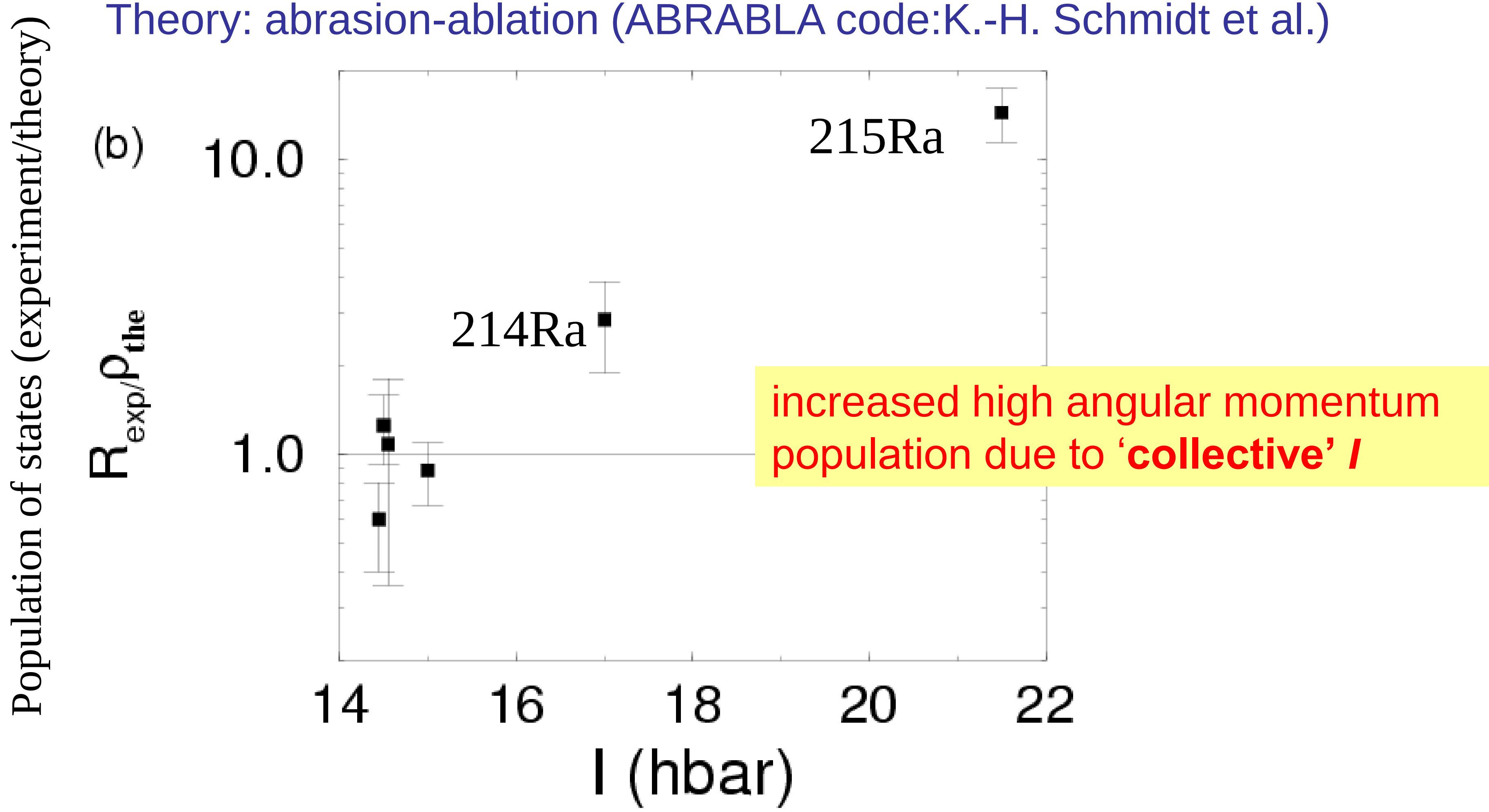






Fragmentation populates high spin states

Theory: abrasion-ablation (ABRABLA code:K.-H. Schmidt et al.)

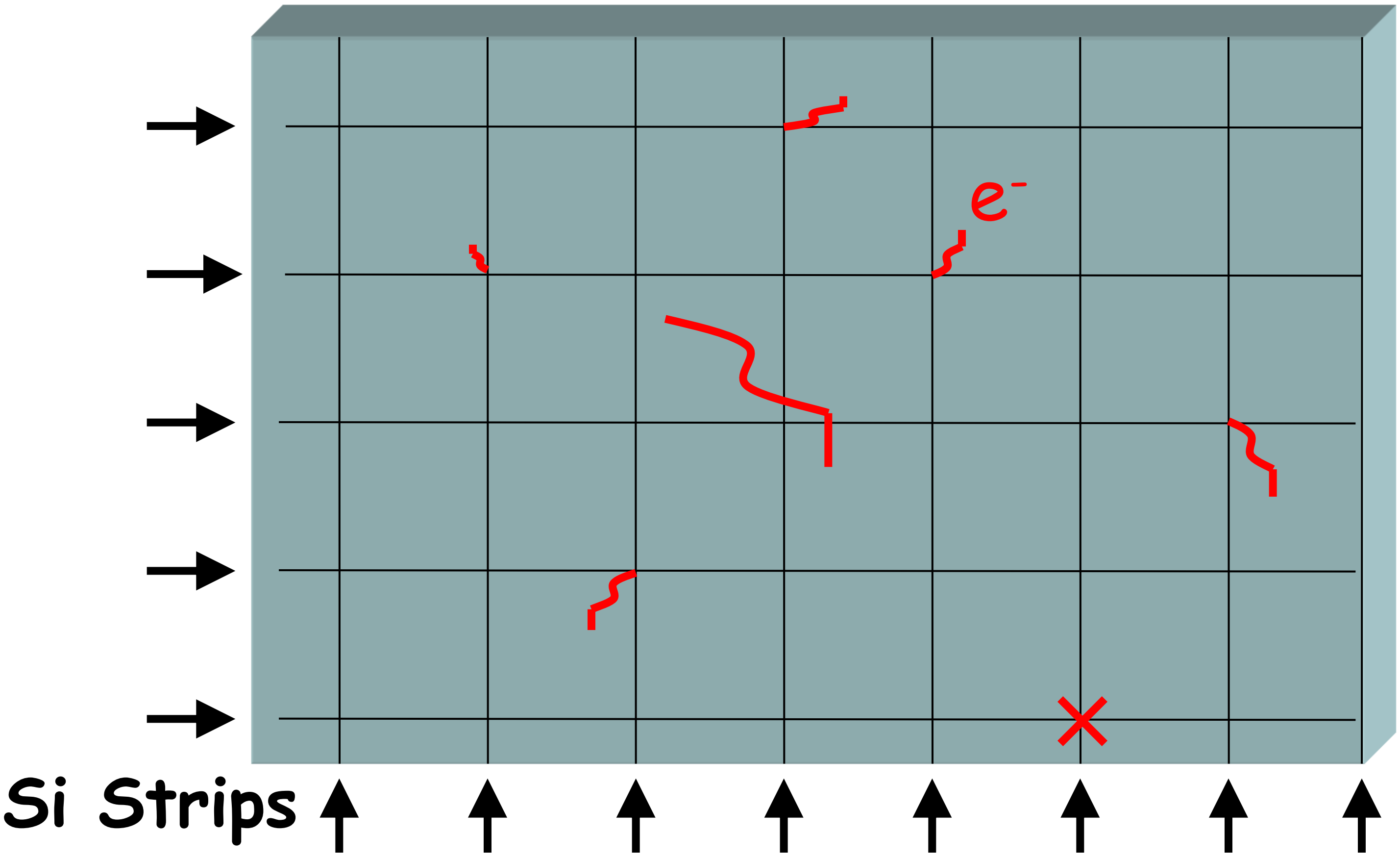


=> isomeric beams

Zs. Podolyák *et al*., Phys. Lett. B632 (2006) 203.

The Principle of the Active Stopper

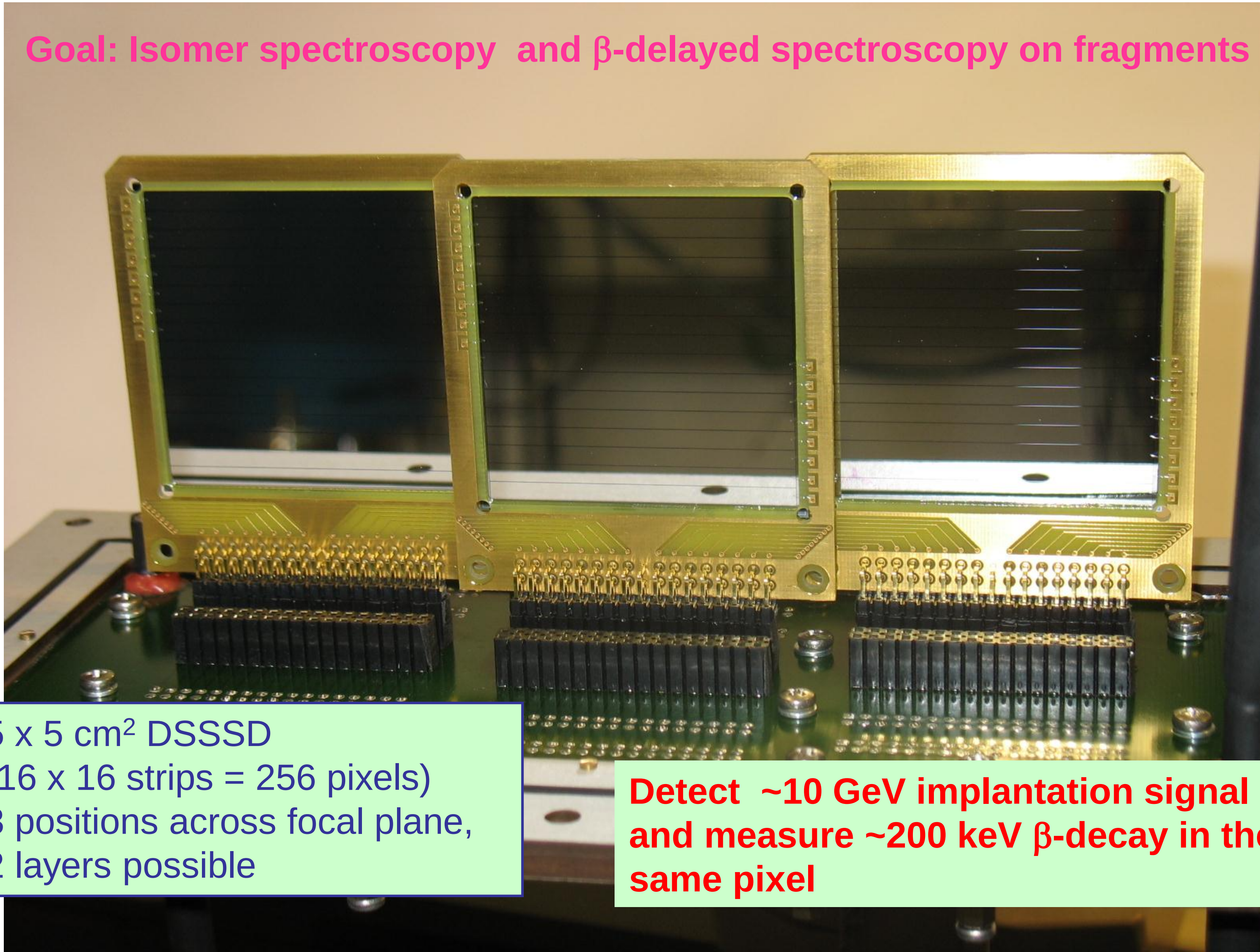
Focal plane implantation detector sensitive to electron emission



The waiting time between particle implantation and β-particle (or i.c. electron) emission is a measure of the decay half-life. Gamma rays emitted following these decays are detected by the RISING array.

Active Stopper RISING

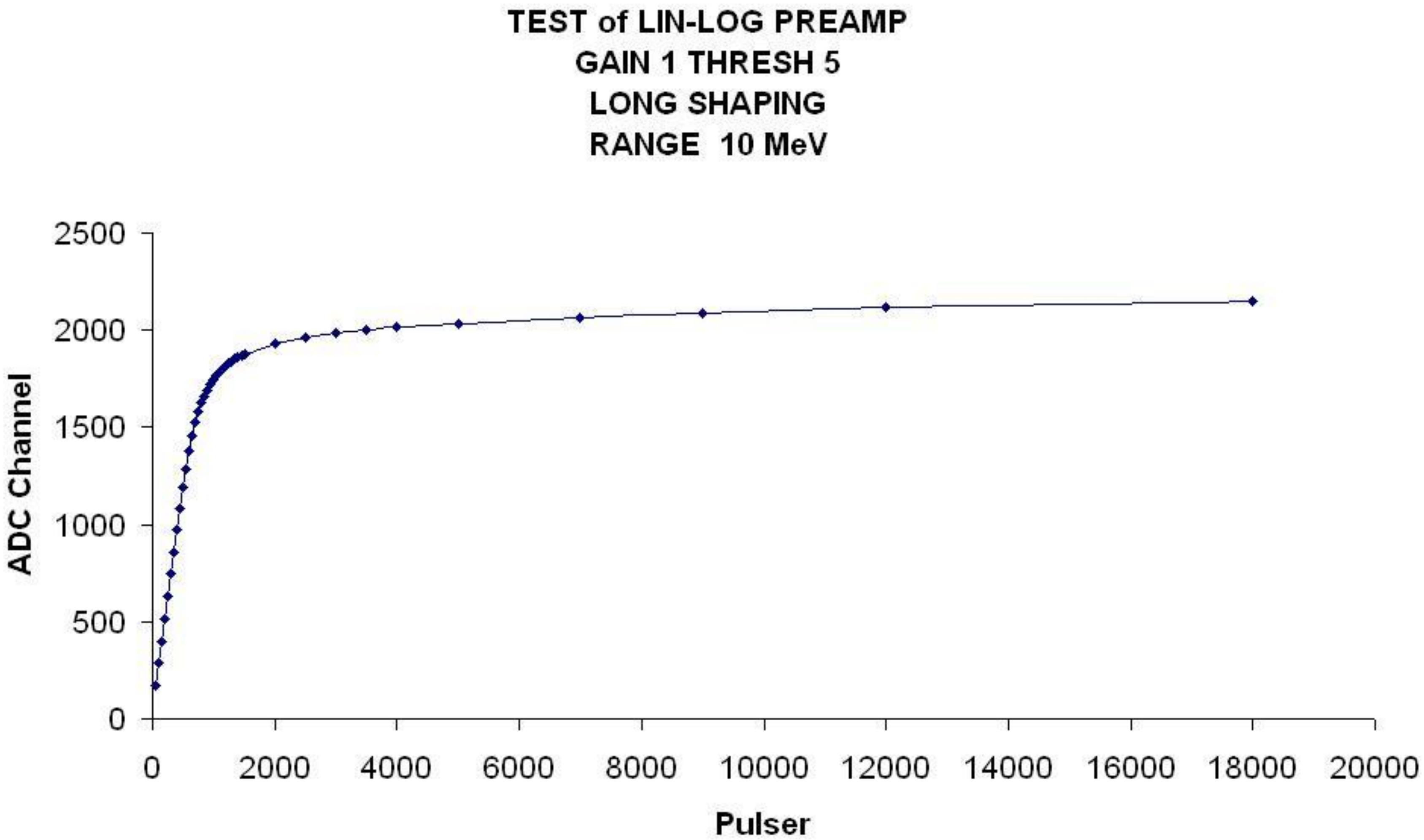
Goal: Isomer spectroscopy and β-delayed spectroscopy on fragments

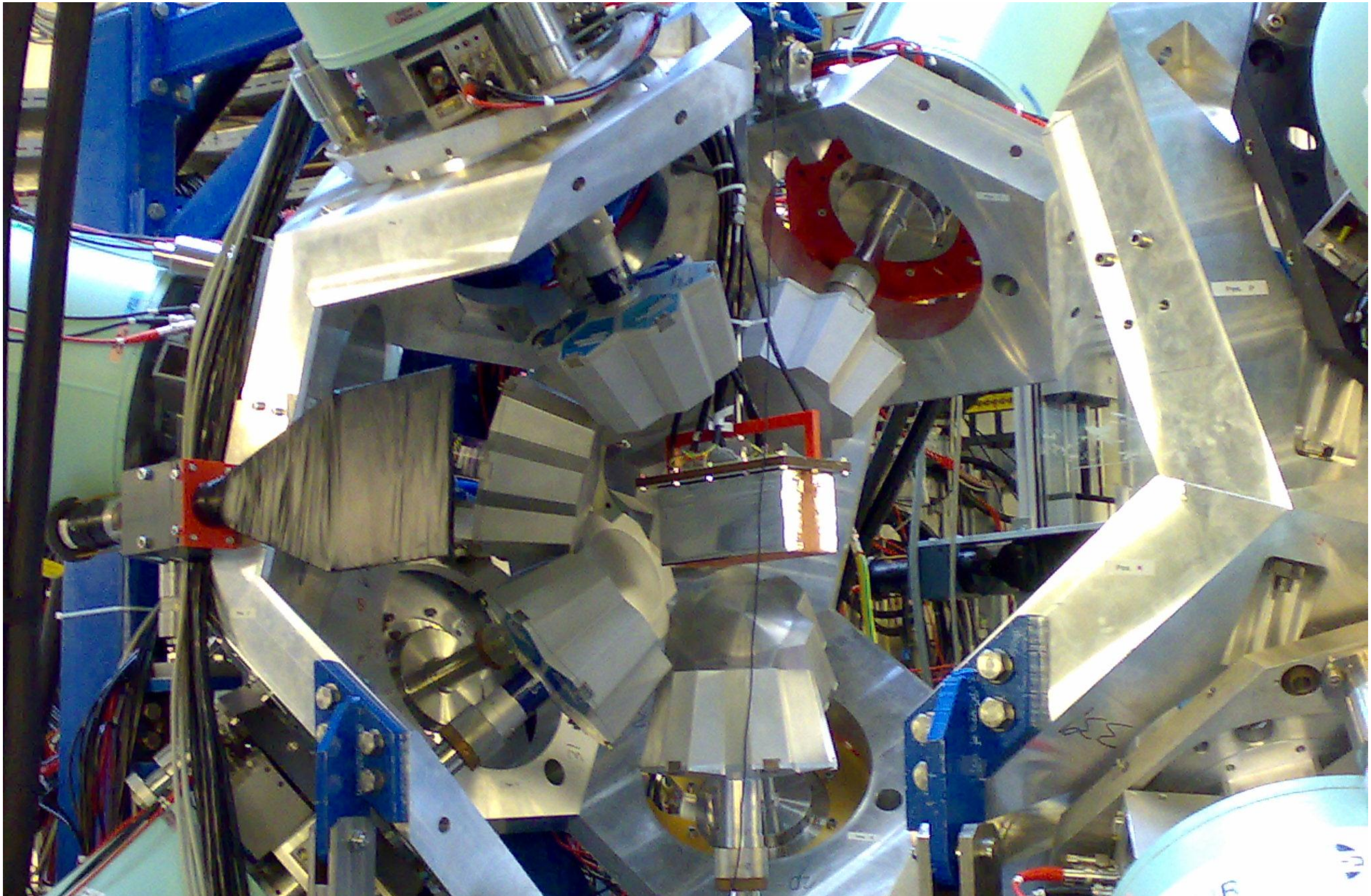


5 x 5 cm^2 DSSSD
(16 x 16 strips = 256 pixels)
3 positions across focal plane,
2 layers possible

Detect ~10 GeV implantation signal and measure ~200 keV β-decay in the same pixel

How do you measure signals with 0.1 MeV & 20 GeV in the same detector ?

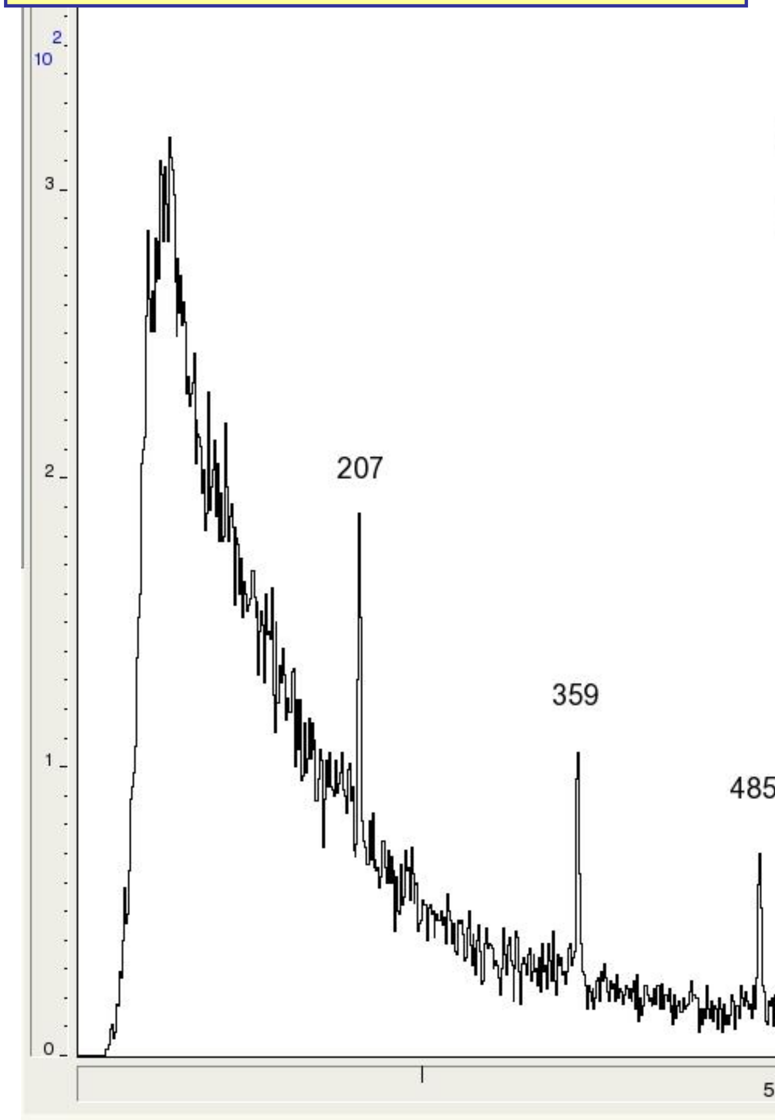


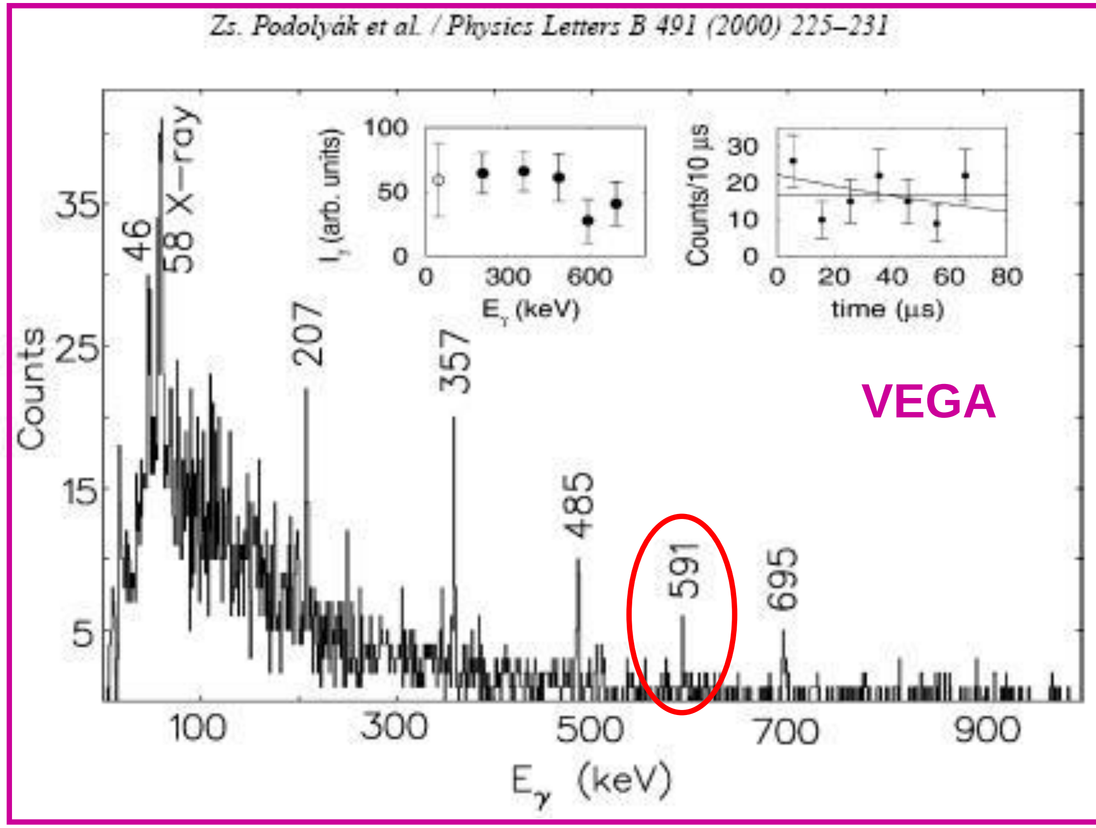


Passive Stopper measurements: γ-rays from isomer with $T_{1/2}$ for 10 ns → 1 ms.

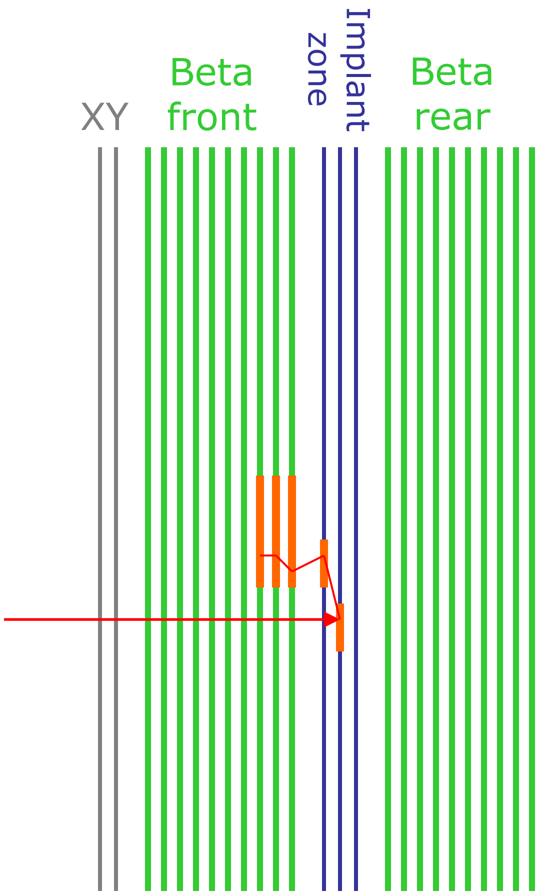
Active Stopper measurements: β *–particles*, *i.c.* electrons, $T_{1/2}$ ms →mins

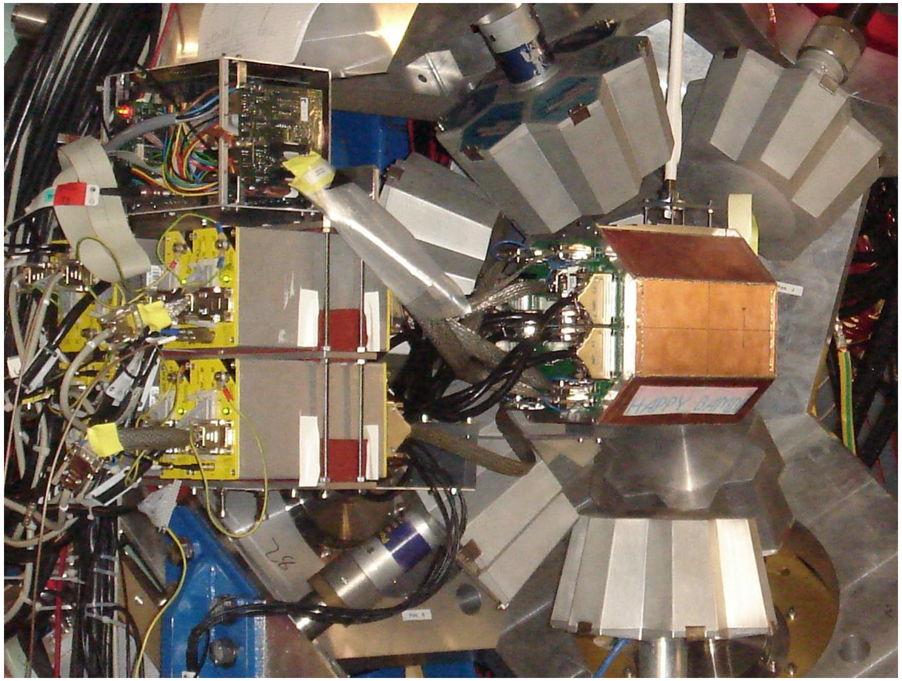
^{190}W isomer decay from ^{208}Pb beam

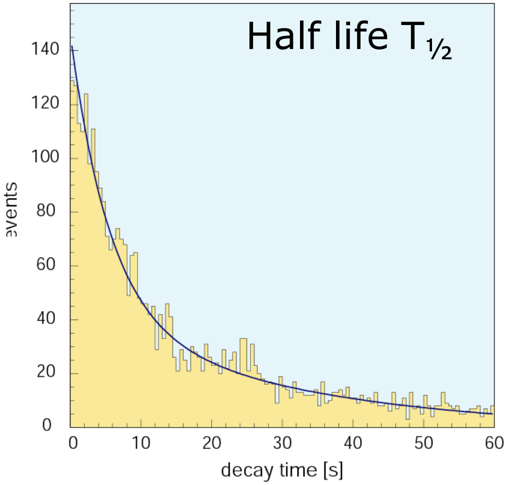


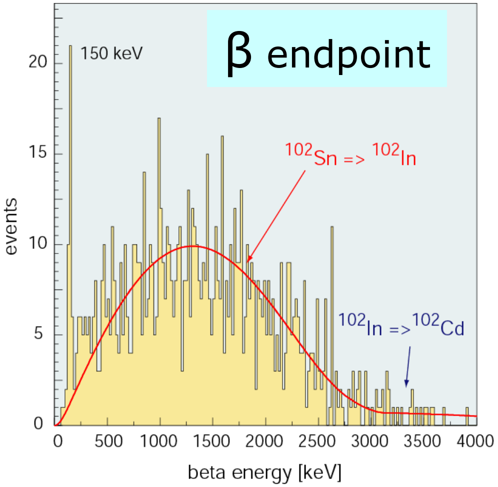


Implantation detector SIMBA (TU München)



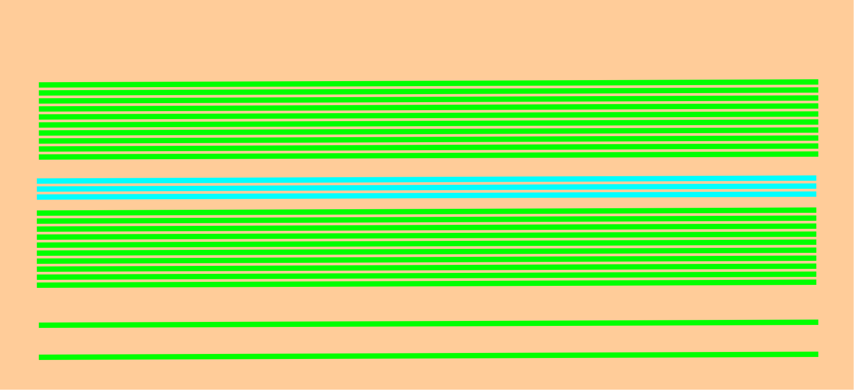


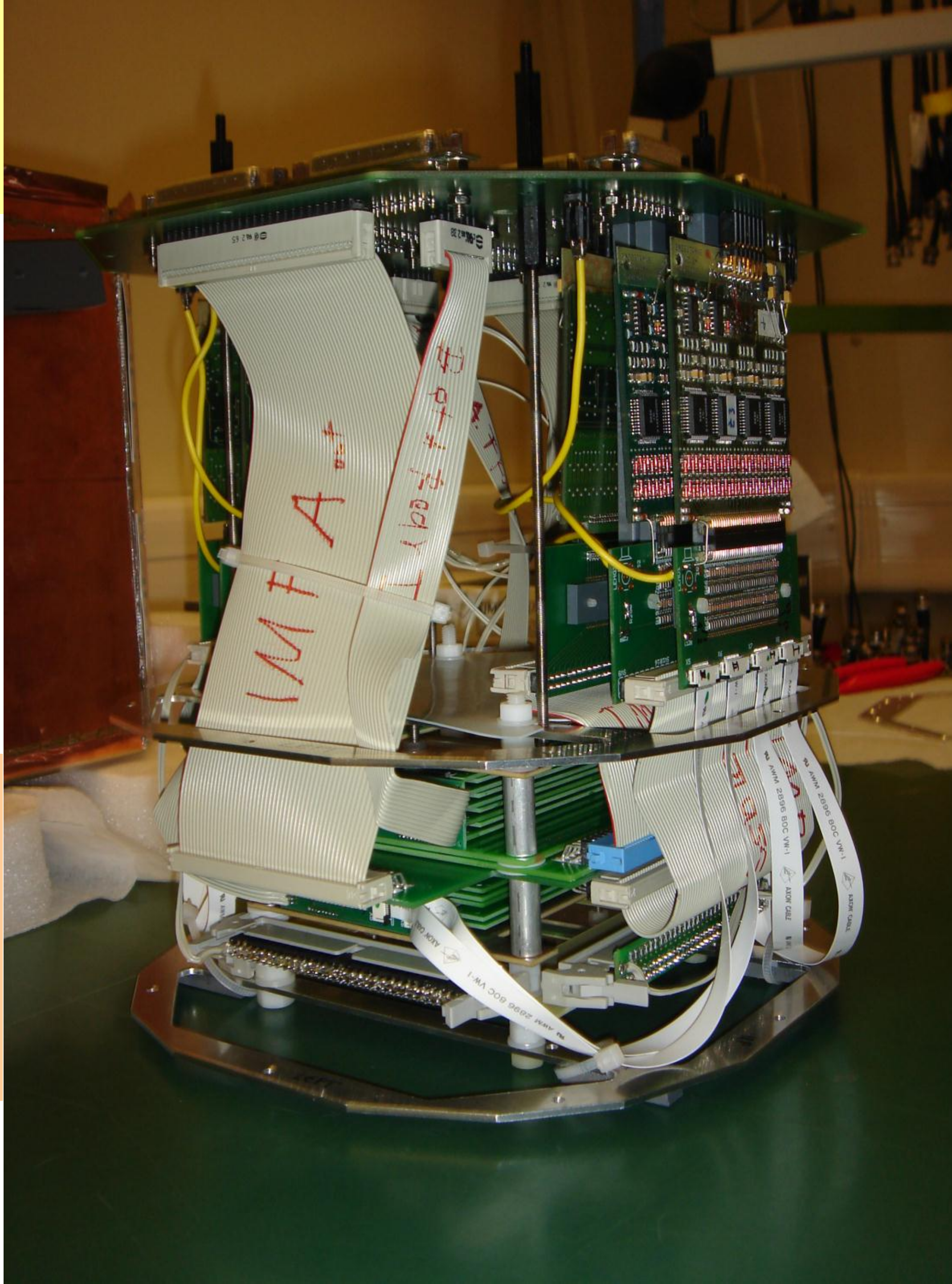


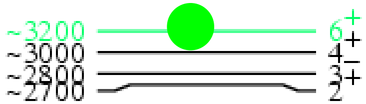


Implantation zone
3 x 60 x 40 = 7200 pixels
Calorimeter for decay particles
2 x 10 layers + x,y layer

and how it looks inside





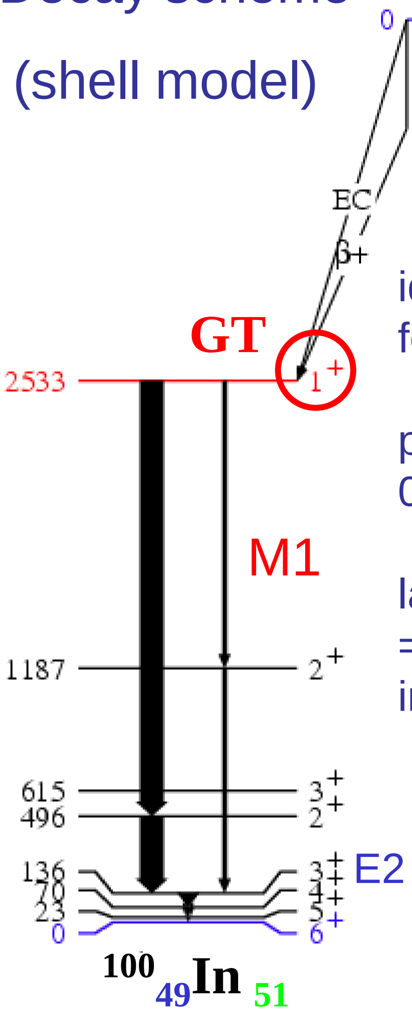


^{100}Sn

- GT strength in the decay
- rp process end point
- 6^+ spin gap isomer
- particle stability of neighbours

Decay scheme

(shell model)



ideal testing ground for GT-strength:

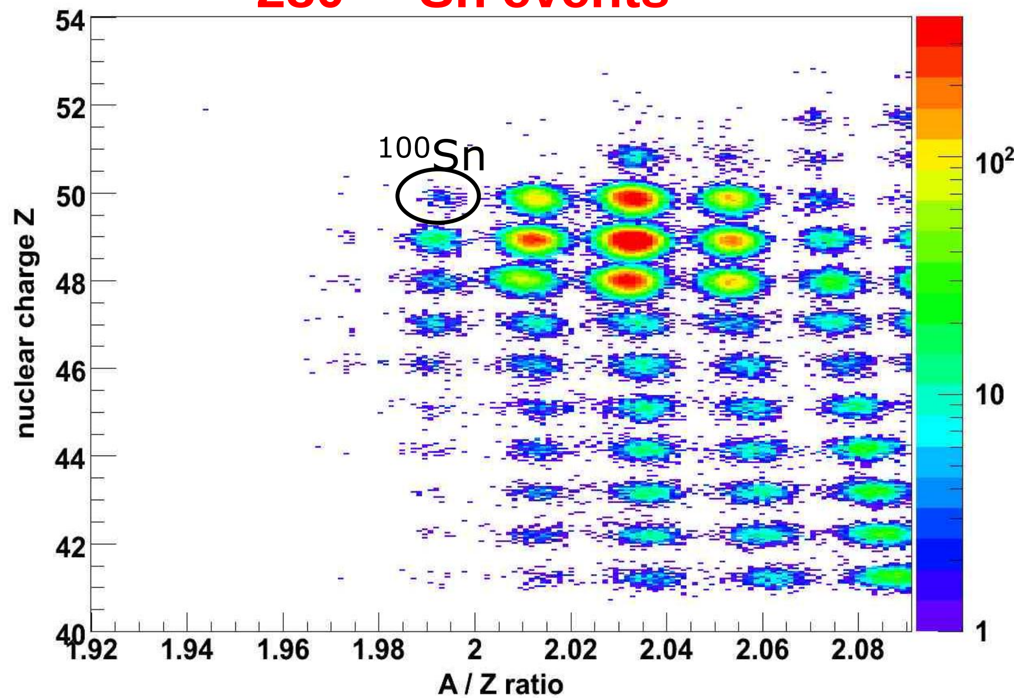
pure spin-flip transition
$0^+ \Rightarrow (\pi g_{9/2}^{-1}\ \nu g_{7/2})1^+$

large decay energy
=> most of GT resonance in β-decay window

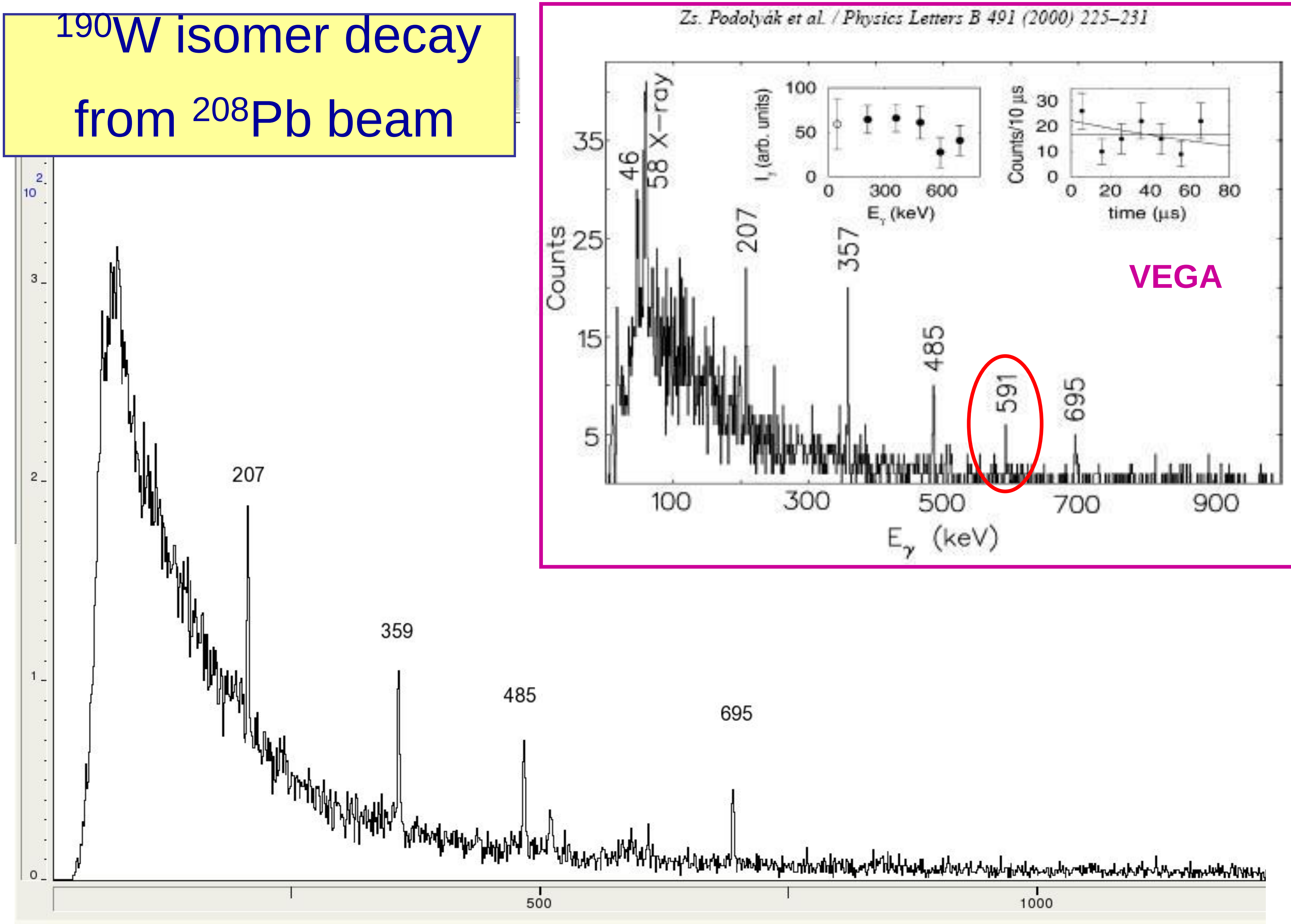
measure:
$T_{1/2}$
endpoint energy
(branching)
=> GT-strength

^{124}Xe fragmentation, 1 evt/h

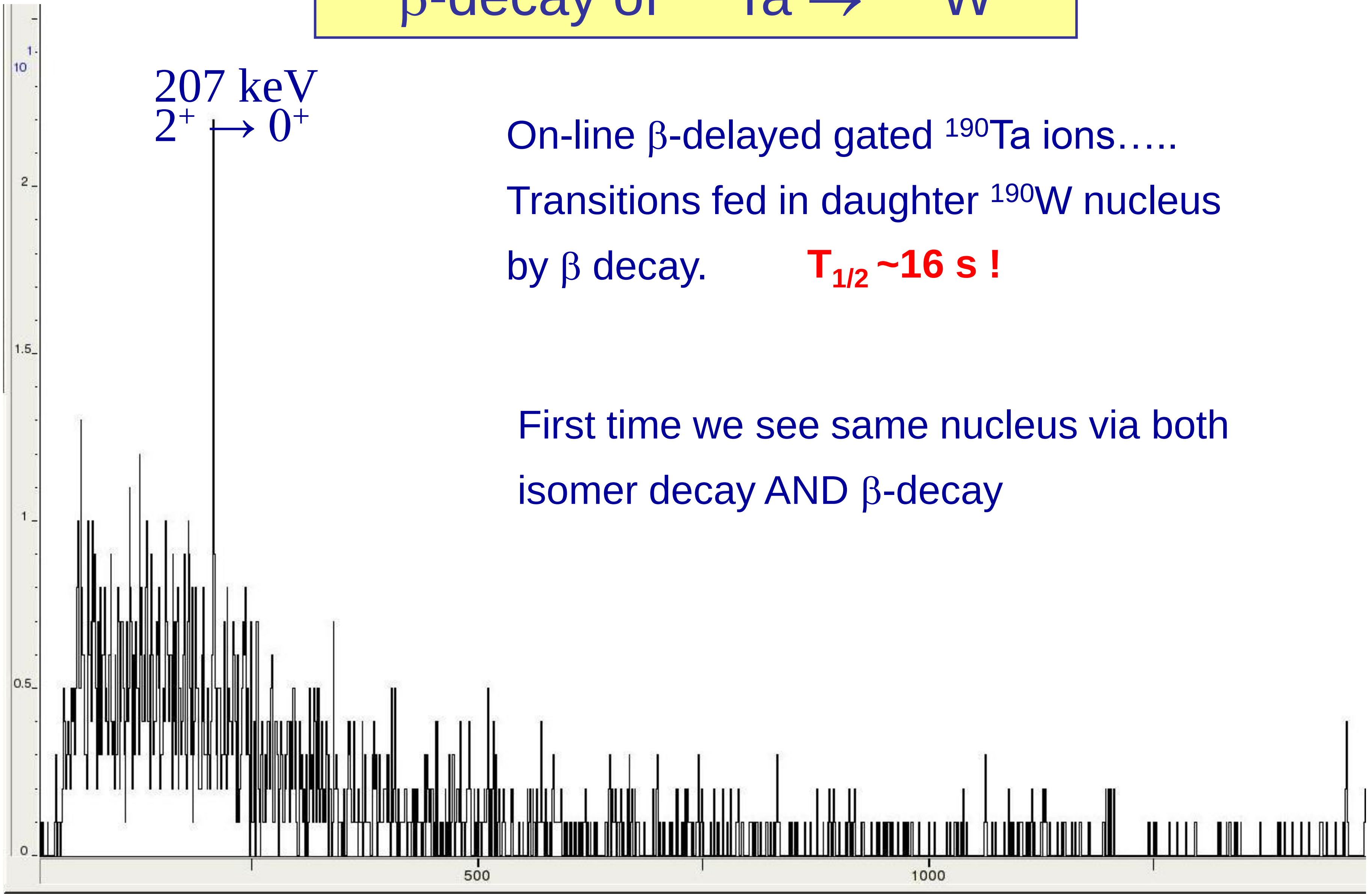
≈280 ^{100}Sn events



^{190}W isomer decay from ^{208}Pb beam



β-decay of ^{190}Ta $\rightarrow$ ^{190}W



On-line β-delayed gated ^{190}Ta ions…..

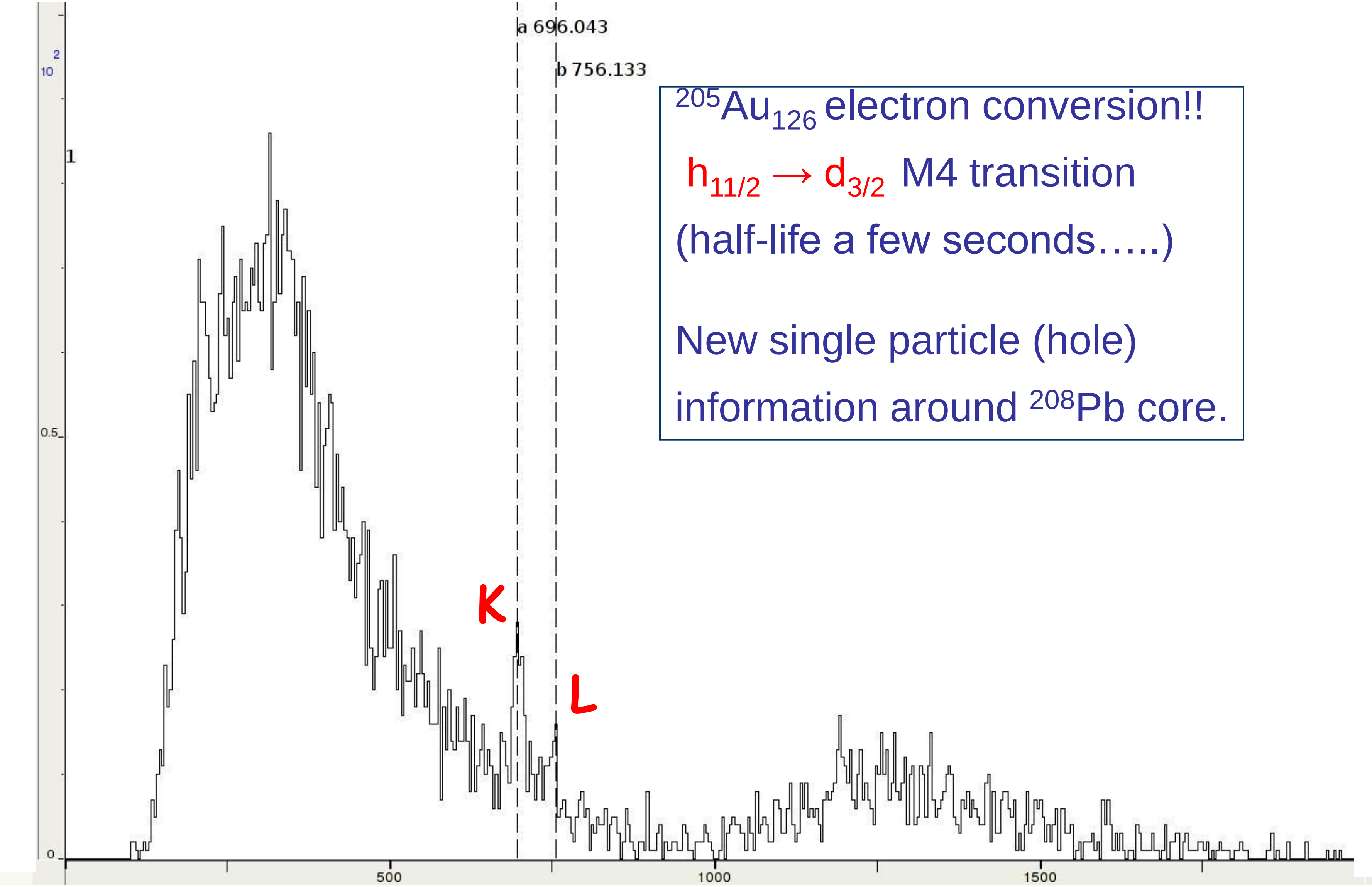
Transitions fed in daughter ^{190}W nucleus

by β decay. **$T_{1/2}$ ~16 s !**

First time we see same nucleus via both isomer decay AND β-decay

N. Al-Khomashi, PhD thesis

Conversion electron spectroscopy in ^{205}Au



$^{205}Au_{126}$ electron conversion!!

$h_{11/2} \rightarrow d_{3/2}$ M4 transition

(half-life a few seconds…..)

New single particle (hole) information around ^{208}Pb core.

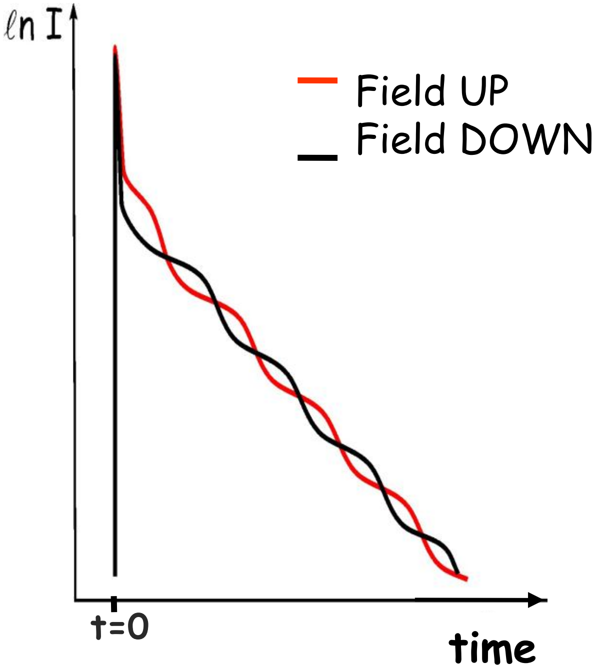
g-factor measurements at RISING

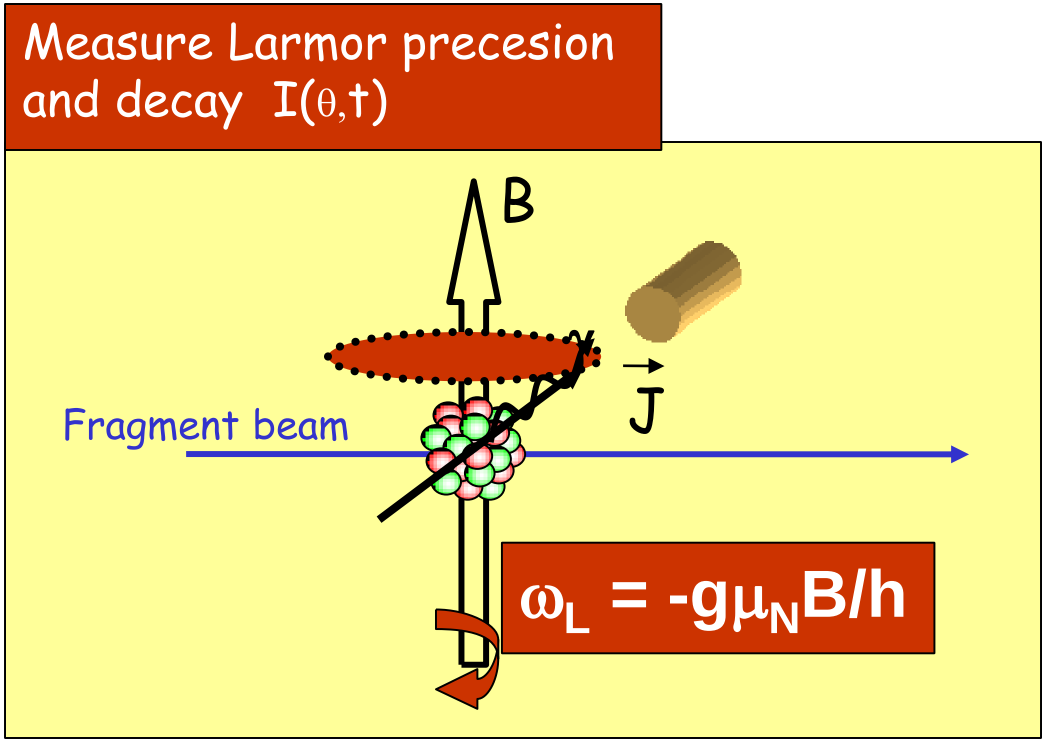
(a) g-factors → reveal information about the nuclear single particle structure:
wave function, spin, magnetic dipole operator, …
→ unique probe to study changes in nuclear shell structure far from stability
→ second step: quadrupole moments (deformation)

(b) spin-alignment in relativistic fission
→ never experimentally proven !
→ exotic neutron rich nuclei become accessible for moments studies

WHY AT THE FRS ?
= unique facility to study *g*-factors and quadrupole moments of spin-aligned isomeric beams not accessible at other places:
- lifetime range 100 ns – 100 μs (not at ISOL facilities)
- in neutron rich nuclei with mass *A*>70
(not with intermediate energy fragmentation)
(not with fusion-evaporation)

Time Differential Perturbed Angular Distribution

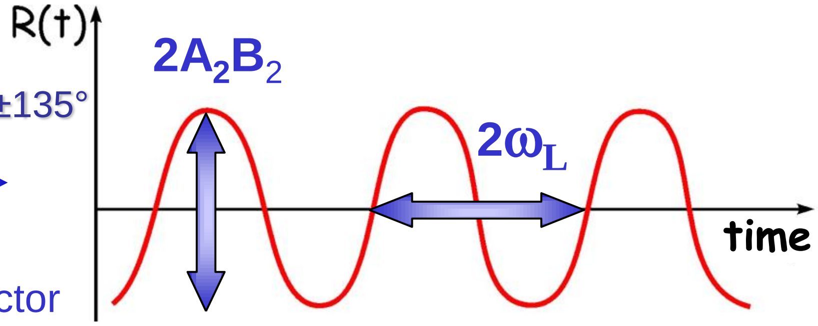




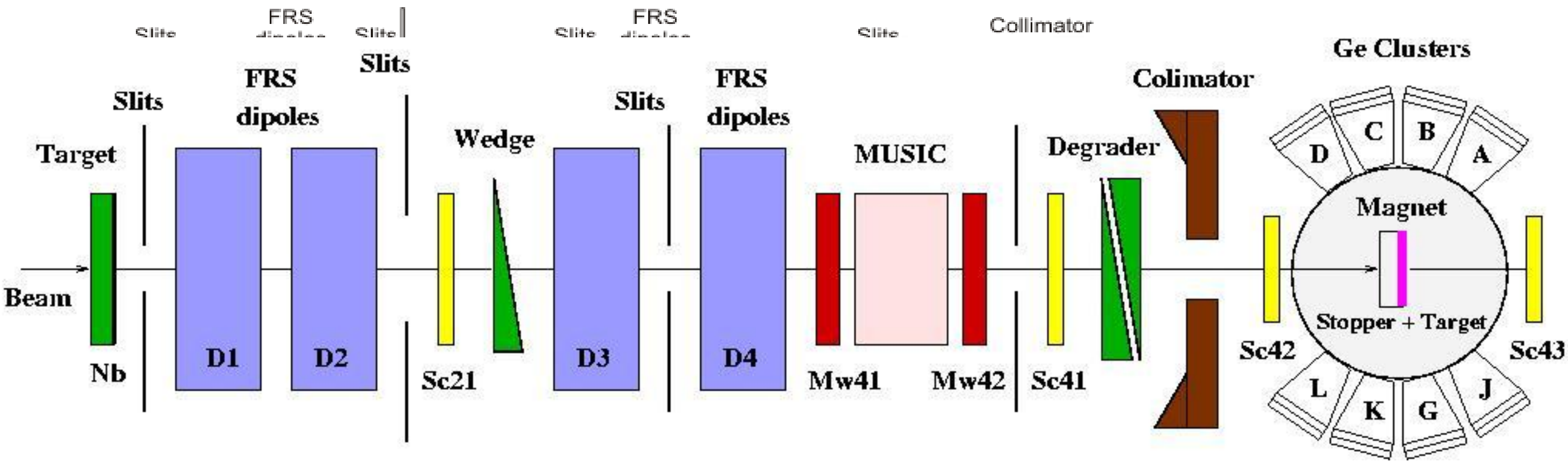
$$R(t) = \frac{I_1 - \varepsilon I_2}{I_1 + \varepsilon I_2}$$

detectors at ±45° and ±135°

the relative phases depend on the g-factor



THE EXPERIMENTAL SET-UP AT GSI: g-RISING

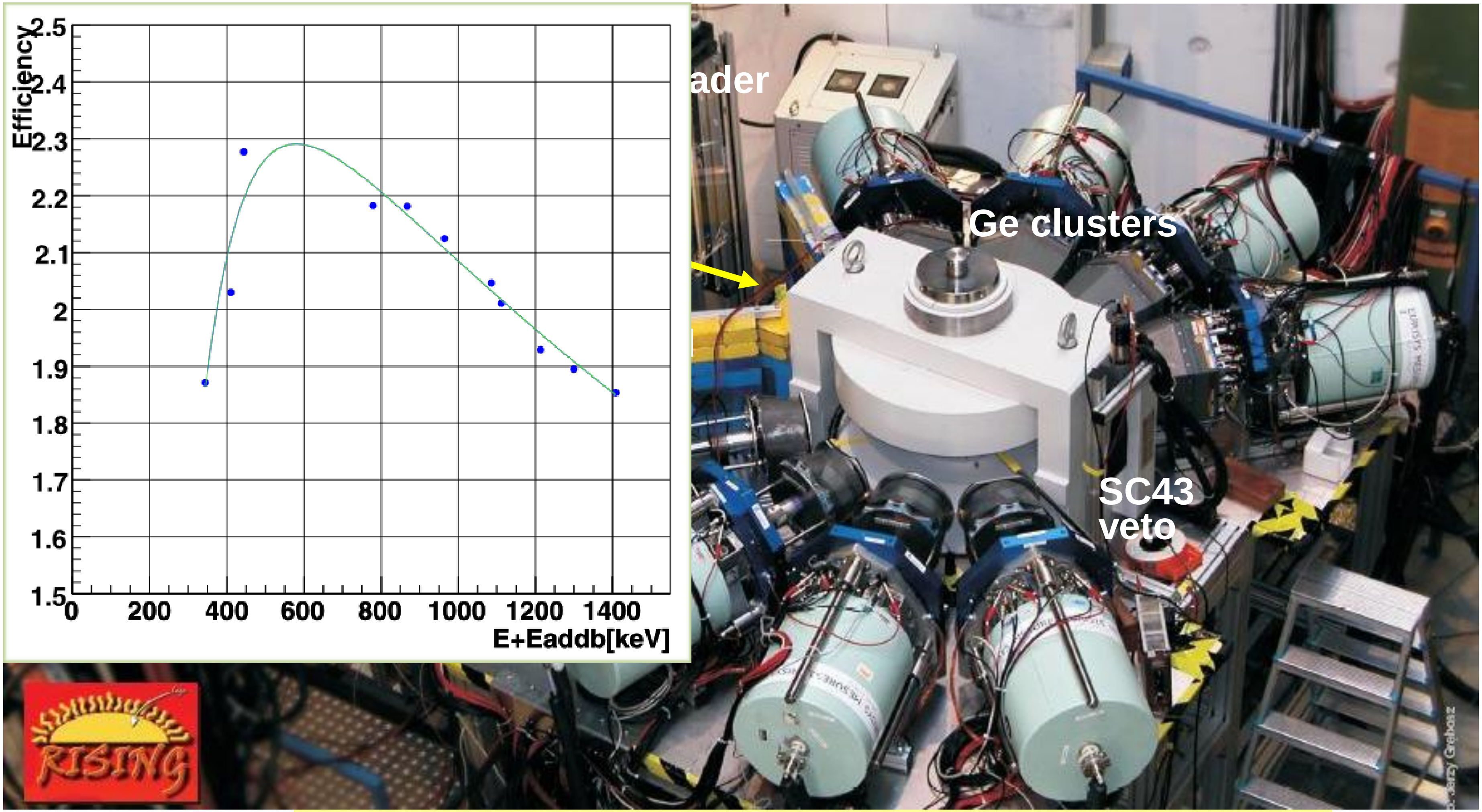


Spin-aligned secondary beam selected
(S2 slits + position selection in **SC21**)

SC41 gives t=0 signal for γ-decay time measurement

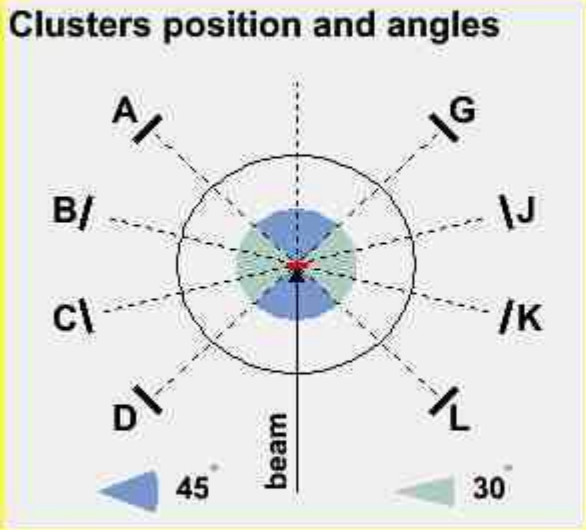
Implantation: plexiglass degrader + 2 mm Cu (annealed)

SC42 and SC43 validates the event



4 clusters with BGO anticompton shields and short collimators
4 clusters with the former RISING shields
Total efficiency (Eu source) = 1.9 – 2.3 % (from Liliya Atanosova, Sofia)

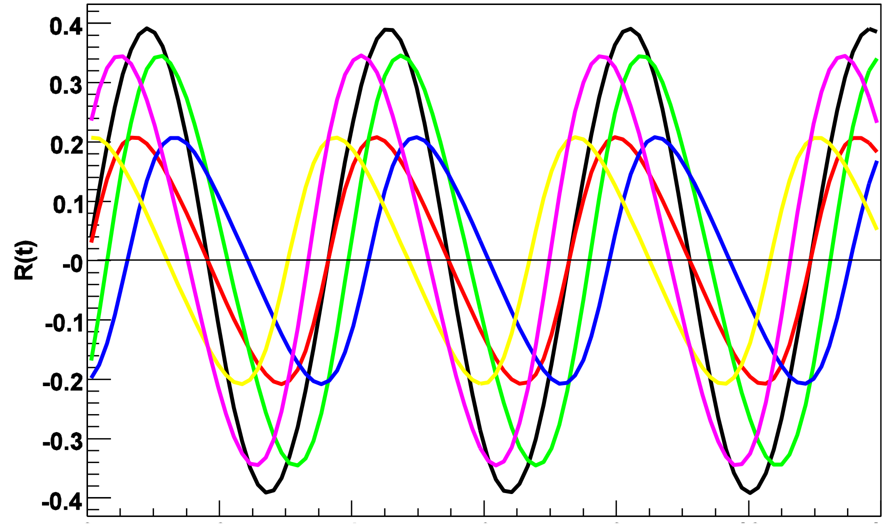
RISING collaborators are committed and highly motivated ....



$$R(t) = \frac{I_1 - \varepsilon I_2}{I_1 + \varepsilon I_2}$$

$I_1 = (A+L)\uparrow + (D+G)\downarrow$

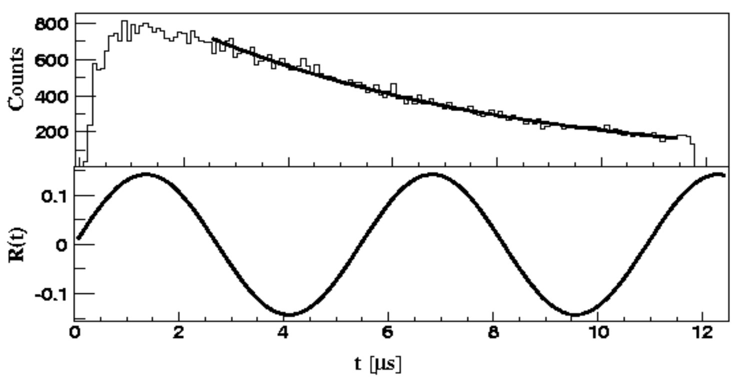
$I_2 = (A+L)\downarrow + (D+G)\uparrow$

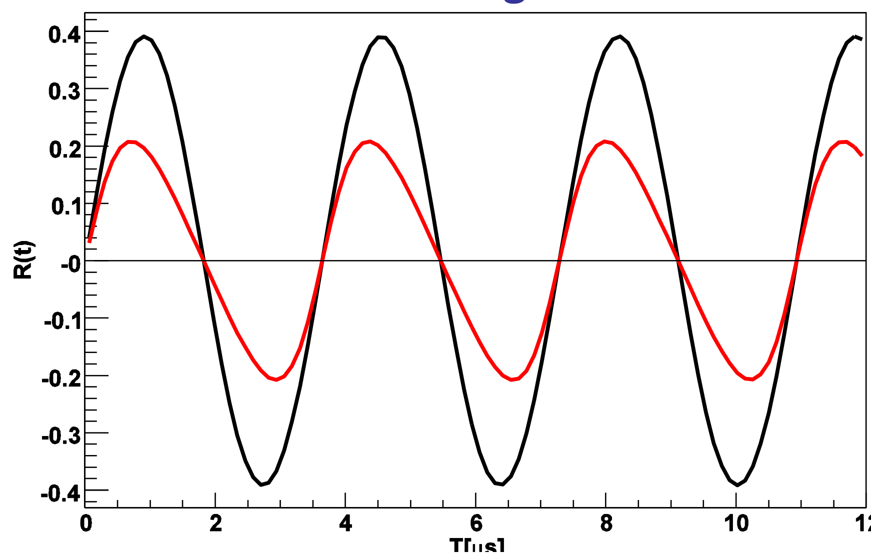


g = 0.16

Choice of the magnetic field

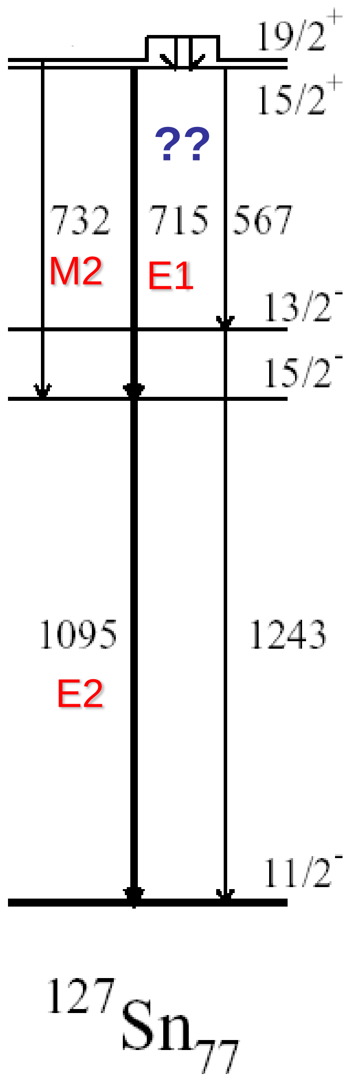
B = 0.12 T **g = - 0.1**

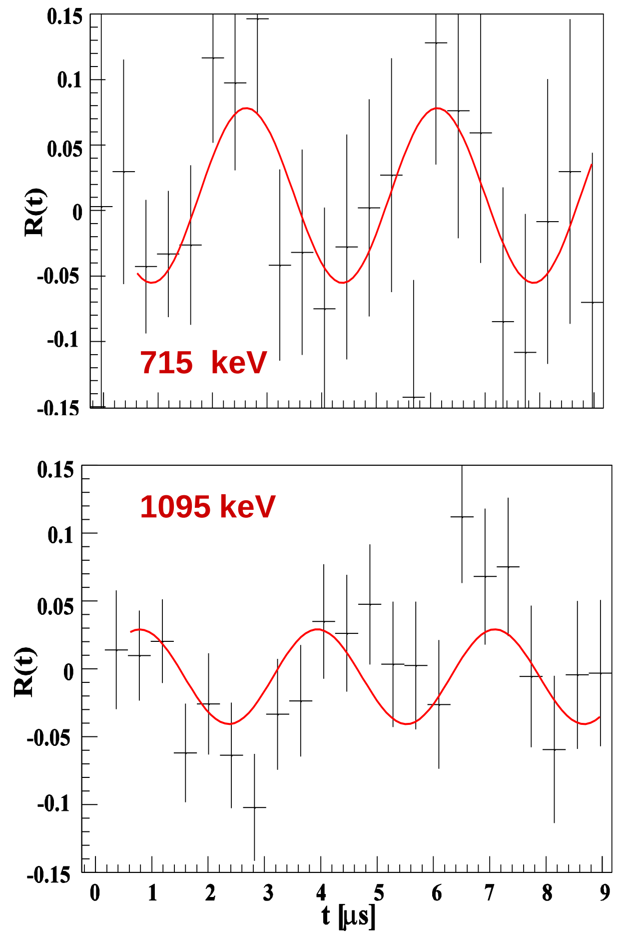


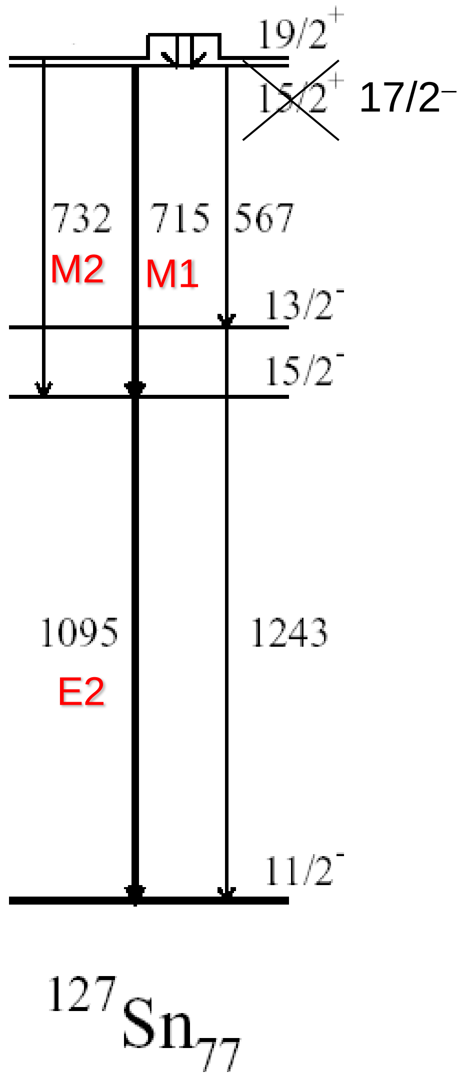


$$R(t, \pm B) = \frac{3A}{4+A}\sin(2\omega_L t)$$

Structure of 127Sn investigated







Some RISING collaborators

39 groups

9 countries

... has been a great time!!!