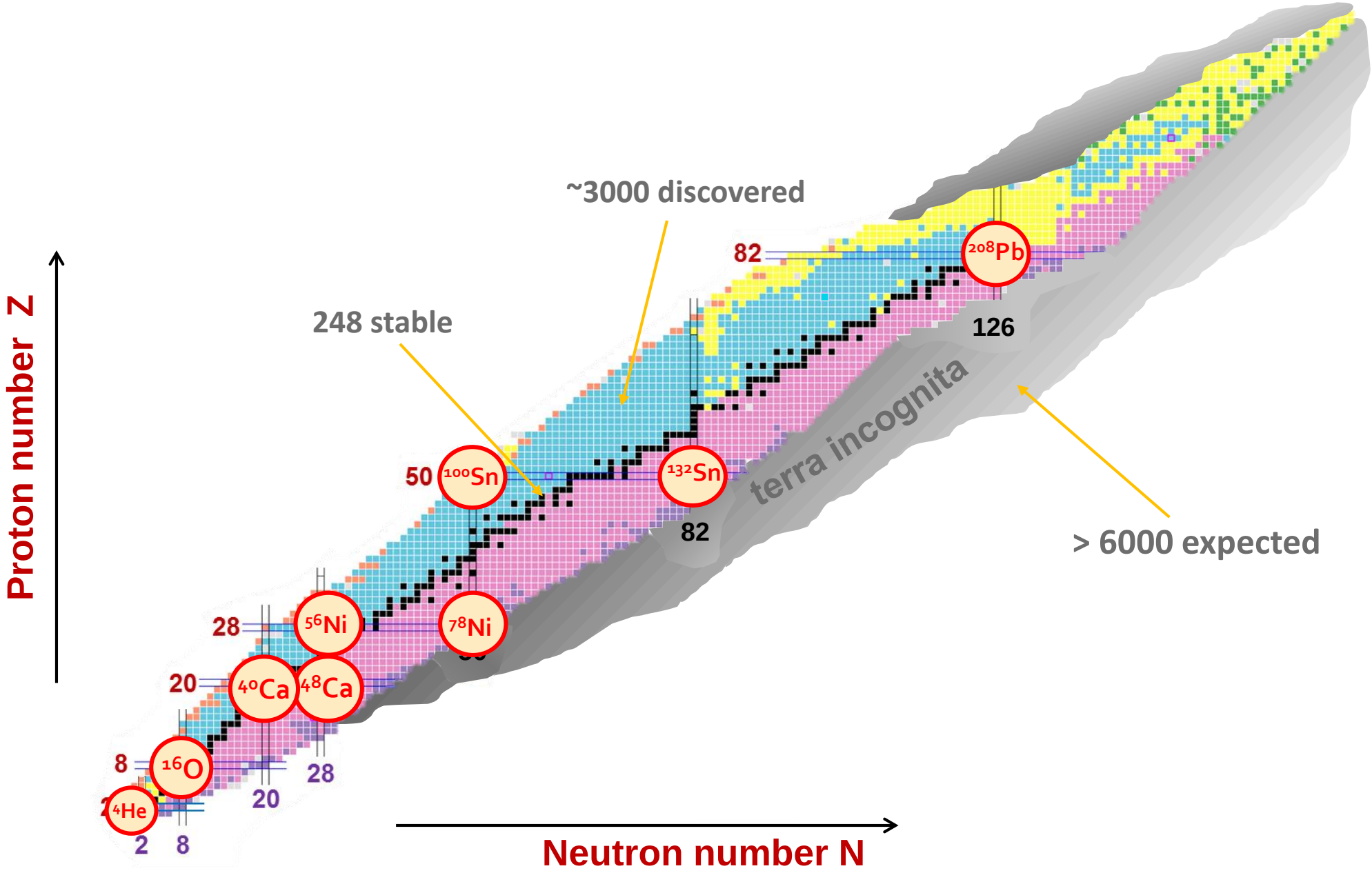
# Prompt and isomer γ-ray spectroscopy at the edges of neutron-induced fission product distributions at IFMIF/DONES

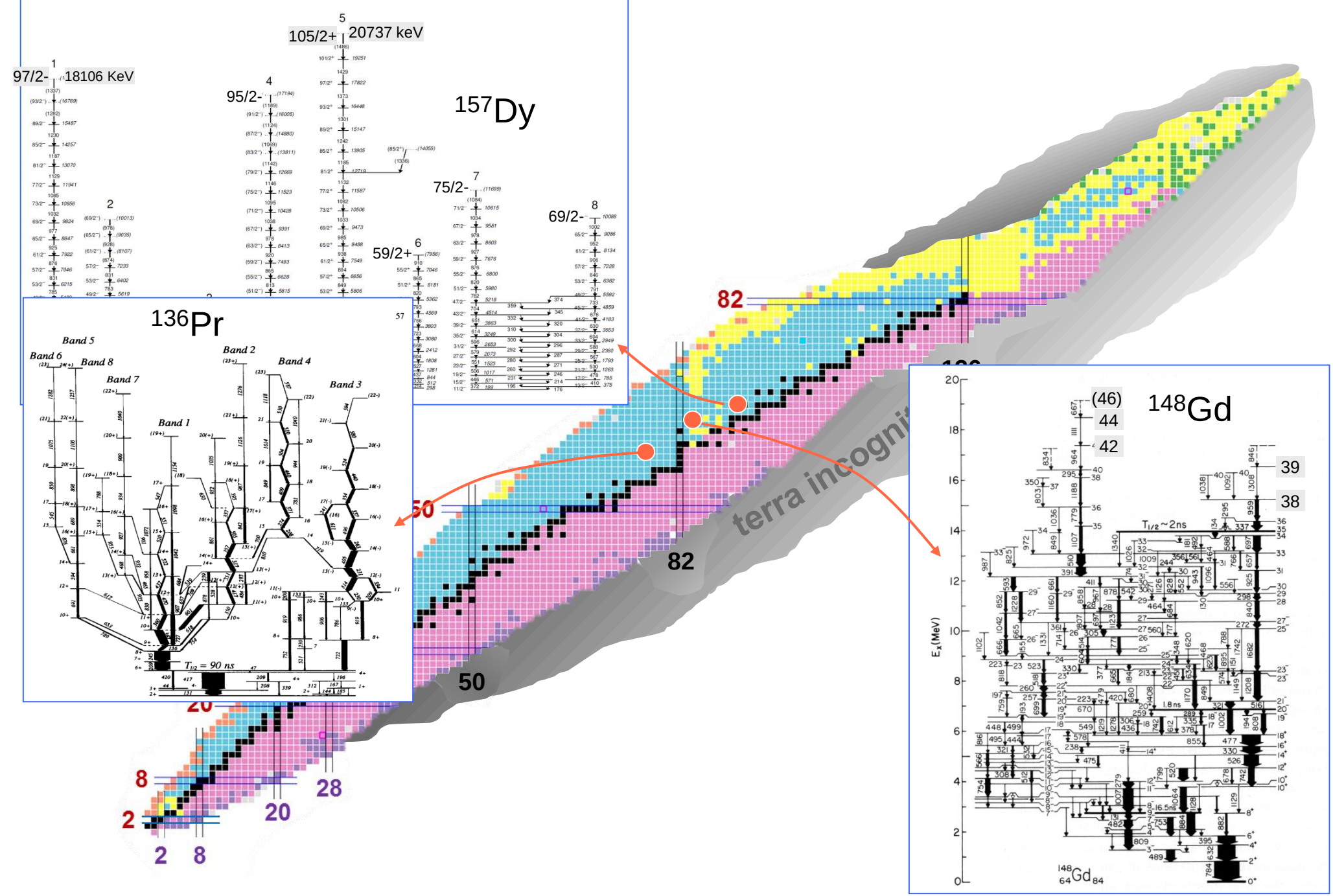
**Bogdan Fornal**

*Institute of Nuclear Physics,Polish Academy of Sciences*
*Krakow, Poland*

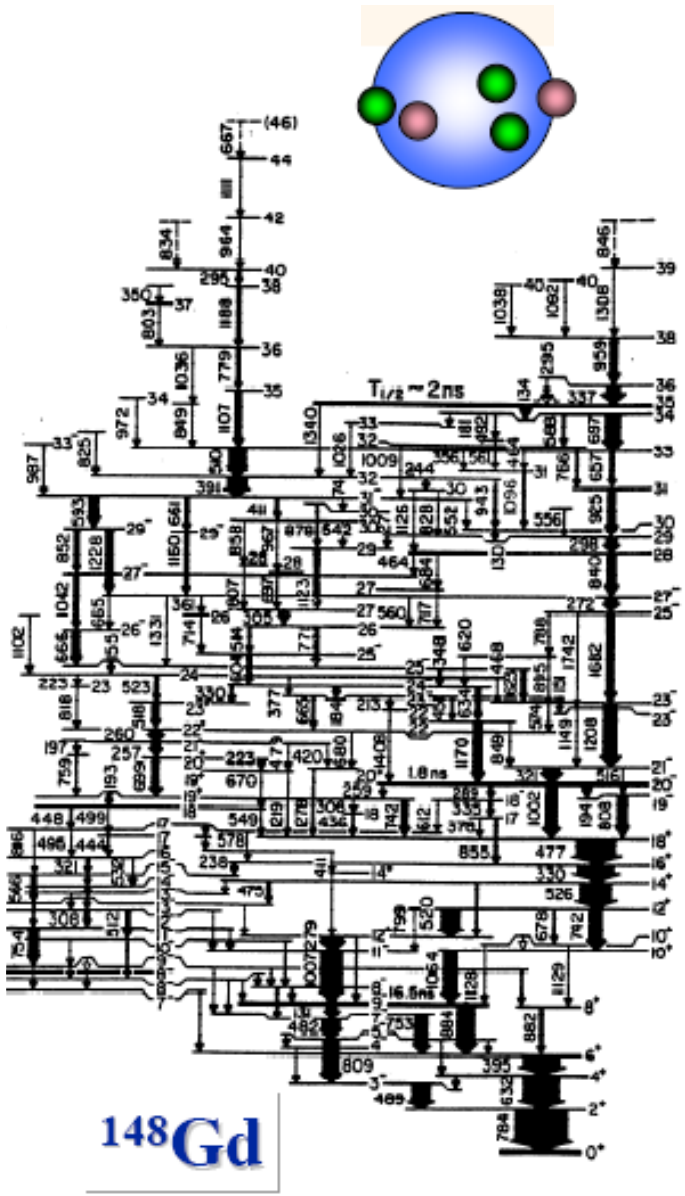
**Town Meeting on IFMIF/ELAMAT Complementary Scientific Program,**
**Rzeszow, April 14-15, 2016**

The Podkarpacie Region

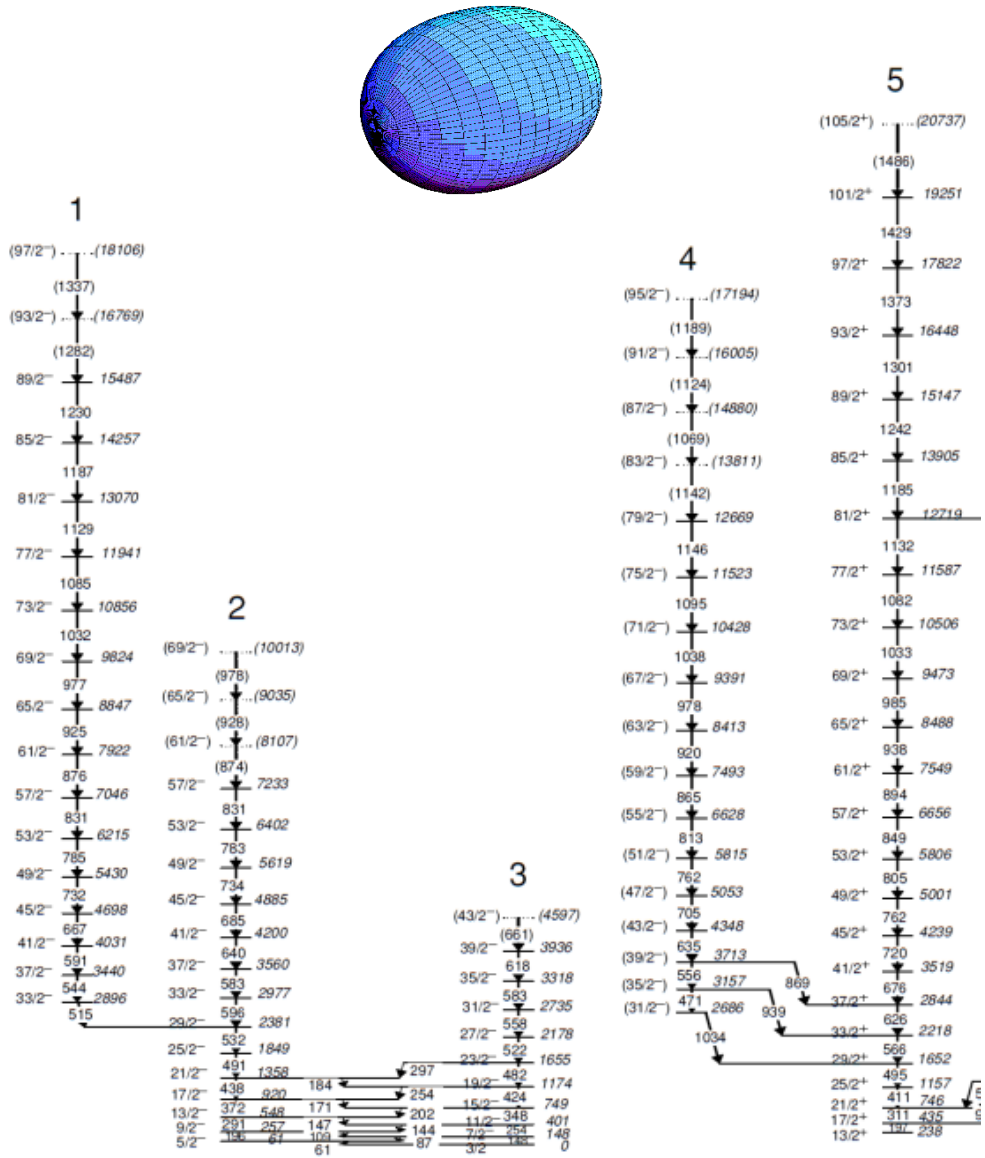

Proton number Z
Neutron number N
~3000 discovered
248 stable
> 6000 expected
terra incognita
82
126
50
82
28
20
8
2
$^{208}$Pb
$^{132}$Sn
$^{100}$Sn
$^{78}$Ni
$^{56}$Ni
$^{48}$Ca
$^{40}$Ca
$^{16}$O
$^{4}$He


97/2- 18106 KeV
105/2+ 20737 keV
95/2-
75/2-
59/2+
69/2-
157Dy
136Pr
Band 1
Band 2
Band 3
Band 4
Band 5
Band 6
Band 7
Band 8
T1/2 = 90 ns
terra incognita
82
50
28
20
8
2
148Gd
T1/2 ~2ns
1.8 ns
16.5ns
Ex (MeV)

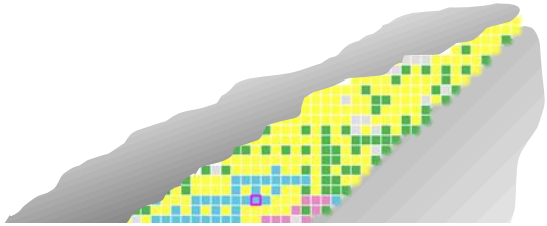
## Spherical nucleus

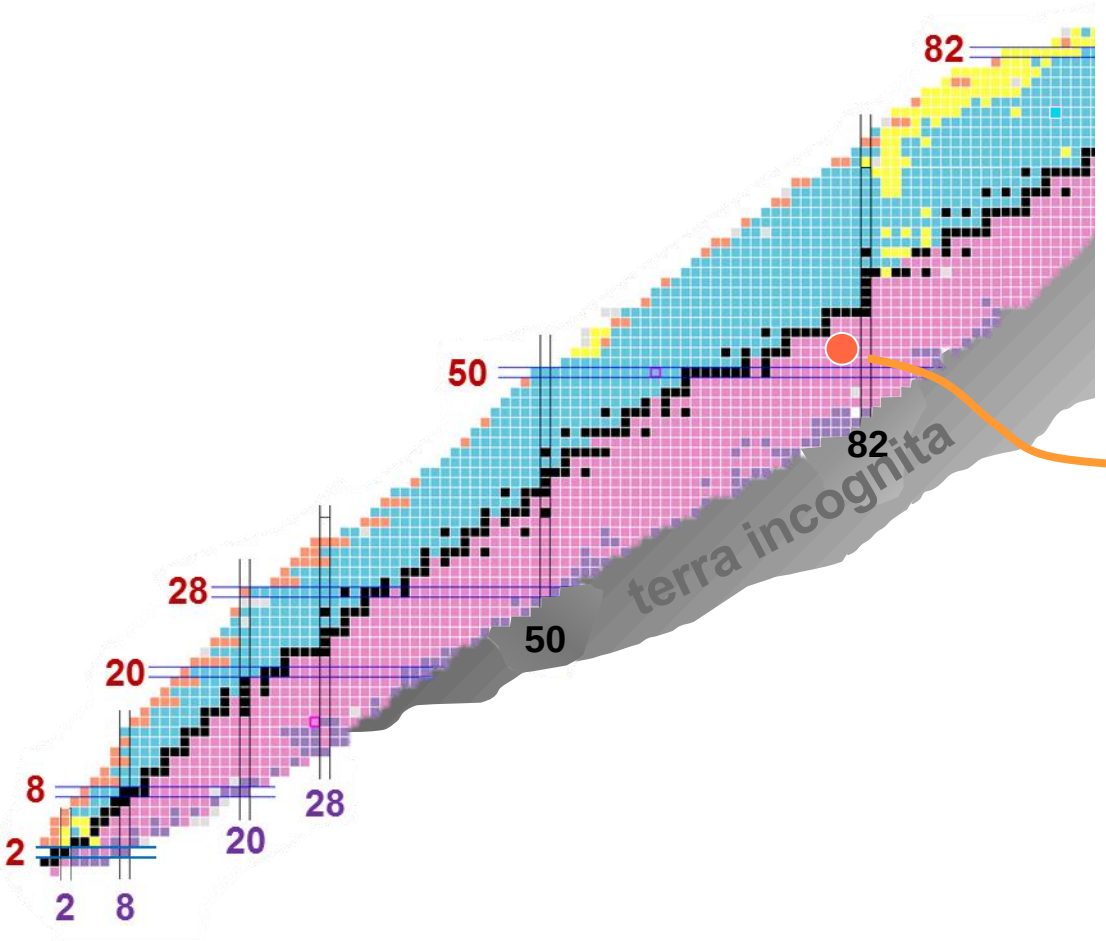


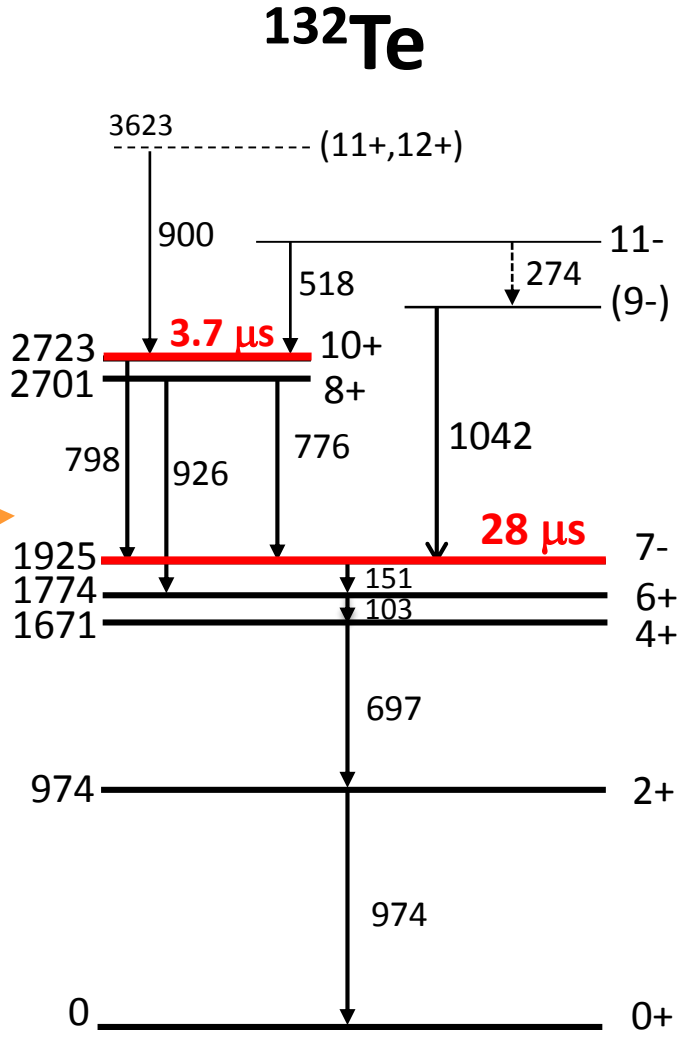

## Deformed nucleus

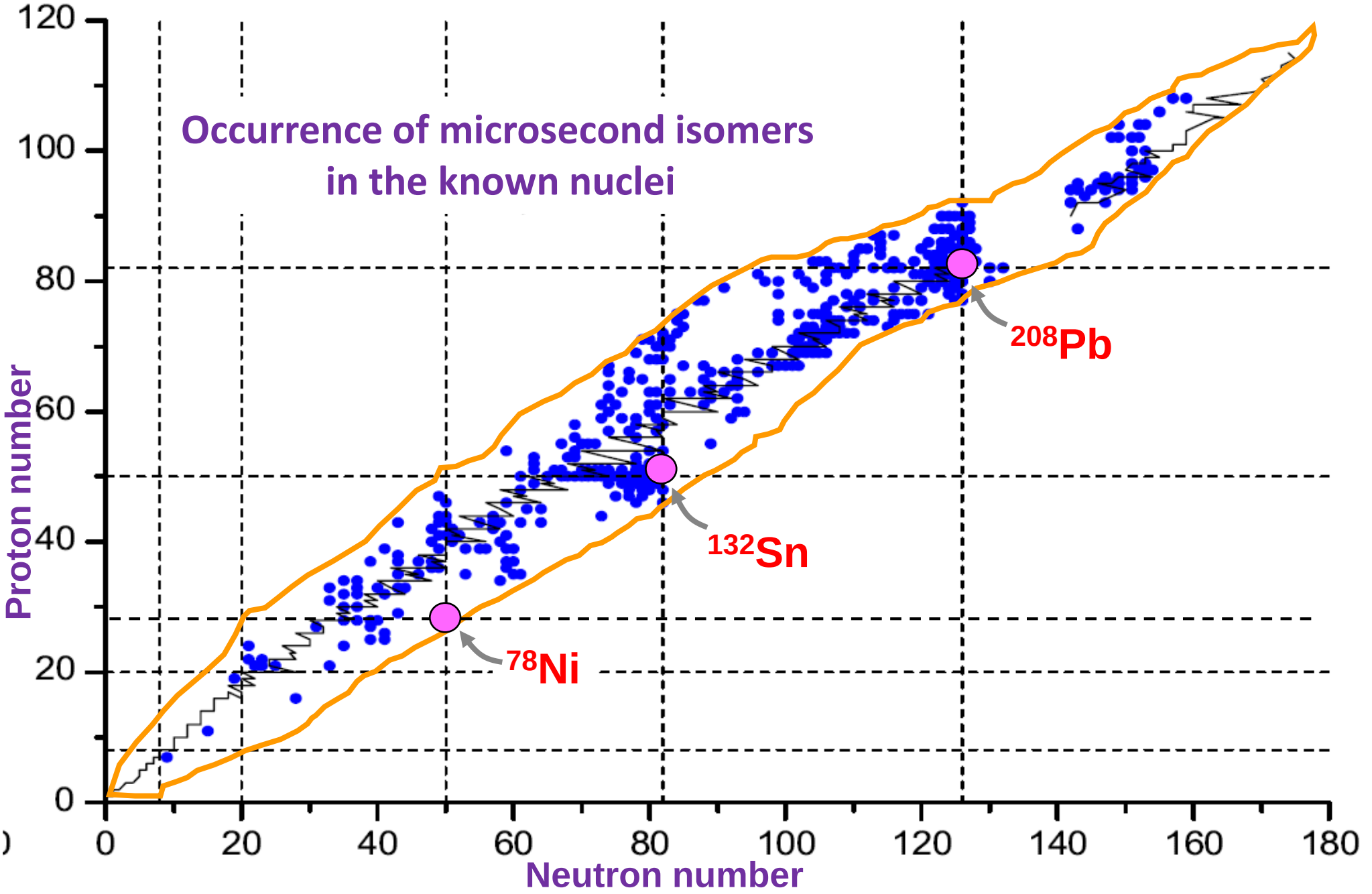


Nuclear isomers – states with half-lives ranging from nanoseconds to years - make key contributions to the understanding of nuclear structure physics.

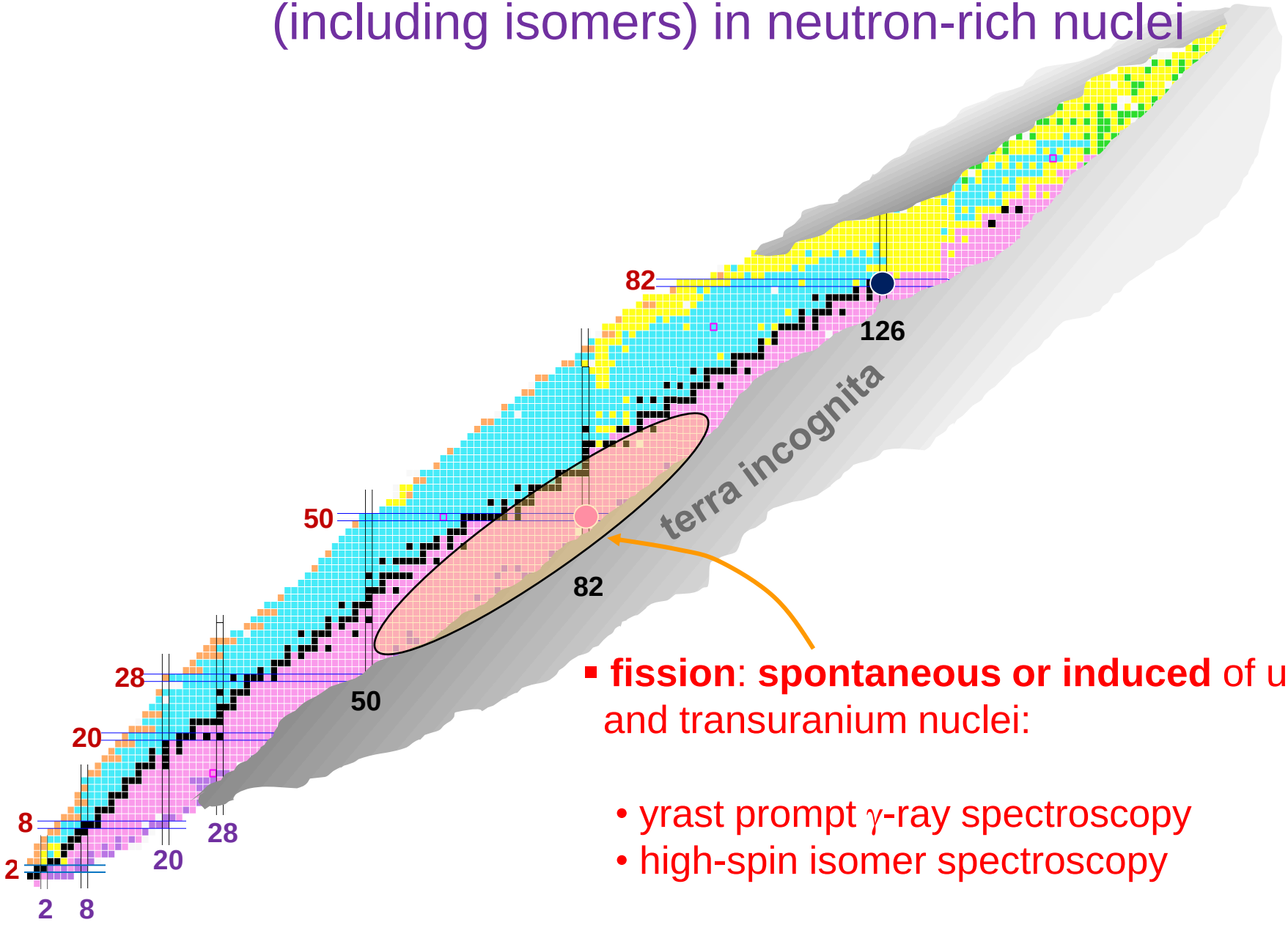




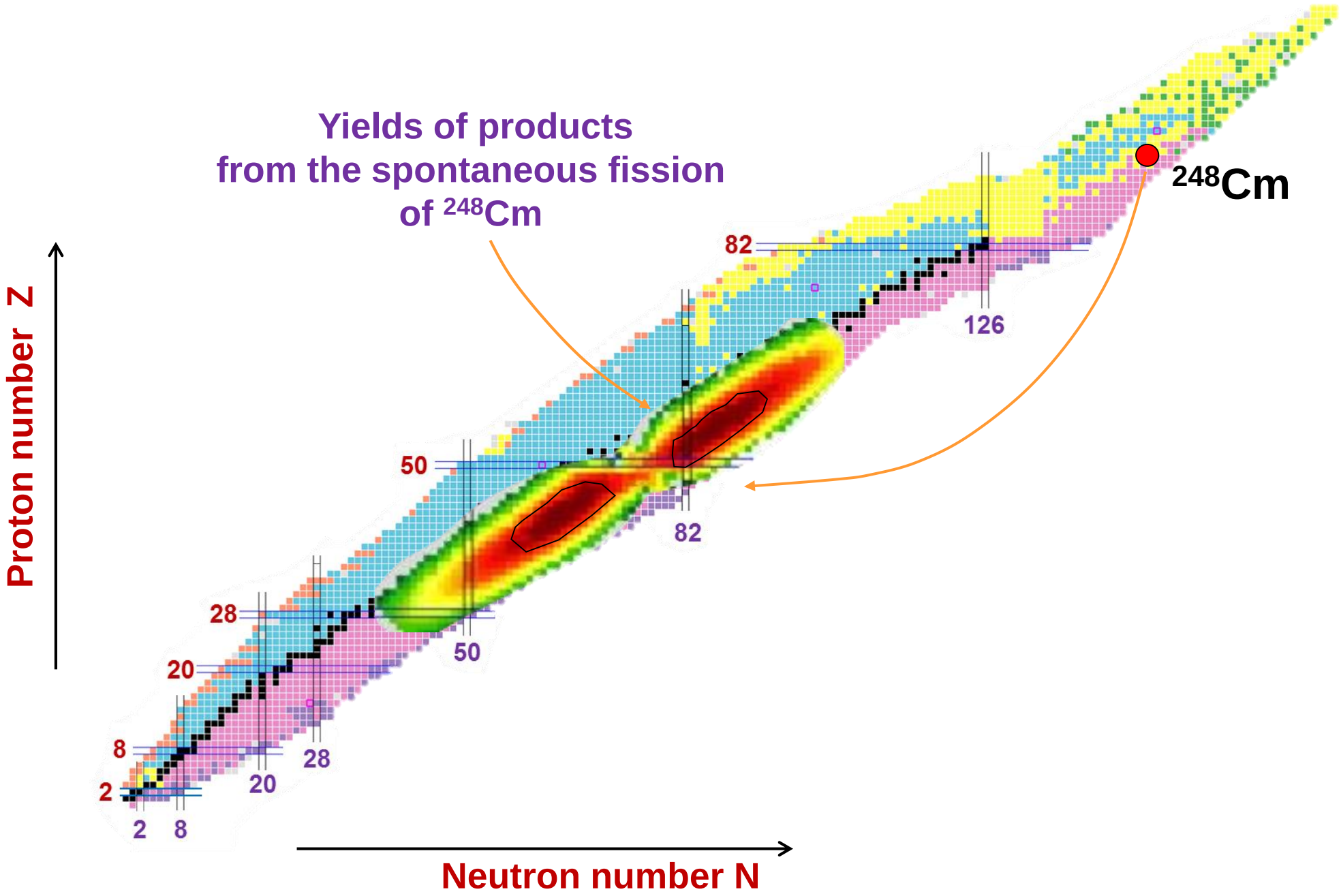

Occurrence of microsecond isomers
in the known nuclei
Proton number
Neutron number
0
20
40
60
80
100
120
140
160
180
$^{208}$Pb
$^{132}$Sn
$^{78}$Ni

# Experimental techniques used to access **excited** states (including isomers) in neutron-rich nuclei

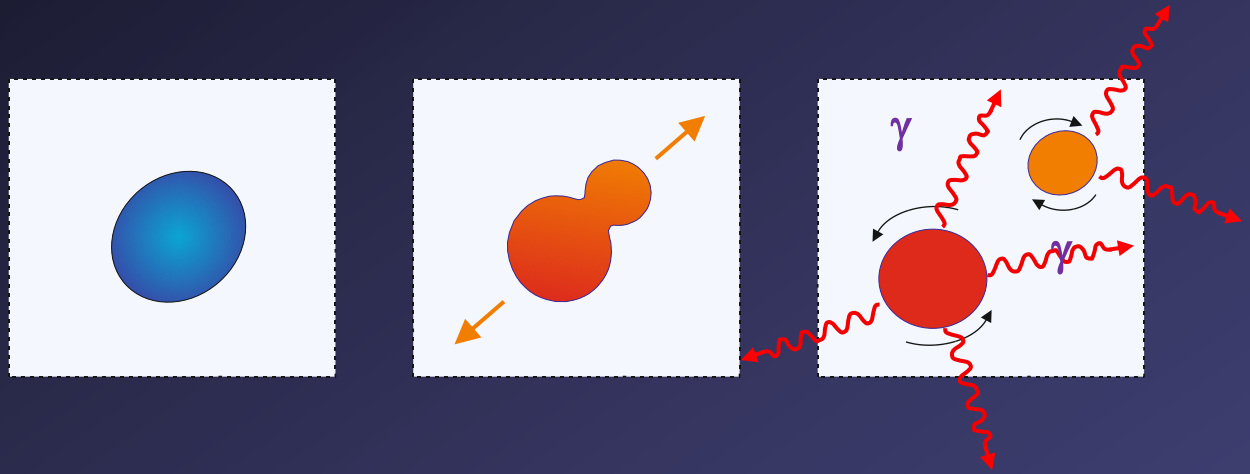



- **fission**: **spontaneous or induced** of uranium and transuranium nuclei:

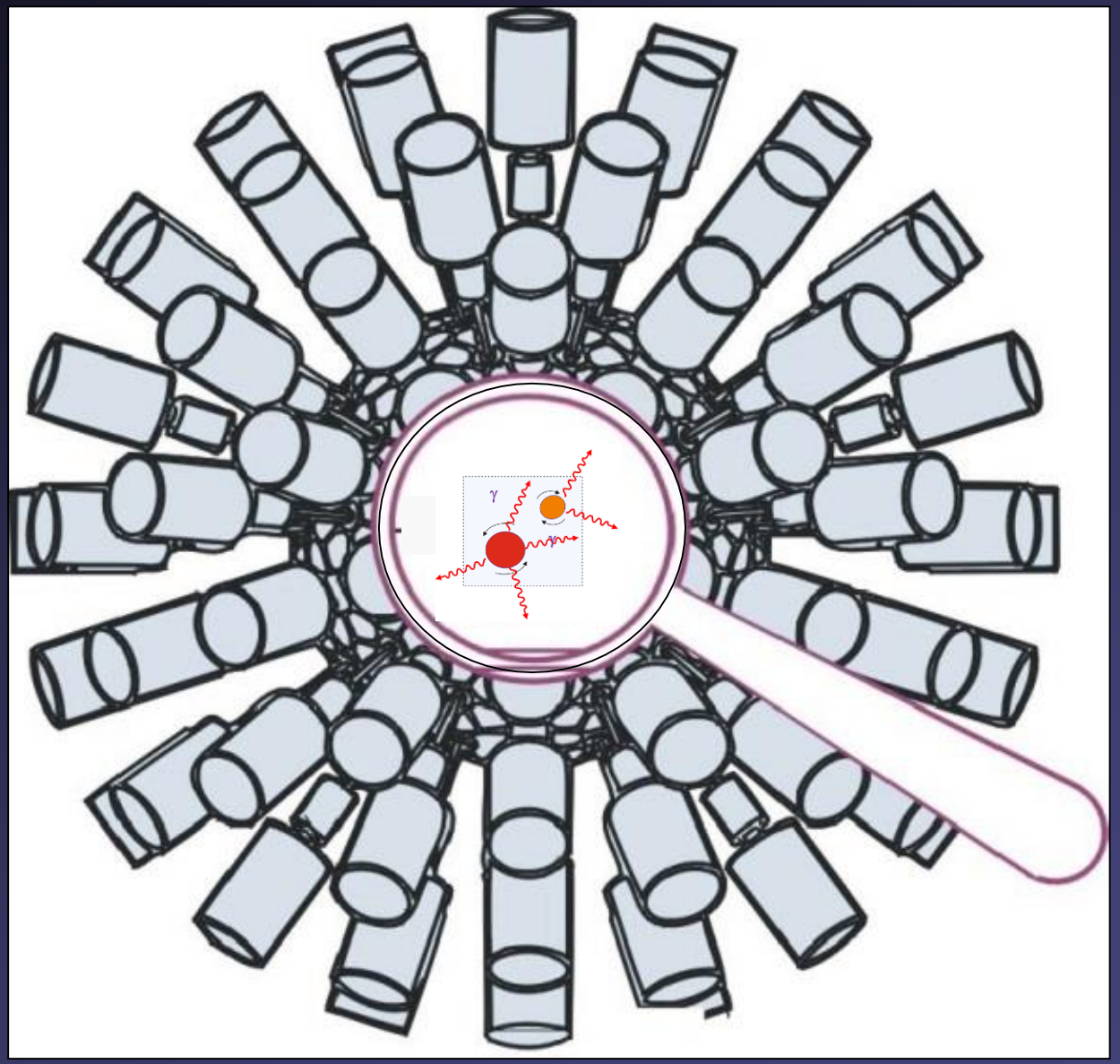
  - yrast prompt $\gamma$-ray spectroscopy
  - high-spin isomer spectroscopy


Yields of products
from the spontaneous fission
of 248Cm
248Cm
Proton number Z
Neutron number N
82
126
50
82
28
50
20
8
28
2
20
2
8

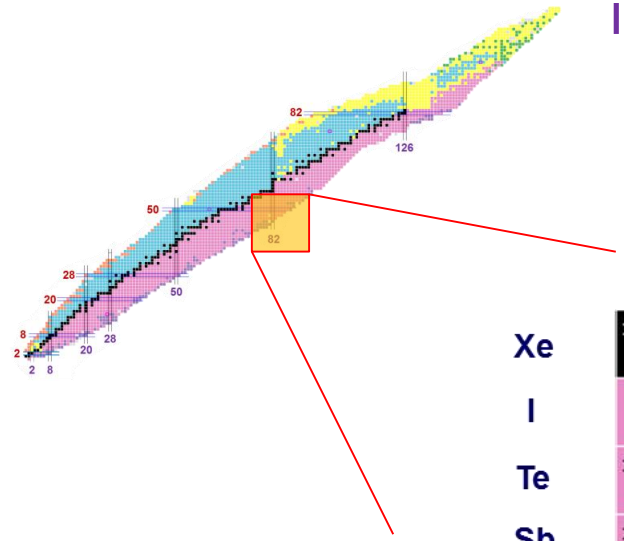
# Discrete gamma-ray spectroscopy of neutron-rich nuclei by using spontaneous fission and the thick target technique

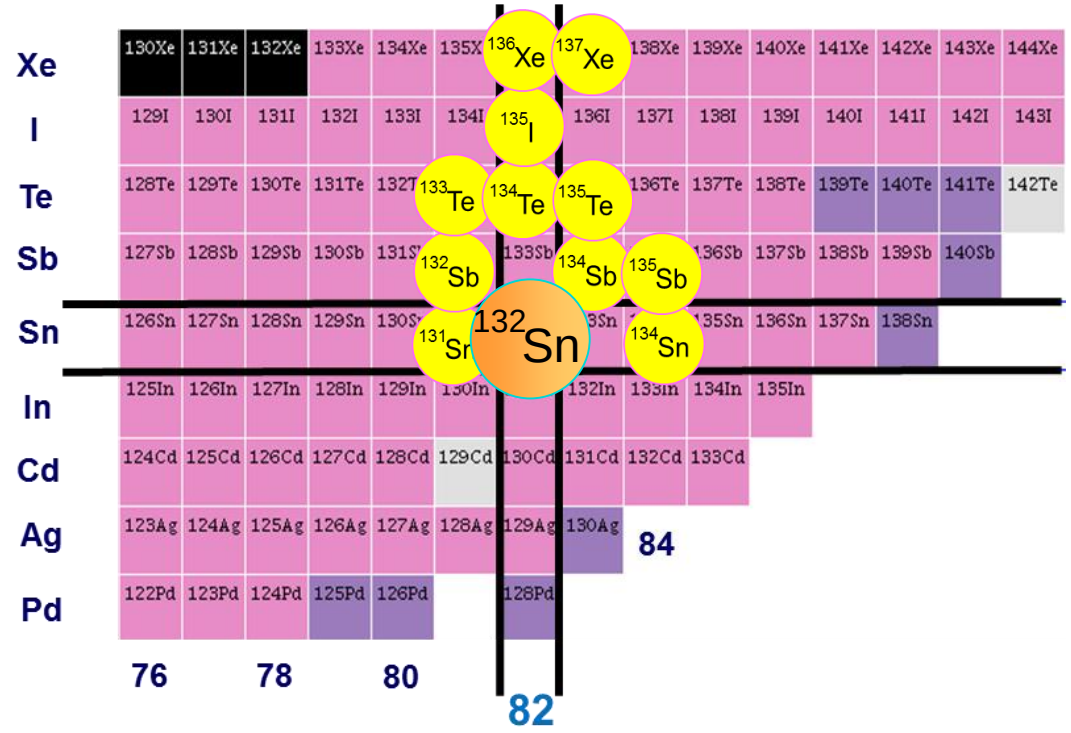


# Measuring γ rays from spontaneous fission products by using the thick-target technique

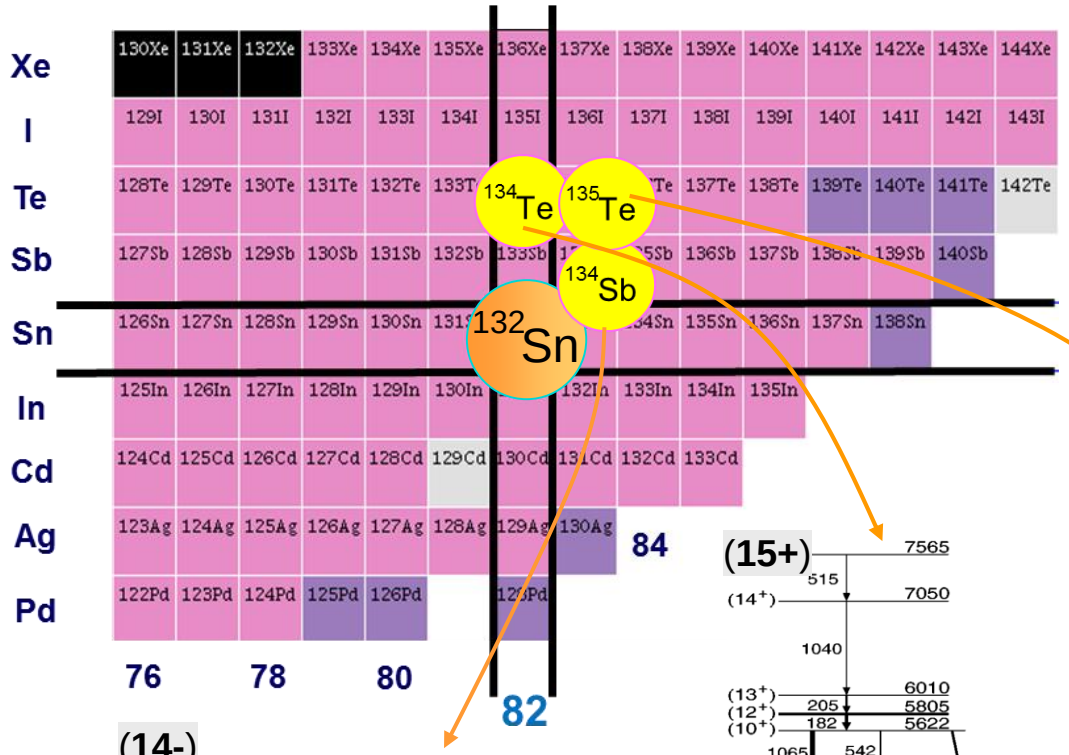


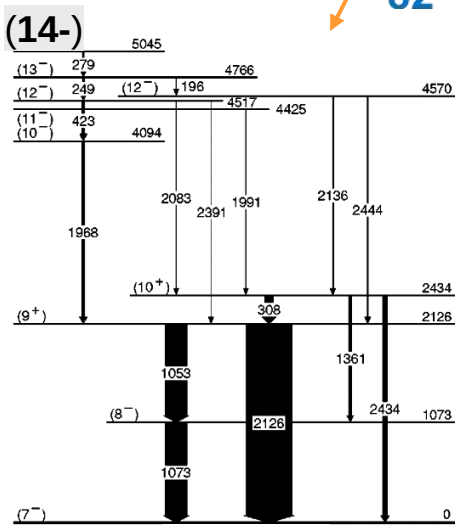
# The nuclei around $^{132}$Sn produced in <u>spontaneous fission of $^{248}$Cm</u> in which we have identified excited structures by using $\gamma$–$\gamma$–$\gamma$ coincidence thick-target technique with GAMMASPHERE at Argonne NL (USA)



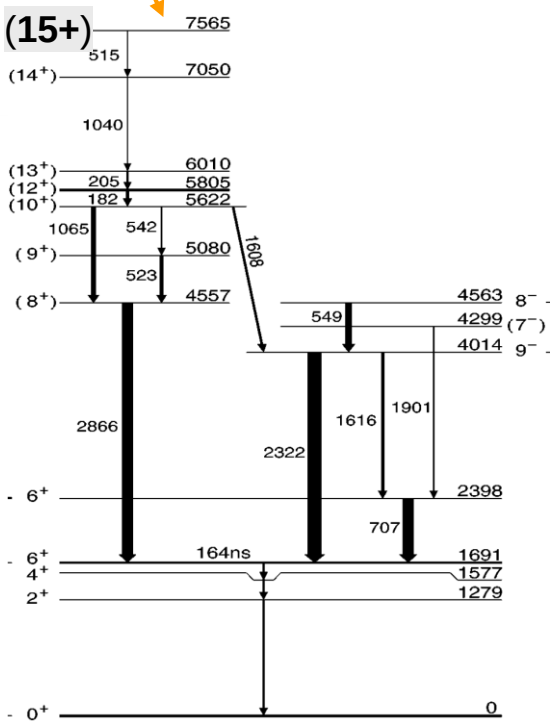
Structure of most neutron-rich nuclei around $^{132}$Sn produced in the spontaneous fission of $^{248}$Cm studied by using γ–γ–γ coincidence thick-target technique with GAMMASPHERE (USA)



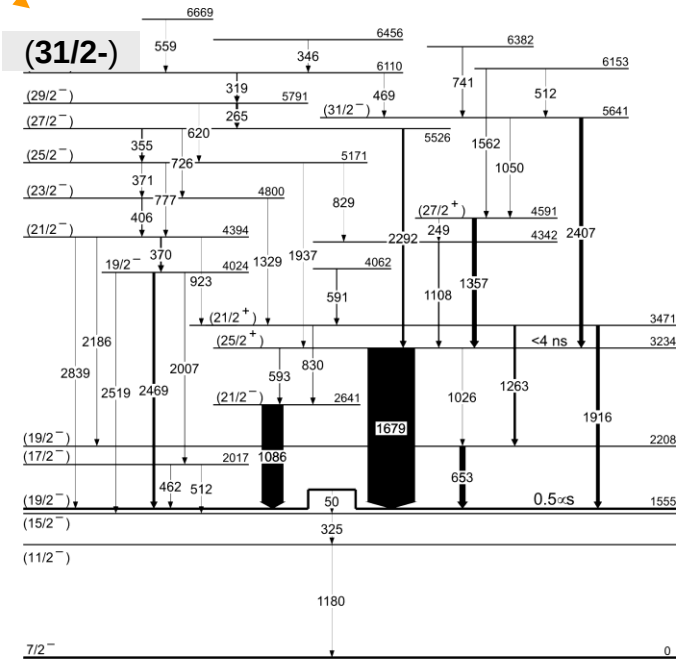

$^{134}$Sb

B. F. *et al.*, PRC 63, (2001)



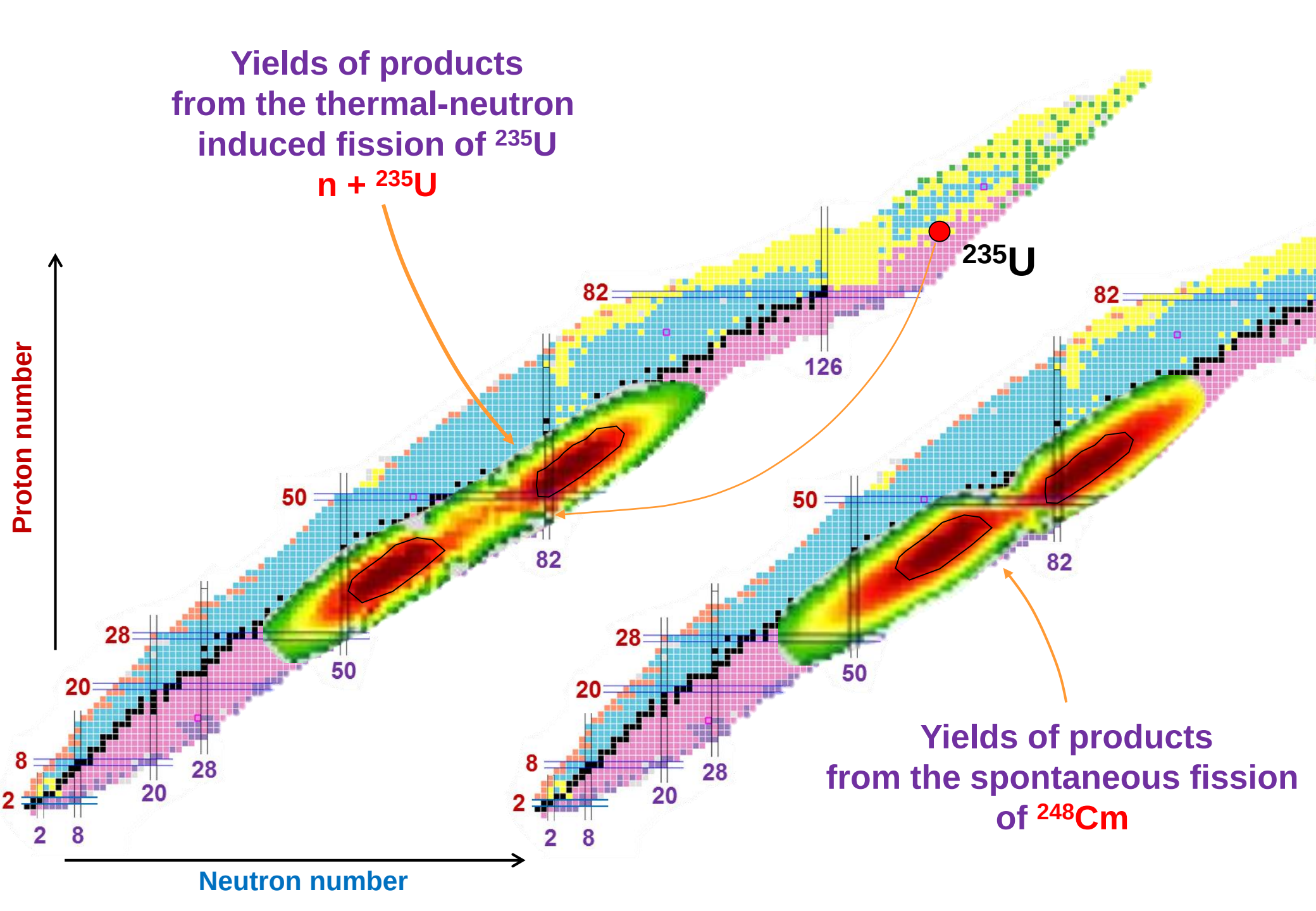

$^{134}$Te

C.T. Zhang *et al.*, PRL 77, (1996)

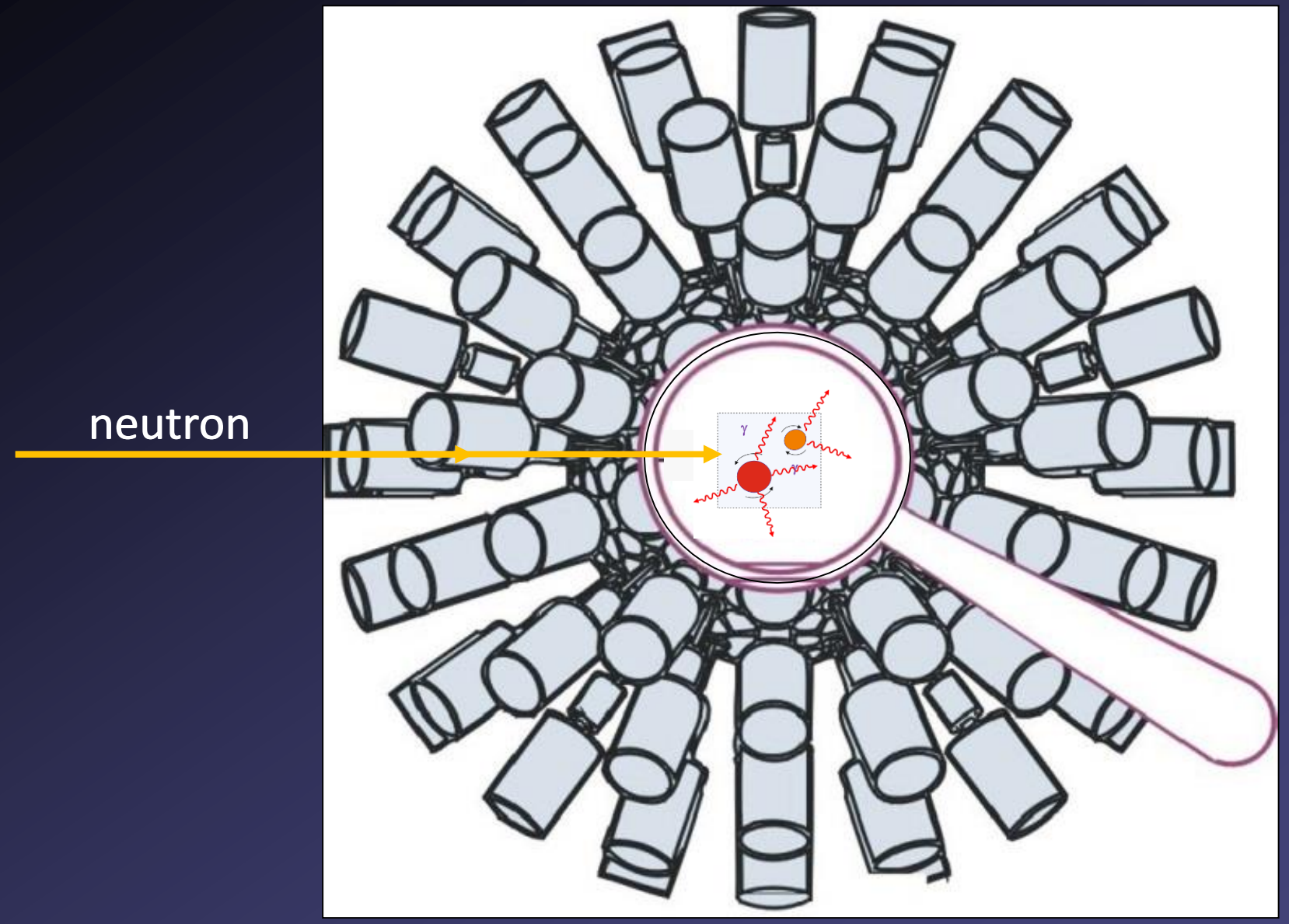



$^{135}$Te

B. F. *et al.*, PRC 63, (2001)

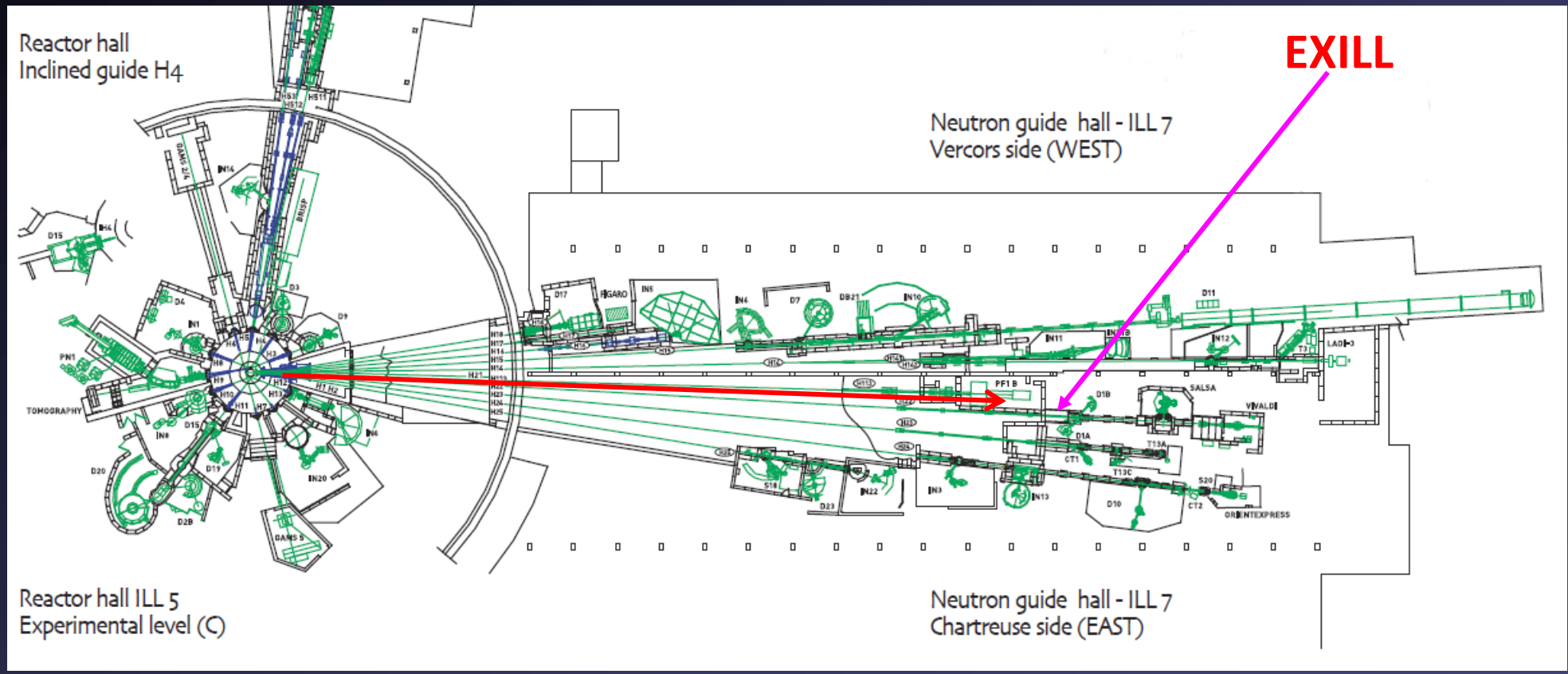

Yields of products
from the thermal-neutron
induced fission of $^{235}U$
n + $^{235}U$
$^{235}U$
Proton number
Neutron number
82
126
50
82
28
50
20
28
8
20
2
2
8
82
50
82
28
50
20
28
8
20
2
2
8
Yields of products
from the spontaneous fission
of $^{248}Cm$

# Measuring gamma rays from the neutron-induced fission products by using a thick-target technique



# The γ-spectroscopy campaign @ ILL-Reactor (Grenoble)

## 2012-2013: 100 days, 95% DATA taking




**World brightest continuum neutron source.**

In pile

$\Phi_n = 5\times10^{14}$ n cm$^{-2}$ s$^{-1}$

**Dedicated ballistic neutron guide; highly collimated beam (1 cm$^2$); cold neutrons (meV);**

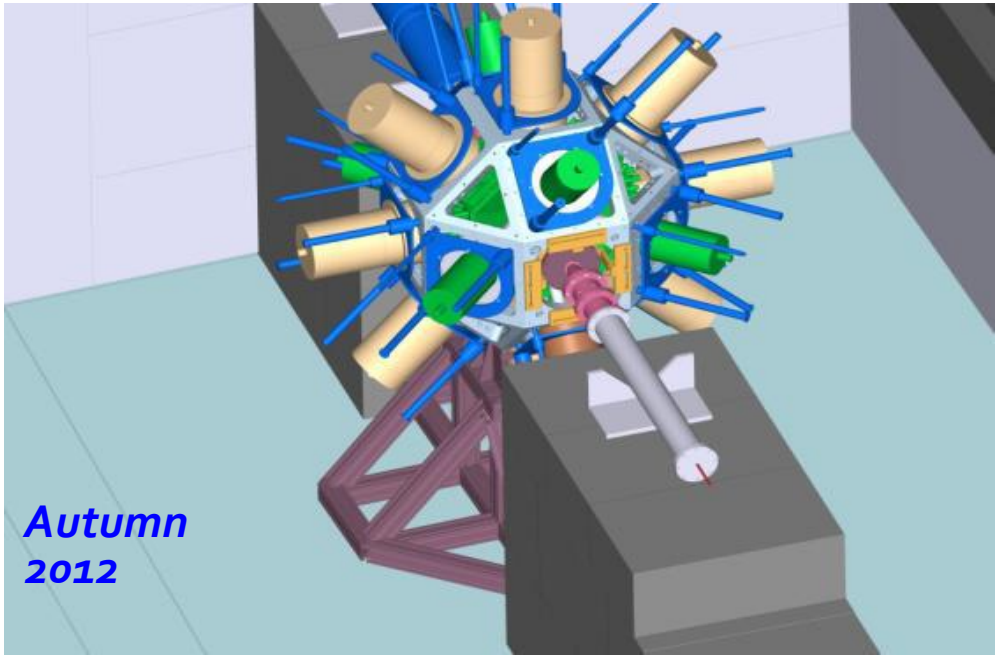
$\Phi_n = 2\times10^{8}$ n cm$^{-2}$ s$^{-1}$

**First time** a **large HPGe array** (52 Ge crystals)
installed around a **highly collimated cold-neutron beam**

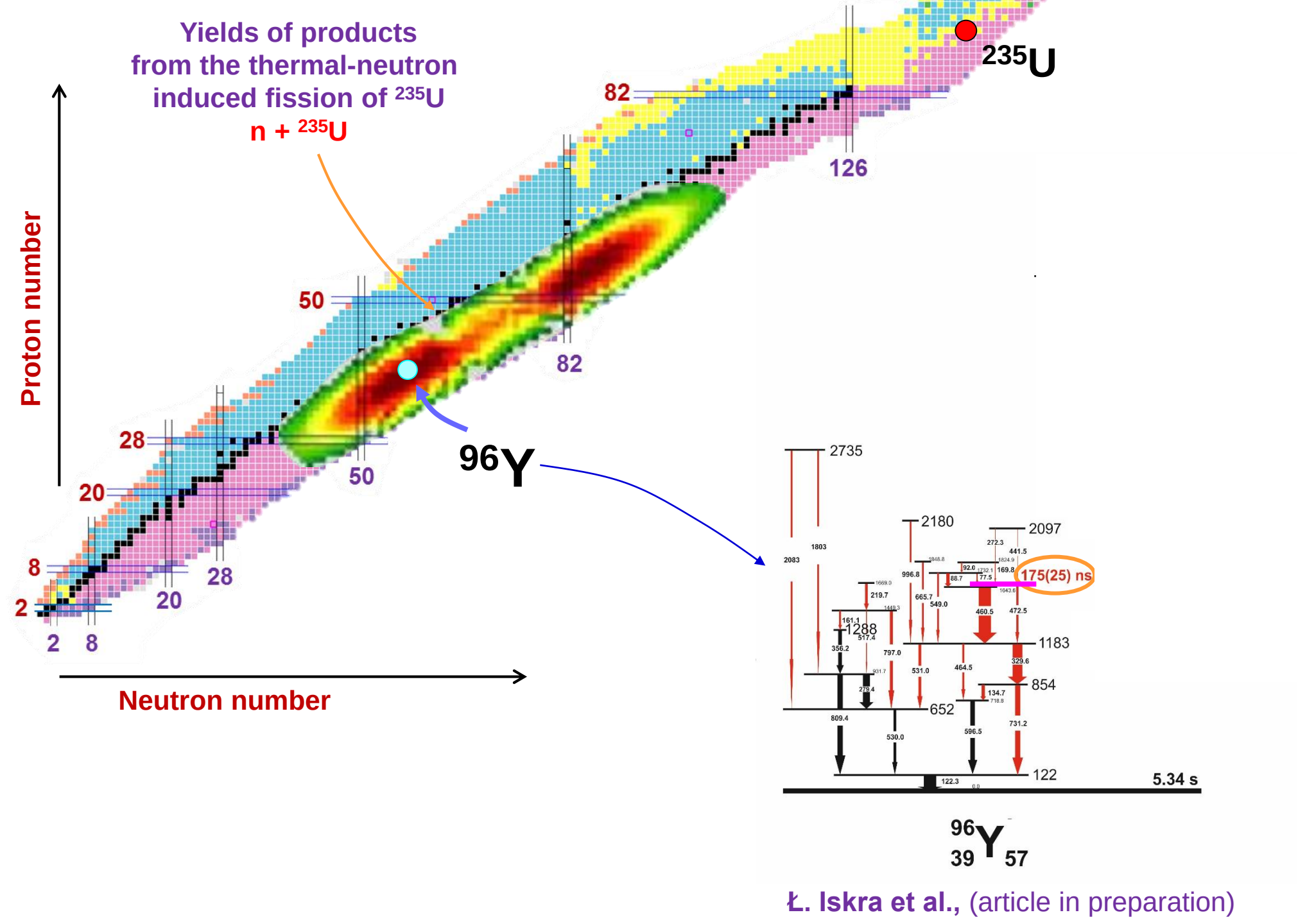
**SETUP 1**

**$\gamma$ – spectroscopy**

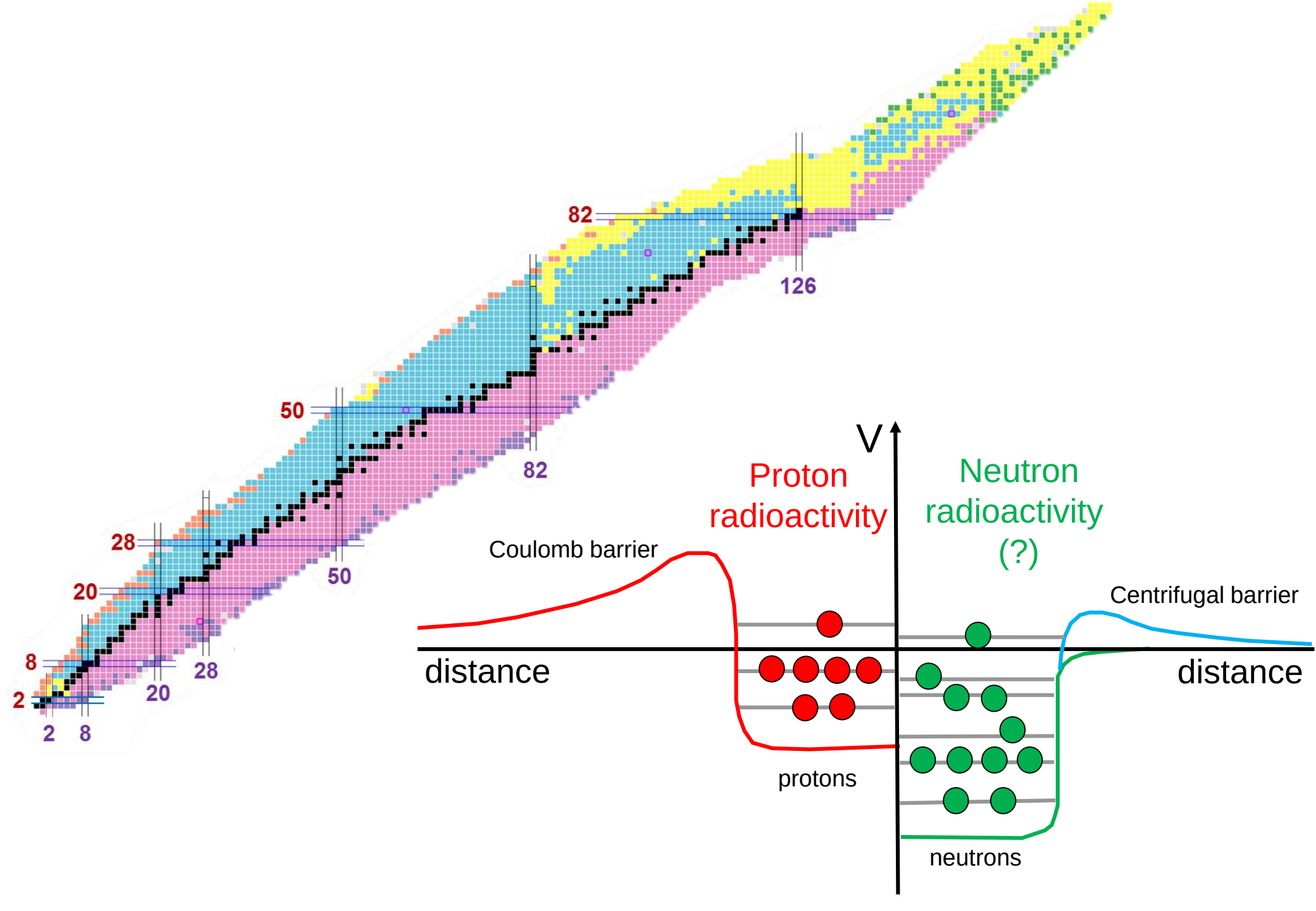
10 EXOGAM – Clovers + 6 Ge GASP
**6% efficiency**



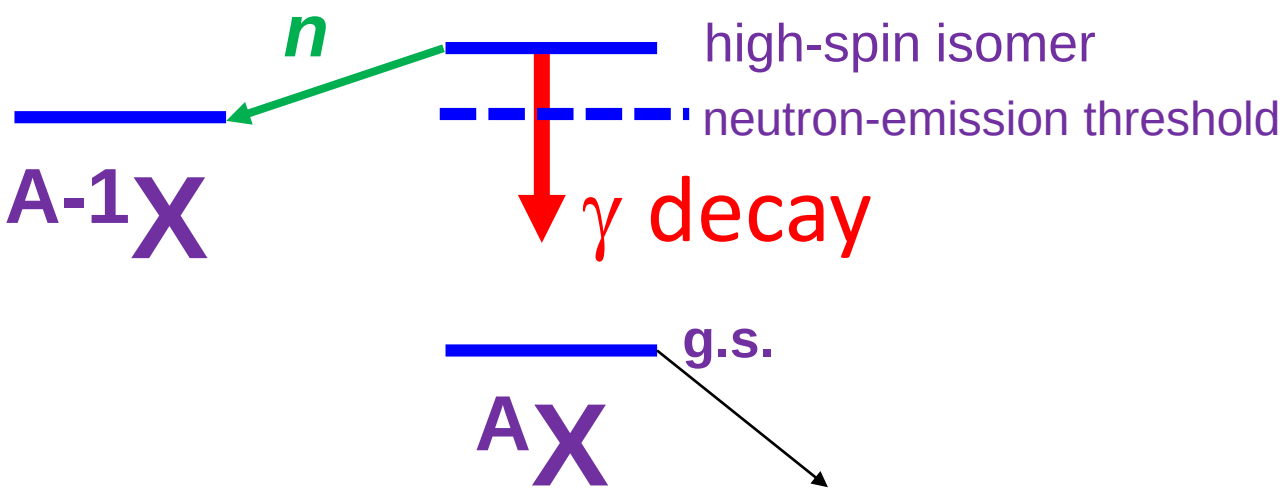

→ cold-neutron induced **fission** on $^{235}$**U** and $^{241}$**Pu**

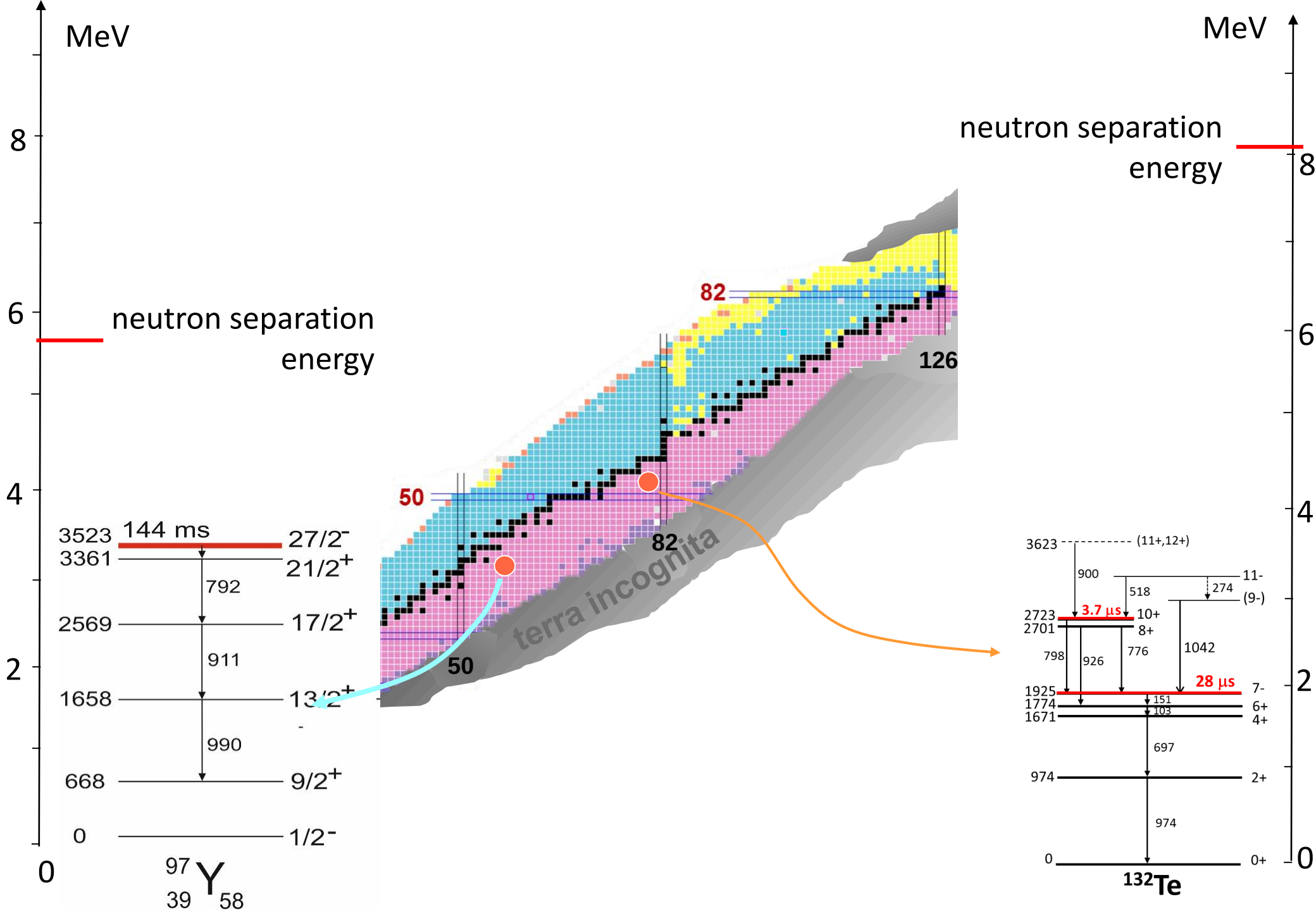


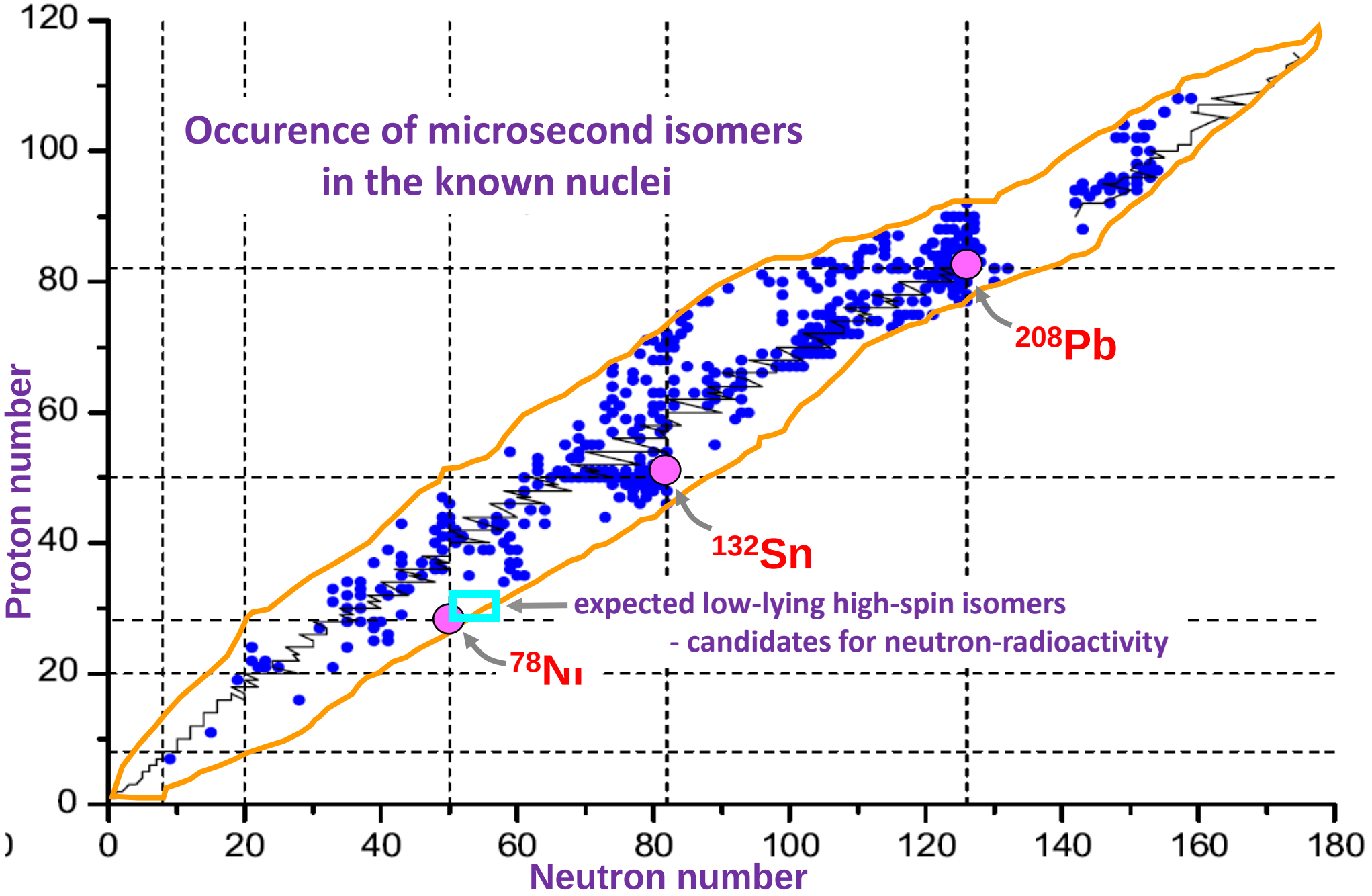

**Ł. Iskra et al.,** (article in preparation)

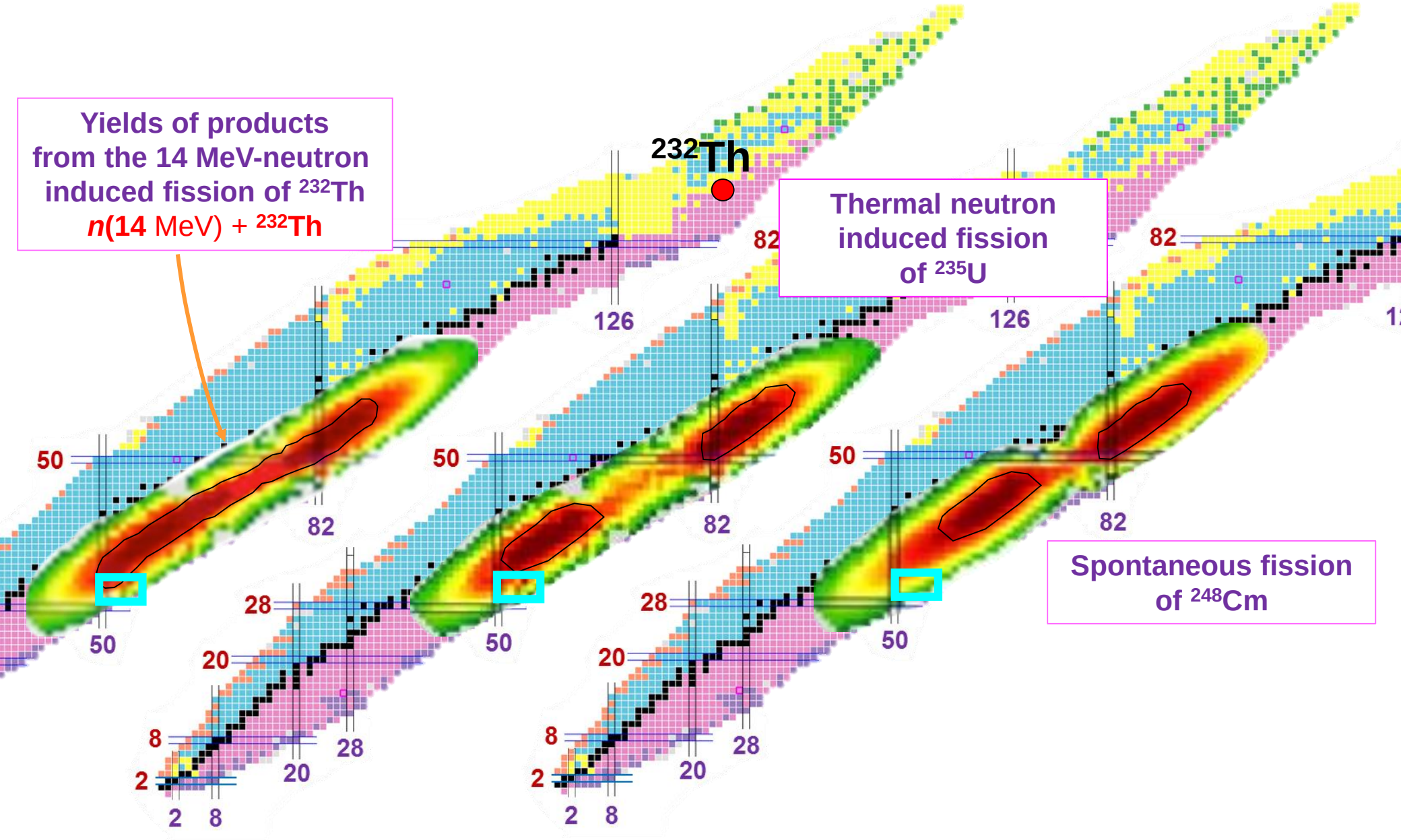

82
126
50
82
28
50
20
28
8
20
2
2
8
V
Proton
radioactivity
Neutron
radioactivity
(?)
Coulomb barrier
Centrifugal barrier
distance
distance
protons
neutrons

# Neutron radioactivity




MeV
8
6
4
2
0
neutron separation energy
3523 144 ms 27/2⁻
3361 21/2⁺
792
2569 17/2⁺
911
1658 13/2⁺
990
668 9/2⁺
0 1/2⁻
97 39 Y 58
50
82
126
terra incognita
MeV
neutron separation energy
3623 (11+,12+)
900
518
274
11-
(9-)
2723 3.7 µs 10+
2701 8+
798
926
776
1042
1925 28 µs 7-
1774 6+
1671 4+
151
103
697
974 2+
974
0 0+
132Te

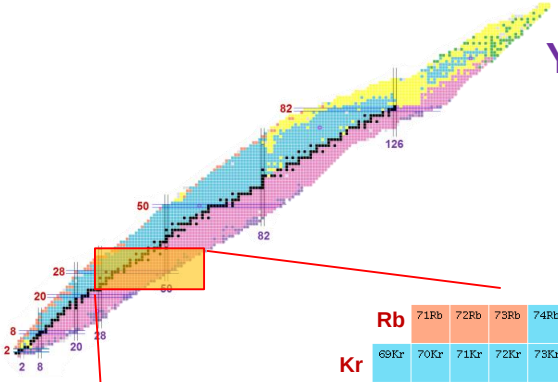

Occurence of microsecond isomers
in the known nuclei
$^{208}$Pb
$^{132}$Sn
expected low-lying high-spin isomers
- candidates for neutron-radioactivity
$^{78}$Ni
Proton number
Neutron number
0
20
40
60
80
100
120
140
160
180

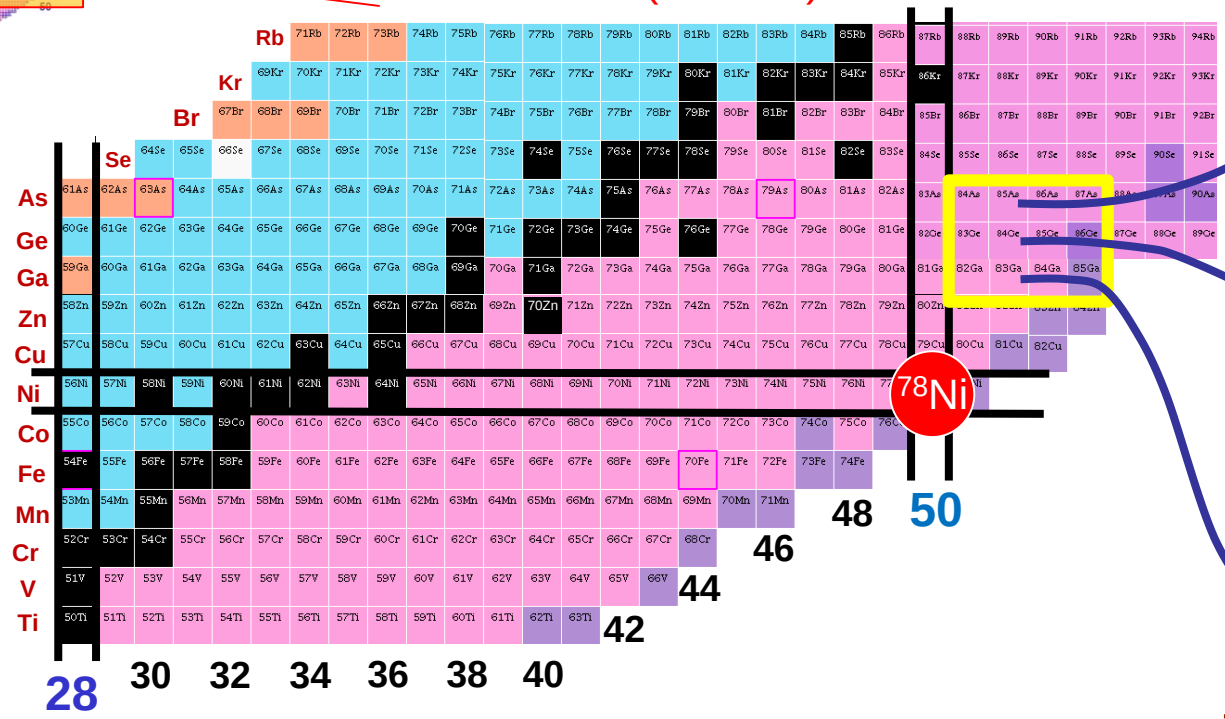

Yields of products from the 14 MeV-neutron induced fission of $^{232}$Th
*n*(14 MeV) + $^{232}$Th
$^{232}$Th
Thermal neutron induced fission of $^{235}$U
Spontaneous fission of $^{248}$Cm
126
82
50
28
20
8
2

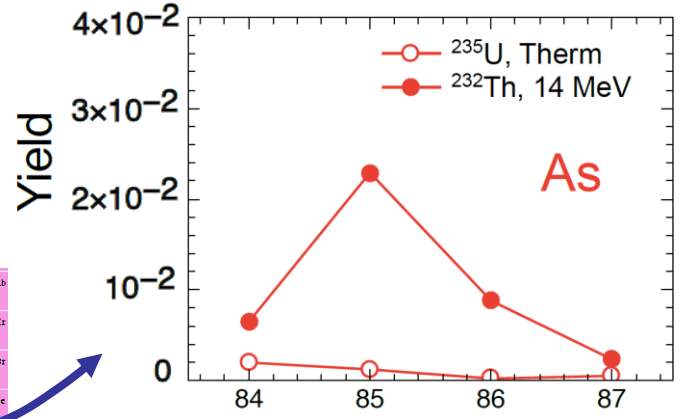
# Yields of products from the neutron induced fission in the region of interest

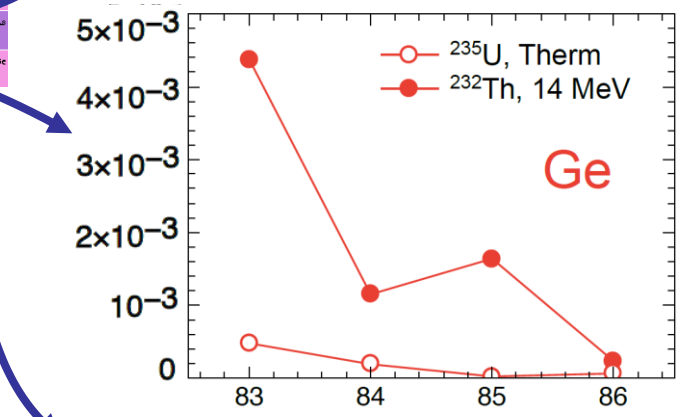
***n***(therm) + $^{235}$U

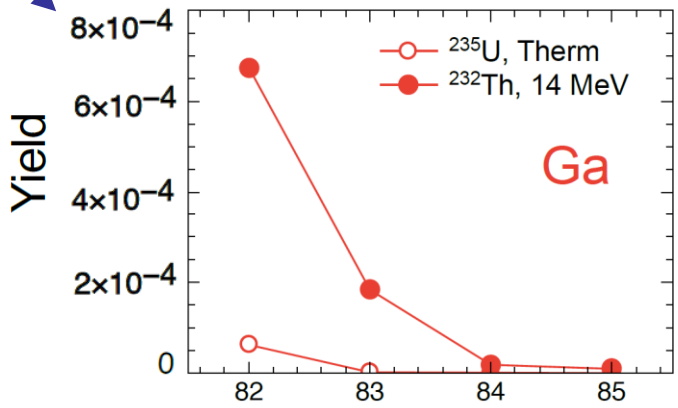
***n***(14 MeV) + $^{232}$Th



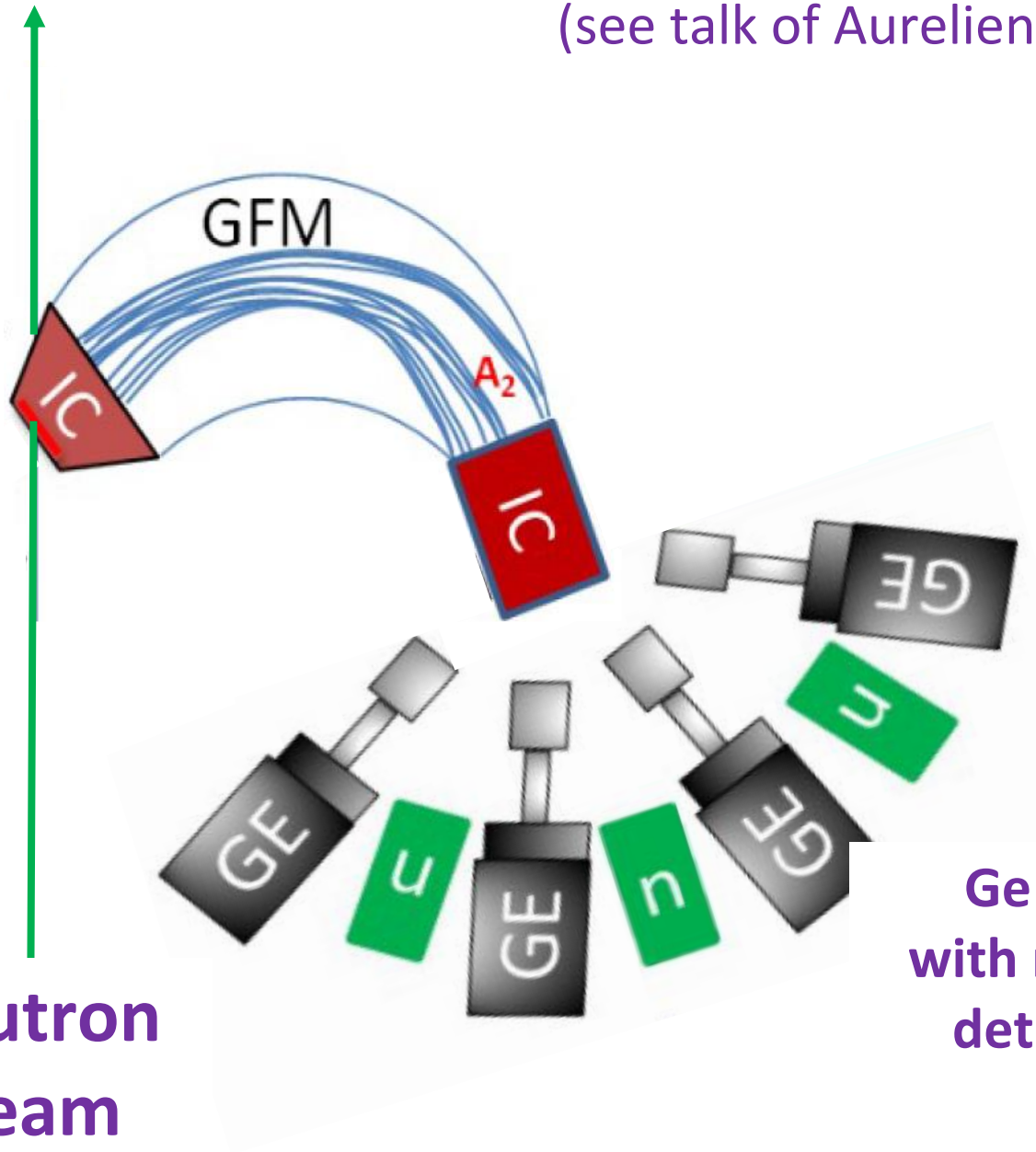



# FIPPS version for the IFMIF beam

(see talk of Aurelien Blanc)




**neutron beam**

**Ge array with neutron detectors**

# Conclusions and Outlook

- Discrete in-beam gamma-ray spectroscopy of products from the spontaneous fission or thermal-neutron induced fission is efficient in identifying **high-spin states** in hard-to-reach neutron-rich nuclei around $^{132}$Sn, and in neutron-rich nuclei around the shape transition region at N=60.

- Fission induced by fast (14 MeV) neutrons on a $^{232}$Th target is most promising in populating very neutron-rich nuclei around the $^{78}$Ni doubly magic nucleus. In that region **high-lying (in energy) and high-spin isomers are expected**.

- These nuclei have low neutron separation energy, of the order of 3-4 MeV, so neutron emission from high-spin isomers might be possible!

- **IFMIF/DONES would be a place where one could search for neutron radioactivity**.

# Collaborators

## Studies with the EXILL array, using cold-neutron induced fission at ILL

| | |
|---|---|
| N. Cieplicka-Orynczak, L. Iskra, B. Szpak, B. Fornal | *IFJ PAN Krakow, Poland* |
| S. Leoni, G. Bocchi, G. Colo', S. Bottoni, N. Cieplicka-Orynczak, F.C.L. Crespi, A. Bracco et al. | *University and INFN, Milano, Italy* |
| D. Bazzacco, D. Mengoni, C. Ur et al. | *Univ. and INFN Padova, LNL Legnaro* |
| G. De France, C. Michelagnoli et al. | *GANIL, Caen, France* |
| M. Jentschel, U. Koster, A. Blanc, P. Mutti, G. Simpson, T. Soldner et al. | *ILL Grenoble, France* |
| W. Urban et al. | *Univ. of Warsaw, Poland* |
| J.-M. Regis et al. | *Univ. of Koeln, Germany* |

## Studies with GAMMASPHERE at ANL: spontaneous fission of $^{248}$Cm around $^{132}$Sn

| | |
|---|---|
| R. Broda, N. Cieplicka, W. Krolas, K.H. Maier, T. Pawlat, B. Szpak, J. Wrzesinski, B. Fornal | *IFJ PAN Krakow, Poland* |
| R.V.F. Janssens, S. Zhu, M.P. Carpenter, D. Seweryniak et al. | *ANL Argonne, USA* |
| P.J. Daly, Z. Grabowski. C.T. Zhang | *Purdue Univ., USA* |
| G. Dracoulis , G. Lane et al. | *ANU Canberra, Australia* |

The Podkarpacie Region