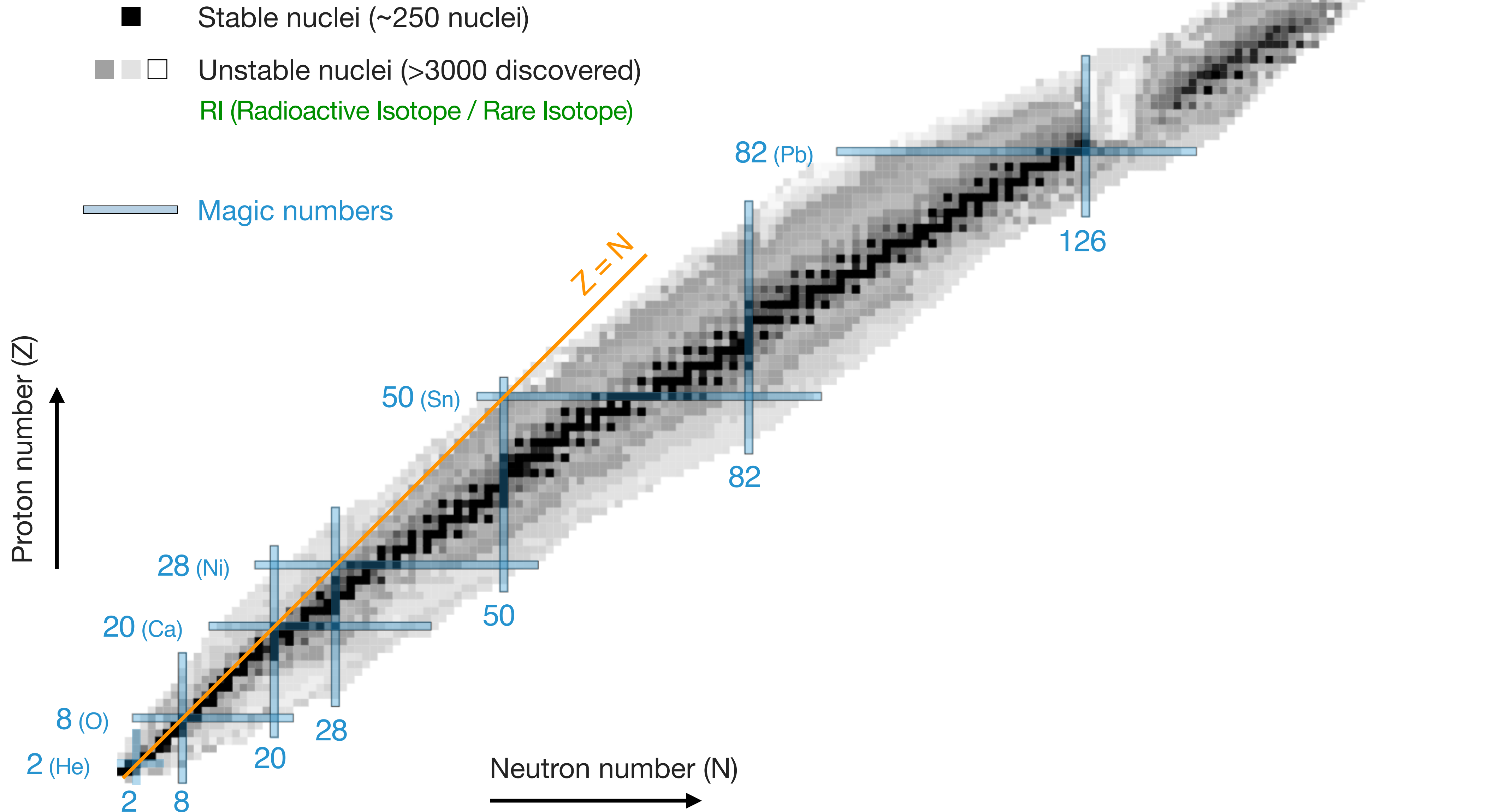


Study of muon-induced fission for spectroscopy of the muonic atom with unstable nuclei

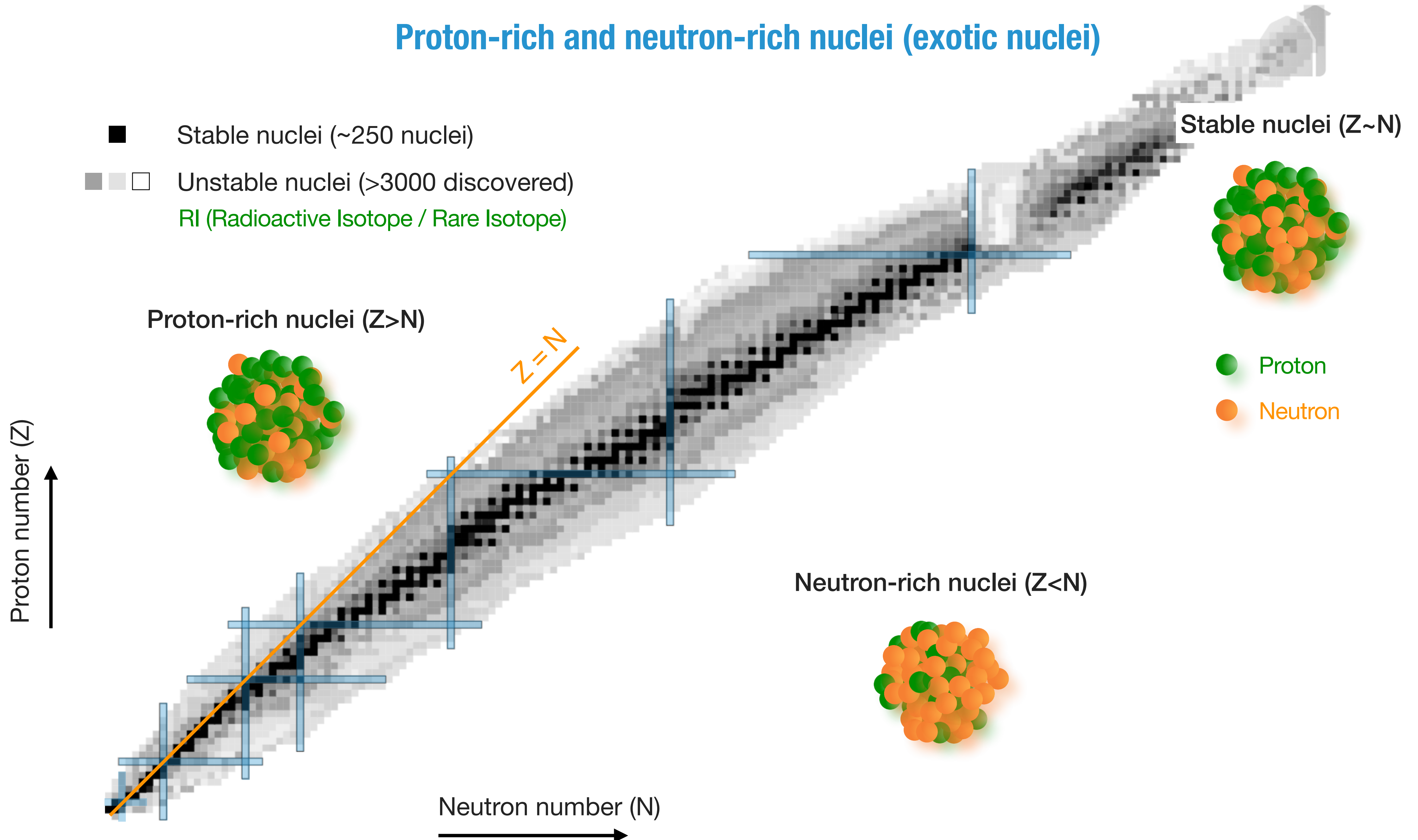
M. Niikura¹, R. Mizuno², T.Y. Saito², T. Matsuzaki¹, T.E. Cocolios⁵, M. Deseyn⁵, S. Go¹, M. Heines⁵, K. Hirose⁶, E. Ideguchi⁷, S. Kawase¹¹, A. Knecht³, K. Ninomiya⁸, K. Nishio⁶, H. Nishibata¹⁰, H. Sakurai¹, M. Sasano¹, A. Sato⁹, K. von Schoeler^{4,3}, M. Tanaka¹, D. Tomono⁷, S.M. Vogiatzi^{3,4}

*¹ RIKEN Nishina Center, ² Univ. Tokyo, ³ PSI, ⁴ ETH Zürich,
⁵ KU Leuven, ⁶ JAEA, ^{7,8,9} Osaka Univ. ^{10,11} Kyushu Univ.*

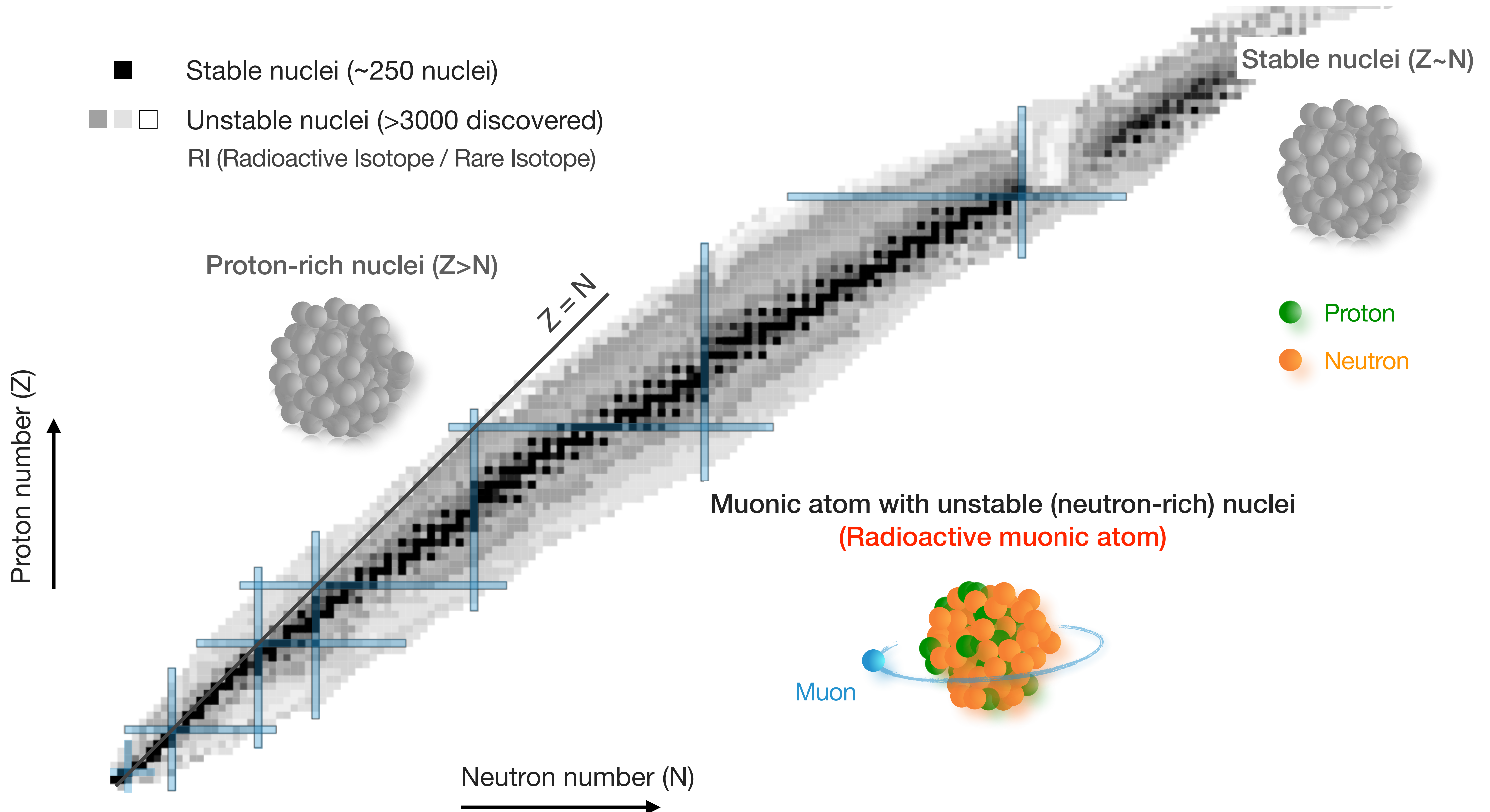
Chart of nuclides



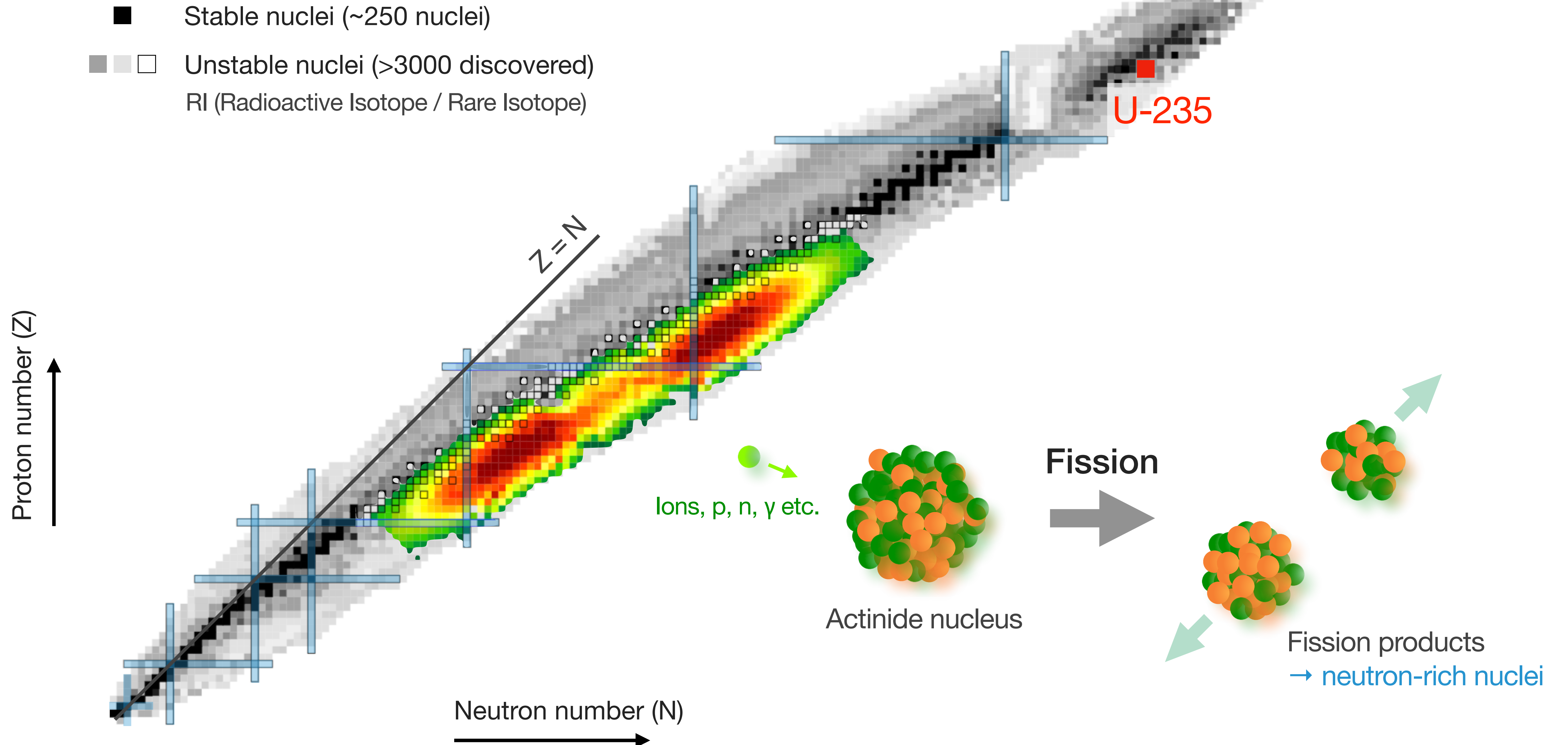
Proton-rich and neutron-rich nuclei (exotic nuclei)



Final Goal of the project —X-ray spectroscopy for radioactive muonic atom

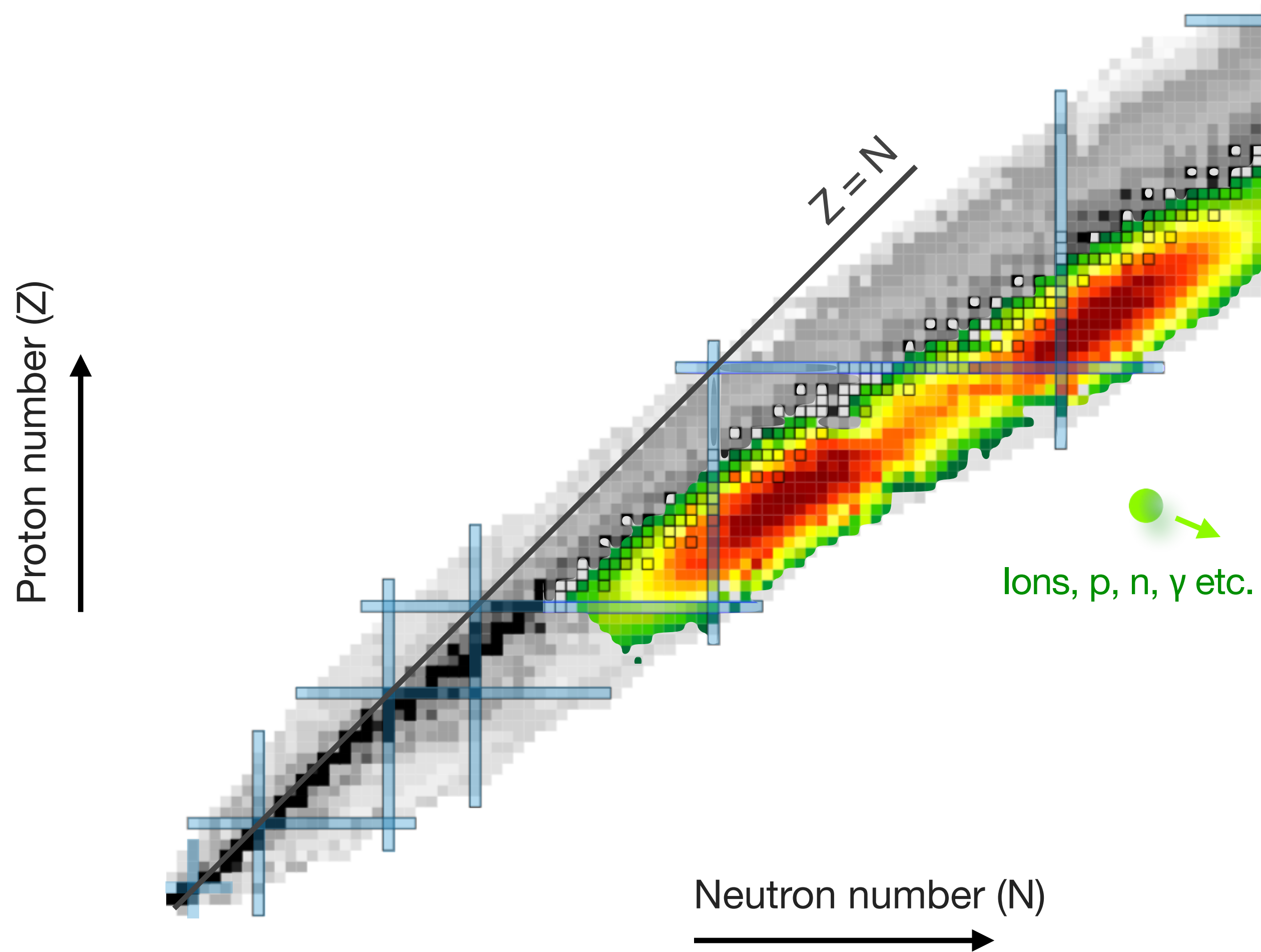


Fission reaction to produce neutron-rich nuclei

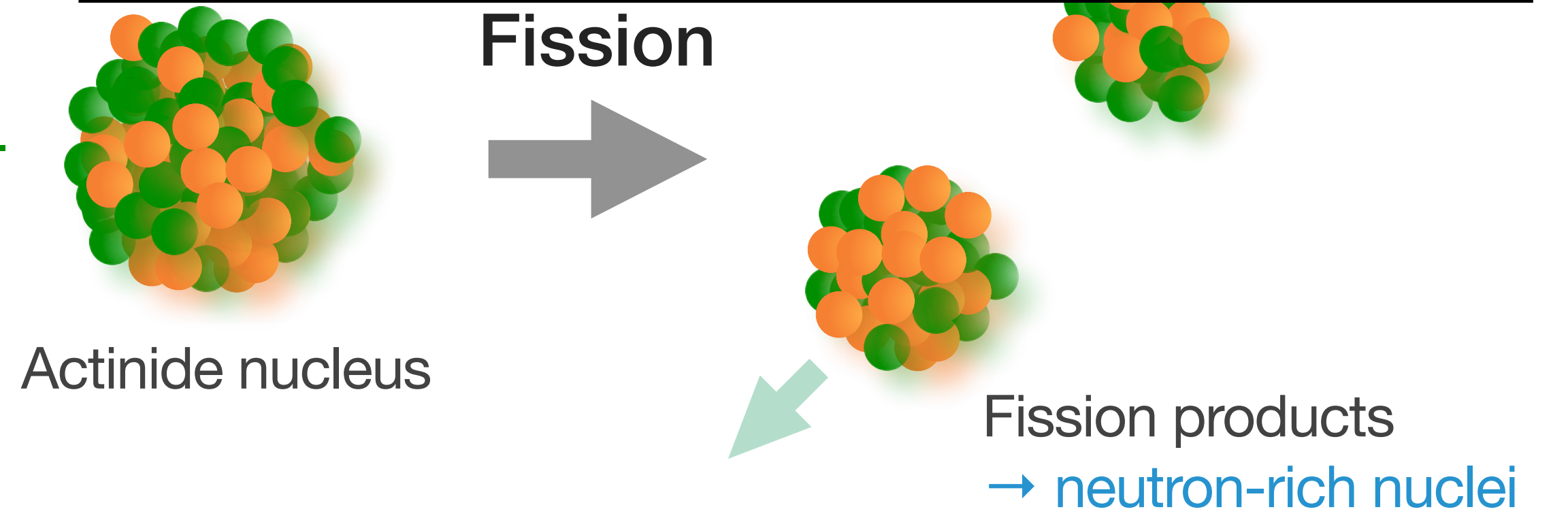


Fission reaction to produce neutron-rich nuclei

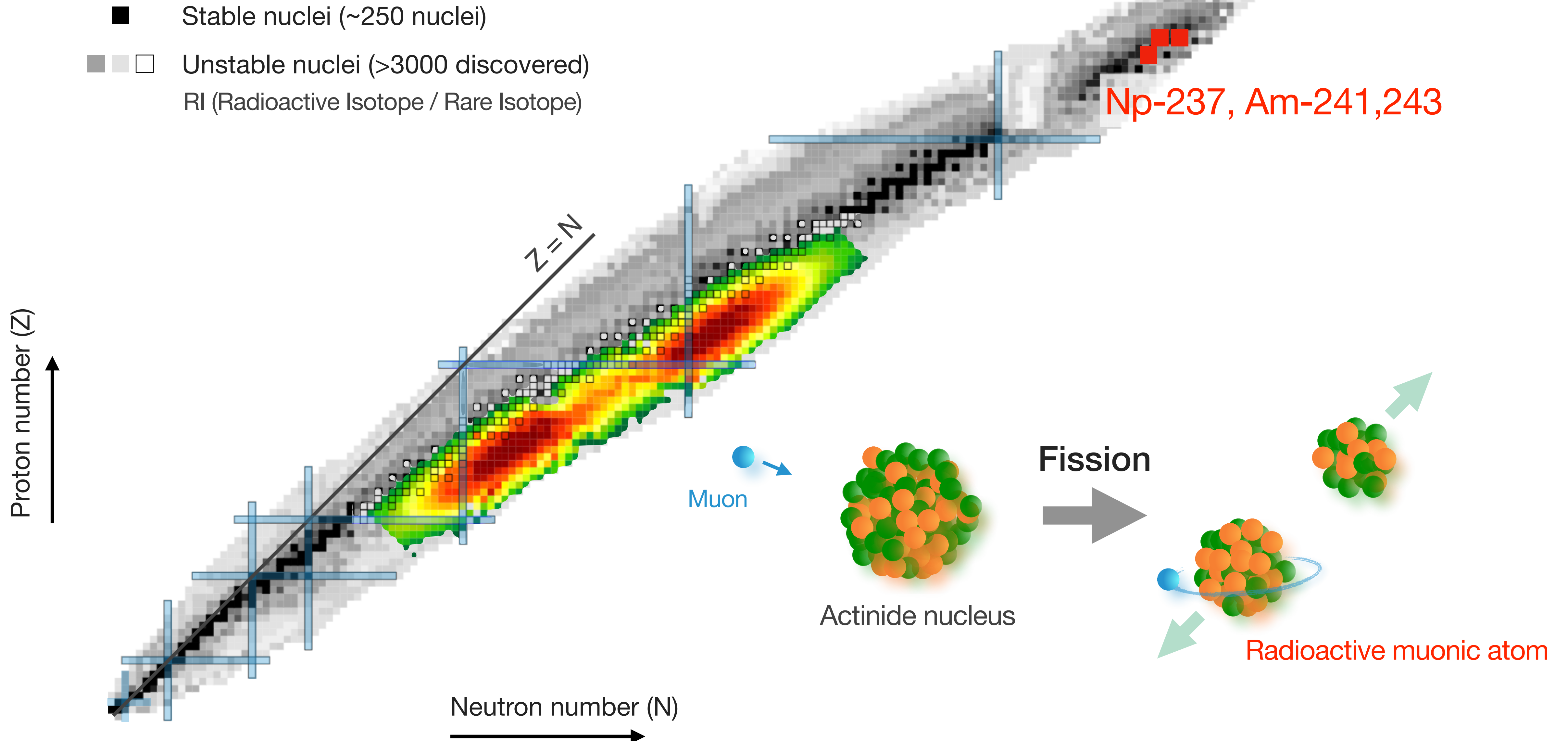
- Stable nuclei (~250 nuclei)
- □ Unstable nuclei (>3000 discovered)
RI (Radioactive Isotope / Rare Isotope)



RI beam facilities	Beam
RIKEN, RI beam factory (RIBF), Japan	Ions (inv. kinematics)
RIKEN, SCRIT, Japan	γ (e- beam)
J-PARC, MLF-ANNRI, Japan	Neutron
Michigan State Univ., FRIB, US	Ions (inv. kinematics)
Argonne Nat. Lab., CARIBU, US	Spontaneous fission
TRIUMF, ISAC/ARIEL, Canada	Proton
GSI, FAIR, Germany	Ions (inv. kinematics)
GANIL, VAMOS, France	Ions (inv. kinematics)
GANIL, Spiral-2, France	Neutron
IJCLab, ALTO, France	Neutron/ γ (e- beam)
ILL Grenoble, France	Neutron
LNL, SPES, Italy	Proton
CERN, ISOLDE, Switzerland	Proton

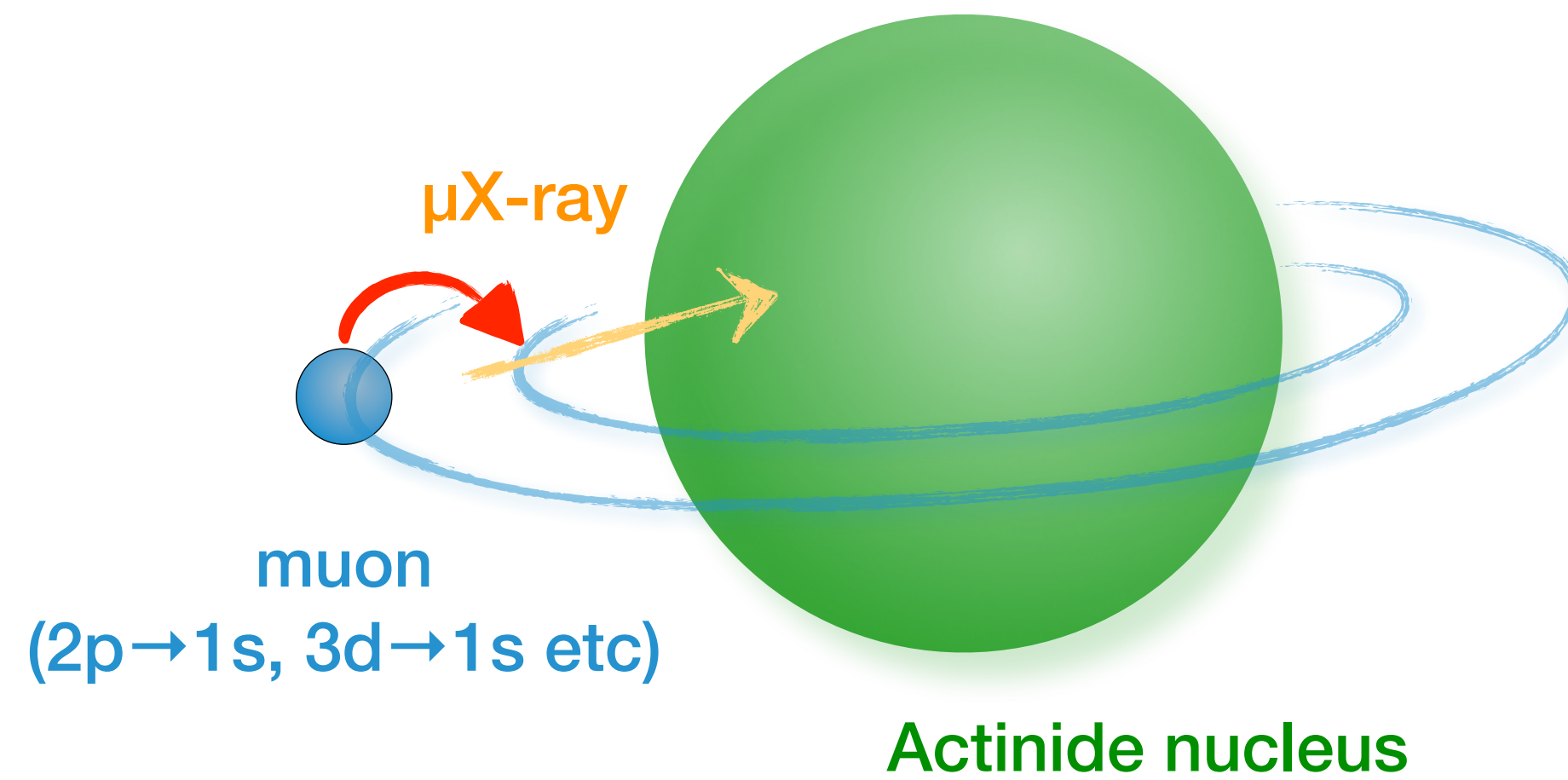


Muon-induced fission reaction to produce radioactive muonic atom



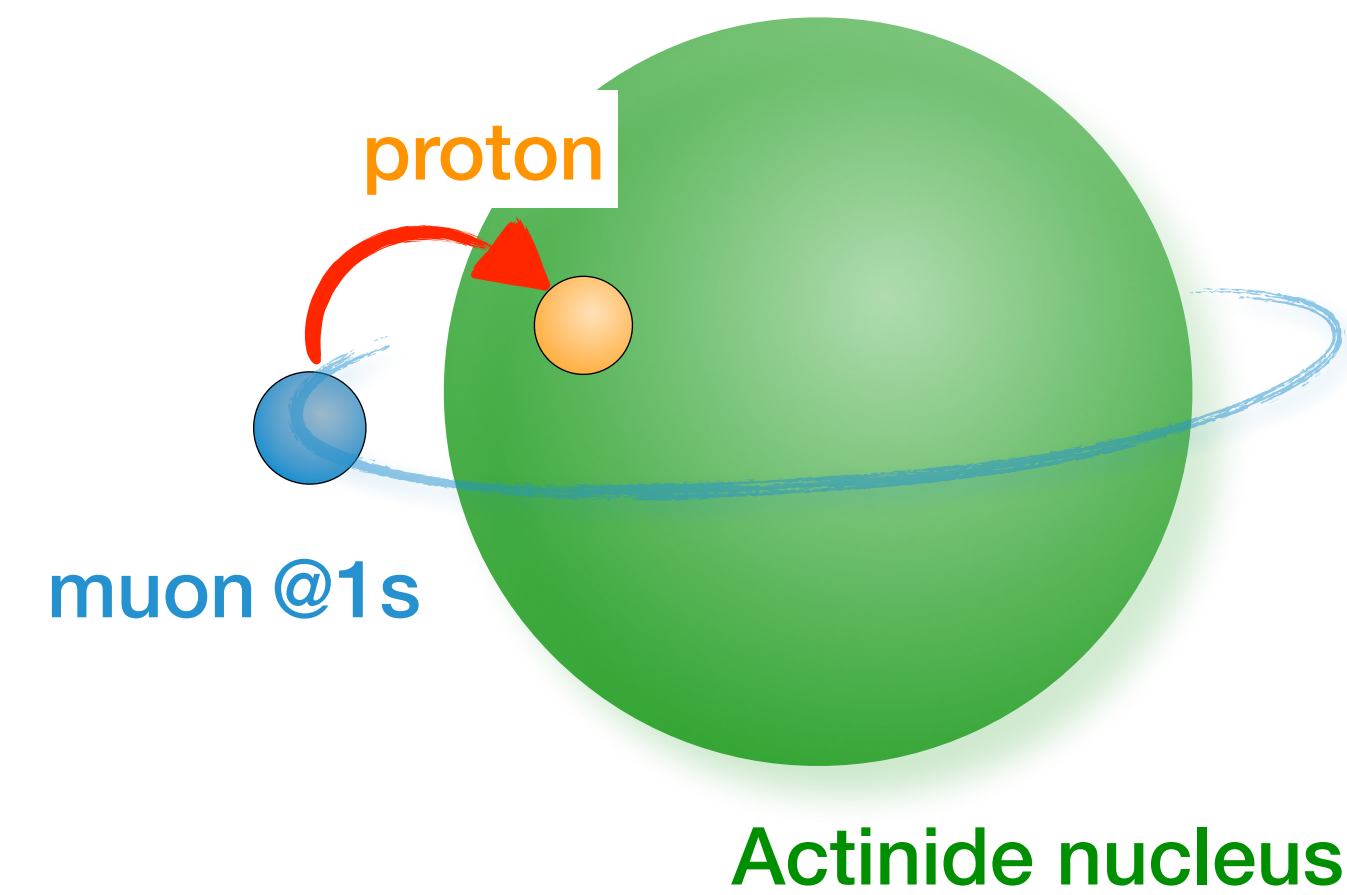
Two muon-induced fission processes —prompt and delayed fission

prompt fission (radiationless fission)

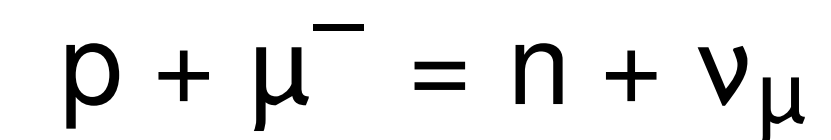


Photon induced fission reaction (< psec)
μX-ray energy = excitation energy = ~ 6 MeV

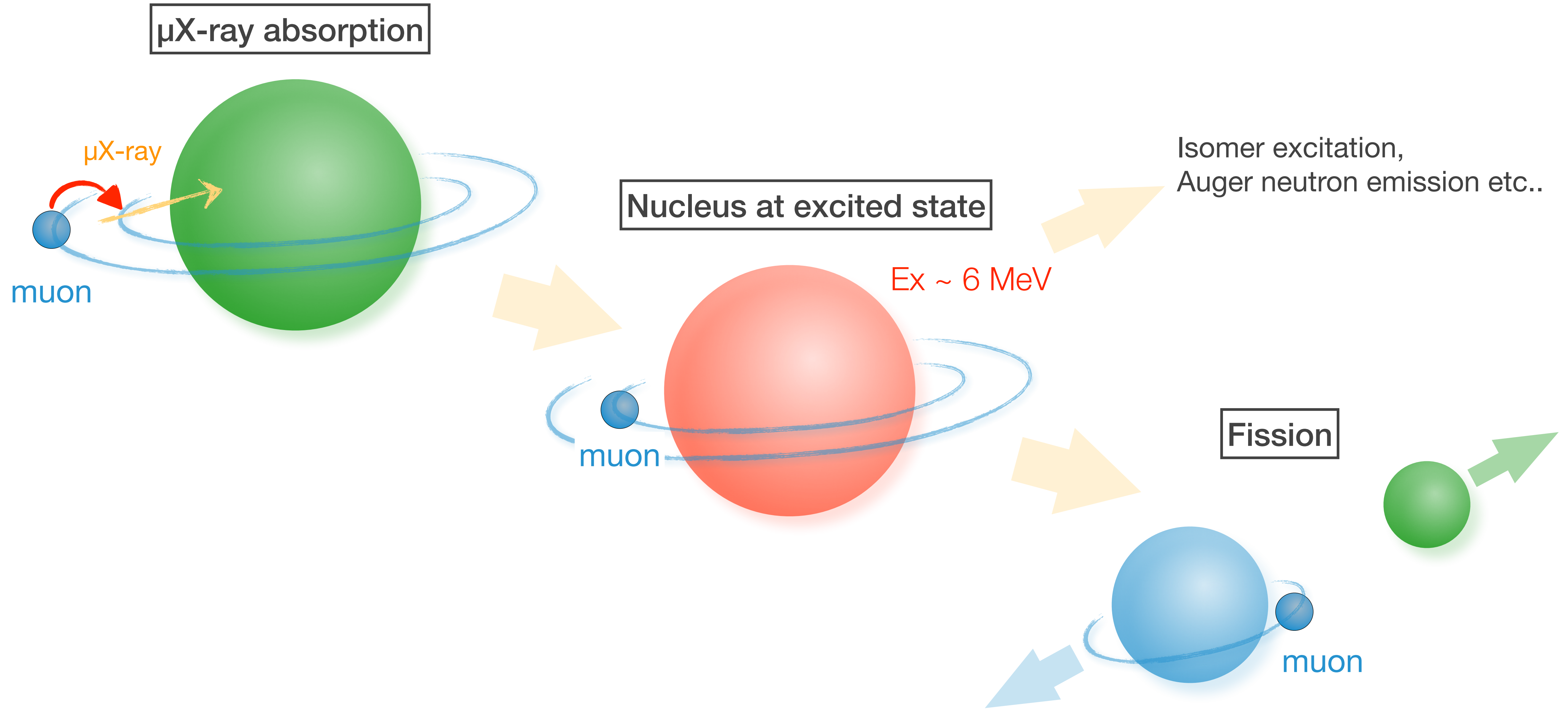
delayed fission (nuclear muon capture)



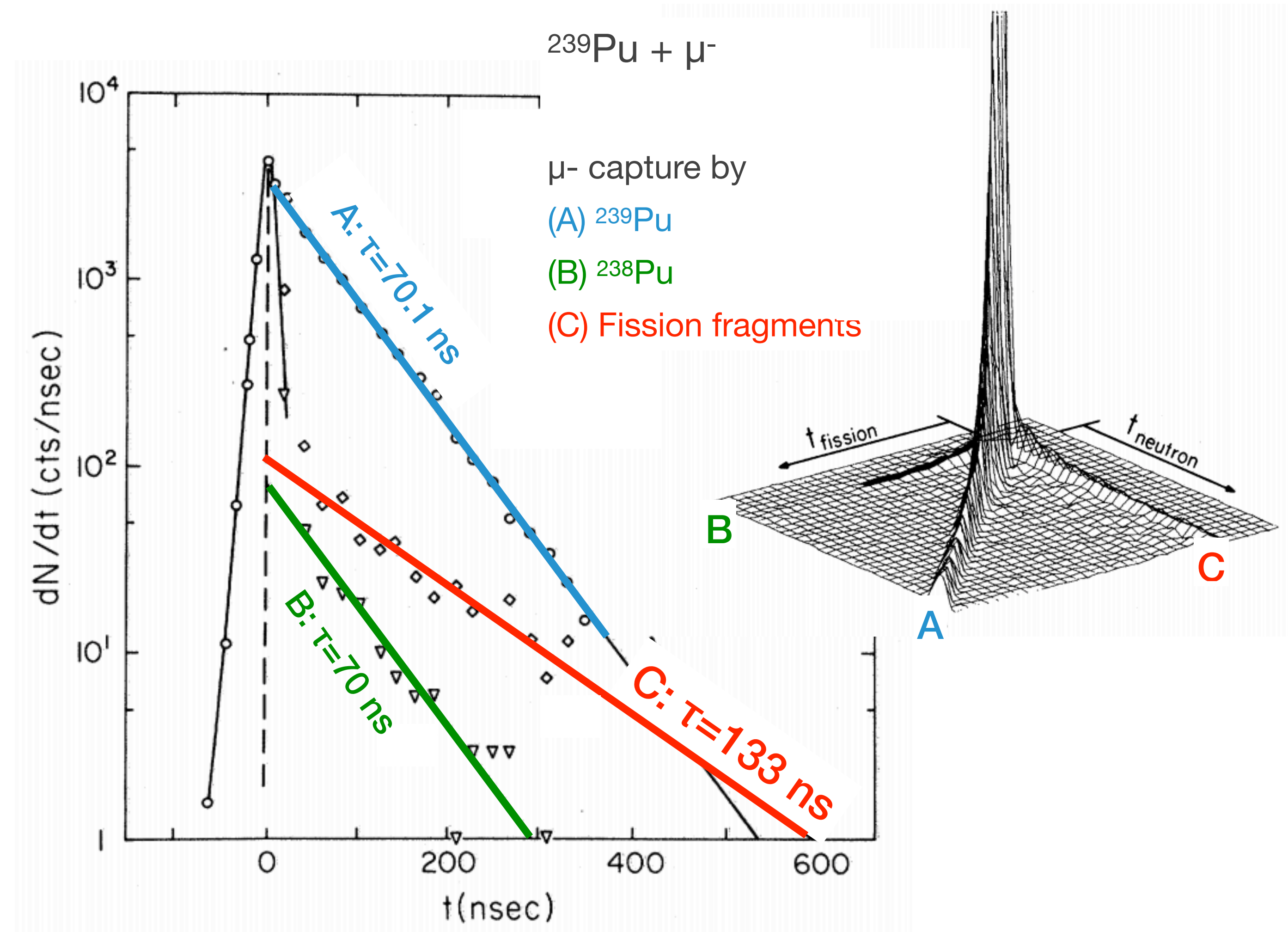
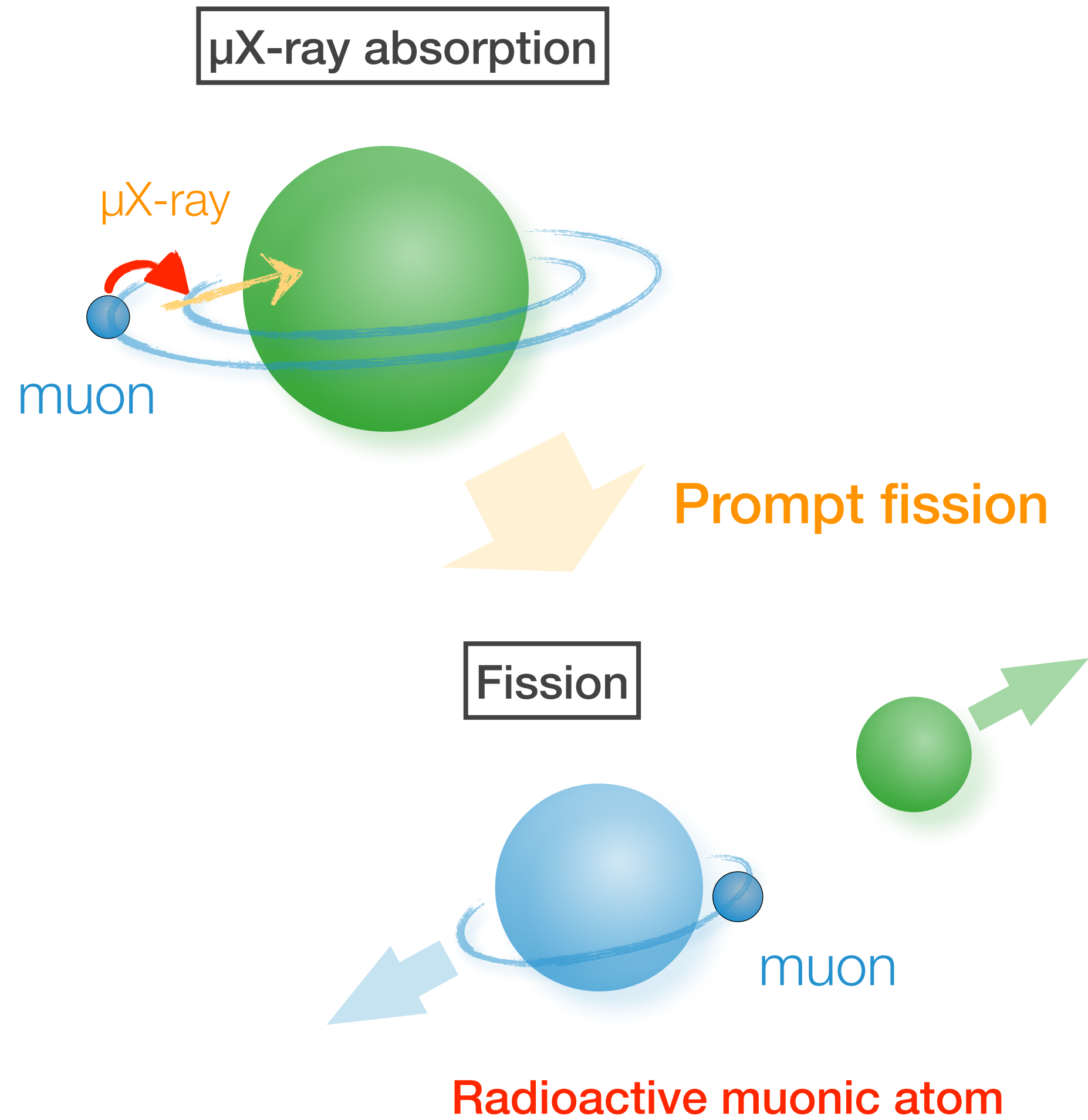
Fission induced by the weak interaction (~70 ns)
(Nuclear muon capture reaction)



Muon stays around the nucleus during the prompt fission process

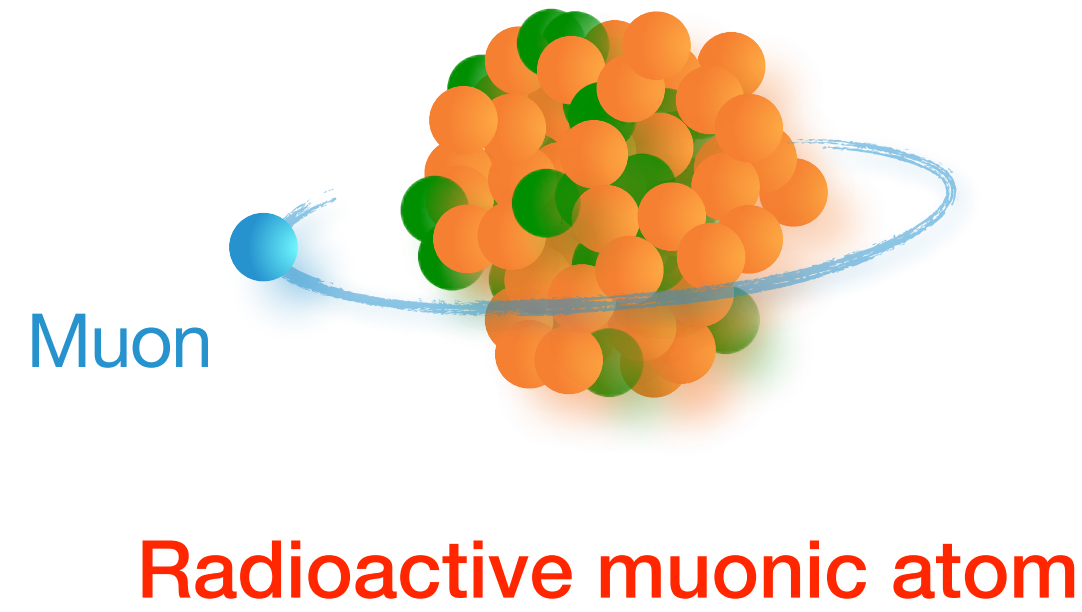


The muon sticking to the heavier fission fragment after the prompt fission



W. U. Schröder et al., Phys. Rev. Lett. 43, 672 (1979).

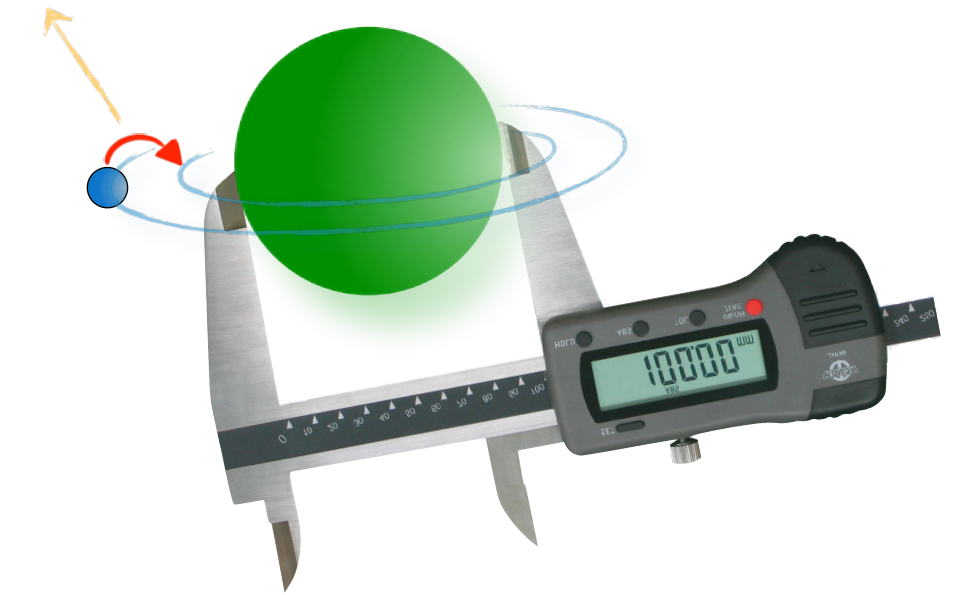
Final Goal of the project —X-ray spectroscopy for radioactive muonic atom



Muonic X-ray spectroscopy provides nuclear moments

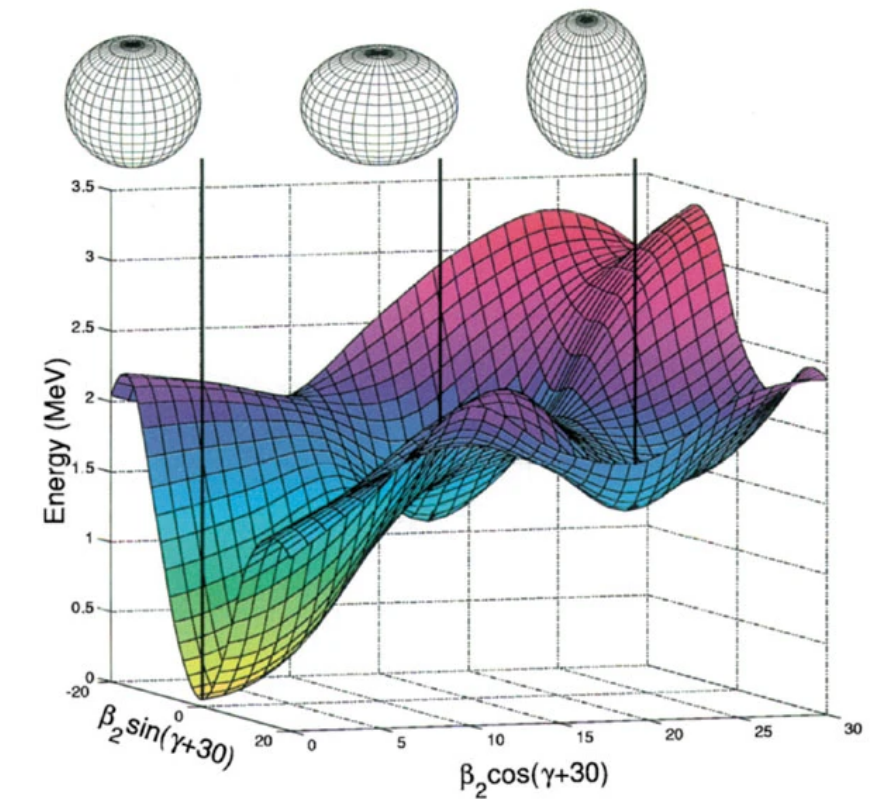
Nuclear charge radius (2nd order moment)

cf. T.Y. Saito et al., arXiv:2204.03233 (nucl-ex).



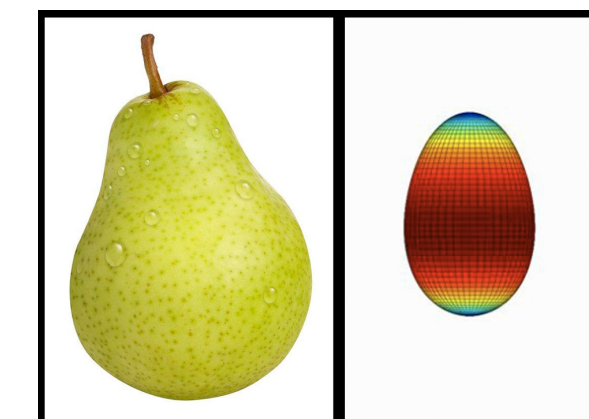
Nuclear quadrupole moments
→ quadrupole deformation

cf. A.N. Andreyev et al., Nature 405, 430 (2000).
A. Antognini et al., Phys. Rev. C **101**, 054313 (2020).



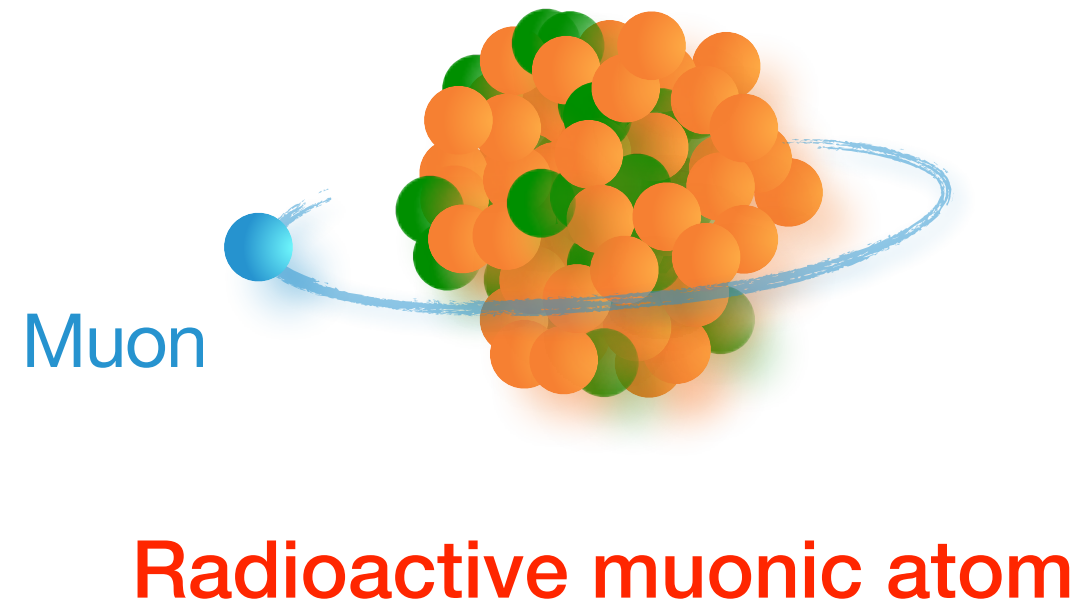
Nuclear octupole moments
→ exotic deformations

cf. L.P. Gaffney et al., Nature 497, 199 (2013).
P.A. Butler et al., Nature Comm. 10, 2473 (2019).



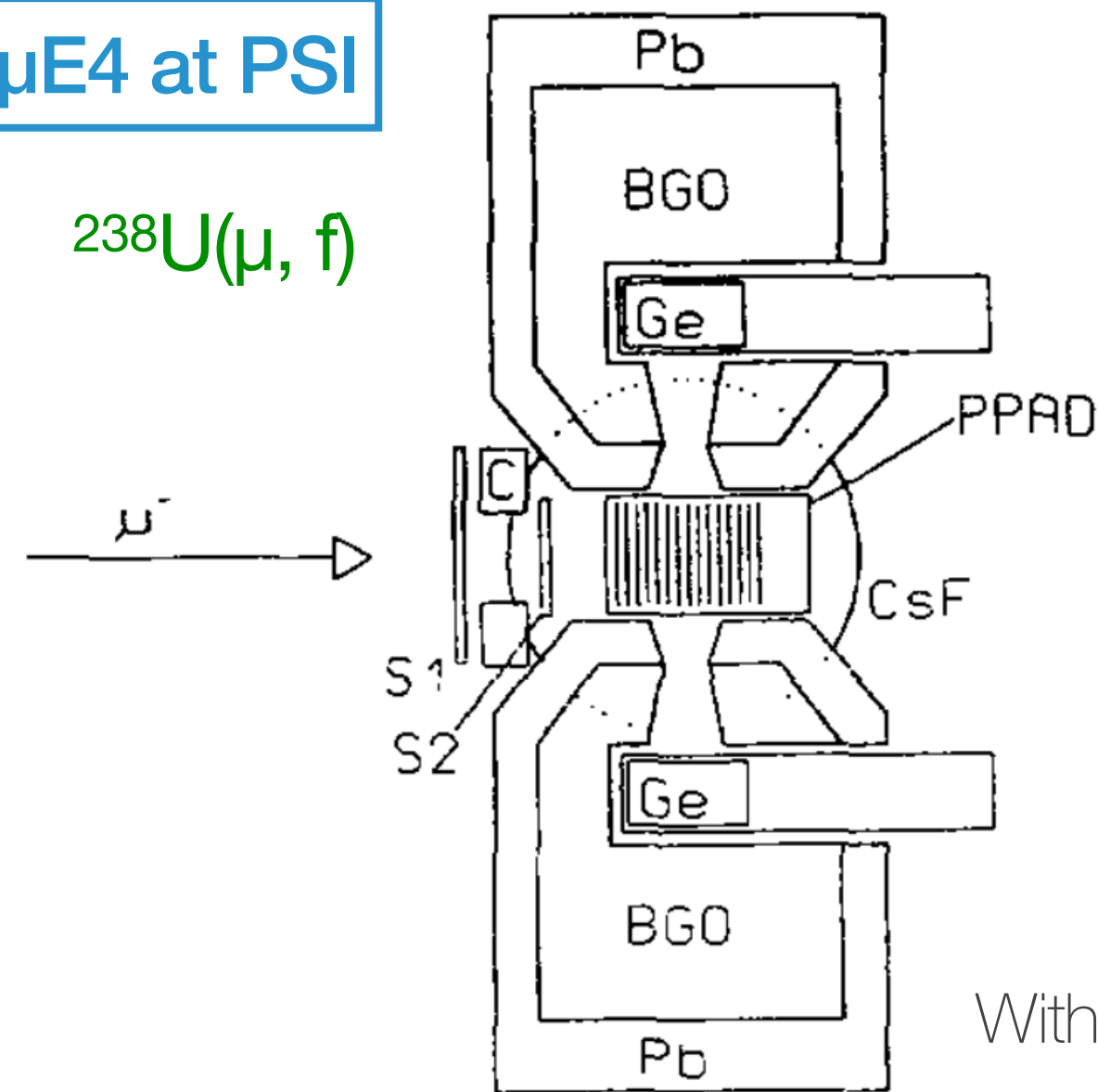
Pear-shaped nuclei

Evidence of muonic X-rays from fission fragments in the past



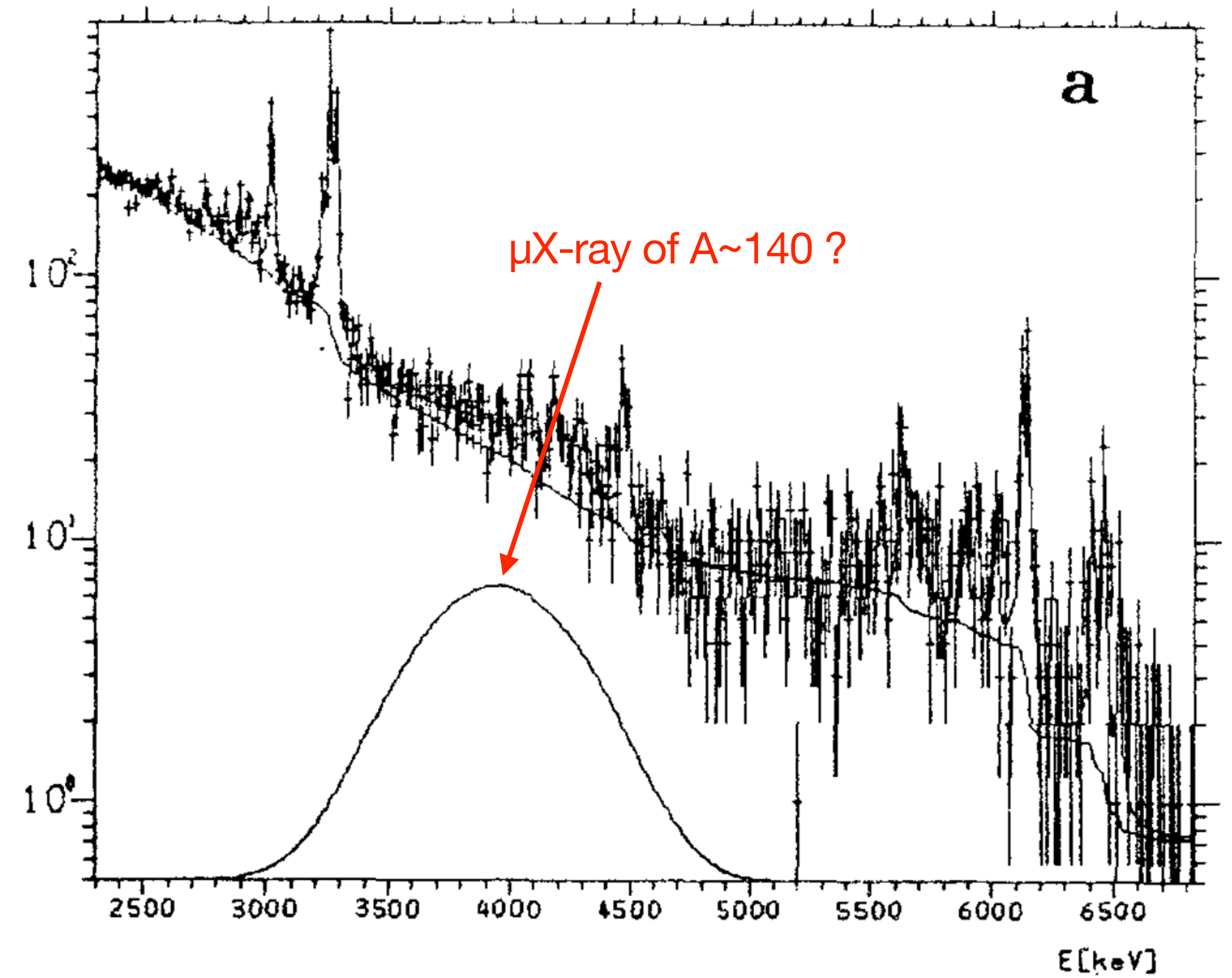
μ E4 at PSI

$^{238}\text{U}(\mu, f)$



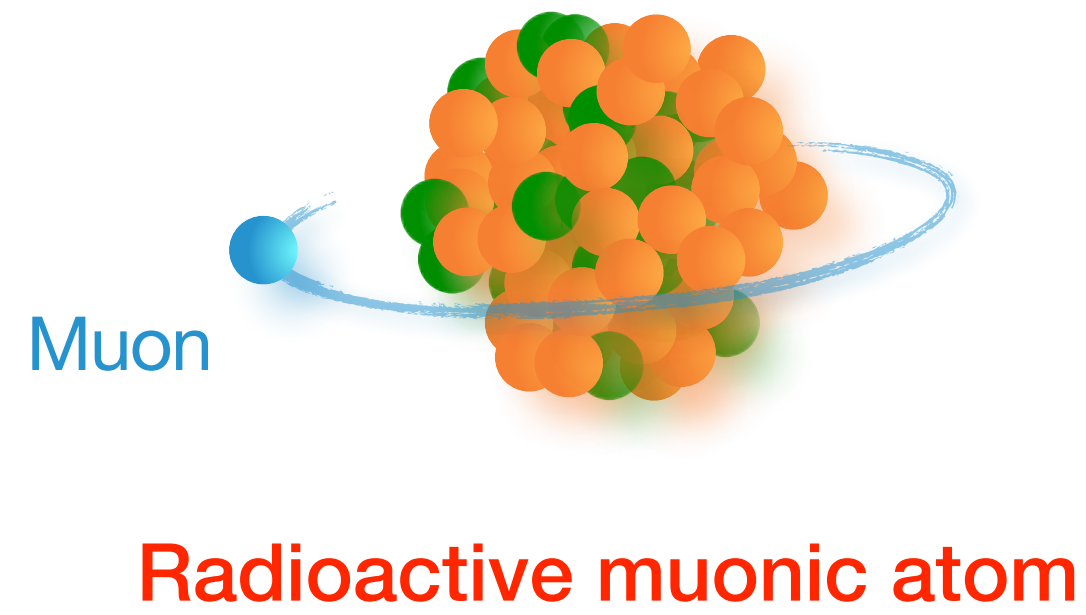
- S1,S2 scintillators
- C collimator
- PPAD fission detector
- Ge germanium detectors
- CsF CsF-detector
- BGO $\text{Bi}_4\text{Ge}_3\text{O}_{16}$ -detector
- Pb lead shield

With two Ge's with 30% rel. efficiency

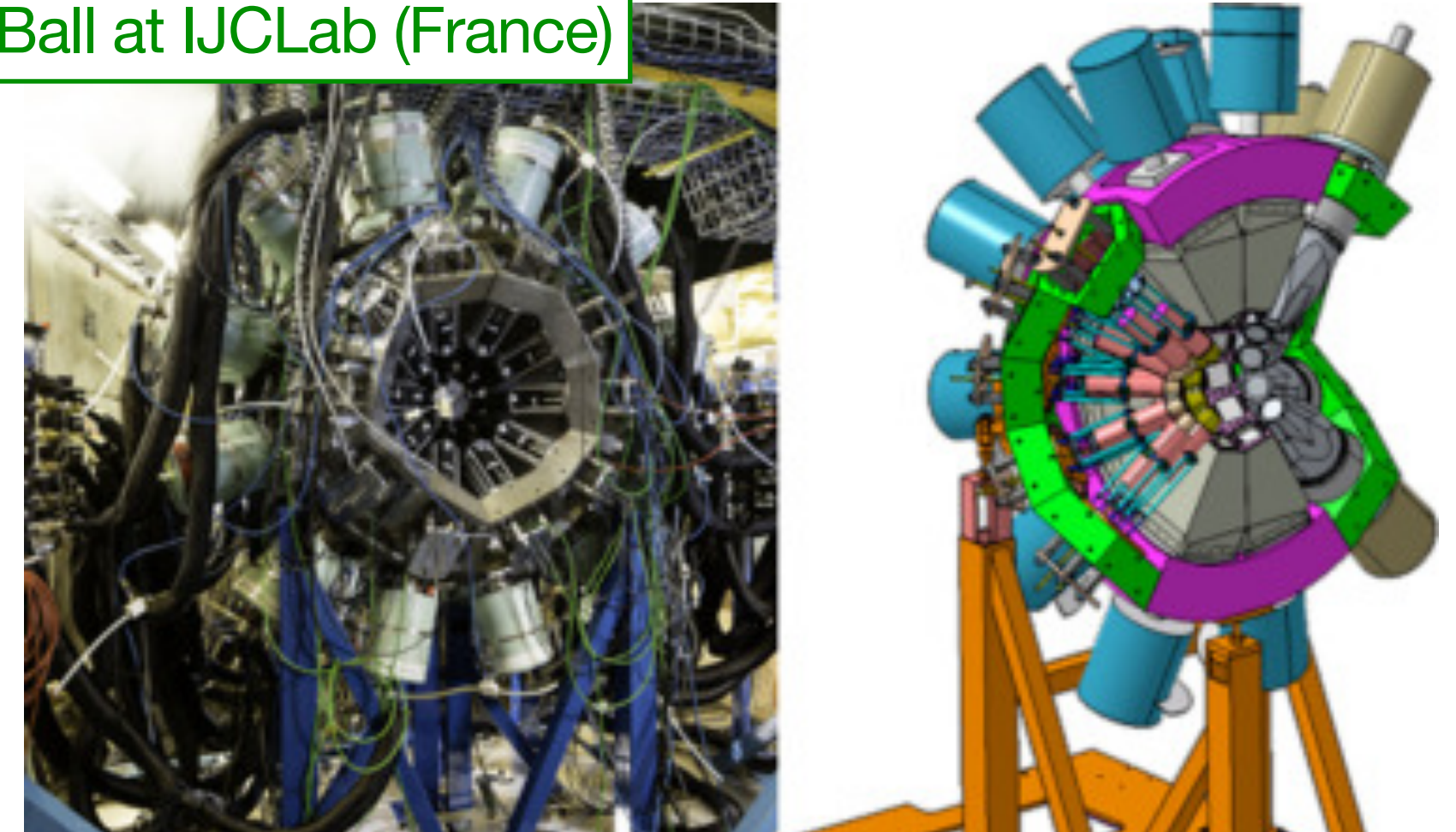


H. Hänscheid et al., Z. Phys. A342, 111 (1992).
 C. Rösel et al., Z. Phys. A345, 425 (1993).

Muonic X-ray spectroscopy of radioactive muonic atom should be possible with states-of-art Ge arrays



v-Ball at IJCLab (France)



M. Lebois et al., Nucl. Instrum. Meth. A960, 163580 (2020).

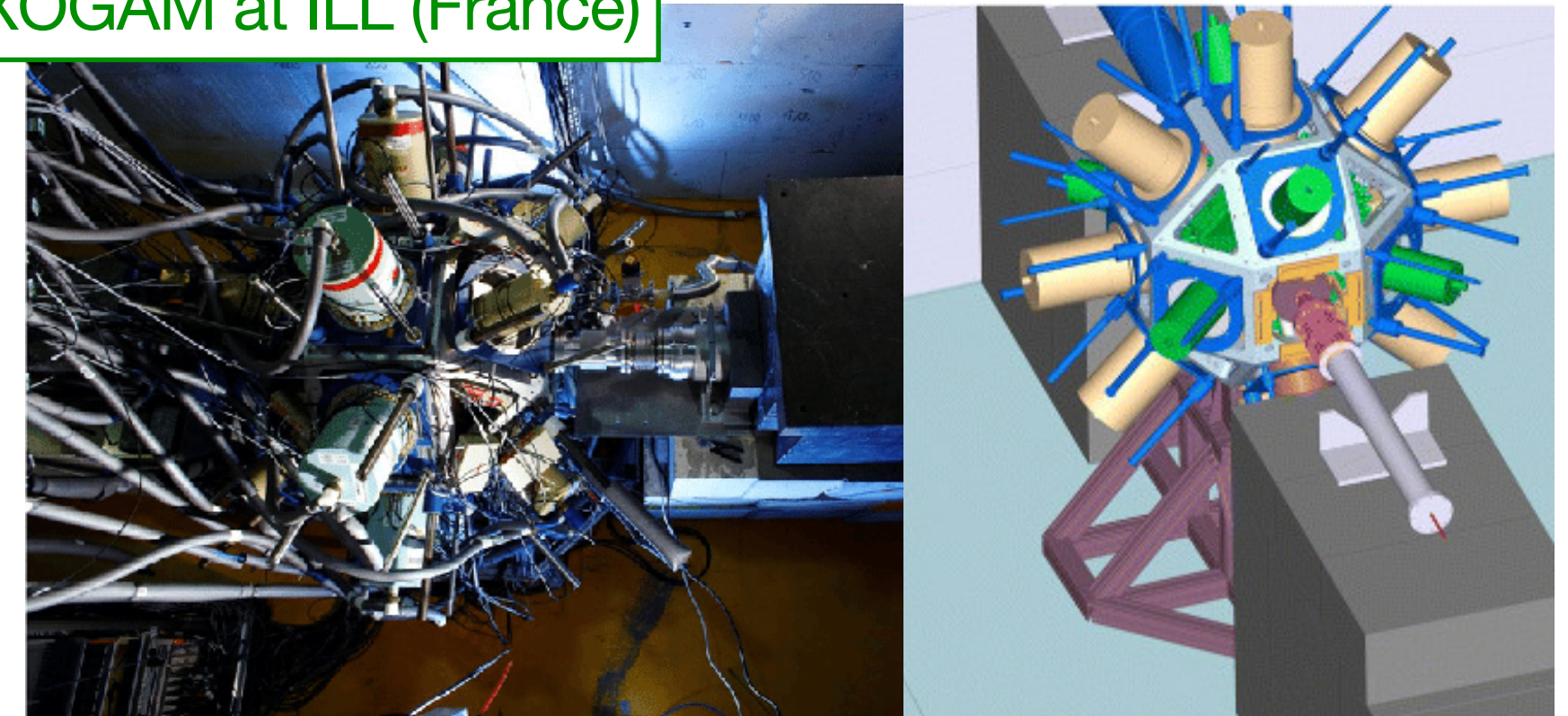
Gammasphere (US)



EuroBall array (Europe)



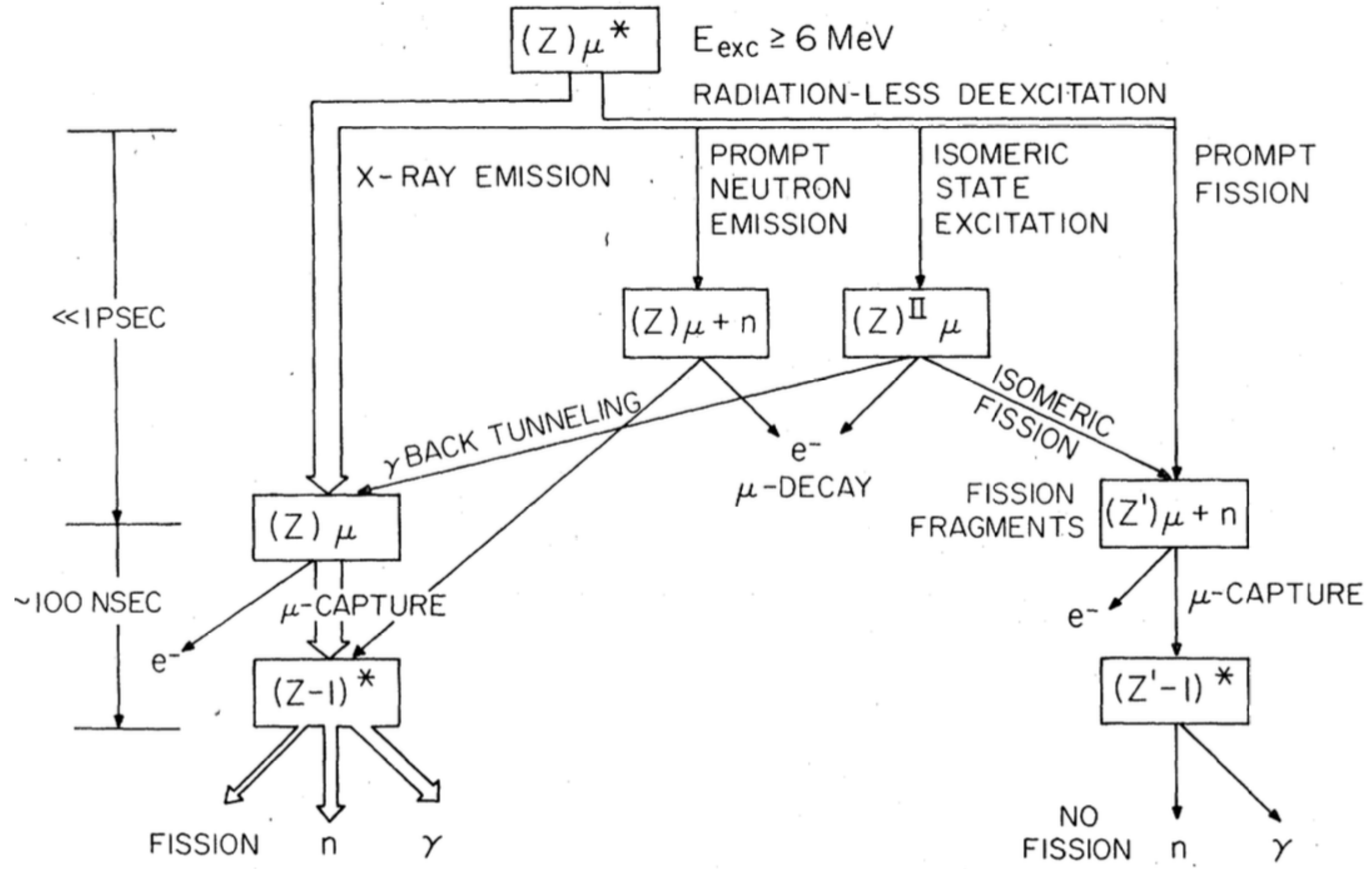
EXOGRAM at ILL (France)



G. de France et al., EPJ Web. Conf. 178, 01004 (2018).

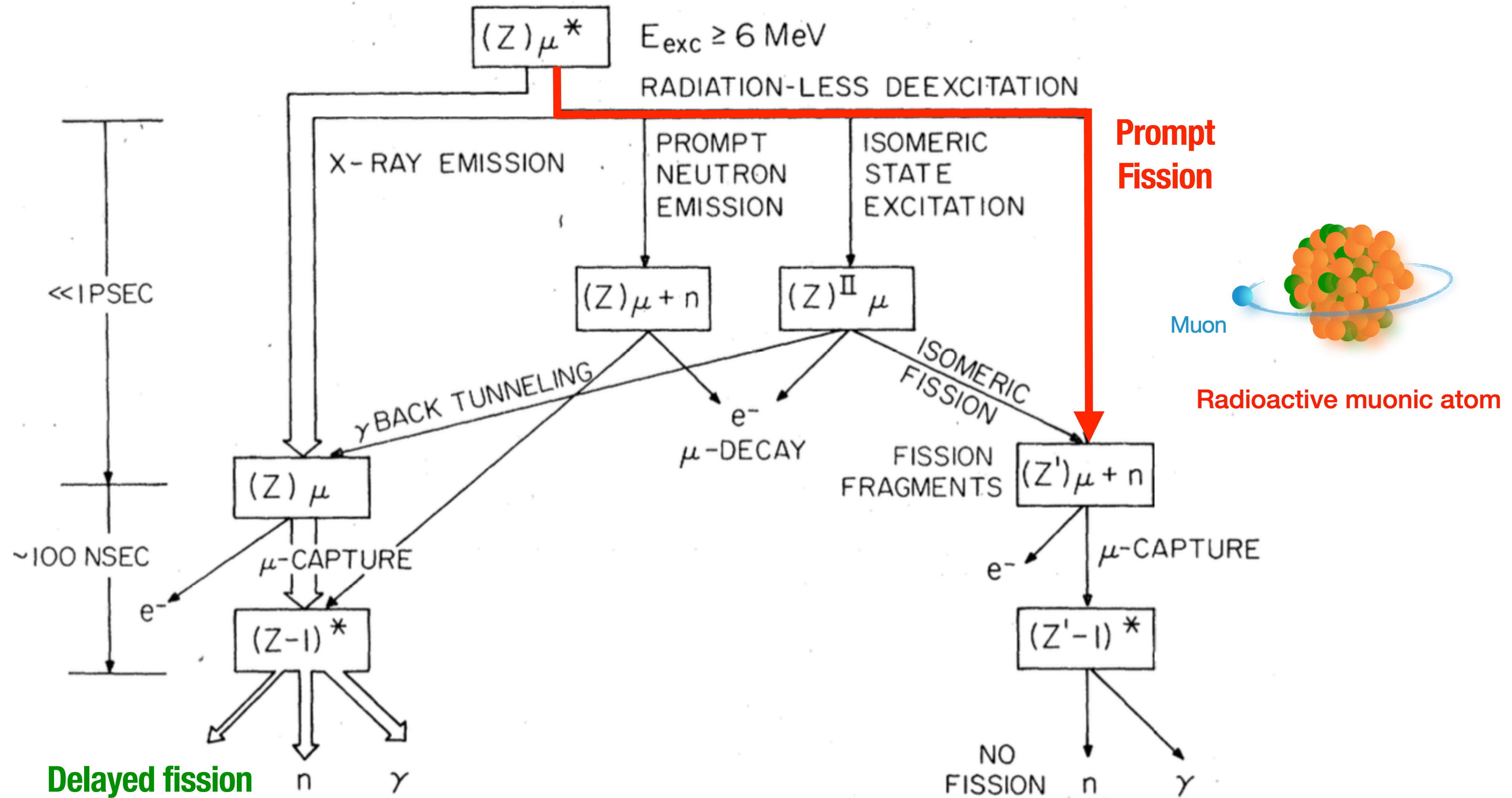
Goal of the proposed experiment —Measurement of muon induced fission probability

Goal of the proposed experiment — Measurement of muon induced fission probability



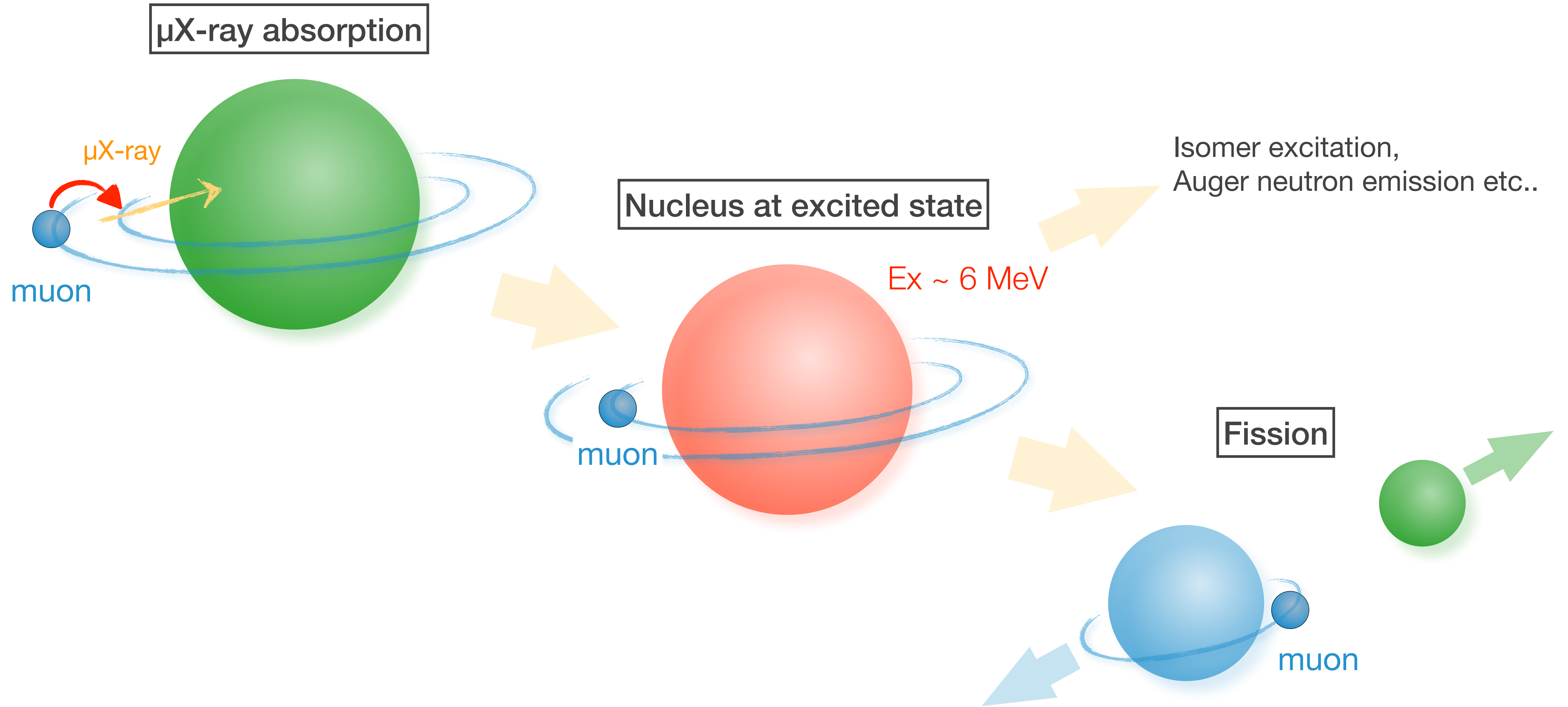
D. Ganzorig et al., Nucl. Phys. A **350**, 278 (1980).

Goal of the proposed experiment — Measurement of muon induced fission probability

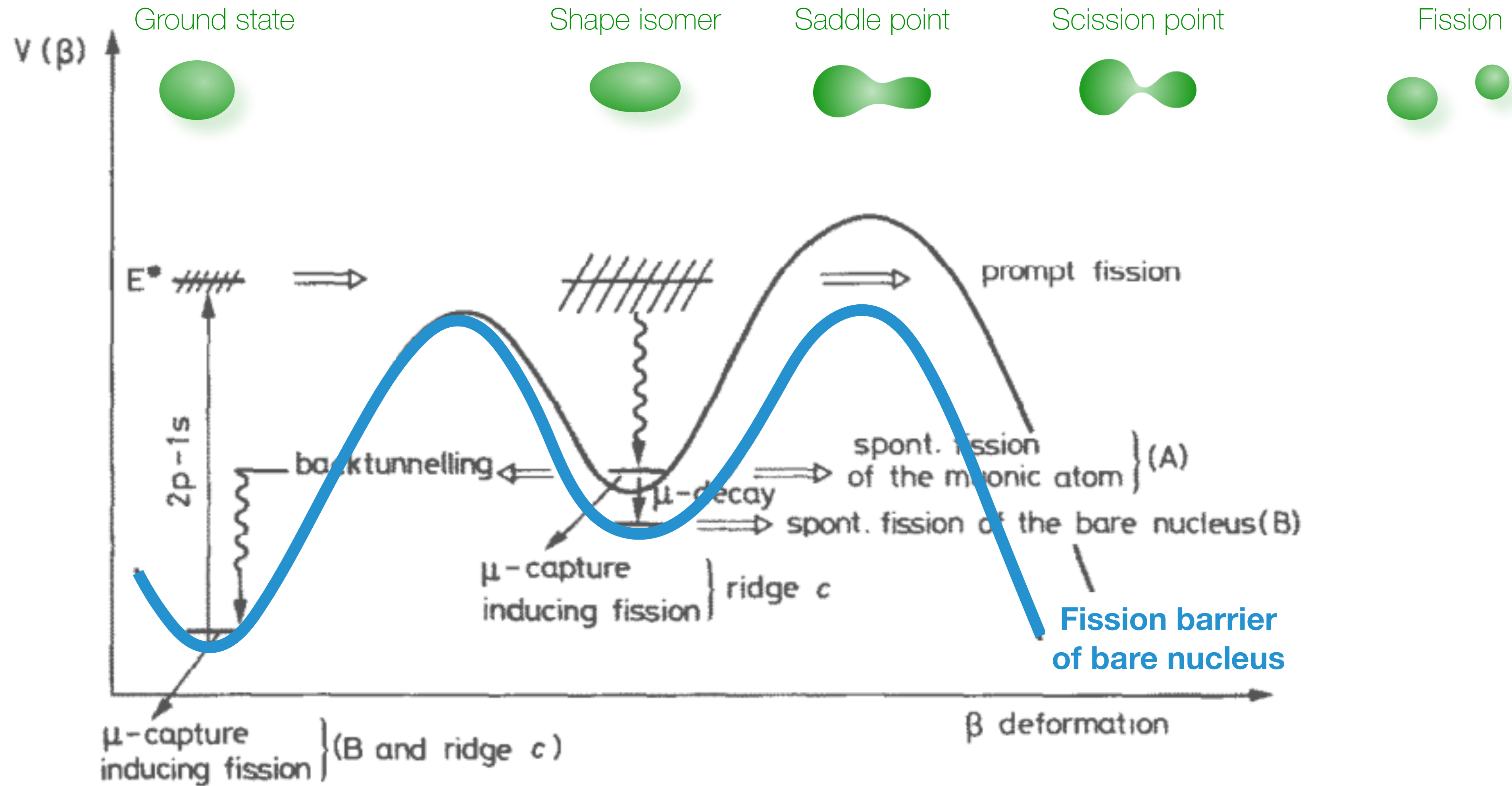


D. Ganzorig et al., Nucl. Phys. A **350**, 278 (1980).

Muon stays around the nucleus during the prompt fission process

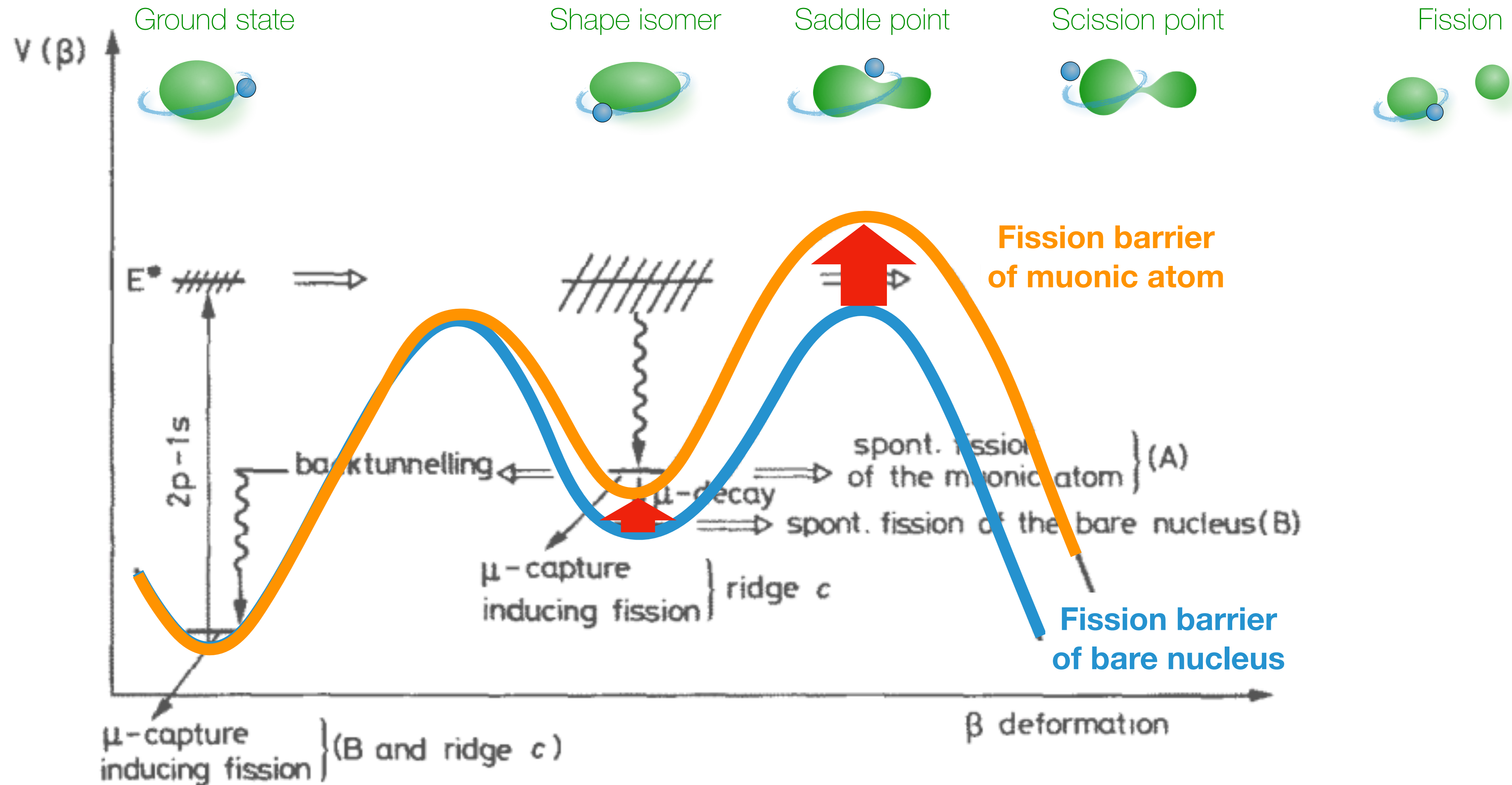


Height of the fission barrier is changed by muon in the prompt fission



W. W. Wilcke et al., Phys. Rev. C, 18 (1978) 1452.

Height of the fission barrier is changed by muon in the prompt fission



W. W. Wilcke et al., Phys. Rev. C, 18 (1978) 1452.

Systematic measurement for fission probabilities for five MA targets

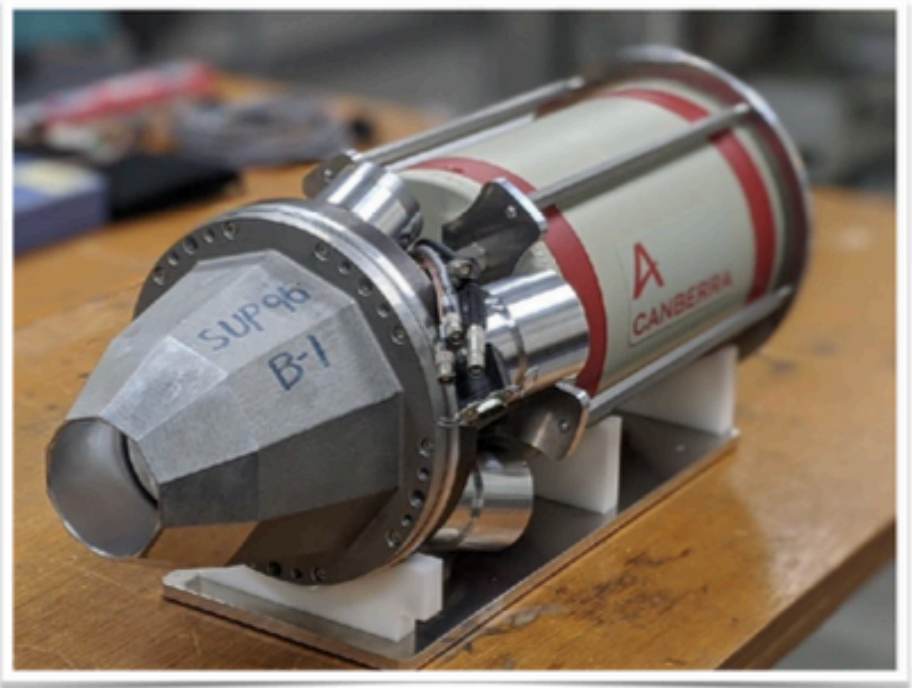
Nuclide	K_{α} X-ray energy (MeV)	Inner barrier height (MeV)	Outer barrier height (MeV)	Lifetime of 1s state (ns)	Prompt fission (%)	Delayed fission (%)
^{207}Pb	5.78, 5.96			75.4(10)		
^{209}Bi	5.84, 6.03			73.5(4)	0.0042(7) ¹	
^{232}Th	6.06, 6.36	5.8(2)	6.2(2)	77.3(3)	0.10(5)	1.90(5)
^{233}U	6.18, 6.47	-	-	68.9(3)	8(2)	40(2)
^{234}U		5.6(2)	5.5(2)	70.6(2)	4.7(12)	26.3(12)
^{235}U	6.16, 6.46	5.9(2)	5.6(2)	72.2(2)	3.4(9)	27.6(9)
^{236}U		5.6(2)	5.5(2)	74.3(3)	3.1(8)	16.9(8)
^{237}U		6.1(2)	5.9(2)	-	17(5) ¹	
^{238}U	6.14, 6.41	5.7(2)	5.7(2)	77.1(3)	1.1(3)	12.9(3)
^{237}Np	?	5.7(2)	5.4(2)	69.8(2)	12(4)	42(4)
^{239}Pu	6.23, 6.56	6.2(2)	5.5(2)	70.1(7)	13(6)	67(6)
^{242}Pu		5.6(2)	5.1(2)	75.4(9)	10(4)	50(4)
^{244}Pu		5.4(2)	5.0(2)	78.4(9)	12(4)	48(4)
^{241}Am	6.29, 6.63	6.0(2)	5.1(3)			
^{243}Am	6.28, 6.62	5.9(2)	5.4(3)			

MA

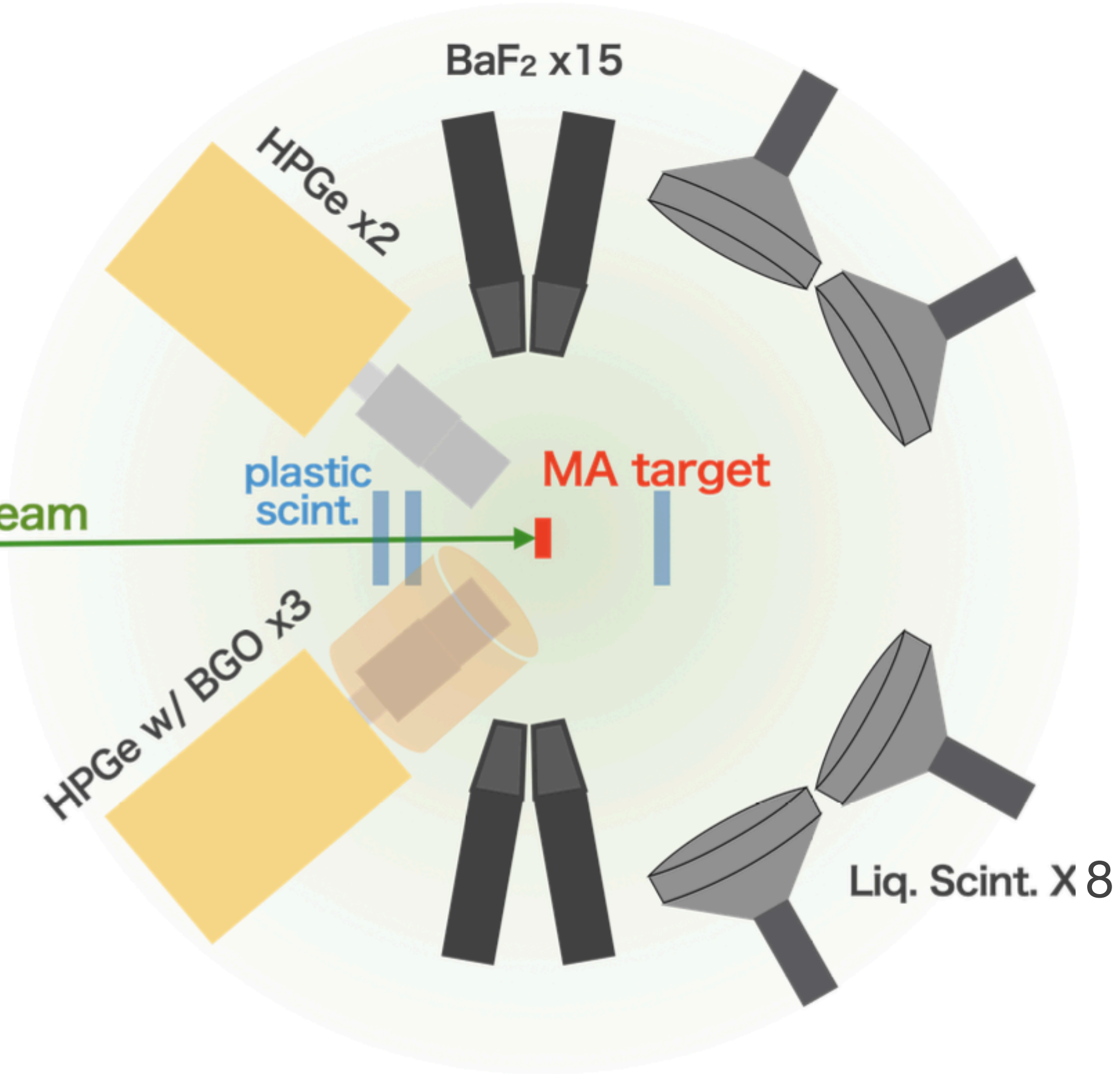
Experimental setup at piE1



BaF₂ x15



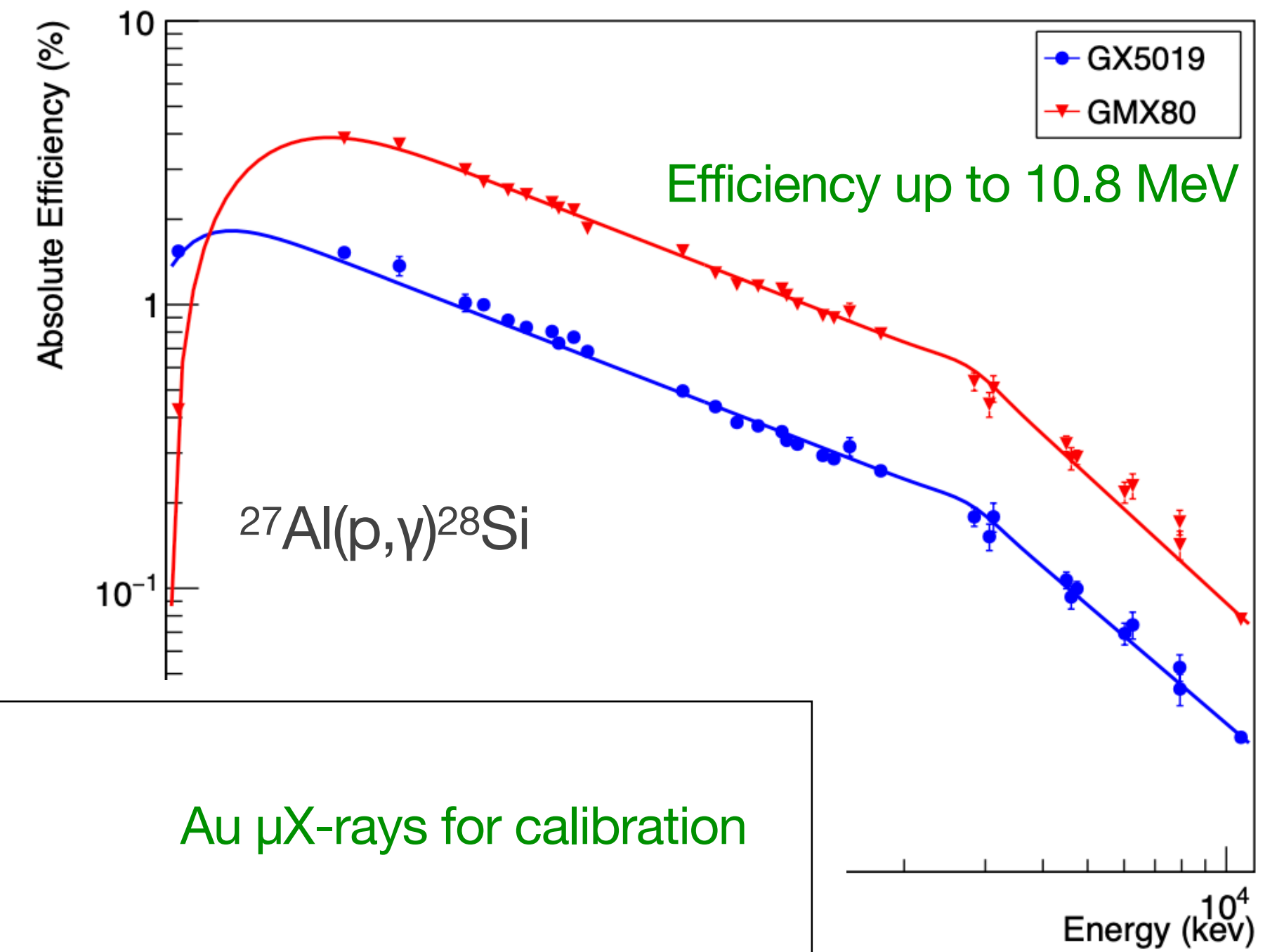
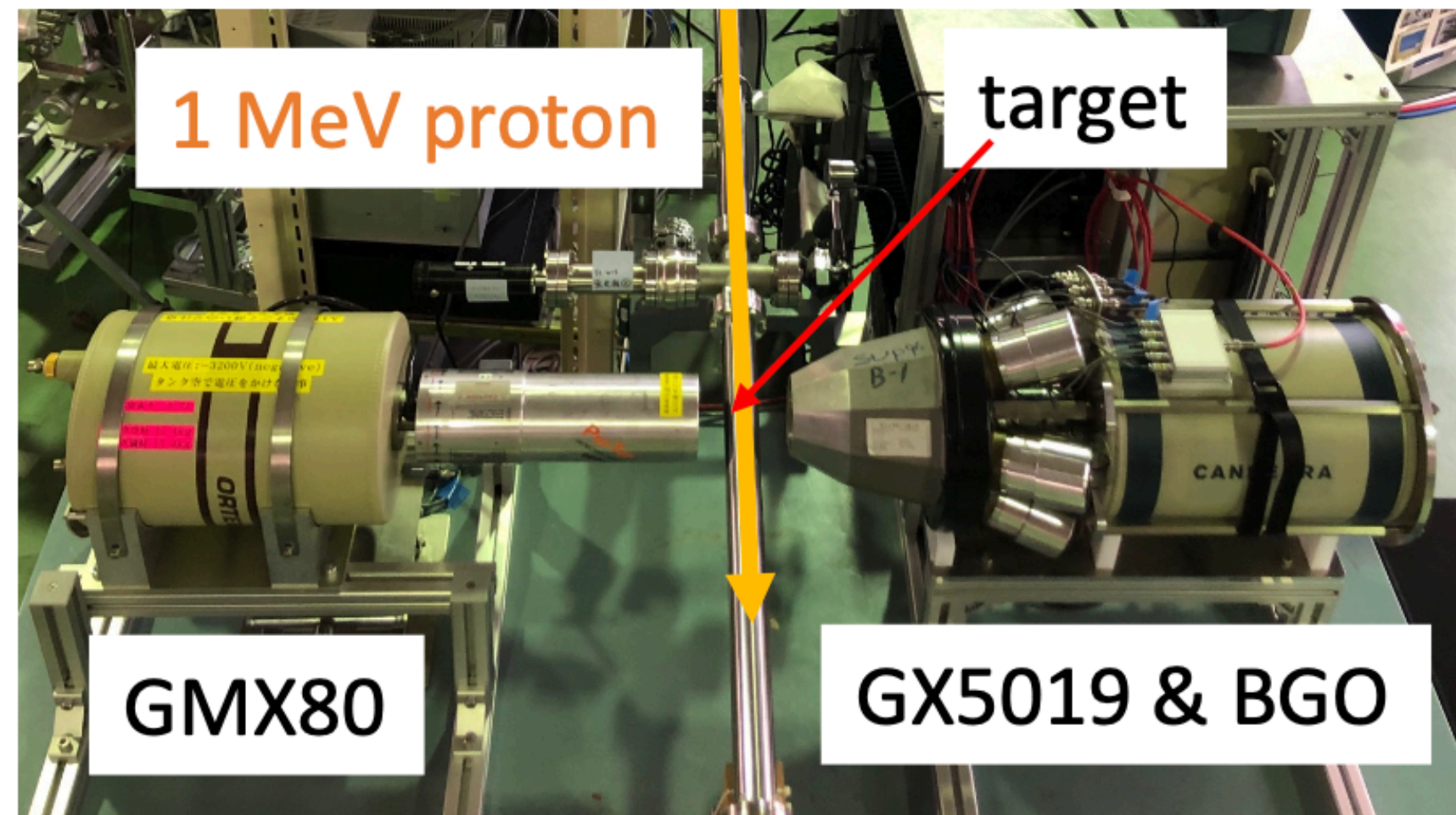
HPGe w/ BGO



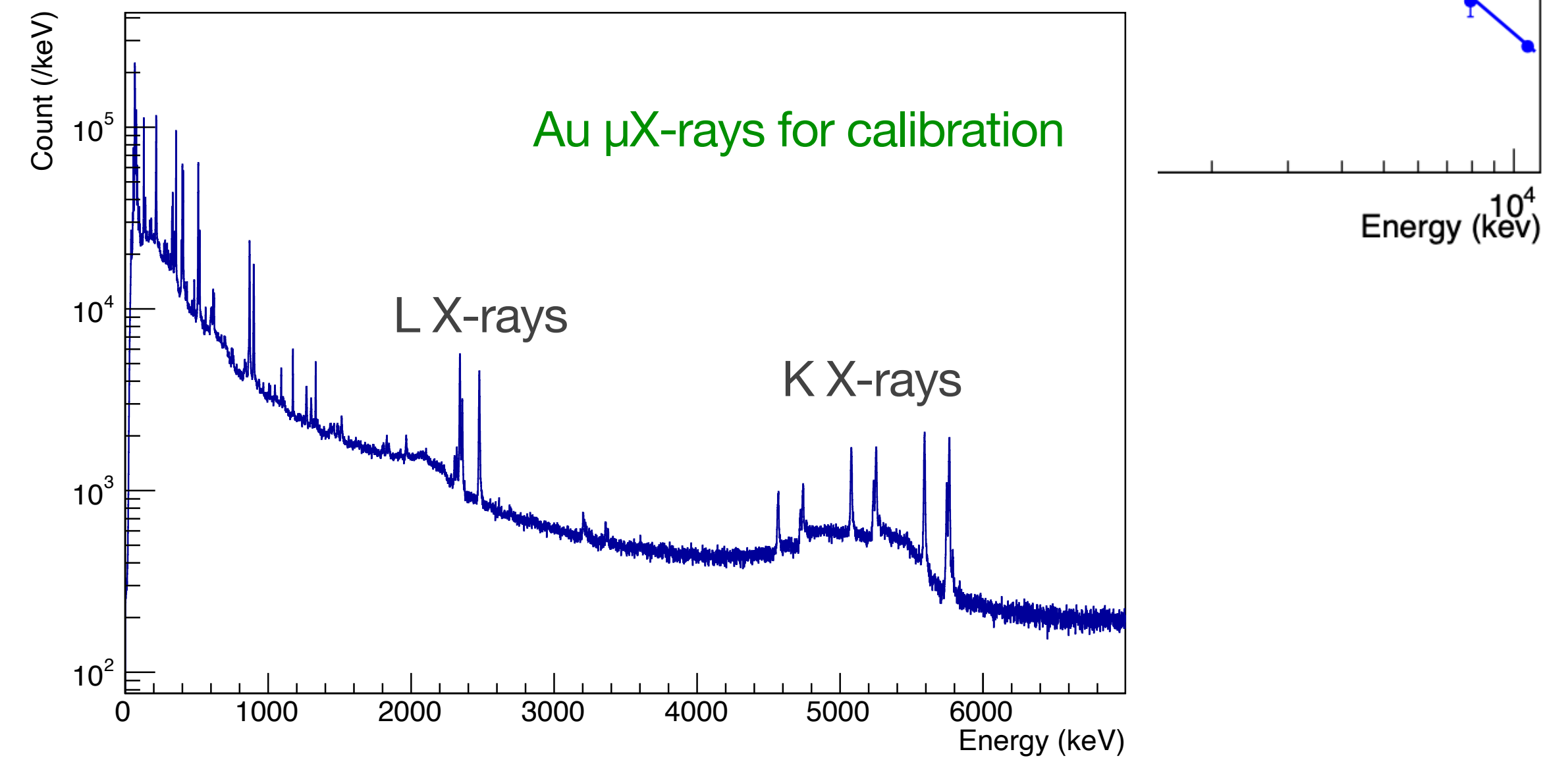
Liq. Scint.

Development of Ge detector with BGO for muonic X-ray spectroscopy

RIKEN Tandem (2021)



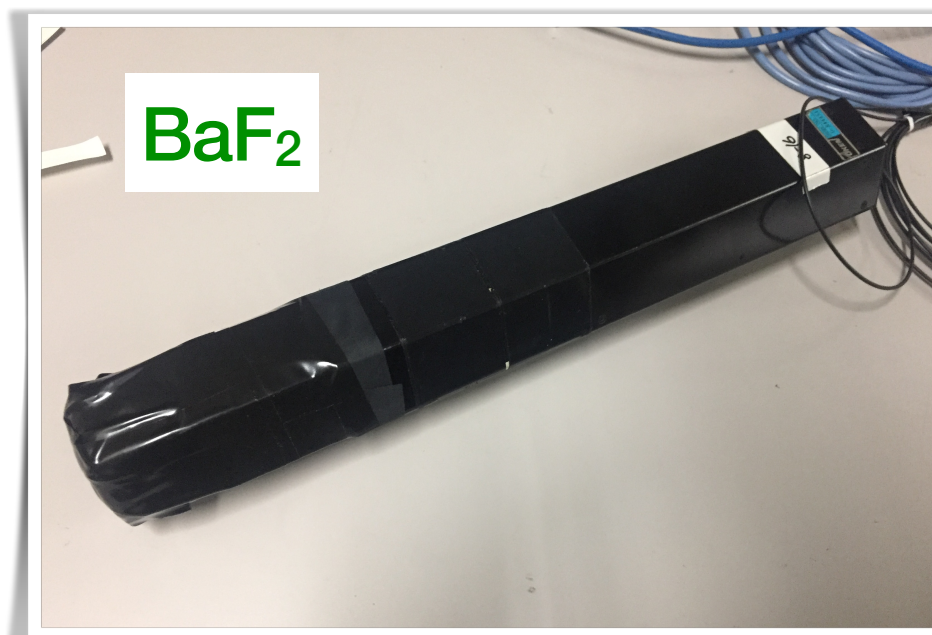
PSI piE1 (MIXE) (2022)



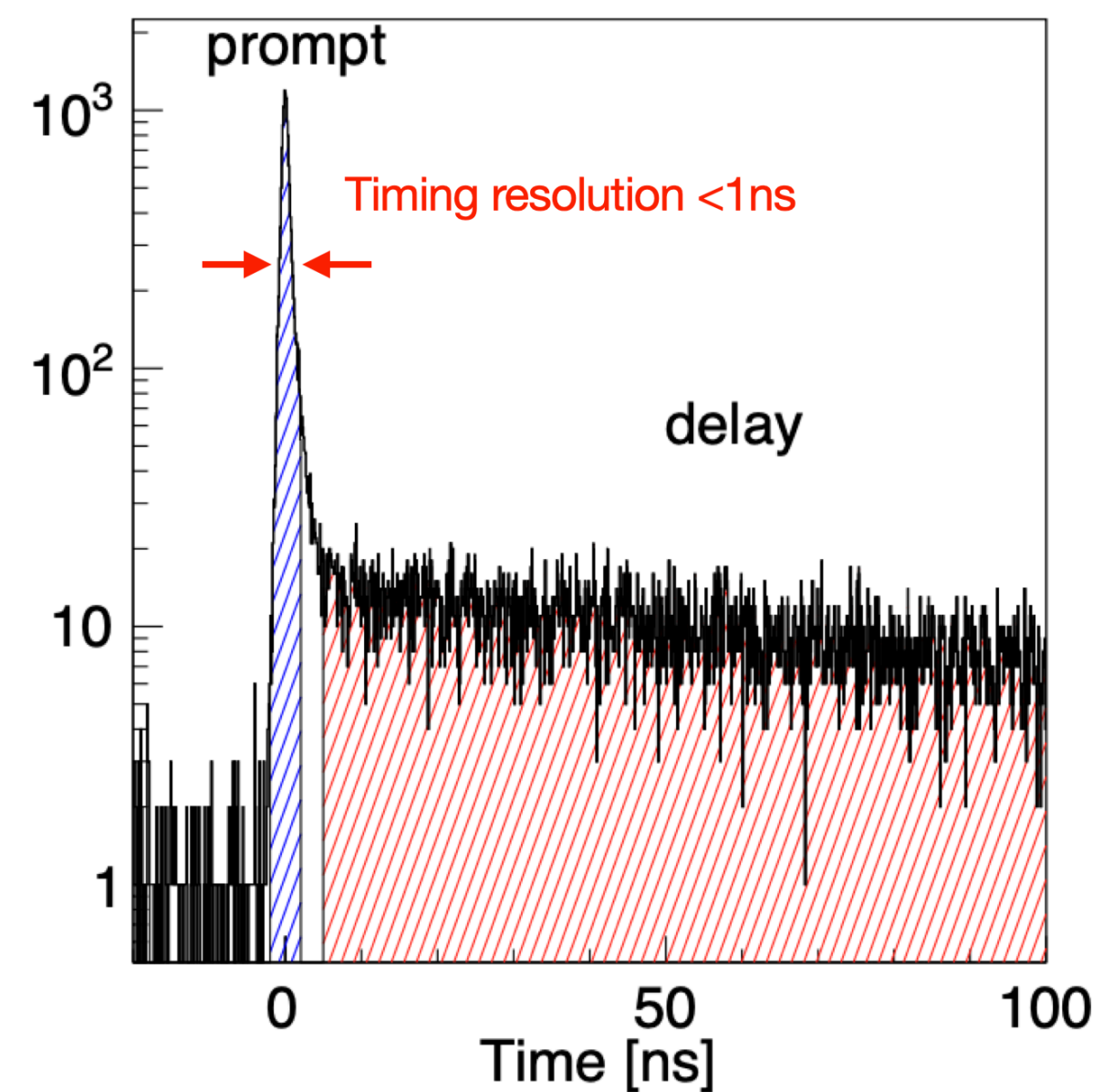
R. Mizuno et al., submitted to PTEP
 R. Mizuno et al., in preparation.

How to identify the fission events

Gamma-ray multiplicity



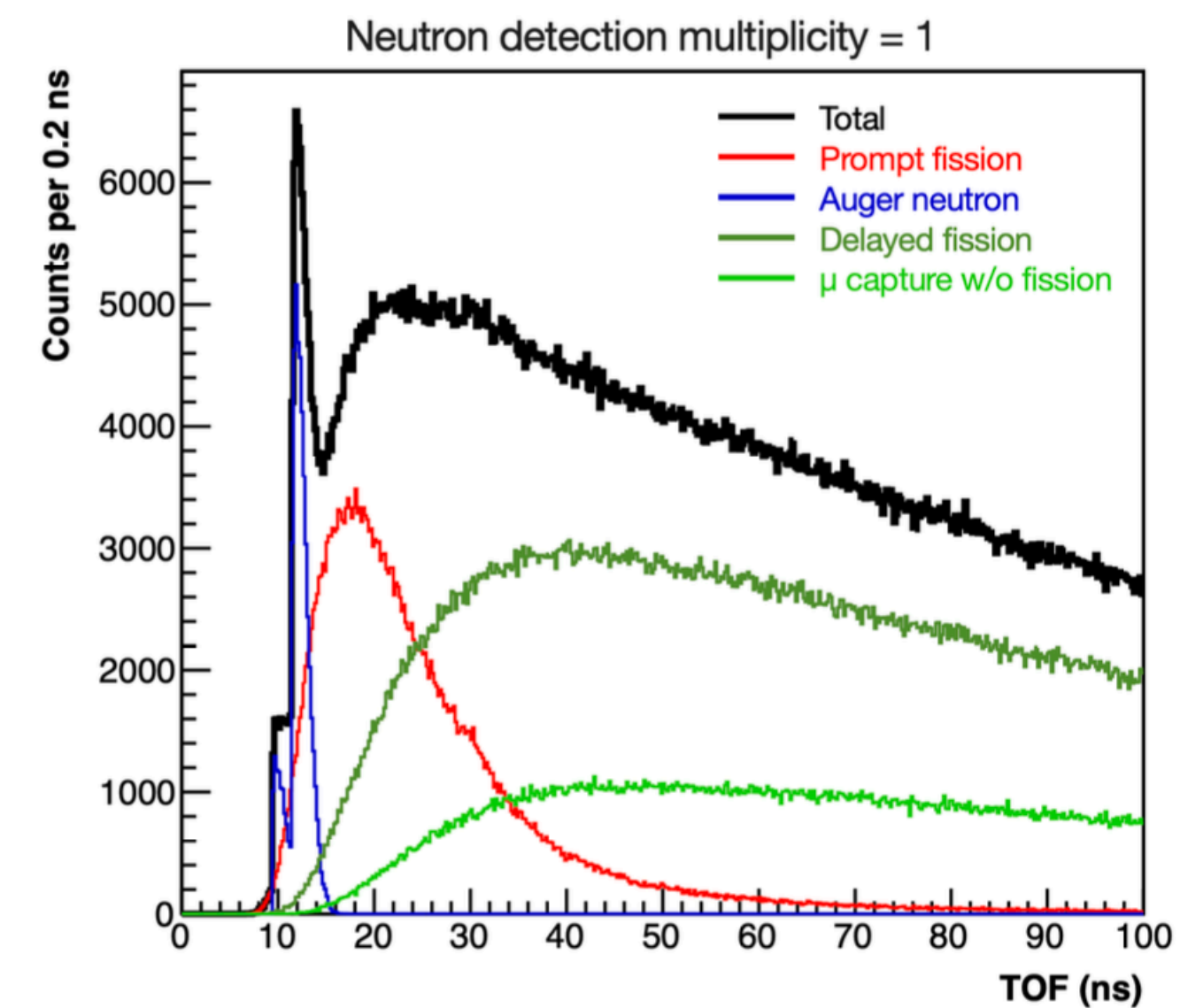
More than 30 detectors are available
High detection efficiency (~0.1%/det.)
Good timing resolution (<1ns)



Neutron multiplicity



21 detectors are available
High detection efficiency (1%/det.)
Other by-products
Auger neutron emission events
Neutron multiplicity



T.Y. Saito, PhD thesis, Univ. Tokyo (2022).

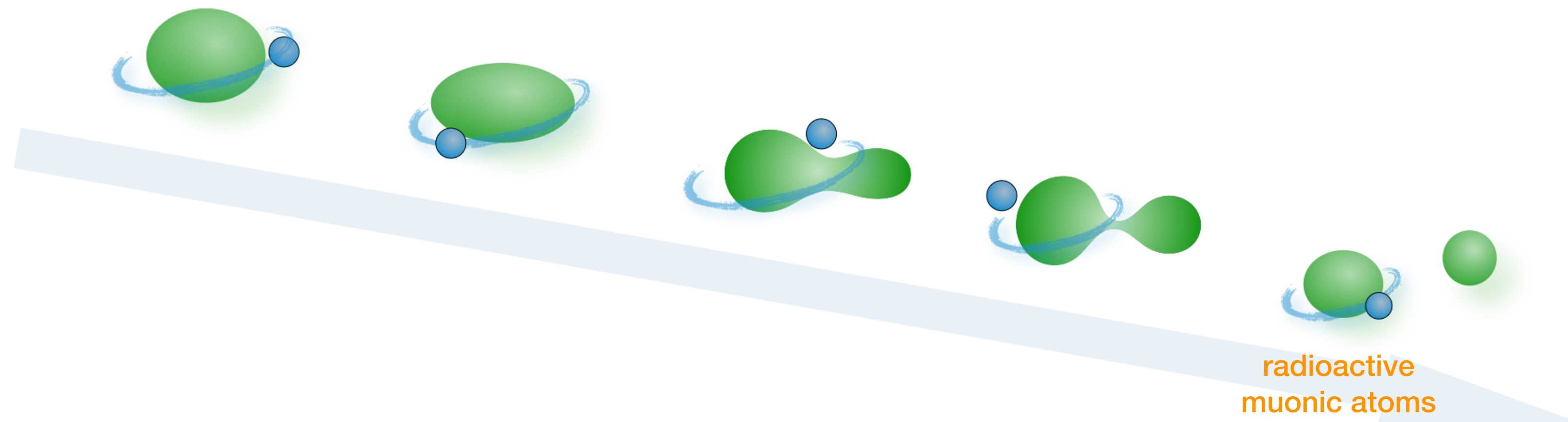
We request 3-days for preparation and 3-days for beam run

Tuning of the beam, data acquisitions, calibration with beam, etc.	1 shift
Production run for ^{237}Np	2 shifts
Production run for ^{241}Am	2 shifts
Production run for ^{243}Am	3.5 shifts
Background measurement without target	0.5 days
<hr/>	
Total	9 shifts (3 days)

There are procedural issues and we have no target available now...

Summary

- We propose to study muon-induced fission for minor-actinide (MA) isotopes at PSI.
- The final goal of the project is X-ray spectroscopy of muonic atoms with unstable nuclei (**radioactive muonic atoms**)
- The primary goal of the present proposal is to measure the muon-induced fission probabilities of three minor actinides (MA) of ~~^{237}Np , ^{241}Am , and ^{243}Am~~ .



Thank you for your attention