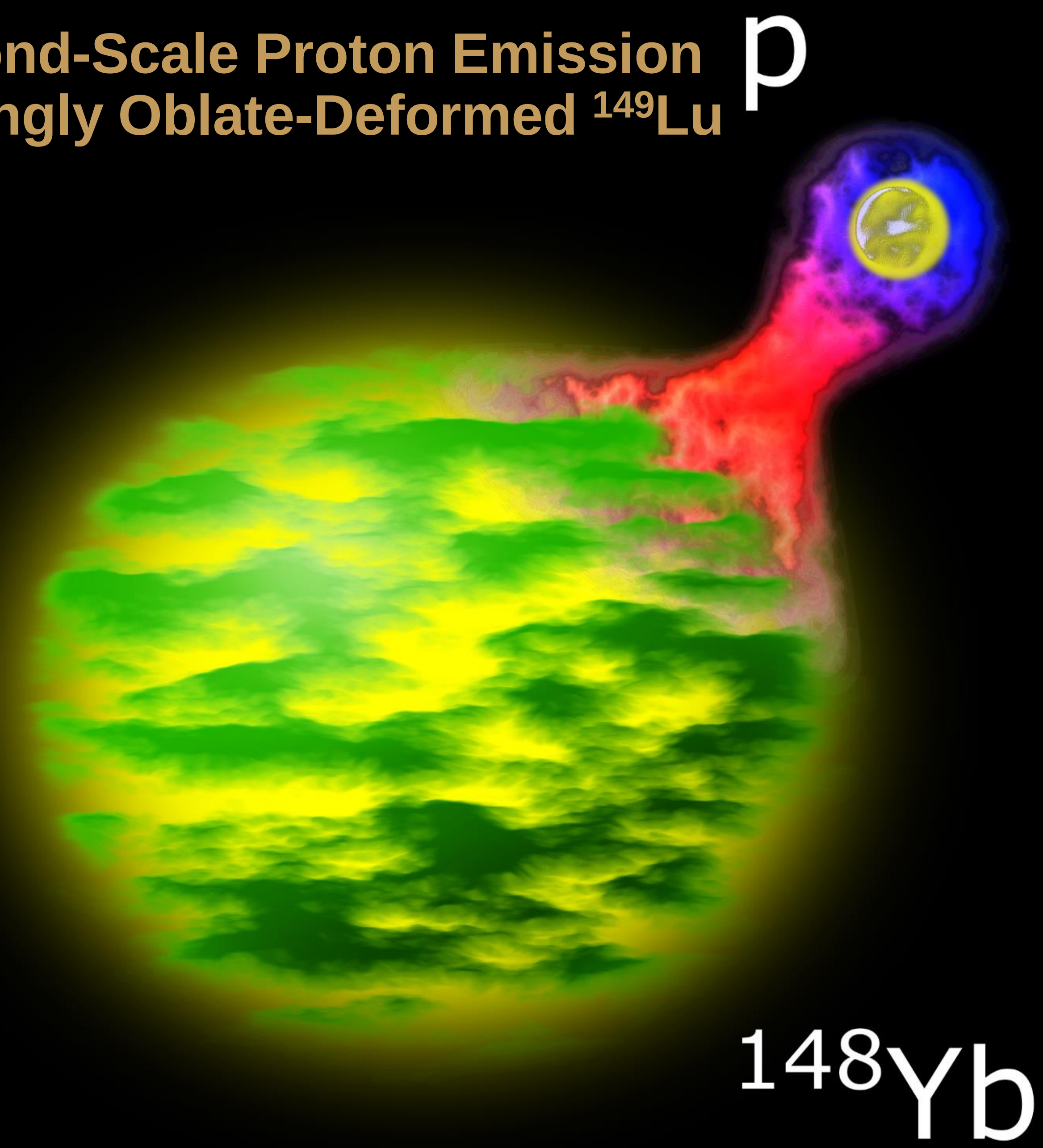
Nanosecond-Scale Proton Emission from Strongly Oblate-Deformed ^{149}Lu



UK NP ECR workshop

Kalle Auranen

Edinburgh, 17.1.2025

Outline

- Brief introduction to Nuclear Spectroscopy group activities and JYFL-ACCLAB
  - MARA and RITU setups, and their focal-plane spectrometers
- Motivation to study ^{149}Lu
- Experiment
- Results and interpretation
- Aftermath
- (Bonus: Trace analyses)

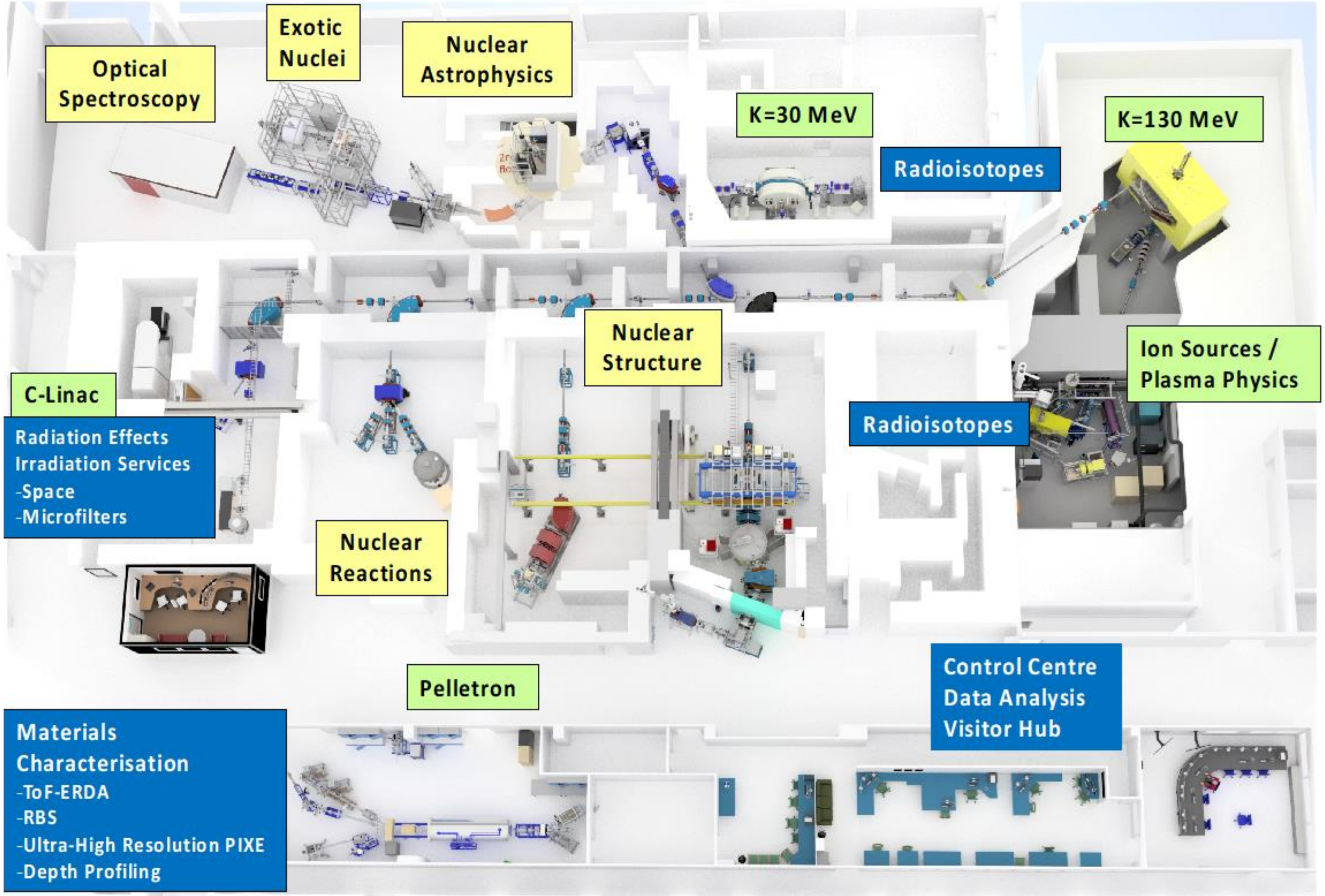
Outline

- Brief introduction to Nuclear Spectroscopy group activities and JYFL-ACCLAB
  - MARA and RITU setups, and their focal-plane spectrometers
- Motivation to study ^{149}Lu
- Experiment
- Results and interpretation
- Aftermath
- (Bonus: Trace analyses)

Outline

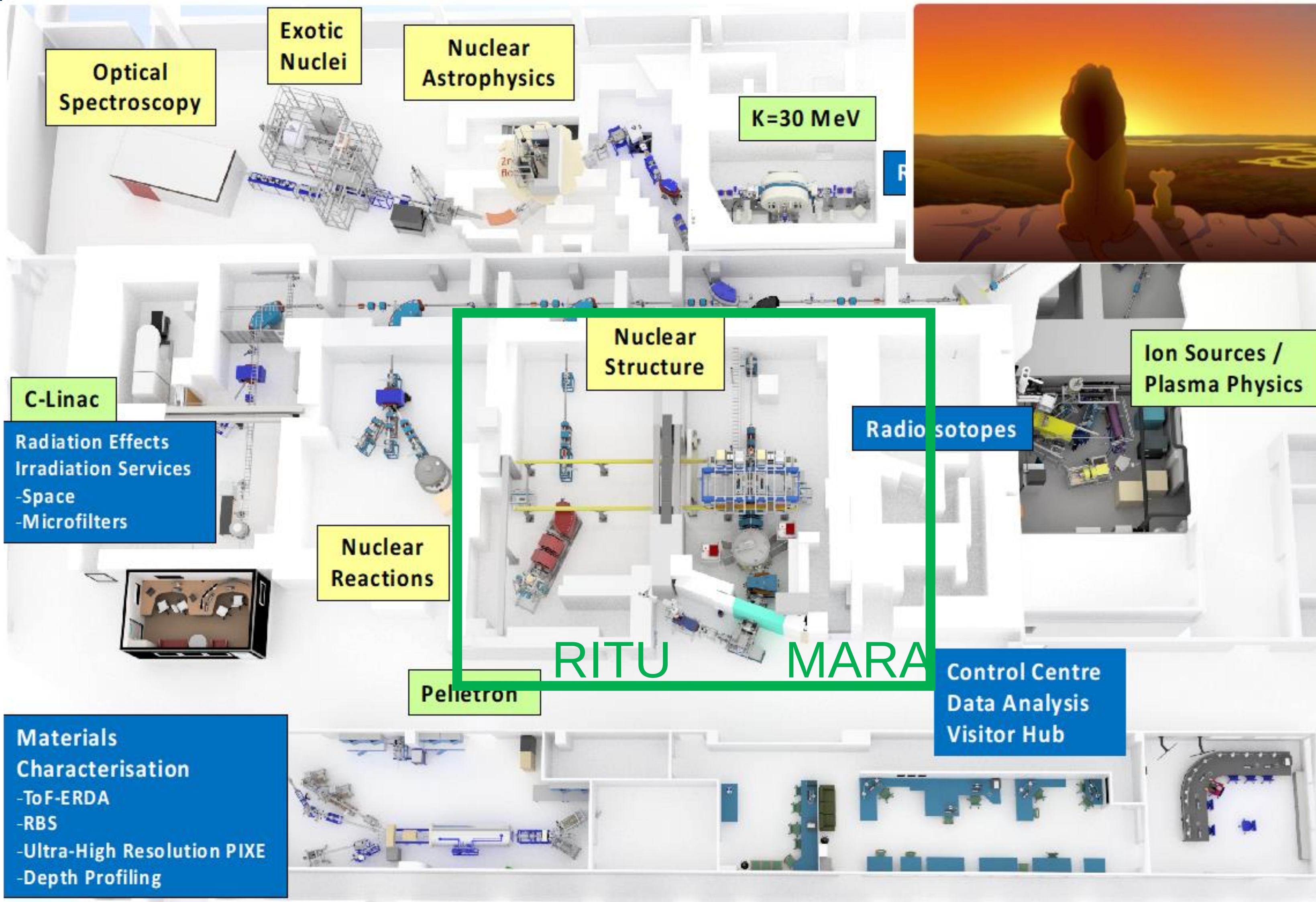
- Brief introduction to Nuclear Spectroscopy group activities and JYFL-ACCLAB
  - MARA and RITU setups, and their focal-plane spectrometers
- Motivation to study ^{149}Lu
- Experiment
- Results and interpretation
- Aftermath
- (Bonus: Trace analyses)

JYFL-ACCLAB



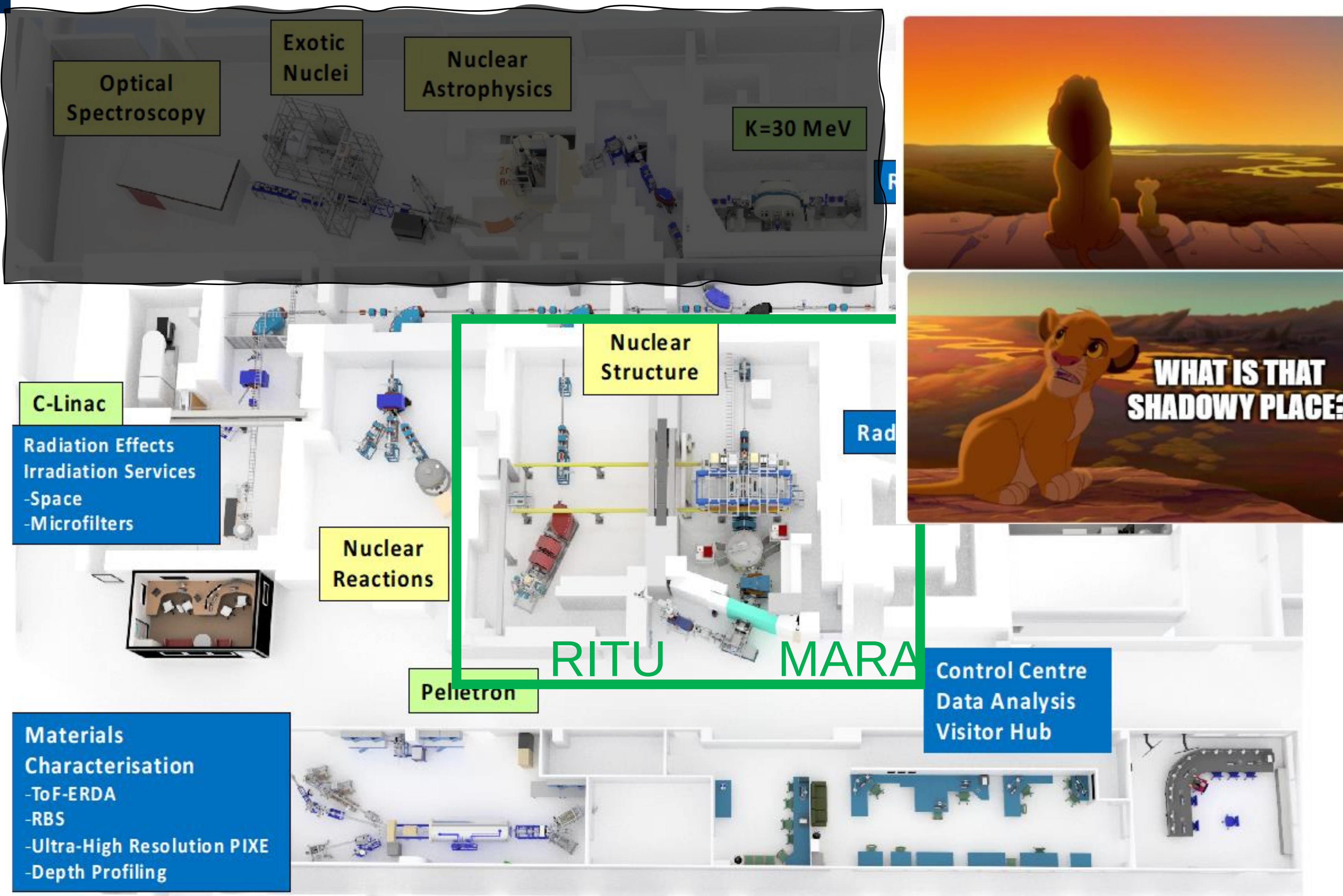
Optical Spectroscopy
Exotic Nuclei
Nuclear Astrophysics
K=30 MeV
Radioisotopes
K=130 MeV
Nuclear Structure
Ion Sources / Plasma Physics
C-Linac
Radiation Effects
Irradiation Services
-Space
-Microfilters
Radioisotopes
Nuclear Reactions
Pelletron
Control Centre
Data Analysis
Visitor Hub
Materials Characterisation
-ToF-ERDA
-RBS
-Ultra-High Resolution PIXE
-Depth Profiling

JYFL-ACCLAB



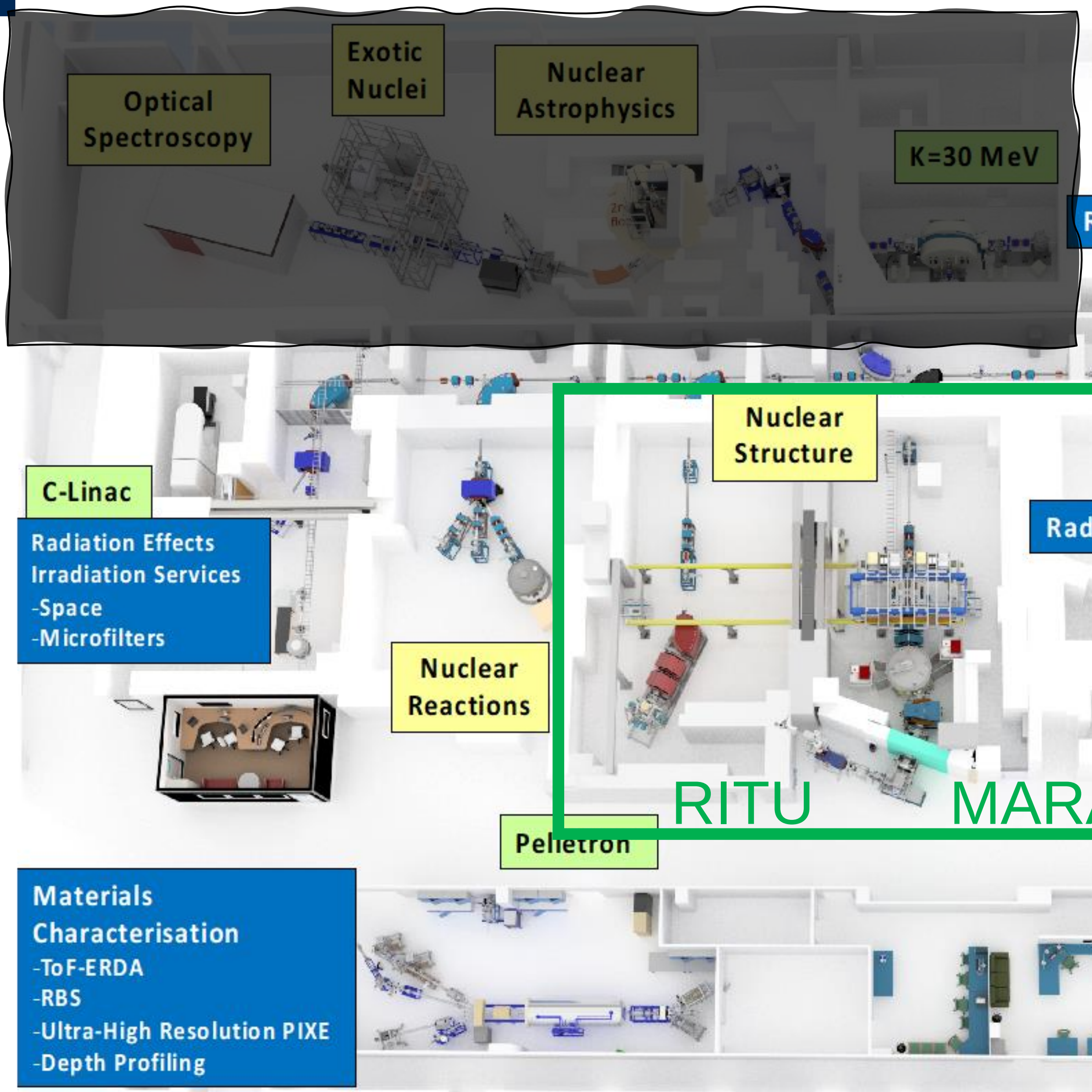
Optical Spectroscopy
Exotic Nuclei
Nuclear Astrophysics
K=30 MeV
C-Linac
Radiation Effects
Irradiation Services
-Space
-Microfilters
Nuclear Reactions
Nuclear Structure
Radioisotopes
Ion Sources / Plasma Physics
RITU
MARA
Pelletron
Control Centre
Data Analysis
Visitor Hub
Materials Characterisation
-ToF-ERDA
-RBS
-Ultra-High Resolution PIXE
-Depth Profiling

JYFL-ACCLAB

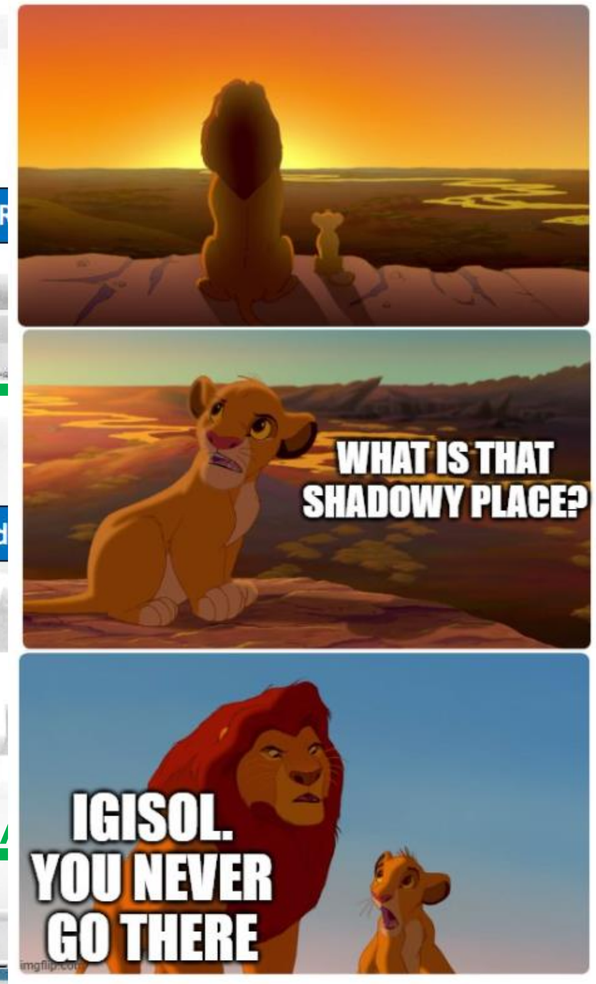


Optical Spectroscopy
Exotic Nuclei
Nuclear Astrophysics
K=30 MeV
C-Linac
Radiation Effects
Irradiation Services
-Space
-Microfilters
Nuclear Reactions
Nuclear Structure
RITU
MARA
Pelletron
Control Centre
Data Analysis
Visitor Hub
Materials Characterisation
-ToF-ERDA
-RBS
-Ultra-High Resolution PIXE
-Depth Profiling
WHAT IS THAT SHADOWY PLACE?

JYFL-ACCLAB



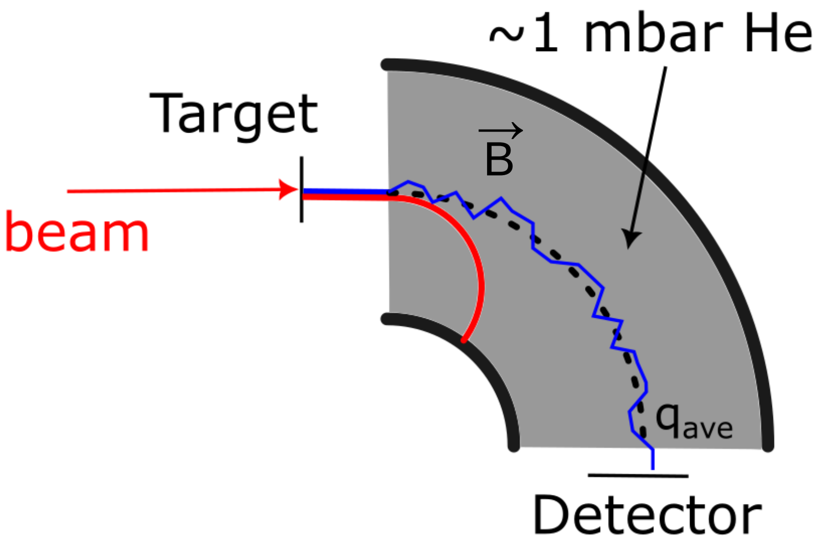
Optical Spectroscopy
Exotic Nuclei
Nuclear Astrophysics
K=30 MeV
C-Linac
Radiation Effects
Irradiation Services
-Space
-Microfilters
Nuclear Structure
Nuclear Reactions
RITU
MARA
Pelletron
Materials Characterisation
-ToF-ERDA
-RBS
-Ultra-High Resolution PIXE
-Depth Profiling



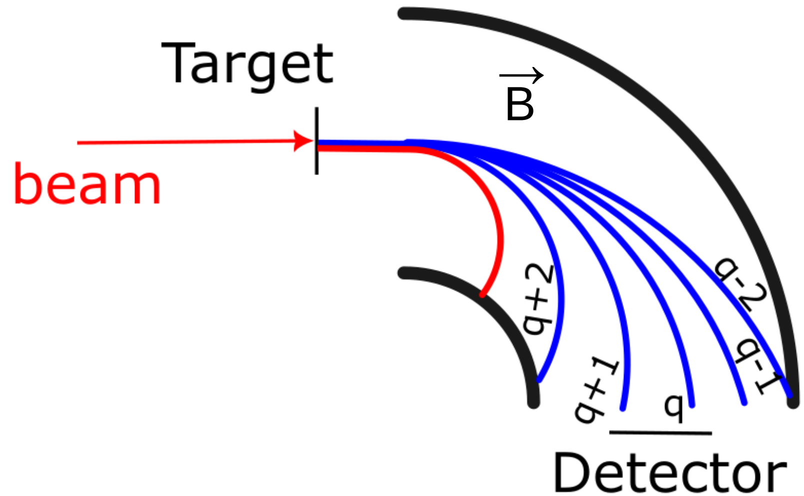
WHAT IS THAT SHADOWY PLACE?
IGISOL. YOU NEVER GO THERE

Two complementary recoil separators
(to collect fusion-evaporation residues)

- Recoil Ion Transport Unit (RITU)*
  – Gas filled
  – No mass information
  + Collects all charge states



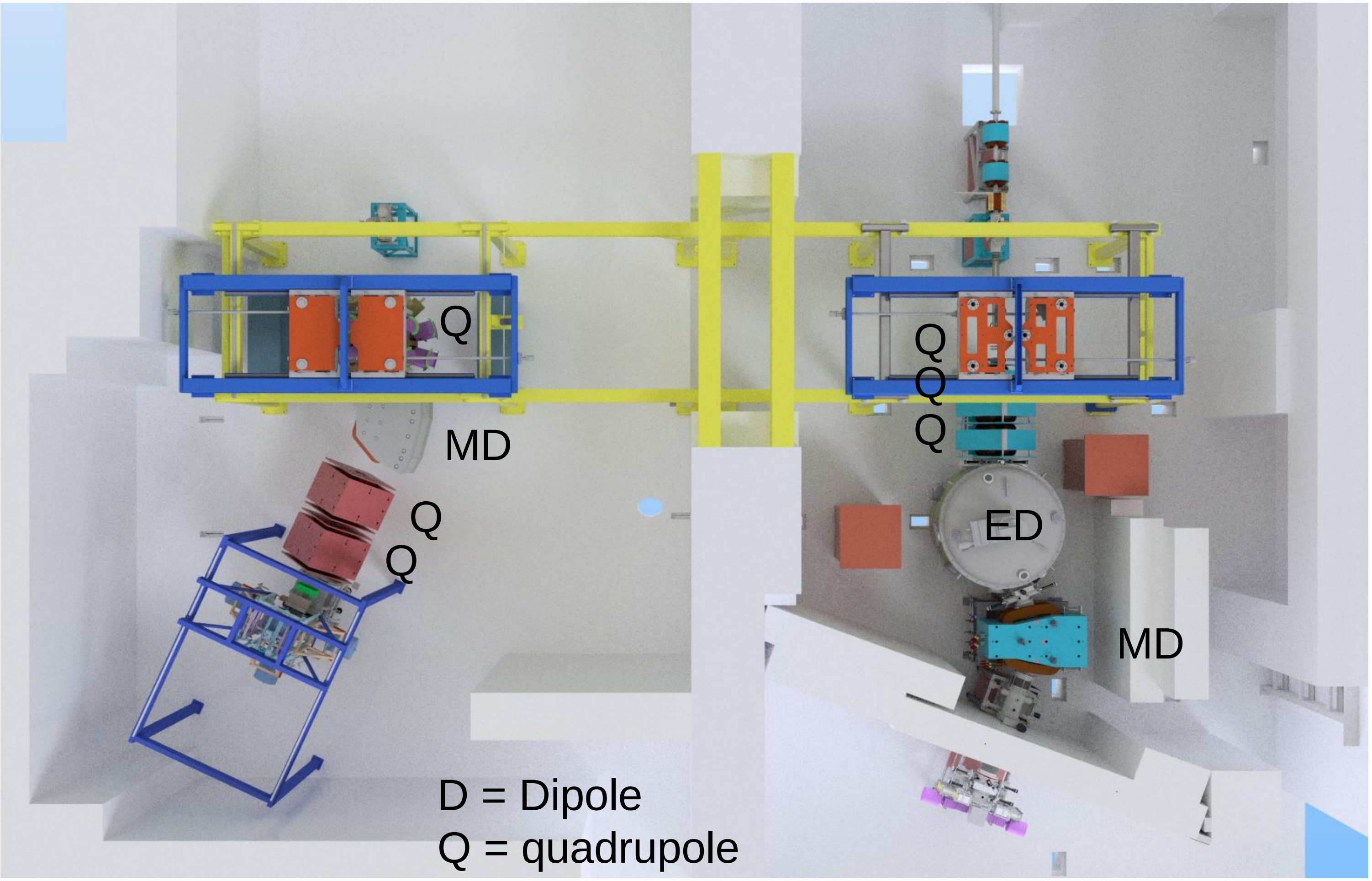
- Mass Analyzing Recoil Apparatus (MARA)*
  – Vacuum mode
  + A/q information
  - A few (~ 2 - 4) charge states collected at once



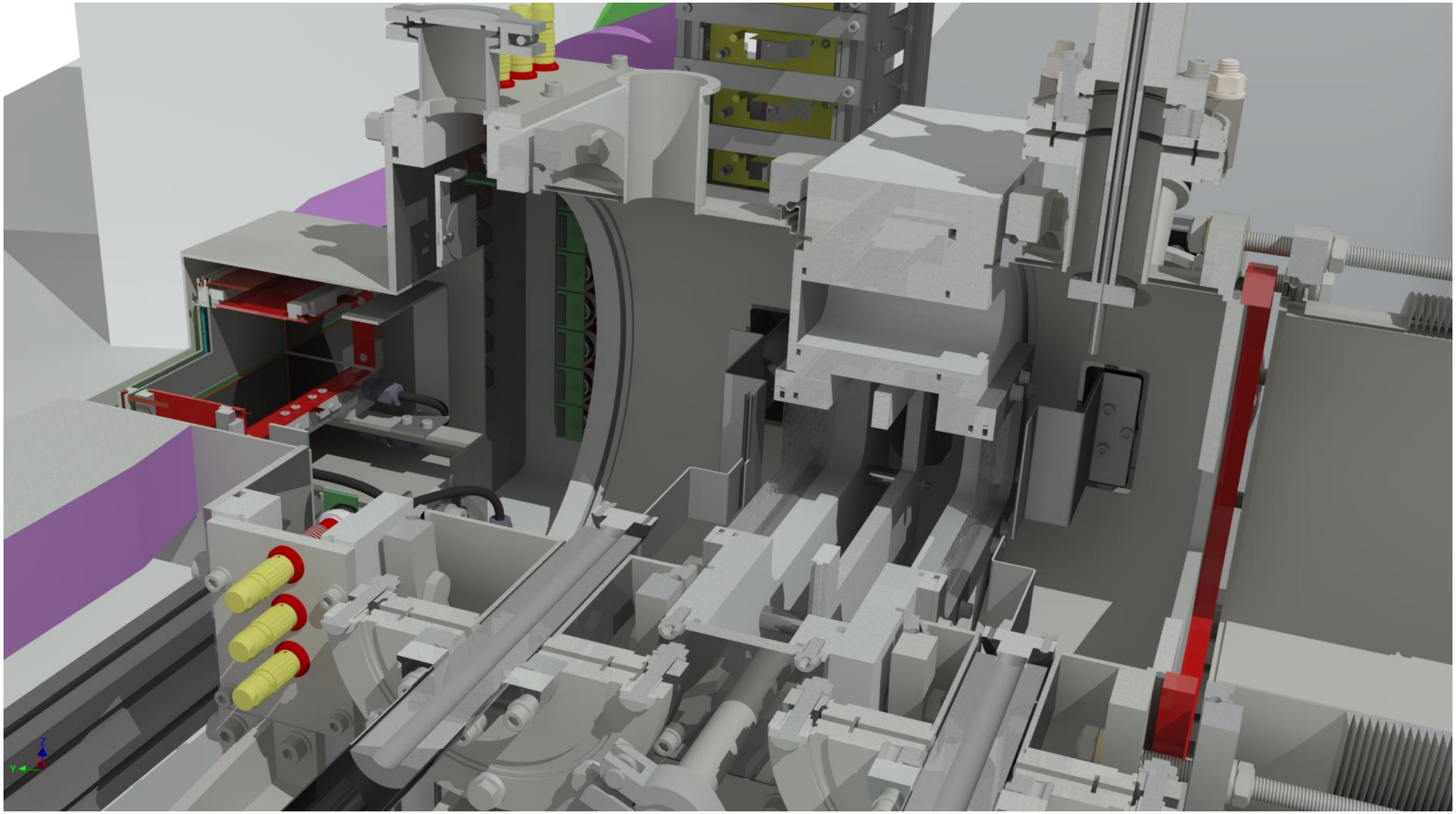
*Simplified sketches

Two complementary recoil separators
(to collect fusion-evaporation residues)

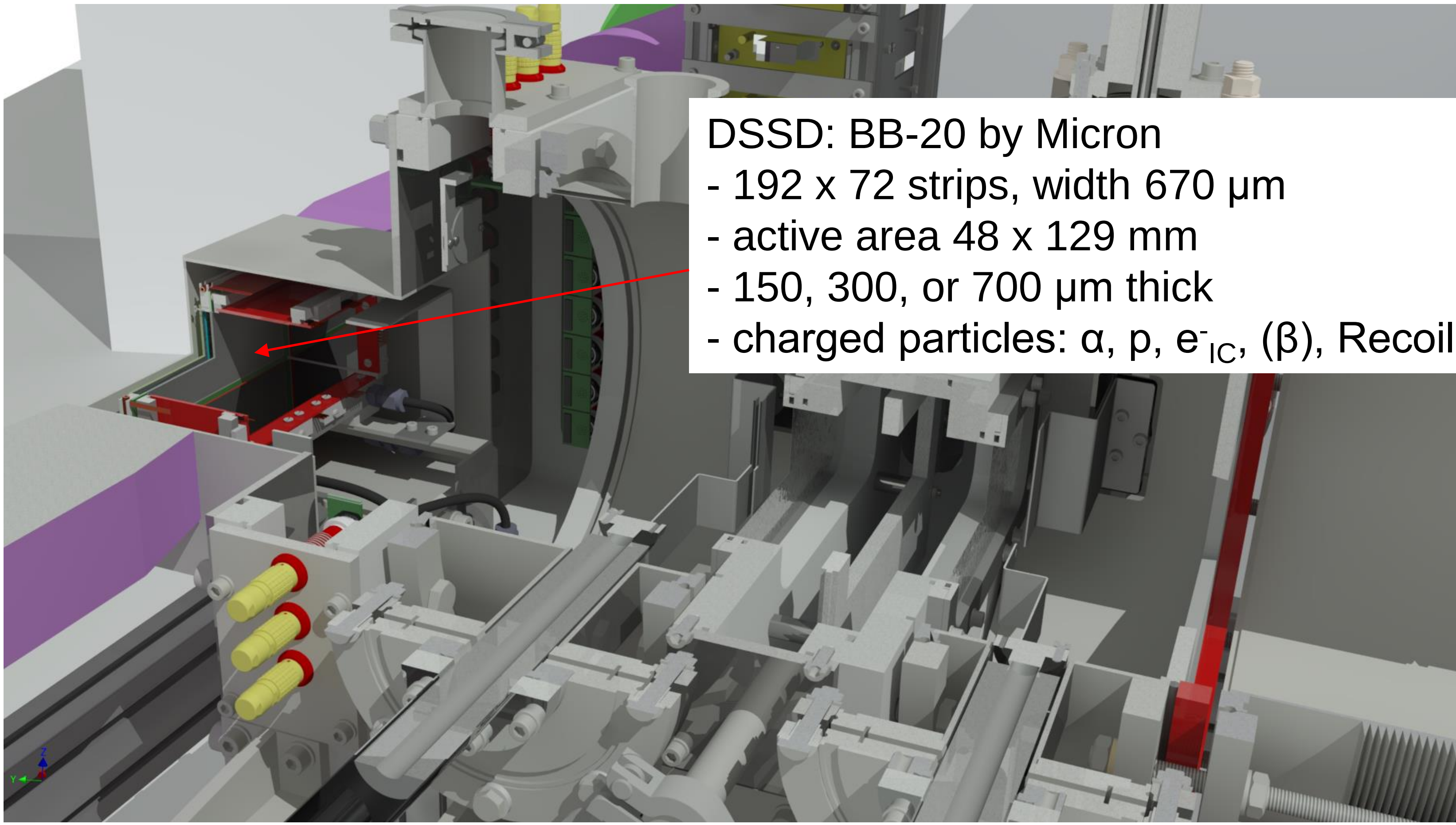
- Recoil Ion Transport Unit (RITU)
- Mass Analyzing Recoil Apparatus (MARA)



Focal-plane spectrometers
(~ identical for RITU and MARA)



Focal-plane spectrometers
(~ identical for RITU and MARA)

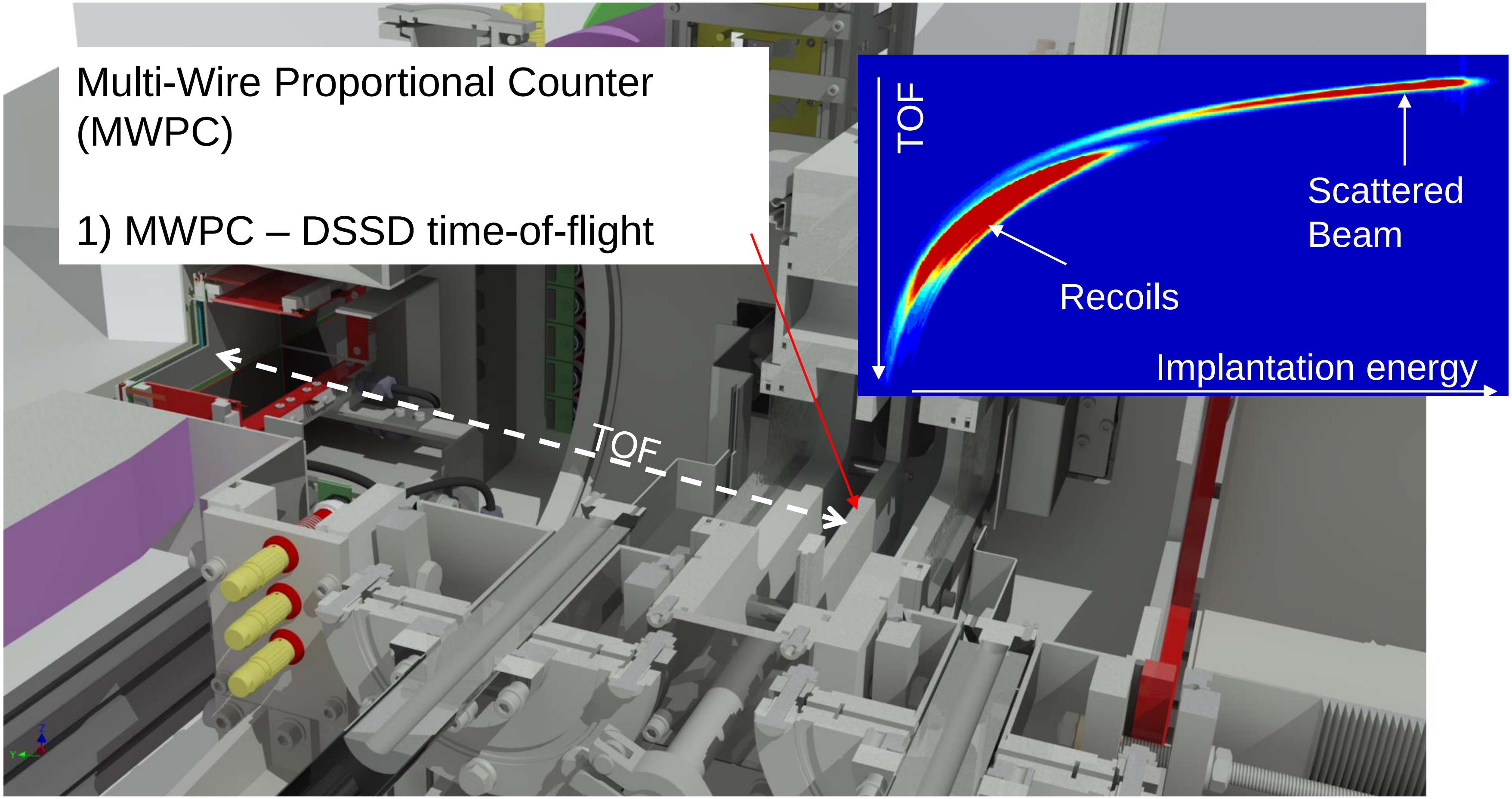


DSSD: BB-20 by Micron
- 192 x 72 strips, width 670 μm
- active area 48 x 129 mm
- 150, 300, or 700 μm thick
- charged particles: α, p, e^{-}_{IC}, (β), Recoils

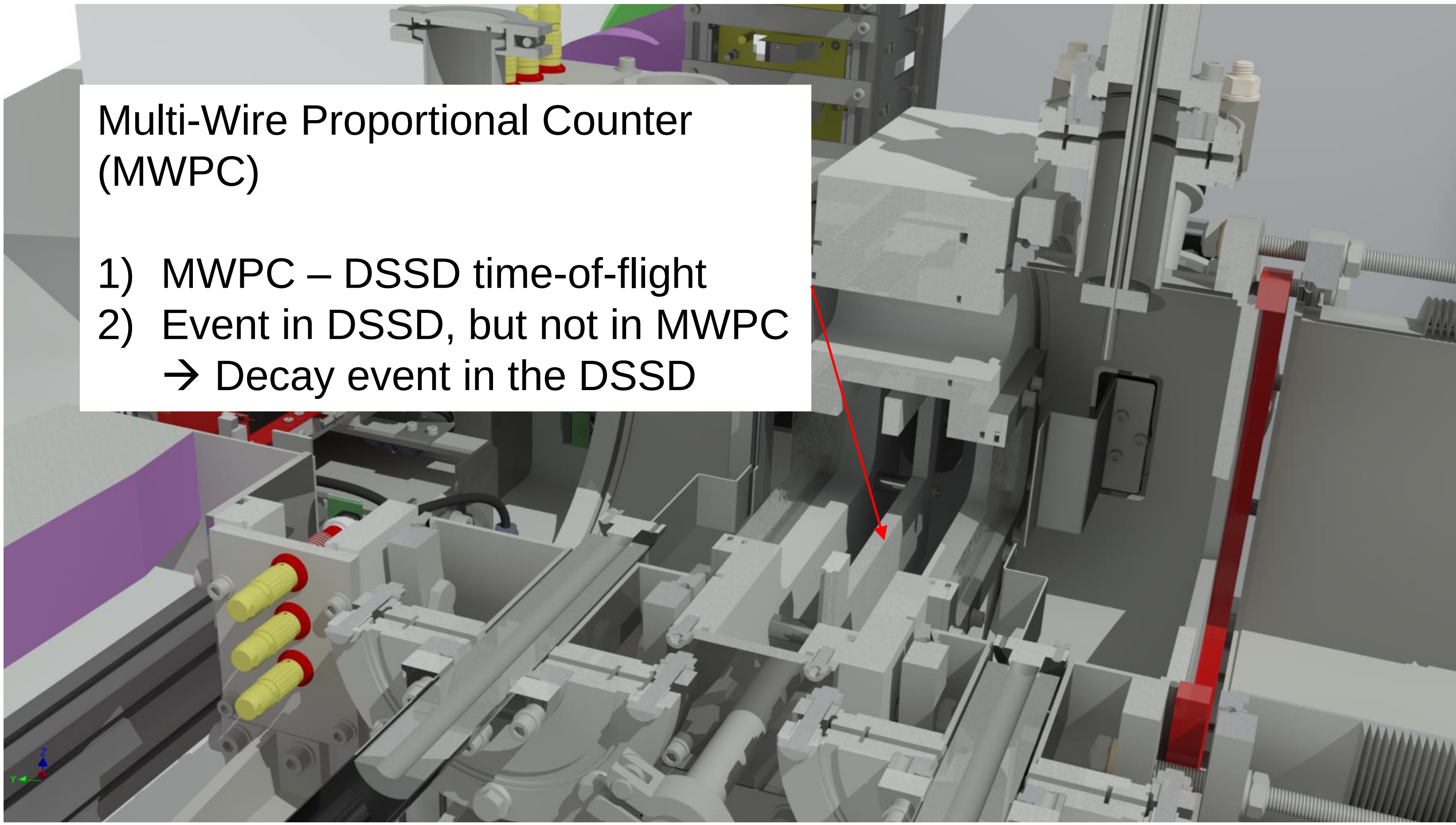
Focal-plane spectrometers
(~ identical for RITU and MARA)

Multi-Wire Proportional Counter (MWPC)

1) MWPC – DSSD time-of-flight



Focal-plane spectrometers
(~ identical for RITU and MARA)



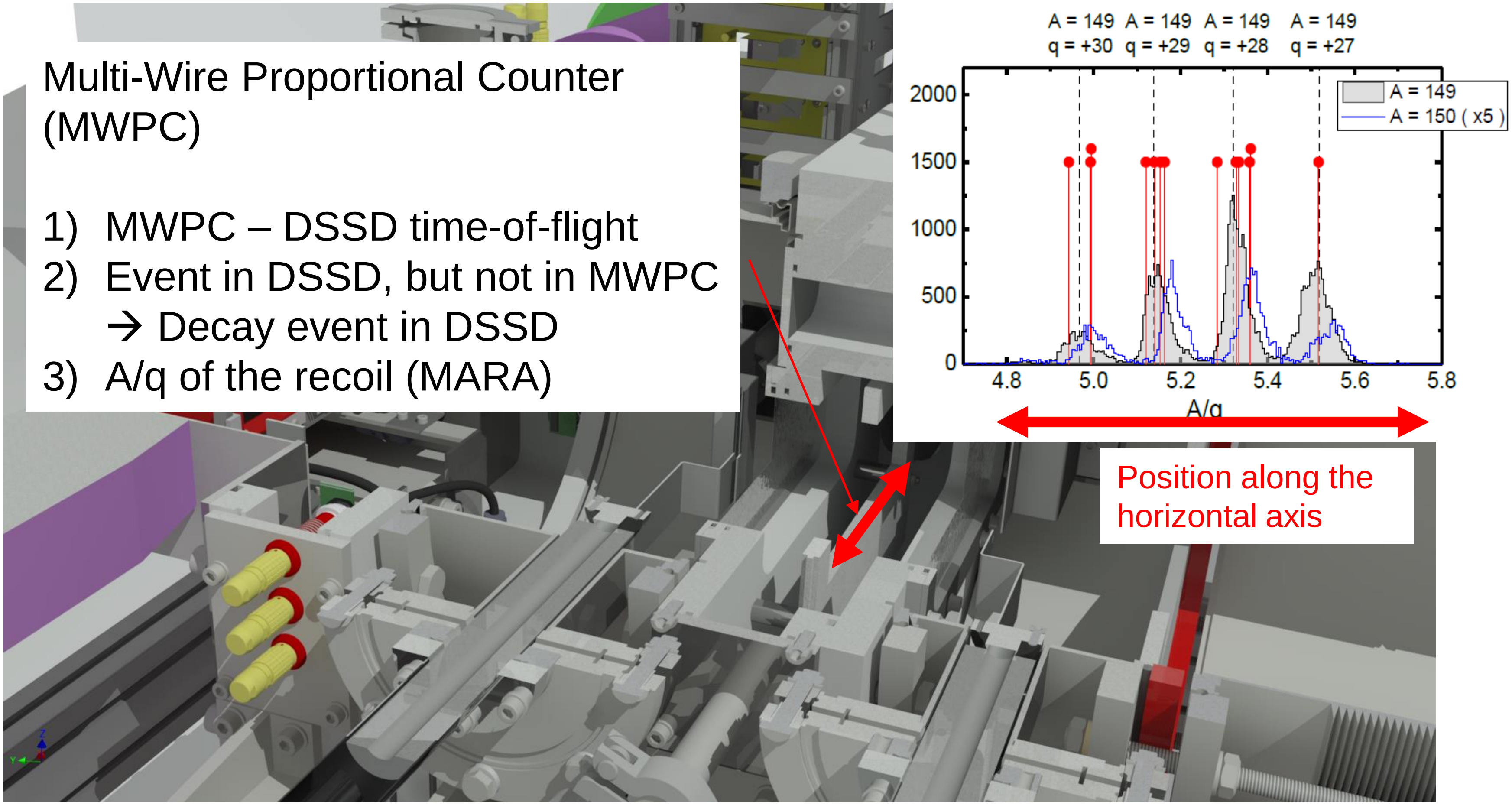
Multi-Wire Proportional Counter (MWPC)

1) MWPC – DSSD time-of-flight
2) Event in DSSD, but not in MWPC
   → Decay event in the DSSD

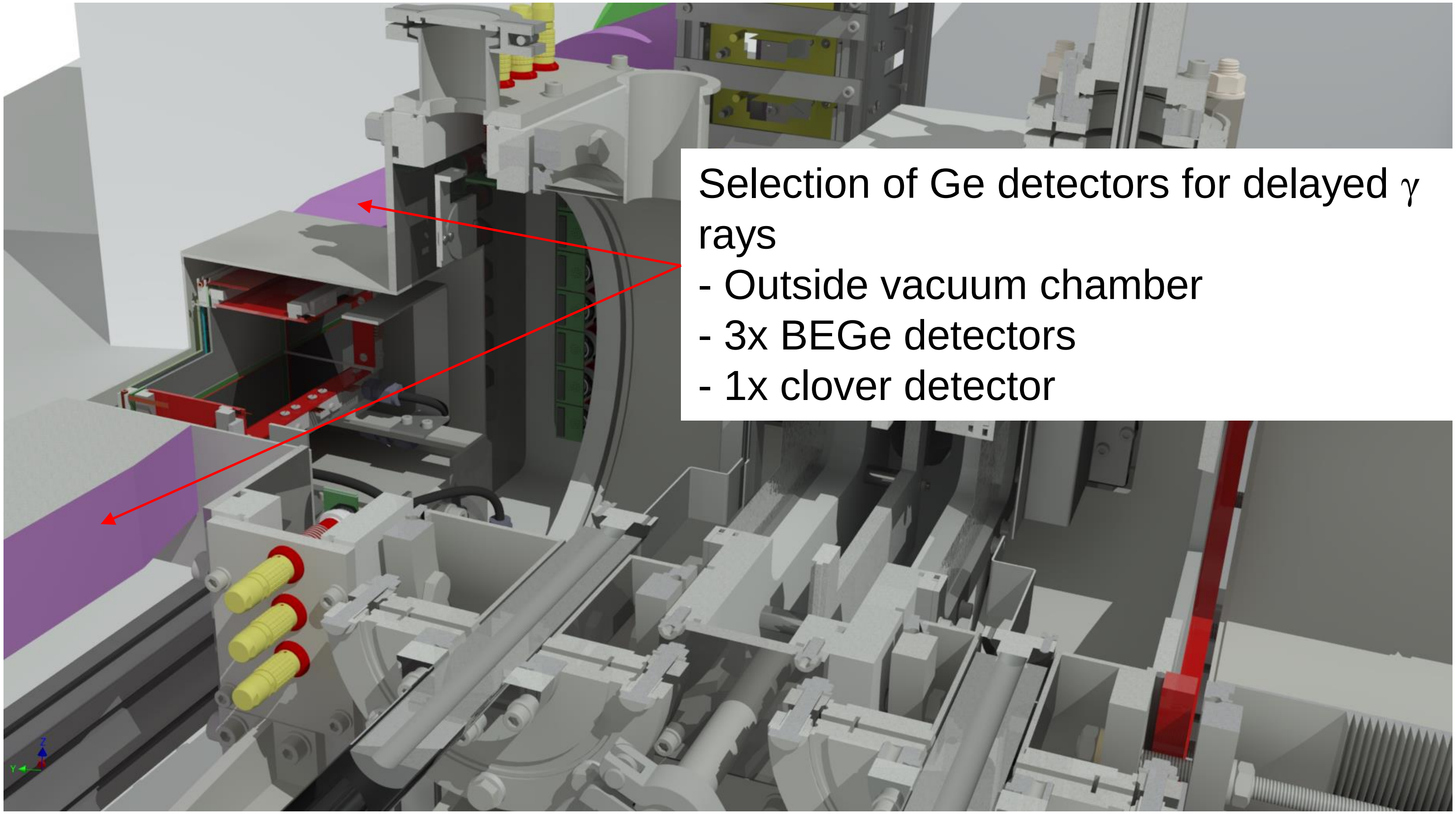
Focal-plane spectrometers
(~ identical for RITU and MARA)

Multi-Wire Proportional Counter (MWPC)

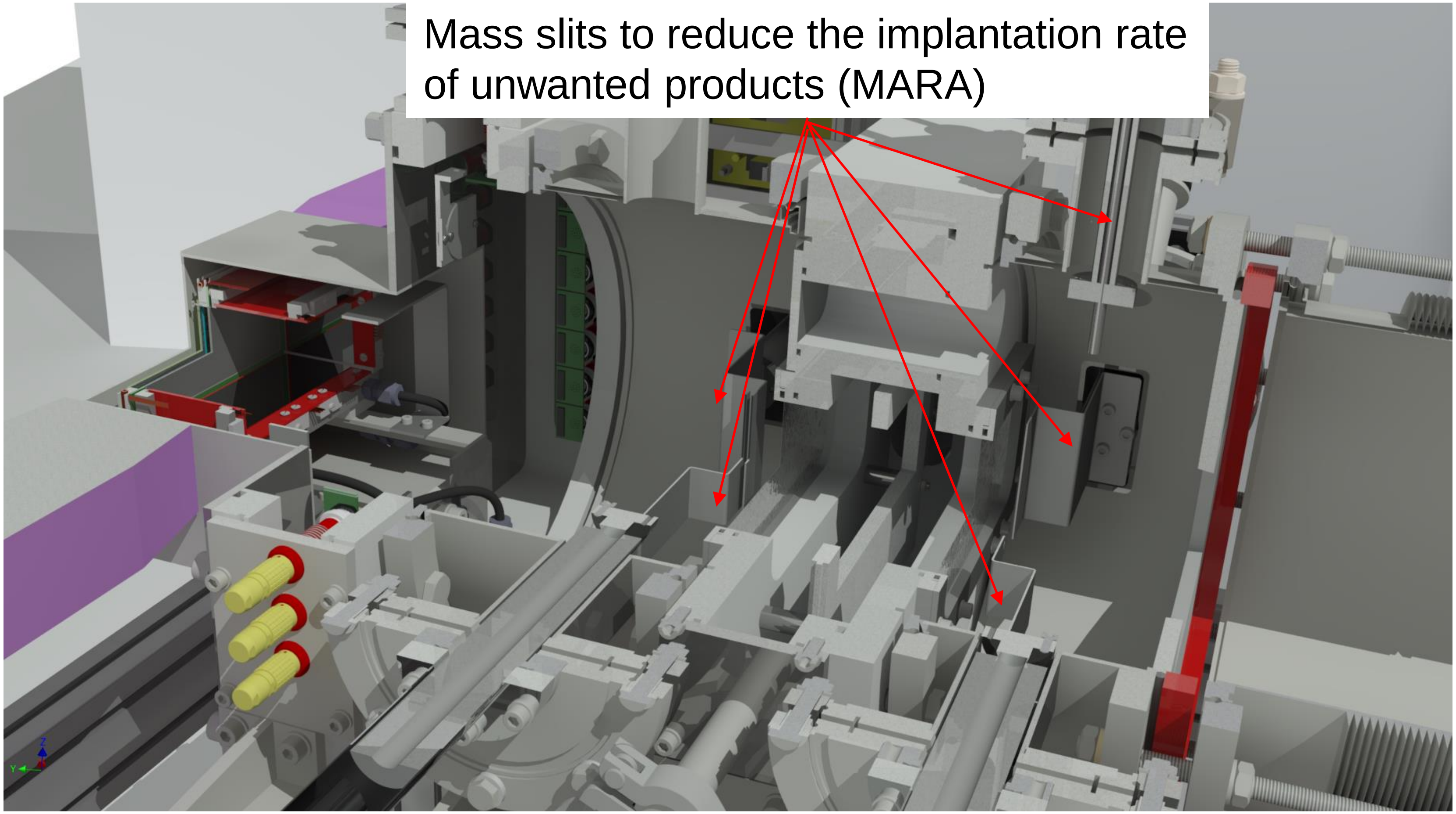
1) MWPC – DSSD time-of-flight
2) Event in DSSD, but not in MWPC
   → Decay event in DSSD
3) A/q of the recoil (MARA)



Focal-plane spectrometers
(~ identical for RITU and MARA)



Focal-plane spectrometers



Outline

- Brief introduction to Nuclear Spectroscopy group activities and JYFL-ACCLAB
  - MARA and RITU setups, and their focal-plane spectrometers
- Motivation to study ^{149}Lu
- Experiment
- Results and interpretation
- Aftermath
- (Bonus: Trace analyses)

Proton emission (= “proton decay”)

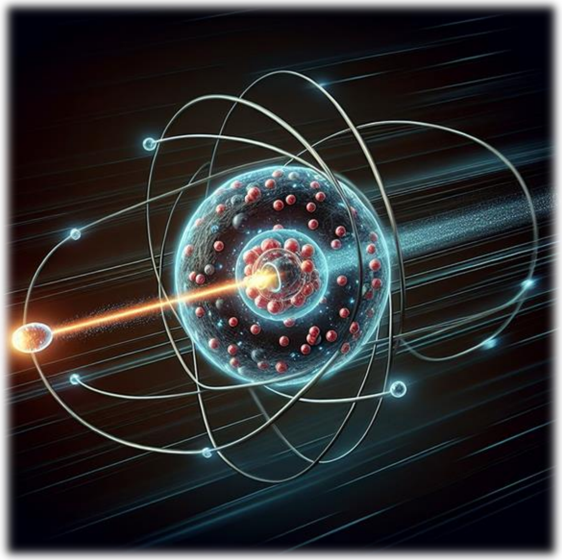
- A rare type of radioactivity where a proton is emitted from a nucleus
  - Similar to α decay
  - First evidence in 1970’s: 19^{-} isomeric state in ^{53}Co

    [J. Cerny et al. Phys. Lett., B33 (1970), p. 284]

    [K. P. Jackson et al. Phys. Lett., B33 (1970), p. 281]
  - First ground-state proton emitter: ^{151}Lu

    [S. Hofmann et al. Z. Phys., A305 (1982), p. 111]
  - Approximately 30 ground-state proton emissions are observed

    [B. Blank, M.J.G. Borge, Prog. in Part. and Nucl. Phys. 60 (2008) 403–483] (+2)



Why study Lutetium?

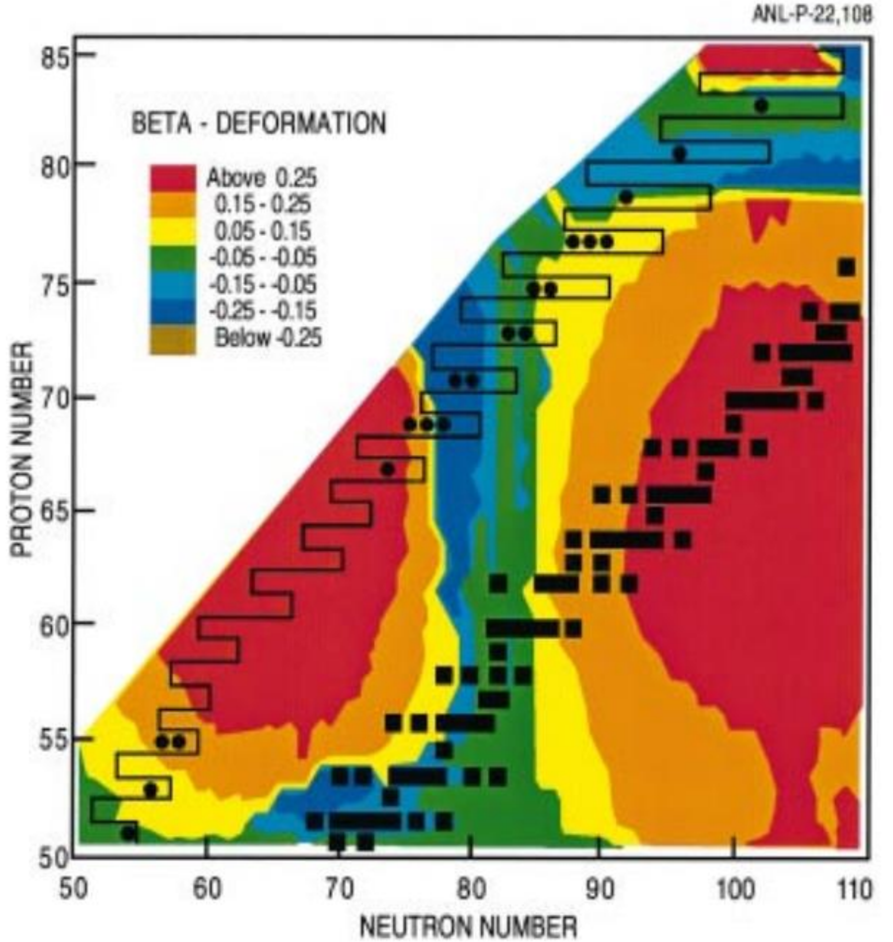


Figure 5 Contour plot of the quadrupole deformation parameter b2 taken from (89), showing the general trend of the deformations. Filled circles are the known proton emitters, and the predicted proton drip-line also taken from (90) is shown as a solid line, modified where experimental evidence is available.

[P.J. Woods, C.N. Davids, Annu. Rev. Nucl. Part. Sci. 47 541 (1997)]

Why study Lutetium?

- Very few oblate deformed proton emitters are known

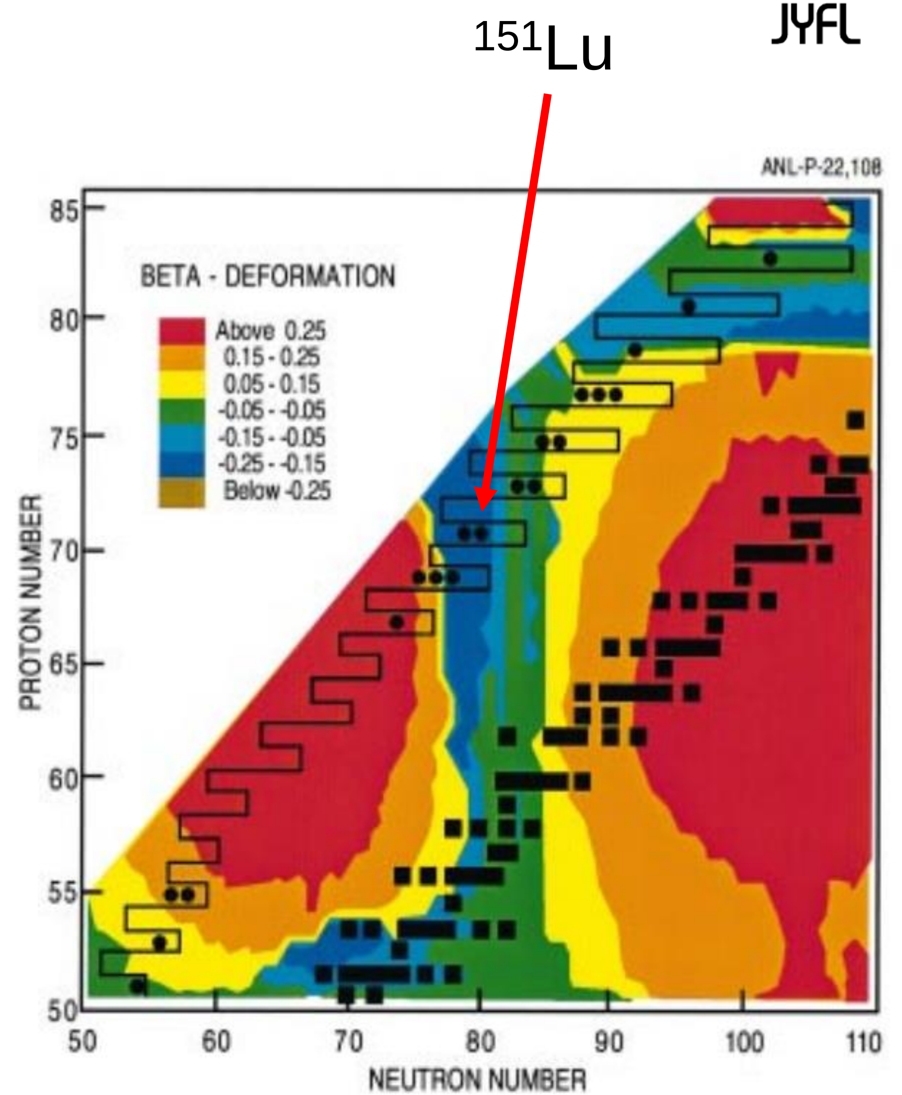


Figure 5 Contour plot of the quadrupole deformation parameter b2 taken from (89), showing the general trend of the deformations. Filled circles are the known proton emitters, and the predicted proton drip-line also taken from (90) is shown as a solid line, modified where experimental evidence is available.

[P.J. Woods, C.N. Davids, Annu. Rev. Nucl. Part. Sci. 47 541 (1997)]

Why study Lutetium?

- Very few oblate deformed proton emitters are known
- ^{151}Lu
  - $\beta_2 = -0.11$ ($11/2^-$ g.s.)

    [Procter et al. PLB 725 79 (2013)]
  - $\beta_2 = -0.12$ ($3/2^+$ m)

    [Taylor et al. PRC 91 044322 (2015)]

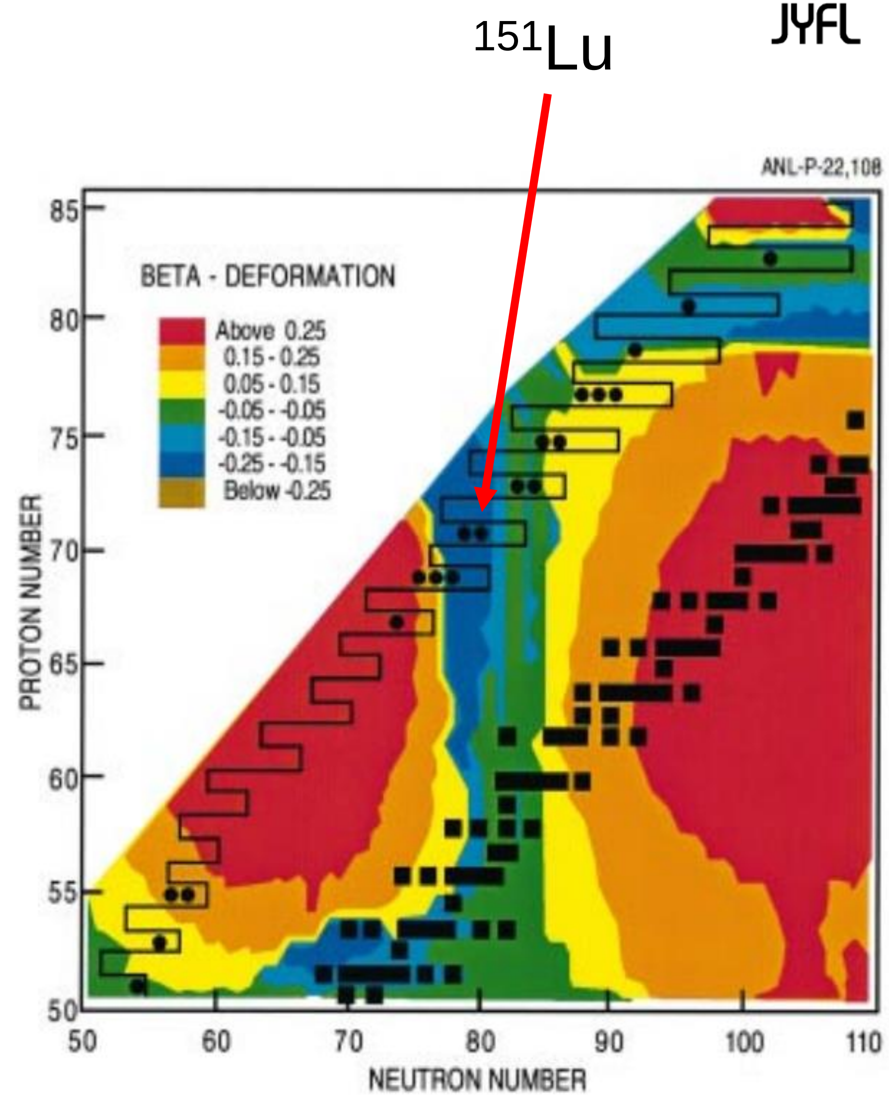


Figure 5 Contour plot of the quadrupole deformation parameter b2 taken from (89), showing the general trend of the deformations. Filled circles are the known proton emitters, and the predicted proton drip-line also taken from (90) is shown as a solid line, modified where experimental evidence is available.

[P.J. Woods, C.N. Davids, Annu. Rev. Nucl. Part. Sci. 47 541 (1997)]

Why study Lutetium?

^{151}Lu

TABLE I. Theoretical predictions for the one proton separation energy ($S_p = -Q_p$) and ground-state deformation β_2 of ^{149}Lu.

Model	S_p(MeV)	β_2
RHB [29]	-1.77	-0.158
FRDM [30, 31]	-1.52	-0.187
RMF [32]	-1.946	-0.166

– β_2 = -0.12 ($3/2^+$ m)

[Taylor et al. PRC 91 044322 (2015)]

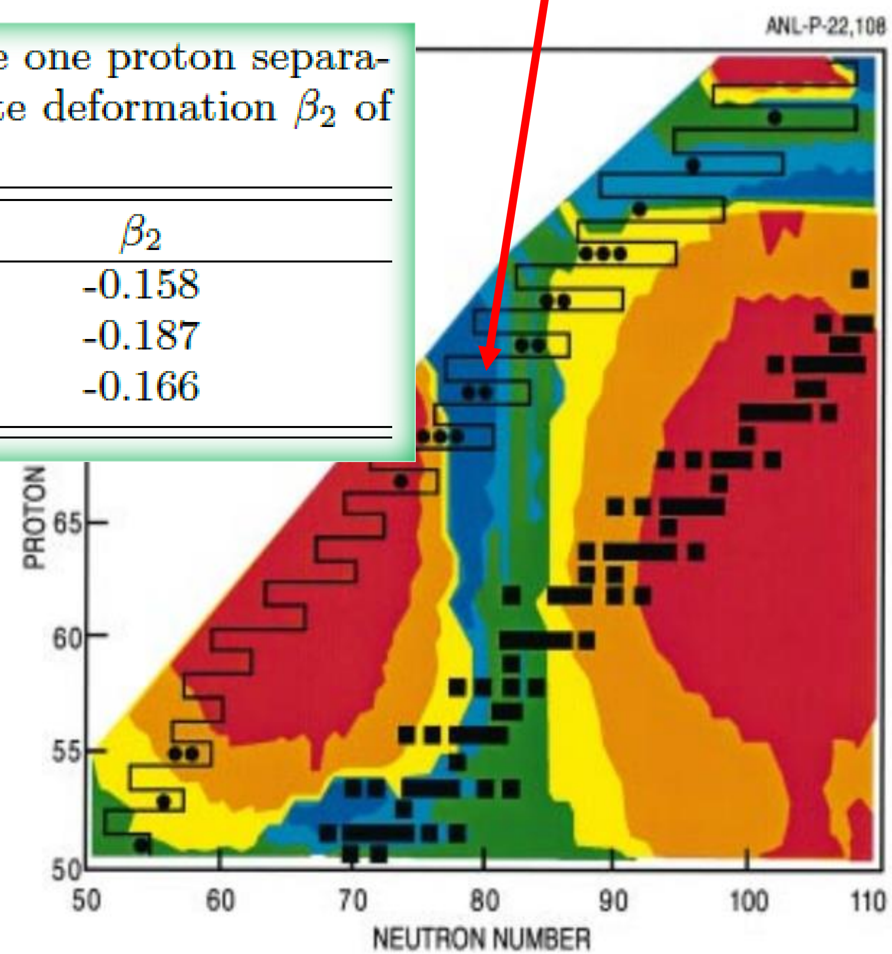


Figure 5 Contour plot of the quadrupole deformation parameter b2 taken from (89), showing the general trend of the deformations. Filled circles are the known proton emitters, and the predicted proton drip-line also taken from (90) is shown as a solid line, modified where experimental evidence is available.

[P.J. Woods, C.N. Davids, Annu. Rev. Nucl. Part. Sci. 47 541 (1997)]

Outline

- Brief introduction to Nuclear Spectroscopy group activities and JYFL-ACCLAB
  - MARA and RITU setups, and their focal-plane spectrometers
- Motivation to study ^{149}Lu
- Experiment
- Results and interpretation
- Aftermath
- (Bonus: Trace analyses)

Experiment

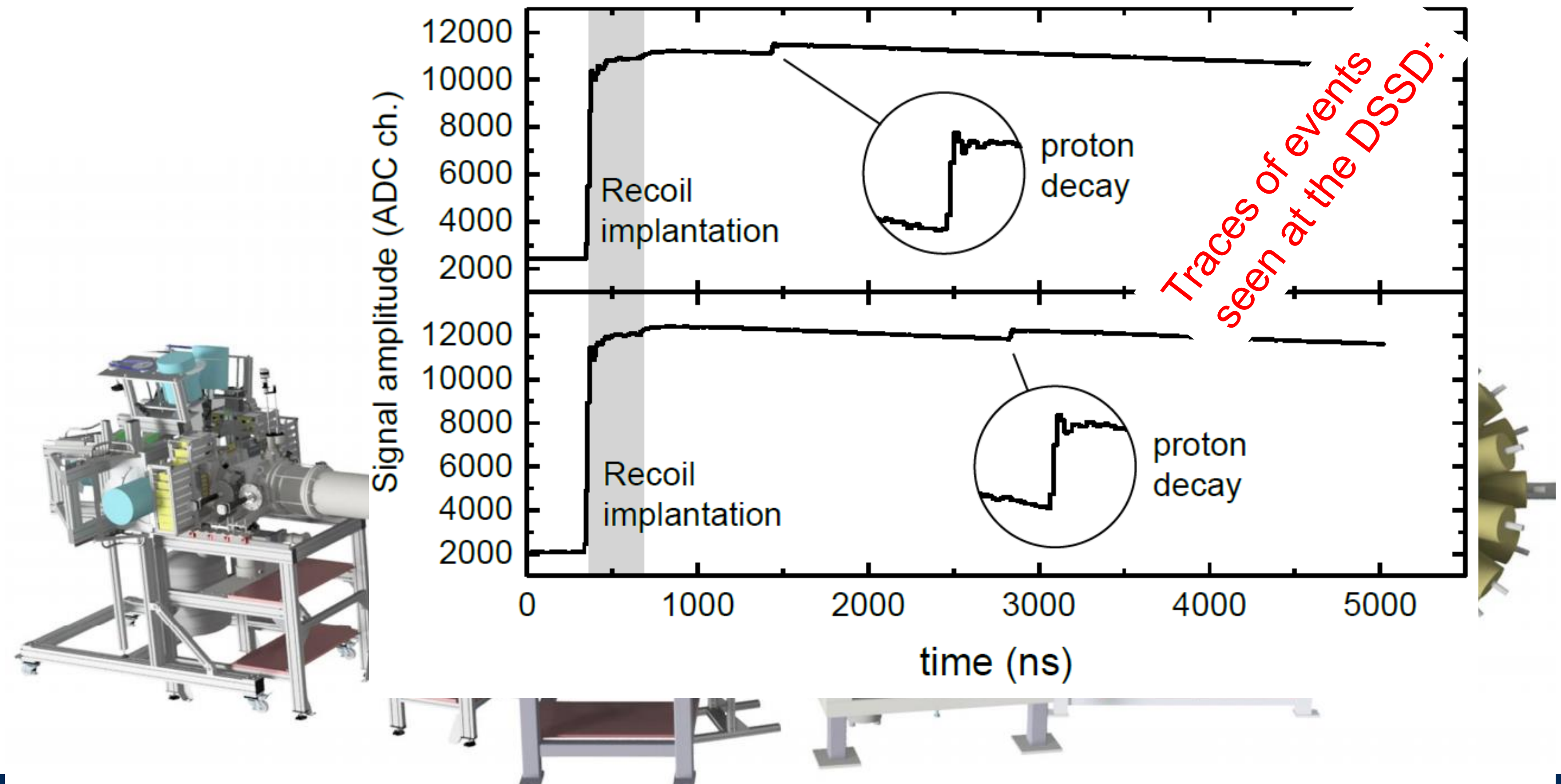
- $^{96}Ru(^{58}Ni,p4n)^{149}Lu$ fusion-evaporation reaction
- MARA
  - A/q identification
- DSSD (159 μm thick)
  - Traces with 10 ns sample rate
- JYTube + (JUROGAM3 γ-ray spectrometer)

Outline

- Brief introduction to Nuclear Spectroscopy group activities and JYFL-ACCLAB
  - MARA and RITU setups, and their focal-plane spectrometers
- Motivation to study ^{149}Lu
- Experiment
- Results and interpretation ←
- Aftermath
- (Bonus: Trace analyses)

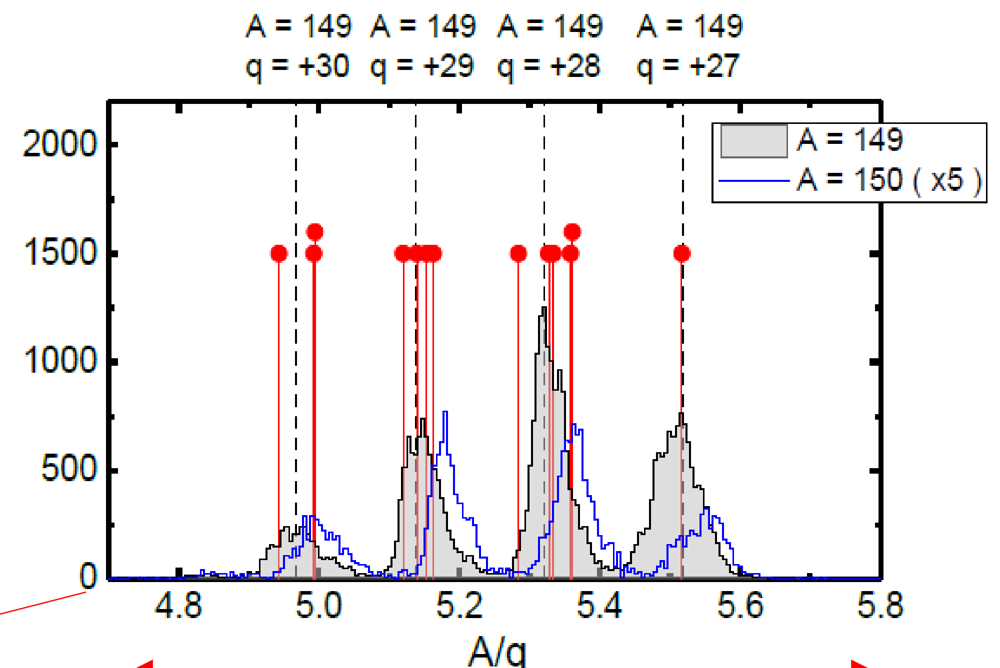
Results

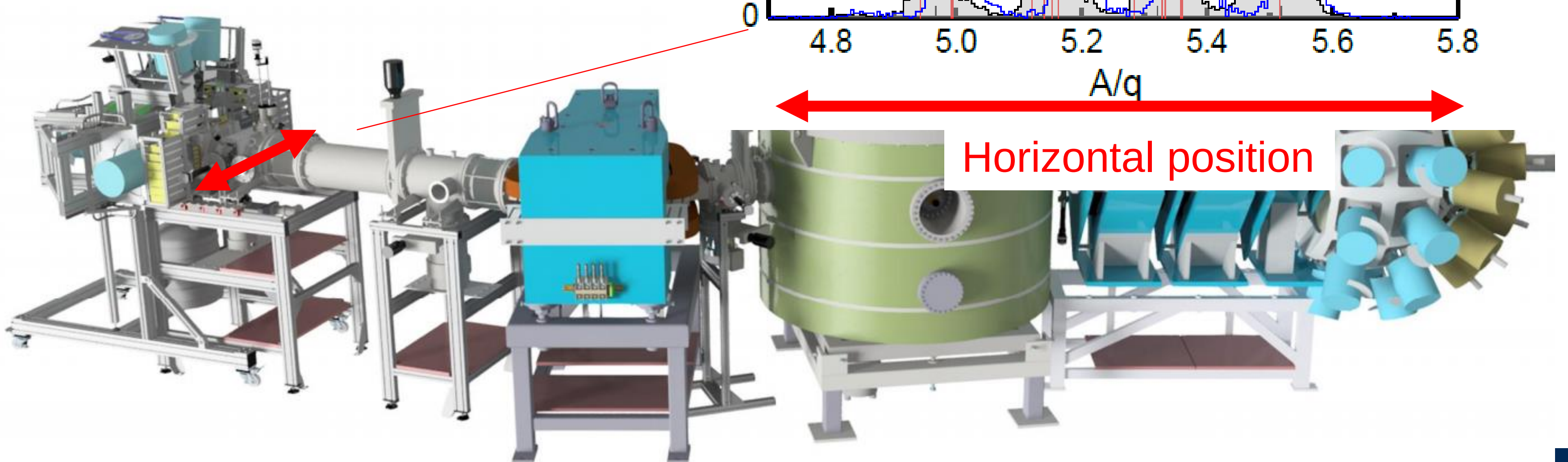
- 14 candidates for fast proton emission
- Experimental fingerprint:



Results

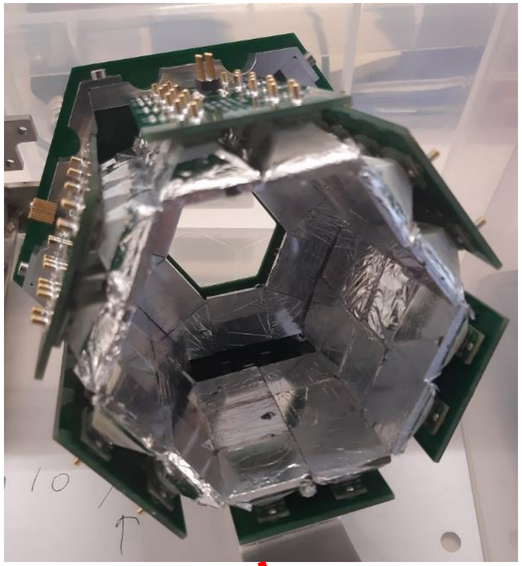
- A/q identification
  - Most likely A = 149
- Reference spectra gated with ^{149,150}Er isomers





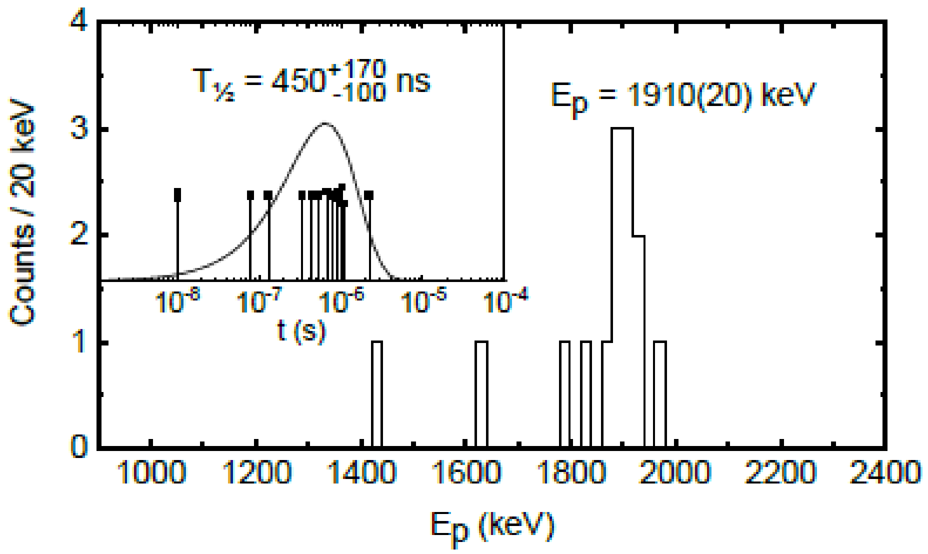
Results

- Element assignment per JYTube data
  - “Barrel” of scintillation detectors
- Candidates correlate with 0 or 1 evaporated charged particles
  - *pxn* evaporation channel (Lutetium)

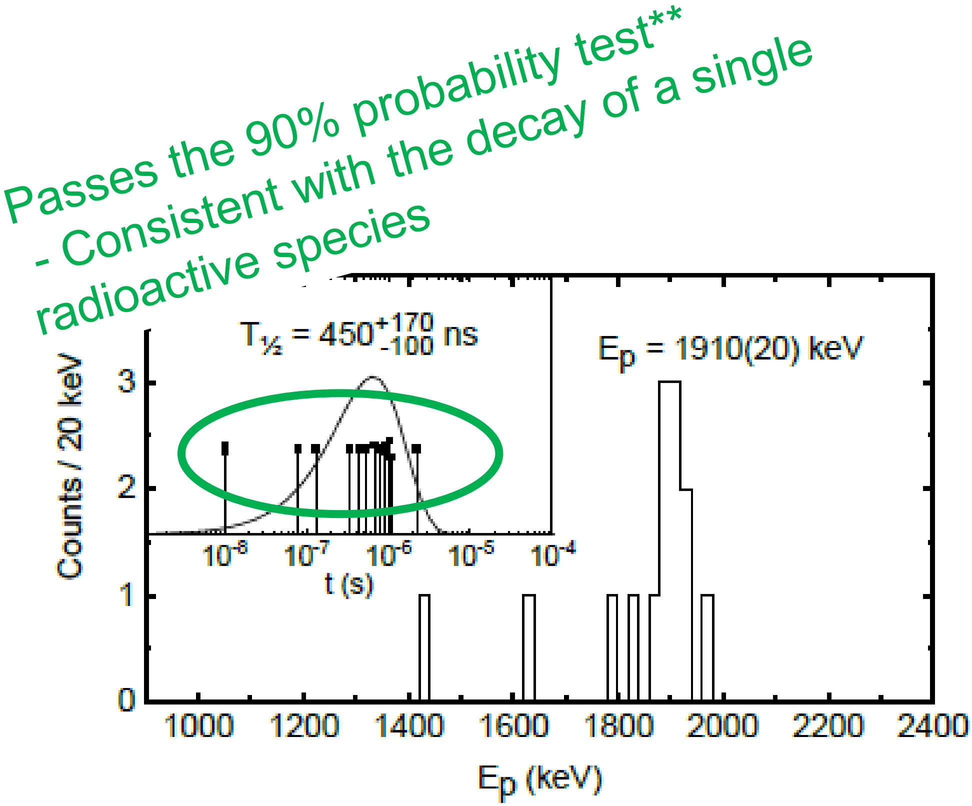


Results

- E_p = 1910(20) keV
  - Highest measured for a g.s. proton emitter



Results

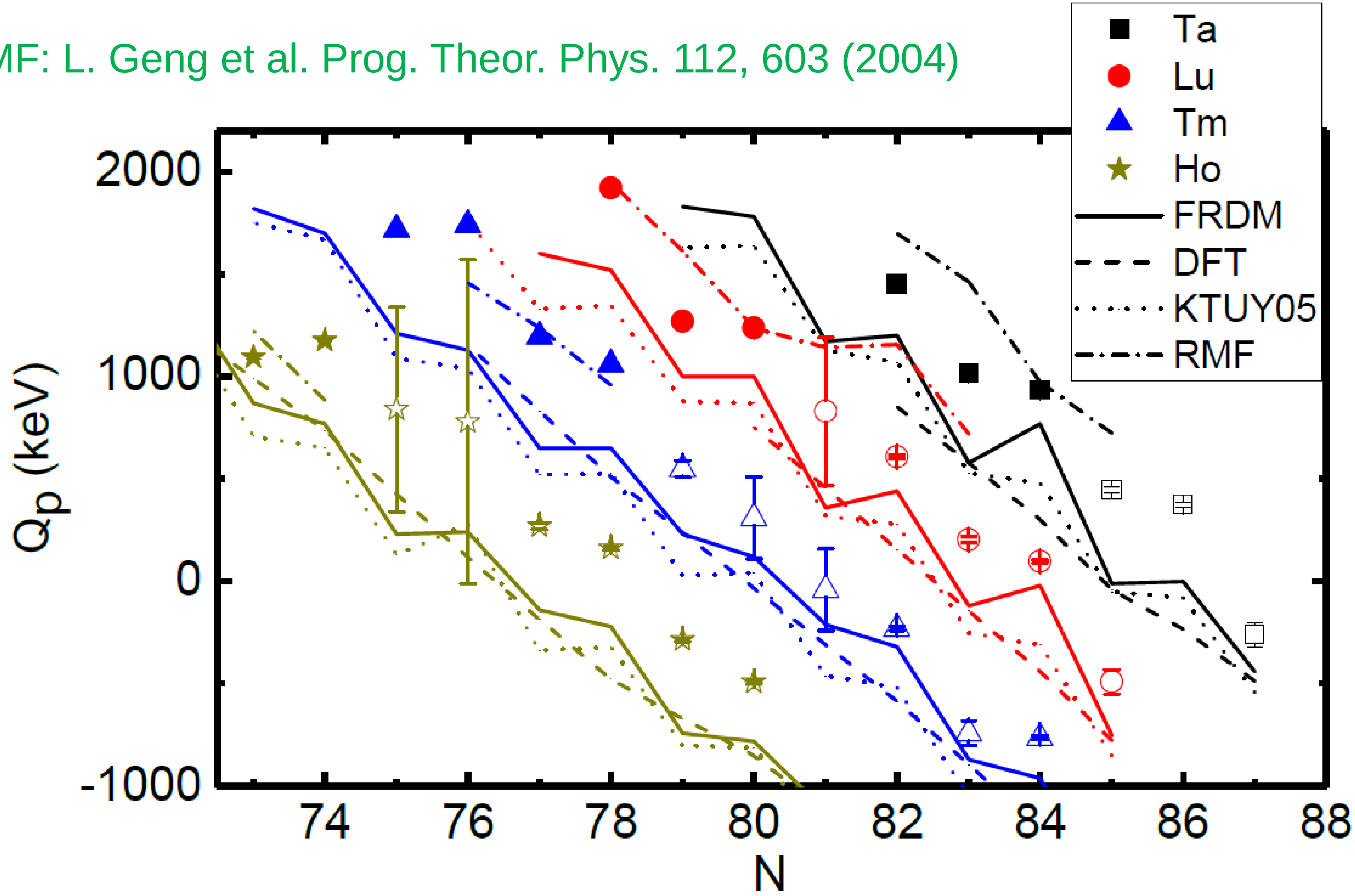


- E_p = 1910(20) keV
  - Highest measured for a g.s. proton emitter
- $T_{½}$ = 450($^{+170}_{-100}$) ns
  - Shortest *directly* measured for a g.s. proton emitter
- Geiger-Nuttall law
  [Chen EPJA 55, 214 (2019)]
  - 956 ns (l_p = 5 ; within 1σ)
  - $\pi(h_{11/2})$

**K. H. Schmidt, EPJA 8, 141 (2000).

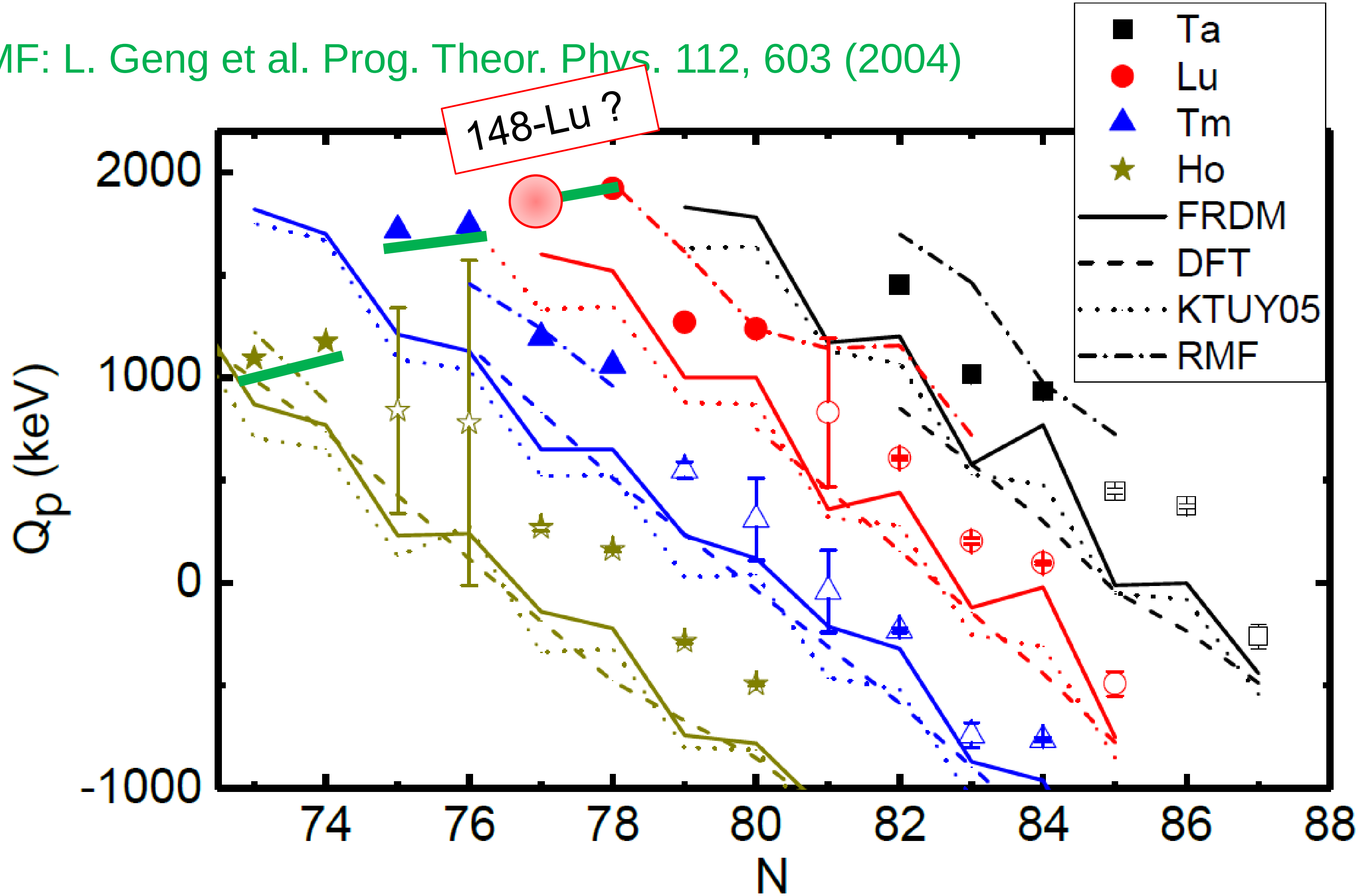
Systematics

RMF: L. Geng et al. Prog. Theor. Phys. 112, 603 (2004)

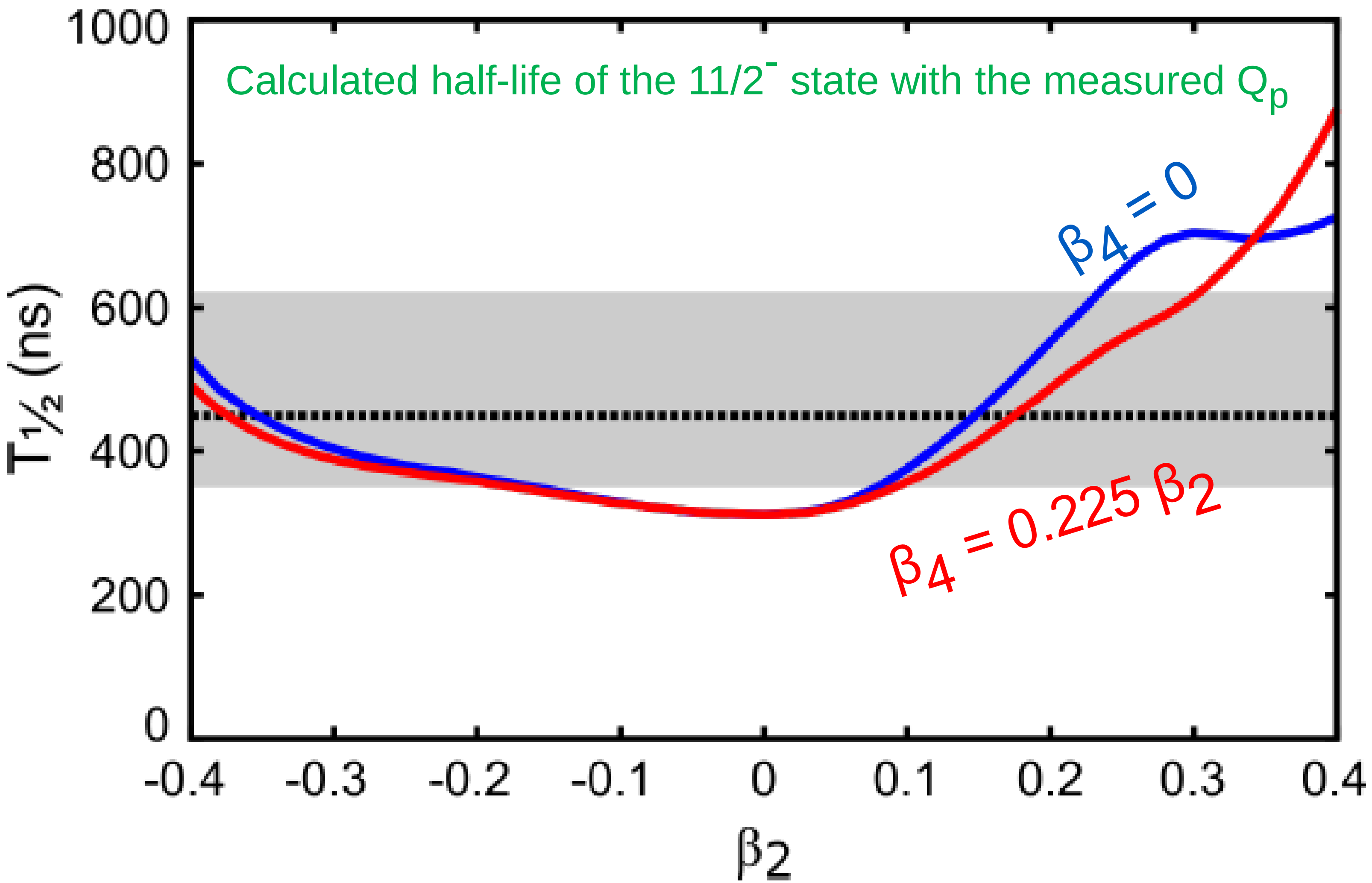


Systematics

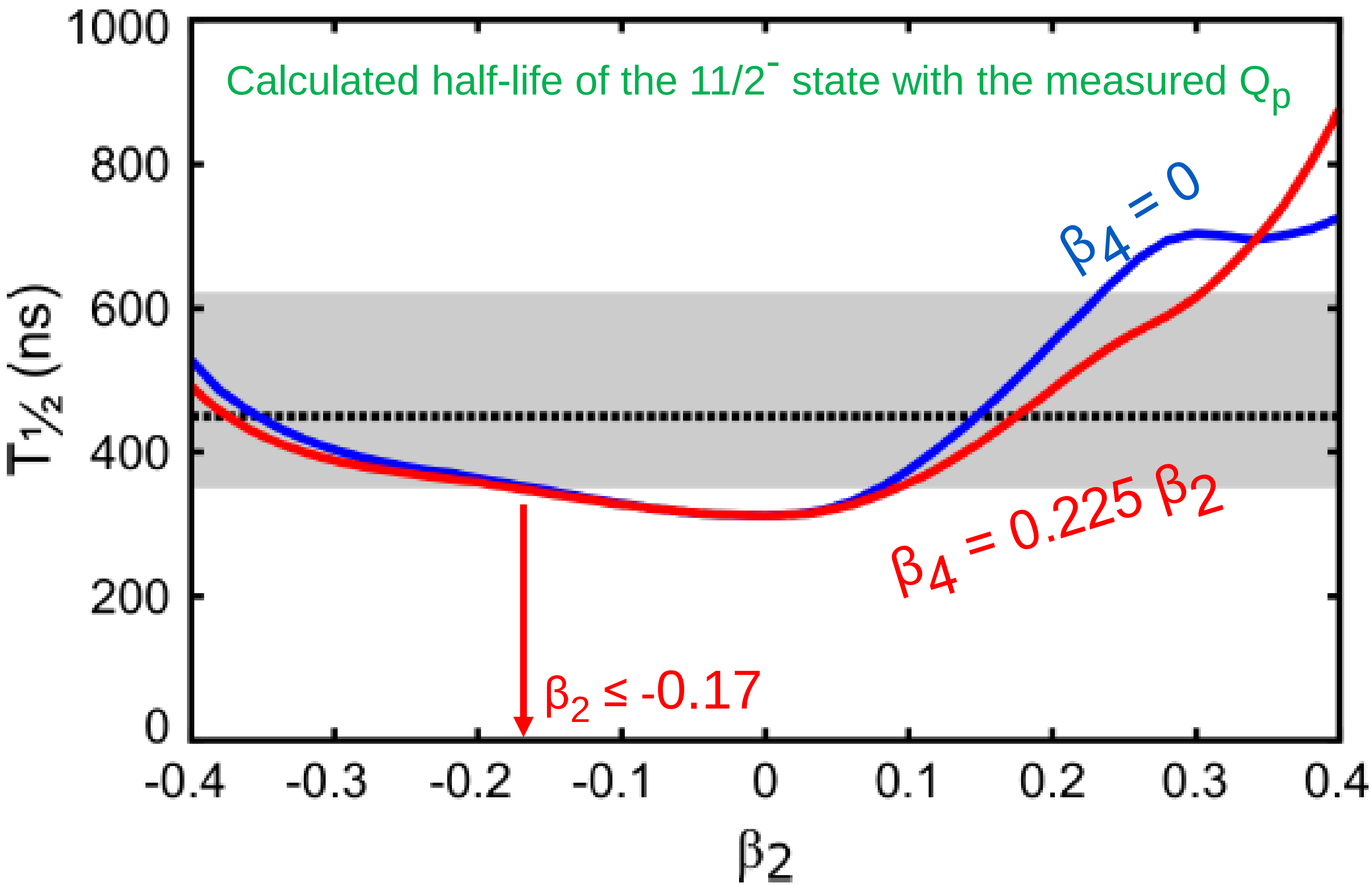
RMF: L. Geng et al. Prog. Theor. Phys. 112, 603 (2004)



Non-adiabatic quasiparticle model
(L.S. Ferreira, E. Maglione)



Non-adiabatic quasiparticle model
(L.S. Ferreira, E. Maglione)



Publication

PHYSICAL REVIEW LETTERS **128,** 112501 (2022)

Editors' Suggestion

Nanosecond-Scale Proton Emission from Strongly Oblate-Deformed ^{149}Lu

K. Auranen,[1,*] A. D. Briscoe,[1] L. S. Ferreira,[2] T. Grahn,[1] P. T. Greenlees,[1] A. Herzáň,[3] A. Illana,[1] D. T. Joss,[4] H. Joukainen,[1] R. Julin,[1] H. Jutila,[1] M. Leino,[1] J. Louko,[1] M. Luoma,[1] E. Maglione,[2] J. Ojala,[1] R. D. Page,[4] J. Pakarinen,[1] P. Rahkila,[1] J. Romero,[1,4] P. Ruotsalainen,[1] M. Sandzelius,[1] J. Sarén,[1] A. Tolosa-Delgado,[1] J. Uusitalo,[1] and G. Zimba[1]

[1]*Accelerator Laboratory, Department of Physics, University of Jyväskylä, FI-40014 Jyväskylä, Finland*

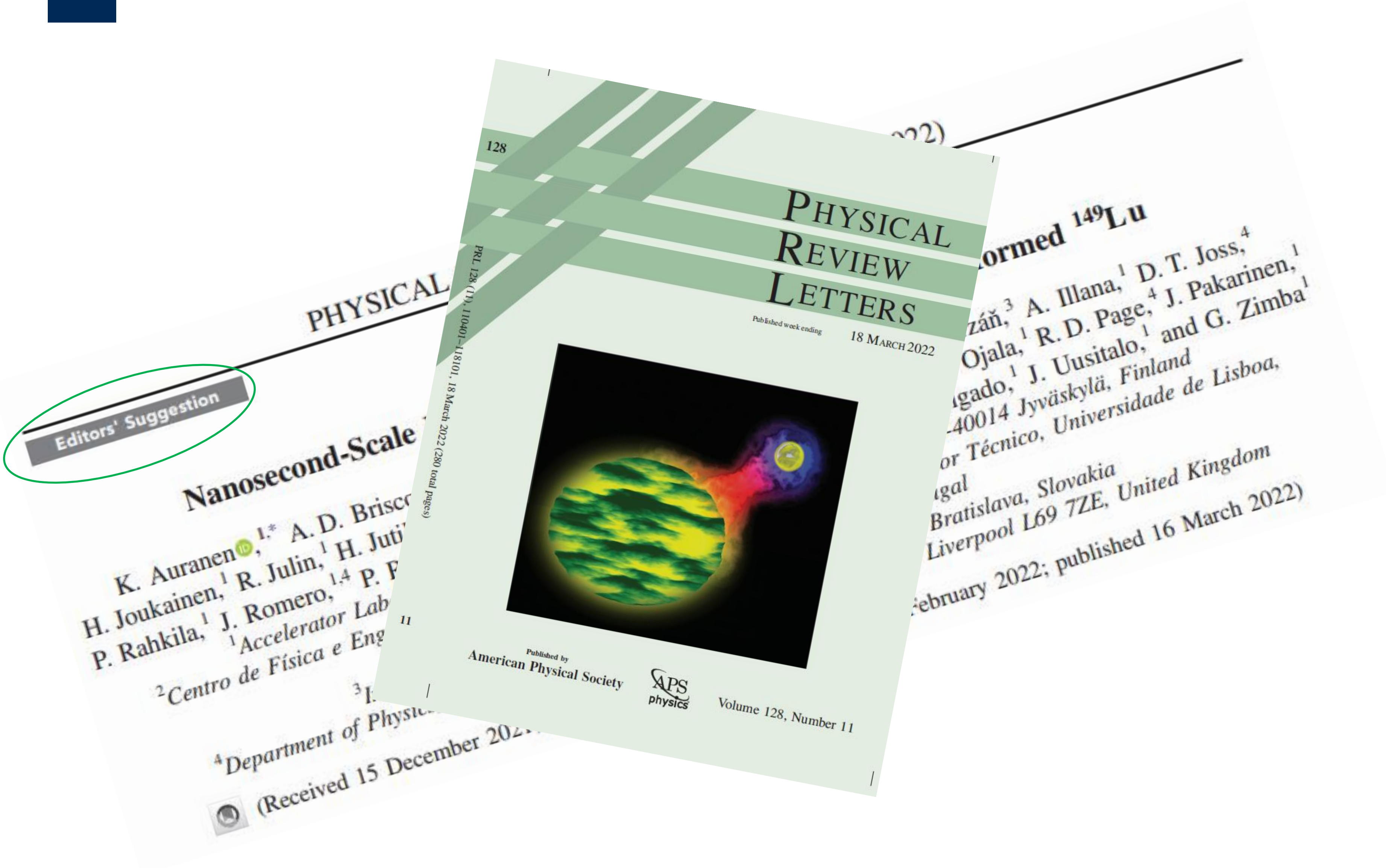
[2]*Centro de Física e Engenharia de Materiais Avançados CeFEMA, Instituto Superior Técnico, Universidade de Lisboa, Avenida Rovisco Pais, P1049-001 Lisbon, Portugal*

[3]*Institute of Physics, Slovak Academy of Sciences, SK-84511 Bratislava, Slovakia*

[4]*Department of Physics, Oliver Lodge Laboratory, University of Liverpool, Liverpool L69 7ZE, United Kingdom*

(Received 15 December 2021; revised 2 February 2022; accepted 22 February 2022; published 16 March 2022)

Publication



Publication

Selections from the scientific literature

Research highlights

COMPOUND RISK: COASTAL CITIES SINK AS SEA LEVELS RISE

Many coastal cities around the world are sinking as sea levels rise, a combination of trends that drastically increases the risk of urban flooding.

Scientists use ground-based instruments to determine whether the local land is rising or falling. But these instruments are not available everywhere. For a global view, Matt Wei at the University of Rhode Island in Narragansett and his colleagues analysed satellite data gathered between 2015 and 2020 for 99 coastal cities. By comparing measurements of the ground surface taken every two months, the researchers could watch as the land subsided in various parts of a city.

Most of the cities had at least some neighbourhoods where land was sinking faster than the rate of sea-level rise. In Karachi, Pakistan, the land dropped by a maximum of more than 10 millimetres per year — 5 times the mean sea-level rise. In Tianjin, China, and Jakarta, subsidence reached more than 30 millimetres per year. In most cases, people are thought to be causing the drop by pumping groundwater from beneath the cities.

This improved global view could help officials to develop better policies to track groundwater extraction and reduce the risks of flooding.

Geophys. Res. Lett. **49**, e2022GL098477 (2022)

HOW NATIONS CAN DIG THEIR WAY OUT OF FUTURE SAND CRISIS

Global use of sand for building will surge by 45% by 2060, even if population and economic growth are moderate, according to new modelling. But the analysis suggests that there's hope: if countries cooperate, building-sand demand in 2060 could be 30% of projected levels.

Sand is a key ingredient in many building materials. This has led to sand overexploitation and trafficking, mostly of that from rivers, lakes and shorelines — the only natural sand that is not too smooth, too fine or too corrosive for building.

Xiaoyang Zhong at Leiden University in the Netherlands and his colleagues modelled the use of sand in concrete and glass. They found that, if population and economic growth are moderate, sand demand will drop slightly in middle- and high-income regions by 2060. But it will more than triple in lower-middle-income regions, such as India and Western Africa.

Even so, strategies such as reducing new construction, concrete reuse, smart urban planning and use of sand substitutes could help. If the world implements all of these to their full potential by 2060, sand demand will drop by 71%.

Nature Sustain. https://doi.org/hnhf (2022)

JUST A MOMENT: 'SQUASHED' NUCLEUS DECAYS AT SPEED

A newly discovered pumpkin-shaped atomic nucleus that spits out a proton just after being formed could help scientists to understand how heavy elements are made in the Universe.

The ejection of a proton from an atomic nucleus is a rare type of radioactive decay. This process, called proton emission, is not seen in naturally occurring nuclei and was first spotted in an artificially created nucleus only about 50 years ago.

Kalle Auranen at the University of Jyväskylä in Finland and his colleagues fired a beam of nickel atoms at a target containing the metal ruthenium. Among the collision products, they detected a previously unidentified nucleus of the element lutetium that consists of 71 protons and 78 neutrons.

The authors found that this nucleus decays through proton emission (pictured, artist's impression) in a very short time, just half a microsecond after forming. They also determined that the nucleus is the most oblate, or pumpkin shaped, proton ejector seen so far.

The team says that its observations of this exotic nucleus will improve nuclear-physics models that are needed to elucidate the cosmic origins of heavy elements.

Phys. Rev. Lett. **128**, 112501 (2022)

A BLAST OF LIGHT SAVES POLYSTYRENE FROM LANDFILL

A new processing method can transform waste polystyrene — a common type of plastic — into valuable small molecules.

Polystyrene makes up products ranging from foam egg cartons to compact-disc cases. It also accounts for about one-third of the contents of landfills worldwide, prompting scientists to look for a scalable, energy-efficient process for converting it into useful compounds.

Sewon Oh and Erin Stache at Cornell University in Ithaca, New York, have discovered such a process. The team dissolved 20 milligrams of commercial polystyrene, together with the compound iron chloride, in the liquid solvent acetone. They illuminated the resulting mixture with white light in an oxygen-rich environment. After 20 hours, the polystyrene had broken down to small molecules, mainly of benzoic acid — a crystalline solid that is commonly used as a food preservative.

The researchers applied their approach to several types of commercial polystyrene and found that the molecular breakdown is highly efficient. They also demonstrated how the technique could be scaled up to convert gram quantities of polystyrene to benzoic acid in just a few hours.

J. Am. Chem. Soc. https://doi.org/hn3d (2022)

10 | Nature | Vol 604 | 7 April 2022

Aftermath

Deformed Relativistic Hartree-Bogoliubov theory in Continuum (DRHBc, 2023):

- $\beta_2 \sim -0.18$

Physics Letters B 845 (2023) 138160

Contents lists available at ScienceDirect

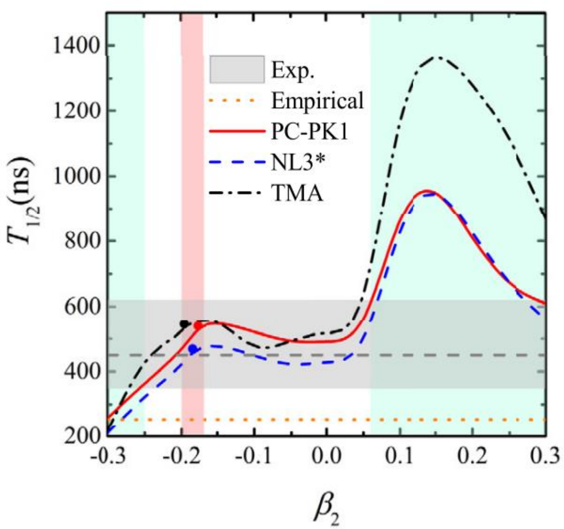
Physics Letters B

journal homepage: www.elsevier.com/locate/physletb

ELSEVIER

One-proton emission from $^{148-151}$Lu in the DRHBc+WKB approach

Yang Xiao[a,b], Si-Zhe Xu[b], Ru-You Zheng[b], Xiang-Xiang Sun[c,d], Li-Sheng Geng[b,e,f,g,*], Shi-Sheng Zhang[b,*]



Aftermath

Deformed Relativistic Hartree-Bogoliubov theory in Continuum (DRHBc, 2023):

- $\beta_2 \sim -0.18$

Physics Letters B 845 (2023) 138160

Contents lists available at ScienceDirect

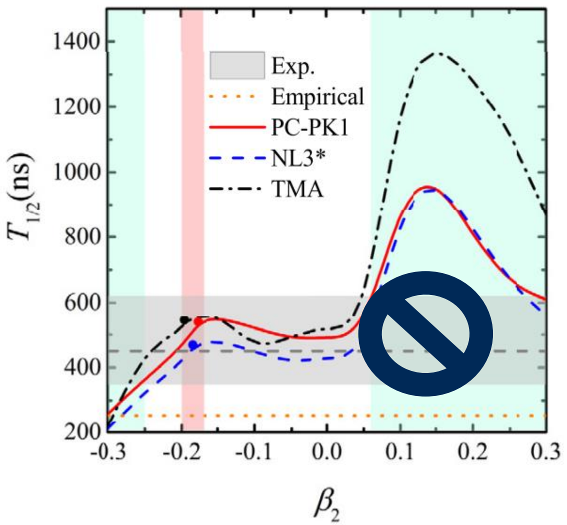
Physics Letters B

journal homepage: www.elsevier.com/locate/physletb

ELSEVIER

One-proton emission from $^{148-151}$Lu in the DRHBc+WKB approach

Yang Xiao[a,b], Si-Zhe Xu[b], Ru-You Zheng[b], Xiang-Xiang Sun[c,d], Li-Sheng Geng[b,e,f,g,*], Shi-Sheng Zhang[b,*]



Aftermath

Deformed Relativistic Hartree-Bogoliubov theory in Continuum (DRHBc, 2023):

- $\beta_2 \sim -0.18$


Physics Letters B 845 (2023) 138160

Contents lists available at ScienceDirect

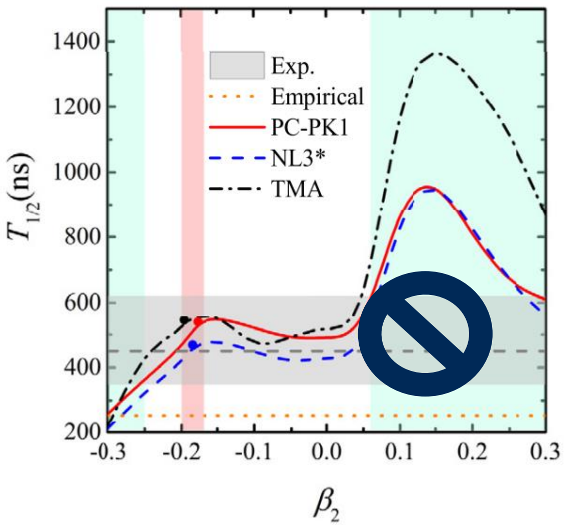
Physics Letters B

journal homepage: www.elsevier.com/locate/physletb

ELSEVIER

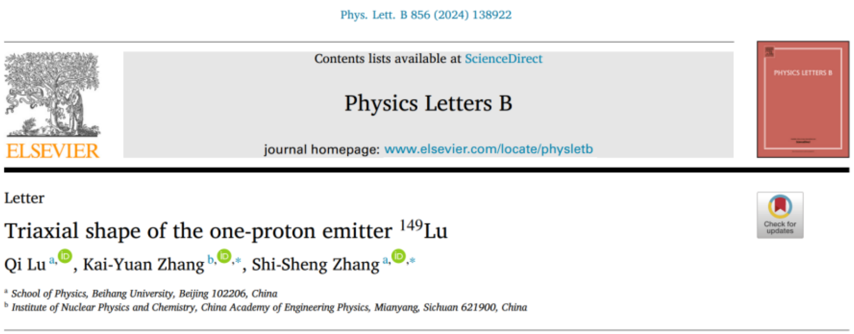
One-proton emission from $^{148-151}$Lu in the DRHBc+WKB approach

Yang Xiao[a,b], Si-Zhe Xu[b], Ru-You Zheng[b], Xiang-Xiang Sun[c,d], Li-Sheng Geng[b,e,f,g,*], Shi-Sheng Zhang[b,*]



Triaxial Relativistic Hartree-Bogoliubov theory in Continuum (TRHBc, 2024):

- $\beta \sim 0.17$, $\gamma = 31°$


Phys. Lett. B 856 (2024) 138922

Contents lists available at ScienceDirect

Physics Letters B

journal homepage: www.elsevier.com/locate/physletb

ELSEVIER

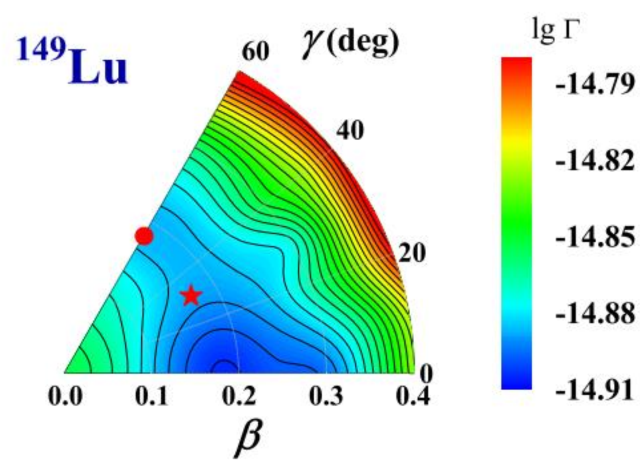
Letter

Triaxial shape of the one-proton emitter ^{149}Lu

Qi Lu[a], Kai-Yuan Zhang[b,*], Shi-Sheng Zhang[a,*]

[a] School of Physics, Beihang University, Beijing 102206, China

[b] Institute of Nuclear Physics and Chemistry, China Academy of Engineering Physics, Mianyang, Sichuan 621900, China

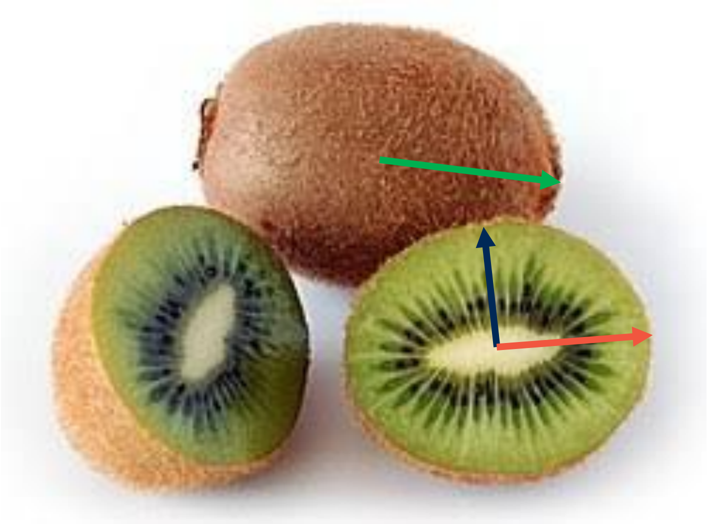


Summary

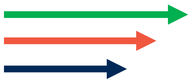
- New proton emitting isotope ^{149}Lu
- High decay energy of 1910(20) keV
- Shortest directly measured $T_{½}$ = 450($^{+170}_{-100}$) ns
- Most oblate deformed proton emitter with β_2 ~ -0.18 (?)
  - In-beam RDT γ-ray spectroscopy might be possible, though very difficult, to probe the possible triaxiality (σ ~ 50 nb)

Summary

- New proton emitting isotope ^{149}Lu
- High decay energy of 1910(20) keV
- Shortest directly measured $T_{½}$ = 450($^{+170}_{-100}$) ns
- Most oblate deformed proton emitter with β_2 ~ -0.18 (?)
  - In-beam RDT γ-ray spectroscopy might be possible, though very difficult, to probe the possible triaxiality (σ ~ 50 nb)



Triaxial ellipsoid:

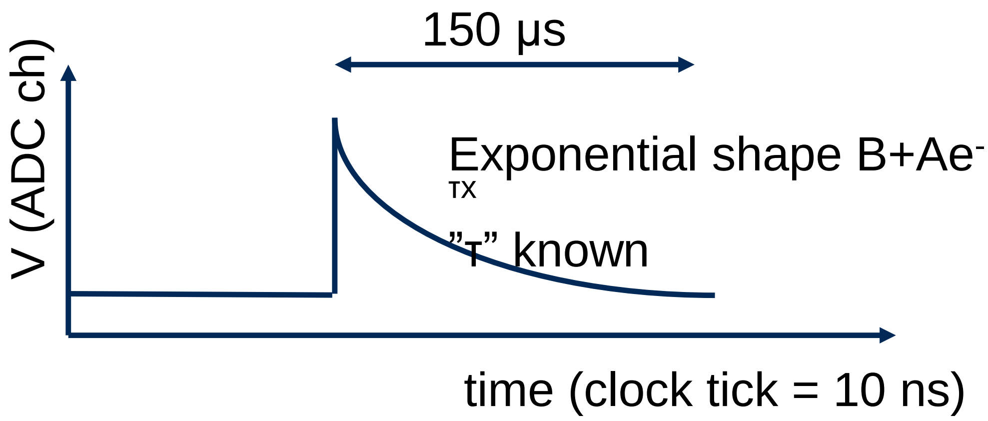


Kiwi = karvaperuna* = ”hairy potato”

Thank you

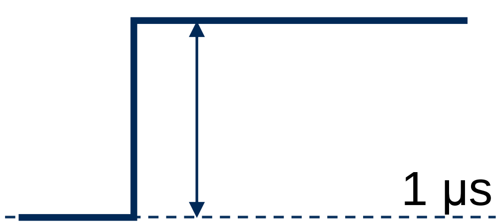
- Nuc. Spec. Group at Ladunmaja (Spring 2023)

Trace analyses – how to extract the energy of a pile-up event
("Ideal case")

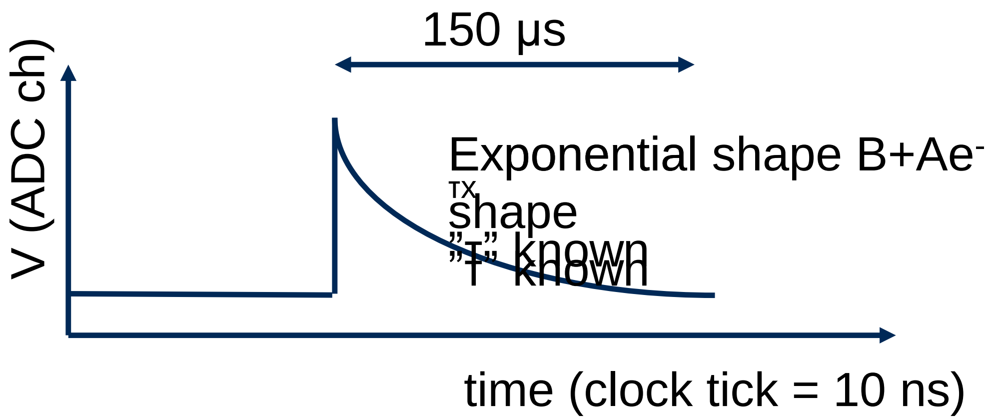


First 5 μs after the event were recorded = "trace"

No offset, no noise
- Just read the amplitude



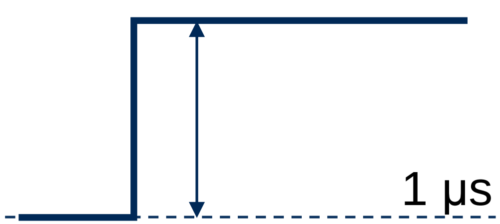
Trace analyses – how to extract the energy of a pile-up event
(“Ideal case”)

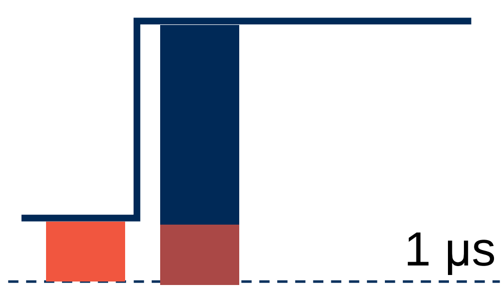


First 5 µs after the event were recorded = ”trace”

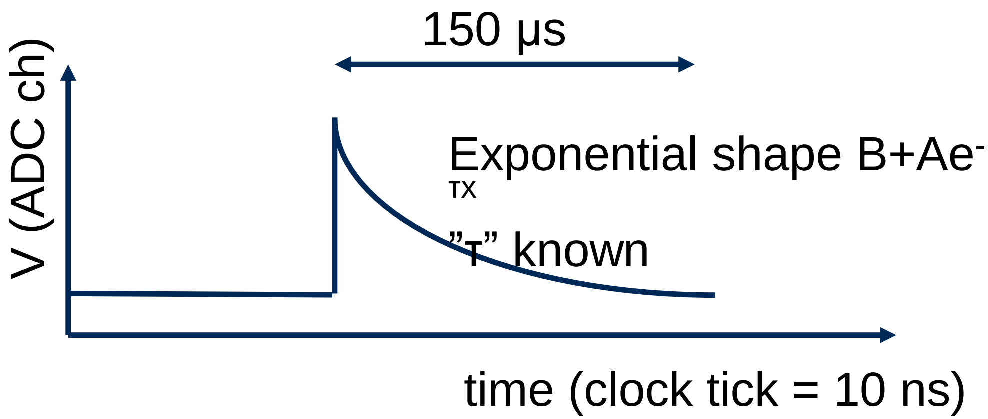
No offset, no noise
- Just read the amplitude

DC Offset, noise
- Integrate to cancel noise
- Substract the baseline



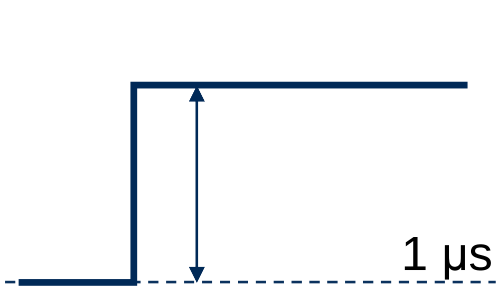


Trace analyses – how to extract the energy of a pile-up event
("Ideal case")

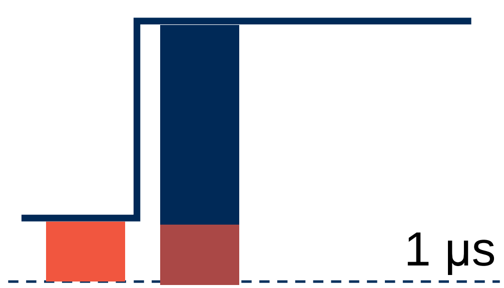


First 5 μs after the event were recorded = "trace"

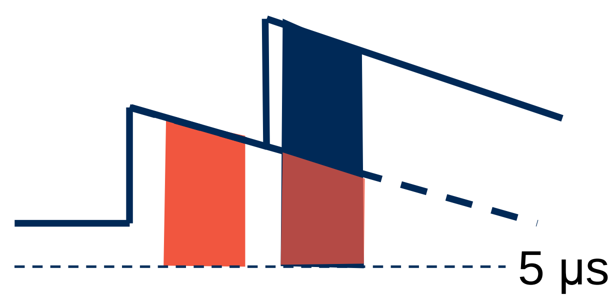
No offset, no noise
- Just read the amplitude



DC Offset, noise
- Integrate to cancel noise
- Substract the baseline



DC Offset, noise and pile up
- Integrate baseline before the pile-up event
- Calculate (using τ) the baseline under the pile-up event
- Substract the baseline



Trace analyses – how to extract the energy of a pile-up event
(Real case)

Good exponential part

Oscillation and spurious step due to impedance mismatch somewhere along the signal processing electronics
-> Software dead time of 300 ns

Trace analyses – how to extract the energy of a pile-up event
(Real case)

Good exponential part

Oscillation and spurious step due to impedance mismatch somewhere along the signal processing electronics
-> Software dead time of 300 ns

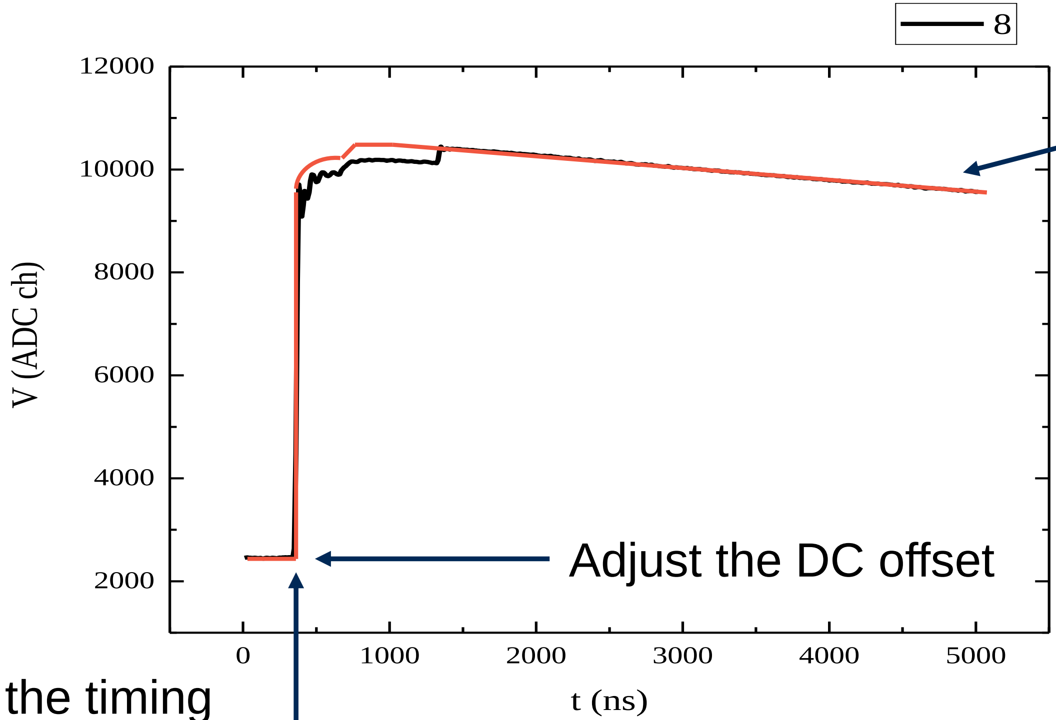
Trace analyses – how to extract the energy of a pile-up event

Real case, Approach #2 (“Reference trace”)

- Create a ”reference trace” from large number of traces recorded for regular recoil-implantation events of a given strip

Trace analyses – how to extract the energy of a pile-up event

Real case, Approach #2 (“Reference trace”)



Scale the amplitude to the end of the trace

Adjust the timing on the leading edge

Substract the two:

Pile-up decay event in trace

No pile-up decay event