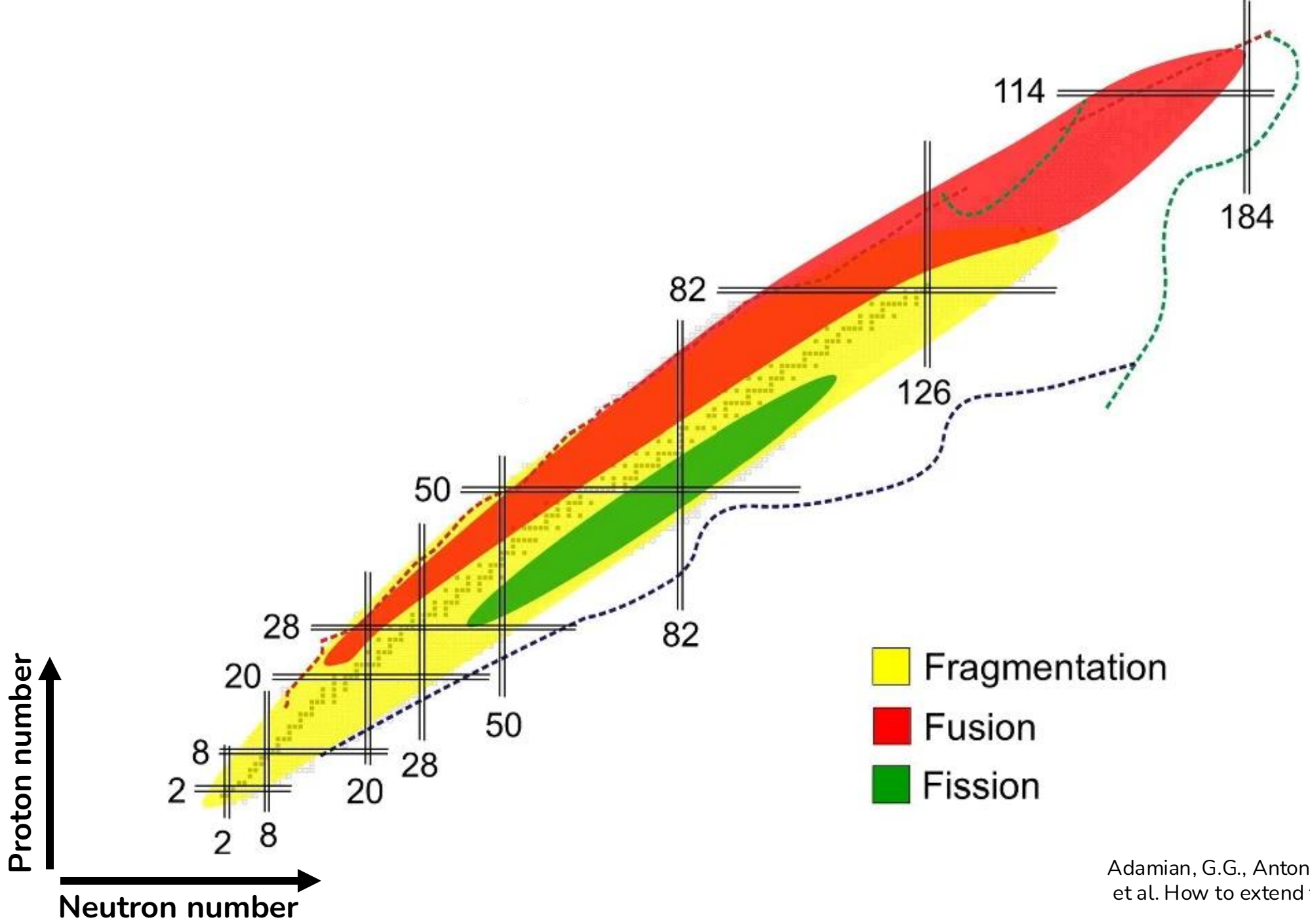
university of groningen

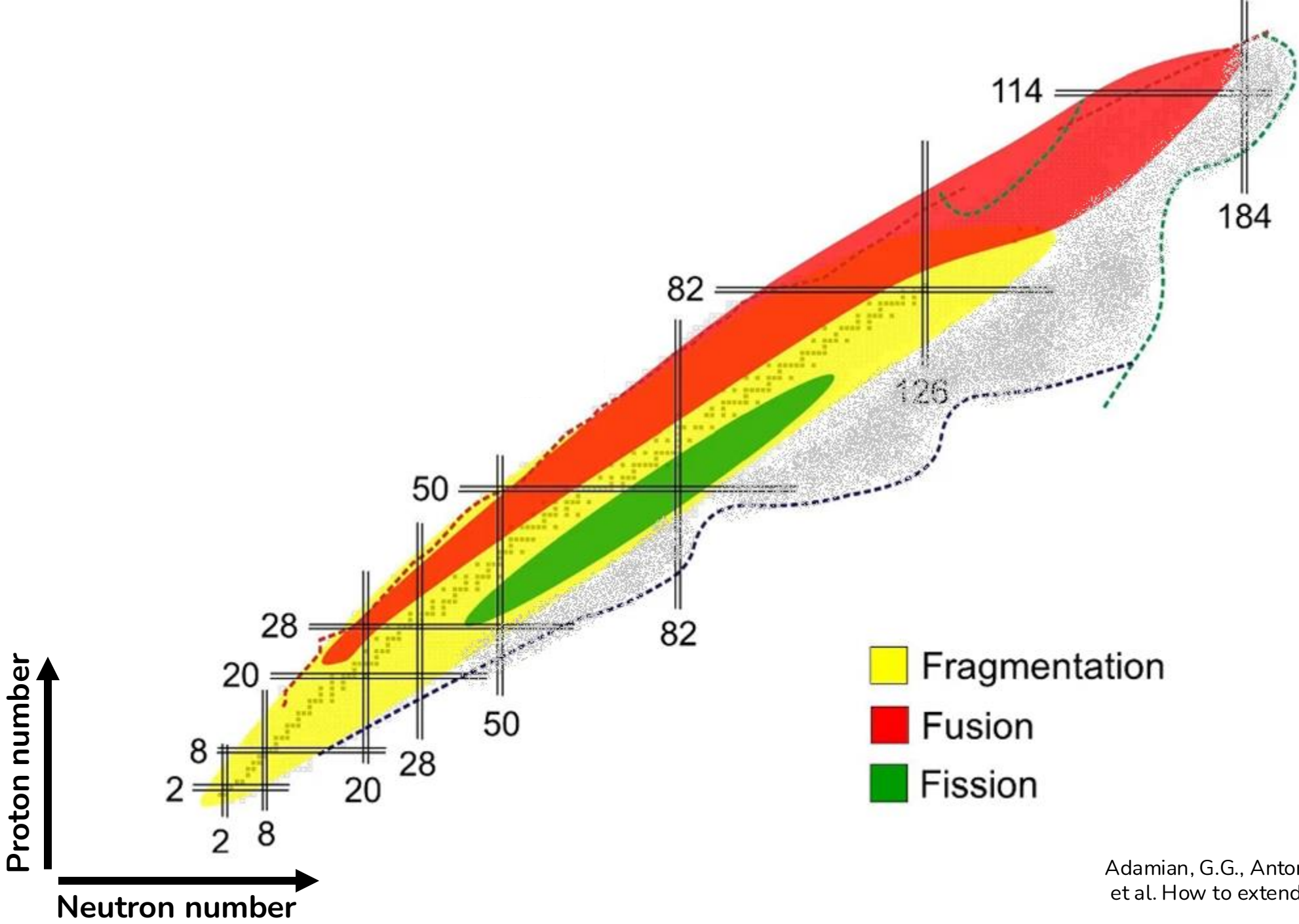
Exploring the reaction $^{64}Ni + ^{238}U$ and the Measurement of Isomeric State Lifetimes of Target-Like Transfer Products

Jennifer B. Cipagauta Mora

erc



Adamian, G.G., Antonenko, N.V., Diaz-Torres, A. et al. How to extend the chart of nuclides?. Eur. Phys. J. A 56, 47 (2020)



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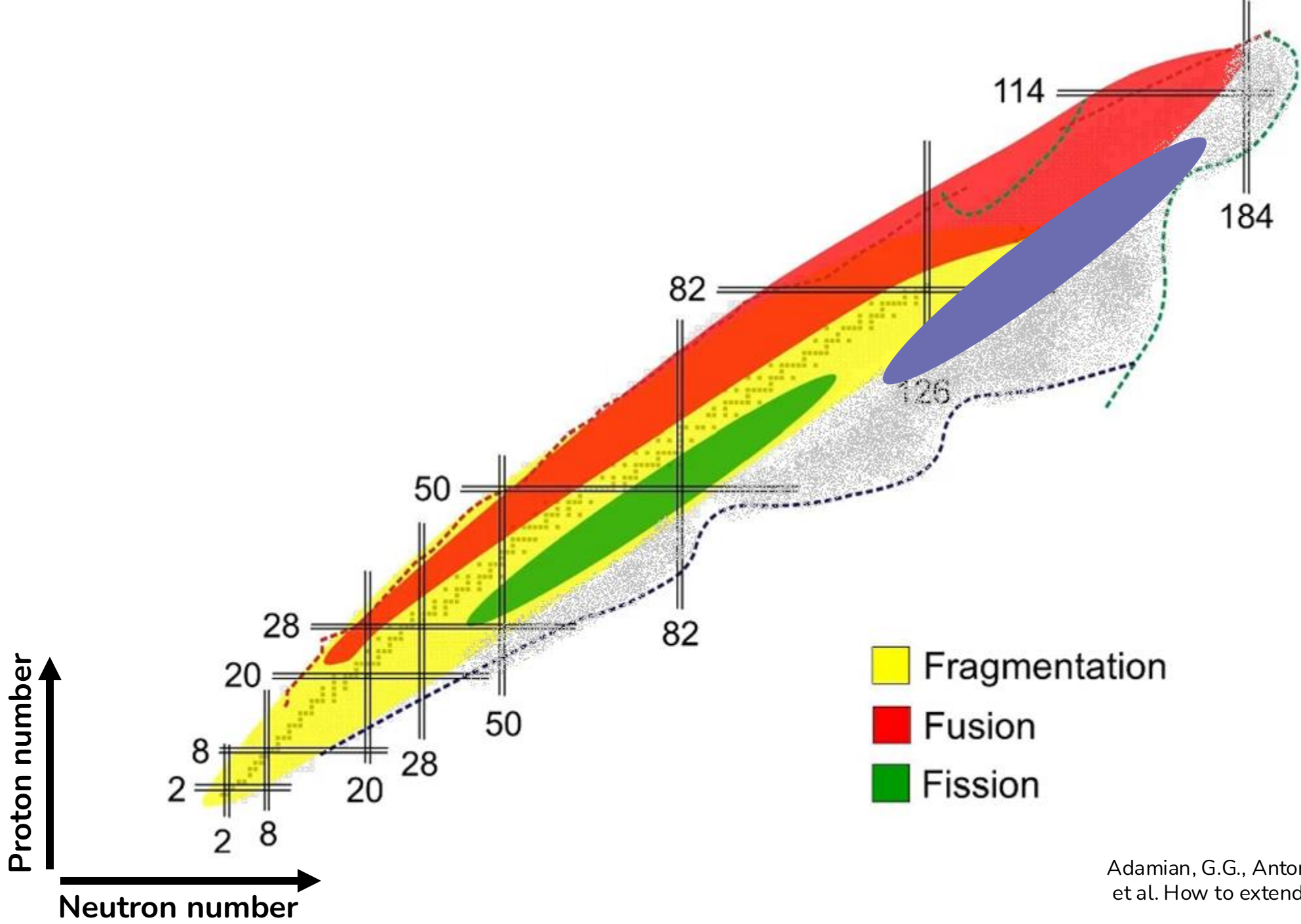
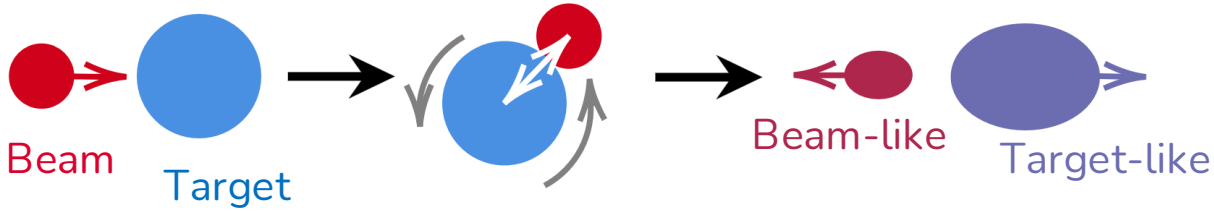


Adamian, G.G., Antonenko, N.V., Diaz-Torres, A. et al. How to extend the chart of nuclides?. Eur. Phys. J. A 56, 47 (2020)

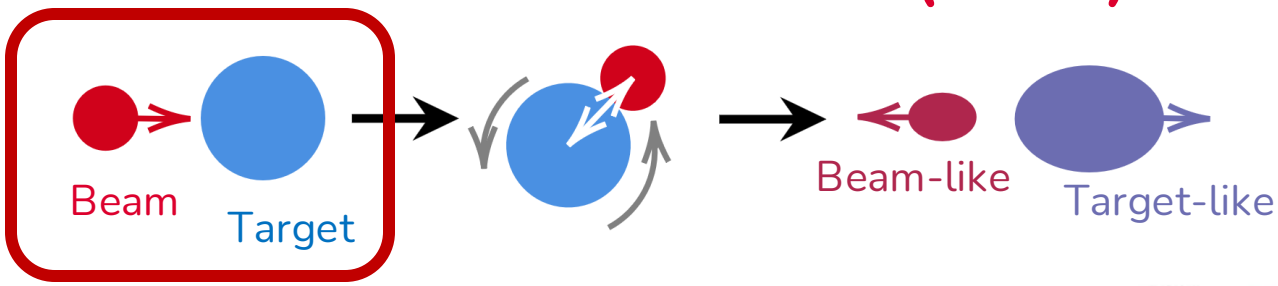
Multinucleon transfer (MNT)



MNT?

Adamian, G.G., Antonenko, N.V., Diaz-Torres, A. et al. How to extend the chart of nuclides?. Eur. Phys. J. A 56, 47 (2020)

Multinucleon transfer (MNT)



MNT?

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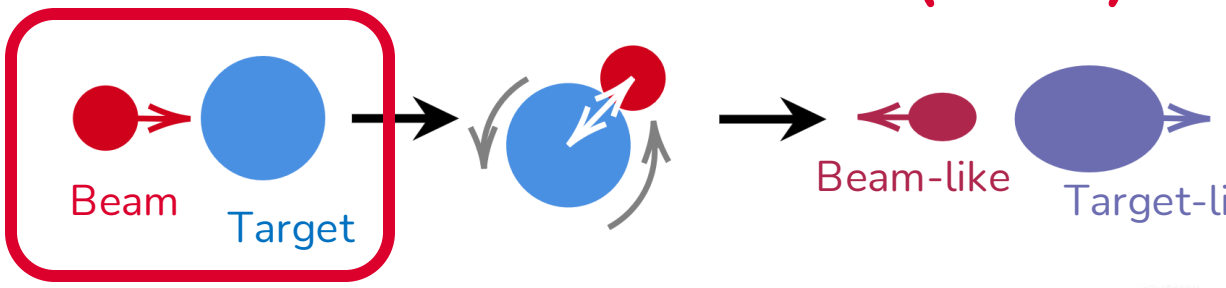
Multinucleon transfer (MNT)



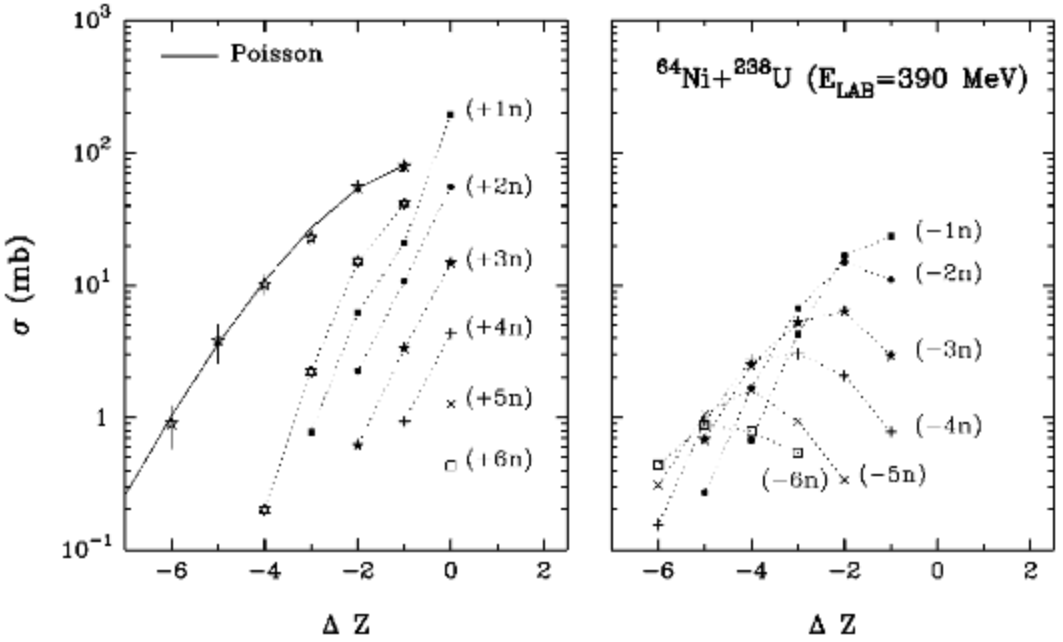
^{64}Ni + ^{238}U

@ E_{lab} = 300 MeV, 333 MeV and 366 MeV

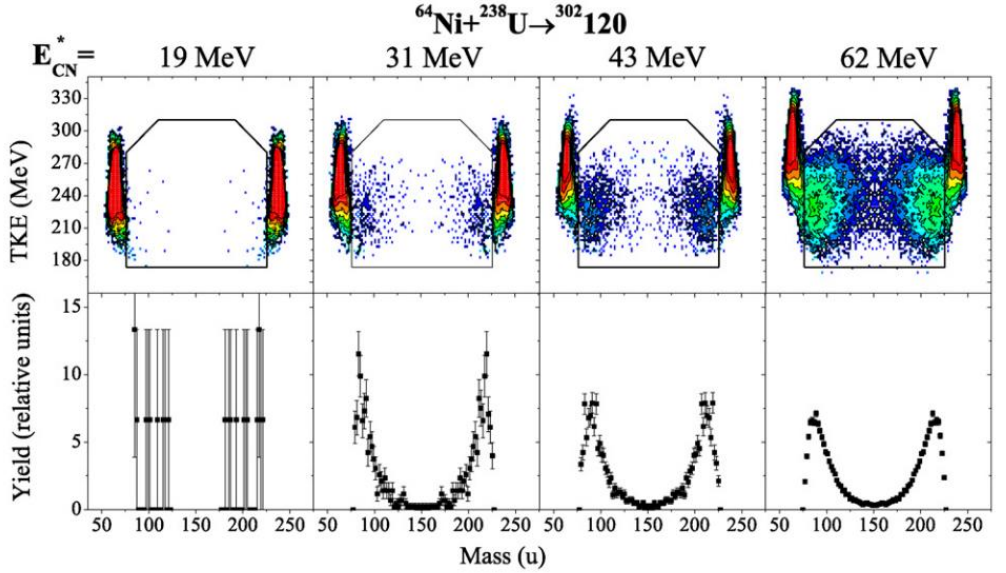
MNT?

Adamian, G.G., Antonenko, N.V., Diaz-Torres, A. et al. How to extend the chart of nuclides?. Eur. Phys. J. A 56, 47 (2020)

^{64}Ni + ^{238}U cases



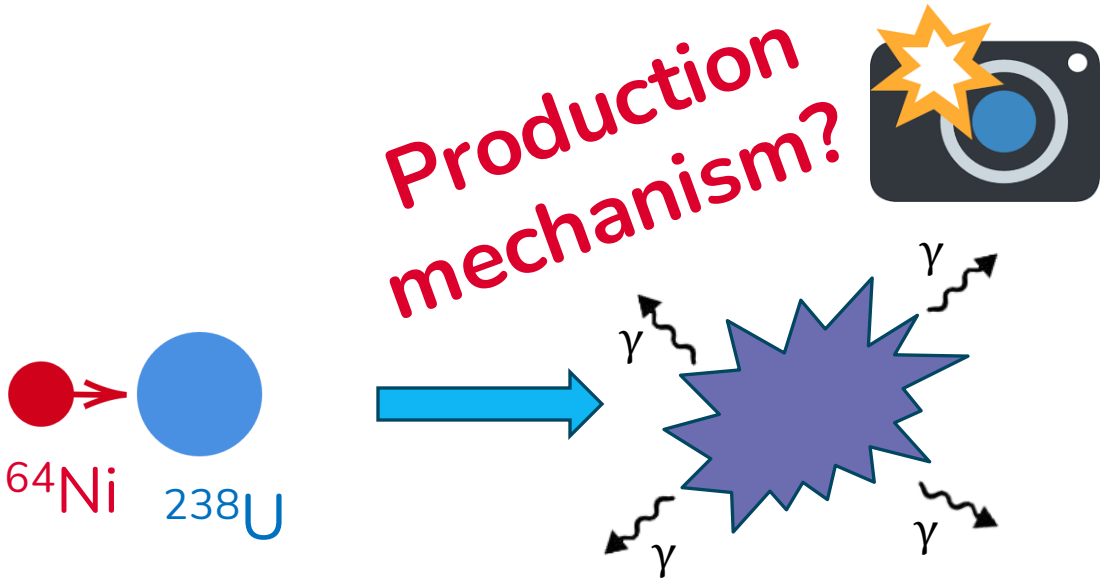
Corradi, L., Stefanini, A. M. & Lin, C. J. (1999), *Phys. Rev. C* 59, 261–268. "Multinucleon transfer processes in ^{64}Ni + ^{238}U."



E_{lab}= 330 MeV E_{lab}= 343 MeV E_{lab}= 358 MeV E_{lab}= 382 MeV

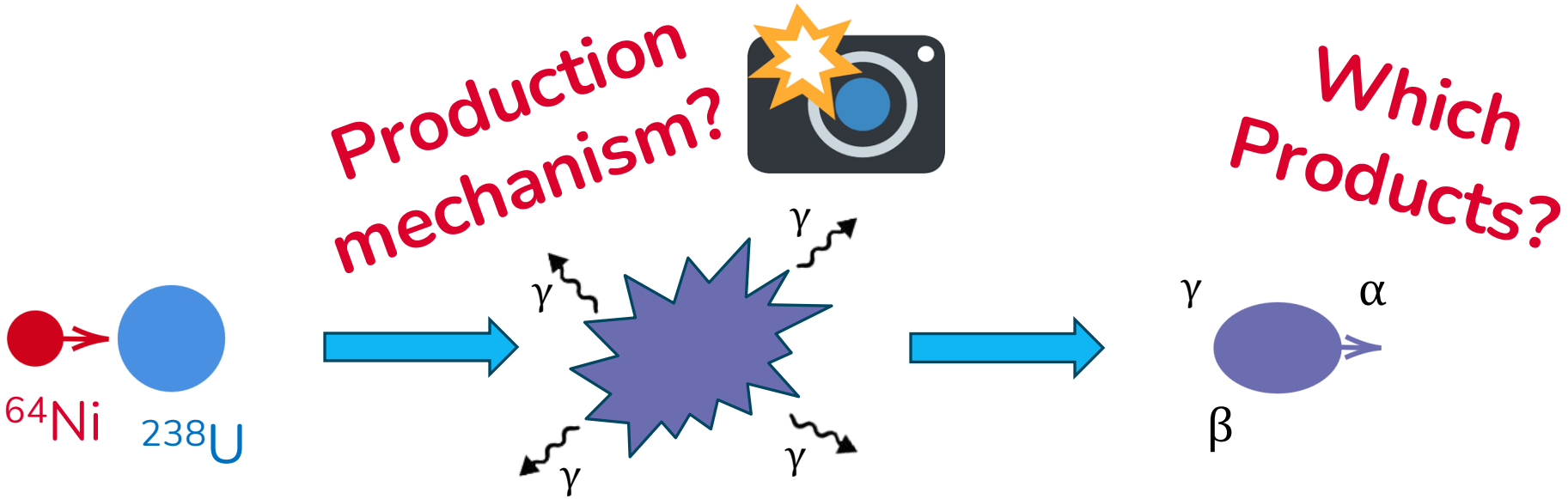
E. M. Kozulin et al. (2010), *Phys. Lett. B* 686, 227-232 "Investigation of the reaction ^{64}Ni + ^{238}U being an option of synthesizing element 120."

The experiment



@ E_{lab} = 300 MeV, 333 MeV and 366 MeV

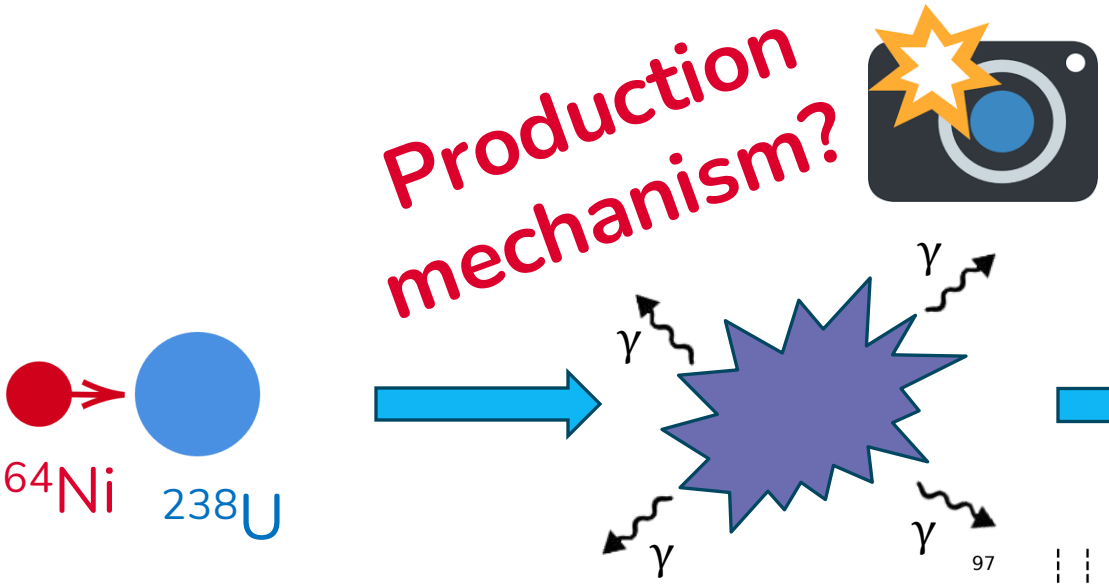
The experiment



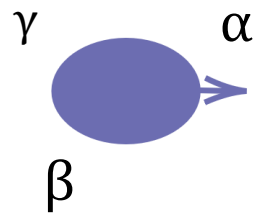
@ E_{lab} = 300 MeV, 333 MeV and 366 MeV

The experiment

Production mechanism?

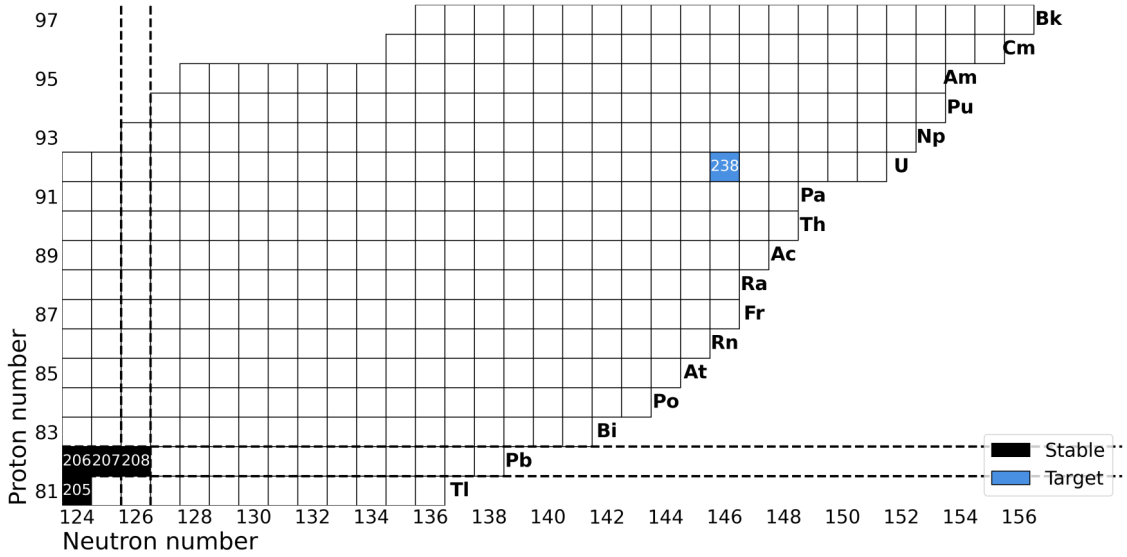


Which Products?



^{64}Ni ^{238}U

@ E_{lab} = 300 MeV, 333 MeV and 366 MeV

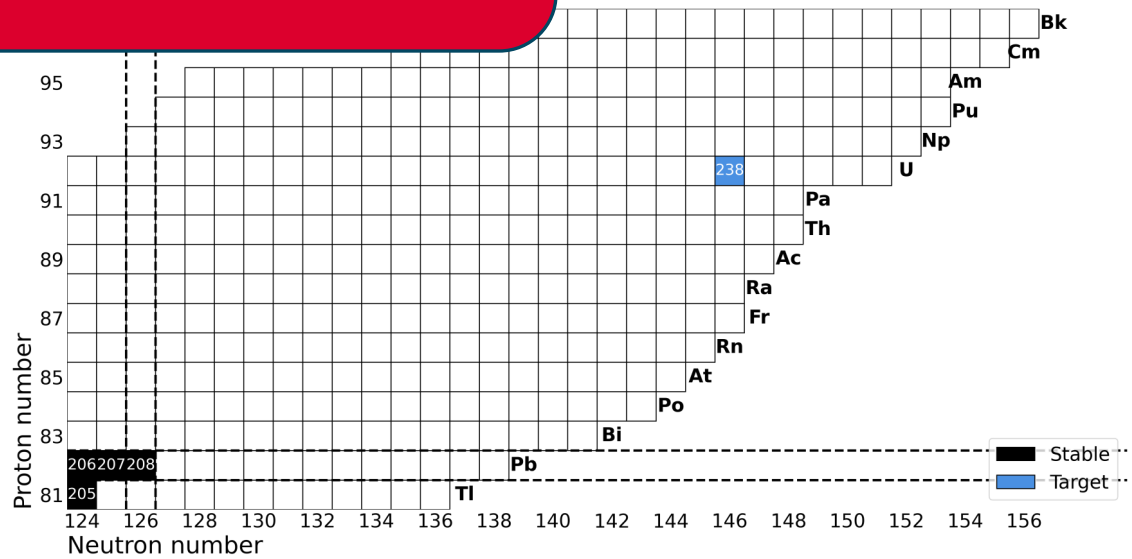


The experiment

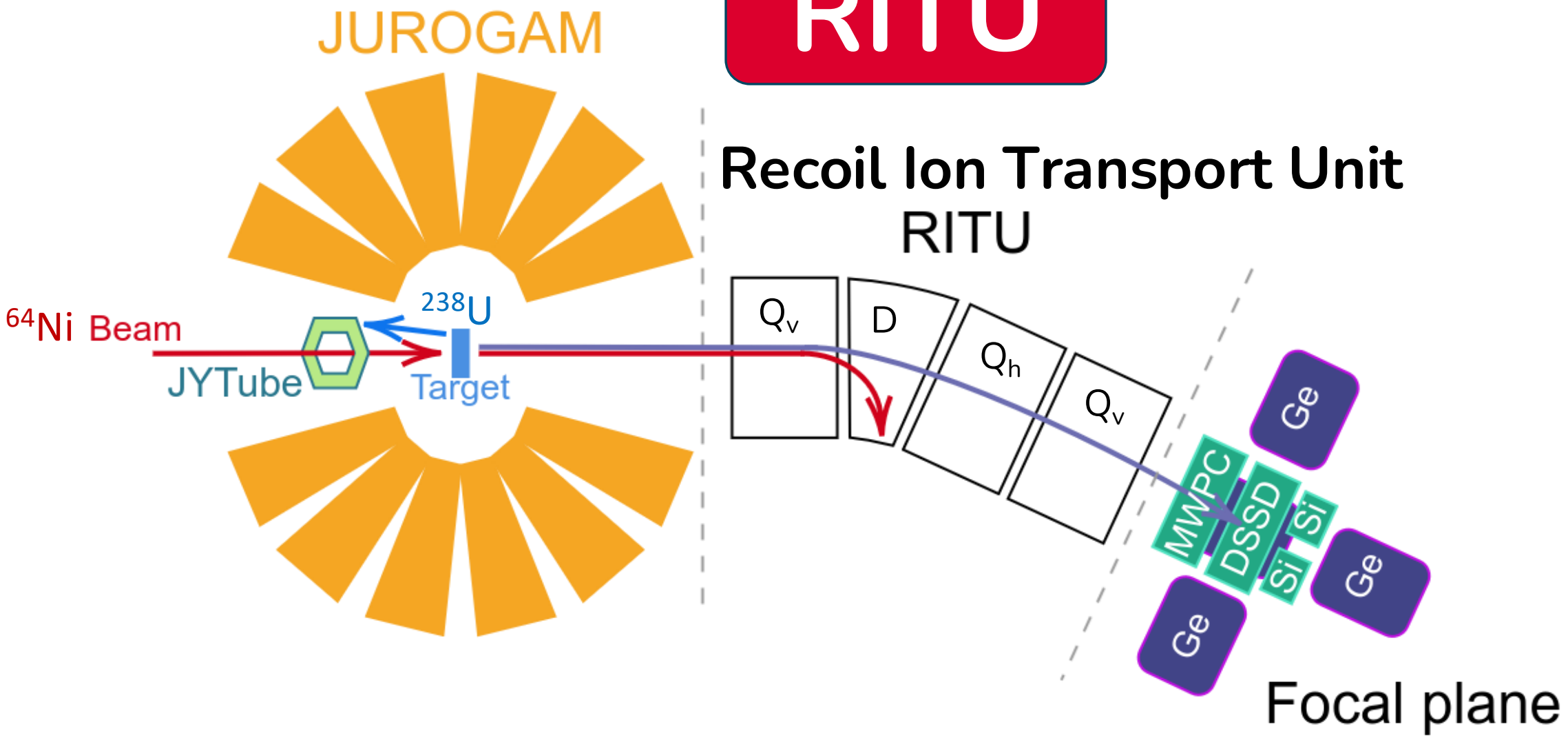
Production mechanism?

Which Products?

@ E_{lab} = 300 MeV, 333 MeV and 366 MeV



RITU



Eur. Phys. J. A (2020) 56:149
Nuclear Inst. and Methods in Physics Research, B 541 (2023) 33–36

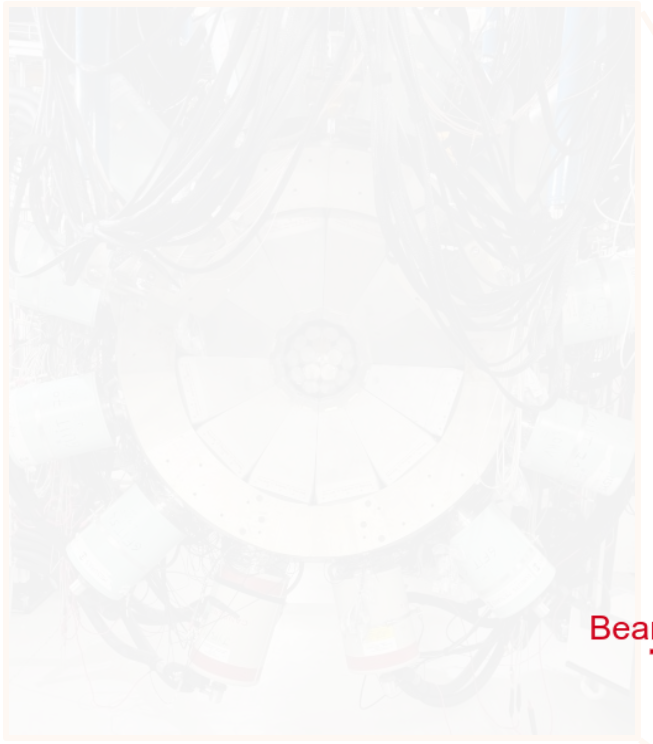
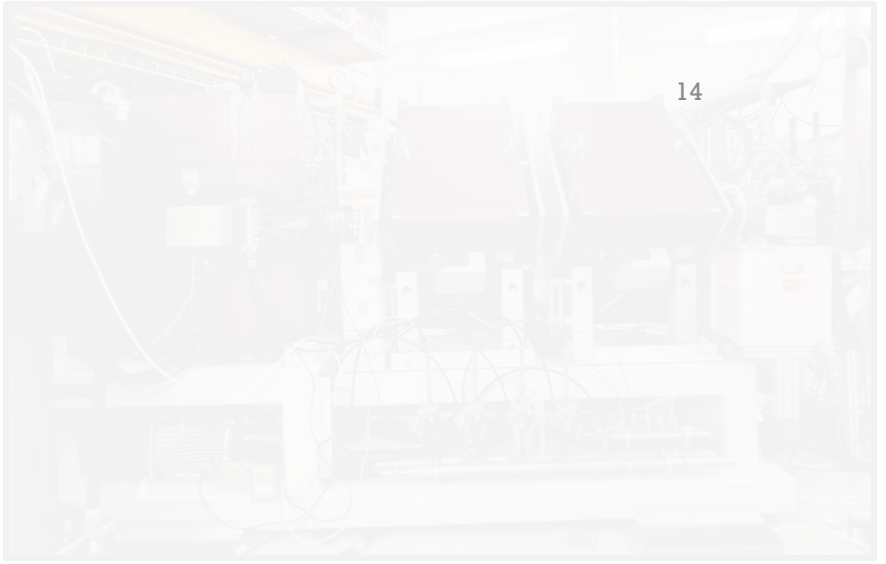


Photo: A.J. McCarter, PhD Thesis, University of Liverpool (2025)



JUROGAM

RITU

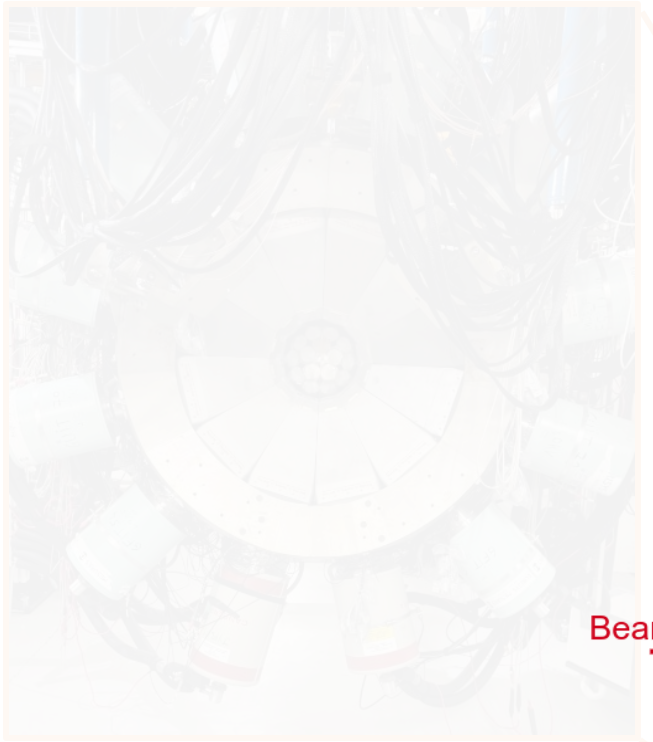
Focal plane

JYTube

RITU

Photo: A.J. McCarter, PhD Thesis, University of Liverpool (2025)

Eur. Phys. J. A (2020) 56:149
Nuclear Inst. and Methods in Physics Research, B 541 (2023) 33–36



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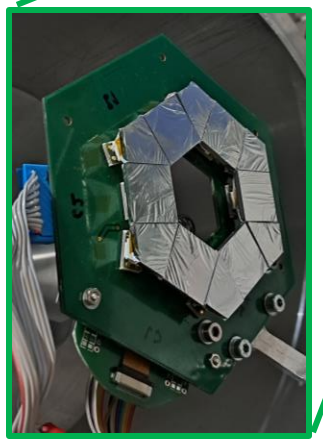
JYTube



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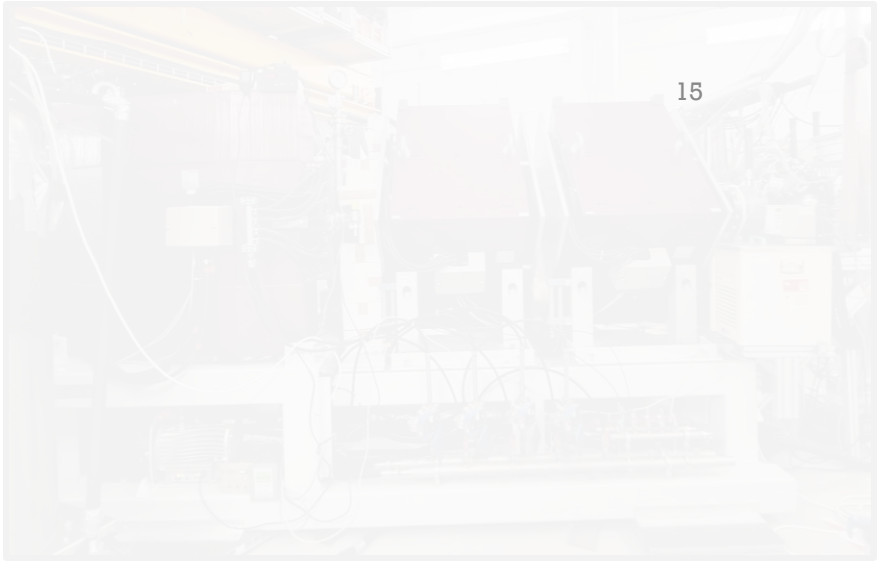

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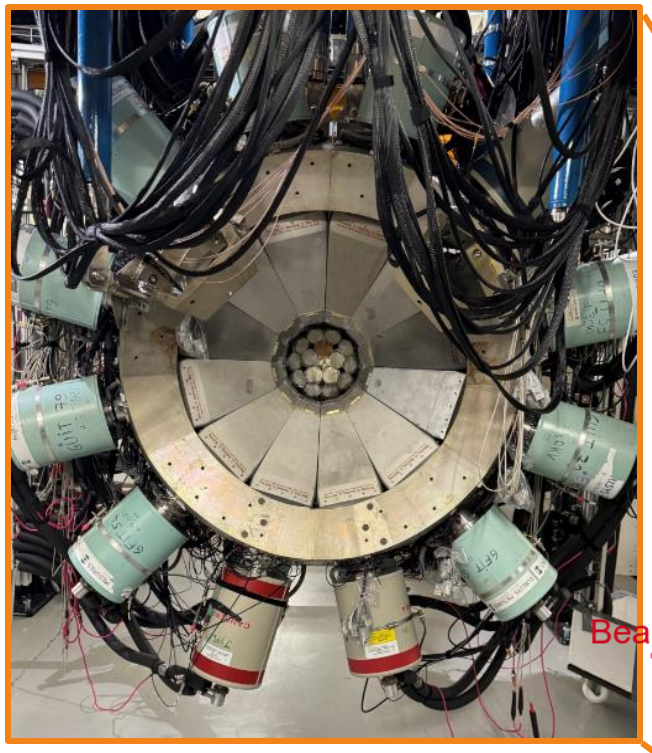

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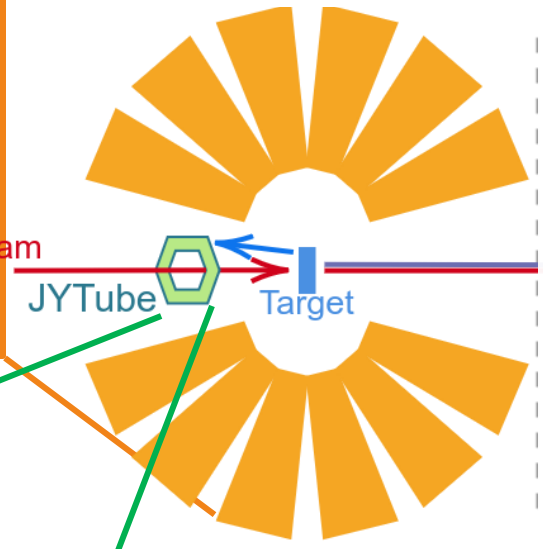

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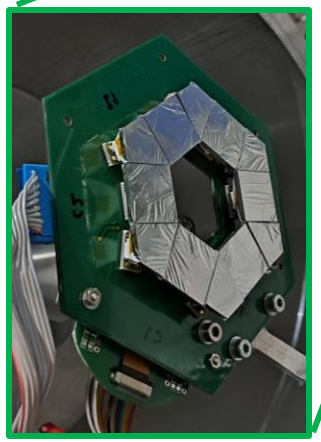

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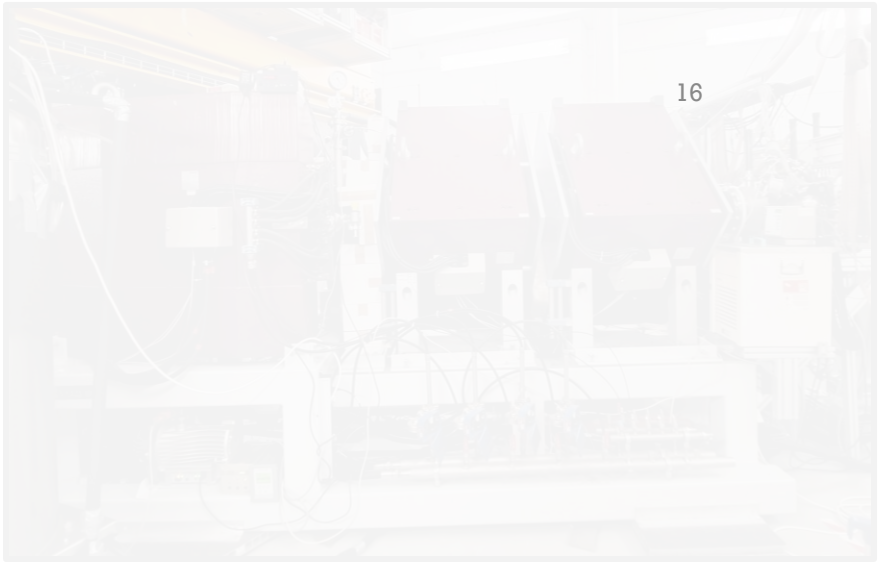

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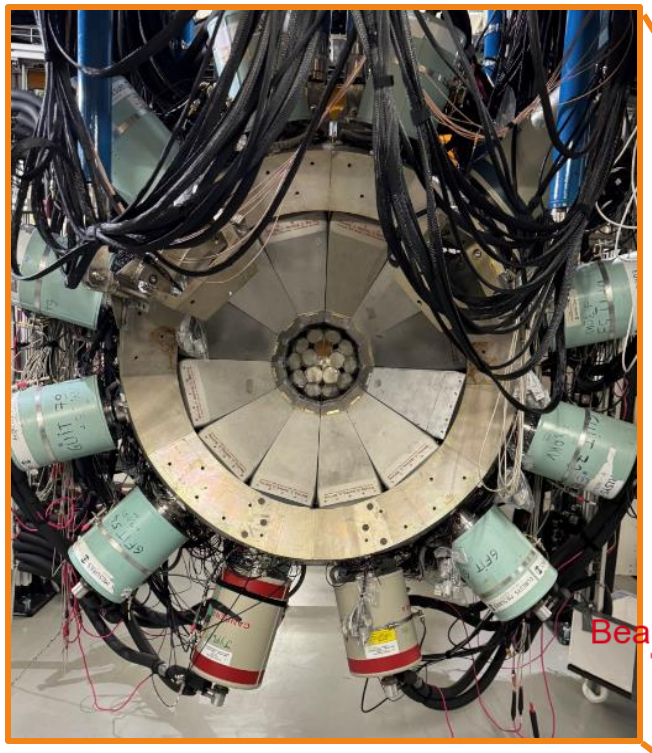

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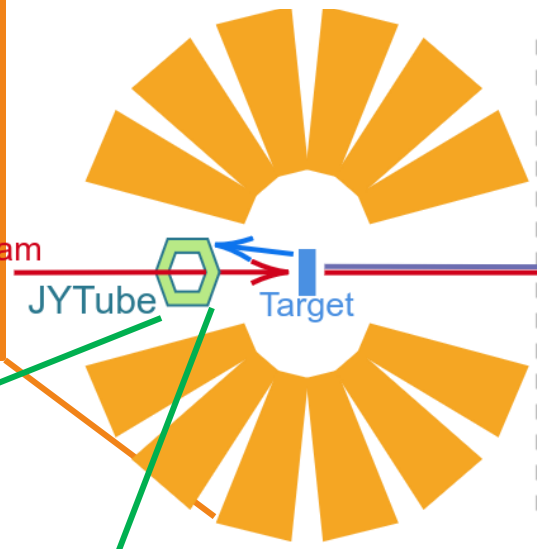

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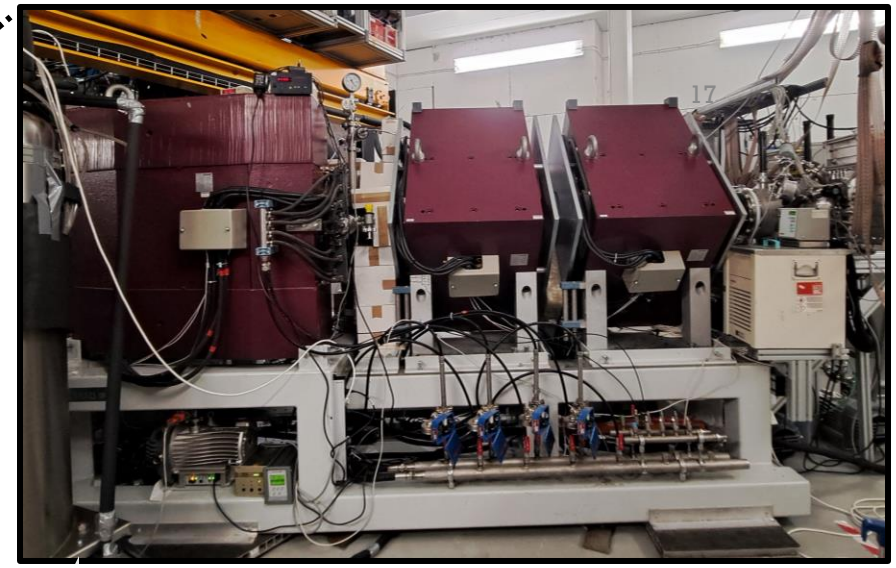
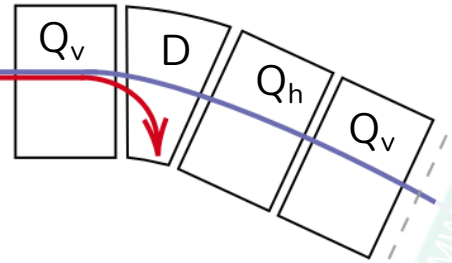
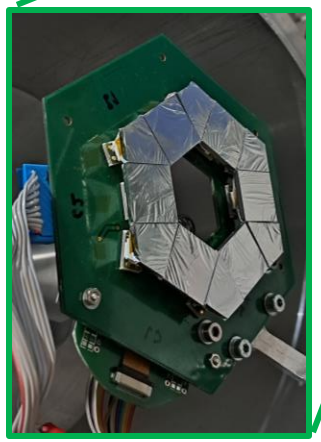




Bρ from 1.66 Tm to 1.92 Tm

Horizontal/vertical acceptance: ±25/±85 mrad

JYTube



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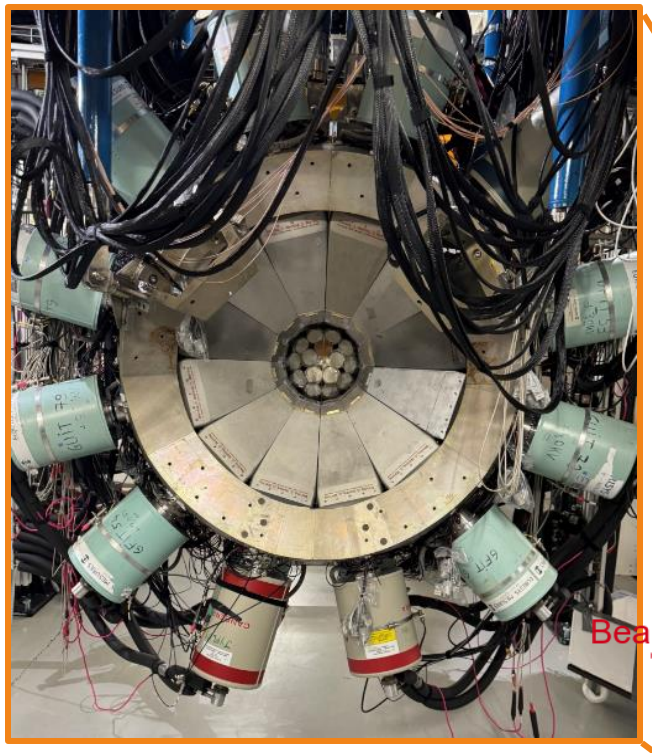

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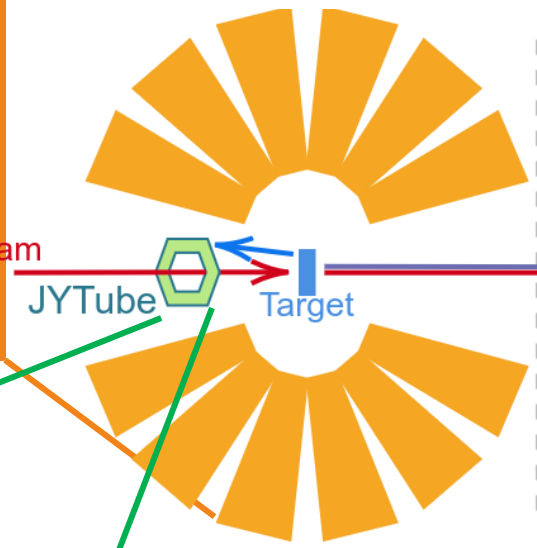

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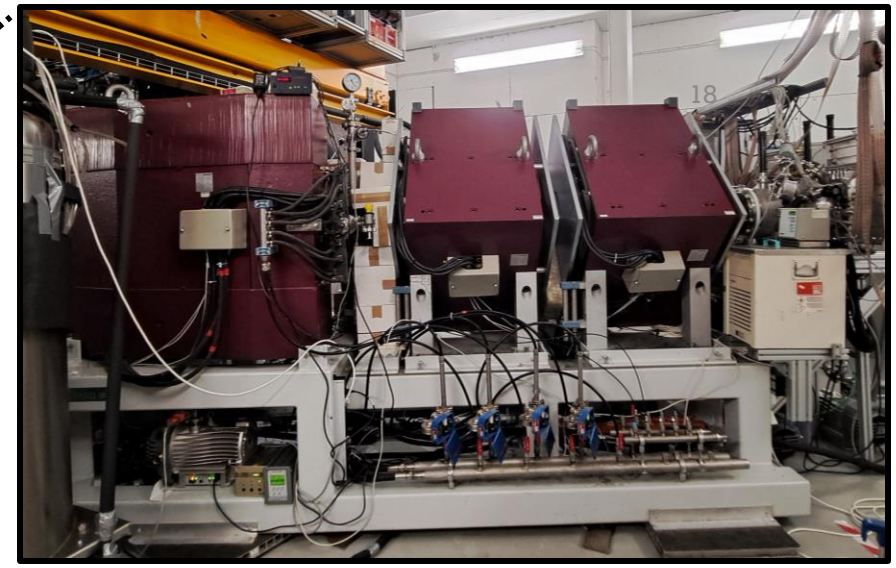
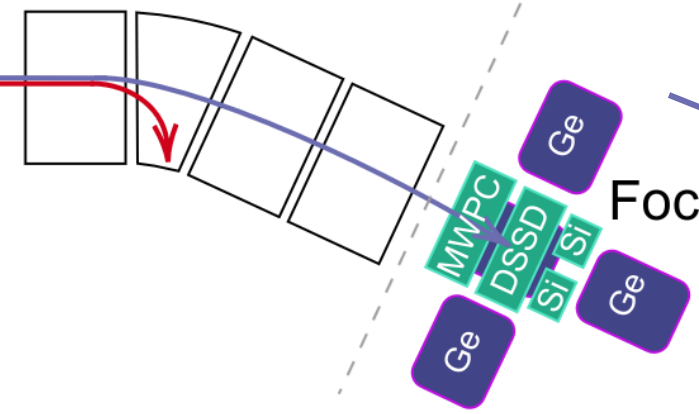
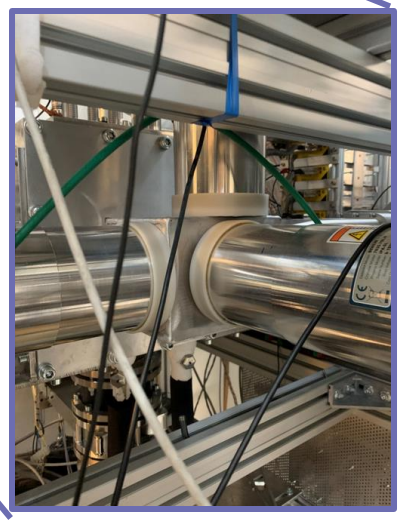




Focal plane



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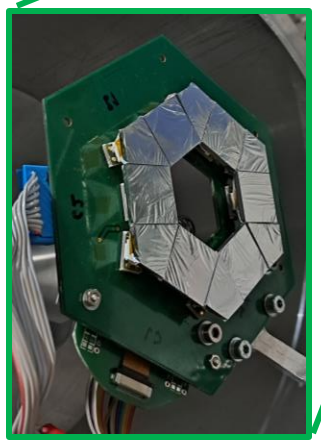

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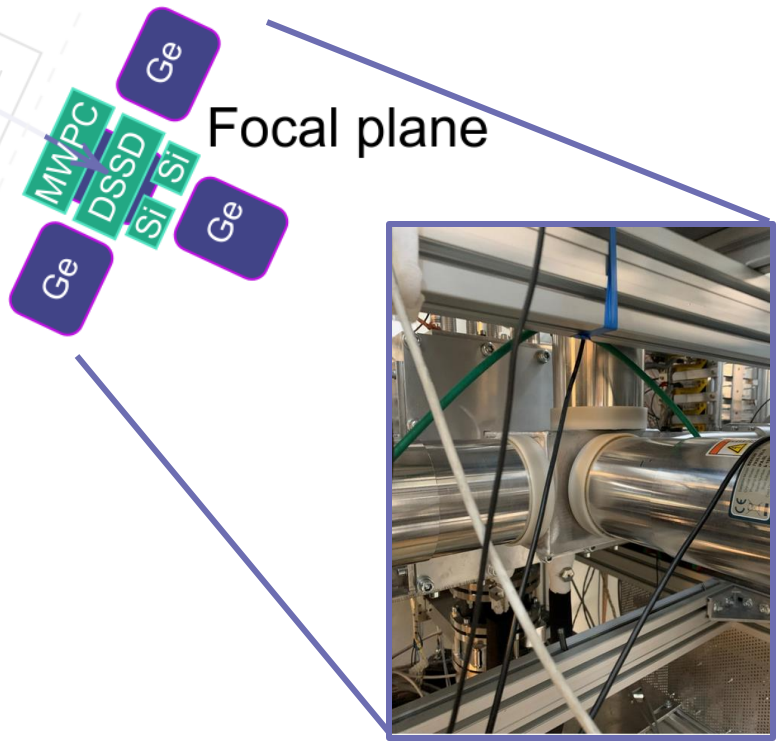

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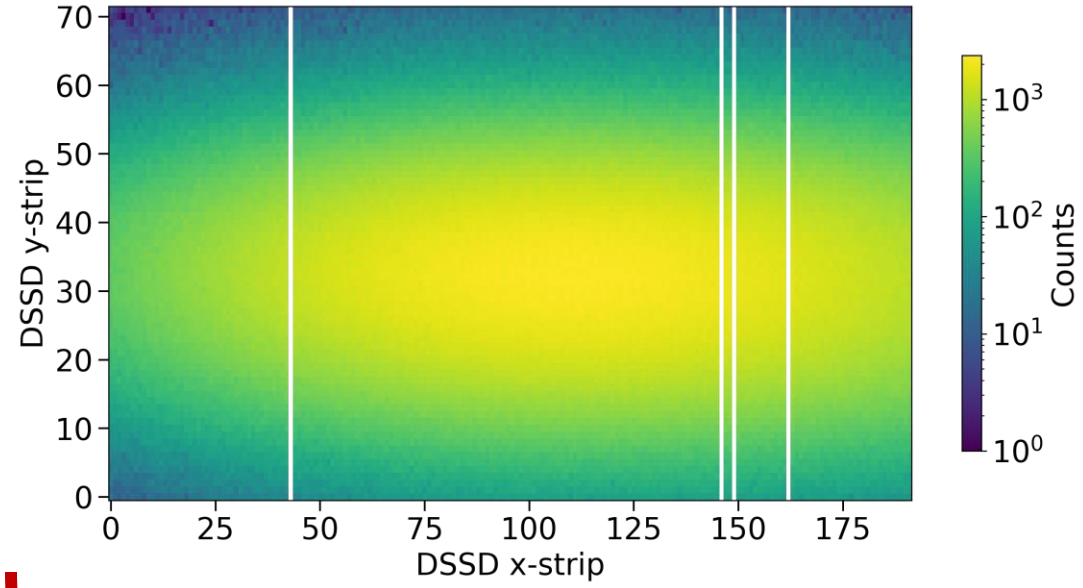

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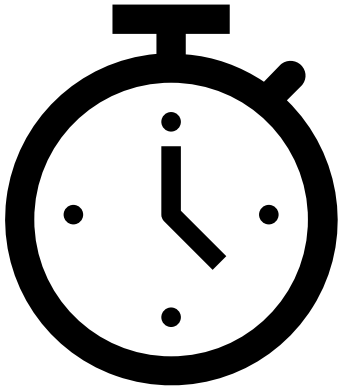
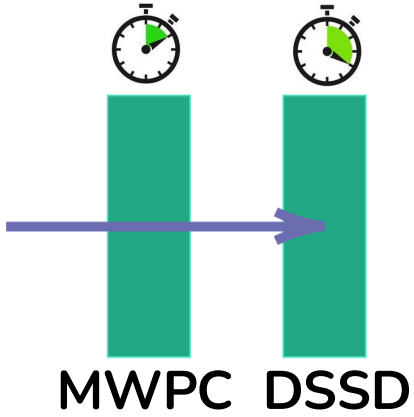
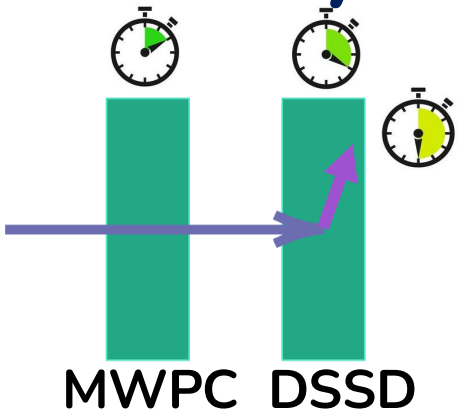


100 MHz clock

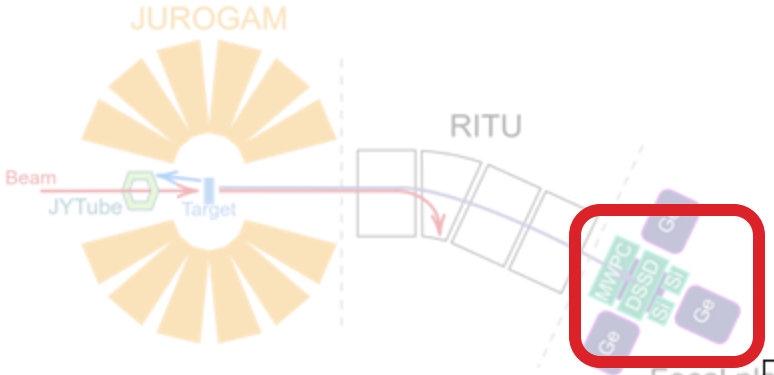
Recoil

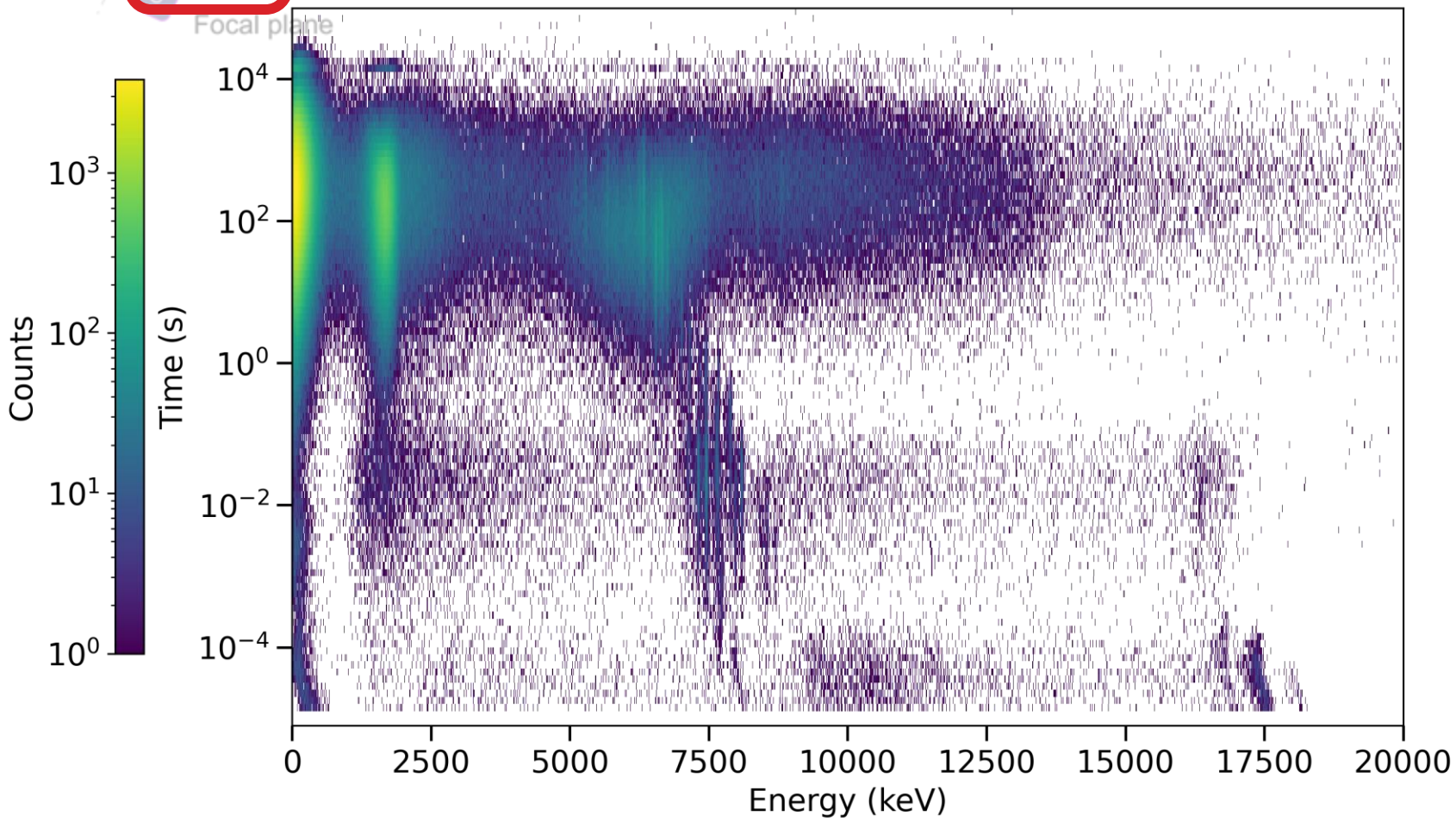


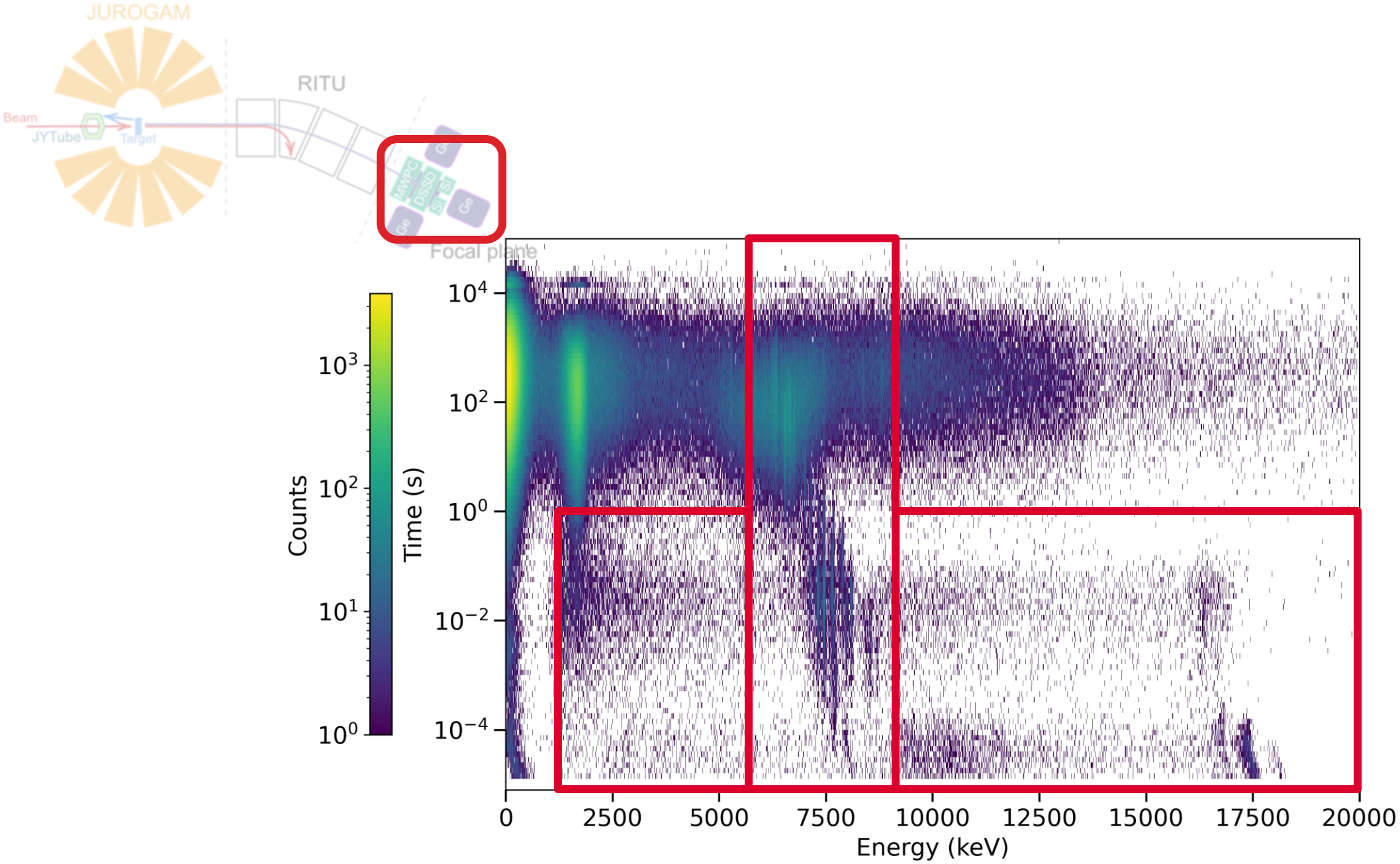
Decay

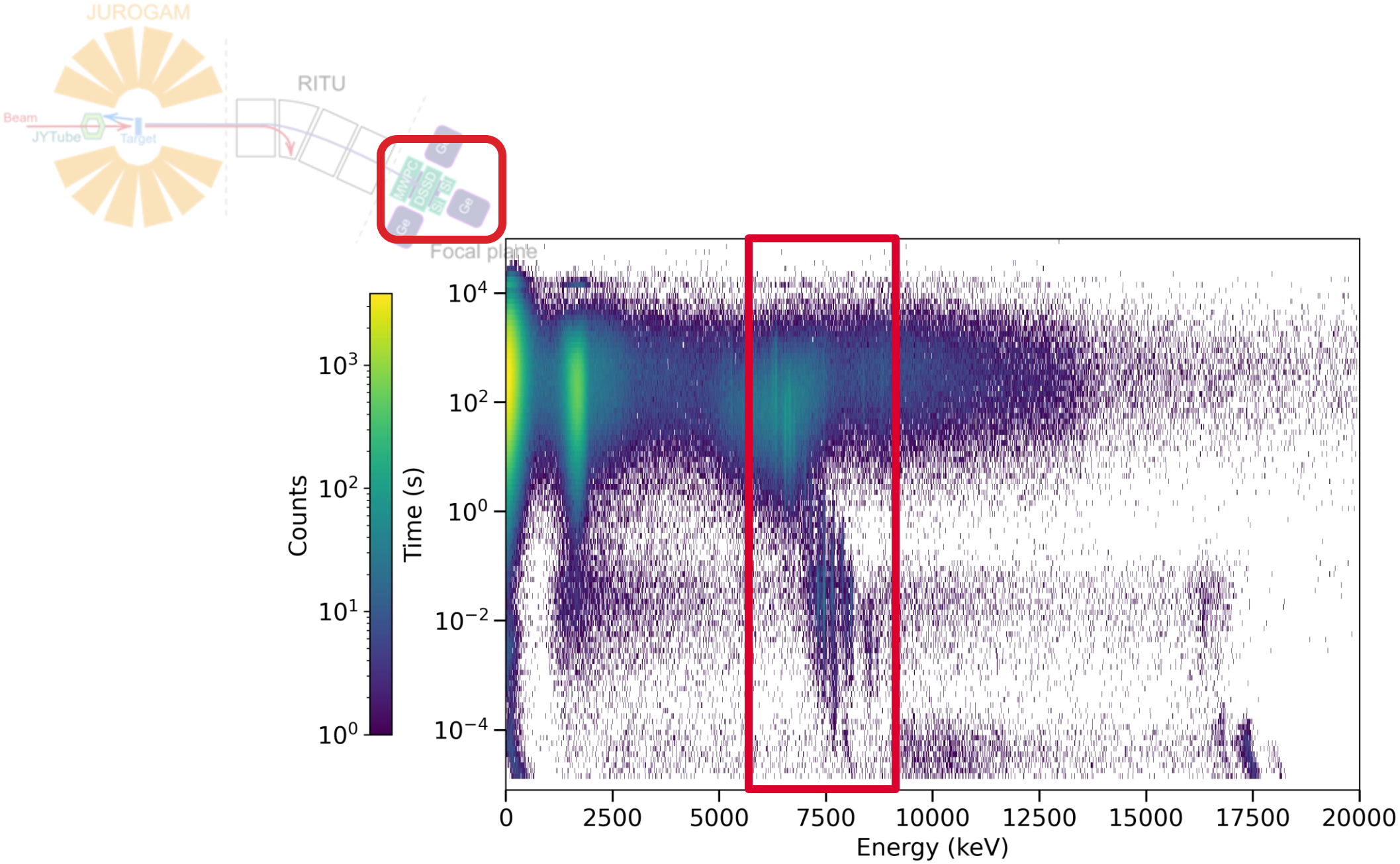


Correlated decays






JUROGAM
RITU
Beam
JYTube
Target
MWPC
DSSD
Si
Si
Ge
Ge
Ge
Focal plane
Counts
Time (s)
10^3
10^2
10^1
10^0
10^4
10^2
10^0
10^{-2}
10^{-4}
0
2500
5000
7500
10000
12500
15000
17500
20000
Energy (keV)


JUROGAM
RITU
Beam
JYTube
Target
MWPC
DSSD
Si
Si
Ge
Ge
Ge
Focal plane
Counts
Time (s)
10^3
10^2
10^1
10^0
10^4
10^2
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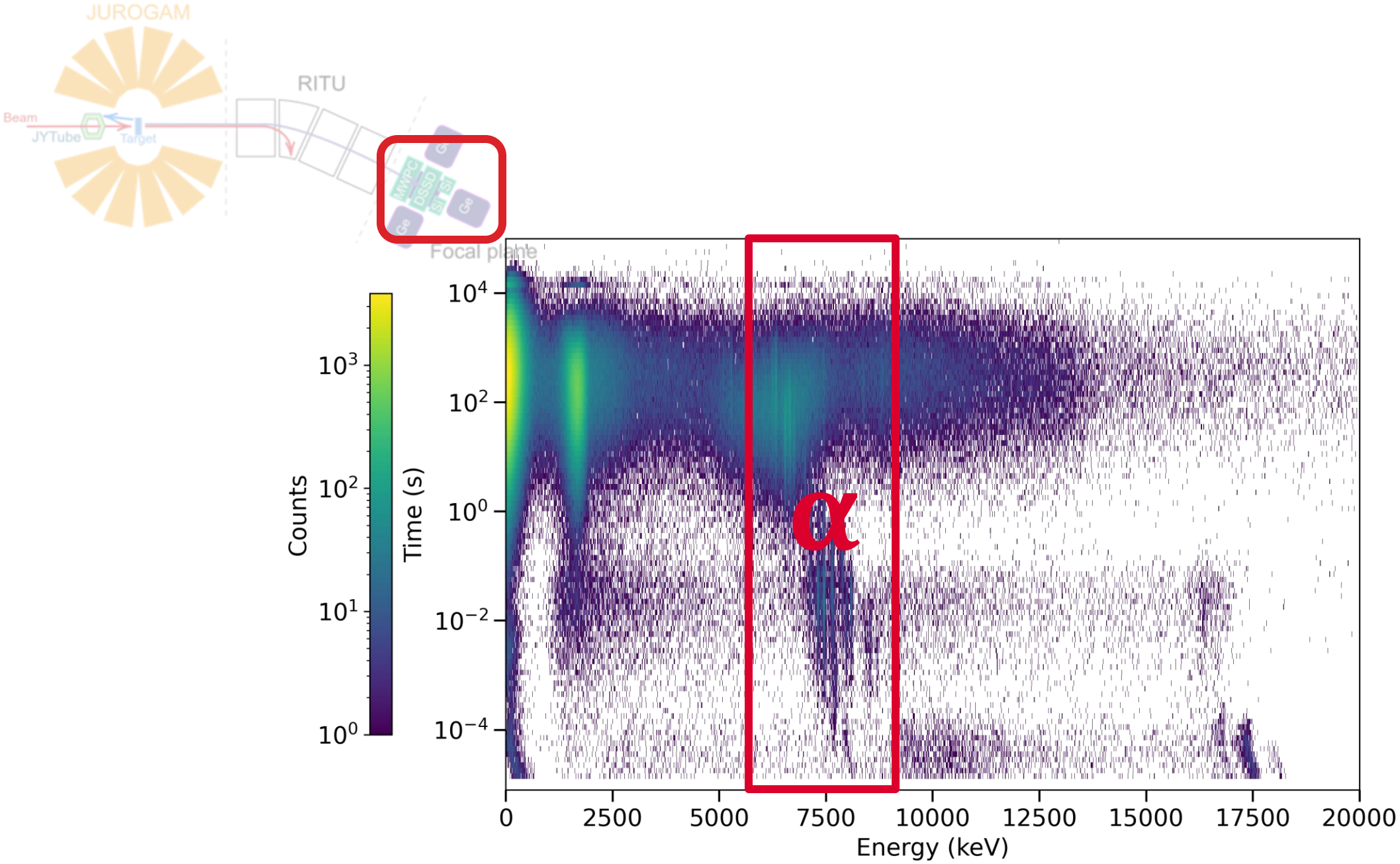
10^{-4}
0
2500
5000
7500
10000
12500
15000
17500
20000
Energy (keV)


JUROGAM
RITU
Beam
JYTube
Target
MWPC
DSSD
Si
Si
Ge
Ge
Focal plane
Counts
Time (s)
10^3
10^2
10^1
10^0
10^4
10^2
10^0
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10^{-4}
α
0
2500
5000
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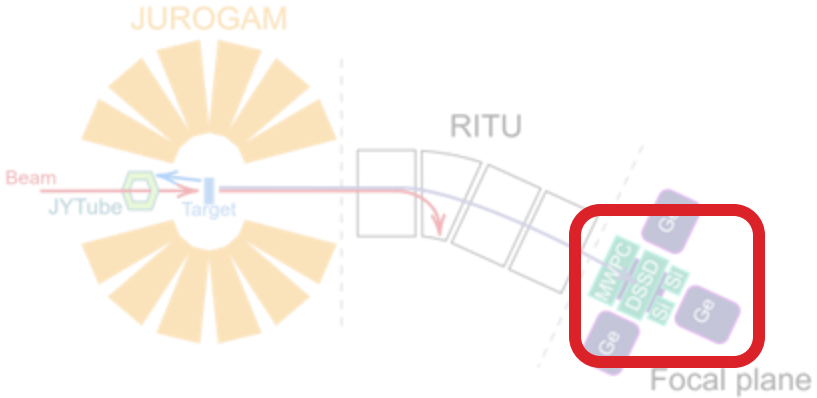
12500
15000
17500
20000
Energy (keV)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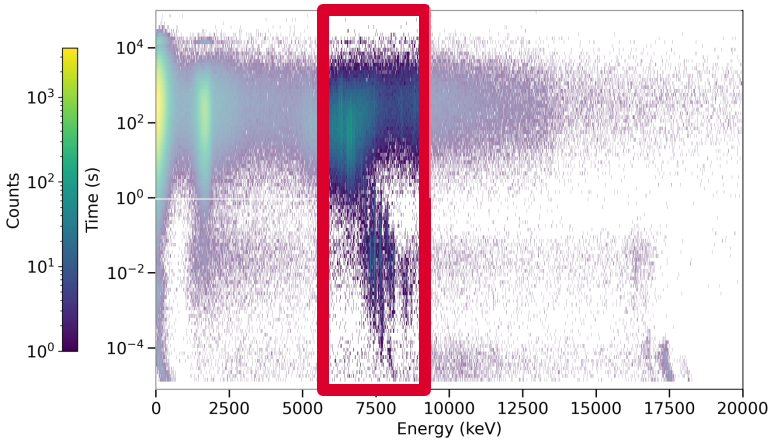
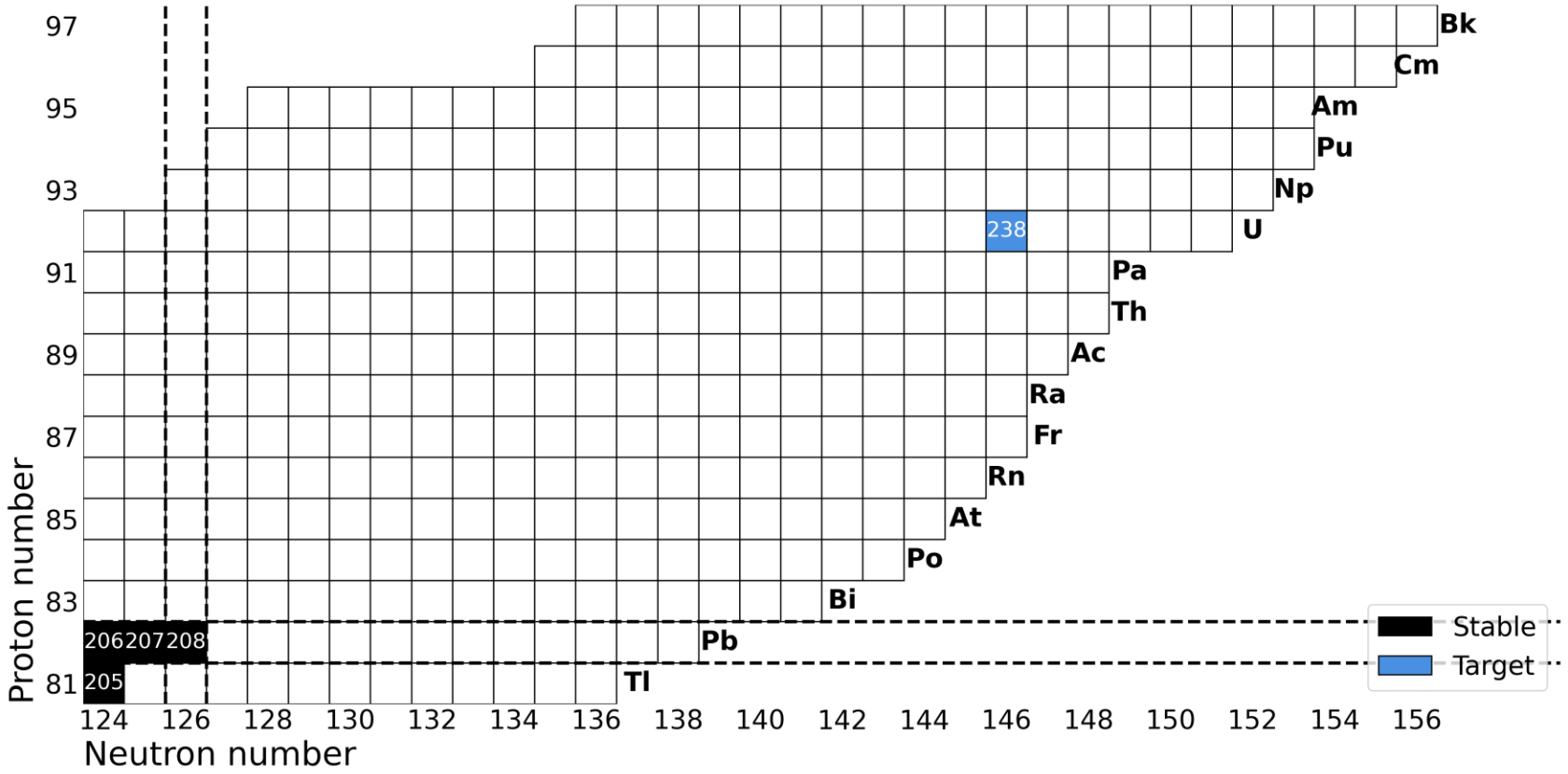
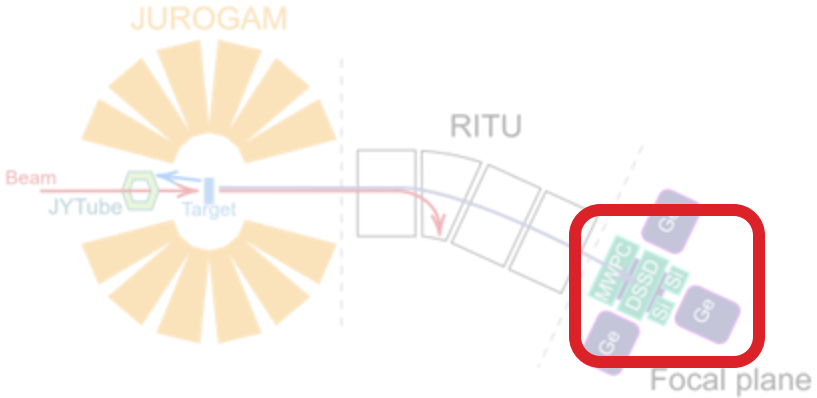
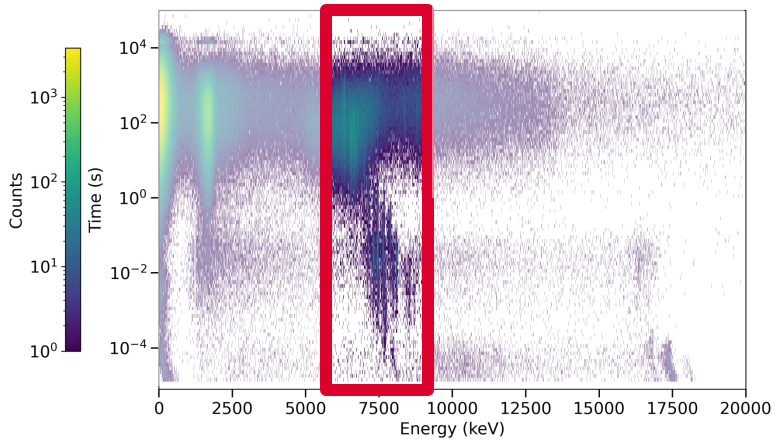
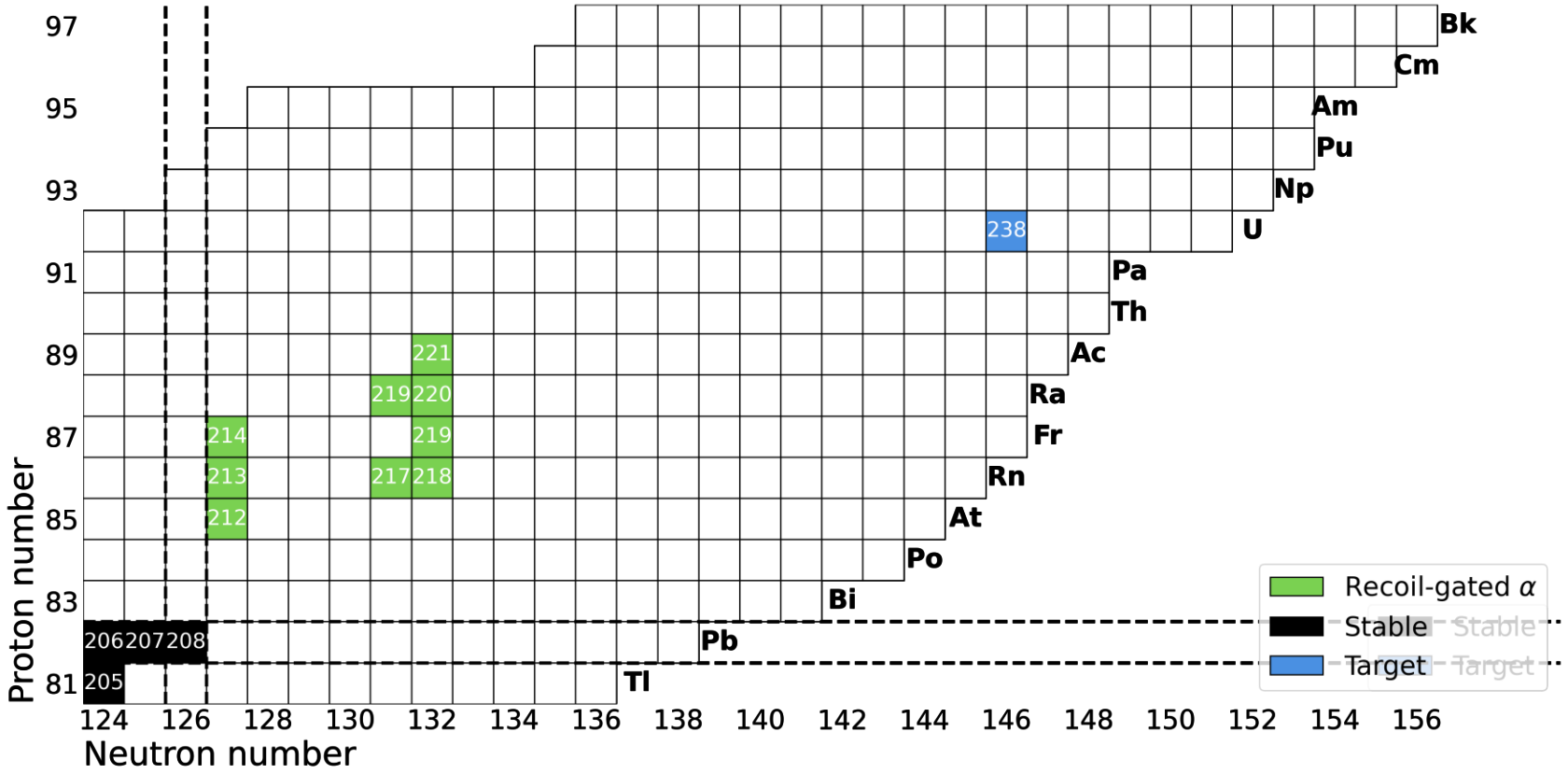
RITU
Beam
JYTube
Target
MWPC
DSSD
Si
Si
Ge
Ge
Ge
Focal plane

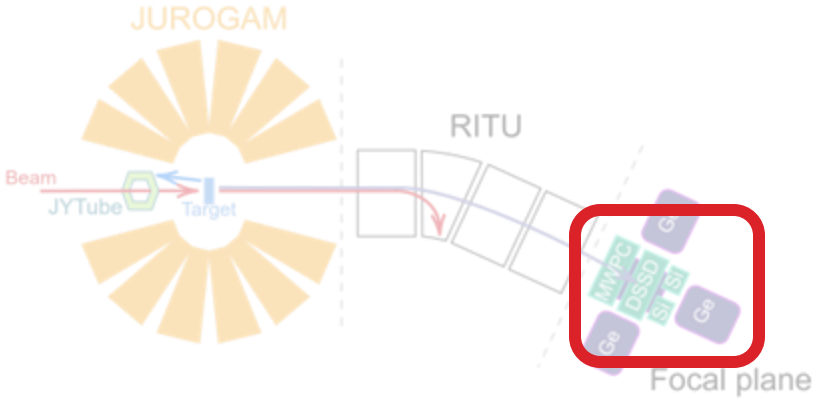

Counts
Time (s)
Energy (keV)

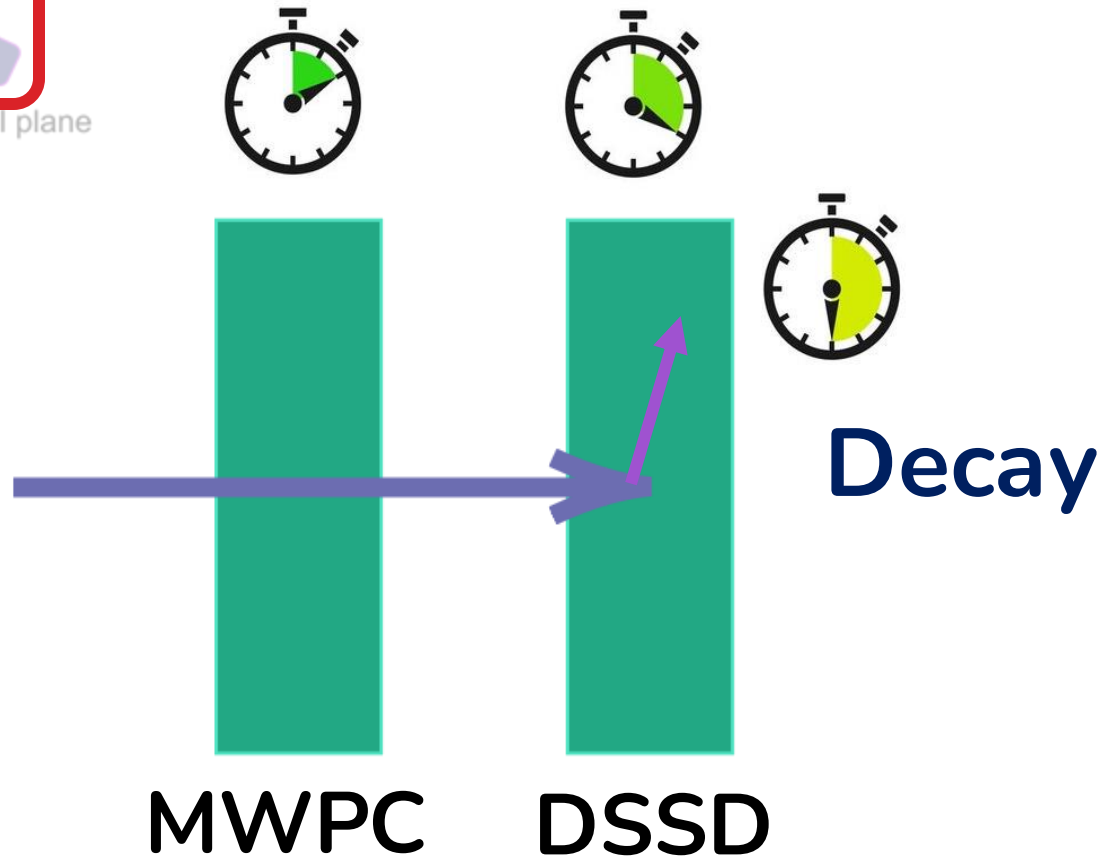

Proton number
Neutron number
Bk
Cm
Am
Pu
Np
U
Pa
Th
Ac
Ra
Fr
Rn
At
Po
Bi
Pb
Tl
238
206207208
205
Stable
Target


JUROGAM
RITU
Beam
JYTube
Target
MWPC
DSSD
Si
Si
Ge
Ge
Ge
Focal plane

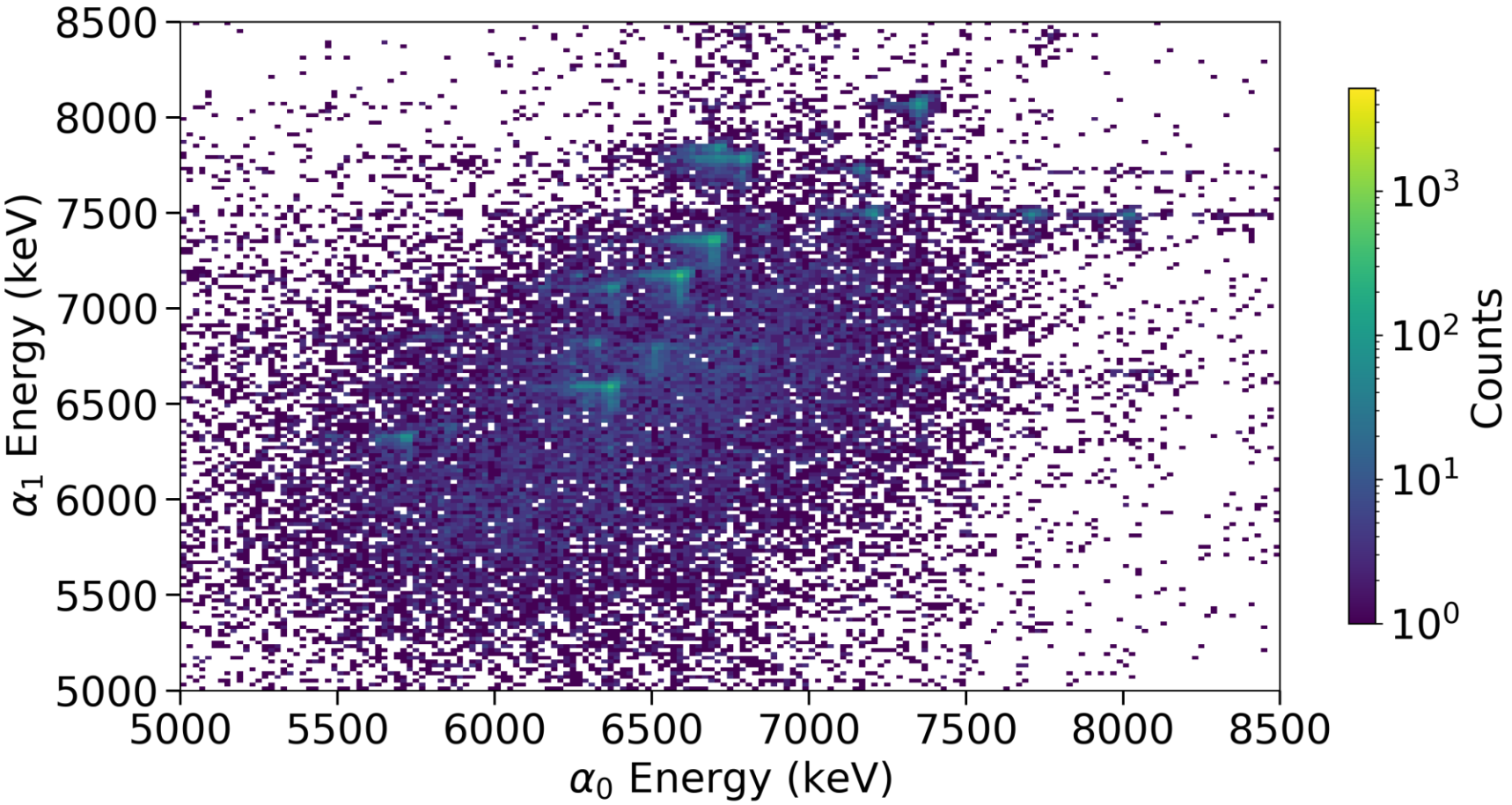

Counts
Time (s)
Energy (keV)

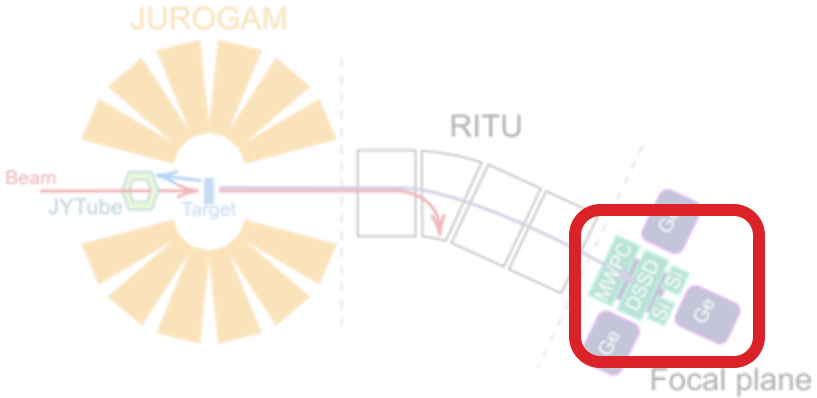

Proton number
Neutron number
Bk
Cm
Am
Pu
Np
U
Pa
Th
Ac
Ra
Fr
Rn
At
Po
Bi
Pb
Tl
238
221
219
220
214
219
213
217
218
212
206
207
208
205
Recoil-gated α
Stable
Target

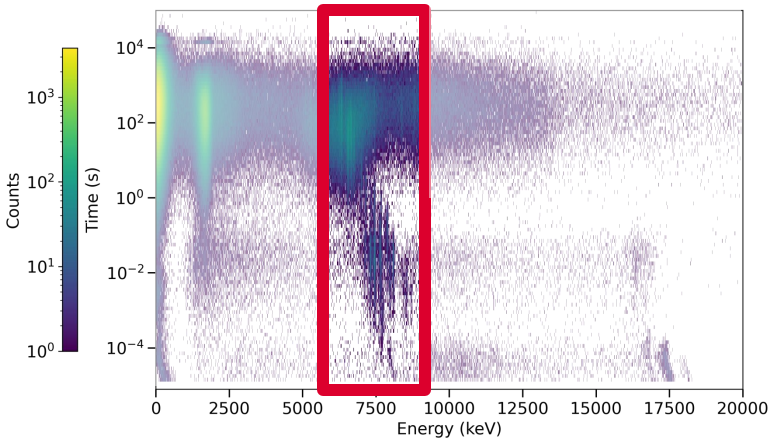

JUROGAM
RITU
Beam
JYTube
Target
MWPC
DSSD
Si
Si
Ge
Ge
Ge
Focal plane

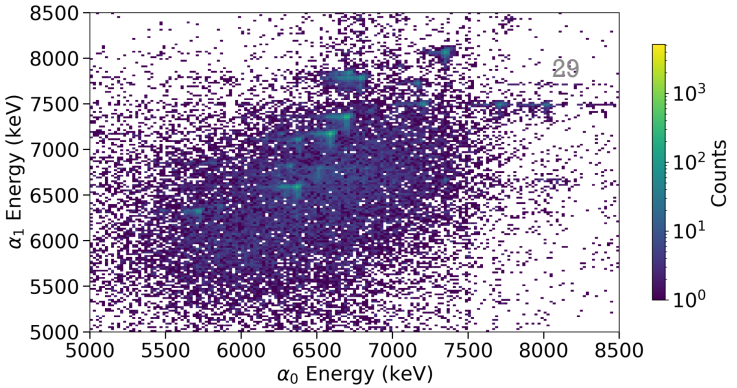

Decay
MWPC
DSSD

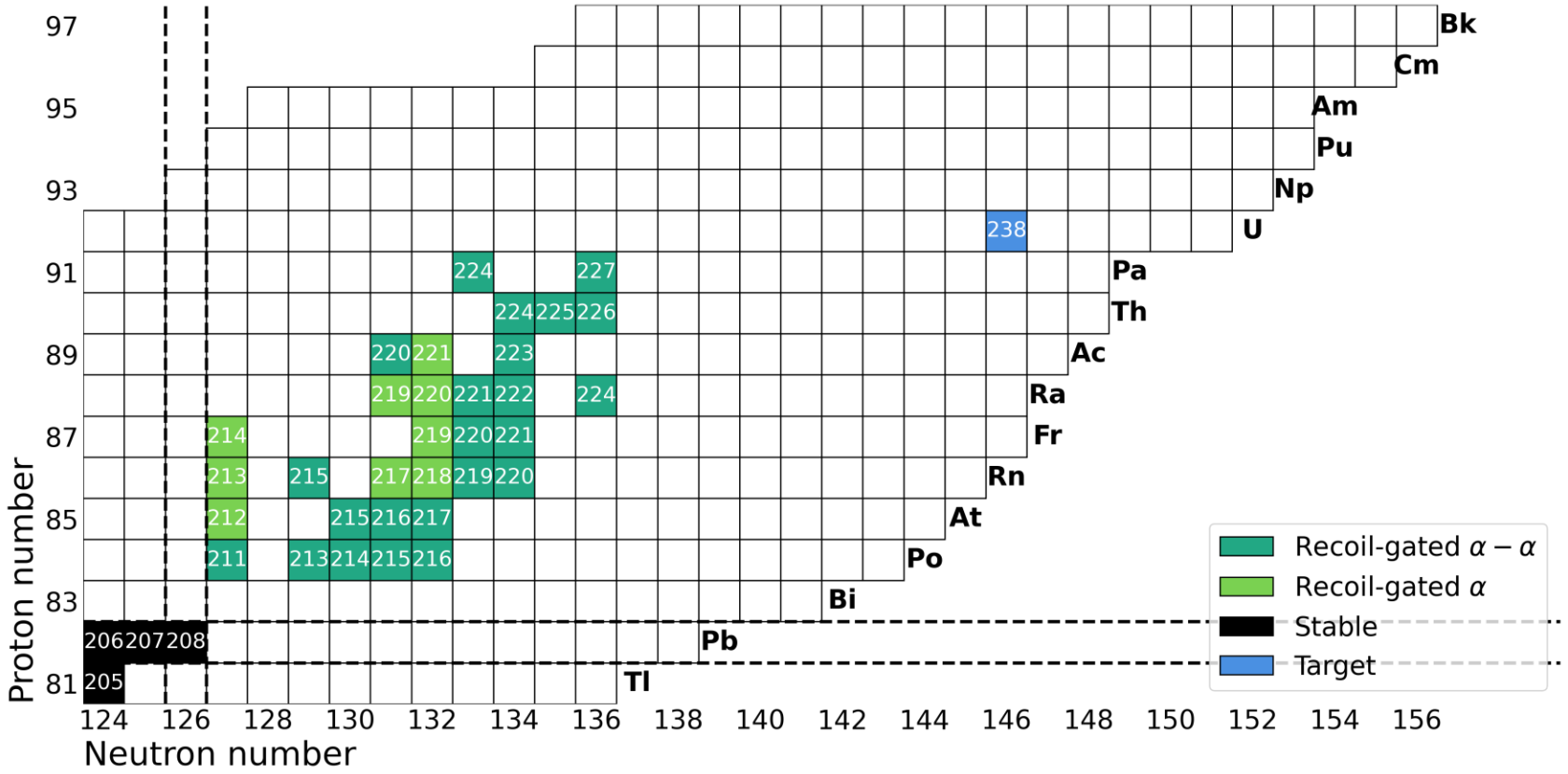
α-α correlations




JUROGAM
RITU
Beam
JYTube
Target
MWPC
DSSD
Si
Si
Ge
Ge
Ge
Focal plane


Counts
Time (s)
Energy (keV)


29
α_1 Energy (keV)
α_0 Energy (keV)
Counts


Proton number
Neutron number
Bk
Cm
Am
Pu
Np
U
Pa
Th
Ac
Ra
Fr
Rn
At
Po
Bi
Pb
Tl
238
224
227
224
225
226
220
221
223
219
220
221
222
224
214
219
220
221
213
215
217
218
219
220
212
215
216
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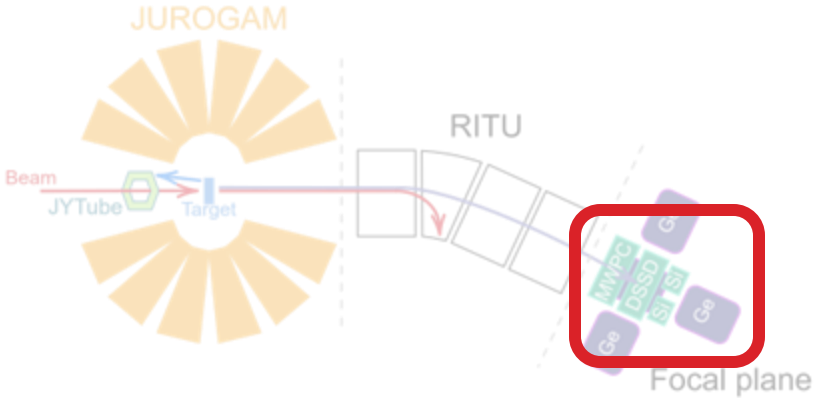
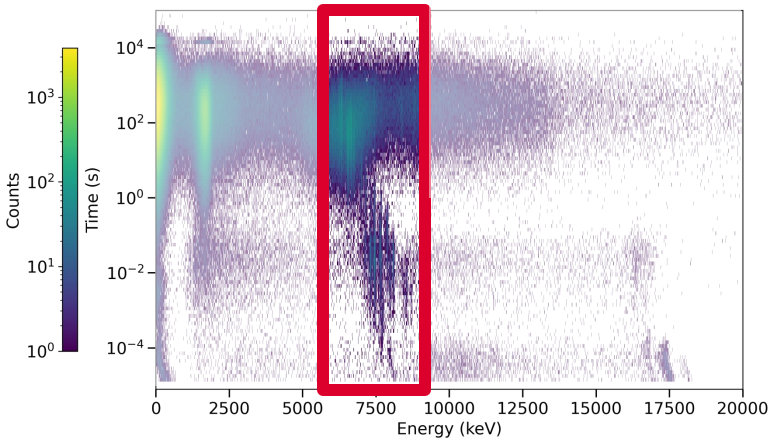
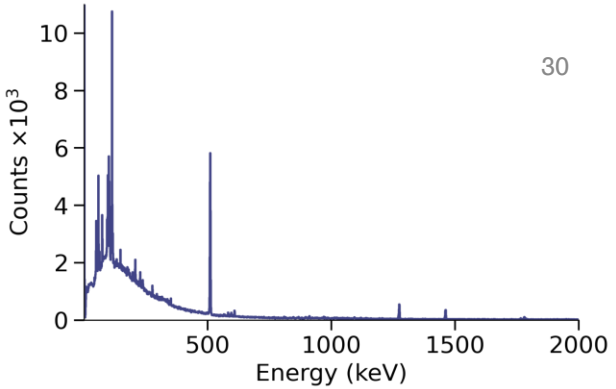
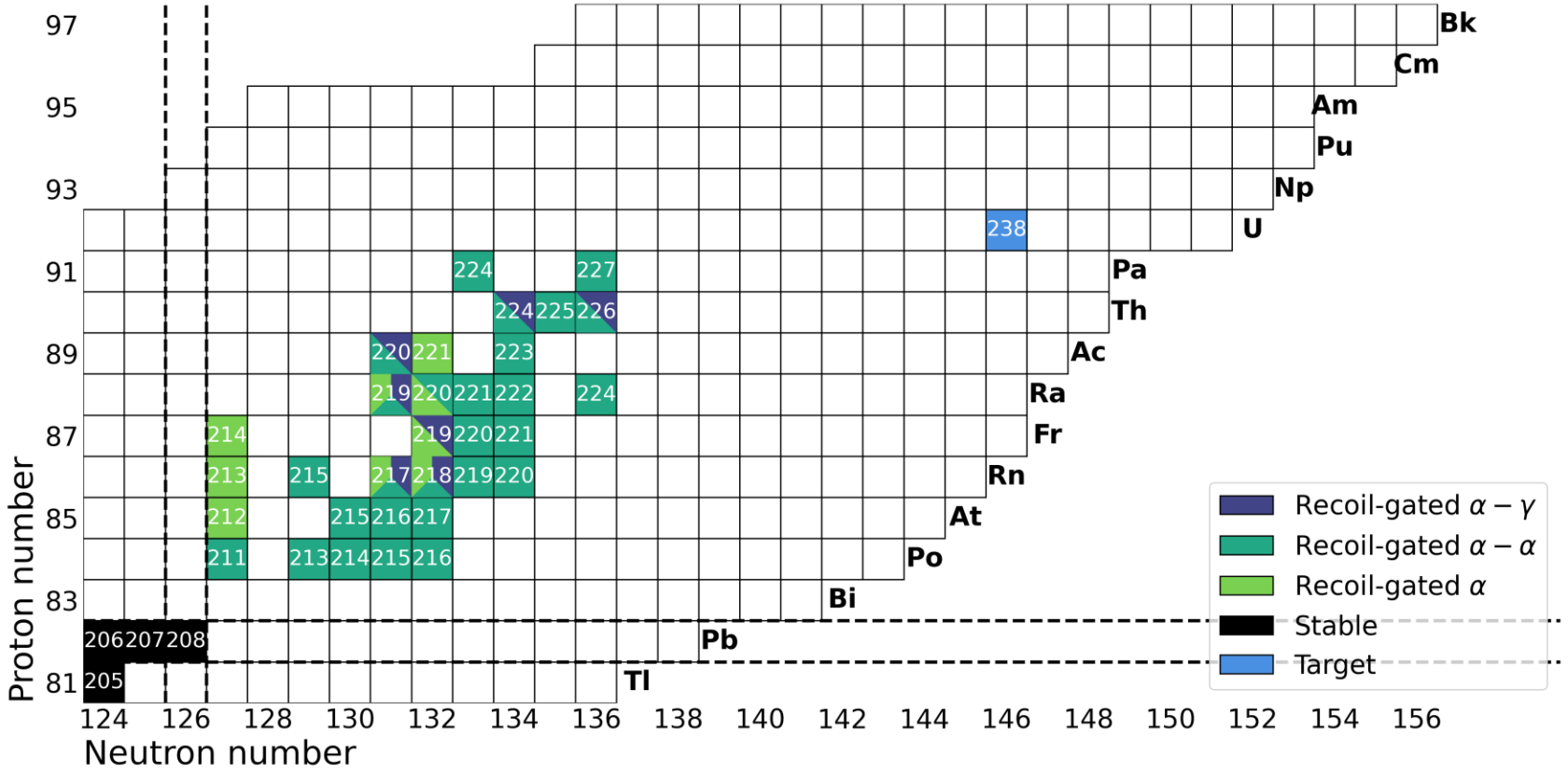
211
213
214
215
216
206
207
208
205
Recoil-gated $\alpha - \alpha$
Recoil-gated α
Stable
Target


JUROGAM
RITU
Beam
JYTube
Target
MWPC
DSSD
Si
Si
Ge
Ge
Ge
Focal plane


Counts
Time (s)
Energy (keV)


Counts ×10³
Energy (keV)


Proton number
Neutron number
Bk
Cm
Am
Pu
Np
U
Pa
Th
Ac
Ra
Fr
Rn
At
Po
Bi
Pb
Tl
238
224
227
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213
215
217
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212
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216
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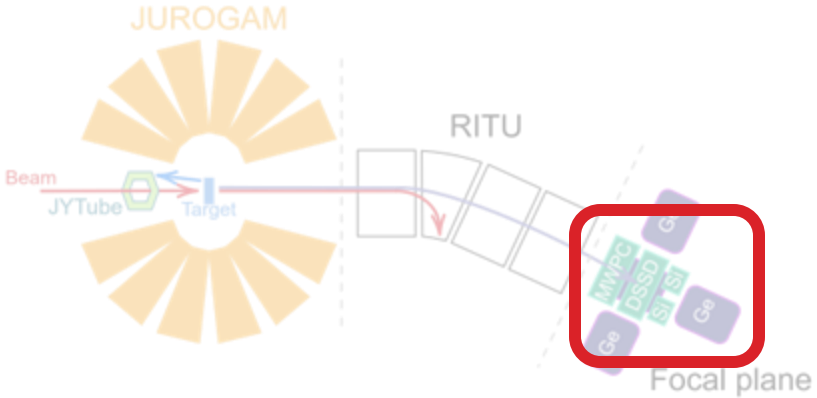
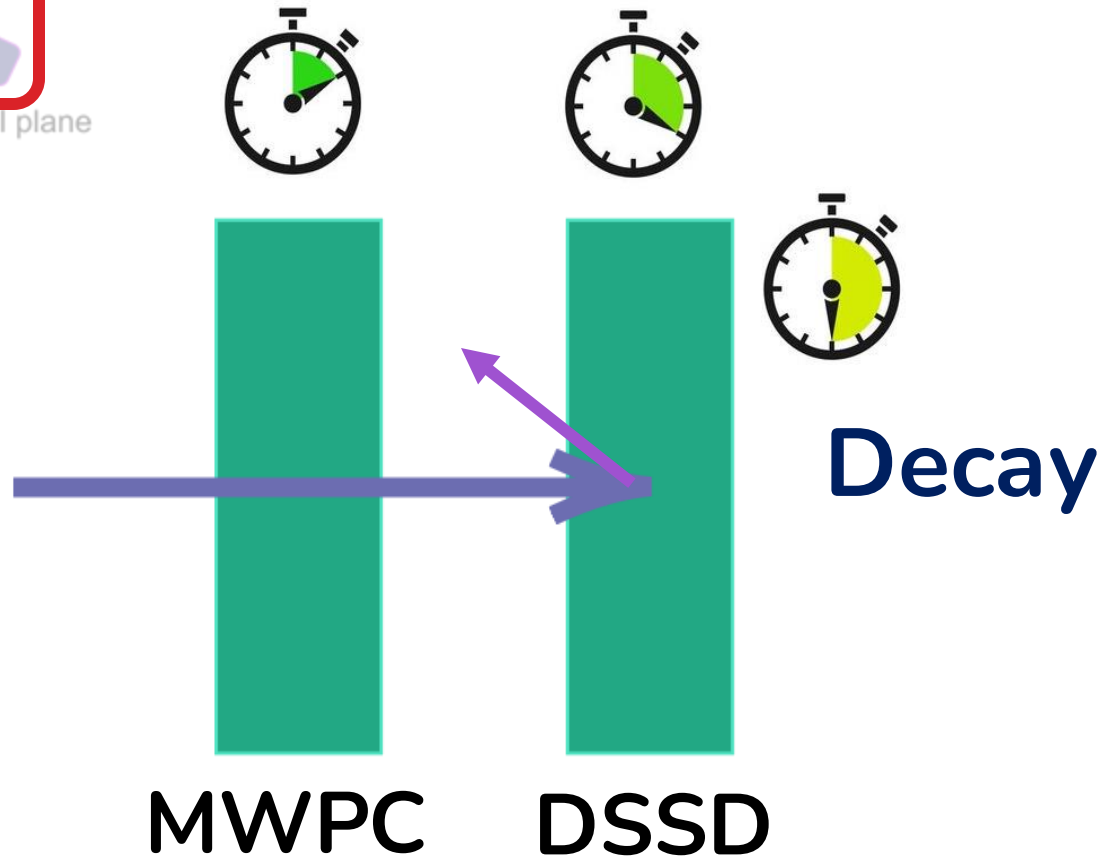
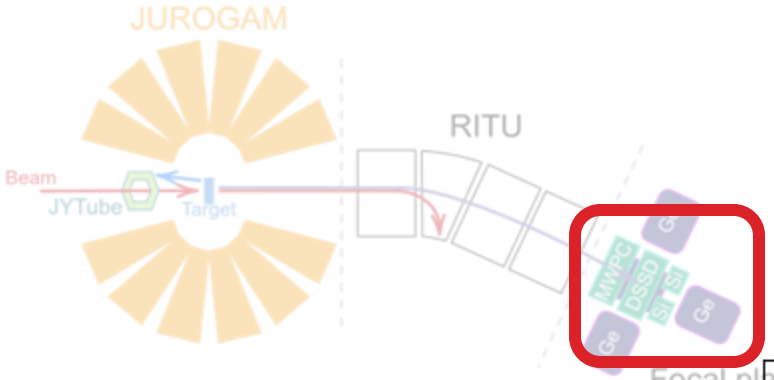
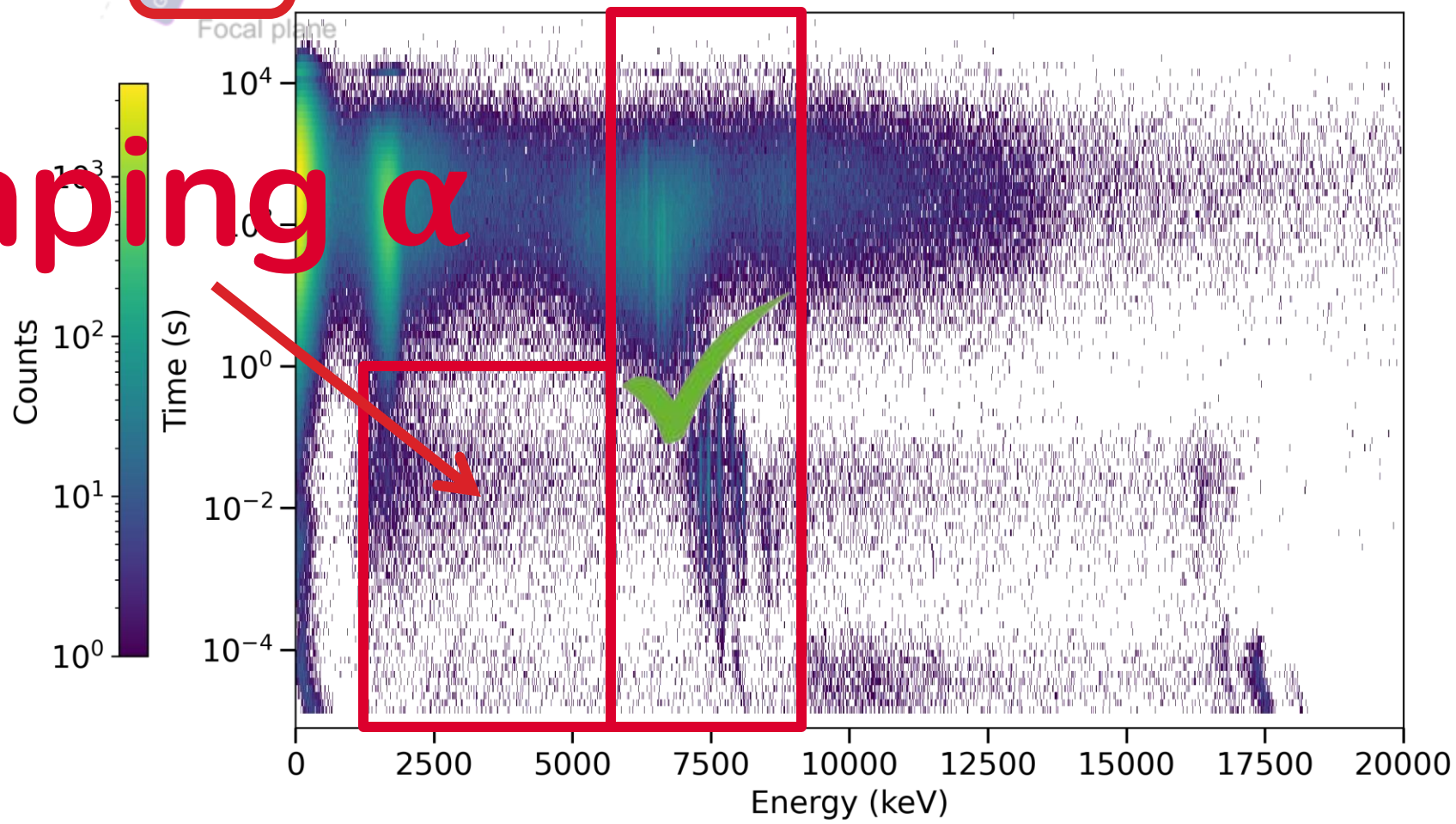
211
213
214
215
216
206
207
208
205
Recoil-gated α − γ
Recoil-gated α − α
Recoil-gated α
Stable
Target


JUROGAM
RITU
Beam
JYTube
Target
MWPC
DSSD
Si
Si
Ge
Ge
Ge
Focal plane

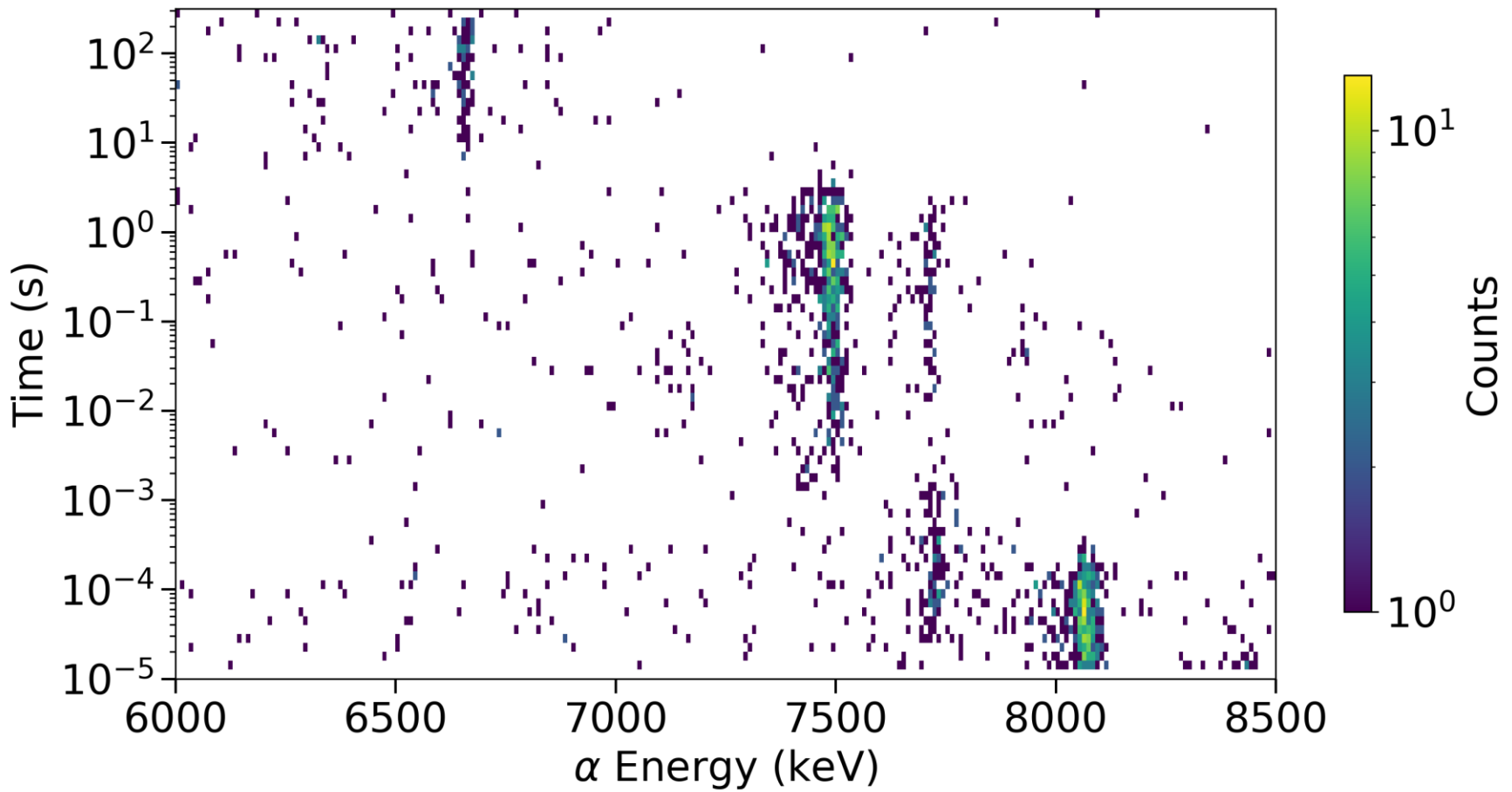

Decay
MWPC
DSSD

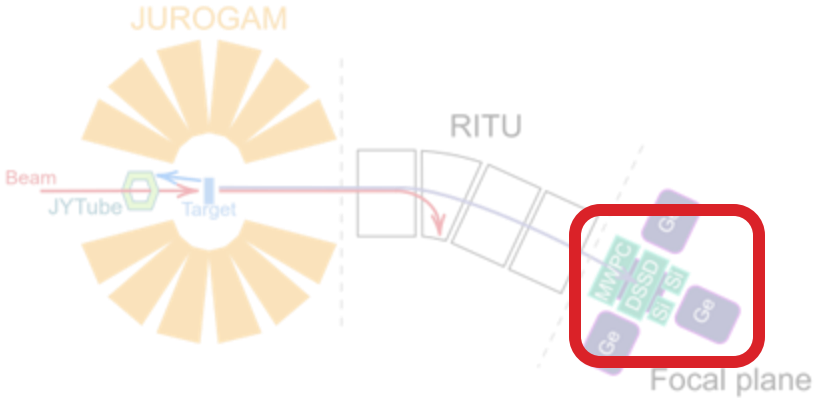

JUROGAM
RITU
Beam
JYTube
Target
MWPC
DSSD
Si
Si
Ge
Ge
Ge
Focal plane

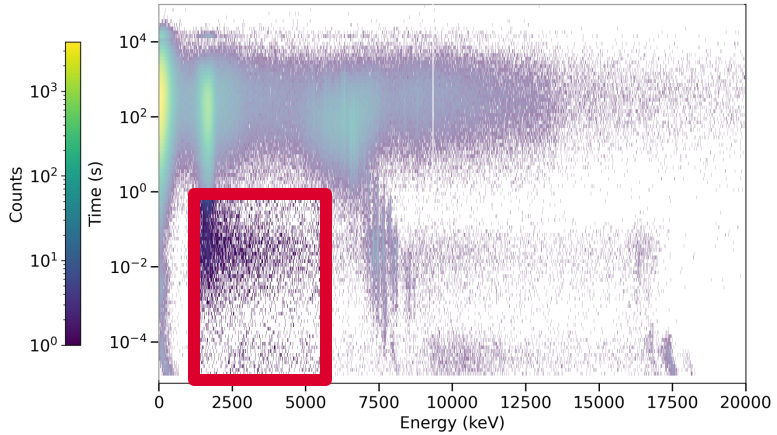
Escaping α

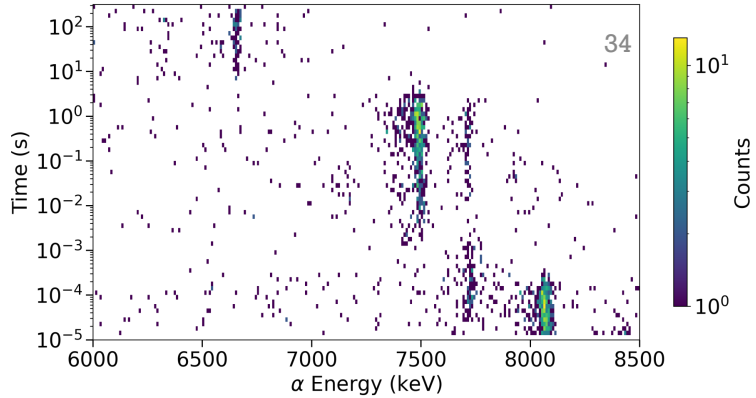

Counts
Time (s)
10^4
10^3
10^2
10^1
10^0
10^0
10^{-2}
10^{-4}
0
2500
5000
7500
10000
12500
15000
17500
20000
Energy (keV)

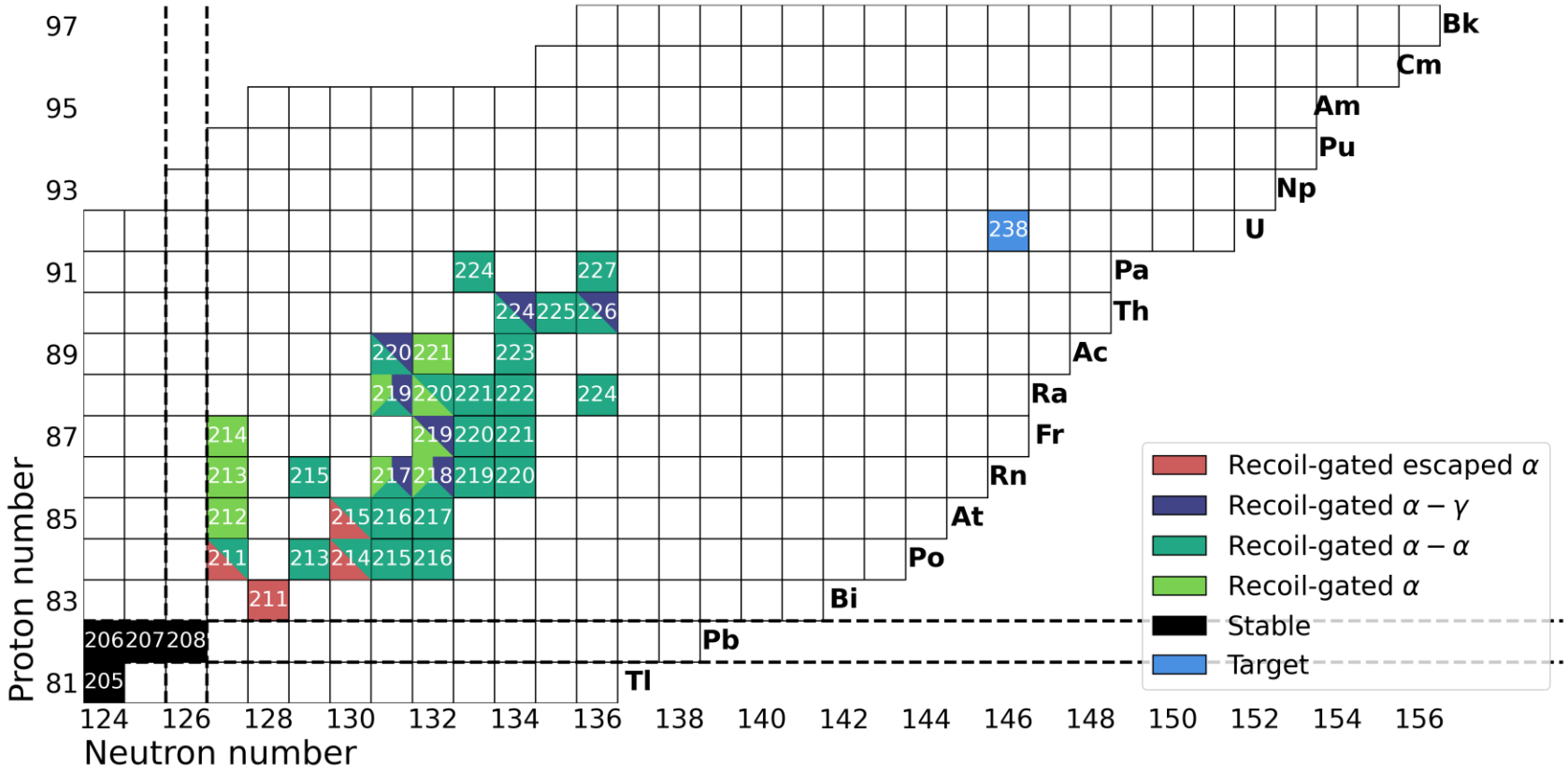
Escaped α correlations

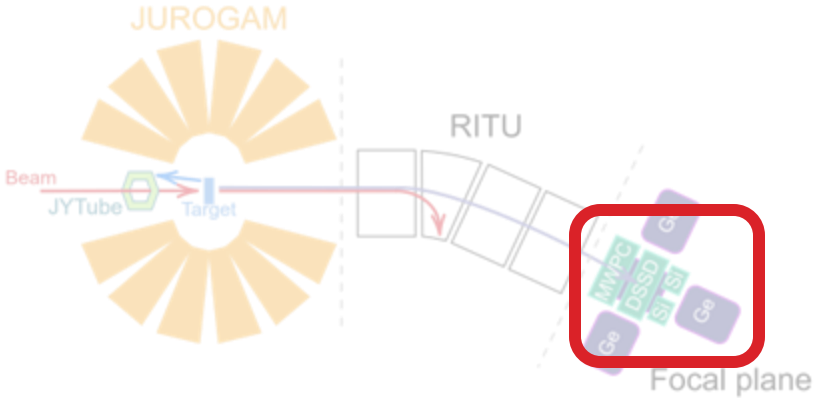


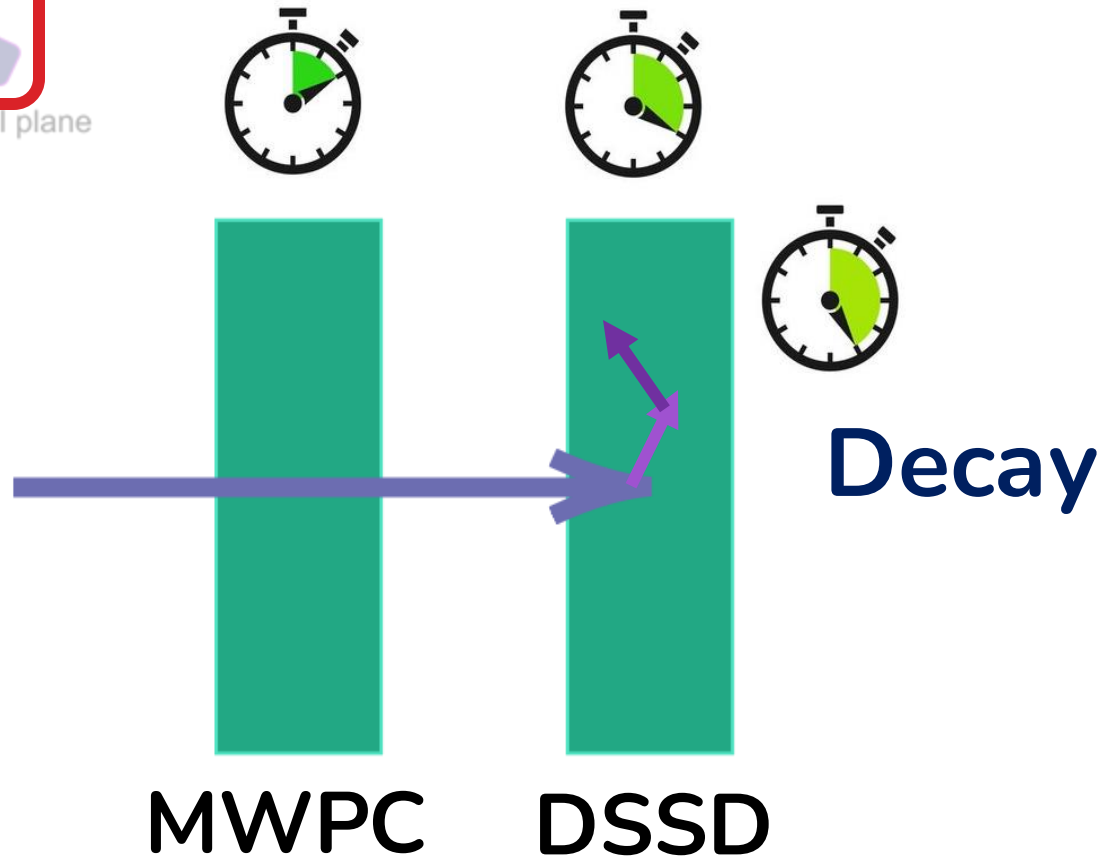

JUROGAM
RITU
Beam
JYTube
Target
MWPC
DSSD
Si
Si
Ge
Ge
Ge
Focal plane

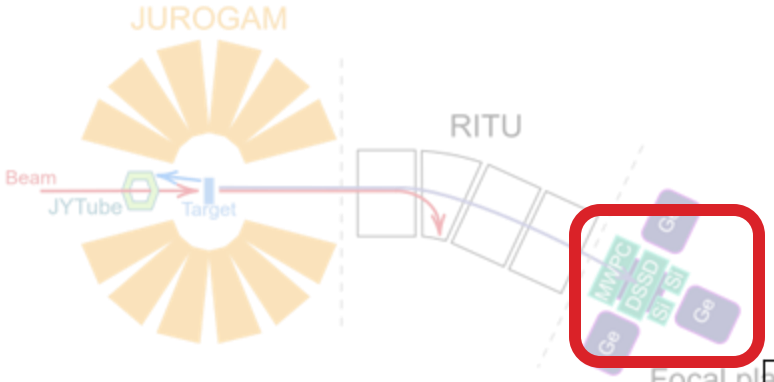

Counts
Time (s)
Energy (keV)


34
Time (s)
Counts
α Energy (keV)

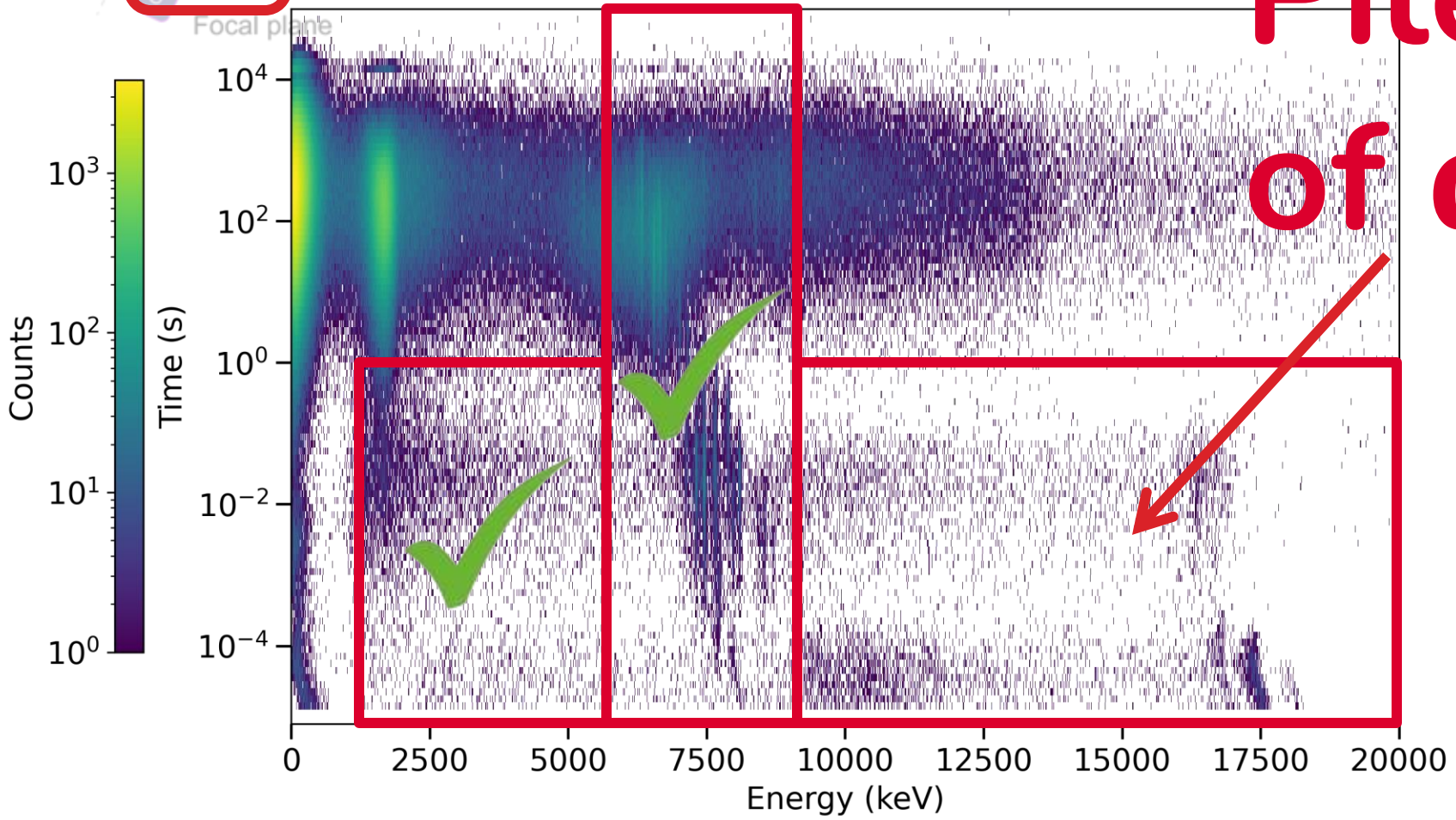

Proton number
Neutron number
Bk
Cm
Am
Pu
Np
U
Pa
Th
Ac
Ra
Fr
Rn
At
Po
Bi
Pb
Tl
Recoil-gated escaped α
Recoil-gated α − γ
Recoil-gated α − α
Recoil-gated α
Stable
Target

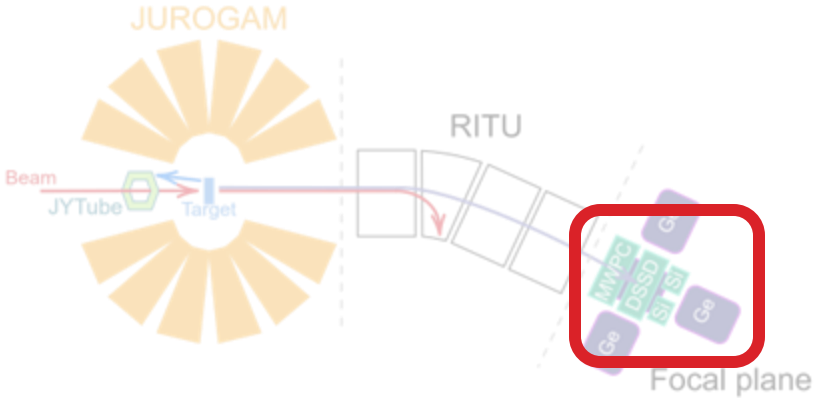

JUROGAM
RITU
Beam
JYTube
Target
MWPC
DSSD
Si
Si
Ge
Ge
Ge
Focal plane

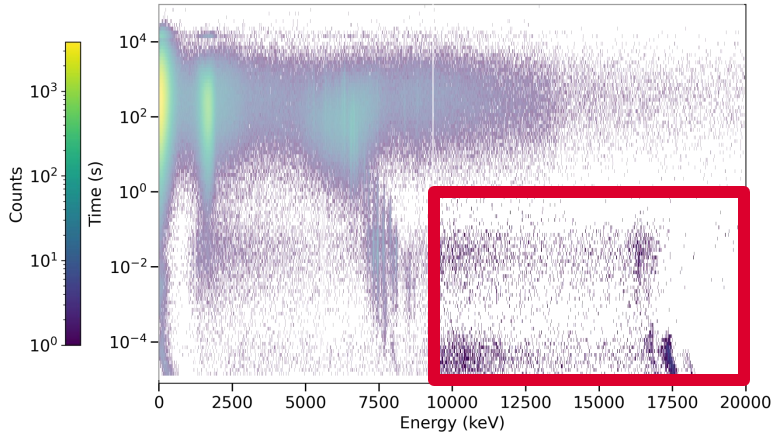

Decay
MWPC
DSSD

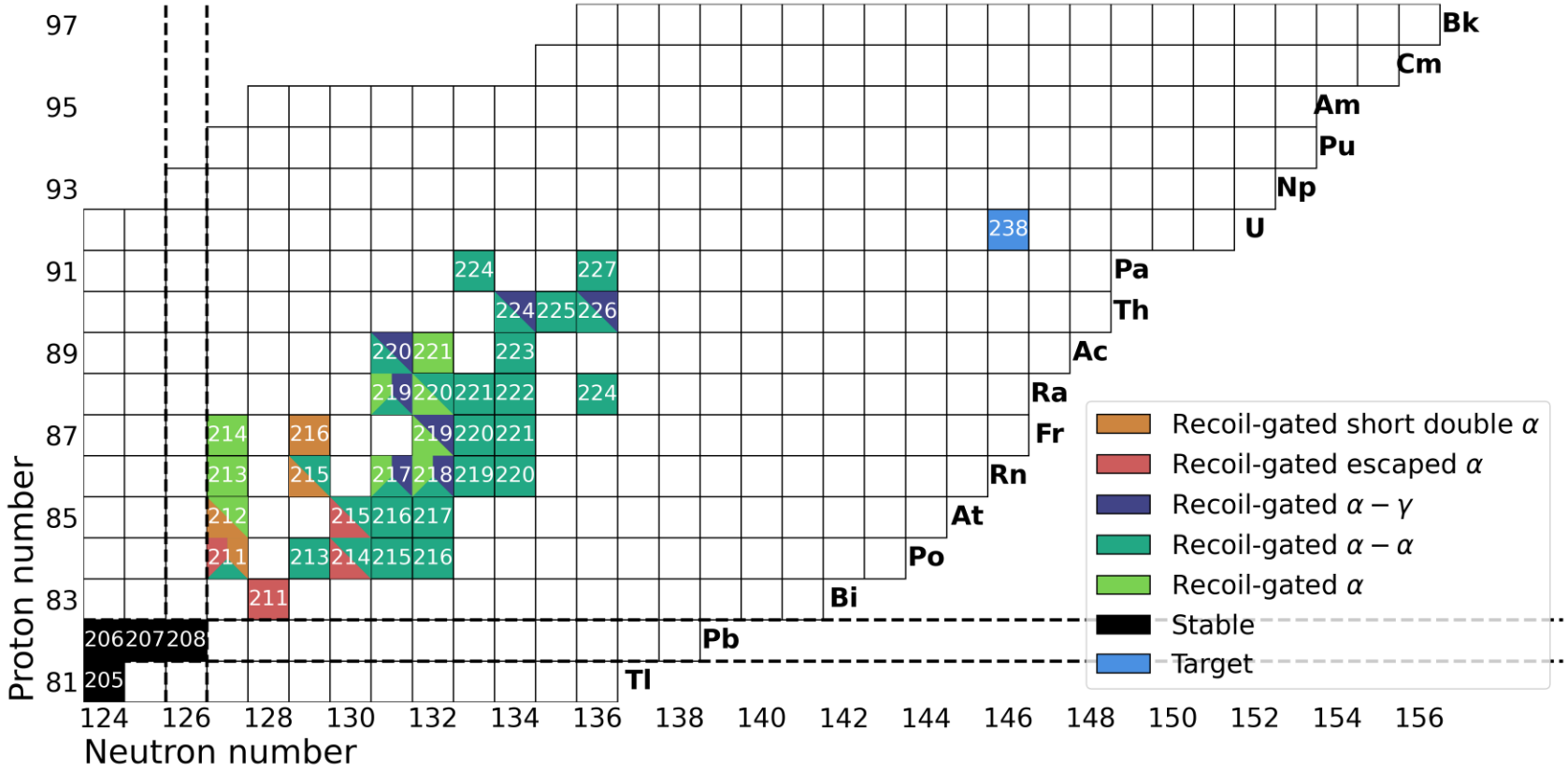

JUROGAM
RITU
Beam
JYTube
Target
MWPC
DSSD
Si
Si
Ge
Ge
Ge
Focal plane

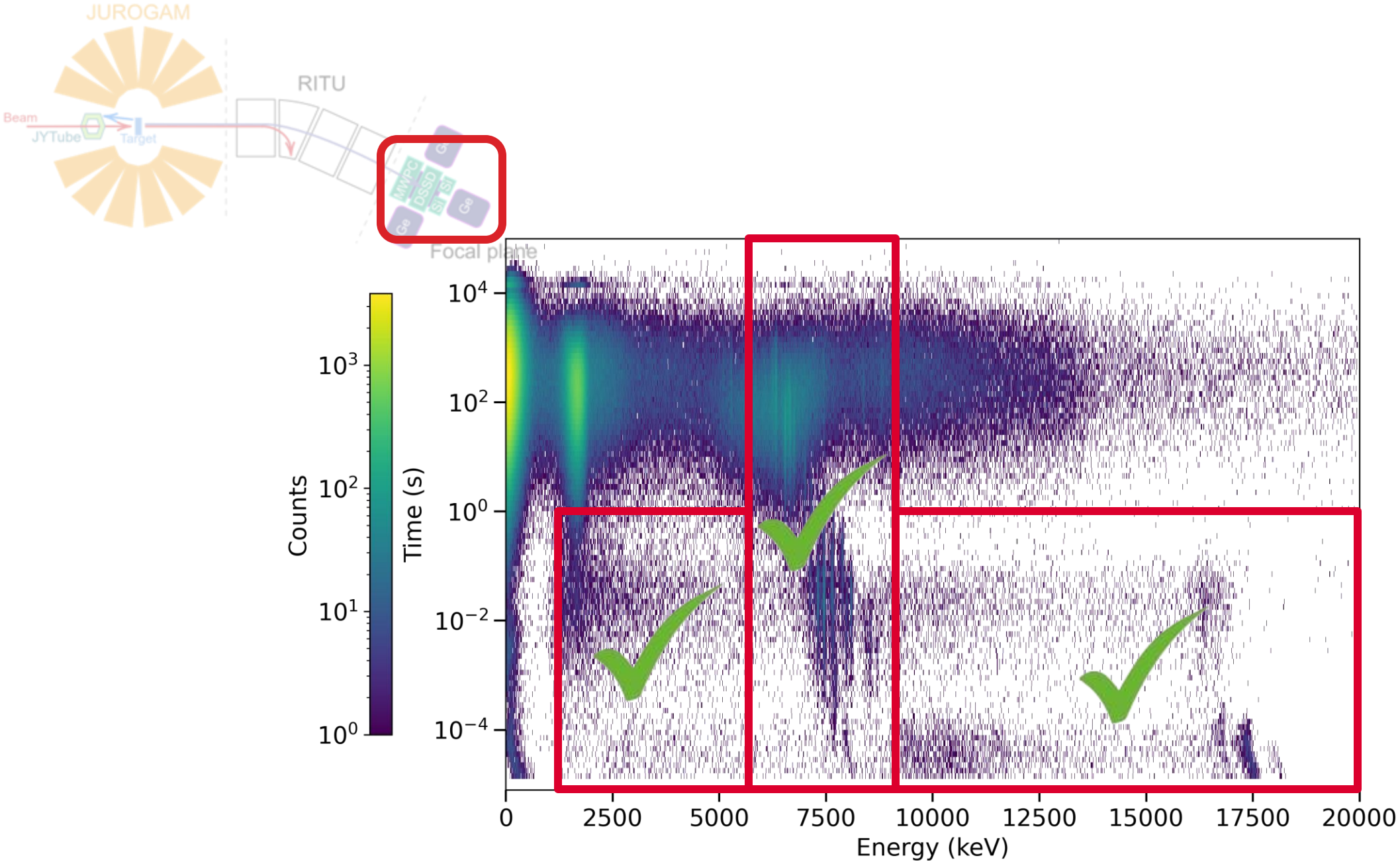
Pile up of α-α

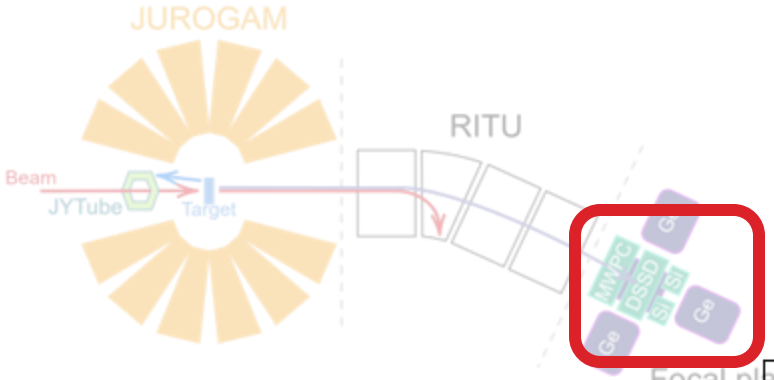

Counts
Time (s)
10^3
10^2
10^1
10^0
10^4
10^2
10^0
10^{-2}
10^{-4}
0
2500
5000
7500
10000
12500
15000
17500
20000
Energy (keV)

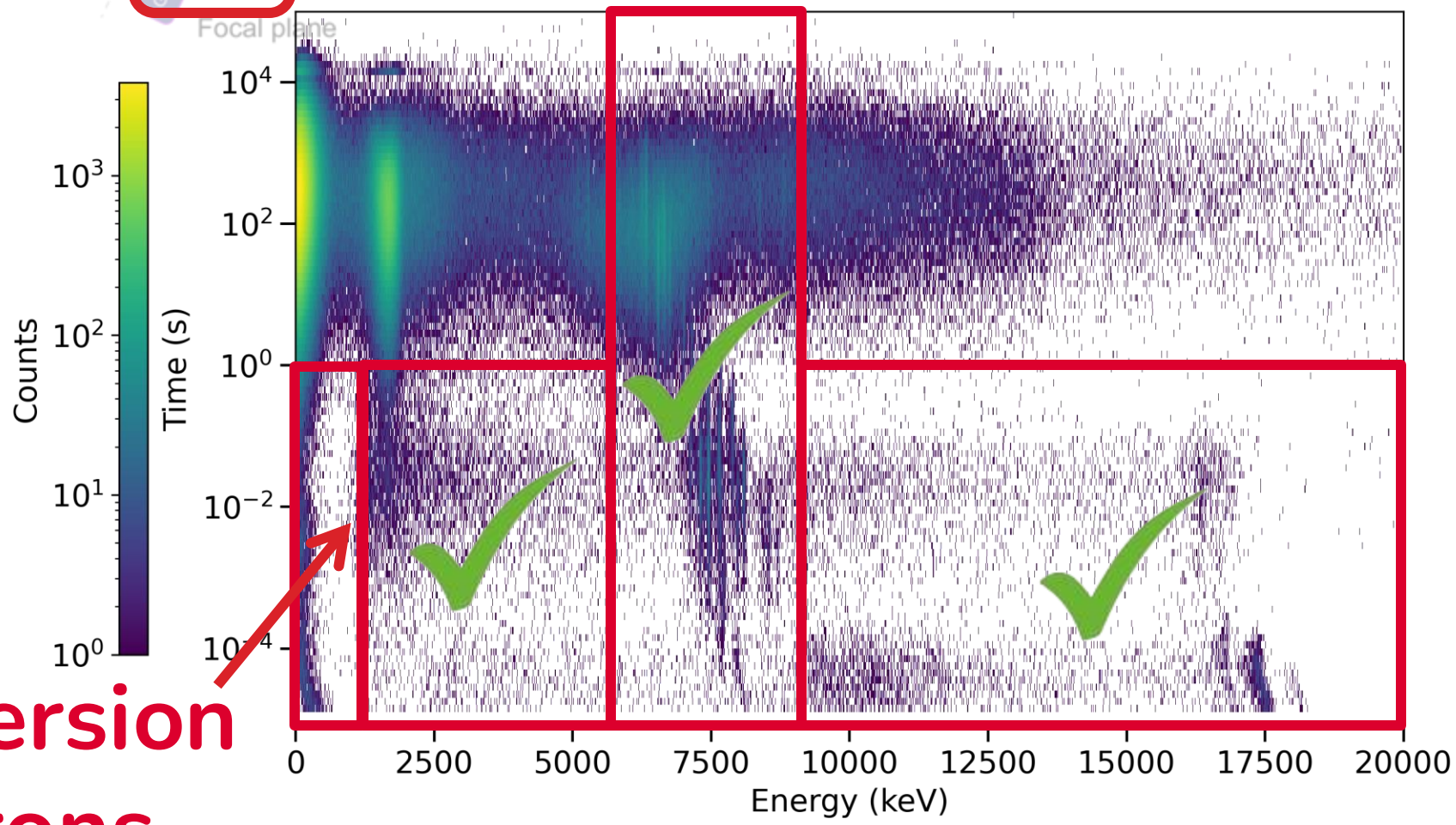

JUROGAM
RITU
Beam
JYTube
Target
MWPC
DSSD
Si
Si
Ge
Ge
Ge
Focal plane


Counts
Time (s)
Energy (keV)

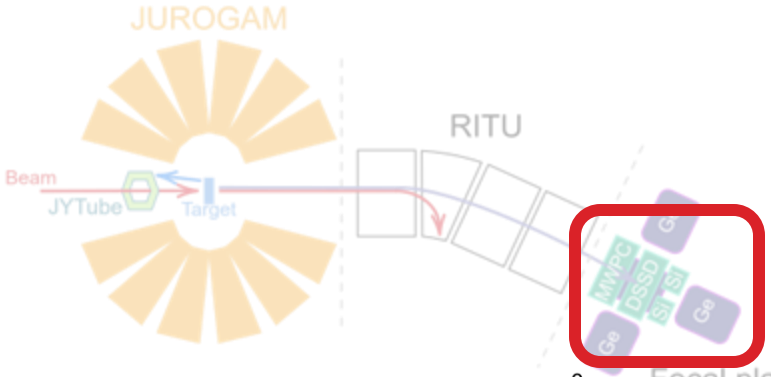

Proton number
Neutron number
Bk
Cm
Am
Pu
Np
U
Pa
Th
Ac
Ra
Fr
Rn
At
Po
Bi
Pb
Tl
Recoil-gated short double α
Recoil-gated escaped α
Recoil-gated α − γ
Recoil-gated α − α
Recoil-gated α
Stable
Target

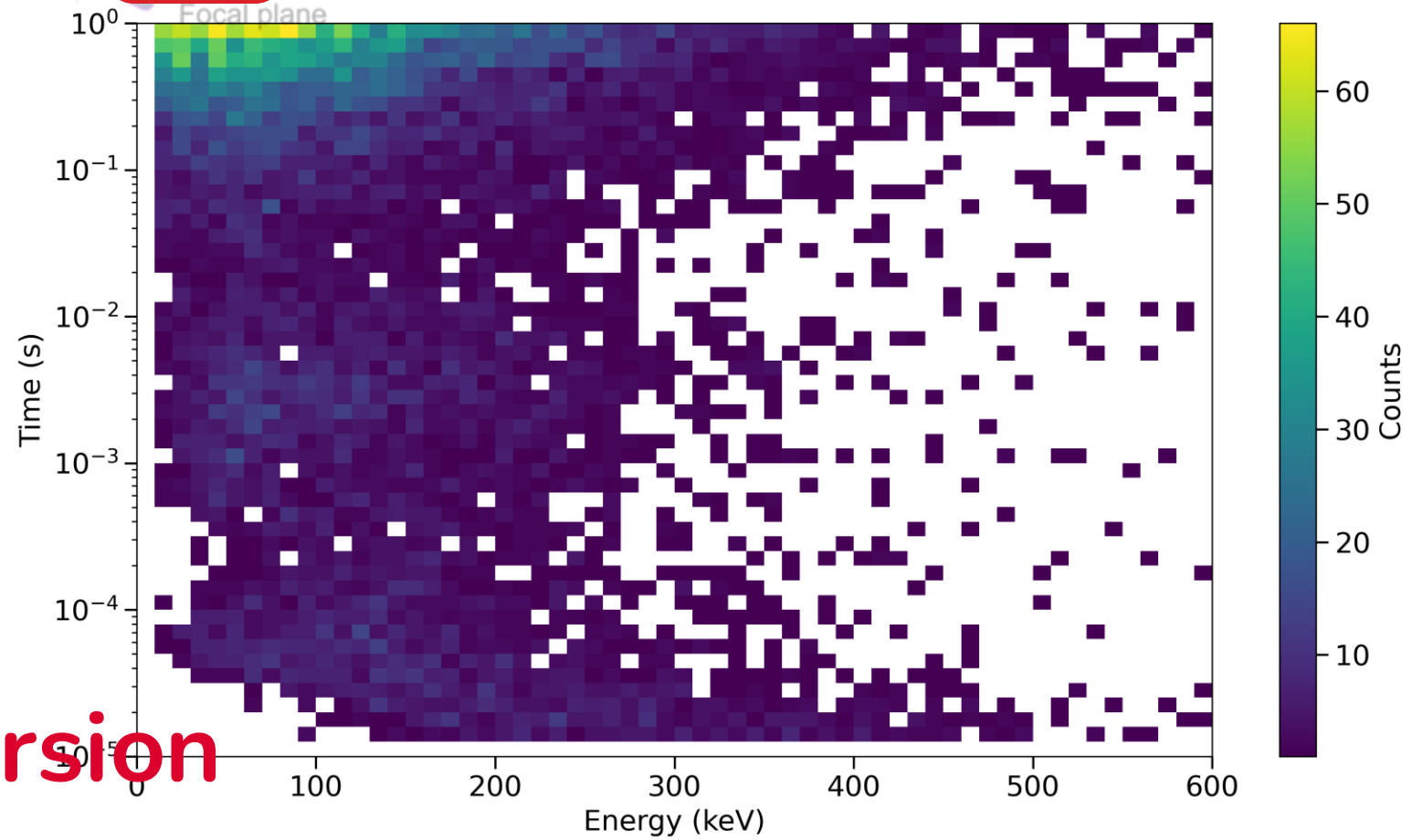

JUROGAM
RITU
Beam
JYTube
Target
MWPC
DSSD
Si
Si
Ge
Ge
Ge
Focal plane
Counts
10^3
10^2
10^1
10^0
Time (s)
10^4
10^2
10^0
10^{-2}
10^{-4}
0
2500
5000
7500
10000
12500
15000
17500
20000
Energy (keV)





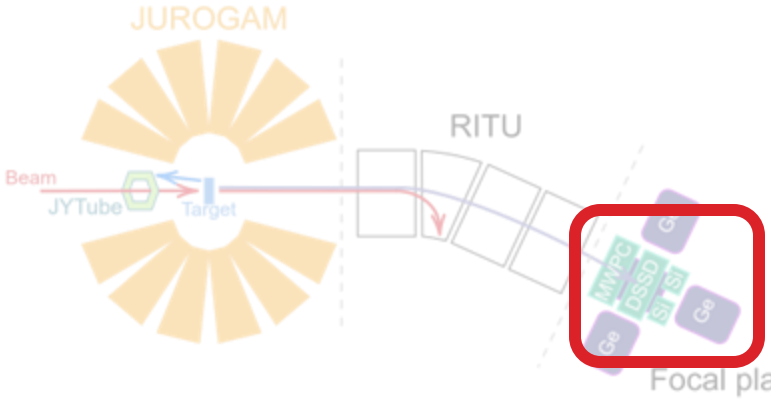
Conversion electrons

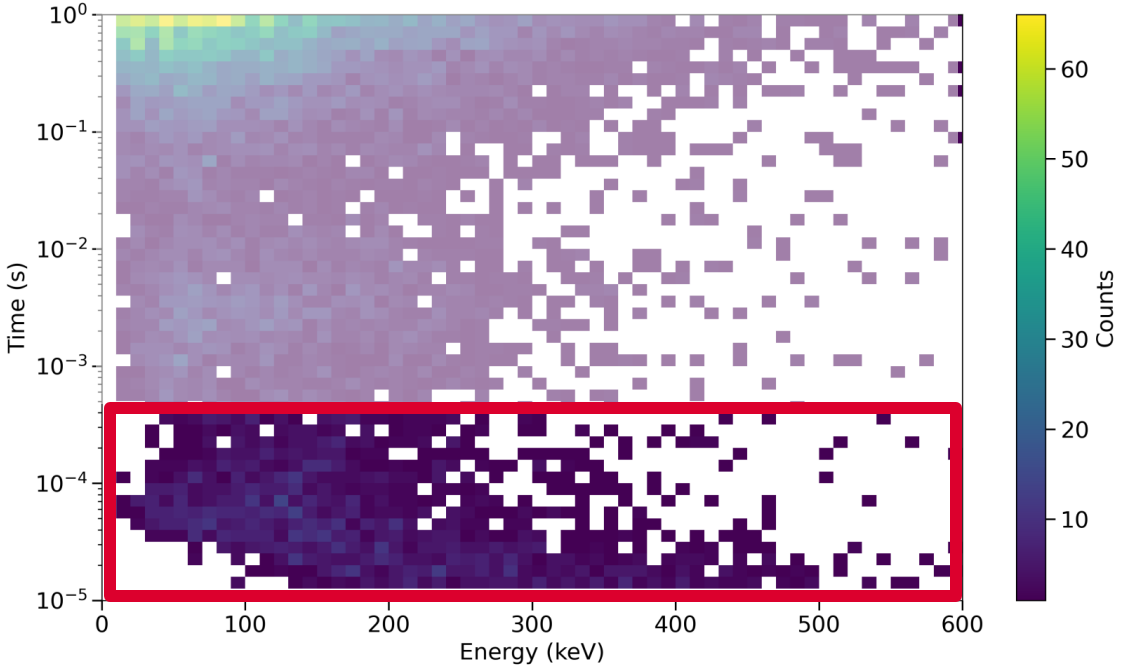


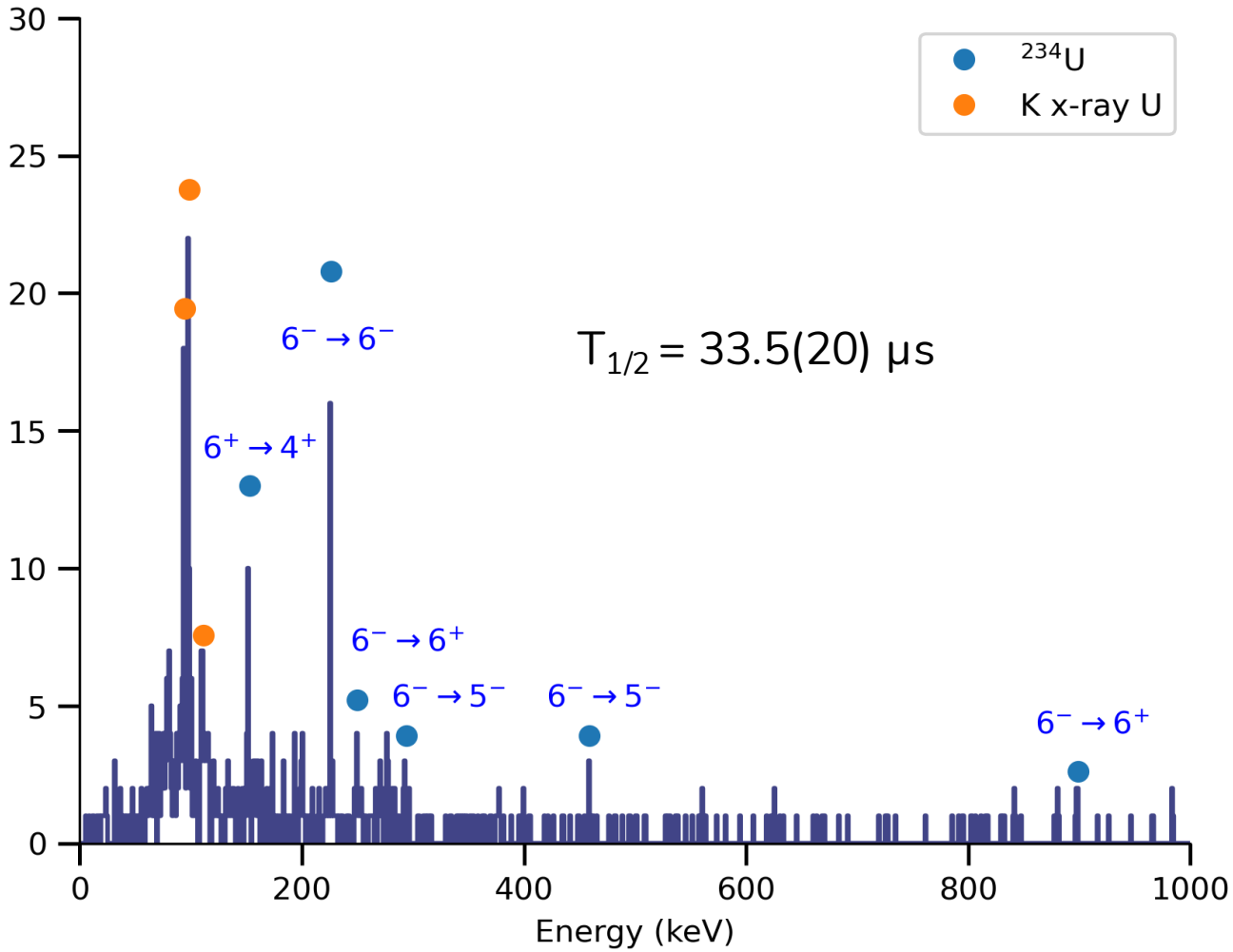


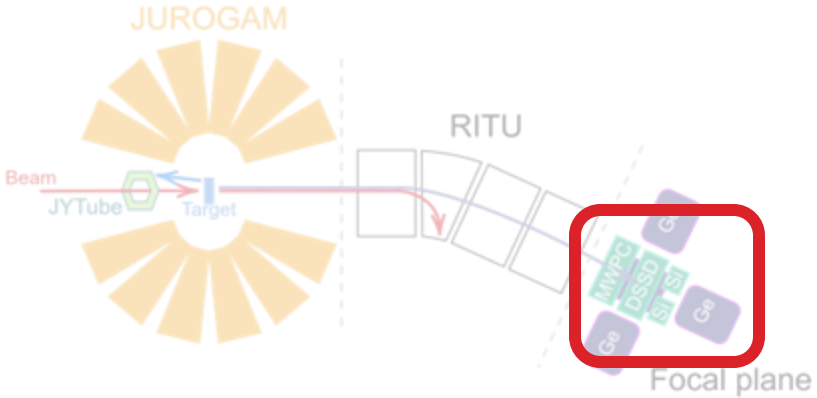
Conversion electrons

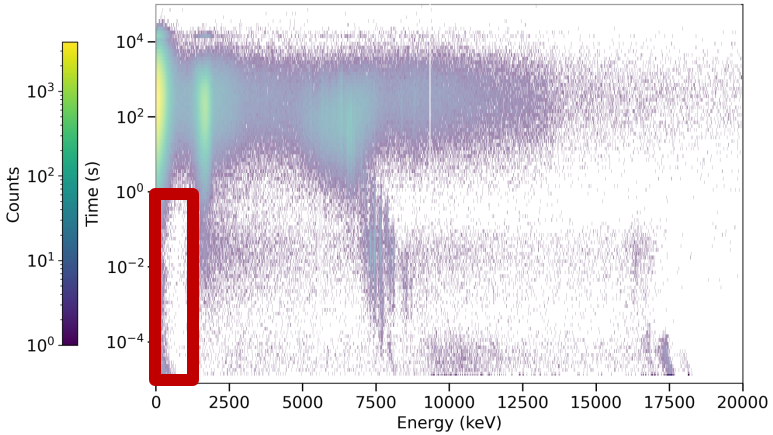
CE - γ correlations

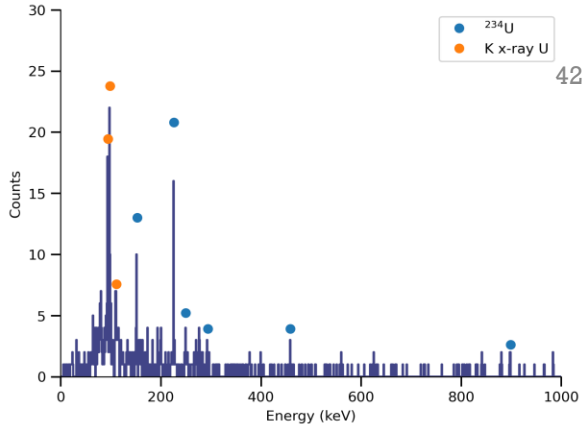


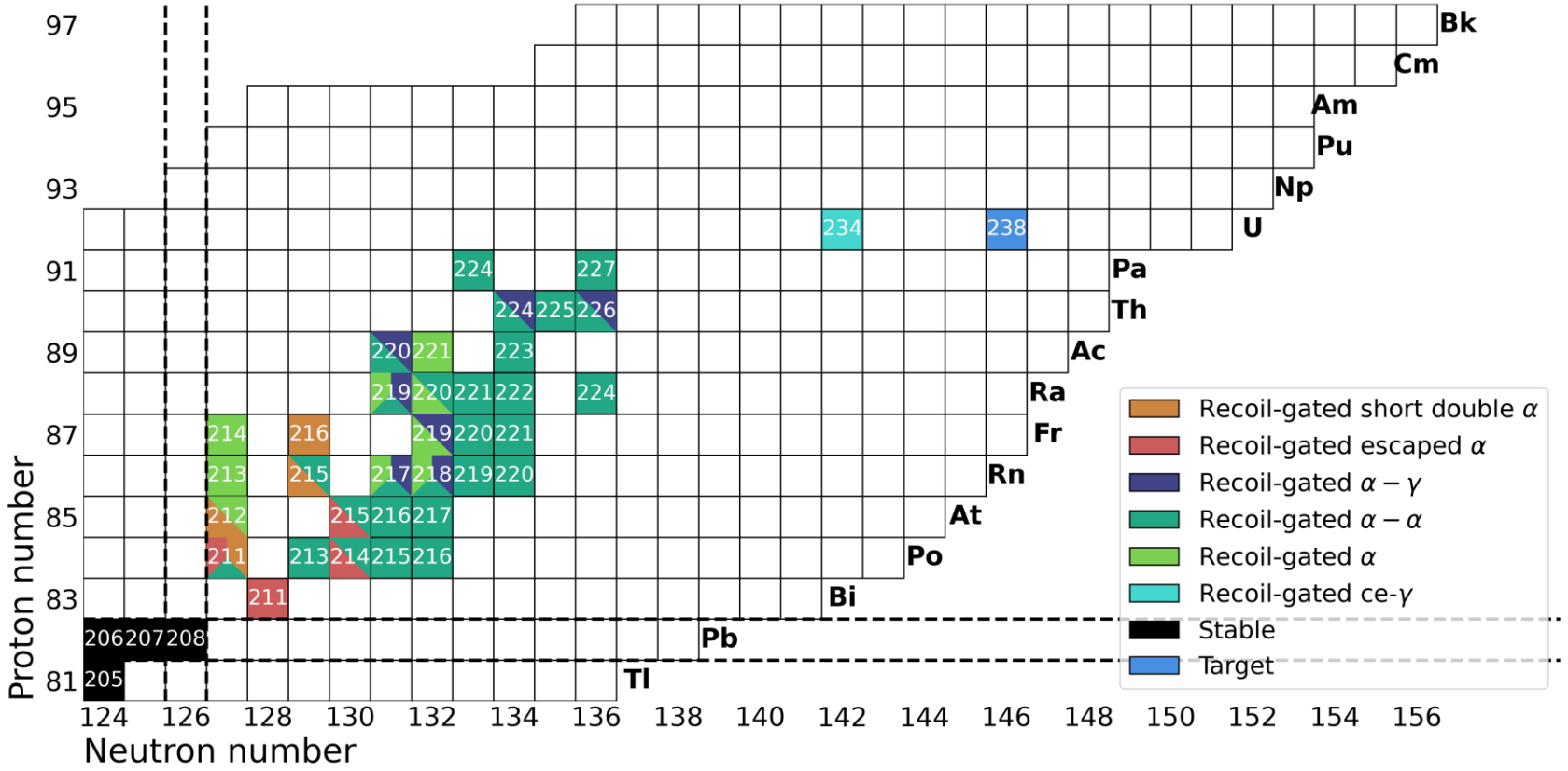


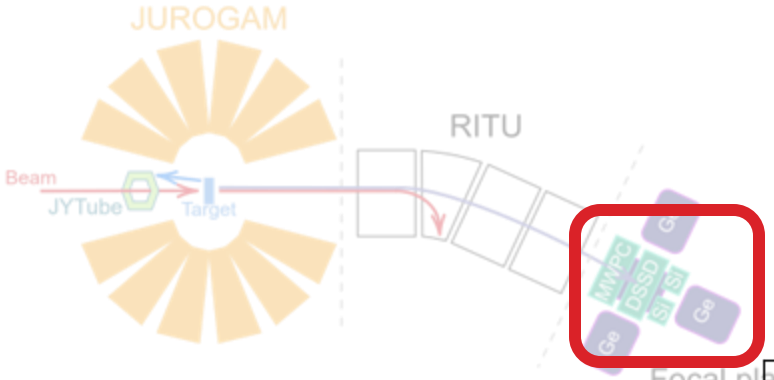


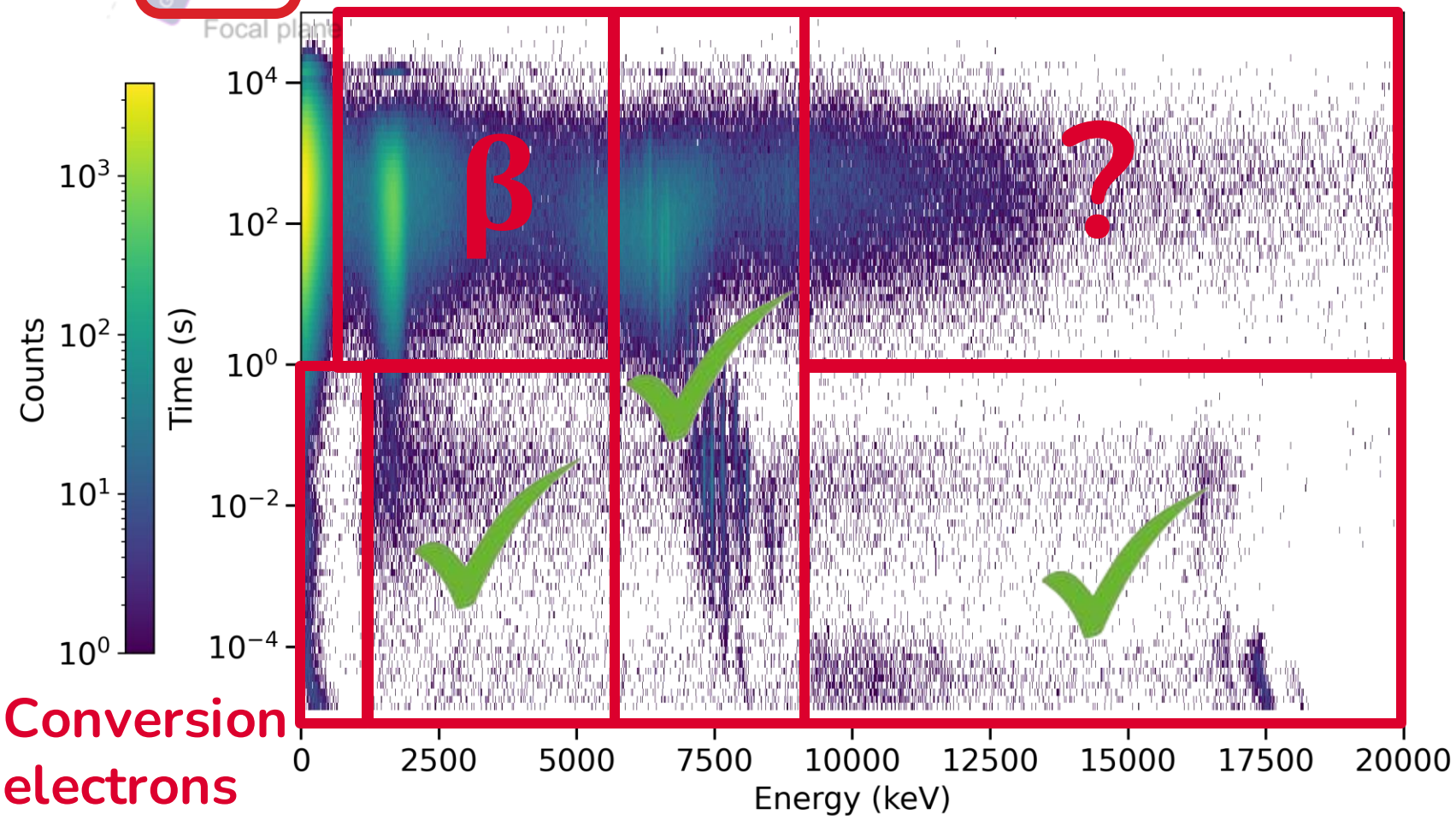

JUROGAM
RITU
Beam
JYTube
Target
MWPC
DSSD
Si
Si
Ge
Ge
Ge
Focal plane


Counts
Time (s)
Energy (keV)

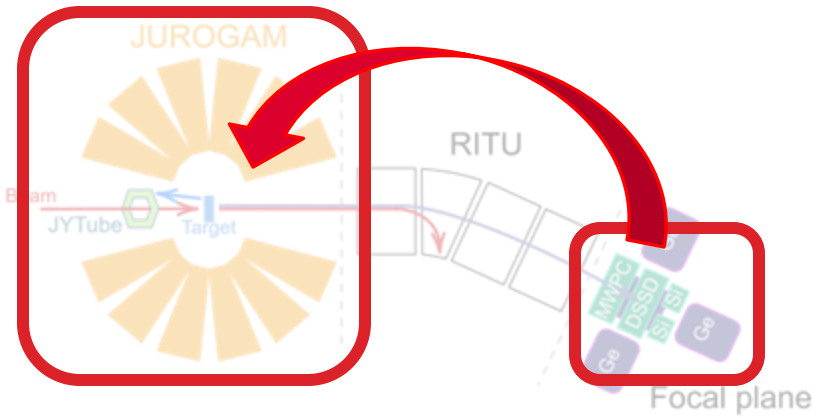

234U
K x-ray U
Counts
Energy (keV)

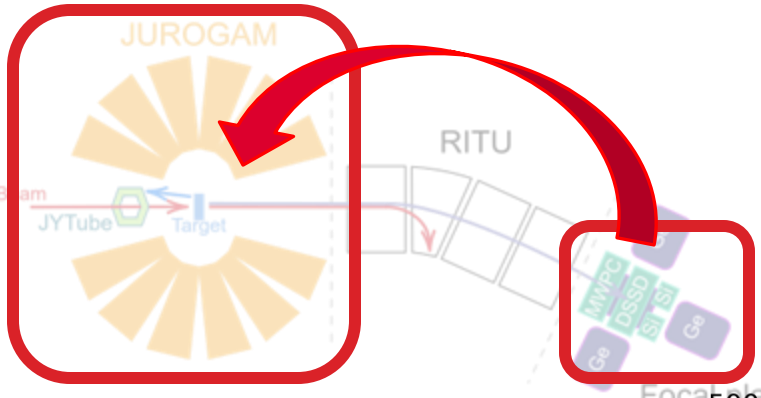

Proton number
Neutron number
Bk
Cm
Am
Pu
Np
U
Pa
Th
Ac
Ra
Fr
Rn
At
Po
Bi
Pb
Tl
Recoil-gated short double α
Recoil-gated escaped α
Recoil-gated α − γ
Recoil-gated α − α
Recoil-gated α
Recoil-gated ce-γ
Stable
Target



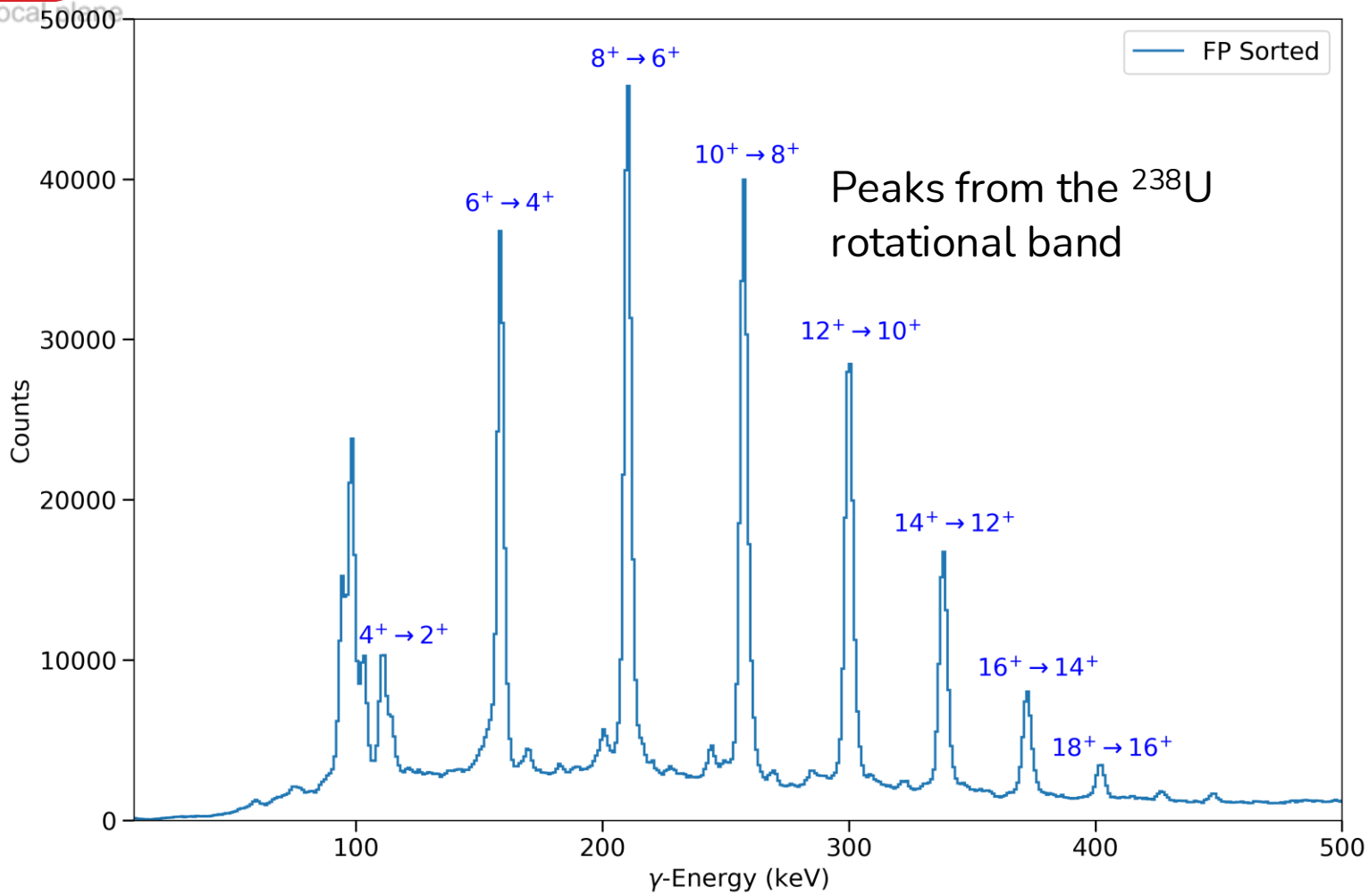


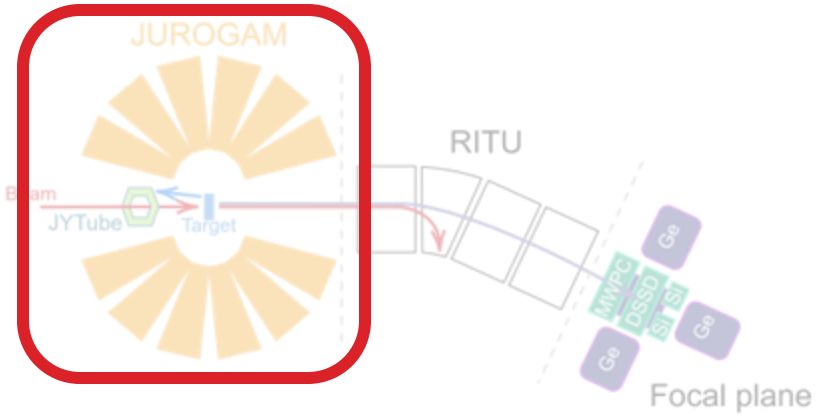
Conversion electrons


JUROGAM
RITU
Beam
JYTube
Target
MWPC
DSSD
Si
Si
Ge
Ge
Focal plane

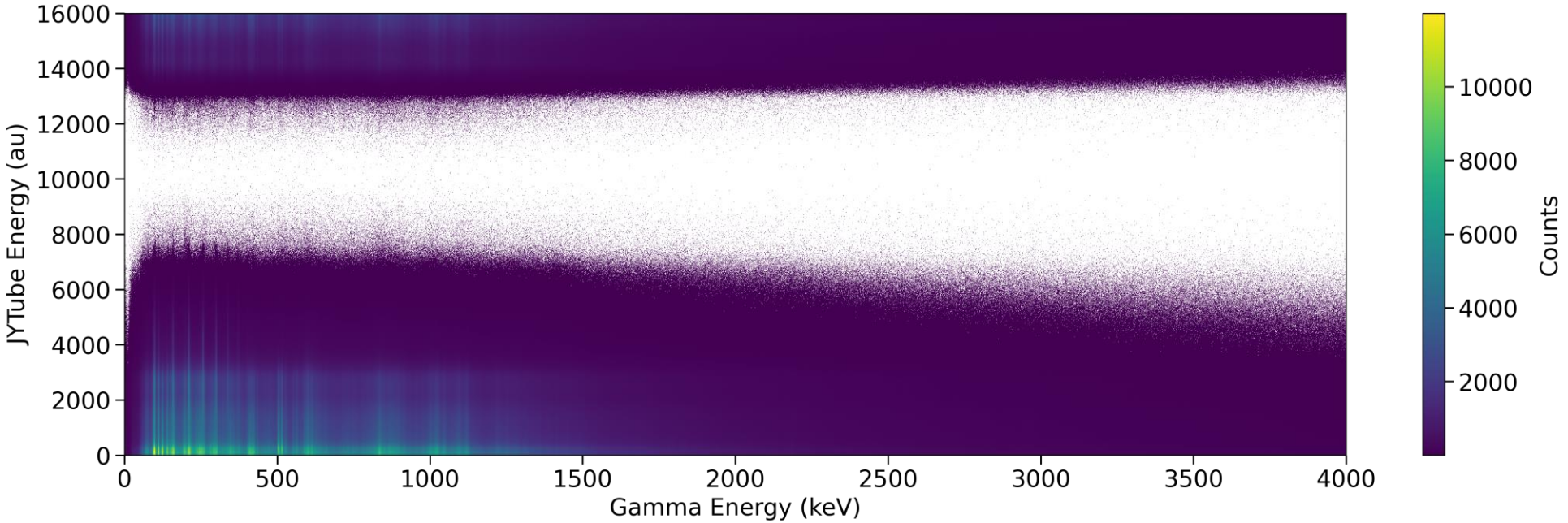


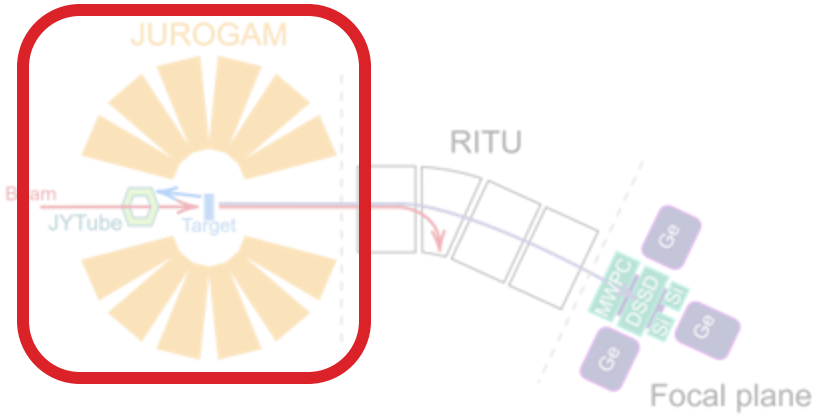
Recoil – prompt γ



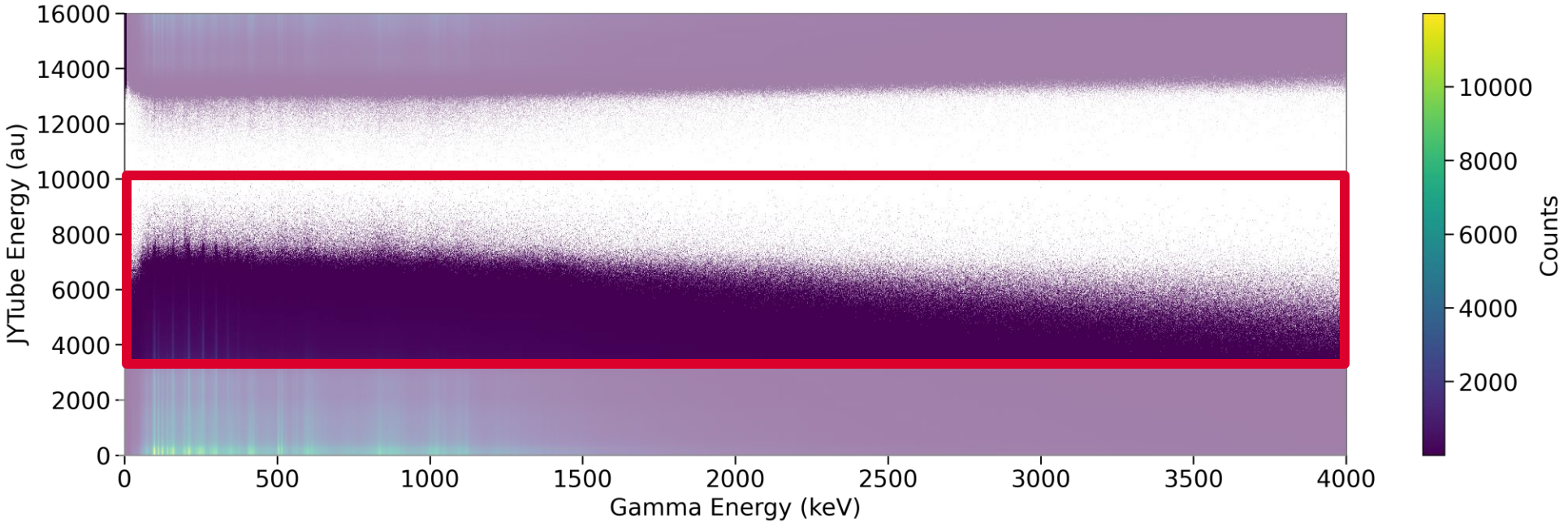


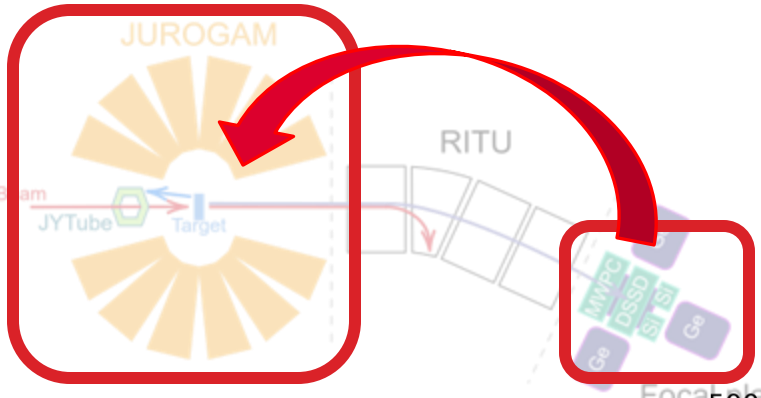
JUROGAM vs. JYTube



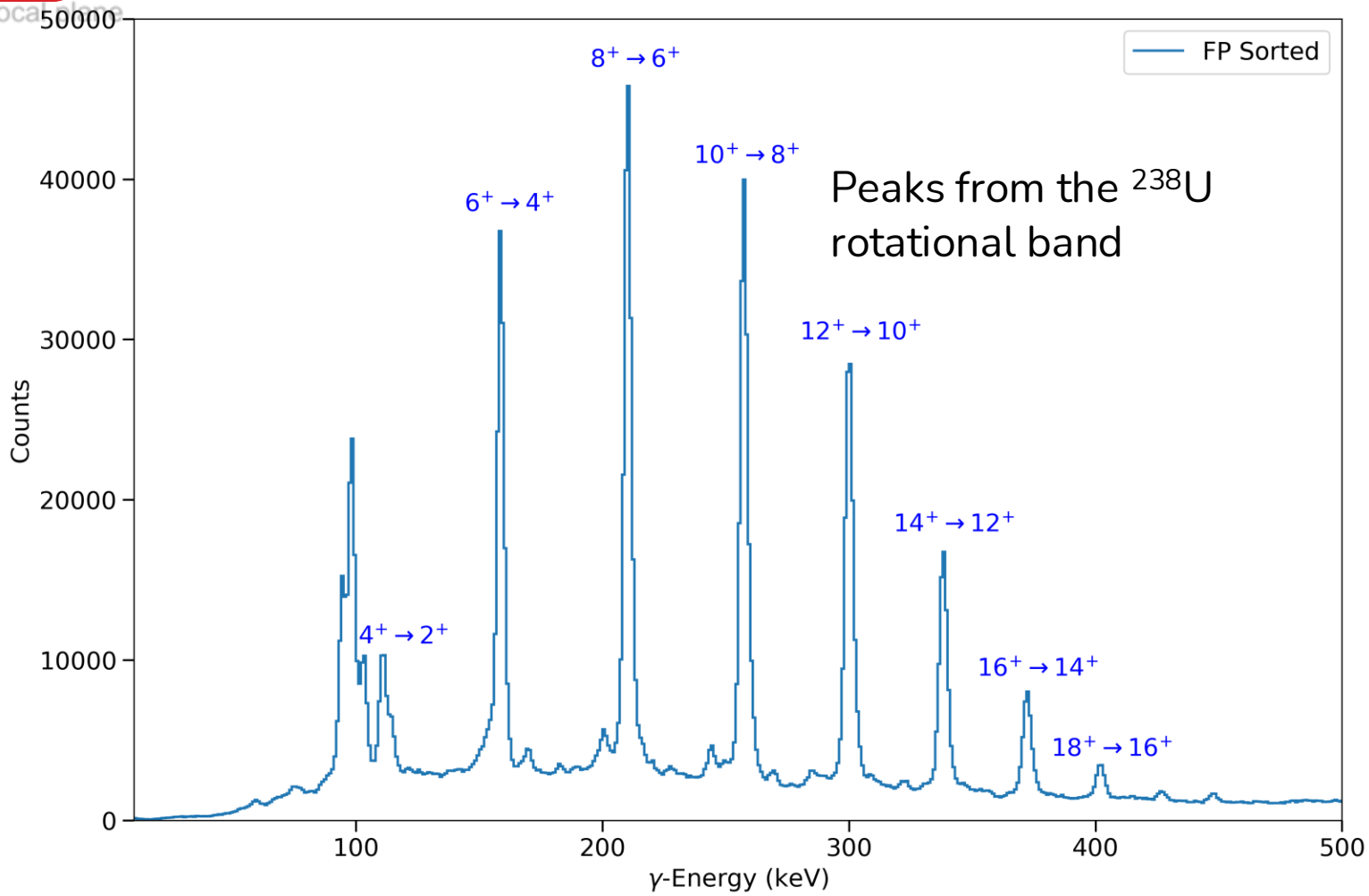


JUROGAM vs. JYTube

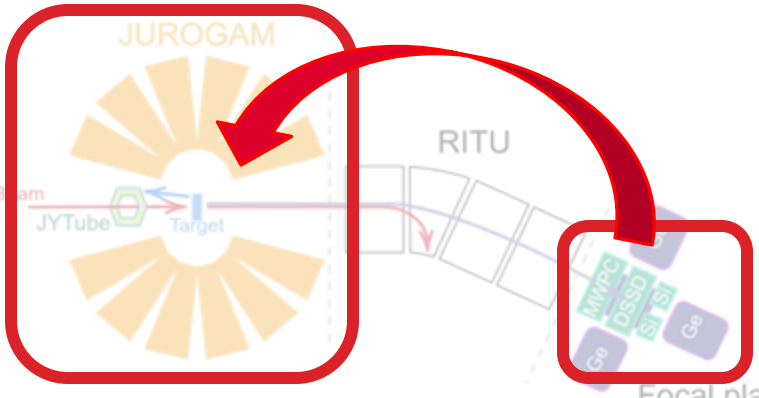


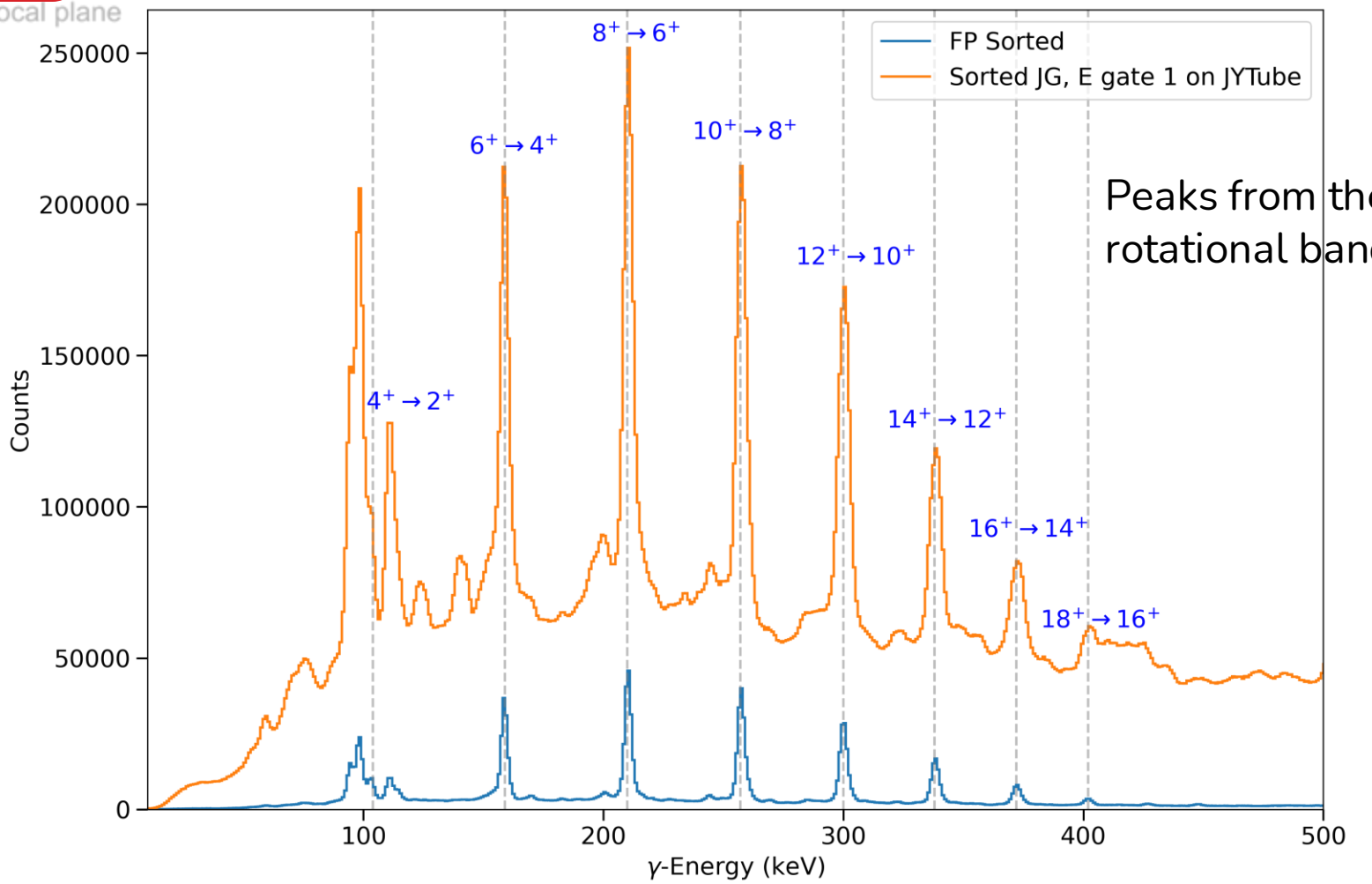


Recoil – prompt γ

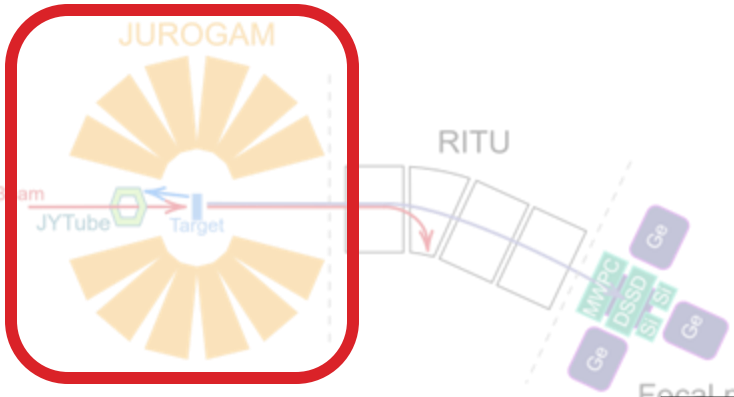


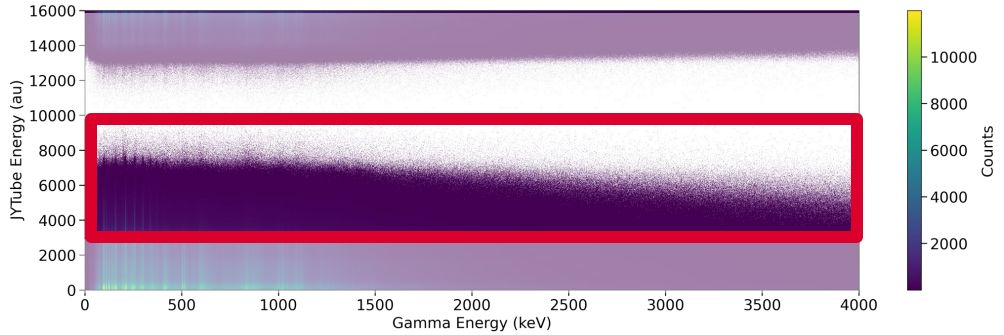
Prompt γ

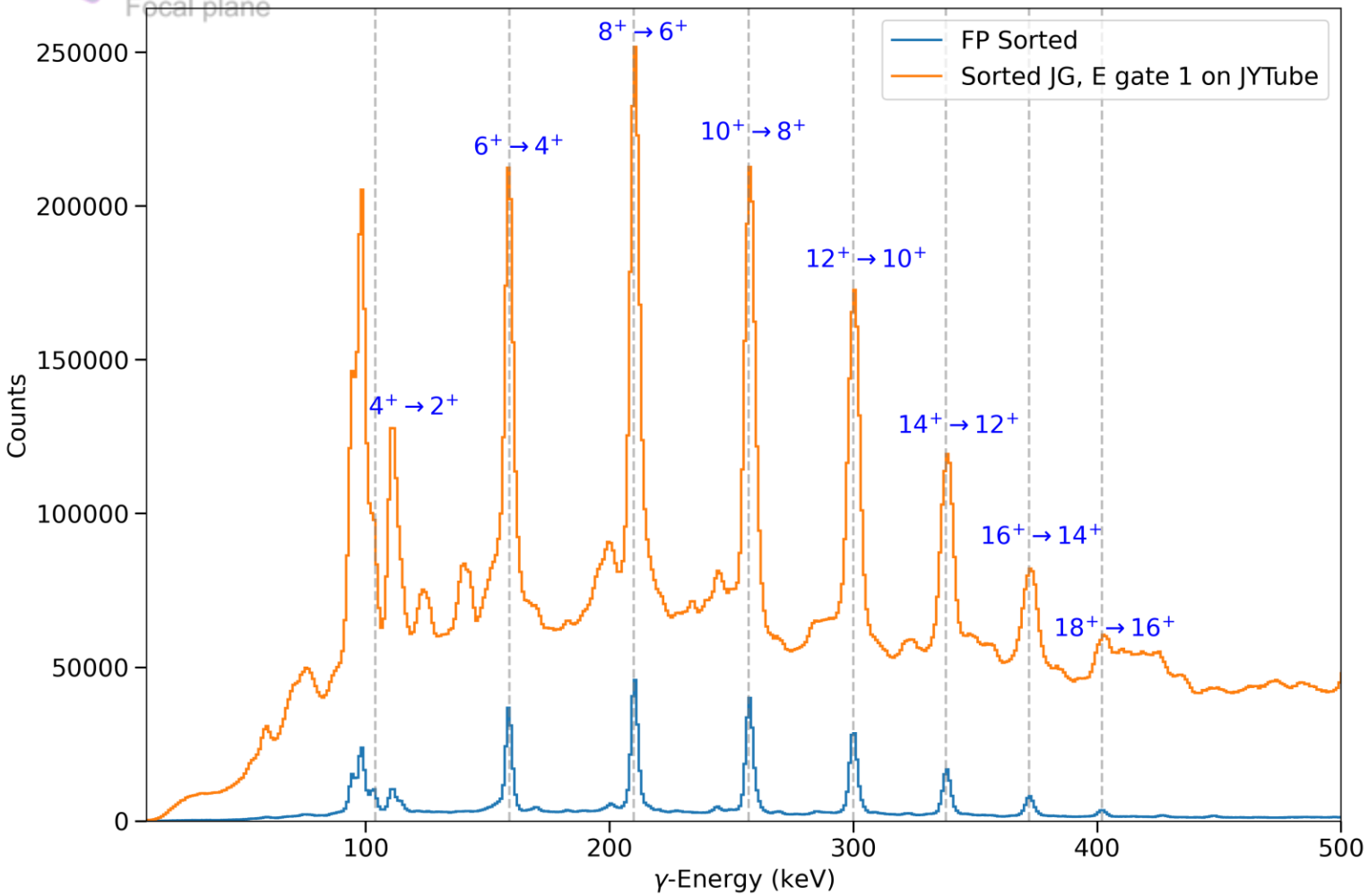


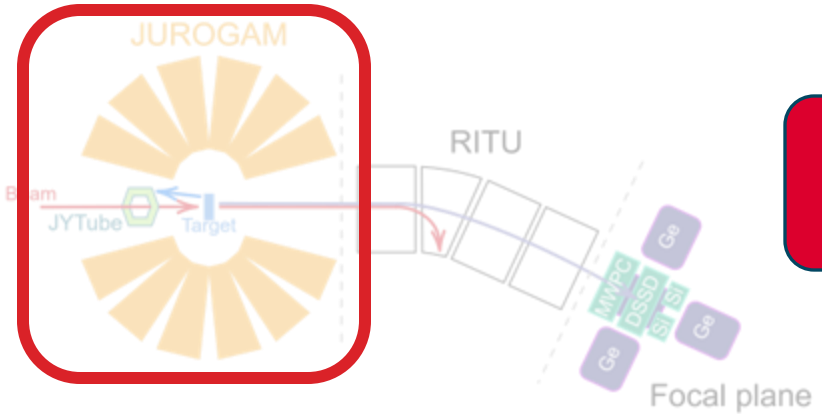


Peaks from the ^{238}U rotational band

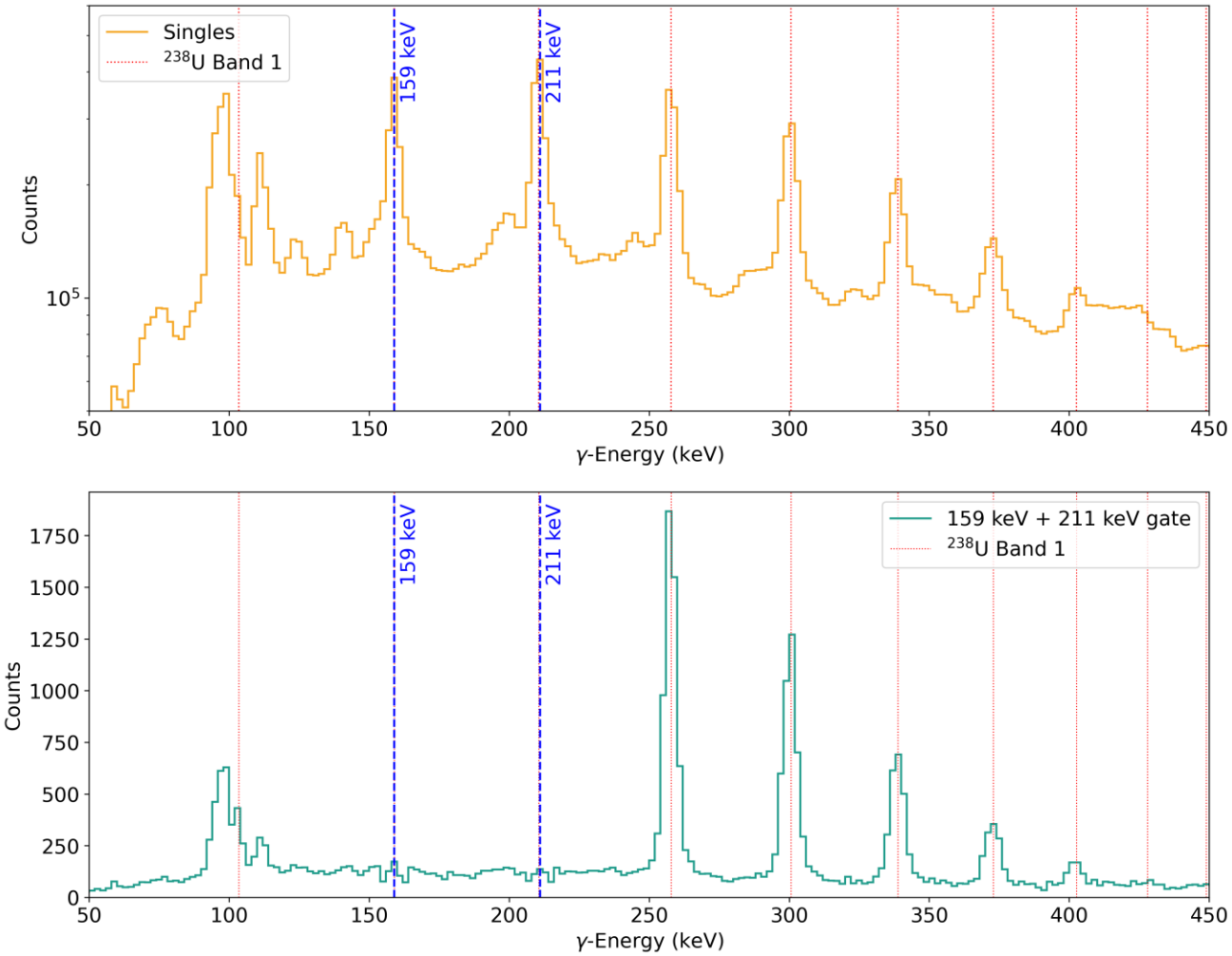

JUROGAM
RITU
Beam
JYTube
Target
Ge
MWPC
DSSD
Si
Si
Ge
Ge
Focal plane

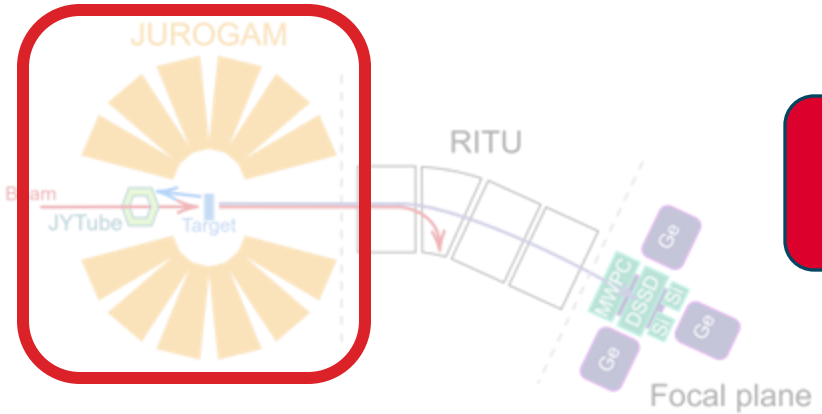

JYTube Energy (au)
Gamma Energy (keV)
Counts


FP Sorted
Sorted JG, E gate 1 on JYTube
$8^+ \rightarrow 6^+$
$6^+ \rightarrow 4^+$
$10^+ \rightarrow 8^+$
$12^+ \rightarrow 10^+$
$4^+ \rightarrow 2^+$
$14^+ \rightarrow 12^+$
$16^+ \rightarrow 14^+$
$18^+ \rightarrow 16^+$
Counts
γ-Energy (keV)

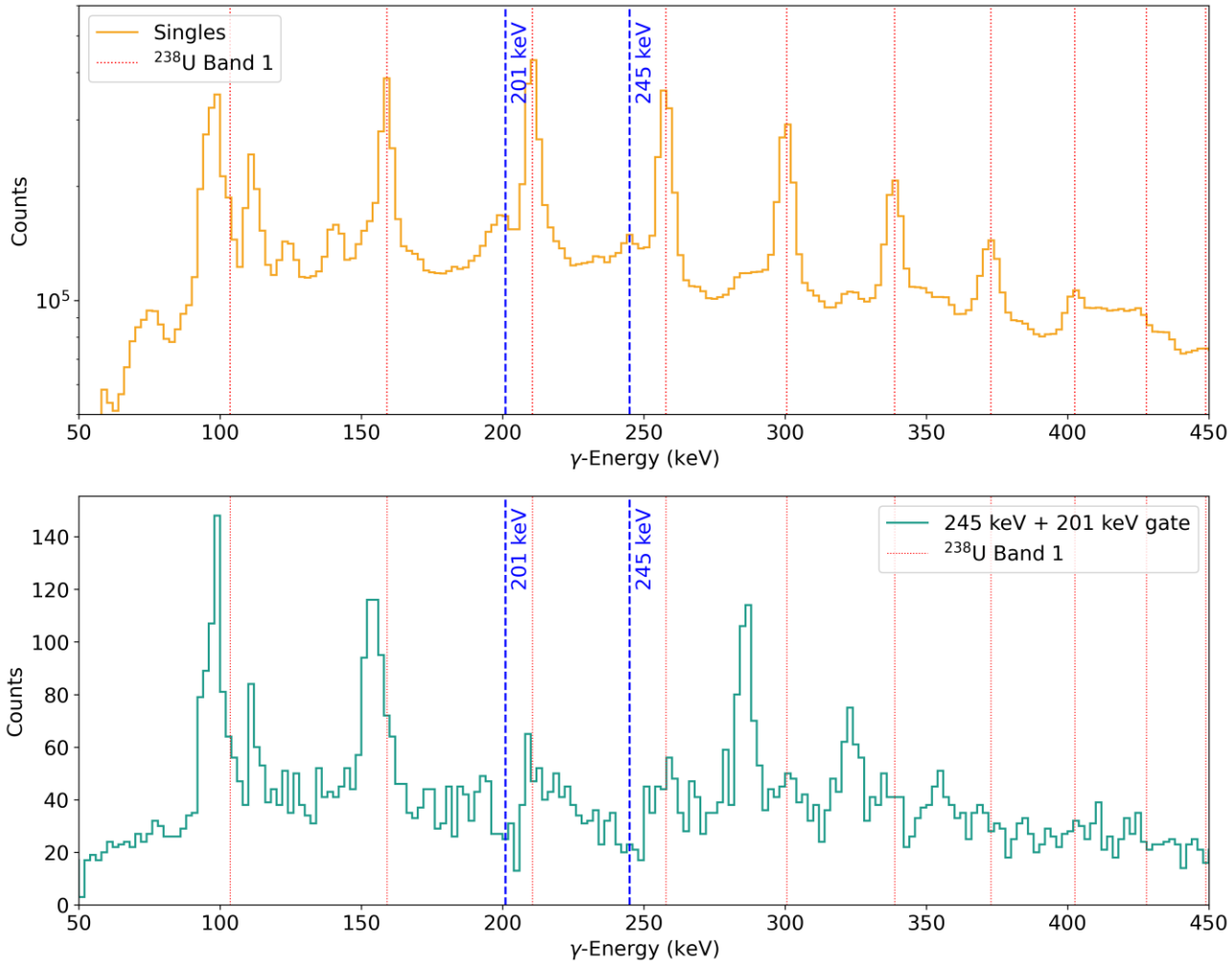


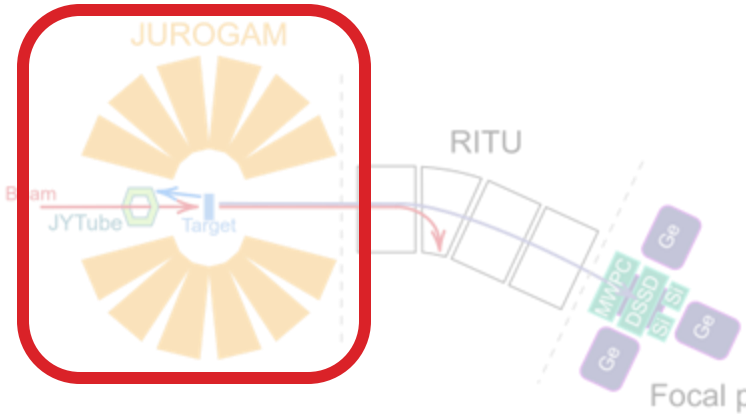
γ-γ-γ correlations: ^{238}U



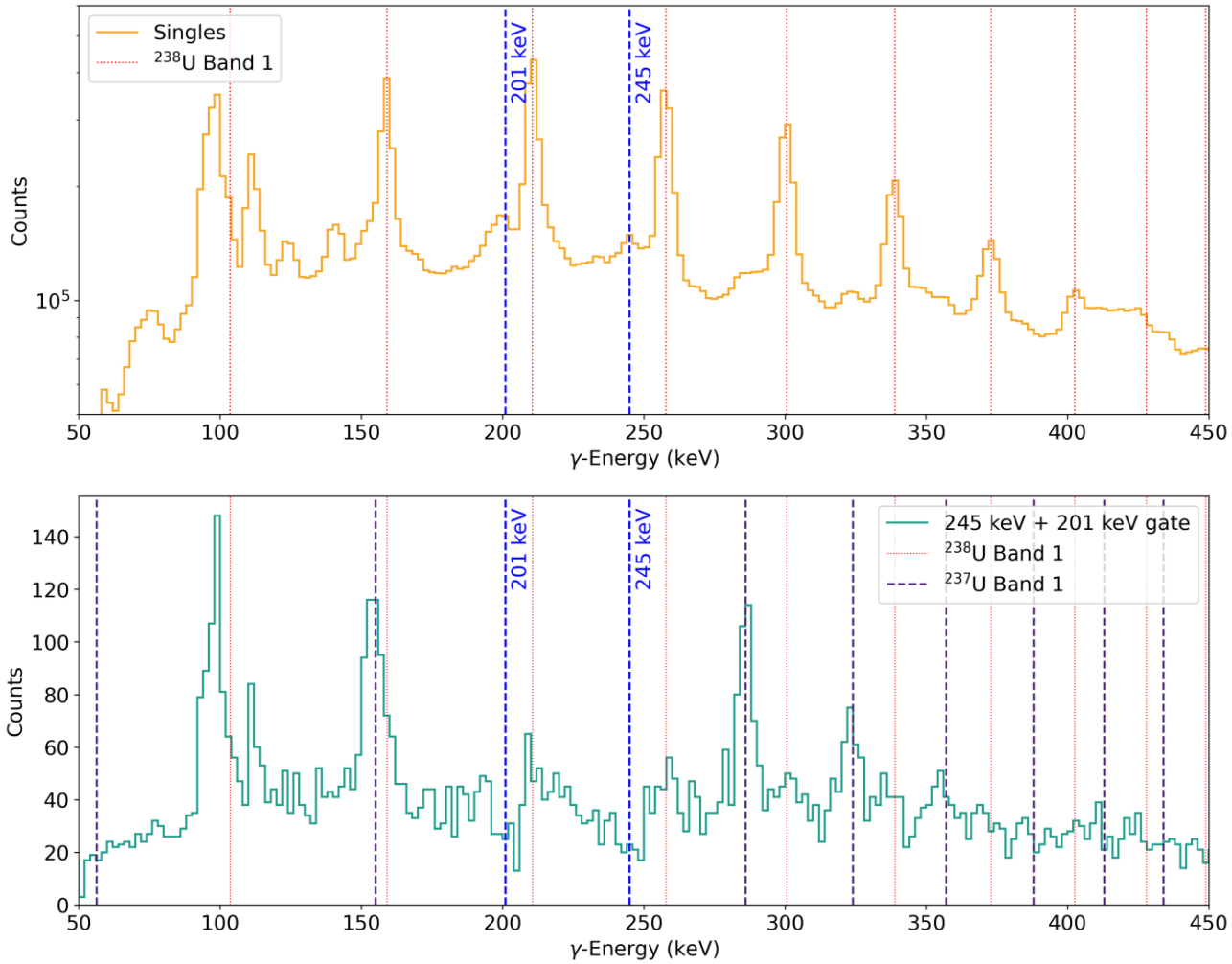


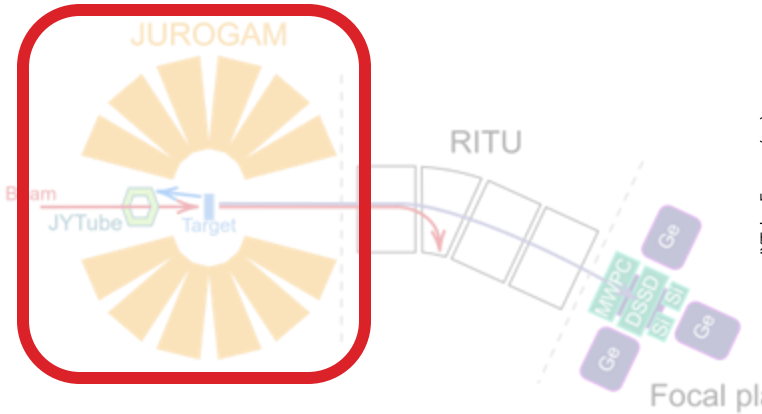
γ-γ-γ correlations: ~~^{238}U~~

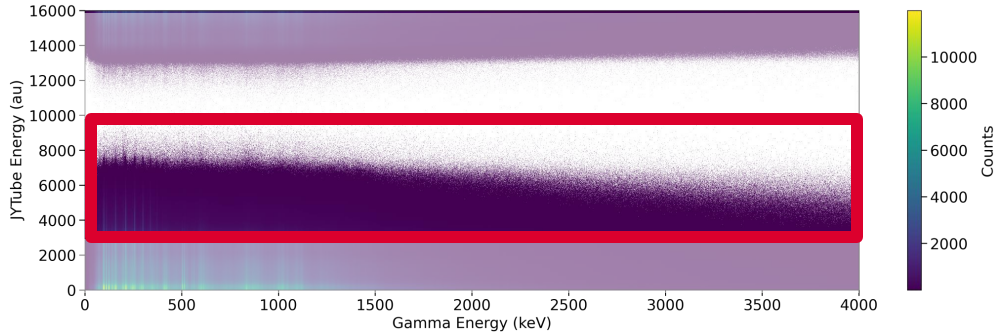


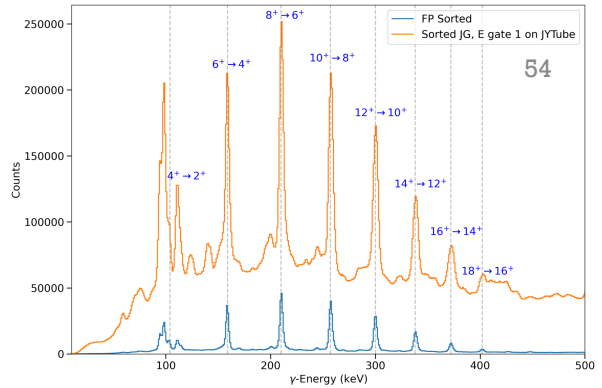


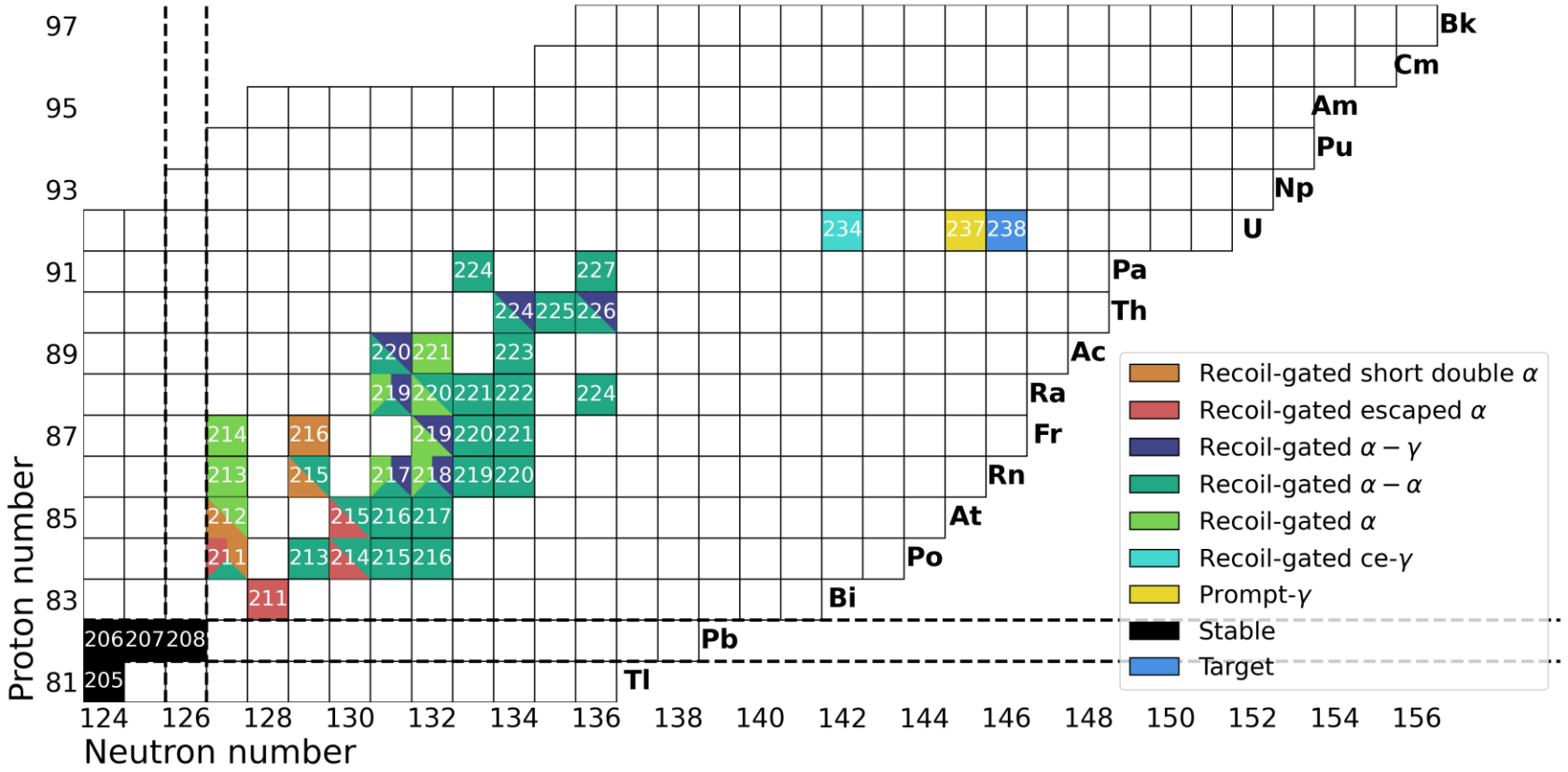
γ-γ-γ correlations: ^{237}U

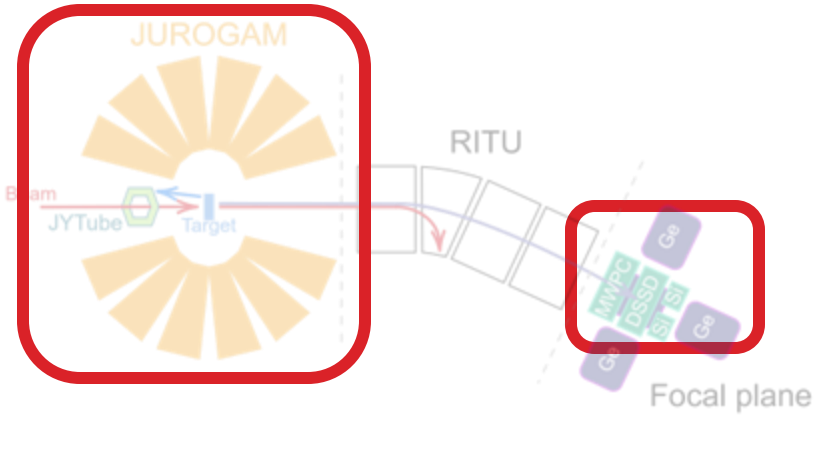


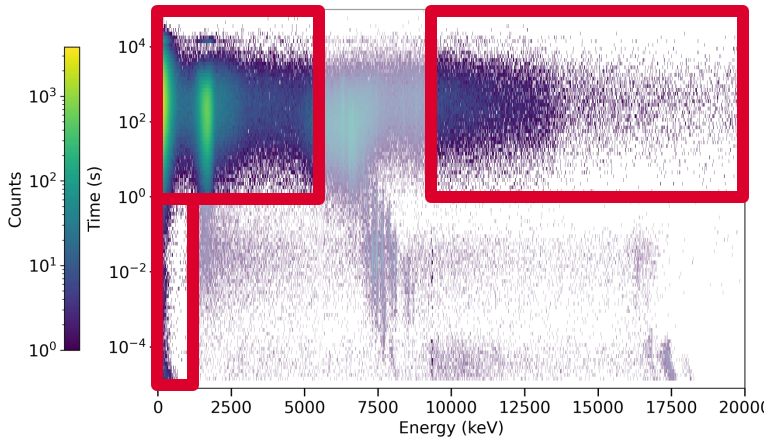

JUROGAM
RITU
Beam
JYTube
Target
Ge
MWPC
DSSD
Si
Si
Ge
Ge
Focal plane

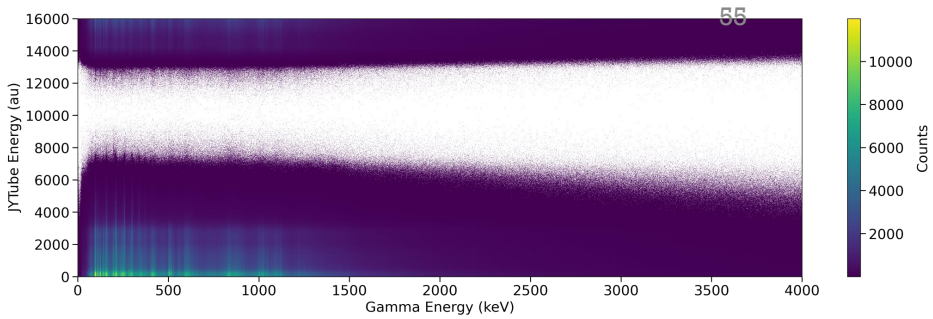

JYTube Energy (au)
Gamma Energy (keV)
Counts

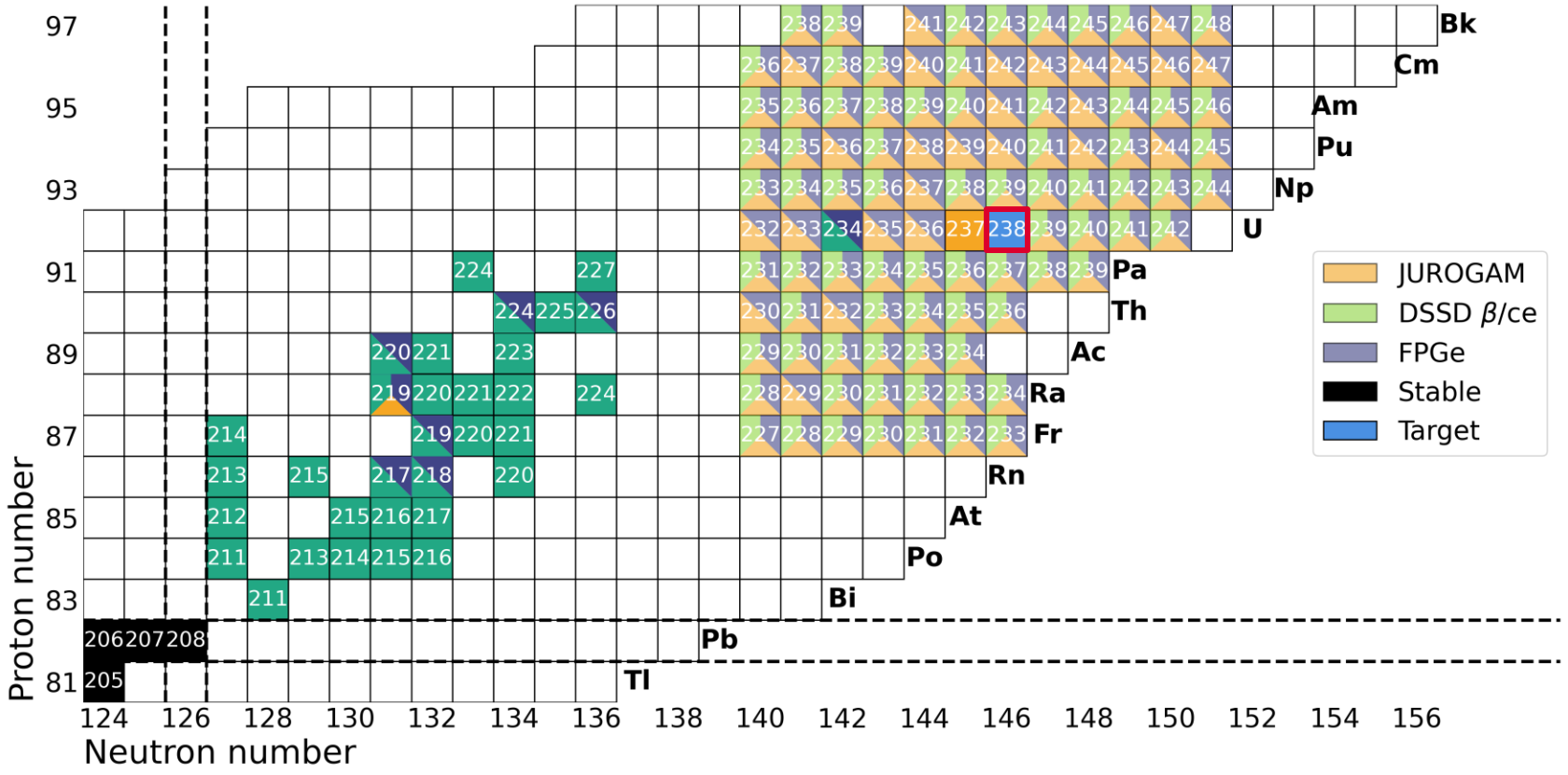

FP Sorted
Sorted JG, E gate 1 on JYTube
54
Counts
γ-Energy (keV)


Proton number
Neutron number
Recoil-gated short double α
Recoil-gated escaped α
Recoil-gated α − γ
Recoil-gated α − α
Recoil-gated α
Recoil-gated ce-γ
Prompt-γ
Stable
Target

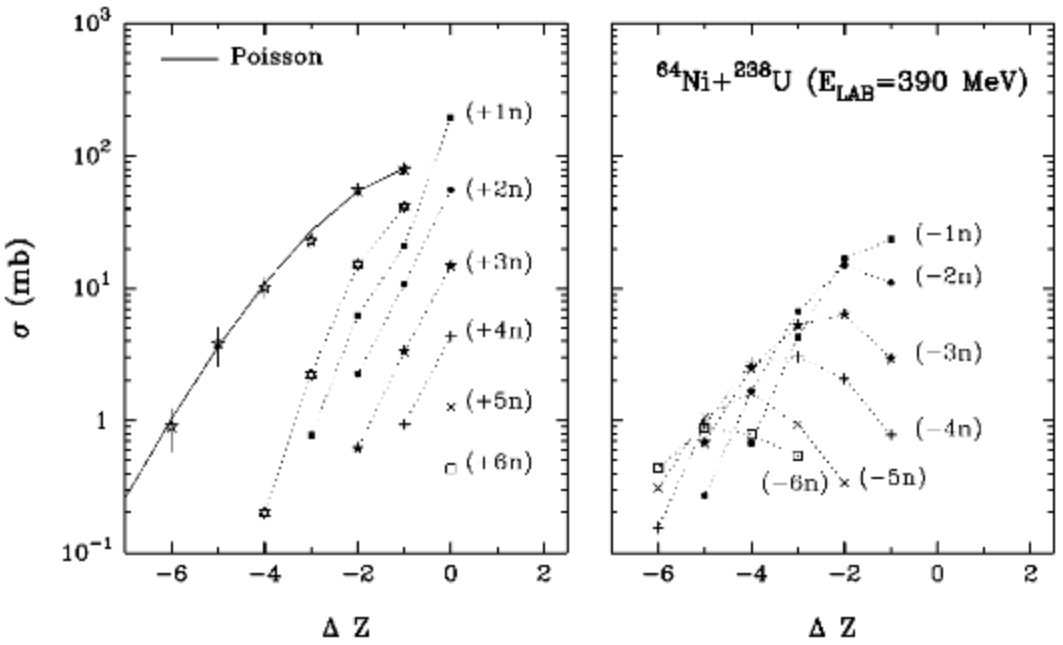

JUROGAM
RITU
Beam
JYTube
Target
Ge
MWPC
DSSD
Si
Si
Ge
Ge
Focal plane

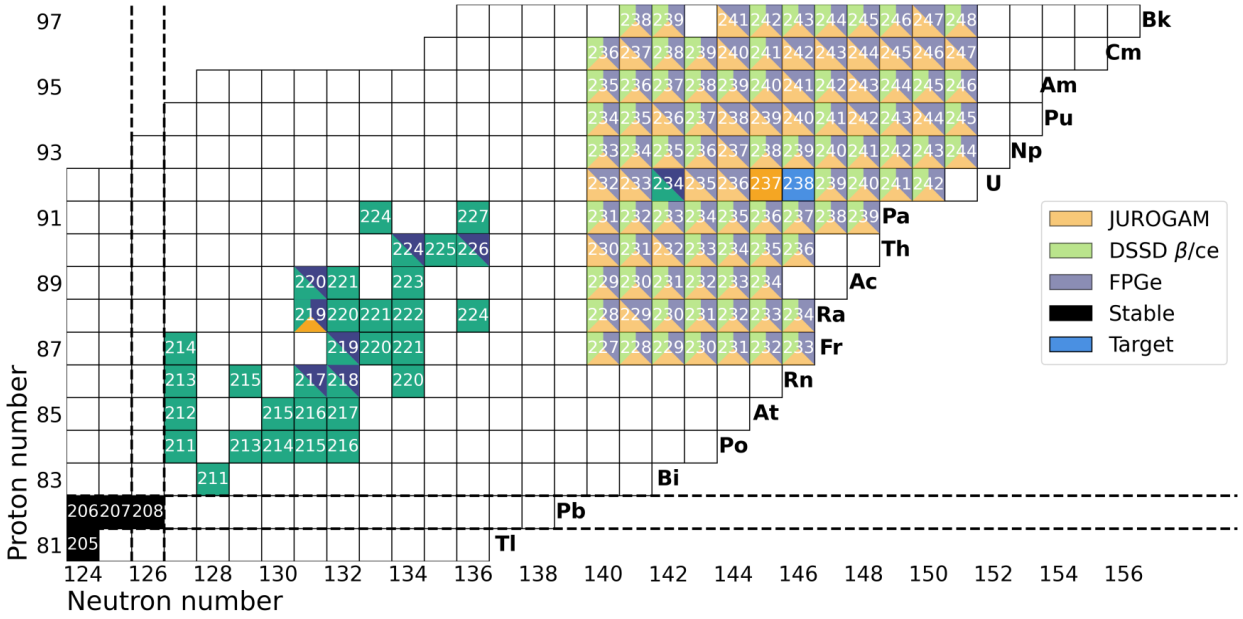

Counts
Time (s)
Energy (keV)


JYTube Energy (au)
Gamma Energy (keV)
Counts


Proton number
Neutron number
JUROGAM
DSSD β/ce
FPGe
Stable
Target
Bk
Cm
Am
Pu
Np
U
Pa
Th
Ac
Ra
Fr
Rn
At
Po
Bi
Pb
Tl

^{64}Ni + ^{238}U cases

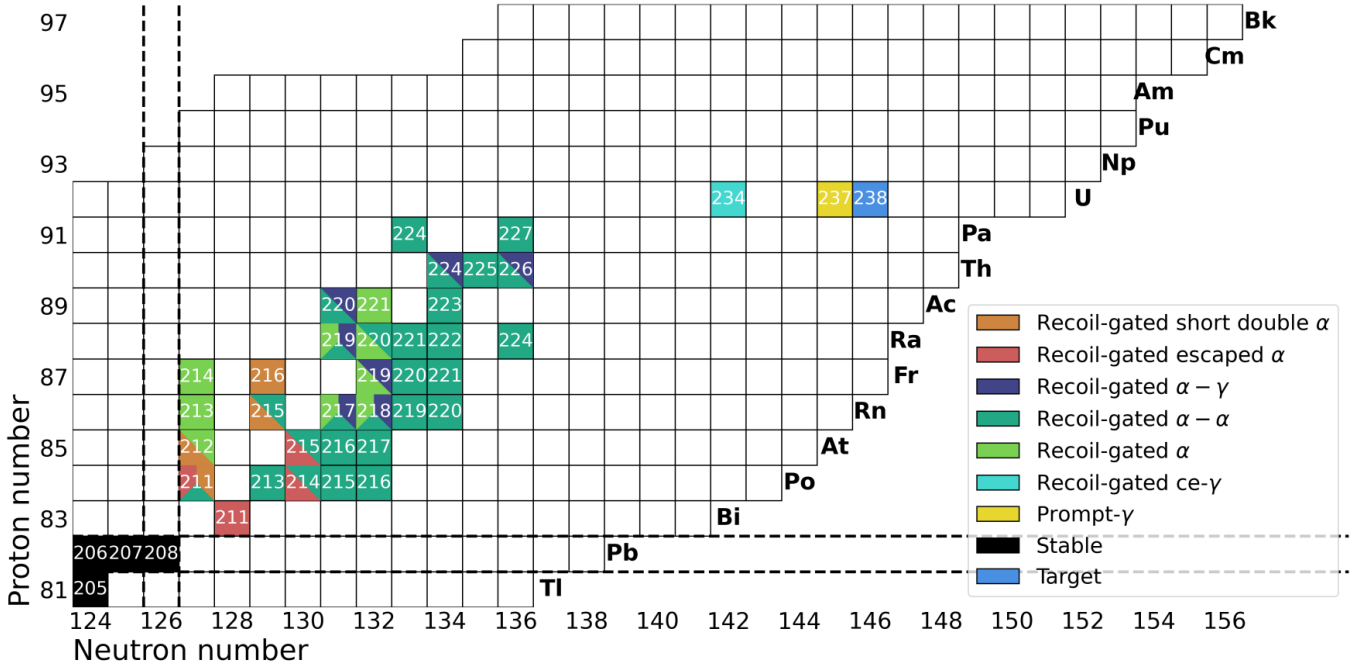


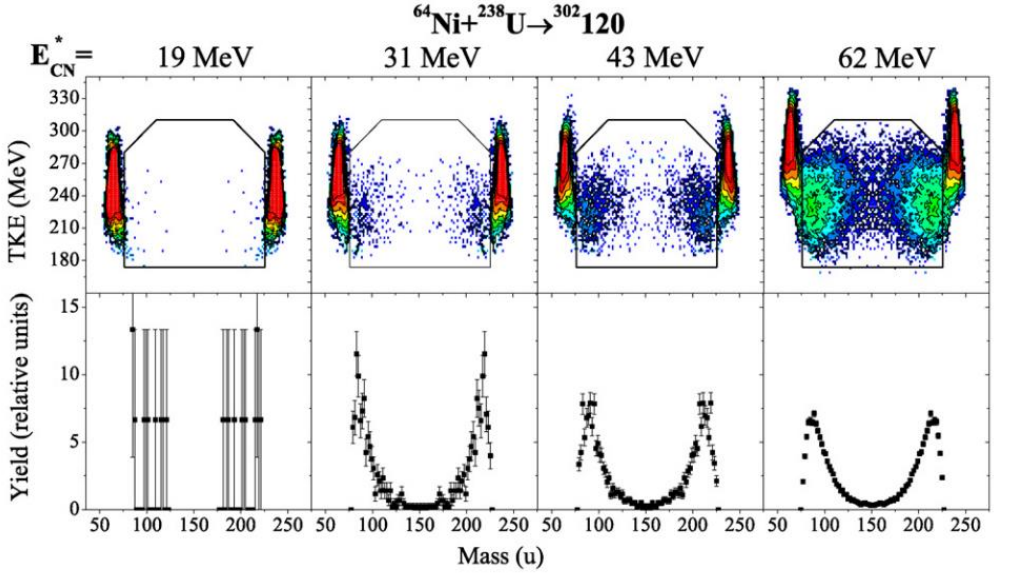


@ E_{lab} = 300 MeV, 333 MeV and 366 MeV

Corradi, L., Stefanini, A. M. & Lin, C. J. (1999), *Phys. Rev. C* 59, 261–268. "Multinucleon transfer processes in ^{64}Ni + ^{238}U."

$^{64}Ni + ^{238}U$ cases





E_{lab}= 330 MeV E_{lab}= 343 MeV E_{lab}= 358 MeV E_{lab}= 382 MeV

@ E_{lab} = 300 MeV, 333 MeV and 366 MeV

E. M. Kozulin et al. (2010), *Phys. Lett. B* 686, 227-232 "Investigation of the reaction ^{64}Ni + ^{238}U being an option of synthesizing element 120."

Status and Outlook

- RITU, combined with its focal plane detector setup and JUROGAM, provides a direct view of the reaction mechanism.
- So far, 34 isotopes have been identified, and the search for more is ongoing.
- There is evidence of isomeric states (^{234}U)
- The next steps include:
  - Further analysis of the gamma spectra of JUROGAM,
  - Search for beam-like partners,
  - Determination of cross-sections.

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[4]IPHC Strasbourg, France;
[5]GSI Helmholtzzentrum für Schwerionenforschung, Germany;
[6]Complutense University of Madrid, Spain

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