Detecting β-delayed Neutron Emission using Recoil-Ion Spectroscopy

Gemma L. Wilson
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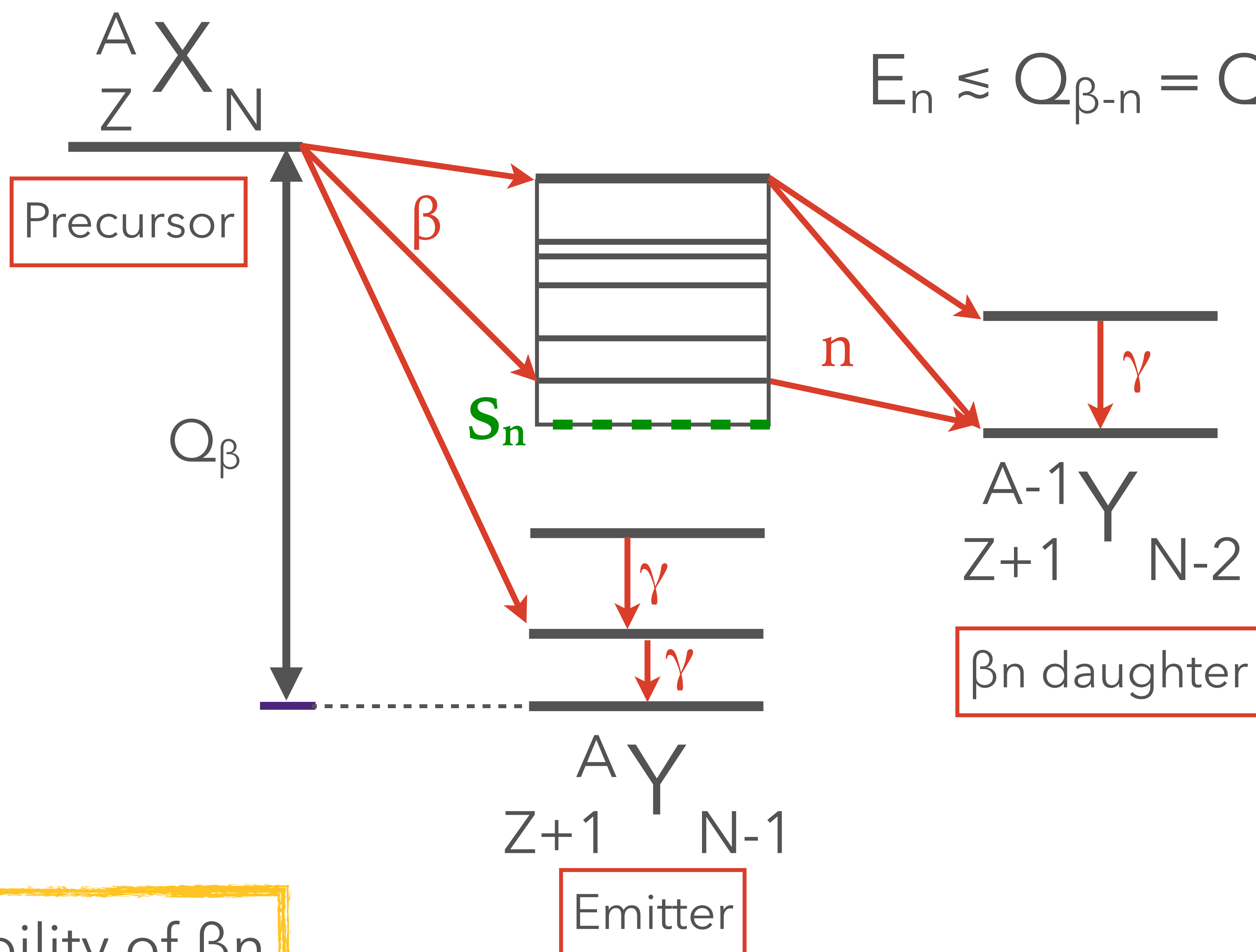
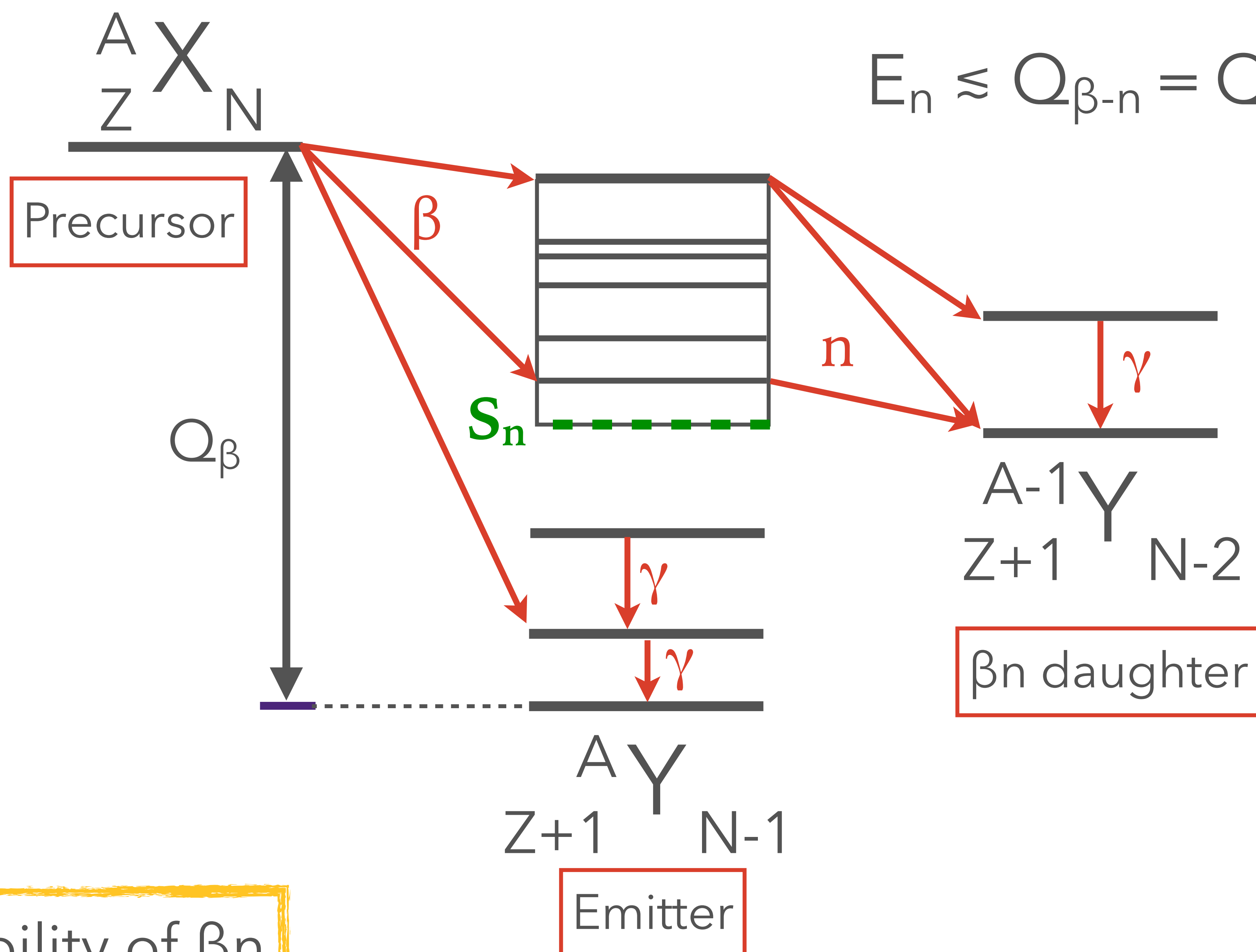
Beta-delayed Neutron Emission (βn)



$E_n \lesssim Q_{\beta\text{-}n} = Q_\beta - S_n$

P_{1n} = probability of βn

Beta-delayed Neutron Emission (βn)



$E_n \lesssim Q_{\beta\text{-}n} = Q_\beta - S_n - E_R$

P_{1n} = probability of βn

The importance of βn measurements

Nuclear structure:
- Common decay mode
- Level densities
- Structure above S_n
- Neutron emission in competition with γ decay

Nuclear astrophysics:
- Provides a source of neutrons in late stages of the *r* process, affecting final abundances
- β lifetimes and P_n, P_{2n}, P_{3n}… needed to constrain models

Nuclear reactor physics:
- Delayed neutrons change the dynamic time response of a reactor
- Delayed neutron production persists after shutdown, contributing to decay heat

TABLE 1. Number of energetically possible vs. measured βxn-emitters. ("Energetically possible" means every case where $Q_{\beta xn} > 0$ keV (using masses from the AME2012 [14]).

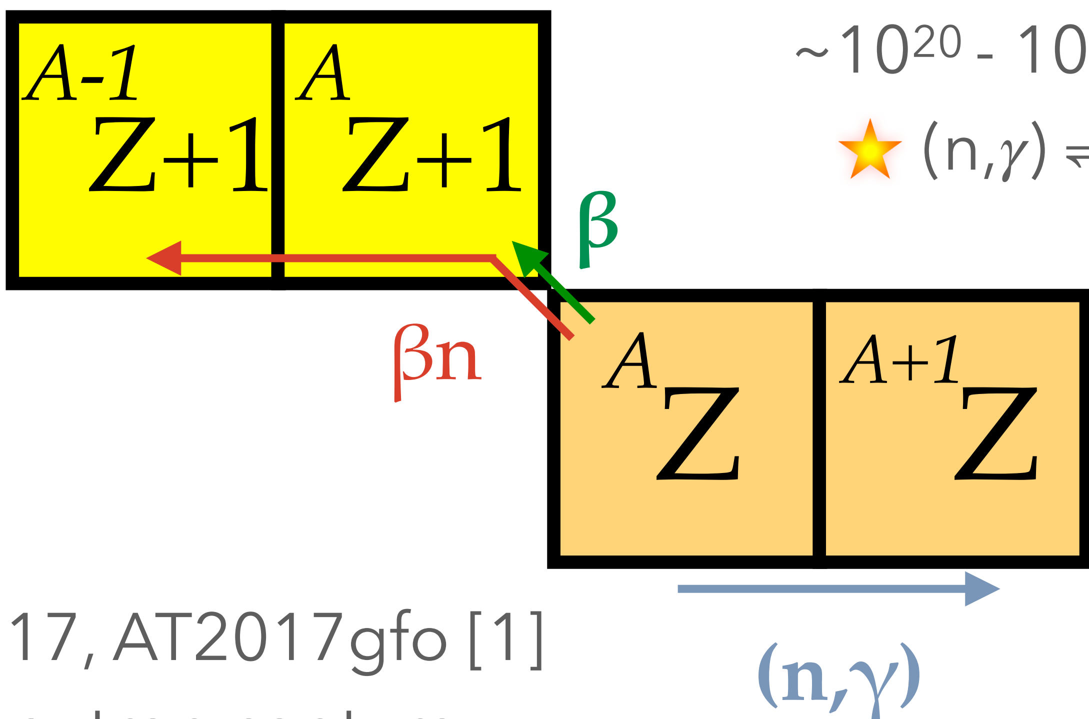
	Energetically possible cases	Measured cases	Fraction measured	Mass region
β1n	606	227	37.5%	^{8}He-^{150}La (^{210}Tl)
β2n	295	24	8.1%	^{11}Li-^{100}Rb
β3n	104	6	5.8%	^{11}Li, ^{14}Be, ^{17,19}B, ^{23}N, ^{31}Na
β4n	60	1	1.7%	^{17}B

I. Dillmann et al, AIP Conference Proceedings **1594**, 332 (2014)

The *r* process

☆Produces very neutron-rich nuclei in high neutron-flux environments.

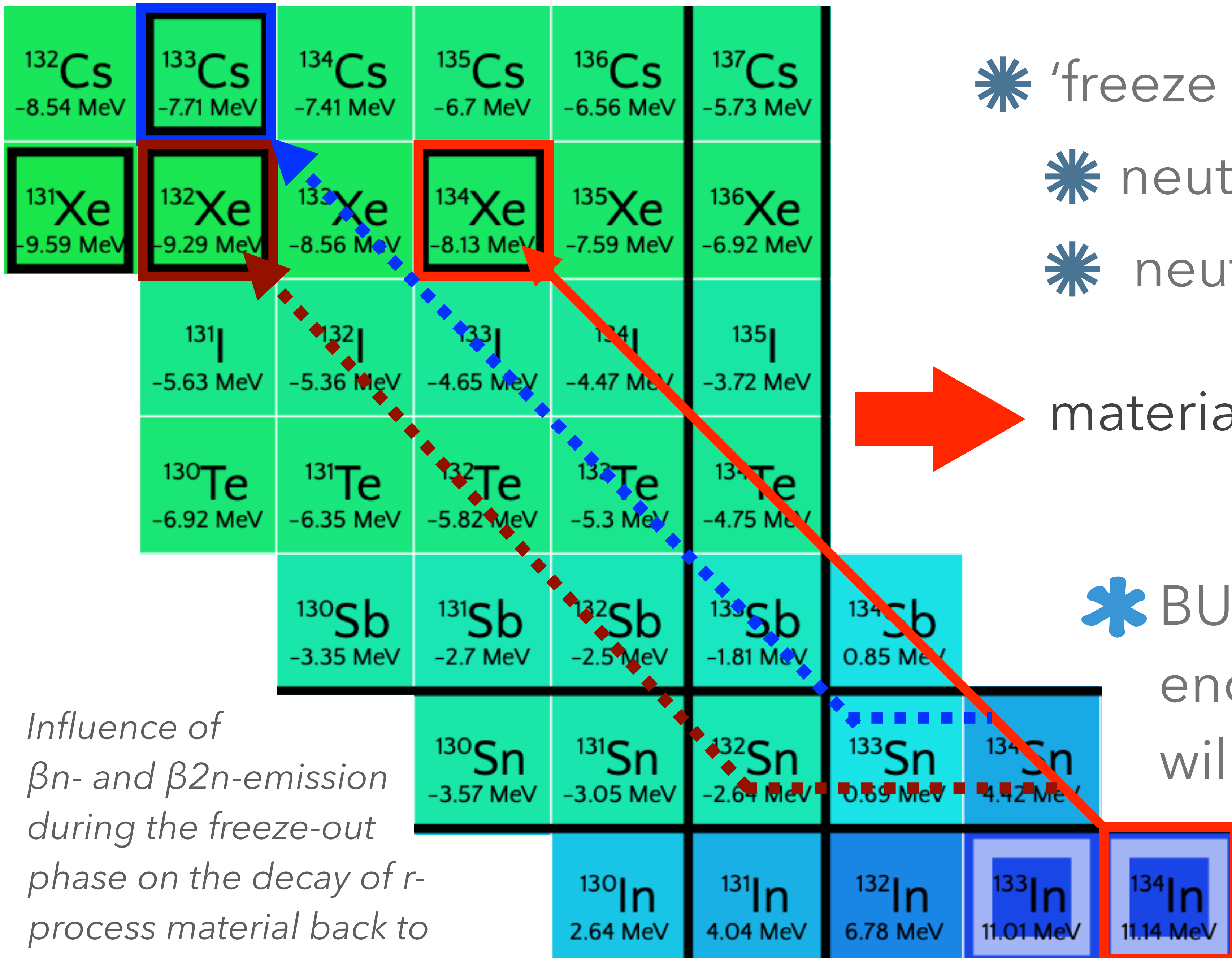
- Hot r process: core-collapse supernova (with neutron densities ~10^{20} - 10^{30} cm^{-3})
  - (n,γ) ⇌ (γ,n) for a considerable time
  - S_n plays an important role



- Cold r process: neutron star mergers
- (n,γ) ⇌ (γ,n) rapidly breaks down before neutrons used up
- Observations: GW170817, AT2017gfo [1]
- Competition between neutron capture and β decay:
  - a nuclide will continue to capture neutrons until the β-decay half-life is too short, and the nuclide will β decay before it can capture a neutron.

[1] B. P. Abbott, Phys Rev Lett 119, 161101 (2017)

The *r* process



- ‘freeze out’ of the *r* process:
  - neutron density drops
  - neutron capture stops.

→ material β decays back to stability

- BUT if P_{1n} or P_{2n} is large enough, then the decay path will change

Influence of βn- and β2n-emission during the freeze-out phase on the decay of r-process material back to stability

- Adapted from Beta-delayed neutron emission evaluation, IAEA, 2011

Without detailed information on βn-emitters, we do not have a complete understanding of r-process nucleosynthesis.

Experimental techniques for measuring βn emission

Direct neutron measurements:

- gas-filled proton-recoil proportional counters [1,2]
- ^{3}He counters [BELEN, BRIKEN]

Measure P_n well and can infer E_n with complications. Issues with beam background

via neutron time of flight:

- plastic scintillator [VANDLE]

Can measure E_n, P_n. Trade off between efficiency and resolution. Issues with beam background

Indirect neutron measurements:

- measure β-delayed γ emission

Can measure P_n. Least complicated experimentally, but needs prior assumptions about spectroscopy.

- Recoil-ion spectroscopy

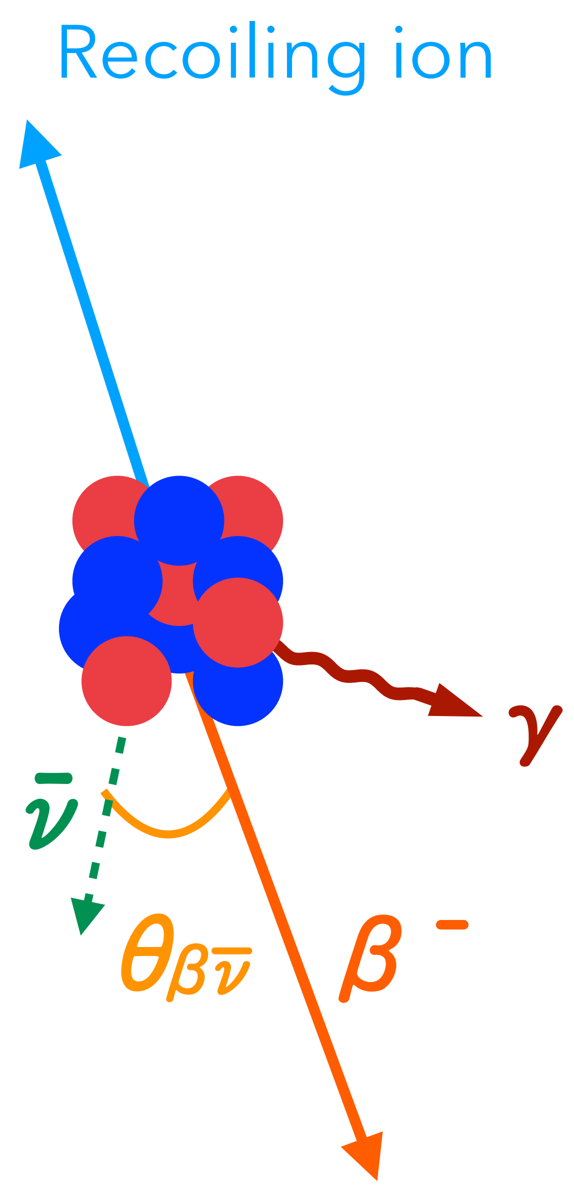
Can measure E_n, P_n *simultaneously*. Avoid difficulties with neutron detection. Low background. Can't measure P_{2n}, P_{3n}...

[1] R. C. Greenwood and A. J. Caffrey, Nucl. Sci, Eng. **91**, 305 (1985);
[2] R. C. Greenwood and K. D. Watts, Nucl. Sci. Eng. **126**, 324 (1997)
[3] H. Ohm *et al.*, Z. Phys. A **296**, 23 (1980); [4] S. Shalev *et al.*, Nucl. Phys. A **275**, 76 (1977)

Principle of Recoil-ion Spectroscopy

<u>β^- decay</u>

- β^-, $\bar{\nu}$ emitted
- daughter ion recoils
- γ rays potentially emitted from excited states in daughter



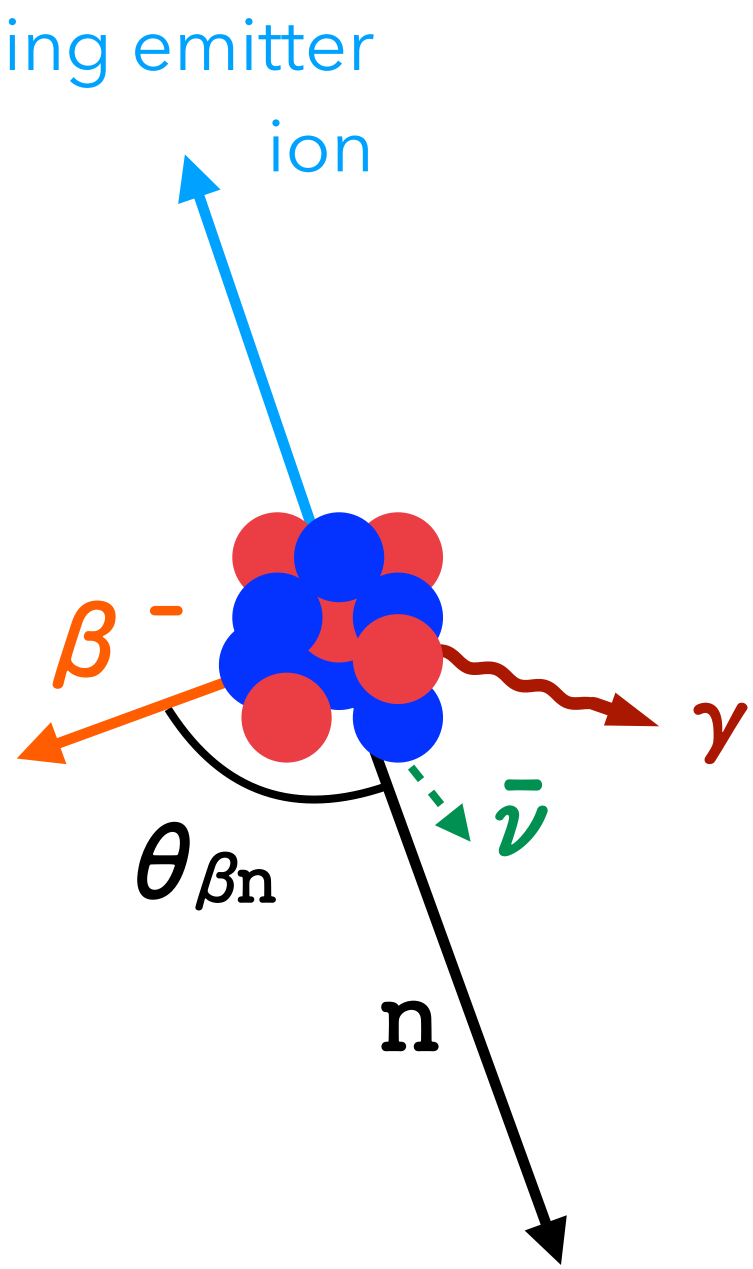
Principle of Recoil-ion Spectroscopy

β^- decay

- β^-, $\bar{\nu}$ emitted
- daughter ion recoils
- γ rays potentially emitted from excited states in daughter

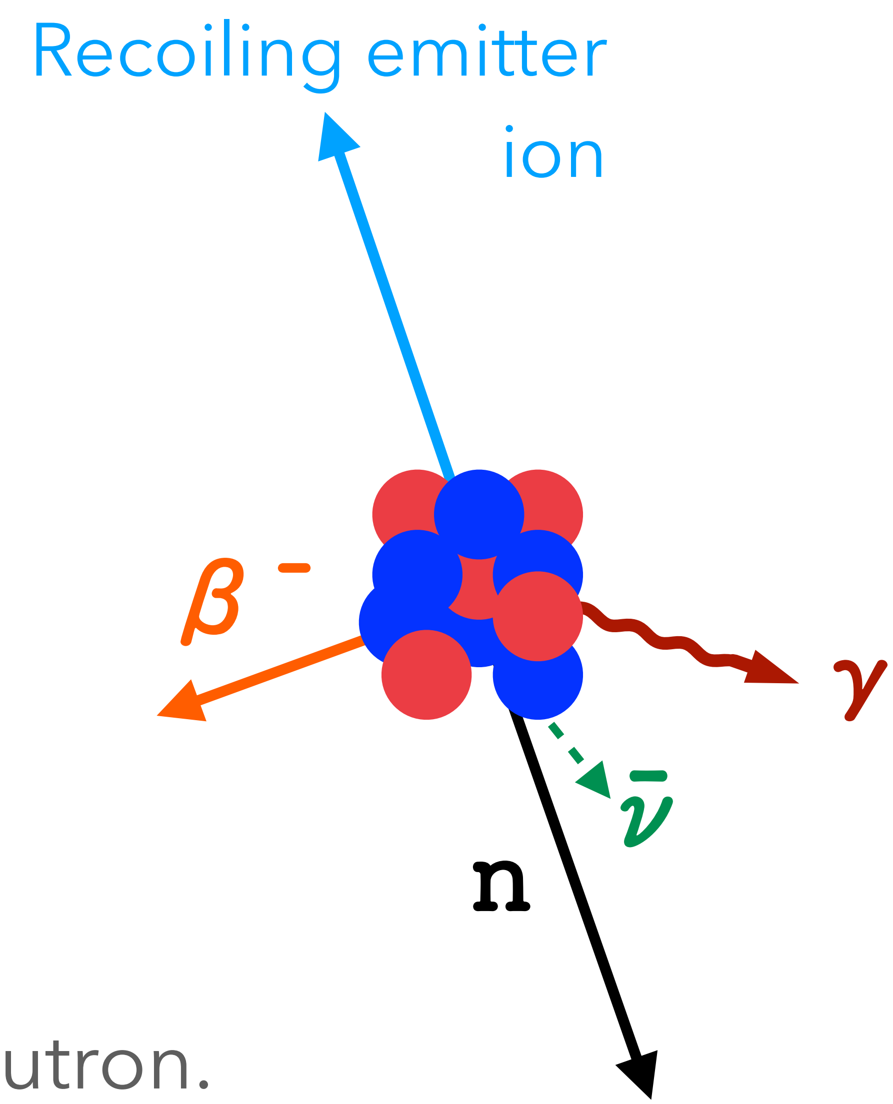
βn decay

- β^-, $\bar{\nu}$, neutron emitted
- *emitter* ion recoils
- γ rays potentially emitted from excited states in βn daughter
- occurs with branching ratio of P_{1n}



Principle of Recoil-ion Spectroscopy

If the precursor is confined to an ion trap, it is possible to access the low-energy nuclear recoil after β and βn decay.

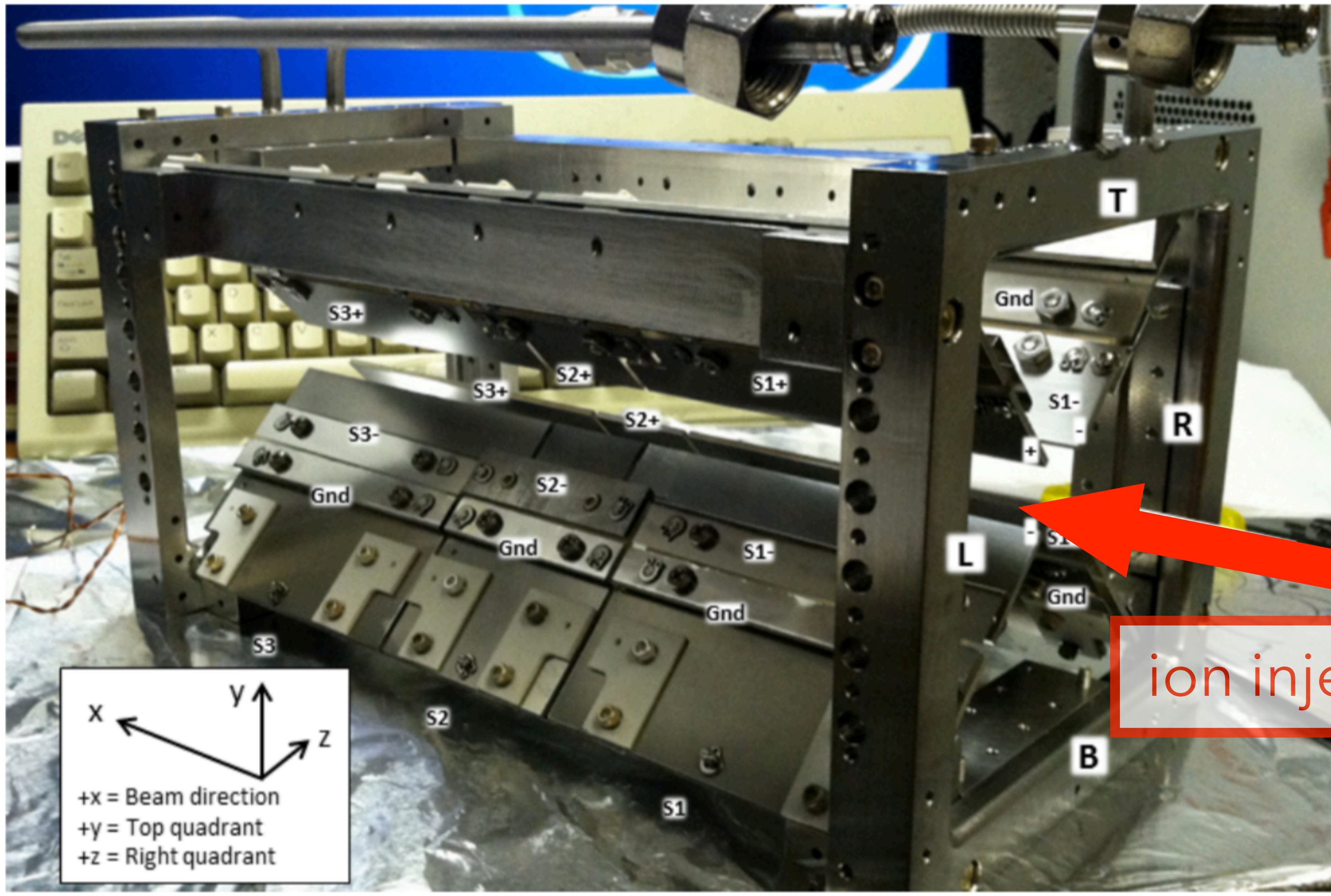


⏱ The decay modes are distinguishable from the time of flight of the recoiling ion.

By detecting the recoiling emitter ion, we can reconstruct information about the emitted neutron.

🔑 This is the key to recoil-ion spectroscopy.

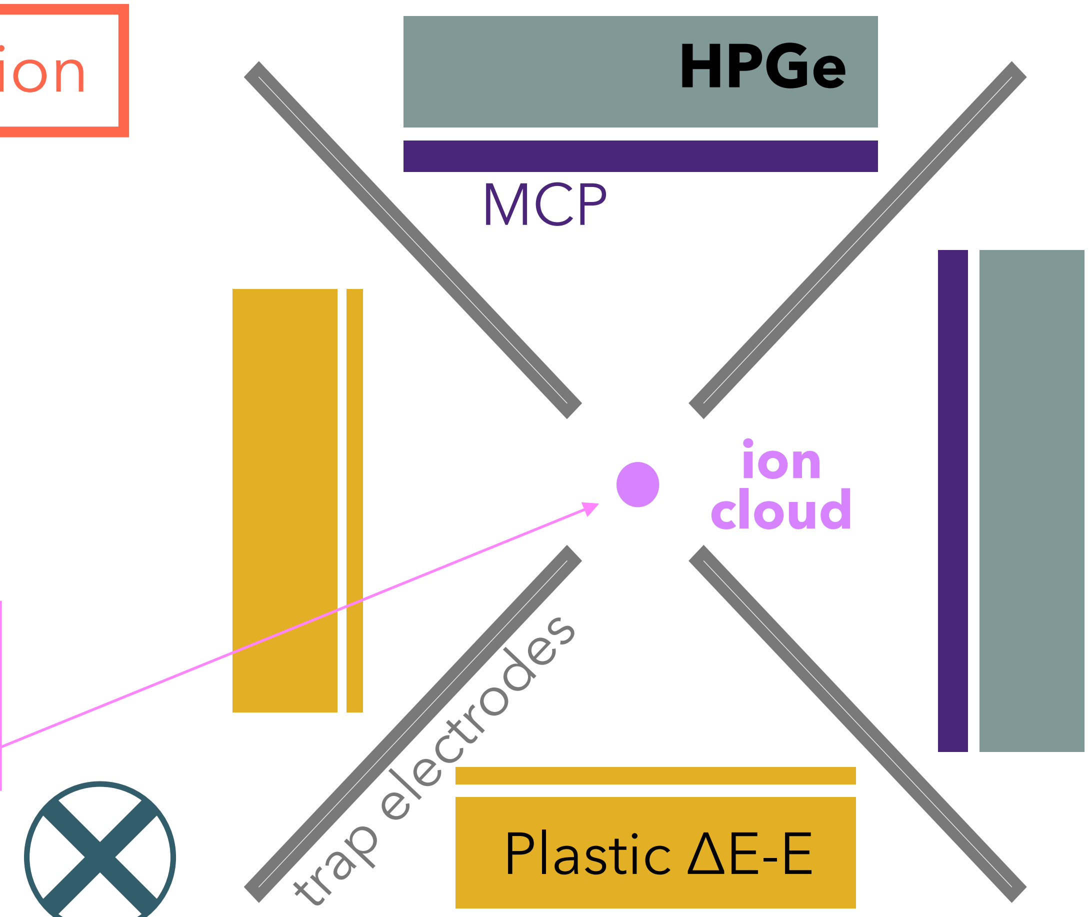
BPT: Beta-decay Paul Trap at ANL



Electrodes and frame of the BPT - A. Czeszumska, PhD Thesis, University of California, Berkeley, 2016

- The BPT was built for precision β-decay studies
  N.D. Scielzo et al., NIM A 681 (2012) 94-100
- Used to measure $a_{\beta\nu}$, β-$\bar{\nu}$-α of ^{8}Li
  M Sternberg et al., PRL 115 182501 (2015)
- Adapted to be used for βn
  R Yee et al., PRL 110 092501 (2013)

ion injection



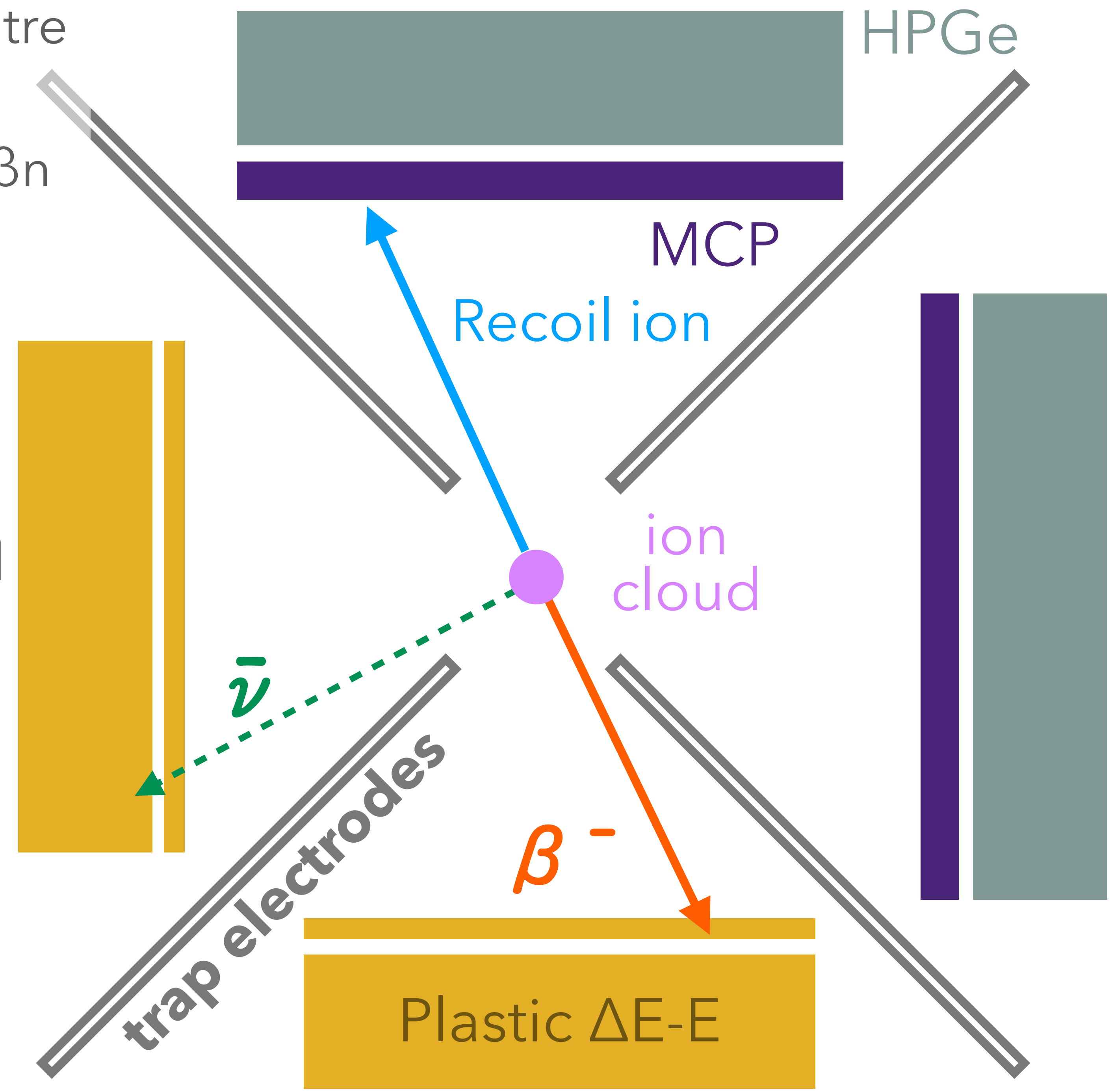
~10^4 ions confined in the centre of the trap in an 'ion cloud'

Recoil-ion Spectroscopy with the BPT

- Cooled ion bunch confined at the centre of a Paul trap.
- The precursor undergoes β decay or βn decay, depending on P_n

β decay

- Detect recoil ion and β in coincidence
- Recoil ion time of flight (TOF) measured



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β decay

- Detect recoil ion and β in coincidence
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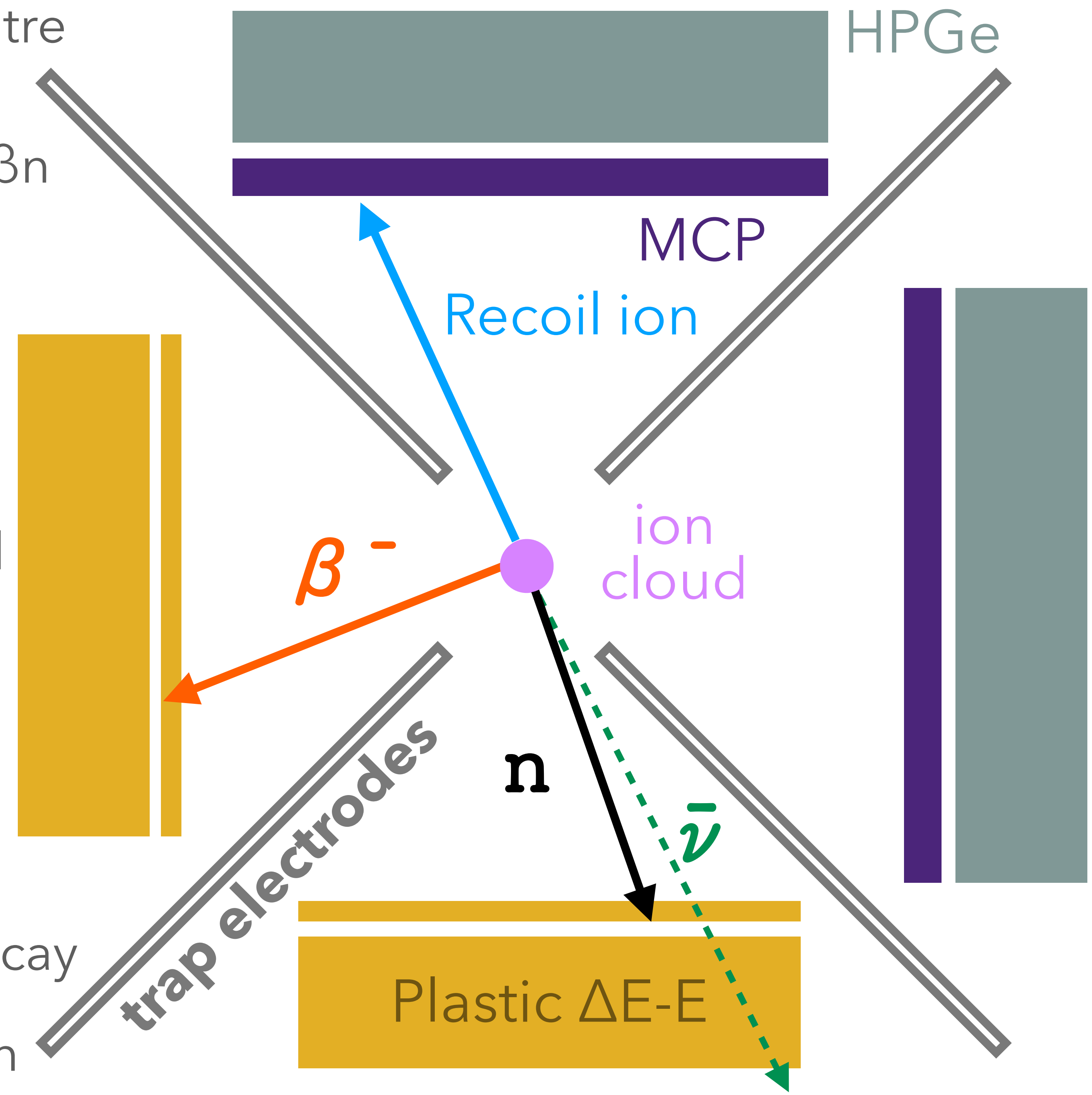
βn decay

- Recoiling emitter ion is given a 'kick' of momentum from the emitted neutron
- Recoil ion TOF is shorter than after β decay
- E_n and P_n can be inferred from detection of β-ion coincidences



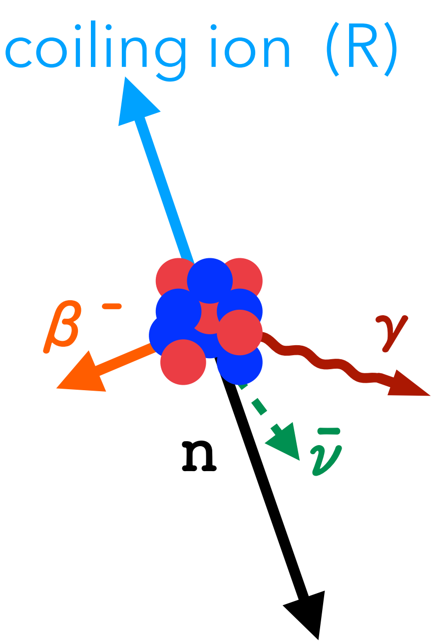
BPT: β-decay Paul Trap at ANL

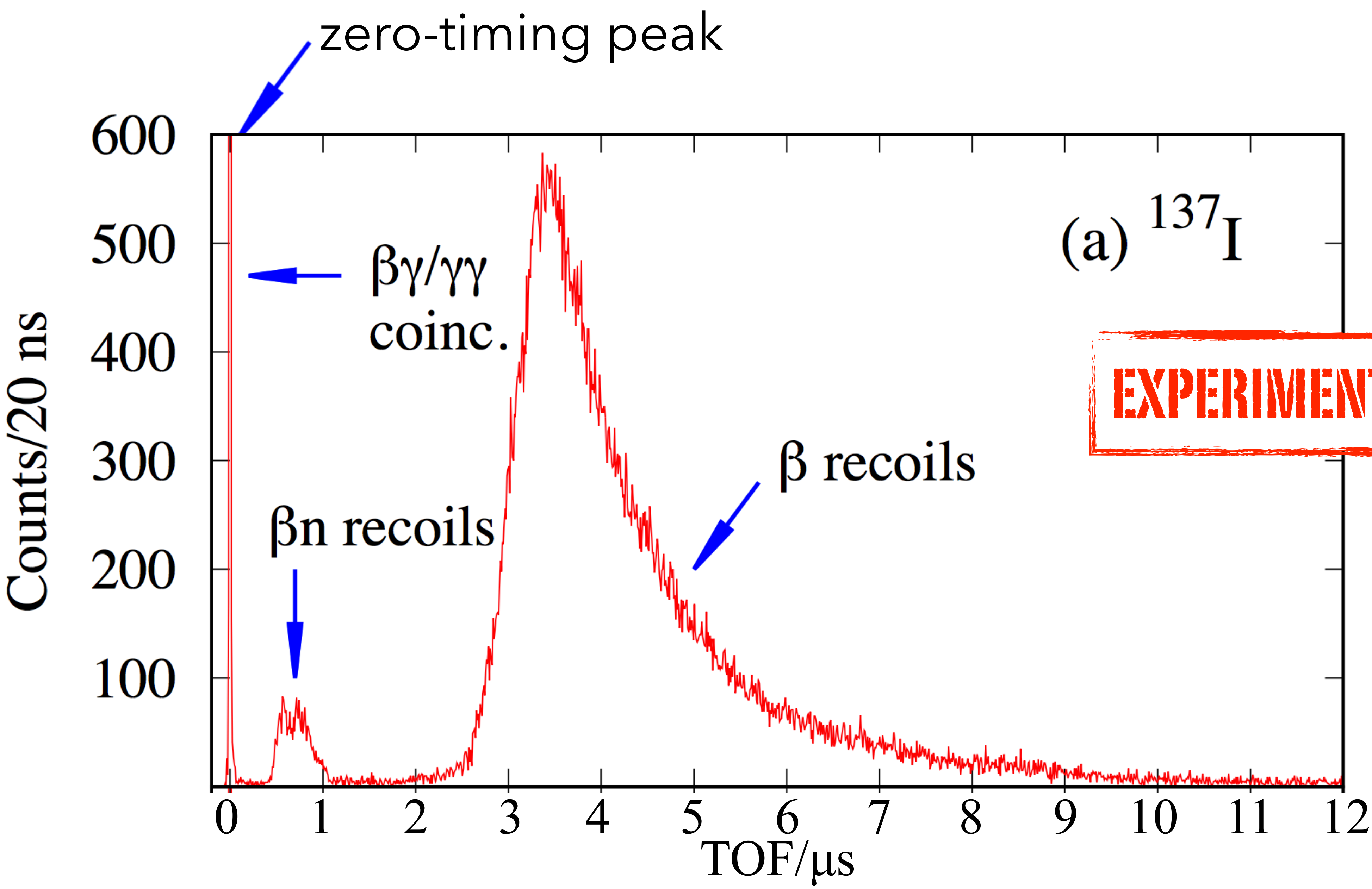
Differentiating between β and βn events

Extra momentum kick to recoiling nucleus:

β (1 MeV): ~0.01 keV recoil

n (1 MeV): ~10 keV recoil

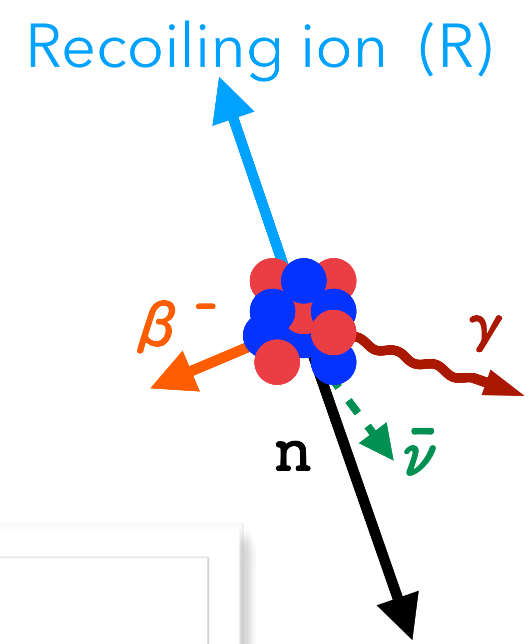




TOF: starts with ΔE, ends with MCP

A. Czeszumska *et al.*, Phys. Rev. C 101, 024312 (2020)

Measuring E_n without direct detection



If we assume that $\mathbf{p_n} \approx \mathbf{-p_R}$, and small contributions from β^-, $\bar{\nu}$ and any γ rays are ignored:

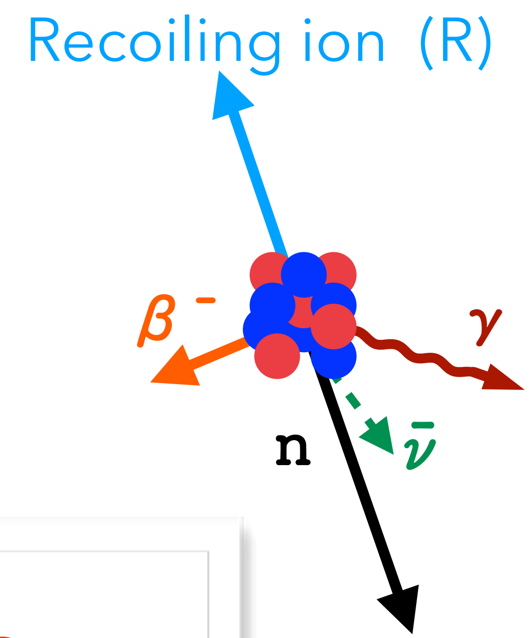
$$E_n = \frac{|\mathbf{p_R}|^2}{2m_n} = \frac{m_R^2 v_R^2}{2m_n}$$

mass of neutron

mass of recoiling ion

Velocity of recoiling ion

Measuring E_n without direct detection



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$$E_n = \frac{|\mathbf{p_R}|^2}{2m_n} = \frac{1}{2}\frac{m_R^2 (d/TOF)^2}{m_n}$$

Distance from ion cloud to impact location of recoiling ion on MCP

Time difference between β detected in ΔE and recoil detected in MCP

We can infer neutron energy from the detection of the recoiling ion

Quantities measured via Recoil-ion Spectroscopy

<table>
<tr><th colspan="2">Quantity</th><th colspan="3">From which observables?</th></tr>
<tr><td colspan="2">E_n</td><td colspan="3">Reconstructed from distance to trap centre, d, and TOF.
$E_n = \frac{|\mathbf{p_R}|^2}{2m_n} = \frac{1}{2}\frac{m_R^2 (d/TOF)^2}{m_n}$</td></tr>
<tr><td rowspan="3">$P_n \approx \frac{N_{\beta n}}{N_\beta}$</td><td>$N_{\beta n}$</td><td colspan="3">Number of recoil ions with short TOF</td></tr>
<tr><td rowspan="2">N_β</td><td>β singles</td><td>β-γ singles</td><td>β-recoil ion</td></tr>
<tr><td>• detected in ΔE-E
✔ less sensitive to decay details
✘ prone to background</td><td>• Detected in HPGe
✔ Insensitive to other decays
✘ Must know γ branching</td><td>• Measured in MCP
✘ Affected by details of β decay and RF-electric fields</td></tr>
</table>

✓ Three independent ways of determining P_n

✓ Neutron energy spectrum reconstructed without detecting the neutron

✓ Selective signature; can use very weak beams (~0.1 ions/s)

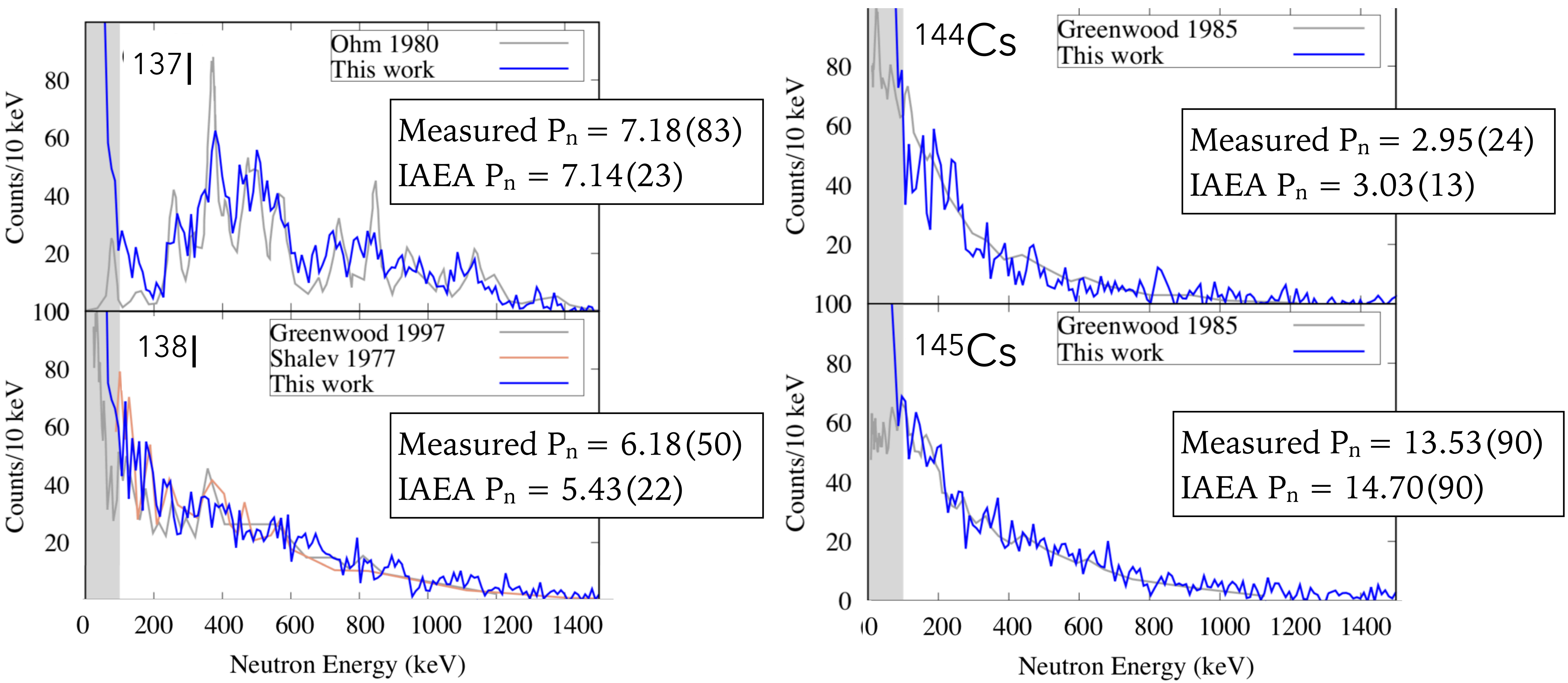
BPT Measurements

EXPERIMENTAL DATA

Neutron energy spectra from the BPT, compared with previous measurements:

Greenwood 1985, 1997: gas-filled proton-recoil proportional counters

Ohm 1980: ^{3}He ionisation chambers; Shalev 1977: ^{3}He/Ar ionisation chambers



A Czeszumska *et al.*, Phys. Rev. C 101, 024312 (2020); H. Ohm *et al.*, Z. Phys. A **296**, 23 (1980);
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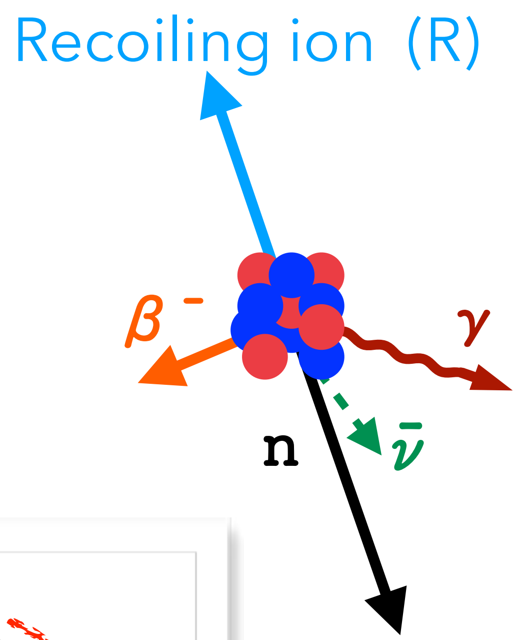


$$E_n = \frac{|\mathbf{p_R}|^2}{2m_n} = \frac{1}{2}\frac{m_R^2 (d/TOF)^2}{m_n}$$

- Measurements of d and TOF introduce a spread in E_n

How are we investigating this?

- Through simulations:
  - isolate phenomena - we control the physics!
- β-decay input from an event generator, originally developed for β-$\bar{\nu}$ angular correlations [1,2]
- We simulate decays of the precursors to imaginary states to emit neutrons with energy 0.1, …, 1 MeV, up to the $Q_{\beta\text{-}n}$ value
  - compare the inferred neutron energy (E'_n) to the simulated neutron energy (E_n)
- Simulations have been benchmarked by data
- We assume that the β decay is allowed Gamow-Teller
  - This sets the β-$\bar{\nu}$ angular correlation coefficient $a_{\beta\nu} = -\frac{1}{3}$

[1] N. D. Scielzo et al., Phys Rev A 68 (022716) (2003); [2] N. D. Scielzo et al., Phys Rev Lett 93 (102501) (2004)

Simulation process

Event generator

Contains physics:

- emitted neutron energy
- correlation coefficients ($a_{\beta\nu}$ etc)
- ion cloud size
- Type of decay: β or βn

SimIon

- computes E-fields based on electrode geometry
- determines trajectories of ions

GEANT4

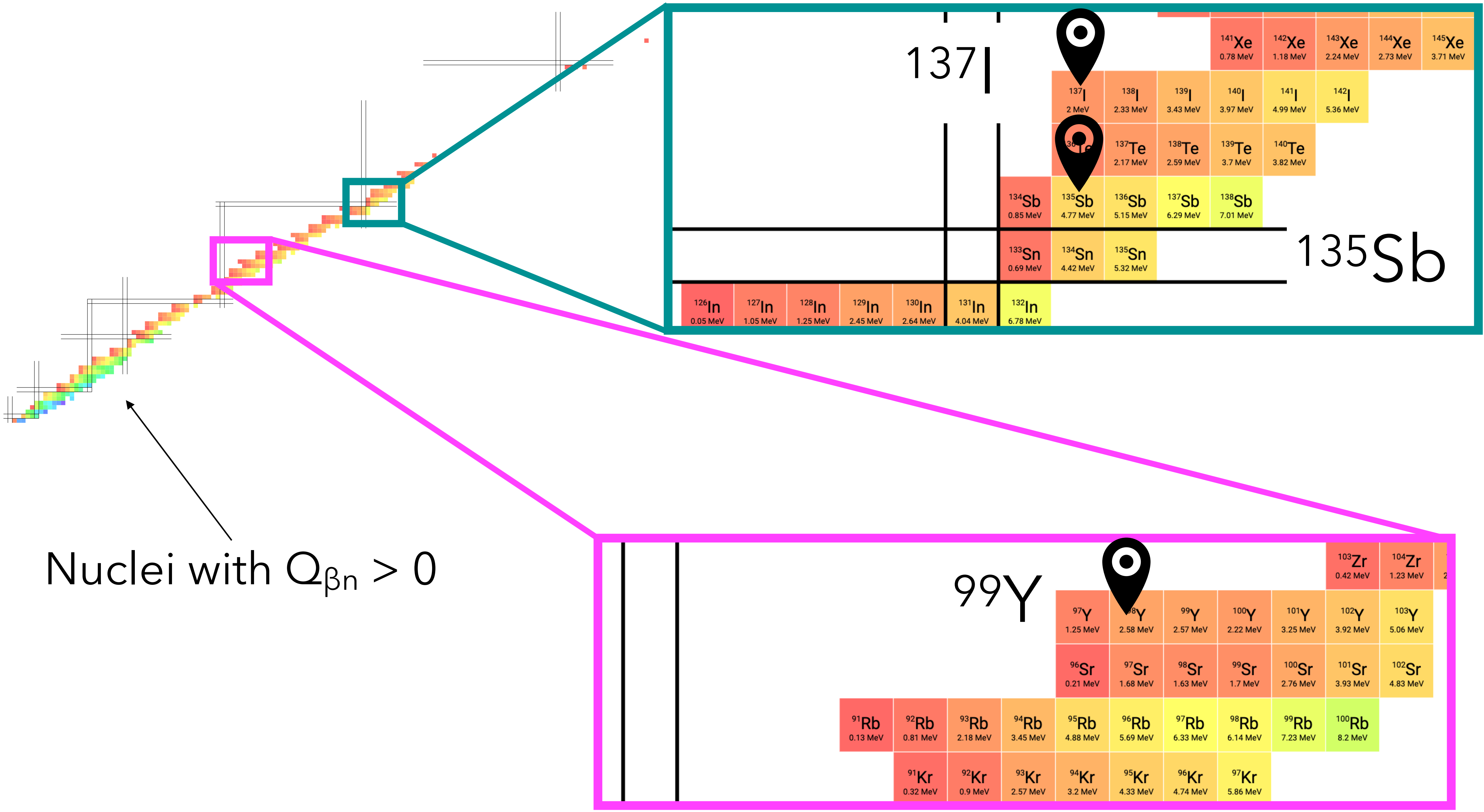
- Energy losses of β,γ,n in materials
- scattering in materials
- energies deposited

Combine

Corrections (to match experiment)

- Detector thresholds
- Efficiency
- MCP fiducial cuts

Precursors used in this study



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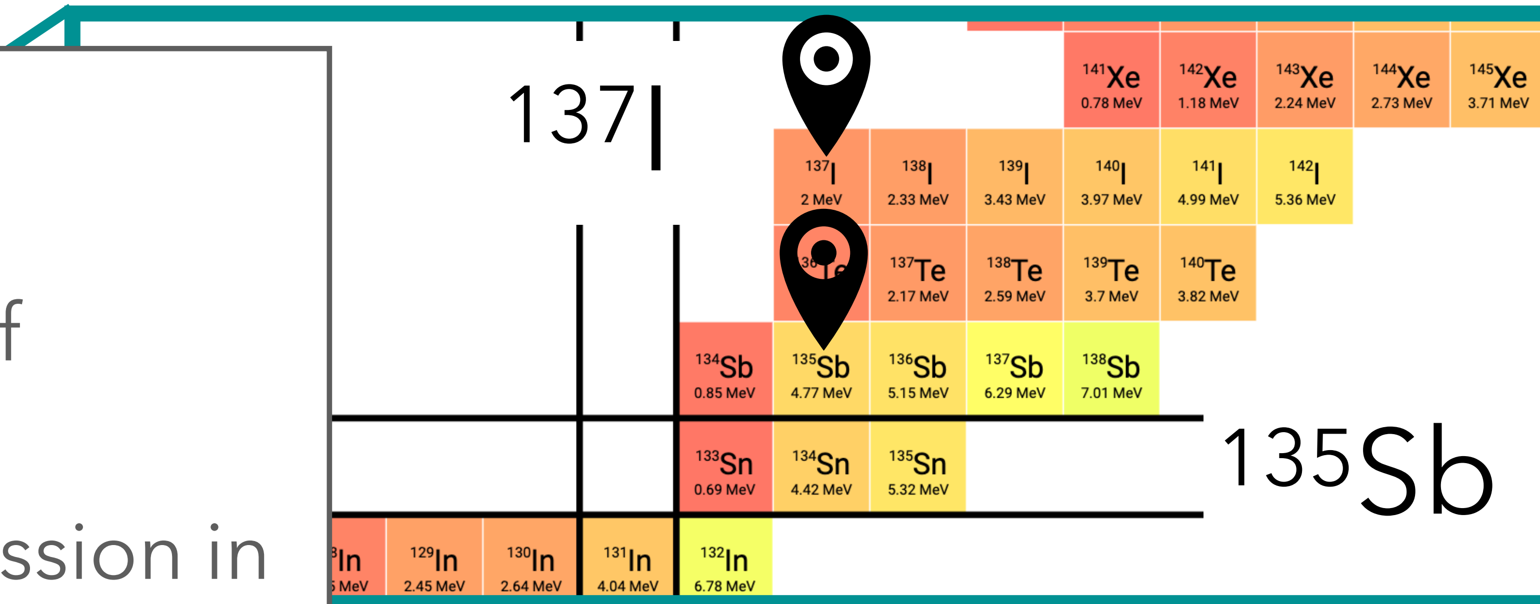
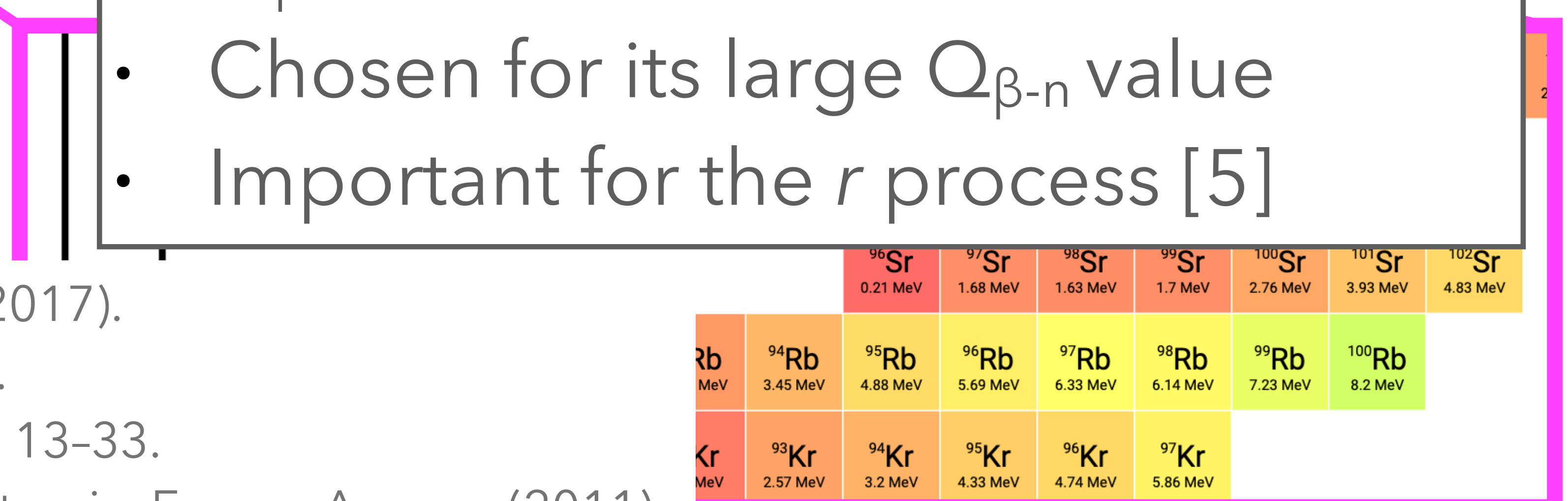


137I:

- $Q_{\beta\text{-}n}$ = 2.002 MeV
- well studied with a variety of different techniques [1-3]
- IAEA benchmark for βn emission in the heavy-mass peak of fission product distributions [4]

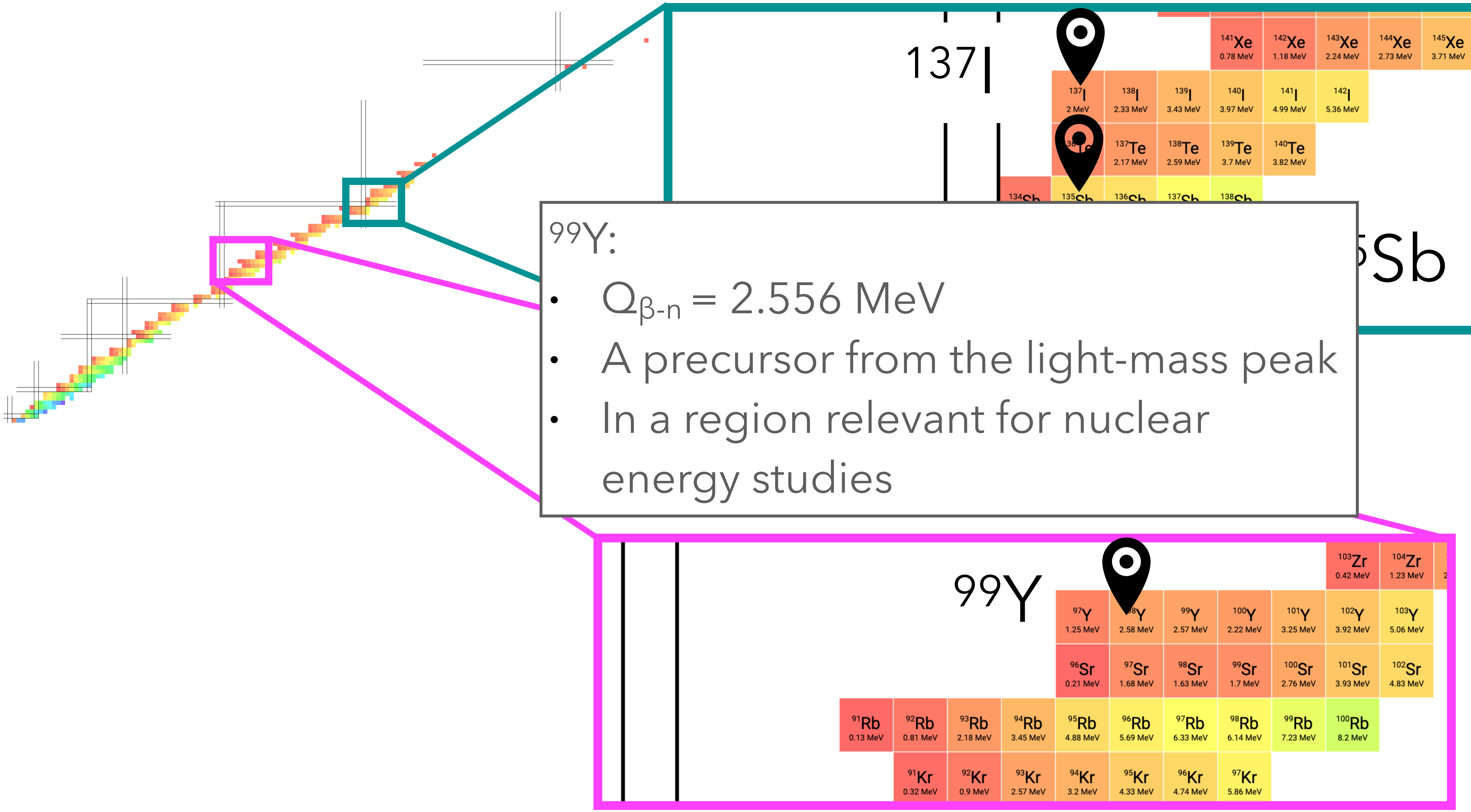


135Sb:

- $Q_{\beta\text{-}n}$ = 4.772 MeV
- Chosen for its large $Q_{\beta\text{-}n}$ value
- Important for the *r* process [5]

[1] B.C. Rasco et al, Phys. Rev. C 95 (054328) (2017).
[2] H. Ohm et al, Z Physik A 296 (1980) 23 – 33.
[3] B. Fogelberg et al, Nucl. Phys. A 345 (1980) 13–33.
[4] D. Abriola et al, Tech. rep., International Atomic Energy Agency (2011).
[5] M. R. Mumpower et al, Prog. Part. Nucl. Phys. 86 (2016) 86-126

Precursors used in this study

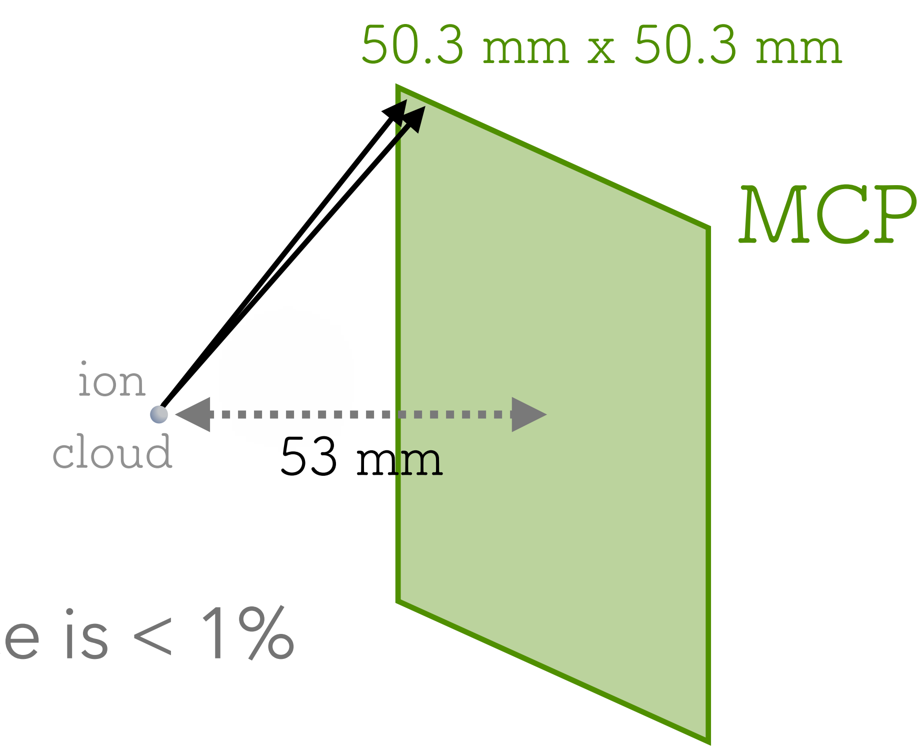


^{99}Y:

- $Q_{\beta\text{-}n}$ = 2.556 MeV
- A precursor from the light-mass peak
- In a region relevant for nuclear energy studies

What affects the neutron energy resolution?

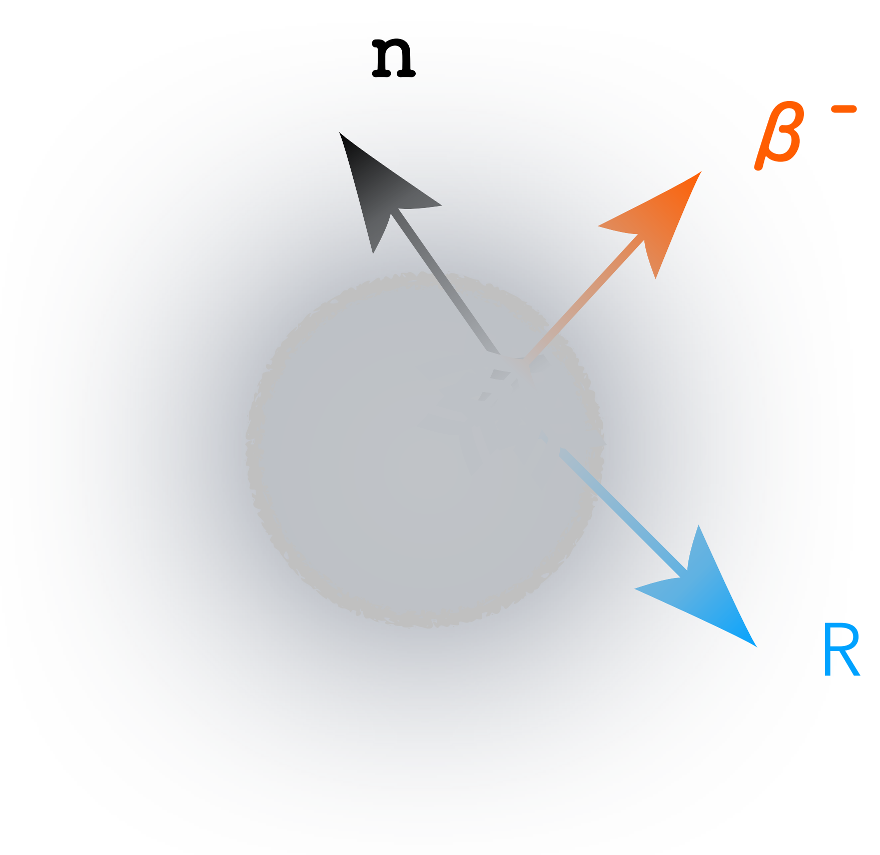
- errors in the measurement of the time of flight:
  - 3 ns timing resolution (so 1% effect on a typical TOF of 300ns)
- approximating the trajectory of the recoil ion as a straight line - this will be slightly curved due to the E field. This is a very small effect (<1%)
- errors in measurement of distance:
  - position resolution on the MCP
    - 1 mm pixel resolution
    - MCP face 53 mm from trap centre
    - in the most extreme case, error in distance is < 1%



What affects the neutron energy resolution?

Where in the ion cloud did the precursor decay?

- Assumed to be a Gaussian distribution in 3 dimensions
- Experimentally determined to be ~1mm^3 for ^{134}Sb [1]

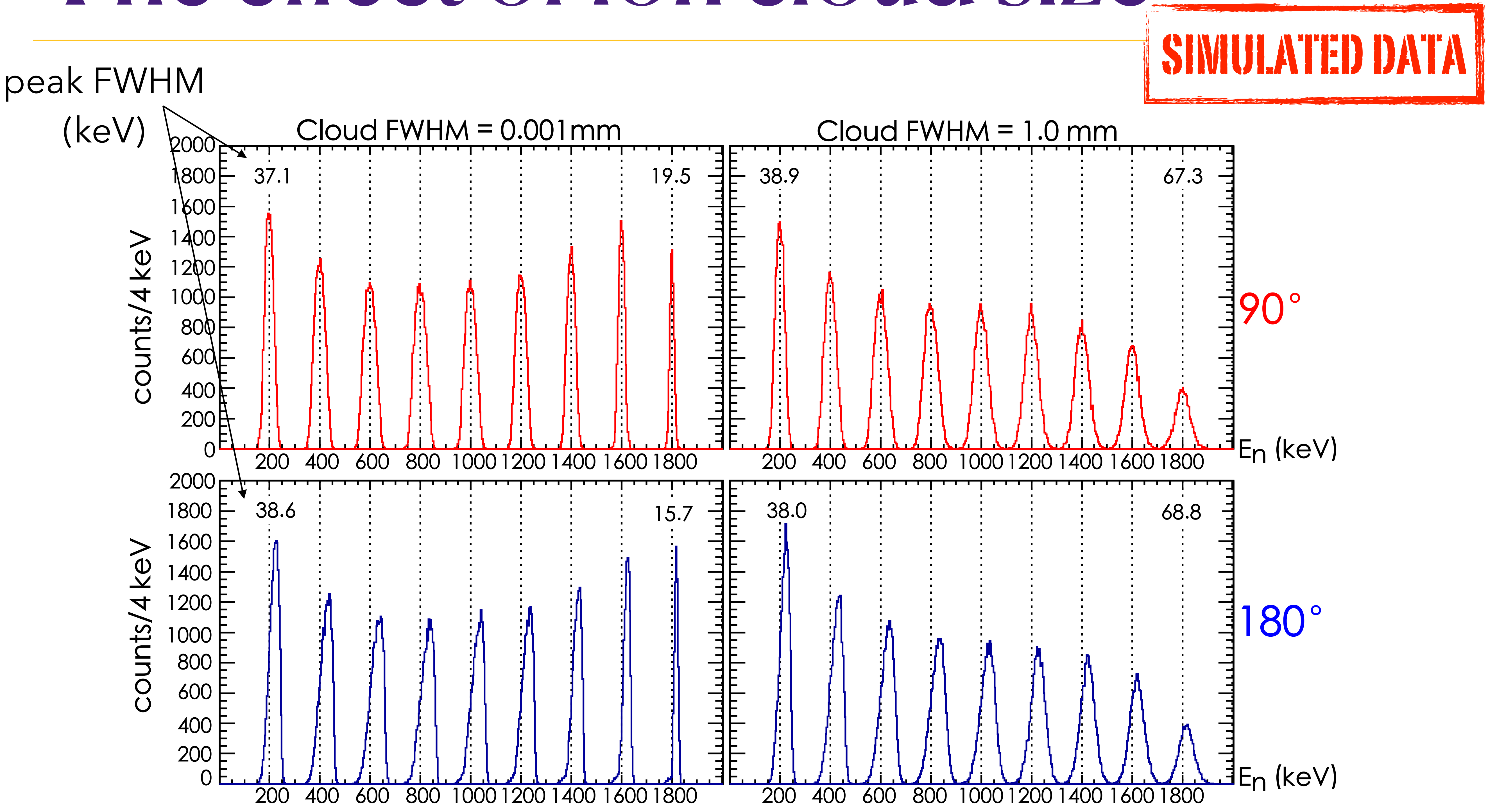


How do we determine the effect of the ion cloud size on E'_n?

- Simulation!
- Simulate both a realistic ion cloud size (1mm^3) and a point-like ion cloud, to 'switch off' the effect

[1] K. Siegl et al., Phys Rev C 97 035504 (2018)

The effect of ion cloud size

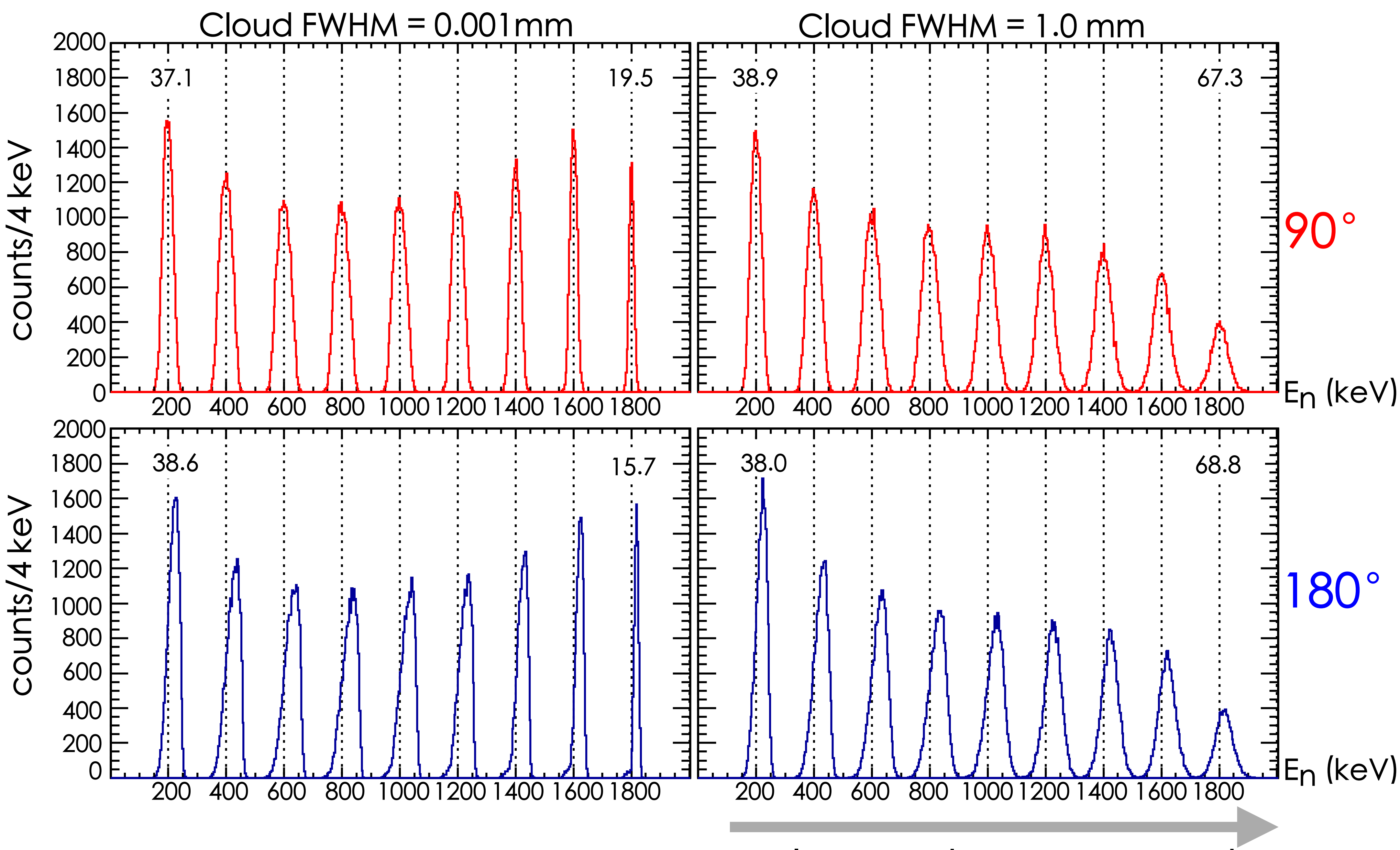


Simulation: ^{137}I precursor, allowed GT decay

GLW et al., in preparation

The effect of ion cloud size

SIMULATED DATA

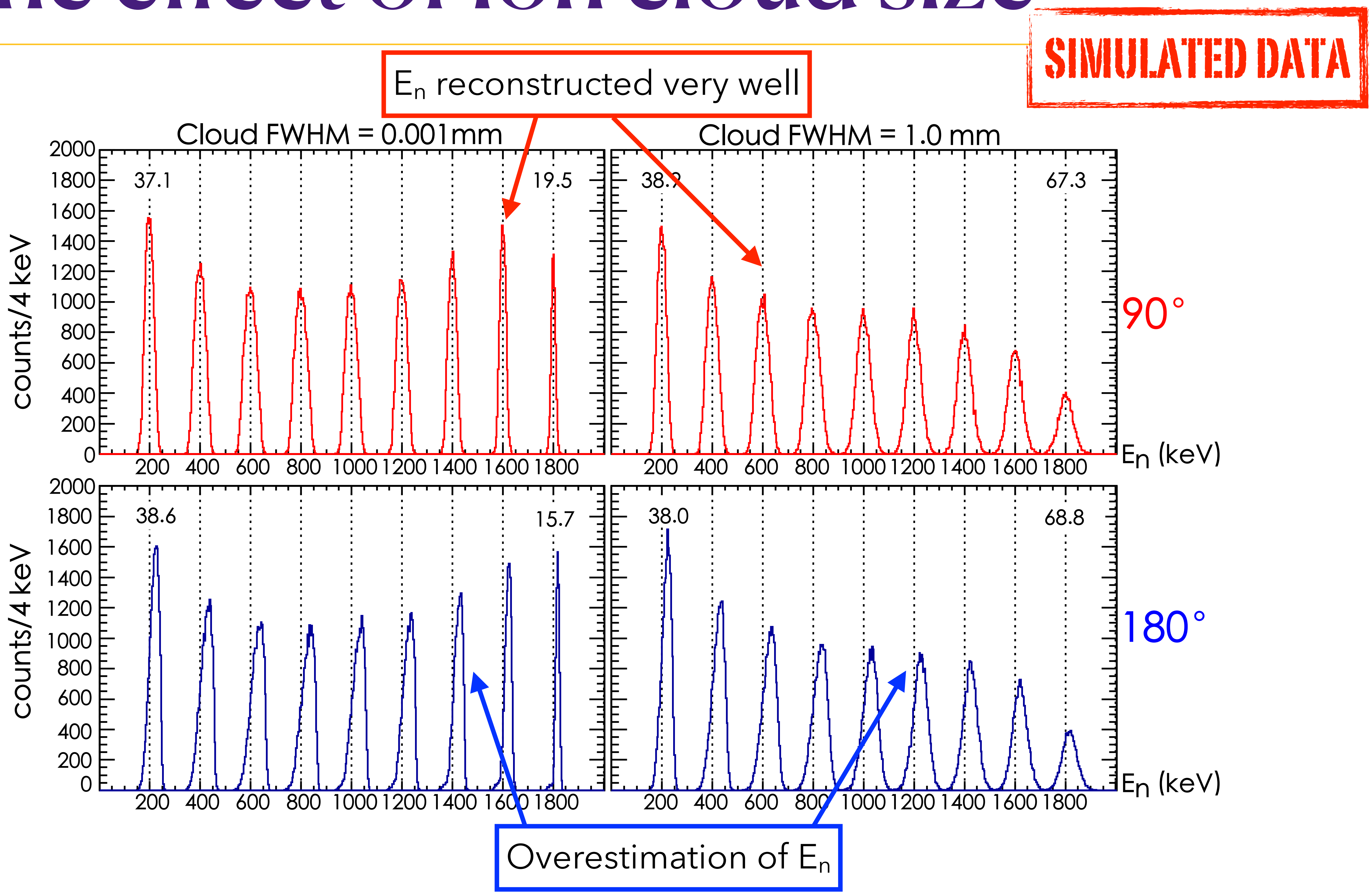


resolution decreases with E_n

Simulation: ^{137}I precursor, allowed GT decay

GLW et al., in preparation

The effect of ion cloud size



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Measuring E_n without direct detection

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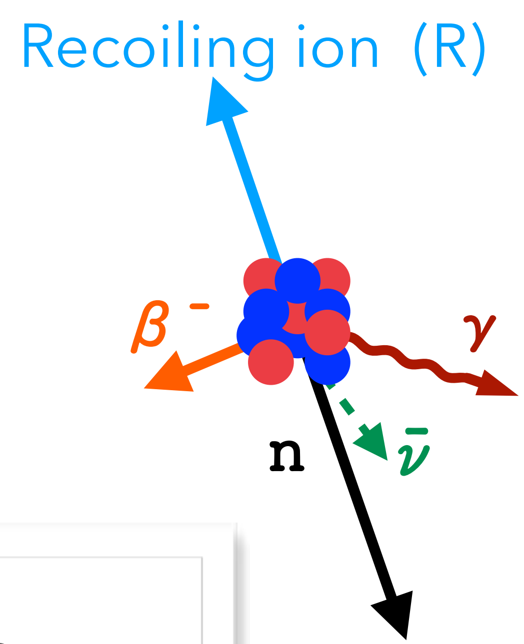


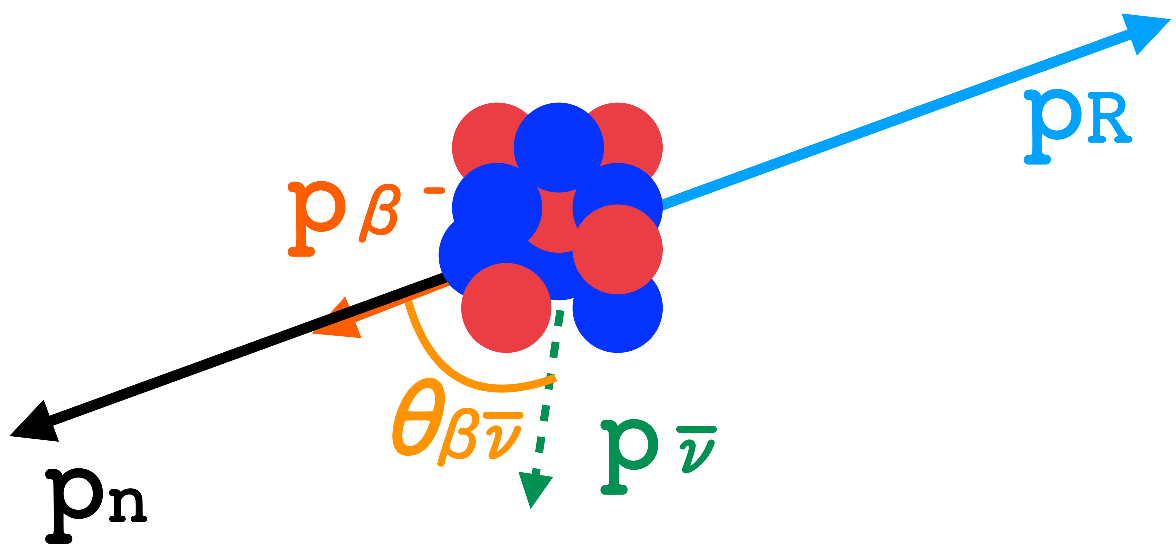
$$E_n = \frac{|\mathbf{p}_R|^2}{2m_n} = \frac{1}{2}\frac{m_R^2 (d/TOF)^2}{m_n}$$

- Measurements of d and TOF introduce broadening in E_n
- Lepton contributions cannot be ignored

How does β-ν̄-n affect E'$_n$?

$\mathbf{p}_\beta \parallel \mathbf{p}_n$ ($\theta_{\beta n}$ = 0°):

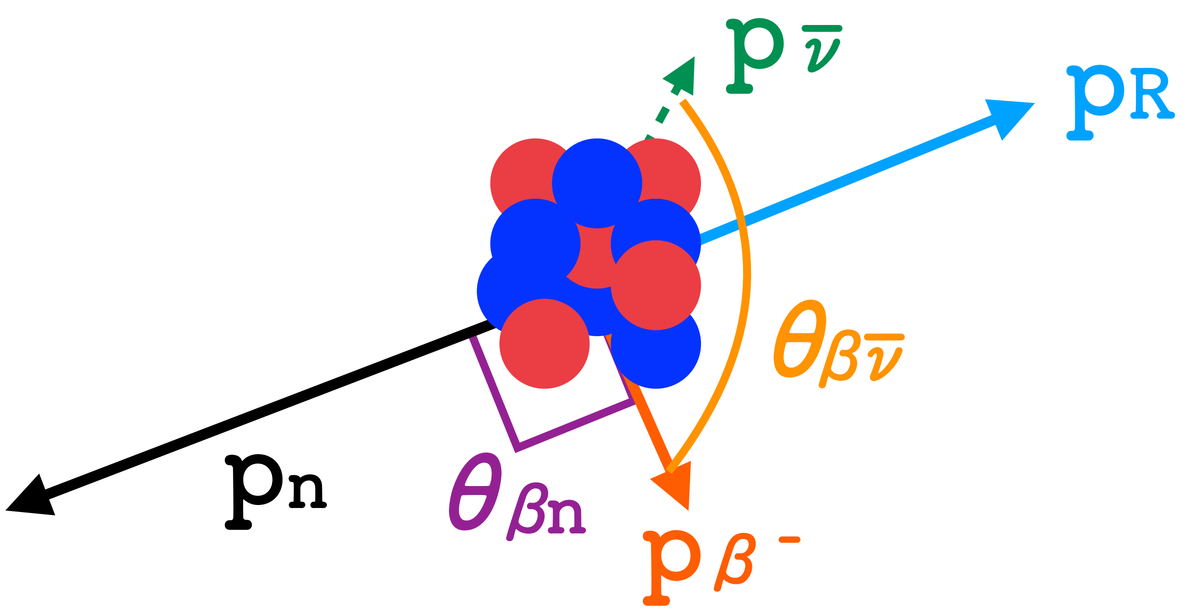
- $\mathbf{p}_\beta$ has a maximum contribution to $\mathbf{p}_R$
- $\mathbf{p}_R$ is boosted by the β^-



…leading to an overestimation of E'$_n$.

$\mathbf{p}_\beta \perp \mathbf{p}_n$ ($\theta_{\beta n}$ = 90°):

- $\mathbf{p}_R$ is not boosted by the β^-



… and so E'$_n \approx$ E$_n$.

β-ν̄-n triple correlations

$$W(\theta) = 1 + a_{\beta\bar{\nu}} \frac{\vec{p}_\beta}{E_\beta} \cos(\theta_{\beta\bar{\nu}}) +$$

$$G_{12} \frac{\vec{p}_\beta}{E_\beta} \left[\cos(\theta_{n\beta}) \cos(\theta_{n\bar{\nu}}) - \frac{1}{3} \cos(\theta_{\beta\bar{\nu}}) \right]$$

adapted from BR Holstein, Rev. Mod. Phys. 46 (4) (1974)

β-ν̄-n triple correlations

phase space

β-ν̄ term, $-1 < a_{\beta\bar{\nu}} < 1$

$$W(\theta) = 1 + a_{\beta\bar{\nu}} \frac{\vec{p}_\beta}{E_\beta} \cos(\theta_{\beta\bar{\nu}}) +$$

$$G_{12} \frac{\vec{p}_\beta}{E_\beta} \left[\cos(\theta_{n\beta}) \cos(\theta_{n\bar{\nu}}) - \frac{1}{3} \cos(\theta_{\beta\bar{\nu}}) \right]$$

β-ν̄-n term

$G_{12} \sim 1$

adapted from BR Holstein, Rev. Mod. Phys. 46 (4) (1974)

The β-ν̄-n term in W(θ)

$$G_{12} \frac{\vec{p}_\beta}{E_\beta}\left[\cos(\theta_{n\beta})\cos(\theta_{n\bar{\nu}}) - \frac{1}{3}\cos(\theta_{\beta\bar{\nu}})\right]$$

$$G_{12} \equiv g_{12} \frac{1}{10} \tau_{j'j''}$$

BR Holstein, Rev. Mod. Phys. 46 (4) (1974); MG Sternberg *et al.*, PRL 115 182501 (2015)

The β-ν̄-n term in W(θ)

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$$G_{12} \equiv g_{12}\,\frac{1}{10}\,\tau_{j'j''}$$

g_{12} depends on the matrix elements (Fermi & Gamow-Teller)

Function that depends on the spin sequence,

Precursor → emitter → βn daughter

$$j \to j' \to j'',$$

and L, the angular momentum of the neutron with respect to the daughter nucleus

BR Holstein, Rev. Mod. Phys. 46 (4) (1974); MG Sternberg *et al.*, PRL 115 182501 (2015)

The β-$\bar{\nu}$-n term in W(θ)

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Function that depends on the spin sequence,

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$$j \to j' \to j'',$$

and *L*, the angular momentum of the neutron with respect to the daughter nucleus

$\mathbf{p}_\beta \parallel \mathbf{p}_n$ ($\theta_{\beta n}$ = 0°): $G_{12}>0$

$\mathbf{p}_\beta \perp \mathbf{p}_n$ ($\theta_{\beta n}$ = 90°): $G_{12}<0$

BR Holstein, Rev. Mod. Phys. 46 (4) (1974); MG Sternberg *et al.*, PRL 115 182501 (2015)

...and what that means for us

$$j \to j' \to j''$$

$$^{137}\mathrm{I}\left(\frac{7}{2}^{+}\right) \to {}^{137}\mathrm{Xe}\left(\frac{9}{2}^{+},\frac{7}{2}^{+},\frac{5}{2}^{+}\right) \to {}^{136}\mathrm{Xe}(0^{+})$$

$$^{99}\mathrm{Y}\left(\frac{5}{2}^{+}\right) \to {}^{99}\mathrm{Zr}\left(\frac{7}{2}^{+},\frac{5}{2}^{+},\frac{3}{2}^{+}\right) \to {}^{98}\mathrm{Zr}(0^{+})$$

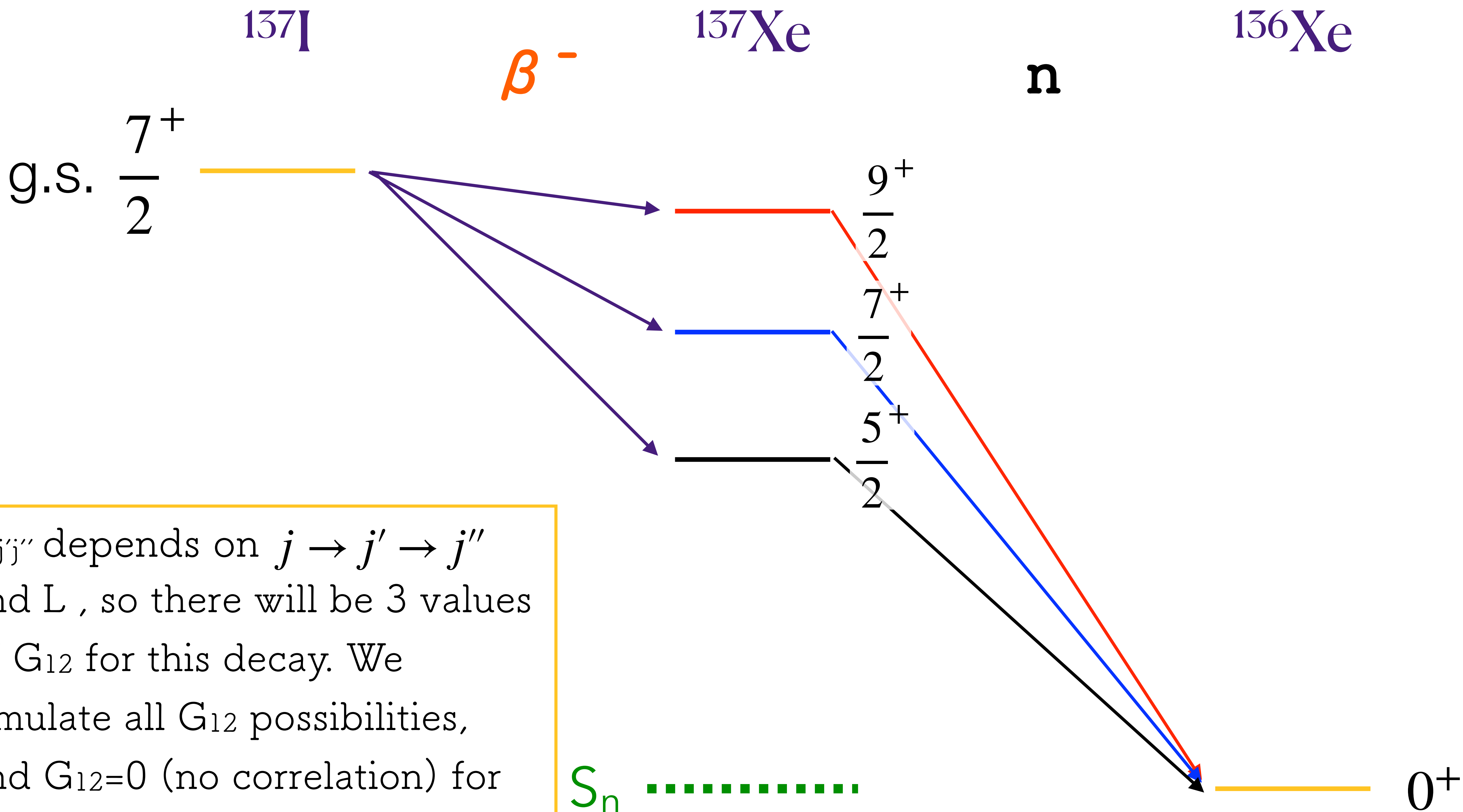
$$^{135}\mathrm{Sb}\left(\frac{7}{2}^{+}\right) \to {}^{135}\mathrm{Te}\left(\frac{9}{2}^{+},\frac{7}{2}^{+},\frac{5}{2}^{+}\right) \to {}^{134}\mathrm{Te}(0^{+},2^{+},4^{+})$$

We don't know the exact branchings of the spin sequences

- ➡ G_{12} has a range of possible values
- ➡ changes the correction we need to apply

Using ^{137}I as an example:

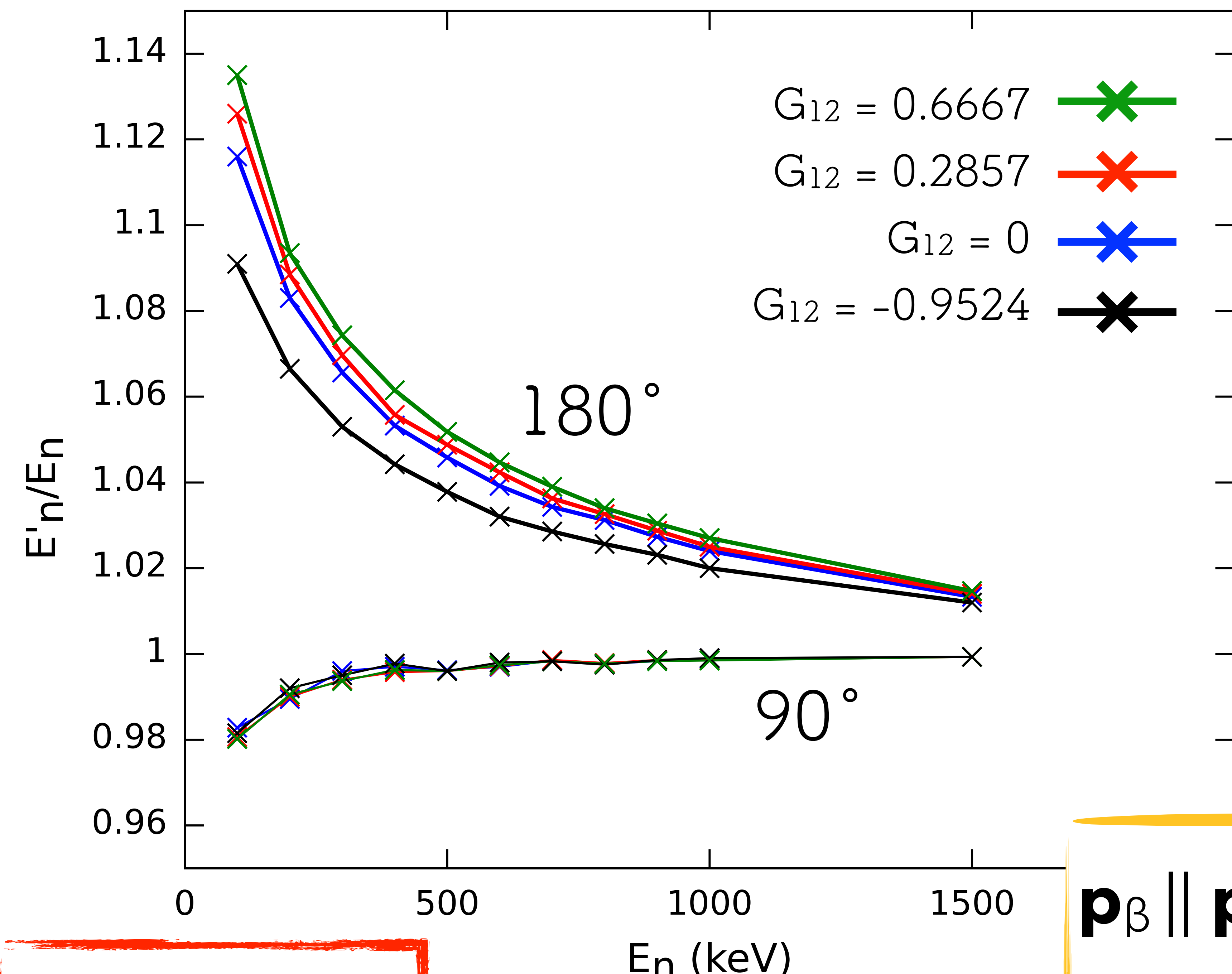
Allowed Gamow-Teller decay



$\tau_{j'j''}$ depends on $j \rightarrow j' \rightarrow j''$ and L , so there will be 3 values of G_{12} for this decay. We simulate all G_{12} possibilities, and G_{12}=0 (no correlation) for reference.

simulated events = #decays x #E_n x #G_{12} x #ion cloud sizes

How does β-$\bar{\nu}$-n affect E'_n? ^{137}I



SIMULATED DATA

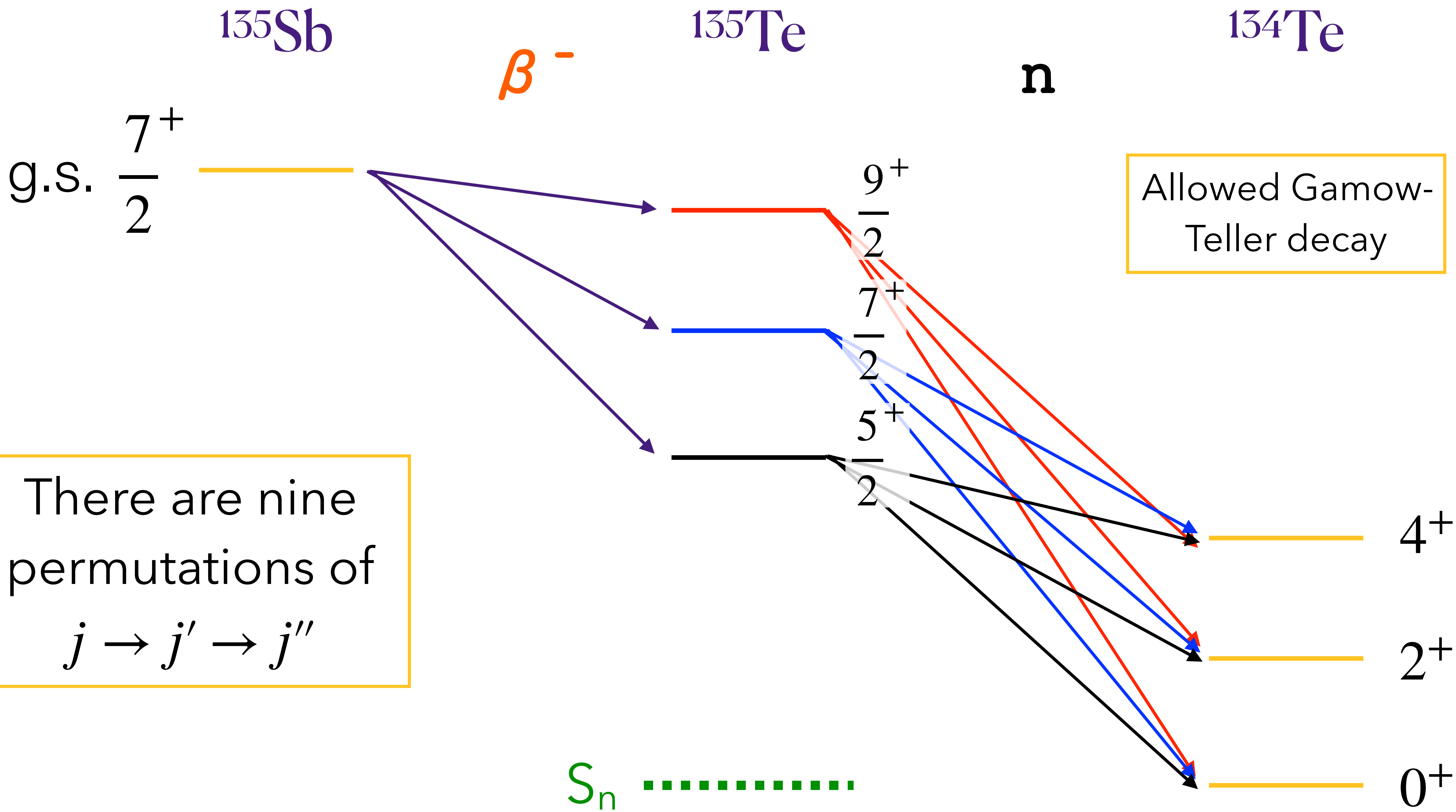
for E_n = 100 keV, β-R detected in 180° detector pair, G_{12} = 0.6667: **E'_n = 113.5 keV**

Spread in E'_n/E_n at 180°, especially for low E_n, but little spread at 90°.

$\mathbf{p}_\beta \parallel \mathbf{p}_n$ ($\theta_{\beta n}$ = 0°): $G_{12}>0$

$\mathbf{p}_\beta \perp \mathbf{p}_n$ ($\theta_{\beta n}$ = 90°): $G_{12}<0$

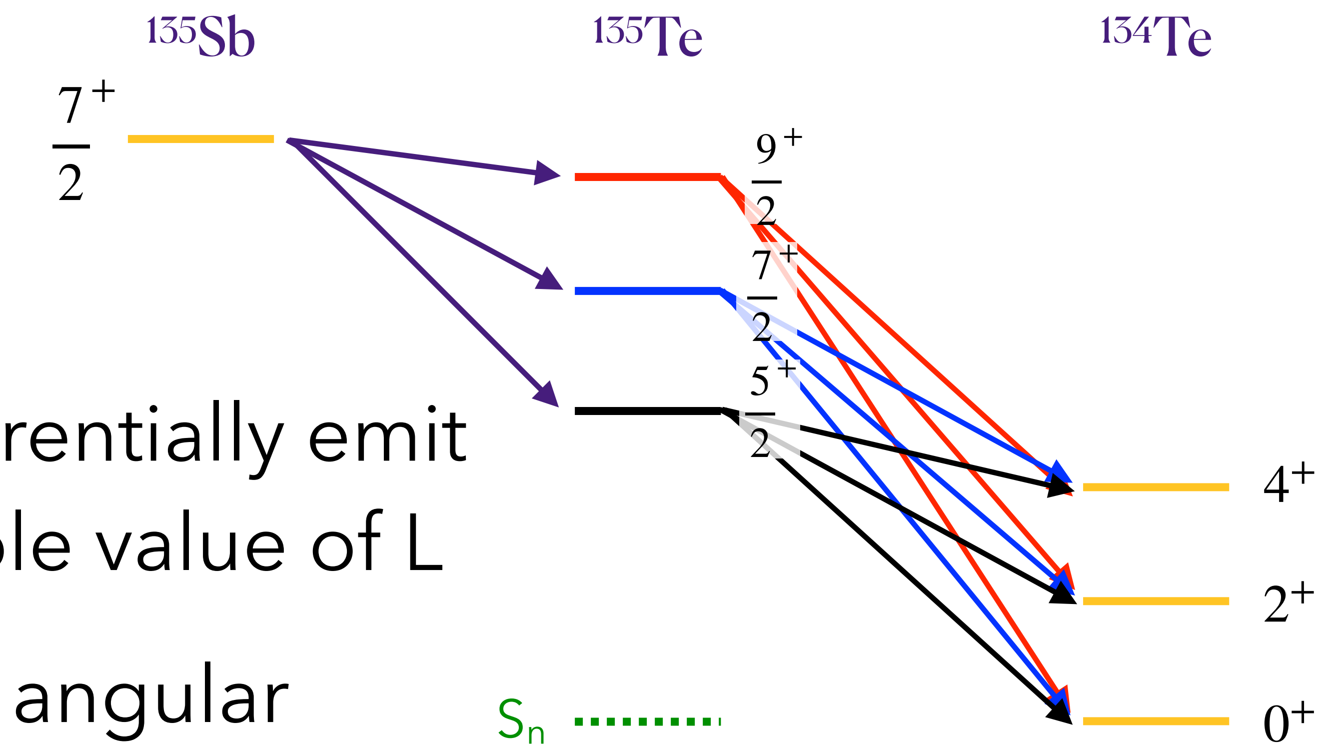
A more complex example: ^{135}Sb



Allowed Gamow-Teller decay

There are nine permutations of $j \rightarrow j' \rightarrow j''$

Using ^{135}Sb as an example:



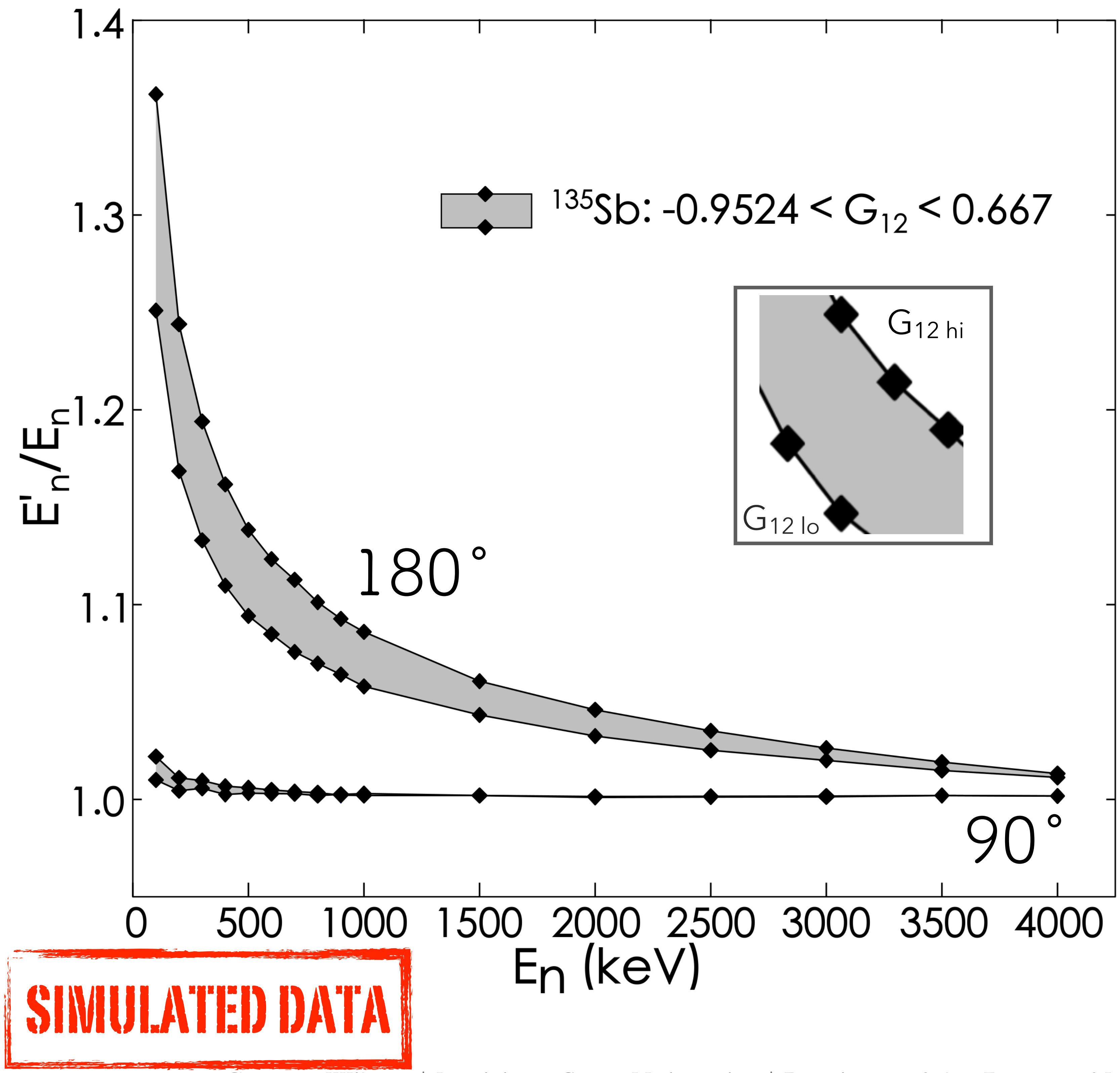
- There are 9 spin sequence permutations possible
- We assume the nucleus will preferentially emit the neutron with the lowest allowable value of L
- There are also two cases in which angular momentum of ^{134}Te ⊗ intrinsic neutron spin has two values for the same L, hence two values of G_{12}:

$$\frac{7}{2}^+ \rightarrow \frac{7}{2}^+ \rightarrow 2^+ \longrightarrow \frac{3}{2} \text{ or } \frac{5}{2}$$

$$\frac{7}{2}^+ \rightarrow \frac{5}{2}^+ \rightarrow 4^+ \longrightarrow \frac{7}{2} \text{ or } \frac{9}{2}$$

depends if the intrinsic neutron spin is aligned with L

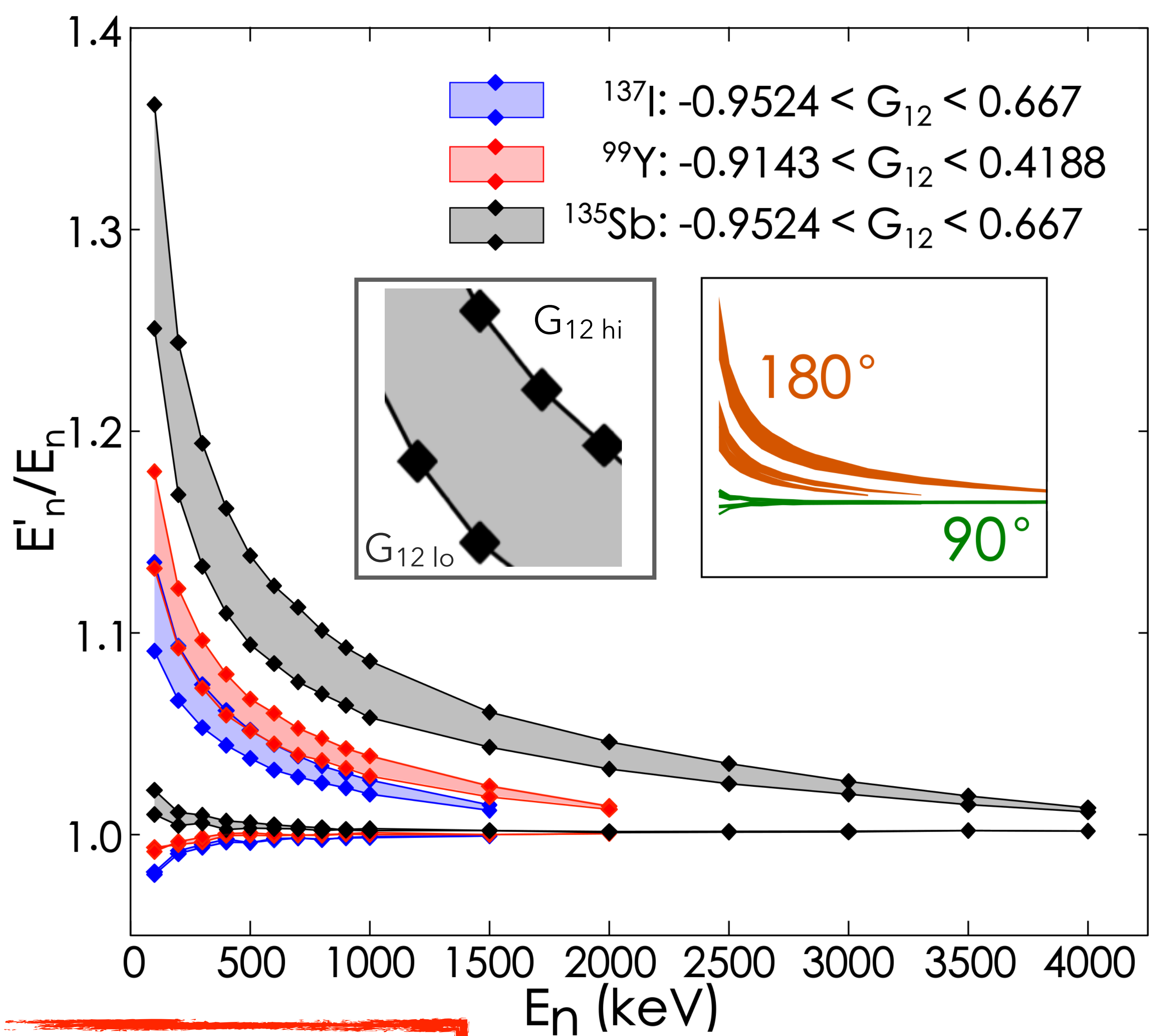
How does β-$\bar{\nu}$-n affect E'_n? ^{135}Sb

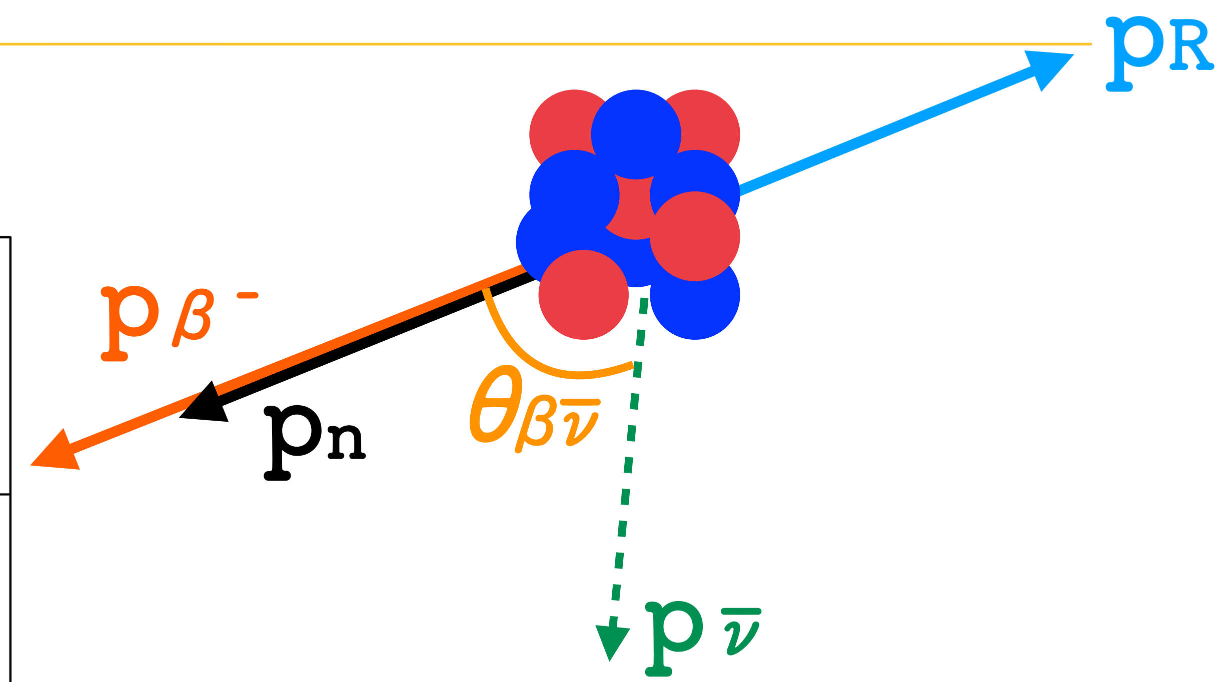


for E_n = 100 keV,
β-R detected in 180° detector pair,
G_{12} = 0.6667:
E'_n = 136.2 keV

Bigger effect than for the case of ^{137}I:
$Q_{\beta\text{-}n}$ (^{137}I) = 2.002 MeV
$Q_{\beta\text{-}n}$ (^{135}Sb) = 4.772 MeV

Effect of lepton recoil on E’n



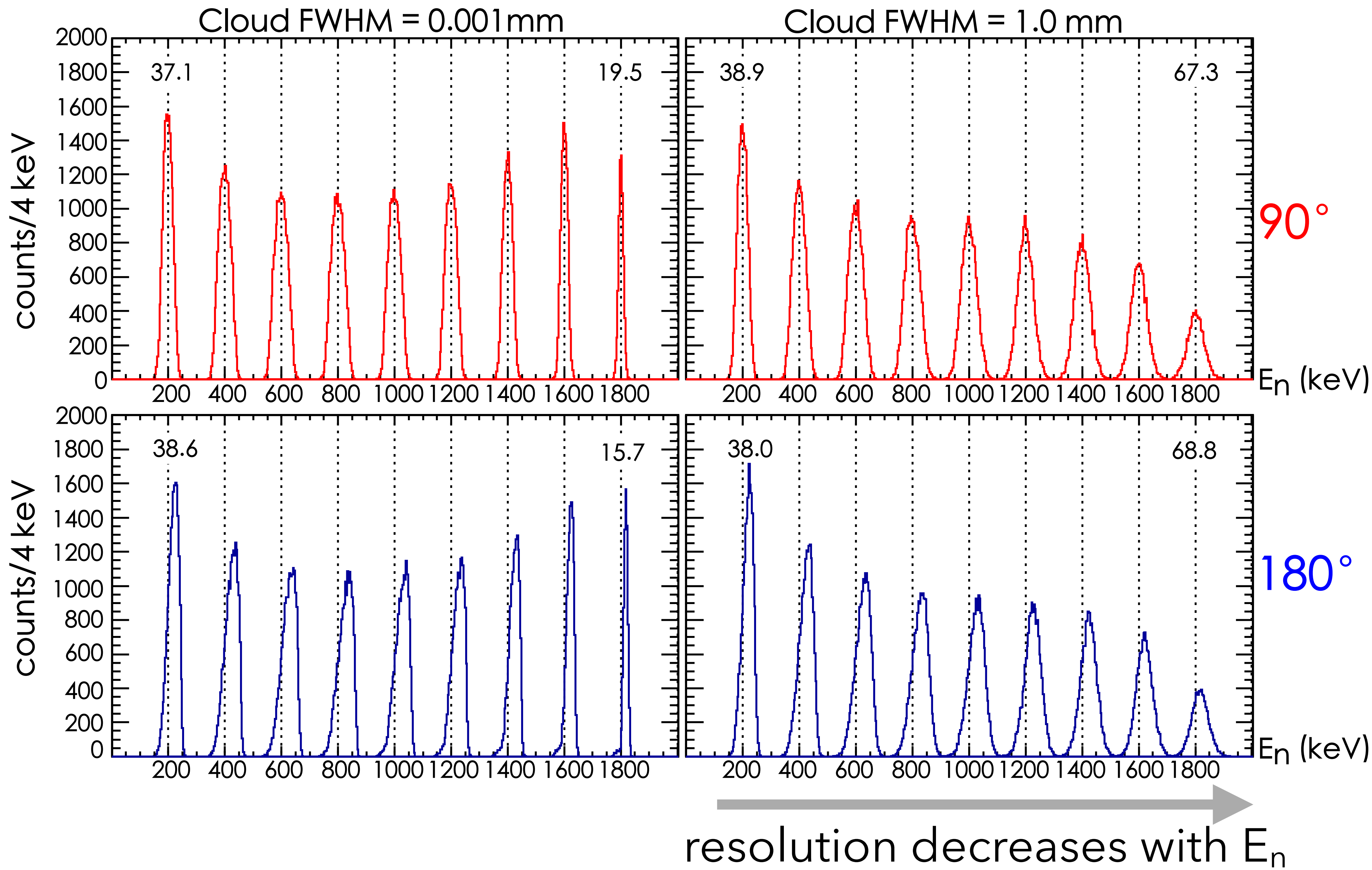


- For each precursor, the two extreme G_{12} values are plotted
- E'_n/E_n is the ratio of reconstructed neutron energy to true neutron energy
- point-size ion cloud
- marked difference for β-recoil coincidences detected at 180°

SIMULATED DATA

The effect of ion cloud size

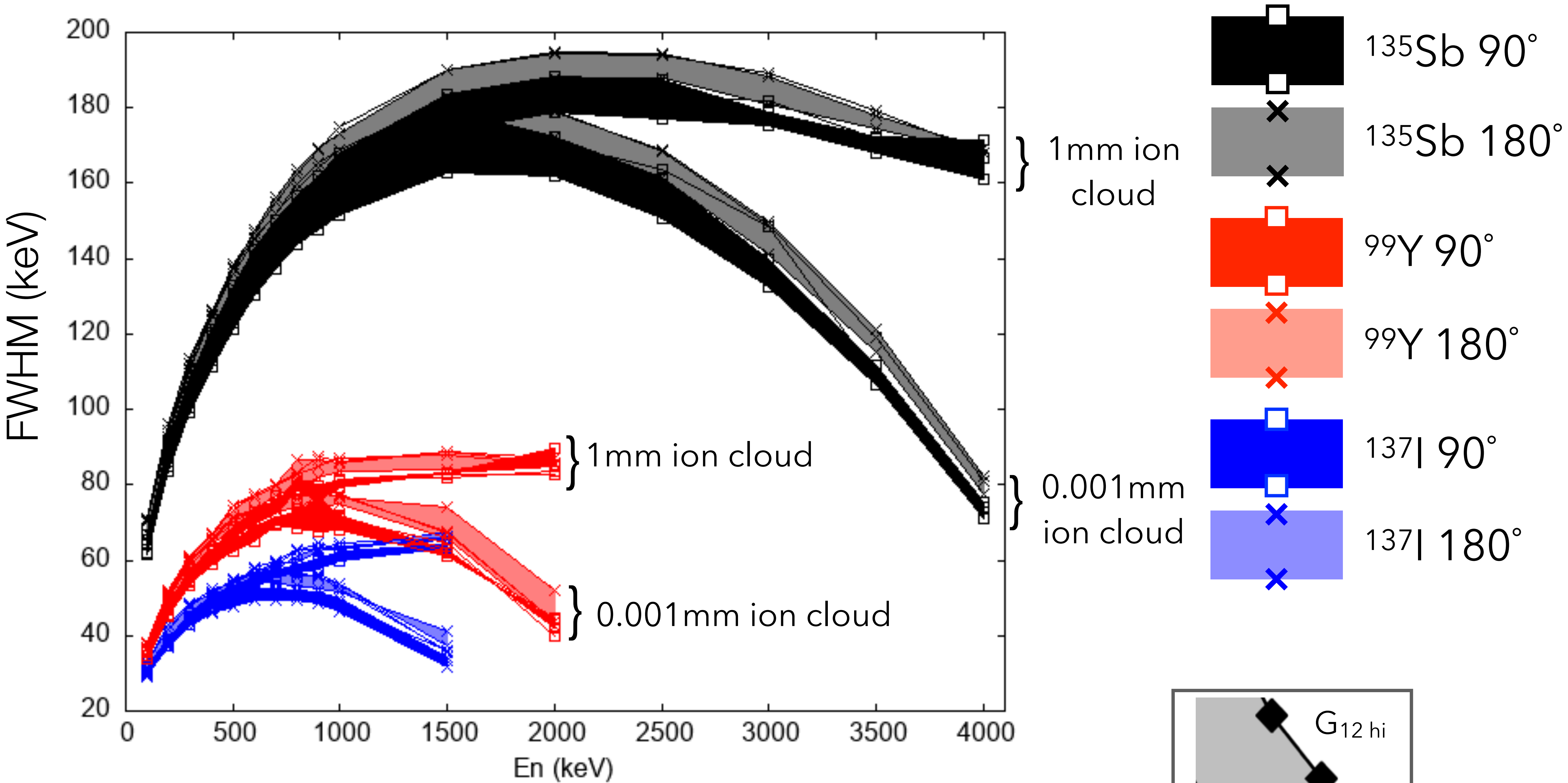
SIMULATED DATA



Simulation: ^{137}I precursor, allowed GT decay

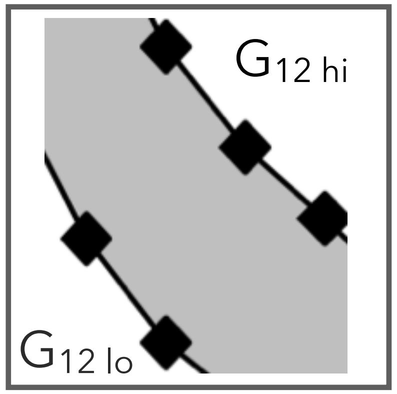
GLW et al., in preparation

Effect of lepton recoil and ion cloud size



SIMULATED DATA

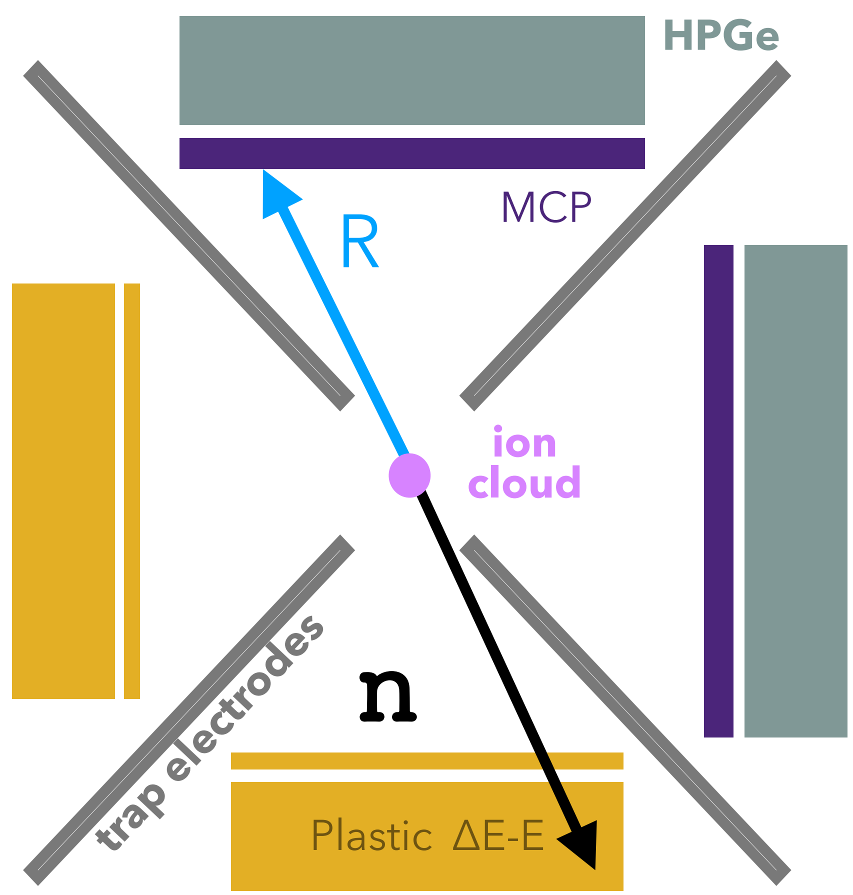
All values of G_{12} plotted

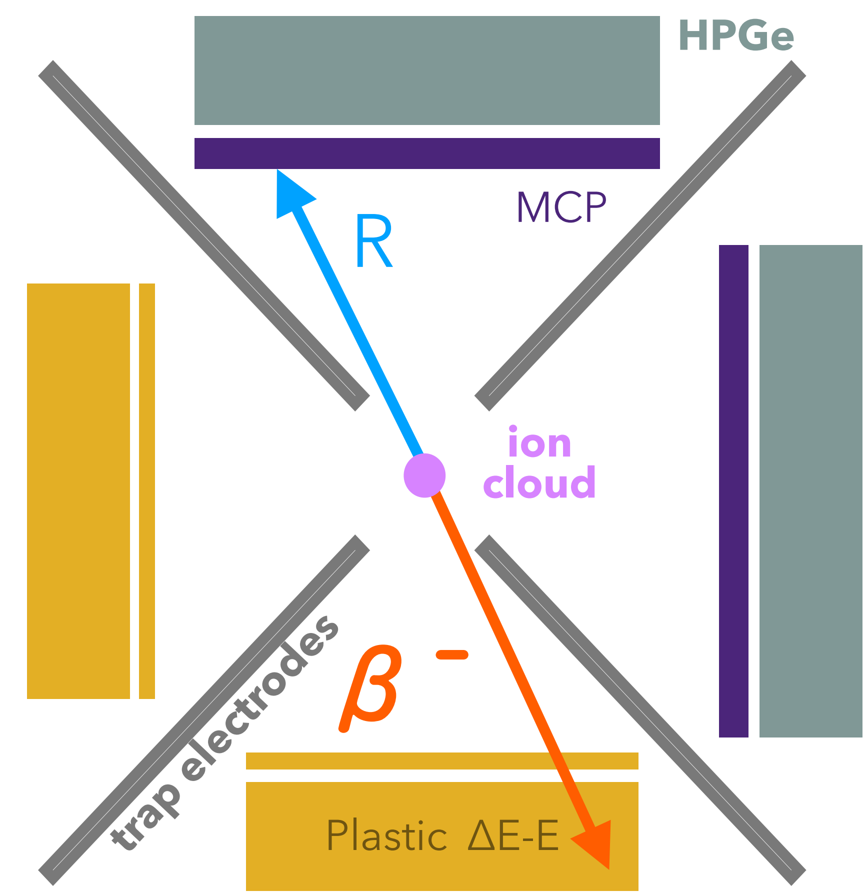


Neutron-induced background

- ΔE detector cannot distinguish between β, n.
- Neutrons rarely trigger the ΔE, ~0.2% were detected
- However, with a neutron incident on the ΔE, it's likely (>50%) that the recoil will be detected in the MCP

- For a β incident on the ΔE, the chance of the recoil hitting the opposite MCP is ~5%.
- This was roughly a 10-15% effect, only seen in detector pairs at 180°.





Conclusions

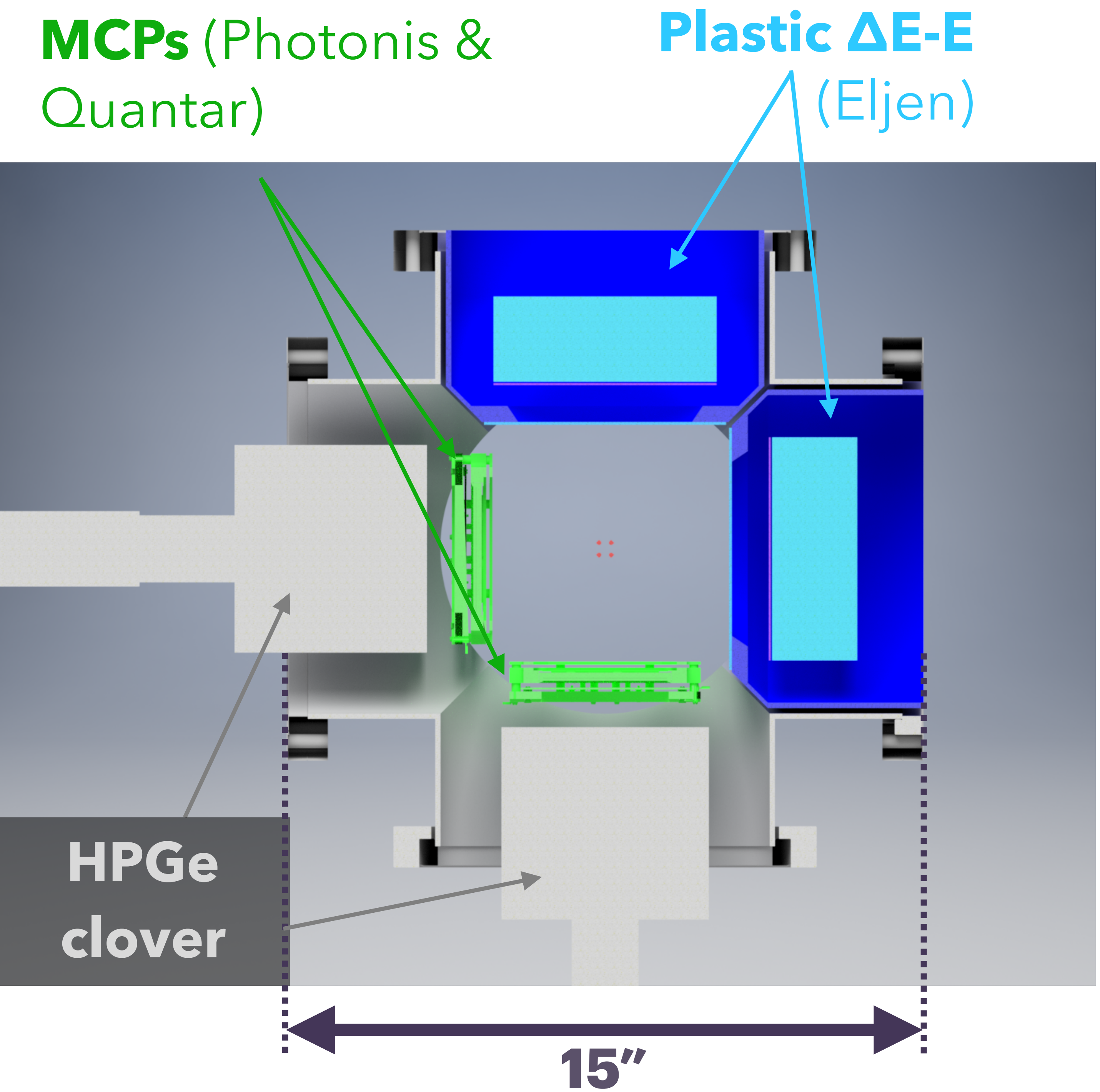
- Recoil-ion spectroscopy is a powerful method for measuring precision β and βn decay
- E_n and P_{1n} can be reconstructed without direct neutron detection

...but can we do better?

The need for a new dedicated setup

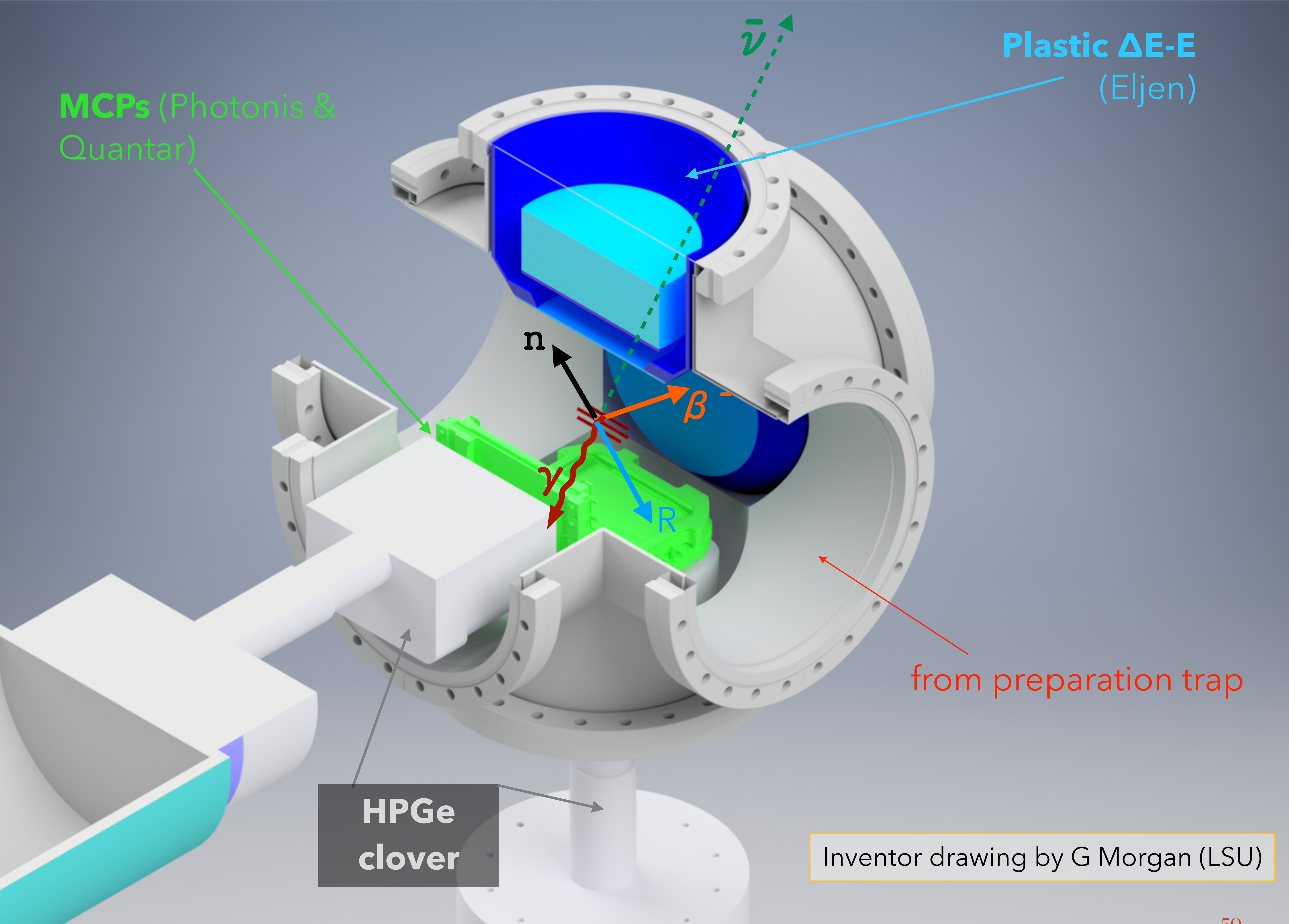
BPT	new setup
large ion cloud size	preparation trap for capture, cooling and bunching
Ions sticking to electrodes and not decaying from trap centre	new rod electrodes with smaller surface area; increased capture efficiency from preparation trap
quantifying backgrounds, especially neutrons	ΔE segmentation
Need better efficiency	3x higher β-recoil ion detection efficiency than BPT
	increased solid angles, new ΔE and light guide design to allow more light
Need better timing resolution	Eventually switch to digital DAQ

BEARtrap: BEtA Recoil ion trap



Inventor drawing by G Morgan (LSU)

- ✓ Increased detector solid angle from 9% (BPT) to 17%; MCP solid angle increased from 12% to 20%
- ✓ 3 x more β-recoil ion detection efficiency
- ✓ Smaller electrode design
- ✓ Use of loading trap prior to BEARtrap
- ✓ 100 mm x 80 mm Z-stack MCP to detect low-energy nuclear recoil
- ✓ 133 mm Ø plastic scintillator telescopes with 4-way segmented ΔE to distinguish recoil ion-neutron coincidences
- ✓ Improved ΔE design to allow more light; ~30 keV β threshold compared to ~70 keV with BPT
- ✓ Funded by ANL, LLNL and LSU (through USDOE Office of Nuclear Physics)



$\bar{\nu}$
Plastic ΔE-E
(Eljen)
MCPs (Photonis &
Quantar)
n
β^-
γ
R
from preparation trap
HPGe
clover
Inventor drawing by G Morgan (LSU)

The need for a new dedicated setup

BPT	new setup
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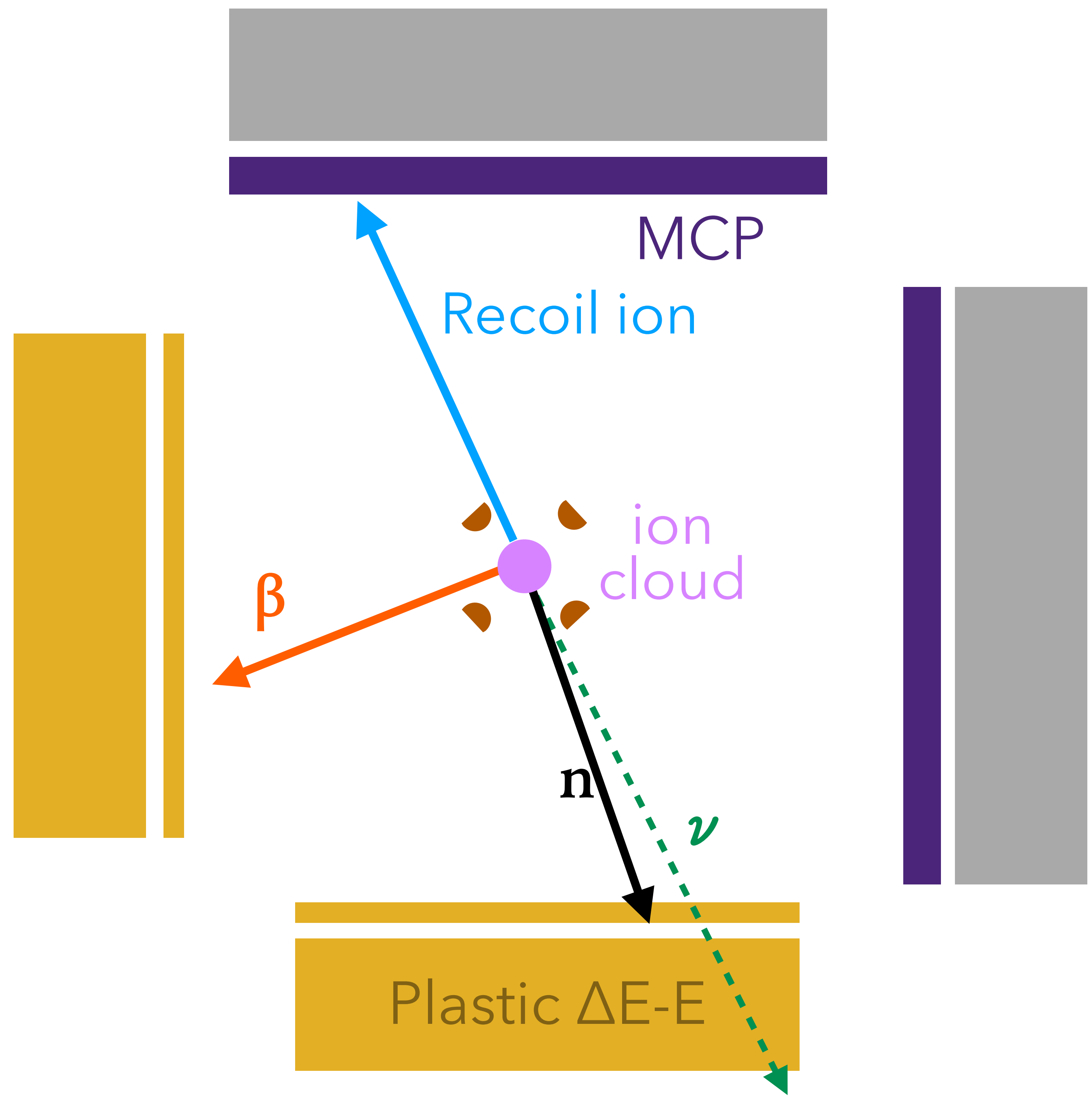
	increased solid angles, new ΔE and light guide design to allow more light
Need better timing resolution	Eventually switch to digital DAQ

Characterising n-induced background with segmented ΔE

- If a neutron is incident on the ΔE, it's highly likely that a recoiling ion will hit the opposite MCP
  - ➡ this leads to a background contribution
- Neutron-recoil coincidences detected at 180°
  - ➡ Use this to identify n-recoil events and remove them from background

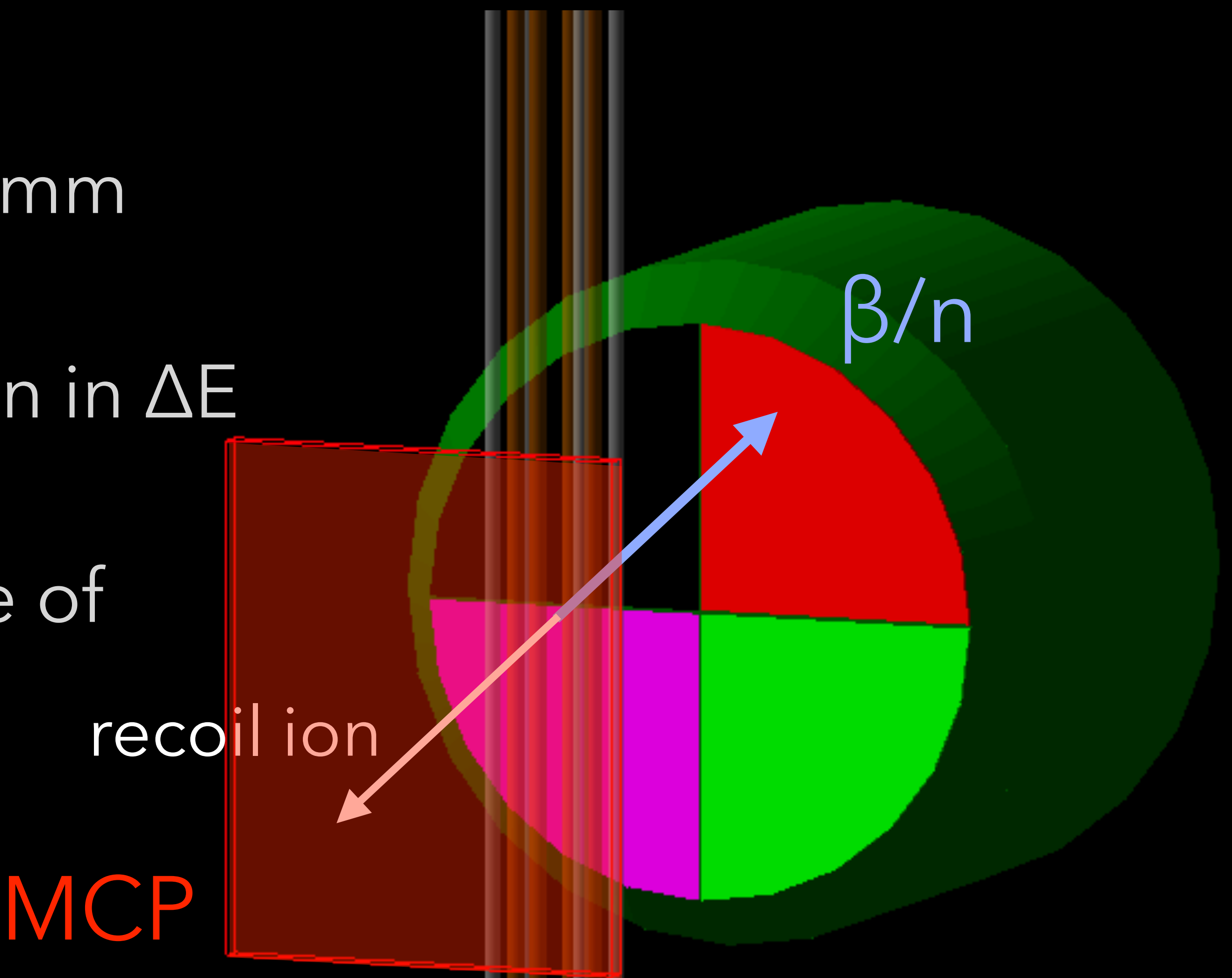


Characterising n-induced background with segmented ΔE

- Gain position sensitivity from segmenting the ΔE detector
- Does this information help to distinguish between recoil ion-β events and recoil ion-neutron events?

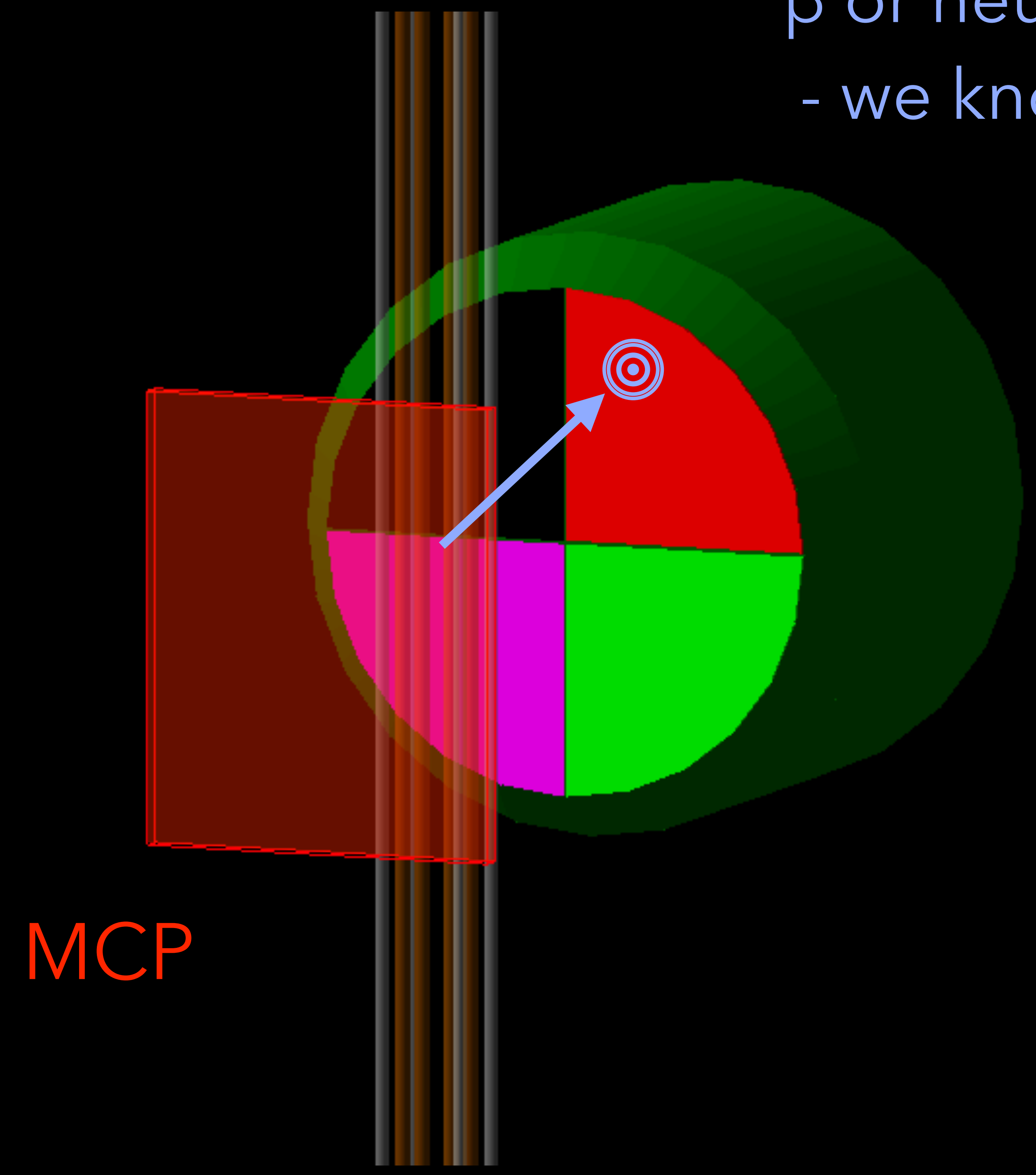
In simulations:

- Detect recoil ion on MCP with ~1mm resolution
- Check for signal from β or neutron in ΔE segment 180˚ from recoil ion
- In reality, we cannot tell what type of particle is hitting the ΔE!



Using simulations to ID particles

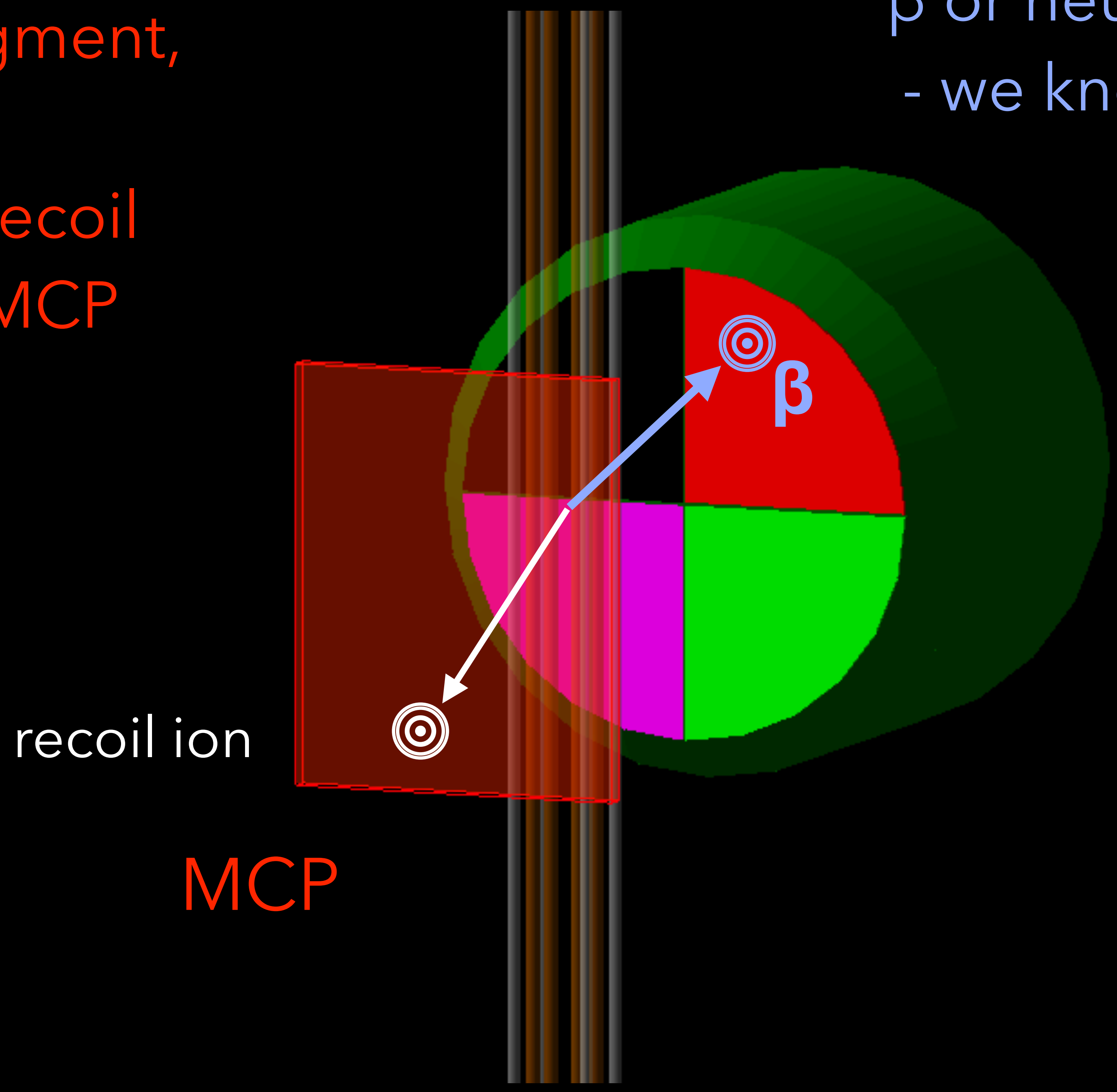
Hit on dE segment:
β or neutron?
 - we know with GEANT4



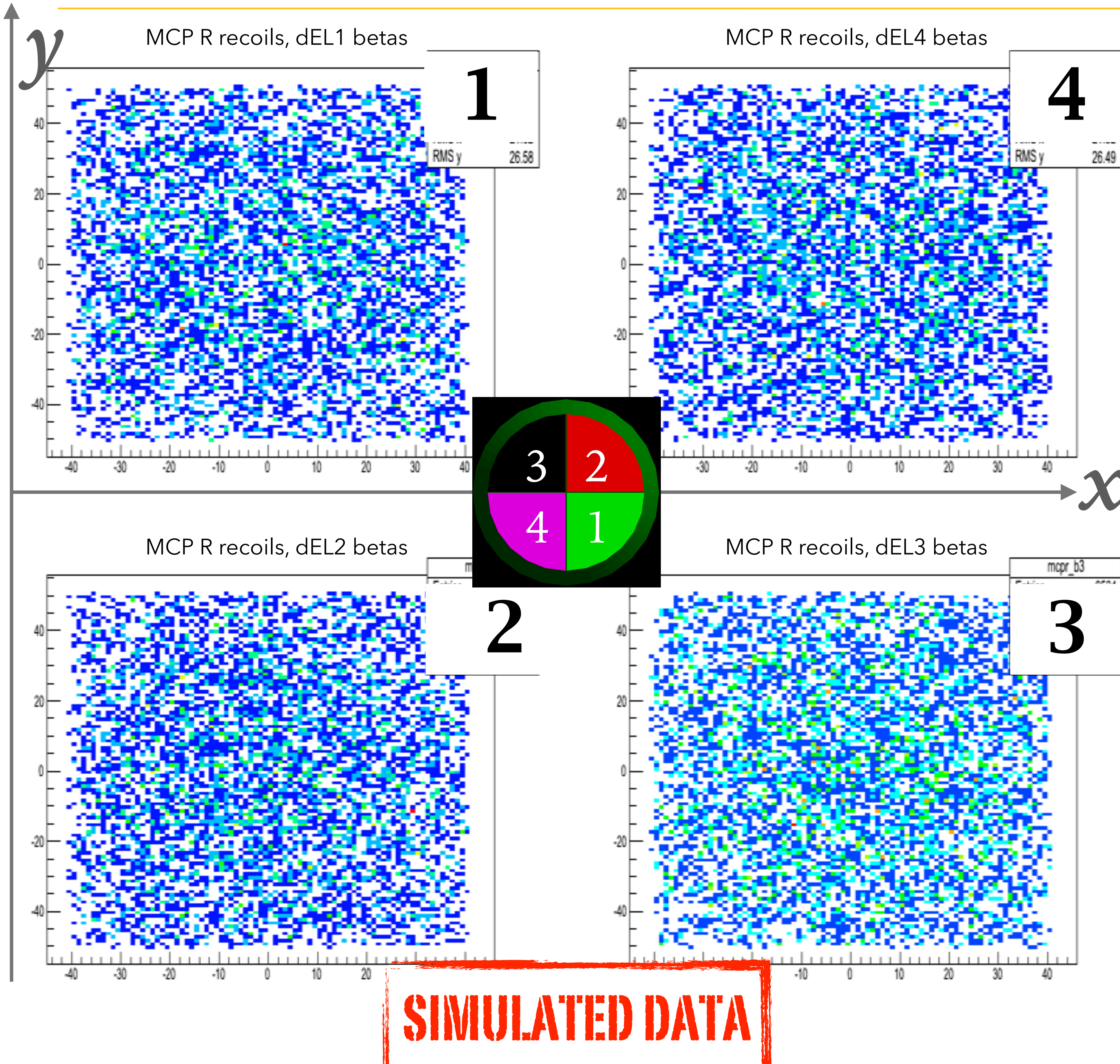
For a β hit on the ΔE, where was the recoil detected?

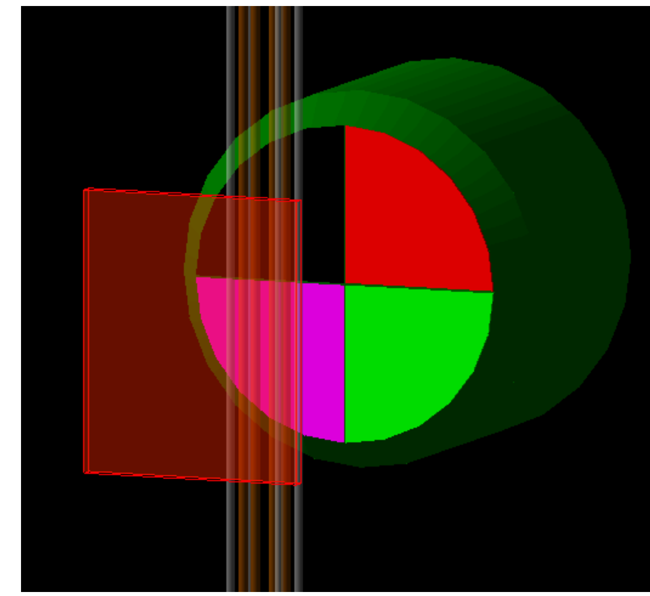
Require that a **β** hit a ΔE segment, and look at where the recoil ion hit the MCP

Hit on dE segment:
β or neutron?
- we know with GEANT4



Recoil ion distribution on MCP for coincident β





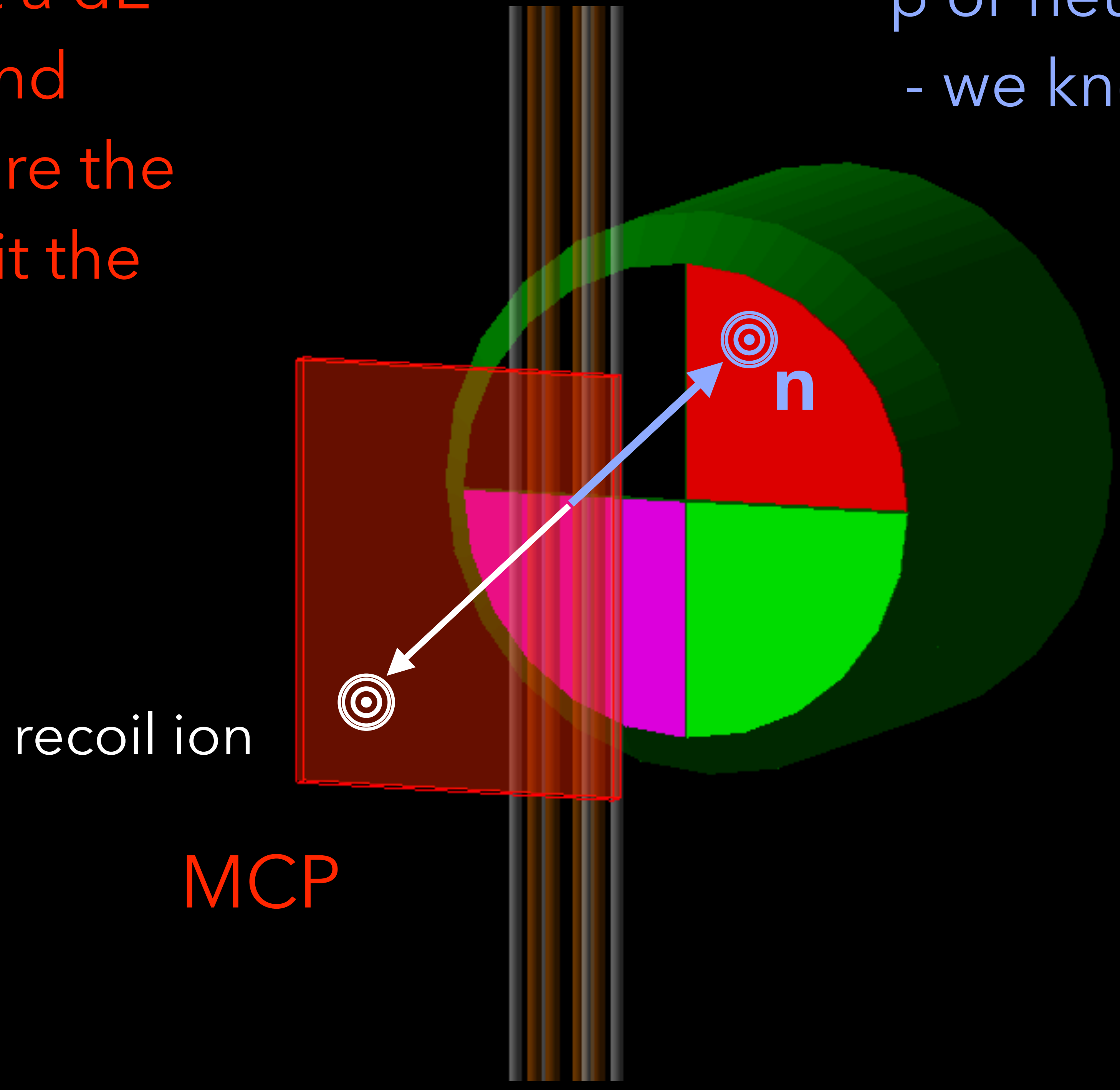
MCP position of recoil, gated on β detected in ΔE segment

For a β detected in a ΔE segment, the recoil ion is **equally likely** to be detected anywhere on the opposite MCP

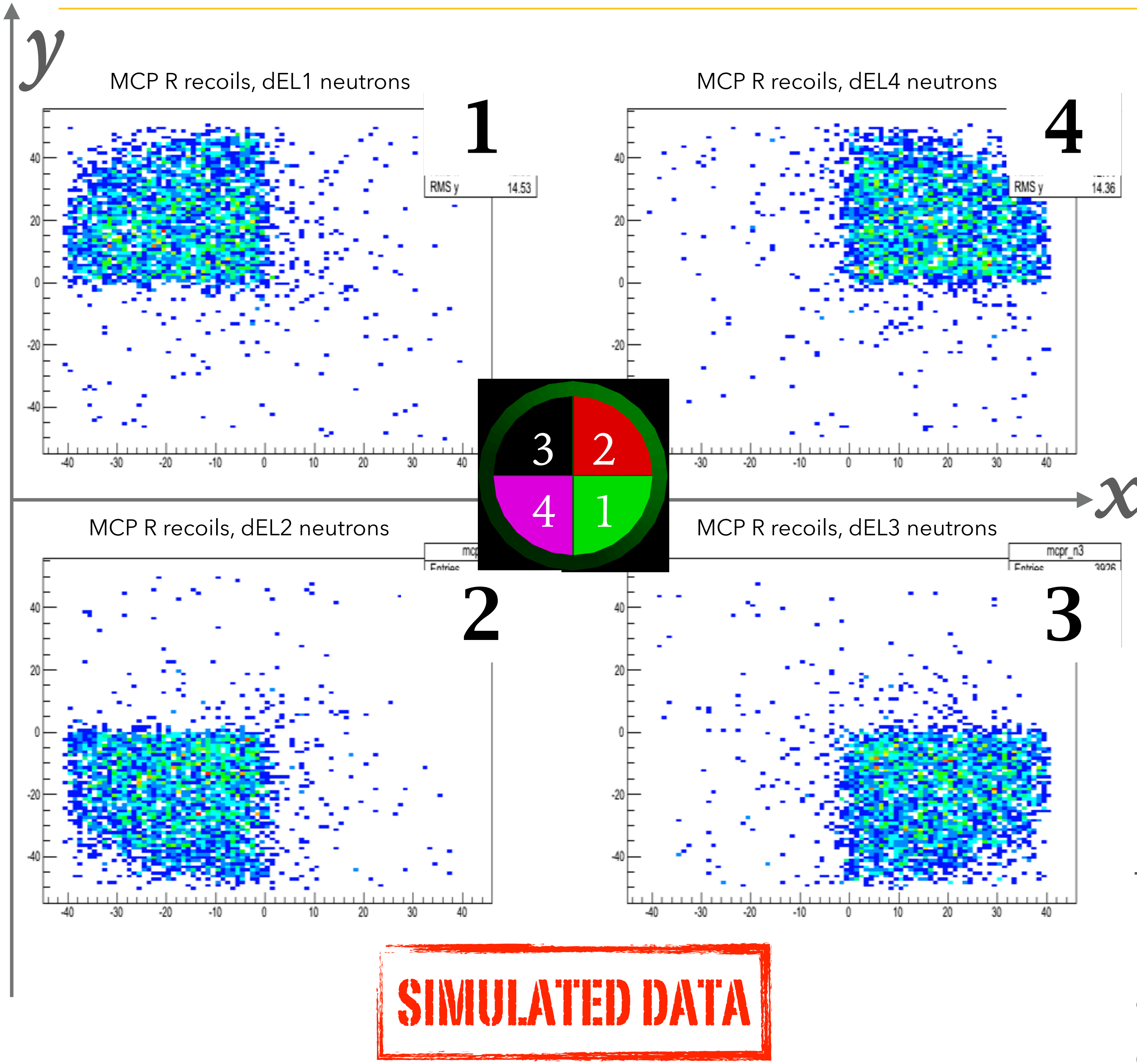
For a n hit on the ΔE, where was the recoil detected?

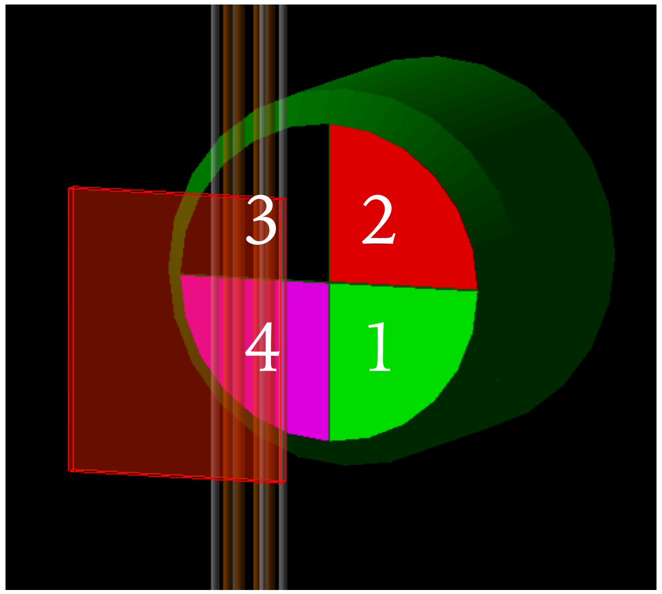
Require that a **neutron** hit a dE segment, and look at where the recoil ion hit the MCP

Hit on dE segment:
β or neutron?
- we know with GEANT4



Recoil ion distribution on MCP for coincident n





MCP position of recoil, gated on neutron detected in ΔE segment

Having position information from the ΔE is powerful - recoil ions are detected 180° away from the neutron **96%** of the time

Current status & approved experiments

Current Status:

- MCPs manufactured and tested by Quantar
- ΔE-E design finalised with Eljen and order placed
- Preparation trap design being finalised
- design of beam line components being finalised and constructed for BEARtrap to be placed in Area 1 @ ANL

CARIBU - Approved experiments:

- Commissioning experiment: ^{137}I (βn emission) and ^{92}Rb (β decay: $0^{+} \rightarrow 0^{-}$ FF transition) - 4 days [PI: G Morgan]
- $^{134\text{-}136}$Sn (r-process nucleosynthesis) - 12 days [PI: S Marley]
- $^{98m,\,99,\,100\text{-}103}$Y (nuclear reactor studies) - 6 days [PI: N Scielzo]

BEARtrap at CARIBU

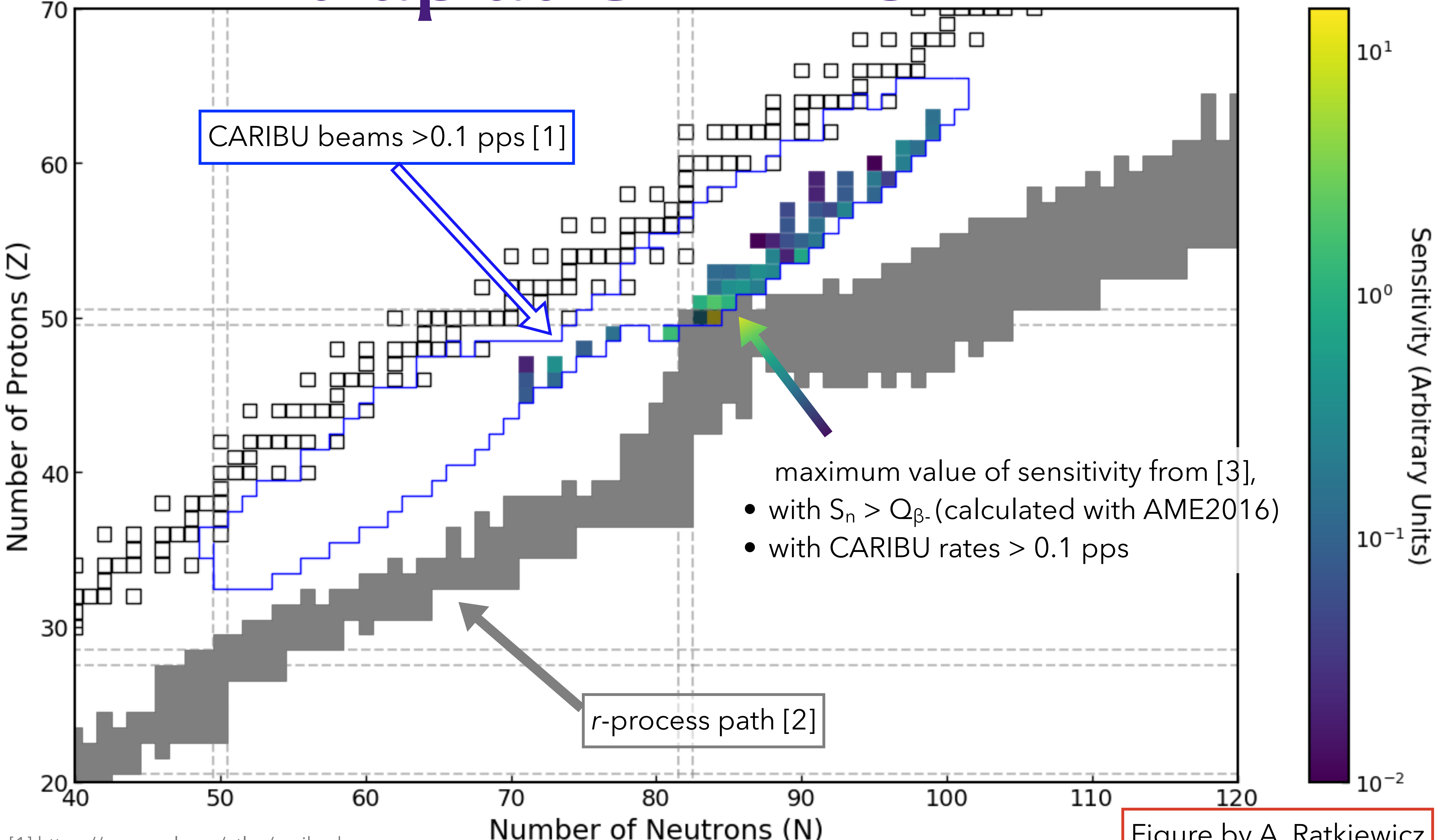


Figure by A. Ratkiewicz

[1] https://www.anl.gov/atlas/caribu-beams

[2] J. Lippuner and L. F. Roberts, "r-process Lanthanide Production and Heating Rates in Kilonovae," *The Astrophysical Journal*, vol. 815, no. 2, p. 82, Dec. 2015, doi: 10.1088/0004-637x/815/2/82.

[3] M. R. Mumpower, R. Surman, G. C. McLaughlin, and A. Aprahamian, "The impact of individual nuclear properties on r-process nucleosynthesis," *Prog. Part. Nucl. Phys.*, vol. 86, pp. 86–126, 2016, doi: http://dx.doi.org/10.1016/j.ppnp.2015.09.001

BEARtrap at nuCARIBU

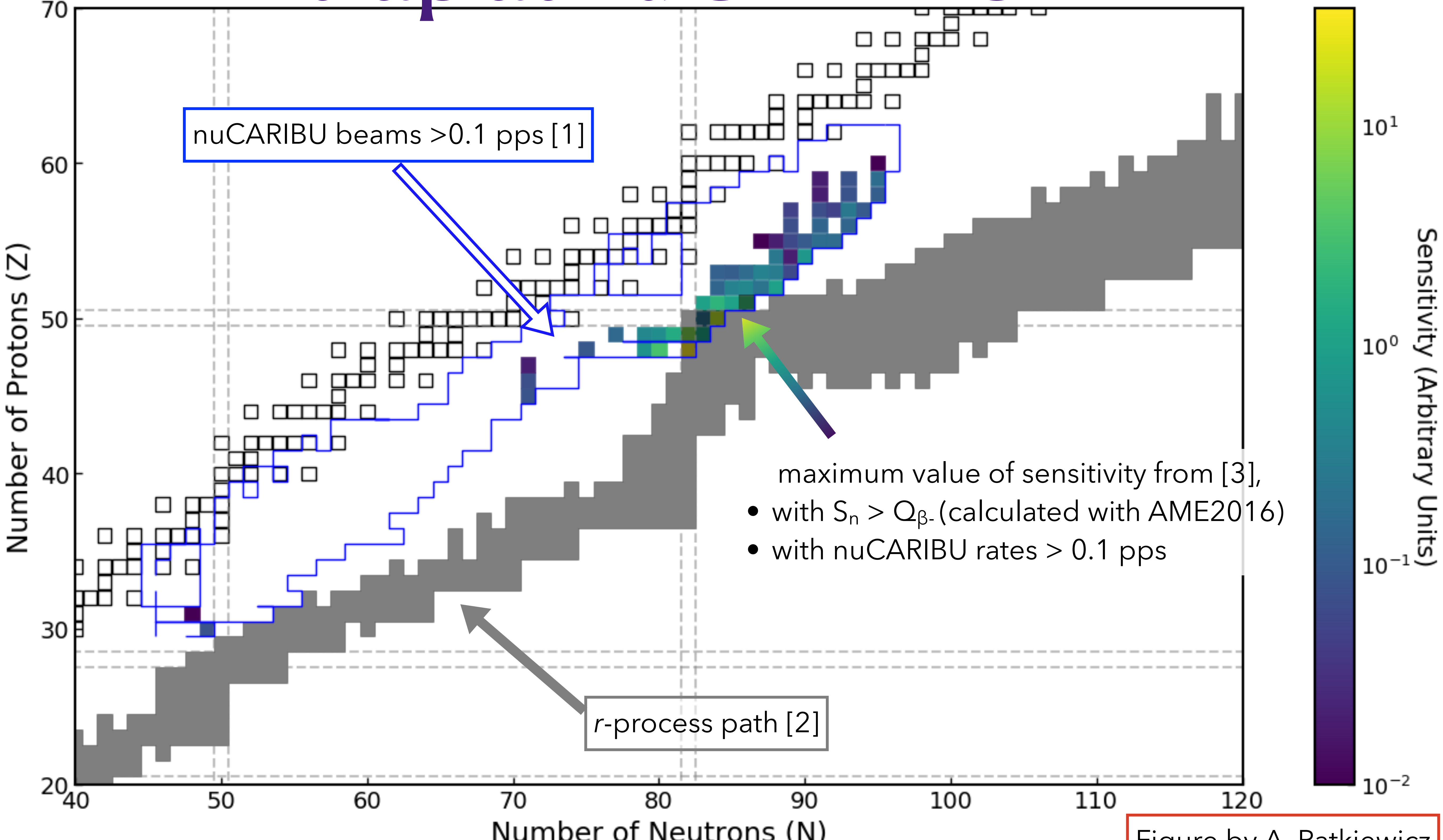
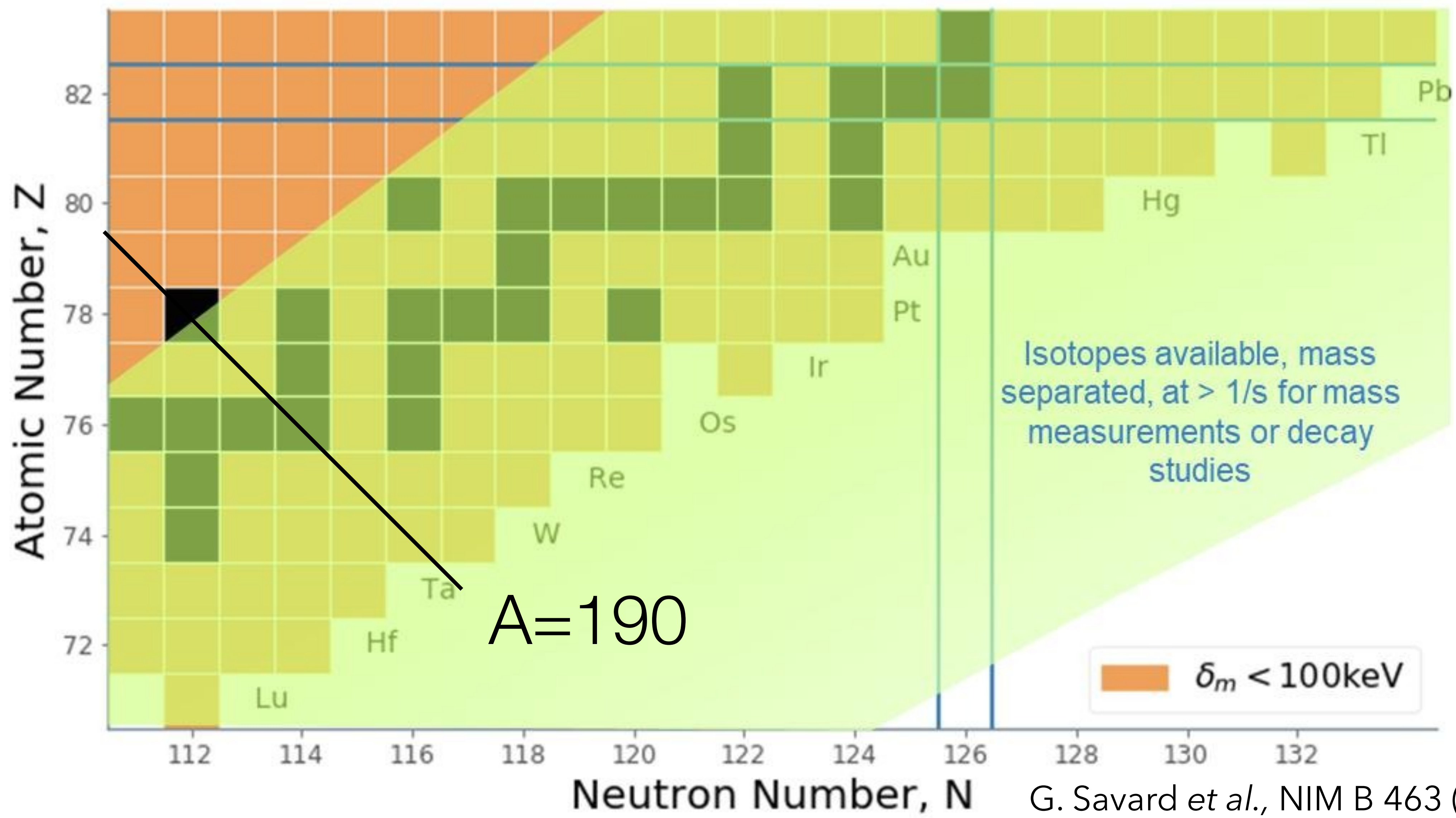


Figure by A. Ratkiewicz

[1] G. Savard, private communication.
[2] J. Lippuner and L. F. Roberts, "r-process Lanthanide Production and Heating Rates in Kilonovae," *The Astrophysical Journal*, vol. 815, no. 2, p. 82, Dec. 2015, doi: 10.1088/0004-637x/815/2/82.
[3] M. R. Mumpower, R. Surman, G. C. McLaughlin, and A. Aprahamian, "The impact of individual nuclear properties on r-process nucleosynthesis," *Prog. Part. Nucl. Phys.*, vol. 86, pp. 86–126, 2016, doi: http://dx.doi.org/10.1016/j.ppnp.2015.09.001

Experiments with the N=126 Factory



G. Savard *et al.*, NIM B 463 (2020) 258-261

Masses, half-lives need to be measured ⟹no Q_β known ⟹ no S_n known

Where is βn happening?

BEARtrap will be ready to help study the isotopes that form the A~190 ‘third’ r-process peak

BEARtrap at FRIB?

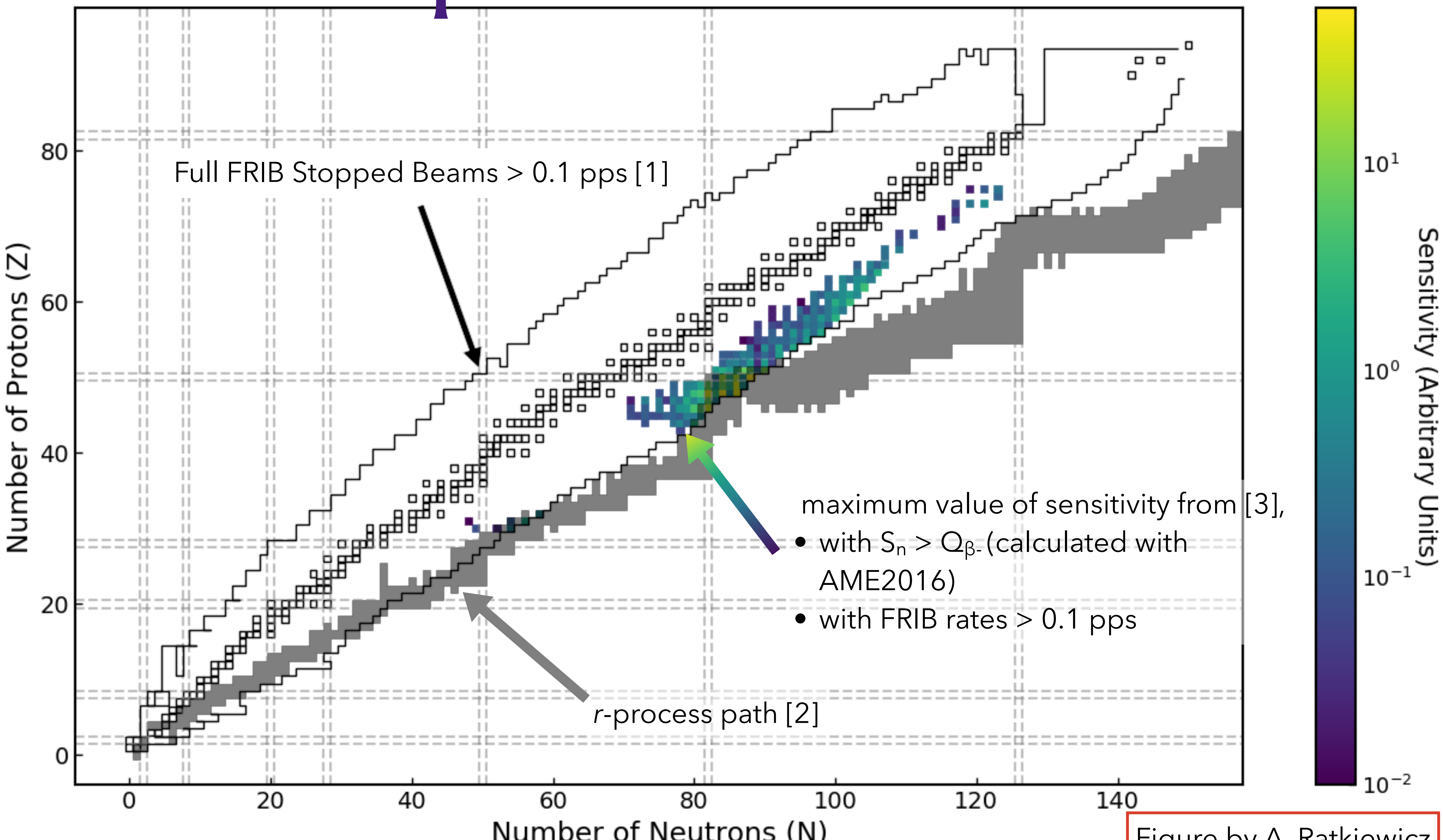


Figure by A. Ratkiewicz

[1] https://groups.nscl.msu.edu/frib/rates/fribrates.html.

[2] J. Lippuner and L. F. Roberts, "r-process Lanthanide Production and Heating Rates in Kilonovae," *The Astrophysical Journal*, vol. 815, no. 2, p. 82, Dec. 2015, doi: 10.1088/0004-637x/815/2/82.

[3] M. R. Mumpower, R. Surman, G. C. McLaughlin, and A. Aprahamian, "The impact of individual nuclear properties on r-process nucleosynthesis," *Prog. Part. Nucl. Phys.*, vol. 86, pp. 86–126, 2016, doi: http://dx.doi.org/10.1016/j.ppnp.2015.09.001

Future opportunities

- Lots to measure at CARIBU after BEARtrap commissioned
- nuCARIBU offers different fission distribution, with more to measure when it comes online
- Expand to β2n, with the addition of neutron detectors
- Potential to collaborate at FRIB with HPGe arrays, neutron detectors
- Collaboration brings opportunities also for precision β, βγ, βn and βγn measurements
- When N=126 ion beam factory comes online, there is lots of work to expand knowledge around A~190
- Work in collaboration with others measuring β decay, to know the spectroscopy first

Conclusions

- Recoil-ion spectroscopy is a powerful method for measuring precision β and βn decay.
- E_n and P_{1n} can be reconstructed without direct neutron detection.

Future plans with BEARtrap

- BEARtrap will be a dedicated setup, with marked improvements over the BPT.
- BEARtrap is fully funded and will be based initially at CARIBU, poised to make many measurements of βn emitters.
- BEARtrap will be able to take advantage of nuCARIBU and the N=126 factory at ANL.
- BEARtrap, in concert with HPGe arrays or neutron detectors, would be able to take advantage of FRIB beams to study precision β, βγ, βn and βγn decays.

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[1]Louisiana State University, [2]Argonne National Laboratory,
[3]University of Notre Dame, [4]Lawrence Livermore National Laboratory,
[5]University of California Berkeley, [6]University of Chicago

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