Simulating the Response Matrix of a Microcalorimeter

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Rochester Symposium for Physics Students

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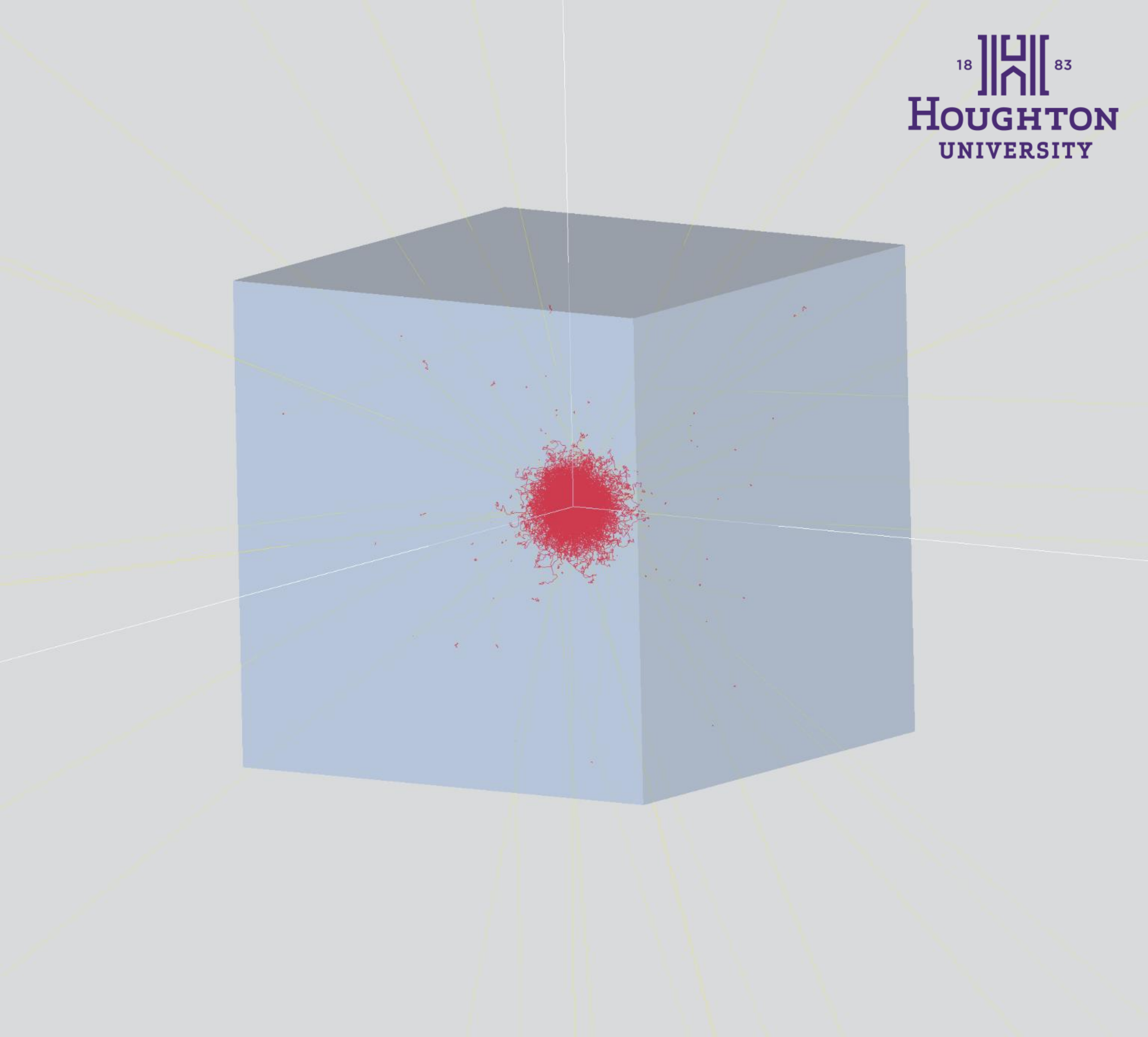
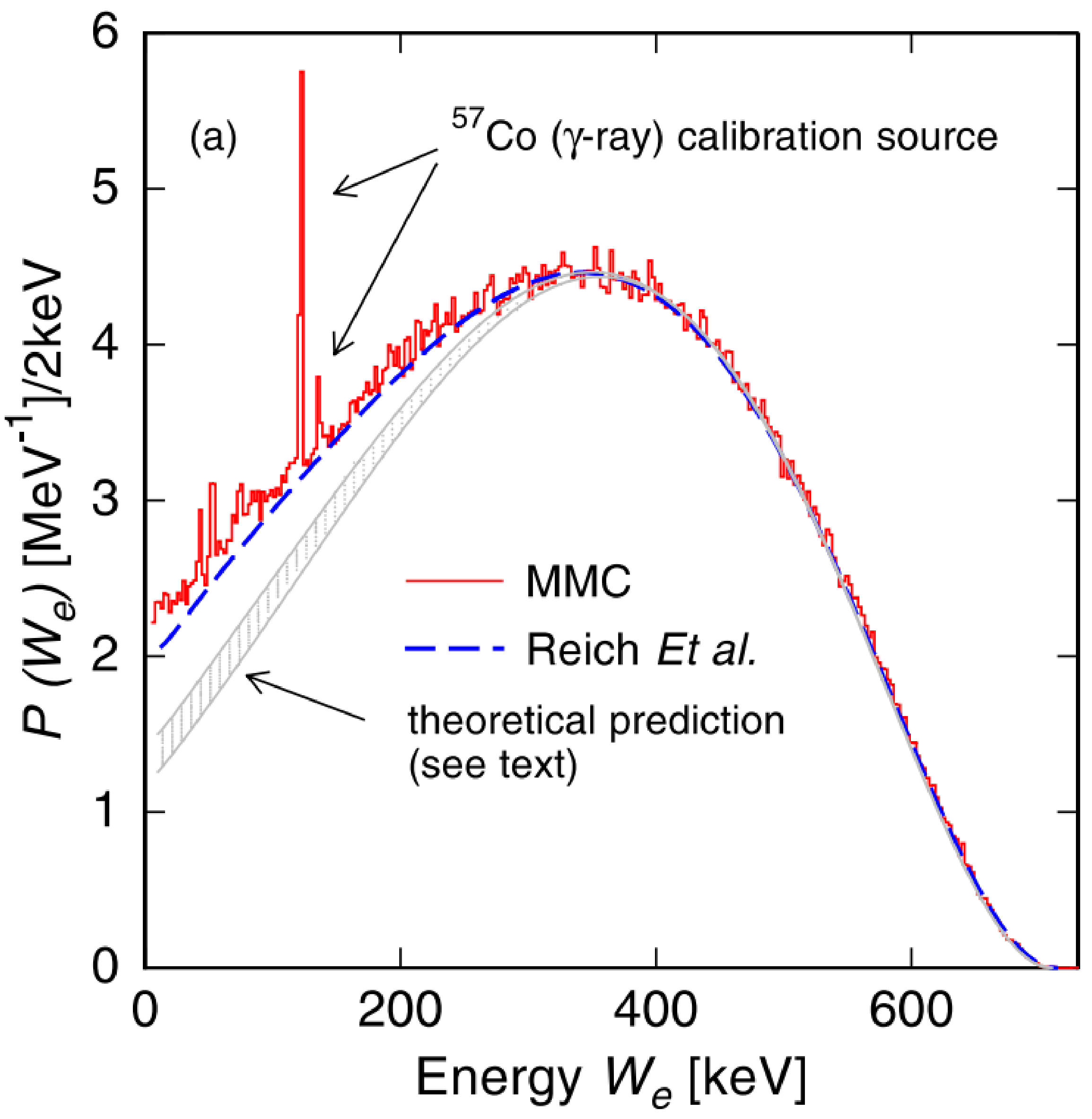


The Systematic Problem



H. Rotzinger, et al., J Low Temp Phys, 2008.

Discrepancy:

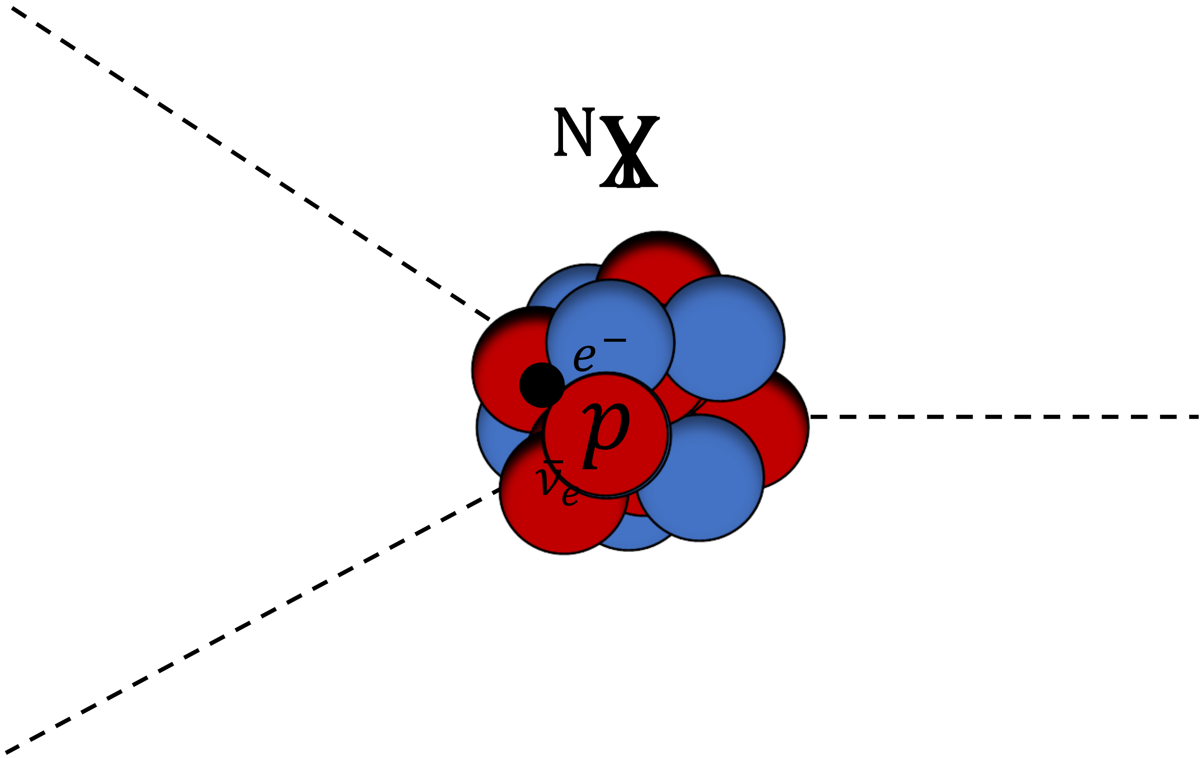
➢ Measurements ≠ Theory Prediction

Potential Causes

1. Measurement
2. Interpretation
3. Theoretical Predictions

Weak Nuclear Decay: Beta

Beta Decay: $n \rightarrow p + e^{-} + \bar{\nu}_e$

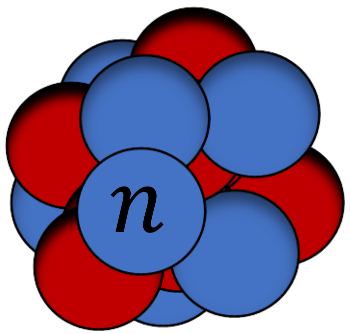


Reaction Energy of Beta Decay

Reaction Energy = Q Value = $(M({}^{N}\mathrm{X}) - M({}^{N}\mathrm{Y}))c^2$

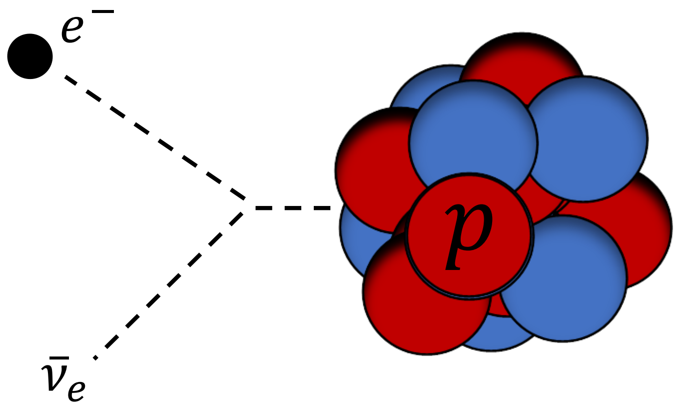
Before Decay:

${}^{N}\mathrm{X}$



After Decay:

${}^{N}\mathrm{Y}$



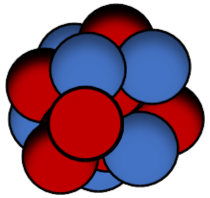
M (^{N}X) > M (^{N}Y)

Distribution of Q Value Among Decay Products

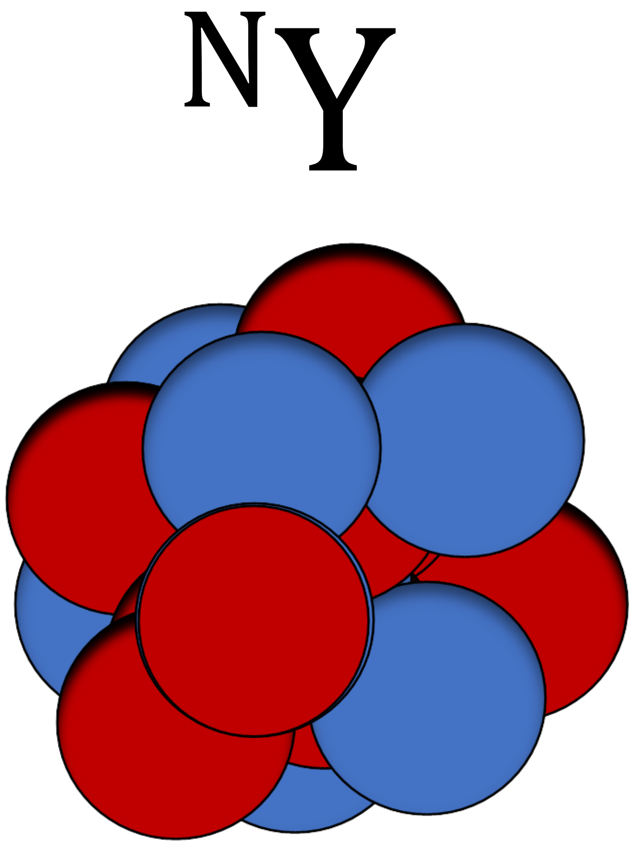
Q Value

Energy of ν_e	Energy of e^-	Energy in Daughter

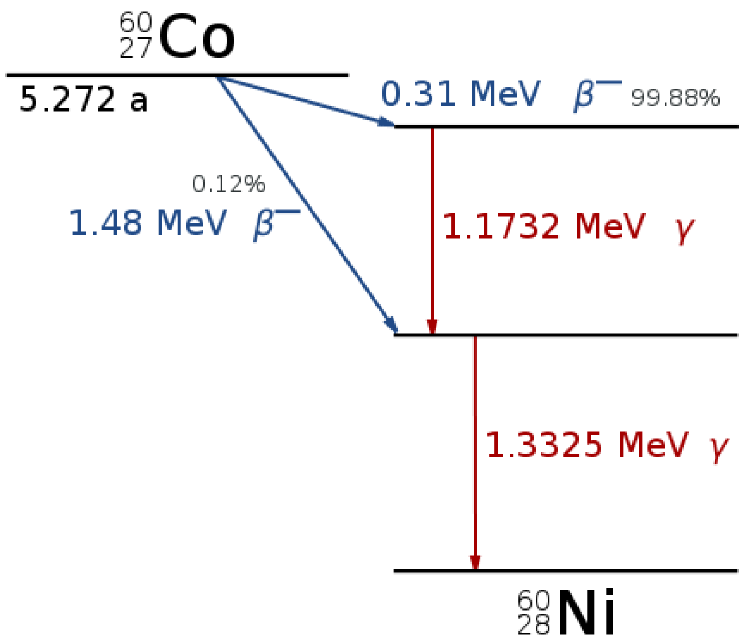
^{N}Y



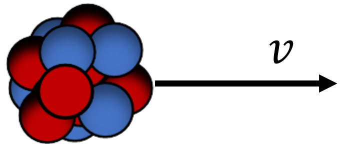
Daughter Energy Components



1. Nuclear Excited States

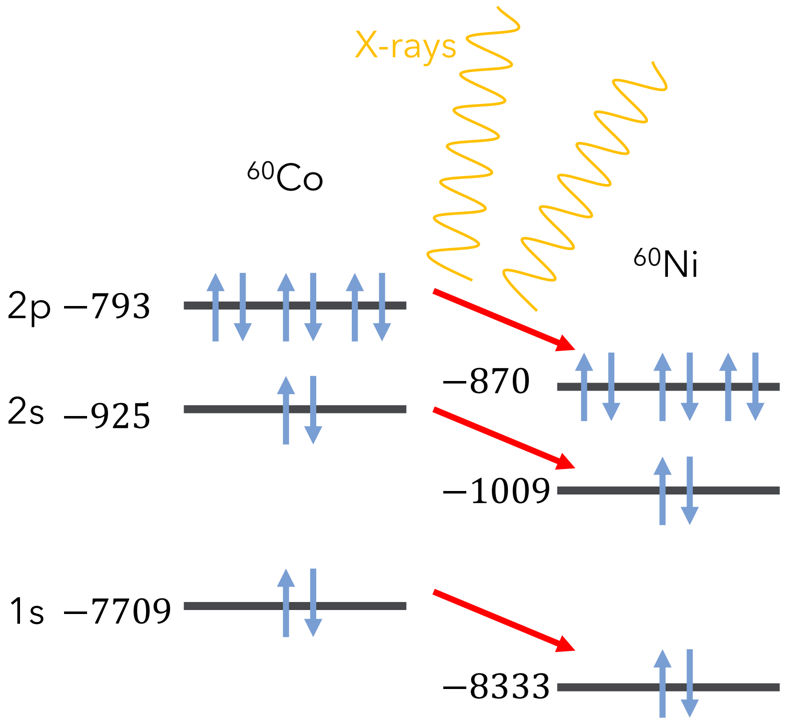


2. Recoil Kinetic Energy



$$\mathrm{KE} = \frac{1}{2}mv^2$$

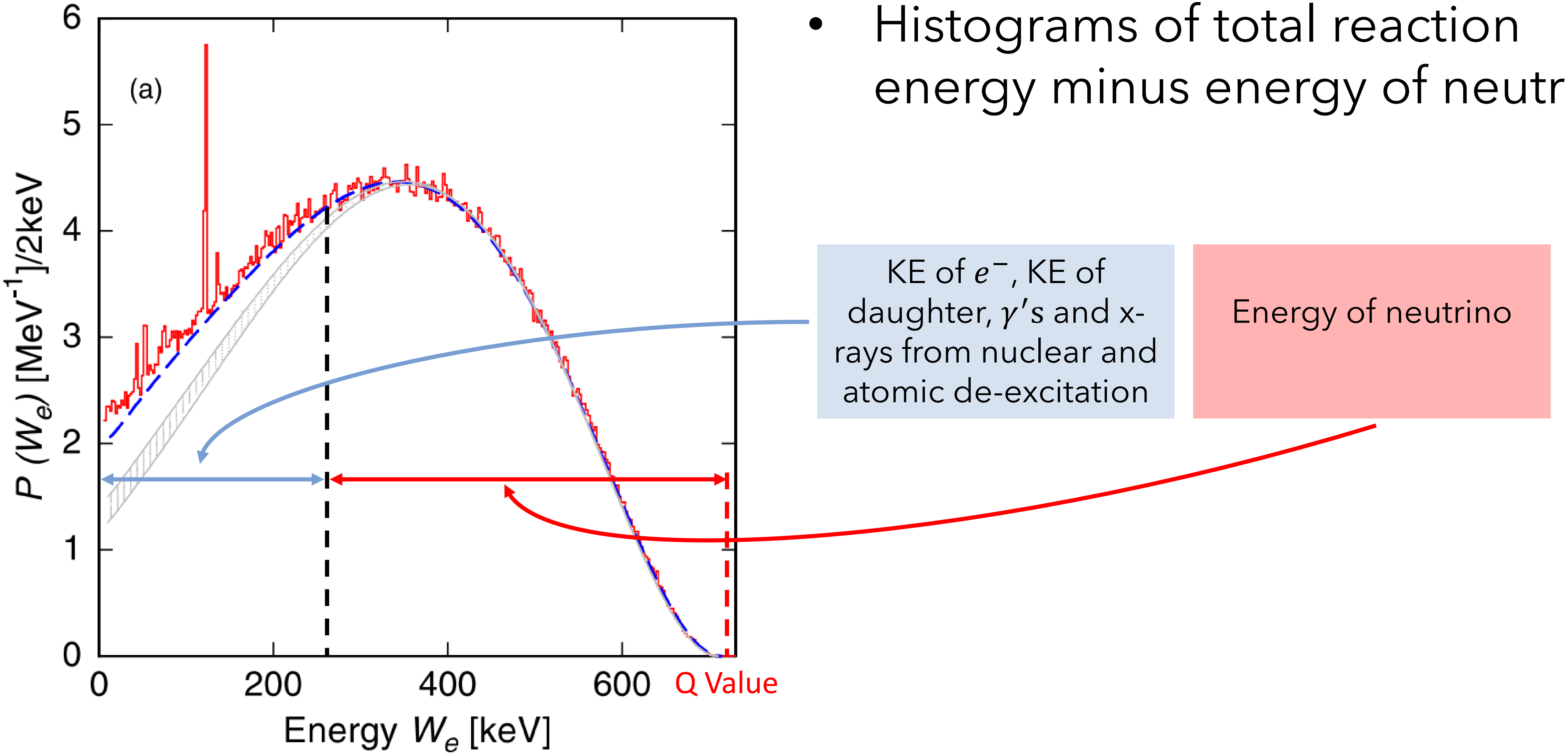
3. Atomic Excited States



Measuring Reaction Energy

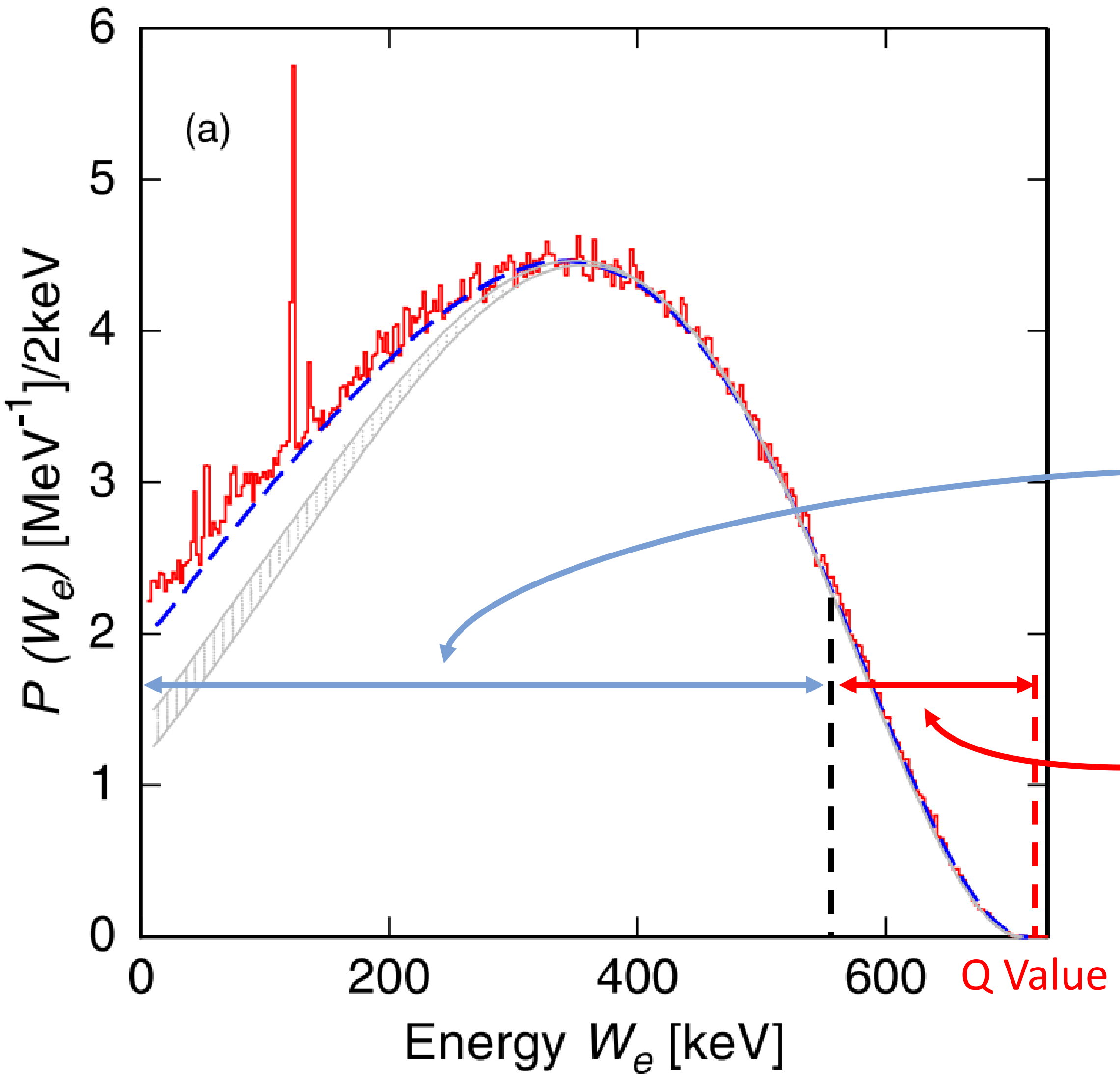
Q Value		
Energy of ν_e	Energy of e^-	Energy in Daughter
Not Measurable	Measurable	

Beta Spectrum



- Histograms of total reaction energy minus energy of neutrino

Beta Spectrum

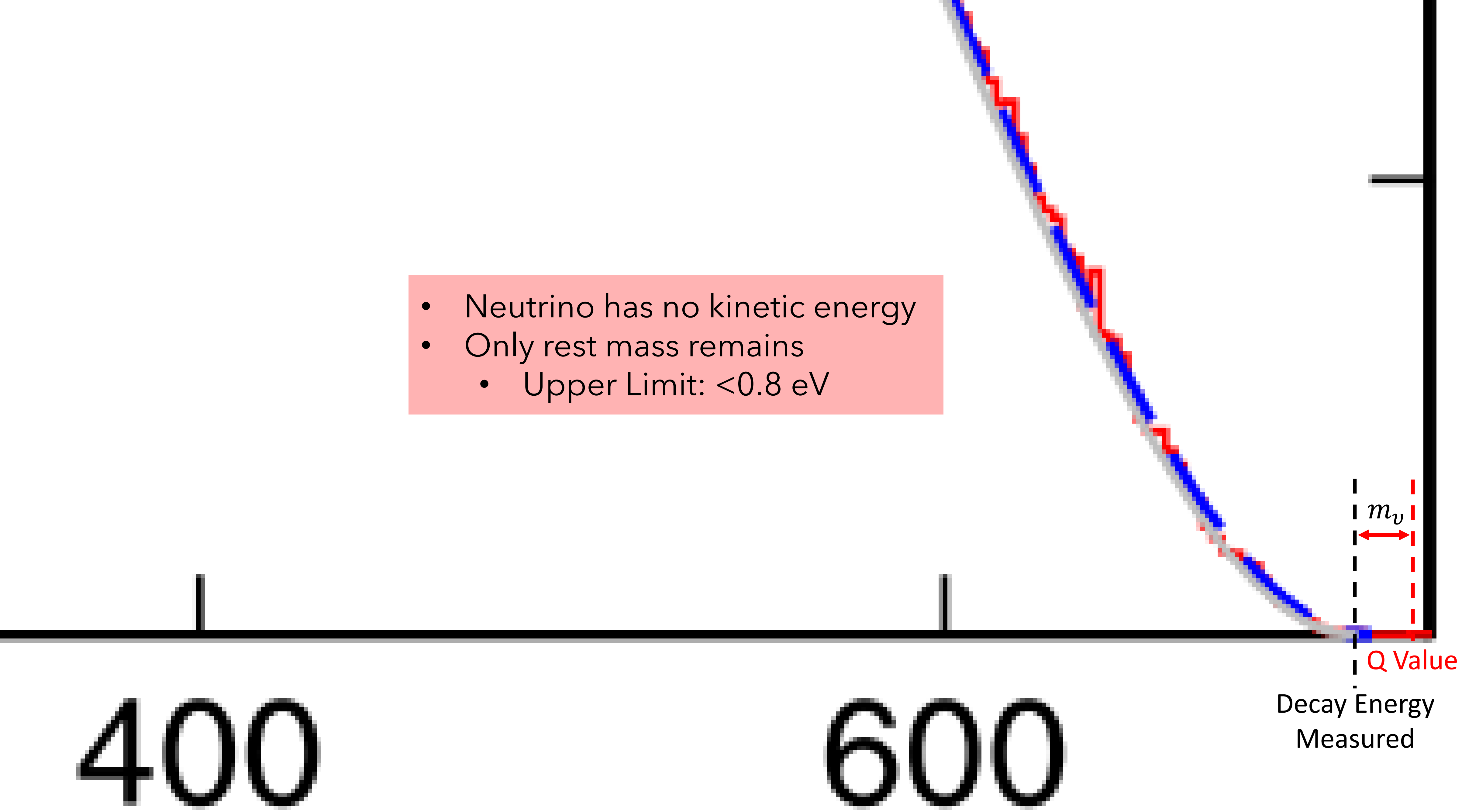


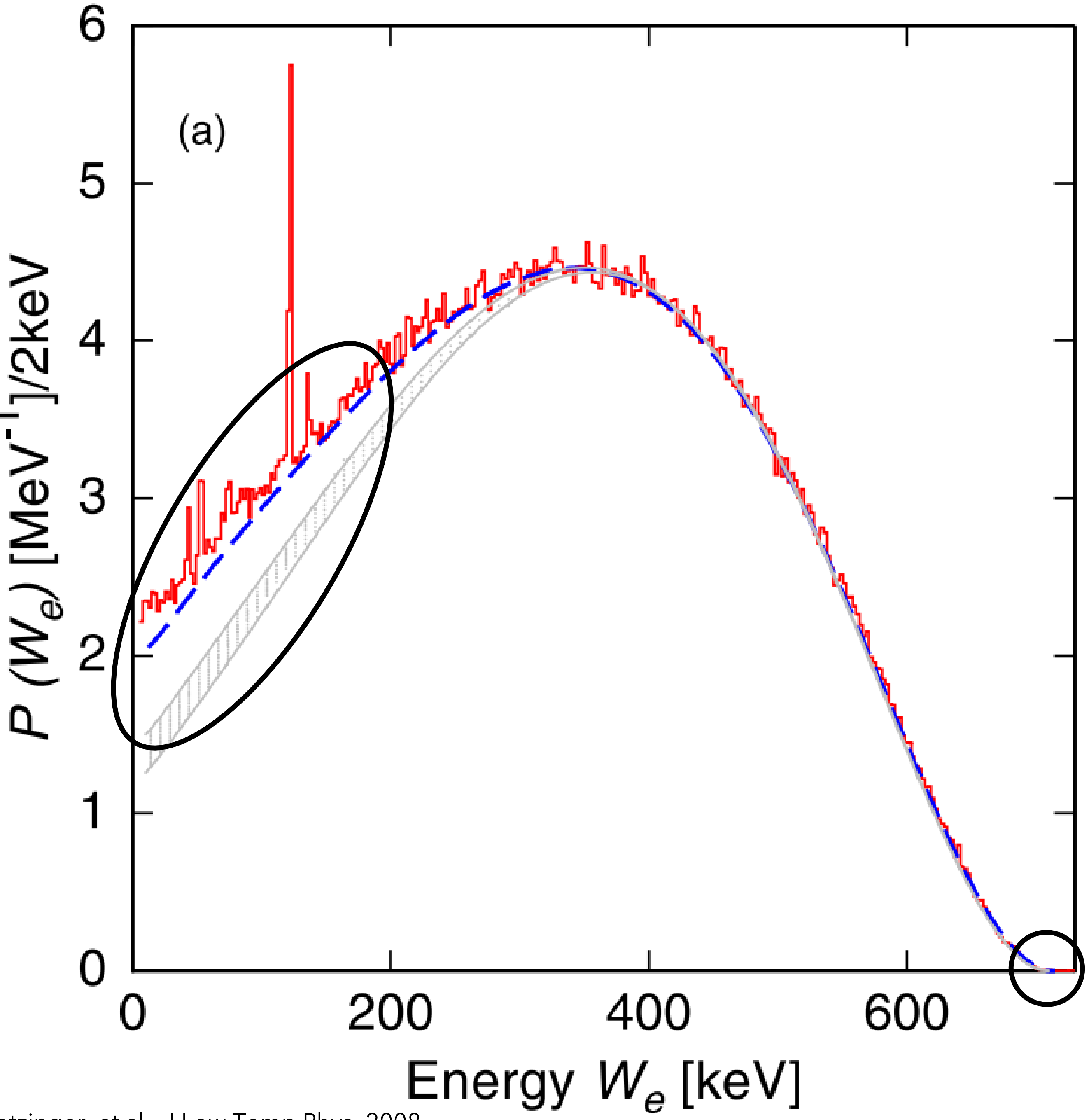
- Less neutrino energy ⇒ more of total decay energy measured

KE of e^-, KE of daughter, γ's and x-rays from nuclear and atomic de-excitation

Energy of neutrino

- Neutrino has no kinetic energy
- Only rest mass remains
    - Upper Limit: <0.8 eV





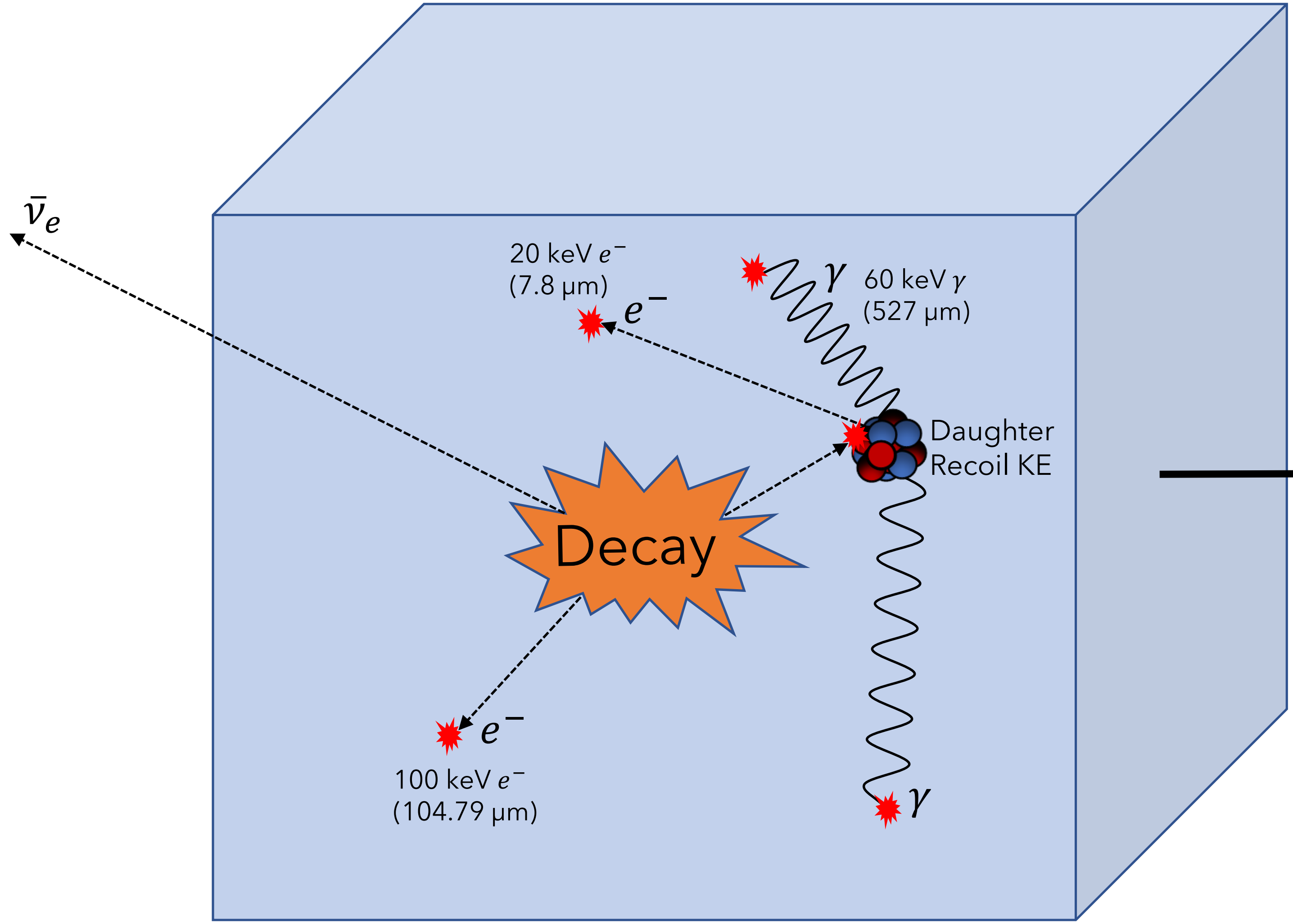
H. Rotzinger, et al., J Low Temp Phys, 2008.

Importance of Beta Spectrum Shape

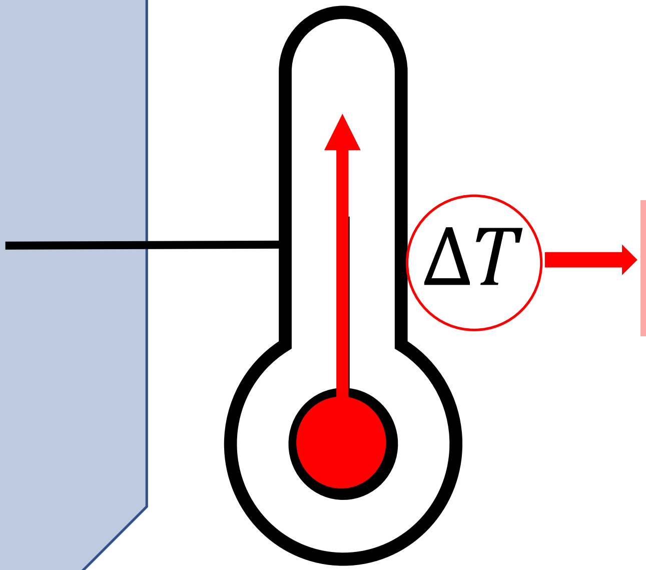
- Determining neutrino rest mass
  - Upper Limit: <0.8 eV

- Understanding Weak nuclear force

Decay Energy Spectroscopy (DES)

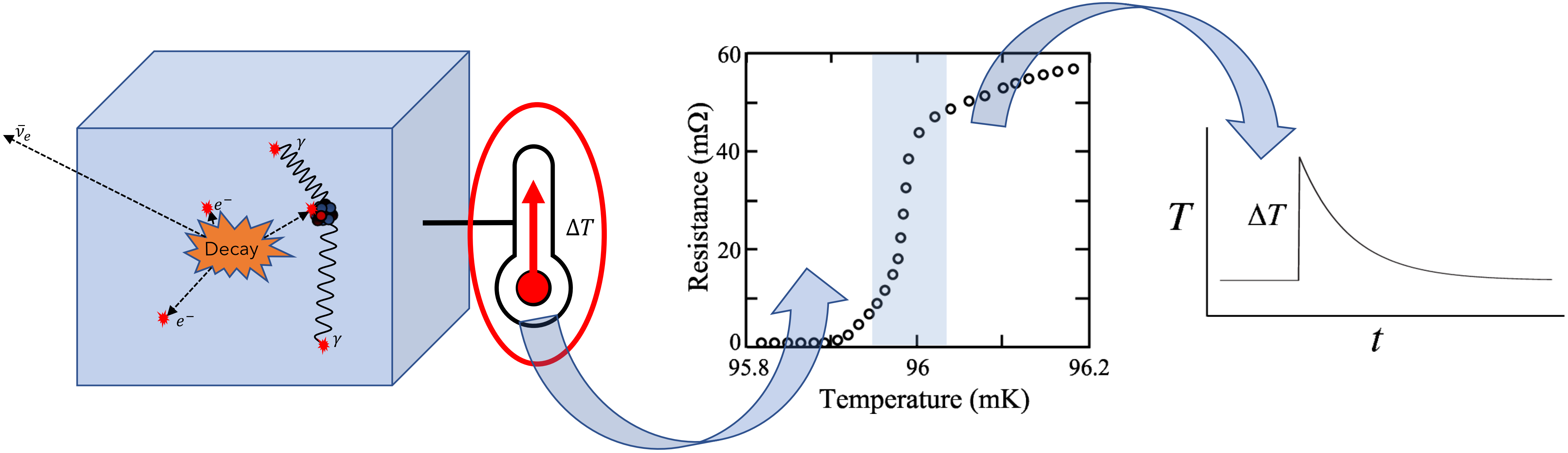


- Decay Energy thermalizes fast
- Slow heat transfer to thermometer



Single ΔT for one decay event

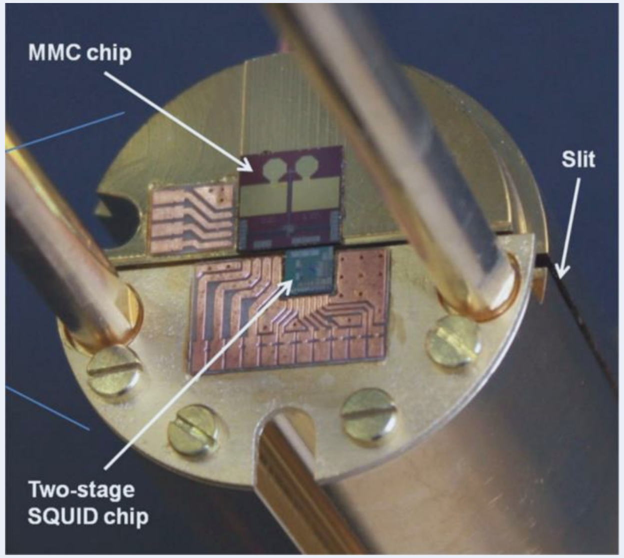
Low Temperature Detectors: Microcalorimeters



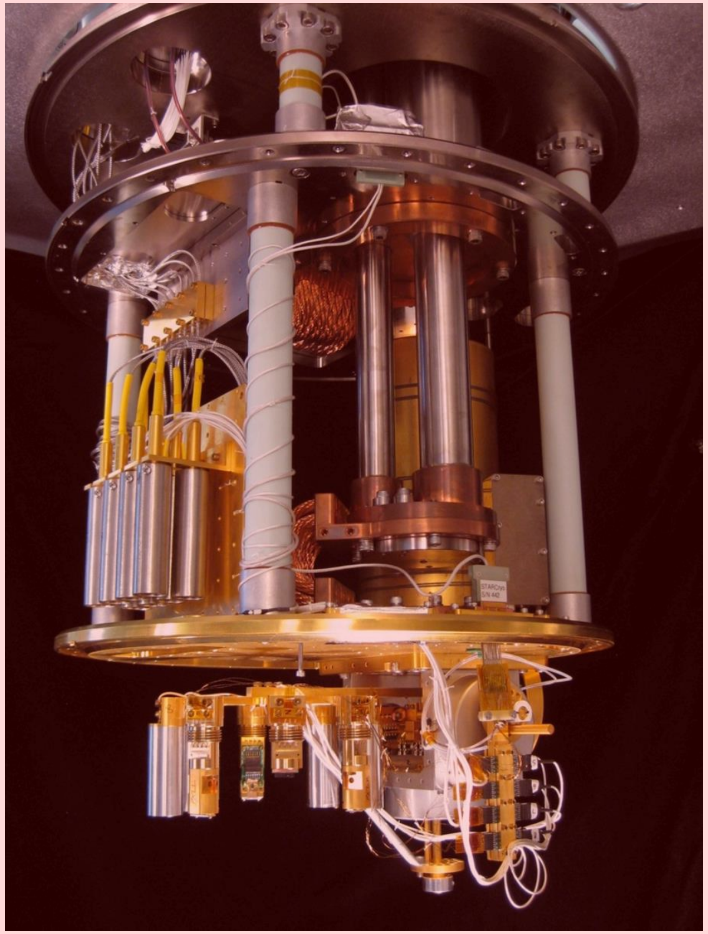
- Thermalize decay energy
- Sensitive thermometers use superconducting state
  - Small ΔT → Measurable change in R

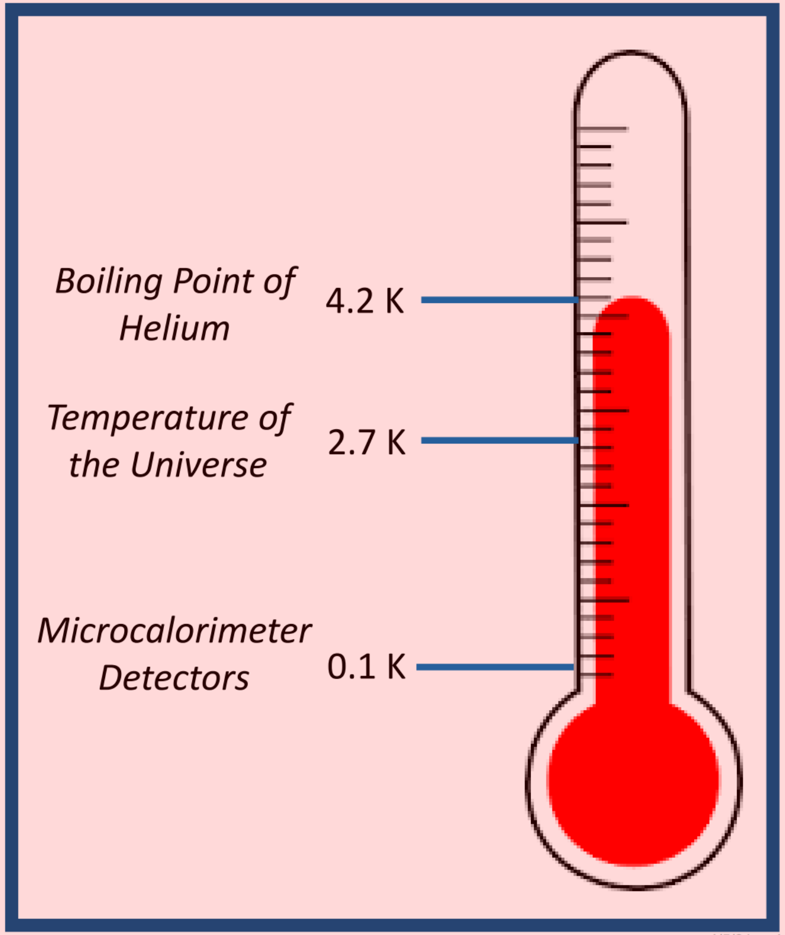
Physical Measurement

$$\Delta E \propto T\sqrt{C}$$



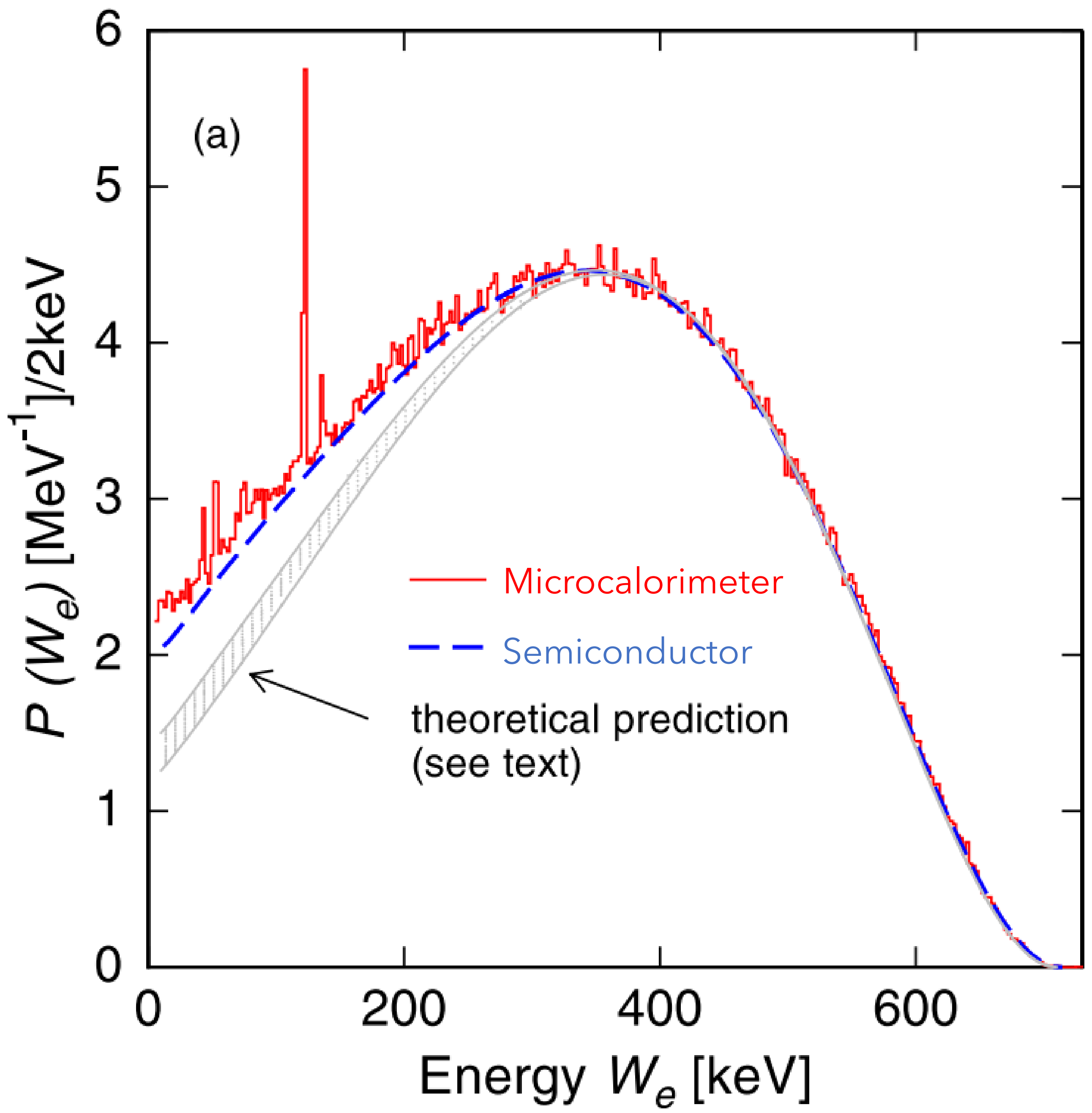
0.7 mm × 1.6 mm absorber





$$\Delta E = 7.5 \text{ eV FWHM at } 6.54 \text{ keV}$$

M.P Croce, et al., J Low Temp Phys, 2016.

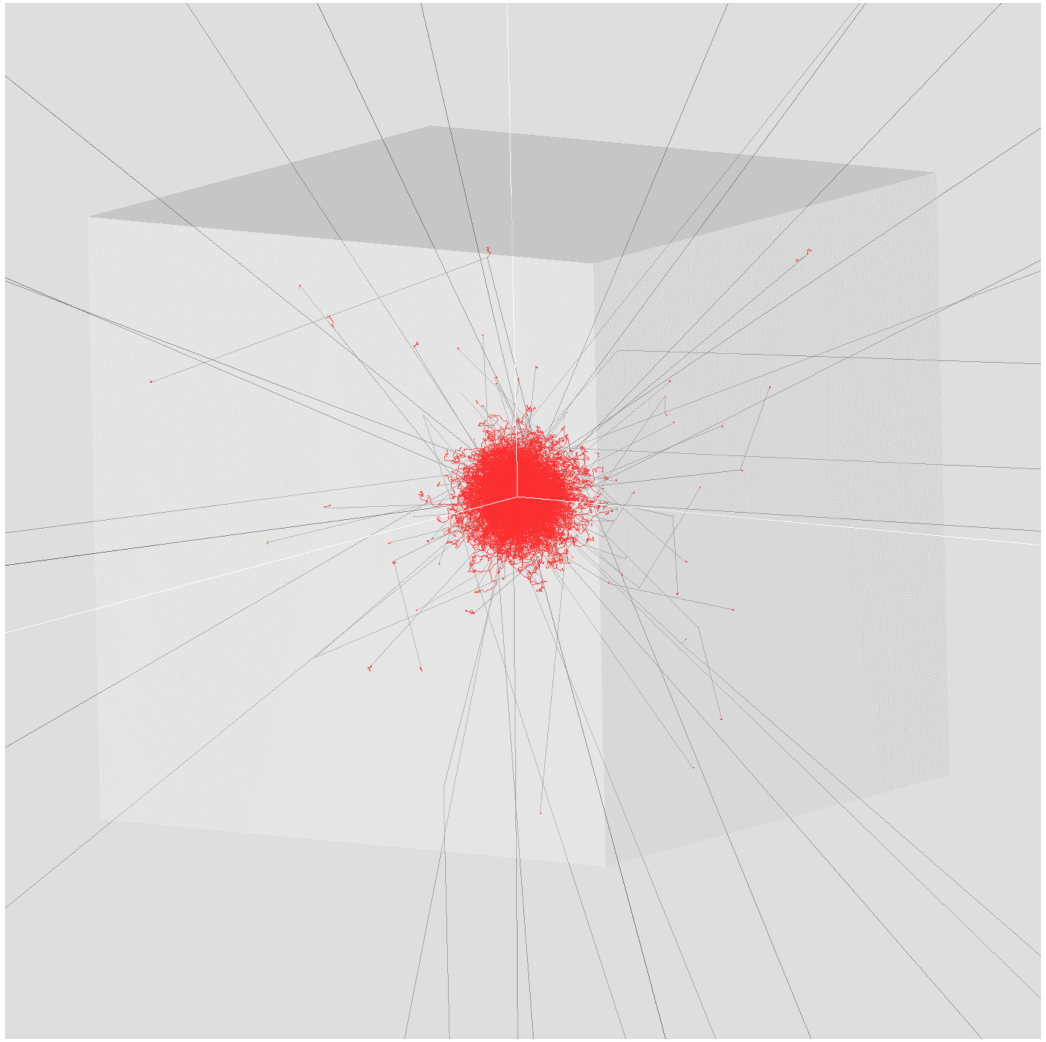


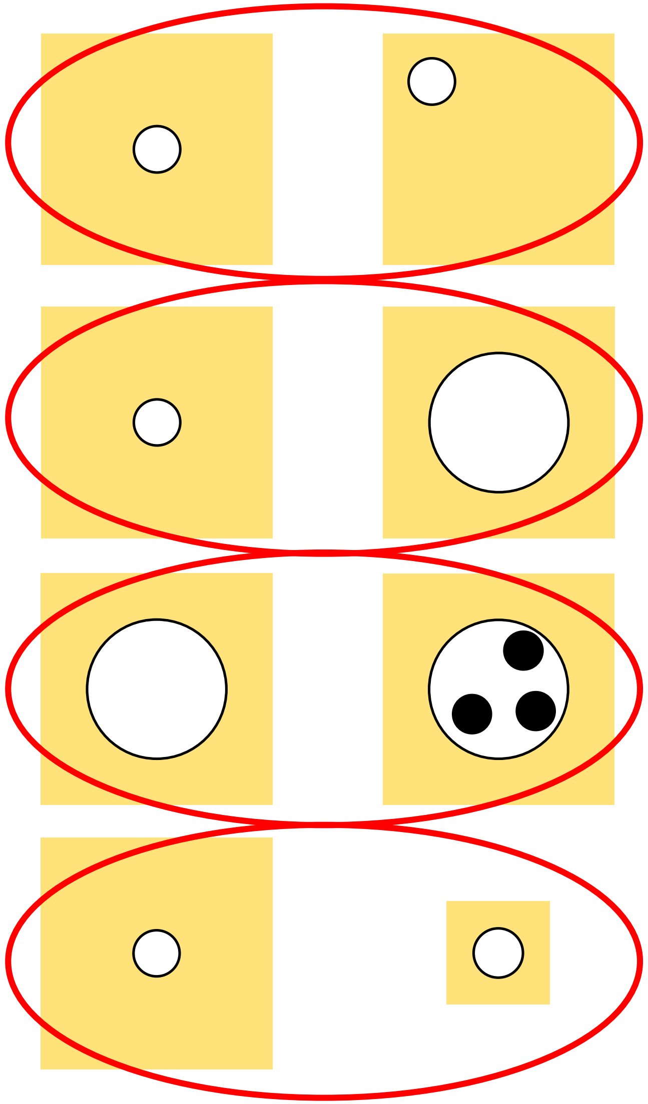
H. Rotzinger, et al., J Low Temp Phys, 2008.

Energy Resolution

- High energy resolution
  → more detail in measurement
    → understand beta spectrum structure

Energy Escape

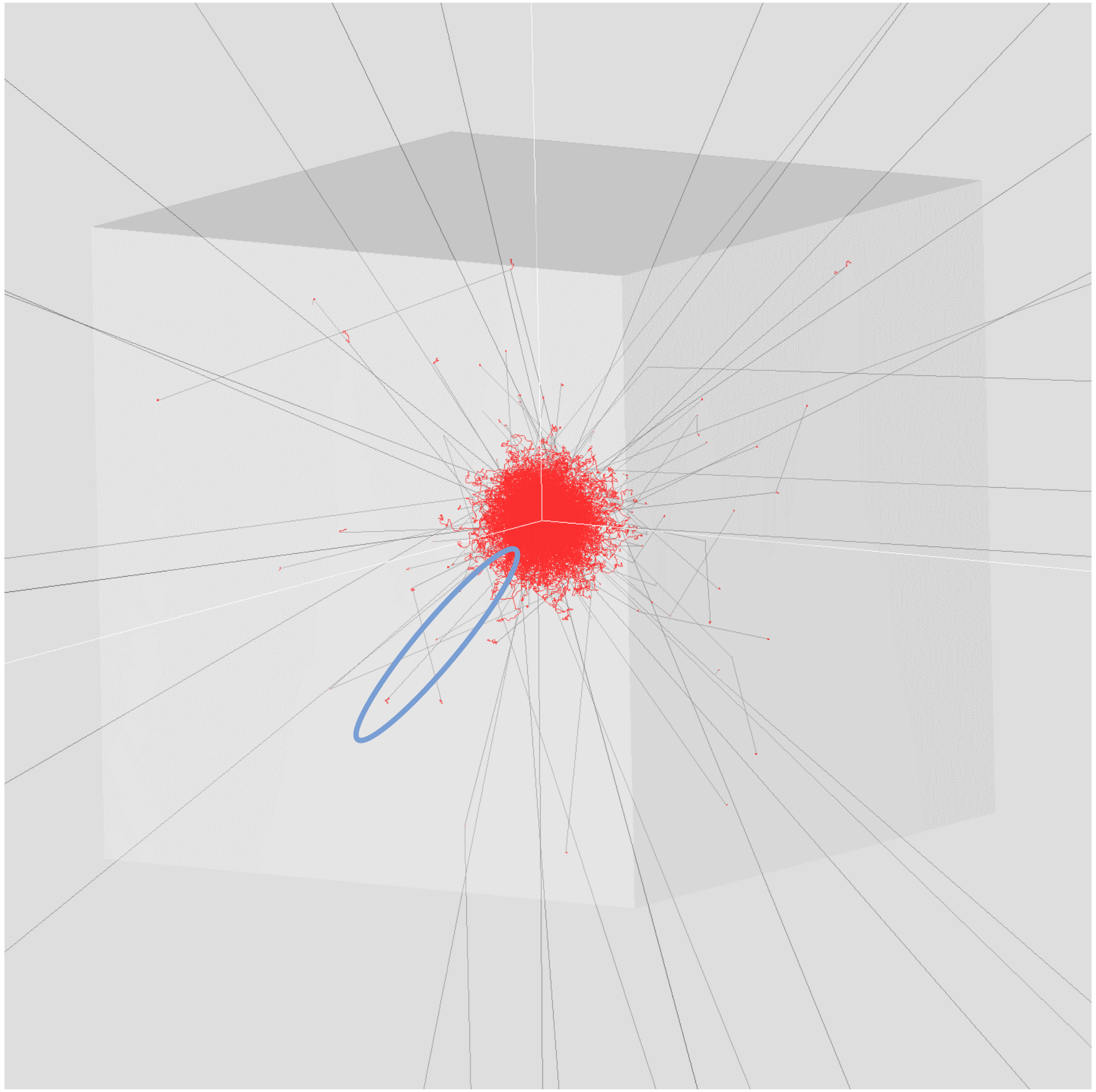




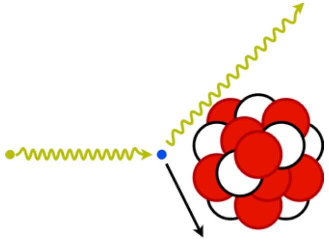
- Location
- Distribution
- Defects in Source
- Absorber size

- Particle type
- Absorber material
- Energy

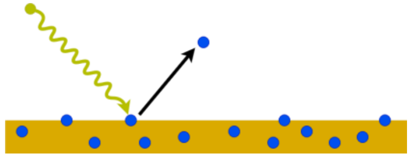
EGSnrc: A Monte Carlo Approach



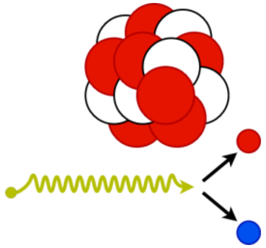
- Monte Carlo Method
- EGSnrc for Particle Transport
  - Simulate energy deposited in absorber



Compton Scattering

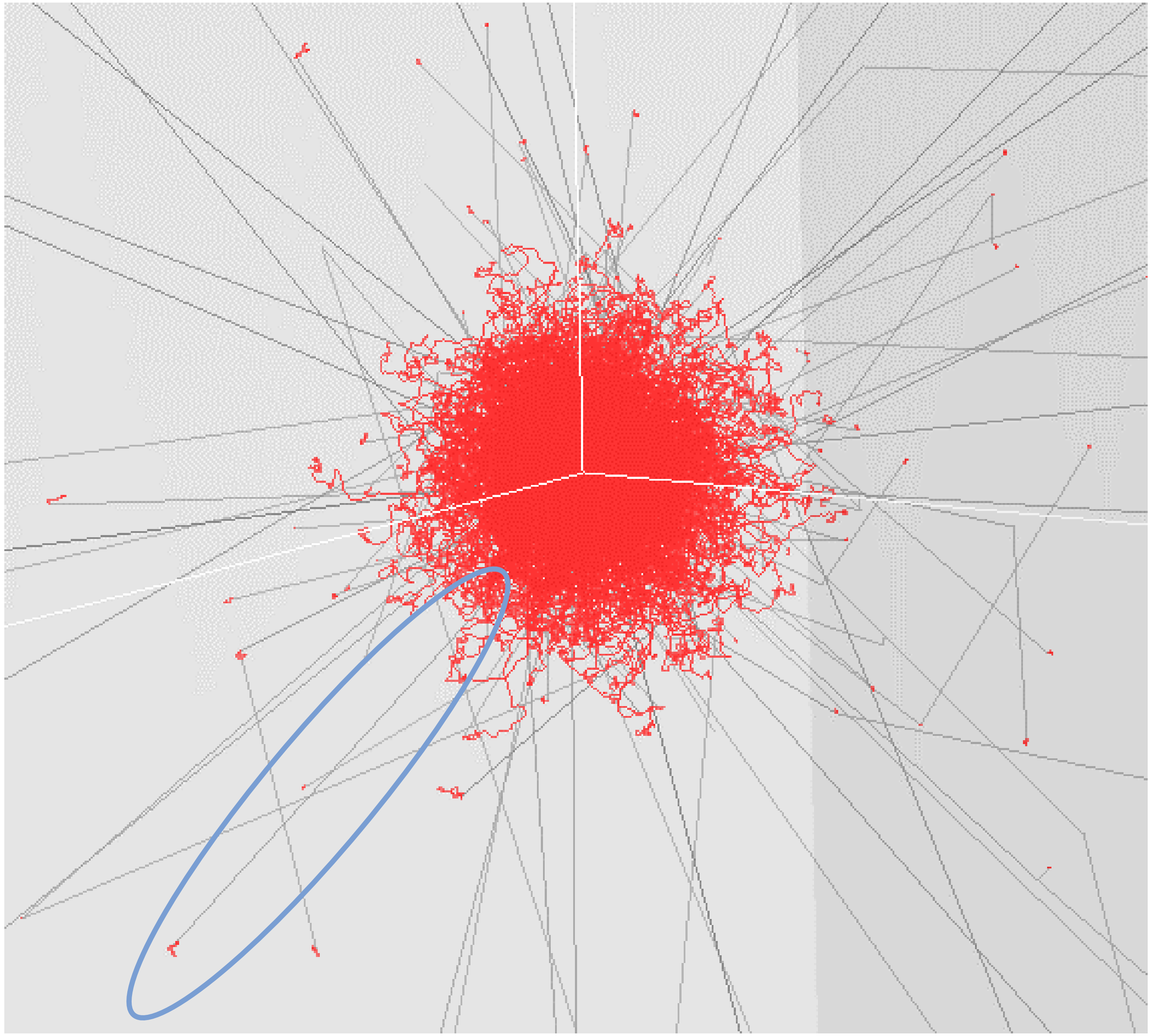


Photoelectric Absorption

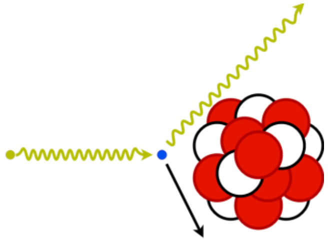


Pair Production

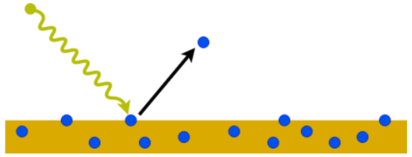
EGSnrc: A Monte Carlo Approach



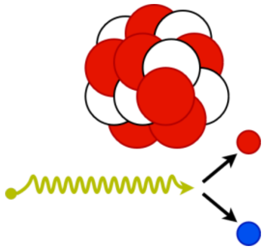
- Monte Carlo Method
- EGSnrc for Particle Transport
  - Simulate energy absorbed by geometry



Compton Scattering



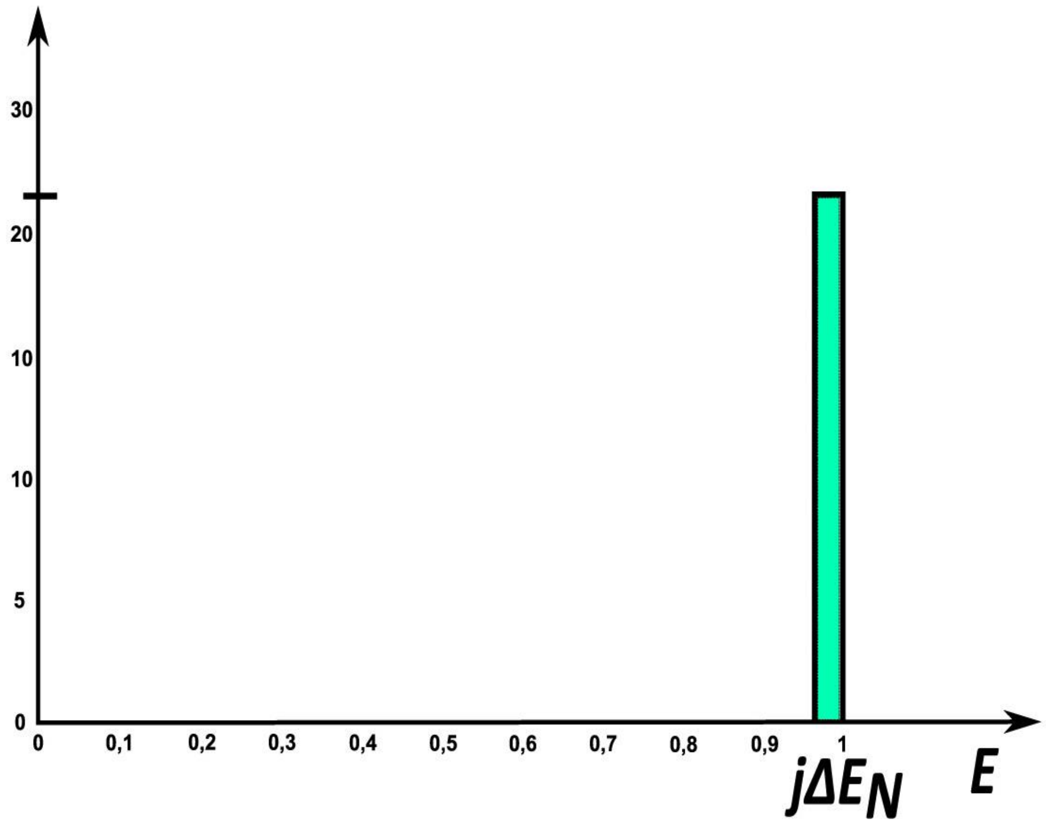
Photoelectric Absorption



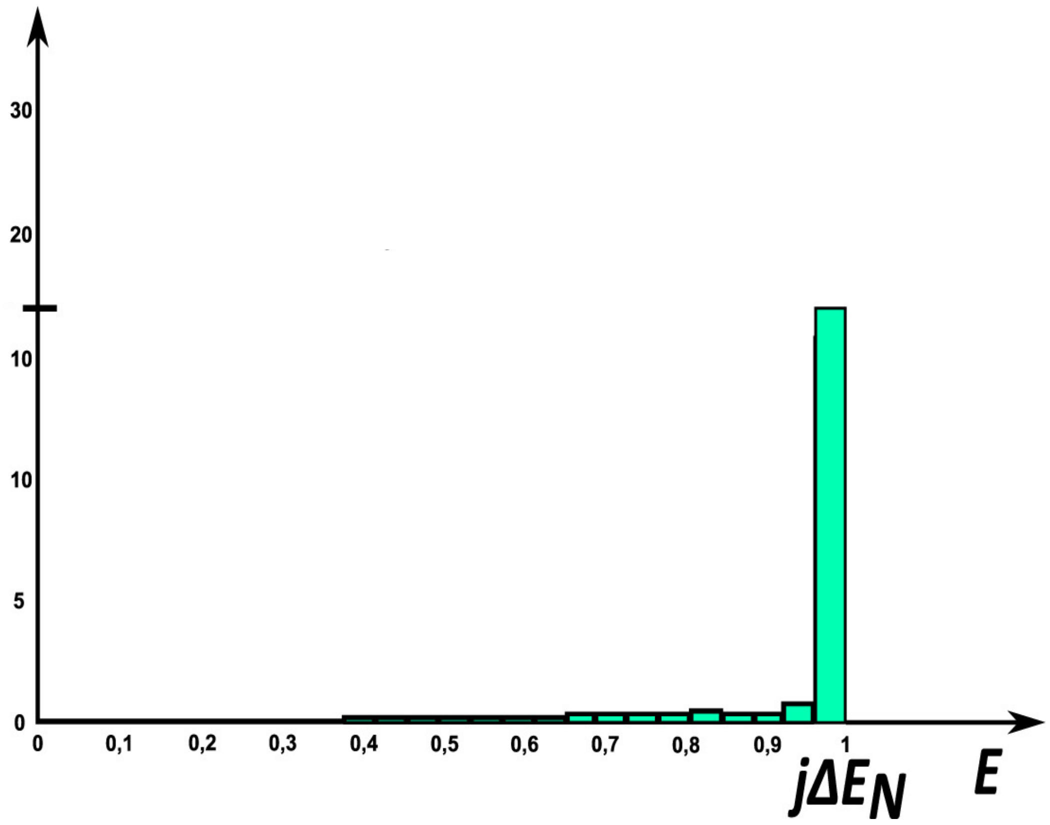
Pair Production

Monoenergetic Source Simulations

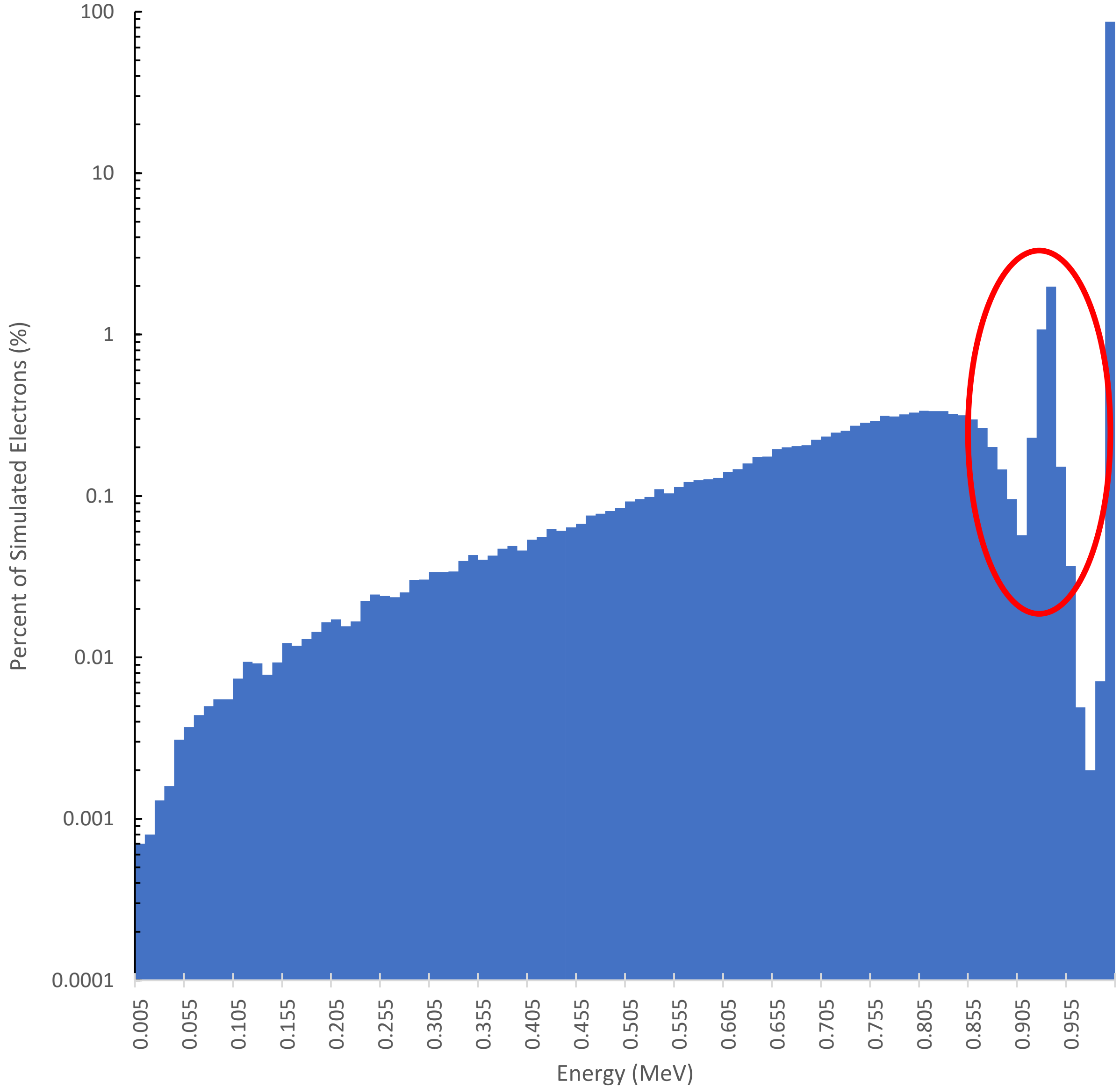
Simulation Input: Total Decay Energy



Simulation Output: Energy Escape



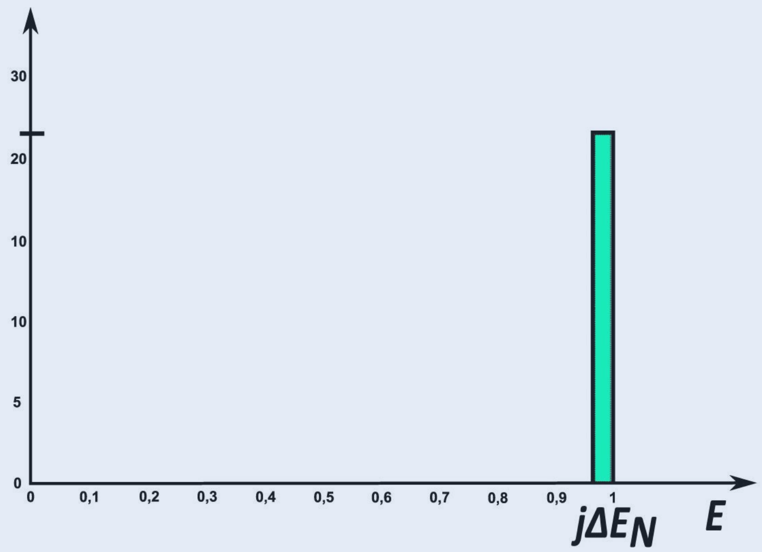
Finding the Detector Response: Escape



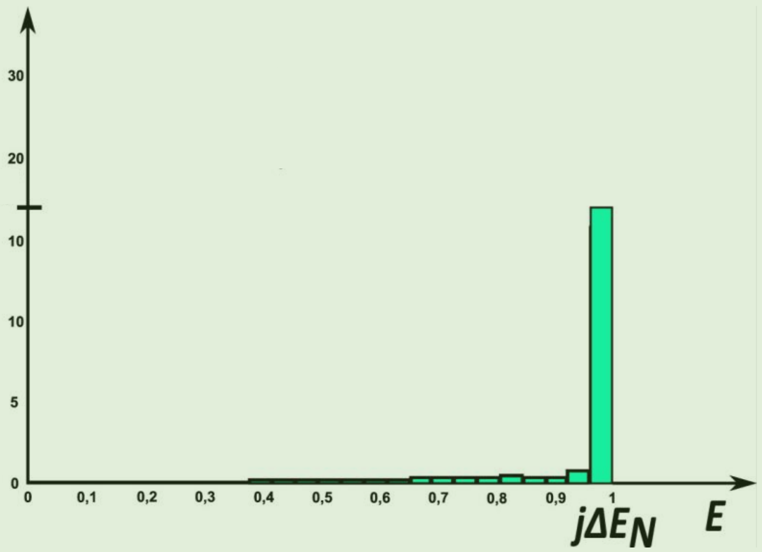
- 1 MeV monoenergetic beta source in $0.6 \times 0.6 \times 0.6\ \mathrm{mm}^3$ Au absorber
- Finer binning on histogram → details on spectrum
  - STRUCTURE
- Highlighted Peak:
  - 2% of electrons are only depositing 930 keV as opposed to 1 MeV
  - 70 keV is escaping absorber
  - Corresponds to Au X-ray fluorescence

Detector Response

Input: Total Decay Energy (D)



Output: Measured Energy (M)

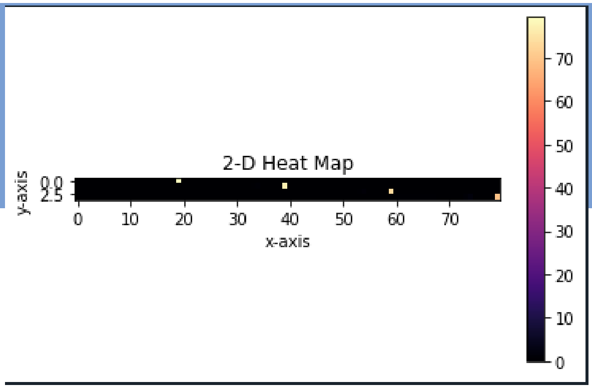


$$R_{ij}D = M$$

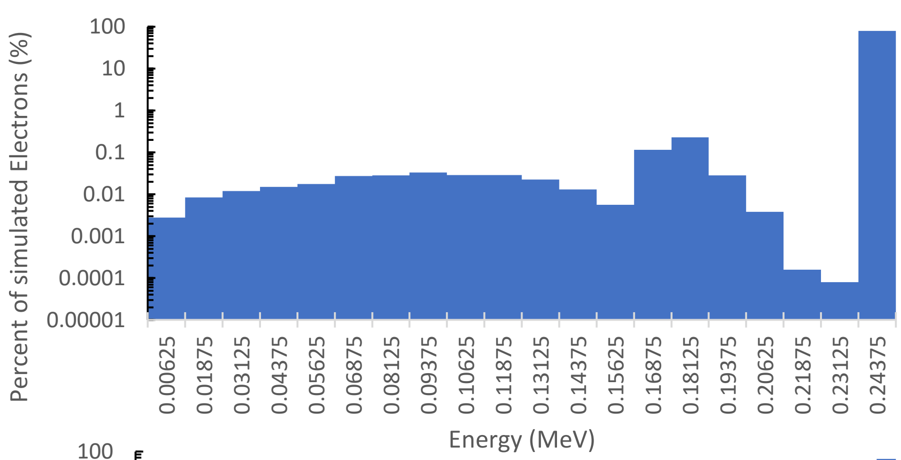
$$D = R_{ij}{}^{-1}M$$

$$\begin{array}{cc} & j \rightarrow \\ \begin{array}{c} i \\ \downarrow \end{array} & \begin{pmatrix} R_{11} & R_{12} & R_{13} & \cdots & R_{1j} \\ R_{21} & R_{22} & R_{23} & \cdots & R_{2j} \\ R_{31} & R_{32} & R_{33} & \cdots & R_{3j} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ R_{i1} & R_{i2} & R_{i3} & \cdots & R_{ij} \end{pmatrix} \end{array} \begin{array}{c} j \\ \downarrow \end{array} \begin{pmatrix} 0 \\ 0 \\ 100 \\ \vdots \\ 0 \end{pmatrix} = \begin{pmatrix} 3 \\ 5 \\ 92 \\ \vdots \\ 0 \end{pmatrix}$$

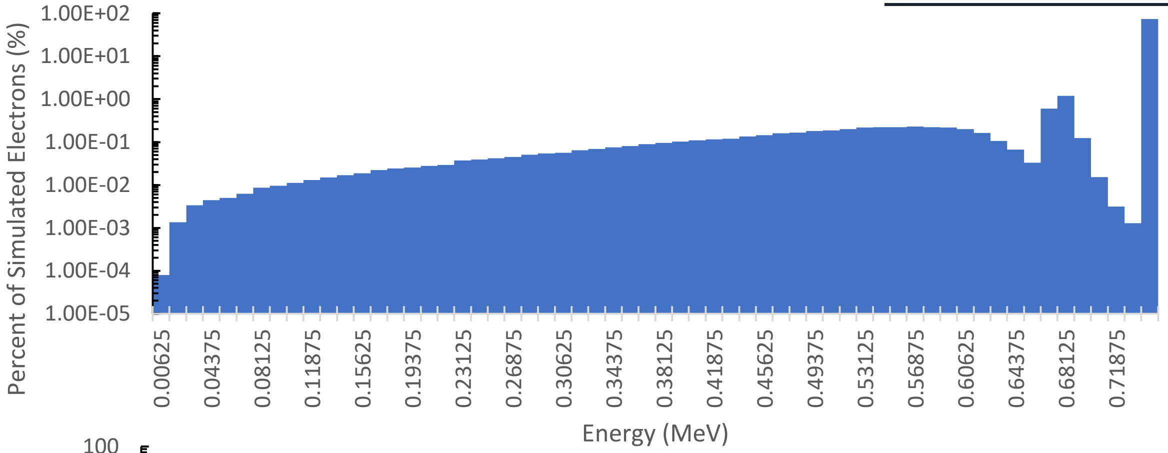
Heat Map of Response Matrix



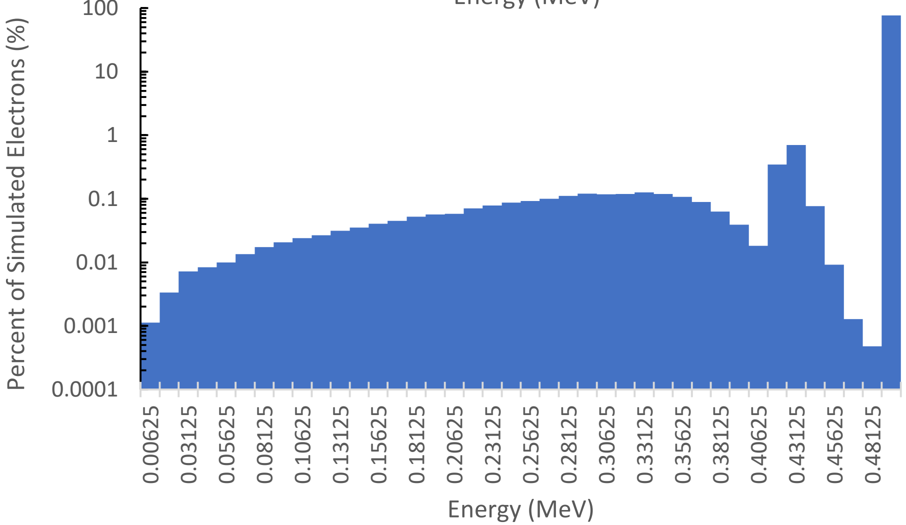
- Initial Coarsely-Binned Response Matrix



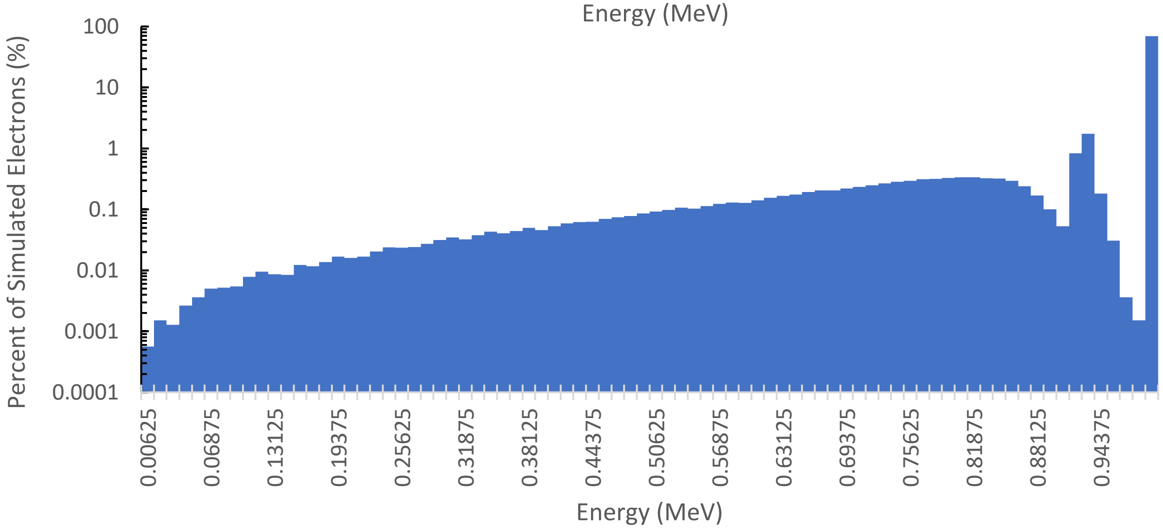
0.25 MeV Betas



0.75 MeV Betas

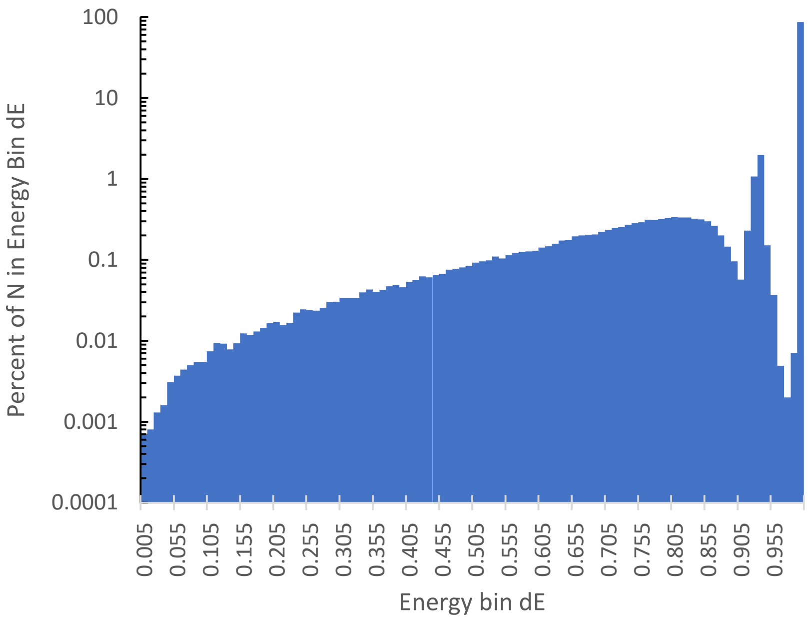


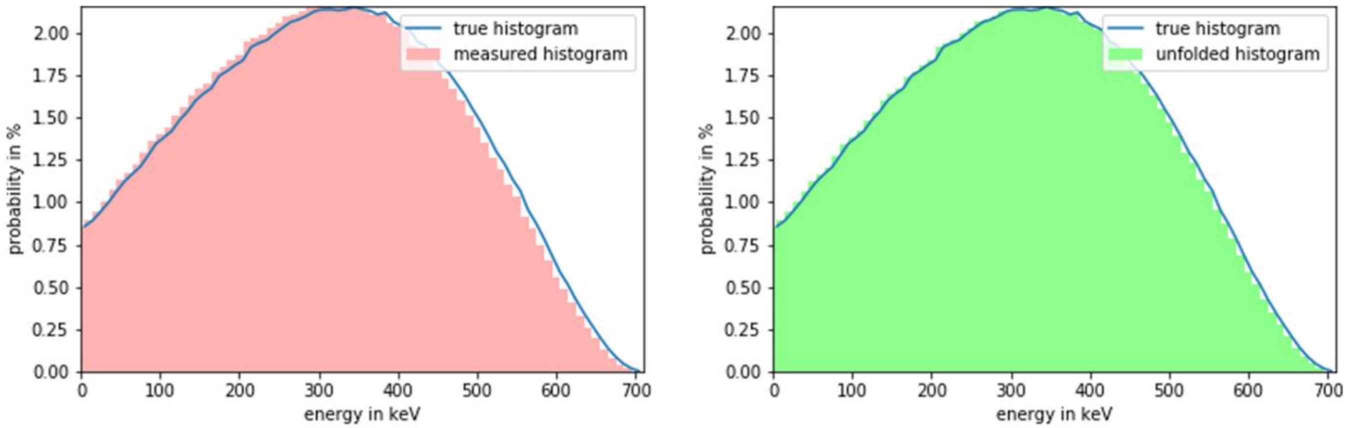
0.50 MeV Betas



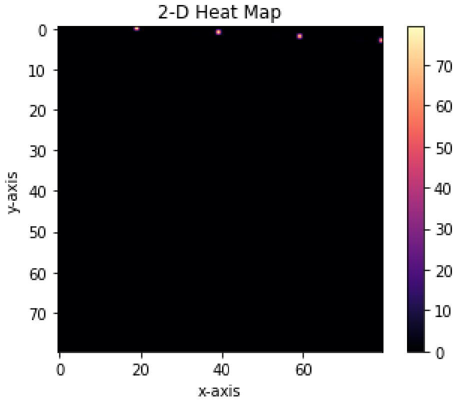
1.00 MeV Betas

What Next?



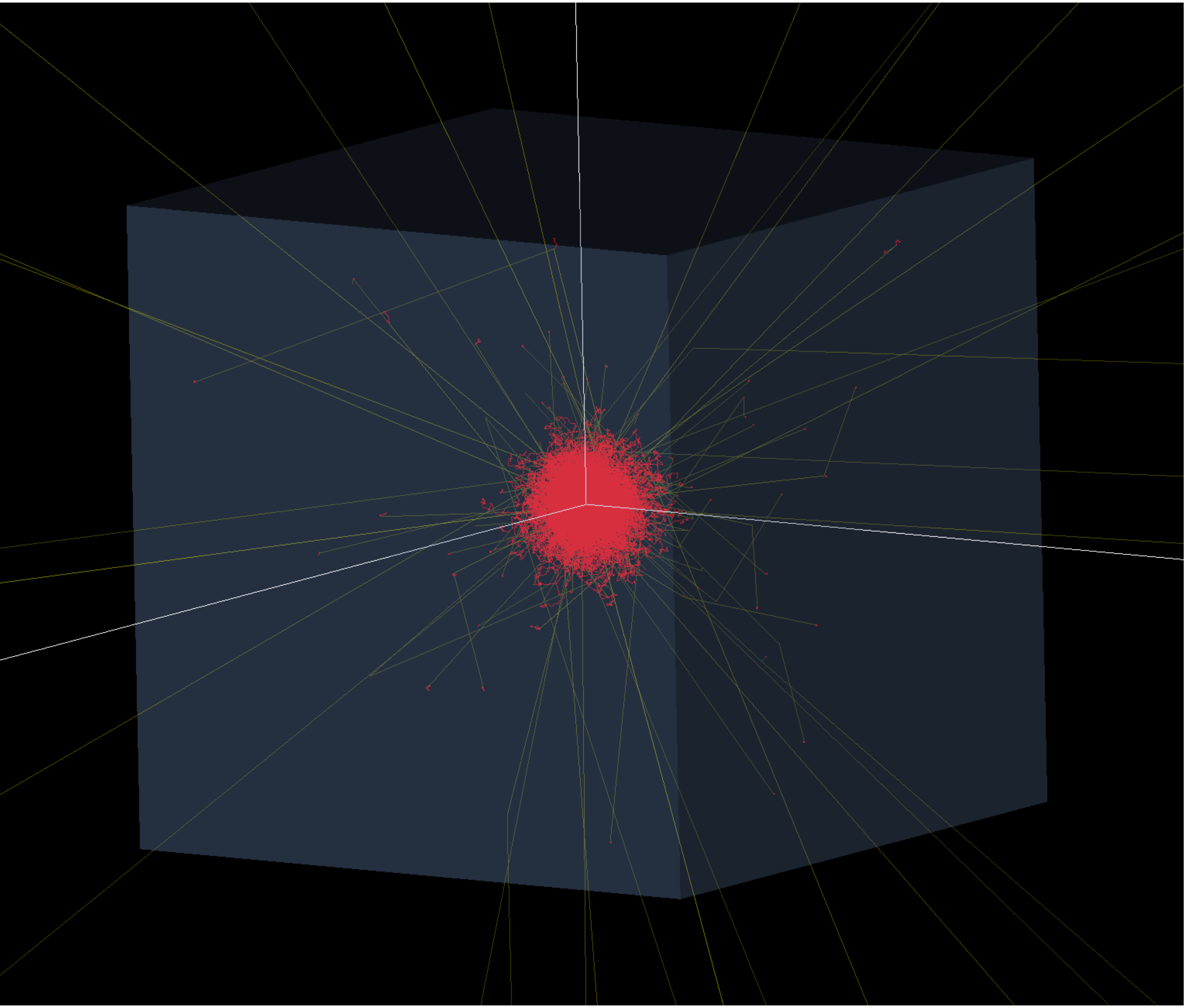


Detector designation	XS	S	M	L	XL
Absorber heat capacity at 20 mK	8 pJ/K	28 pJ/K	110 pJ/K	400 pJ/K	1.70 nJ/K



- Monoenergetic electron sources?

EGSnrc Assumptions



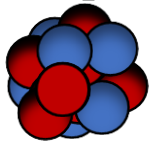
- Perfect heat transfer
  - No heat lost to environment
  - Detector gain is constant

- No time dependence

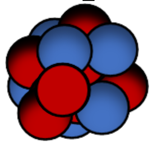
Beta Spectra

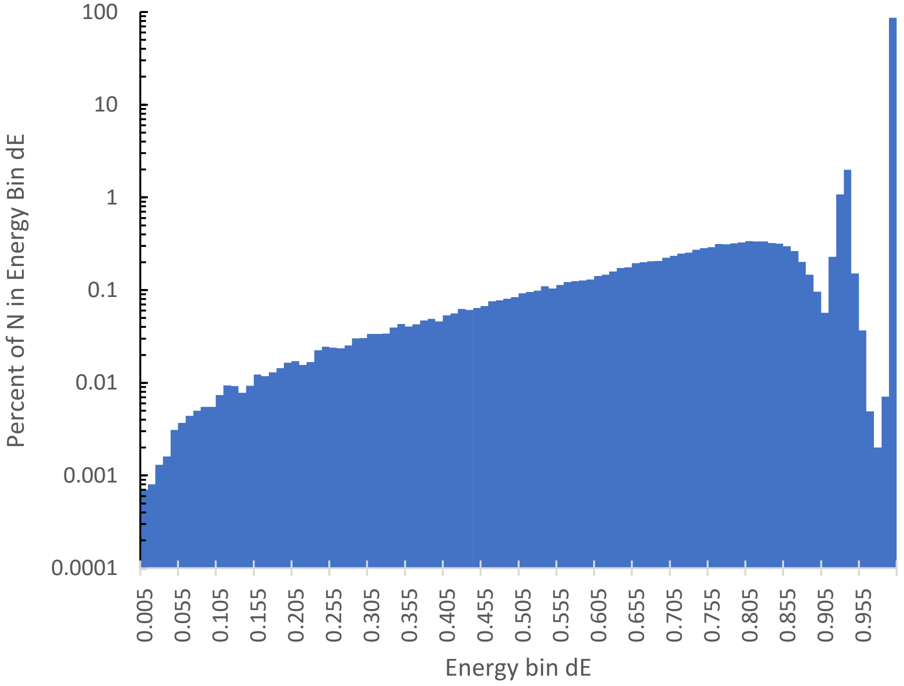
- Histograms of total reaction energy minus energy of neutrino
  - Neutrino has low likelihood of interacting with matter

Low Energy Neutrino:

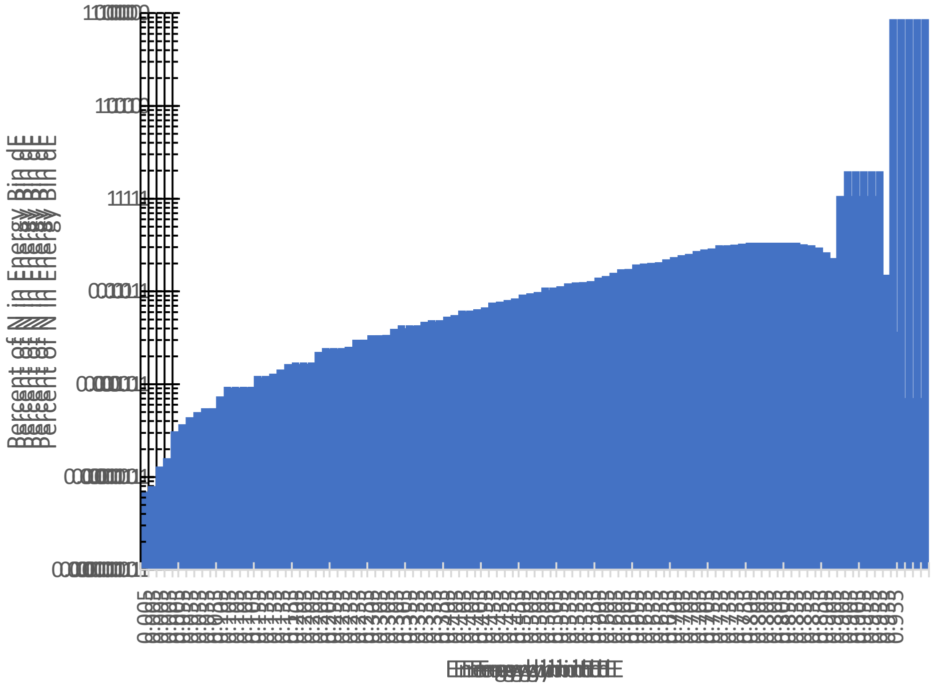
KE ($\bullet^{e^-}$) + E (^{N}Y ) = Q Value – KE (ν_e) = $\Rightarrow$ More Reaction Energy Measured

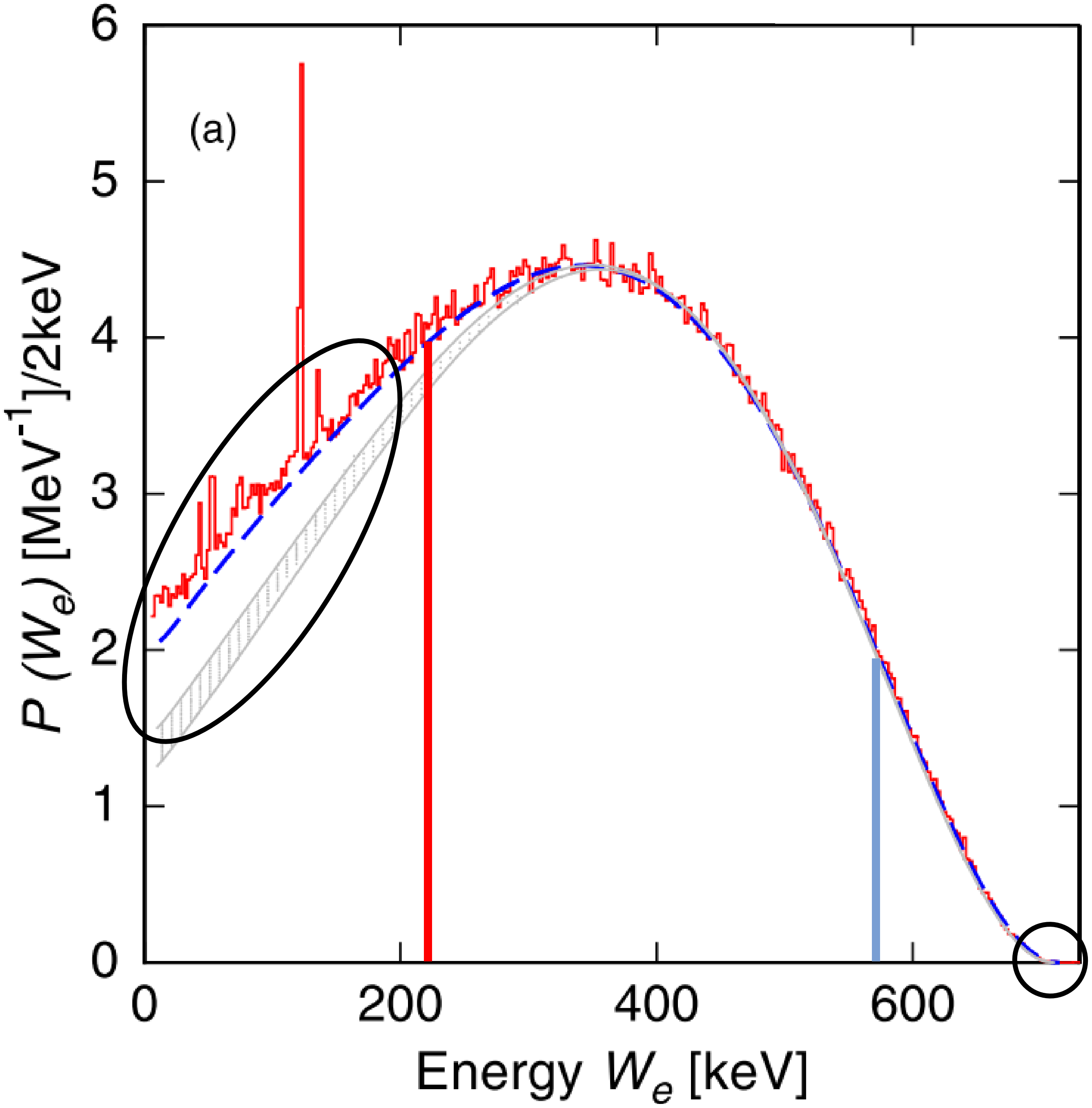
High Energy Neutrino:

KE ($\bullet^{e^-}$) + E (^{N}Y ) = Q Value – KE (ν_e) = $\Rightarrow$ Less Reaction Energy Measured



Percent of N in Energy Bin dE
100
10
1
0.1
0.01
0.001
0.0001
0.005
0.055
0.105
0.155
0.205
0.255
0.305
0.355
0.405
0.455
0.505
0.555
0.605
0.655
0.705
0.755
0.805
0.855
0.905
0.955
Energy bin dE





Importance of Beta Spectrum Shape

x-axis: Energy of all products without neutrino (or Q Value minus energy of neutrino

y-axis: Frequency of energy occurring

Some other notes maybe

Determining neutrino rest mass
Understanding Weak nuclear force

Color Palette