# keV sterile neutrino detection sensitivity of metallic magnetic calorimeter

Ref. [1] Sensitivity of Next-Generation Tritium Beta-Decay Experiments for keV-Scale Sterile Neutrinos
(statistical sensitivity description)

[2] Entwicklung mikrostrukturierter magnetischer Kalorimeter mit verbesserter magnetischer Flusskopplung für die hochauflösende Röntgenspektroskopie
(thermal conductance)

[3] Real Time Pulse Pile-up Recovery in a High Throughput Digital Pulse Processor
(pileup resolving)

# Sterile neutrino mixing with active neutrino ( Ref. [1] )

Assume that

1. In the mass range of few keV, there's only one heavy neutrino mass eigenstate.
2. Active neutrinos mix with it very small compared to mixing amplitude among themselves (PNMS matrix).

- If we ignore the small mass difference between three light neutrinos and simply treat these three as a one, we can simply express the mixing like below.

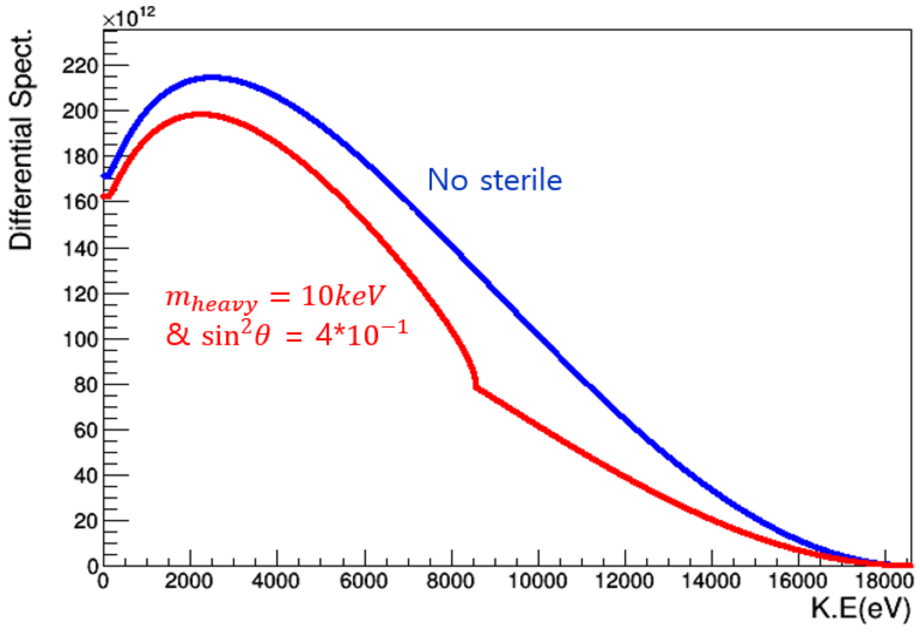
$$\nu_e = \cos\theta\,\nu_{light} + \sin\theta\,\nu_{heavy}$$
$$\nu_s = -\sin\theta\,\nu_{light} + \cos\theta\,\nu_{heavy}$$

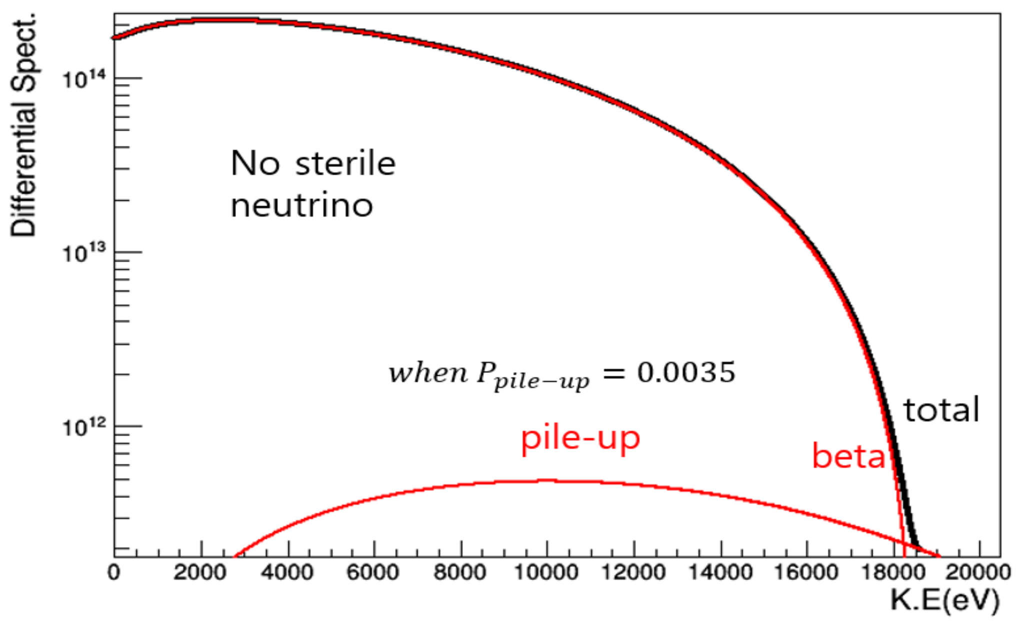
Total differential decay rate spectrum (of one tritium)

$$: \frac{d\lambda_\beta}{dE_e}_{tot} = \cos^2\theta\,\frac{d\lambda_\beta}{dE_e}\left(m_{light}\right) + \sin^2\theta\,\frac{d\lambda_\beta}{dE_e}\left(m_{heavy}\right)$$

$$= \frac{{G_F}^2|\mathrm{V}_{ud}|^2}{2\pi^3}|\mathcal{M}|^2\frac{2\pi\frac{Z\alpha E_e}{\sqrt{{E_e}^2-{m_e}^2}}}{1-\exp\left(\frac{Z\alpha E_e}{\sqrt{{E_e}^2-{m_e}^2}}\right)}\sqrt{{E_e}^2-{m_e}^2}E_e\sqrt{\left(m_e+Q_\beta-E_e\right)^2-{m_\nu}^2}\left(m_e+Q_\beta-E_e\right)\Theta(m_e+Q_\beta-m_\nu-E_e)$$

- Presence of keV sterile neutrino (1) suppress the total number of events and (2) makes a kink in spectral shape.
- Assume zero mass of light neutrino($m_{light} = 0$) because $m_{light} \ll m_{heavy}$.




Neglect the contribution of pile-up events to statistical sensitivity ( but there could be significant systematic uncertainty from finite resolution of determining unresolved signal )

In this case, only total number of events ( $= N_{initial} * \left(1 - e^{-\lambda_\beta T}\right)$ ) matters. ( $N_{initial}$ : $total\ \#\ of\ tritium\ atom, T$ : $running\ time$ )

# Single detector activity ( Ref [2], [3] )

- To get a good enough number of events, we need as high a single detector activity as possible.
- Therefore, two things must be satisfied:

(1) more large thermal conductance between sensor and heat bath ( for faster temperature decay )

(2) pileup recovery algorithm

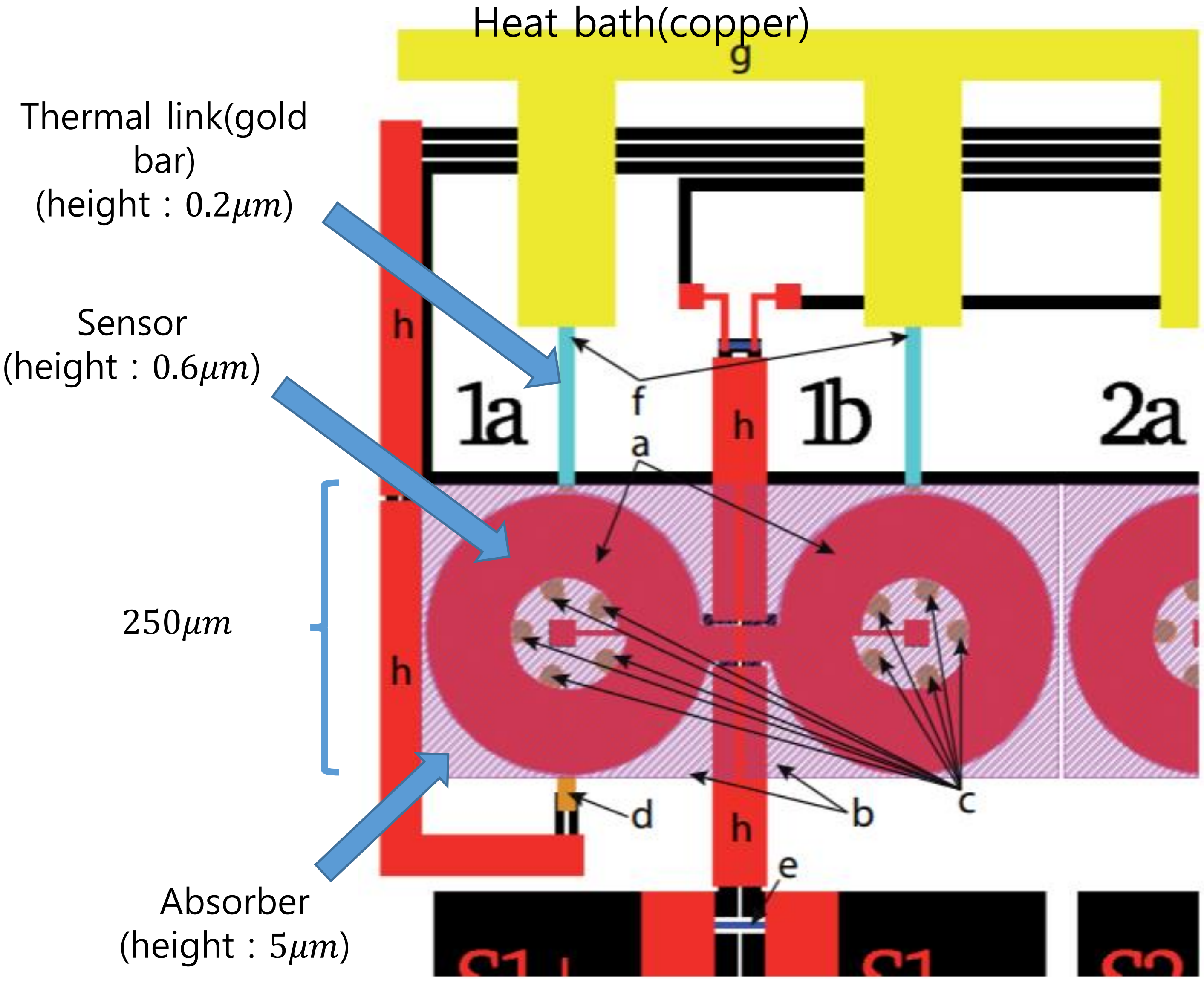
(1)

- $\tau_{decay} \sim C_{absorber+sensor}/G_{mag-bath}$
- $G_{mag-bath}$ can be approximated as thermal conductance of conduction electron in gold thermal link ( $\tau_{rise}$ : spin electron relaxation time ( inverse to temperature of electron ($70ns\ at\ 35mK$) )
- $G_{mag-bath} \sim \alpha T$ ( $\alpha$ is proportional to (area)/(length) )
- $\tau_{decay} \sim 500\mu s$ in the detector of next page.

$\Rightarrow$ $\tau_{decay}$ can becomes much smaller if we **(A)** increase the (area)/(length) or **(B)** increase the temperature of bath

$\Rightarrow$ Increasing (A) and (B) by 60 and 6 respectively gives $\tau_{decay} \sim 1\mu s$ and $\tau_{rise} \sim 10ns$

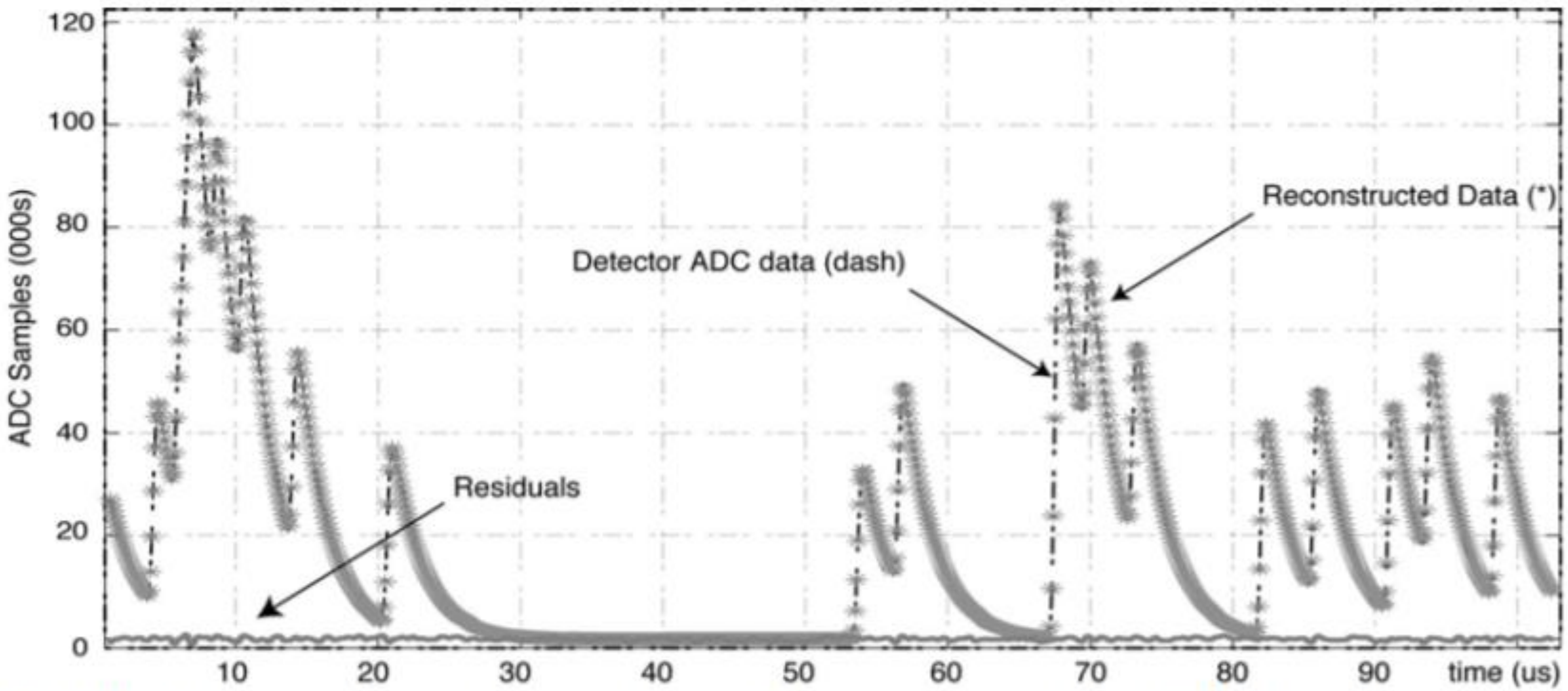
From Ref. [2]



Heat bath(copper)
g
Thermal link(gold bar)
(height : $0.2\mu m$)
Sensor
(height : $0.6\mu m$)
$250\mu m$
Absorber
(height : $5\mu m$)
h
h
h
h
1a
1b
2a
f
a
b
c
d
e

(2)

Ref [3] says that single detector activity of similar size of decay constant is possible by pile-up recovery algorithm



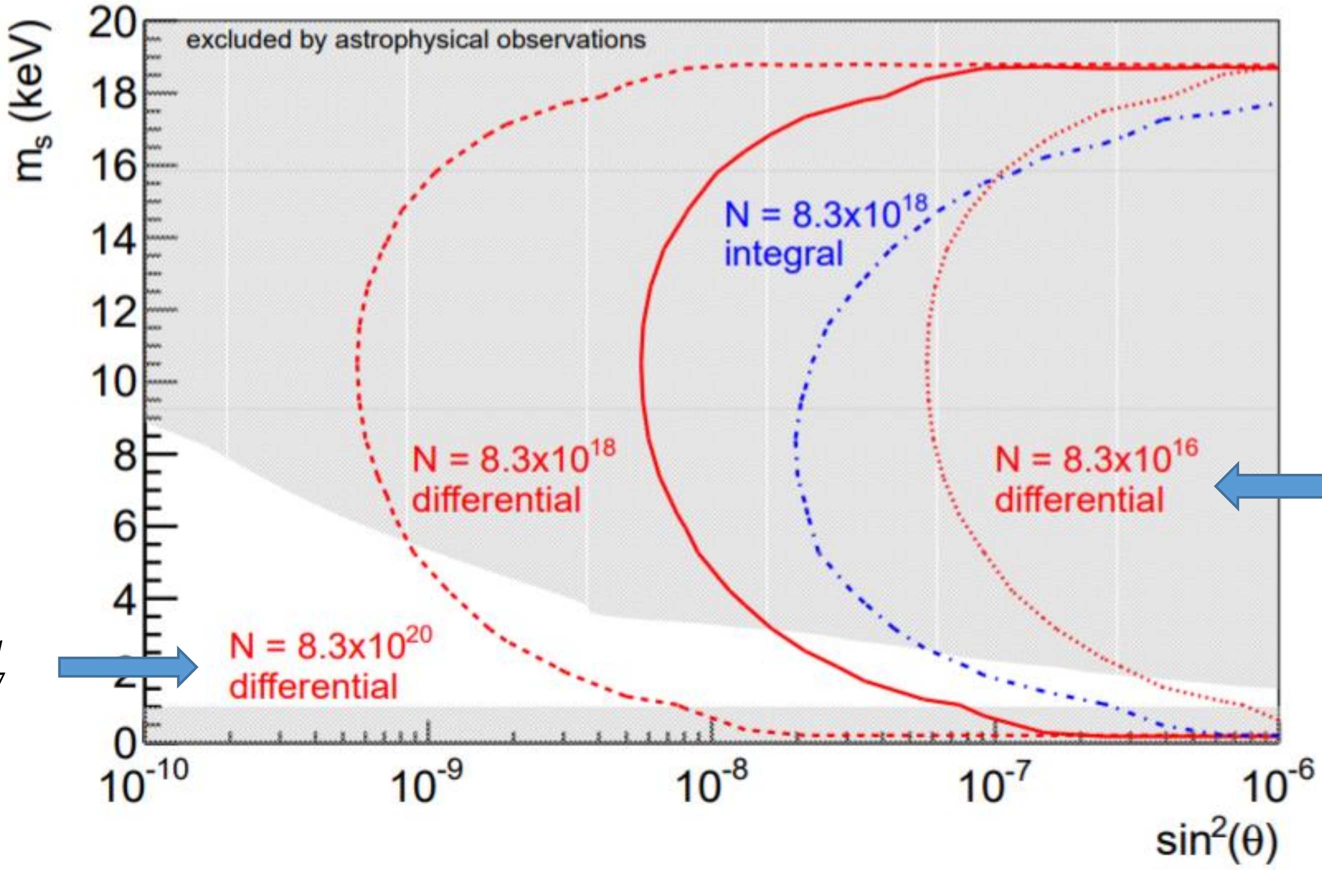

From Ref. [3]

**FIGURE 5.** A 'noise-free' model of the detector data is reconstructed by the "Validation" stage using the parameters which have been determine from previous stages of the algorithm.

→ Combining with (1) let's assume that single detector activity of 1MBq is possible and fix it

## Statistical sensitivity

- KATRIN expects $8.3 * 10^{18}\ events$ in 3 years. It corresponds to $0.4mg$ of tritium for 2 years running
- 1MBq for single detector activity -> need $1.3 * 10^5$ detectors ( single detector activity = $\frac{N_{initial}}{N_{det}}\lambda_\beta$ )

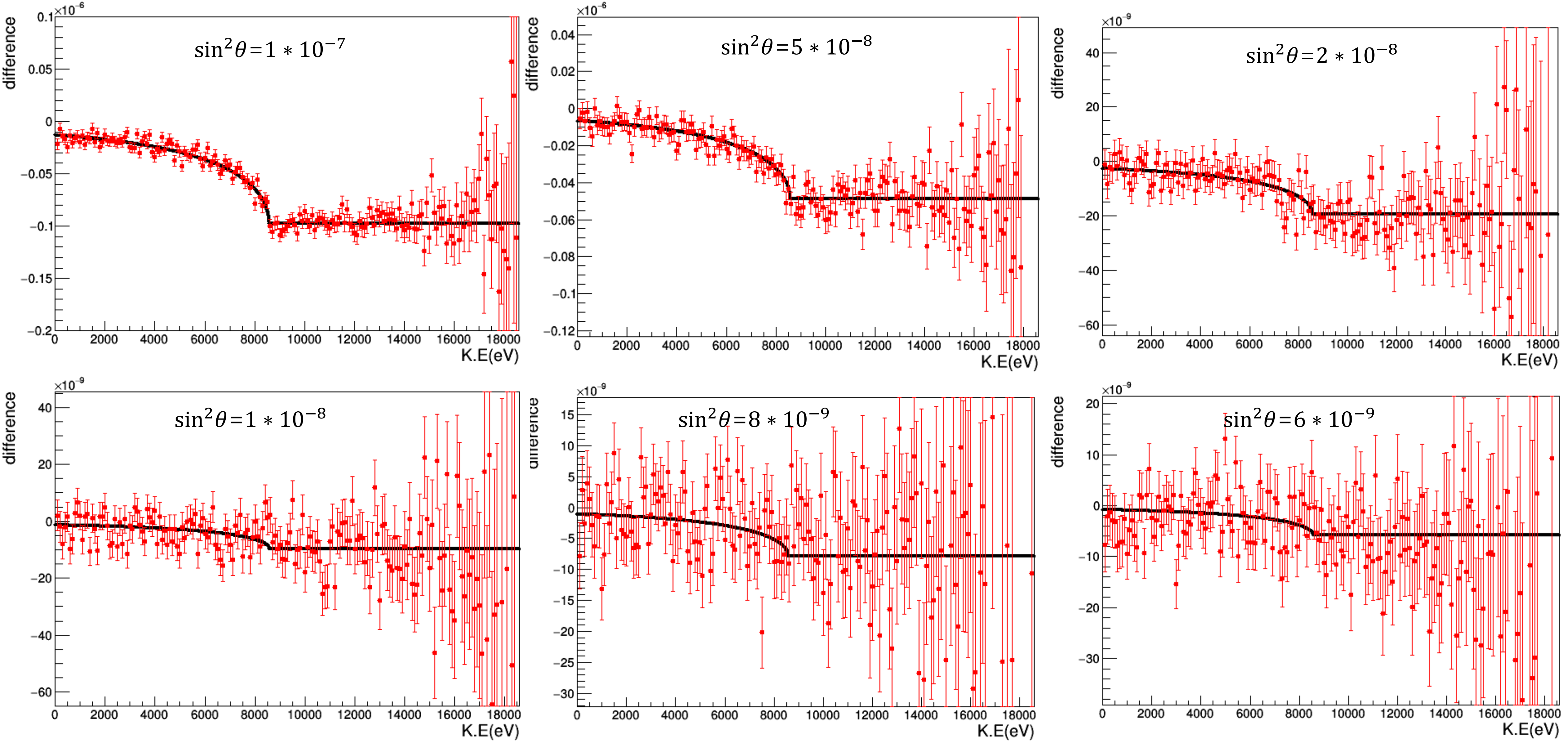



From Ref. [1]

$N_{tritium} = 4\mu g$
$N_{det} = 1.3 * 10^3$

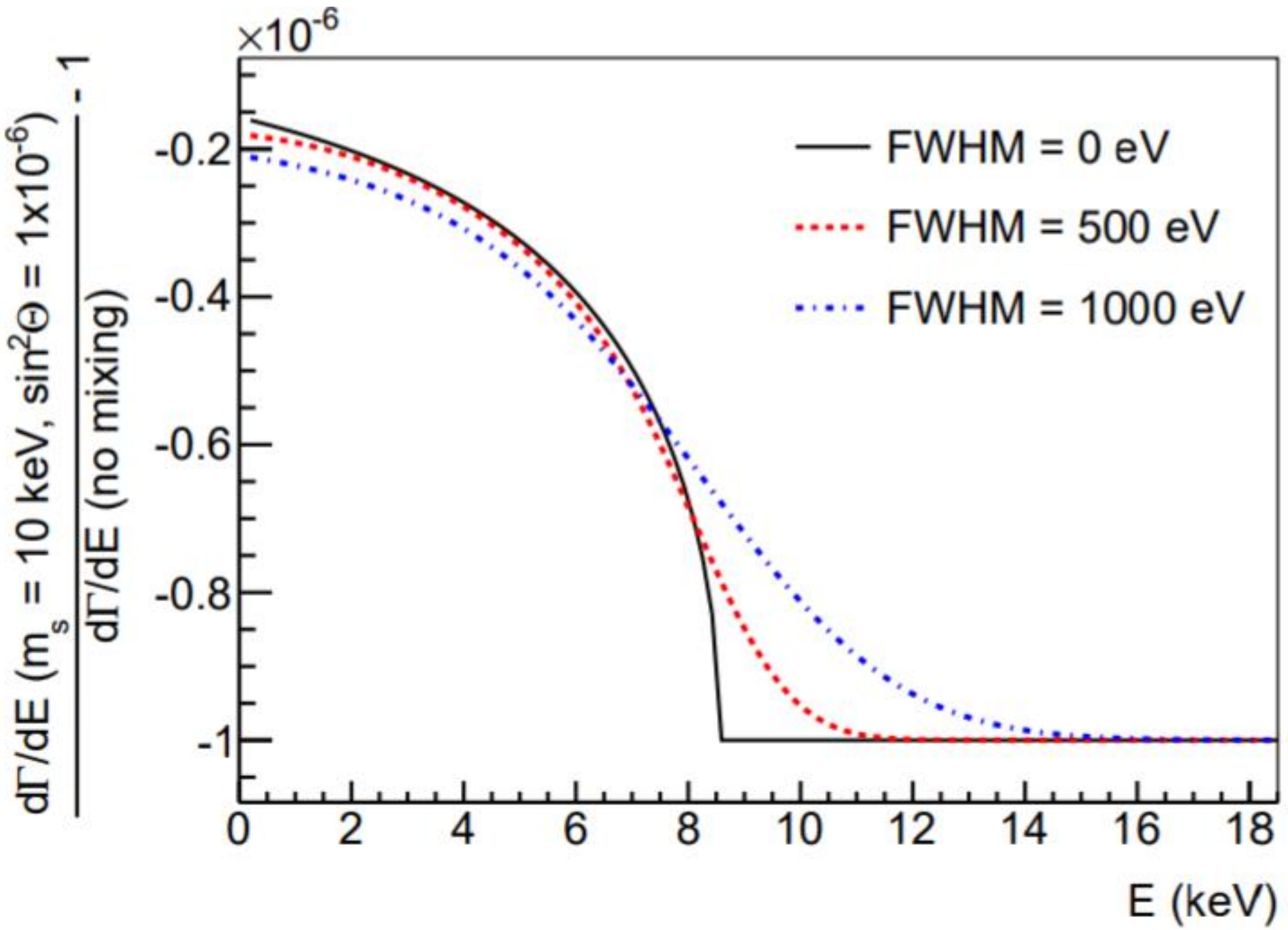
$N_{tritium} = 40mg$
$N_{det} = 1.3 * 10^7$

$$\text{difference} \equiv \left(\frac{dN}{dE}_{mix} - \frac{dN}{dE}_{no\ mix}\right) / \frac{dN}{dE}_{no\ mix}$$



## Energy resolution ( Ref [1] )

- Single detector activity higher than 1MBq might be possible at the expense of energy resolution which does not significantly affect the sensitivity




From Ref. [1]