

# Neutrino mass sensitivity with the Ptolemy demonstrator

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*(On behalf of the LNGS group)*

PTOLEMY Collaboration Meeting  
**Princeton, Nov. 6<sup>th</sup>, 2023**

# Neutrino mass

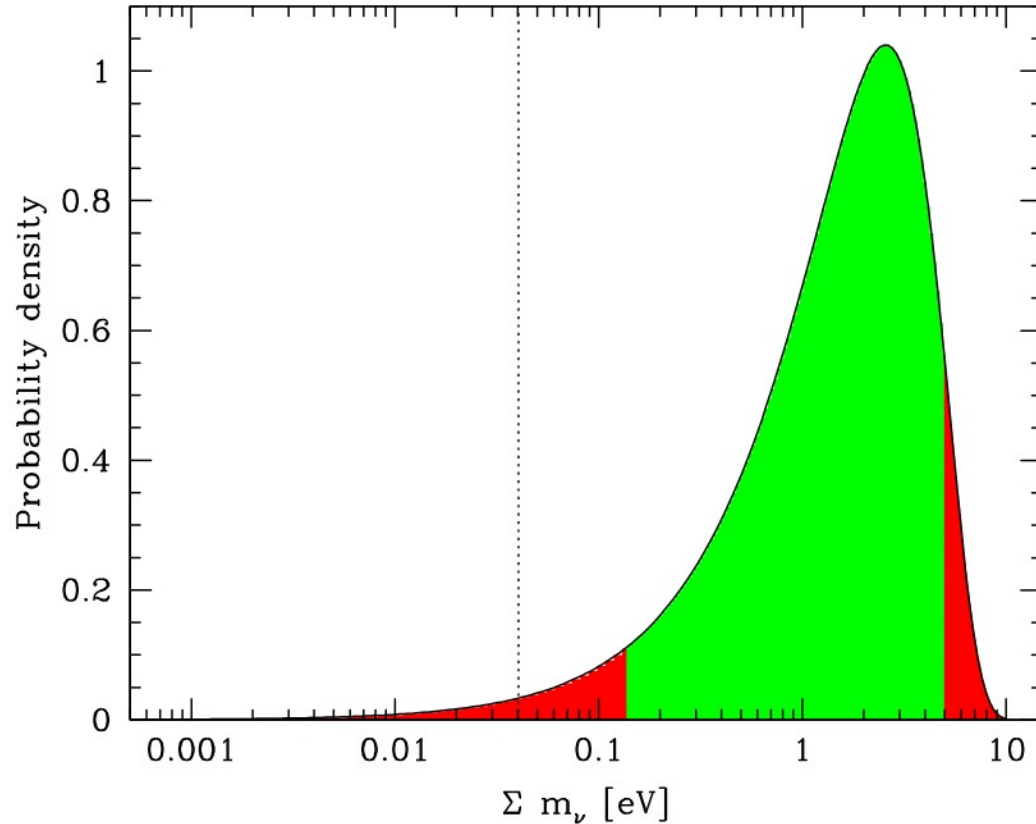
$$m_{\text{eff}}^2 = \sum_i |U_{ei}|^2 m_i^2 \lesssim 800 \text{ meV} \quad \text{KATRIN}$$

$$\sum_i m_i \lesssim 100 \text{ meV} \quad \text{Cosmology}$$

$$m_{\beta\beta} = \left| \sum_i U_{ei}^2 m_i \right| \lesssim 100 - 300 \text{ eV} \quad \begin{array}{l} \beta\beta 0\nu \\ (^{76}\text{Ge}, ^{130}\text{Te}, ^{136}\text{Xe}) \end{array}$$

(If Majorana)

# Anthropic predictions for neutrino masses



[Tegmark et al. (2005)]

# Atropic Principle

THE UNIVERSE  
OBVIOUSLY IS  
A CELLAR  
AUTOMATON!

THERE ARE  
MULTIVERSES  
EVERYWHERE  
OUT THERE

IF ANYTHING IS  
CERTAIN, IT'S  
THAT I MYSELF  
AM NOT A  
MARXIST!

THAT'S  
THEOLOGY

YOU FORGET  
THE GOEDEL'S  
THEOREM

BIENVENUE,  
MONSIEUR  
DE LAPALISSE

THERE'S PLENTY  
OF EXOPLANETS

THAT'S  
TAUTOLOGY!

DO YOU KNOW  
THE NUMBER  
 $10^{500}$ ?

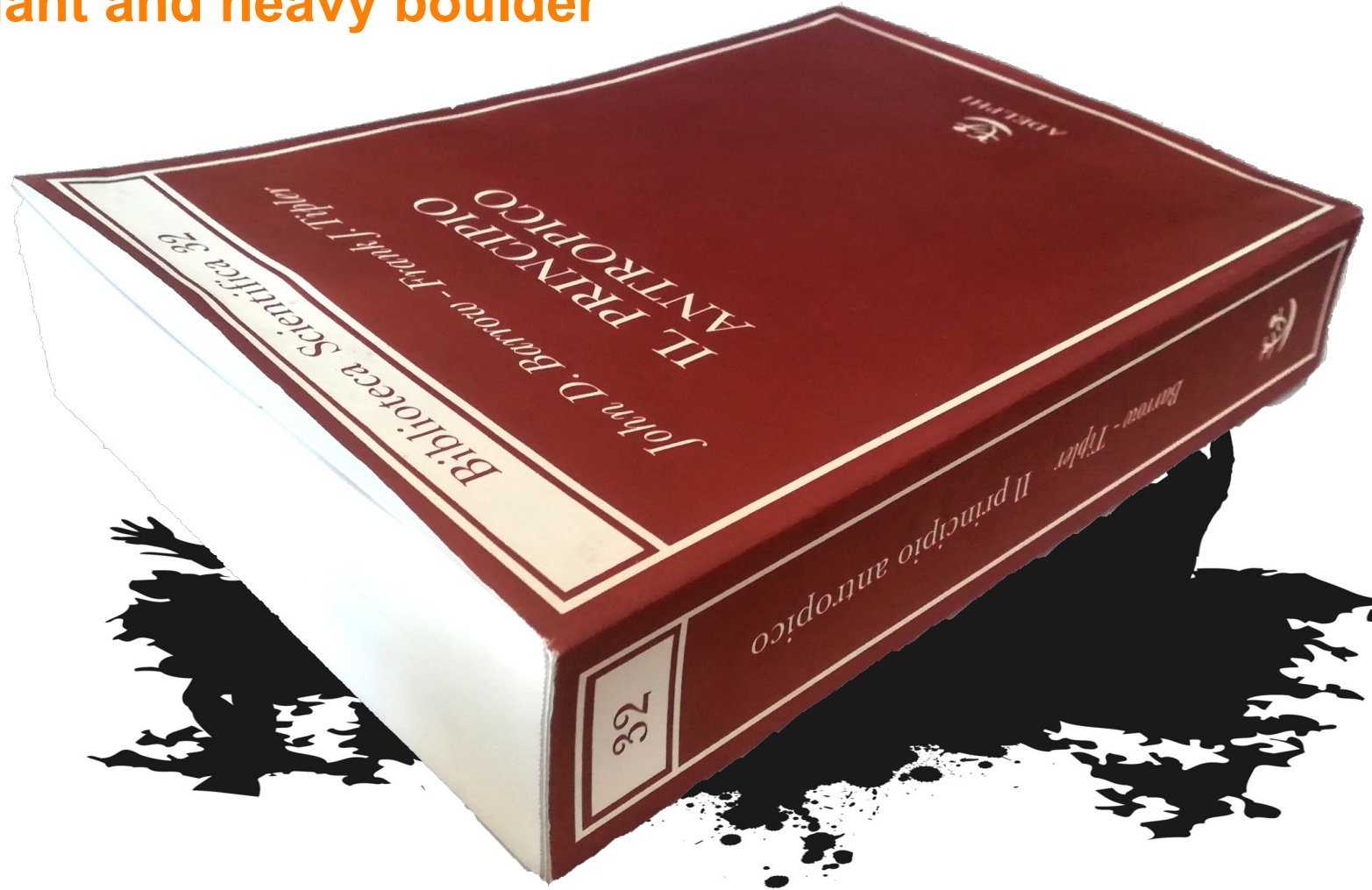
ZUCKERBERG  
HAS JUST  
CREATED  
A METAVERSE

BEWARE THE  
SELECTION RULE!

BOLTZMANN  
BRAIN IS WAY  
MORE APPEALING!



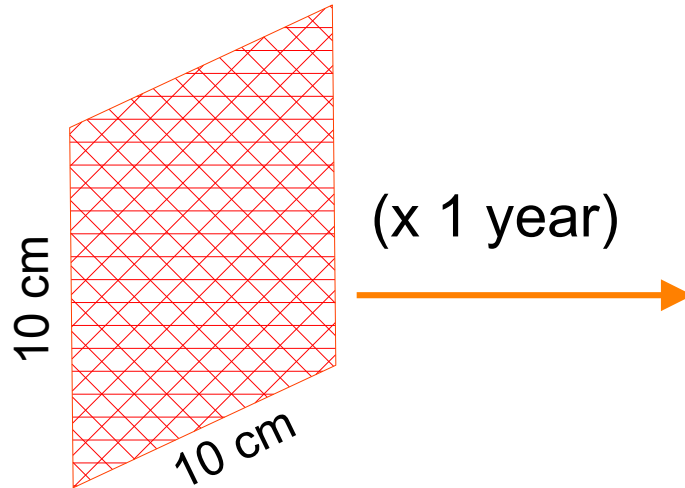
# The Anthropic Principle is a giant and heavy boulder



# Reference source

$$N_{dec} = \frac{1}{2} \left( \frac{m_S \mathcal{N}_A}{A_{(^3H)}} (1 - e^{-t/\tau}) \right) \simeq 1.1 \times 10^{16}$$

(50%  
Efficiency  
for total  
events)



$\rho = 0.2 \text{ mg/m}^2$   
(full loading)

→ 2  $\mu\text{g}$

716 MBq  
(19.3 mCi)

# Formulas

$$S_{\sigma,m}(E) \simeq R(E) \sum_i |U_{ei}|^2 \sqrt{(E_0 - E)^2 - (m_{\nu_e}^{\text{eff}})^2} \otimes \frac{1}{\sqrt{2\pi\sigma}} e^{-\frac{E^2}{2\sigma^2}}$$

Theory

Resolution

## Cases:

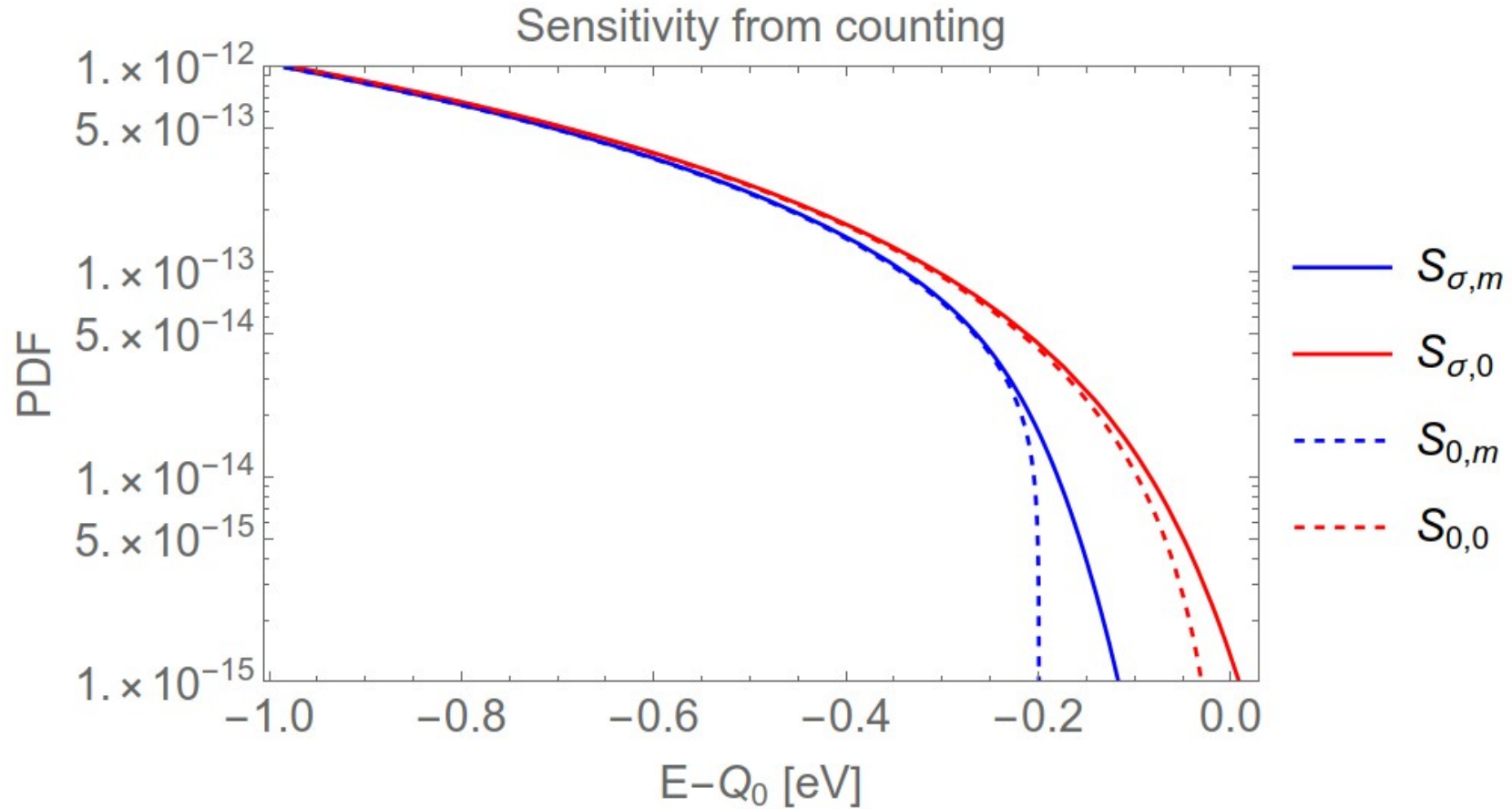
$S_{0,0}$  = Therotical spectrum with massless neutrino

$S_{0,m}$  = Therotical spectrum with massive neutrino

$S_{\sigma,0}$  = Esperimental spectrum with massless neutrino

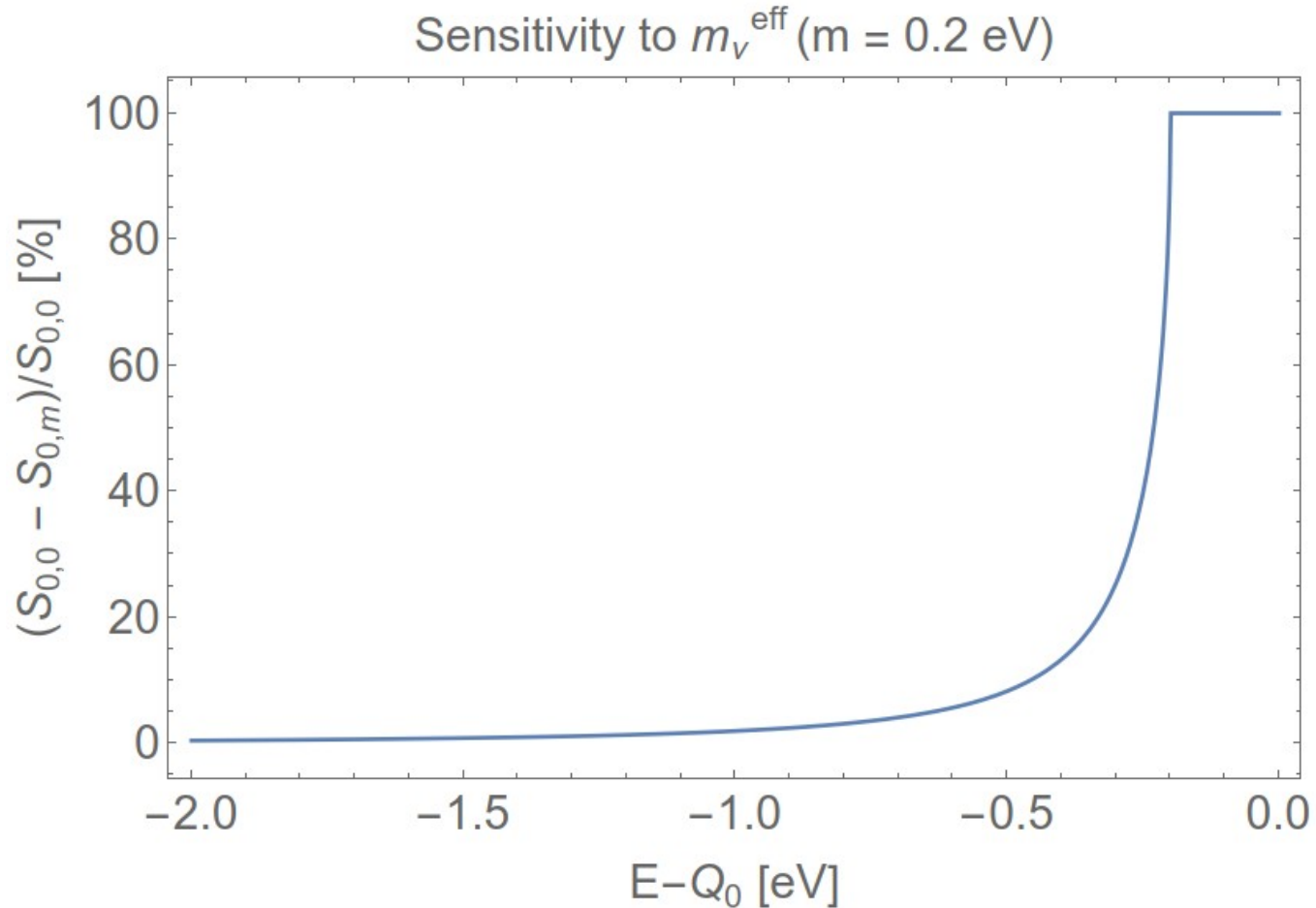
$S_{\sigma,m}$  = Esperimental spectrum with massive neutrino

# End-point

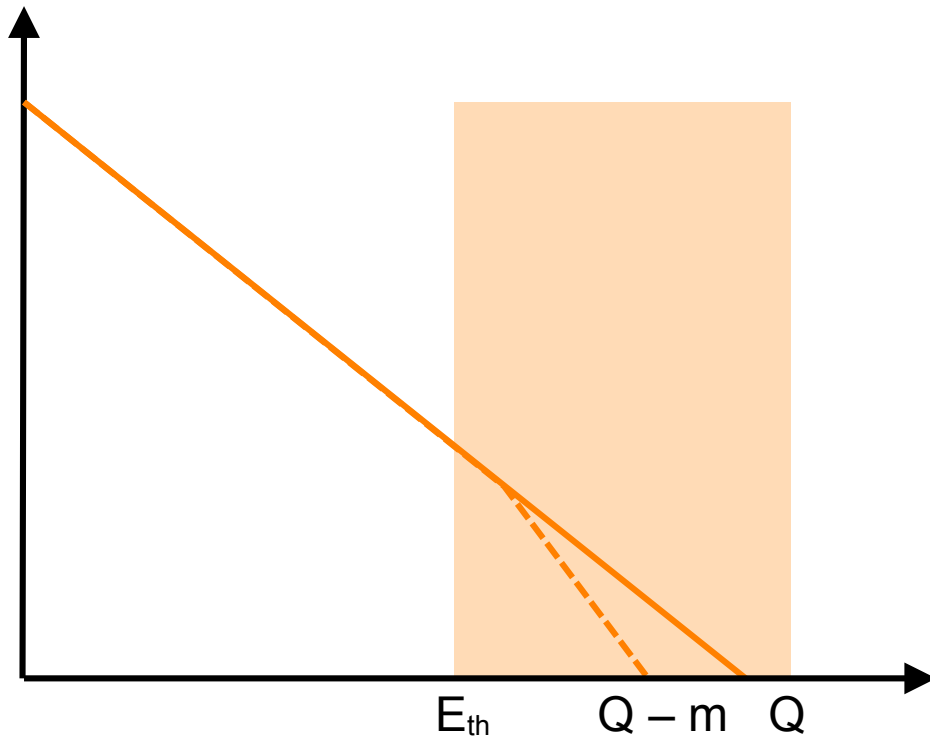




# Sensitivity to neutrino mass



# Counting analysis



$$N_{\sigma,m} = \int_{E_{th}} S_{\sigma,m}(E) dE$$

$$N_{\sigma,0} = \int_{E_{th}} S_{\sigma,0}(E) dE$$

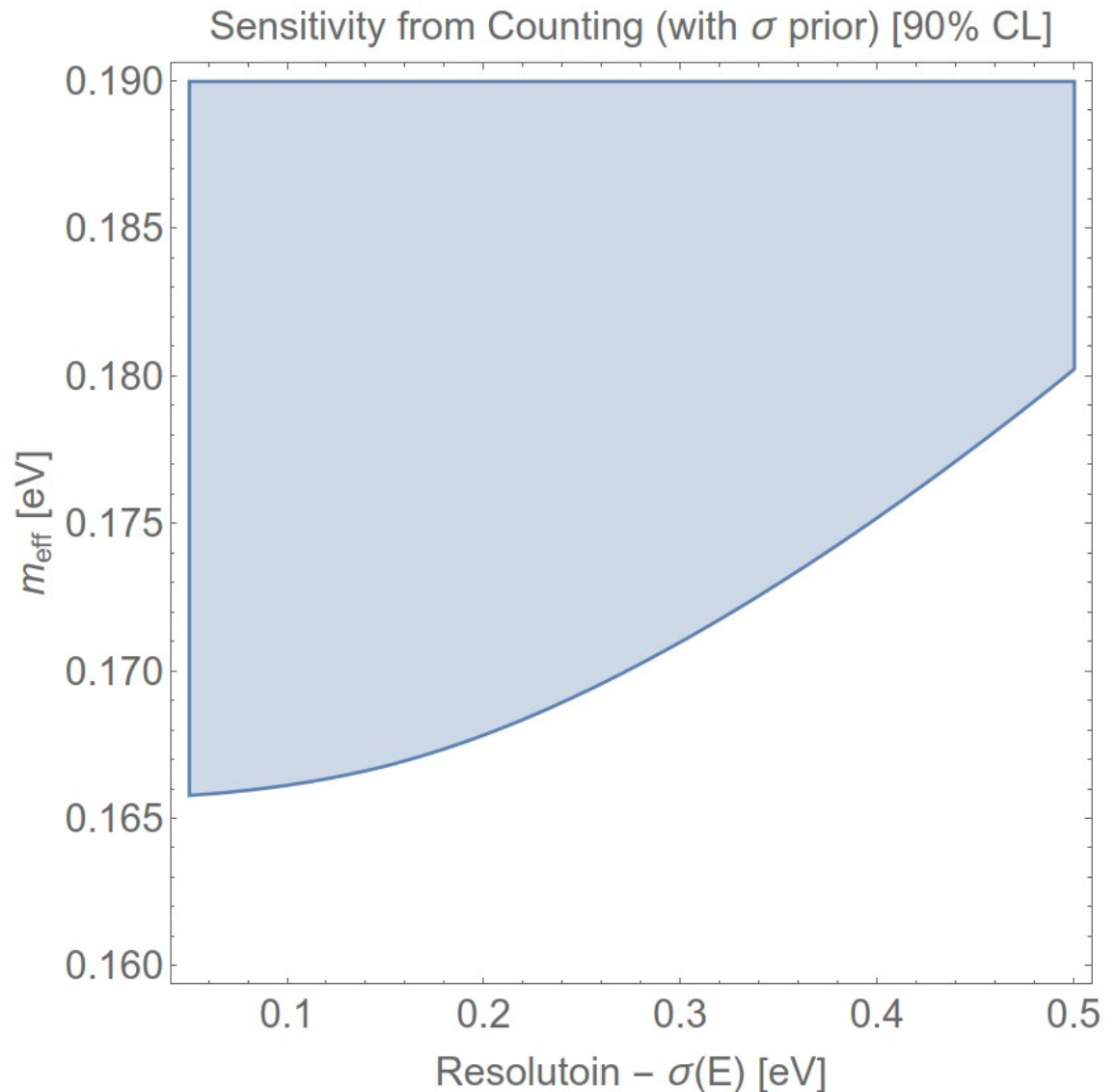
Sensitivity 90%CL :=

$$\frac{N_{\sigma,0} - N_{\sigma,m}}{\sqrt{N_{\sigma,0} + N_{\sigma,m}}} = 1.64$$

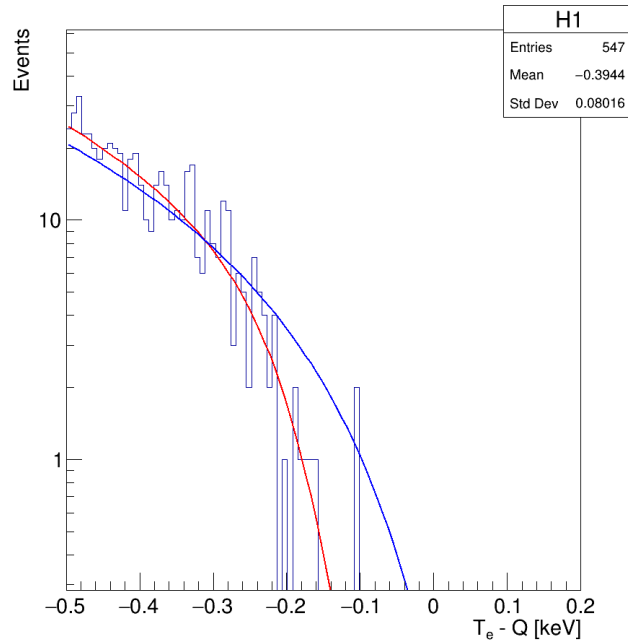
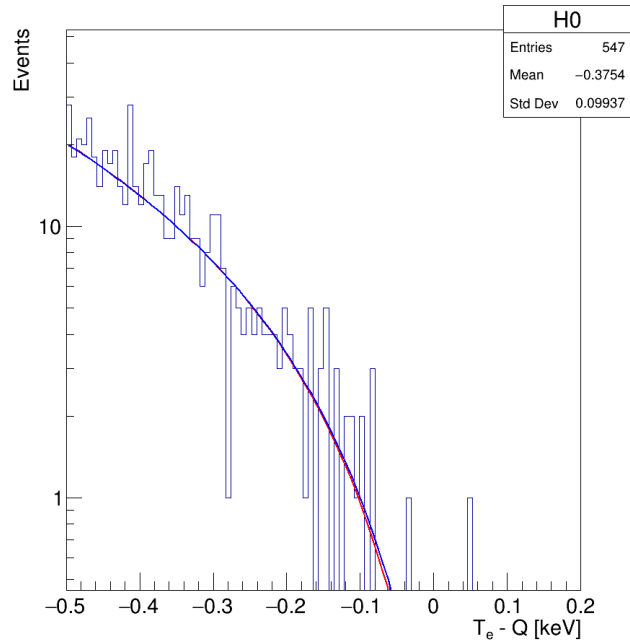
# Sensitivity from counting analysis

**Narrow prior  
on resolution:**

- Experimental resolution
- Uncertainty principle smearing ( $\Delta$ )



# Profile likelihood approach

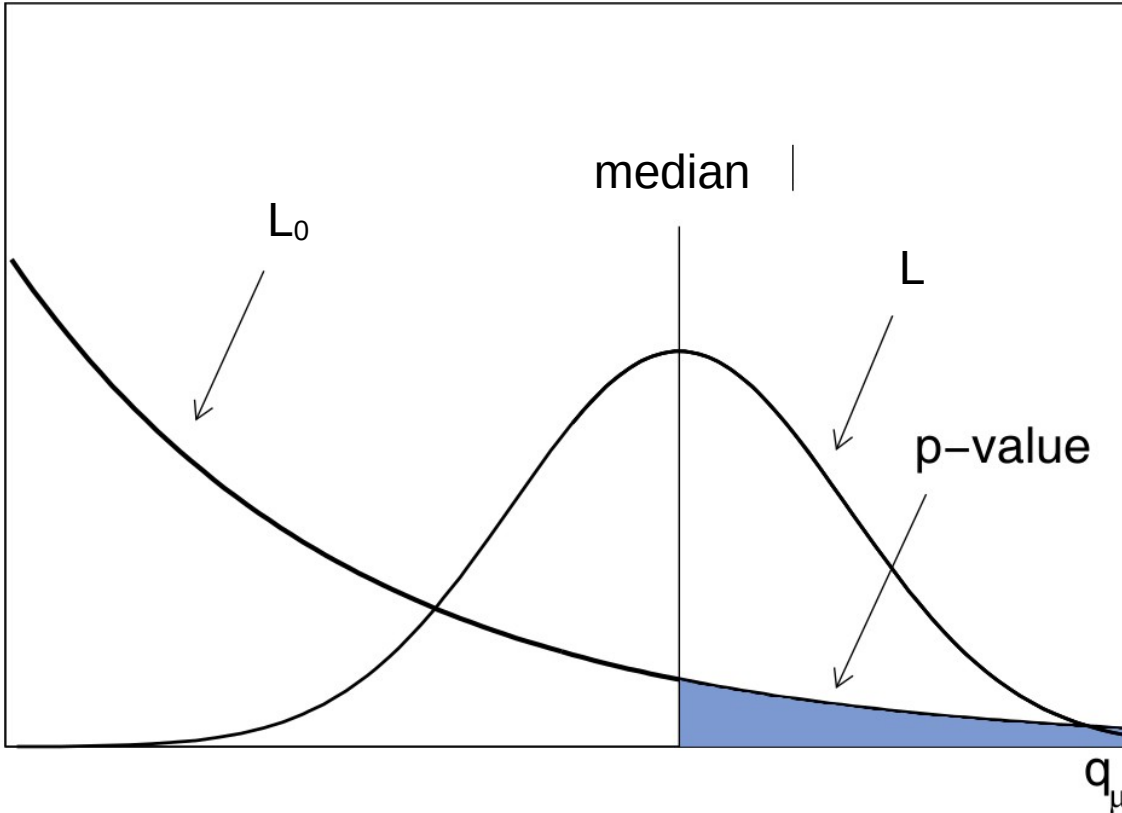


**Sensitivity**

P-value of the L  
medial over the  $L_0$   
distribution

$$\mathcal{L}_0 = -2 \log \frac{\mathcal{L}(S_{\sigma,0} | \text{data}_0)}{\mathcal{L}(S_{\sigma,m} | \text{data}_0)} \quad \mathcal{L} = -2 \log \frac{\mathcal{L}(S_{\sigma,0} | \text{data}_m)}{\mathcal{L}(S_{\sigma,m} | \text{data}_m)}$$

# Median sensitivity



[Cowan et al. (2013)]

# TOOL: PtSens (GitHub)

Plot your spectrum:

```
./ptsens plot mass [eV] sigma [eV]
```

Random sample from toy MC and fit:

```
./ptsens mc mass [eV] sigma [eV]
```

Profile likelihood for discovery (sensitivity):

```
./ptsens pf mass [eV] sigma [eV] nToys
```

# A new option

```
./ptsens nm 0.200 0.050 1000
```

Neutrino  
mass  
option

Neutrino  
mass (m)  
[eV]

Energy  
resolution( $\sigma$ )  
[eV]

Number of  
toy MC  
simulations

Output: `ptolemy.root`

# New cfg file (part 1/2)

```
Open  [icon]  init.cfg  Save  [icon]  [icon]  [icon]  [icon]
~/Desktop/GIT/GitHub/ptsens/cfg
1 # *** TOY MC PARAMS ***
2
3 # total decays ( e.g. 100*10 gy -> 8.64e24, 0.0002/1000/2 -> 1.56e15)
4 Ndec  1.56e16
5
6 # CNB in 10 years
7 Ncnb  100
8
9 # preselected events
10 N    10000
11
12 # *** OTHER CONFIG PARAMS ***
13
14 # convolution range
15 Rmin  -5
16 Rmax  3
17
18 # display y-axis
19 ymin  1e-27
20 ymax  1e-12
21
22 # mass ordering eff = effective, N0: normal, I0: inverted
23 Ordering  eff
24
25 # convolution range: dSigma = integration step
26 Cmin  -0.8
27 Cmax  0.4
28 dSigma  30
29
30 # Nu Mass interval
31 NMmin  -0.5
32 NMmax  0.2
Plain Text  Tab Width: 8  Ln 38, Col 17  INS
```

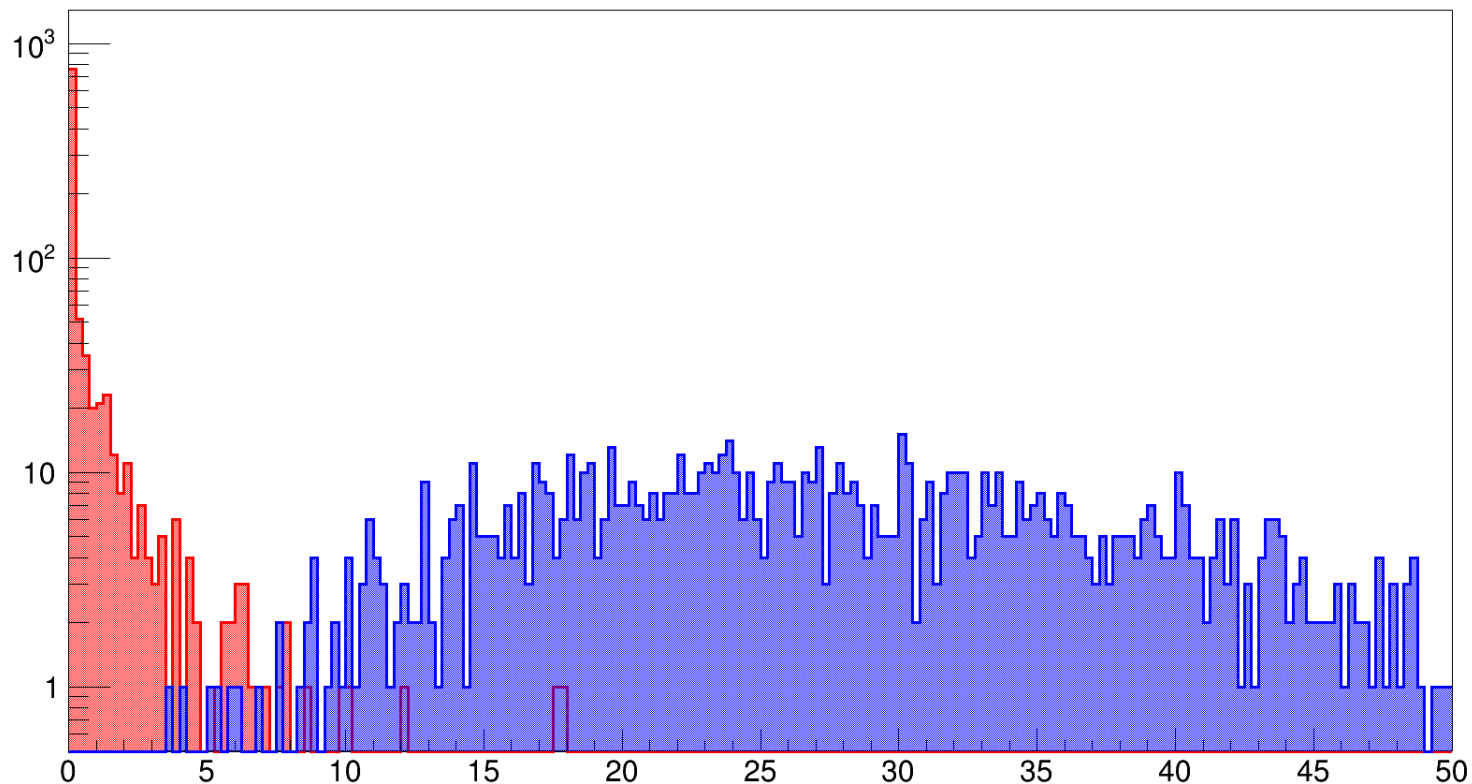
**New option #1**  
Explicit convolution range

**New option #2**  
Nu mass energy interval [eV]



# Example no. 1 ( $m=200$ meV, $\sigma=50$ meV)

Profile Likelihood

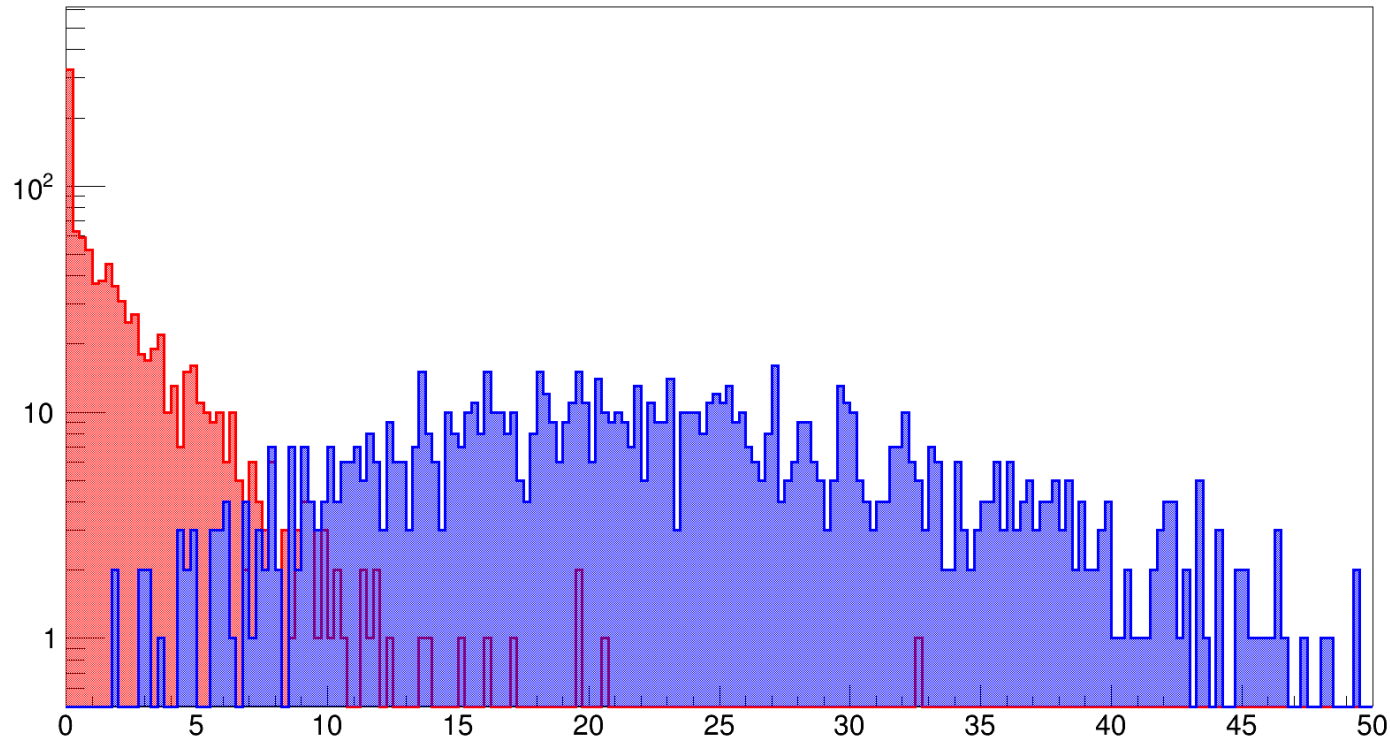


No events  $>$   
medial

$\rightarrow$  Better than  
 $3\sigma$

# Example no. 2 ( $m=200$ meV, $\sigma=500$ meV)

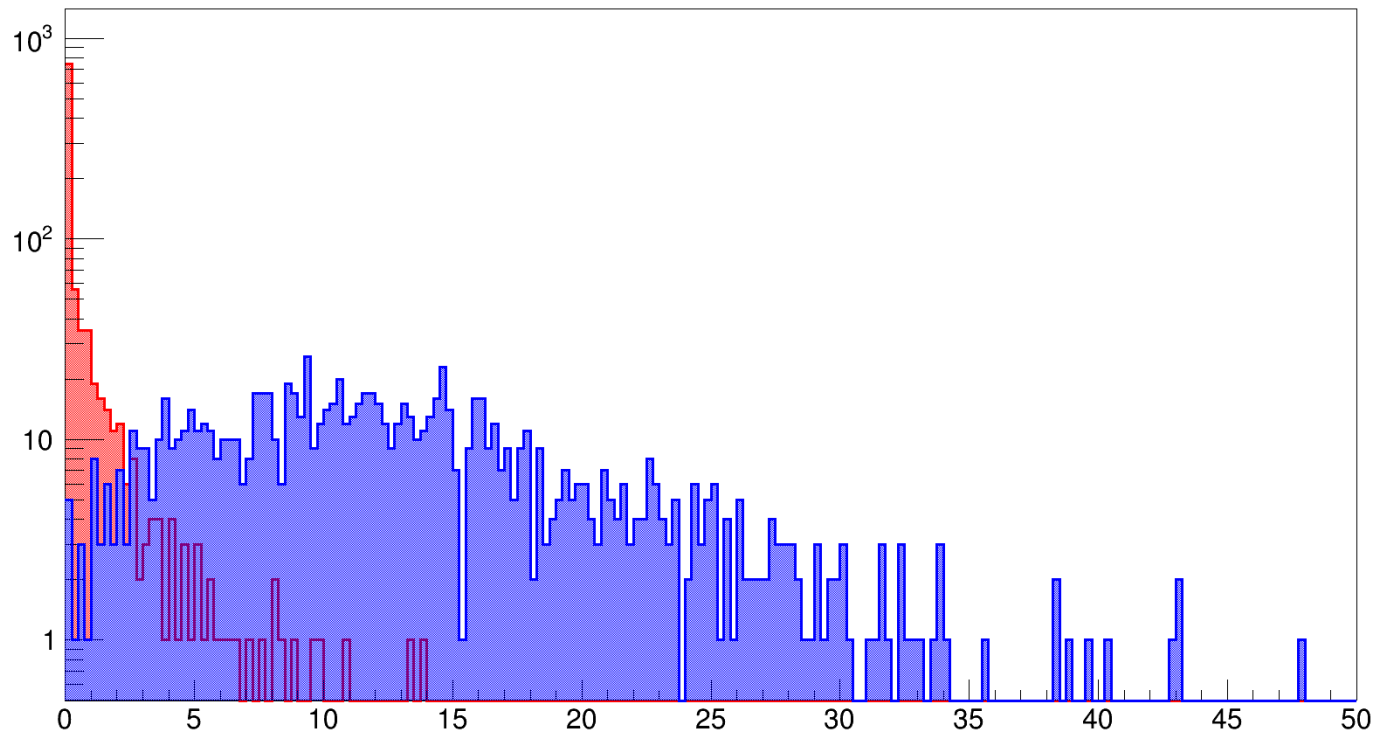
Profile Likelihood



Close to  
 $3\sigma$  anyway

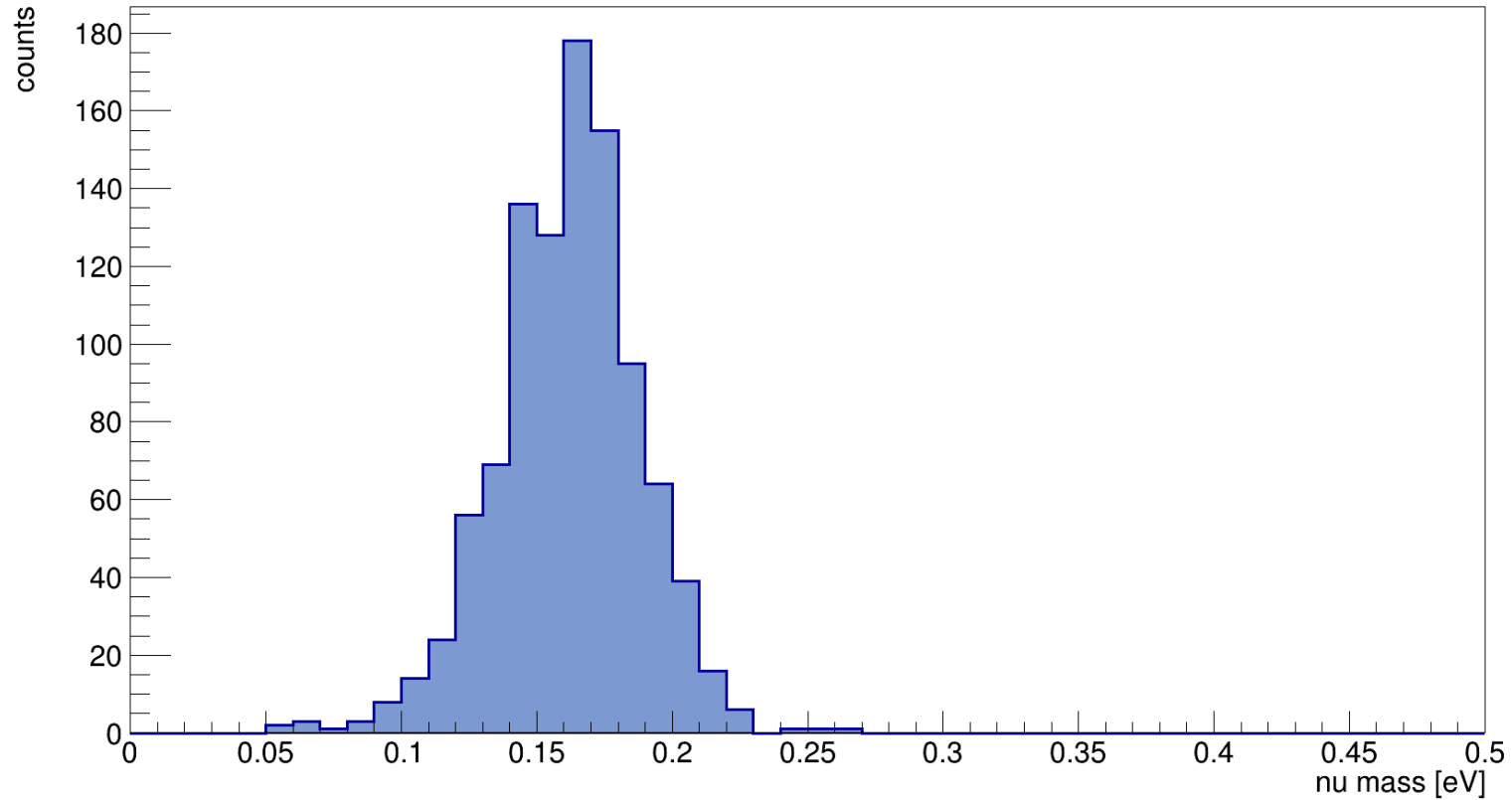
# Example no. 3 ( $m=150$ meV, $\sigma=50$ meV)

Profile Likelihood



Still  
sensitive

# Reconstructed $m$ in Ex. 3



# Comparison KATRIN

**Table 1 | Comparison of key numbers for the KNM campaigns**

	KNM1	KNM2
Number of scans	274	361
Total scan time	521.7 h	743.7 h
Background rate	290 mcps	220 mcps
T <sub>2</sub> column density	$1.11 \times 10^{17} \text{ cm}^{-2}$	$4.23 \times 10^{17} \text{ cm}^{-2}$
Source activity	$2.5 \times 10^{10} \text{ Bq}$	$9.5 \times 10^{10} \text{ Bq}$
Total number of $\beta$ -electrons	$1.48 \times 10^6$	$3.68 \times 10^6$
$\beta$ -electron-to-background ratio	3.7	9.9

KNM1 refers to the first KATRIN campaign results<sup>17</sup> and KNM2 refers to this work. The total number of  $\beta$ -electrons is counted in the last 40 eV interval of the integral spectrum, which is used for the spectral fit. The  $\beta$ -electron-to-background ratio is given by the ratio of this number and the background counts in the same energy range, that is,  $E_0 - 40 \text{ eV}$  to  $E_0$ .

$[E_0 - 40, E_0] \text{ eV}$

$\sim 10^{14}$  events

Current limit  $< 800 \text{ meV}$

Sensitivity  $700 \text{ meV}$

Resolution  $930 \text{ meV}$

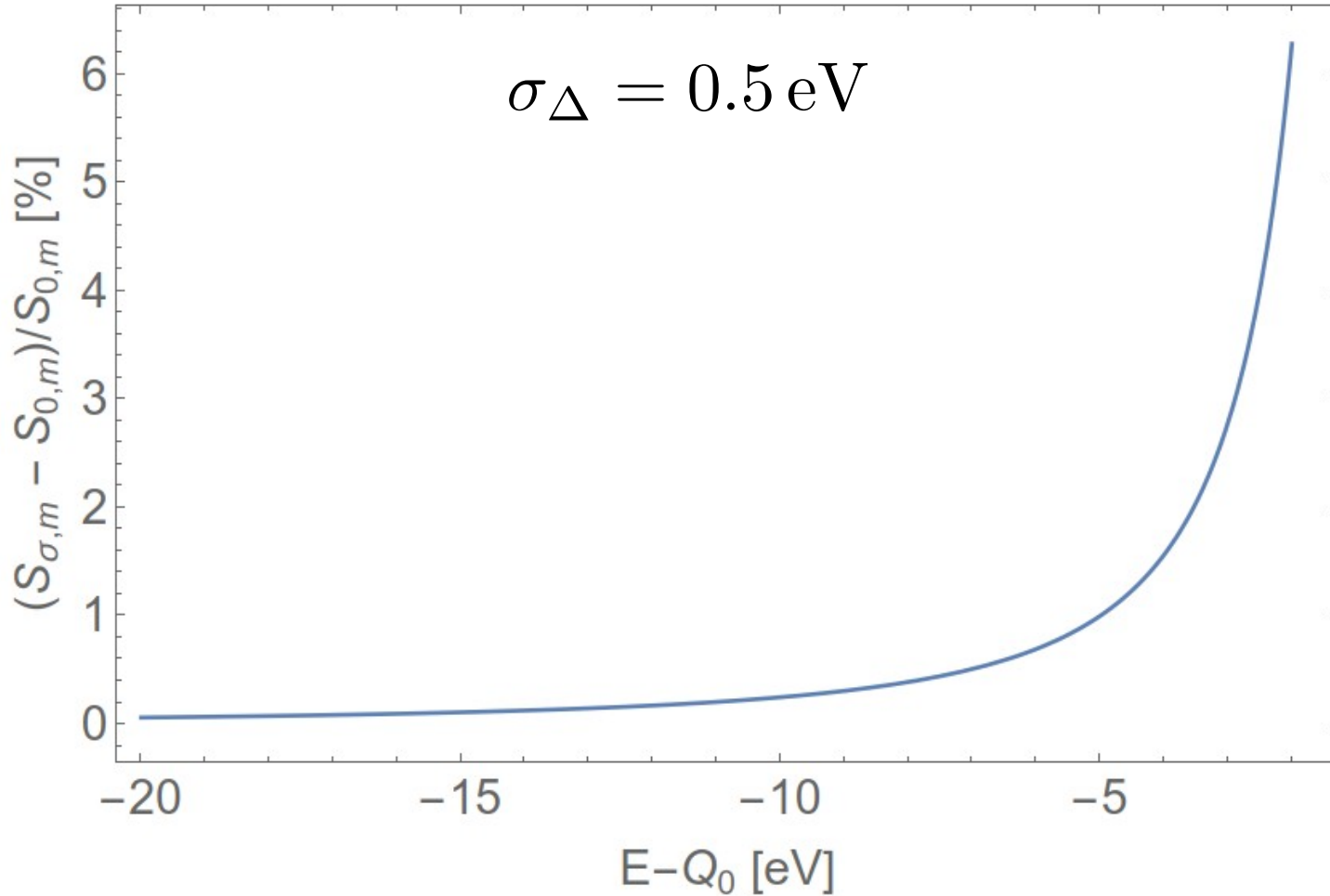
# $\Delta$ : A way out



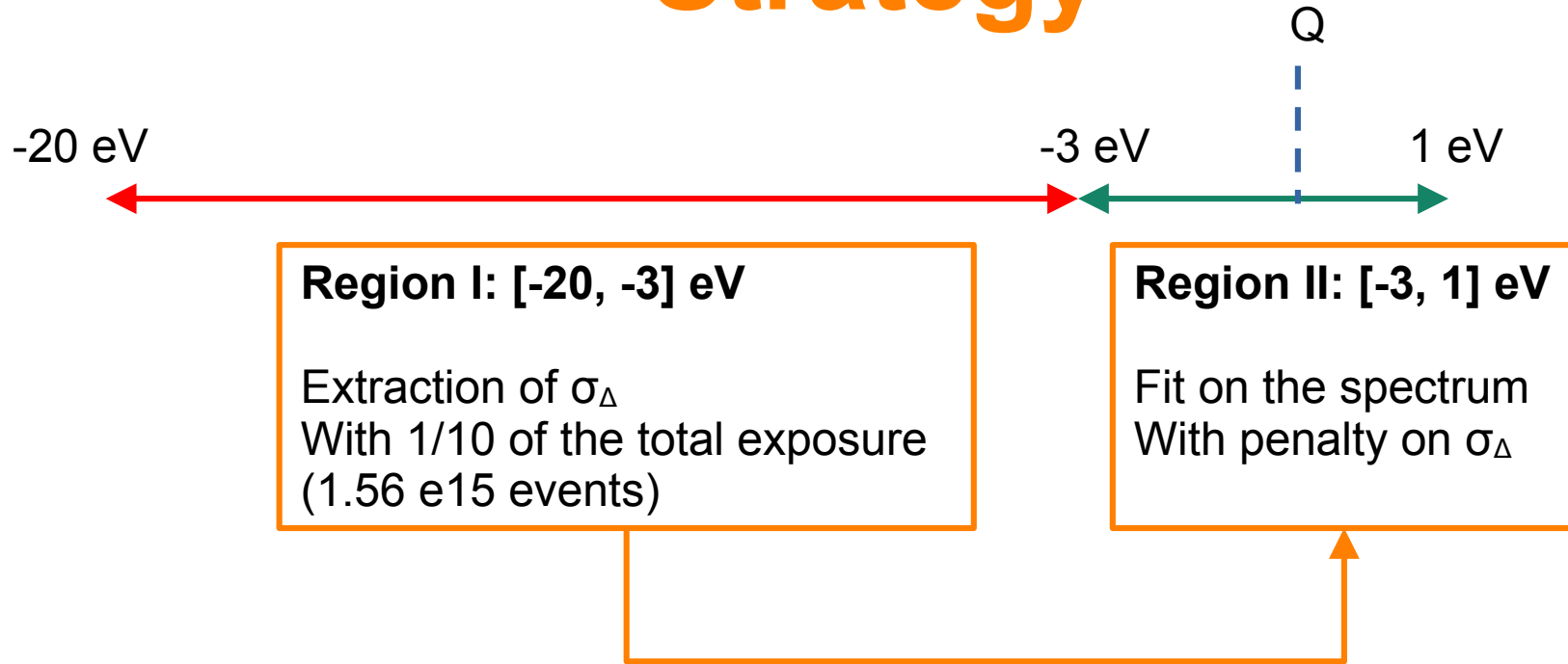
“If you want to prove that pigs fly, show at a least one pig flying and not hundreds of pigs a little jumping”

*(Unknown philosopher)*

# Sensitivity to (unknown) $\Delta$ smearing



# Strategy



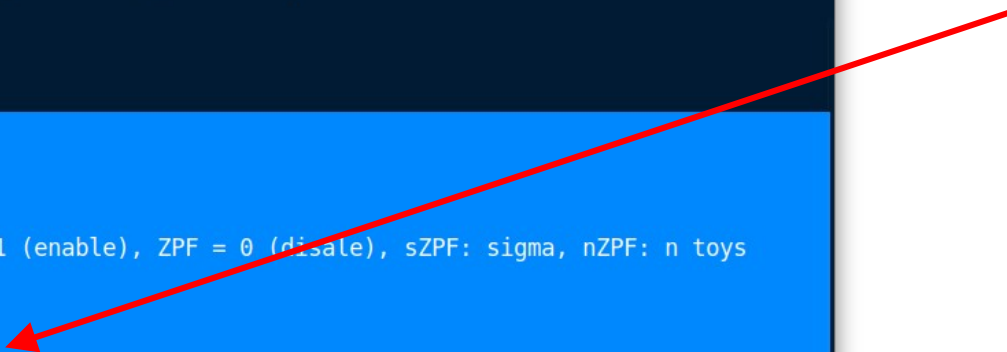
$$\sigma_{\Delta}(\text{R} - \text{I}) = \sqrt{\sigma_{\Delta}^2(\text{R} - \text{II}) - \sigma_{\text{exp}}^2(\text{prior})}$$



# New cfg file (part 2/2)

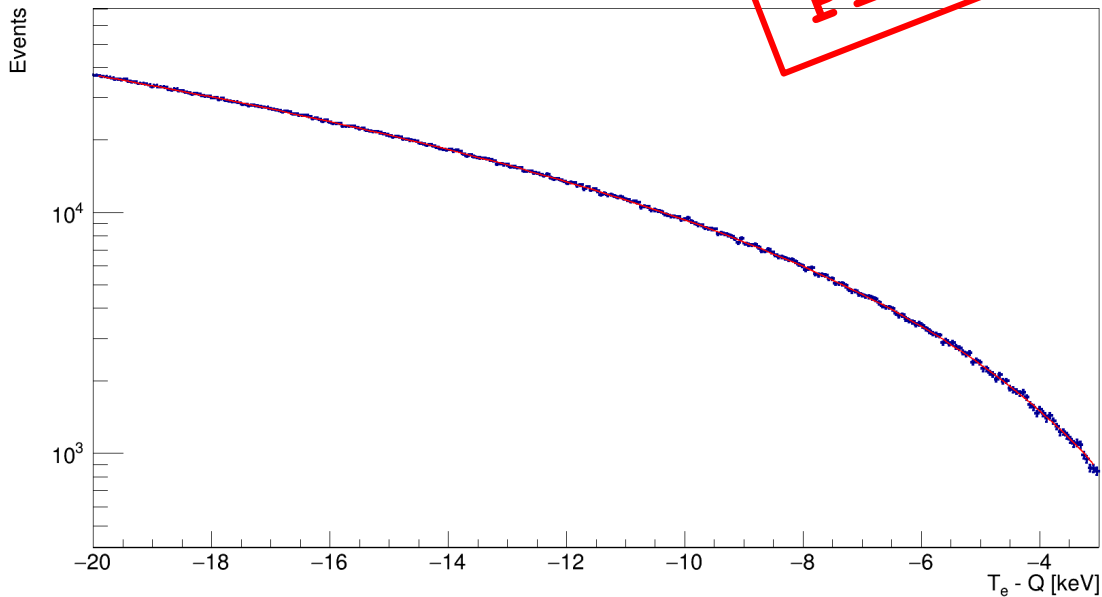
```
Open  [icon]  init.cfg  Save  [icon]  [icon]  [icon]  [icon]
~/Desktop/GIT/GitHub/ptsens/cfg
17
18 # display y-axis
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26 Cmin     -0.8
27 Cmax     0.4
28 dSigma   30
29
30 # Nu Mass interval
31 NMmin    -22
32 NMmax    2
33
34 # ZPF parameters ZPF = 1 (enable), ZPF = 0 (disate), sZPF: sigma, nZPF: n toys
35 ZPF      1
36 sZPF     0.500
37 nZPF     1.56e15
38 Zmin     -20
39 Zmax     -2
Plain Text  Tab Width: 8  Ln 39, Col 15  INS
```

**New option #3**  
 $\Delta$  strategy constraint  
List of parameters



# Example

Preliminary



## Simulated:

$$\sigma_{\Delta} = 500 \text{ meV}$$

$$m_{\nu} = 200 \text{ meV}$$

## Returned from the fit in (-20, -3):

$$\sigma_{\Delta} = 0.49 \pm 0.06 \text{ eV (12\%)}$$

## Mass with prior from fit in (-3, 2):

$$m_{\nu} = 0.196 \pm 0.026 \text{ eV (13\%)}$$

## **Take-home message**

Neutrino mass measurement is an extremely important physical goal, and it is at our reach with the PTOLEMY demonstrator

*Thank you very much  
for your attention!*