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Determination of the Electron-Neutrino Mass with sub-eV Sensitivity by the Decay of ^{159}Dy

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<https://doi.org/10.1016/j.scib.2025.05.038>



Outline

- **Introduction**
 - **Neutrino mass puzzle**
 - **Current experiments**
 - **^{159}Dy with ultra low decay energy**
- **Neutrino mass sensitivity estimation**
 - **MC simulation**
 - **Backgrounds analysis**
 - **Sensitivity result**
- **Experimental design**
 - **Energy spectrum measured by superconducting detector with eV-scale sensitivity**
 - **Signal channel selected by γ detector with keV-scale sensitivity**
 - **Preparation of ^{159}Dy**
- **Summary**



Massive neutrinos

- **Neutrino oscillations confirm neutrino having mass, but the absolute mass remains unknown**

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} V_{e1} & V_{e2} & V_{e3} \\ V_{\mu1} & V_{\mu2} & V_{\mu3} \\ V_{\tau1} & V_{\tau2} & V_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

1998 Atm. ν osc. $\theta_{23}, |\Delta m_{32}^2|$
 2002 Solar ν osc. $\theta_{12}, \Delta m_{21}^2$
 2012 reactor ν osc. θ_{13}

- **Experimental measurements of neutrino mass**

- **Single beta decay or Electron Capture (EC)**
 - Kinematic results, independent and direct
- **Neutrinoless double beta decay ($0\nu\beta\beta$)**
 - Depends on that Neutrino should be Majorana particle
 - E.g., KamLAND-Zen result: PRL130, 051801 (2023)

$$M_{\beta\beta} = \left| \sum_{i=1}^3 M_i |U_{ei}|^2 e^{i\alpha_i} \right| < \mathbf{36-156 \text{ meV}}$$

- **The next generation of $0\nu\beta\beta$ experiment**

	Isotope	Mass(t)	$\langle M_{\beta\beta} \rangle$ [meV]
SNO+	^{130}Te	8	19-46
KamLAND2-Zen	^{136}Xe	1	~20
NEXT-HD	^{136}Xe	1	14-40
nEXO	^{136}Xe	5	7-22
Darwin/Panda-nT	^{136}Xe	3-5	7-22
LEGEND-1000/CDEX-1t	^{76}Ge	1	10-40
AMoRE-II	^{100}Mo	0.1	12-22
CUPID	^{100}Mo	0.24	12-20
CUPID-1T	^{100}Mo	1	4-7
JUNO- $\beta\beta$	^{136}Xe	50	4-10
	^{130}Te	100	3-14

- **Astrophysics from CMB: sum of neutrino mass eigenstates**
 - Depends on cosmological mode

<https://arxiv.org/abs/2404.19322>

$$\Sigma = \sum_{i=1}^3 M_i$$

Cosmological model		Σm_ν [eV]
$+\Sigma m_\nu$	DH	< 0.0866
	NH	< 0.129
	IH	< 0.155
$+\Sigma m_\nu + N_{\text{eff}}$	DH	< 0.0968
	NH	< 0.131
	IH	< 0.163
$+\Sigma m_\nu + \Omega_k$	DH	< 0.111
	NH	< 0.143
	IH	< 0.180
$+\Sigma m_\nu + \alpha_s$	DH	< 0.0908
	NH	< 0.128
	IH	< 0.157
$+\Sigma m_\nu + r$	DH	< 0.0898
	NH	< 0.130
	IH	< 0.156
$+\Sigma m_\nu + w_0$	DH	< 0.139
	NH	< 0.165
	IH	< 0.204
$+\Sigma m_\nu + (w_0 > -1)$	DH	< 0.0848
	NH	< 0.125
	IH	< 0.157
$+\Sigma m_\nu + w_0 + w_a$	DH	< 0.224
	NH	< 0.248
	IH	< 0.265
$+\Sigma m_\nu + A_L$	DH	< 0.166
	NH	< 0.189
	IH	< 0.216
model marginalized	DH	< 0.102

TABLE II. Constraints at 68% and upper limits at 95% CL, for the $\Lambda\text{CDM} + \Sigma m_\nu$ model and its extensions (adapted from Ref. [32]).



Single- β decay or EC

- **Model independent method with kinematic analysis**
- **Precise energy spectrum measuring especially near the endpoint**
 - **Single- β decay: decay rate proportional to $(\Delta E/Q)^3$**
 - **EC: decay rate proportional to $(\Delta E/Q)^2$**

^3H - β decay spectrum

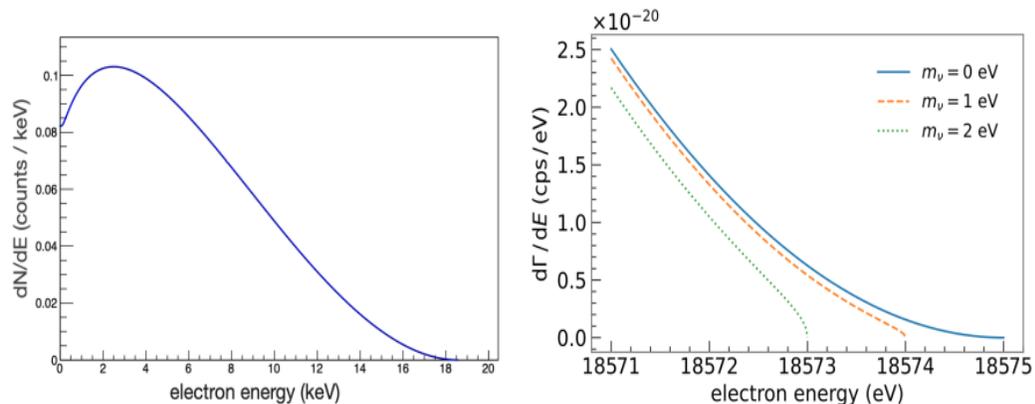


Figure 1: **Left** : The beta spectrum of ^3H . Data is taken from [37]. **Right** : Shape distortion produced by effective electron anti-neutrino mass (m_ν) in ^3H beta spectrum. Image credit [38].

^{163}Ho EC decay spectrum

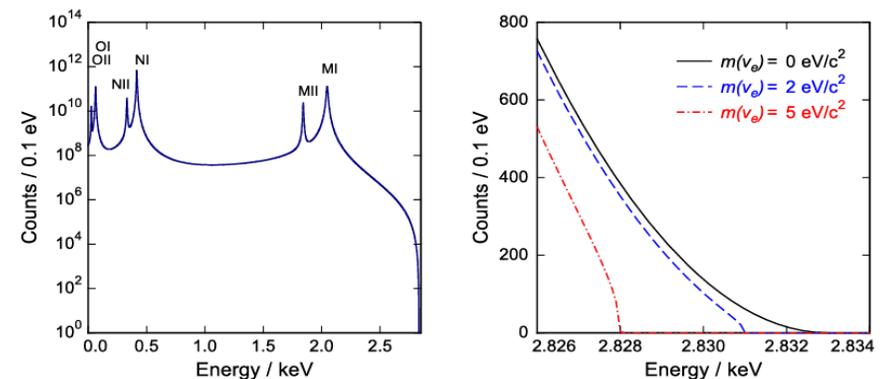
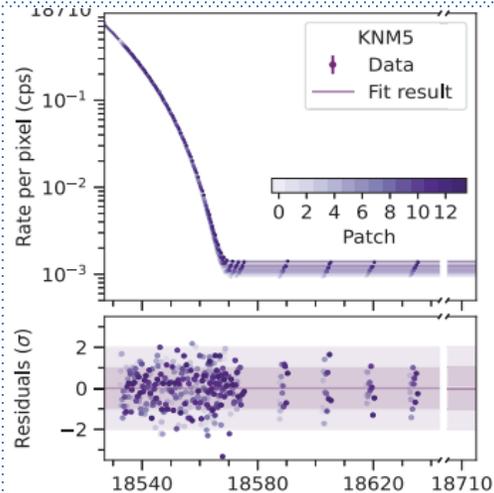


Fig. 1. **Left**: E_{EC} spectrum of the ^{163}Ho decay with 10^{14} events. **Right**: ECHO endpoint energy plot for different Electron-Neutrino energies. [4]



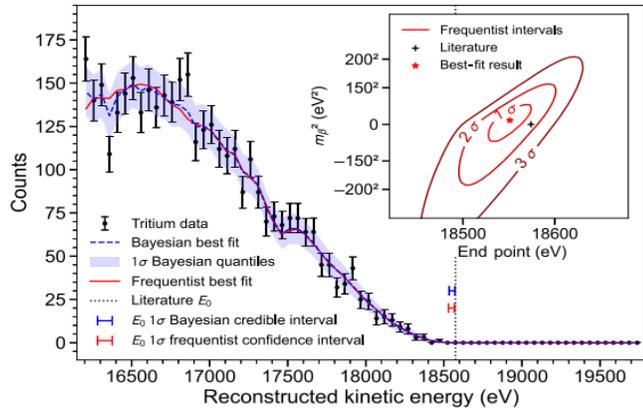
Current Experiments

Tritium-based experiments	Latest upper limit results of m_β	Detection technology
KATRIN	0.45 eV at 90% C.L.	Magnetic-Adiabatic-Collimation-Electrostatic (MAC-E)
Project 8	155 eV at 90% C.L.	Cyclotron Radiation Emission Spectroscopy (CRES)
^{163}Ho -based experiments		
ECHo	150 eV at 95% C.L.	Magnetic microcalorimeters (MMC)
HOLMES	27 eV at 90% C.L.	Transition Edge Sensors (TES)



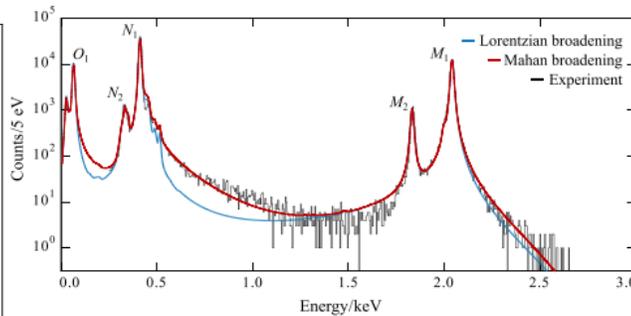
Science 388 (2025)

KATRIN



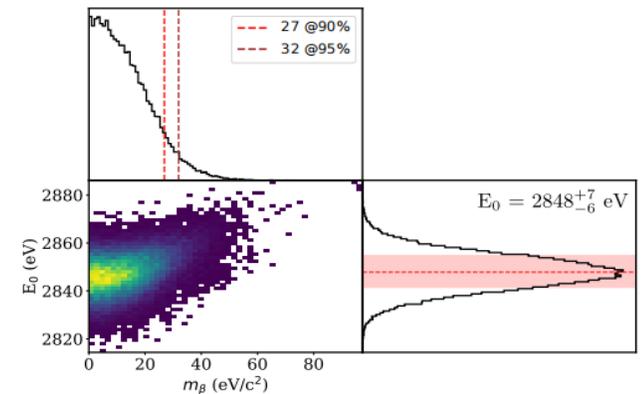
Phys Rev Lett 131 (2023)

Project 8



Eur Phys J C 79 (2019)

ECHo



<https://arxiv.org/abs/2503.19920> (2025)

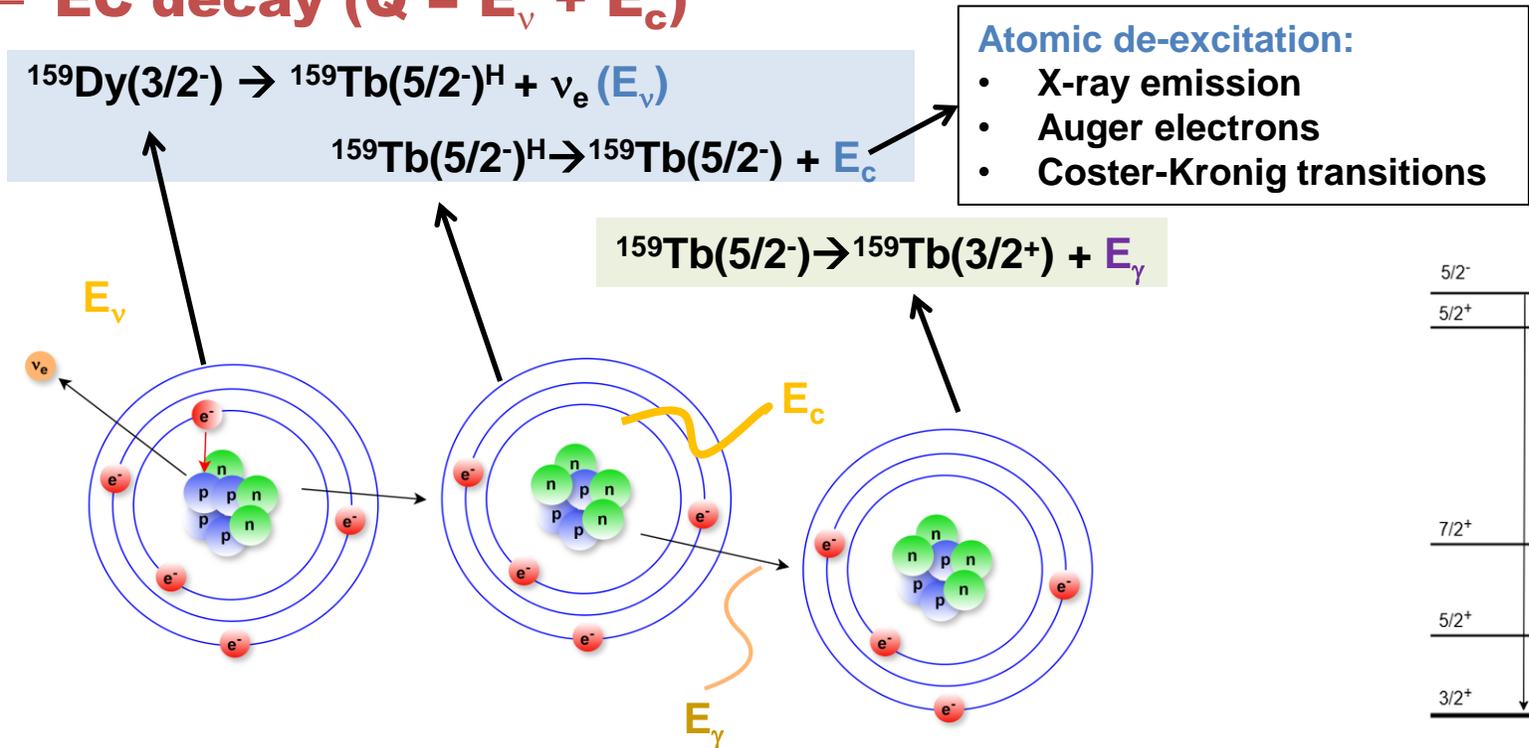
HOLMES



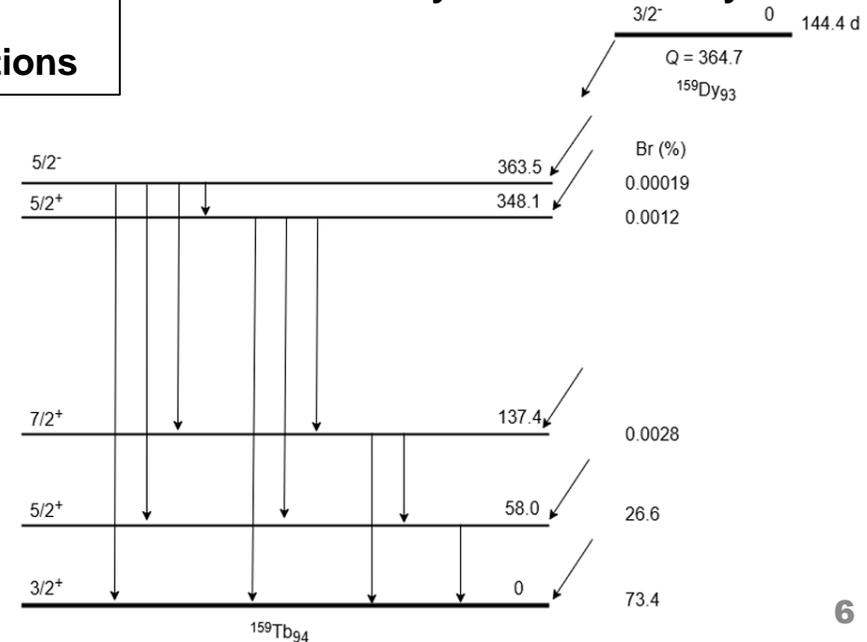
^{159}Dy EC decay

- Synthetic isotope with a half-life of 144.4 d
- Ultra-low Q-value decay channel: $^{159}\text{Dy}(3/2^-) \rightarrow ^{159}\text{Tb}(5/2^-)$
 - The Q-value for the ground-to-excited state transition is 1.18 keV
 - Branching ratio: 1.9×10^{-6} , select by γ detector
 - EC decay ($Q = E_\nu + E_c$)

- Q value of ^{159}Dy was measured using the double Penning trap mass spectrometer JYFLTRA in 2021
- Ge Z, Eronen T, et al., ^{159}Dy Electron-Capture: A New Candidate for Neutrino Mass Determination. Phys Rev Lett. 2021 Dec 31;127(27):272301.



The decay scheme of ^{159}Dy





^{159}Dy EC energy spectrum

• Energy spectrum description

$$\frac{d\lambda_{EC}}{dE_c} = \frac{G_\beta^2}{4\pi^2} (Q - E_c) \sqrt{(Q - E_c)^2 - m_\nu^2} \times \sum_i n_i C_i \beta_i^2 \mathcal{B}_i \frac{\Gamma_i}{2\pi} \frac{1}{(E_c - E_i)^2 + \Gamma_i^2/4}$$

- i means electron orbits,
 - K, L, M are forbidden
 - Transitions from N, O, P are allowed

$G_\beta = G_F \cos \theta_C$ Fermi constant G_F and the Cabibbo angle θ_C

E_i The binding energy of the i -th atomic shell

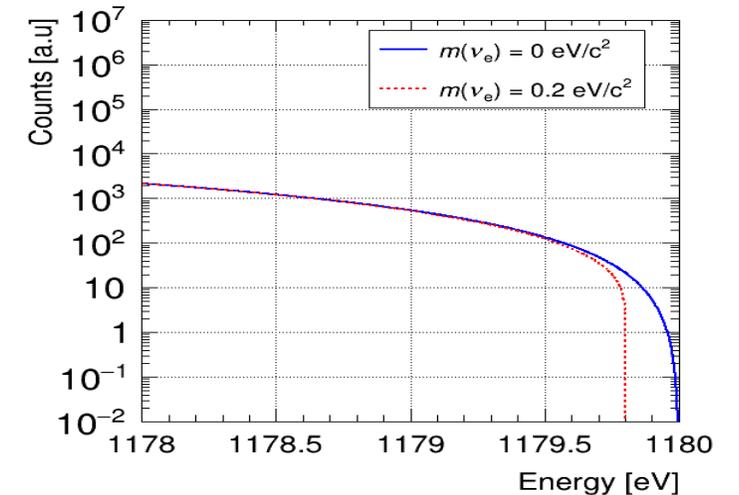
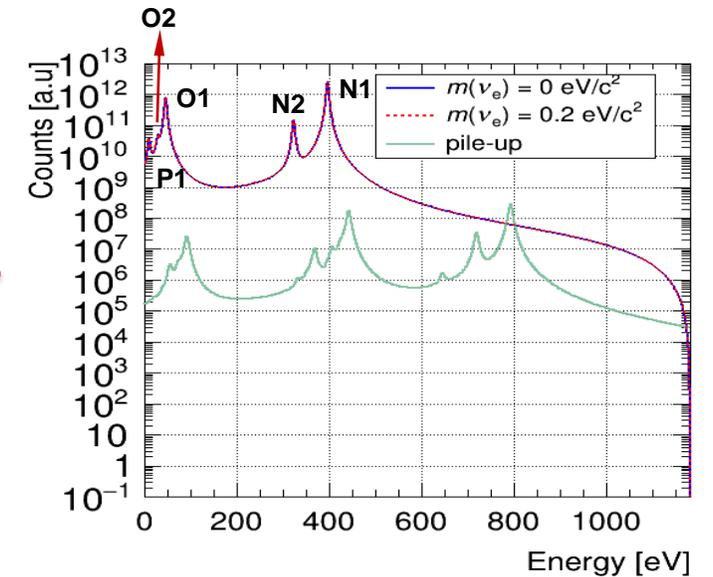
Γ_i The natural width

n_i The fraction of occupancy of the i -th atomic shell, considered to be 1

β_i The Coulomb amplitude of the electron radial wave function

\mathcal{B}_i An atomic correction for electron exchange and overlap

C_i are approximately equal in an allowed transition and can be factored out from summation





How about neutrino mass measuring by ^{159}Dy ? Feasible analysis

- 1 **Ultra-low Q-value** means higher decay rate near the endpoint since $\lambda \propto (\Delta E/Q)^2$
- 2 **Production of ^{159}Dy** via reaction of $^{159}\text{Tb}(p,n)^{159}\text{Dy}$ or $^{158}\text{Dy}(n,\gamma)^{159}\text{Dy}$
- 3 **Feasible source mass:** ~2.5 ng ^{159}Dy yields an activity of 1 decay/s for $^{159}\text{Dy}(3/2^-) \rightarrow ^{159}\text{Tb}(5/2^-)$
- 4 **Feasible data acquisition time: 1 year for 1.6 μg ^{159}Dy** yields average activity of 300 Bq/det considering 144.4d half-life,
- 5 **Feasible detector technology:** superconducting transition edge sensors (TESs) --- eV scale energy resolution
- 6 **Signal selection:** Need coincidence measurement with γ detector for small branch ratio

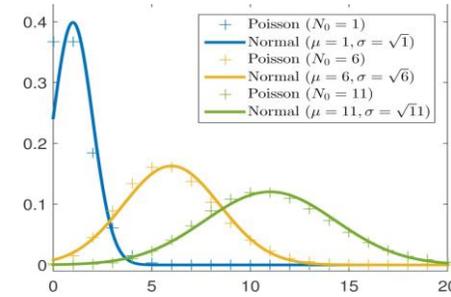
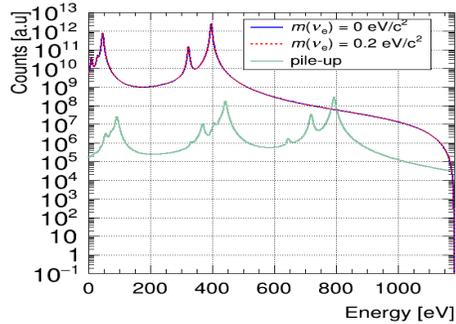


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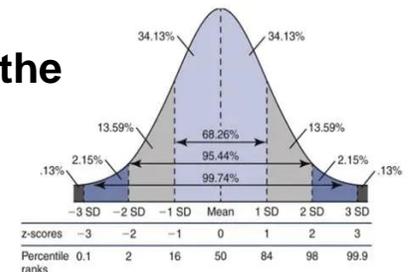
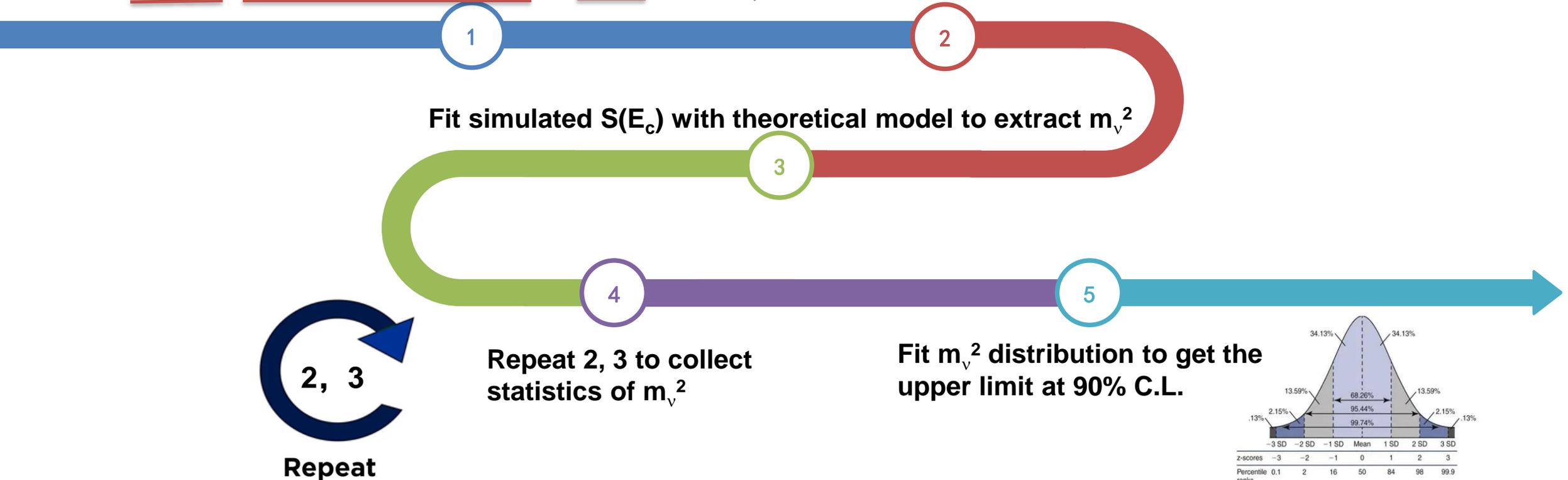
MC simulation workflow



Input total energy spectrum: $S(E_c)$, including signal and BG

$$S(E_c) = [N_{\text{sig}}(E_c) + N_{\text{pileup}}(E_c) + N_{\text{env}}(E_c) + N_{\text{trans}}(E_c)] \otimes G(E_c) \quad G(E_c) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{E_c^2}{2\sigma^2}}$$

Let $S(E_c)$ fluctuate via Poisson statistics with a specific configuration, like $N_{\text{pileup}}, N_{\text{env}}, N_{\text{trans}}$, energy reso.



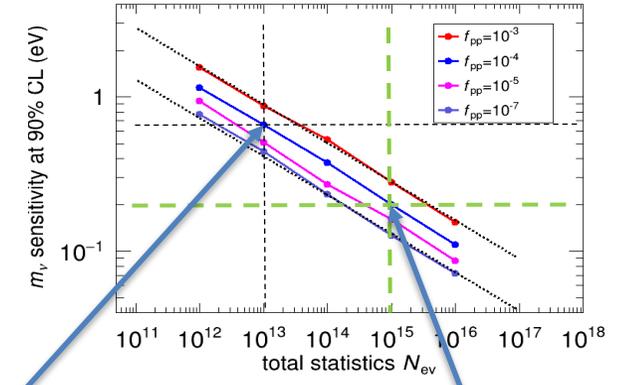
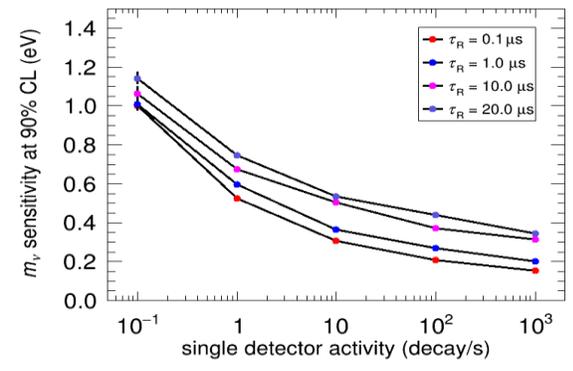
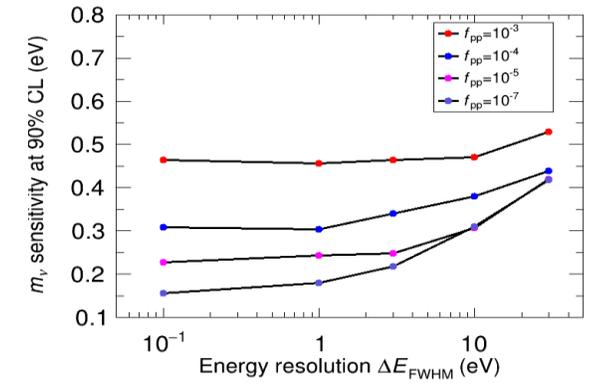
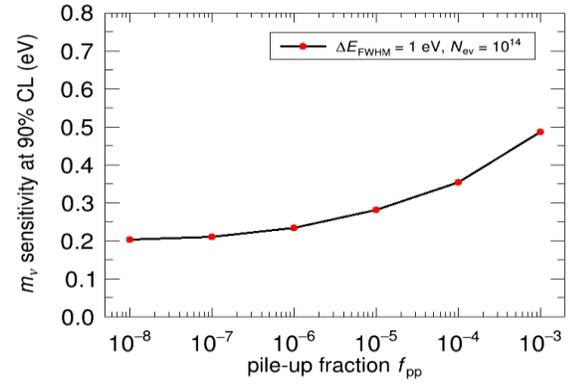


Backgrounds(BG) from pile up

- **Pile up BG:** when the first signal is properly captured in the measurement, the second signal arrives immediately and overlaps with the first one, resulting in inaccurate energy measurement of the signal.
- **BG ratio** is related to the detector's rise time and the isotope's activity:

$$f_{pp} = \tau_R \times A_{EC}$$

- **Some results**
 - A high level of pile-up degrades the sensitivity
 - There exists an optimal value for the influence of energy resolution on sensitivity: ~ 1 eV
 - Balance between τ_R and A_{EC} should be taken into account, the typical values: $\sim \mu s$ and ~ 100 Bq
 - Relationship between Sensitivity and Statistics: $N_{ev}^{-1/4}$, N_{ev} is total signal number



$t_M = 1$ year
 $A_{EC} = 100$ Bq
 $N_{det} \approx 3000$
 $\tau_R = 1 \mu s$
 $\Delta E_{FWHM} = 1$ eV

$m_\nu < 0.66$ eV/c²
 at 90% C.L.

$t_M = 1$ year
 $A_{EC} = 100$ Bq
 $N_{det} \approx 300000$
 $\tau_R = 1 \mu s$
 $\Delta E_{FWHM} = 1$ eV

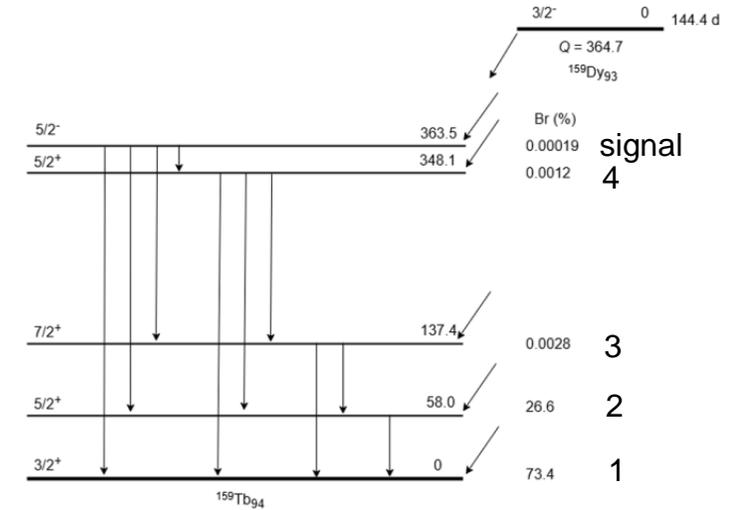
$m_\nu < 0.20$ eV/c²
 at 90% C.L.



BG from other transitions & environment

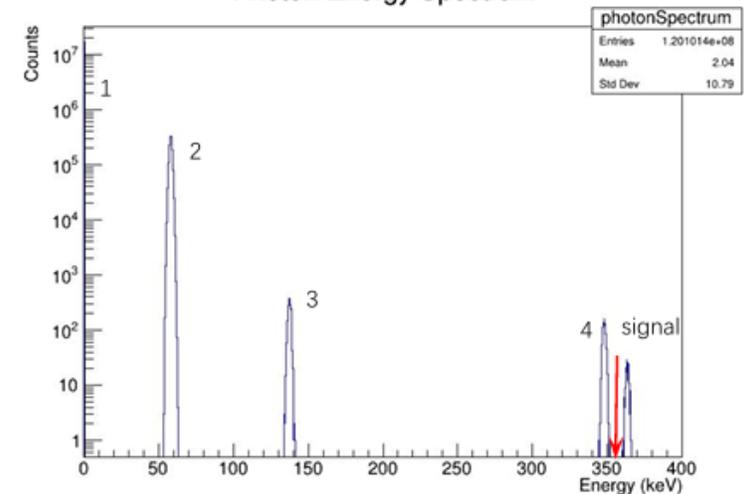
- **BG from ^{159}Dy transition to other states of ^{159}Tb**
 - **Separate signal and background by coincident measurement with γ detector**
 - **BG ratio depends on the energy reso.**
 - **$b_{\text{EC}} = 0.1\%$ (If $\sigma = 2 \text{ keV}$)**
 - **$b_{\text{EC}} = 0.5\%$ (If $\sigma = 2.4 \text{ keV}$)**
- **Environmental BG originates from radioactive background that enters the detector randomly, such as cosmic rays, environmental gamma rays and so on.**
 - **BG ratio: $b_{\text{ext}} = 0.1\%$**

<http://dx.doi.org/10.1155/2016/9153024>



The decay scheme of ^{159}Dy

Photon Energy Spectrum



An assumption of the γ spectrum



Sensitivity result

- Considering all backgrounds, the sensitivity of m_ν at 90% C.L. as a function of the number of detectors is estimated

- Under the same signal statistics:

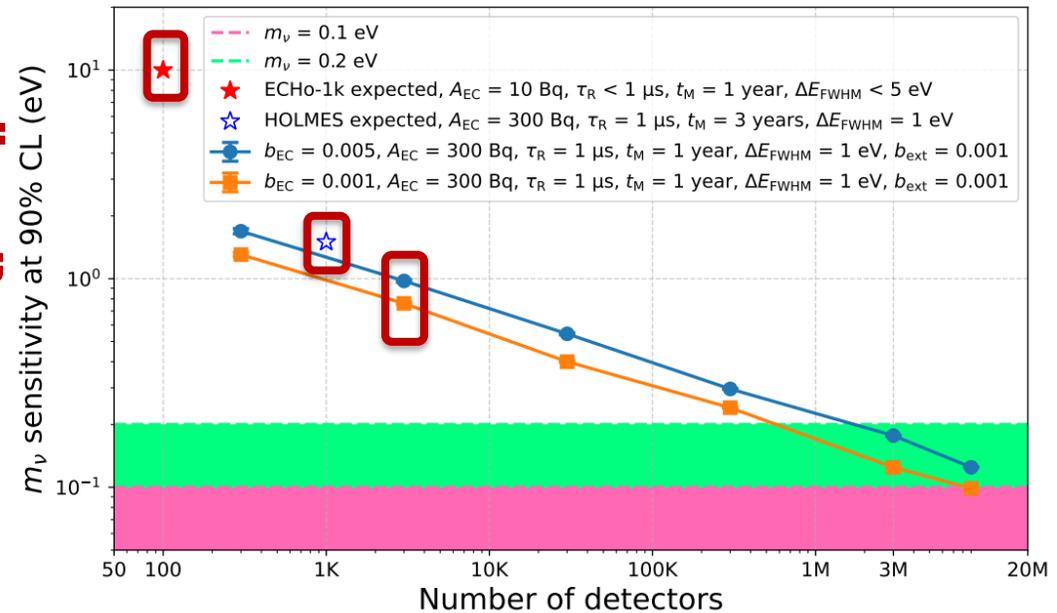
- Given a half-life of 144 days, the effective data acquisition time of each detector is 1 year VS 3 years;
- A larger number of detectors is required: 3000
- The number of events at the final 40 eV (endpoint) is increased by a factor of 10;
- Taking into account the branching ratio and decay rate, a greater total mass is needed, 4.8 mg totally

- Final sensitivity results: 0.8 eV (^{159}Dy) vs. 1.5 eV (^{163}Ho)

Adv. High Energy Phys.,2016:9153024, 2016, Table 4

Source	A_{EC} (Bq/det)	t_M (years)	N_{det}	N_{ev}	Last 40 eV events	τ_R (μs)	ΔE_{FWHM} (eV)	$T_{1/2}$	Total mass	m_ν (at 90% C.L.)
^{163}Ho	300	3	1000	2.8×10^{13}	1.1×10^6	1	1	4750 years	18 μg	1.5 eV
^{159}Dy	300	1	3000	2.8×10^{13}	1.1×10^7	1	1	144.4 days	4.8 mg	0.8 eV

$$S(E_C) = [N_{sig}(E_C) + N_{pileup}(E_C) + N_{env}(E_C) + N_{trans}(E_C)] \otimes G(E_C)$$





Uncertainty from parameters

- **Three main sources of systematic uncertainties from parameters**
 - 1. The widths of the captured orbit M1, M2, N1, N2, O1, O2, and P1**
 - 2. The atomic correction parameters B_i from electron exchange and overlap: according to PRL 127, 272301, B_i values can deviate from unity by up to 25%, from 0.75 to 1.25**
 - 3. The energy resolution $\Delta E_{FWHM} = 1 \pm 0.1$ eV follows Gaussian distribution**

Astropart Phys, 2010; 34:80–89

Table S2 (online): The systematic uncertainties of the upper limit of m_ν at a 90% confidence level.

Orbit	M1	M2	N1	N2	O1	O2	P1
Γ (eV)	13	5.8	5.1	5.26	-	-	-
$\Delta\Gamma$ (eV)	± 2	$\pm 5\text{-}25\%$ (1.45 eV)	$\pm 10\%$ (0.51 eV)	± 0.8	-	-	-

Sources	Systematic uncertainties (in eV)
O1, O2 and P1	0.02
width of M1	0.02
width of M2	0.03
width of N1	0.01
width of N2	0.01
B_i	0.08
energy resolution ΔE_{FWHM}	0.01
total	0.09

The total uncertainty is 0.09 eV for central value 0.8 eV (11%)



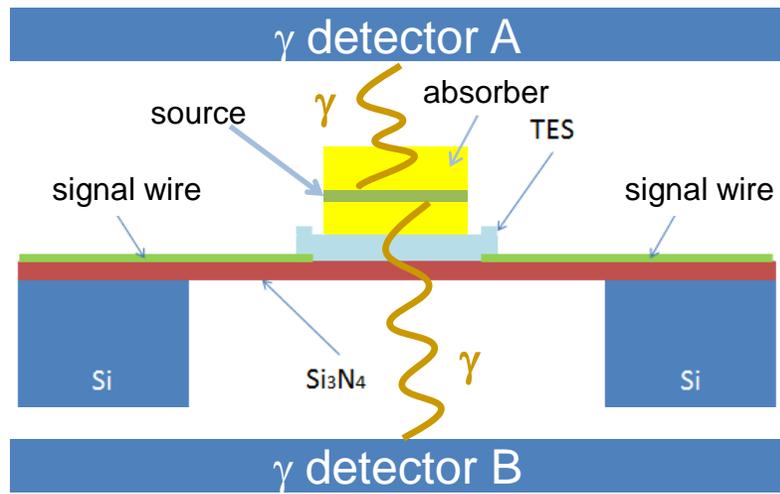
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Detector design

- **^{159}Dy source is embedded in the absorber.**
 - **To prevent self-absorption of the decay signal, the source thickness should be minimized.**
- **TES detector to measure the E_c with eV resolution**
- **To select signal channel, 2 γ detectors should be used for coincident measurement**

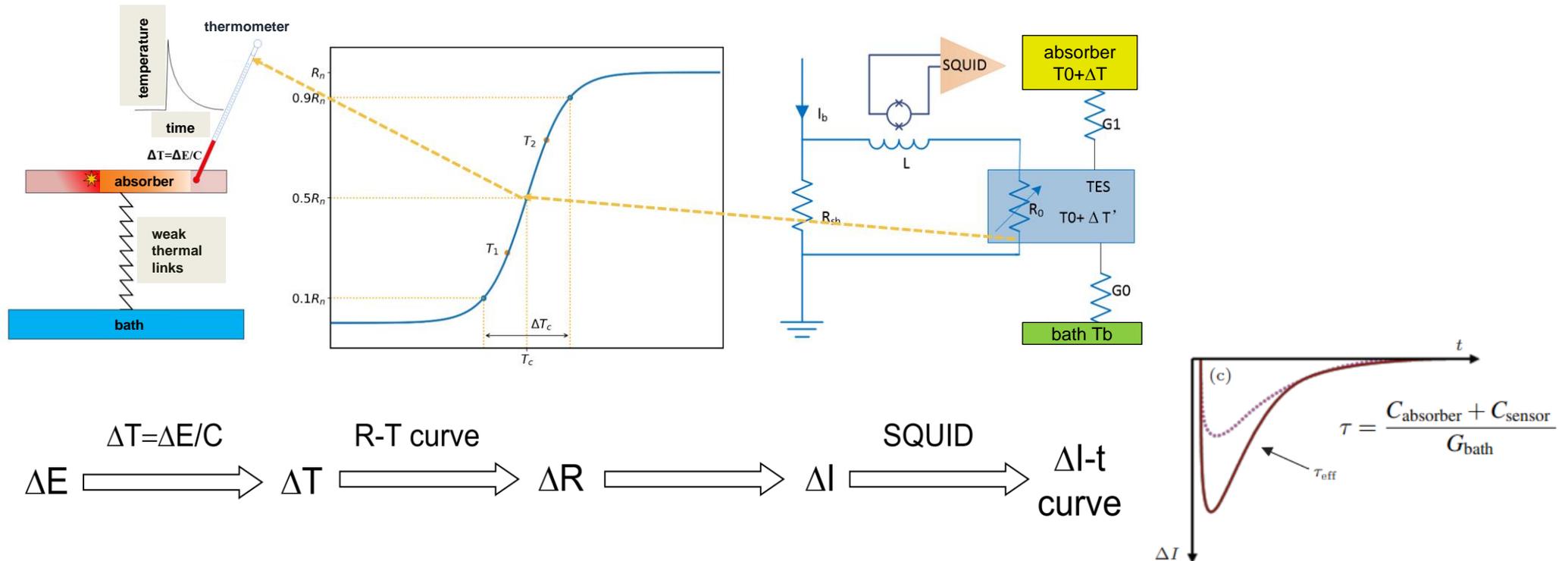


- **Commonly used absorber materials: Au, Bi, Al, Mo, Ti, Si**
- **Commonly used TES materials: W, Ti, Mo, Al, Mo/Cu, AlMn**
- **Candidates for γ detector: TES, HPGe, SDD**



TES technology

- **TES is a low-temperature superconducting detector that comprises a layer of superconducting film biased within the transition region between the superconducting and normal states**
- **It utilizes its steep resistance-temperature (R-T) relationship to measure heat**
- **ΔI -t curve:**
 - **1) $\Delta I \propto \Delta E$; 2) small rise time; reduce the pile-up; 3) heat capacity is the key**





Absorber material selection

- **The commonly used absorber materials for TES include: Au, Bi, Al, Mo, Ti, Si**
 - **The specific heat @100mK and @50mK: the smaller, the more sensitive to energy measuring**
 - **The mass attenuation coefficient @1keV: the smaller, the thinner material to absorber the energy**

Material	Specific Heat (J/K/m ³) @100mK	Specific Heat (J/K/m ³) @50mK	Mass attenuation coefficient μ/ρ (cm ² /g) @ 1 keV
Au	7.14	3.57	4.652×10^3
Bi	3.74×10^{-2}	1.87×10^{-2}	5.441×10^3
Al	13.5	6.75	1.185×10^3
Si	7.0×10^{-3}	8.74×10^{-4}	1.570×10^3
Mo	21.3	10.65	4.942×10^3
Ti	31.6	15.8	5.869×10^3



TES material selection

- **The specific heat of source materials @100mK and @50mK**

Material	Specific Heat (J/K/m ³) @100mK	Specific Heat (J/K/m ³) @50mK	Mass attenuation coefficient μ/ρ (cm ² /g) @ 1 keV
Dy	50	25	2.494×10^3
Ho	53	26.5	2.616×10^3

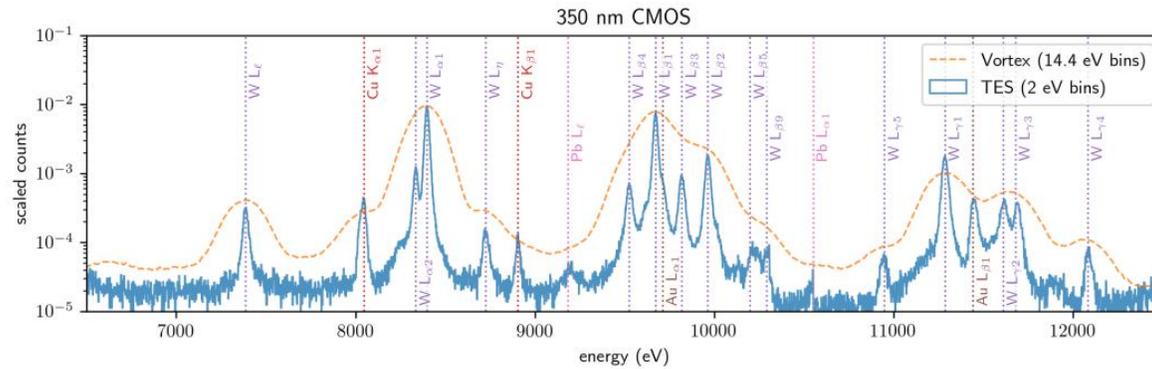
- **Superconduct film materials include: W, Ti, Mo, Al, Mo/Cu, AlMn**
- **The specific heat of source materials @100mK and @50mK**

Material	Specific Heat (J/K/m ³) @100mK	Specific Heat (J/K/m ³) @50mK
W	13.6	6.8
Mo	21.3	10.65
Al	13.5	6.75
Ti	31.6	15.8
Cu	9.8	4.9



TES advantage & application

- **TES has eV-scale energy resolution**



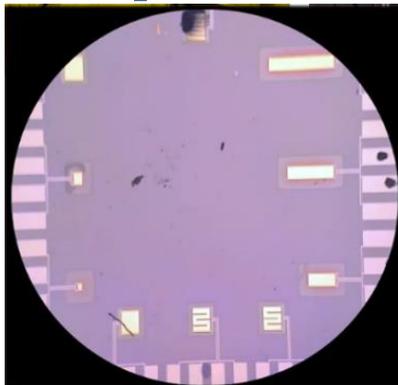
Vortex: $\Delta E_{FWHM} = 130 \text{ eV}$

TES: $\Delta E_{FWHM} = 12\text{-}15 \text{ eV/pixel}$

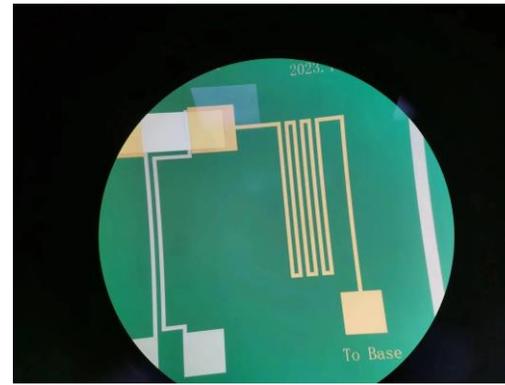
IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, 31 (2021)

Figure 3. Fluorescence spectra of a 350 nm CMOS integrated circuit chip, measured with a TES sensor (blue solid line) and a Vortex silicon-drift detector (orange dashed line). Prominent peaks are labeled with their corresponding element and line name.

- **TES experiences at IHEP**



Ali Cosmic Microwave Background detection



Neutrinoless double beta decay detection



Preparation of ^{159}Dy

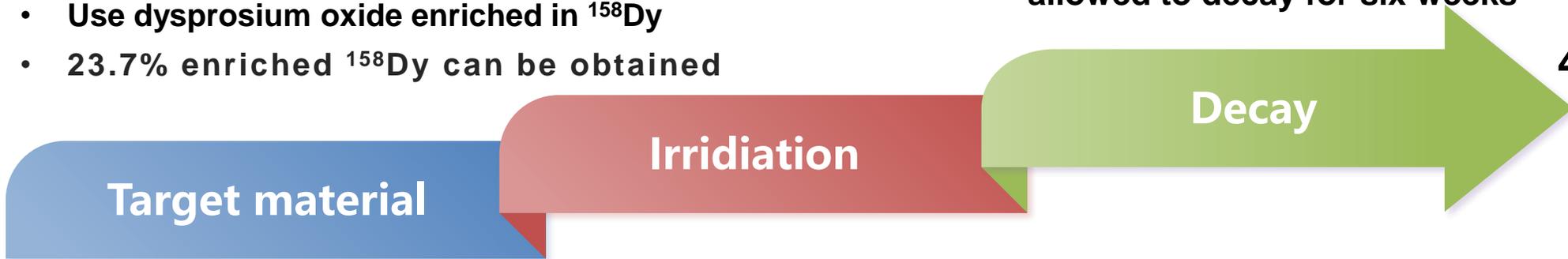
- To achieve $N_{ev} = 2.8 \times 10^{13}$, 4.8 mg ^{159}Dy is needed
- Produce ^{159}Dy via neutron induced reactions on ^{158}Dy

1) Natural ^{158}Dy has low abundance

- Use dysprosium oxide enriched in ^{158}Dy
- 23.7% enriched ^{158}Dy can be obtained

3) To diminish the shorter-lived isotopes, the radioactive sample is allowed to decay for six weeks

4) Separation & Purification



Isotope	Mass/Da	Natural abundance (atom %)
^{156}Dy	155.924277 (8)	0.06 (1)
^{158}Dy	157.924403 (5)	0.10 (1)
^{160}Dy	159.925193 (4)	2.34 (8)
^{161}Dy	160.926930 (4)	18.91 (24)
^{162}Dy	161.926795 (4)	25.21 (26)
^{163}Dy	162.928728 (4)	24.90 (16)
^{164}Dy	163.929171 (4)	28.18 (37)

2) Six-week bombardment of 40 mg of the 14%-enriched Dy_2O_3 ($\sigma=100$ barns) at a flux of 5×10^{14} neutrons/cm²/s yields about 4 curies of ^{159}Dy

<https://escholarship.org/uc/item/60c103cs>



Preparation of ^{159}Dy

- The nuclide composition estimation:**

Before irradiation
23.7% enriched Dy_2O_3

Nuclide	Proportion
^{156}Dy	0.030%
^{158}Dy	23.700%
^{160}Dy	4.850%
^{161}Dy	18.889%
^{162}Dy	21.660%
^{163}Dy	15.730%
^{164}Dy	12.600%

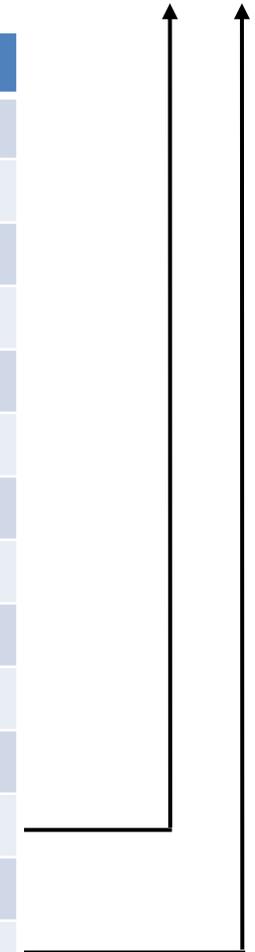
After irradiation

Nuclide	Proportion
^{156}Dy	0.0296%
^{157}Dy (8.14h)	0.0005%
^{158}Dy	23.3331%
^{159}Dy (144d)	0.3669%
^{160}Dy	4.7542%
^{161}Dy	17.2722%
^{162}Dy	23.0101%
^{163}Dy	16.3060%
^{164}Dy	9.5416%
^{165}Dy (2.3h)	2.1235%
^{166}Dy (81.63h)	1.8374%

After 6 weeks decay

Nuclide	Proportion
^{156}Dy	0.0296%
^{157}Tb (71y)	0.0004%
^{157}Gd	0.0000%
^{158}Dy	23.3331%
^{159}Dy (144d)	0.2998%
^{159}Tb	0.0672%
^{160}Dy	4.7542%
^{161}Dy	17.2722%
^{162}Dy	23.0101%
^{163}Dy	16.3060%
^{164}Dy	9.5416%
^{165}Ho	2.1235%
^{166}Dy (81.63h)	0.0004%
^{166}Ho	1.8370%

Remove Ho



- The black characters represent the isotopes of dysprosium
- The green characters represent the prepared ^{159}Dy
- The red characters represent the background isotopes



Summary

- **^{159}Dy , with an EC decay energy of 1.18 keV, is a promising candidate for direct neutrino mass measurement**
 - **Simulations confirm its feasibility in terms of sensitivity, sample quantity, and background suppression.**
 - **Sub-eV sensitivity could be expected**
- **Experimental design**
 - **Superconducting detector with eV reso.: absorber and TES design is critical**
 - **Coincidence γ detector with keV reso.: needed to select the signal**
 - **The preparation of ^{159}Dy is feasible, as successful experience exists in ^{158}Dy enrichment, neutron capture-based preparation.**



Thank you for your attention !