# Review of Direct Measurements of Neutrio Masses

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Heidelberg University

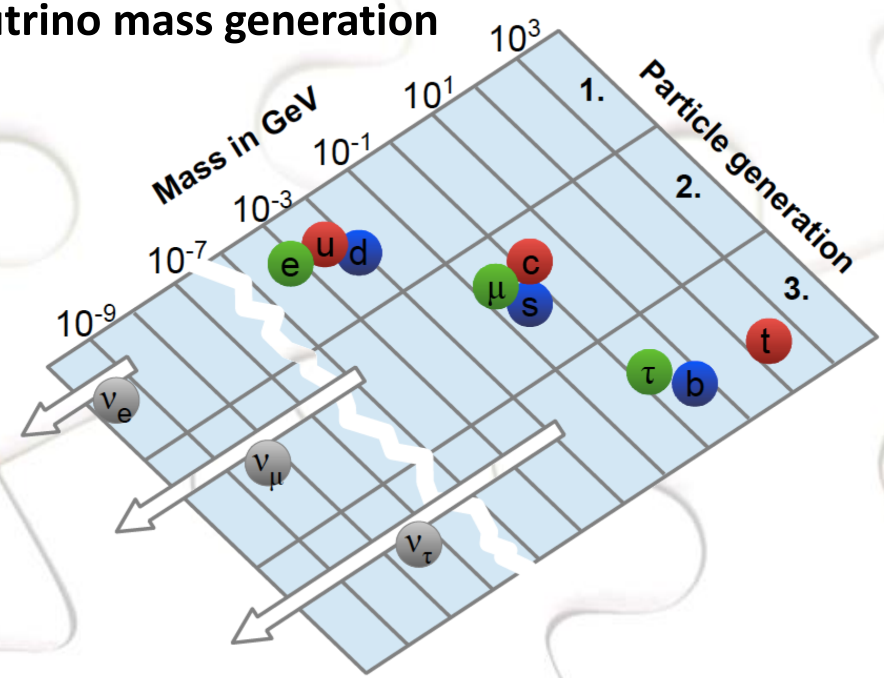
# Knowing neutrino mass scale….

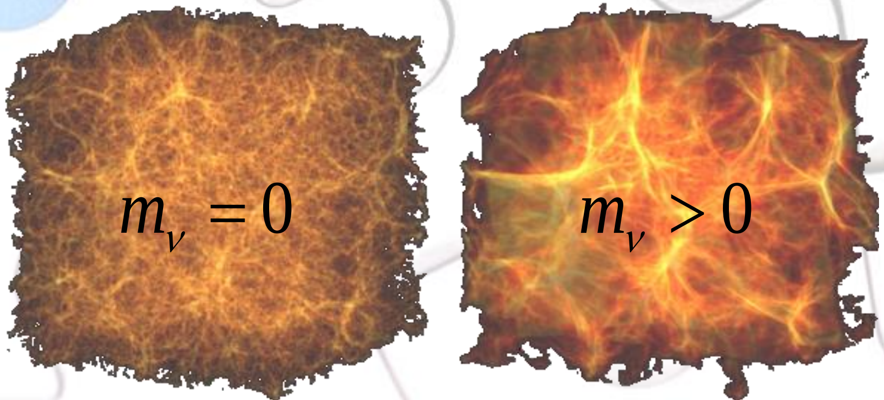
## Astrophysics

**Supernova neutrinos**

## Particle Physics

**Neutrino mass generation**



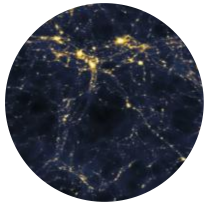




## Cosmology

**Matter distribution in the Universe**

# Status of the art

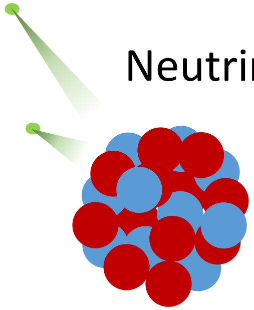
## Cosmology



$$\sum m_i < 0.072 \text{ eV at } 95\% \text{ C. L.}$$

DESI Coll., JCAP 02 (2025) 021

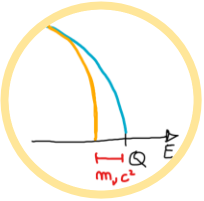
## Neutrinoless double beta decay



$$\left|\sum_{1=1}^{3} U_{ei}^2 m_i\right| < \begin{cases} 0.079 - 0.180 \text{ eV } 90\% \text{ C. L. } {}^{76}\text{Ge} \\ 0.070 - 0.240 \text{ eV } 90\% \text{ C. L. } {}^{130}\text{Te} \\ 0.036 - 0.156 \text{ eV } 90\% \text{ C. L. } {}^{136}\text{Xe} \end{cases}$$

M. Agostini et al., Phys. Rev. Lett. 125, 252502 (2020)
D. Q. Adams et al., arXiv:2404.04453 [nucl-ex] (2024)
S. Abe et al., Phys. Rev. Lett. 130, 051801 (2023)

## Kinematic approach

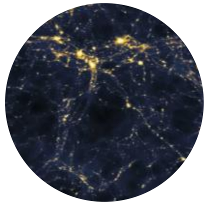


$$\sqrt{\sum_{i=1}^{3} |U_{ei}|^2 m_i^2} < \begin{cases} 0.45 \text{ eV } 90\% \text{ C. L. } {}^{3}\text{H} - m(\bar{\nu}_e) \\ 15 \text{ eV } 90\% \text{ C. I. } {}^{163}\text{Ho} - m(\nu_\text{e}) \end{cases}$$

KATRIN Coll., Science 338 (2025)
ECHo Coll., arXiv:2509.03423v1 [hep-ex]

# Status of the art

Cosmology



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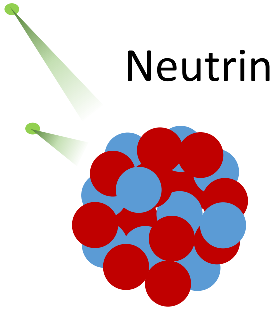
Neutrinoless double beta decay



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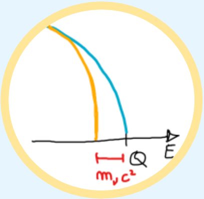
Model independent

Kinematic approach

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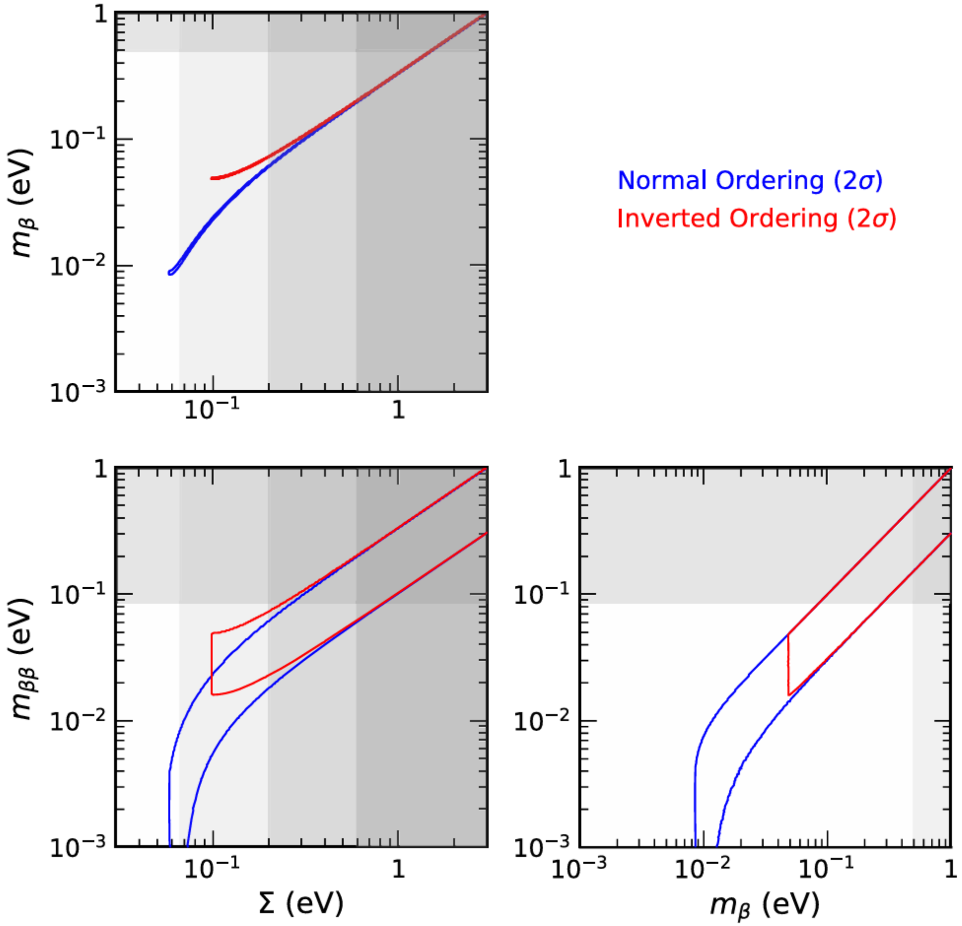


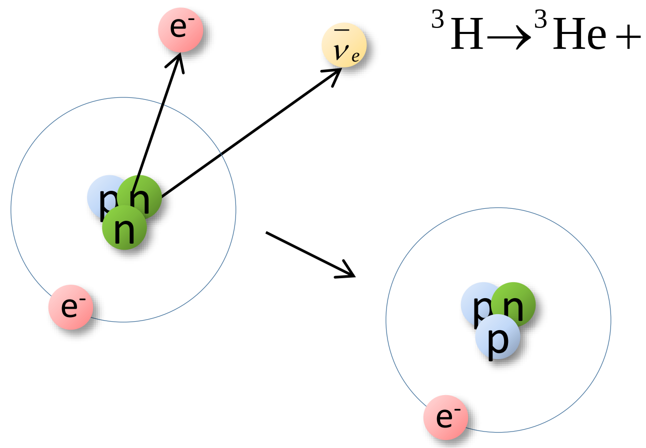

Neutrino mass determination via kinematic approach

- will play major role in understanding the evolution of the Universe
- will guide the design of future DBD experiments

F. Capozzi et al. *Phys. Rev. D* **111** (2025) 093006

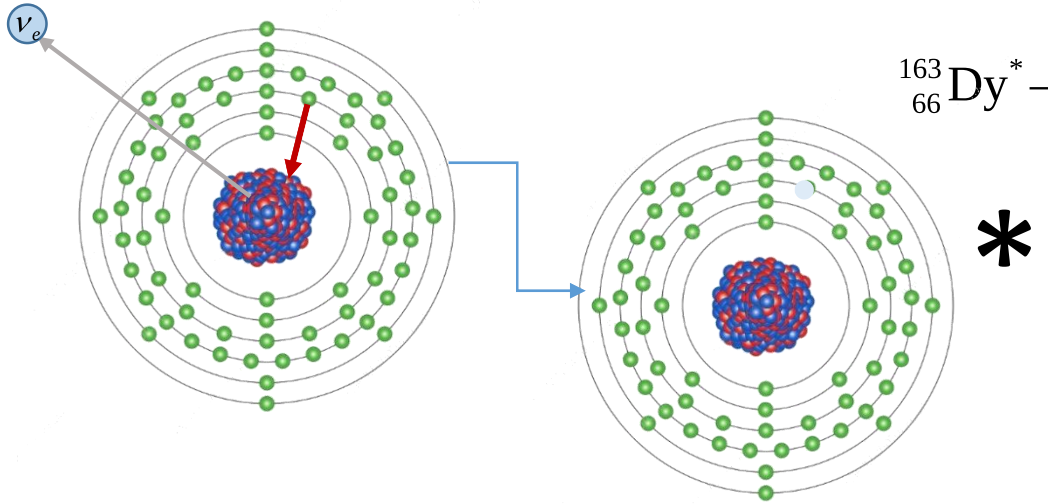
# Beta decay and electron capture

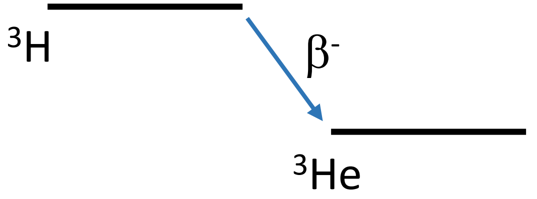
$$^{3}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + e^{-} + \overline{\nu}_{e}$$

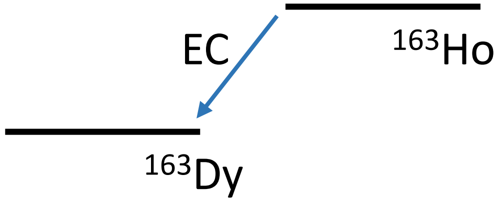



$$^{163}_{67}\mathrm{Ho} \rightarrow {}^{163}_{66}\mathrm{Dy}^{*} + \nu_{e}$$

$$^{163}_{66}\mathrm{Dy}^{*} \rightarrow {}^{163}_{66}\mathrm{Dy} + E_{C}$$



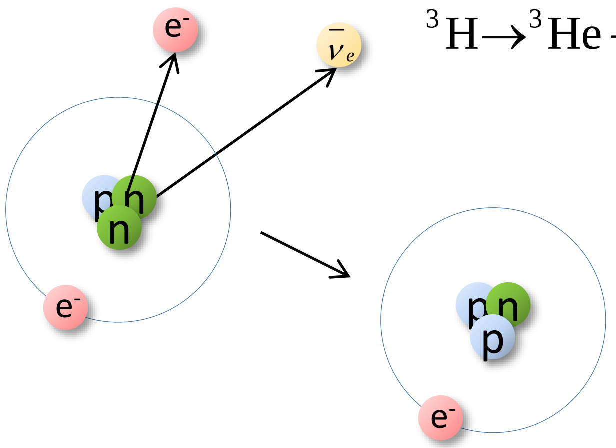

- $\tau_{1/2}$ ≅ 12.3 years (4*10$^{8}$ atoms for 1 Bq)
- $Q_{\beta}$ = 18 592.01(7) eV

E.G. Myers et al., *Phys. Rev. Lett.* **114** (2015) 013003

- $\tau_{1/2}$ ≅ 4570 years (2*10$^{11}$ atoms for 1 Bq)
- $Q_{EC}$ = (2863.2 ± 0.6) eV

Ch. Schweiger et al.,
*Nat. Phys.* **20**, 921–927 (2024)

# Beta decay and electron capture

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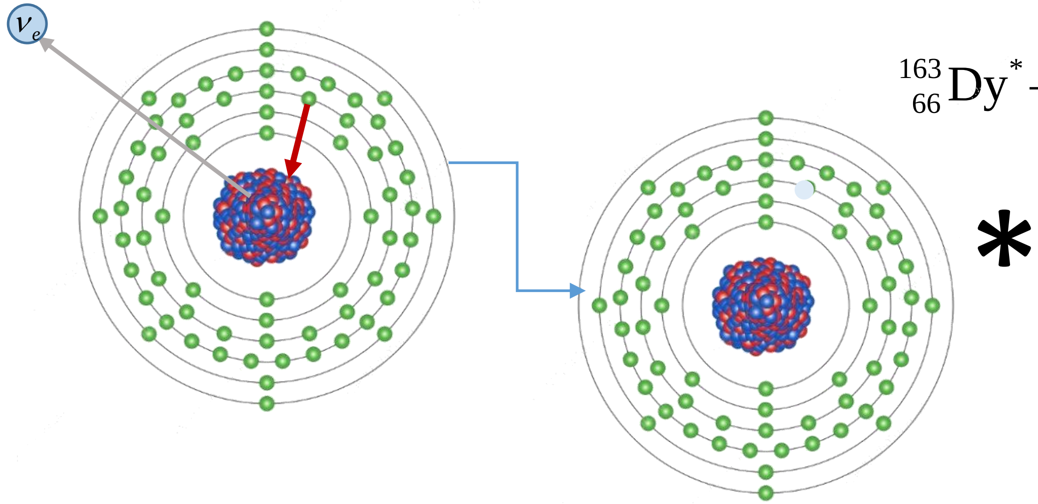

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PTOLEMY

KATRIN — Karlsruhe Tritium Neutrino Experiment

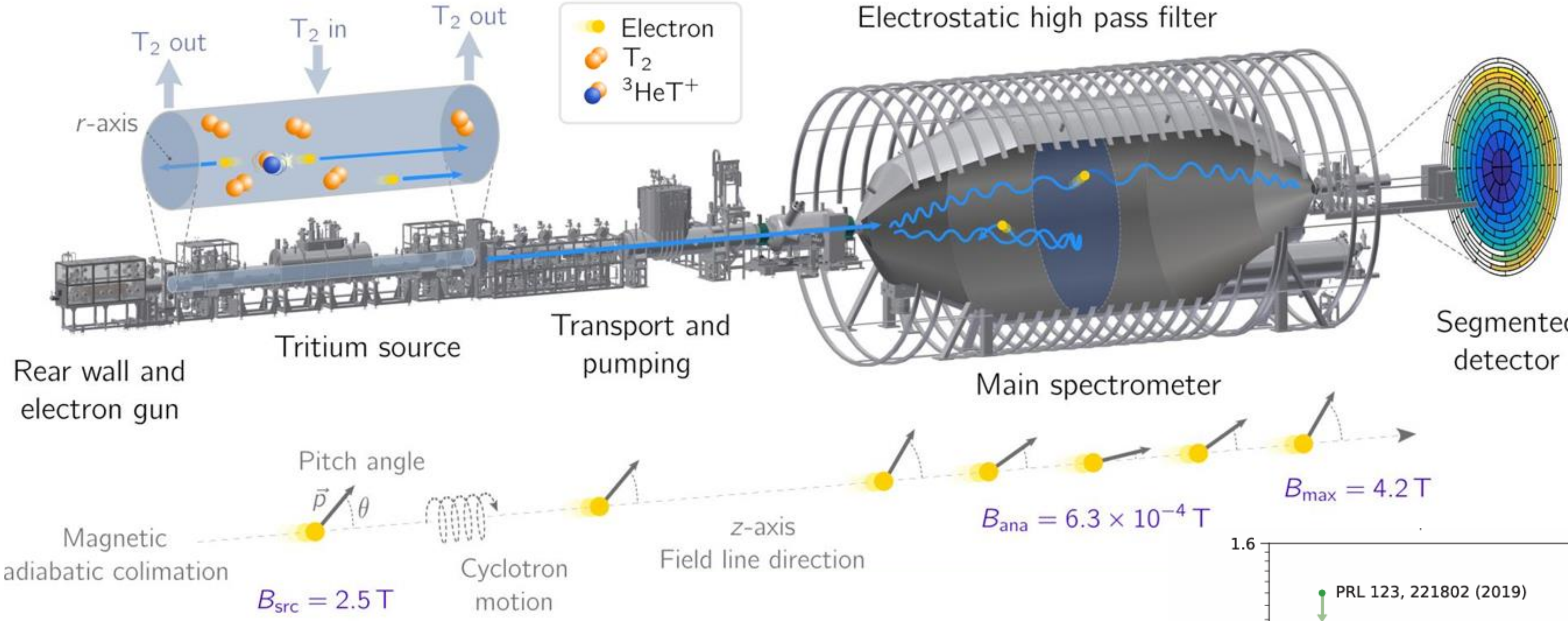
PROJECT 8

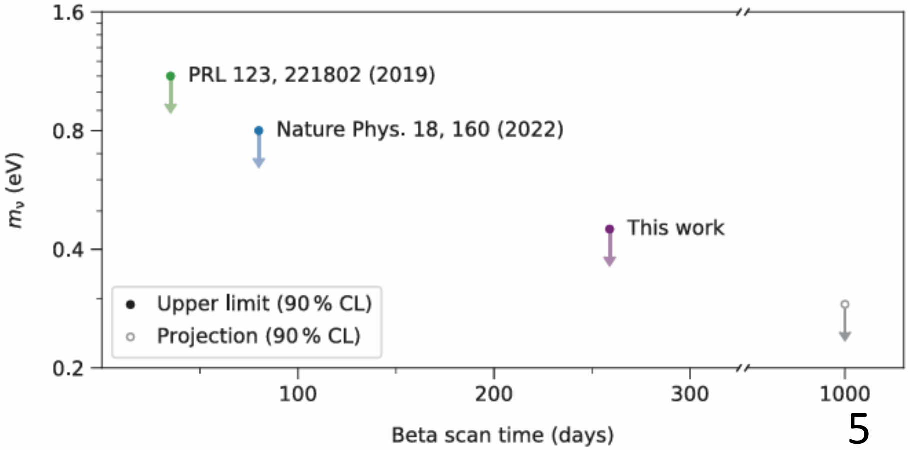
QTNM — Quantum Technologies for Neutrino Mass

ECHo

HOLMES

# $^3$H-based experiments – KATRIN




Most stringent limit on the effective neutrino mass:

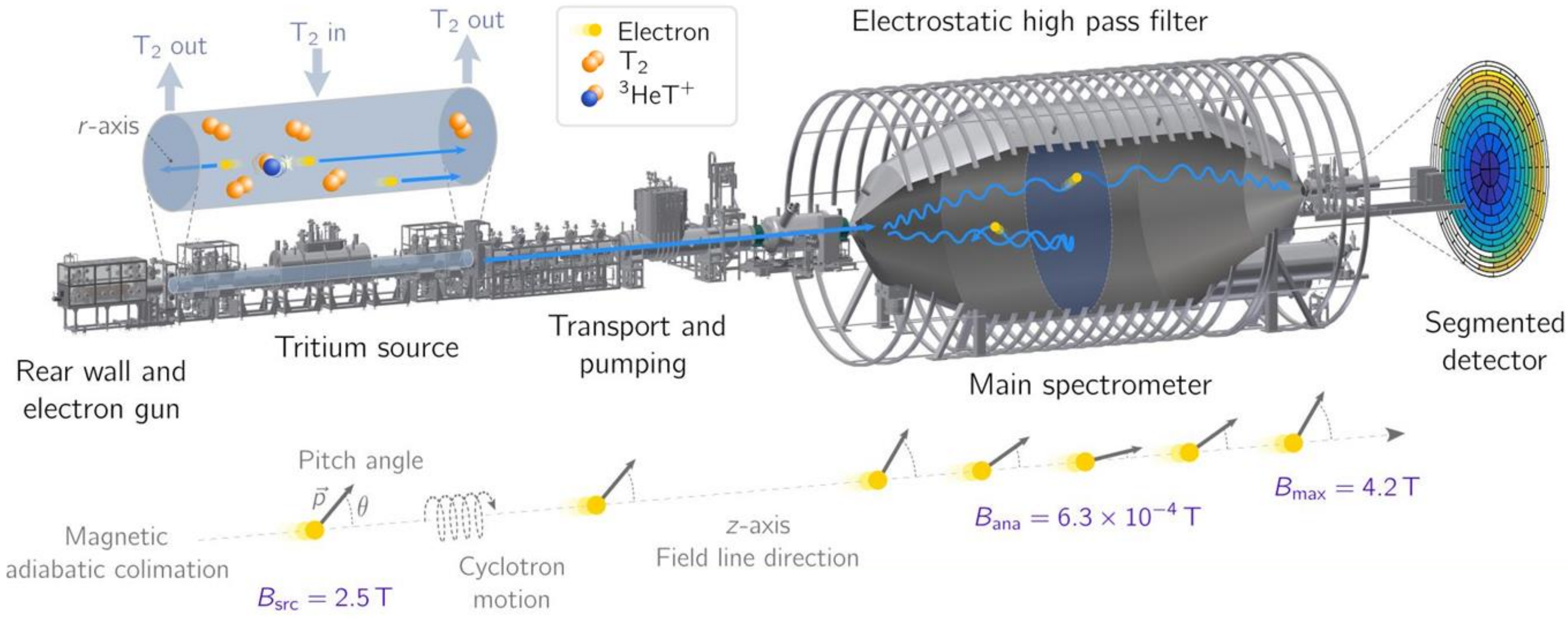
$m_\beta < 0.45$ eV 90% C. L.

Achievable limit for KATRIN:

$m_\beta < 0.3$ eV 90% C. L

KATRIN Collaboration, Science 388, 180 (2025)

# $^3H$-based experiments – KATRIN

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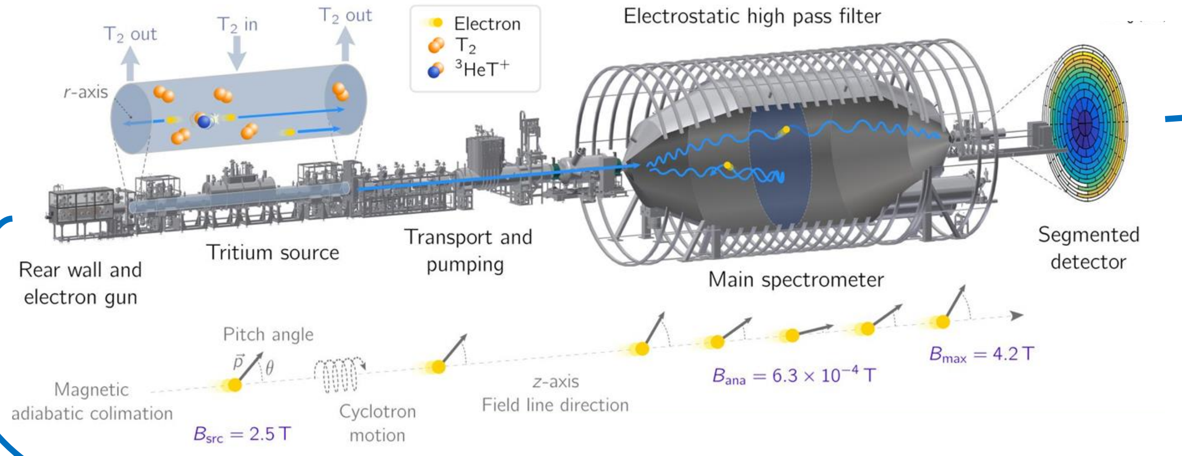
what's next?

KATRIN Collaboration, Science 388, 180 (2025)

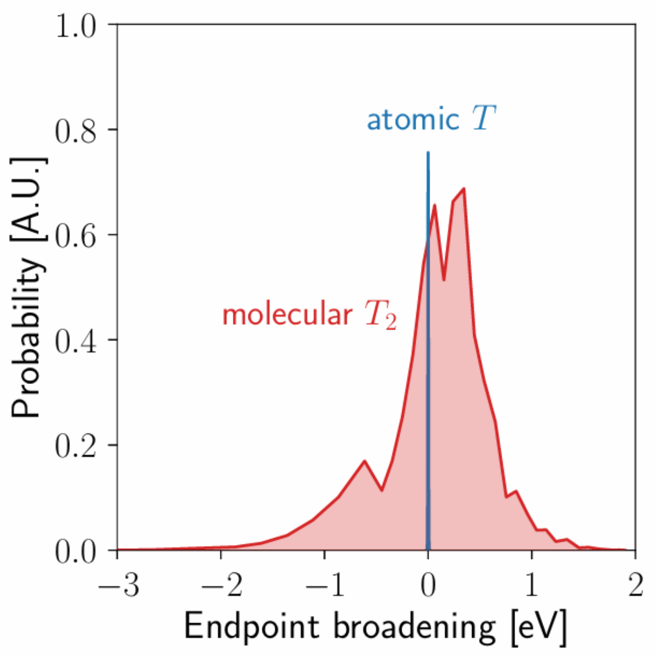
# $^3H$-based experiments – KATRIN ++




## Differential spectrum

better use of acquired events

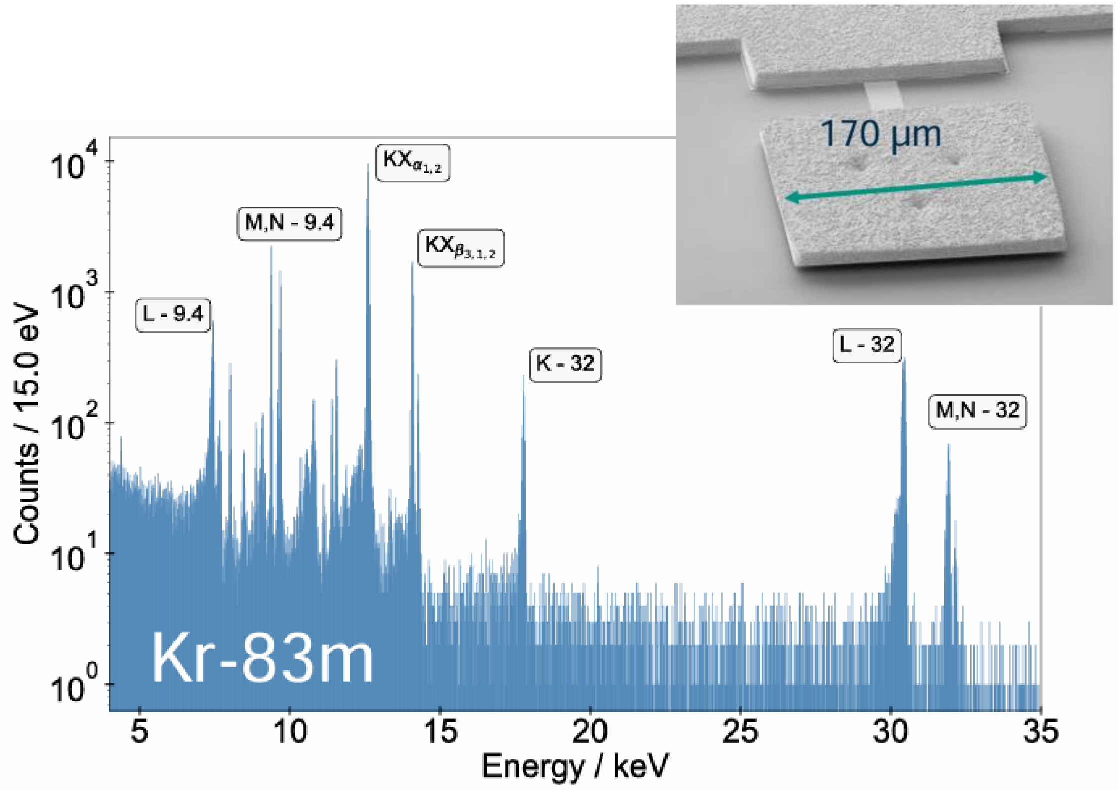
- Time of Flight (electron tagging)
- Microcalorimeters as focal plane detectors




## Atomic $^3H$ source

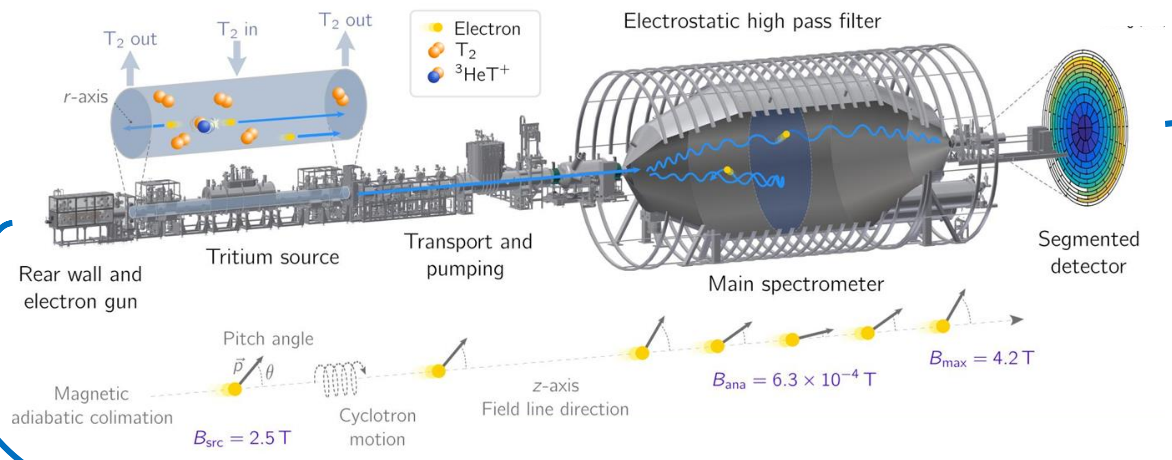
Avoid broadening (~ 1 eV)

Avoid limiting systematics of $T_2$




Kovac et al. 2025, arXiv:2502.05975

# $^3H$-based experiments – KATRIN ++

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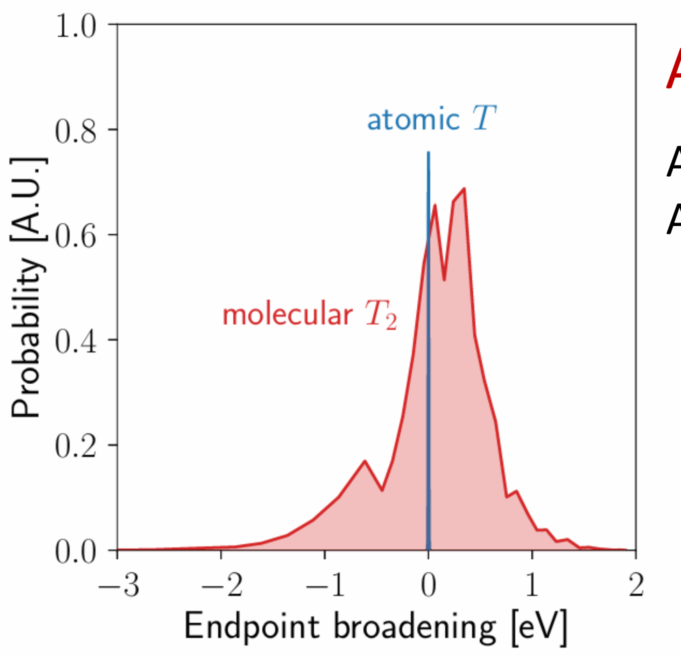


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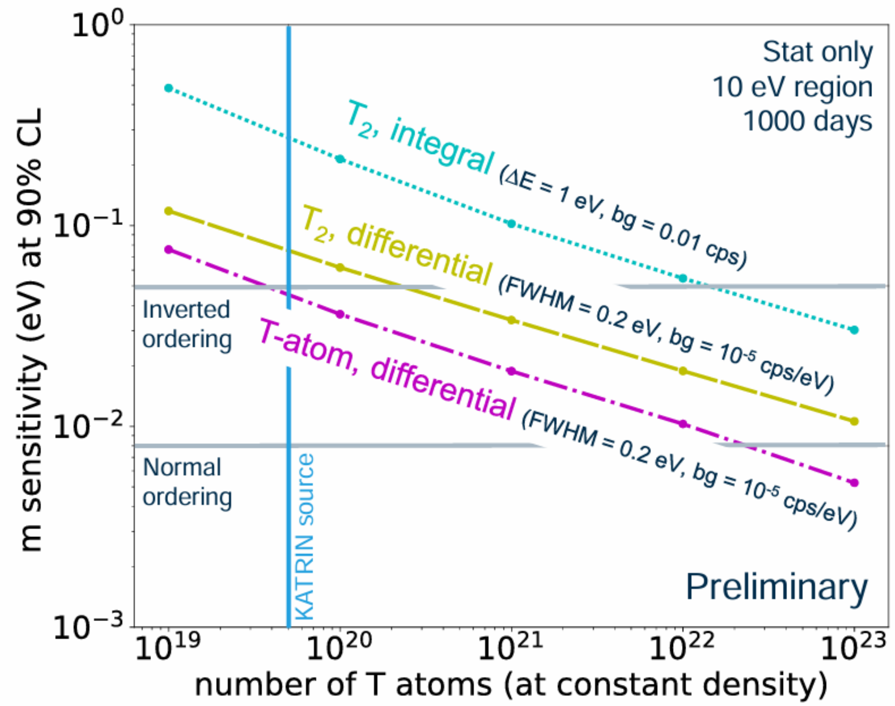
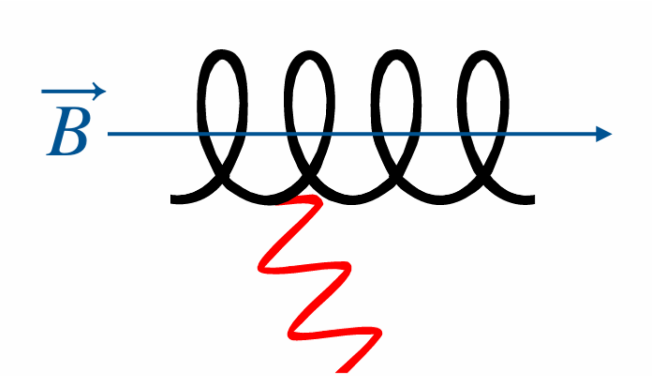



M. Schlösser, Private Communication

# $^3$H-based experiments – Project 8




Example
@ 1 Tesla

ω(18 keV) ~ 26 GHz
P(18 keV) = 1.2 fW

Cyclotron Radiation Emission Spectroscopy

Electrons in **B**-field: cyclotron motion → radiation

$$2\pi f = \frac{e\langle B\rangle}{m_e + K_e/c^2}$$

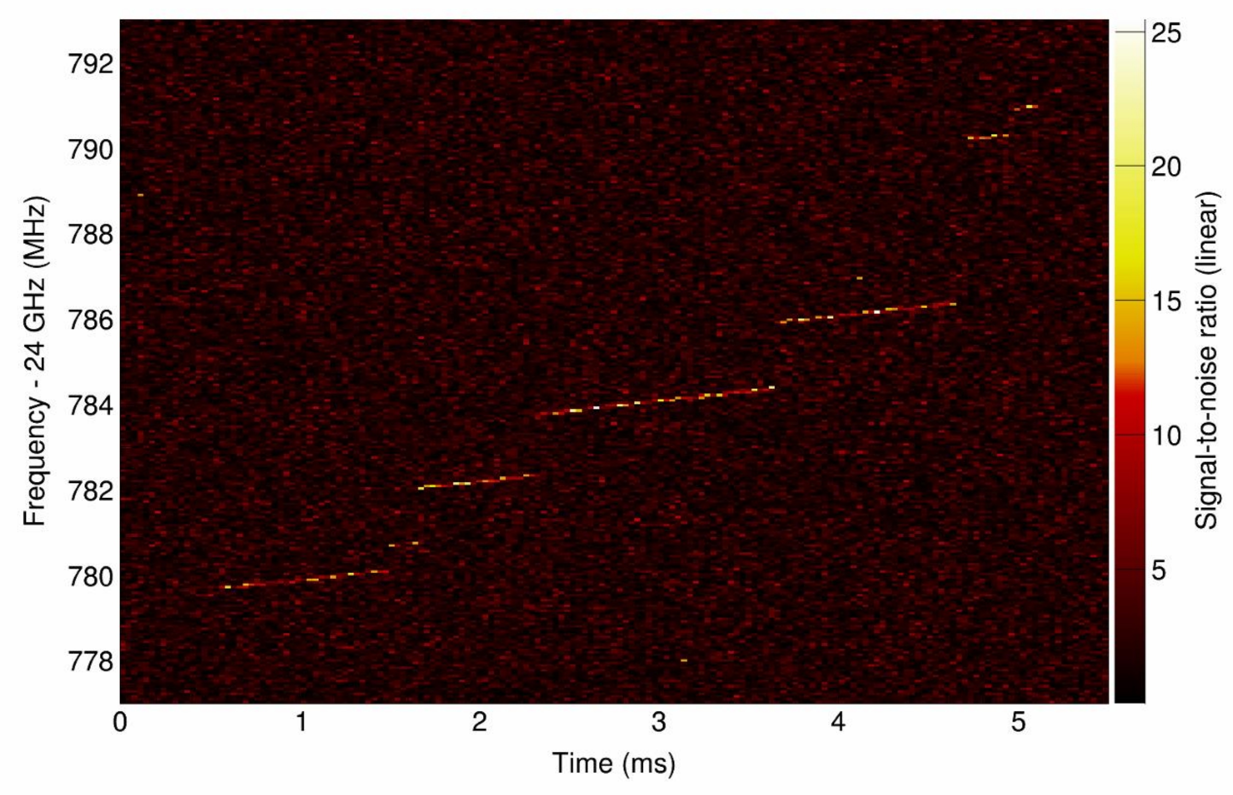
Energy resolution:

$$\frac{\Delta E}{m_e} = \frac{\Delta f}{f}$$

Emitted power:

$$P_{fs} \propto B^2 \propto f^2$$

- Non-destructive measurement of electron energy
- Differential spectrum



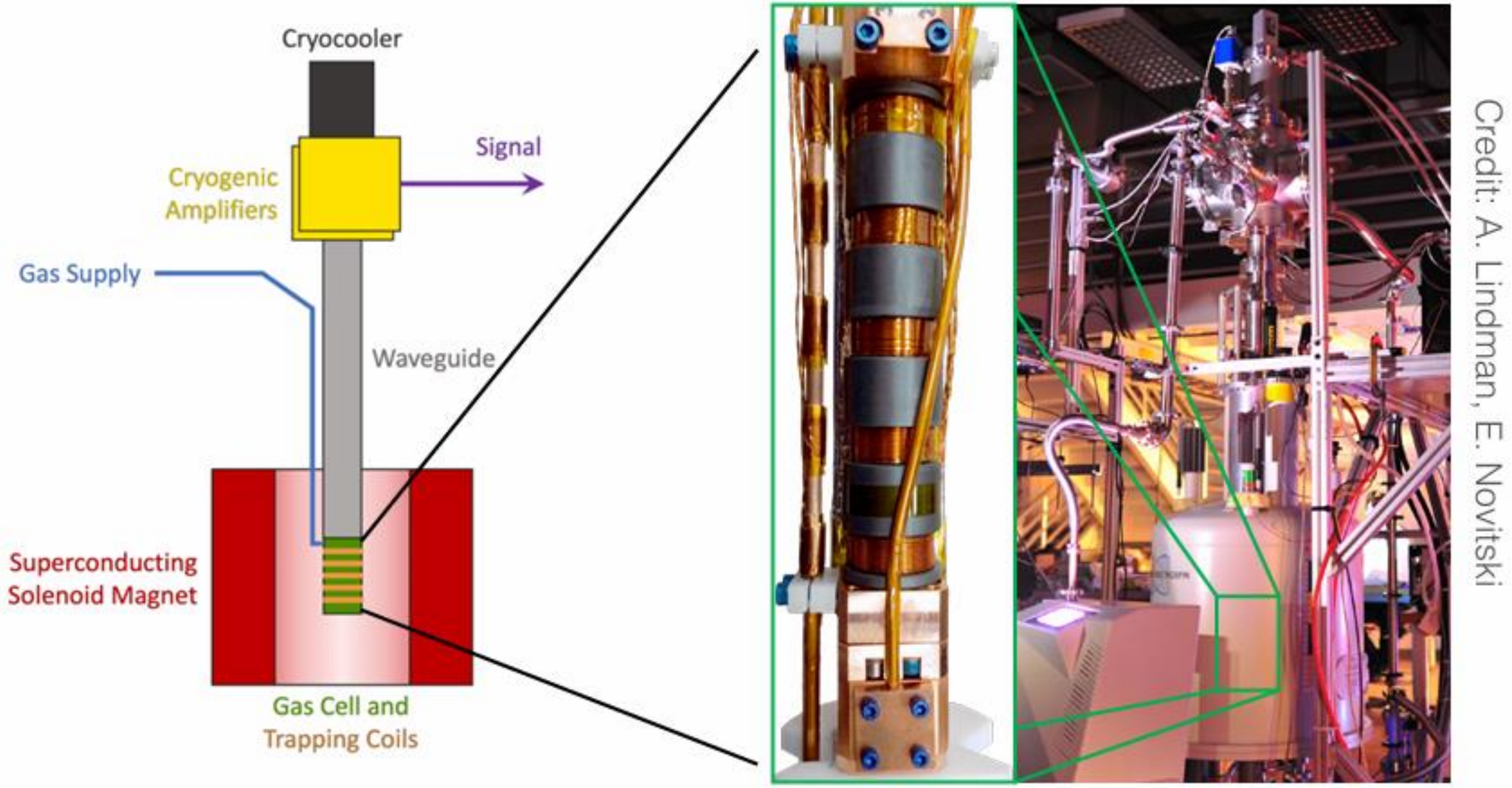

B. Monreal and J. Formaggio, Phys. Rev. D80 051301 (2009)

Project 8 Coll, Phys. Rev. Lett. 114 162501 (2015)

# $^{3}H$-based experiments – Project 8

First CRES measurement of the $^{3}H$ spectrum

- Effective volume: 1mm$^{3}$
- Demonstrated CRES on continuous tritium spectrum (molecular)


Project 8 Coll, Phys. Rev. Lett. 131, 102502 (2023)

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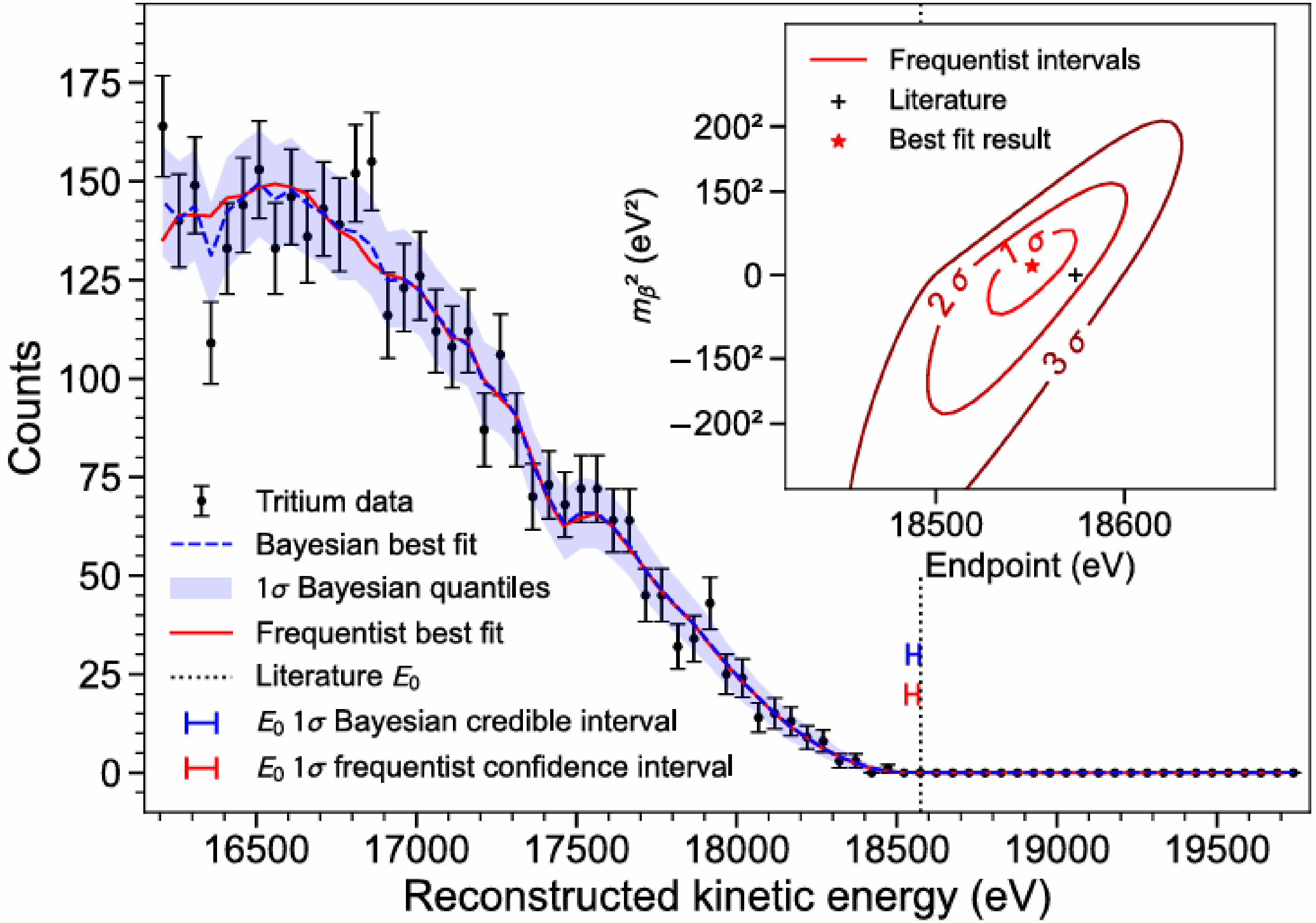
- First neutrino mass upper limit with CRES:
  $m_{\nu_e,eff} \leq 155\ eV/c^2$ (90% C.L.)
- High energy resolution:
  $(1.7\ \pm 0.2)$ eV (FWHM)
- Zero background observed →
  $b\ \leq 3 \times 10^{-10}$ $eV^{-1}\ s^{-1}$ (90% C.L.)




Project 8 Coll, Phys. Rev. Lett. 131, 102502 (2023)

# $^3$H-based experiments – Project 8

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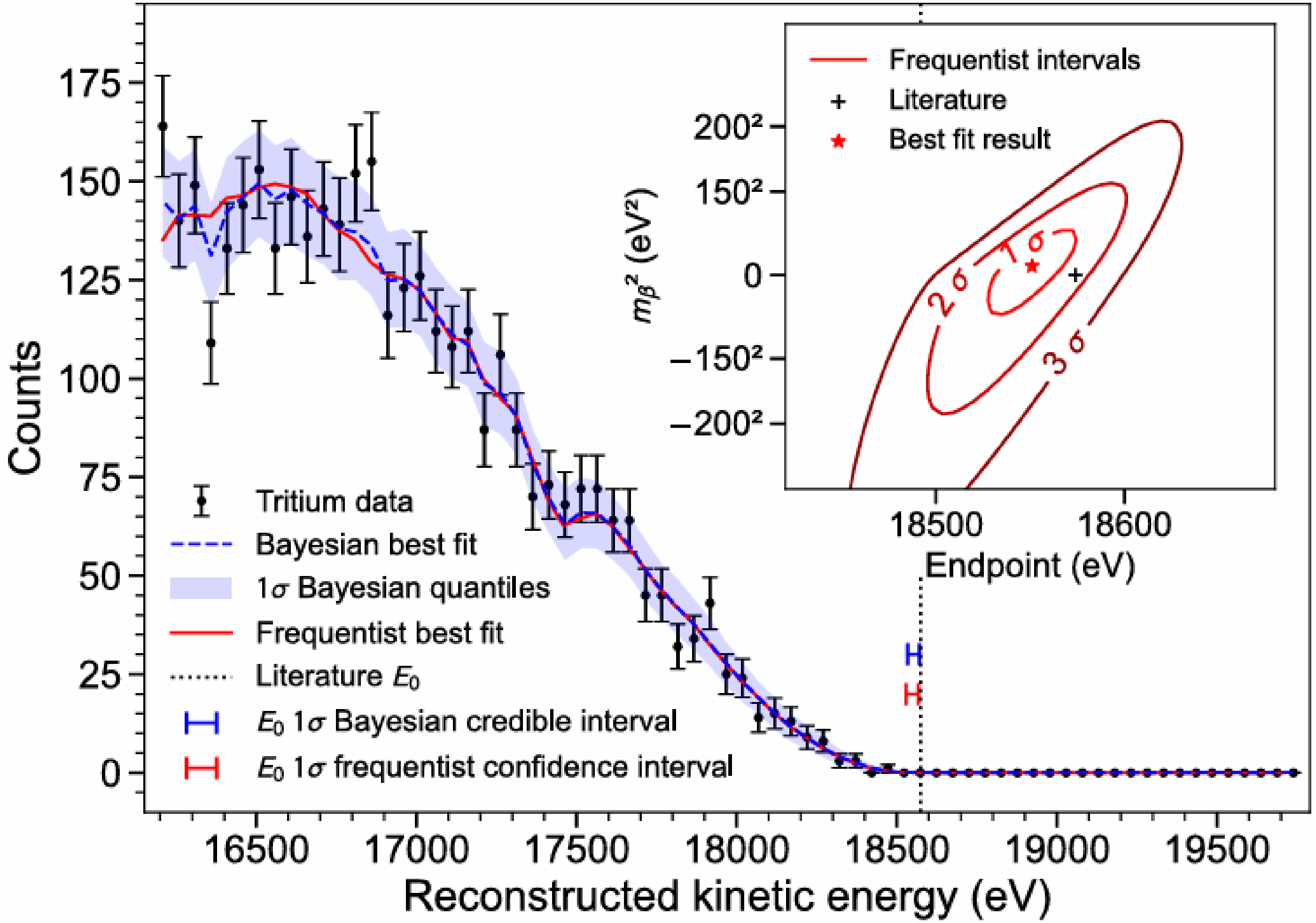



Project 8 Coll, Phys. Rev. Lett. 131, 102502 (2023)

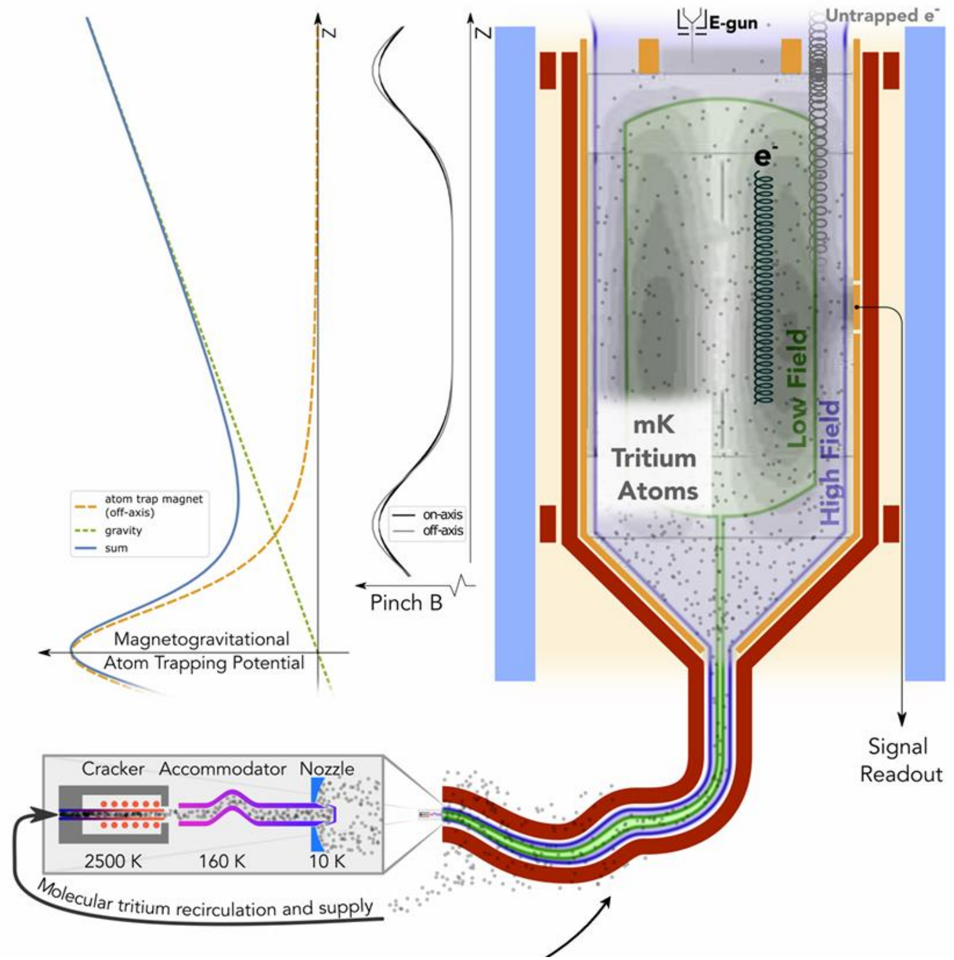
# $^3H$-based experiments – Project 8

PROJECT 8

- Atomic source development

→ $T_2$ molecules need to be broken

→ System with a particular magnetic field configuration for transport and to avoid molecular recombination



# $^3$H-based experiments – Project 8

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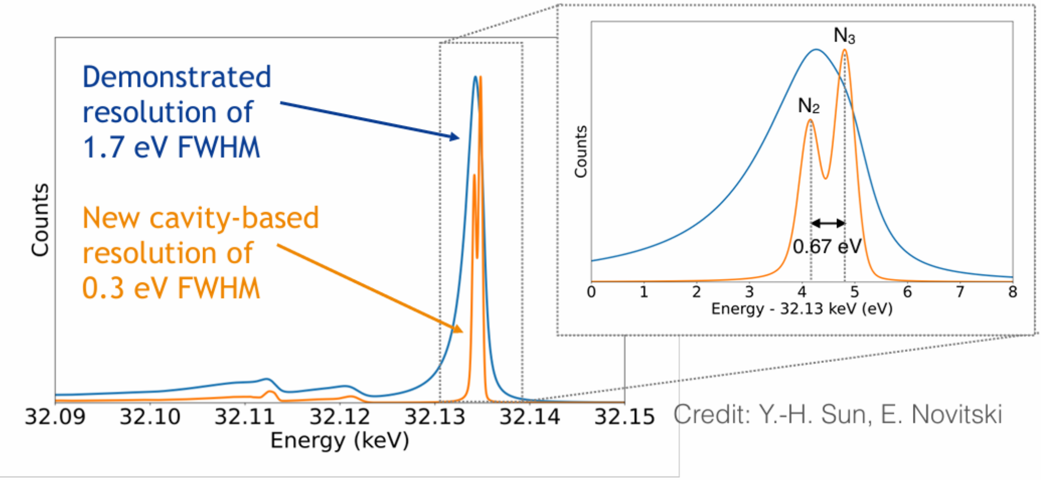
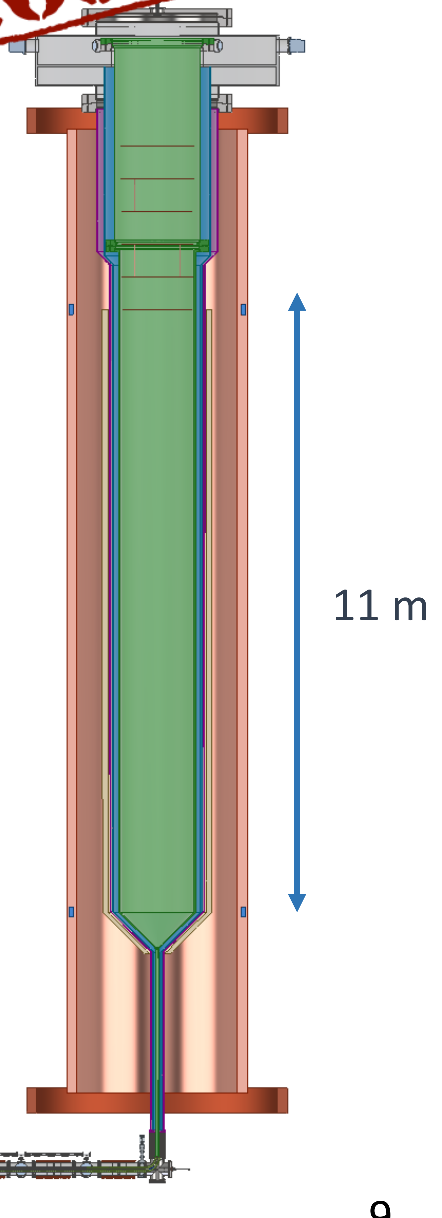
- Large-volume CRES

Cavity-Based CRES Experiment
→ Cavity at 26 GHz: using *TE*01 mode in 1 T MRI magnet

→ Low frequency apparatus: feasibility of CRES in large volume and low fields (frequencies)




Credit: Y.-H. Sun, E. Novitski

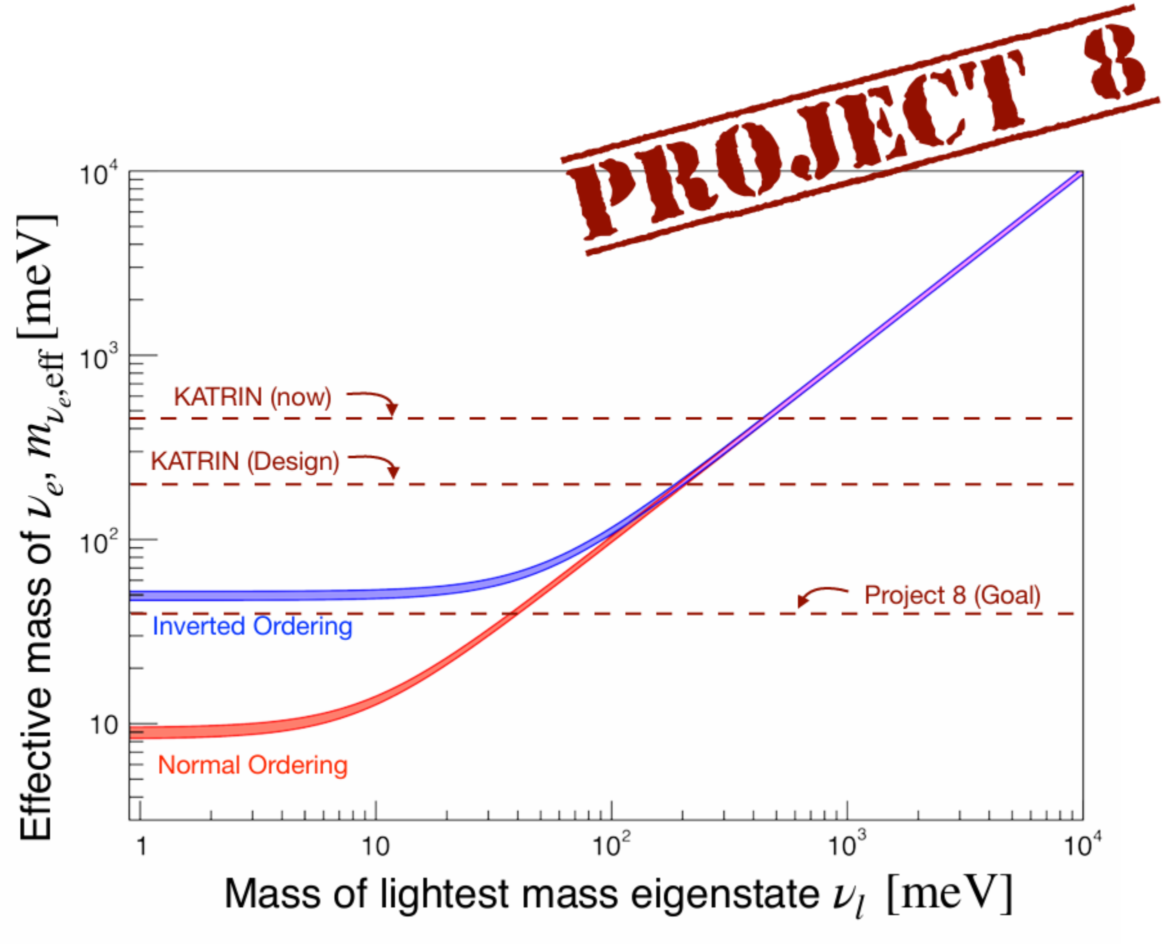


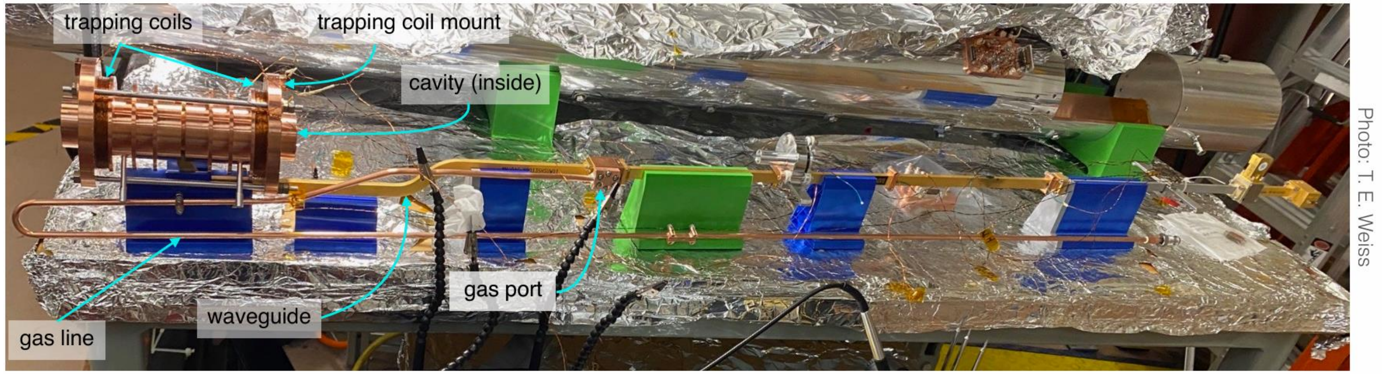
# $^3$H-based experiments – Project 8

Phase III:
Neutrino mass sensitivity $m_\beta \geq 100$ meV

• Atomic source development
→ $T_2$ molecules need to be broken
→ System with a particular magnetic field configuration for transport and to avoid molecular recombination

• Large-volume CRES
Cavity-Based CRES Experiment
→ Cavity at 26 GHz: using *TE*01 mode in 1 T MRI magnet
Same frequency as Phase II: same RF setup, waveguide $L$ = 14 cm, $R$ = 0.7 cm, $V \sim 20$ cm$^3$
→ Low frequency apparatus: feasibility of CRES in large volumes and low fields (frequencies)
$B \approx 0.035$ T, $f_c \approx 1$ GHz, $V \sim 0.3$m$^3$

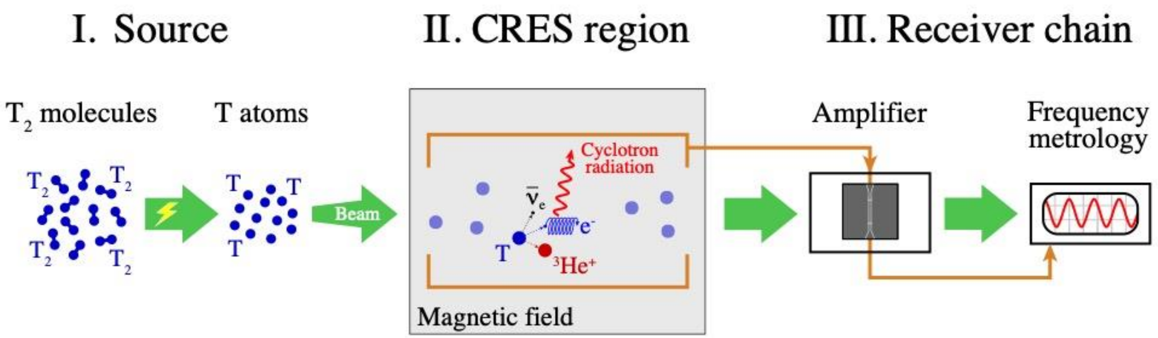


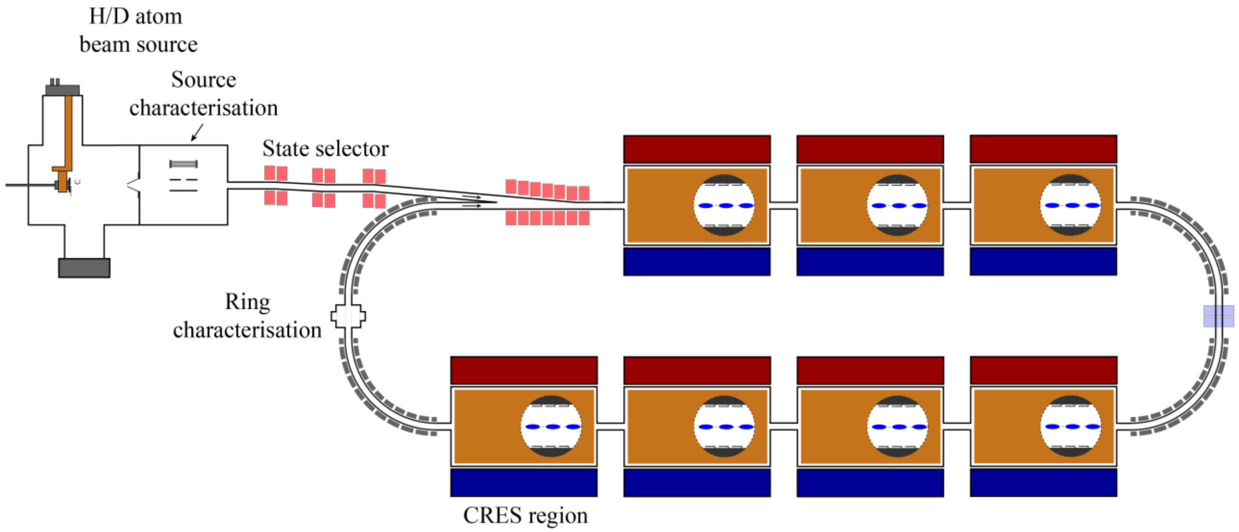




Phase IV:
Neutrino mass measurement if $m_\beta \geq 40$ meV

# $^{3}$H-based experiments – QTMN

Funded as part of the Quantum Technologies for Fundamental Physics programme




Neutrino mass measurement from atomic $^{3}$H β-decay via Cyclotron Radiation Emission Spectroscopy using latest advances in quantum technologies.

Technology Demonstration (2021-2025):
CRESDA-0 = CRES Demonstration Apparatus

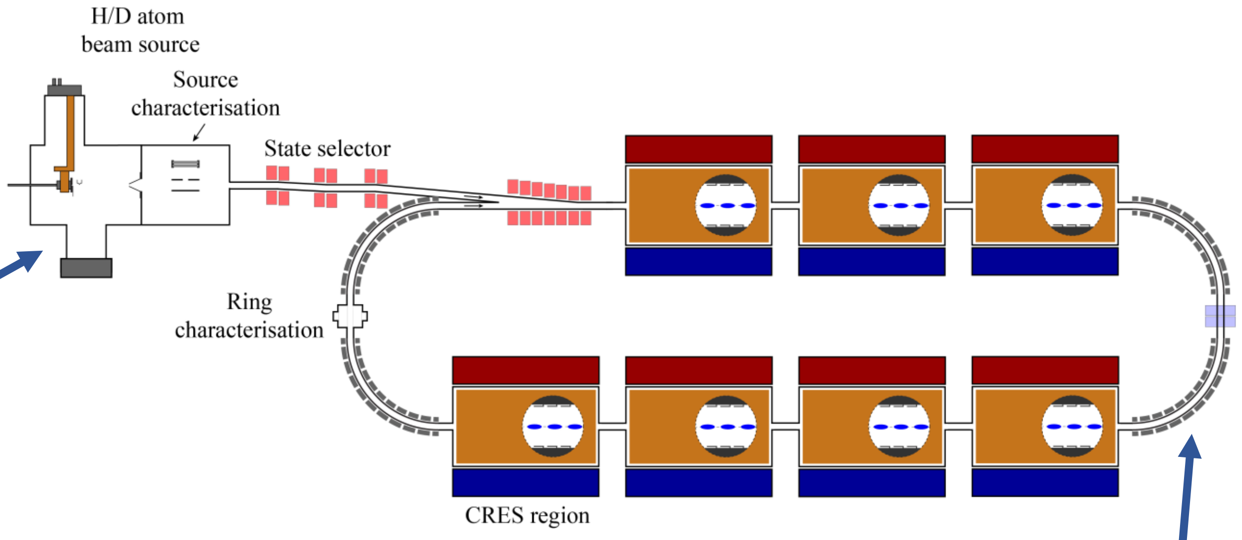
- Quantum noise limited microwave sensors at ~18GHz (corresponding to 0.7T field)
- 3D B-field mapping with $\lesssim 1\ \mu$T precision, using H-atoms as quantum sensors (Rydberg Magnetometry)
- Production and confinement of H-atoms, $\geq 10^{12}$ cm$^{-3}$

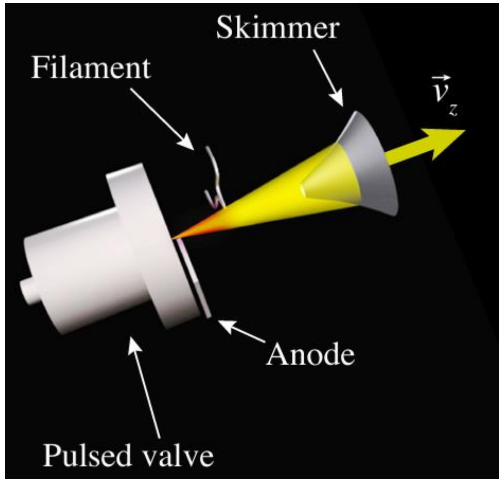
A.A.S. Amad et al., New Journal of Physics, DOI 10.1088/1367-2630/adc624

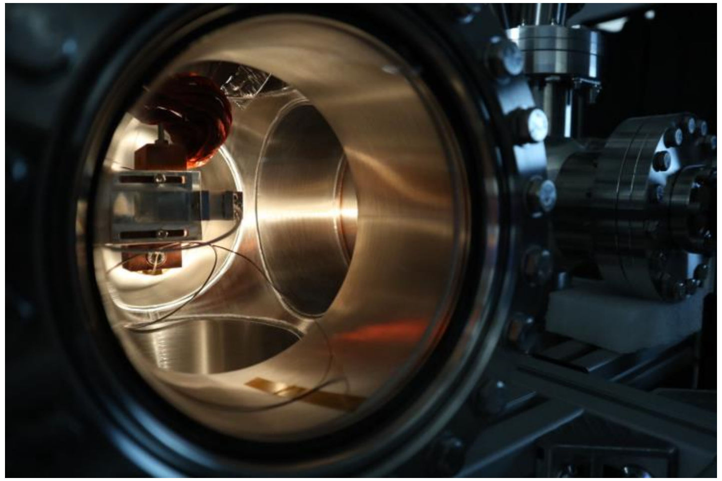
# $^3H$-based experiments – QTMN

Funded as part of the Quantum Technologies for Fundamental Physics programme

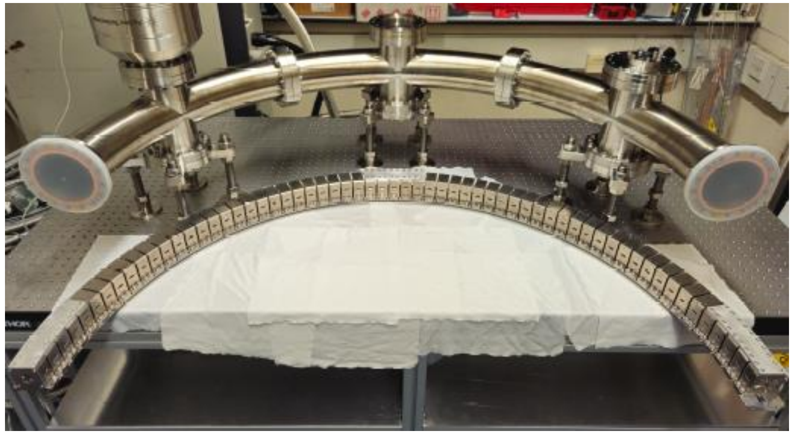
- Cryogenic (30K) pulsed supersonic source
- $H_2/D_2/T_2$ dissociation using DC discharge seeded
- Atomic beam characterisation using **R**esonance **E**nhanced **M**ulti **P**hoton **I**onisation (**REMPI**)

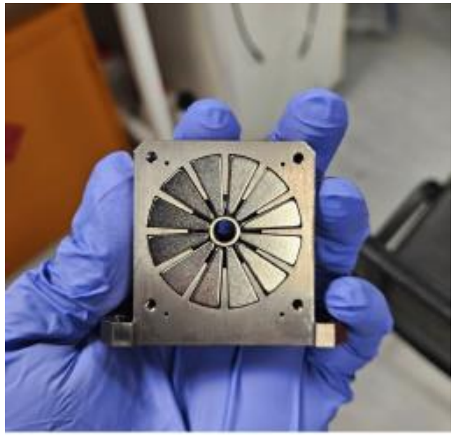


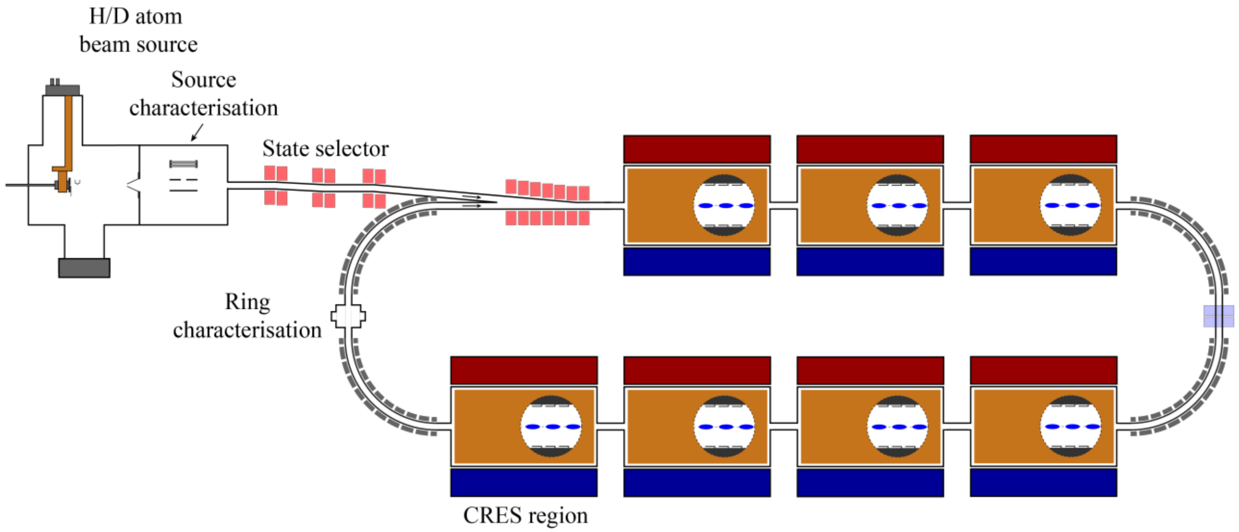
H/D/T-atoms confinement with storage ring



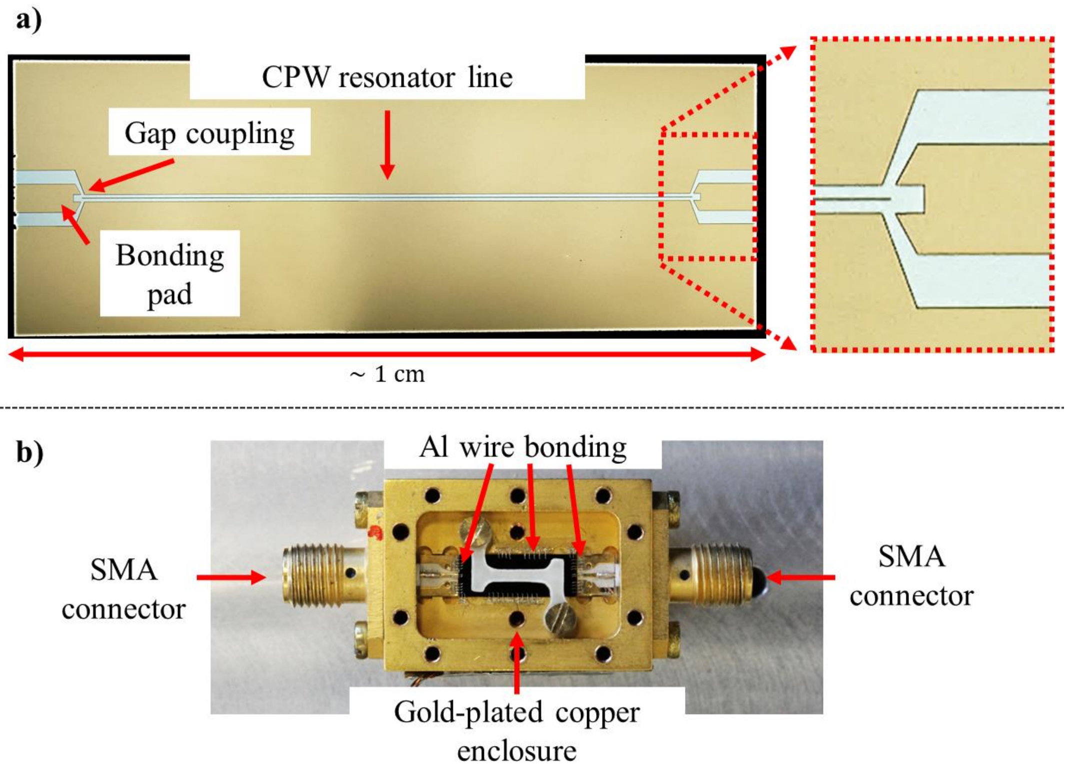


# $^3$H-based experiments – QTMN

Funded as part of the Quantum Technologies for Fundamental Physics programme




Kinetic inductance parametric amplifiers



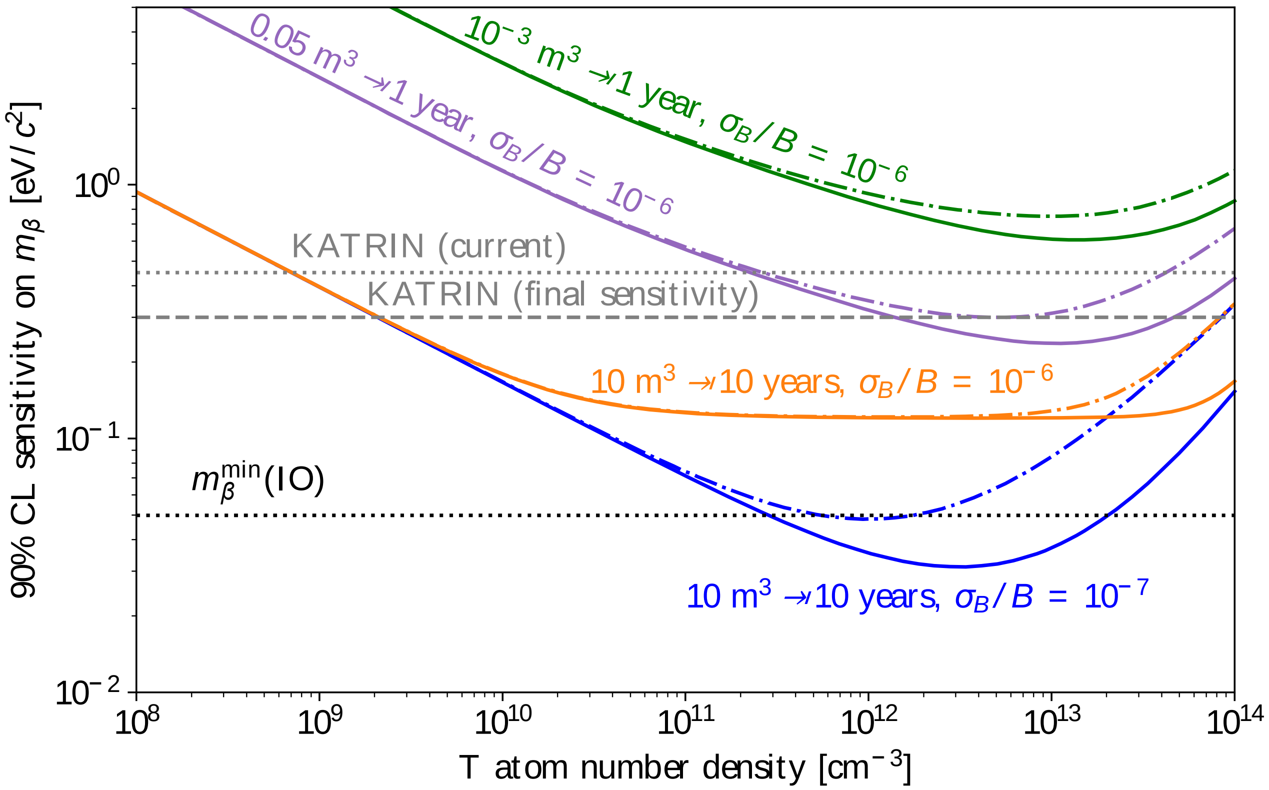

- NbN, Nb, Al, Ti paramps *fabricated* and *tested* at 18 GHz
- Robust and repeatable fabrication, *quantum-noise limited* performance
- Can be operated at 4K – potential for *two-stage* amplification

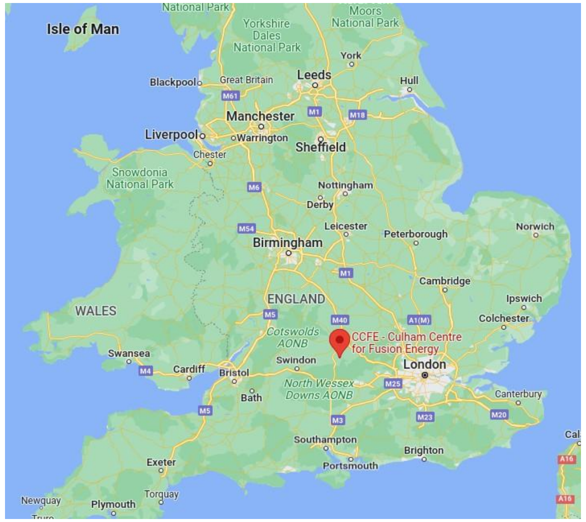
Supercond. Sci. Technol. 36 105010 (2023), arXiv:2406.02455v2 (2024)

# $^{3}$H-based experiments – QTMN

Funded as part of the Quantum Technologies for Fundamental Physics programme

CRESDA-0 (2020 - 2025) → CRESDA+Tritium (2026 - 2030) → 100 meV → 50 meV → 10 meV (2030 – 2040….)




Preferred Location: Culham Centre for Fusion Energy

# $^{3}$H-based experiments – PTOLEMY

**P**on**T**ecorvo **O**bservatory for **L**ight **E**arly-universe **M**assive-neutrino **Y**ield

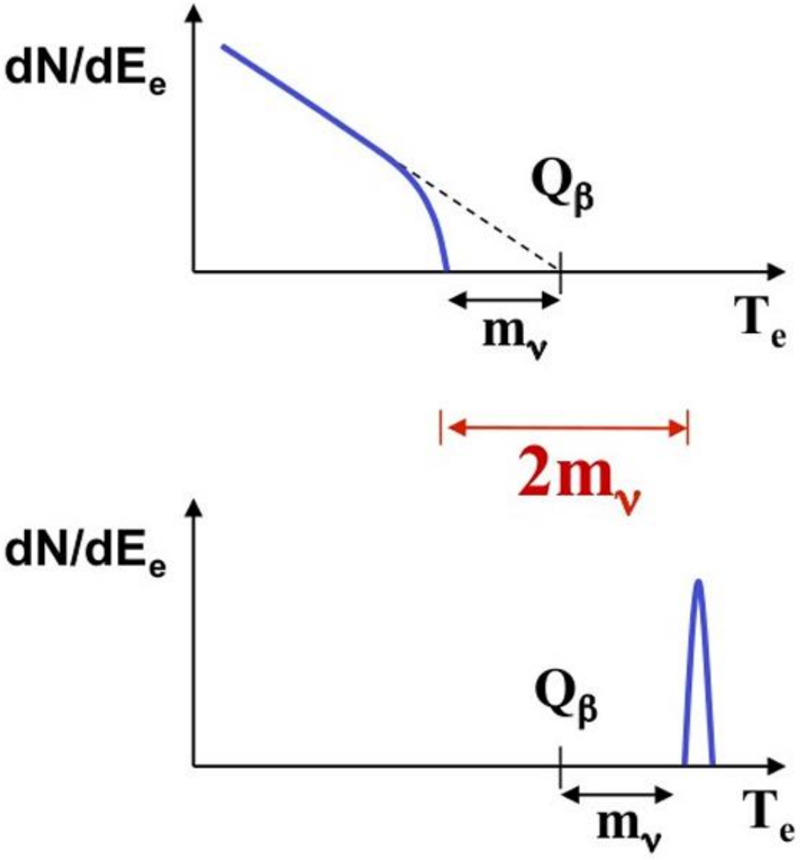
AG.Cocco, G.Mangano, M.Messina JCAP 06(2007)015

Designed for the detection of relic neutrinos

- $\nu_e + \ ^3H \rightarrow e^- + \ ^3He$

Monochromatic peak at *Q*+*m*

Neutrino mass as by-product



# $^3$H-based experiments – PTOLEMY

PTOLEMY

**P**on**T**ecorvo **O**bservatory for **L**ight **E**arly-universe **M**assive-neutrino **Y**ield

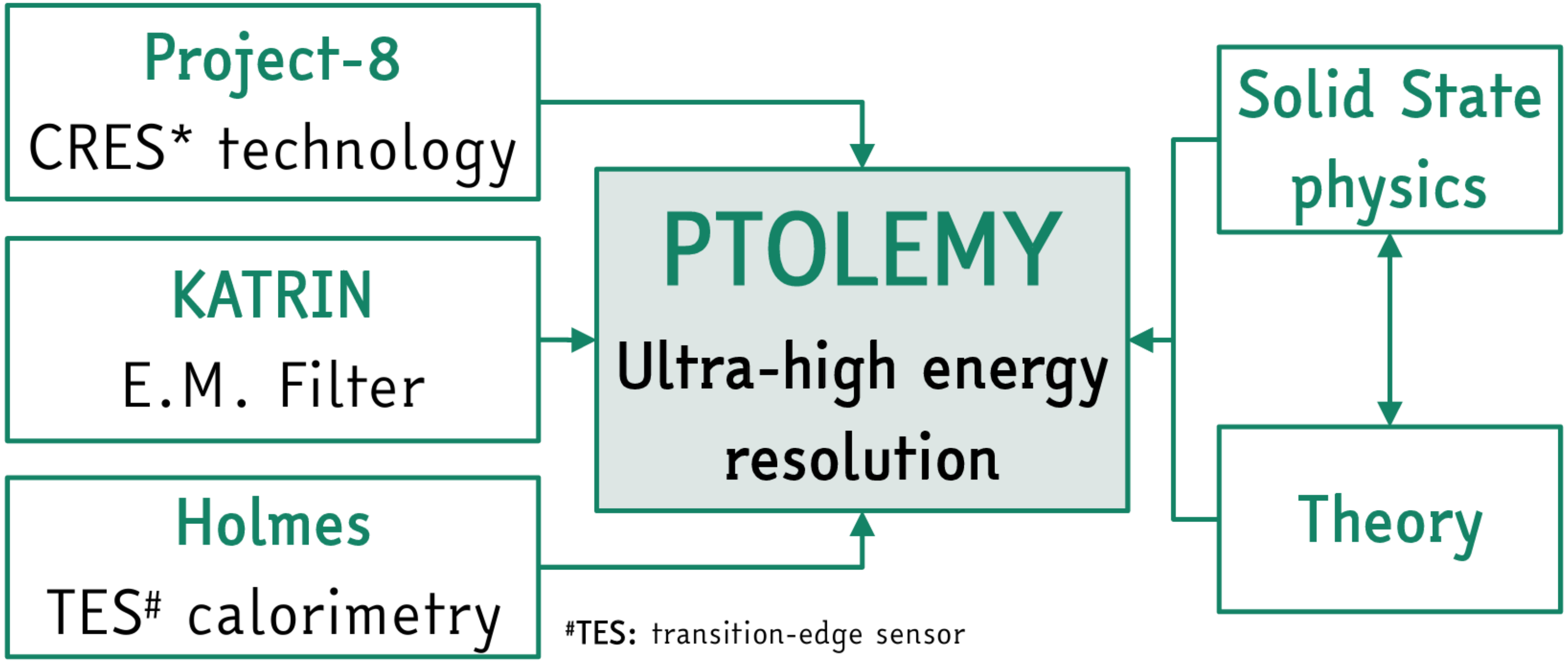
AG.Cocco, G.Mangano, M.Messina JCAP 06(2007)015

Designed for the detection of relic neutrinos

- $\nu_e + {}^3H \rightarrow e^- + {}^3He$

Monochromatic peak at *Q+m*

Neutrino mass as by-product

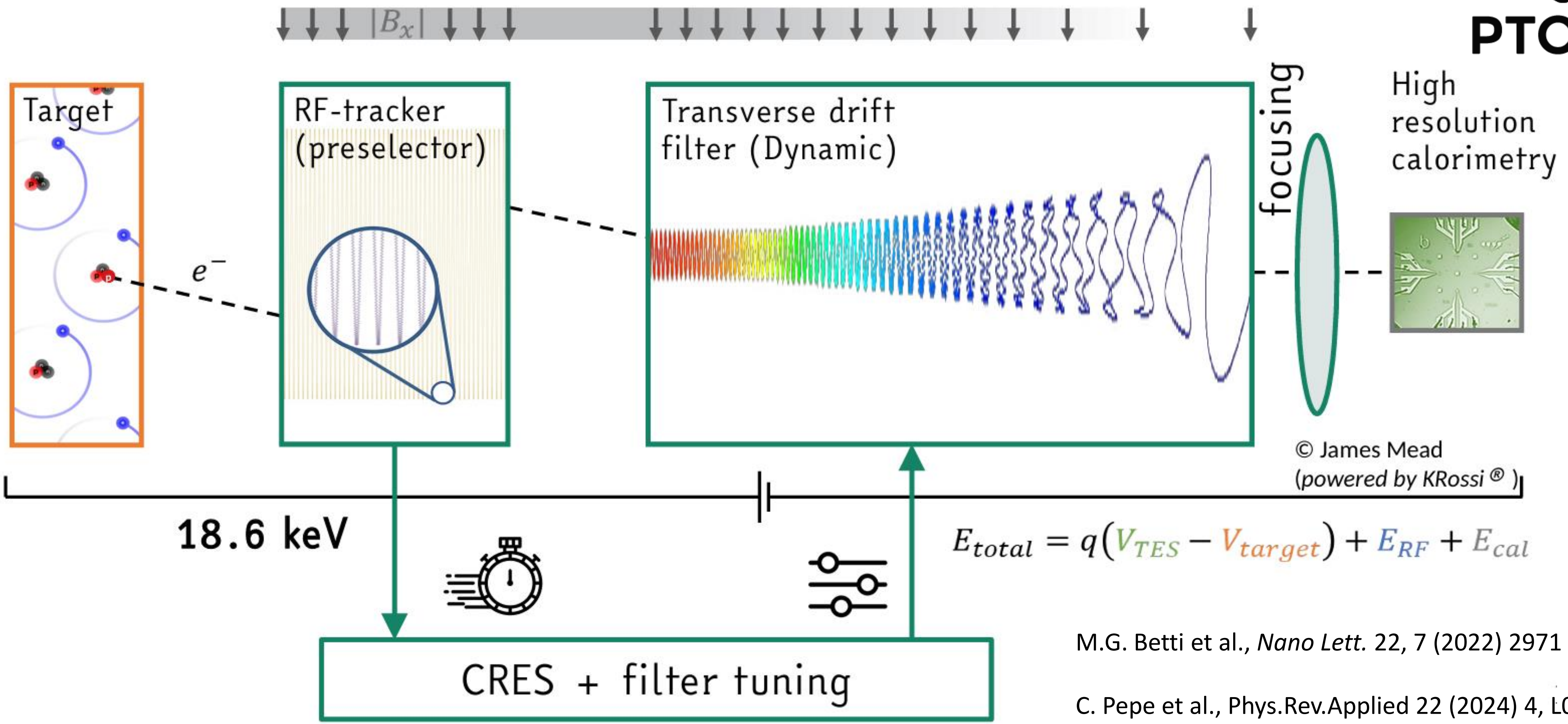



#TES: transition-edge sensor
*CRES: cyclotron radiationemission spectroscopy

PTOLEMY Coll., *JCAP* **07** (2019) 047

# $^3$H-based experiments – PTOLEMY

Prototype set-up in construction at LNGS




M.G. Betti et al., *Nano Lett.* 22, 7 (2022) 2971

C. Pepe et al., Phys.Rev.Applied 22 (2024) 4, L041007

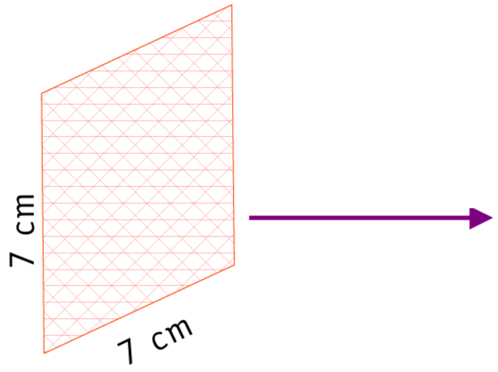
A. Apponi et al., JINST 17 (2022) 05, P05021
PTOLEMY Coll., arXiv:2503.10025

PTOLEMY Coll., *JCAP* **07** (2019) 047

# $^3$H-based experiments – PTOLEMY

PTOLEMY

First goal:
demonstrate feasibility with moderate $^3$H source
on graphite substrate

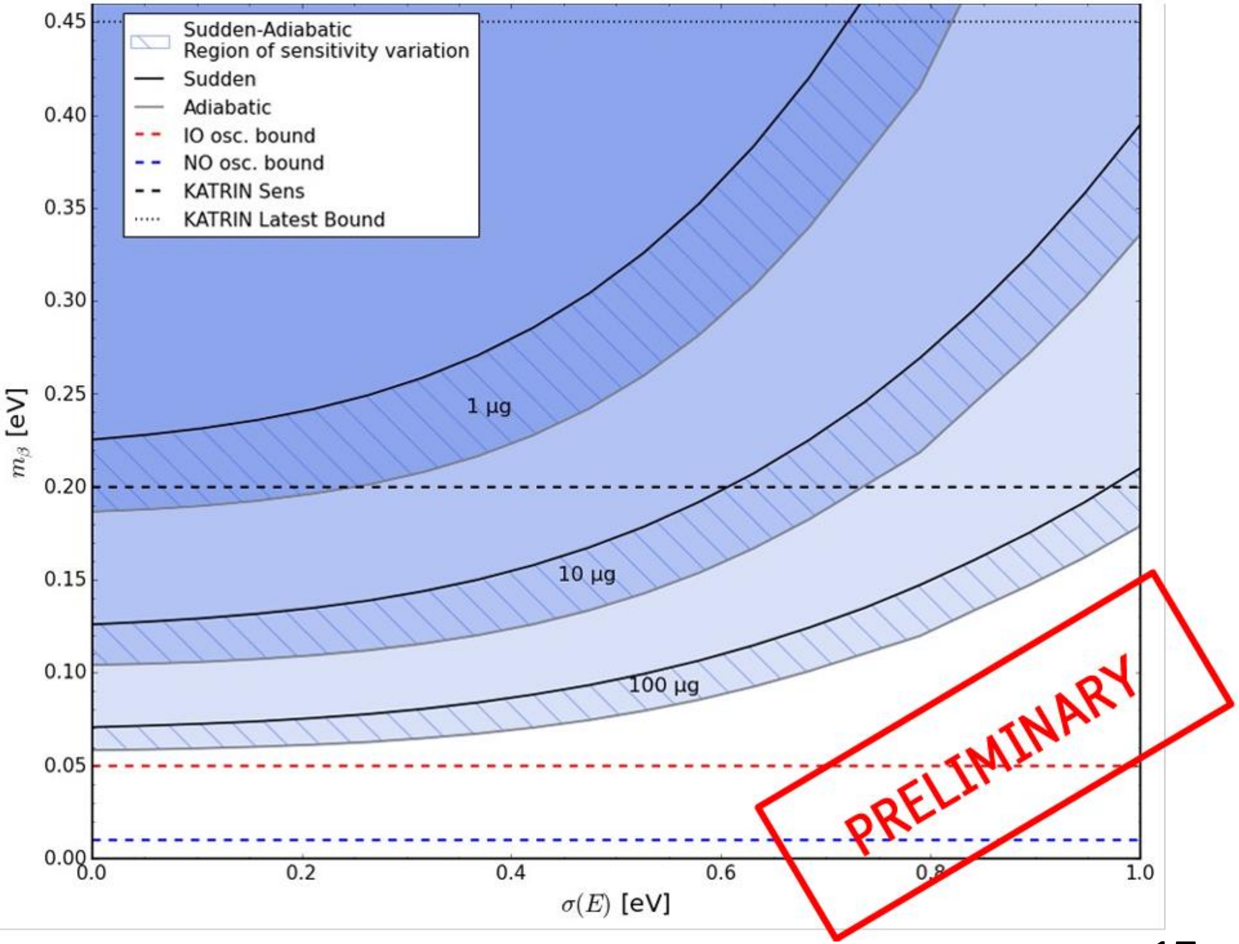



full loading: $\rho = 0.2 \text{ mg/m}^2$

1 μg → 716 MBq

- Weakly dependent upon energy resolution
  (for $\sigma_e$ < 400 meV – 0.94 eV FWHM)
- 1 μg: competitive with the forthcoming generation
- 100 μg (0.5 m$^2$) close to probe the IO scenario

From profile likelihood



# $^{163}$Ho-based experiments

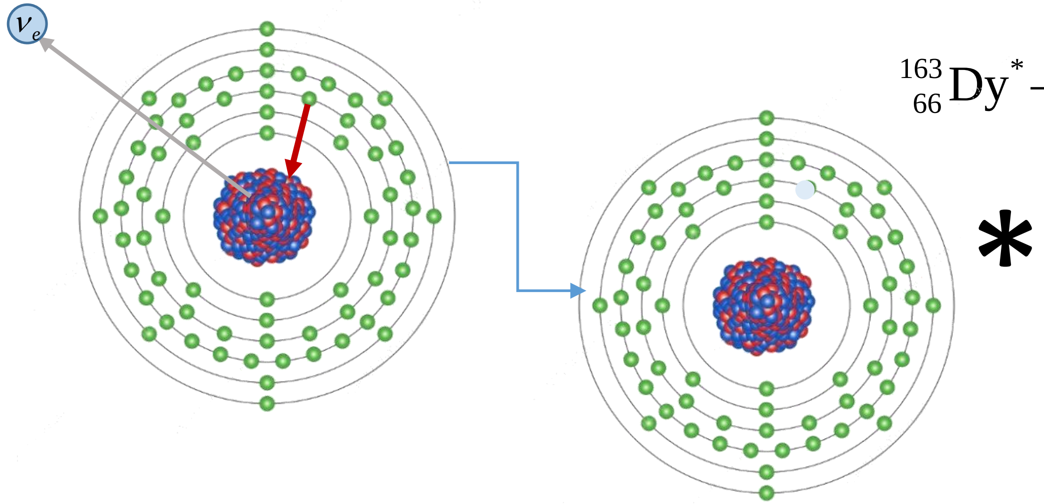
$$^{163}_{67}\mathrm{Ho} \rightarrow ^{163}_{66}\mathrm{Dy}^{*} + \nu_e$$

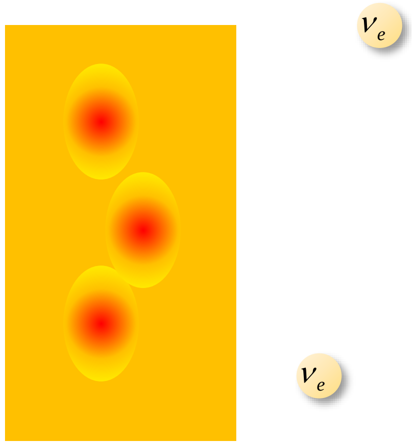
$$^{163}_{66}\mathrm{Dy}^{*} \rightarrow ^{163}_{66}\mathrm{Dy} + E_C$$

Atomic de-excitation via Auger electrons and as subdominant component photons

High resolution measurement only with source enclosed in detectors

→ Low temperature micro-calorimeters!!!




Source = Detector

**Calorimetric measurement**

A. De Rujula and M. Lusignoli, *Phys. Lett.* **118B** (1982)

- $\tau_{1/2} \cong 4570$ years (2*$10^{11}$ atoms for 1 Bq)

- $Q_{EC}$ = (2863.2 $\pm$ 0.6) eV

C. Schweiger et al, arXiv:2402.06464v1 [nucl-ex] (2024)

# $^{163}$Ho-based experiments

Atomic de-excitation via Auger electrons and as subdominant component photons

High resolution measurement only with source enclosed in detectors

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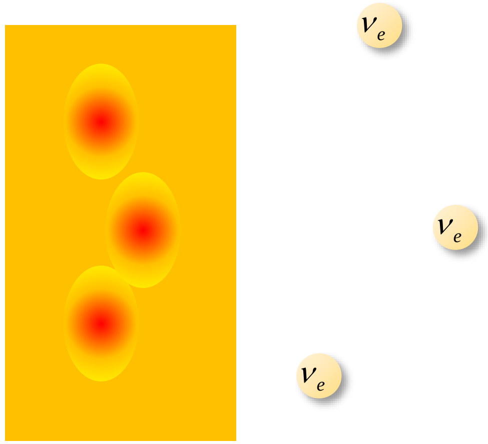



Source = Detector

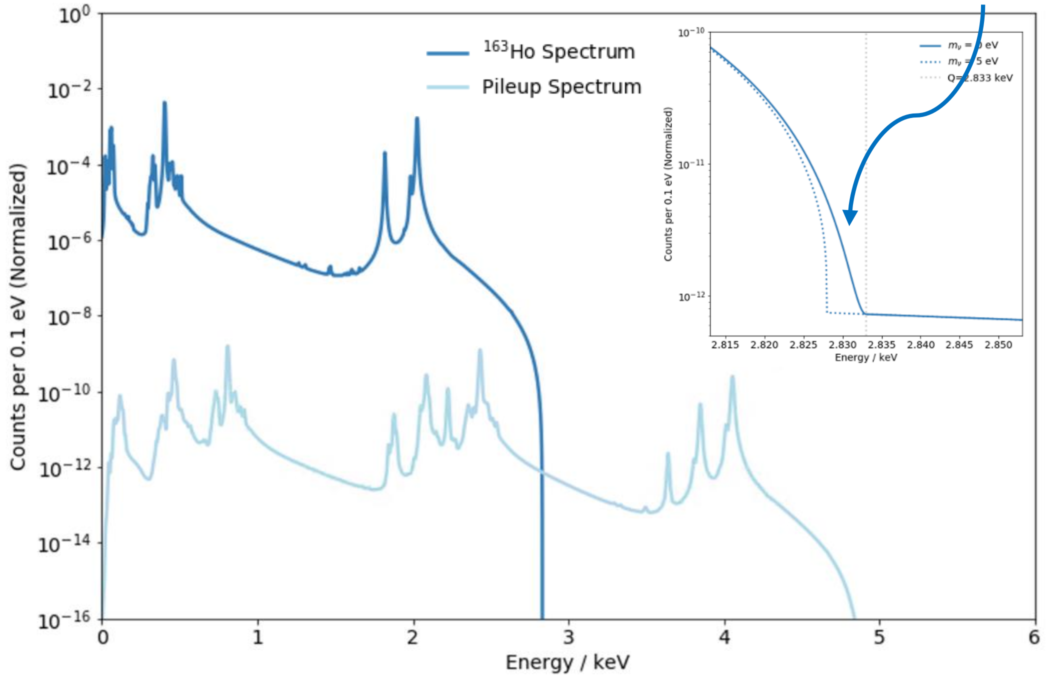
**Calorimetric measurement**

A. De Rujula and M. Lusignoli, *Phys. Lett.* **118B** (1982)

Advantages: No final state problems

Disadvantages: Influence of $^{163}$Ho on detector performance
Unresolved pile-up

Fraction of events in the last eV ~$10^{-12}$




M. Braß and M. W. Haverkort, *New J. Phys.* **22** (2020) 093018

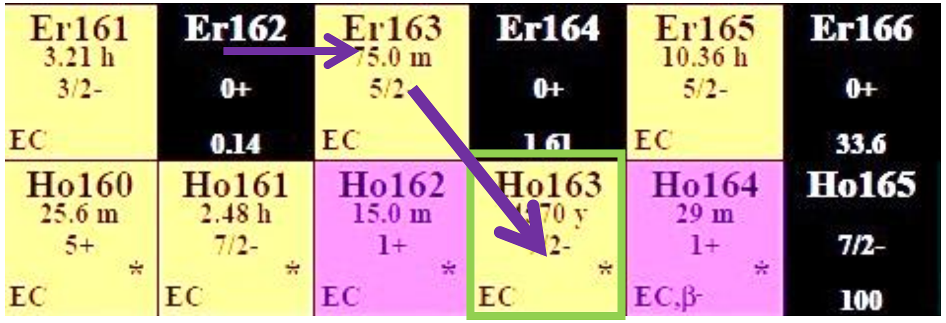
# $^{163}$Ho-based experiments – source production and enclosure

Different methods to produce high purity and high intensity $^{163}$Ho sources have been studied in details

Neutron irradiation

(n,$\gamma$)-reaction on $^{162}$Er

NEUTRONS FOR SCIENCE




S. Heinitz et al., PLoS ONE 13(8): e0200910
H. Dorrer et al, Radiochim. Acta 106(7) (2018) 535–48
J.W. Engle et al., Nucl. Instrum. Meth. B 311 (2013) 131

F. Schneider et al., *NIM B* **376** (2016) 388
T. Kieck et al., Rev. Sci. Inst. 90 (2019) 053304
T. Kieck et al., NIM A 945 (2019) 162602

G. Gallucci et al., JLTP 194 (2019) 453

HOLMES

Mass separation and ion implantation in MMC pixels

RISIKO @ Institute of Physics, Mainz University

- Resonant laser ion source efficiency

  $(69 \pm 5^{stat} \pm 4^{syst})\%$

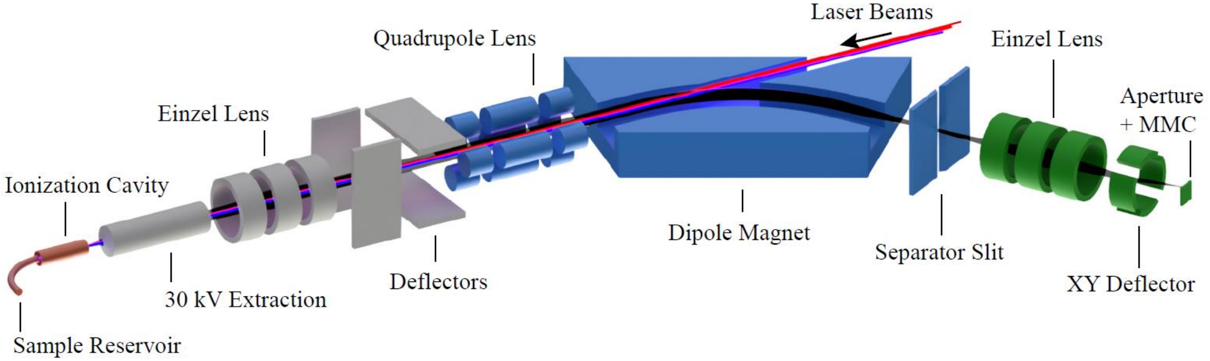
- Reduction of $^{166m}$Ho in MMC

  $^{166m}Ho/^{163}Ho < 4(2)10^{-9}$

- Optimization of beam focalization

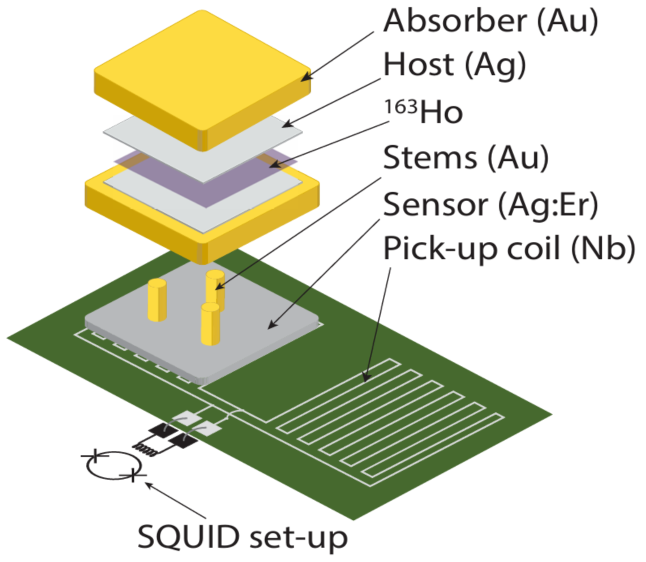
- First test for implantation on wafer scale

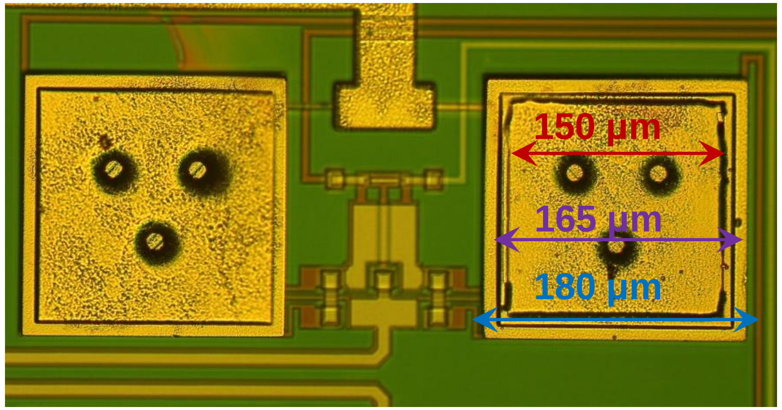
ECHo



# $^{163}$Ho-based experiments – Detector Concept

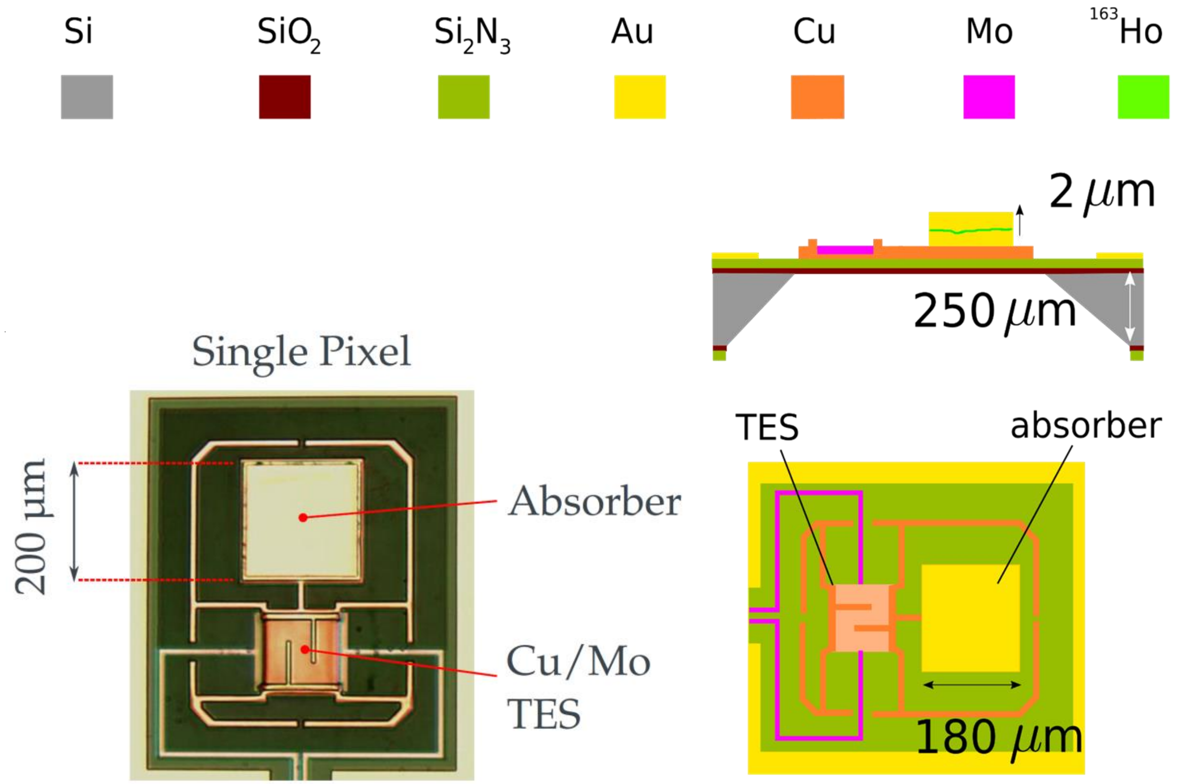
MMC with ion-implanted $^{163}$Ho
operation temperature < 20 mK




F. Mantegazzini et al., *Nucl. Instrum. Meth. A* **1030** (2022) 166406

TES with ion-implanted $^{163}$Ho
operation temperature 80 mK



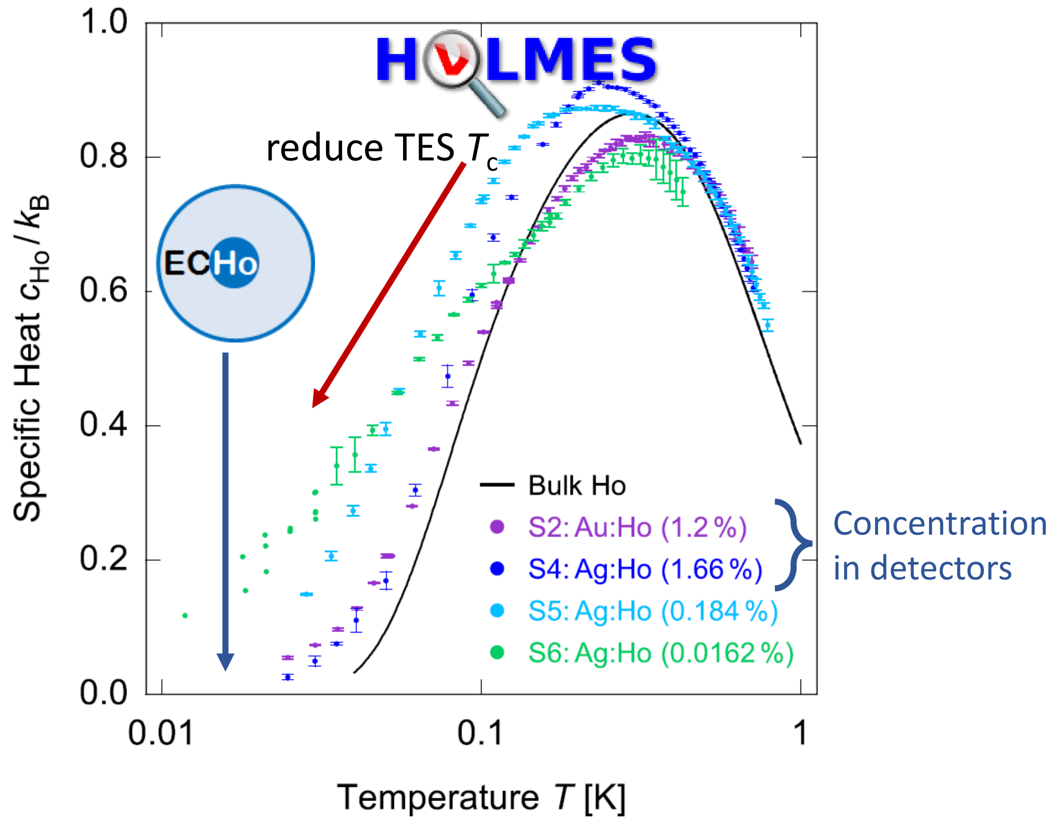

A. Giachero et al., IEEE Transactions on Applied Superconductivity 31 (2021) 2100205

# $^{163}$Ho-based experiments – High resolution detectors

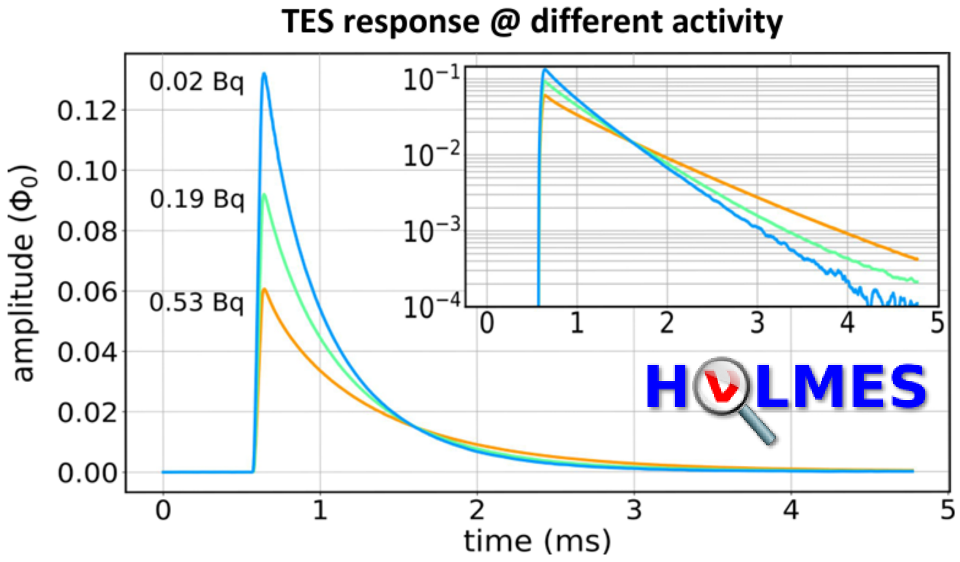
Maximum $^{163}$Ho activity in microcalorimeters affected by:

specific heat per $^{163}$Ho atom → Schottky anomaly at ~ 250 mK
(2*10$^{11}$ atoms for 1 Bq)

allowed unresolved pile-up




M. Herbst et al., *Journal of Low Temperature Physics* **202** (2021) 106




D. Bennett et al., https://doi.org/10.48550/arXiv.2506.13665

# $^{163}$Ho-based experiments – Proof of Concept Experiments

ECHo-0

4 day measurement with 4 pixels loaded with ~0.2 Bq $^{163}$Ho

Energy resolution $\Delta E_{FWHM}$ = 9.2 eV

Background level $b < 1.6 \times 10^{-4}$ events/eV/pixel/day

- $Q_{EC}$ = (2838 ± 14) eV
- $m(\nu_e) < 150$ eV (95% C.L.)

C. Velte et al., EPJC **79** (2019) 1026

**NEW**

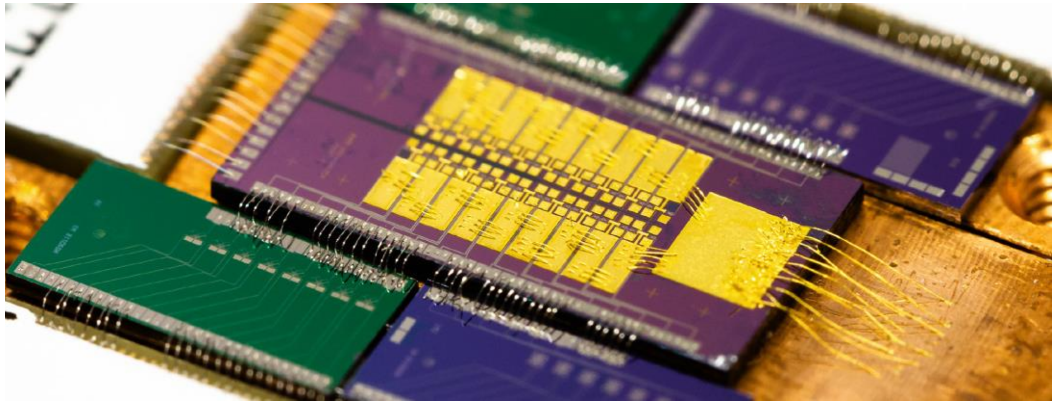
ECHo-1k 2-stage SQUID readout

57 pixel with implanted $^{163}$Ho

9 background pixels

total activity of 46 Bq

Experiment duration: 6 months

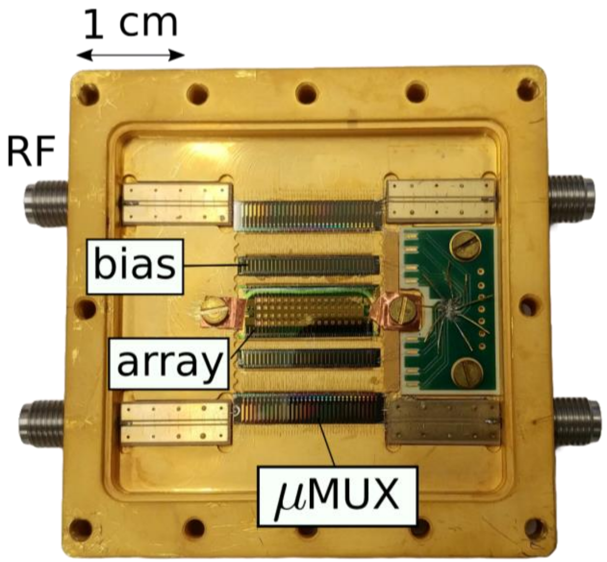


HOLMES Multiplexed readout

48 detectors

15 Bq total activity

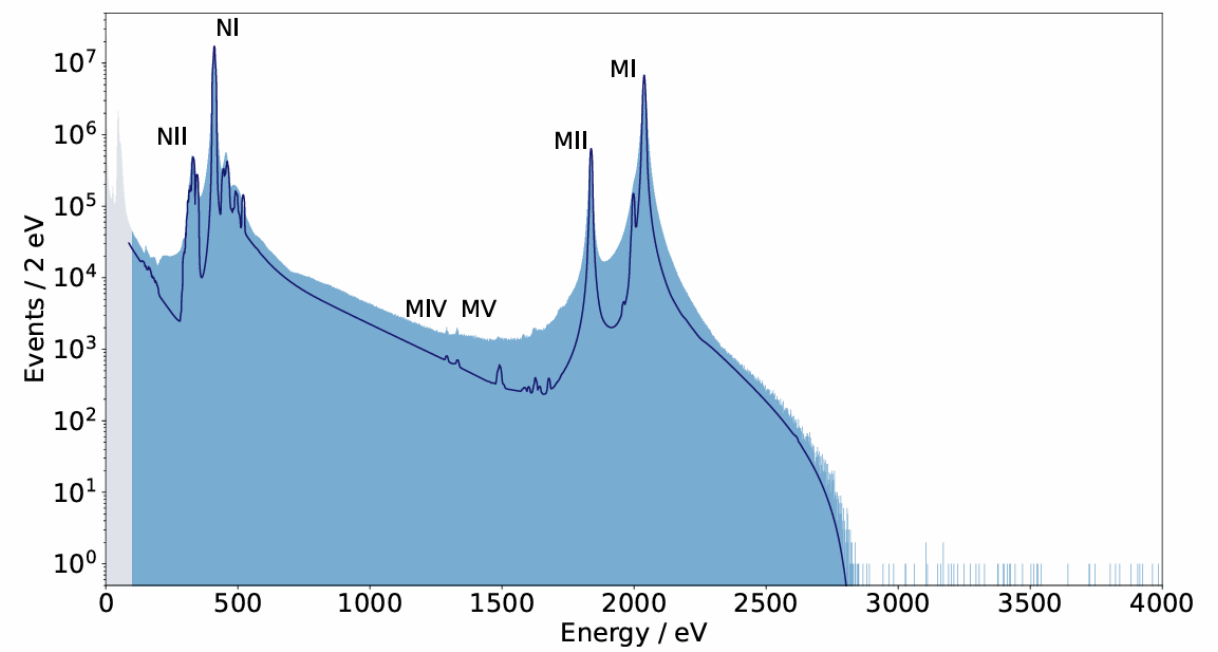
Experiment duration: 2 months



# $^{163}$Ho-based experiments – Proof of Concept Experiments

## ECHo-1k

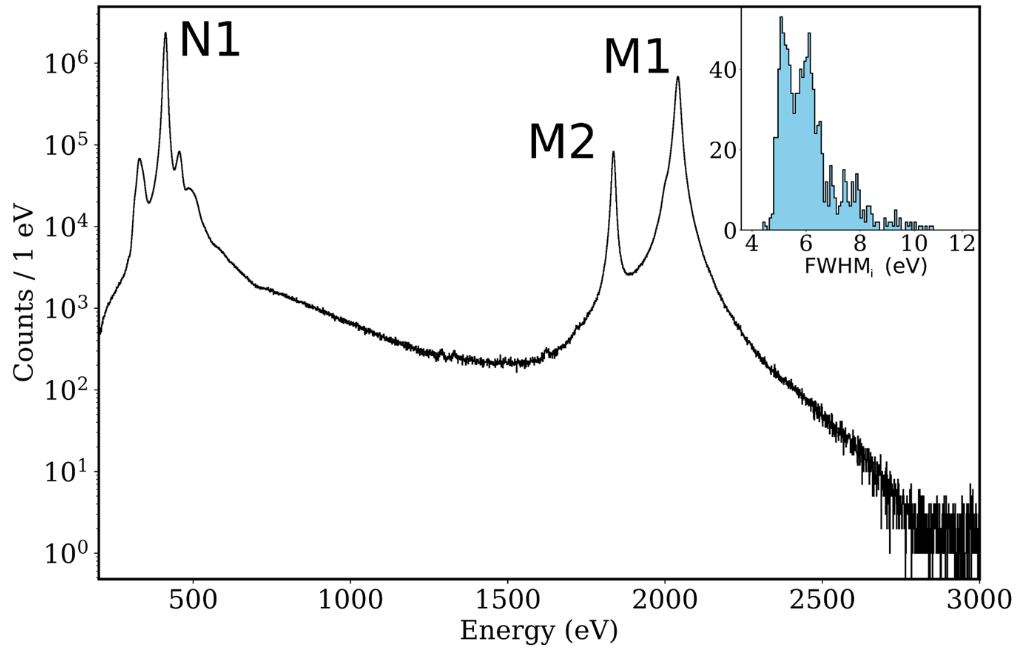
200 million events from 100 eV to 5000 eV
$\Delta E_{\mathrm{FWHM}}$ = (6.59 $\pm$ 0.16) eV
number of events in [2900 – 5000] eV = 80
$b$ = (9.1 $\pm$ 1.3) × $10^{-6}$ /eV/pixel/day




## HOLMES

60 million events above 300 eV
$\Delta E_{\mathrm{FWHM}}$ = (6 $\pm$ 1) eV

$b$= (1.7 ± 0.1) × $10^{-4}$/eV/pixel/day

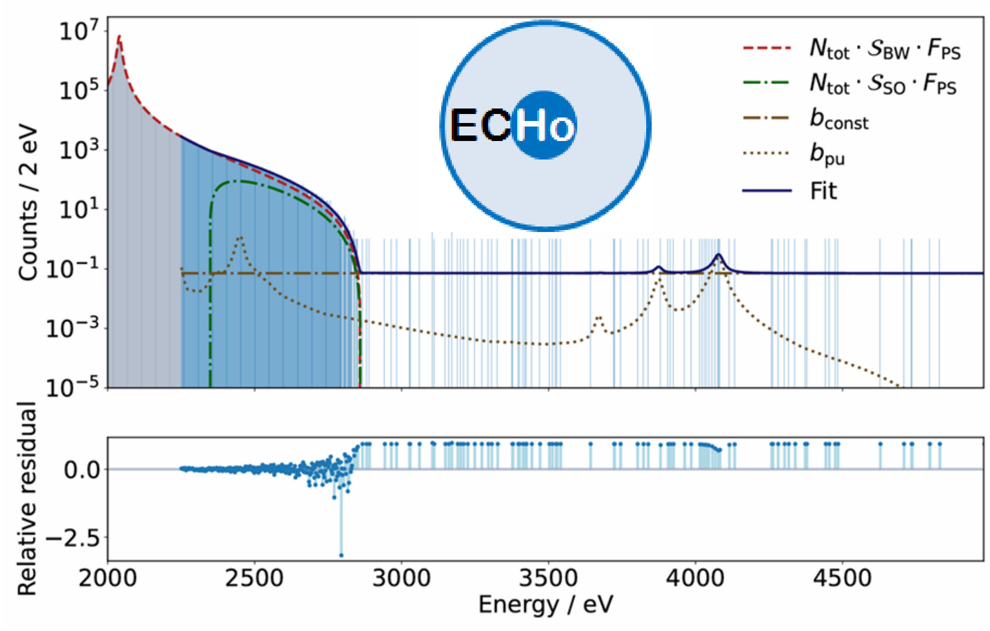


# $^{163}$Ho-based experiments – Proof of Concept Experiments

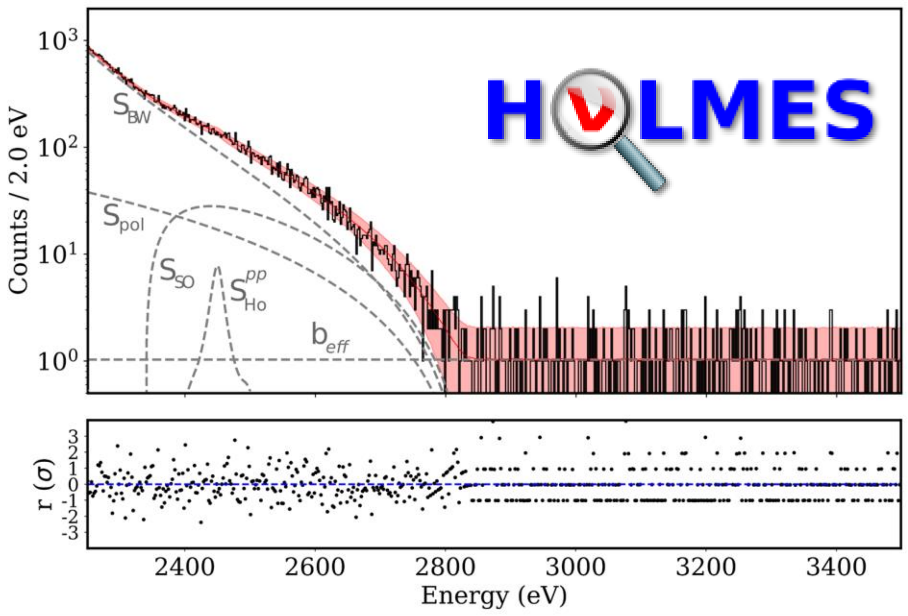
$$\frac{dN}{dE} = C \times [A(E) \times F_{PS}(Q,E)] \otimes g(E,\sigma) + b(E) \qquad F_{PS} = (Q-E)\sqrt{(Q-E)^2 - m_\beta^2}$$

- No analytical function is available to describe $A(E)$, the probability to create excited states with a given energy in the $^{163}$Dy atom
- In M. Braß et al., New J. Phys. 22 (2020) 093018 it is stated that $A(E)$ is very smooth
- Test of different functions has been performed

ECHo-1k



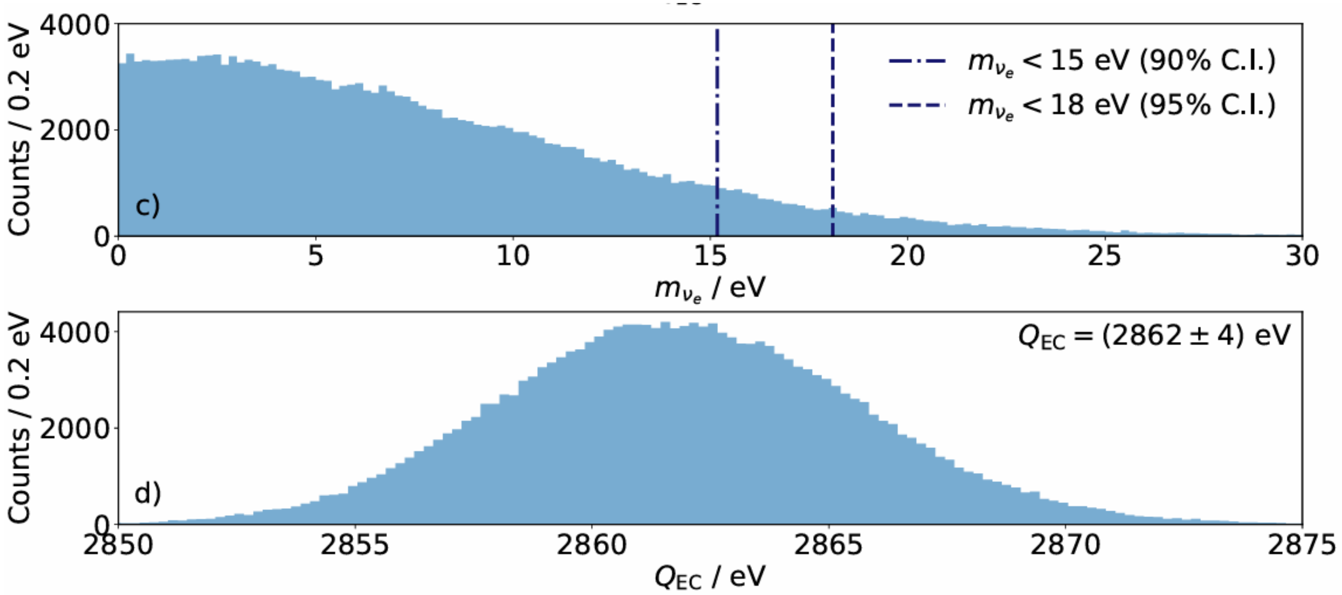

HOLMES



# $^{163}$Ho-based experiments – Proof of Concept Experiments

## ECHo-1k

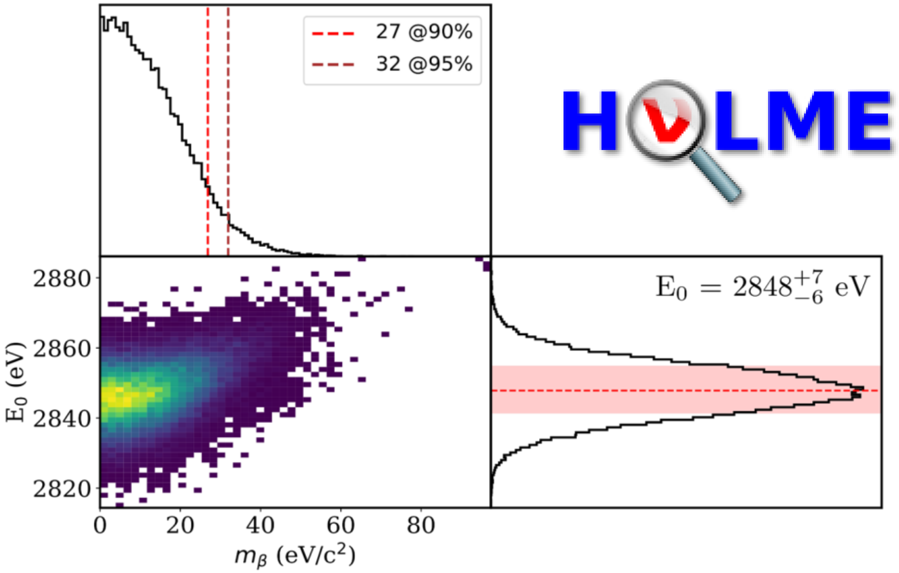
$Q$ = 2862(4) eV
$m_\nu$ < 15 eV/c$^2$ (90% C.I.)




F. Adam et al. (ECHo Coll.), arXiv:2509.03423v1 [hep-ex] submitted to PRL

## HOLMES

Q = $2848^{+7}_{-6}$ eV
$m_\nu$ < 27 eV/c$^2$ (90% C.L)




BK. Alpert et al. (HOLMES Coll.), arXiv:2503.19920v2 [hep-ex] accepted in PRL

# $^{163}$Ho-based experiments – Proof of Concept Experiments

what's next?

## ECHo-1k

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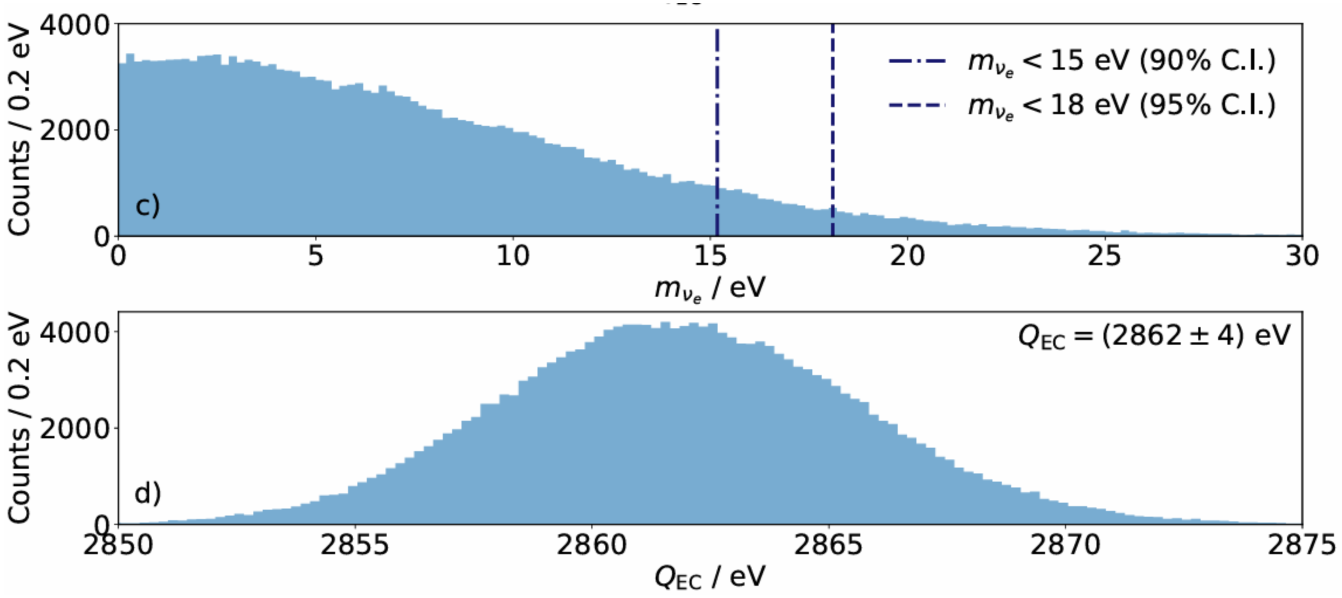
$m_\nu < 15$ eV/c$^2$ (90% C.I.)




F. Adam et al. (ECHo Coll.), arXiv:2509.03423v1 [hep-ex] submitted to PRL

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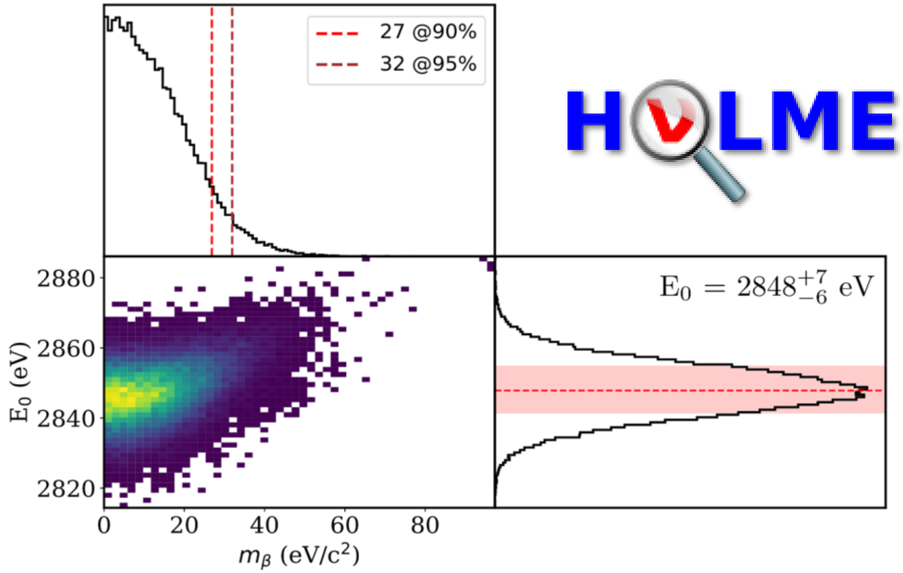



BK. Alpert et al. (HOLMES Coll.), arXiv:2503.19920v2 [hep-ex] accepted in PRL

# $^{163}$Ho-based experiments–Future Perspectives

Aim: reach sub-eV sensitivity in next upgrade

Minimal design:

20000 pixel → Multiplexed readout

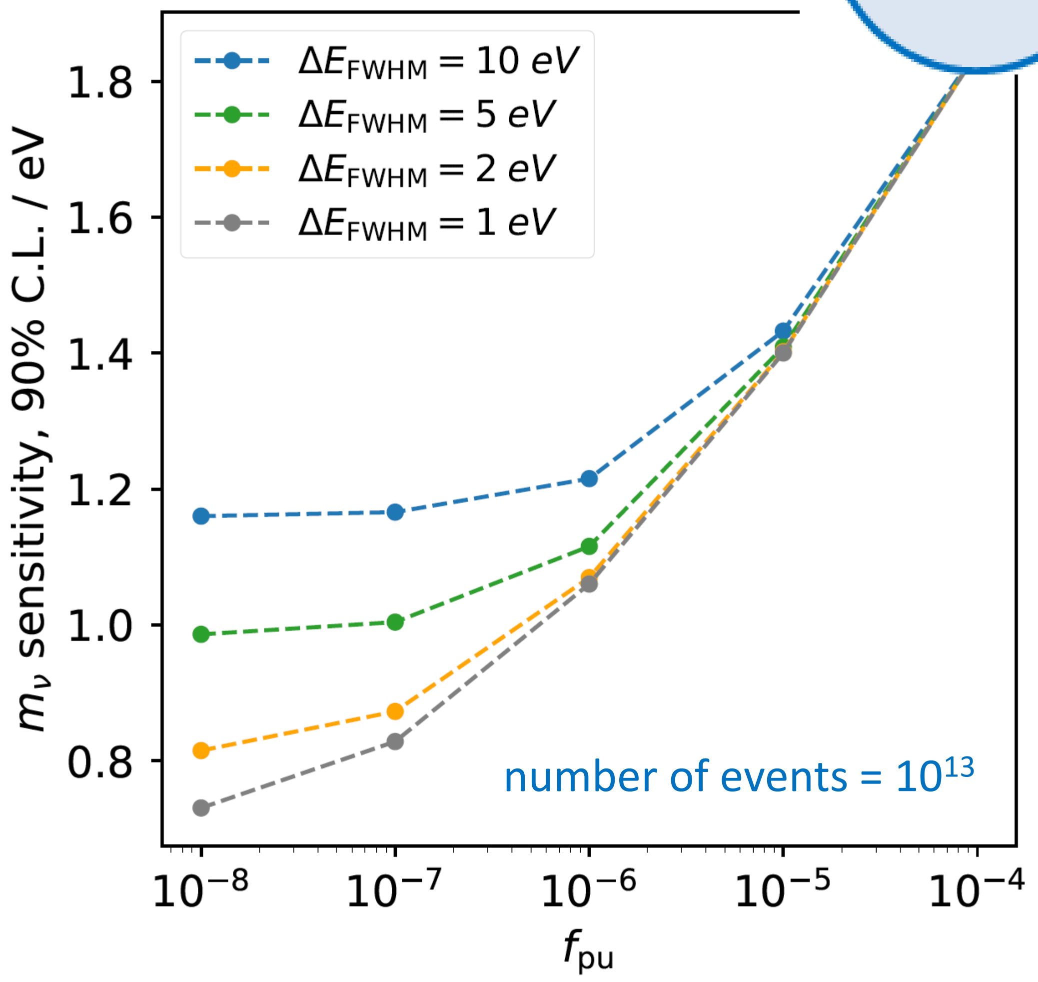
~10 Bq/pixel

$\Delta E_{FWHM}$ < 5 eV

$f_{pu} < 10^{-6}$

$b < 10^{-6}$ /eV/detector/day

Better model of $^{163}$Ho spectrum



# $^{163}$Ho-based experiments–Future Perspectives HOLMES ECHo

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20000 pixel → Multiplexed readout

~10 Bq/pixel

$\Delta E_{FWHM}$ < 5 eV

$f_{pu}$< $10^{-6}$

$b$ < $10^{-6}$ /eV/detector/day

- Fabrication arrays with $\Delta E_{FWHM}$ < 5 eV OK
- Production & purification of the $^{163}$Ho source OK
- Implantation ~10 Bq/pixel possible but not trivial
- still necessary work on background reduction
- Multiplexing big challenge:
  high energy resolution + large bandwidth

Better model of $^{163}$Ho spectrum

A. Faessler et al., *J. Phys. G* **42** (2015) 015108
R. G. H. Robertson, Phys. Rev. C **91**, 035504 (2015)
A. Faessler et al., Phys. Rev. C **91**, 064302 (2015)
A. Faessler and F. Simkovic, Phys. Rev. C **91**, 045505 (2015)
A. De Rujula and M. Lusignoli, JHEP 05 (2016) 015,
A. Faessler et al., Phys. Rev. C **95**, (2017) 045502
M. Braß et al., *Phys. Rev. C* **97** (2018) 054620
M. Braß and M. W. Haverkort, *New J. Phys.* **22** (2020) 093018

# $^{163}$Ho-based experiments–Future Perspectives

HOLMES ECHo

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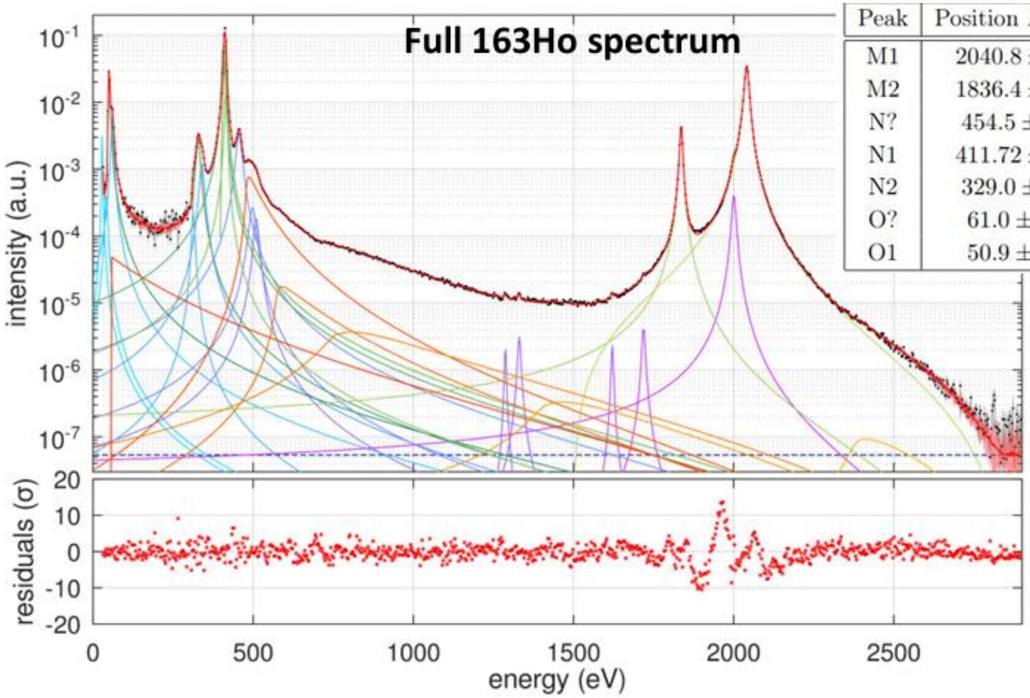



| Peak | Position $E_0$ [eV] |
|---|---|
| M1 | $2040.8 \pm 0.3$ |
| M2 | $1836.4 \pm 0.8$ |
| N? | $454.5 \pm 0.1$ |
| N1 | $411.72 \pm 0.1$ |
| N2 | $329.0 \pm 0.1$ |
| O? | $61.0 \pm 0.8$ |
| O1 | $50.9 \pm 0.8$ |

- Fabrication arrays with $\Delta E_{FWHM} < 5$ eV — OK
- Production & purification of the $^{163}$Ho source — OK
- Implantation ~10 Bq/pixel possible but not trivial
- still necessary work on background reduction
- Multiplexing big challenge:
  high energy resolution + large bandwidth
- Future high statistics spectra will help to constrain model

F. Ahrens et al., arXiv:2507.09240 [nucl-ex]

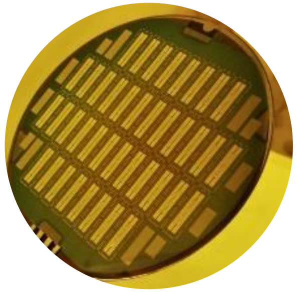
HOLMES

# $^{163}$Ho-based experiments – Next Steps

ECHo-LE (2026 - 2030)

Detector fabrication on going

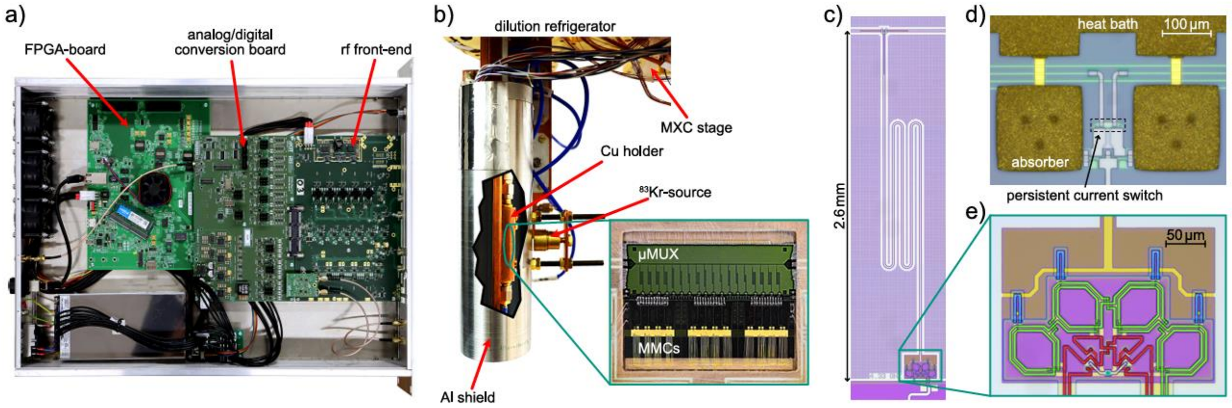
10  wafer with pixel optimization from ECHo-100k phase



Focus on microwave-SQUID multiplexing

400 channels per multiplexing line

Improve energy resolution from proof of concept results




M. Neidig et al., arXiv:2509.07671v1

HOLMES+

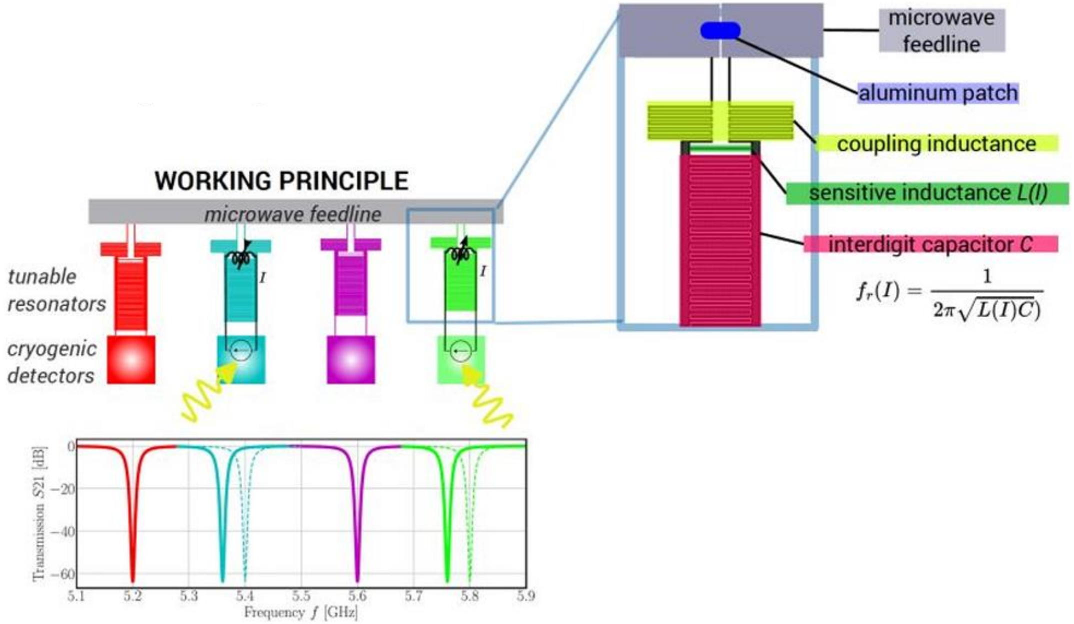
Improving the multiplexing

less cost x channel, higher multiplexing factor

Reducing the critical temperature of the TES

to reduce the effect of Ho specific heat

Kinetic Inductance Current Sensors (KICs)



# Conclusions

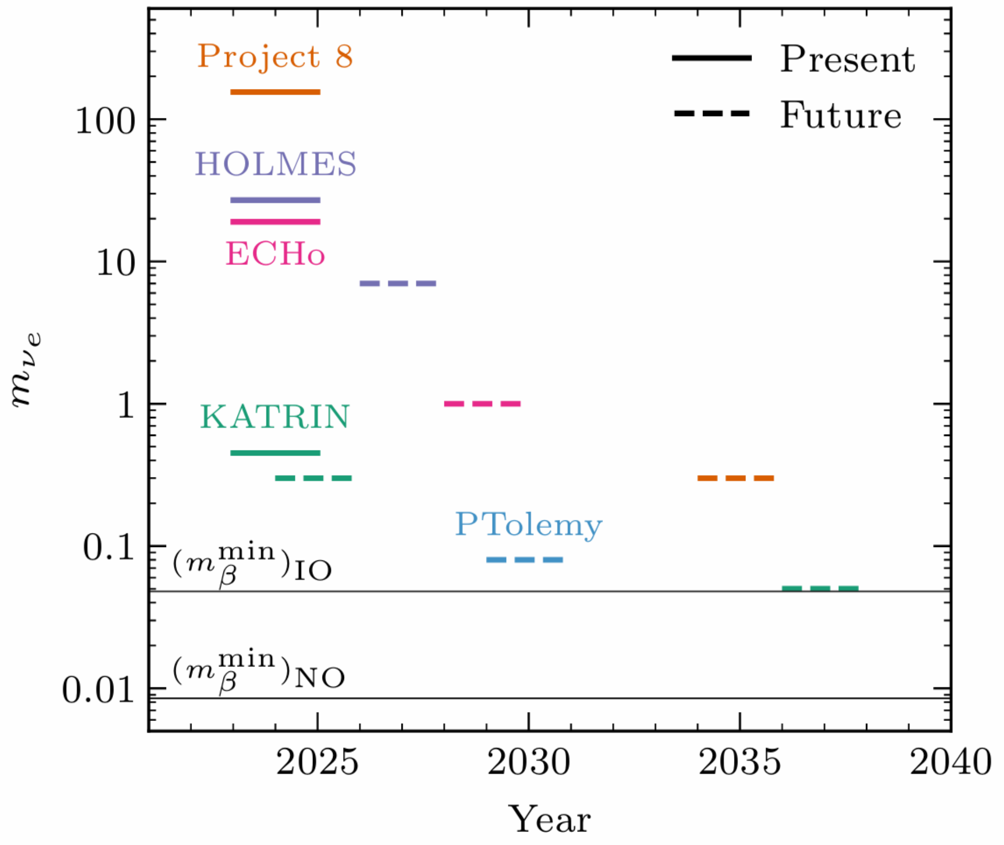
- The determination of the neutrino mass scale will guide beyond Standard Model theories and support our understanding of the Universe

- The study of low energy electron capture and beta spectra provides a less model dependent approach for neutrino mass determination

- $^{3}H$ is an ideal candidate for determining the neutrino mass scale. Different experimental concept have been developed and continuously improved

- $^{163}Ho$ is gaining importance thanks to the successful R&D in ECHo and HOLMES

- Challenging but realistic plans for the determination of the neutrino mass scale are going to be implemented




J. Formaggio, talk @European Startegy for Particle Physics, 23.–27. Juni 2025

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Angelo Nucciotti and Matteo Borghesi for the HOLMES Collaboration
Joe Formaggio and Juliana Stachurska for Project 8
Ruben Saakyan for QTNM
Marcello Messina for PTOLEMY
KATRIN Collaboration and ECHo Collaboration

*Thank you!*