Neutrino Properties

Beta Decay, Electron Capture & Neutrinoless Double Beta Decay

Joseph Formaggio
Massachusetts Institute of Technology

(On behalf of the Neutrinos and Cosmic Messengers Working Group)

Fundamental Questions in Neutrino Physics...

What is the mass scale of neutrinos?

What is the ordering of masses?

Are neutrinos their own anti-particles?

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What is the ordering of masses?

How do neutrinos attain mass?

Do we understand the evolution of our universe?

Is baryon-lepton asymmetry violated?

Fundamental Questions in Neutrino Physics…

Many of these questions can be addressed with neutrino mass probes.

We explore two here:

Direct neutrino mass measurements (β-decay & EC)

Neutrinoless double beta decay ($0\nu\beta\beta$)

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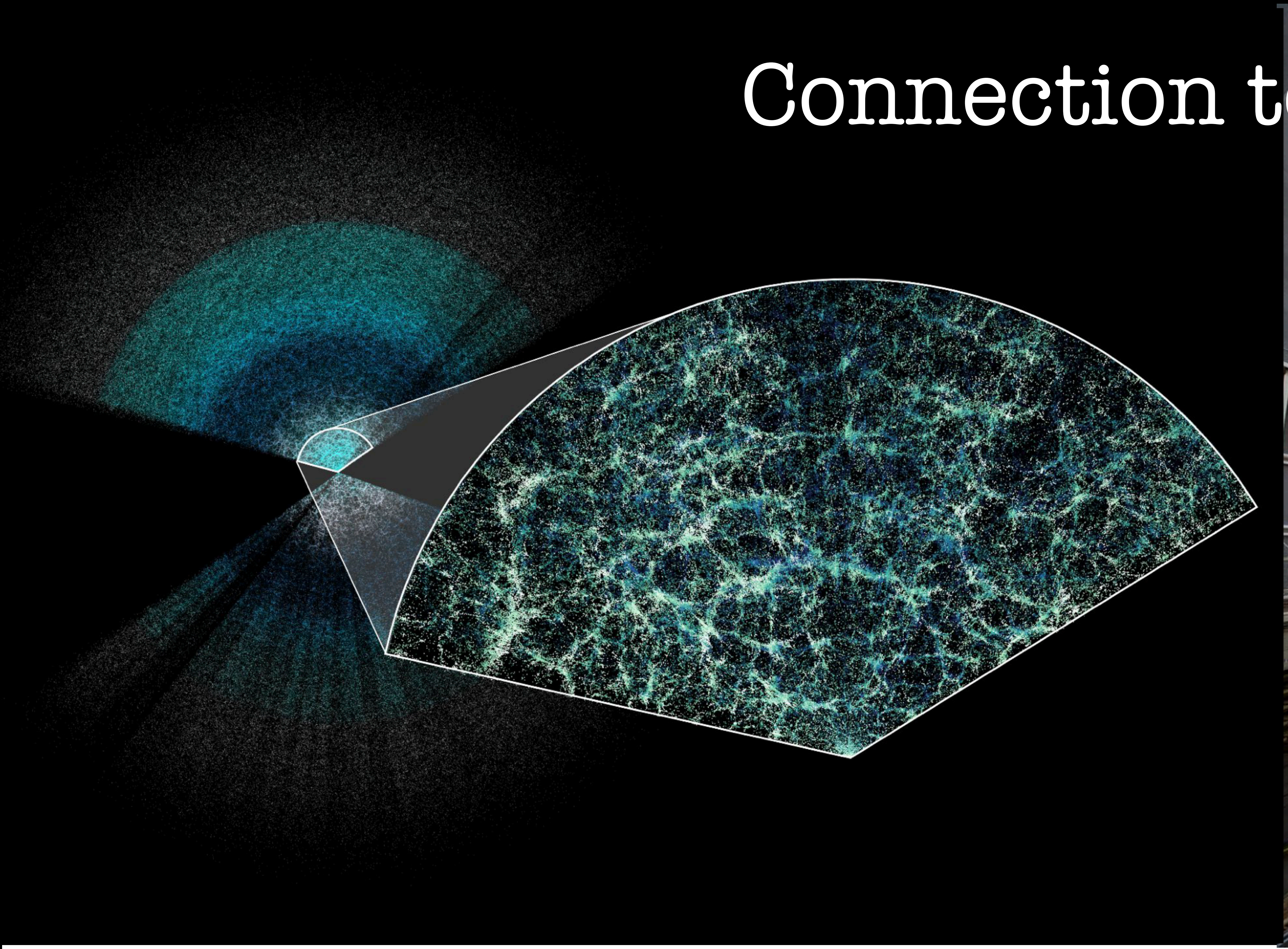
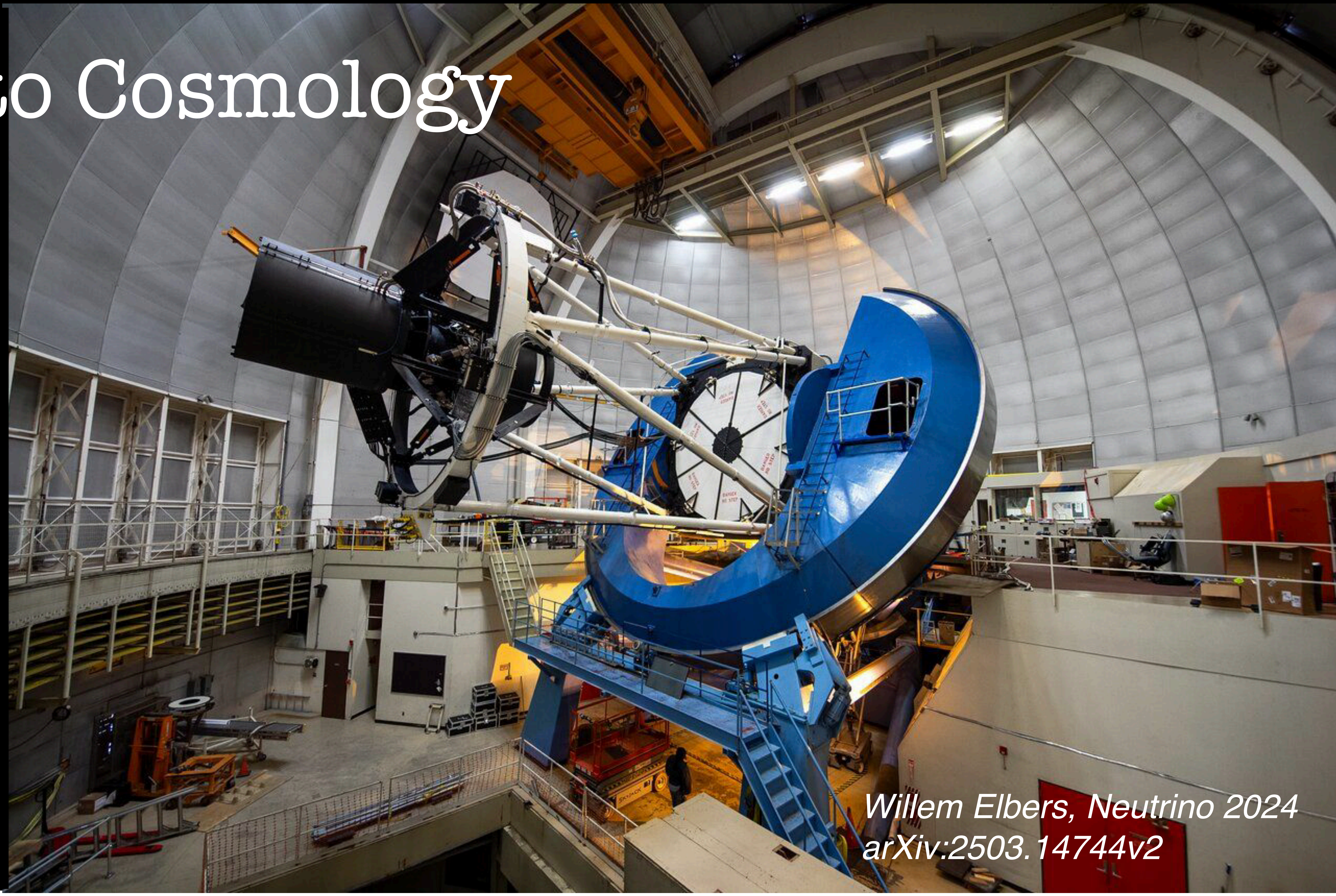
Connection to Cosmology





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- Precision measurements of Baryon Acoustic Oscillations (BAO) and CMB.
- ΛCDM with physical neutrino masses is in tension with BAO+CMB at the level 3-4 σ.

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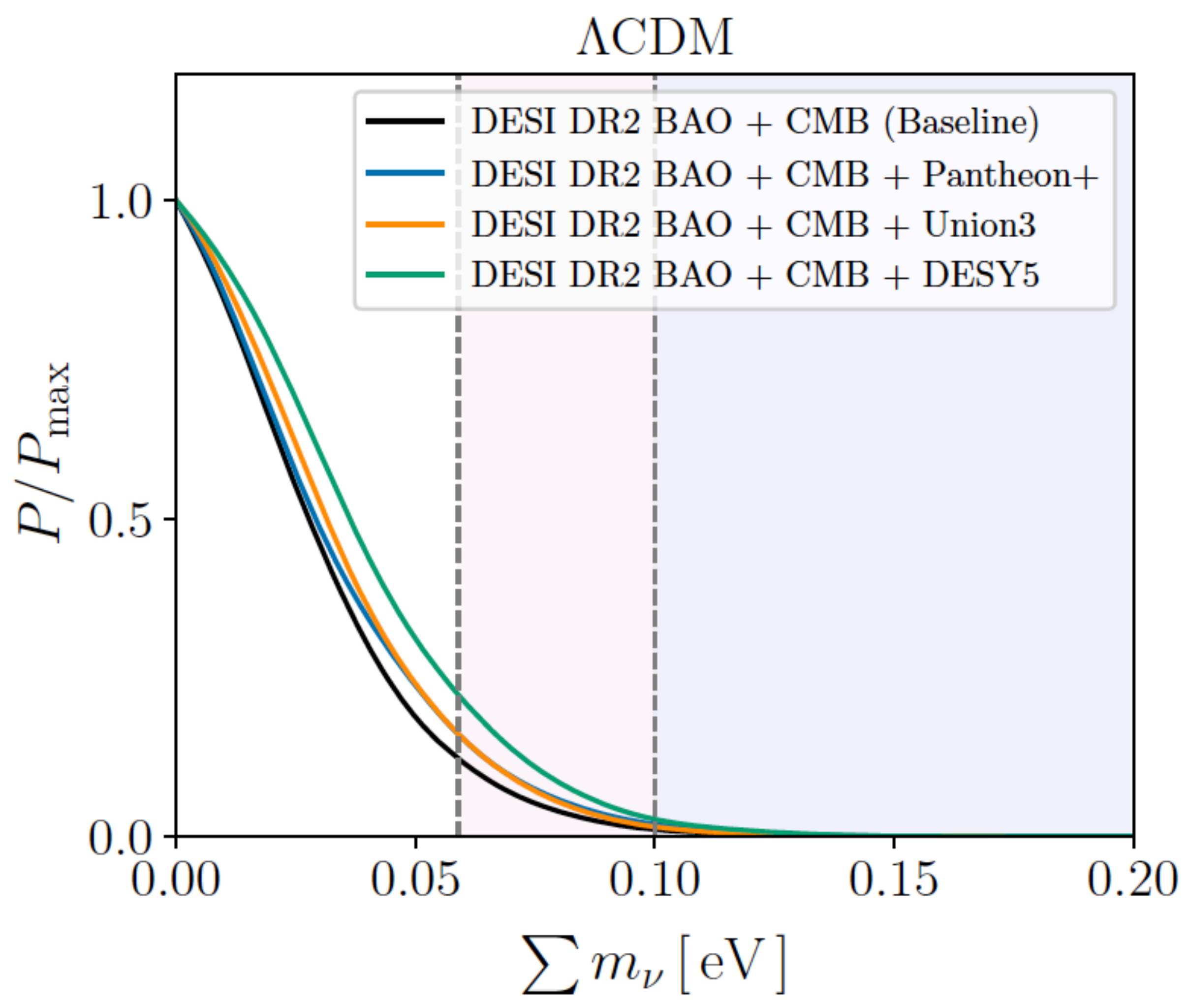
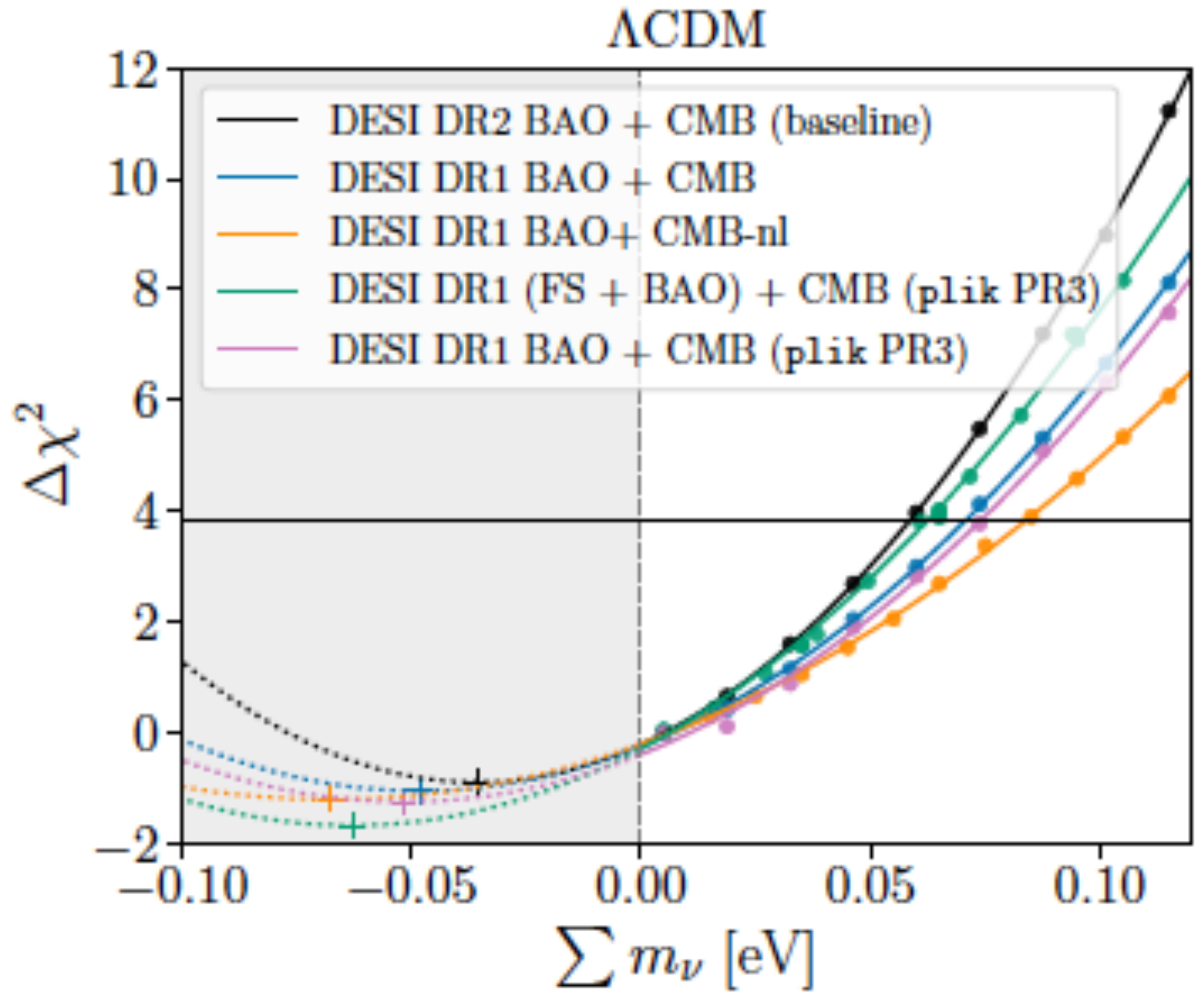


6σ



Serious tension with neutrino oscillation results.

Willem Elbers, Neutrino 2024
arXiv:2503.14744v2

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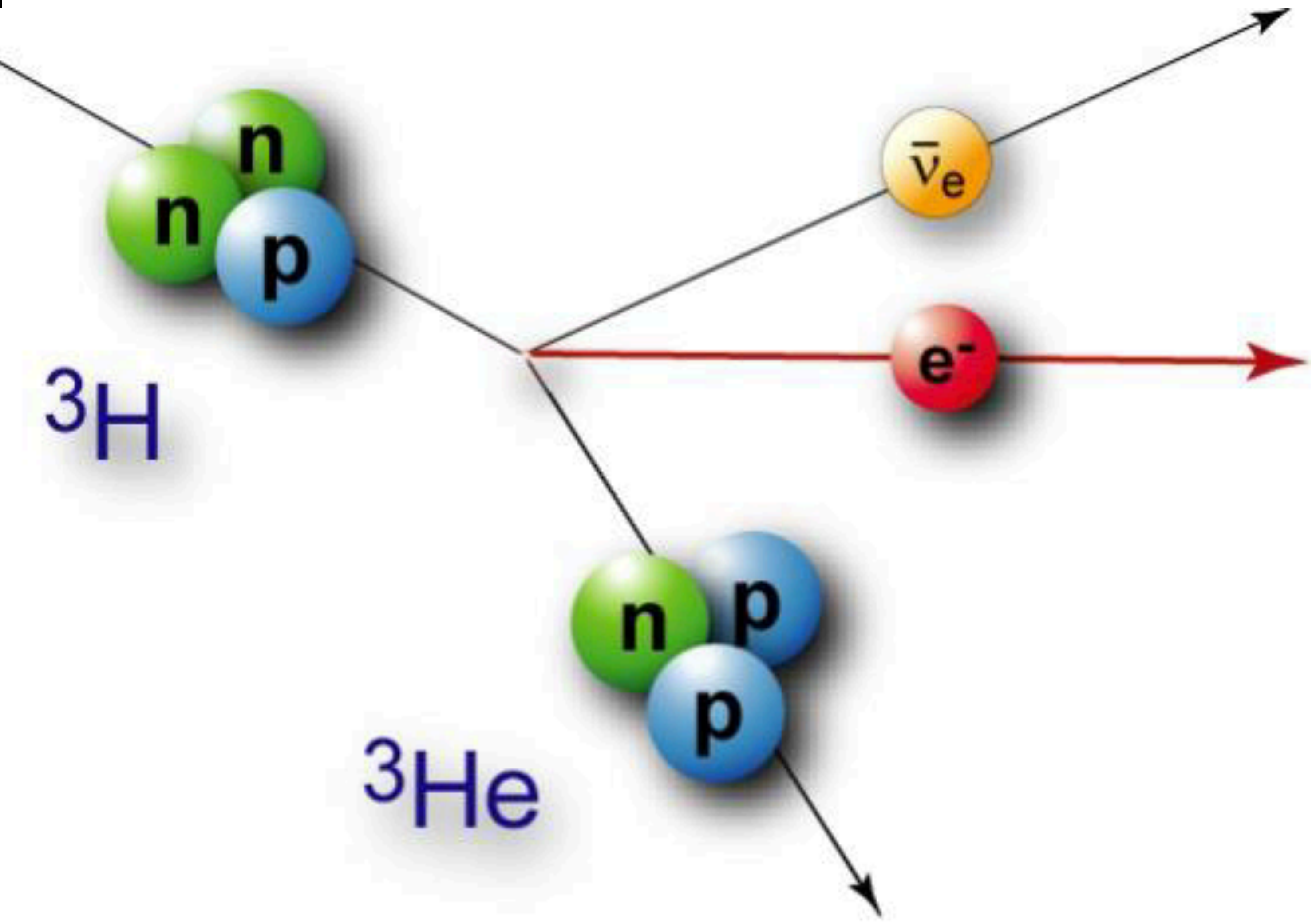
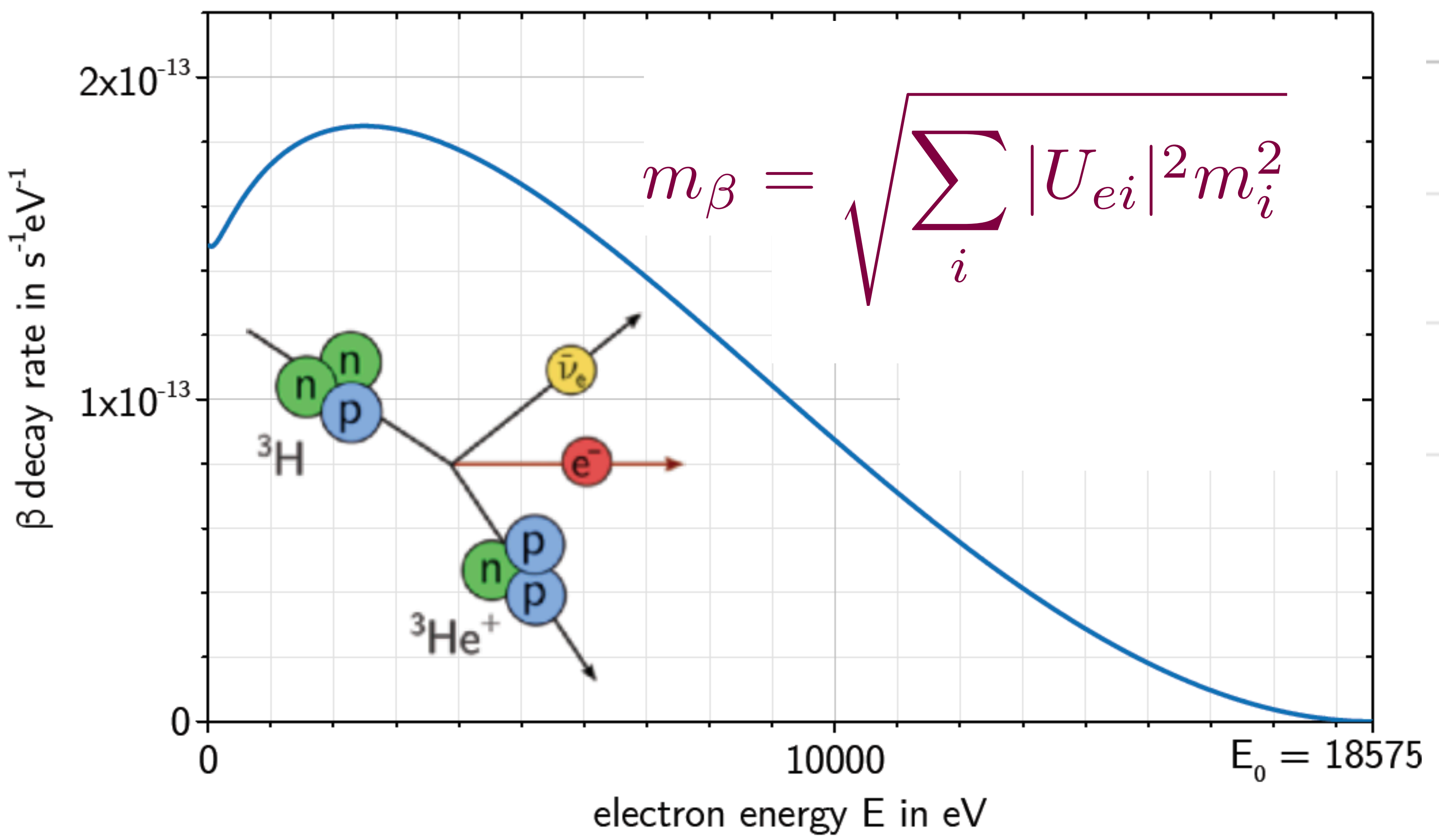
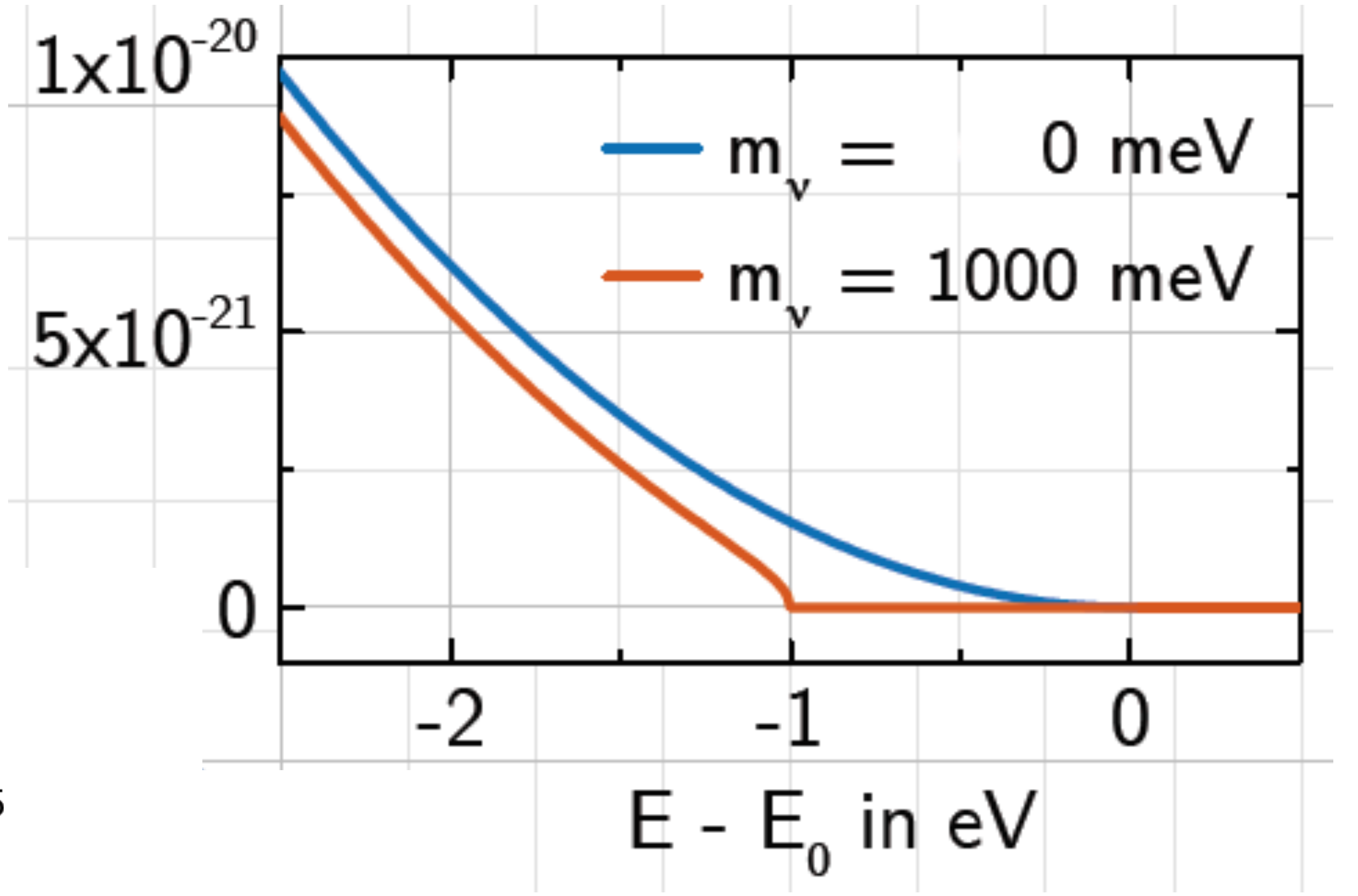
The Basic Idea...



Start with a radioactive isotope
(e.g., ^3H or ^{163}Ho)



Measure the decay
(beta electron or progeny energy spectrum)



Focus on endpoint of spectrum
(Phase space sensitive to m_β)

Key Performance Parameters for Neutrino Mass Sensitivity...

- High energy resolution near endpoint energy
- High activity (m_β scales as $N^{1/4}$), while maintaining low background levels.
- Well-understood source and detector response systematics

High Magnetic Field (Bs)

Low Field B_A

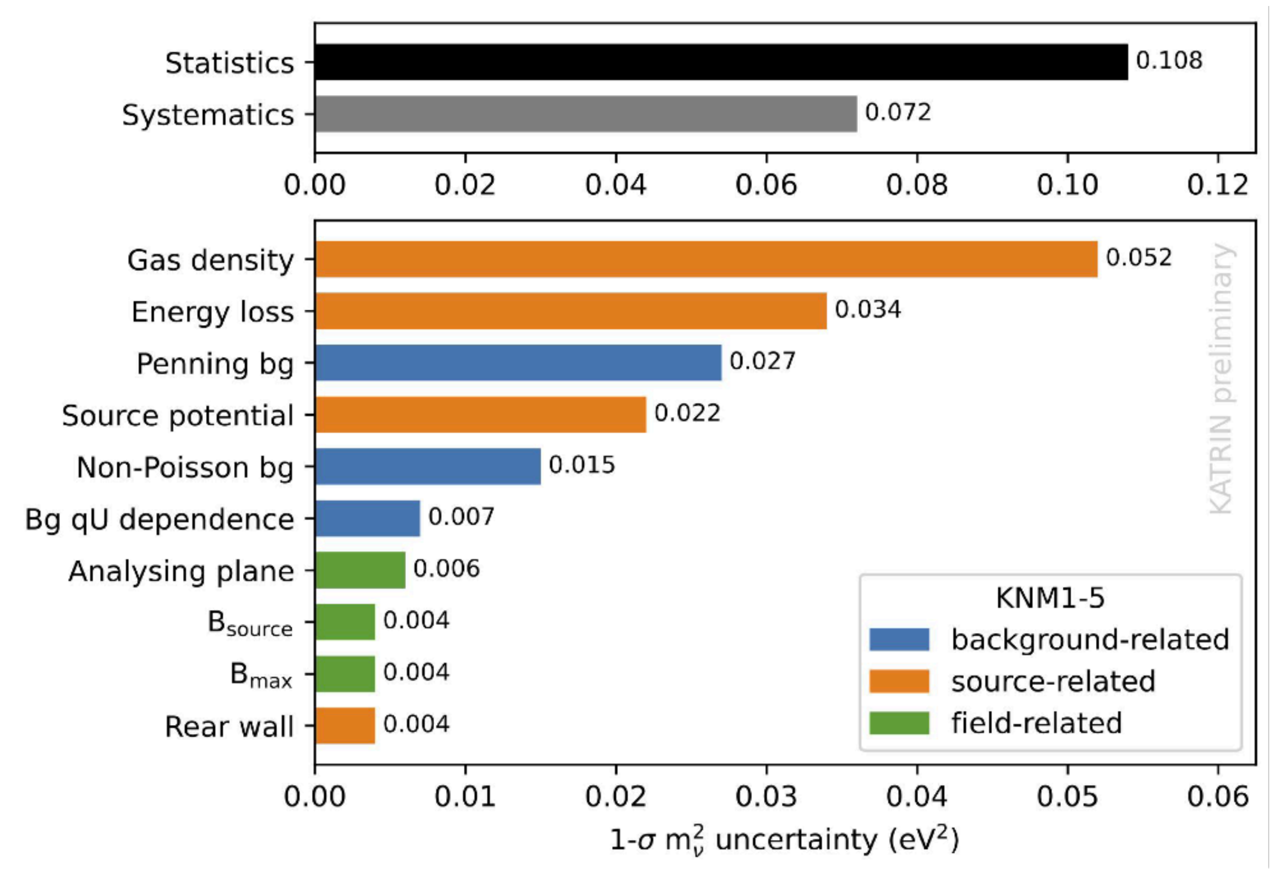
High Magnetic Field (Bs)

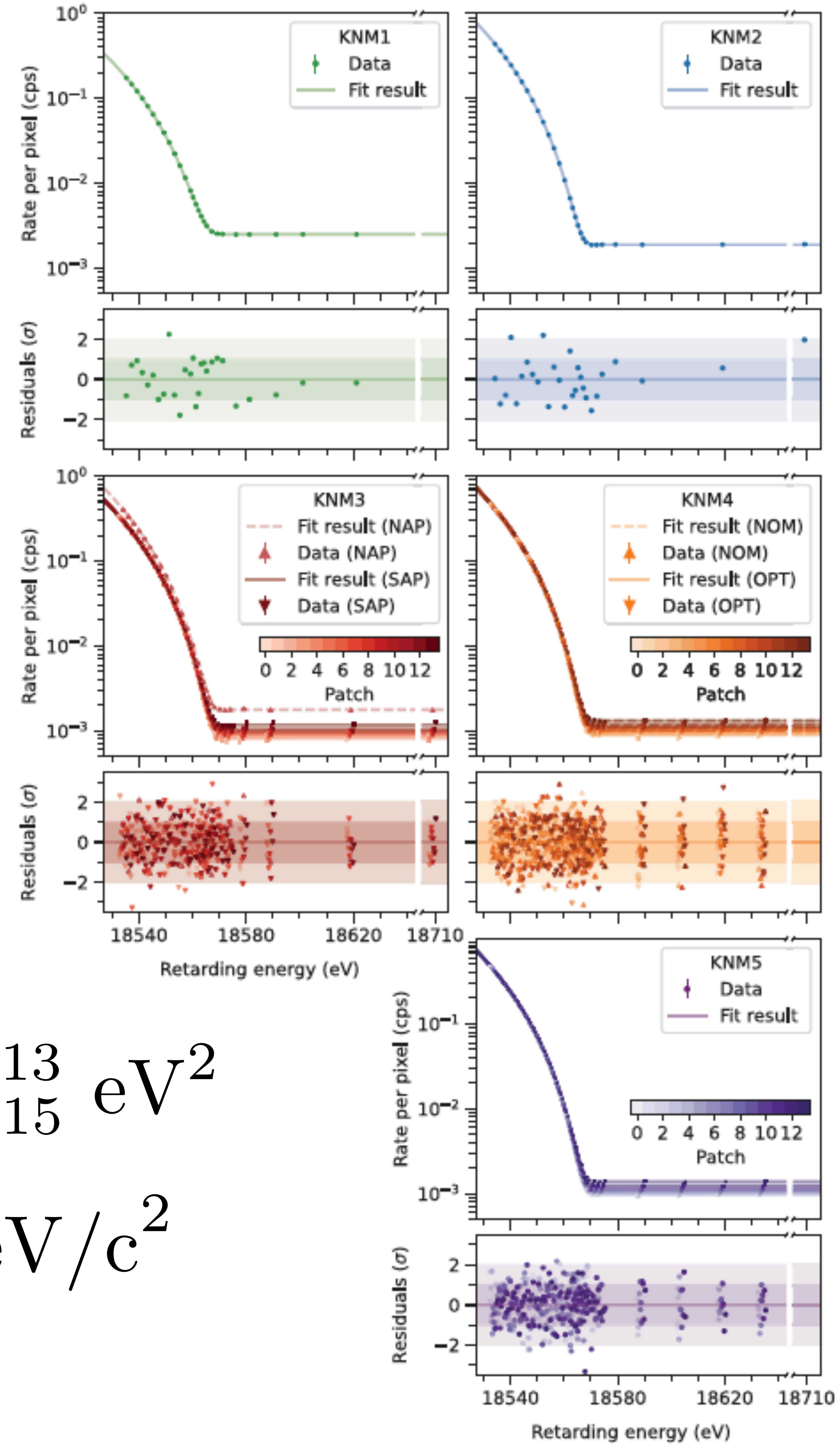
Current state of the art: The KATRIN Neutrino experiment

Technique: Magnetic Adiabatic Collimation with Electrostatic Filtering (MAC-E) with T_2.

Running since 2019. The data collected provides constraints on neutrino mass scale, and Beyond Standard Model physics.

KATRIN Collaboration *et al.*, *Science* 388, 180–185 (2025)





$$m_\beta^2 = -0.14^{+0.13}_{-0.15}\ \mathrm{eV}^2$$

$$m_\beta \leq 450\ \mathrm{meV/c}^2$$

KATRIN

- **KATRIN** releases results from combined KNM1-5 data (about 20% of the final projected dataset).
- Strong control of systematics (with gas density and energy loss as the largest components). Reduction of impact from molecular final states.
- New limit at $\mathbf{m_\beta \leq 450\ meV/c^2}$ (90% C.L.)
- Data collection is expected to conclude by 2025 (approximately 1000 days). Well-poised to hit a final sensitivity of **300 meV/c²**.
- Ultimately limited by molecular source and backgrounds.

How do we access the next scale of neutrino masses?

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General Principles…

- High energy resolution
- Background-free operation
- Better target mass scaling (m_β scales as $N^{1/4}$)
- Well-understood, highly resolved source

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Current Approaches...

Holmium-Based
(HOLMES, ECHO)

Tritium-Based
(Project 8, QTNM, KATRIN++, PTOLEMY)

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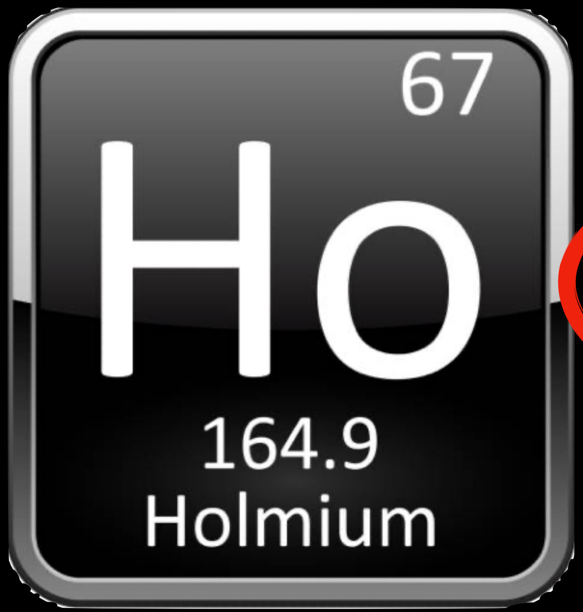

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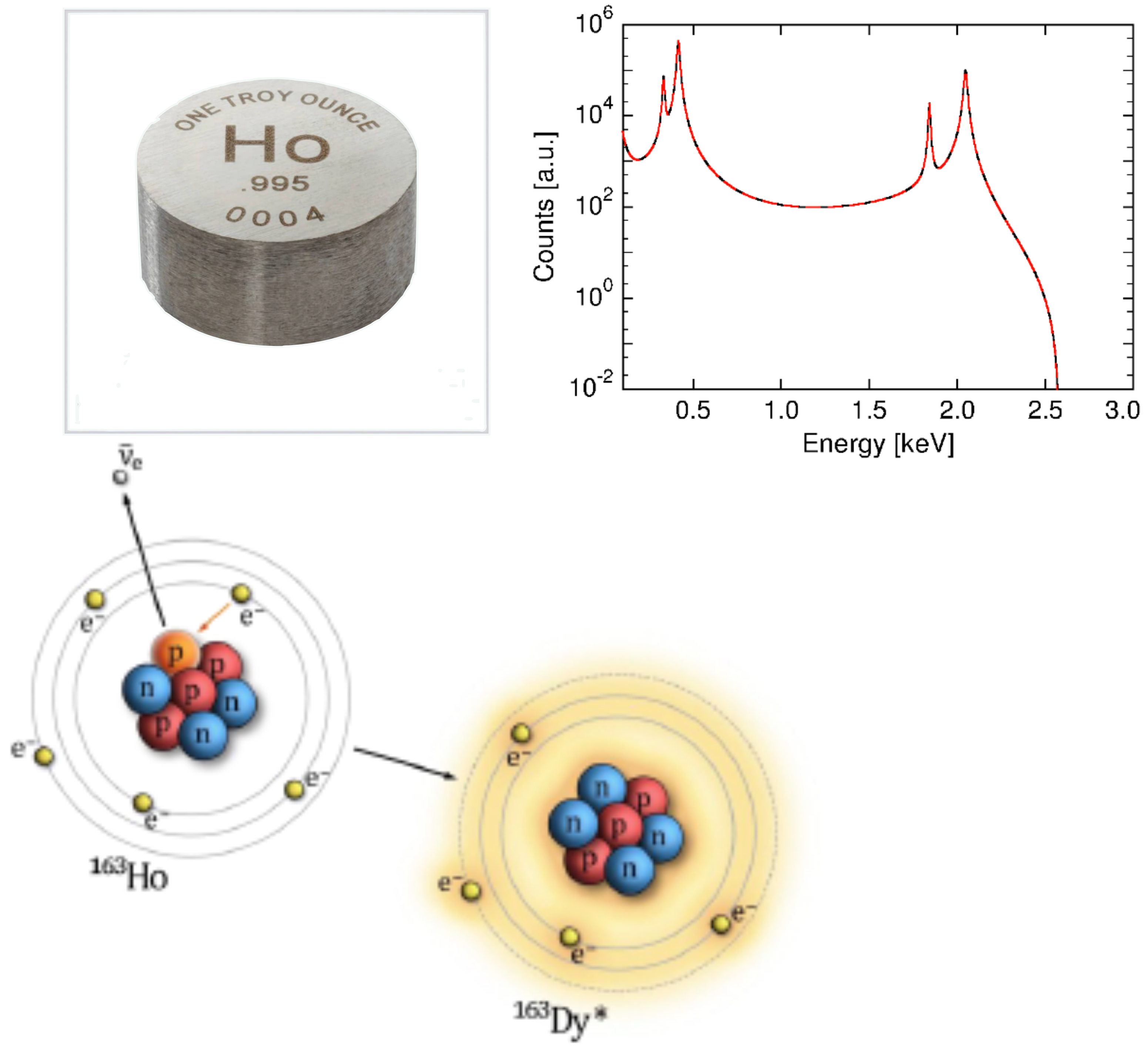
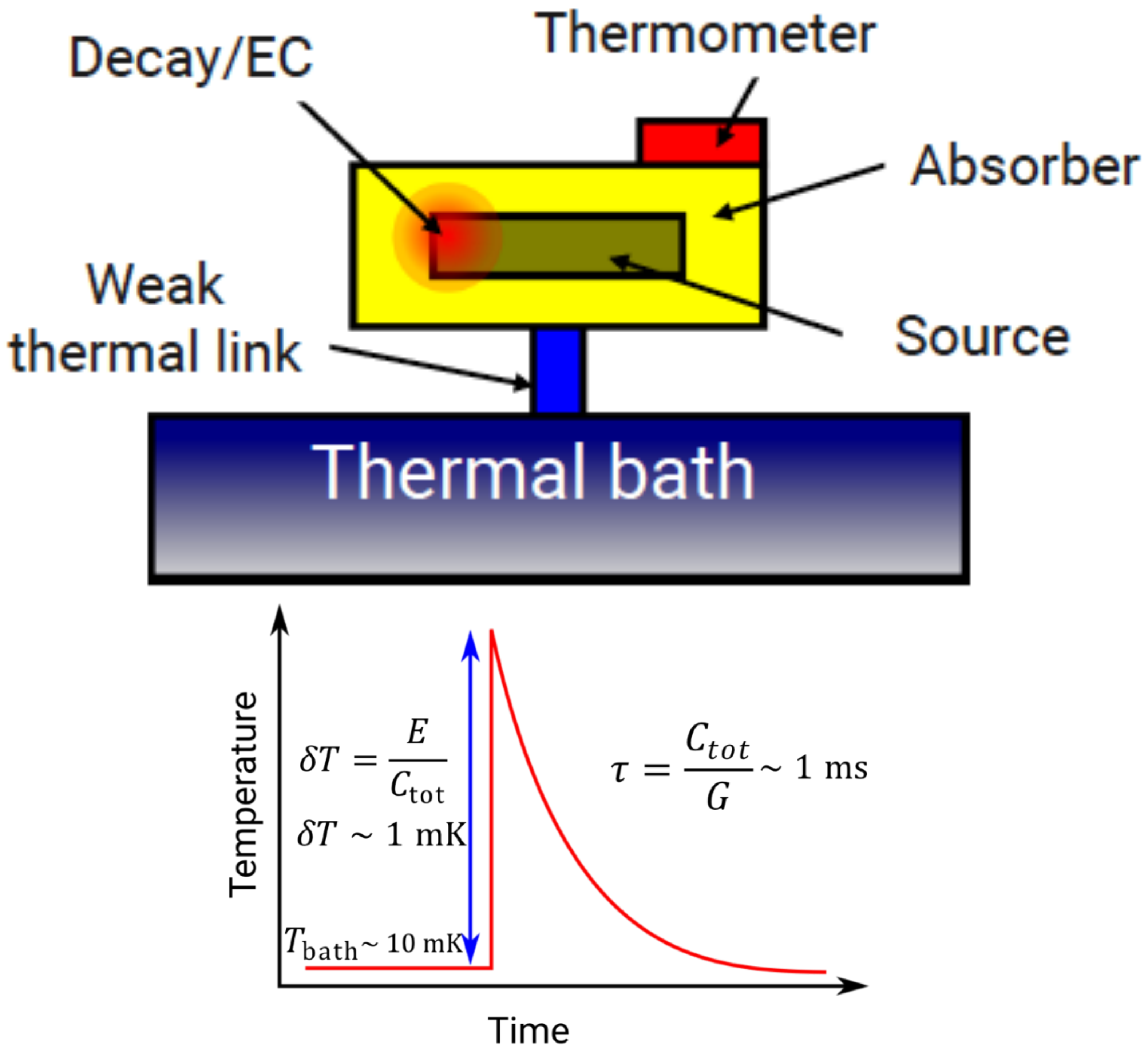
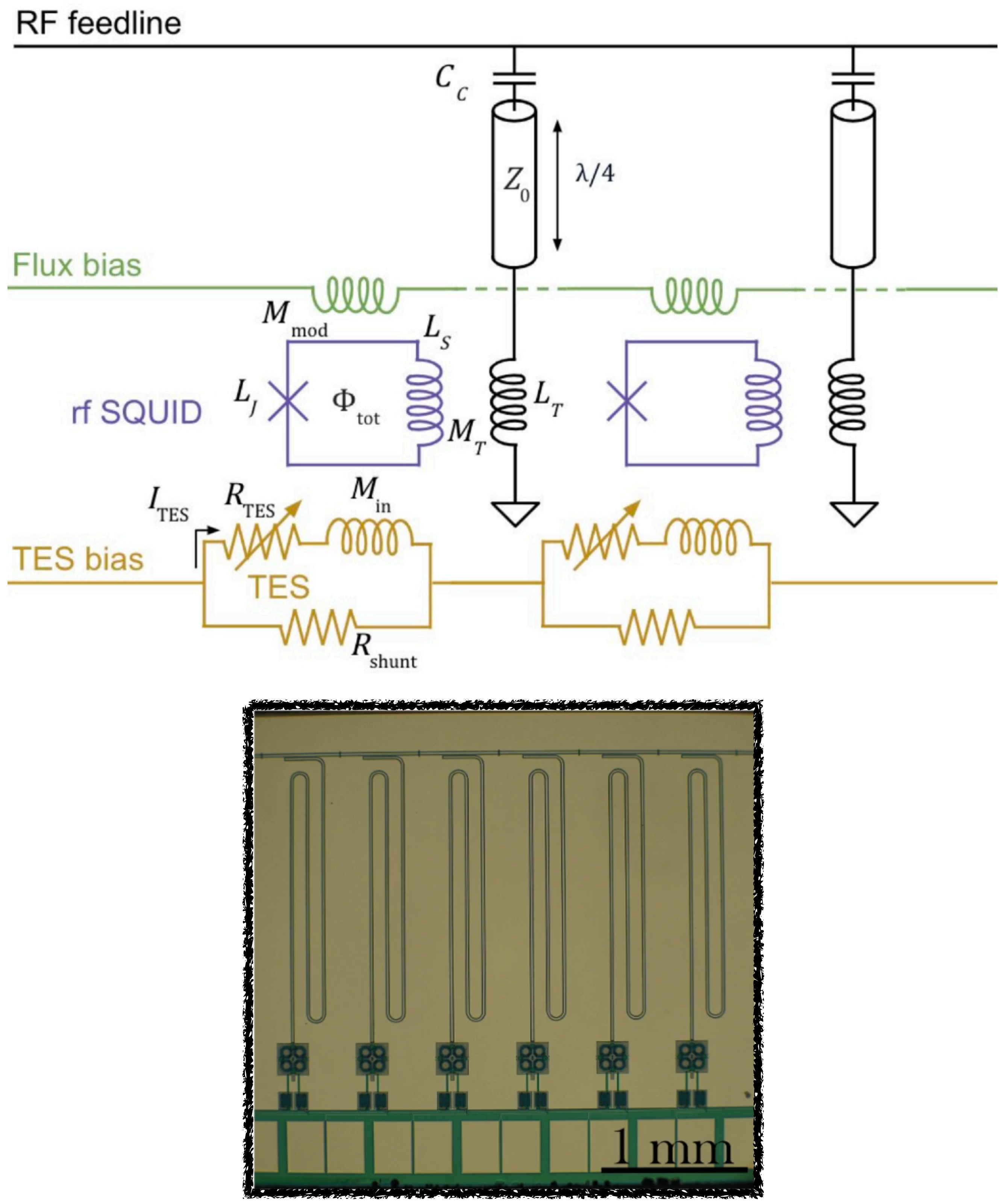
Electron Capture



μ-calometer

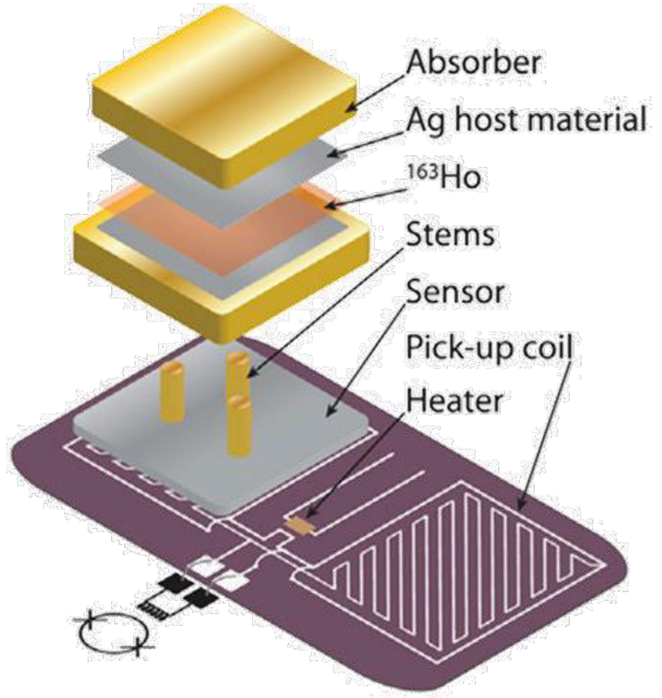


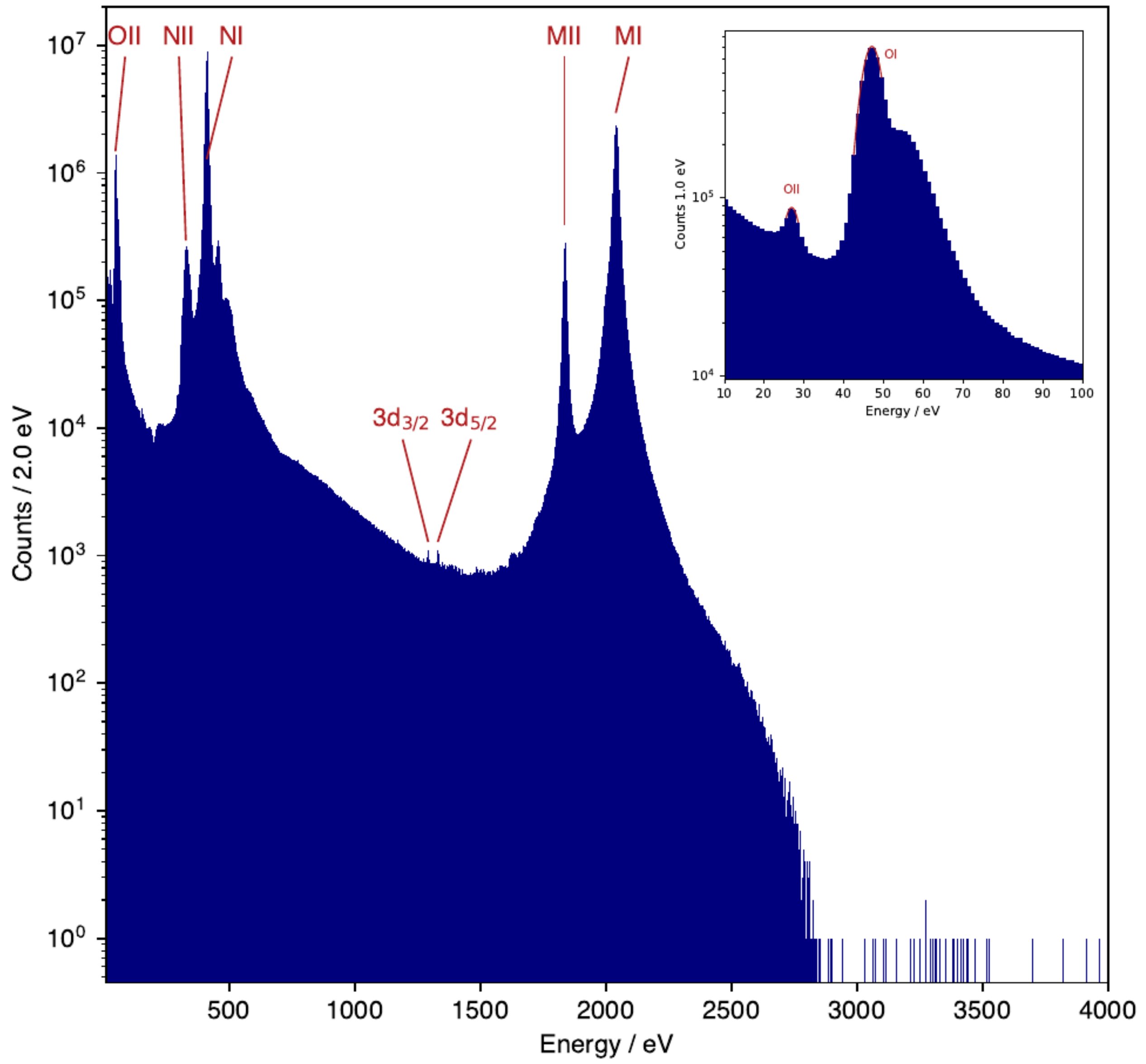
Multiplexing



Holmium efforts focus on multiplexed cryogenic bolometers to measure the energy near the endpoint.

Main experimental efforts: ECHo & HOLMES (each with limits)





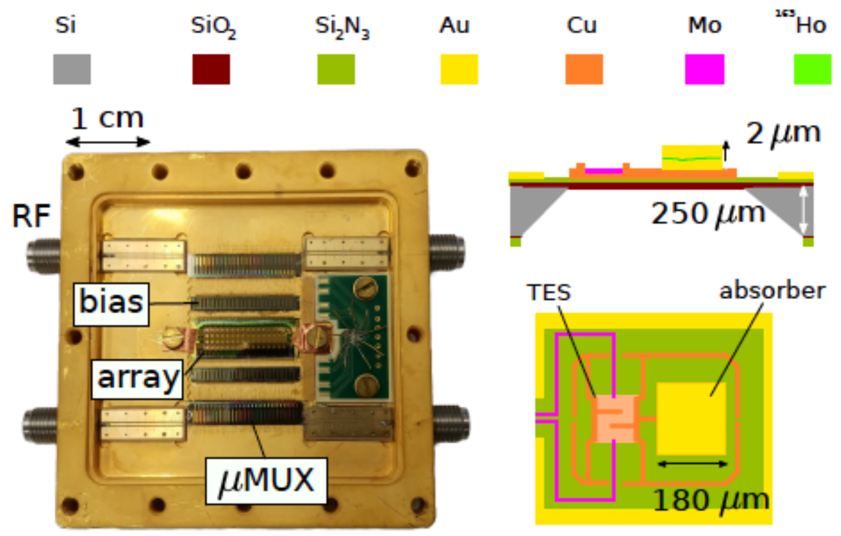
ECHO & HOLMES

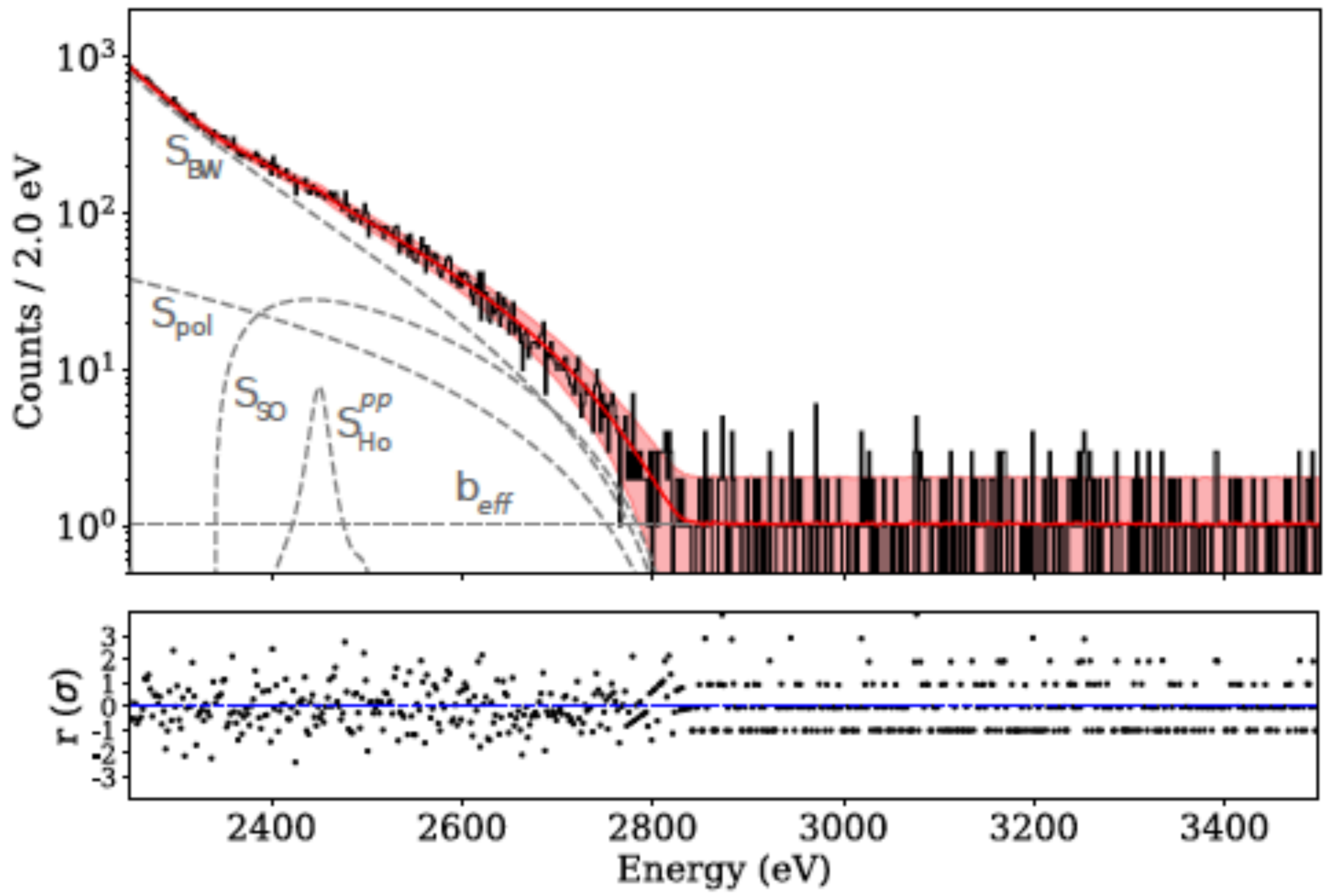
^{163}Ho implantation on multiplexed detectors

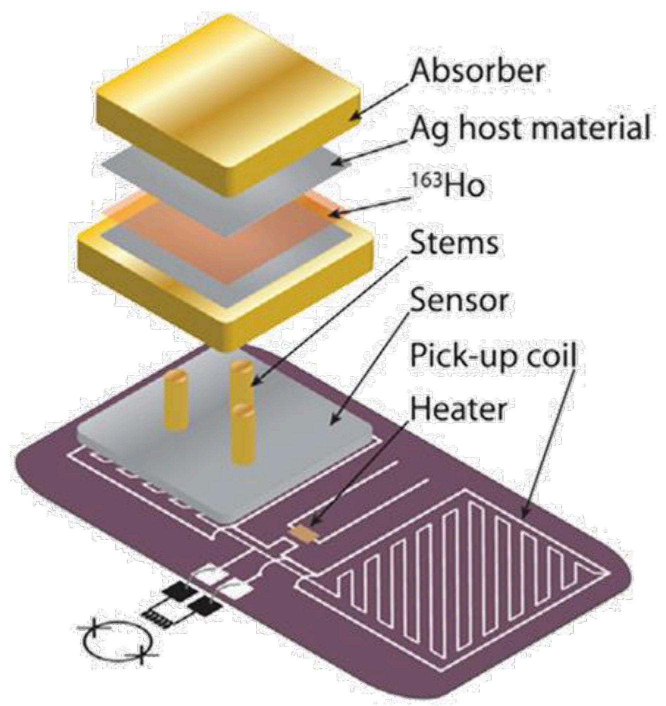
Use TES or MMC heat sensors

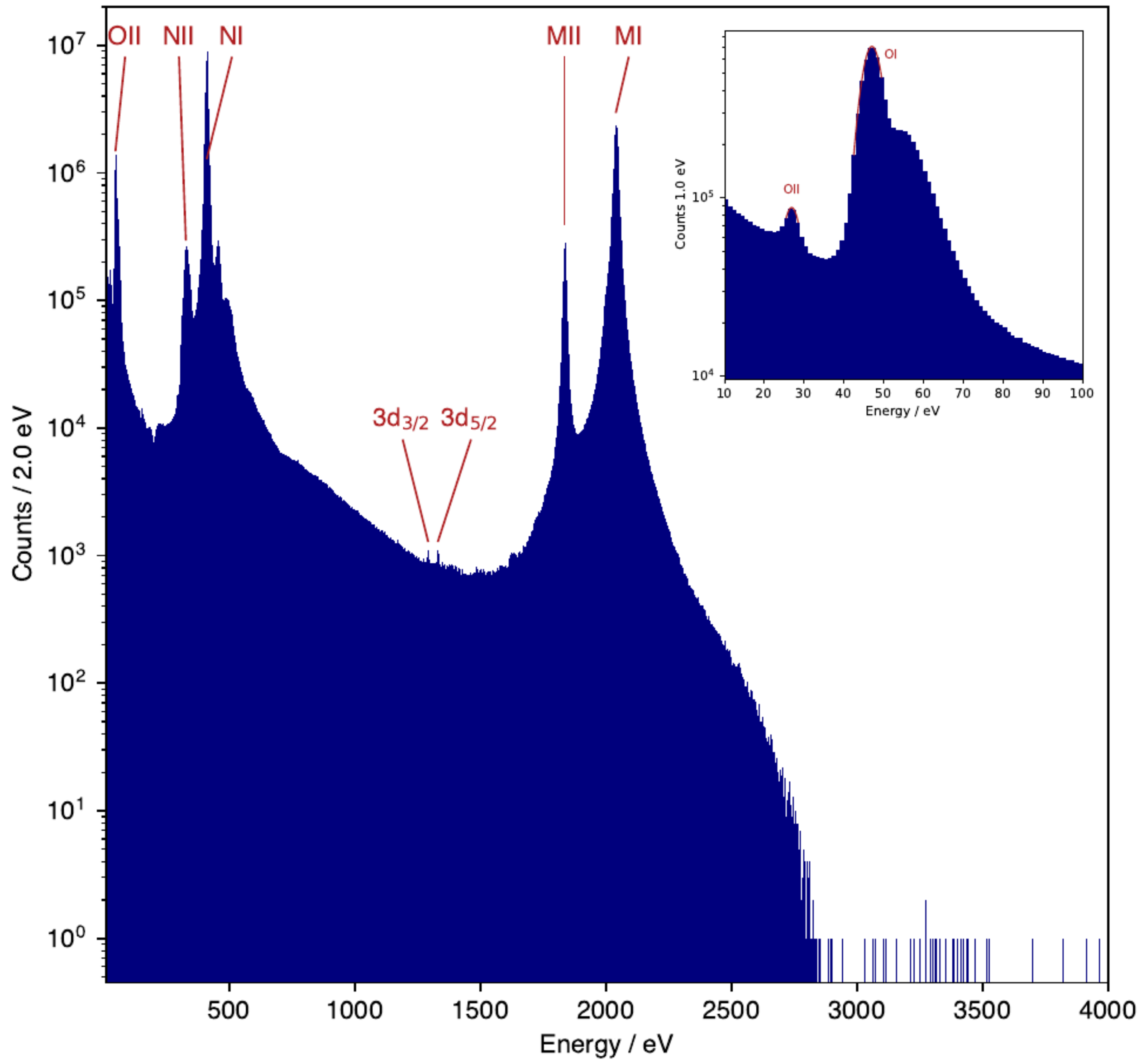
Recent mass limits released

ECHO	*HOLMES*
m_β < 19 eV @ 90% C.L. *Q = (2862.1 ± 1.7) eV*	*m_β < 28 eV @ 90% C.L.* *Q = 2848^{+11}_{-6} eV*









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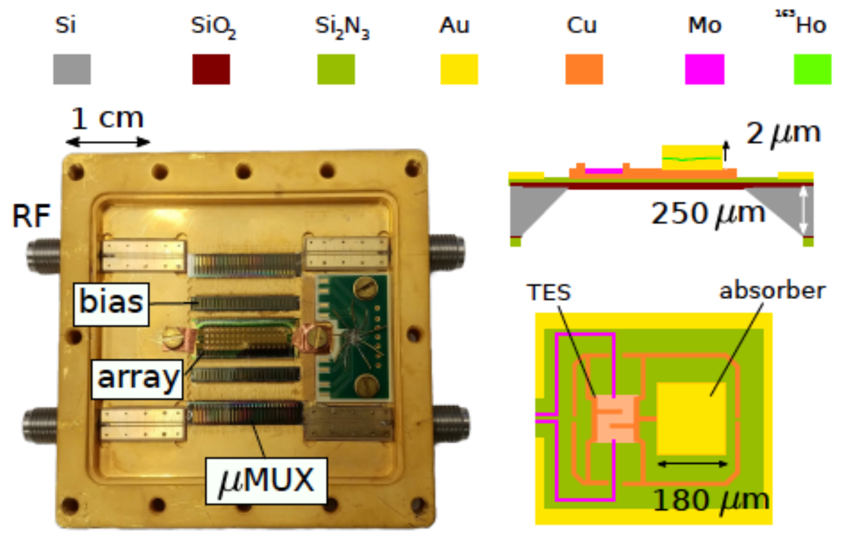
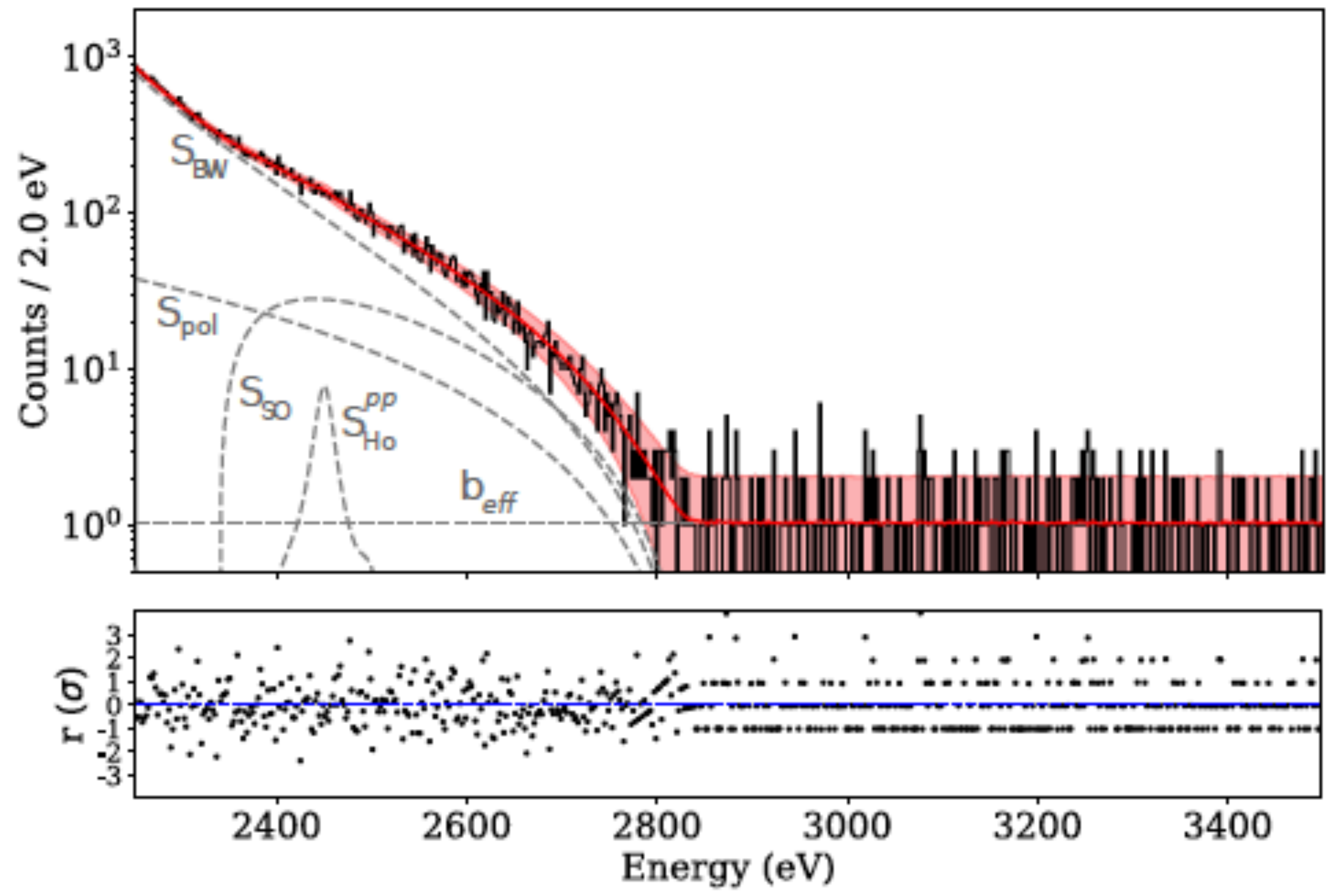


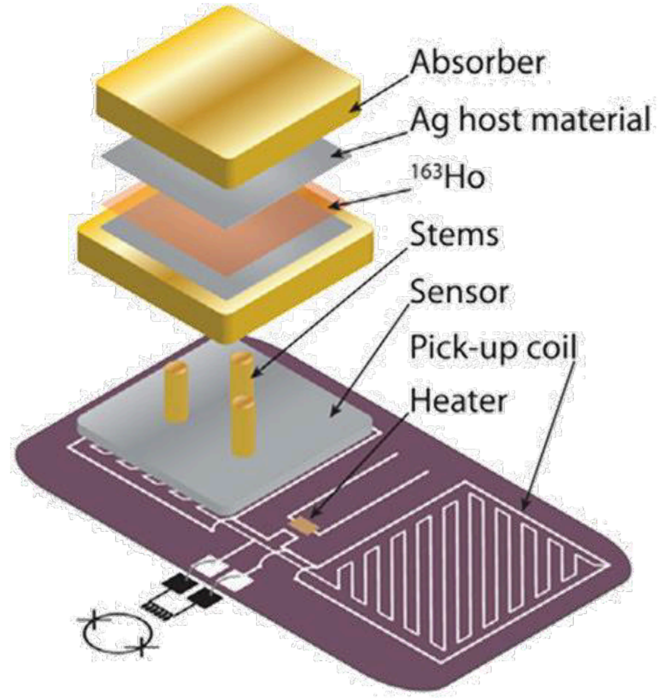


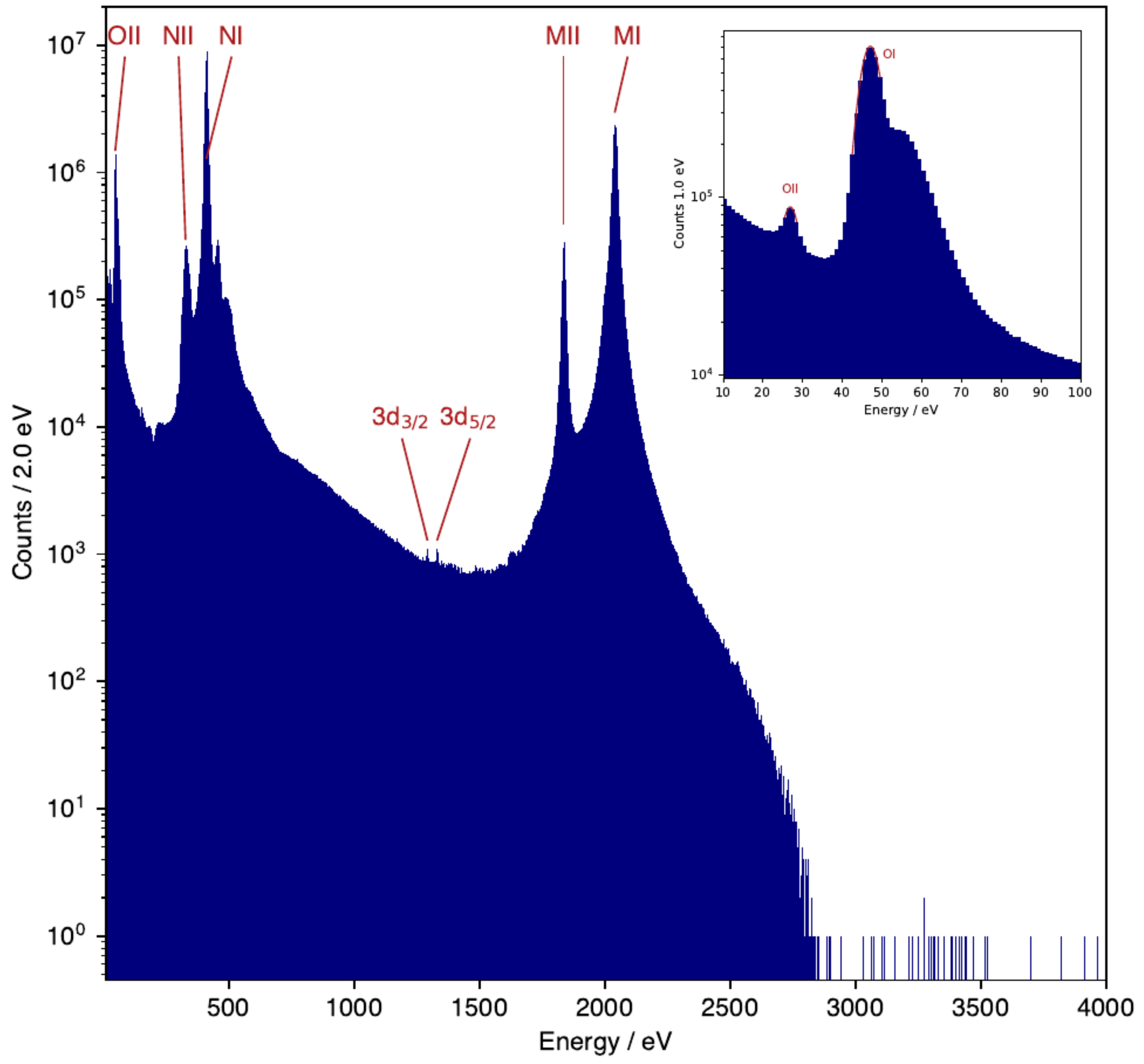
Highlights:

Experimental limits (m_β <19 and 27 eV) from both collaborations.

Self-calibrating peaks.

High energy resolution and linearity.





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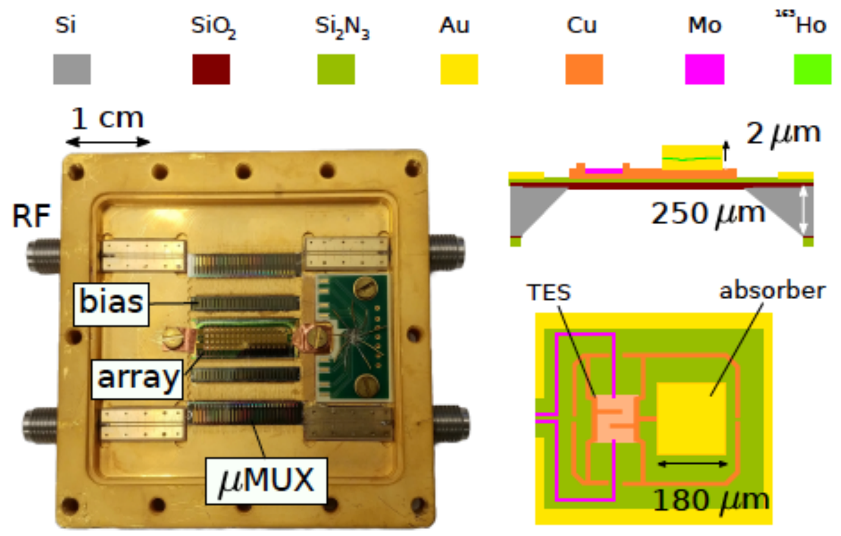

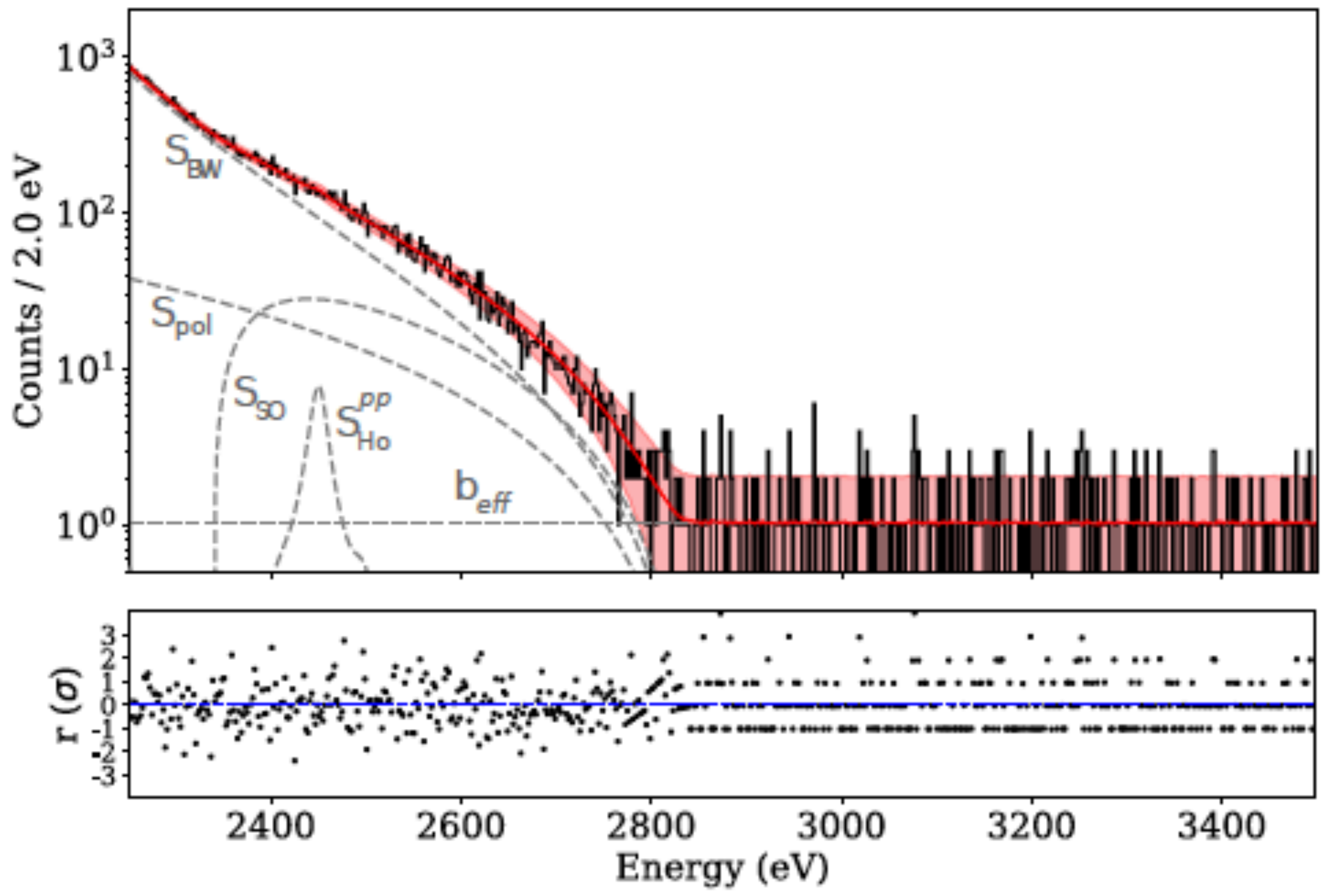

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Challenges:

Scalability: Need >10^6 detectors with high activity (w/o pileup)

Source: No ab initio electron capture spectrum prediction from ^{163}Ho.

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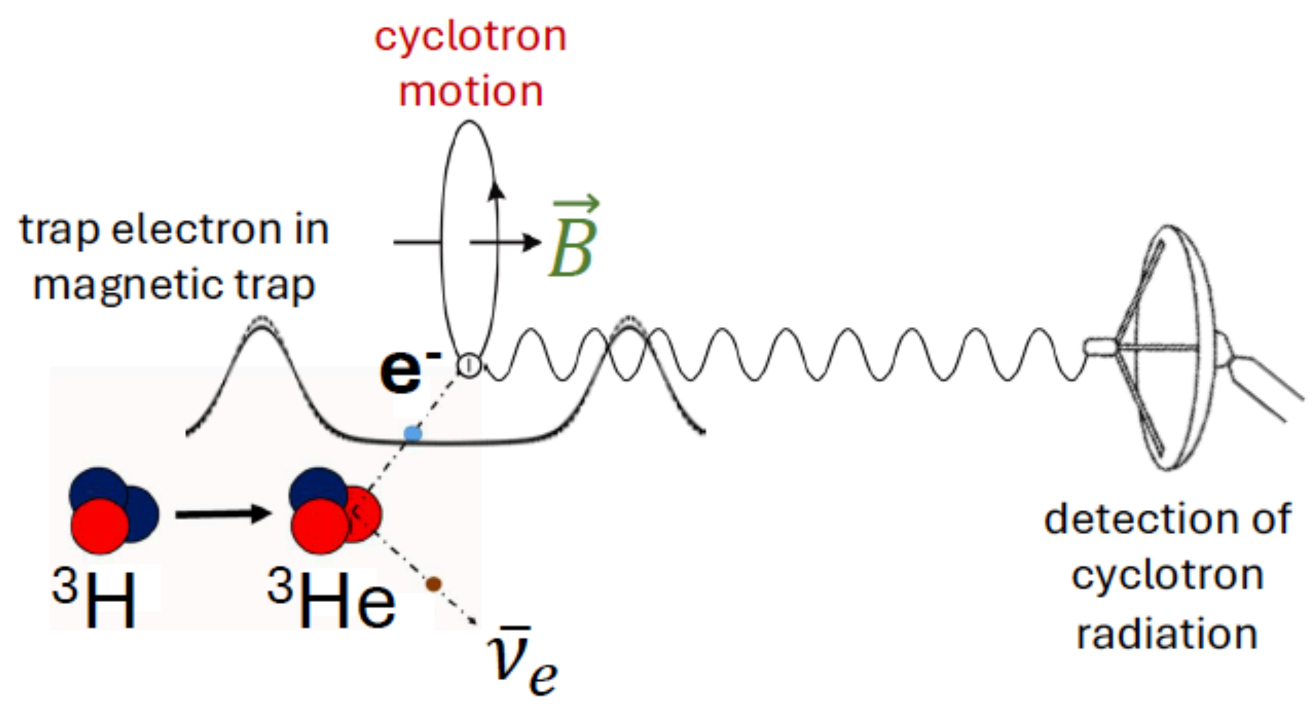
- A new technique to measure electron energy from cyclotron emission from radiating electrons.

- Pioneered by the Project 8 Collaboration.
  - Also being persued by the QTNM Collaboration (UK)

- <u>Advantages</u>:
  - Frequency measurement, high precision
  - Differential measurement
  - Reduced backgrounds (Metric: $3\text{x}10^{-10}$ cps/eV)
  - Amenable to using an atomic tritium source.
  - Demonstrated technique on molecular tritium



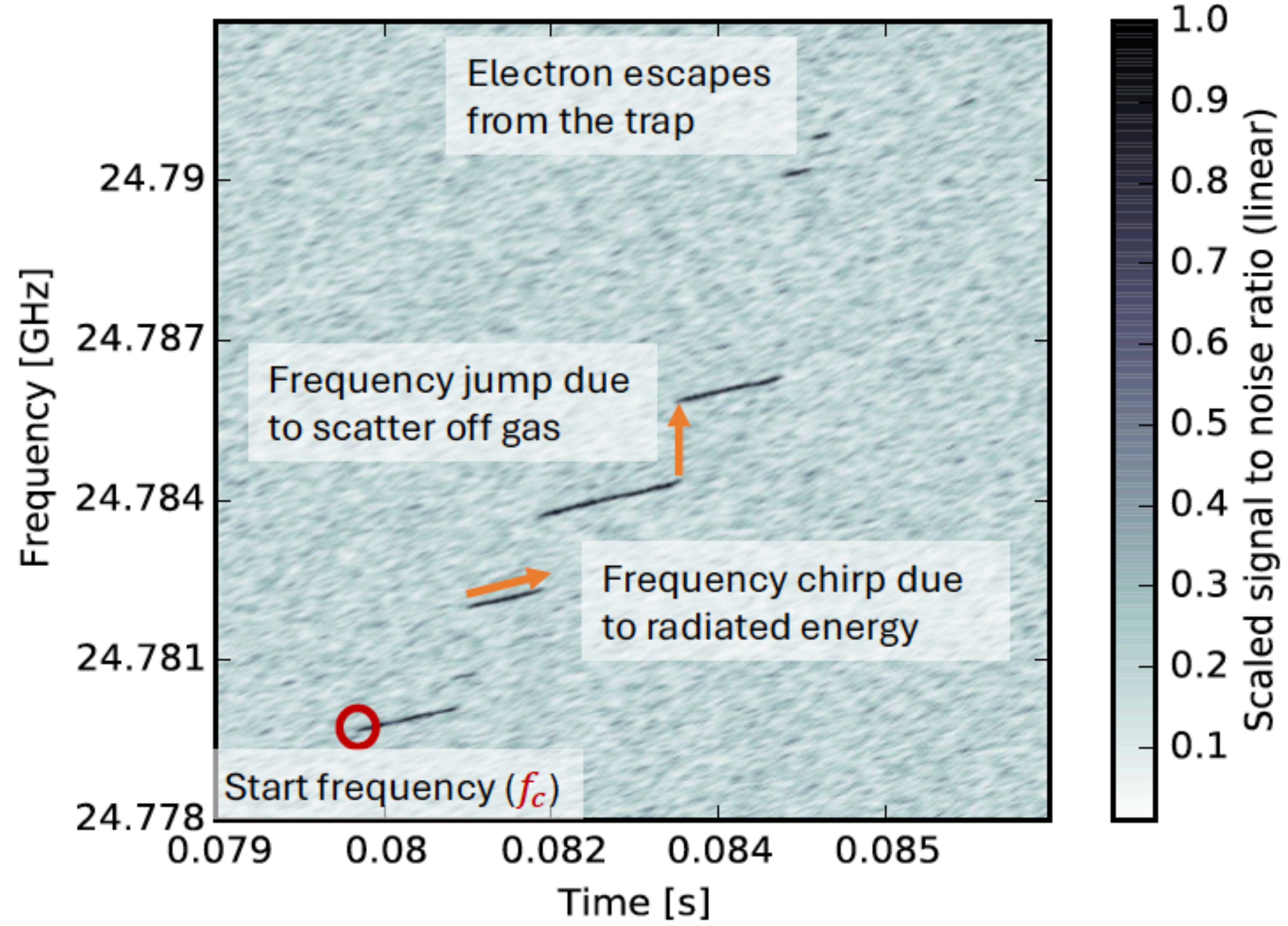
to measure

$$f_c = \frac{1}{2\pi}\frac{e\langle B\rangle}{m_e + E_{kin}/c^2}$$

cyclotron frequency

average magnetic field experienced by electron

kinetic energy



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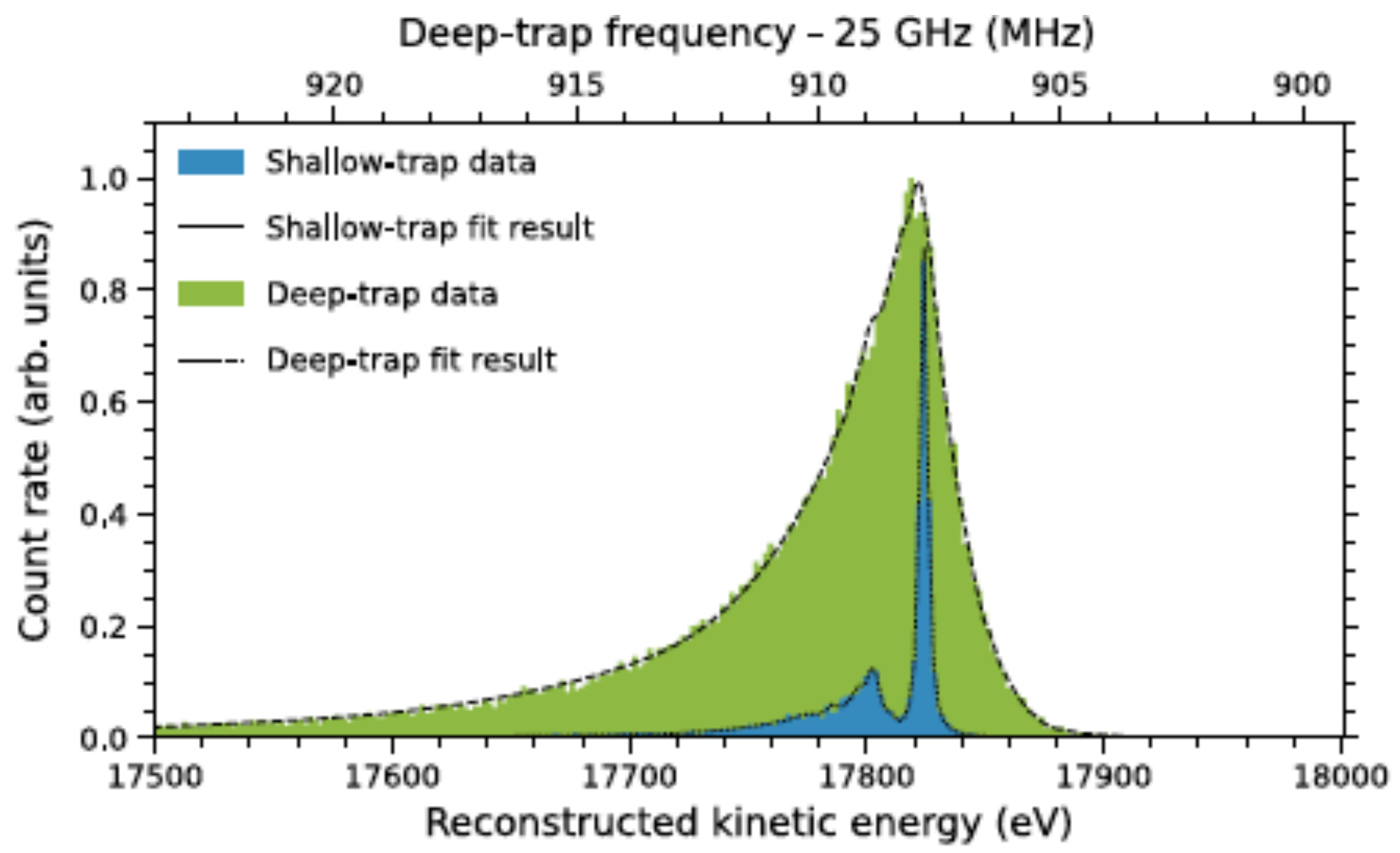
$m_\beta < 155$ eV

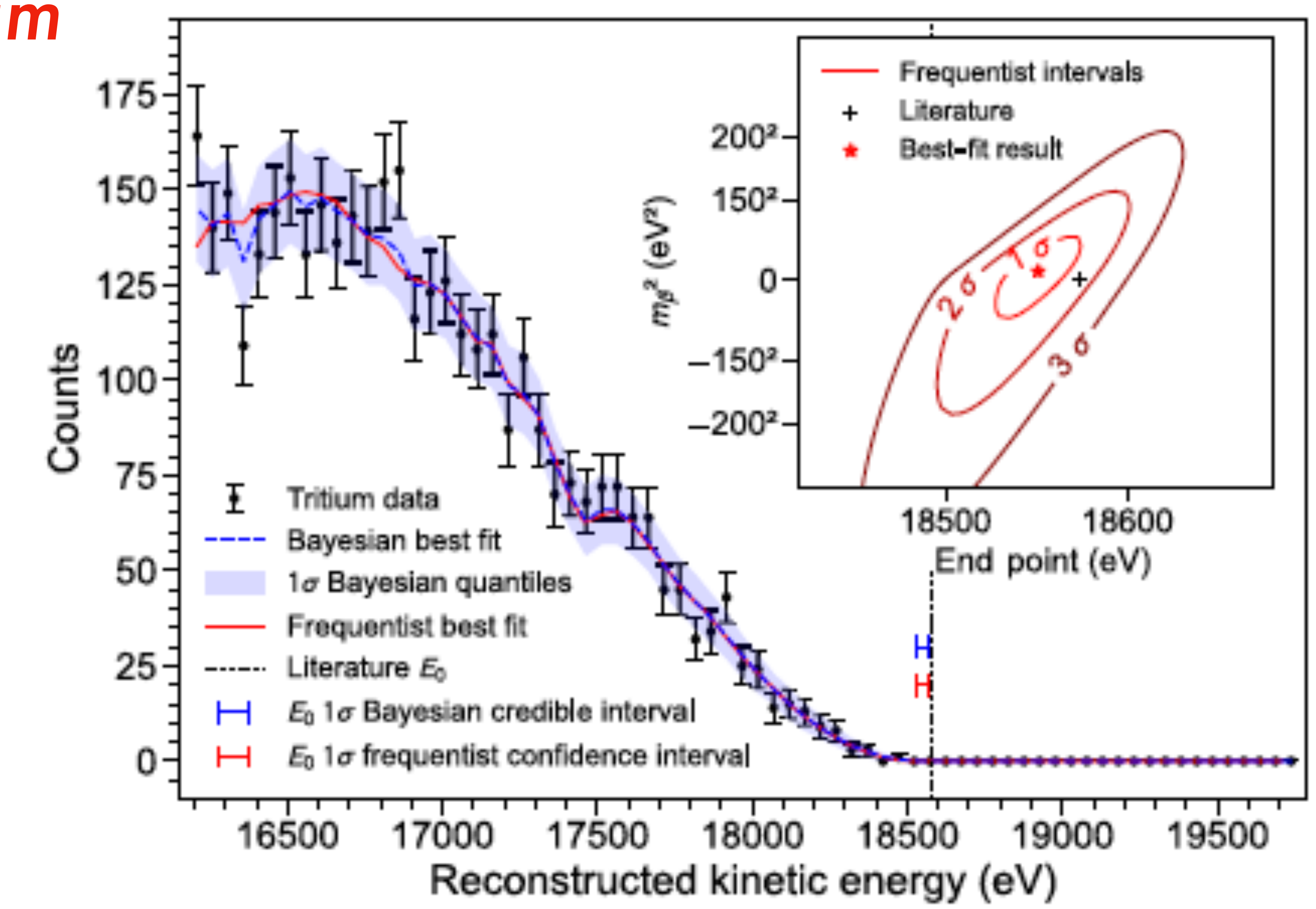
^{83m}Kr Spectrum



Ashtari Esfahani et al Phys. Rev. Lett. 131, 102502 (2023)

Ashtari Esfahani et al. Phys.Rev.C 3, 035503 (2024)

1st Tritium Spectrum



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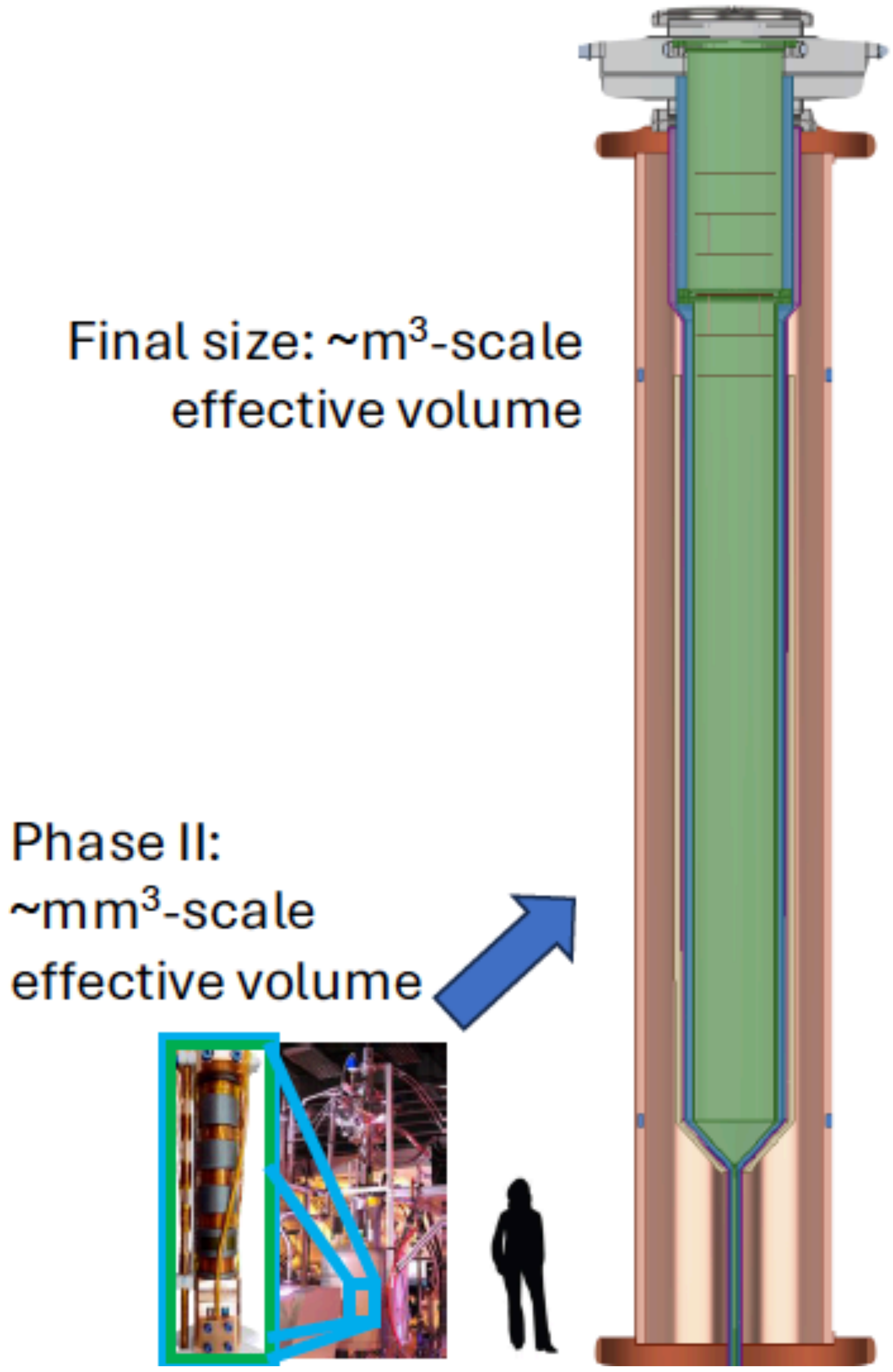
- <u>Experimental Challenges</u>:
  - Complex magnetic system.
  - Power at lower frequencies reduced to aW level. Ultra-low-noise measurement is required.
  - Atomic tritium source development needed.



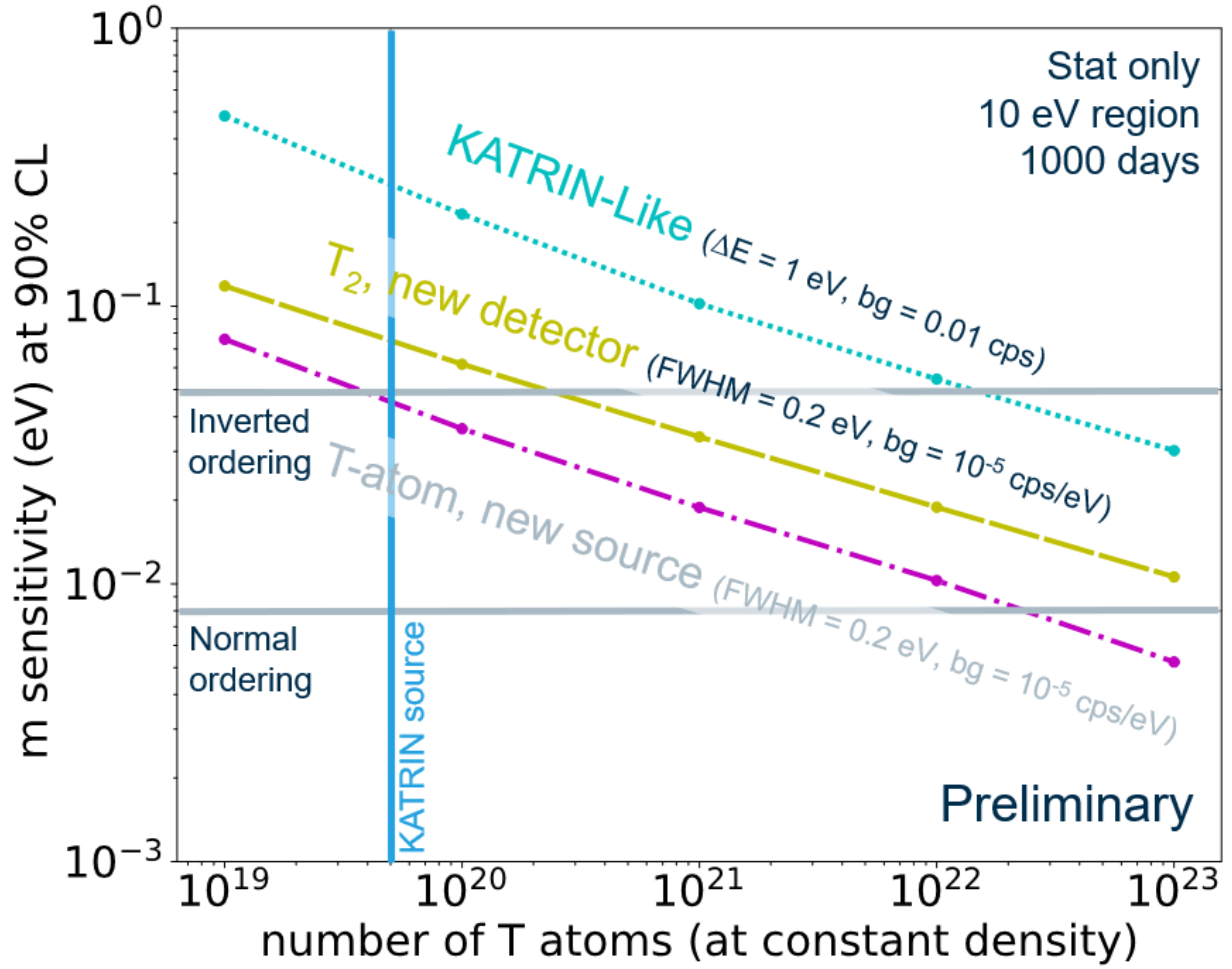
KATRIN++

- KATRIN will conclude its neutrino measurement program, followed by a one-year keV-sterile neutrino search (TRISTAN).

- **Goal for KATRIN++:** 50 meV sensitivity with 0.2 eV sensitivity in 1000 days) using **atomic tritium.**

- The atomic tritium effort requires production, cooling, and trapping with extremely high purity levels. Leveraging TLK facility for atomic tritium R&D.

- Switch to a differential spectrometer with tagging: CRES or superconducting quantum sensor arrays (e.g. MMCs).



Common Challenge:

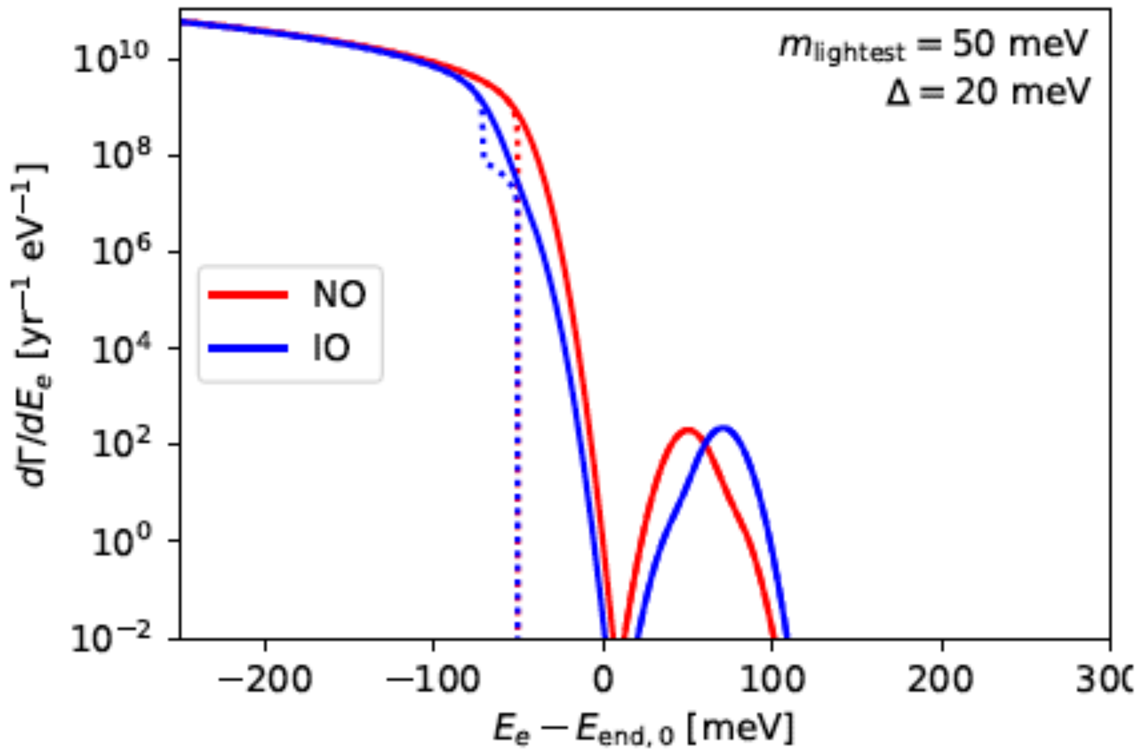
Need to develop an atomic tritium source

Joint effort from KATRIN++, QTNM, Project 8 and others for R&D.

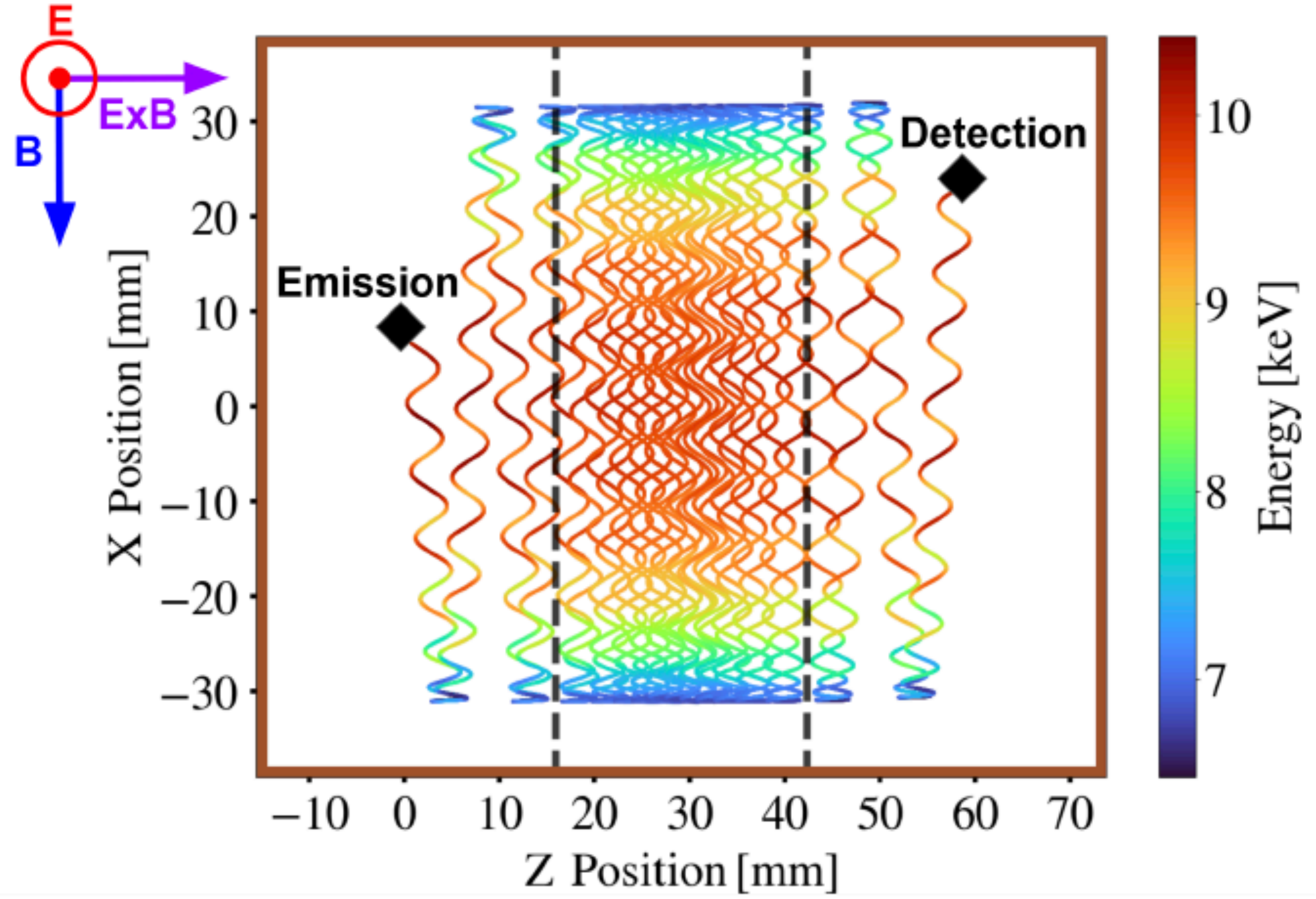
Leveraging the TLK tritium facility.

PTOLEMY

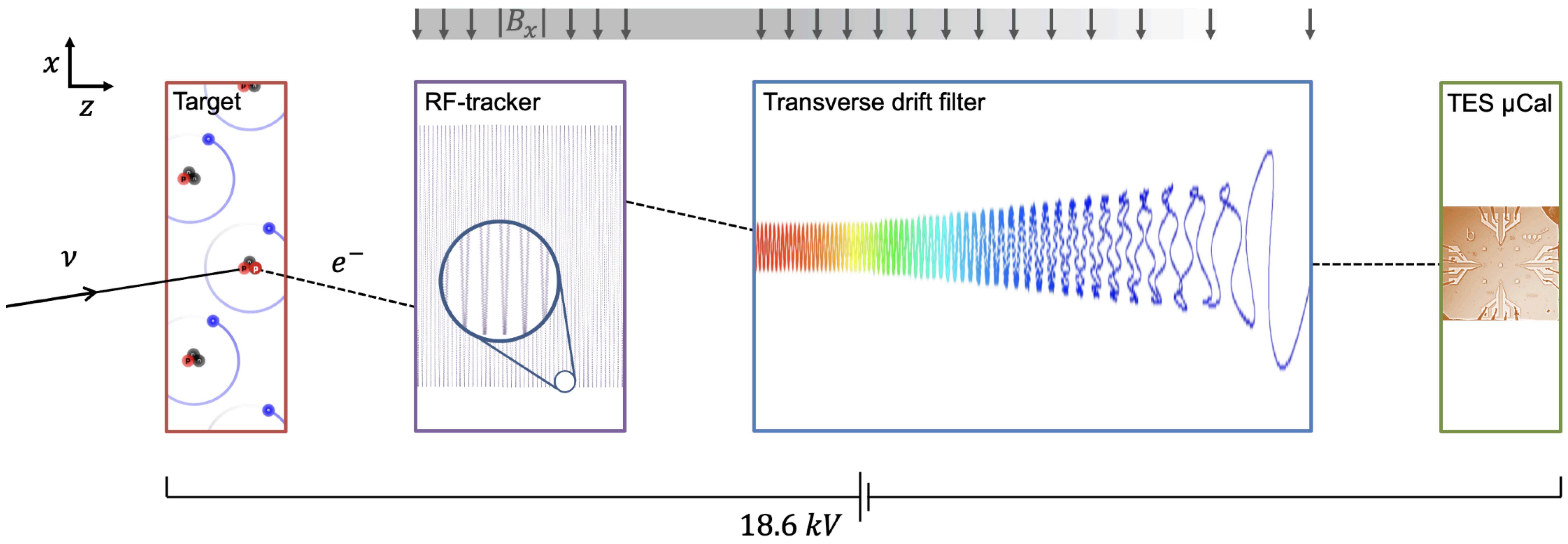
$$^3\mathrm{H} \to {}^3\mathrm{He}^+ + e^- + \bar{\nu}_e$$



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



$E_\parallel \to E_\perp$, $\Delta E \sim \mathcal{O}(100meV)$ $\sigma \sim \mathcal{O}(10\ meV)$



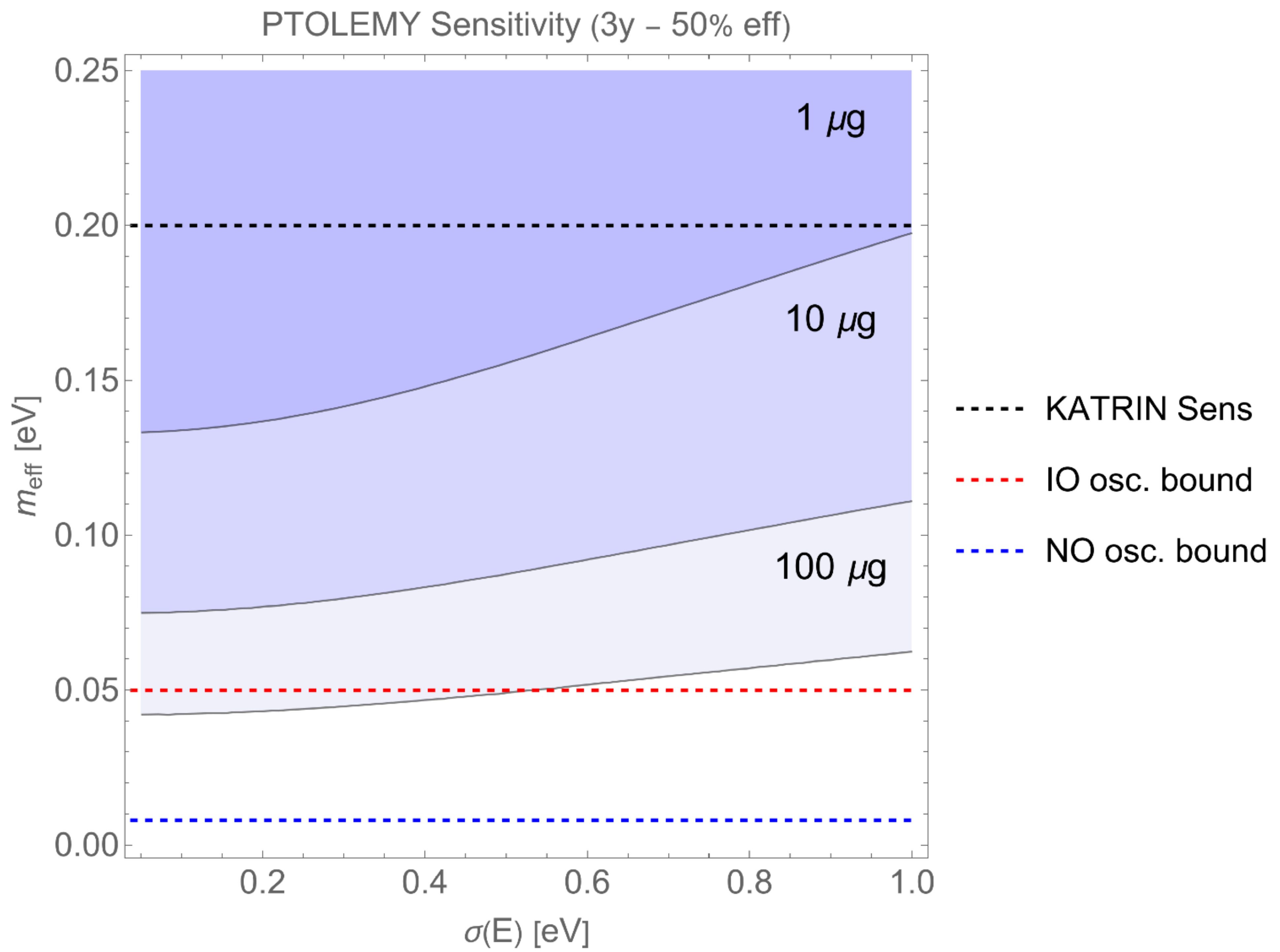
$$E_{total} = q(V_{TES} - V_{target}) + E_{RF} + E_{cal}$$

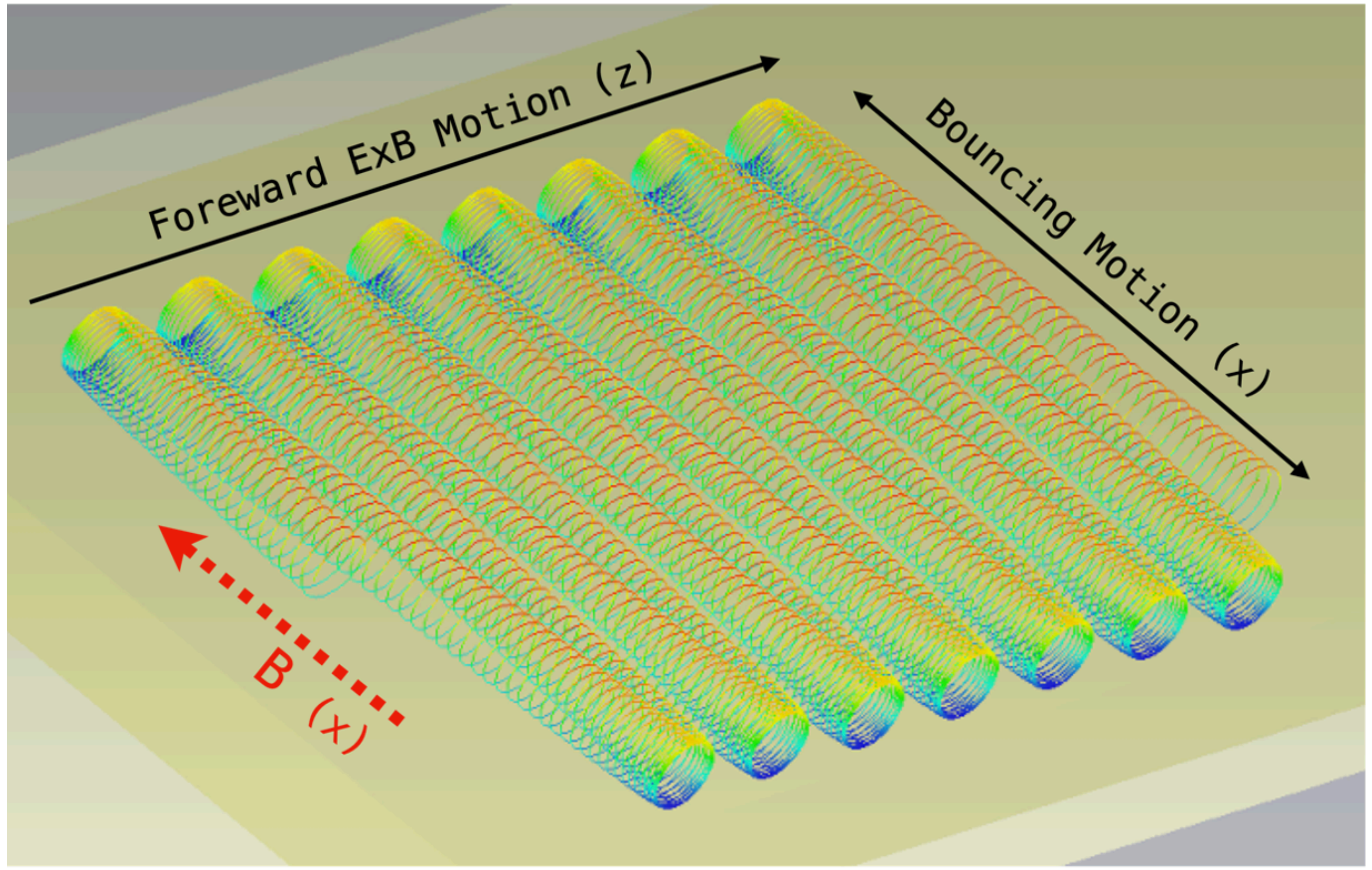
Uses E x B Drift to extract energy of electrons from an embedded tritium source on graphene.

Intended for operation with very high (gram-level) tritium.

Aiming to measure the CvB directly.

PTOLEMY





Experimental Challenges:

Numerous final states of the tritium-graphene system. Each would need precise modeling.

High levels (1-100 µg) of tritium implantation are needed.

No demonstrated end-to-end measurement to anchor scalability (e.g. CRES tagging).

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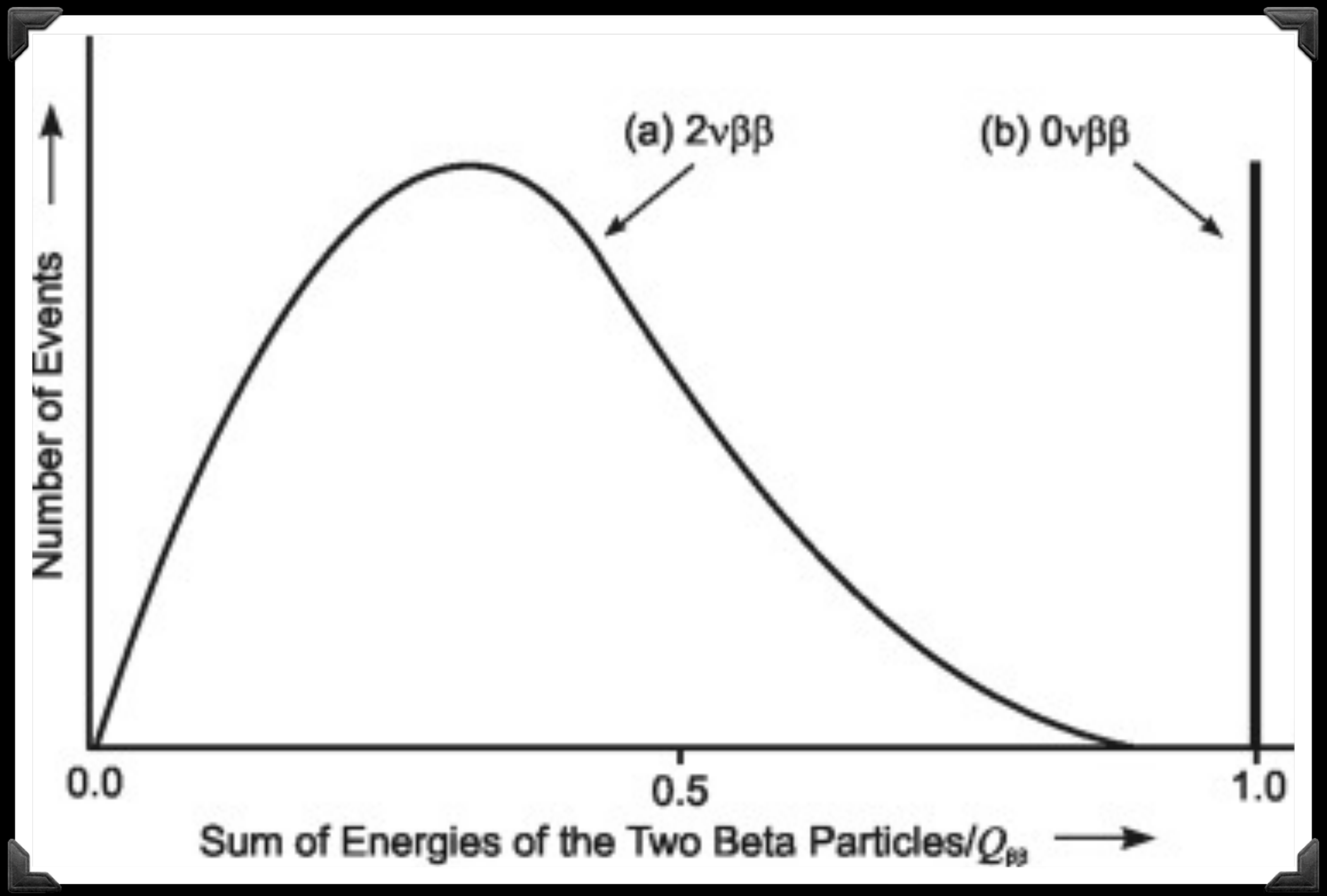
New Physics from 0νββ

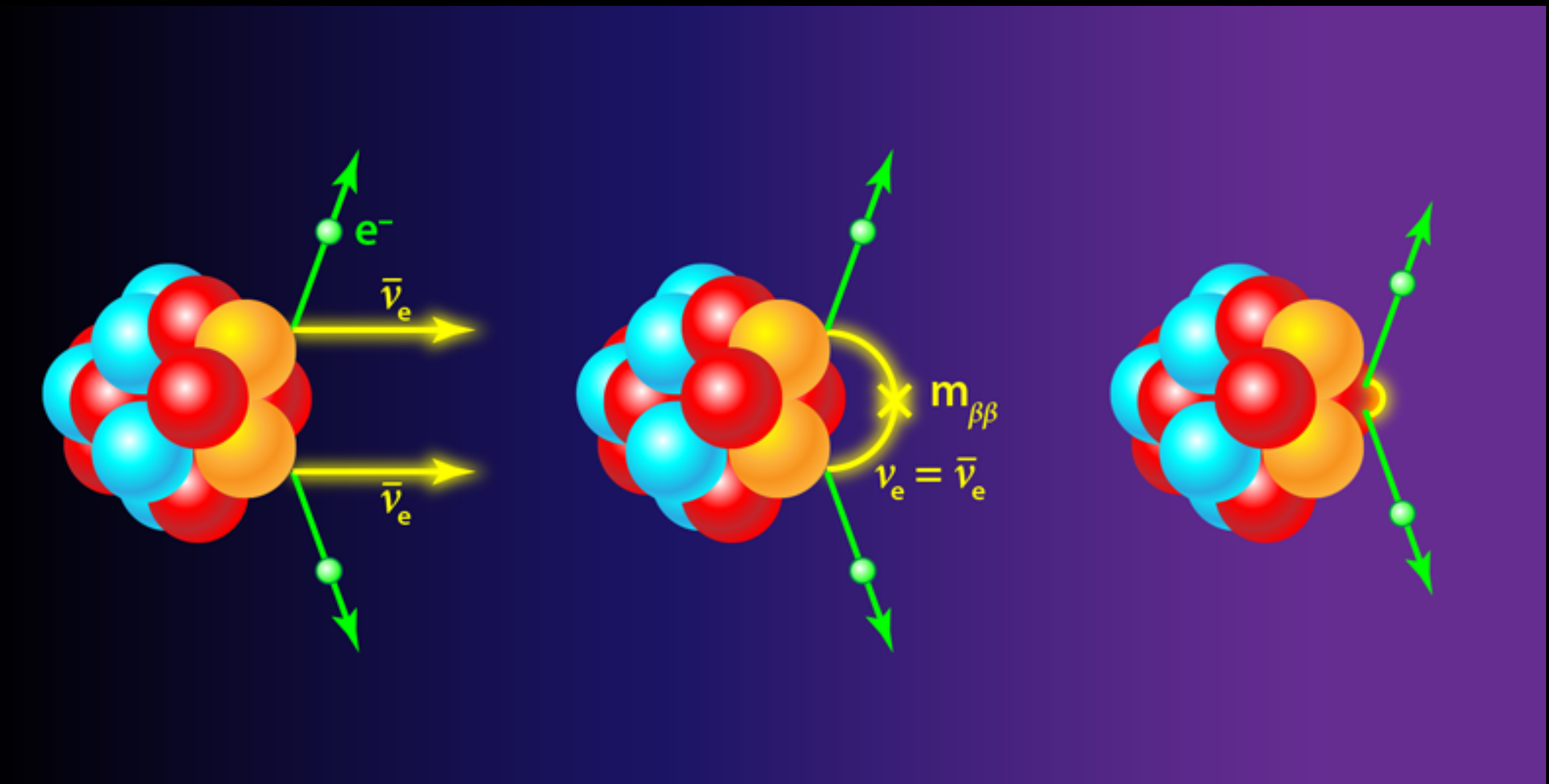
Process (A,Z) → (A,Z+2) + 2e$^-$: a gateway to new physics

- Leptonic number not conserved (BSM), ΔL ≠ 0
- Neutrinos are Majorana particles
- Non-conservation of leptonic number; Connects to matter–antimatter asymmetry in the universe.
- High statistics spectrum for 2νββ allows for precision BSM tests.



Observable: $T_{1/2}$

- Only a limited number of nuclei
- Mono-energetic peak at the Q value.
- Isotope choice
  - High $Q_{\beta\beta}$ for low background
  - High isotopic abundance for low cost



$T_{1/2}^{0\nu} \approx 10^{27-28}\,(0.01\text{ eV} / m_{\beta\beta})^2$ y

Neutrinoless Double Beta Decay

Energy resolution:

- Necessary for discrimination against backgrounds.
- In particular, ^{208}TI with gamma at 2.615 MeV, and ^{222}Rn
- Low Q-value isotopes are especially prone to these backgrounds
- Separation from $2\nu\beta\beta$ is true for all isotopes.

$$\frac{S}{B} \propto \left(\frac{Q_{\beta\beta}}{\Delta E}\right)^{6} \frac{T_{1/2}^{2\nu}}{T_{1/2}^{0\nu}}$$

Background Reduction:

- Cosmic ray reduction via deep underground deployment.
- High purity, low background radioactivity of all materials.

$$T_{1/2}^{0\nu} \propto \begin{cases} a\, M\, \varepsilon\, t, & \textit{background free} \\ a\, \varepsilon \sqrt{\dfrac{M\, t}{b\, \Delta E}}, & \textit{with background} \end{cases}$$

Isotope Enrichment:

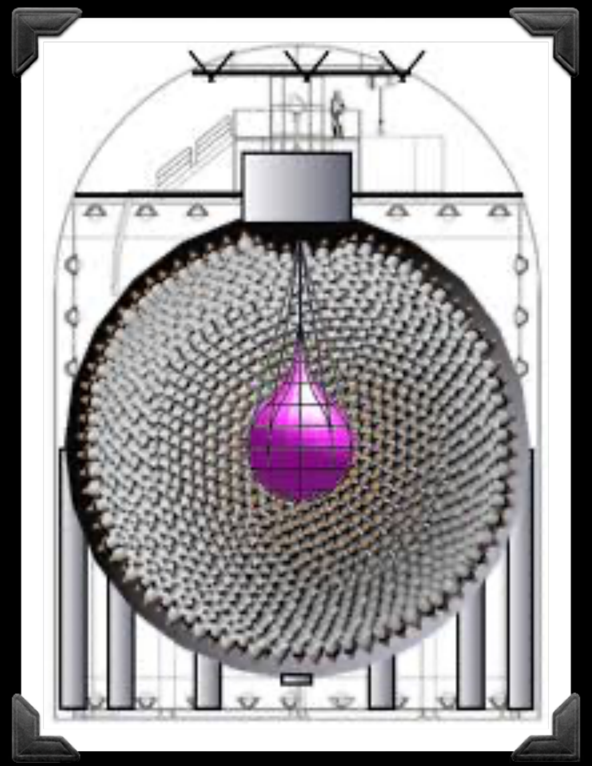
- Only ^{130}Te has a natural abundance above 10%.
- All others require some form of enrichment.

For probing 10^{28} years

Background metric: < 0.1 cts/FWHM/ton/y or 10^{-5} cts/keV/kg/y

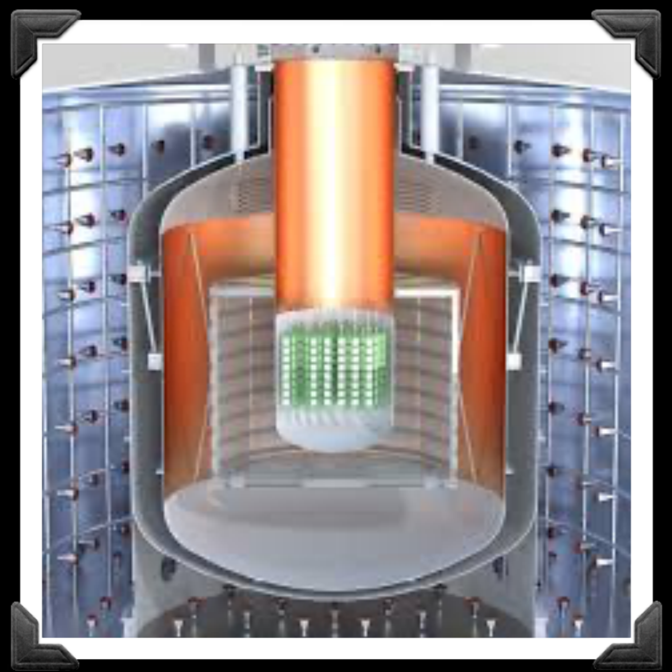
Current Detector Technologies

Liquid/Gas Xenon
(nEXO, XLZD, NEXT)

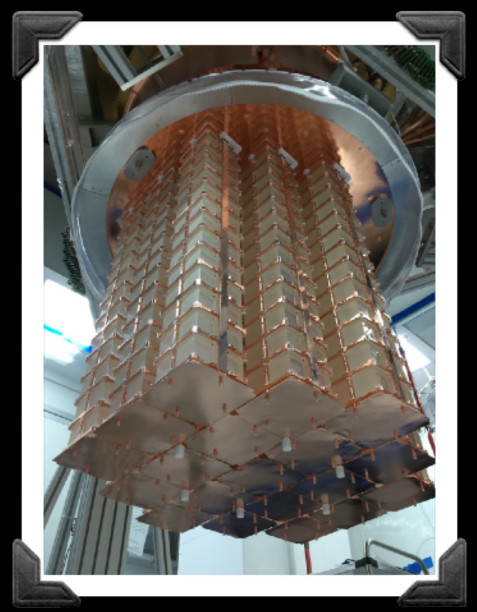


Liquid Scintillators
(SNO+, Kamland2-Zen)

Semiconductors
(LEGEND)



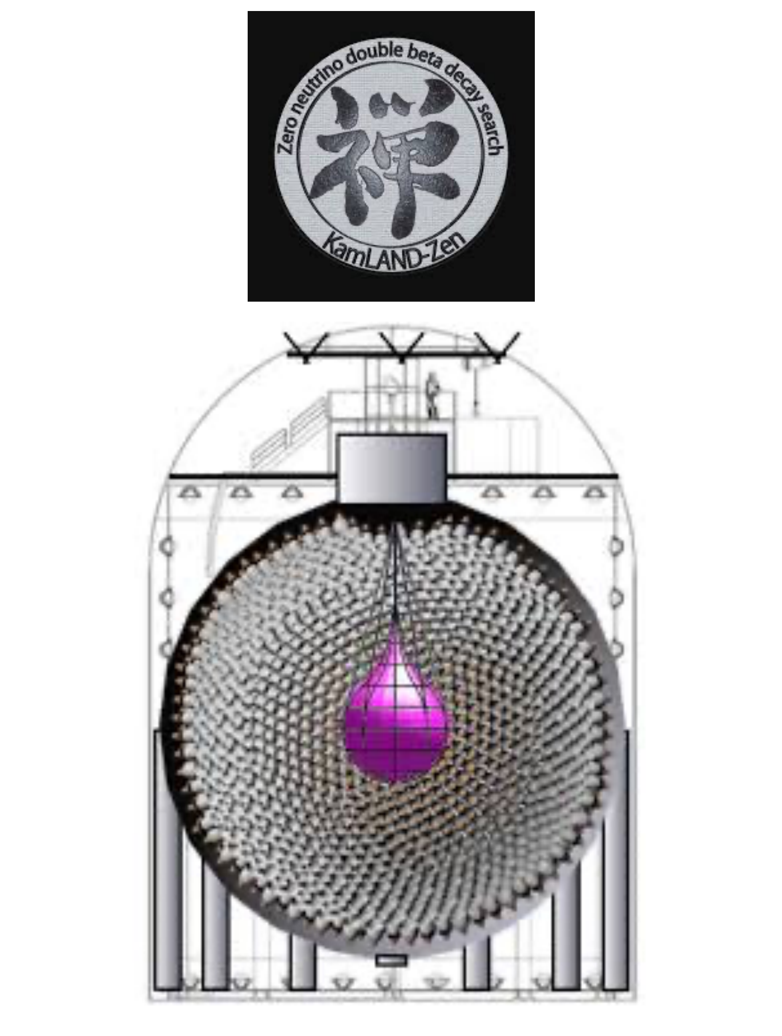
Cryogenic Bolometers
(CUPID, AMoRE)

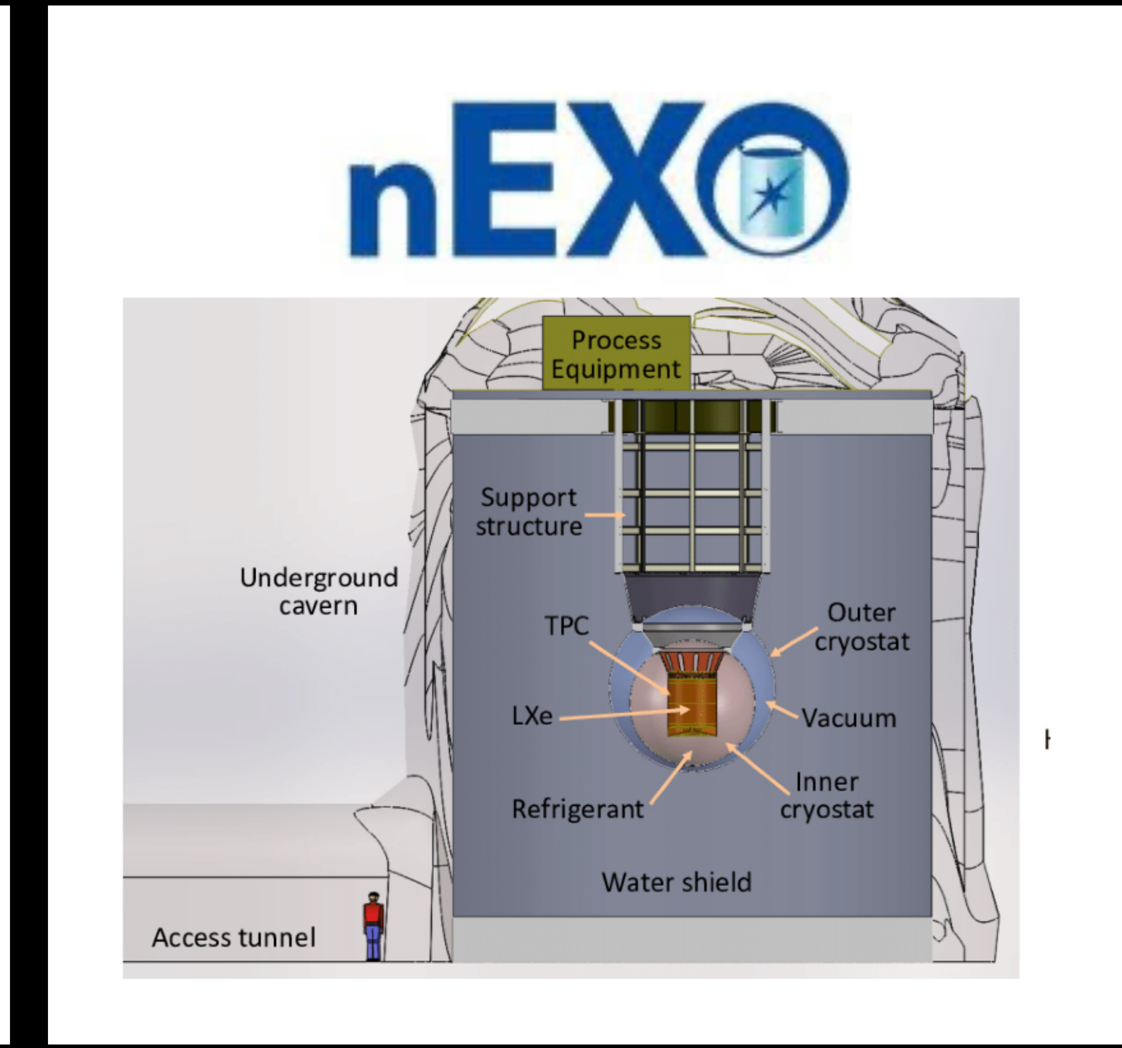


Massive Xenon Detectors (nEXO, KamLAND-Zen)

Two main experiments within this category:

- Liquid Xenon Time Projection Chamber
  - Current EXO upgrade to nEXO
  - Isotopically enriched with optical and charge readout
- Gas Xe dissolved in Liquid Scintillator:
  - Current Kamland-Zen upgrade to Kamland2-Zen
  - Higher radiopurity





Key Metrics (EXO)

Δ_E (FWHM) at $Q_{\beta\beta}$ = 69 keV

Background: 4×10^{-3} cts/keV/kg/y

Key Metrics (KamLAND-ZEN)

Δ_E (FWHM) at $Q_{\beta\beta}$ = 240 keV

Background: 1.5×10^{-4} cts/keV/kg/y

Main Advantages

Currently, it possesses the highest sensitivity of modern experiments.

High target volumes are achievable

Main Challenges

Displays a high rate for $2\nu\beta\beta$.

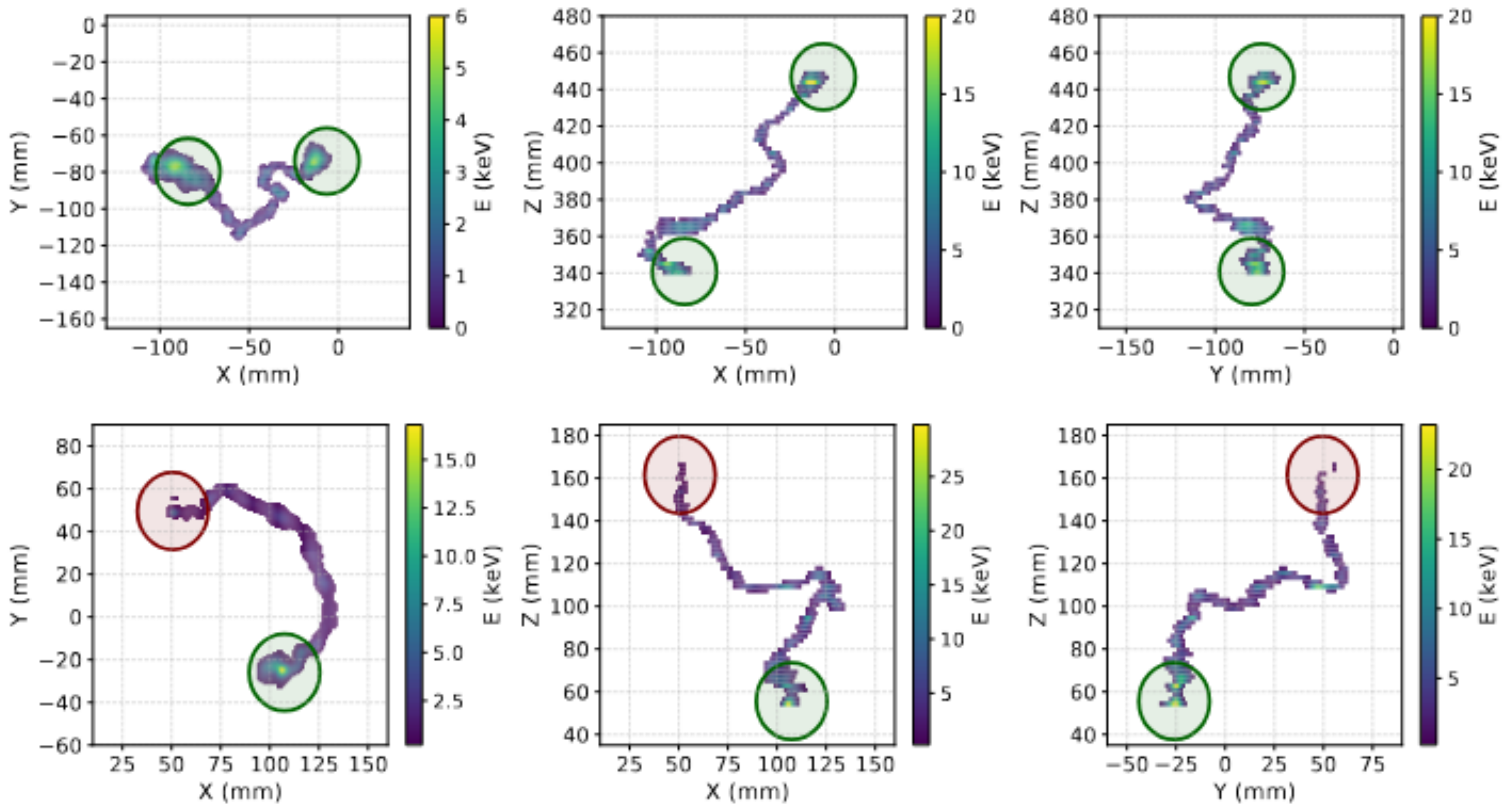
Radon decay chain with decay only 10 keV below Q-value.

Stringent energy and background requirements.

Gas Xenon TPC (NEXT)

Use high-pressure gaseous Xenon as a target.

Uses the topology of two electrons (“double blob”) to discriminate against background radioactivity.



Main Advantages

High energy resolution (0.9% already demonstrated {for 10 bar pressure}).
Intrinsic background rejection via event topology.

Main Challenges

Keep high pressure at larger volumes with similar detector performance.
Being tested currently with NEXT-100

(Loaded) Liquid Scintillators

Main experiments within this category:

SNO+ with Te Loading

Larger and interesting physics program:

- Geo-neutrinos: after KamLAND and Borexino
- Solar neutrinos: measure ^{8}B neutrinos above 2.5 MeV of survival probability
- If Phase I is successful, this could have a positive impact on the future use of Te loading in JUNO.

Main Advantages

Large (34%) natural abundance of Te (no need enrichment)

Background index of 10^{-4} cts/keV/y/kg

Wide science program

Main Challenges

Energy resolution: 5%

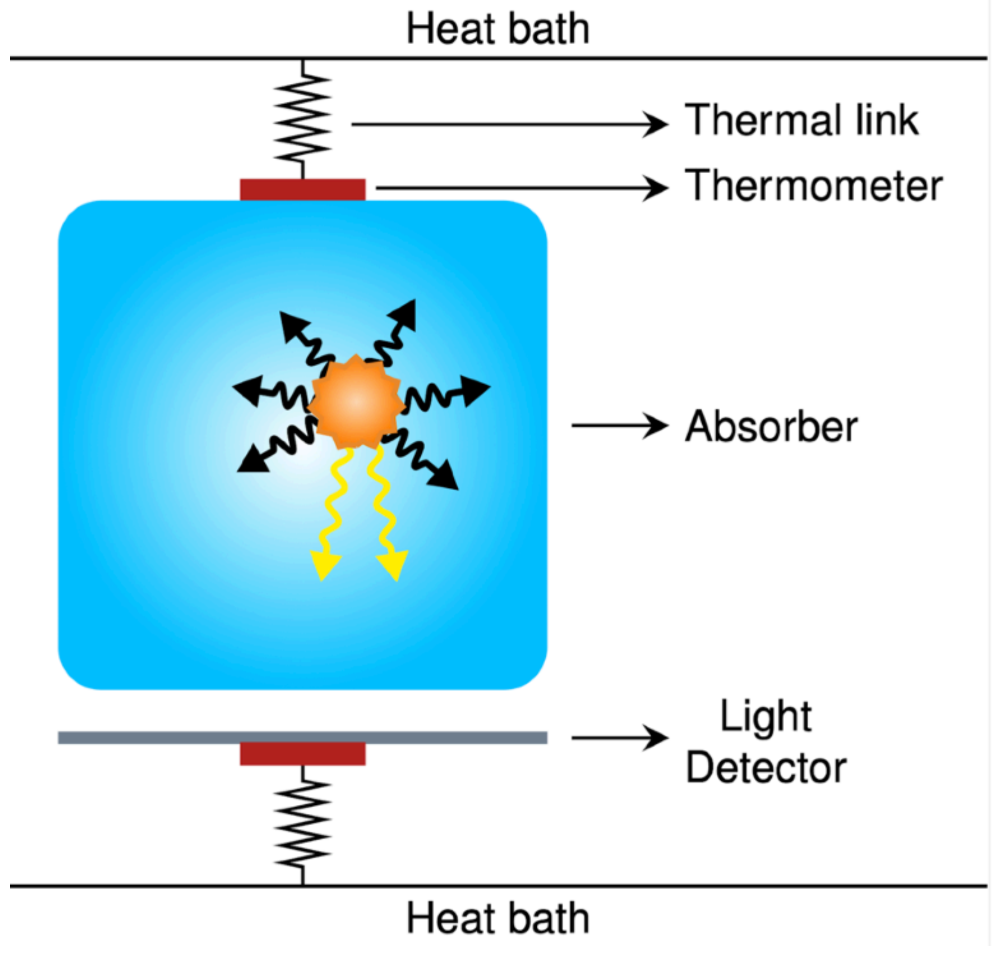
Low Q-value for $0\nu\beta\beta$

(Similar issues as Xenon loading)

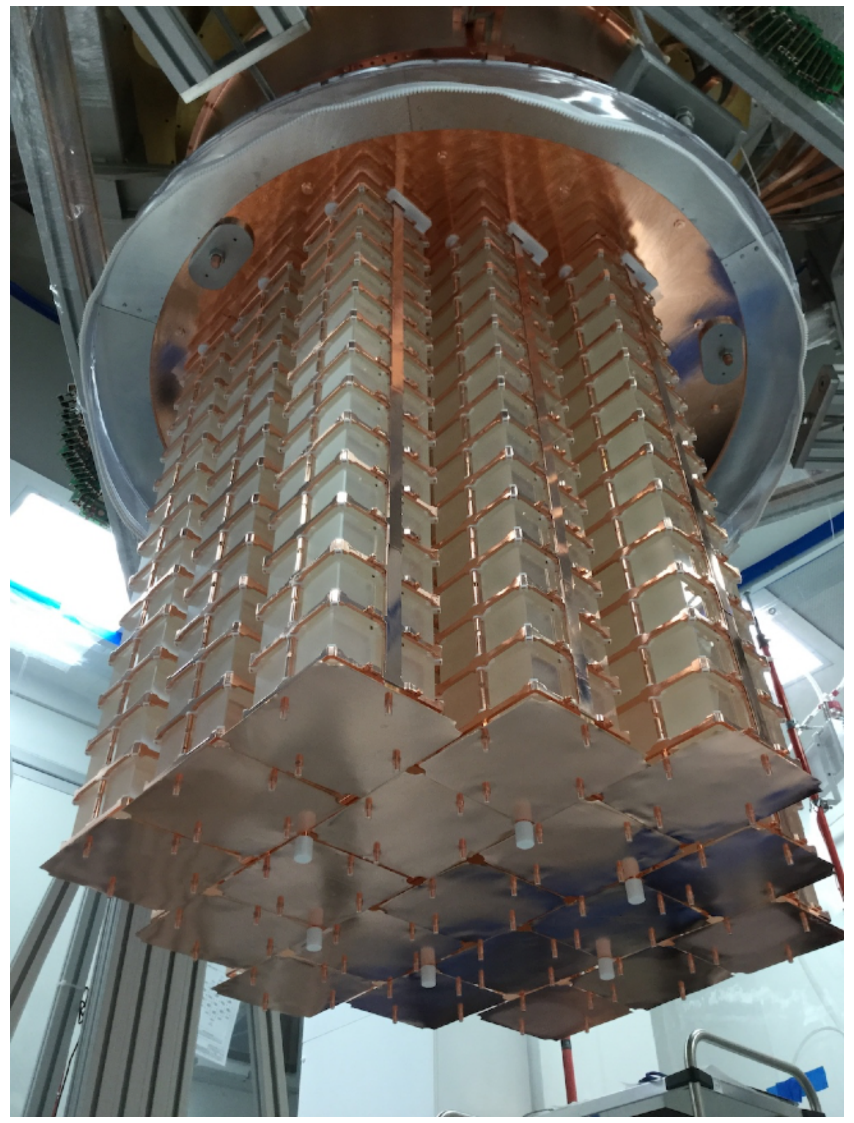
Cryogenic Bolometers

Experiments include:

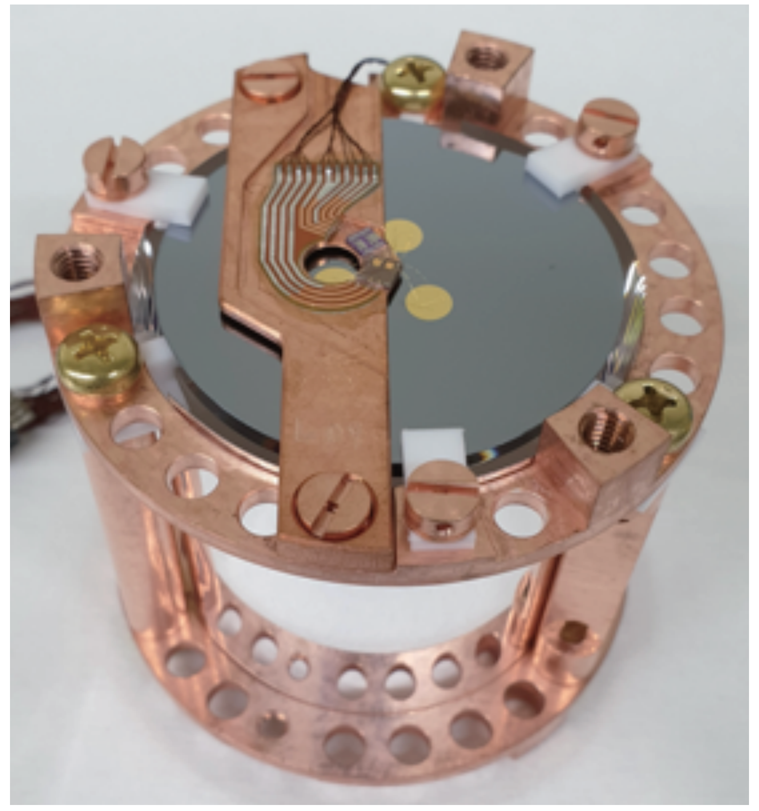
Predecessor: CUORE (^{130}Te, prior/current)
CUPID-Mo & AMoRE (enriched ^{100}Mo)
Use heat+light for background rejection



Heat/Light detection



CUORE



AmoRE Crystal

CUPID-Mo

Proven: Energy: Δ_E (FWHM) 0.2%.
Background: 2.7x10^{-3} cts/keV/kg/y
Projected Background: 1x10^{-4} cts/keV/kg/y

AMoRE

Proven: Energy: Δ_E (FWHM) 0.4%.
Background: 2.5x10^{-2} cts/keV/kg/y
Projected Background: 1x10^{-4} cts/keV/kg/y

Main Advantages

Excellent energy resolution.
For ^{100}Mo, high Q-value moves signal above many backgrounds.

Main Challenges

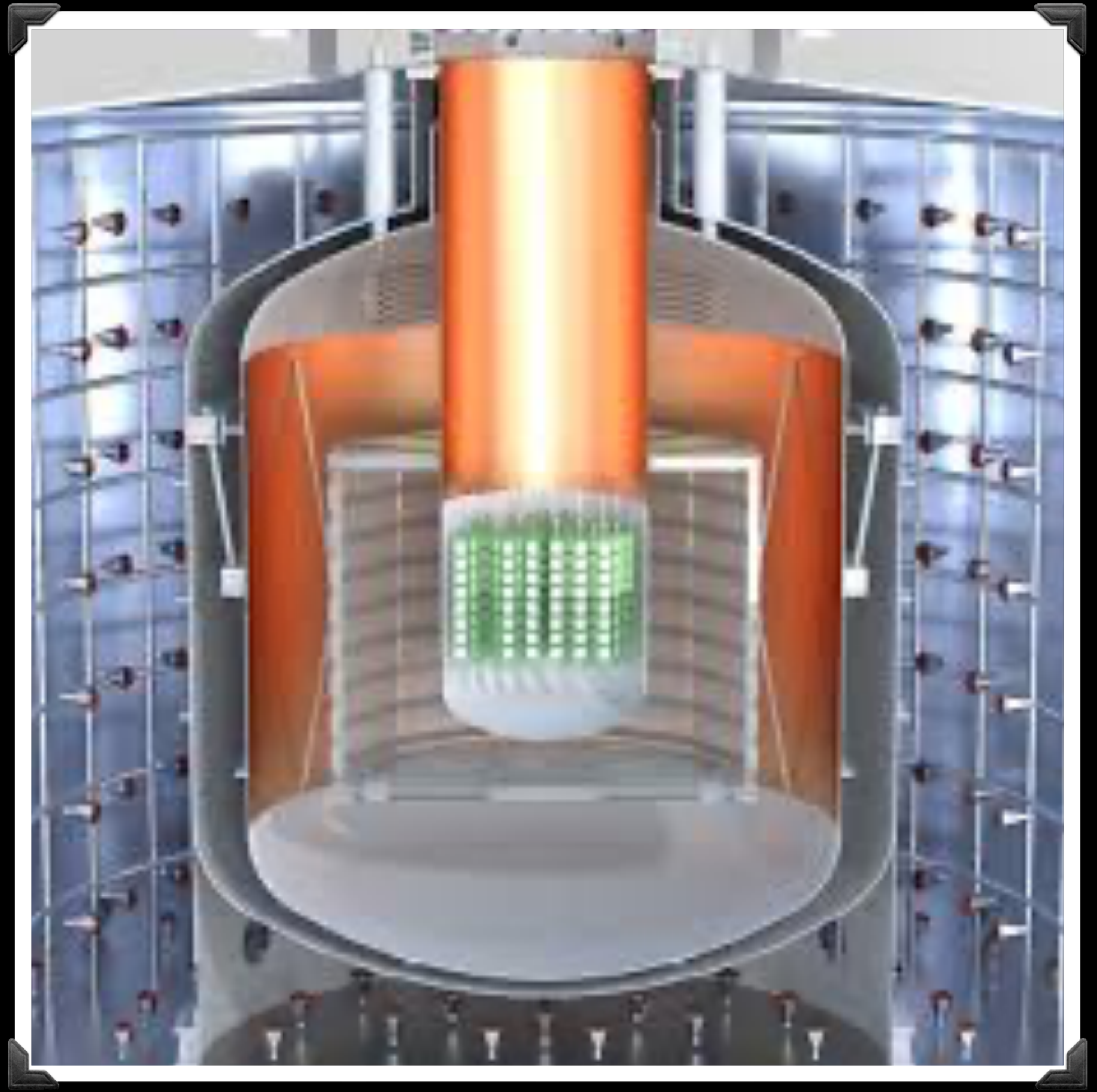
No single volume; cannot do fiducialization
Need enrichment & complex crystal production

Enriched Germanium Detectors

Experiments include:

MAJORANA & GERDA (earlier demonstrators)
LEGEND-200 & LEGEND-1000

Operating Legend-200 already. Switching to depleted UG Argon for shielding upgrade.



Key Metrics

Proven (Legend-200): Energy: Δ_E (FWHM) 0.1%. Background: 5×10^{-4} cts/keV/kg/y
Projected (Legend-1000): Energy: Δ_E (FWHM) <0.1%. Background: 1×10^{-5} cts/keV/kg/y

Main Advantages

Excellent resolution and background control.
Large scale already in operation.

Main Challenges

No single volume; cannot do fiducialization
Need enrichment & complex crystal production

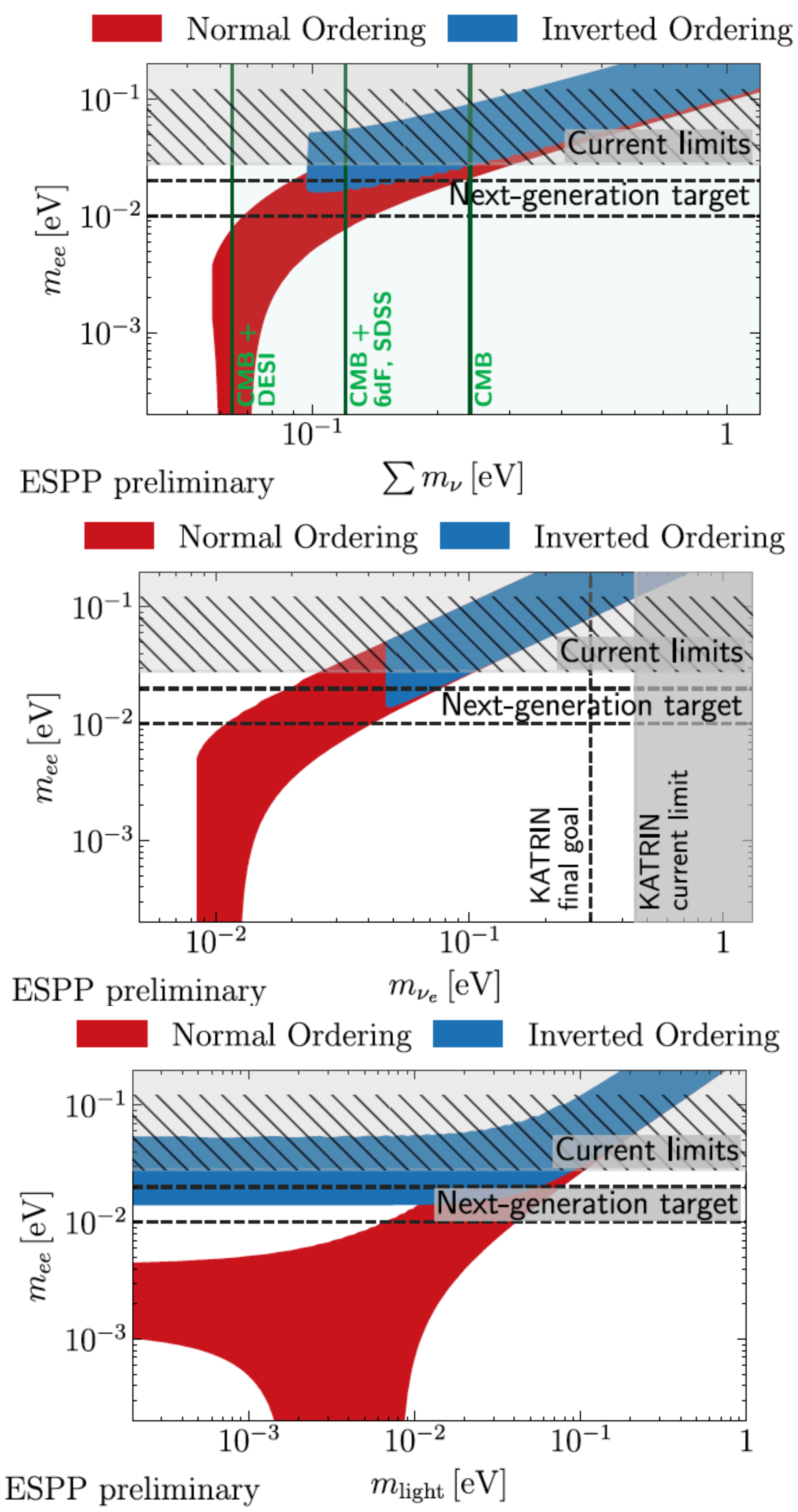
Looking Forward

Projected Resolutions:

- Current Generation: $m_{\beta\beta} \geq$ 40-100 meV ($T_{1/2}$ 10^{27} y)
- Next Generation: $m_{\beta\beta} \geq$ 9-25 meV ($T_{1/2}$ 10^{28} y)
- Current technologies need to demonstrate their ability to reach 10^{27} y.

Multiple Experiments Necessary:

- Extremely challenging technologically
- Need to pursue different roads, no clear winning technology emerges as of today
- Need confirmation from at least two different technologies to order to support such a crucial discovery
- Once discovery is established, different isotopes bring complementary information



Beyond 10^{28} Years

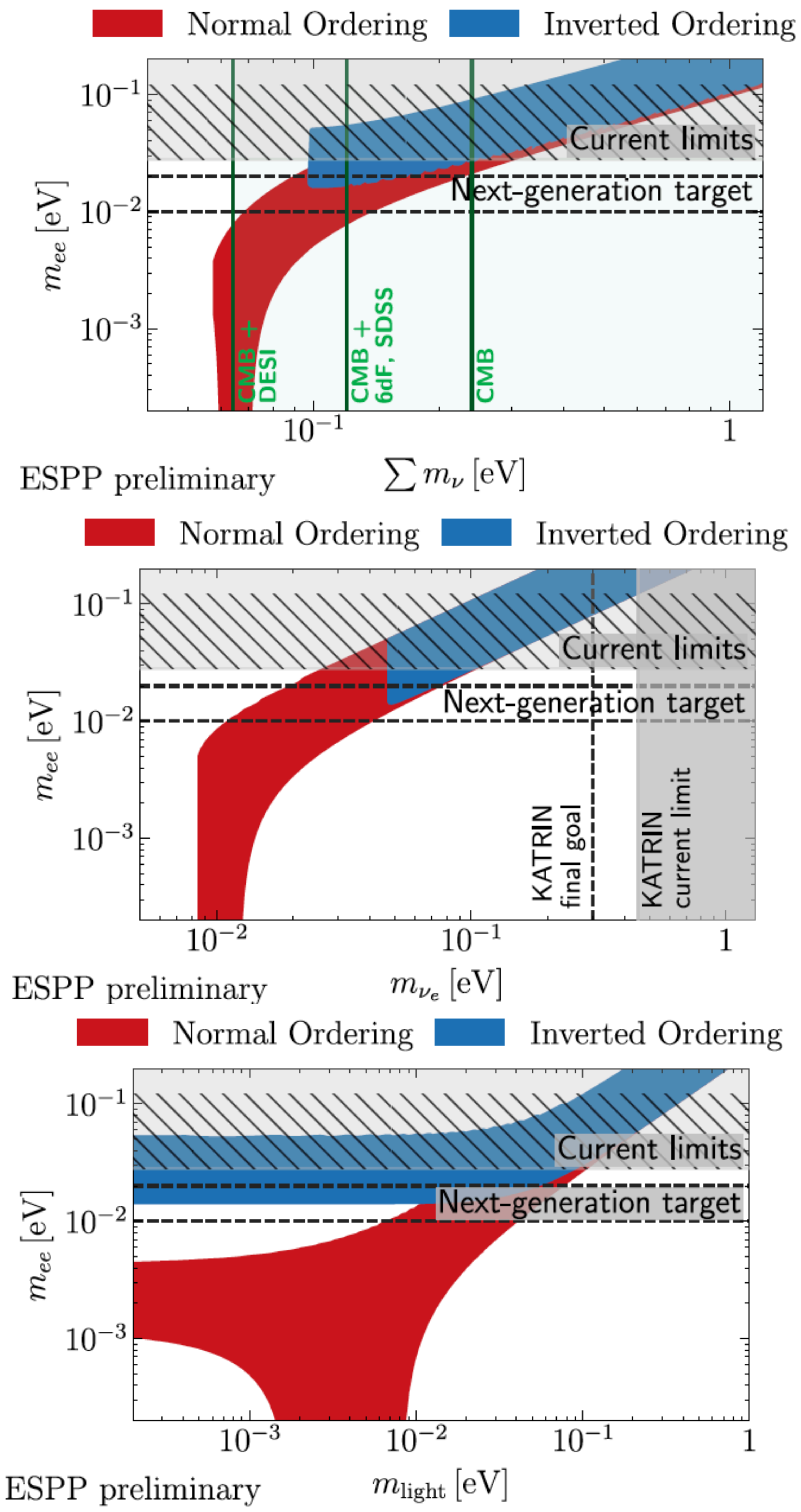
Need to develop new technologies:

Ba^{2+} tagging in the framework of NEXT project:

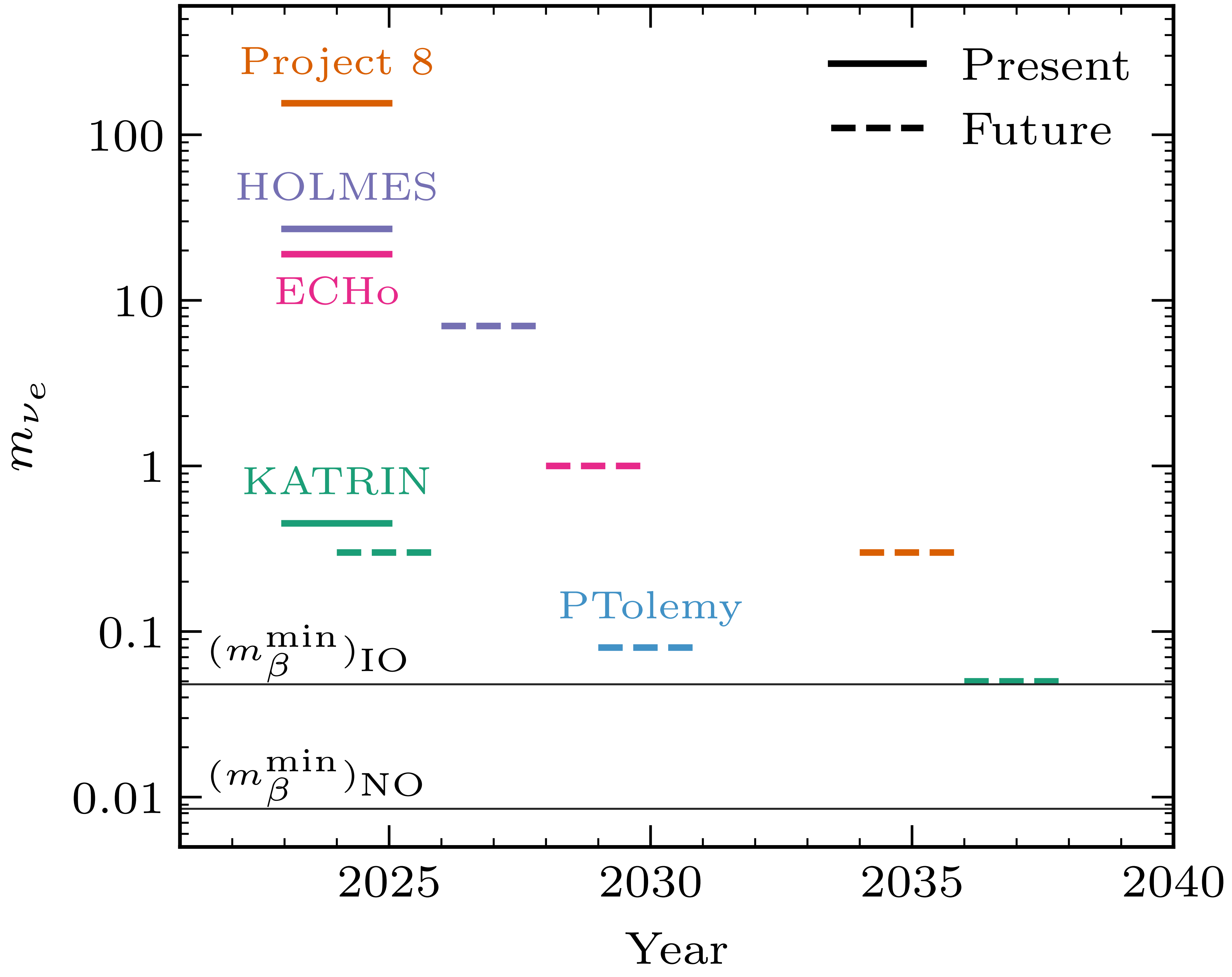
- Barium ion produced in ^{136}Xe $0\nu\beta\beta$ decay drifted towards the cathode and was imaged through single-molecule fluorescence imaging.
- Efficiency only 50% but no real backgrounds.

R&D on bolometers: exploration of new isotopes at high Q on-going

- Examples include Ca, Zr, and Nd

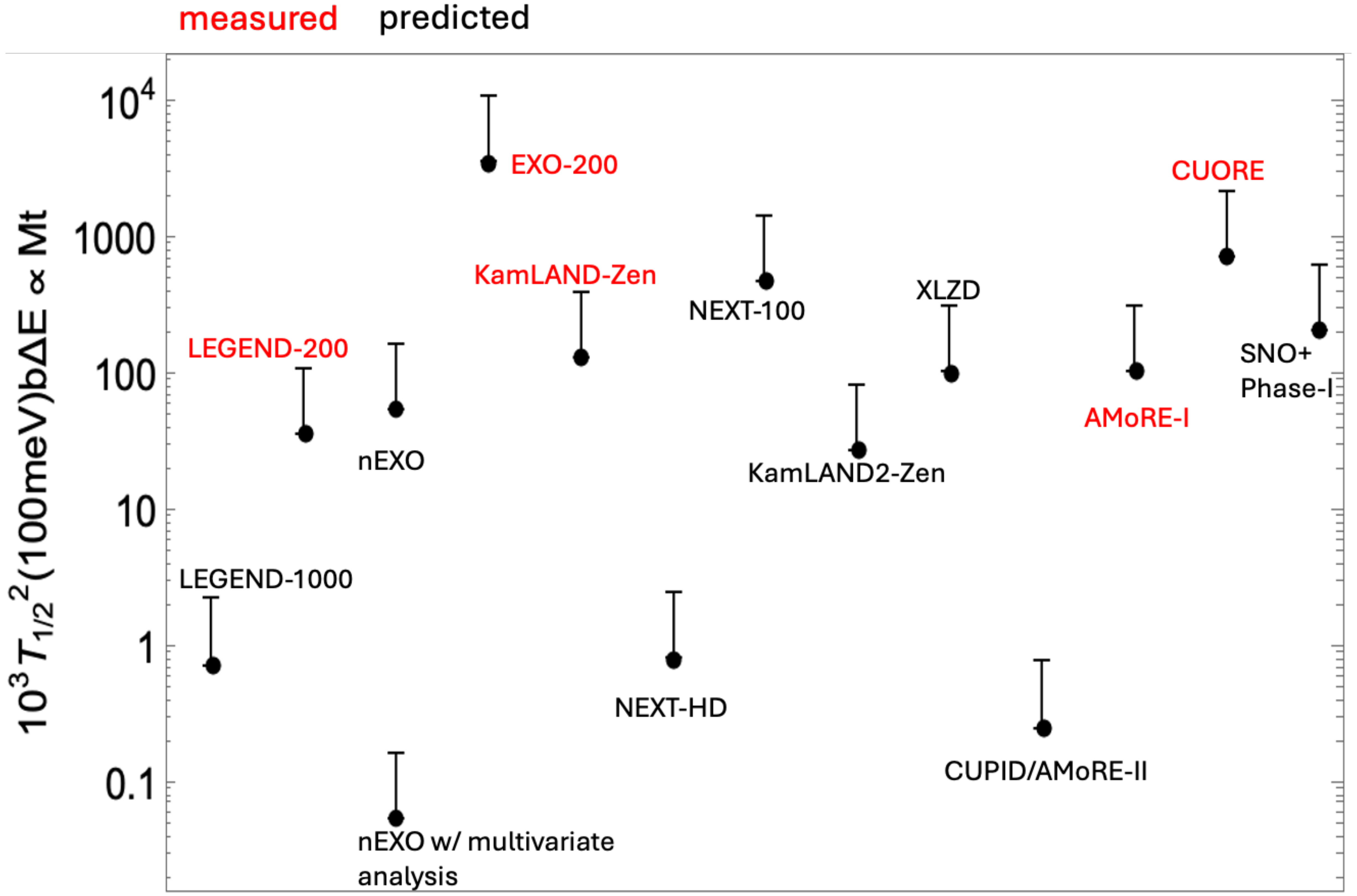


Direct Measurements



ESPP preliminary

0νββ Measurements



Direct neutrino mass measurements will be in the R&D phase over next decade, to establish the scalability of each technology.

As for 0νββ Experiments, key metrics in background reduction and energy resolution will push to the IO and possibly NO scale over next decade.

Summary

Neutrino mass probes (single and neutrinoless double beta decay) open new and vital windows into fundamental, open questions about the Standard Model of particle physics and cosmology.

Direct neutrino mass measurements will push new technologies that hope to scale toward the inverted scale.

Neutrinoless double beta decay technologies are now scalable to the ton-scale, able to probe toward the normal ordering scale.