PROJECT 8

UNIVERSITY of WASHINGTON

Direct neutrino mass measurements

Summiting the Unknown: New Voices, New Opportunities

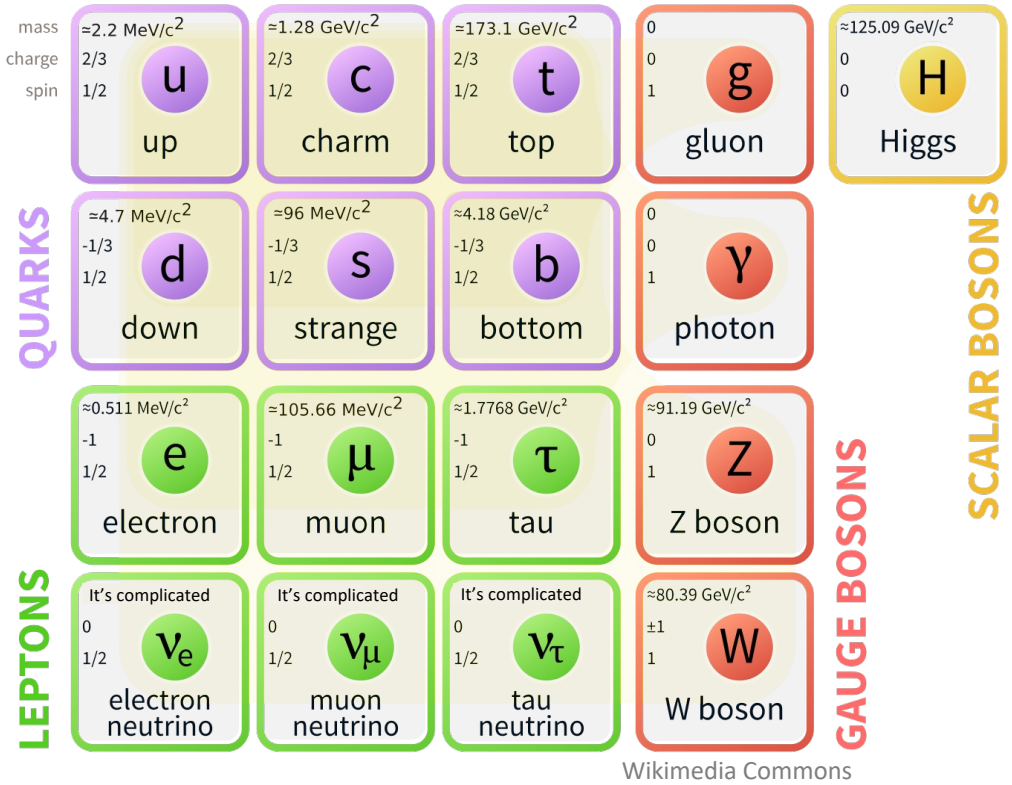
University of Washington, Seattle

July 15, 2022

Elise Novitski

There’s a lot we don’t know about neutrinos

- Original Standard Model prediction: neutrinos are massless
- Not massless; just very, very light. Why?
- What is the origin of their mass?
- Dirac or Majorana nature of mass?
- Role in the history of the universe
  - Possible CP violation and leptogenesis?
  - Evolution of structure



Wikimedia Commons

What is the neutrino mass ordering?

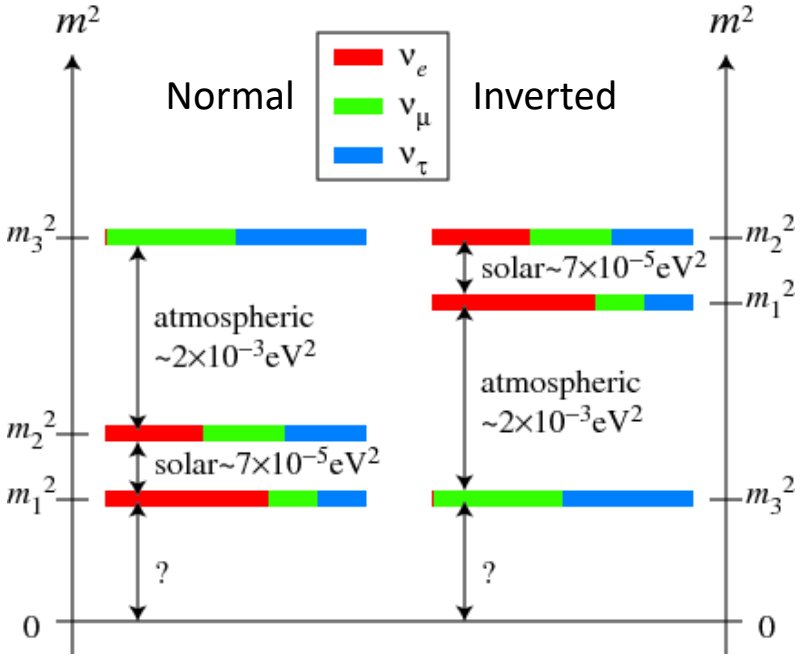
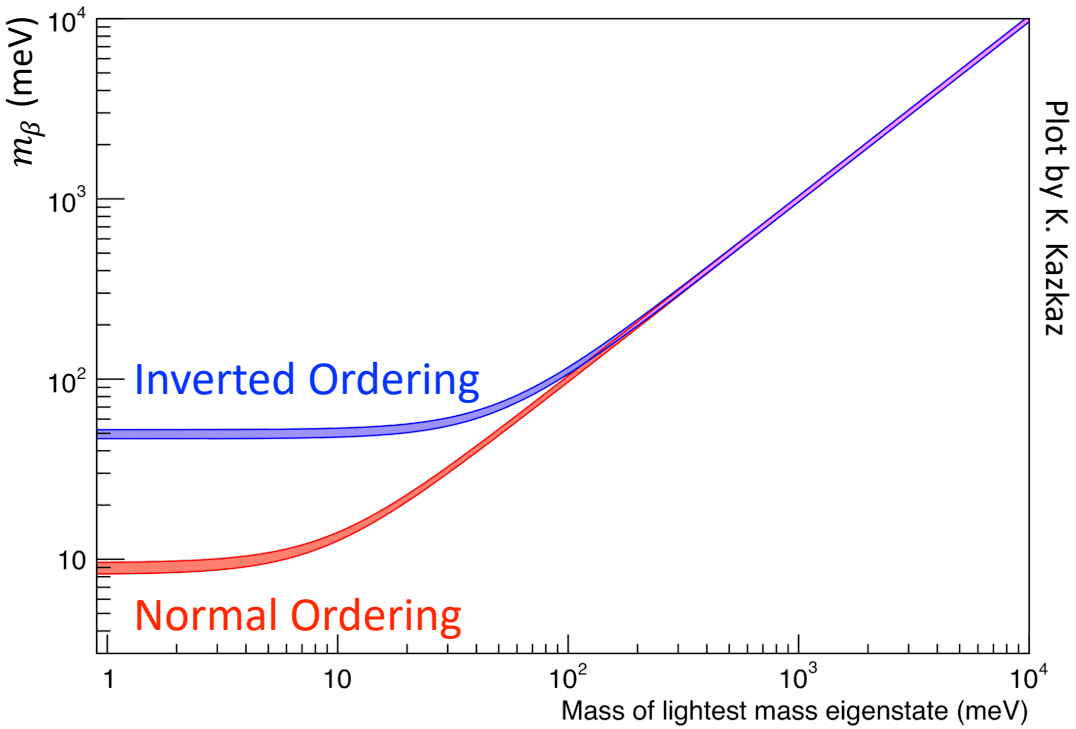
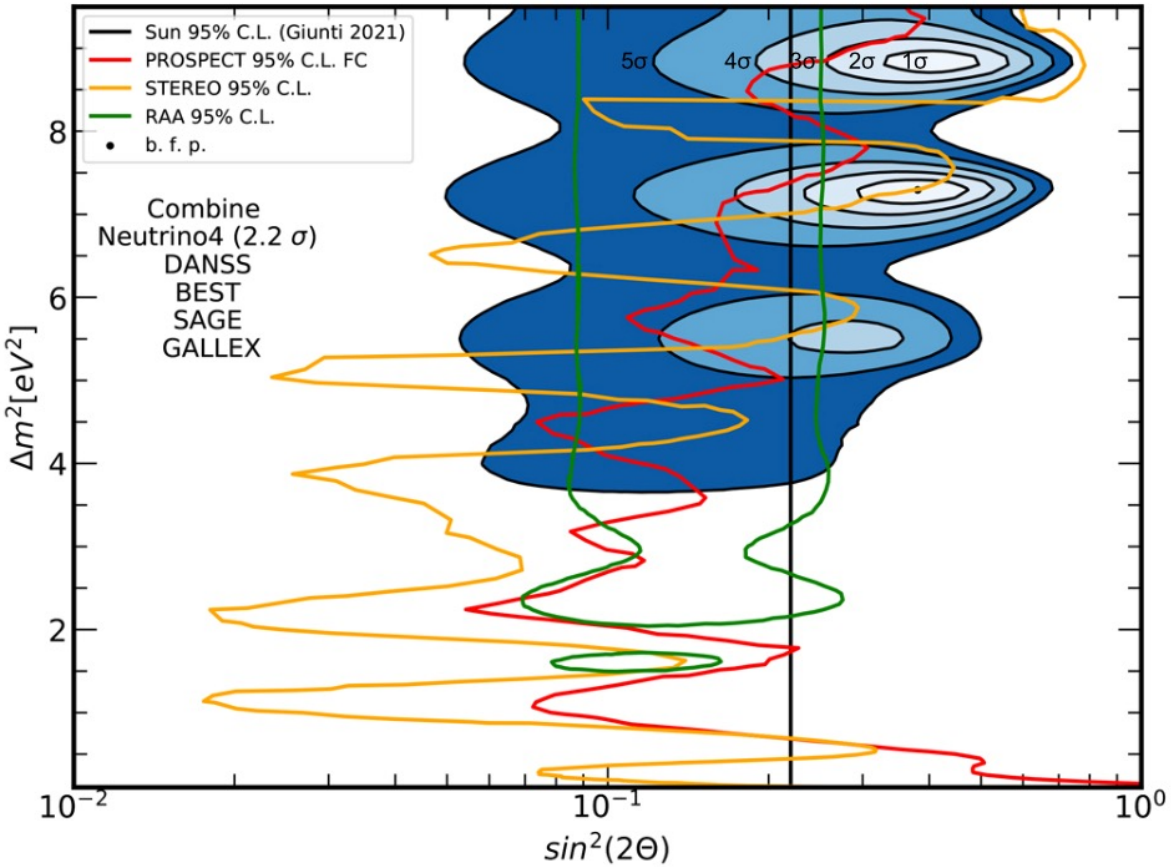


Fig from A. Nucciotti. AHEP (2016) doi:10.1155/2016/9153024



Could there be sterile neutrinos?

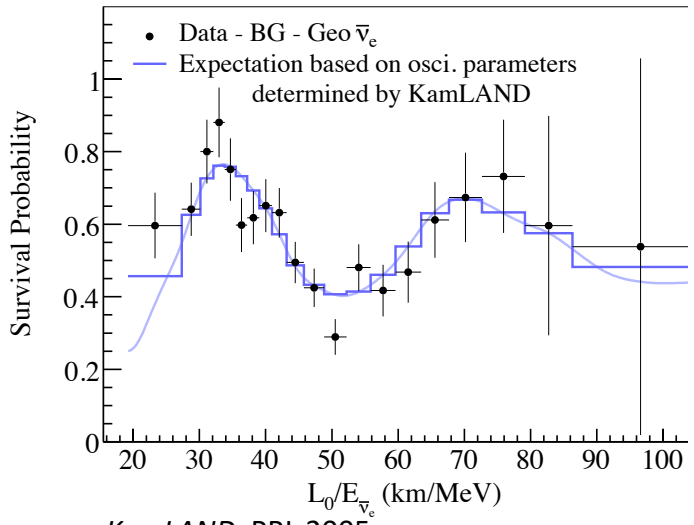
- Sterile neutrinos are a proposed particle that do not interact via the weak force, but may mix with the "active" neutrinos
- Suggestions of sterile neutrino in few-eV range from several types of experiments:
  - Reactor neutrino anomaly
  - Gallium anomaly (BEST)
  - Neutrino-4 short baseline
- keV sterile neutrinos (different from eV-scale shown at right) are also a dark matter candidate



Barinov, V. & Gorbunov, D. BEST Impact on Sterile Neutrino Hypothesis. *arXiV* (2021).

Probes of the physics of neutrino mass

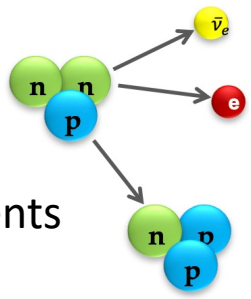
Oscillation experiments
(reactor, solar, accelerator)



KamLAND, PRL 2005

$$P_{\alpha\to\beta} = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Direct
(endpoint)
mass
measurements



$$m_\beta \equiv \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 m_i{}^2}$$

Cosmology $\sum m_\upsilon \equiv \sum_{i=1}^{3} m_i$

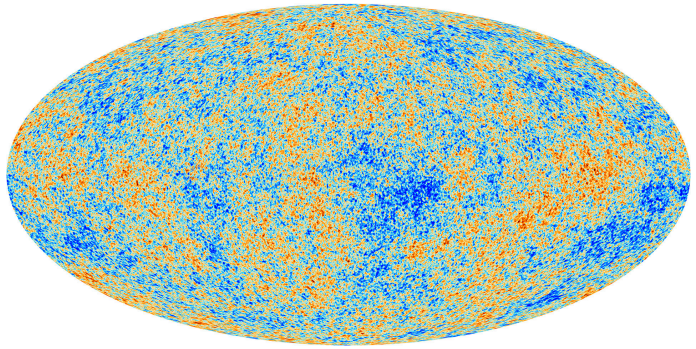
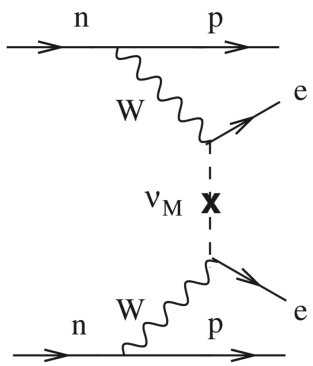


Image: ESA and the Planck Collaboration

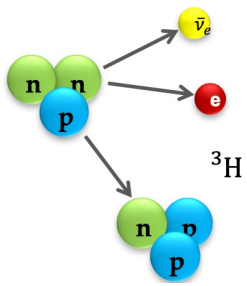
Neutrinoless
double beta
decay



$$\langle m_{\beta\beta}\rangle = \left|\sum_{i=1}^{3} U_{ei}^2 m_i\right|$$

What do “direct” neutrino mass experiments measure?

Beta decay of tritium

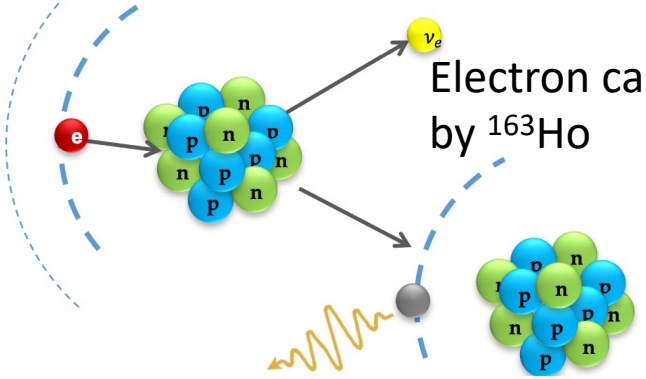


$^{3}\mathrm{H} \rightarrow {}^{3}\mathrm{He}^{+} + e^{-} + \bar{\nu}_e$

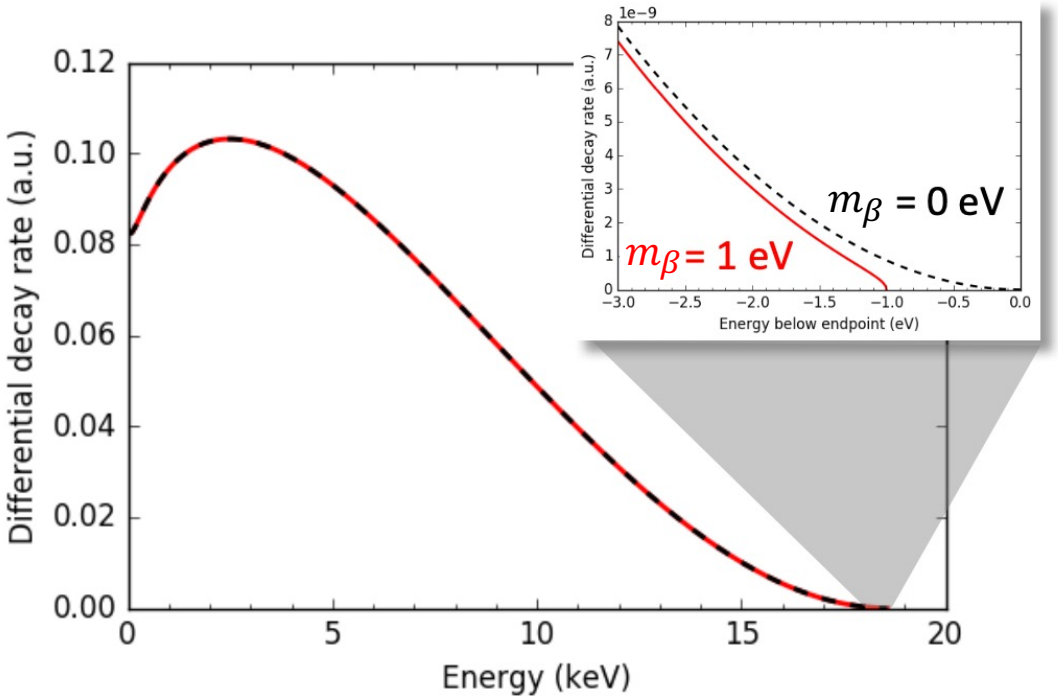
$$m_\beta \equiv \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 m_i{}^2}$$

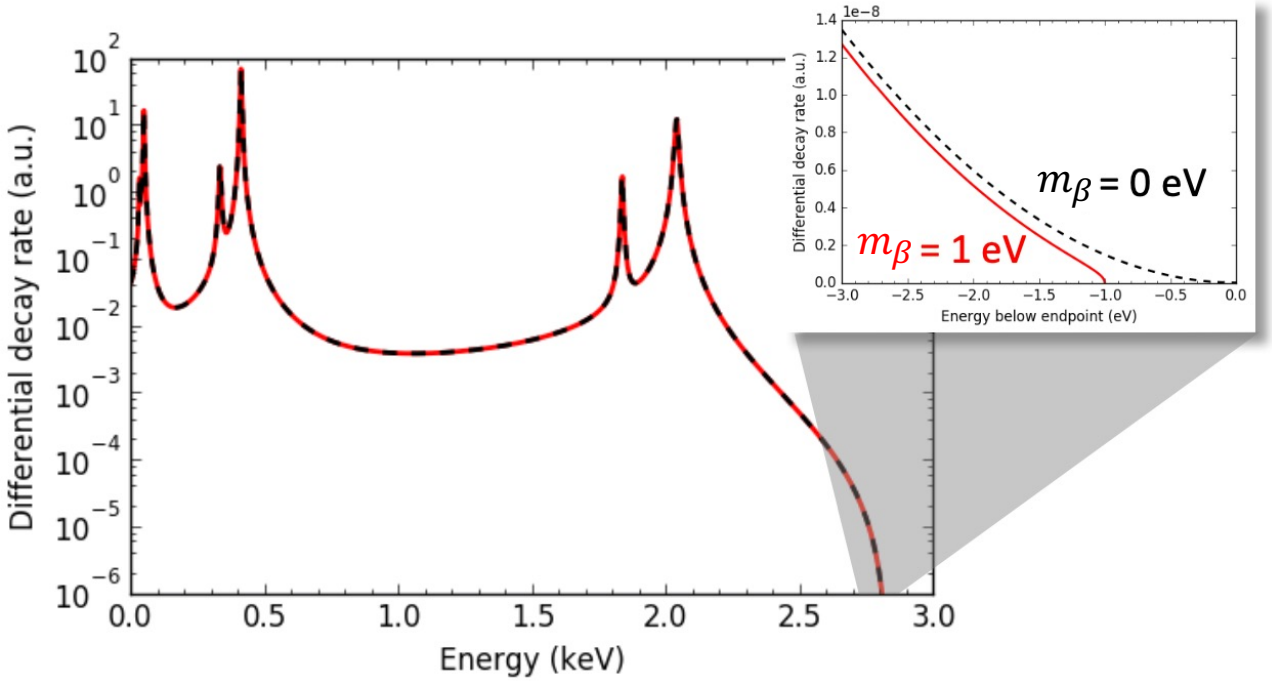
$^{163}\mathrm{Ho} \rightarrow {}^{163}\mathrm{Dy}^{*} + \nu_e$

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



Electron capture by ^{163}Ho





Figures courtesy of Susanne Mertens

Comparing neutrino mass observables

Cosmology

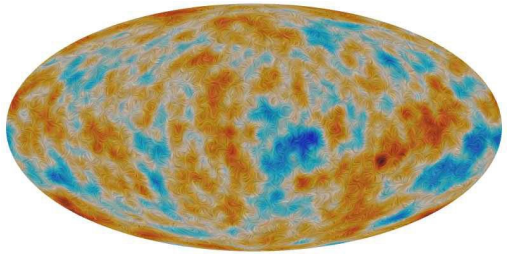
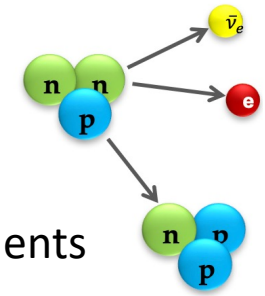


Image: cmb-s4.org

ΛCDM
+ Standard Model
+ neutrino masses

$$\sum m_\upsilon \equiv \sum_{i=1}^{3} m_i$$

Direct
(Endpoint)
Mass
Measurements



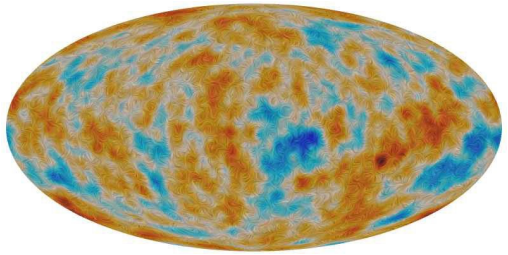
Standard Model
+ neutrino masses

$$m_\beta \equiv \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 {m_i}^2}$$

- Note: $\sum_{i=1}^{3} |U_{ei}|^2 = 1$, so in the degenerate mass regime where $m_\beta \gtrsim 200$ meV, $\sum m_\upsilon \approx 3m_\beta$

Direct mass measurements and ΛCDM

Cosmology



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Direct
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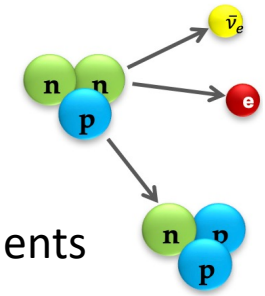
Mass
Measurements



Standard Model
+ neutrino masses

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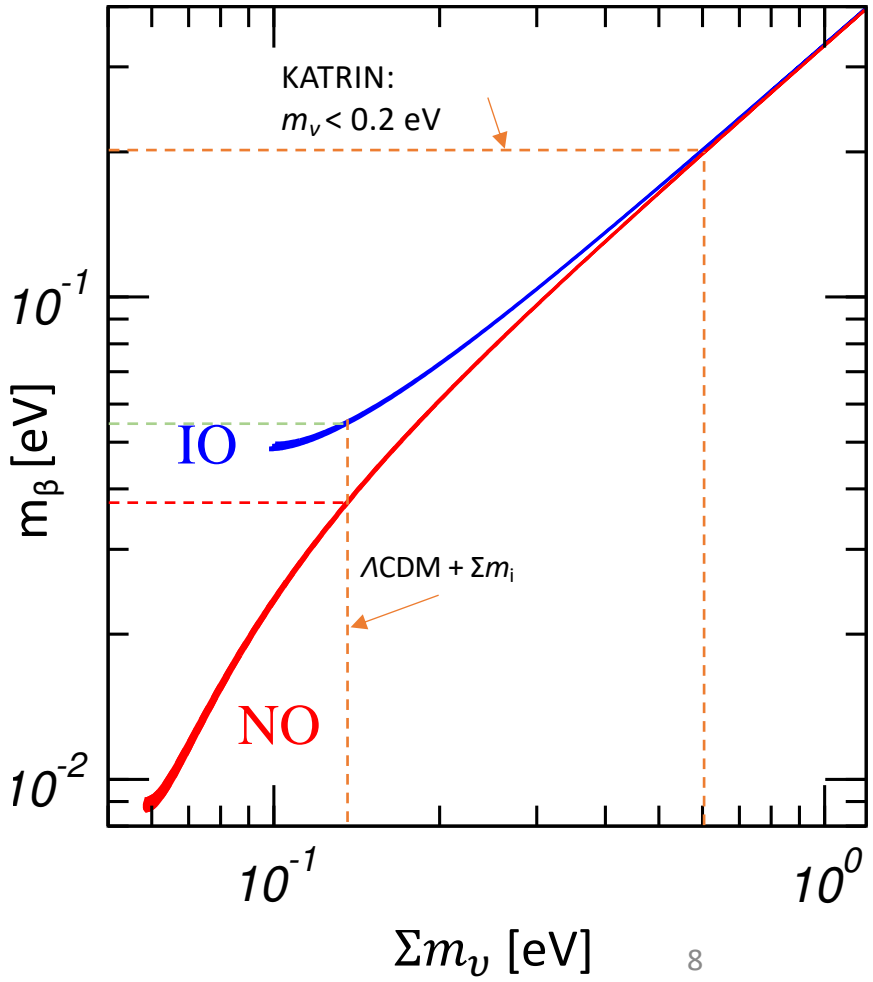
NuFIT 4.1 (2019) www.nu-fit.org,
Esteban *et* al., JHEP 106 (2019).



Complementarity within the framework of ΛCDM+SM+m_υ:

- Independent measurements with completely different systematics
- Breaking degeneracies between ΛCDM parameters (e.g., $\sum m_\upsilon$ and τ)

Direct mass measurements and extensions to ΛCDM

Cosmology

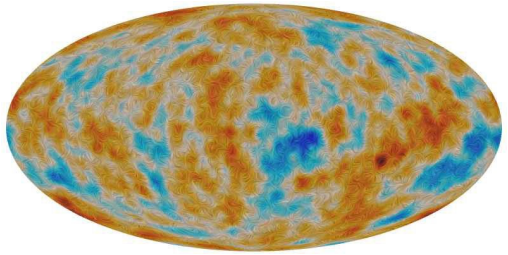


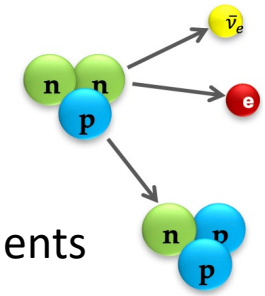
Image: cmb-s4.org

ΛCDM
+ Standard Model
+ neutrino masses

$$\sum m_\upsilon \equiv \sum_{i=1}^{3} m_i$$

Tests of ΛCDM +SM+m_υ

Direct (Endpoint) Mass Measurements



Standard Model
+ neutrino masses

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NuFIT 4.1 (2019) www.nu-fit.org,
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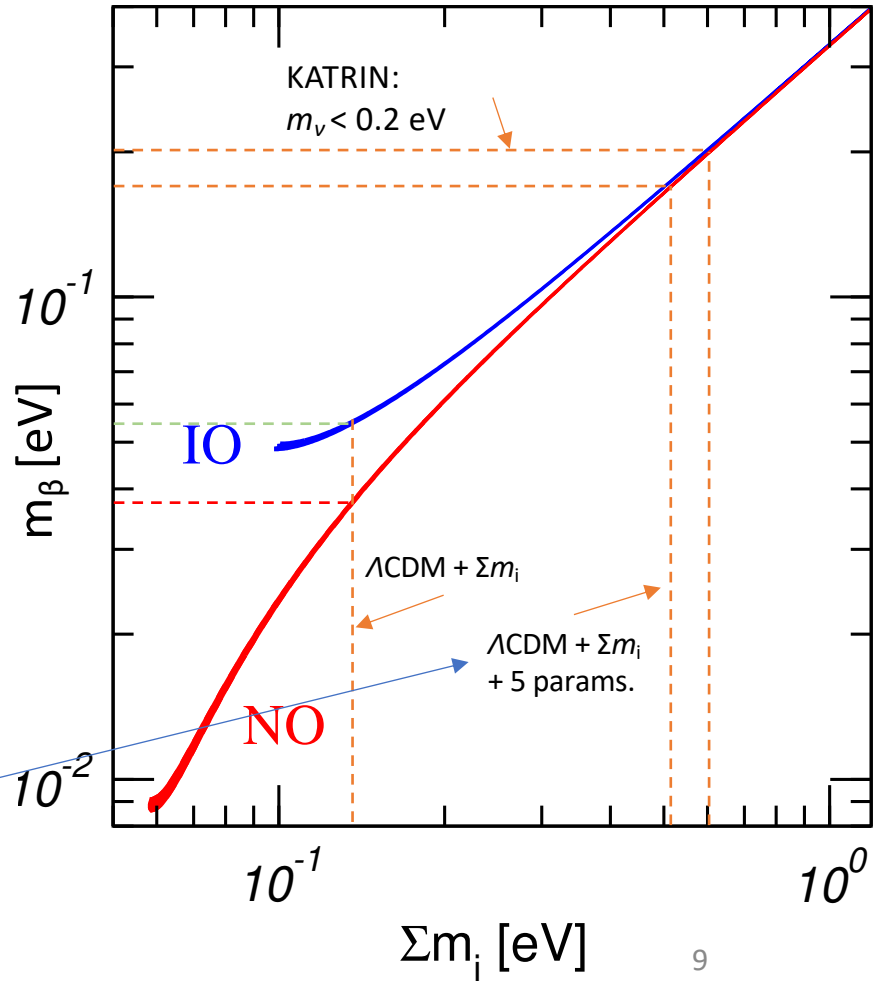


- If measured $\sum m_\upsilon$ & m_β not compatible, clues to physics & cosmology beyond ΛCDM+SM+m_υ
- Relationship of $\sum m_\upsilon$, m_β is relaxed in some beyond ΛCDM+SM+m_υ theories

Direct mass measurements and extensions to ΛCDM

Cosmology

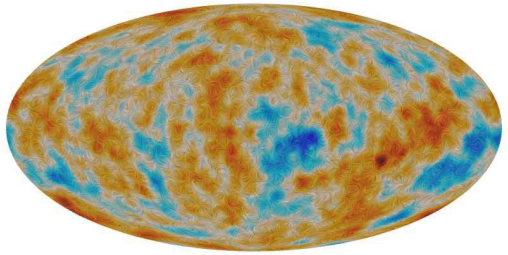


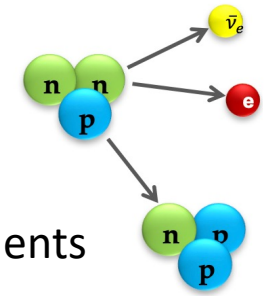
Image: cmb-s4.org

ΛCDM
+ Standard Model
+ neutrino masses

$$\sum m_\upsilon \equiv \sum_{i=1}^{3} m_i$$

Tests of ΛCDM +SM+m_υ

Direct (Endpoint) Mass Measurements



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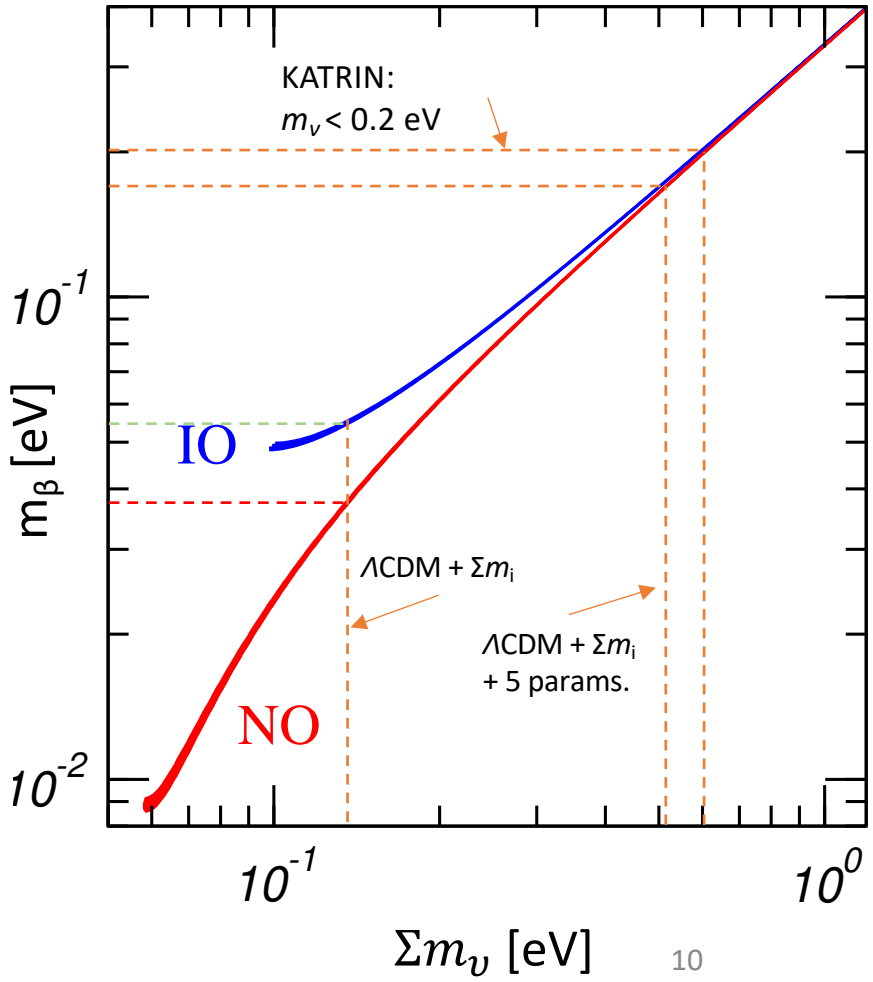
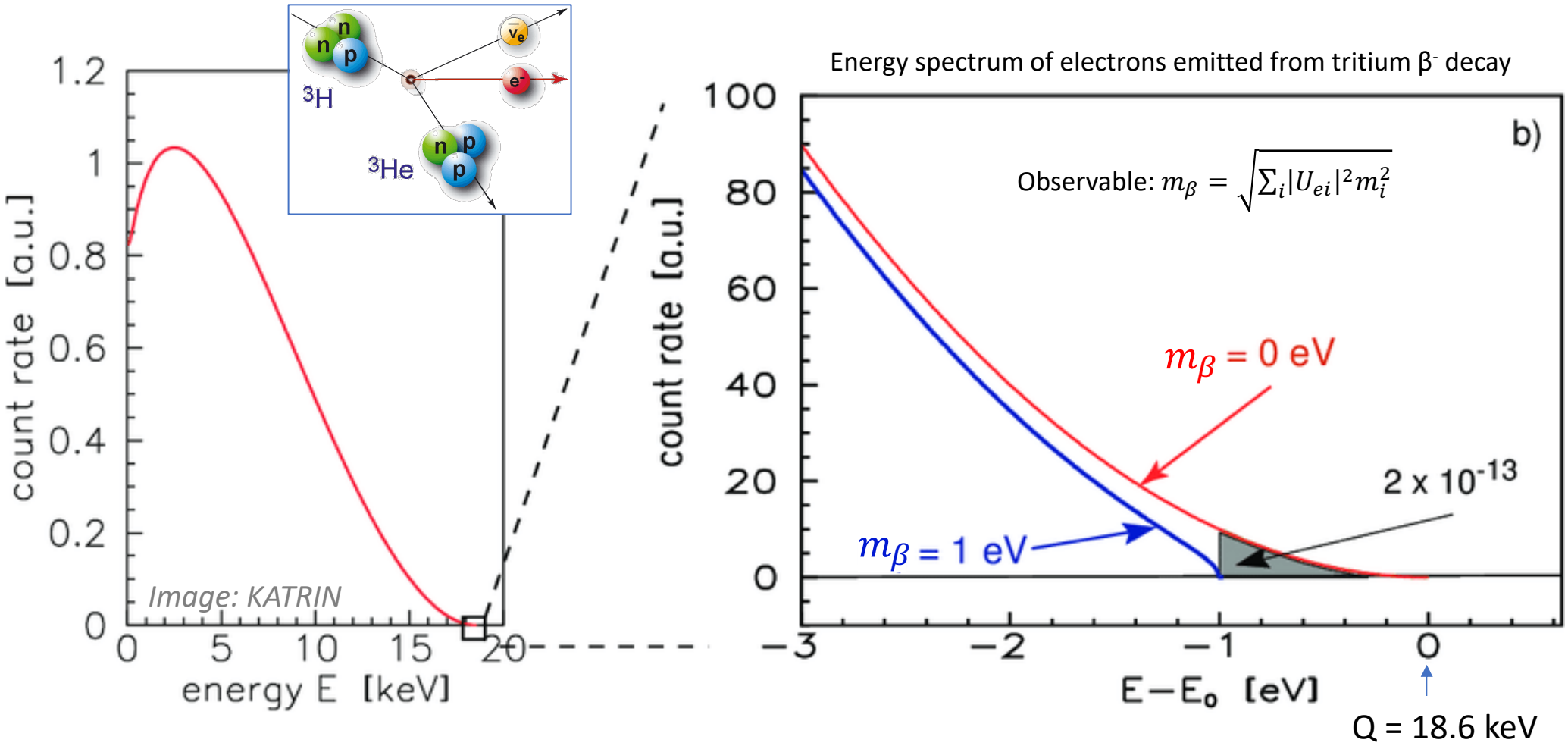


Some possible extensions to ΛCDM and the Standard Model that could affect measured Σm_υ:

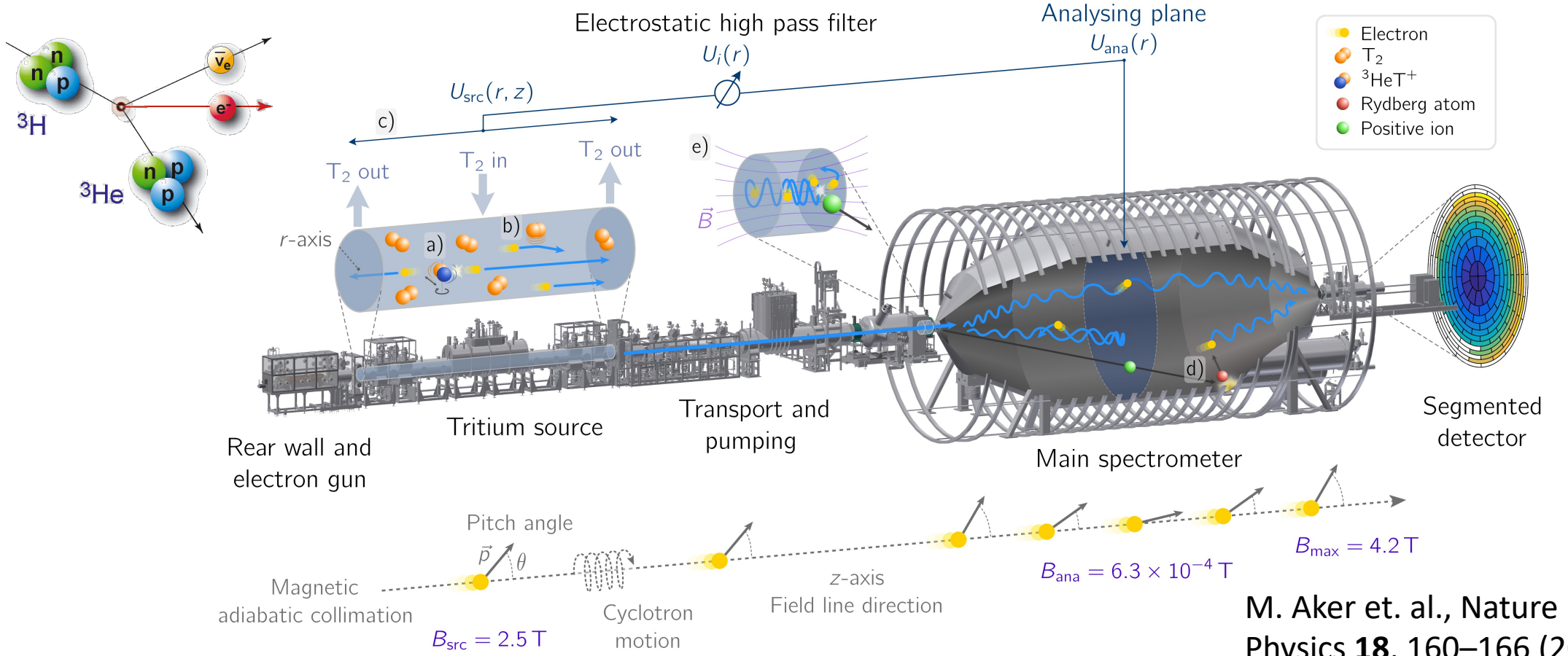
- ΛCDM + extra params (e.g., w_a, w_0, Ω_k...):
  - S. Mishra-Sharma, D. Alonso, and J. Dunkley, PRD **97**, 123544 (2018)
  - R. Allison, P. Caucal, E. Calabrese, J. Dunkley, and T. Louis, PRD **92**, 123535 (2015)
  - E. Di Valentino, A. Melchiorri, and J. Silk, PRD **92**, 121302 (2015)
- ν decay: Z. Chacko et. Al., PRD 103, 043519 (2021)
- ν self-interaction: C. D. Kreisch, F.-Y. Cyr-Racine, and O. Doré, PRD **101**, 123505 (2020).
- ν-dark energy interactions: J. Sakstein and M. Trodden, PRL **124**, 161301 (2020).

The last two ideas are also motivated by the Hubble tension.

Tritium β⁻ spectroscopy is the leading technique for direct neutrino mass measurements



KATRIN's MAC-E integral spectrometer

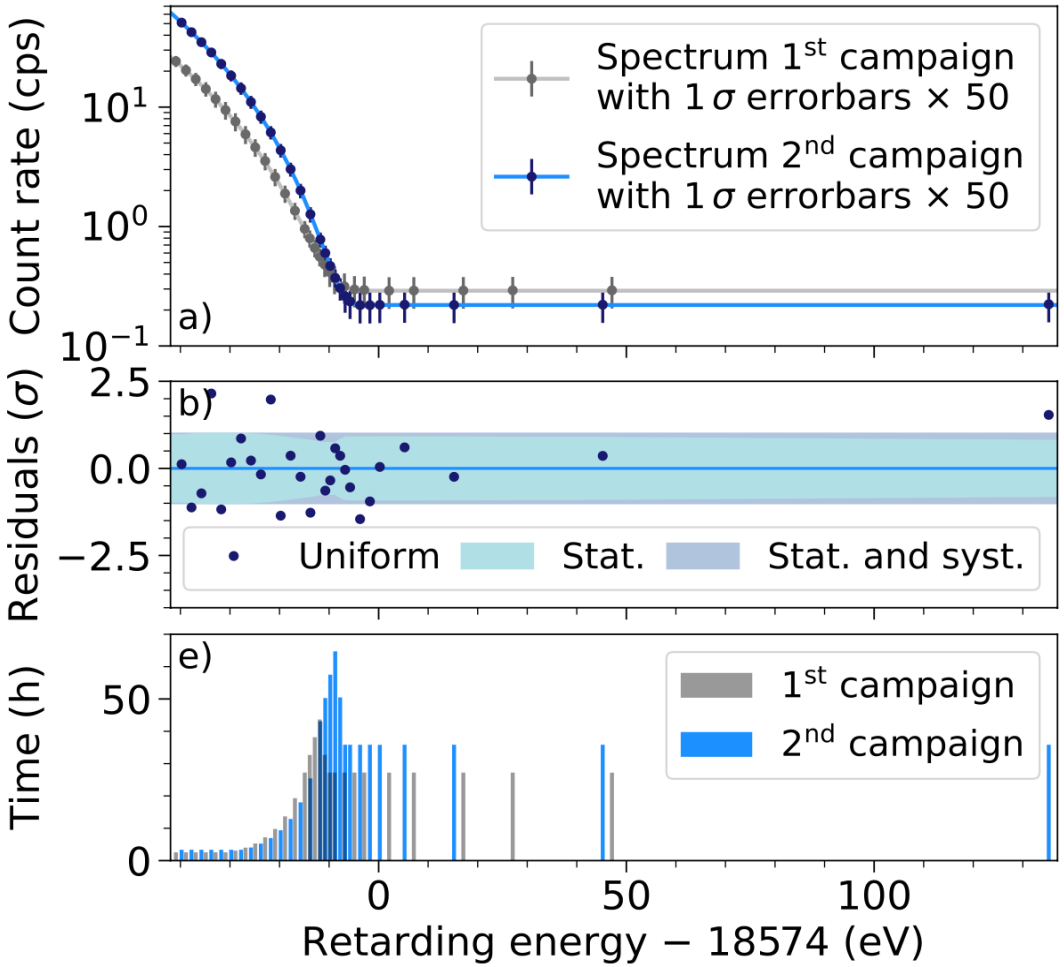


M. Aker et. al., Nature Physics **18**, 160–166 (2022)

The KATRIN experiment sets the best direct neutrino mass limit

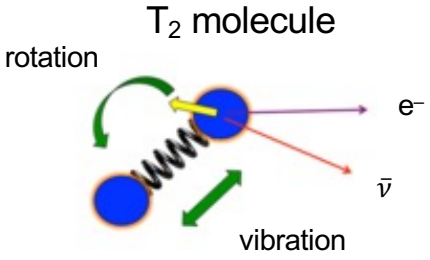
$m_\beta \leq 0.8$ eV/c^2 (90% CL)

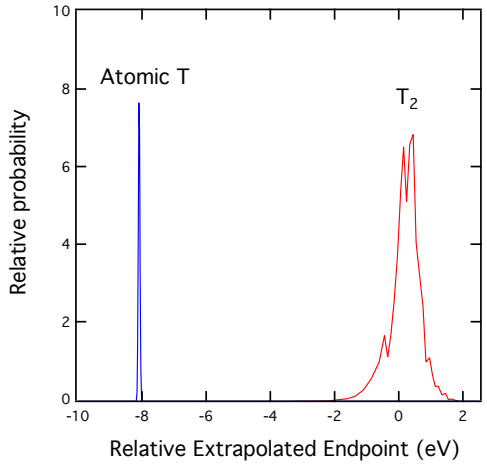
KATRIN Collab, *Nat. Phys.* **18,** 160–166 (2022)



Challenges for future tritium β^- experiments

- KATRIN is designed to reach an ultimate sensitivity of 200 meV/c^2 in 2025
- Statistical sensitivity to m_β scales as ~$1/N^{1/4}$
  - Existing detector technology has reached limit of scalability
- MAC-E filter method subject to backgrounds from slow electrons
- Irreducible systematics associated with molecular final states at ~100 meV
- If the mass is smaller, is there a way to access it?

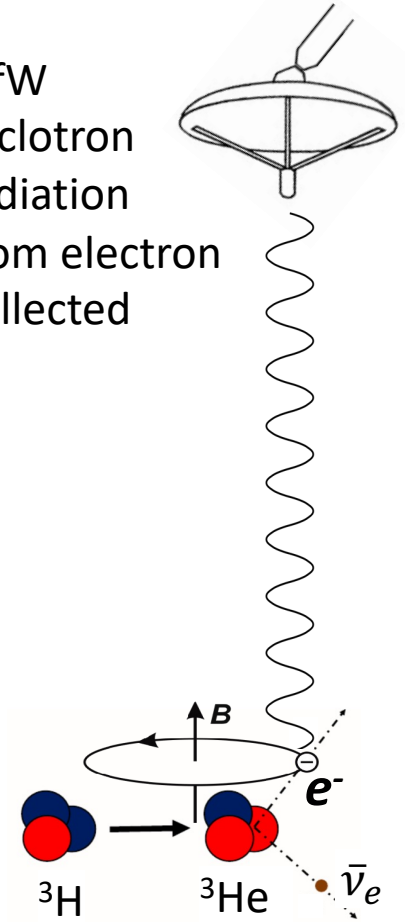




J. Formaggio, A. L. C. De Gouvêa, and R. G. H. Robertson, Physics Reports 914 (2021) 1–54

A new approach: Cyclotron Radiation Emission Spectroscopy (CRES)

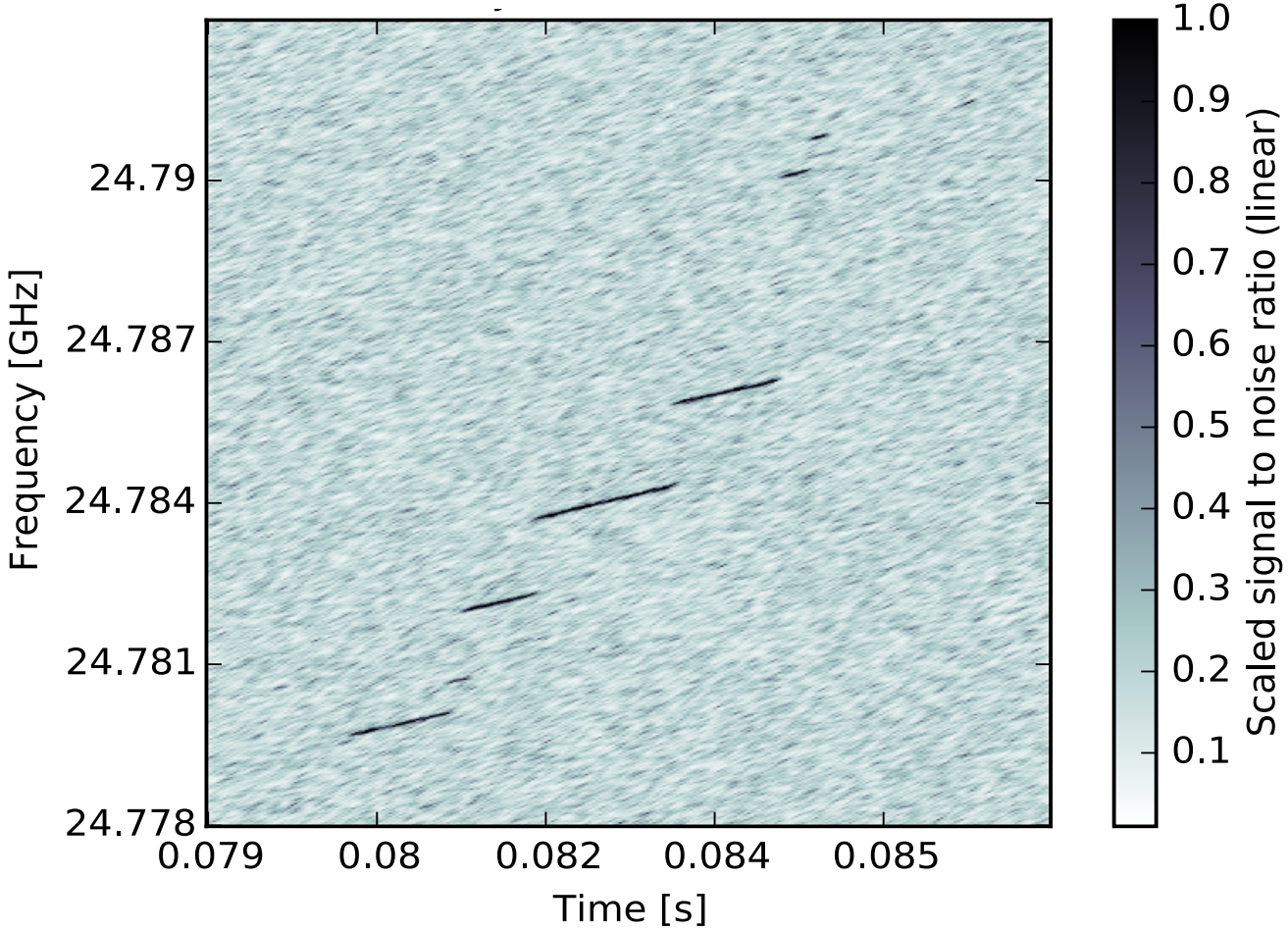
1 fW cyclotron radiation from electron collected



Electron undergoes cyclotron motion in magnetic field

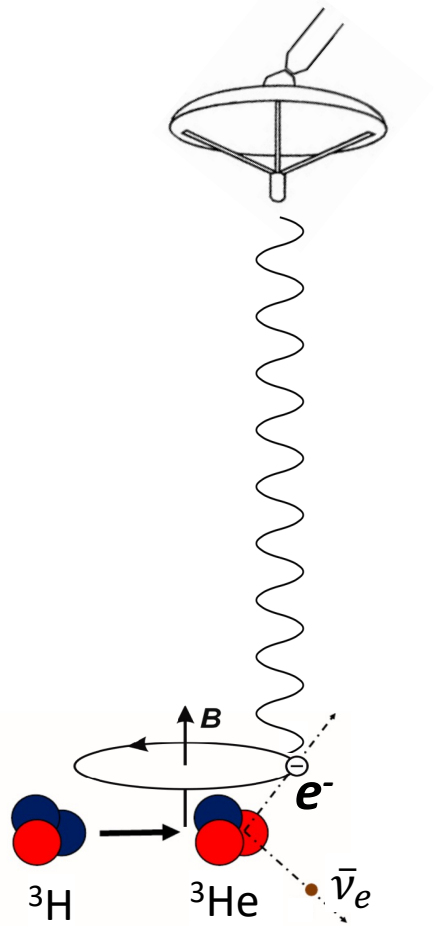
Electron produced in beta decay

Fourier-transform →

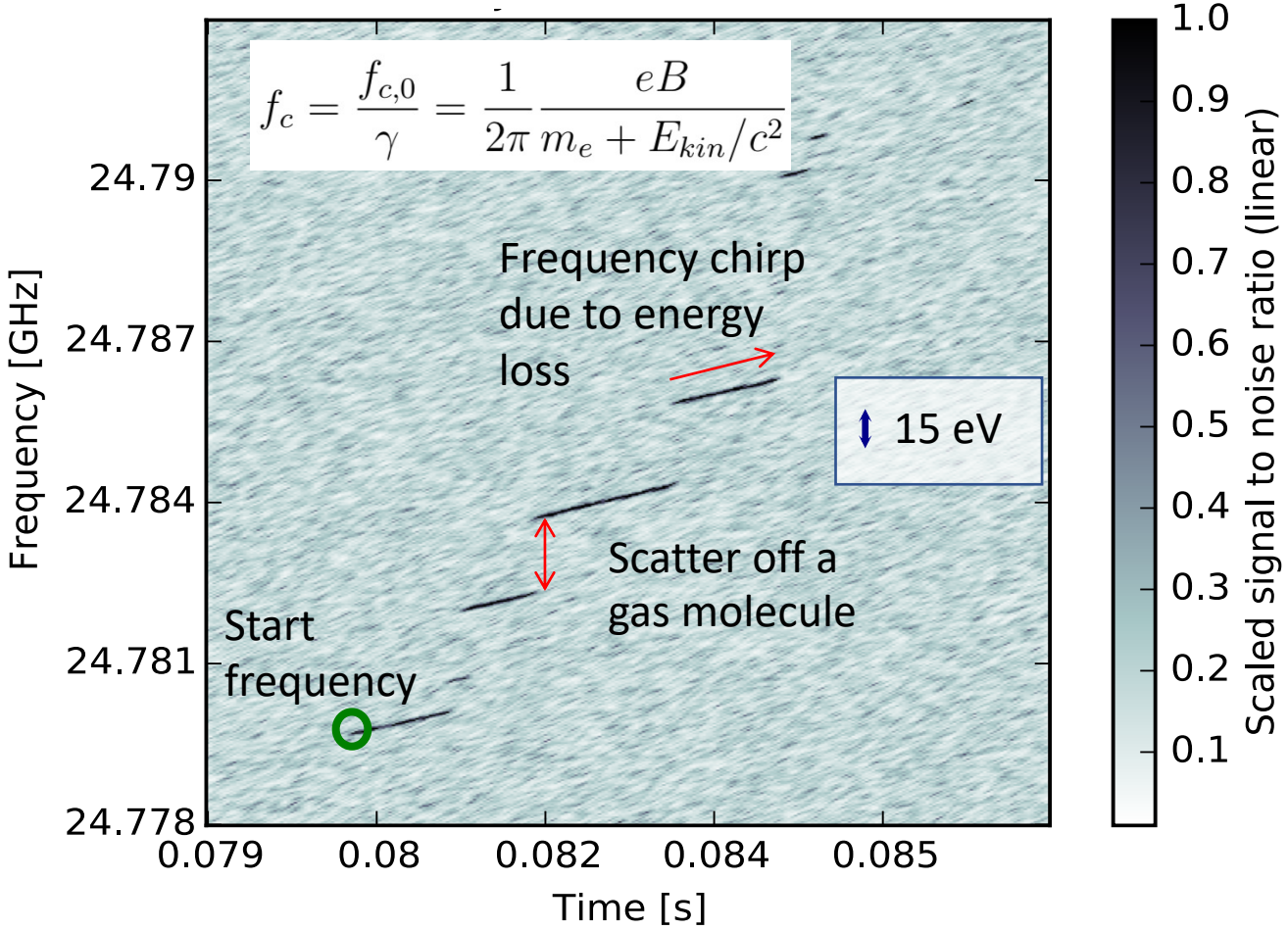


First proposal of CRES: B. Monreal and J. Formaggio, Phys. Rev. D 80, 051301(R) (2009)

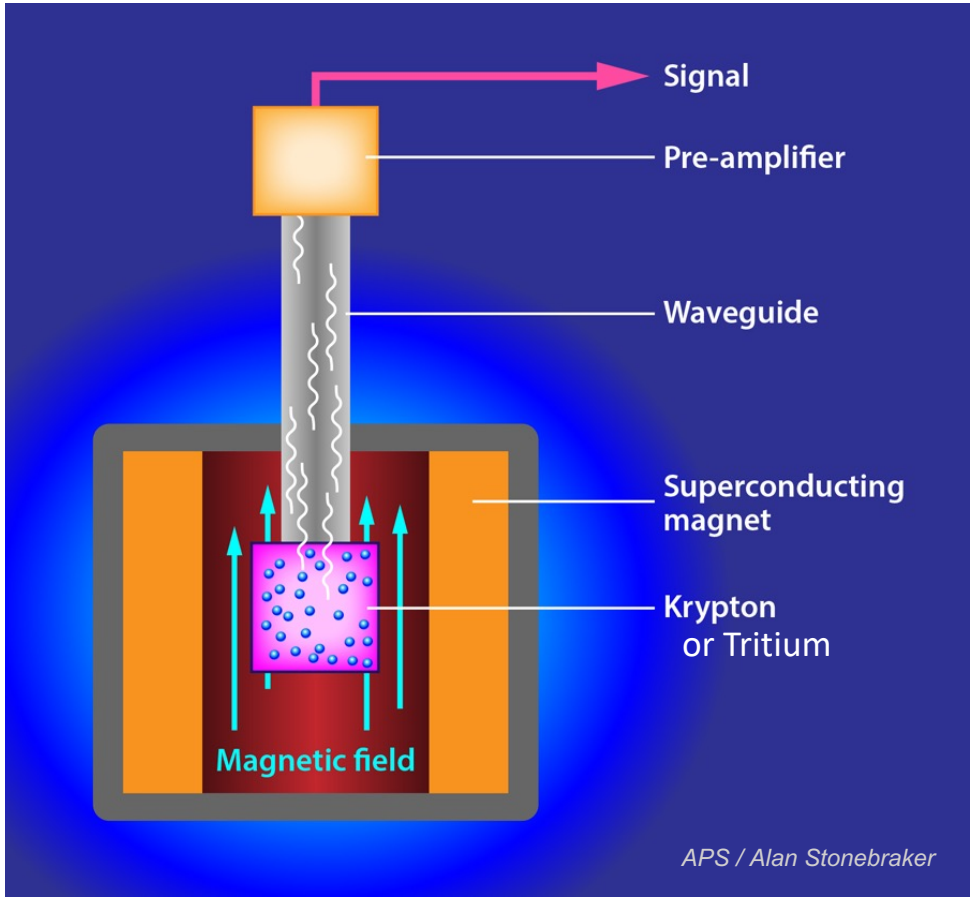
A new approach:
Cyclotron Radiation Emission Spectroscopy (CRES)

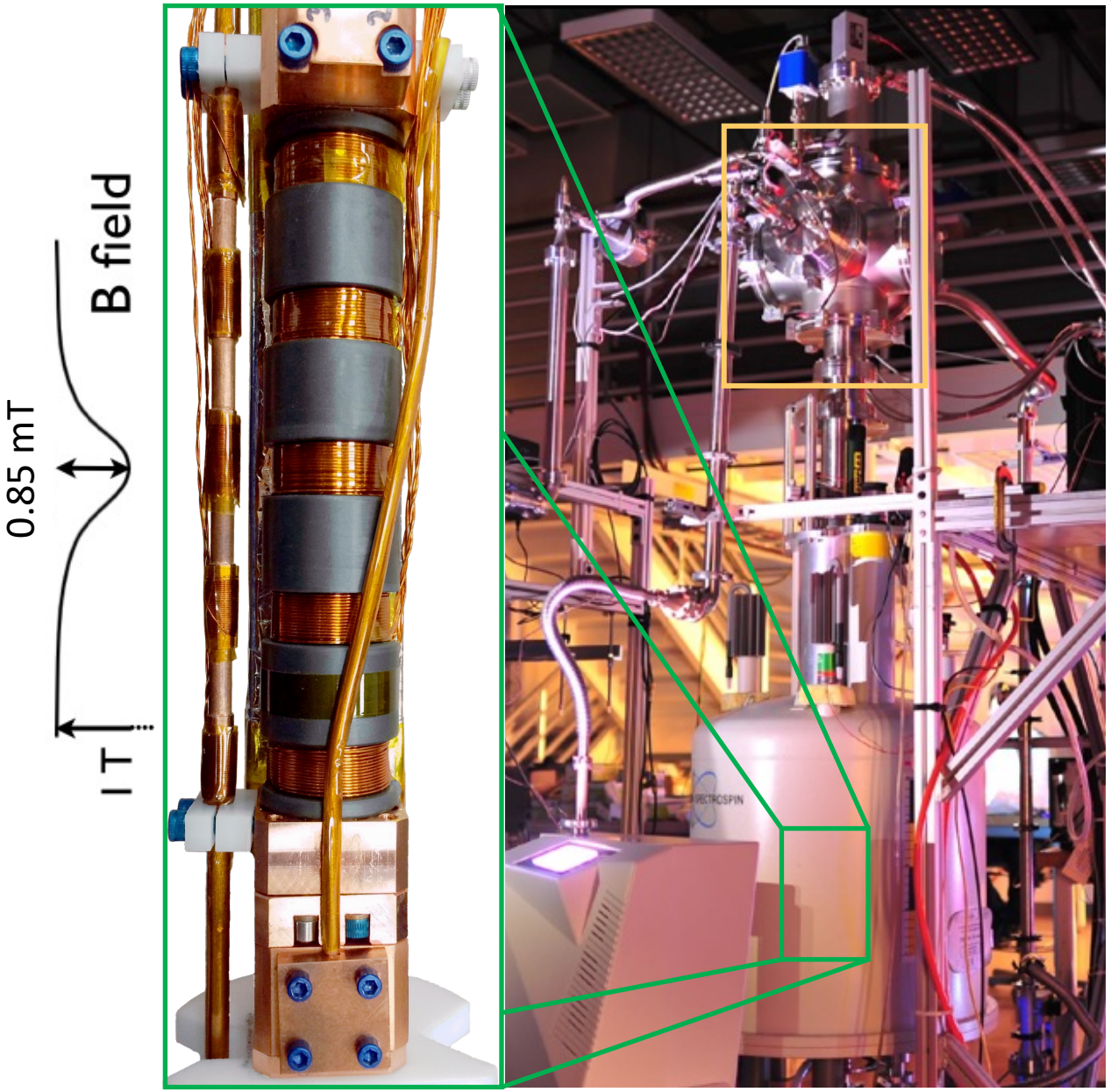


Fourier-transform →



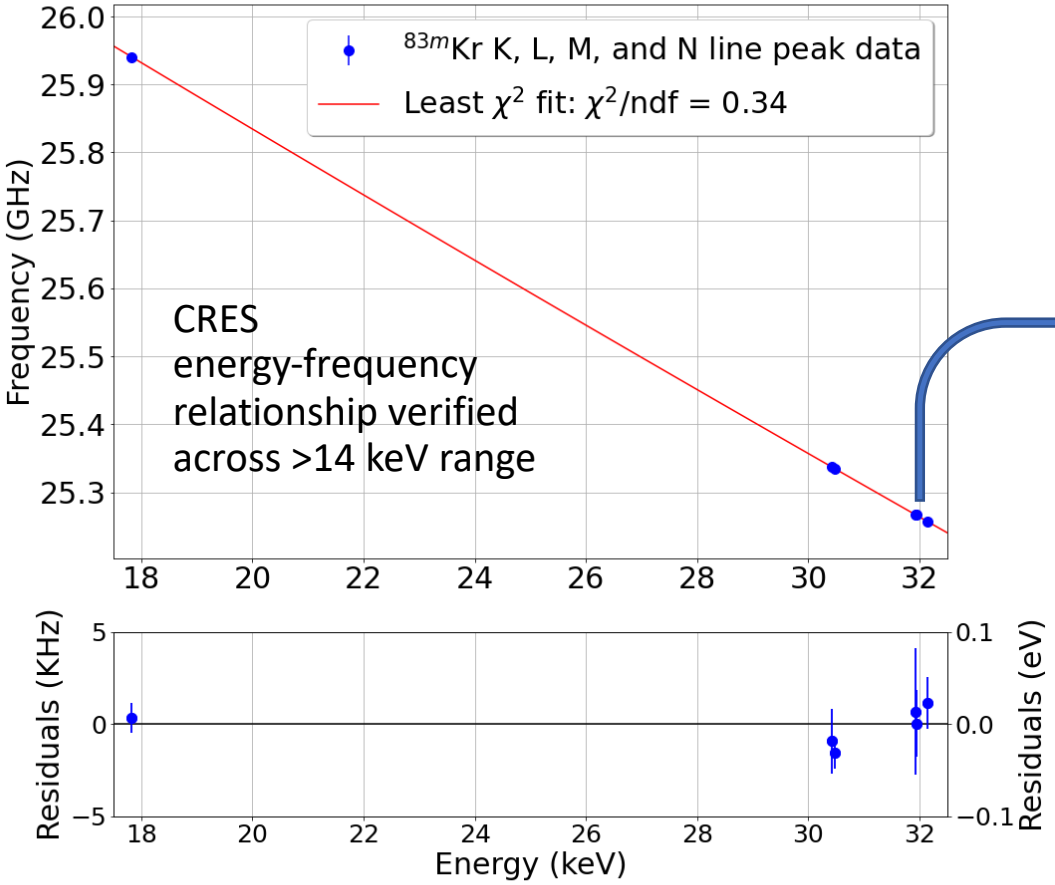
Project 8 Phase II: tritium spectrum with 1 mm^3 effective volume apparatus



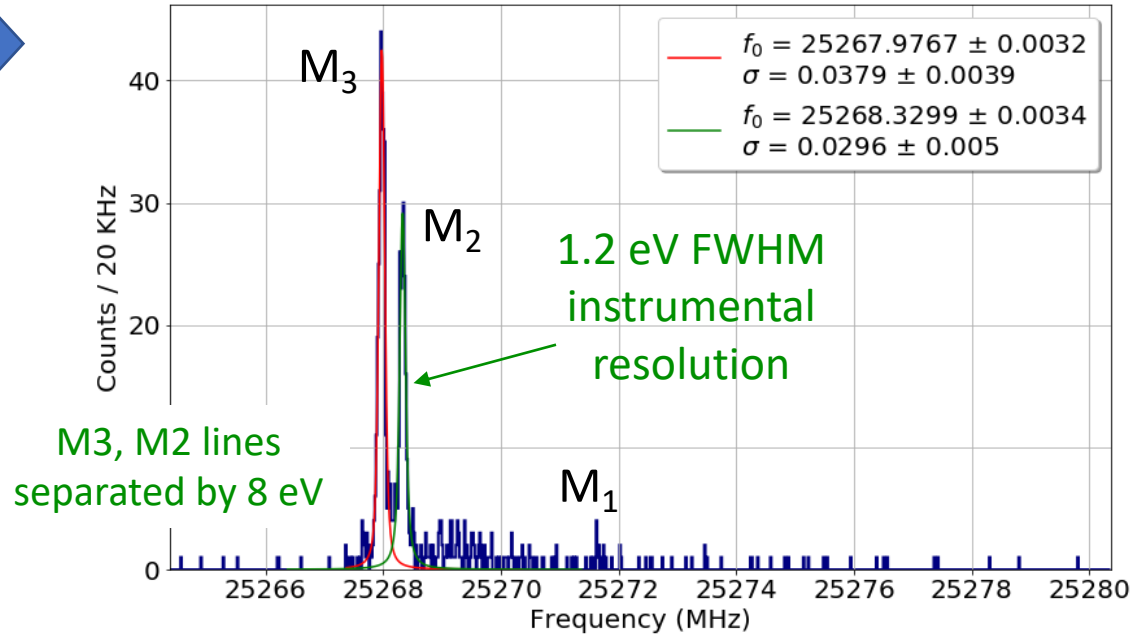


^{83m}Kr measurements reveal eV-scale resolution

Monoenergetic conversion electrons at 18, 30, 32 keV, bookending the 18.6 keV tritium endpoint
Allow for magnetic field calibration, detector response characterization



$$f_c = \frac{f_{c,0}}{\gamma} = \frac{1}{2\pi}\frac{eB}{m_e + E_{kin}/c^2}$$



Phase II tritium spectroscopy results

- T_2 endpoint measurement in agreement with literature
- First neutrino mass measurement using CRES
- Demonstrated understanding of detector response, control of systematic effects from scattering & field inhomogeneity
- Stringent background limit—no events above endpoint!

T_2 endpoint

Frequentist: $E_0 = (18550^{+22}_{-18})$ eV (1σ)

Bayesian: $E_0 = (18553^{+17}_{-17})$ eV (1σ)

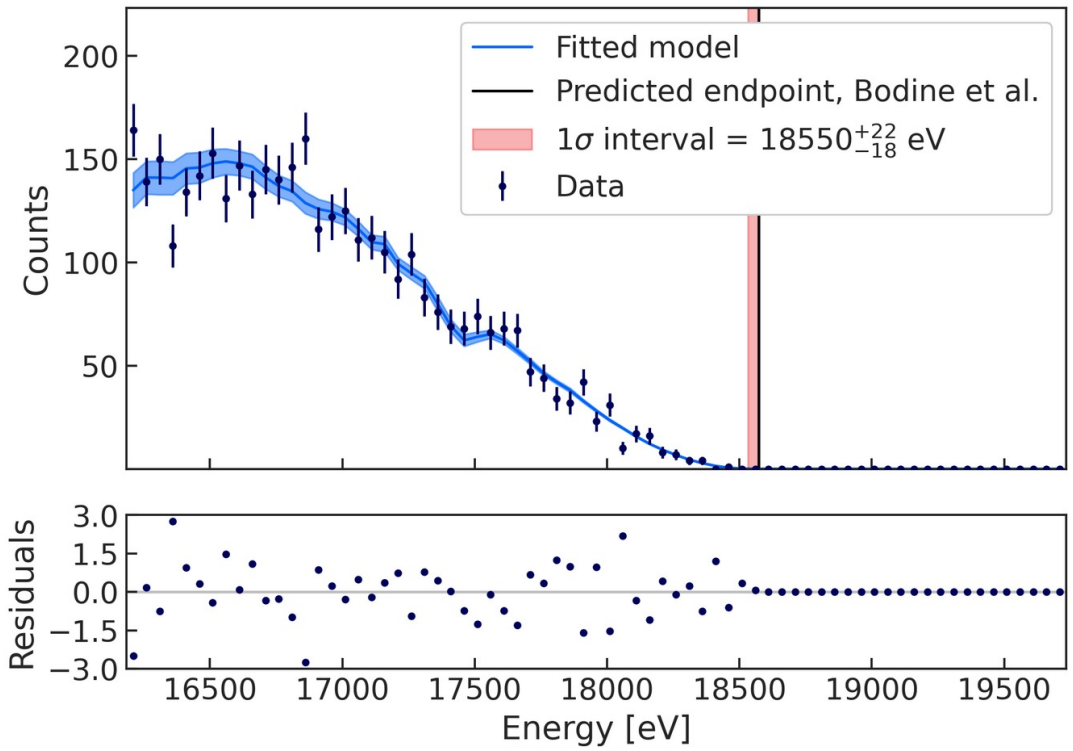
Neutrino mass

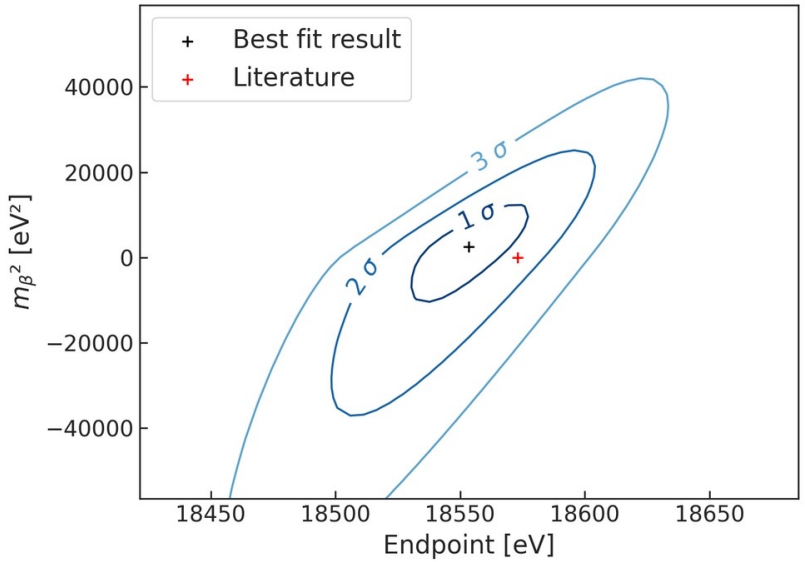
Frequentist: ≤ 178 eV/c² (90% C.L.)

Bayesian: ≤ 169 eV/c² (90% C.L.)

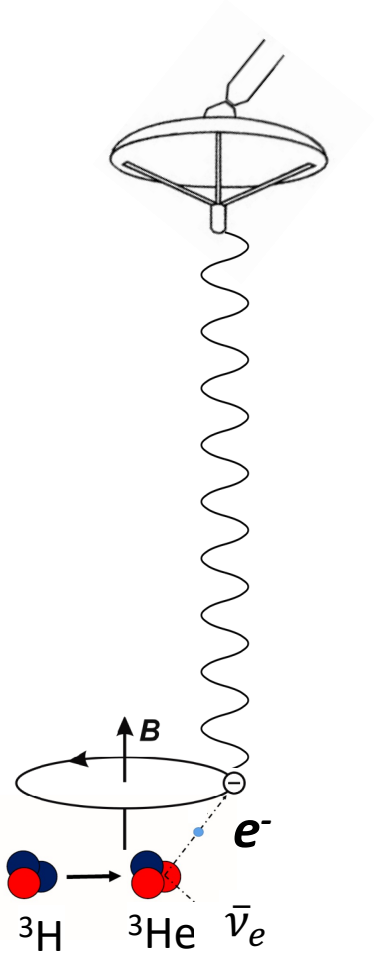
Background rate

$\leq 3\times10^{-10}$ eV^{-1}s^{-1} (90% C.I.)

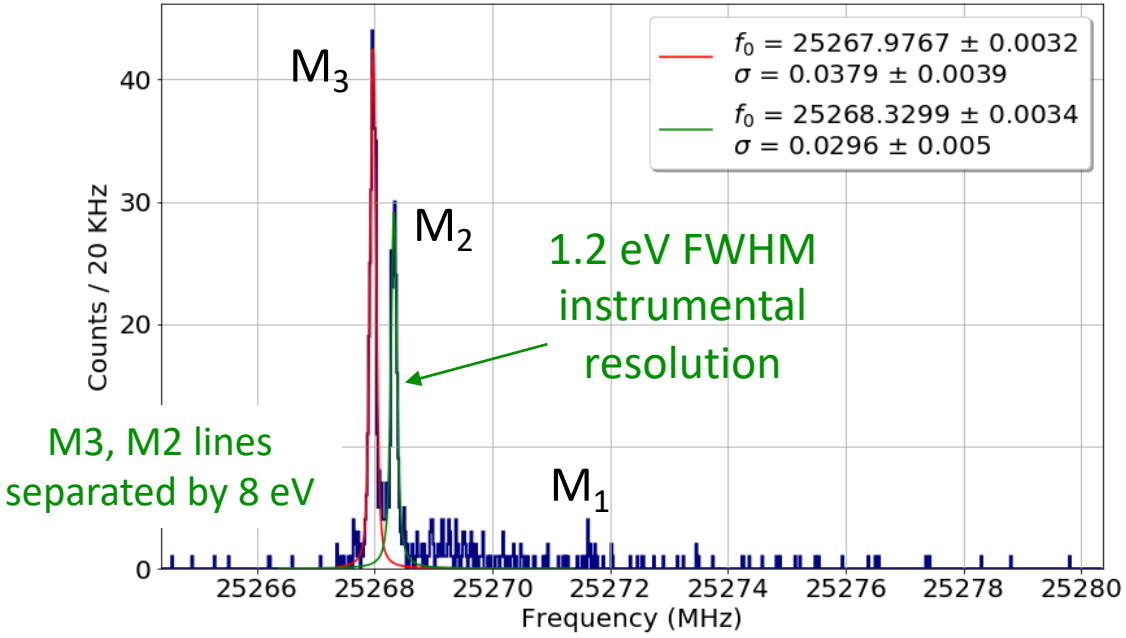




Advantages of CRES for tritium beta spectroscopy



Frequency measurement ➡ High precision



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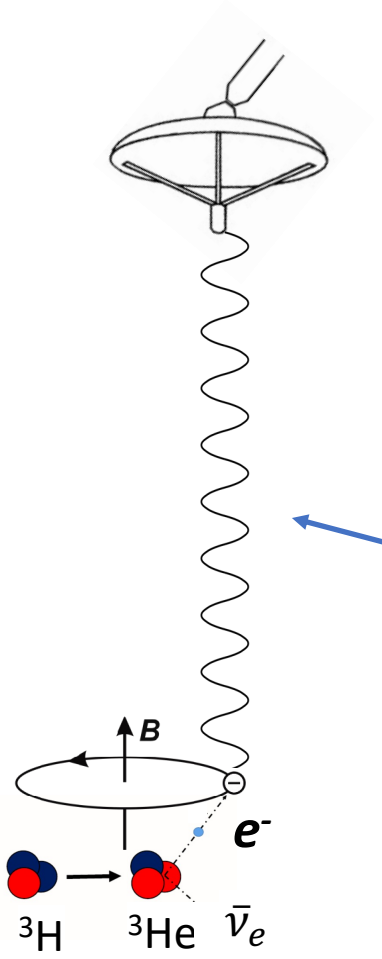
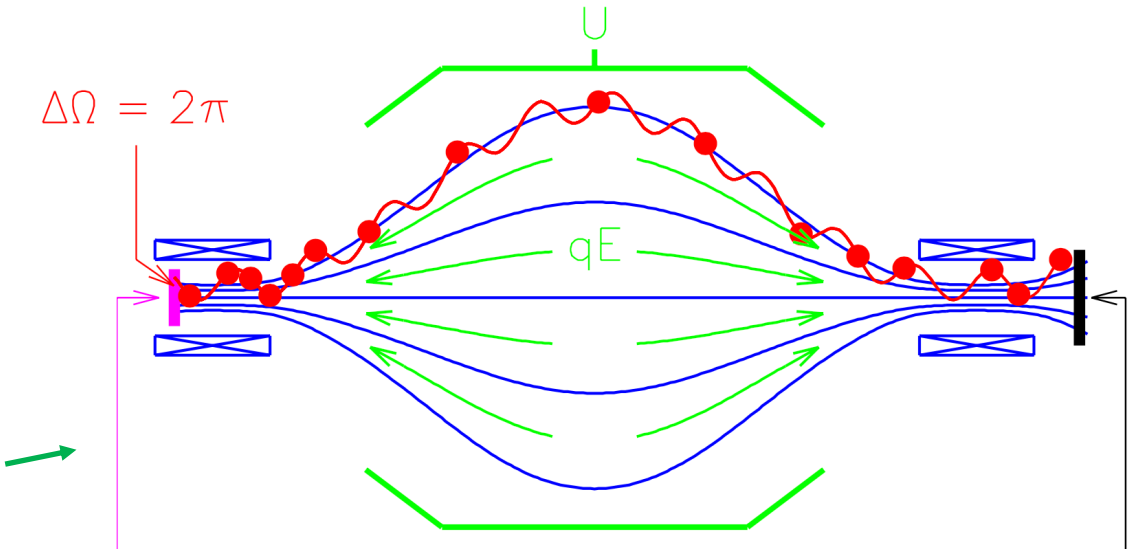


Source is transparent to microwave radiation → No electron transport; volume scaling

It's easier to listen to radio waves (like receiving a cell phone signal) than to transport an electron 10s of meters without perturbing its energy or letting the riffraff in!



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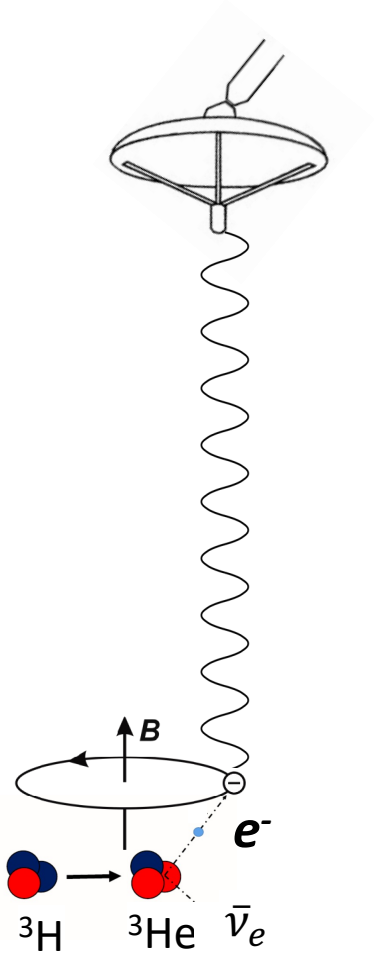
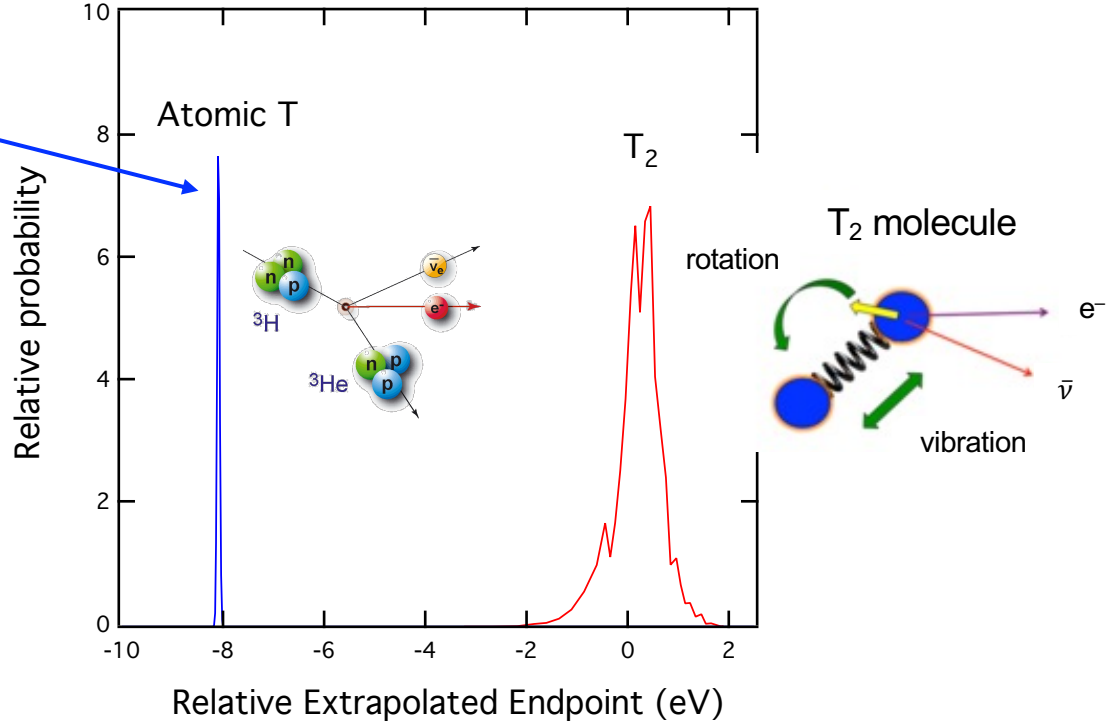


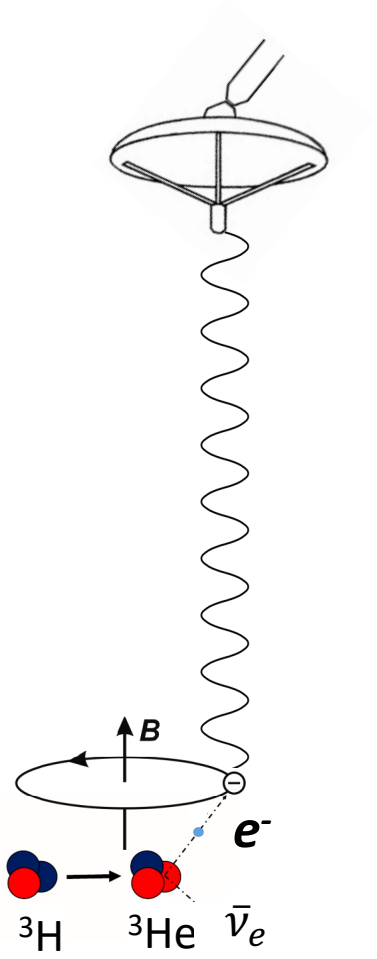
Potentially compatible with atomic tritium (T) → Avoids molecular tritium (T_2) final-state broadening

No rovibrational energy levels to worry about with atomic tritium

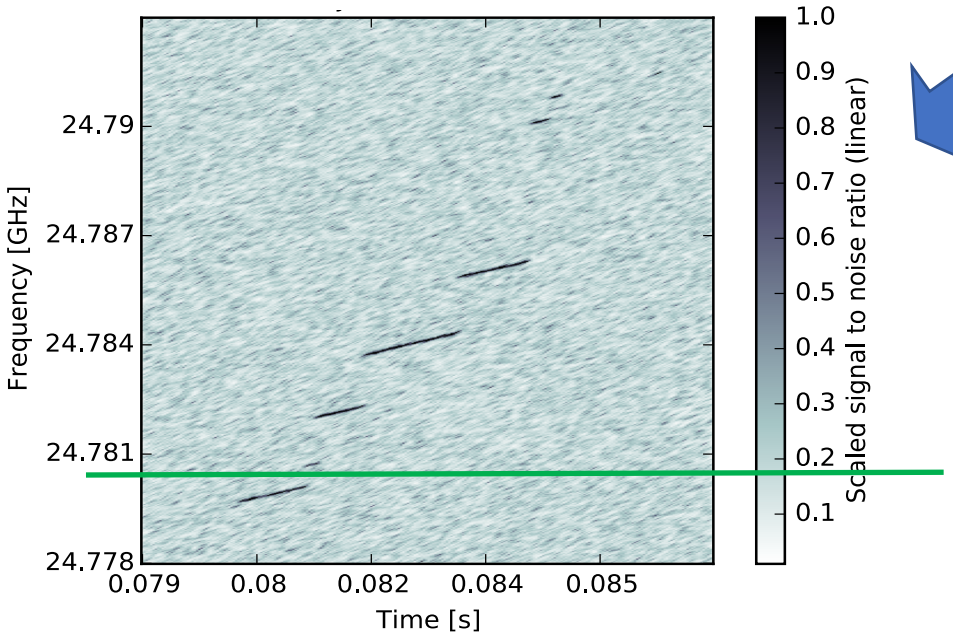
Need to trap the atomic tritium…



Advantages of CRES for tritium beta spectroscopy



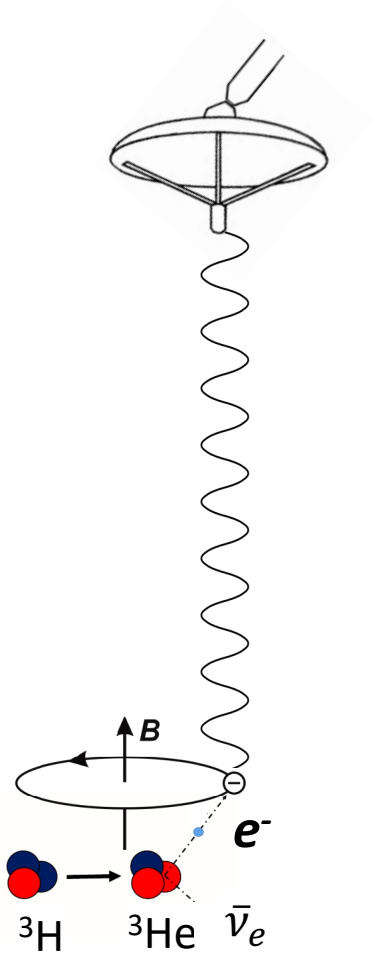
Differential spectrometer → Increased statistical efficiency



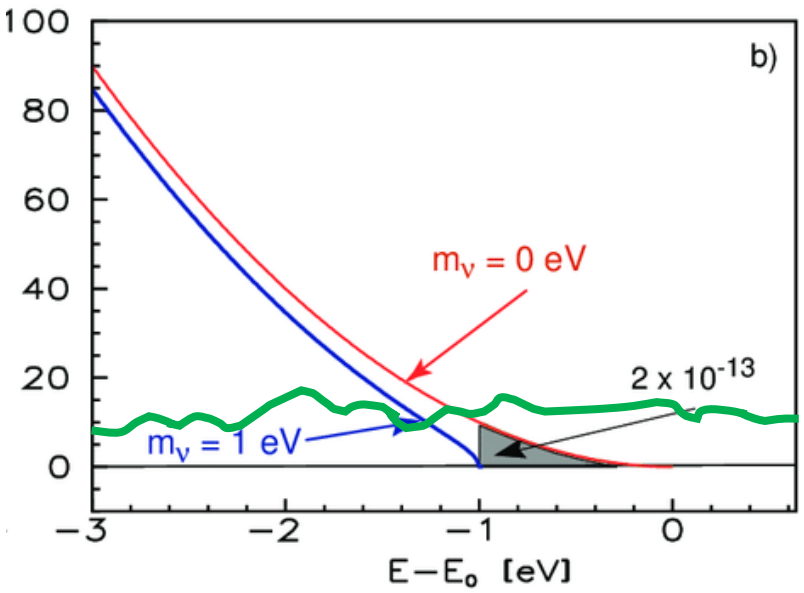
CRES can see this whole spectrum at once

A MAC-E spectrometer is a high-pass filter: can only tell if the electron's energy was greater than X for one X at a time

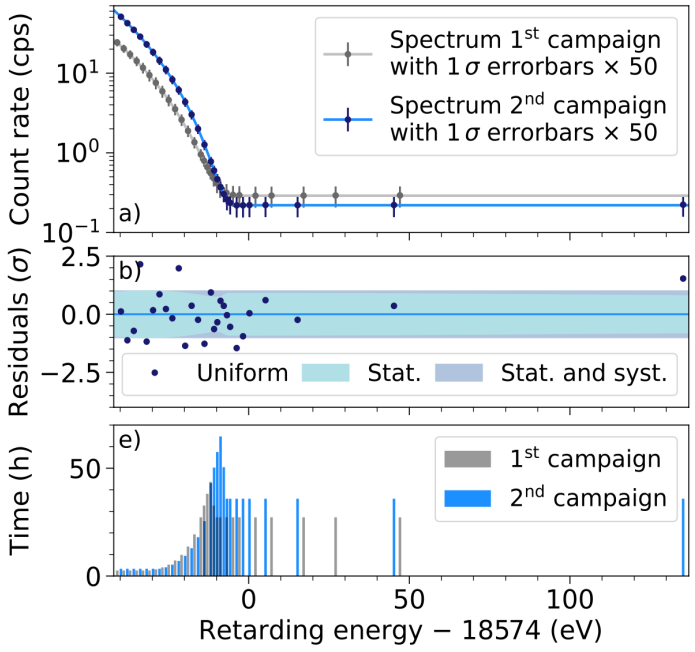
Advantages of CRES for tritium beta spectroscopy



Low background ➡ More info near endpoint

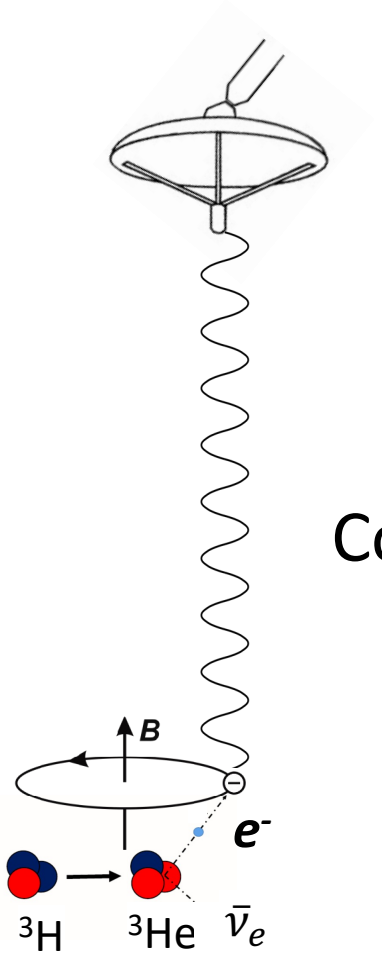


Lowering background gives you more visibility into the most informative region



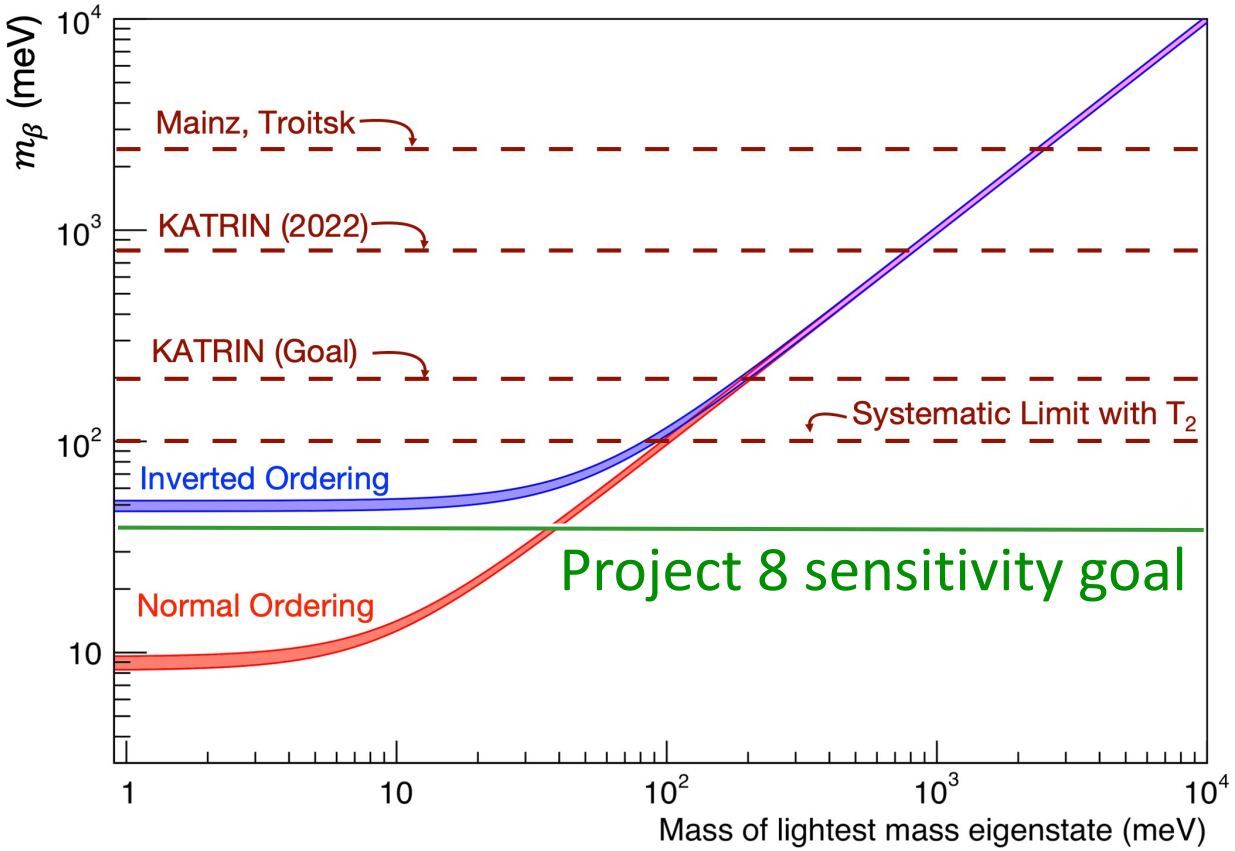
KATRIN Collab, *Nat. Phys.* **18,** 160–166 (2022)

Advantages of CRES for tritium beta spectroscopy



Frequency measurement	➡	High precision
Source is transparent to microwave radiation	➡	No electron transport; volume scaling
Compatible with atomic tritium	➡	Avoids T_2 final-state broadening
Differential spectrometer	➡	Increased statistical efficiency
Low background	➡	More info near endpoint

Pushing down in neutrino mass with Project 8



Goals:

- Sensitivity to 40 meV/c^2 neutrino mass
- Measure neutrino mass or exclude inverted hierarchy
- Simultaneous sensitivity to active and sterile neutrinos

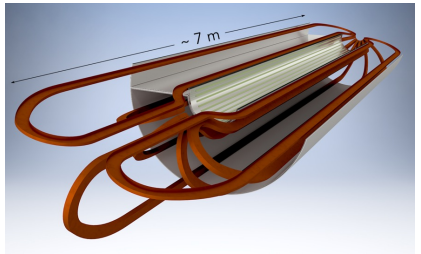
Increasing sensitivity in Phase III

PROJECT 8

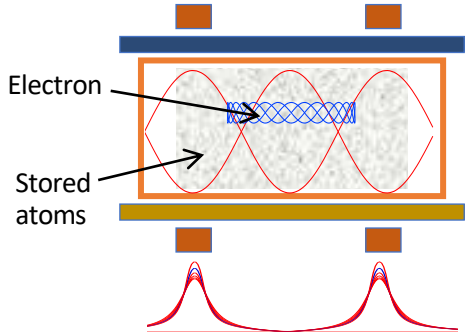
<u>Step 1</u>

~Two-pronged, 5-year R&D program in critical technology demonstrations

Atomic Trap Demonstrator



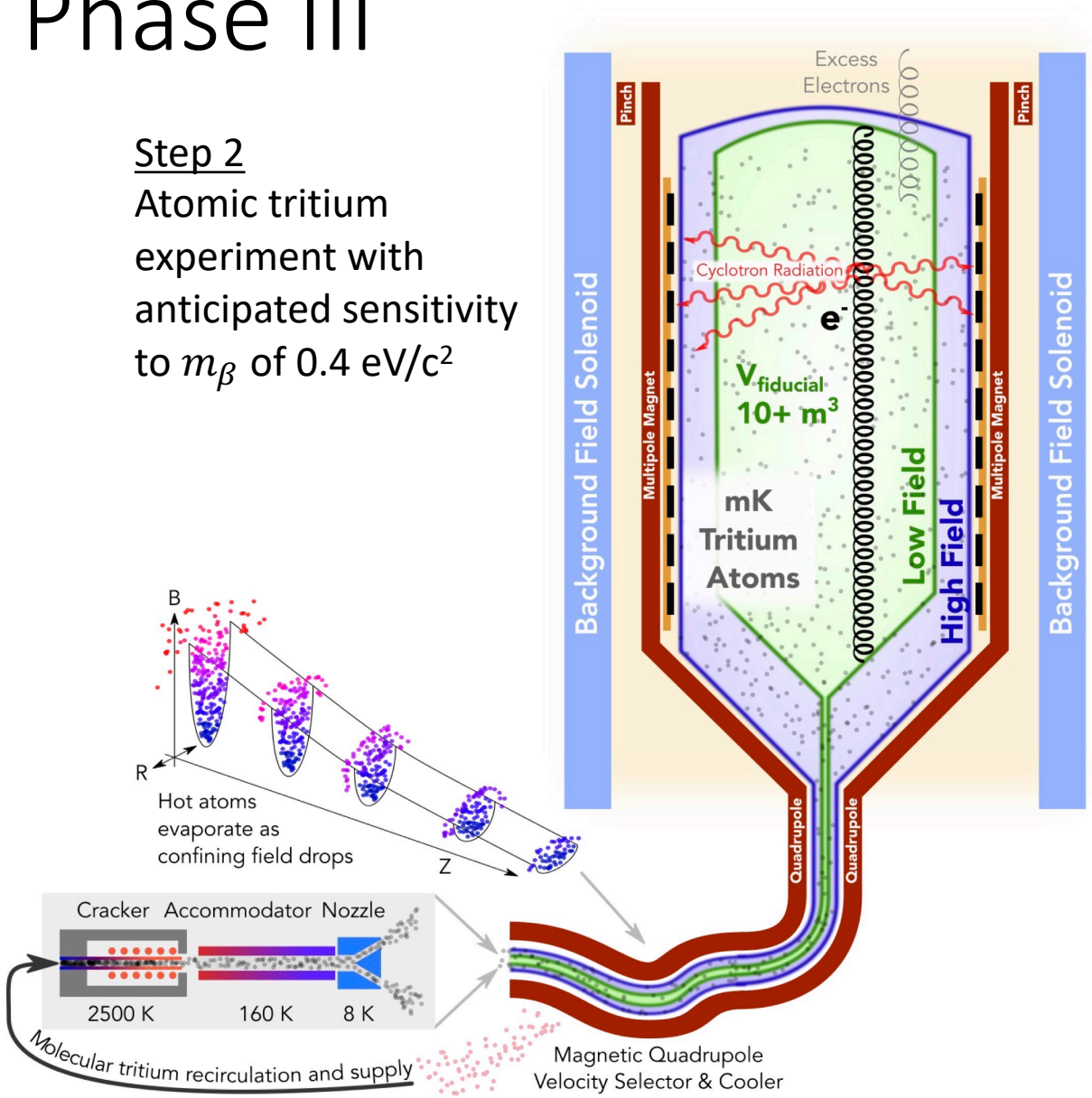
Large Volume (Cavity) CRES Demonstrator



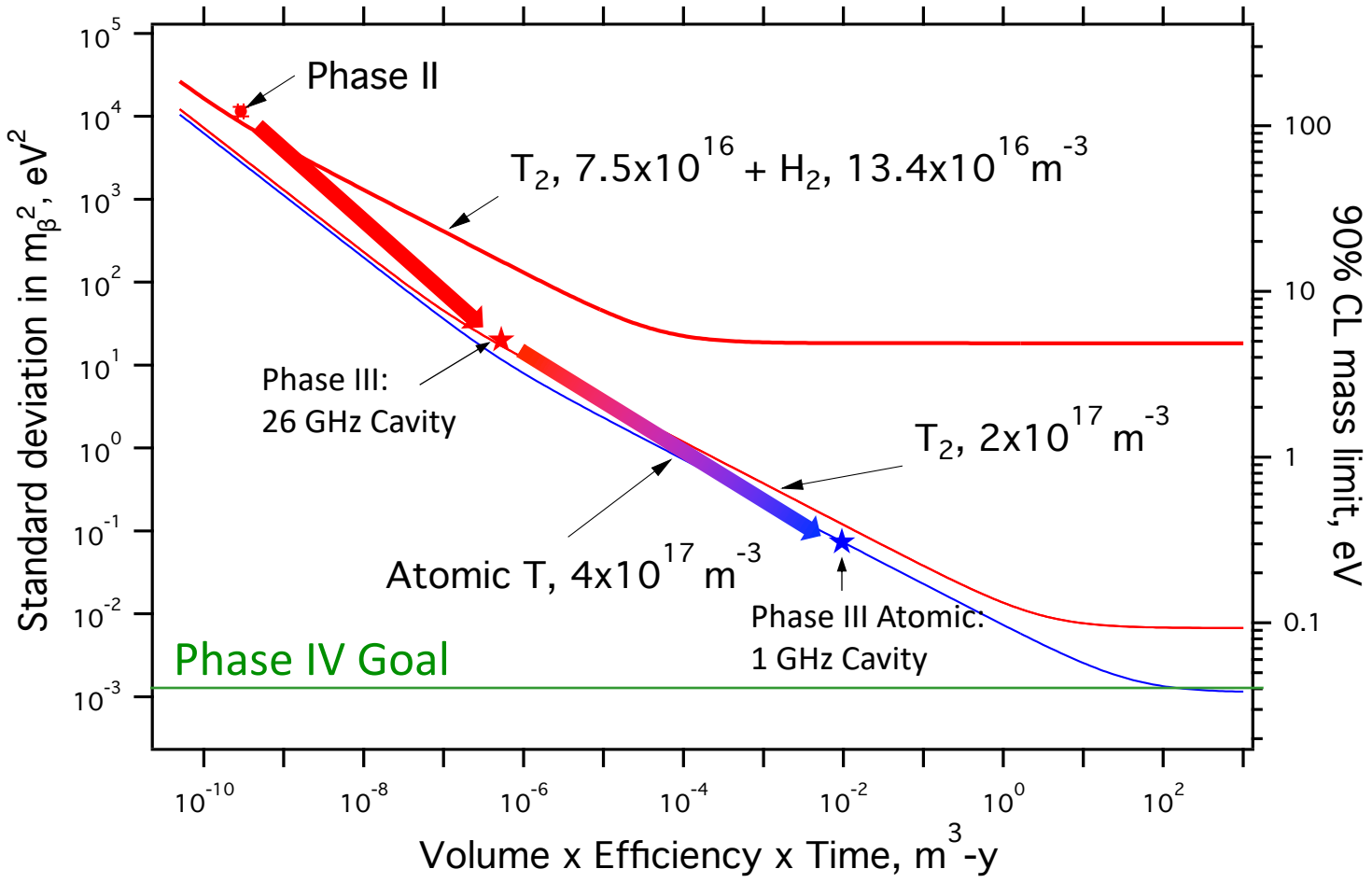
A. Ashtari Esfahani *et al.* arXiv:2203.07349

<u>Step 2</u>

Atomic tritium experiment with anticipated sensitivity to m_β of 0.4 eV/c^2



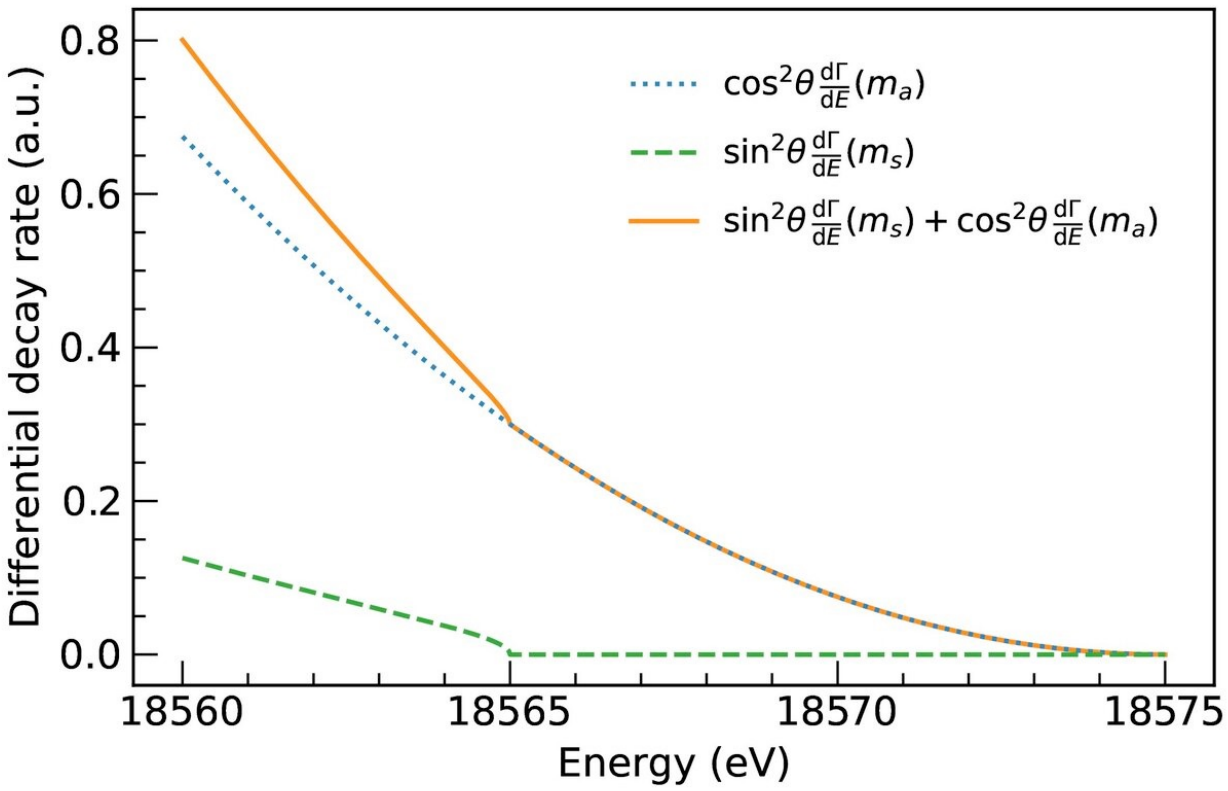
The path to eventual 40 meV sensitivity

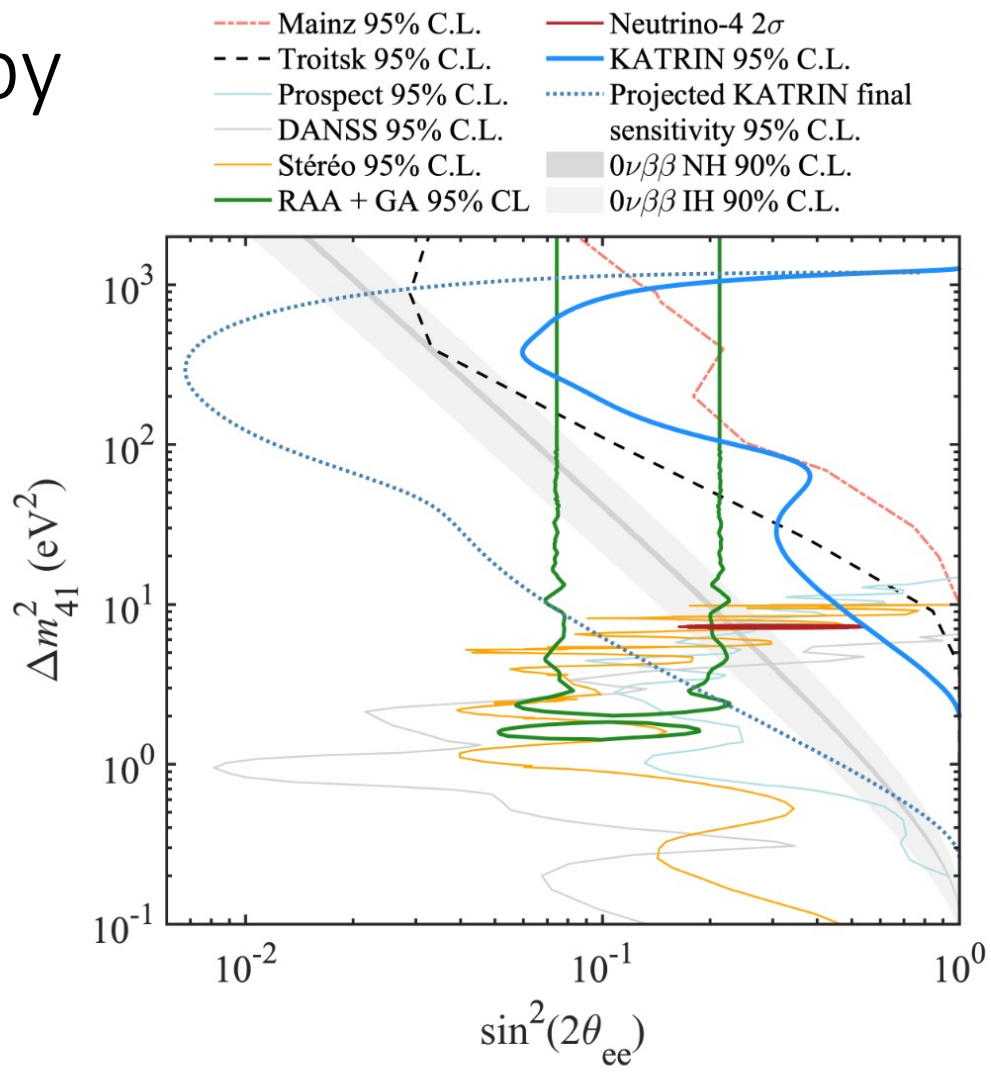


- Develop atomic source
  - Overcome systematic of molecular final states
- Increase volume
- Improve control of systematics, field homogeneity, scattering effects
- Higher density
  - Shorter tracks -> need to improve SNR -> need quantum amplifiers

Sterile neutrinos and β⁻ spectroscopy

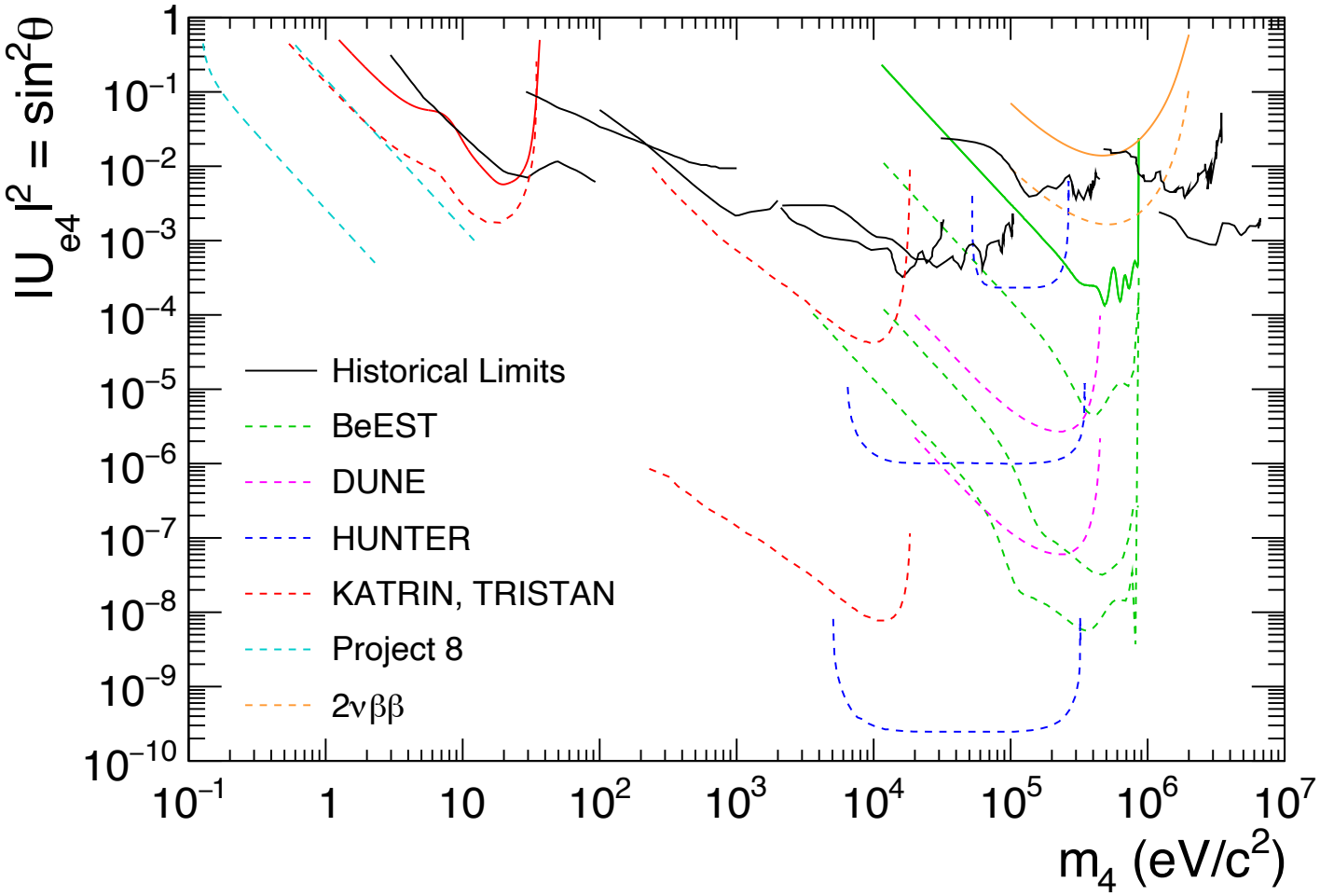
"Kink" signature of sterile neutrinos:





M. A. Acero et al, White Paper on Light Sterile Neutrino Searches and Related Phenomenology, Snowmass 2022, arXiv:2203.07323

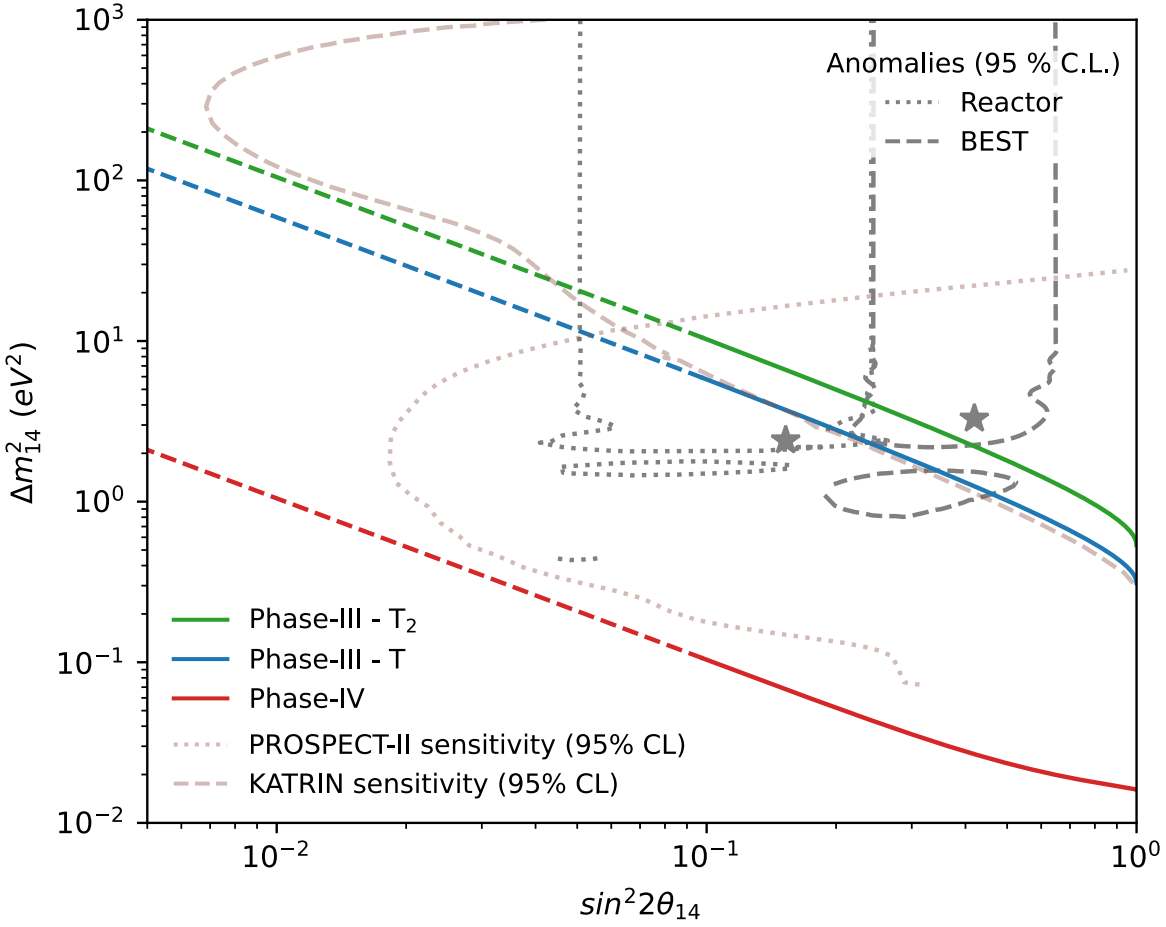
Sterile neutrinos and β⁻ spectroscopy



- eV-scale searches come as a natural complement to active neutrino mass measurements
- keV-scale searches (dark matter candidate) require handling higher event rates deeper in the spectrum.
  - Few keV: Detection technology needs reoptimization for this range (e.g., the planned TRISTAN module for KATRIN).
  - Many keV: need higher endpoint. See specialty EC experiments (e.g., BeEST)

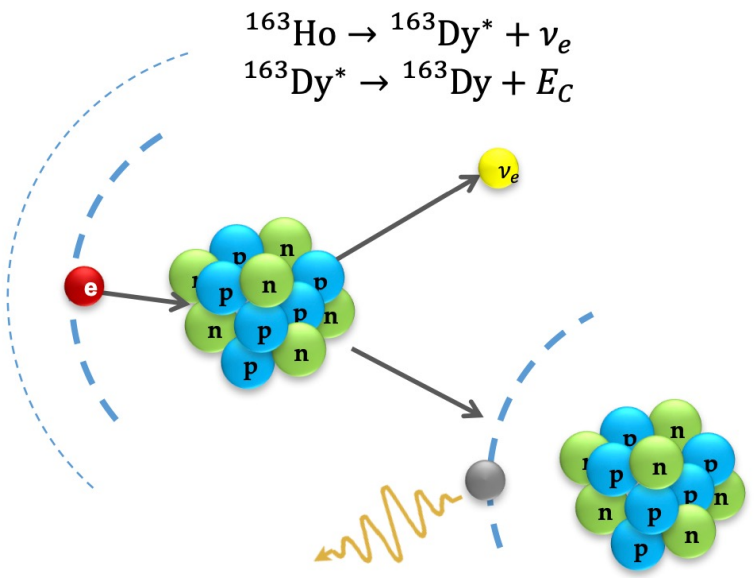
Project 8's sensitivity to sterile neutrinos

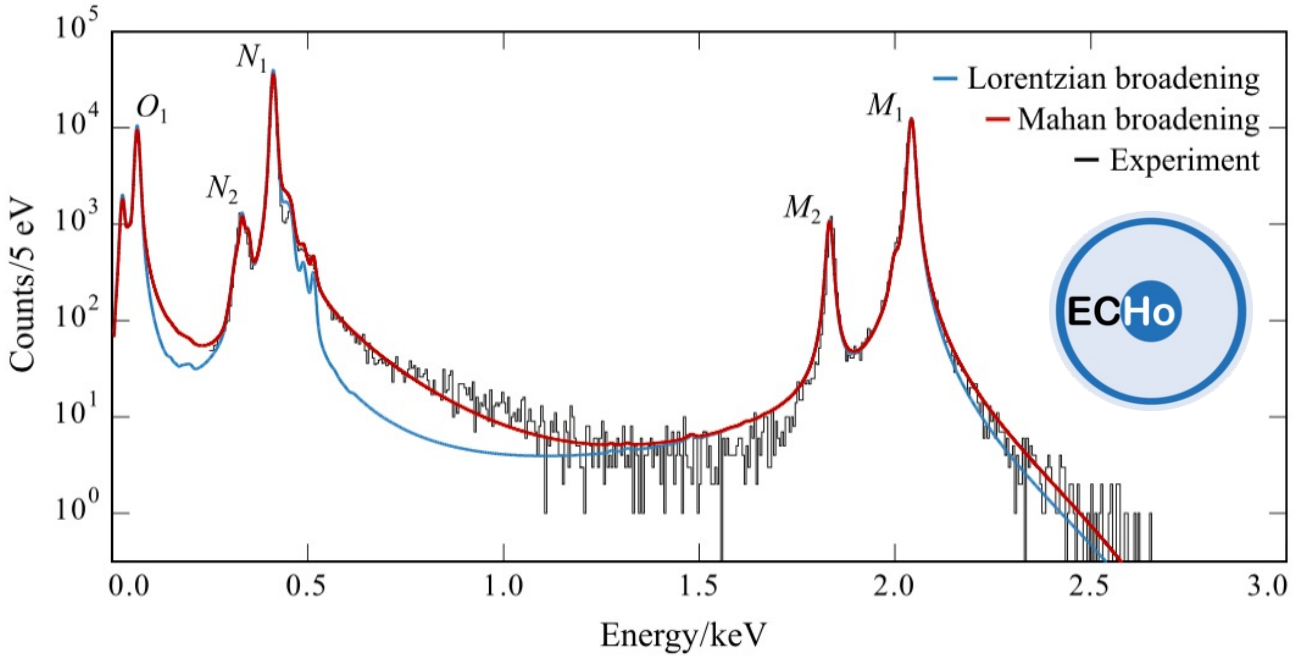
- eV-scale sterile search planned (differential measurement, so simultaneous active mass measurement and sterile search)
- Low backgrounds and good resolution also benefit search for steriles
- Sterile sensitivity will be statistics-limited
- Could potentially be extended to search for keV-scale steriles (depending on the detection and readout technology)



Electron capture on ^{163}Ho: recent theoretical progress in understanding the spectrum

Recent work has improved the understanding of the entire spectrum and indicated that the region near the endpoint has a simple shape.

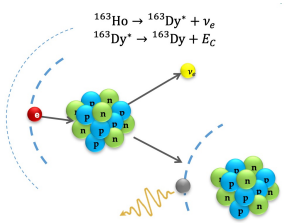




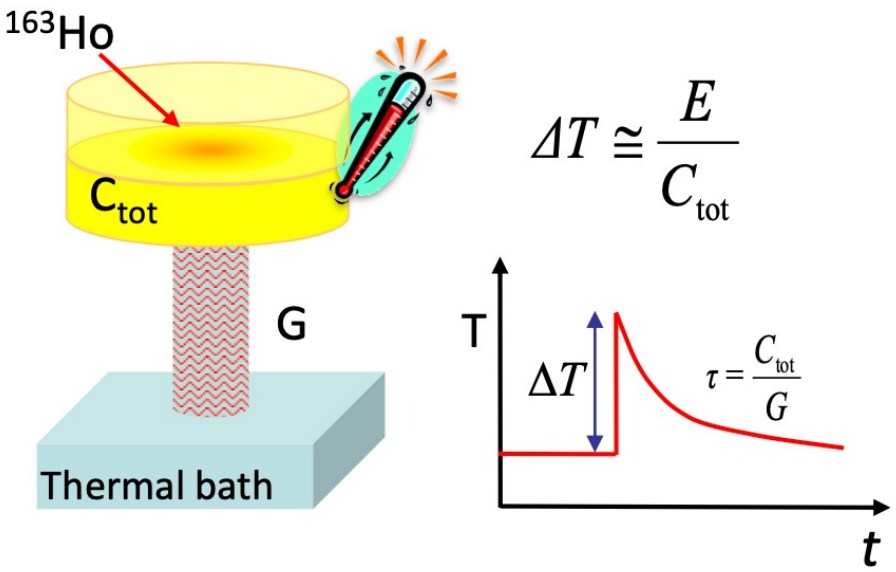
C. Velte et al., Eur. Phys. J. C (2019) 79:1026
M. Brass, M. Haverkort, New J. Phys. (2020) **22** 093018

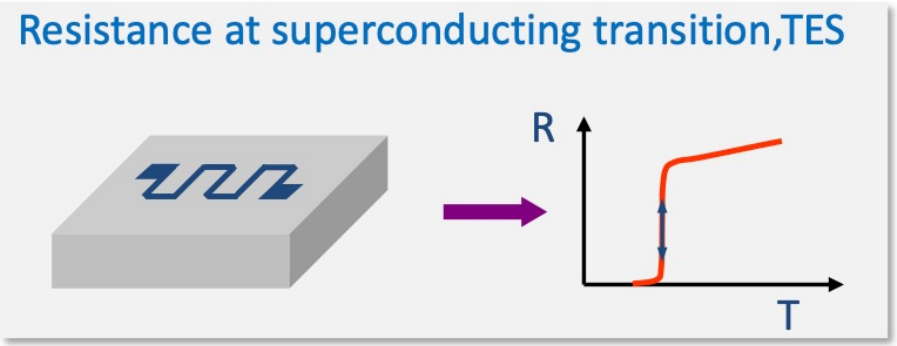
Slide content courtesy of Loredana Gastaldo

Electron capture on ^{163}Ho: experimental method



Microcalorimeters held at <100 mK detect decays from the whole spectrum



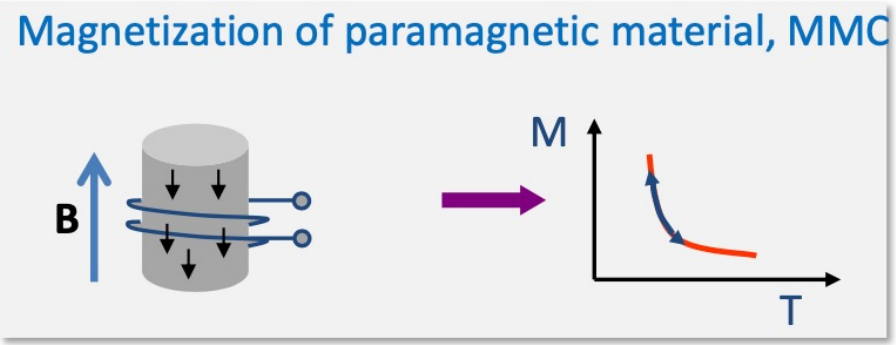


HOLMES

NuMECS

Detector arrays produced at NIST (Boulder US)

K.D. Irwin and G.C. Hilton, Topics in Applied Physics 99 (2005) 63



ECHo

Detector arrays produced at KIP, Heidelberg University

A.Fleischmann, C. Enss and G. M. Seidel, Topics in Applied Physics 99 (2005) 63

T.R. Stevenson et al., J. of Astronomical Telescopes, Instruments, and Systems, 5(2) (2019) 021009 – Group at NASA Goddard also leader in MMC development

Slide content courtesy of Loredana Gastaldo

General approach: more sensors, multiplexing, lower cost per sensor

ECHo-100k baseline: large arrays of metallic magnetic calorimeters

Number of detectors: 12000

Activity per pixel: 10 Bq (2×10^{12} ^{163}Ho atoms)

Present status:

High Purity ^{163}Ho source:

- available about 30 MBq

Ion implantation system:

- demostrated and continuously optimized

Metallic magnetic calorimeters

- reliable fabrication of large MMC array
- succesfull characterization of arrays with ^{163}Ho

Multiplexing and data acquisition:

- demostrated for 8 channels
- still to show scaling of the system
- development of the SDR electronics

Data reduction

- optimized energy independent algorithm to identify spurious traces

Overview of ECHo: The ECHo Collaboration EPJ-ST 226 8 (2017) 1623

General approach: fewer sensors, counteract pileup with fast detector recovery, analysis techniques

HOLMES baseline: large arrays of Transition Edge Sensors

Number of detectors: 1000

Activity per pixel: 300 Bq (6×10^{13} ^{163}Ho atoms)

Present status:

High Purity ^{163}Ho source:

- available about 100 MBq

Ion implantation system:

- commissioning to be concluded in 2022

Transition Edge Sensor arrays

- reliable fabrication of large TES array
- succesfull characterization of empty arrays
- still to demonstrate performance with 300 Bq

Multiplexing and data acquisition:

- completed and demonstrated for 32 channels

Data reduction

- optimized algorithms to reduce unresolved pile-up background

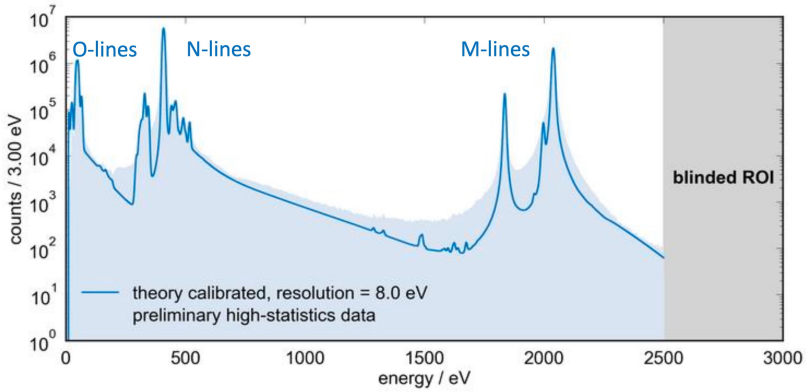
B. Alpert et al, Eur. Phys. J. C (2015) 75:112
A. Nucciotti, Eur. Phys. J. C (2014) 74:3161
M. Borghesi et al., Eur. Phys. J. C (2021) 81:385
M. Borghesi et al., Eur. Phys. J. C (2022) 82:421

Slide courtesy of Loredana Gastaldo

ECHo's goals, phases, and timeline

ECHO-1k:
Full data set collected; analysis ongoing

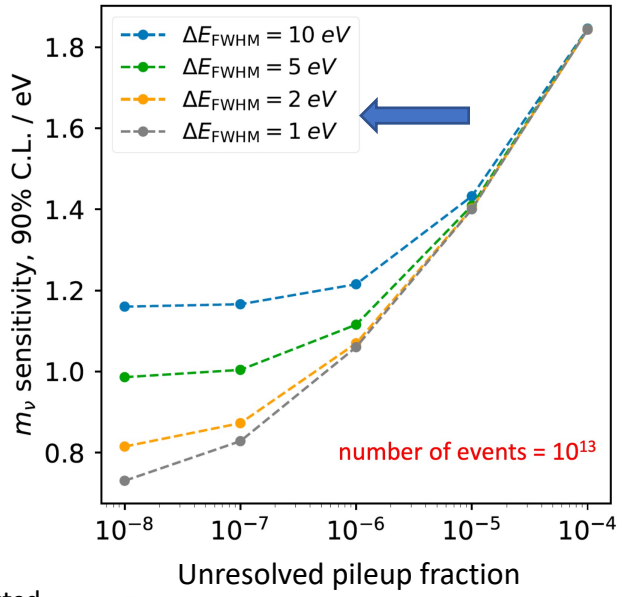
<150 eV limit set from data subset:



Expected sensitivity: $m(\nu_e) < 20$ eV 90% C.L.

Activity per pixel: 1 - 5 Bq
Number of detectors: 60 - 100
Readout: parallel two stage SQUID

ECHO-100k:
3-yr data run starts 2023



Expected sensitivity: $m(\nu_e) < 1.5$ eV 90% C.L.

Activity per pixel: 10 Bq
Number of detectors: 12000
Readout: microwave SQUID multiplexing

The ECHo Collaboration EPJ-ST 226 8 (2017) 1623

Sub-eV experiment:
timescale depends on results of ECHO-100k

Specifications needed for sub-eV m_β measurement:

Statistics in the end point region
- $N_{ev} > 10^{14}$ → **A ≈ 1 MBq**

Unresolved pile-up ($f_{pu} \sim a \cdot \tau_r$)
- $f_{pu} < 10^{-5}$
- τ_r < 1 µs → a ~ 10 Bq
- 10^5 pixels

Precision characterization of the endpoint region
- $\Delta E_{FWHM} < 3$ eV

Background level
- **< 10^{-6} events/eV/det/day**

Pileup and background reduction, as well as a multiplexed readout able to ensure good energy resolution, are needed for sub-eV and will be demonstrated in ECHo-100k

Slide content courtesy of Loredana Gastaldo

The near future holds ∼200 meV sensitivity and proof of the path to sub-200-meV

- m_β from direct mass measurements is complementary to $\sum m_\upsilon$ from cosmology
  - independent measurement with different systematics
  - breaking degeneracies within ΛCDM
  - could give clues to possibilities beyond ΛCDM and the Standard Model
- KATRIN: $m_\beta <$ 800 meV now, ∼200 meV limit within ∼2 years
- CRES-based tritium β^- spectroscopy and bolometric ^{163}Ho electron capture: eV-scale results expected within a few-years timescale
- eV-scale measurements also serve as technology demonstrations and systematic effect explorations for sub-eV experiments; 40 meV goal for Project 8
- Timelines for sub-eV depend on eV-scale R&D

The Project 8 collaboration

Case Western Reserve University
- Razu Mohiuddin, Benjamin Monreal, Yu-Hao Sun

University of Illinois
- Chen-Yu Liu

Indiana University
- Walter Pettus

Johannes Gutenberg-Universität Mainz
- Sebastian Böser, Martin Fertl, Alec Lindman, Christian Matthé, René Reimann, Florian Thomas, Larisa Thorne

Karlsruher Institut für Technologie
- Thomas Thümmler

Lawrence Livermore National Laboratory
- Kareem Kazkaz

Massachusetts Institute of Technology
- Nicholas Buzinsky, Joseph Formaggio, Mingyu Li, Junior Peña, Juliana Stachurska, Wouter Van de Pontseele

Pacific Northwest National Laboratory
- Maurio Grando, Xueying Huyan, Mark Jones, Benjamin LaRoque, Erin Morrison, Noah Oblath, Dan Rosa de Jesús, Malachi Schram, Jonathan Tedeschi, Brent VanDevender, Mathew Thomas

Pennsylvania State University
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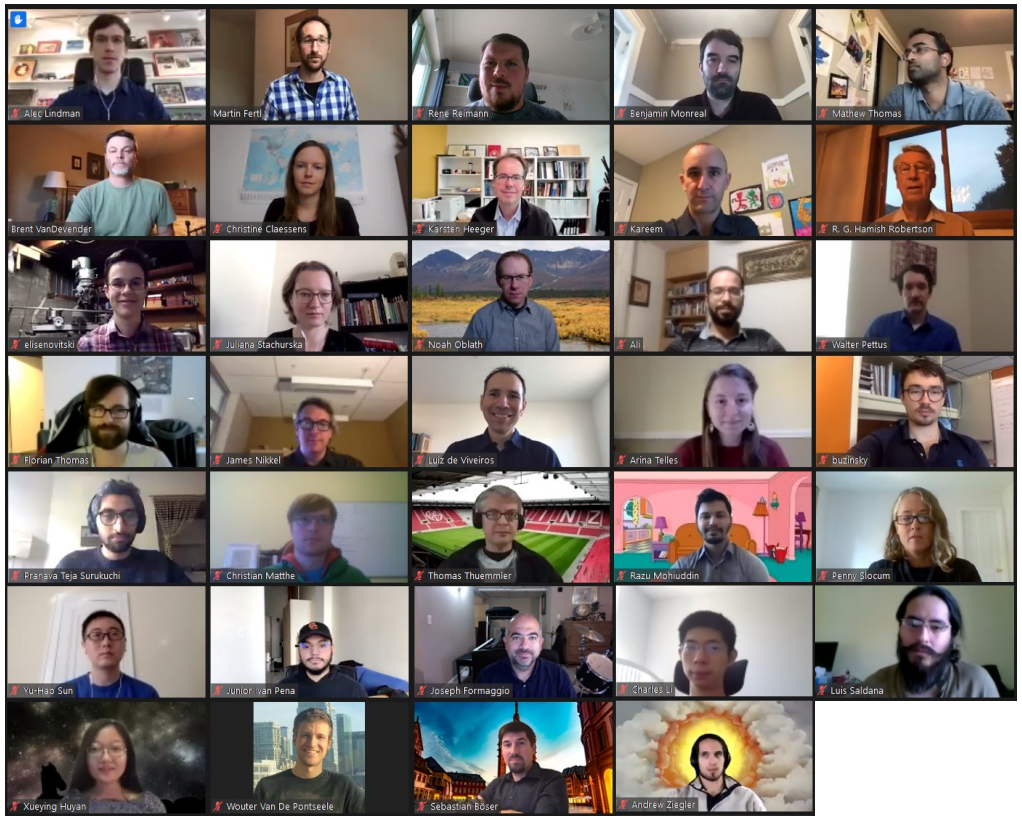
University of Washington
- Ali Ashtari Esfahani, Raphael Cervantes, Christine Claessens, Peter Doe, Sanshiro Enomoto, Eris Machado, Alexander Marsteller, Elise Novitski, Hamish Robertson, Leslie Rosenberg, Gray Rybka

Yale University
- Karsten Heeger, James Nikkel, Luis Saldaña, Penny Slocum, Pranava Teja Surukuchi, Arina Telles, Talia Weiss



This work was supported by the US DOE Office of Nuclear Physics, the US NSF, the PRISMA+ Cluster of Excellence at the University of Mainz, and internal investments at all collaborating institutions.

Thank you!