Walter C. Pettus

Neutrino Mass Experiments

International Neutrino Summer School

11 August 2023

INDIANA UNIVERSITY

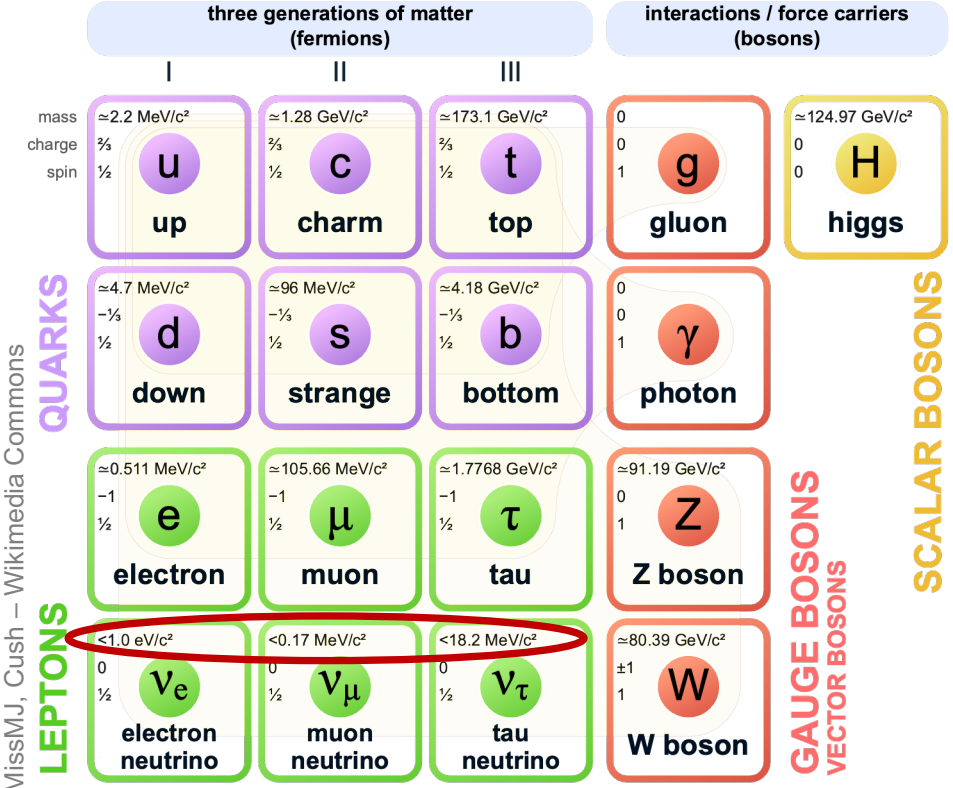
PROJECT 8

About Me

- Ph.D. from University of Wisconsin
  - DM-Ice & COSINE : WIMP NaI dark matter
  - Short postdoc at Yale University
- Postdoc at University of Washington
  - *Switched to neutrino physics*
- Faculty at Indiana University

- Experiments
  - Project 8 neutrino mass experiment
  - MAJORANA DEMONSTRATOR and LEGEND ^{76}Ge neutrinoless double beta decay experiments
  - *I deliberately measure no neutrinos in my experiments*

Opportunity of Neutrino Mass



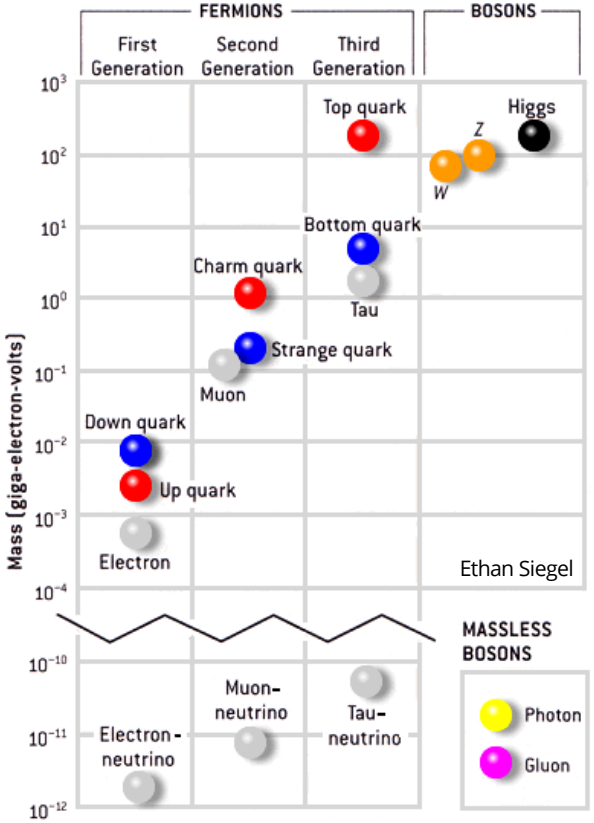
MissMJ, Cush – Wikimedia Commons

Neutrino mass is BSM physics!

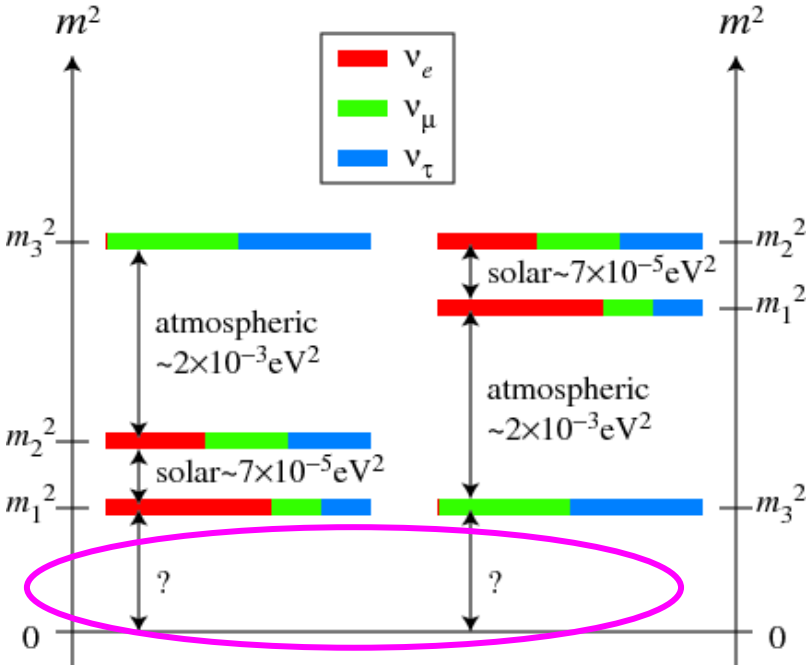
- What is the neutrino mass?
- Why is the neutrino mass so much smaller than other fermion masses?
- How much CP violation in lepton sector?
- Other new physics hiding with neutrinos?

Mystery of the Neutrino Mass Scale

- Scale of neutrino mass sets them apart from all other particles of Standard Model
- Physics behind neutrino mass linked to many interesting questions in nuclear, particle, and astro physics



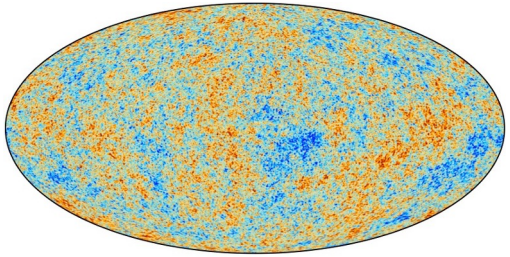
Neutrino Oscillation Input



A. Nucciotti, AHEP **2016** (2016) 9153024

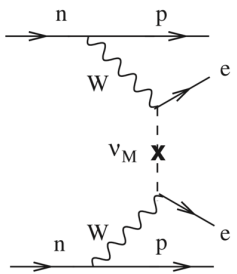
- Oscillation experiments have nailed down Δm_{ij}^2 parameters
- But these parameters can't constrain the *absolute scale* of neutrino mass

Probing the Neutrino Mass Scale



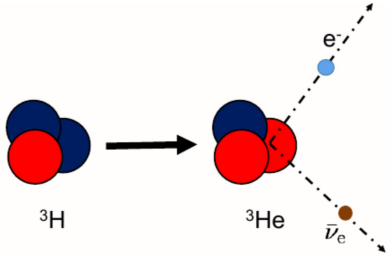
Cosmology

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



Neutrinoless Double-Beta Decay

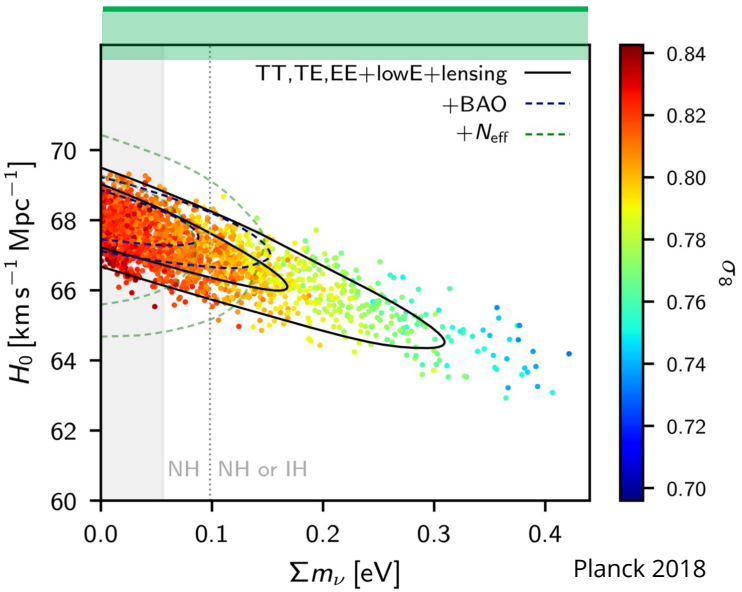
$$\langle m_{\beta\beta} \rangle = \left| \sum_{i=1}^{3} U_{ei}^2 m_i \right|$$



Endpoint Measurements (β-decay and EC)

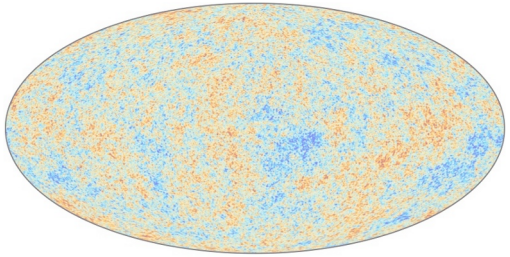
$$m_\beta = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 m_i^2}$$

Cosmological Limitations



- Neutrino mass added to ΛCDM as a seventh parameter
  - Constraint on Σm_ν weakens with additional floating parameters
- H_0 tension between early universe (CMB, BAO, weak lensing) and late universe (distance-ladder and quasar) measures

Probing the Neutrino Mass Scale



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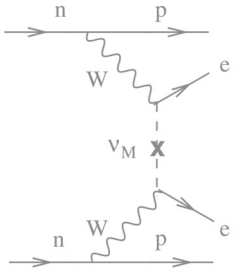

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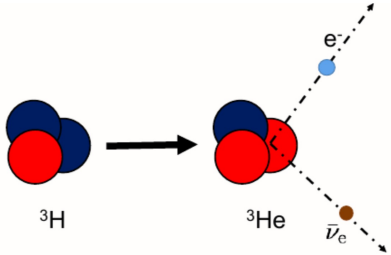
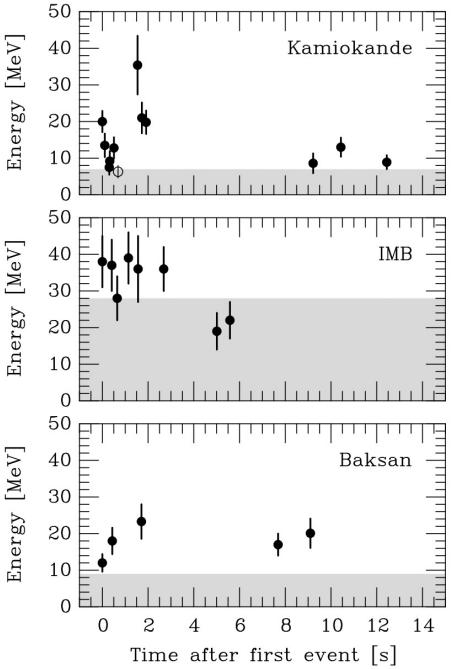


Endpoint Measurements (β-decay and EC)

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

Time of Flight – Supernovae

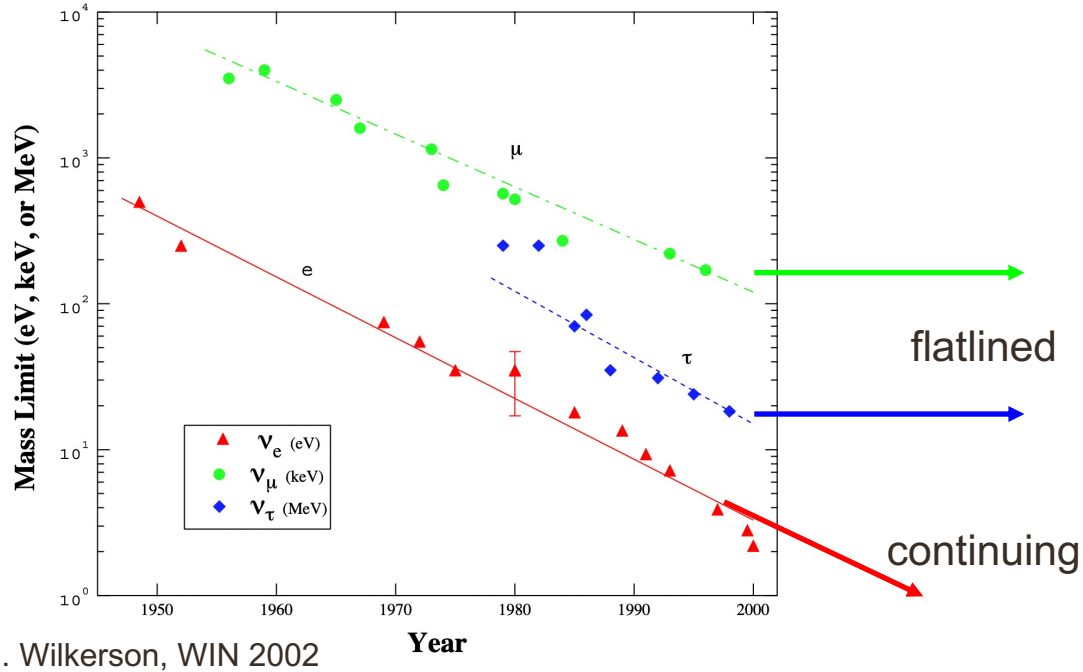
- "Direct" neutrino mass sensitivity can be derived from a time-of-flight measurement on supernova neutrinos
  - Is there spread in arrival times consistent with higher-energy neutrinos traveling closer to speed of light?
- SN 1987a places limit of $m_\nu < 5.7$ eV
- Future prospects?
  - Sensitivity down to $m_\nu > 0.5$ (1.0) eV reasonable for DUNE and Hyper-K (JUNO) estimated
  - Closer is better due to statistics
  - No room for improvement by including gravitational waves



G. Raffelt, Ann. Rev. Nucl. Part. Sci. **49** (1999) 163

Global Kinematic Neutrino Limits

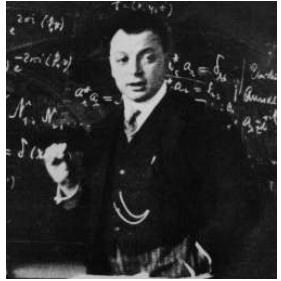
- Kinematic limits can be (and have been) done for all neutrino flavors



J. Wilkerson, WIN 2002

Endpoint Measurements

R. Church



Physics Insitute
ETH Zürich

Zürich, Dec. 4 1930
Gloriastrasse

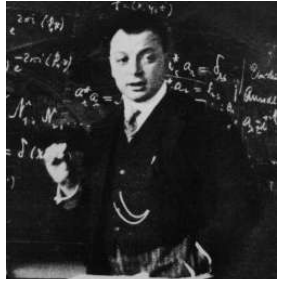
Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, because of the "wrong" statistics of the N- and Li-6 nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" (1) of statistics and the law of conservation of energy. Namely, the possibility that in the nuclei there could exist electrically neutral particles, which I will call neutrons, that have spin 1/2 and obey the exclusion principle and that further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton mass. - The continuous beta spectrum would then make sense with the assumption that in beta decay, in addition to the electron, a neutron is emitted such that the sum of the energies of neutron and electron is constant.

...

Endpoint Measurements

R. Church



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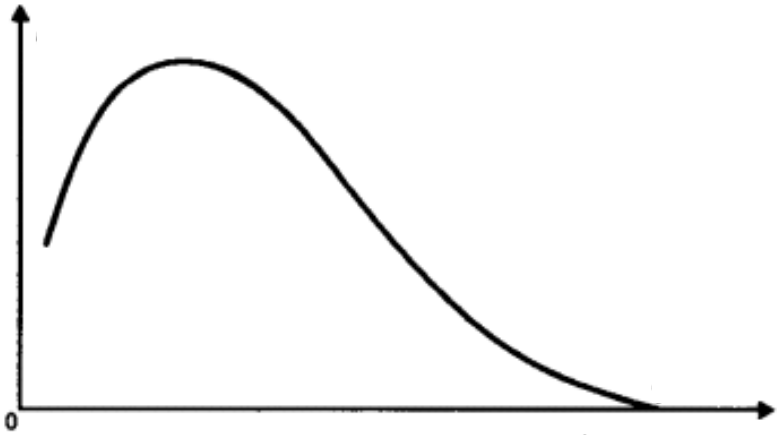
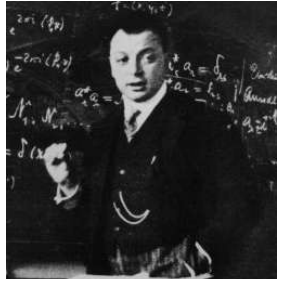
I admit that my remedy may seem almost improbable because one probably would have seen those neutrons, if they exist, for a long time. But nothing ventured, nothing gained, and the seriousness of the situation, due to the continuous structure of the beta spectrum, is illuminated by a remark of my honored predecessor, Mr Debye, who told me recently in Bruxelles: "Oh, It's better not to think about this at all, like new taxes." Therefore one should seriously discuss every way of rescue. Thus, dear radioactive people, scrutinize and judge. - Unfortunately, I cannot personally appear in Tübingen since I am indispensable here in Zürich because of a ball on the night from December 6 to 7. With my best regards to you,

Endpoint Measurements



R. Church

β Energy



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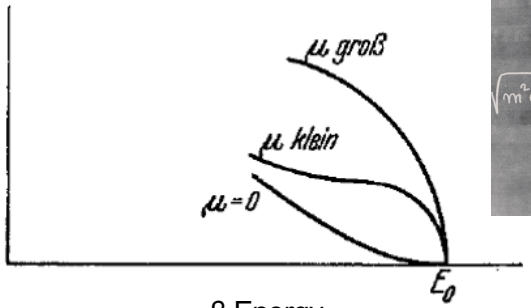

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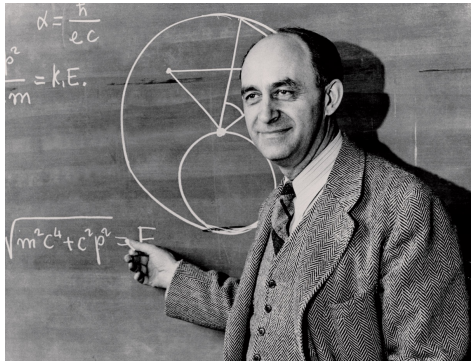
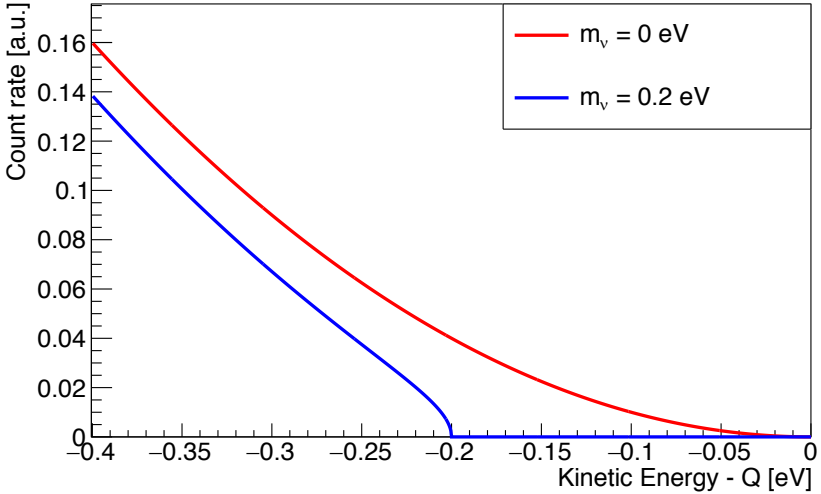


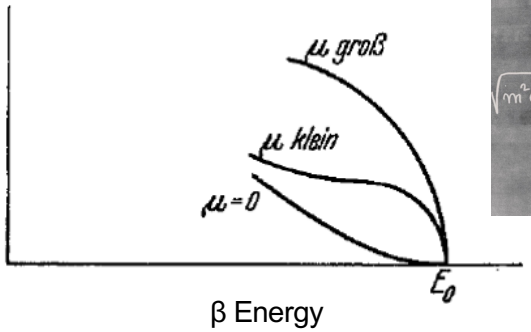
Evidence of neutrino mass imprinted in endpoint of spectrum

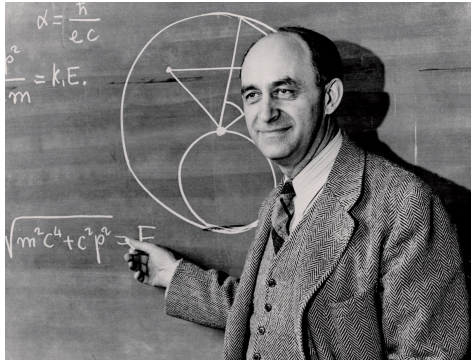
E. Fermi, Zeitschrift fur Physik (1934)

Endpoint Measurements



$$\frac{dN}{d\epsilon} \propto \epsilon\sqrt{\epsilon^2 - m_\beta^2}$$





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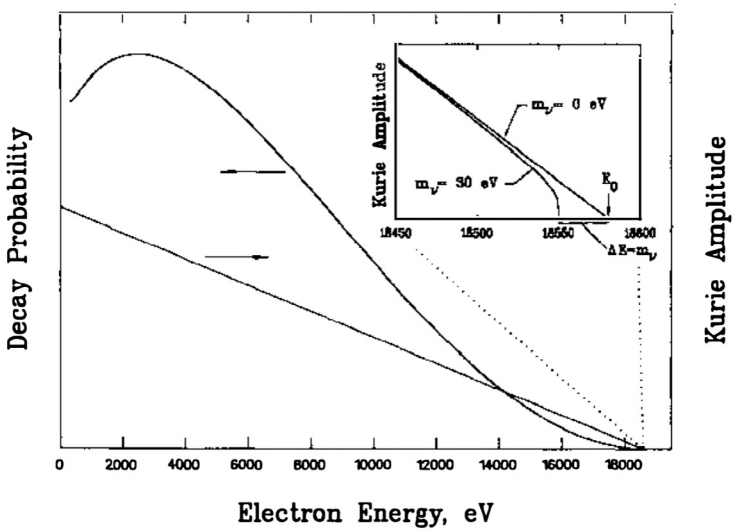
E. Fermi, Zeitschrift fur Physik (1934)

Endpoint Measurements

H. Robertson & D. Knapp.
Ann. Rev. Nucl. Part. Sci. **38** (1988) 185



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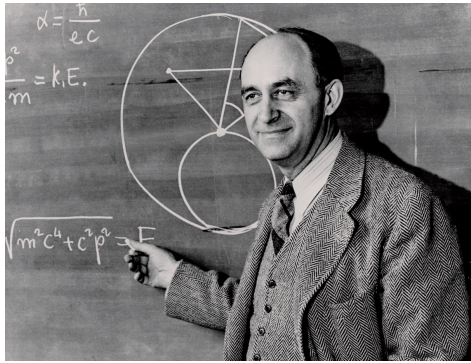


Kurie plot: traditional method for plotting endpoint

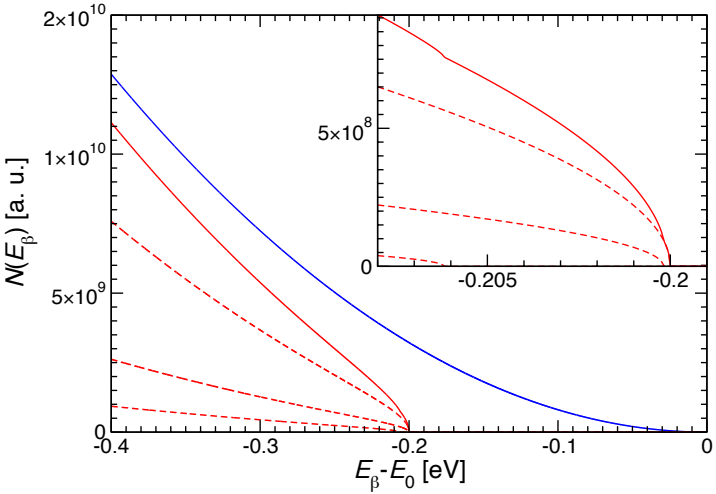
- Determine endpoint, see neutrino mass effect
- At the endpoint, just square root of spectrum

E. Fermi, Zeitschrift fur Physik (1934)

Endpoint Measurements

- "Direct" or "endpoint" measurements can individually determine the neutrino mass state masses
  - In practice, detector energy resolution and experimental statistics are typically insufficient to resolve individual state contributions, so we use m_β instead
- m_β has an absolute backstop
  - $m_\beta > 9$ meV (48 meV) for NO (IO)

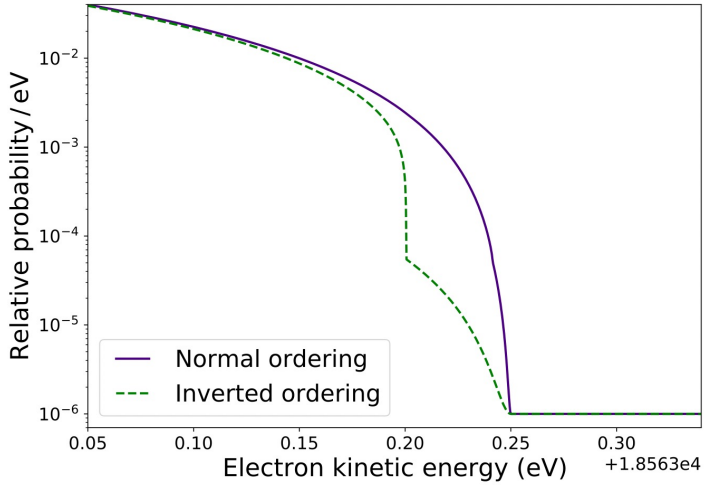
"electron-weighted" $m_\beta = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 m_i^2}$



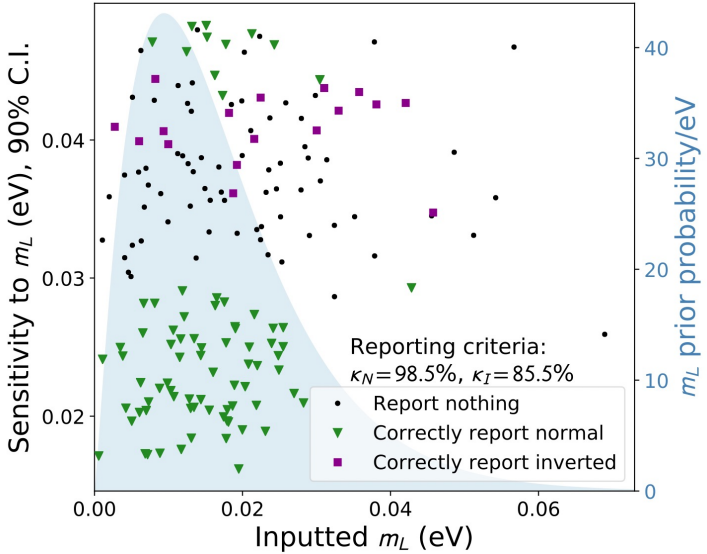
A. Nucciotti, AHEP **2016** (2016) 9153024

Ordering Determination

- Mass splitting information is always encoded in the spectrum



- Next-generation endpoint experiments could resolve the ordering



(Project 8) Phys. Rev. C **103** (2021) 065501

Experiment Sandbox

- Source
- Detector
- *Compatibility of two*

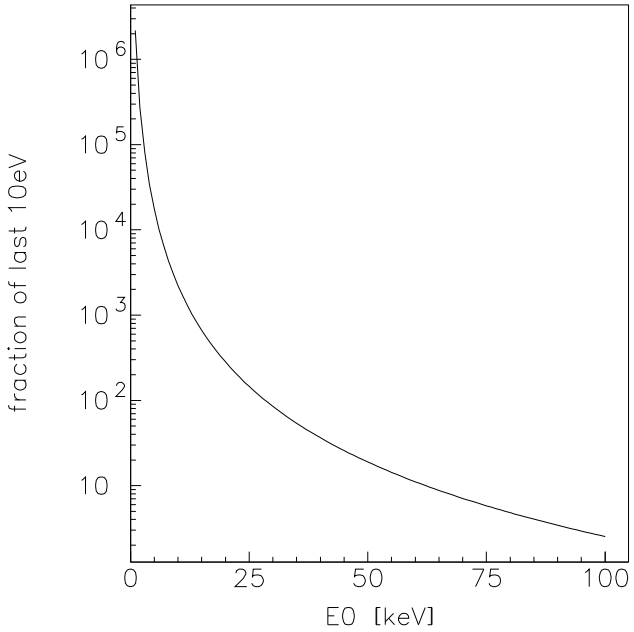
Experiment Sandbox

- Source
  - Low Q-value

  - Neutrino mass imprint is shape distortion and shift *at the endpoint*

  - Lower Q-value puts greater fraction of decays in ROI

Superallowed Decays:



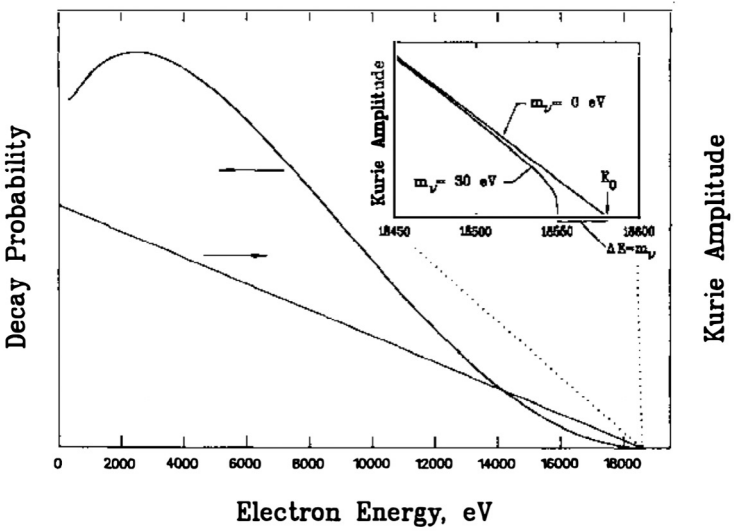
G. Drexlin *et al*. AHEP **2013** (2013) 293986

Experiment Sandbox

- Source
  - Low Q-value
  - Intense

- Neutrino mass imprint is shape distortion and shift *at the endpoint*

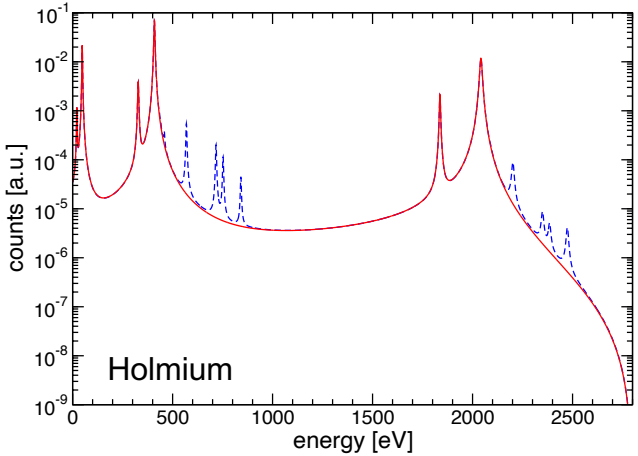
- Only $2 \cdot 10^{-13}$ decays in last eV of the spectrum



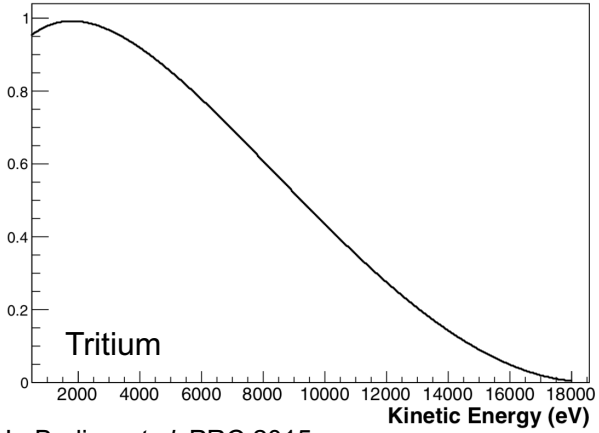
H. Robertson & D. Knapp.
Ann. Rev. Nucl. Part. Sci. **38** (1988) 185

Experiment Sandbox

- Source
  - Low Q-value
  - Intense
  - Well-understood spectrum
- Need control of source-related systematics
  - Exactly calculable spectrum
  - Featureless or at least understood features



A. Nucciotti, AHEP **2016** (2016) 9153024

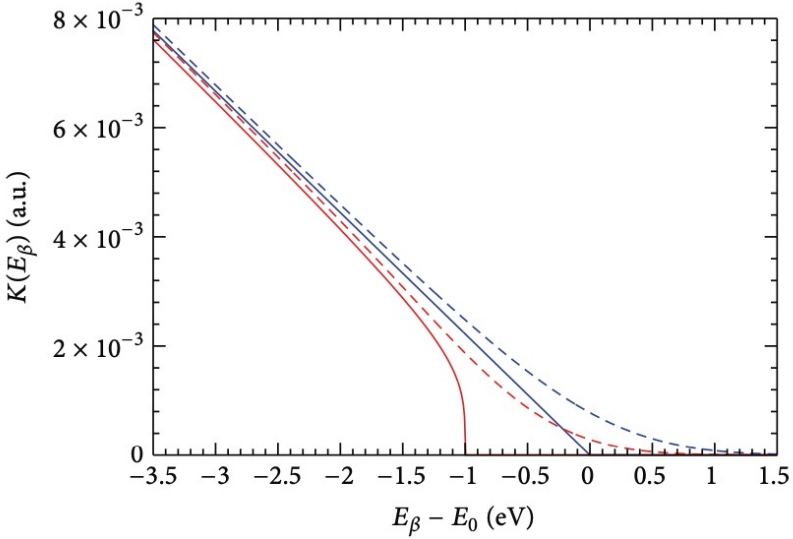


L. Bodine *et al*. PRC 2015

Experiment Sandbox

- Source
  - Low Q-value
  - Intense
  - Well-understood spectrum
- Detector
  - Energy resolution and detector response
  - Low-background
  - Controlled systematics

Impact of Resolution (σ = 0.5 eV)



A. Nucciotti, AHEP **2016** (2016) 9153024

Candidate Isotope Suitability

- Low Q-value decay
  - ^{3}H (18.6 keV), ^{163}Ho (2.9 keV), ^{187}Re (2.5 keV), ^{115}In (0.15 keV)…
- Modest half-life
- Favorable branching ratio to desired state

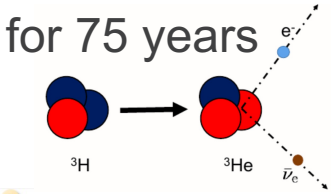
Isotope	Spin-Parity	Half-life	Specific Activity	Q_A	Branching ratio	Last eV	Source Mass
		y	Bq/g	eV			g
$^{3}H_2$	$1/2^+ \rightarrow 1/2^+$	12.3	3.6×10^{14}	18591	0.57	2.9×10^{-13}	2.0×10^{-7}
^{115}In	$9/2^+ \rightarrow 3/2^+$	4.4×10^{14}	0.26	147	1.2×10^{-6}	5.0×10^{-7}	7.5×10^{7}
^{135}Cs	$7/2^+ \rightarrow 11/2^-$	1.5×10^{6}	6.8×10^{7}	440	$(0.04 - 16) \times 10^{-6}$	2.2×10^{-8}	0.4 - 217
^{187}Re	$5/2^+ \rightarrow 1/2^-$	4.3×10^{10}	1.6×10^{3}	2470	1.0	1.2×10^{-10}	57
^{163}Ho	$7/2^- \rightarrow 5/2^-$	4750	1.8×10^{10}	2858		$\sim 10^{-12}$	$\sim 1.0 \times 10^{-5}$

- Compatibility with integrating into detector
- Theoretical understanding of spectral shape

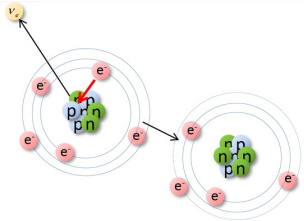
Formaggio, de Gouvêa, Robertson, Physics Reports **914** (2021) 1

Endpoint Search Candidates

- Tritium beta decay has yielded leading direct limits for 75 years
  - $^{3}_{1}H \rightarrow ^{3}_{2}He^{+} + e^{-} + \overline{\nu_e}$
  - Endpoint: 18.6 keV; half-life: 12.3 yr



- Holmium electron capture decay
  - $^{163}_{67}Ho \rightarrow ^{163}_{66}Dy^{*} + \nu_e$
  - Endpoint: 2.8 keV; half-life: 4570 yr



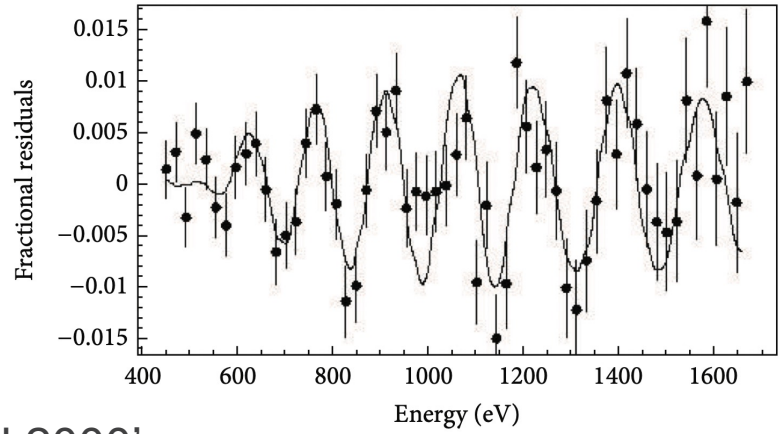
- Other isotopes have received attention: ^{187}Re, ^{115}In
  - No currently viable experimental program
  - Orders of magnitude worse figure-of-merit for quantity of isotope per decay in last eV

^{187}Re Experiments

- Rhenium beta decay
  - $^{187}_{75}Re \rightarrow {}^{187}_{76}Os^{+} + e^{-} + \overline{\nu_e}$
  - Endpoint: 2.47 keV; half-life 4.3e10 yr

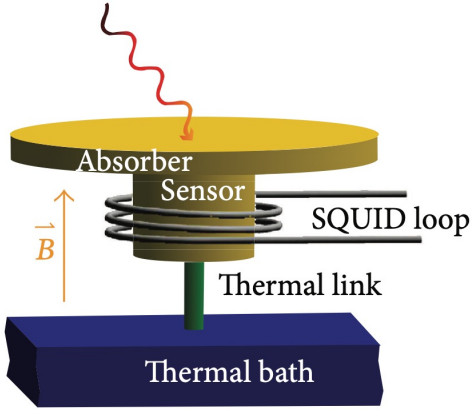
- Significant experimental work in 1990's and 2000's
  - Experiments were MANU & MIBETA, followed by MARE
  - Based on bolometers of metallic rhenium and $AgReO_4$

- Concluded holmium was more viable option
  - Energy resolution was inconsistent and poor (~tens of eV)
  - Materials effects led to energy-dependent distortions
    - Beta Environmental Fine Structure (BEFS)



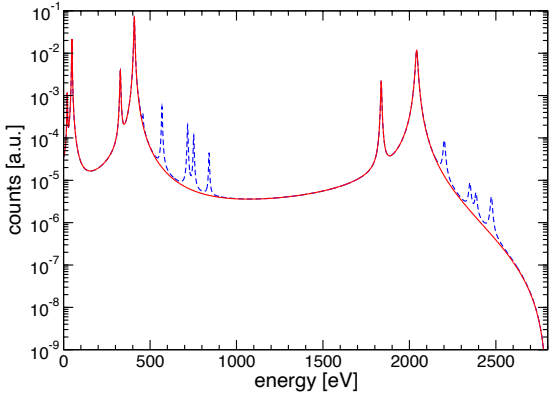
A. Nucciotti, AHEP **2016** (2016) 9153024

^{163}Ho Concept



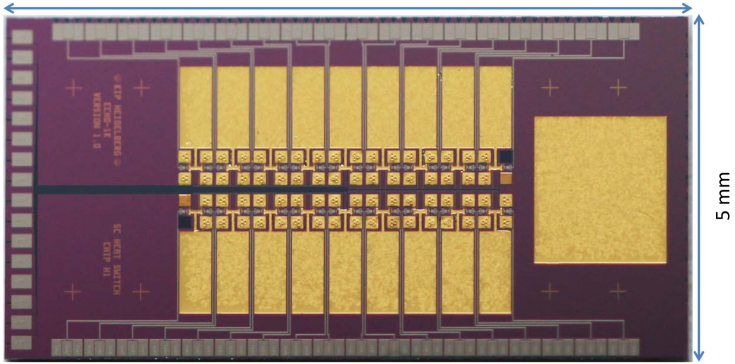
- Holmium electron capture
  - $^{163}_{67}Ho \rightarrow {}^{163}_{66}Dy^{*} + \nu_e$
  - Endpoint: Q = 2.86 keV; half-life: 4570 yr
- Deexcitation physics is complicated…
  - But if you use a bolometer, you collect all the deexcitation energy
  - Spectral shape is superposition of Lorentzians with a cutoff energy
- Significant advances in last ~decade
  - Experiments: HOLMES, ECHo, NuMECS

A. Nucciotti, AHEP **2016** (2016) 9153024

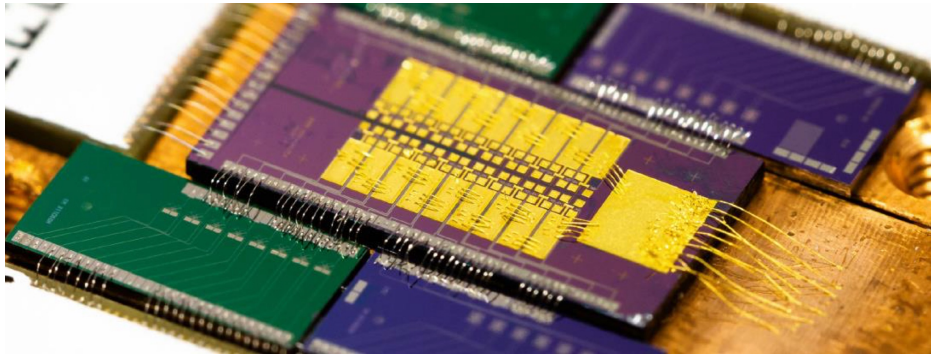


^{163}Ho Experiment

- Microcalorimeters are preferred method
  - Small (~Bq) activity per pixel
    - Slow readout requires low activity
  - Ultimately require ~10^{13} events for sub-eV sensitivity
    - Multiplexing the >10^5 pixels to control channel count

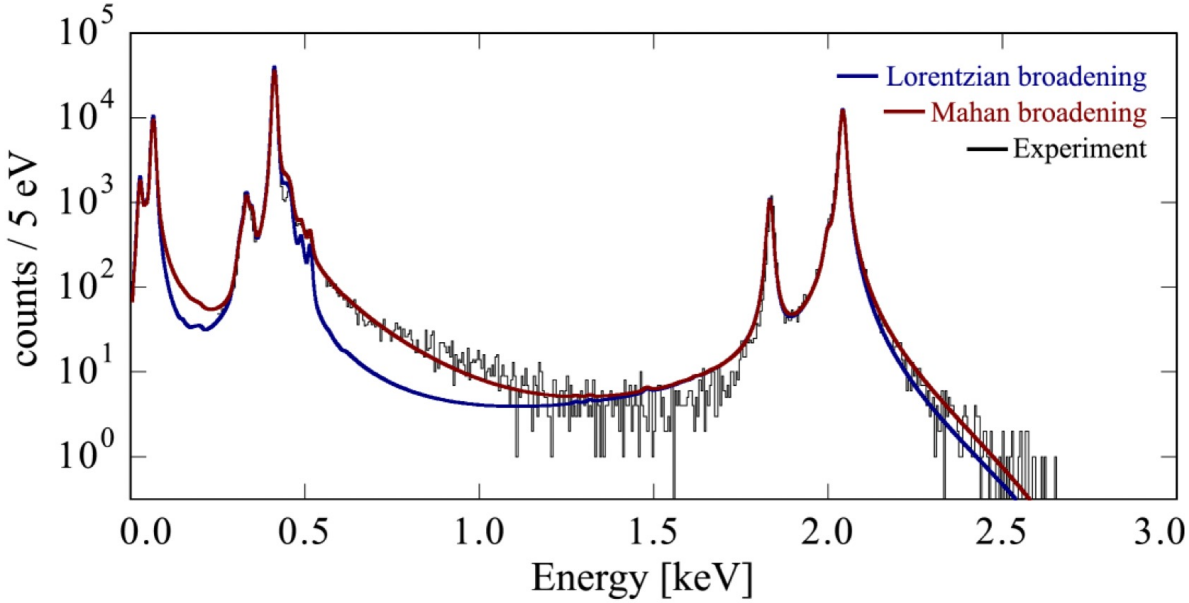


M. Wegner. ECT* Trento (2018)



^{163}Ho Highlights – Spectral Modeling

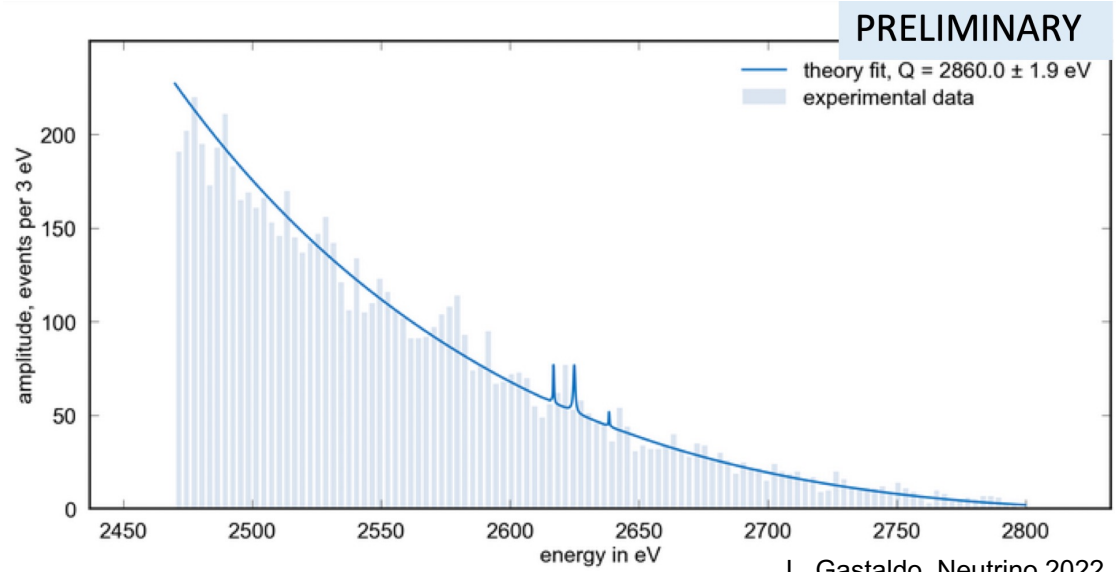
- Higher statistics measurements agreeing with improved spectrum calculations



(ECHo) Eur. Phys. J. C **79** (2019) 1026

^{163}Ho Highlights – Endpoint Determination

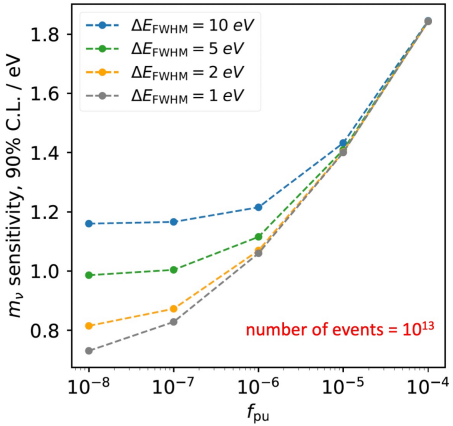
- Most precise endpoint determination
  - Q_{EC} = (2860 ± 2 stat ± 5 syst) eV
  - Awaiting new PENTATRAP measurement

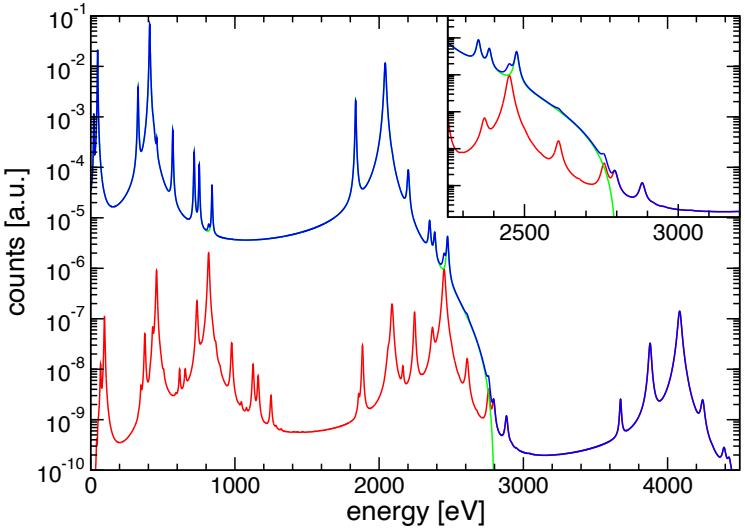


L. Gastaldo, Neutrino 2022

^{163}Ho Challenges – Pileup

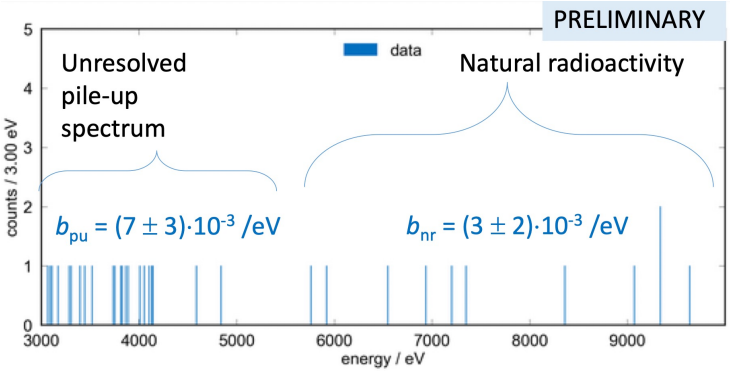
- Slow microcalorimeter readout creates pileup in spectrum
  - Even with low-activity pixels
  - Pileup determination is critical limiting factor in sensitivity





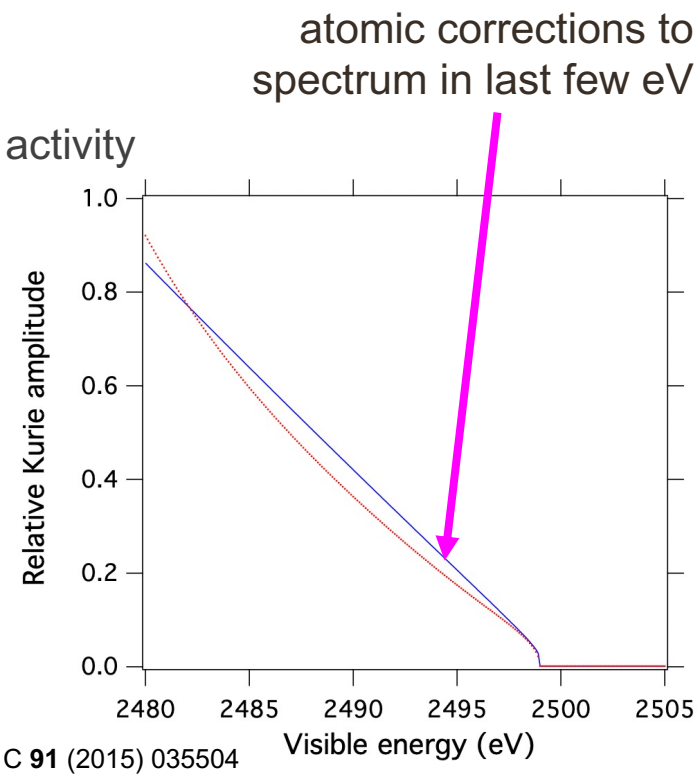
A. Nucciotti, AHEP **2016** (2016) 9153024

L. Gastaldo, Neutrino 2022



^{163}Ho Challenges

- ^{163}Ho is not naturally abundant
  - Typically produced by neutron irradiation of ^{162}Er
    - Extraction does yield clean sample with high activity
- Endpoint isn't precisely known
  - No good measurement from Penning trap
  - 10% uncertainty in endpoint up to ~5 years ago
- Spectral shape is complicated
  - Need solid match of experiment with theory



H. Robertson, Phys. Rev. C **91** (2015) 035504

Tritium Beta Decay

- Tritium has been the workhorse of the direct neutrino mass field
  - Best limits for 75 years (since 1948), and counting

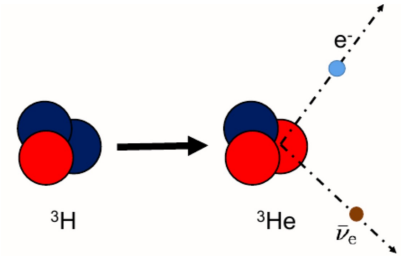
- Endpoint: 18.6 keV
- Half-life: 12.3 yr
- Superallowed decay

$$^{3}_{1}H \rightarrow {}^{3}_{2}He^{+} + e^{-} + \overline{\nu_e}$$

nuclear matrix element
(energy independent)

$$\frac{dN}{dE_e} = \frac{G_F^2 m_e^5 \cos^2\theta_C}{2\pi^3\hbar^7} |M_{nuc}|^2 \cdot p \cdot (E + m_e) \cdot (E_0 - E) \cdot \sqrt{(E_0 - E)^2 - m^2(\nu_e)}$$

constants *pure kinematics*



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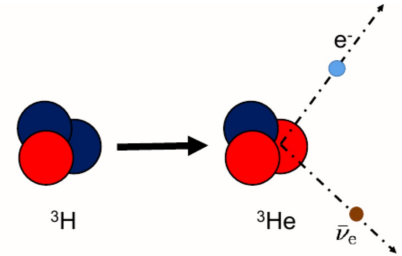

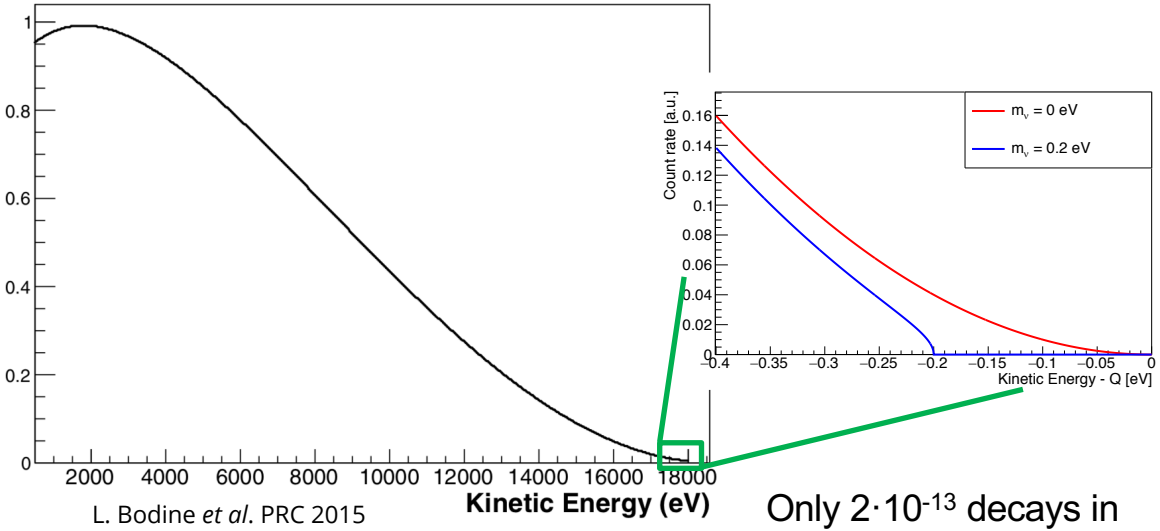

L. Bodine *et al.* PRC 2015

Only $2 \cdot 10^{-13}$ decays in last eV of the spectrum

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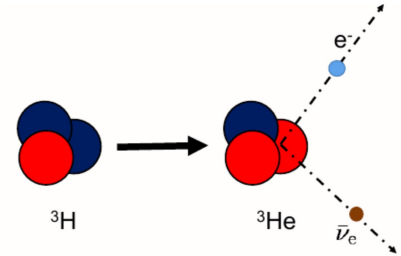

H^3 and the Mass of the Neutrino

Emil J. Konopinski
Indiana University, Bloomington, Indiana

July 28, 1947

THE maximum energy of the β-particles from H^3 has most recently[1] been reported as 11 ± 2 kev. The unusually low energy of this β-spectrum makes it extremely sensitive as an indicator of a non-vanishing rest mass for the neutrino. Coupled with measurements of the H^3 half-life, it shows that the neutrino cannot have a mass greater than 2 to 3 percent of the electron's rest mass. Moreover, the H^3 decay rate as presently known seems 6 to 10 times too rapid in comparison with that of heavier elements unless the neutrino is attributed a finite mass of the magnitude mentioned.

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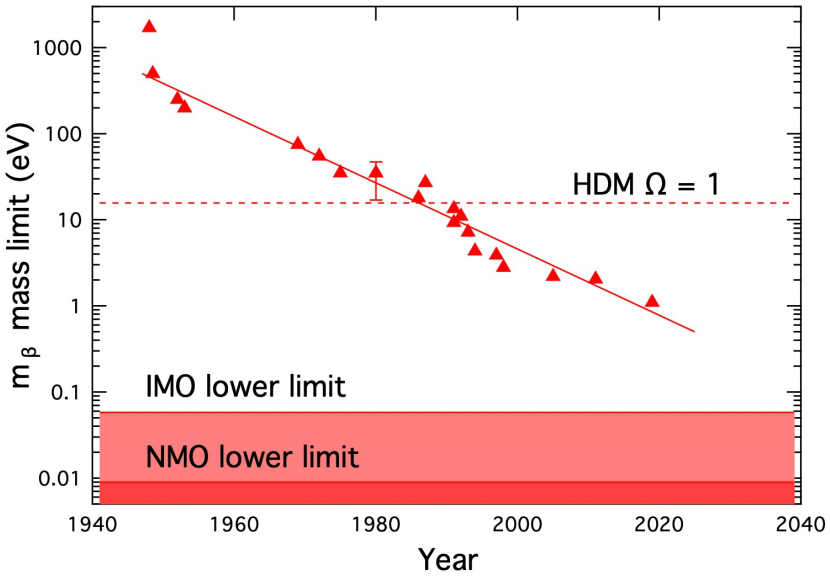

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THE

PHYSICAL REVIEW

A journal of experimental and theoretical physics established by E. L. Nichols in 1893

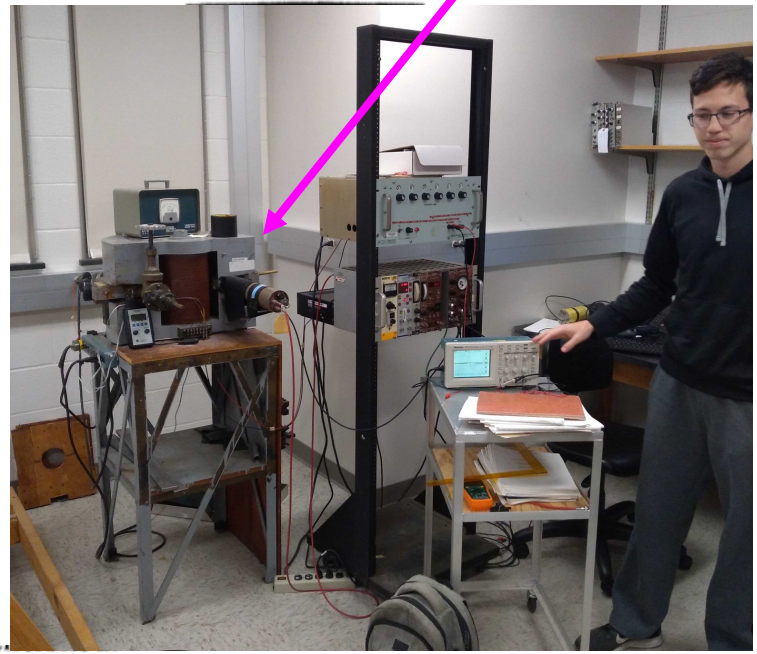
SECOND SERIES, VOL. 88, NO. 4 NOVEMBER 15, 1952

The Beta-Spectrum of Tritium and the Mass of the Neutrino*

L. M. LANGER AND R. J. D. MOFFAT
Department of Physics, Indiana University, Bloomington, Indiana

(Received June 23, 1952)

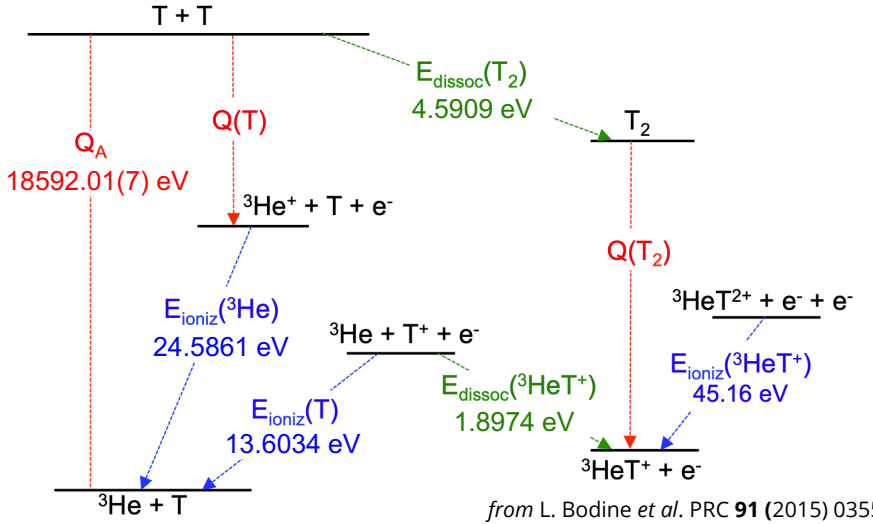
A direct determination of the beta-spectrum of H^3 has been made in a high resolution magnetic spectrometer. The experimental data are fitted by a straight line Fermi plot from 5.5 kev to the maximum energy at 17.95±0.10 kev. An upper limit of 250 volts or 0.05 percent of the mass of the electron is obtained for the rest mass of the neutrino. New estimates are obtained for the H^3 comparative half-life, the neutron half-life, and the value of the Fermi universal constant of beta-decay.



Sidenote: Endpoint vs. Q-value

- The "endpoint" (E_0) is subtly different from the Q-value
  - Q-value: energy difference measured by Penning traps
  - Endpoint: maximum energy the electron can have in decay
- Make sure you understand atomic effects!!!

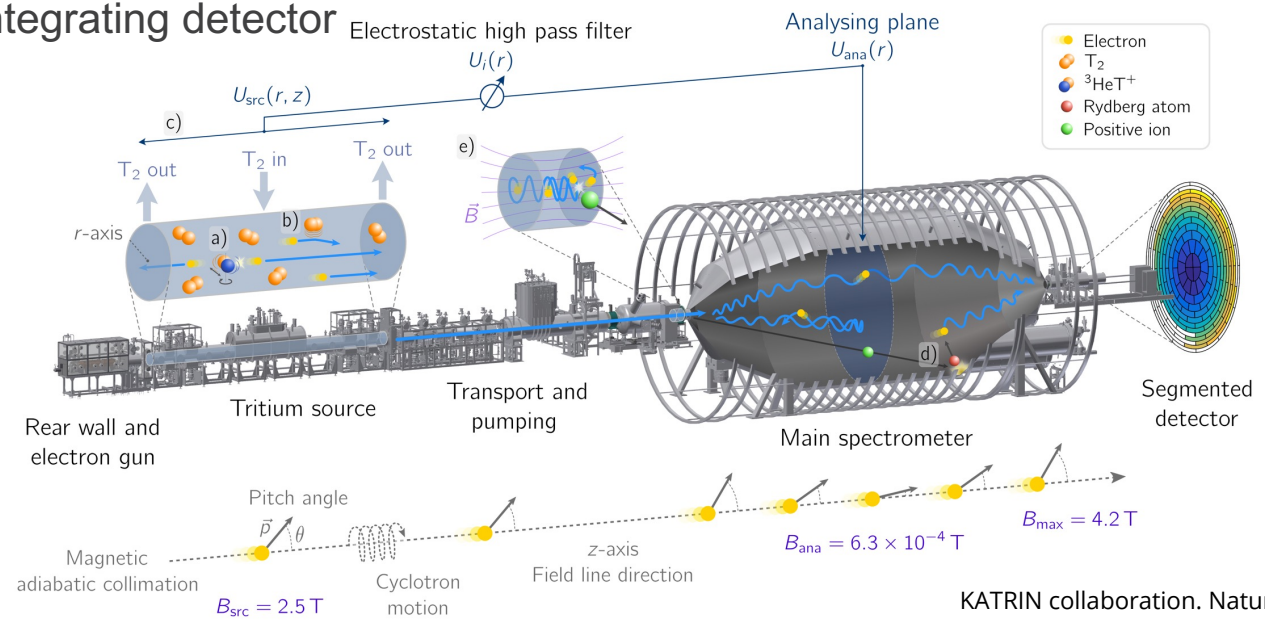
E_0 (T_2) = 18 574.01(7) eV



from L. Bodine *et al*. PRC **91** (2015) 035505, updated

KATRIN: State-of-the-Art

- Culmination of decades of experience in magnetic + electrostatic spectrometers
  - Electrons guided from tritium source, through filtering spectrometer, to integrating detector

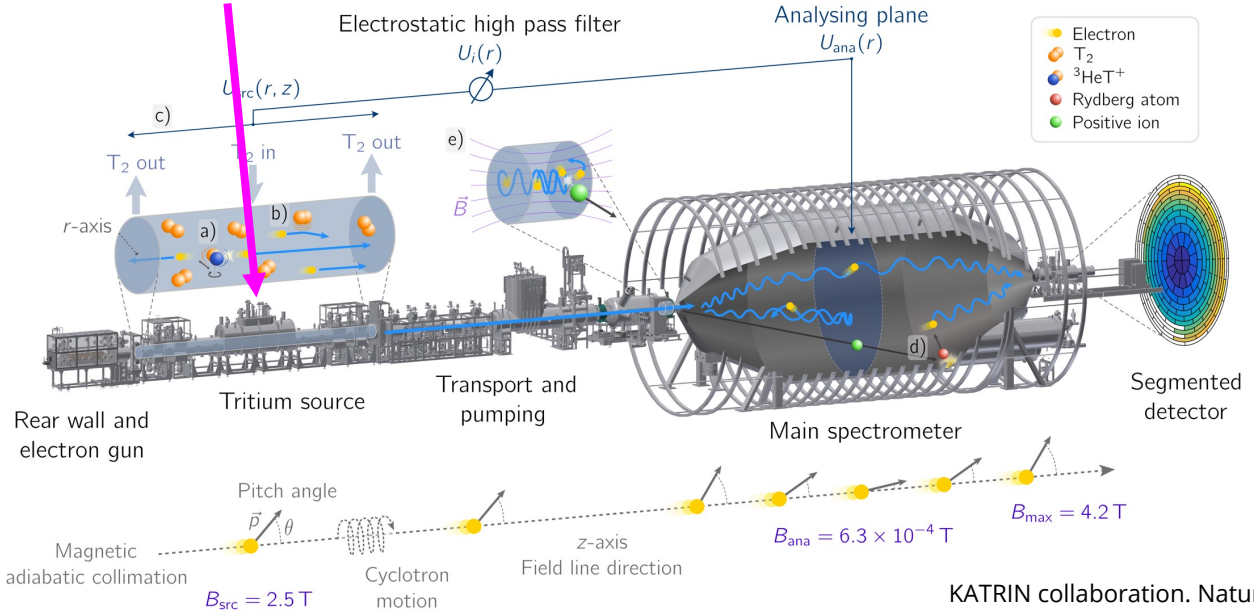


KATRIN collaboration. Nature Physics **18**, 160 (2022)

KATRIN: WGTS

Windowless Gaseous Tritium Source (WGTS)

- Intense and pure tritium source
- Uniform field region for tritium decays

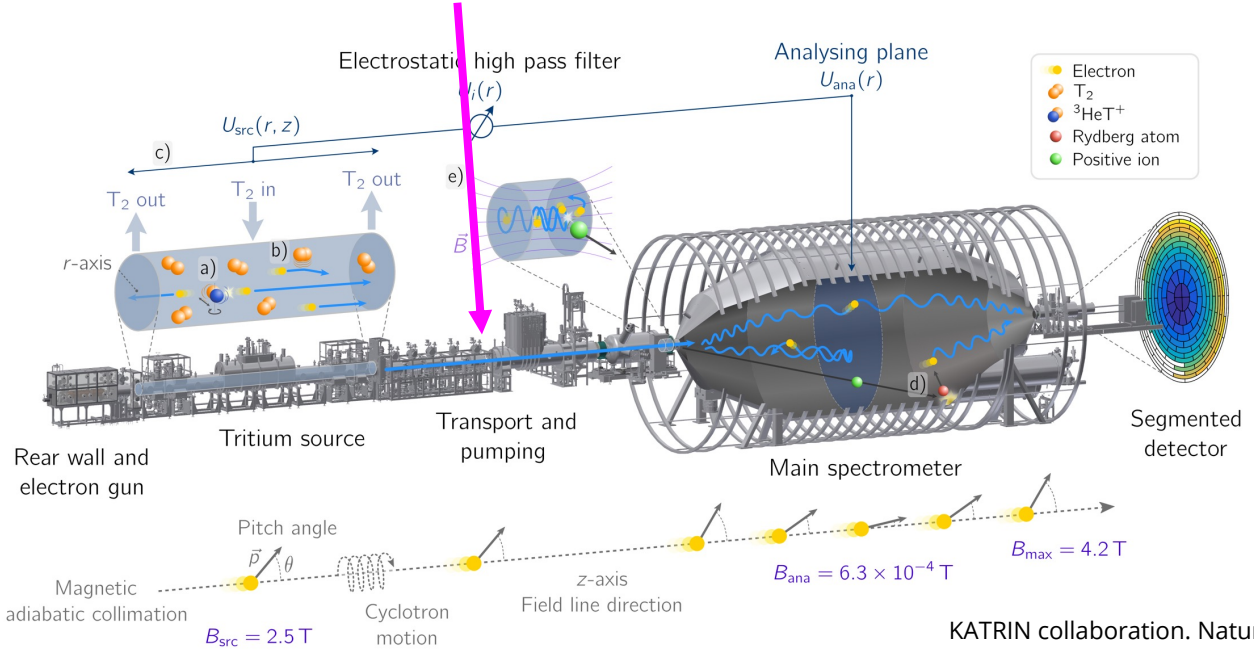


KATRIN collaboration. Nature Physics **18**, 160 (2022)

KATRIN: Pumping

Differential and Cryogenic Pumping

- Reduces tritium flow by ~14 orders of magnitude

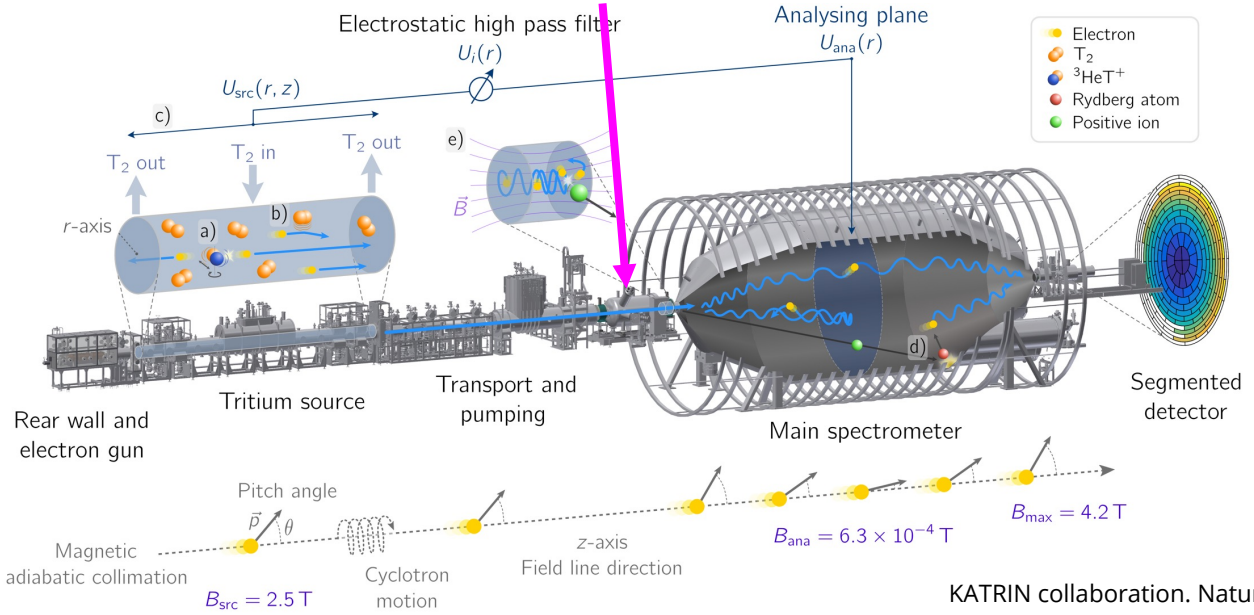


KATRIN collaboration. Nature Physics **18**, 160 (2022)

KATRIN: Pre-Spectrometer

Pre-Spectrometer

- Rejects low-energy electrons back to source
- Miniature version of main spectrometer

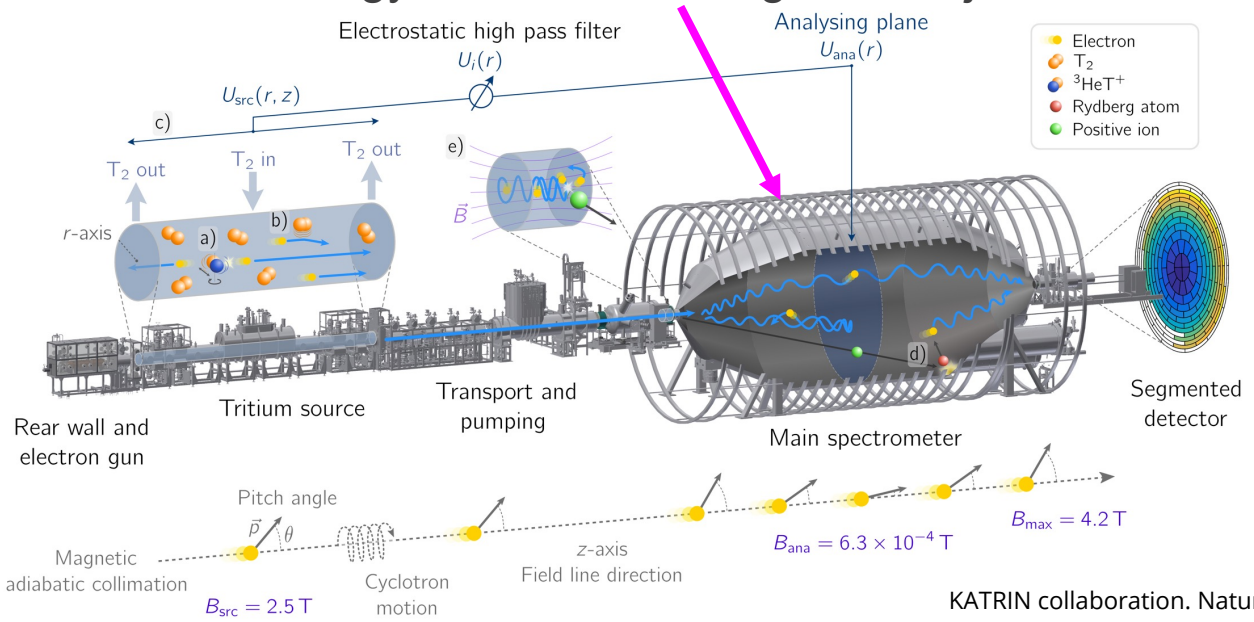


KATRIN collaboration. Nature Physics **18**, 160 (2022)

KATRIN: Main Spectrometer

Main Spectrometer

- Defines energy threshold of experiment
- Sets energy resolution, background rejection

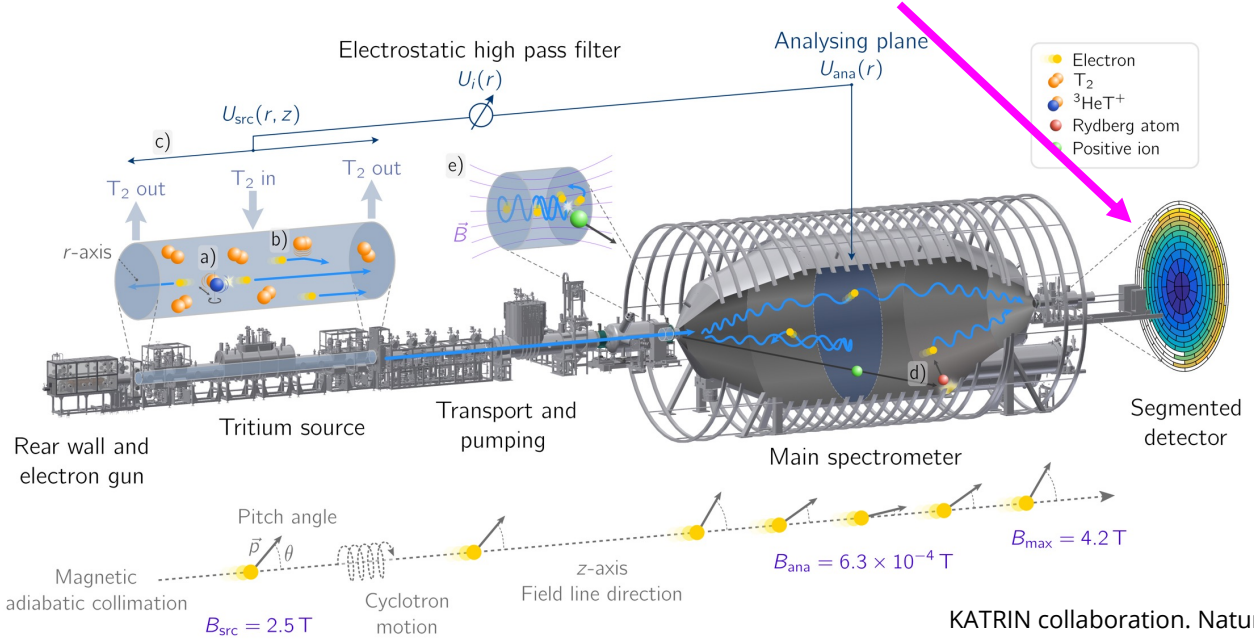


KATRIN collaboration. Nature Physics **18**, 160 (2022)

KATRIN: Detector

Detector

- Counting detector



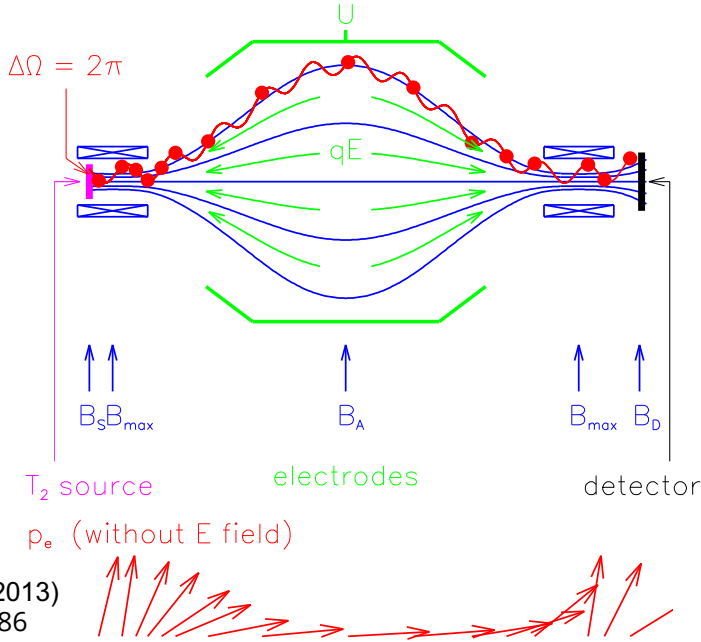
KATRIN collaboration. Nature Physics **18**, 160 (2022)

MAC-E Filter Principle

- Magnetic Adiabatic Collimation with Electrostatic (MAC-E) filter

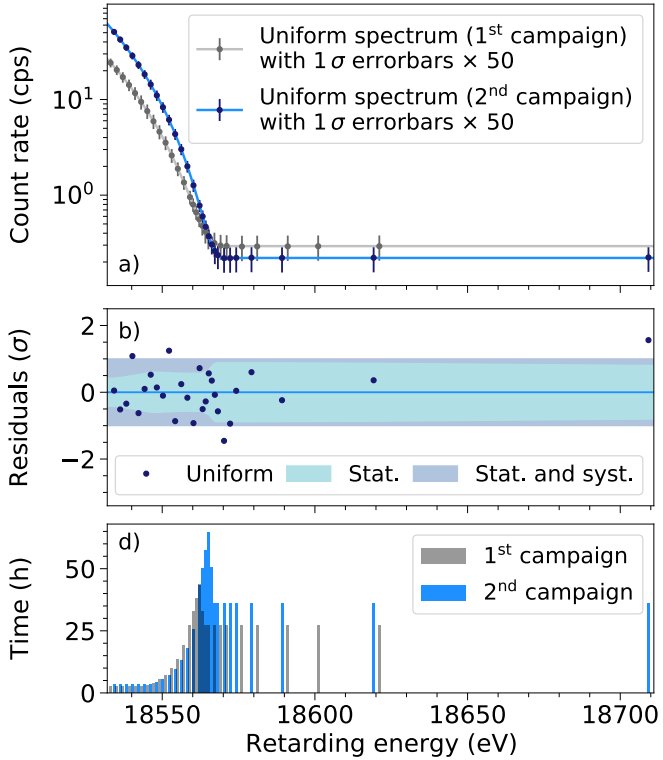
- Magnetic field adiabatically guides electrons
- Weakest field region aligns momentum
  - Maximizes longitudinal velocity
- Electrostatic potential here at analyzing plane sets high pass filter
- Electrons passing filter re-accelerate to detector

- Energy resolution set by magnetic field
  - $\frac{\Delta E}{E} = \frac{B_{min}}{B_{max}}$



G. Drexlin *et al*. AHEP (2013)
doi:10.1155/2013/293986

KATRIN: State-of-the-Art



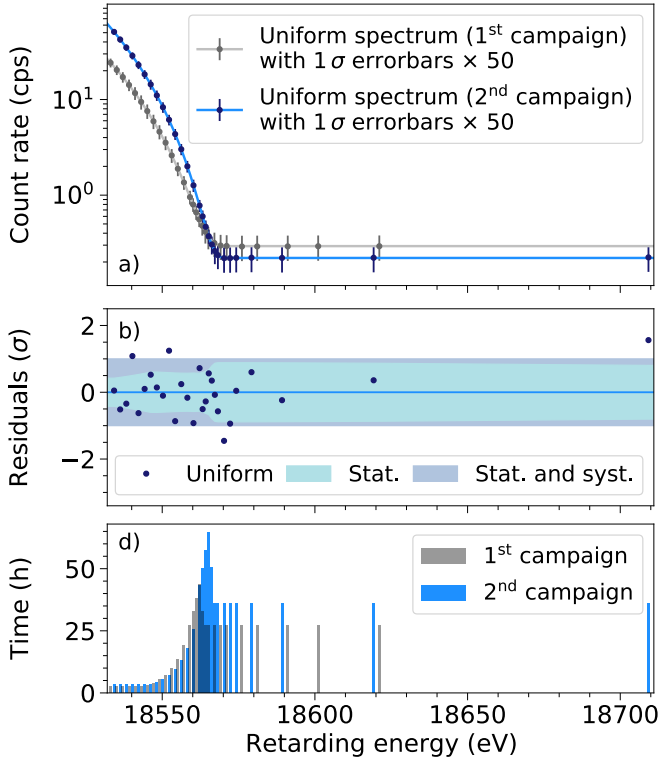
(KATRIN) Nature Physics **18**, 160 (2022)

- Released first two "campaigns"
  - Campaign 1: world-leading mass limit
    - 3 weeks of data at 20% source intensity
  - Campaign 2: (world leading) sub-eV mass limit
    - $m_\beta < 0.8$ eV
    - 1 month of data, also from 2019

Effect (1σ uncertainty on m_ν^2)	KNM1 (eV^2)	KNM2 (eV^2)
Statistical	0.97	0.29
Non-Poissonian background	0.30	0.11
Source-potential variations (plasma effects)	Neglected	0.09
Scan-step-duration-dependent background	Neglected	0.07
qU-dependent background	0.07	0.06
Magnetic fields	0.05	0.04
Molecular final-state distribution	0.02	0.02
Column density × inelastic scat. cross-section ($\rho d\sigma$)	0.05	0.01
Total uncertainty	1.02	0.34

(KATRIN) J. Phys. G **49** (2022) 100501

KATRIN: State-of-the-Art



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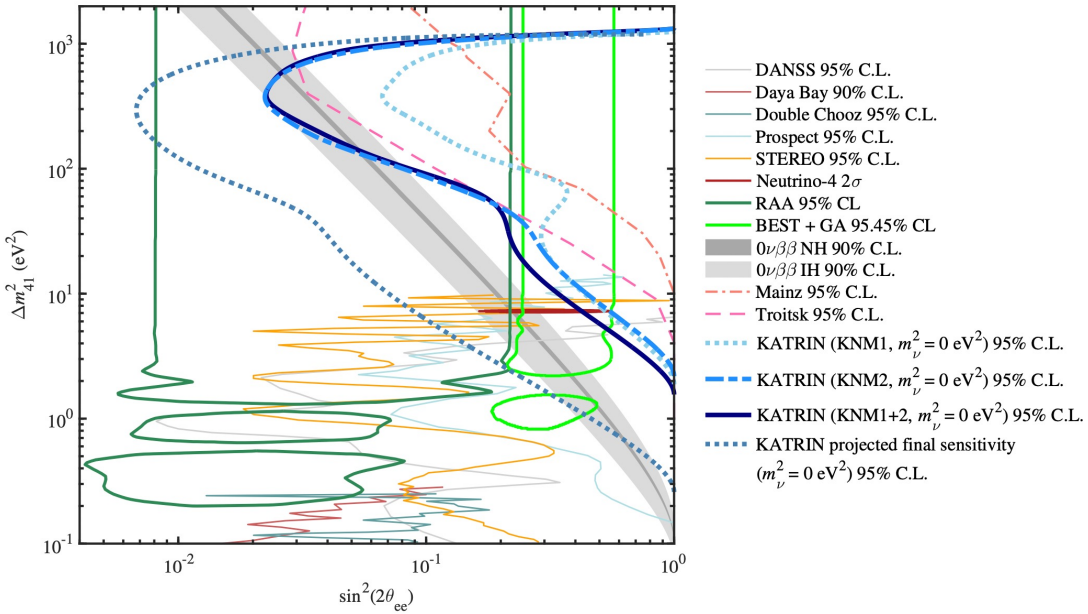
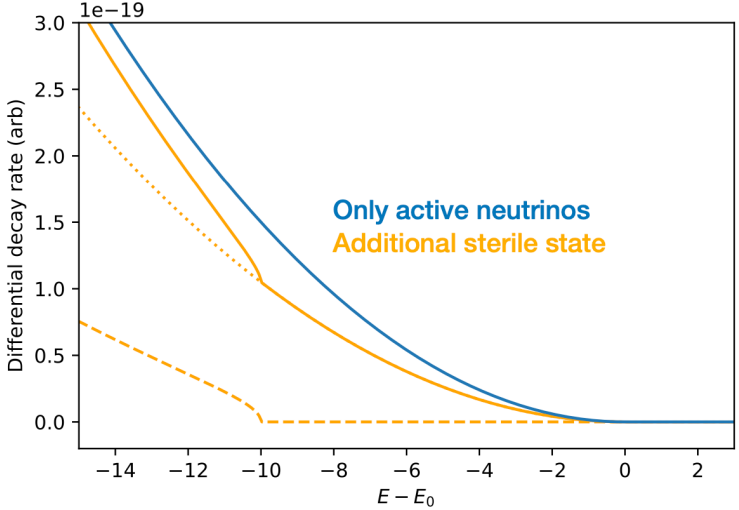
    - $m_\beta < 0.8$ eV
    - 1 month of data, also from 2019
- Further results expected this year with ~10x statistics, $m_\beta \sim 0.5$ eV sensitivity
  - Cruel reminder that m_β sensitivity only improves with $\sqrt[4]{N}$
- Neutrino mass operations continue through 2025 down to ~0.2 eV sensitivity

KATRIN: Sterile Neutrino Sensitivity

- World leading limits on sterile neutrinos via spectral distortion

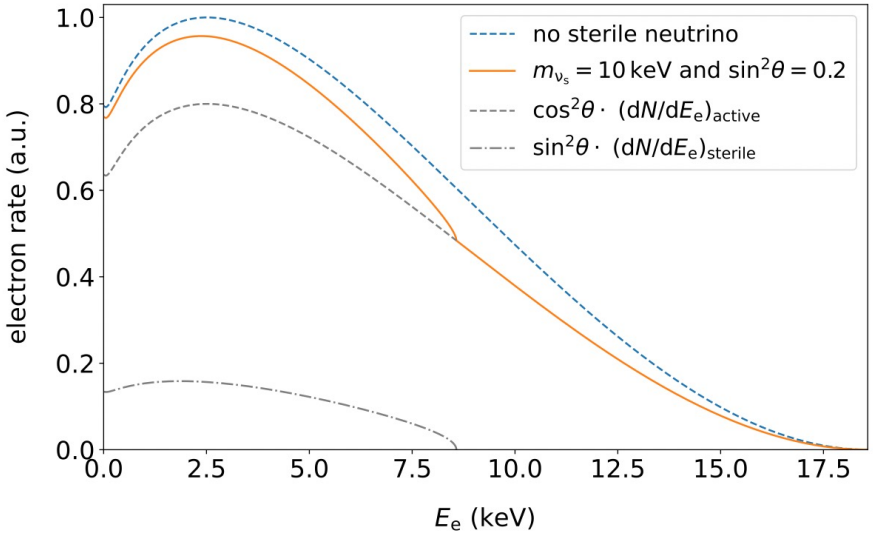


(KATRIN) Phys. Rev. D **105** (2022) 072004

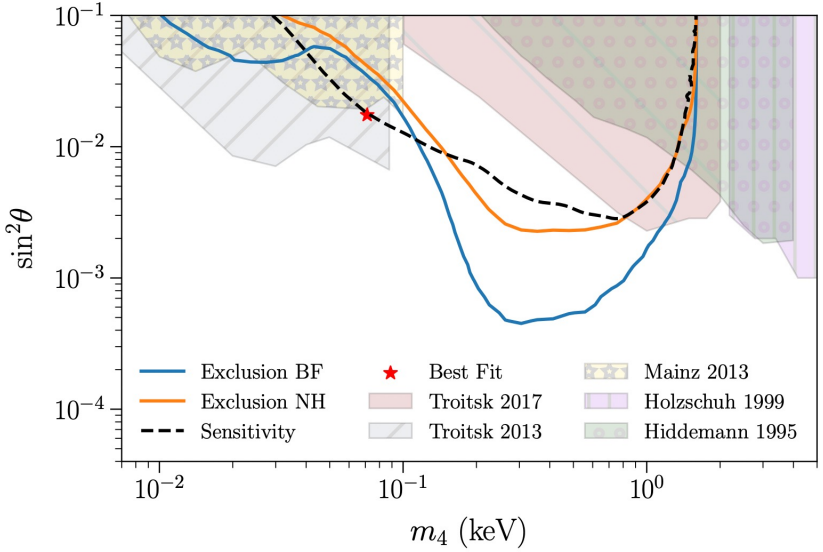


KATRIN: Sterile Neutrino Sensitivity

- Follow-on keV sterile neutrino search with TRISTAN detector
  - Current sensitivity based on low-intensity commissioning data
  - Push $\sin^2\theta$ down below 10^{-6} with upgraded detector to handle rate



(KATRIN) J. Phys. G **49** (2022) 100501

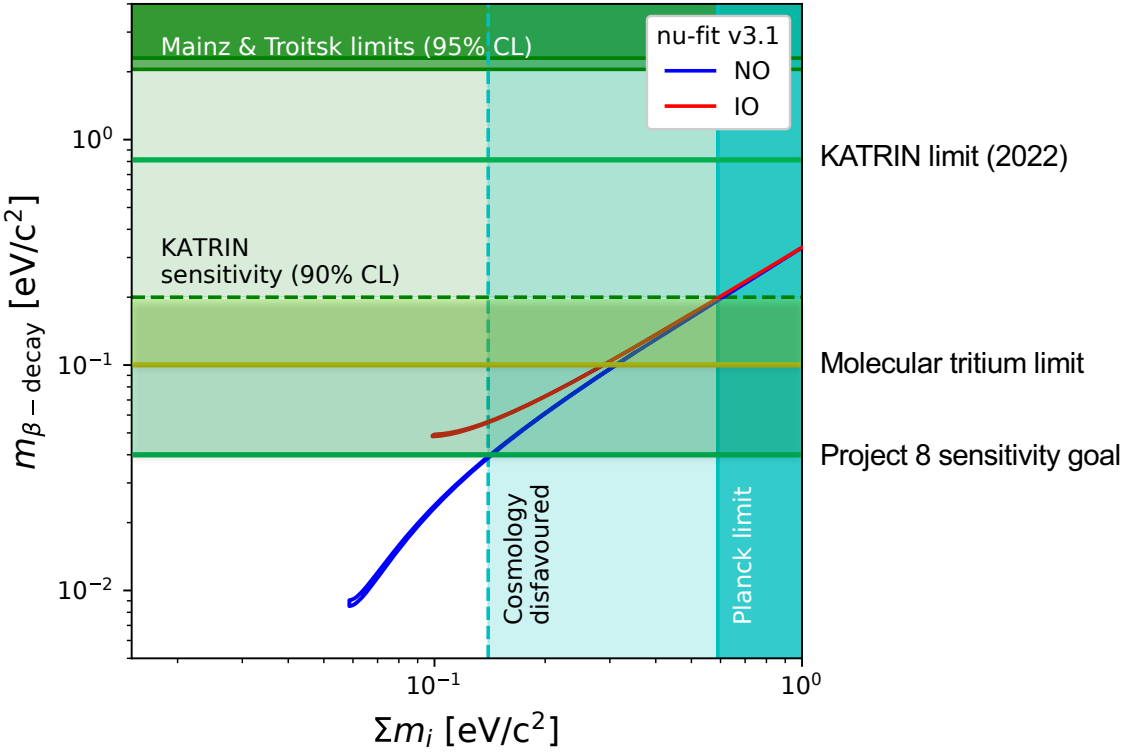


(KATRIN) arXiv:2207.06337

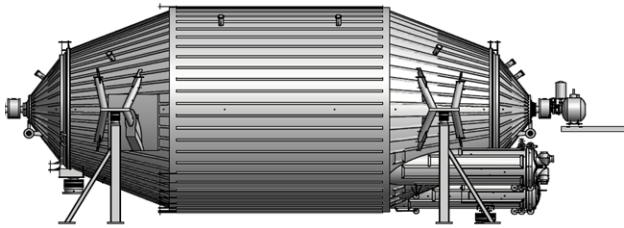
Beyond KATRIN

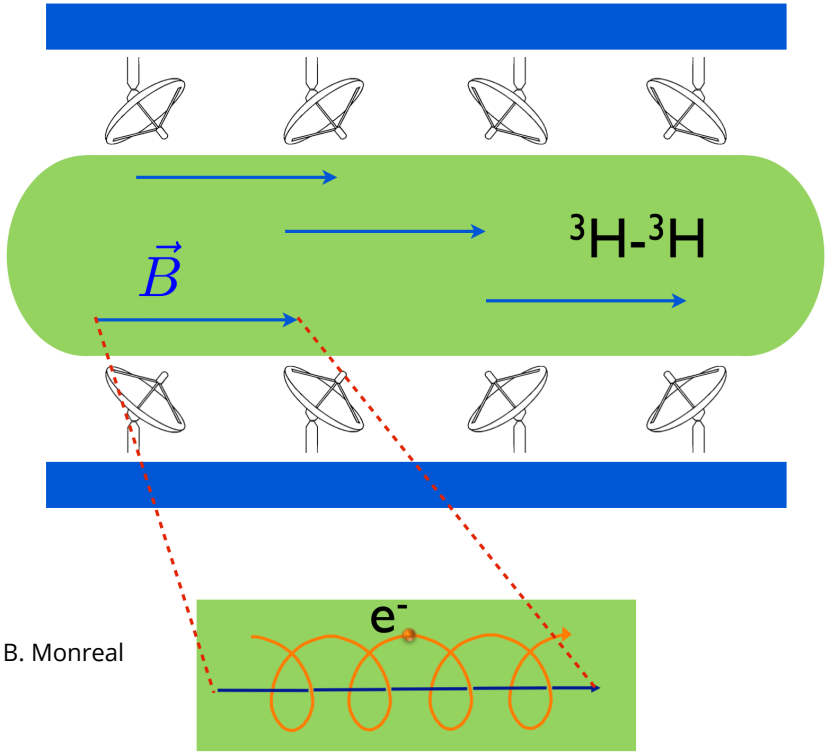
- MAC-E technology reaching technical scaling limit with KATRIN
  - Larger spectrometer required for improved resolution
  - Integrating spectroscopy reduces statistical power
  - New spectrometer-related backgrounds discovered at KATRIN scale
- Molecular tritium source introduces statistical and systematic penalties due to molecular effects

Sensitivity after KATRIN



Beyond KATRIN Concept



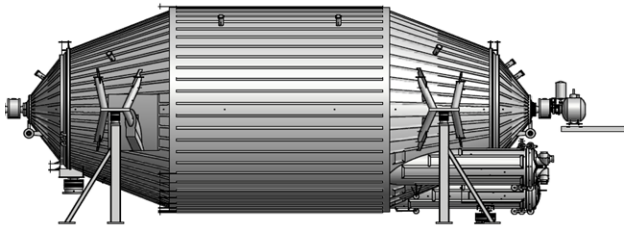


B. Monreal

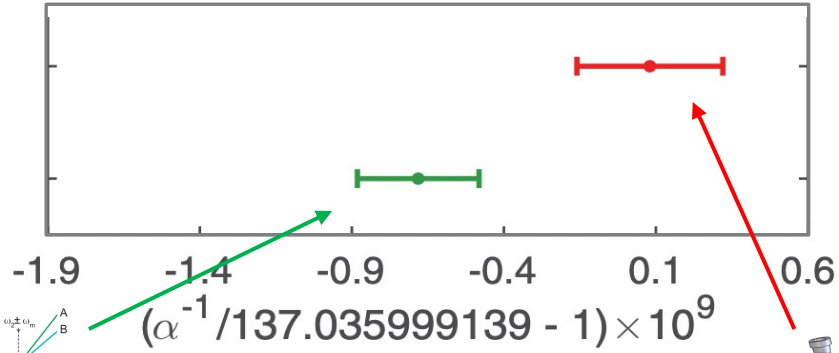
Never measure anything but frequency.

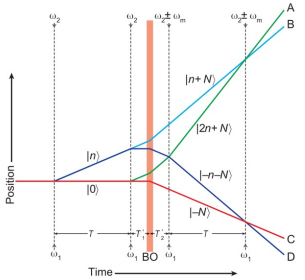
– Arthur Schawlow

Beyond KATRIN Concept

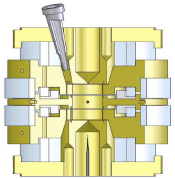


If you liked the *muon* g-2 result…





Parker et al., Science **360** (2018) 191



D. Hanneke, S. Fogwell, and G. Gabrielse, *Phys. Rev. Lett.* **100** (2008) 120801

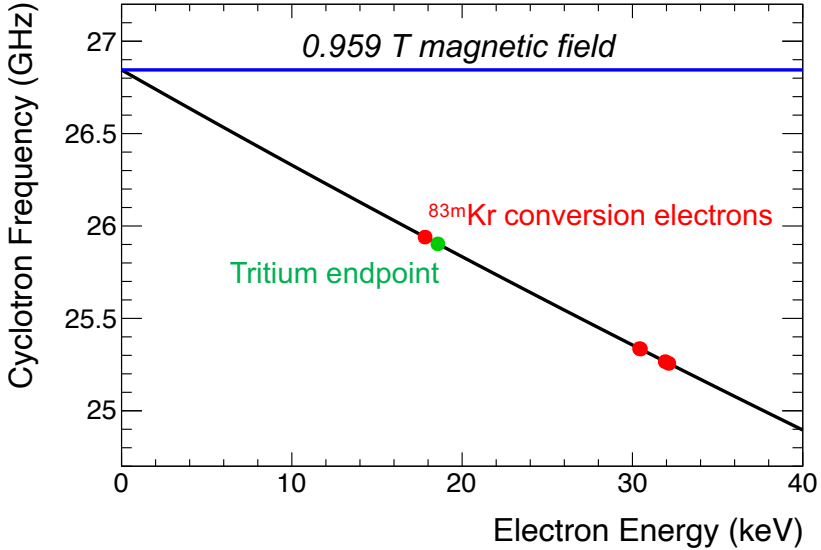
Never measure anything but frequency.

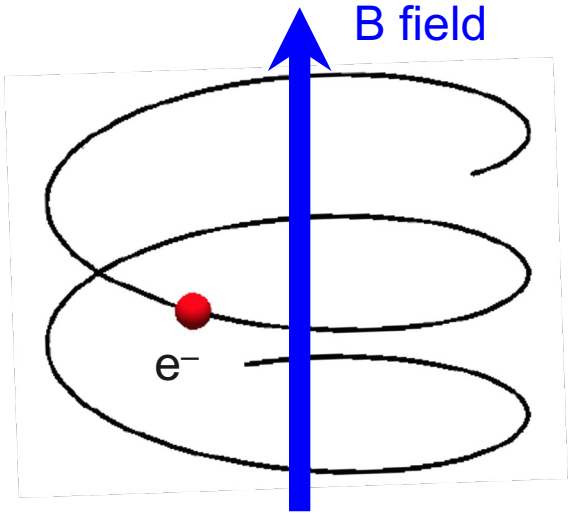
– Arthur Schawlow

Cyclotron Radiation Emission Spectroscopy (CRES)

- Harness frequency-energy relation for relativistic electrons

$$f_c = \frac{1}{2\pi}\frac{eB}{(m + E_{kin})}$$





Project 8 Experiment

- A phased tritium beta endpoint experiment to measure the electron neutrino mass

2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027 2028

Phase I

- Proof-of-principle demonstration of CRES technique
  - ^{83m}Kr measurement in waveguide apparatus

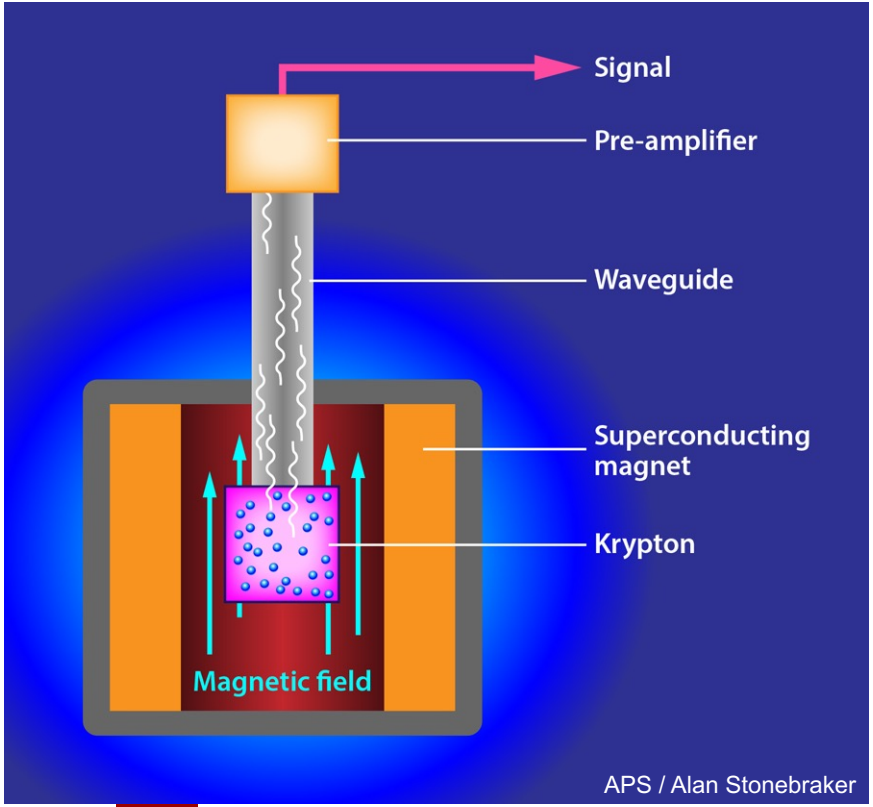
Phase II Commission | Operations | Analysis

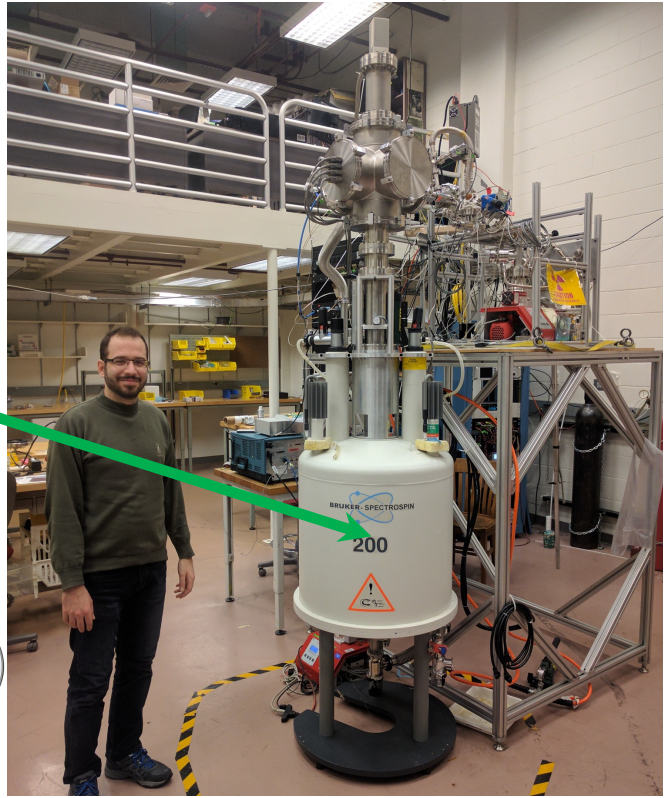
Final results, see:
- arXiv:2212.05048 (accepted in PRL)
- arXiv:2303.12055 (submitted to PRC)

- High-resolution Kr measurements
- First tritium measurement and first neutrino mass limit with CRES
  - Zero-background beyond endpoint
  - Control of systematics effects

Waveguide Experimental Concept

PROJECT 8





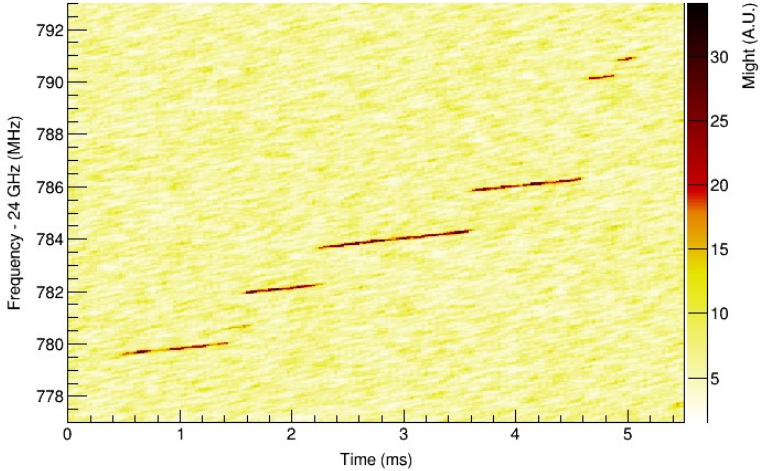
Waveguide CRES Results

Featured in Physics Editors' Suggestion

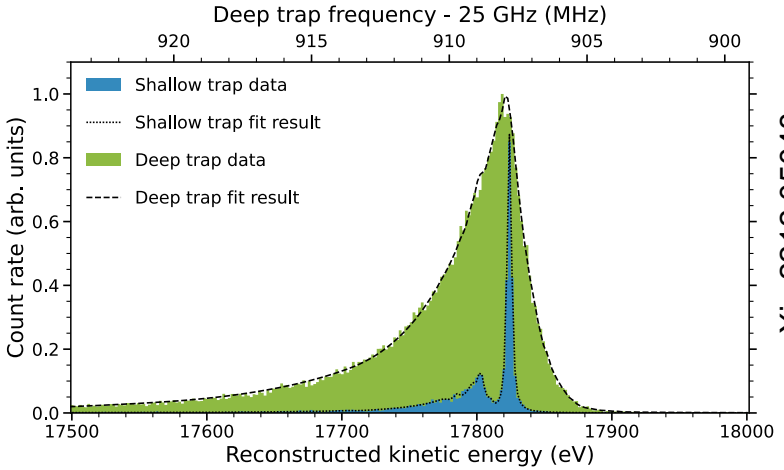
Single-Electron Detection and Spectroscopy via Relativistic Cyclotron Radiation

D. M. Asner *et al.* (Project 8 Collaboration)
Phys. Rev. Lett. **114**, 162501 – Published 20 April 2015

Physics See Viewpoint: Cyclotron Radiation from One Electron



D. Asner *et al*. Phys. Rev. Lett. 114, 162501 (2015) (reprocessed)

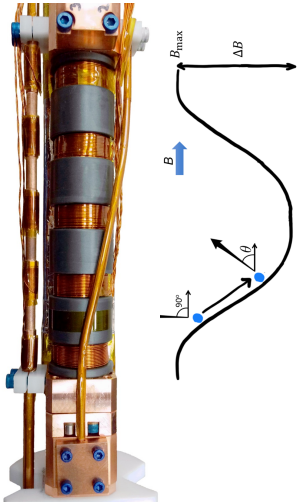


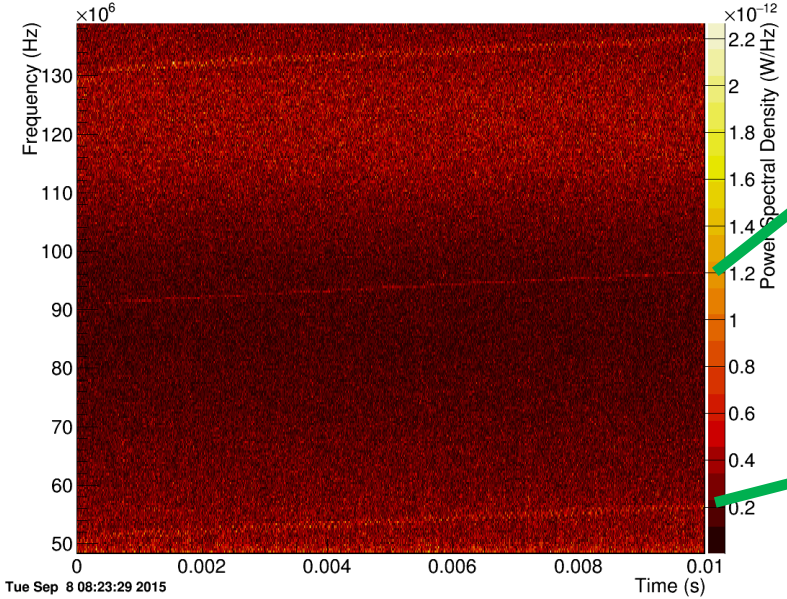
arXiv:2212.05048

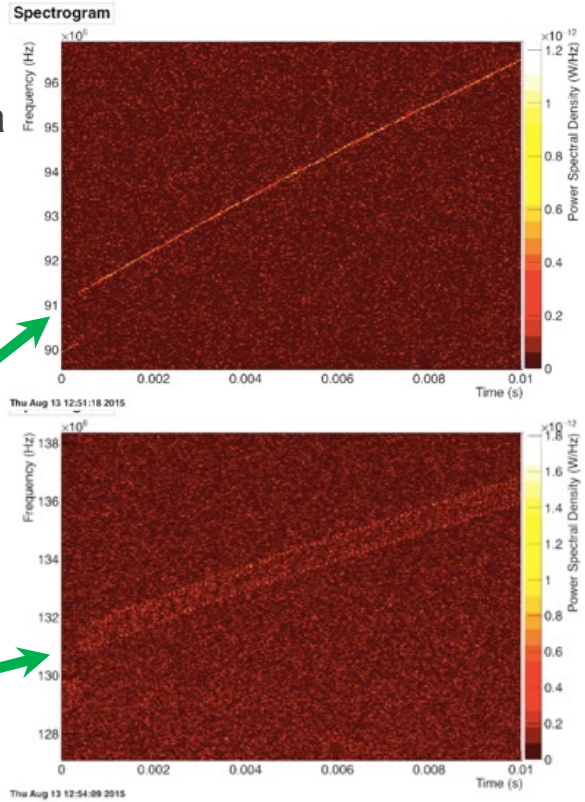
Instrumental resolution (1.7±0.2 eV) now better than natural CE linewidth (2.8 eV)

Waveguide CRES Signals

- Motion in magnetic trap gives rise to signal features
  - Frequency modulation (FM) for end-on observation (wa



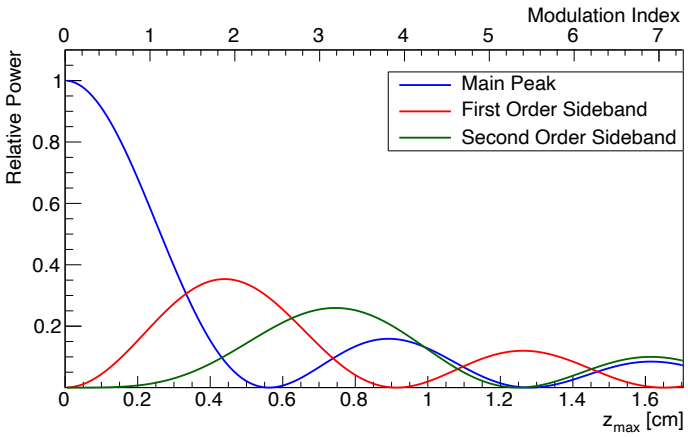




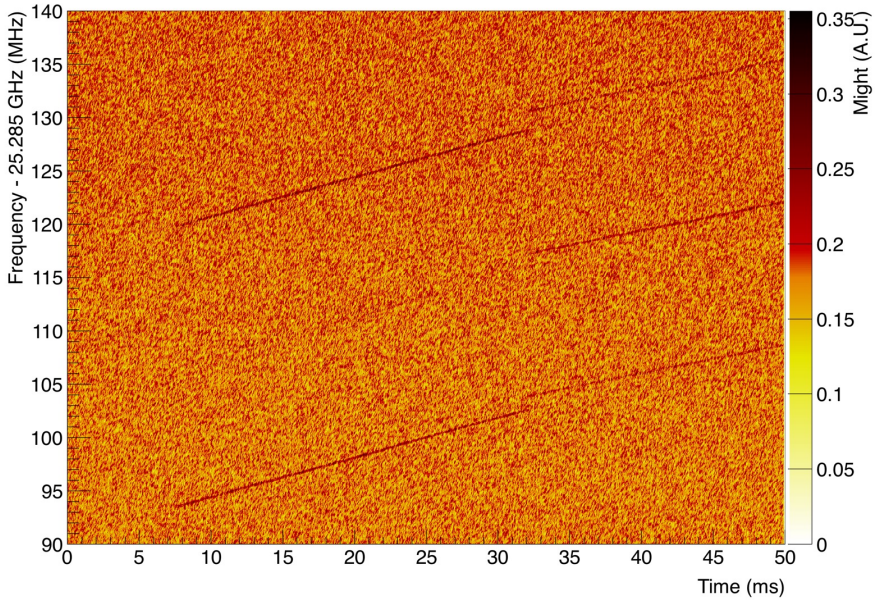
Sidebands and Disappearing Tracks

PROJECT 8

- Interference pattern and frequency modulation give rise to (dis)appearing tracks, variable intensity between carrier and sideband

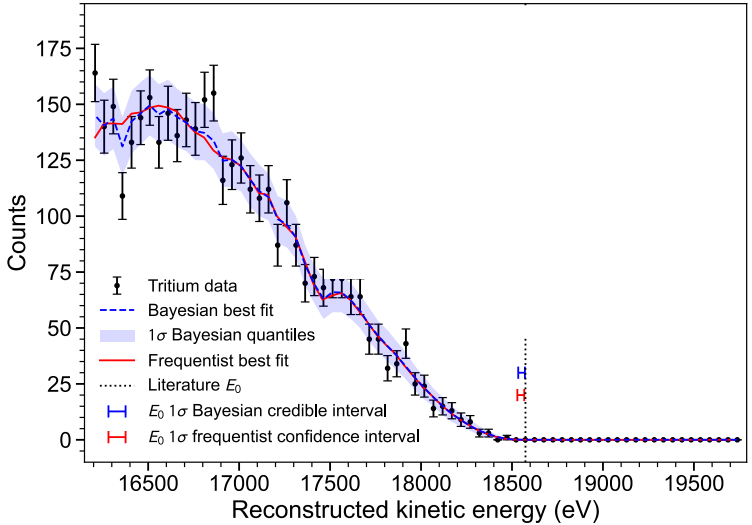


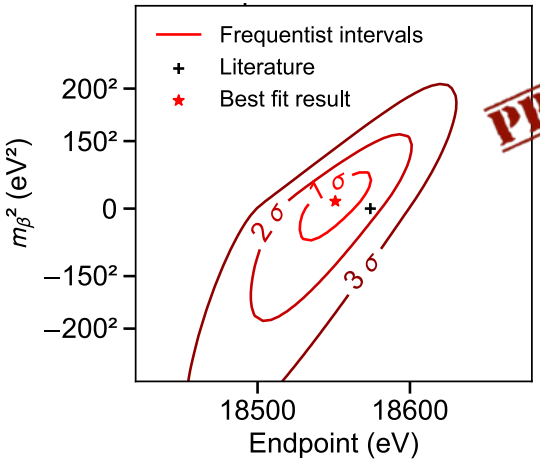
A. Ashtari Esfahani *et al.*, PRC **99**, 055501 2019



First Tritium Spectrum

- Collected 3 months stable run of tritium
  - ~4000 events across all signal channels
  - Zero background beyond endpoint





PROJECT 8

T_2 endpoint:

$$E_0 = \left(18553^{+18}_{-19}\right) \text{ eV (90\% C.I.)}$$

Neutrino mass:

≤ 155 eV/c² (90% C.I.) *Bayesian*

≤ 152 eV/c² (90% C.L.) *Frequentist*

Background rate:

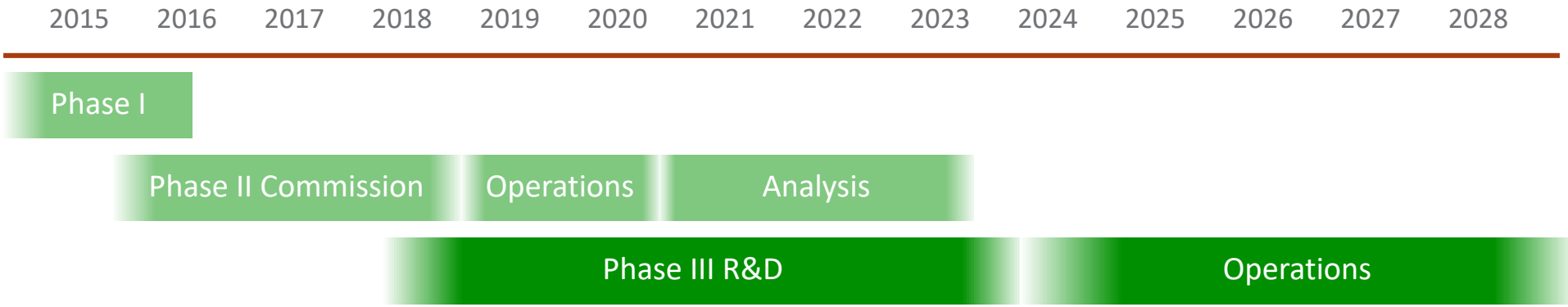
$\leq 3\times10^{-10}$ eV^{-1}s^{-1} (90% C.I.)

Final results, see:

- arXiv:2212.05048 (accepted in PRL)
- arXiv:2303.12055 (submitted to PRC)

Project 8 Experiment

- A phased tritium beta endpoint experiment to measure the electron neutrino mass

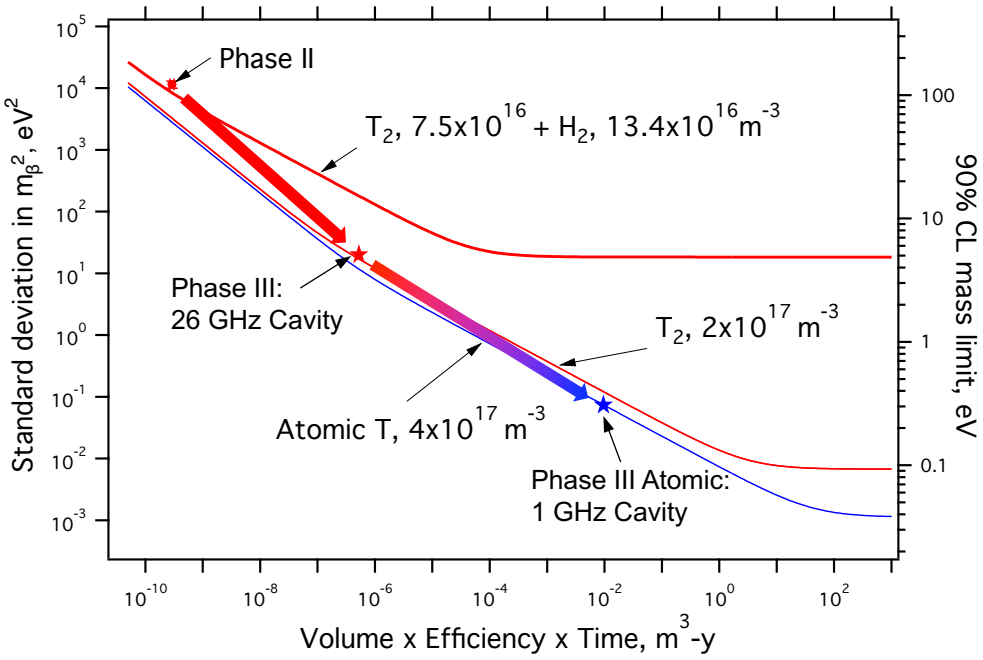


- Critical R&D demonstrations of technologies
  - Large-volume CRES measurement, first with single-mode cavity
  - Atomic tritium production, transport, and trapping
  - Culminates with first atomic tritium endpoint measurement

CRES – The Path Forward

PROJECT 8

Phase II was heavily statistics-limited

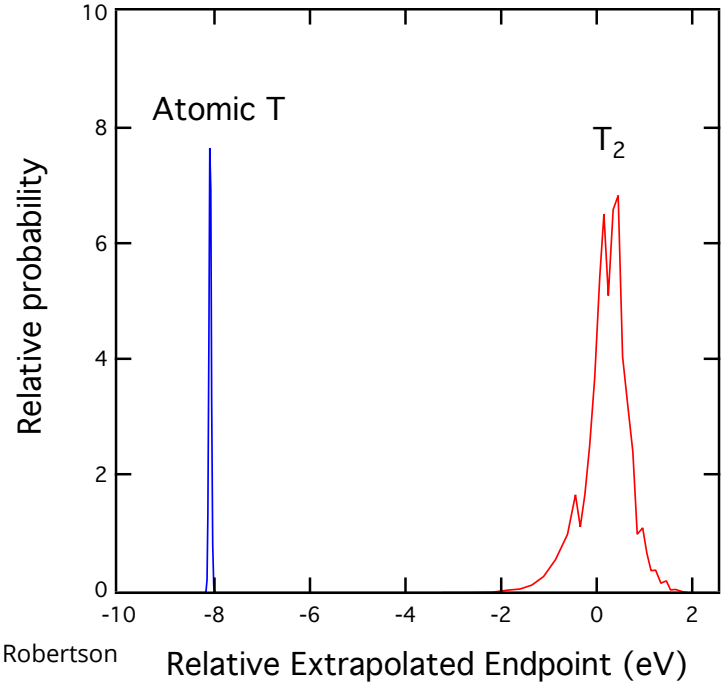


- Develop atomic source
  - Overcome systematic of molecular final states
- Increase volume
- Improve SNR
  - Higher density with shorter tracks
- Improve control of systematics, field homogeneity, scattering effects

Phase III ATD – Molecular Limitation

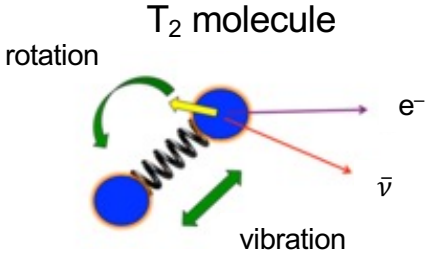
PROJECT 8

- Sensitivity beyond inverted hierarchy requires atomic tritium



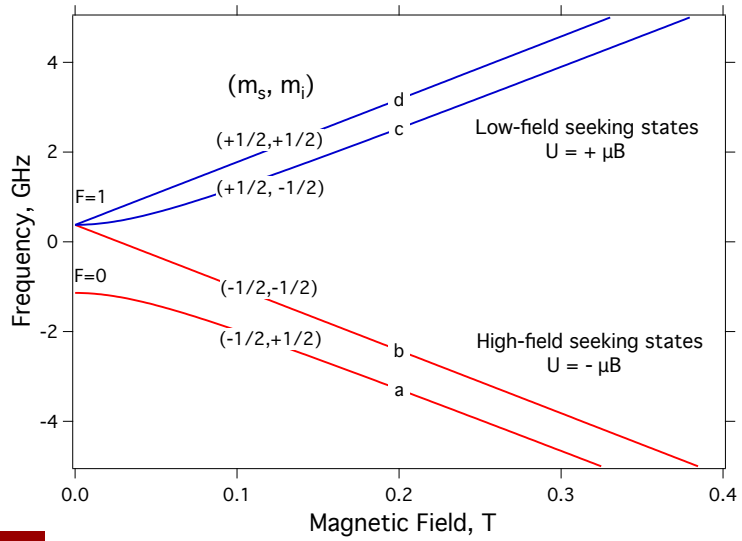
H. Robertson

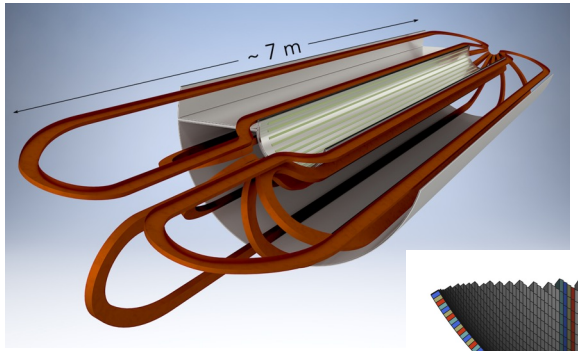
…and pure atomic tritium, as molecular endpoint is higher

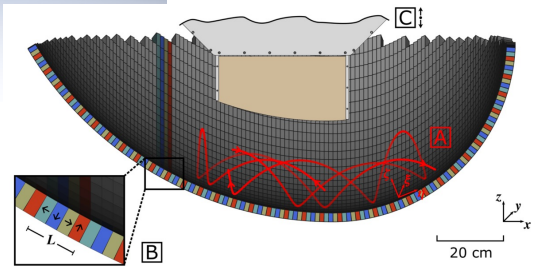


Phase III ATD – Trapping Atoms

- Magnetic moment of atomic species allows for guiding and trapping
  - Unpaired electron of atomic T (or H, D) gives it magnetic moment
  - “Low-field-seeking” states trapped by magnetic bottle
  - Requires high-multipole trap to achieve uniform CRES field region





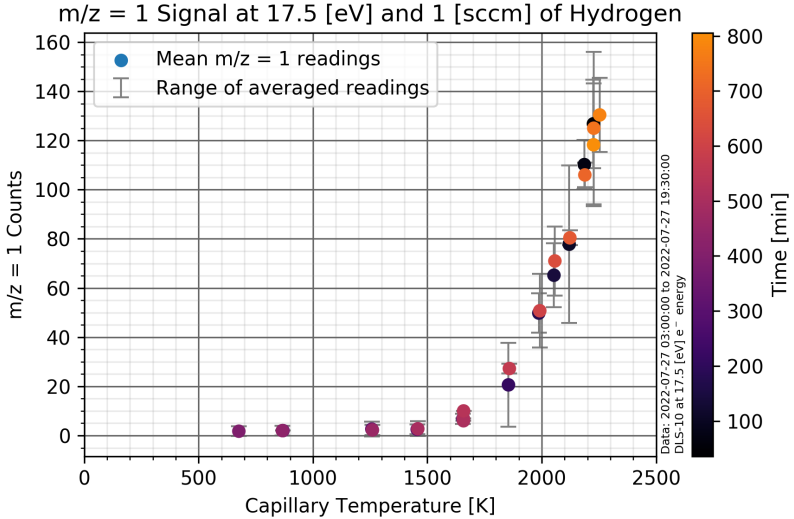


UCNτ, PRC **100**, 015501 (2019)

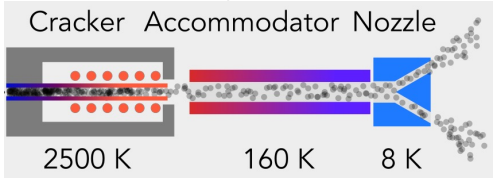
Phase III ATD – Atomic Tritium Source

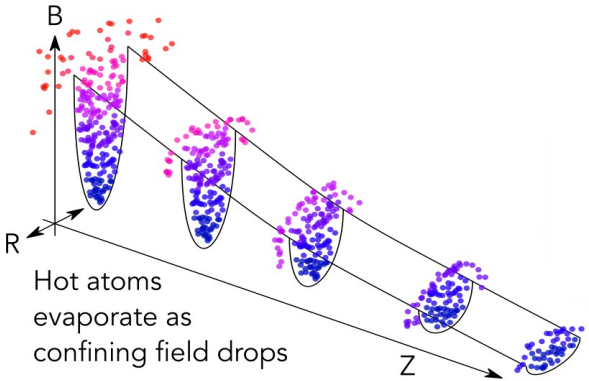
PROJECT 8

- Molecular tritium thermally cracked at ~2500 K



- Then cooled by accommodator to ~10 K



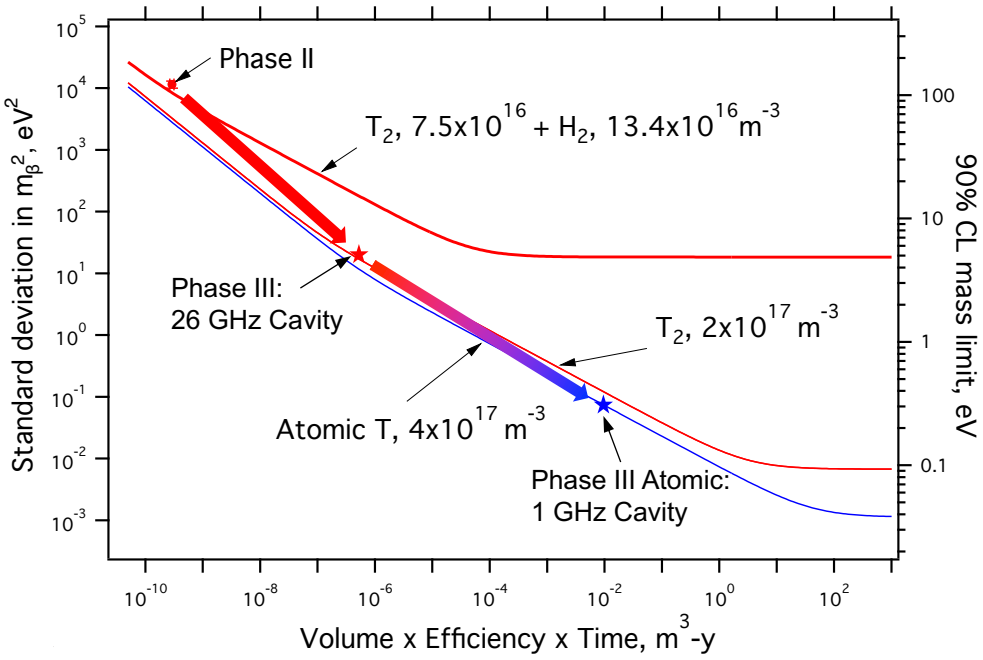


- Then cooled evaporatively down to mK

CRES – The Path Forward

PROJECT 8

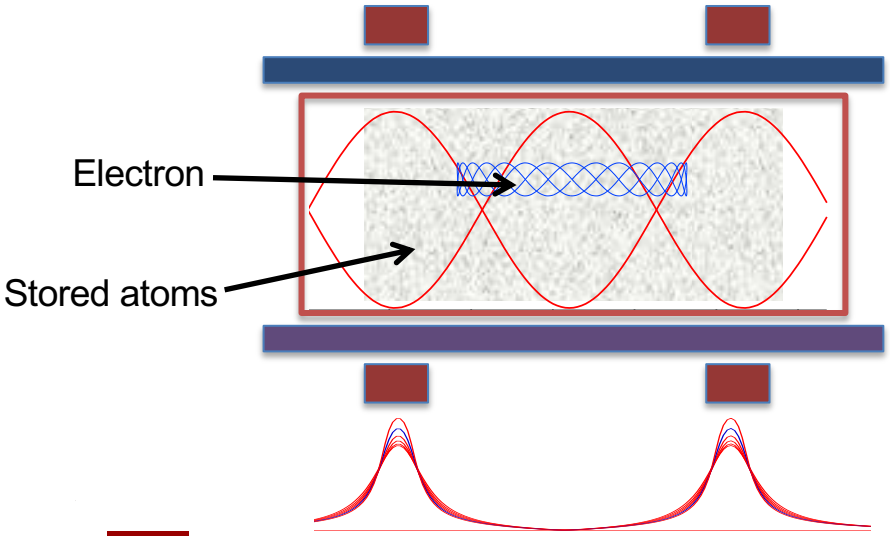
Phase II was heavily statistics-limited



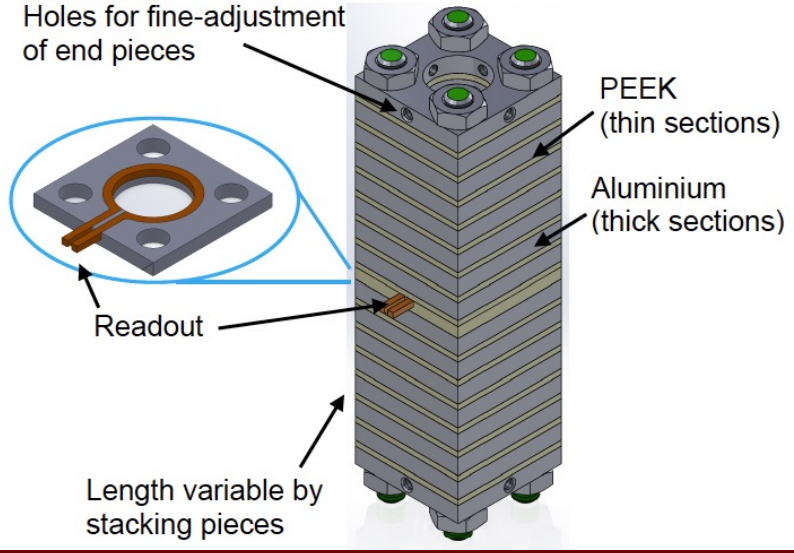
- Develop atomic source
  - Overcome systematic of molecular final states
- Increase volume
- Improve SNR
  - Higher density with shorter tracks
- Improve control of systematics, field homogeneity, scattering effects

Phase III – Beyond Waveguide

- Demonstrate scalability of CRES technique
- Cavity efficiently couples electron power to readout antenna
  - Mode-filtering reduces complexity of mode structure
  - Open-ended terminated cavity still allows gas injection



26 GHz Cavity Model



Phase III – Beyond Waveguide

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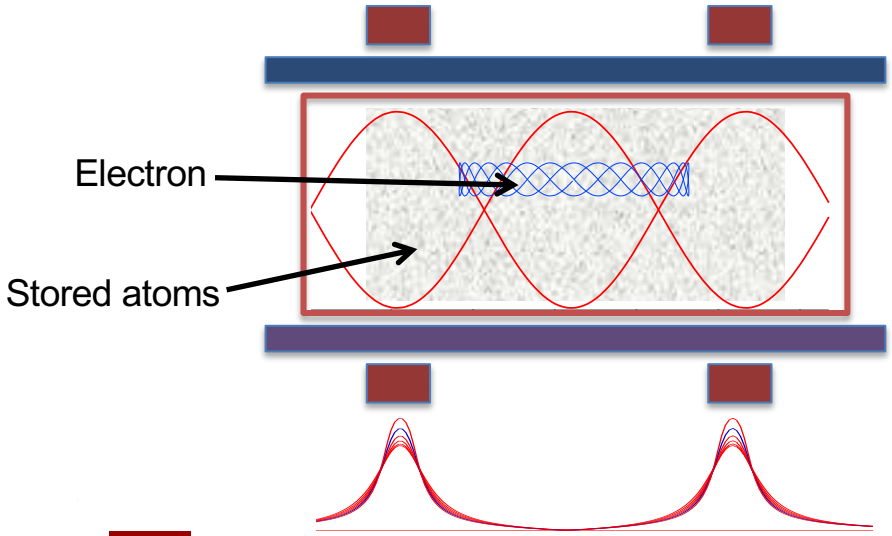
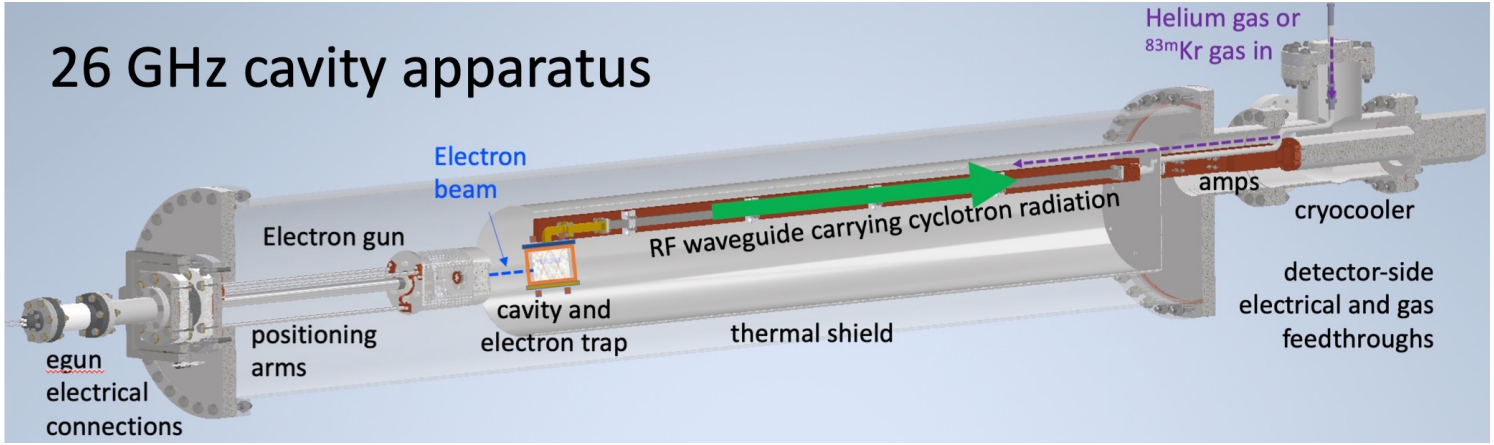


26 GHz Cavity CRES Demonstrator

PROJECT 8

- First cavity demonstrator will operate at 26 GHz / 1 T
  - Installation this fall at University of Washington

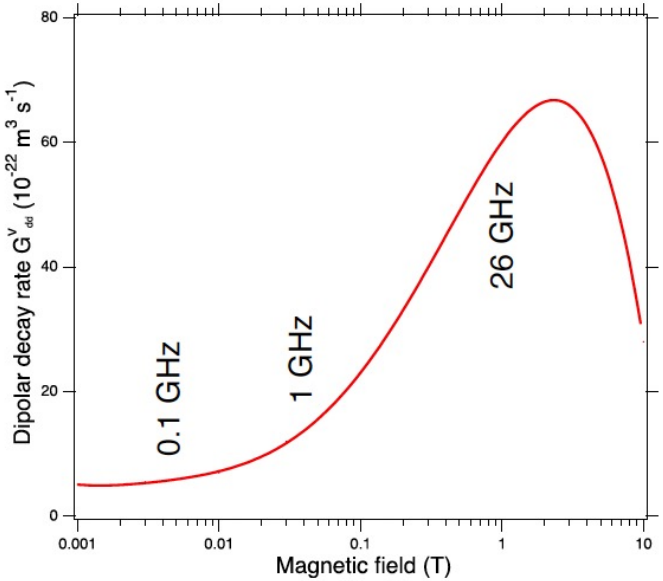


- Demonstration of high-precision calibration with electron gun source
- Science from ^{83m}Kr spectroscopy measurements

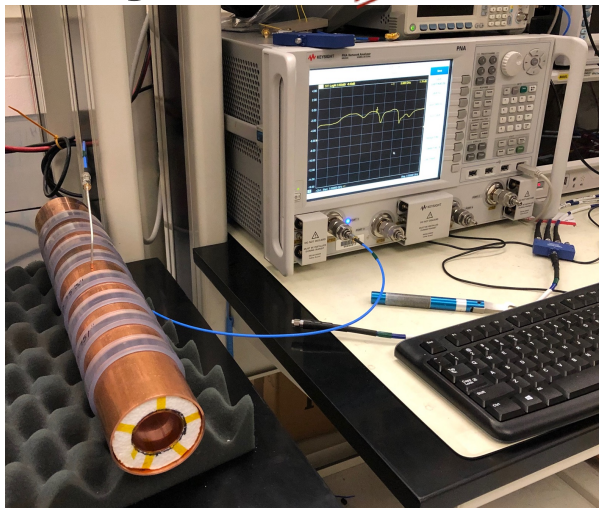
Future Cavities & Lower Frequency

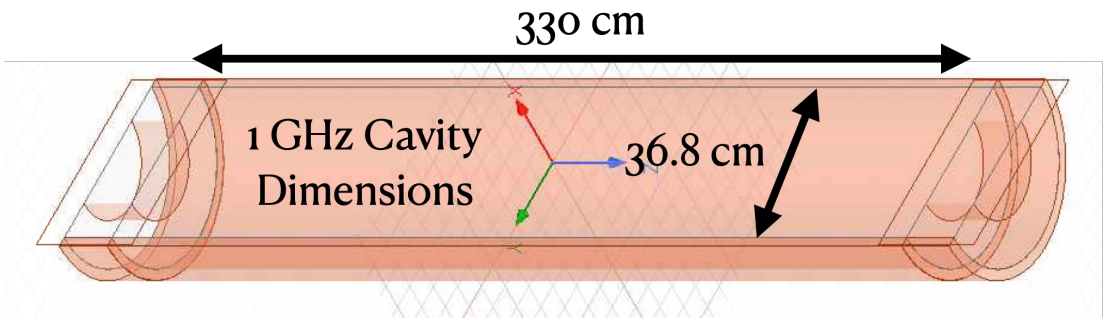
PROJECT 8

- Cavity R&D must press to lower frequency
  - 26 GHz has unacceptably high dipolar spin flip losses
  - Targeting 1 GHz or lower



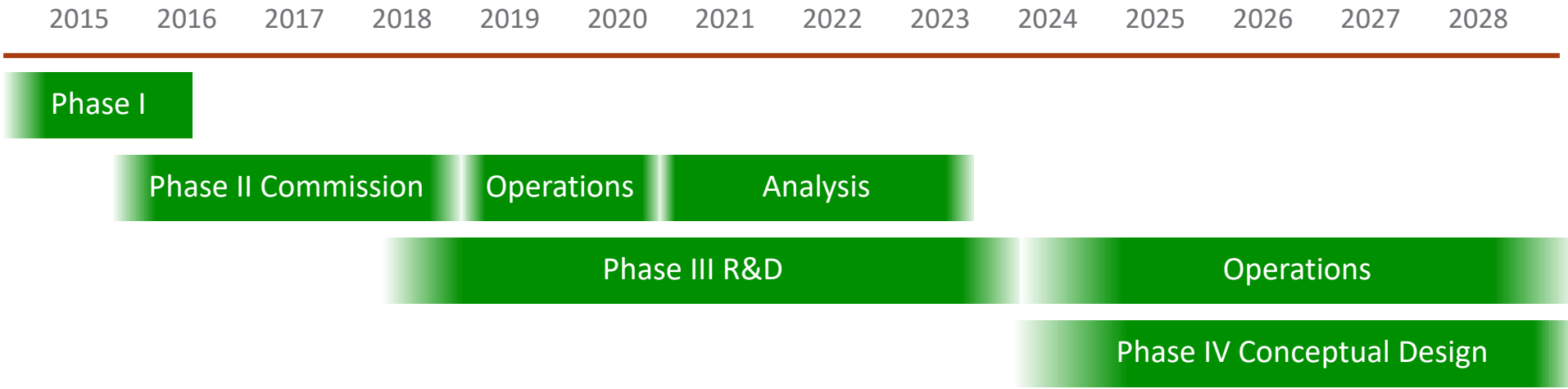
6 GHz Prototype
@ Penn State





Project 8 Experiment

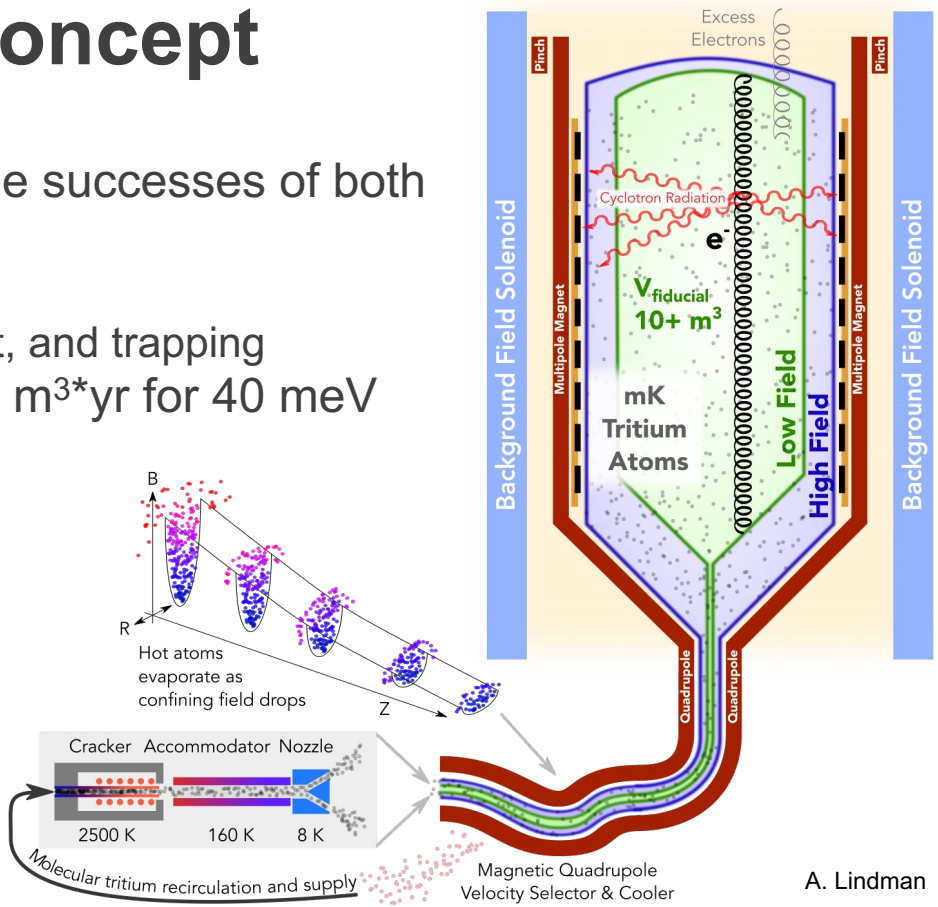
- A phased tritium beta endpoint experiment to measure the electron neutrino mass



- Atomic tritium endpoint measurement covering inverted ordering allowed region

Atomic Experiment Concept

- Experiment must ultimately combine successes of both R&D pathways:
  - Large-volume CRES detection
  - Atomic tritium production, transport, and trapping
- Requires effective exposure of ~10 m^3*yr for 40 meV (inverted ordering) sensitivity



A. Lindman

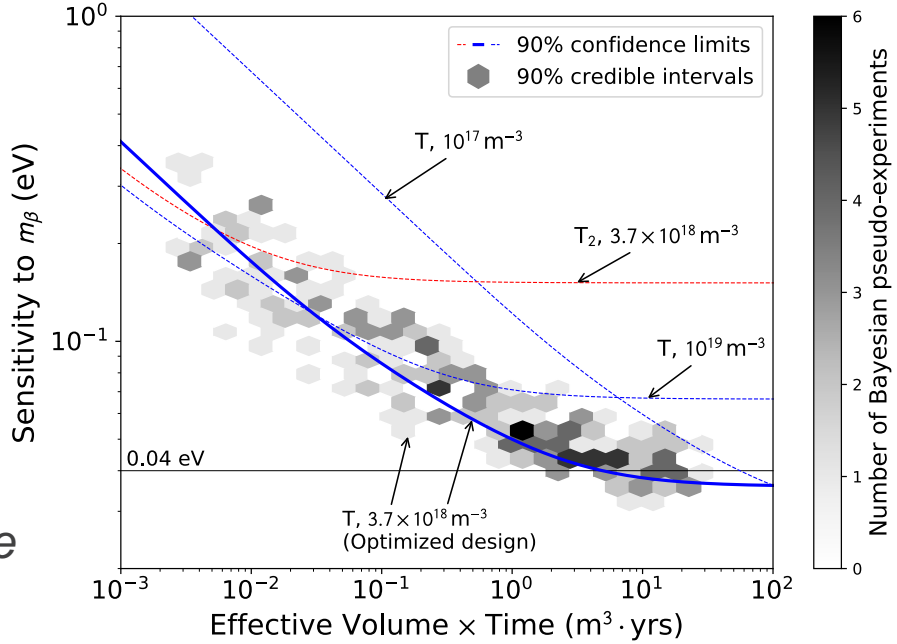
Phase IV Sensitivity

Framework developed for investigating sensitivity of ultimate experiment

Achieving 40 meV sensitivity requires

- Multi $m^3 \cdot yr$ effective exposure
- High flux atomic tritium source
- ~0.1 eV resolution
- 10^{-7} field uniformity

With potential to independently measure hierarchy

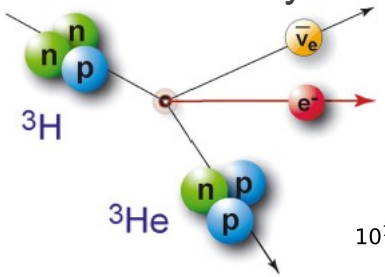


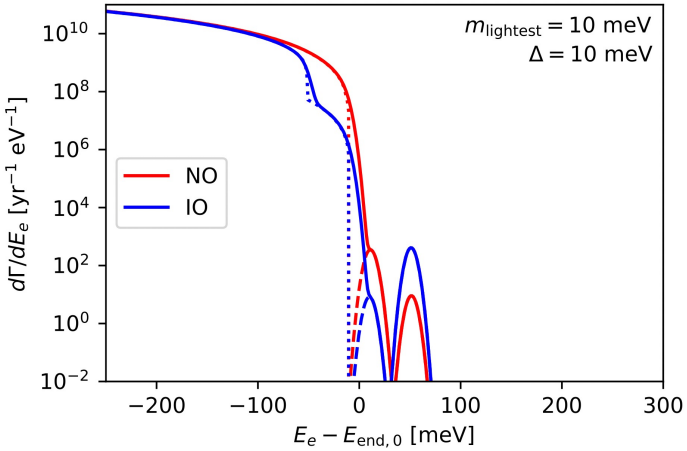
(Project 8) Phys. Rev. C **103** (2021) 065501

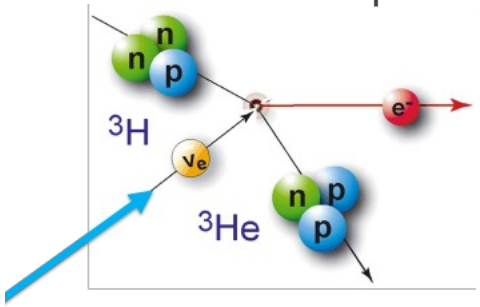
PTOLEMY

- What happens when you flip an endpoint experiment?

Beta decay vs. Neutrino capture



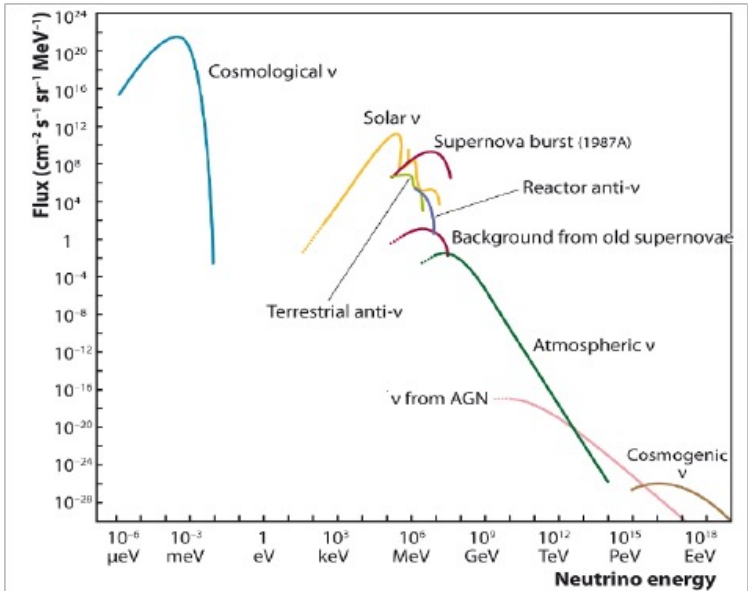




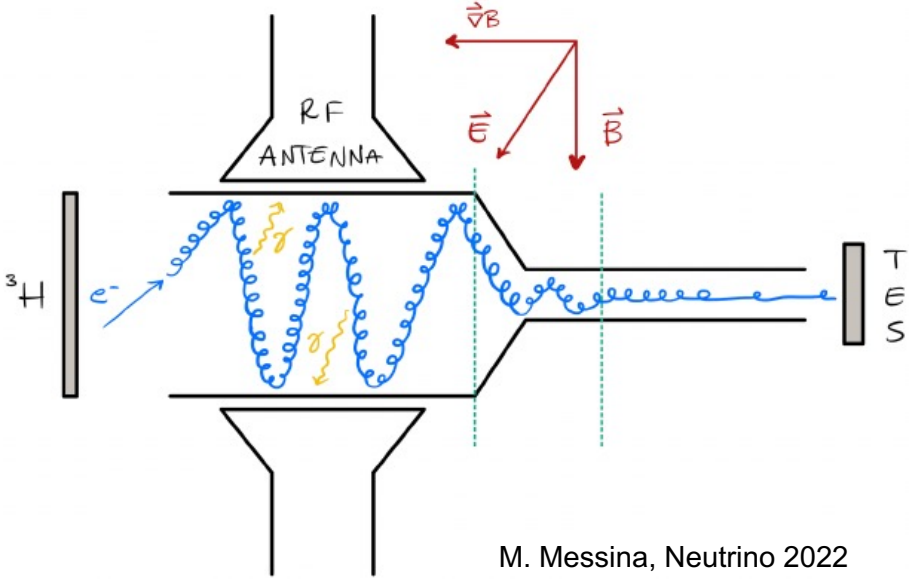
(PTOLEMY) JCAP **07** (2019) 047

PTOLEMY

- Physics: the lowest energy and most abundant neutrinos in the universe



- With an insanely difficult experimental concept



M. Messina, Neutrino 2022

Conclusions

- Direct (endpoint) searches are a critical piece of the neutrino physics program
  - The definitive method to pin the neutrino mass scale
- KATRIN is delivering world-leading limits
  - Expect sensitivity to $m_\beta > 0.2$ eV after run finishes in 2025
- Beyond KATRIN, lots of R&D required
  - ^{163}Ho making great advances over last decade
  - Project 8 presents most complete plan
  - PTOLEMY working towards CνB, but very hard