Inferring neutrino mass from β-decay kinematics

Christine Claessens – University of Washington
Seattle Snowmass Summer Study Workshop 2022

Neutrinos in the Standard Model

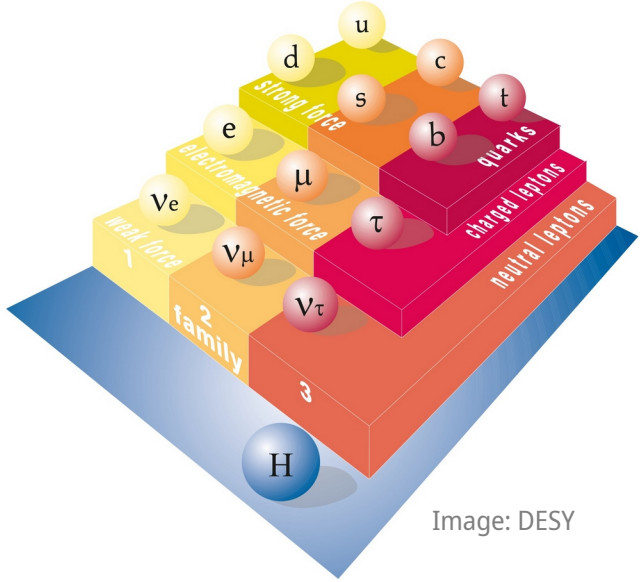
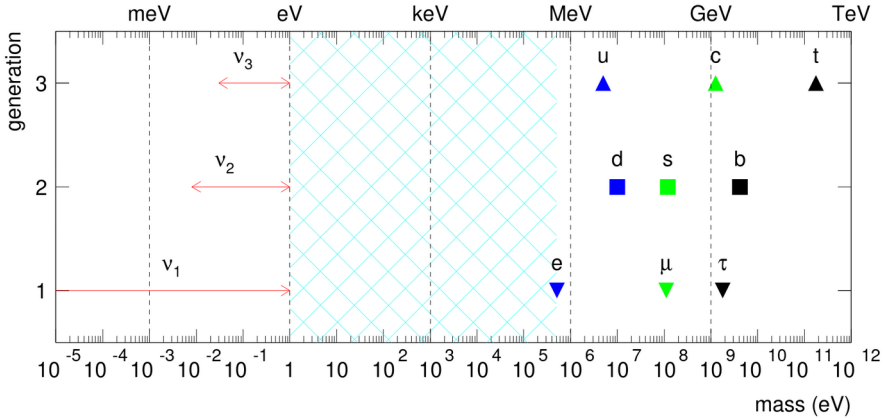


Image: DESY

Neutrino mass is new physics

- Neutrinos are massless in the minimal Standard Model
- Neutrino flavor oscillation is evidence that neutrino masses are nonzero
- So not massless but very light. Why?
- Mass origin could be Beyond-Standard-Model physics
- Other open questions:
  - Normal or inverted ordering?
  - Dirac or Majorana nature of mass?
  - Leptogenesis?
  - Sterile neutrinos?



A. de Gouvêa, 2004 TASI Lectures on Neutrino Physics

→ All of this is informed by measuring the mass directly

Probing the neutrino mass

Oscillation experiments

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

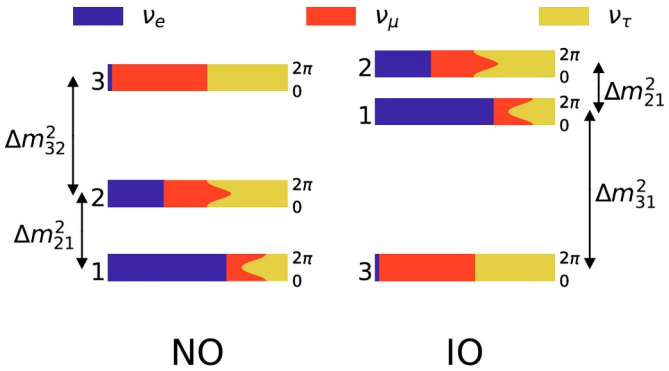


Image: De Salas et al., Front. Astron. Space Sci. 5, 36

Cosmology

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

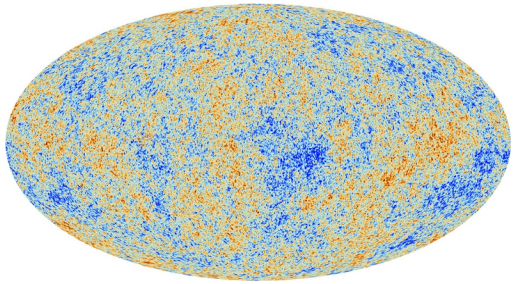
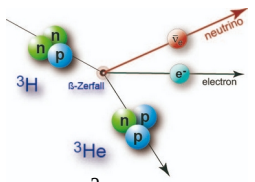
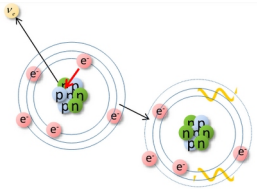


Image: ESA and the Planck Collaboration

Beta decay and electron capture



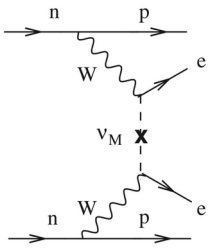


$$m_\beta^2 = \sum_{i=1}^{3} |U_{ei}|^2 m_i^2$$

Images: ECHo & KATRIN

Neutrinoless double beta decay

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



Direct mass measurement from decay kinematics

Beta decay or electron capture spectroscopy

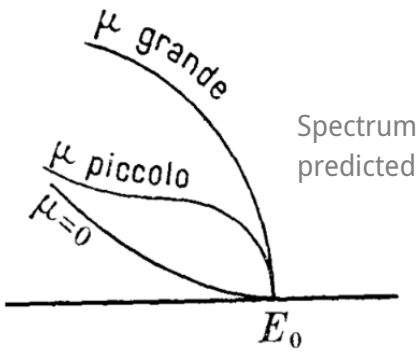
- Spectral shape is distorted by neutrino masses
- Impact is largest near the spectrum endpoint
- Sensitive to incoherent sum: $m_\beta^2 = \sum_{i=1}^{3} |U_{ei}|^2 m_i^2$

Based on kinematics and energy conservation

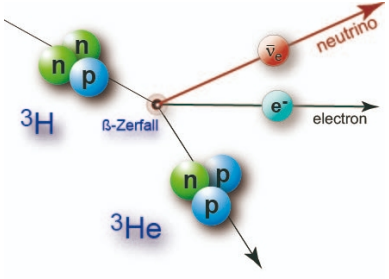
- Independent of cosmological models
- Independent of Majorana or Dirac nature

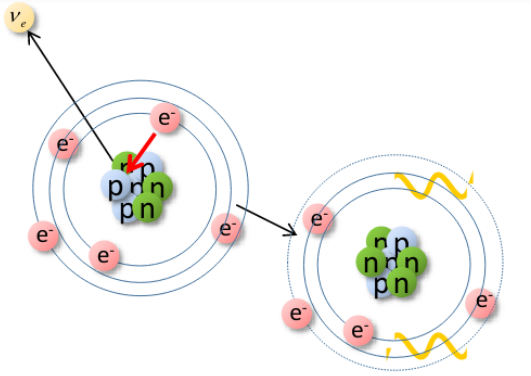
Isotope requirements

- Short half life
- Low endpoint
- Well understood spectral shape



Spectrum distortion predicted by Fermi, 1934





Most promising candidates: ^{3}H (β^-) and ^{163}Ho (EC)

Images: ECHo & KATRIN

Neutrino mass impact on decay spectra

Shape distortion most noticeable near endpoint

- Decay rate proportional to phase space factor:

$$\frac{d\Gamma}{dE} \sim \sum_i |U_{ei}^2| (E_0 - E) \sqrt{(E_0 - E)^2 - m_i^2} \cdot \Theta(E_0 - E - m_i)$$

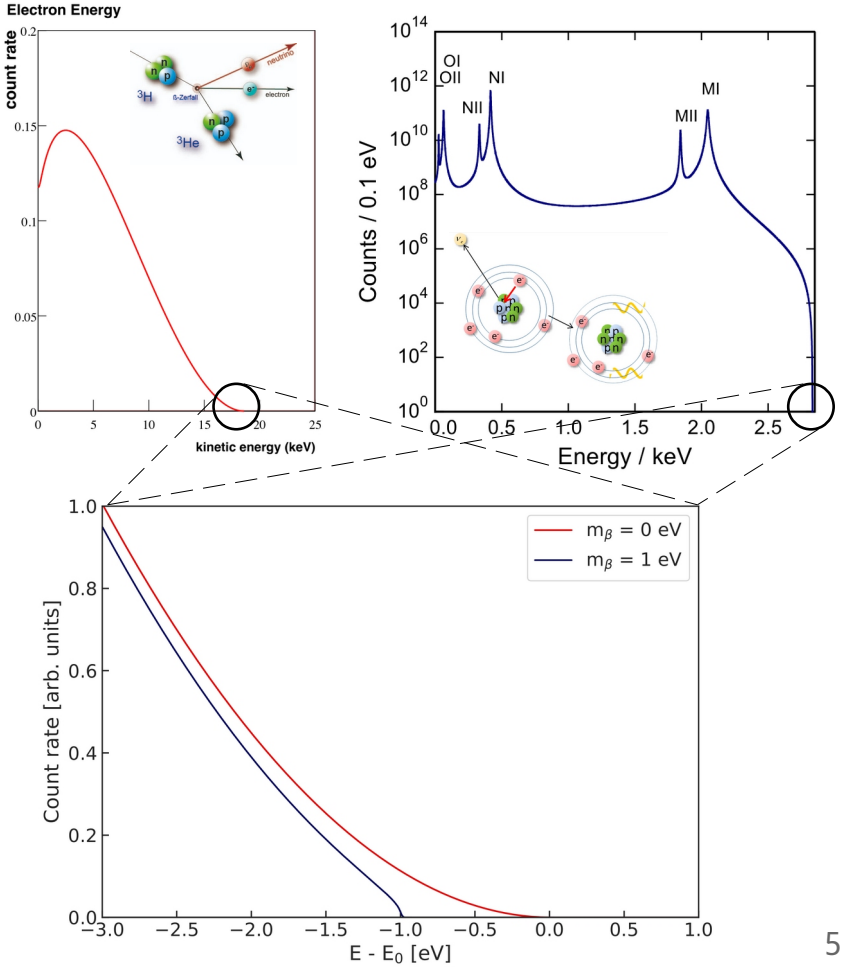
→ Sum of incoherent spectra for all masses m_i

- Approximate spectrum using effective mass (for masses >0.05 eV):

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

$$\rightarrow \frac{d\Gamma}{dE} \sim (E_0 - E) \sqrt{(E_0 - E)^2 - m_\beta^2} \cdot \Theta(E_0 - E - m_\beta)$$

- Fit spectrum shape in endpoint region to measure / limit effective mass

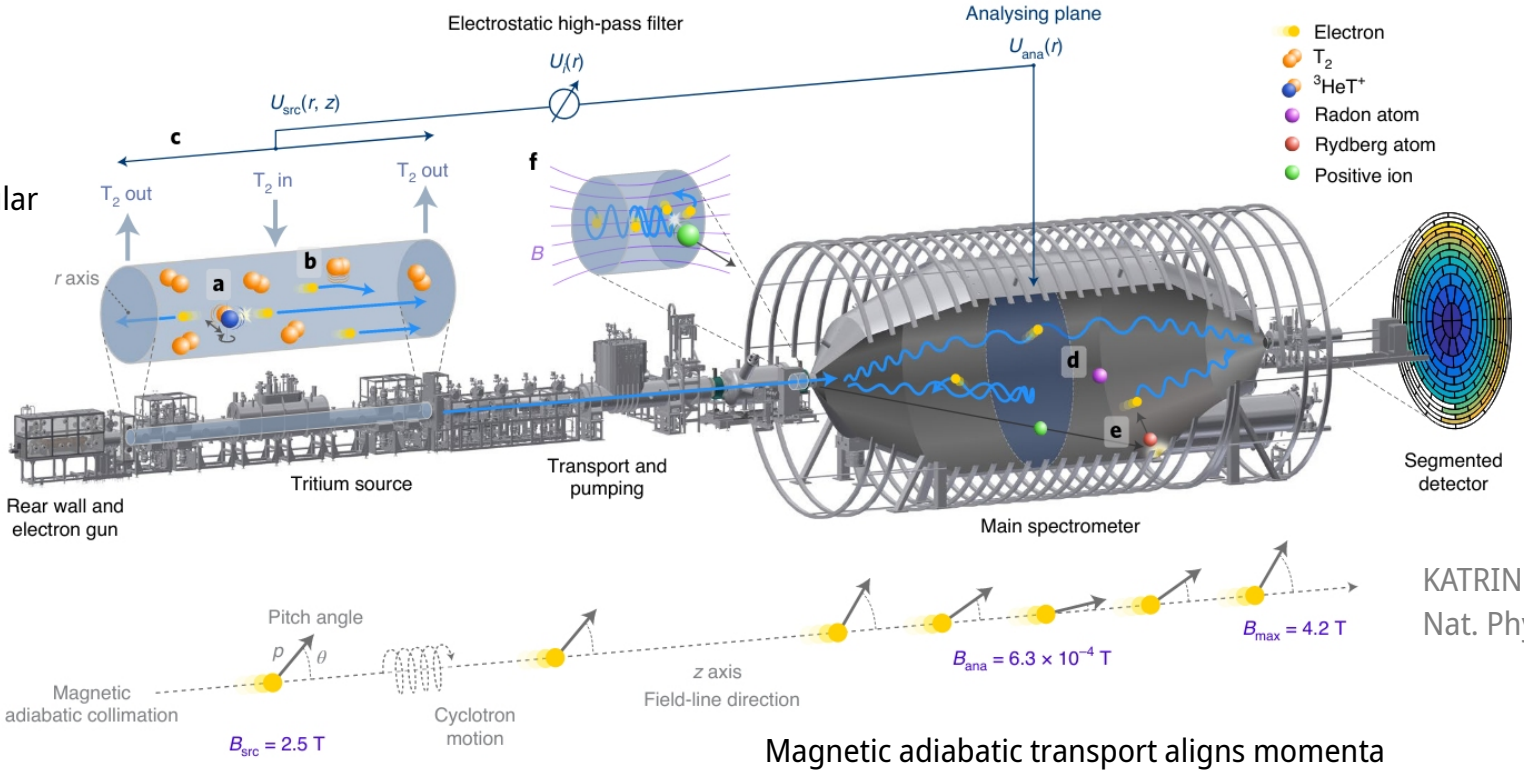


State of the art tritium spectroscopy: The KATRIN experiment

Working principle

Retarding potential filters high energy electrons

Electrons are emitted in gaseous molecular tritium source



Segmented detector counts electrons above filter energy

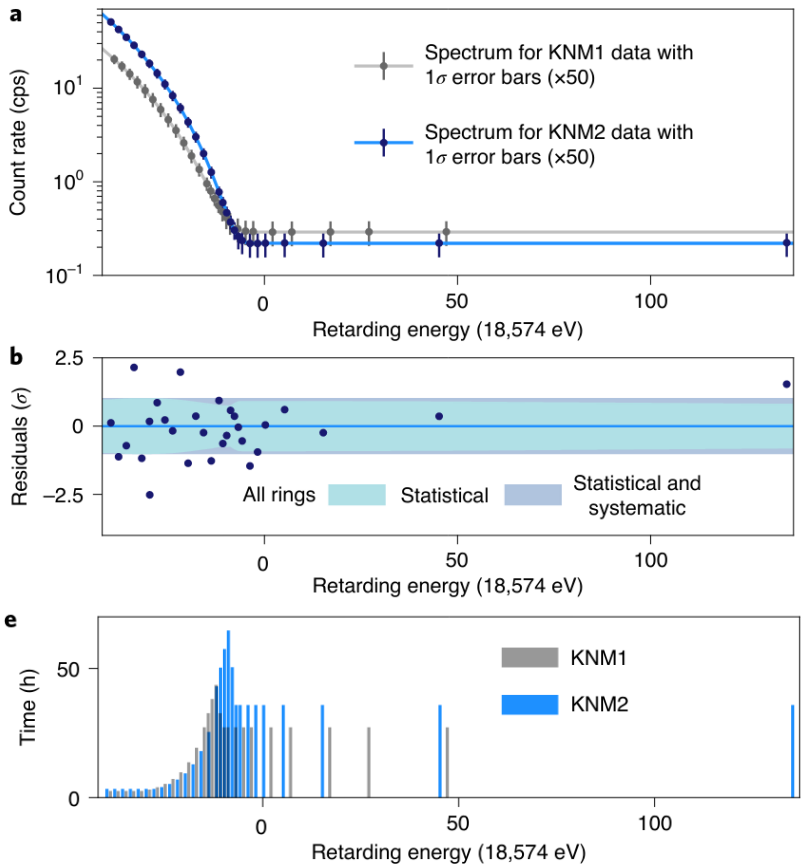
KATRIN Collaboration, Nat. Phys. 18, 160–166 (2022)

Magnetic adiabatic transport aligns momenta with electric field in main spectrometer

KATRIN's current world-best laboratory limit

Best limit from decay experiments (unless Majorana)

- First campaign (spring 2019): $m_\beta < 1.1$ eV (90% CL)
- Second campaign (autumn 2021): $m_\beta < 0.9$ eV (90% CL)
- Integral spectrum: Scan 30 HV set points
- Combined result: **$m_\beta < 0.8$ eV (90% CL)**



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

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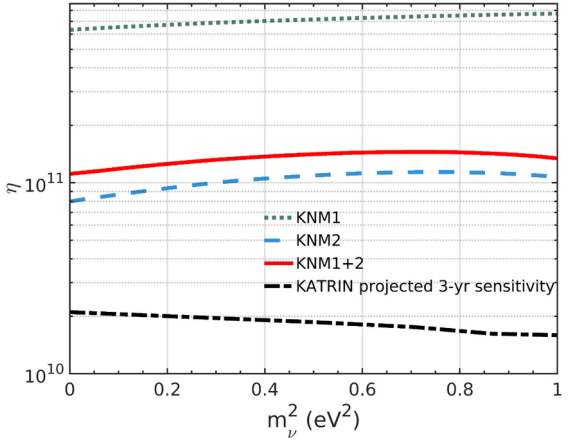
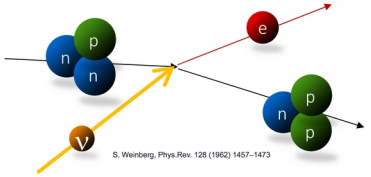
Limit on cosmic relic neutrinos

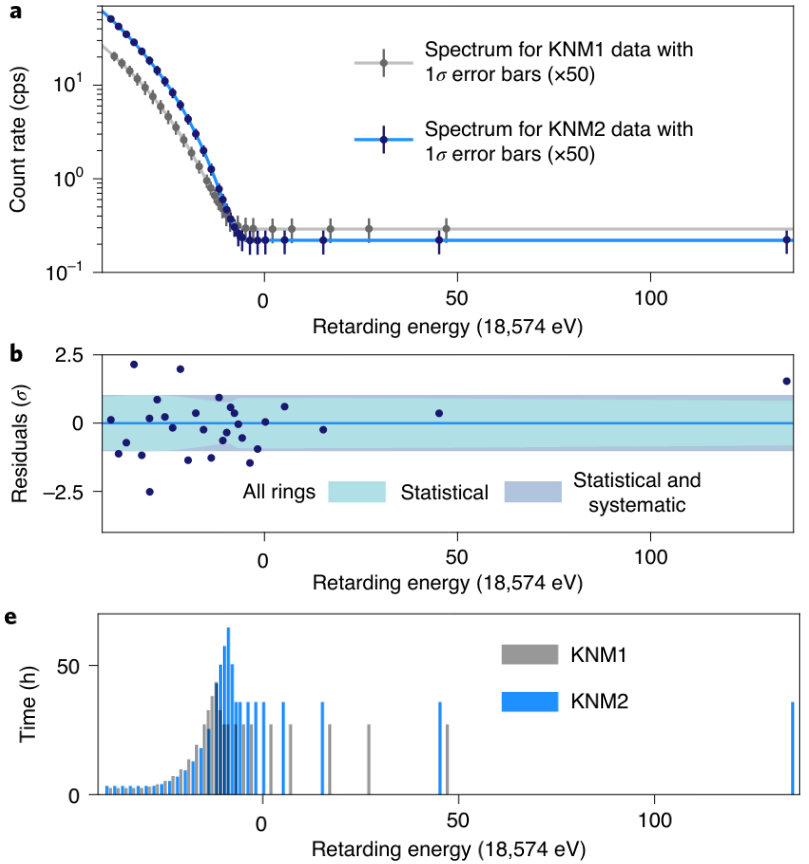
Over-density of 10^{11} excluded



Relic neutrino capture



KATRIN Collaboration, Phys.Rev.Lett. 129 (2022)

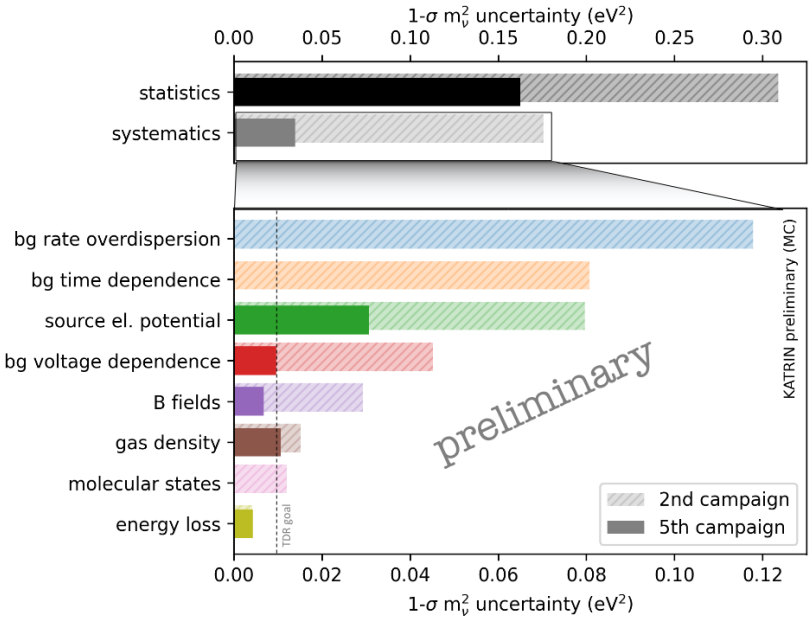


KATRIN Collaboration, Nat. Phys. 18, 160–166 (2022)

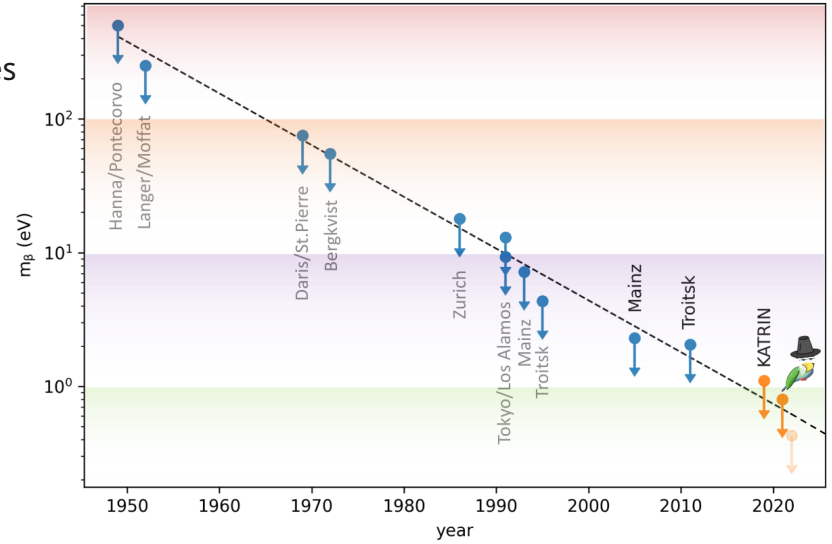
Near future: KATRIN will reach design sensitivity

Systematic uncertainties will be much reduced

- Major improvement of background and source potential uncertainties
- Next unblinding of 30e6 electrons in ROI this year



Lasserre @ Neutrino 2022



Lasserre @ Neutrino 2022

Sensitivity of 0.2 – 0.3 eV in reach within few years

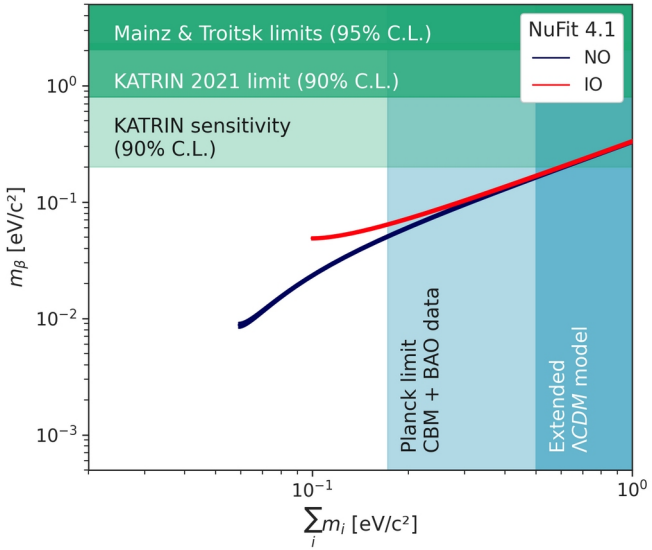
- Measurement or upper limit?
- KATRIN reduces previous mass limits by order of magnitude

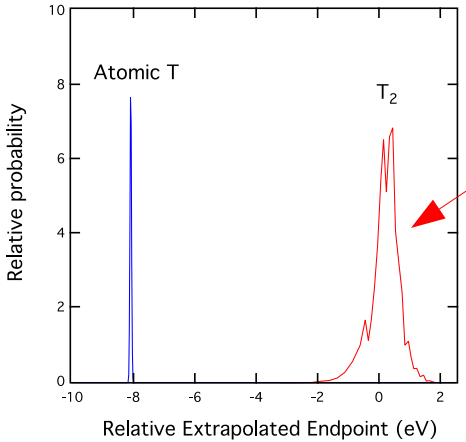
Challenges for future tritium decay experiments

Sensitivity limitations

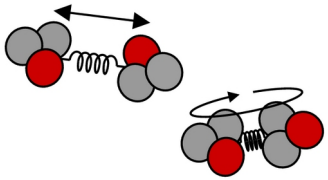
- Sensitivity beyond KATRIN requires higher statistics ~$N^{1/4}$
- Increasing density or volume not feasible
- Molecular final states yield irreducible systematic uncertainty ~100meV

→ Need atomic decay experiment to reach below that





Rotational and vibrational excitation broaden molecular ground state



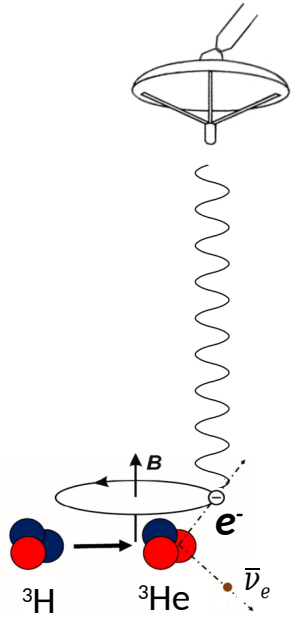
Lasserre @Neutrino 2022

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

Project 8: Cyclotron Radiation Emission Spectroscopy

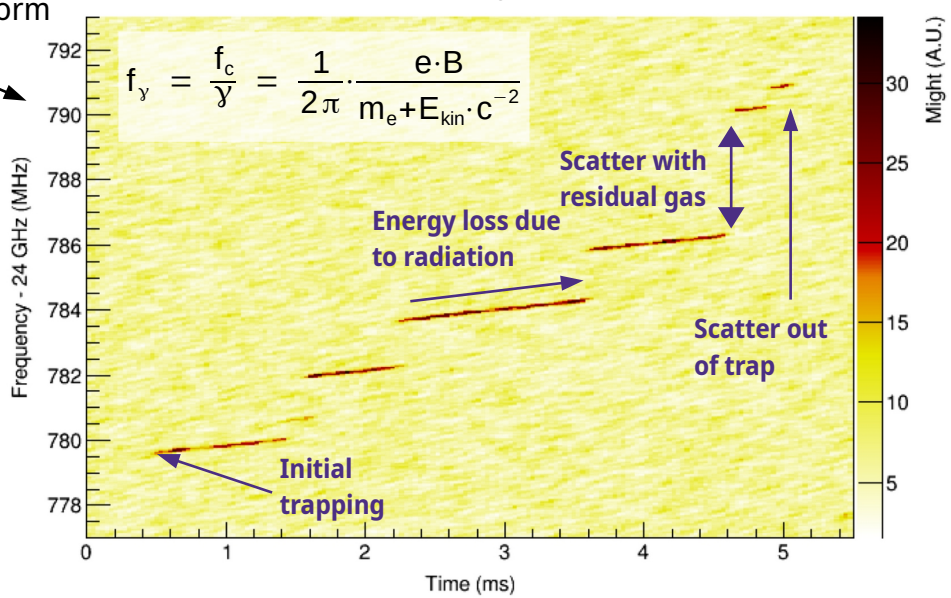
Working principle

- Source gas in strong homogeneous magnetic field
- Electrons emit cyclotron radiation
- Magnetic bottle trap increases observation time
- Detect radiation and reconstruct kinetic energy
- Decay spectrum is reconstructed from **start frequencies**

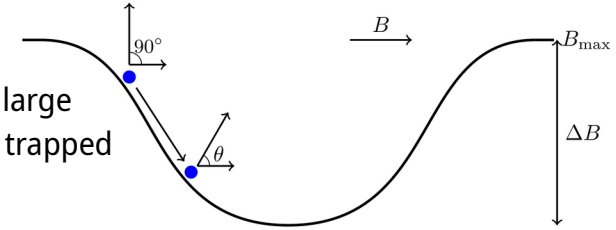


Fourier transform

Plot modified from: Phys. Rev. Lett. 114, 162501 (2015)



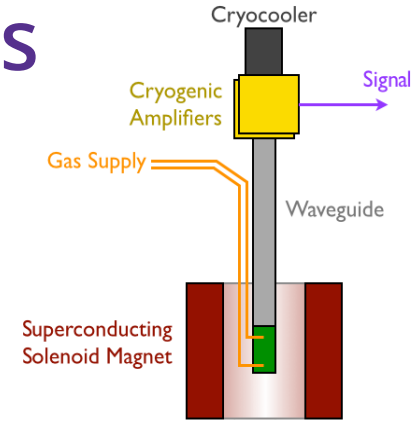
Electron with large pitch angle is trapped

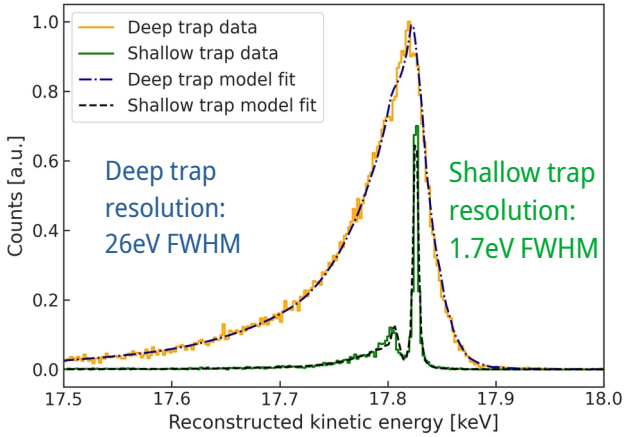


PROJECT 8

Project 8 Phase II results

Tritium and ^{83m}Kr data recorded with waveguide setup:



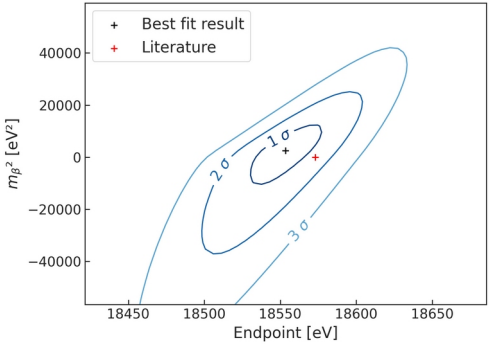


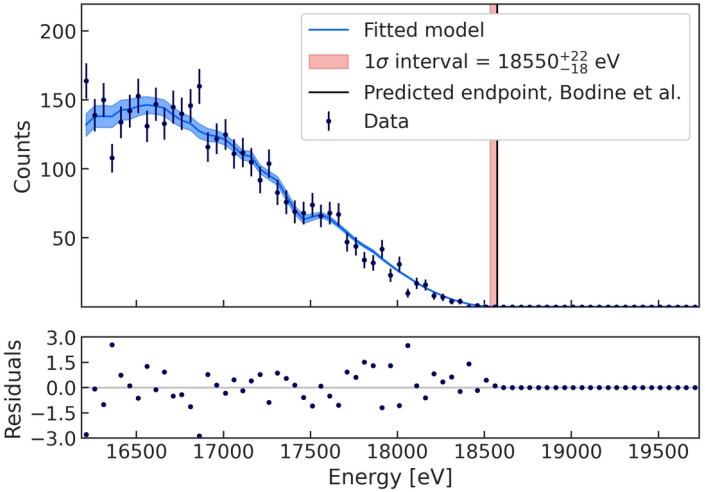
Demonstrated energy resolution

- ΔE_{FWHM} = 1.7 eV (at 17.8 keV)

Endpoint result in agreement with literature

- Frequentist: 18549^{+22}_{-18} eV
- Bayesian : 18553^{+17}_{-17} eV





First neutrino mass limit with CRES

- Frequentist: m_β < 178 eV/c^2 (90% C.L.)
- Bayesian: m_β < 169 eV/c^2 (90% C.L.)

Low background

- Zero background counts above endpoint
- Sets limit < $3 \cdot 10^{-10}$ eV^{-1}s^{-1} (90% C.L.)

Project 8 aims for 40 meV final sensitivity

CRES is compatible with atomic tritium

- Gas source is transparent to microwave radiation

  → No need to extract electrons from source
- Atomic T has to be isolated from walls to avoid recombination
- Trap magnetically by coupling to spin of unpaired electron

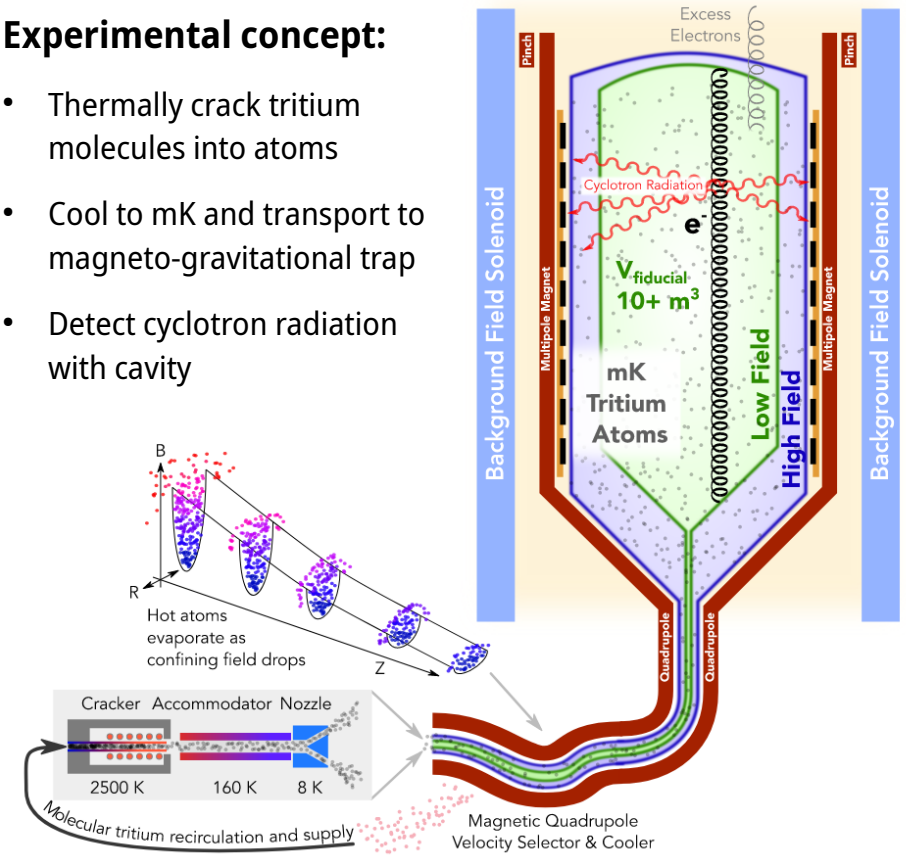
Other advantages

- Frequency measurement → High precision
- Low background → More info near endpoint
- Differential spectrum → Increases statistics

Experimental concept:

- Thermally crack tritium molecules into atoms
- Cool to mK and transport to magneto-gravitational trap
- Detect cyclotron radiation with cavity

Source = Detector



How to estimate sensitivity to m_β

Analytic estimation for differential spectrum measurement

- m_β decreases signal counts N_{signal} in energy interval ΔE below endpoint
- **Statistical uncertainty** on m_β^2 is related to the standard deviation of $N_{total} = N_{signal} + N_{background}$:

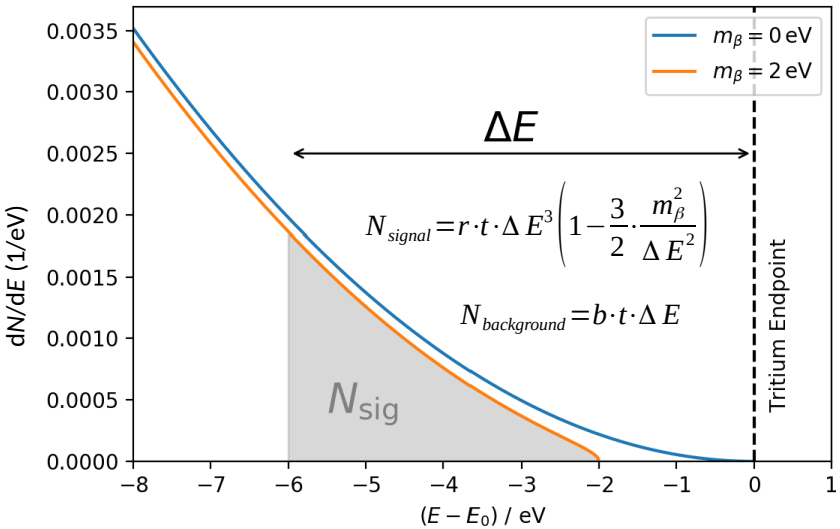
$$\sigma_{m_\beta^2,\,stat} \approx \frac{2}{3rt}\sqrt{r\cdot t\cdot \Delta E + \frac{bt}{\Delta E}}$$

- **Systematic uncertainty** on m_β^2 results from all contributions to energy resolution σ_i and their uncertainties δ_i:

$$\sigma_{m_\beta^2,\,sys} = 4\sqrt{\sum_i \left(\sigma_{sys,i}^2\,\delta_{sys,i}\right)^2}$$

- Contributions to energy resolution in tritium decay experiments:
  - Instrumental resolution
  - Thermal Doppler broadening
  - Final states
  - ...

Plot by R. Reimann



t : measurement duration
r : branching ratio to ΔE for $m_\beta = 0$ eV
b : background rate

Derivation in: Formaggio, De Gouvêa, and Robertson, Physics reports 914 (2021) 1-54

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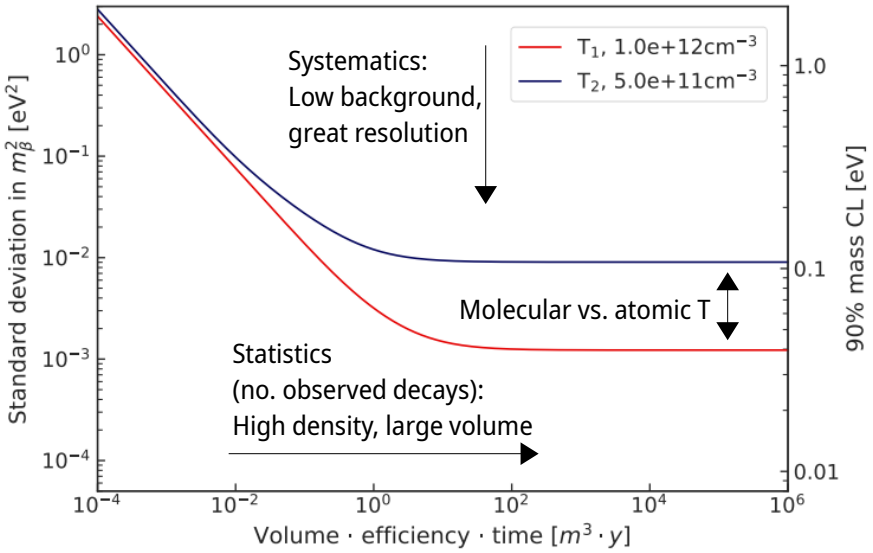
Plot uncertainty / limit vs. exposure

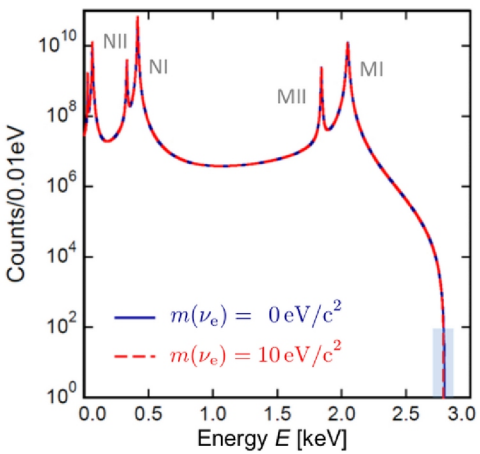


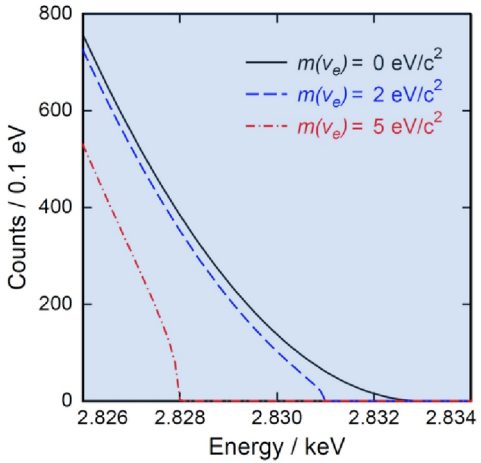
Derivation in: Formaggio, De Gouvêa, and Robertson, Physics reports 914 (2021) 1-54

Neutrino mass in ^{163}Ho electron-capture decays

^{163}Ho decay spectral shape impacted by neutrino mass

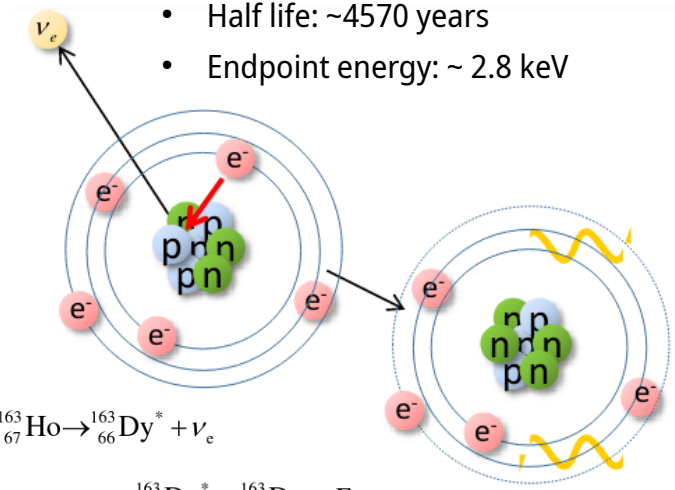
- ^{163}Ho decays to ^{163}Dy* by EC, emitting one ν_e
- Record de-excitation energy spectrum with microcalorimeters
- Neutrino mass extracted from spectral shape near endpoint
- Low endpoint is advantageous for accumulating required statistical power





^{163}Ho decay:

- Half life: ~4570 years
- Endpoint energy: ~ 2.8 keV



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

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

Endpoint spectroscopy with microcalorimeters first suggested by De Rújula et al.

Slide content courtesy of Loredana Gastaldo

Neutrino mass in ^{163}Ho electron-capture decays

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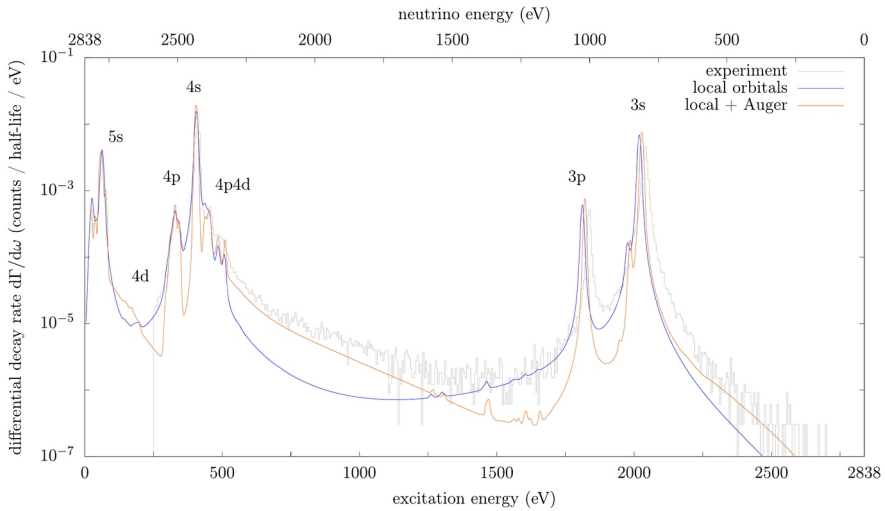

Braß and Haverkort, New J. Phys. **22** (2020) 093018

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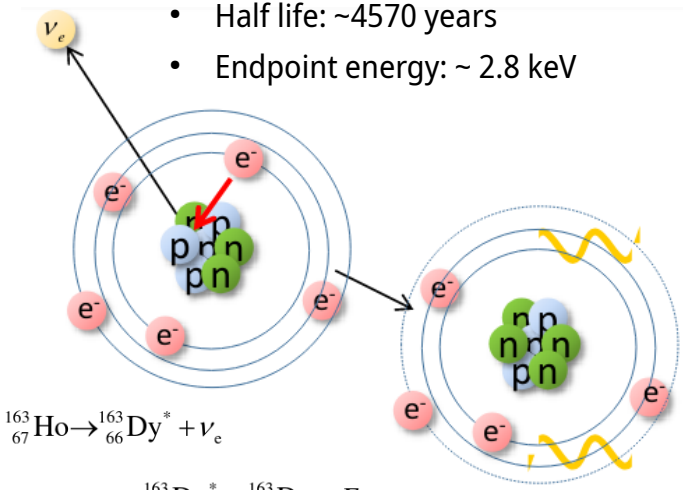


Spectrum shape is more complex than initially assumed

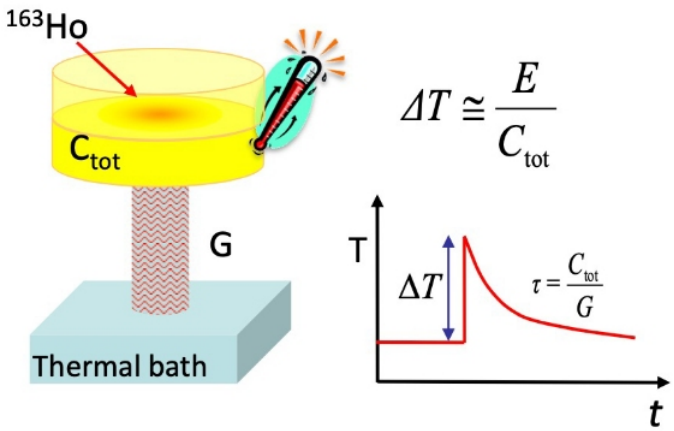
- Demonstrated by high-resolution data of ECHo and NuMECS
- Theoretical description much improved over past years
- Endpoint region is smooth and dominated by phase space factor

Slide content courtesy of Loredana Gastaldo

Experimental methods to measure electron capture on ^{163}Ho

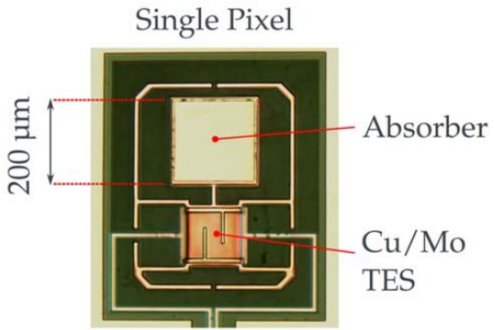
Measuring the decay spectrum with microcalorimeters

- Detect temperature increase from released de-excitation energy with very sensitive temperature sensors
- Two methods pursued: Measure resistance (HOLMES, NuMECS) or magnetization (ECHo) changes at superconducting temperatures



$$\Delta T \cong \frac{E}{C_{tot}}$$

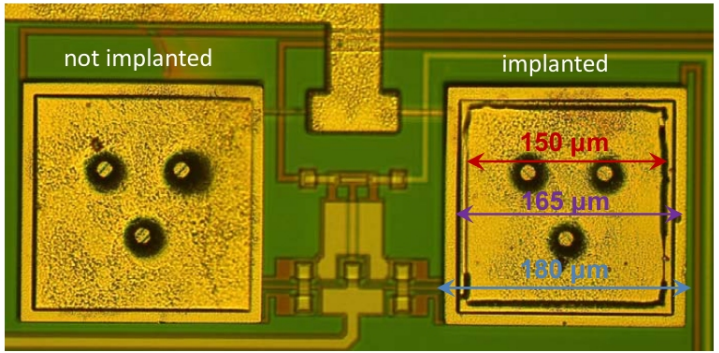
$$\tau = \frac{C_{tot}}{G}$$



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

HOLMES

Detector arrays produced at NIST (Boulder US)



F. Gatti et al., Physics Letters B 398 (1997) 415

ECHo

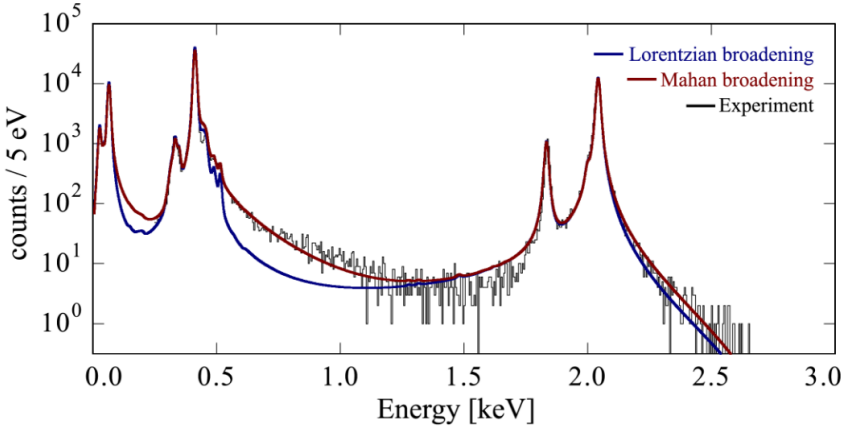
Detector arrays produced at KIP, Heidelberg University

Slide content courtesy of Loredana Gastaldo

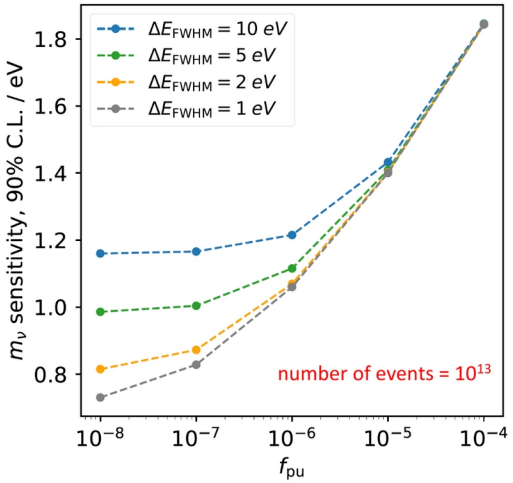
^{163}Ho experiments are headed towards sub-eV sensitivity

ECHo's current result

- With improved theoretical description of decay spectrum
- Measured Q_{EC} = (2838 +/- 14) eV
- **m_β < 150 eV (95% C.L.)**
- Background < $1.6 \cdot 10^{-4}$ $eV^{-1}day^{-1}pixel^{-1}$



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



Achievable sensitivity for ^{163}Ho EC experiment with 10^{13} events

Experimental requirements for sub-eV sensitivity

- Events near endpoint 10^{14} → 1 MBq
- Energy resolution ΔE_{FWHM} < 3eV / Background level < 10^{-6} – 10^{-4}
- Pile-up in calorimeters < 10^{-5} – 10^{-4}
- Multiplexing read out for large number of channels

  → Successfully demonstrated for small arrays

Slide content courtesy of Loredana Gastaldo

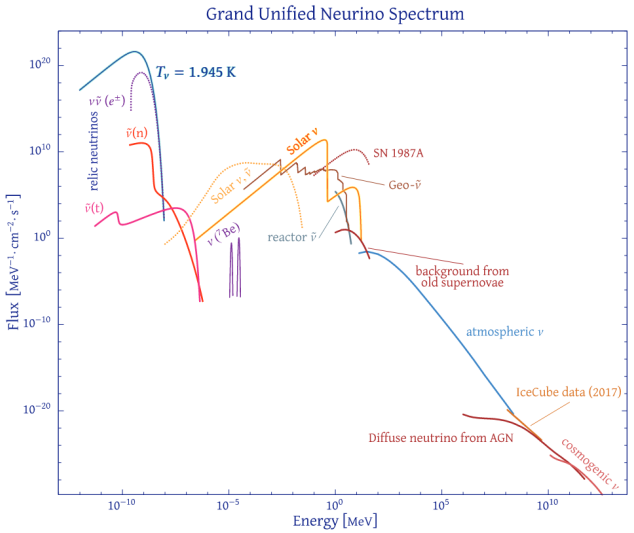
Cosmic neutrino background: The PTOLEMY experiment

Goal: Measure the cosmic neutrino background

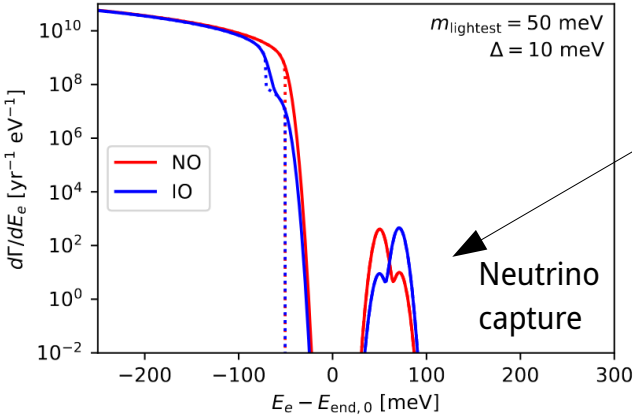
- Neutrinos decoupled since 1s after BB: start of nucleosynthesis
- Expected number density $n_\nu = 112/cm^3$ per neutrino
- Velocity distribution $\langle v_\nu \rangle \sim T_\nu/m_\nu$

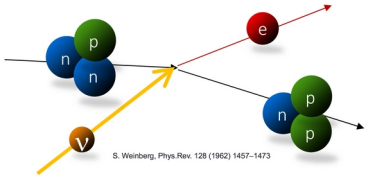
Neutrino capture spectrum

- Peak above β-decay endpoint separated by $2 \cdot m_\nu$
- Shape depends on ordering
- Also sensitive to m_β
- Need excellent energy resolution to resolve



Yurchenko & Ivanchik, Astroparticle Physics **127** (2017) 102537





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

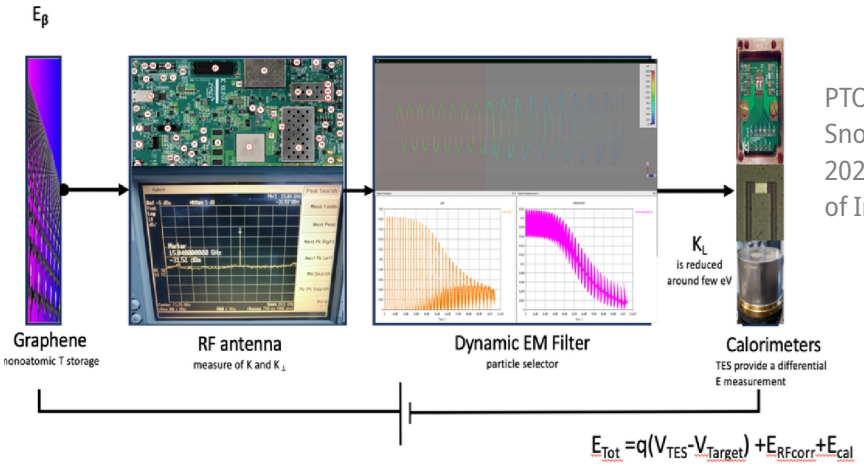
The PTOLEMY experiment

Experimental concept:

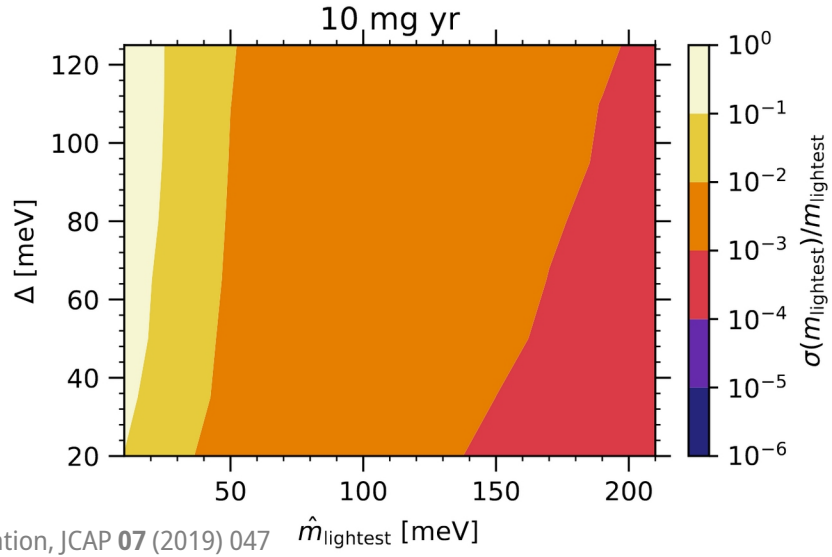
- Atomic tritium embedded on graphene substrate
- Single electron detection with RF
- Transverse drift filter removes low energy electrons
- Differential spectrum measurement of slow electrons with TES detectors (ΔE ~ 0.05 eV)

Demonstrator under development:

- Ultimate demonstrator goal: hundreds of μg tritium, energy resolution of 50 to 100 meV
- Demonstrator time scale 5 years



PTOLEMY, Snowmass 2021 Letter of Intent



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

Summary and conclusion

Decay kinematics give laboratory access to neutrino mass

- Inferring the neutrino mass from decay kinematics is direct, model independent approach
  - Complementary to cosmological limits with different systematics
  - Could give clues to beyond ΛCDM and the Standard Model
- **In a few years**
  - KATRIN will find mass or set limit of 200 meV
  - CRES based tritium decay and bolometric ^{163}Ho capture are moving towards eV-scale sensitivity
- **On longer term timescale**
  - Next-generation experiments will reach sub-eV / 40 meV
  - PTOLEMY plans to measure CνB by neutrino capture on atomic tritium

Thank you for your attention!

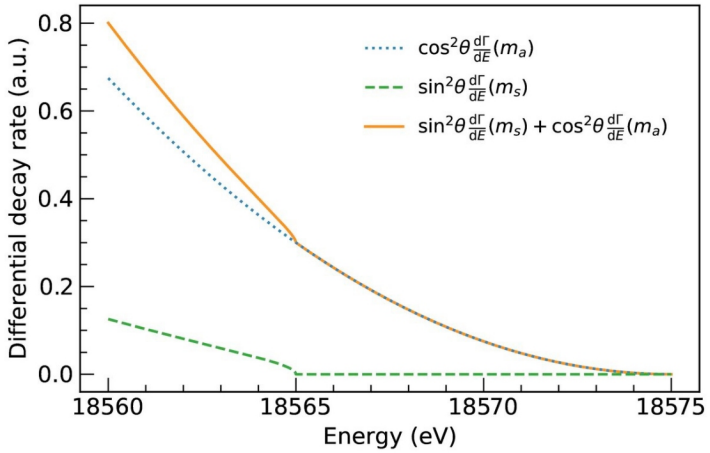
Beta spectroscopy is sensitive to sterile neutrinos

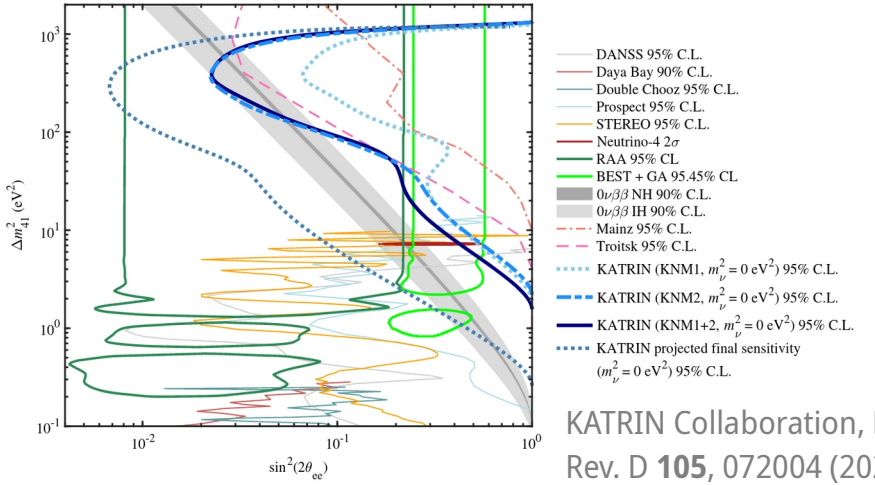
Sterile neutrinos

- Proposed particles that do not interact via weak force but mix with "active" neutrinos
- Few-eV scale neutrino could explain anomalies in oscillation experiments
  - Reactor neutrino anomaly
  - Gallium anomaly (BEST)
  - Neutrino-4 short baseline

β-decay spectrum shows superposition of all mixing masses

- Sterile neutrino would show as kink in decay spectrum
- Neutrino mass measurements can set limits on sterile mass/mixing
- Large sterile mass searches require looking deeper into the spectrum





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

Tritium spectrum endpoint

Neutrino mass in beta decay

- Endpoint E_0 is highest electron energy for m_β=0 eV

  → Released energy Q minus recoil energy

- Q is calculated from the mass difference (Penning trap) corrected for dissociation / ionization energies

- For atomic tritium: $Q(\mathrm{T}) = Q_A - E_{ion}(^3\mathrm{He})$

  → With minimum recoil of 3.410 eV: E_0 = 18564.01(7) eV

- For molecular tritium:

  $Q(\mathrm{T}_2) = Q_A - E_{ion}(\mathrm{T}) - E_{dissoc}(\mathrm{T}_2) + E_{dissoc}(^3\mathrm{HeT}^+)$

  → With minimum recoil of 1.705 eV: E_0 = 18574.01(7) eV

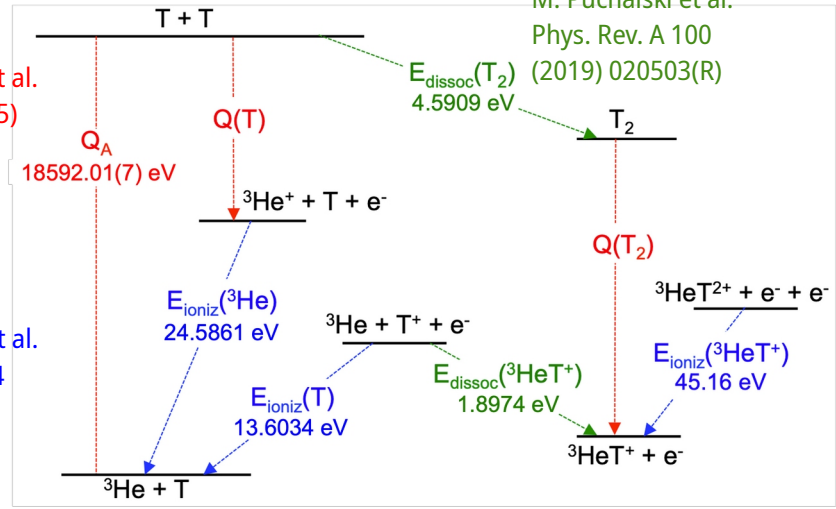
- Uncertainty dominated by mass difference measurement

- For neutrino mass analysis, fixing the endpoint would require accuracy of ≤1 meV → Endpoint is left floating

Updated from Bodine et al. Phys. Rev. C **91** (2015) 035505 by W. Pettus

E. G. Myers et al. PRL 114 (2015) 013003

M. Puchalski et al. Phys. Rev. A 100 (2019) 020503(R)



D. C. Morton et al. Can. J. Phys. 84 (2006) 83

A. E. Kramida. At. Data Nucl. Data Tables 96 (2010) 586

N. Doss, Ph.D Thesis, Univ London (2007)