PROJECT 8

UNIVERSITY of WASHINGTON

Laboratory neutrino mass measurements

Elise Novitski

Developing New Directions in Fundamental Physics (DND) 2020

November 5, 2020

TRIUMF, CENPA, AND Zoom

An ultra-brief introduction to neutrino mass

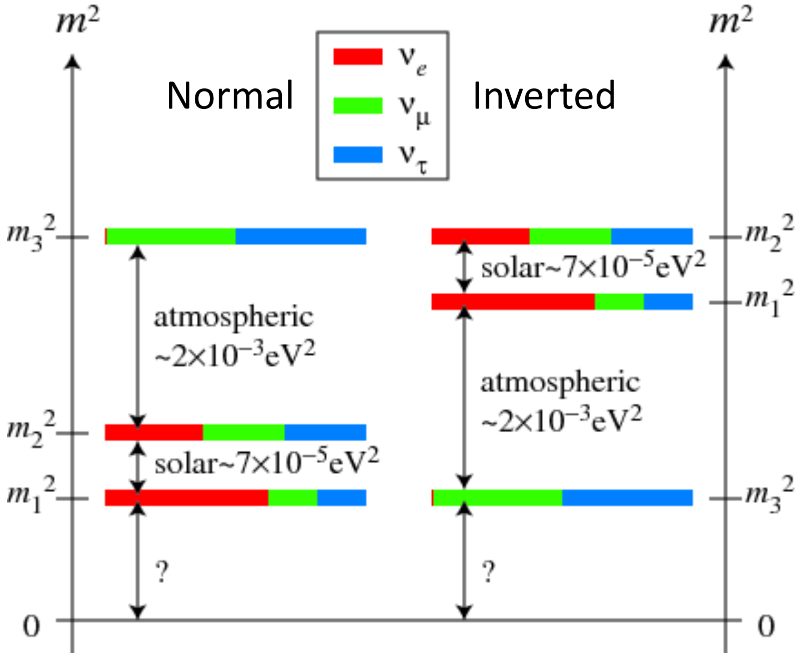
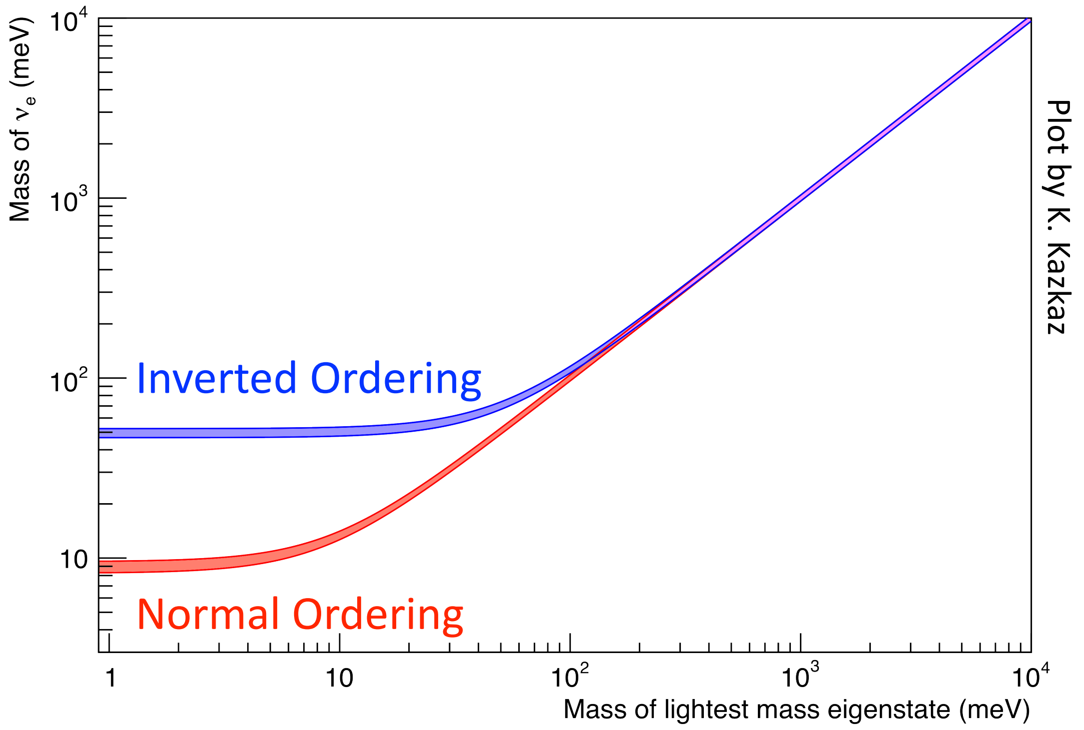
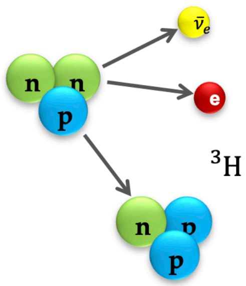


Fig from A. Nucciotti. AHEP (2016) doi:10.1155/2016/9153024



What do “direct” neutrino mass experiments measure?

Beta decay of tritium



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

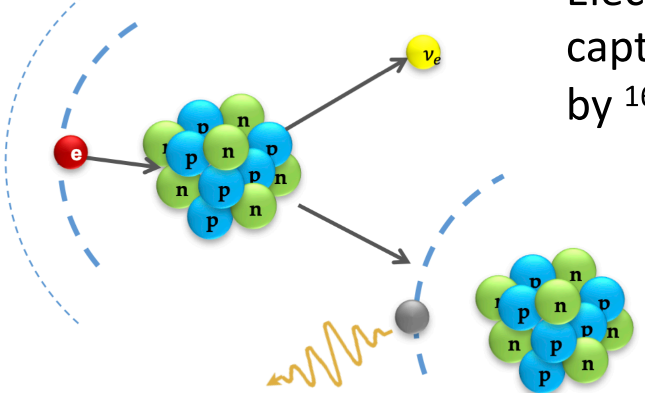
Observable:

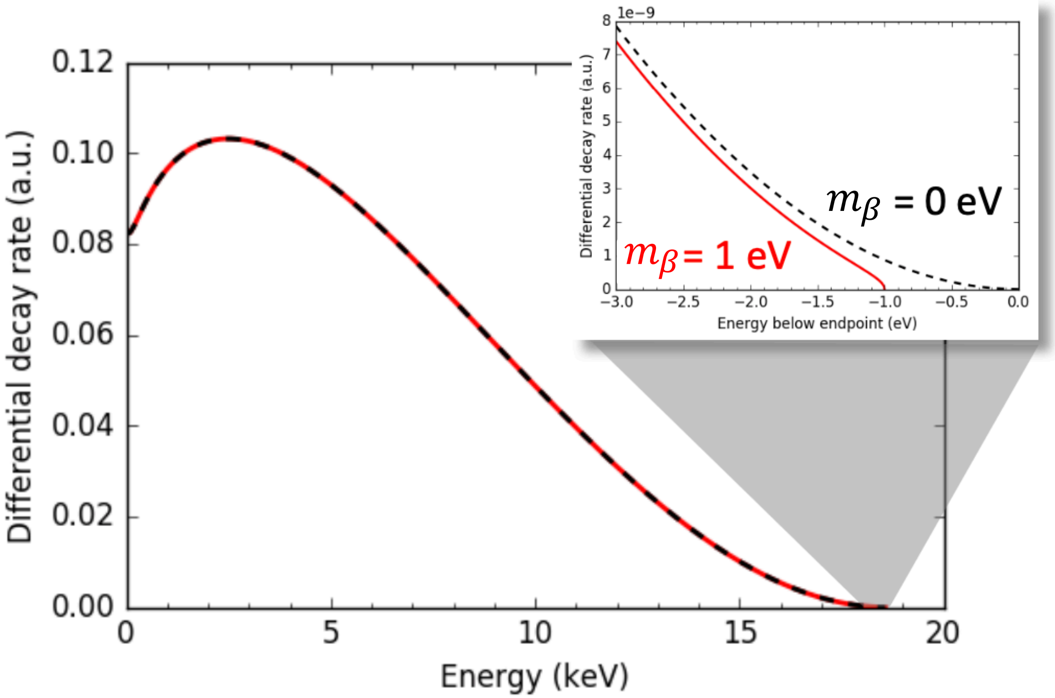
$$m_\beta = \sqrt{\sum_i |U_{ei}|^2 m_i^2}$$

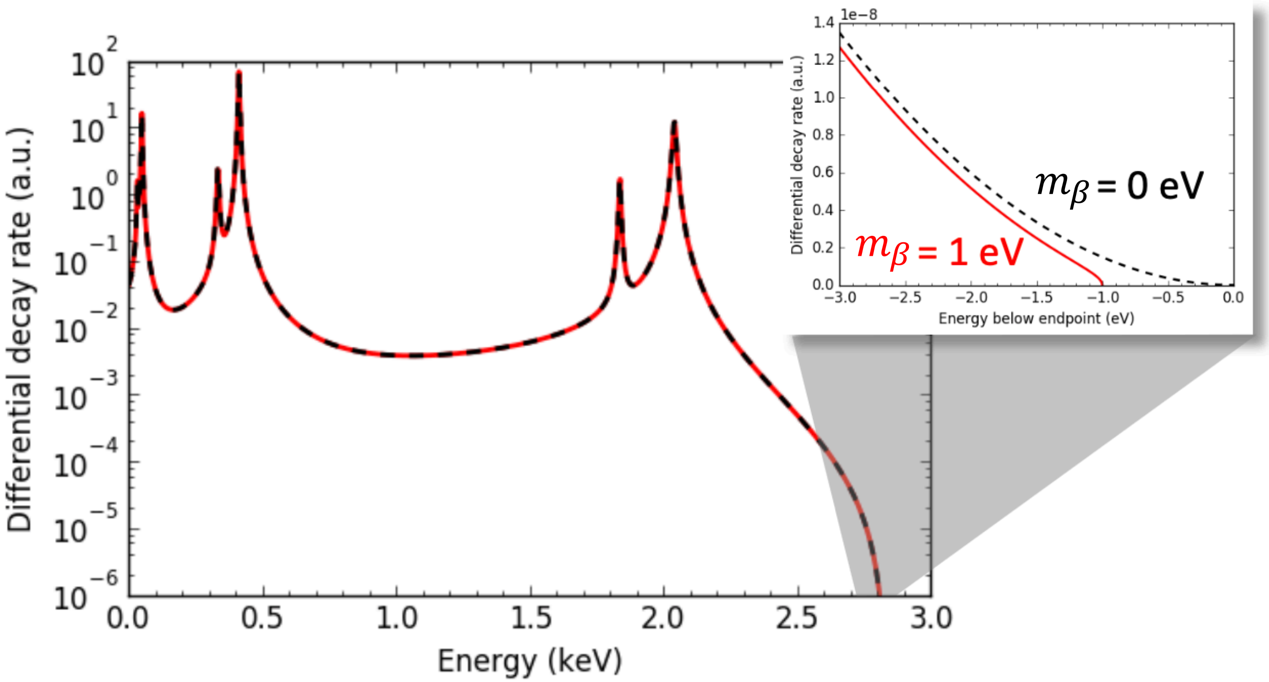
$^{163}\mathrm{Ho} \rightarrow {}^{163}\mathrm{Dy}^{*} + \nu_e$

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

Electron capture by ^{163}Ho

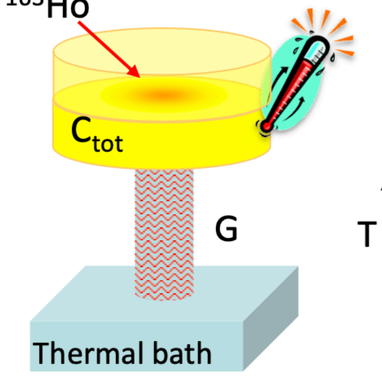




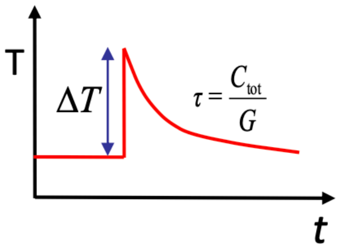


Figures courtesy of Susanne Mertens

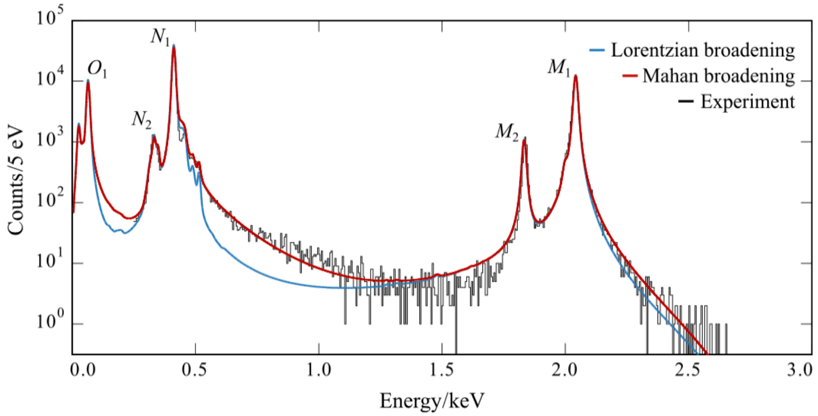
Electron capture on ^{163}Ho: overview



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

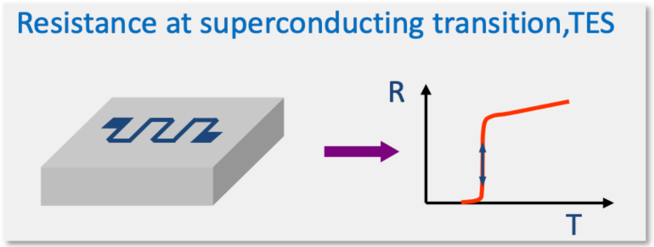


Microcalorimeters held at <100 mK detect decays from the whole spectrum



C. Velte et al., Eur. Phys. J. C (2019) 79:1026
M. Brass, M. Haverkort, arXiv:2002.05989

Recent progress understanding ^{163}Ho spectrum

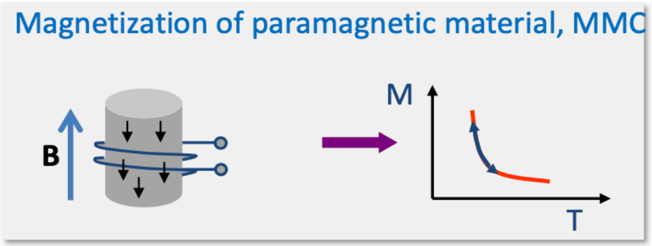


HOLMES

NuMECS

Detector arrays produced at NIST (Boulder US)

Overview of HOLMES: B. Alpert et al, Eur. Phys. J. C 75 (2015) 112



ECHo

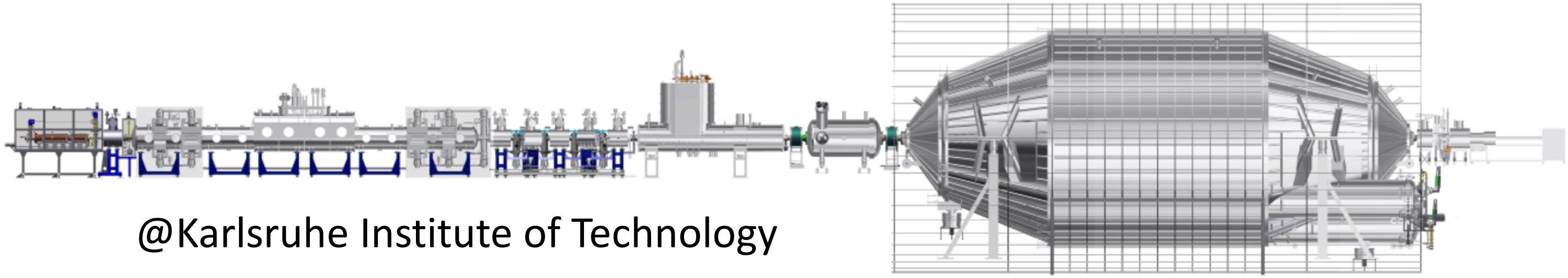
Detector arrays produced at KIP, Heidelberg University

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

- Challenges: spectral complexity, pileup, background reduction, multiplexing, source and sensor fabrication
- ECHo expects first result from prototype device this year
- Experiments to demonstrate scaling are in development

Slide content courtesy of Loredana Gastaldo

State of the art: KATRIN's tritium β^- spectroscopy



@Karlsruhe Institute of Technology

Image: KATRIN

An electron's journey through the KATRIN MAC-E spectrometer

- Produced via β decay in windowless gaseous tritium source
- Magnetic collimation directs momentum vector forward
- Passes (or doesn't) over precise electrostatic barrier, which acts as high-pass filter (=integral spectrometer)
- Detected (or isn't) at far end

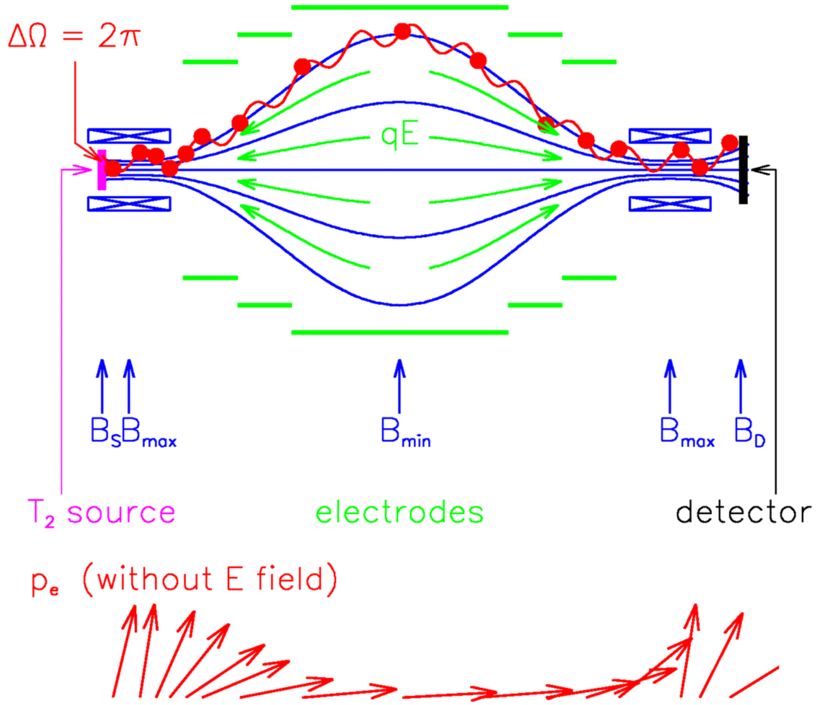
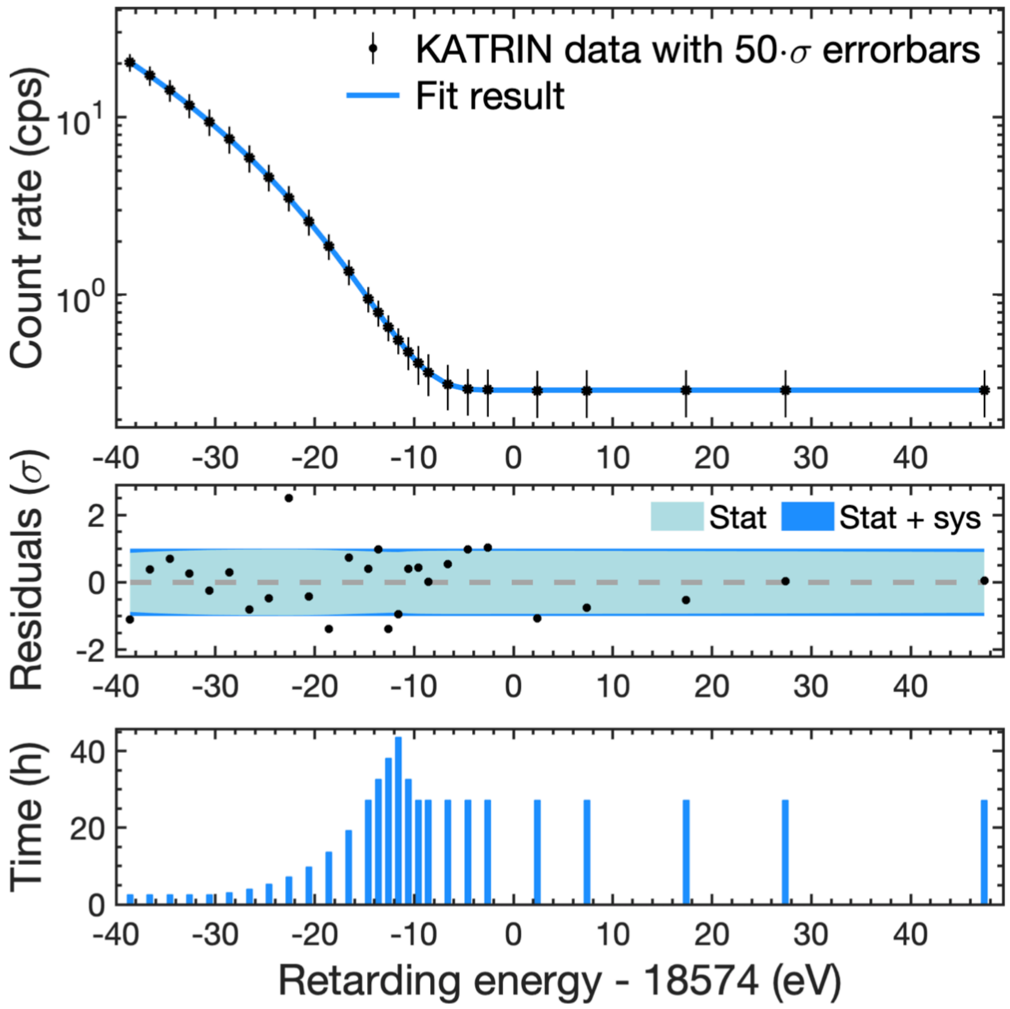


Image: KATRIN

KATRIN's first neutrino mass measurement

- 2019: KATRIN released its first neutrino mass measurement
  - m_β<1.1 eV/c2 (90% CL)
  - Aker et al. (KATRIN), PRL 123 221802 (2019)
  - Statistics-limited
- Goals
  - 1000 days of measurement time
  - Sensitivity to m_β≈ 200 meV, covering the rest of the quasi-degenerate mass possibilities



Challenges in pushing to lower neutrino mass

- Statistics scale like cross-sectional area; difficult to scale up more
- Interactions during electron transport limit density
- Irreducible uncertainty due to final state distribution of ^3HeT sets a systematic floor at about 100 meV


Image: KATRIN

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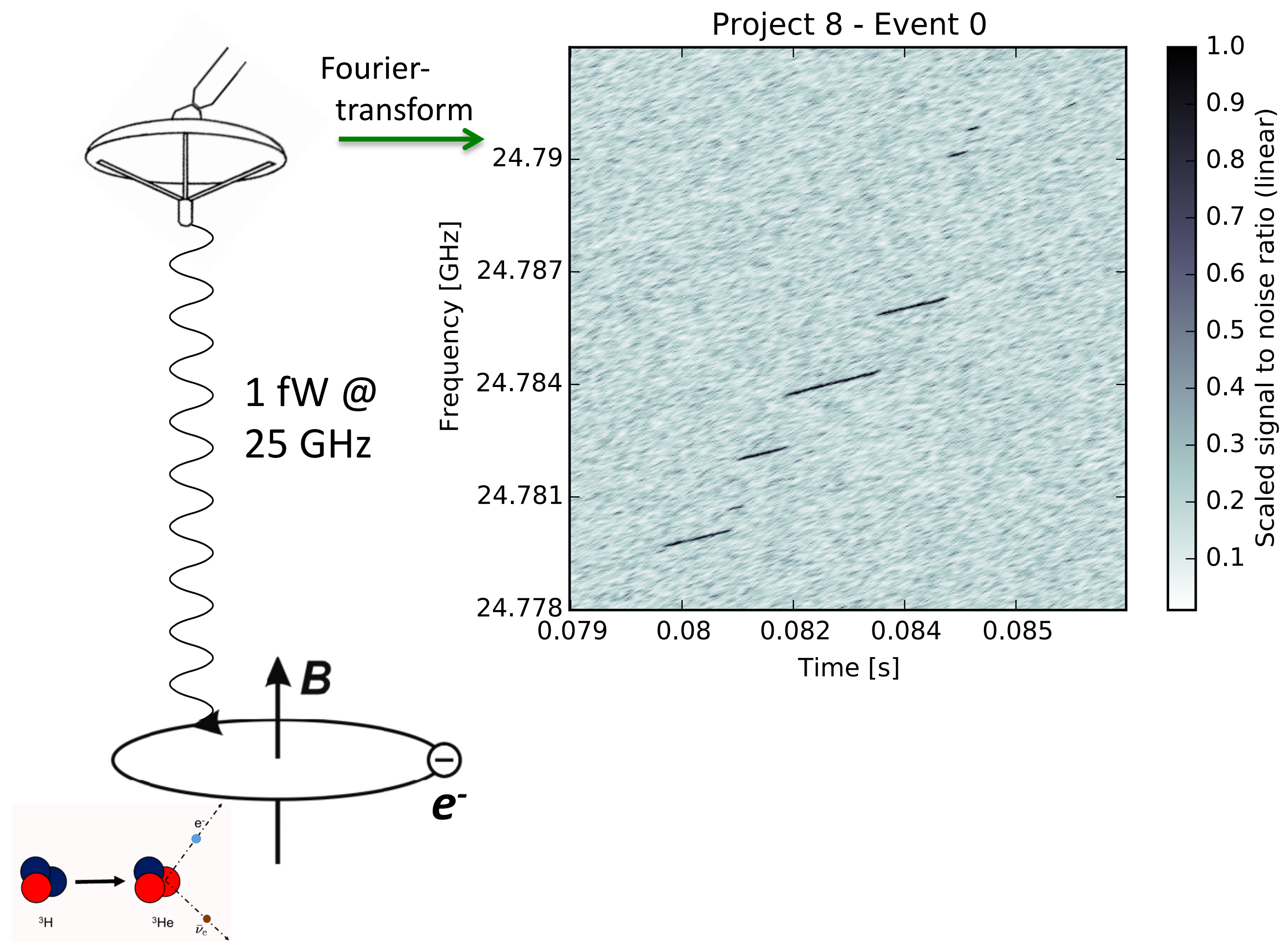
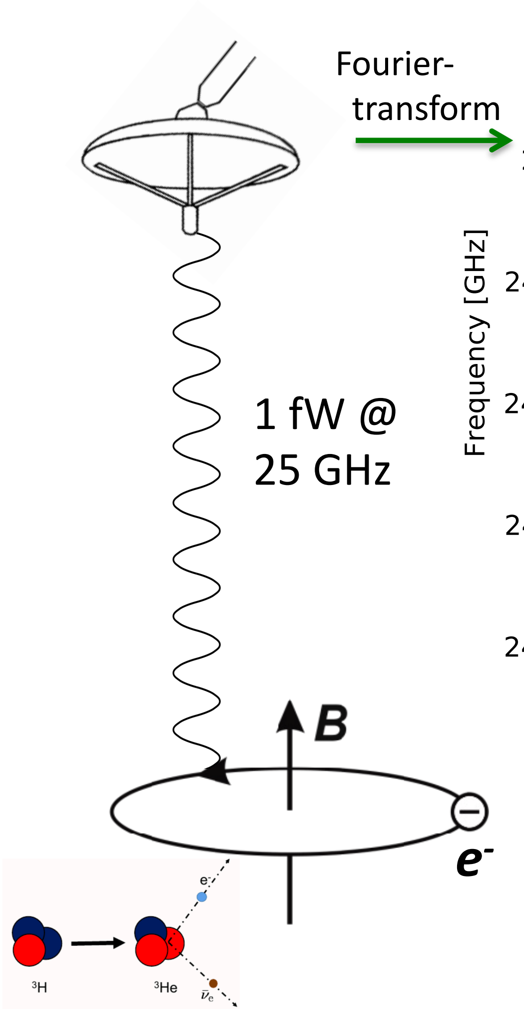
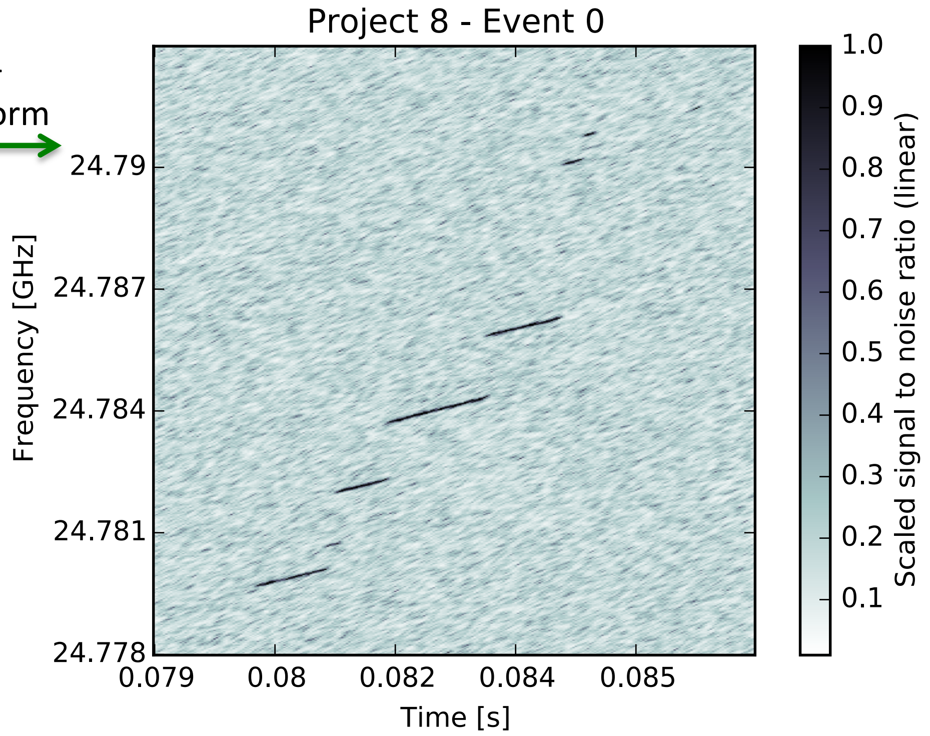
Cyclotron Radiation Emission Spectroscopy (CRES)



PROJECT 8

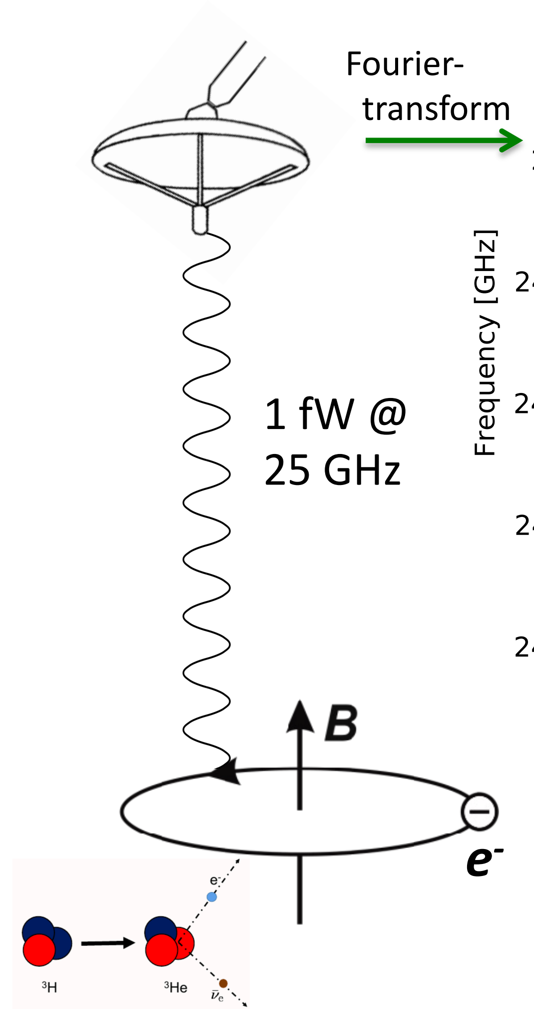
Cyclotron Radiation Emission Spectroscopy (CRES)

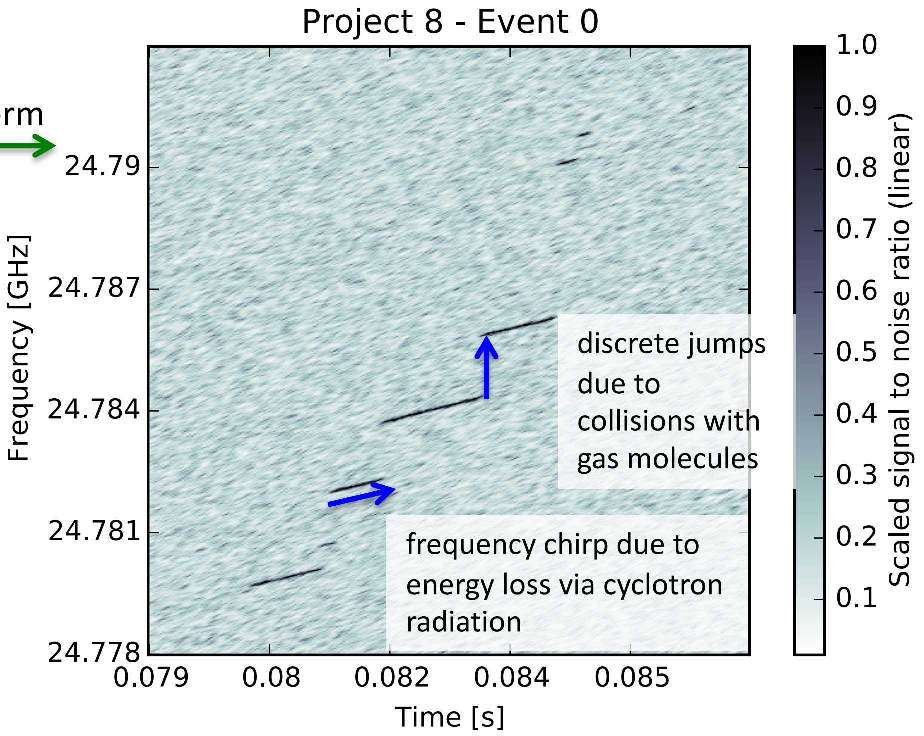




$$f_c = \frac{f_{c,0}}{\gamma} = \frac{1}{2\pi} \frac{eB}{m_e + E_{kin}/c^2}$$

Cyclotron Radiation Emission Spectroscopy (CRES)





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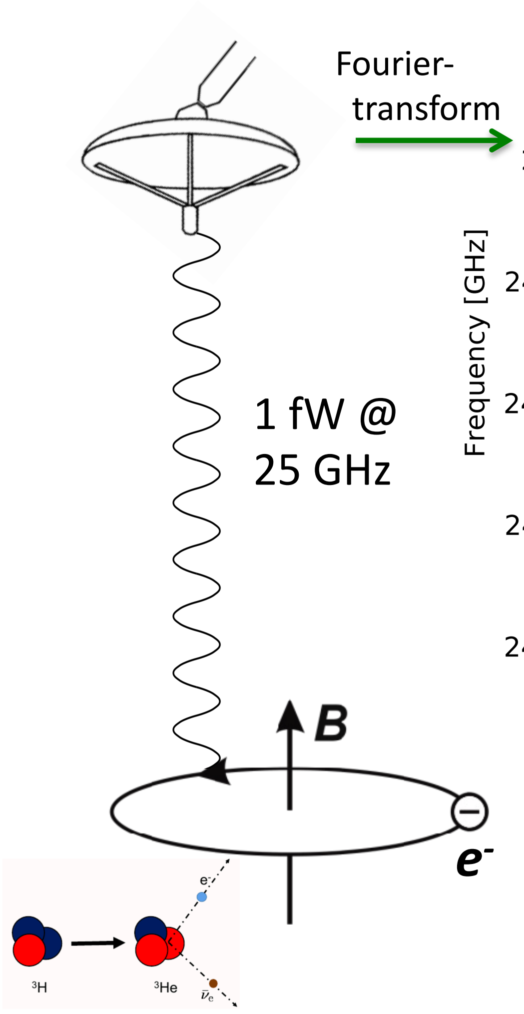

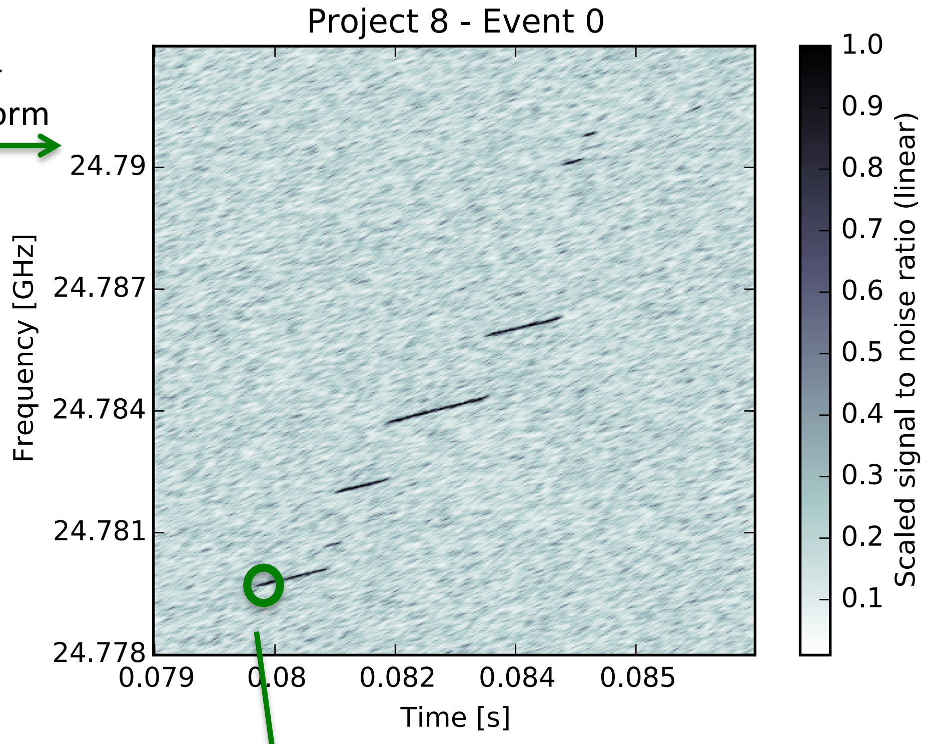

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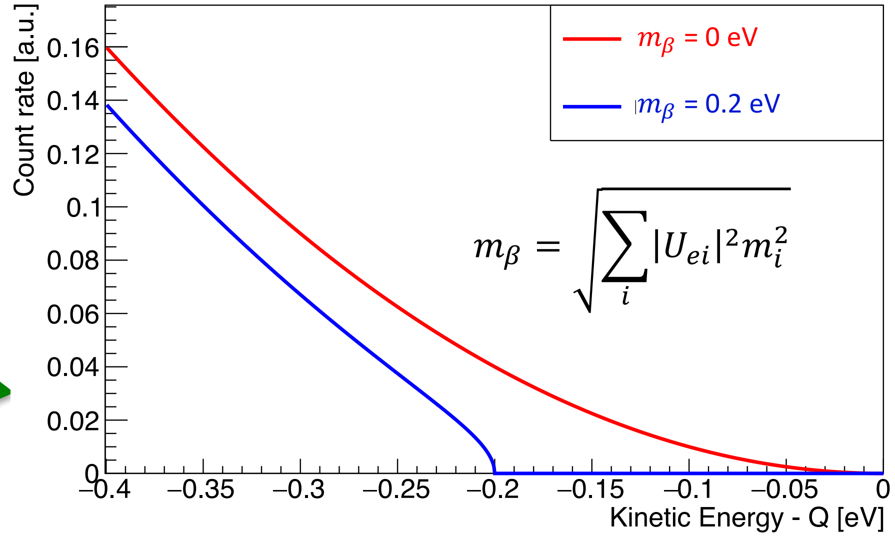

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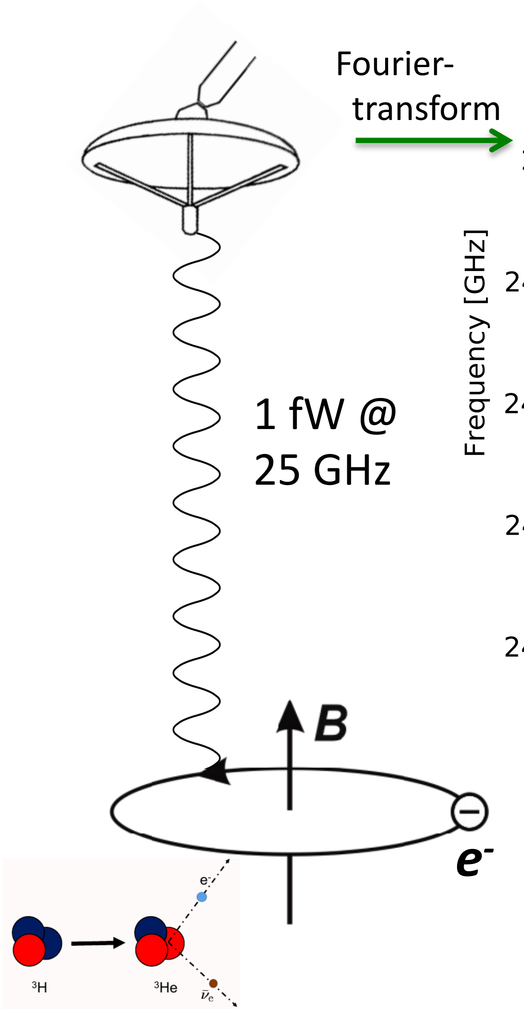
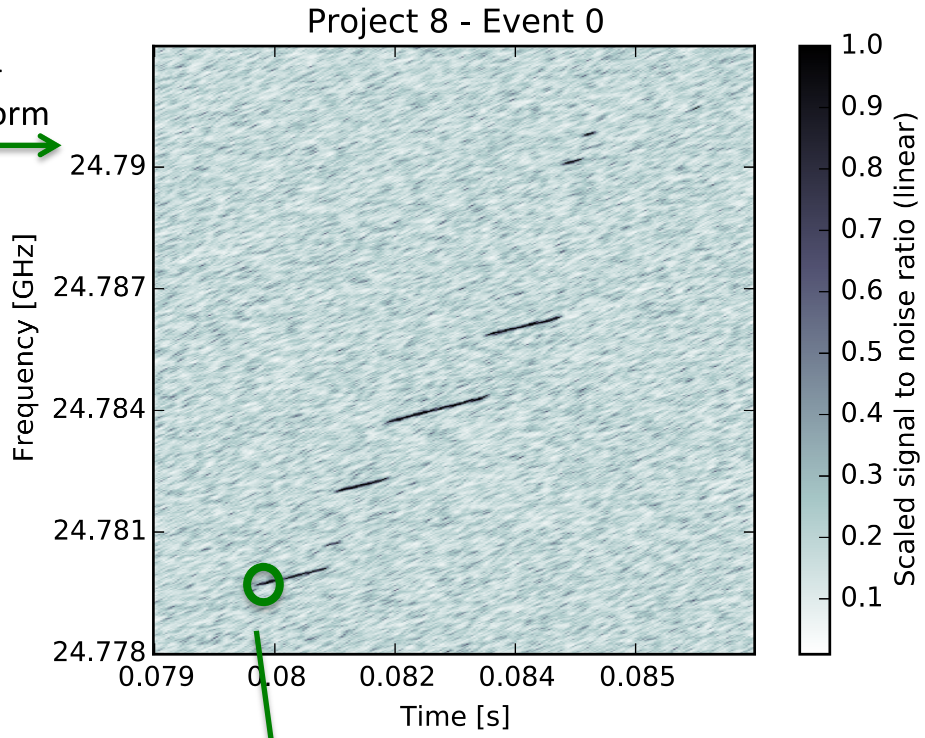
Cyclotron Radiation Emission Spectroscopy (CRES)

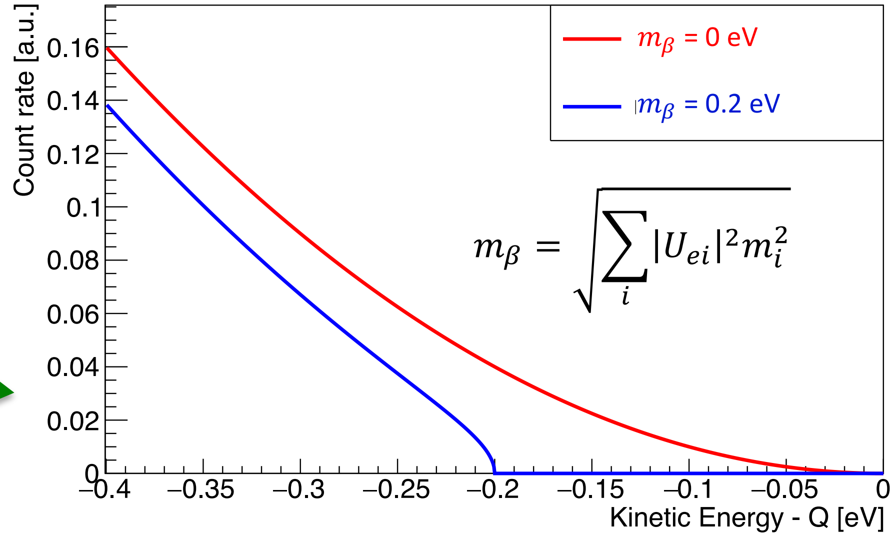




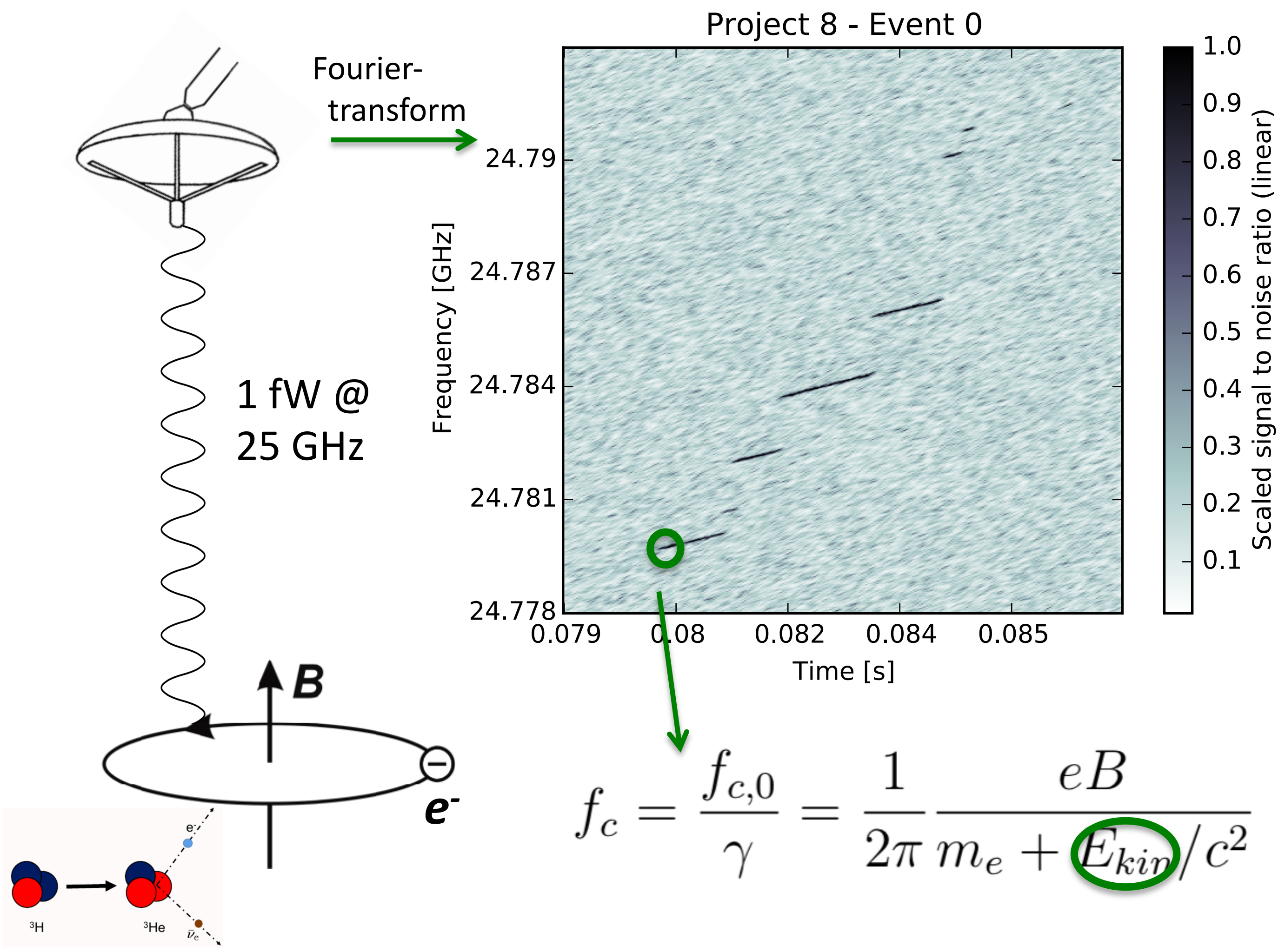
$$f_c = \frac{f_{c,0}}{\gamma} = \frac{1}{2\pi}\frac{eB}{m_e + E_{kin}/c^2}$$

Advantages of CRES

- Frequency measurement ➔ high precision
- Source is transparent to microwave radiation ➔ no electron transport ➔ volume scaling
- Differential spectrometer ➔ increased statistical efficiency
- Compatible with atomic tritium ➔ avoids final-state spectral broadening of T_2



Pushing direct neutrino mass limits with Project 8



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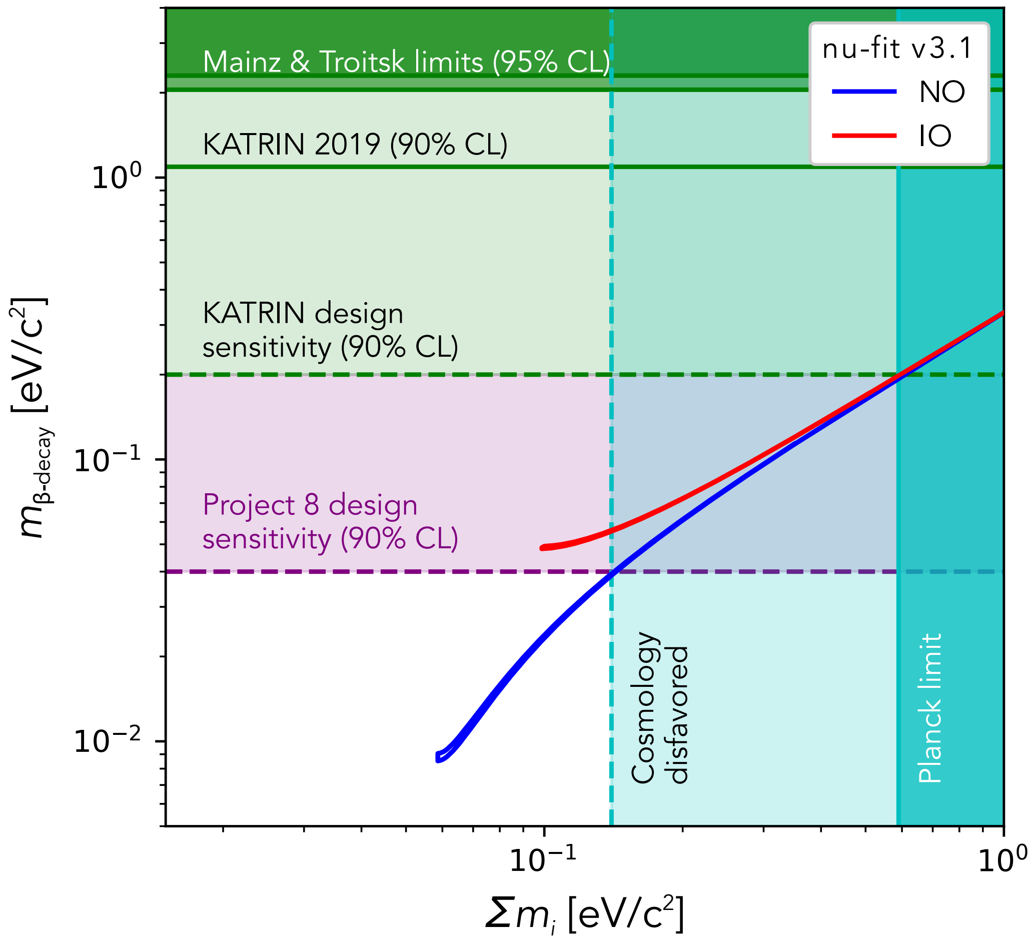


PROJECT 8

A phased approach to neutrino mass

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

Phase I

→ Single-electron detection; spectroscopy
→ ^{83m}Kr conversion-electron spectrum

First CRES demonstration: PRL 114: 162501, 2015
~eV Resolution J. Phys. G. 44, 2017
Machine learning: New J. Phys. 22 (2020)

Phase II

→ Systematic studies; background assessment
→ T_2 spectrum and endpoint measurement

Phenomenology: Phys. Rev. C. 99 (2019) 055501
RF simulation: New J. Phys. 21 (2019) 113051

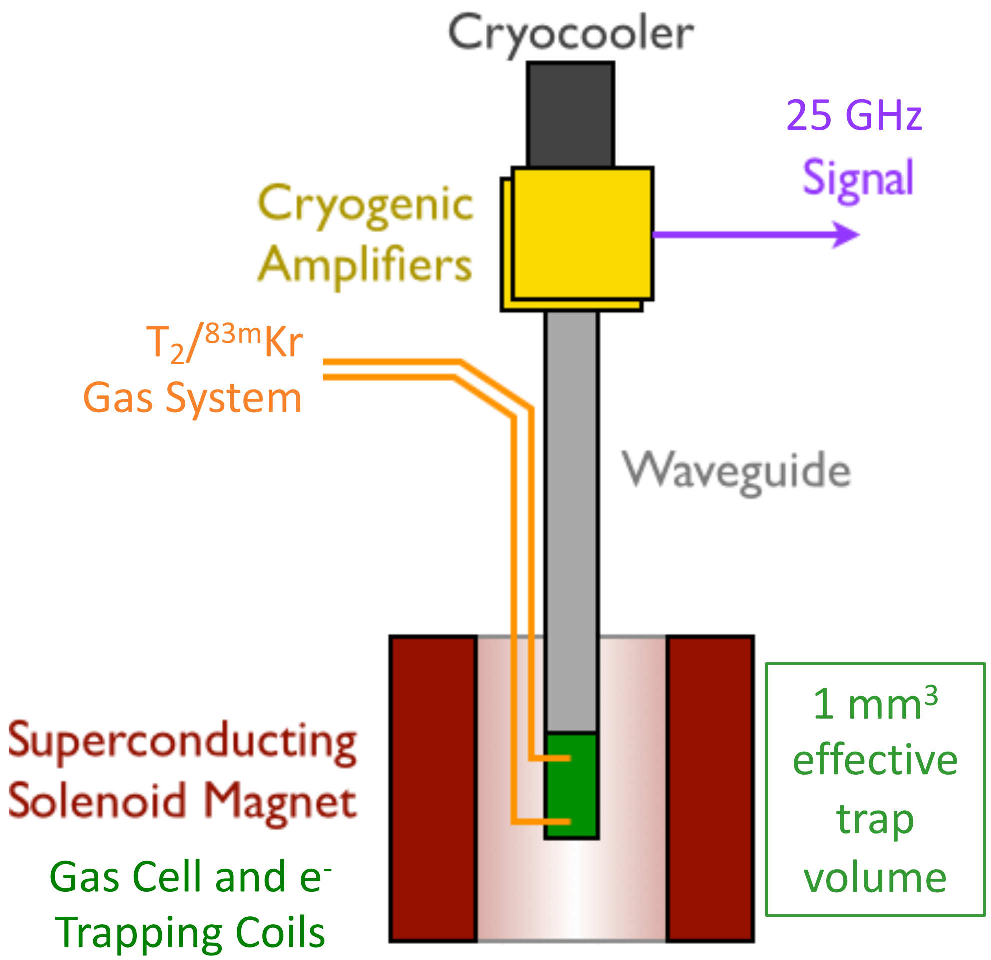
Phase III R&D **Phase III Operations**

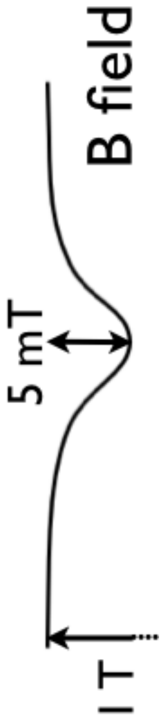
→ 200 cm^3 active volume; free-space detection with antenna array; m_β < 2 eV/c^2
→ Demonstration of atomic tritium production, cooling, and trapping

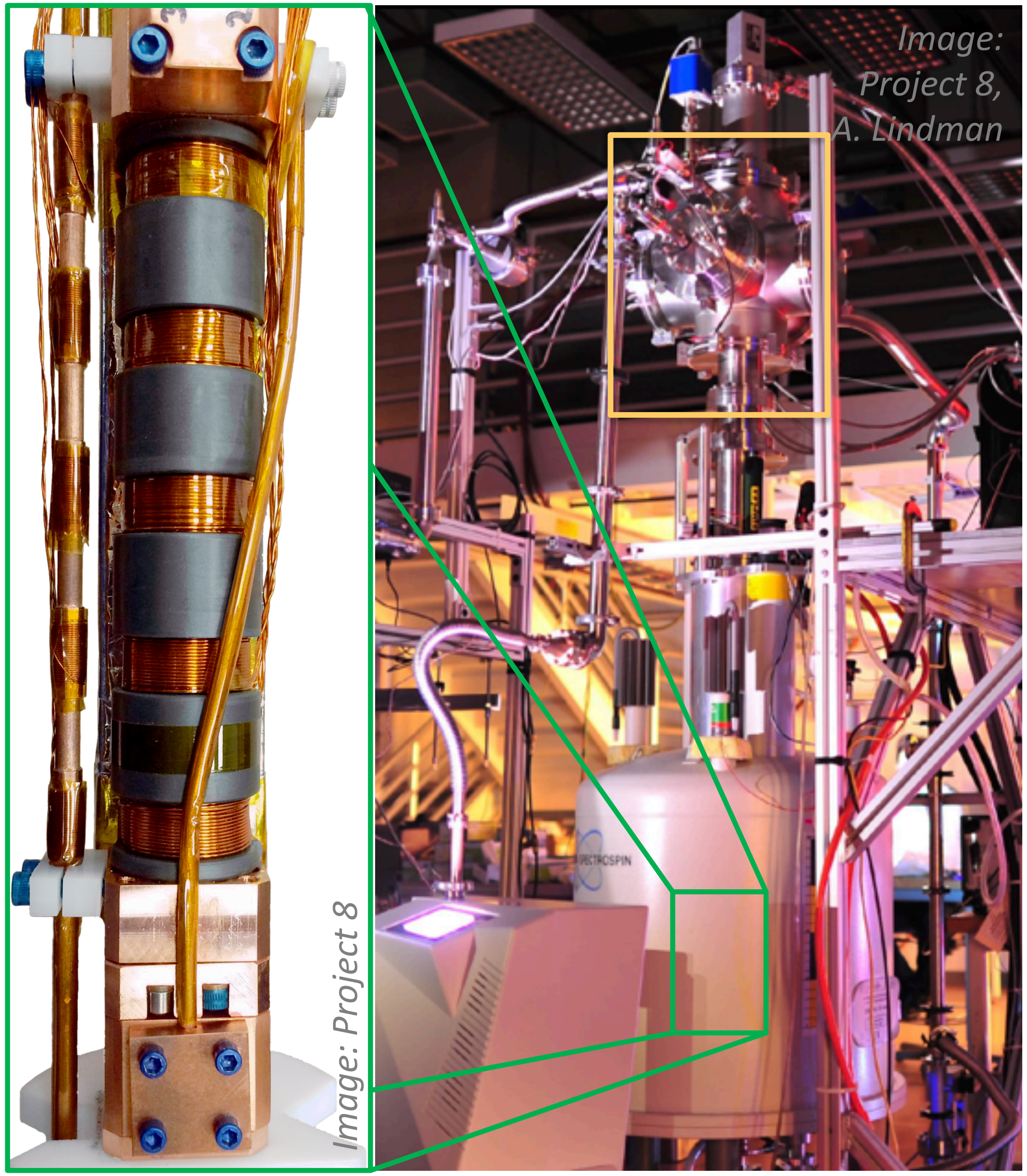
Phase IV

→ m_β < 40 meV/c^2
→ Mass hierarchy

CRES in the small Phase II apparatus

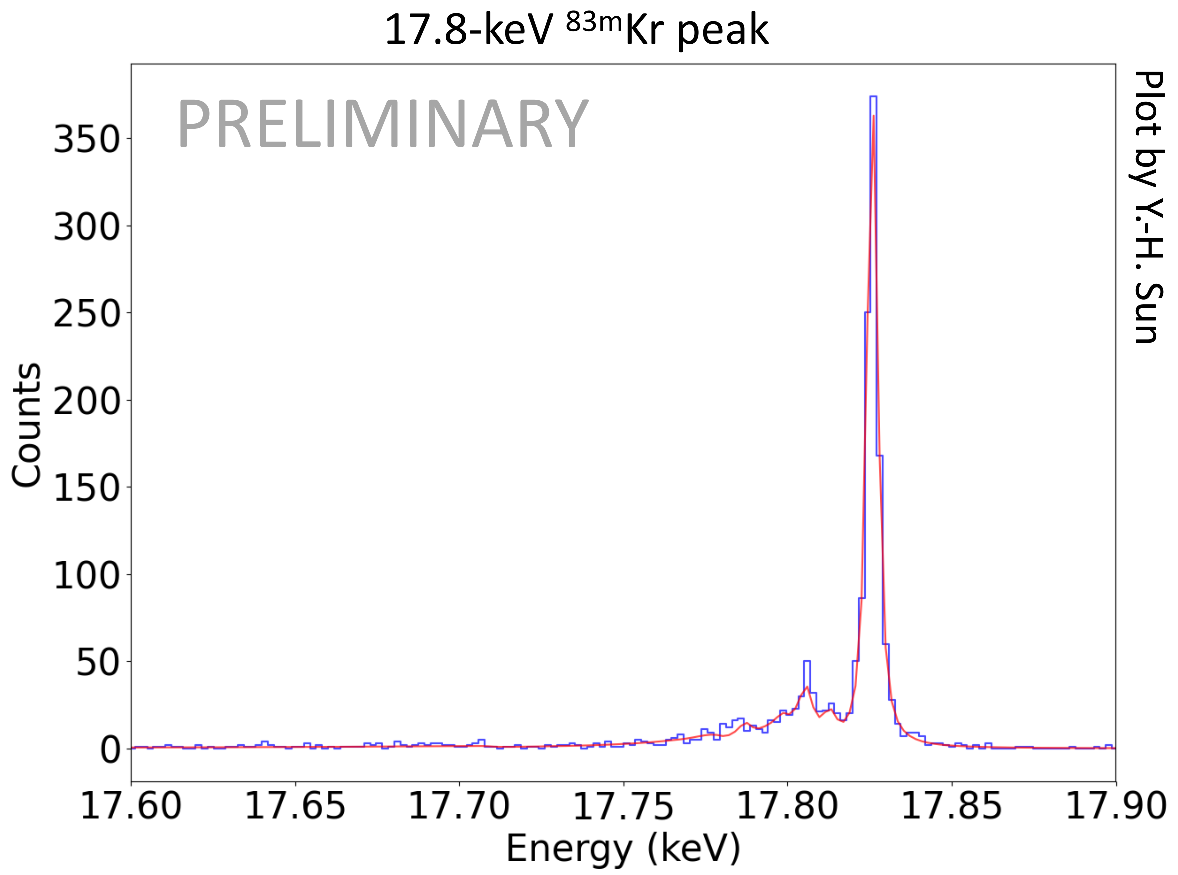






Energy resolution demonstrated with ^{83m}Kr

- 18, 30, and 32 keV conversion peaks observed
- Best demonstrated instrumental width, in a shallow trap (shown at right):
  2.0 ± 0.5 eV (FWHM)
  - Natural linewidth of 18 keV line:
    2.8 ± 0.1 eV (FWHM)
- Tail is primarily due to scattering, described well by an analytical model (red in plot)
- Deeper trap with lower resolution used for tritium data in Phase II to increase statistics and compensate for small 1 mm^3 effective volume



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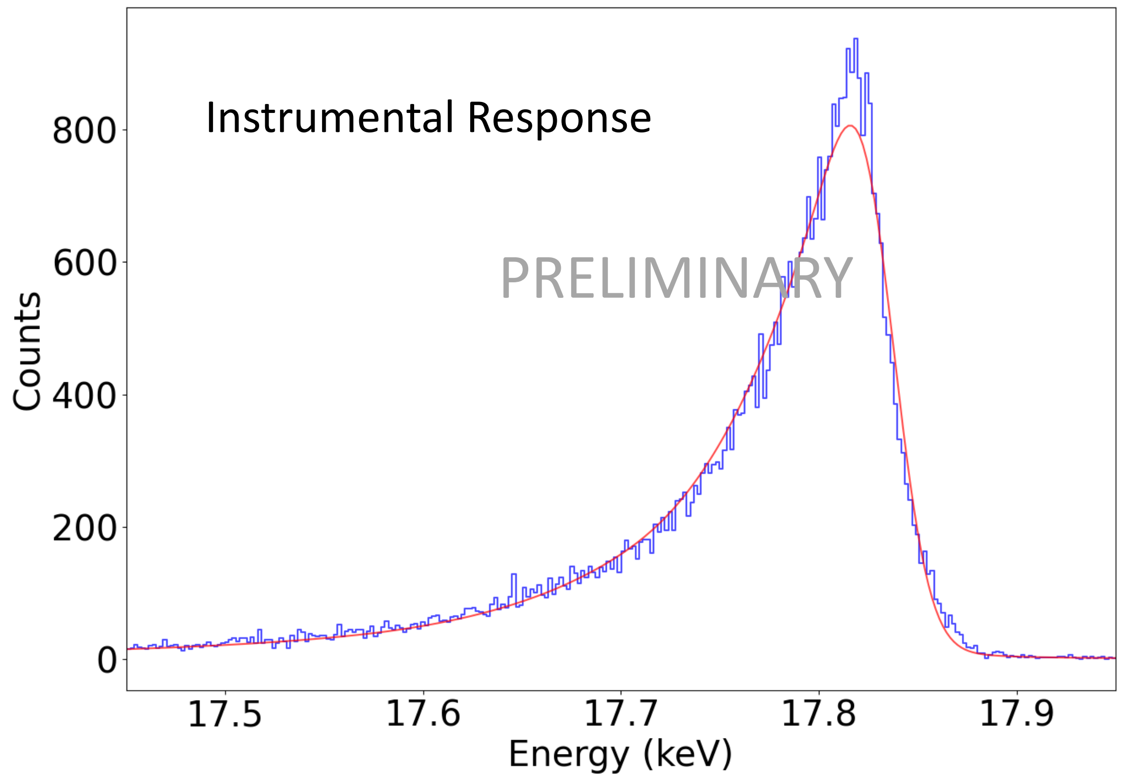
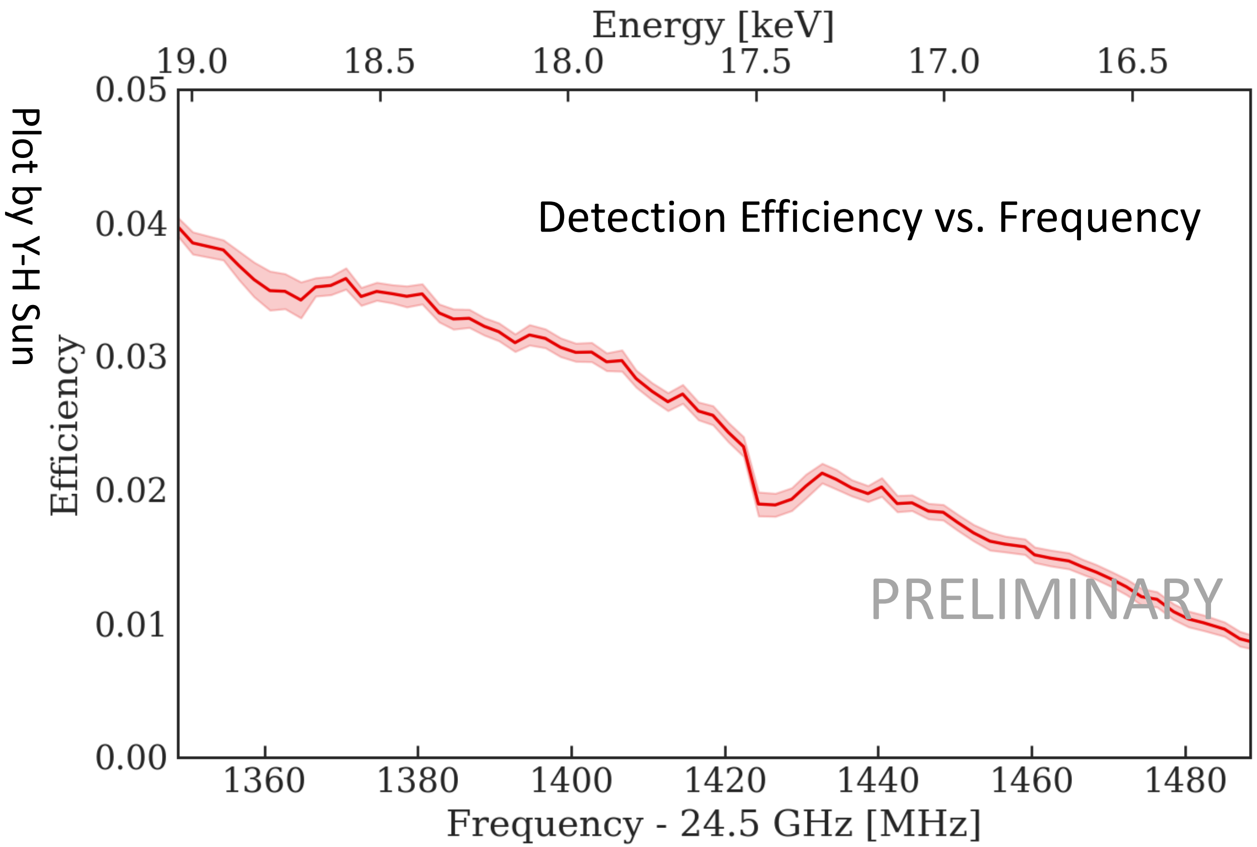
Systematics and calibration





- Lineshape extracted from ^{83m}Kr spectroscopy
- Very sensitive to gas composition and other experimental parameters

- Detection efficiency varies with frequency
- Measured by using magnetic field shifts to sweep the frequency of the ^{83m}Kr 17.8-keV peak

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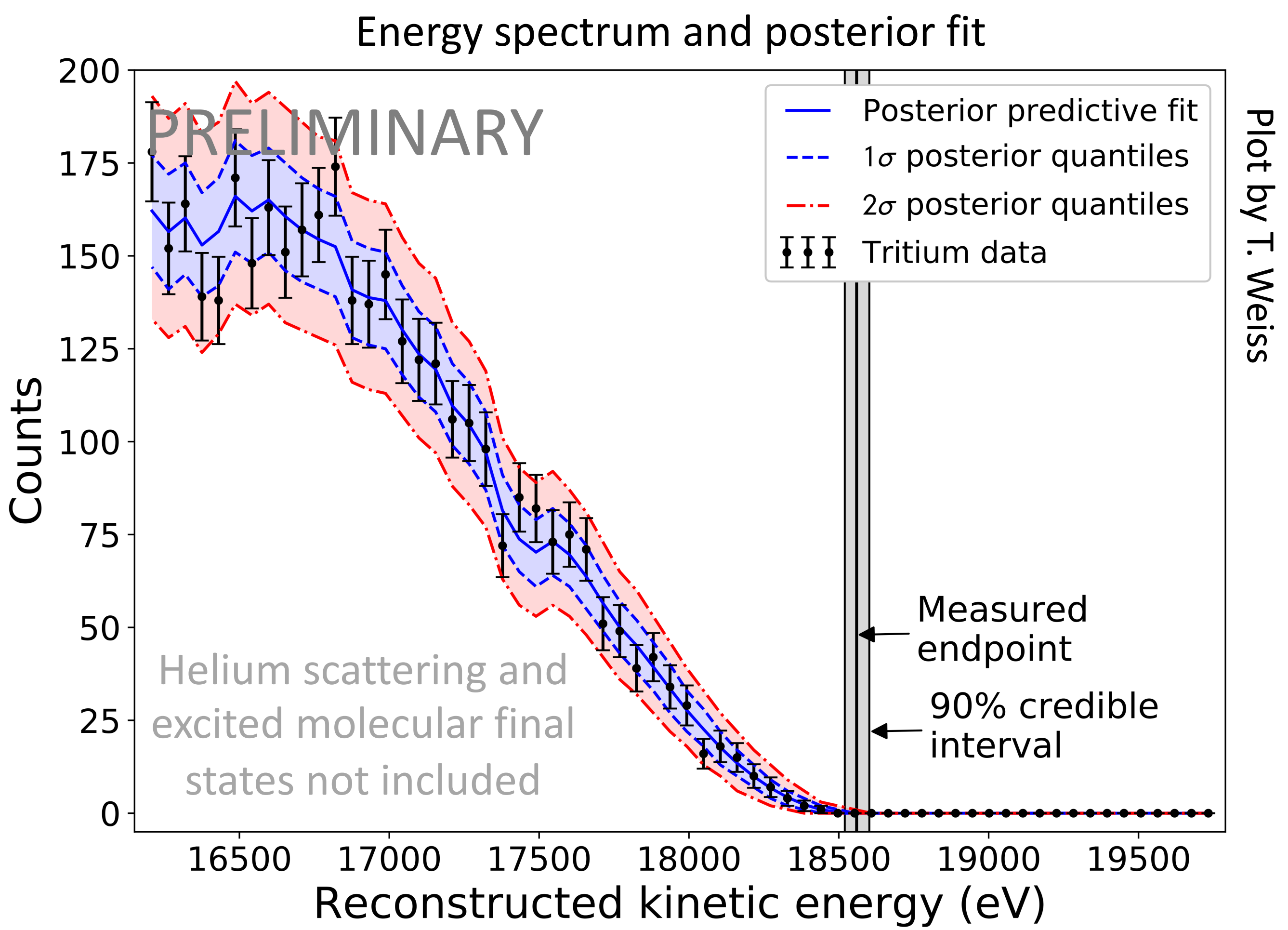
Preliminary measurement of the T_2 β^- endpoint

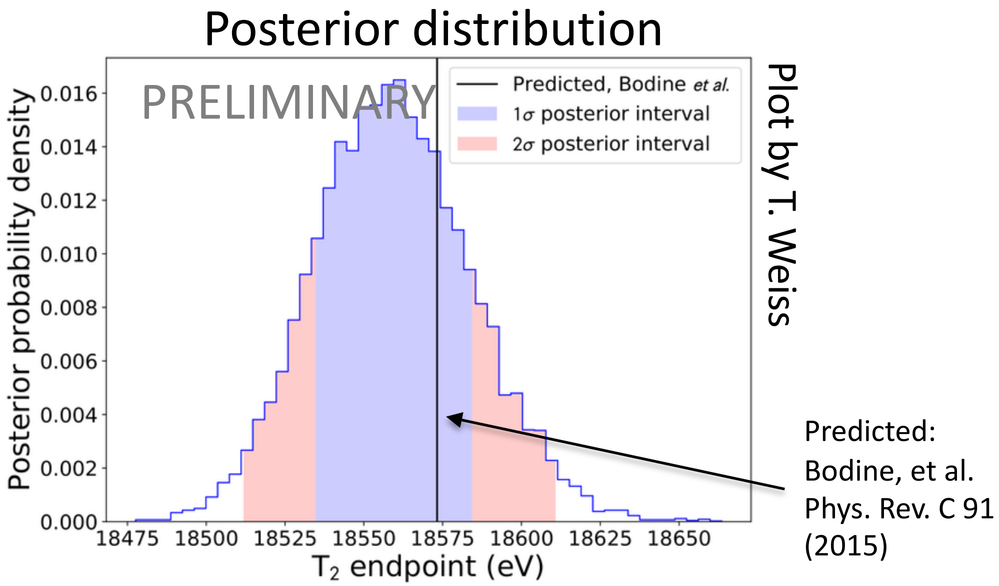


Preliminary T_2 endpoint result:

$$E_0 = \left(18559.4^{+24.9}_{-24.7}\right)\ \mathrm{eV}$$

Background rate:

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



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Phase IV

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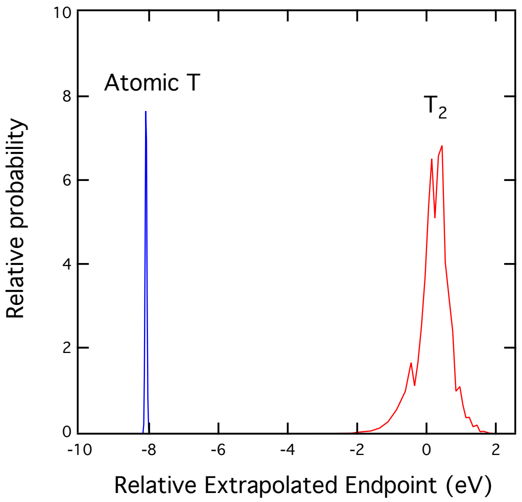
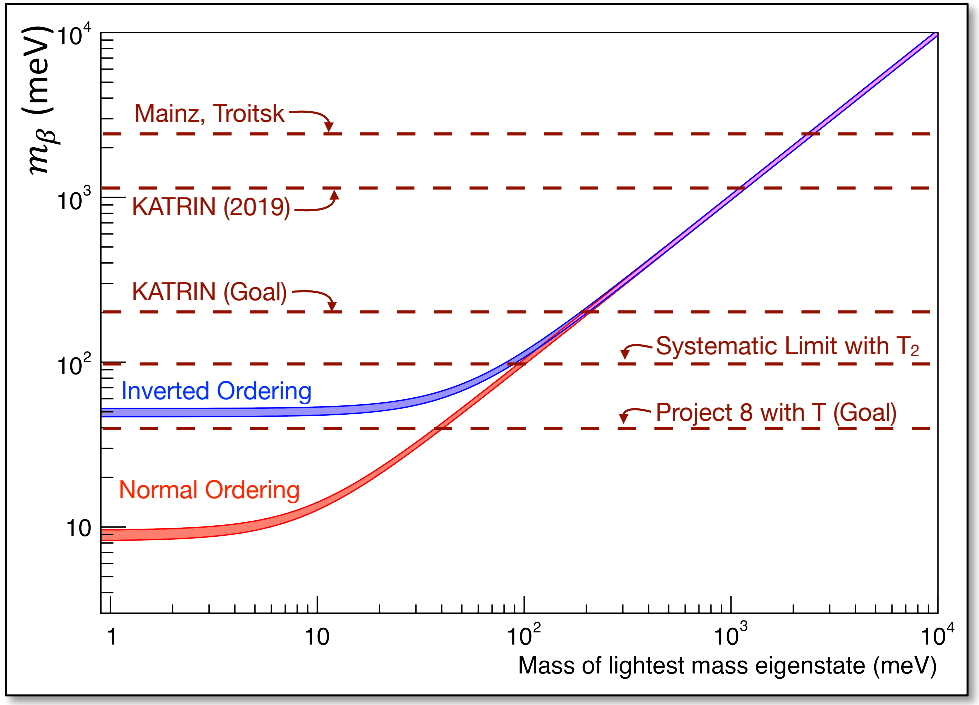
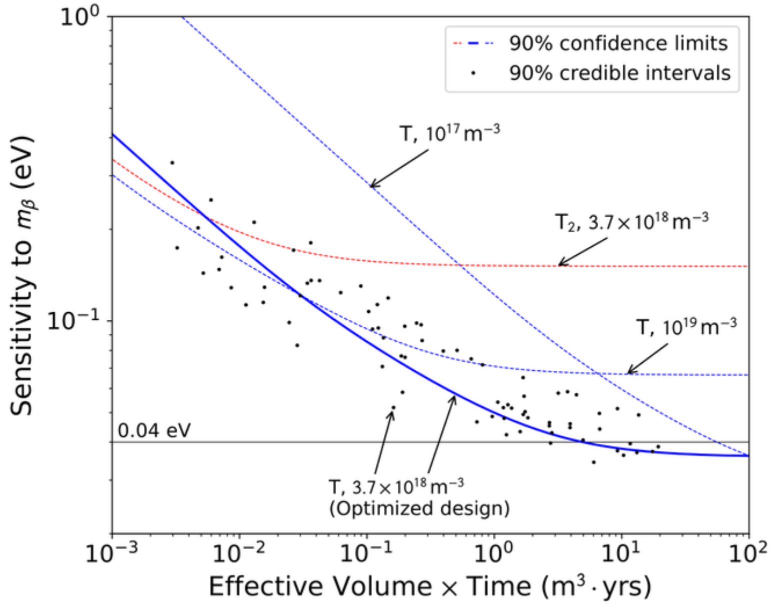
→ Mass hierarchy

How can we reach the Phase IV goals of sensitivity to 40 meV/c^2 and to the mass ordering?







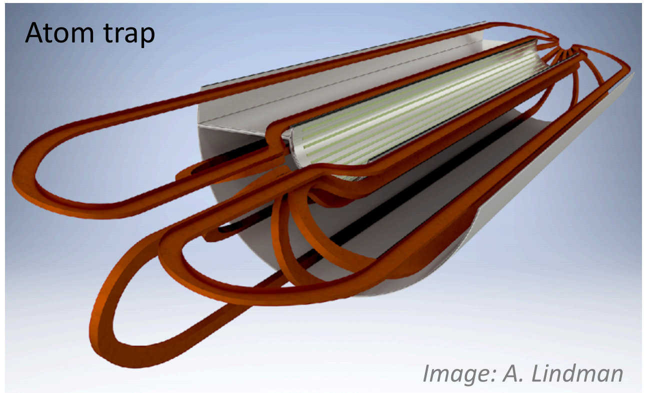
Atomic tritium must be used to avoid uncertainty due to final states of molecular ion

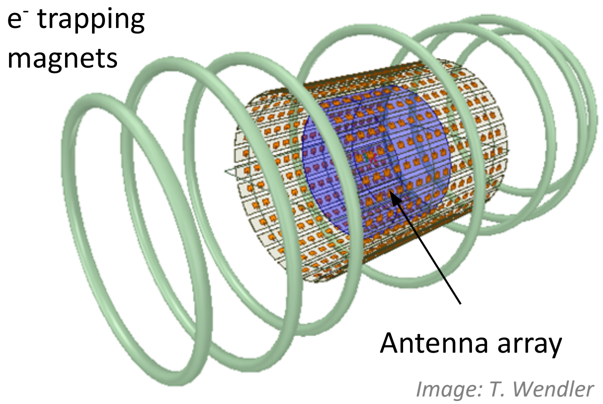
Statistics must be scaled up: improved efficiency, higher density, larger volume
→ incompatible with single-mode waveguide detection; must move to a free space

Phase III: technology and scalability demonstrations for Phase IV

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

Phase III R&D — Phase III Operations





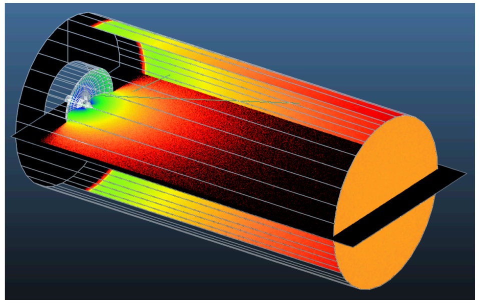
<u>Atomic Tritium Demonstrator</u>

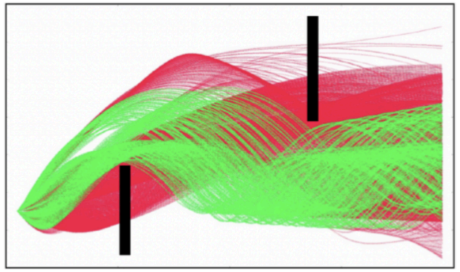
- atomic T production and cooling to <50 mK with high purity, high density
- neutral atom trapping with Ioffe trap or Halbach array

<u>Free-Space CRES Demonstrator</u>

- detection with antenna array, spatial tracking
- scaling to larger volume and higher densities
- improving energy resolution and efficiency
- on-line data reduction
- 2 eV sensitivity to m_β

Phase III Atomic Tritium Demonstrator: Cooling, guiding, and velocity-selecting T atoms





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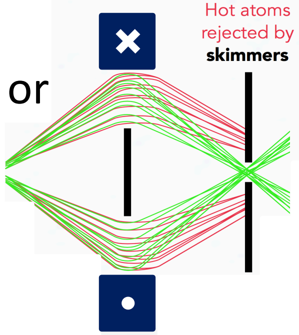

T_2 molecules 300 K

Cracker ~2500 K

T atoms 2500 K

Accommodators 160 K, 8 K

T atoms 8 K

Inhomogenous magnetic field: velocity, temp, state selection

Hot atoms blocked

Cold atoms blocked

~77-80 m/s atoms

~0-20 m/s atoms

~1-T field step

Trap entrance

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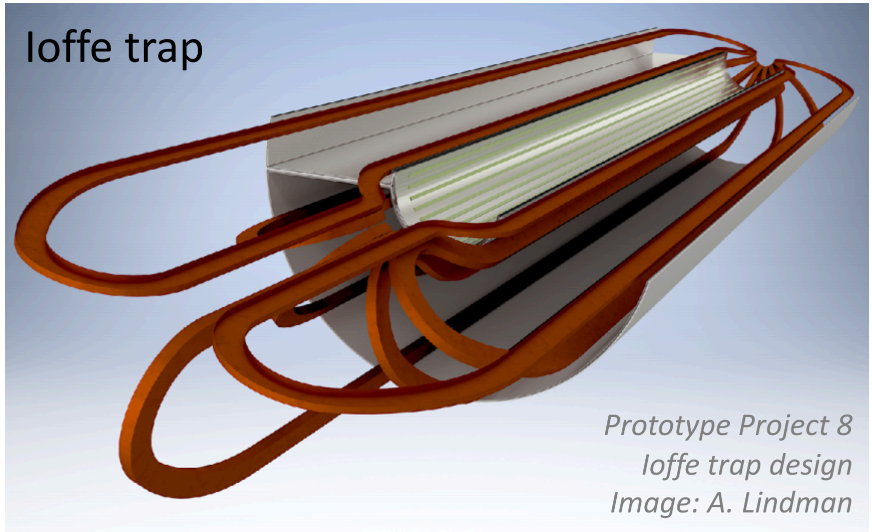
Phase III Atomic T Demonstrator: Atom trapping

- Neutral tritium atoms will be magnetically trapped with a superconducting Ioffe trap or a Halbach array of permanent magnets
- Need large volume, a high B field wall, and good field homogeneity
- ~1 m^3 demonstrator planned to validate atom production, cooling, selection, and trapping methods



Prototype Project 8 Ioffe trap design
Image: A. Lindman

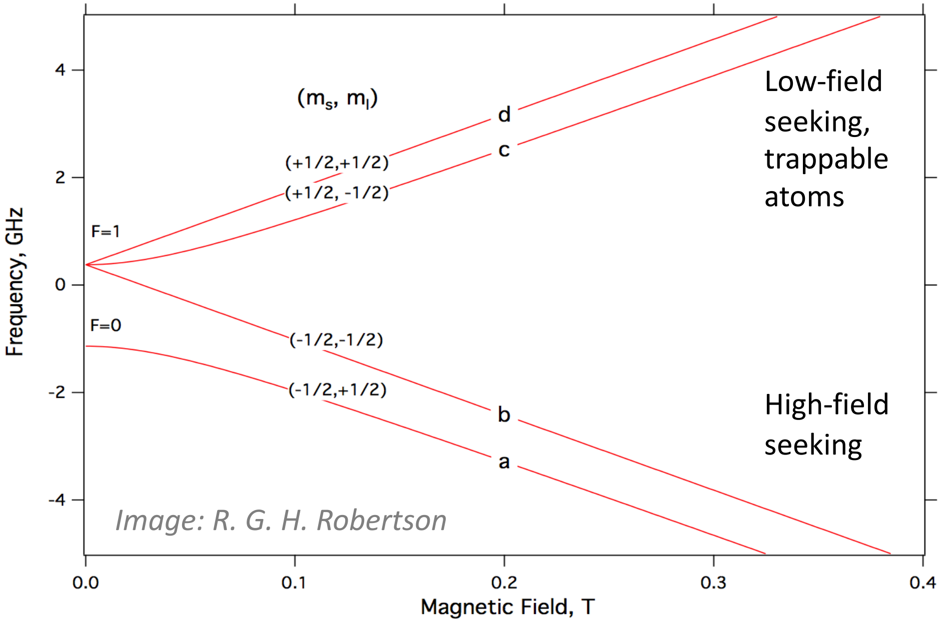


Image: R. G. H. Robertson

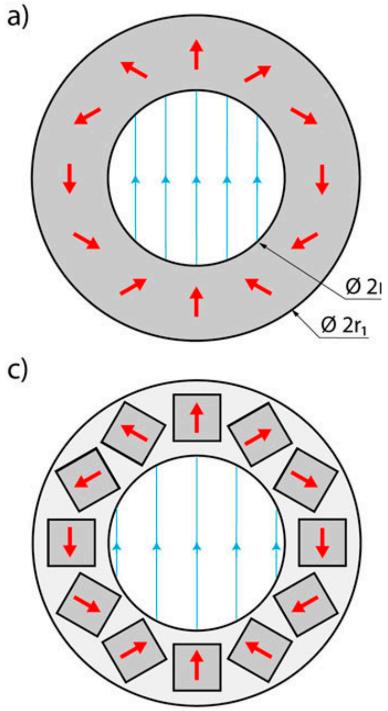


Image: O. Tretiak, P. Blümler, and L. Bougasa.
AIP Advances 9, 115312 (2019)

Halbach arrays

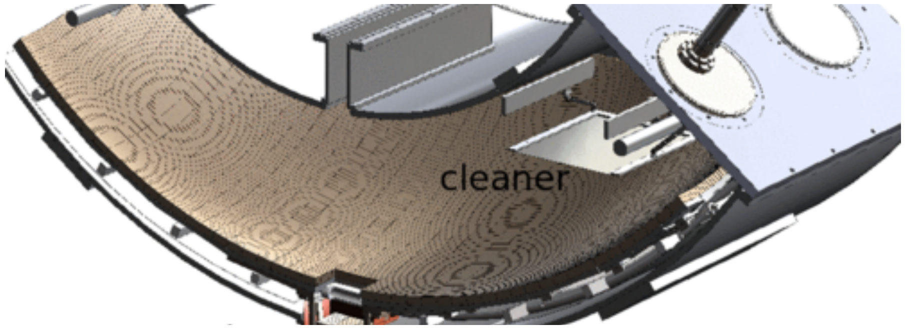
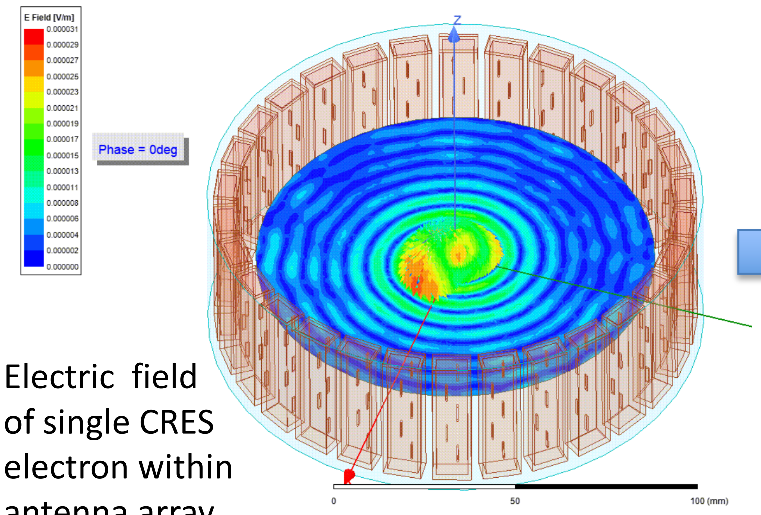
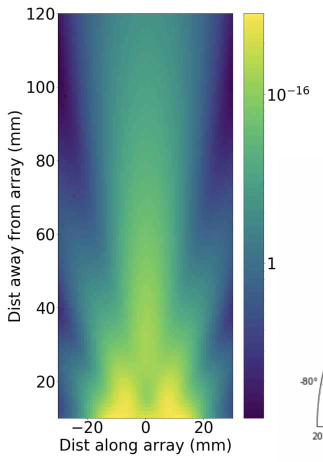


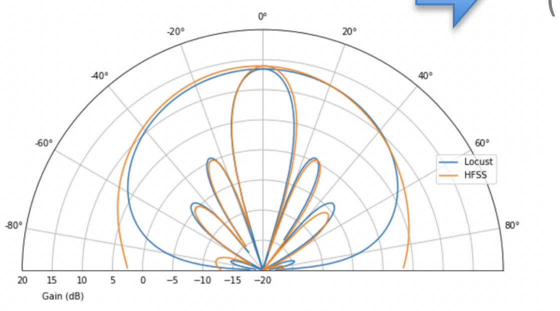
Image: UCNtau Collaboration
Phys. Rev. C 89,052501

Simulating and detecting CRES in free space: radio astronomy in the near field

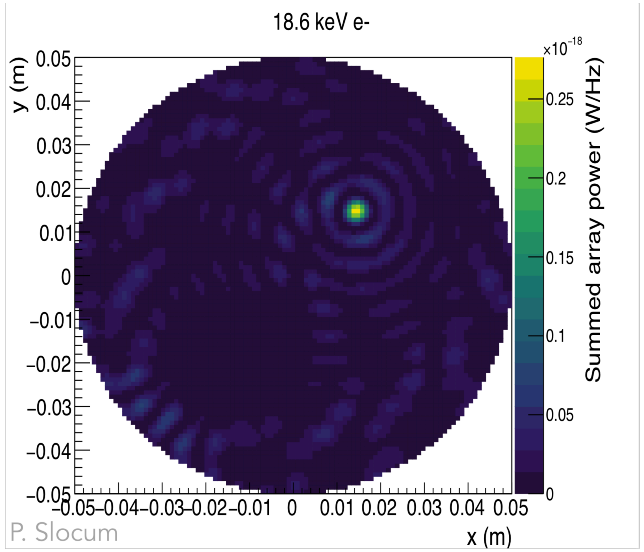


Electric field of single CRES electron within antenna array
(A. Telles)





Antenna array field of view and gain pattern
(A. Telles)



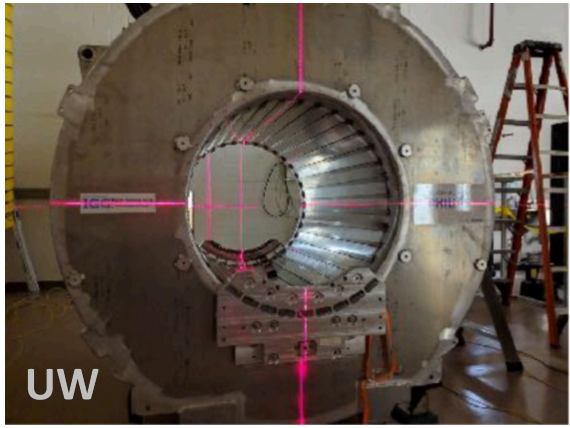
Electron signal power vs. position
(P. Slocum)

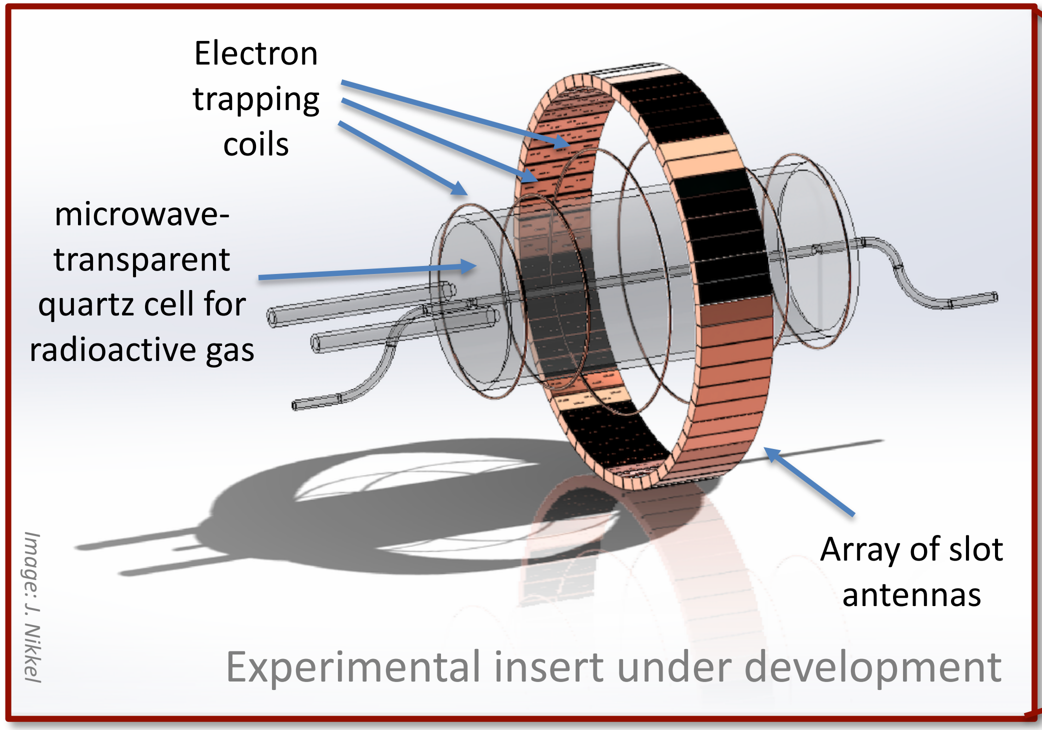
- Phase-sensitive detection with an array of slot antennas
- RF simulation of time-dependent CRES fields with Project 8 Locust software and HFSS
- Real-time digital beamforming and track reconstruction
- Spatial tracking of electrons -> reduced pileup, corrections for magnetic field inhomogeneities

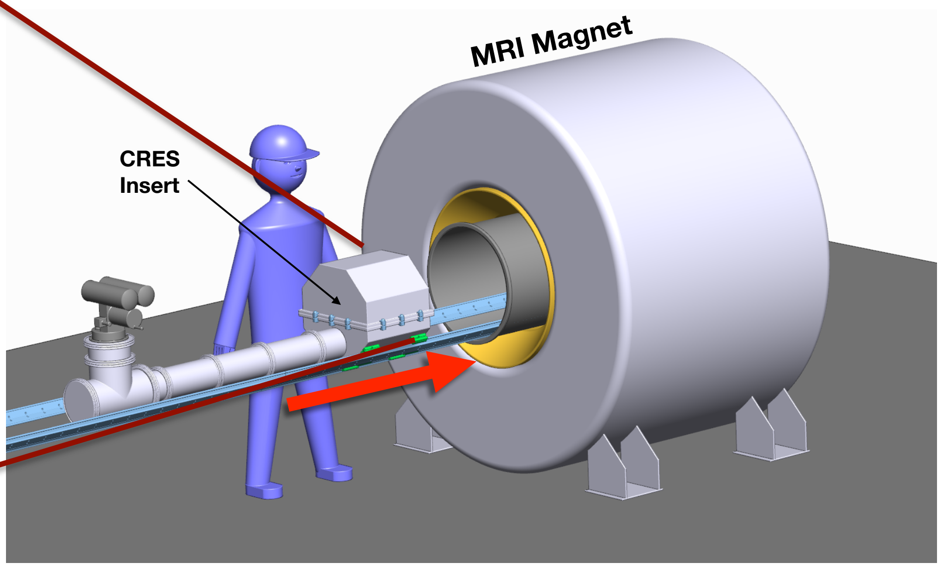
Phase III Free-Space CRES Demonstrator

- Design work is ongoing on many fronts: cryogenic gas cell, electron trap, antennas, high-purity gas handling system, calibration methods
- We might start with single ring of antennas, then upgrade to multiple rings stacked axially

Commercial MRI magnet with 1T magnetic field, 1 ppm homogeneity over 200 cm^3 volume

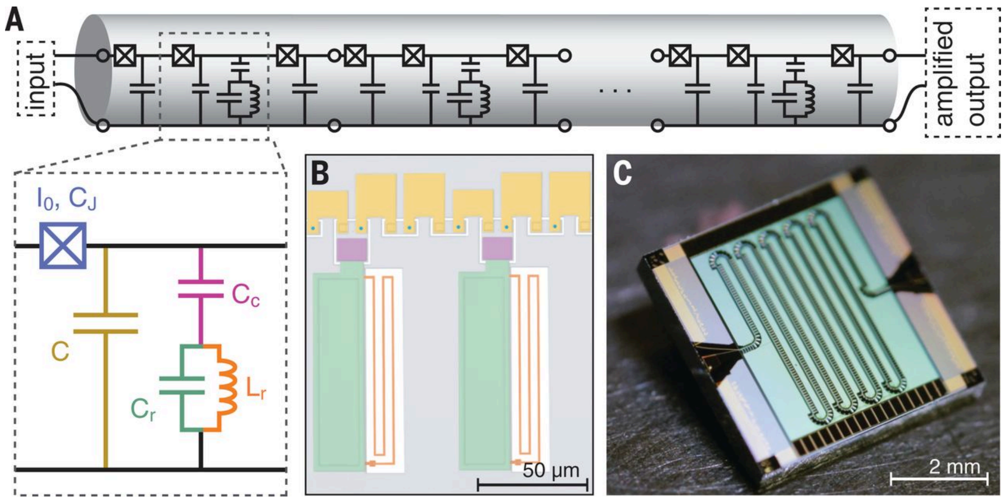






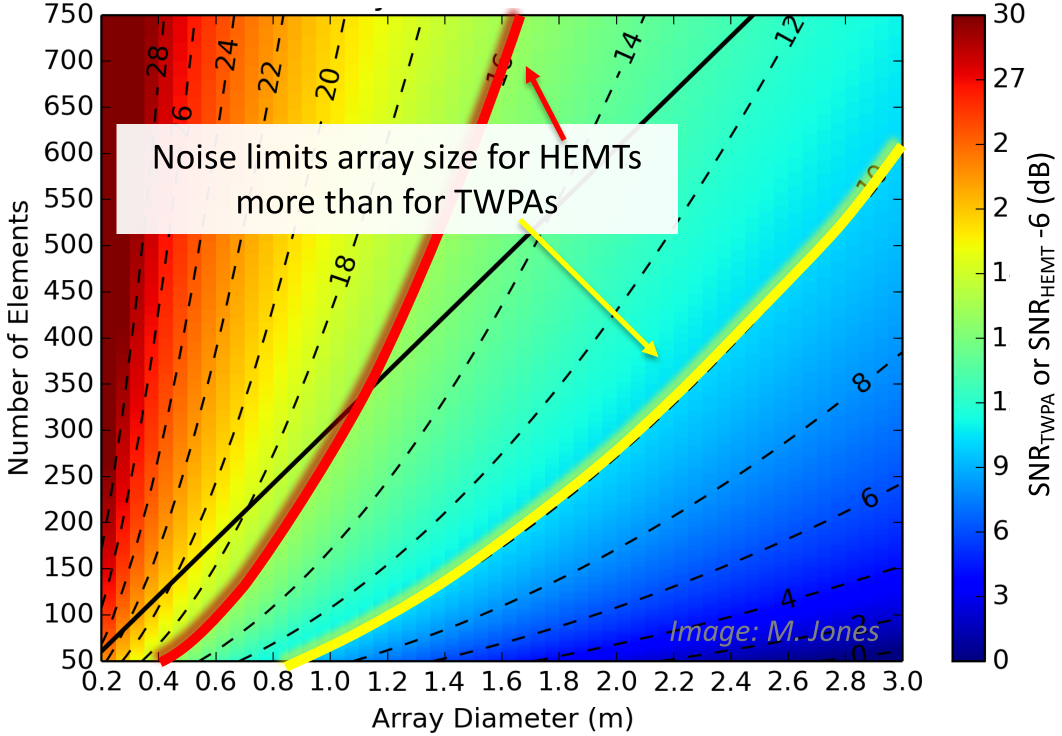
The next frontier in sensitivity: quantum amplifiers

- Josephson traveling-wave parametric amplifiers (TWPAs) are quantum-limited, microwave-frequency superconducting amplifiers based on a transmission-line chain of Josephson junctions and capacitors
- In discussions with Will Oliver at MIT Lincoln Laboratory to potentially develop TWPAs for Project 8



TWPA, from C. Macklin et al. Science 2015;350:307-310

Expected SNR vs. Project 8 antenna array size

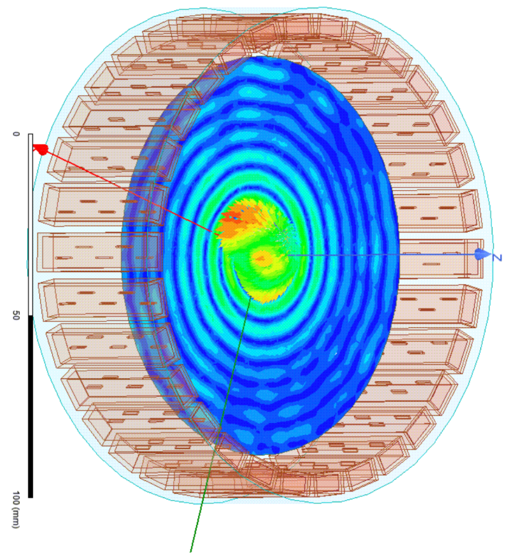


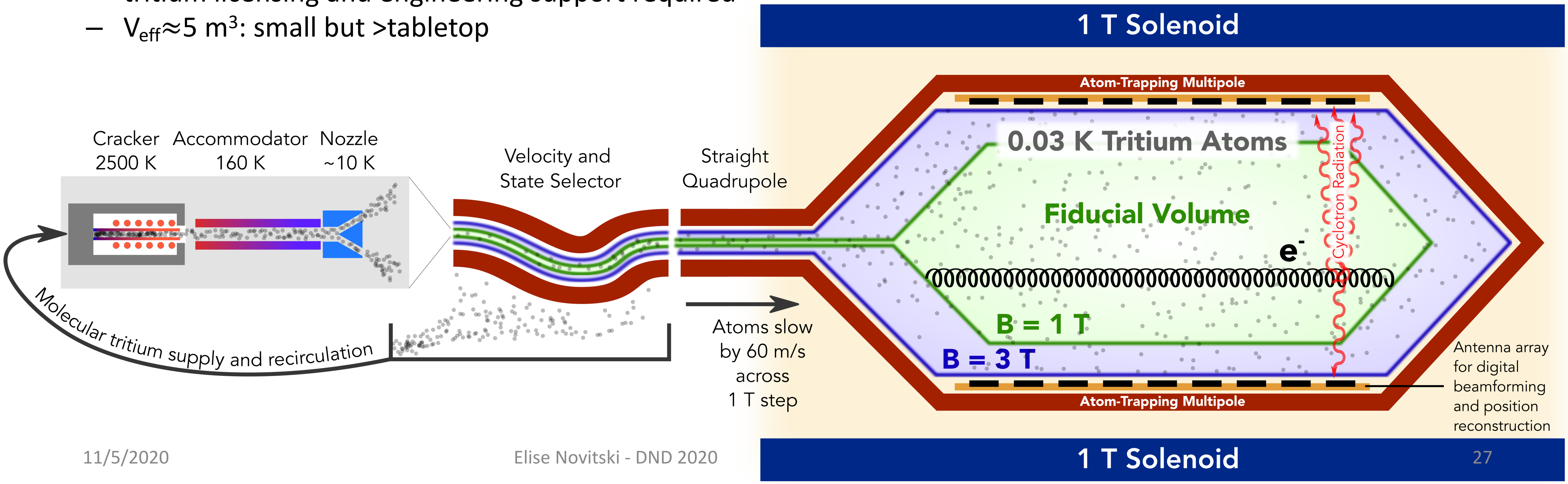
- HEMT: $T_{noise} \approx 5$ K
- TWPA: $T_{noise} \approx 1.2$ K

PROJECT 8

Project 8's near future

- Project 8 is poised to reveal new physics by pushing the limits of knowledge of neutrino mass
- We're developing innovative, yet feasible, new technologies to accomplish this
- There are opportunities for new collaborator to make contributions
- The scale of the final Phase IV experiment is perfect for siting at a national lab
  - tritium licensing and engineering support required
  - $V_{eff} \approx 5\ m^3$: small but >tabletop





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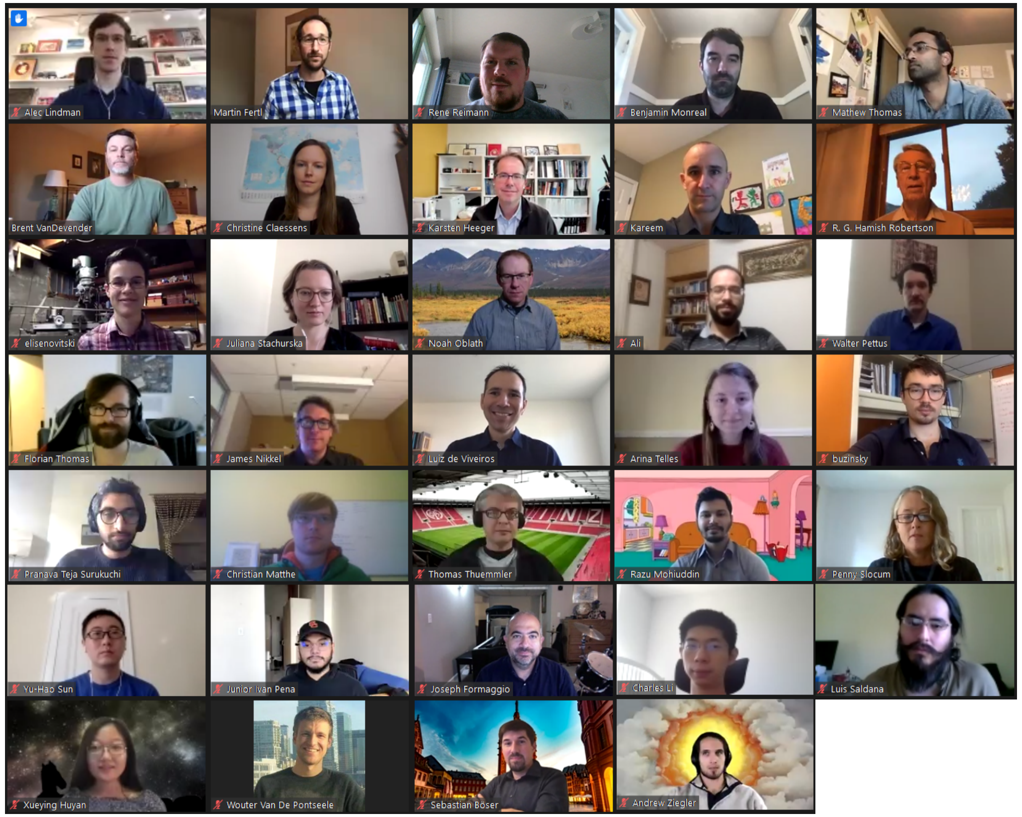

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Acknowledgments: direct neutrino mass community

KATRIN – Karlsruhe Tritium Neutrino Experiment

- Max-Planck-Institut für Kernphysik Heidelberg
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- Massachusetts Institute of Technology
- Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)
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- Case Western Reserve University
- University of Washington

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