Project 8: results and prospects

The XXX International Conference on Neutrino Physics and Astrophysics

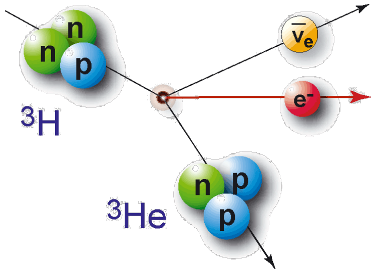
Virtual Seoul, Republic of Korea

June 4, 2022

Elise Novitski for the Project 8 Collaboration

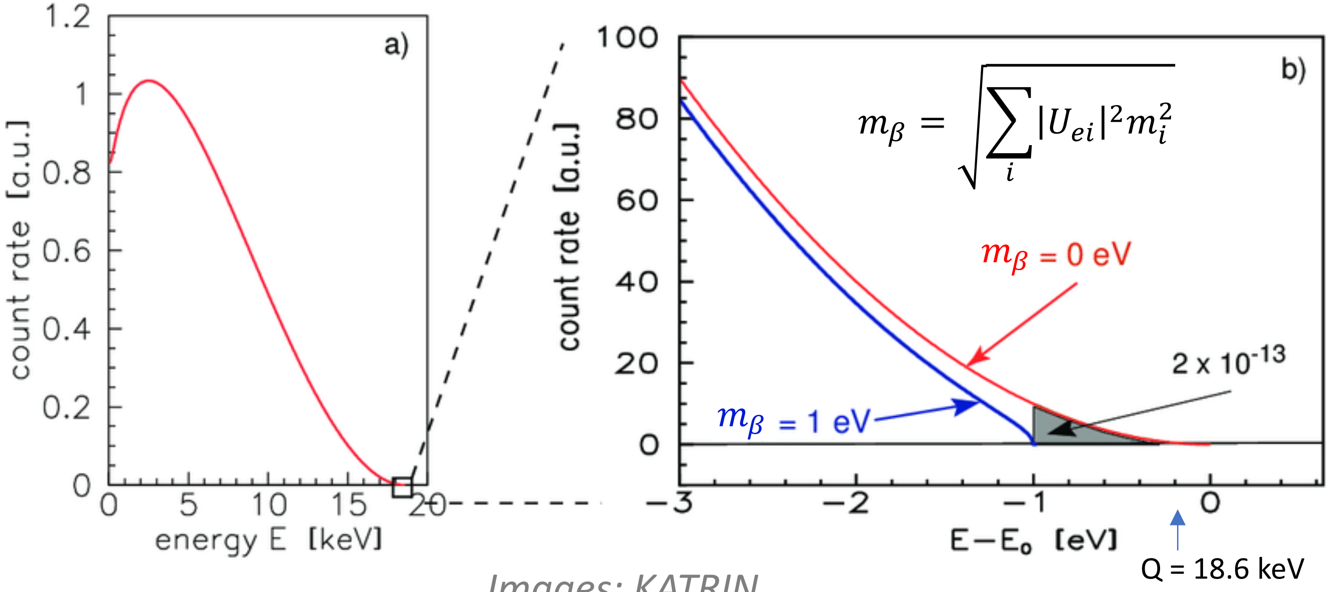
Neutrino mass from tritium β⁻ spectroscopy

- Neutrino mass is linked to Beyond-the-Standard-Model physics
- Absolute mass scale and ordering are still unknown
- Tritium β⁻ spectroscopy is the leading technique for direct neutrino mass measurements



Recent result from KATRIN:
$m_\beta \leq 0.8$ eV/c² (90% CL)
Aker et al. (KATRIN), Nat. Phys. 18, 160–166 (2022)

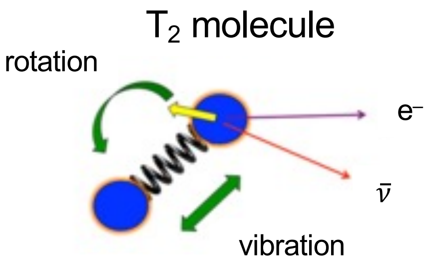
Energy spectrum of electrons emitted from tritium β⁻ decay

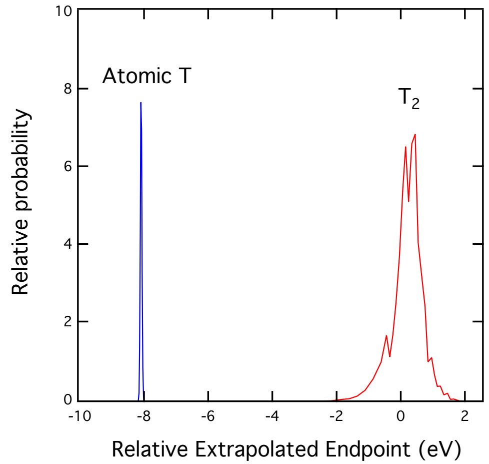


Images: KATRIN

Challenges for future experiments

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

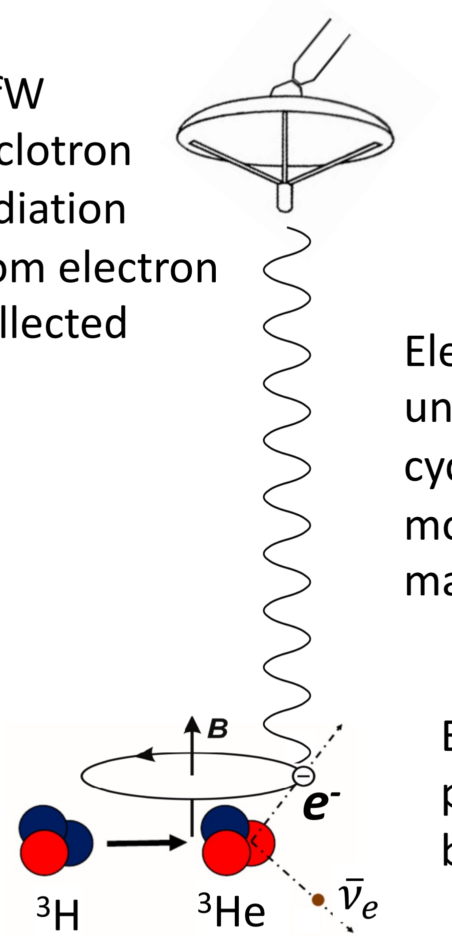




J. Formaggio, A. L. C. De Gouvêa, and R. G. H. Robertson, Physics Reports 914 (2021) 1–54

A new approach: Cyclotron Radiation Emission Spectroscopy (CRES)

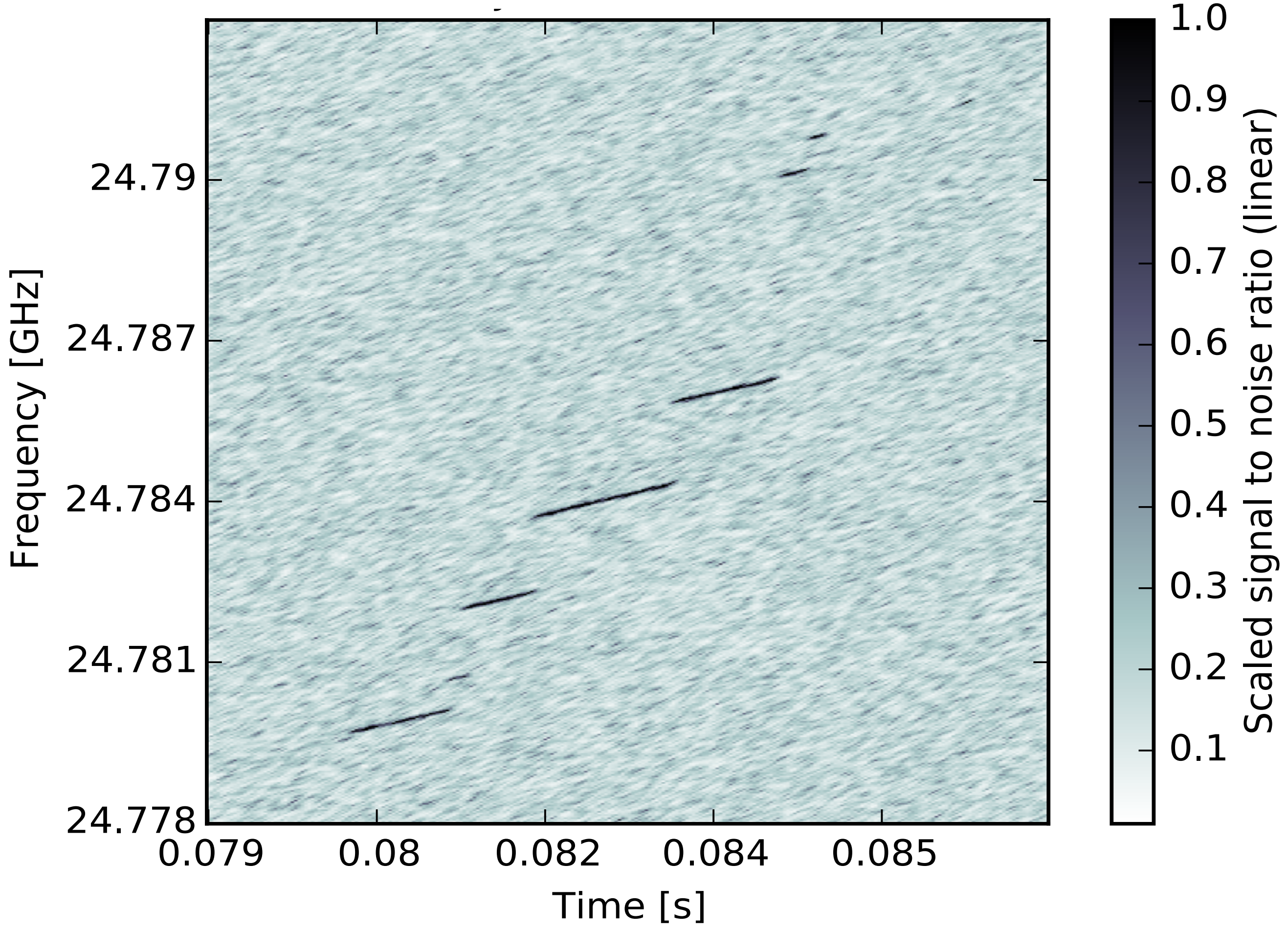
1 fW cyclotron radiation from electron collected



Electron undergoes cyclotron motion in magnetic field

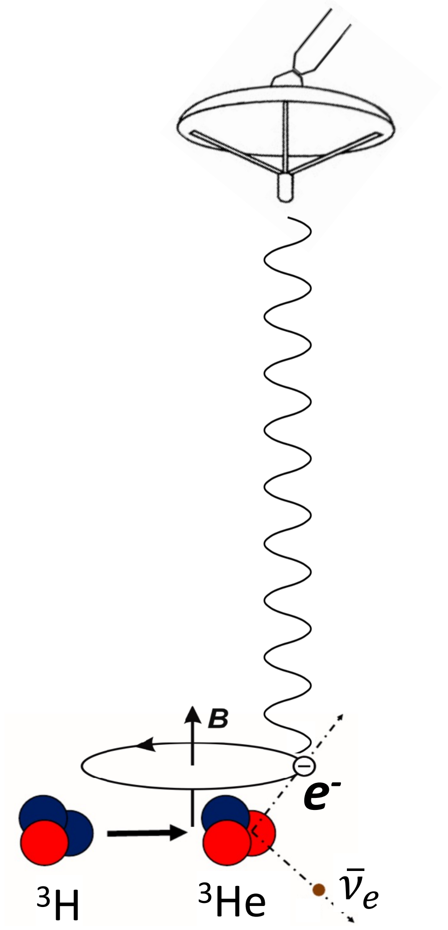
Electron produced in beta decay

Fourier-transform

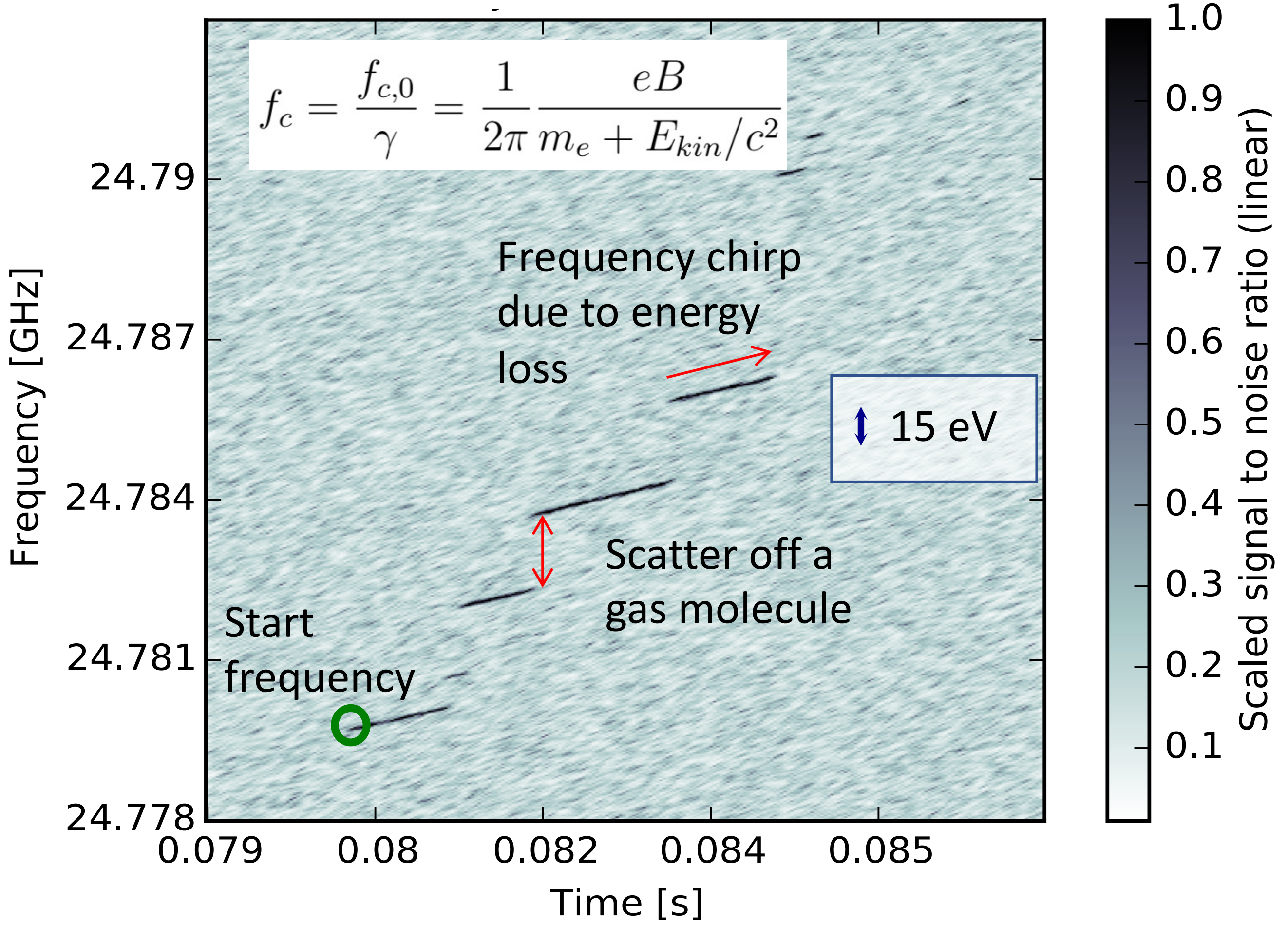


First proposal of CRES: B. Monreal and J. Formaggio, Phys. Rev. D 80, 051301(R) (2009)

A new approach:
Cyclotron Radiation Emission Spectroscopy (CRES)



Fourier-transform



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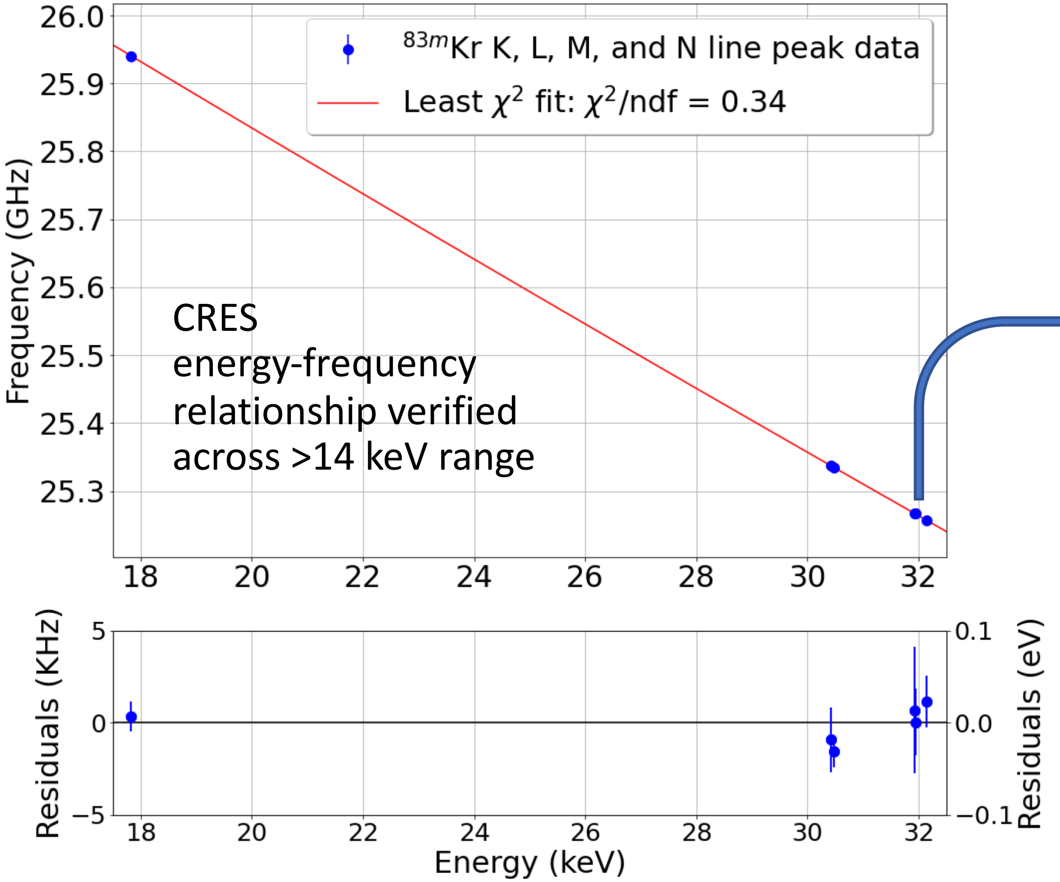
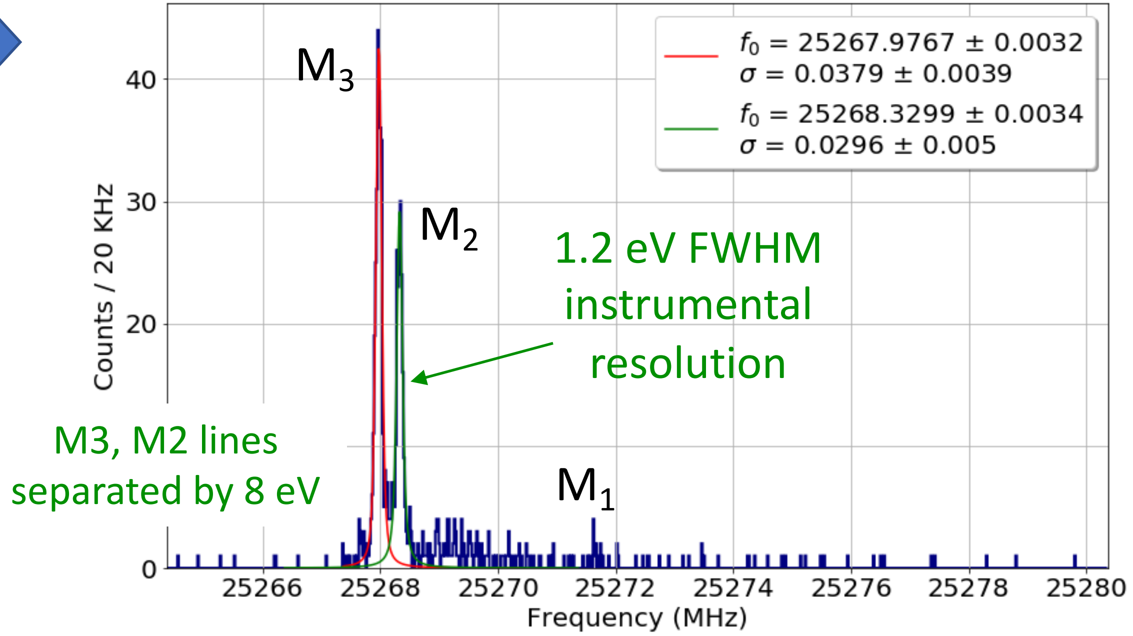
^{83m}Kr measurements reveal eV-scale resolution

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



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



The expanding use of Cyclotron Radiation Emission Spectroscopy (CRES)

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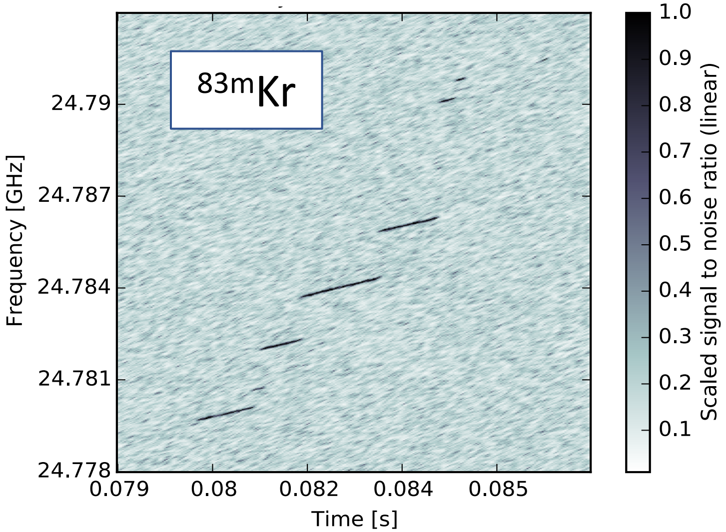
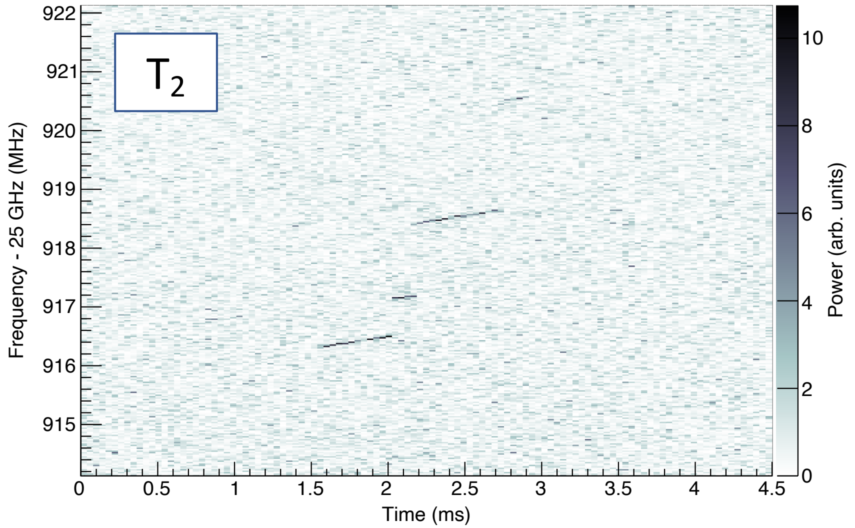
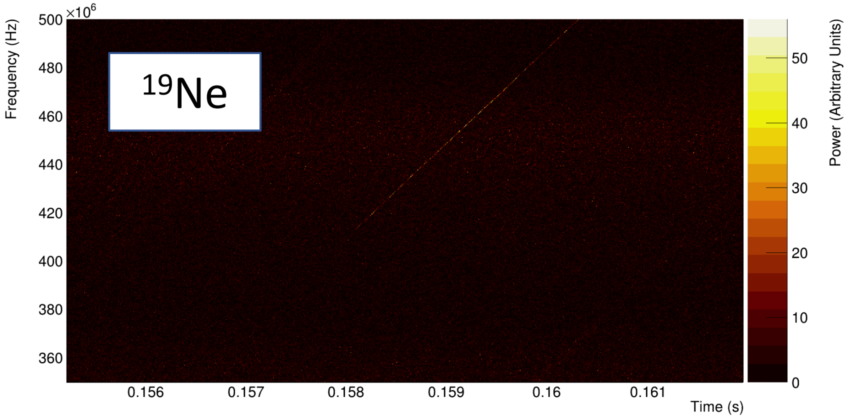
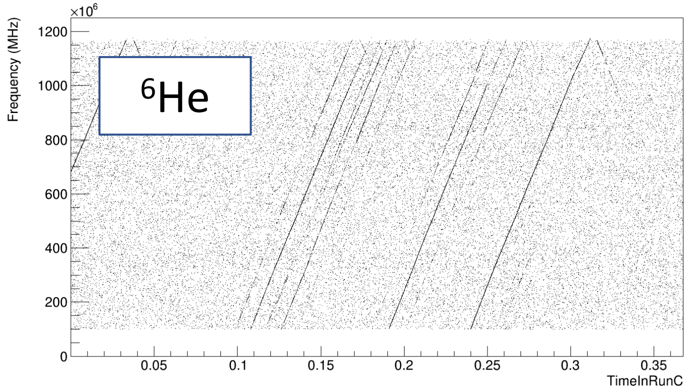


PROJECT 8





6He-CRES



Advantages of CRES for tritium beta spectroscopy

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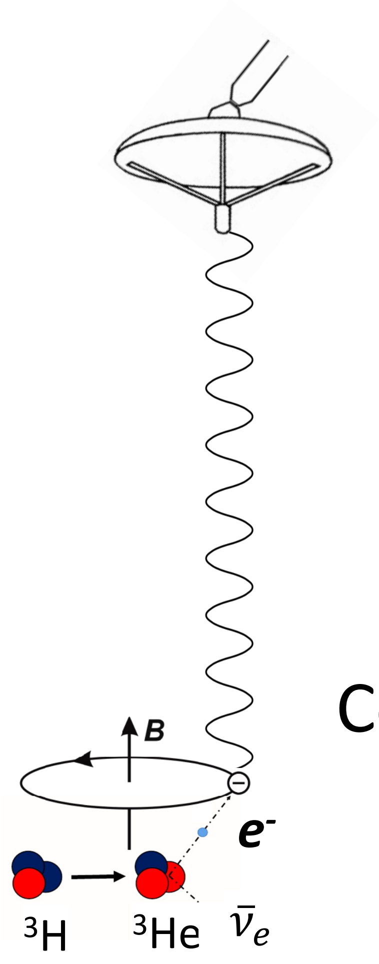
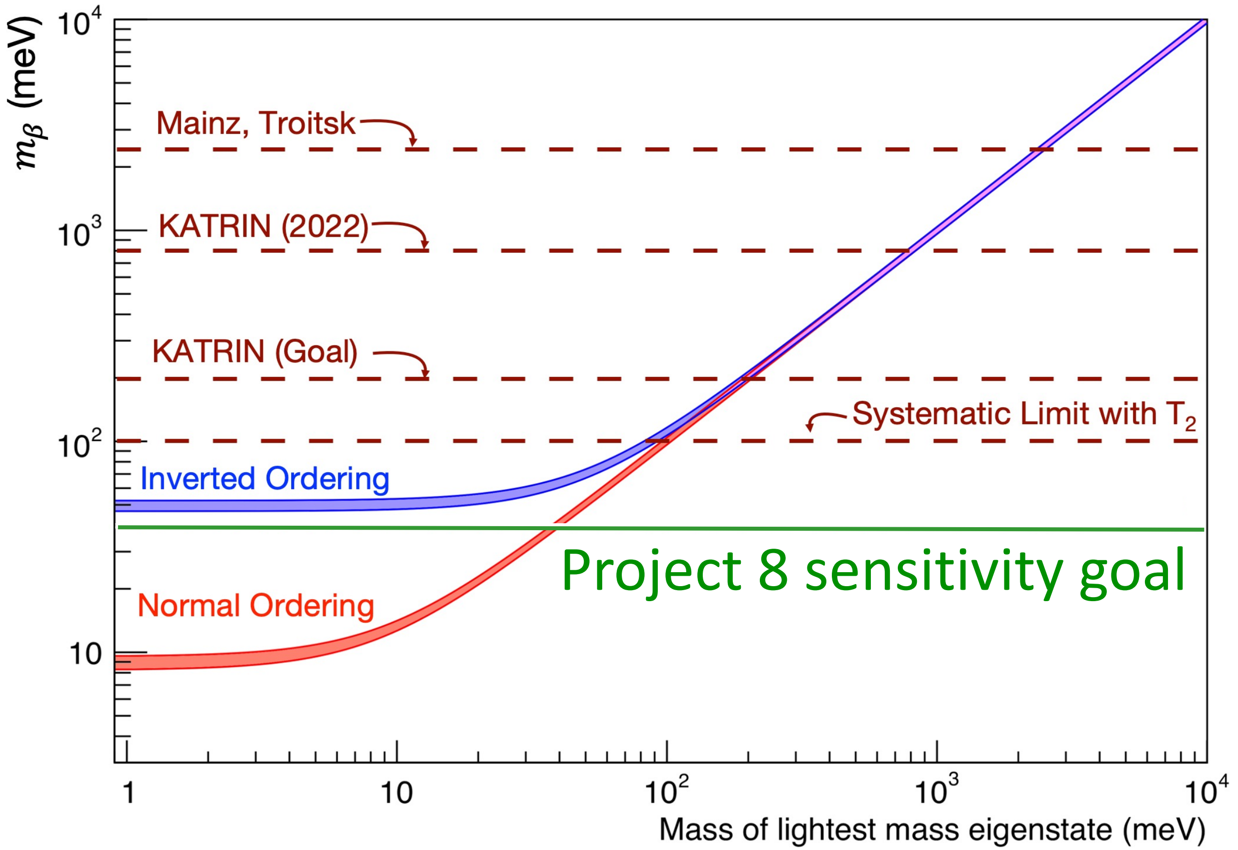


Frequency measurement	➡	High precision
Source is transparent to microwave radiation	➡	No electron transport; volume scaling
Differential spectrometer	➡	Increased statistical efficiency
Compatible with atomic tritium	➡	Avoids T_2 final-state broadening
Low background	➡	More info near endpoint

Project 8: a CRES-based direct neutrino mass experiment



Goals:

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

Phase II: first tritium endpoint measurement

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

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

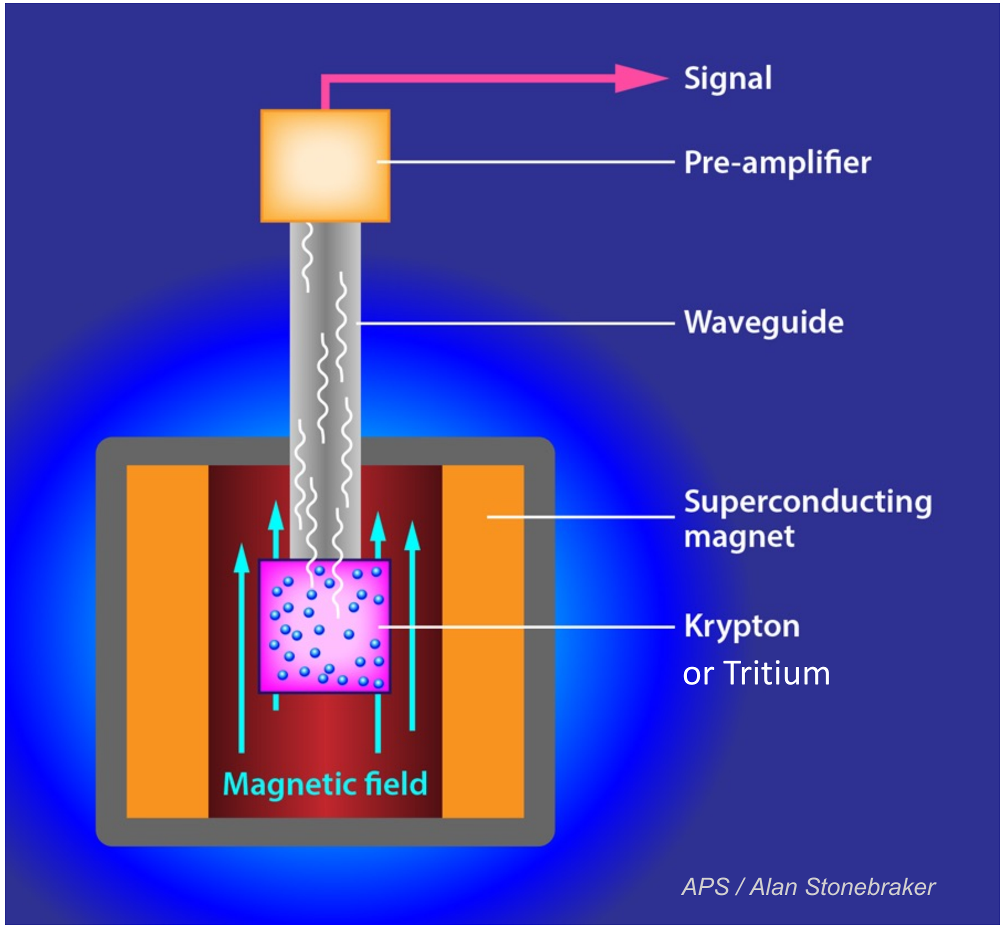
Neutrino 2022

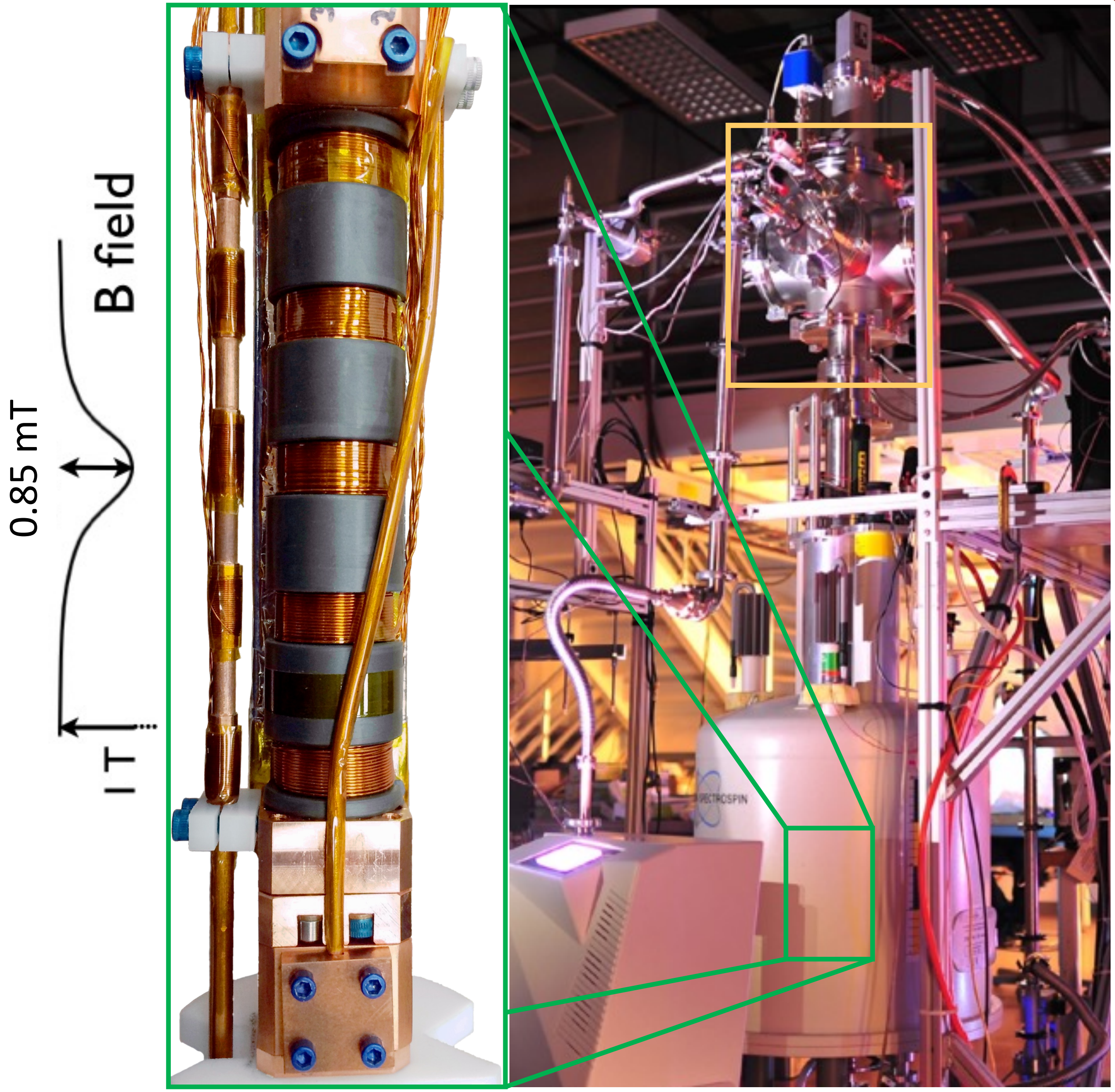
1 mm^3 effective volume

Phase II: Construction | Data-taking | Analysis
→ Systematic & background studies
→ T_2 spectrum and endpoint measurement

- First **tritium spectroscopy** using CRES
  (and first CRES measurement of any **continuous spectrum**)
- First **neutrino mass limit** using CRES
- Demonstration of **high resolution**
- Demonstration of a **zero background** experiment
- Demonstration of **control of systematic effects**

Project 8 Phase II tritium apparatus

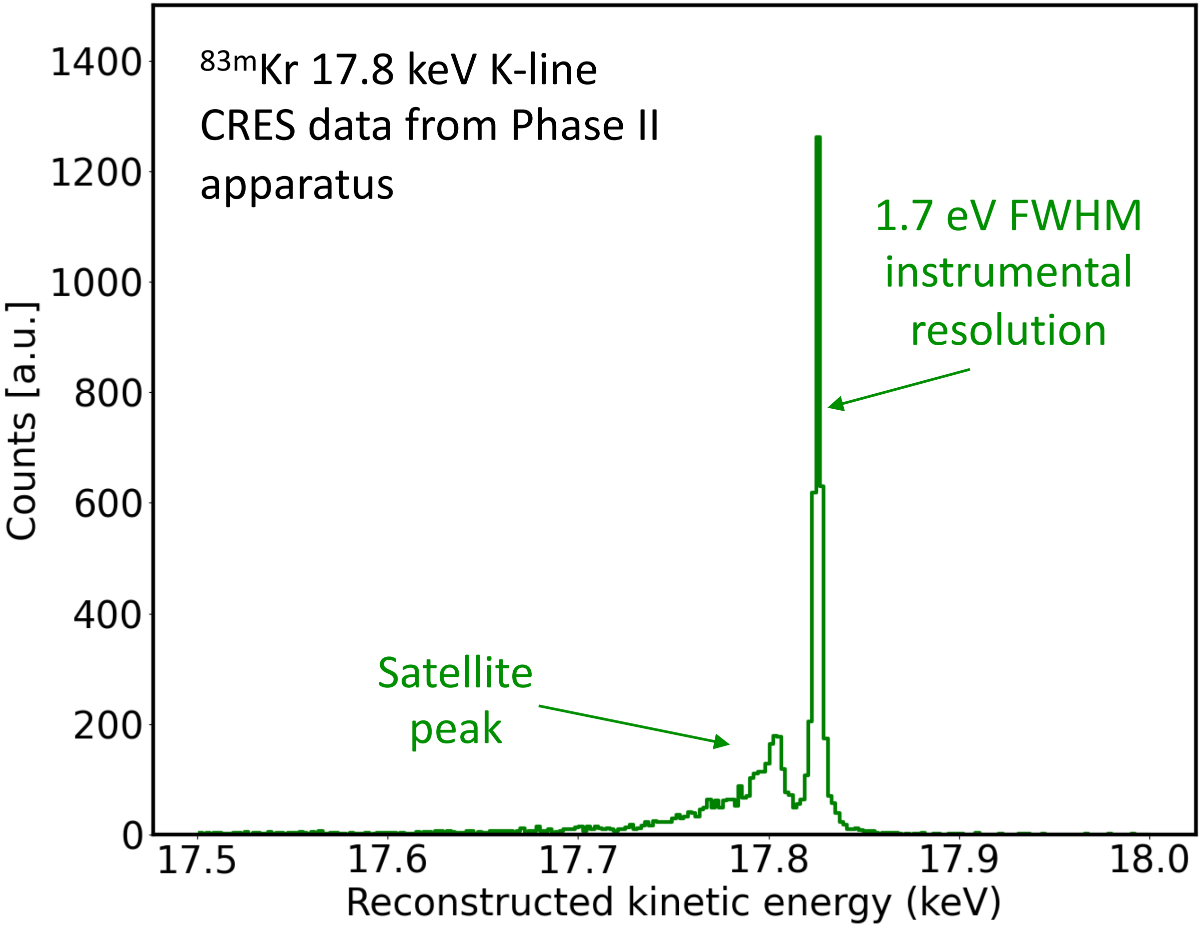




^{83m}Kr measurements: magnetic field calibration

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

- Known K-line energy allows for magnetic field calibration
- 1.7 ± 0.2 FWHM eV instrumental resolution on 2.8 ± 0.1 FWHM eV natural linewidth main peak
- Satellite peak from shake-up/shake-off and scattering from residual gas



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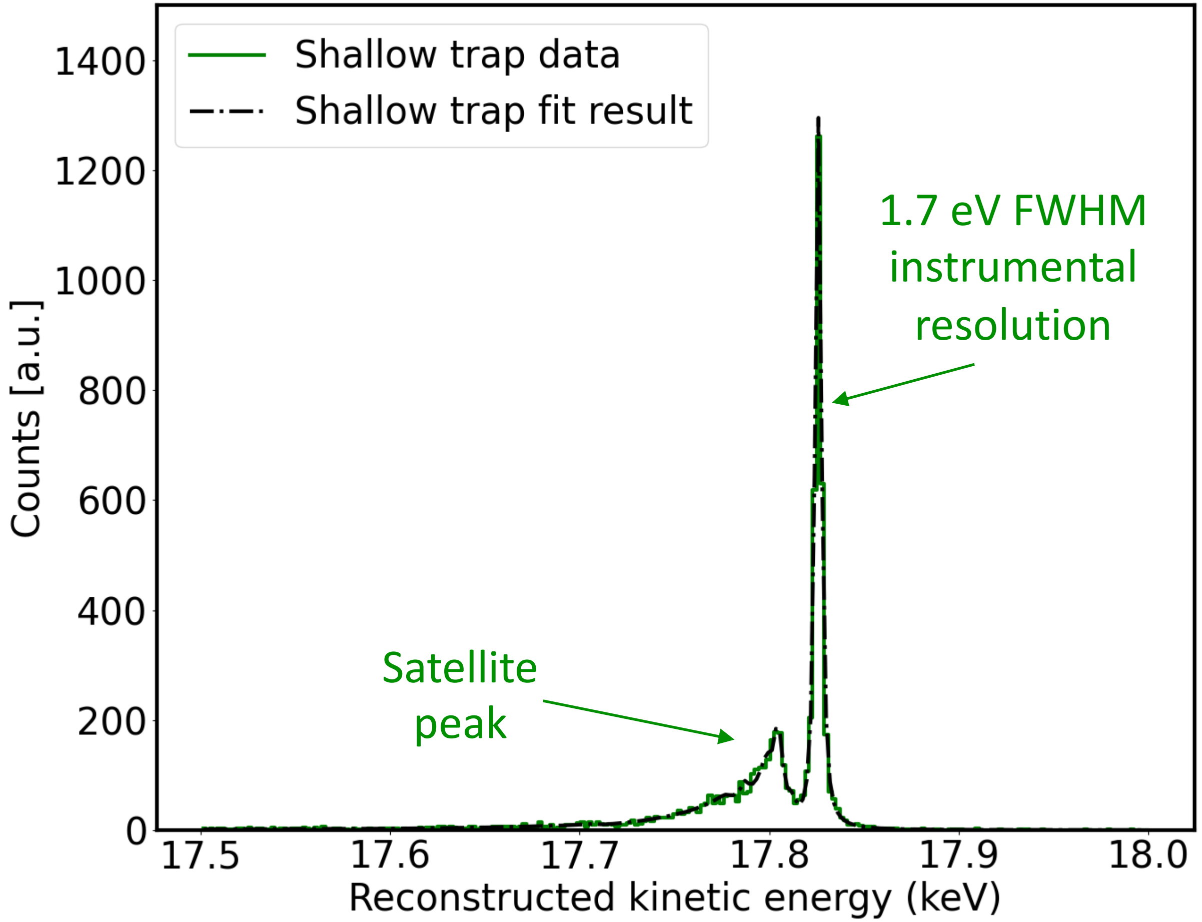
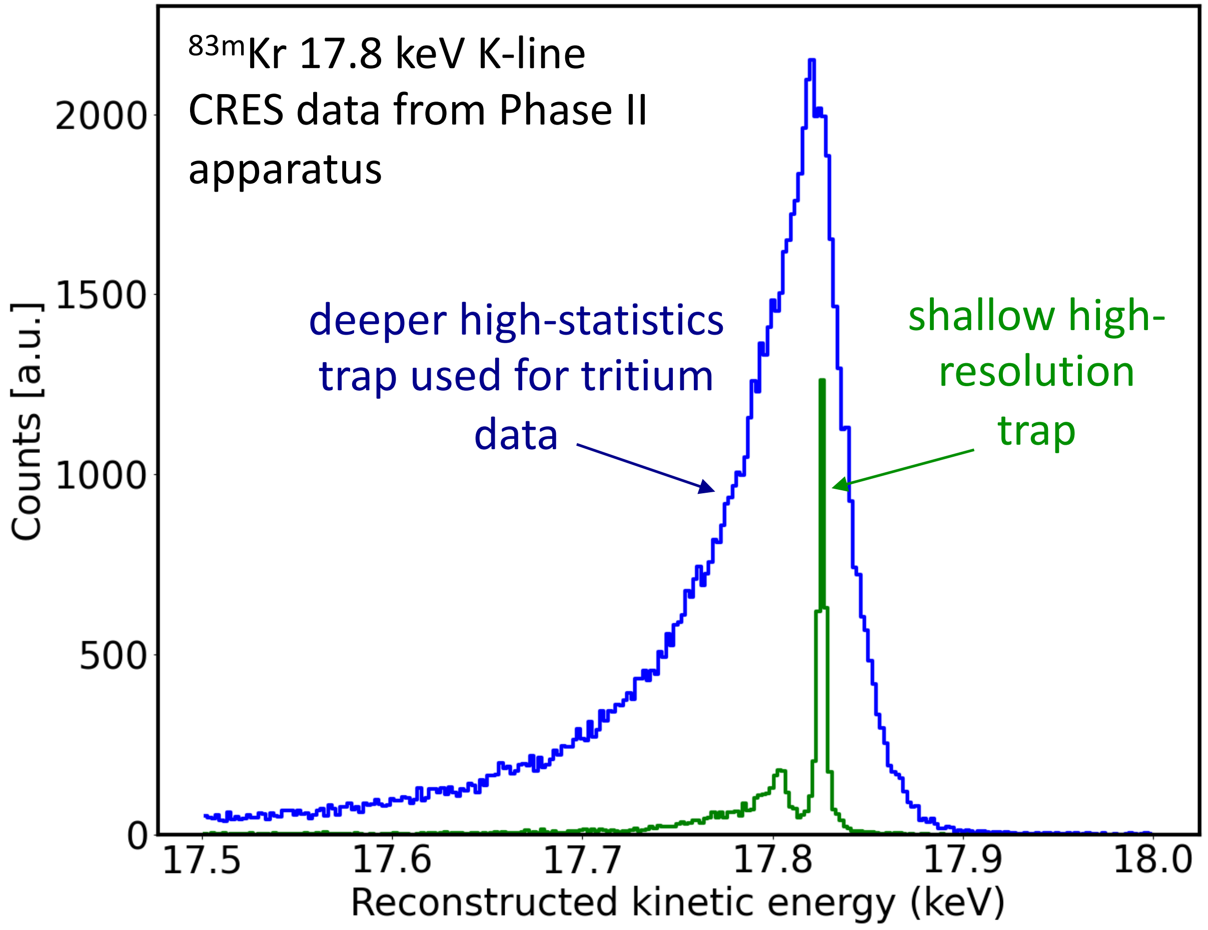
- Satellite peak from shake-up/shake-off and scattering from residual gas
- Detected line shape well-described by model



^{83m}Kr measurements: statistics

- Deeper trap with lower resolution used for tritium data acquisition
  - increase statistics
  - compensate for small 1 mm^3 effective volume



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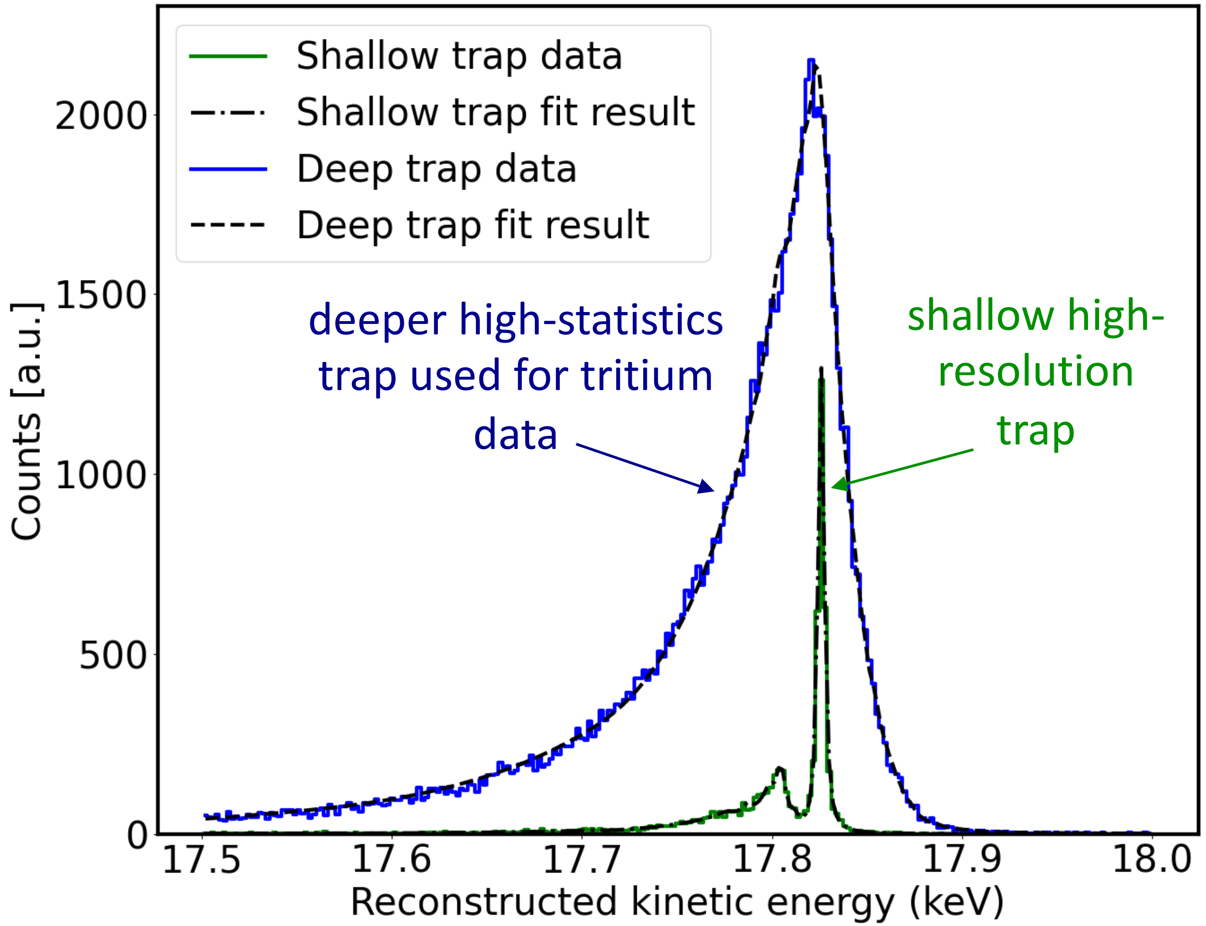

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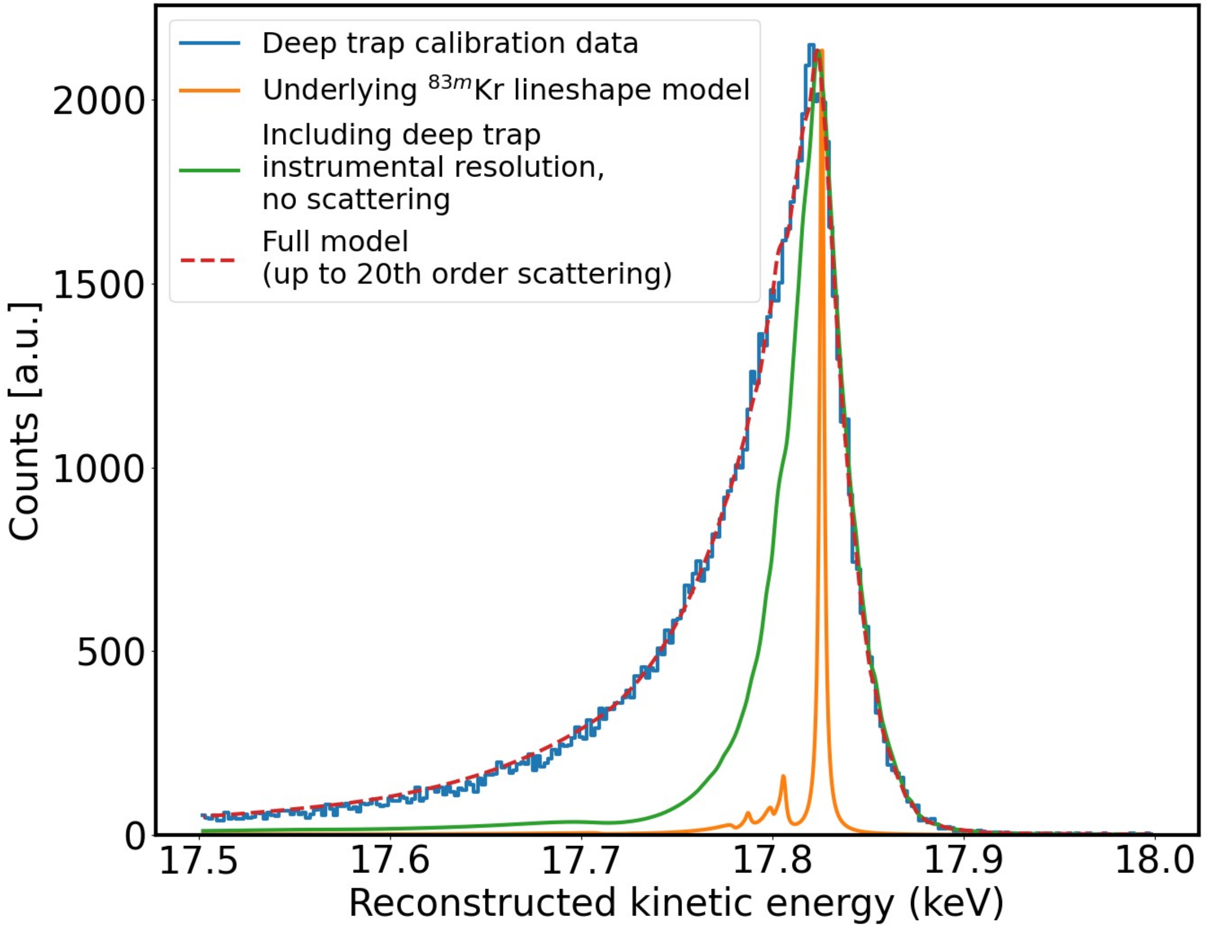
  - Effects from magnetic field inhomogeneity, scattering, and missed tracks are understood



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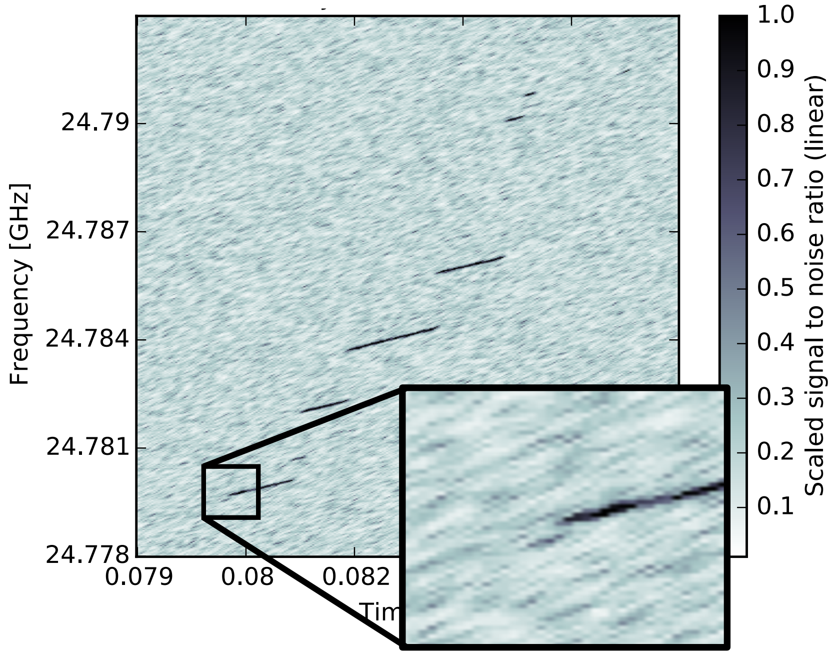

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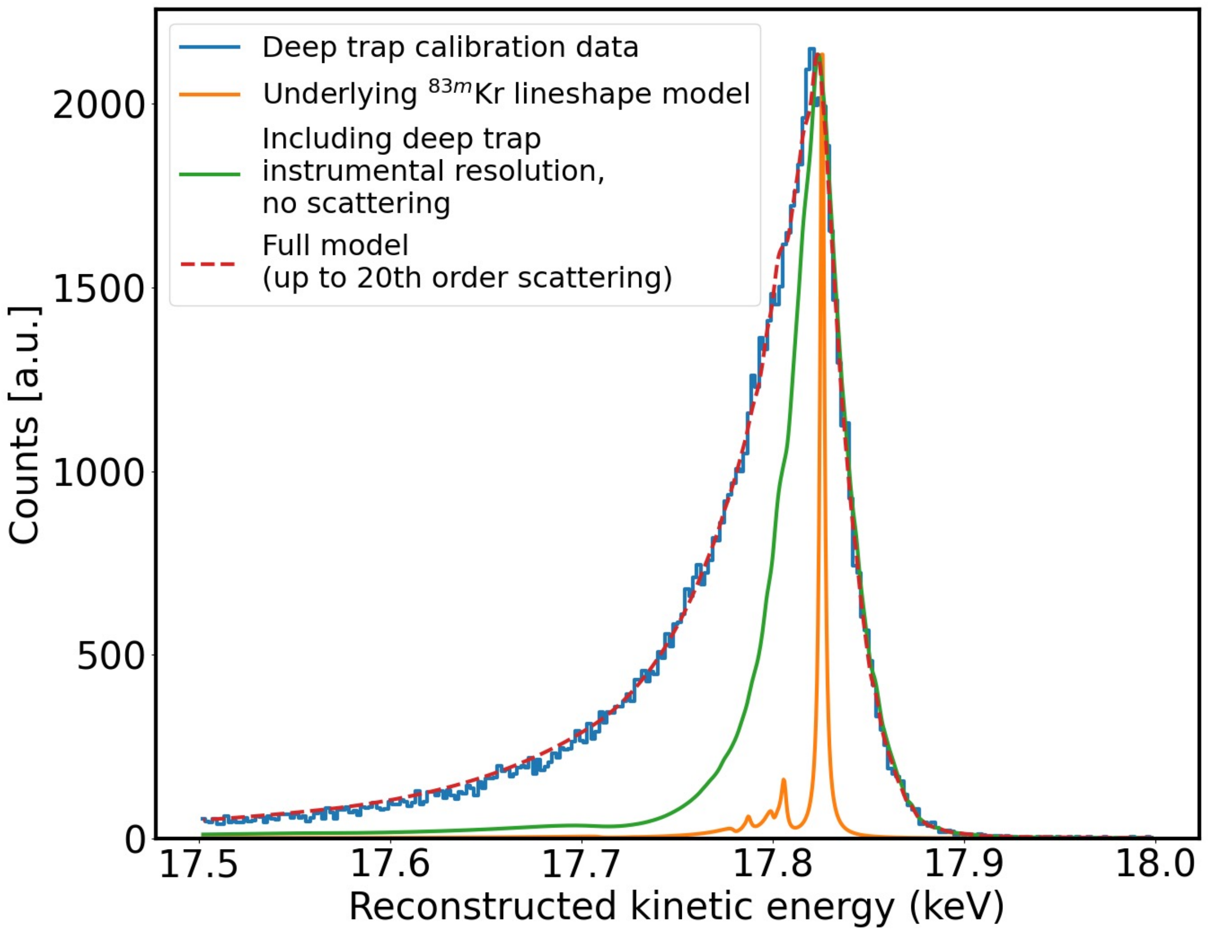
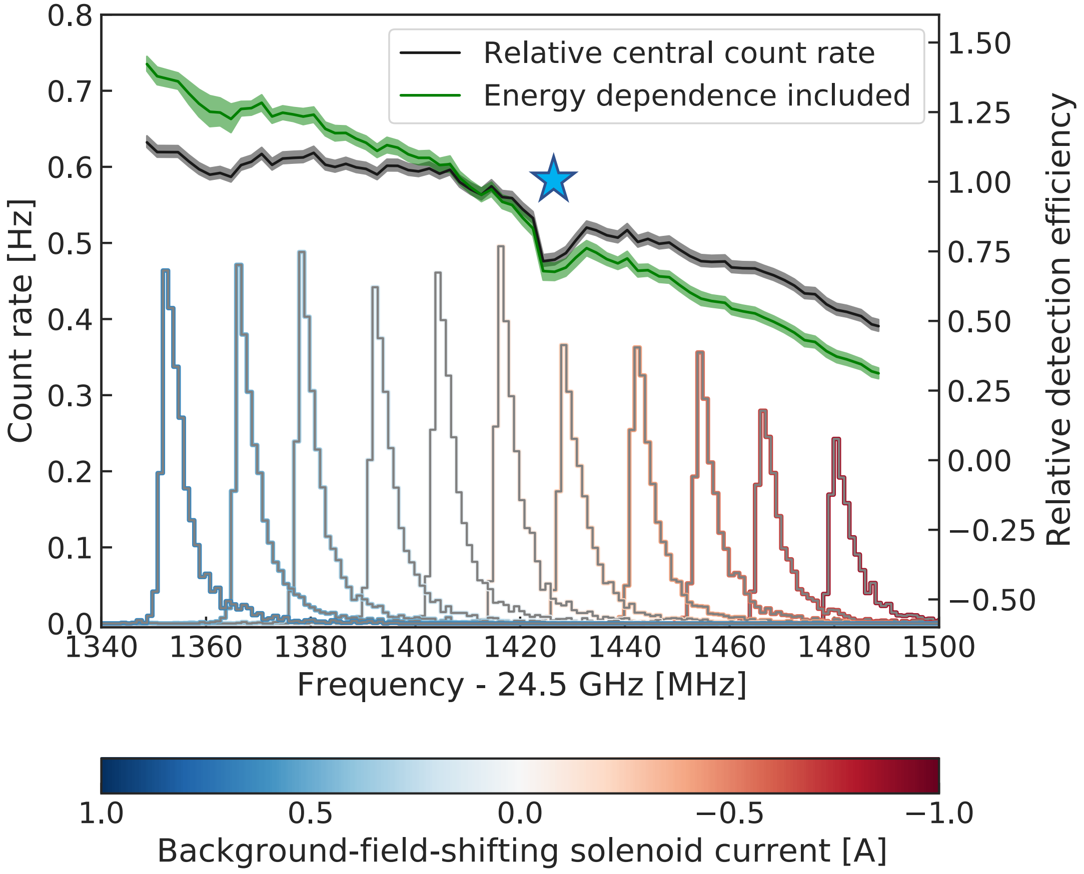


^{83m}Kr measurements: frequency dependence

- Magnetic field swept to study efficiency and scattering effects across frequency ROI
  - Using 17.8 keV Kr line

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

- Direct characterization of significant RF response variation of waveguide
- ★ Notch in efficiency is understood
  - Caused by the interaction with TM01 mode of detection cavity
  - Quantitatively characterized and is accounted for in analysis



PROJECT 8

Phase II tritium spectroscopy results

- T_2 endpoint measurement in agreement with literature
- First neutrino mass measurement using CRES
- Extremely low background rate—no events above endpoint!

T_2 endpoint

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

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

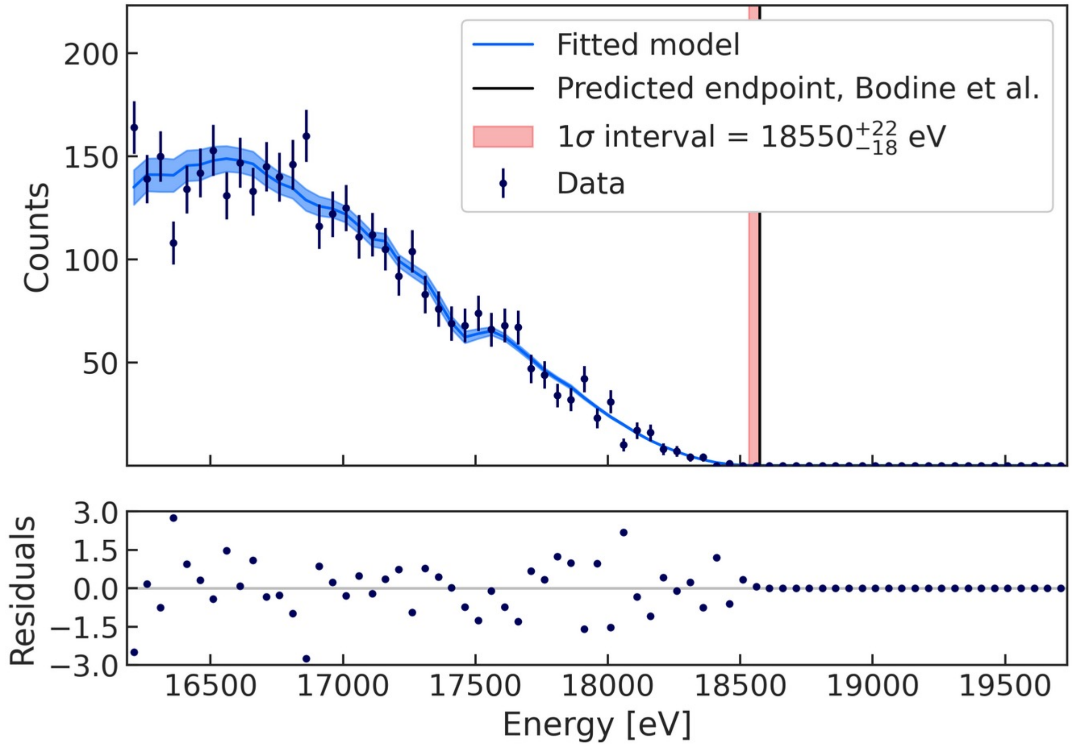
Neutrino mass

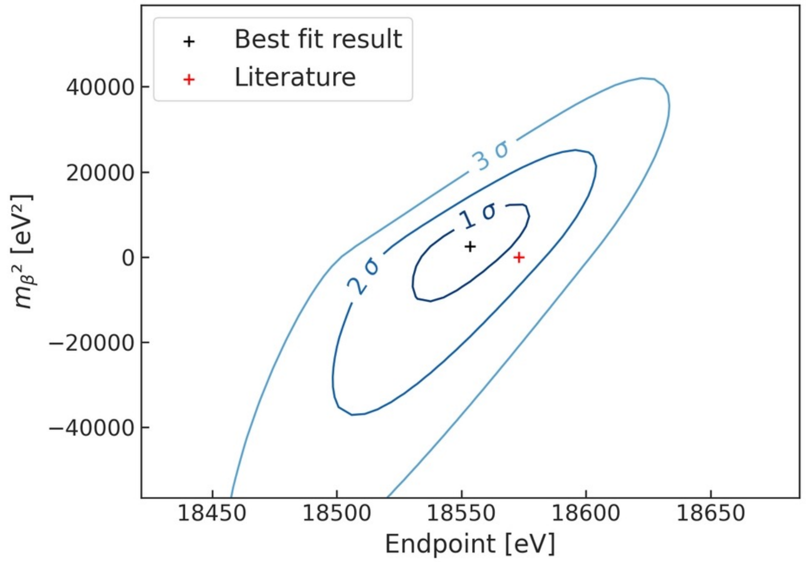
Frequentist: $\lesssim 178$ eV/c² (90% C.L.)

Bayesian: $\lesssim 169$ eV/c² (90% C.L.)

Background rate

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

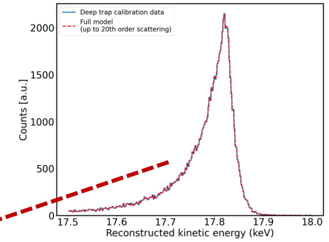


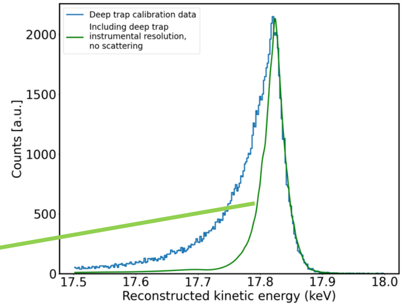


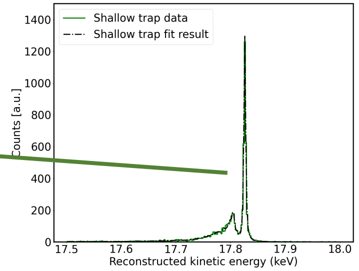
Phase II tritium results: uncertainties

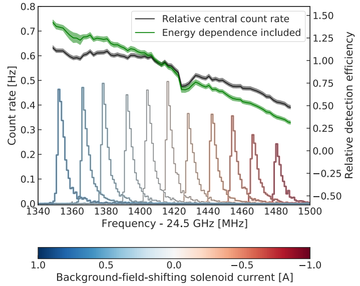
- Statistics-limited; demonstrates understanding and control of systematics
- We have paths to improving all these sources of uncertainty

Source of uncertainty		Contribution to endpoint uncertainty (eV)
Statistics		**± 17**
Systematics		**+13/-9**
	Scattering	±5
	Magnetic field broadening	±4
	Magnetic field fit from ^{83m}Kr data	±4
	Frequency-dependence of detector response	+11, -6

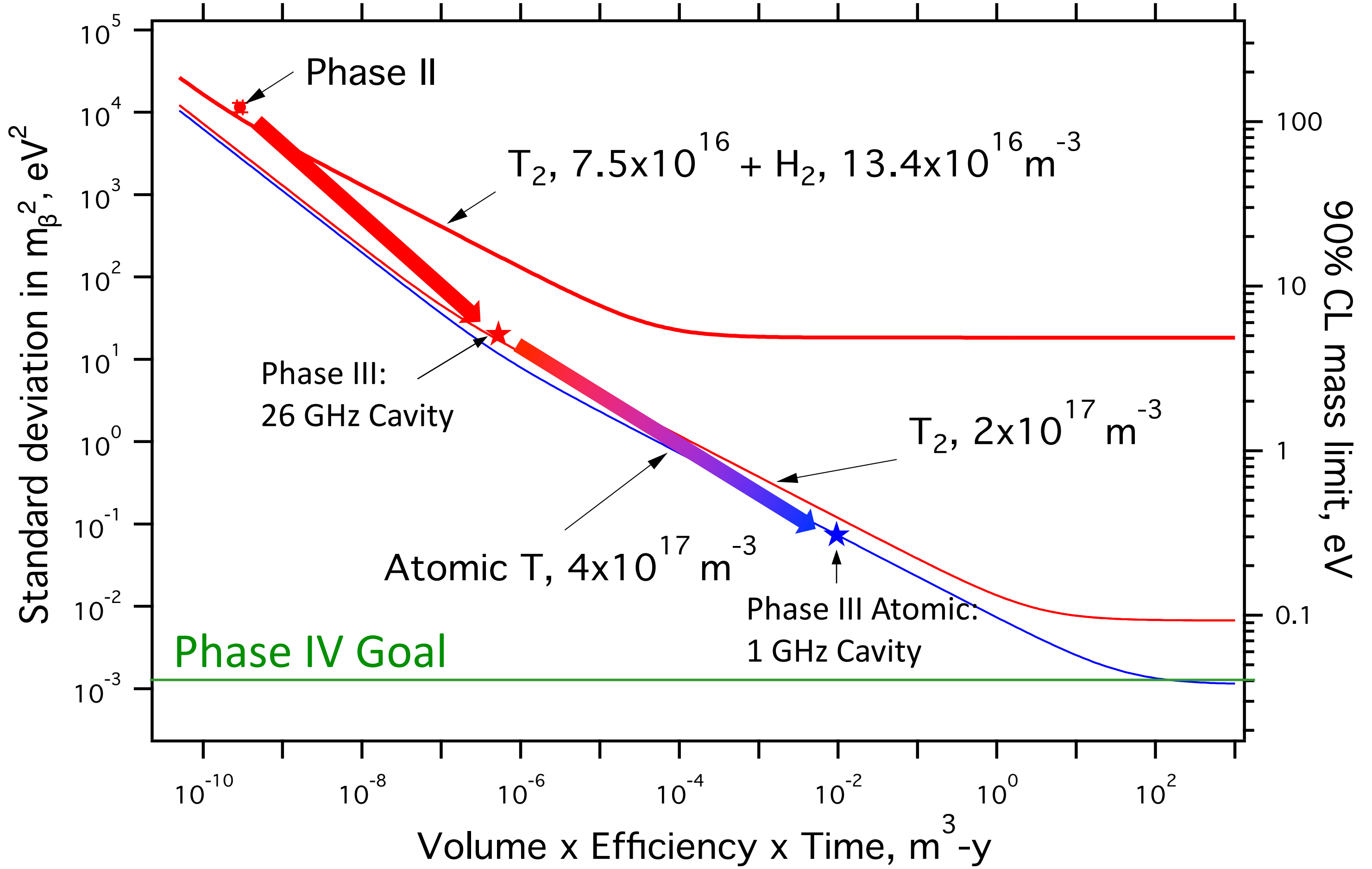








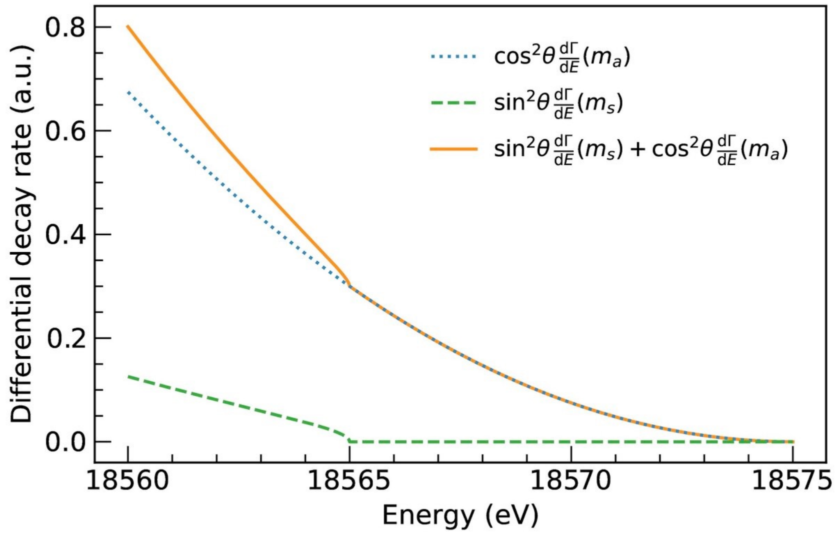
The path to higher sensitivity

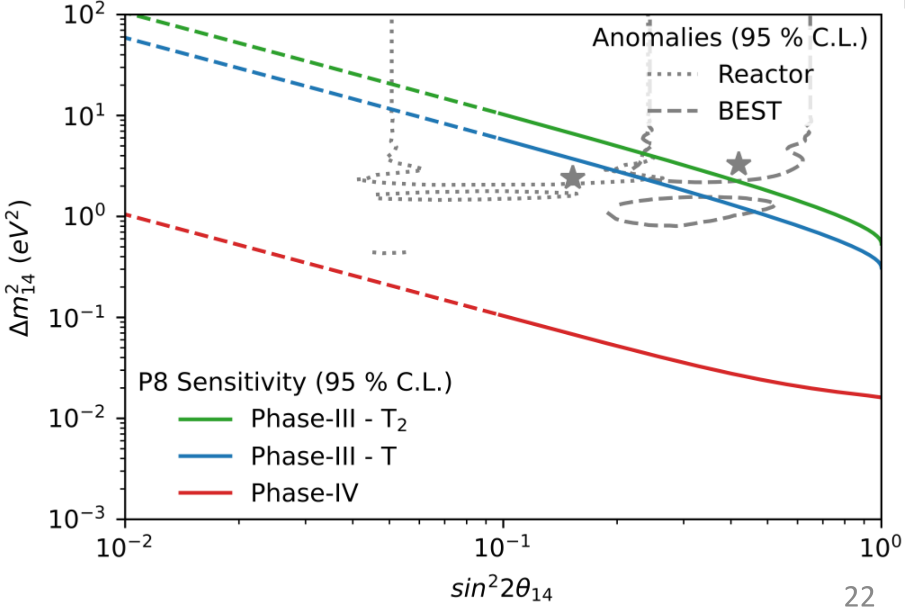


- Improve control of systematics, field homogeneity, scattering effects
- Increase volume
- Higher density
  - Shorter tracks -> need to improve SNR
- Develop atomic source
  - Overcome systematic of molecular final states

Project 8's sensitivity to sterile neutrinos

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





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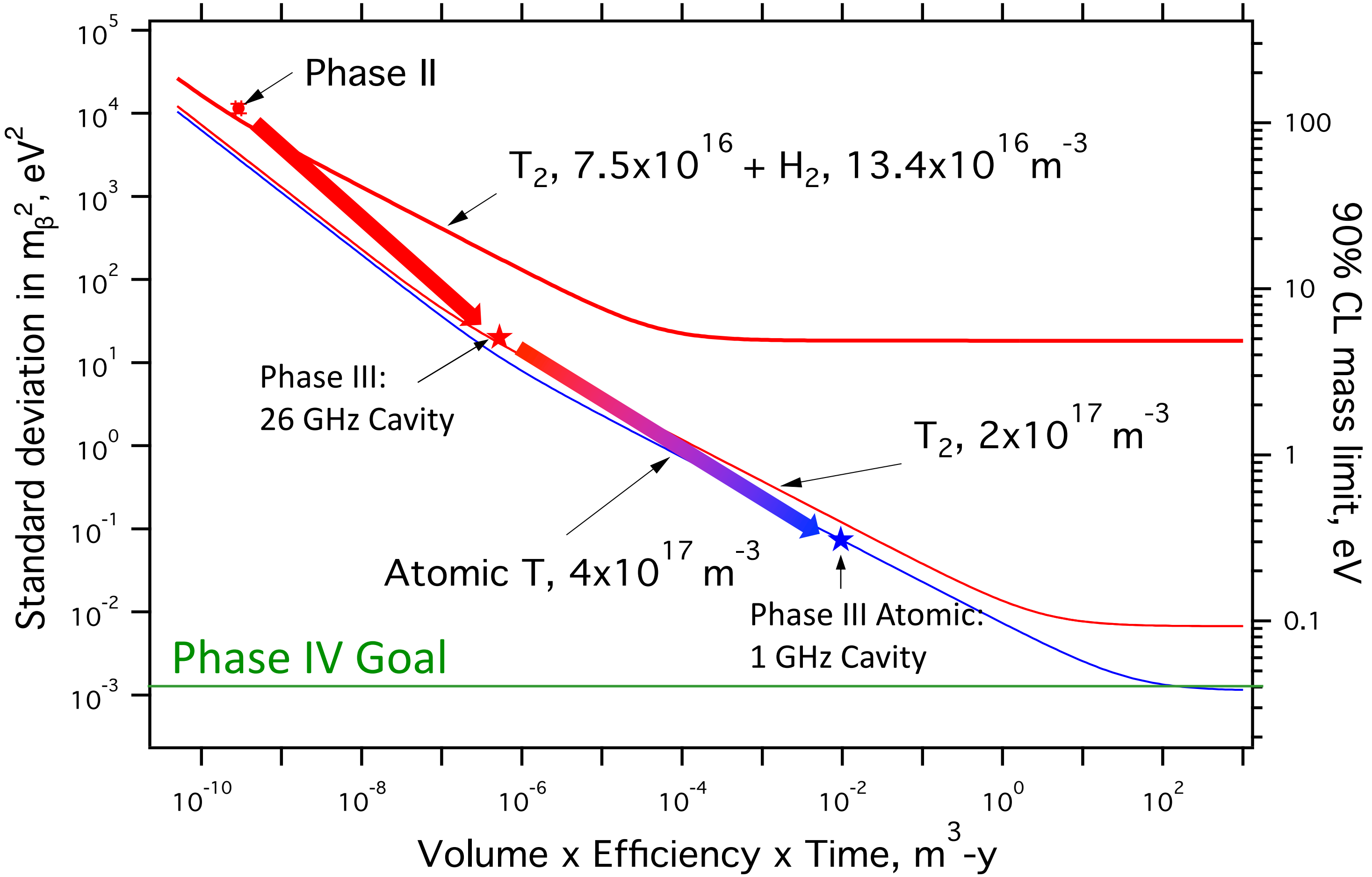

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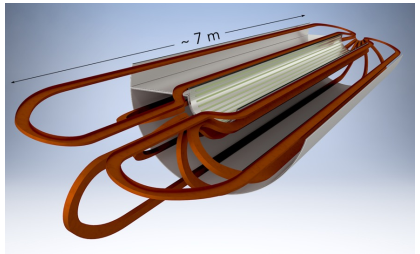
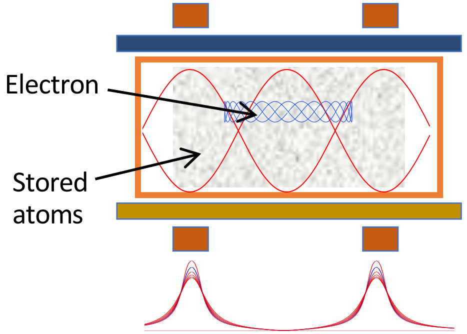
Increasing sensitivity in Phase III

Step 1:
~Two-pronged, 5-year R&D program in critical technology demonstrations

Atomic Trap Demonstrator



Large Volume (Cavity) CRES Demonstrator



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

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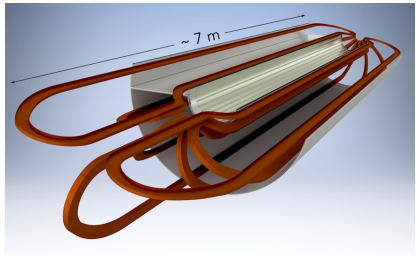

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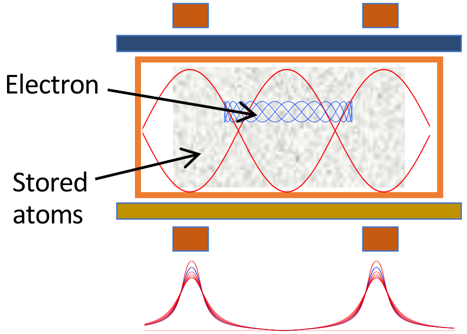
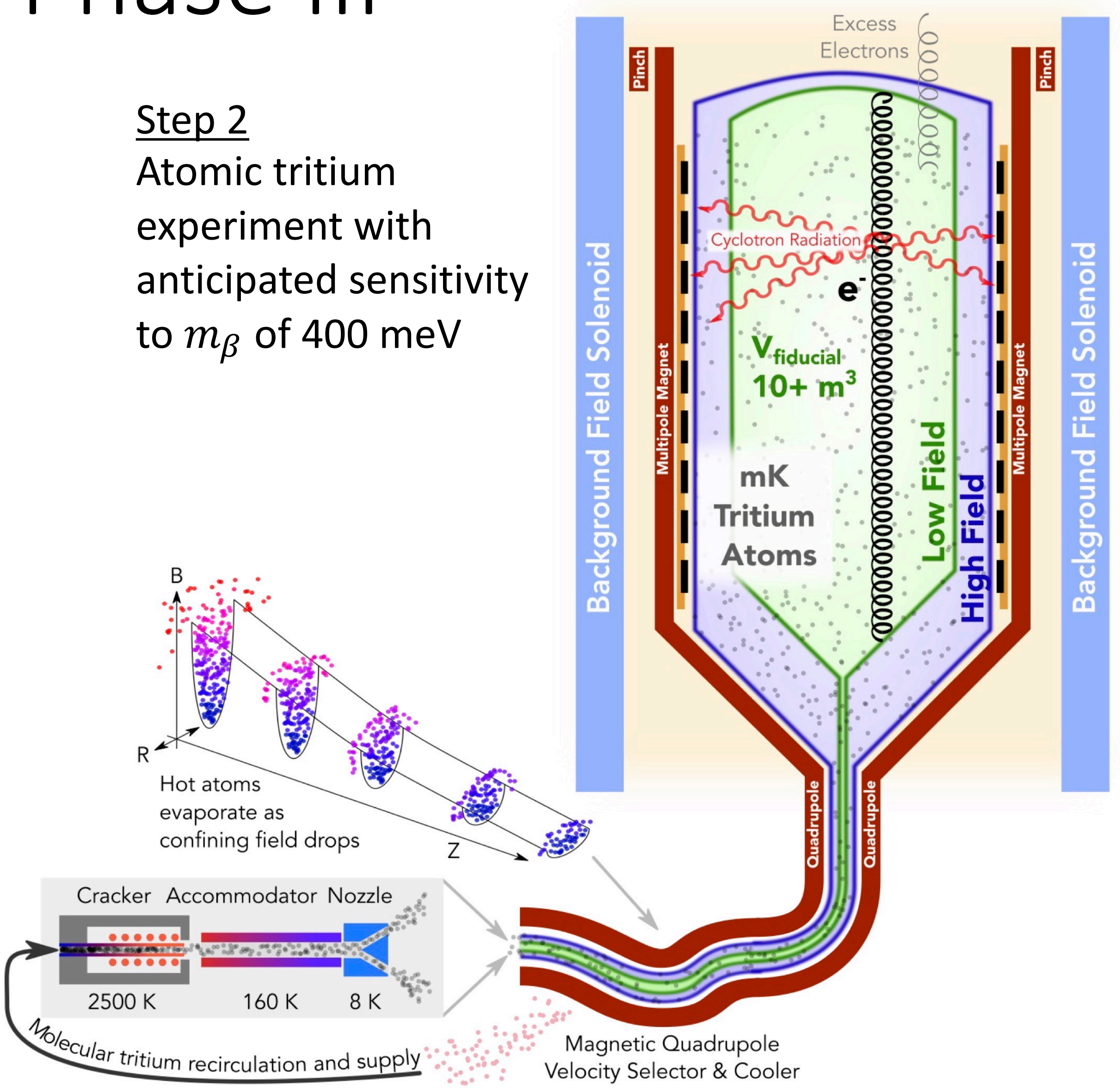


See A. Ashtari Esfahani *et al.* arXiv:2203.07349

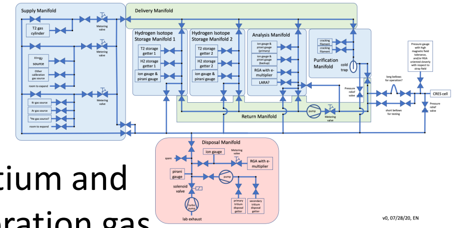
Step 2

Atomic tritium experiment with anticipated sensitivity to m_β of 400 meV

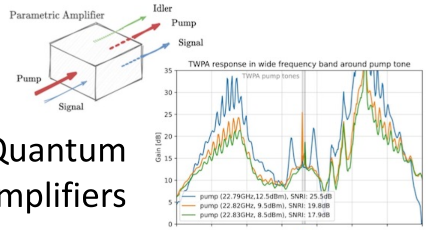


Research areas

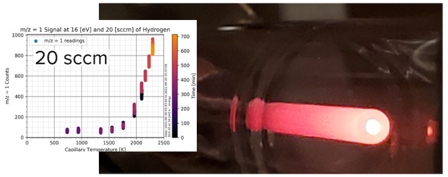
Tritium and calibration gas handling



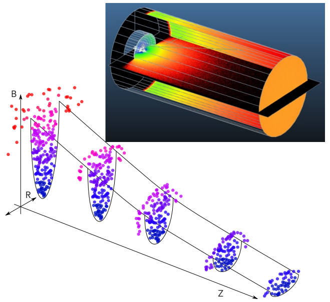
Quantum amplifiers



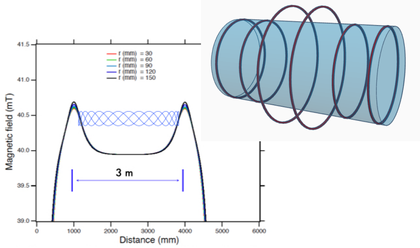
Molecule cracking



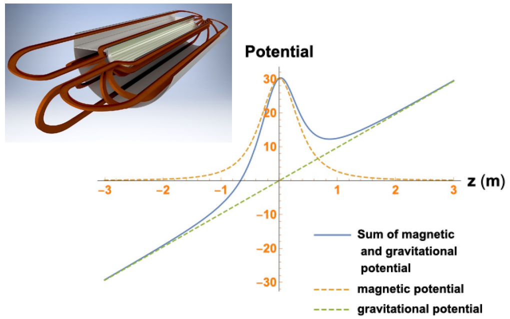
Cooling



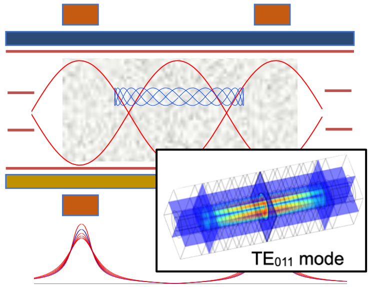
Electron trap design



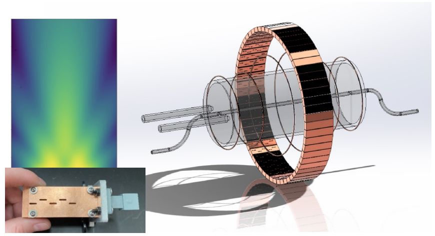
Neutral atom trapping



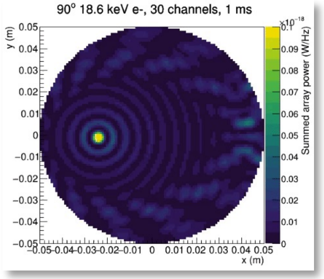
Cavity design



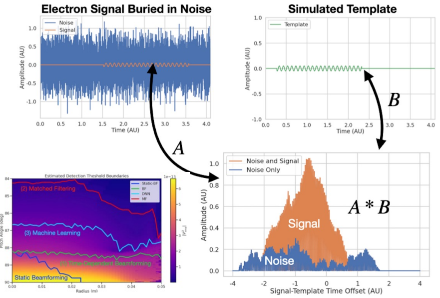
Phased antenna array design



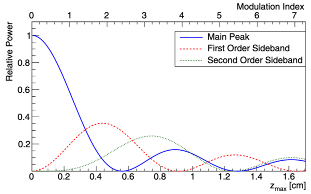
Simulation software development



Matched filtering event reconstruction

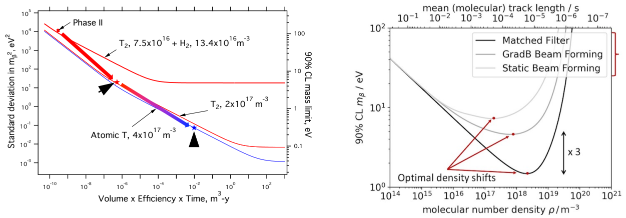


Phenomenology of CRES

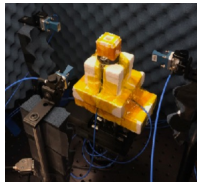


Electron gun for calibration

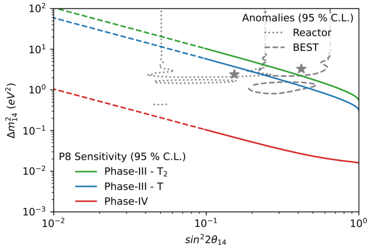
Sensitivity to m_β



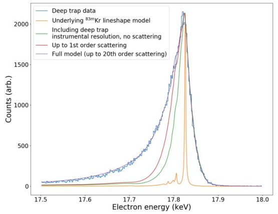
Synthetic CRES antenna



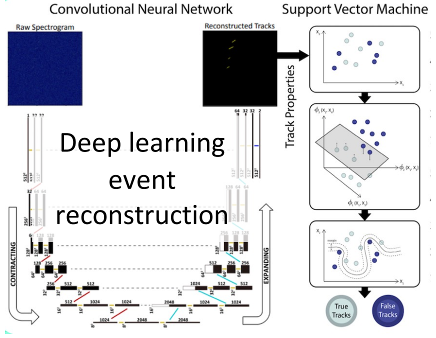
Sensitivity to steriles



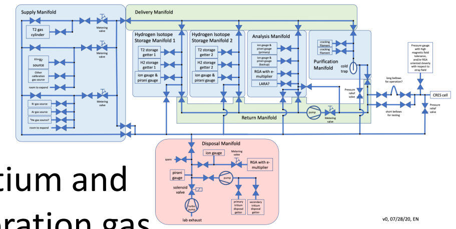
Spectrum analysis



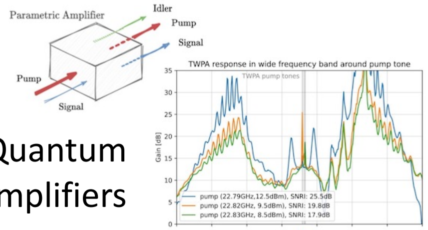
Deep learning event reconstruction



Research areas

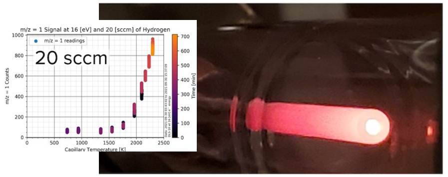


Tritium and calibration gas handling

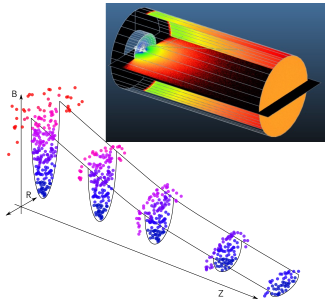


Quantum amplifiers

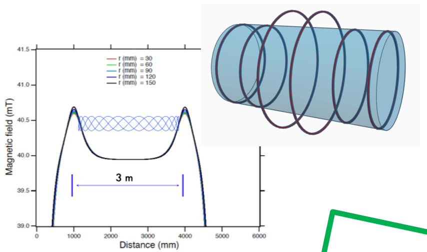
Molecule cracking



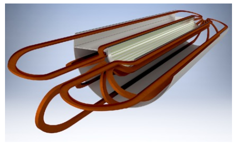
Cooling

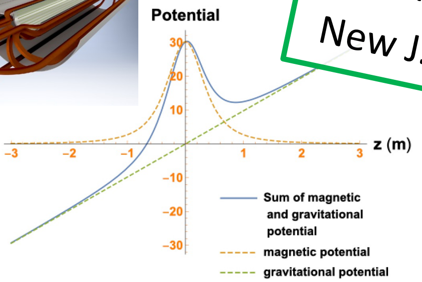


Electron trap design

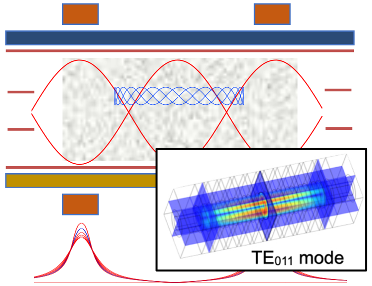


Neutral atom trapping

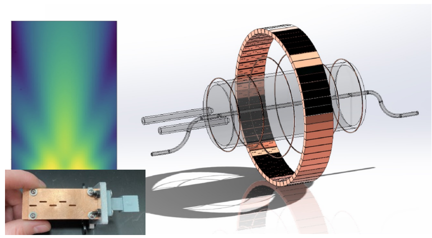




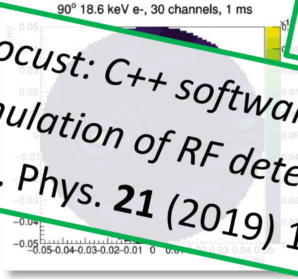
Cavity design



Phased antenna array design

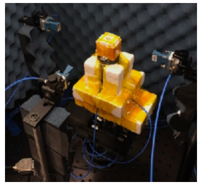


Simulation software development



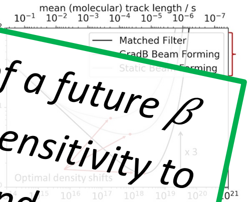
Electron gun for calibration

Synthetic CRES antenna

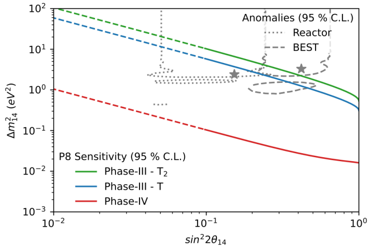


Phenomenology of CRES

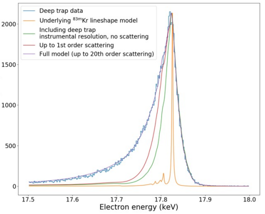
Sensitivity to m_β



Sensitivity to steriles



Spectrum analysis



Event reconstruction algorithms (e.g. matched filtering)

Deep learning event reconstruction

Electron radiated power in cyclotron radiation emission spectroscopy
Phys. Rev. C. **99** (2019) 055501

Bayesian analysis of a future β decay experiment's sensitivity to neutrino mass scale and ordering
Phys. Rev. C. **103** (2021) 065501

Viterbi decoding of CRES signals in Project 8
New J. Phys. **24** (2022) 053013

Cyclotron radiation emission spectroscopy signal classification with machine learning in project 8
New J. Phys. **22** (2020) 033004

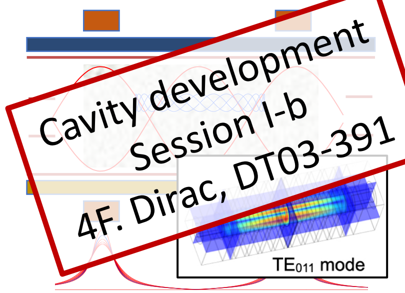
Locust: C++ software for simulation of RF detection
New J. Phys. **21** (2019) 113051

PROJECT 8

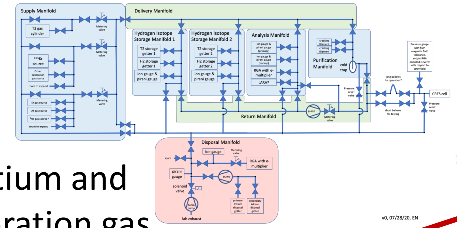
Research areas

Learn more at Project 8's posters!

Cavity design



Cavity development
Session I-b
4F. Dirac, DT03-391

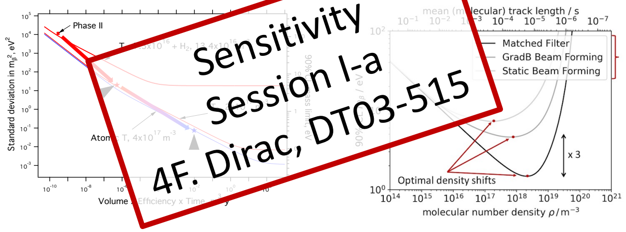


Tritium and calibration gas handling

Quantum-based amplification
Session III-b
4F. Majorana, MT16-698

Electron gun for calibration

Sensitivity to m_β

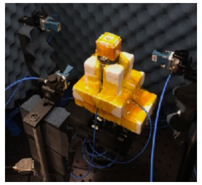


Sensitivity
Session I-a
4F. Dirac, DT03-515

Phased antenna array design

Antenna development
Session I-b
4F. Dirac, DT03-666

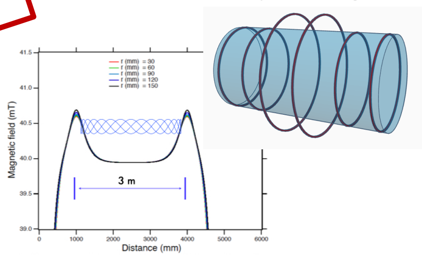
Synthetic CRES antenna



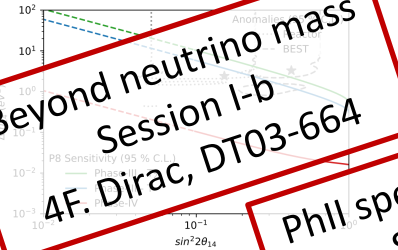
Molecule cracking

Atom source development
Session I-a
4F. Dirac, DT03-780

Electron trap design

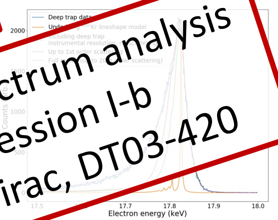


Sensitivity to steriles



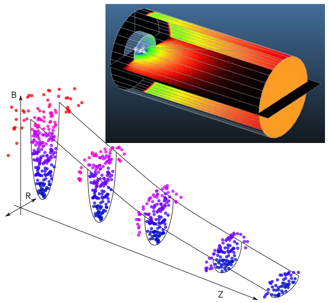
Beyond neutrino mass
Session I-b
4F. Dirac, DT03-664

Spectrum analysis

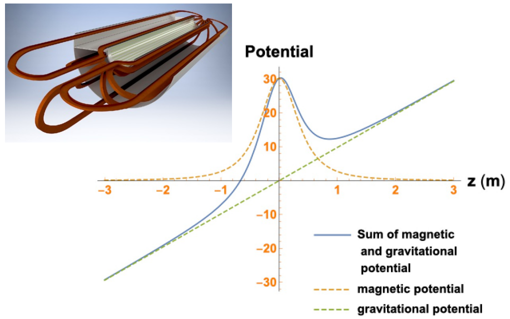


PhII spectrum analysis
Session I-b
4F. Dirac, DT03-420

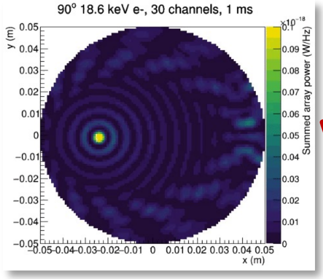
Cooling



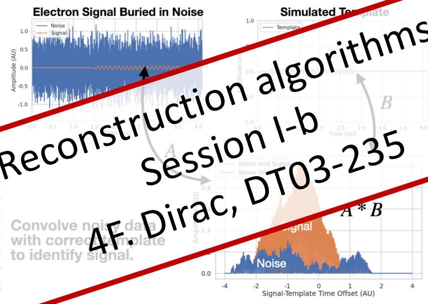
Neutral atom trapping



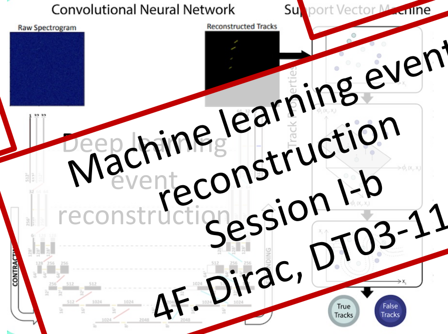
Simulation software development



Event reconstruction algorithms (*e.g.*, matched filtering)

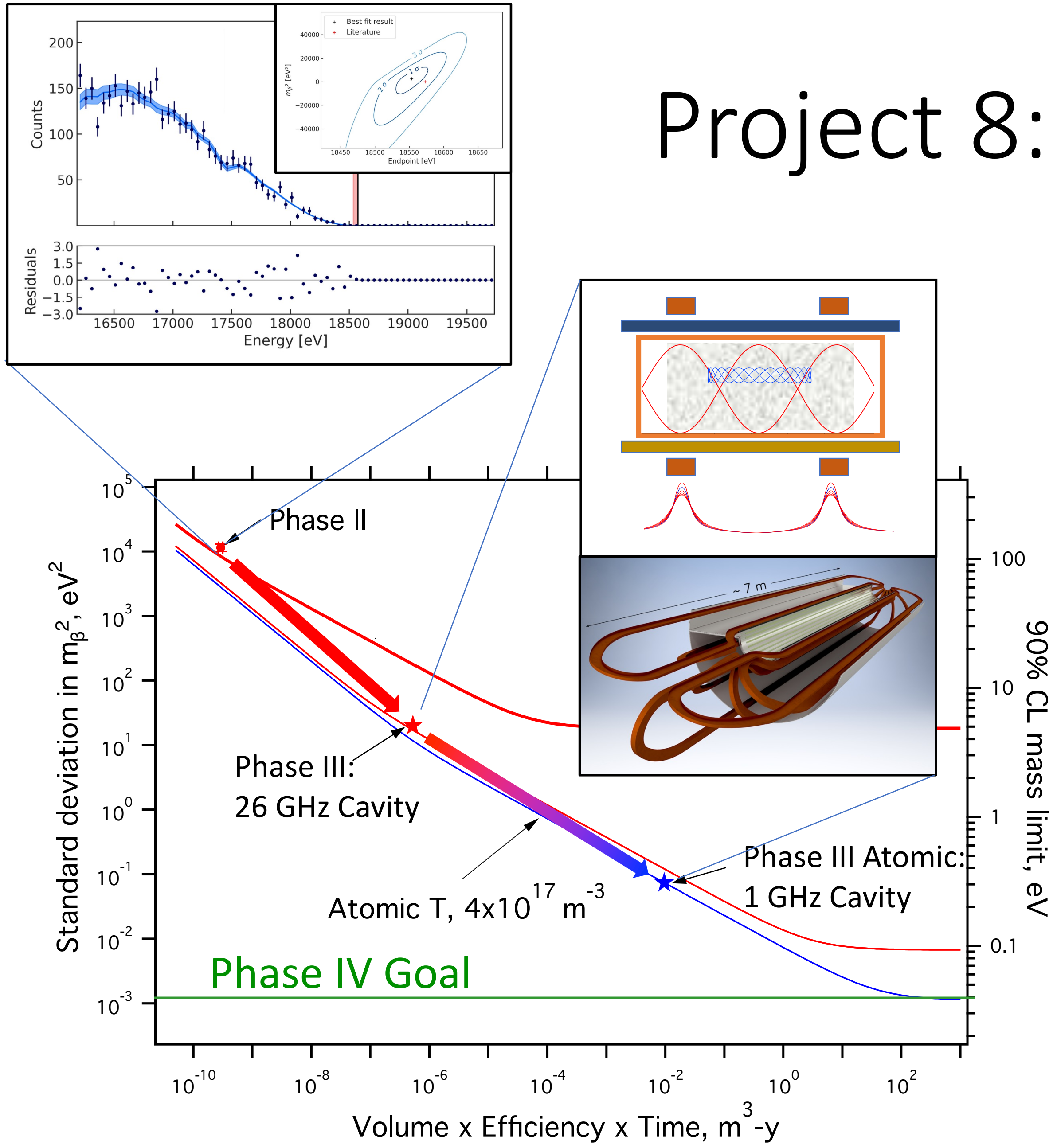


Reconstruction algorithms
Session I-b
4F. Dirac, DT03-235



Machine learning event reconstruction
Session I-b
4F. Dirac, DT03-116

Project 8: results and prospects



- CRES established as promising technique for next generation neutrino mass experiment
  - Also other physics applications
- Phase II demonstrated background-free operation, control of systematics, first CRES m_β limit
- Work ongoing toward key technology demonstrations on the path to the 40 meV experiment

The Project 8 collaboration

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

Harvard-Smithsonian Center for Astrophysics
- Sheperd Doeleman, Jonathan Weintroub, André Young

Indiana University
- Walter Pettus

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

Karlsruher Institut für Technologie
- Thomas Thümmler

Lawrence Livermore National Laboratory
- Kareem Kazkaz

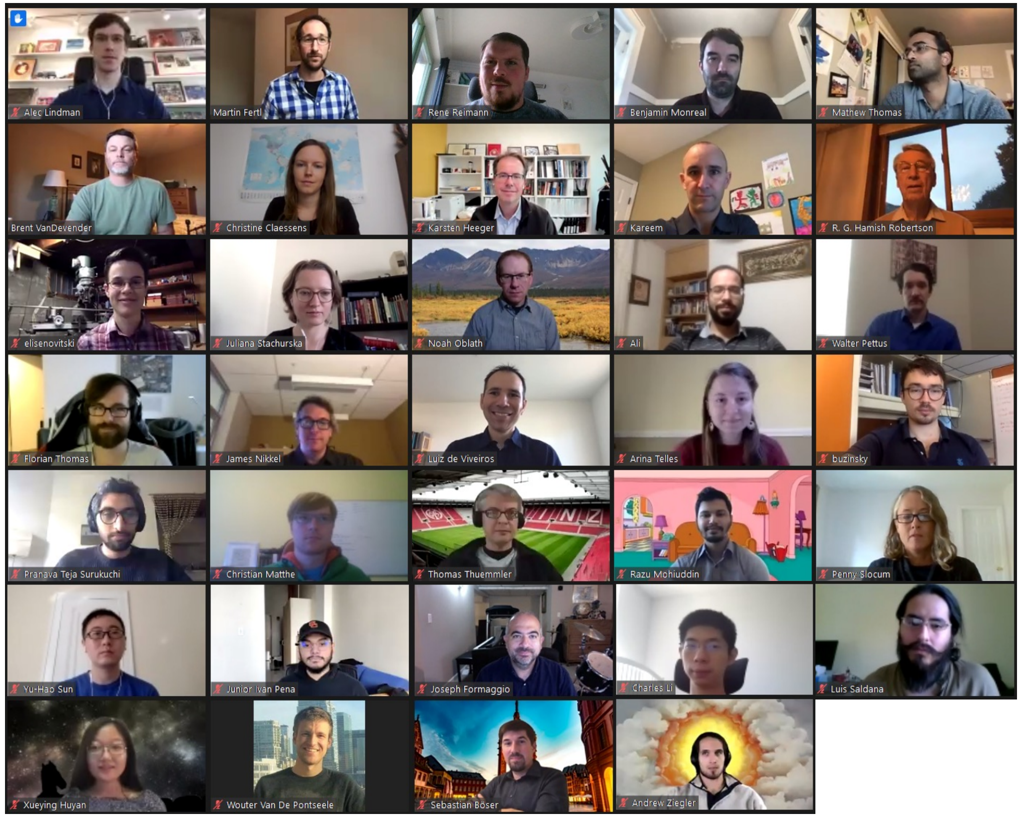
Massachusetts Institute of Technology
- Nicholas Buzinsky, Joseph Formaggio, Mingyu Li, Junior Peña, Juliana Stachurska, Wouter Van de Pontseele

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

Pennsylvania State University
- Carmen Carmona-Benitez, Richard Mueller, Luiz de Viveiros, Timothy Wendler, Andrew Ziegler

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

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



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