Cyclotron radiation emission spectroscopy for neutrino mass measurement and exotic interaction searches

Prof. Dr. Martin Fertl

6th Workshop on the
Physics of Fundamental Symmetries and Interactions - PSI 2022

Paul Scherrer Institut

Oct 21st, 2022

Outline

Short introduction to neutrino masses

The current state of the art: KATRIN and its latest results

Project 8: Narrow-range CRES for a neutrino mass measurement

He-6: Broad-band CRES to search for chirality flipping interactions

Summary

Non-zero neutrino masses are firmly established …

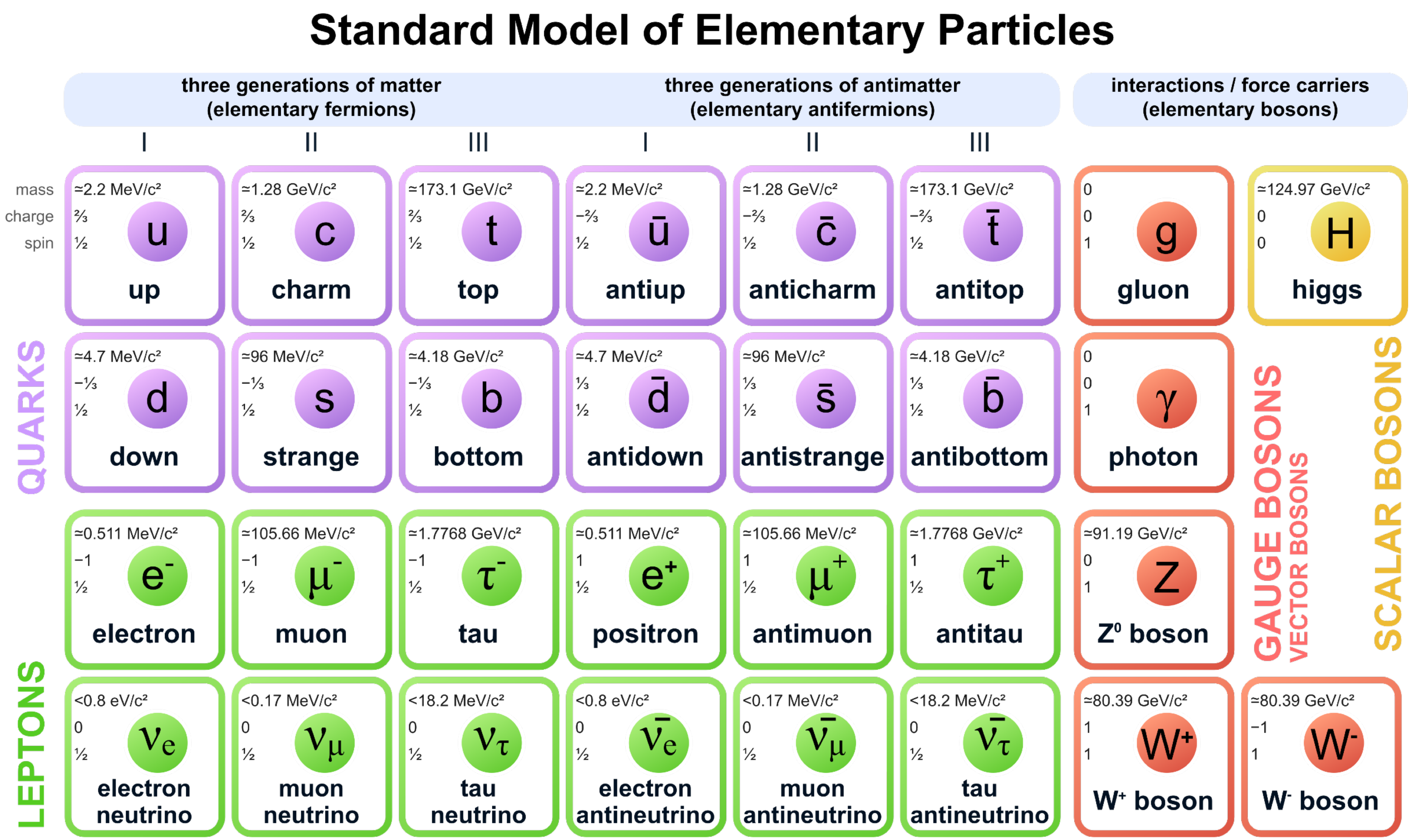


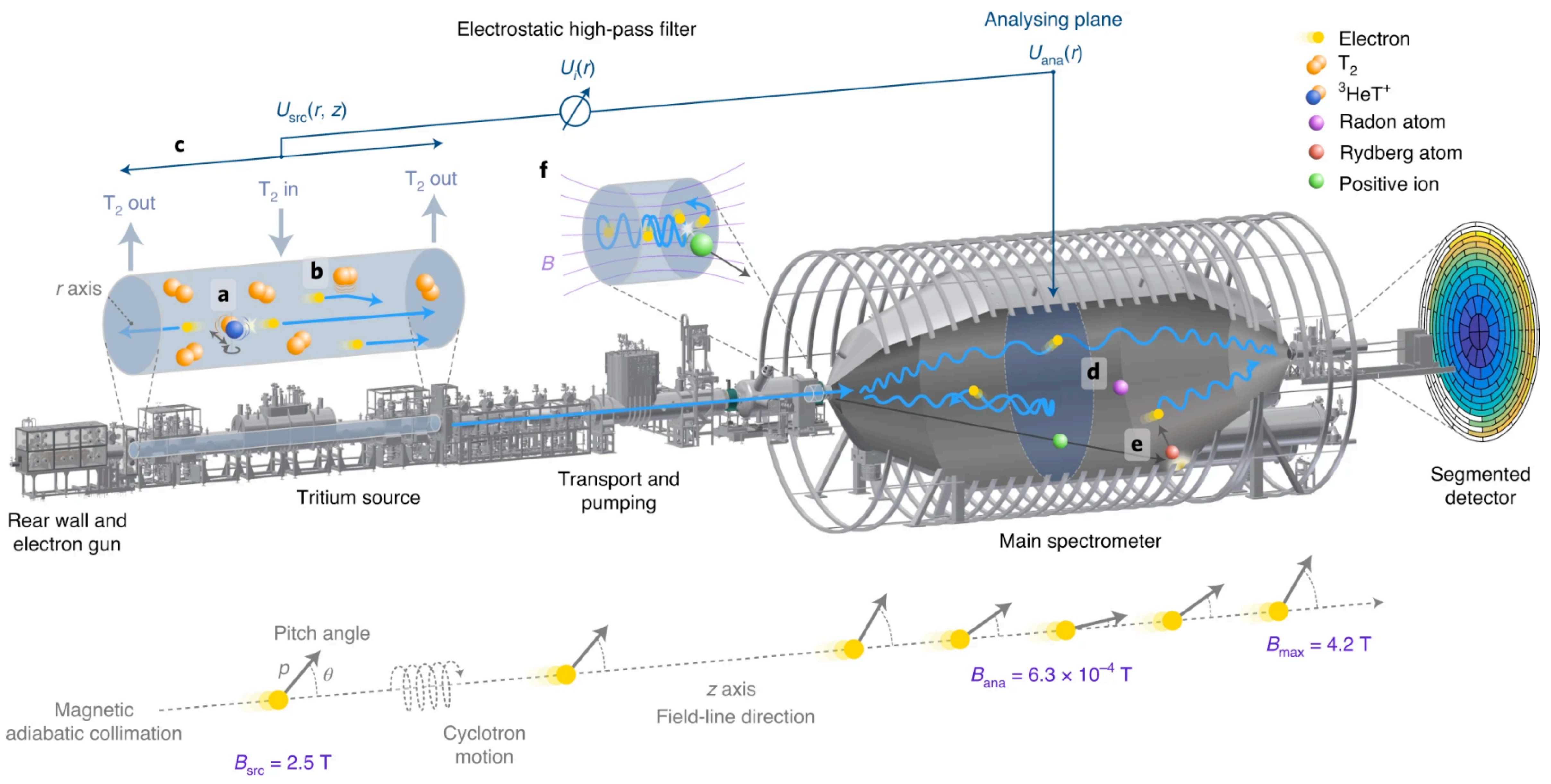
Figure adapted and updated from https://commons.wikimedia.org/wiki/File:Standard_Model_of_Elementary_Particles_Anti.svg

… through neutrino flavor oscillation experiments …

…, but neutrinos remain only particle without measured mass …

… and the mass generation mechanism remains unclear.

KATRIN: pushing a MAC-E filter at all boundaries to the extremes!



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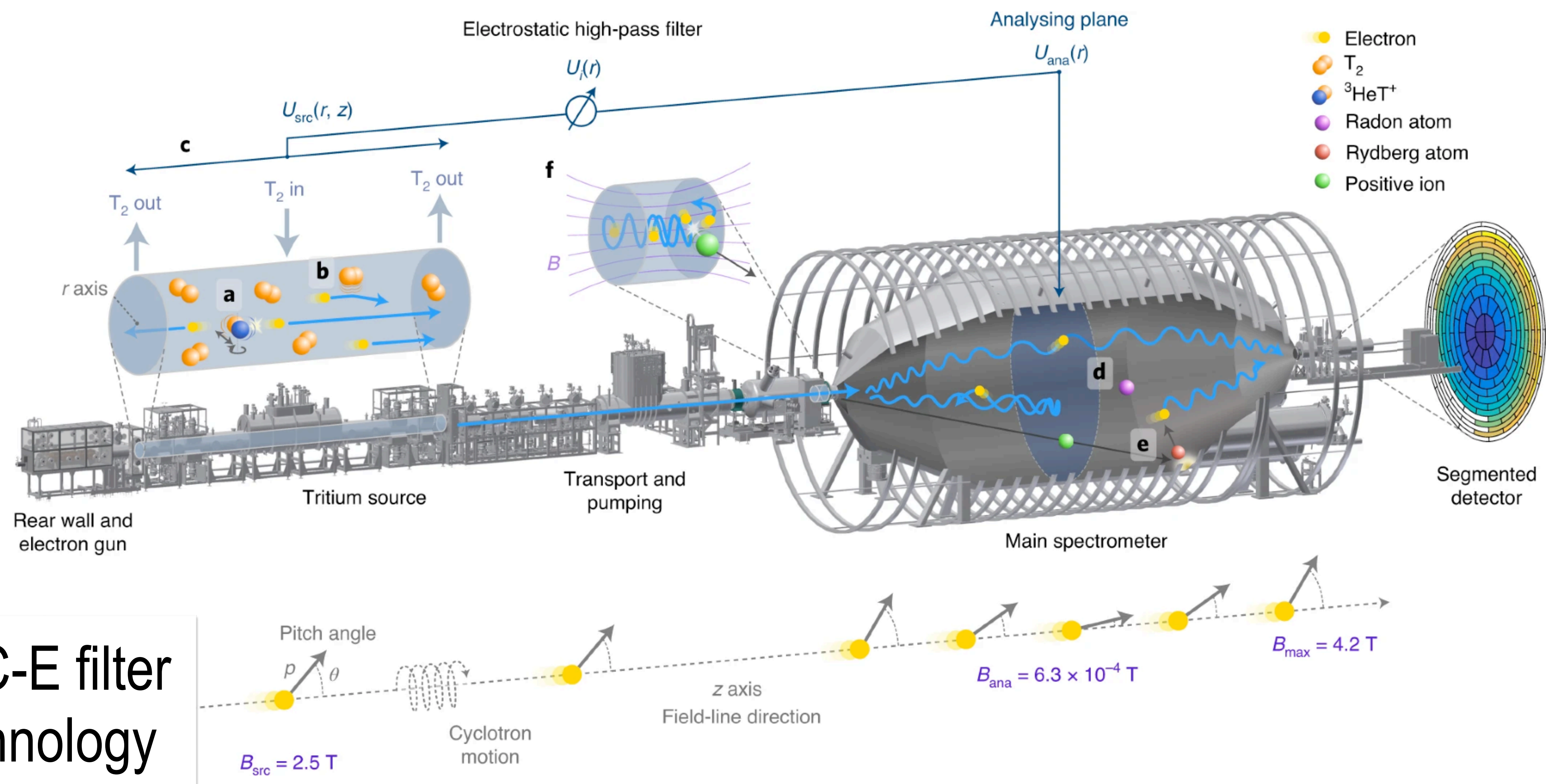

MAC-E filter technology

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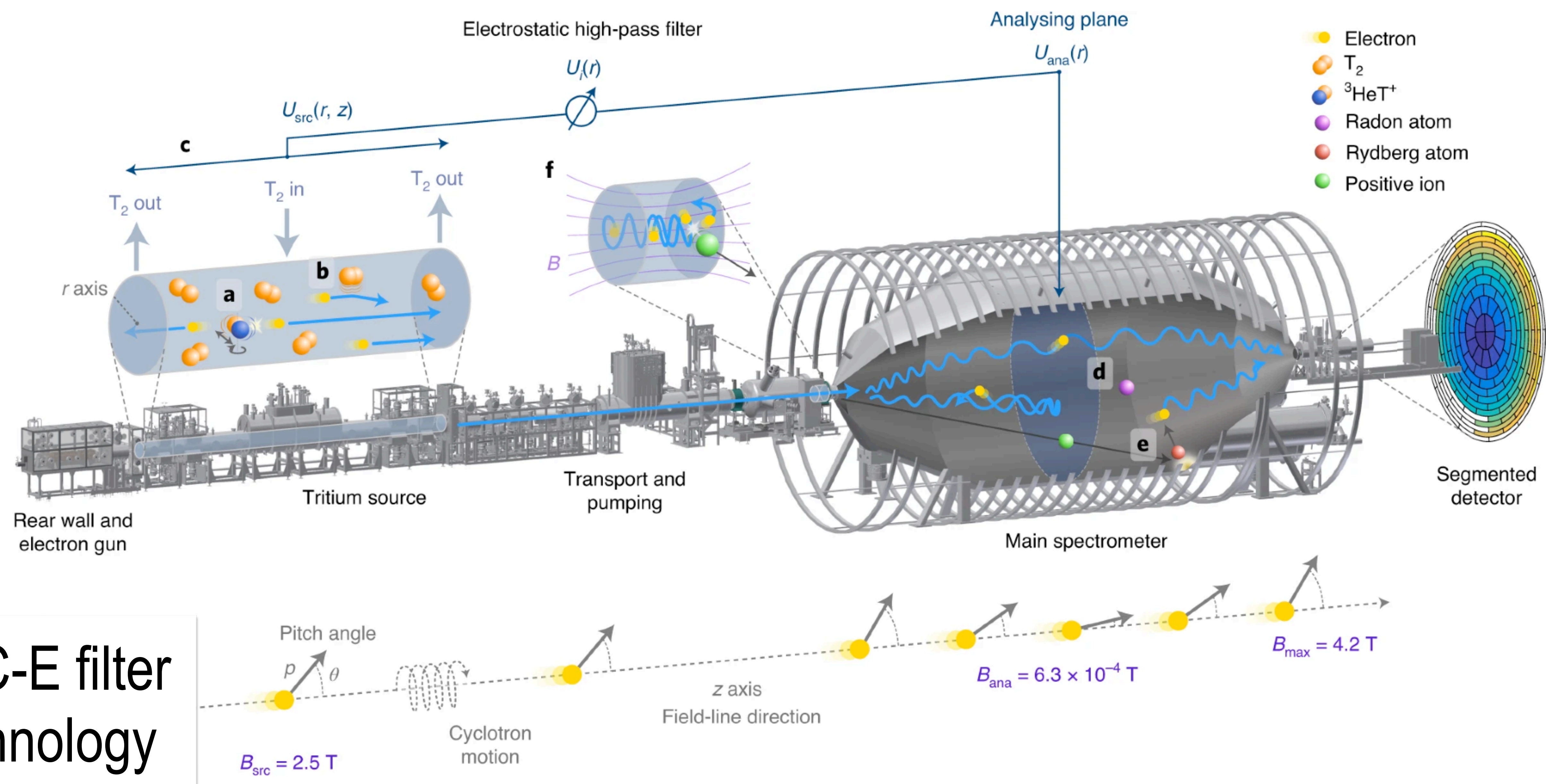

MAC-E filter technology

- Source decay rate > 10^{11} Bq
- Tritium suppression > 10^{12}
- MAC-E filter width: 0.93 eV @ 18.6 keV
- Main spectrometer at < 10^{-10} mbar
- Exquisite MC model of experiment

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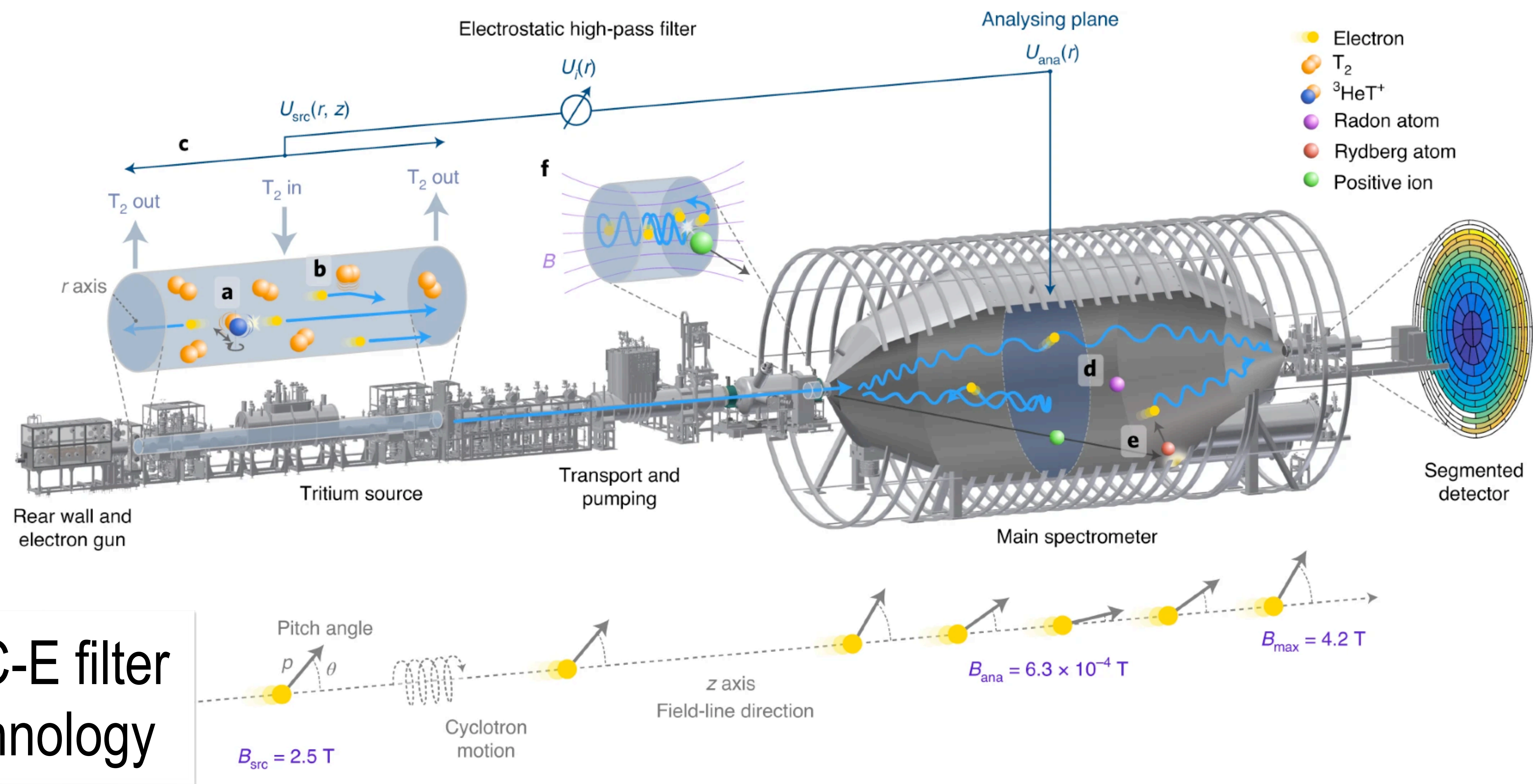

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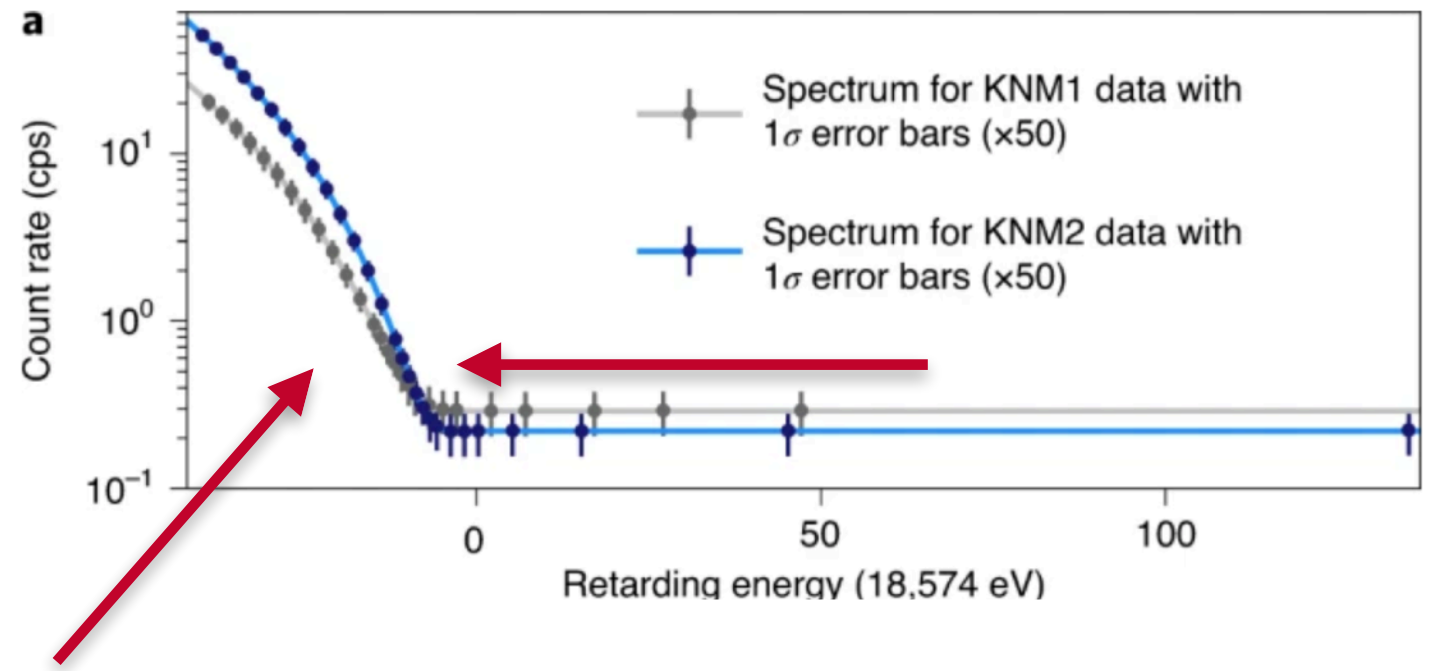

Neutrino mass signature:
change of shape and shift of endpoint

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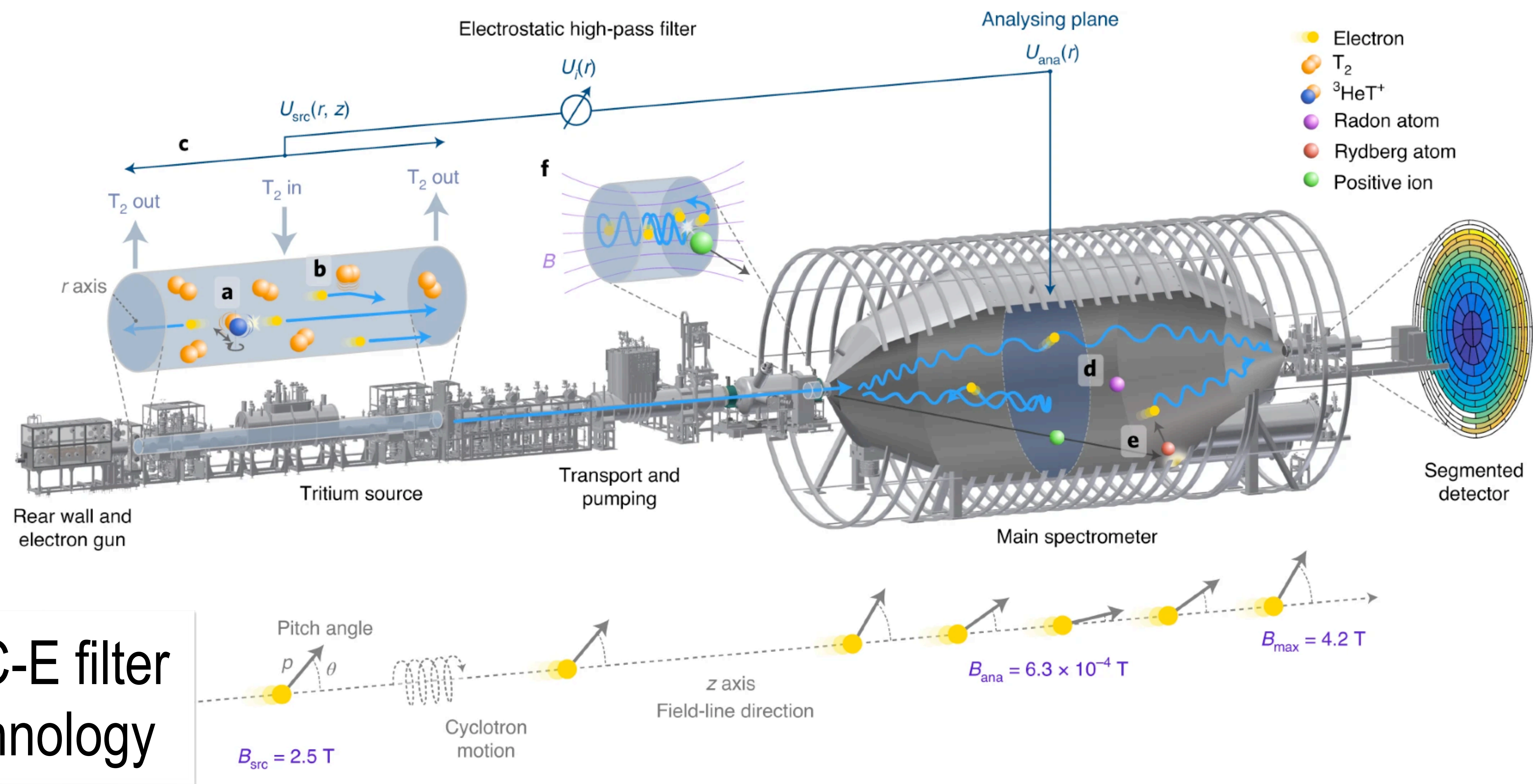

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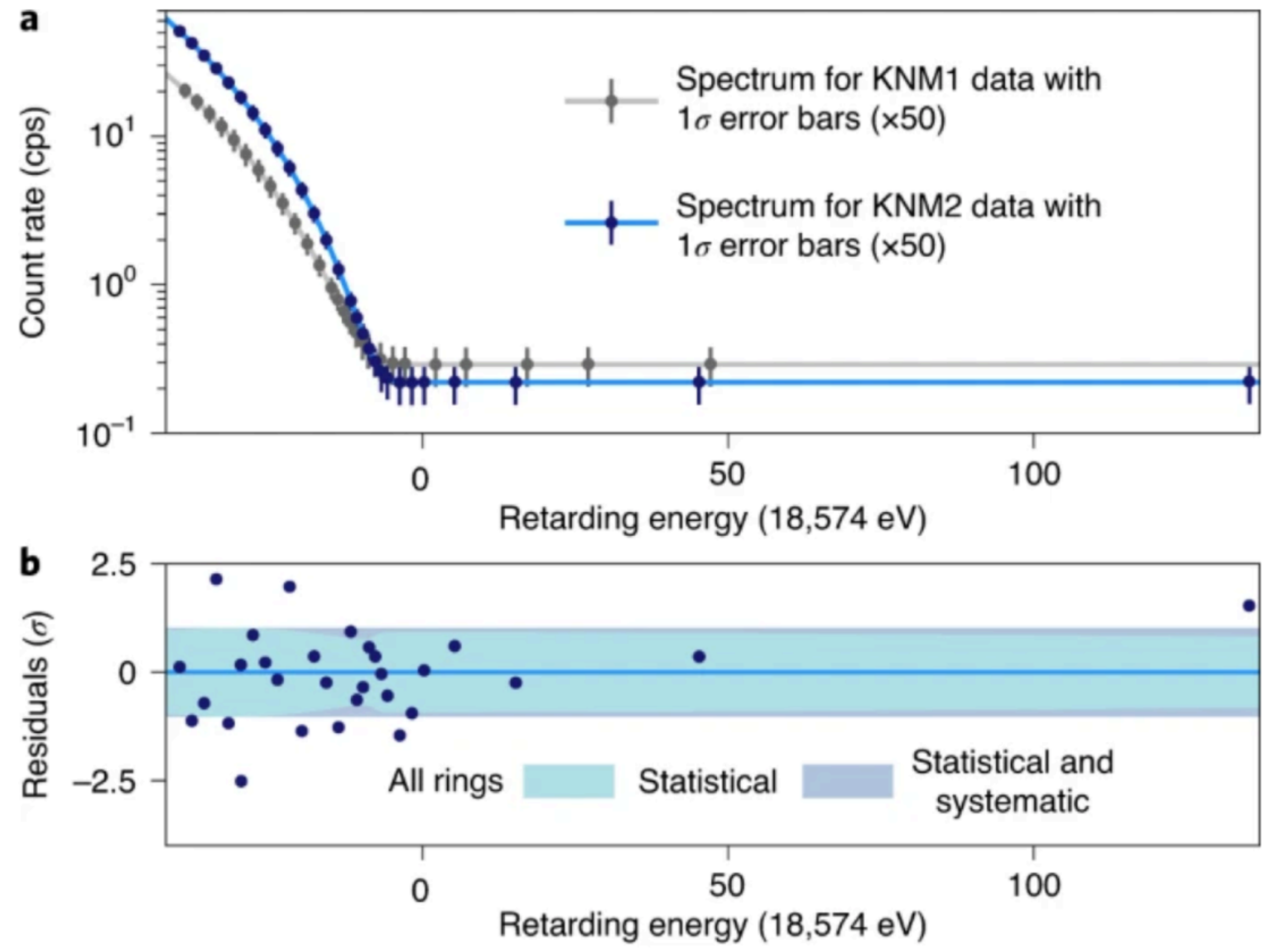

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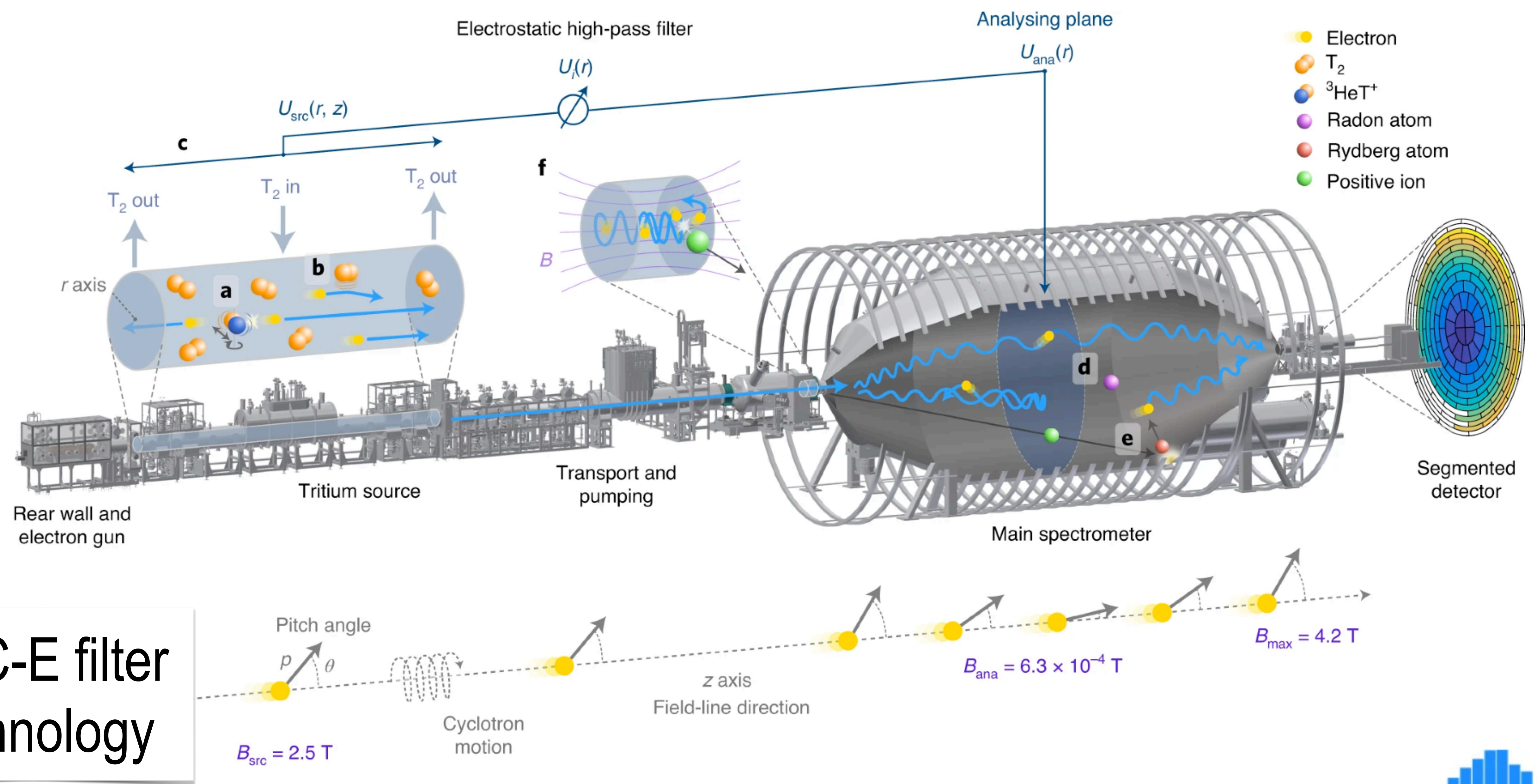

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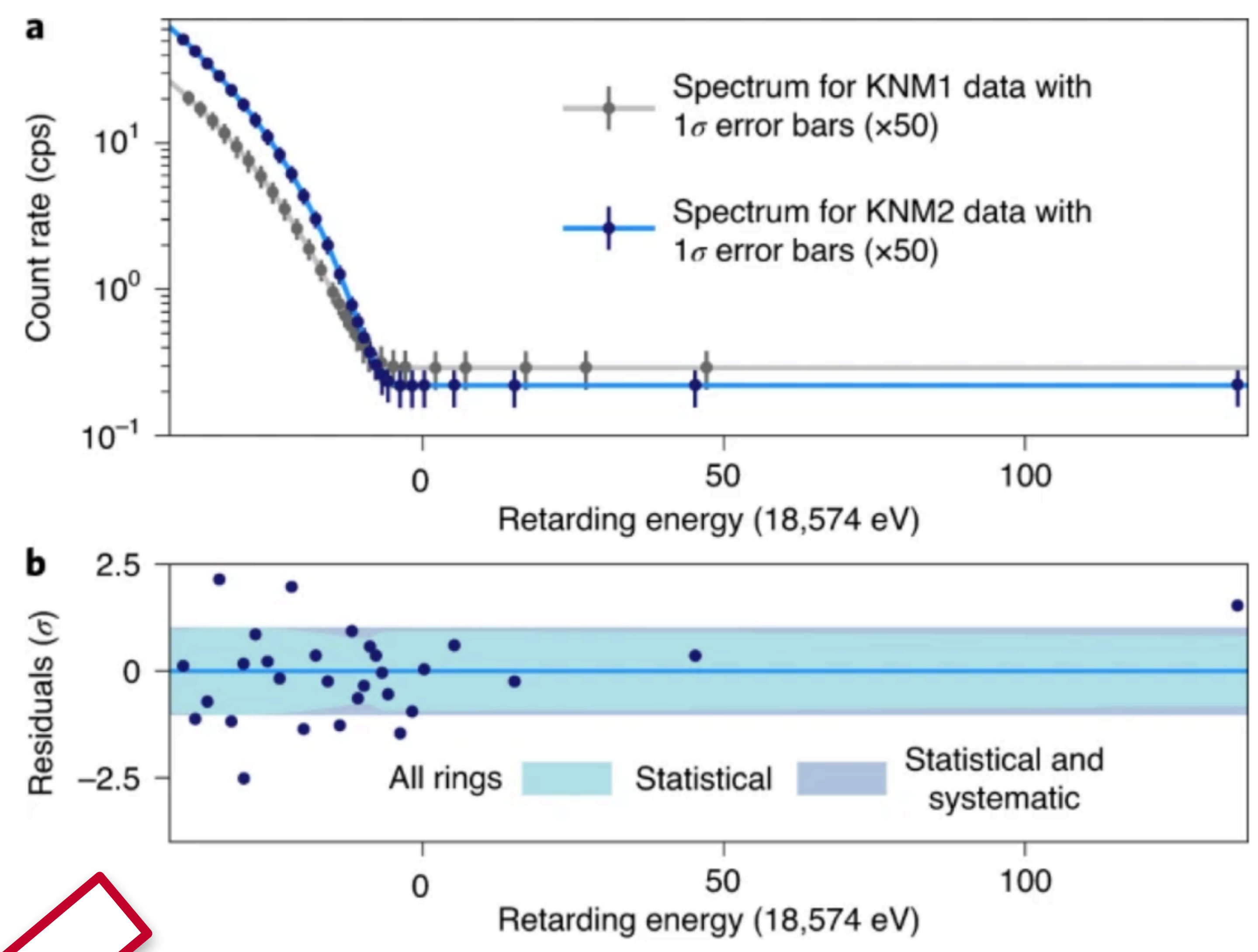

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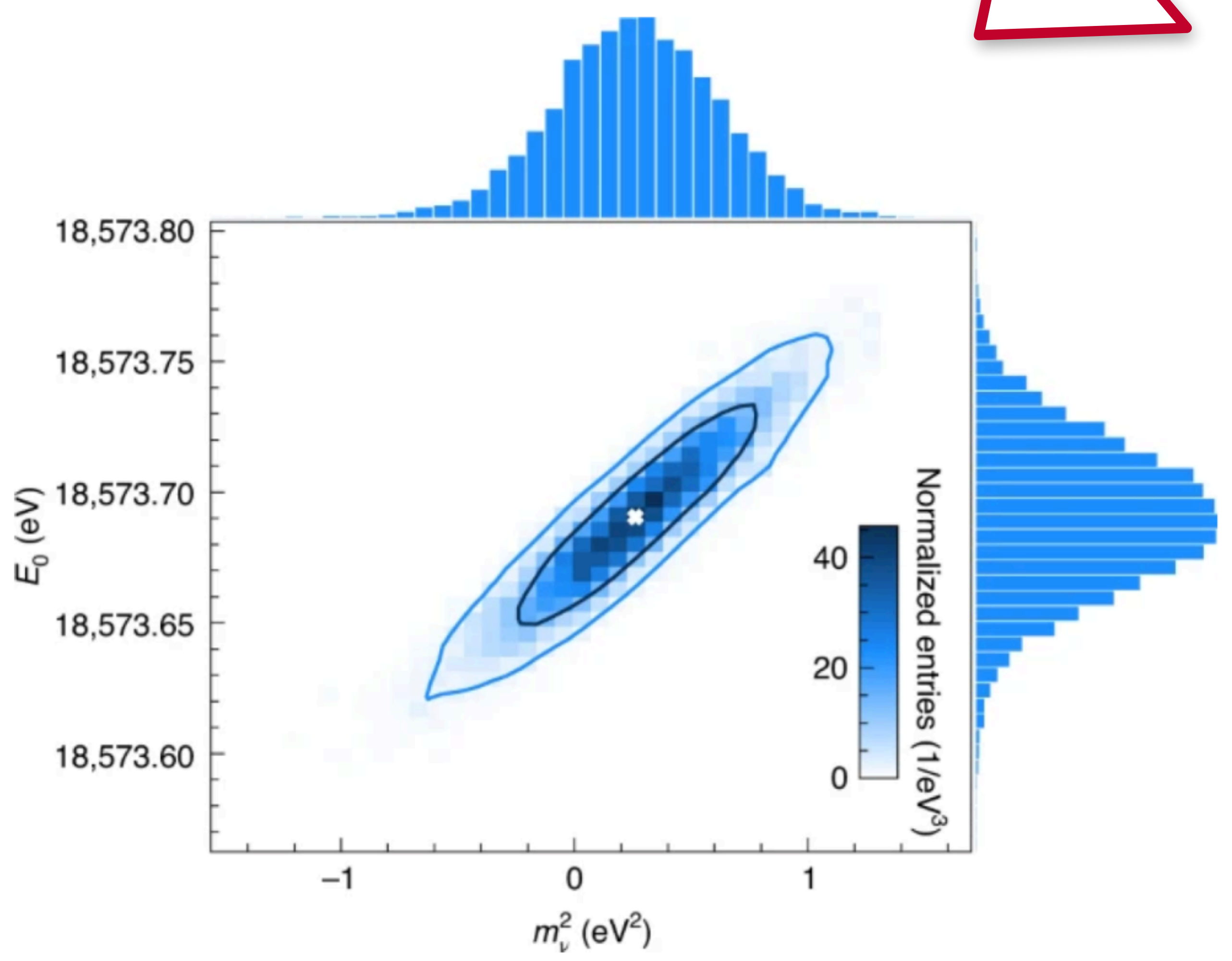

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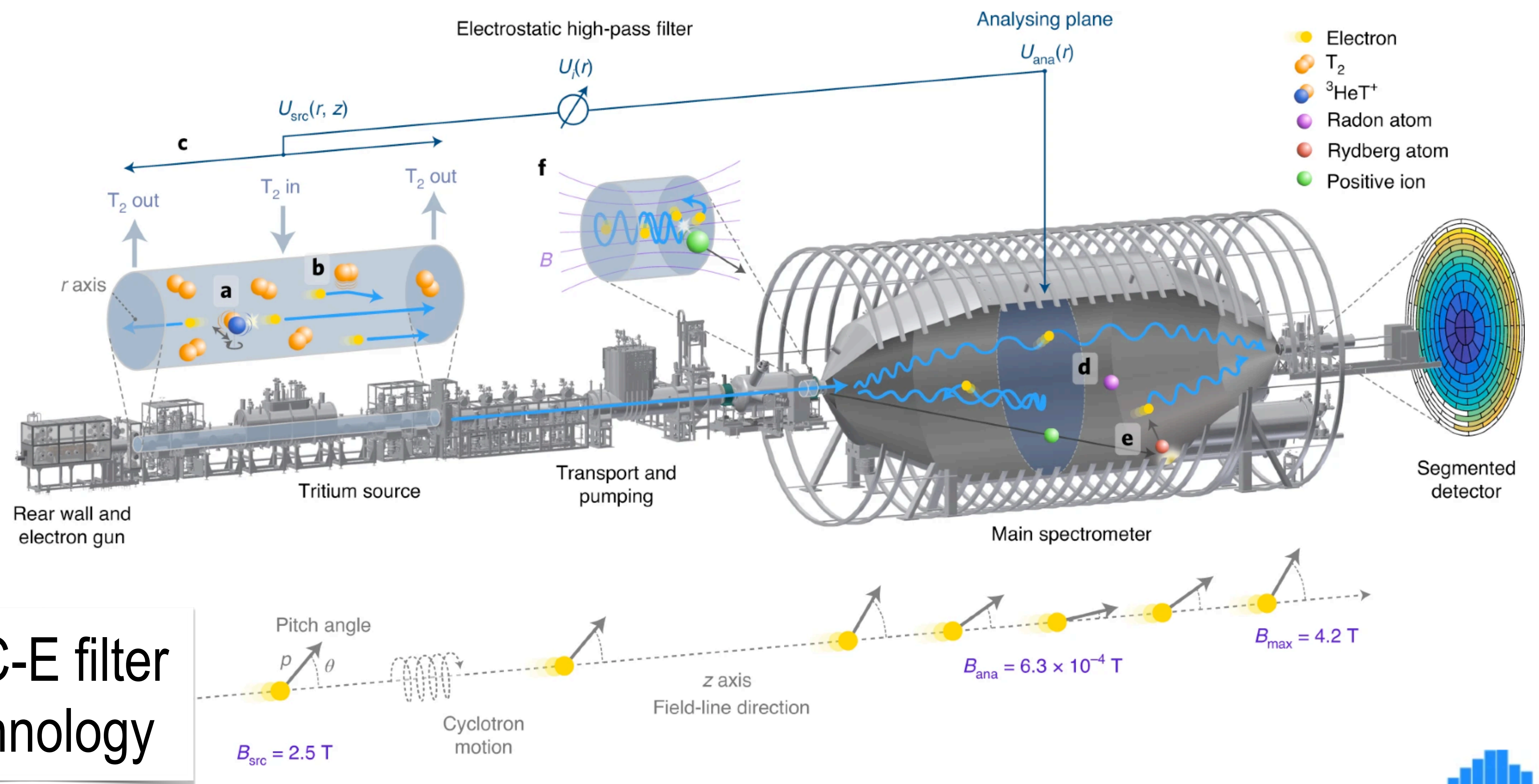

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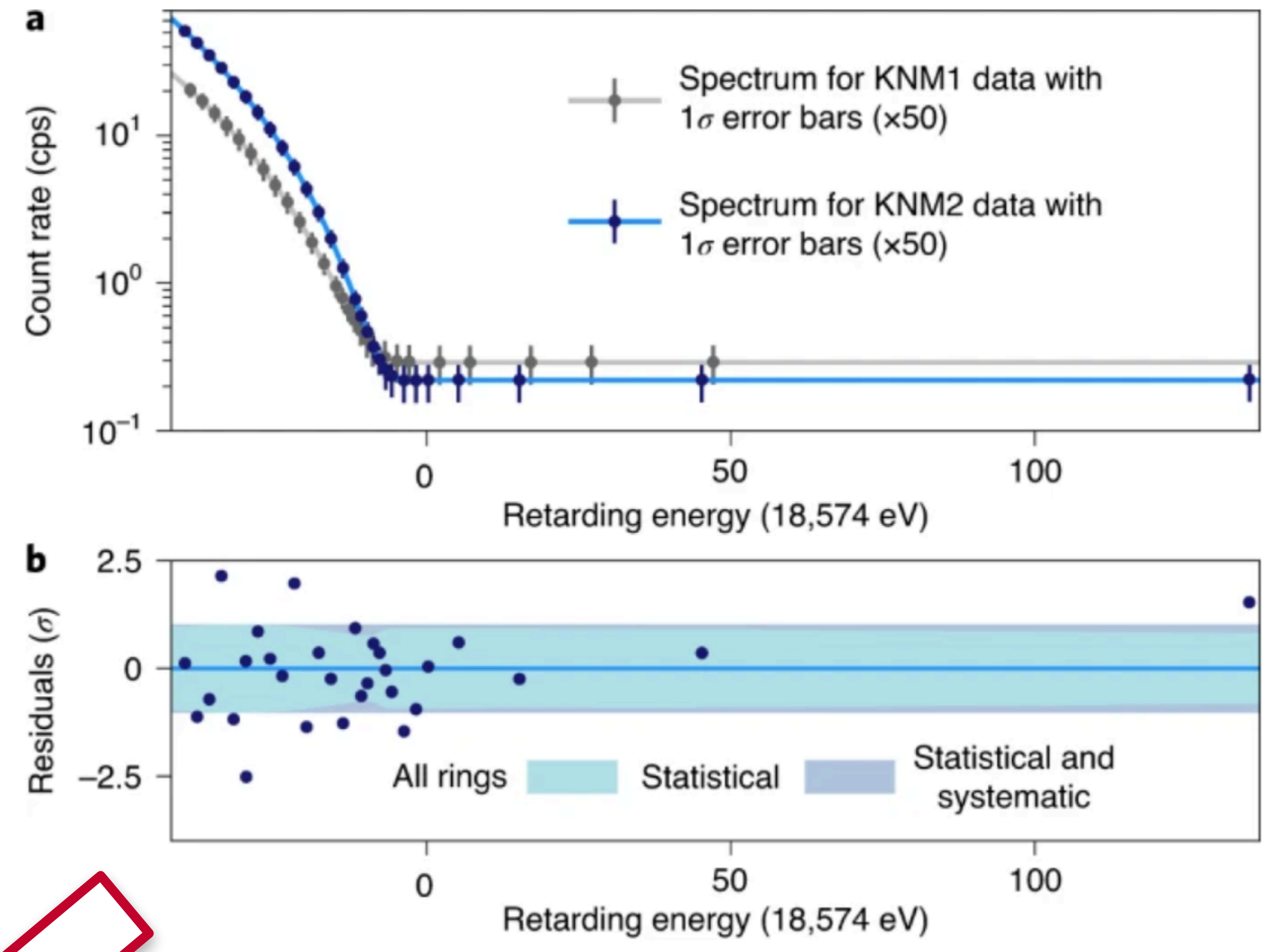

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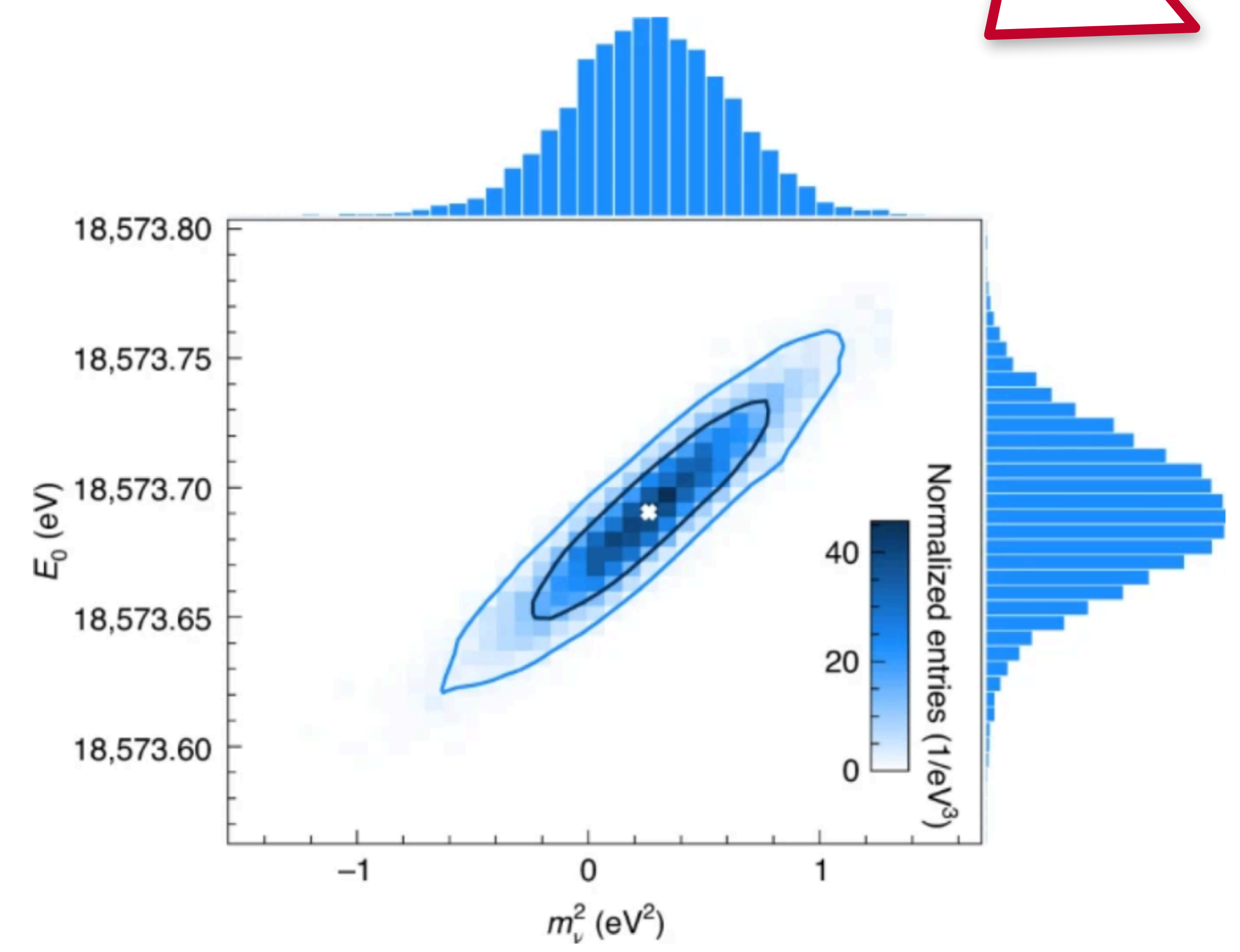

Best upper limit on neutrino mass
$m_\nu < 0.8\,\mathrm{eV/c^2}$ at 90 % CL

Anticipated sensitivity:
$m_\nu < 0.2\,\mathrm{eV/c^2}$ at 90 % CL

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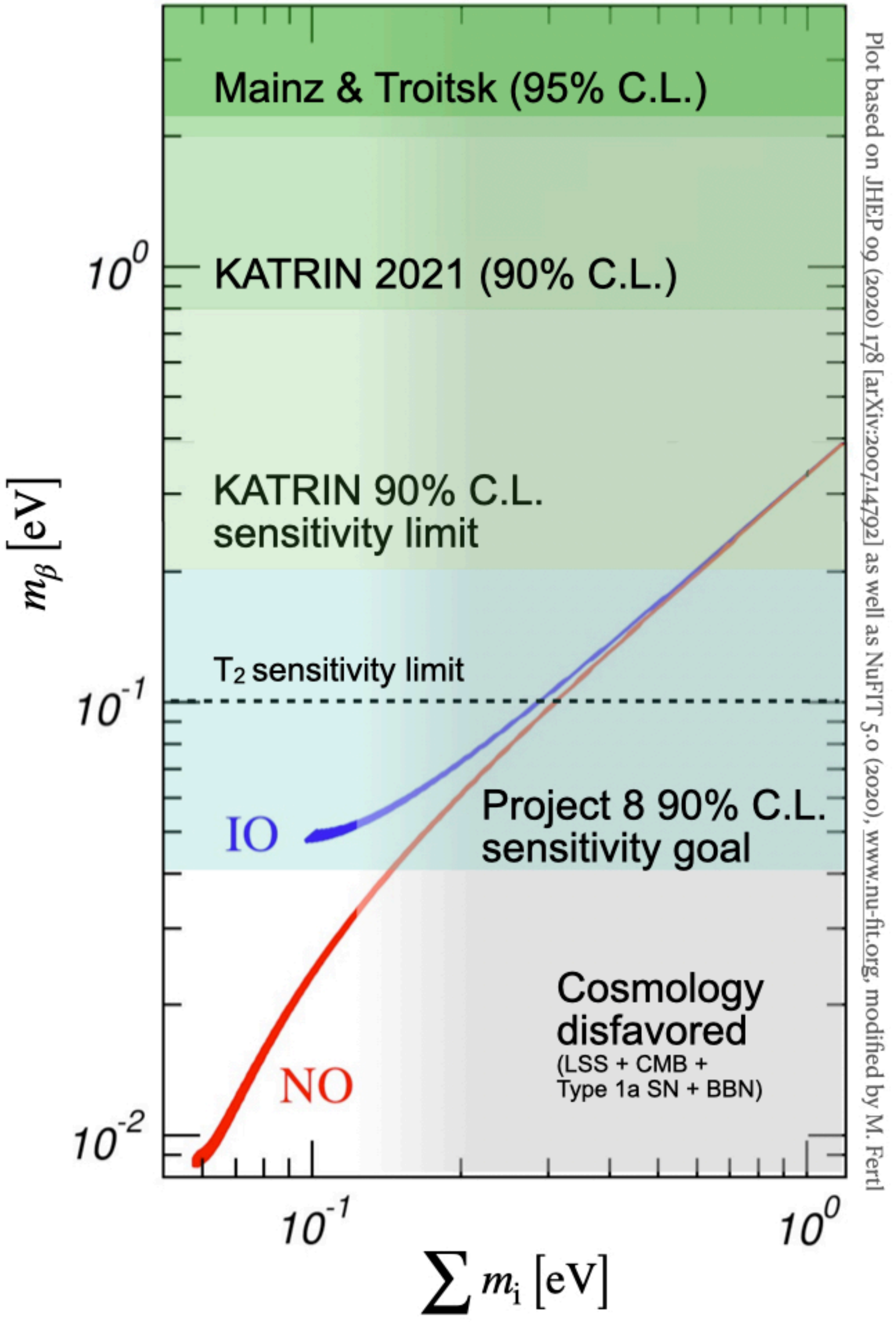
The challenges to higher mass sensitivity: systematics and statistics



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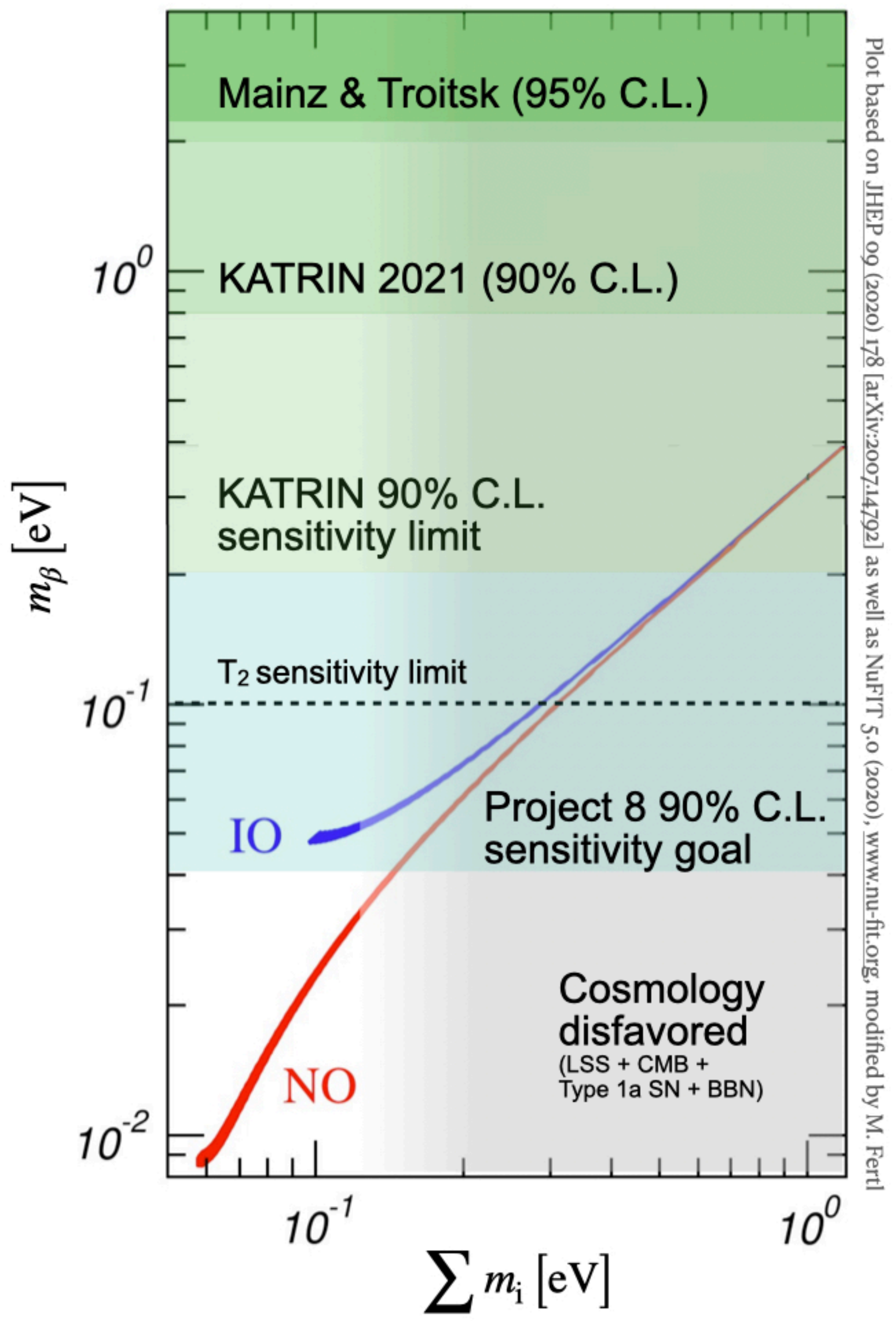

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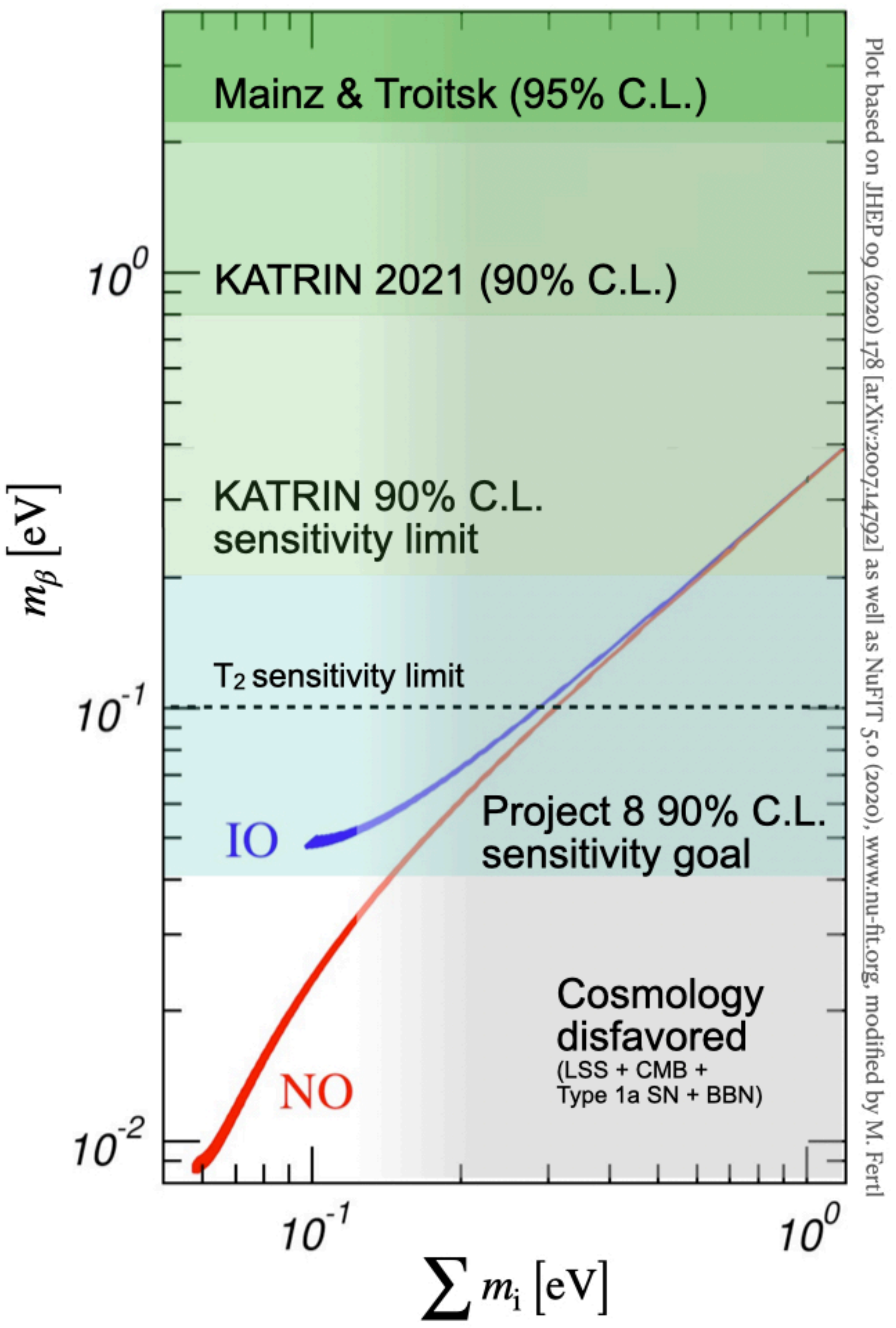

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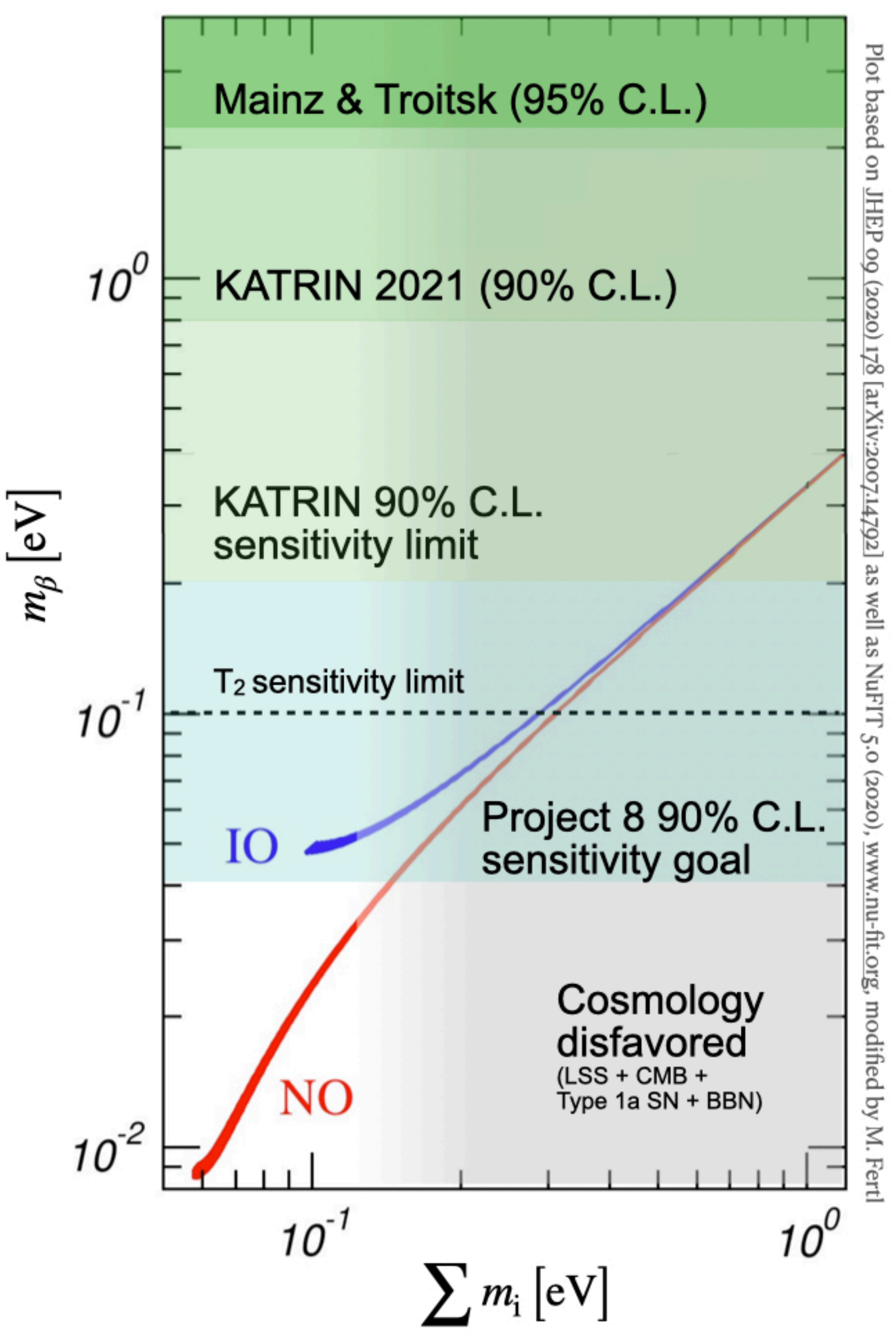

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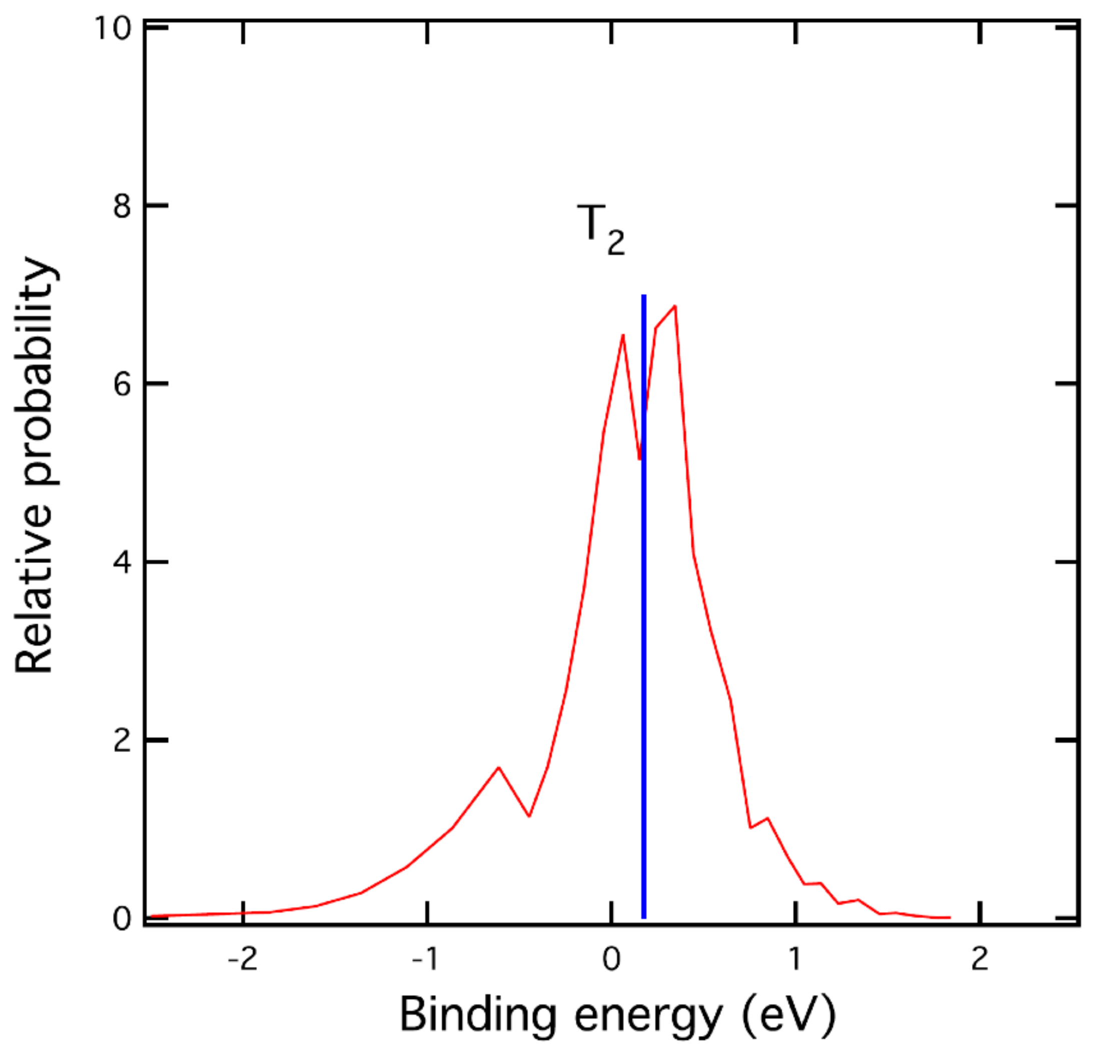
- Intrinsic final state distribution of $^3HeT^+$ molecular ion causes smearing of decay endpoint



L. Bodine, et al, Phys. Rev. C 91, 035505 , 2015

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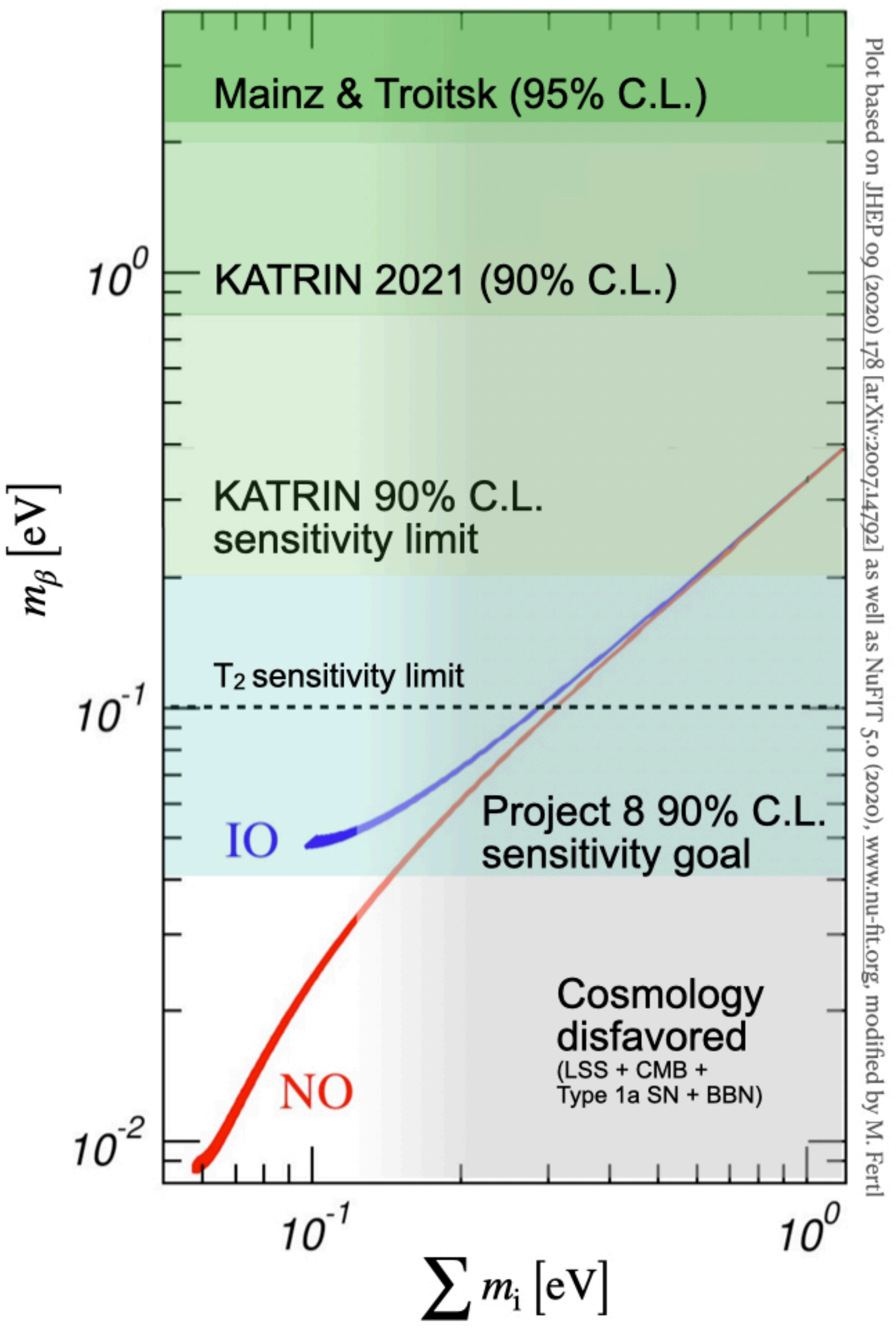

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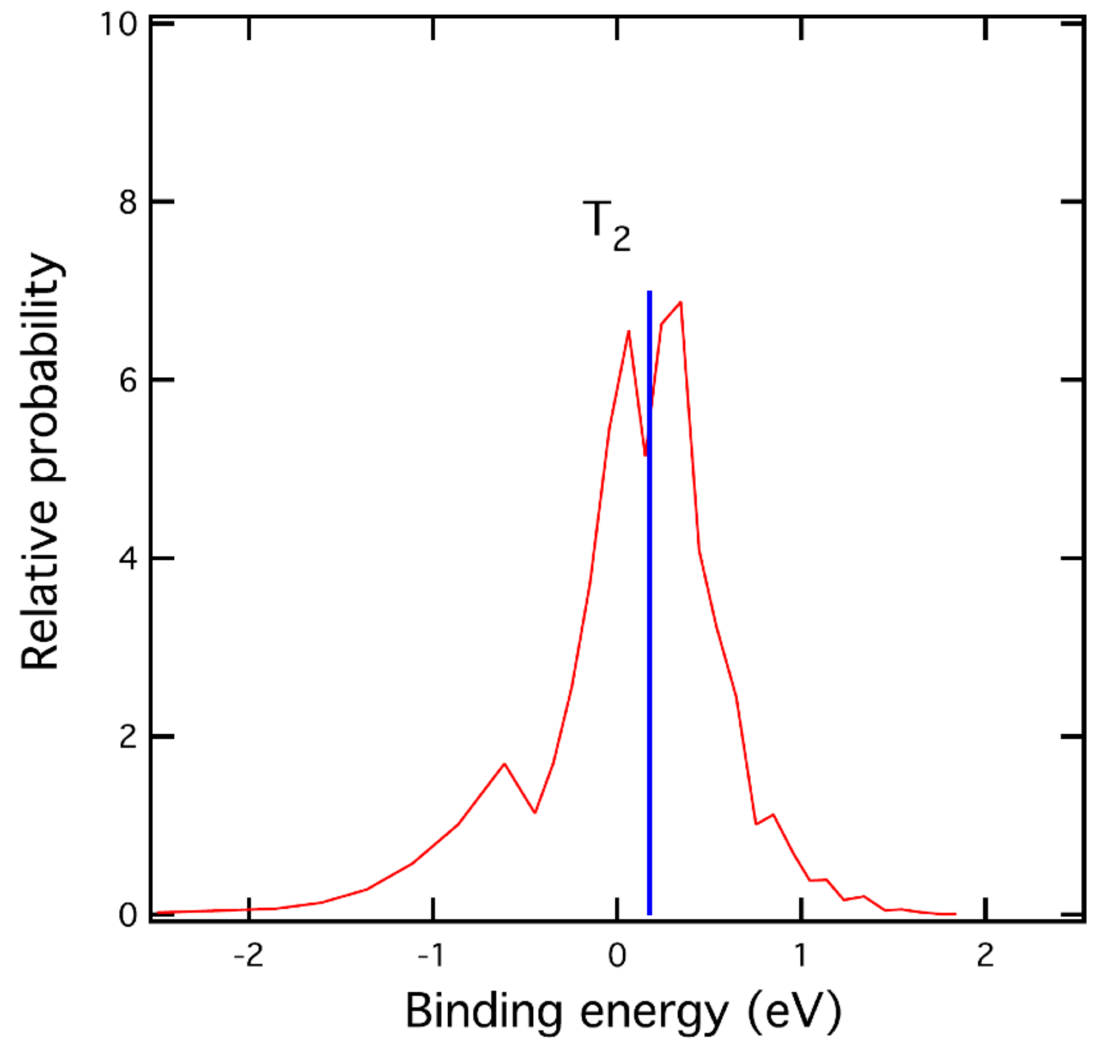

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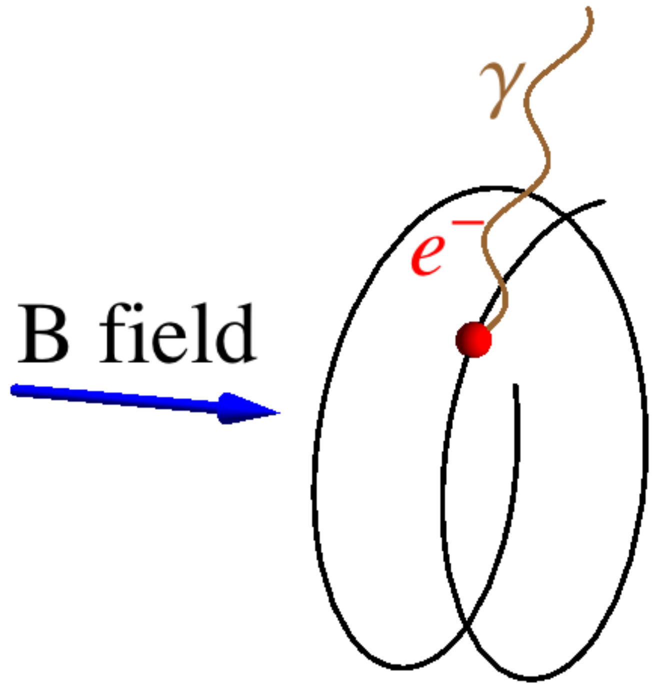
Project 8

A *frequency-based* approach towards the measurement of the neutrino mass using ultra cold *atomic* tritium with 40 meV/c² sensitivity

Project 8: Cyclotron radiation emission spectroscopy of $T_{(2)}$



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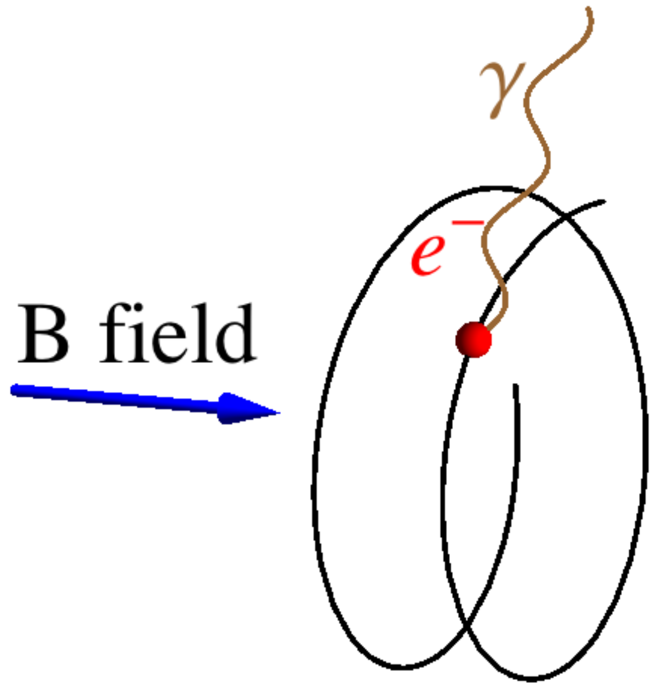

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- Cyclotron radiation from single electrons
- Source transparent to microwave radiation
- No e- transport from source to detector
- Highly precise frequency measurement

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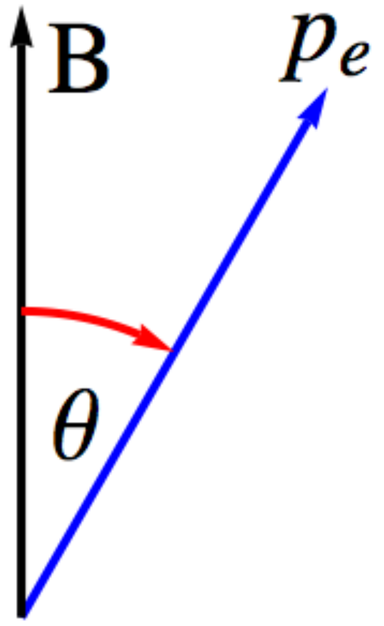

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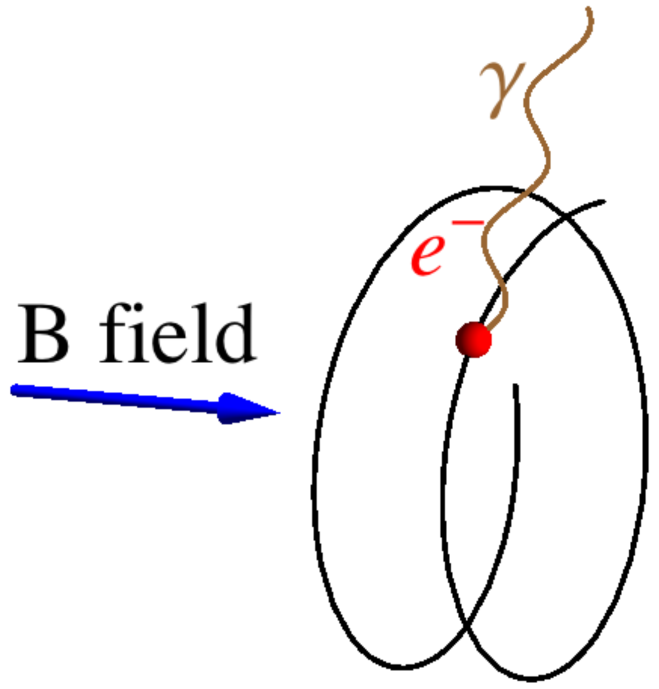

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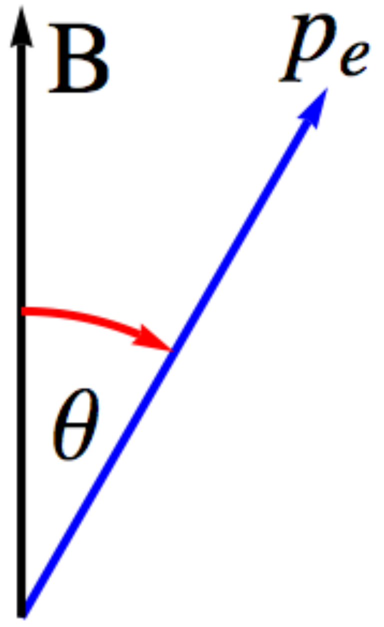

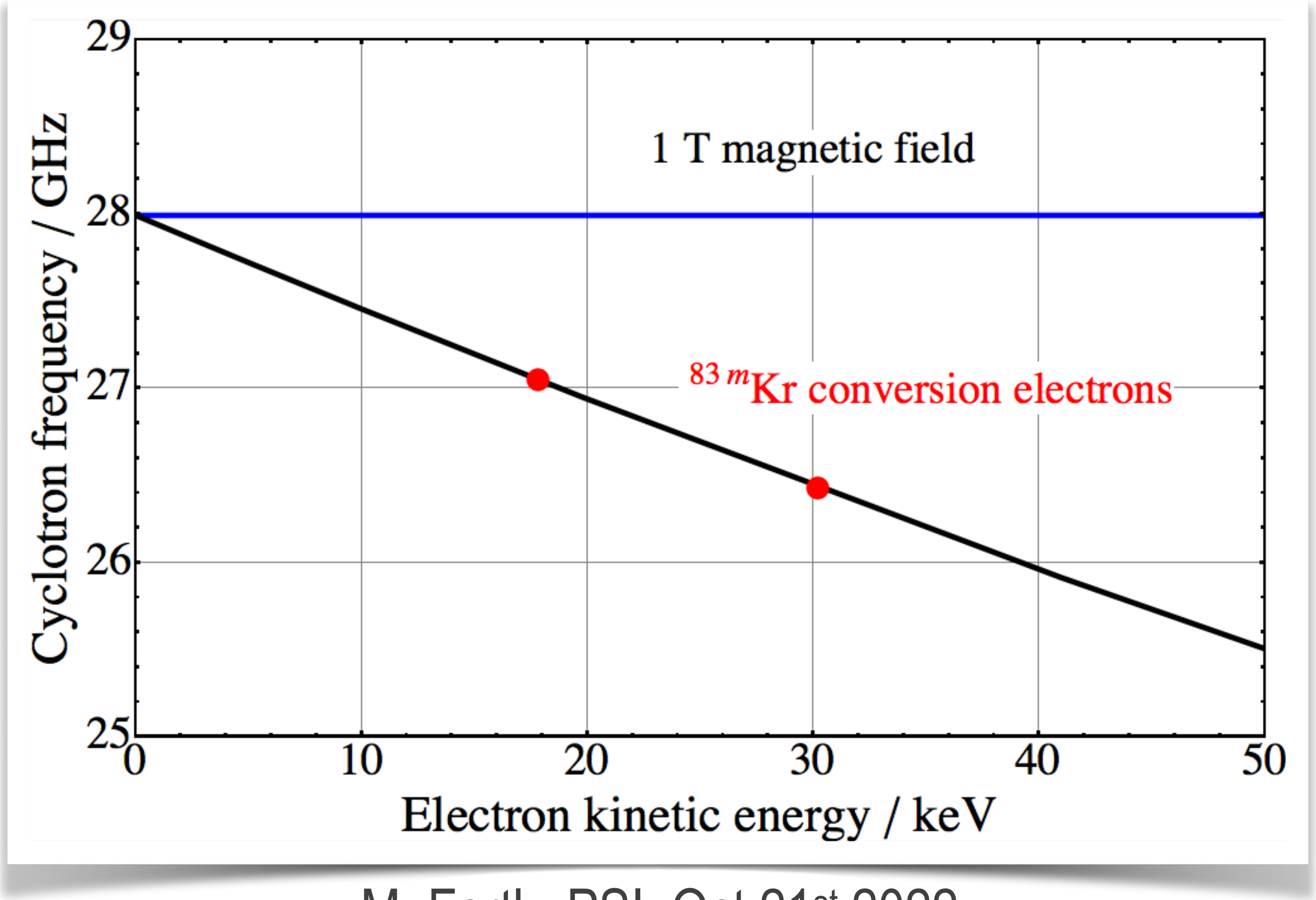

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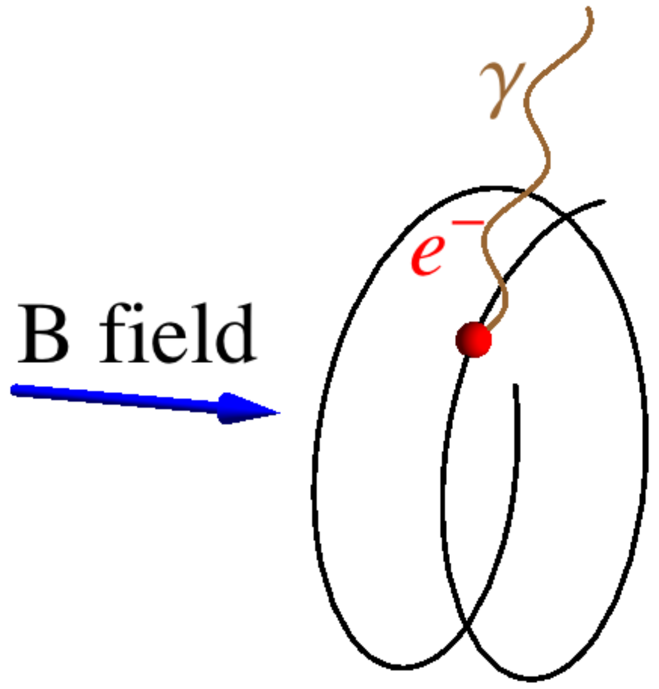

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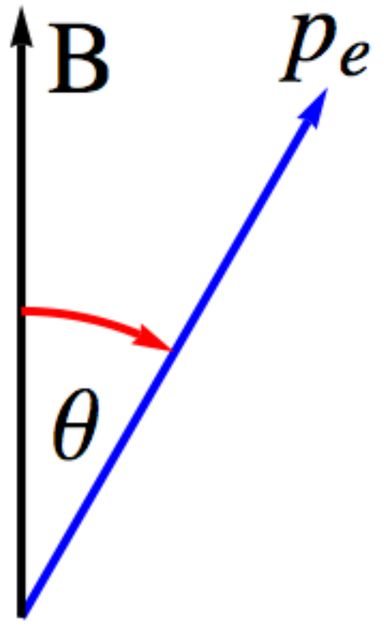

$$P\left(E_{kin}, m, \theta\right) = \frac{1}{4\pi\epsilon_0}\frac{2}{3}\frac{e^4}{m^4c^5}B^2\left(E_{kin}^2 + 2\,E_{kin}\,m\,c^2\right)\sin^2\theta$$

$$P\left(17.8\,\mathrm{keV}, 90^\circ, 1\,\mathrm{T}\right) = 1\,\mathrm{fW}$$
$$P\left(30.2\,\mathrm{keV}, 90^\circ, 1\,\mathrm{T}\right) = 1.7\,\mathrm{fW}$$

Small but readily detectable with state of the art detectors

Project 8 phase I: First demonstration of CRES

Demonstrate the path to an electron neutrino mass experiment step by step!

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

Phase I Proof of principle to show the feasibility of CRES: Use mono-energetic conversion electrons from ^{83m}Kr gas in waveguide

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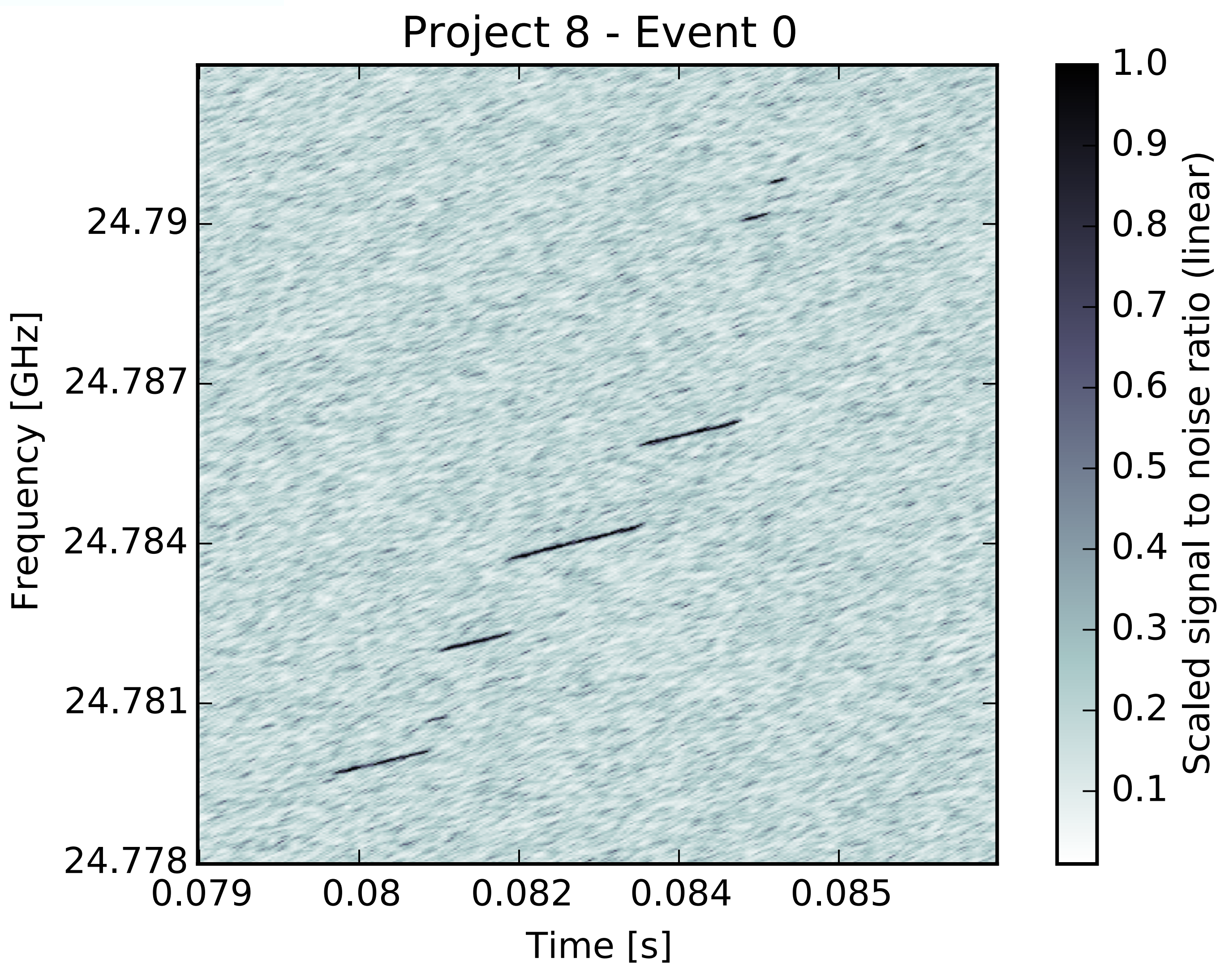

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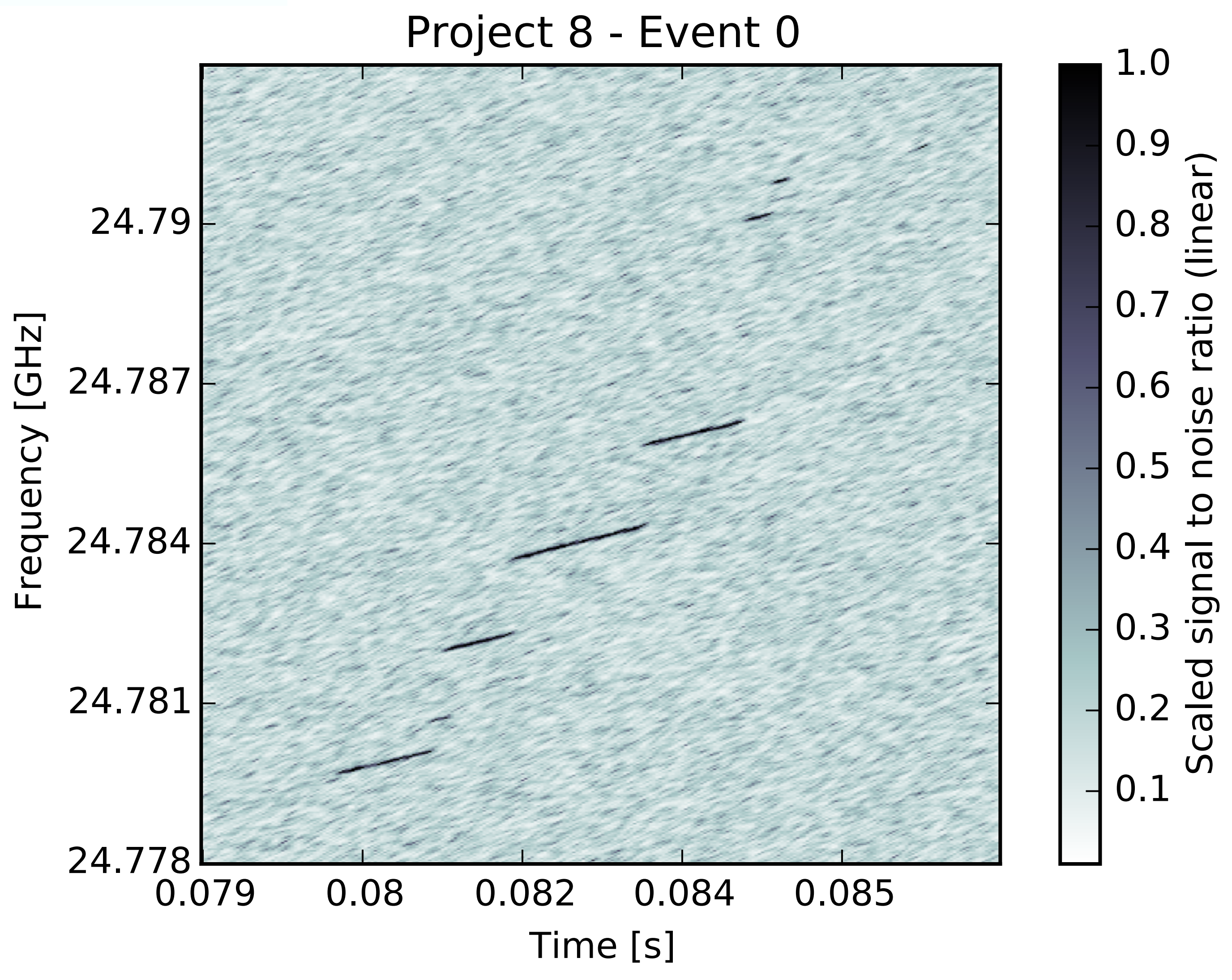
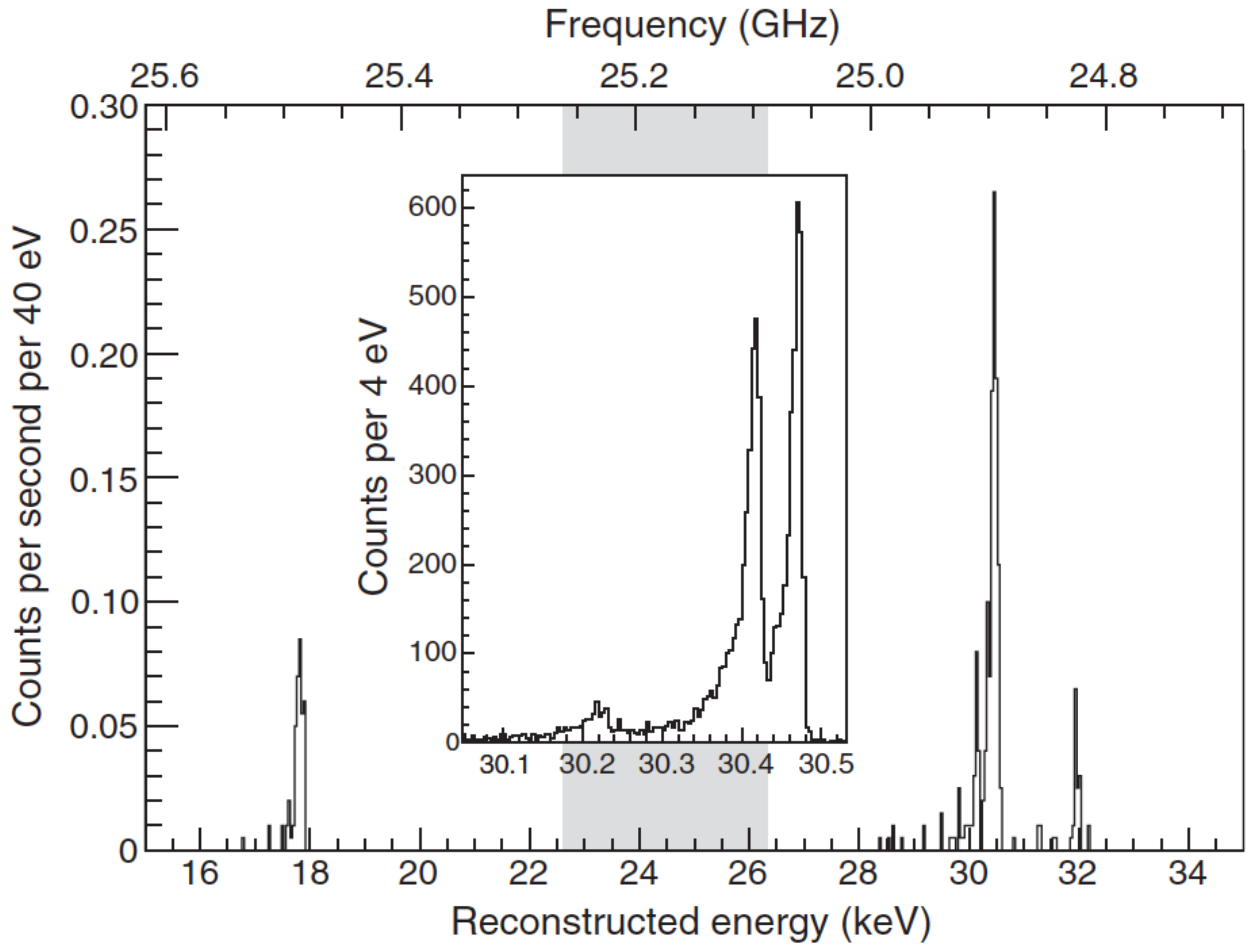


Very first CRES spectrum of ^{83m}Kr



Asner et al., Physical Review Letters, 114, 162501 (2015)

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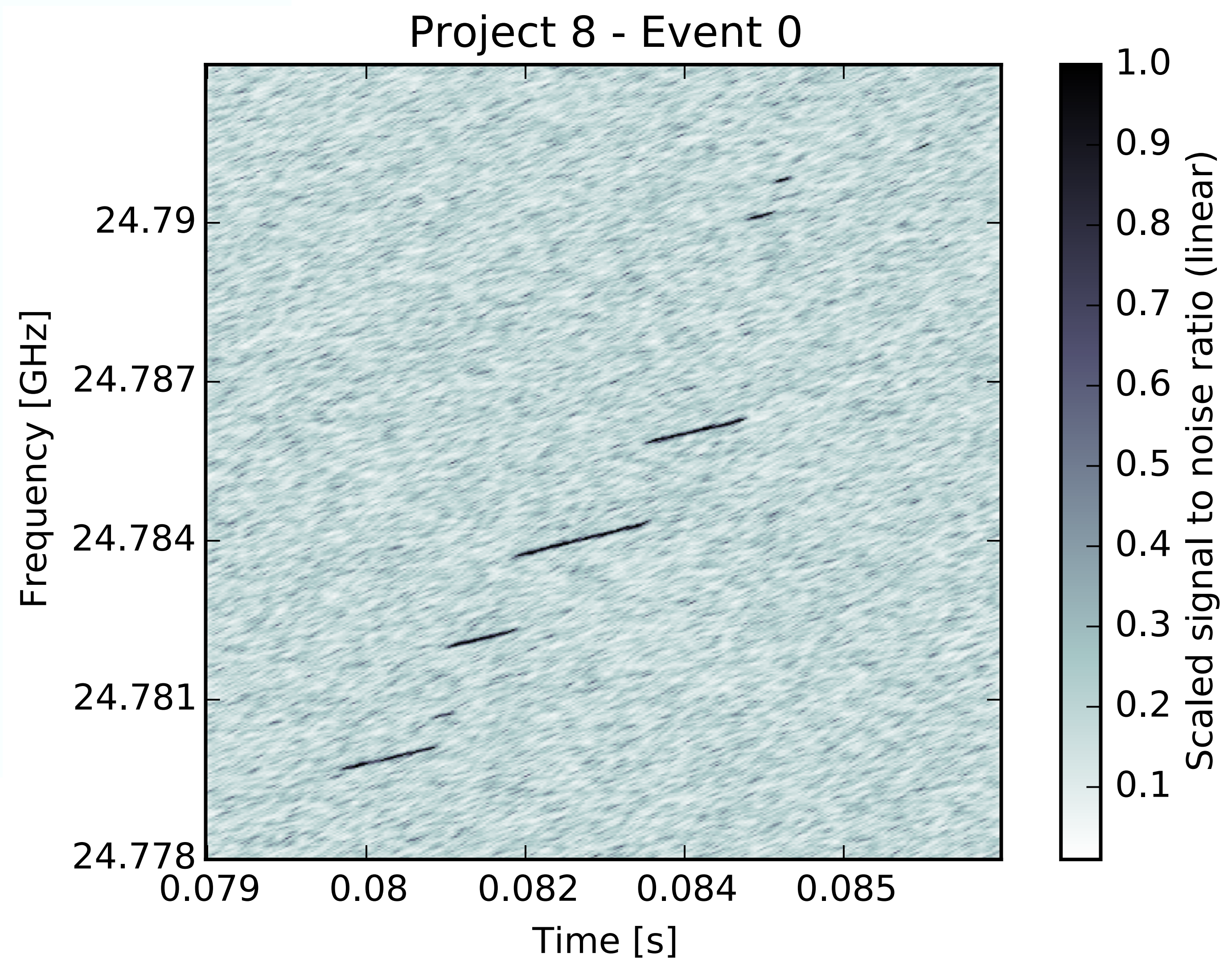

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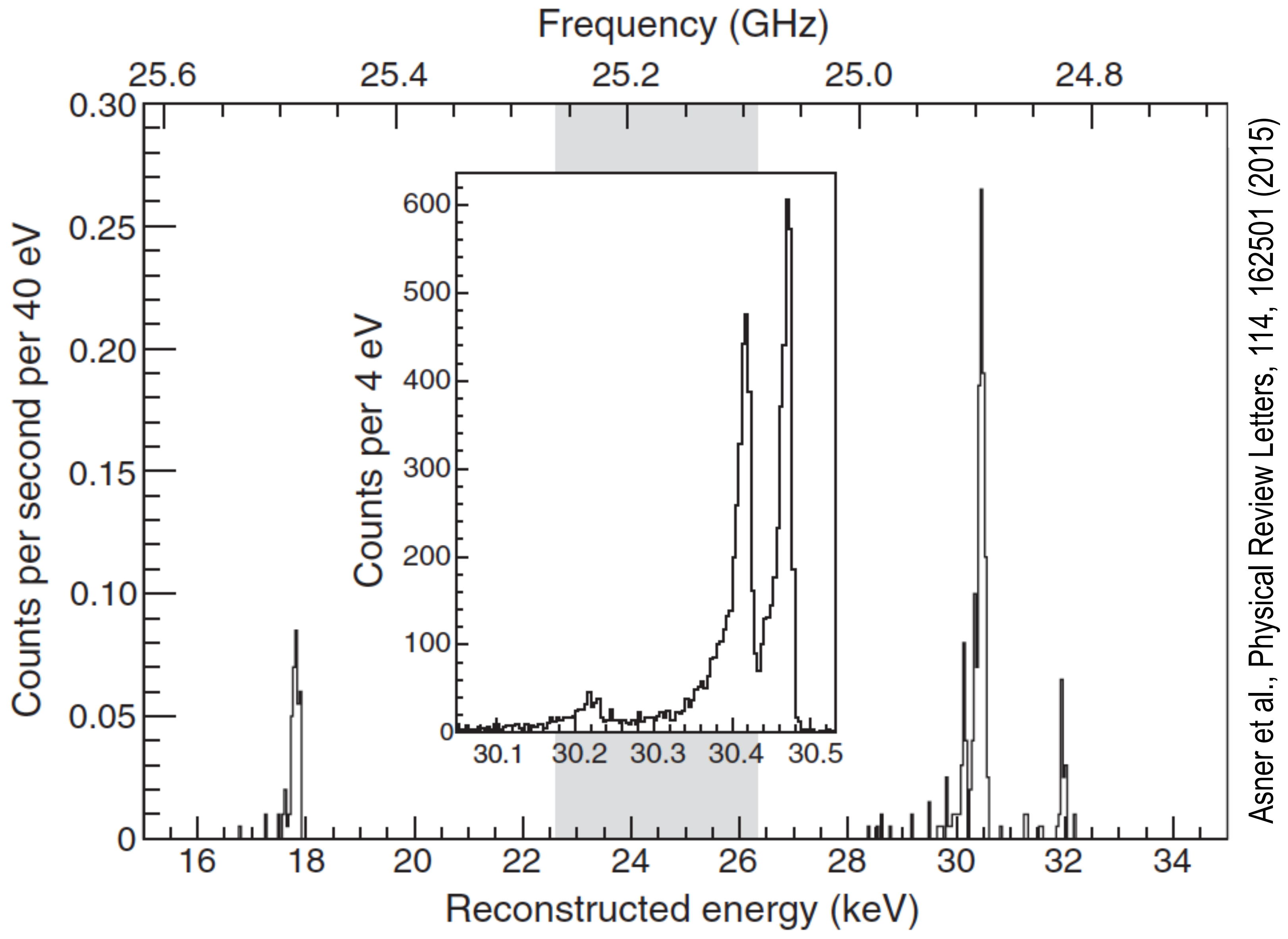
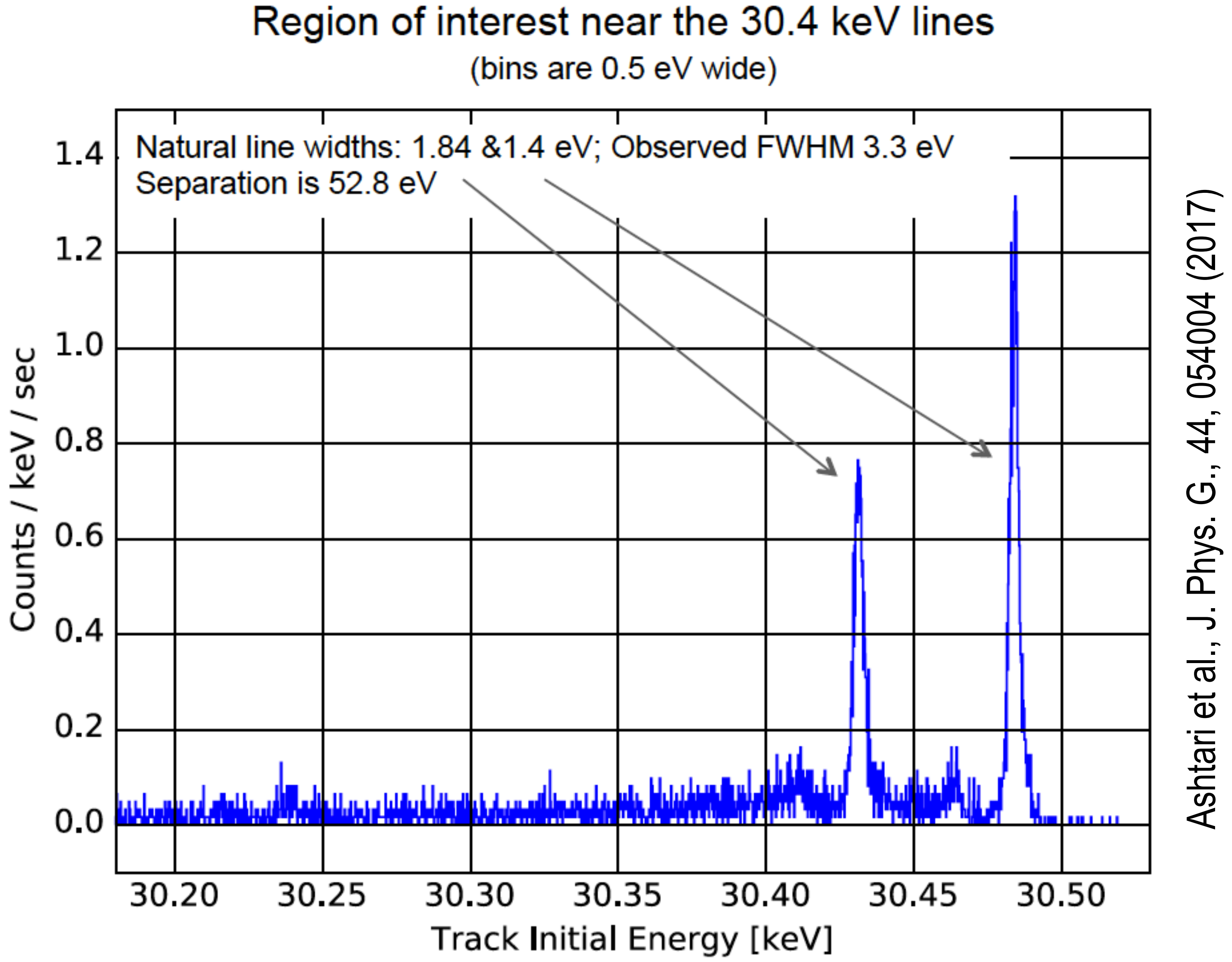


High res. CRES spectrum of ^{83m}Kr



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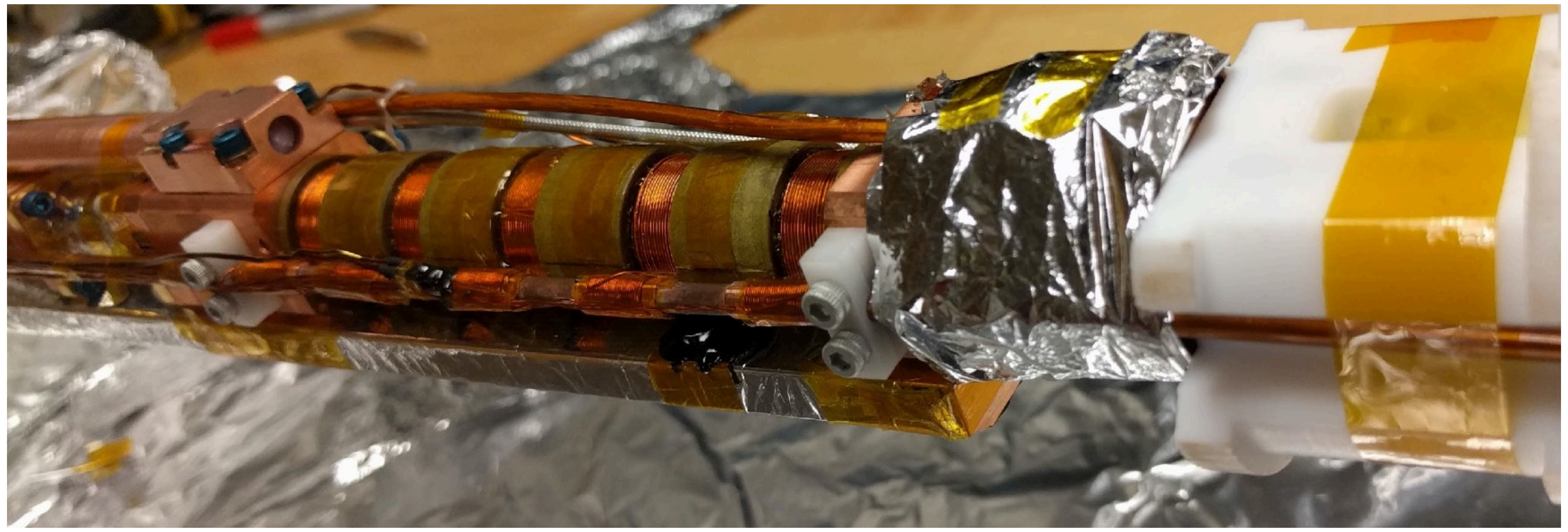
Phase II: Construction | Data taking | Analysis

<u>Goals:</u>

- 1st application of CRES to continuous β spectrum
- 1st frequency-based neutrino mass limit
- Demonstration of:
  - high energy resolution
  - zero background
  - control of systematic effects



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Trap depth determines the energy resolution and the line shape!
→ Calibration with mono-energetic ^{83m}Kr conversion electrons

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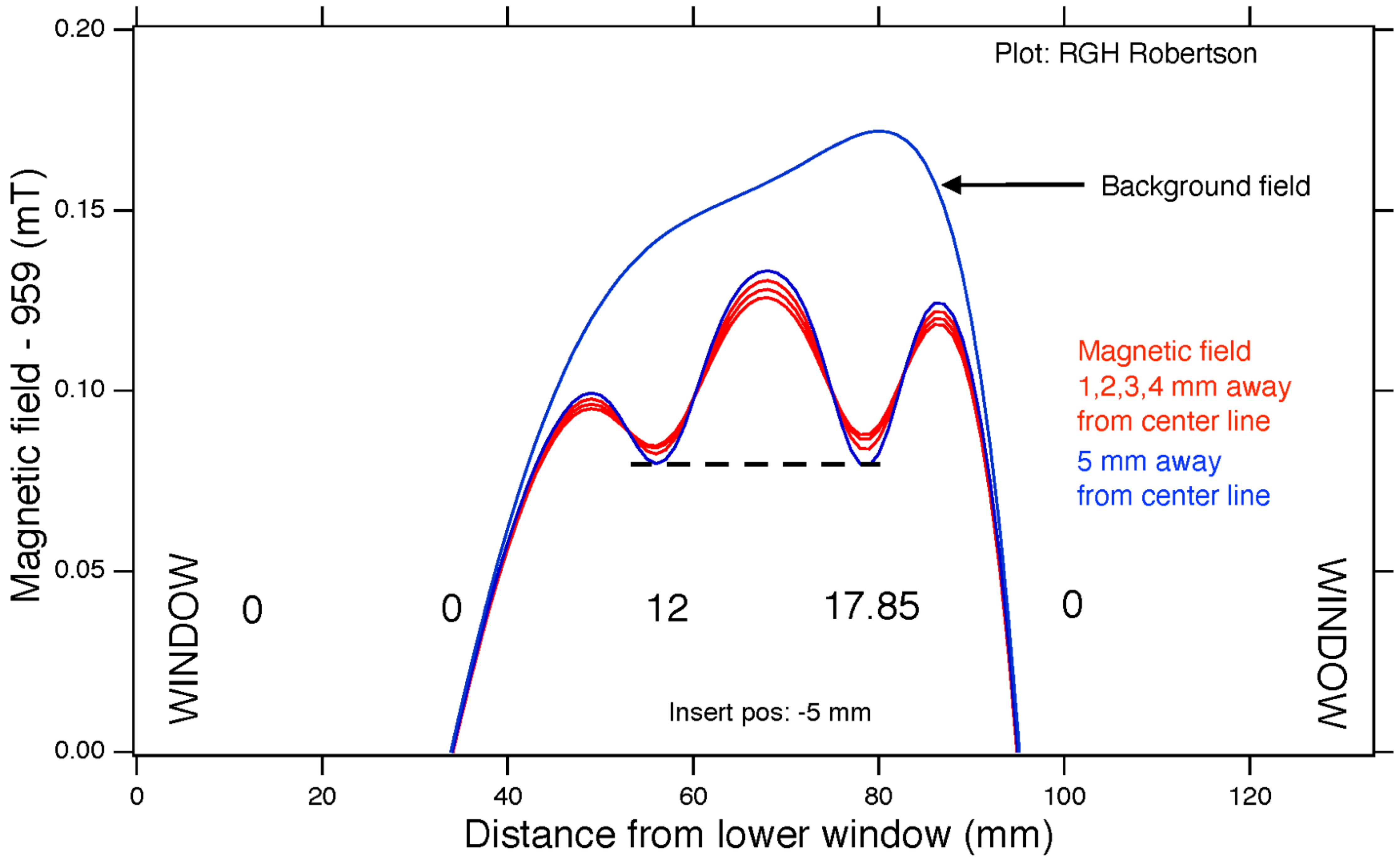
"Shallow trap" configuration with:

- small pitch angle acceptance
- small magnetic field variation
- but high energy resolution



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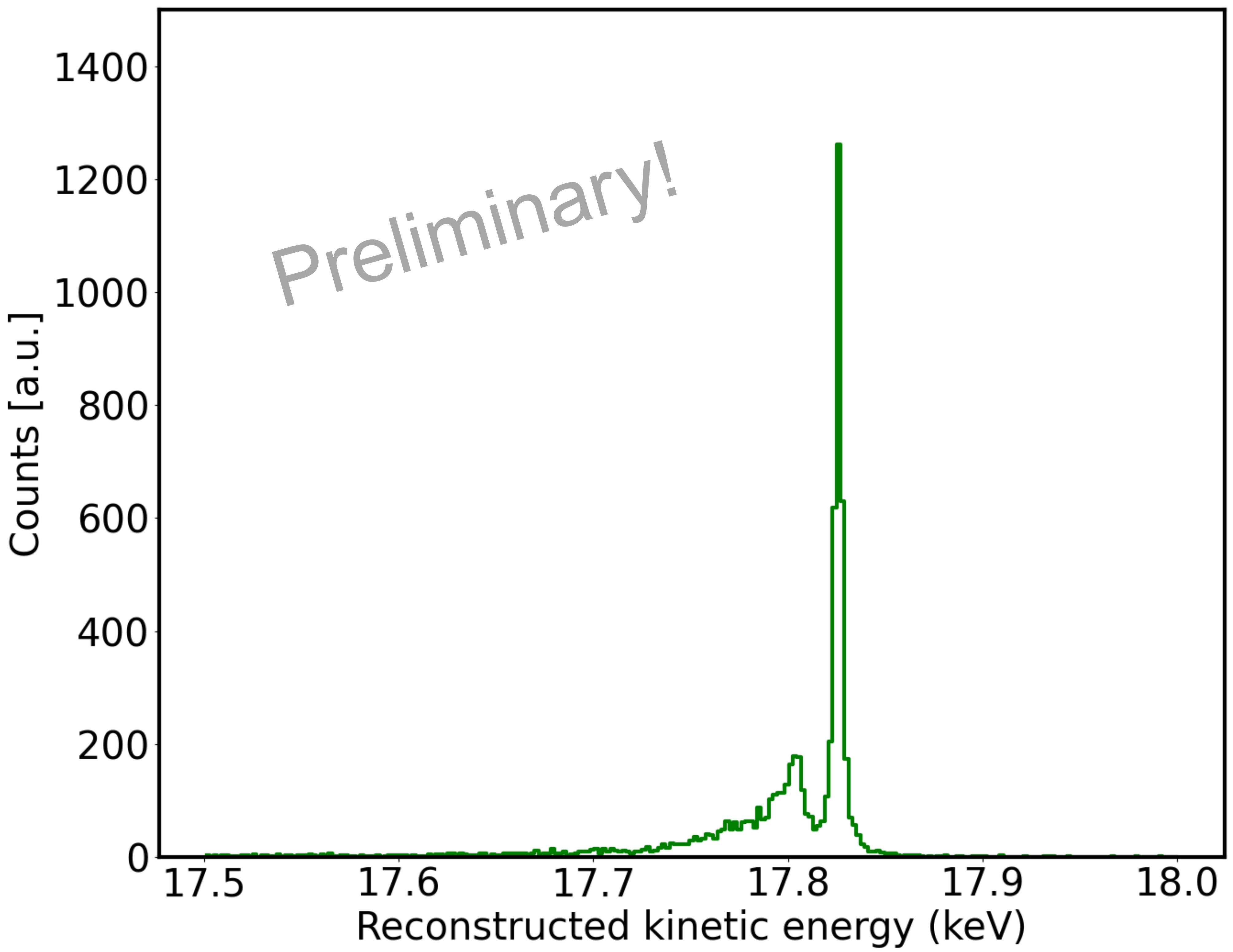
- Kr decay physics: shake-up and shake-off
  - ^{83m}Kr used in many other experiment too
    New paper: H. Robertson and *V. Venkatapath*, Phys. Rev. C 102, 035502, 2020
- e^{-} - scattering in (high-density) gas column, background gases, missed first track



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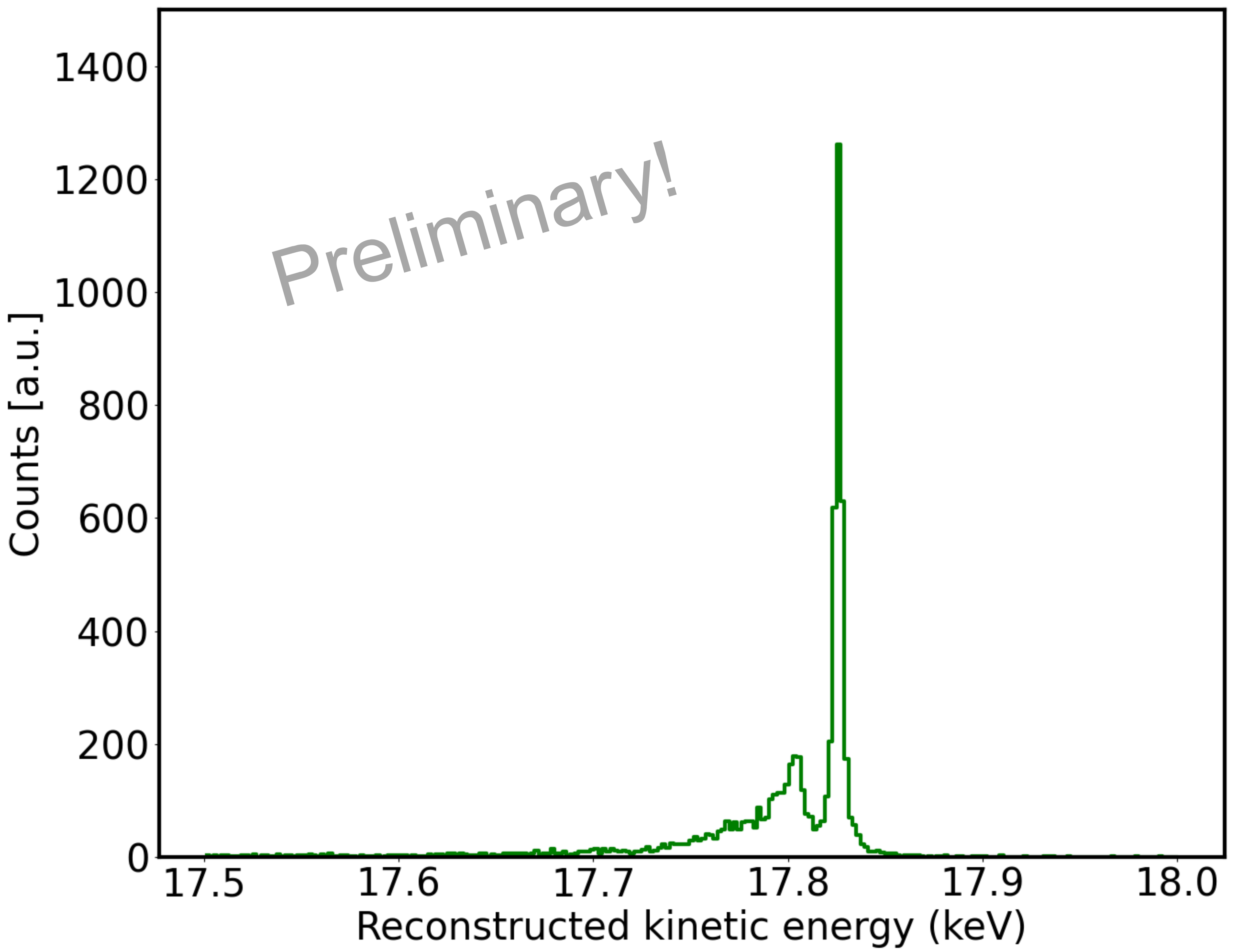
Measured line width: (2.8 ± 0.1) eV
Instrumental width: (1.7 ± 0.1) eV



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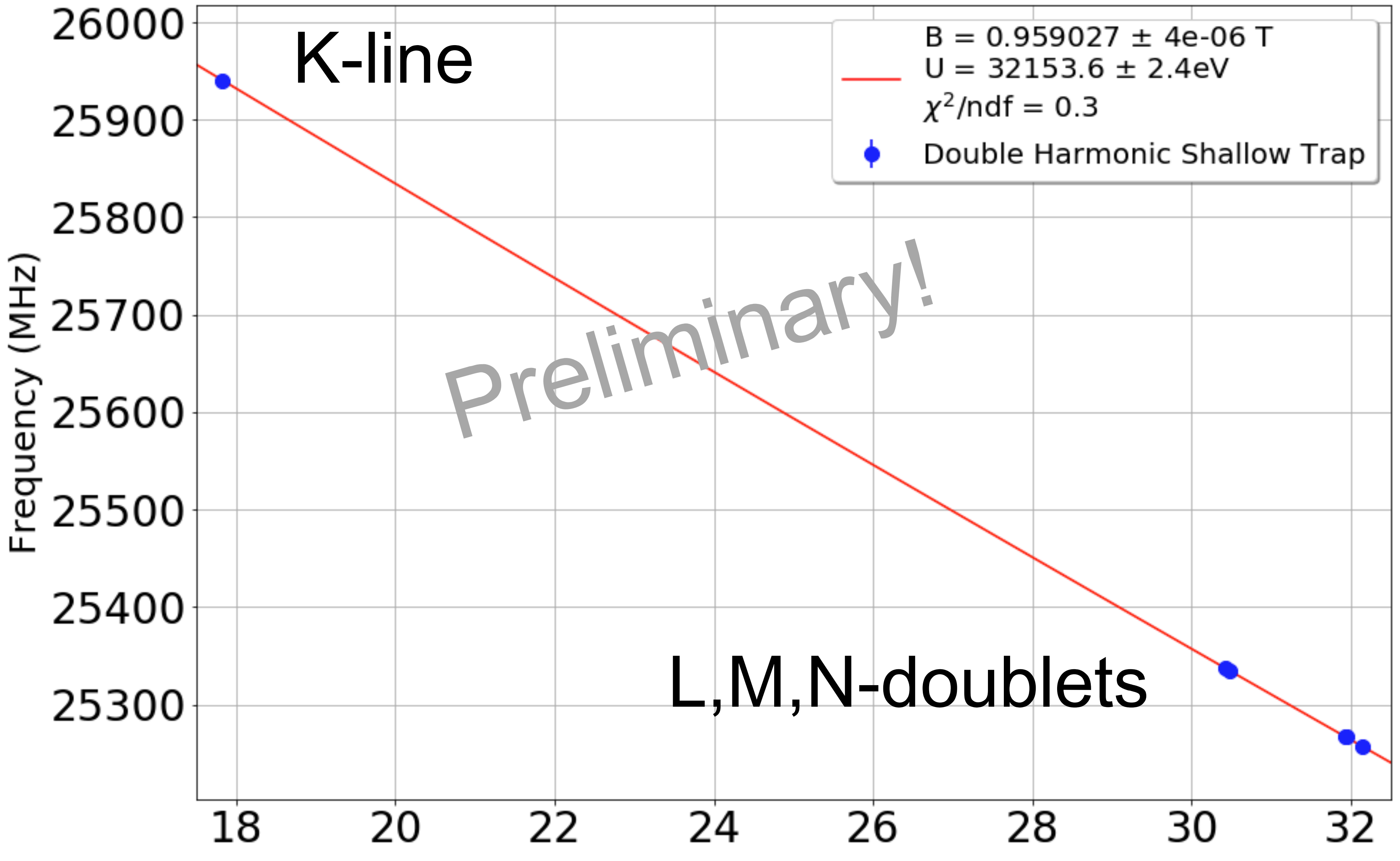
Plot by A. Ashtari Esfahani



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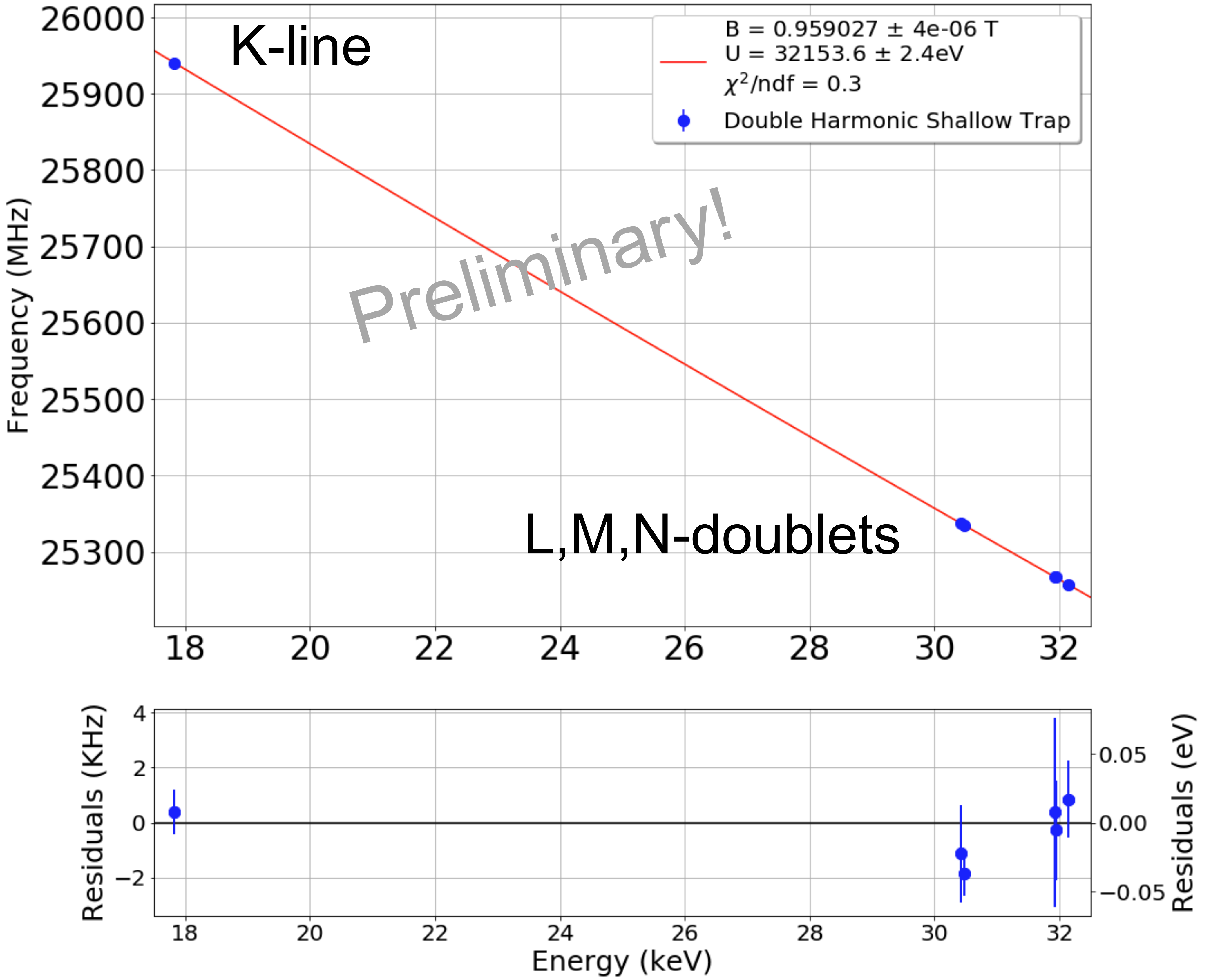

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- Determine energy of 32-keV γ-line: (32153.6 ± 2.4) eV
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  Venos et al., NIM A 560, 2, 352-359, 2006

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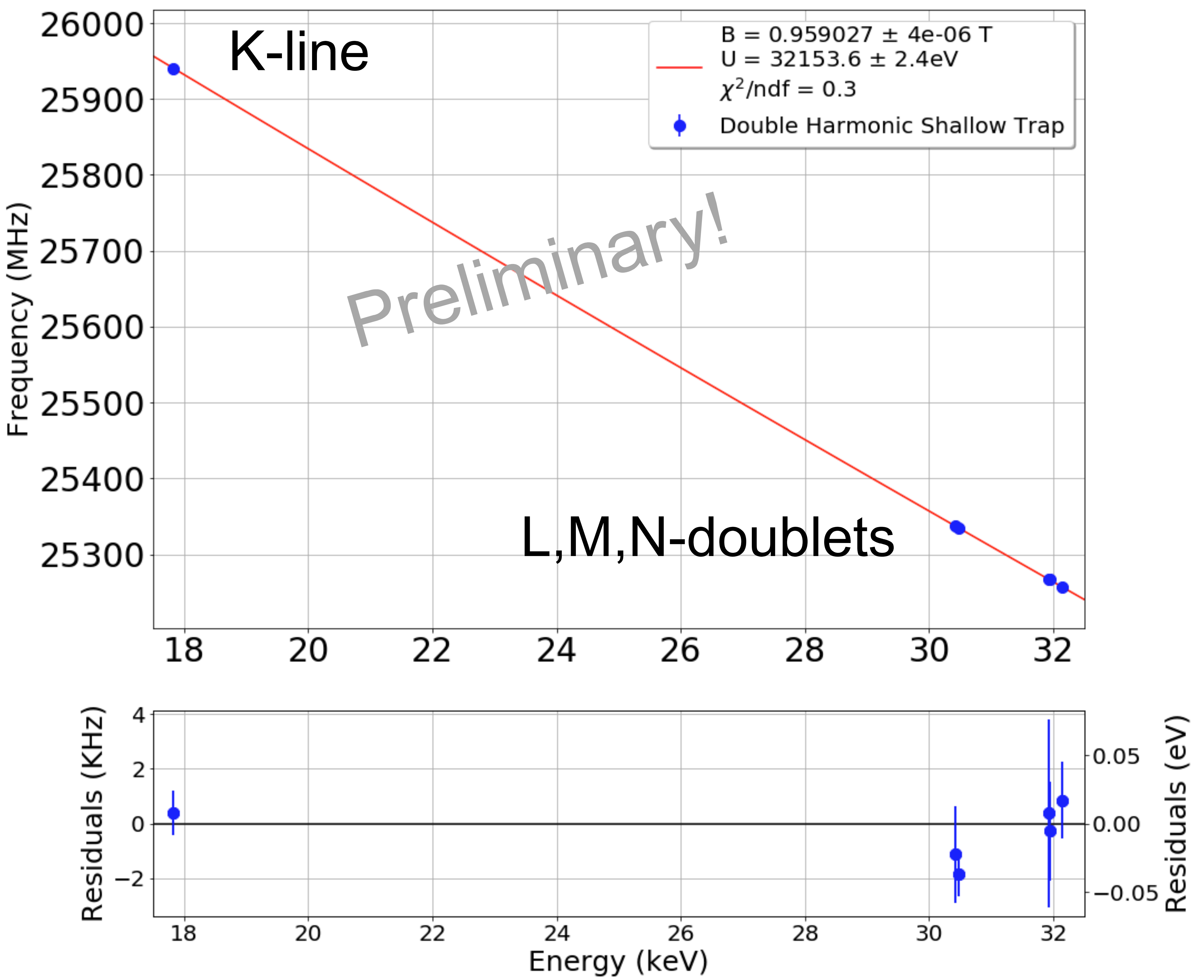

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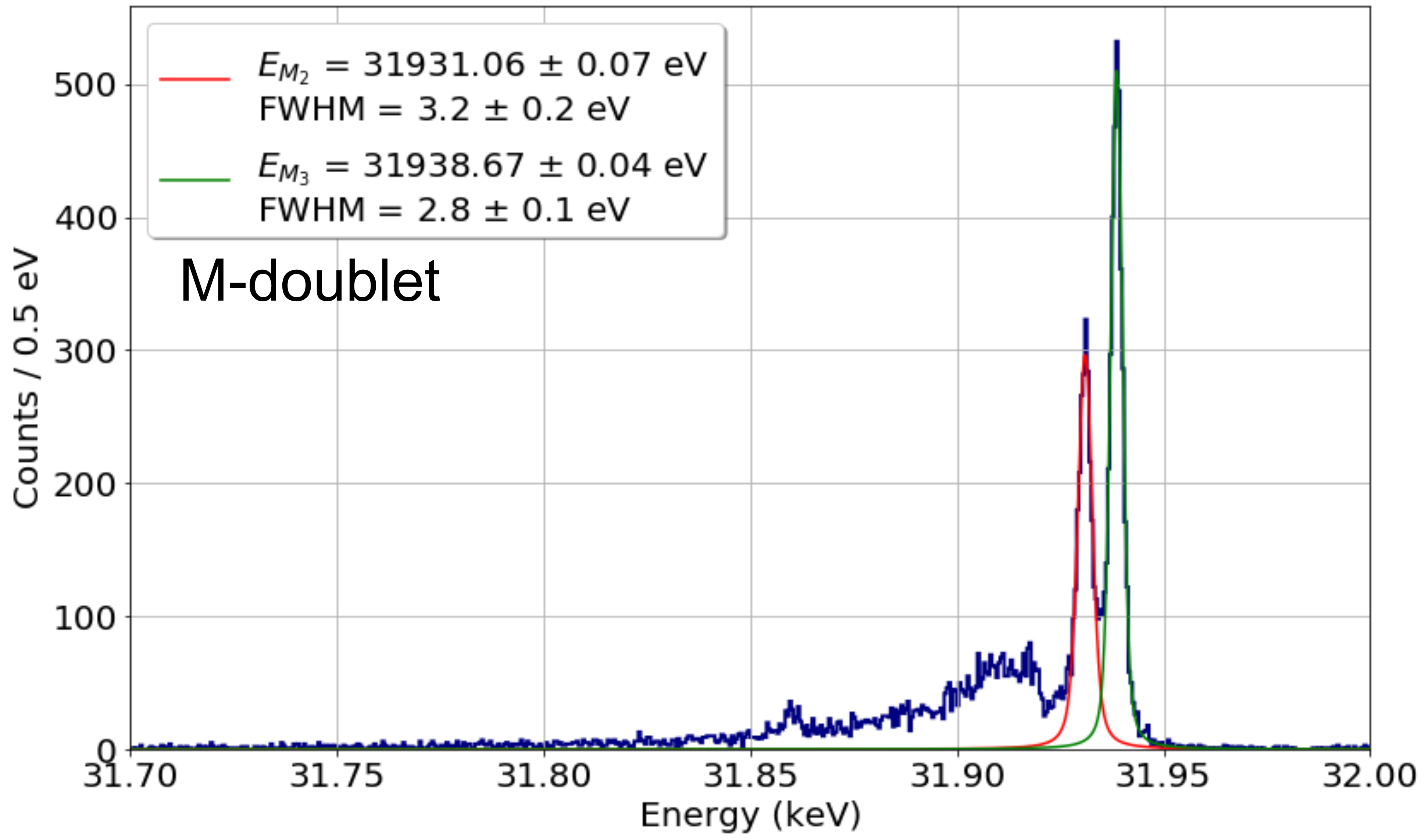
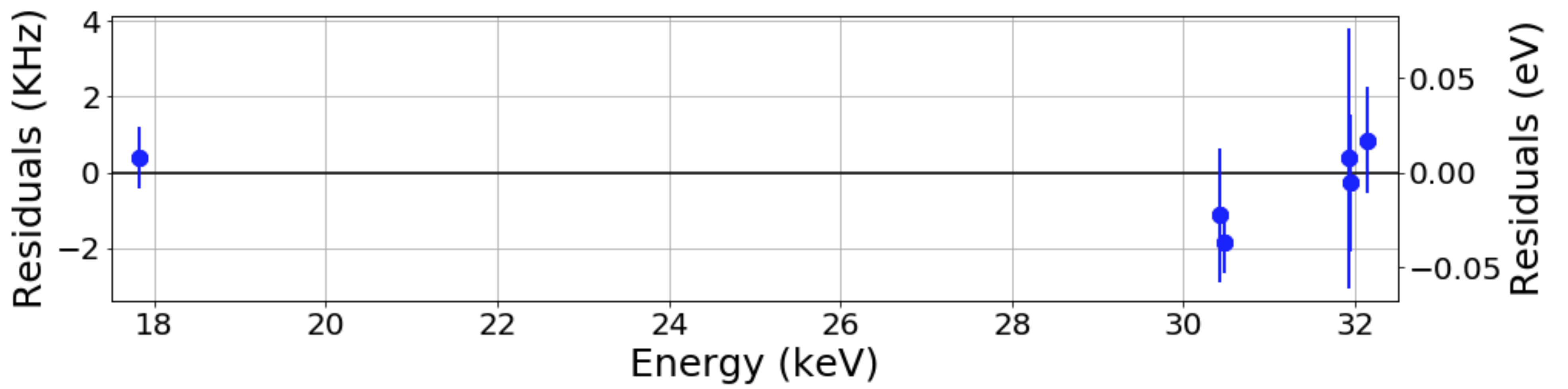
  Residuals < 50 meV (across 14 keV, $< 3 \cdot 10^{-6}$)

- Determine energy of 32-keV γ-line: (32153.6 ± 2.4) eV
  Excellent agreement with literature value: (32151.7± 0.5) eV
  Venos et al., NIM A 560, 2, 352-359, 2006

Plot by A. Ashtari Esfahani





JG|U

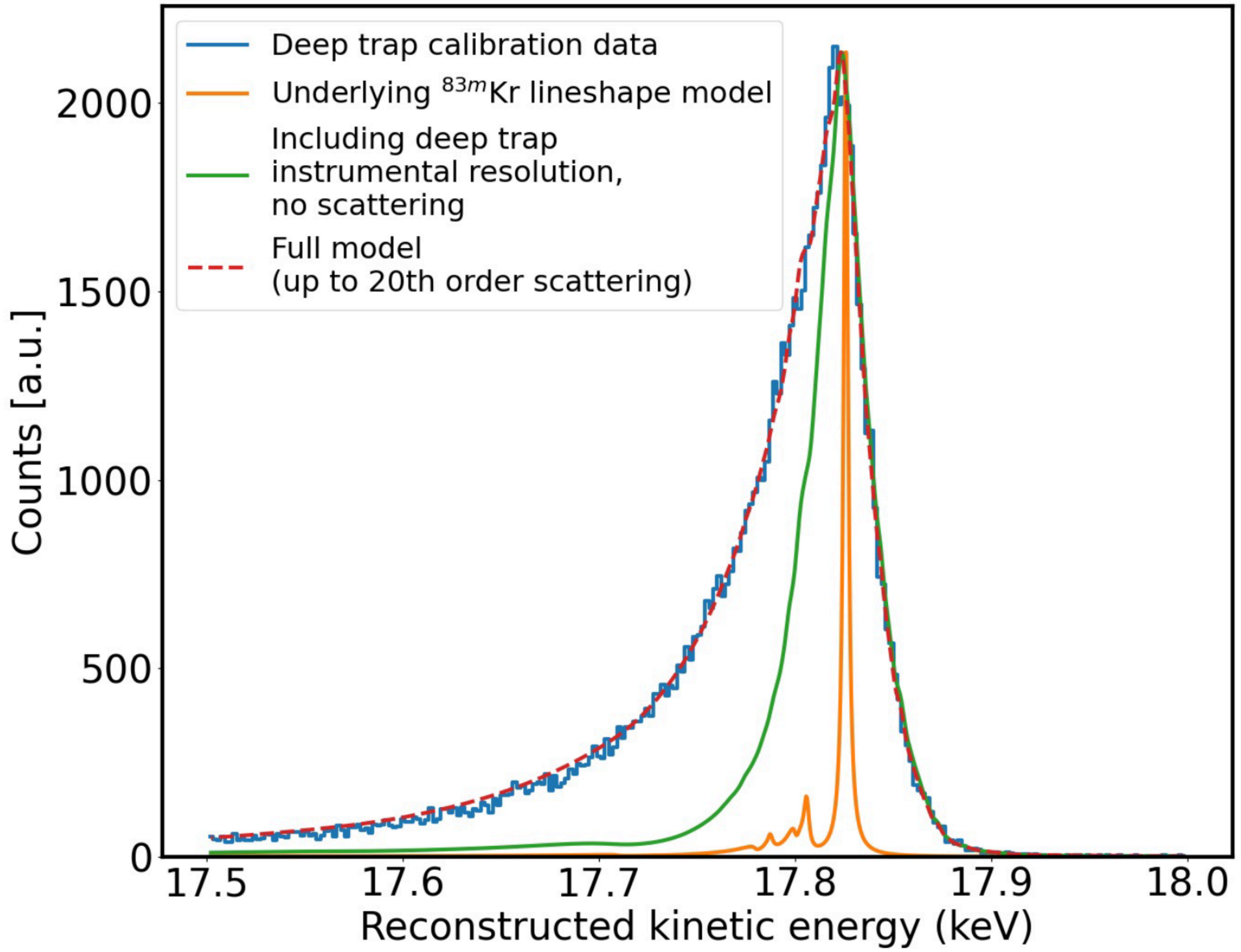
Project 8 phase II: Calibration measurement using ^{83m}Kr

Low T_2 decay rate!

“Deep trap” configuration with:

- large pitch angle acceptance
- larger magnetic field variation
- but lower energy resolution

Detector response model
verified for deep trap configuration!



Project 8 phase II: Calibration measurement using ^{83m}Kr

Project 8 phase II: Calibration measurement using ^{83m}Kr

Detector response is frequency dependent!

Sweep position of 17.8 keV ^{83m}Kr across frequency ROI by changing the background field!

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

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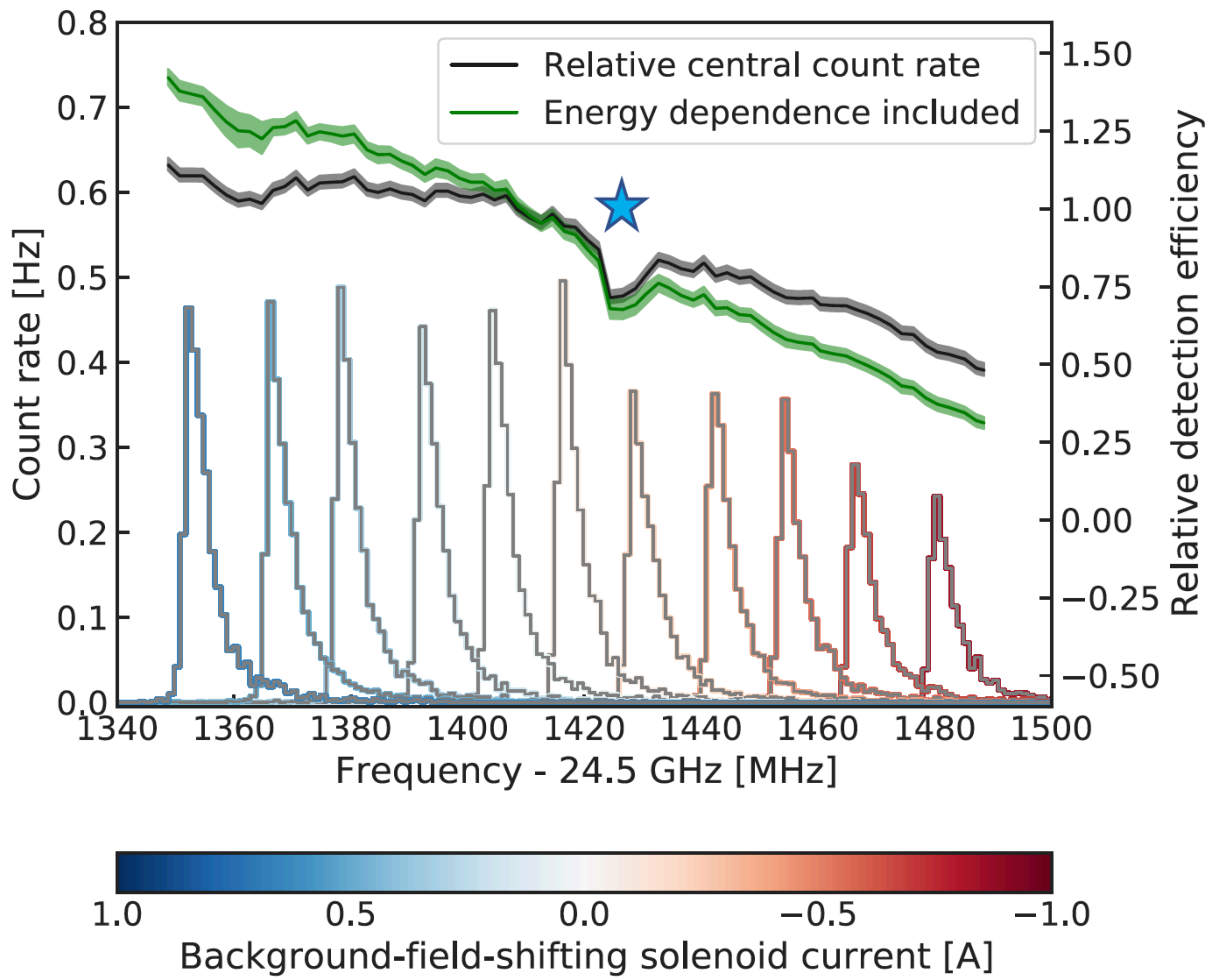
Direct characterization of frequency response variation of waveguide setup

Notch in detection efficiency:

- TM01 mode interaction in the waveguide "cavity" due to imperfections
- Characterized, quantitatively understood and accounted in the spectral analysis



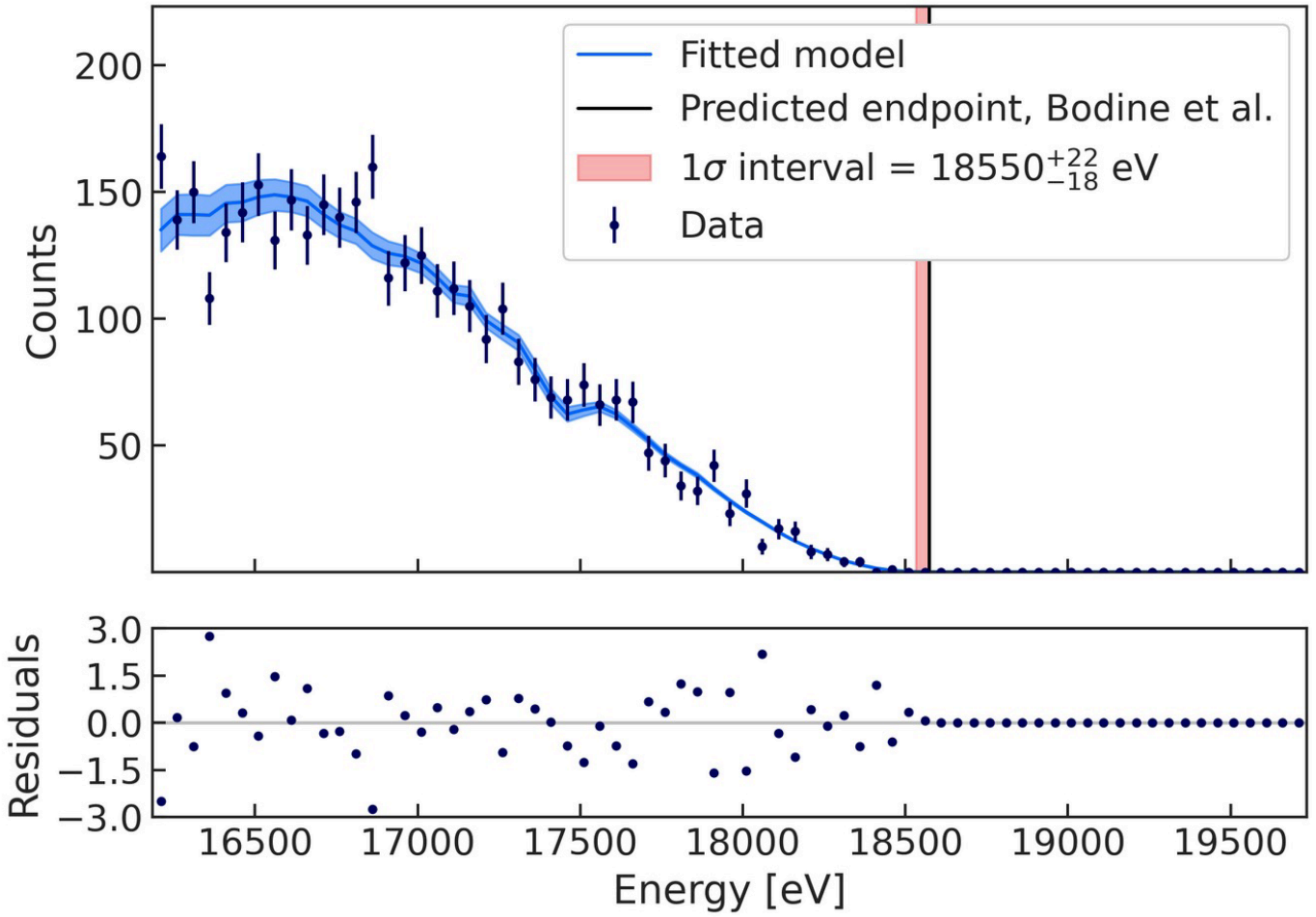
JG|U

Project 8 phase II: results from molecular tritium

T_2 endpoint consistent with literature value

First frequency-based neutrino mass measurement

Extremely low background rate, no events beyond the endpoint region



Frequentist and Bayesian analyses:

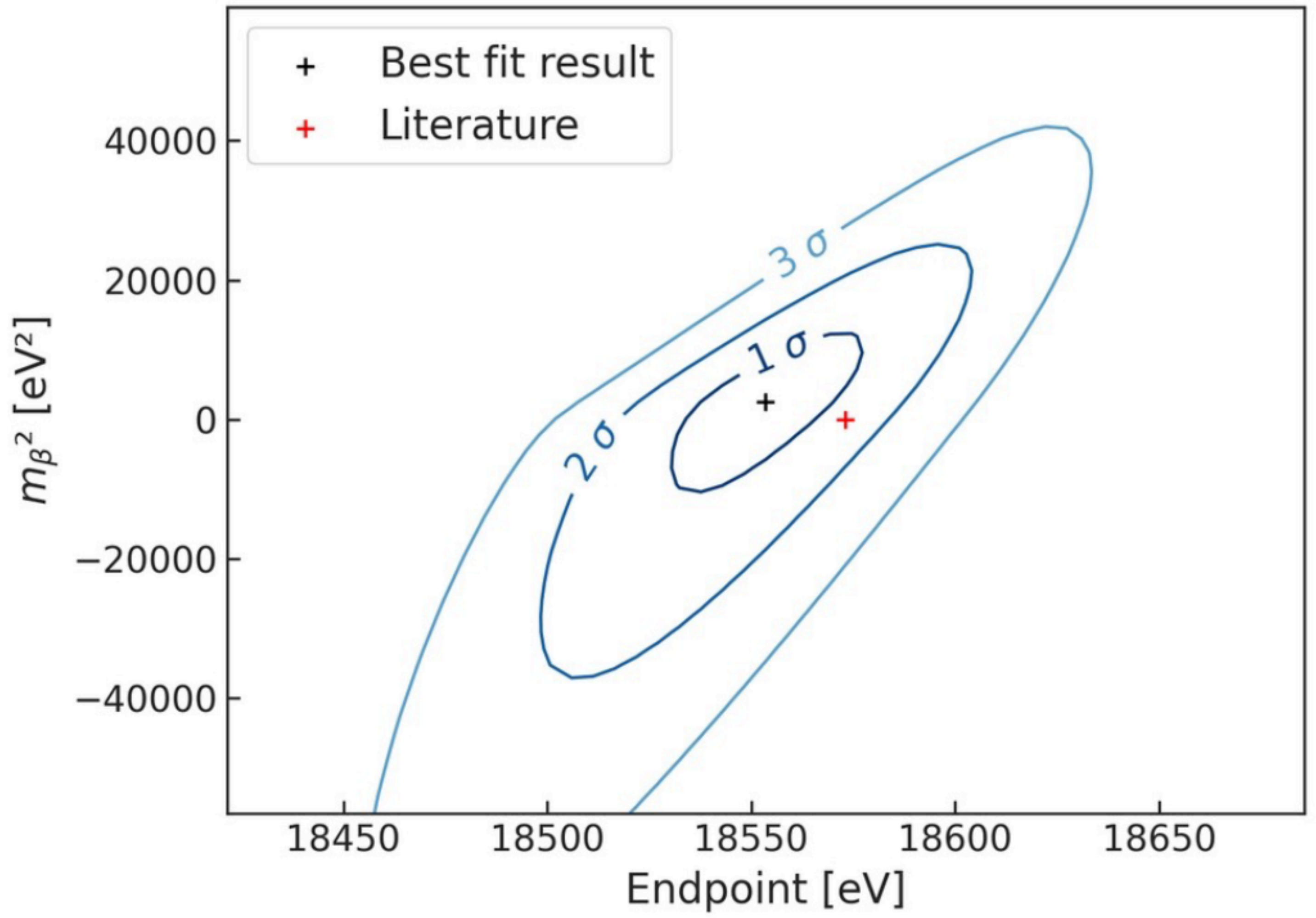
T2 endpoint:

$$E_0^{\text{Freq.}} = \left(18550^{+22}_{-18}\right)\ \text{eV}\ (1\sigma)$$
$$E_0^{\text{Bay.}} = \left(18553^{+17}_{-17}\right)\ \text{eV}\ (1\sigma)$$

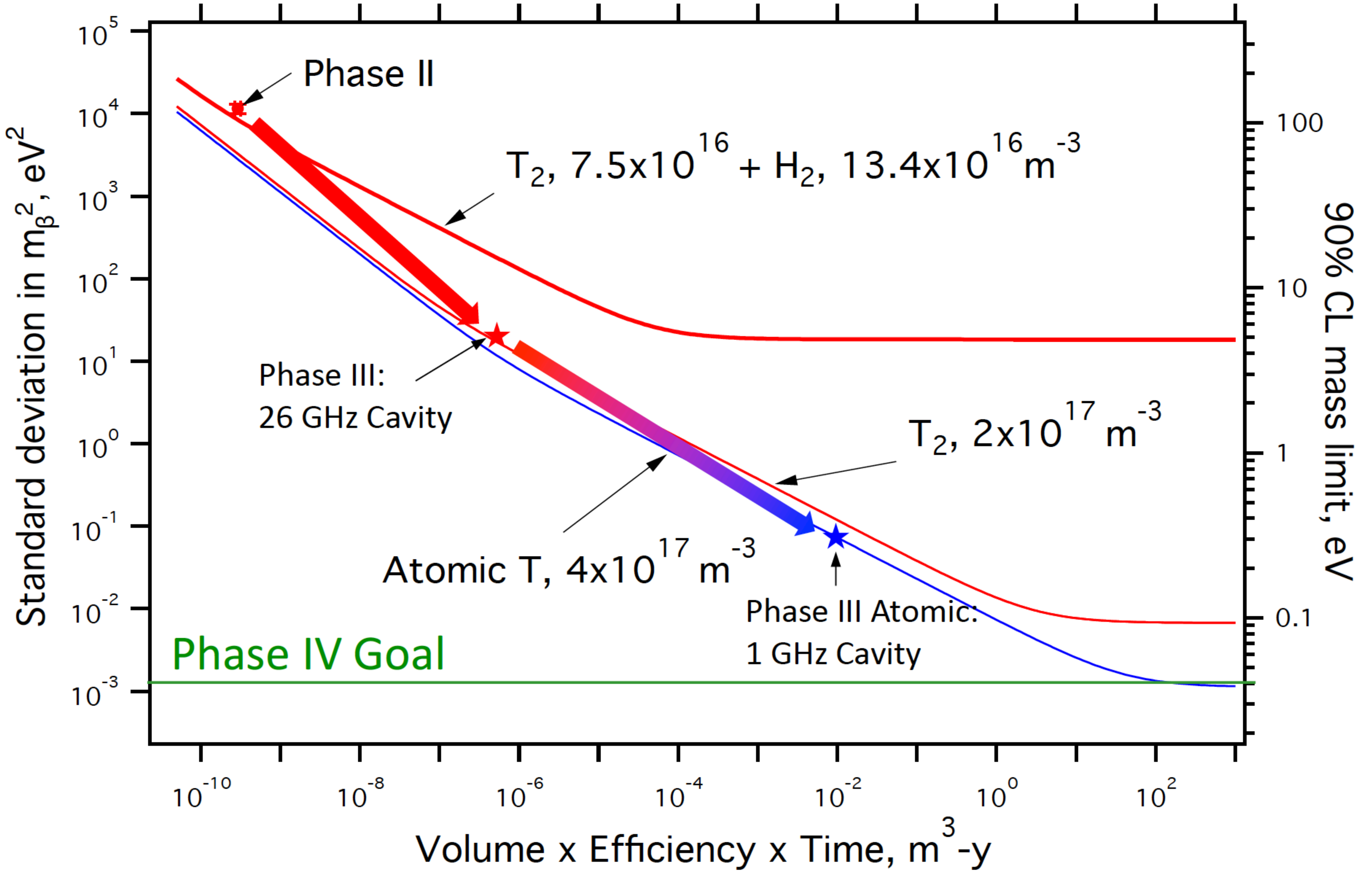
Neutrino mass:

$$m_\beta^{\text{Freq.}} \leq 178\,\text{eV/c}^2\ (90\,\%\,\text{C.L.})$$
$$m_\beta^{\text{Bay.}} \leq 169\,\text{eV/c}^2\ (90\,\%\,\text{C.I.})$$

Background rate: $\leq 3 \times 10^{-10}\,\text{eV}^{-1}\text{s}^{-1}\ (90\,\%\,\text{C.I.})$



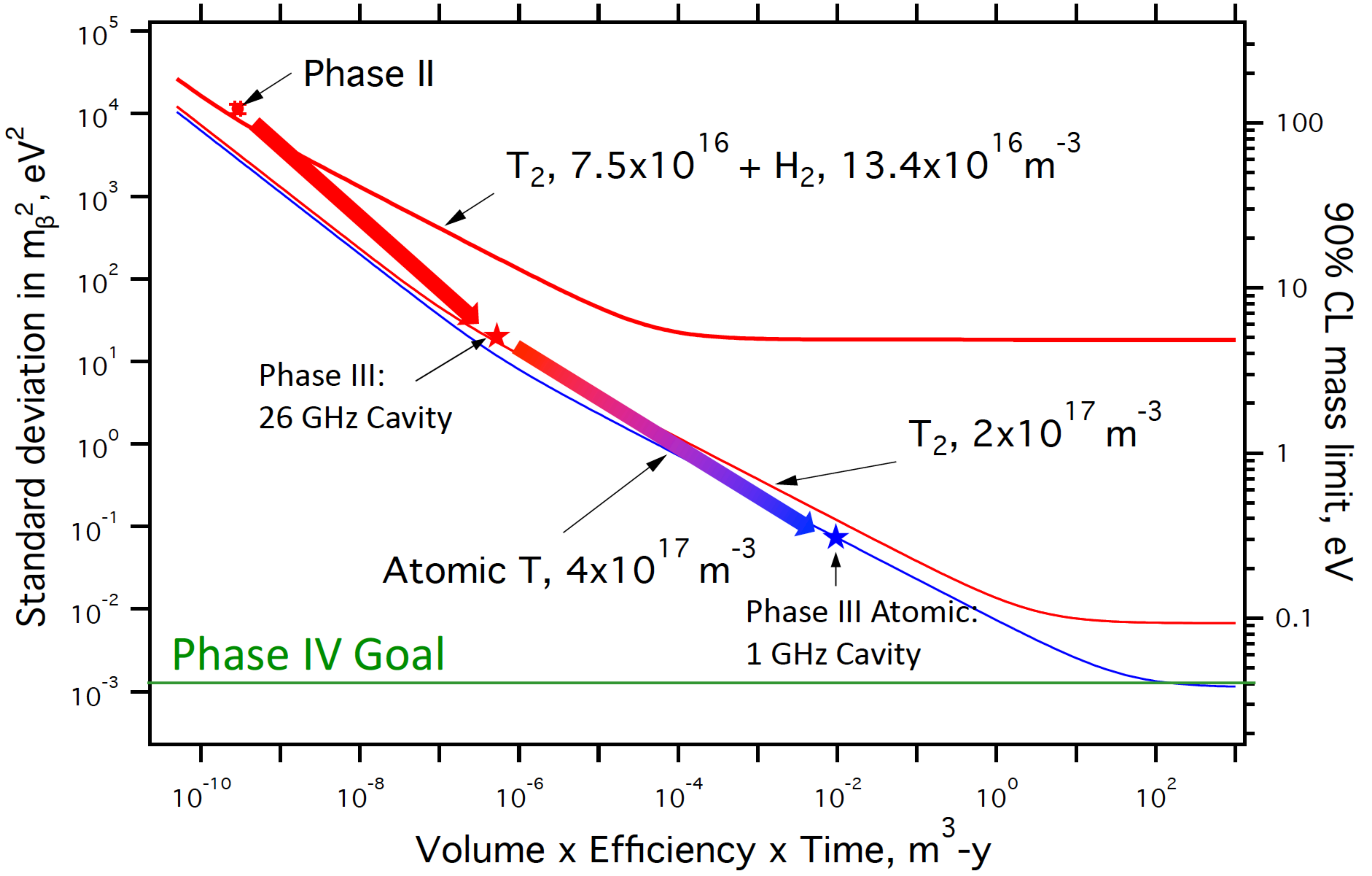
Project 8: The next steps to higher neutrino mass sensitivity …



Project 8: The next steps to higher neutrino mass sensitivity …

Improved control of systematic effects:

- Magnetic field characterization
- Control of scattering
- Gas column composition and stability



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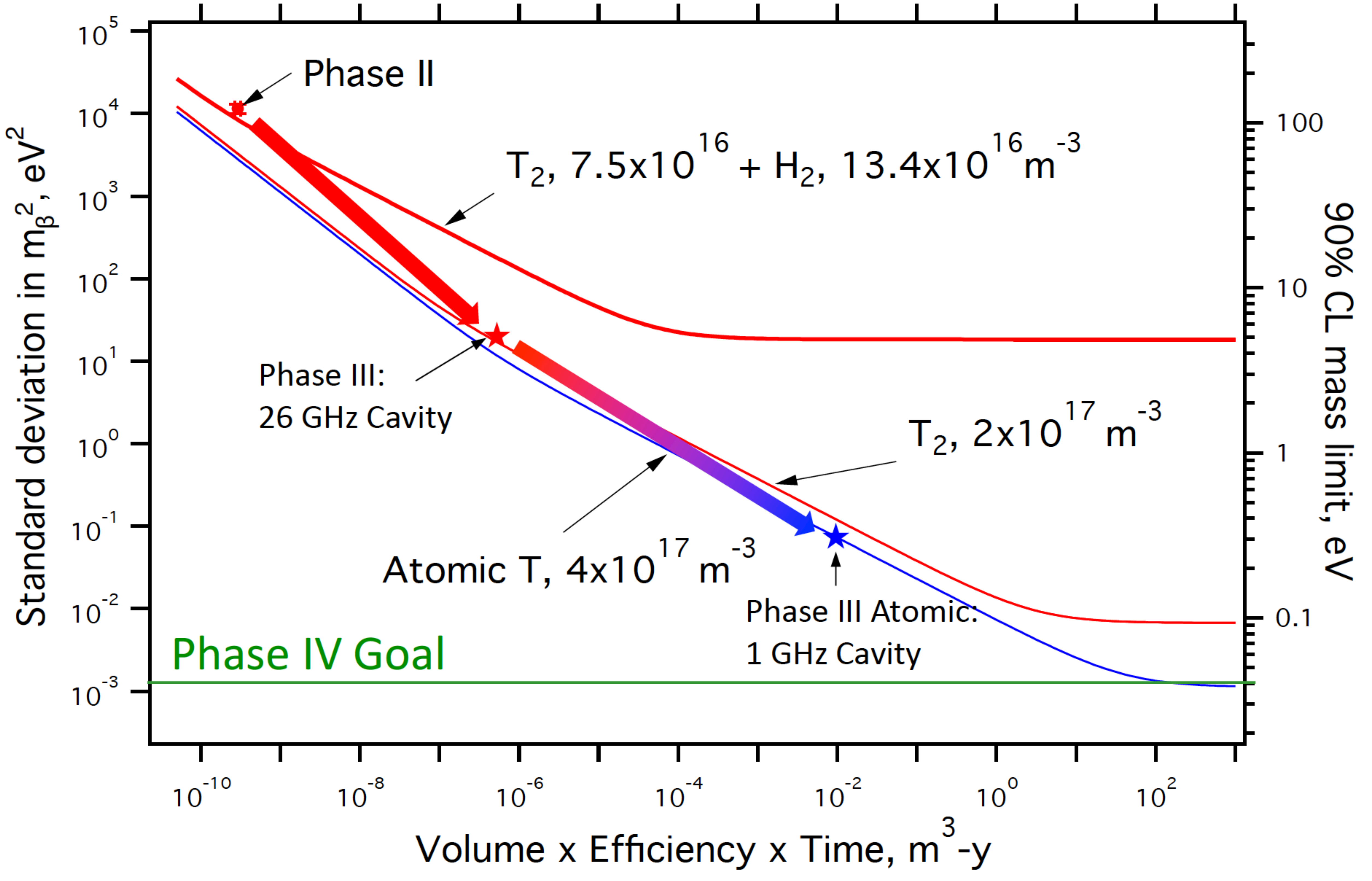
Larger volume ⇒ higher statistics, but signal dilution



Project 8: The next steps to higher neutrino mass sensitivity …

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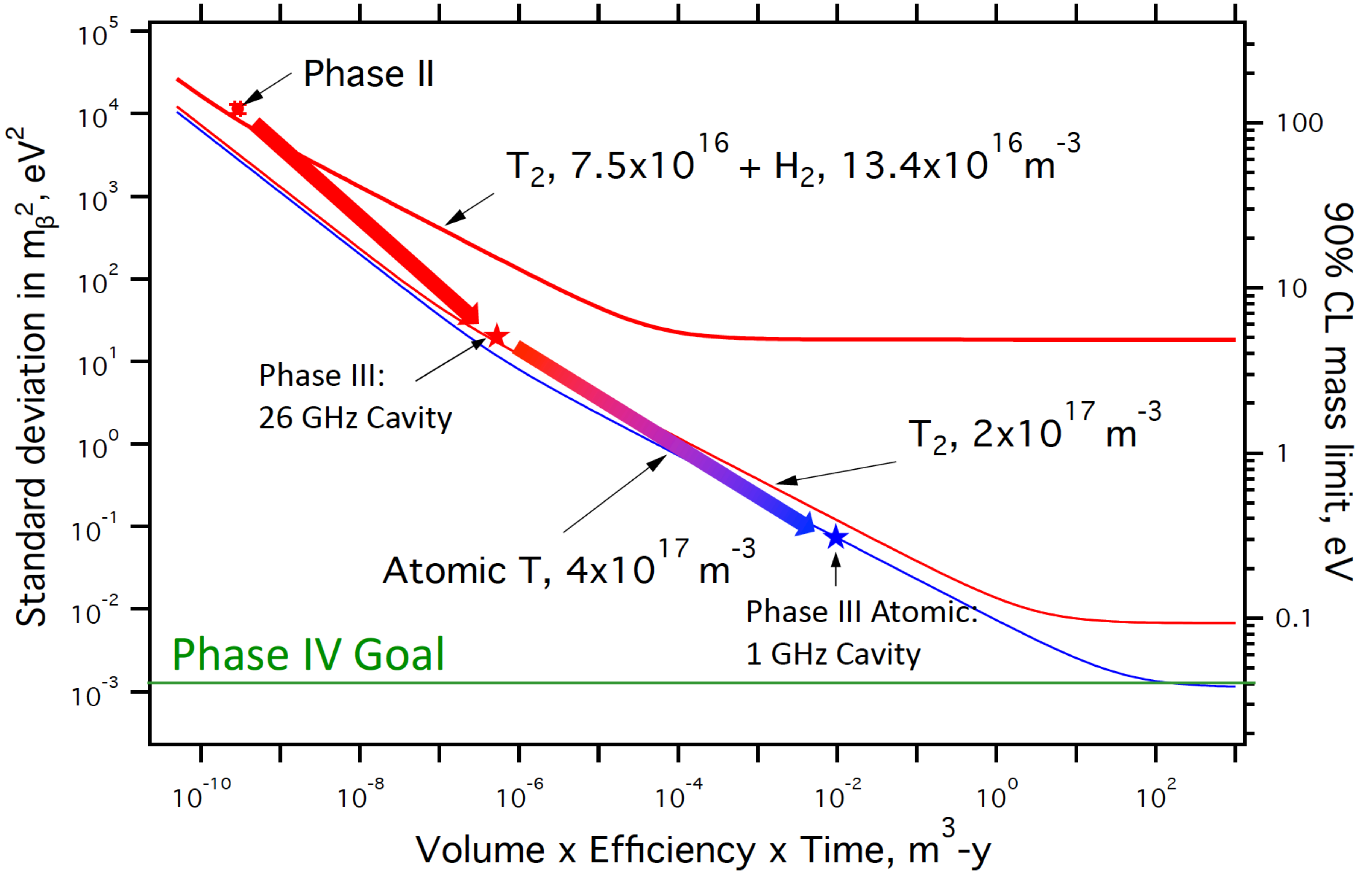
Larger volume ⇒ higher statistics, but signal dilution

Higher density ⇒ higher statistics, but much shorter tracks



Project 8: The next steps to higher neutrino mass sensitivity …

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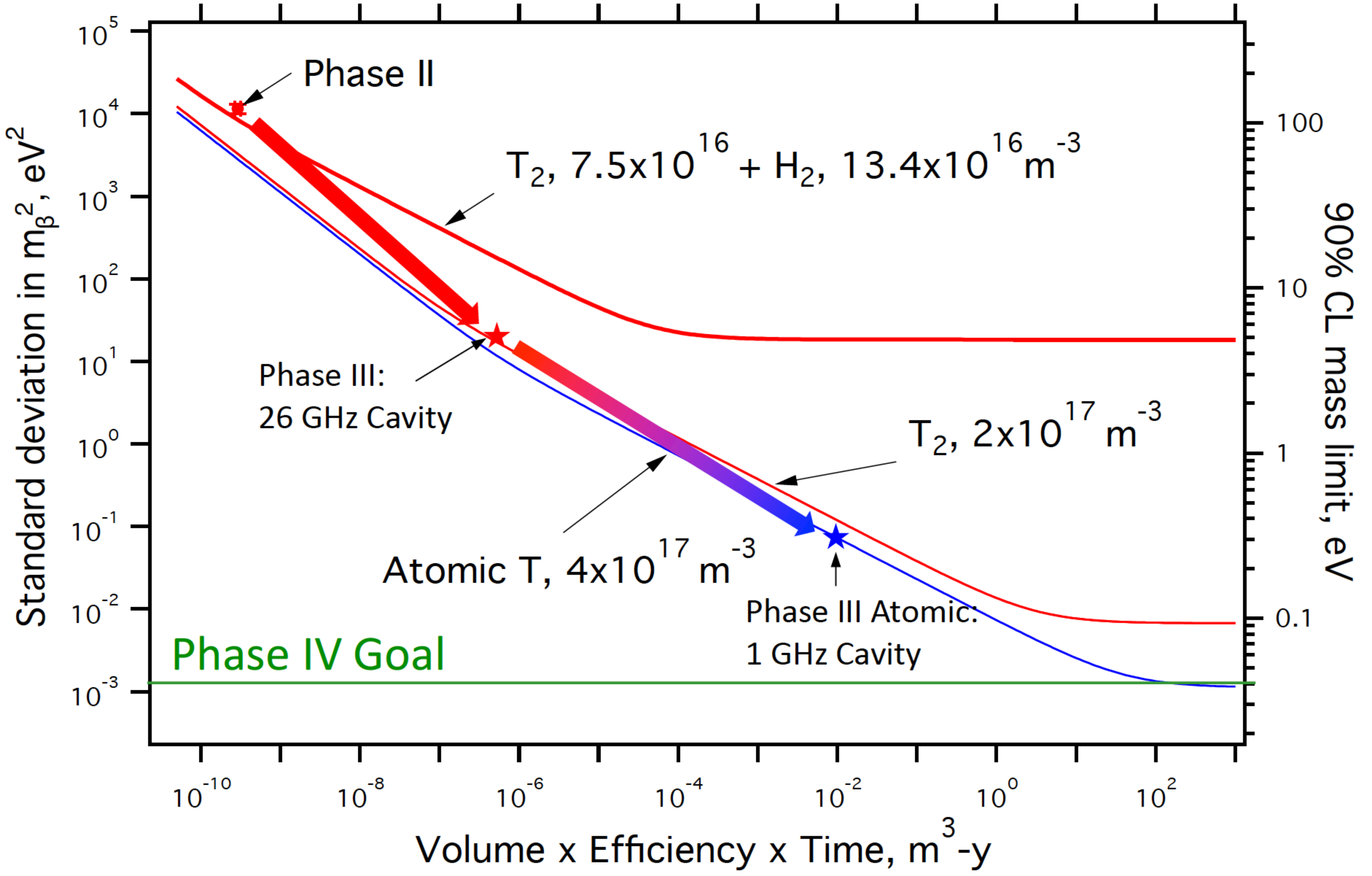
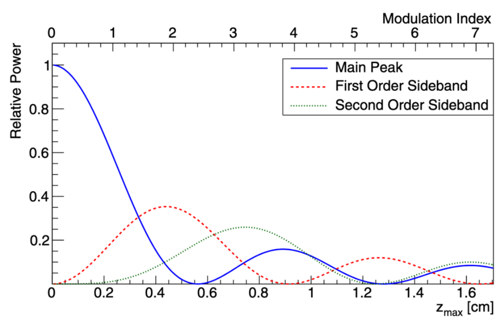
Development of cold atomic hydrogen/tritium sources

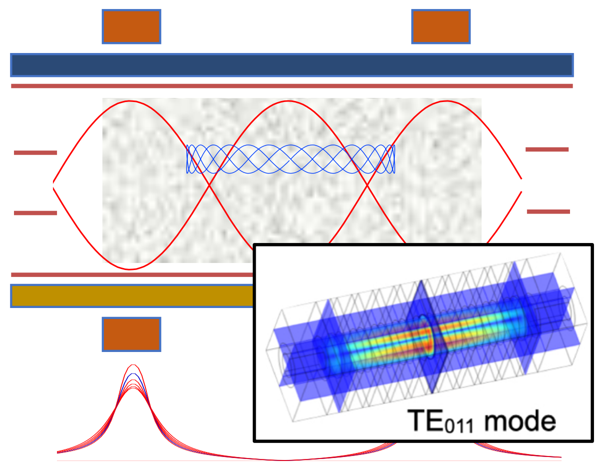


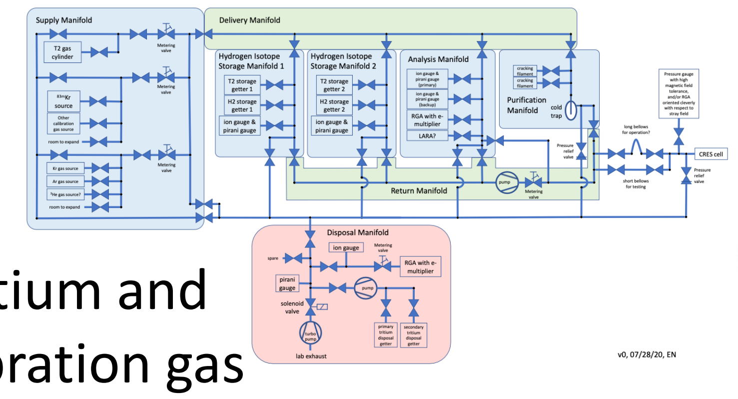
… provide many research opportunities…

Phenomenology of CRES

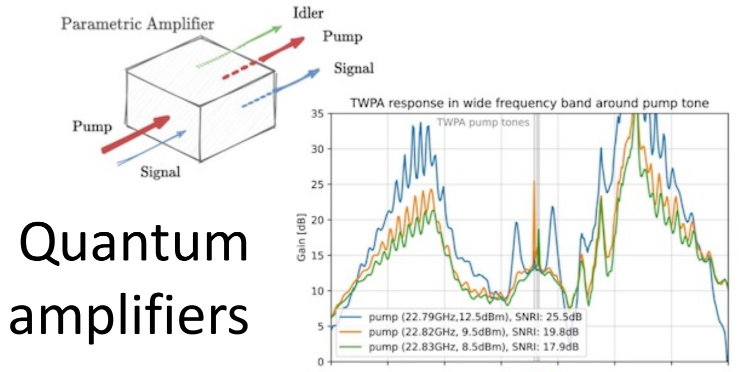


Cavity design





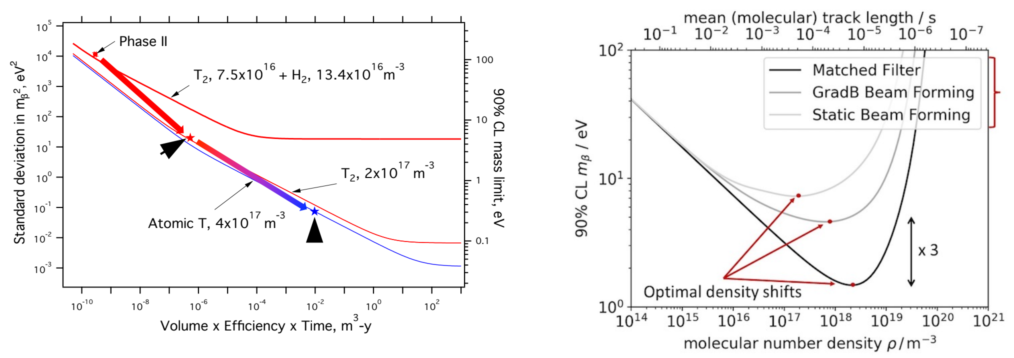
Tritium and calibration gas handling



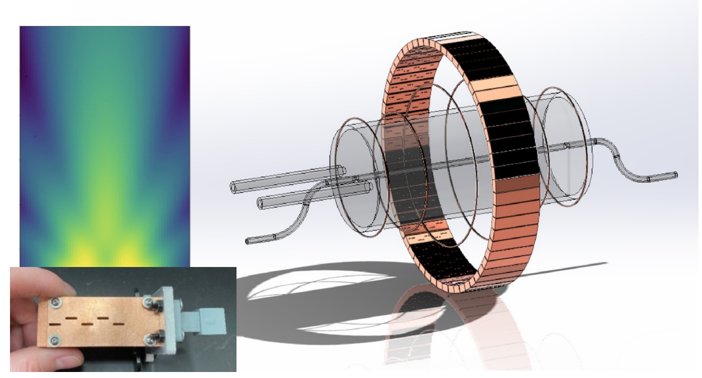
Quantum amplifiers

Electron gun for calibration

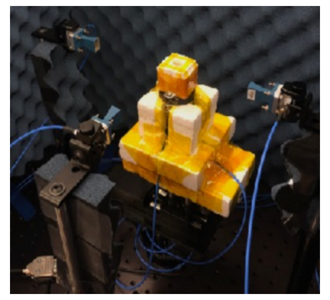
Sensitivity to m_β



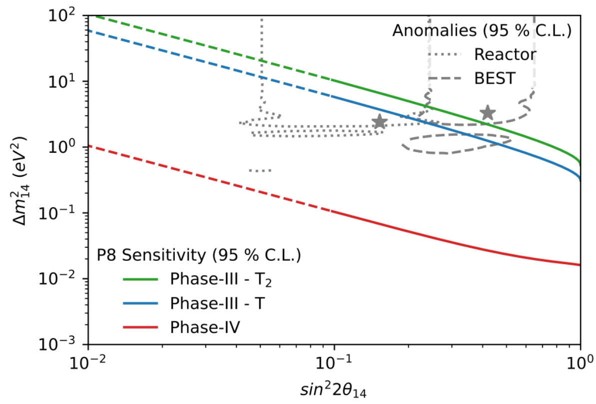
Phased antenna array design



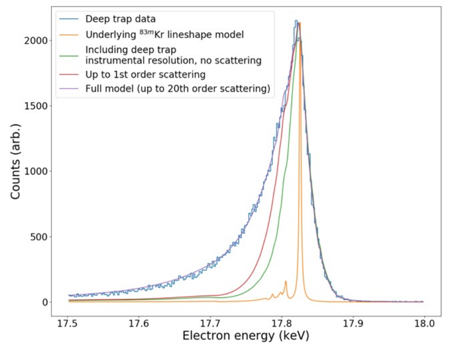
Synthetic CRES antenna



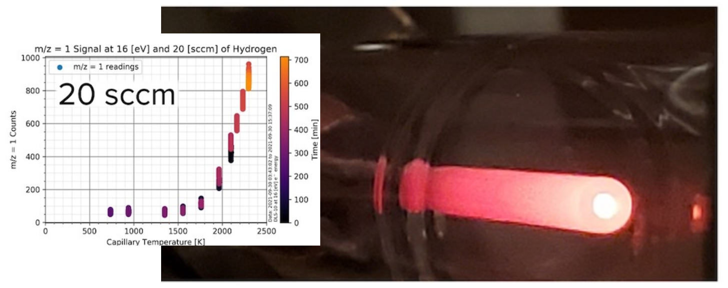
Sensitivity to steriles



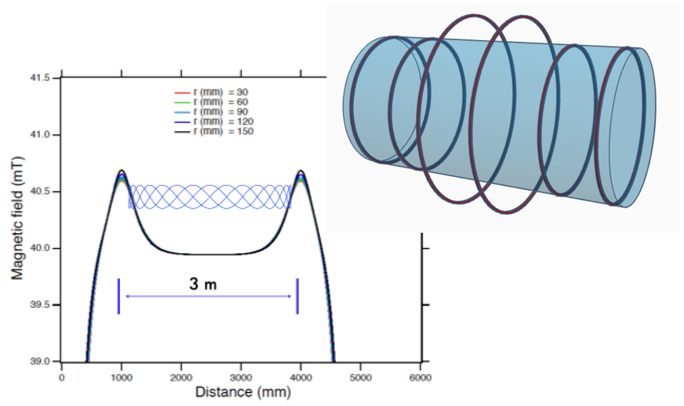
Spectrum analysis



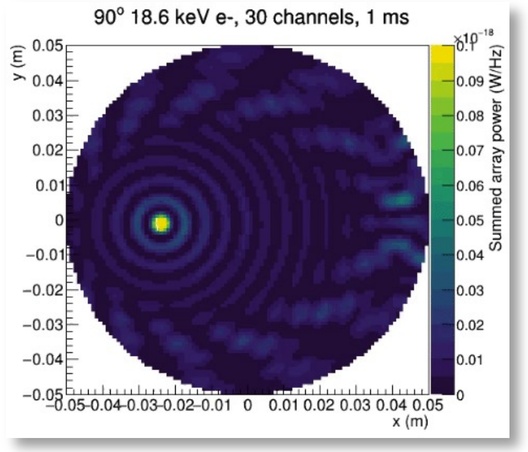
Molecule cracking



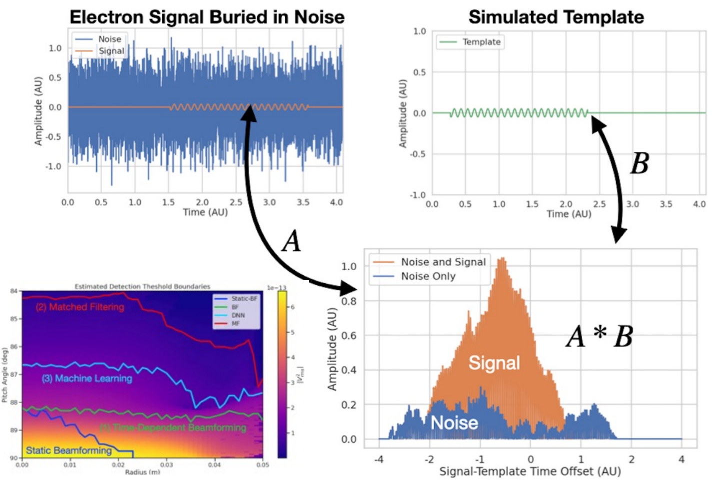
Electron trap design



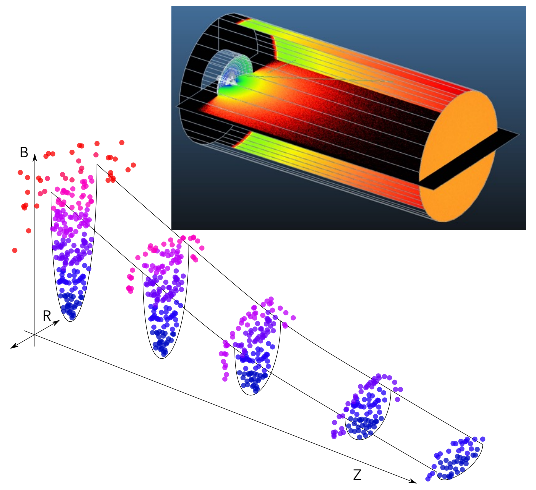
Simulation software development



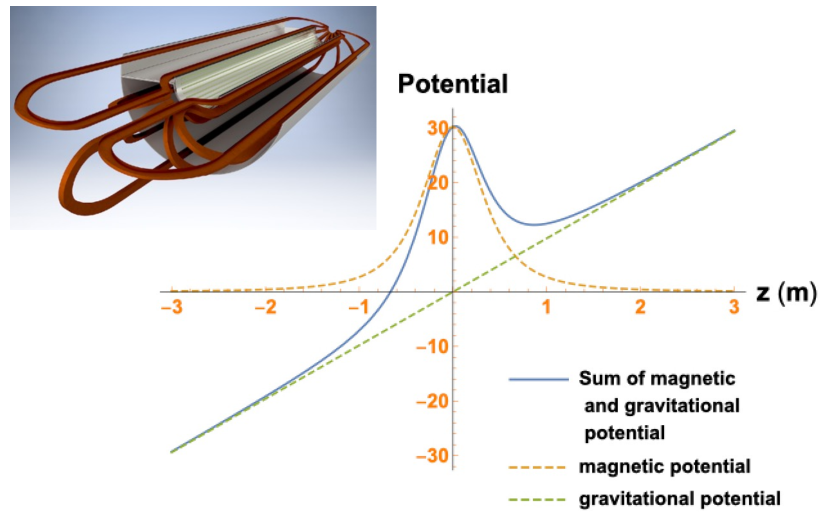
Matched filtering event reconstruction

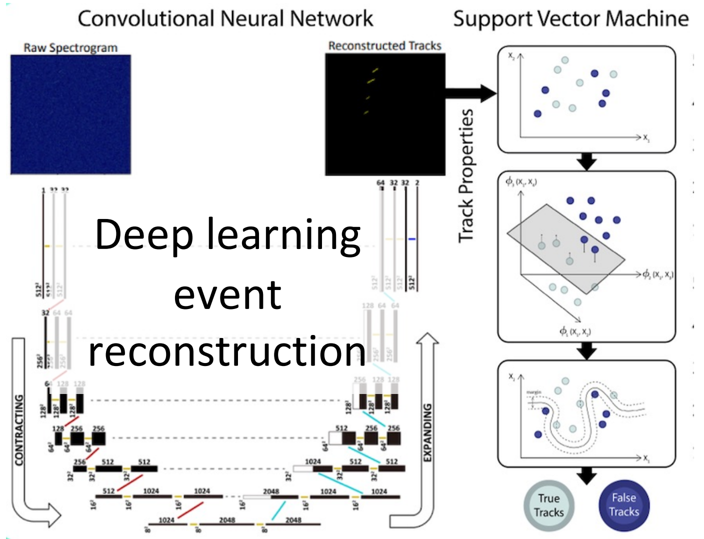


Cooling



Neutral atom trapping

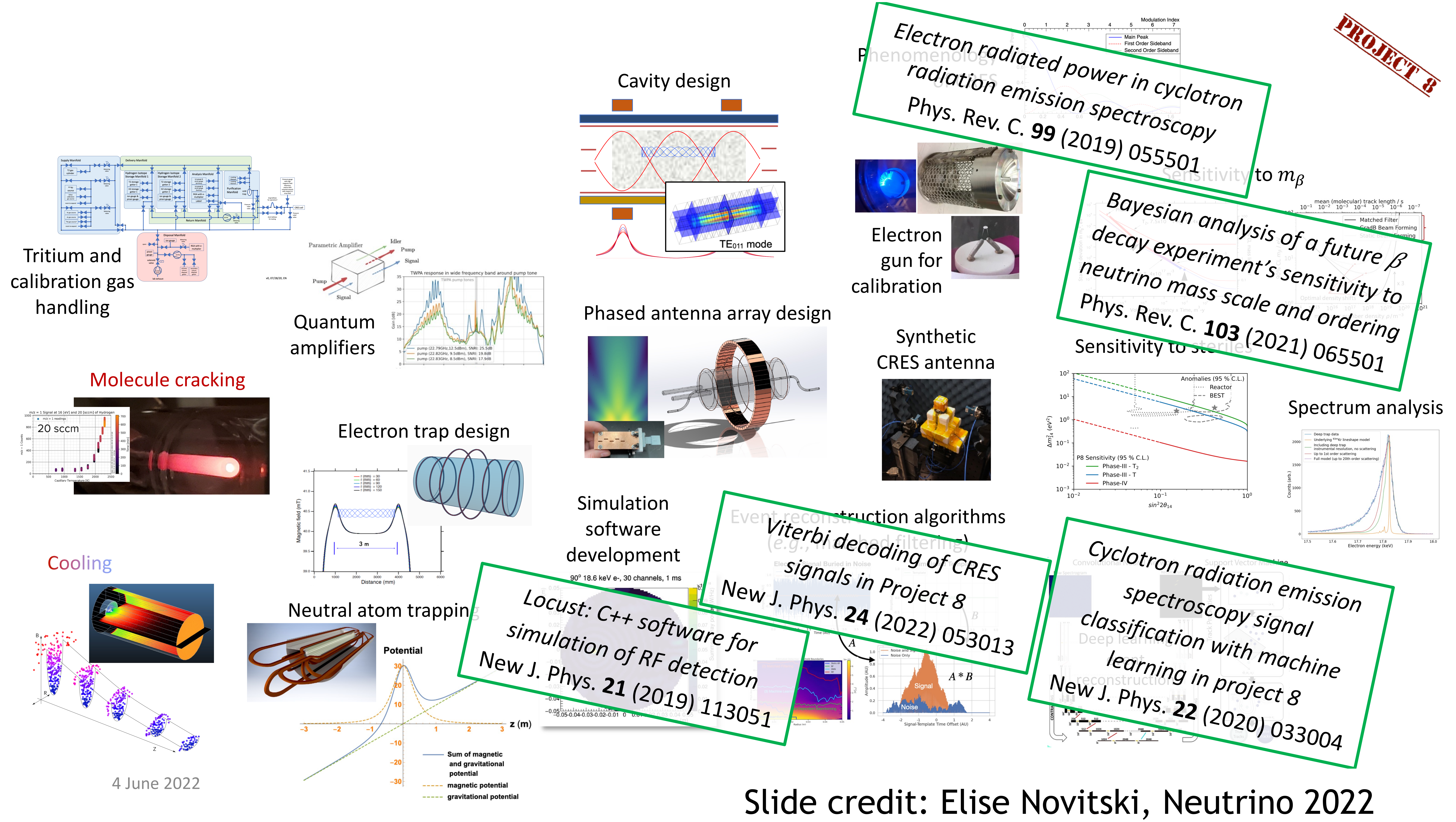




Deep learning event reconstruction

Slide credit: Elise Novitski, Neutrino 2022

… and novel results.



Slide credit: Elise Novitski, Neutrino 2022

^{6}He-CRES: Fierz interference searches with broad-band CRES

Fierz term contribution to differential decay rate

$$w(\langle \mathbf{J} \rangle | E_e, \Omega_e, \Omega_\nu) dE_e d\Omega_e d\Omega_\nu = \frac{F(\pm Z, E_e)}{(2\pi)^5} p_e E_e (E_0 - E_e)^2 dE_e d\Omega_e d\Omega_\nu \times$$

$$\xi \left\{ 1 + a \frac{\mathbf{p}_e \cdot \mathbf{p}_\nu}{E_e E_\nu} + b \frac{m_e}{E_e} + \frac{\langle \mathbf{J} \rangle}{J} \cdot \left[A \frac{\mathbf{p}_e}{E_e} + B \frac{\mathbf{p}_\nu}{E_\nu} + D \frac{\mathbf{p}_e \times \mathbf{p}_\nu}{E_e E_\nu} \right] \right\} ,$$

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First order sensitivity to new physics: $b \propto \mathrm{Re}\left(\left| M_F \right|^2 \frac{C_S + C_S'}{C_V} + \left| M_{GT} \right|^2 \frac{C_T + C_T'}{C_A} \right)$

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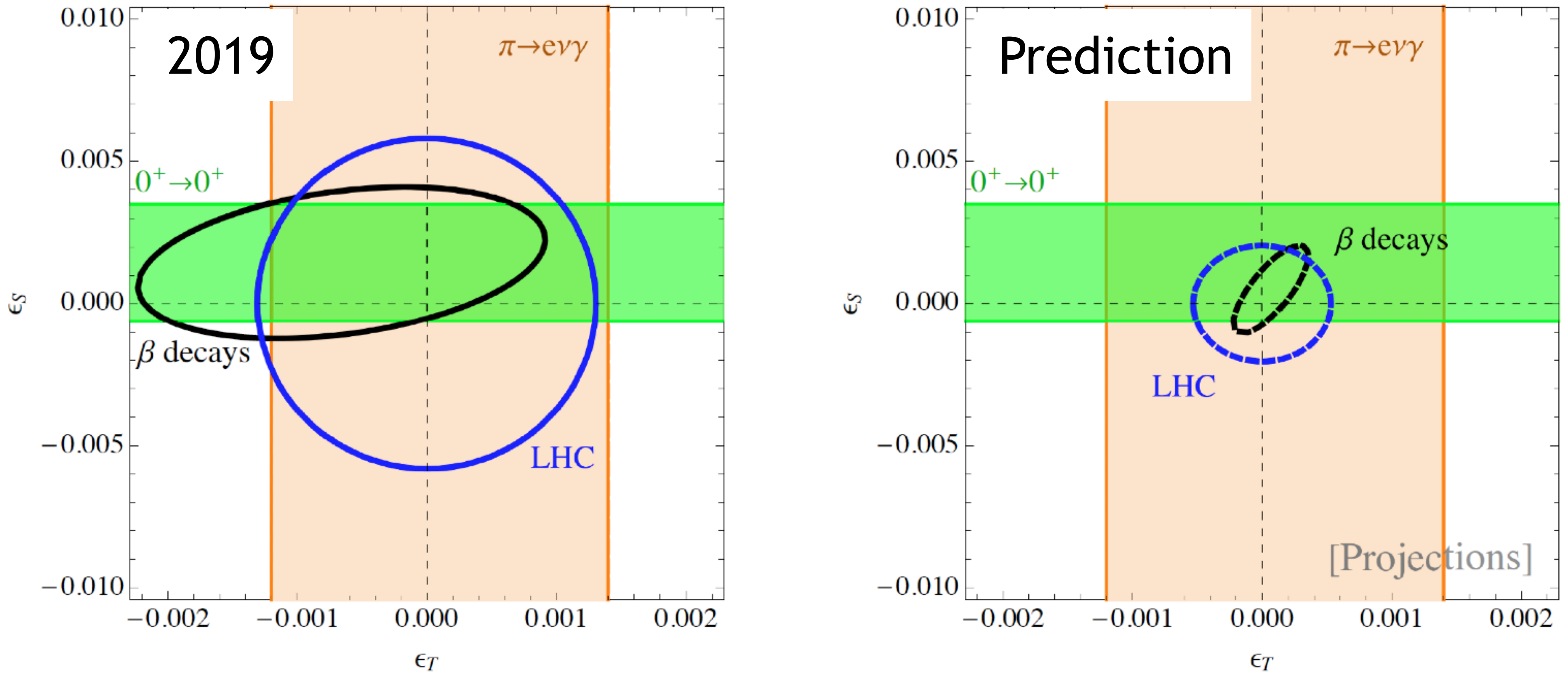

Gonzalez-Alonso, et al., Progress in Particle and Nuclear Physics, Volume 104, January 2019, Pages 165-223

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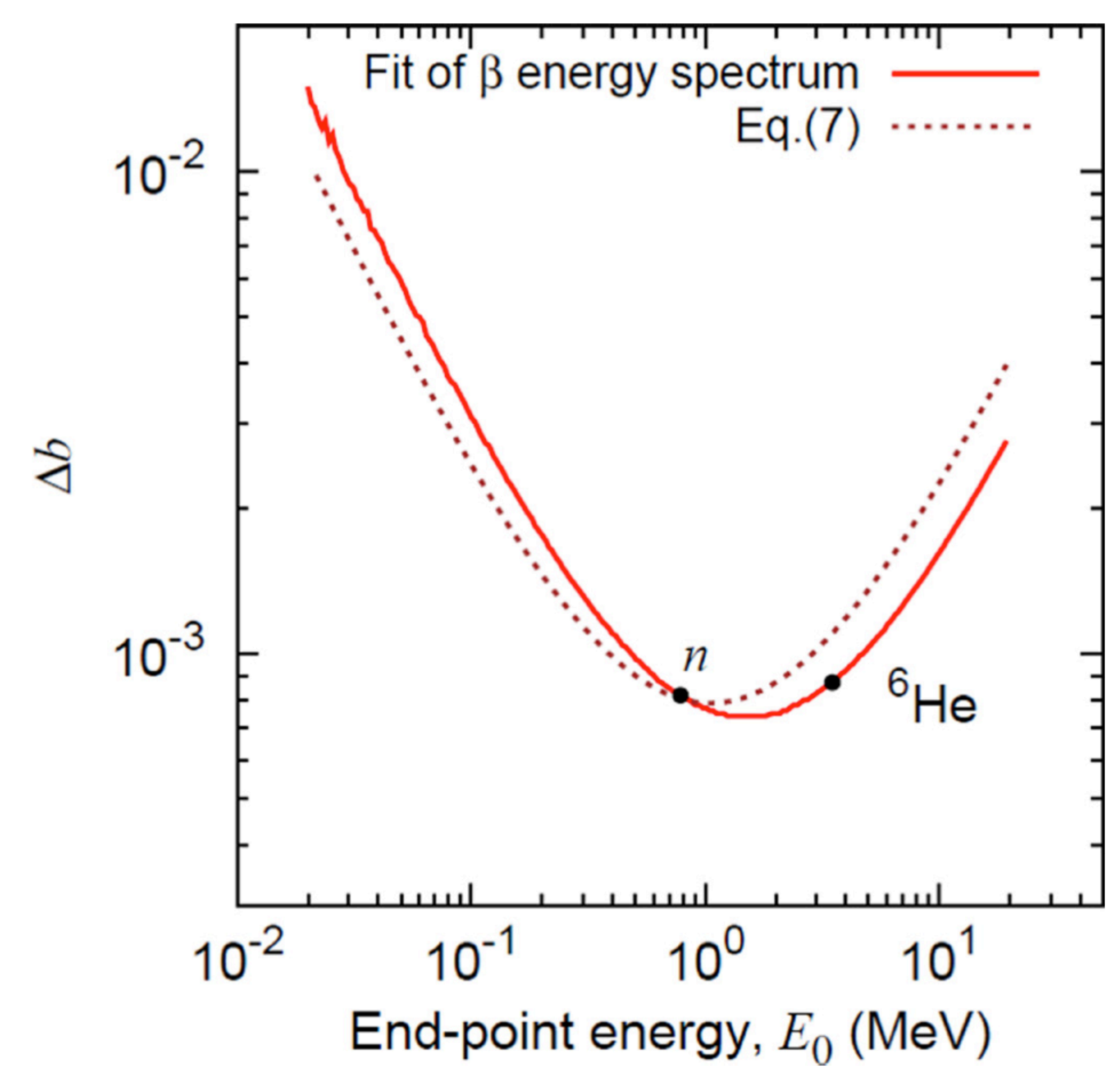
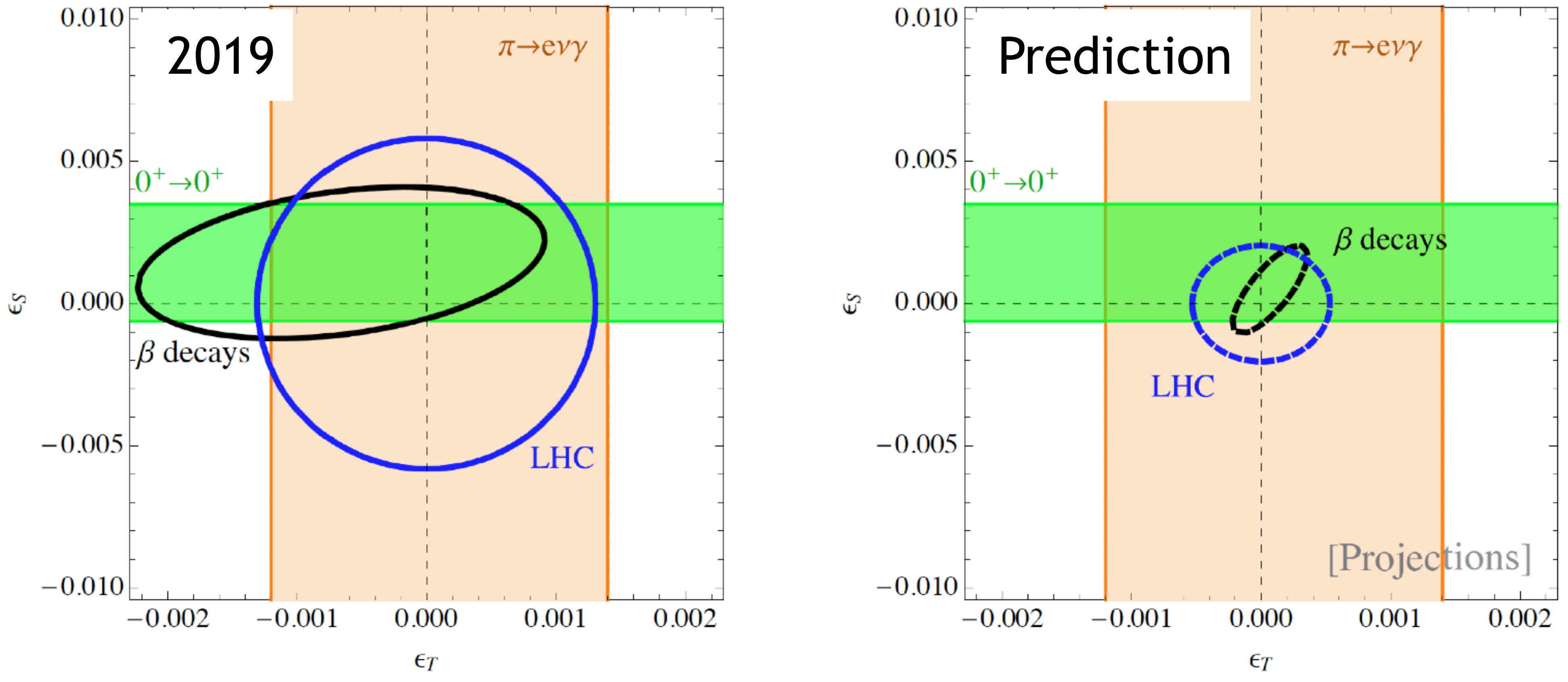


M. Gonzalez-Alonso and O Naviliat-Cuncic, PRC 94, 035503 (2016)



Gonzalez-Alonso, et al., Progress in Particle and Nuclear Physics, Volume 104, January 2019, Pages 165-223

^{6}He:

1. 100 % Gamow-Teller transition ⇒ C_T sensitivity
2. No γ emission with β^- decay
3. Short half-life time: 807 ms
4. Theoretically well understood

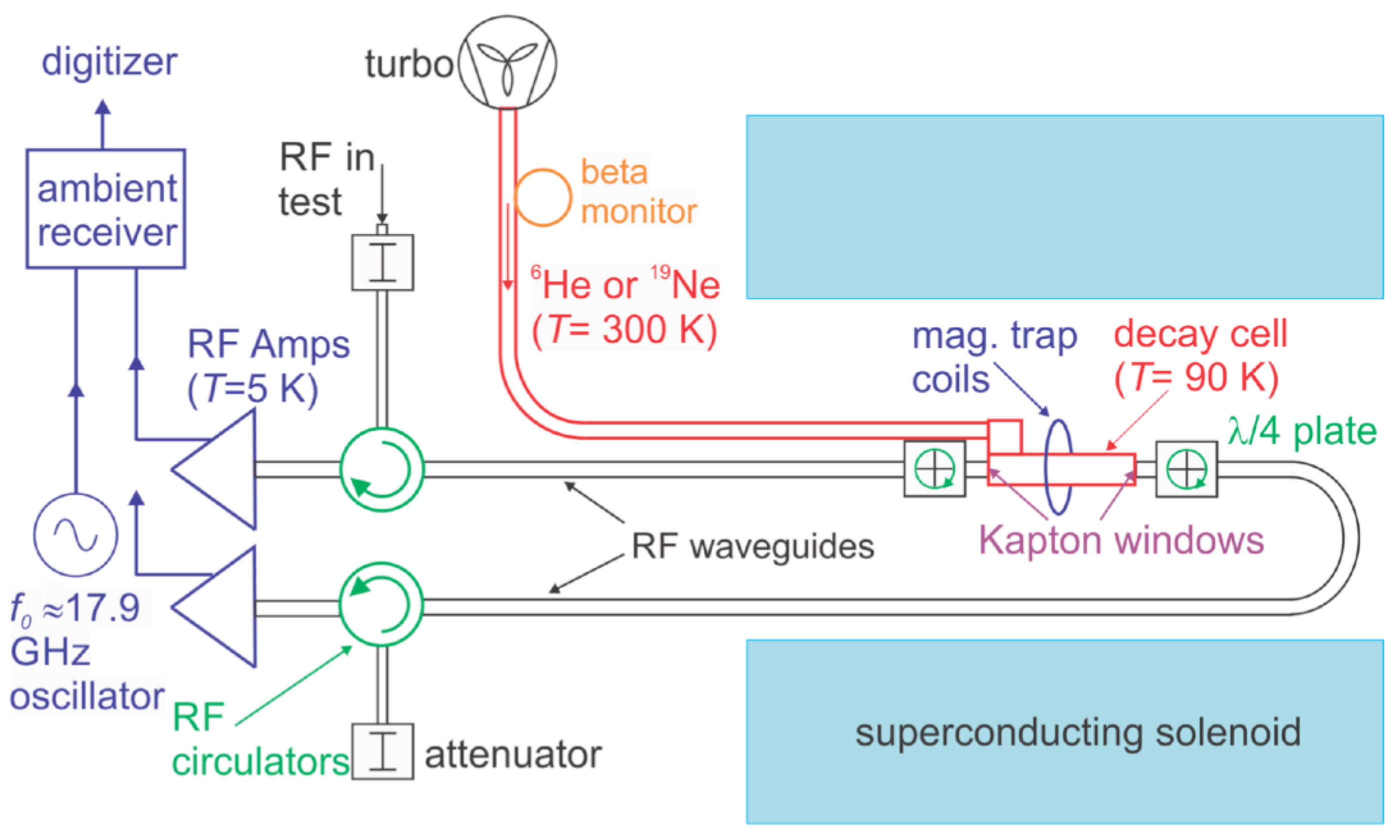
^{6}He-CRES

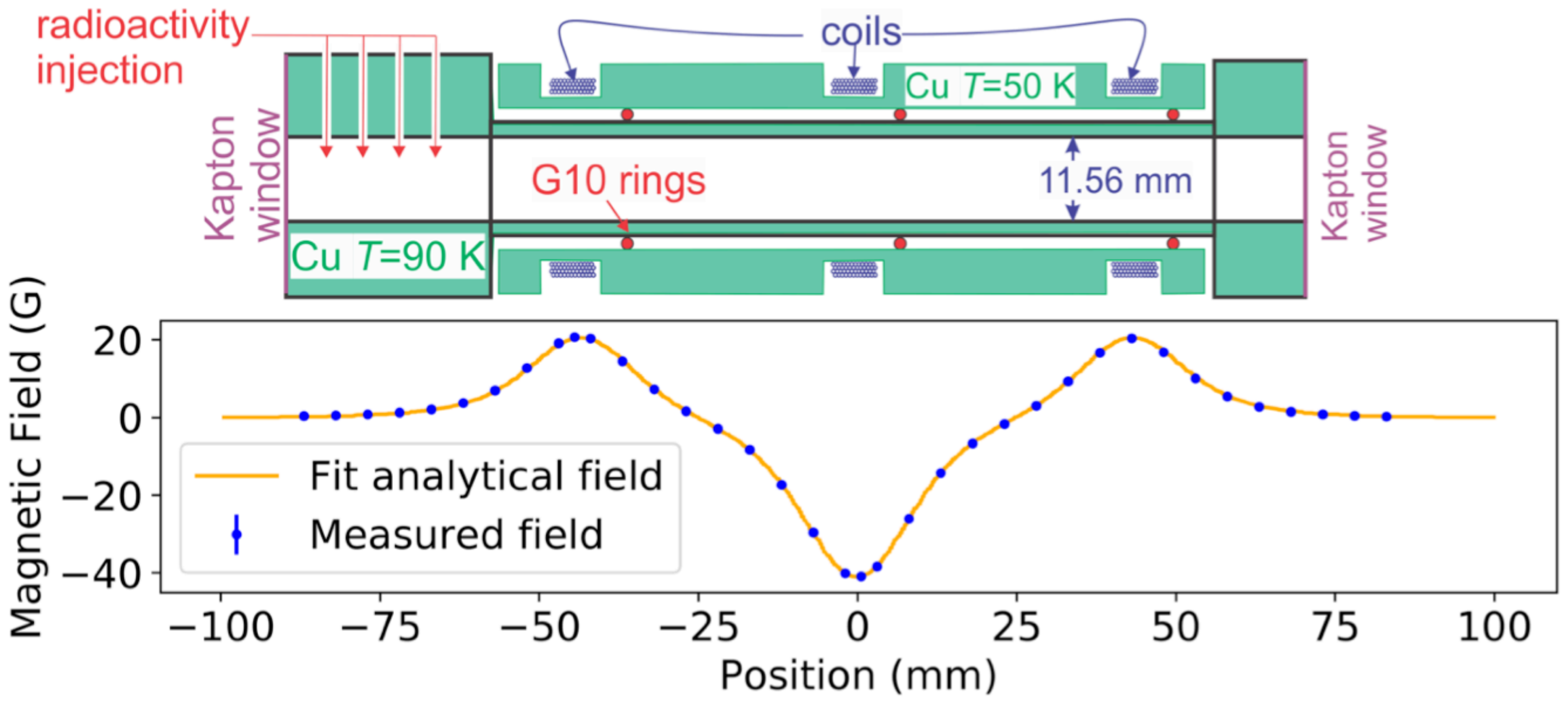
Neutrons:

Most fundamental semi-leptonic weak decay

First cyclotron radiation signals from MeV-scale e± from $^{6}He/^{19}Ne$ decays

arXiv:2209.02870





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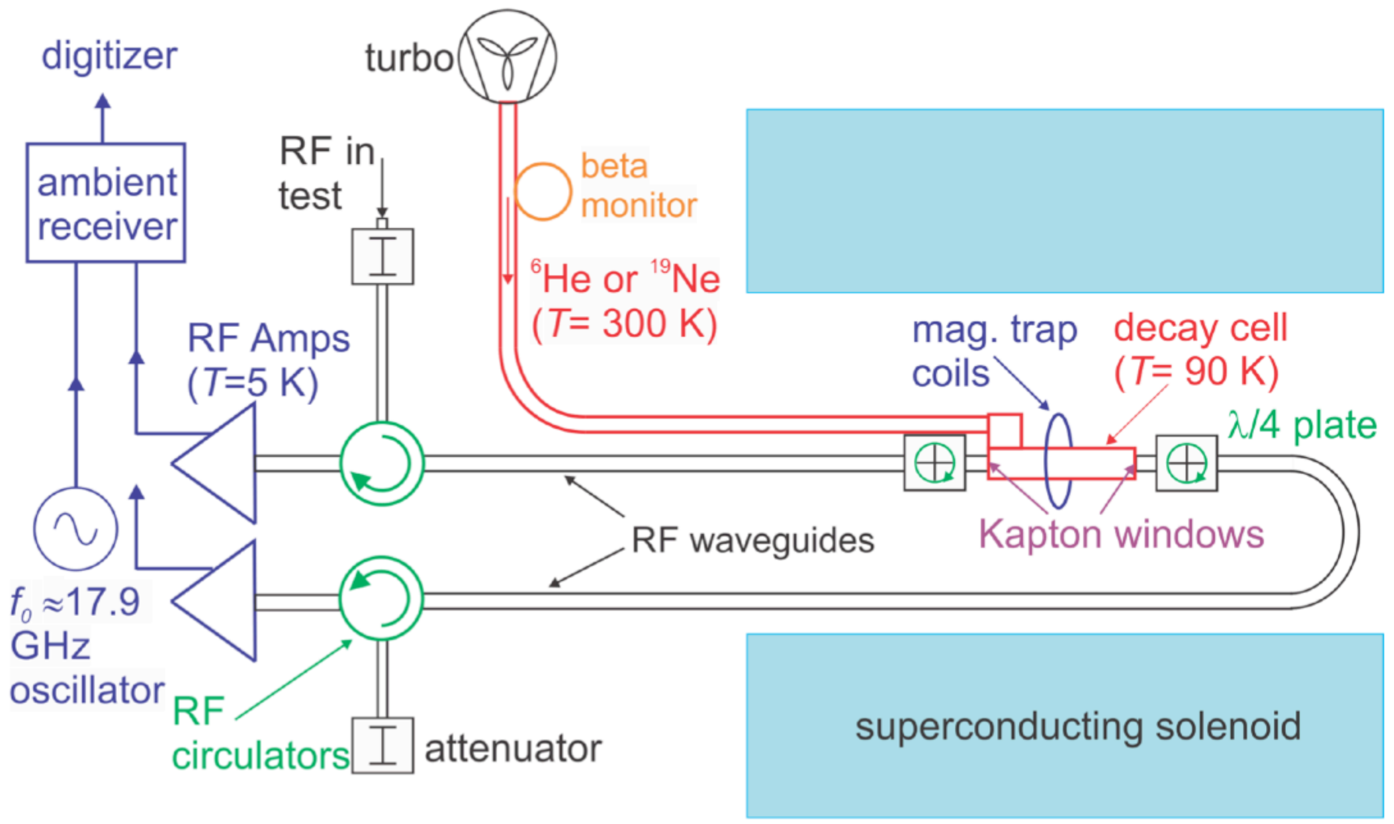
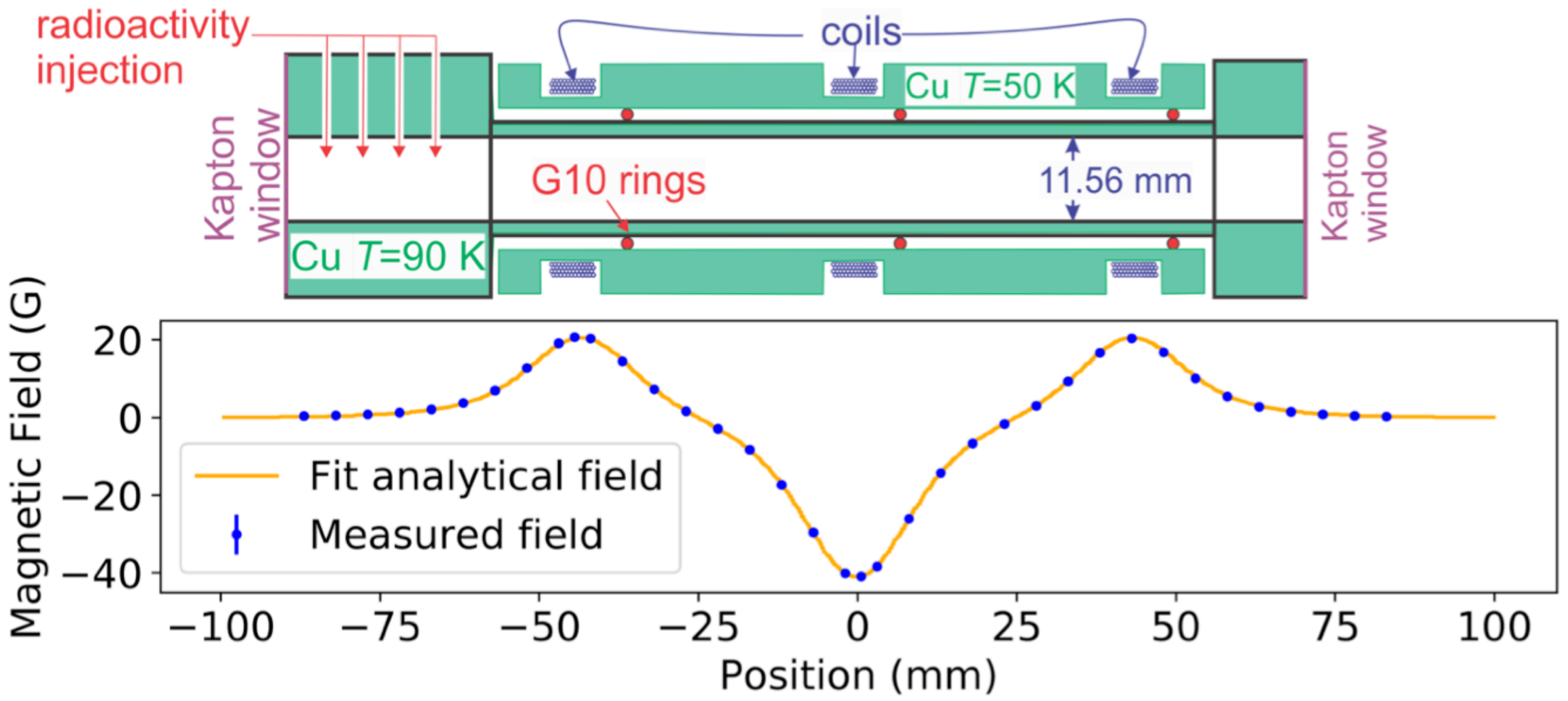
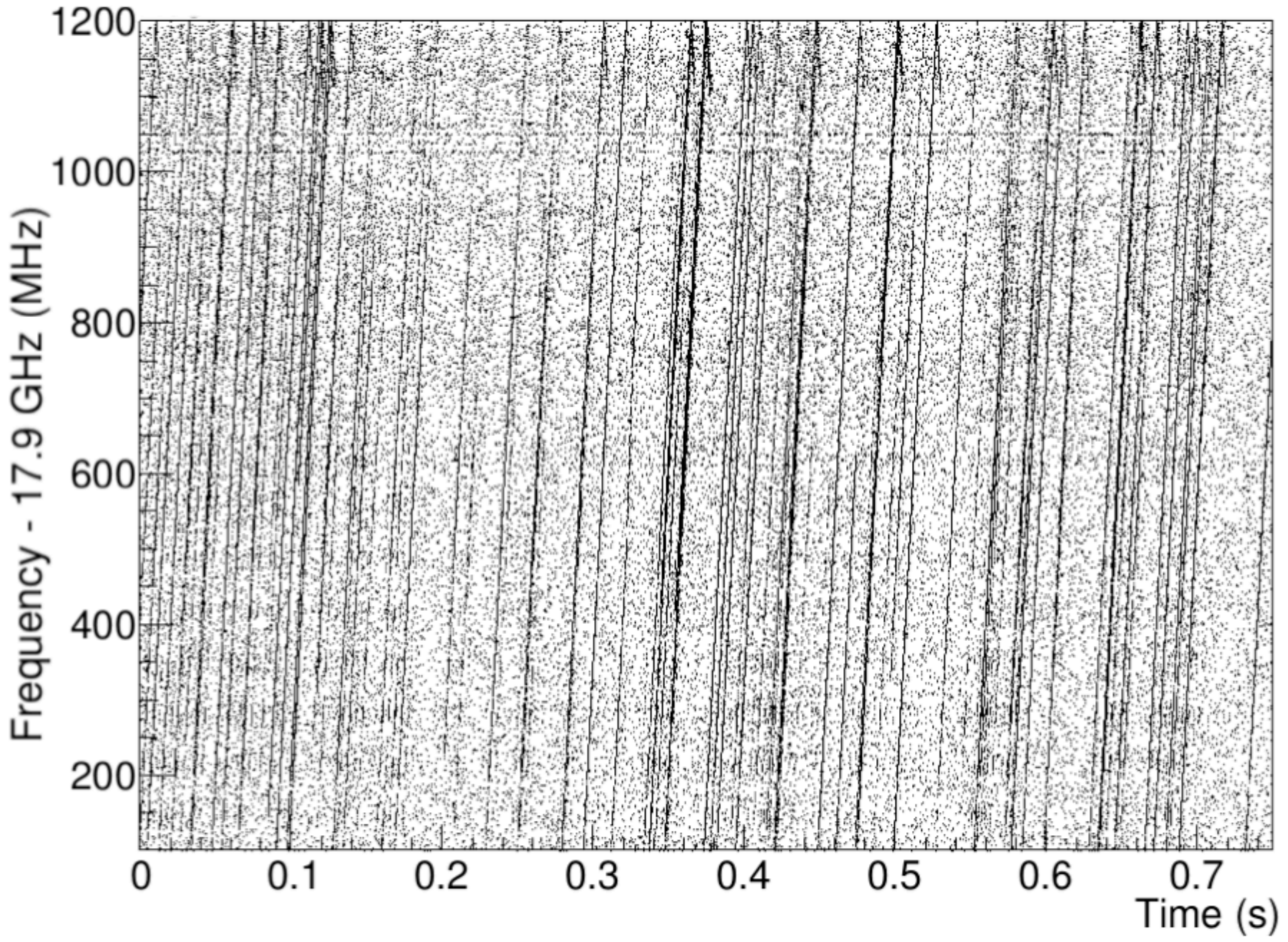




Very high-density of ^{6}He tracks at 2T



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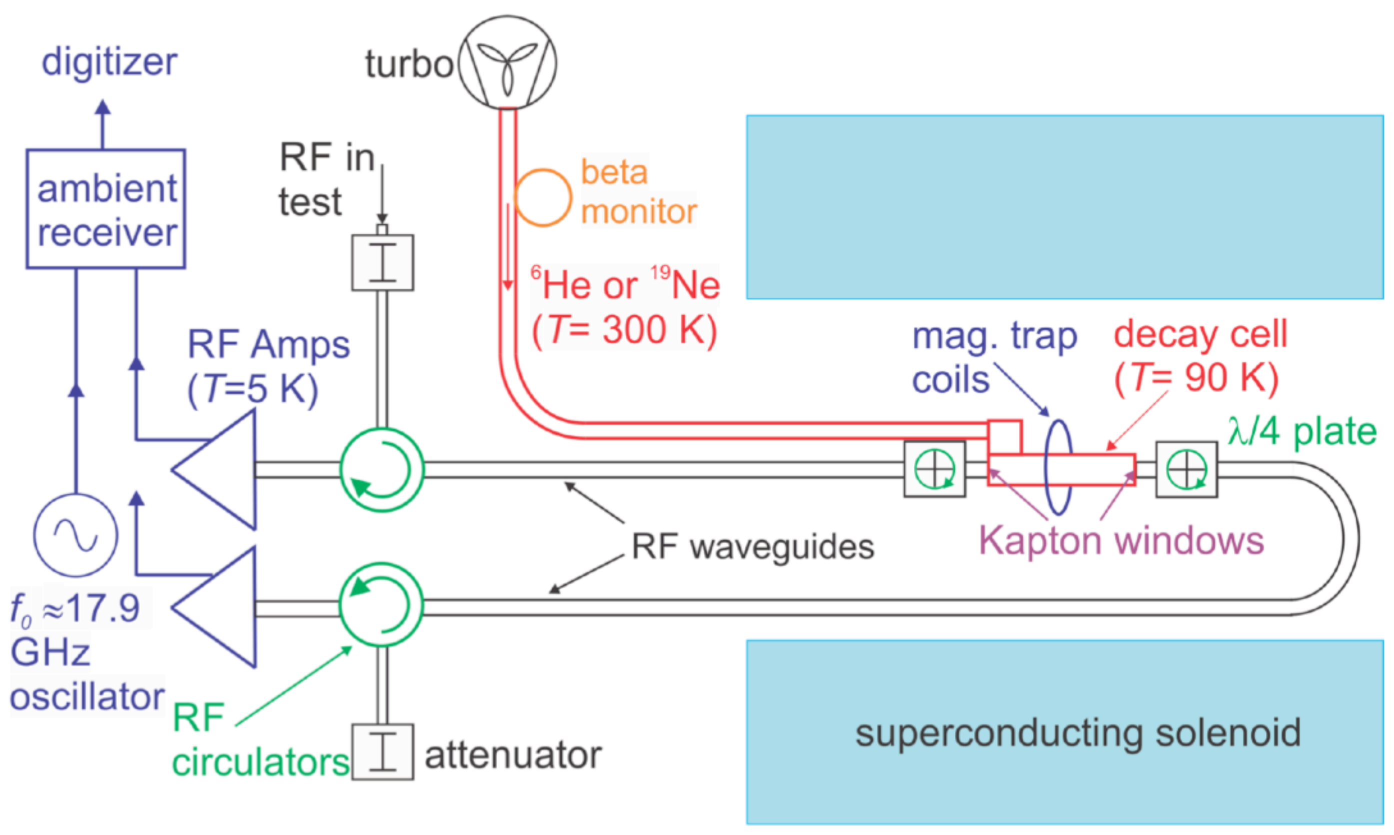

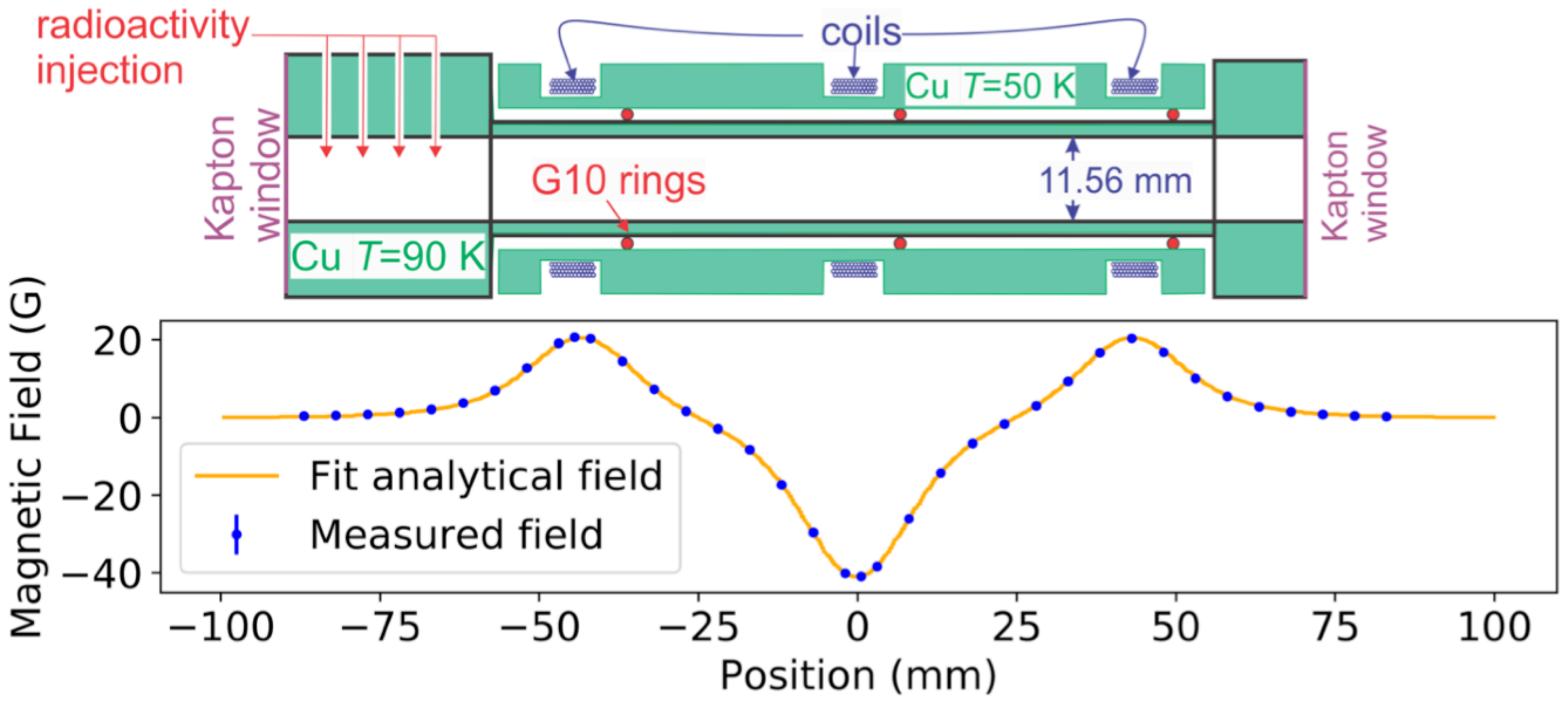

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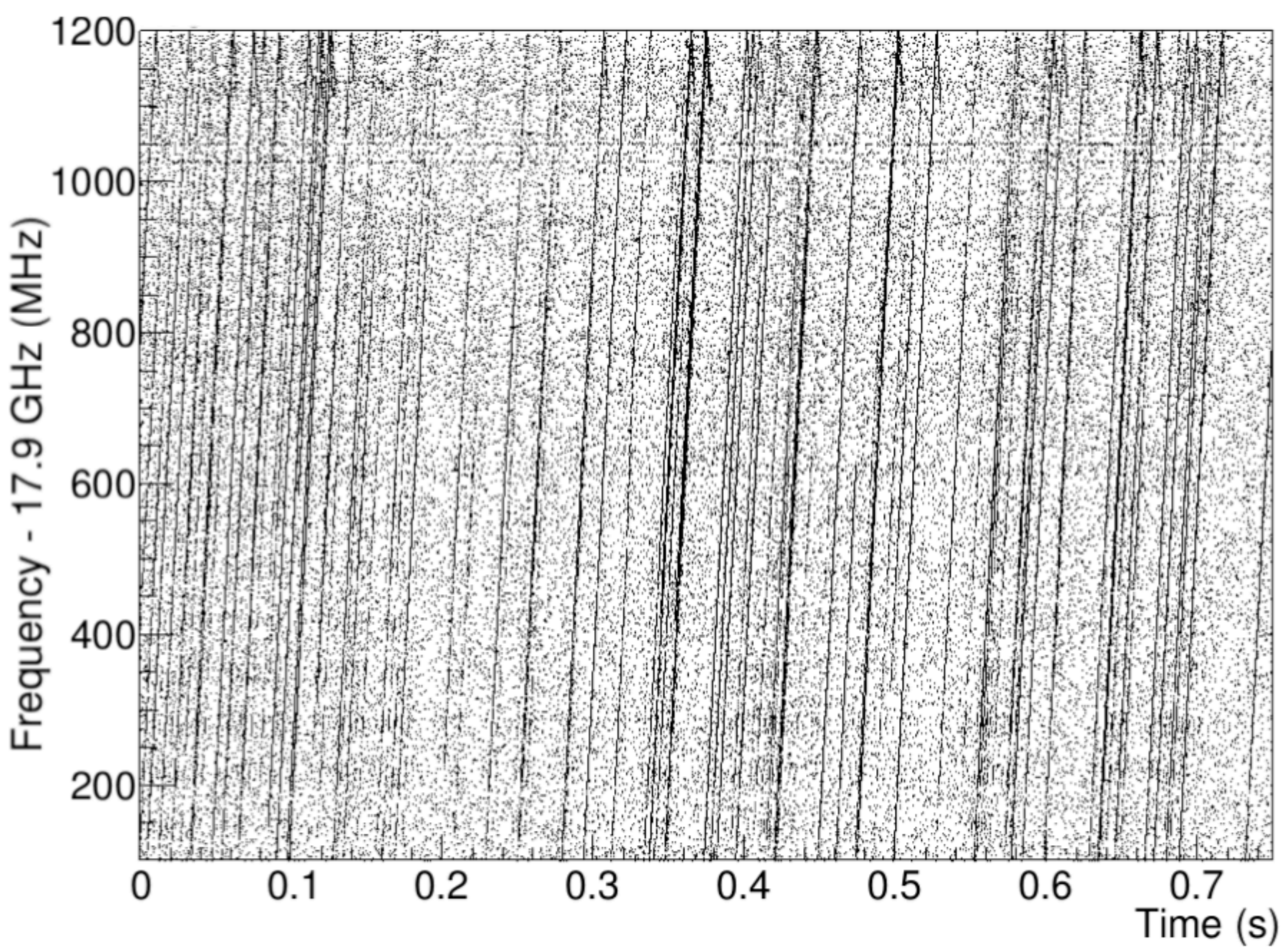
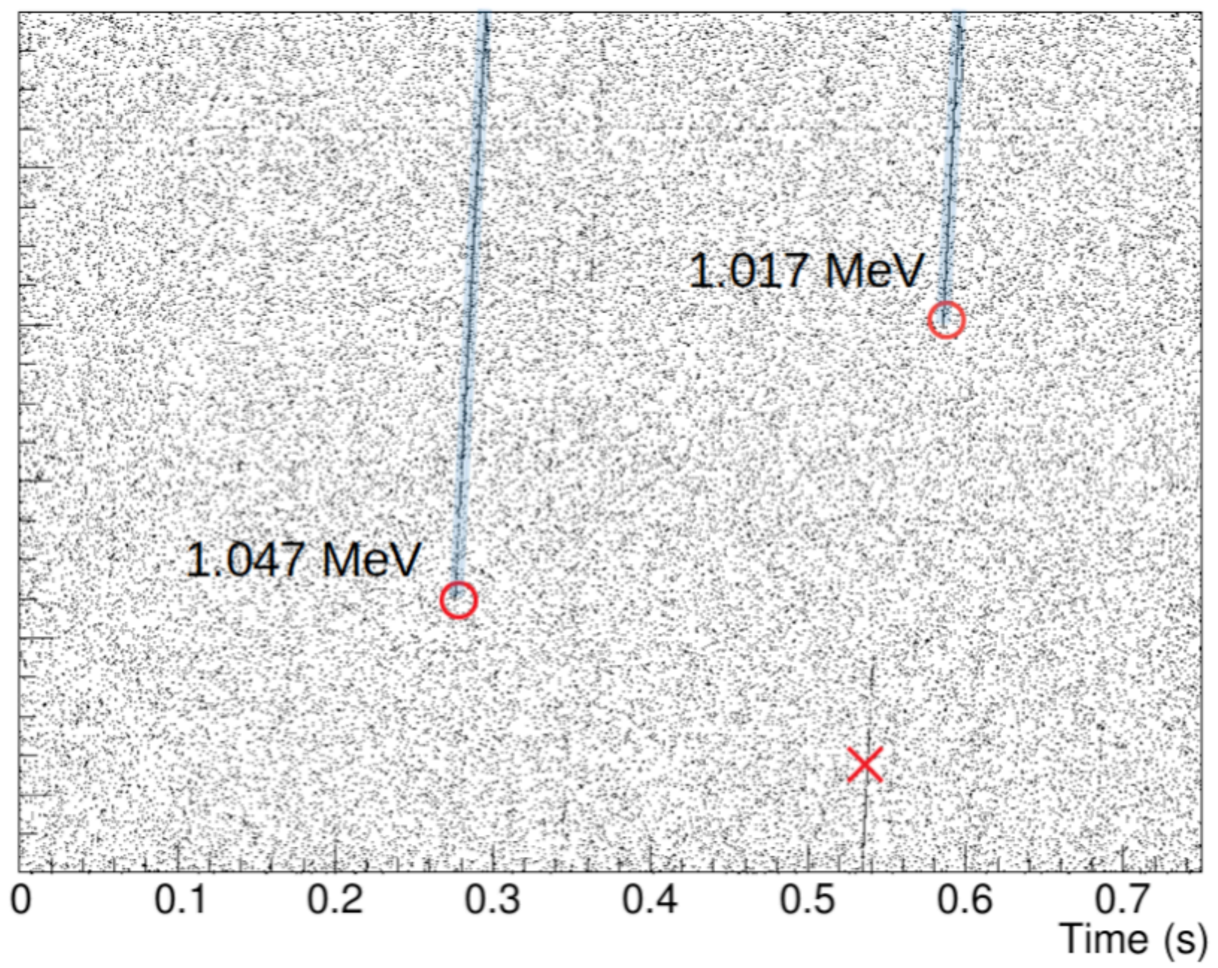


Two ^{19}Ne tracks in detail



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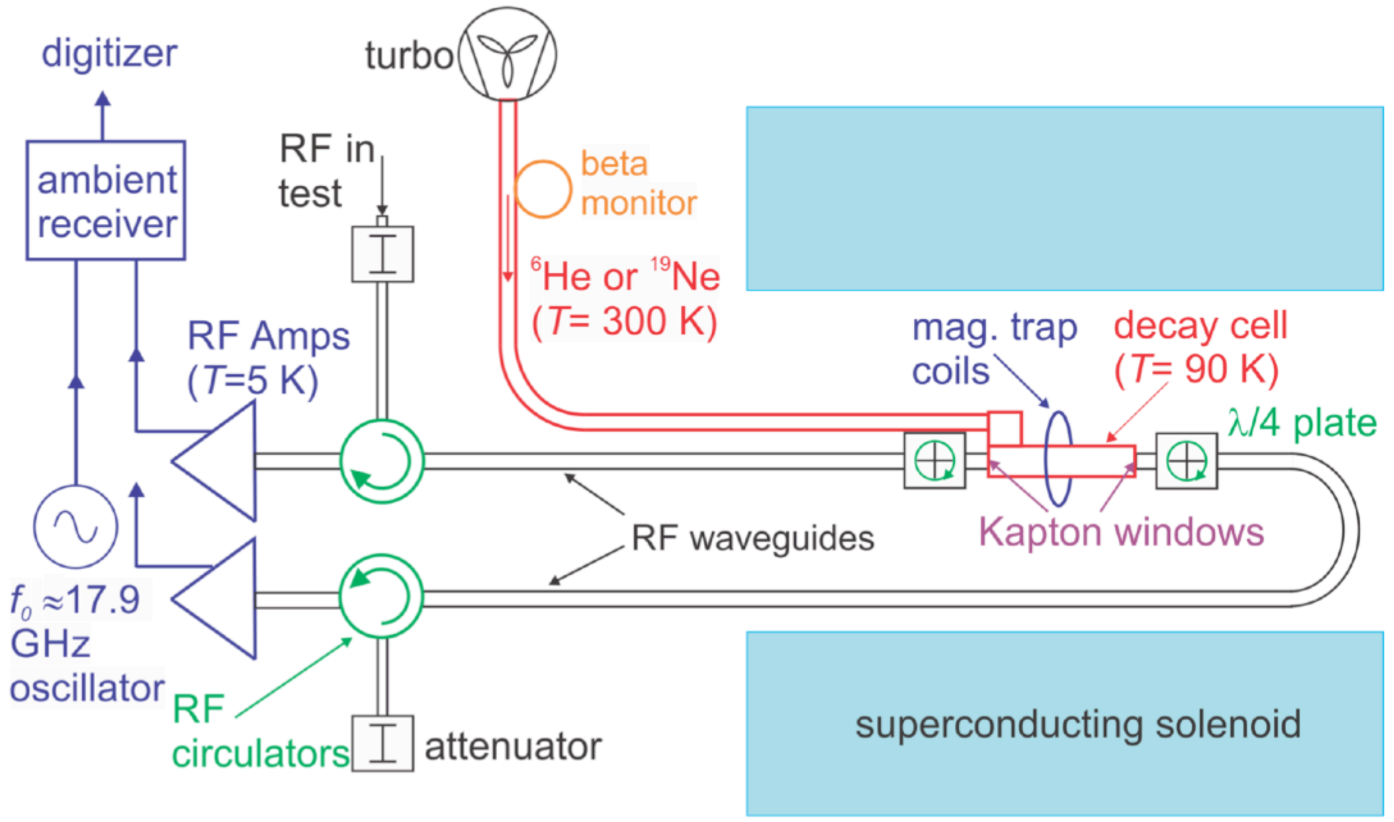
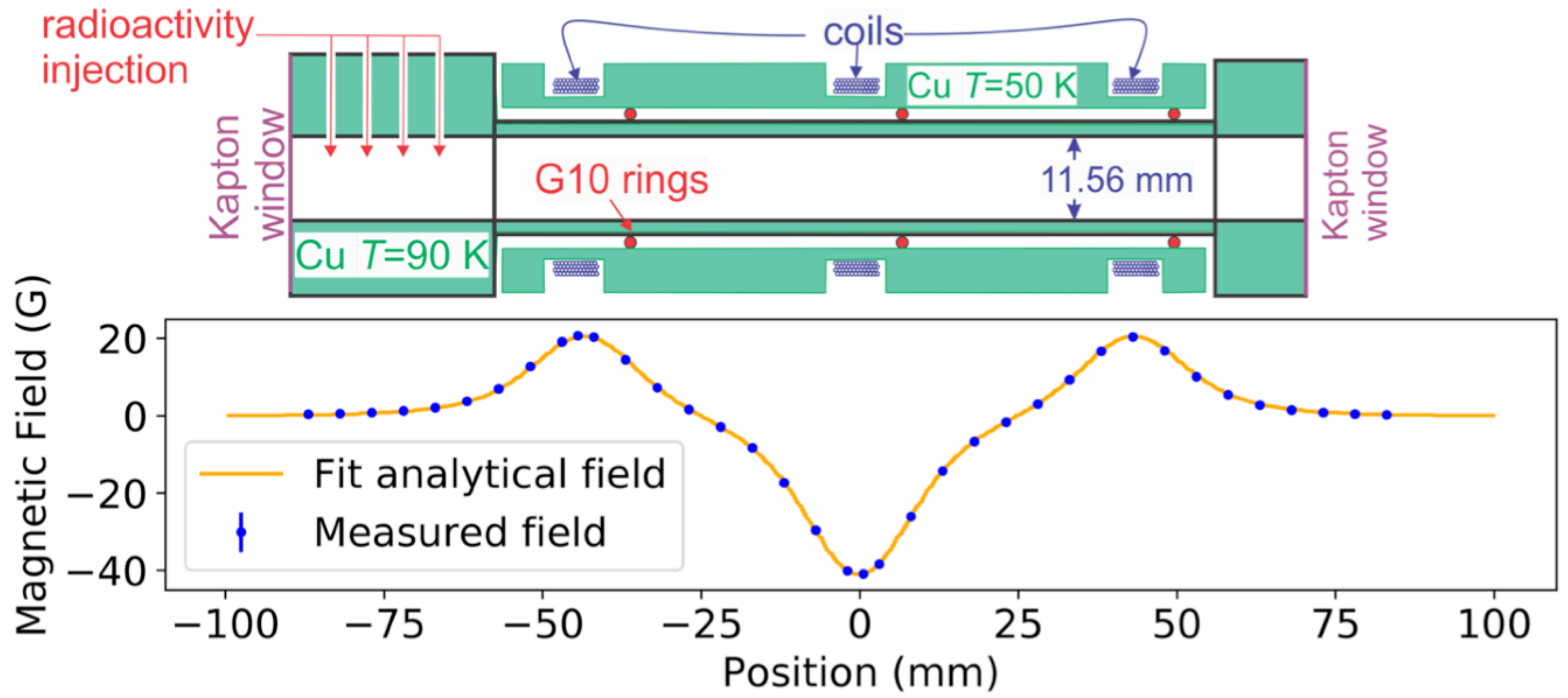
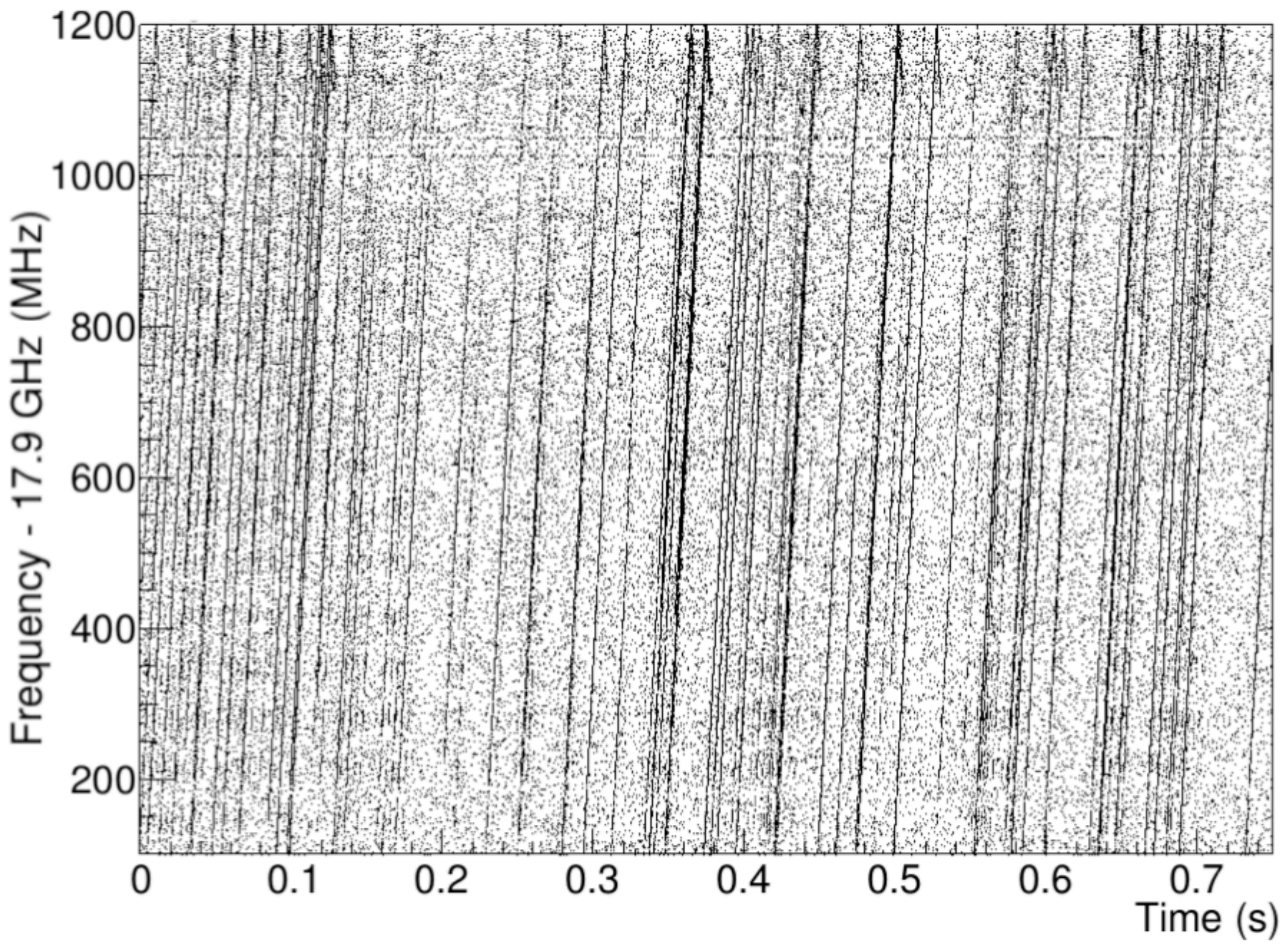




Very high-density of ^{6}He tracks at 2T



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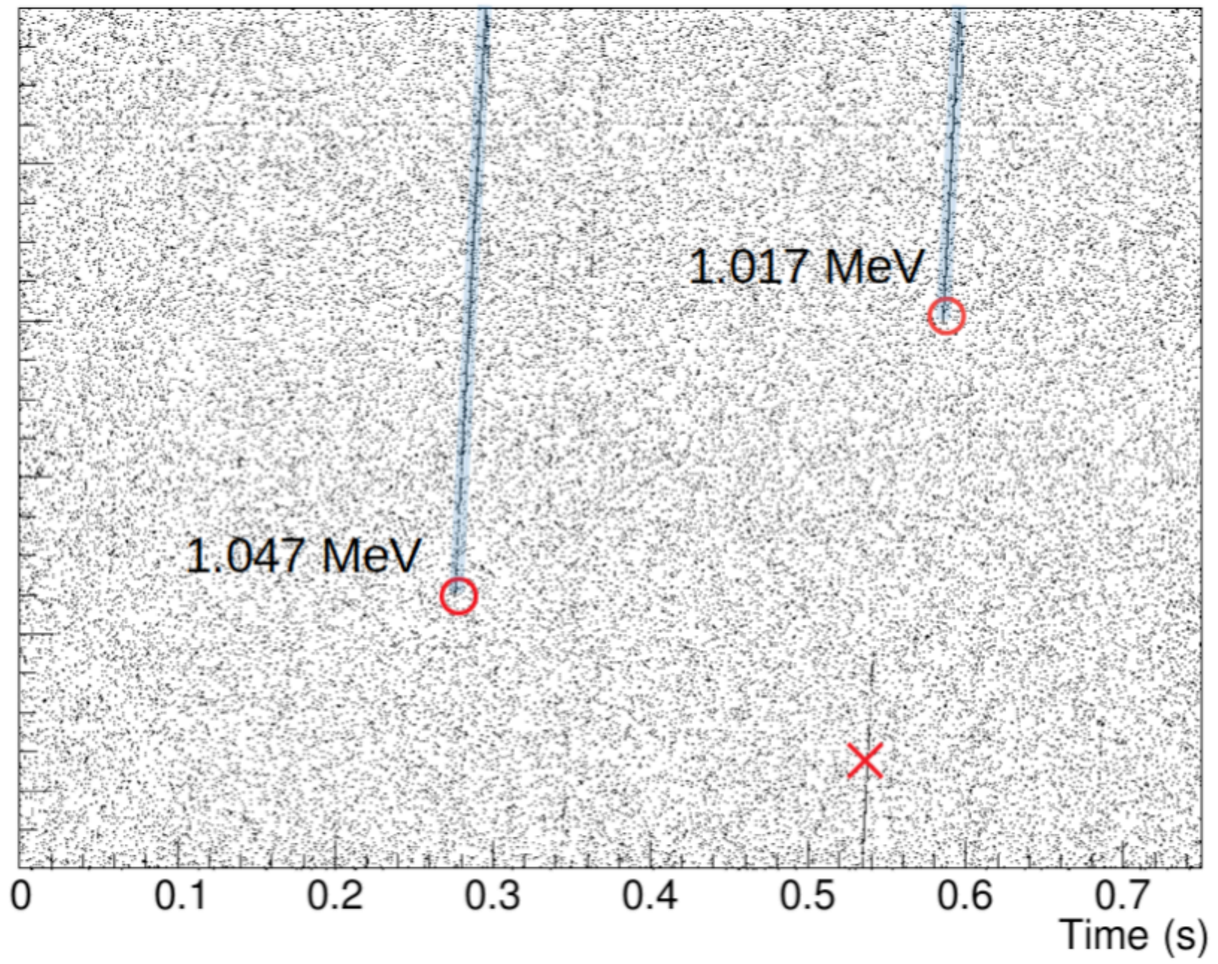
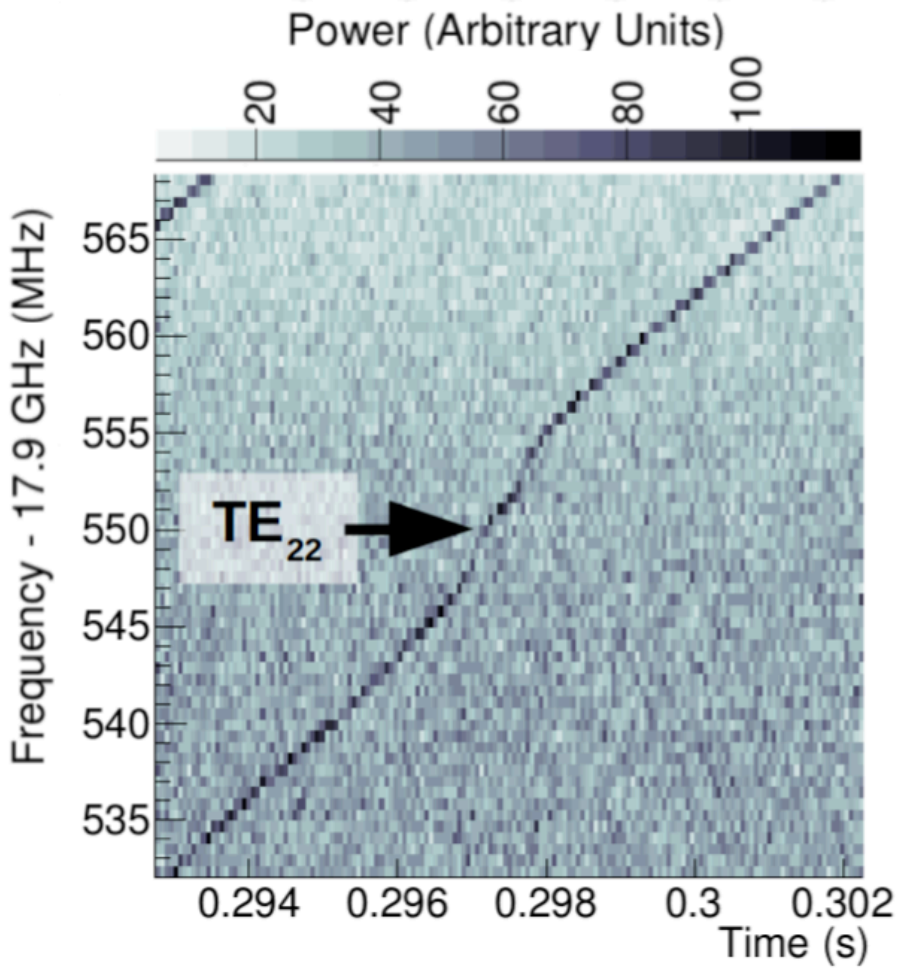
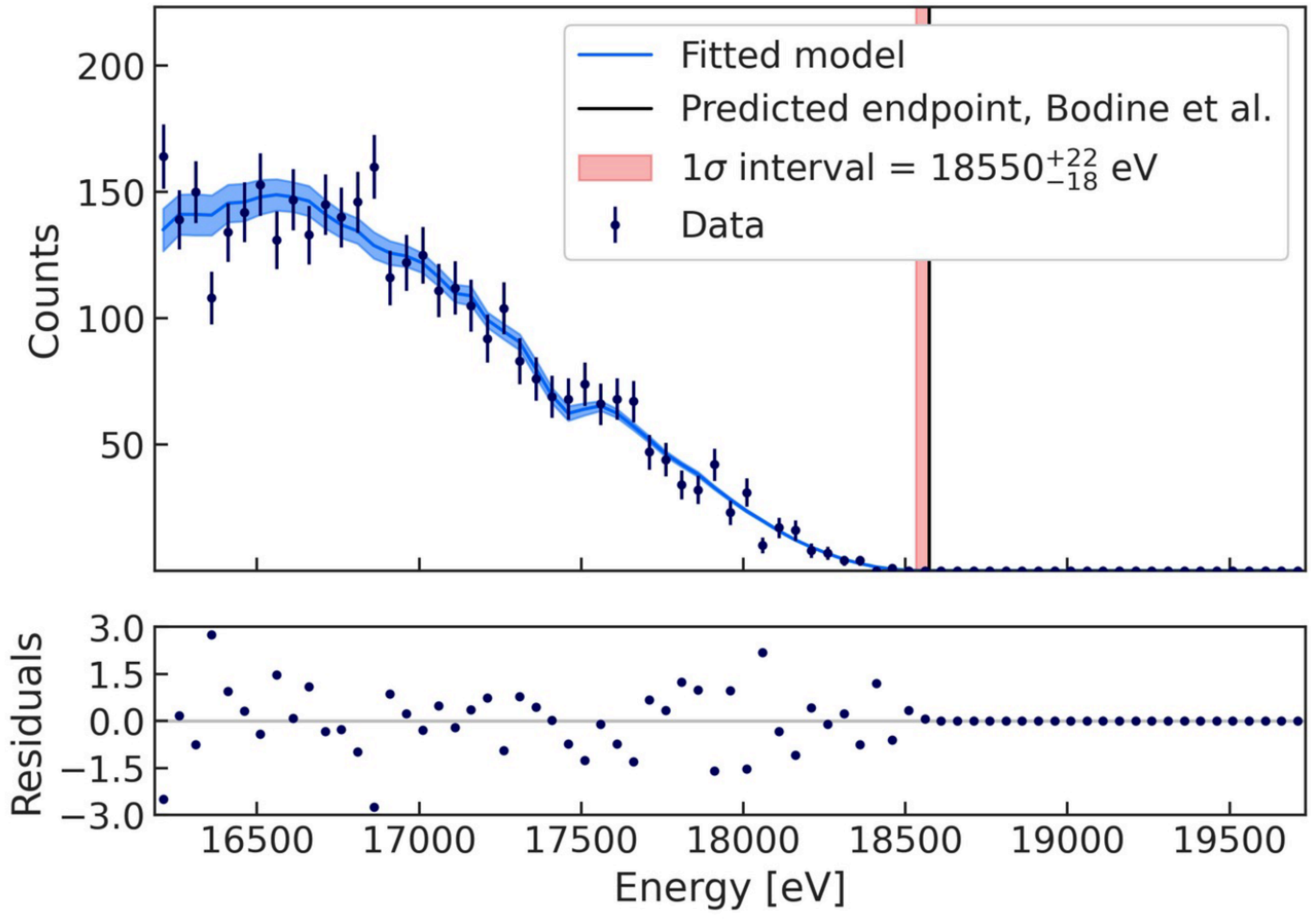
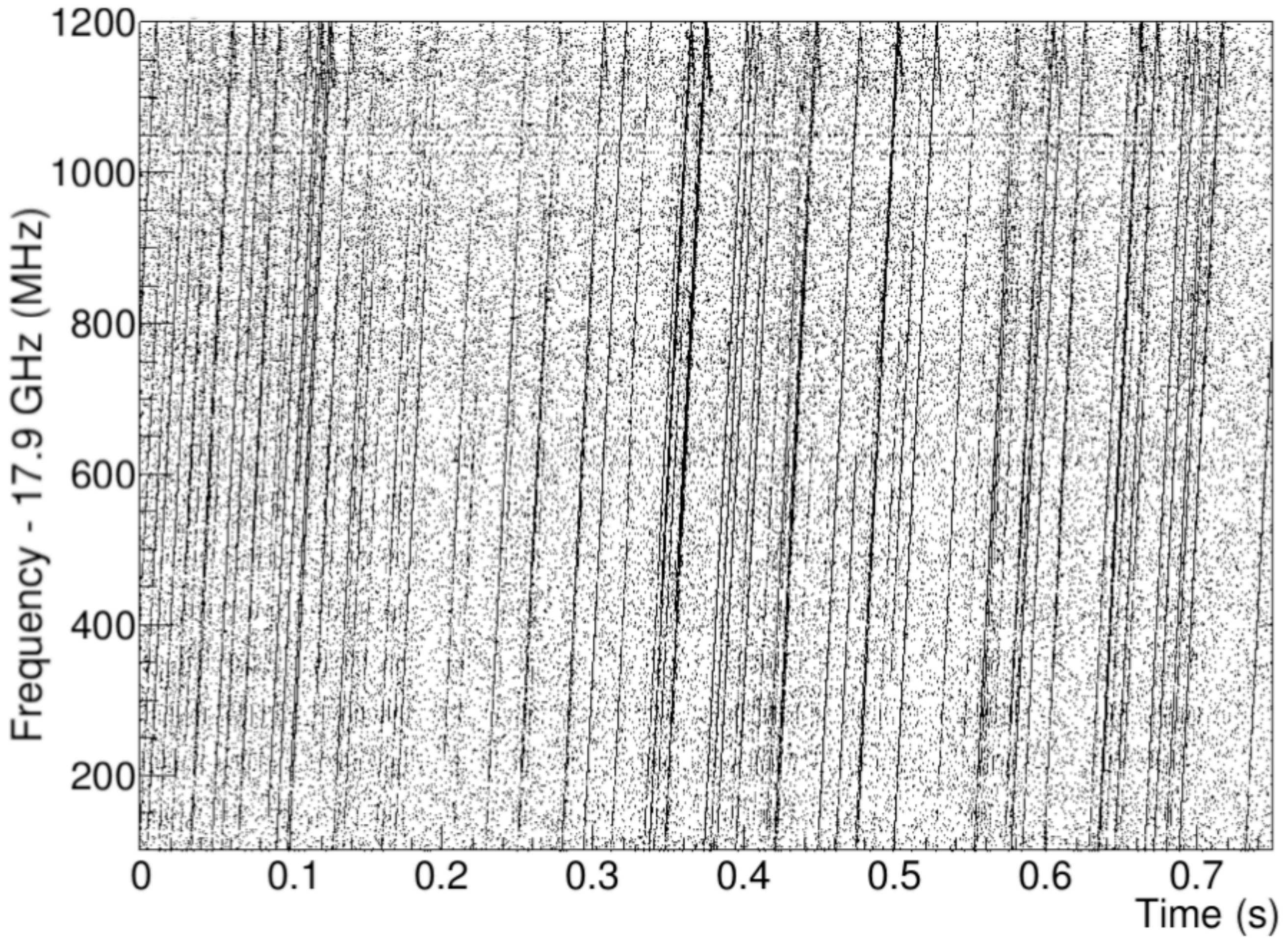


^{19}Ne track affected by waveguide resonance



Summary





- CRES established as promising technique for next generation neutrino mass experiment

- 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

- First cyclotron radiation emission signals from MeV-scale $e^\pm$ pave the way for wide-application frequency based precision spectroscopy.

Acknowledgments: Project 8 and ^{6}He collaborations

B. Monreal, R. Mohiuddin, Y.-H. Sun,
Case Western Reserve University
C.-Y. Liu
University of Illinois, Urbana-Champaign
W. Pettus
Indiana University
S. Böser, M. Fertl, A. Lindman, Ch. Matthé, B. Mucogllava, R. Reimann, F. Thomas, L. A. Thorne
Johannes Gutenberg University Mainz
T. Thümmler
Karlsruhe Institute of Technology
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N. Buzinsky, J. A. Formaggio, M. Li, J.I. Peña, J. Stachurska, W. Van De Pontseele
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Pennsylvania State University
C. Claessens, P. J. Doe, S. Enemoto, A. Marsteller, E. Novitski, R. G. H. Robertson, G. Rybka
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