Neutrino mass measurement: Current and future

Larisa Thorne
Johannes Gutenberg University Mainz

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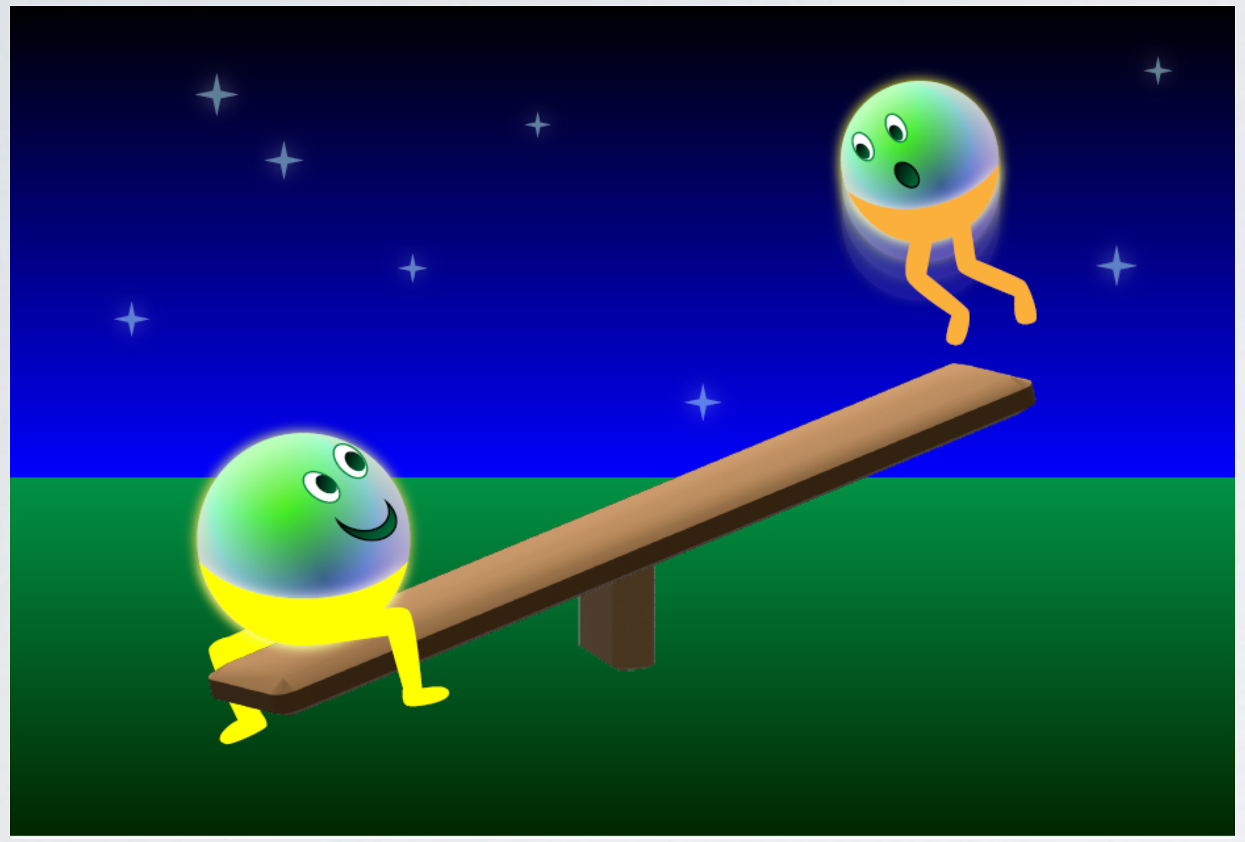
Credit: L. Thorne

PROJECT 8

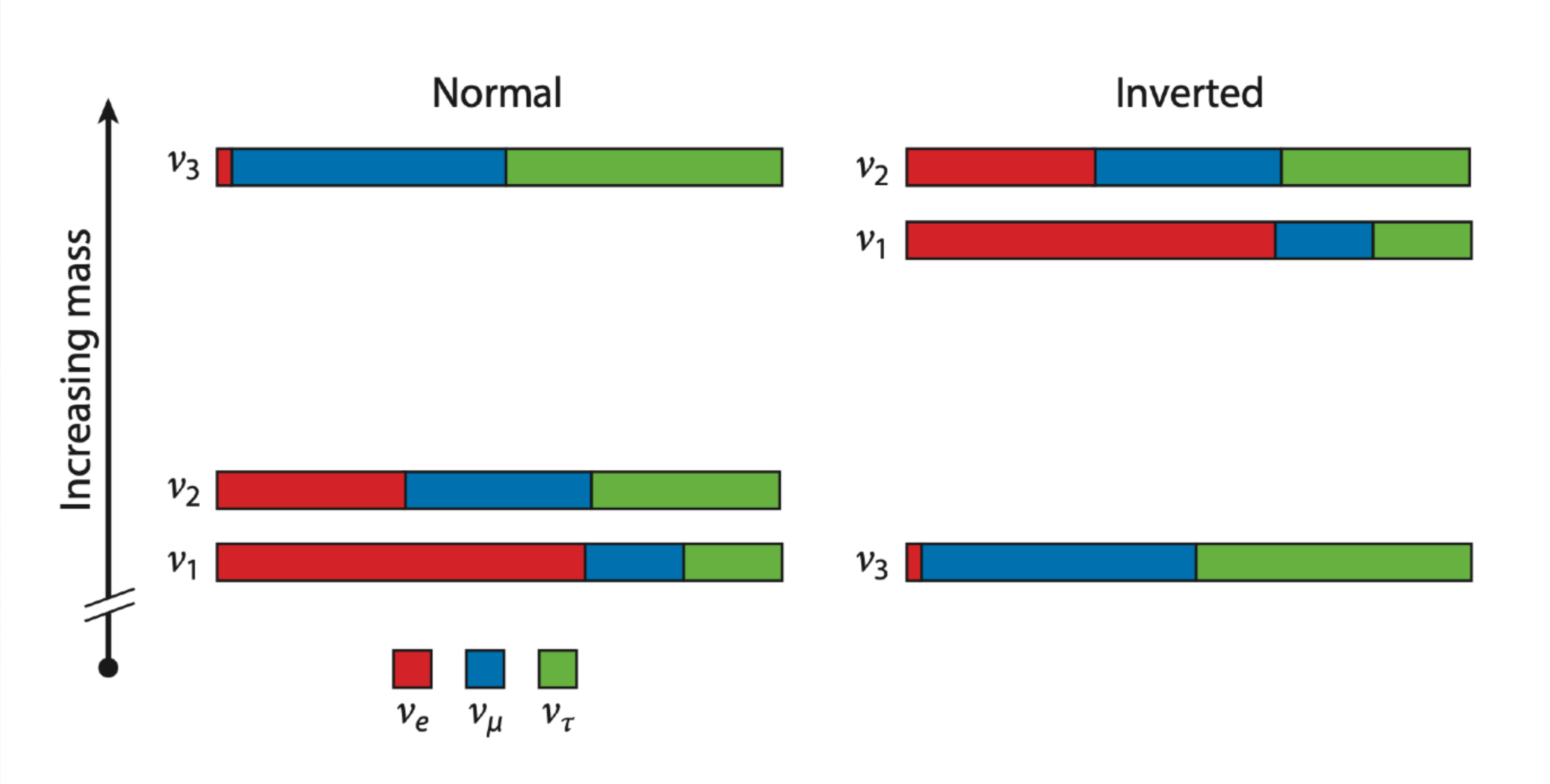
JG|U

PRiSMA+ Cluster of Excellence
Precision Physics, Fundamental Interactions and Structure of Matter

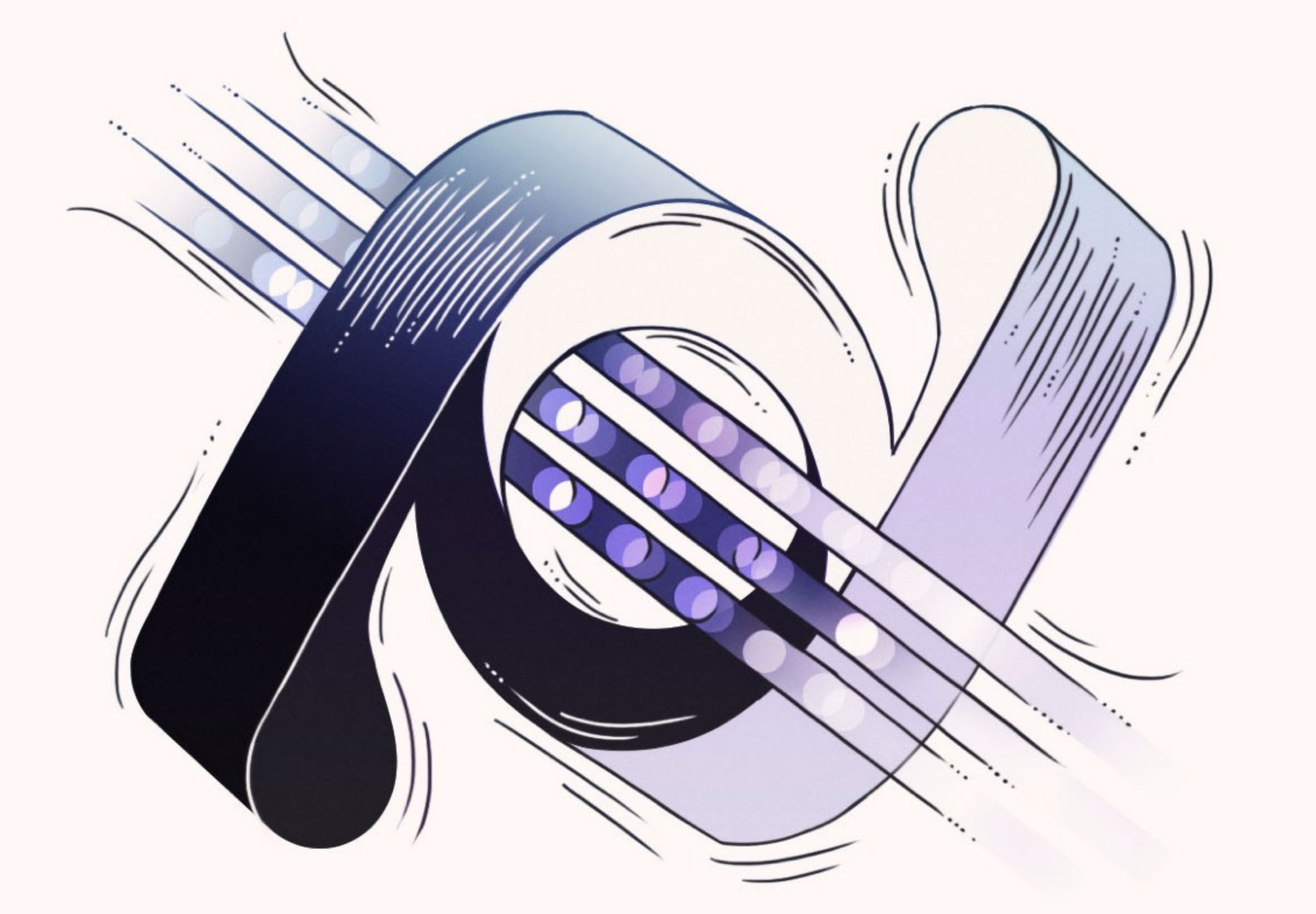
NEUTRINO MASS: WHY?



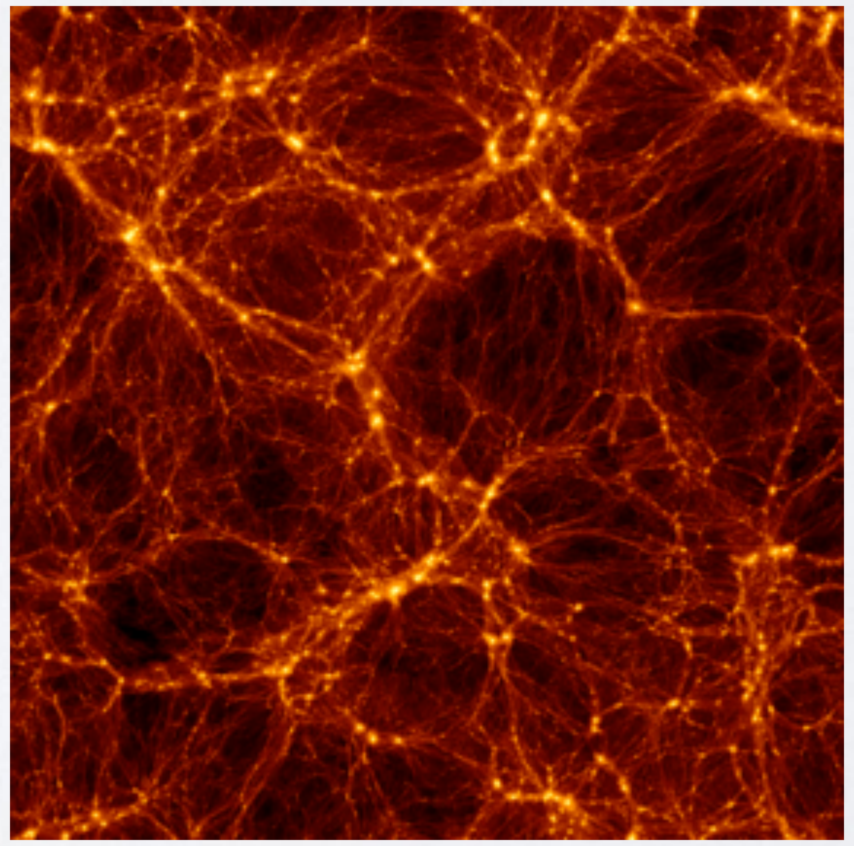
Source: https://physics.aps.org/articles/v16/20



Source: Formaggio et al, 2021



Source: Symmetry Magazine , 2016



Source:https://arxiv.org/abs/1806.08395

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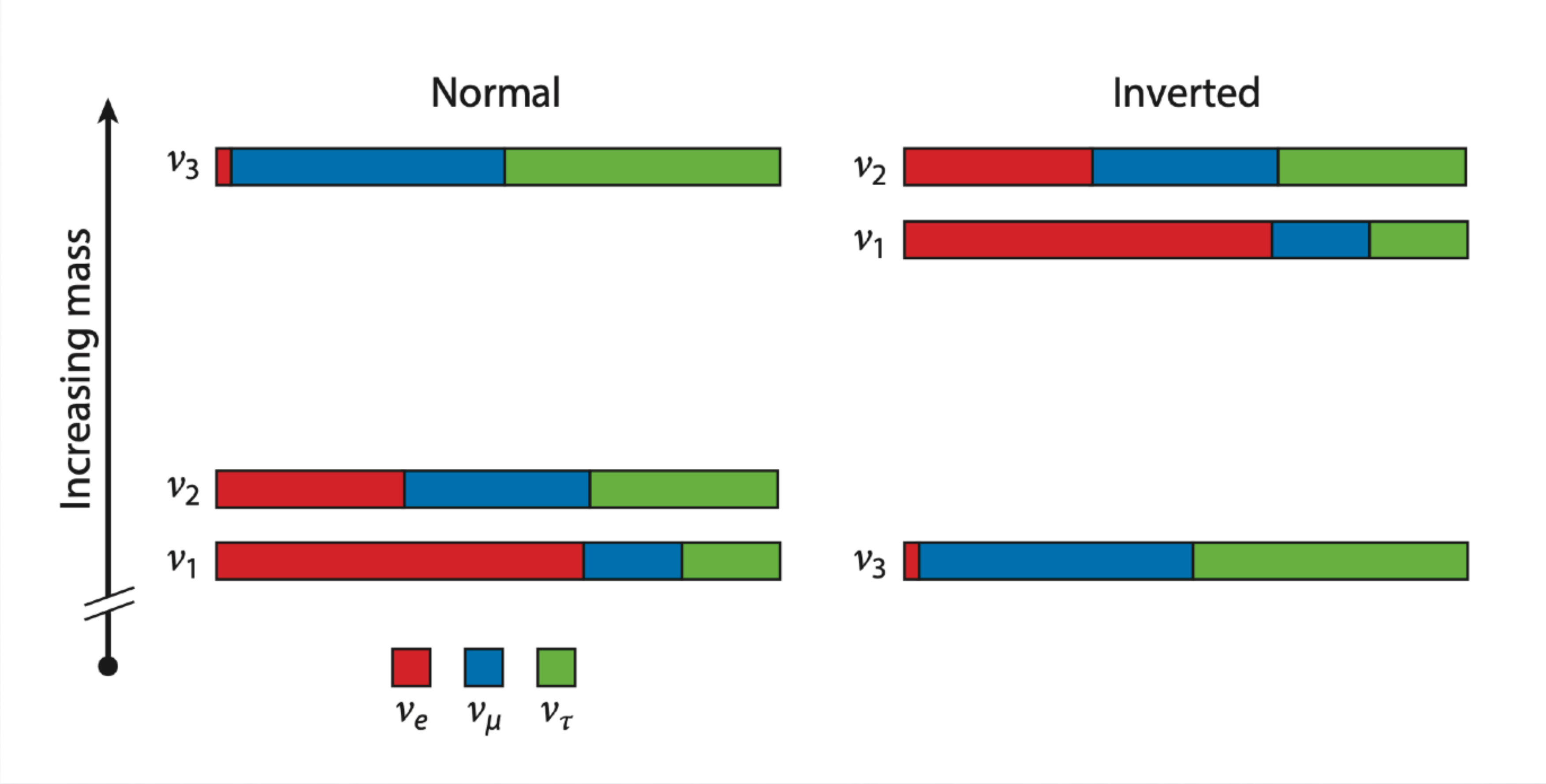

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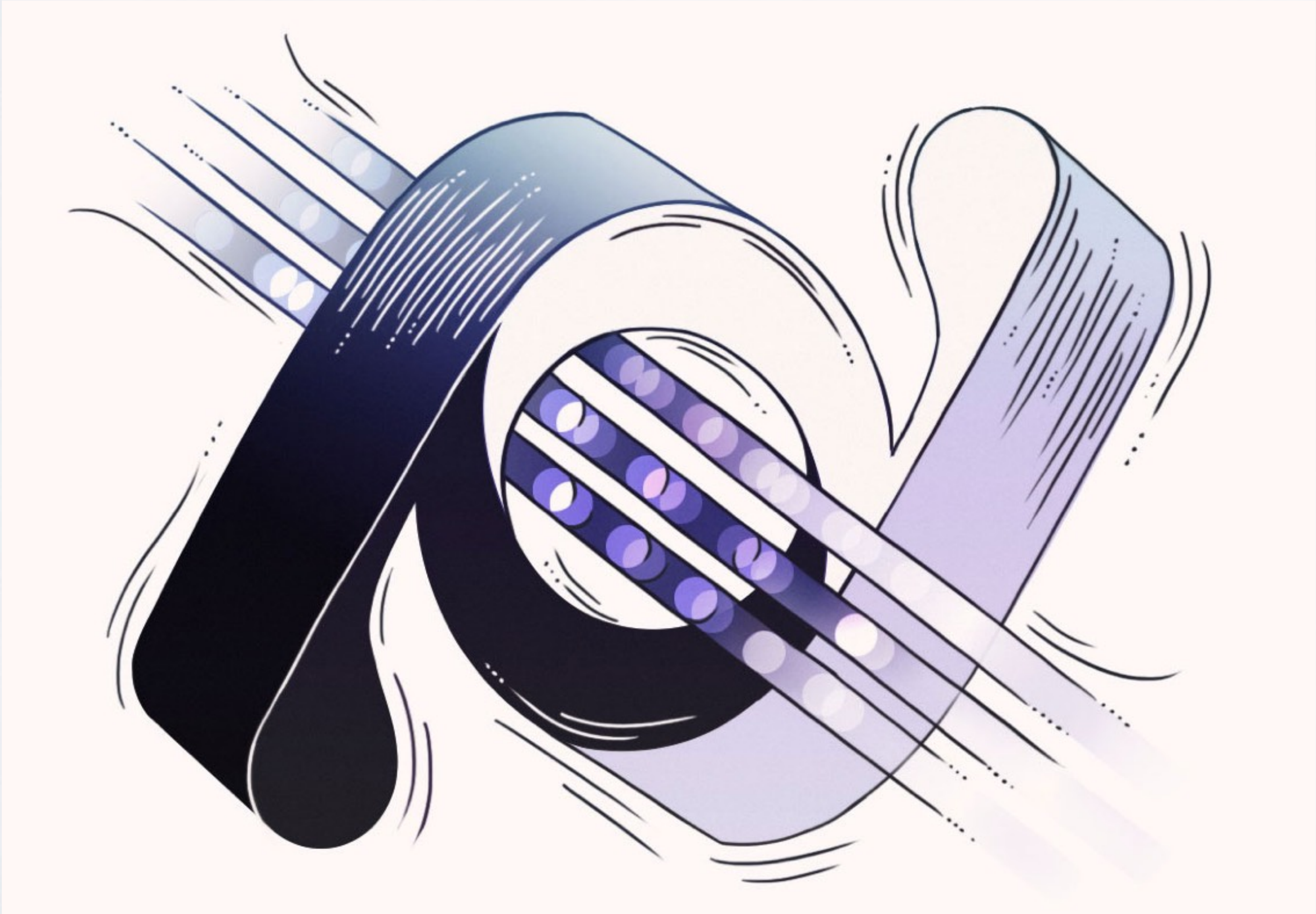

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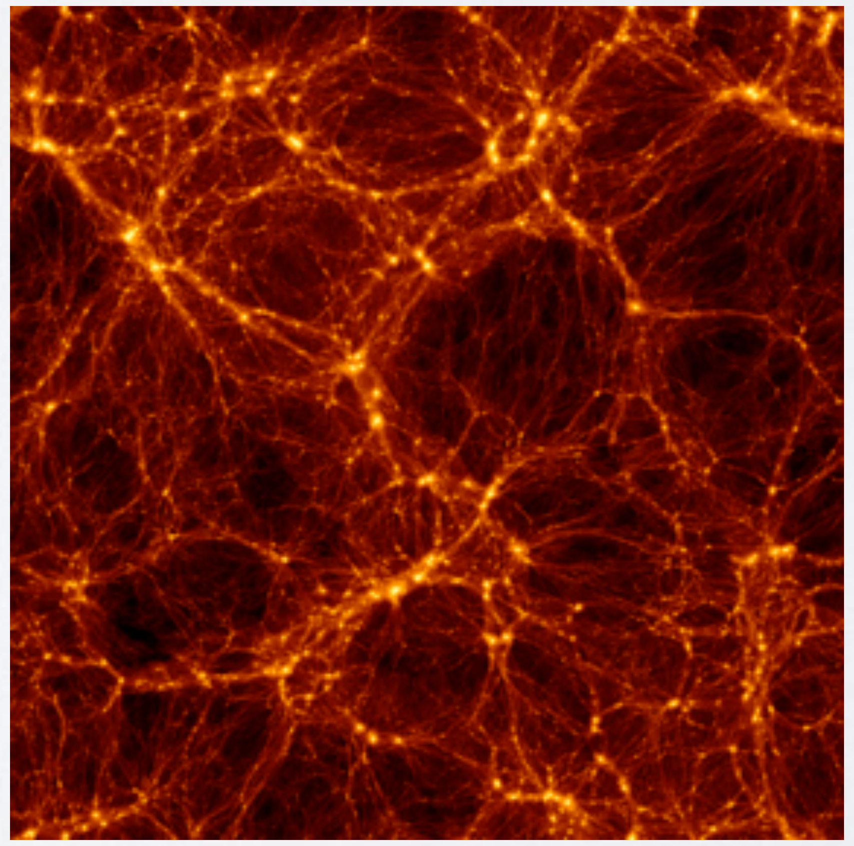

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OUTLINE

- Neutrinos and their properties
- Neutrino mass measurement methods
- Current experiments
  - Special focus: KATRIN, Project 8
- The future

A PRIMER ON NEUTRINOS

- Neutrino oscillation:

PMNS mixing matrix

Flavor eigenstates $|\nu_l>$ →

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

Mass eigenstates $|\nu_i>$

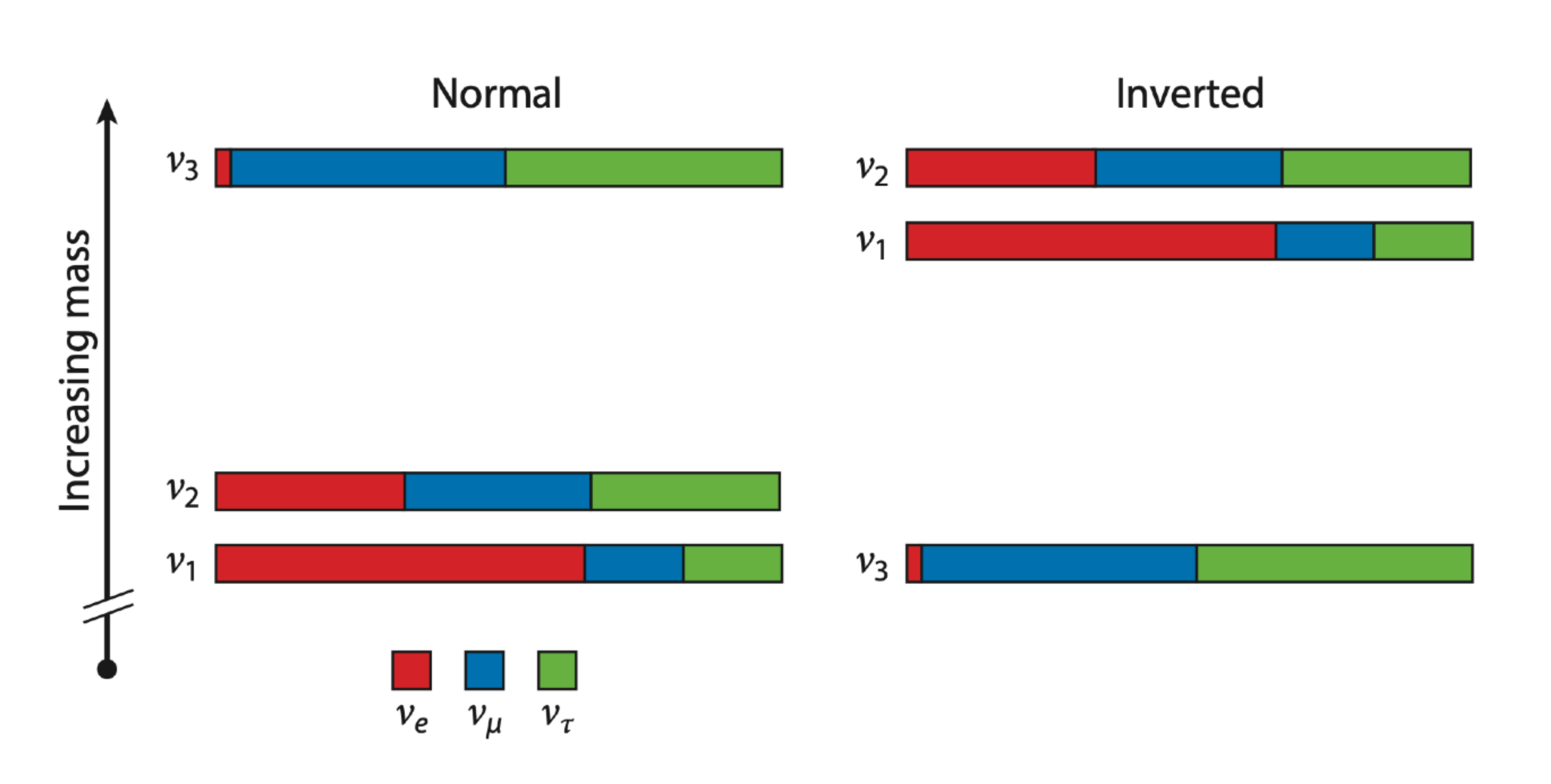
Probability upon detection:

$$P_{ii'} \propto \frac{(m_i^2 - m_{i'}^2)L}{E}$$

Example decay:

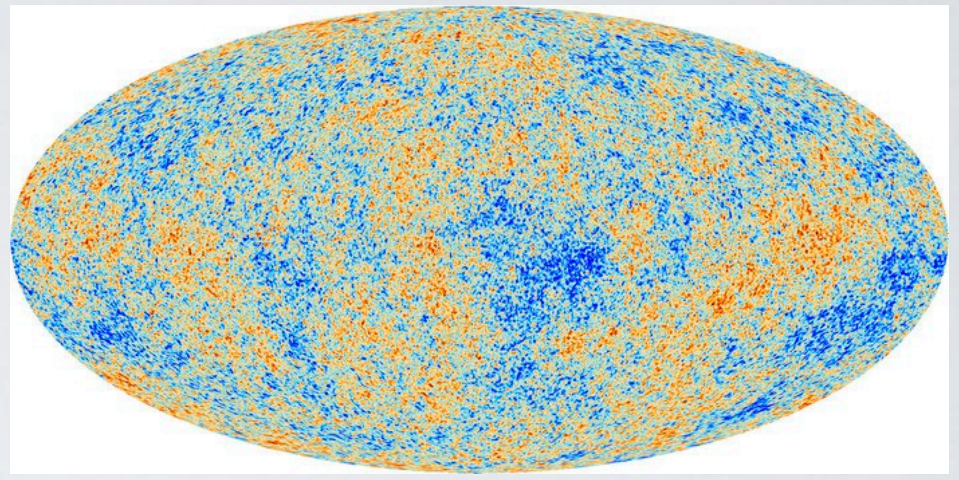
$$n \rightarrow p + e^- + \bar{\nu}_e$$

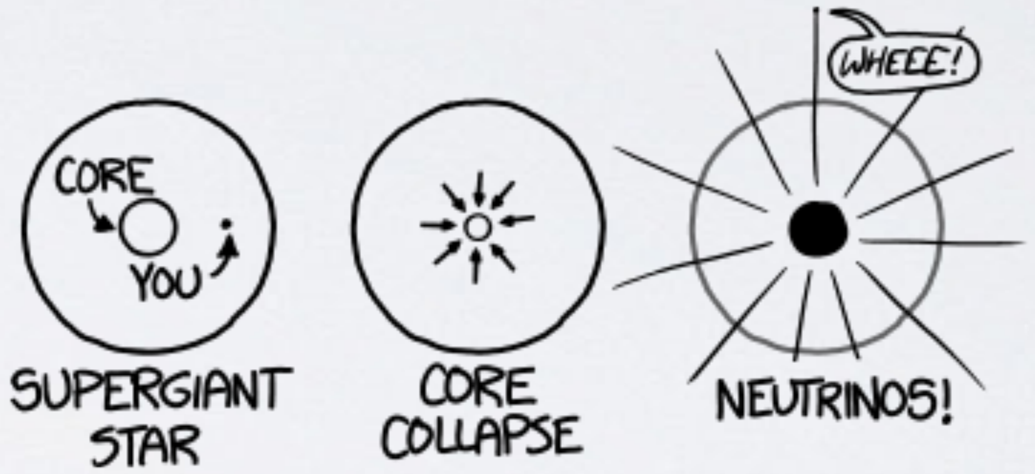
- Neutrino sector has many other interesting features:
  - Mass ordering: normal vs. inverted
  - Type: Majorana vs. Dirac
  - Absolute mass scale ← !

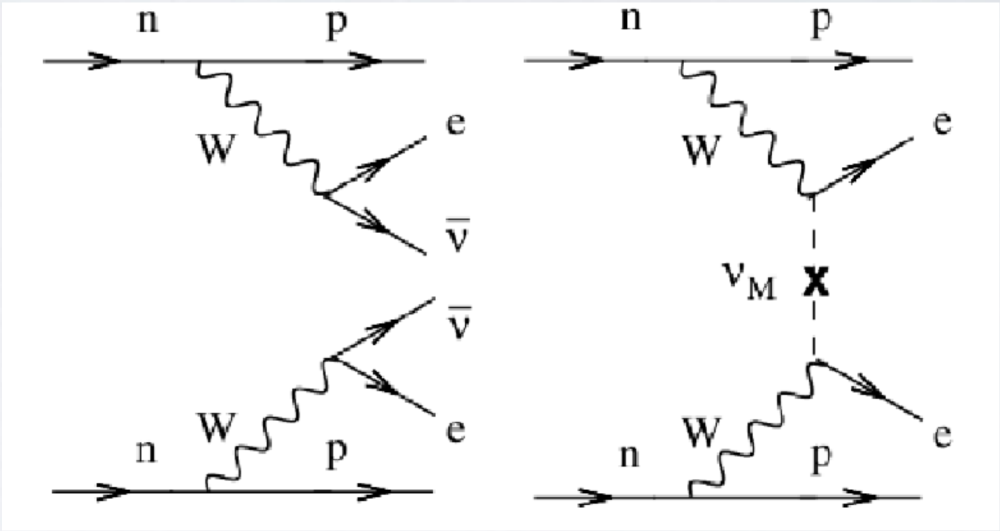


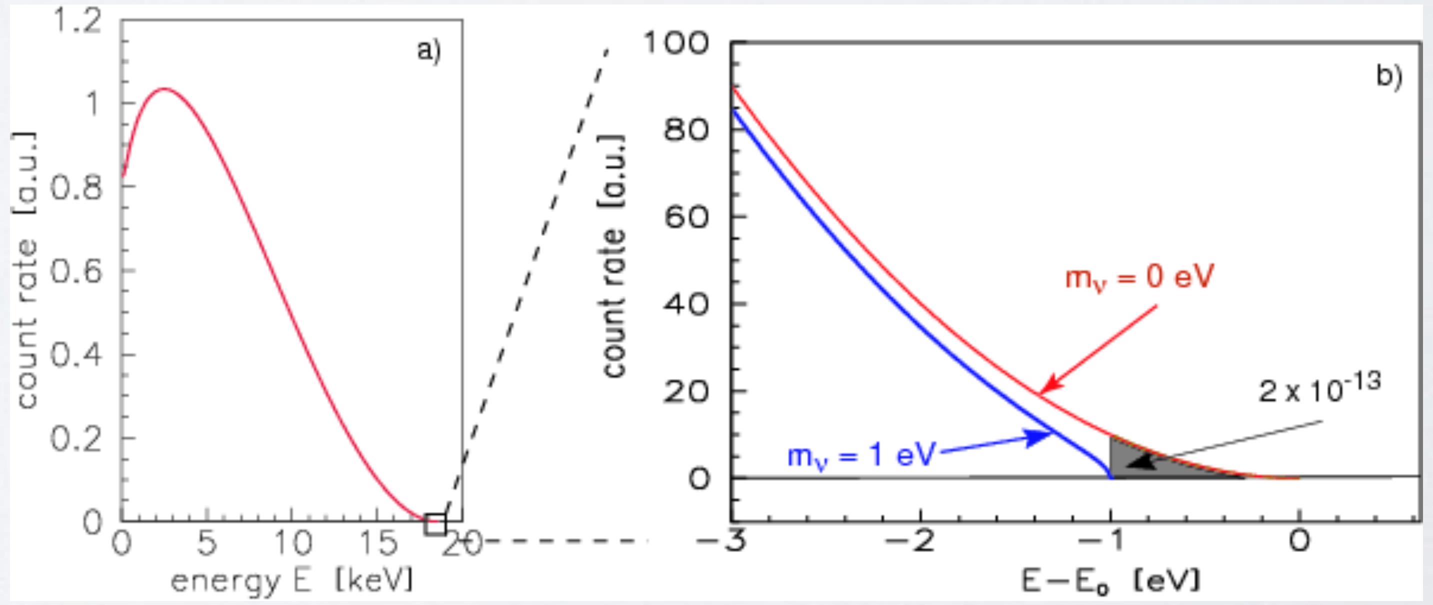
NEUTRINO MASS: HOW?

- 4 approaches to absolute neutrino mass measurement:
  1. Cosmology
  2. Supernova time-of-flight
  3. Search for neutrinoless double beta decay
  4. Kinematic methods (beta decay)





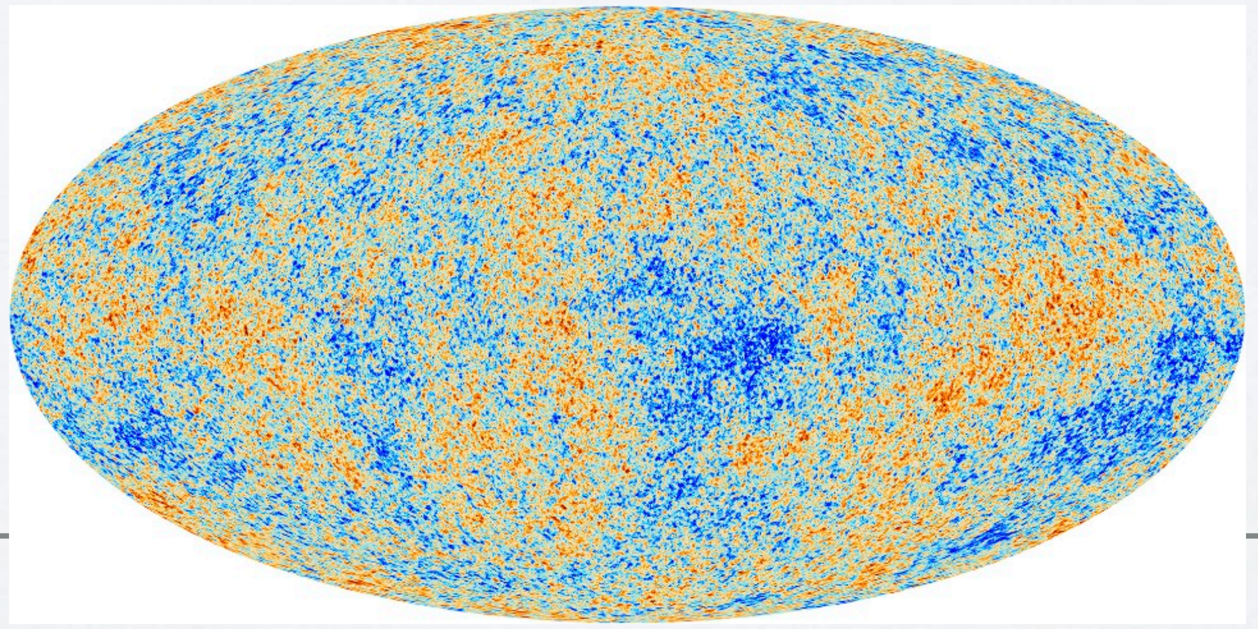




$$M_\nu = \sum_{i=1}^{3} m_i$$

COSMOLOGY

- *Technique*: fit various models to cosmological data (CMB, BAO, BBN)
- *Neutrino mass*: see table
- *Advantages*: data from varied, complimentary data sets
- *Challenges*: model-dependent
- Recent DESI results: if include M_ν and ξ_3, can resolve some long-standing tensions (Yeung 2024: $M_\nu = 0.58^{+0.17}_{-0.13}$ eV)



Credit: ESA & the Planck Collaboration

Cosmological model		$\sum m_\nu$[eV]
$+\sum m_\nu$	DH	< 0.0866
	NH	< 0.129
	IH	< 0.155
$+\sum m_\nu + N_{\rm eff}$	DH	< 0.0968
	NH	< 0.131
	IH	< 0.163
$+\sum m_\nu + \Omega_k$	DH	< 0.111
	NH	< 0.143
	IH	< 0.180
$+\sum m_\nu + \alpha_s$	DH	< 0.0908
	NH	< 0.128
	IH	< 0.157
$+\sum m_\nu + r$	DH	< 0.0898
	NH	< 0.130
	IH	< 0.156
$+\sum m_\nu + w_0$	DH	< 0.139
	NH	< 0.165
	IH	< 0.204
$+\sum m_\nu + (w_0 > -1)$	DH	< 0.0848
	NH	< 0.125
	IH	< 0.157
$+\sum m_\nu + w_0 + w_a$	DH	< 0.224
	NH	< 0.248
	IH	< 0.265
$+\sum m_\nu + A_{\rm L}$	DH	< 0.166
	NH	< 0.189
	IH	< 0.216
model marginalized	DH	< 0.102

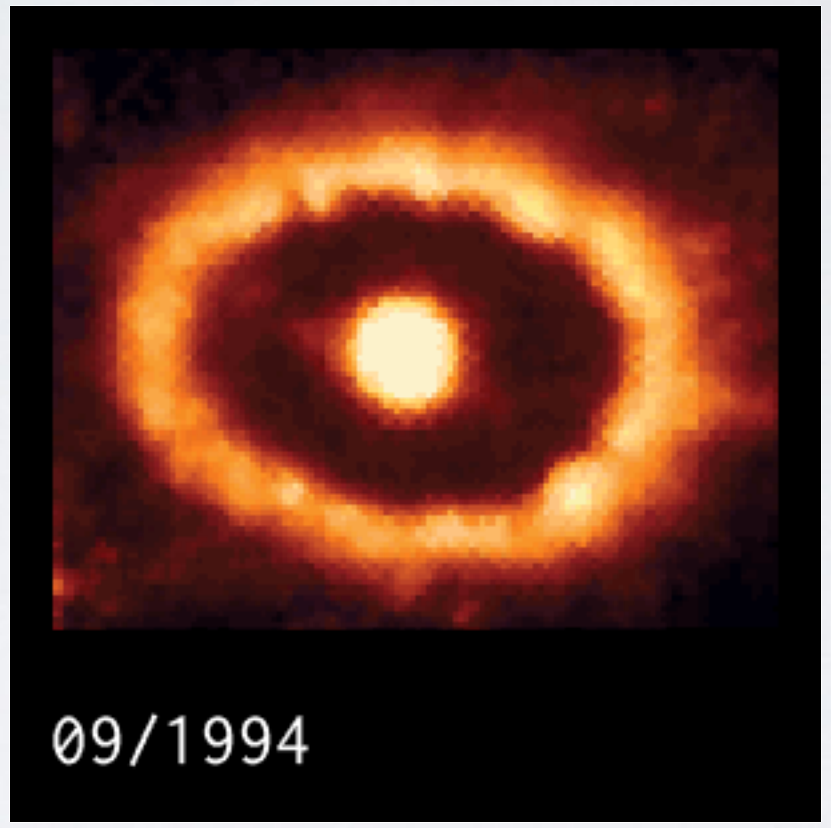
TABLE II. Constraints at 68% and upper limits at 95% CL, for the ΛCDM+$\sum m_\nu$ model and its extensions (adapted from Ref. [32]).

Source: https://arxiv.org/abs/2404.19322

$$m_{\bar{\nu}_e}^2 = \sum_{i=1}^{3} |U_{e,i}|^2 m_i^2$$

SUPERNOVA

- Supernova 1987a
- *Technique*: time-of-flight analysis on ~25 neutrinos
- *Neutrino mass:* $m_{\bar{\nu}_e} \leq 5.7$ eV @ 95 % C.L. (Loredo 2001)
- *Advantages*:
  - Multiple detectors
  - Information on mass hierarchy (MSW: 1-3 mixing), stellar structure, and equation of state
- *Challenges*:
  - Low statistics
  - Best signal (from $p + e^- \rightarrow n + \nu_e$) is not main detection channel



Credit: Hubble

Credit: JWST

Table 2: Neutrino Data

Time (UT) February	Detector (threshold*/size)	# of Events (E-range/Duration)
23 2h 52m	Mt. Blanc (7 MeV/90 T)+	5 (6–10 MeV/7 sec)
"" ±1 min	Kamioka (8 MeV/2.14 kT)	2 (7–12 MeV/10 sec)
"	IMB (30 MeV/5 kT)	none reported
"	Baksan (11 MeV/130 T)+	none reported
23 7h 35m (± min)	Kamioka (7 MeV/90 T)	11 (7–35 MeV/13 sec)
23 7h 35m	IMB (30 MeV/5 kT)	8 (20–40 MeV/4 sec)
"	Baksan (11 MeV/130 T)+	3 (12–17 MeV/10 sec)
"	Mt. Blanc (7 MeV/90 T)+	2 (7–9 MeV/13 sec)
sum of pulses	Homestake ν_e (0.7 MeV/615 T)**	consistent with background
	Optical	
23 9h 25m	lack of sighting	$m_v \gtrsim 8$ magnitude
23 10h 40m	photograph	$m_v = 6$ magnitude
24 10h 53m	discovery	$m_v = 4.8$ magnitude

*Threshold is when efficiency drops to $\lesssim 50\%$ (sub-threshold events are therefore possible).

+These detectors are liquid scintalators with $H_{2n+n}C_n$, thus have ~ 1.39 more free protons than H_2O detectors of same mass.

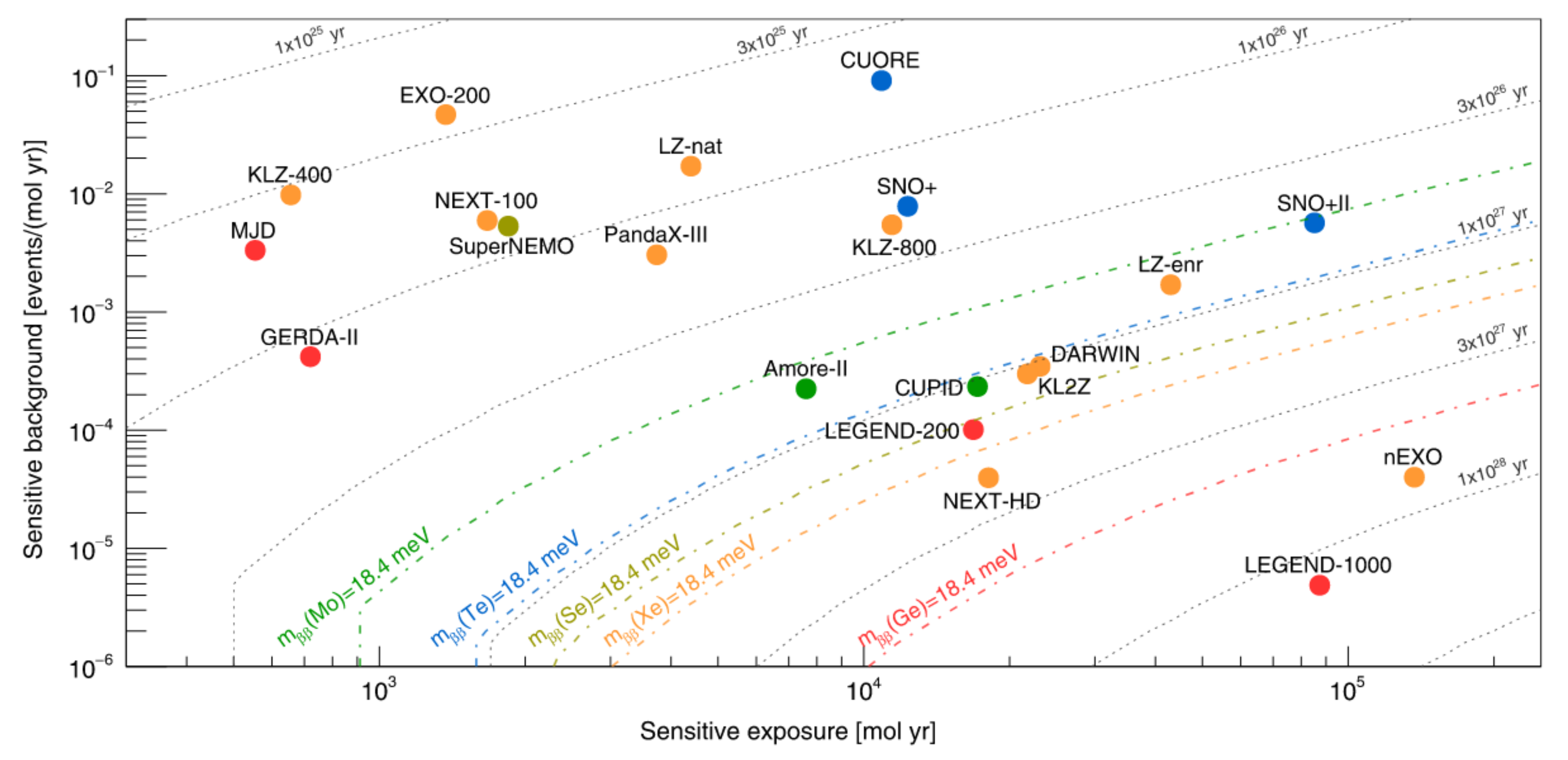
**The Homestake detector is only sensitive to ν_e's. It is made of C_2Cl_4.

Source: Schramm 1987

$$m_{\beta\beta} = \left|\sum_{i=1}^{3} |U_{e,i}|^2 m_i e^{i\alpha_i}\right|$$

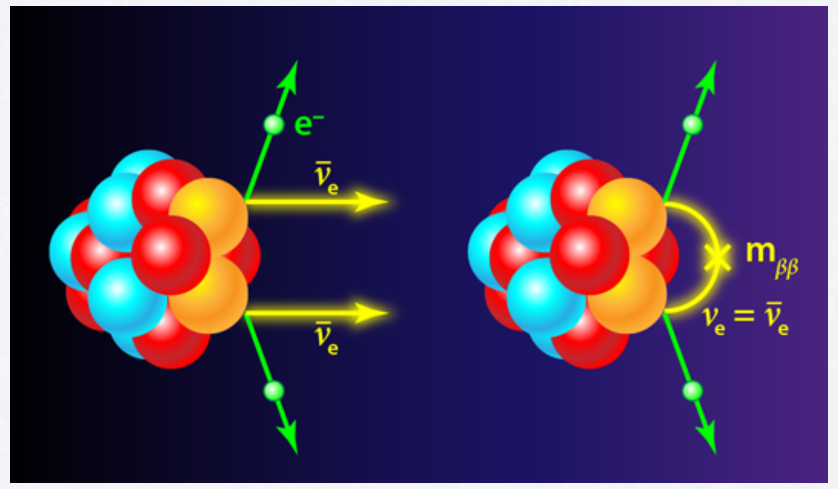
NEUTRINO-LESS DOUBLE BETA DECAY

- *Technique*: measurement of decay rate
- *Neutrino mass*: $m_{\beta\beta} \leq 36 - 156$ meV (Mei 2024)
- *Advantages*:
  - Many candidate isotopes, detectors, techniques
  - Addresses "is the neutrino its own antiparticle?" (Majorana vs. Dirac nature)
- *Challenges*:
  - Backgrounds
  - Precision of nuclear matrix element calculations
  - Unknown phase parameters, sign of Δm^2_{13}

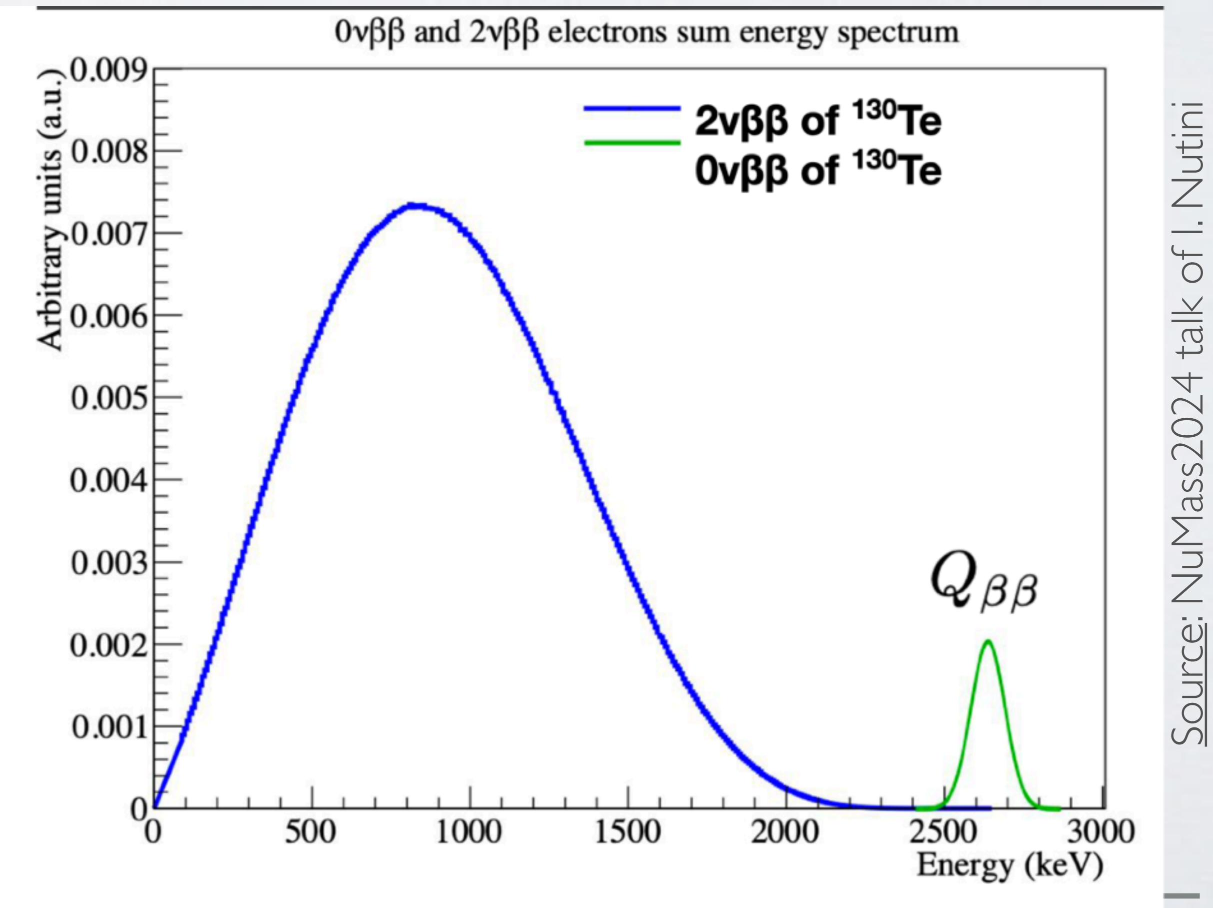


Source: Agostini 2023

$$(T^{0\nu}_{\beta\beta})^{-1} = G^{0\nu}(E_0, Z)|(\frac{m_{\beta\beta}}{m_e})^2||M^{0\nu}_f - (\frac{g_A}{g_V})^2 M^{0\nu}_{GT}|^2.$$



Source: APS / Stonebreaker



Source: NuMass2024 talk of I. Nutini

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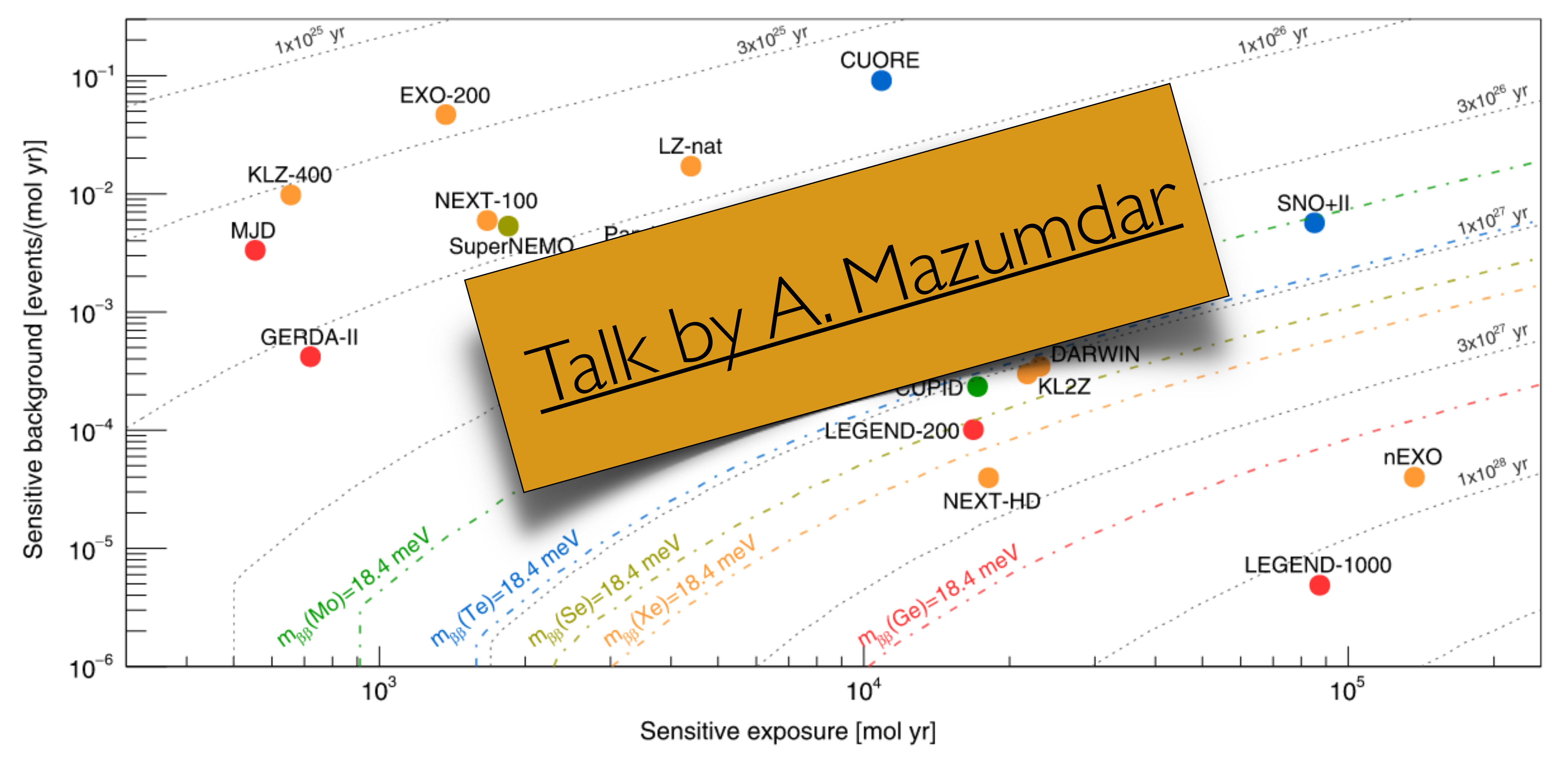

Talk by A. Mazumdar

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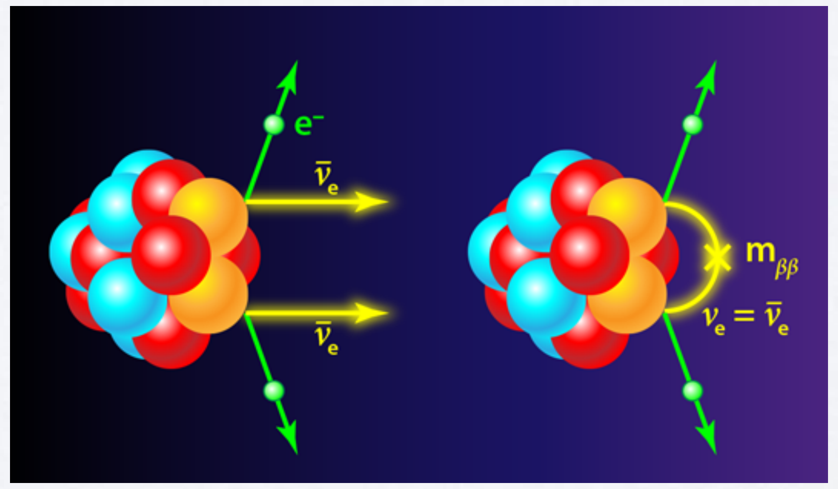
$$(T^{0\nu}_{\beta\beta})^{-1} = G^{0\nu}(E_0, Z)\left|\left(\frac{m_{\beta\beta}}{m_e}\right)^2\right|\left|M^{0\nu}_f - \left(\frac{g_A}{g_V}\right)^2 M^{0\nu}_{GT}\right|^2.$$



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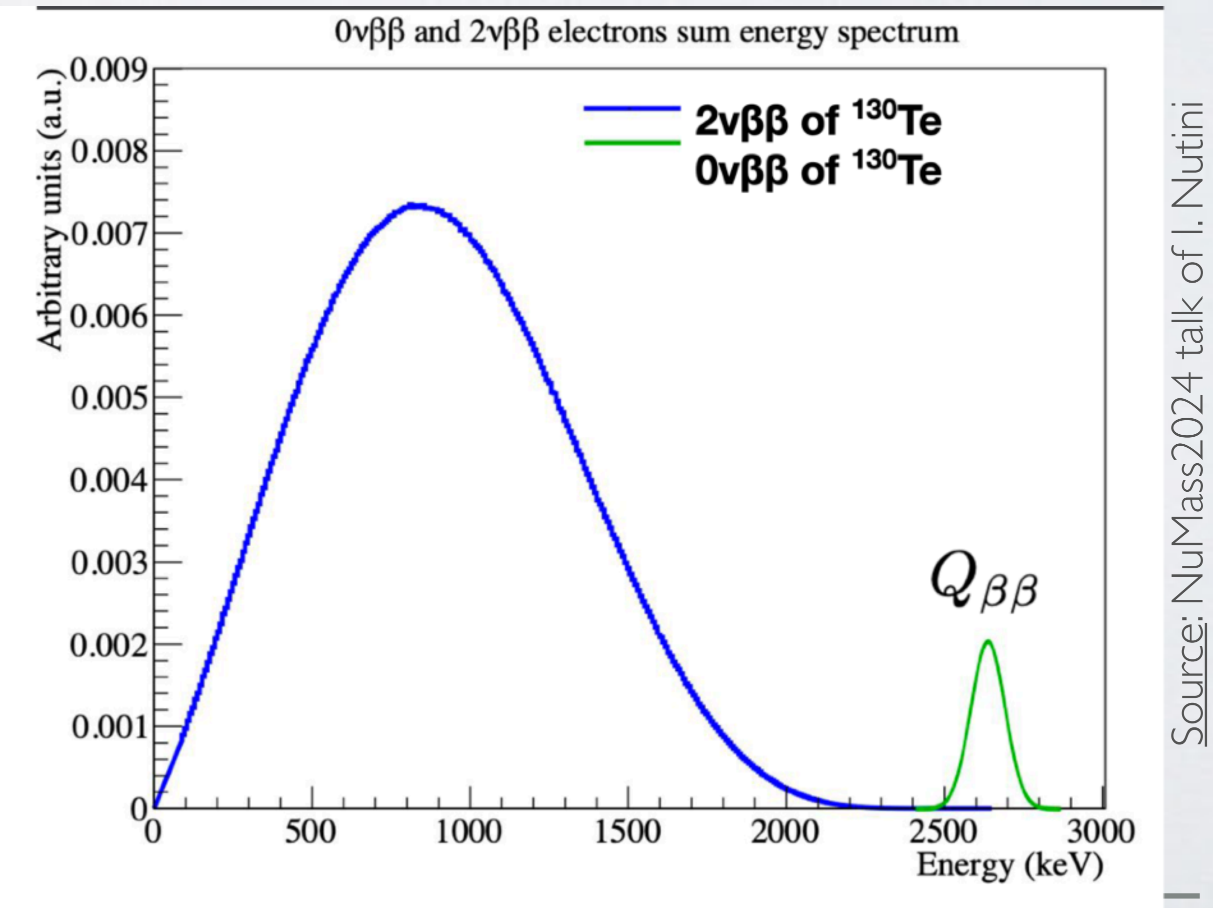

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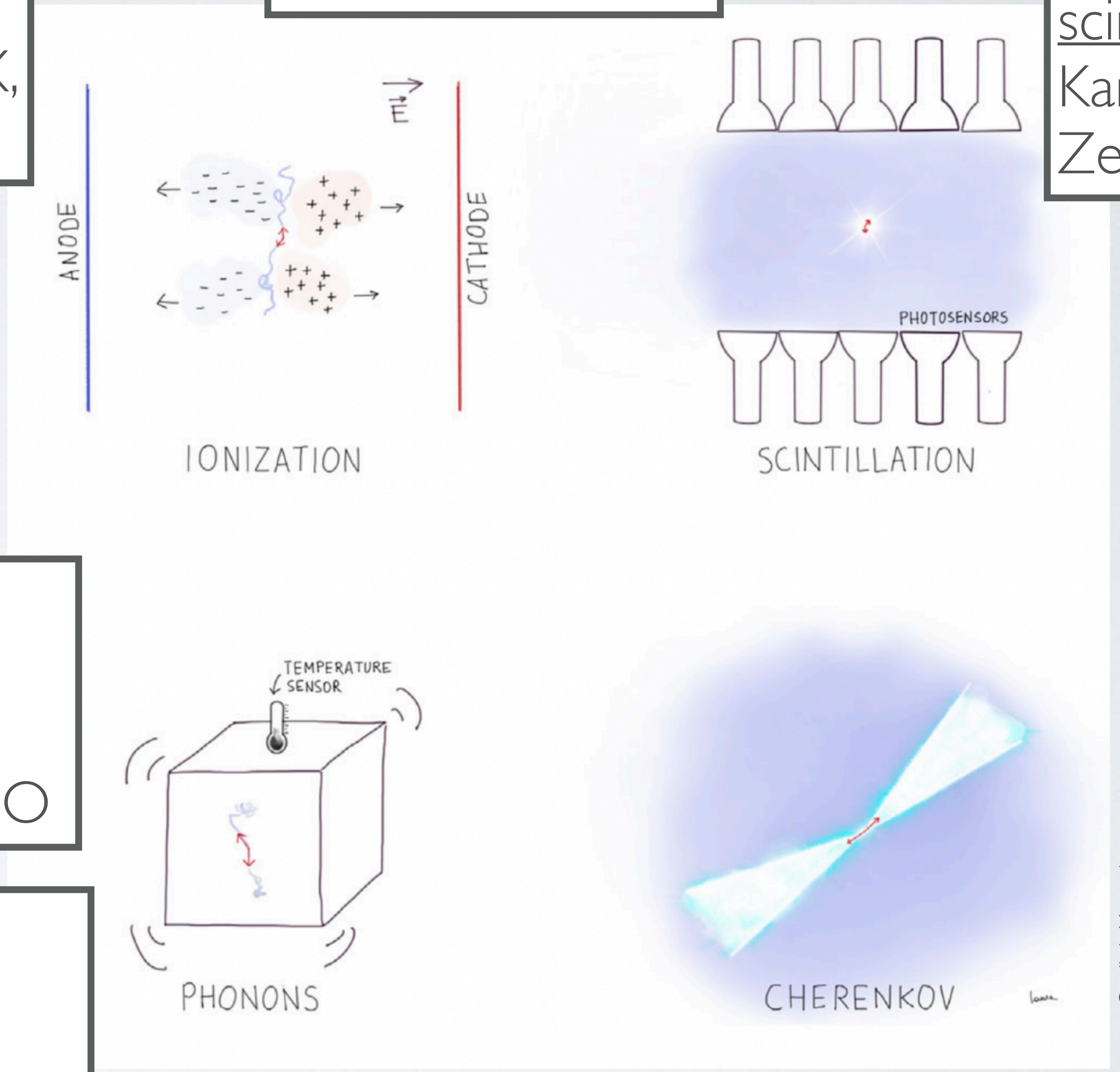
Time projection chambers: EXO-200, nEXO, NEXT, PANDA-X, LZ, Darwin

HPGe: GERDA, MAJORANA, LEGEND

Liquid scintillator: Kamland-Zen, SNO+



Tracking calorimeter: NEMO-3, SUPERNEMO

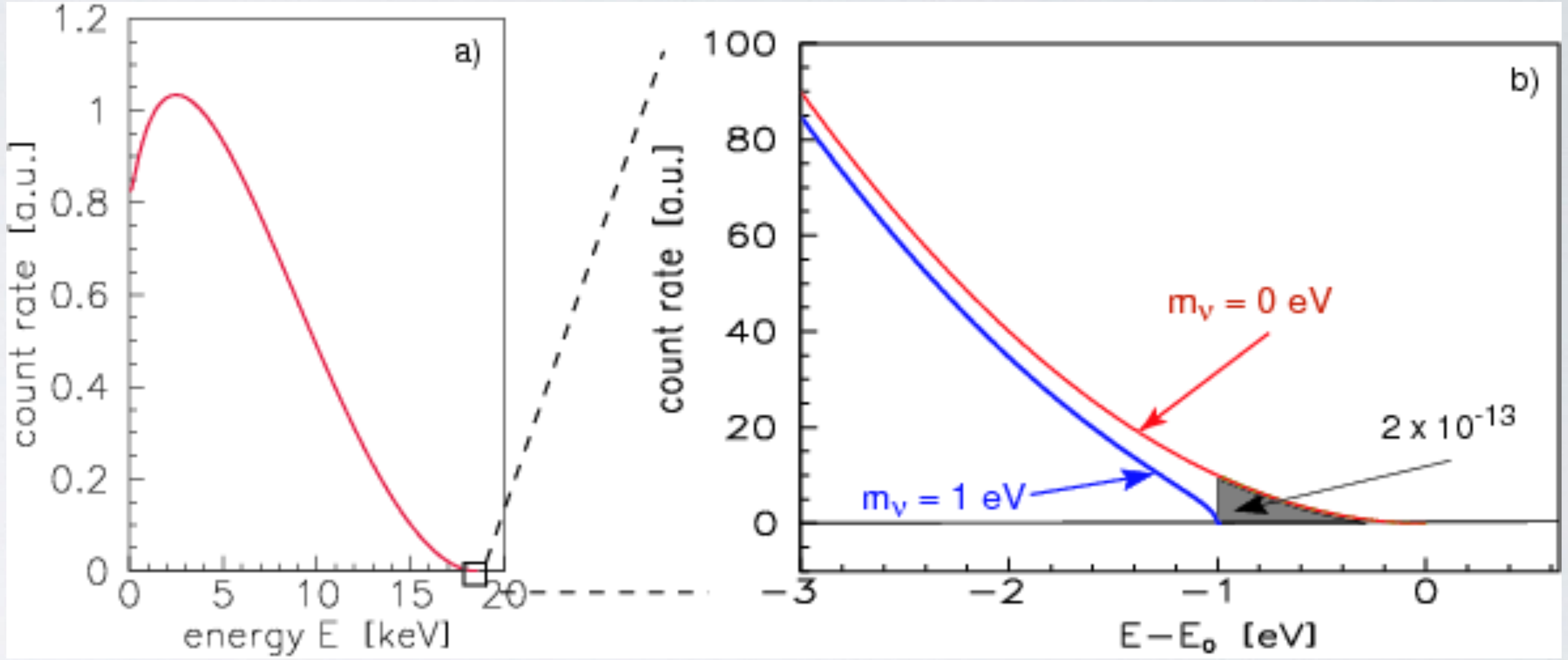
Cryogenic calorimeter: CUPID-Mo, CROSS, CUPID/0, AMoRE-II, CUORE

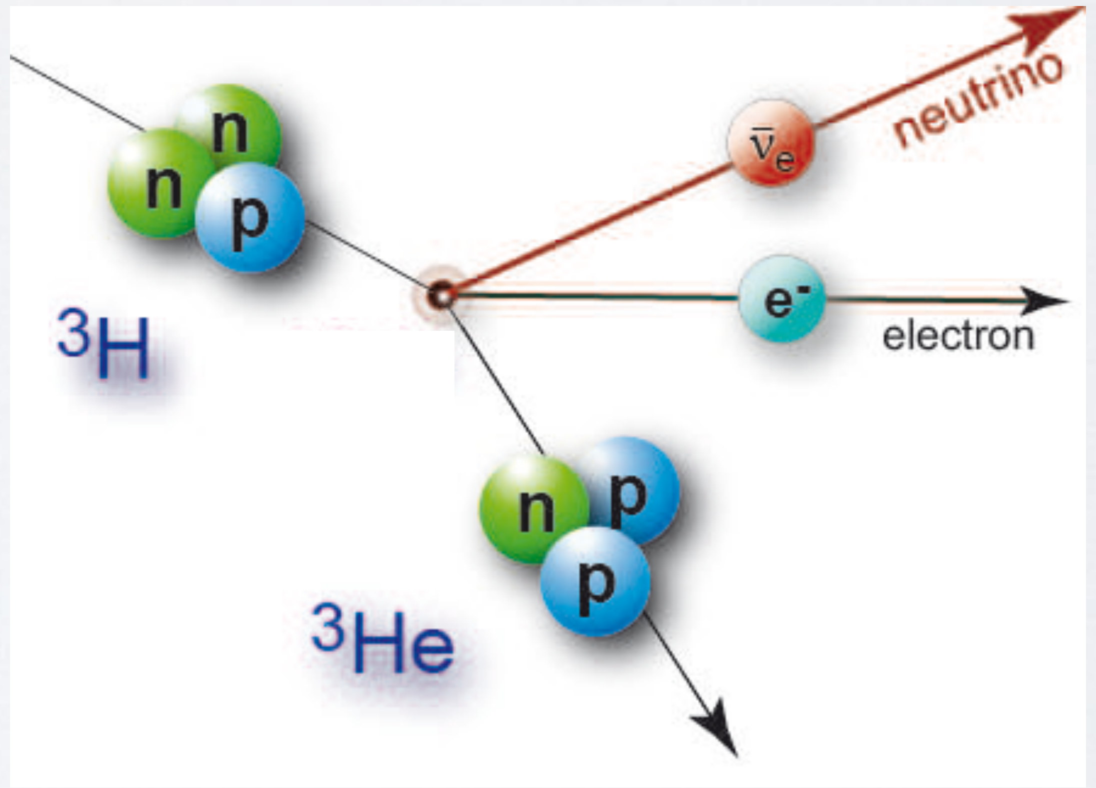
Credit: L. Manenti

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

BETA DECAY

- Various isotopes for beta decay
- *Technique*: measurement of beta particle energy
- *Neutrino mass*: $m_{\nu,e} \leq 0.8$ eV @ $90\ \%$ C.L. (KATRIN 2022)
- *Advantages*:
  - Cross checks to other experiments (Q values, isotopes)
- *Challenges*:
  - Statistics
  - Systematics (molecular final states, backgrounds)





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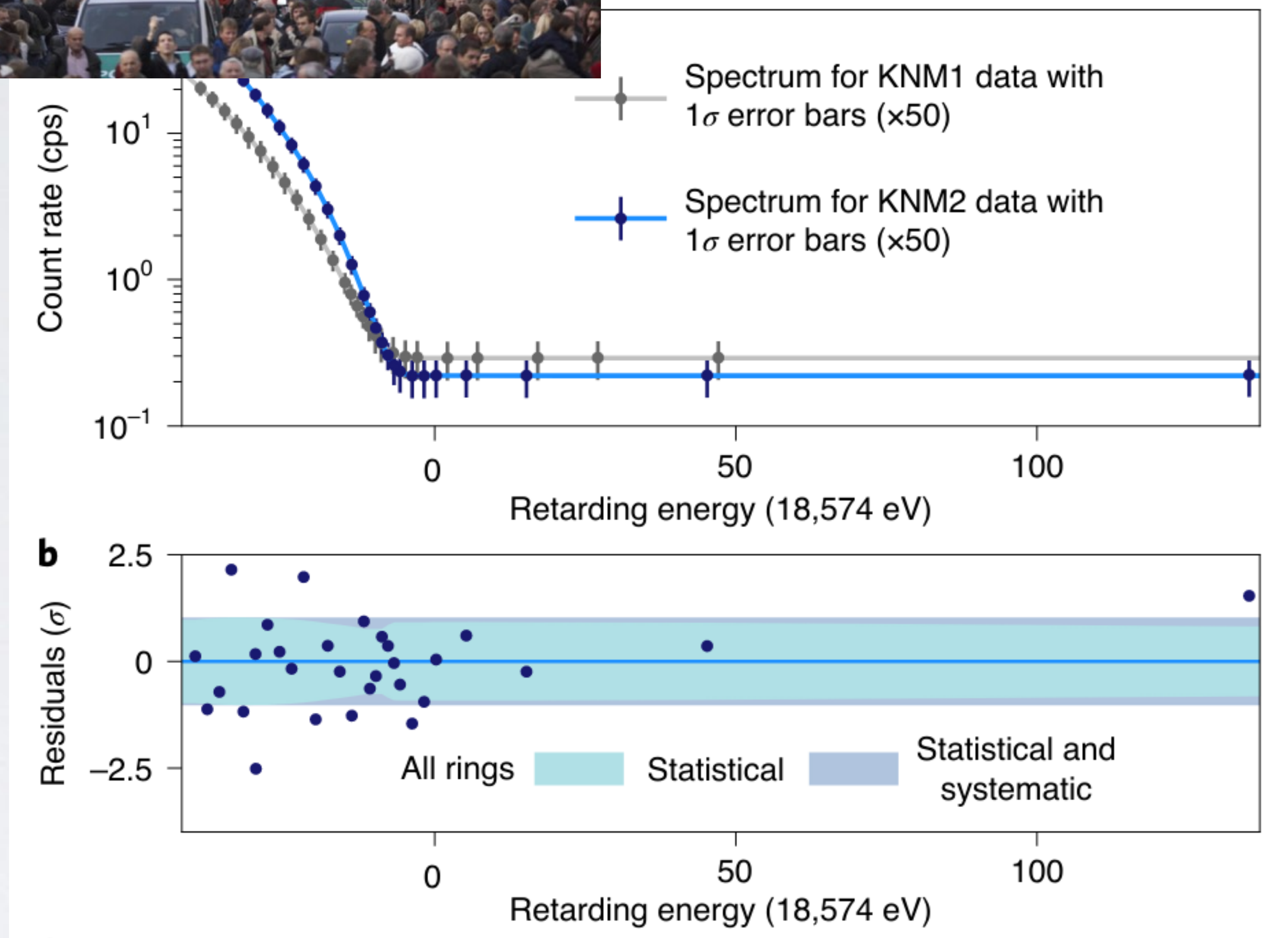
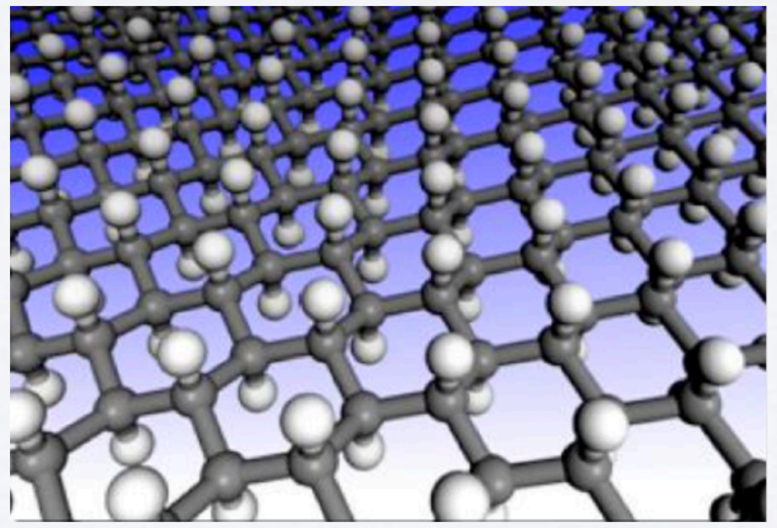
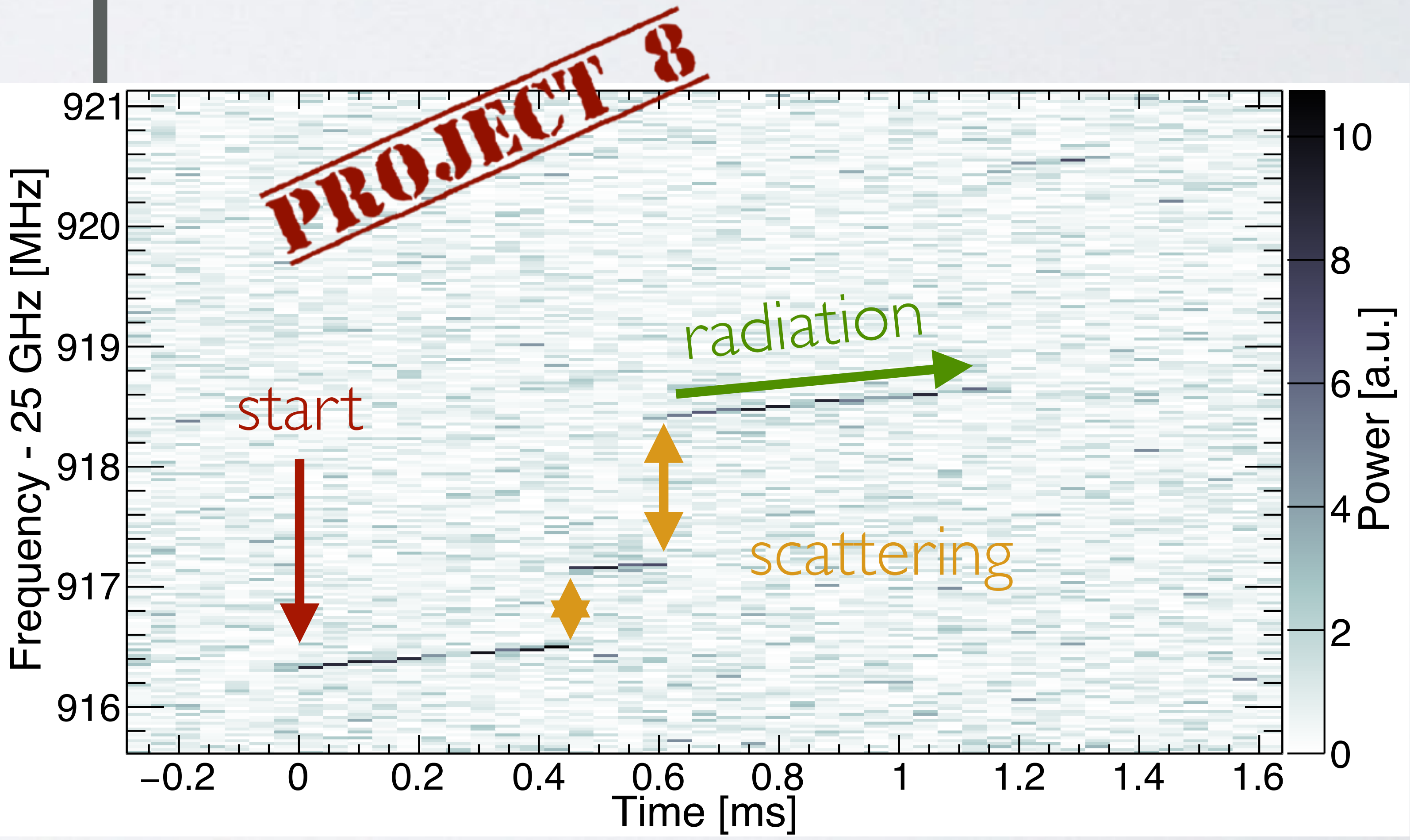
Tritium: $^3H \rightarrow ^3He^+ + e^- + \bar{\nu}_e$

- Endpoint: 18.6 keV
- Half-life: 12.3 yr
- Experiments: KATRIN, Project 8, PTOLEMY

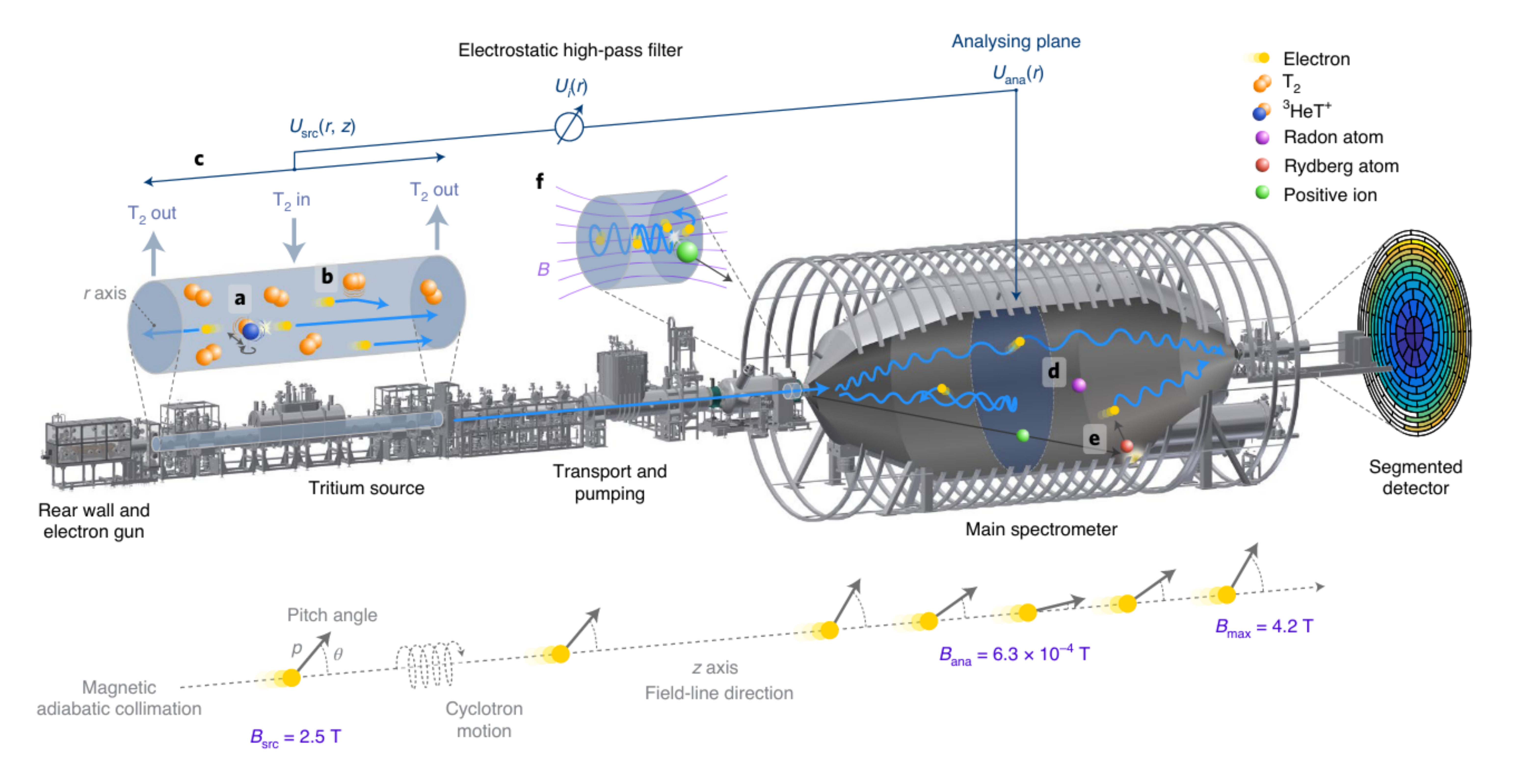


Source: KATRIN sub-eV result, Nature 2022





BETA DECAY: KATRIN



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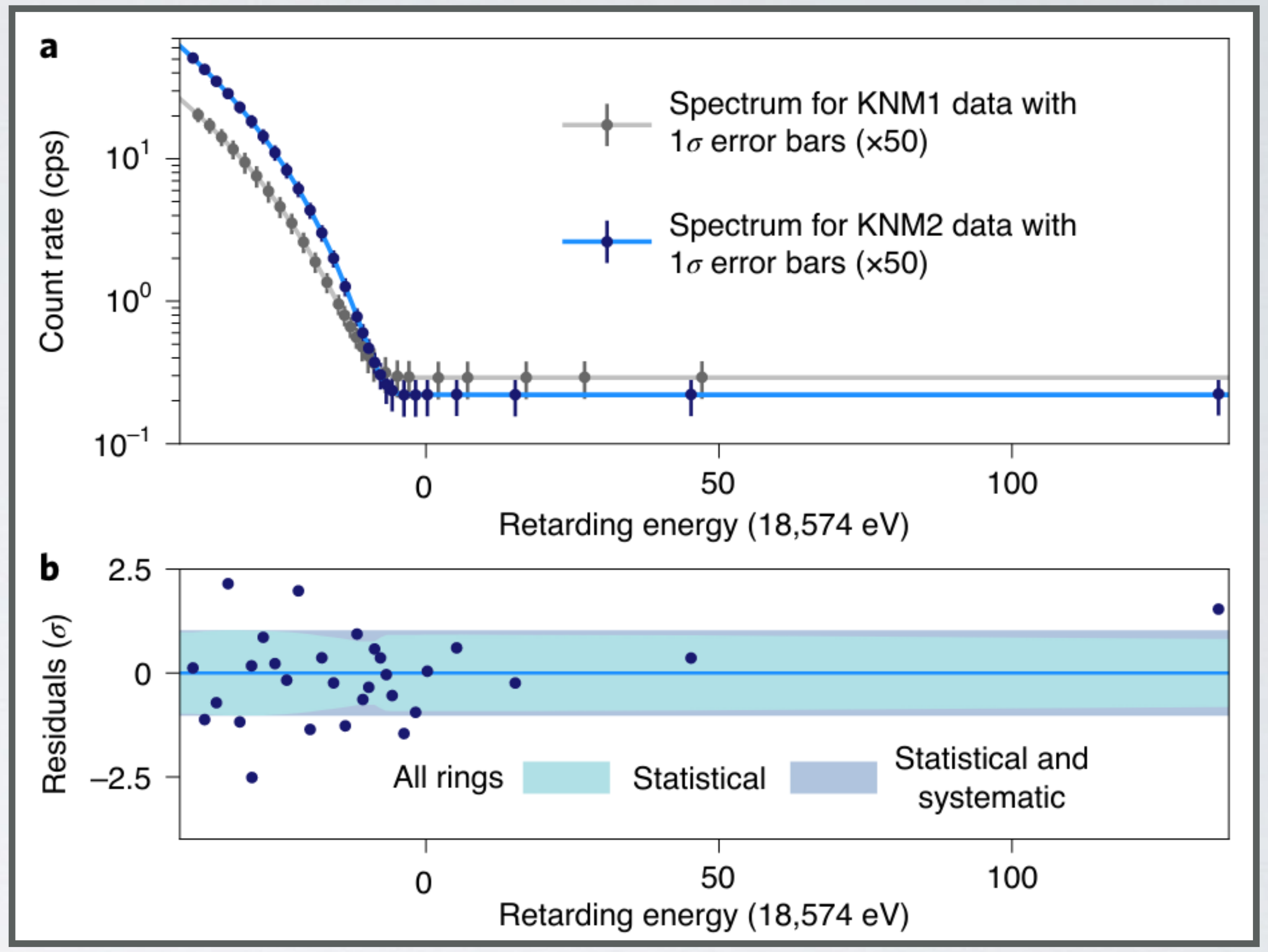


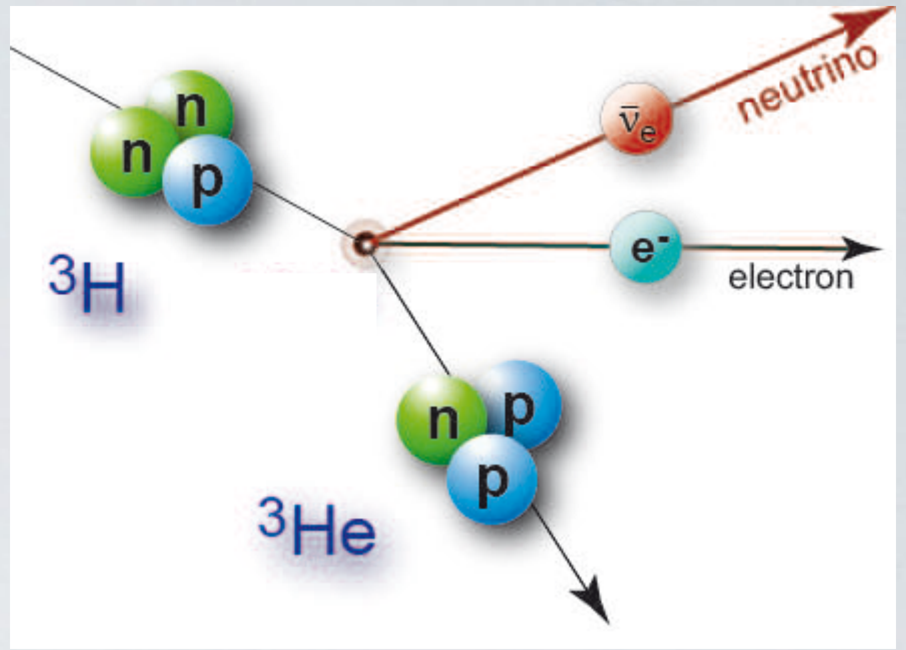
Source: KATRIN sub-eV result, Nature 2022

Current result:

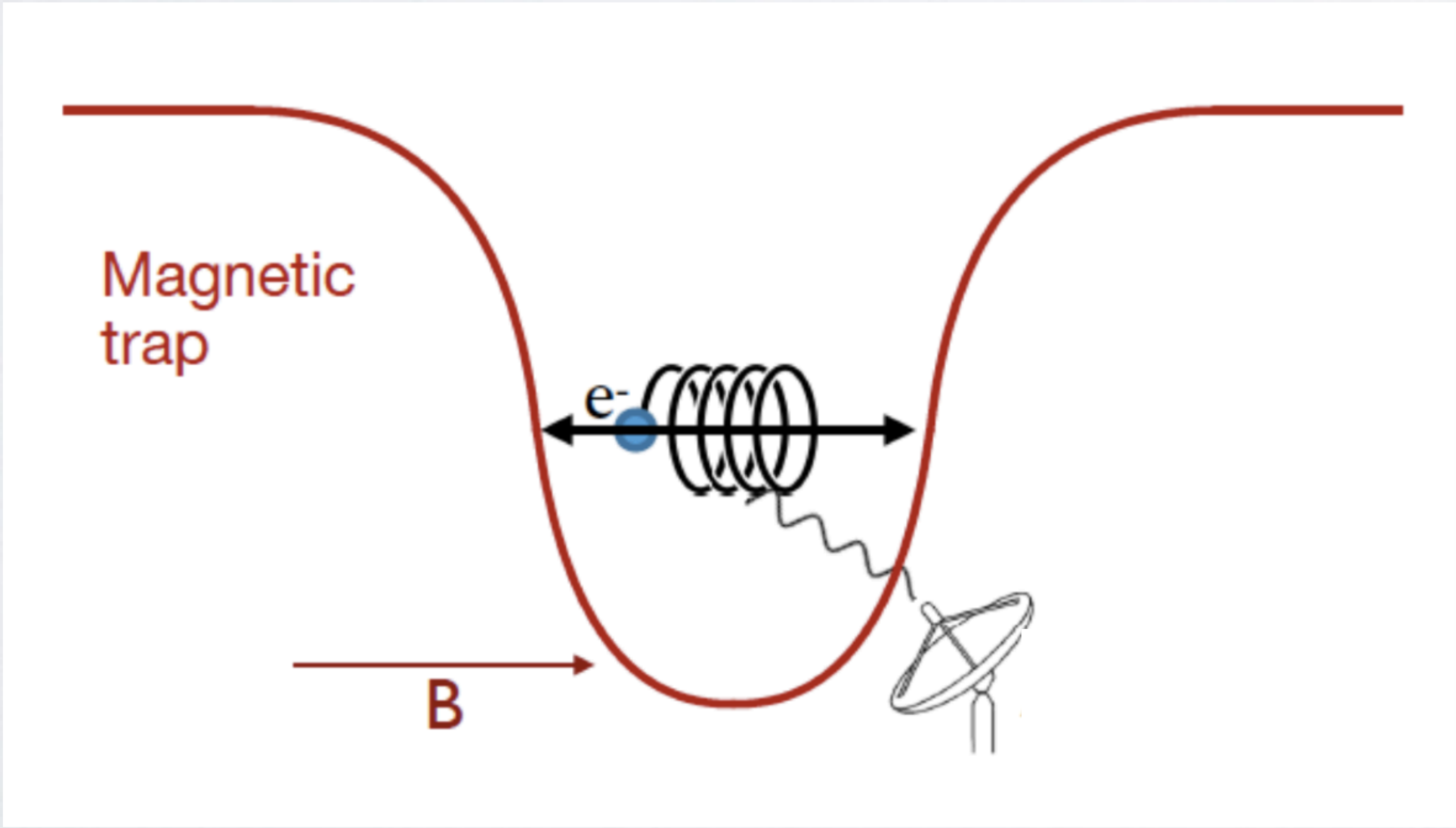
$m_{\nu,e} \leq 0.8$ eV @ 90 % C.L.

Design sensitivity: 0.3 eV

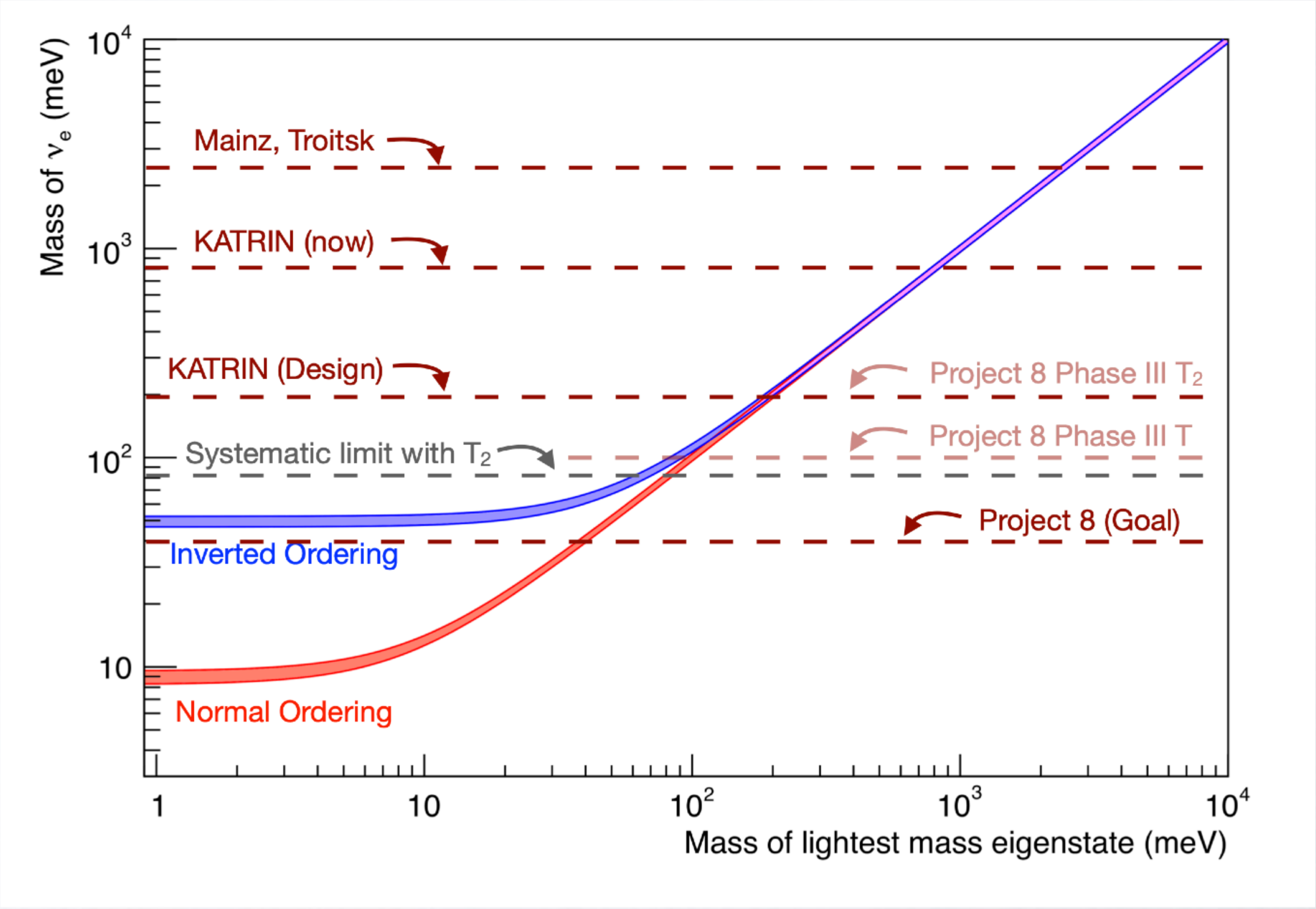
BETA DECAY: PROJECT 8



- Goal: absolute neutrino mass measurement
- Technique: measure cyclotron radiation from trapped atomic tritium beta decay electrons ("CRES": **c**yclotron **r**adiation **e**mission **s**pectroscopy)
- Design sensitivity: 40meV at 90% C.L.



https://www.project8.org

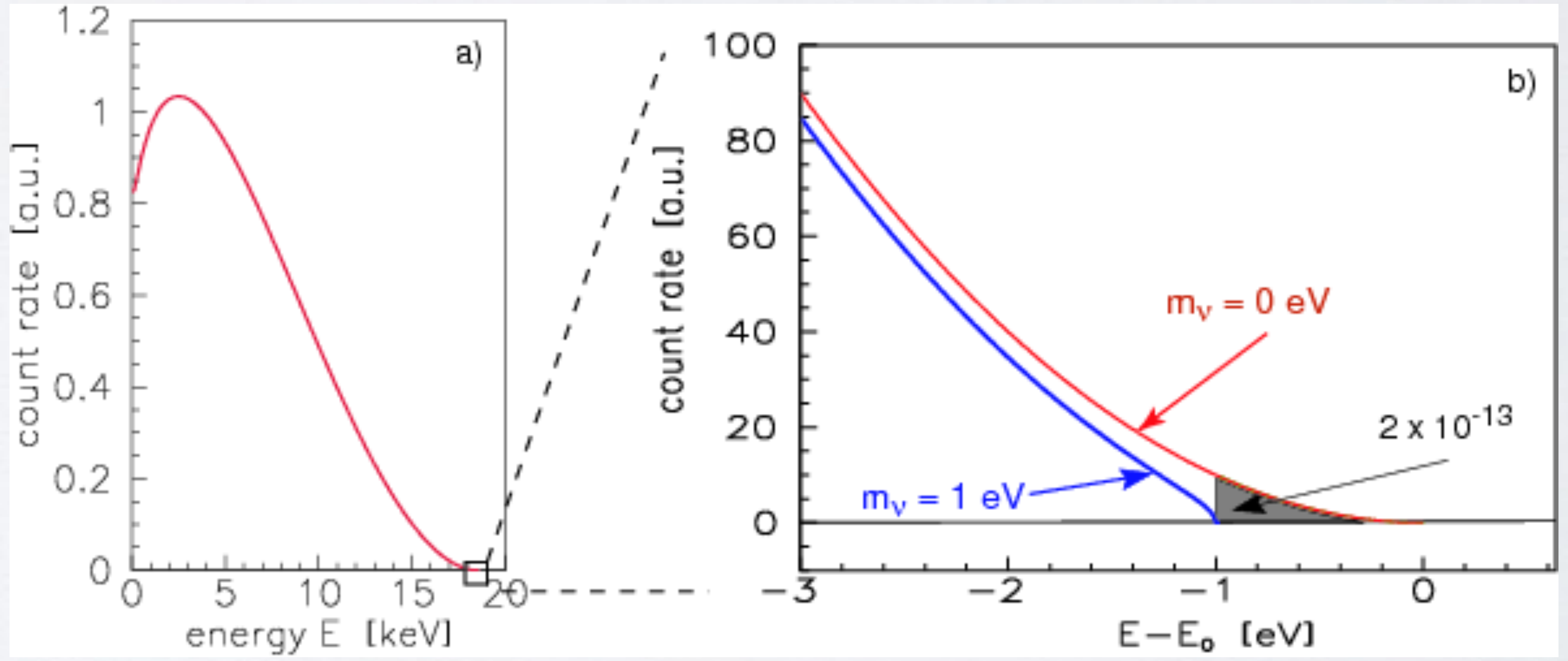


PROJECT 8: MEASUREMENT TECHNIQUE

CRES: cyclotron radiation emission spectroscopy

1. Trap decay electrons from tritium source gas within local minimum of a homogeneous B field →
2. Beta decay electron undergoes cyclotron motion with frequency ***f_cyc***
3. Radiation detected

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



Tritium isotope has attractive beta decay properties: decay is **super-allowed**, practical **half-life** (~12.3yr), fairly low **endpoint energy** (~18.6keV)

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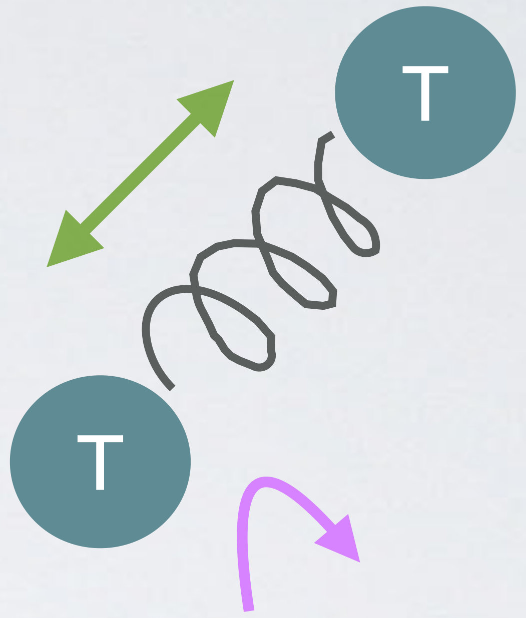
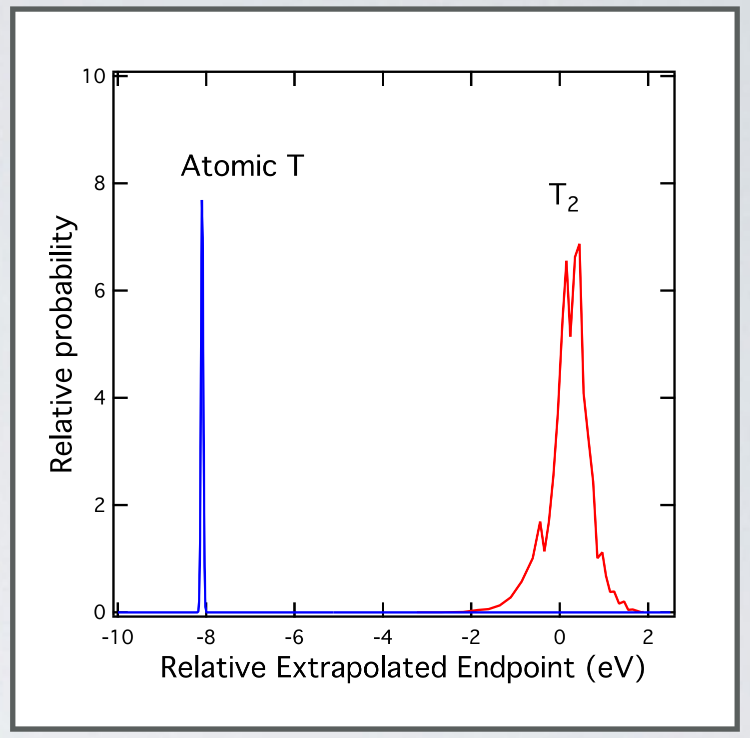
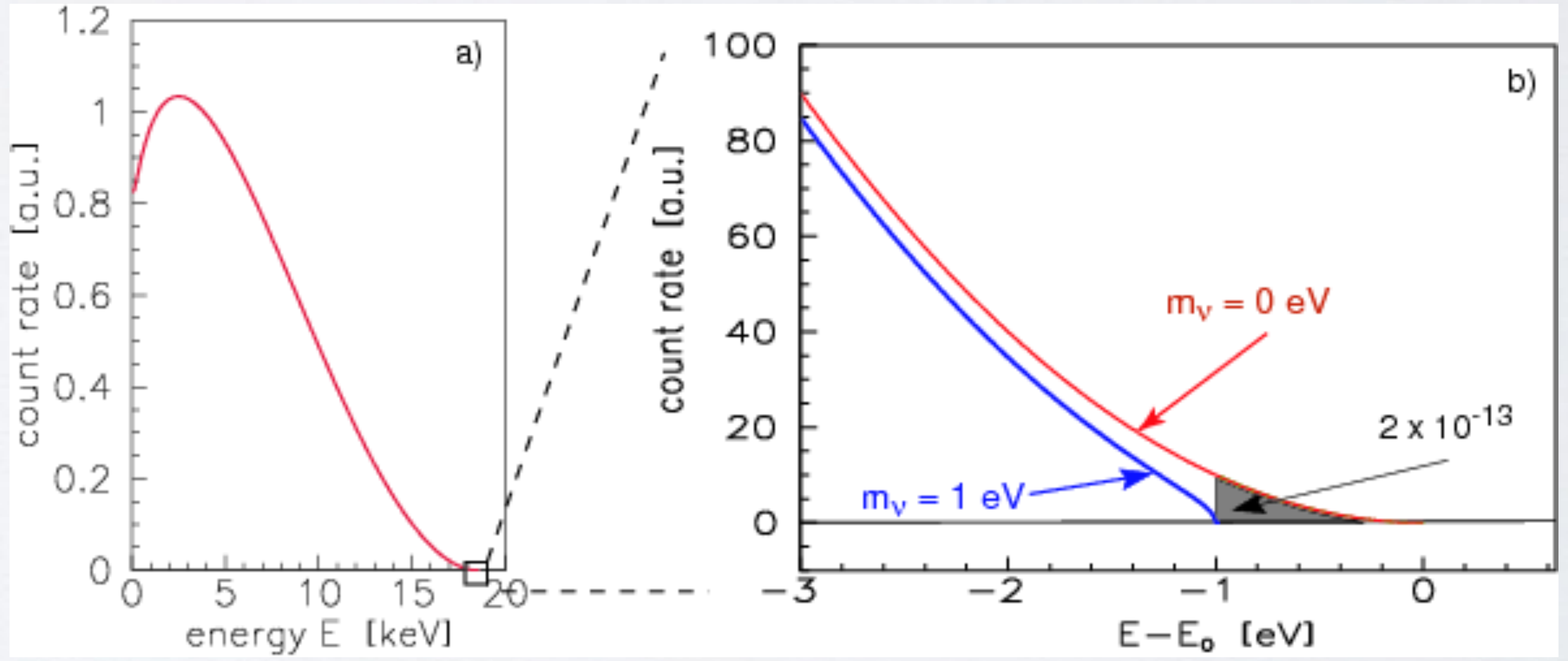




Adapted from L. Bodine

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



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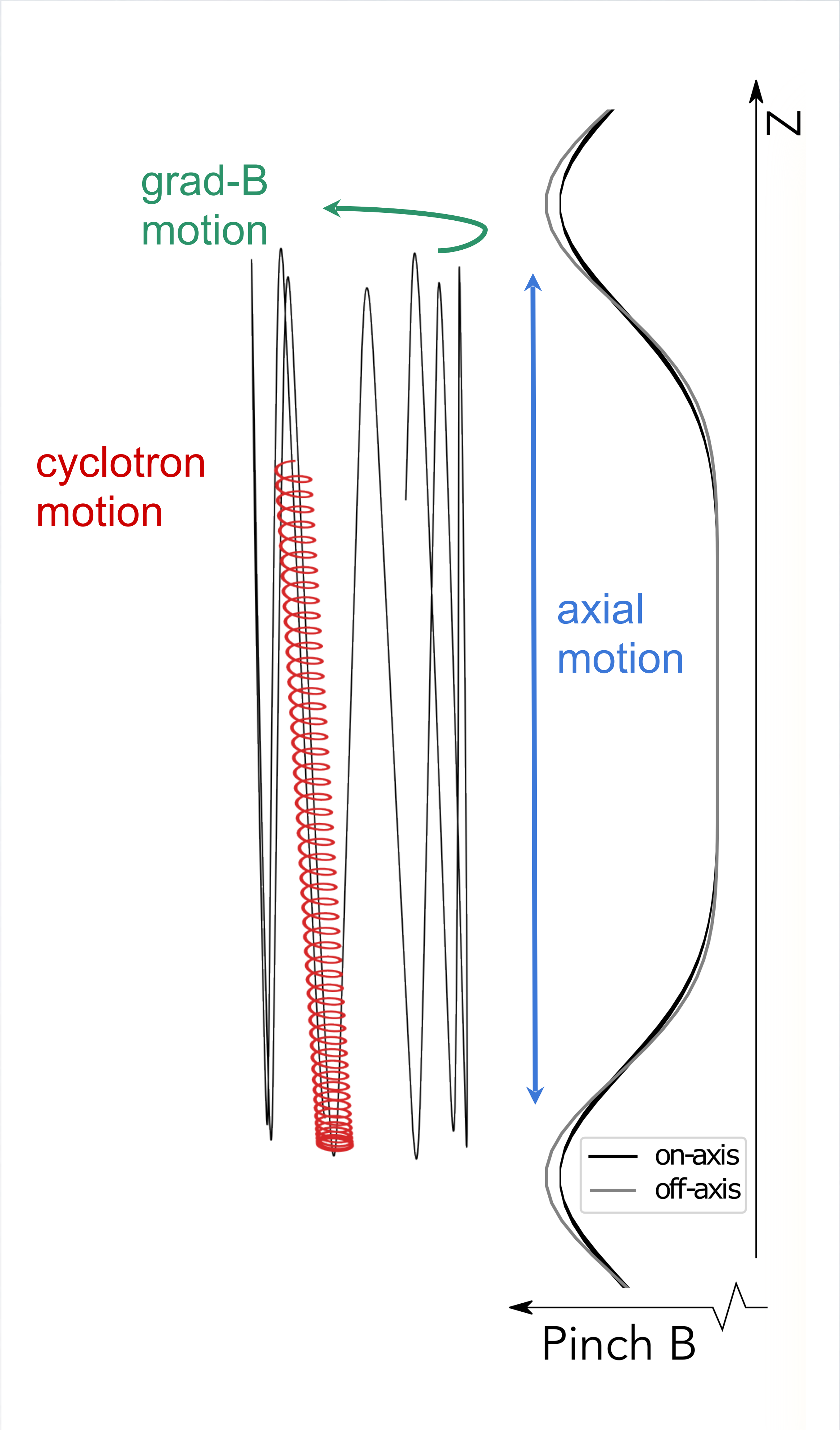
$$f_{cyc} \propto \frac{q\langle B\rangle}{m_e + E_{kin}}$$



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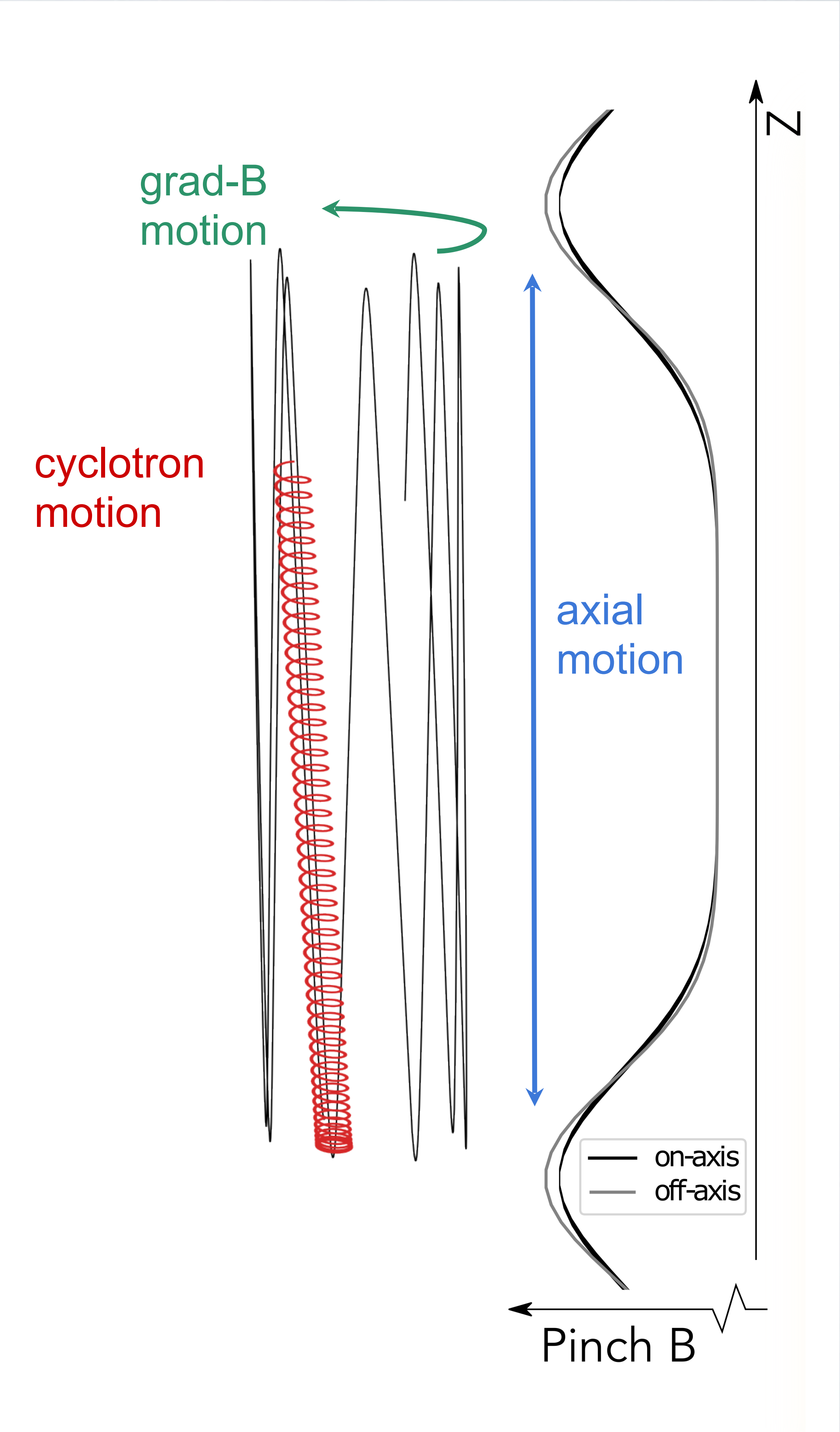
~1 GHz ~0.1 T

$$f_{cyc} \propto \frac{q\langle B \rangle}{m_e + E_{kin}}$$

~18.6 keV



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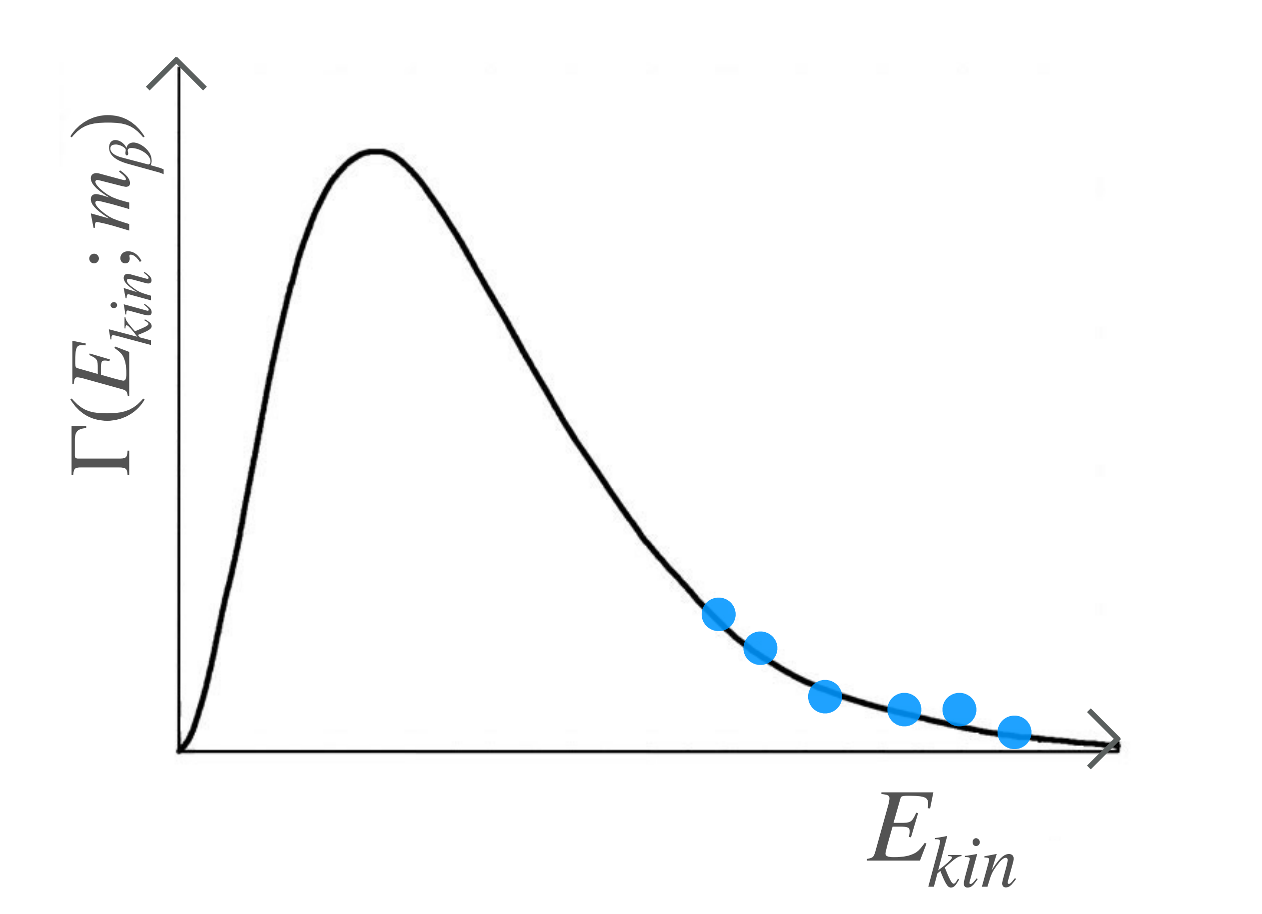
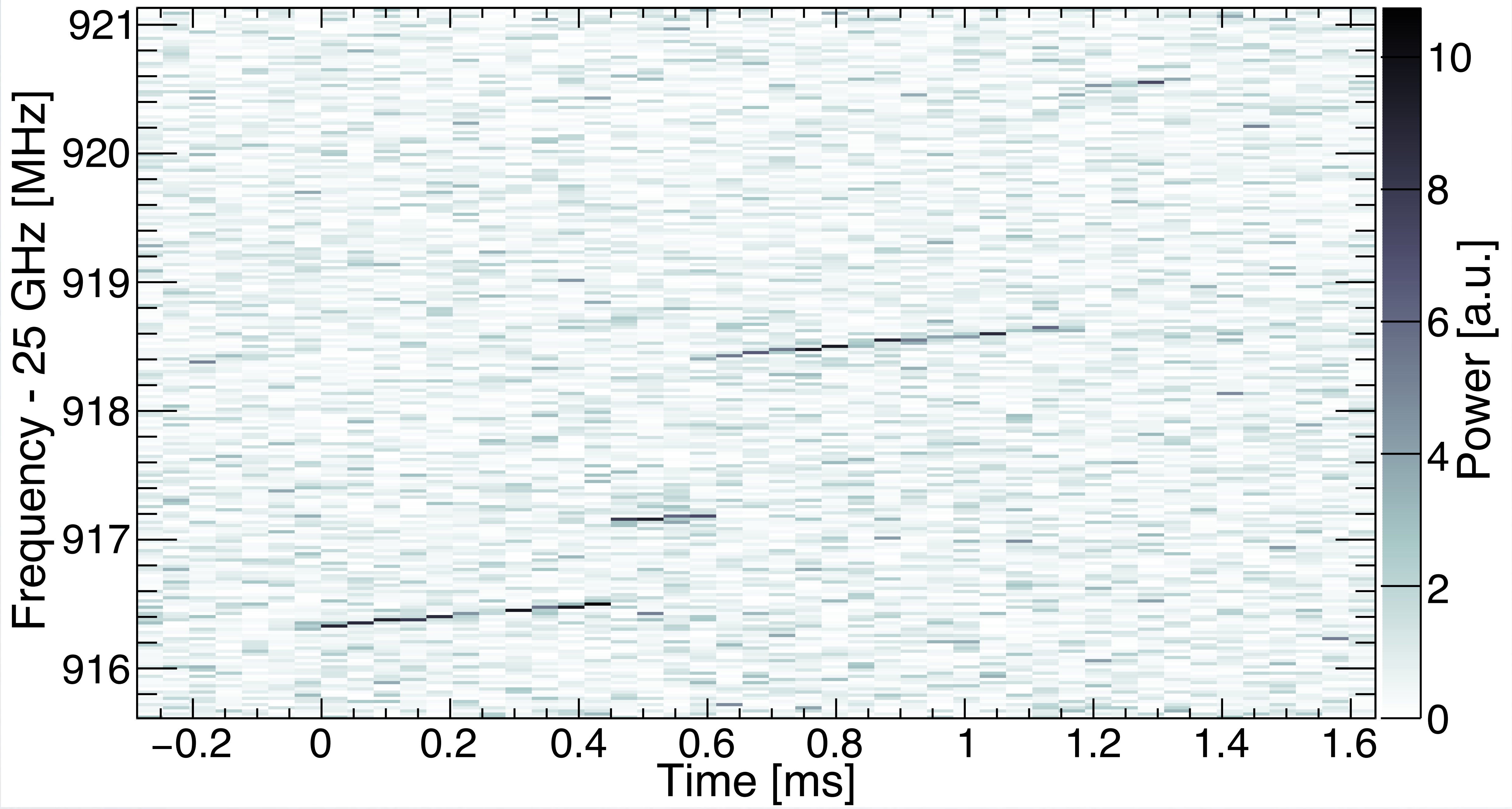
Reconstruct differential spectrum:

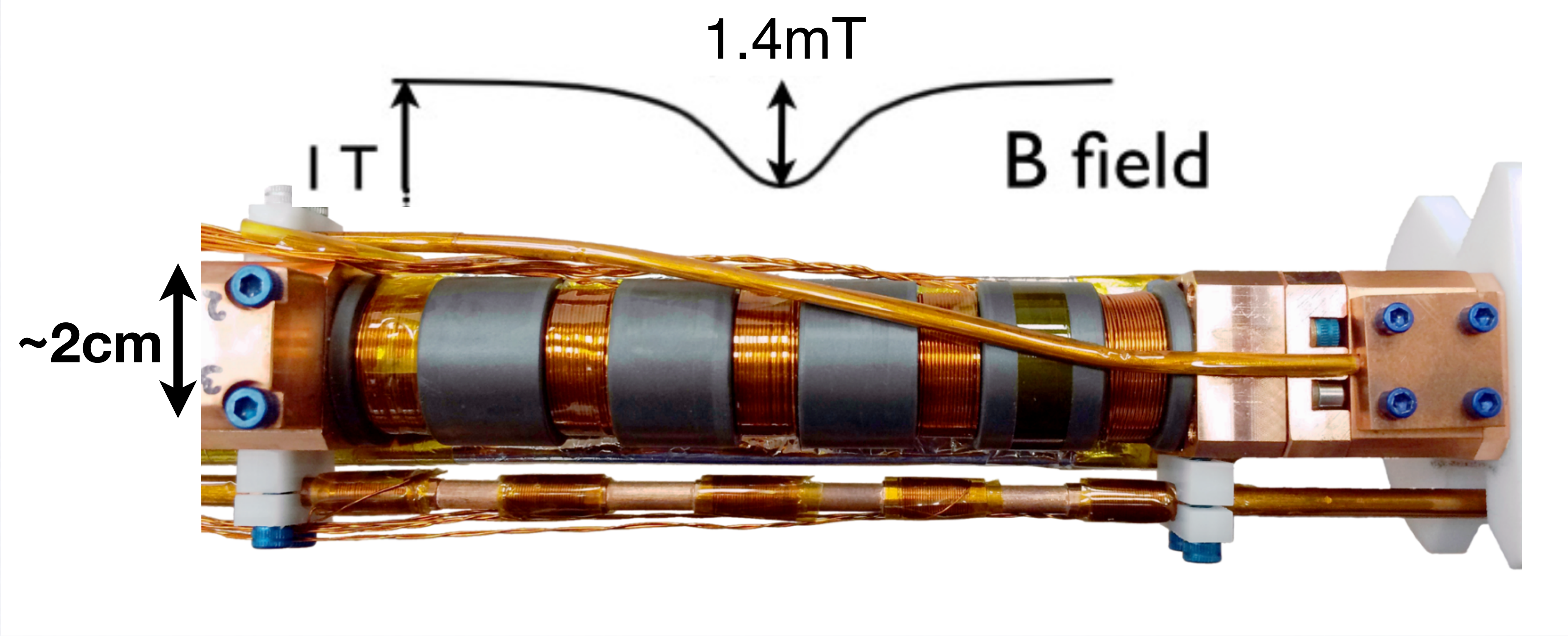


PROJECT 8: MEASUREMENT TECHNIQUE

Sample (tritium) CRES event:

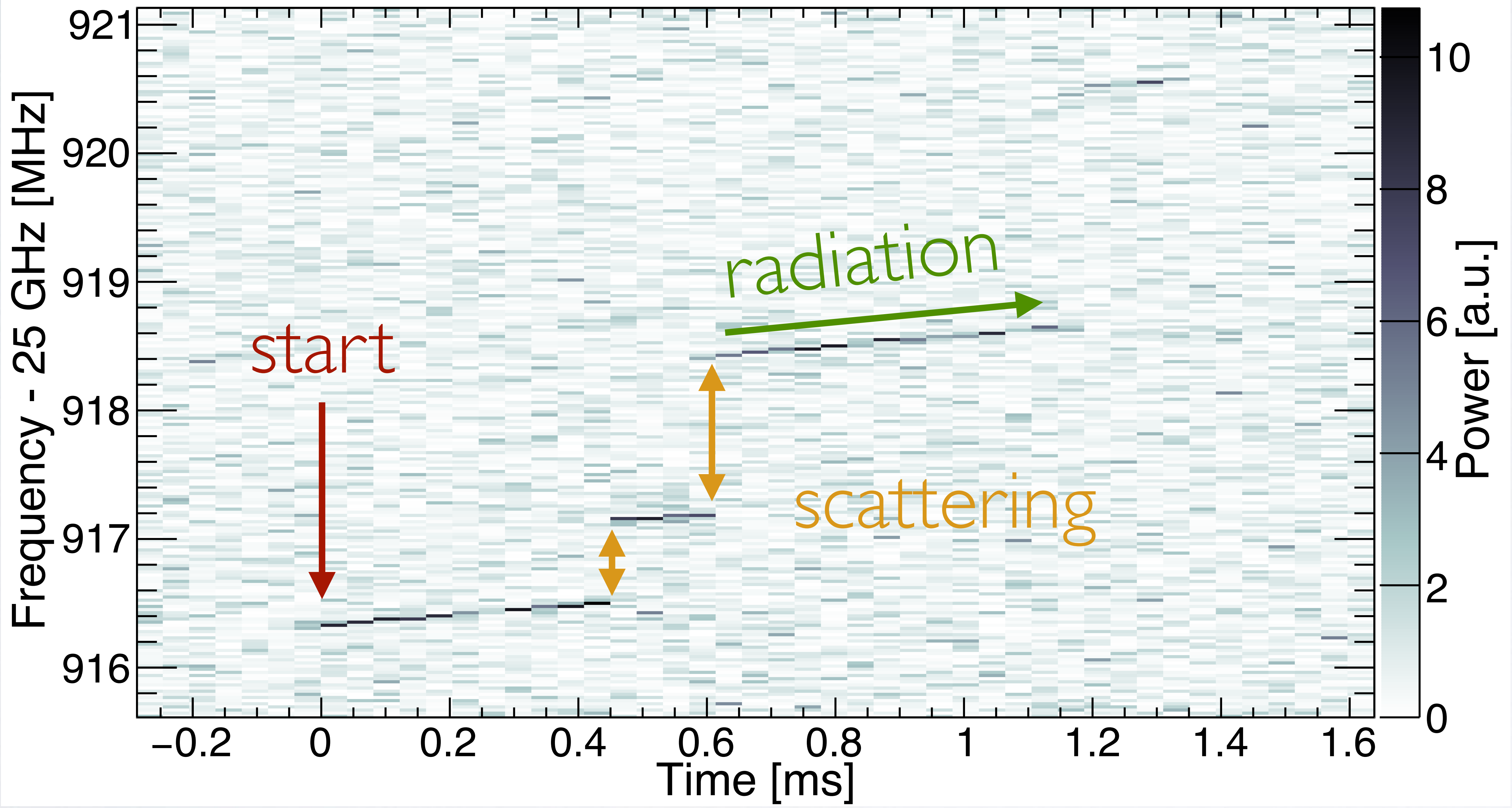


- First detection of single ^{83m}Kr electrons using CRES: Phys. Rev. Lett. 114, 1162501 (2015)
- First results with tritium (T_2), both Frequentist and Bayesian: Phys. Rev. Lett.131.102502



PROJECT 8: MEASUREMENT TECHNIQUE

Sample (tritium) CRES event:



$$f_{cyc} \propto \frac{q\langle B \rangle}{m_e + E_{kin}}$$

- First detection of single ^{83m}Kr electrons using CRES: Phys. Rev. Lett. 114, 1162501 (2015)
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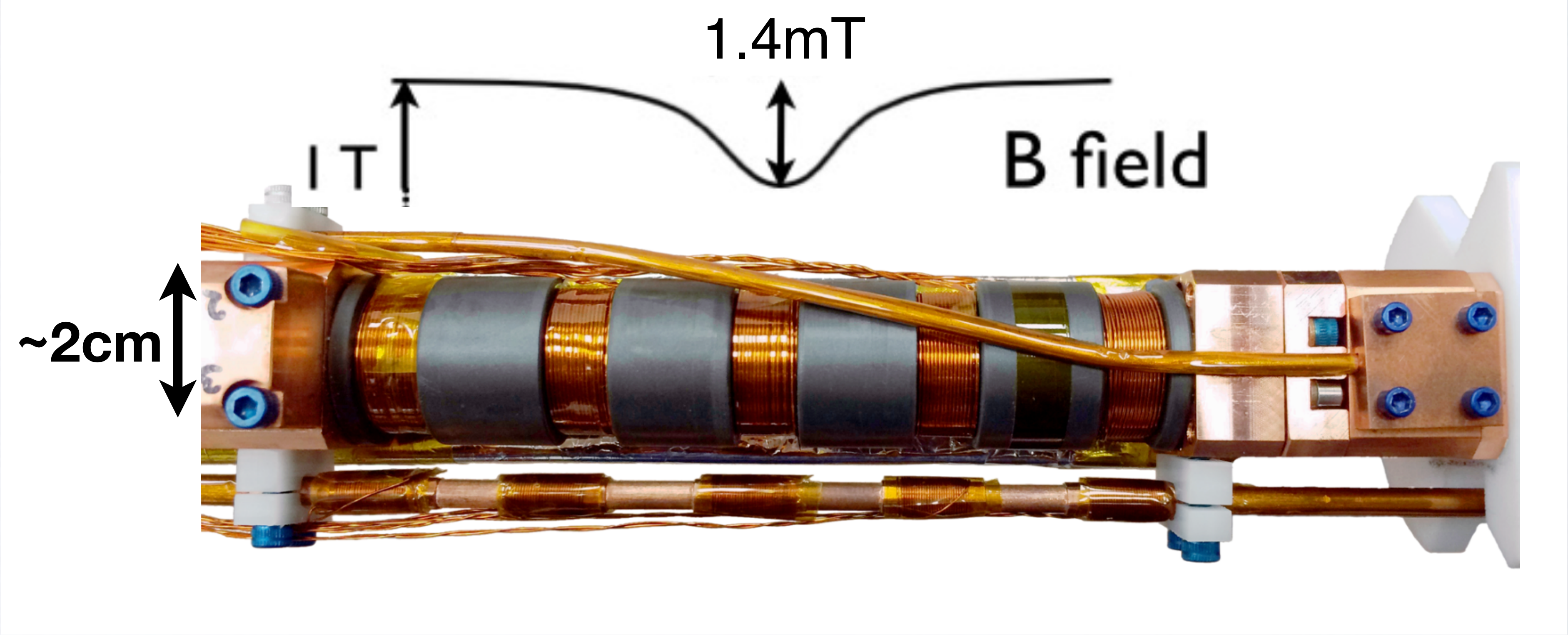
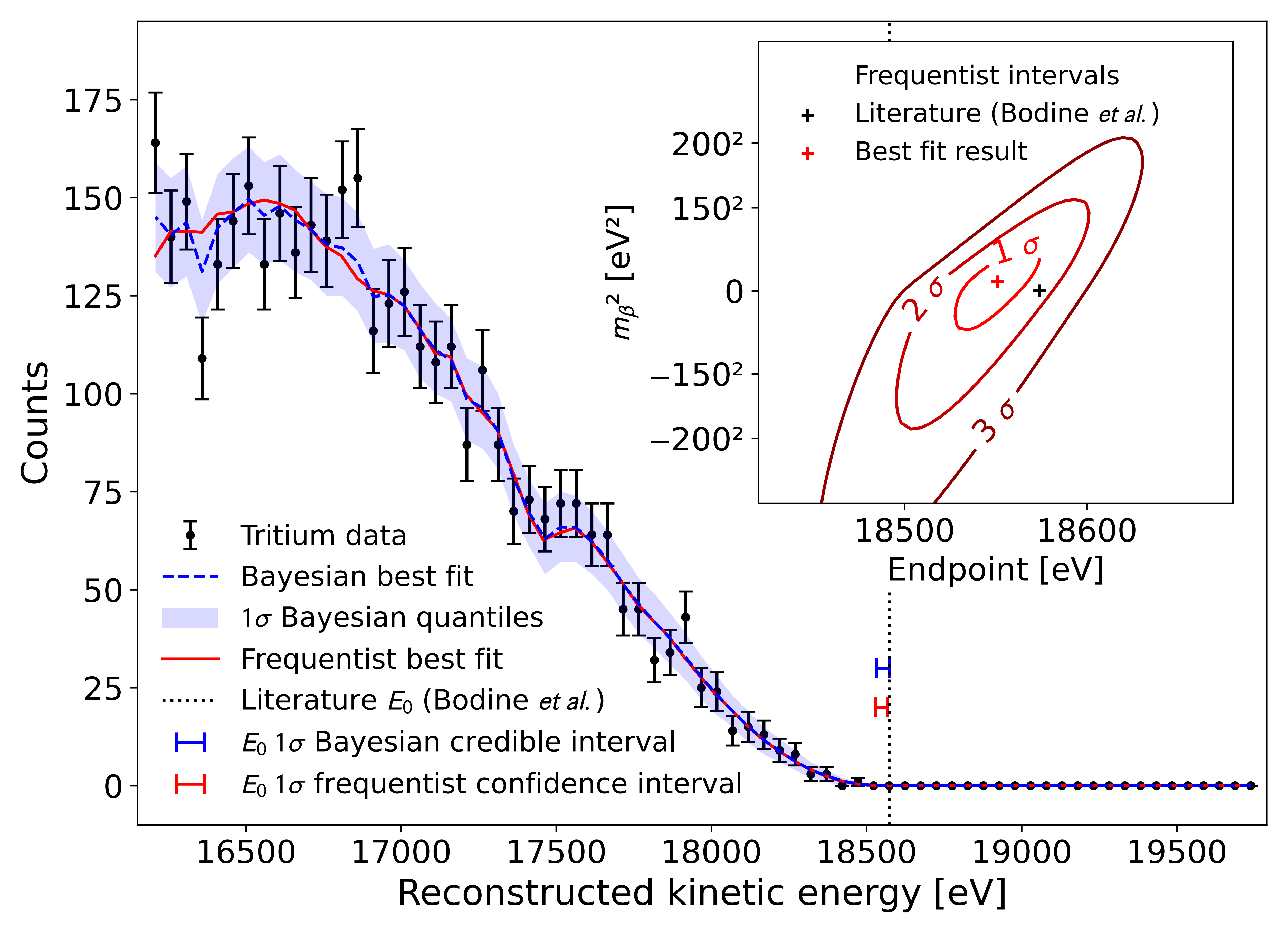


PROJECT 8: FIRST RESULTS



Source: Phys.Rev.Lett. 131, 102502 (2023)

Tritium beta decay endpoint (90% C.L.):

- Frequentist: 18548^{+19}_{-19} eV
- Bayesian: 18553^{+18}_{-19} eV

Neutrino mass (90% C.L.):

- Frequentist: ≤ 152 eV/c^2
- Bayesian: ≤ 155 eV/c^2

Background count rate (90% C.L.):

- No events above endpoint!
- $\leq 3 \times 10^{-10}$cps/eV

Resolution:

- 54.3 eV (FWHM)

Effective volume:

- 1.20 ± 0.09 mm^3 eV

Statistics-limited (3 months' worth of data)

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

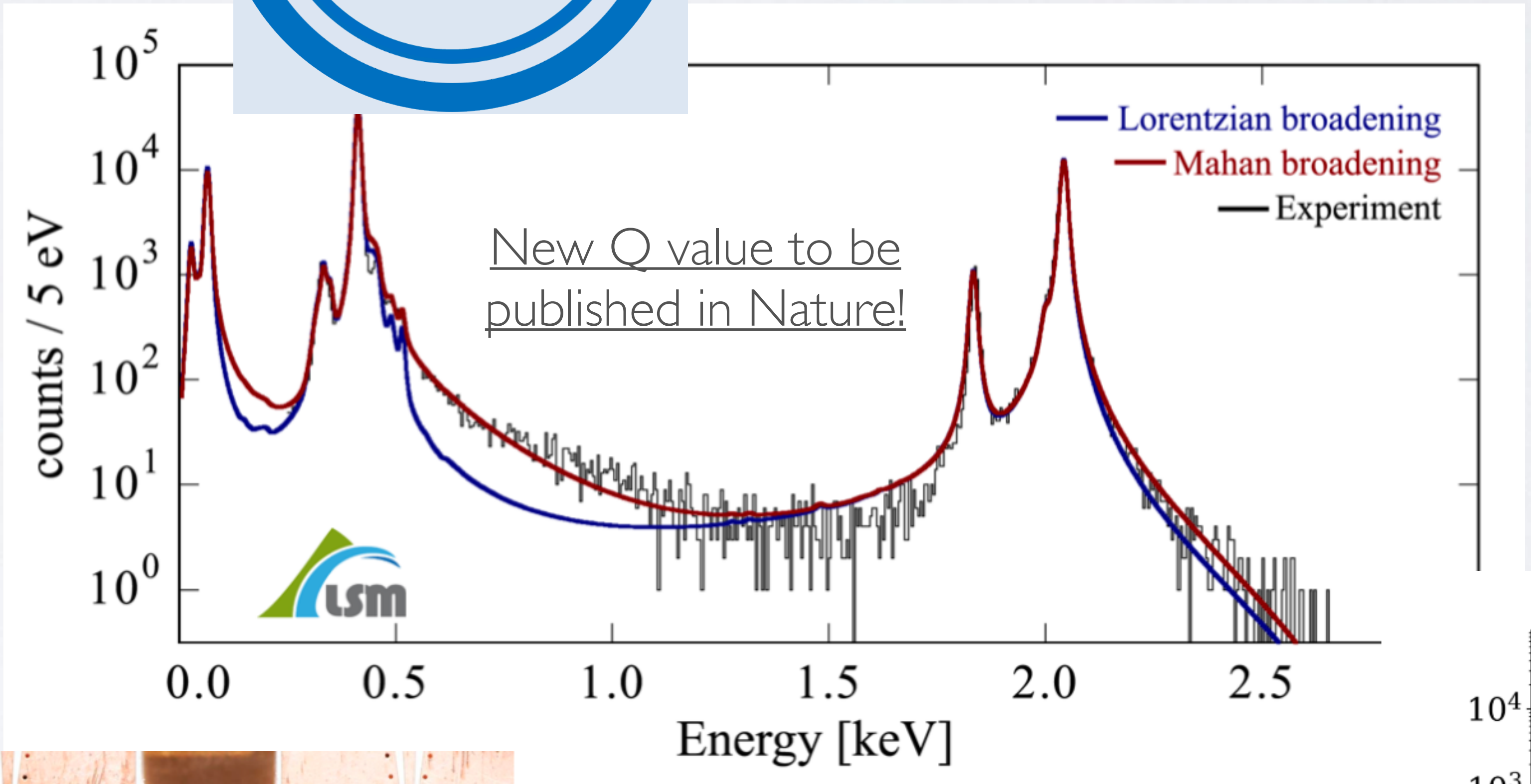
BETA DECAY

- Various isotopes for beta decay
- *Technique*: measurement of beta particle energy
- *Neutrino mass*: $m_{\nu,e} \leq 0.8$ eV @ 90 % C.L. (KATRIN 2022)
- *Advantages*:
  - Cross checks to other experiments (Q values, isotopes)
- *Challenges*:
  - Statistics
  - Systematics (molecular final states, backgrounds)

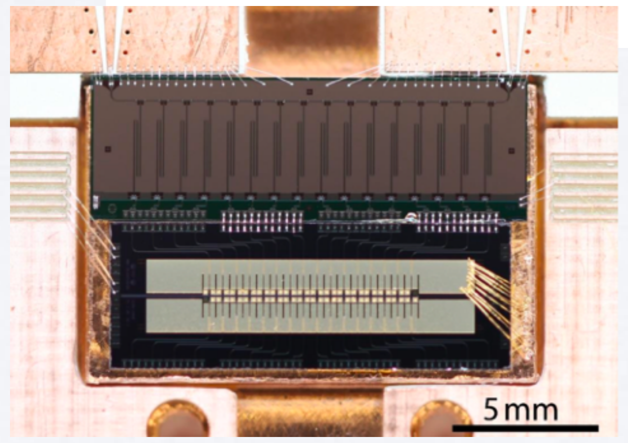
Holmium:

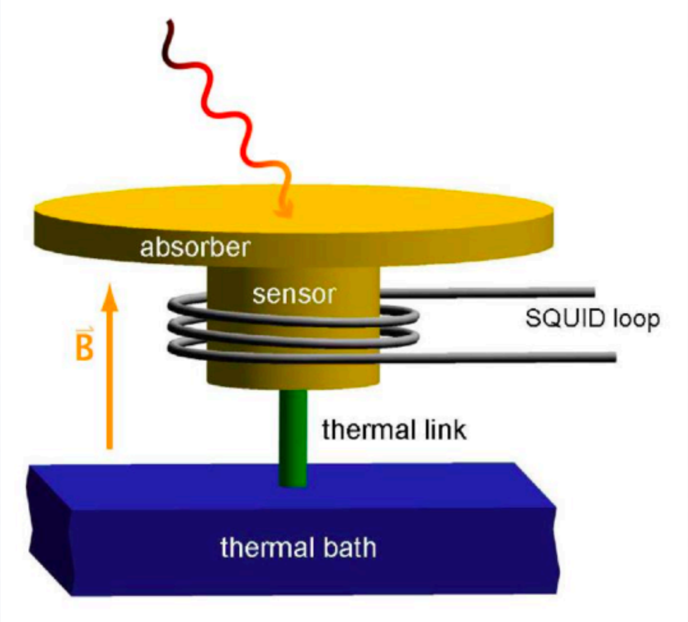
$^{163}\text{Ho} + e^- \rightarrow (^{163}\text{Dy}^* \rightarrow ^{163}\text{Dy} + E_c) + \nu_e$

- Endpoint: 2.8 keV
- Half-life: 4570 yr
- Experiments: ECHo, Holmes, NuMECS

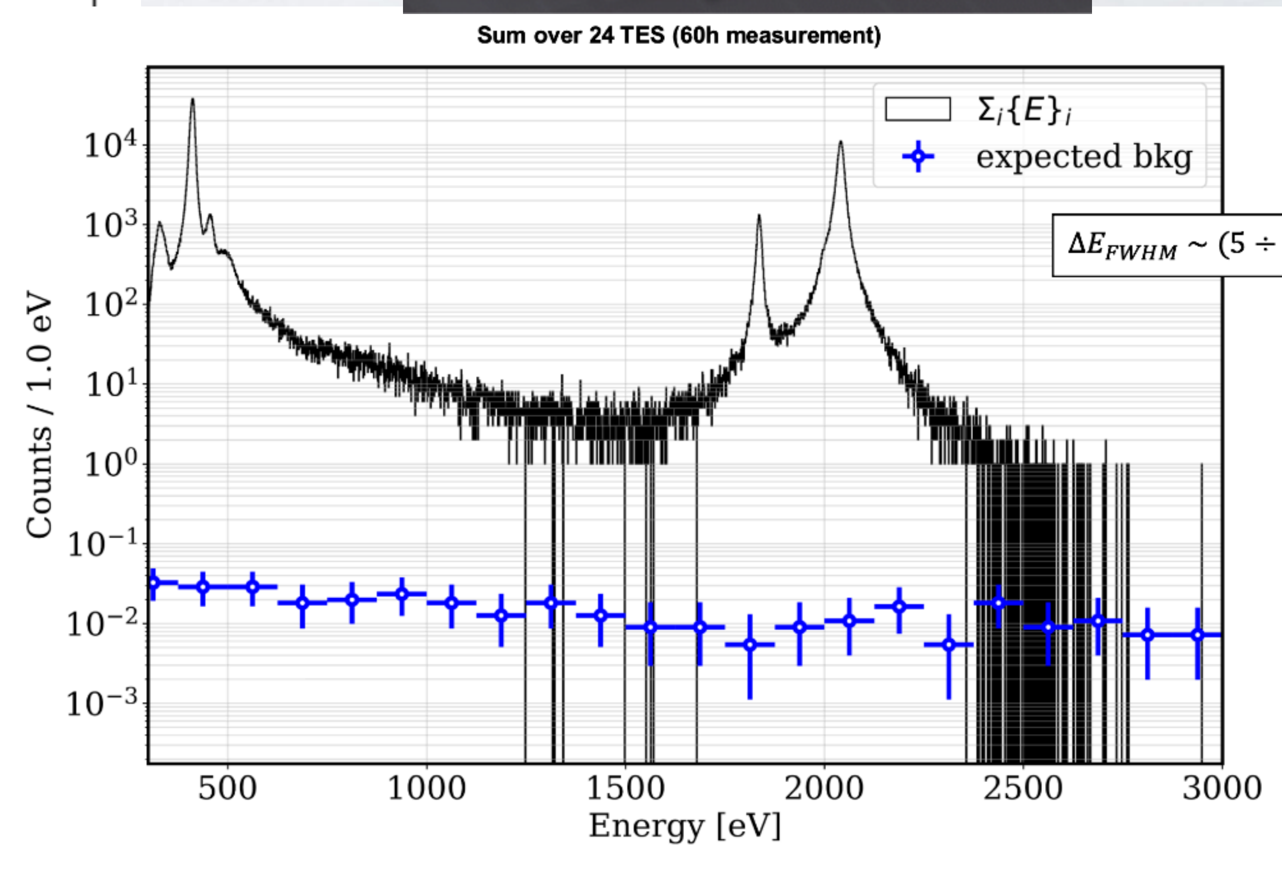


Source: Velte 2019





Credit: L. Gestaldo



Source: M. Borghesi

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

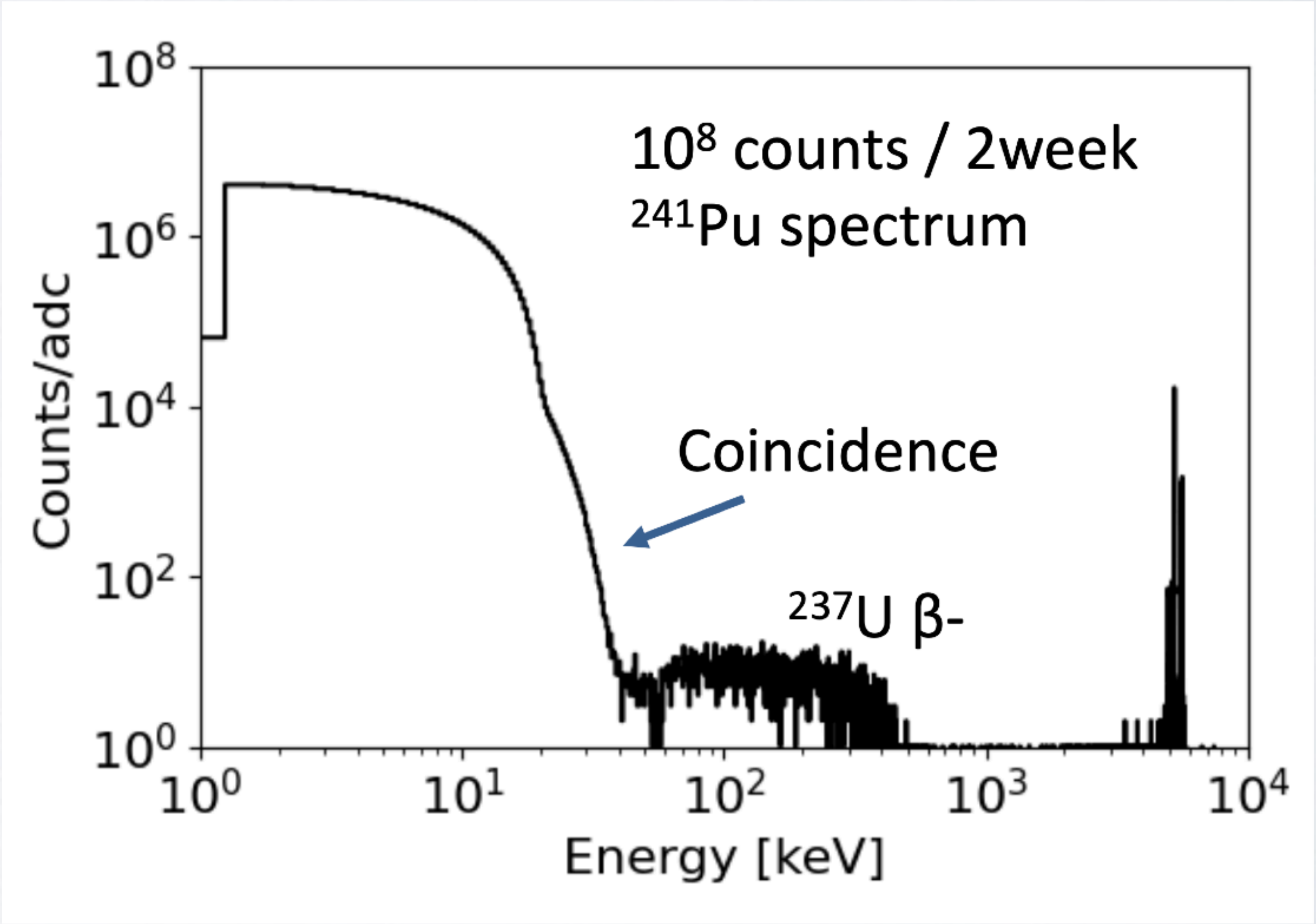
BETA DECAY

- Various isotopes for beta decay
- *Technique*: measurement of beta particle energy
- *Neutrino mass*: $m_{\nu,e} \leq 0.8$ eV @ 90 % C.L. (KATRIN 2022)
- *Advantages*:
  - Cross checks to other experiments (Q values, isotopes)
- *Challenges*:
  - Statistics
  - Systematics (molecular final states, backgrounds)

Plutonium:

$^{241}\mathrm{Pu} \rightarrow ^{241}\mathrm{Am}^+ + e^- + \bar{\nu}_e$

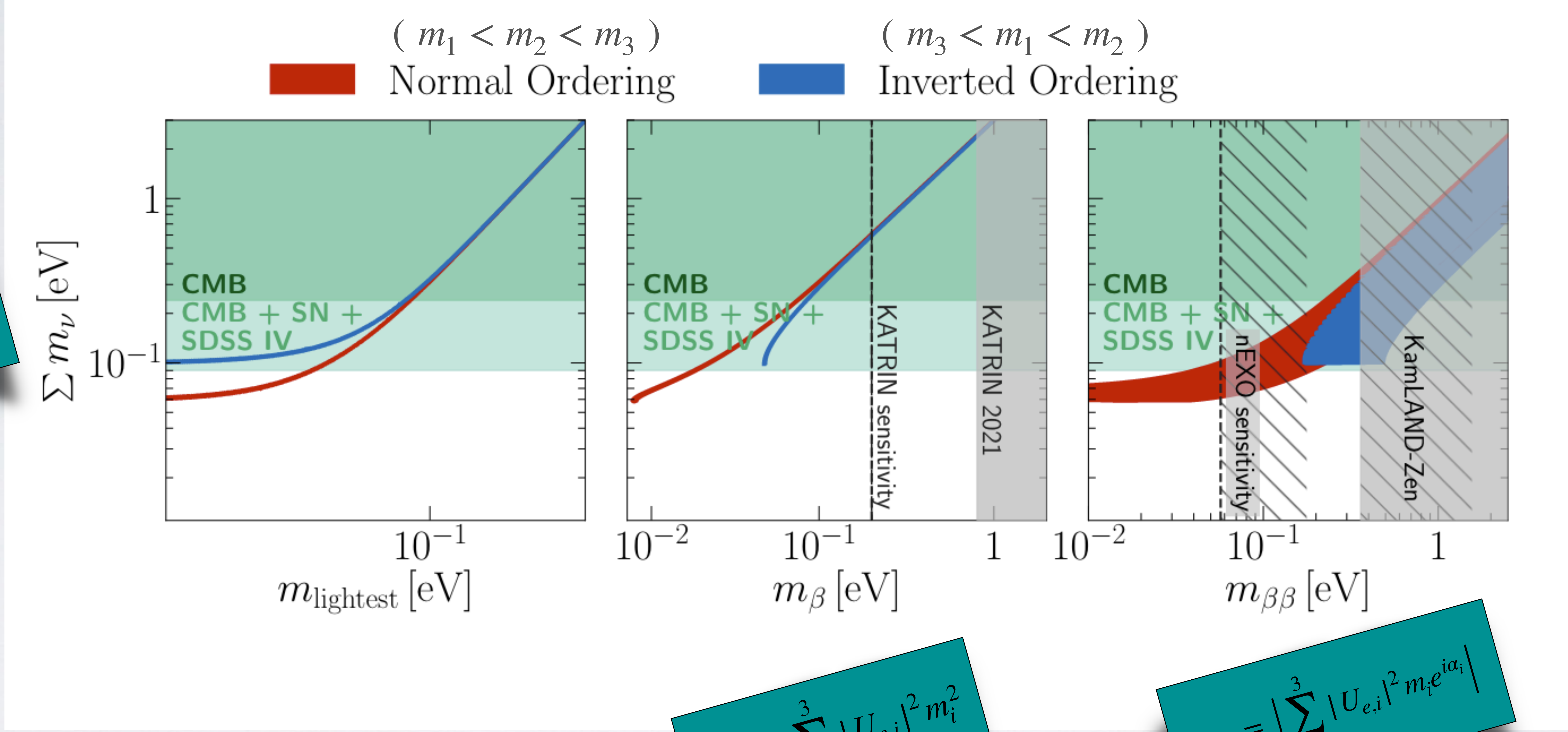
- Endpoint: 20.8 keV
- Half-life: 14.3 yr
- Experiment: MAGNETO-ν



Source: Kim, NuMass 2024

HOW TO COMPARE RESULTS?

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

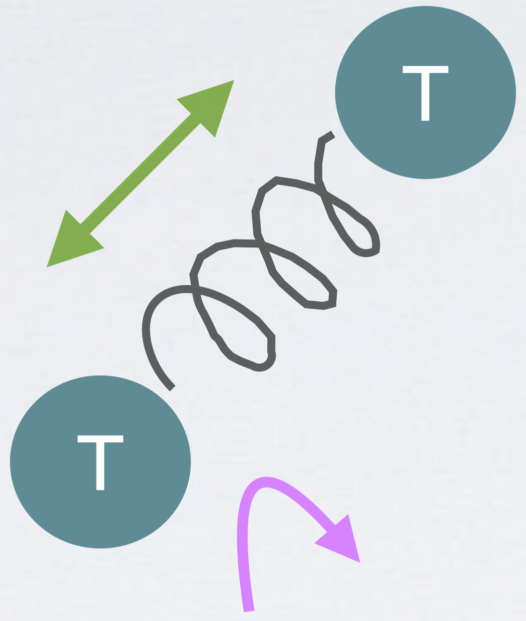


$$m_\beta^2 = \sum_{i=1}^{3} |U_{e,i}|^2 m_i^2$$

$$m_{\beta\beta} = \left| \sum_{i=1}^{3} |U_{e,i}|^2 m_i e^{i\alpha_i} \right|$$

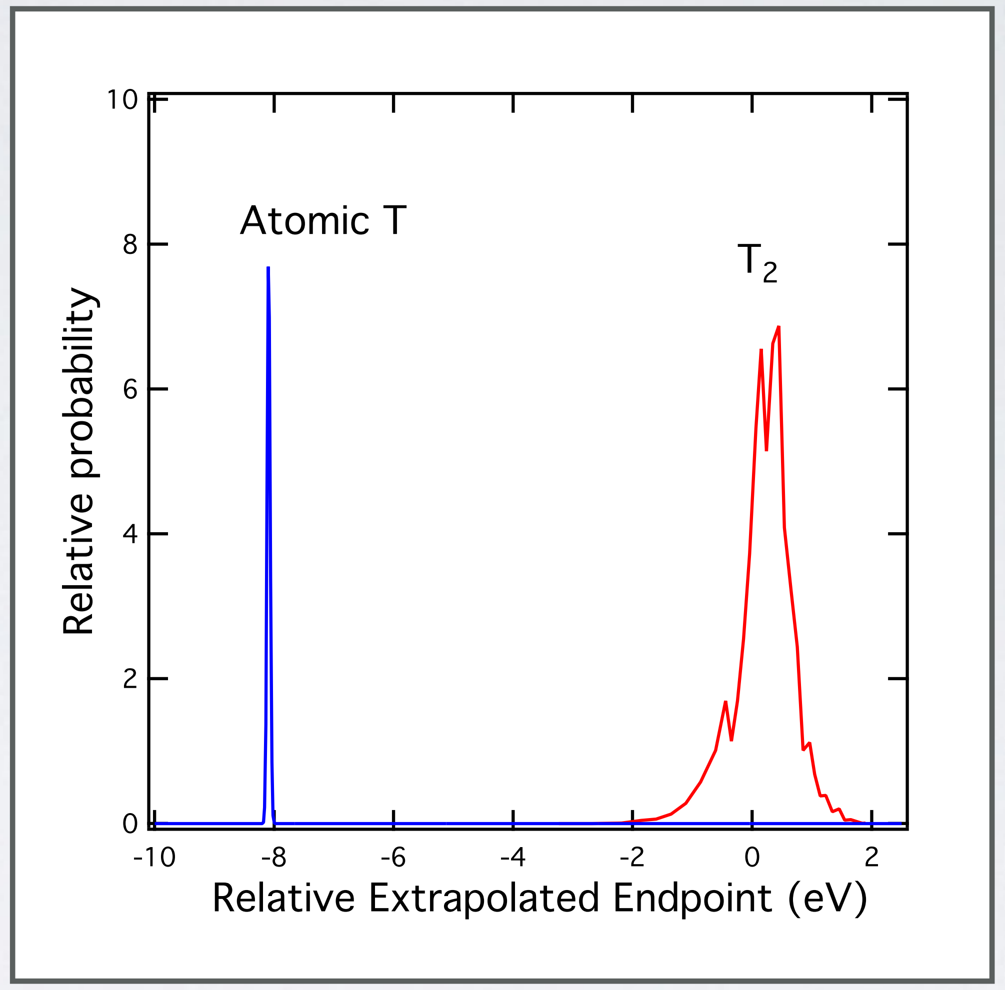
THE FUTURE

- Increase statistics
- Understand systematics
- Develop new techniques
- Combined analysis
- Complimentary searches

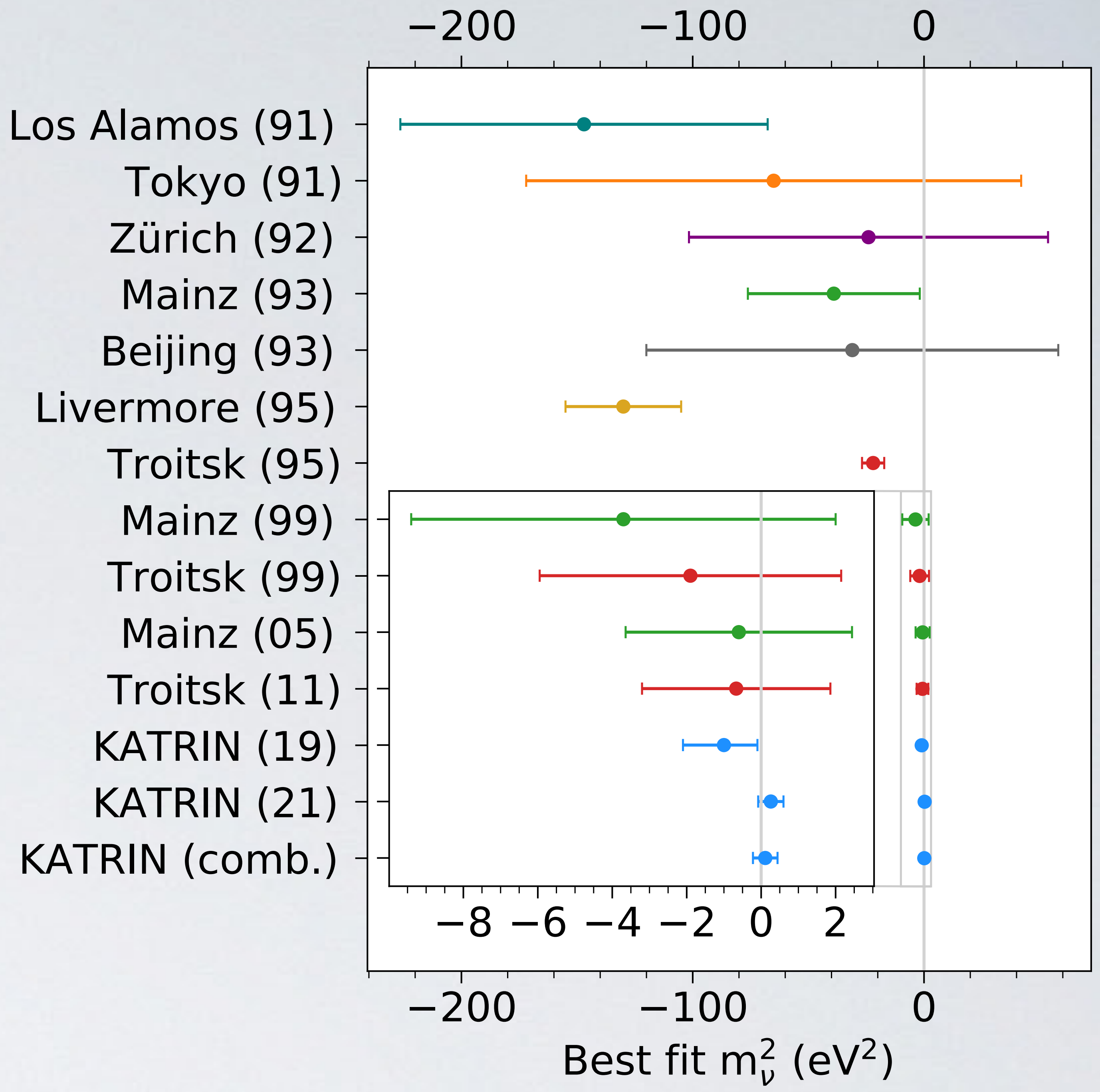


$$\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix} = \begin{bmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu1} & U_{\mu2} & U_{\mu3}\\ U_{\tau1} & U_{\tau2} & U_{\tau3}\end{bmatrix}\begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\end{bmatrix}$$

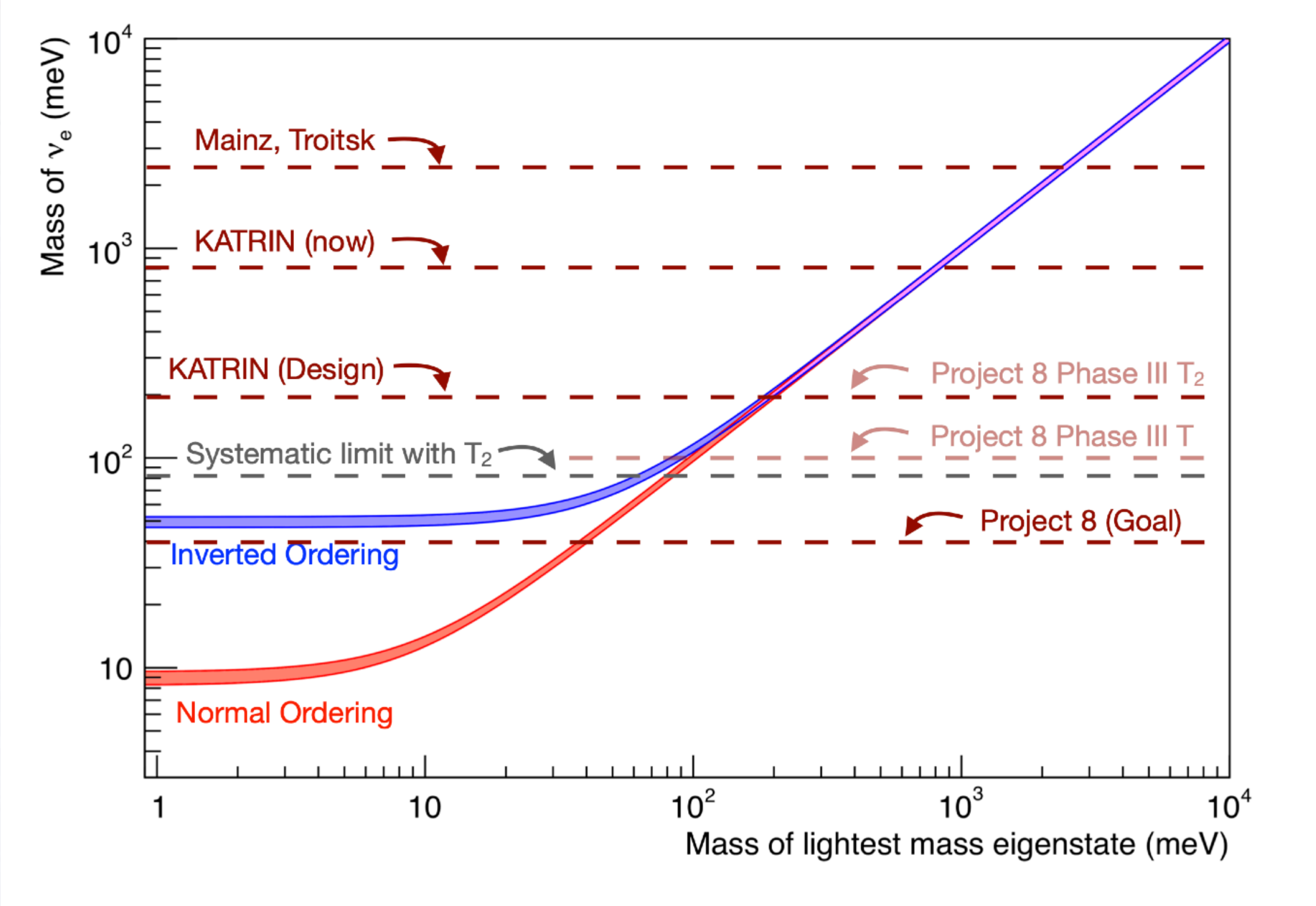
$[\nu_s?]$ $[\nu_4?]$



Adapted from L. Bodine



Credit: L. Koellenberger

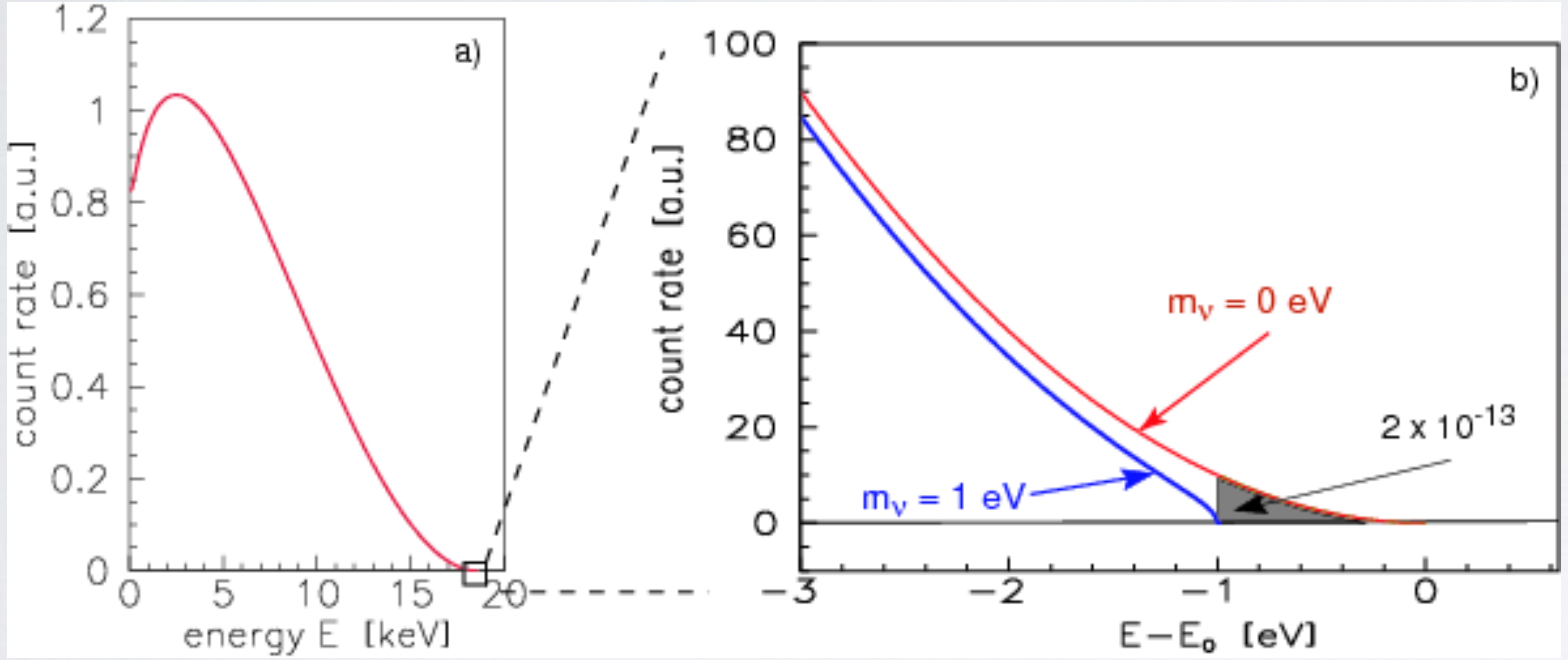



Special thanks to:
JGU Mainz colleagues
Project 8 collaborators
Funding agencies (PRISMA+)
Thank you.

Supplemental slides

PROJECT 8: DESIGN PRINCIPLE

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



Select tritium because its beta decay is **super-allowed**, has appropriate **half-life** (~12.3yr), **endpoint energy** fairly low (~18.6keV)

Via Fermi's Golden Rule:

$$\frac{d^2N}{dEdt} = \frac{G_F |V_{ud}|^2}{2\pi^3} |M_{nucl}|^2 F(Z,E) p_e (E + m_e)$$

$$\cdot \sum_f G_f P_f \epsilon_f \sqrt{\epsilon_f^2 - m_\beta^2}\, \Theta(\epsilon_f - m_\beta)$$

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

$$\approx m_\beta^2$$

PROJECT 8: SPECTRUM ANALYSIS

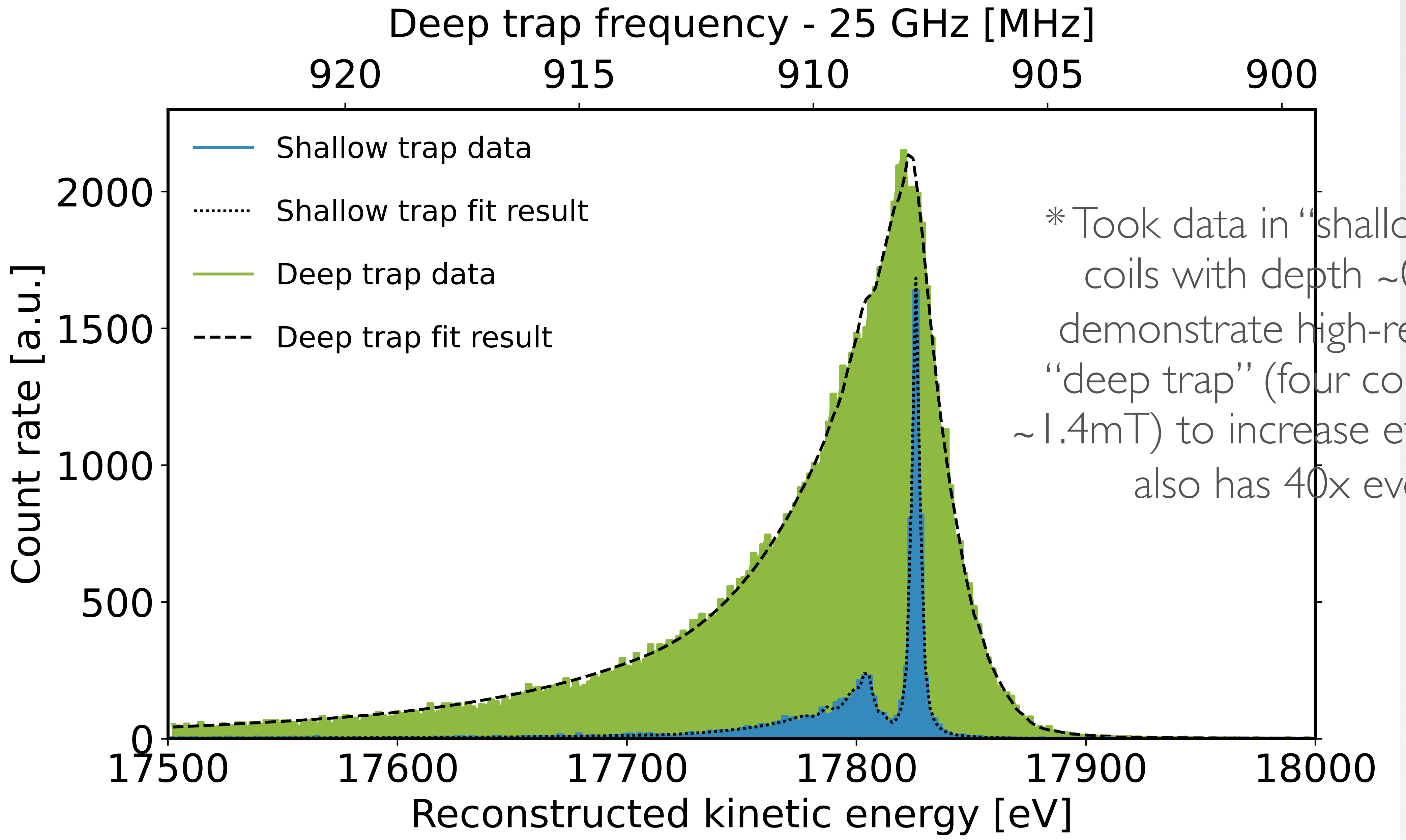


FIG. 3. Data and fits of the 17.8 keV ^{83m}Kr conversion electron K-line, as measured in the shallow (high-resolution) and the deep (high-statistics) electron trapping configurations. The shallow trap exhibits an instrumental resolution of 1.66±0.16 eV (FWHM), while the deep trap provides direct calibration of the tritium data-taking conditions.

* Took data in "shallow trap" (two coils with depth ~0.08mT) to demonstrate high-res CRES, and "deep trap" (four coils with depth ~1.4mT) to increase effective volume; also has 40x event rate.

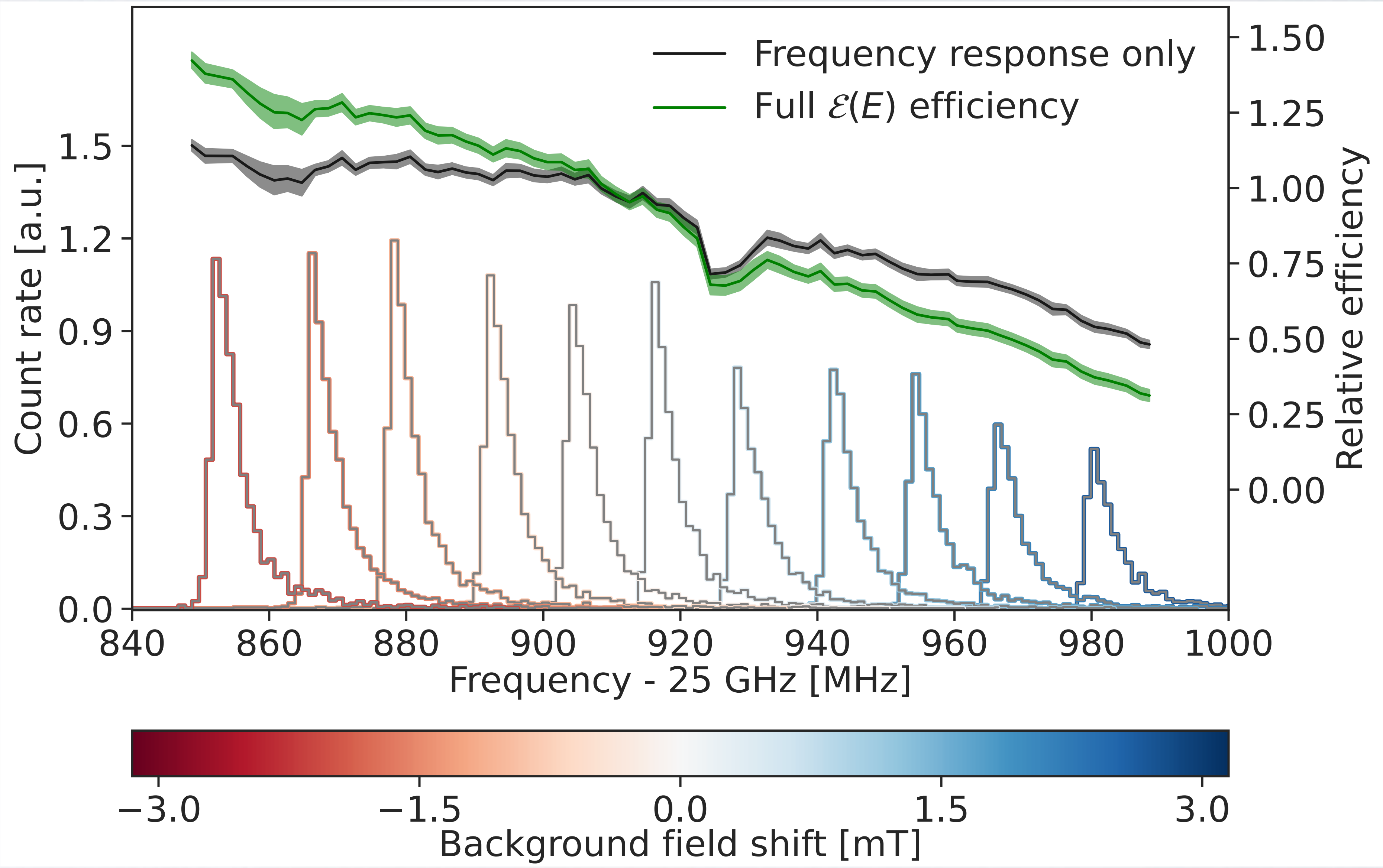


FIG. 4. The 17.8 keV ^{83m}Kr conversion electron line recorded in the deep trap with varying magnetic background fields (red to blue). The gray curve shows the efficiency response to frequency variation, extrapolated from single trap data. The green curve is corrected for energy dependence and shows the relative efficiency predicted for tritium data.

* Use 17.8 keV Kr line and sweep magnetic field (0.07mT steps, over a ±3.2mT range)

* Notch in efficiency is caused by the interaction with TM01 mode of detection cavity

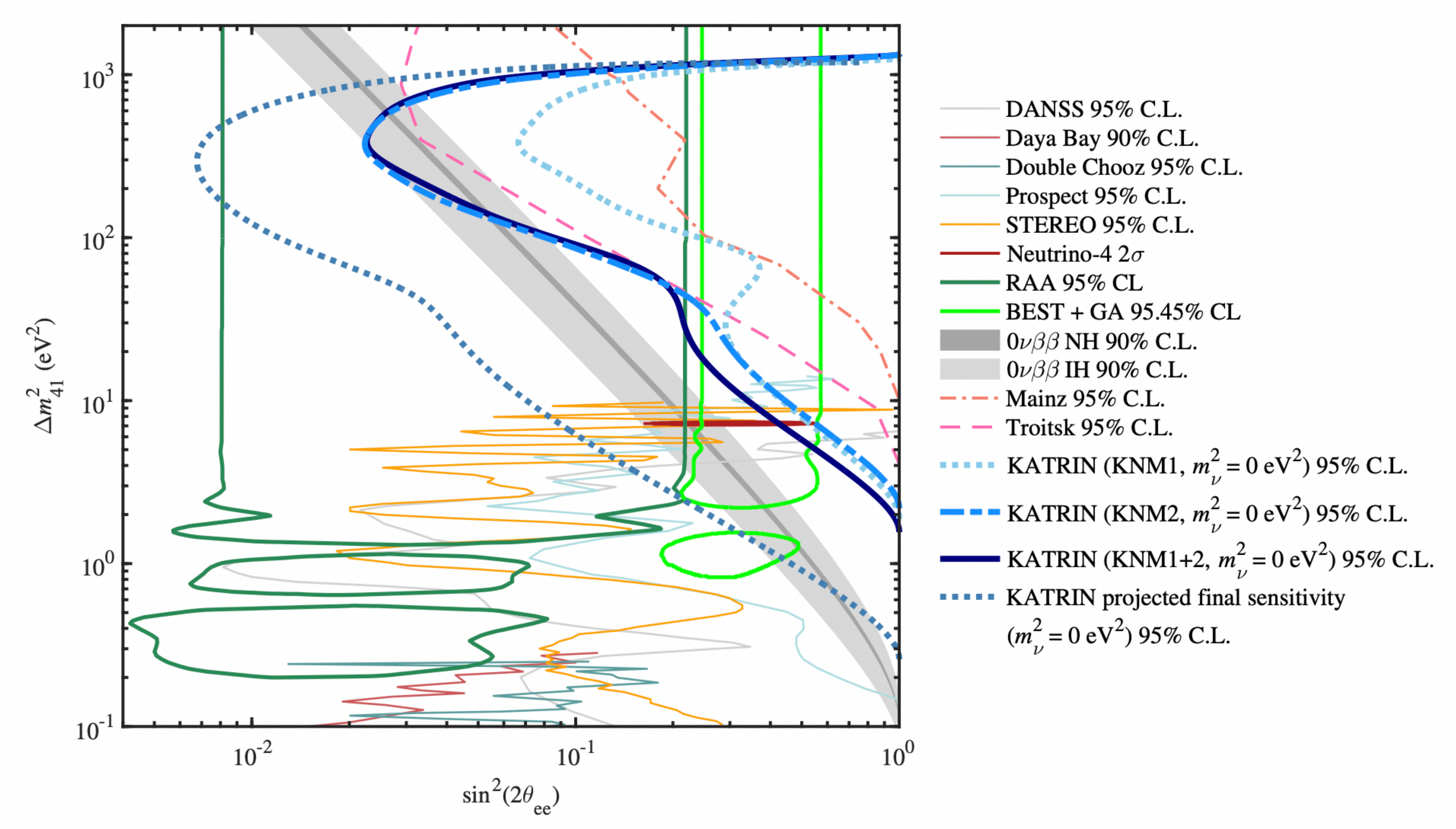
Resolution: $\frac{\Delta f}{f} \approx \frac{\Delta E}{m_e}$

$0\nu\beta\beta$

$$(T_{\beta\beta}^{0\nu})^{-1} = G^{0\nu}(E_0, Z)|(\frac{m_{\beta\beta}}{m_e})^2||M_f^{0\nu} - (\frac{g_A}{g_V})^2 M_{GT}^{0\nu}|^2. \quad (1)$$

In Equation 1, $G^{0\nu}(E_0, Z)$ includes couplings and a phase space factor, where g_A and g_V represent the axial vector and vector coupling constants, and $M_f^{0\nu}$ and $M_{GT}^{0\nu}$ denote the Fermi and Gamow-Teller nuclear matrix elements, respec-

STERILE NEUTRINOS



Source: KATRIN 2022