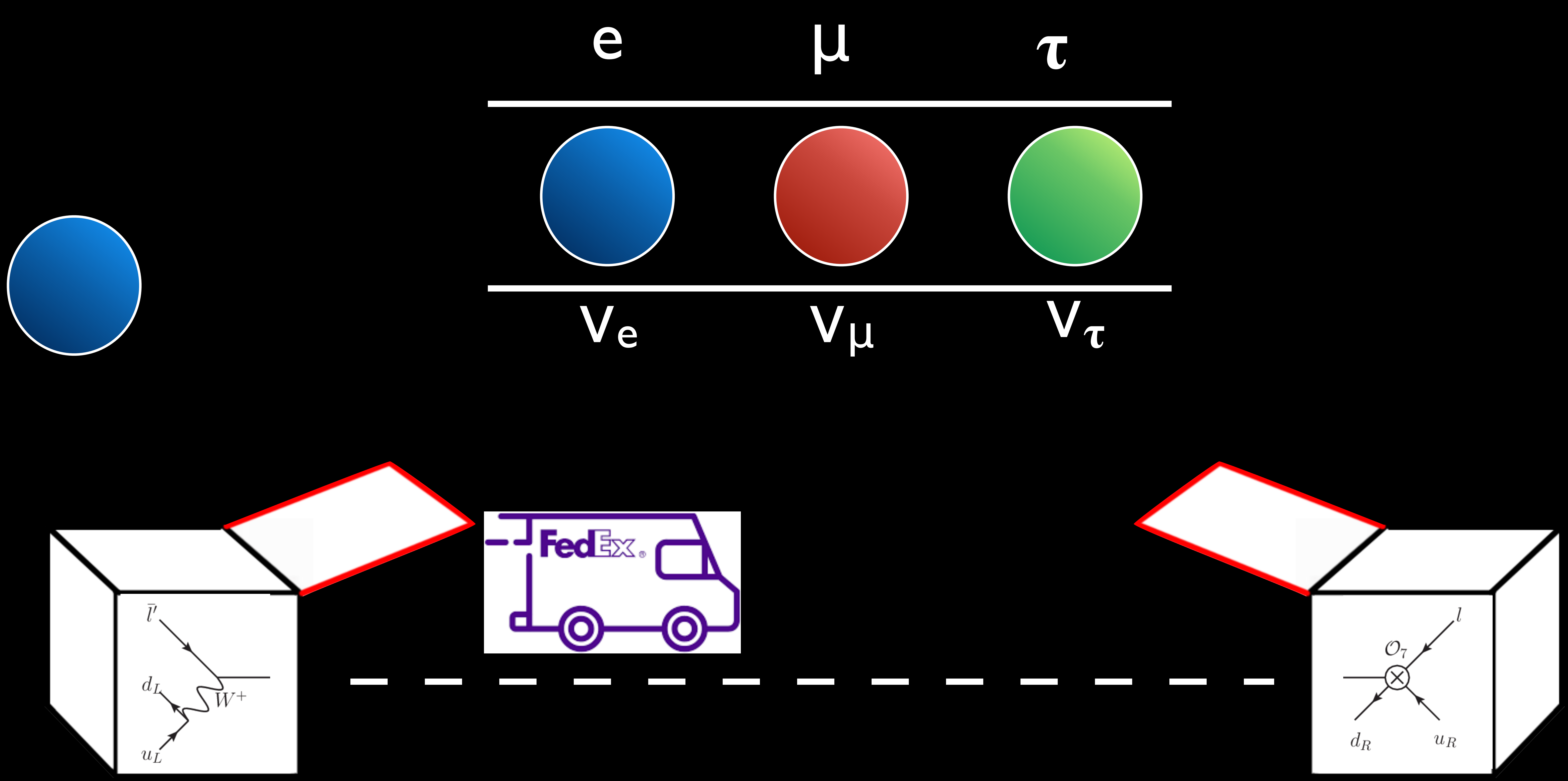
Direct Neutrino Mass Measurements

Brookhaven National Lab
April 4th 2023

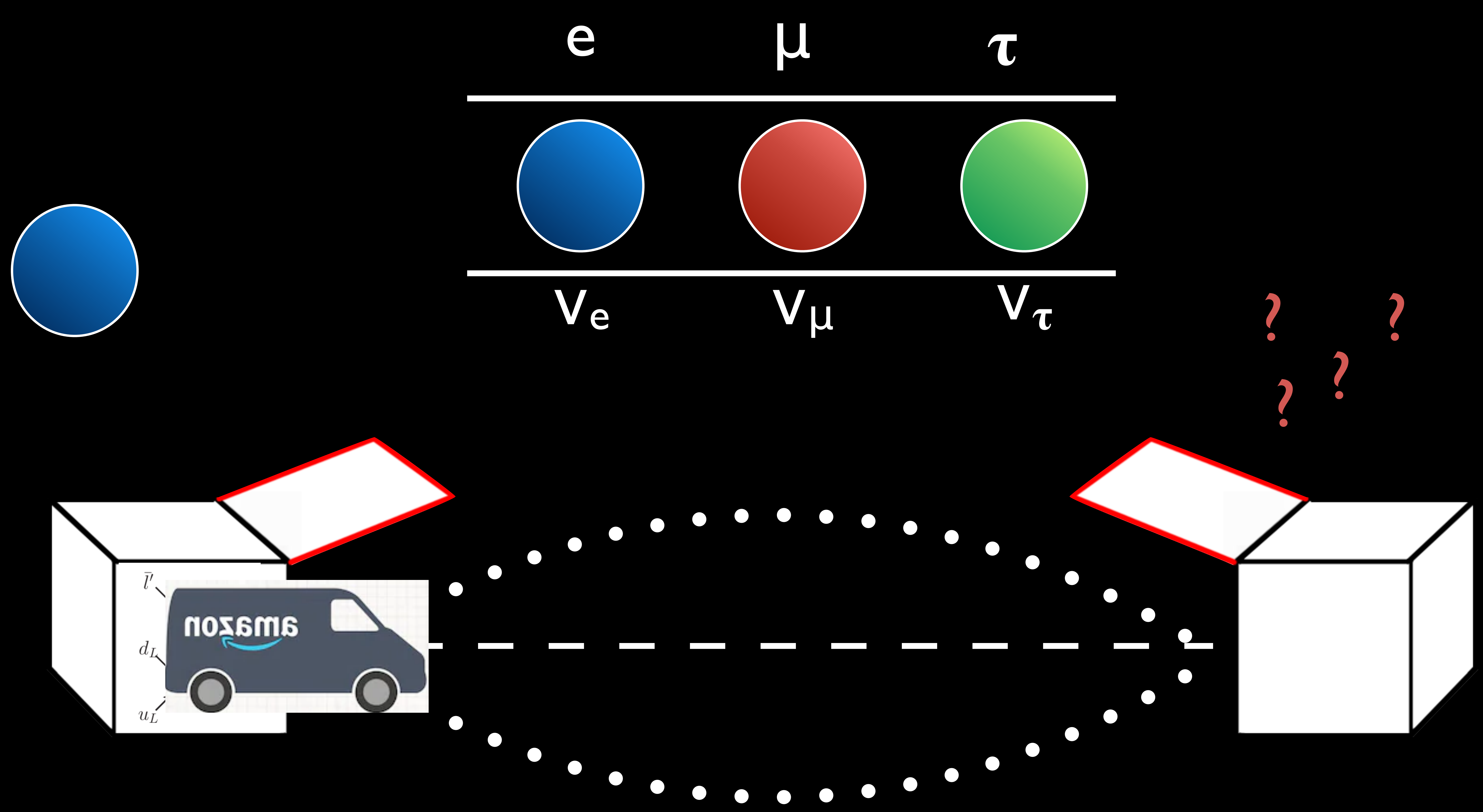
Joseph A. Formaggio
Massachusetts Institute of Technology

We now know neutrinos have mass.

How do we know that?



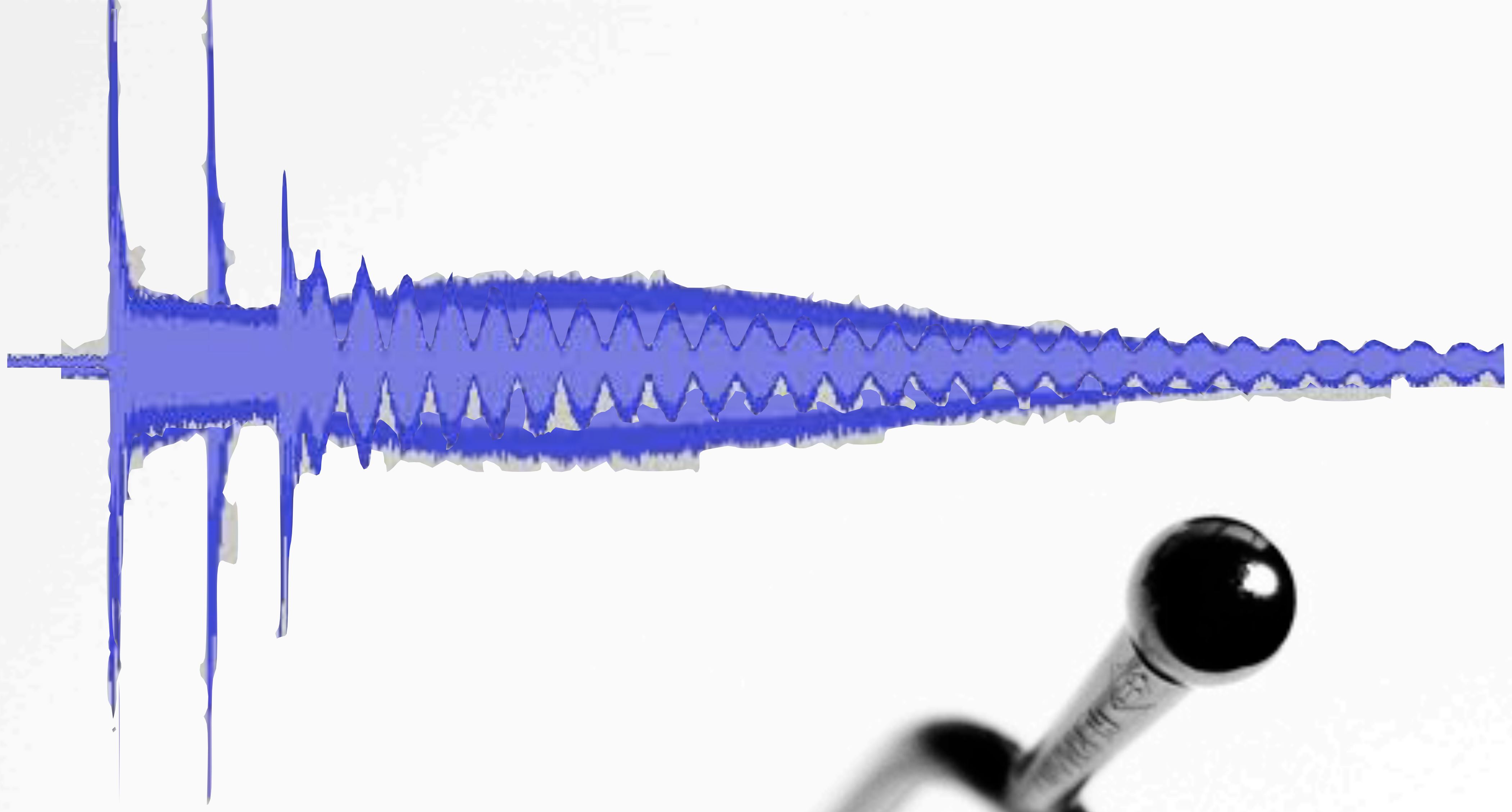
Neutrino flavors can be tagged by
their partner leptons
(e, μ, and τ)



But if neutrinos have different masses, then the propagating neutrino can interfere (mix) with the other mass states.

Flavor oscillations imply mass *differences*.

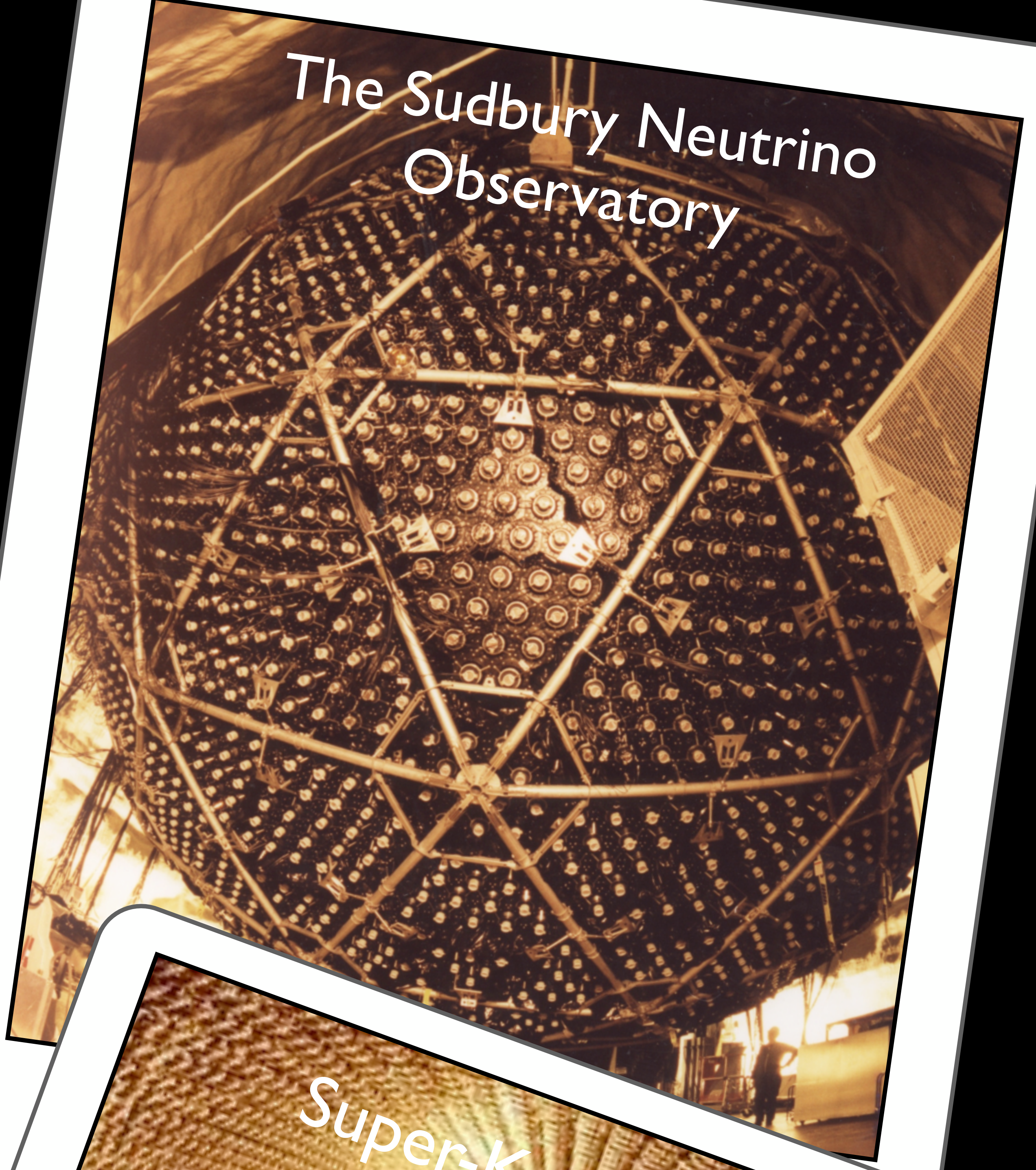
The Perfect Quantum Mechanics Problem...



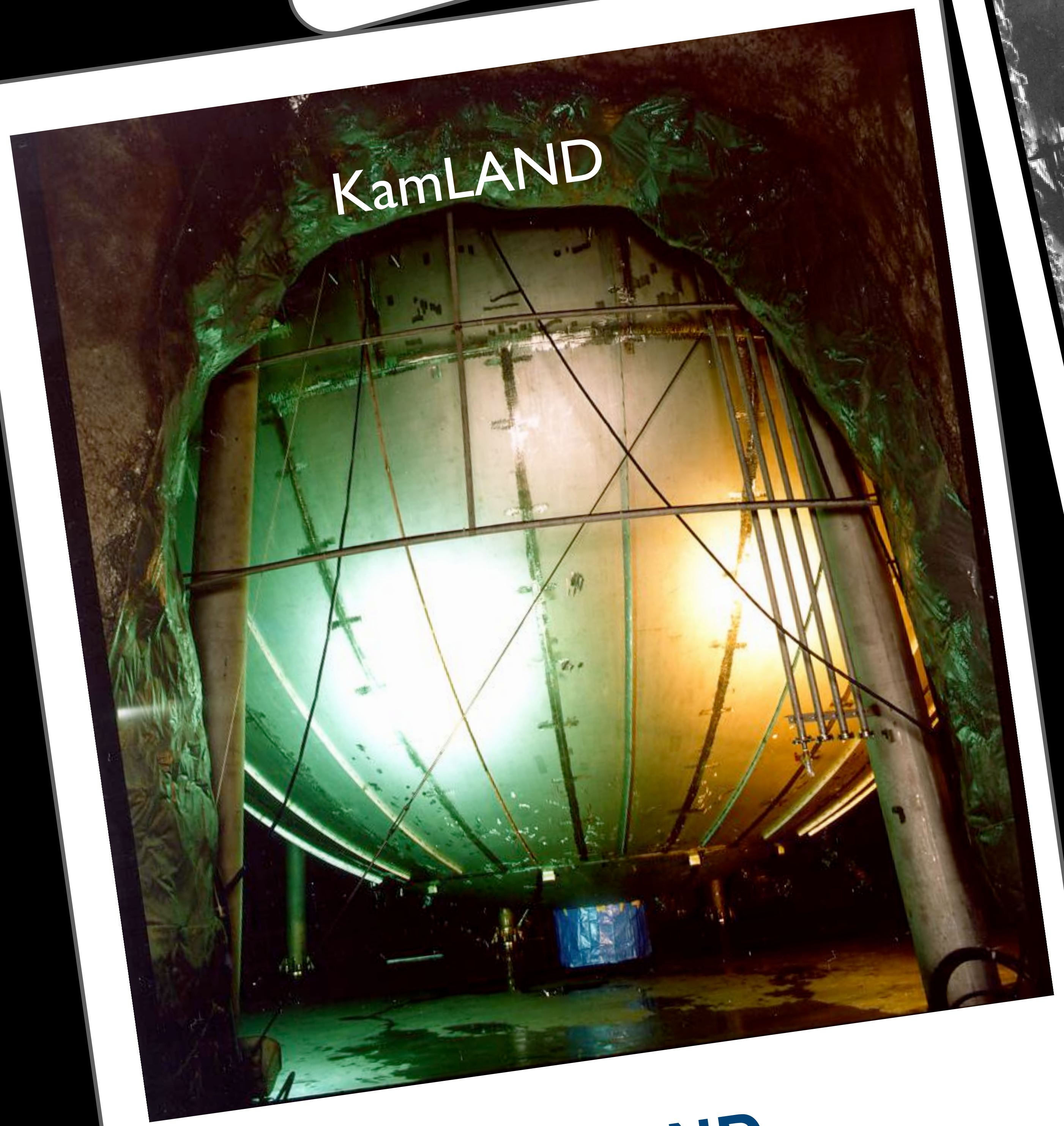
- *At heart, neutrino oscillations is an interference problem between different states.*

- *Allows one to probe extremely small mass differences.*

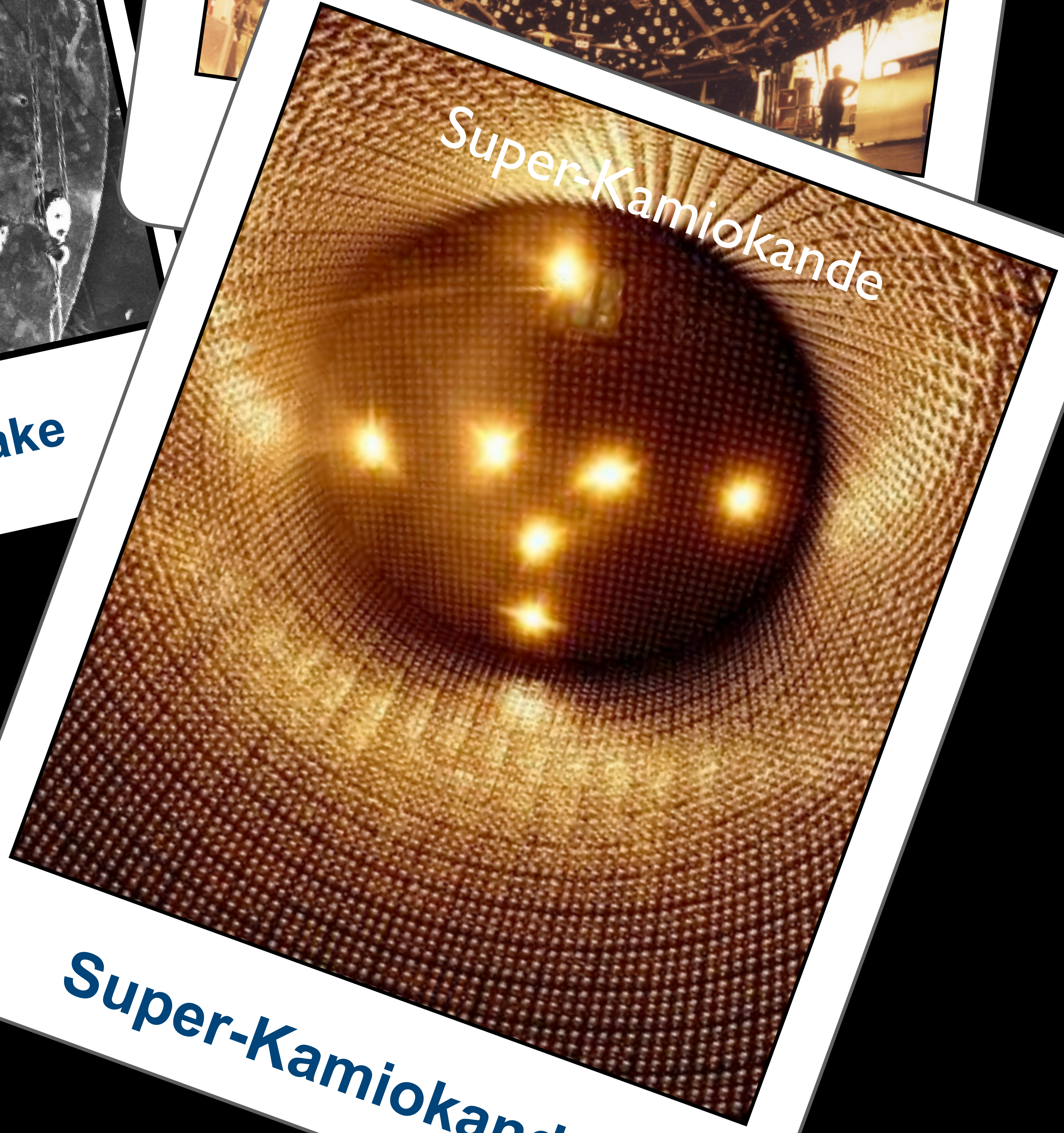
MINOS




Ray Davis Jr., Homestake

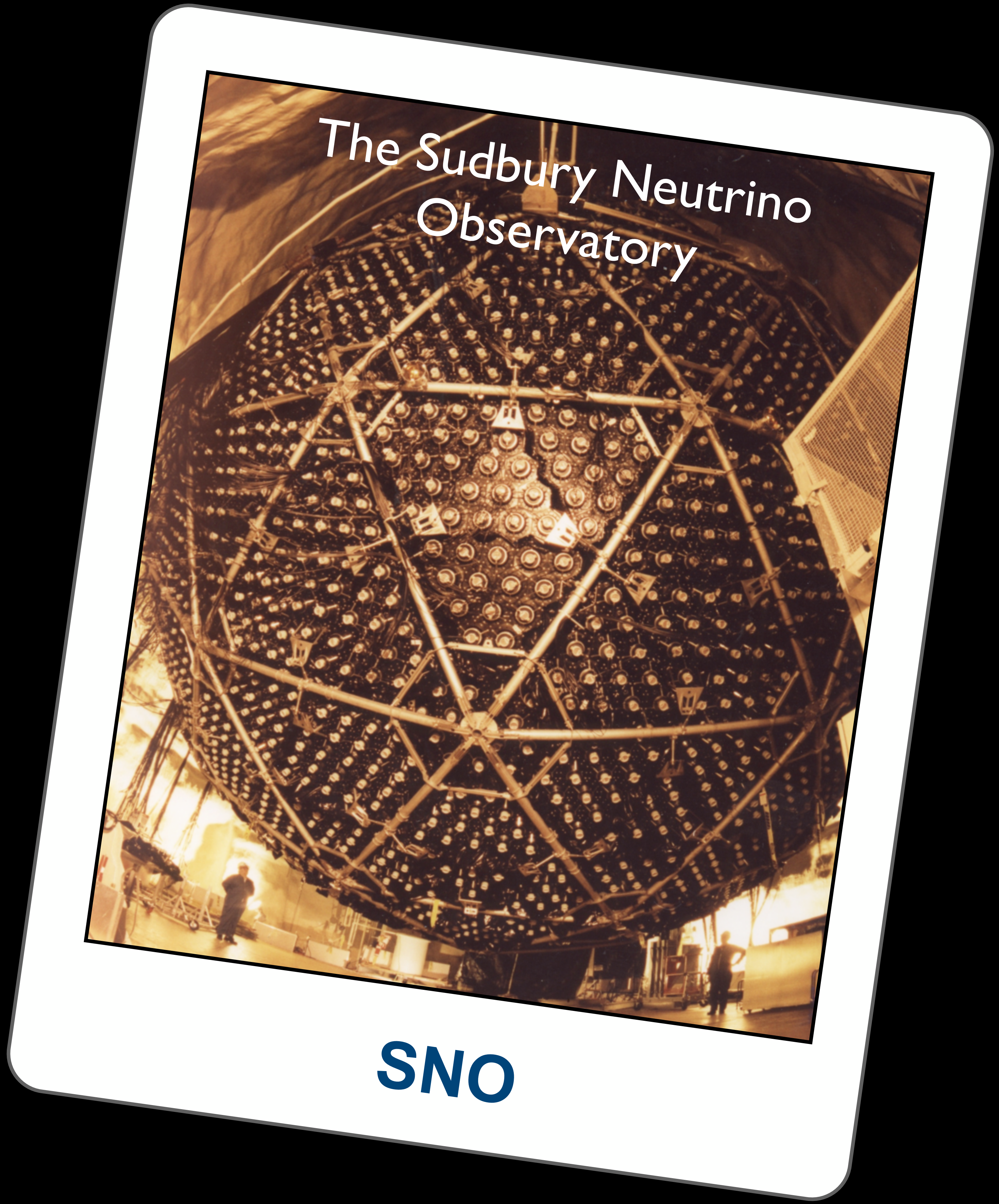


KamLAND



Super-Kamiokande

A myriad of experiments helped demonstrate that neutrinos transmute flavor (oscillations).

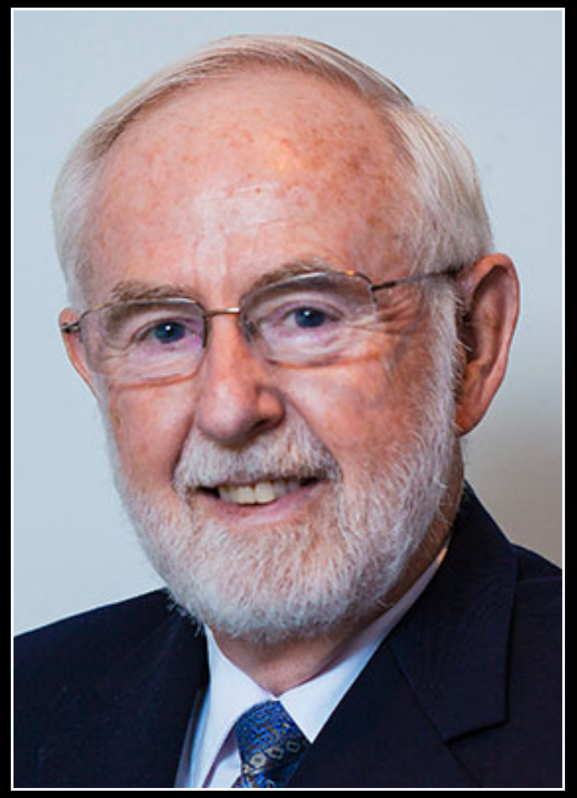


There are predictions that stem from alteration of the Standard Model.

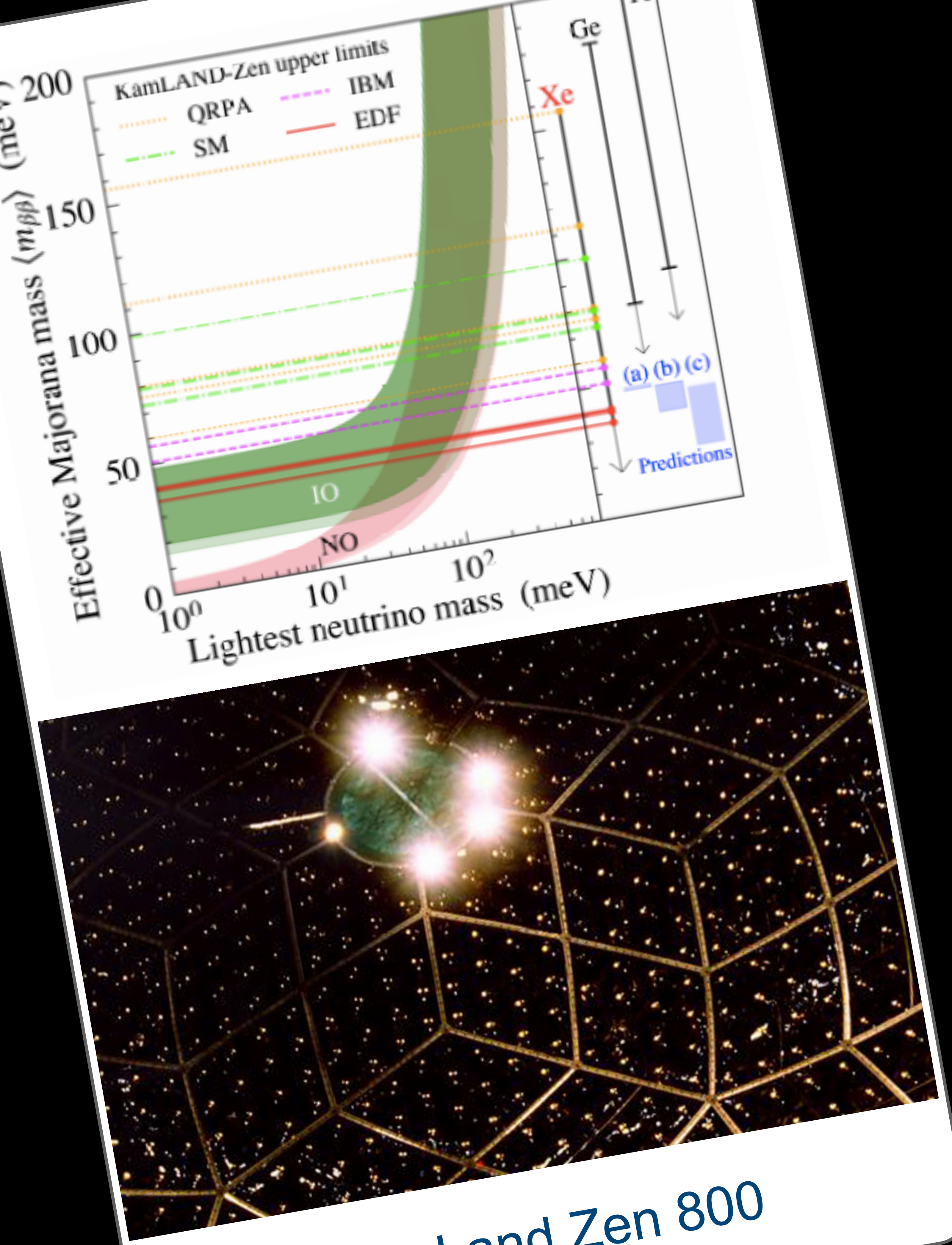
However, oscillation experiments <u>cannot</u> reveal the neutrino mass scale directly.

Takaaki Kajita
(Super-Kamiokande)

Arthur B. McDonald
(Sudbury Neutrino Observatory)



So... how do we access what is the scale of neutrino masses?



KamLand Zen 800

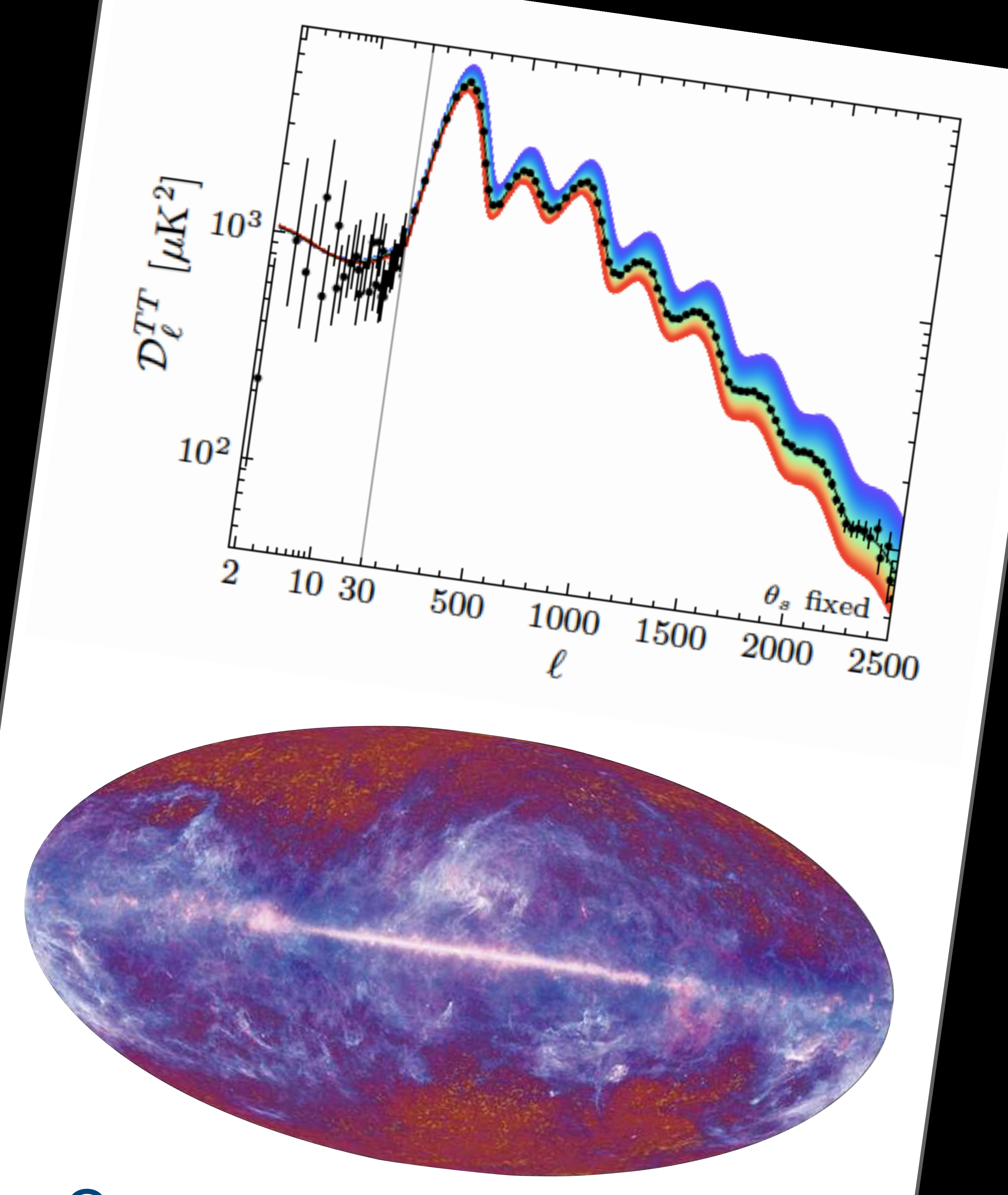
Neutrino oscillations,

neutrinoless double beta decay

and

cosmology

all help shed light on the neutrino mass scale



Cosmological Constraints

However, these methods rely on underlying assumptions (ΛCDM, lepton number violation)

All these methods indirectly access the neutrino mass scale

$$E \stackrel{?}{=} p\,c$$

A **direct** method must rely on kinematics to determine the neutrino mass.

First suggested by Francis Perrin in 1933

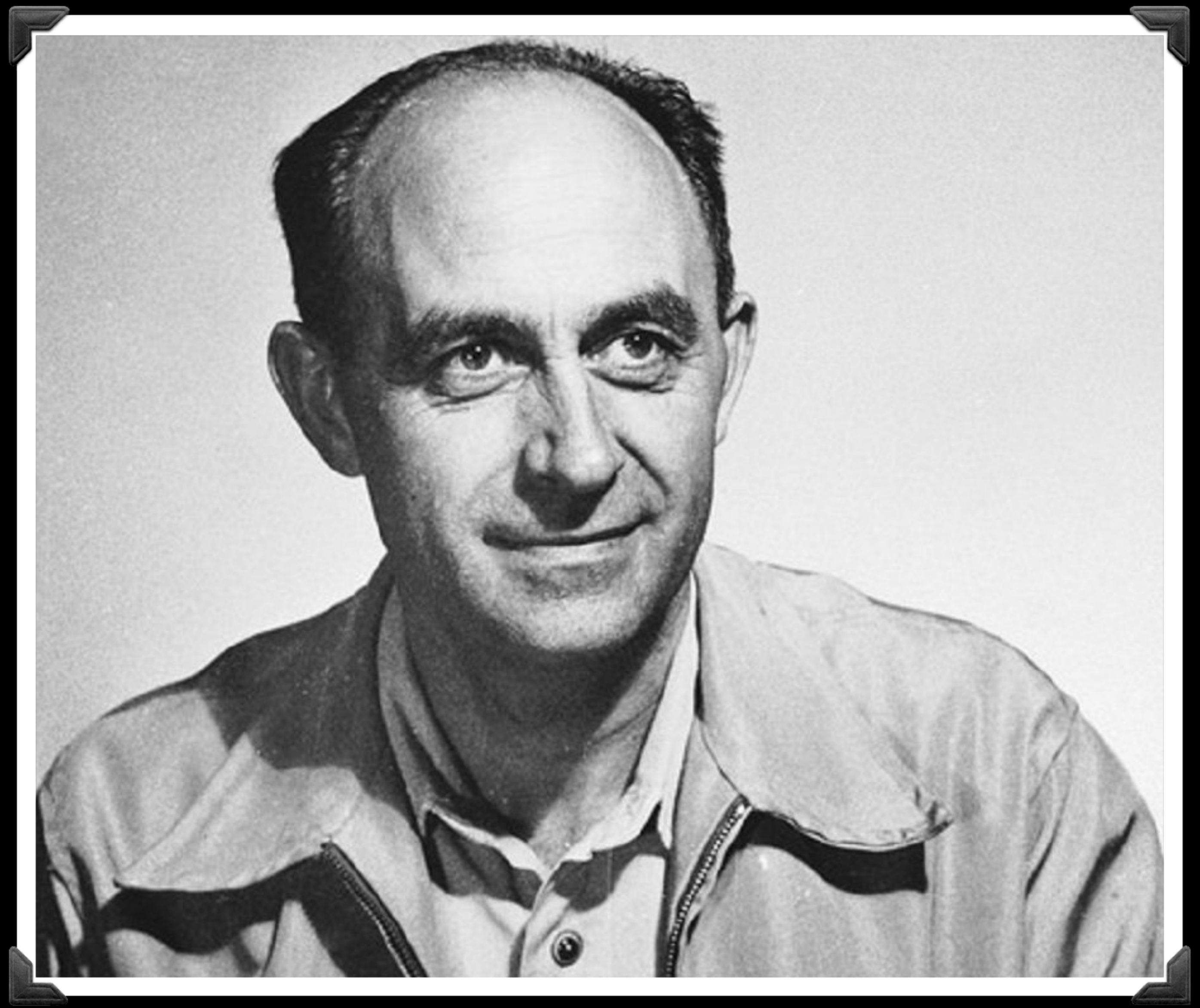
“On peut essayer de d́eduire de la forme des spectres continus d’ ́emission une indication sur la valeur de cette masse inconnue...”

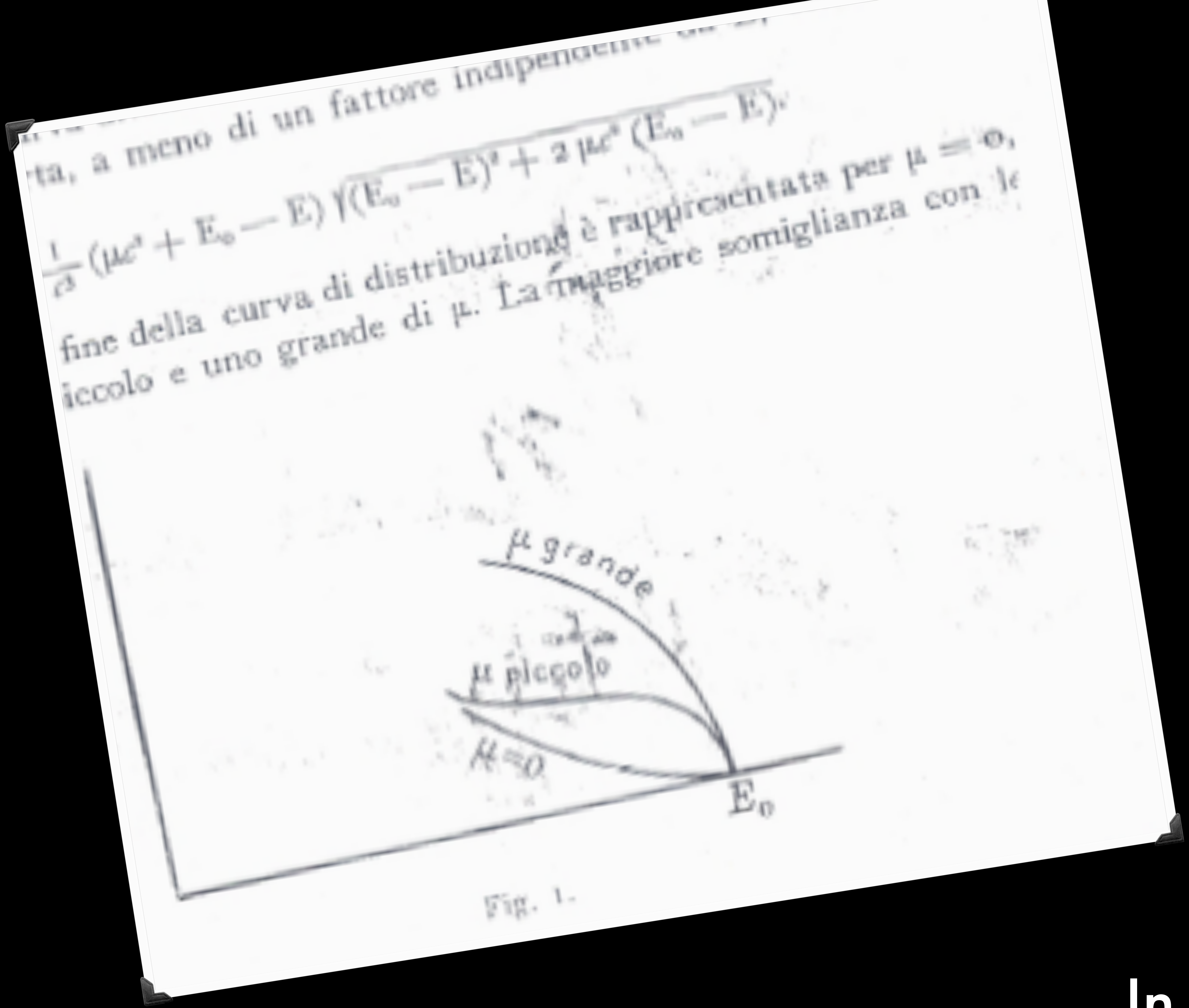
[One could attempt to deduce from the shape of the continuous emission spectra an indication of the value of this unknown mass...]

Enrico Fermi independently came to the same conclusion in his seminal 1934 paper on weak decay.

“Arriviamo cosi a concludere che l a massa del neutrino e uguale a zero o, in ogni caso, piccola in confronto della massa dell'elettrone (~) ...”

[We thus conclude that the mass of the neutrino is equal to zero or, in any case, small enough in comparison to the mass of the electron.]





ta, a meno di un fattore indipendente

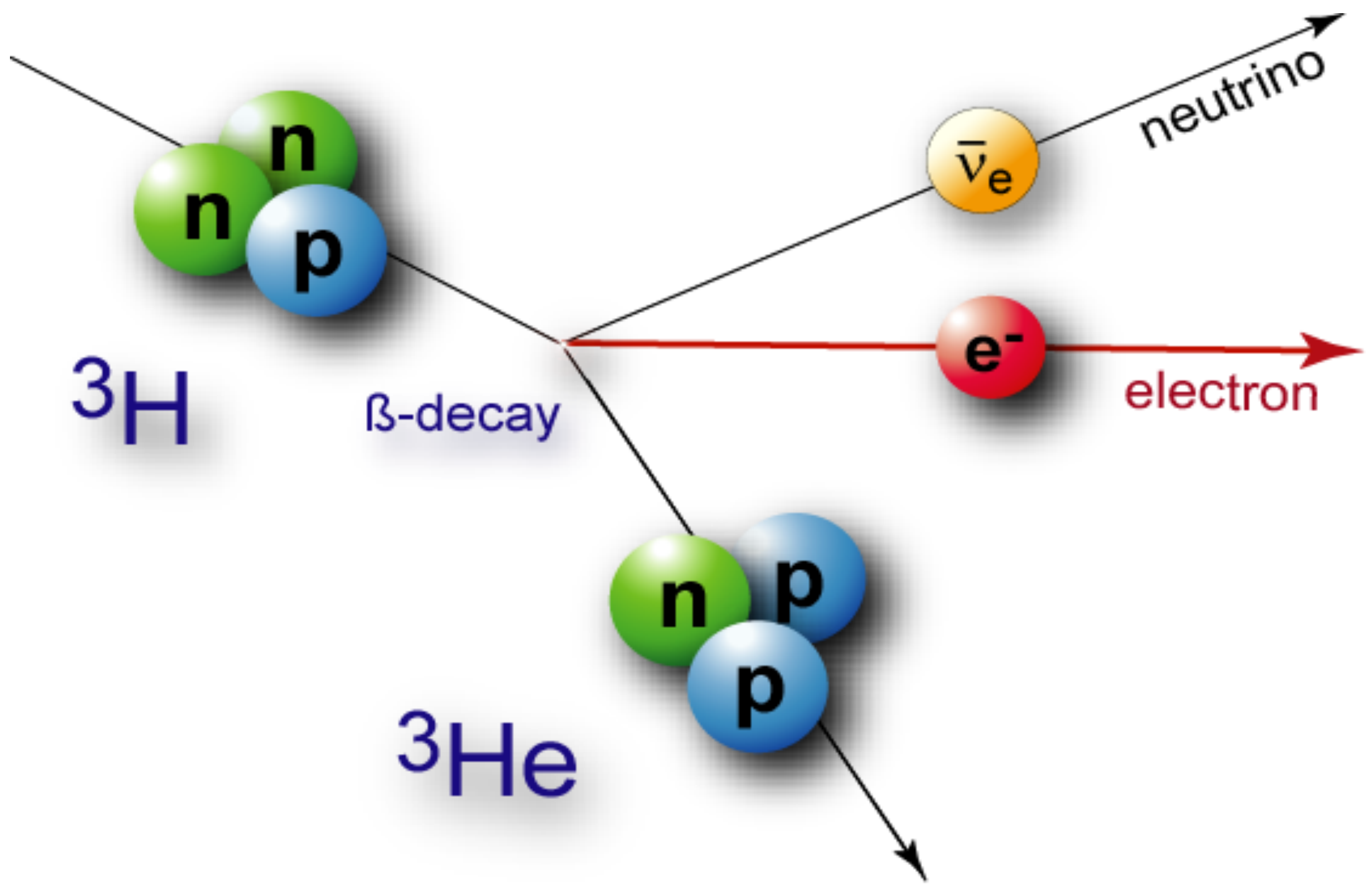
$$\frac{1}{c^3}(\mu c^2 + E_0 - E)\sqrt{(E_0 - E)^2 + 2\mu c^2 (E_0 - E)}.$$

fine della curva di distribuzione è rappresentata per $\mu = 0$,
piccolo e uno grande di μ. La maggiore somiglianza con le

Fig. 1.

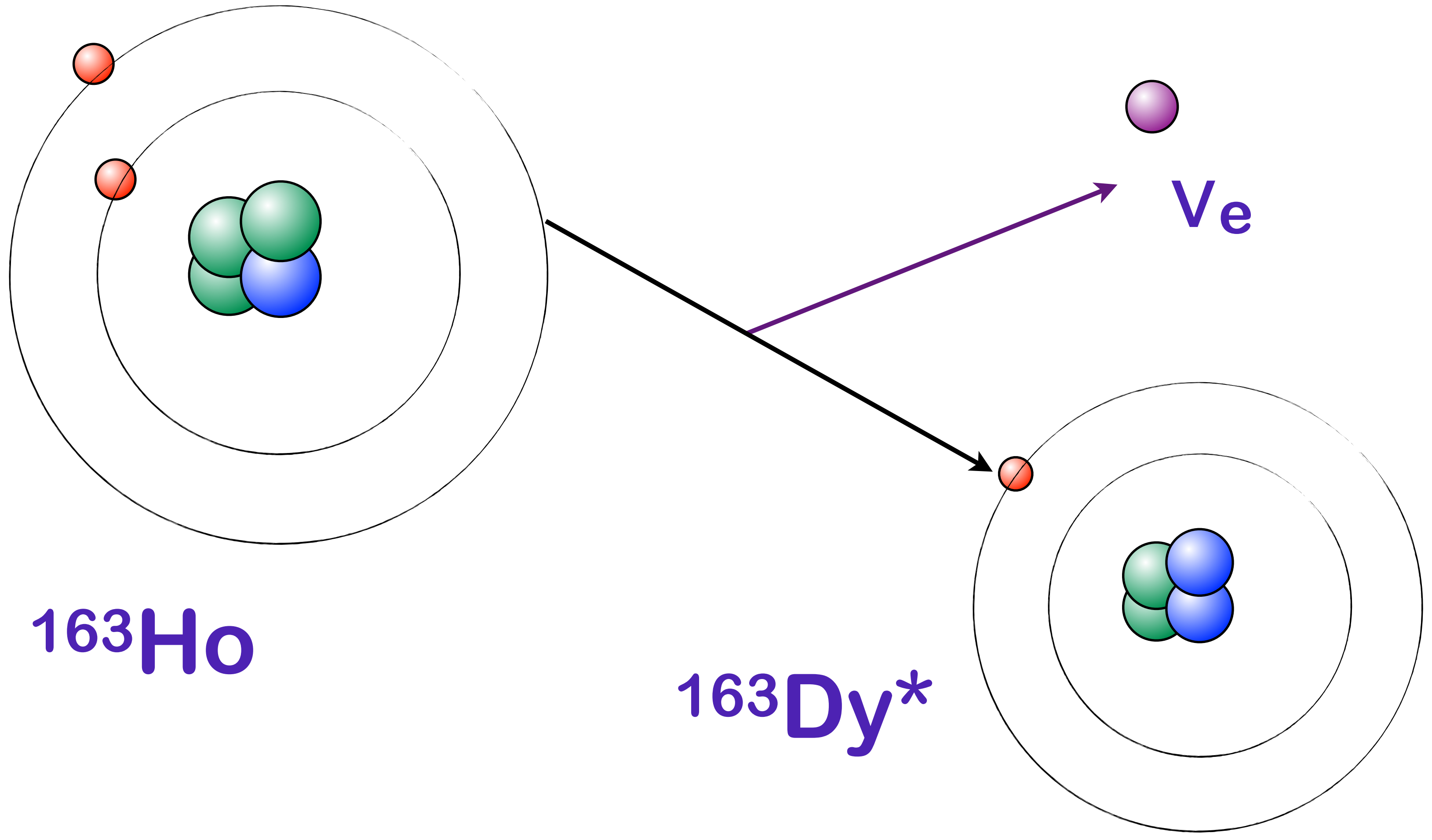
In his paper, Fermi already sketches out how one can do this.

Tritium beta decay



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

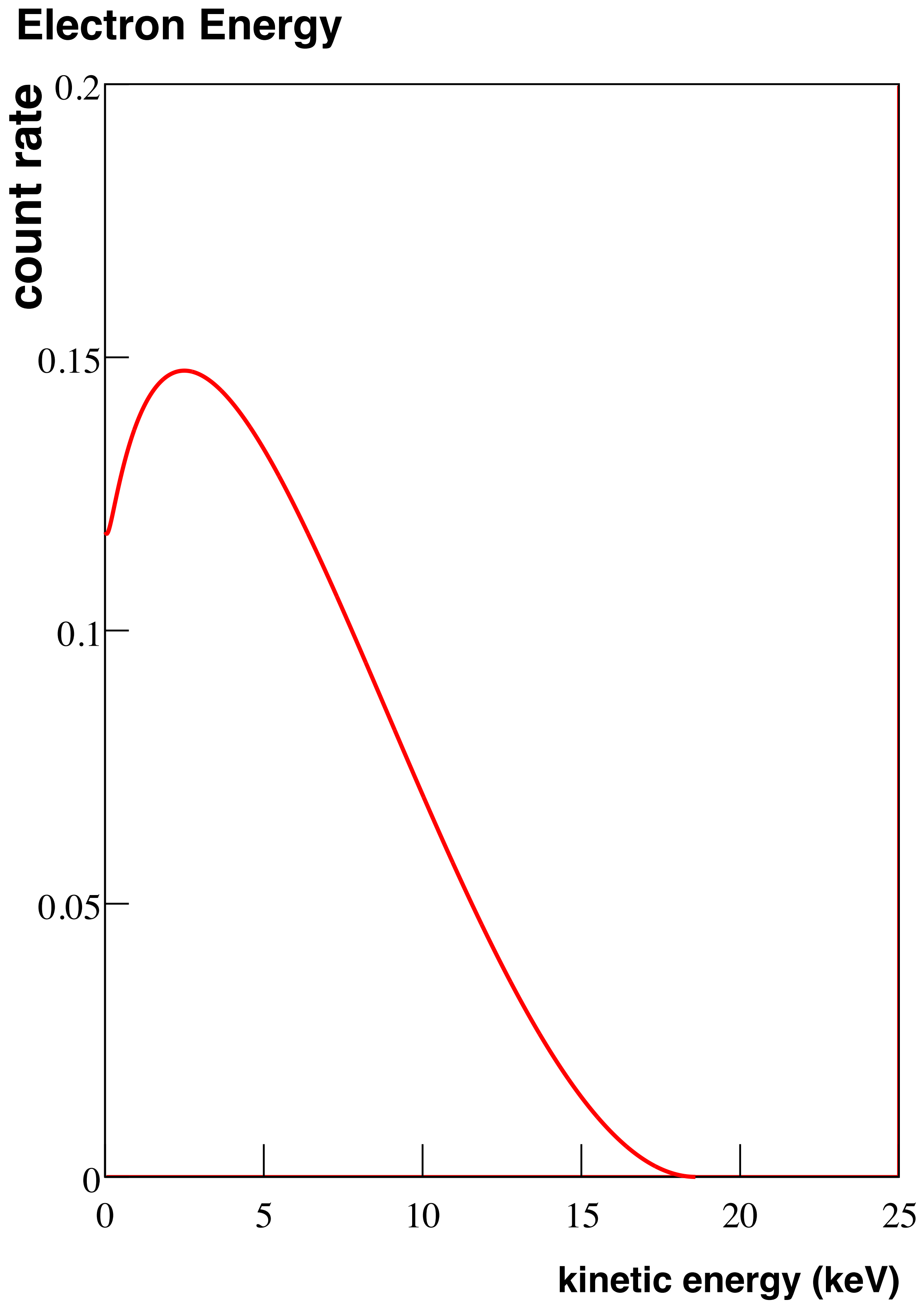
Holmium electron capture



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

For both beta decay and electron capture, the information about the neutrino mass comes from the phase space dependence on the neutrino momentum.

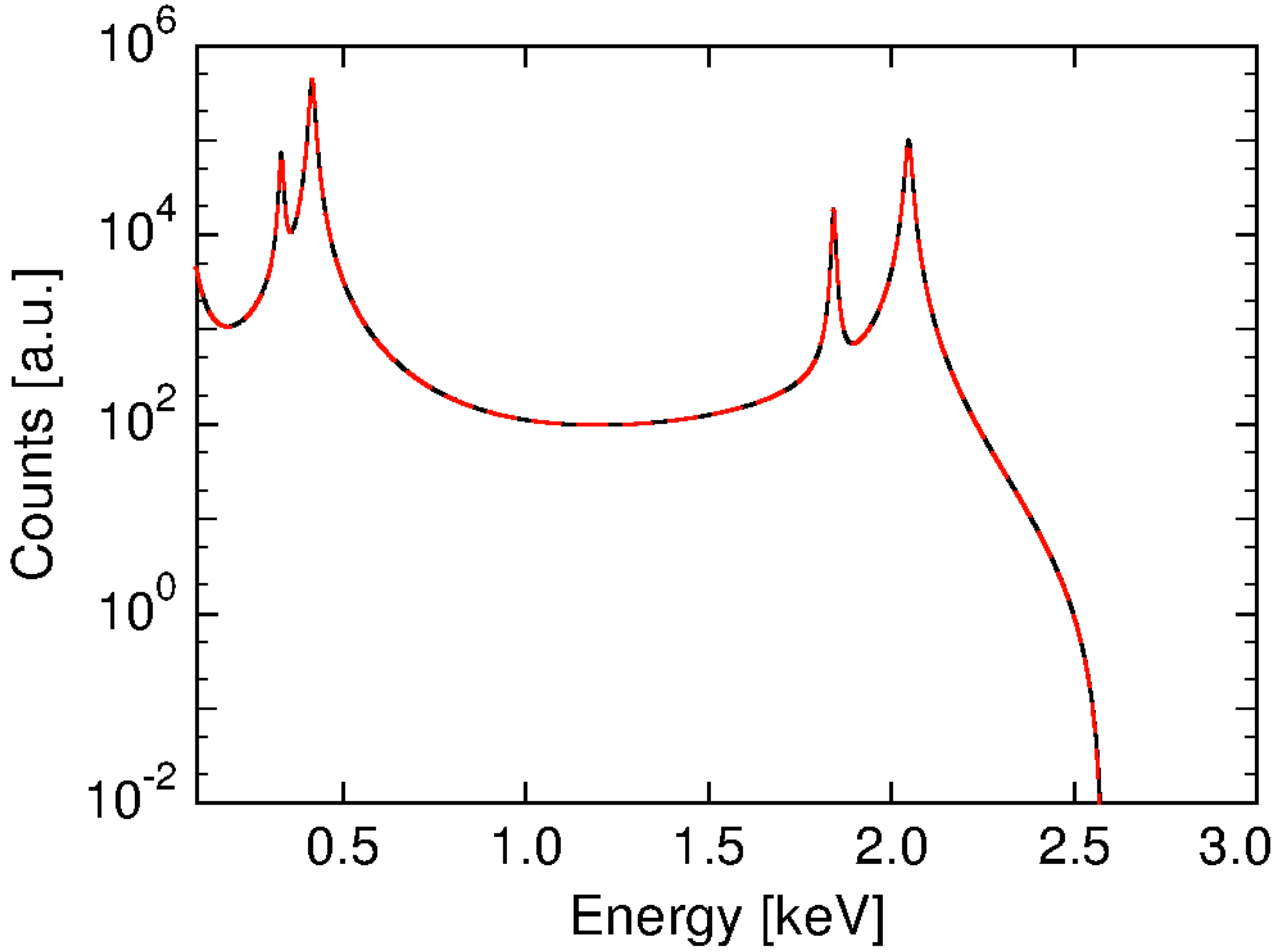
Tritium beta decay



In both cases, differential spectrum depends on the neutrino momentum.

$$\dot{N} \propto p_\nu E_\nu$$

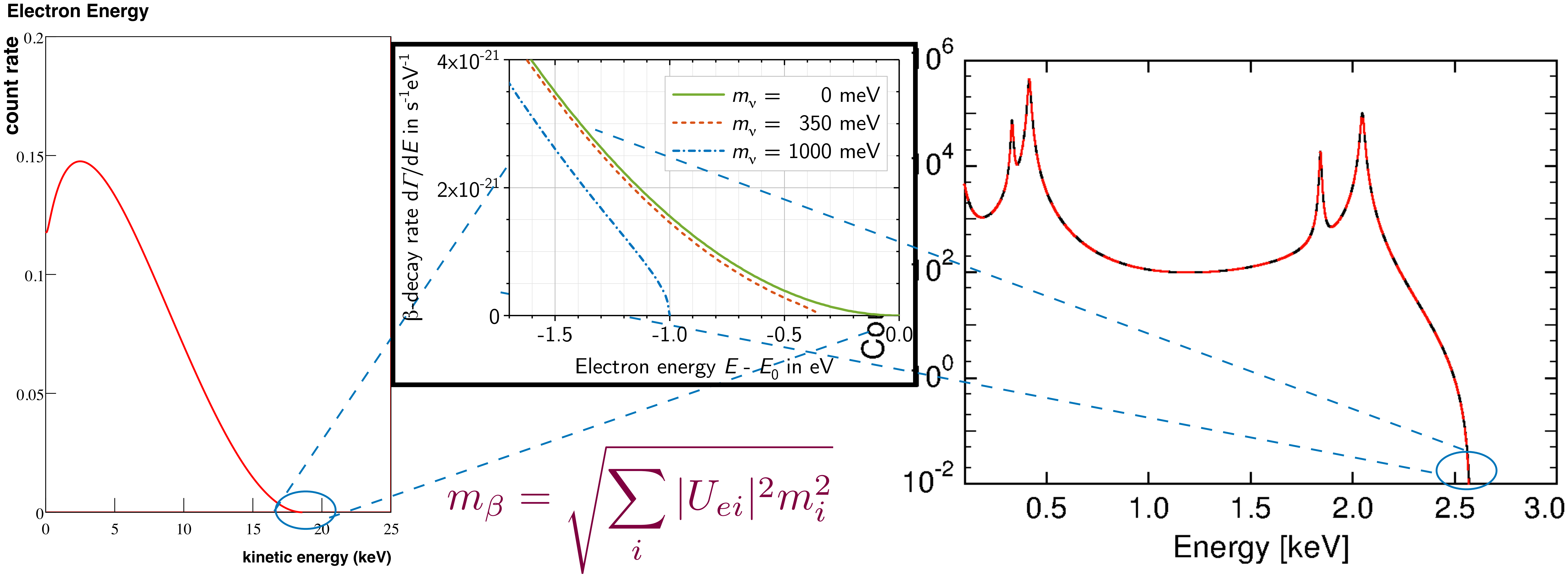
Holmium electron capture



For both beta decay and electron capture, the information about the neutrino mass comes from the phase space dependence on the neutrino momentum.

Tritium beta decay

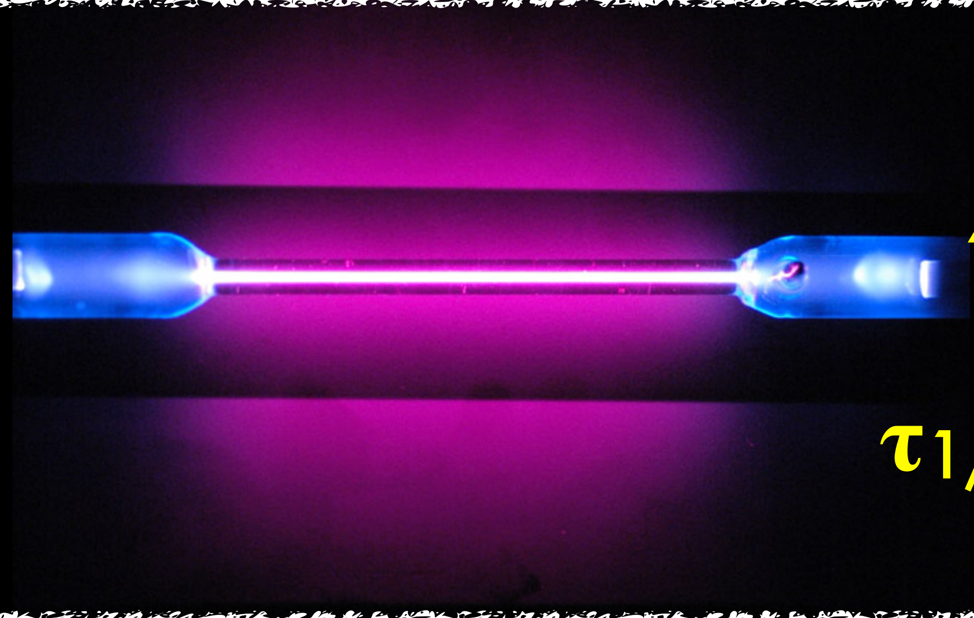
Holmium electron capture



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

We define m_β as the incoherent weighted sum of the neutrino mass eigenvalues.

The neutrino mass effect is most pronounced at the end of the decay spectrum.



$^{3}H_2$

18.5 keV

$\tau_{1/2}$ 12.3 yrs

^{163}Ho

2.83 keV

$\tau_{1/2}$ 4570 yrs

^{187}Re

2.5 keV

$\tau_{1/2}$ 4.5 Gyrs

^{115}In

155 eV

$\tau_{1/2}$ 4.4×10^{14} yrs

First,
pick a source...

^{135}Cs

440 eV

$\tau_{1/2}$ 1.5×10^{6} yrs

Isotope	Spin-Parity	Half-life y	Specific Activity Bq/g	Q_A eV	Branching ratio	Last eV	Source Mass g
$^{3}H_2$	$1/2^+ \to 1/2^+$	12.3	3.6×10^{14}	18591	0.57	2.9×10^{-13}	2.0×10^{-7}
^{115}In	$9/2^+ \to 3/2^+$	4.4×10^{14}	0.26	147	1.2×10^{-6}	5.0×10^{-7}	7.5×10^{7}
^{135}Cs	$7/2^+ \to 11/2^-$	1.5×10^{6}	6.8×10^{7}	440	$(0.04 - 16) \times 10^{-6}$	2.2×10^{-8}	0.4 - 217
^{187}Re	$5/2^+ \to 1/2^-$	4.3×10^{10}	1.6×10^{3}	2470	1.0	1.2×10^{-10}	57
^{163}Ho	$7/2^- \to 5/2^-$	4750	1.8×10^{10}	2858		$\sim 10^{-12}$	$\sim 1.0 \times 10^{-5}$

Amount needed to see 1 event per day in last eV

^{135}Cs and ^{115}In look attractive for their low endpoint and because decays can be tagged. But they suffer from minuscule branching ratios.

Other new ultra-low β/EC targets, such as ^{76}As and ^{155}Tb, currently under study.

Issues with ^{187}Re make it impractical.

Tritium and holmium are the top candidates of study for now.

Next,
Pick a method...

Electron transfers all of its energy to the absorbing medium.

Calorimetric
(Cryogenic Bolometers)

Electromagnetic filtering of electrons of selected energy.

Electromagnetic Collimation
(MAC-E Filter)

Use photon spontaneous emission from electron in magnetic field.

Frequency-Based
(Cyclotron Radiation Emission Spectroscopy)

Electron transfers all of its energy to the absorbing medium.

Calorimetric

(Cryogenic Bolometers)

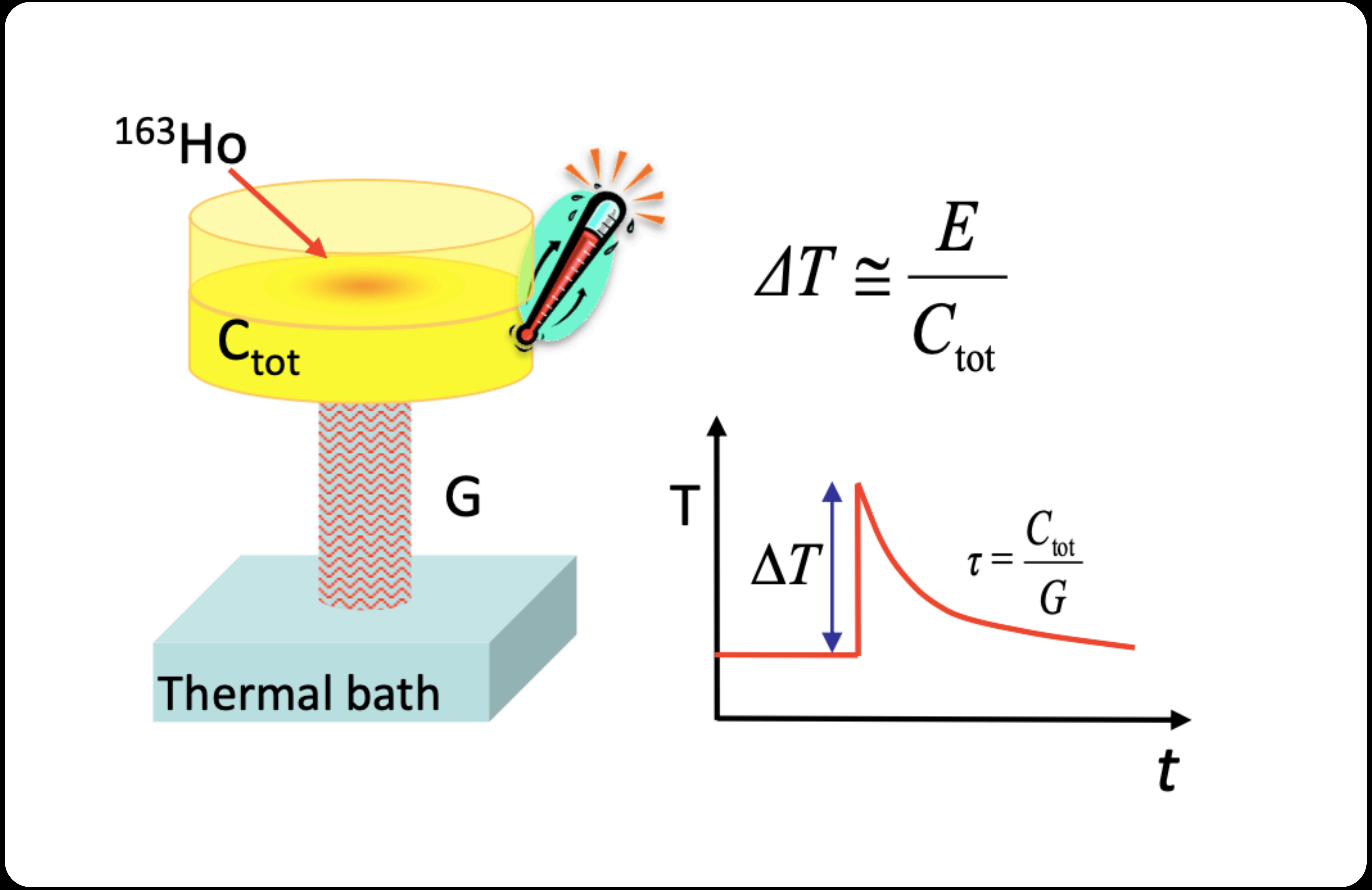
Calorimetric approaches convert the *total* deposited energy of the decay into heat (phonons).

Usually very small detectors operated at extremely low (< 100 mK) temperatures.

Small detectors (small heat capacitance)

Cryogenic temperatues

Highly sensitive thermal detectors

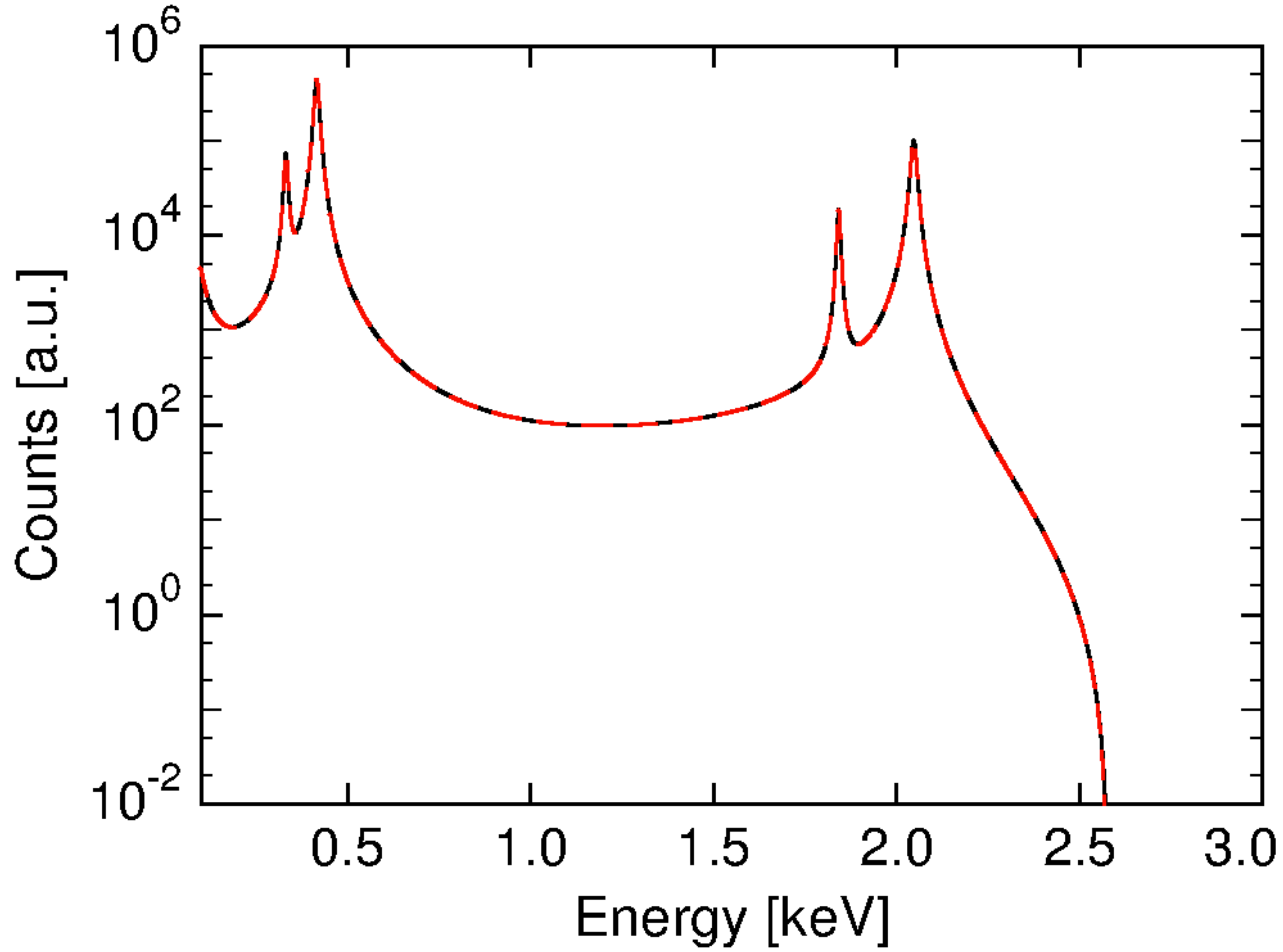


Sensitivity of the detectors governed by the total heat capacitance (C_{tot}) of the detector and the thermal coupling (G).

Superconductors and semi-conductors	Metals
$C(T) \propto T^3$	$C(T) \propto T$

In 1981, DeRujula proposed an alternate method for measuring the neutrino mass.

Make use of the internal bremsstrahlung in electron capture (IBEC), with a spectrum analogous to beta decay.

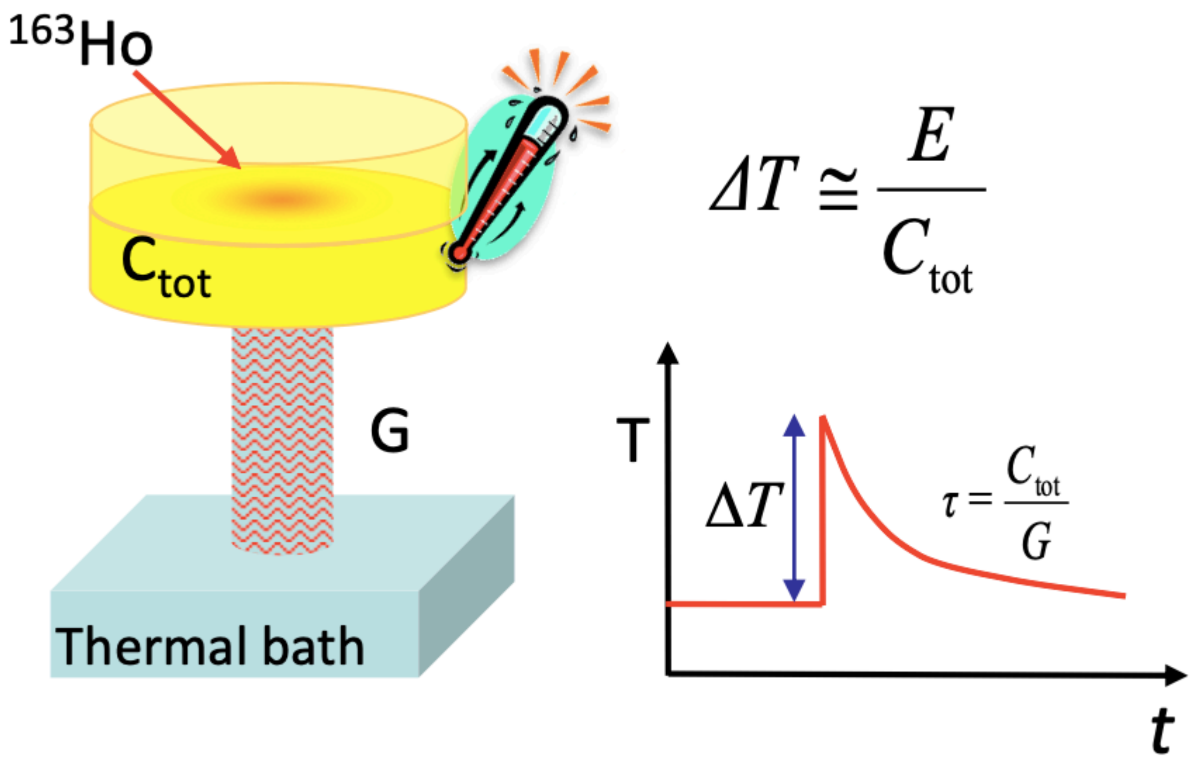


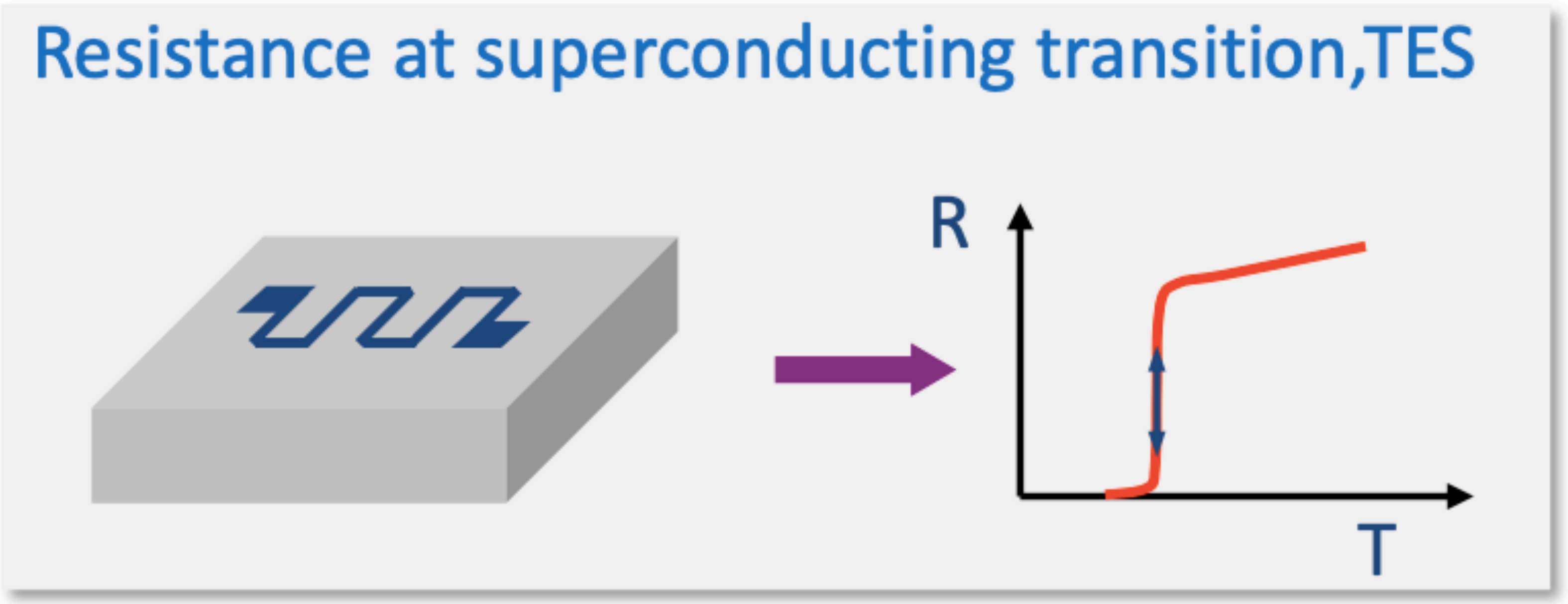
$$\frac{d\lambda_{\mathrm{EC}}}{dE_c} = \frac{G_F^2 |V_{ud}|^2}{2\pi^3}(Q - E_c) \times \sum_j \beta_j^2 C_j \, |M_{j0}|^2 \, \frac{\Gamma_j}{4(E_c - E_j)^2 + {\Gamma_j}^2} \times \sum_i |U_{ei}|^2 \left[(Q - E_c)^2 - m_i^2\right]^{1/2}$$

Neutrino phase space term

This opened up the possibility of using ^{163}Ho as a source for calorimetric detectors.

Modern Calorimetric Experiments



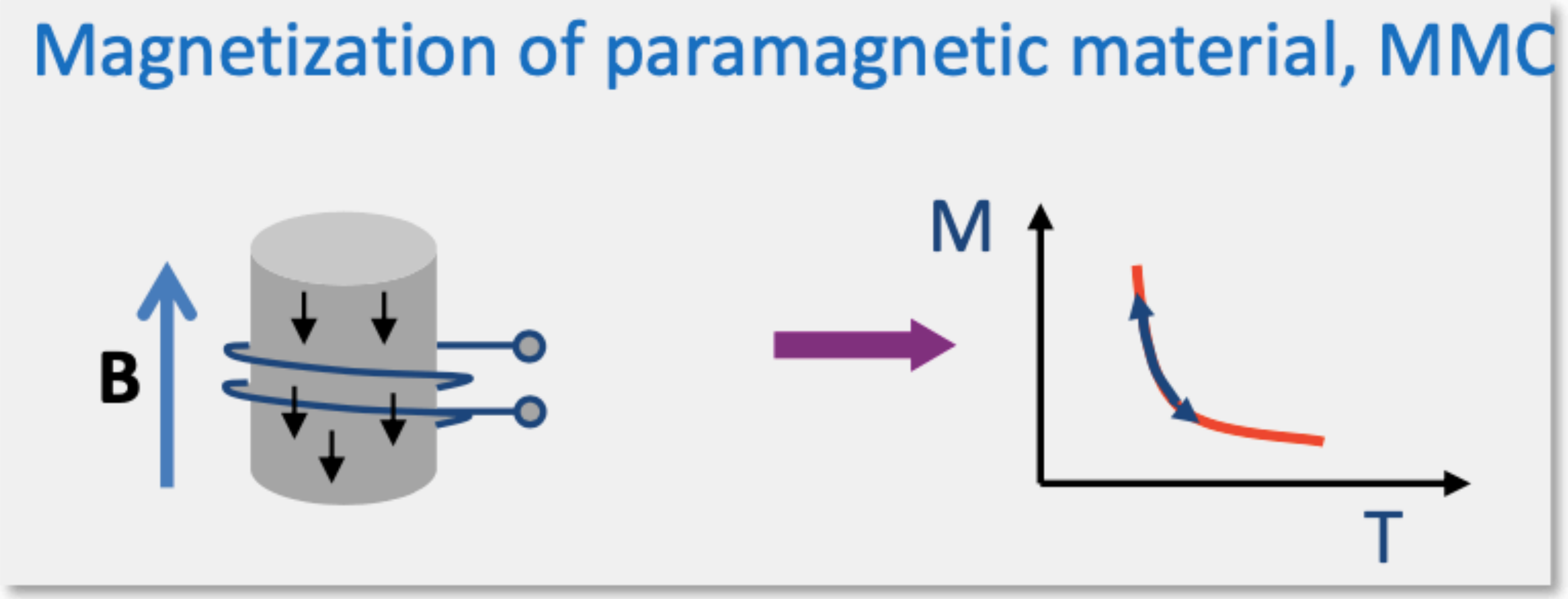


K.D. Irwin and G.C. Hilton, Topics in Applied Physics 99 (2005) 63

HOLMES

NuMECS

Detector arrays produced at NIST (Boulder US)



A.Fleischmann, C. Enss and G. M. Seidel, Topics in Applied Physics 99 (2005) 63

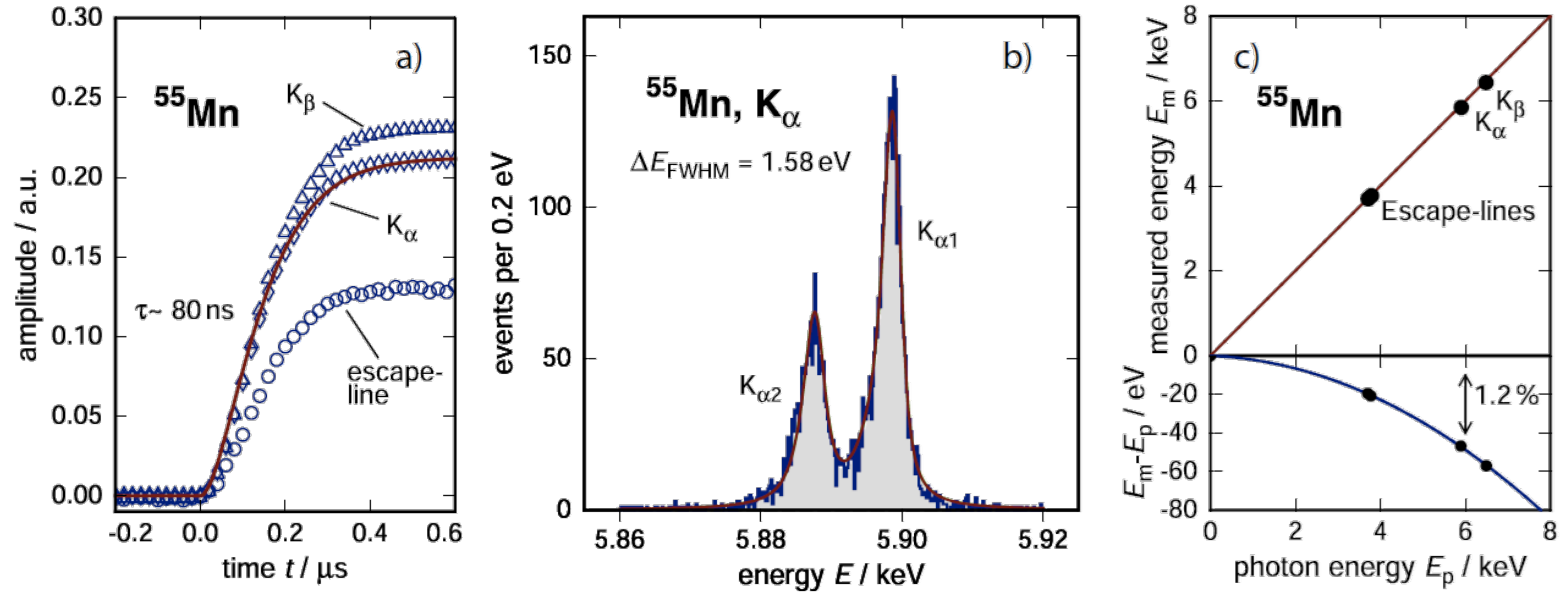
ECHo

Detector arrays produced at KIP, Heidelberg University

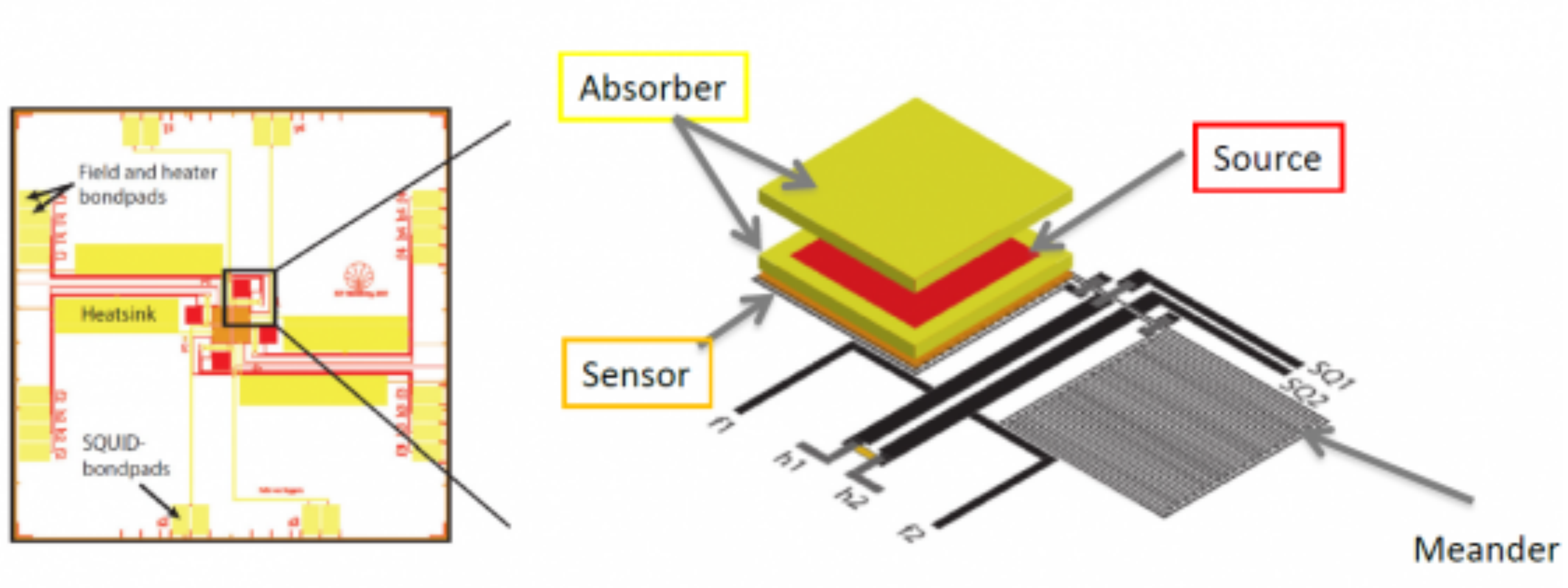
Micro calorimeters which are sensitive to changes in temperature (energy deposition).

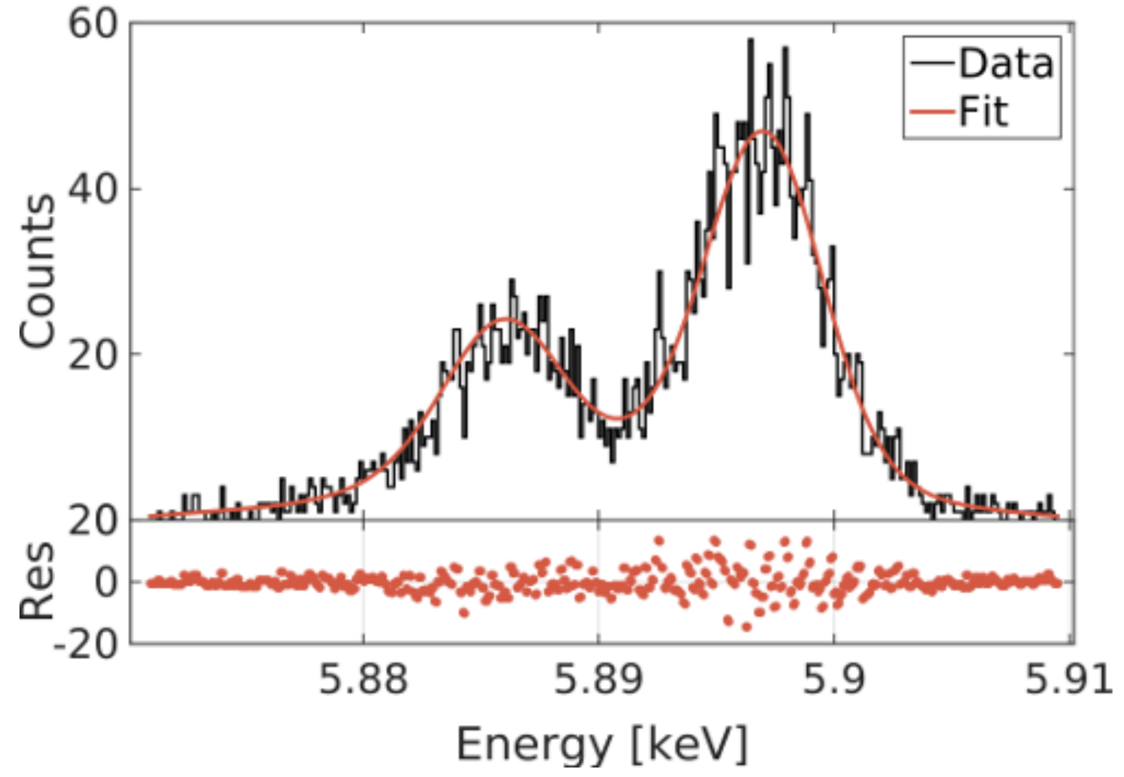
Contains the full decay energy.

Modern Calorimetric Experiments

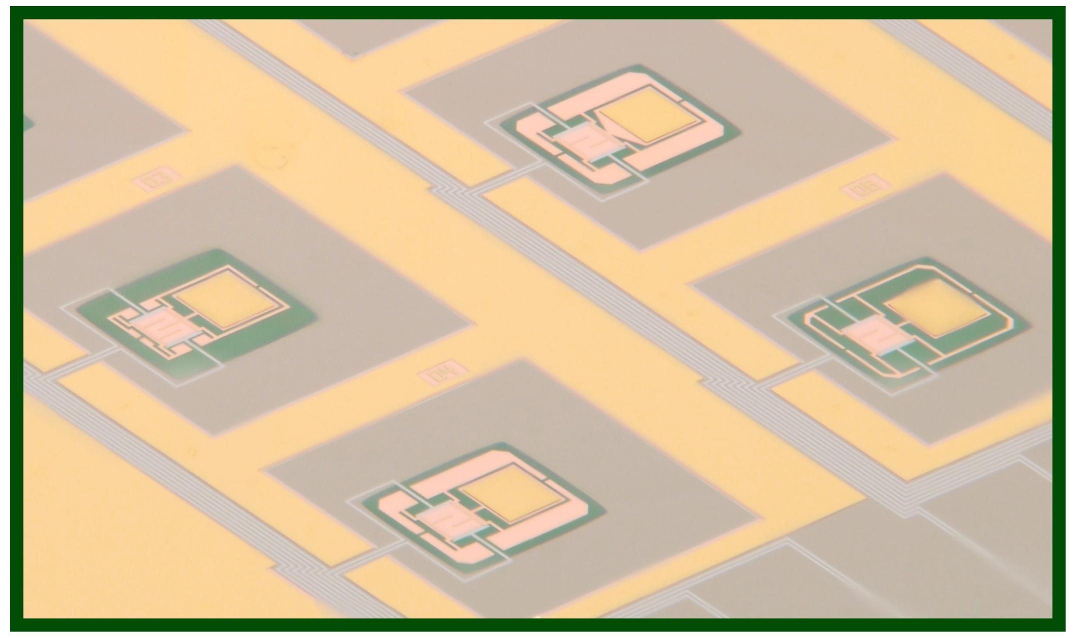


MMC Response
(ECHo)





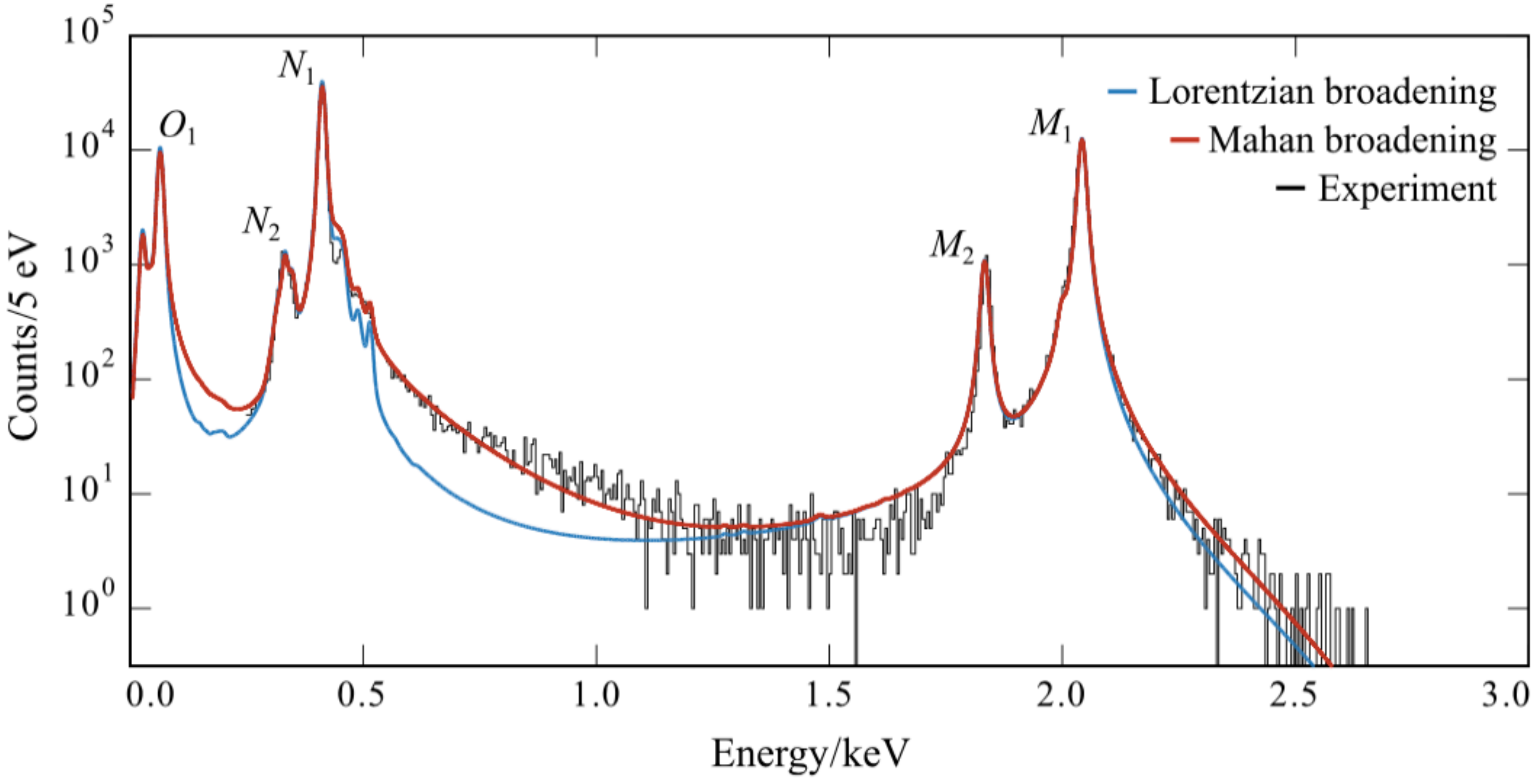
TES Resolution
(HOLMES)

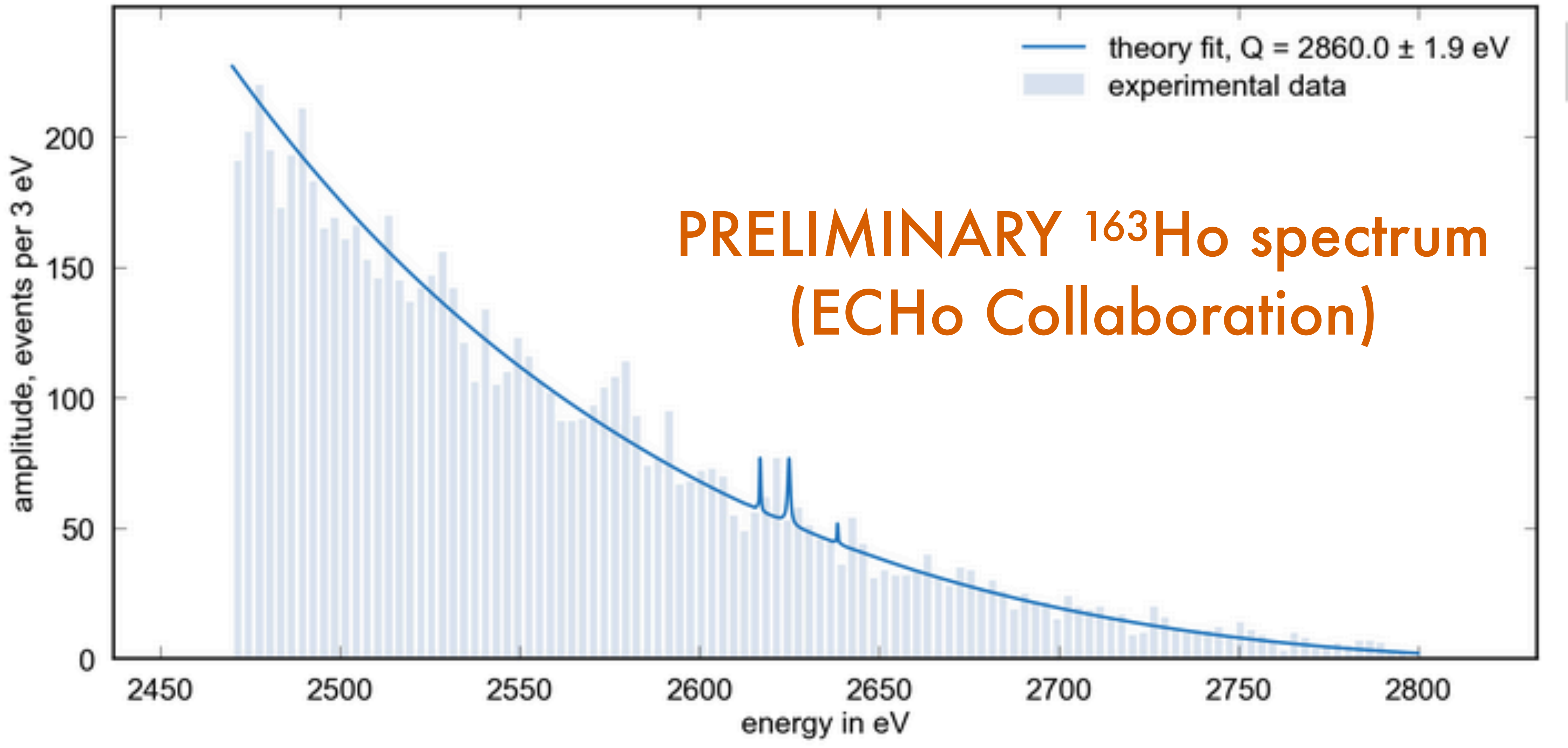


^{163}Ho is implanted onto gold absorbers and cooled to cryogenic temperatures for energy readout.

Need very high energy resolution (for spectrum) and fast timing resolution (to avoid pile-up of events).

Modern Calorimetric Experiments





Upcoming generation of ECHo and HOLMES experiments aim to reach the eV mass scale.

eV sensitivity is within reach for next-generation large array of detectors.

New results from ECHo expected soon.

Electromagnetic filtering of electrons of selected energy.

Electromagnetic Collimation
(MAC-E Filter)

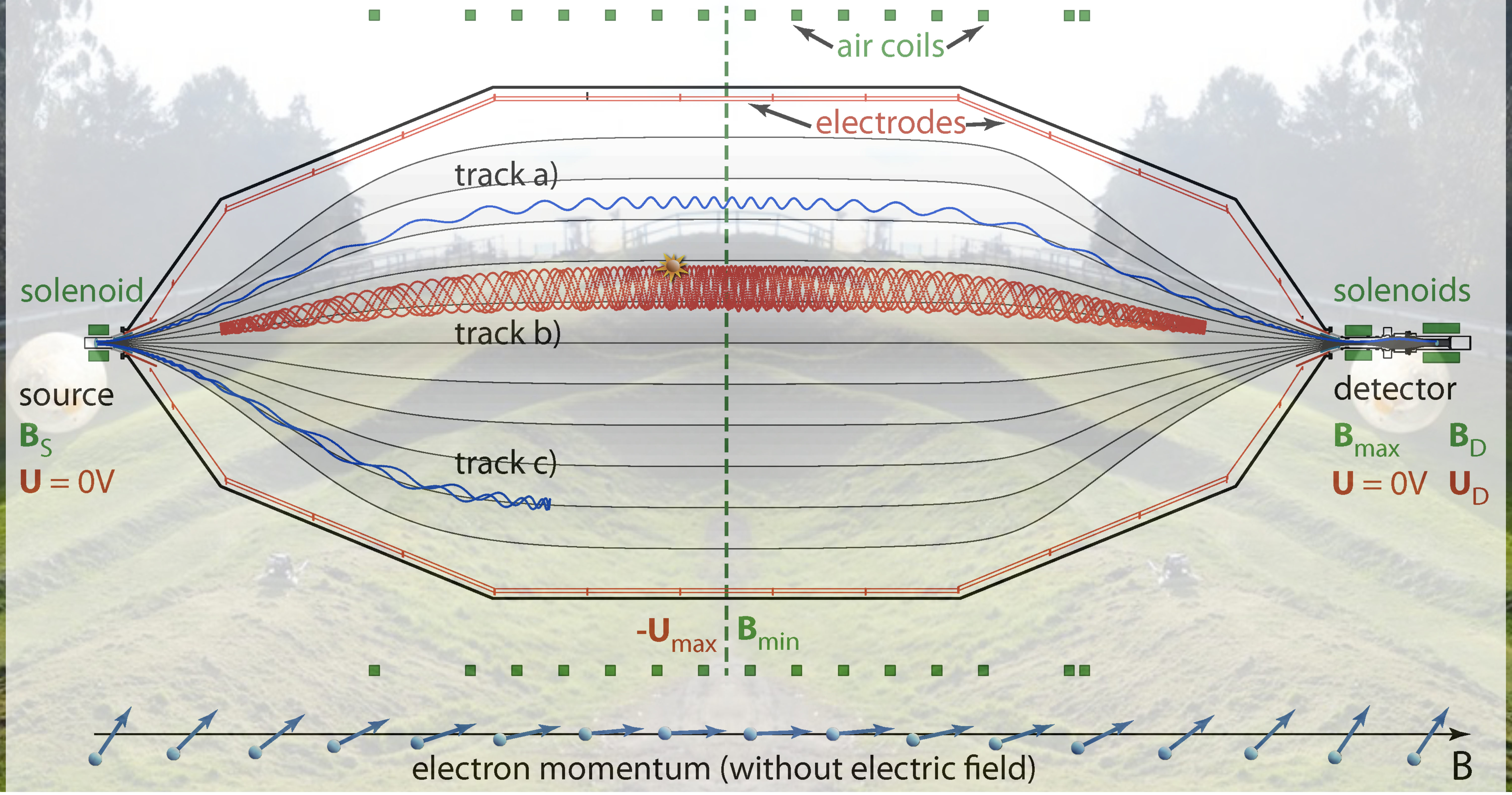
High Magnetic Field (Bs)

Low Field B_A

High Magnetic Field (Bs)

Magnetic Adiabatic Collimation w/ Electrostatic Filtering

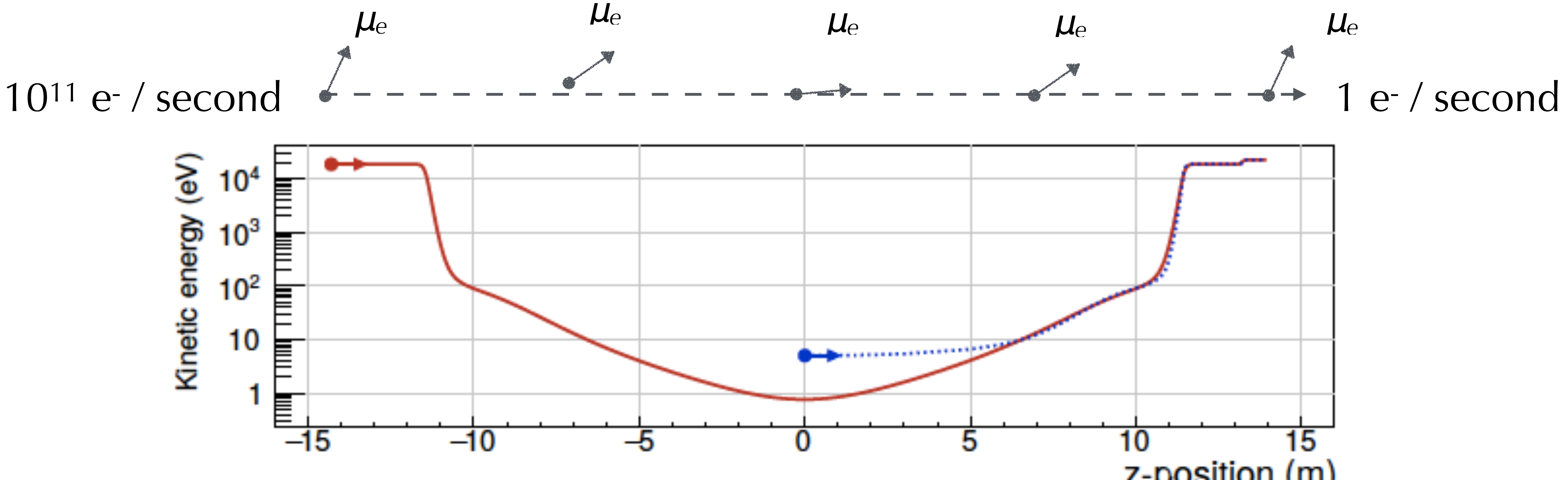
(only electrons with enough energy can overcome potential barrier)



High Magnetic Field (Bs)

Low Field B_A

High Magnetic Field (Bs)

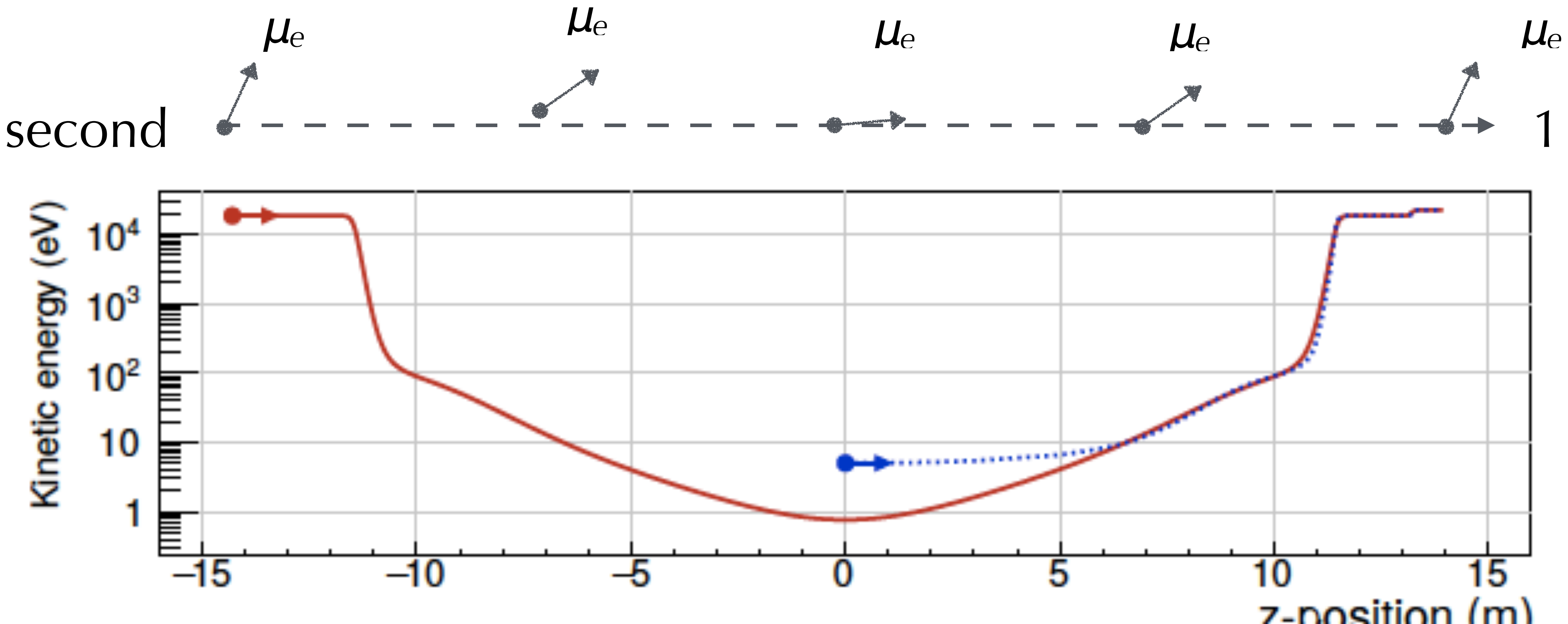


High Magnetic Field (Bs)

Low Field B_A

High Magnetic Field (Bs)

10^{11} e^- / second

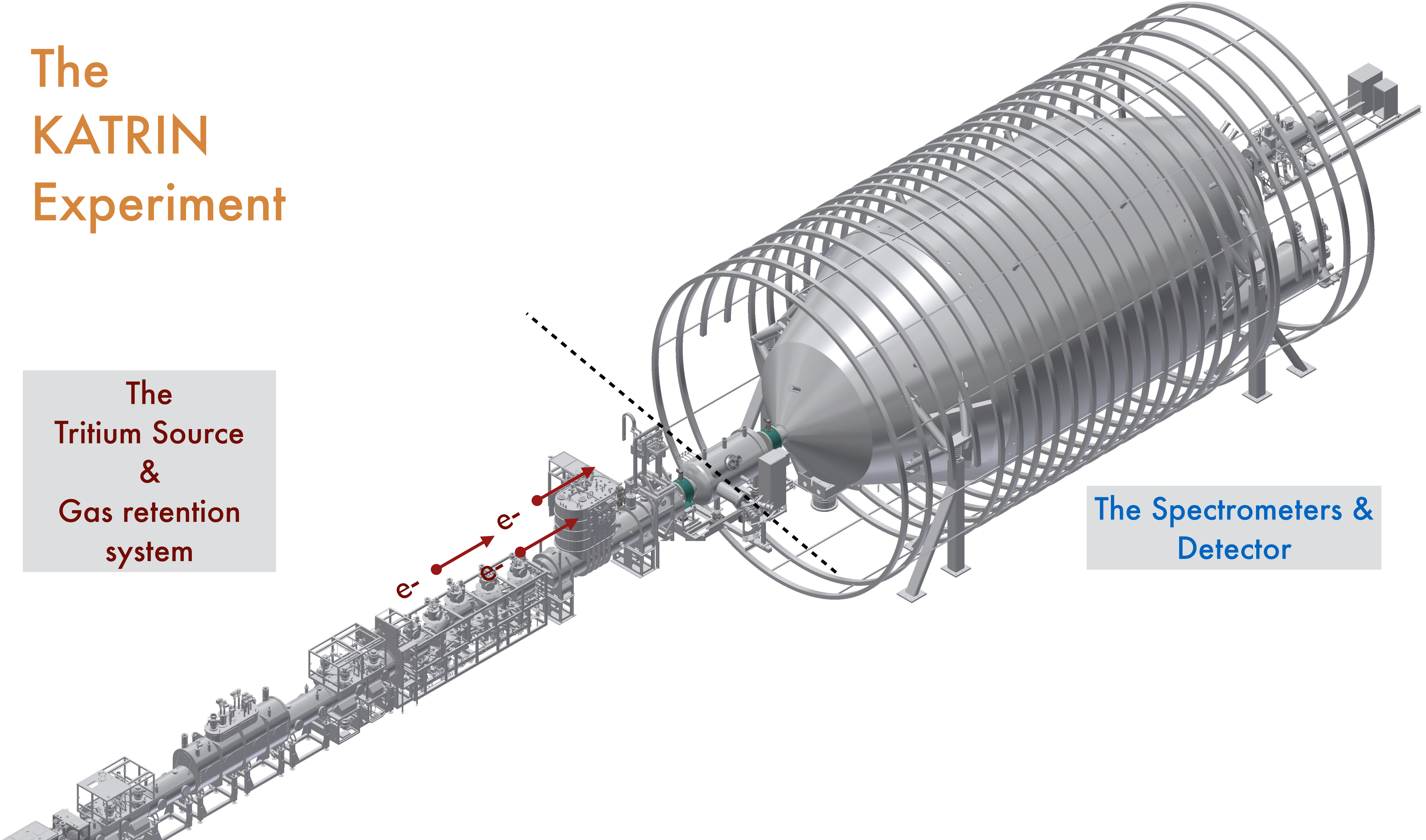


1 e^- / second

Predecessors: Mainz & Troitsk

Three years of data taking. Limit $m_\beta < 2$ eV

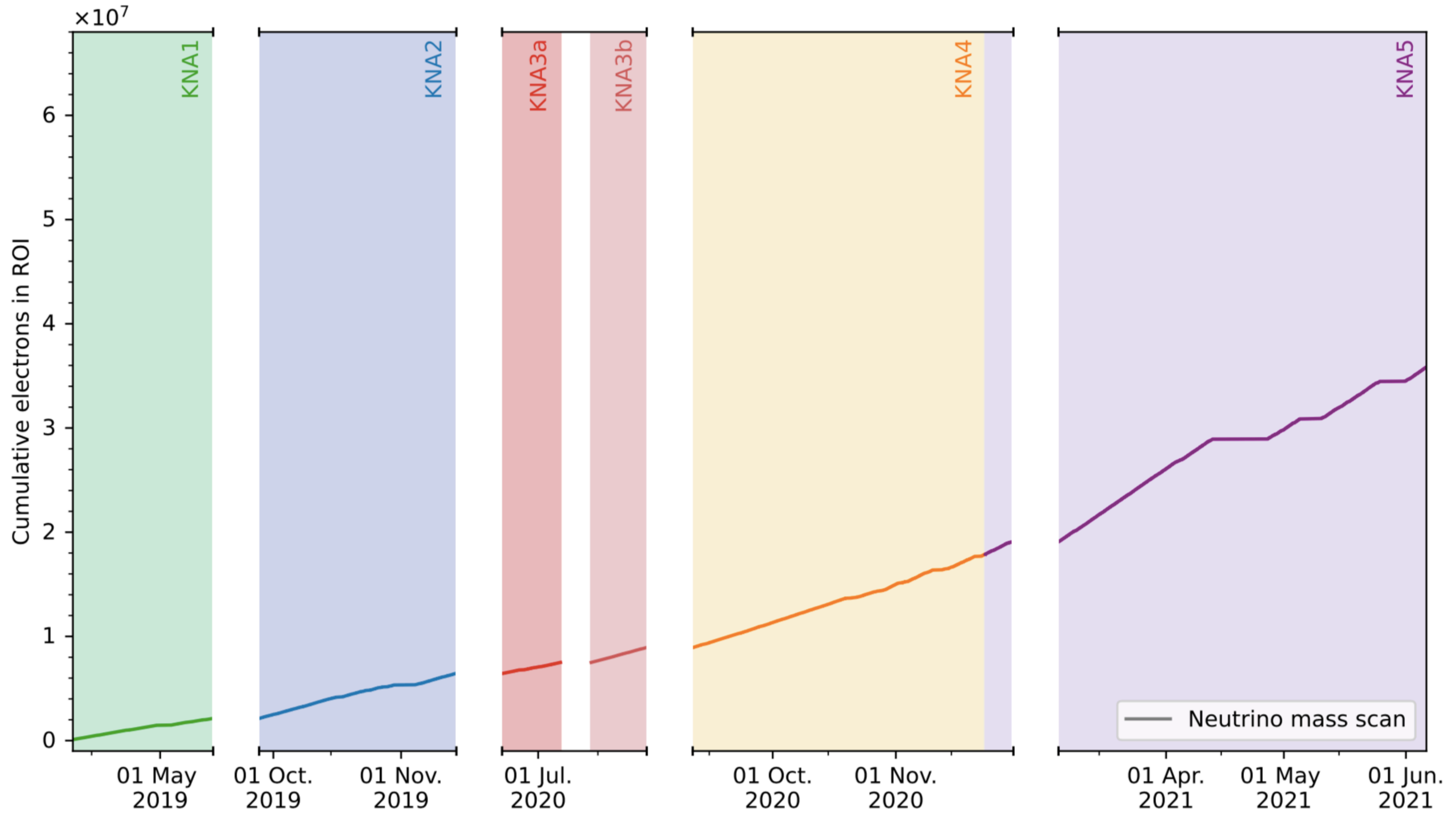
The KATRIN Experiment

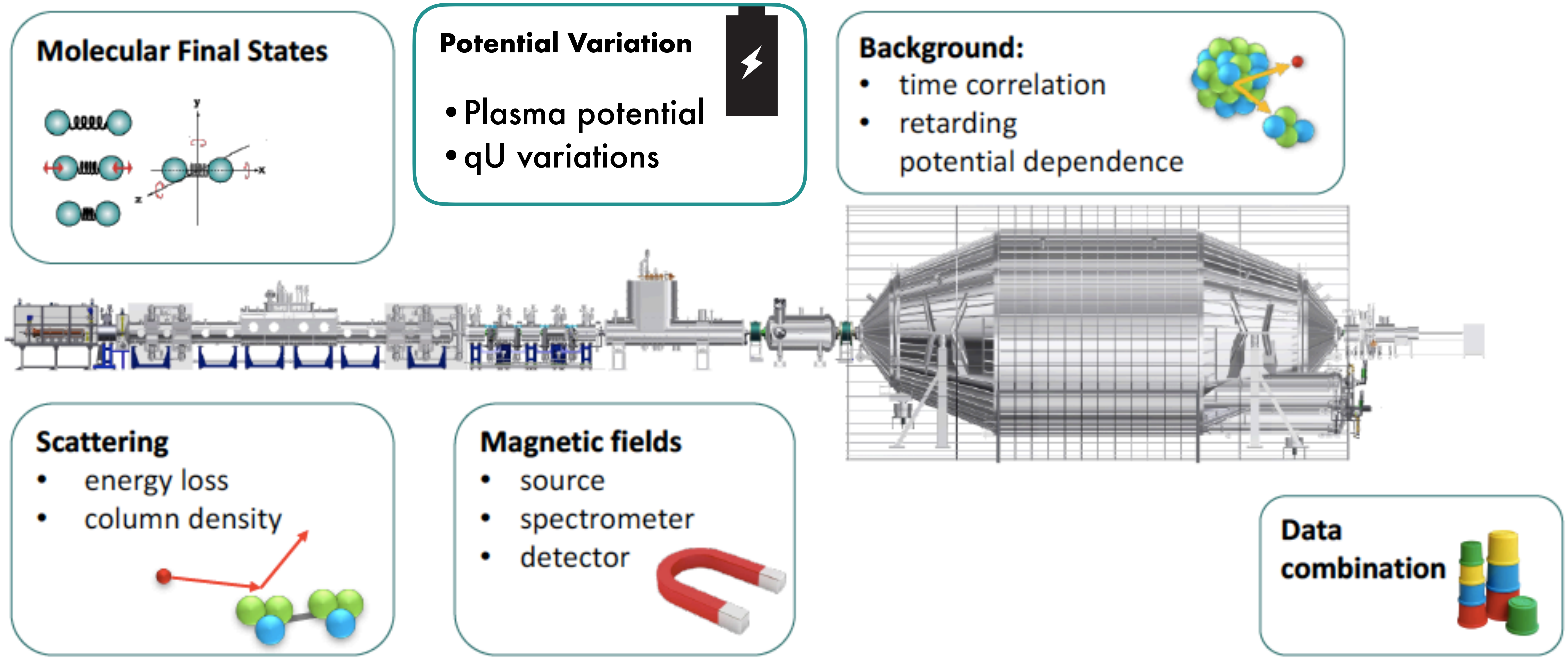


A long journey in the making...

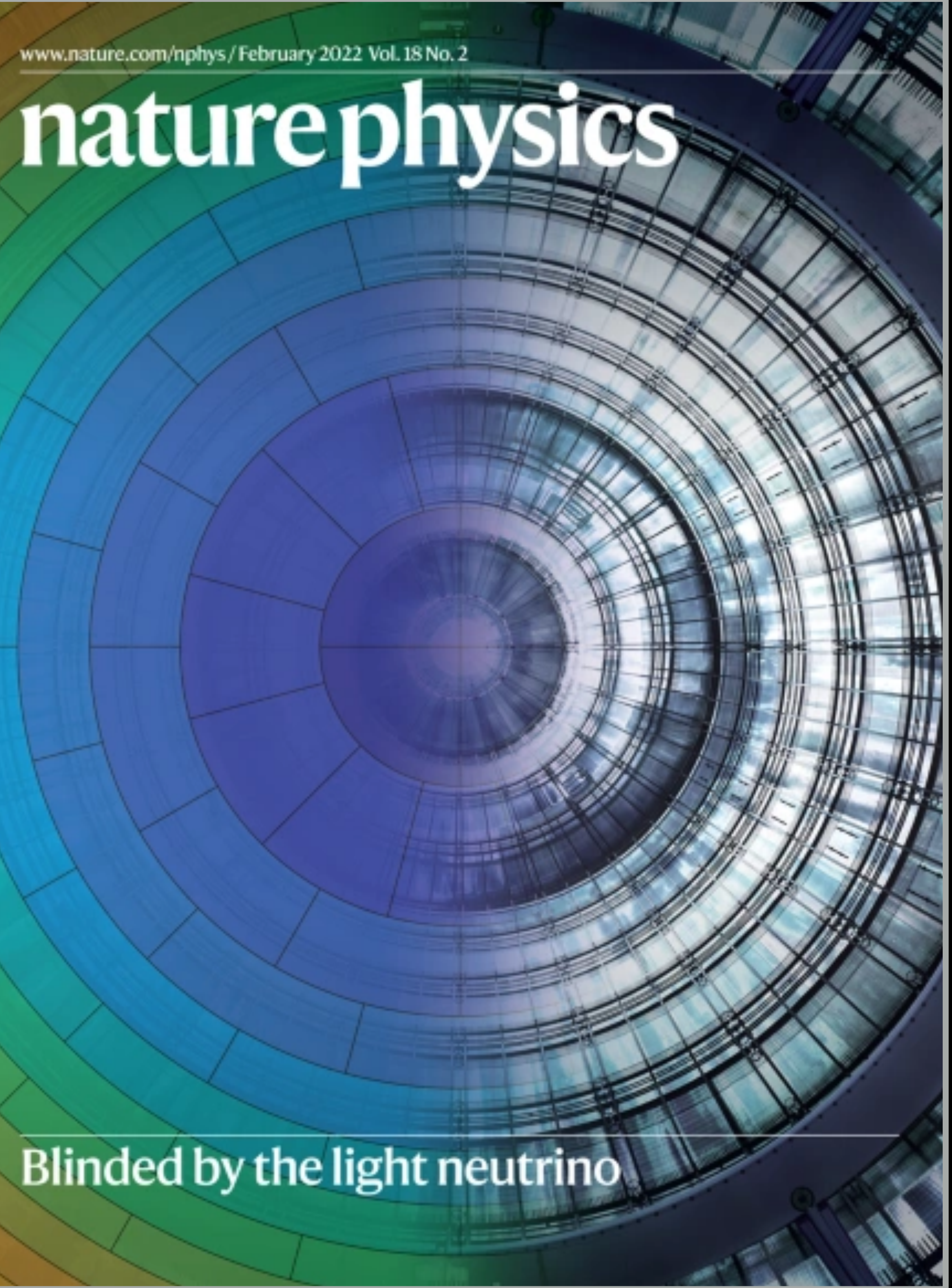
Data taking commenced in May 2019 and is ongoing.

Statistical Uncertainty

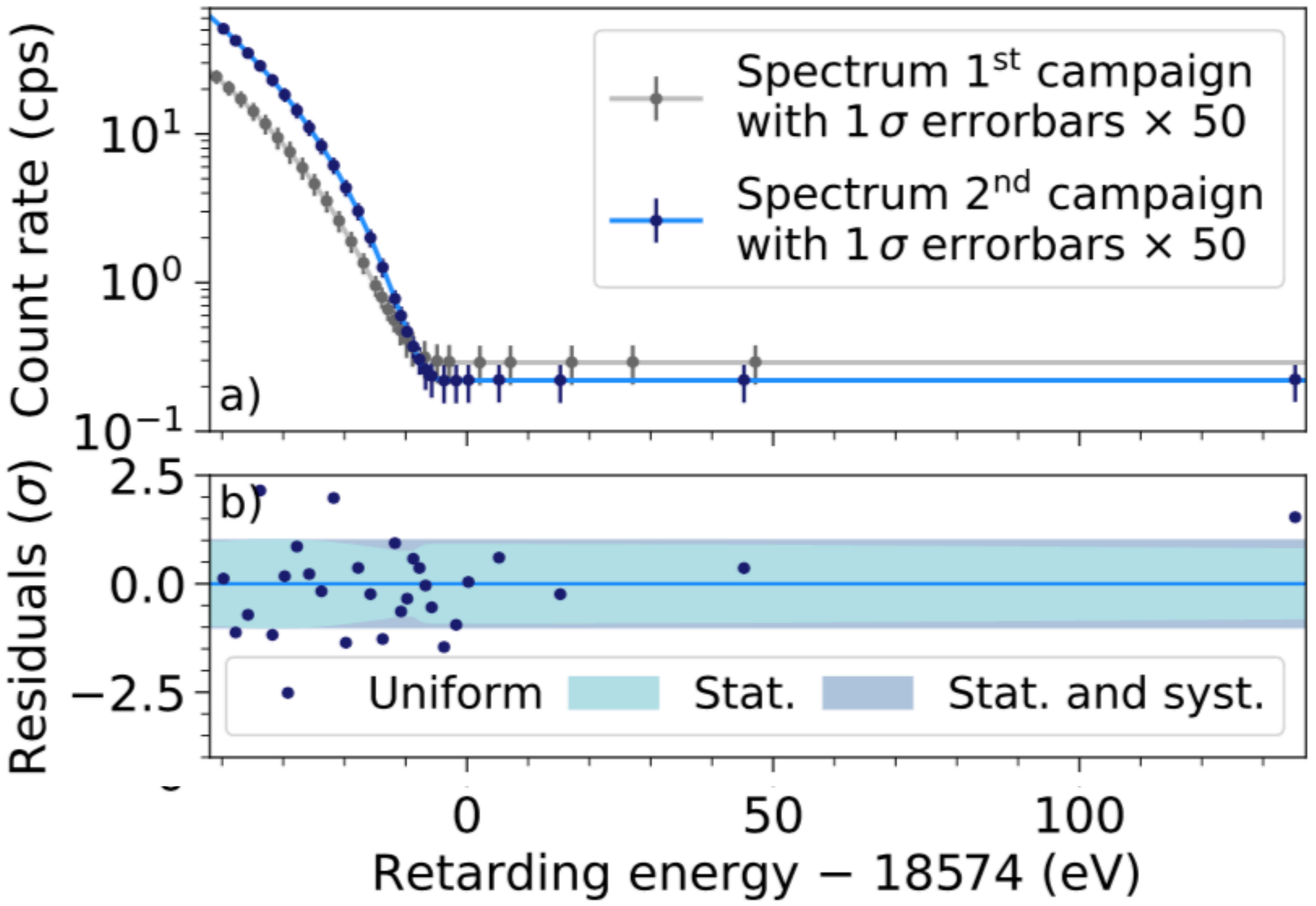




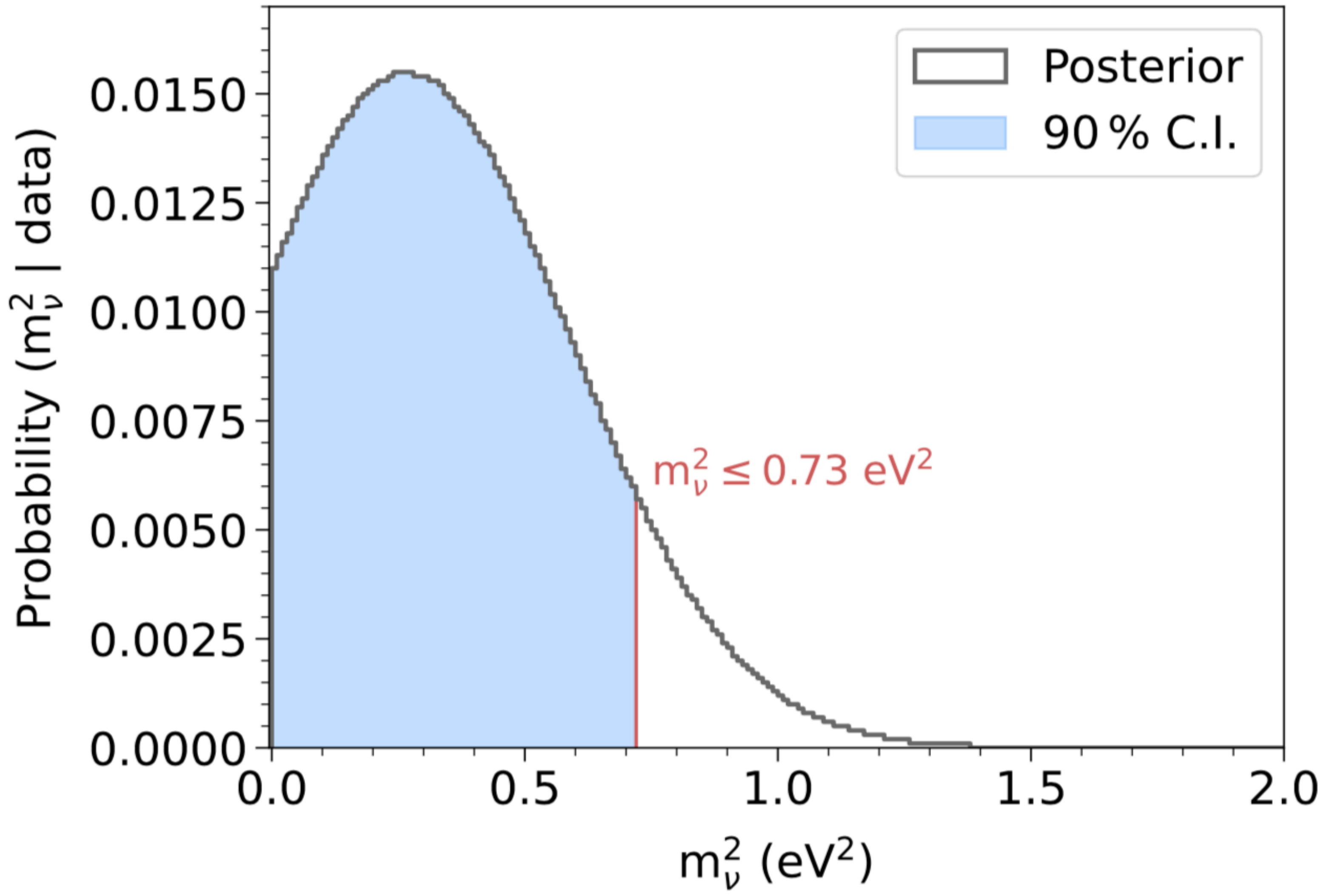
Detailed control of systematics and backgrounds.

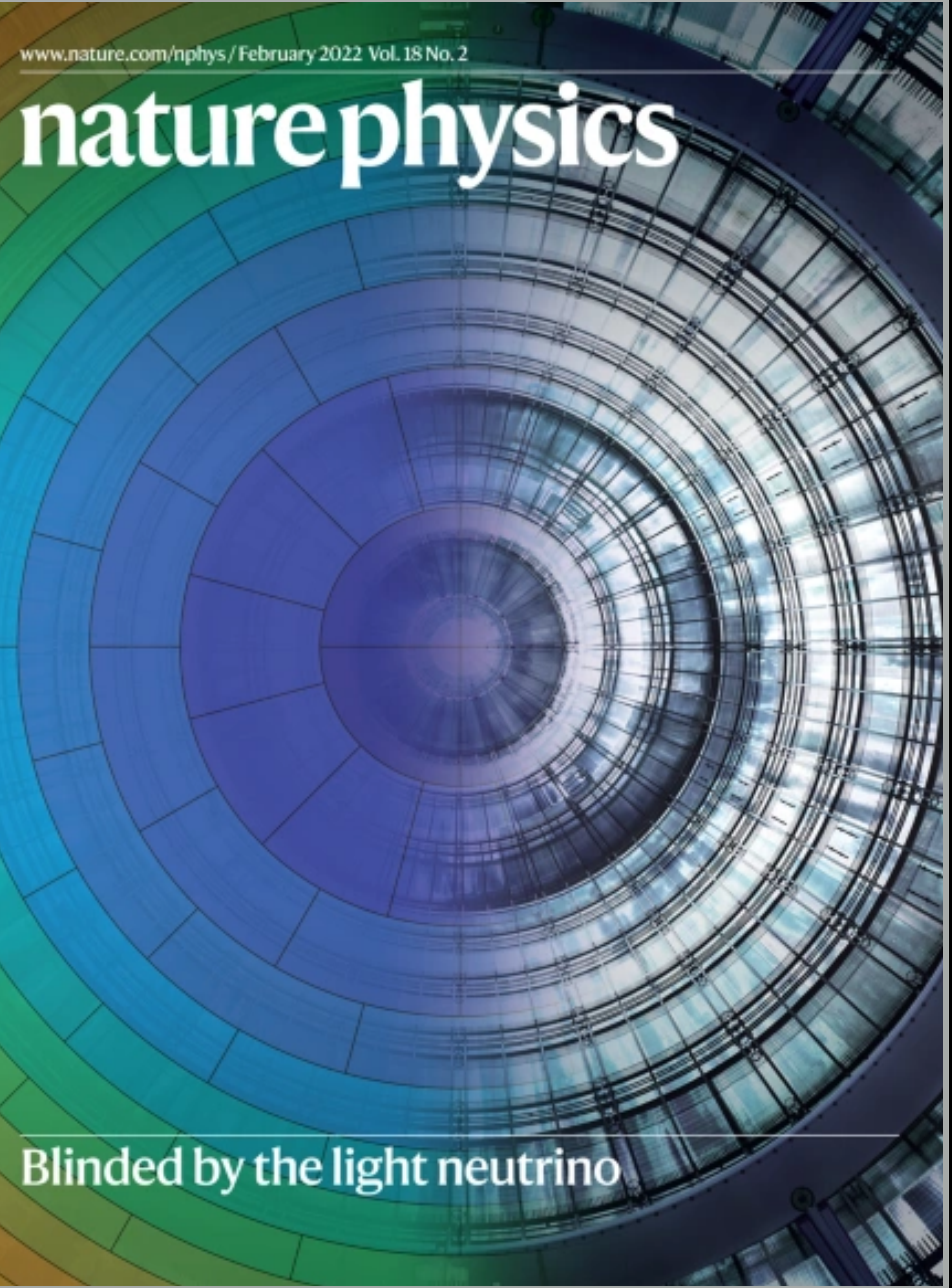


For the first time the eV scale is broken!



Limits (LT & FC)	$m_\beta < 0.8$ eV
Limits (Bayesian)	$m_\beta < 0.73$ eV





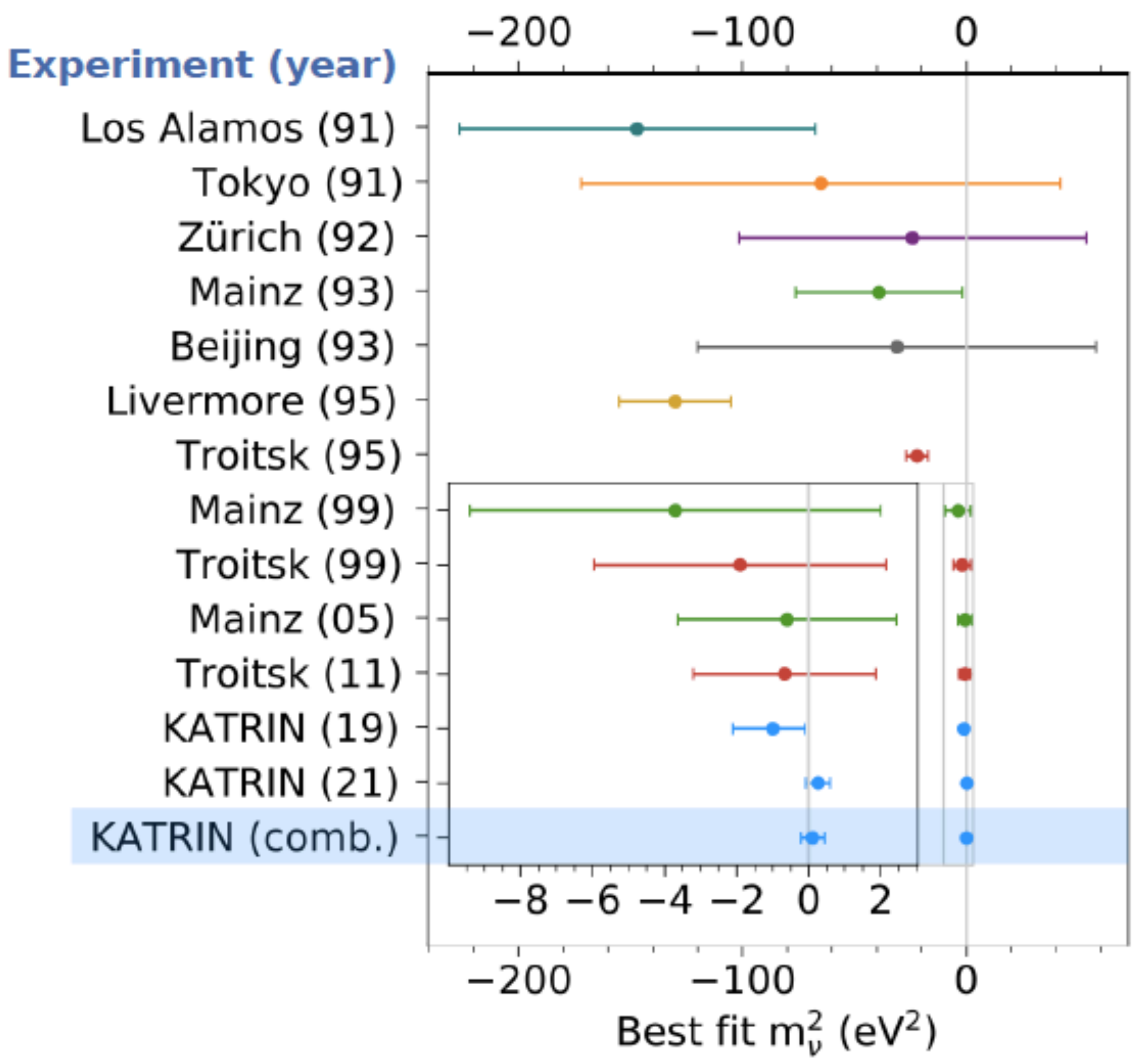
For the first

time

the eV

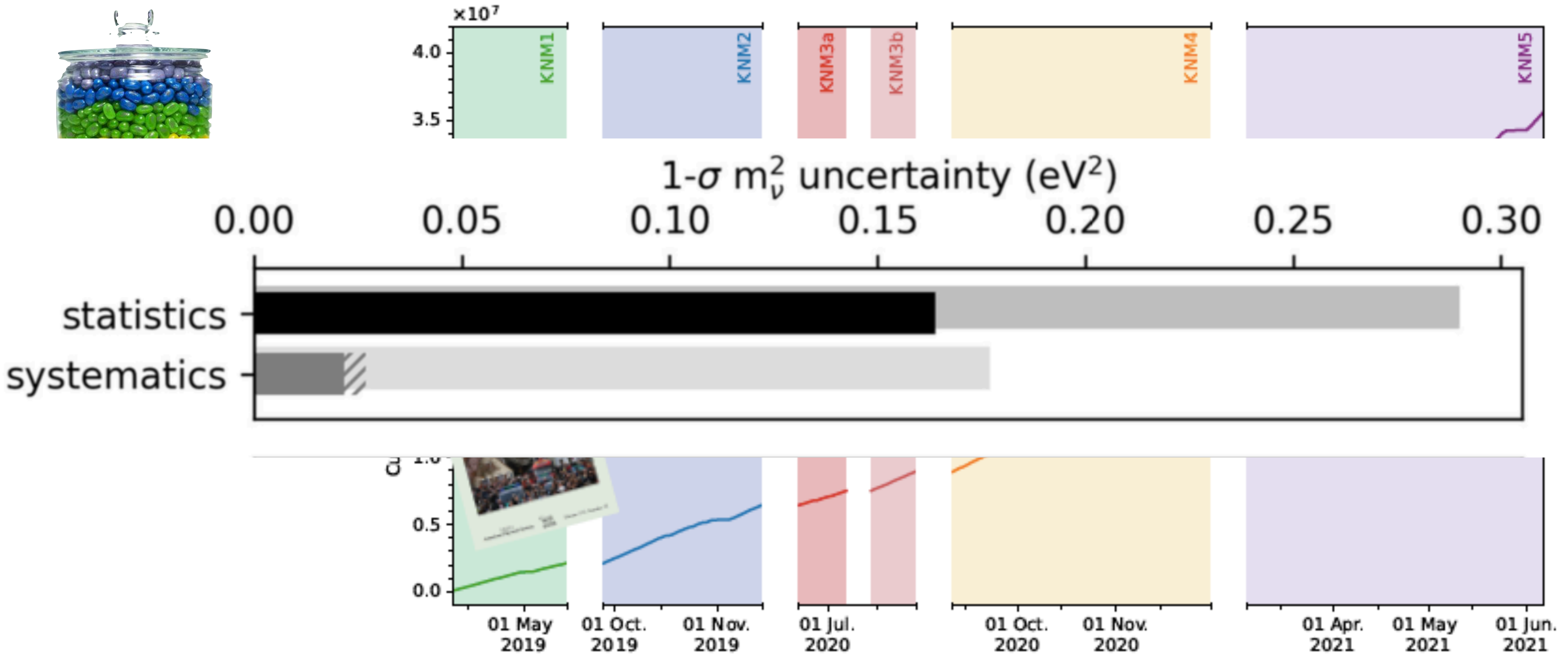
scale is

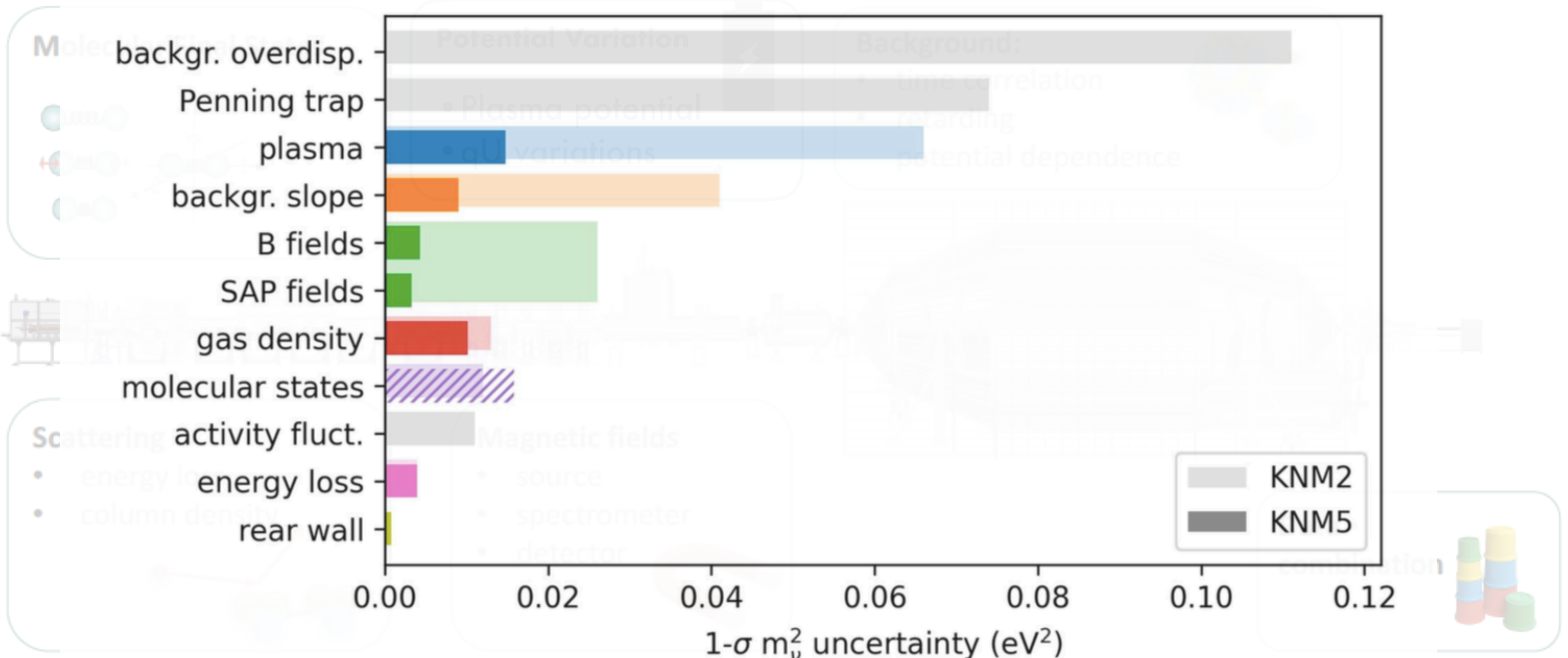
broken!



Systmatics and statistics continuously improving

Current collected sensitivity @ 500 meV/c²





Aim to reach a final limit of 200 meV/c²
(@90% C.L.)

Use photon spontaneous emission from electron in magnetic field.

Frequency-Based

(Cyclotron Radiation Emission Spectroscopy)

PROJECT 8

CASE WESTERN RESERVE UNIVERSITY
EST. 1826
think beyond the possible

CfA

JG|U

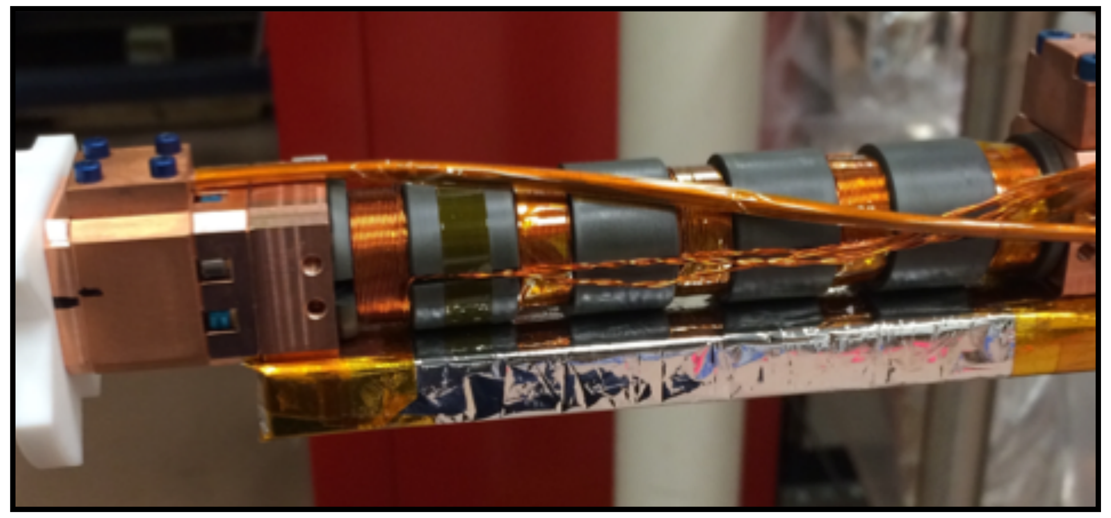
KIT
Karlsruher Institut für Technologie

Pacific Northwest
NATIONAL LABORATORY

UNIVERSITY OF WASHINGTON 1861

Yale

Cyclotron Radiation Emission Spectroscopy (CRES)



PROJECT 8

Frequency Approach

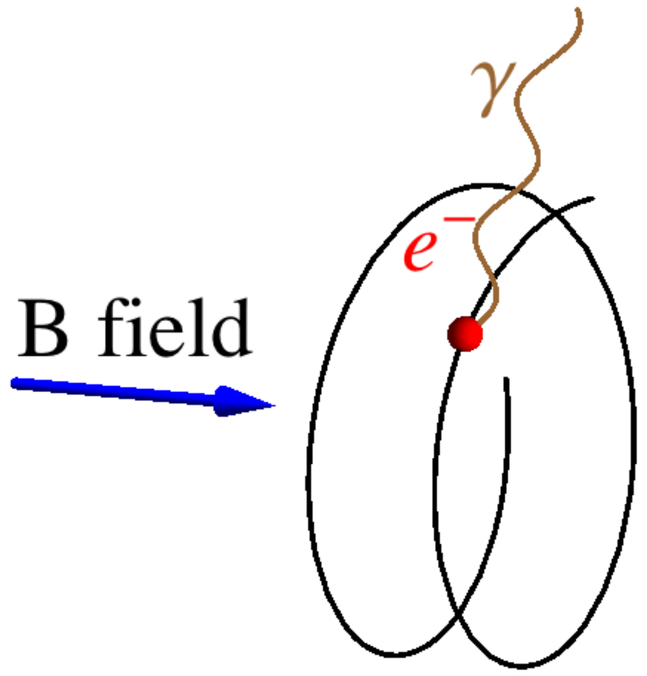
$$^{3}\mathrm{H} \rightarrow {}^{3}\mathrm{He}^{+} + e^{-} + \bar{\nu}_e$$

A. L. Schawlow

"Never measure anything but frequency."

O. Heaviside

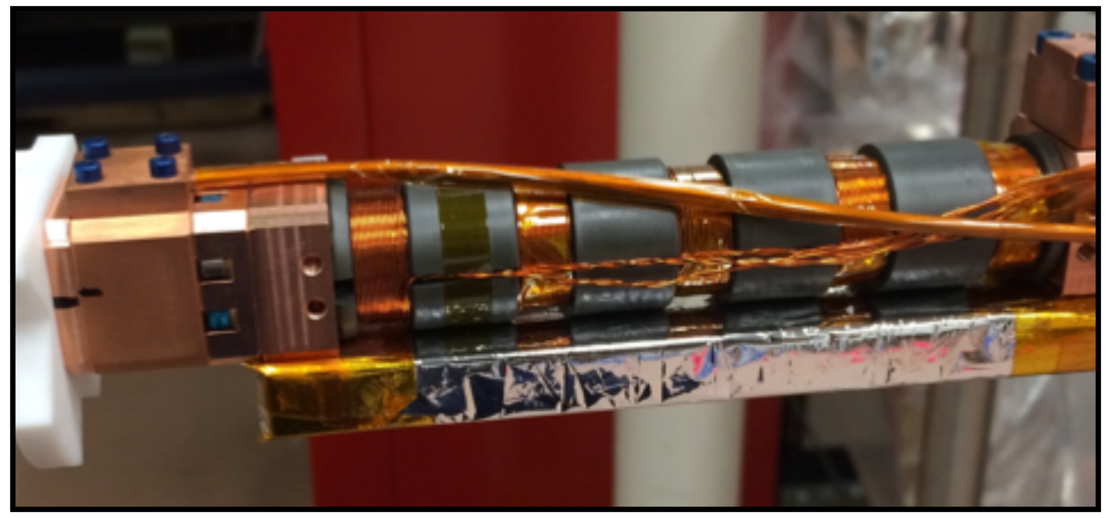
Measure the cyclotron radiation from a single electron



- Source transparent to microwave radiation
- No e- transport from source to detector
- Leverages precision inherent in frequency techniques

B. Monreal and JAF, Phys. Rev D80:051301

Cyclotron Radiation Emission Spectroscopy (CRES)

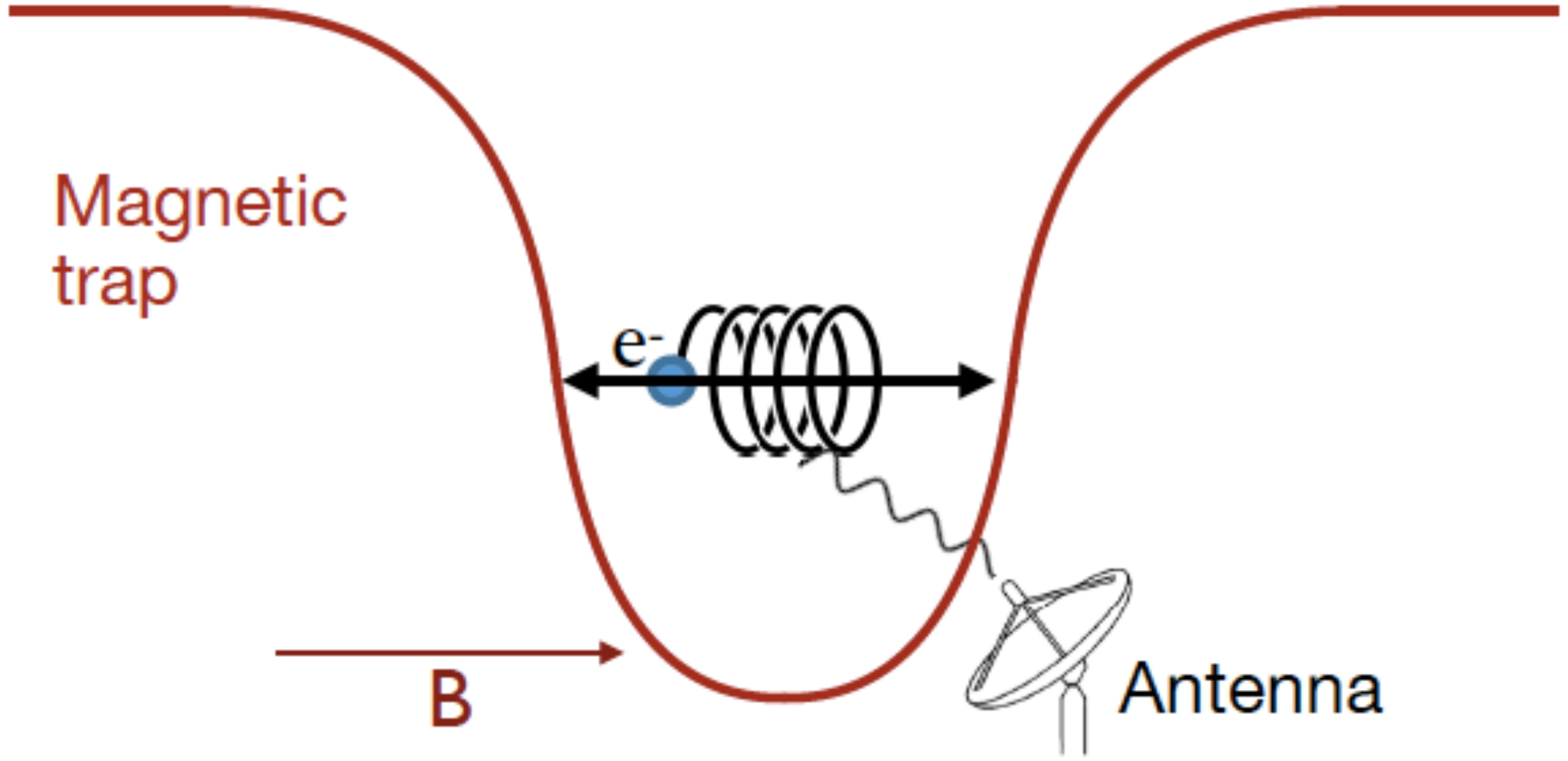


PROJECT 8

Frequency Approach

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

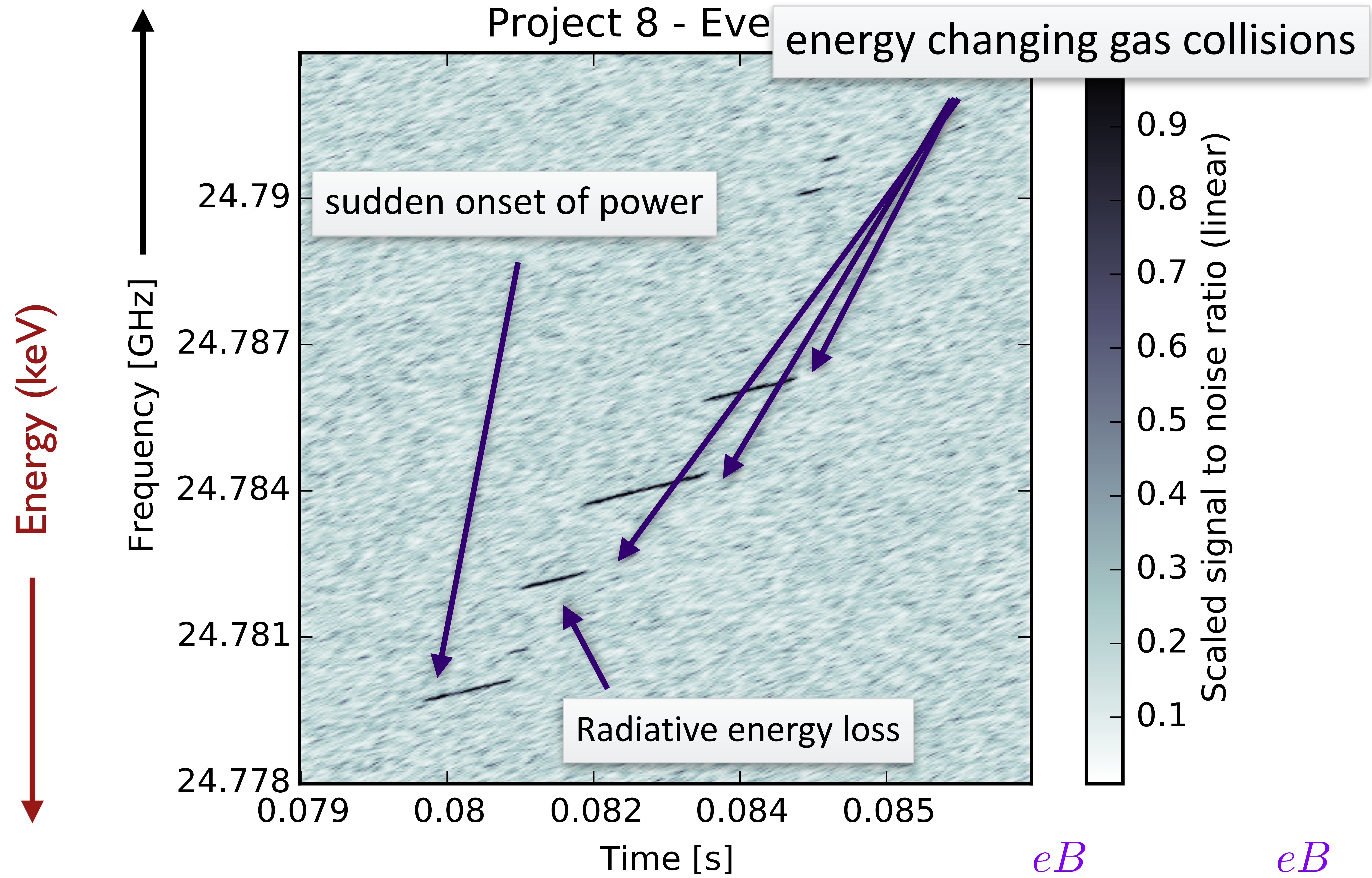
$$f_c = \frac{f_{c,0}}{\gamma} = \frac{1}{2\pi}\frac{eB}{m_e c^2 + E_{\mathrm{kin}}}$$



$$f_{c,0} = 27.992\ 491\ 10(6)\ \mathrm{GHz\ T}^{-1}$$

- *Narrow band region of interest (@26 GHz).*
- *Small, but detectable power emitted.*

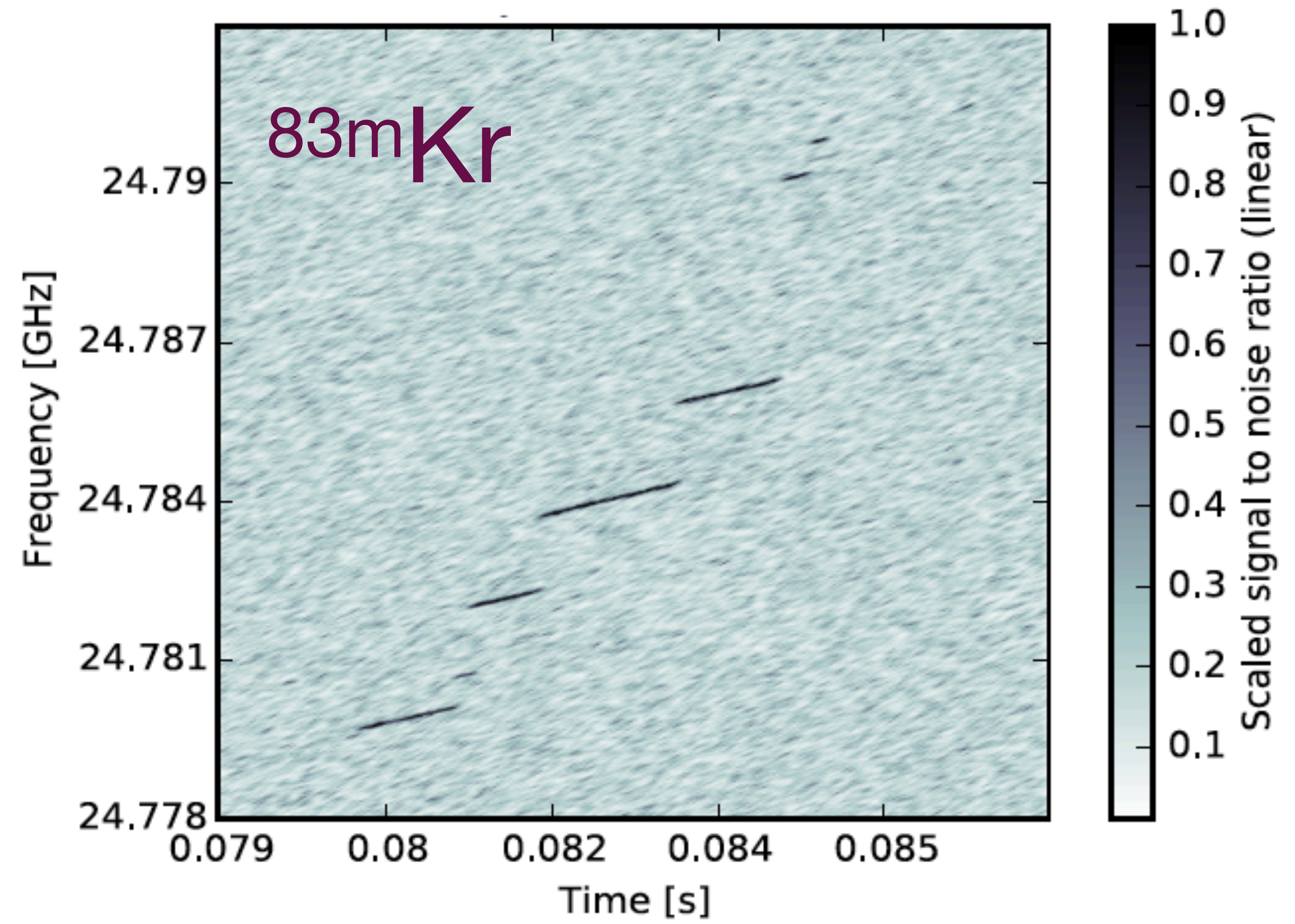
$$P\,(17.8\,\mathrm{keV}, 90^\circ, 1\,\mathrm{T}) = 1\,\mathrm{fW}$$
$$P\,(30.2\,\mathrm{keV}, 90^\circ, 1\,\mathrm{T}) = 1.7\,\mathrm{fW}$$



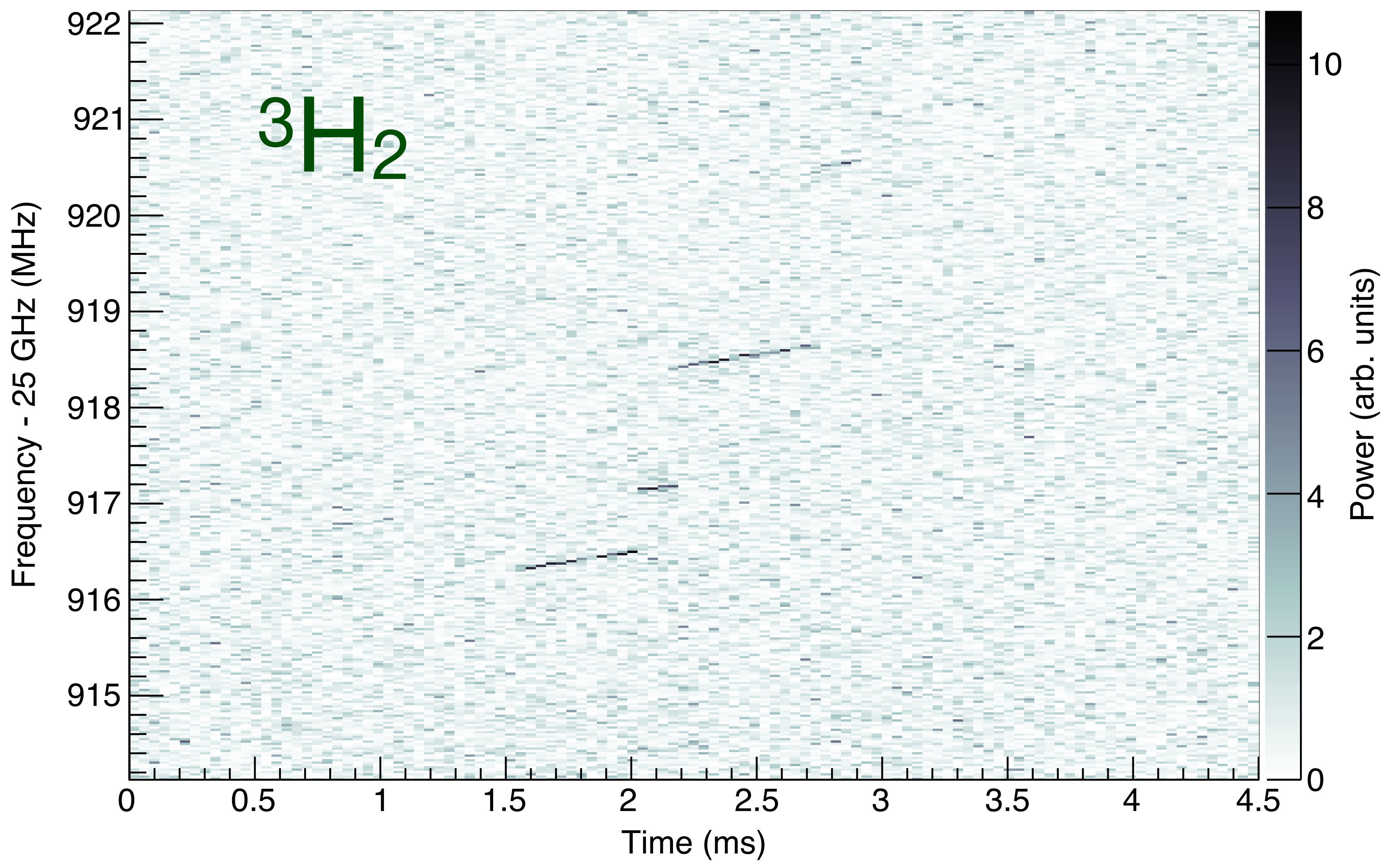
$$\omega = \frac{eB}{\gamma m_e} = \frac{eB}{m_e + K/c^2}$$

A "typical" event

(actually, this was our first event)

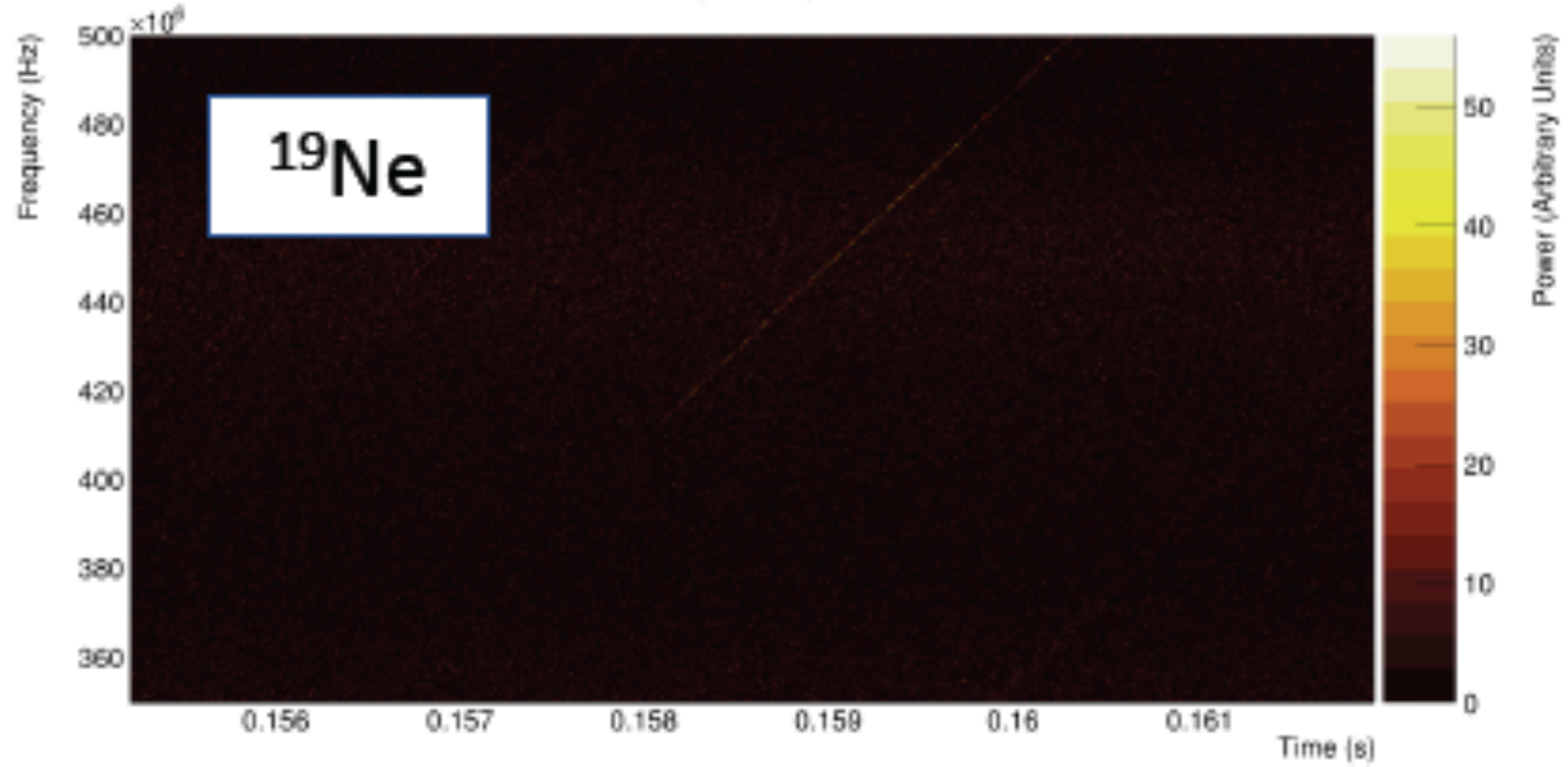


PROJECT 8

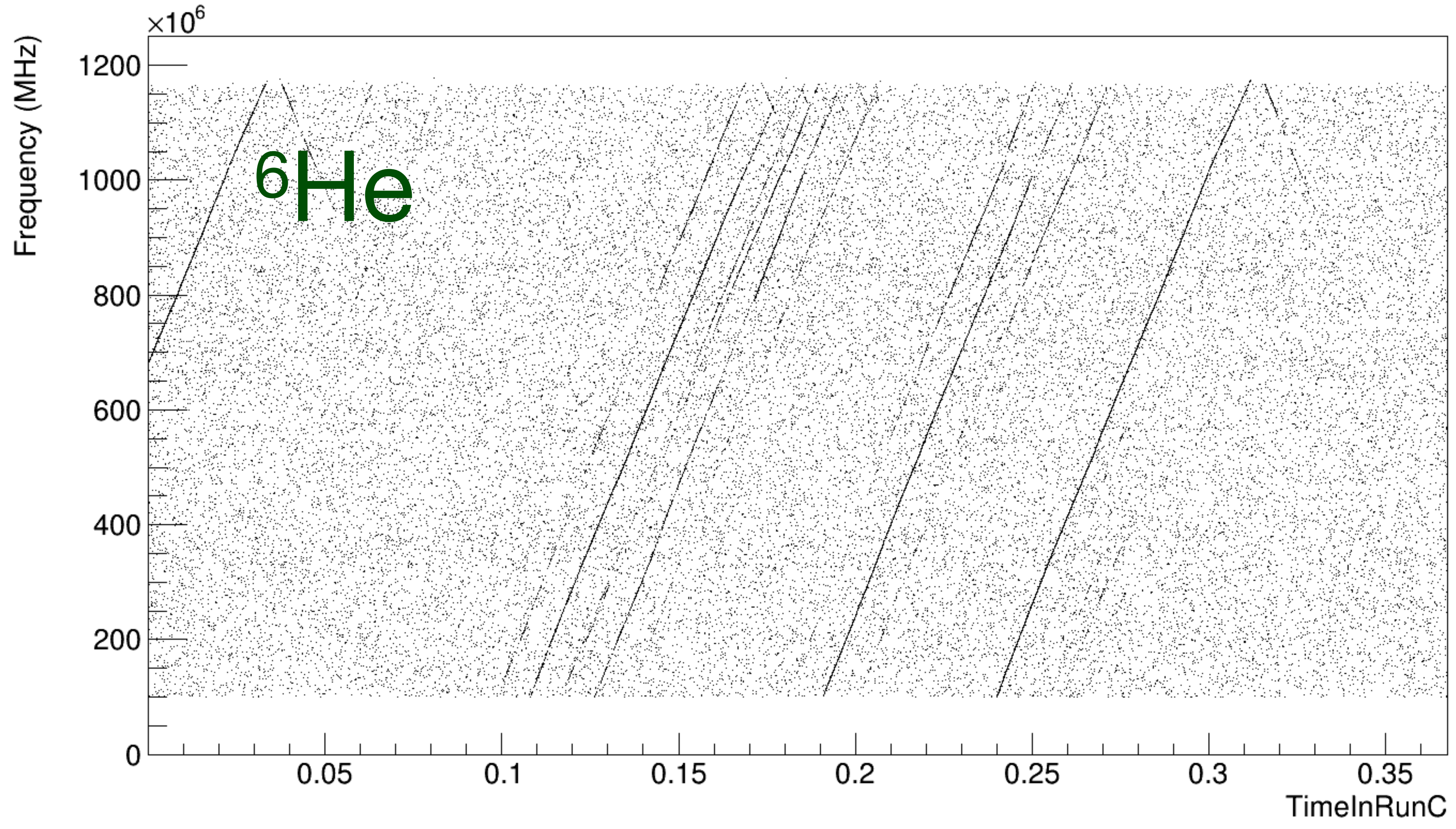


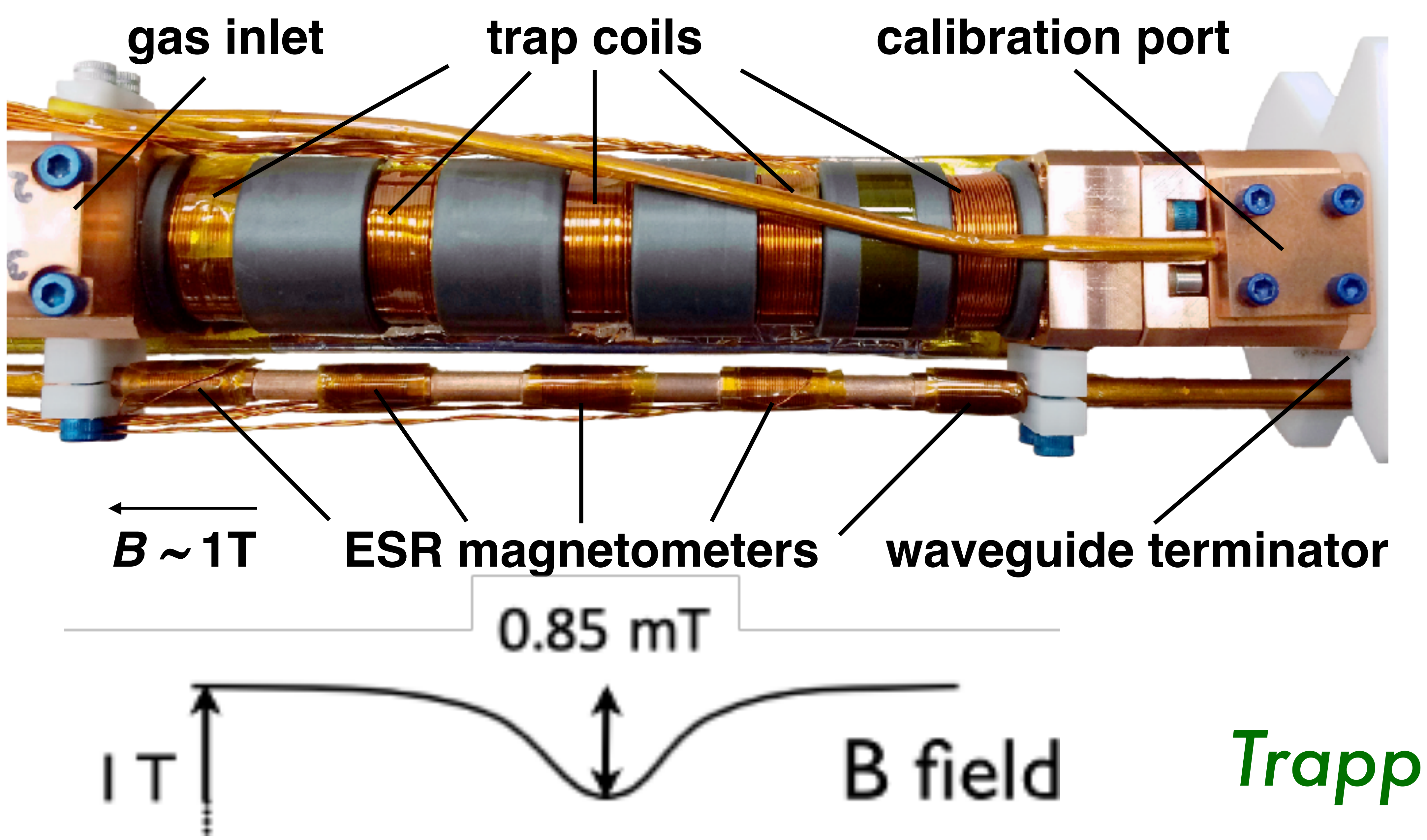
CRES technique now employed in other, new experiments.

Not alone anymore



6He-CRES





Phase II CRES waveguide insert

Trapping field

CRES waveguide insert focuses microwaves from cyclotron emission.

Small trapping field superimposed onto 1 T cyclotron field.

HEMT amplifier used to magnify signal (not shown)

Known K-line energy allows for magnetic field calibration.

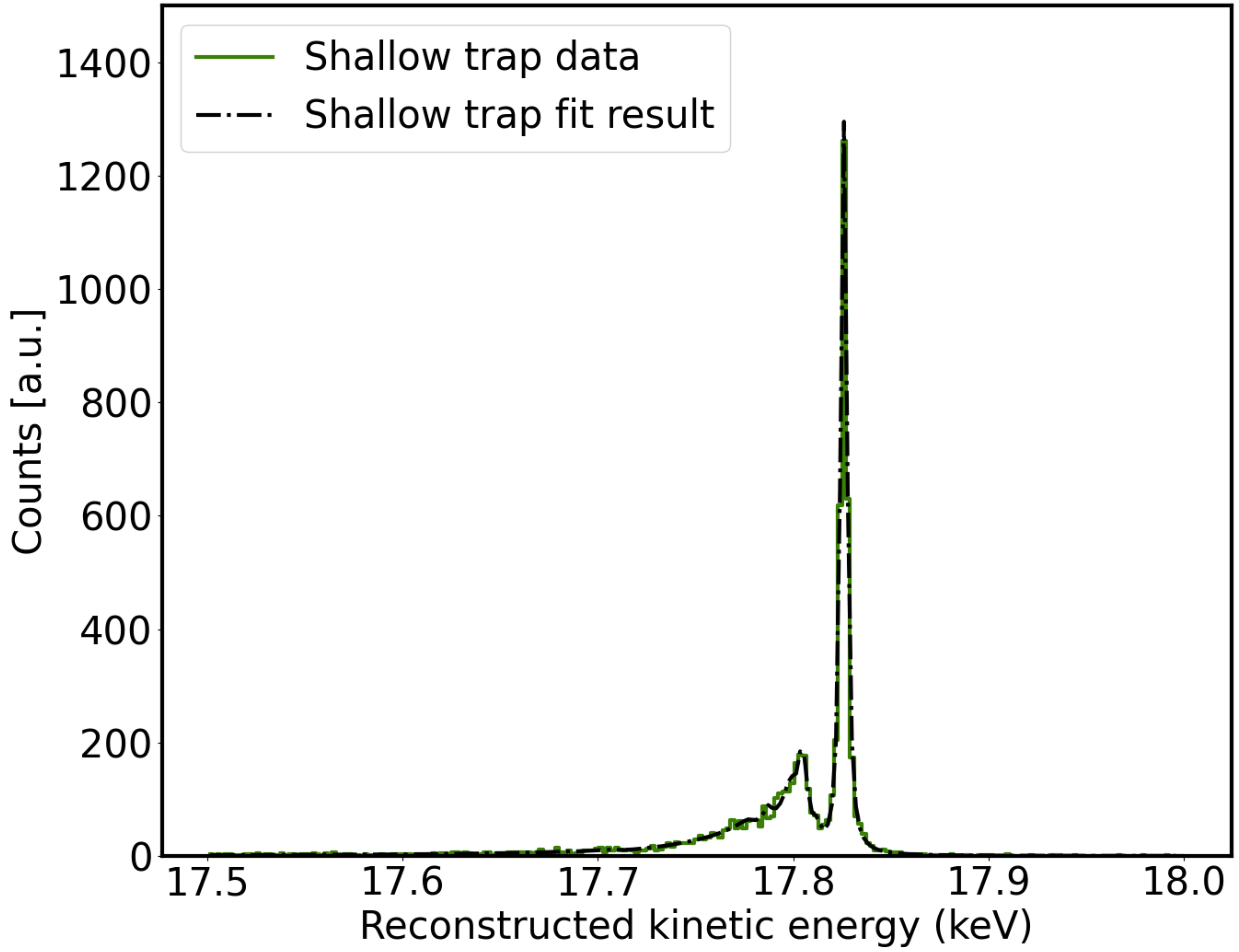
Instrumental Resolution (FWHM)	Natural Line Width (FWHM)
1.66 ± 0.19 eV	2.77 ± 0.1 eV

Satellite peaks from shake-up/ shake-off and scattering from residual gas visible.

Detected line shape well-described by model.

K-Shell line from ^{83m}Kr

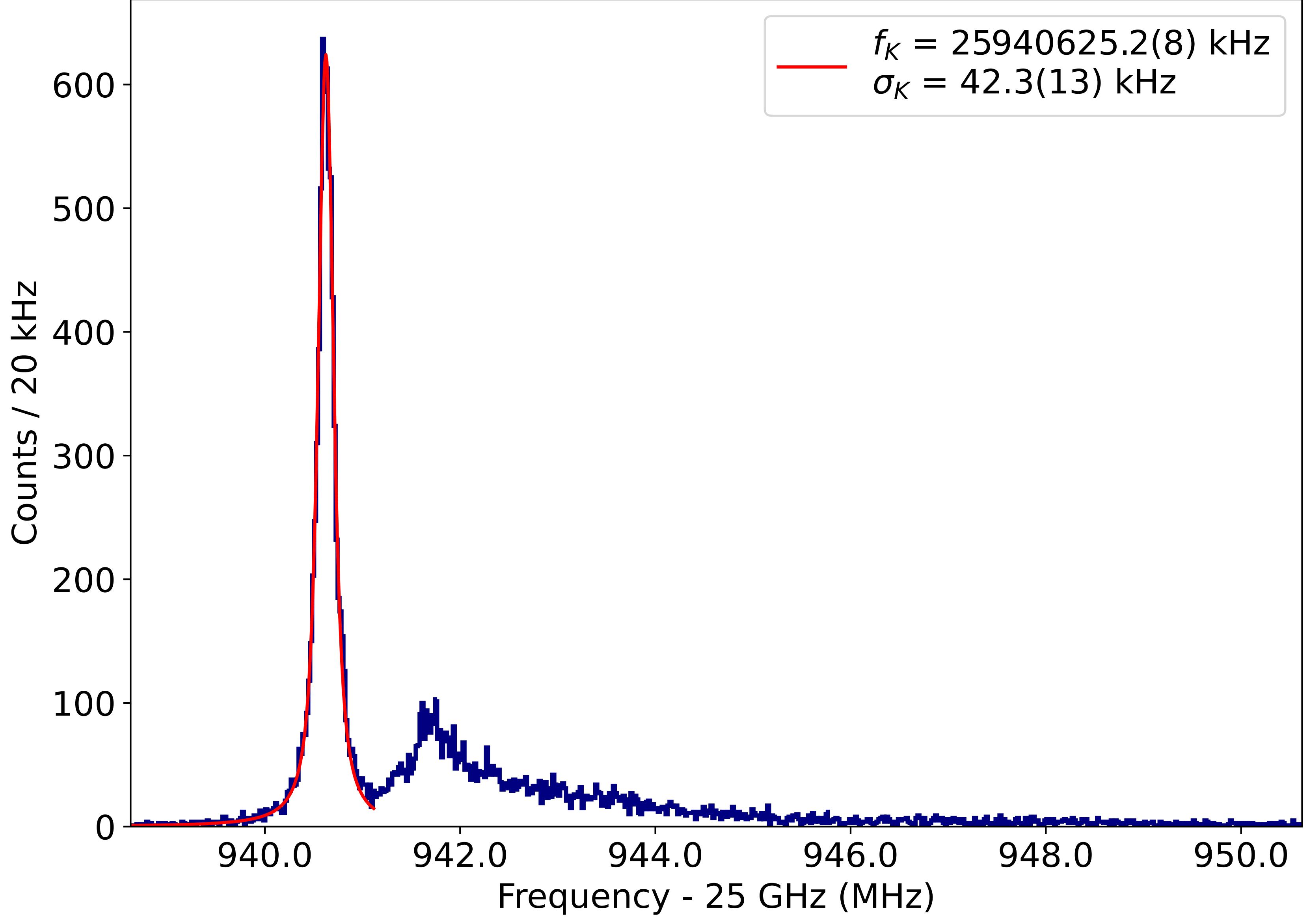
(Shallow trap calibration)



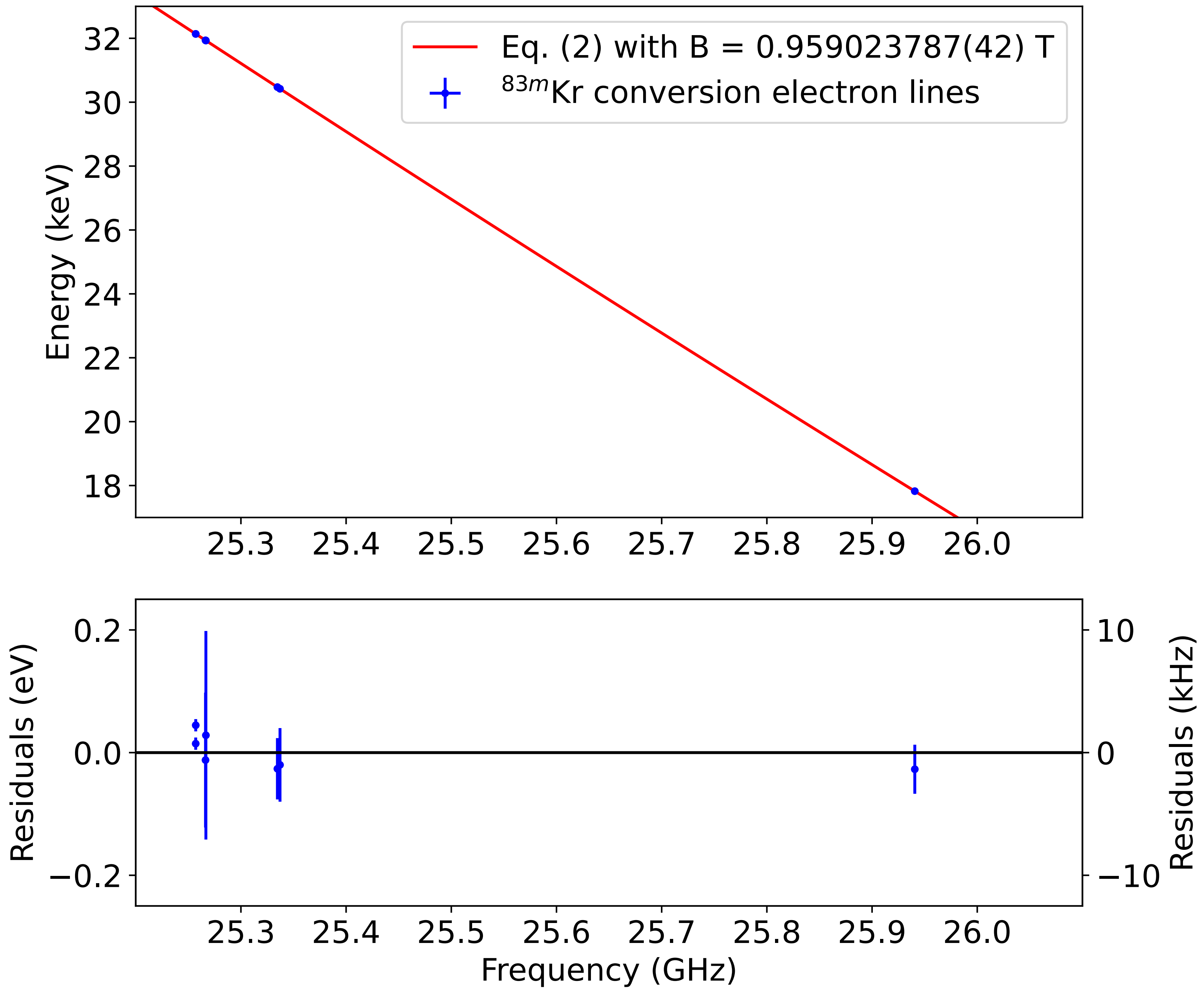
By using all visible conversion lines, it is also possible to extract energy linearity of CRES technique.

Linearity tested across 14 keV of energy, with excellent linearity.

L-conversion lines from ^{83m}Kr



Linearity extraction from shallow ^{83m}Kr data



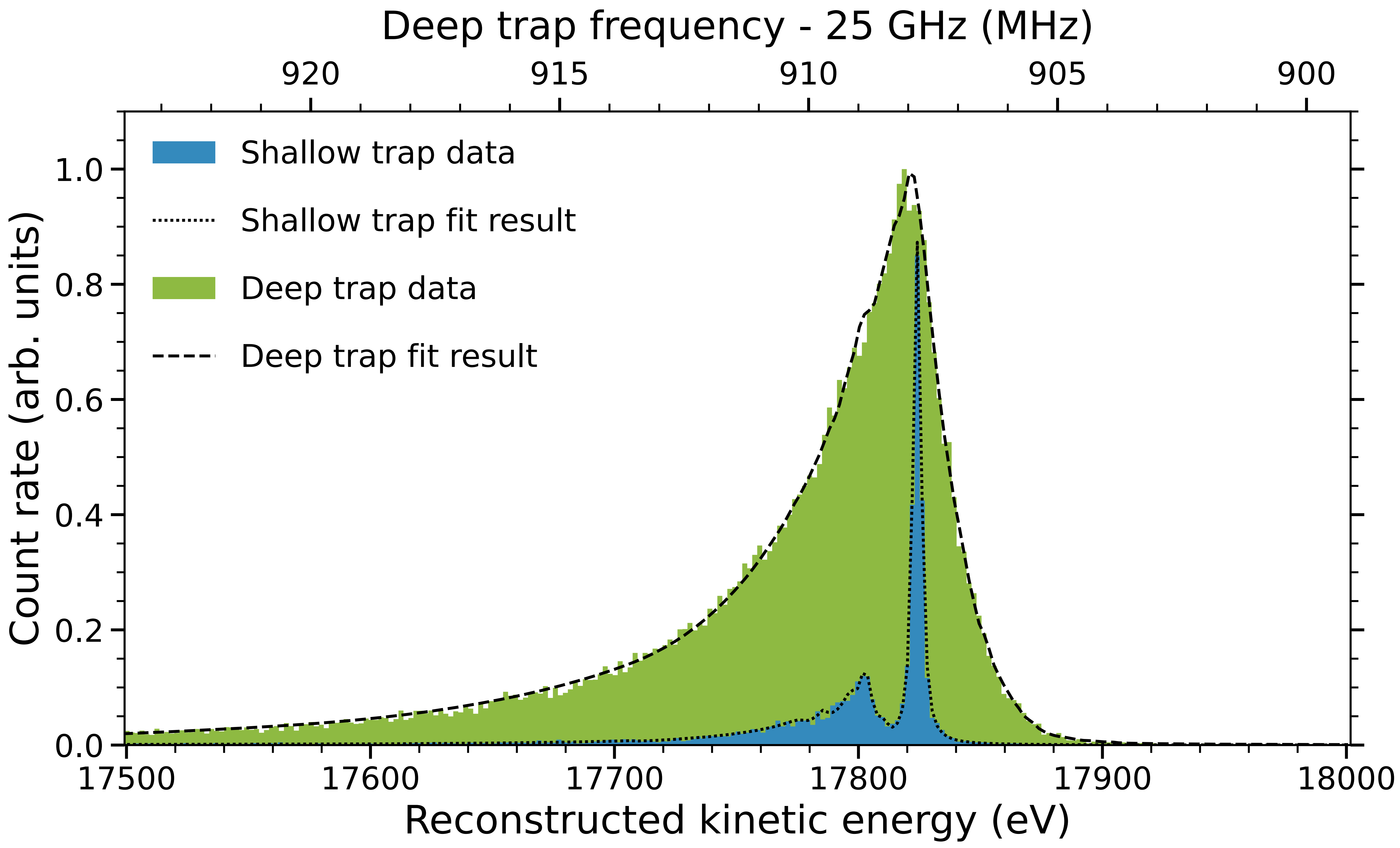
To gain better statistics during tritium running, we switch the magnetic field configuration to trap more electrons

(Deep trap configuration)

Deeper tracks introduce magnetic field inhomogeneity, inelastic gas scattering and missed tracks.

Effects are well understood and properly modeled.

Shallow & Deep Trap Response Function



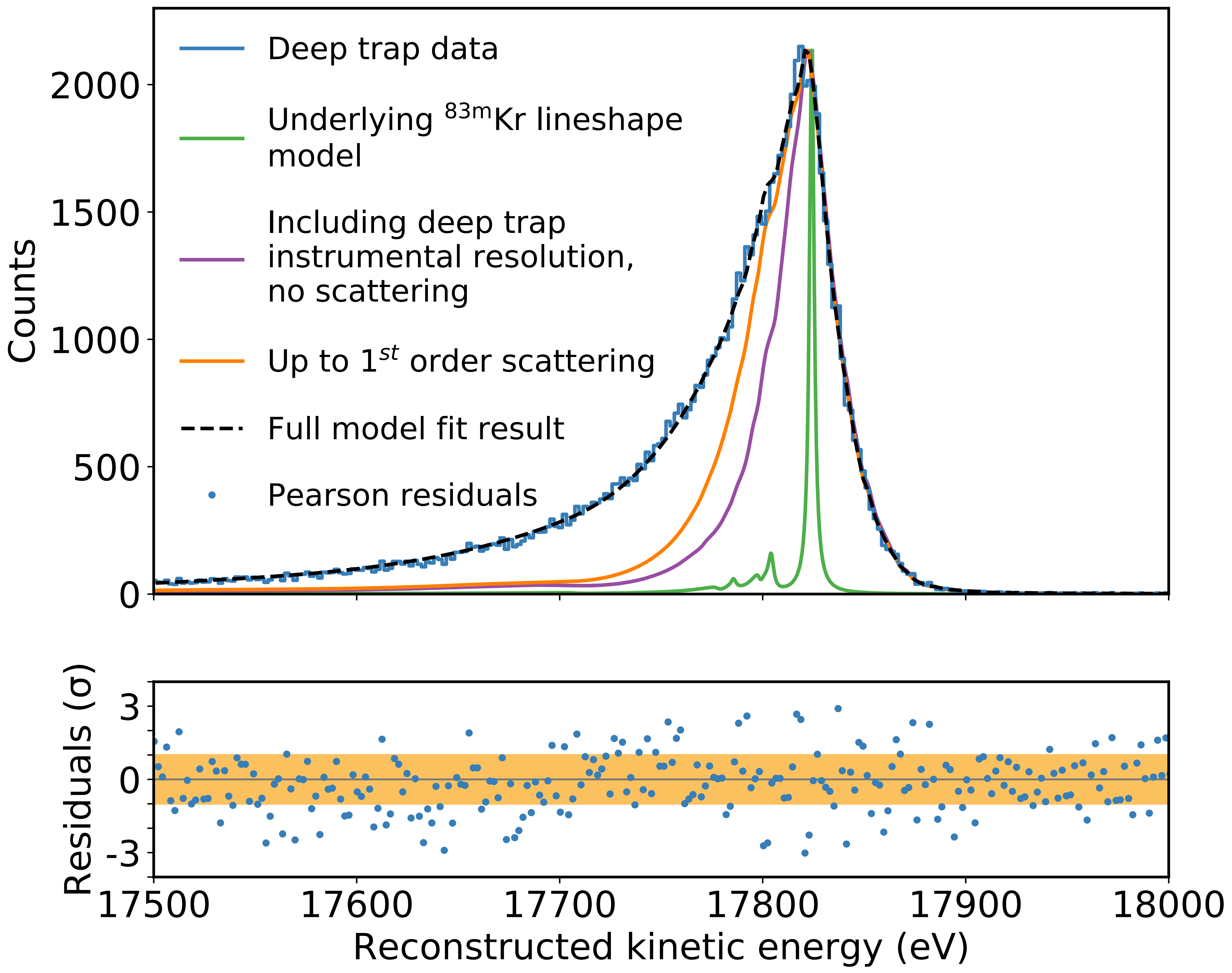
To gain better statistics during tritium running, we switch the magnetic field configuration to trap more electrons

(Deep trap configuration)

Deeper tracks introduce magnetic field inhomogeneity, inelastic gas scattering and missed tracks.

Effects are well understood and properly modeled.

Shallow & Deep Trap Response Function



Systematics

Mainly dominated by statistical uncertainties.

Other uncertainties constrained by shallow-trap calibration and CRES electron data.

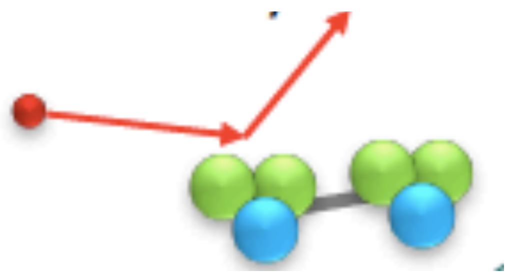
Statistics: *± 17 eV*

Total Systematics: *± 9 eV*

Statistics

± 17 eV

Scattering

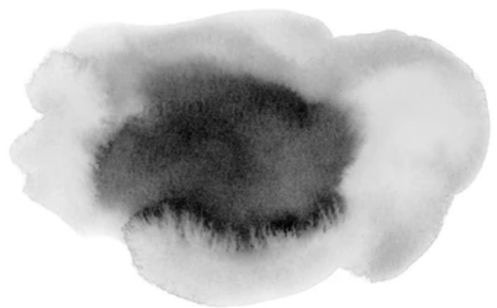


± 6 eV

Frequency & Efficiency

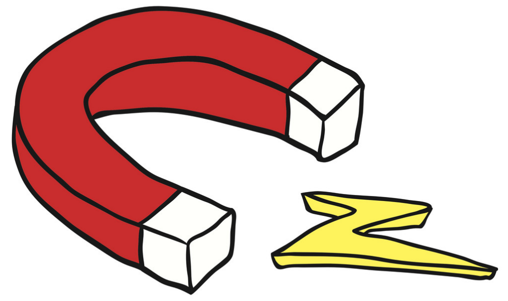
± 7 eV

Magnetic broadening



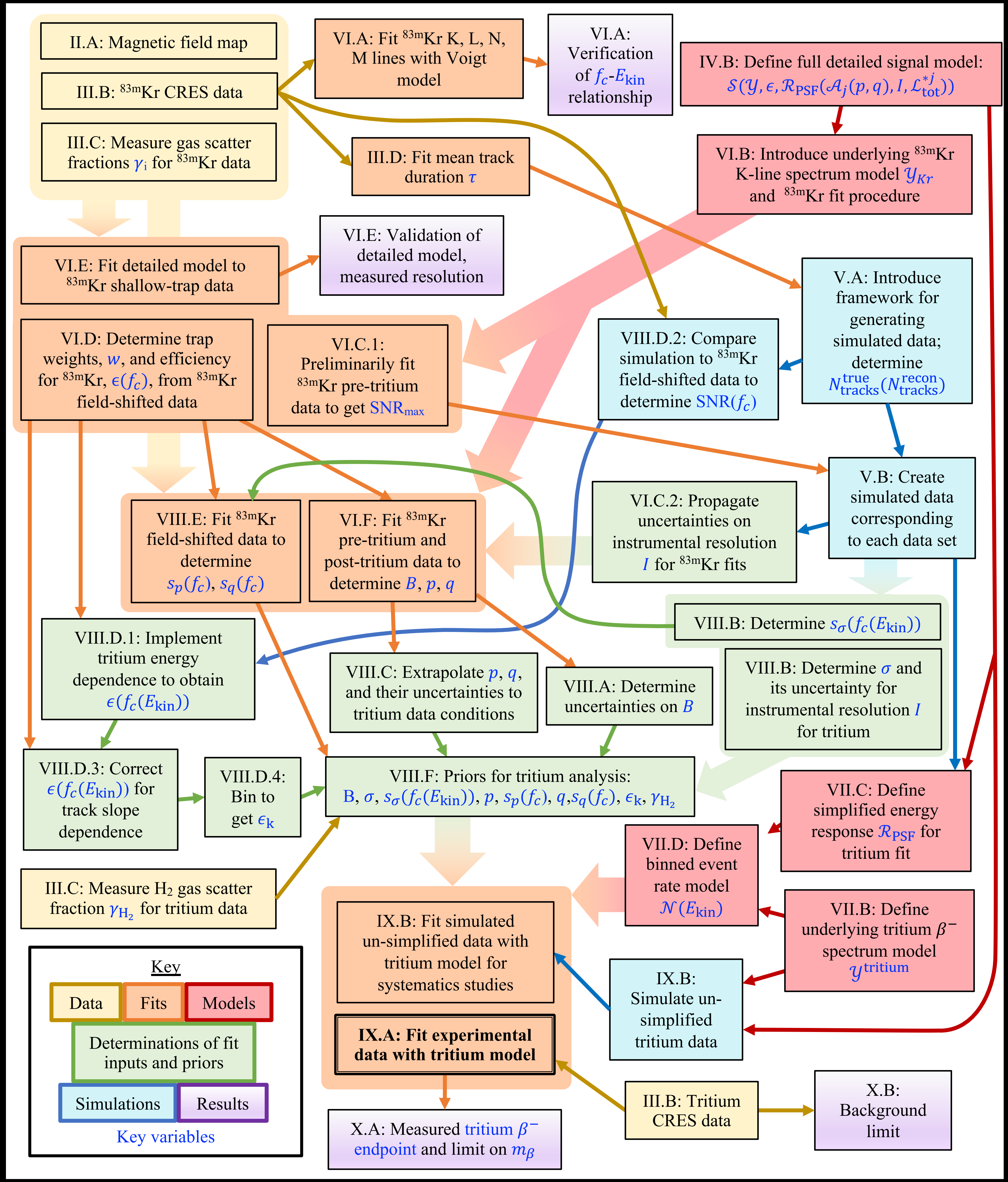
± 4 eV

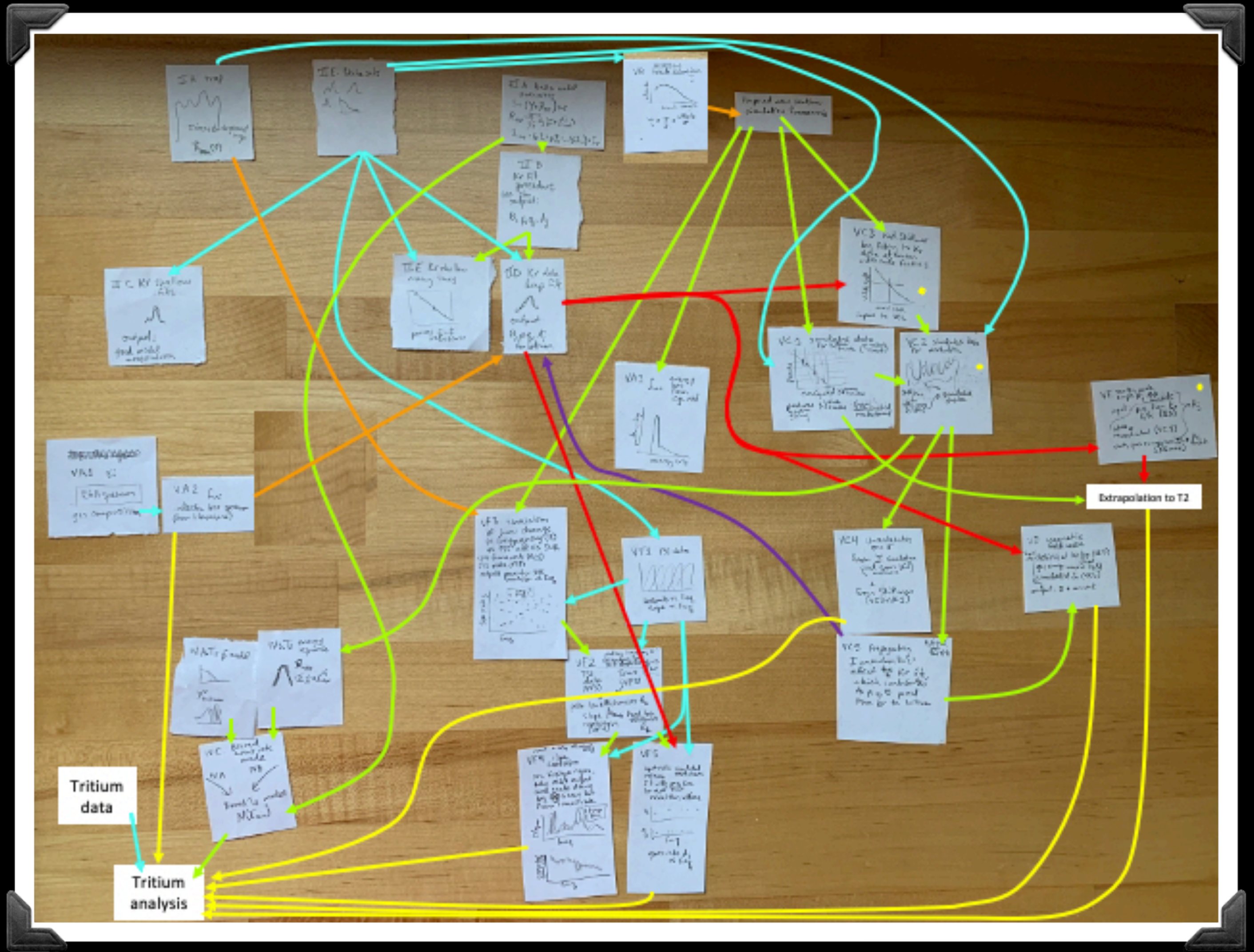
Magnetic Field



± 4 eV

Uncertainties quoted on endpoint measurement.





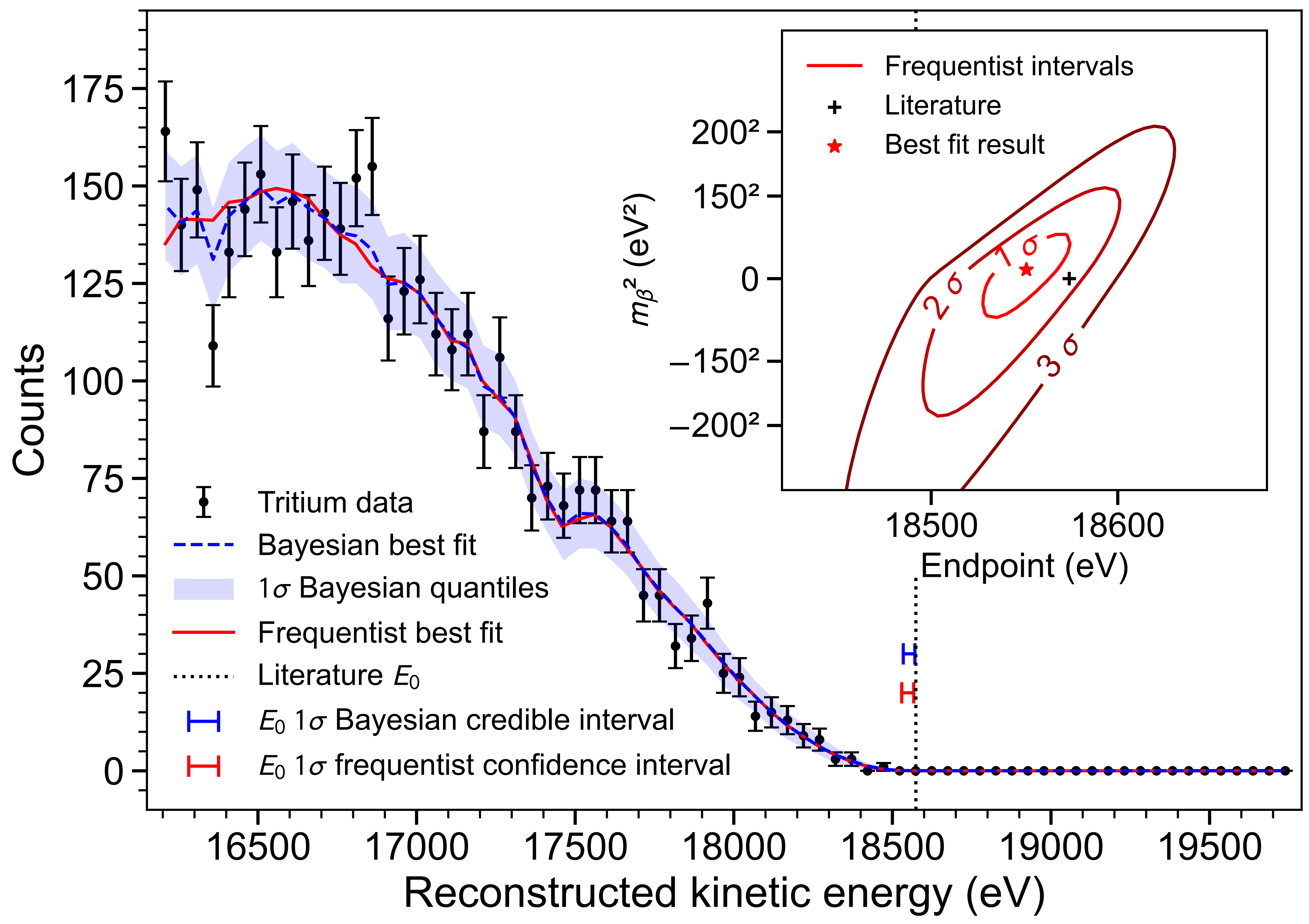
Not a Straightforward Analysis...

Phase II Results

For more info, see...
arXiv 2212.05048 (submitted to PRL)
arXiv 2303.12055 (submitted to PRC)

Phase II CRES instrument provides 1mm³ volume inside waveguide. Total of 3770 events observed over 82 days of data taking.

First endpoint CRES measurement conducted with no observed background in 81 days of data taking.



First CRES Mass Limit

	Bayesian	Frequentist	Unit
Endpoint	18553^{+18}_{-19}	18548^{+19}_{-19}	eV
m_β	57^{+61}_{-39}		eV
90% C.L.	$m_\beta < 155$	$m_\beta < 152$	eV
Background	$< 3 \times 10^{-10}$		events/eV/s

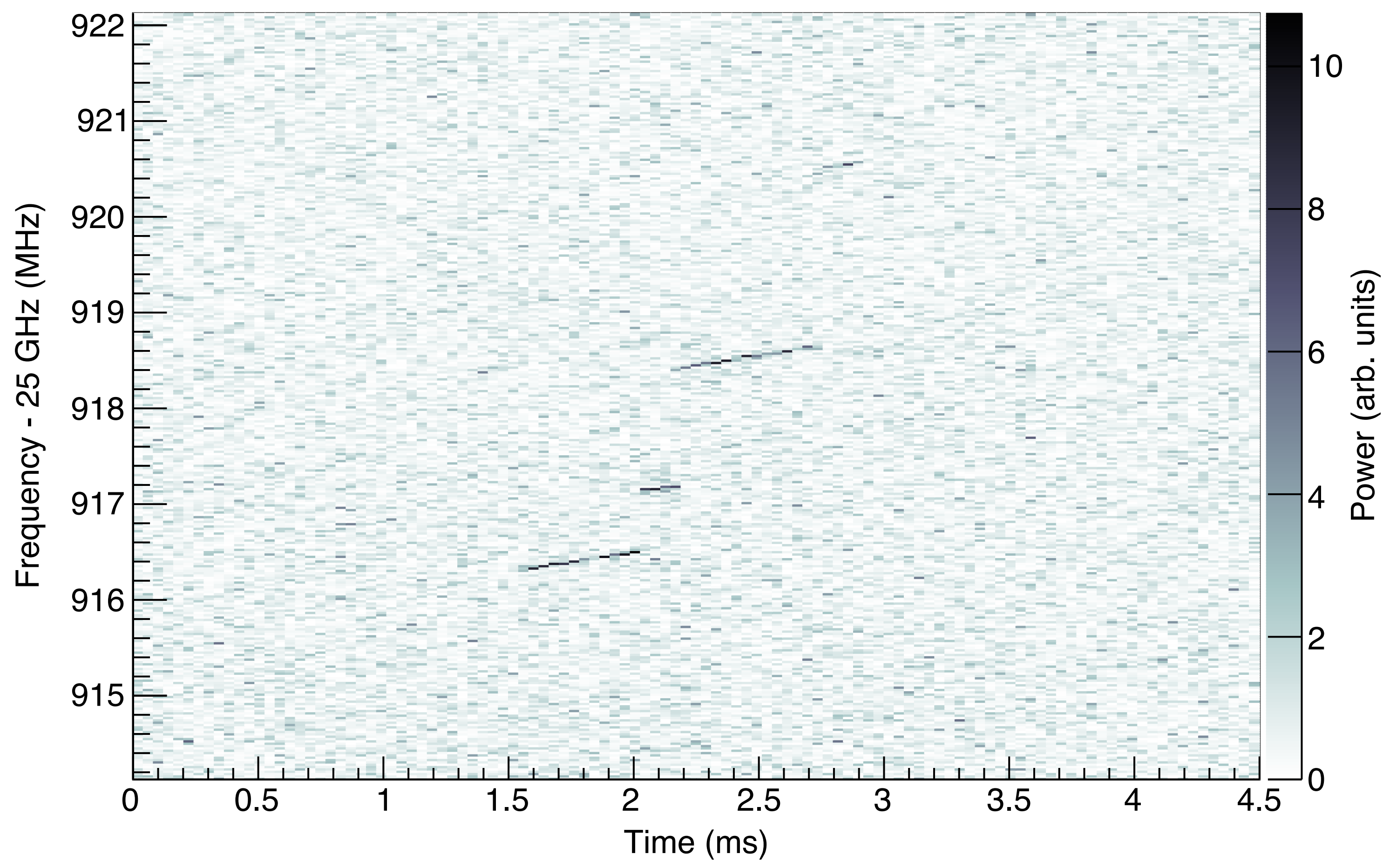
Phase II Result Summary

Goals for Phase II now achieved.

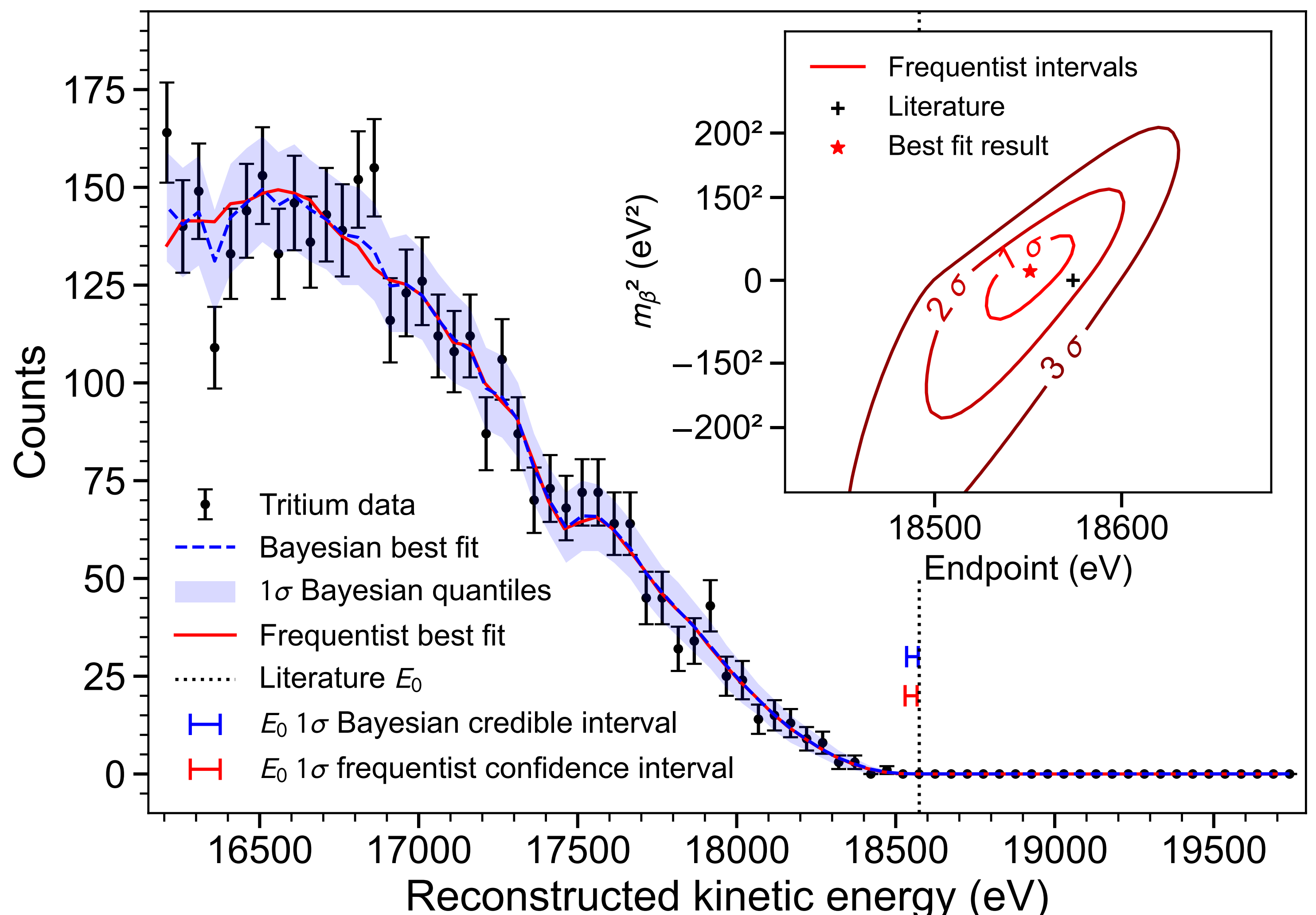
We plan to use what we have learned in Phase II to expand our sensitivity.

- *First tritium spectroscopy using CRES* ✔
- *First neutrino mass limit using CRES* ✔
- *Demonstration of high energy resolution* ✔
- *Demonstration of a zero background experiment* ✔
- *Demonstration of control of systematic effects* ✔

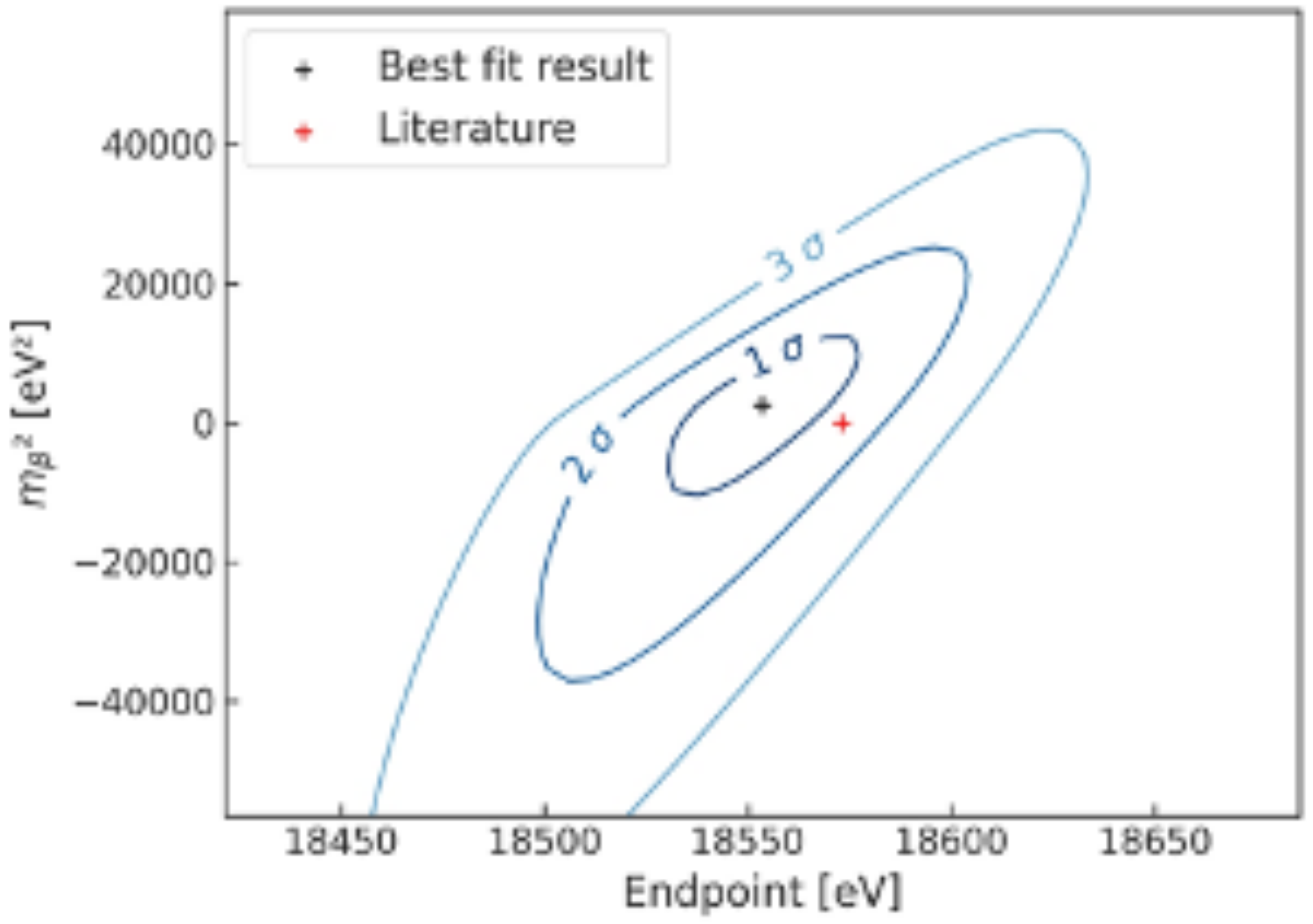
First CRES Tritium Event

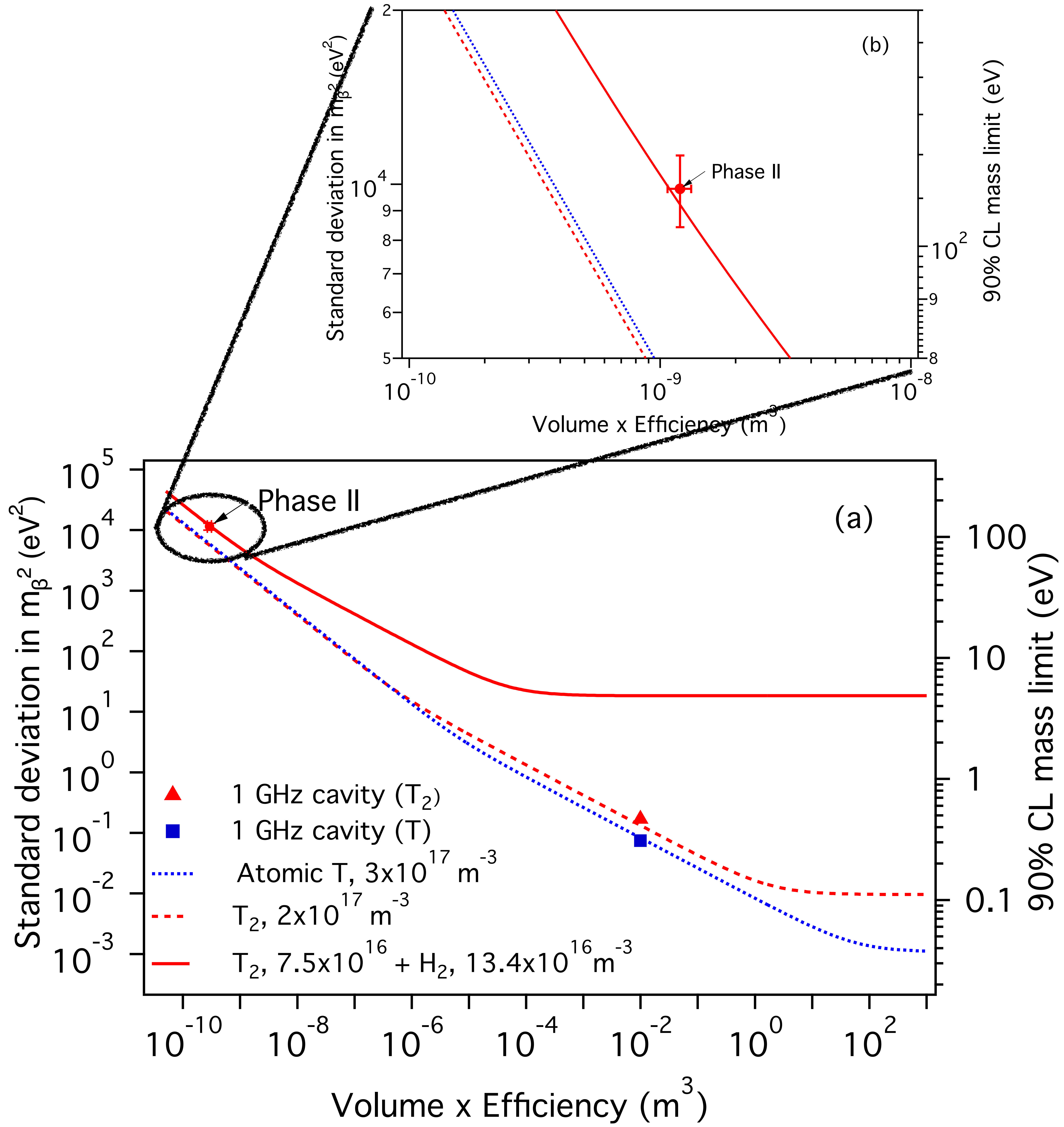


First CRES Tritium Spectrum



First CRES Mass Limit



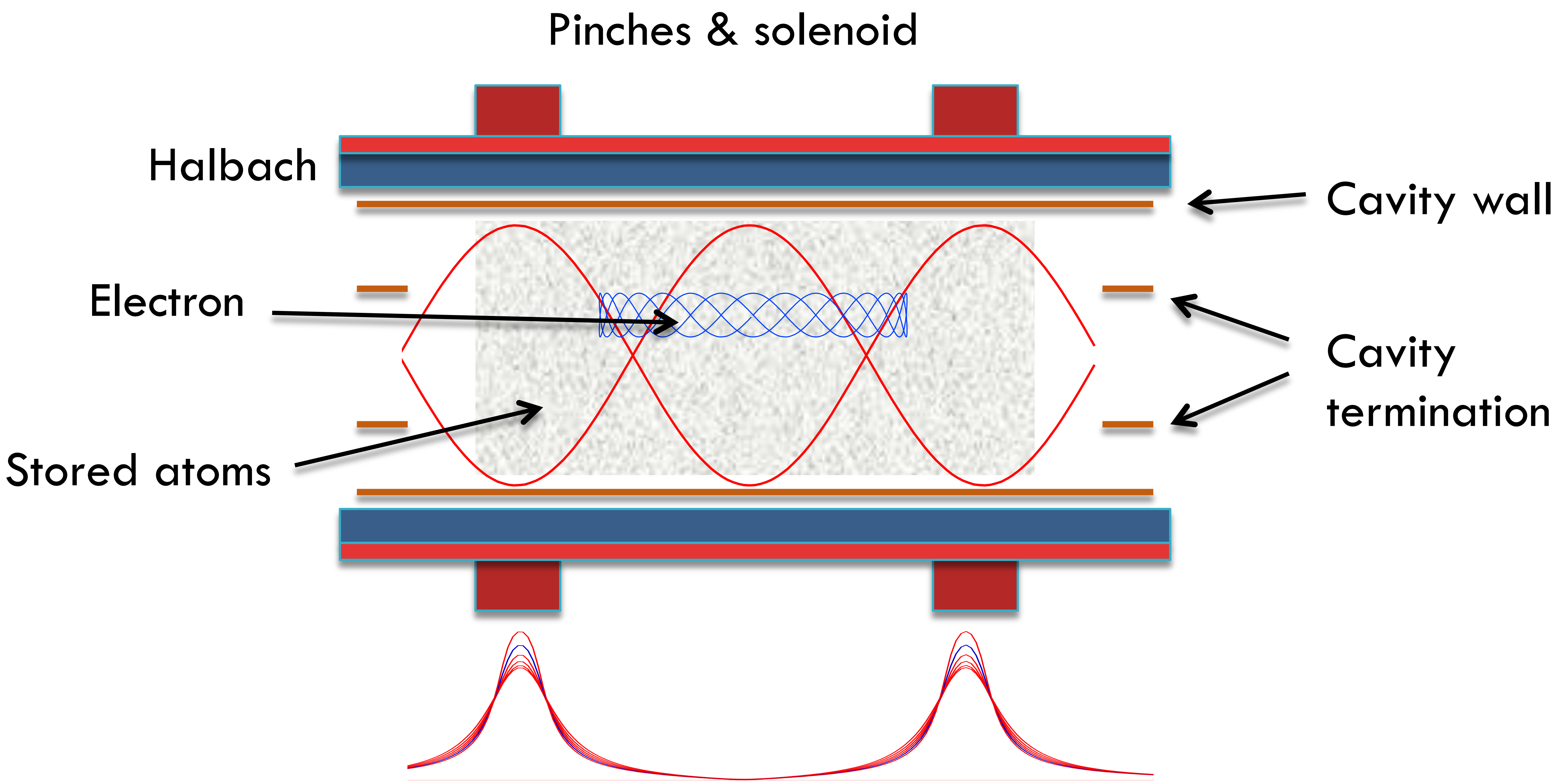


Our Phase II limit agrees well with our projected sensitivity model.

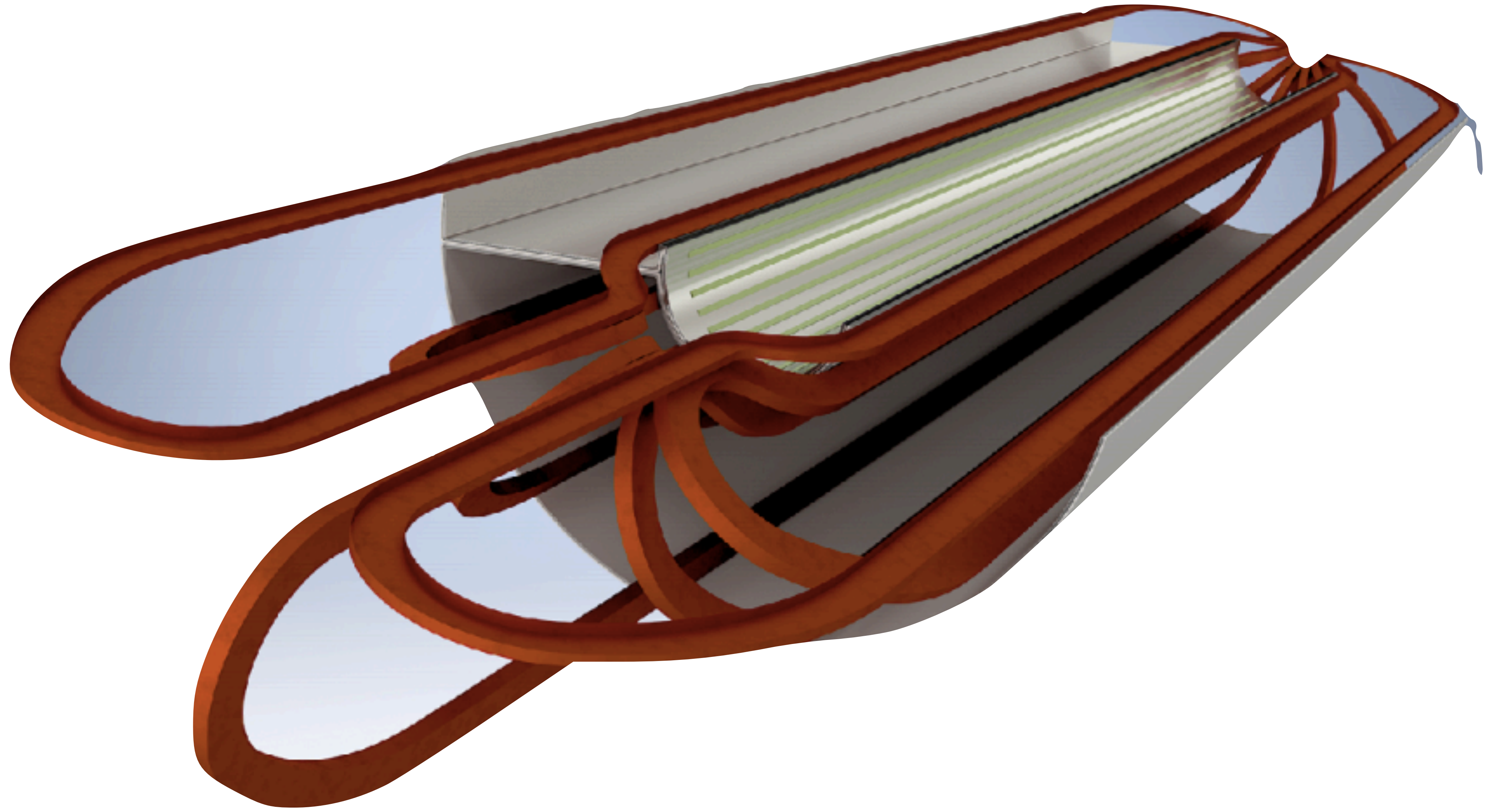
For Phase III, we will need to retain (and improve) our energy resolution while increasing our fiducial volume.

In addition, we will need to continue to control our systematics.

Large Volume CRES Demonstrator

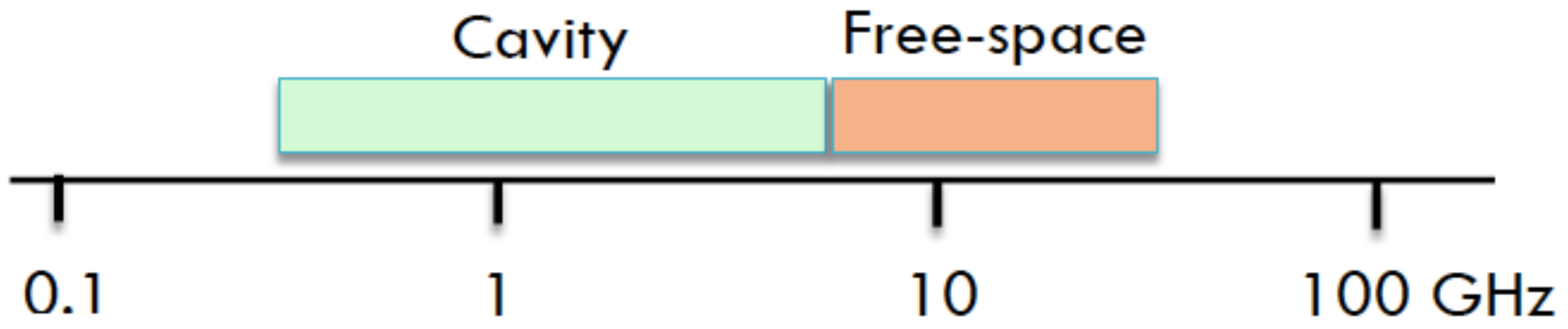


Atomic Trap Demonstrator

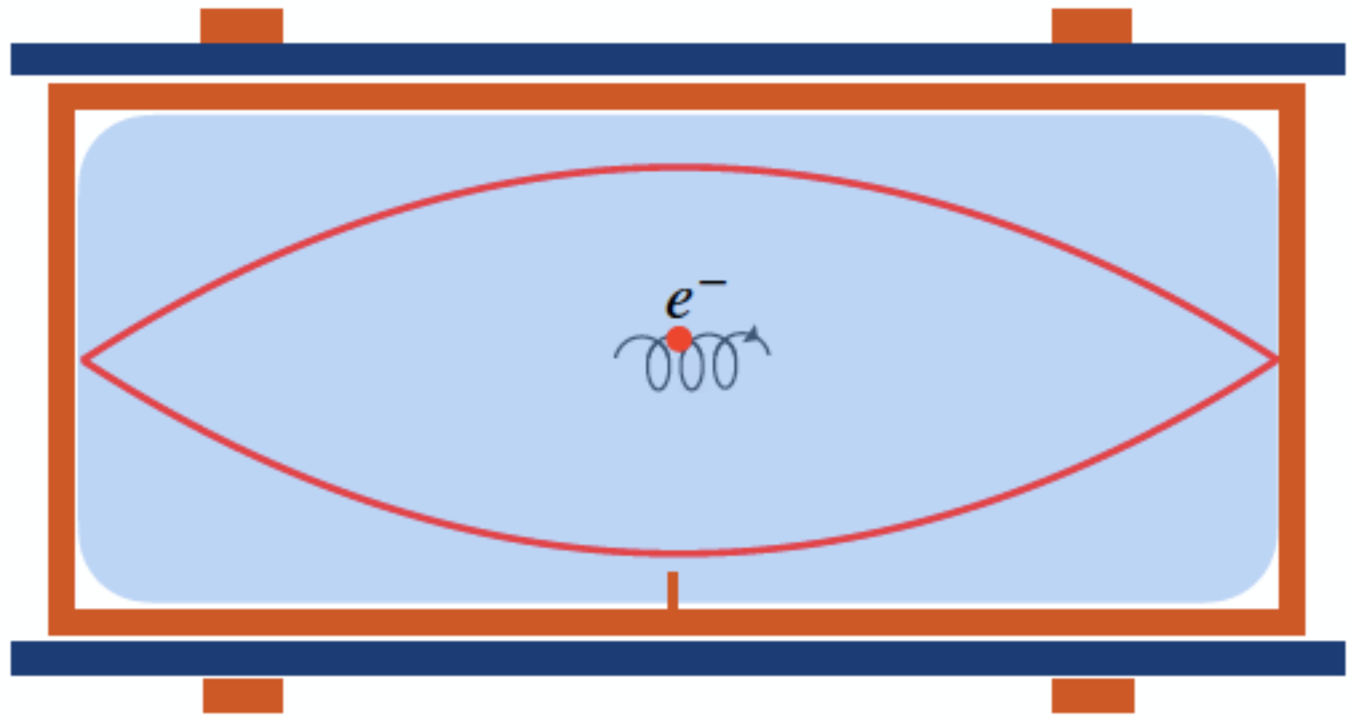


Two main R&D efforts underway:
a large volume (cavity) CRES demonstrator
and an atomic trap demonstrator.

Both intended to tackle statical limitations of CRES thus far, and remove systematic uncertainties induced from using molecular tritium sources.



CRES Cavity



- *Optional for low frequency operation.*
- *High electron coupling, high SNR.*
- *Reduced frequency modulation.*
- *High volume and trapping efficiency.*
- *Position reconstruction unknown.*

Phase II Waveguide

Vol ~1 mm^3, Q ~ O(few)

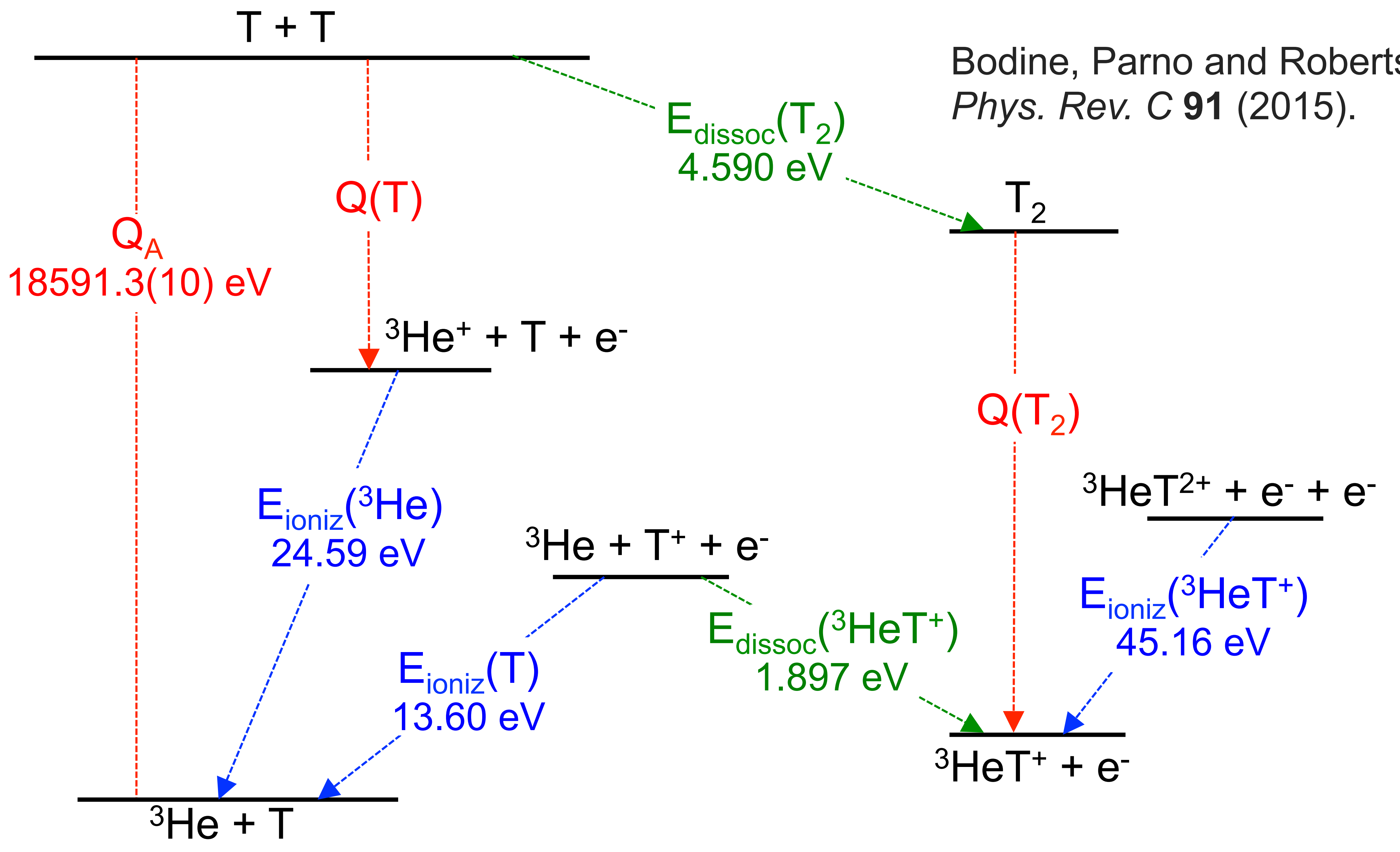
Two options going forward

Free Space Antenna Array

- *Vessel volume and frequency decoupled.*
- *Possibility of position reconstruction.*
- *Doppler frequency modulation decreases volume.*
- *Synthetic combination of many antennas needed to achieve necessary SNR.*

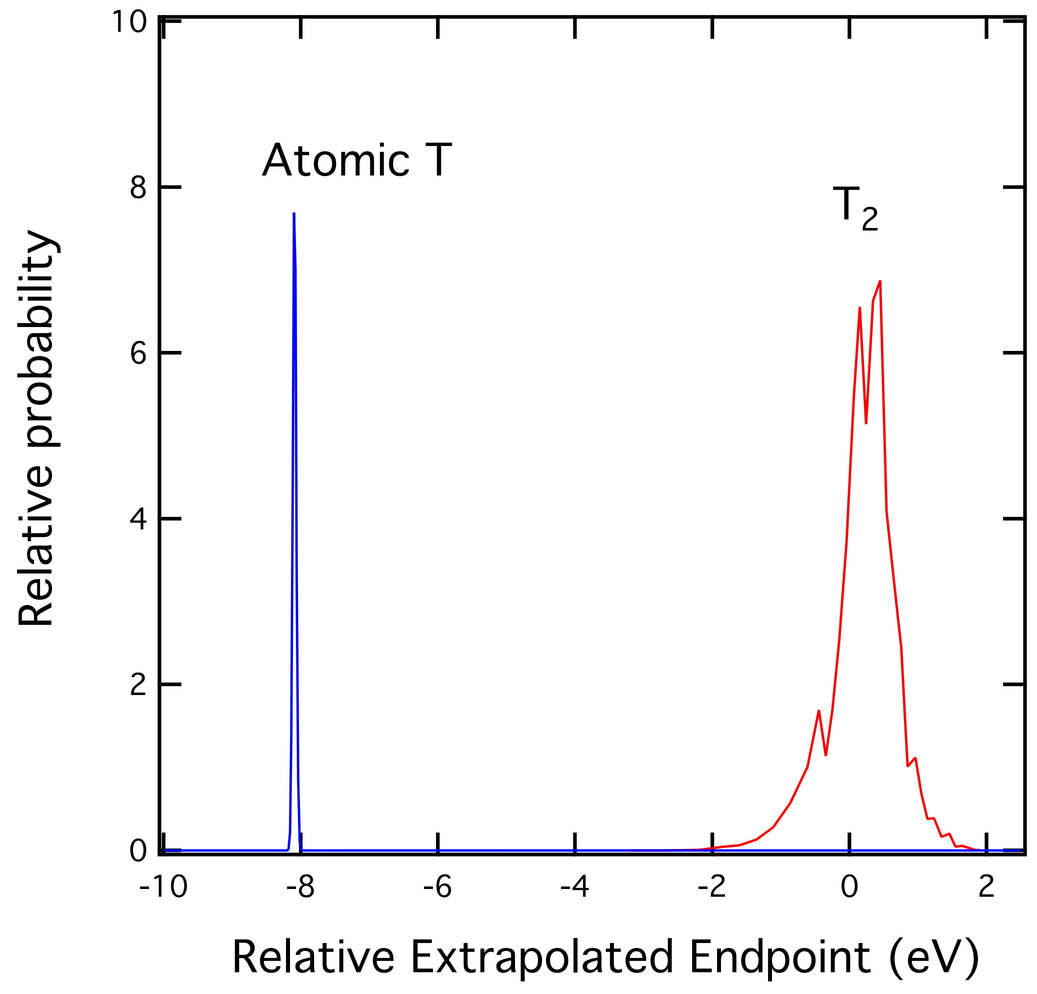
Any experiment with a molecular tritium (T_2) source will have a systematic penalty associated with uncertainty from rotational and vibrational states of the daughter $^3HeT^+$ populated in the decay.

In order to push to the inverted ordering scale, future experiments will need to switch from molecular to atomic sources.

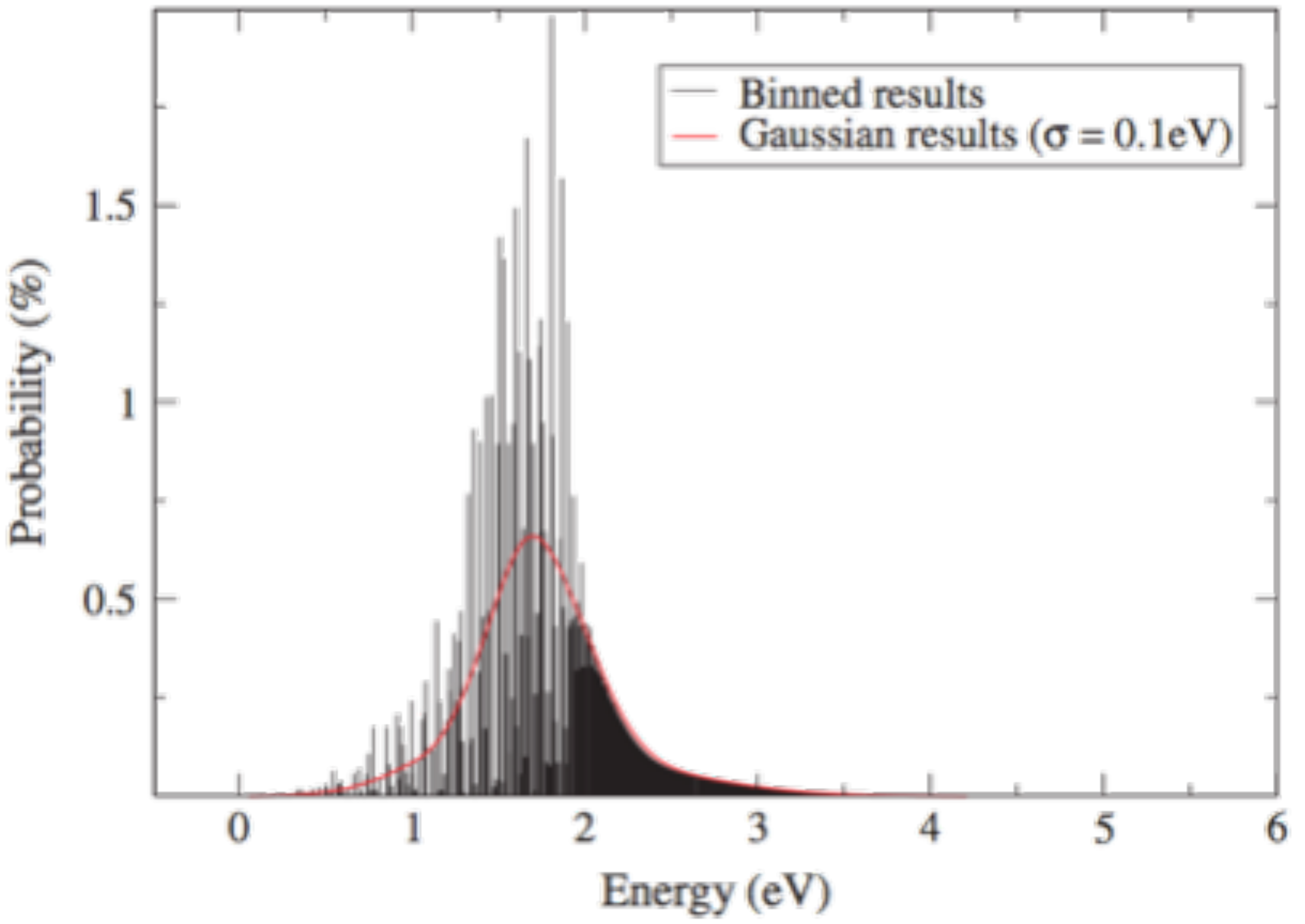


Bodine, Parno and Robertson, *Phys. Rev. C* **91** (2015).

Comparison of T_2 and T ground states



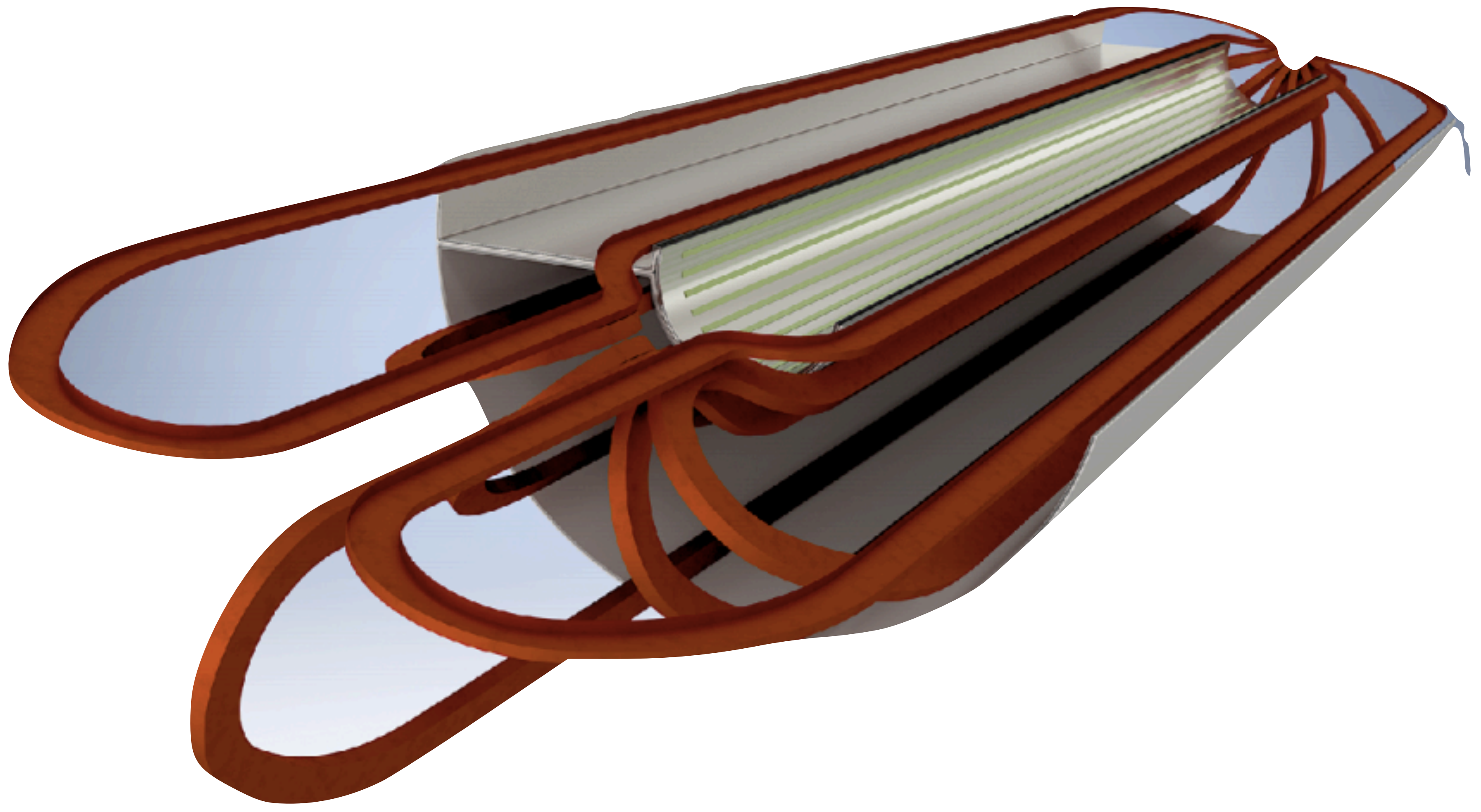
rotation and vibration of *molecular* $^3HeT^+$ daughter



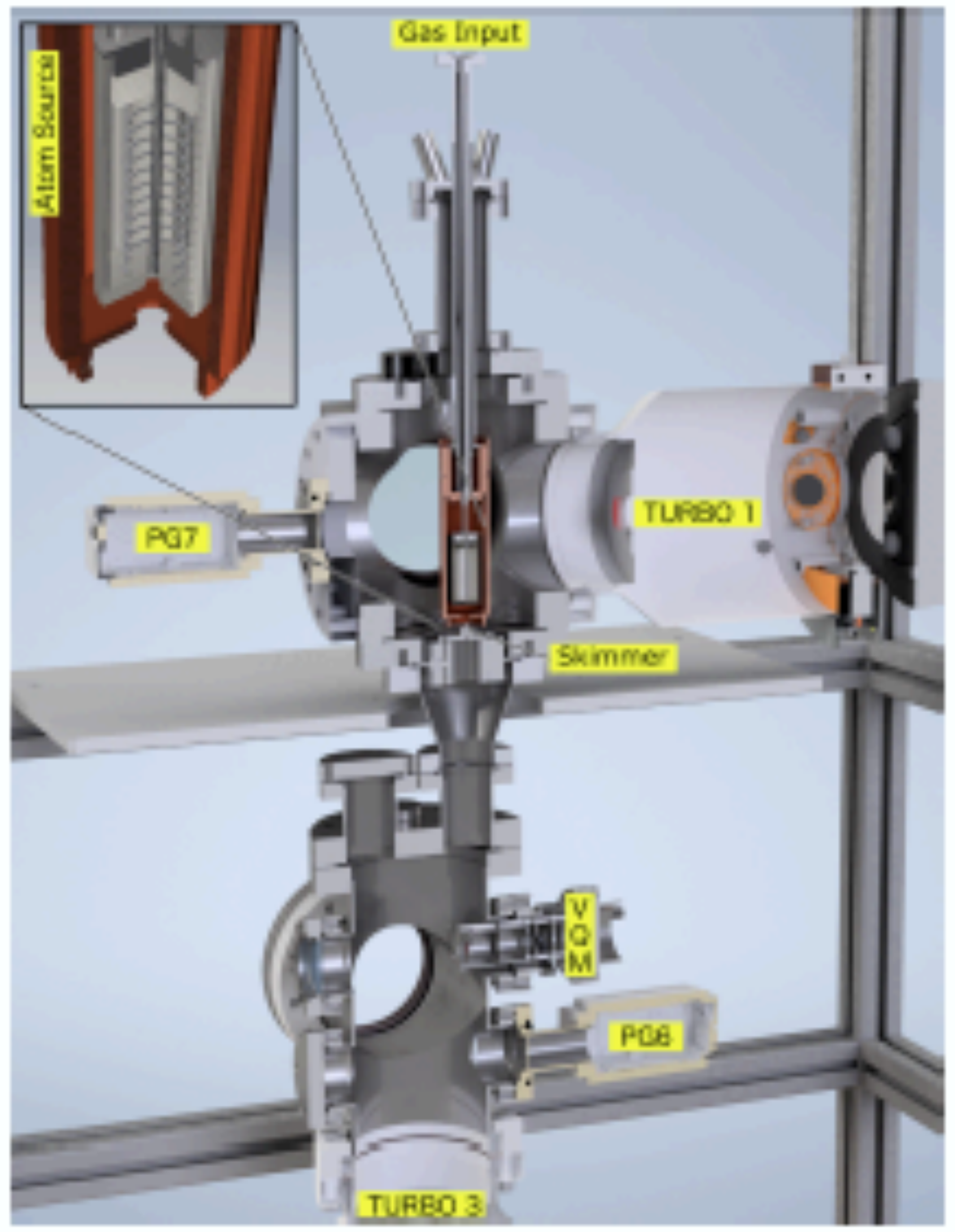
- Need to magnetically trap polarized atomic tritium, but to do so it needs to be magnetically and gravitationally confined.

- Dissociate ⟹ Cool ⟹ Trap ⟹ Purify ⟹ Recirculate

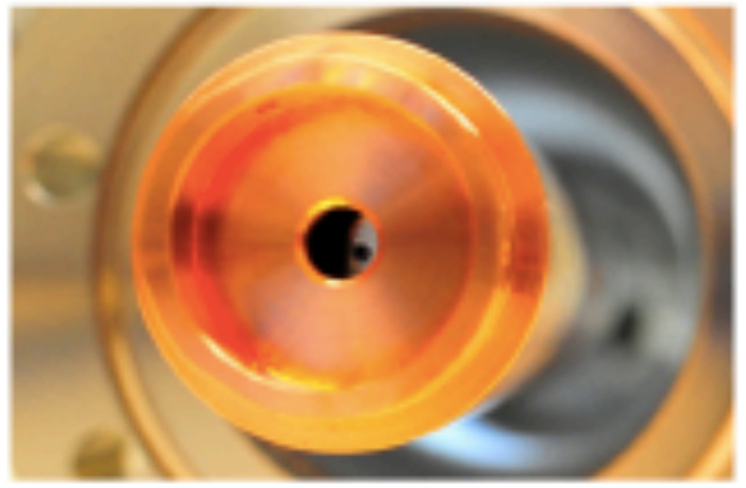
Atomic Trap Demonstrator

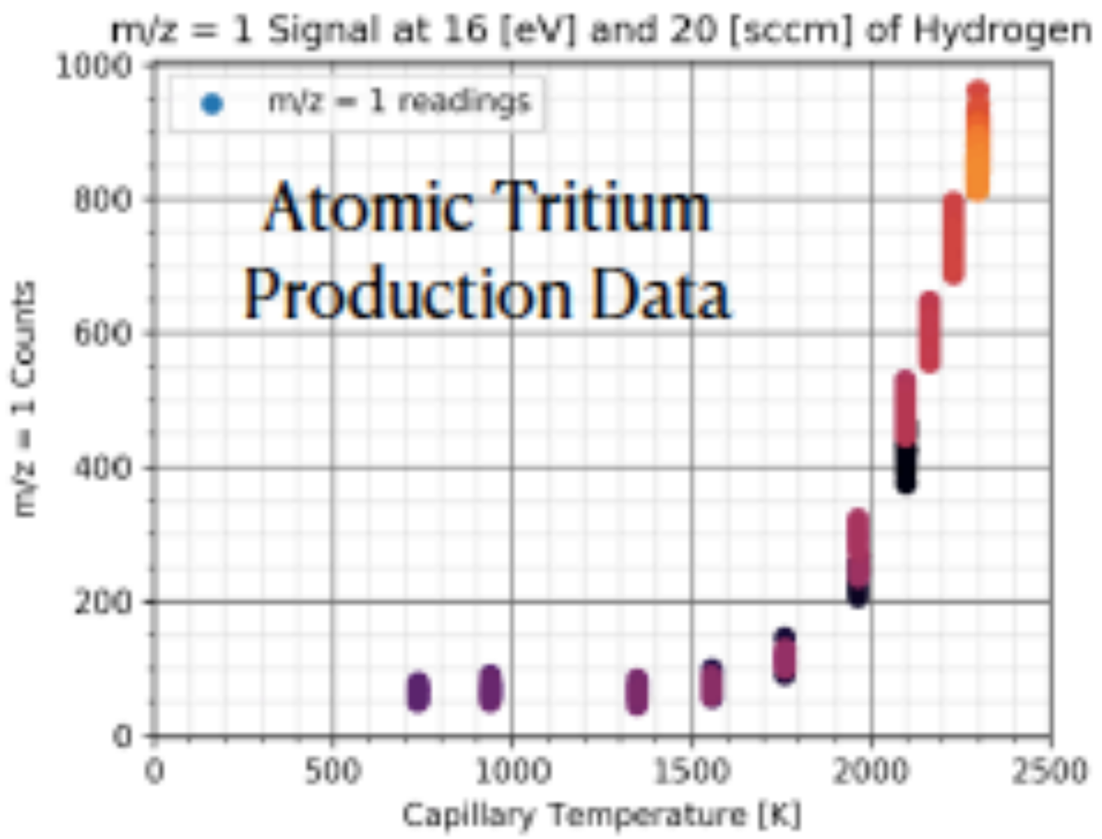


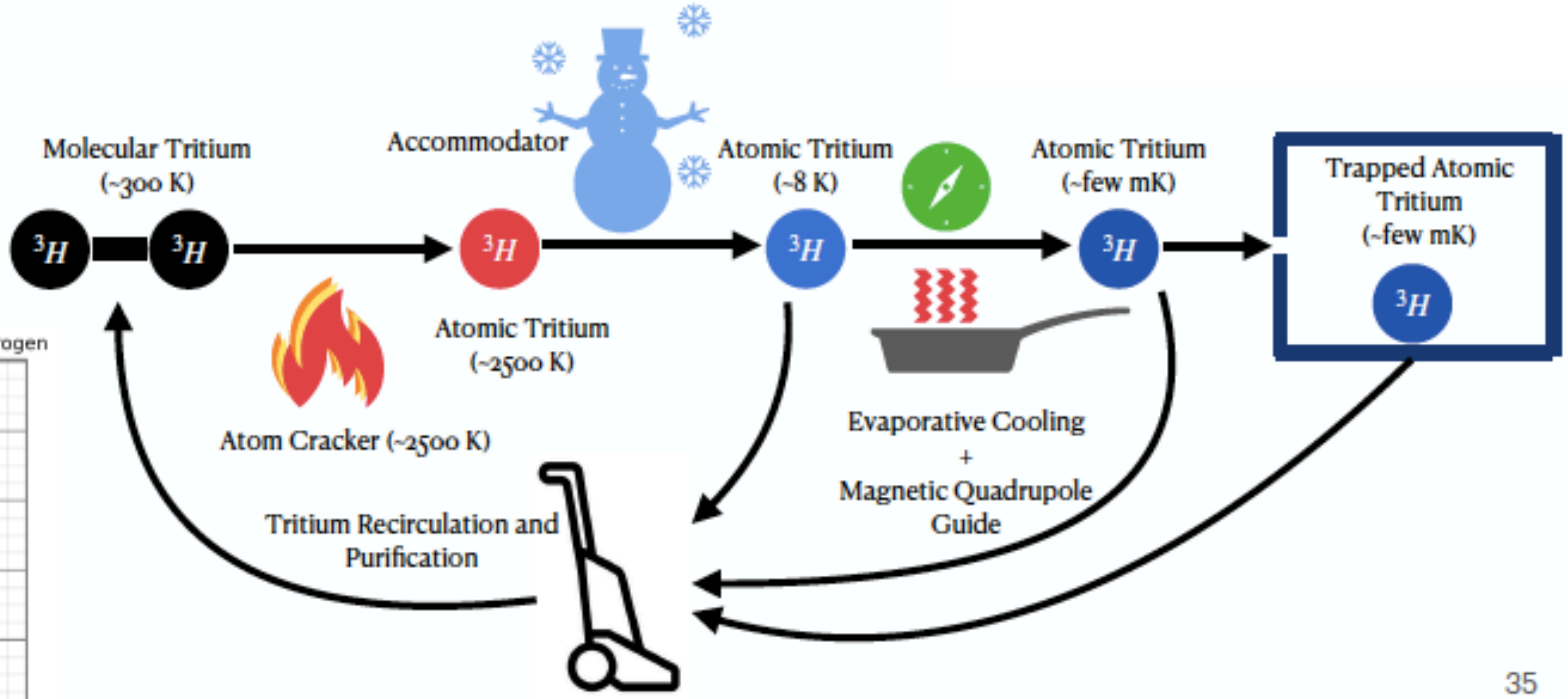
Atomic Test Stand



Atom Cracker



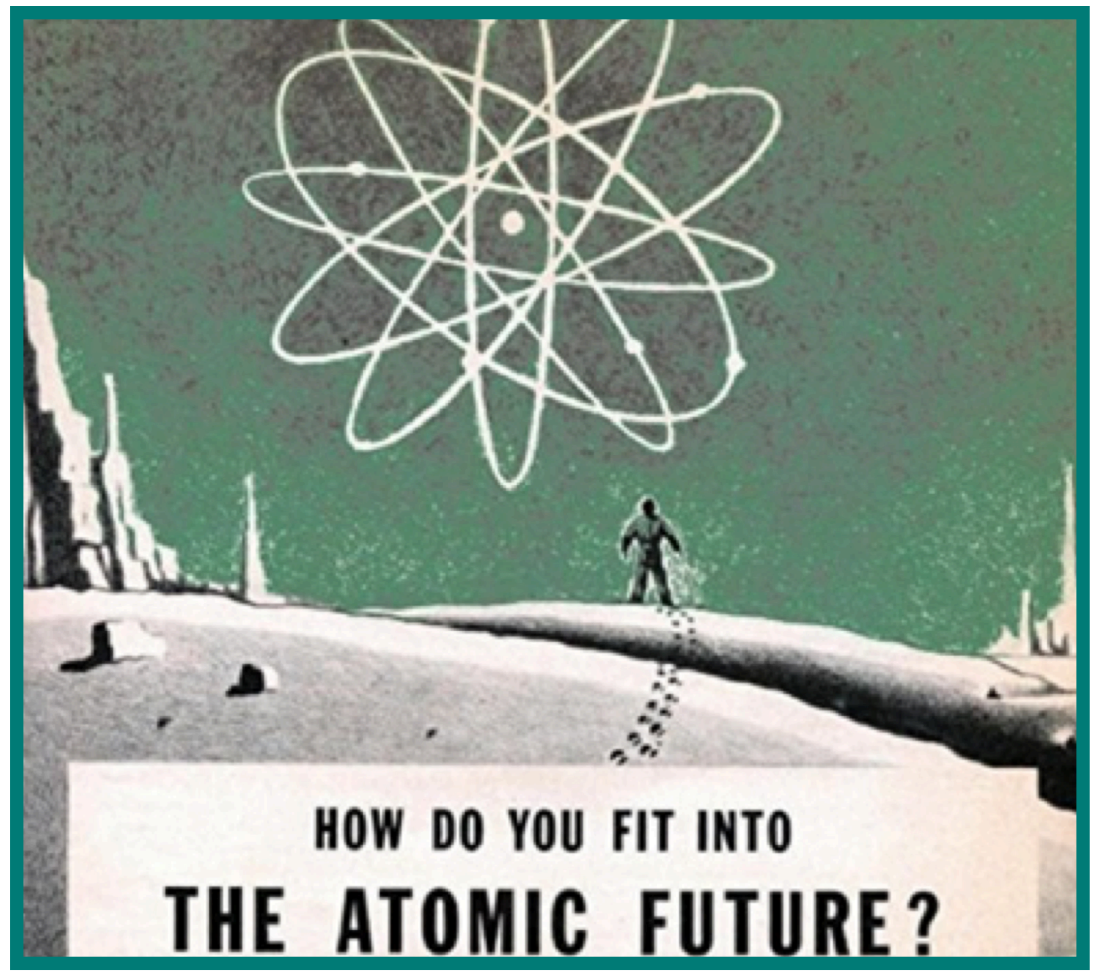




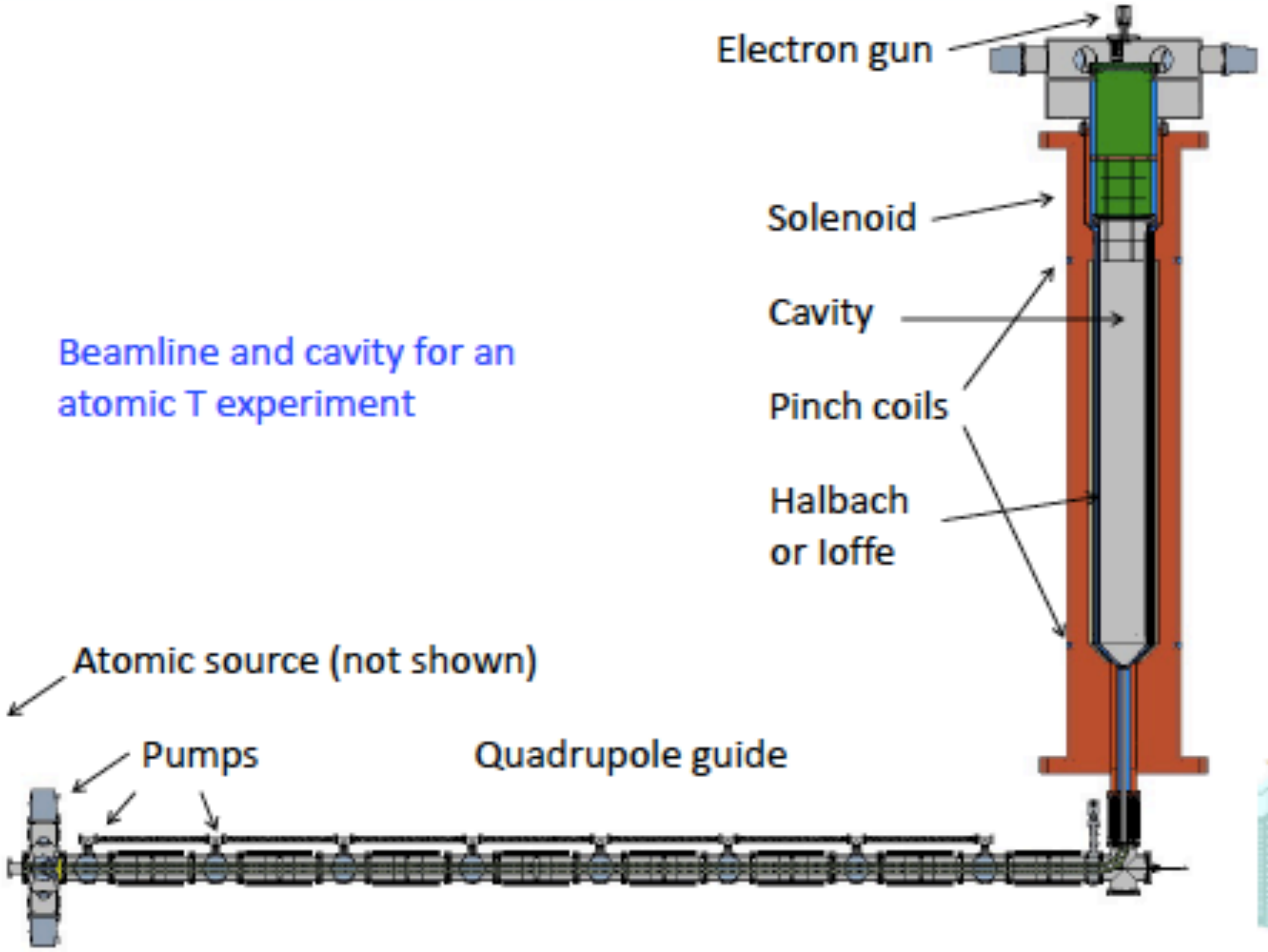
The collaboration will set out to build a pilot experiment next that demonstrates both the extended cavity volume and eventually a first measurement using atomic tritium

The pilot experiment will set the stage for the ultimate experiment with a target mass limit of

$m_\beta \leq 40$ meV/c^2.



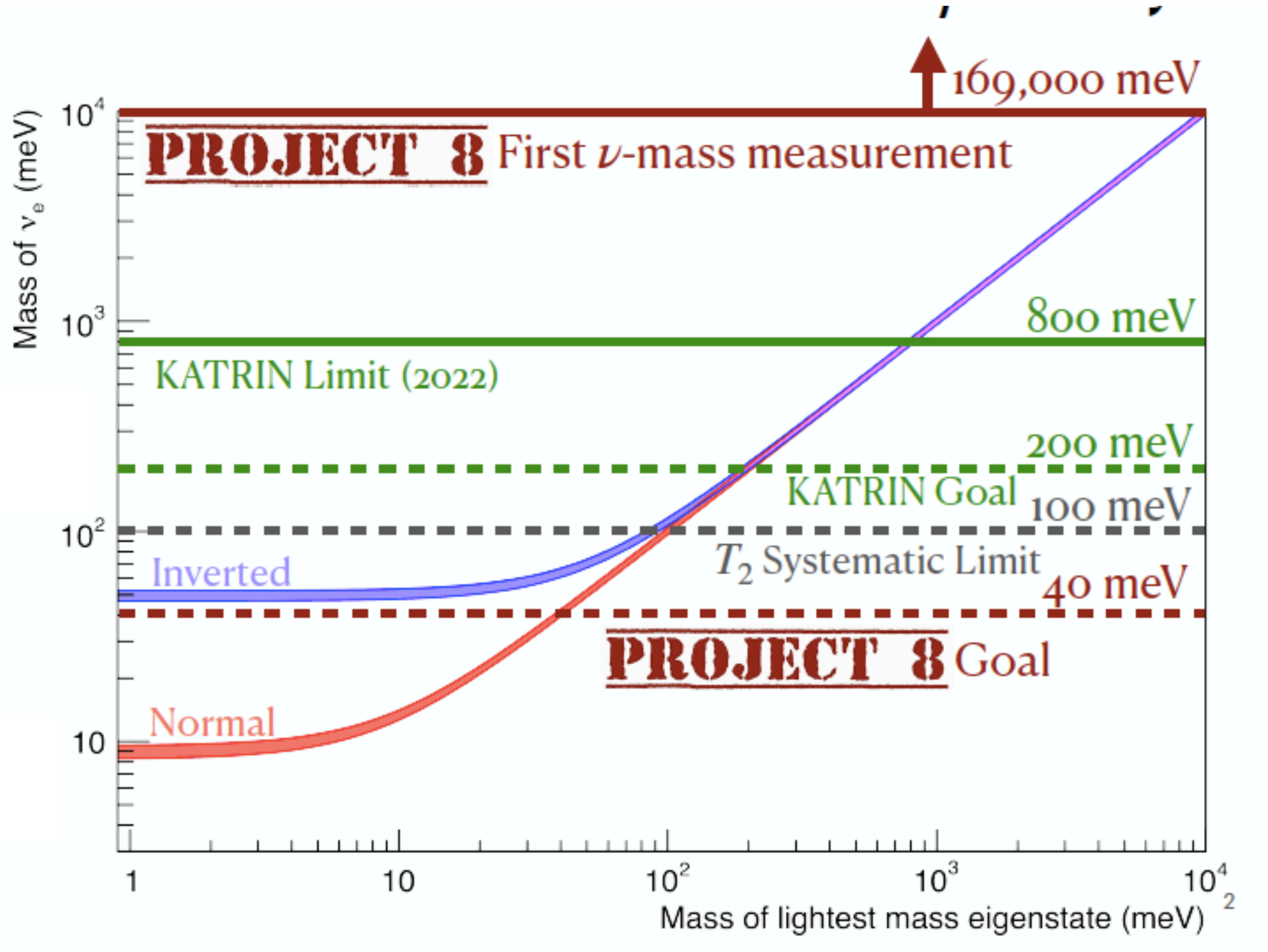
Phase III Atomic Demonstrator



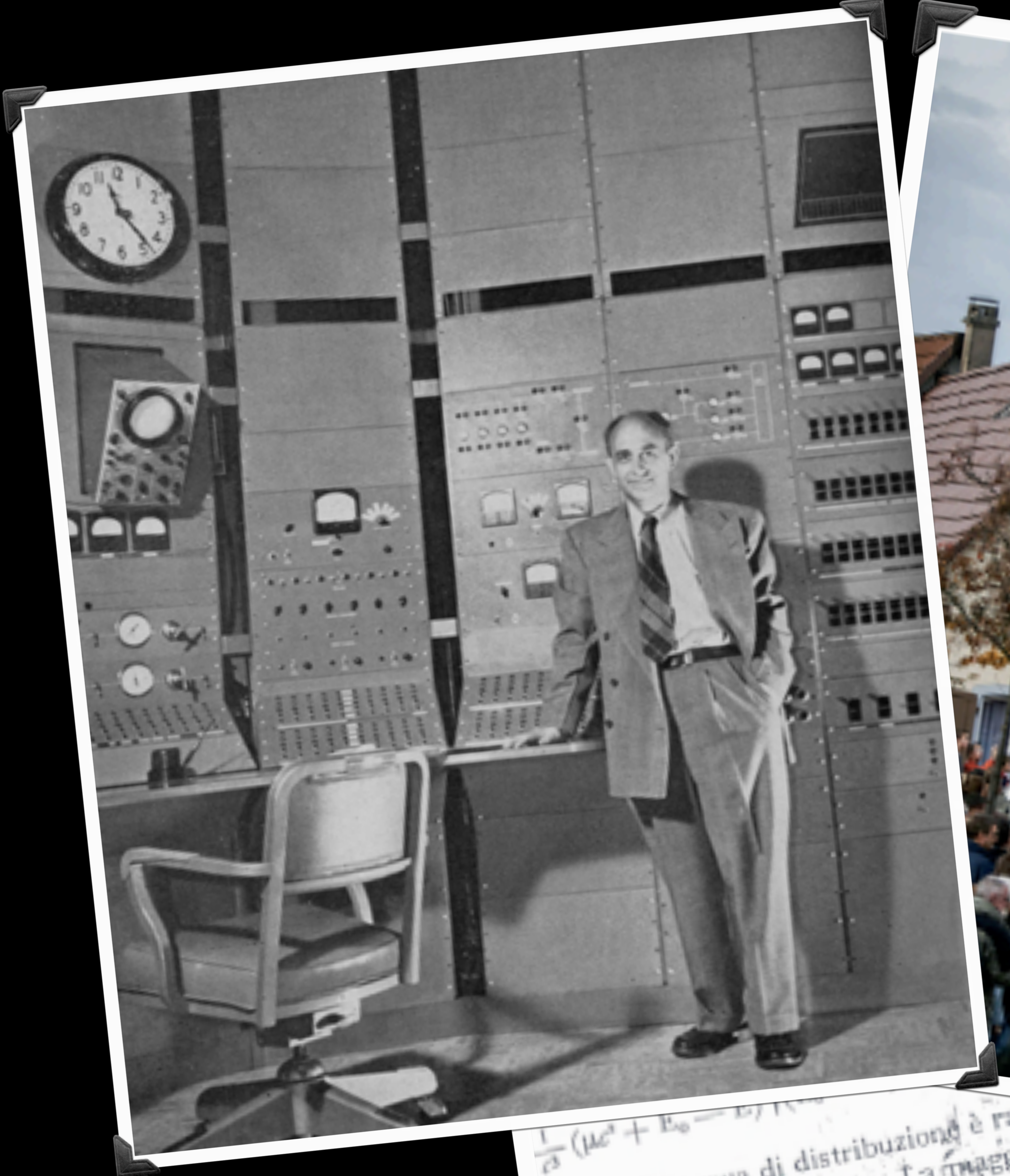
The collaboration will set out to build a pilot experiment next that demonstrates both the extended cavity volume and eventually a first measurement using atomic tritium

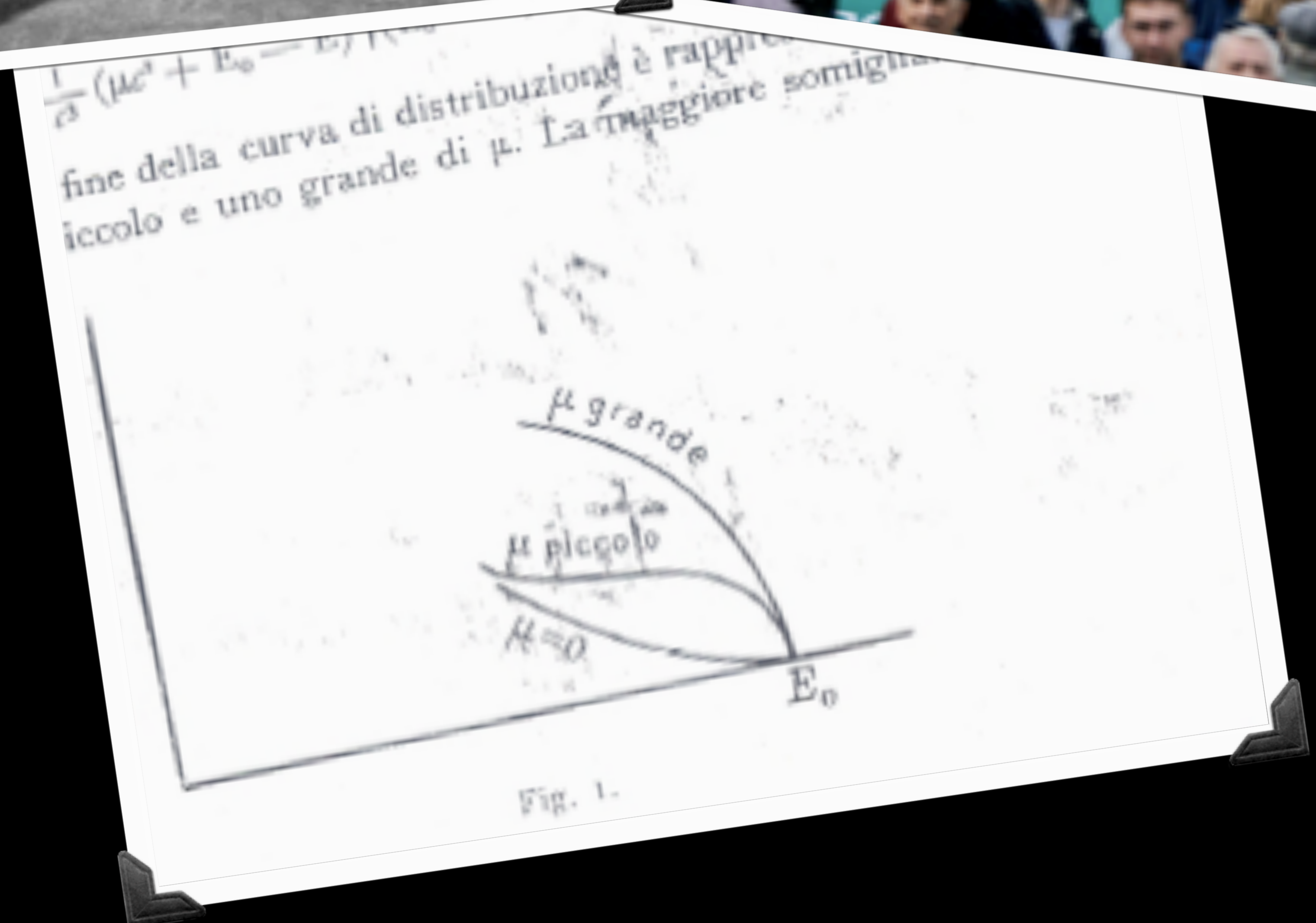
The pilot experiment will set the stage for the ultimate experiment with a target mass limit of

$m_\beta \leq 40\ \mathrm{meV}/c^2$.



See Snowmass contribution arXiv:2203.07349 for more details

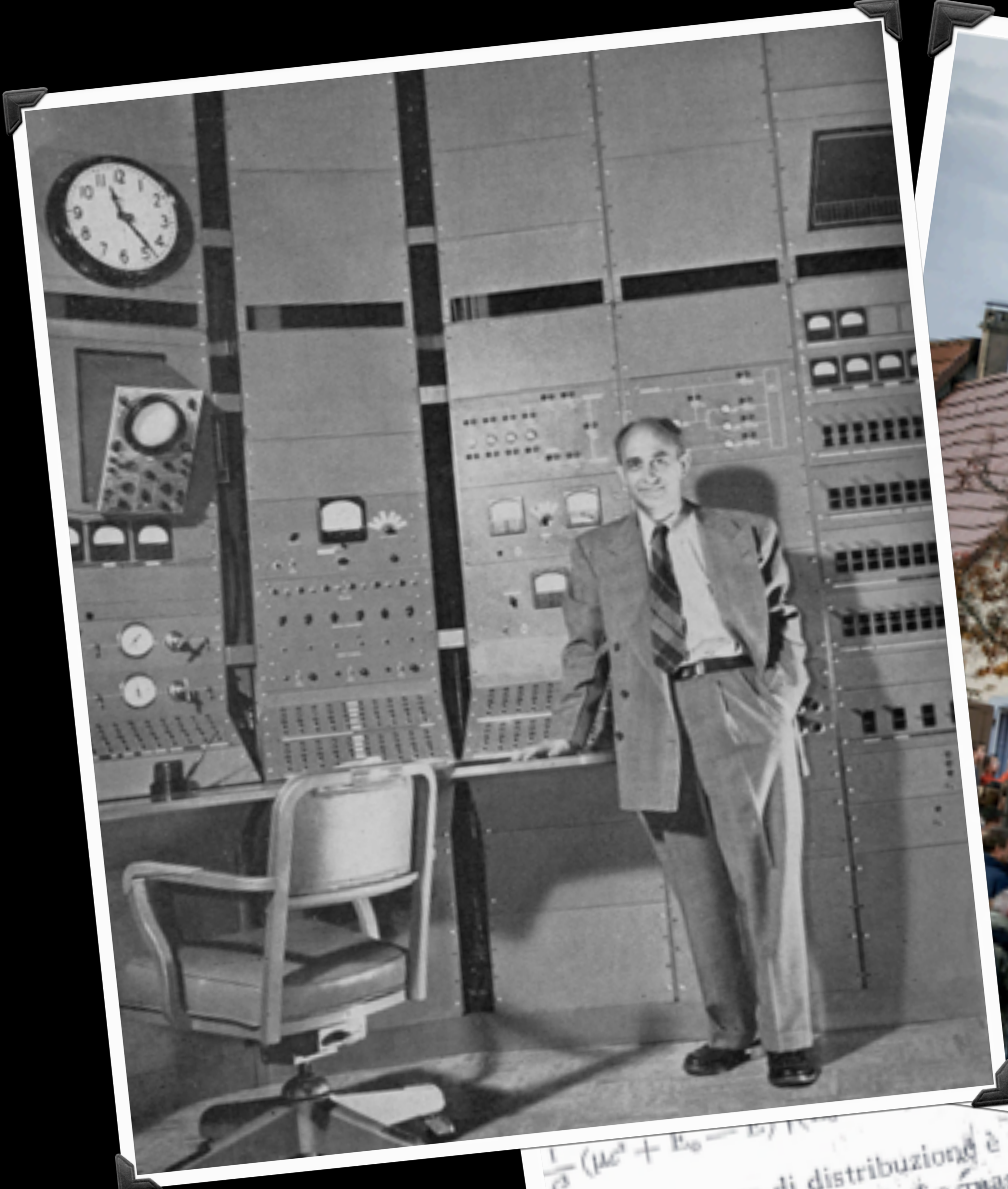


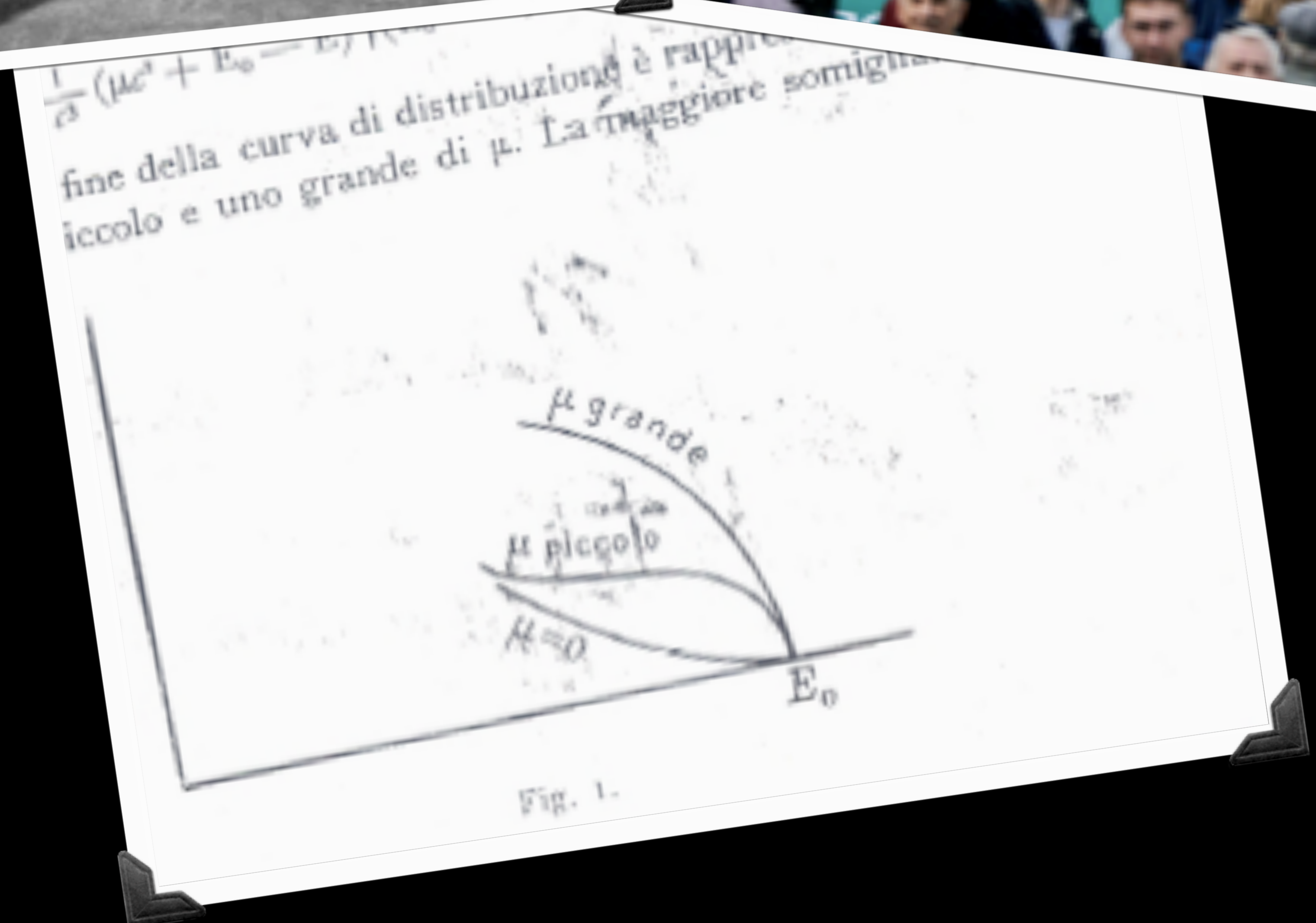

fine della curva di distribuzione è
iccolo e uno grande di μ. La maggiore

This is a good decade for direct neutrino mass measurements.

KATRIN is taking data! The eV scale is broken.

Project 8, ECHo and HOLMES pushing the next generation of direct neutrino mass detectors.





Thank you for your attention.