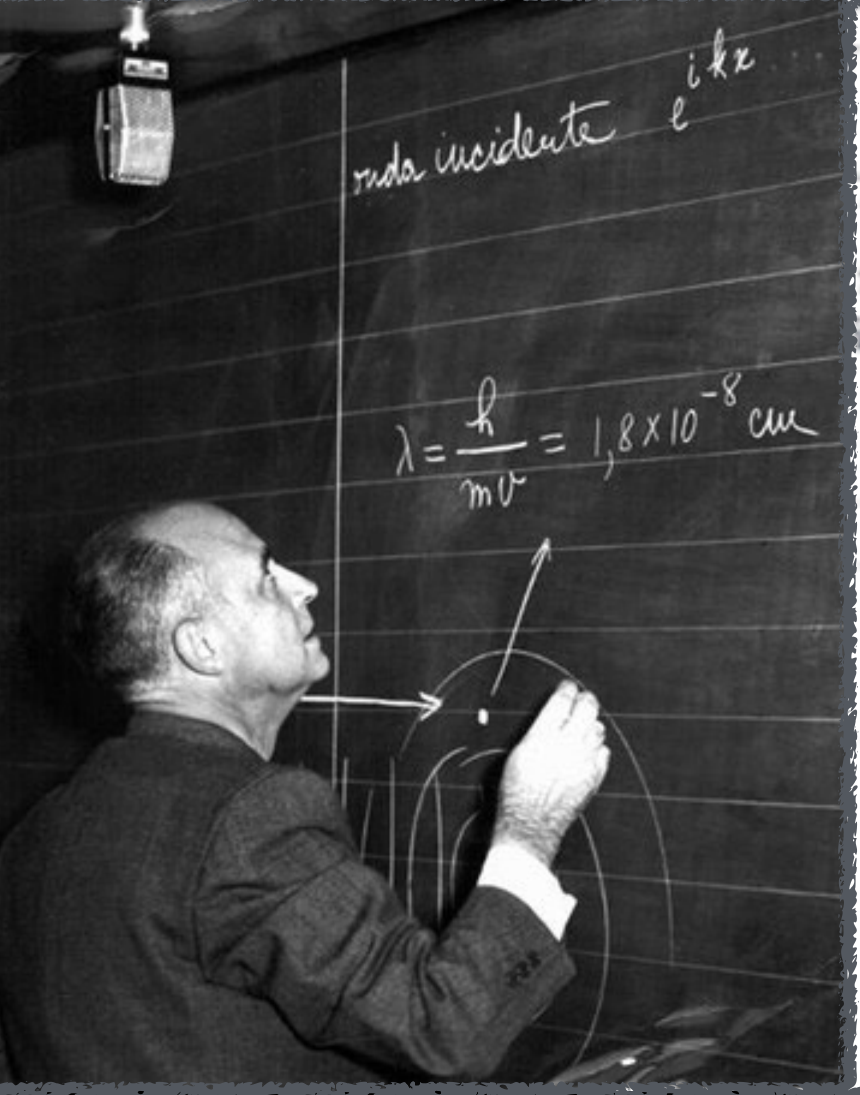
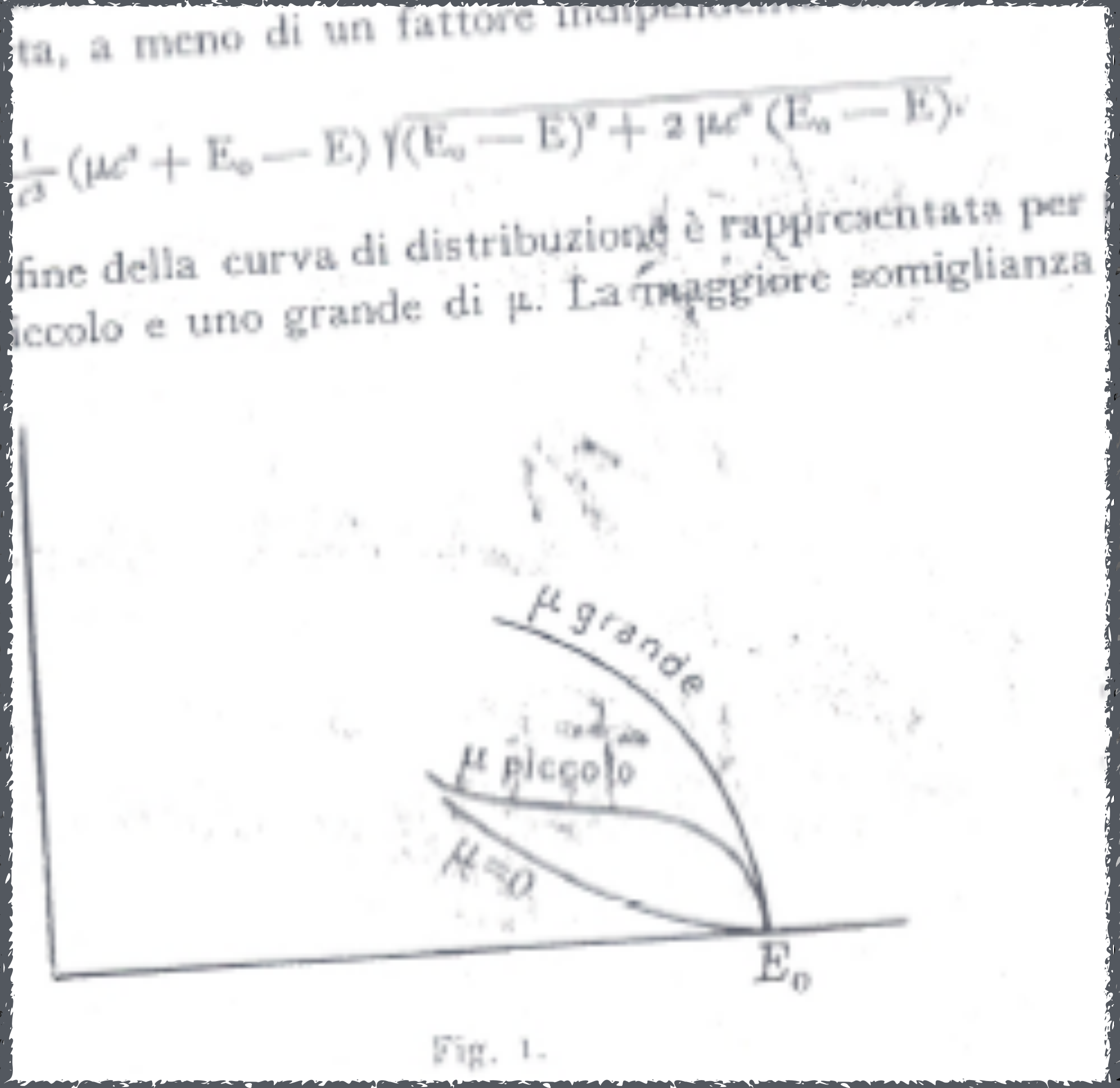
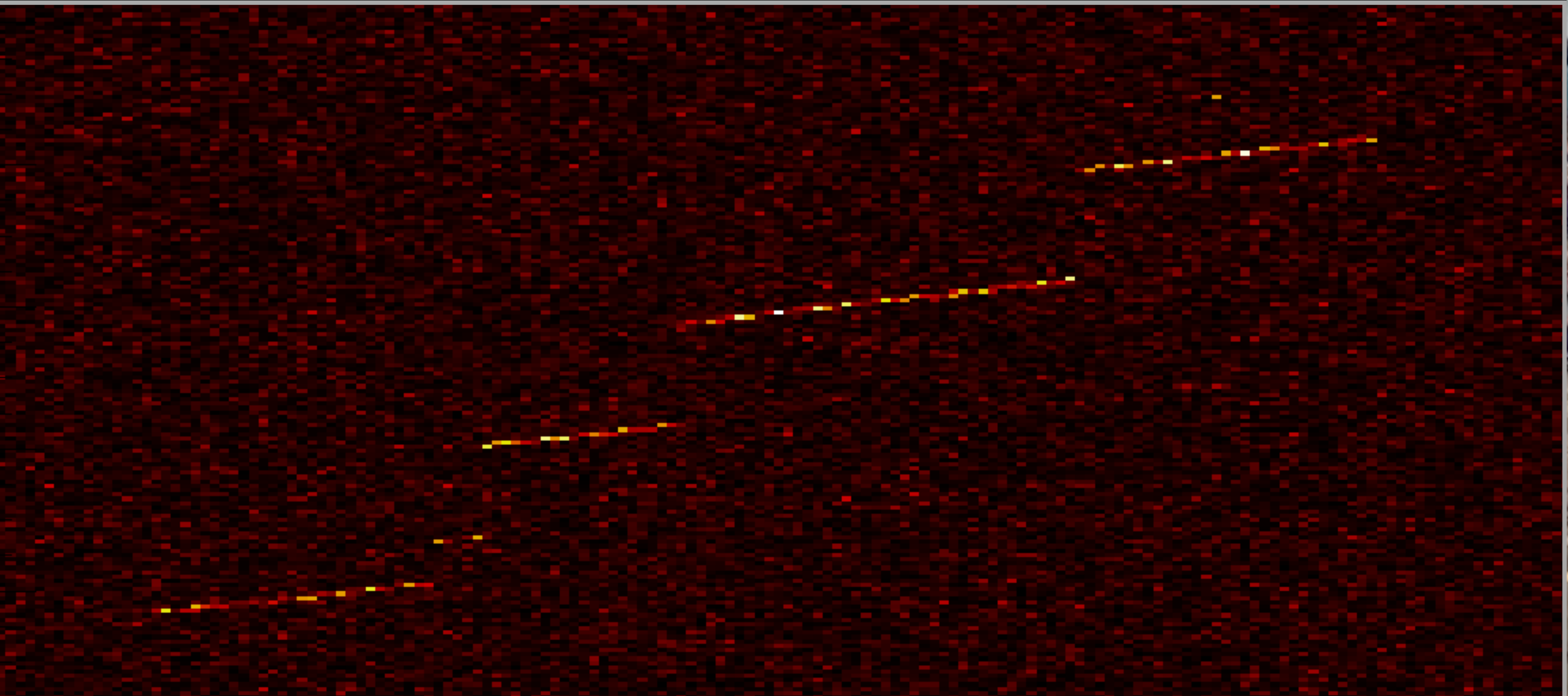


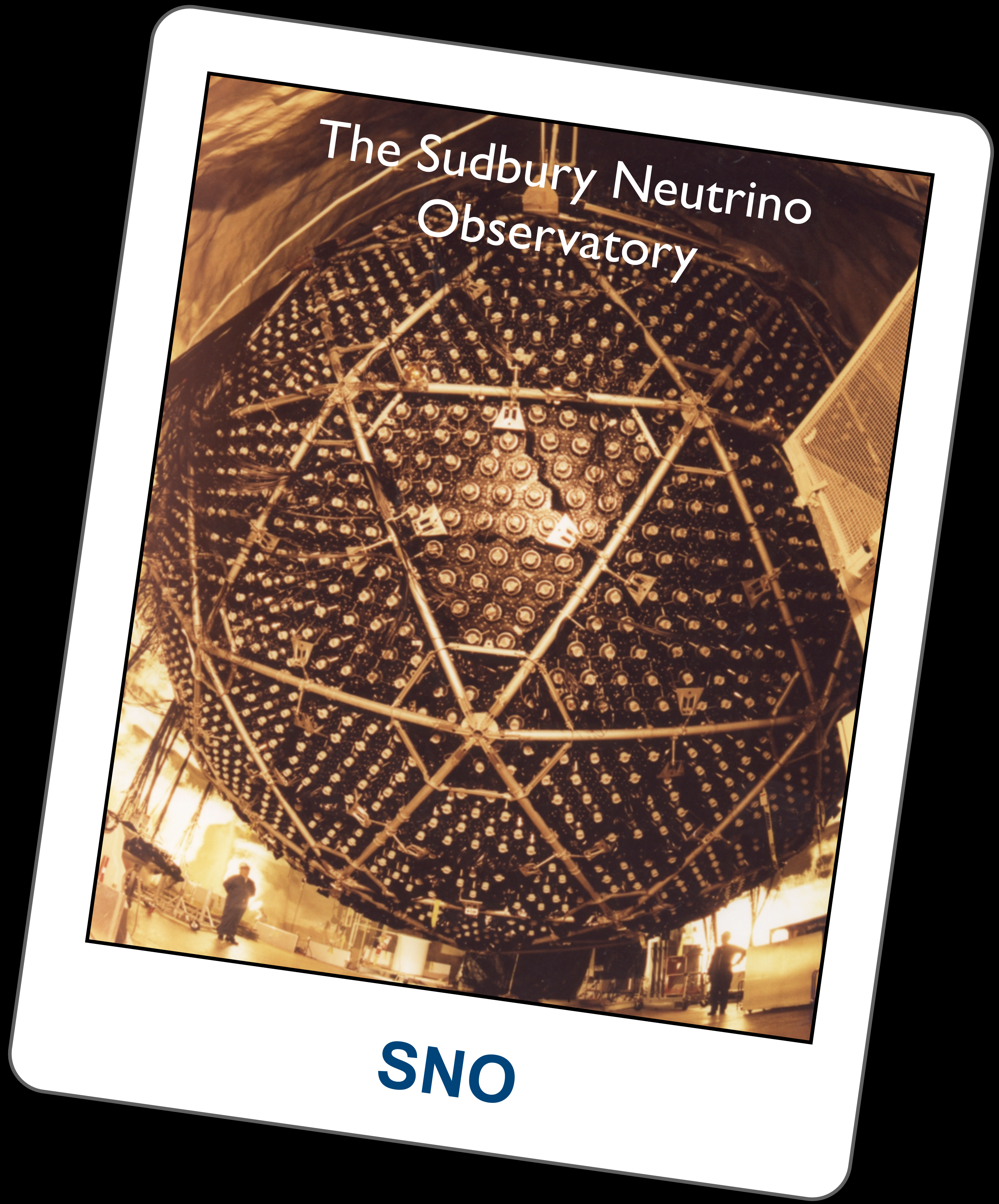


Probing the Mass Scale of Neutrinos



Neutrino Telescopes

Joseph A. Formaggio
Massachusetts Institute of Technology

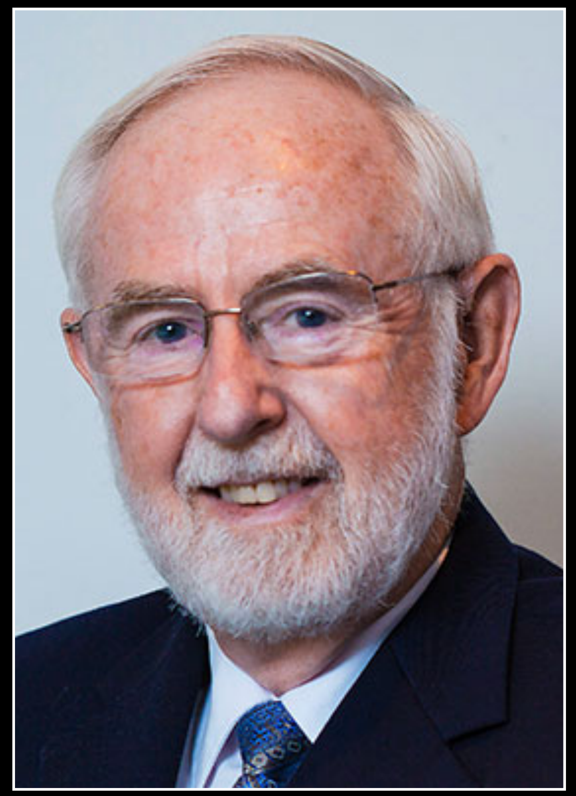


A myriad of experiments helped demonstrate that neutrinos transmute flavor (oscillations).

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

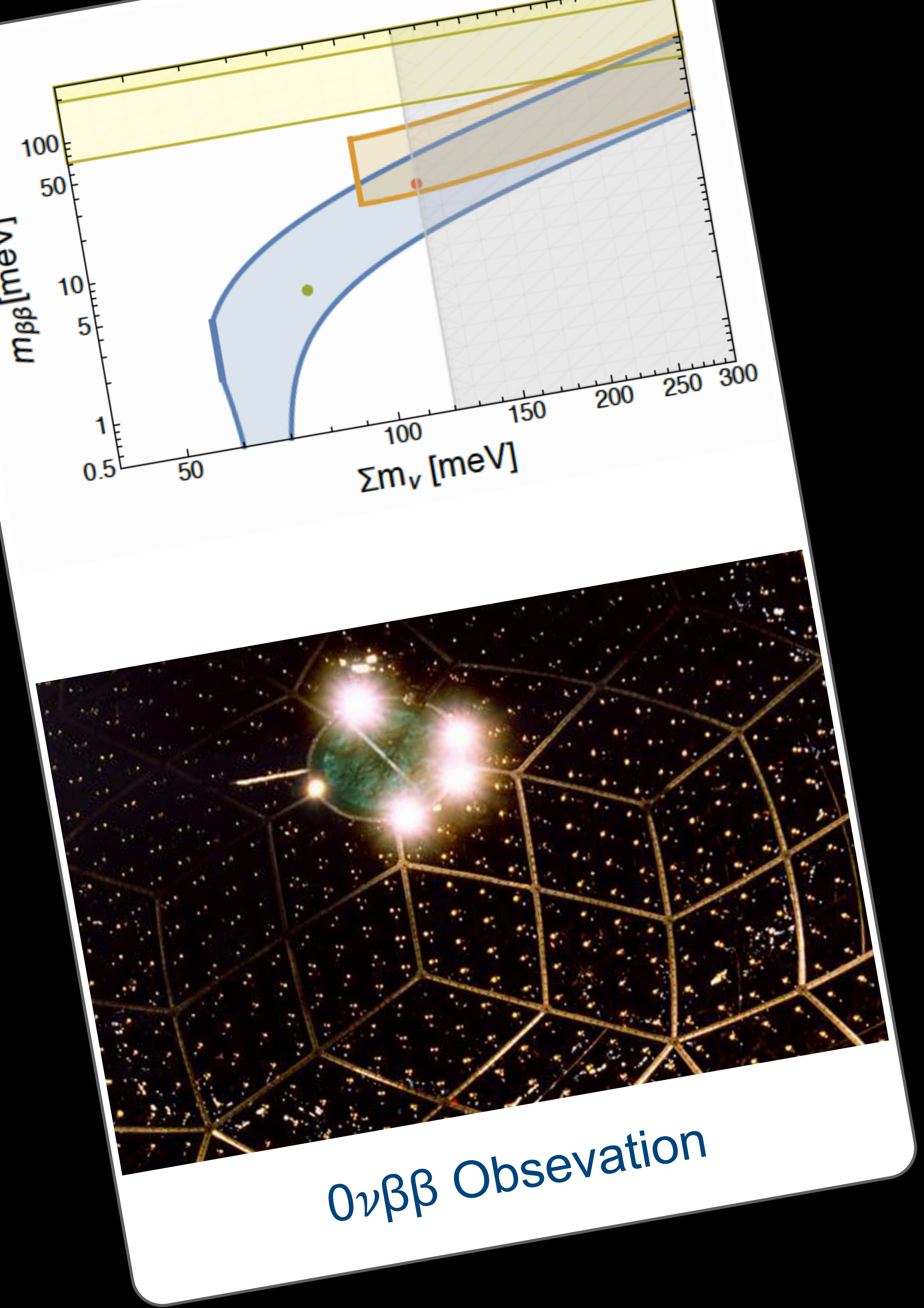
However, oscillation experiments <u>cannot</u> reveal the neutrino mass scale directly.

Takaaki Kajita
(Super-Kamiokande)



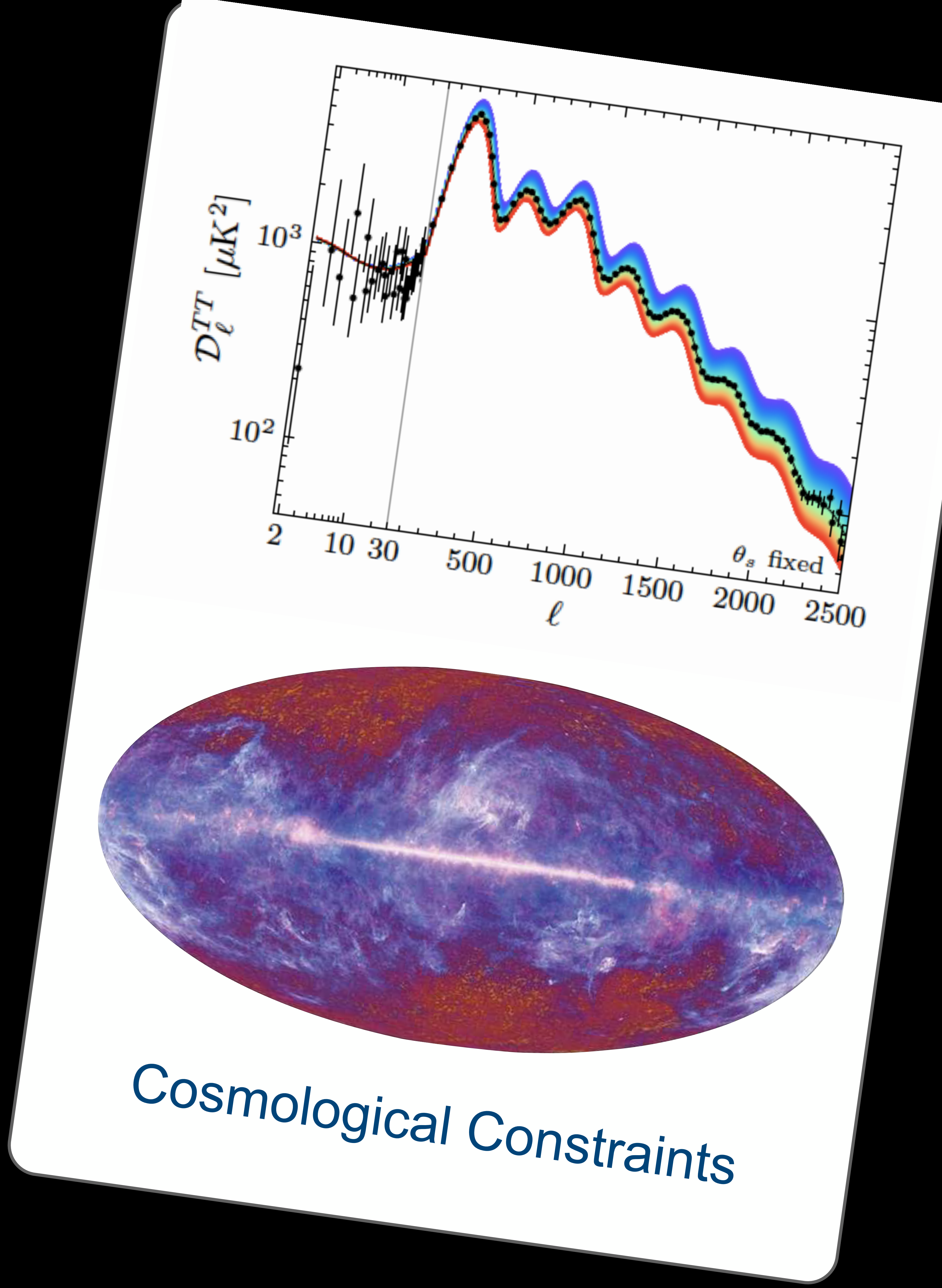
Arthur B. McDonald
(Sudbury Neutrino Observatory)

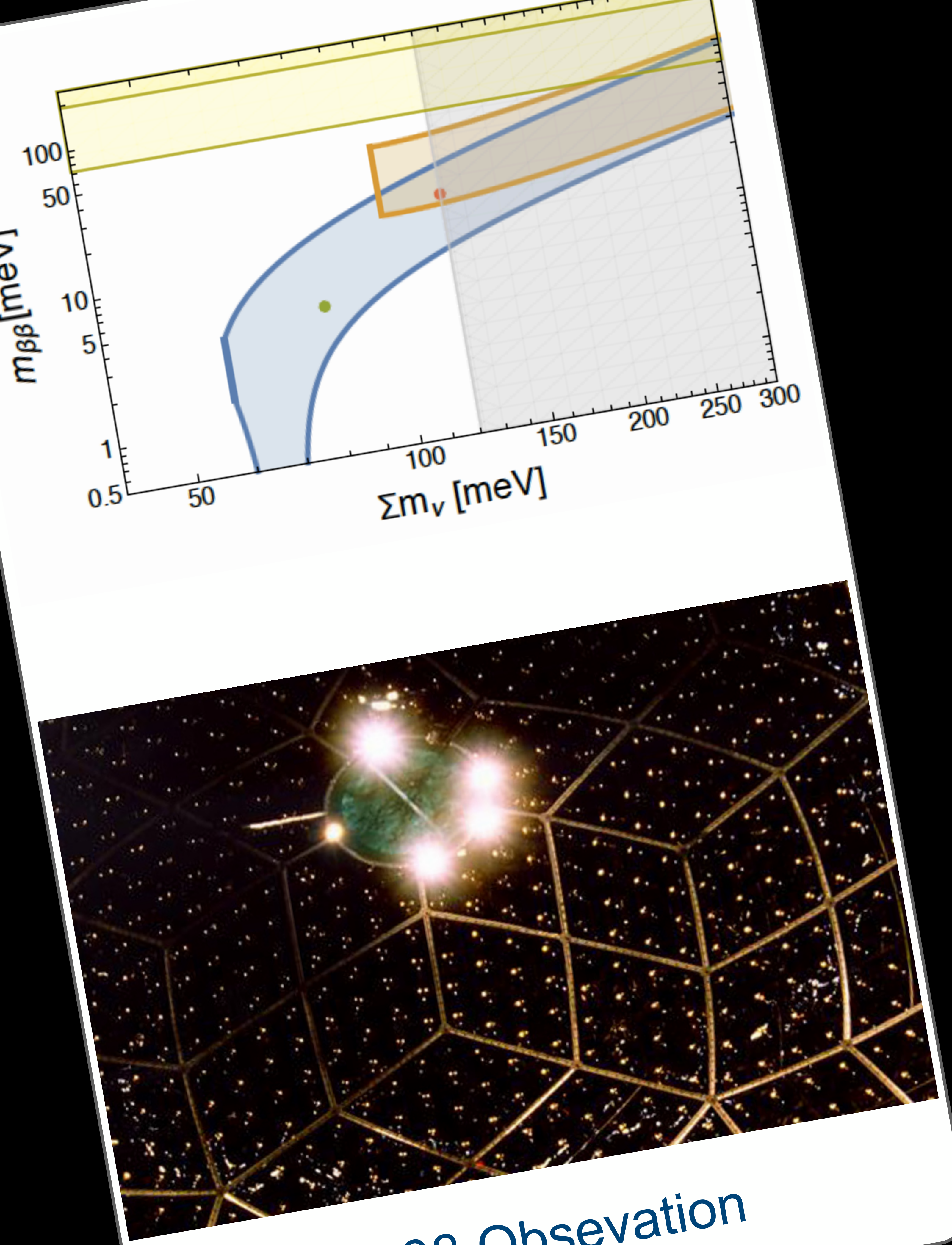
So... how do we access what is the scale of neutrino masses?



Neutrino oscillations,
neutrinoless double beta decay
and
cosmology
all help shed light on the neutrino mass scale
(see talks in this conference).

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





0νββ Observation

Neutrino oscillations,

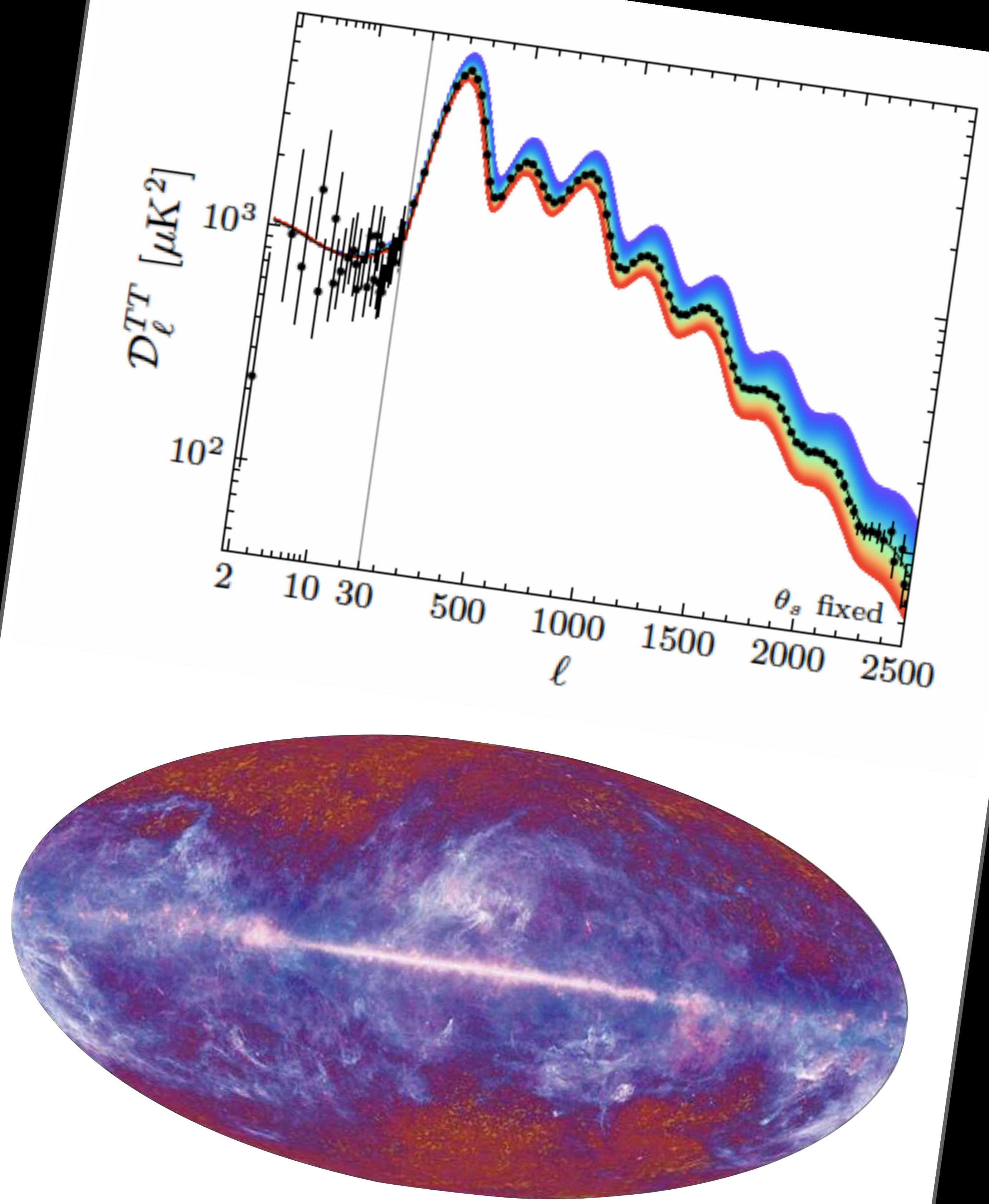
neutrinoless double beta decay

and

cosmology

all help shed light on the neutrino mass scale

(see talks in this conference).



Cosmological Constraints

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

⇐ Monday's Talk

Thursday's Talk ⇒

All these methods indirectly access the neutrino mass scale

All these methods indirectly access the neutrino mass scale

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

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...]

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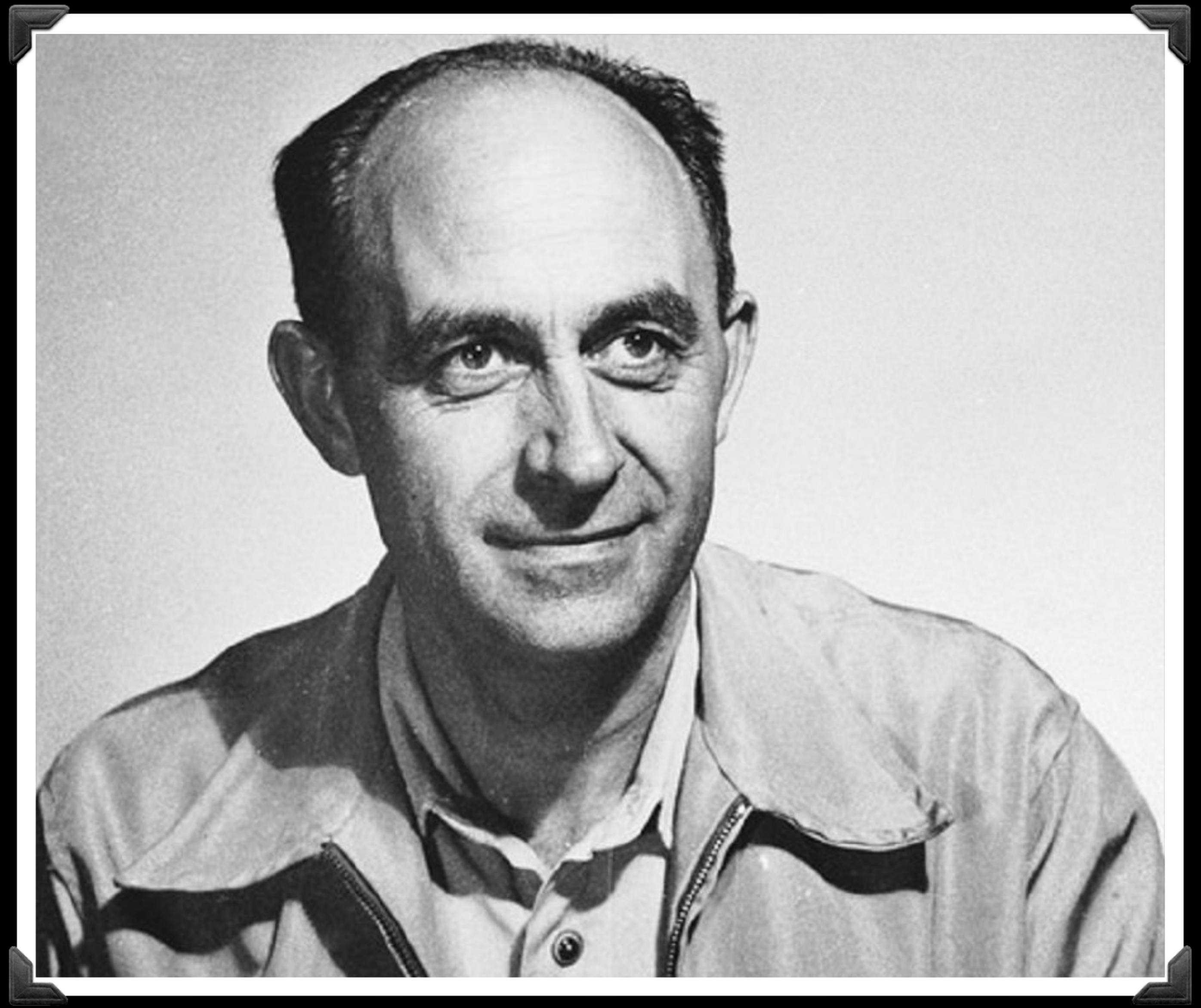
“On peut essayer de d́eduire de la forme des spectres continus d’ ´emission une indication sur la valeur de cette masse inconnue...”

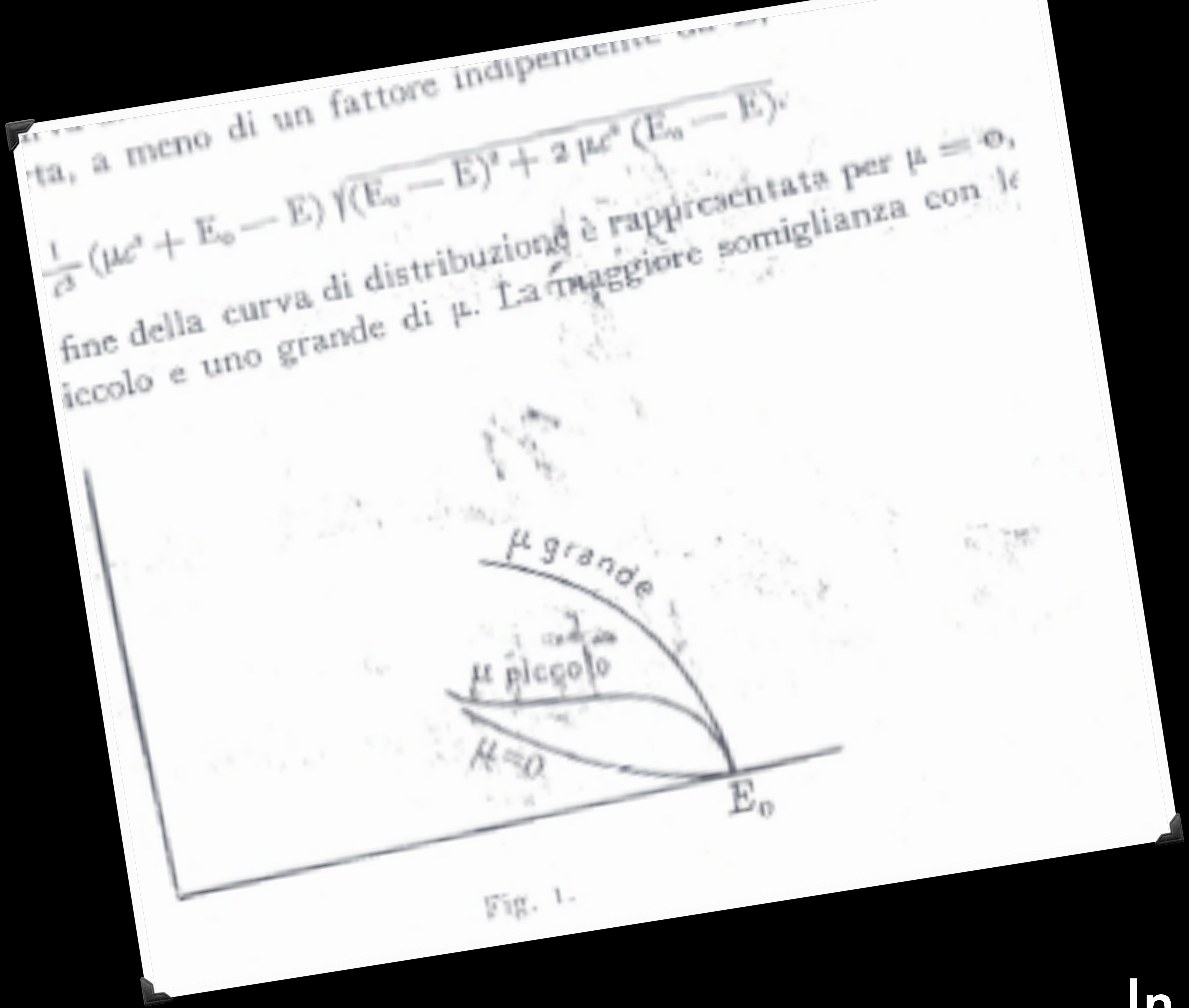
[One could attempt to deduce from the shape of the continuous emission spectra an indication of the value of this unknown mass...]

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.]

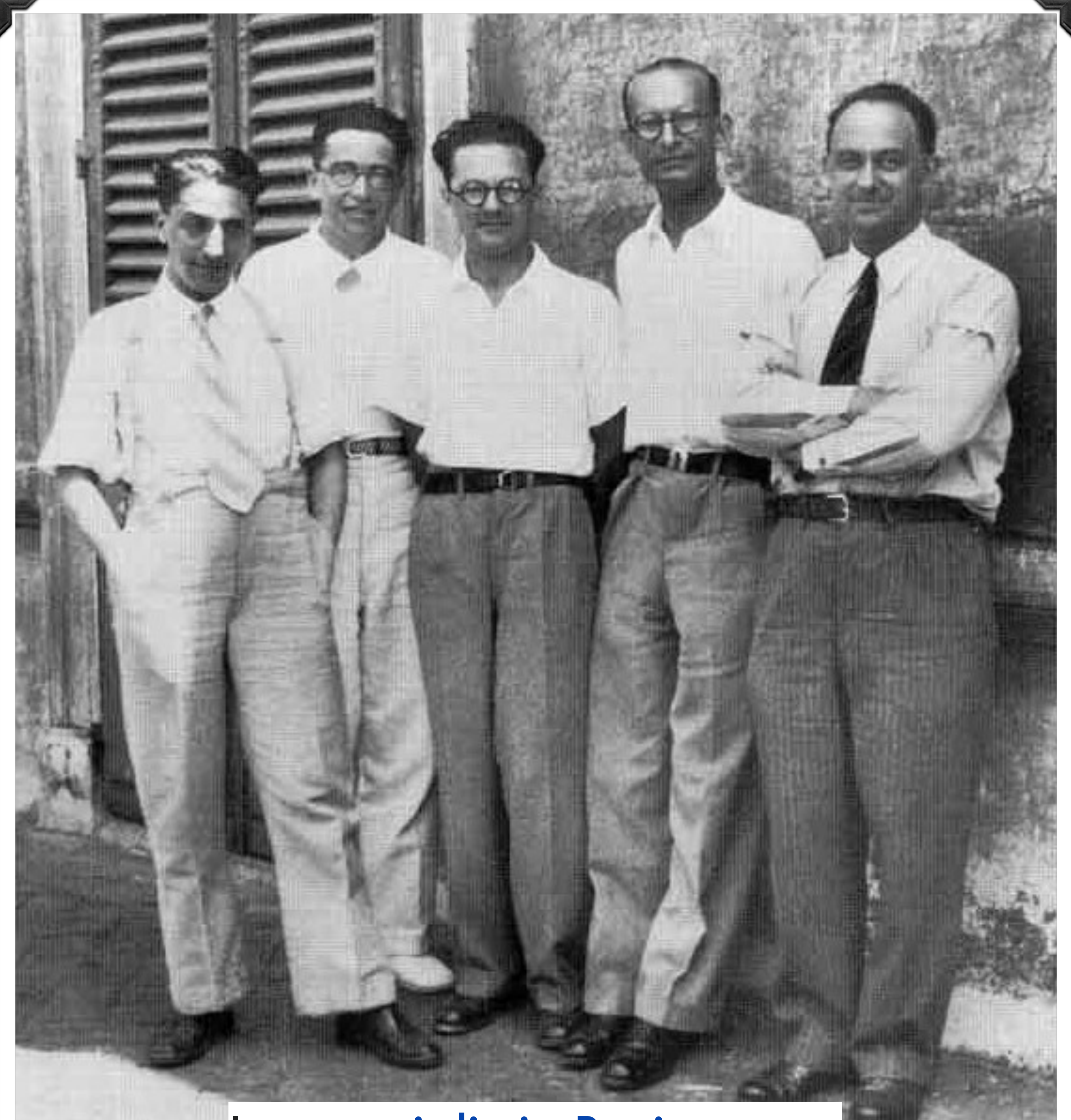


ta, a meno di un fattore indipendente da E,

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

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

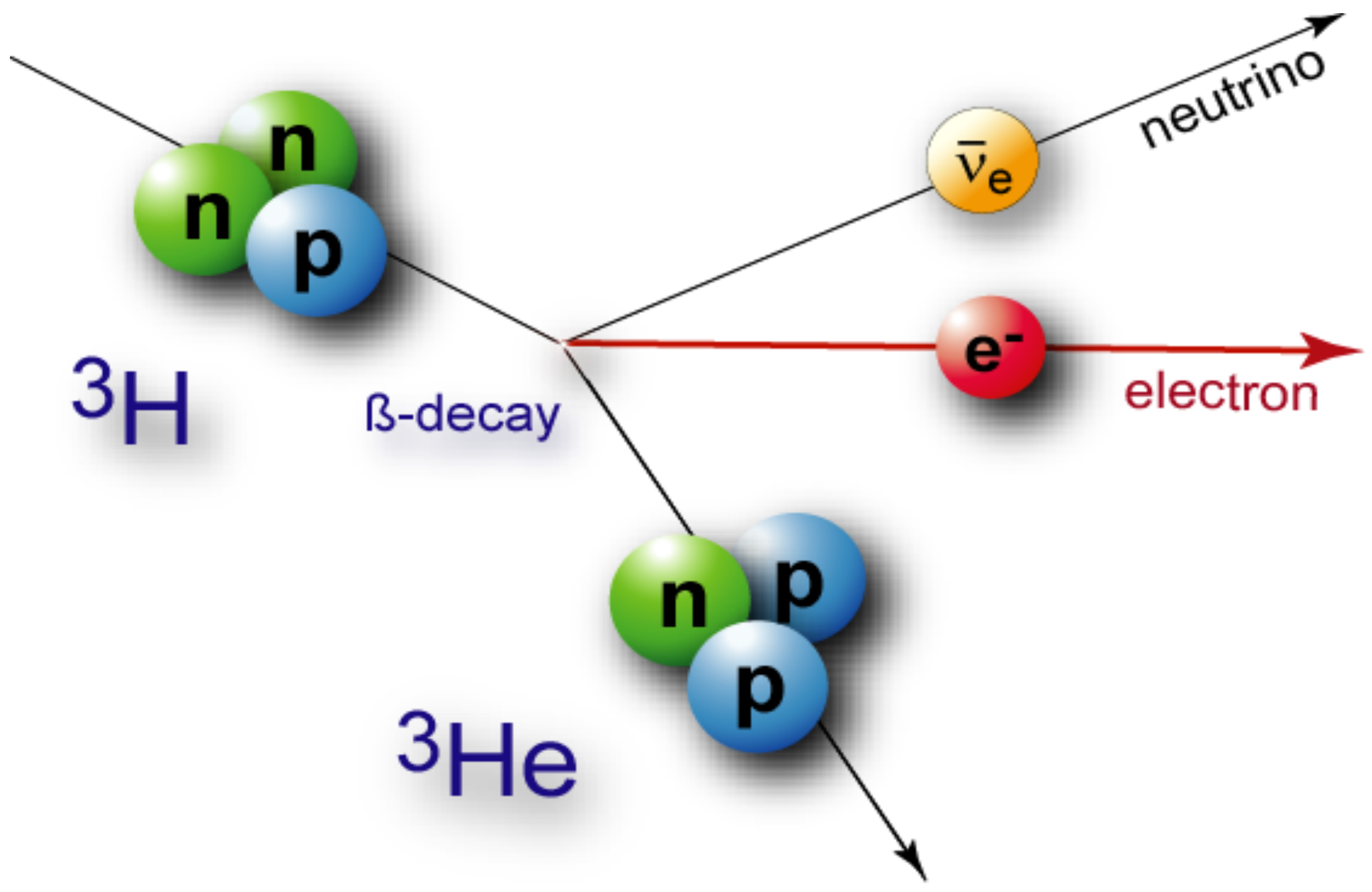
Fig. 1.



I ragazzi di via Panisperna.

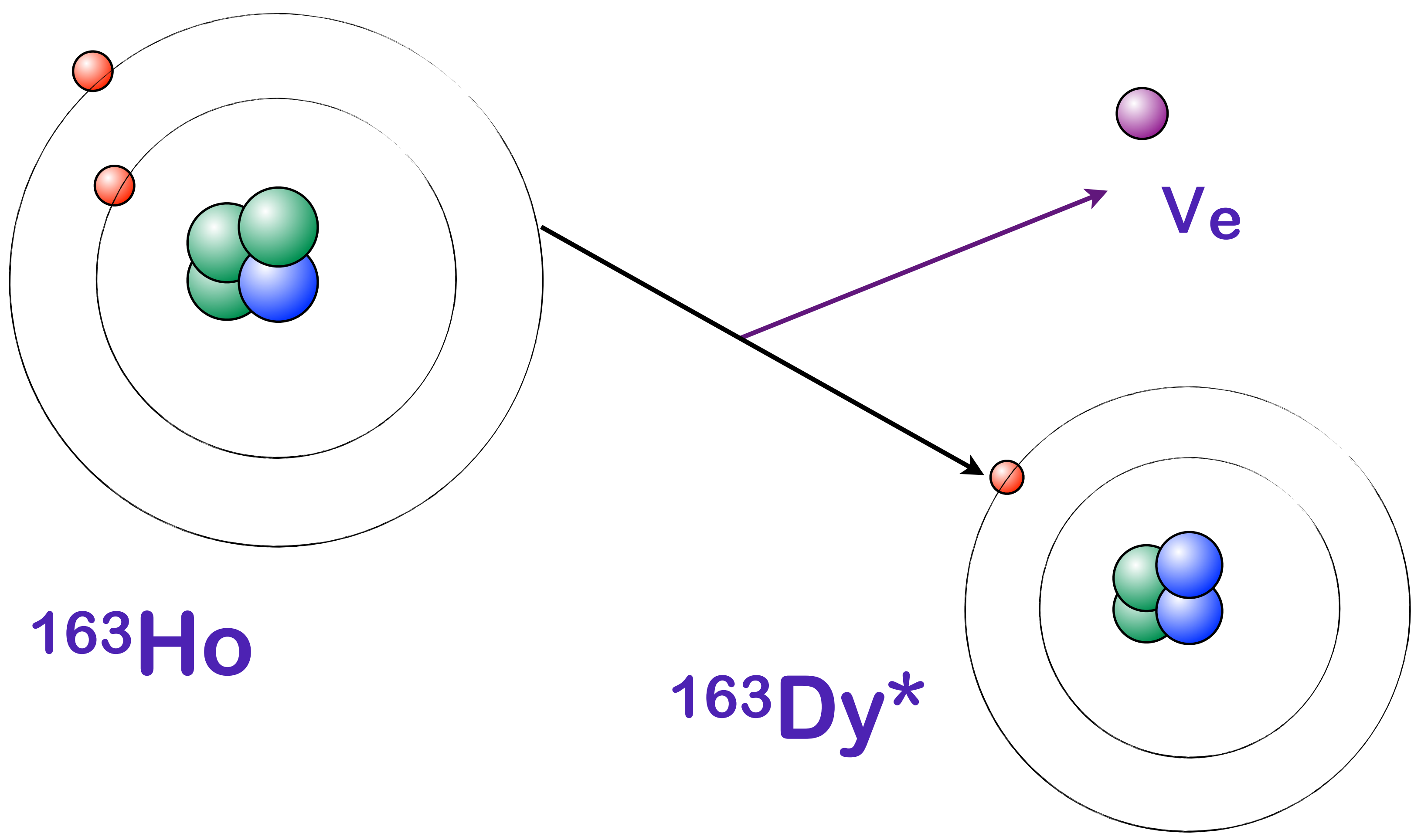
In his paper, Fermi already sketches out how one can do this.

Tritium beta decay



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

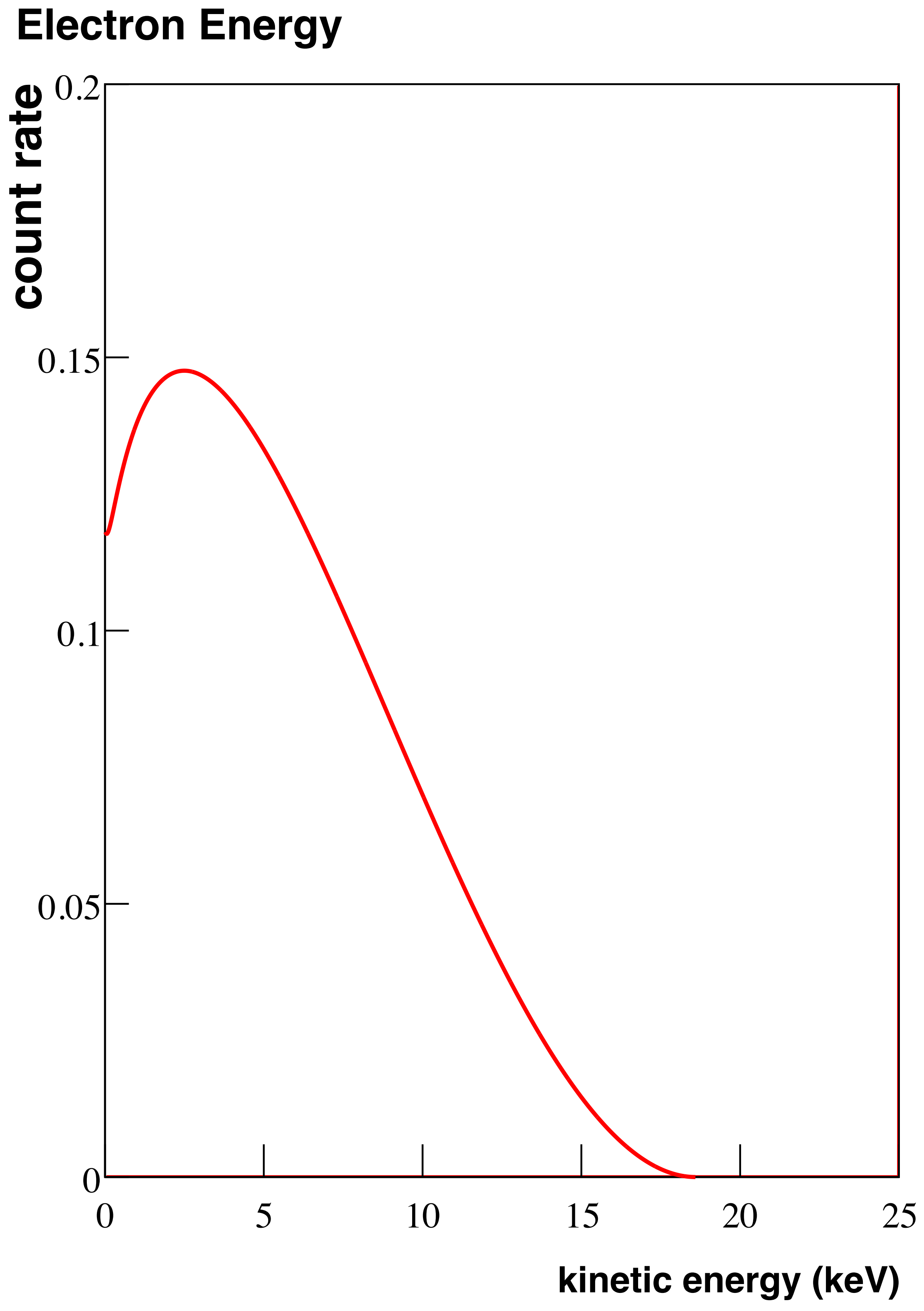
Holmium electron capture



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

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

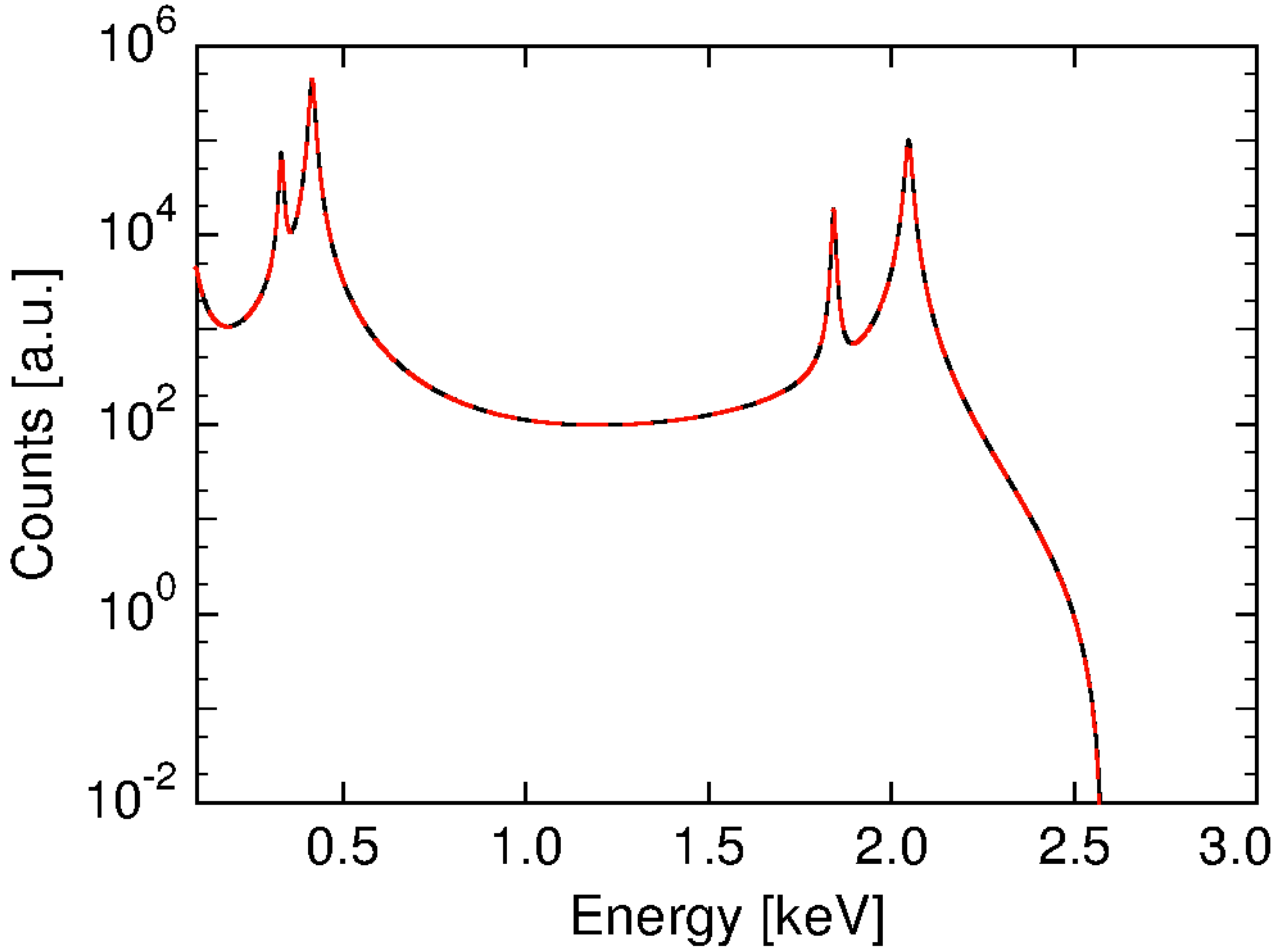
Tritium beta decay



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

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

Holmium electron capture



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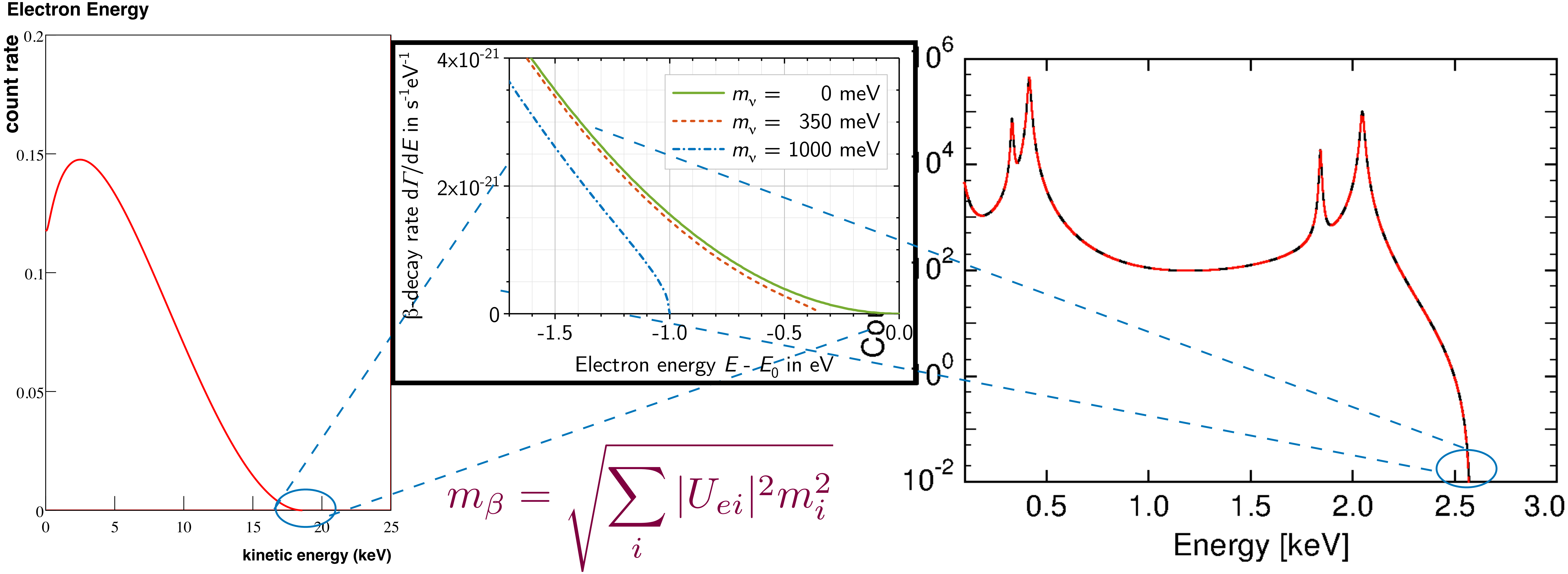
Tritium beta decay

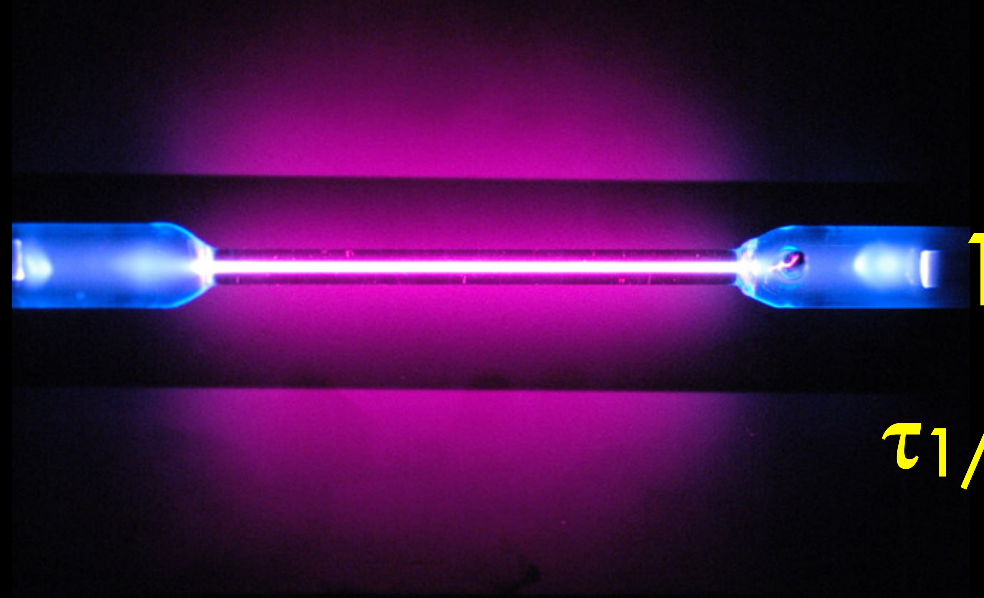
Holmium electron capture



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

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.



$^3H_2$

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	Specific Activity	Q_A	Branching ratio	Last eV	Source Mass
		y	Bq/g	eV			g
$^3H_2$	$1/2^+ \to 1/2^+$	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		$\sim 10^{-12}$	$\sim 1.0 \times 10^{-5}$

^{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.

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Amount needed to see 1 event per day in last eV

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MAC-E Filter

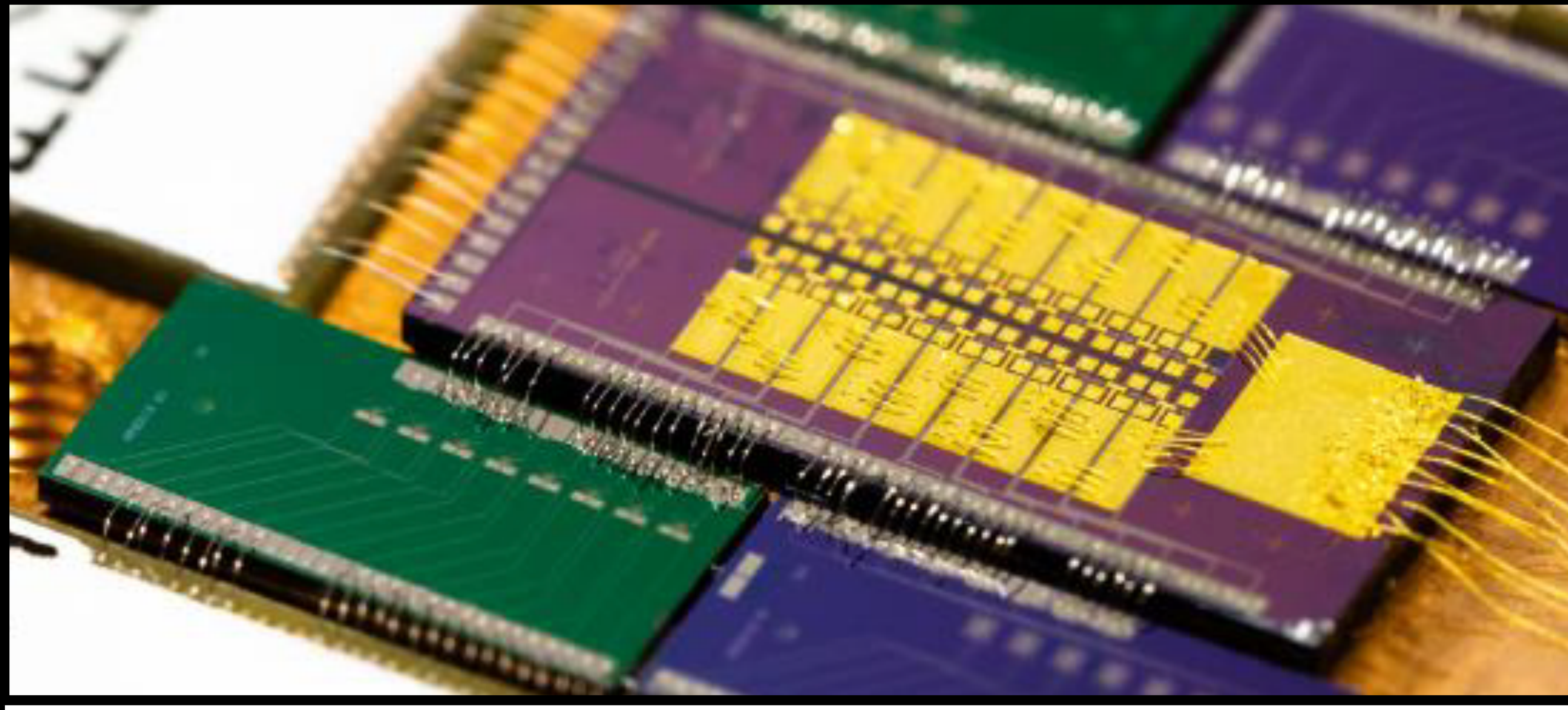
Magnetic Adiabatic Collimation with Electromagnetic filtering

Experiment(s): Mainz, Troisk, **KATRIN**

Calorimetry

Total energy absorption using bolometers.

Experiment(s): **ECHO, HOLMES**



Cyclotron Radiation Emission Spectroscopy

Microwave frequency measurement.

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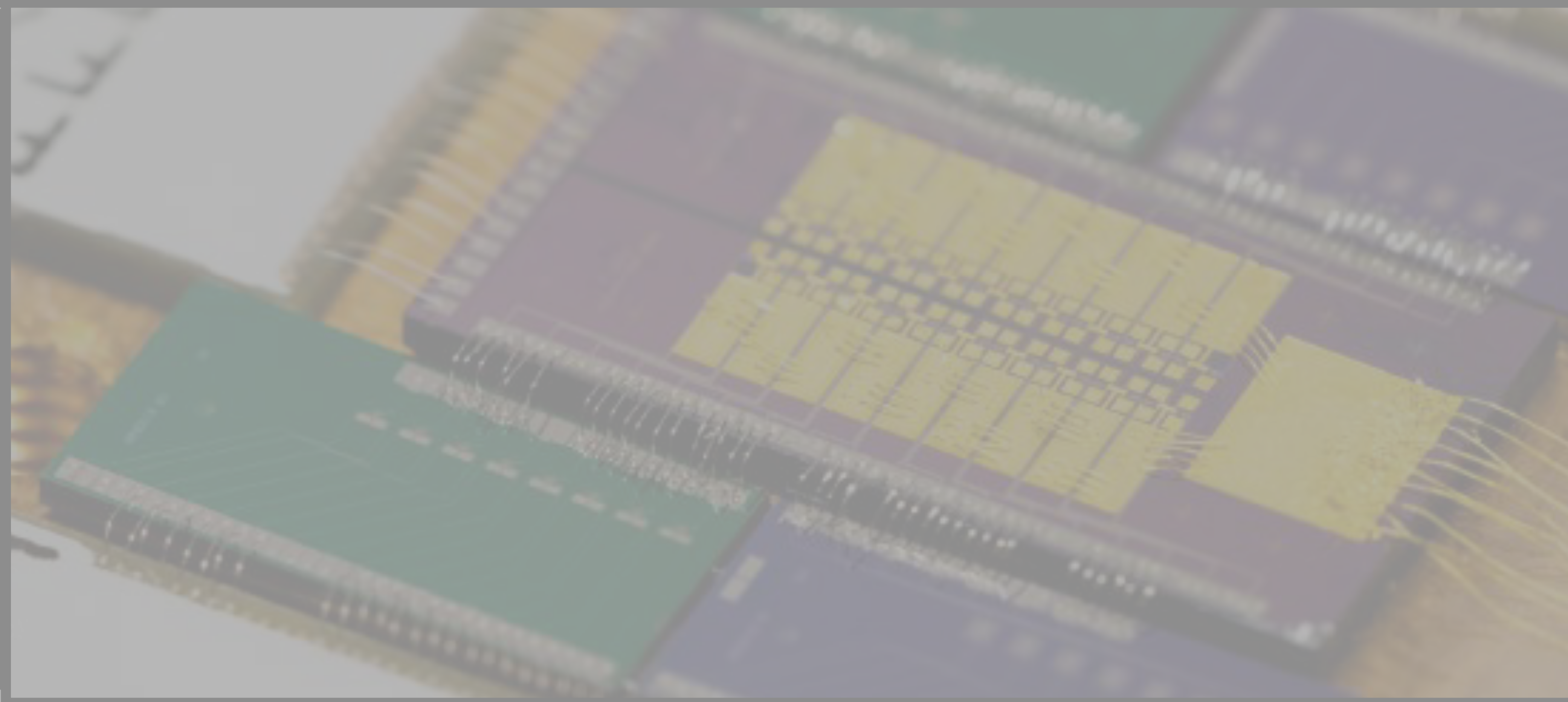

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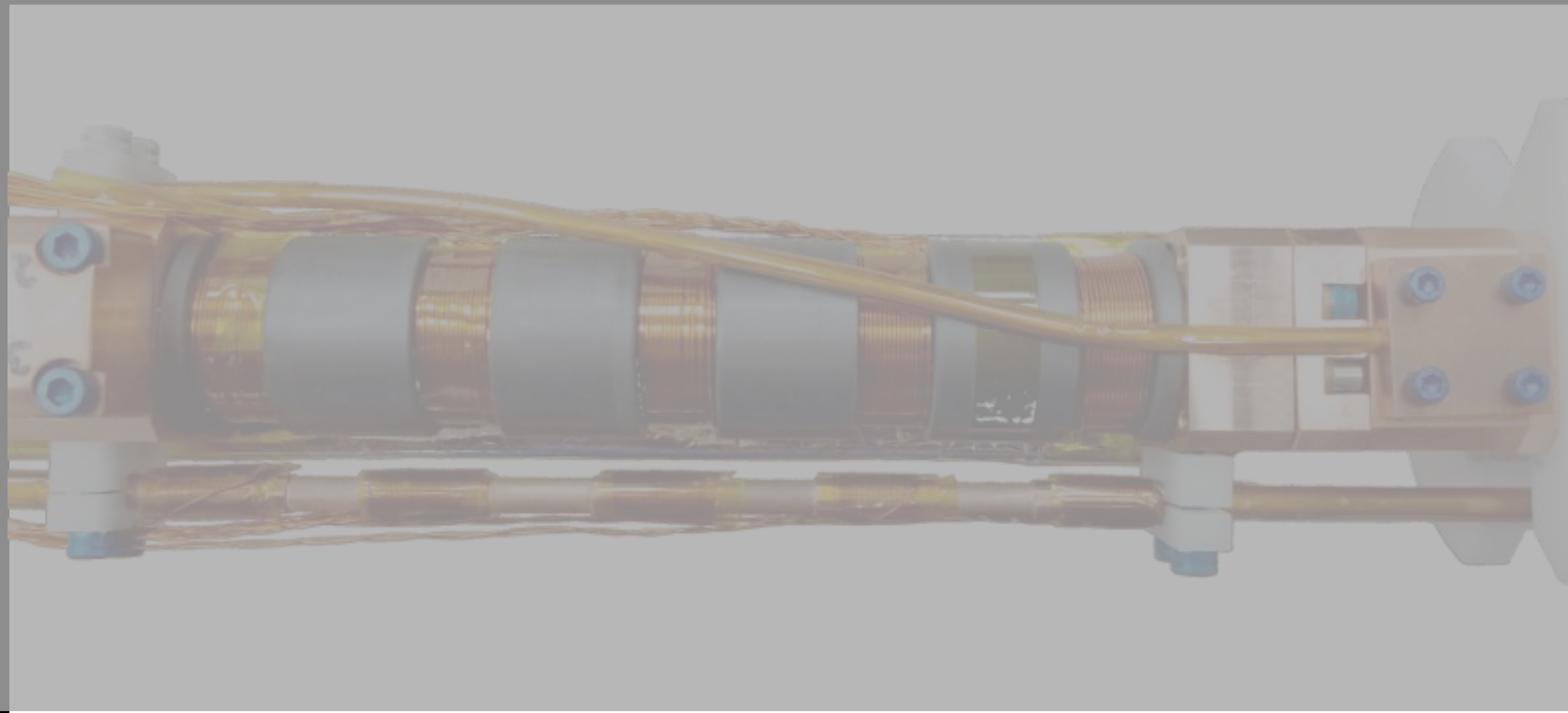

High Magnetic Field (Bs)

Low Field B_A

High Magnetic Field (Bs)

Magnetic Adiabatic Collimation w/ Electrostatic Filtering

(only electrons with enough energy can overcome potential barrier)

Karlsruhe Tritium Neutrino Experiment: Sensitivity goal of $m_\beta \leq 200$ meV/c^2 (at 90% C.L.).

Use molecular T_2 as source, using *filtering* to measure electron energies.

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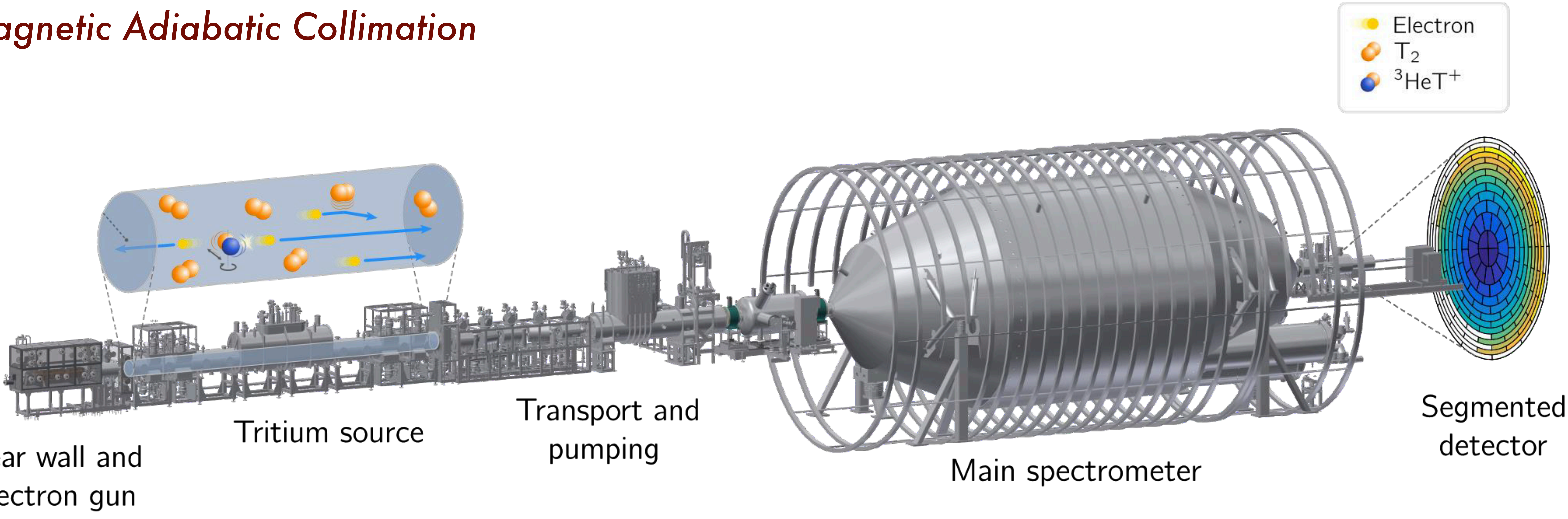

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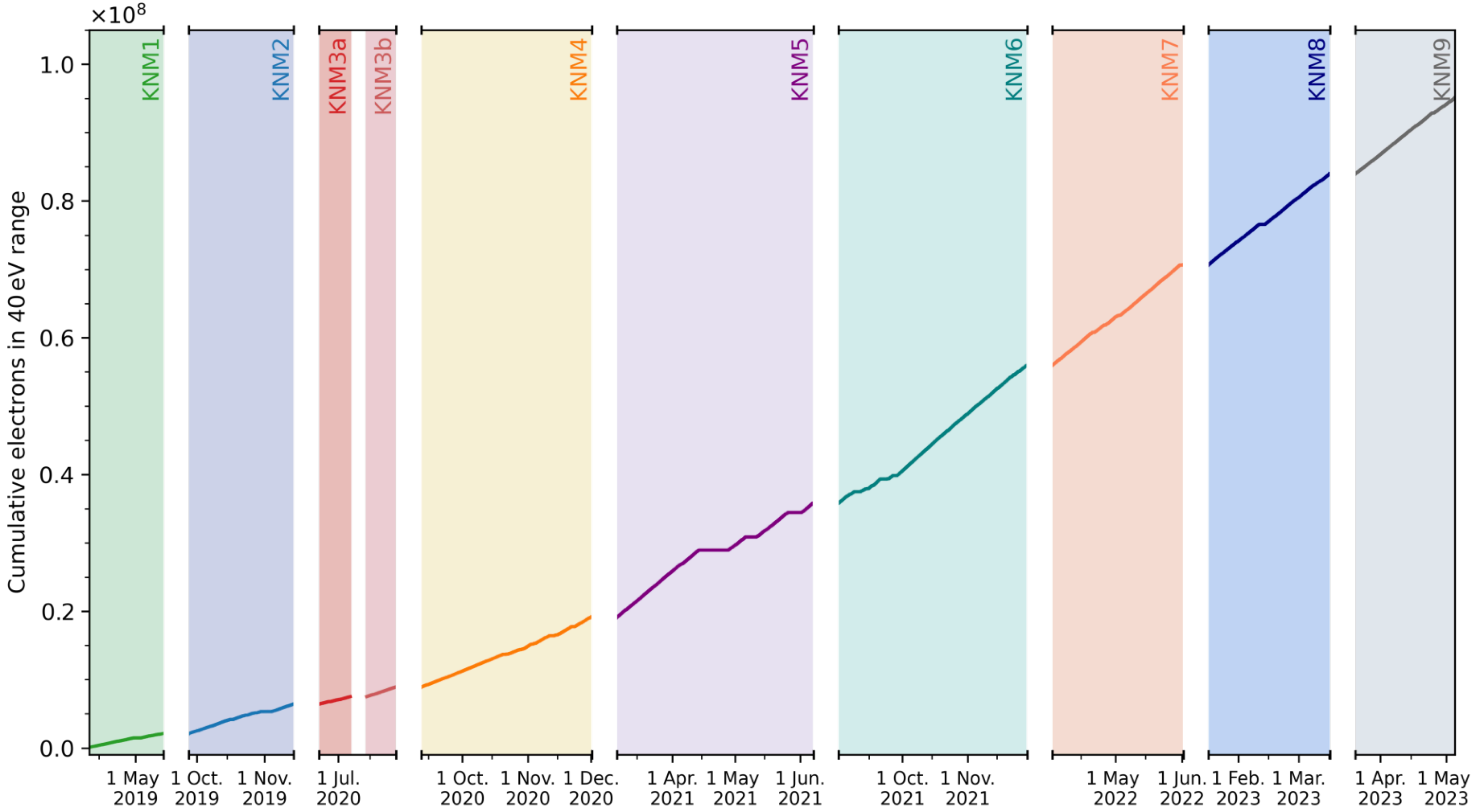
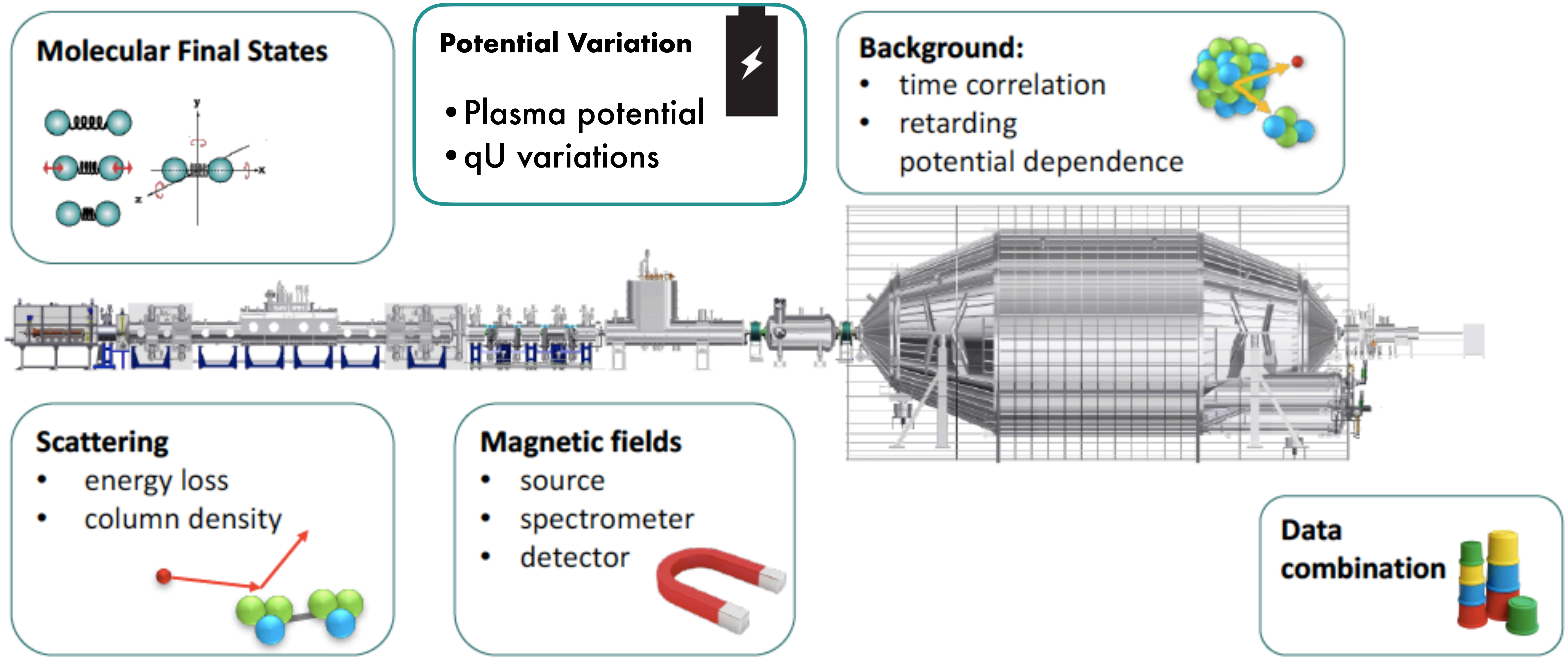
A long journey in the making...

Data taking commenced in May 2019 and is ongoing.

Statistical Uncertainty



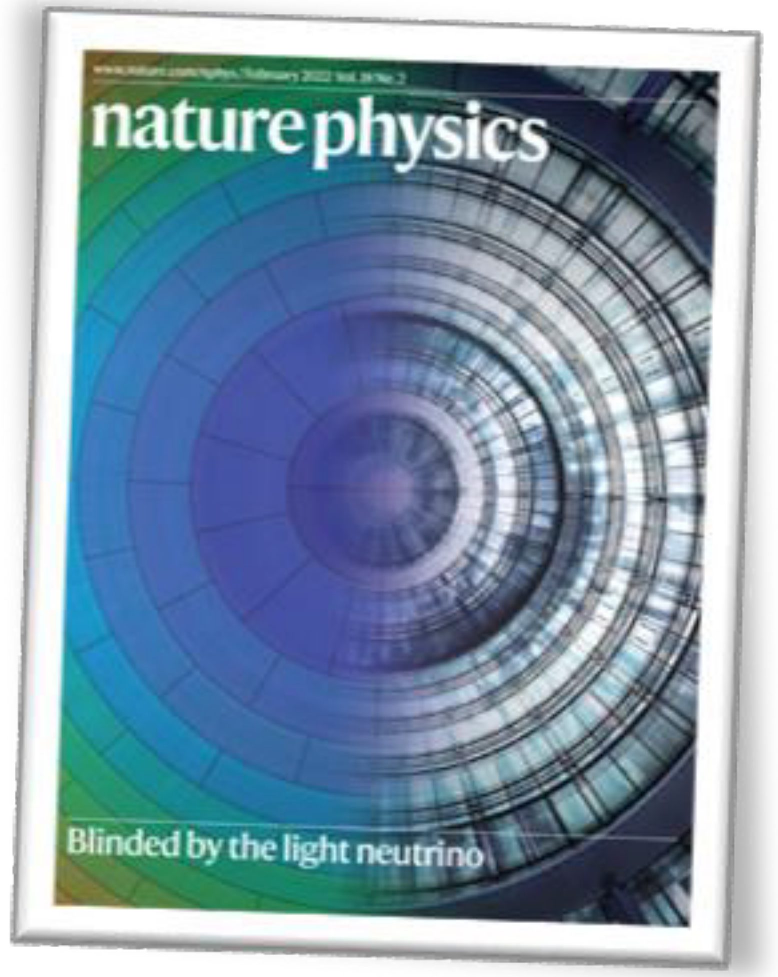


Detailed control of systematics and backgrounds.

Phys. Rev. Lett. 123, 221802 (2019)
Phys. Rev. D. 104 (1), 012005 (2021)

Limits from 1st Campaign:

m_β < 1.1 eV (@ 90 % C.L.)

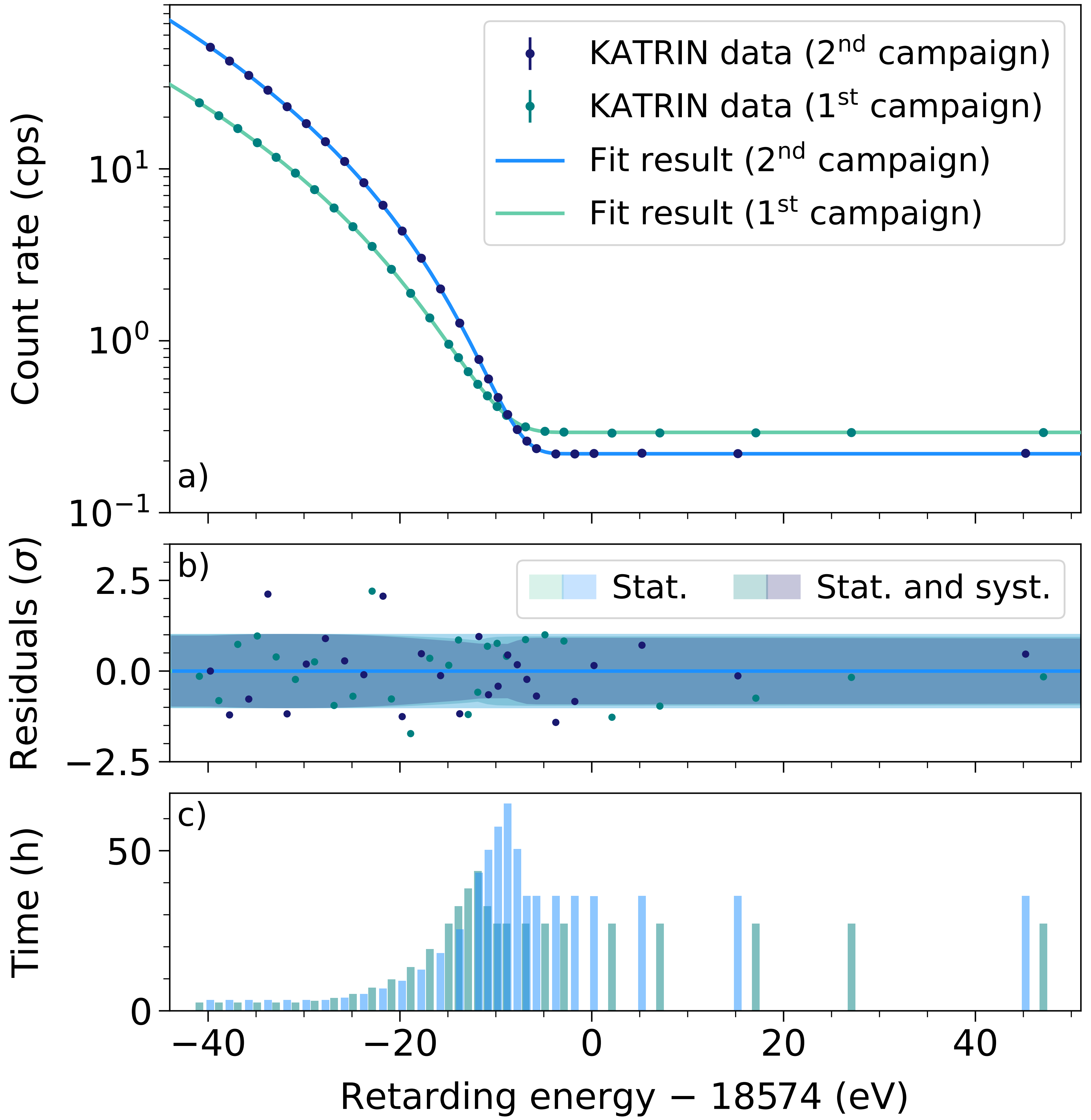


Nat. Phys. 18, 160–166 (2022)

Combined 1st & 2nd Campaign:

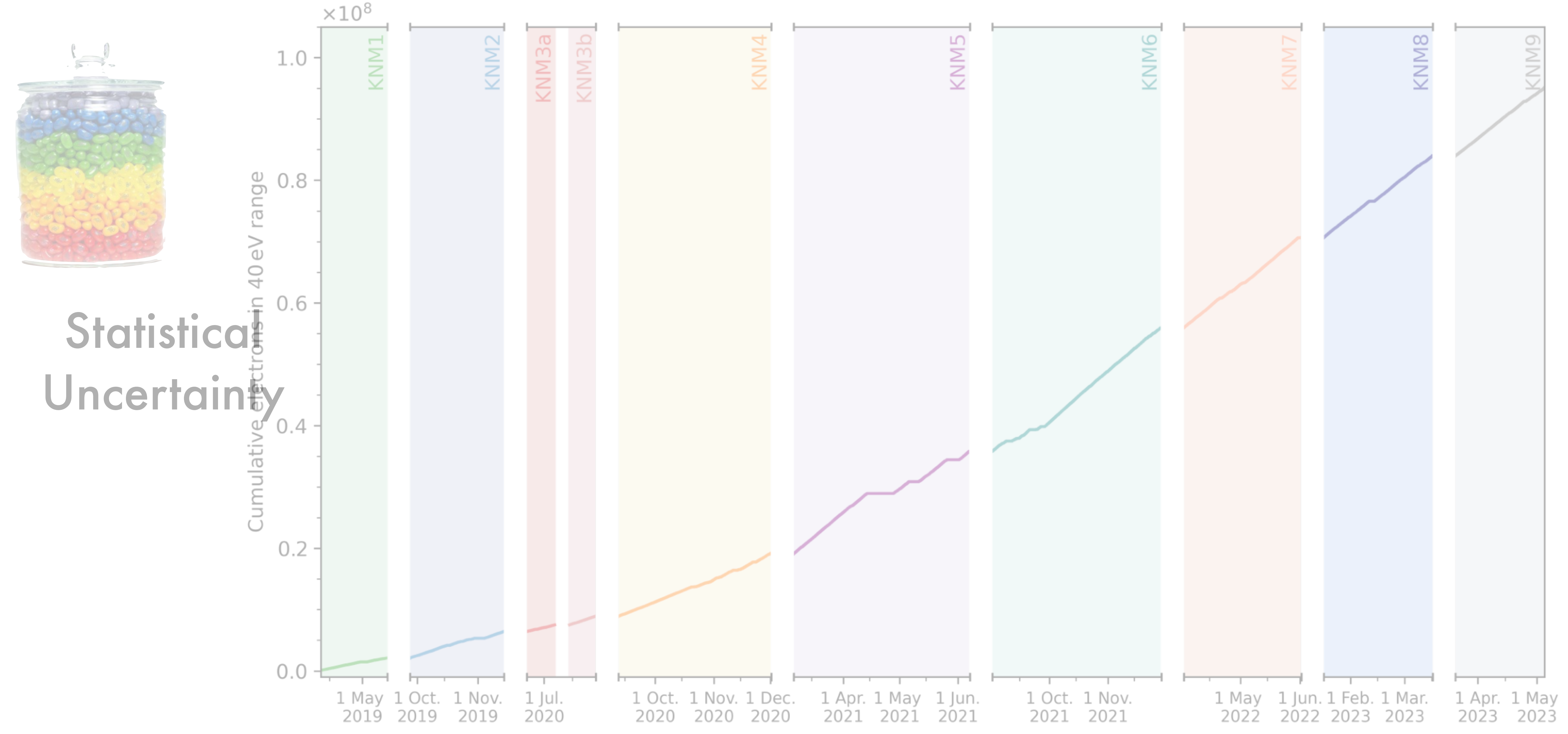
m_β < 0.8 eV (@ 90 % C.L.)

For the first time the eV scale is broken!



Up Next...

Systmatics and statistics continuously improving



Analysis of first five runs is being finalized:

Sensitivity: 0.5 eV (90% C.L.)

KNM11 data taking ongoing

Planned data taking until 2025 to complete 1000 days of measurement.

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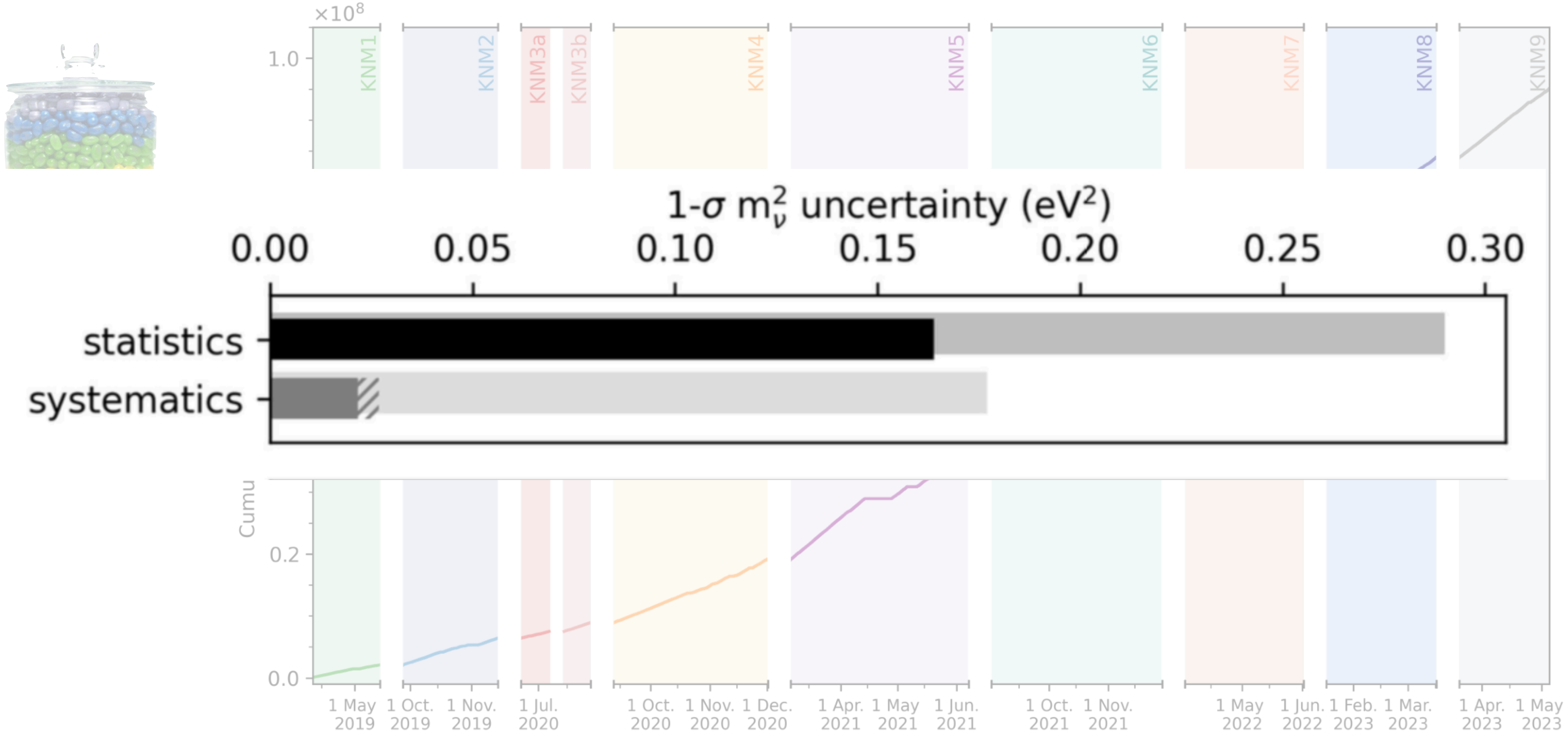

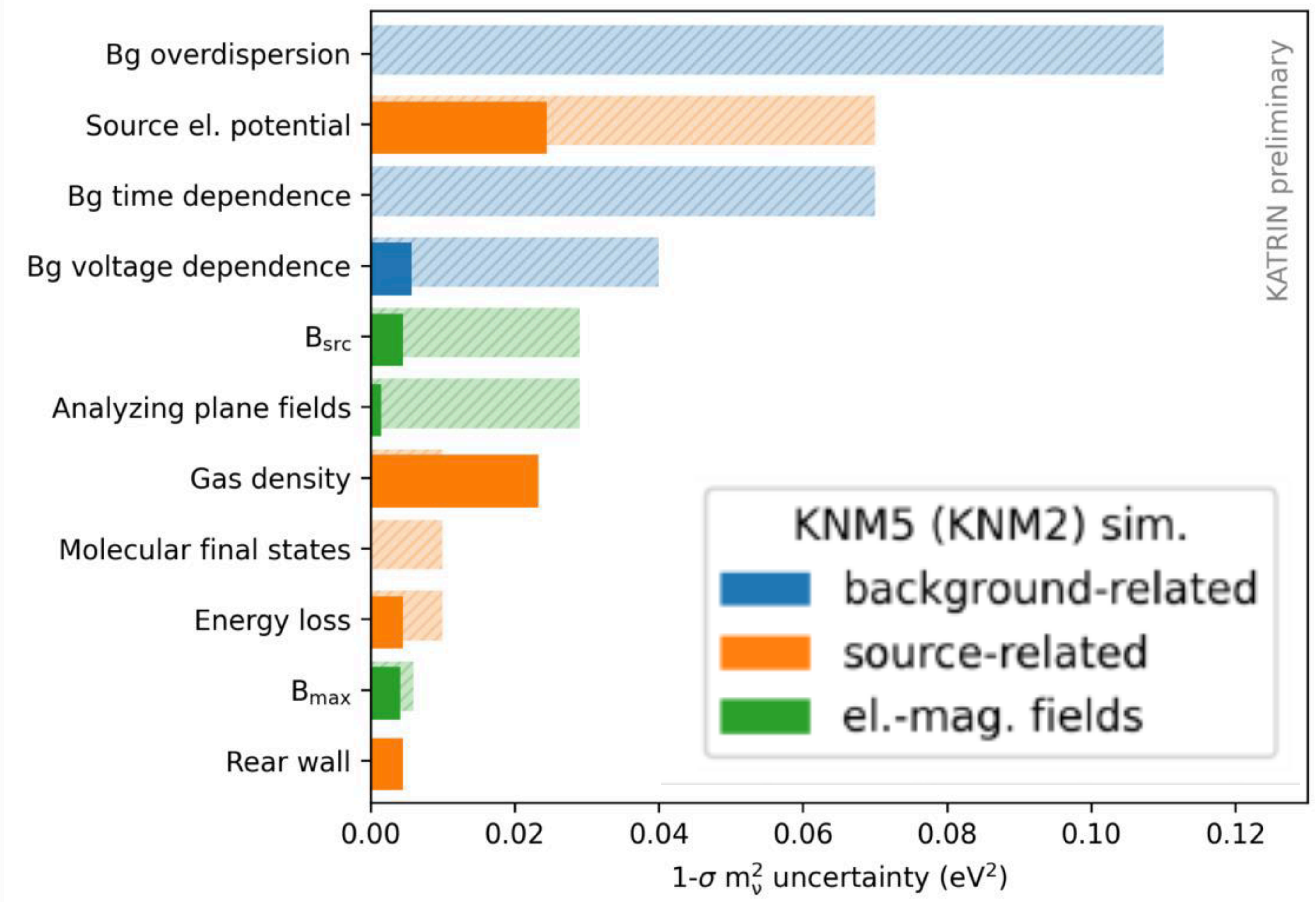

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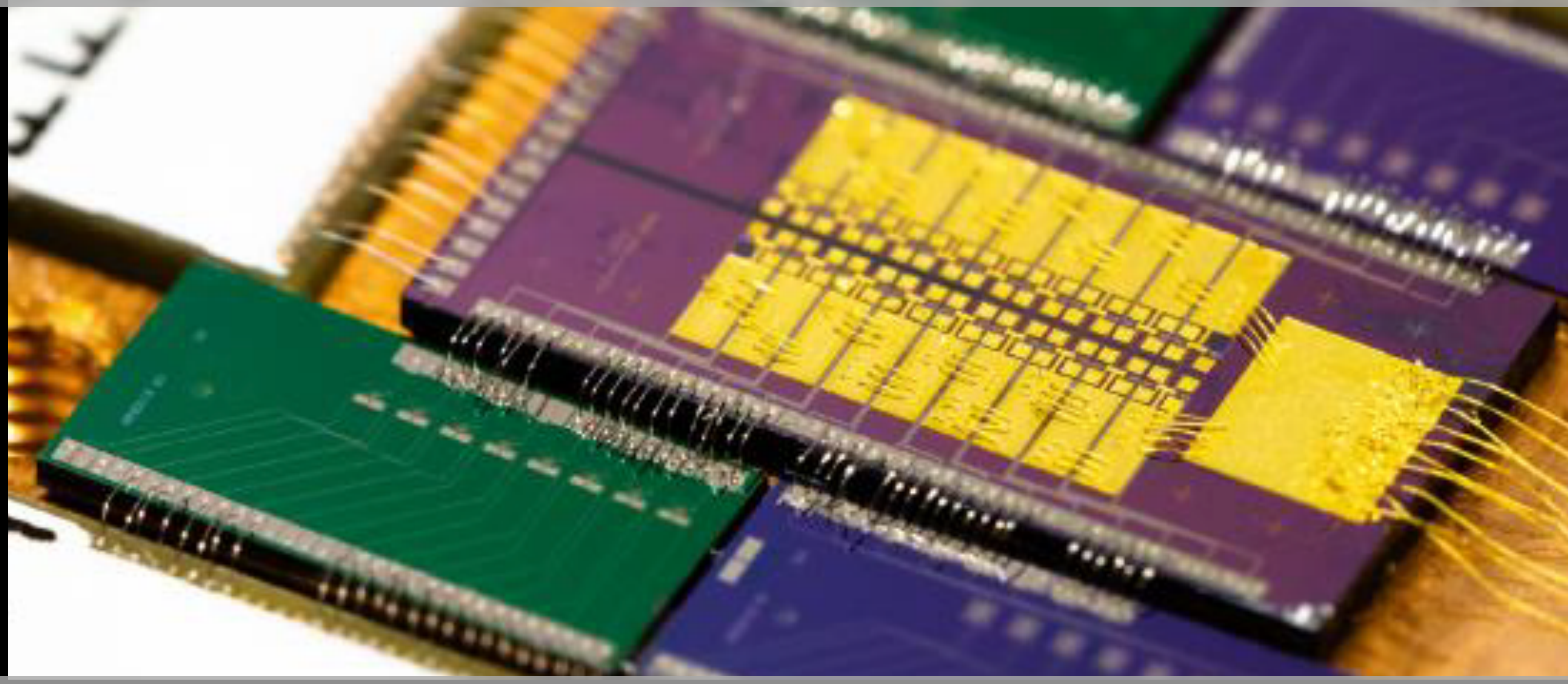

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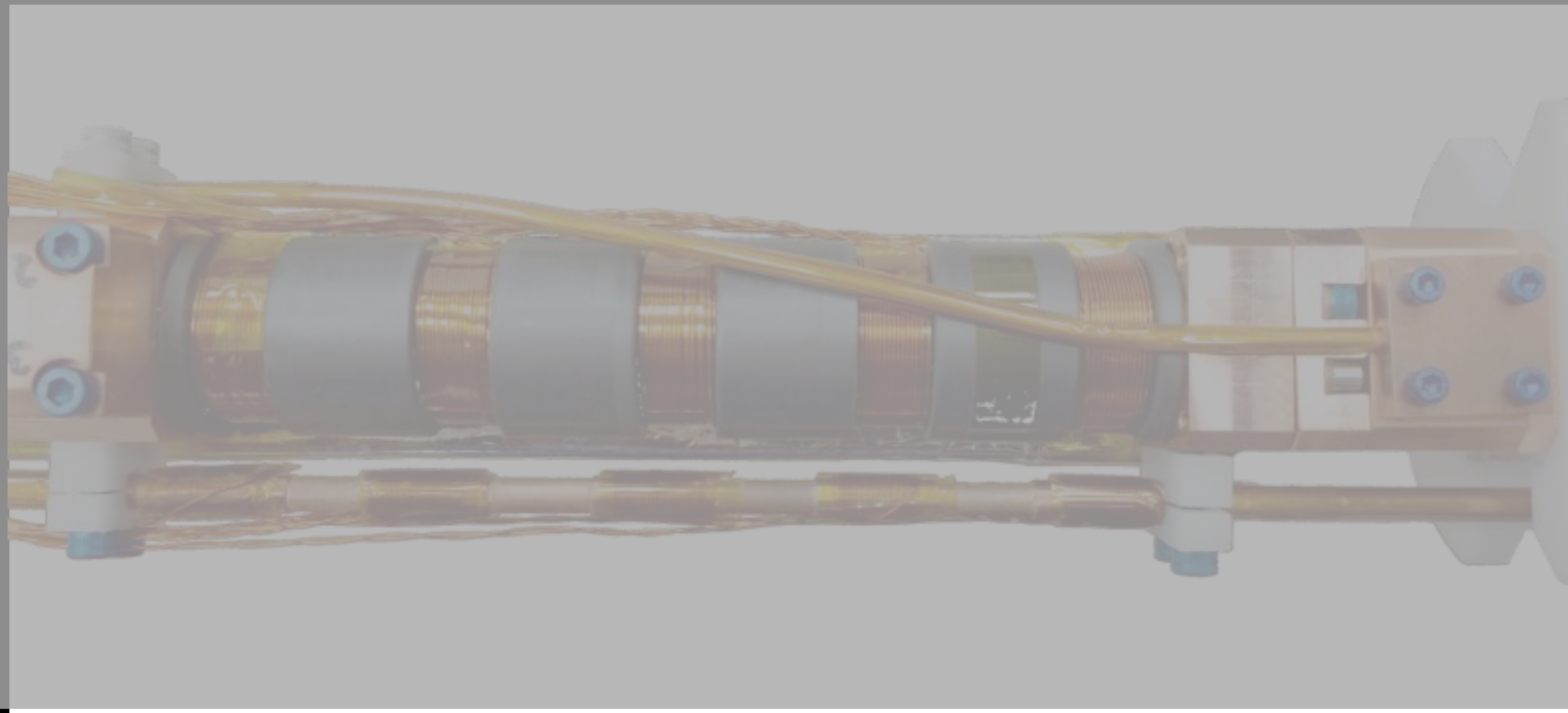
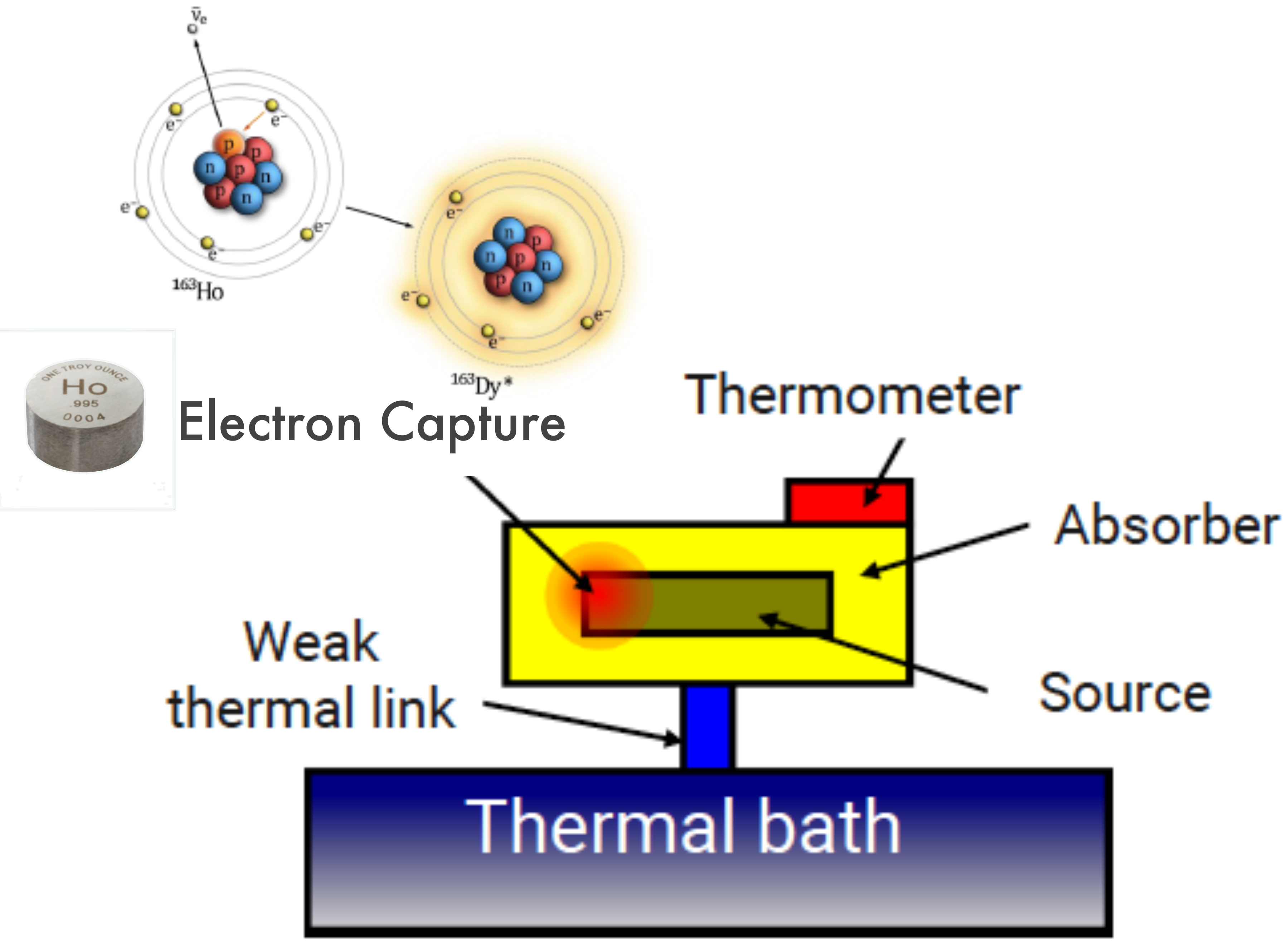
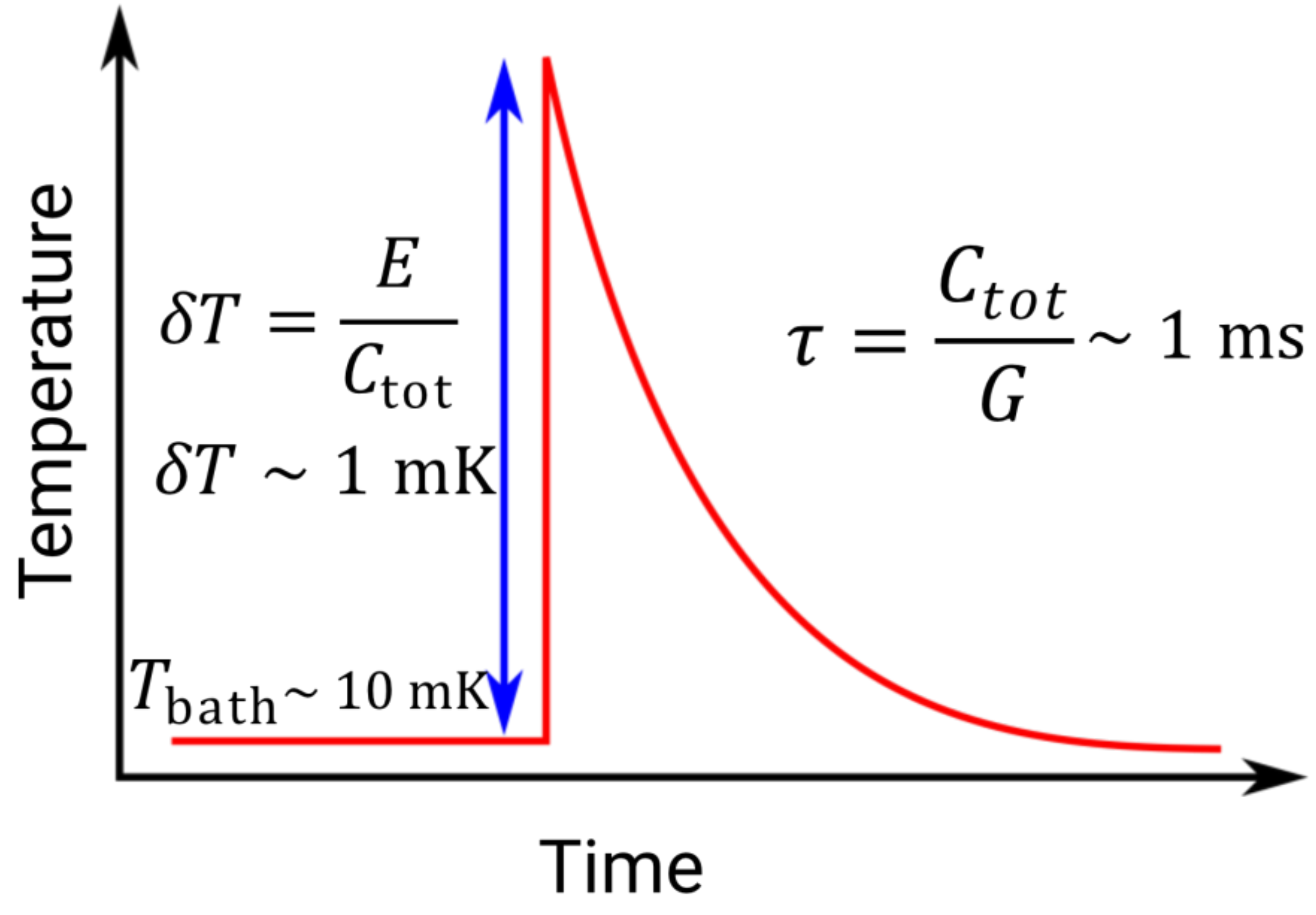


μ-calometer



Energy Measurement

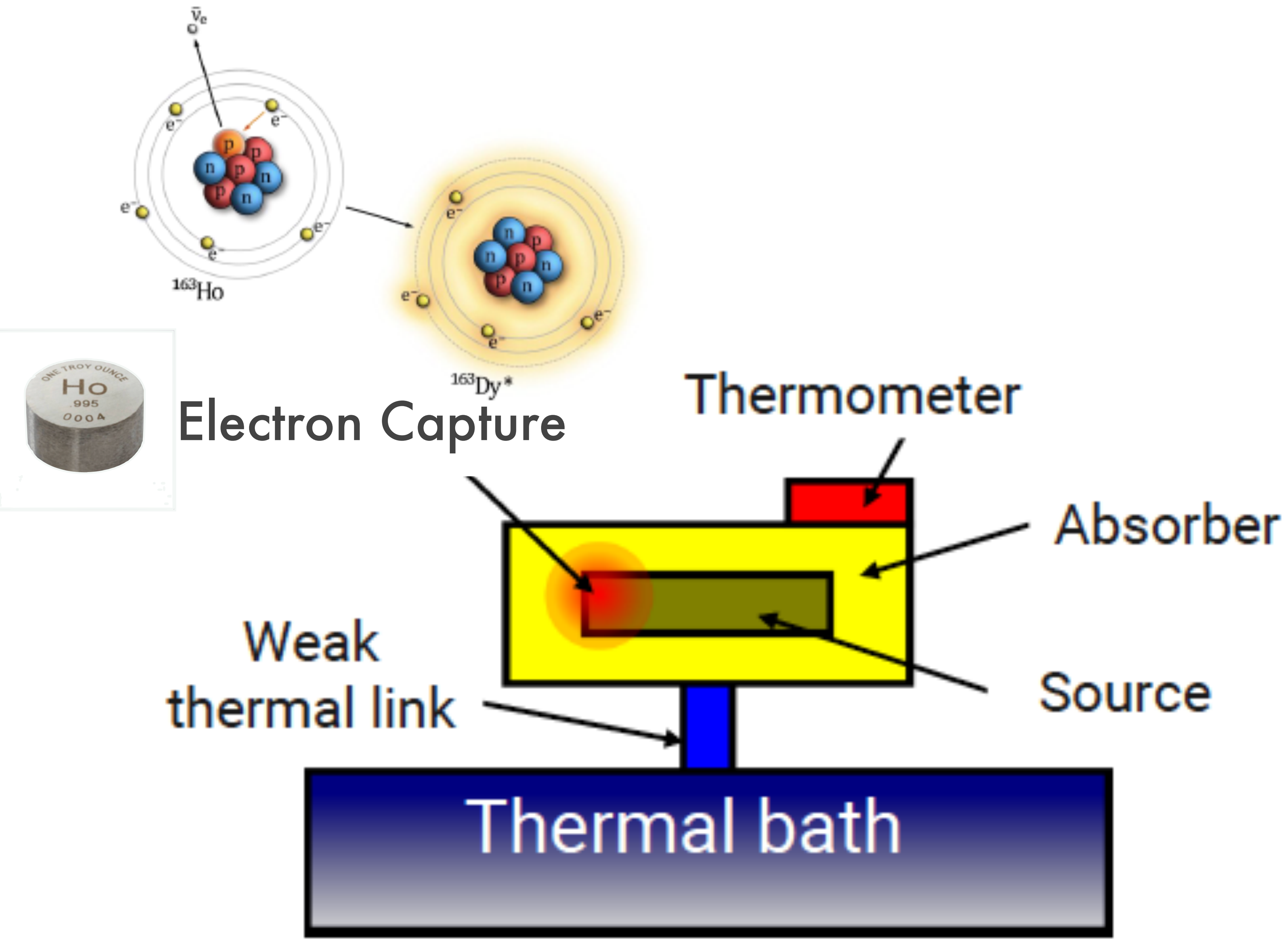


Calorimeters can access full decay of electron capture process of ^{187}Ho.

Leverage high energy resolution of micro-calorimeters to measure EC spectrum.

Readout?

μ-calometer



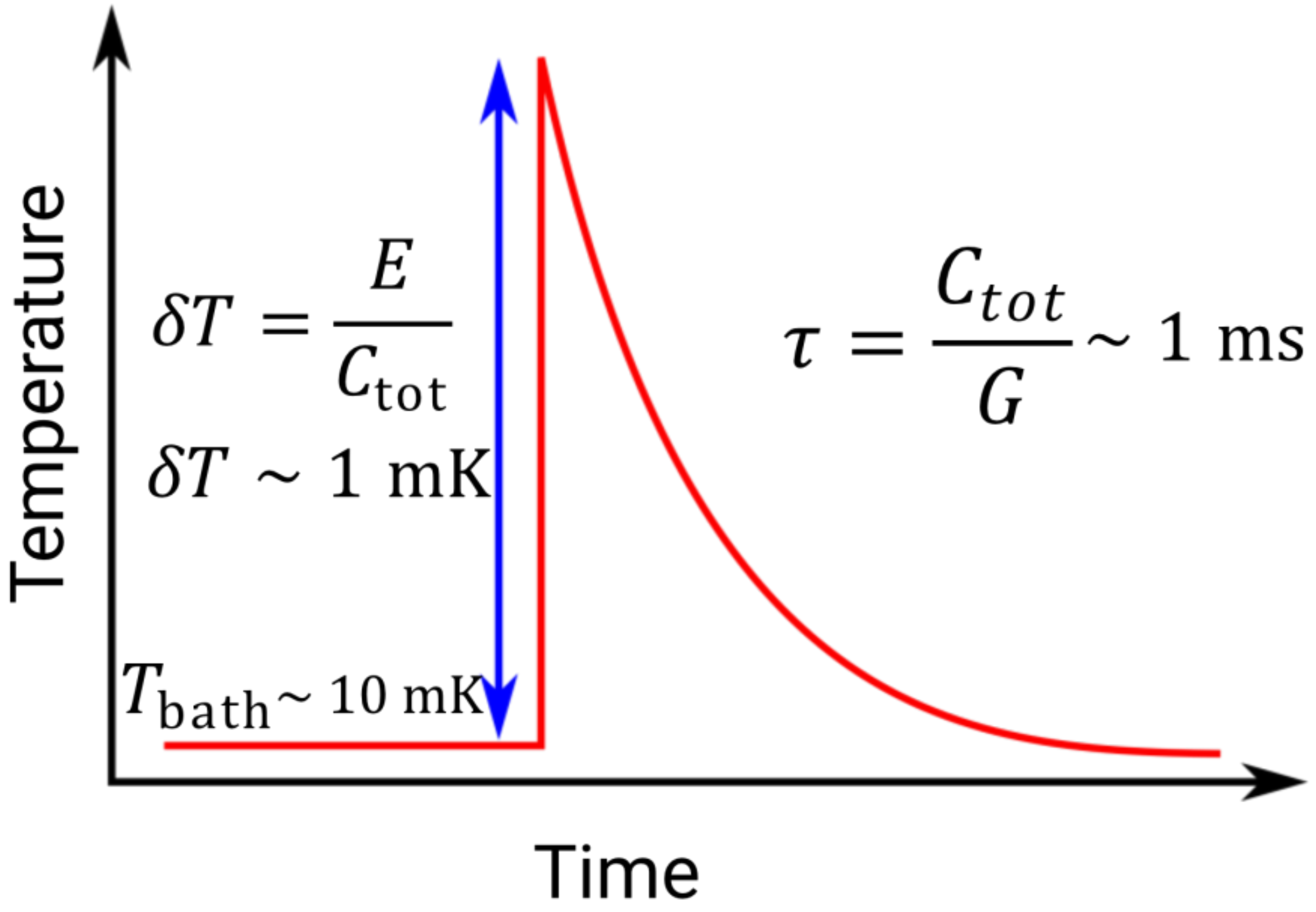
Magnetic microcalorimeters?

ECHo

Transition Edge Sensors?

HOLMES

Energy Measurement



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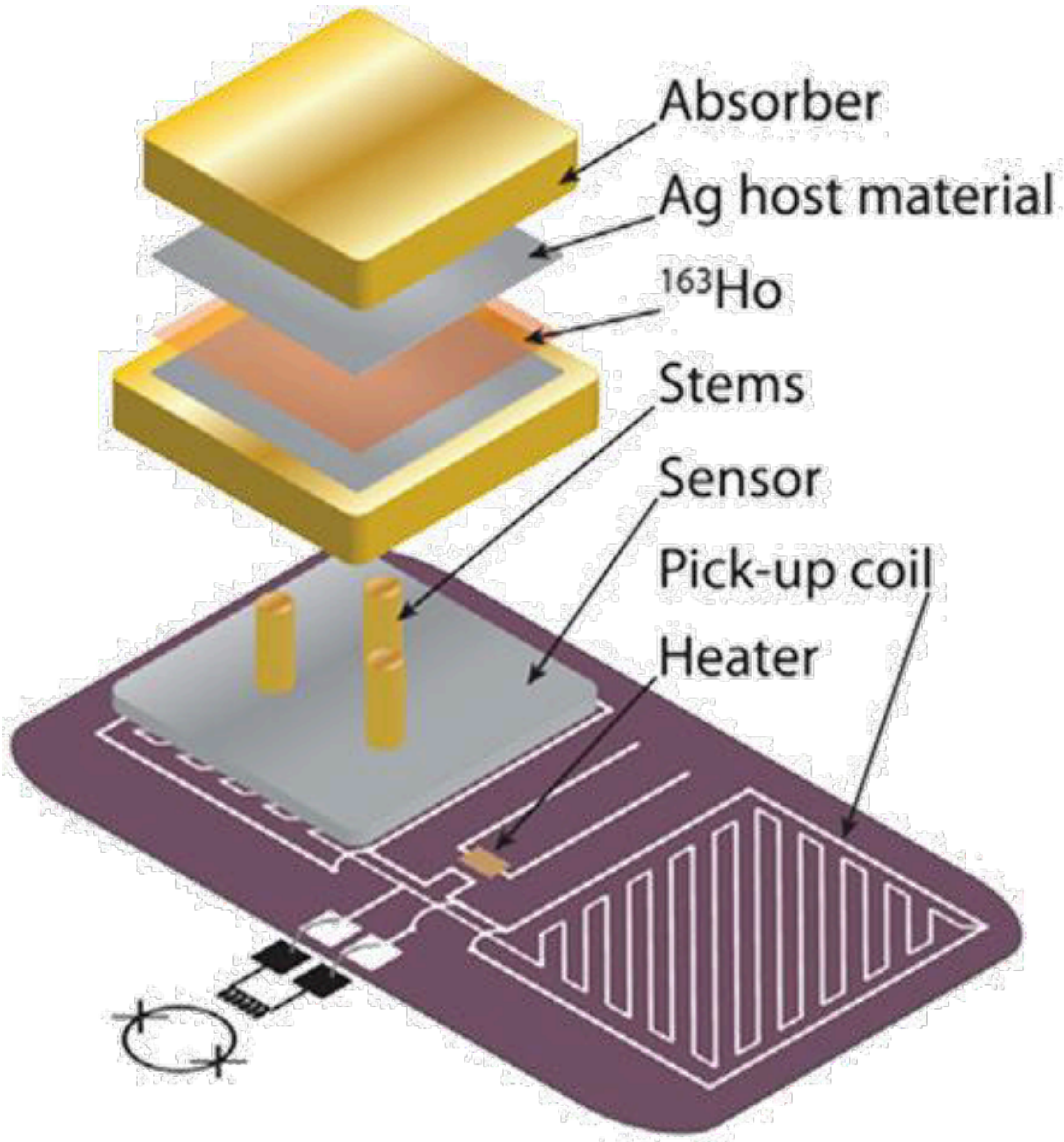
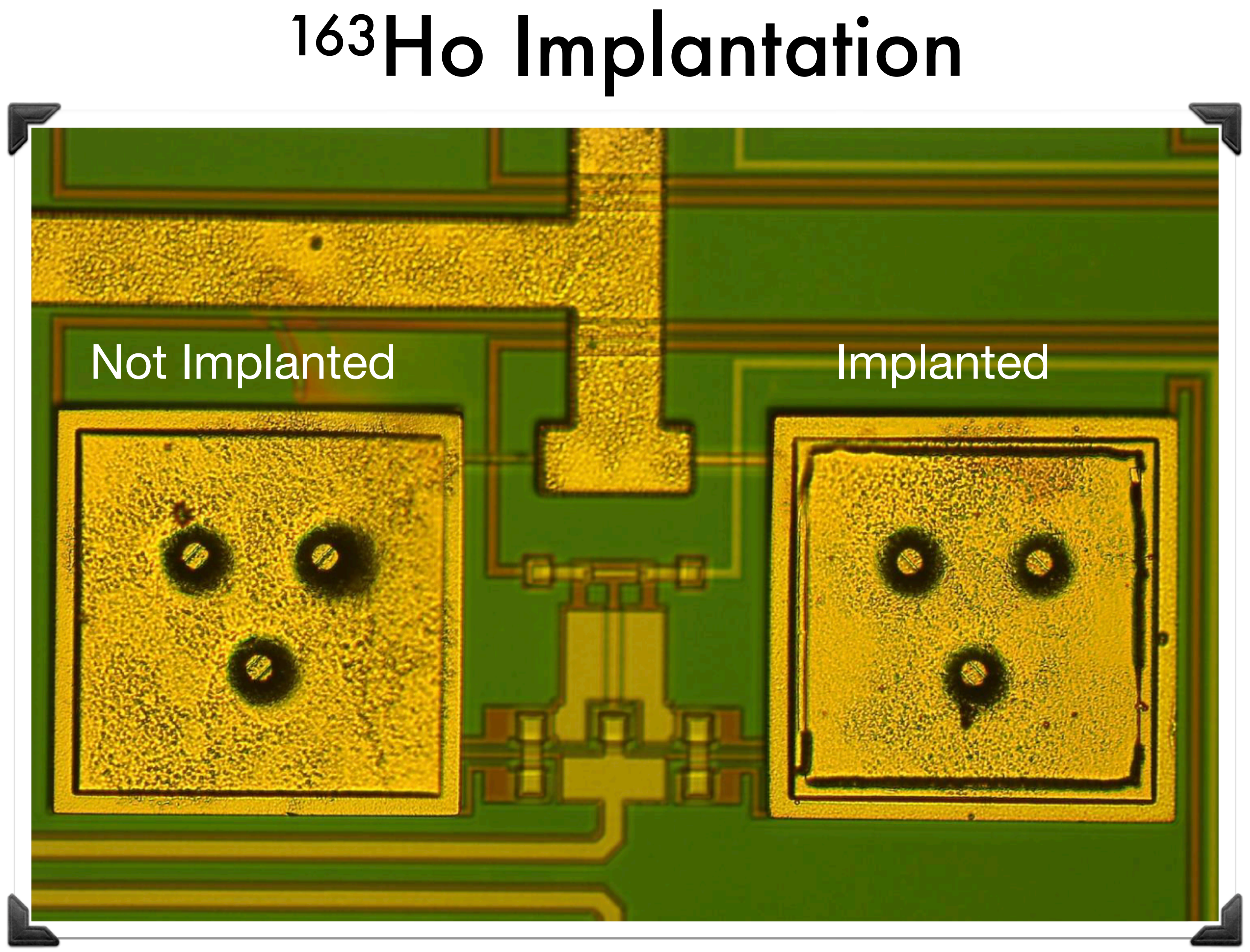
: Proof-of-Principle



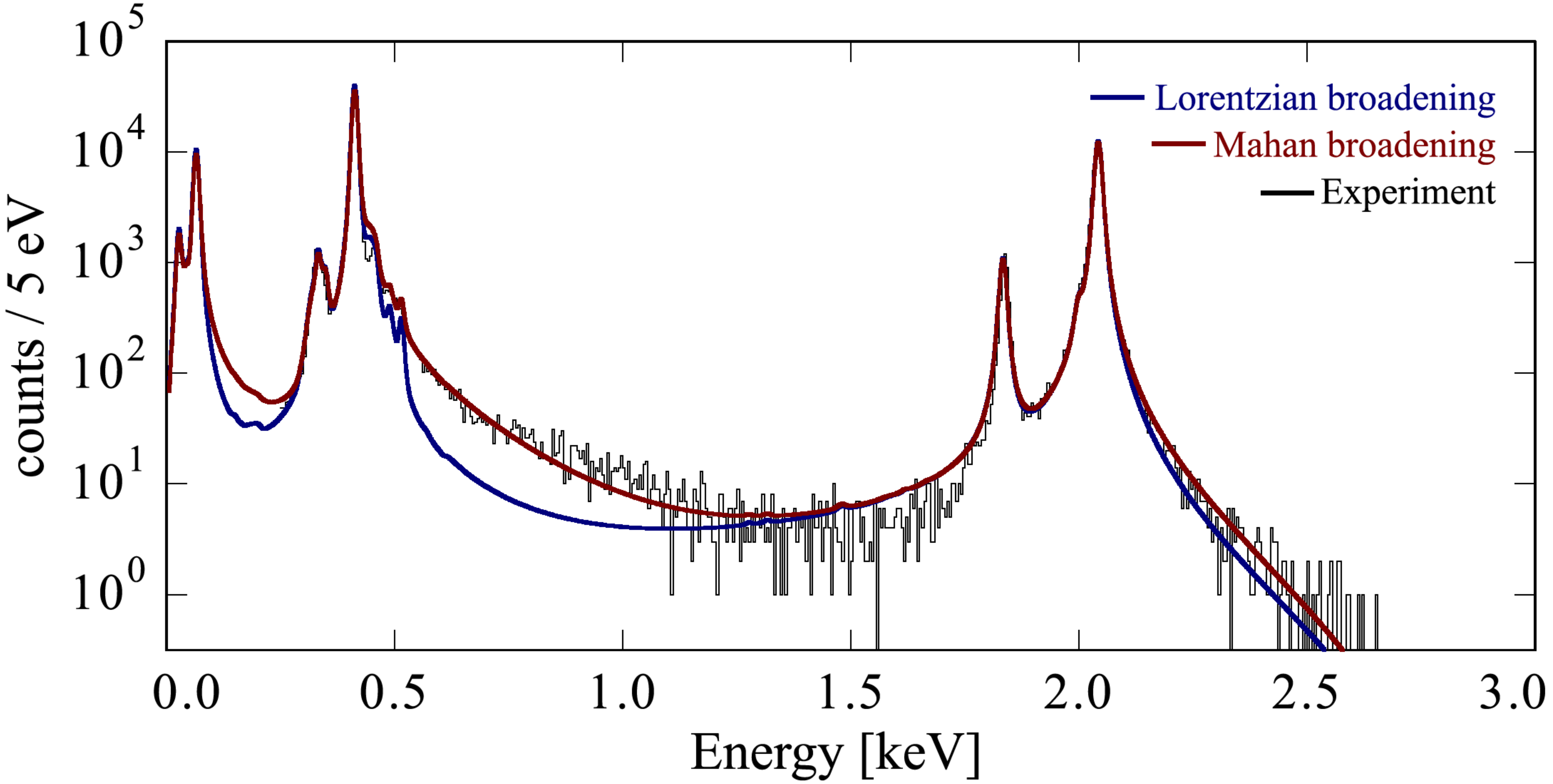


Proof of principle measurement taken with 4 day measurement with 4 pixels.

Q_{EC} : (2838 ±14) eV

m_β < 150 eV (95% C.L.)

Also demonstrated low background & high energy resolution.



ECHo : Coming Up

<u>ECHo-1k –high-statistics spectrum</u>

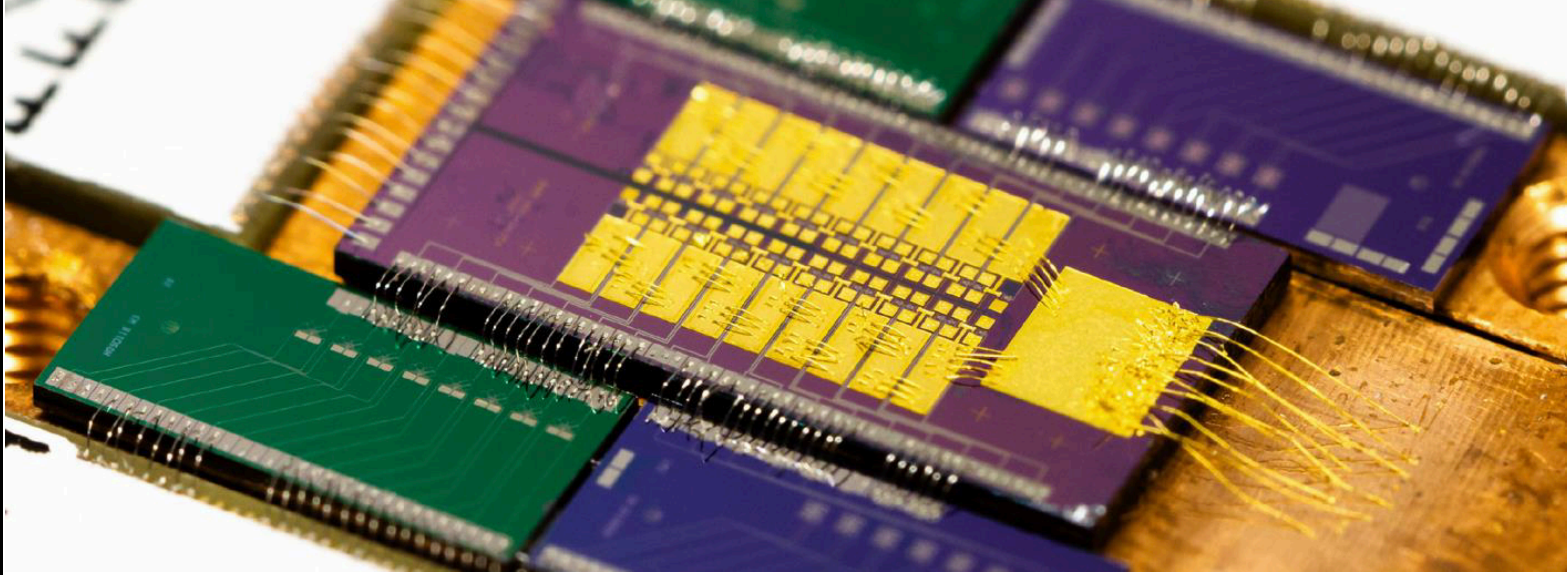
Au-chip : 23 pixel with implanted ^{163}Ho

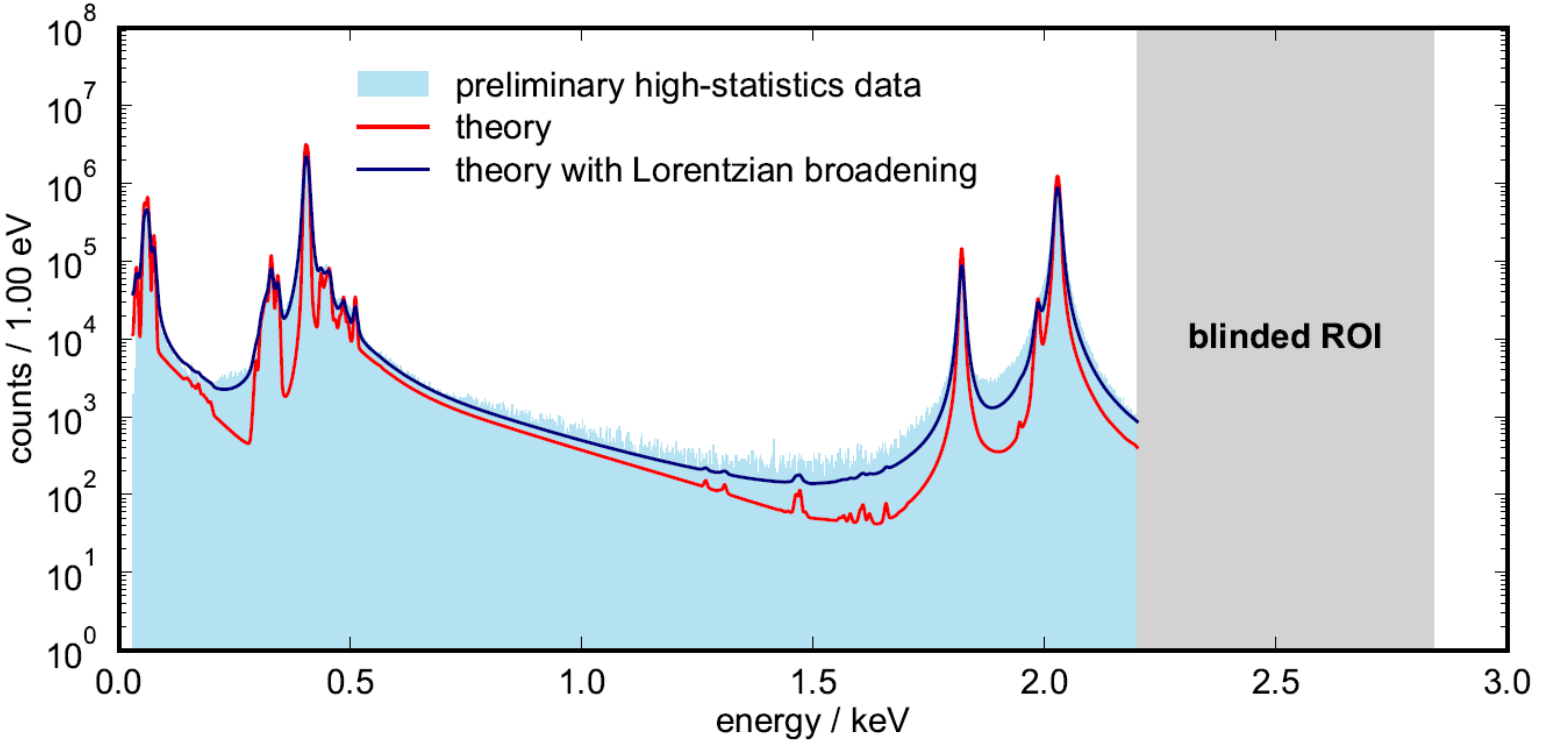
Ag-chip : 32 pixel with implanted ^{163}Ho

100M decay events collected.

Ongoing analysis of systematics

Expected sensitivity: $m_\beta < 20$ eV (95% C.L.)





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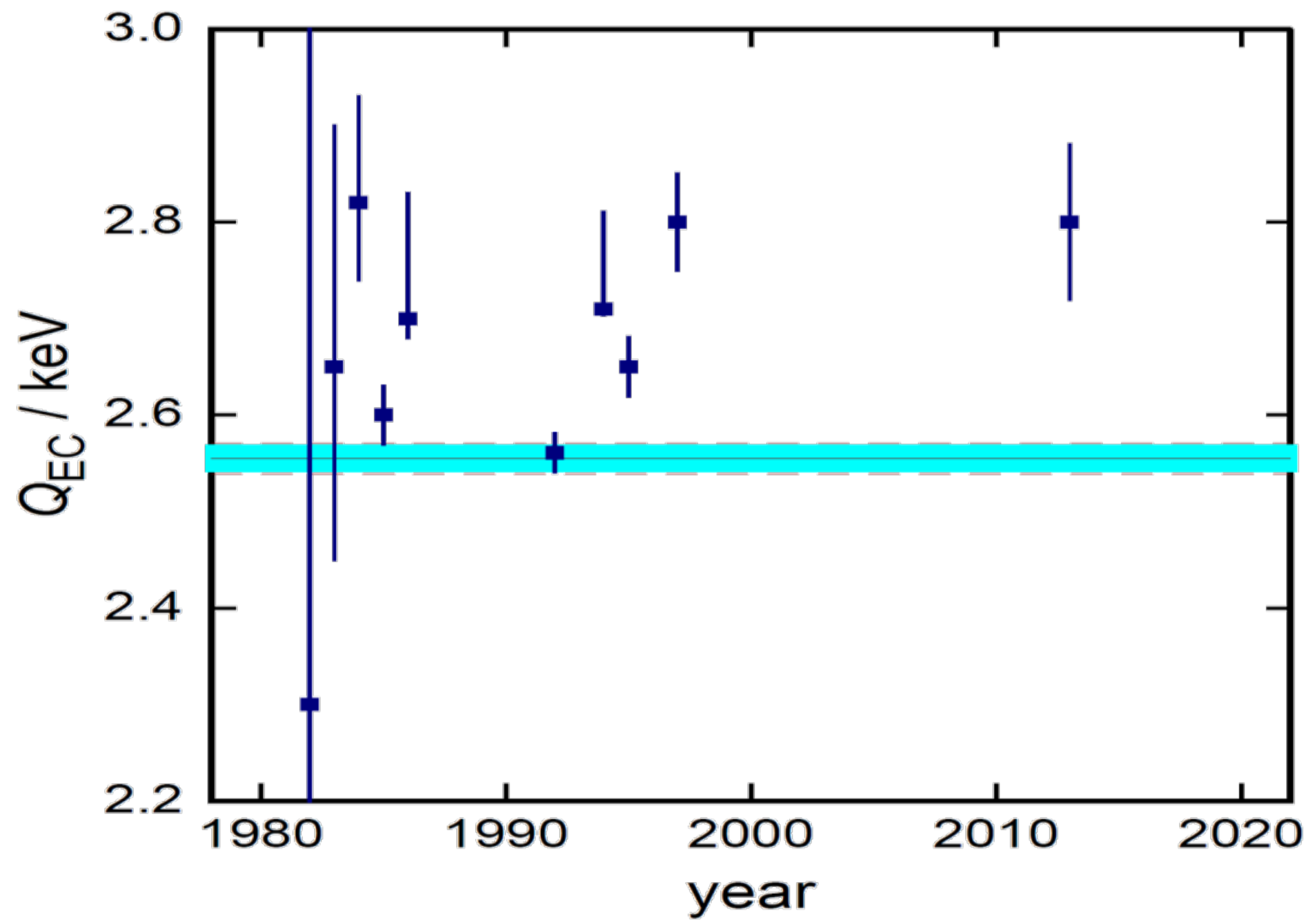
ECHo-100k

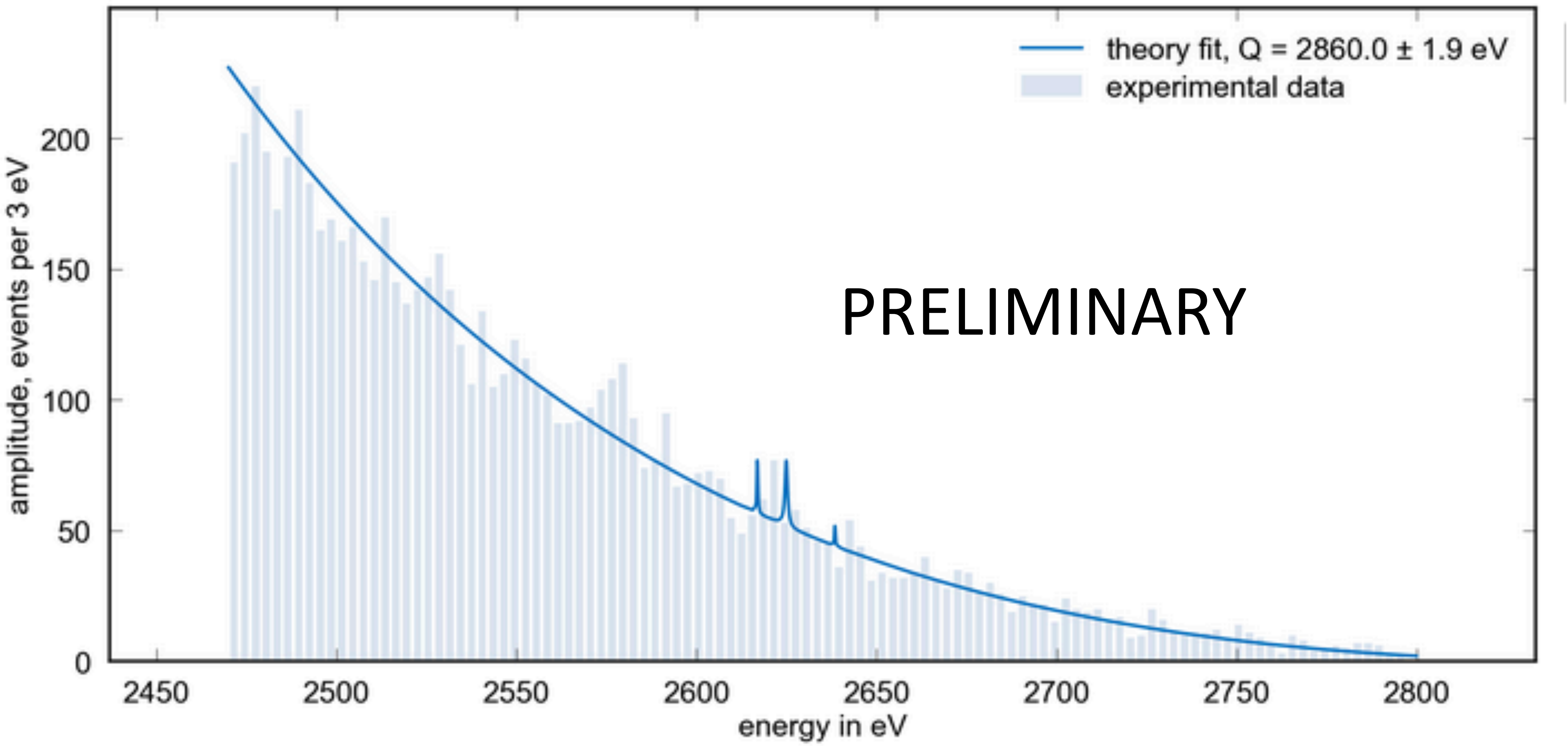
(1200 detectors)

under construction for eV level sensitivity.



PRELIMINARY

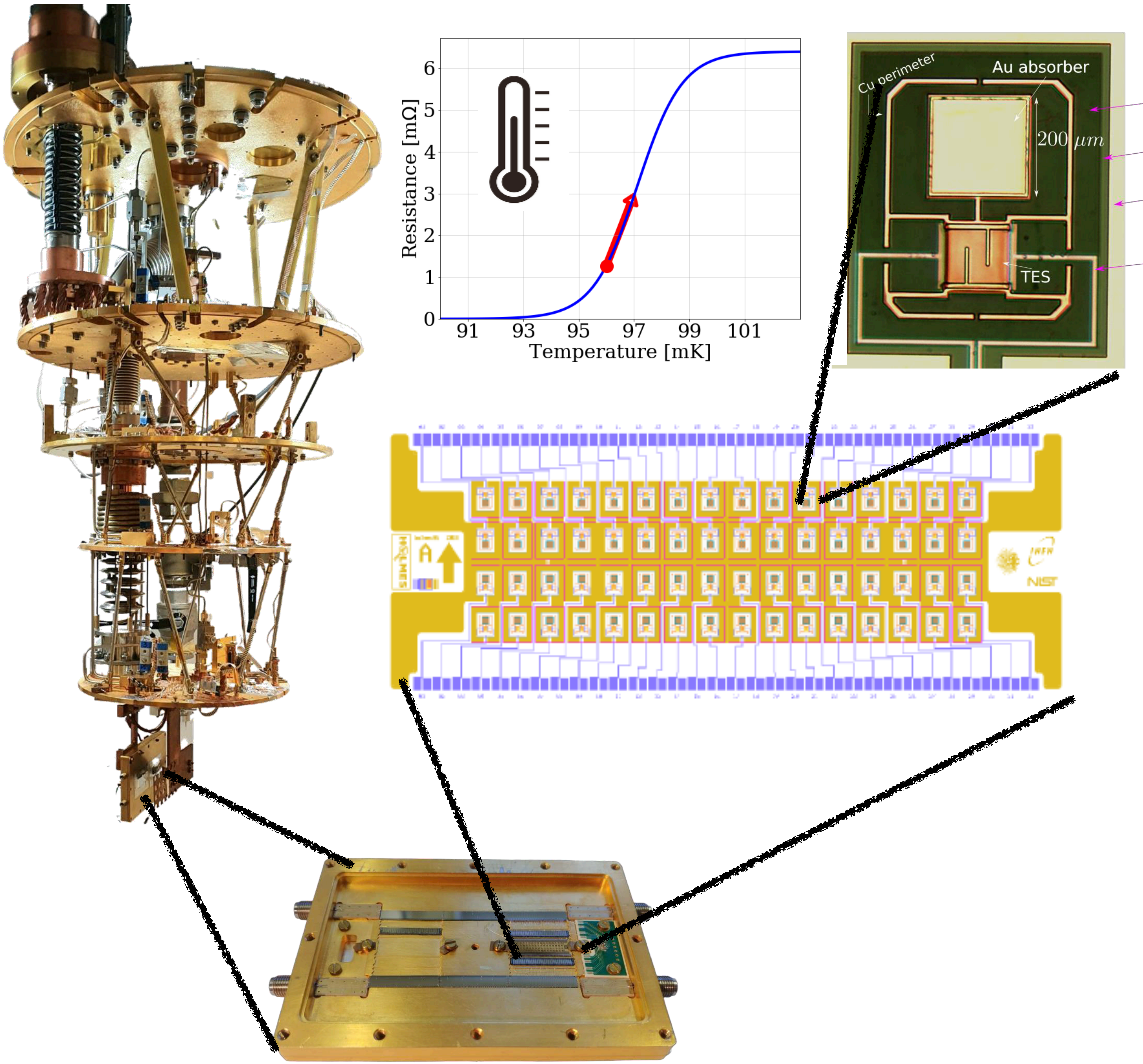
Q_{EC} = (2860 ± 2$_{stat}$ ± 5$_{syst}$) eV



HOLMES

Transition edge sensors, consisting of superconductor film operated in the region between resistive and the superconducting state.

Very sensitive thermometer, able to detect a temperature variation on the order of a fraction of mK.



First detector array finalized in June 2023. First spectrum shows:

No. of pixels: 4

Acquisition time: 48.5 hours

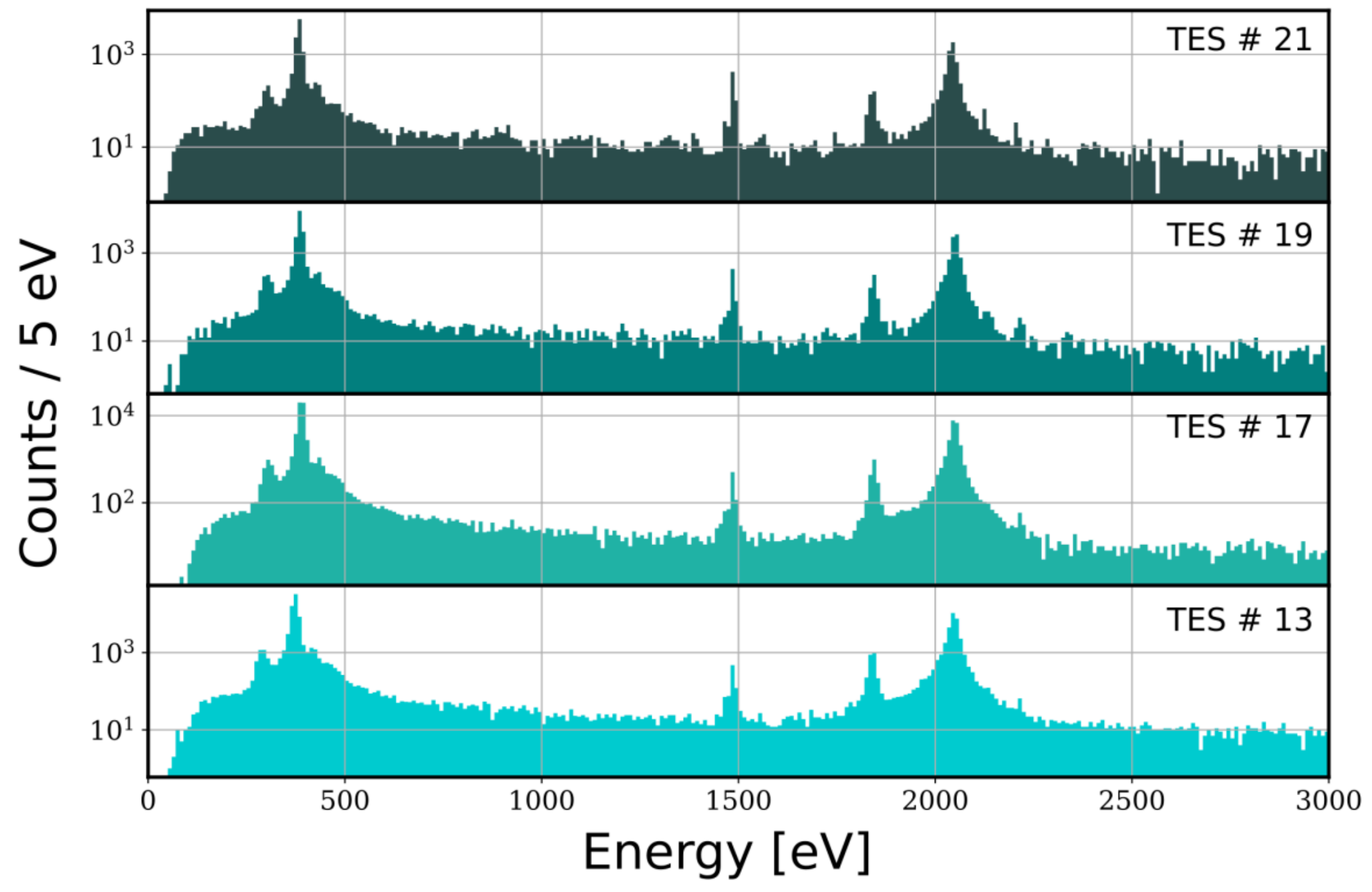
Activity ≈ 0.5 Bq (0.1 –1 Bq)

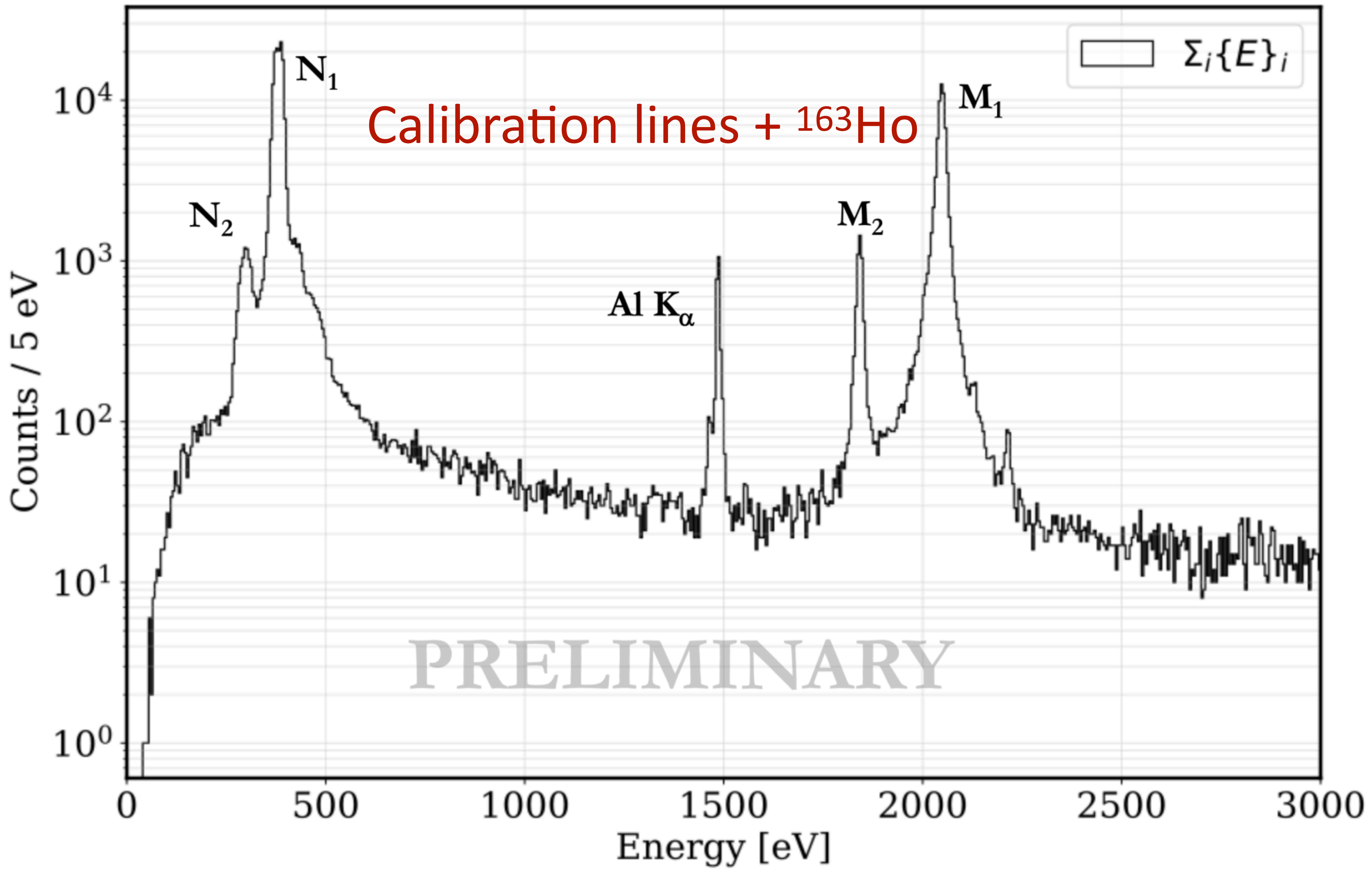
Energy Resolution= 6–8 eV @6keV

New array implantation should be completed soon. Mass limit expected around 10 eV.

PRELIMINARY

Spectra from 1st 4 pixels





MAC-E Filter

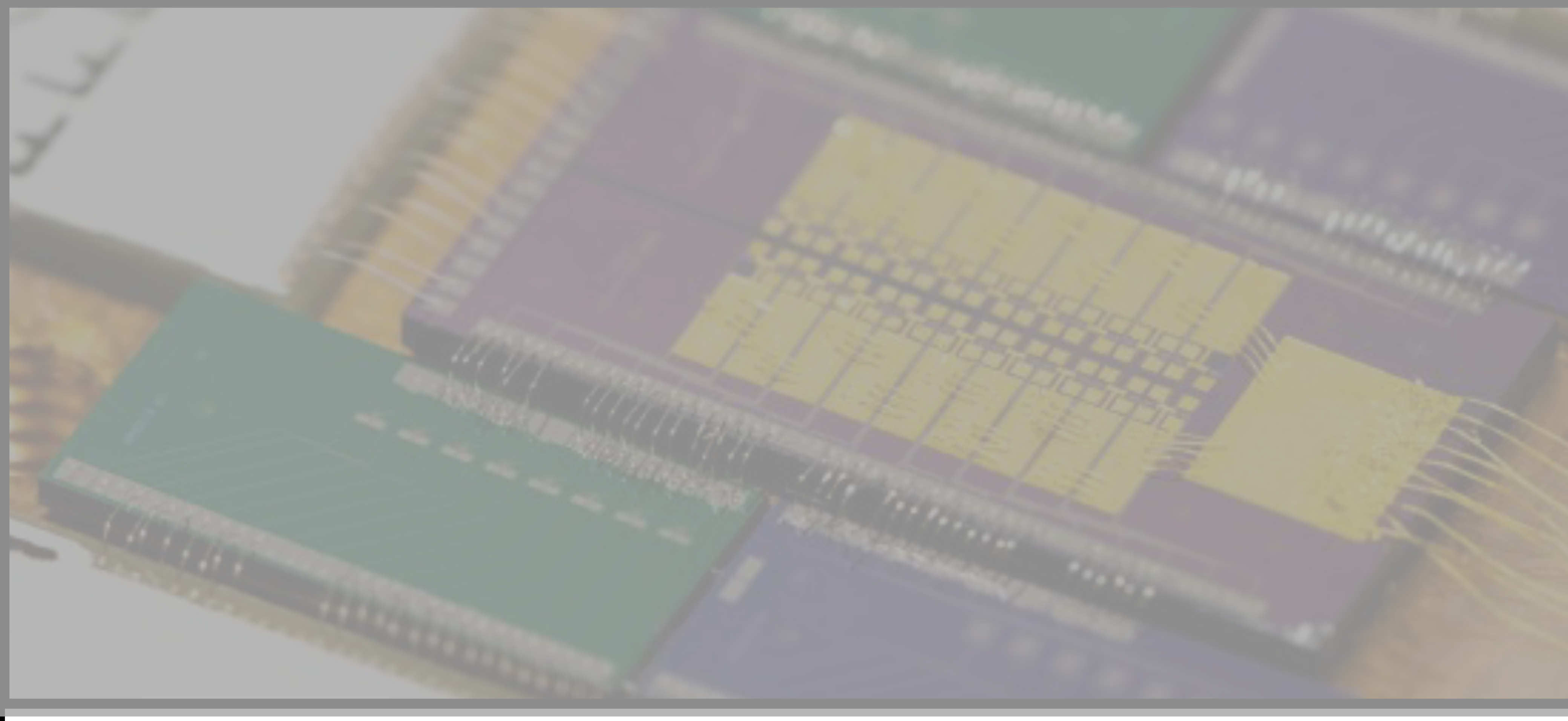
Magnetic Adiabatic Collimation with Electromagnetic filtering

Experiment(s): Mainz, Troisk, **KATRIN**

Calorimetry

Total energy absorption using bolometers.

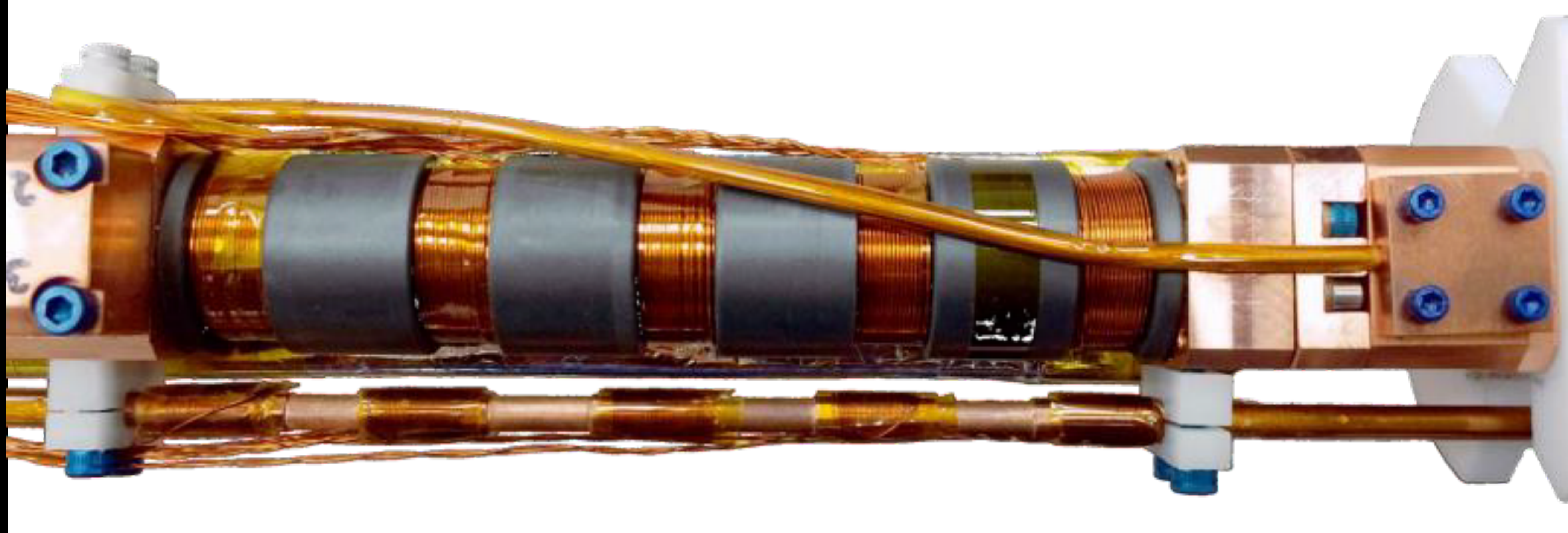
Experiment(s): **ECHO, HOLMES**



Cyclotron Radiation Emission Spectroscopy

Microwave frequency measurement.

Experiment(s): **Project 8, CRESDA**



Cyclotron Radiation Emission Spectroscopy (CRES)

Leverages relativistic frequency shift of an electron's cyclotron radiation to measure the kinetic energy of the beta decay electron.

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

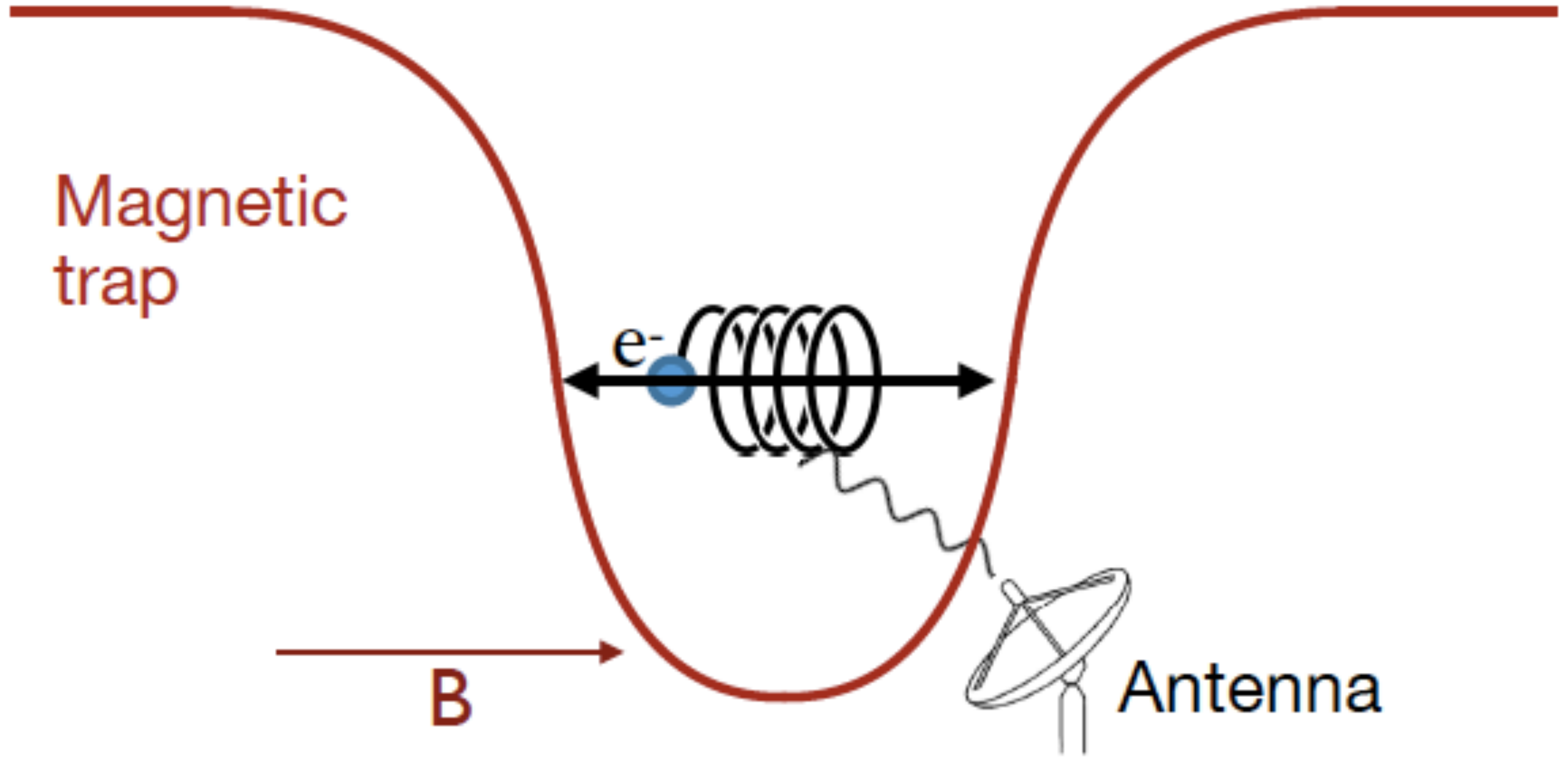
B. Monreal and JAF, Phys. Rev D80:051301, 2009

A. L. Schawlow

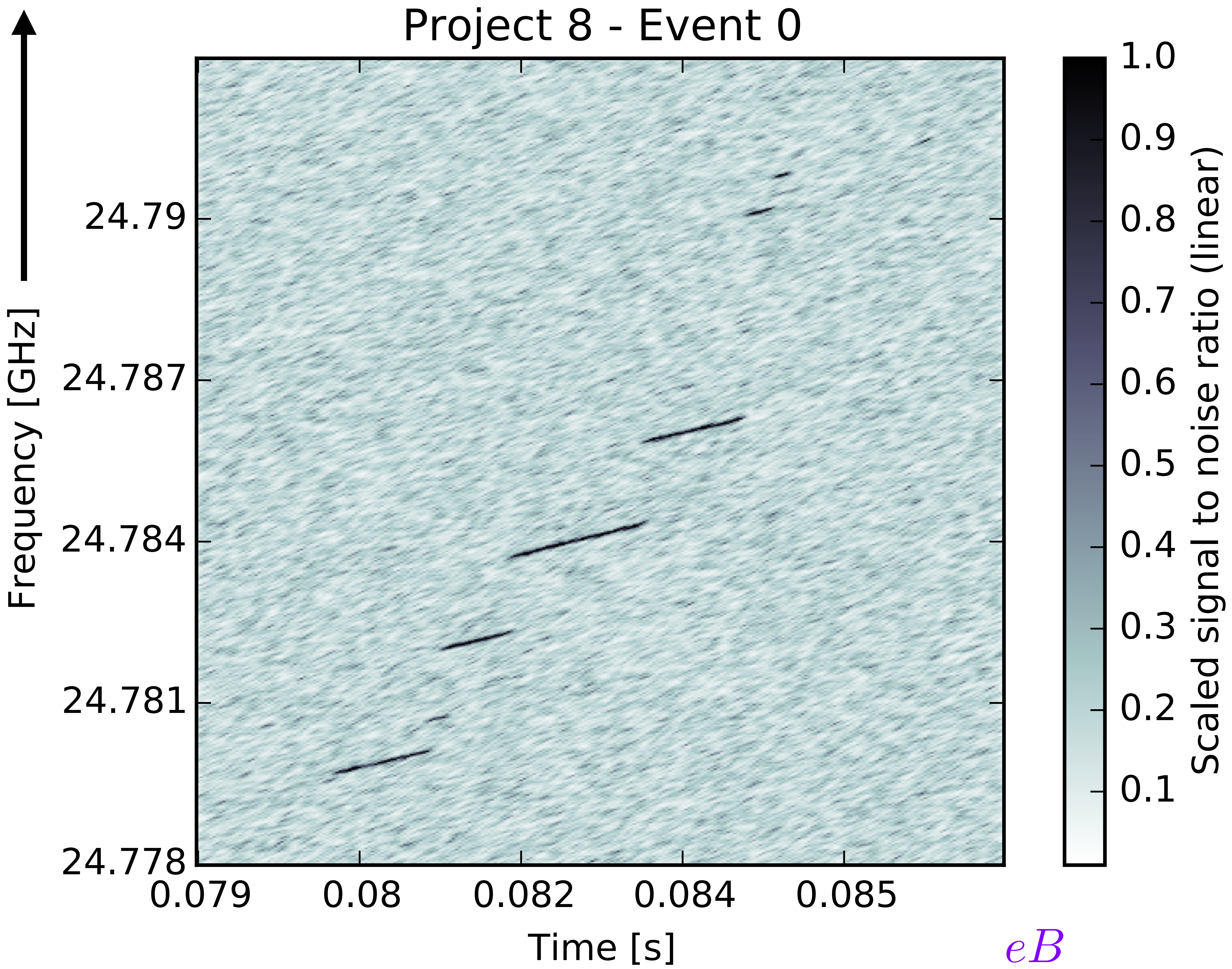
PROJECT 8

O. Heaviside

"Never measure anything but frequency."



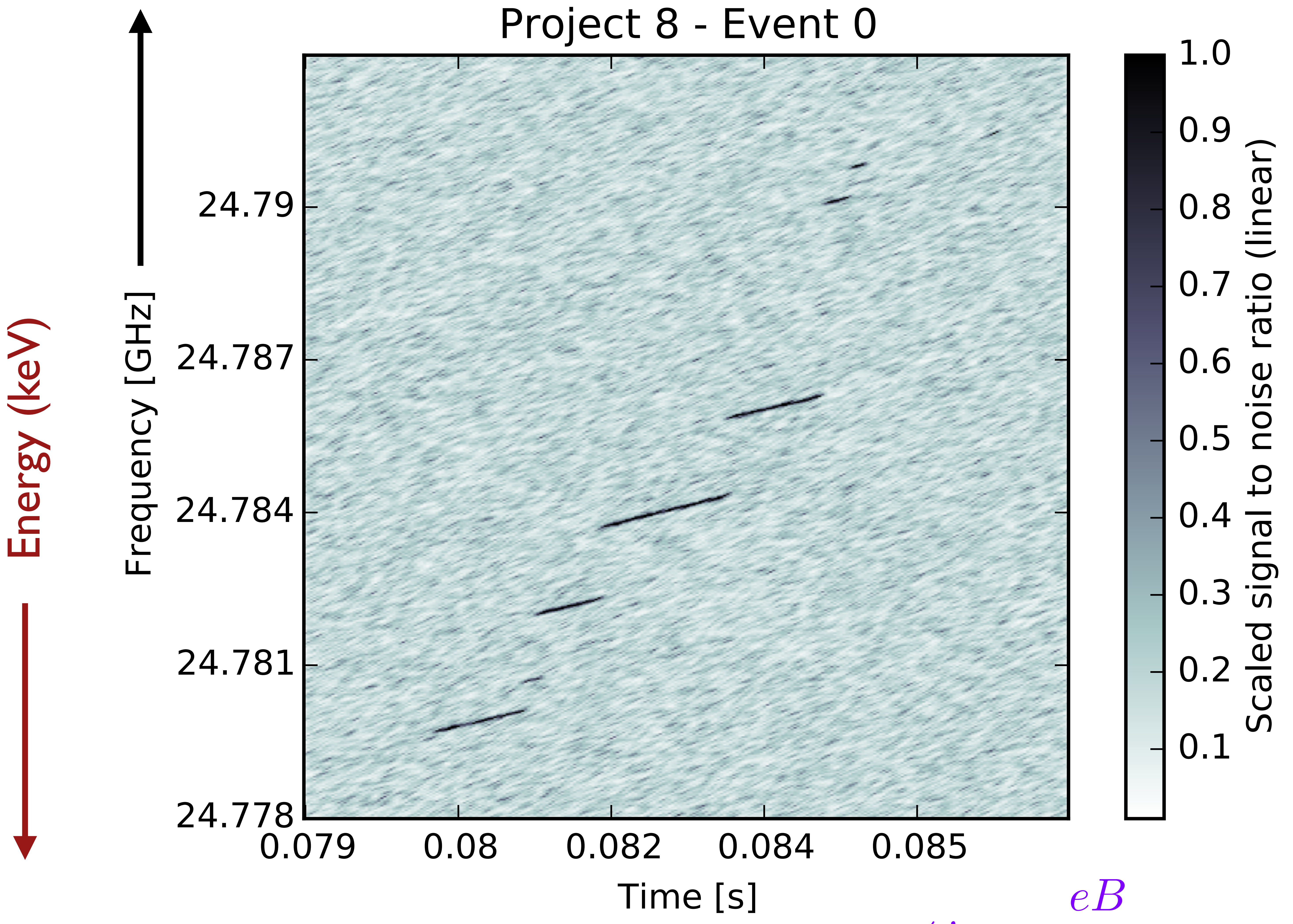
$$f_c = \frac{f_{c,0}}{\gamma} = \frac{1}{2\pi}\frac{eB}{m_e c^2 + E_{\mathrm{kin}}}$$



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

A "typical" event

(actually, this was our first event)



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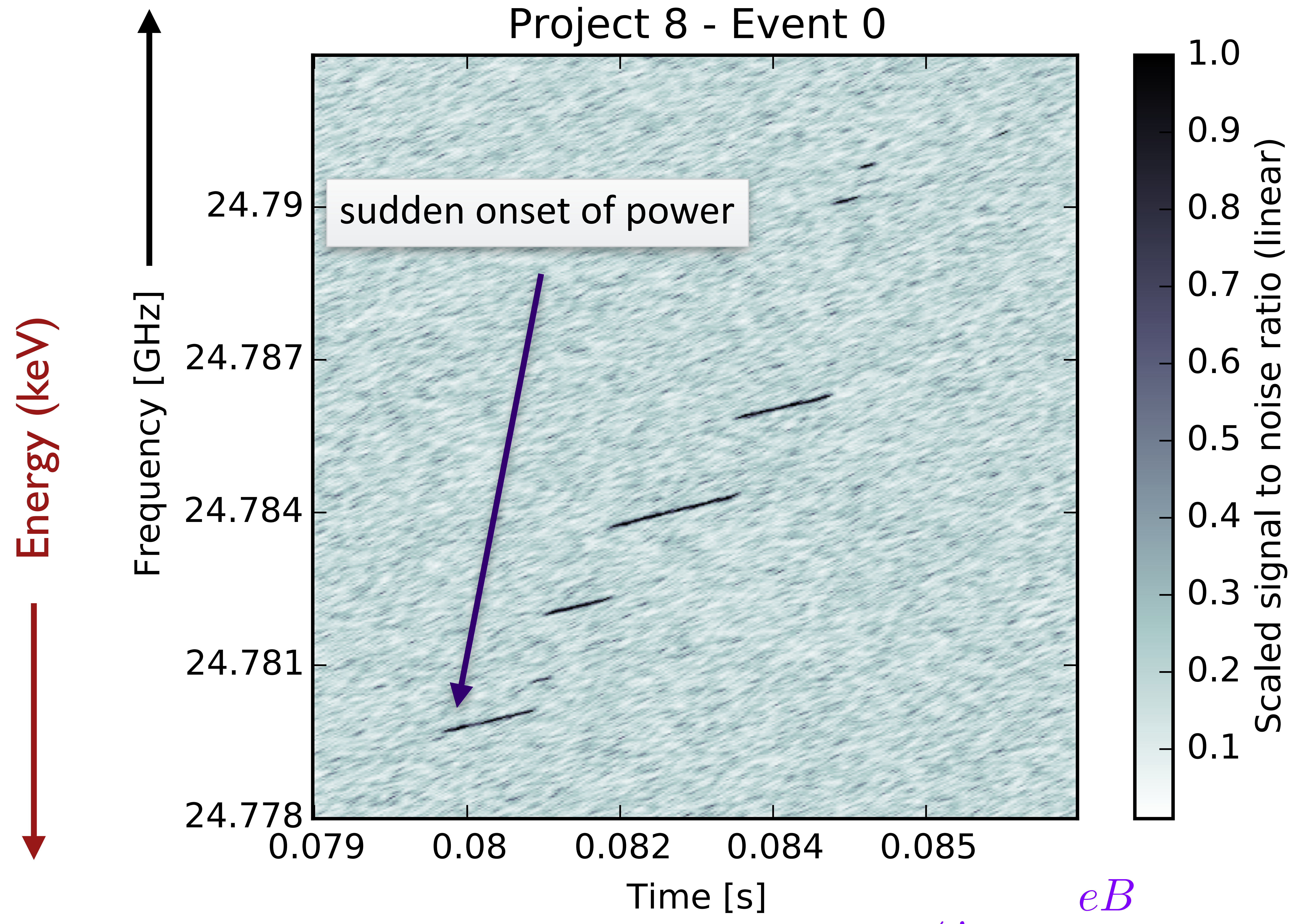

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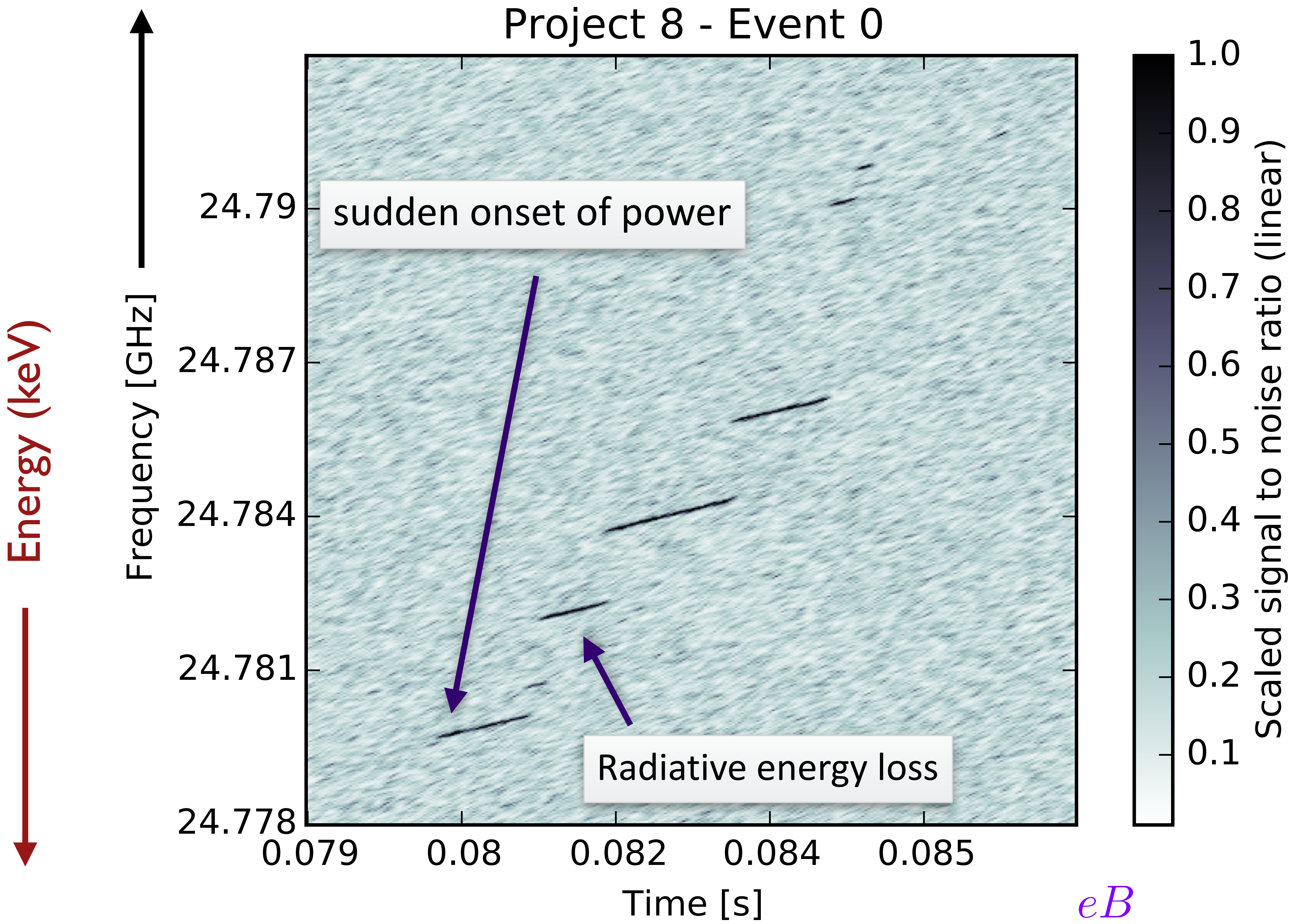

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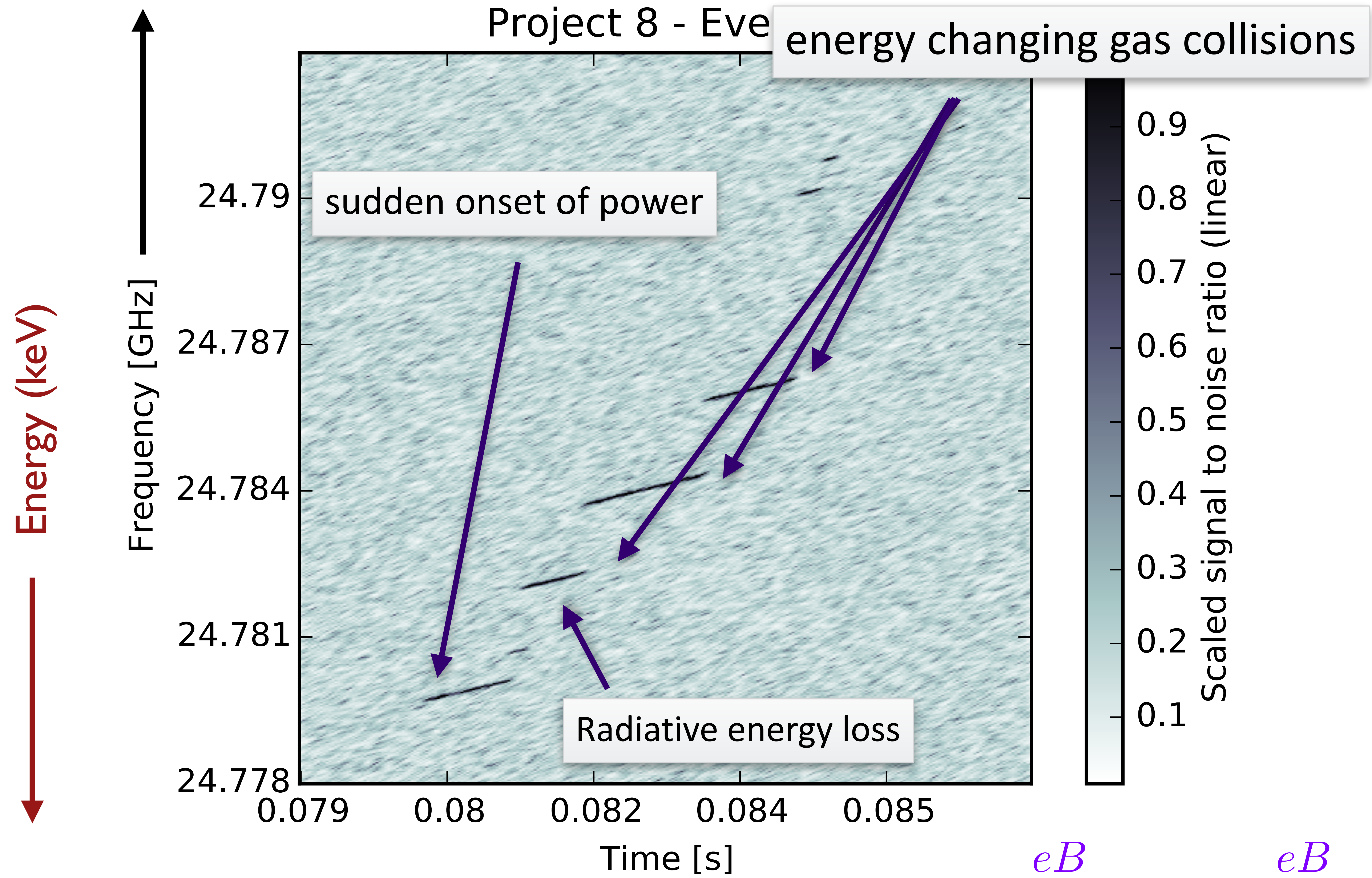

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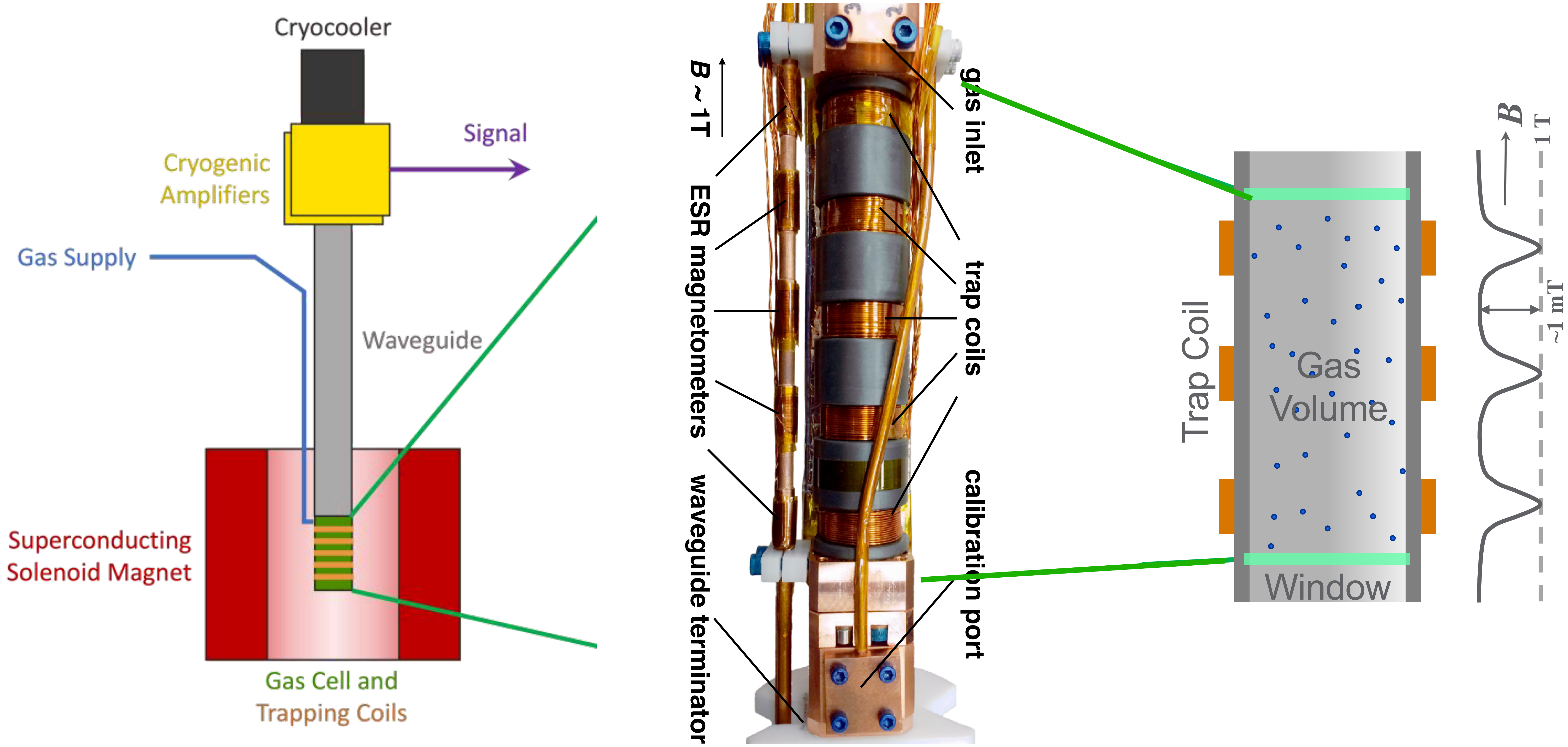
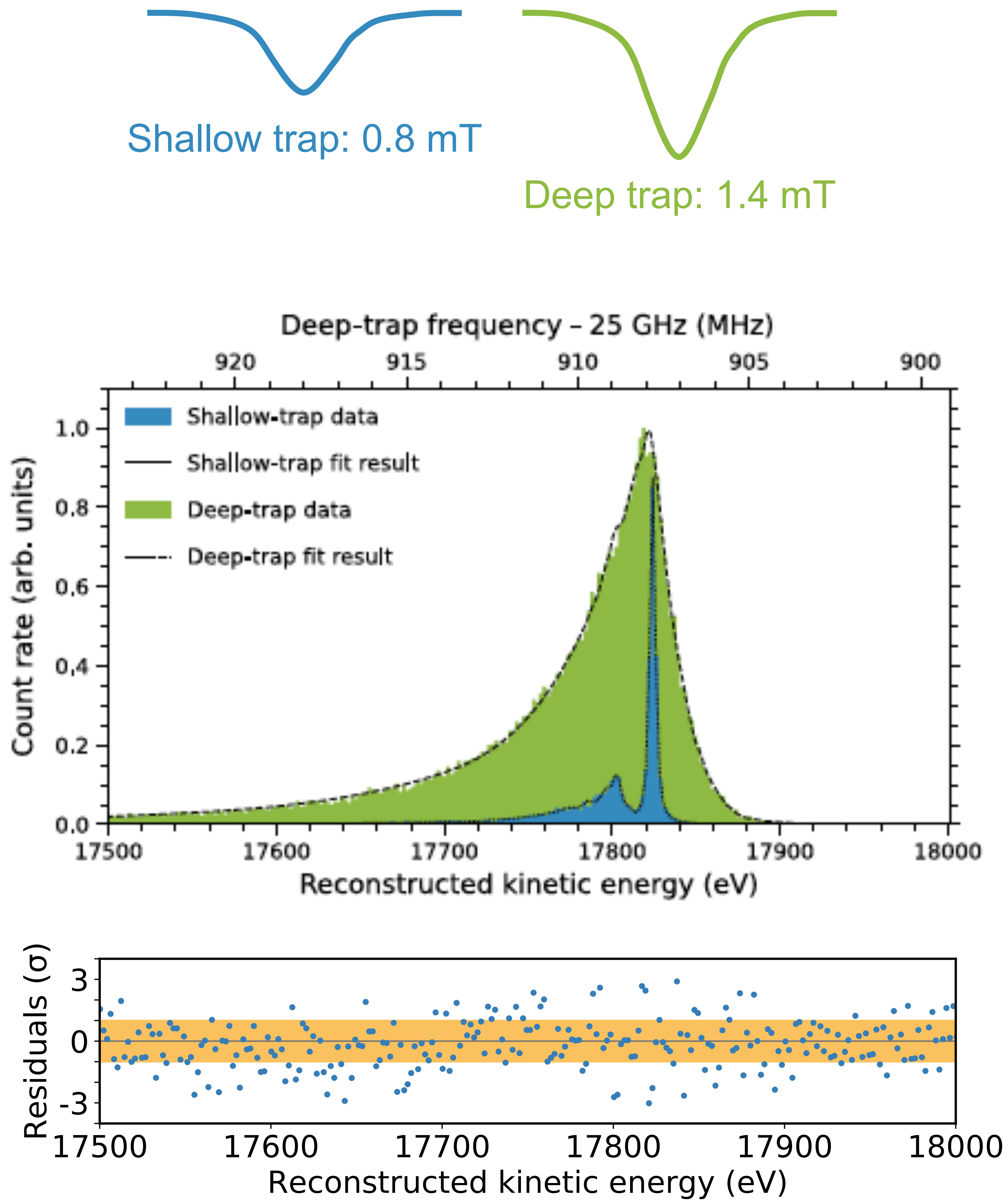
Phase II Results



Phase II CRES instrument provides 1mm³ volume inside waveguide

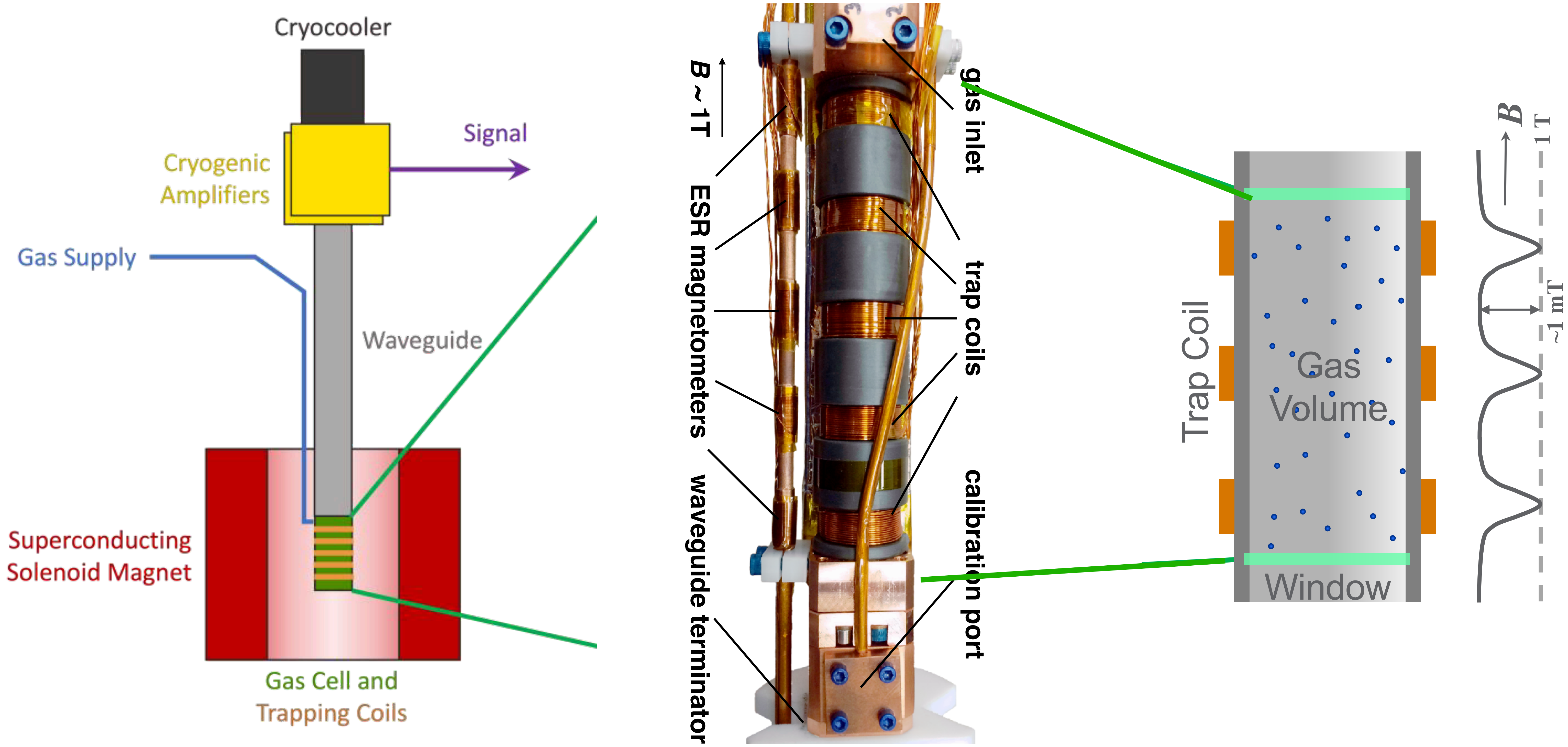
First endpoint CRES measurement conducted with no observed background in 81 days of data taking.

^{83m}Kr Spectrum



Ashtari Esfahani et al
Phys. Rev. Lett. 131, 102502 (2023)

Phase II Results



Phase II CRES instrument provides 1mm³ volume inside waveguide

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

T2 Endpoint

Bayesian: $E_0 = (18553^{+18}_{-19})$ eV

Frequentist: $E_0 = (18548^{+19}_{-19})$ eV

Neutrino Mass

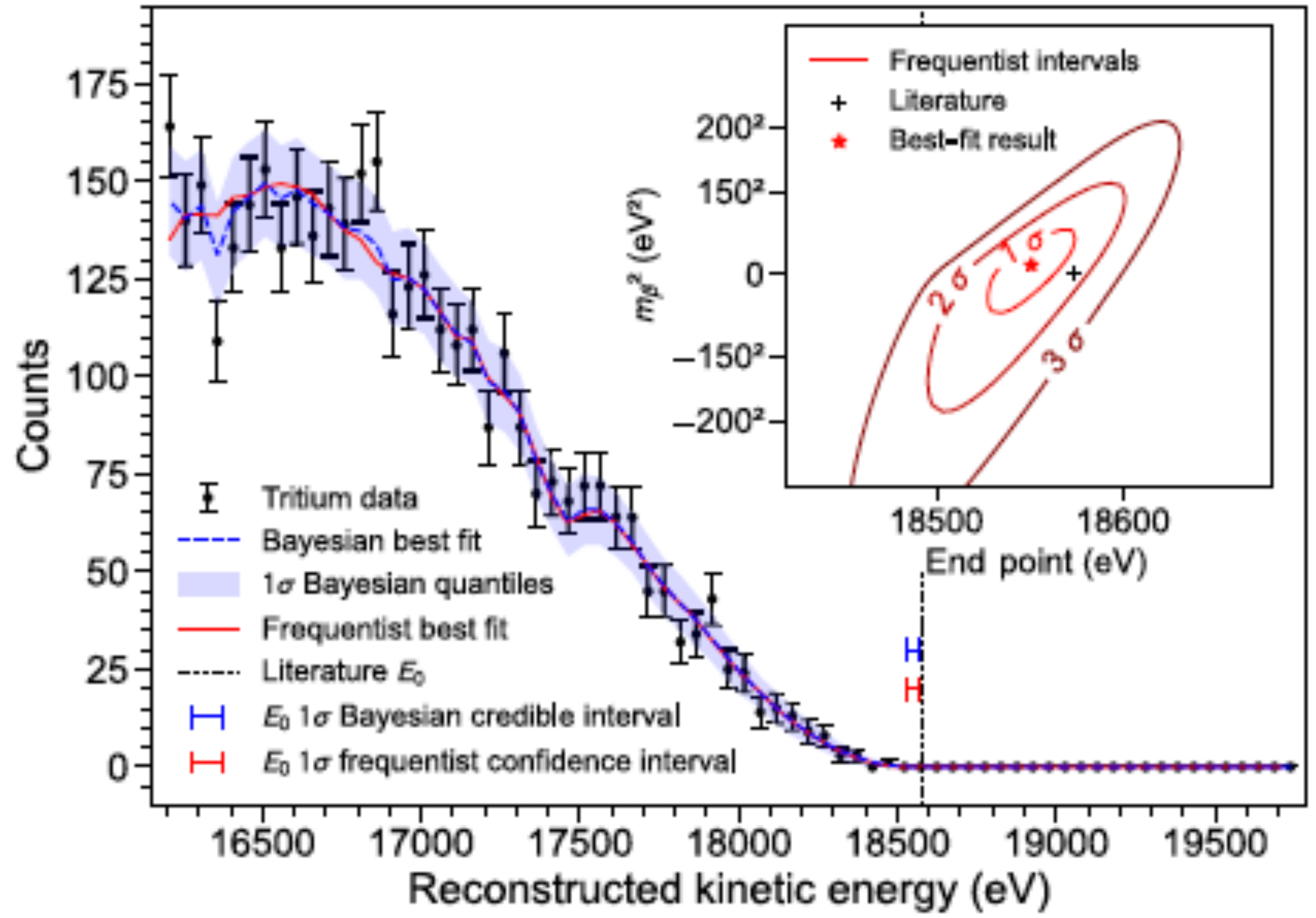
Bayesian: $m_\beta < 155$ eV

Frequentist: $m_\beta < 152$ eV

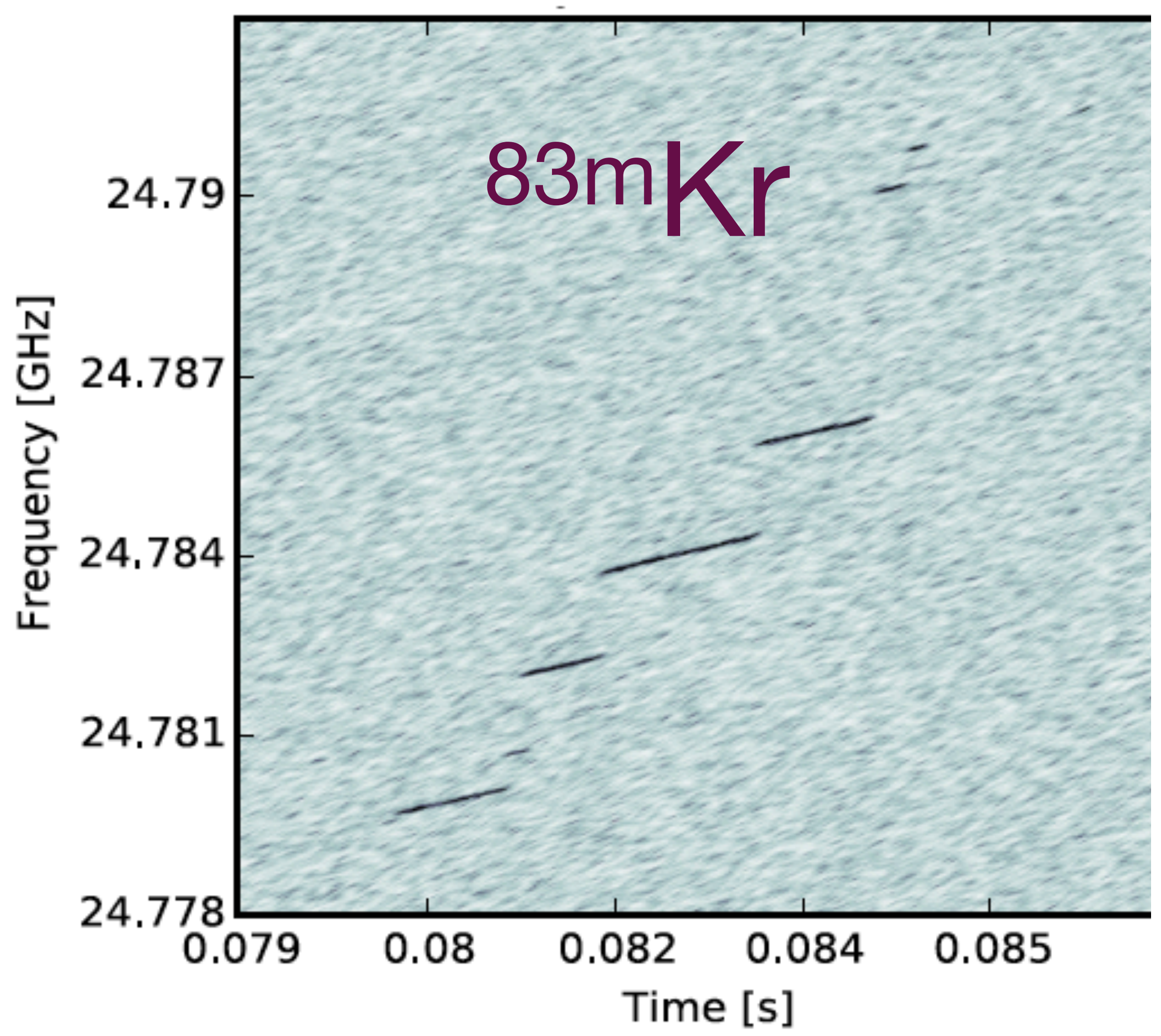
Background rate

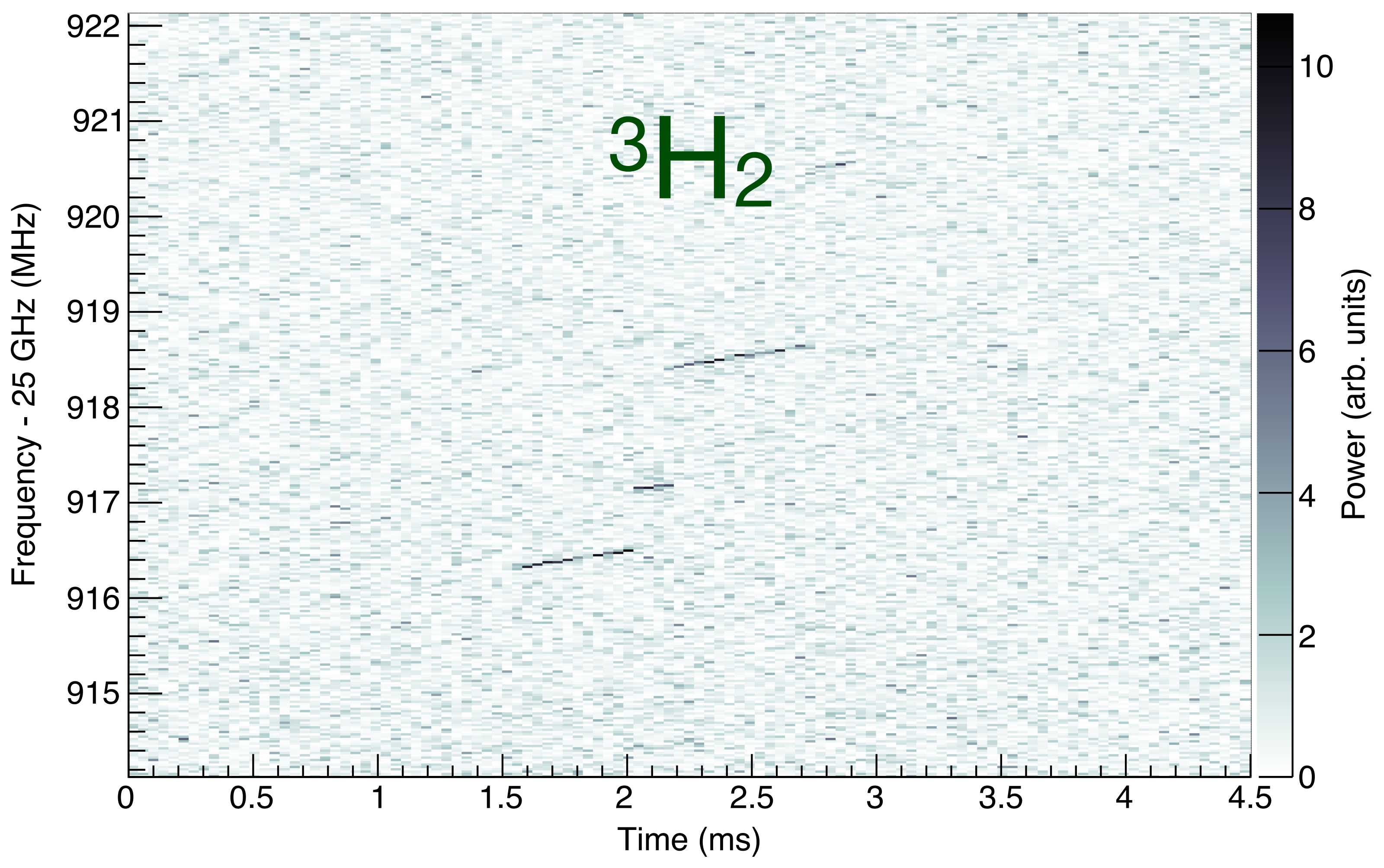
$< 3 \times 10^{-10}\ \mathrm{eV}^{-1}\mathrm{s}^{-1}$

1st Tritium Spectrum



Ashtari Esfahani et al Phys. Rev. Lett. 131, 102502 (2023)

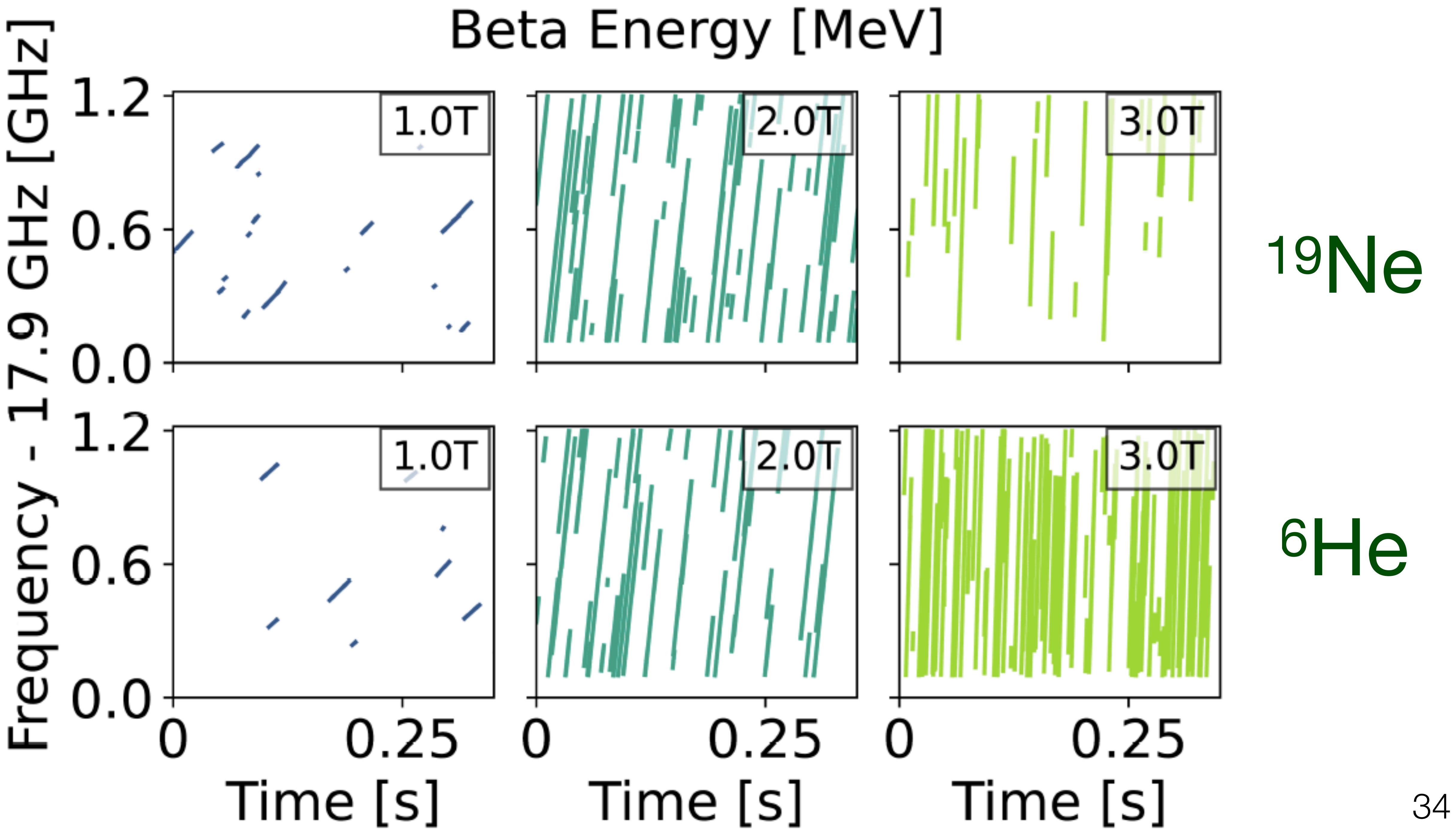




PROJECT 8

6He-CRES

QTNM
Quantum Technologies for Neutrino Mass



Who Else Uses CRES?

- 6He-CRES: For beta decay spectrum (^{6}He, ^{19}Ne) (spectrum courtesy of ^{6}He coll.)
- CRES-X: For gamma detection & non-proliferation.
- QTNM / CRESDA: For neutrino mass measurements. Collaborative with Project 8.

CRES is no longer unique to Project 8 experiments.

How do we access the next scale of neutrino masses?

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General Principles...

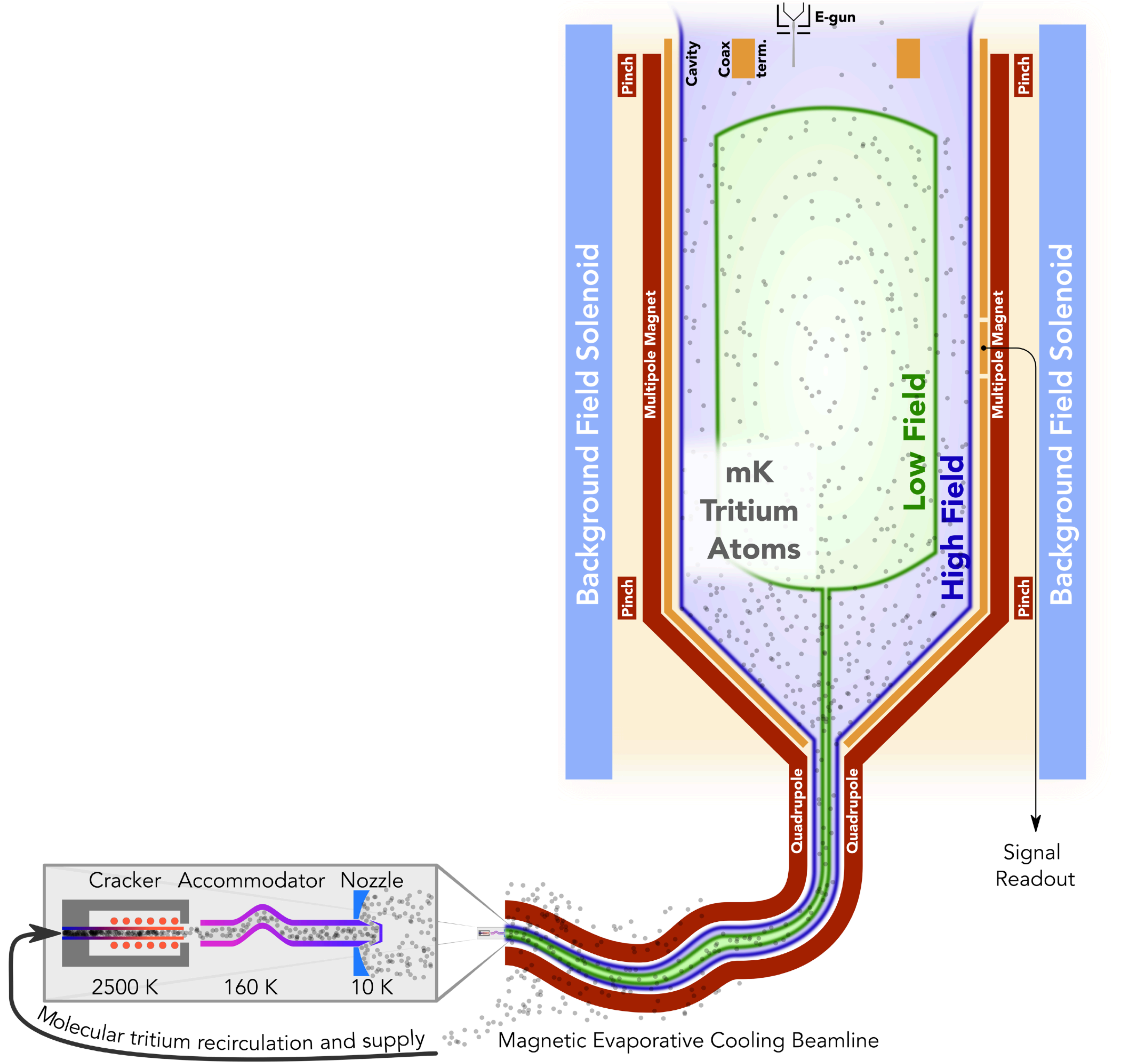
- High energy resolution
- Background-free operation
- Better target mass scaling
- Well-understood, highly resolved source

How do we access the next scale of neutrino masses?

General Principles...

- *High energy resolution*
- *Background-free operation*
- *Better target mass scaling*
- *Well-understood, highly resolved source*

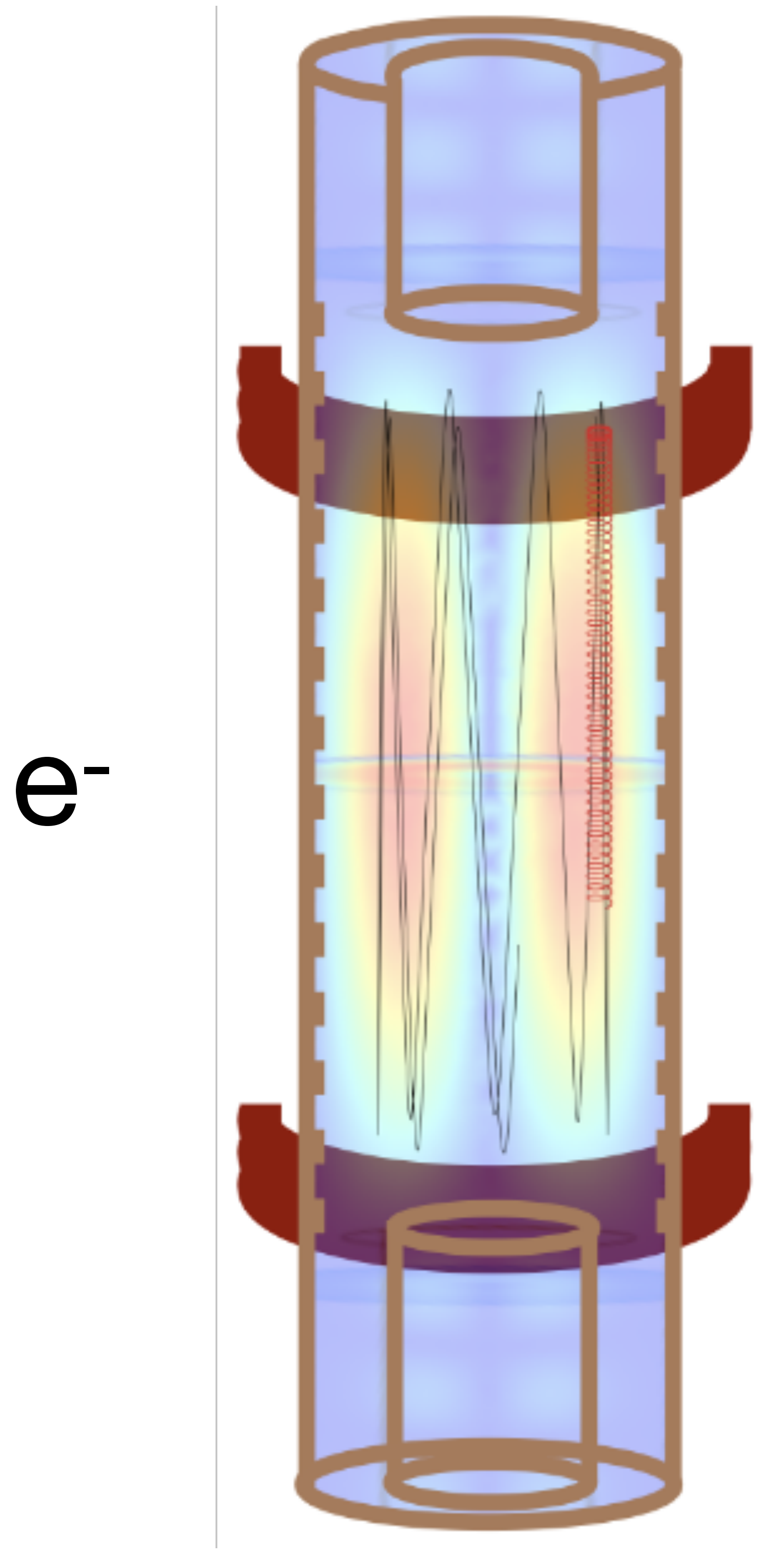
N.B.: I will focus on the tritium efforts, revealing my own biases and prejudices. But the principles still apply broadly.

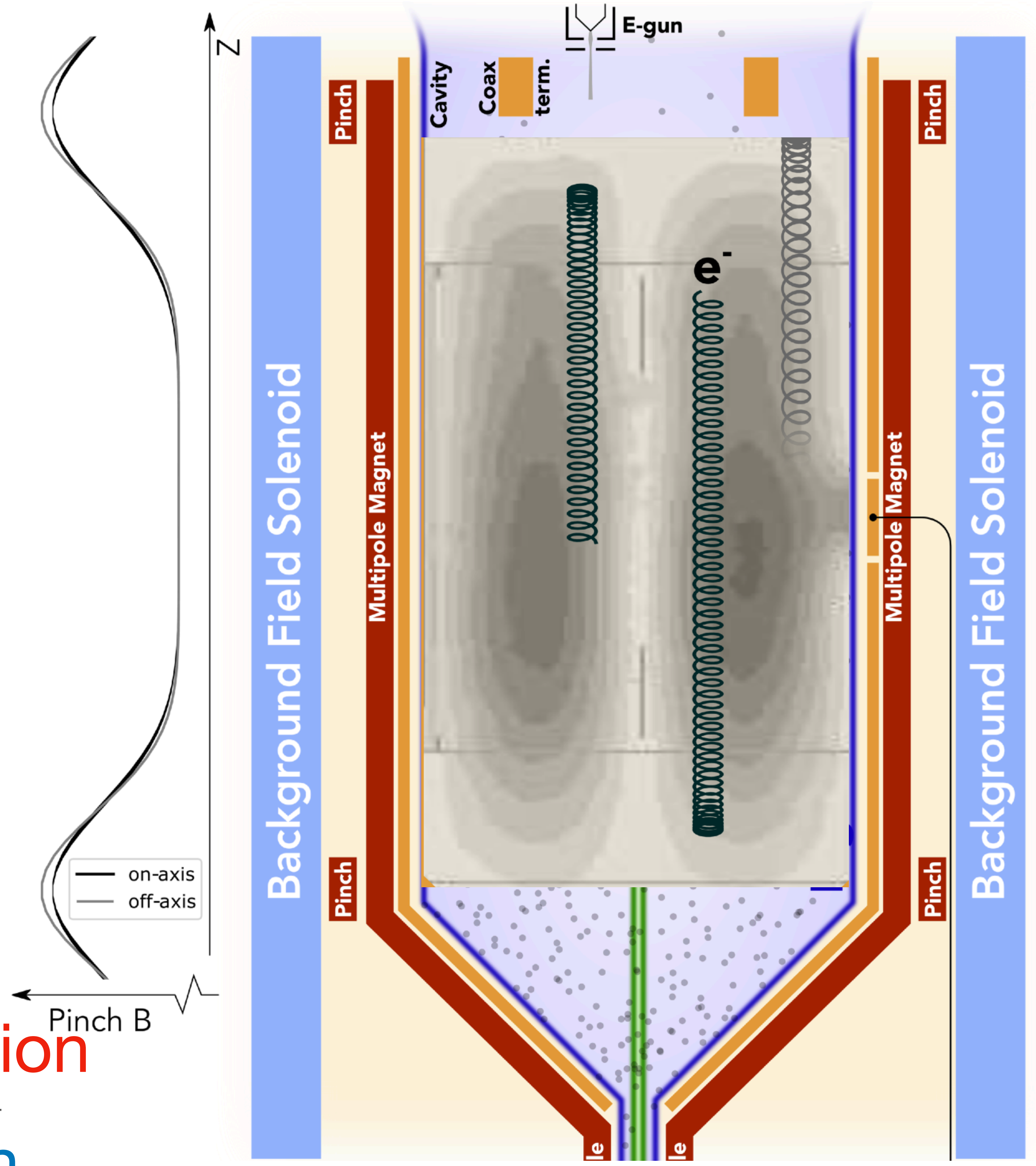


Project 8 Phase III

Two main R&D focal points:

- Expand the volume $\Longrightarrow$ Cavities
- Clean source $\Longrightarrow$ Atomic tritium





f_c : cyclotron motion

f_a : axial motion

$f_{\nabla B}$: grad-B motion

Need to expand volume by using a cavity apparatus at a lower magnetic field.

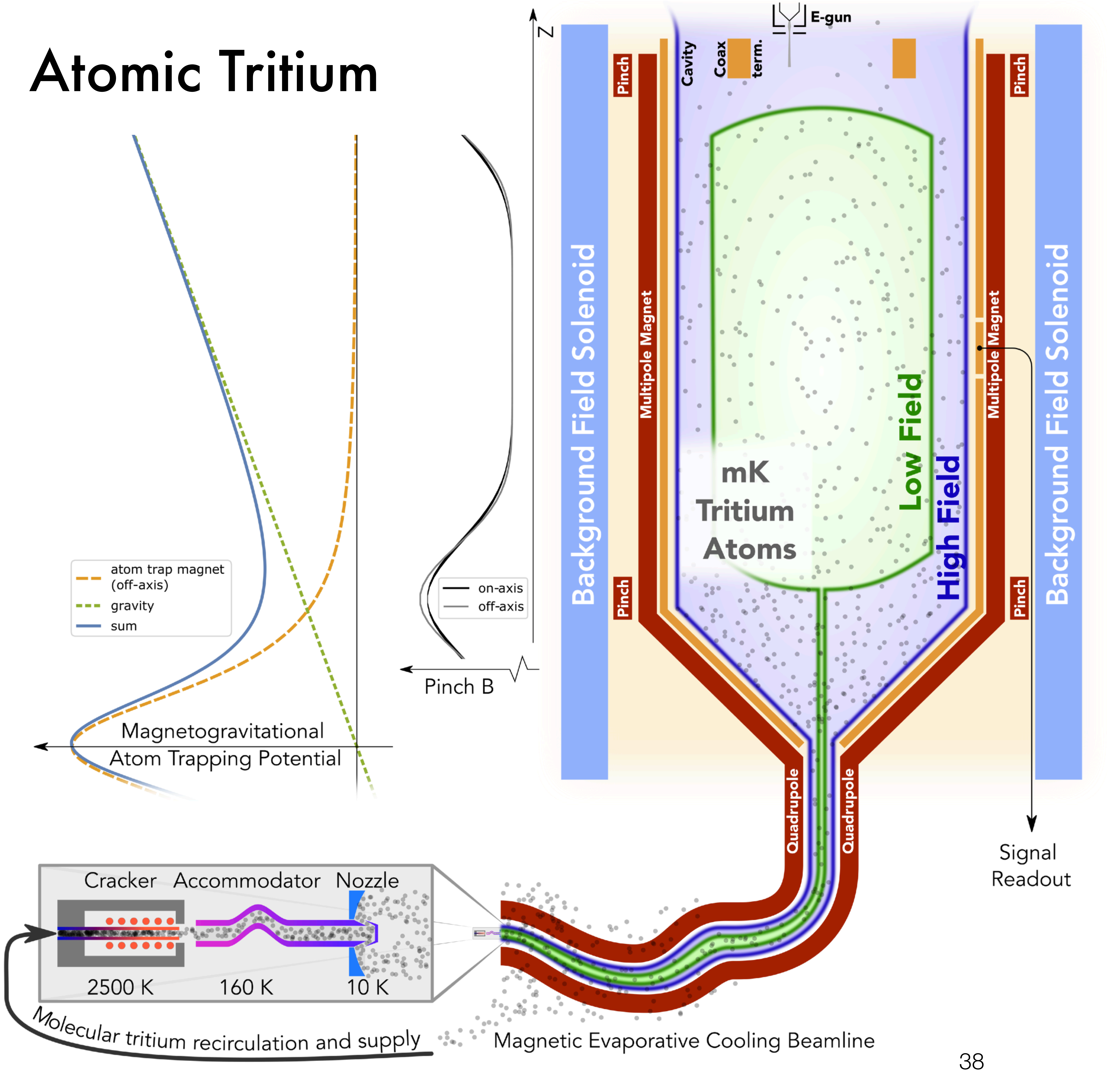
Low Field Cavities

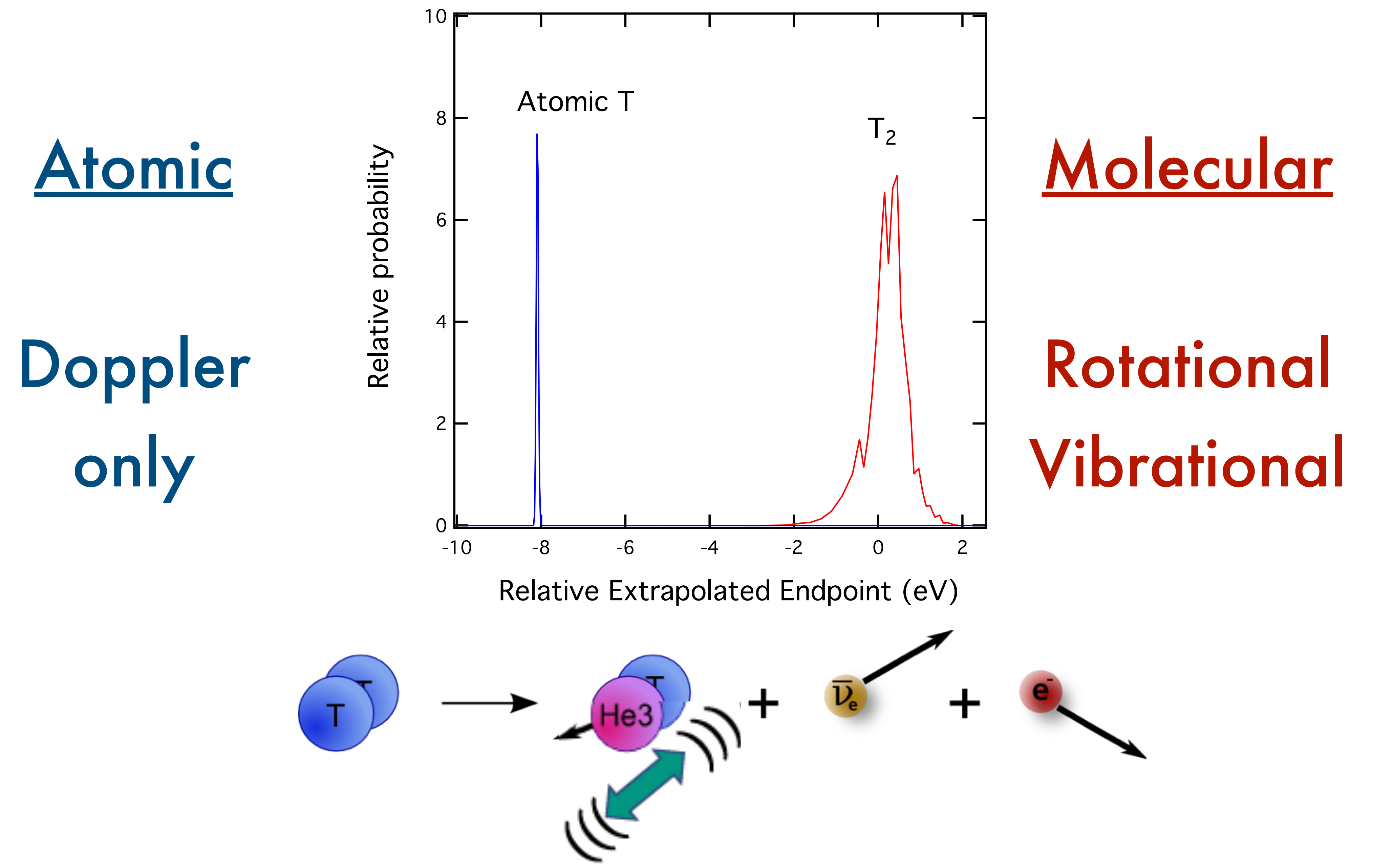
Droping field/frequency increases effective volume.

$f_c \approx 325$ MHz
$V_{eff} \approx 11$ m^3

Extremely low power signals (zeptowatts), but is detectable over predicted thermal noise.

Atomic Tritium





Rotational and vibrational states both broaden the final states, and add theoretical uncertainty.

Switching to an atomic source removes this uncertainty, but requires magneto-graviational trapping. Prefers lower magnetic fields.

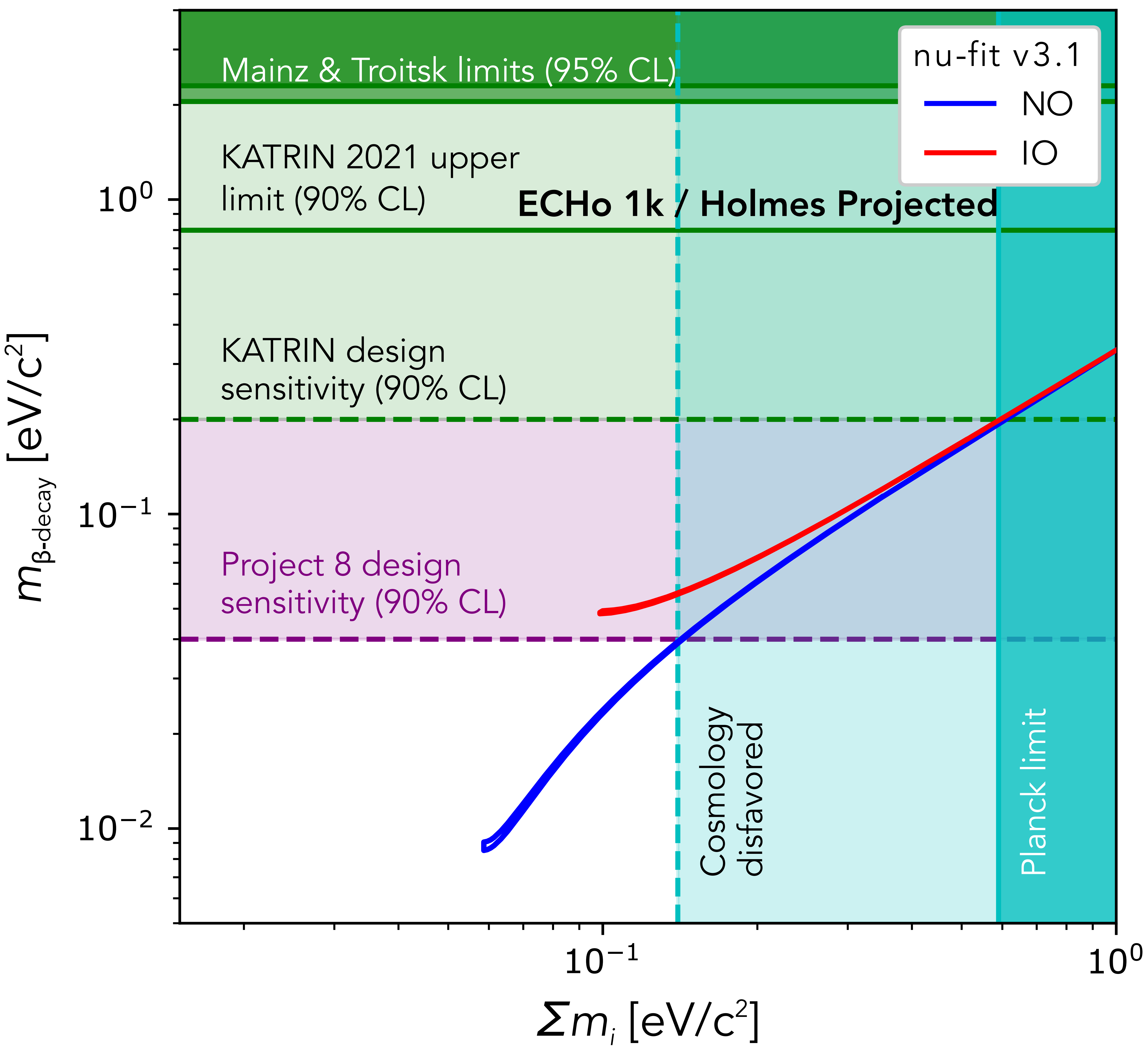
Next-Generation Experiments

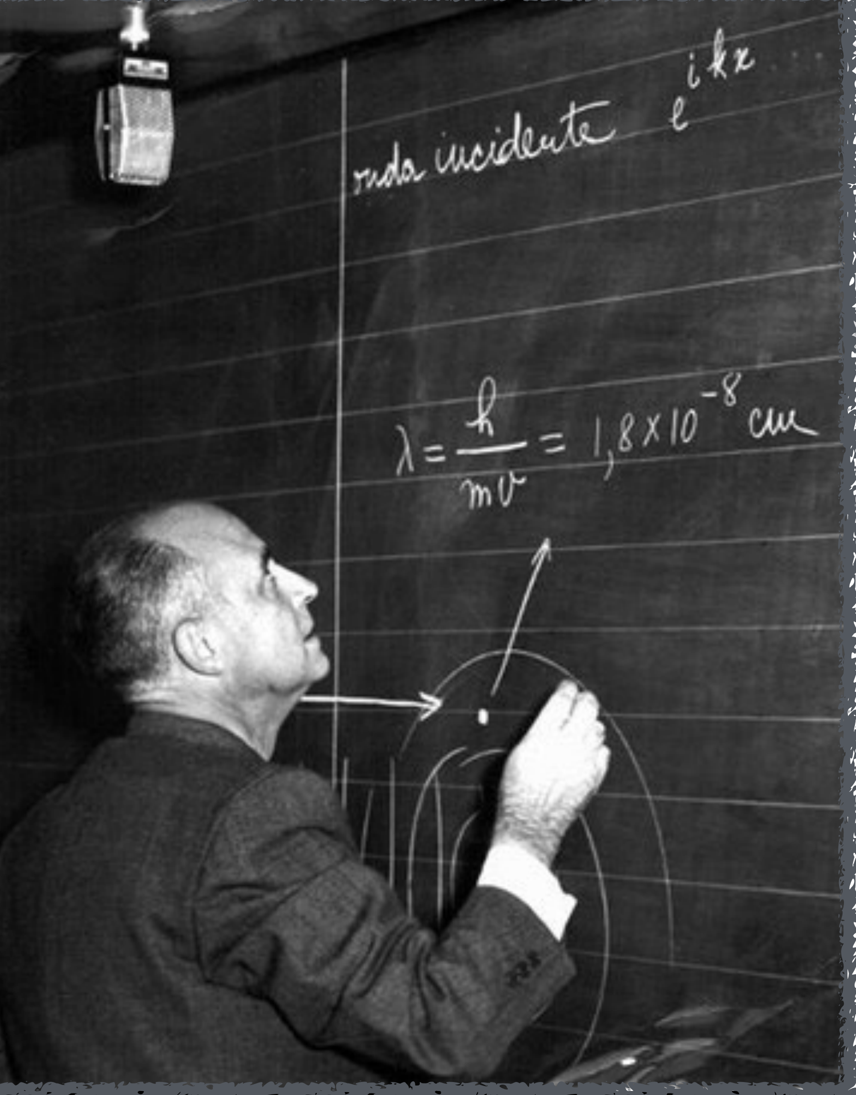
The next stage of direct matter experiments would need to satisfy a number of criteria.

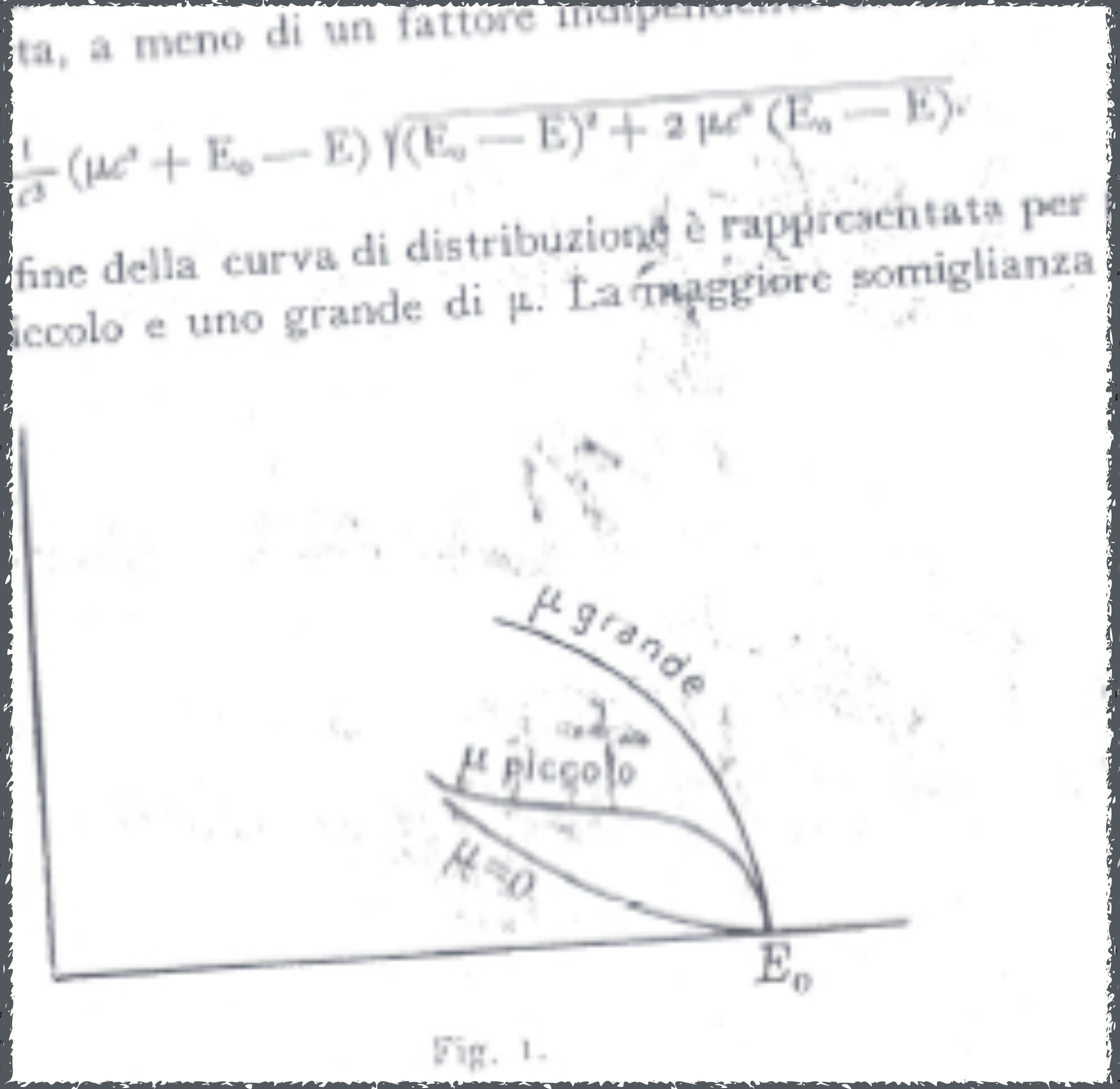
- Higher energy resolution
- Background-free operation
- Differential spectrum
- Well-understood, highly resolved source

A push that drives going from molecular to atomic tritum.

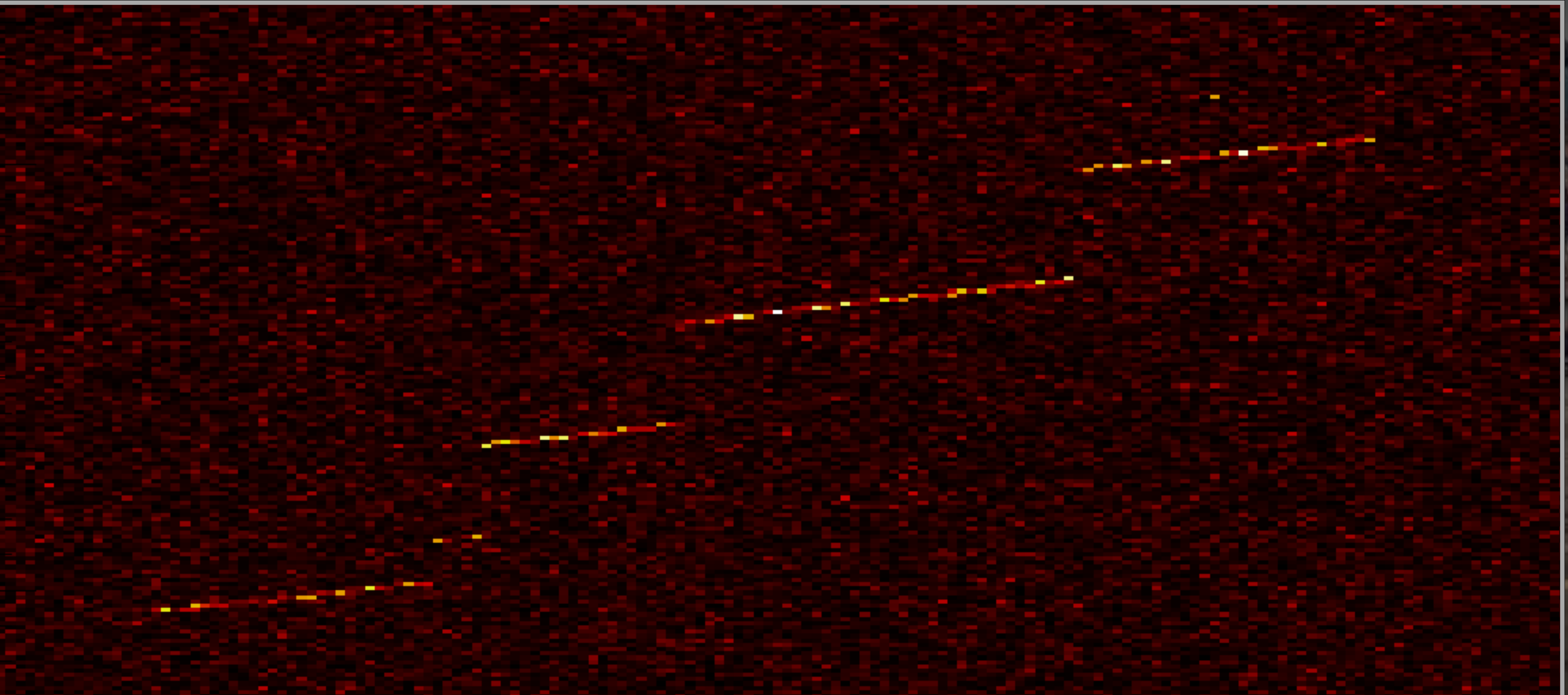
- High resolution spectrum
- No vibrational/rotational broadening.







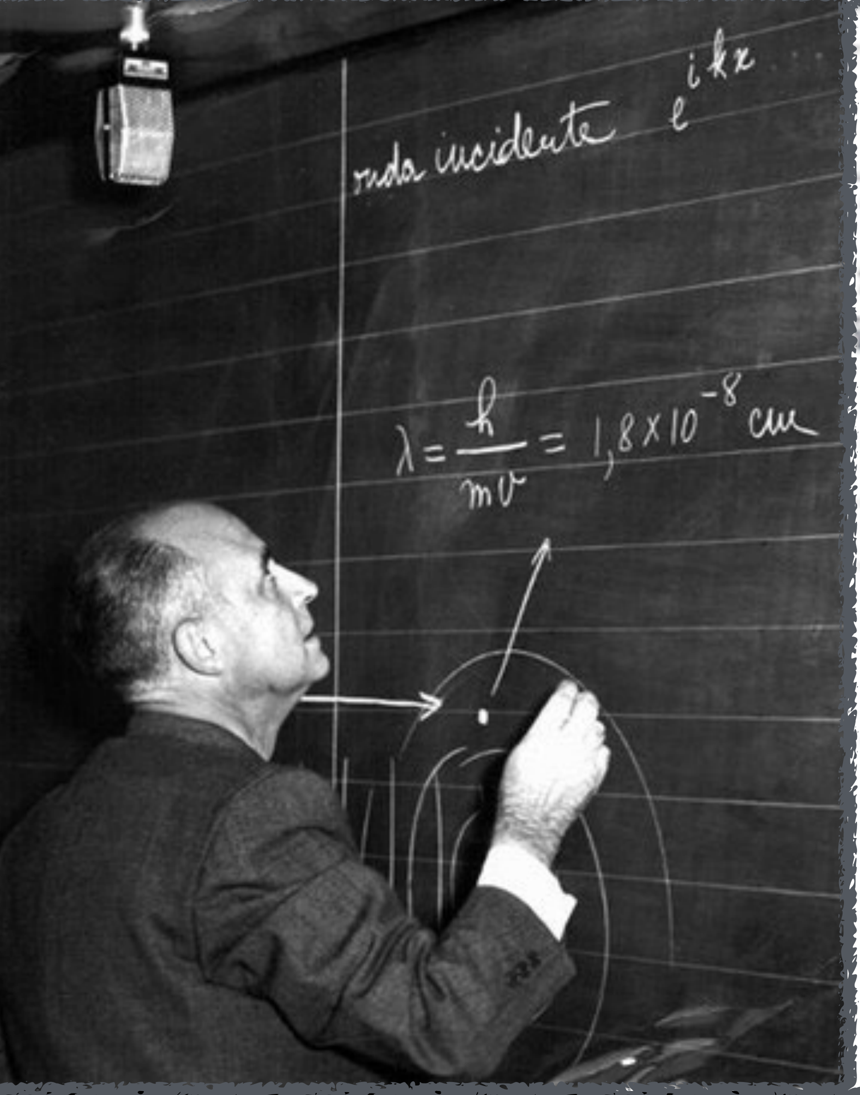
Summary

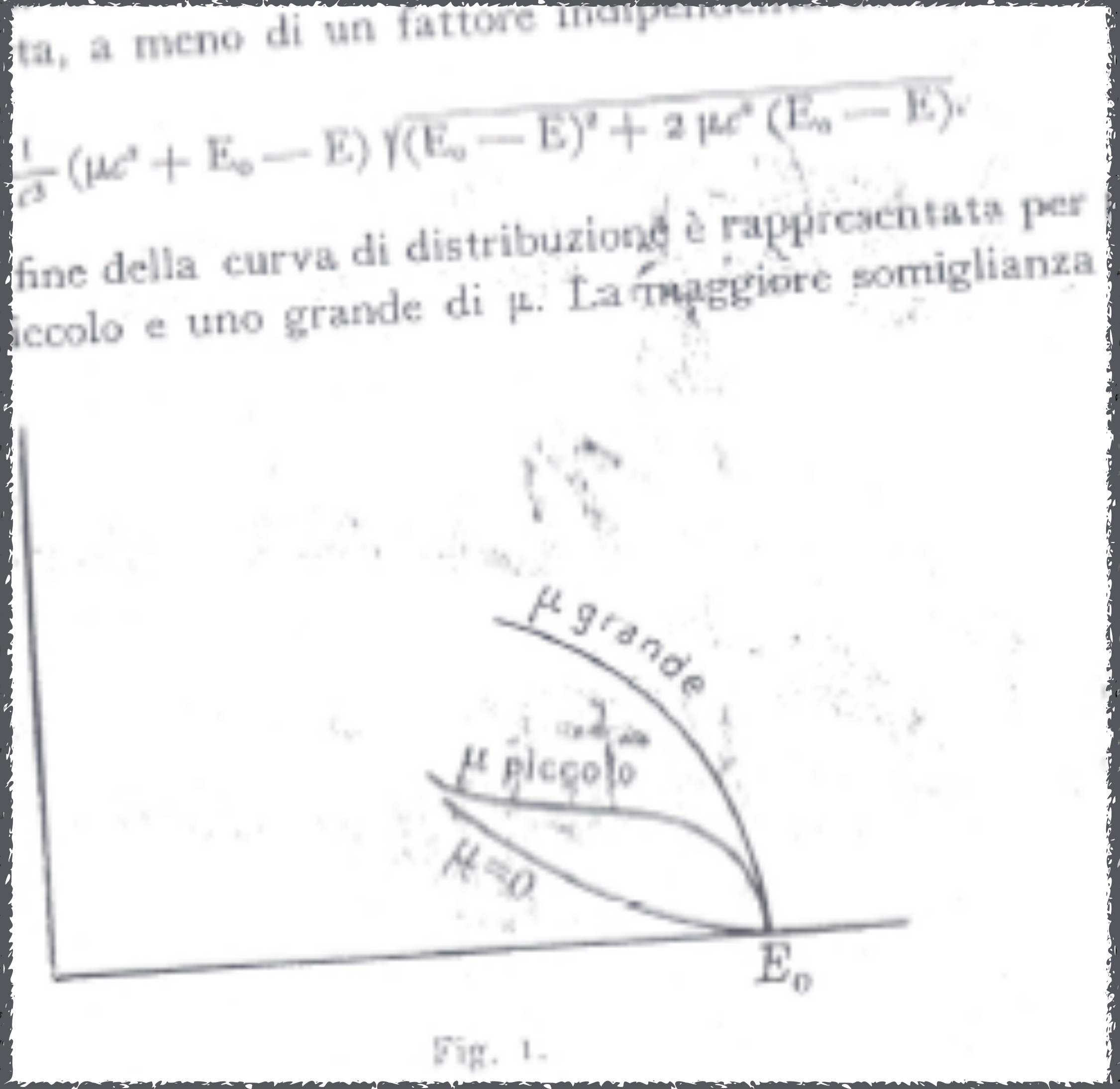


KATRIN nears completion of its mission, with a projected sensitivity at the quasi-degenrate scale.

Both calorimetry and CRES style experiments have demonstrated their proof-of-principle measurements. All are next expanding to the eV scale.

Strong push for atomic tritium source, as a path toward the inverted scale in next-generation tritium experiments.

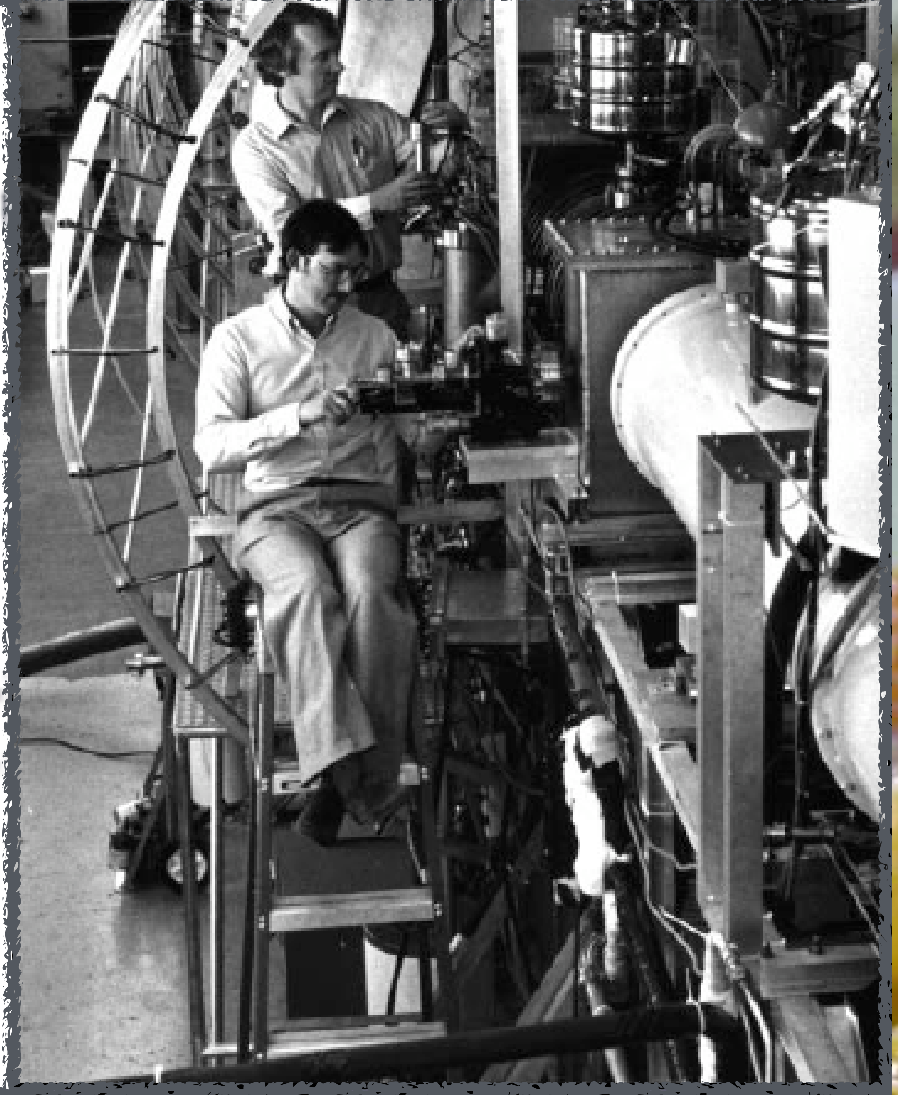



ta, a meno di un fattore indipendente

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

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

Fig. 1.



Thank you for your attention