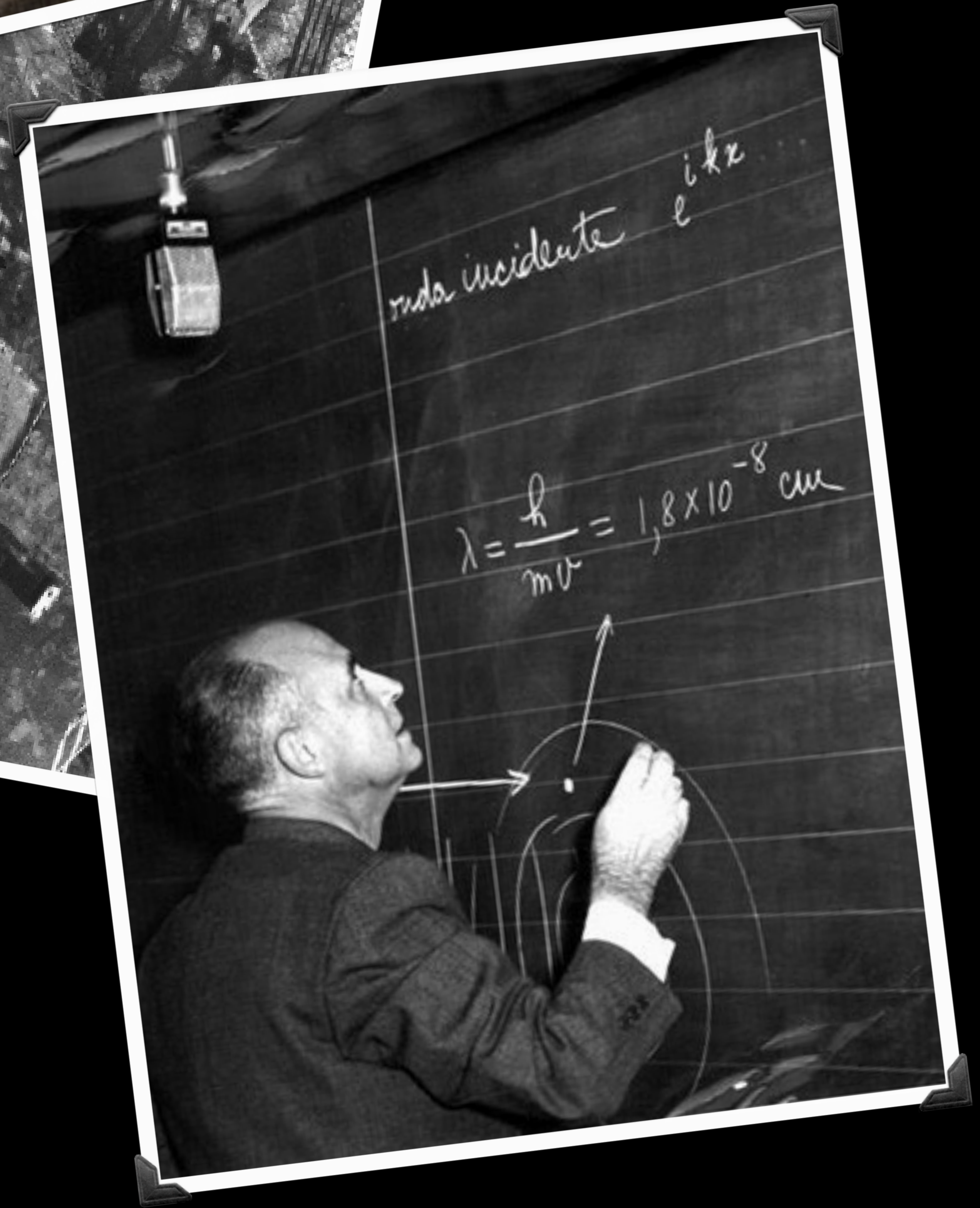

onda incidente e^{ikx}
λ = h/mv = 1,8×10^-8 cm

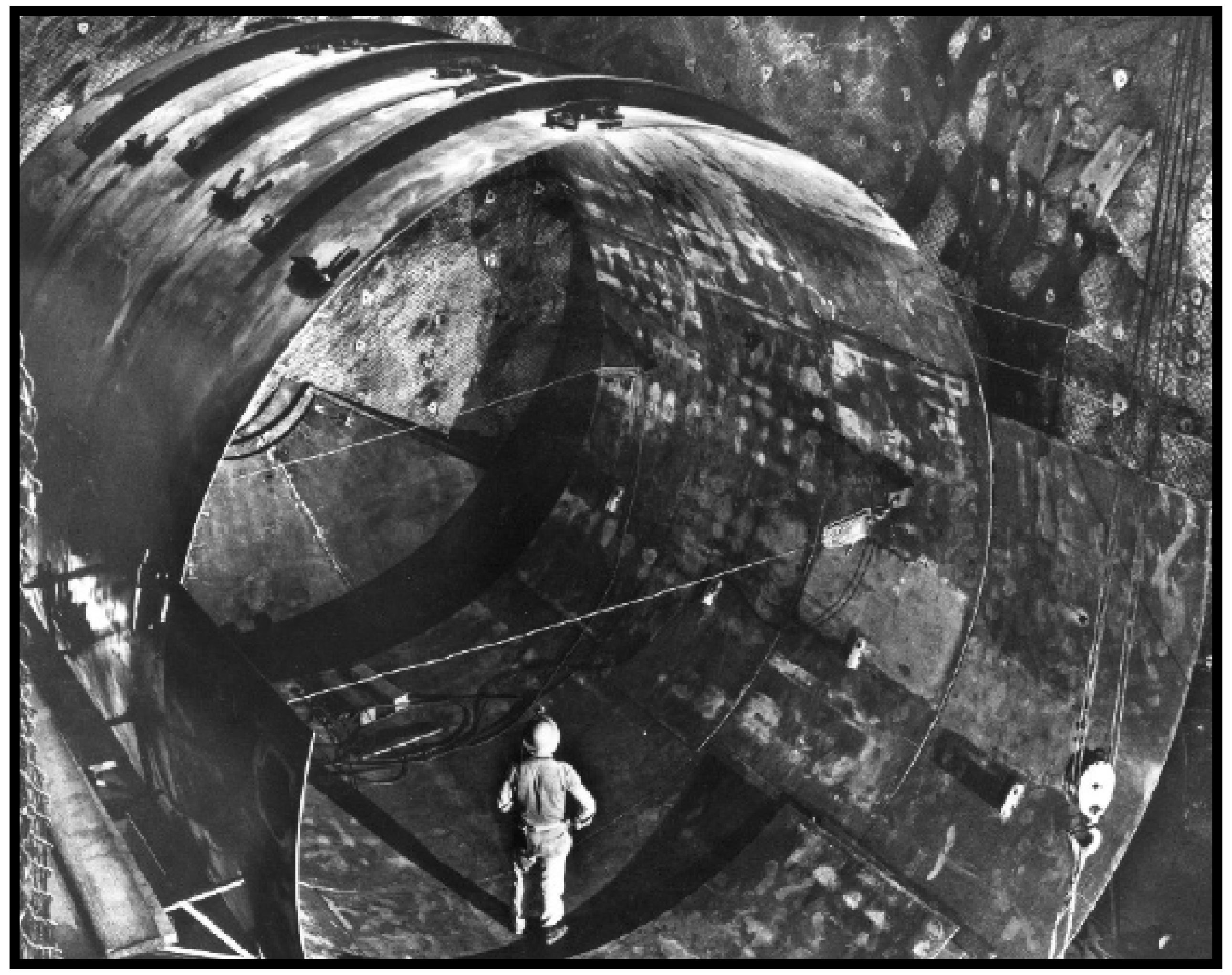
Weighting Neutrinos

MAYORANA Summer School

June 20th 2025

Joseph A. Formaggio
MIT

A myriad of experiments later showed that neutrinos indeed oscillate



Ray Davis Jr., Homestake

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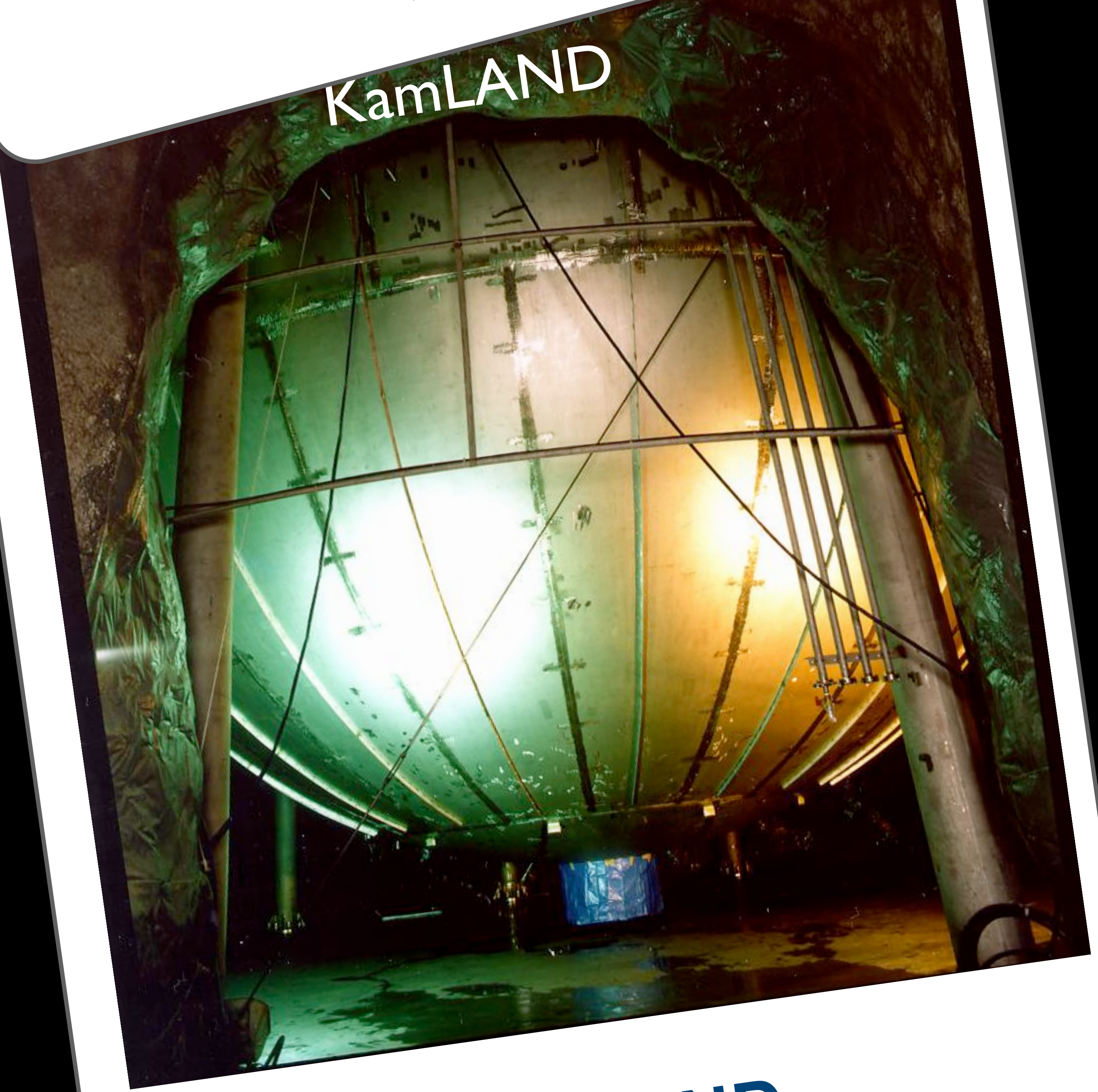
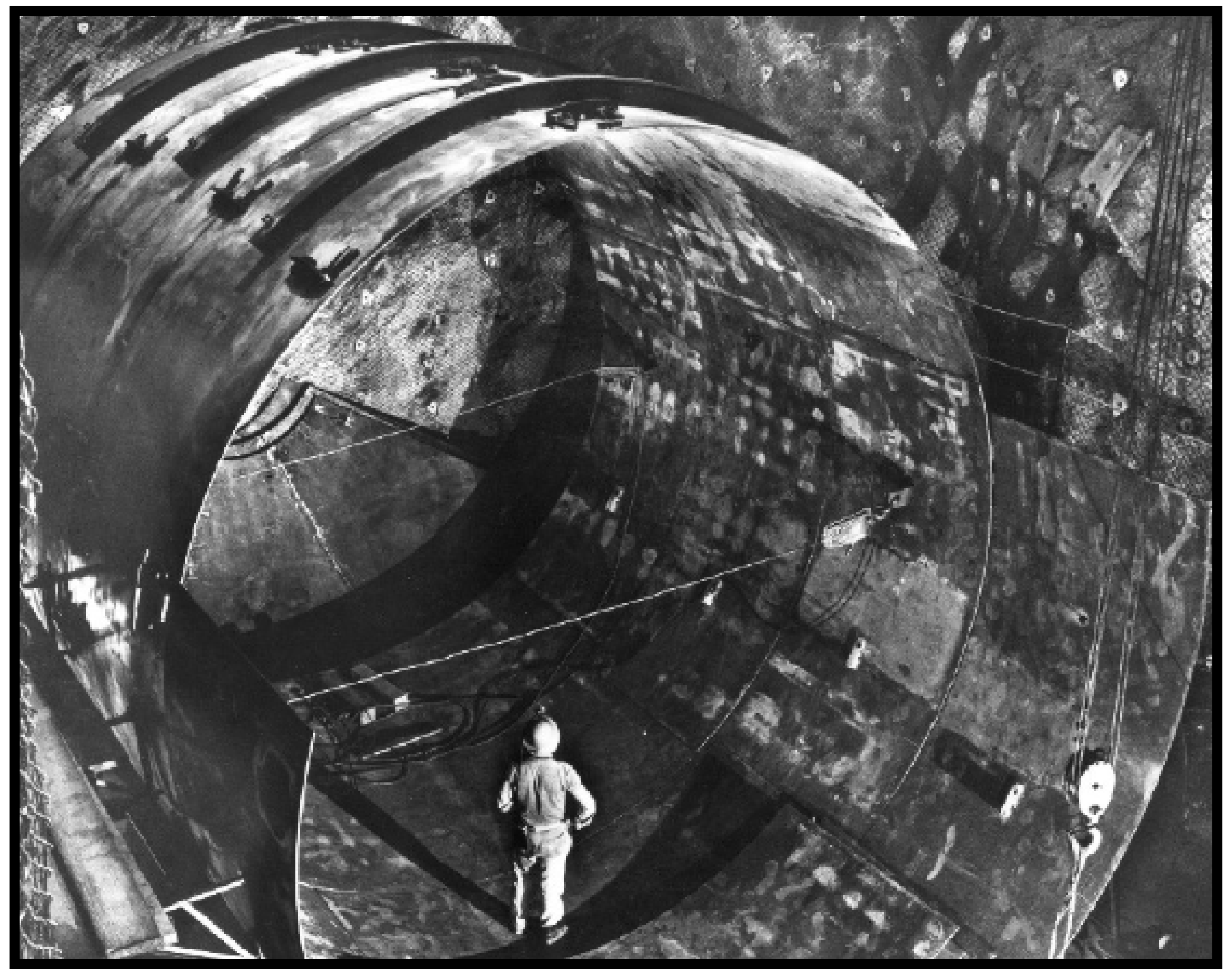
MINOS



KamLAND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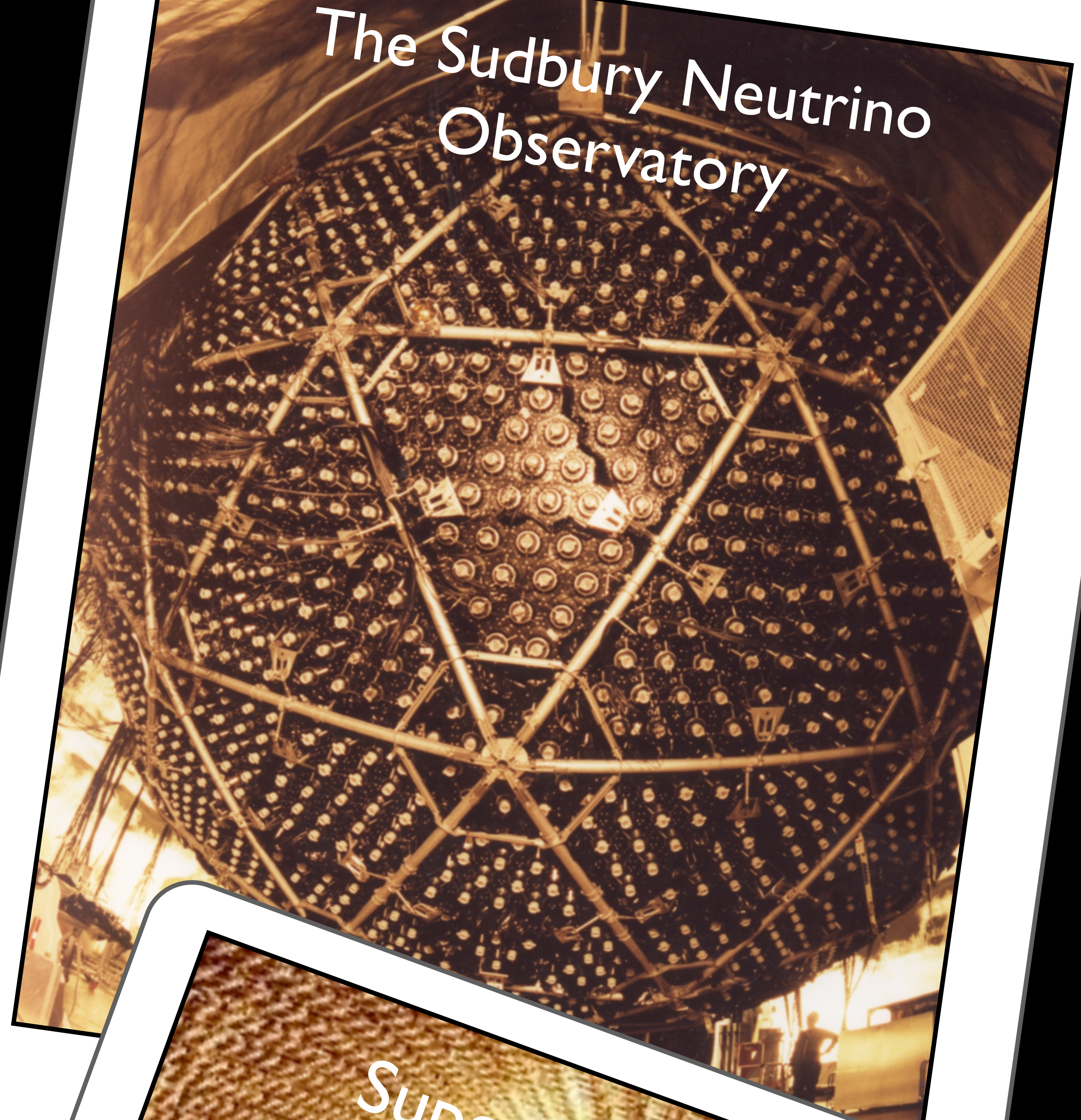
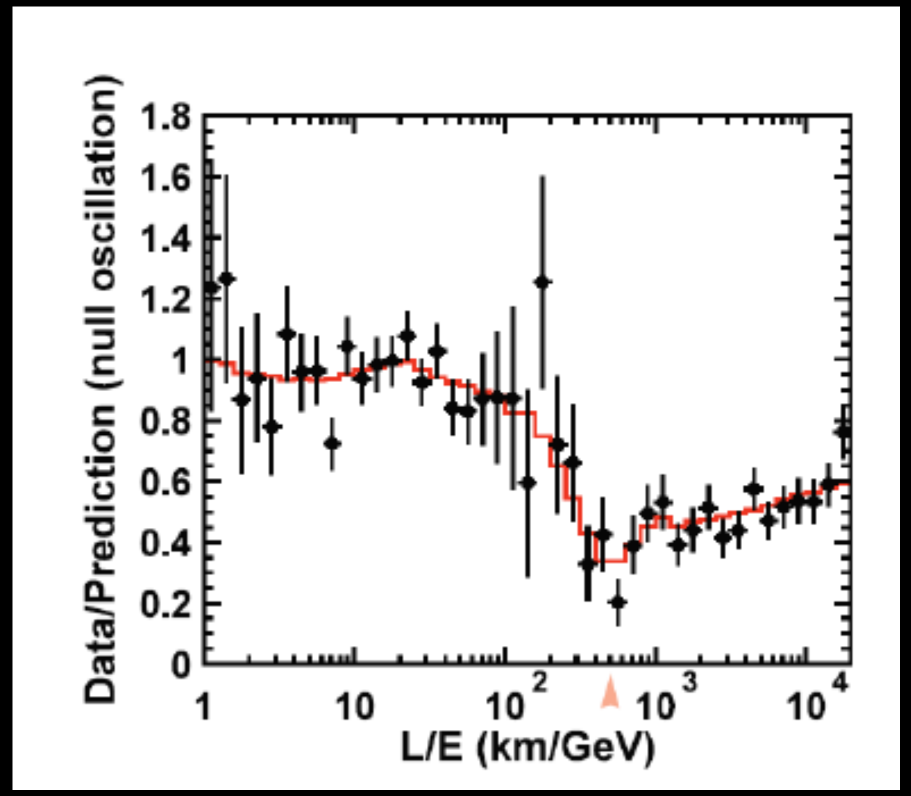
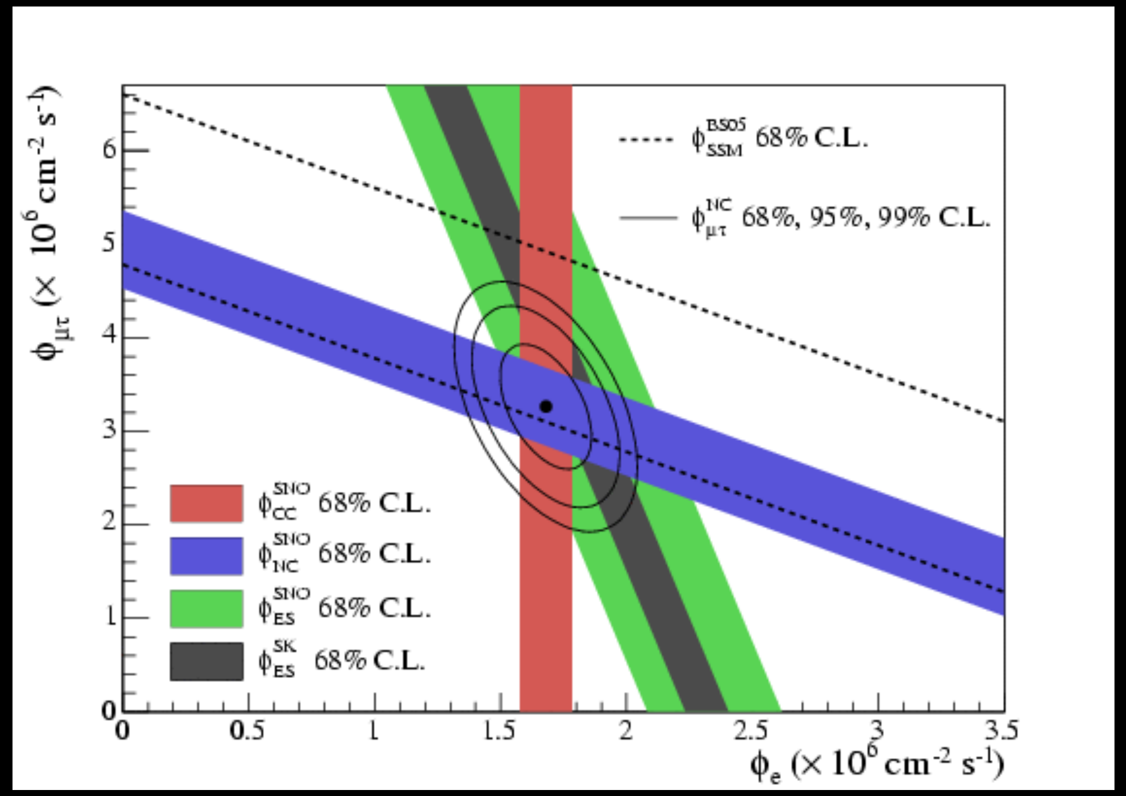


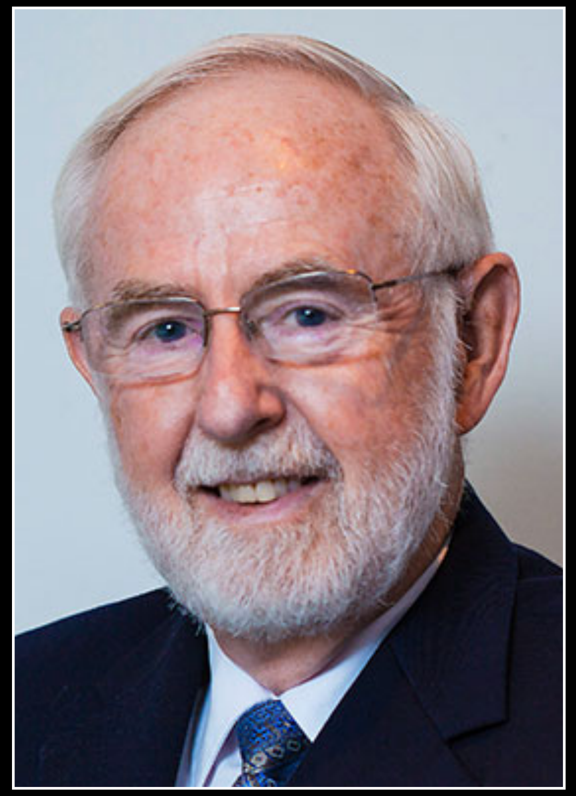
Super-Kamiokande

Neutrino oscillations (And by fiat neutrino masses) are now firmly established **departures** from the original prediction of the Standard Model.



So, what else can we learn from the fact that neutrinos have mass?





Takaaki Kajita
(Super-Kamiokande)

Arthur B. McDonald
(Sudbury Neutrino Observatory)

Are they massive the same as other particles?

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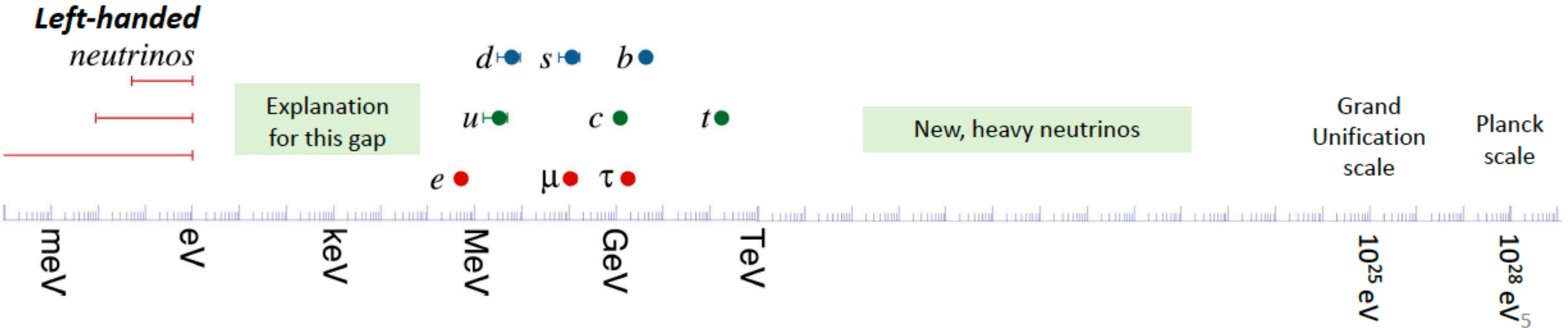
No, definitely not.



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Well…

Neutrino oscillations can only tell us about neutrino mass differences

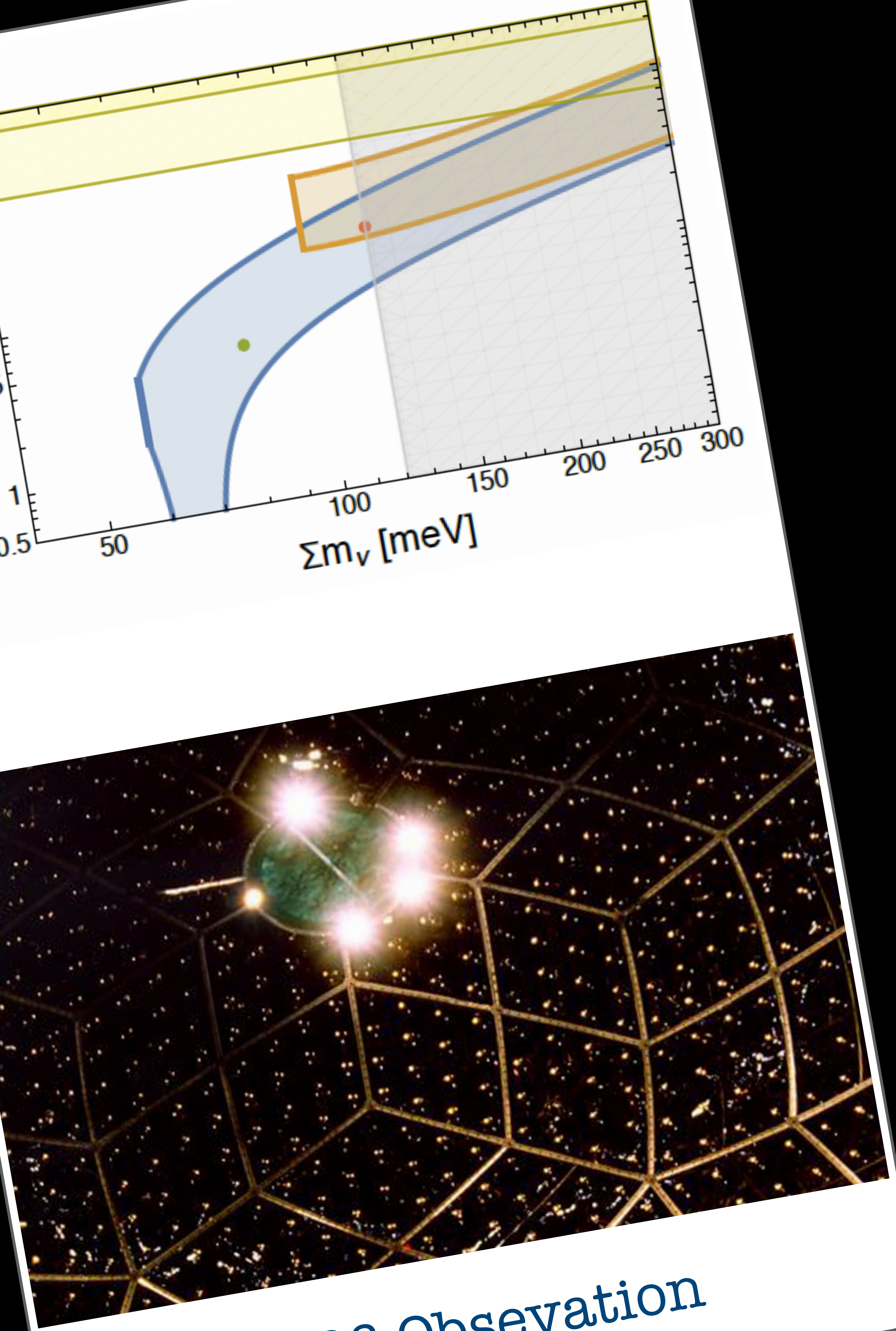
Not the mass scale itself.

Neutrino oscillations can only tell us about neutrino mass differences

Not the mass scale itself.

*ChatGPT's version of "weighing neutrinos"

For that, you need a different method.



0νββ Observation

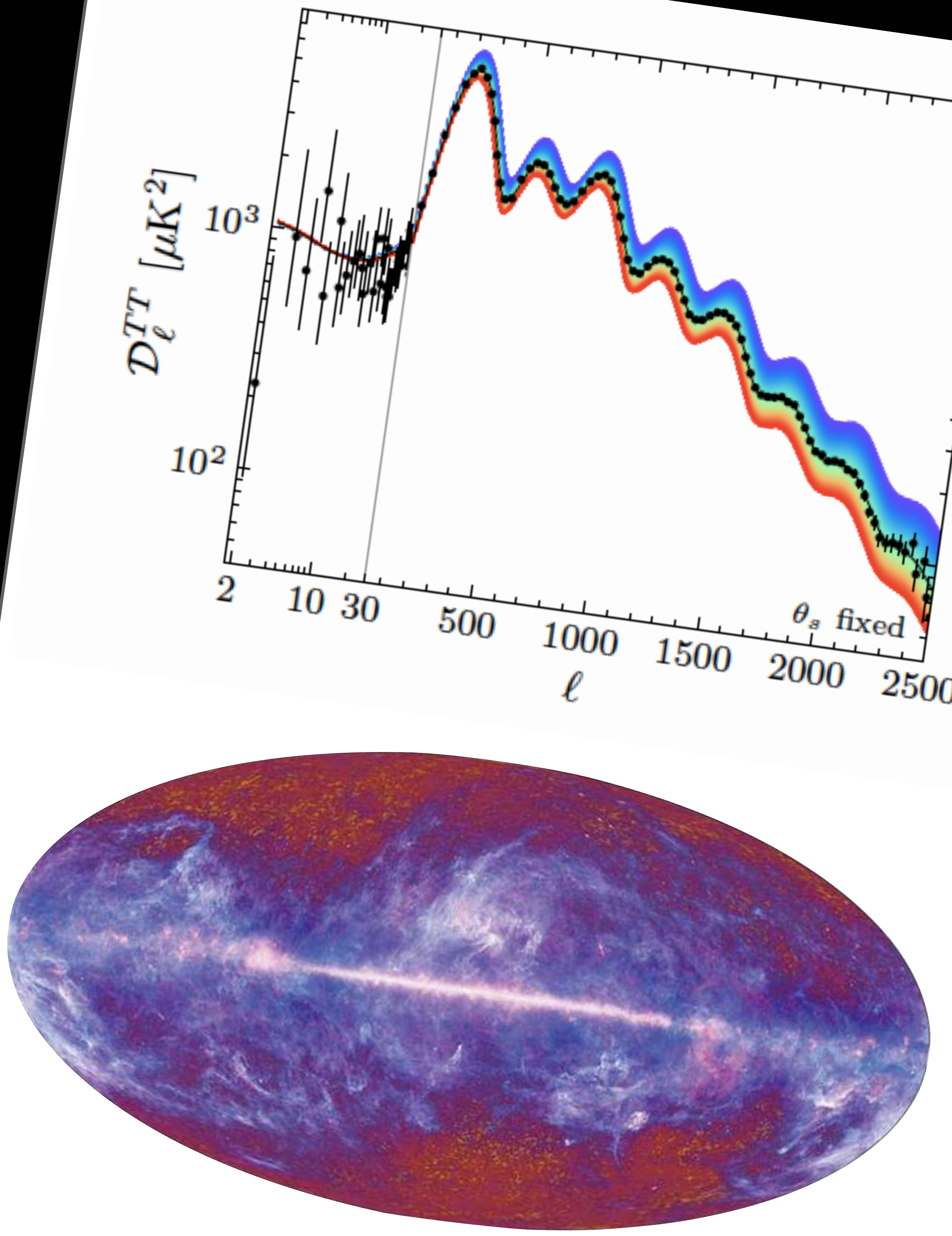
There are other ways to measure the mass scale.

You can take advantage of the neutrinos from the early universe to constrain masses (cosmology)

Or look at extremely rare decay processes (0νββ)

However, these all carry model dependencies.

These are indirect methods



Cosmological Constraints

A better method would hone into what it actually means to have mass.

That means taking advantage of the dispersion relation between energy and momentum.

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

That means taking advantage of the dispersion relation between energy and momentum.

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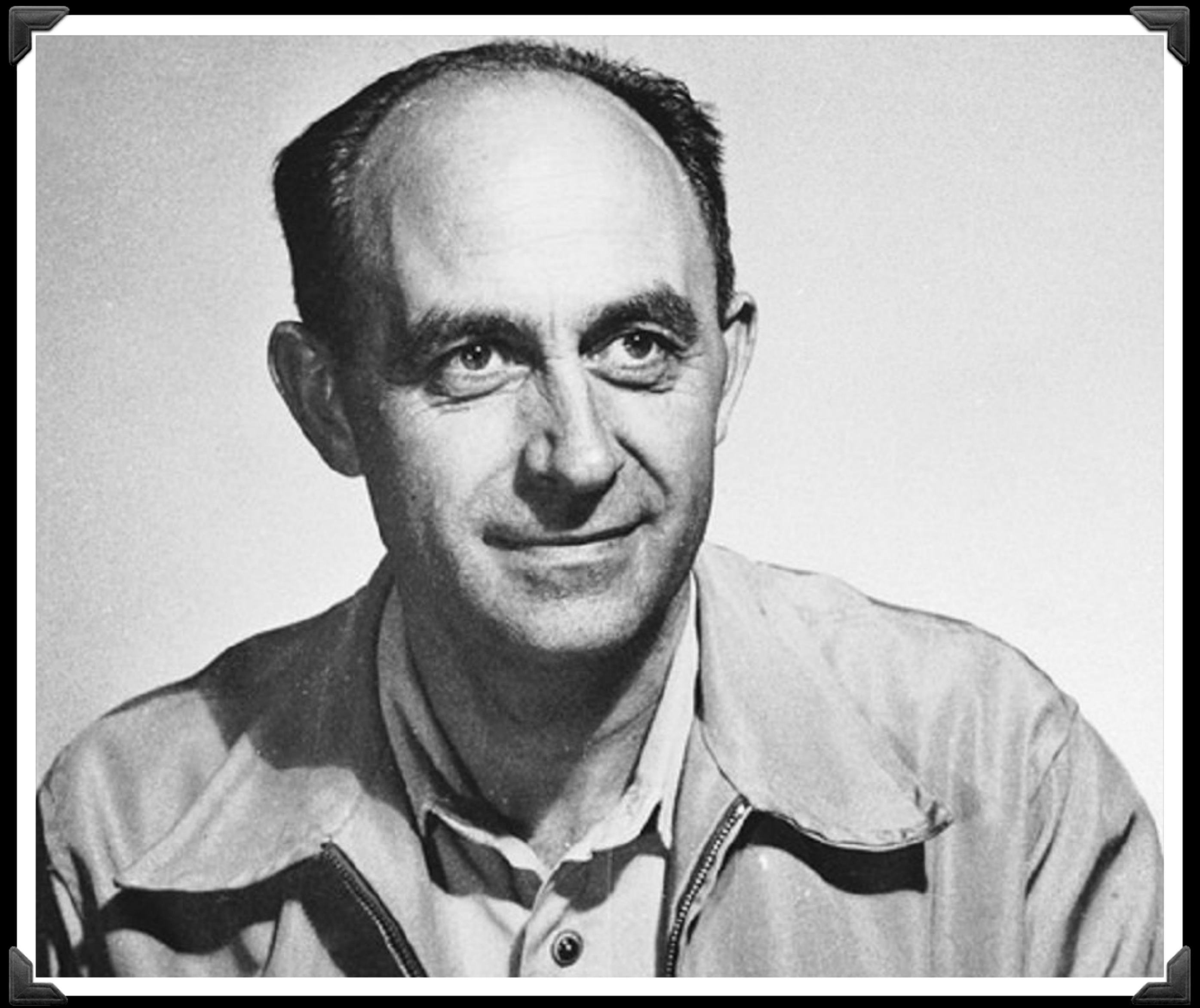
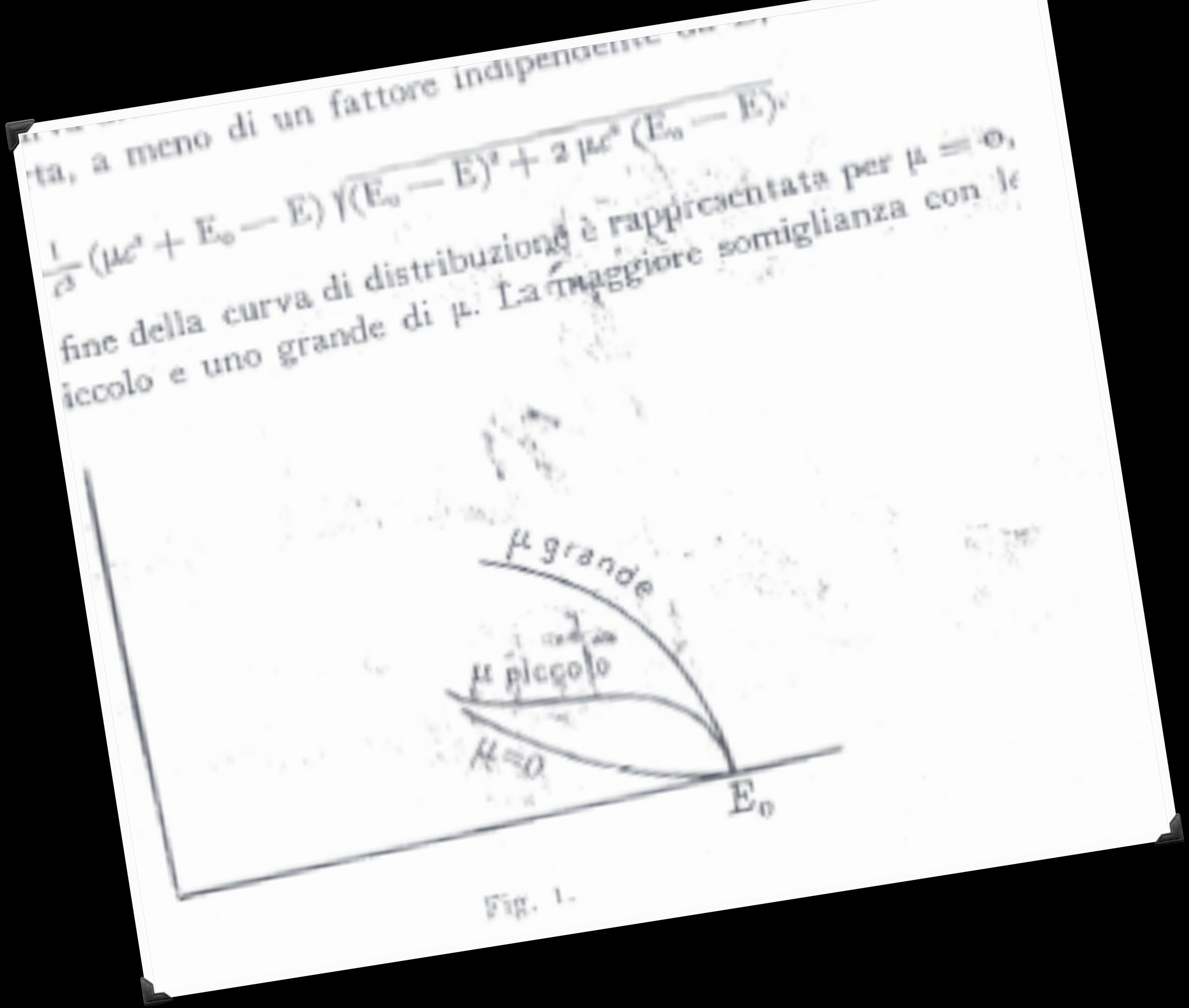
[One could attempt to deduce from the shape of the continuous emission spectra an indication of the value of this unknown mass...]

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.]



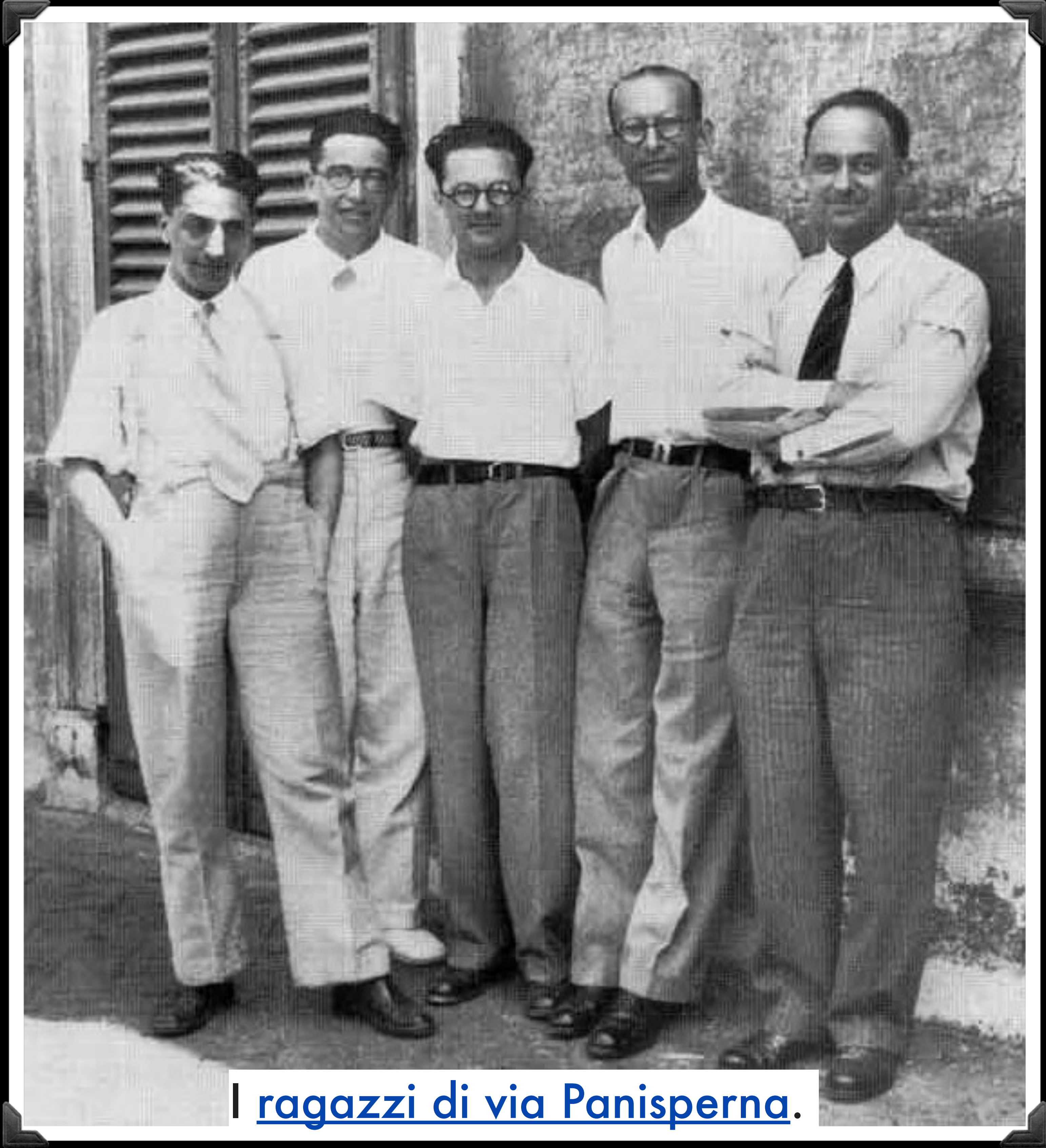


...ta, a meno di un fattore indipendente ...

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

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

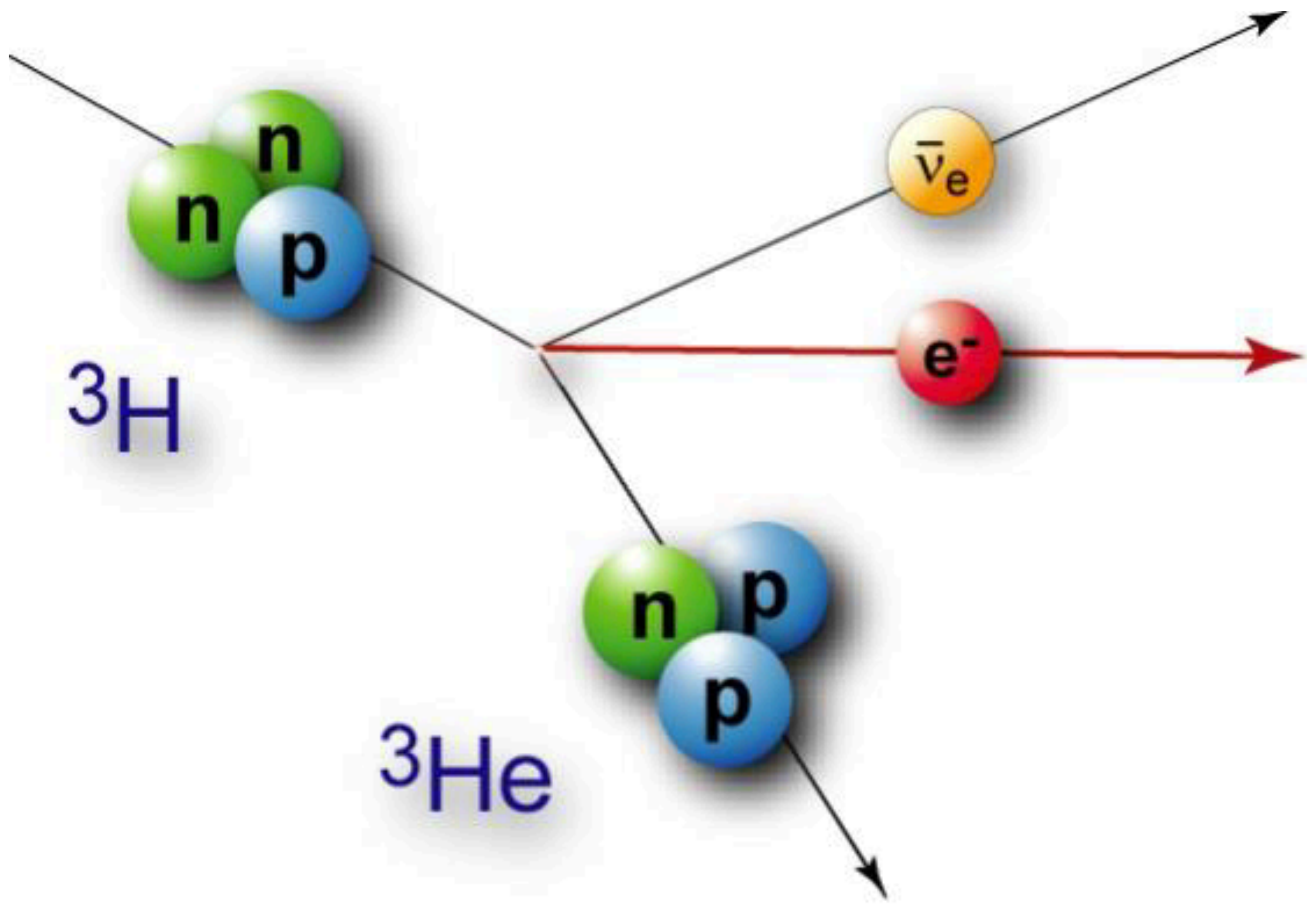
Fig. 1.



I ragazzi di via Panisperna.

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

The Basic Idea...



Start with a radioactive isotope
(My favorite, tritium)

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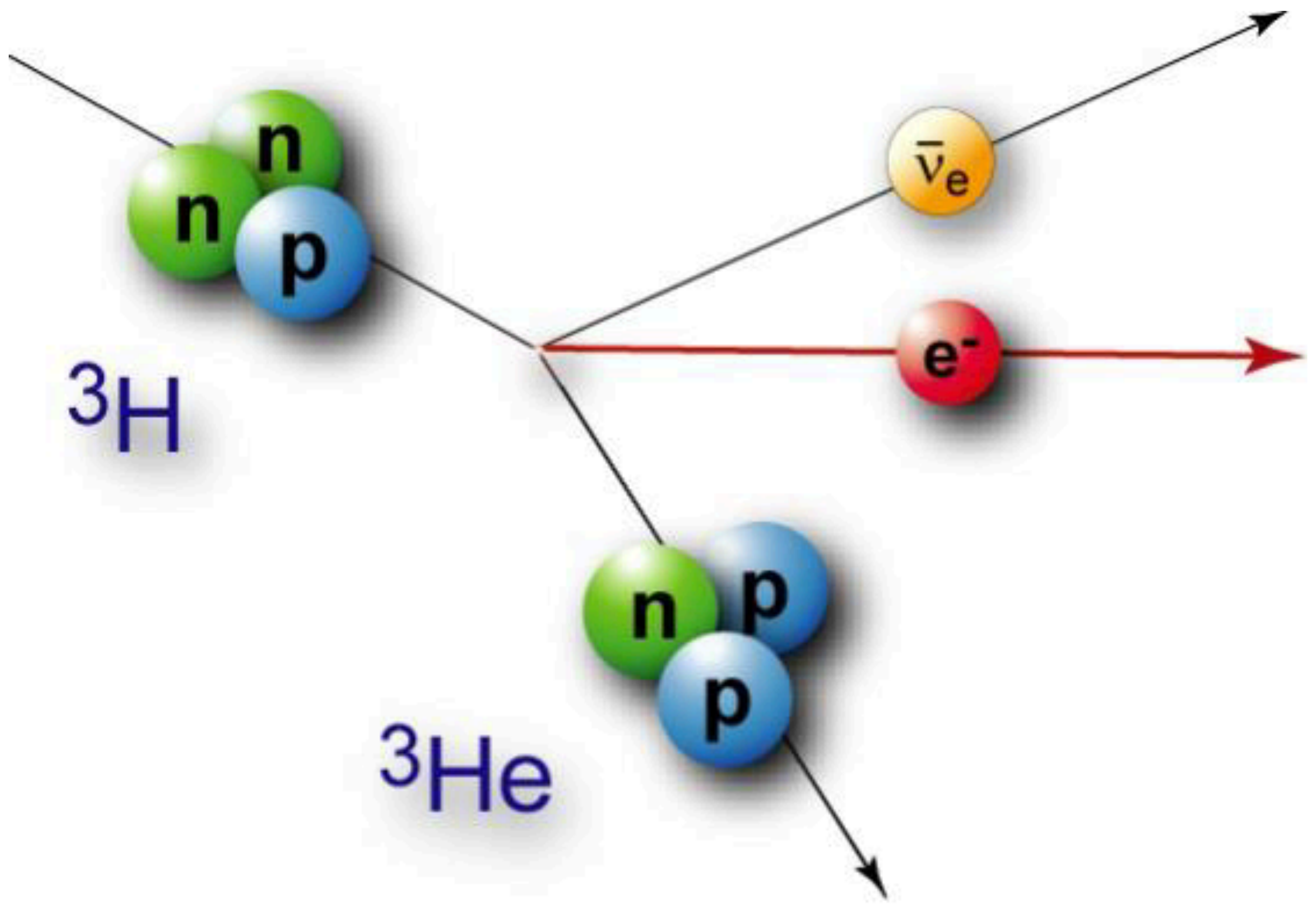

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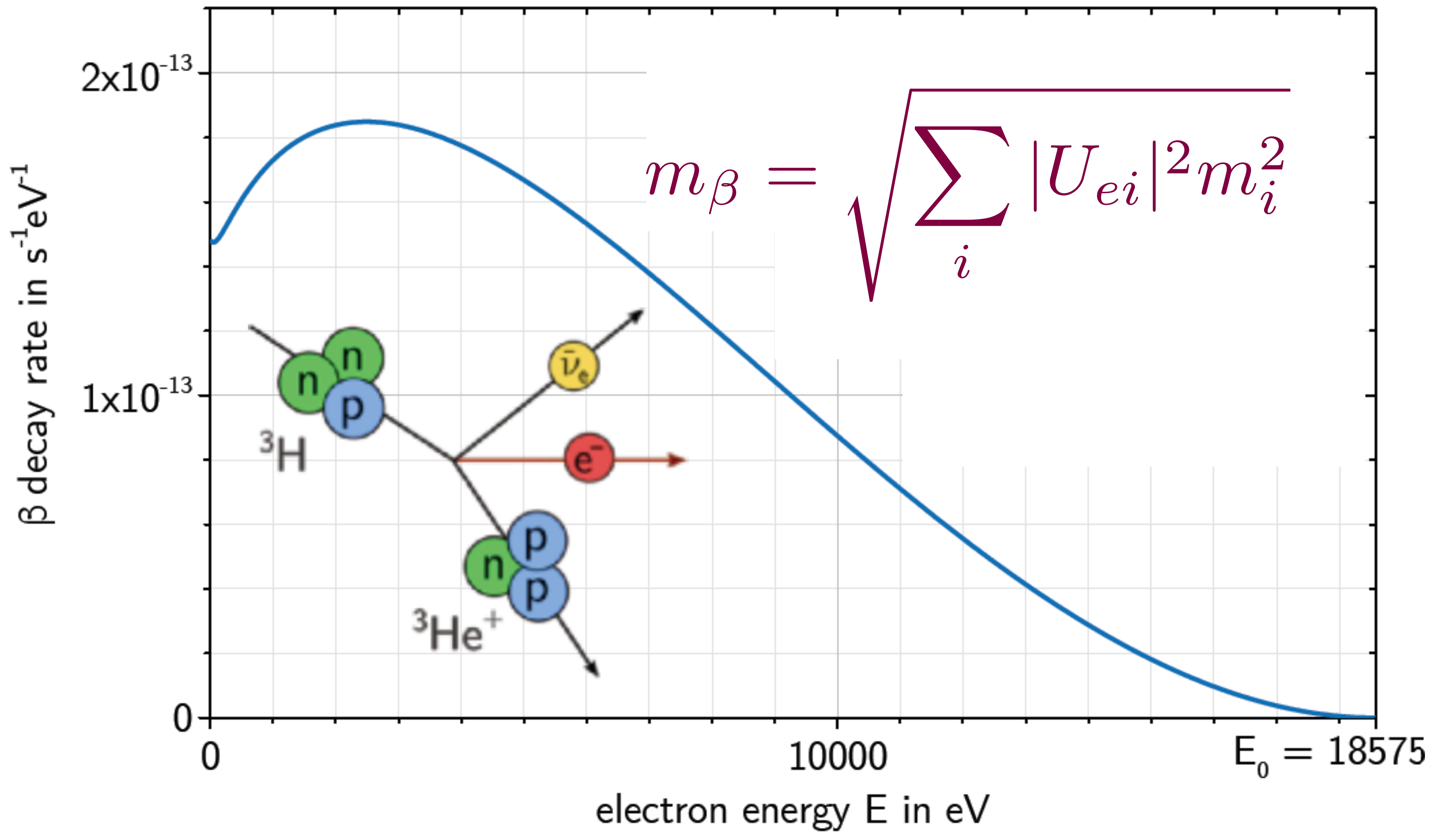
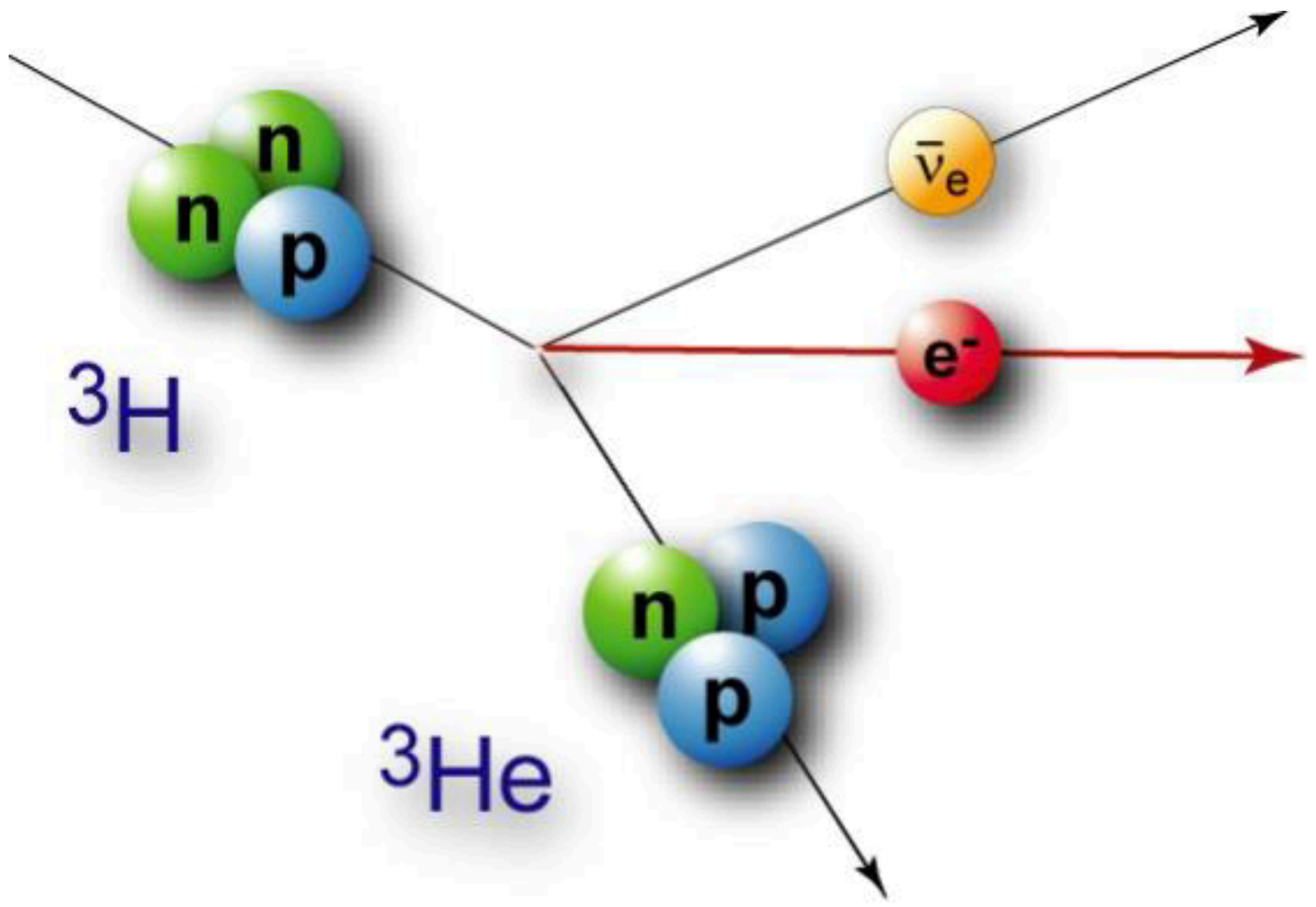


Then measure the outgoing electron's energy

The Basic Idea…



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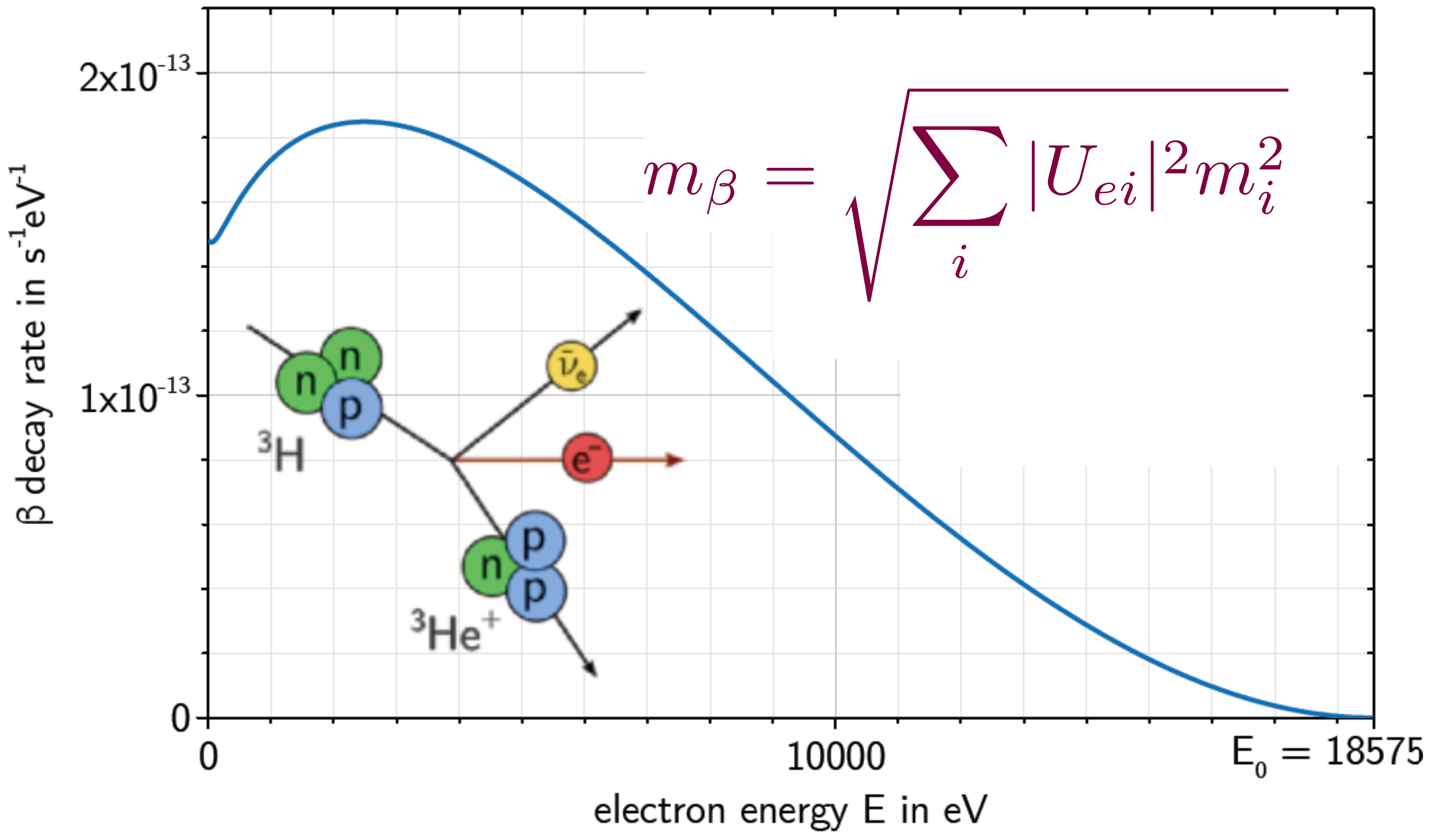

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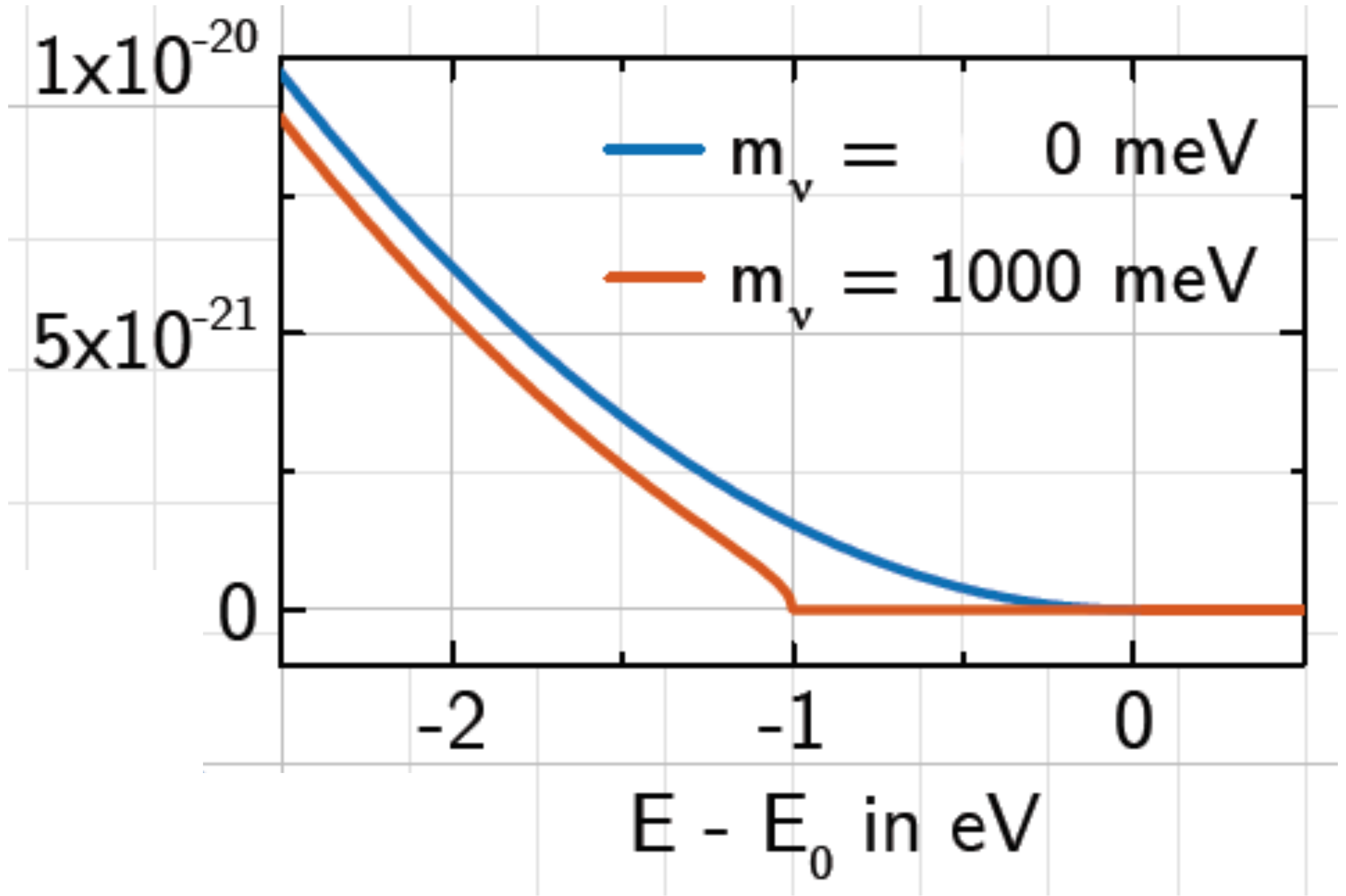
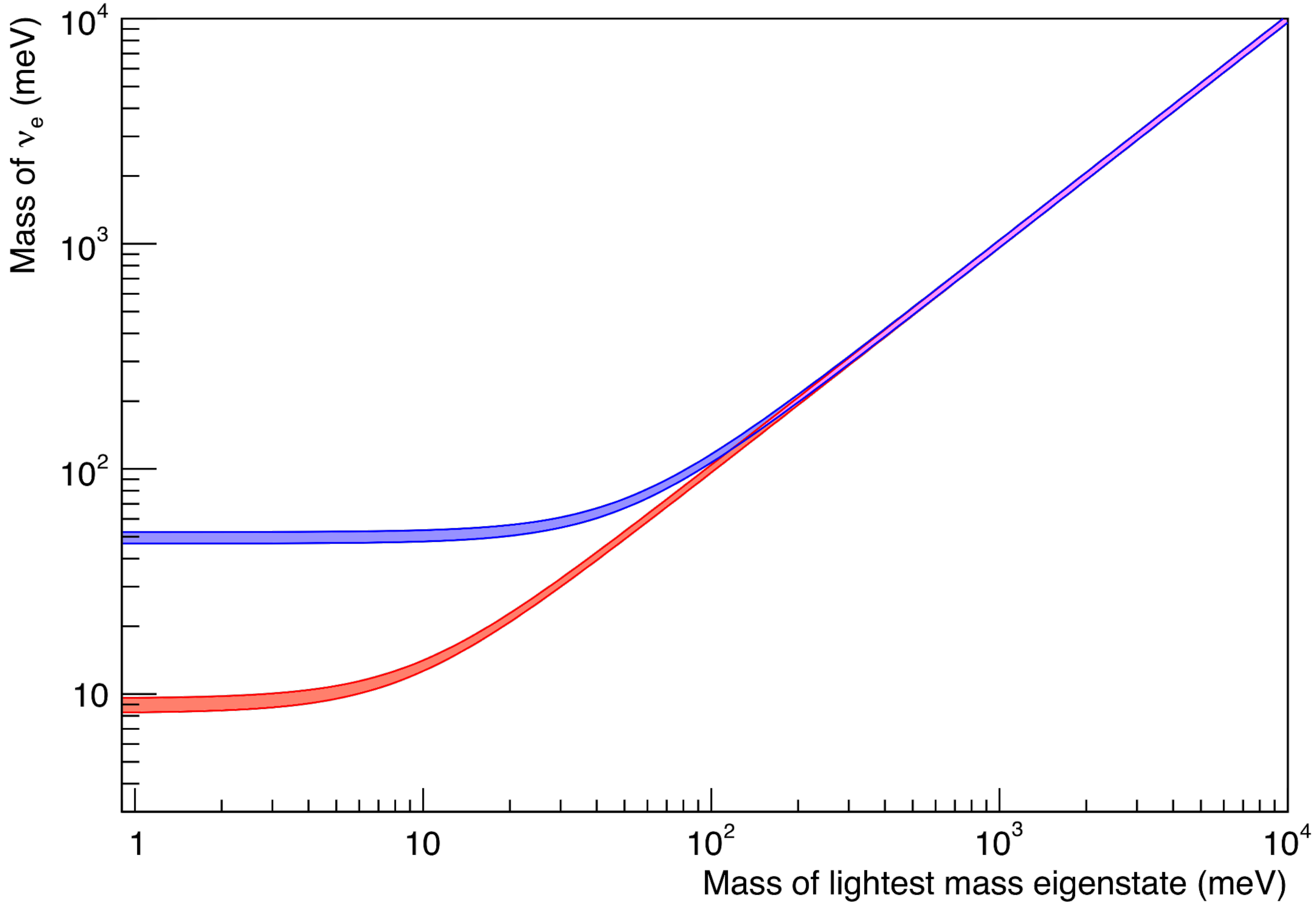


Really zoom in at its maximum energy

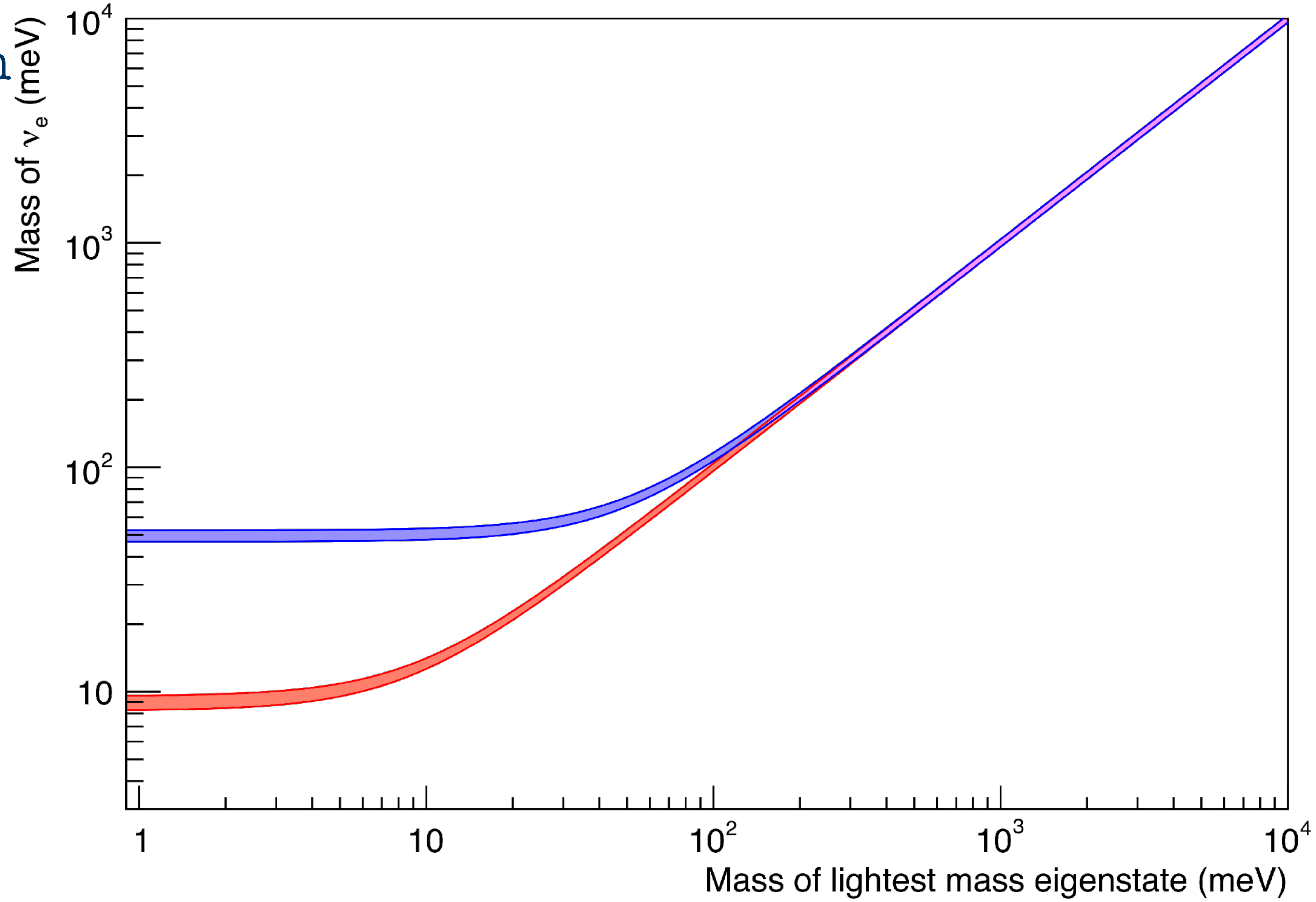
The information about the neutrino mass comes from the distortion of the decay energy spectrum.

We are going to see this graph a few times, so it is worth a minute…



We are going to see this graph a few times, so it is worth a minute...

This shows the electron neutrino mass (what we measure)



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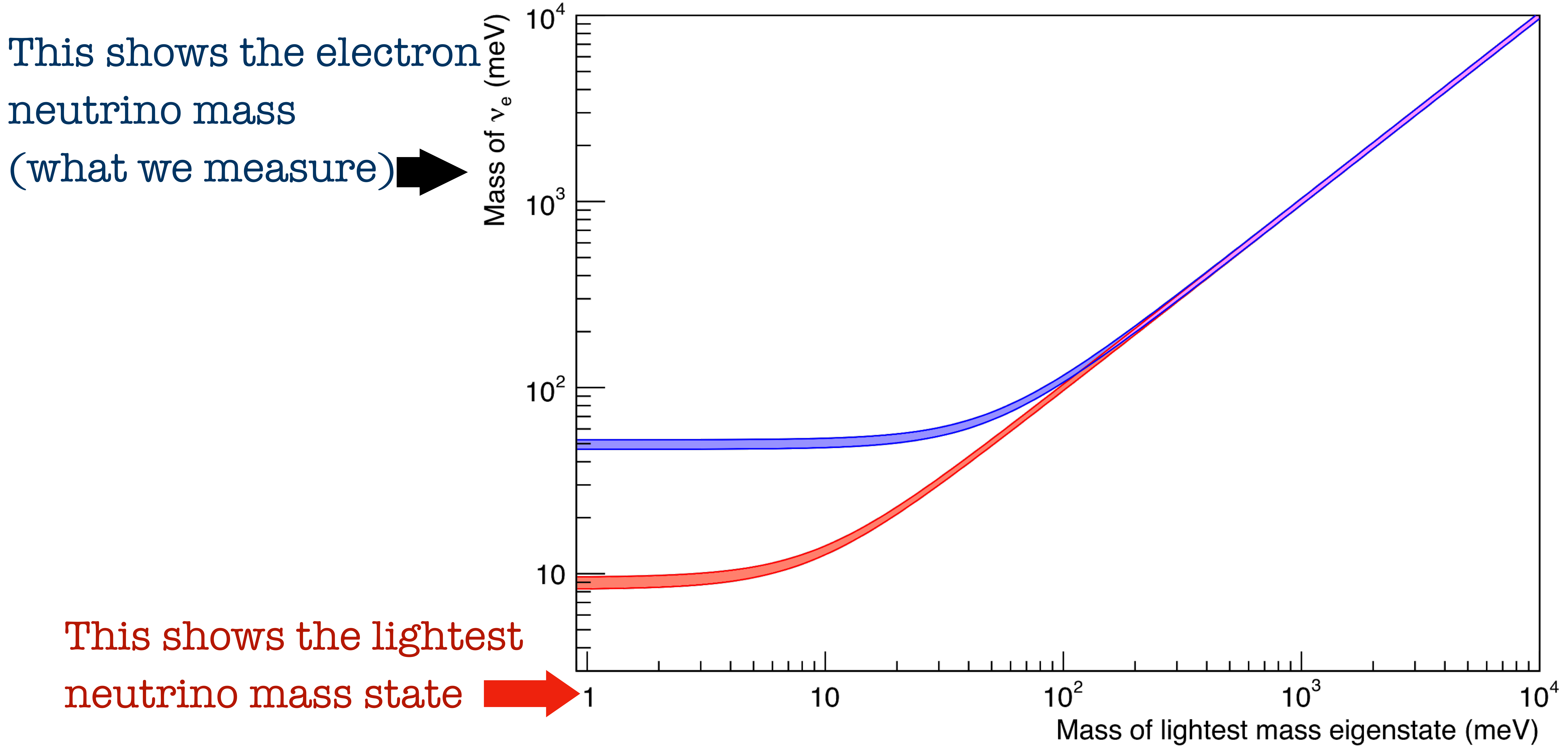

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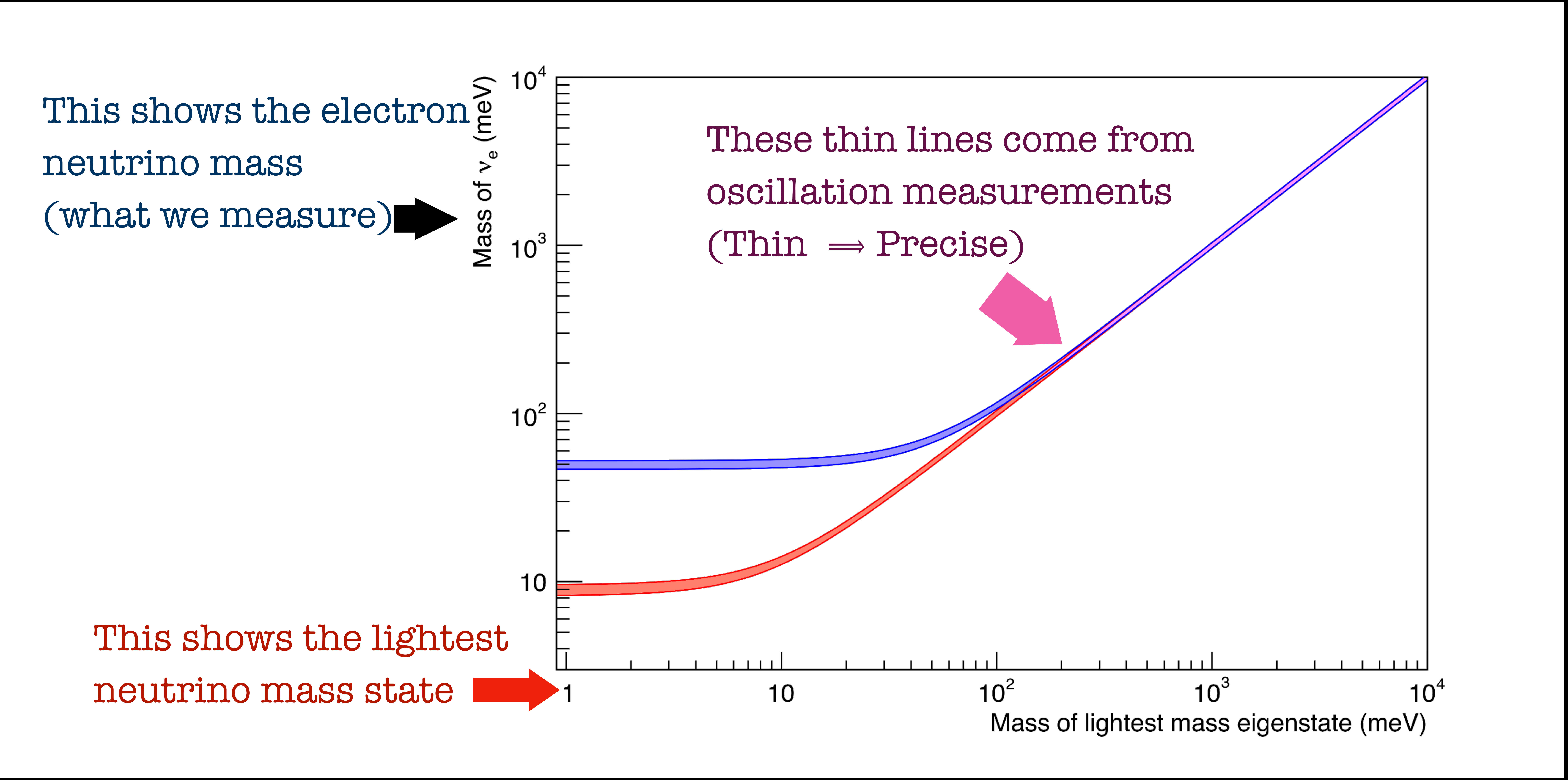

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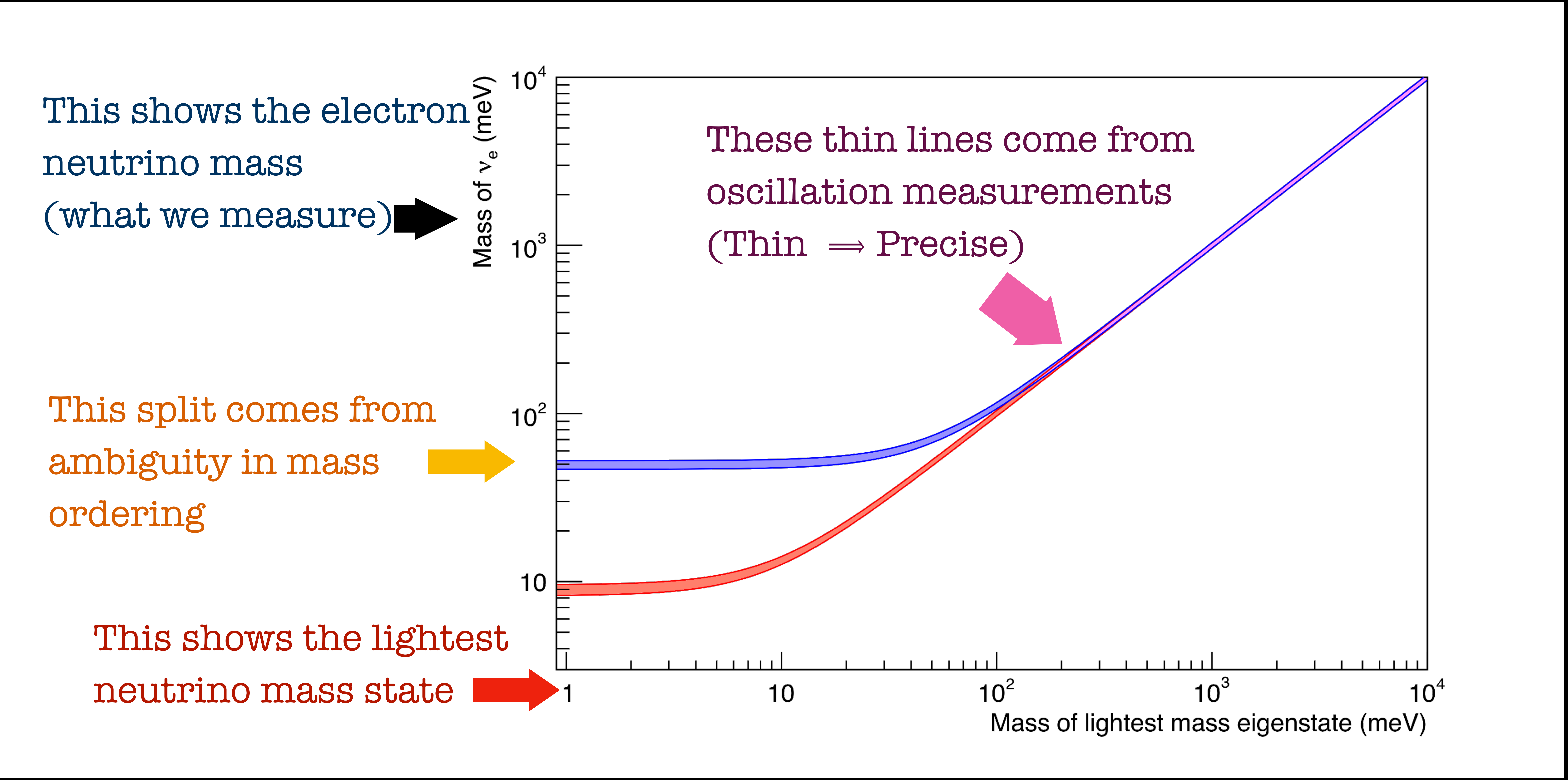
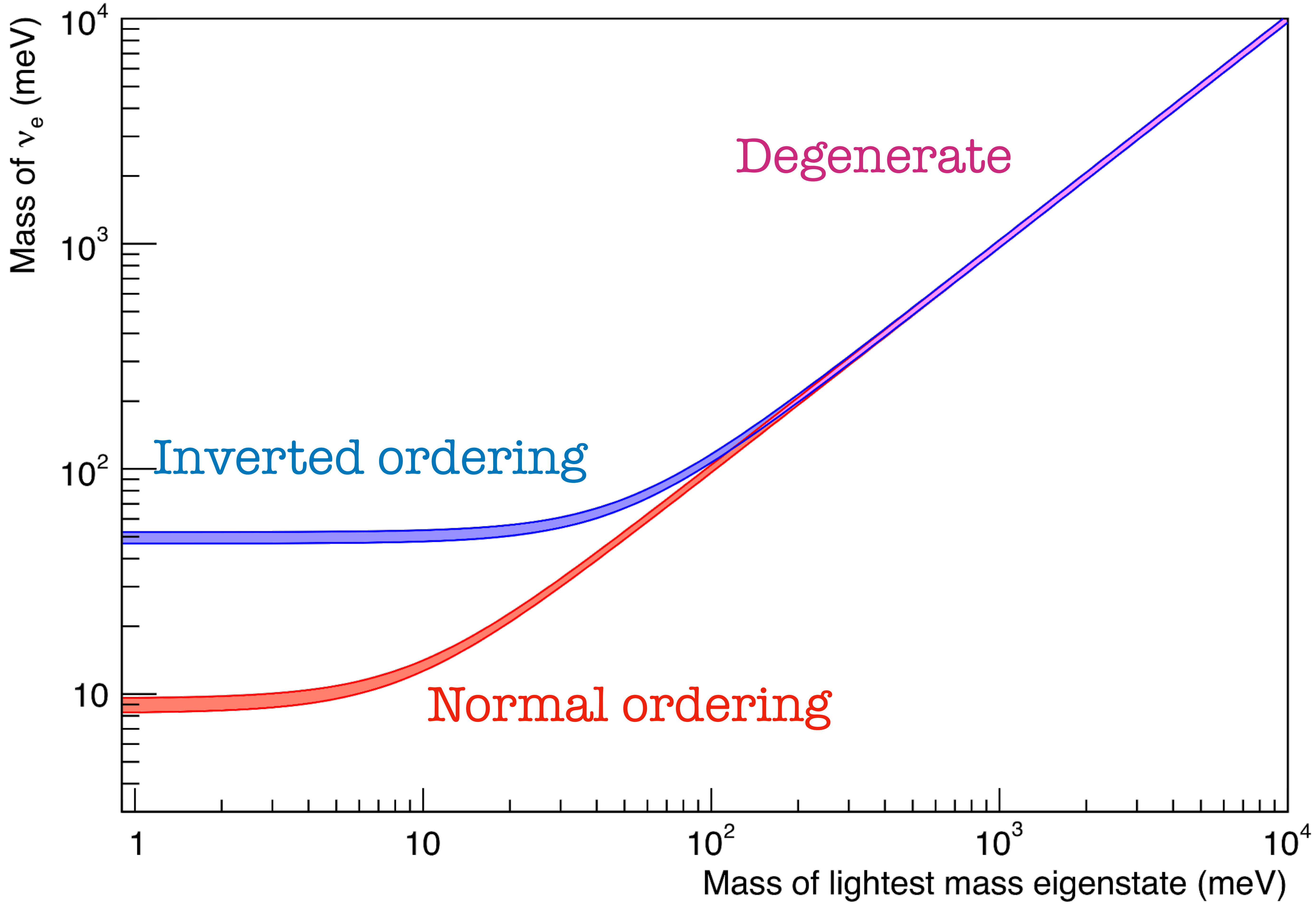


We are going to see this graph a few times, so it is worth a minute…

Since we don't know which neutrino is "lightest", there is an ordering ambiguity

(Or they might be all about the same)



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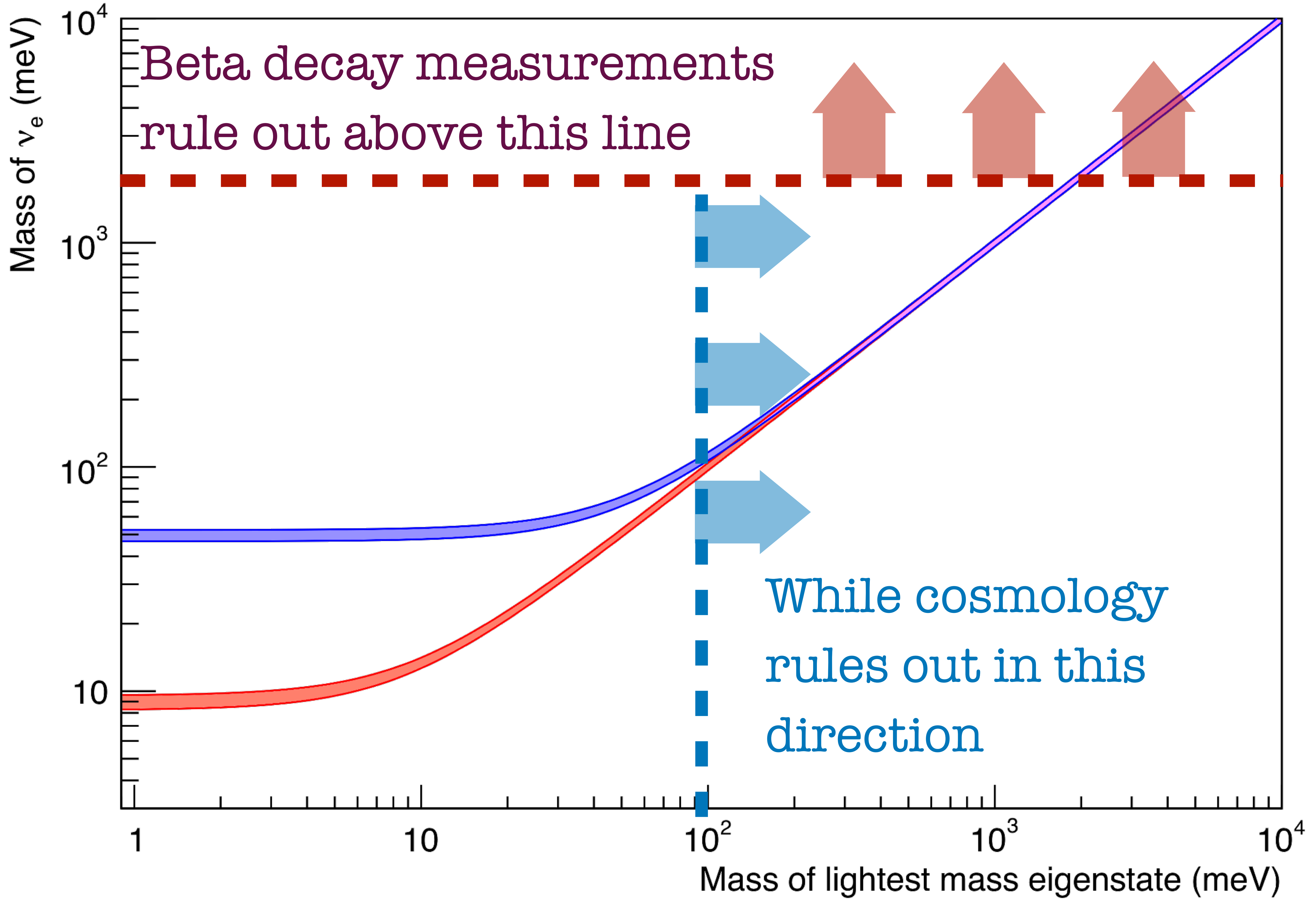
Beta decay measurements (& cosmology) squeeze what's allowed.

Note that there exists a "floor" for what beta decay can measure.



The $\pi\sqrt{2}$ Magnetic Spectrometer

- Bergkvist constructs first tritium source experiment in Stockholm.
- Double focusing spectrometer; first to fully tackle energy resolution, energy loss and final states coherently.
- Achieved best limit of the time (m_ν < 55 eV).

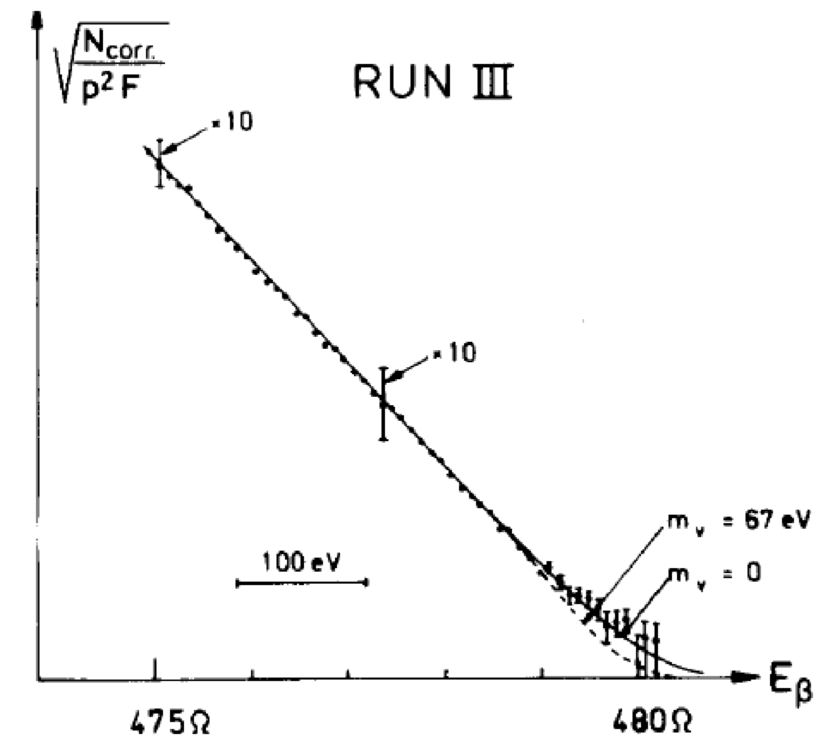


Fig. 20. Kurie plots of data from runs I–III. The data exhibited have been subjected to a very slight correction for distortion in the measured spectrum. The theoretical curves have been fitted to the data in the way discussed in connection with fig. 18.

Nuclear Physics B39 (1972) 317–370. North-Holland Publishing Company

A HIGH-LUMINOSITY, HIGH-RESOLUTION STUDY OF THE END-POINT BEHAVIOUR OF THE TRITIUM β-SPECTRUM (I). BASIC EXPERIMENTAL PROCEDURE AND ANALYSIS WITH REGARD TO NEUTRINO MASS AND NEUTRINO DEGENERACY

Karl-Erik BERGKVIST
Research Institute for Physics, and University of Stockholm, Stockholm, Sweden

Received 23 September 1971
(Revised 13 December 1971)

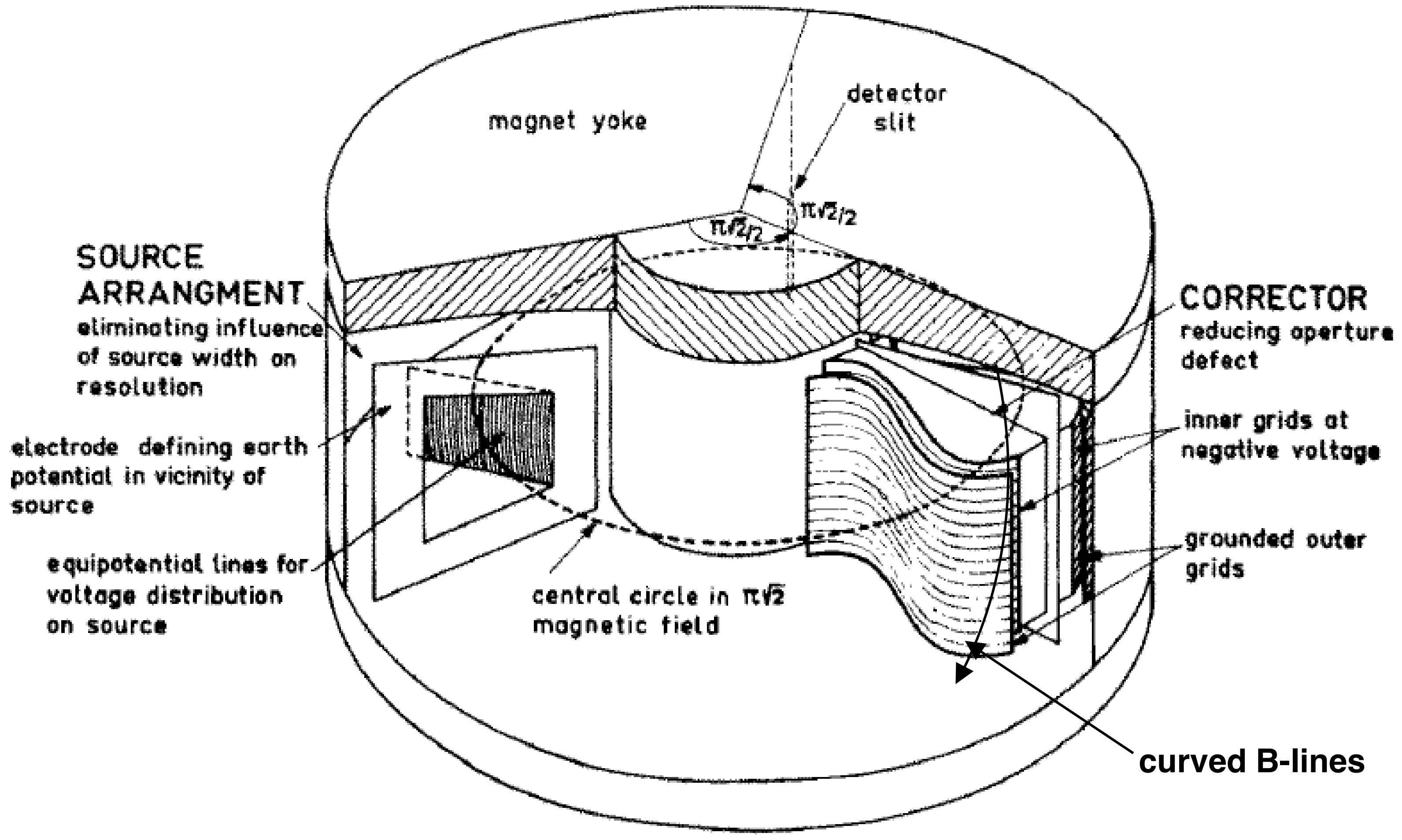
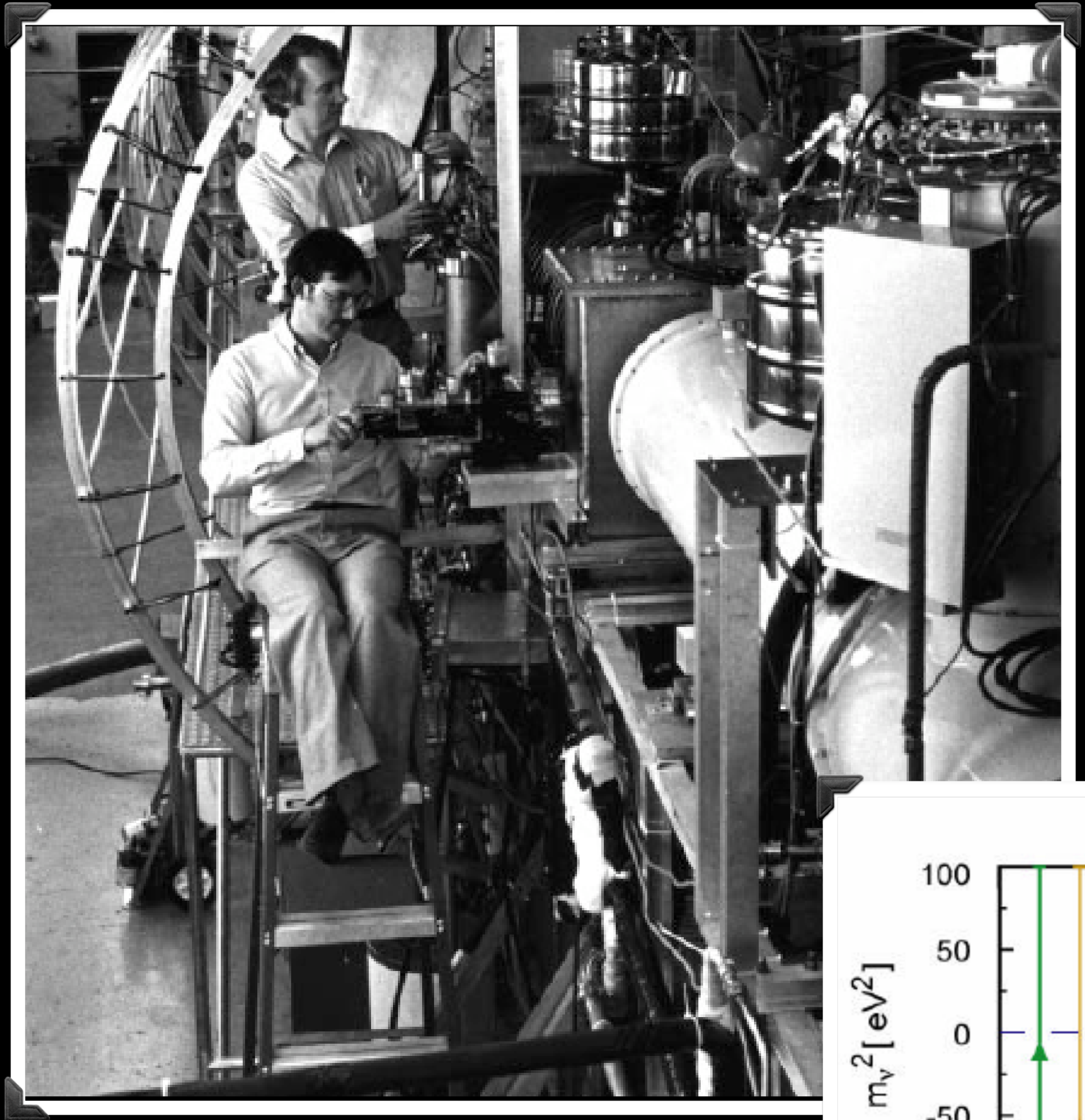


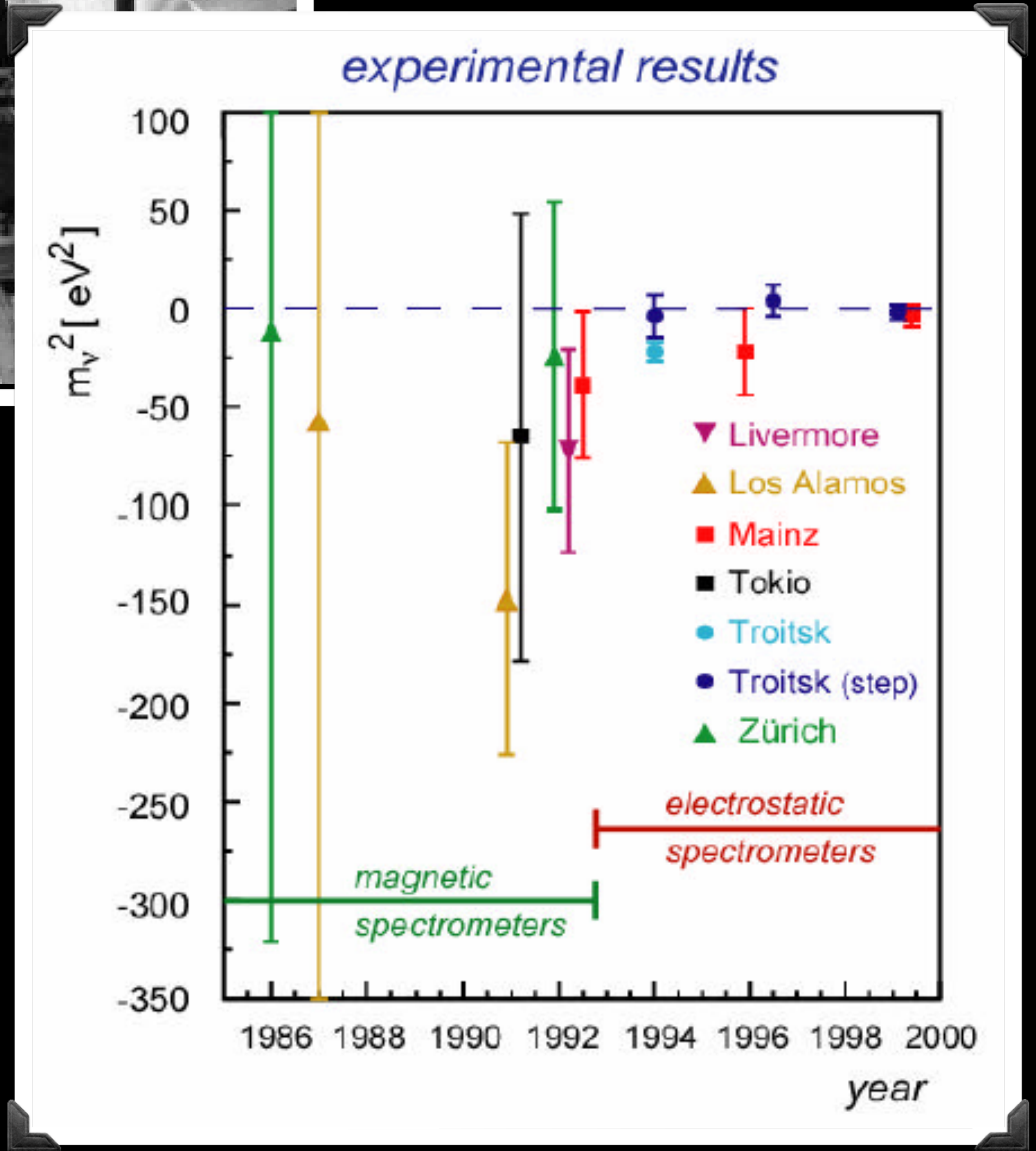
Fig. 3. Basic components of electrostatic-magnetic spectrometer employed in the present investigation of the end-point region of the tritium β-spectrum.

Los Alamos

- Robertson, Bowles, Wilkerson and others at Los Alamos devise the first gaseous tritium source experiment to circumvent earlier issues seen with solid state sources.

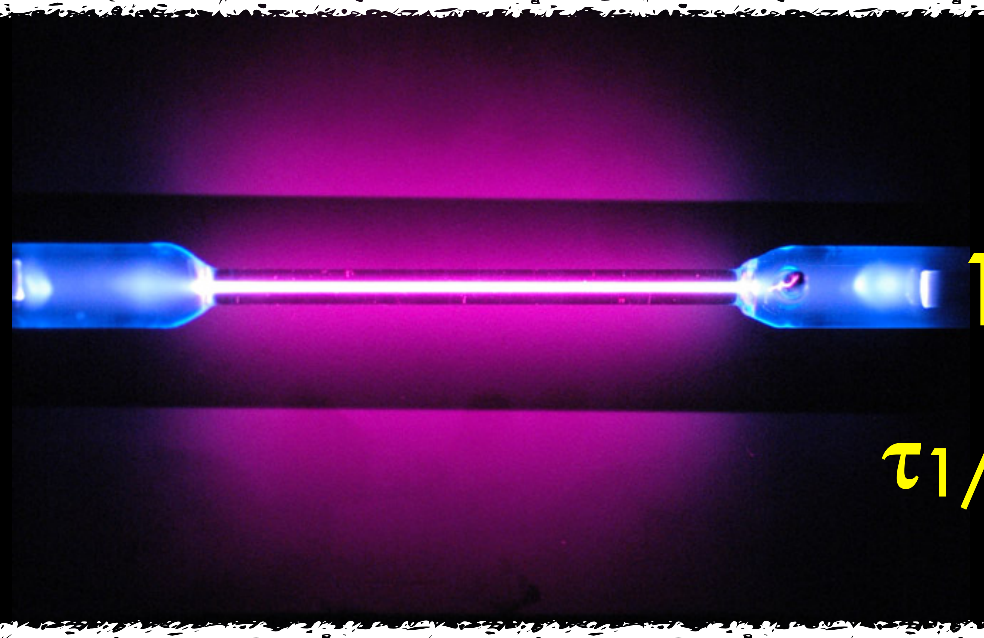
- Their limit of 27 eV rules out a previous signal for neutrino mass. Sets stage for gaseous sources in future designs.





Mainz & Troitsk

Choice of Sources



$^{3}H_2$

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

^{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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Calorimetric

(Cryogenic Bolometers)

Electromagnetic Filtering

(MAC-E Filters)

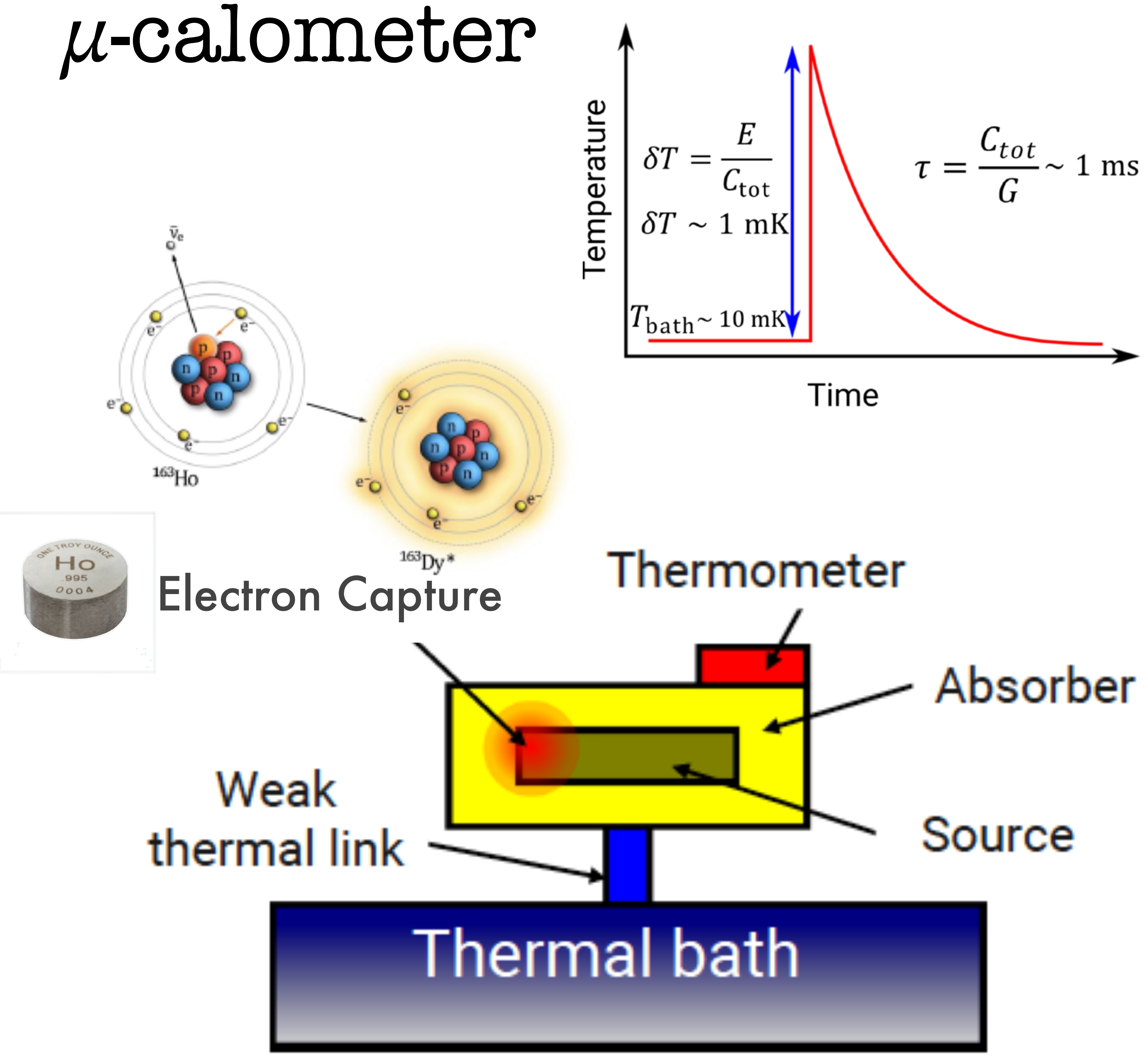
Frequency-Based

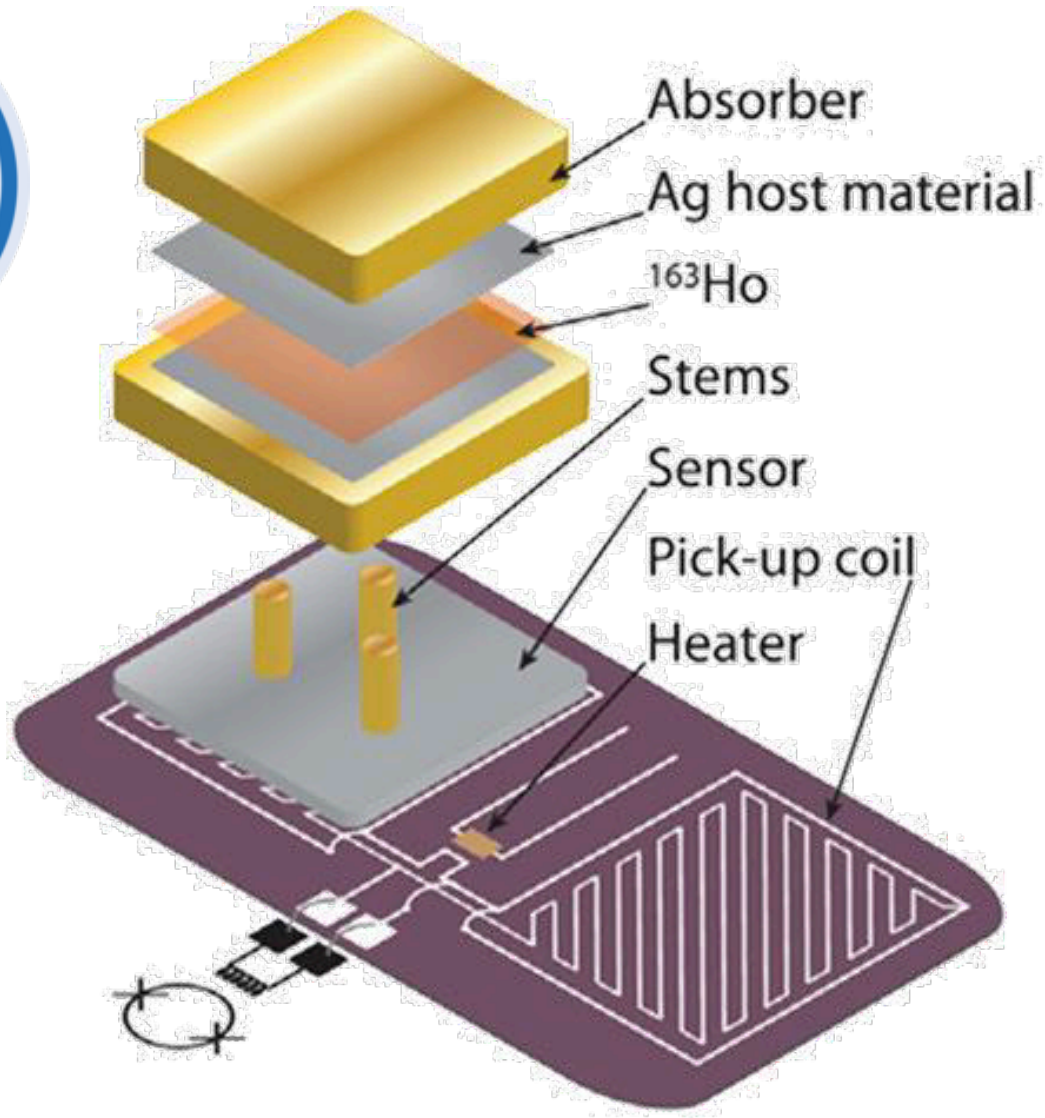
(Cyclotron Radiation Emission Spectroscopy)

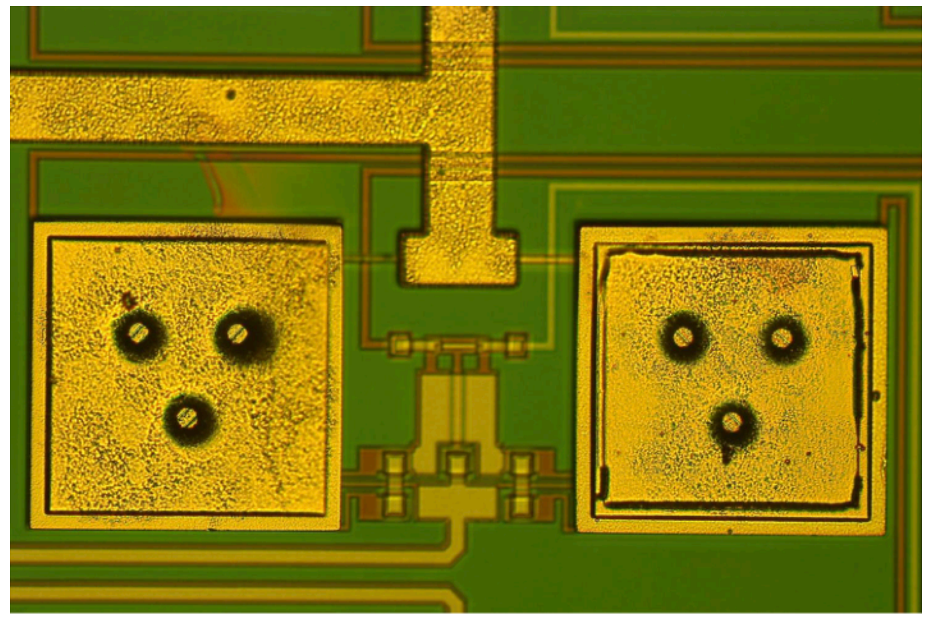
Calorimetric

(Cryogenic Bolometers)

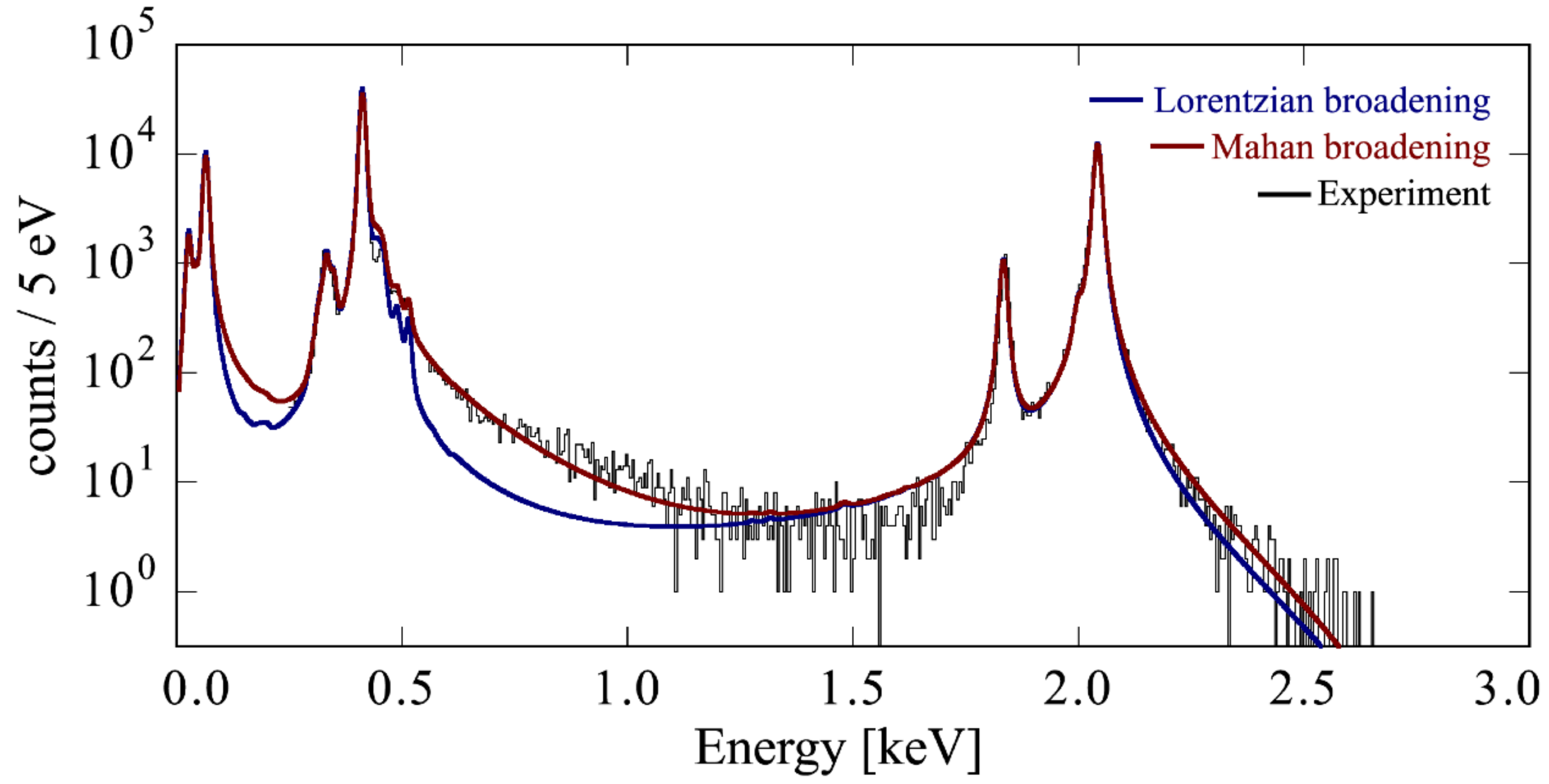
μ-calometer







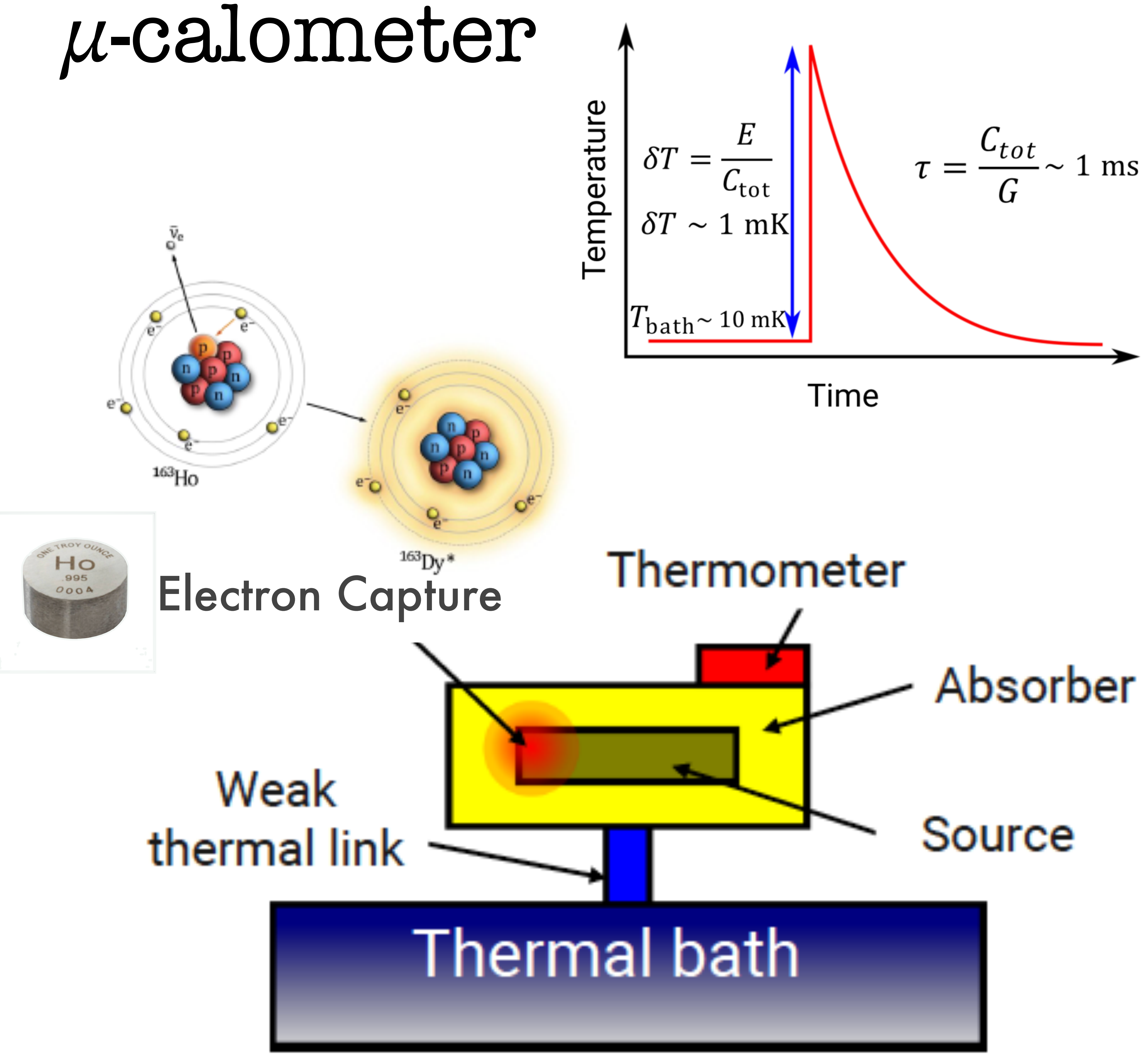
Energy Spectra



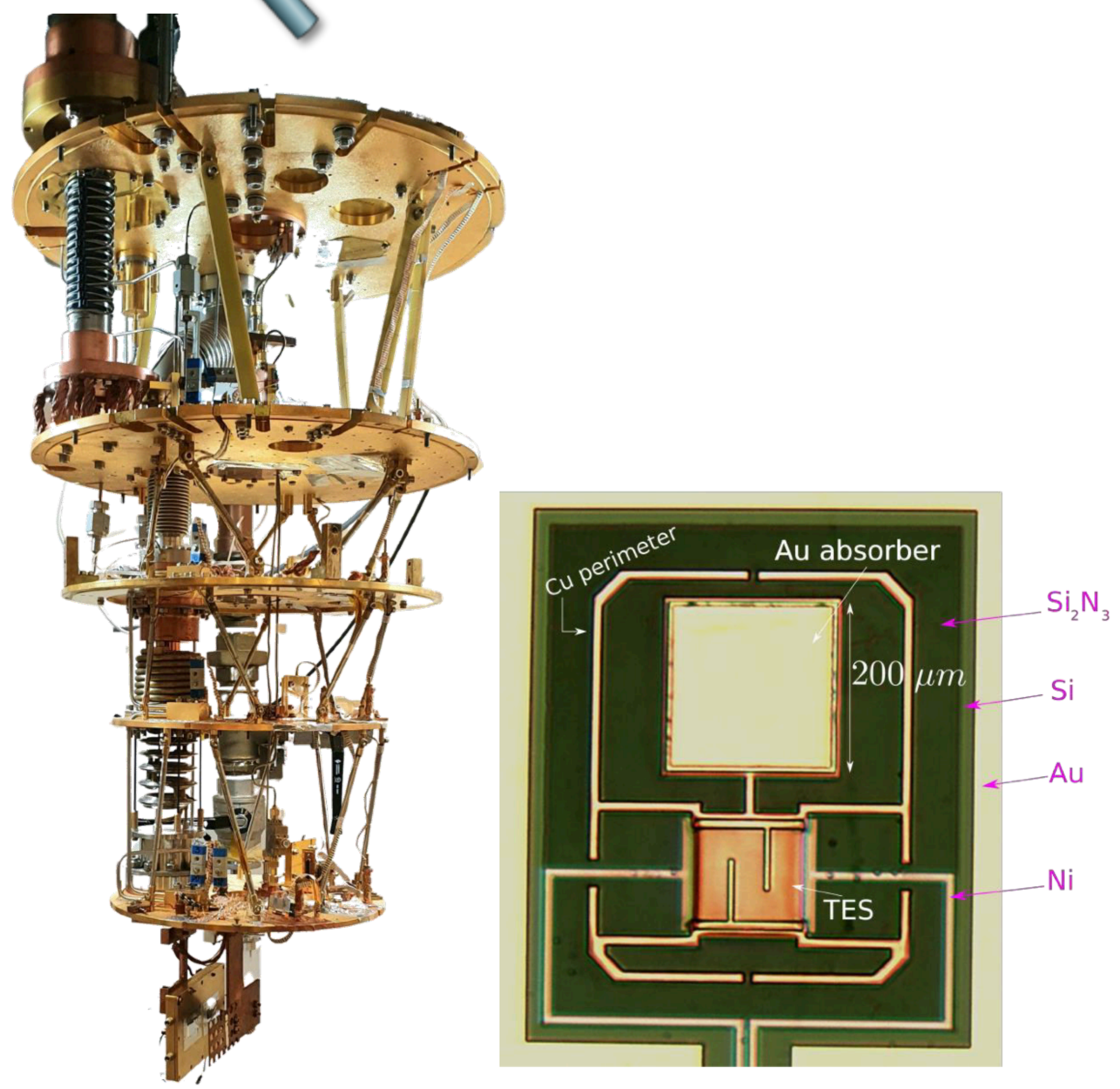
Using micro-calorimeters doped with radioactive material to measure endpoint.

(They use ^{163}Ho instead of tritium)

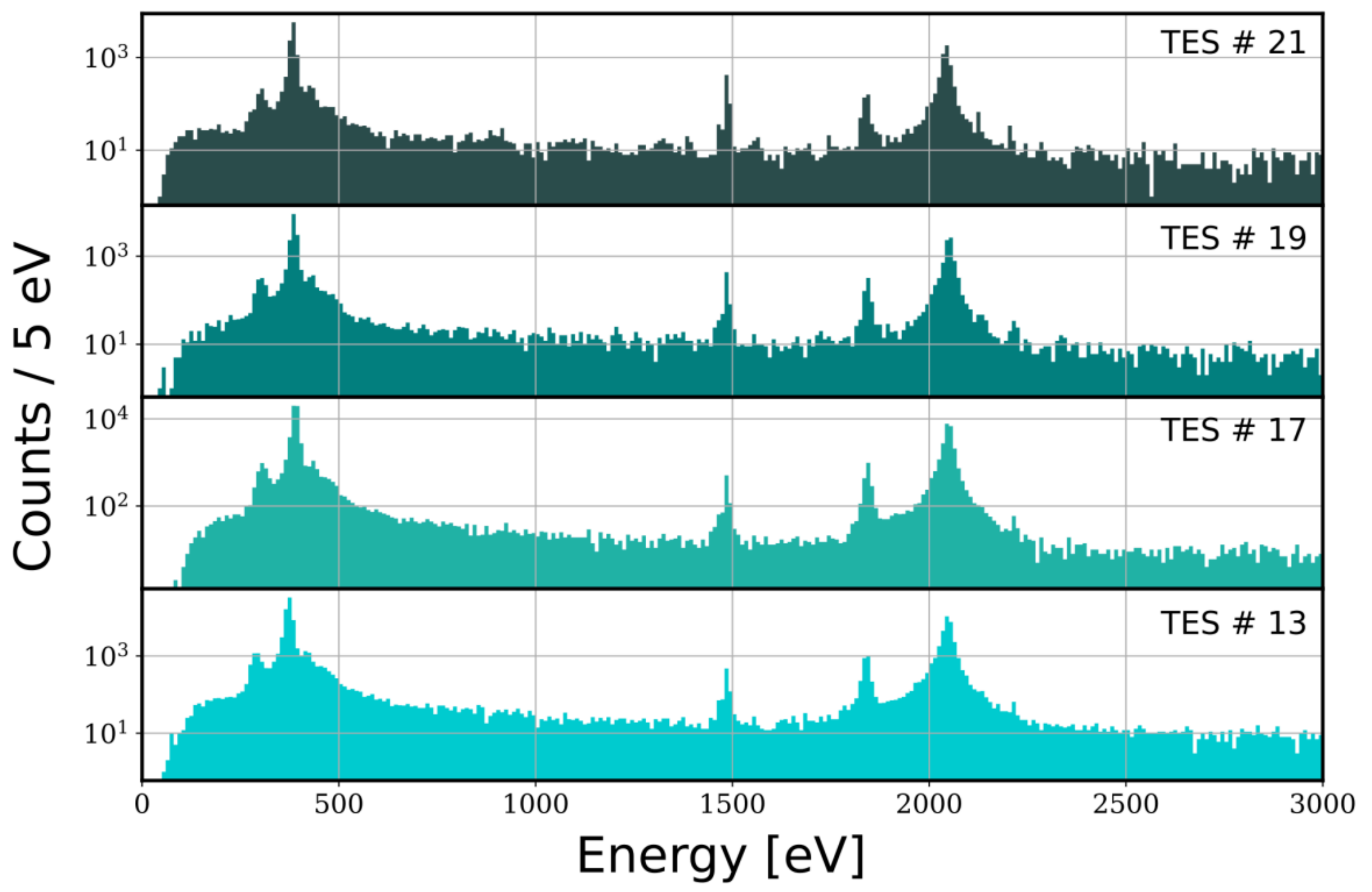
μ-calometer



HOLMES



Energy Spectra



Using micro-calorimeters doped with radioactive material to measure endpoint.

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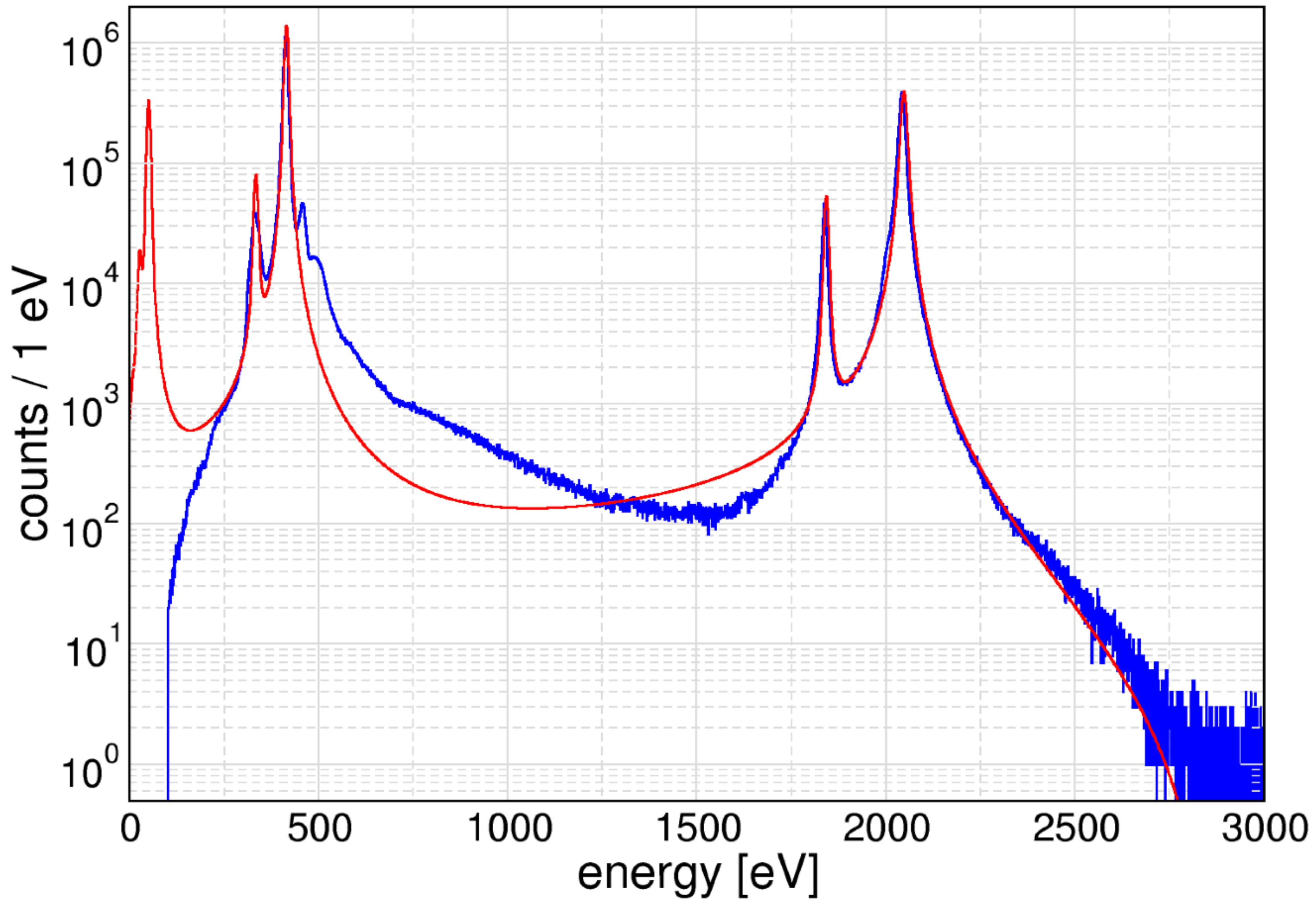
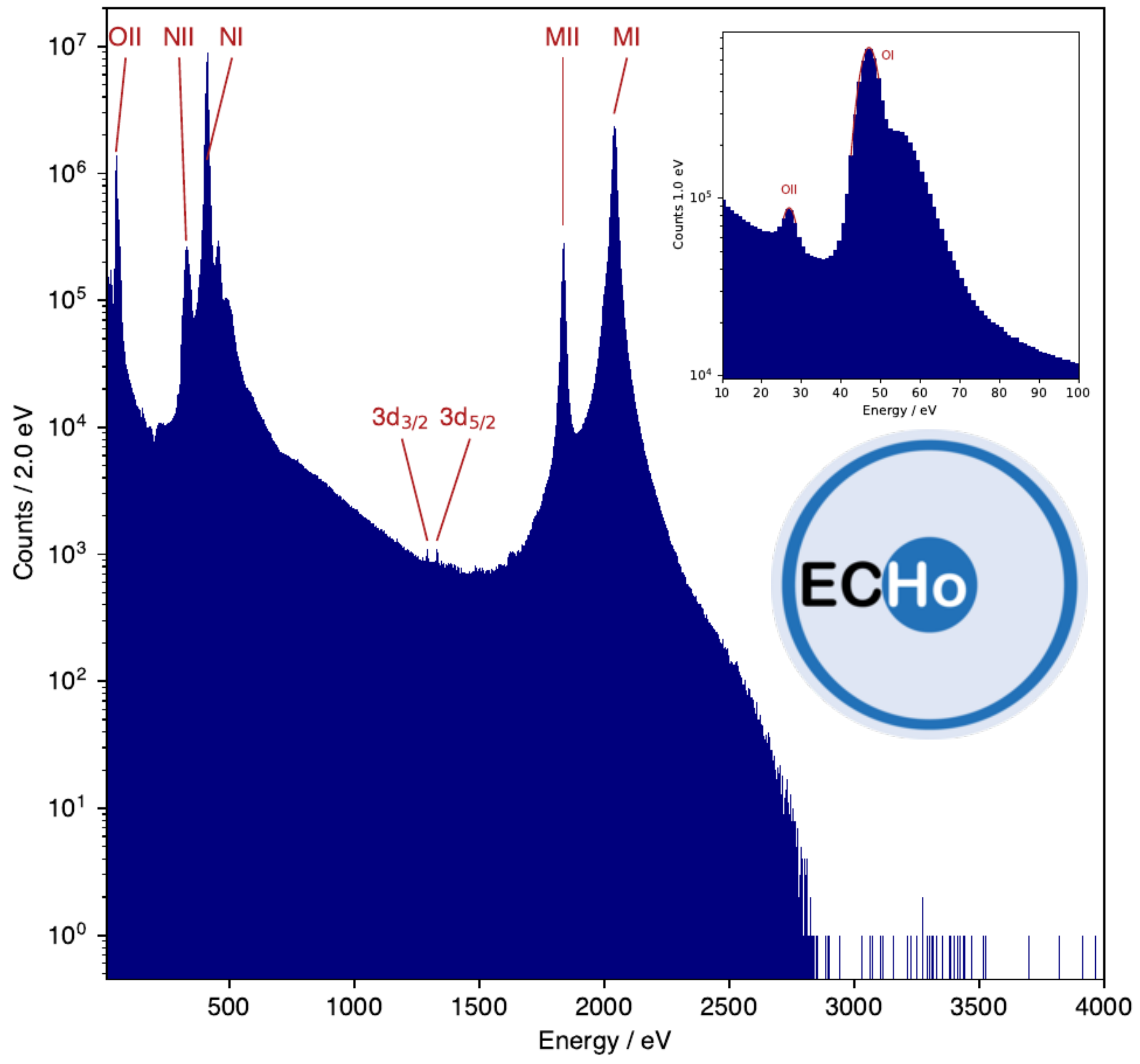
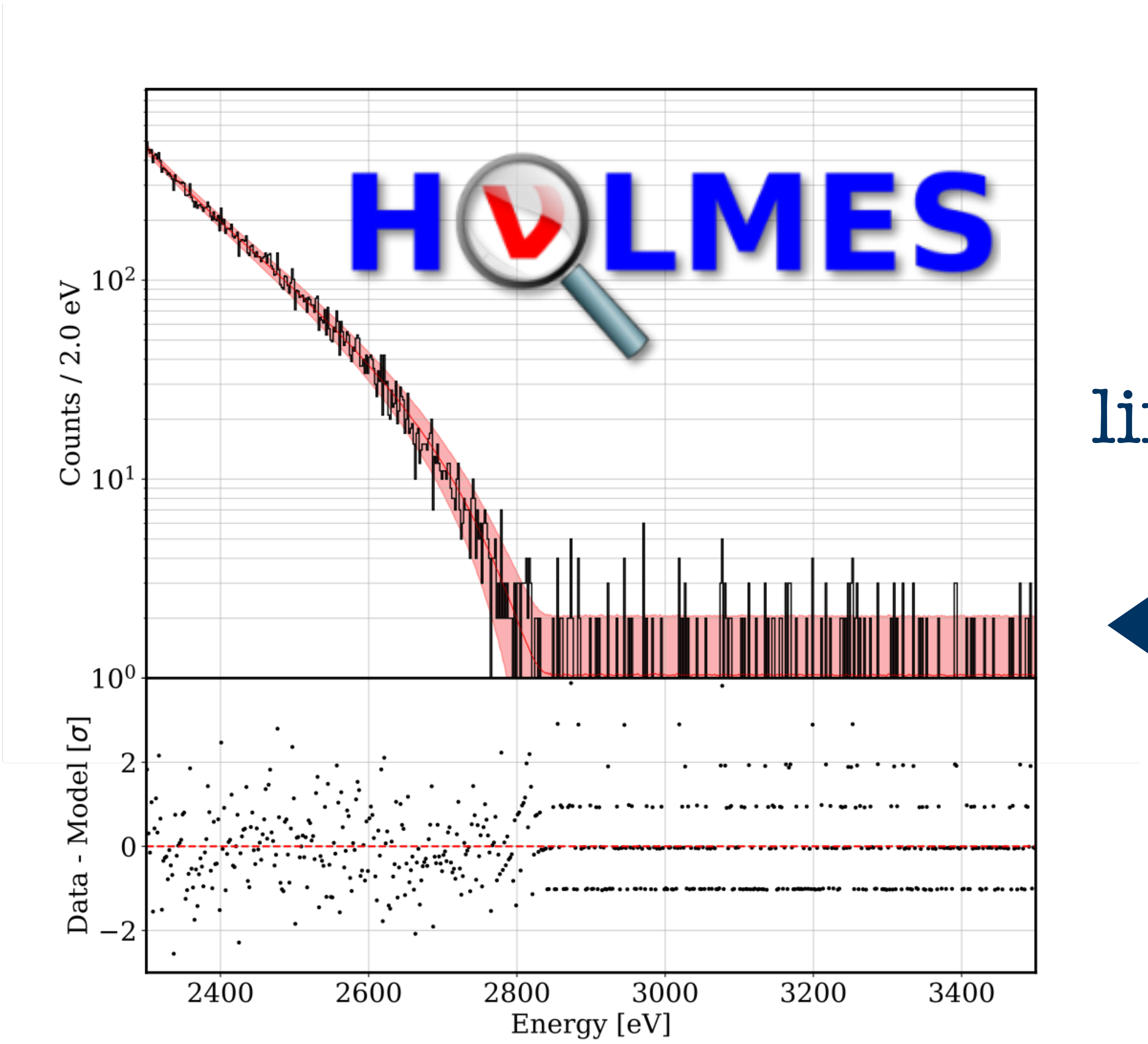
New (!) results from Neutrino 2024:



New (preliminary) limits from ECHO:

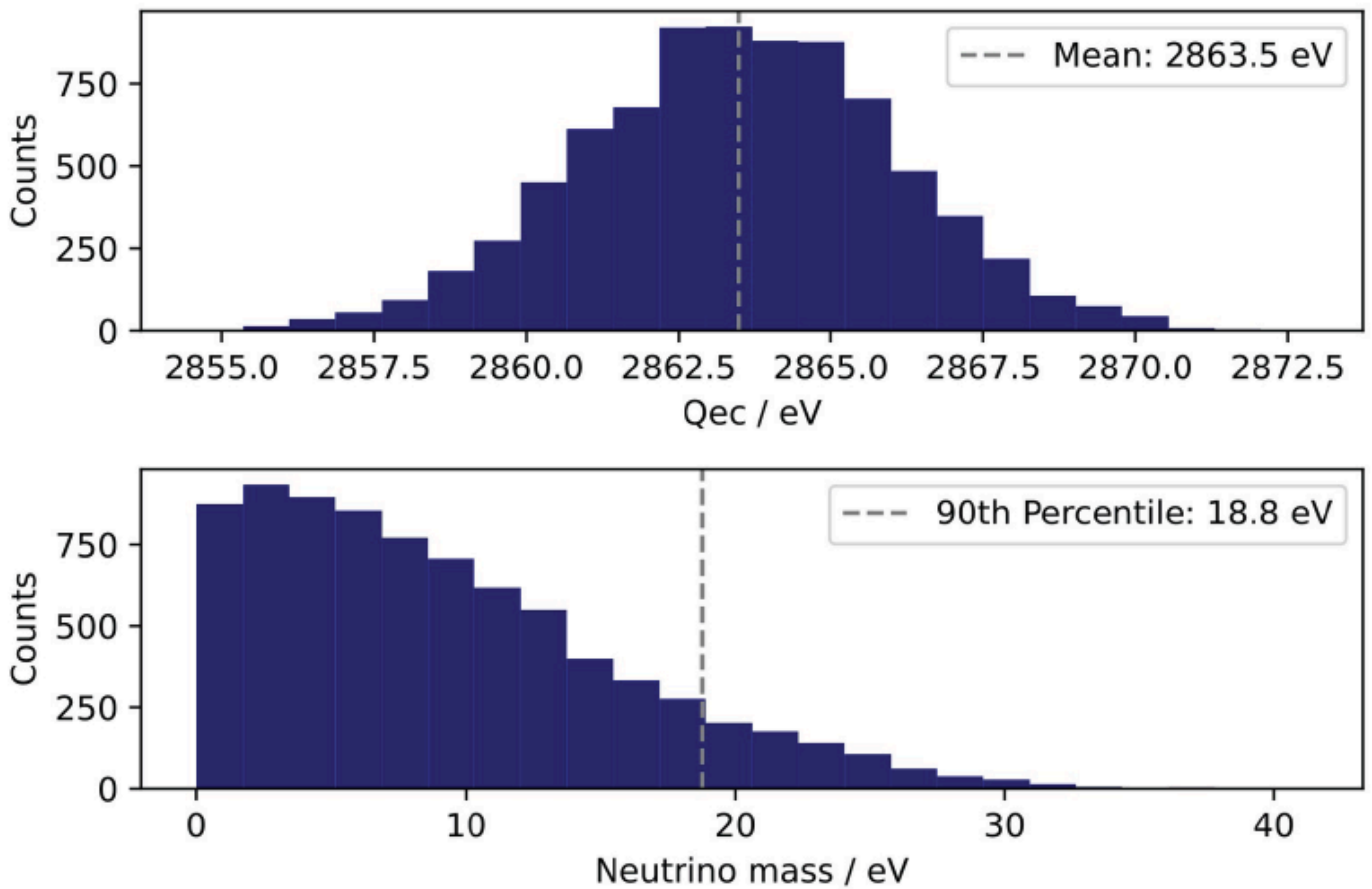
$m_\beta \leqq 19$ eV

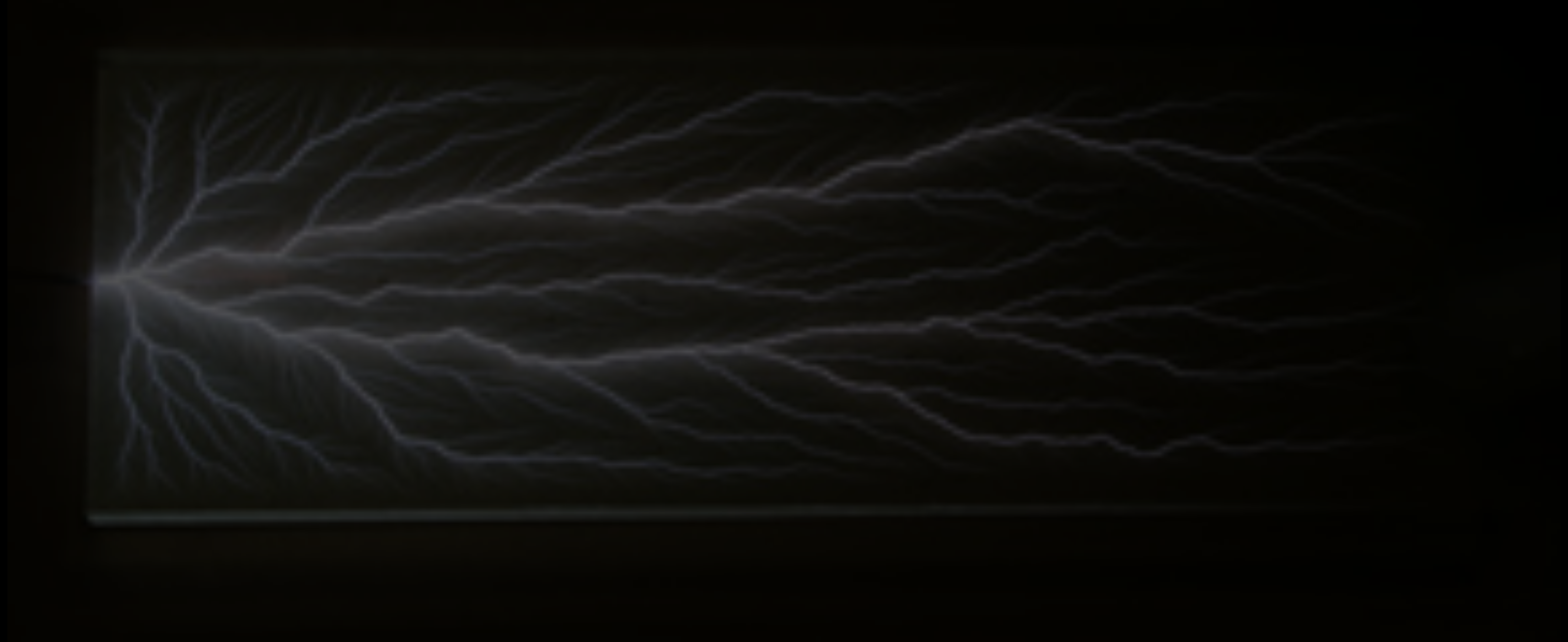




New (preliminary) limits from HOLMES:

$m_\beta \leqq 28$ eV





Electromagnetic Filtering

(MAC-E Filters)

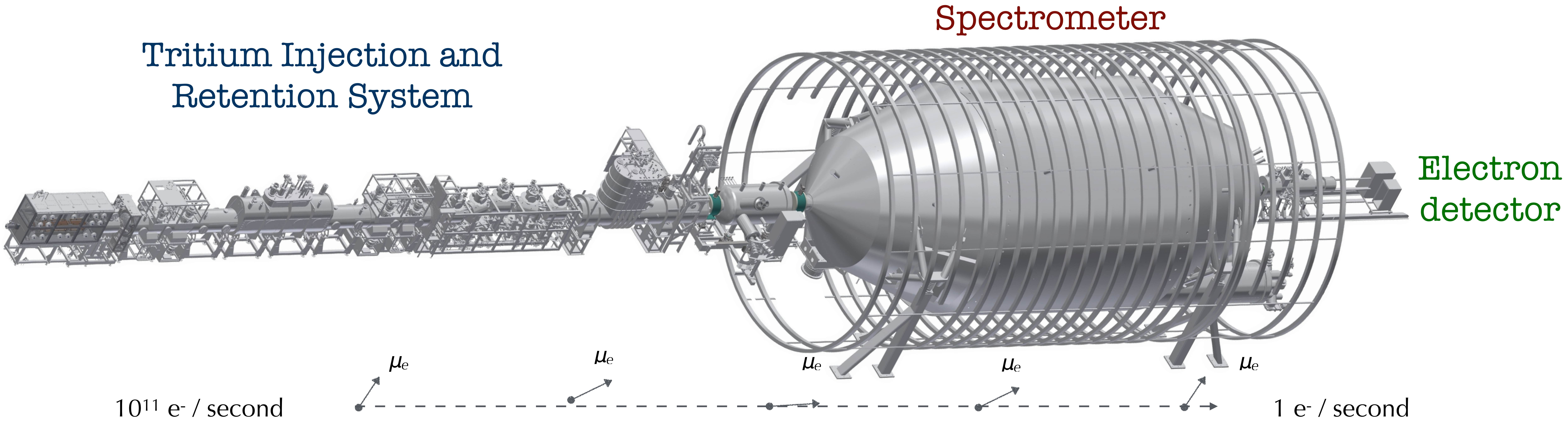
High Magnetic Field (Bs)

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)

Magnetic Adiabatic Collimation w/ Electrostatic Filtering

(only electrons with enough energy can overcome potential barrier)

In order to get high energy resolution, you need a large ratio of magnetic fields.

But magnetic field lines are conserved, so the tighter you squeeze on one end, the larger they are on the other.

How much bigger?

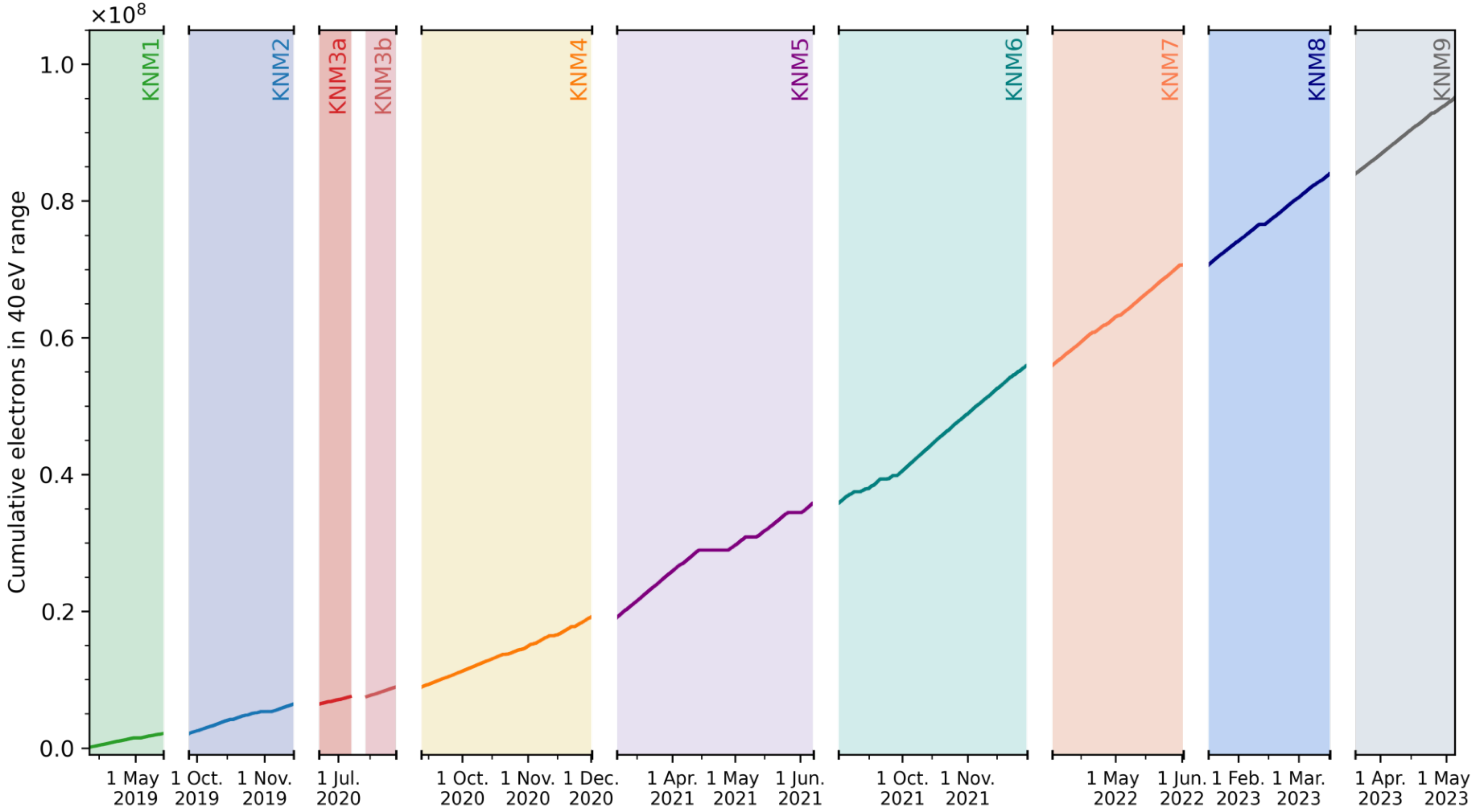
This big.

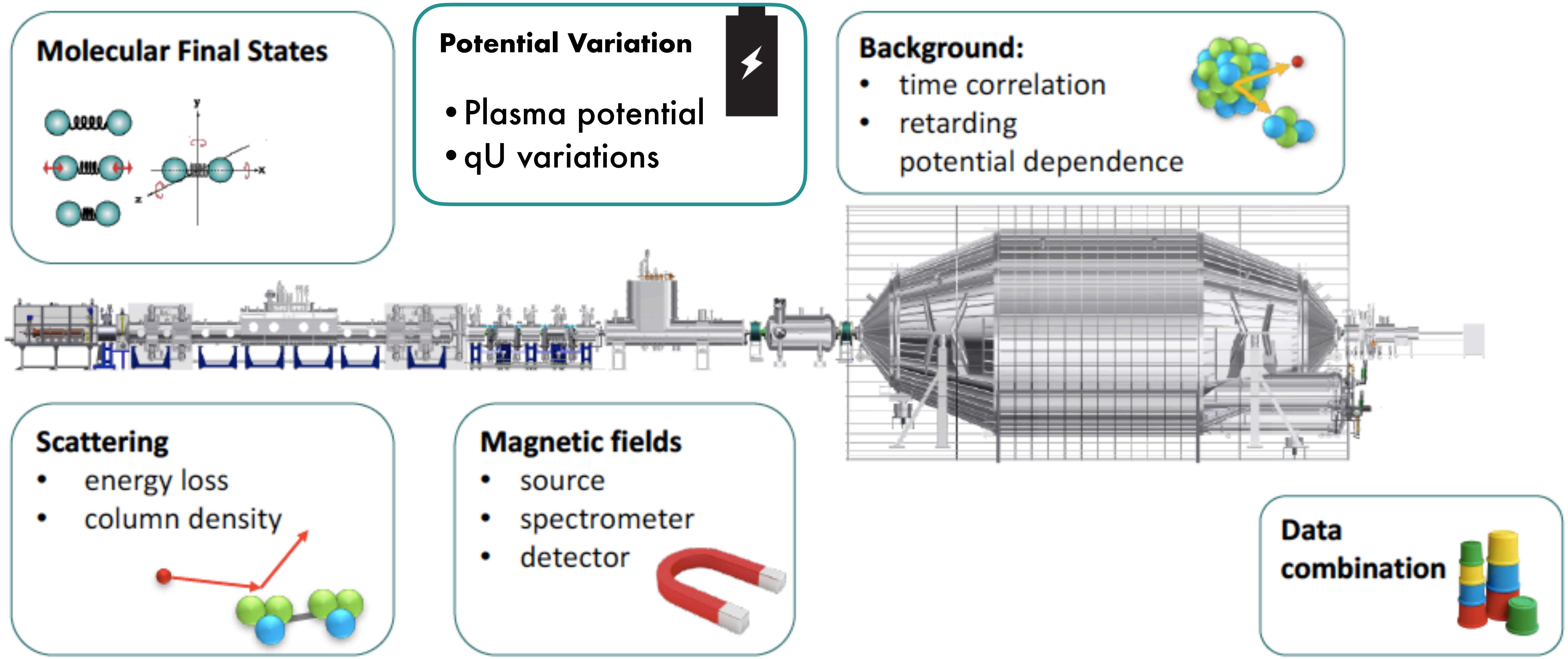
A long journey in the making...

A long journey in the making...

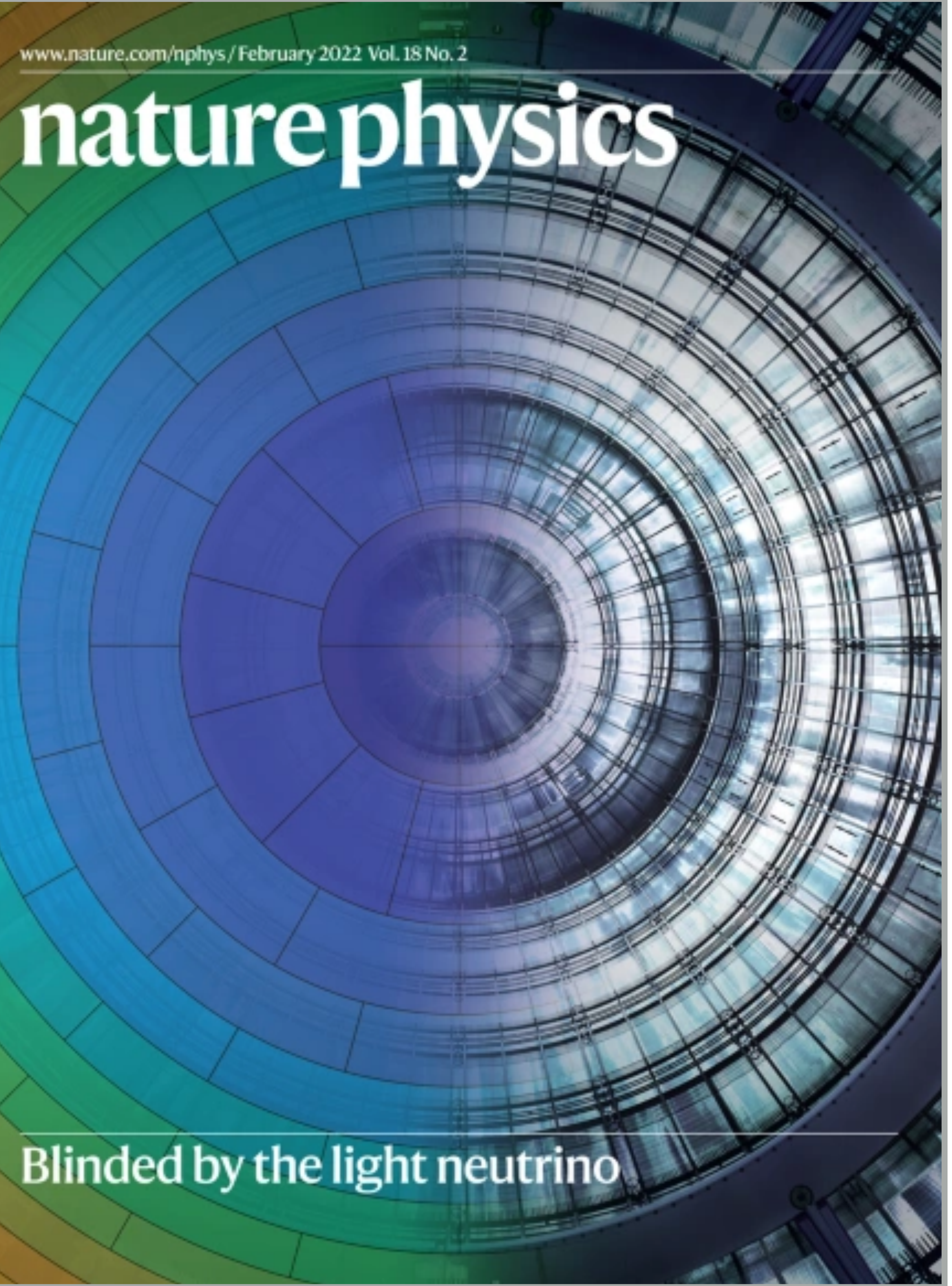
Data taking started in May 2019 and continues to this day.

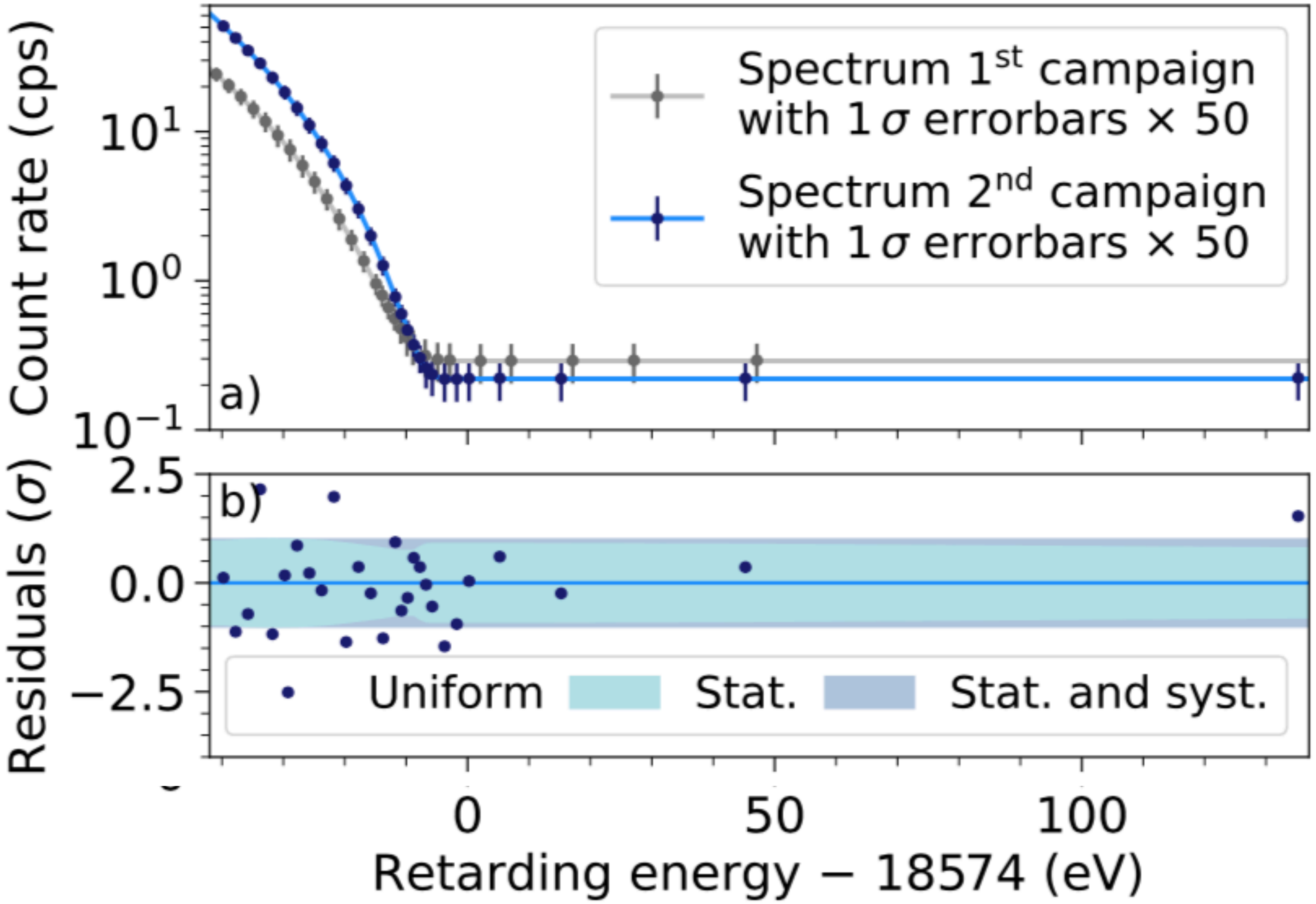
Statistical Uncertainty





Experiment relies on esquisite control of many systematic uncertainties.

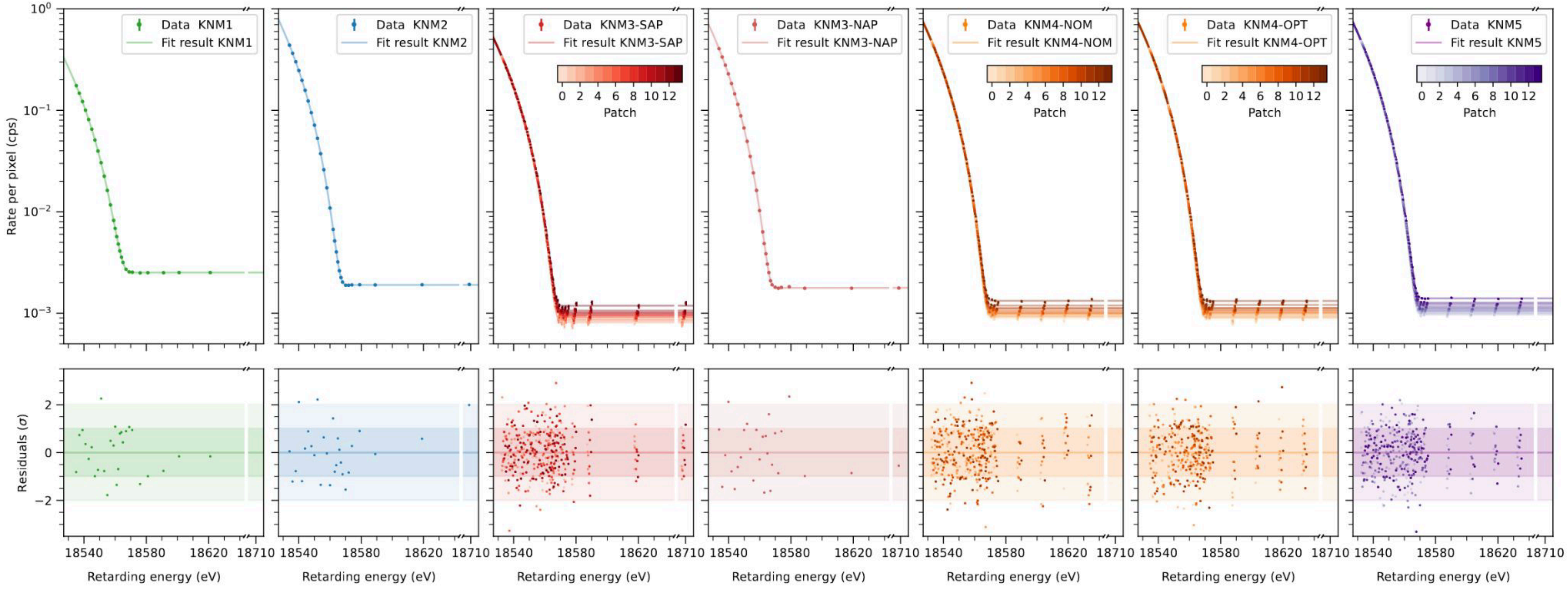




$$\boxed{m_\beta \lesssim 0.8\ \mathrm{eV/c^2}\ (90\%\ \mathrm{CL})}$$

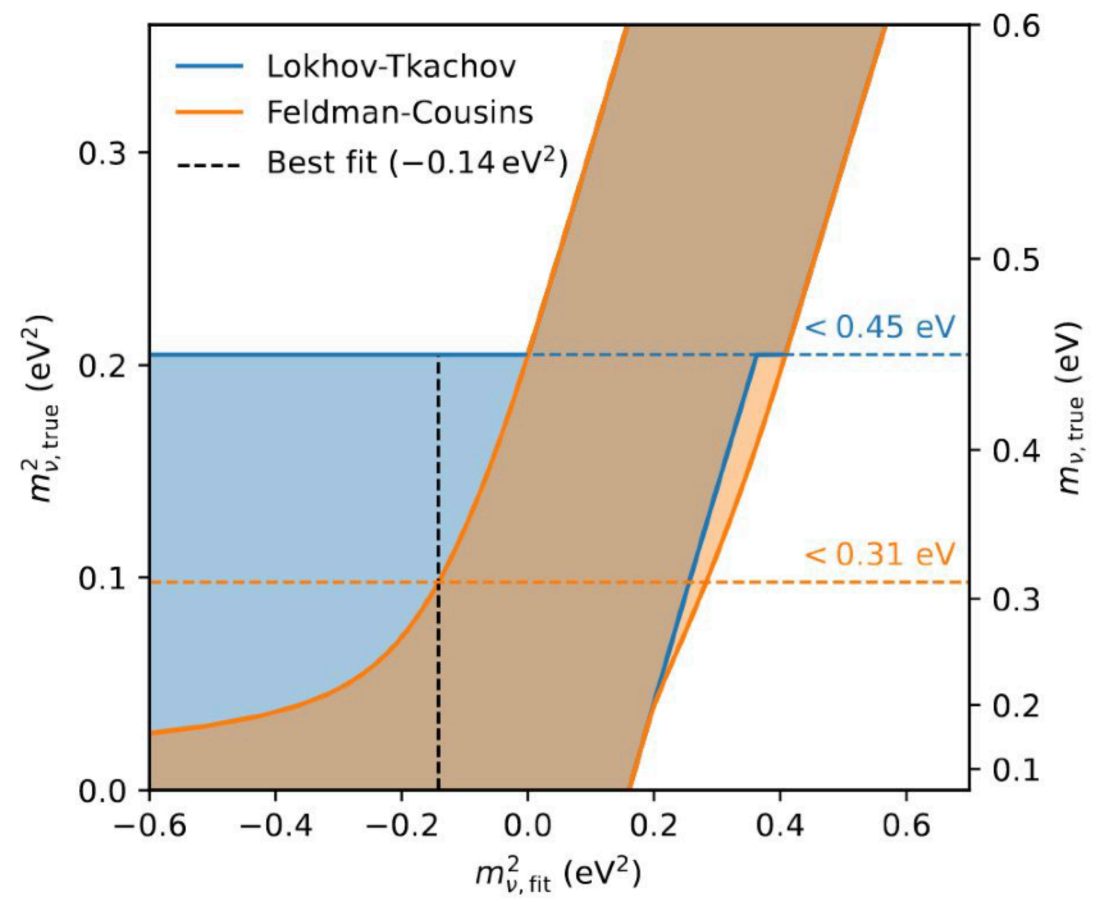
For the first time

the eV scale is broken!



New (!) results from Neutrino 2024:

$$\boxed{m_\beta \leq 0.45\ \mathrm{eV/c^2}\quad (90\%\ \mathrm{C.\ L.})}$$

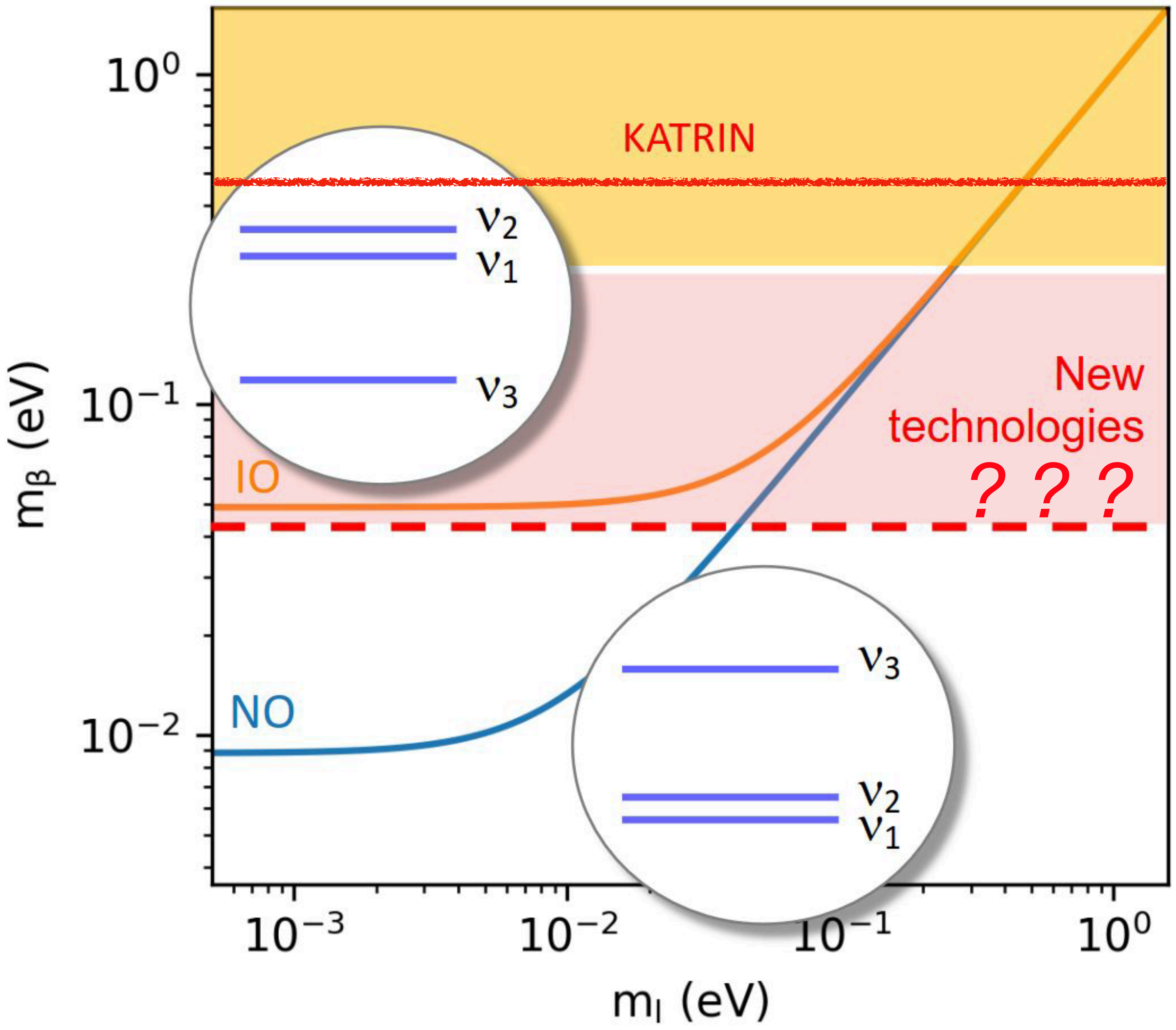


Remember that plot I showed you earlier?

KATRIN already limits the electron neutrino mass to 800 meV/c²

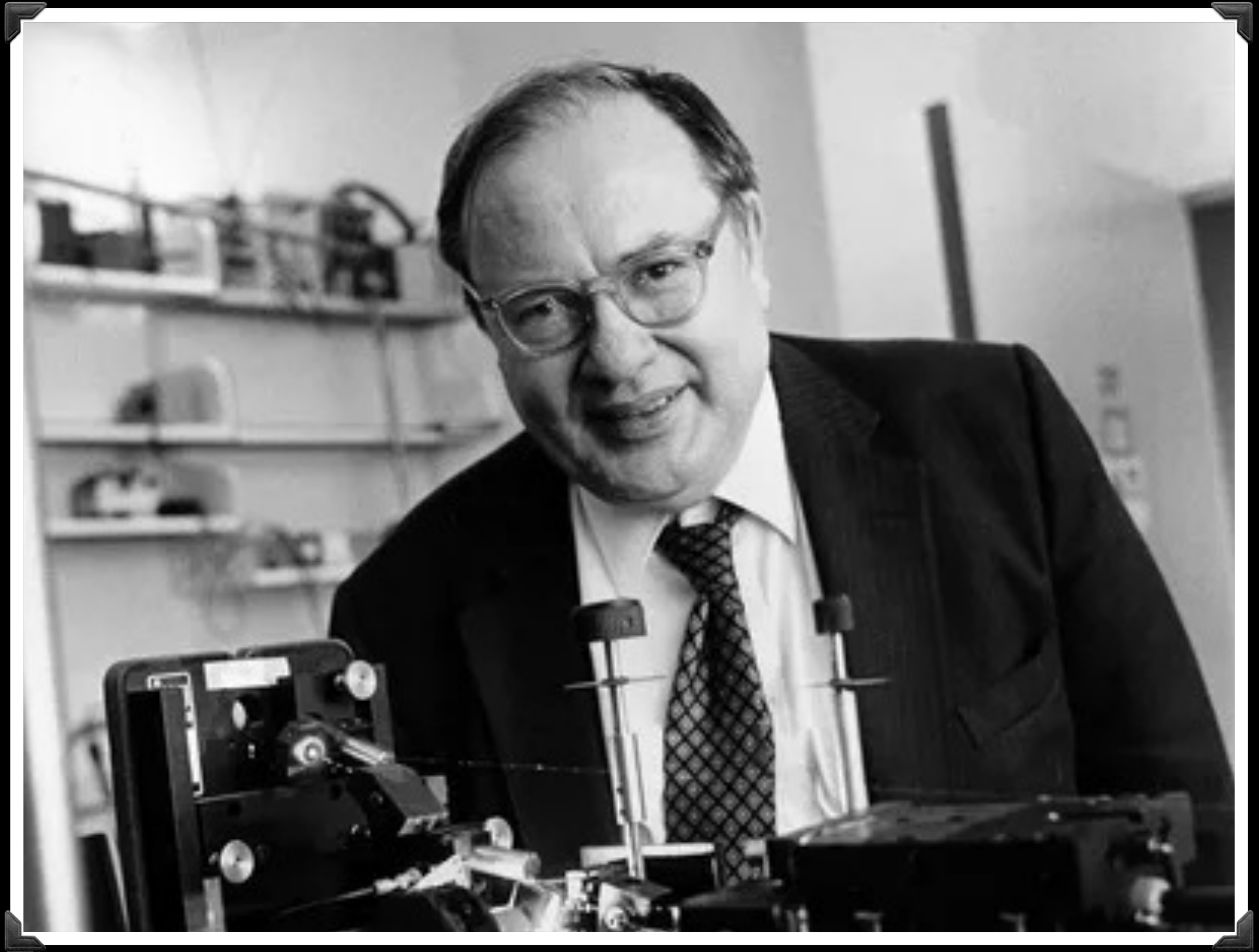
Will reach ~300 meV/c² by 2025.

But what if it's lower?



Frequency-Based

(Cyclotron Radiation Emission Spectroscopy)



Inspiration:

“Never measure anything but frequency!”

Arthur Schawlow, co-inventor of the laser
and 1981 Nobel Prize winner

Cyclotron Radiation Emission Spectroscopy (CRES)

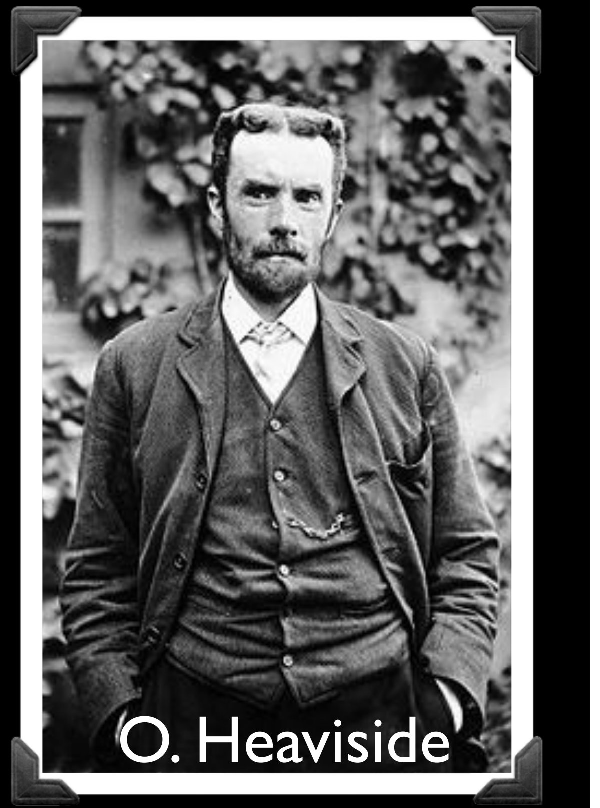
Use radiation from cyclotron motion to measure energy of electron.

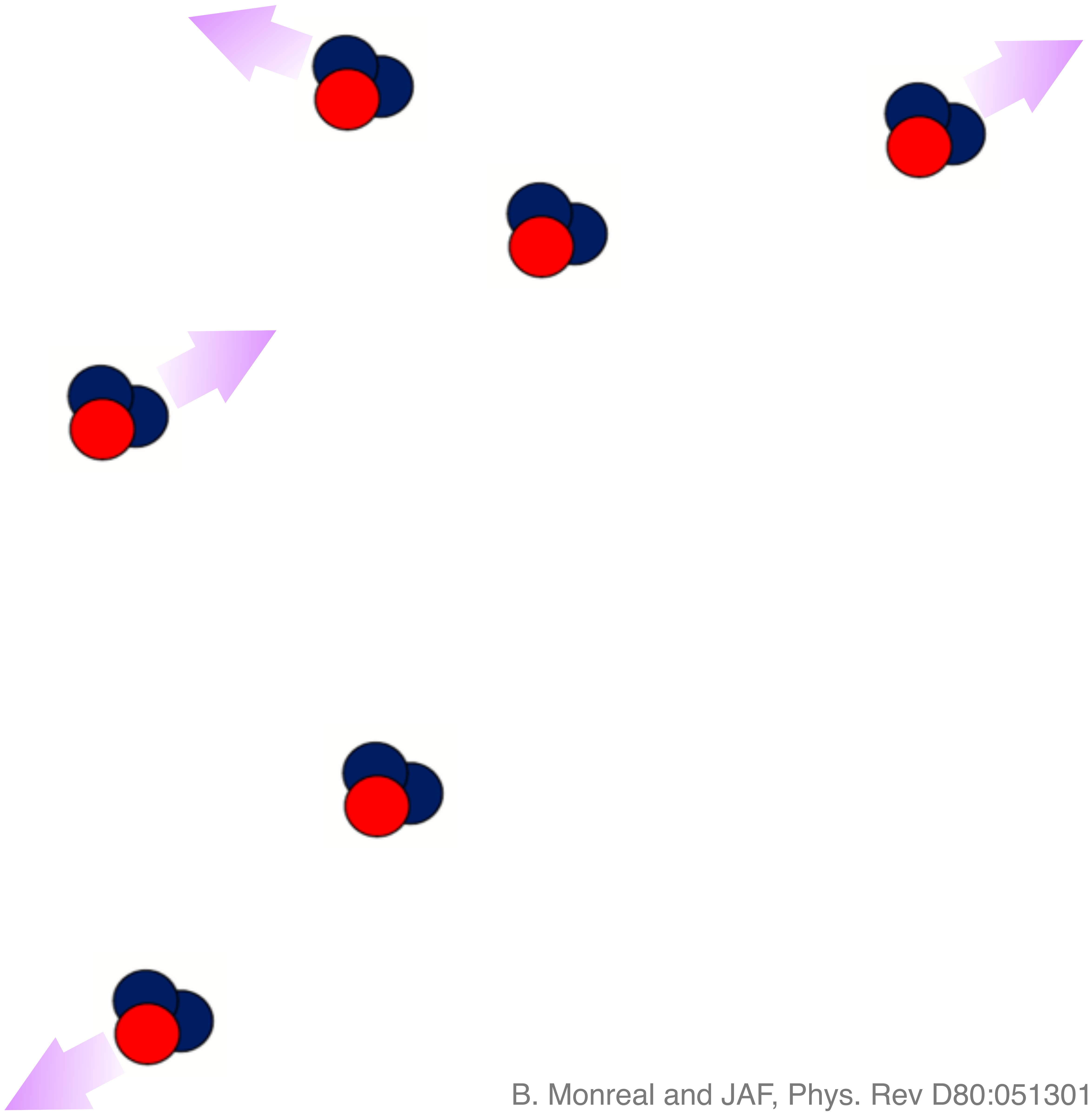
Frequency of radiation

↓

Kinetic energy

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





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

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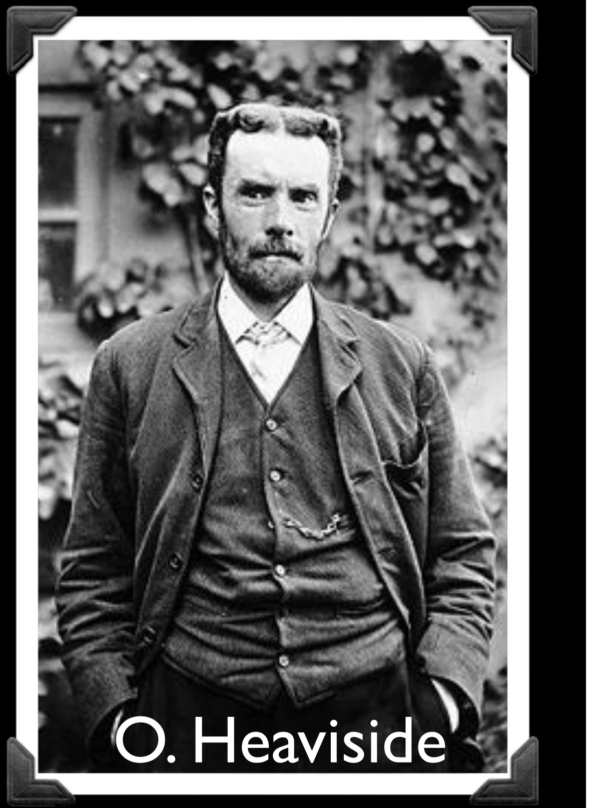

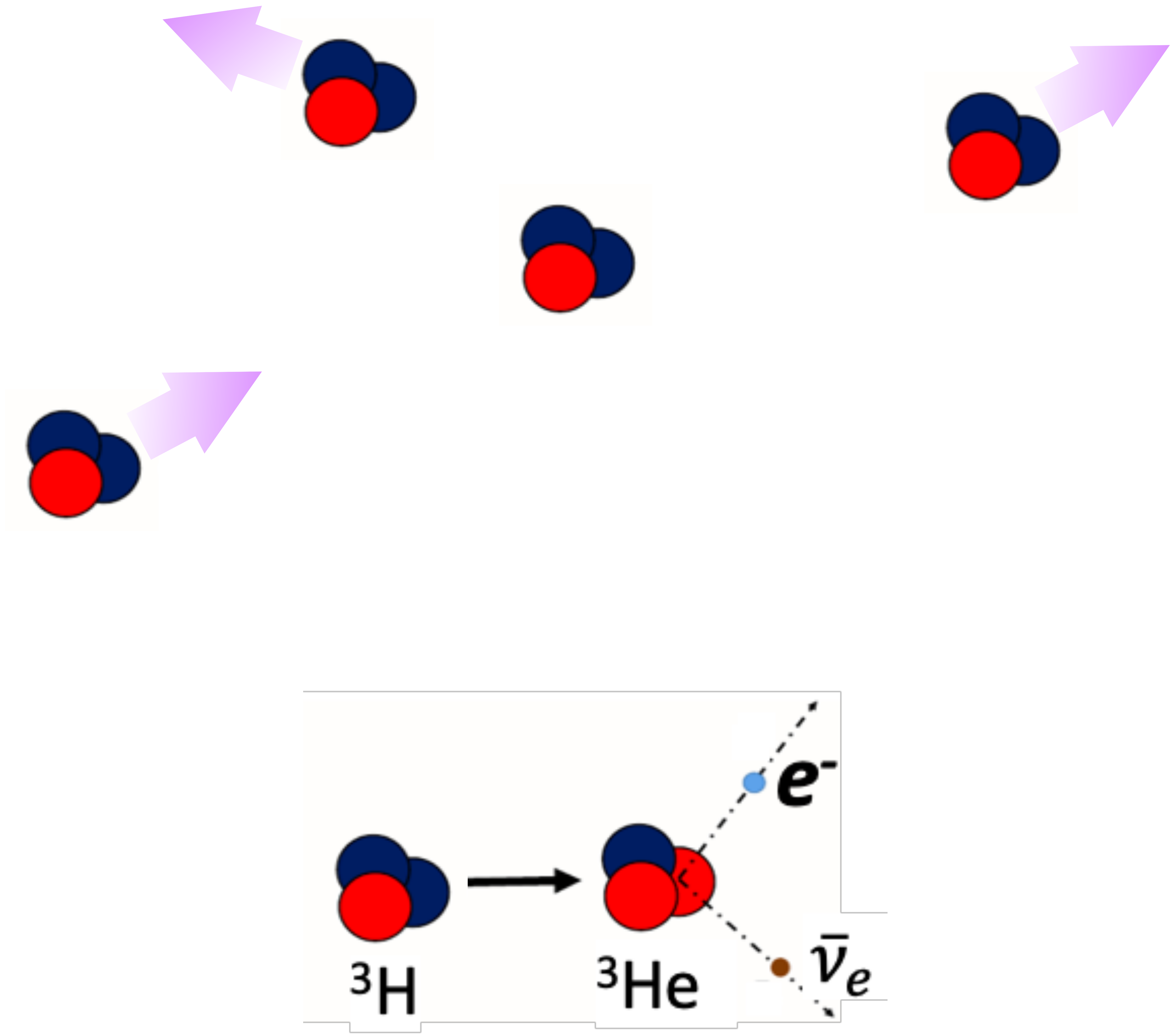

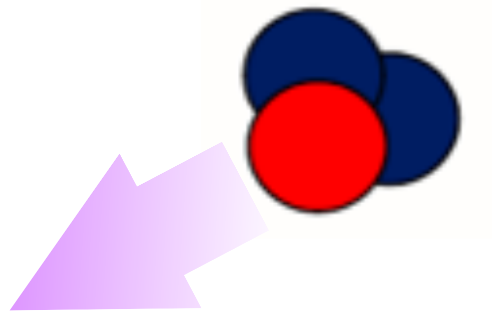

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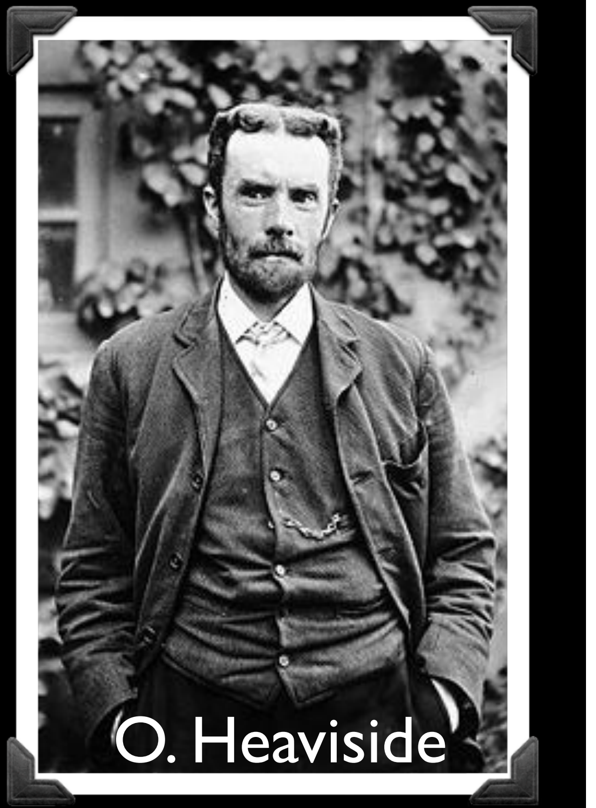

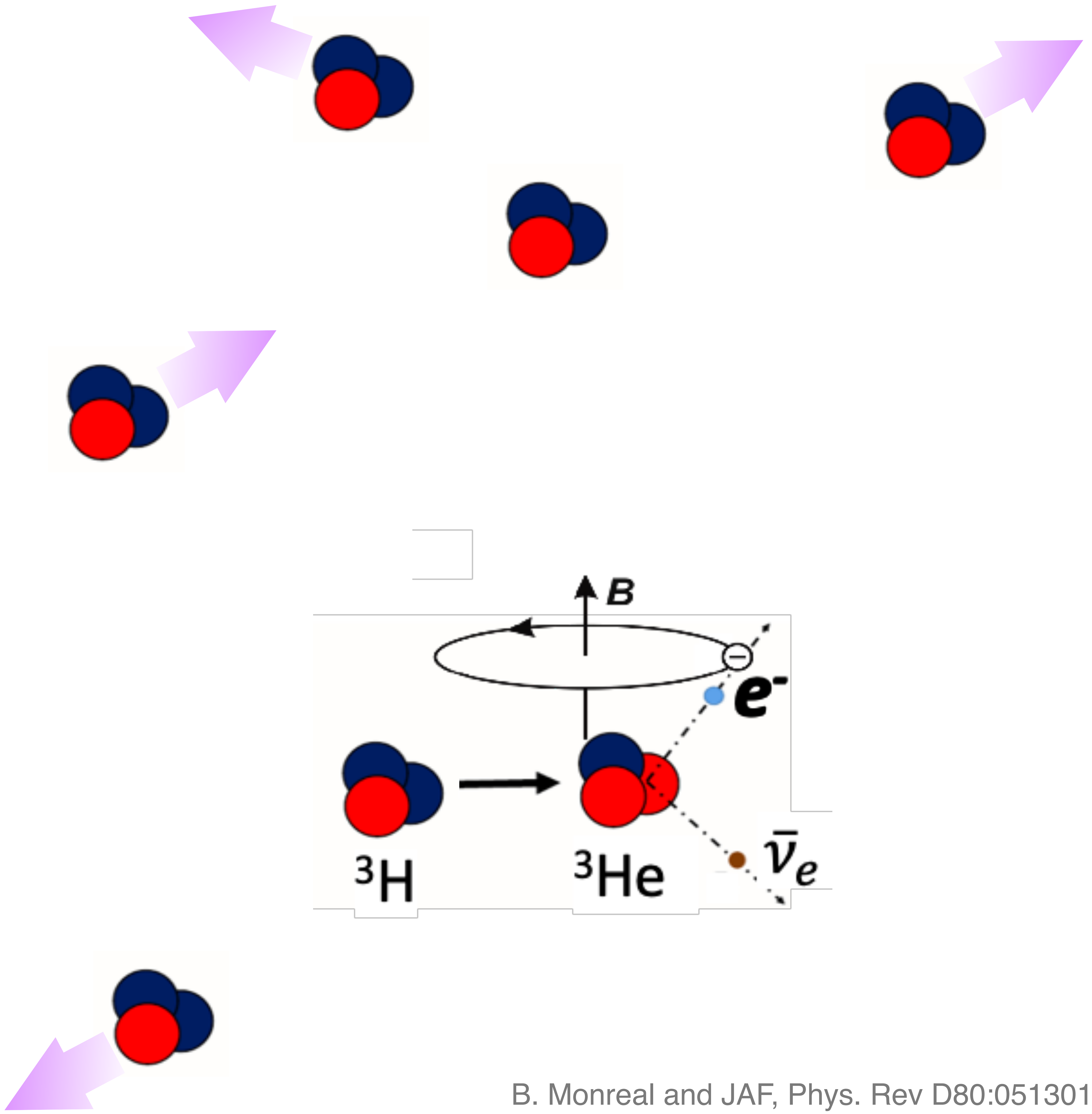

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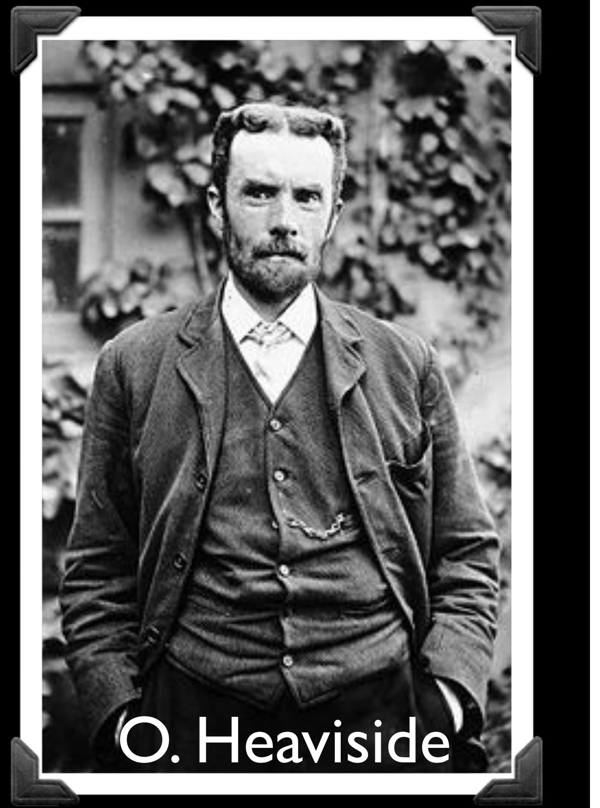

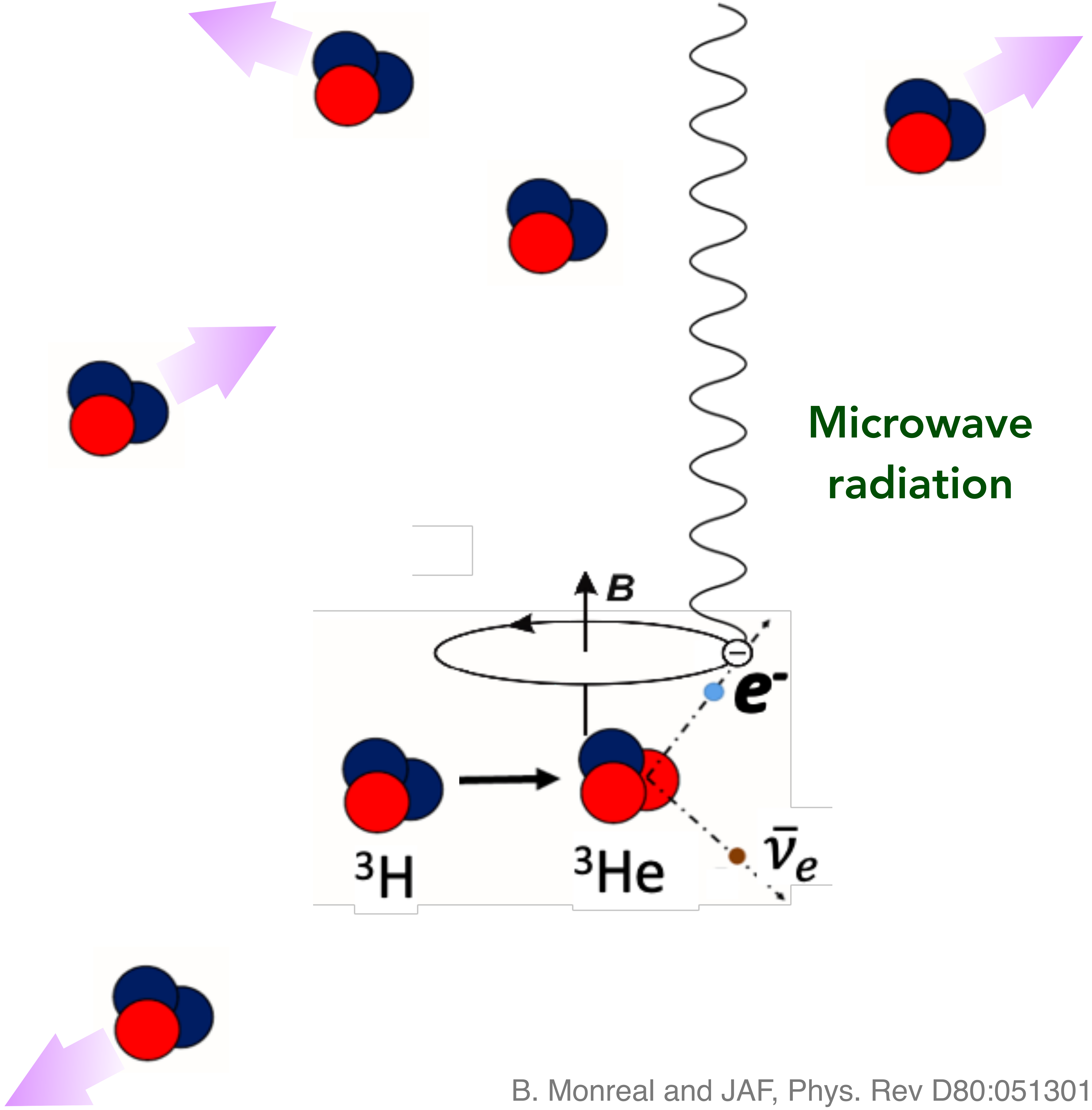

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A. L. Schawlow

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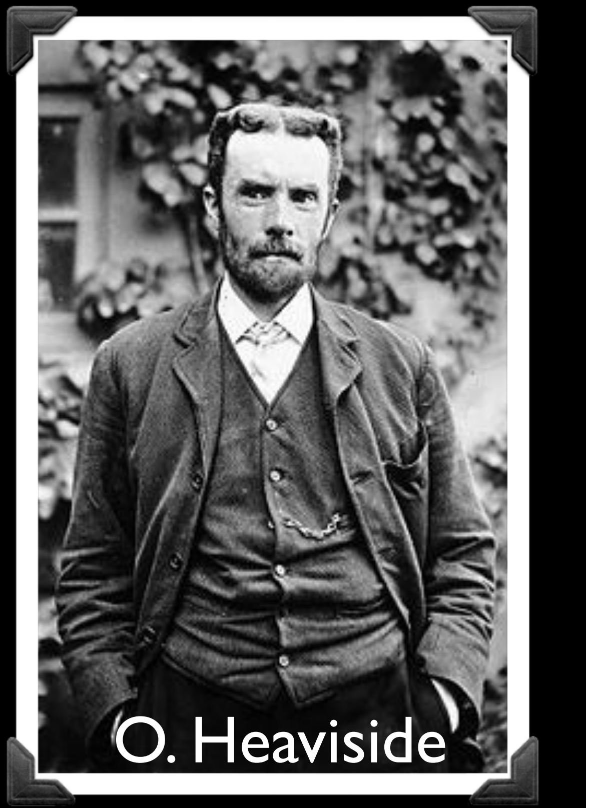
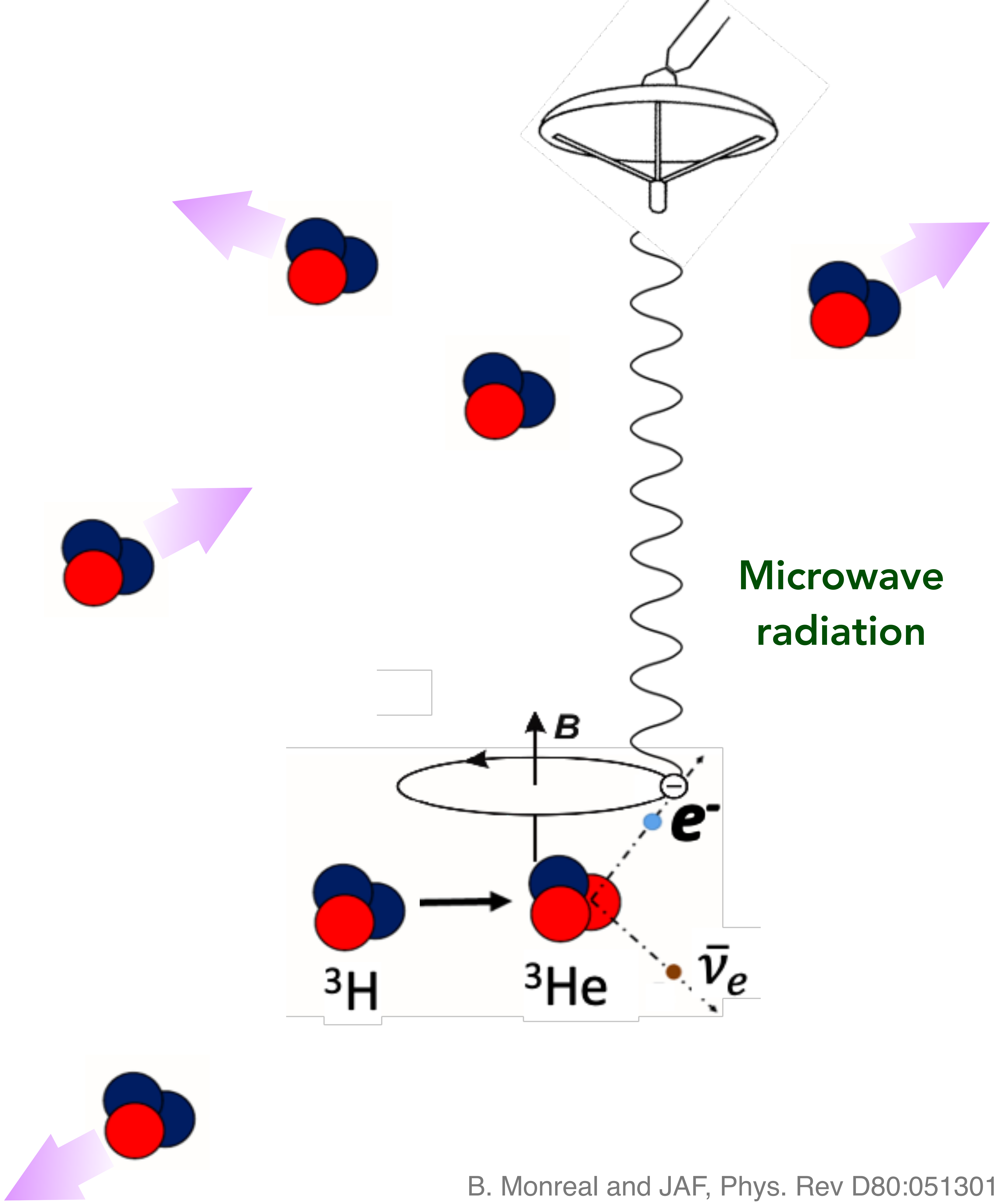

O. Heaviside



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

Advantages of CRES

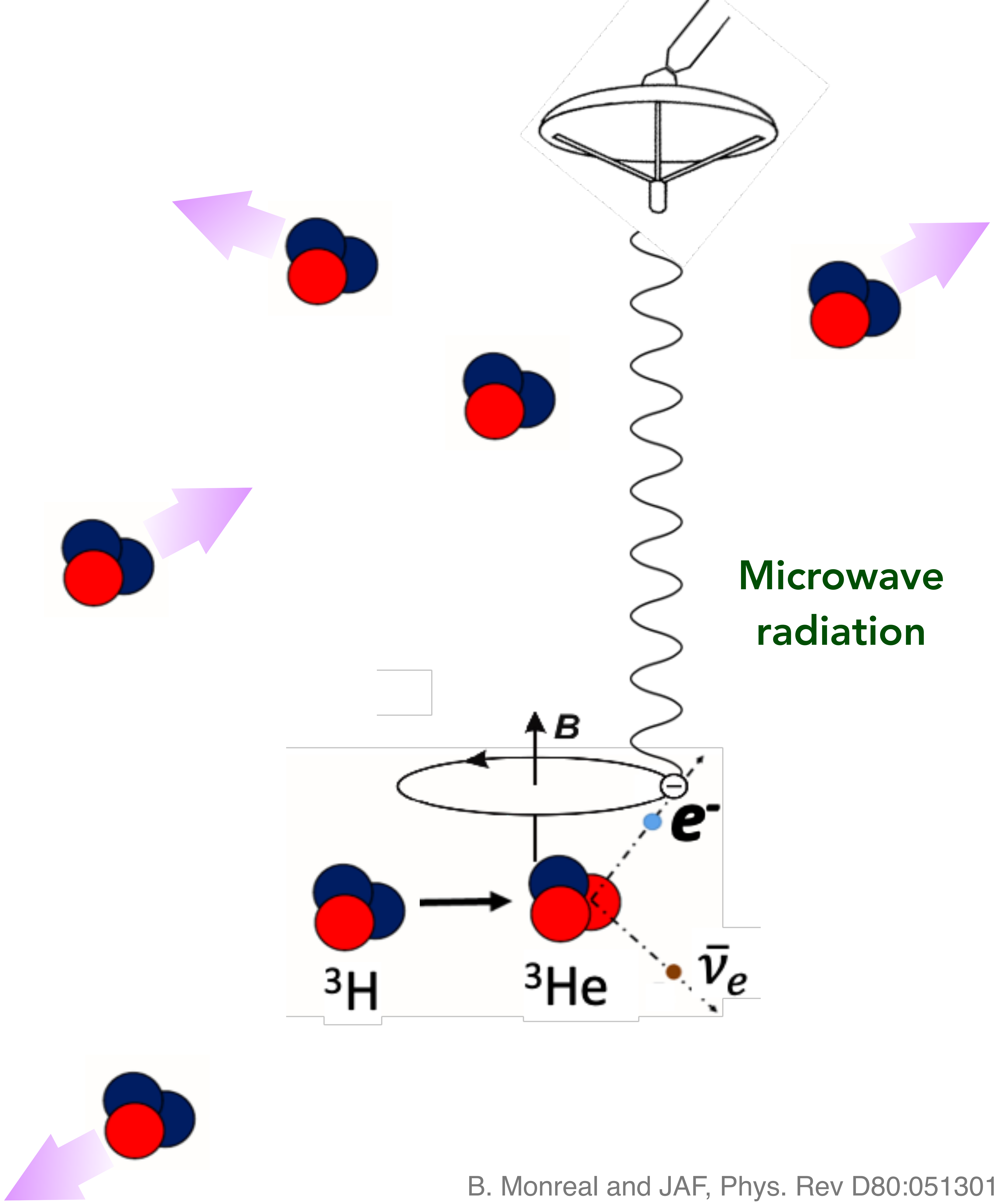
Frequency measurement

Transparancy to microwave radiation

Differential spectrometer

Compatible with atomic tritium

Low background



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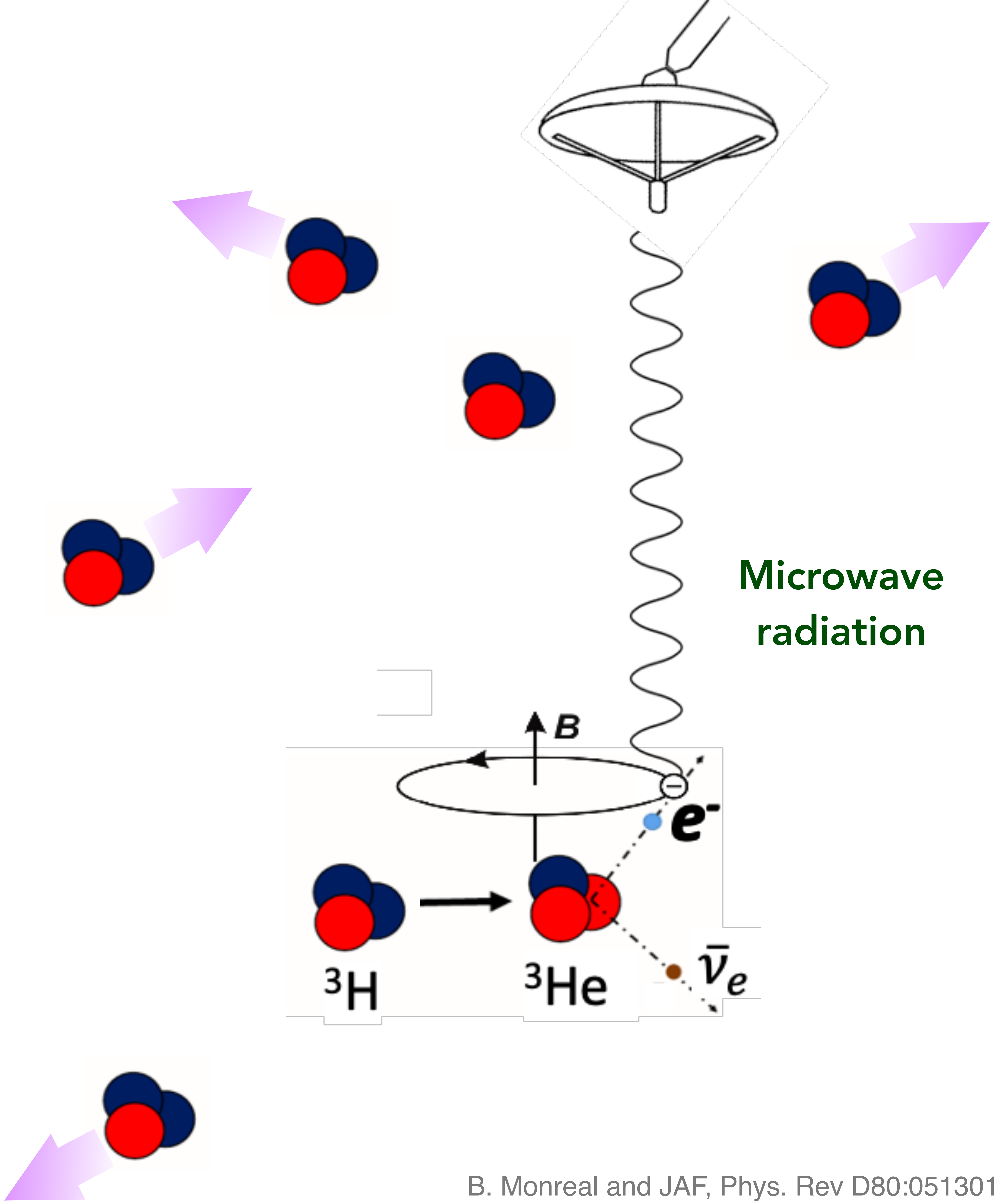

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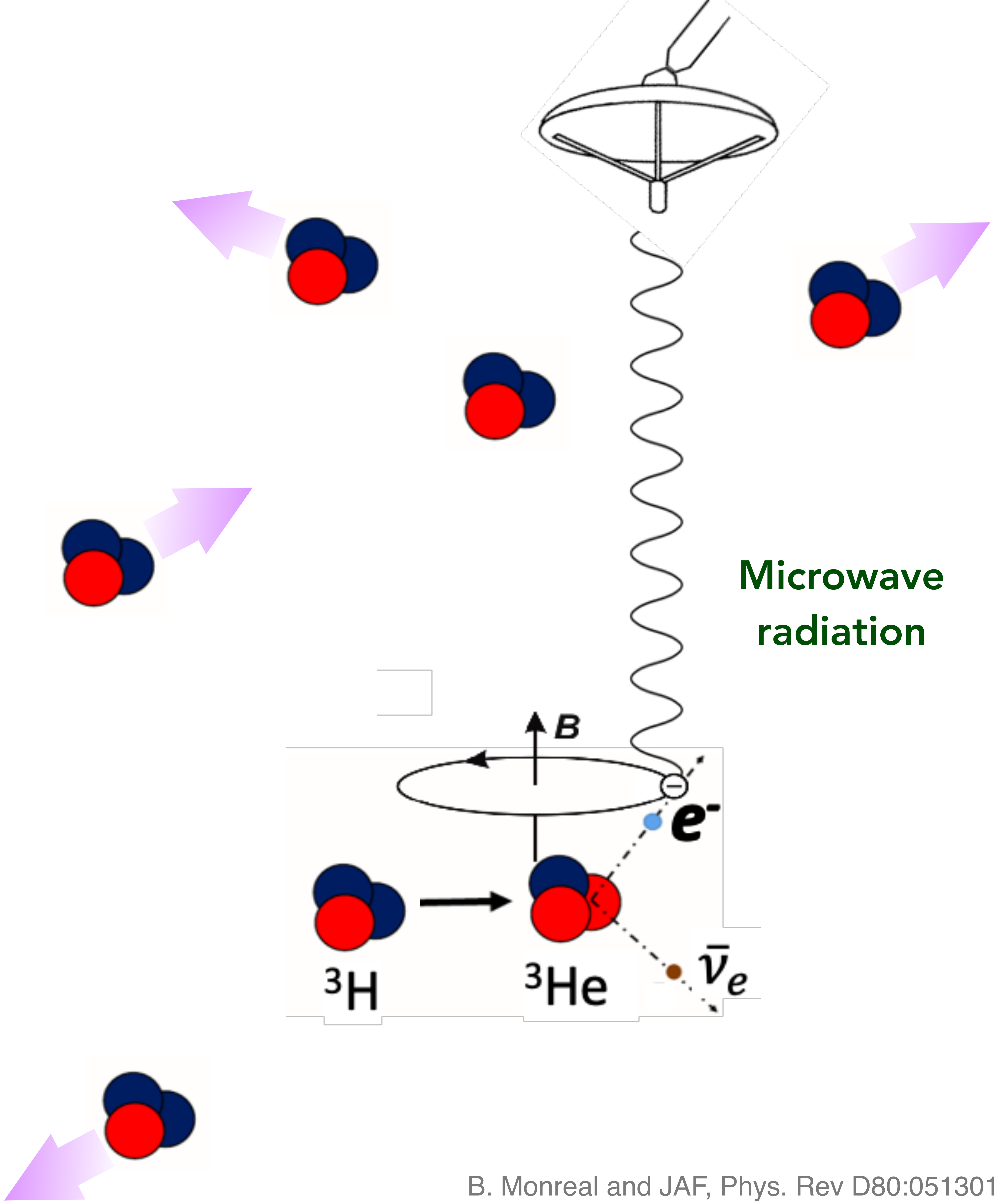

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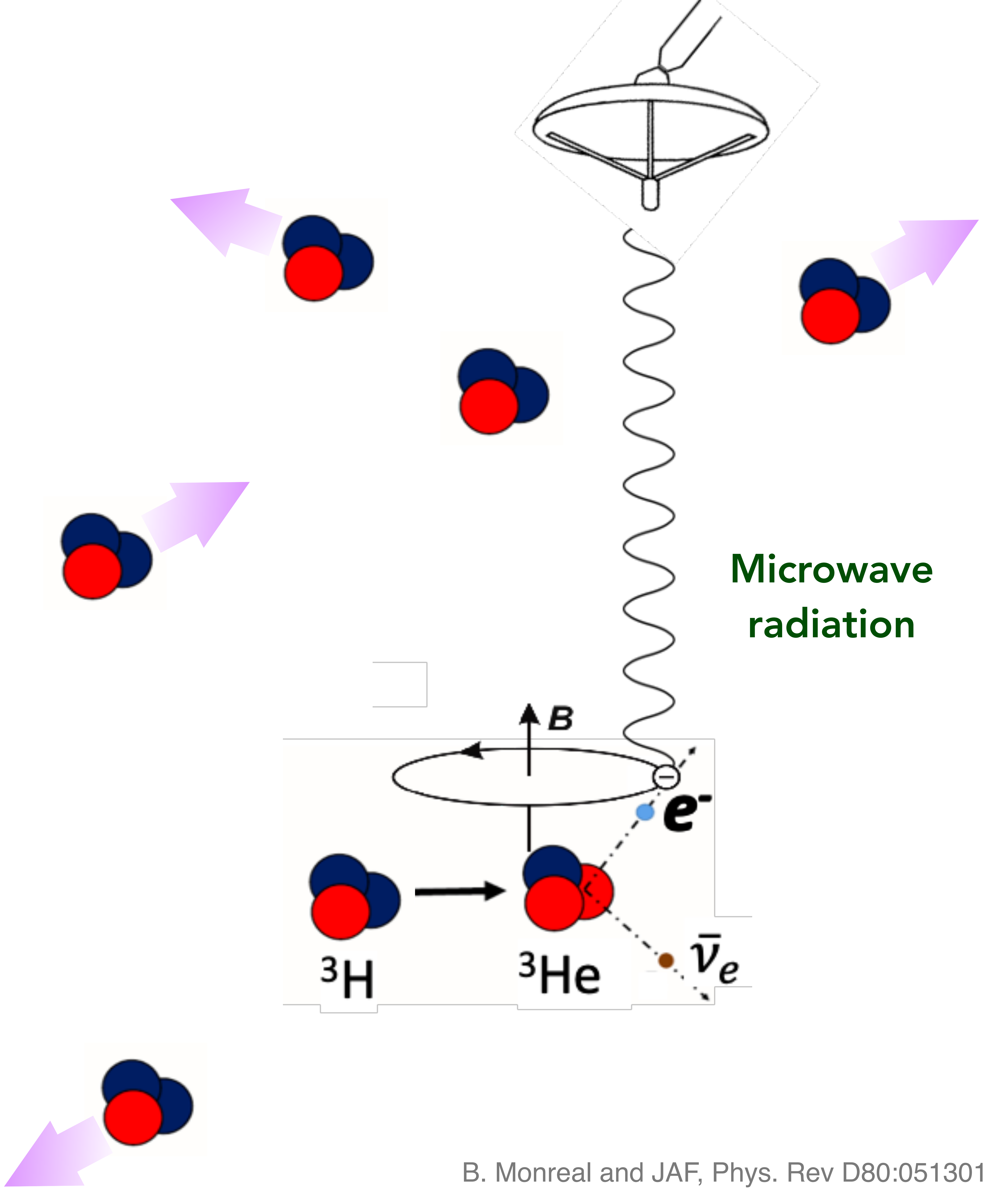

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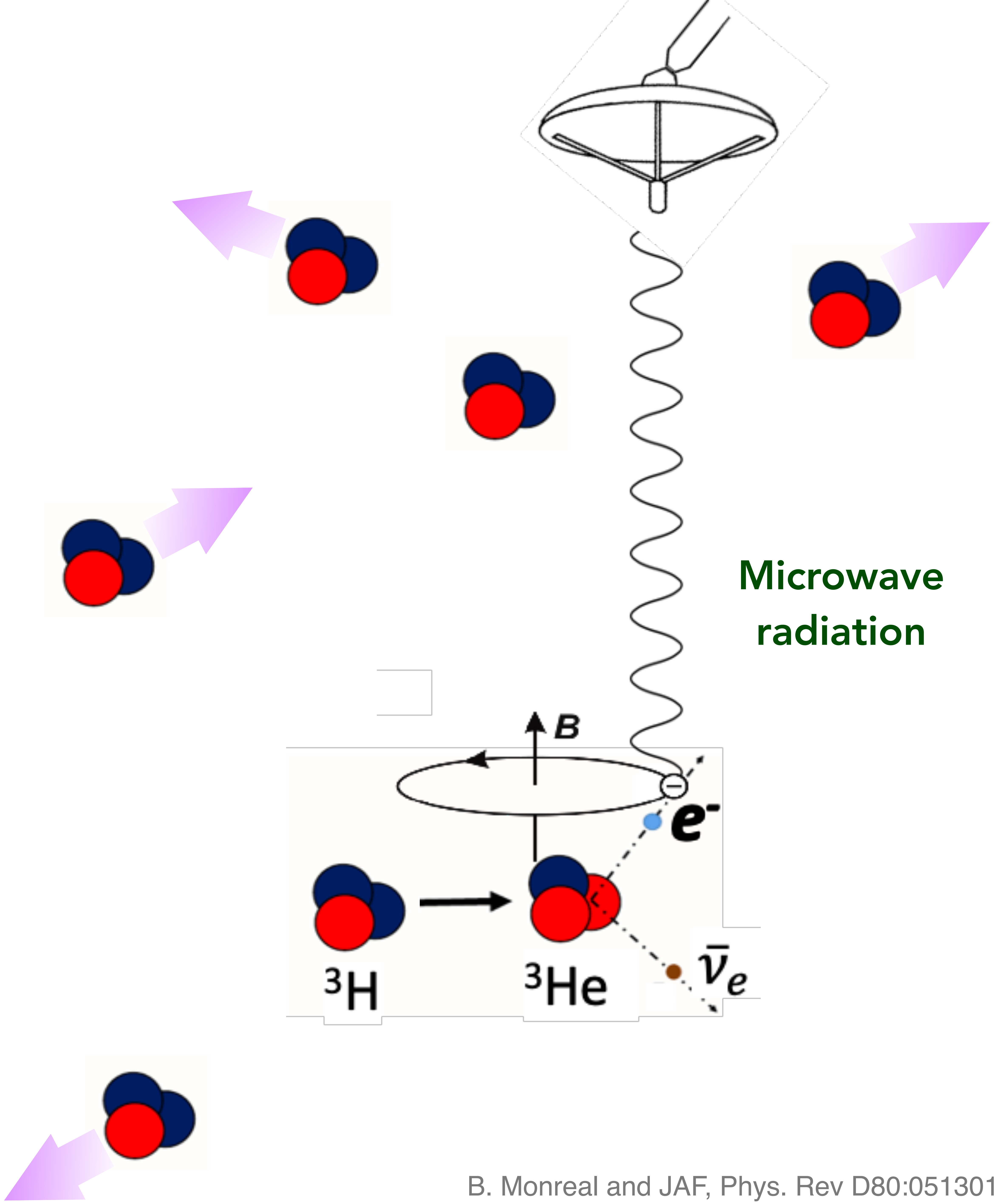

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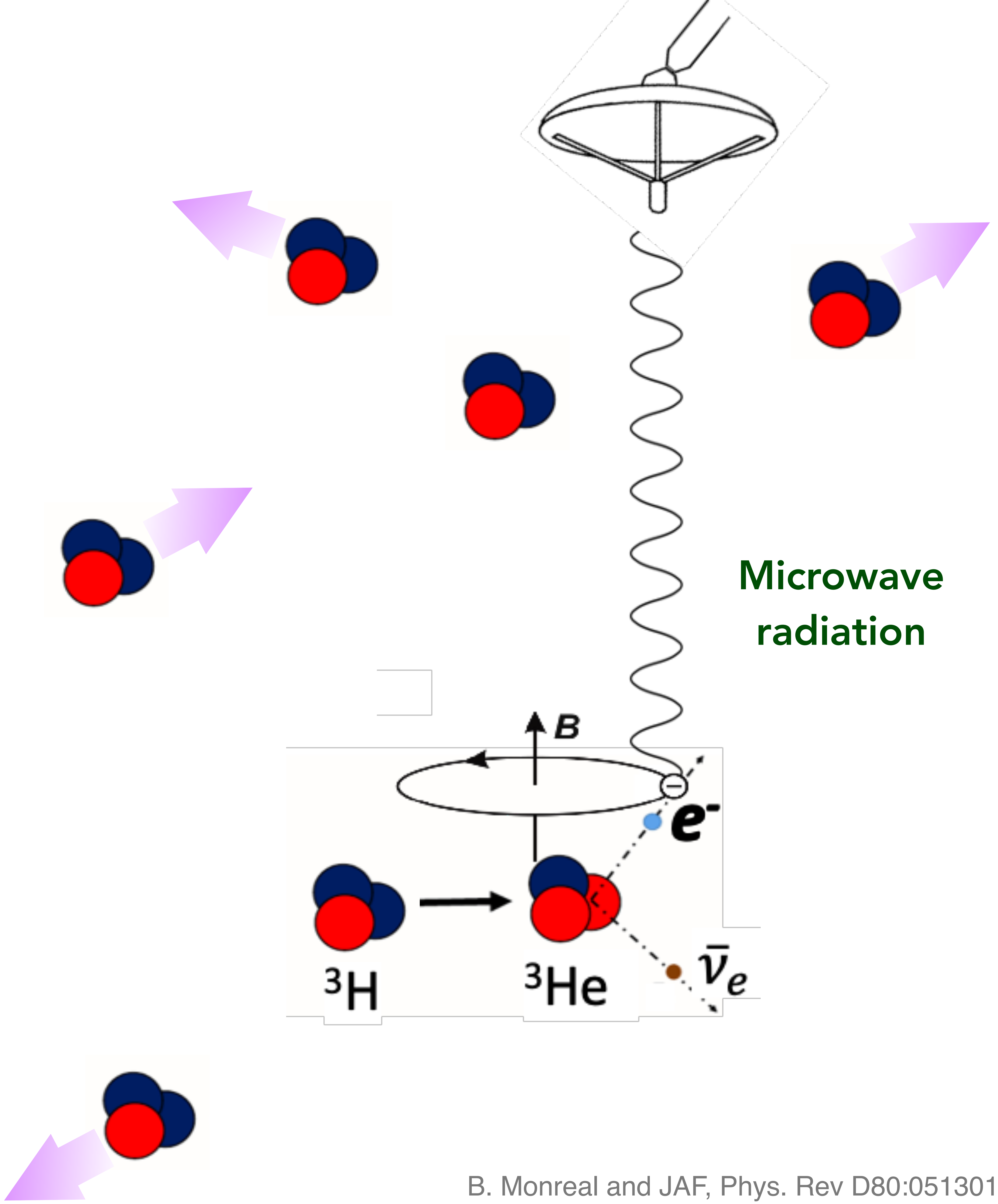
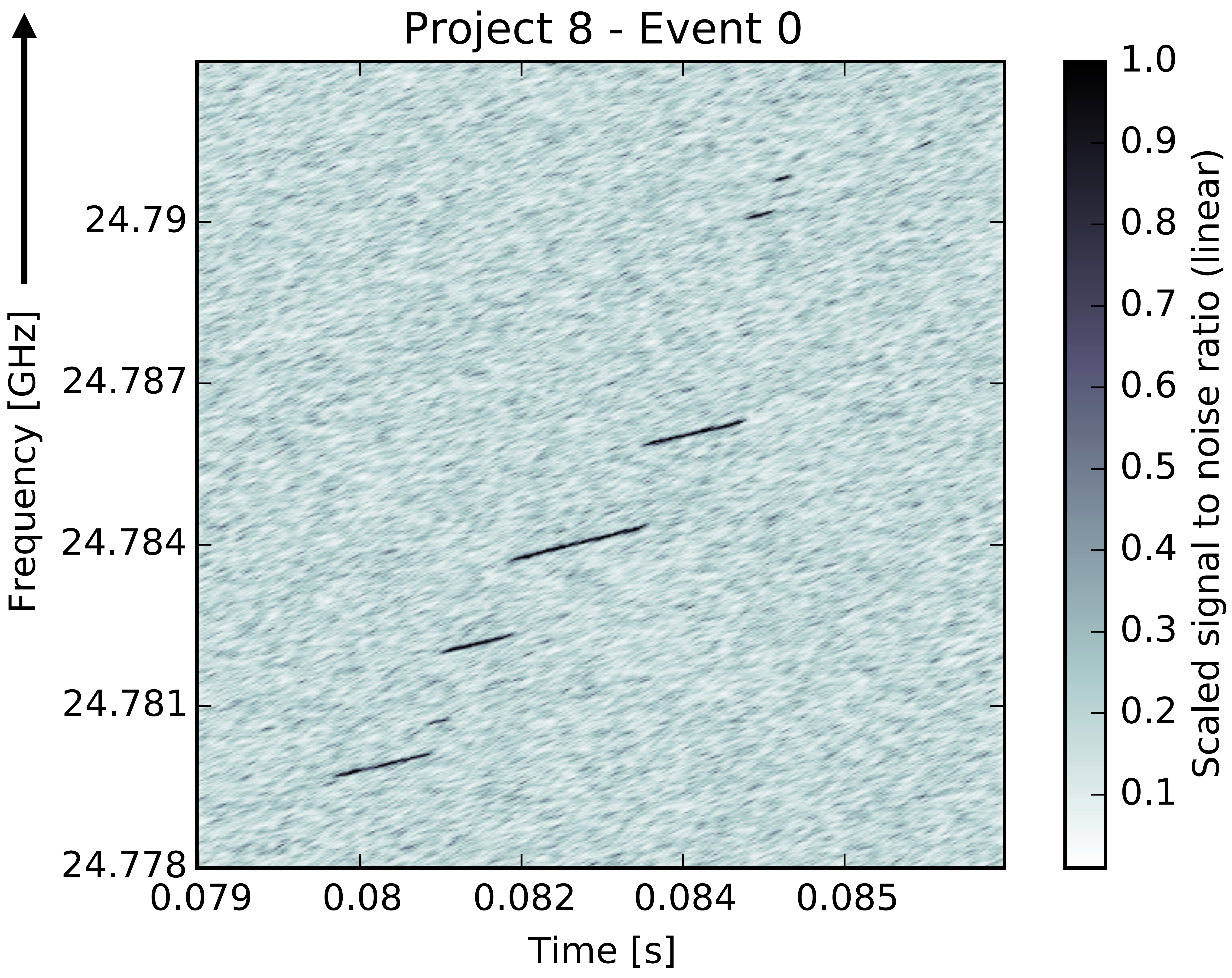


B. Monreal and JAF, Phys. Rev D80:051301

A moment to acknowledge the Project 8 collaboration...

PROJECT 8

What does a "typical" event look like?



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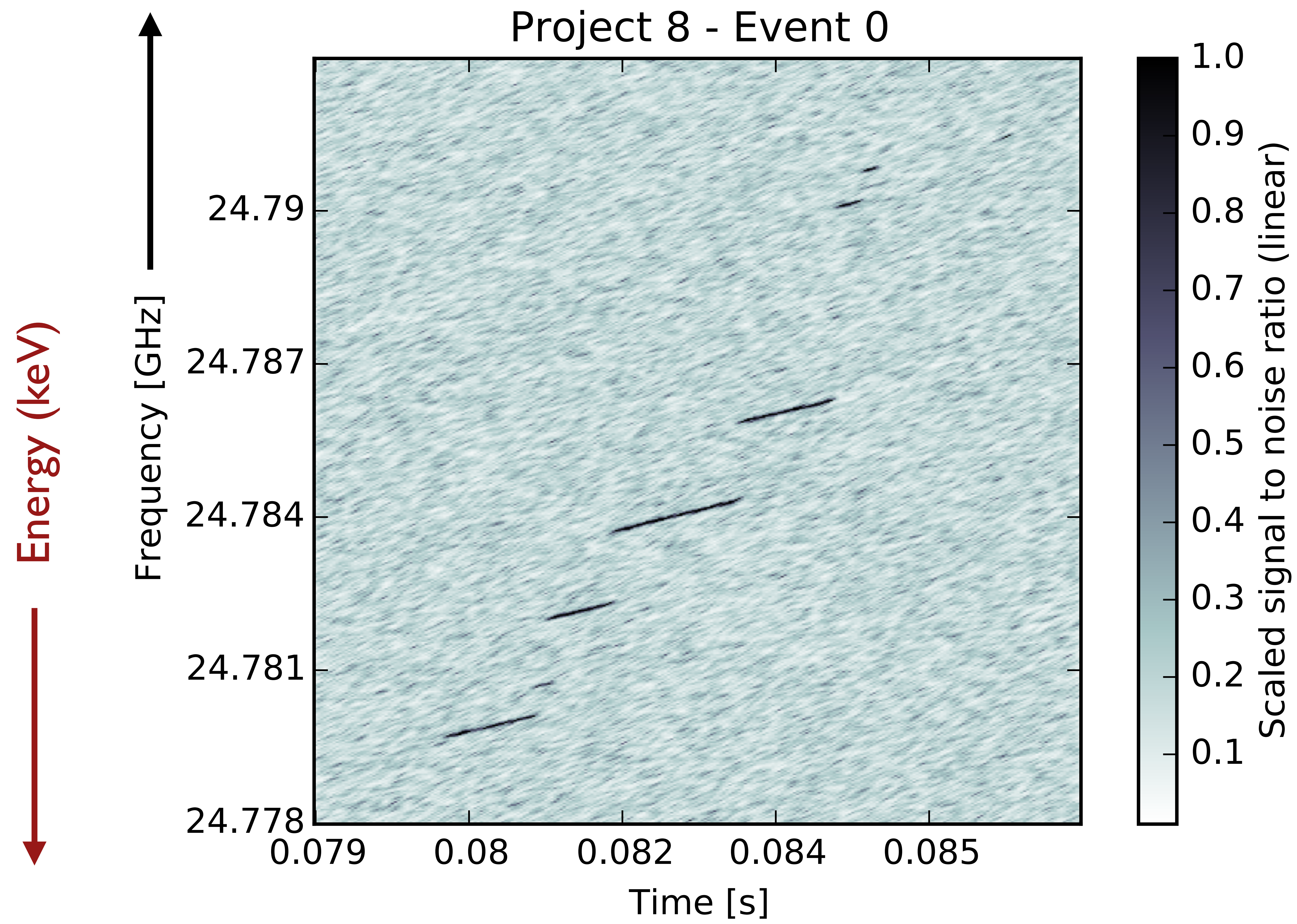

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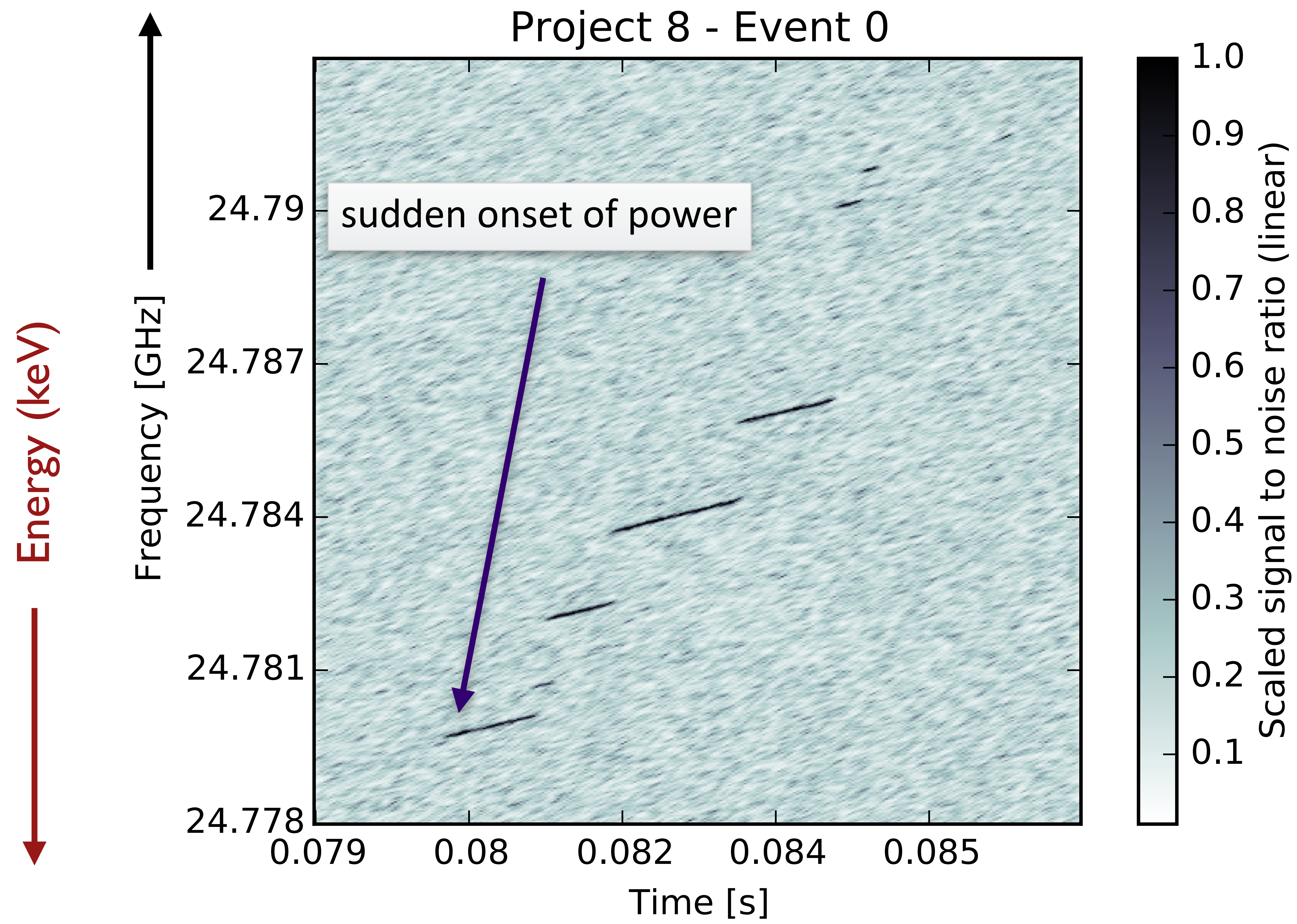

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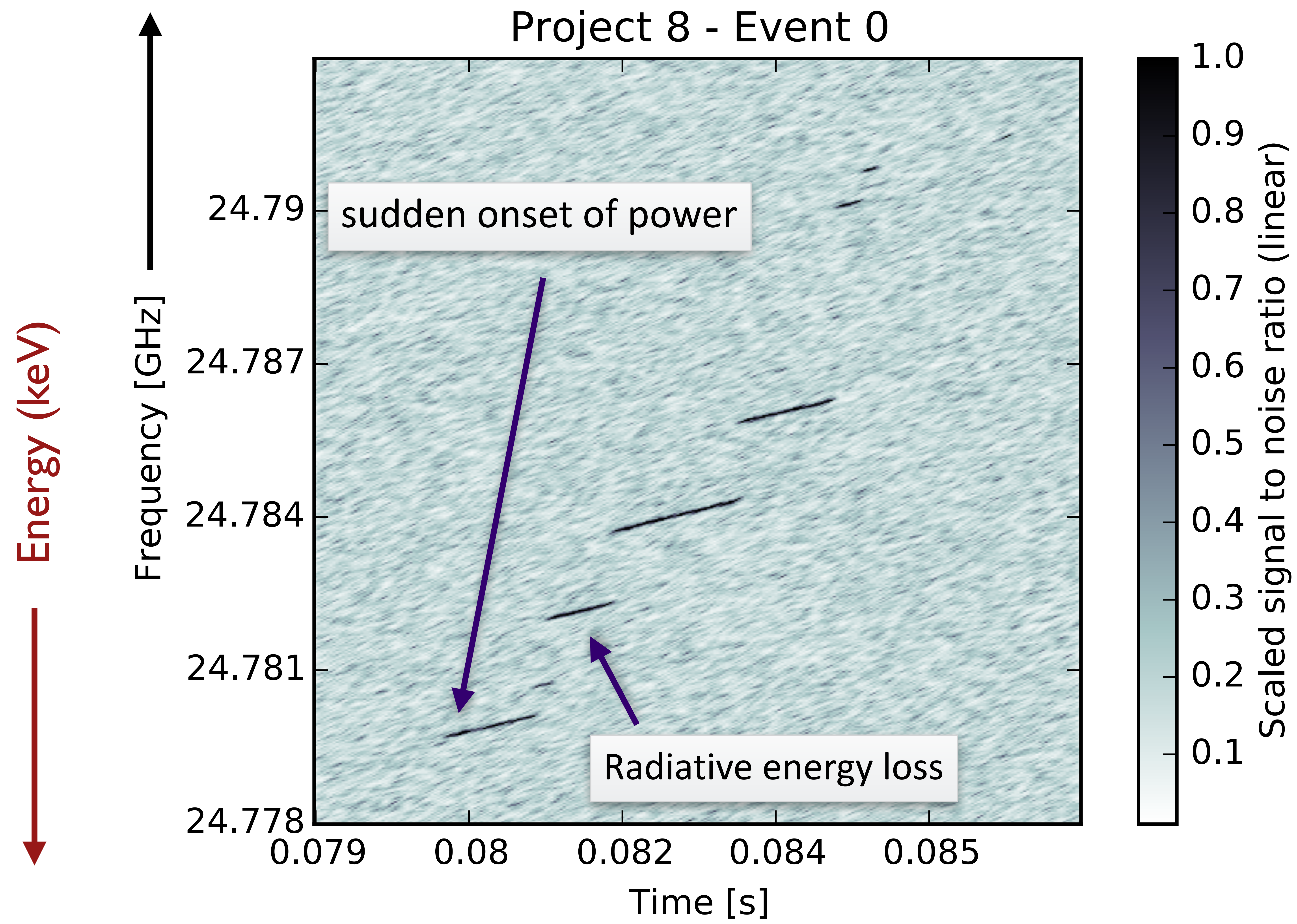

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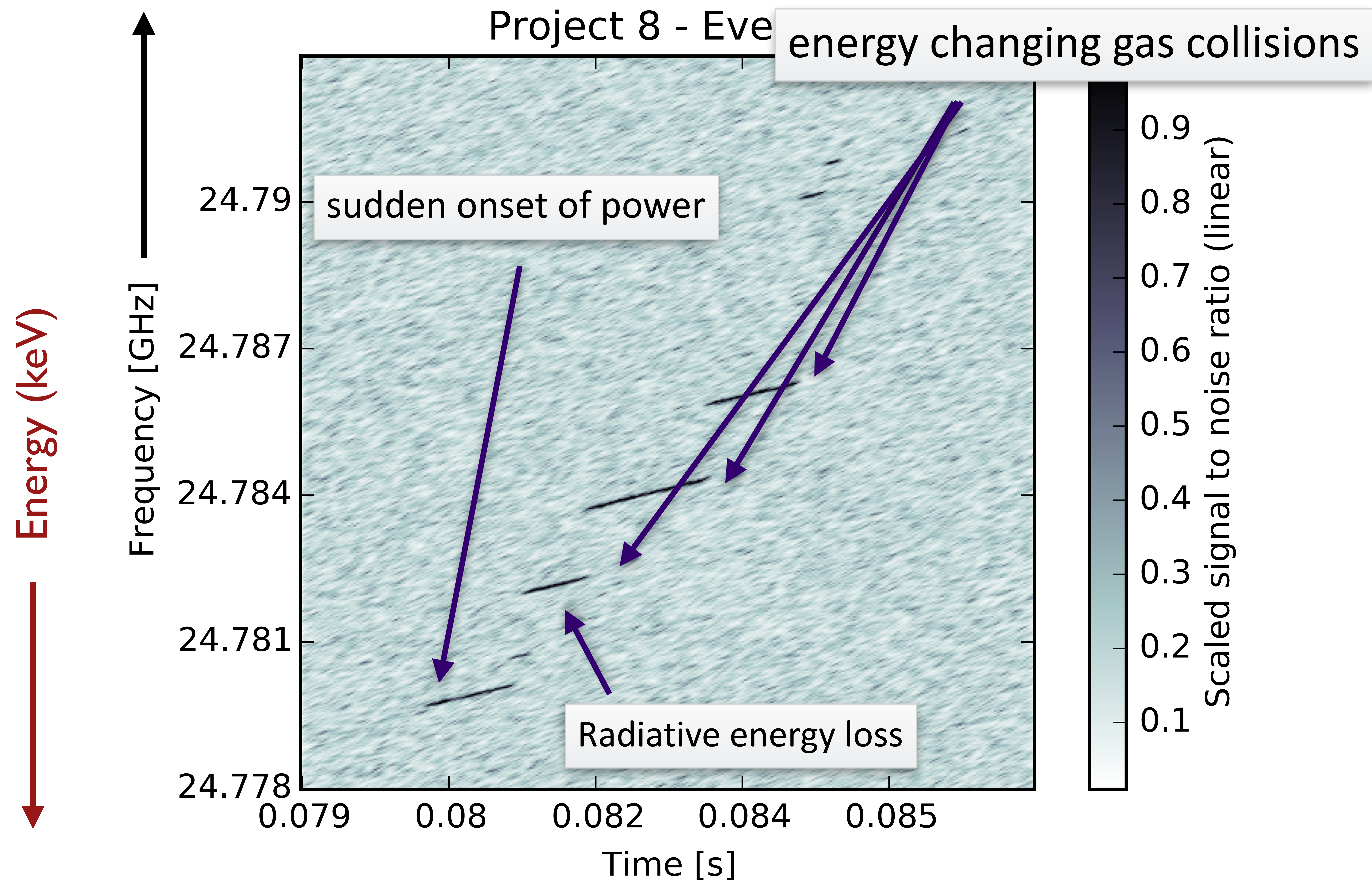

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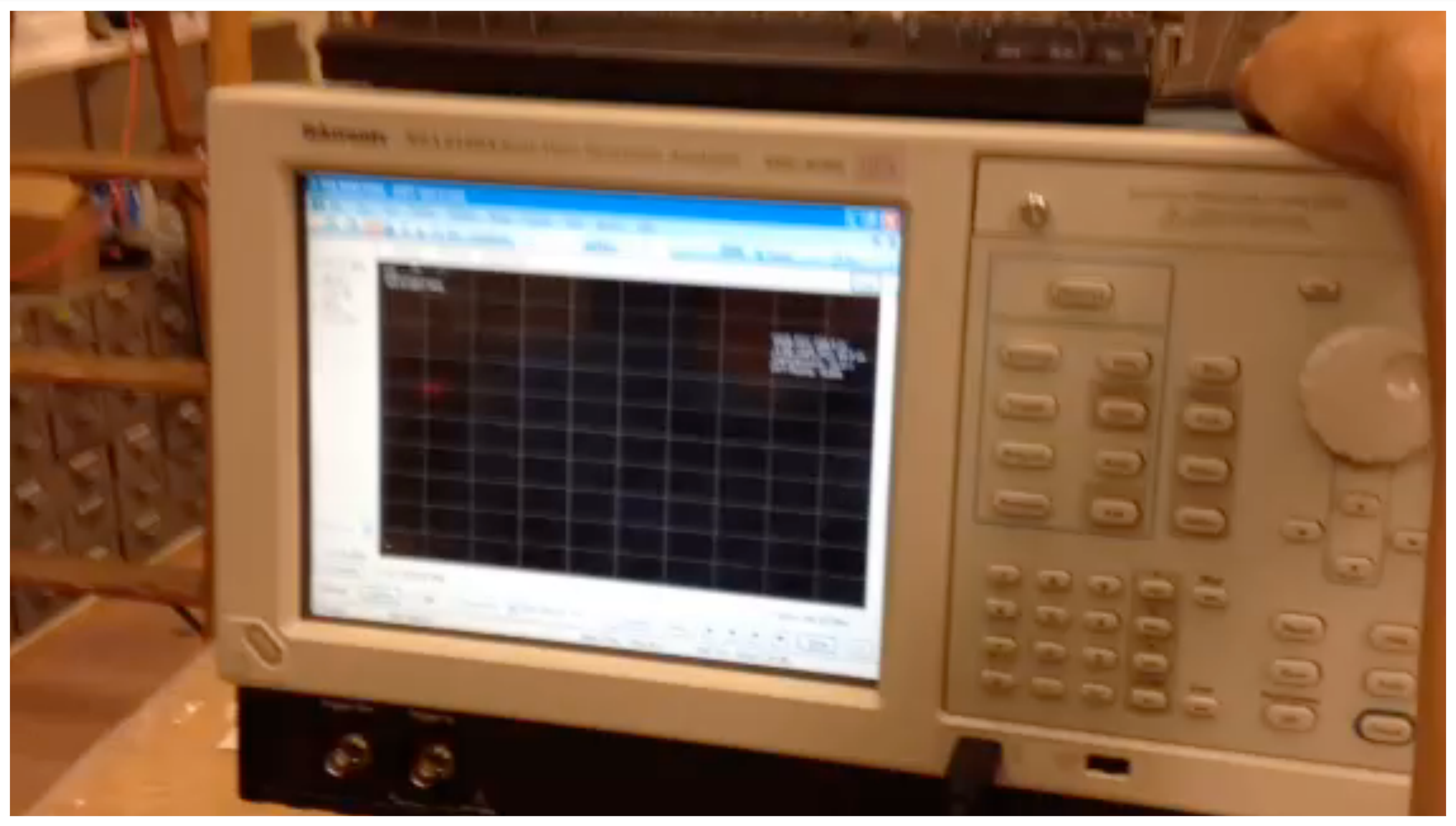
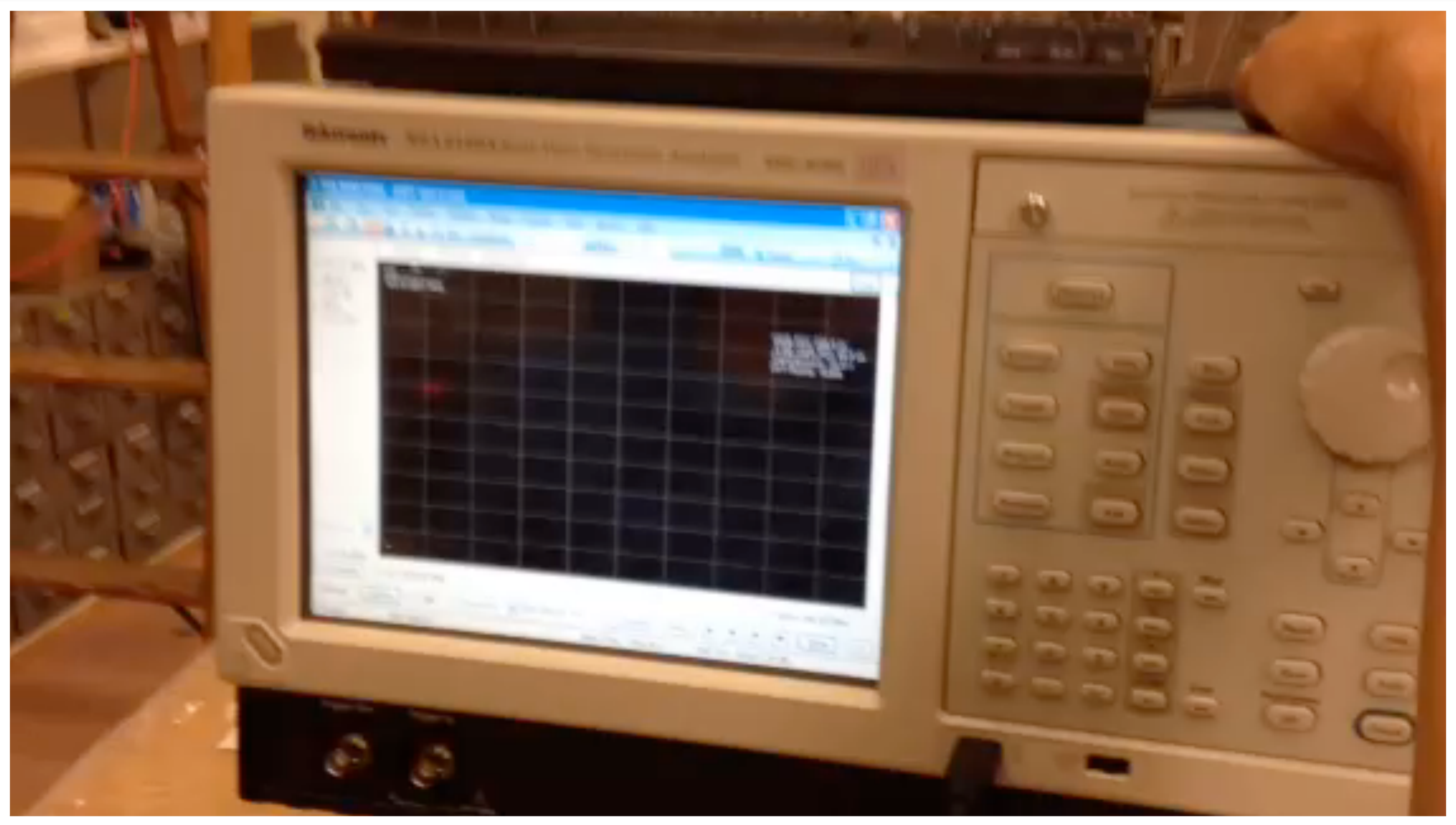
Rare moments in physics



*Brent VanDevender as he watches 30.2 keV CRES electrons come in.

Rare moments in physics

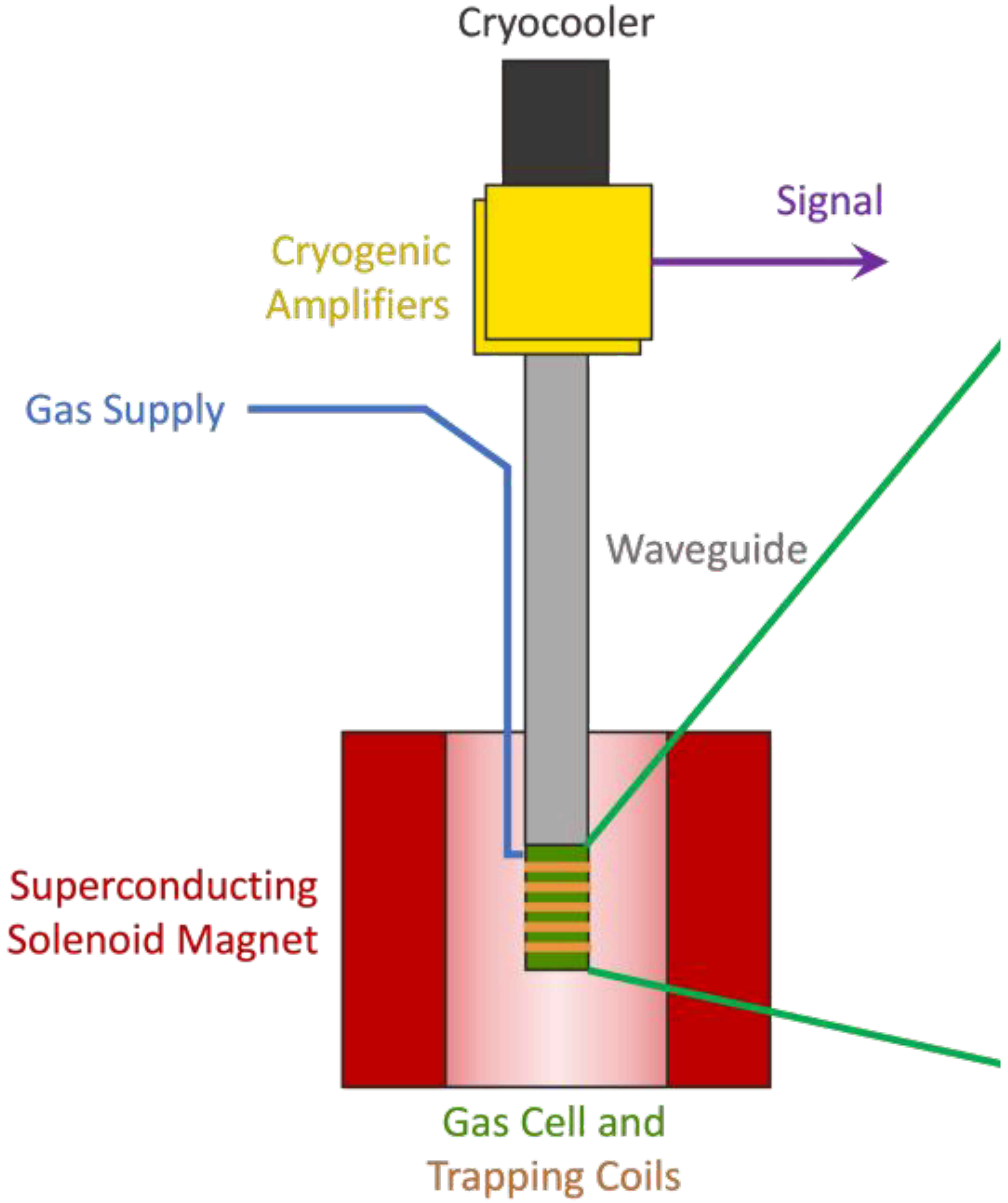


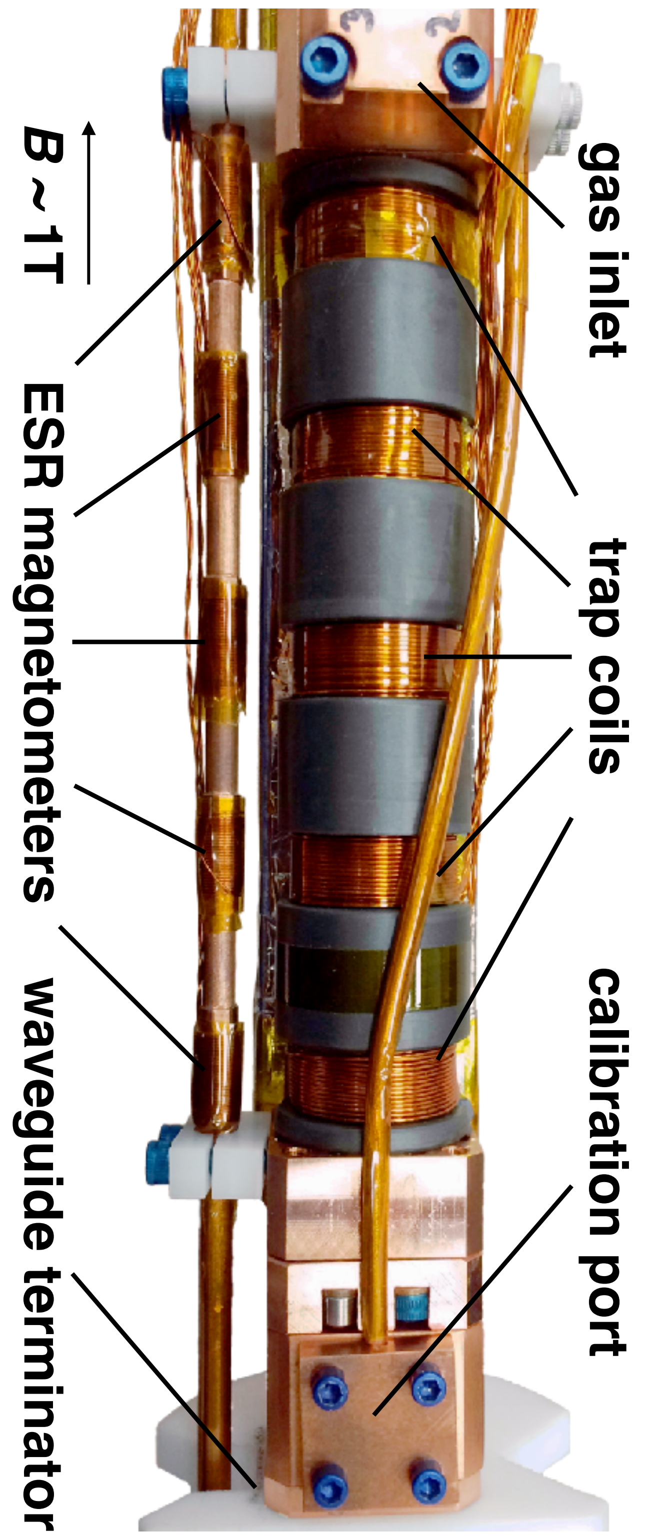
*Brent VanDevender as he watches 30.2 keV CRES electrons come in.

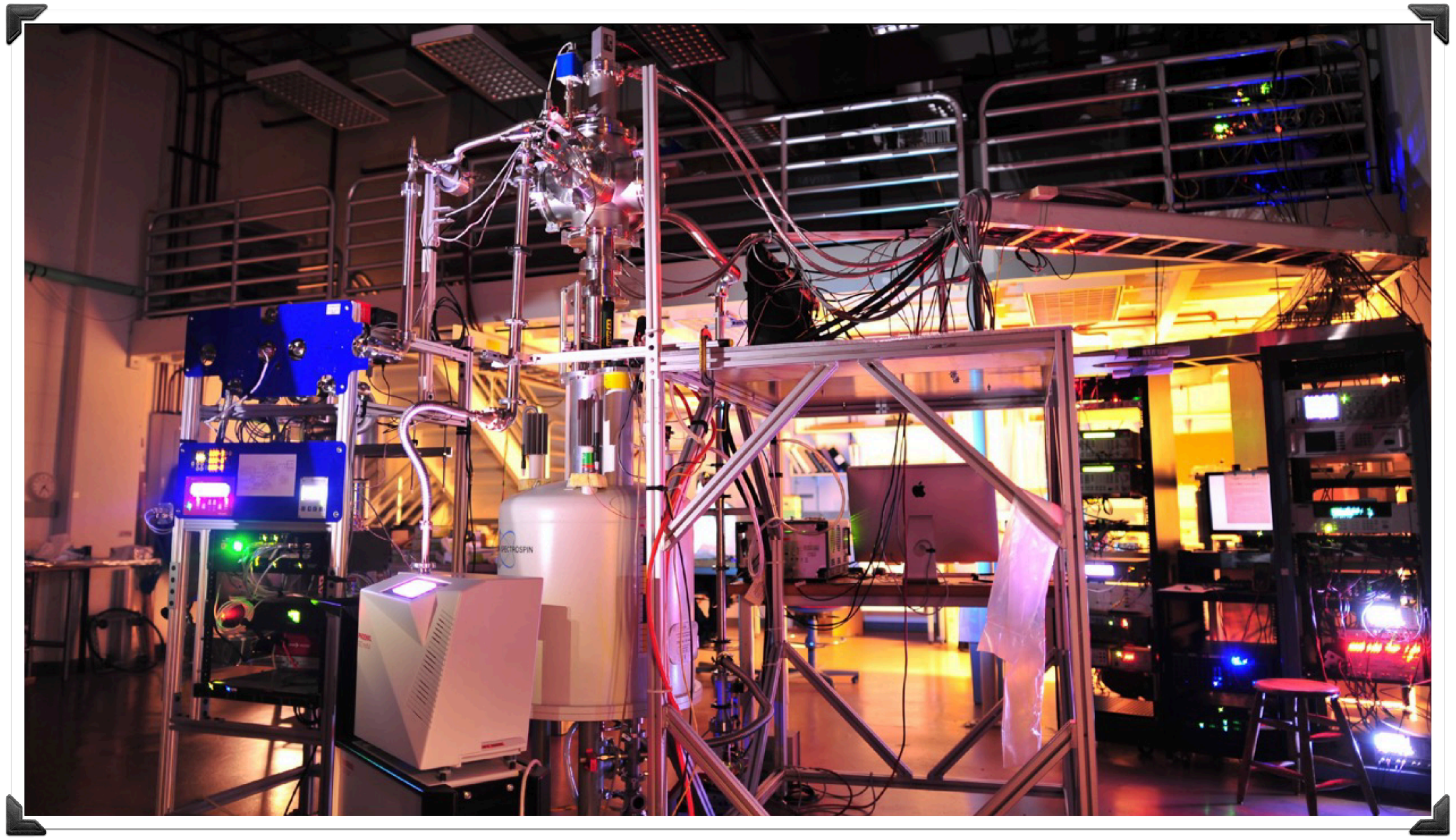
What does the apparatus look like?

Concept

Reality







How did we do?

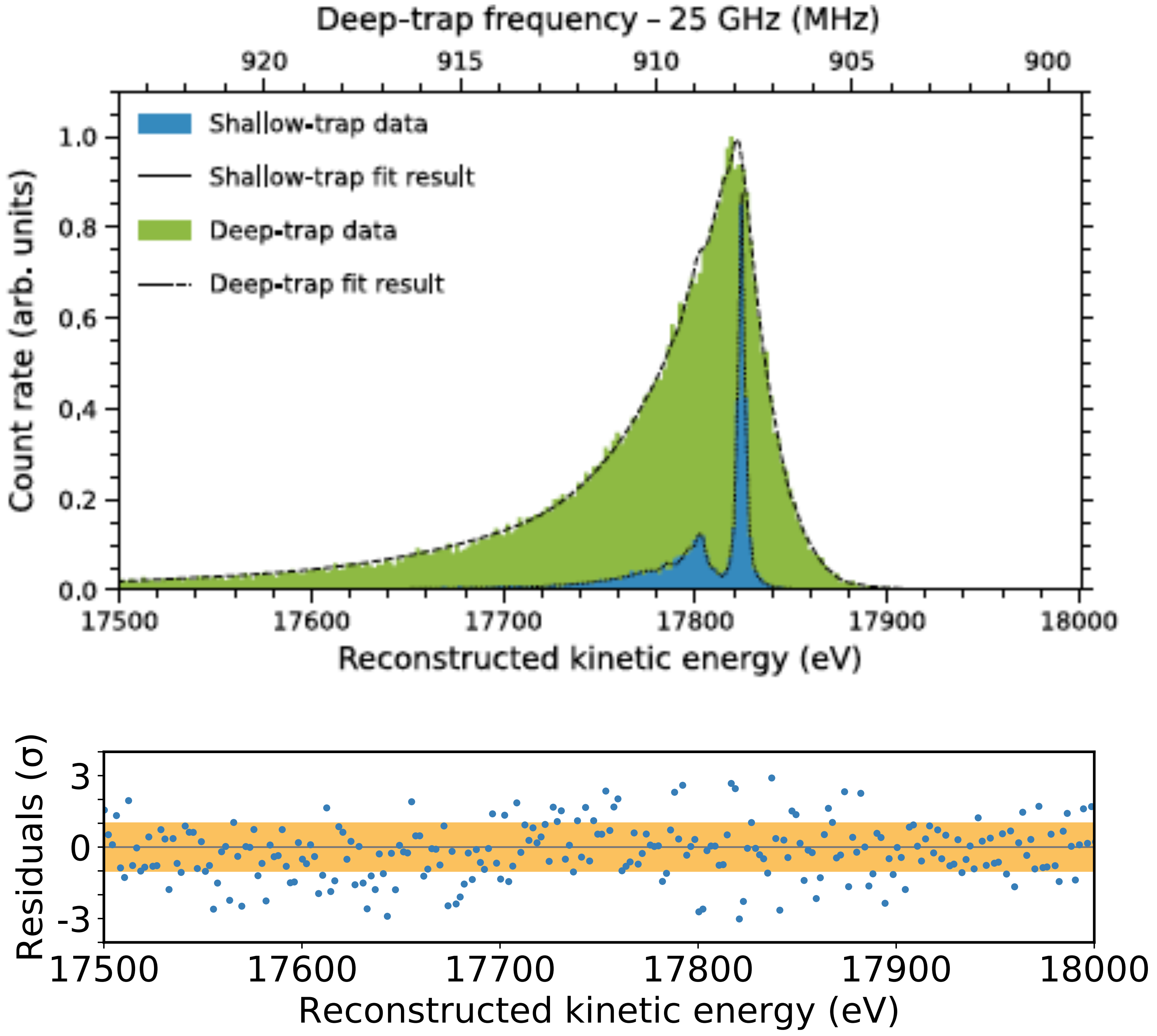
Energy resolution on ^{83m}Kr: 1.66 eV

(That's a frequency measurement of 3 parts per million)

First CRES mass measurement: m_β < 155 eV

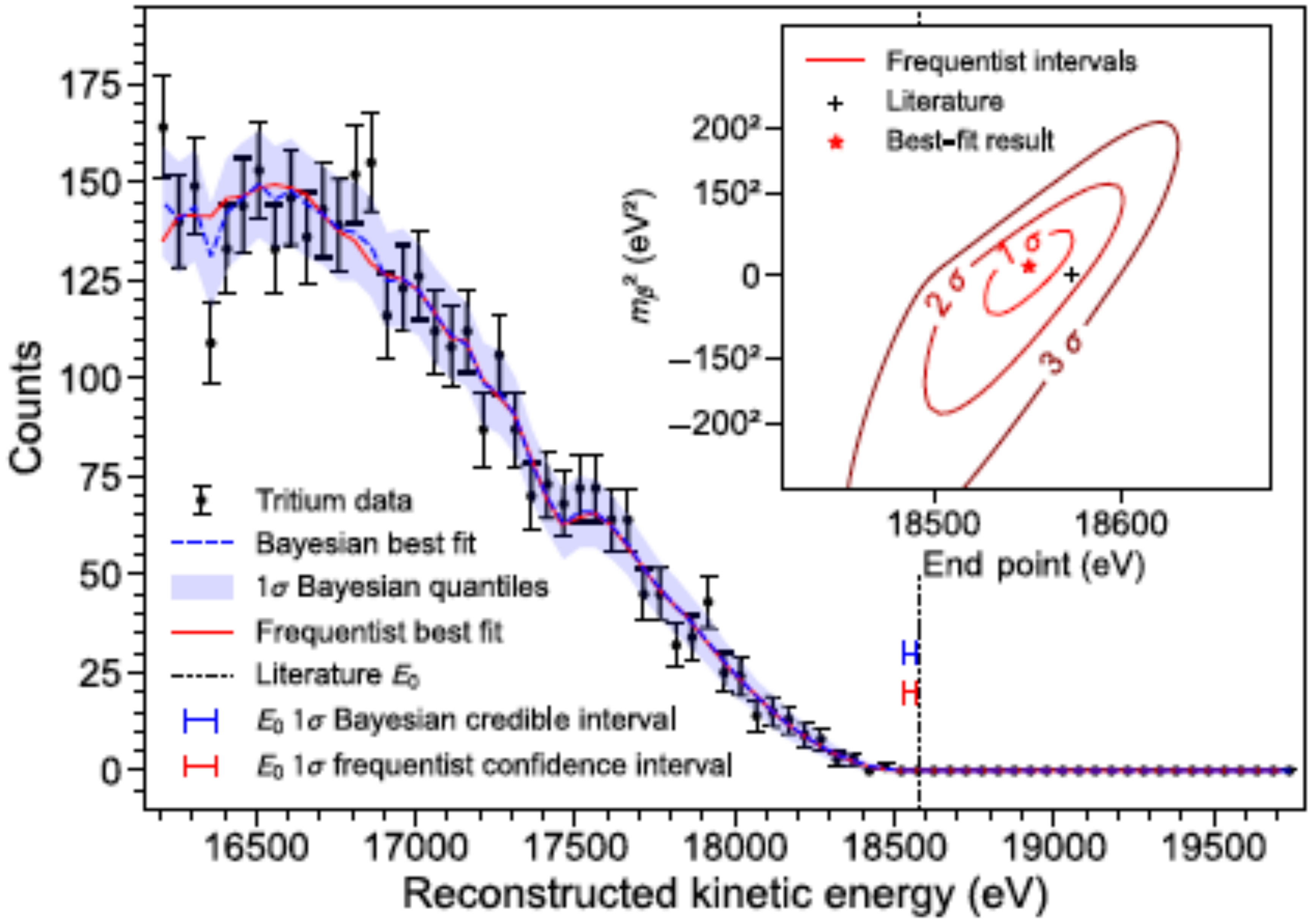
(And **no** background seen!)

^{83m}Kr Spectrum



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

1st Tritium Spectrum!

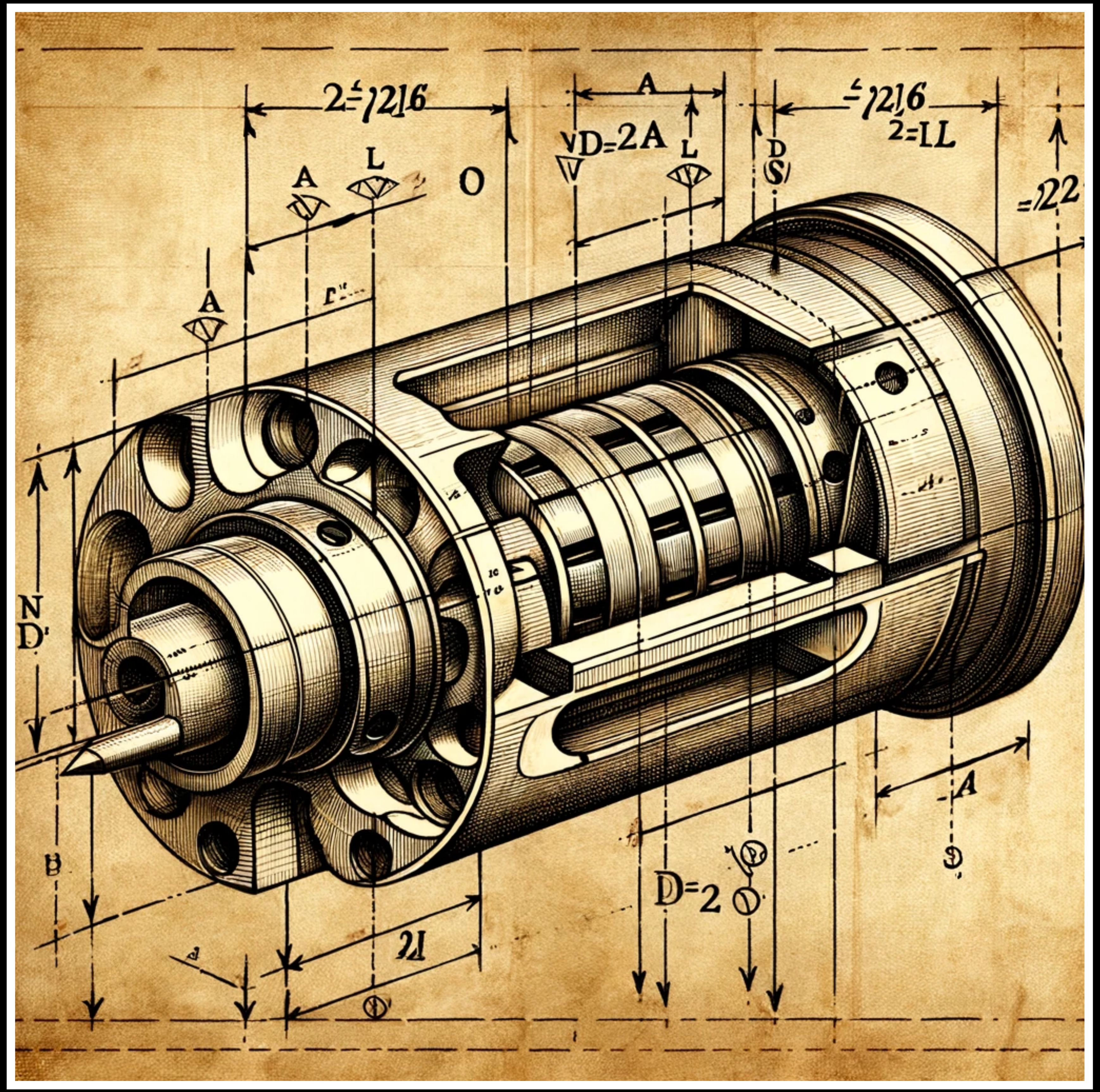


Ashtari Esfahani et al. arXiv 2303.12055 Accepted to PRC


KATRIN

Project 8 Phase II
Spectrometer
(To scale)

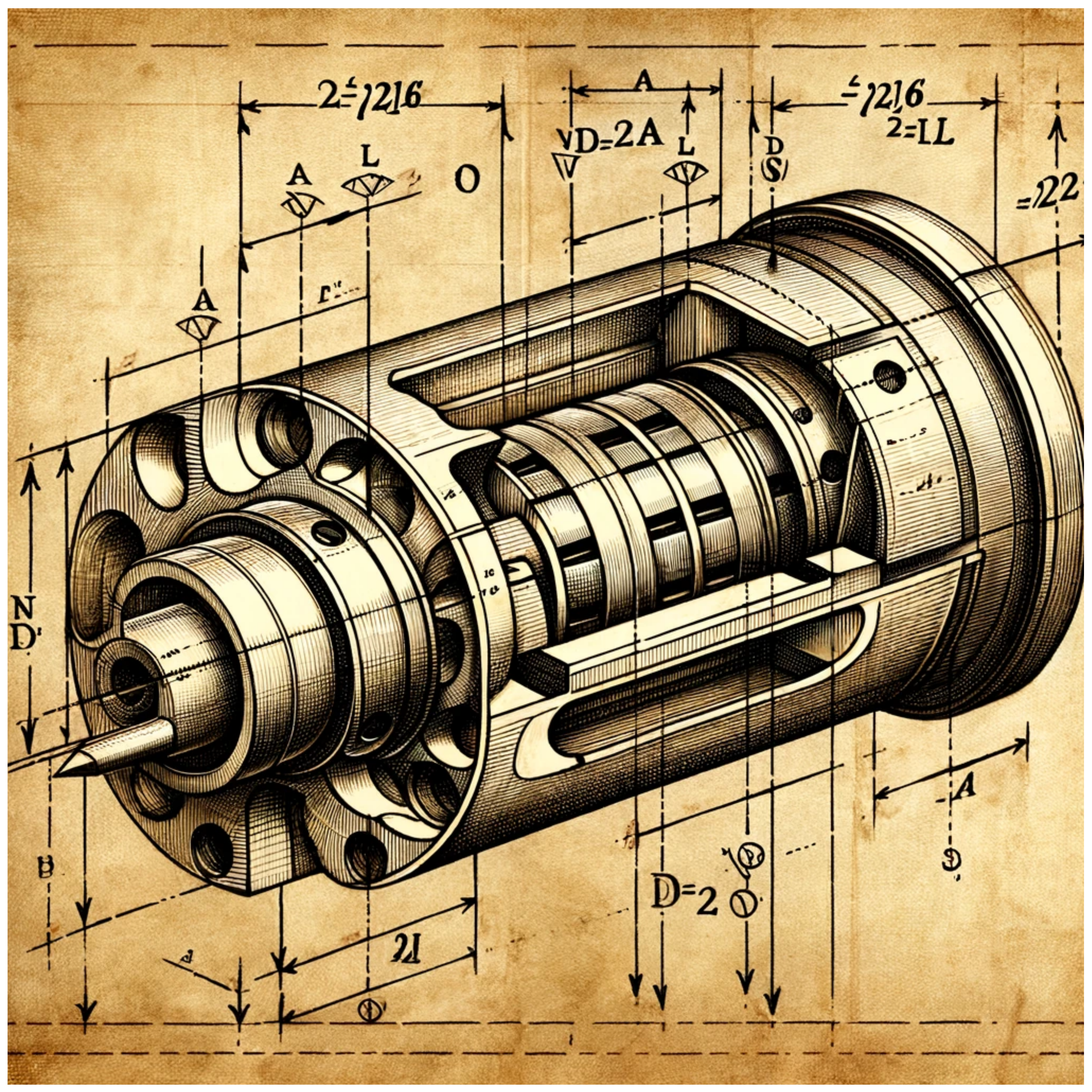
What next?



More* (!)

What next?

*ChatGPT's version of "large cavity"



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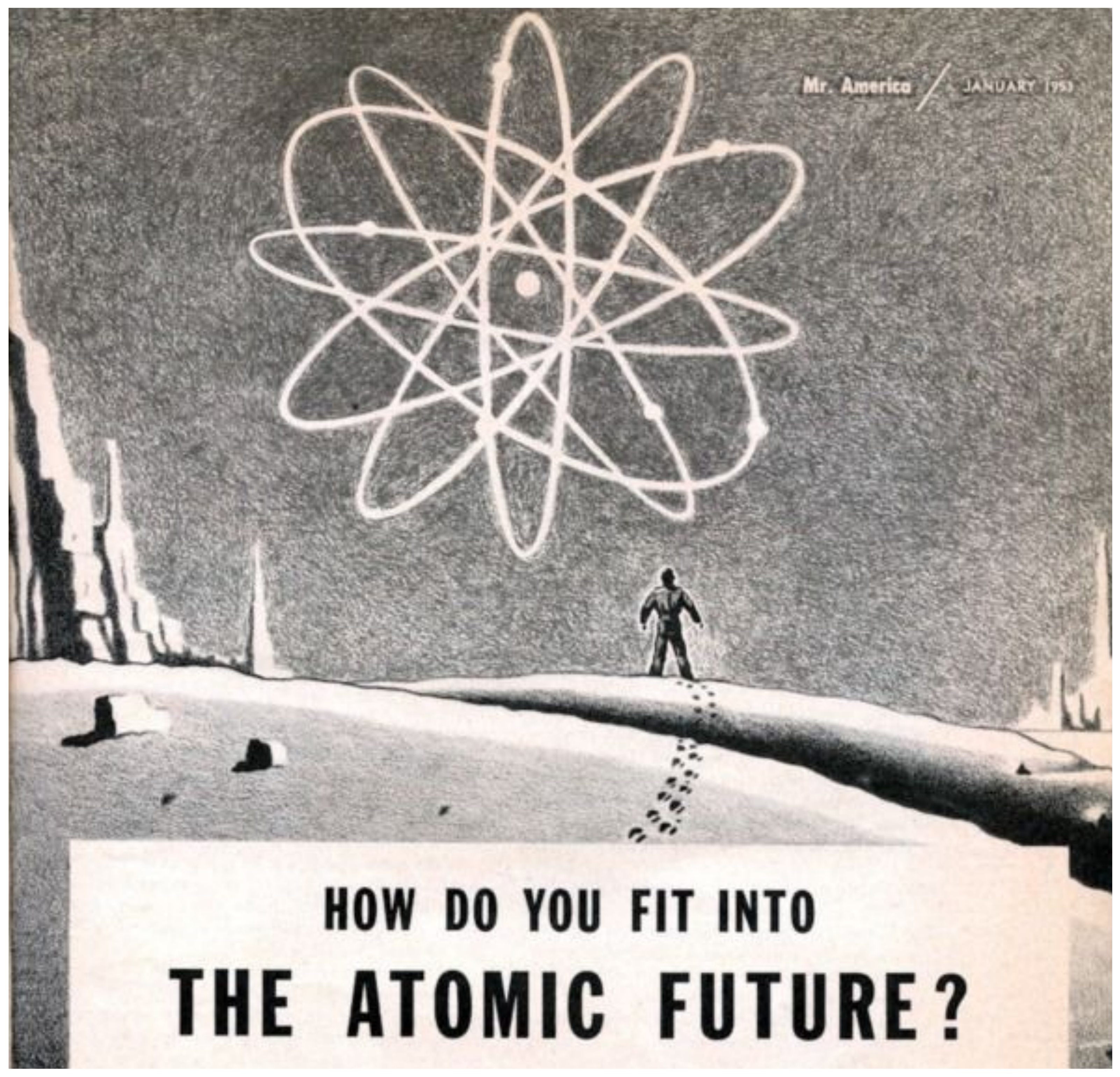

Atoms

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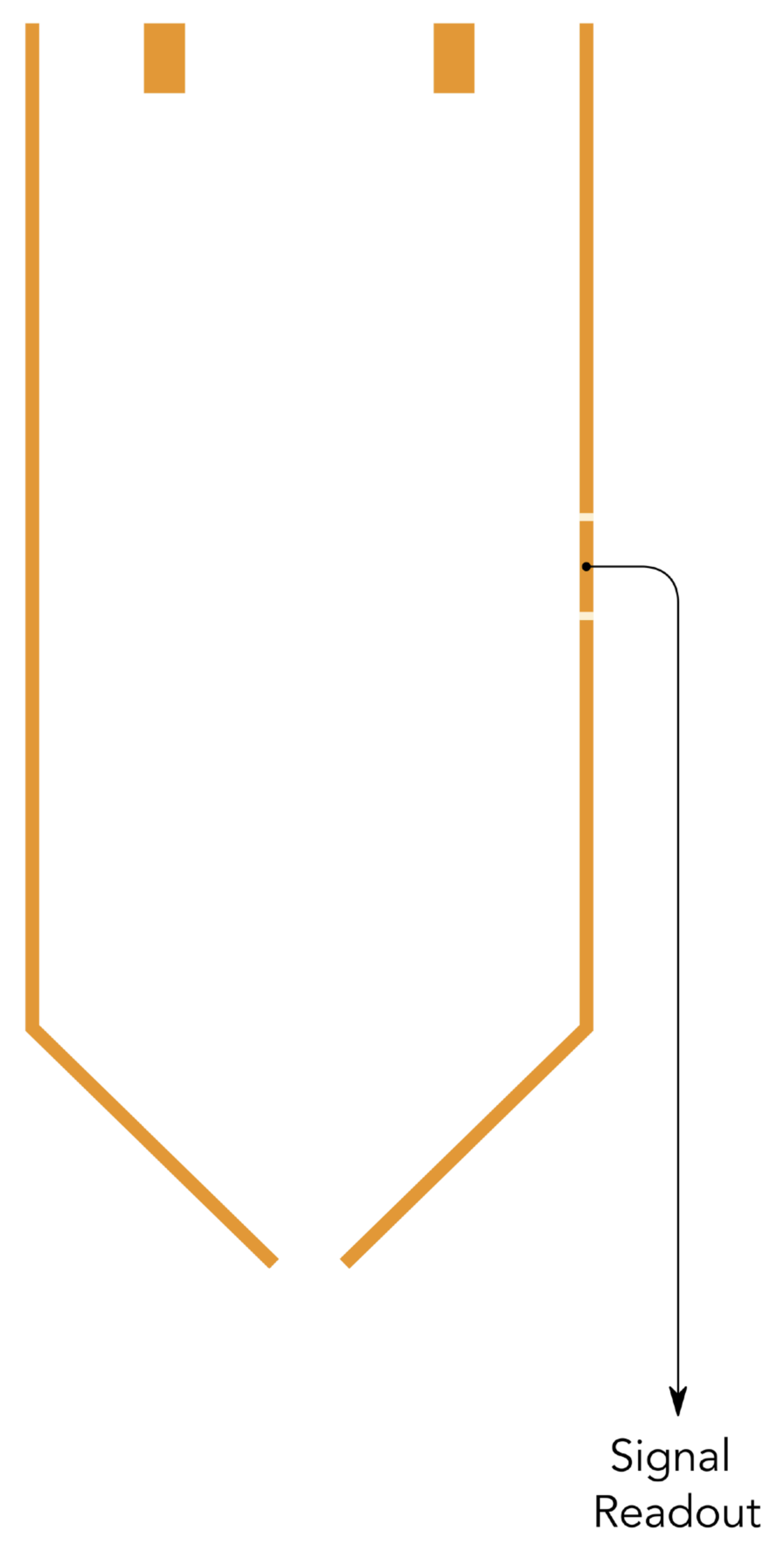

More (!)

Greater volume and efficiency can be gain if we switch to low freq. cavities:

Open-ended cavity with appropriately loaded Q

Atom trapping magnet at cavity walls

Solenoid to provide CRES field

Pinch coils provide electron trapping

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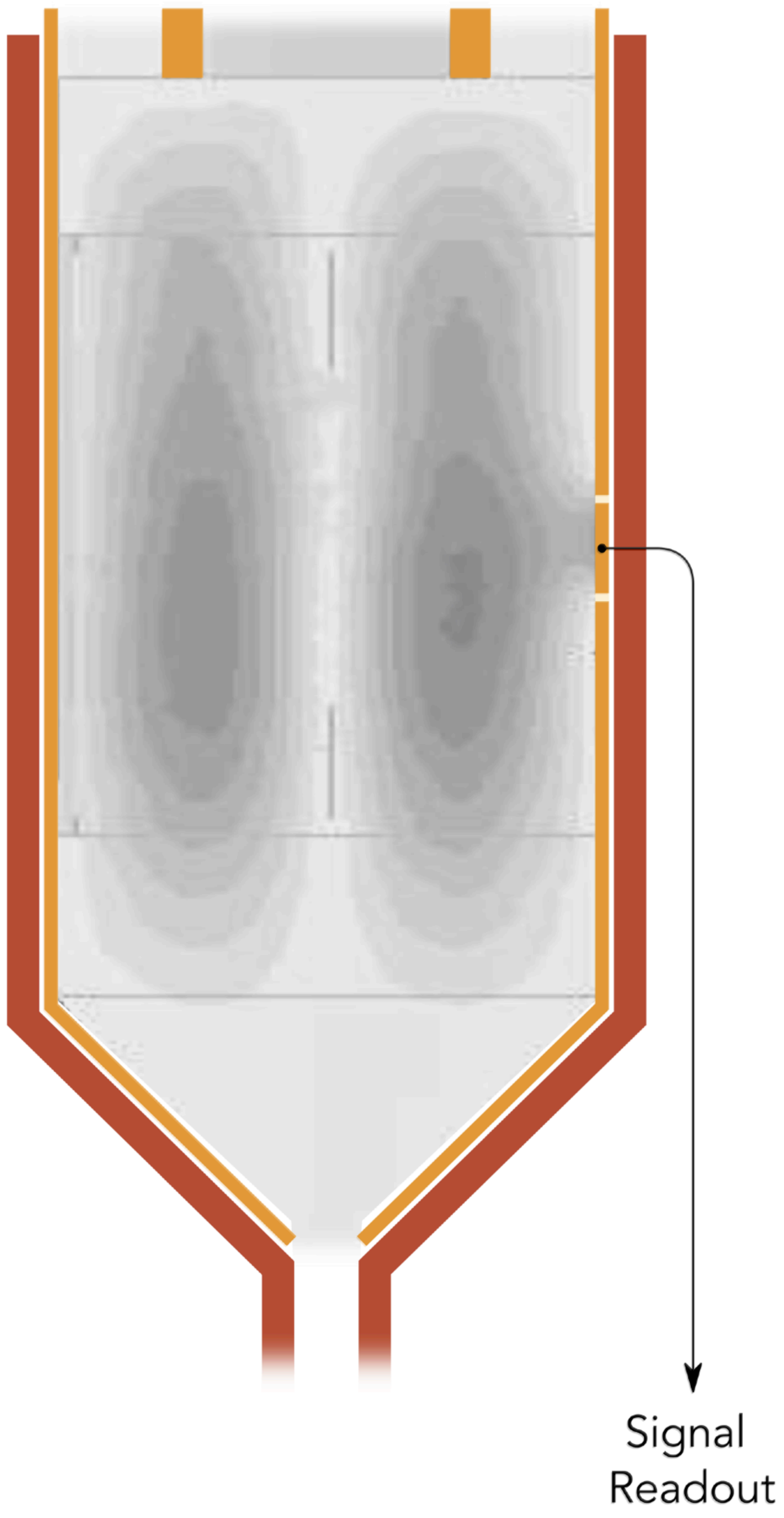

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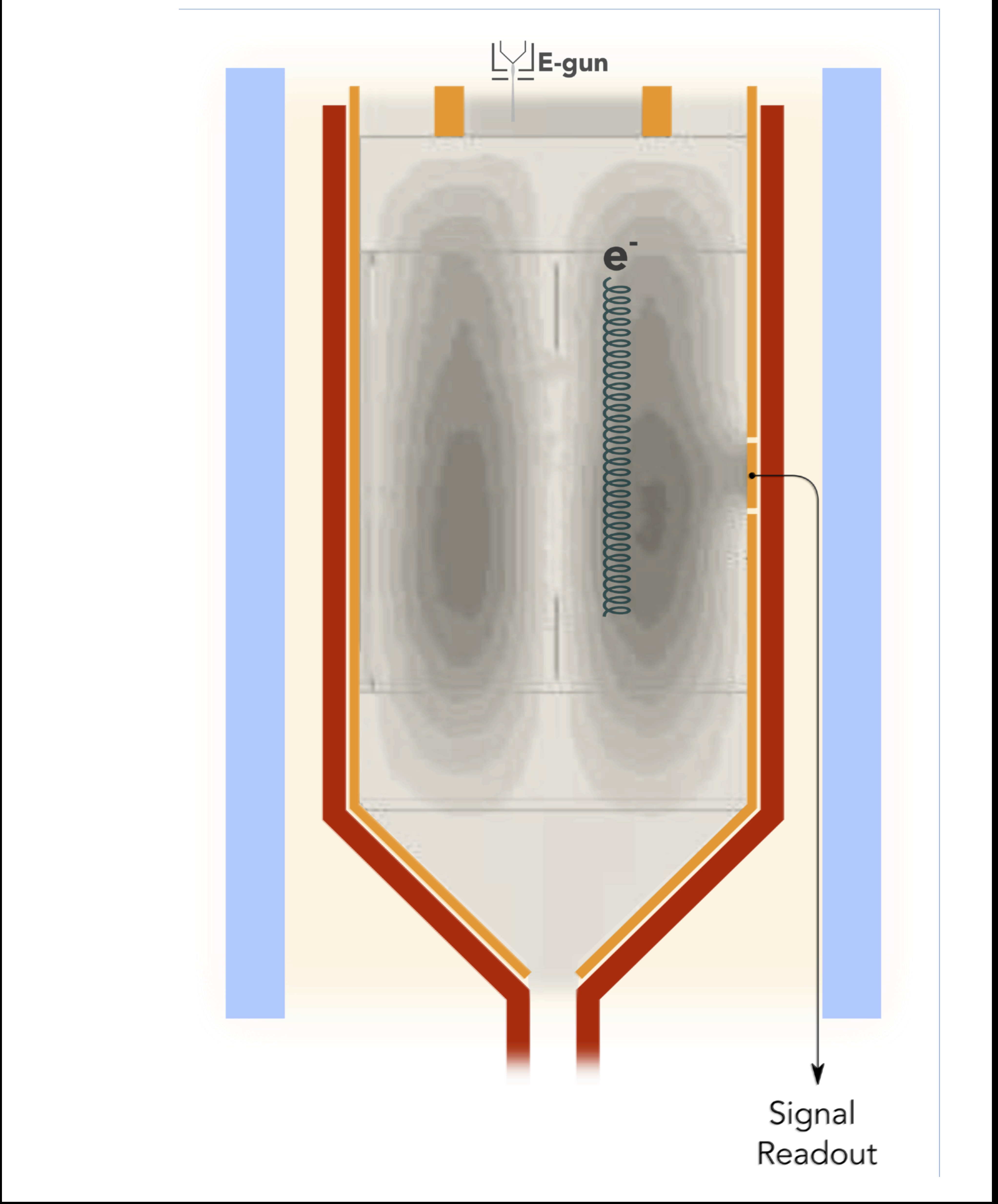

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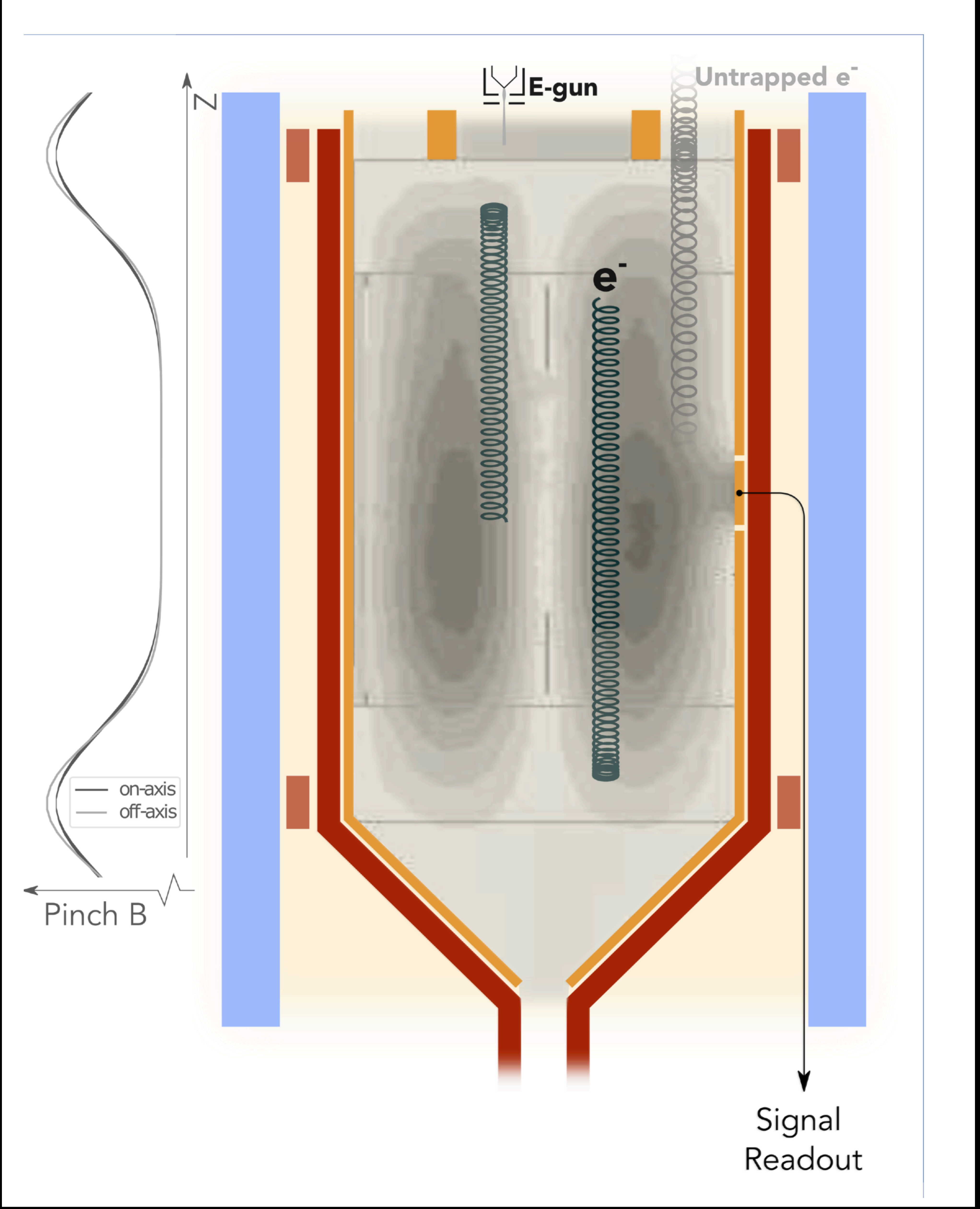

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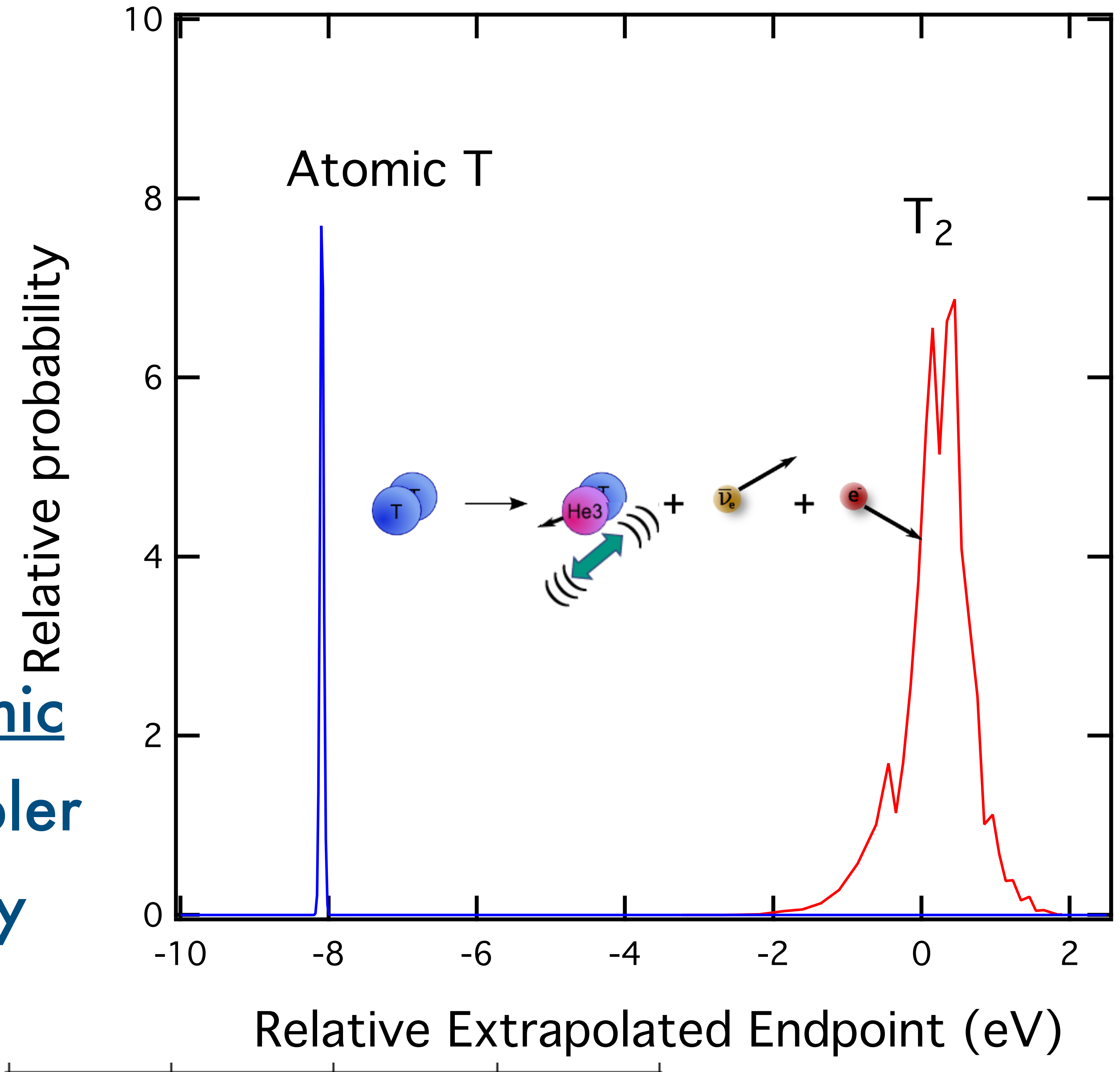
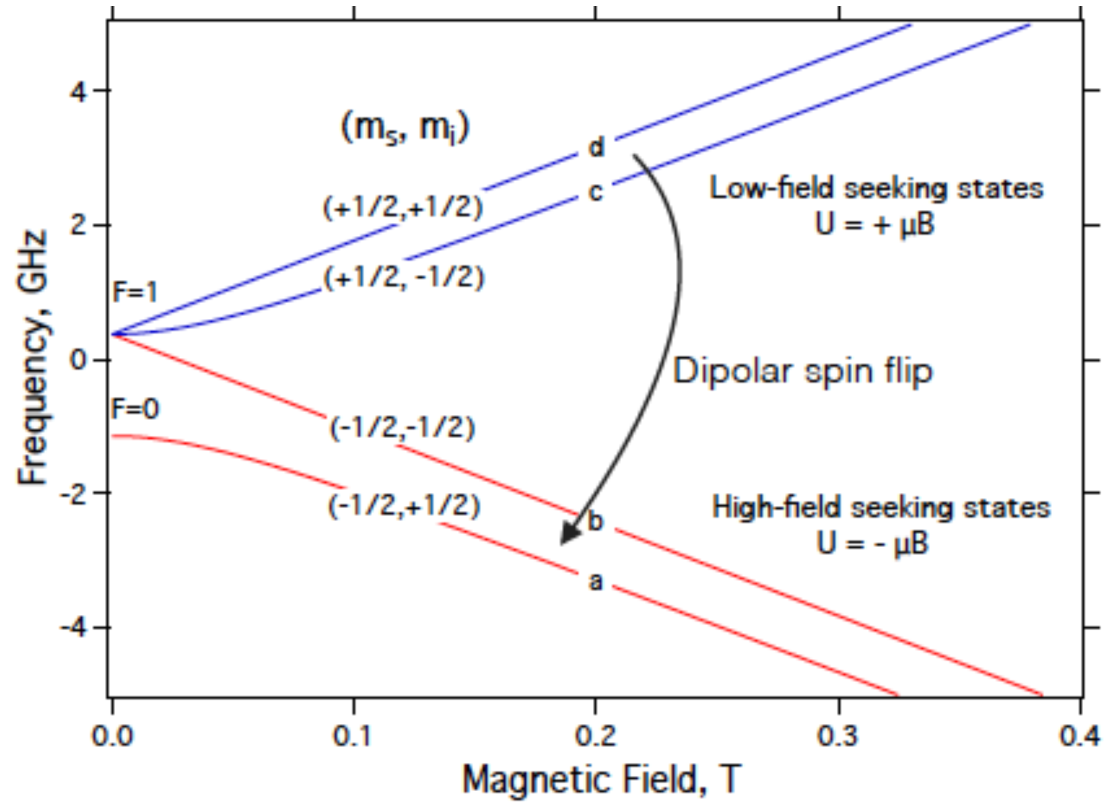
The problem with molecular tritium…

molecules **VIBRATE** and rotate

This smears the energy of the spectrum (generates a potential systematic uncertainty).

Need to magnetically trap atomic tritium (@ mK temperatures)





Magnetic confinement of atoms

Atoms (!)

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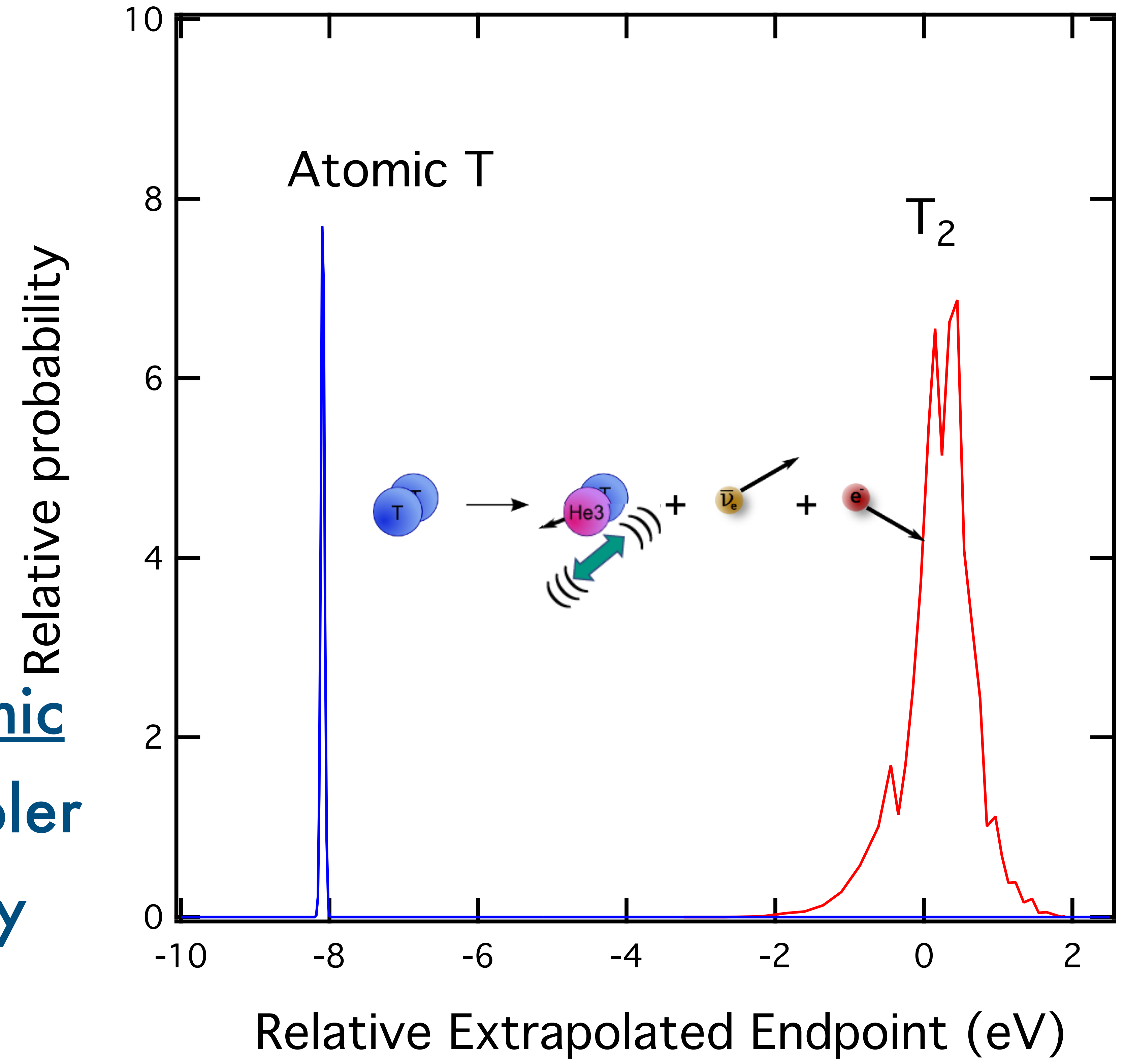
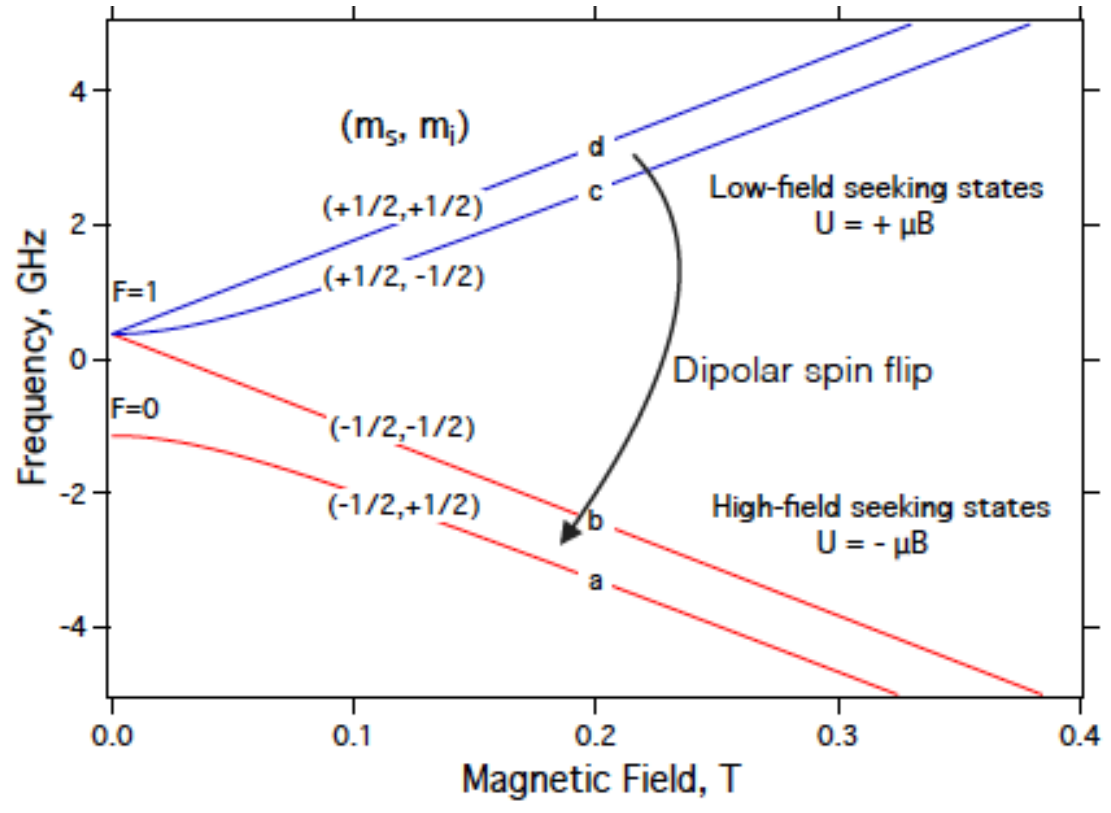
Atomic Doppler only



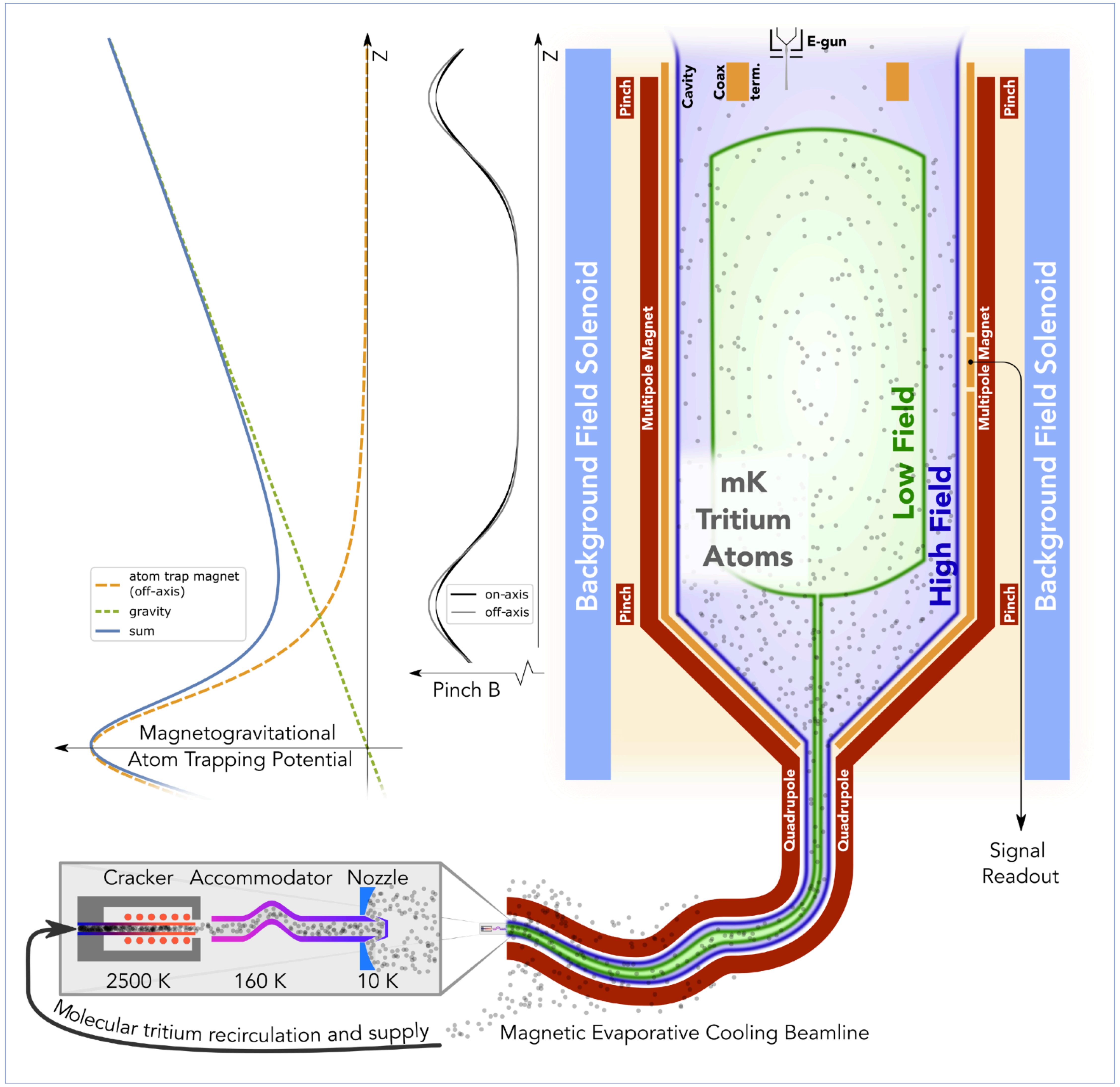
Molecular Rotational Vibrational



Magnetic confinement of atoms

Atoms (!)

Envisioned Phase III Experiment
(Ask me for details)



PROJECT 8

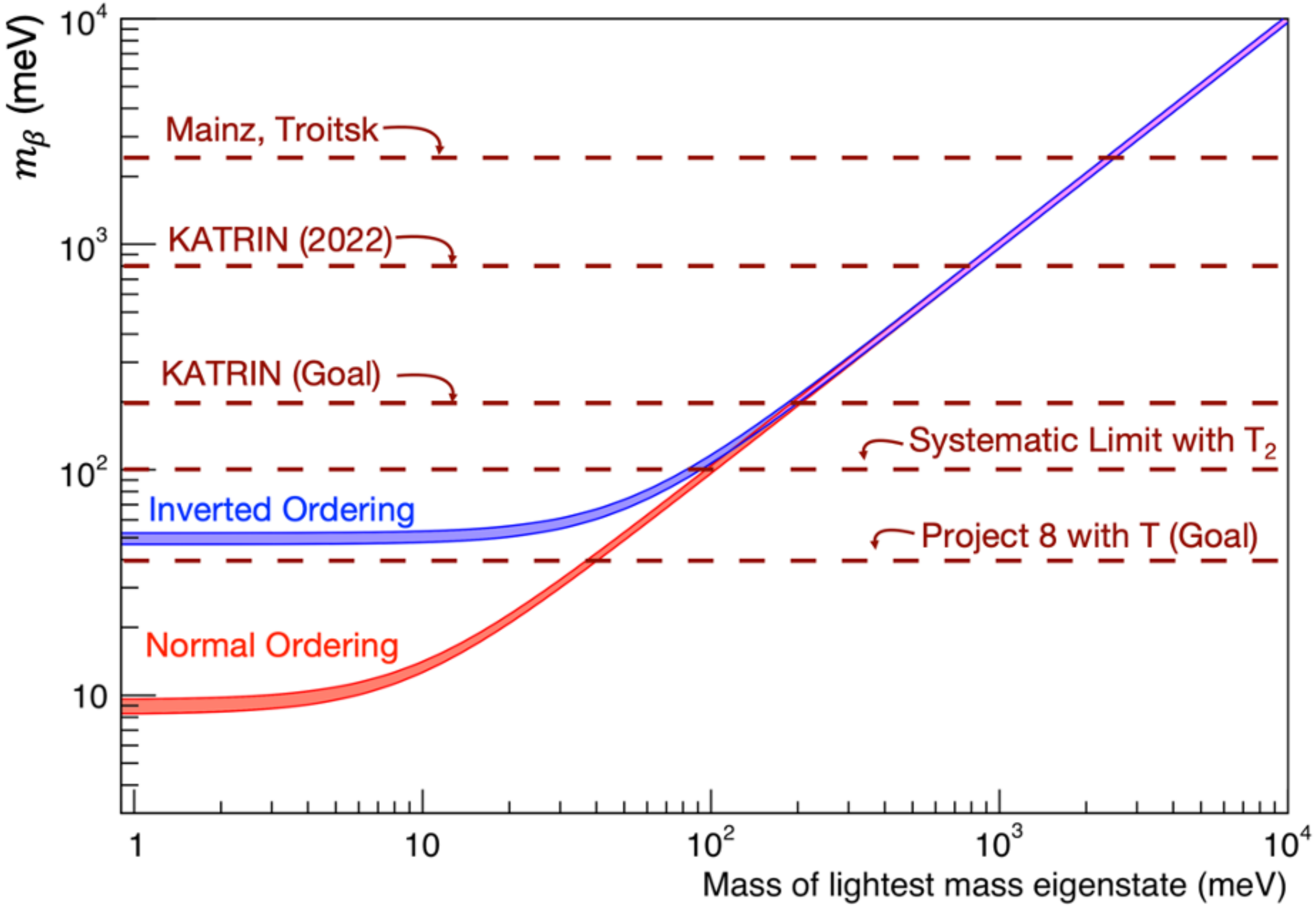
Goals:

Sensitivity to m_β < 40 meV/c^2

Measure neutrino mass or exclude inverted hierarchy

Simultaneous sensitivity to active and sterile neutrinos

Towards the neutrino mass “floor”;
finally fulling Fermi’s prediction



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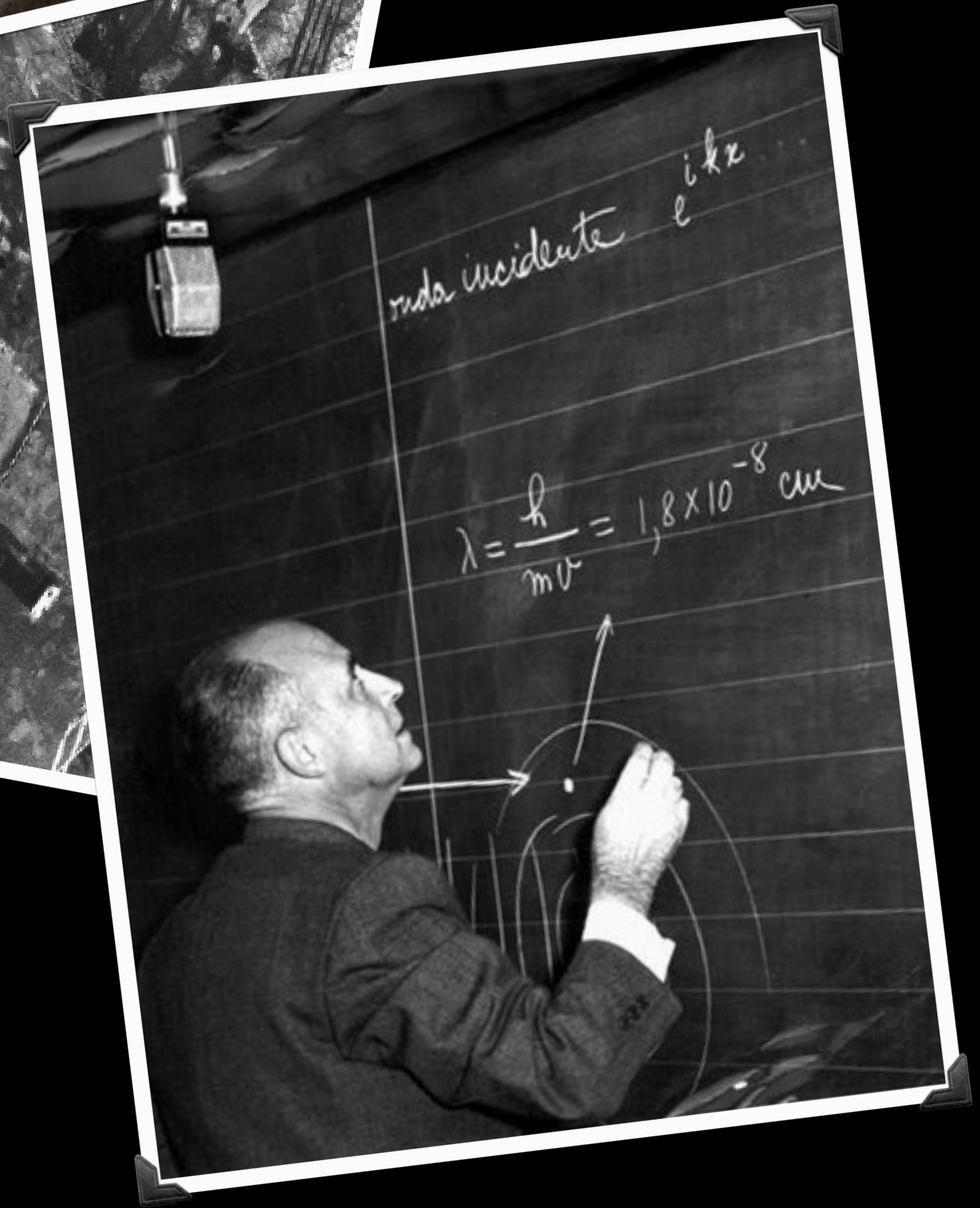
onda incidente e^{ikx}
$\lambda = \frac{h}{mv} = 1,8 \times 10^{-8}$ cm

This is truly an exciting time to study neutrinos.

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New experiments may finally answer the question: “How much does a neutrino weigh?”

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And fun new ways to learn cutting edge techniques.

Thank you for your time.