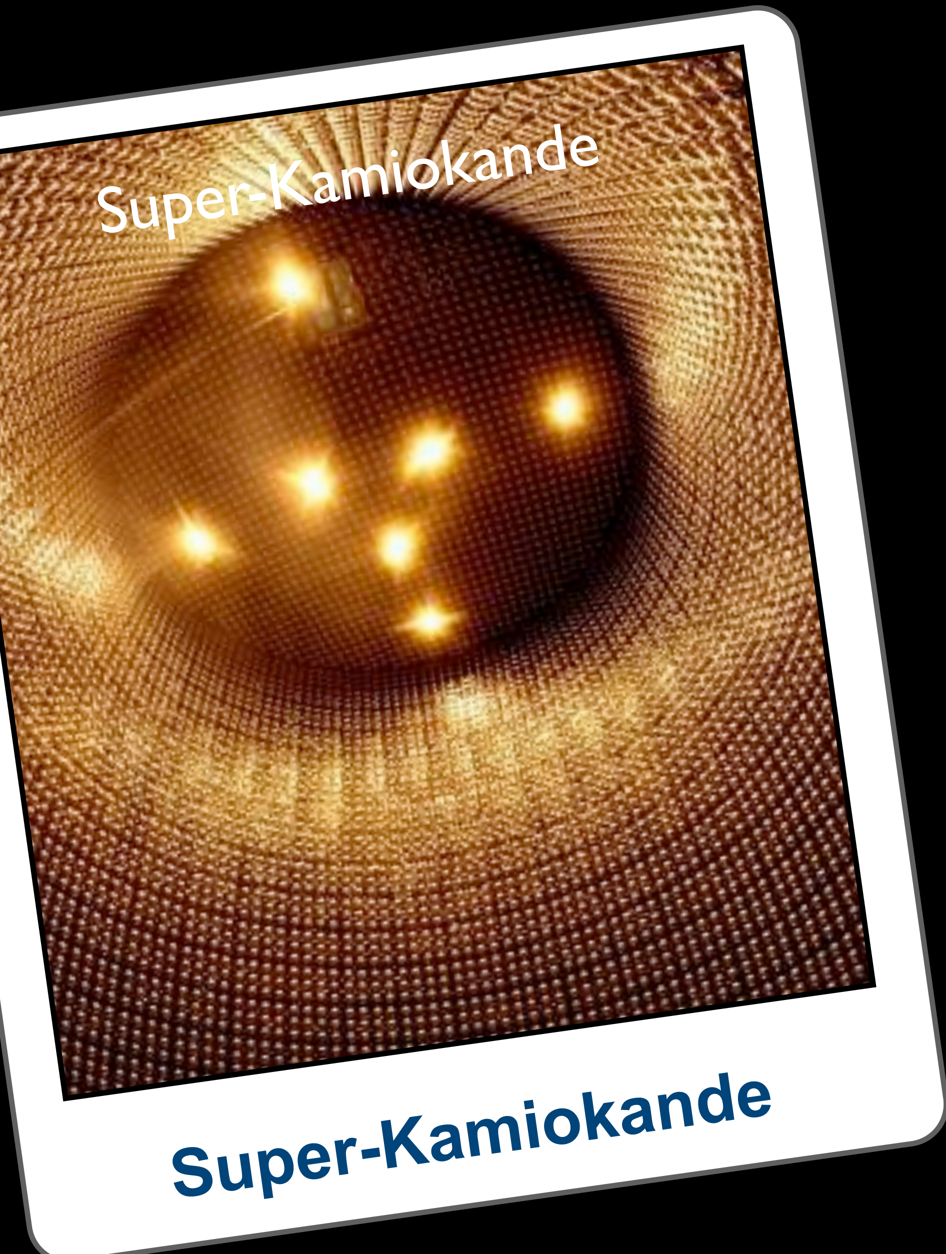
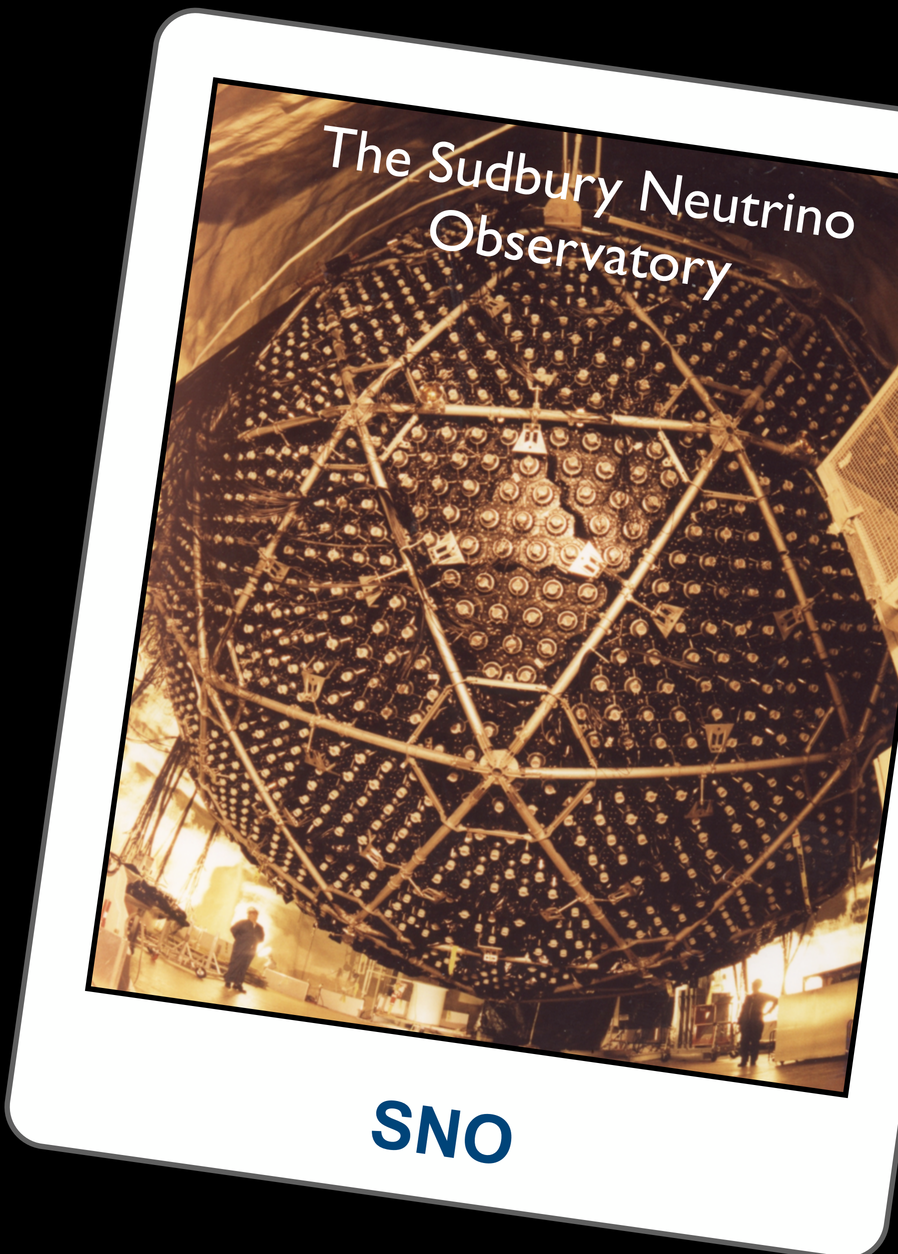
Direct Neutrino Mass Measurements

20th Lomonosov Conference

Joseph A. Formaggio
Massachusetts Institute of Technology

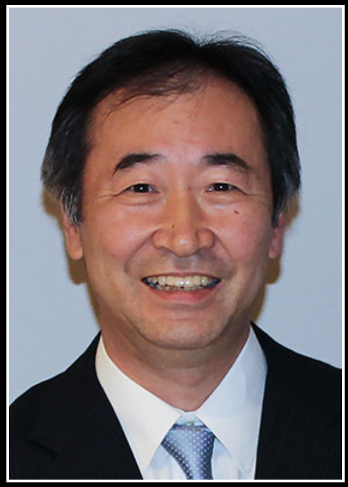




A myriad of experiments demonstrated that neutrinos transmute flavor (oscillations).

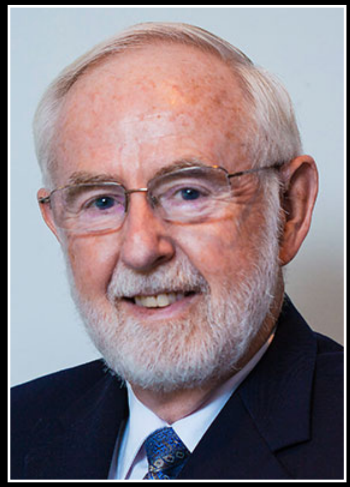
There are predictions that stem from alteration of the Standard Model.

However, oscillation experiments *cannot* reveal the neutrino mass scale.

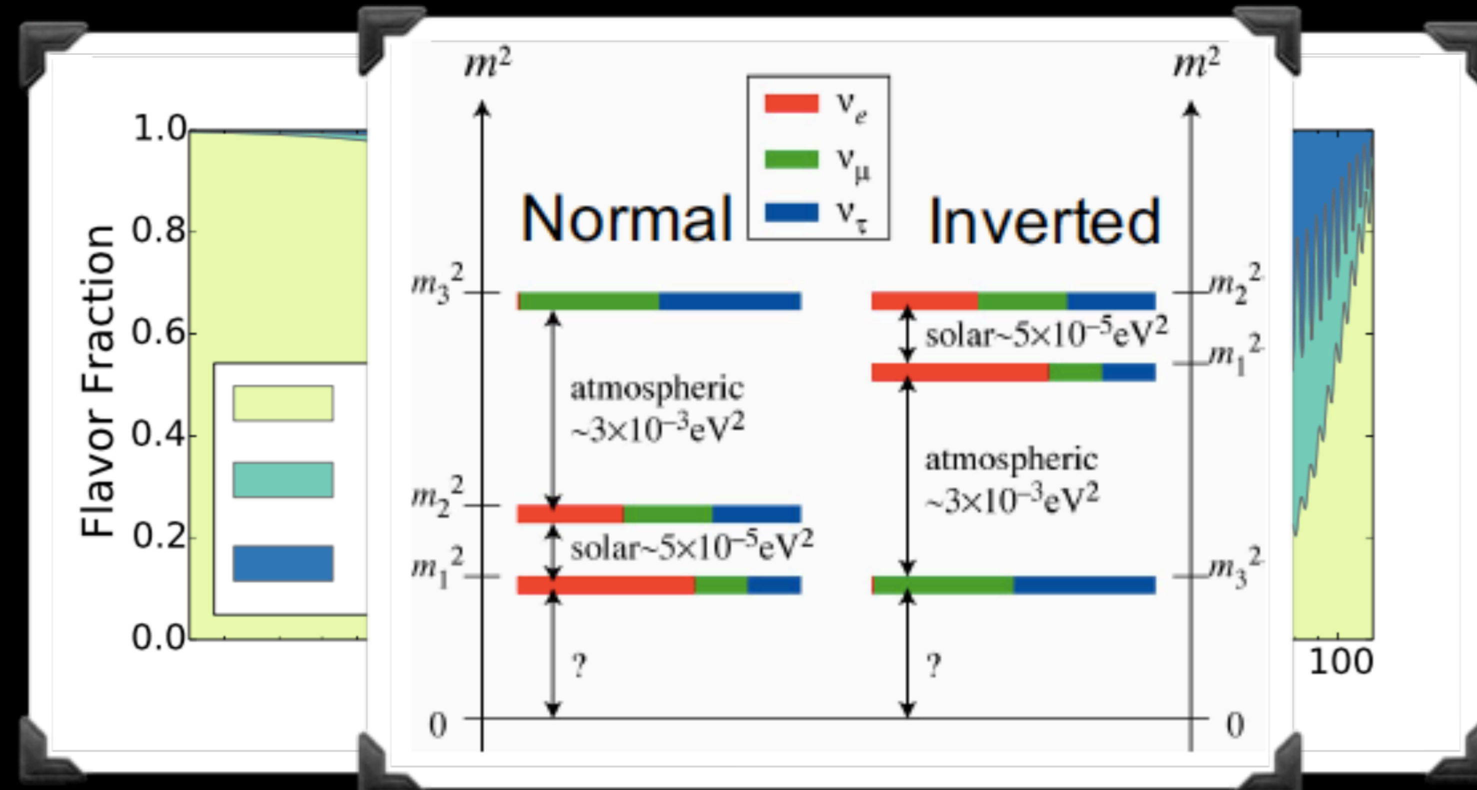


Takaaki Kajita
(Super-Kamiokande)

Arthur B. McDonald
(Sudbury Neutrino Observatory)



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



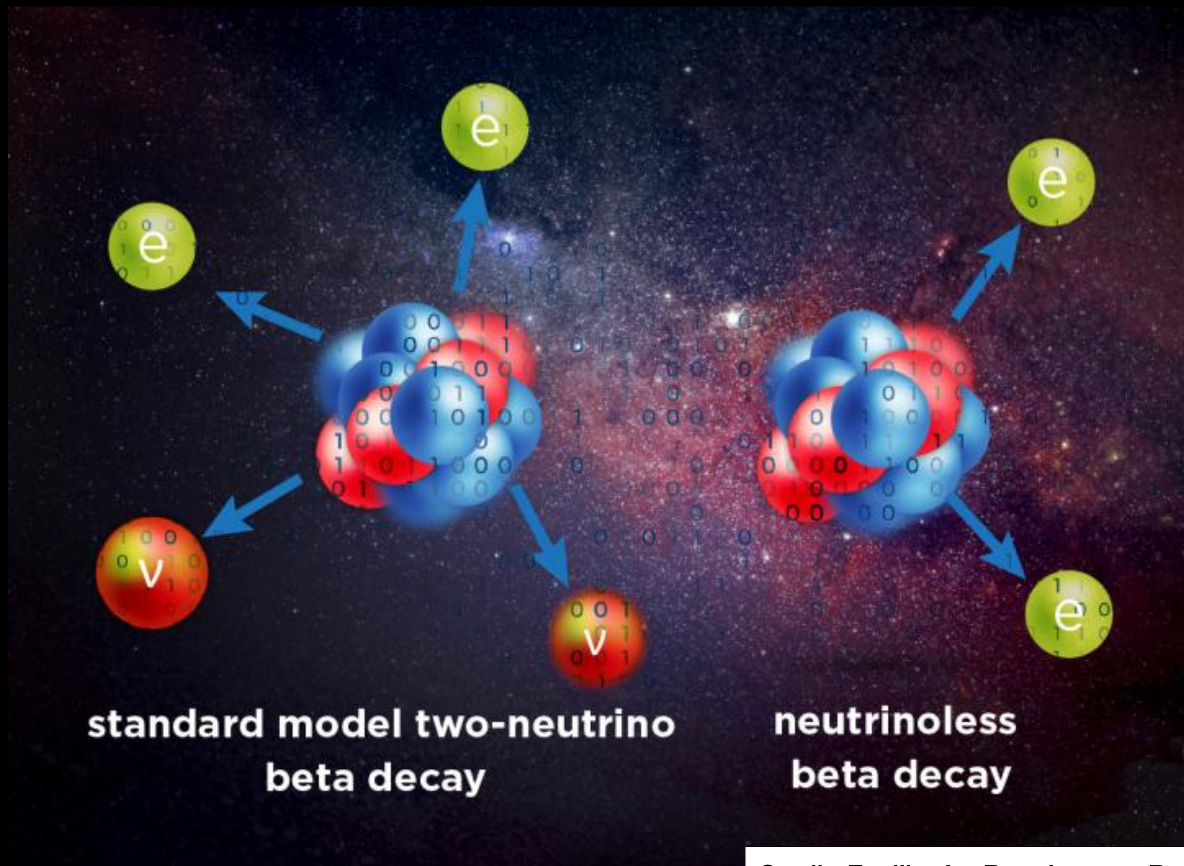
Nat. Commun. 6:6935 doi: 10.1038/ncomms7935 (2015)

Method	*Observable*
Neutrino Oscillations	$\Delta m^2_{ij} \equiv m_i^2 - m_j^2$
Neutrinoless double beta decay	$m_{\beta\beta} \equiv \sum_i (U_{ei})^2 m_i$
Cosmology	$\Sigma \equiv \sum_i m_i$

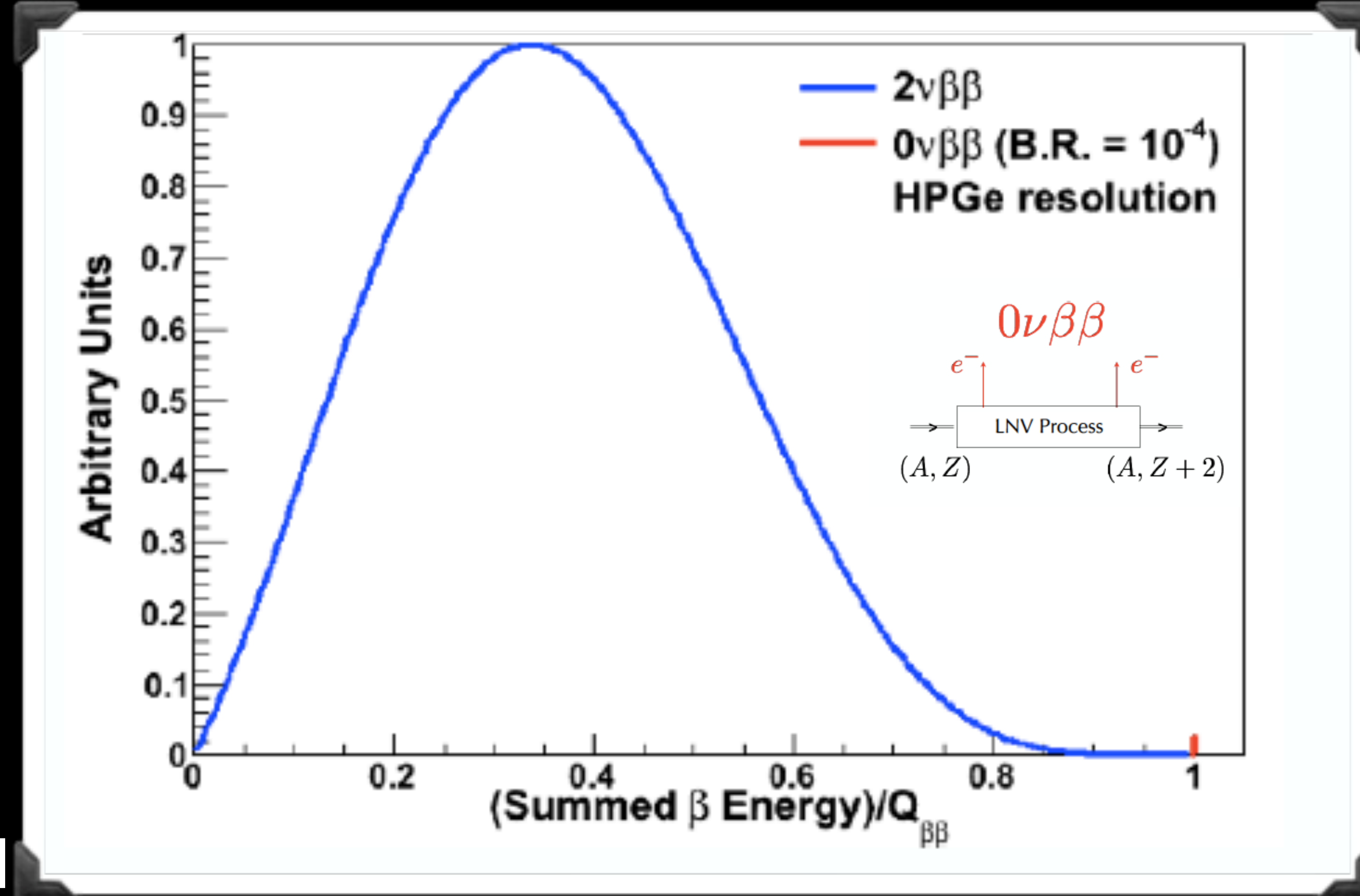
As mentioned, neutrino oscillations provide our most accurate measurement of neutrino masses, but are only sensitive to mass *differences*.

However, they simplify the problem: measuring one mass scale yields *all* the neutrino masses.

The ordering (IMO or NMO) can also be uncovered, if matter effects are at play.



Credit: Facility for Rare Isotope Beams



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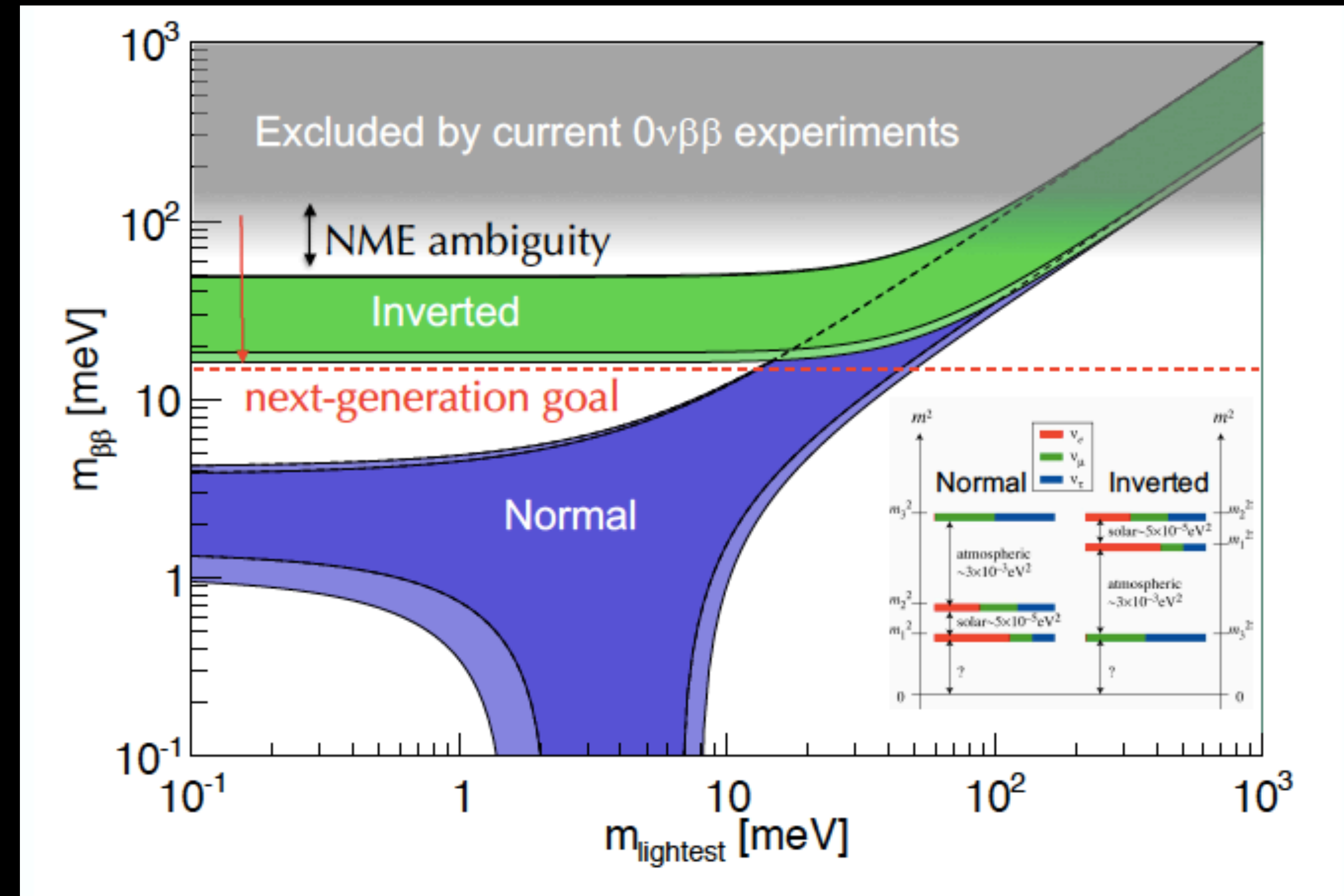
Cosmology	$\Sigma \equiv \sum_i m_i$

These are really our most powerful probes for lepton number conservation ($\Delta L = 2$).

If Majorana-neutrino exchange is the dominant contribution to 0νββ, the rate for 0νββ is a function of the neutrino masses.



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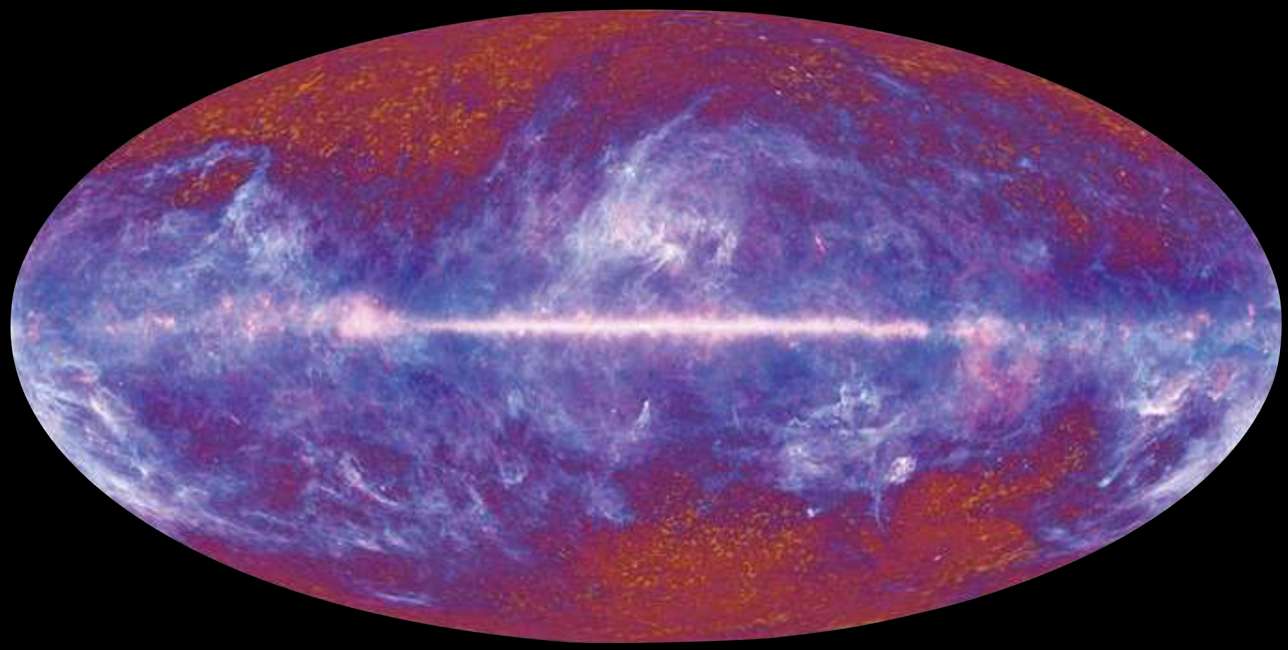
$$(Z, A) \rightarrow (Z+2, A) + e^- + e^-$$

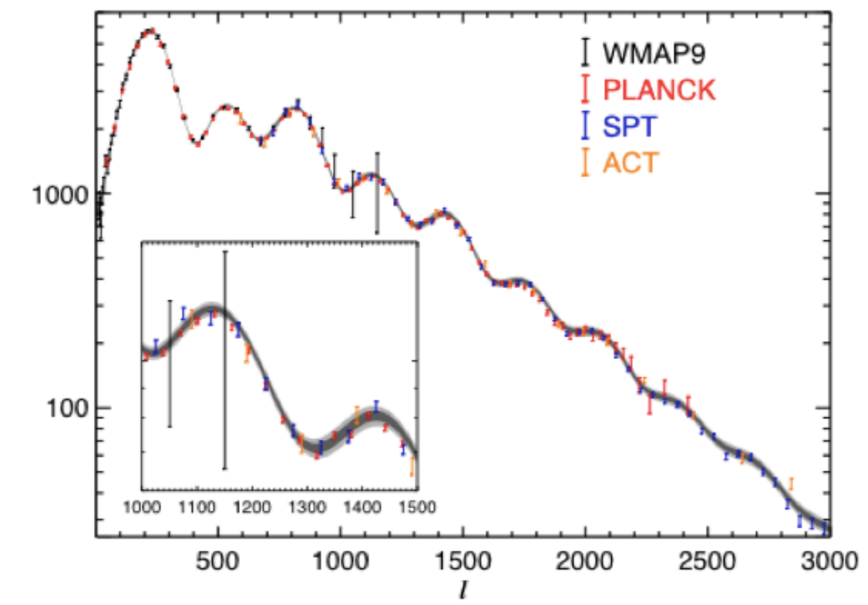
Large uncertainties in the determination of the matrix elements that govern the measured decay rate.

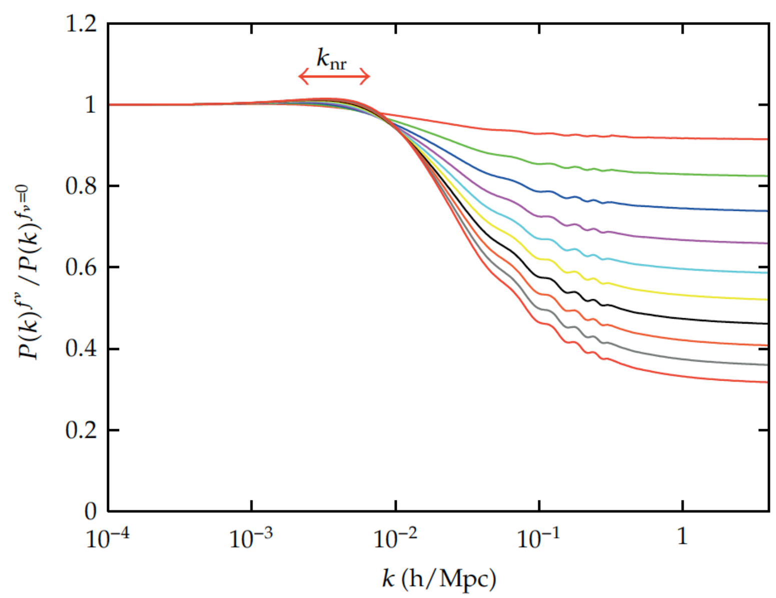
No guarantee that neutrino mechanism is dominant (or that neutrinos are Majorana particles).

Inverted ordering in reach for next generation of experiments.



PLANCK's image of the microwave sky





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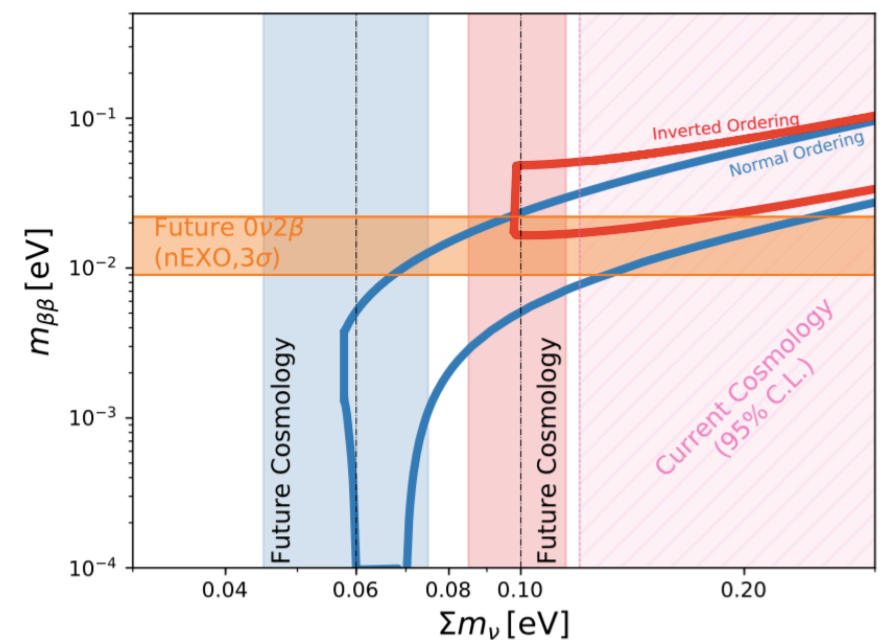
Neutrinos are also remnants of the Big Bang; their masses contributing to the matter density of the observable universe.

The neutrino energy density can be constrained by observations of the CMB, the distribution of clusters of galaxies, and the Lyman-alpha forest.

	Model	95% CL (eV)
CMB alone		
Pl18[TT+lowE]	ΛCDM+$\sum m_\nu$	< 0.54
Pl18[TT,TE,EE+lowE]	ΛCDM+$\sum m_\nu$	< 0.26
CMB + probes of background evolution		
Pl18[TT+lowE] + BAO	ΛCDM+$\sum m_\nu$	< 0.16
Pl18[TT,TE,EE+lowE] + BAO	ΛCDM+$\sum m_\nu$	< 0.13
Pl18[TT,TE,EE+lowE]+BAO	ΛCDM+$\sum m_\nu$+5 params.	< 0.515

Zyla *et al.* Prog Theor. Exp. Phys 083C01 (2020).



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Measured as part of a full fit to ΛCDM model. This introduces dependencies on other cosmological parameters.

Limits on the neutrino mass scale from cosmology are affected by model extensions (such as additional parameters) or new physics (neutrino self-interaction or dark matter interactions).

Current Limits ~ 0.2 eV

Projected Limits ~ 0.05 eV!!

All these methods indirectly access the neutrino mass scale (usually under some underlying model assumption).

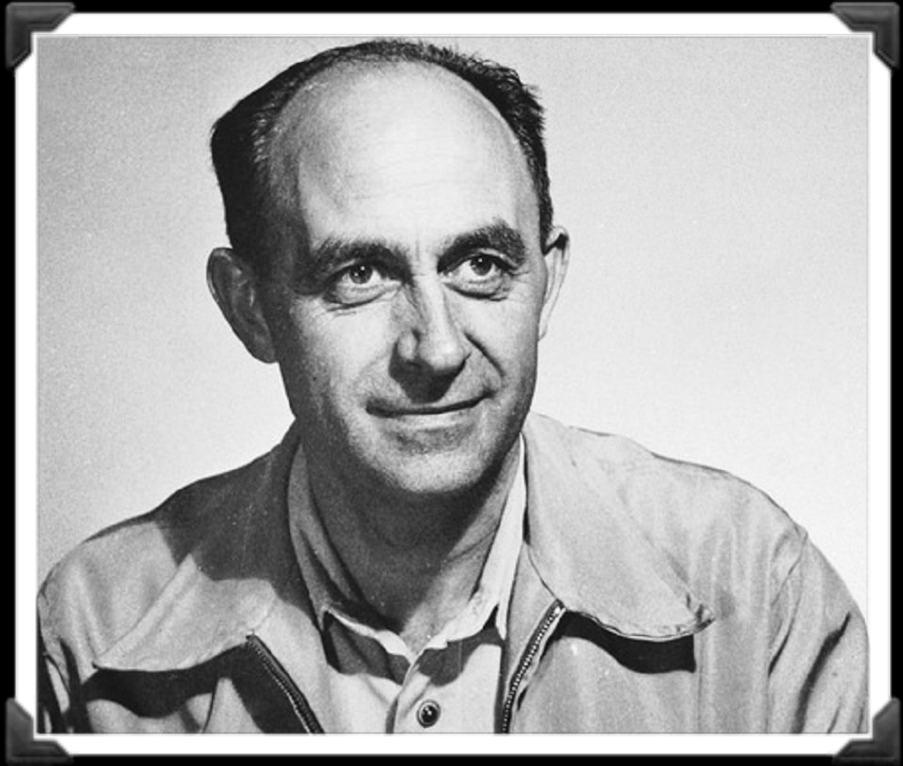
A direct method must rely on kinematics to determine the neutrino mass.

First suggested by Francis Perrin in 1933

"On peut essayer de d́eduire de la forme des spectres continus d́ 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 indipen…

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

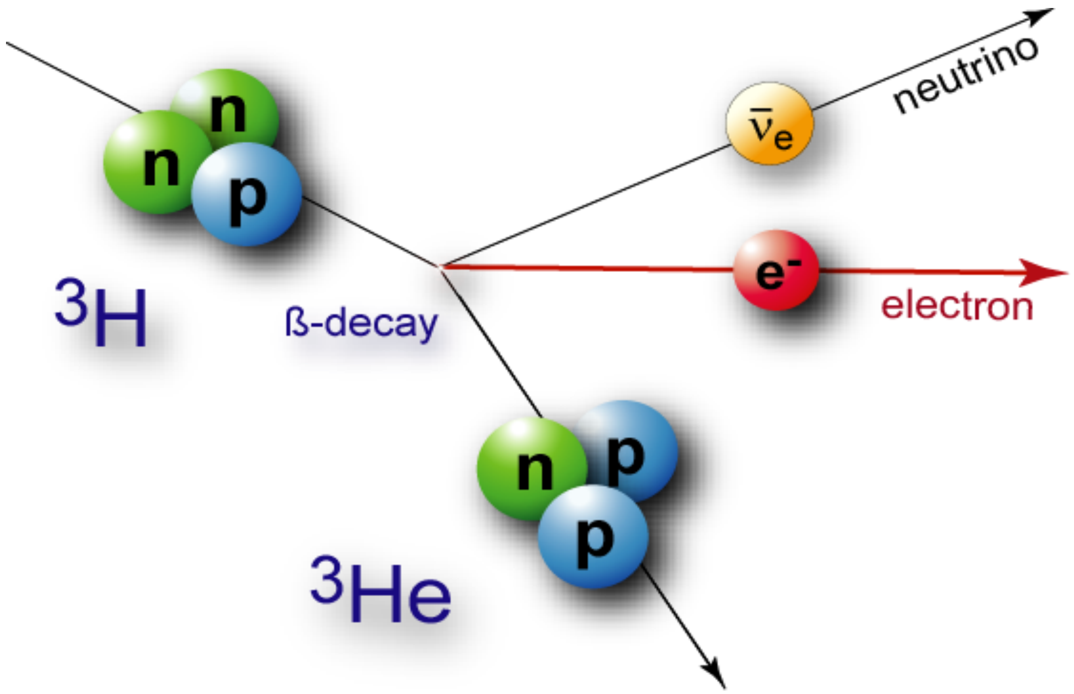
fine della curva di distribuzione è rappresentata per $\mu = 0$,

iccolo e uno grande di μ. La maggiore somiglianza con le

Fig. 1.

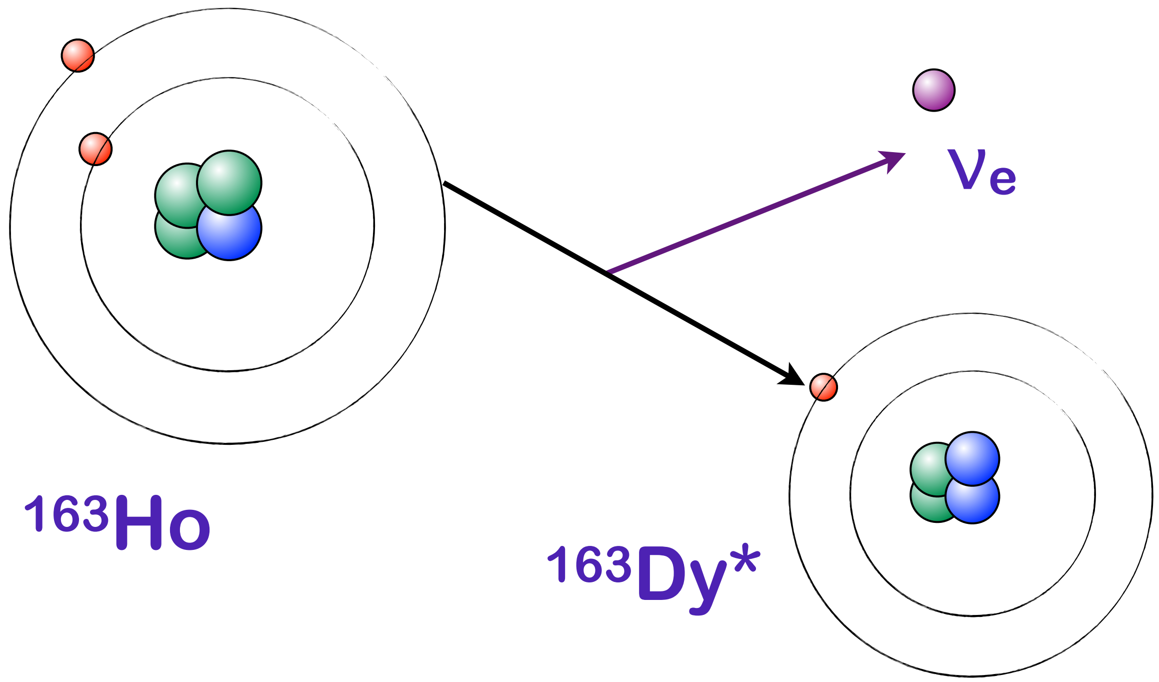
In his paper, Fermi already sketches out how one can use the weak decay to explore the neutrino mass scale.

Tritium beta decay



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

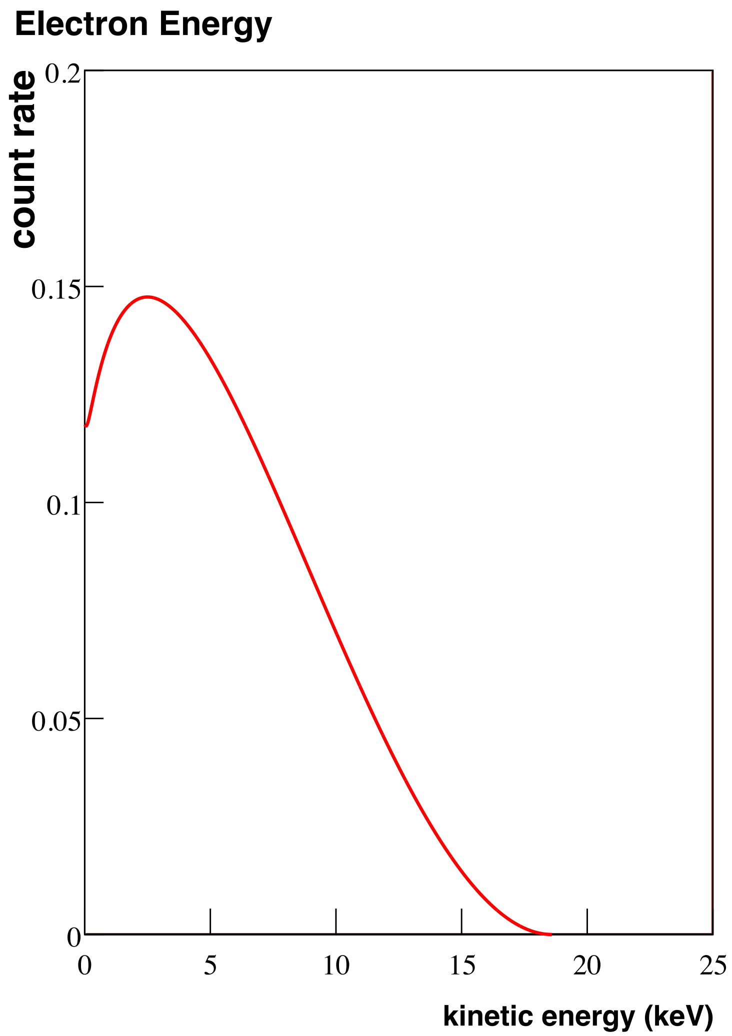
Holmium electron capture



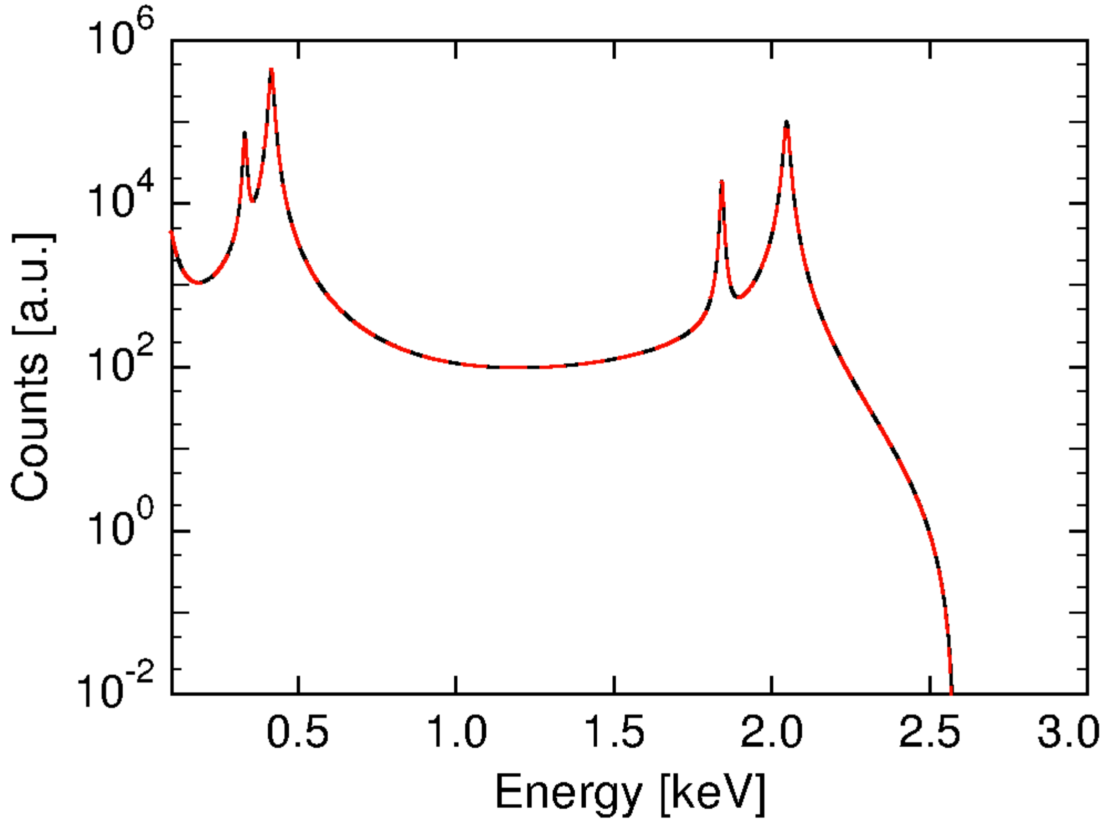
$$^{163}\mathrm{Ho} + e^- \rightarrow {}^{163}\mathrm{Dy}^* + \nu_e$$

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

Tritium beta decay



Holmium electron capture



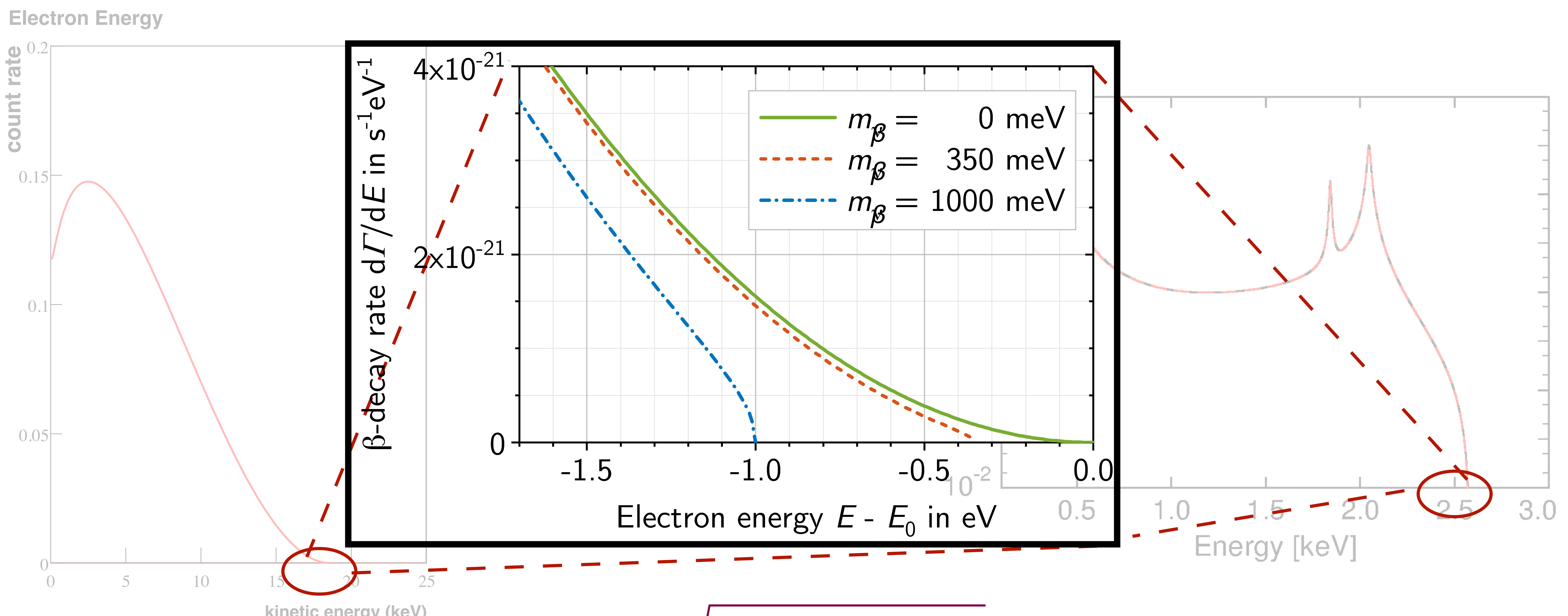
In both cases, differential spectrum depends on the neutrino momentum.

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

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

Tritium beta decay

Holmium electron capture

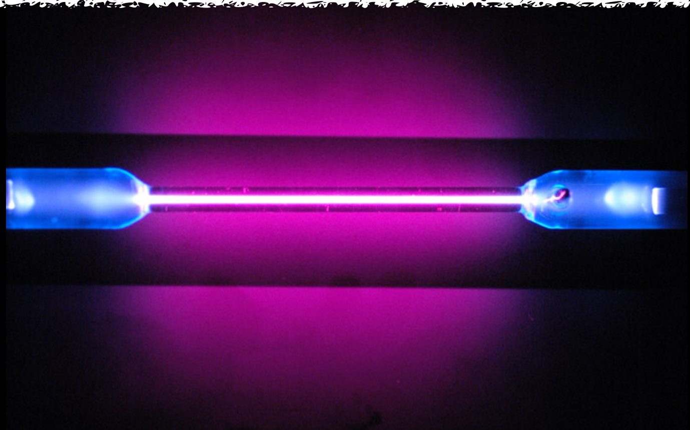


$$m_\beta = \sqrt{\sum_i |U_{ei}|^2 m_i^2}$$

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

The neutrino mass effect is most pronounced at the end of the beta or electron capture portion of the decay spectrum.

First,
pick a source...



$^{3}H_2$

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

$\tau_{1/2}$ $4.4\text{x}10^{14}$ yrs

^{135}Cs

440 eV

$\tau_{1/2}$ $1.5\text{x}10^{6}$ yrs

Isotope	Spin-Parity	Half-life y	Specific Activity Bq/g	Q_A eV	Branching ratio	Last eV	Source Mass 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		$\sim 10^{-12}$	$\sim 1.0 \times 10^{-5}$

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.

Issues with ^{187}Re make it impractical.

That mainly leaves tritium and holmium.

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)

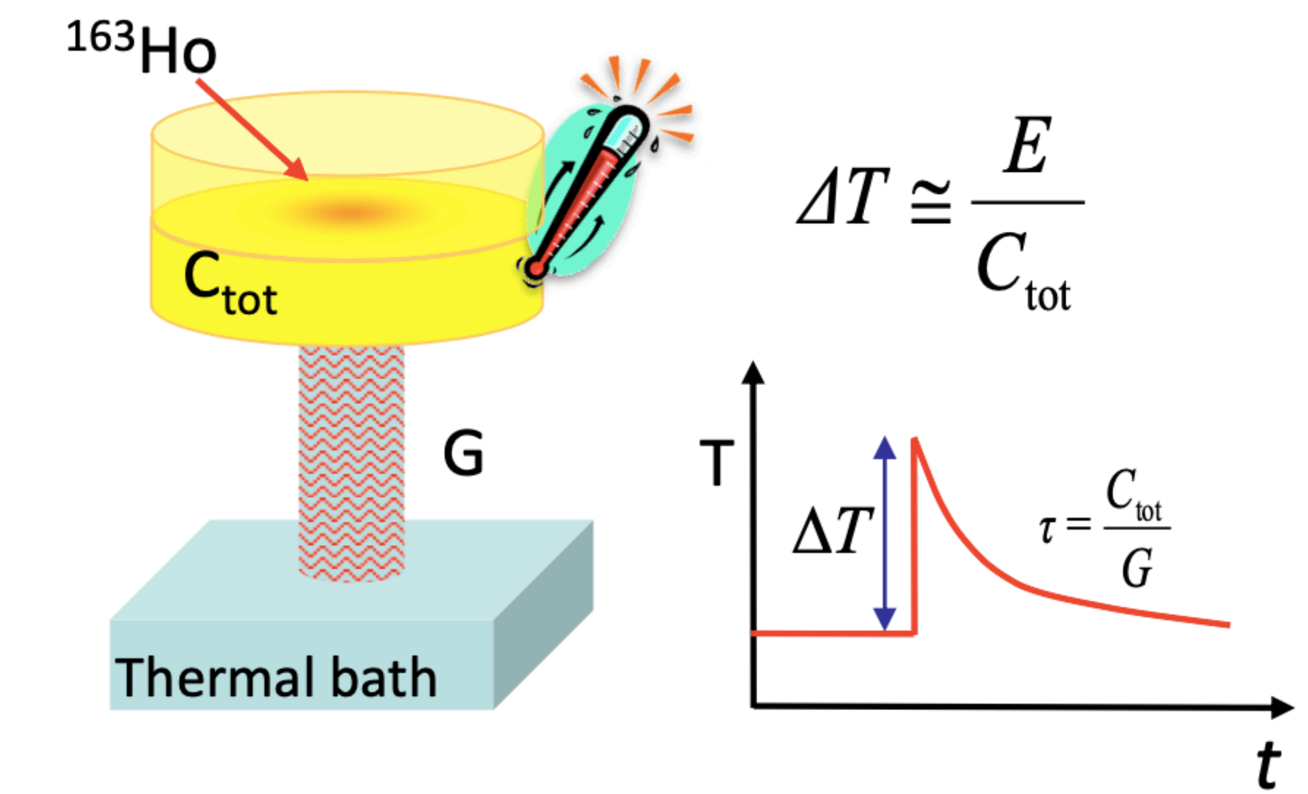
Electron transfers all of its energy to the absorbing medium.

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

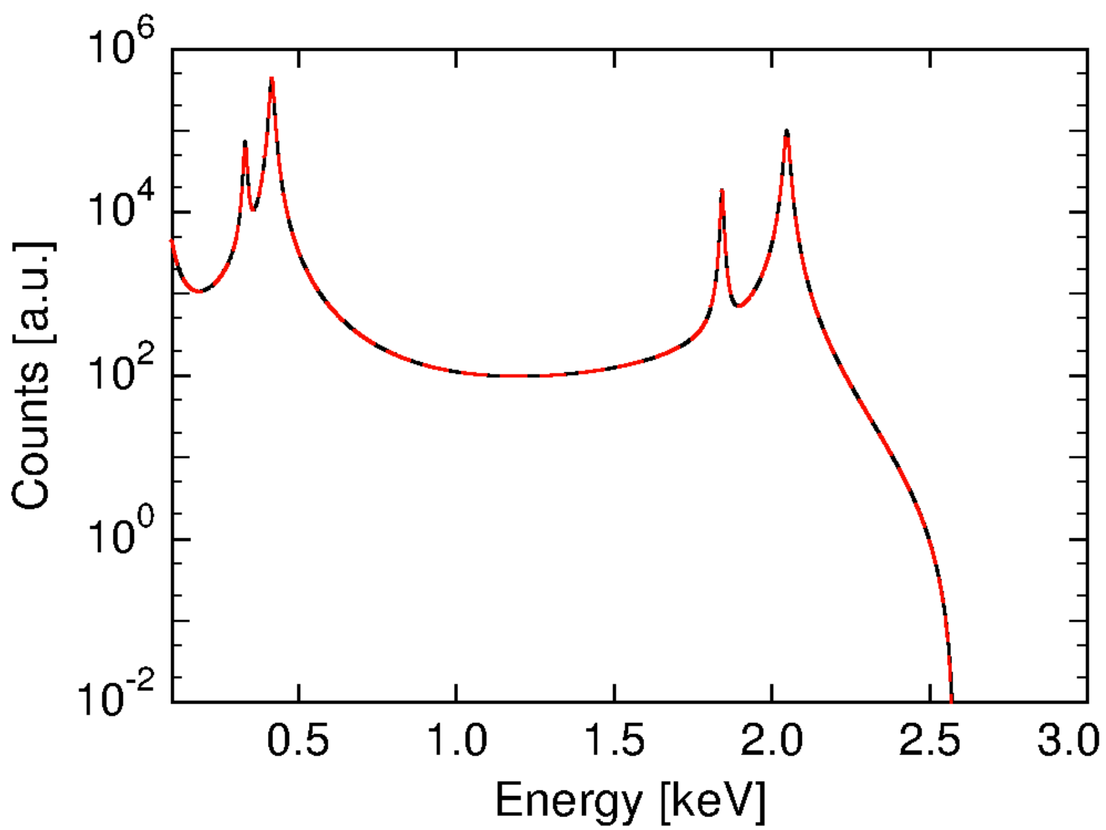
Highly sensitive thermal detectors

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

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.

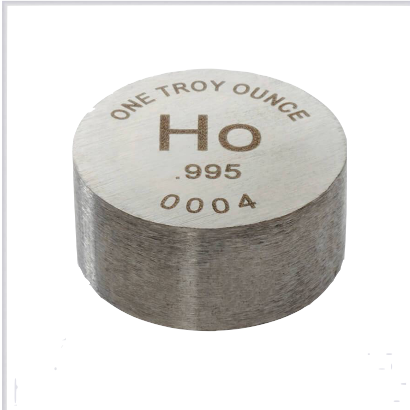


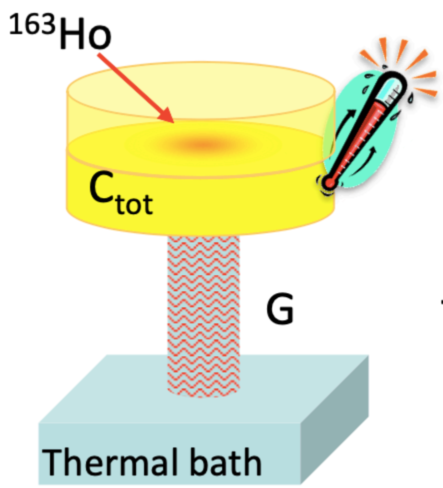
$$\frac{d\lambda_{\mathrm{EC}}}{dE_c} = \frac{G_F^2 |V_{ud}|^2}{2\pi^3}(Q - E_c) \times \sum_j \beta_j^2 C_j \, |M_{j0}|^2 \, \frac{\Gamma_j}{4(E_c - E_j)^2 + {\Gamma_j}^2} \times \boxed{\sum_i |U_{ei}|^2 \left[(Q - E_c)^2 - m_i^2\right]^{1/2}}$$

Neutrino phase space term

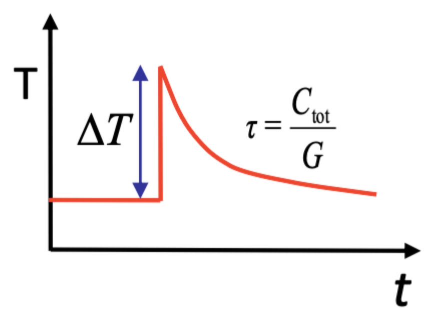
This opened up the possibility of using ^{163}Ho as a source for calorimetric detectors.

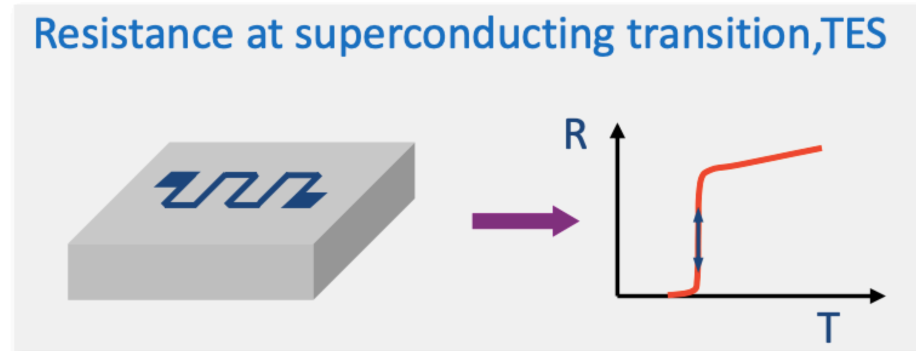
Modern Calorimetric Experiments





$$\Delta T \cong \frac{E}{C_{tot}}$$



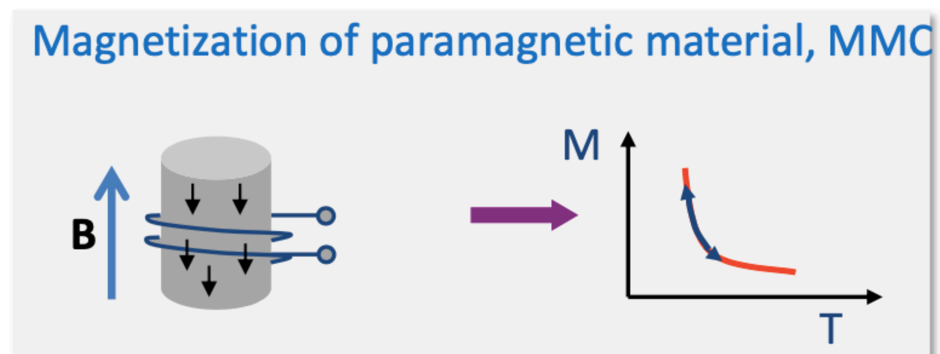


HOLMES

NuMECS

Detector arrays produced at NIST (Boulder US)

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



ECHo

Detector arrays produced at KIP, Heidelberg University

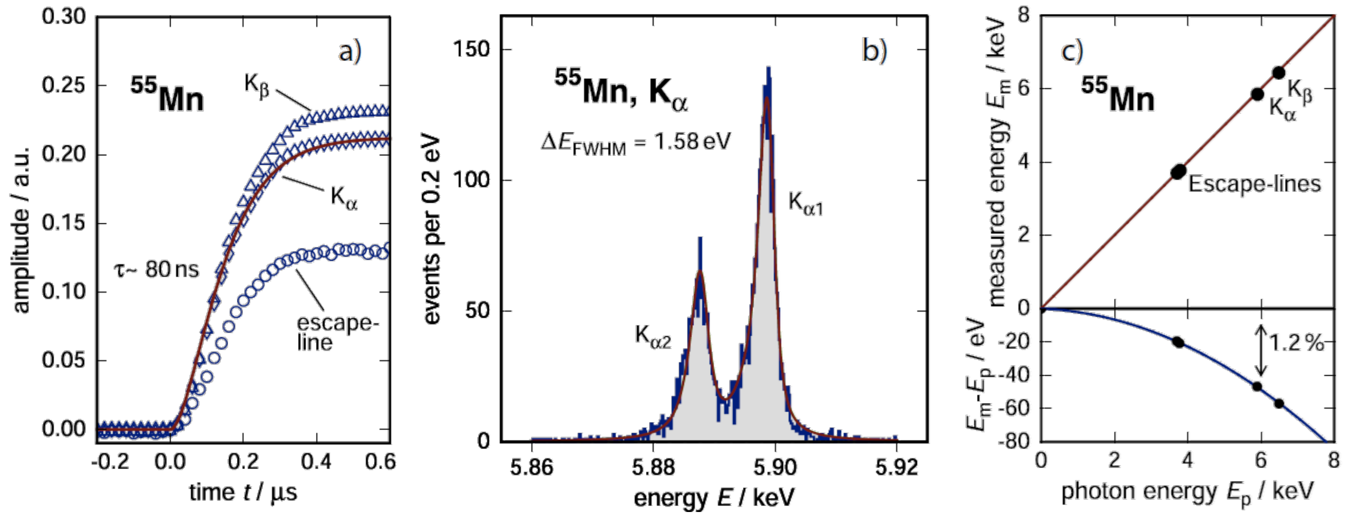
A.Fleischmann, C. Enss and G. M. Seidel, Topics in Applied Physics 99 (2005) 63

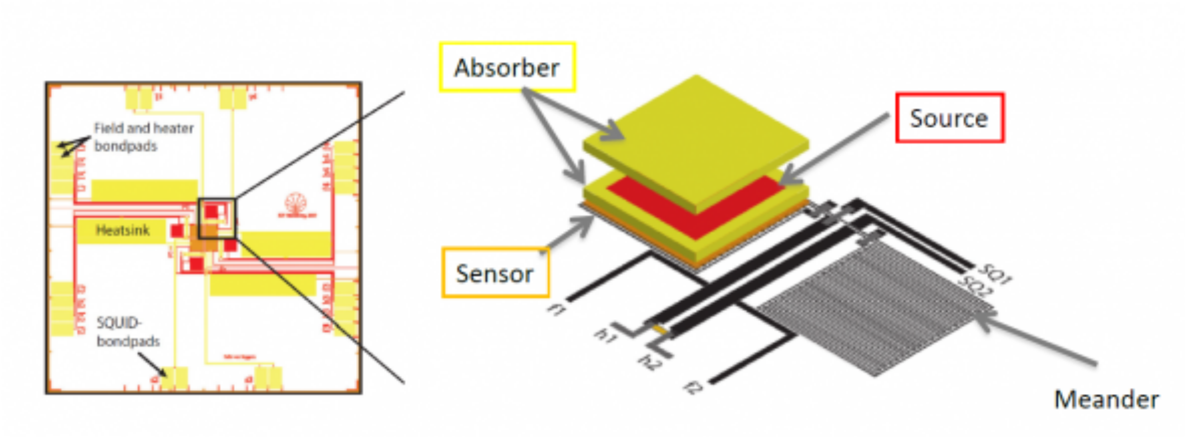
Micro calorimeters which are sensitive to changes in temperature (energy deposition).

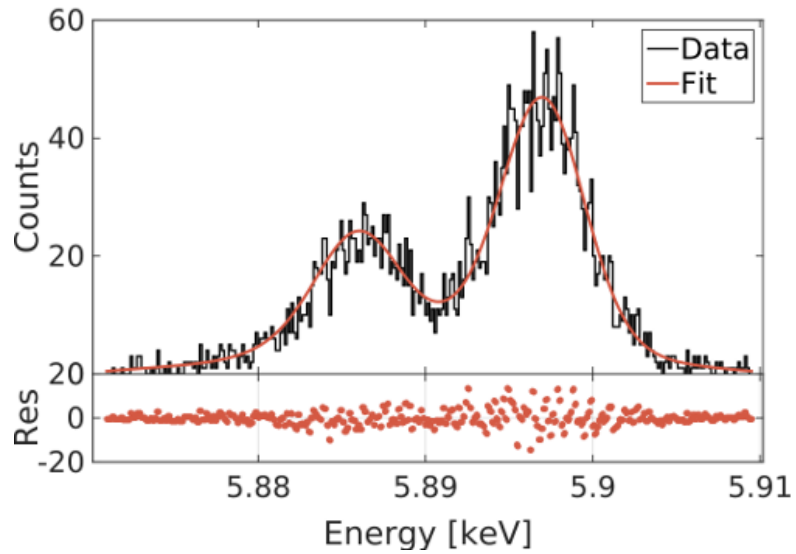
Contain the full decay energy.

Modern Calorimetric Experiments

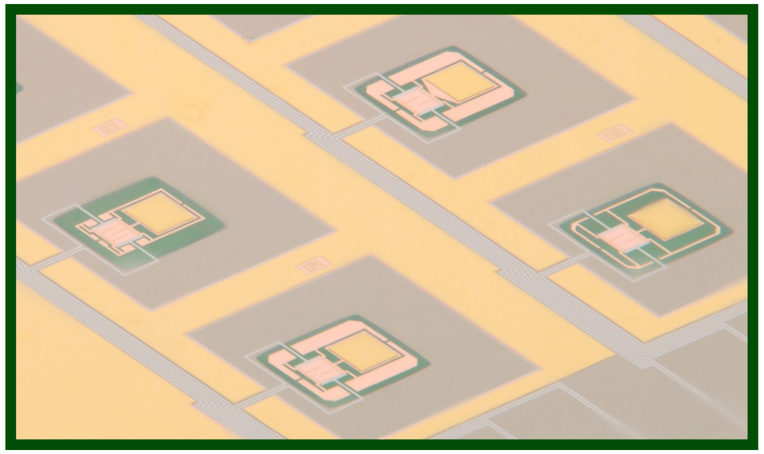
MMC response (ECHO)







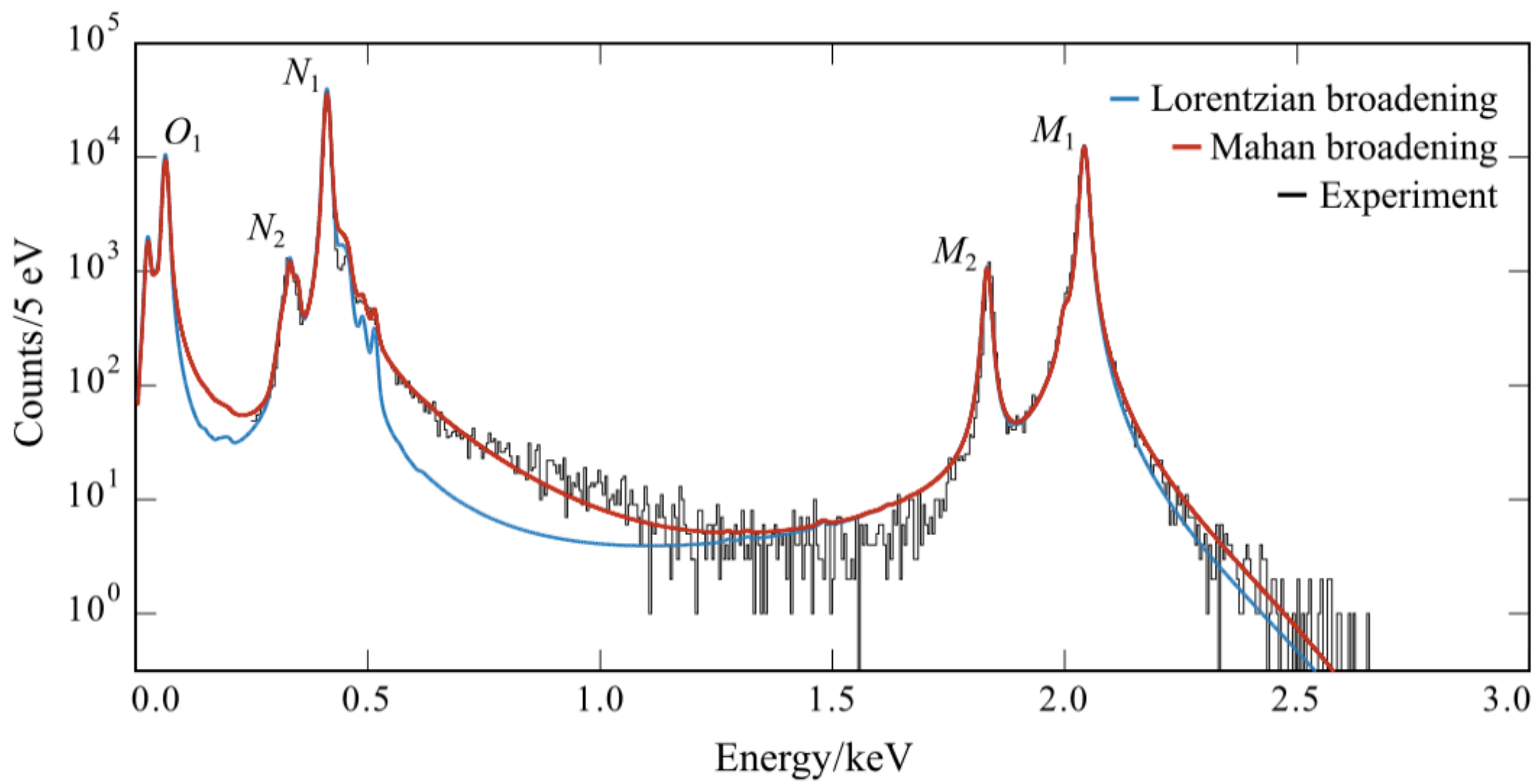
TES Resolution (HOLMES)

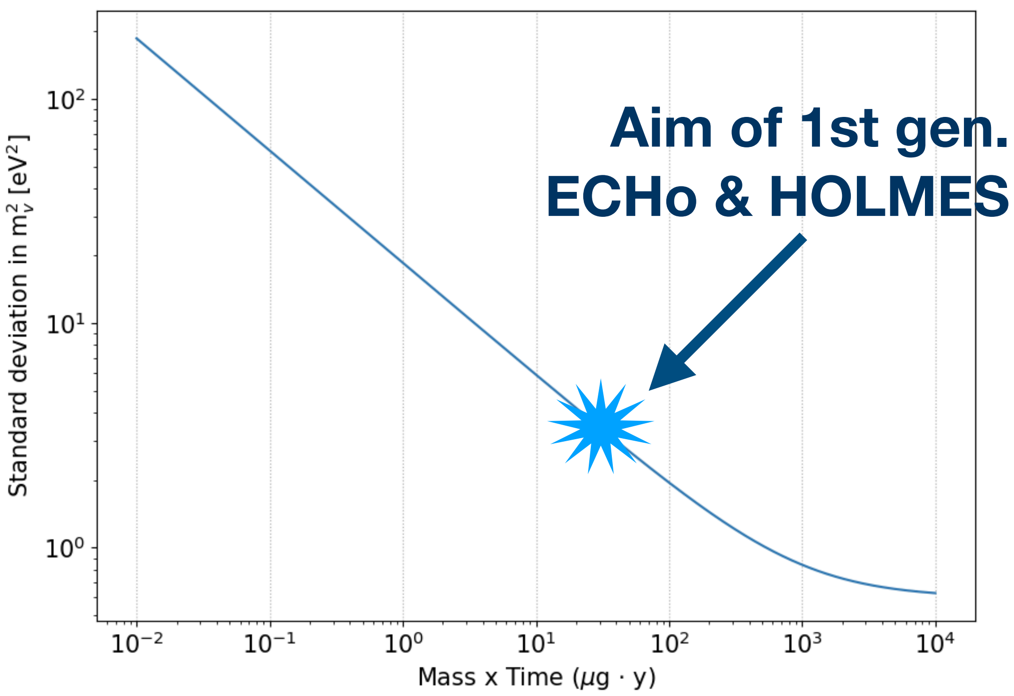


^{163}Ho is implanted onto gold absorbers and cooled to cryogenic temperatures for energy readout.

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

Modern Calorimetric Experiments





See L. Gastaldo's talk (Friday)

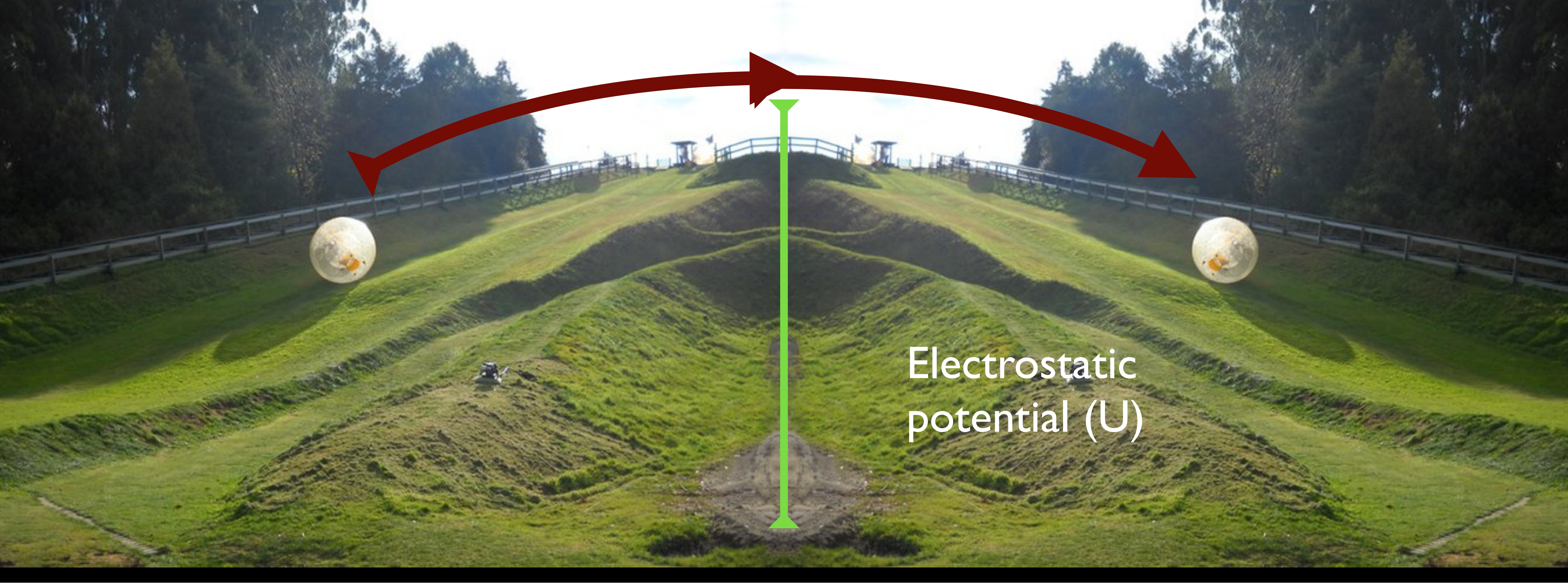
Upcoming generation of ECHo & HOLMES aim at the eV neutrino mass scale.

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

Electromagnetic filtering of electrons of selected energy.

Electromagnetic Collimation

(MAC-E Filter)



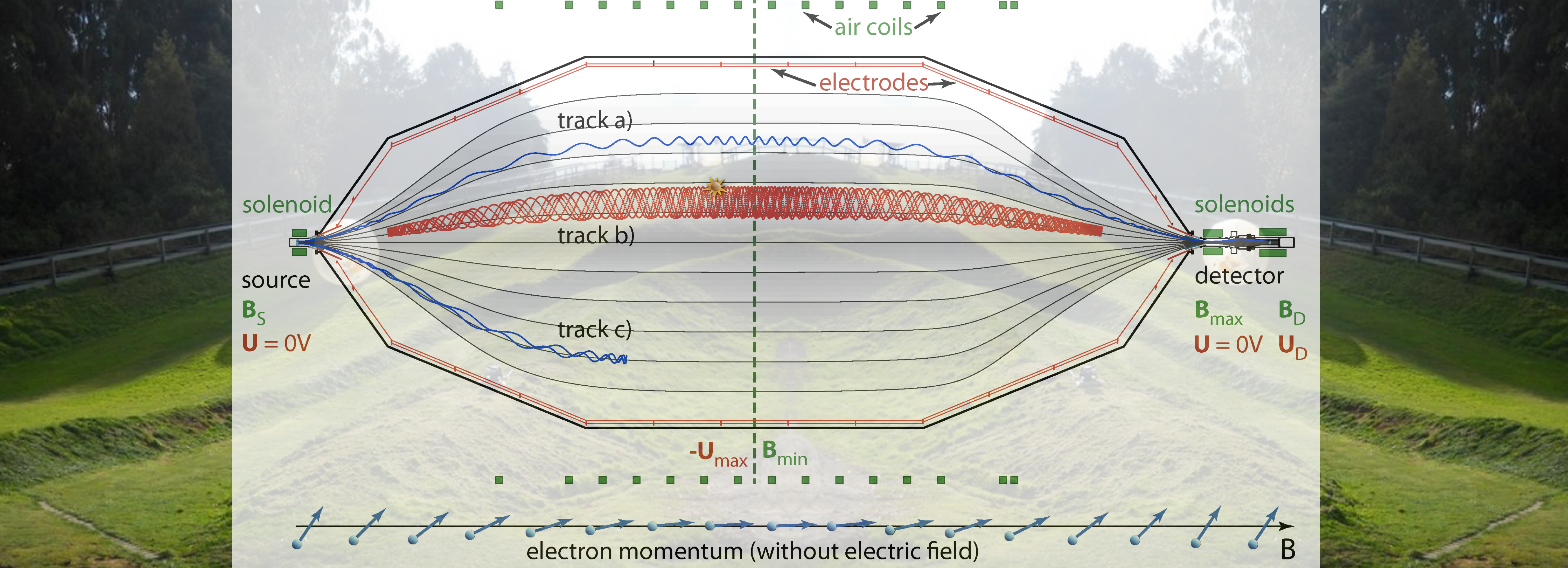
High Magnetic Field (Bs)

Low Field
B_A

High Magnetic Field (Bs)

Magnetic Adiabatic Collimation
with
Electrostatic Filtering

(only electrons with enough energy can overcome potential barrier)

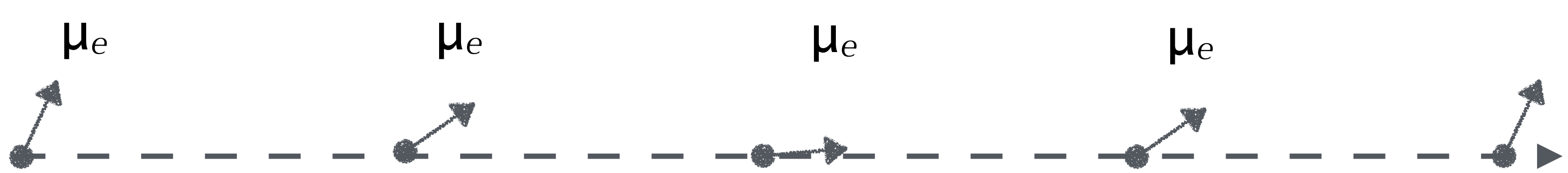


High Magnetic Field (Bs)

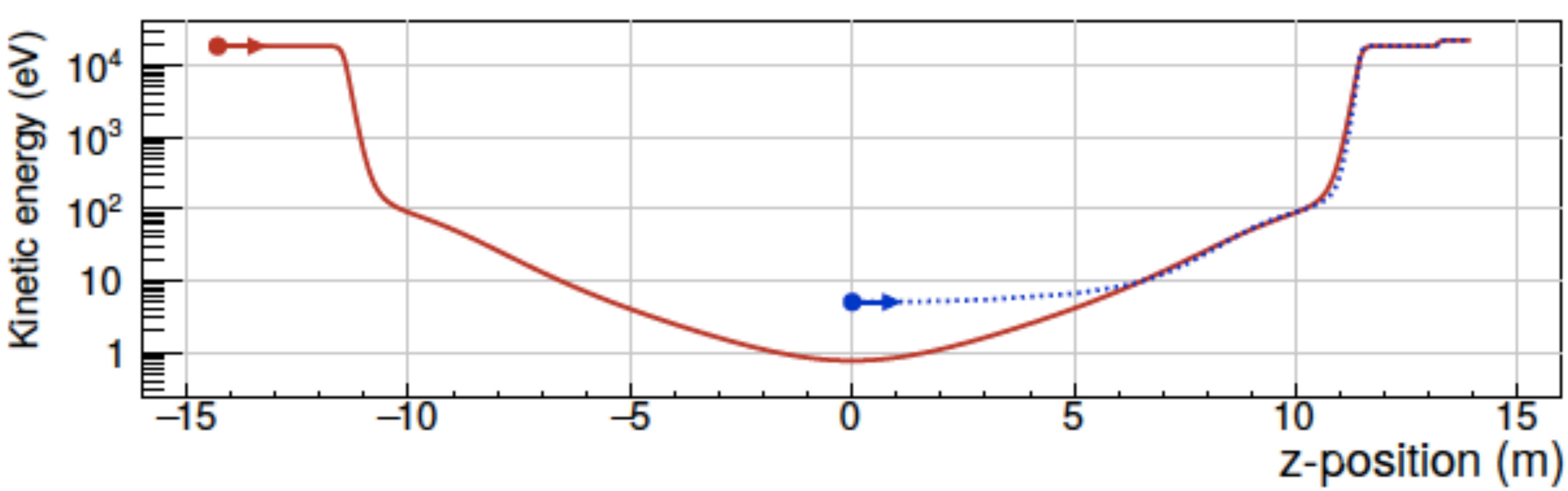
Low Field B_A

High Magnetic Field (Bs)

10^{11} e- / second



1 e- / second

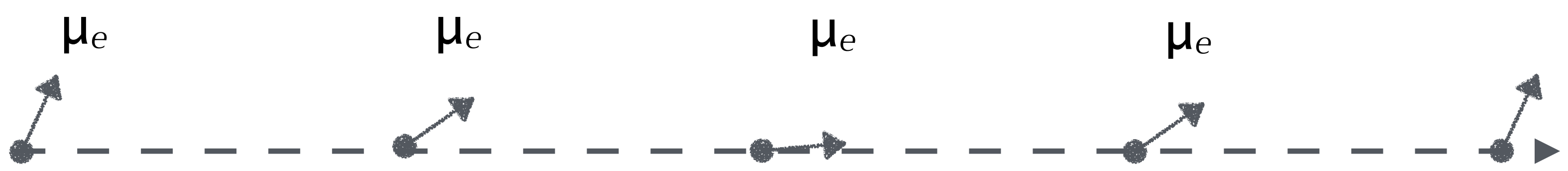


High Magnetic Field (Bs)

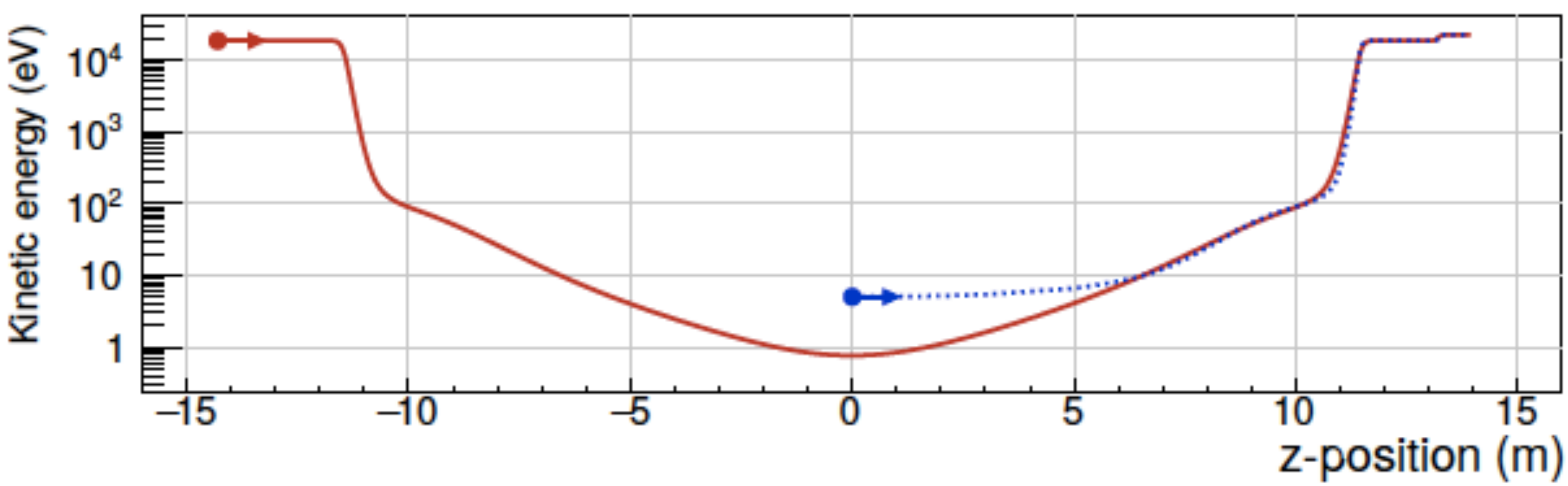
Low Field B_A

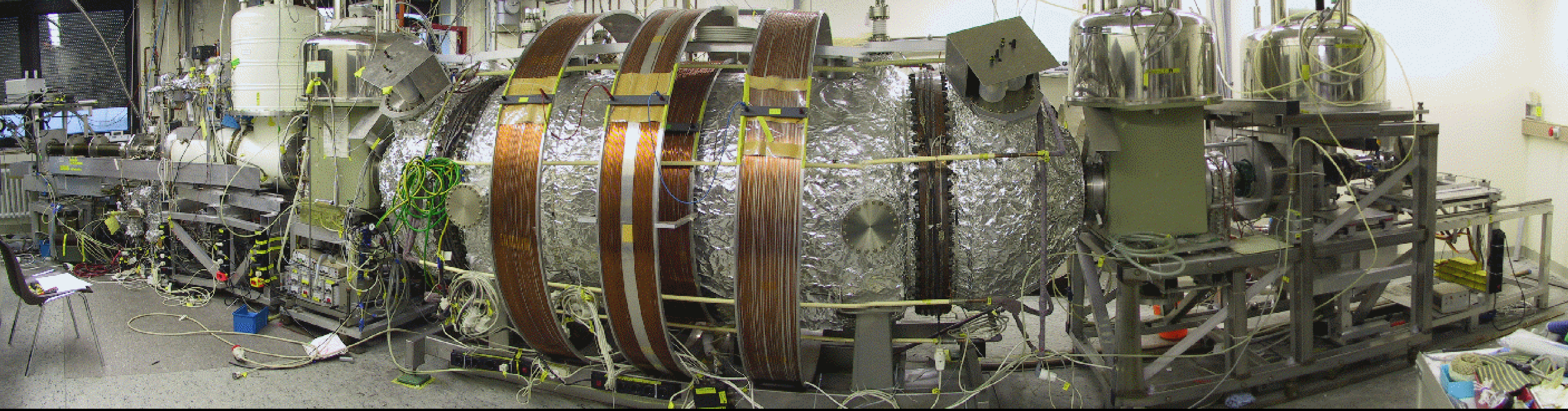
High Magnetic Field (Bs)

10^{11} e- / second

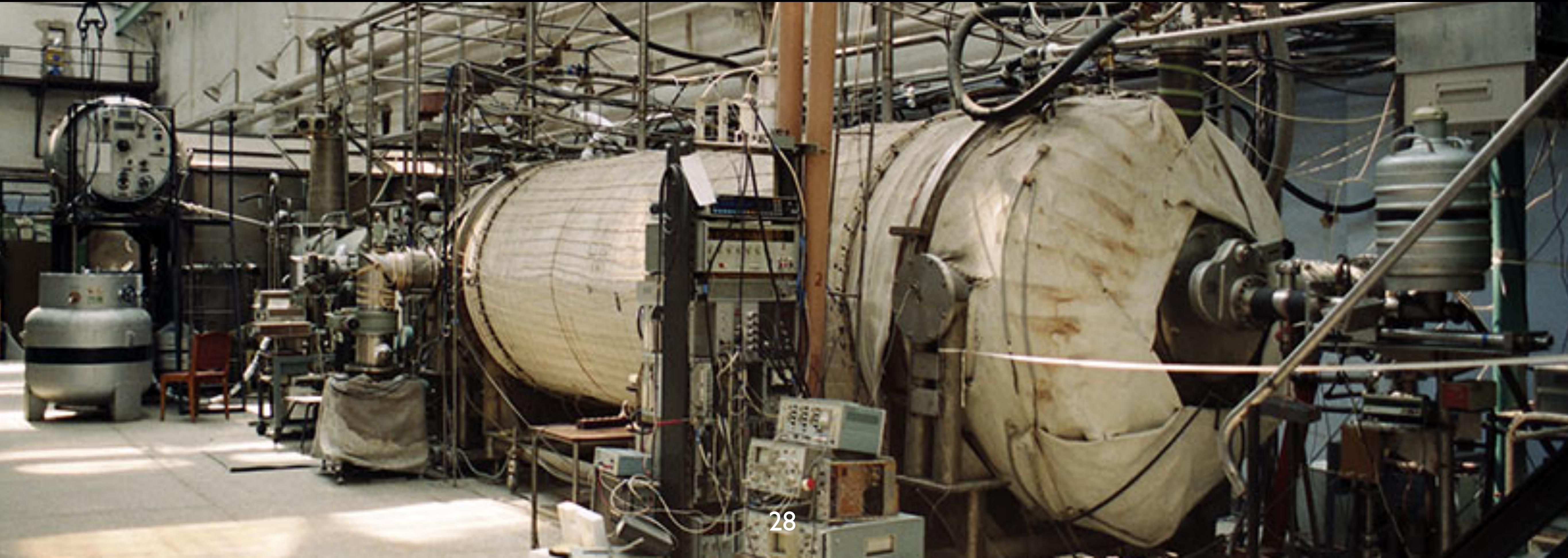


1 e- / second

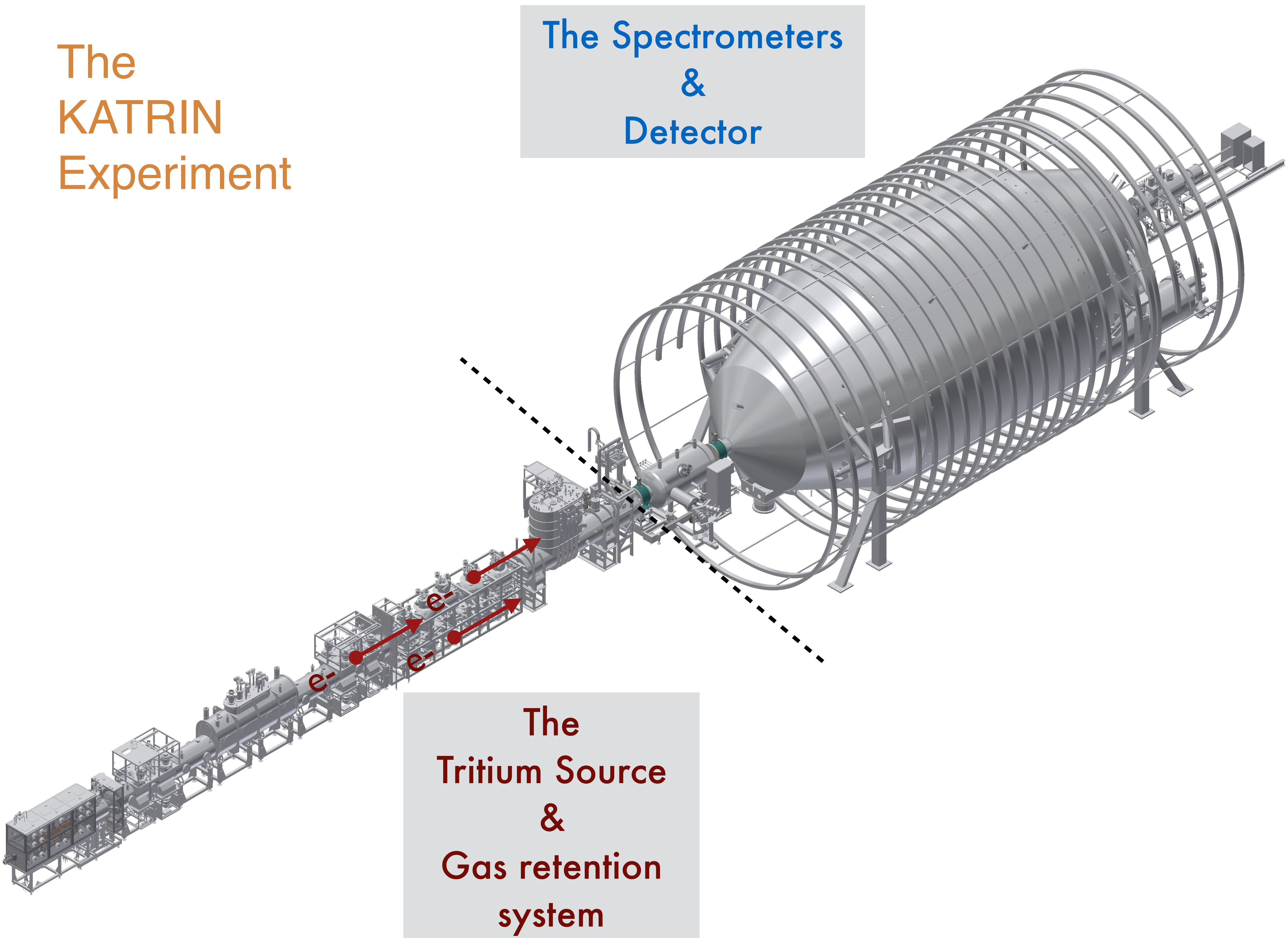




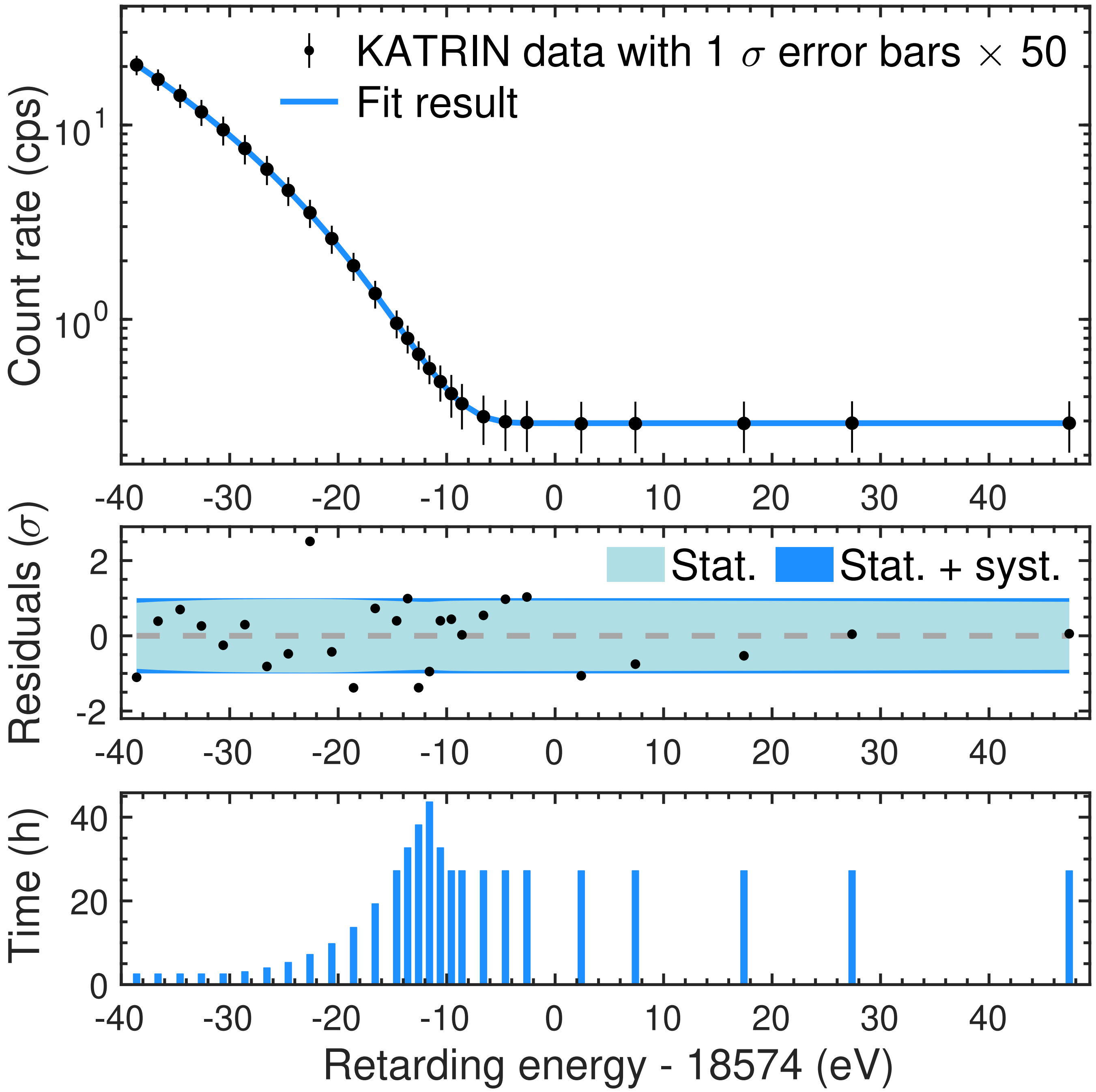
Predecessors: Mainz & Troitsk (Limit $m_\beta < 2$ eV)



The KATRIN Experiment



KATRIN's 1st Results++

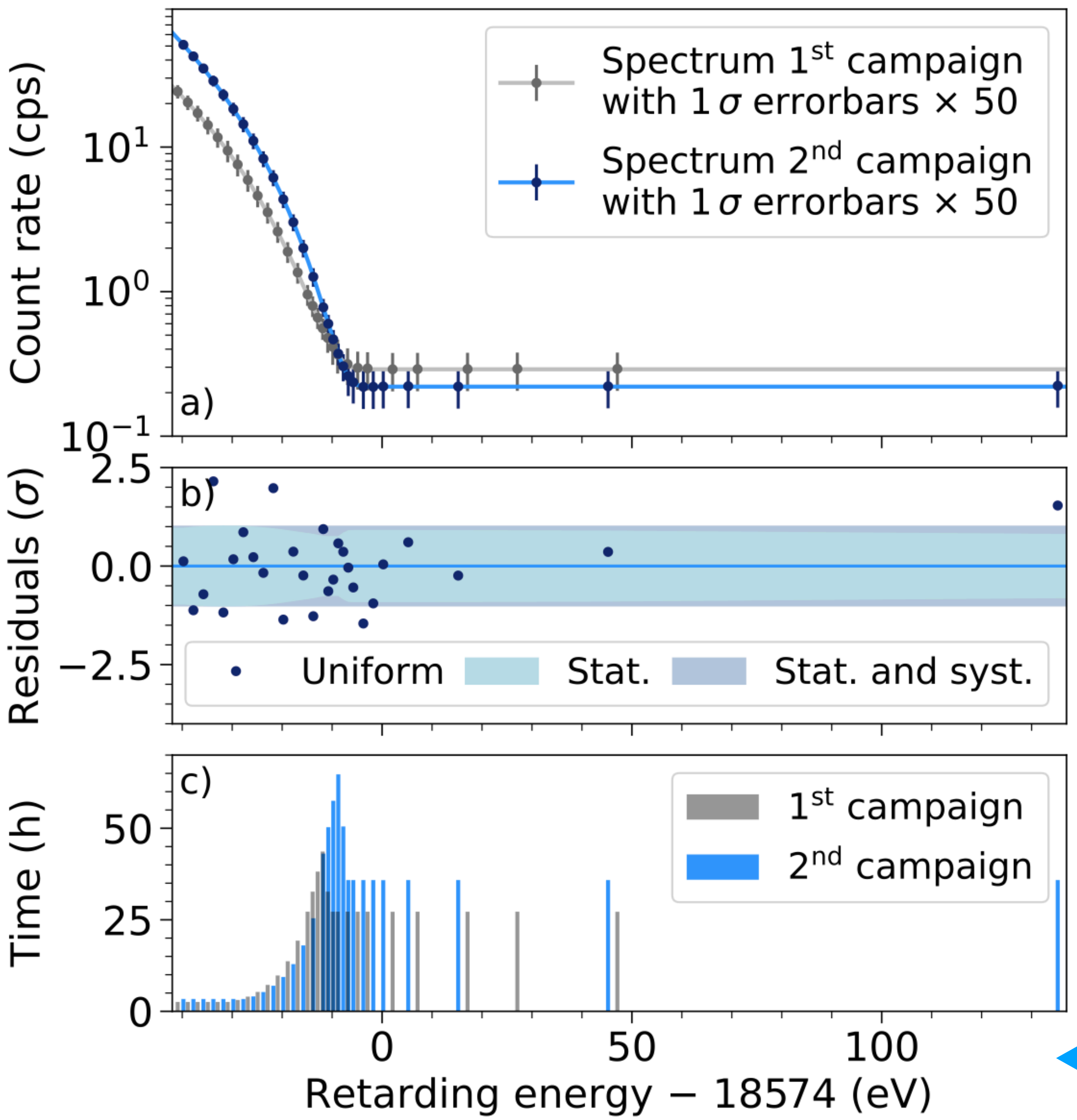


Results from first measurement campaign yielded an eV scale limit

$$m_\beta \leq 1.1 \text{ eV } (90\% \text{ C.L.})$$

Phys.Rev.D 104 (2021) 1, 012005

KATRIN's 2nd Results



Results from first measurement campaign yielded an eV scale limit

$$m_\beta \leq 1.1 \text{ eV } (90\% \text{ C.L.})$$

Phys.Rev.D 104 (2021) 1, 012005

Recently, a statistically improved limit was also released…

$$m_\beta \leq 0.8 \text{ eV } (90\% \text{ C.L.})$$

e-Print: 2105.08533 [hep-ex]

See A. Lokhov's talk (Friday)

KATRIN Outlook

KATRIN continues to collect data.

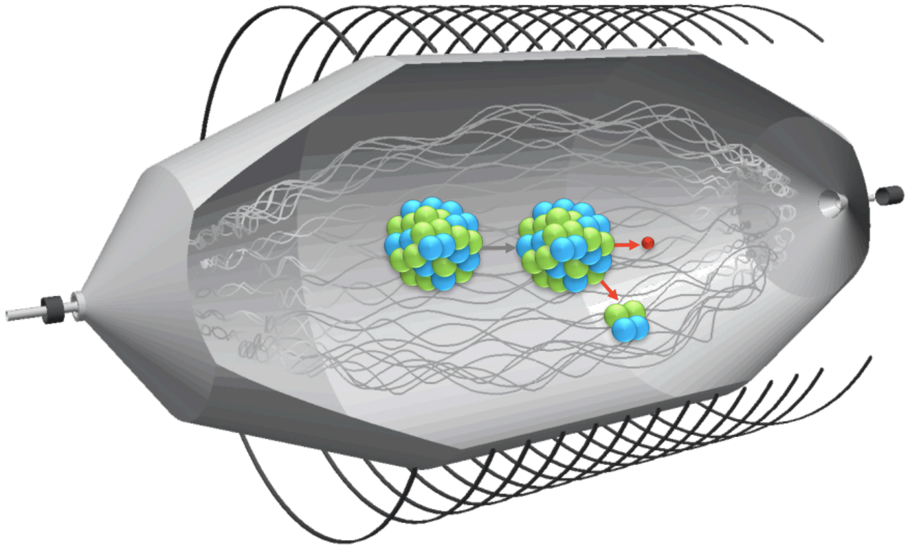
Comprehensive campaign to reduce and mitigate backgrounds, including radon and Rydberg events.

Better measurement/control of plasma instabilities in source.

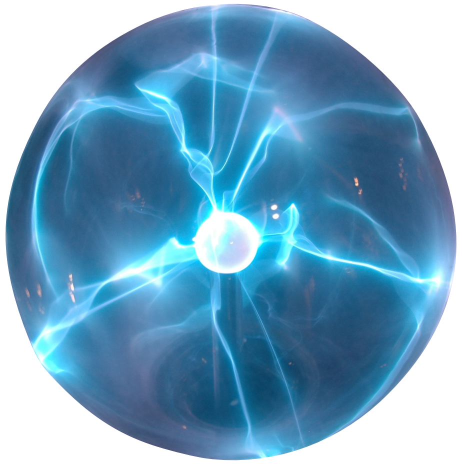
Target Sensitivity:

200 meV (90% C.L.)

Increased statistics



Background mitigation



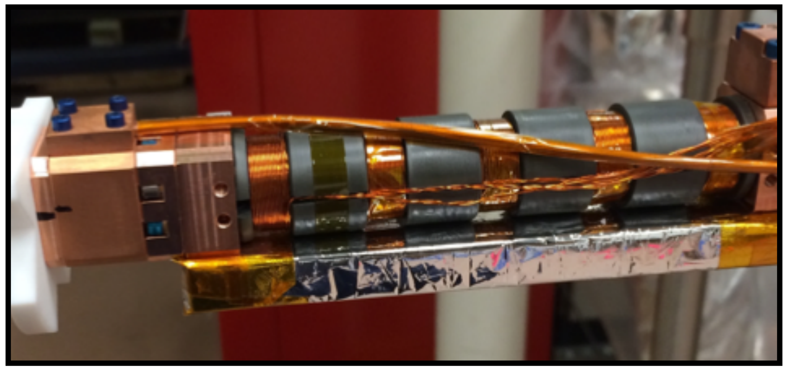
Assessment of plasma effects

Use photon spontaneous emission from electron in magnetic field.

Frequency-Based

(Cyclotron Radiation Emission Spectroscopy)

Cyclotron Radiation Emission Spectroscopy (CRES)



PROJECT 8

Frequency Approach

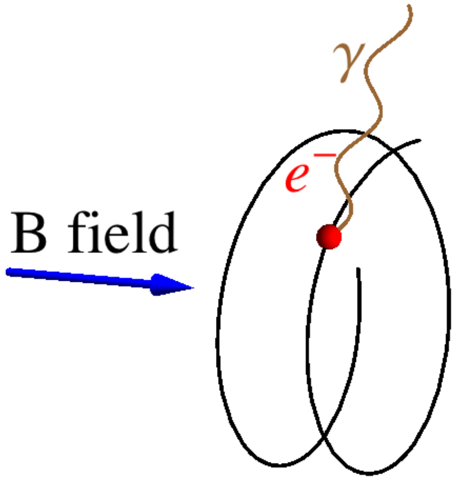
$$^{3}\mathrm{H} \rightarrow {}^{3}\mathrm{He}^{+} + e^{-} + \bar{\nu}_e$$

A. L. Schawlow

"Never measure anything but frequency."

O. Heaviside

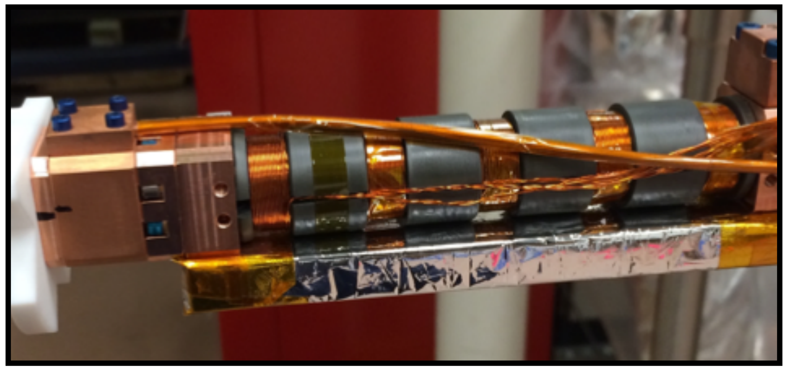
Use frequency measurement of cyclotron radiation from single electrons:



- *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

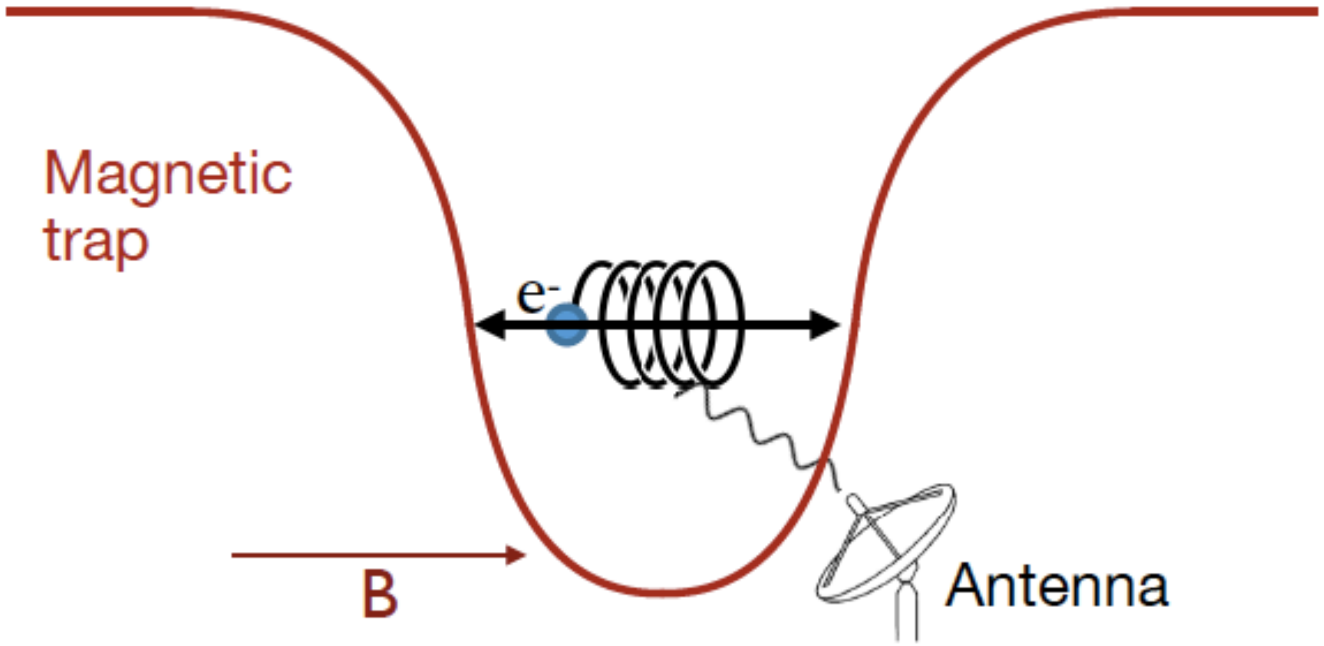
Cyclotron Radiation Emission Spectroscopy (CRES)



Frequency Approach

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

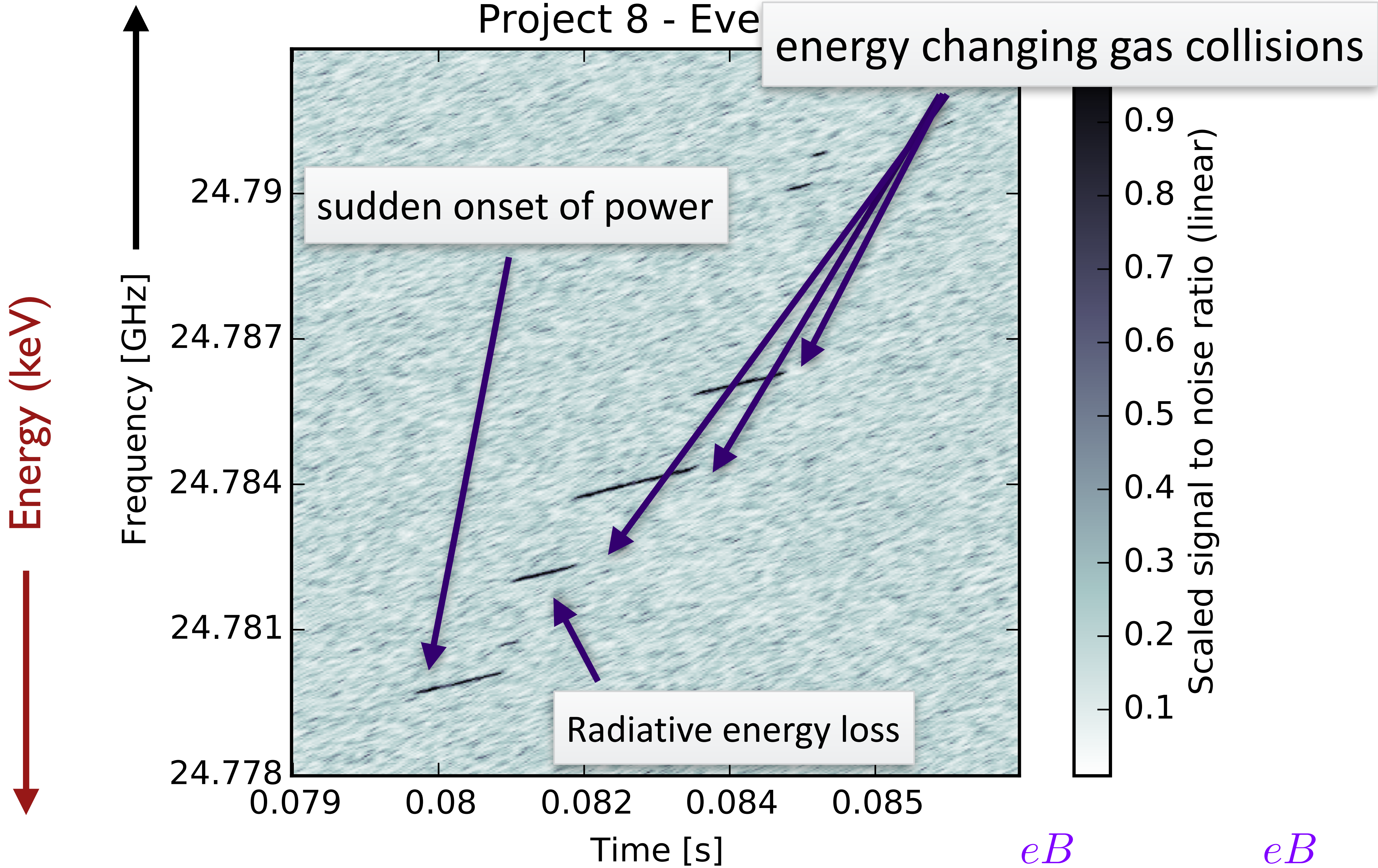
$$f_c = \frac{f_{c,0}}{\gamma} = \frac{1}{2\pi} \frac{eB}{m_e c^2 + E_{\mathrm{kin}}}$$



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

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

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

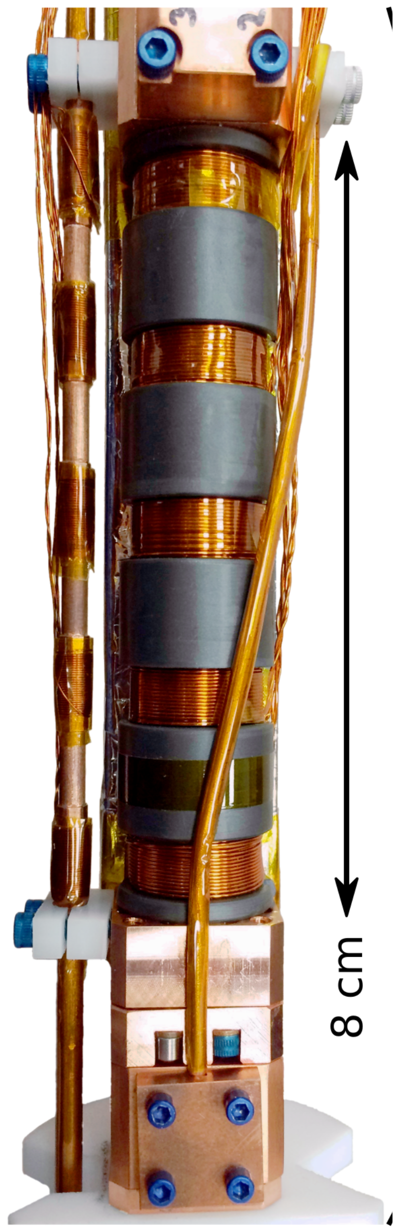


$$\omega = \frac{eB}{\gamma m_e} = \frac{eB}{m_e + K/c^2}$$

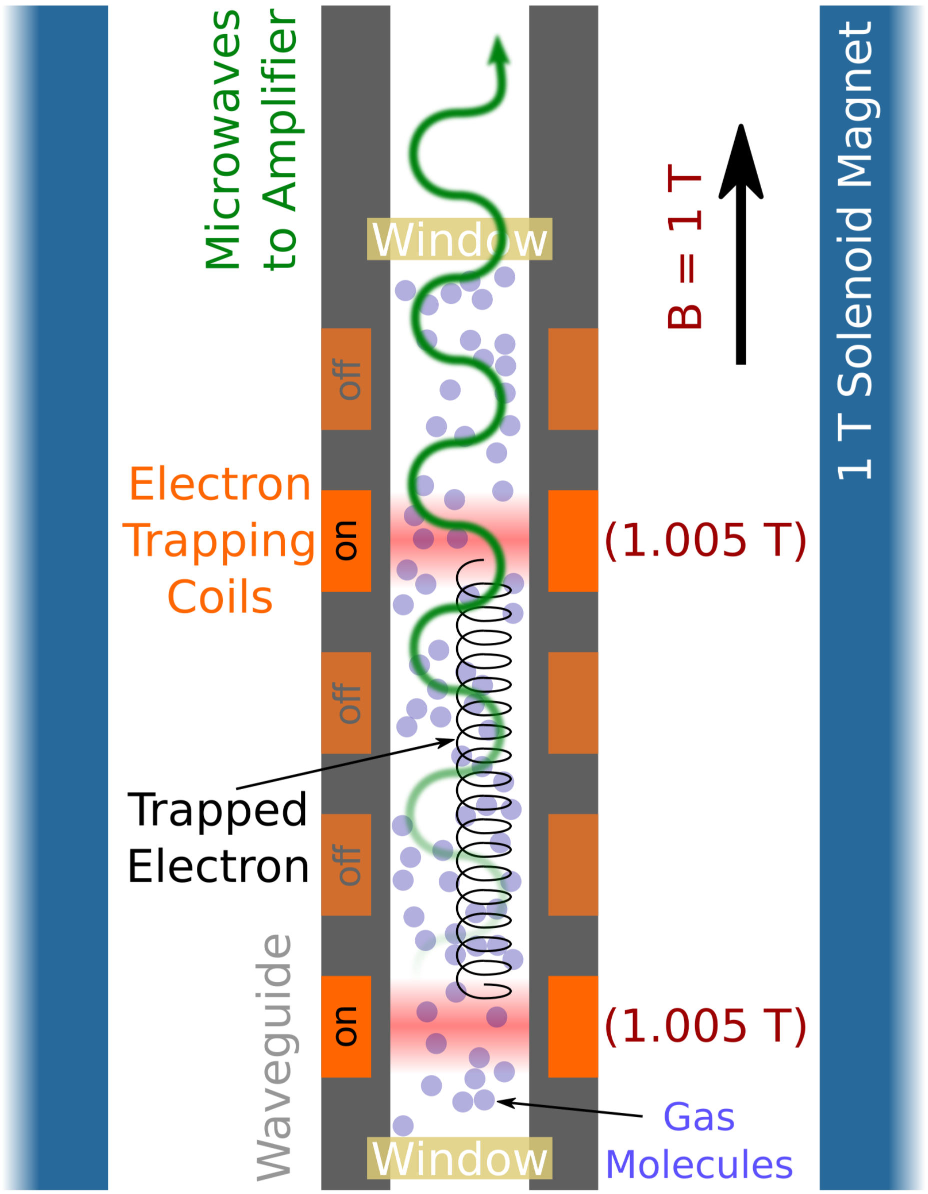
A *"typical" event*

(actually, this was our first event)

Project 8 Phase II



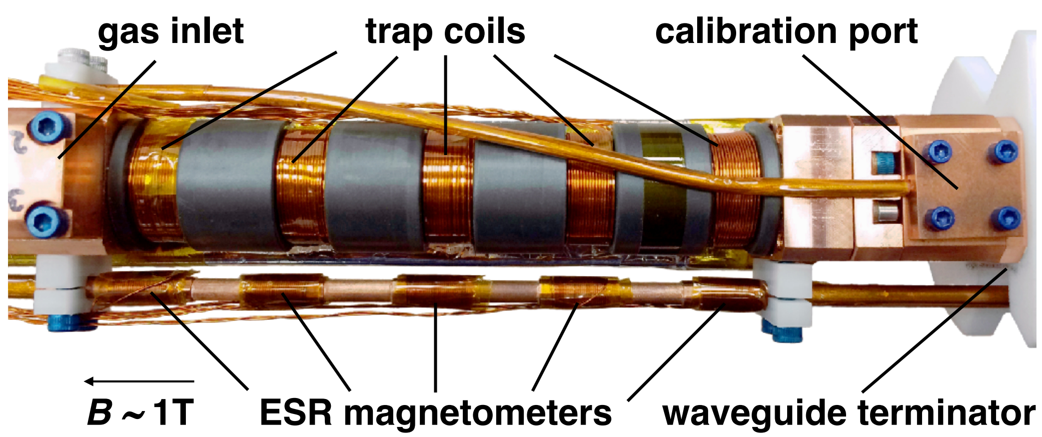
- Trapping coils arranged to provide deep and shallow traps.
- Commissioned using krypton gas, but optimized for tritium gas flow.



Electrons are magnetically trapped inside a circular waveguide to allow enough time to reconstruct event.

Microwave photons from electron provide energy reconstruction.

First CRES Tritium Measurement



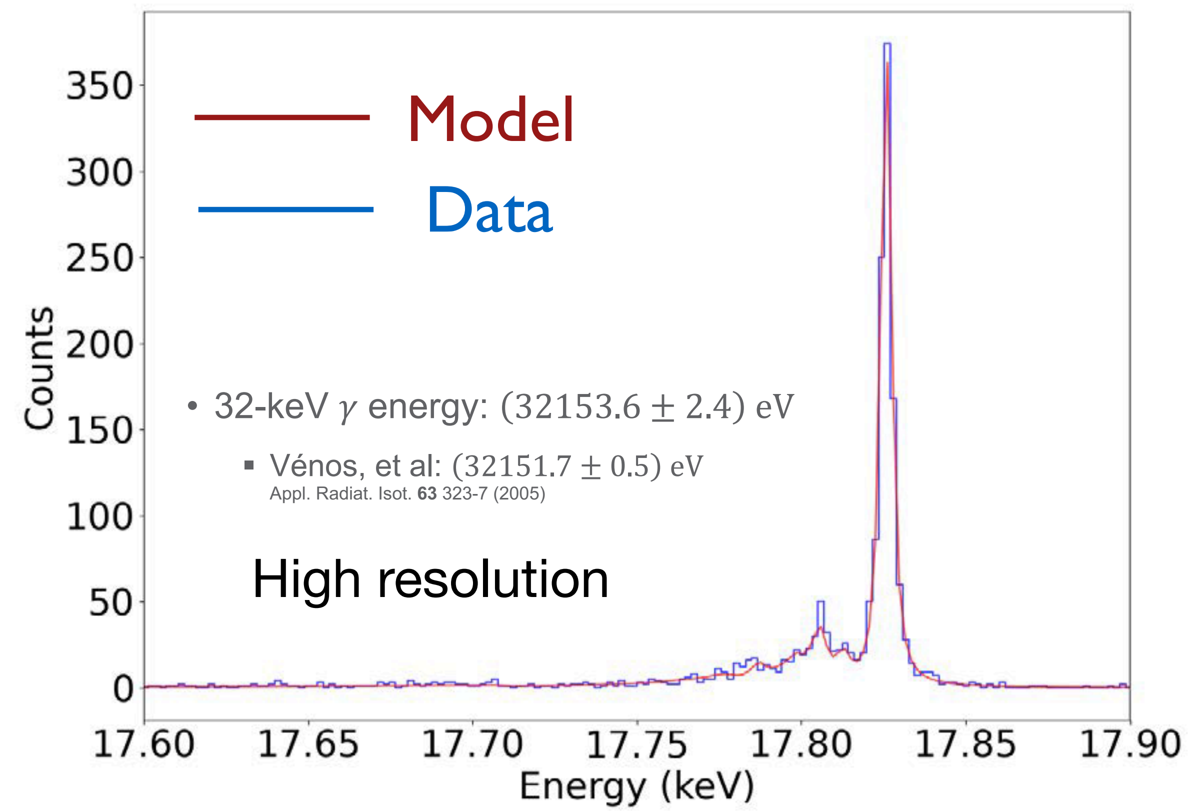
Phase II Insert

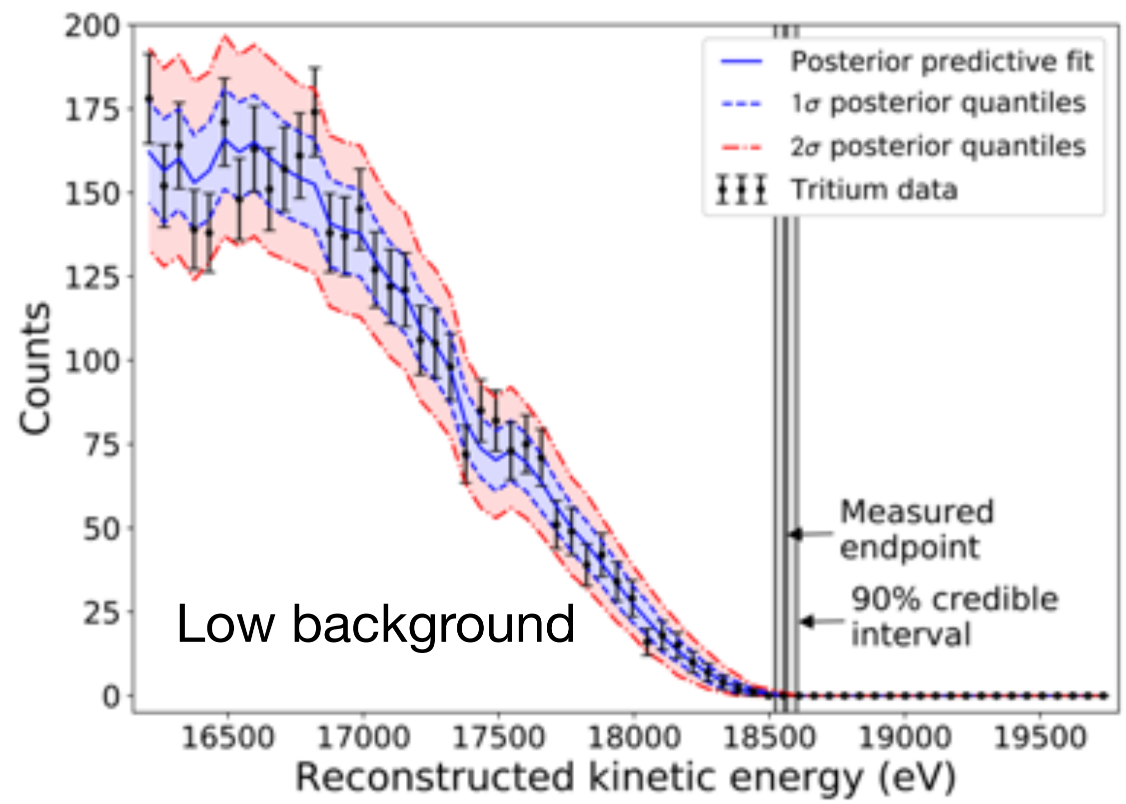
Phase II CRES instrument provides 1mm³ inside waveguide

Permits measurements of ^{83m}Kr and T_2

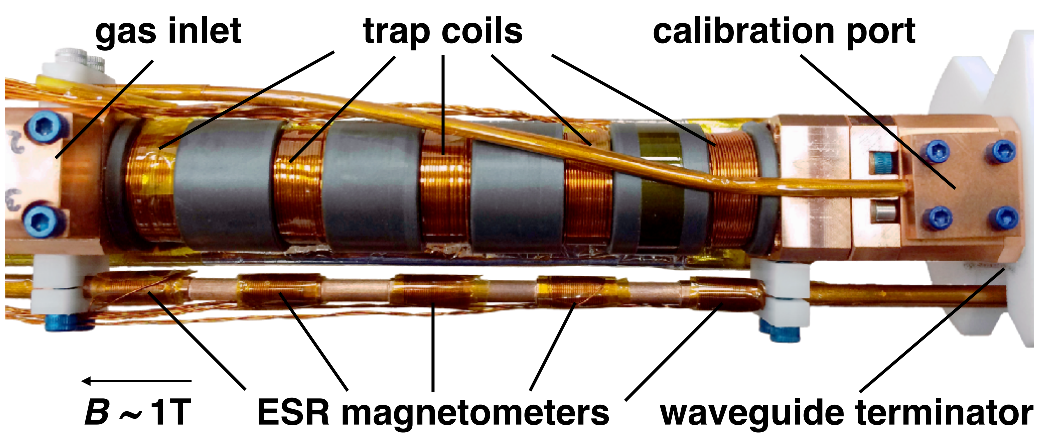
Shallow trap configurations sacrifice efficiency for instrumental resolution, as good as 2.0 ± 0.1 eV (^{83m}Kr, above)

First endpoint CRES measurement conducted with no observed background.





First CRES Tritium Measurement



Phase II Insert

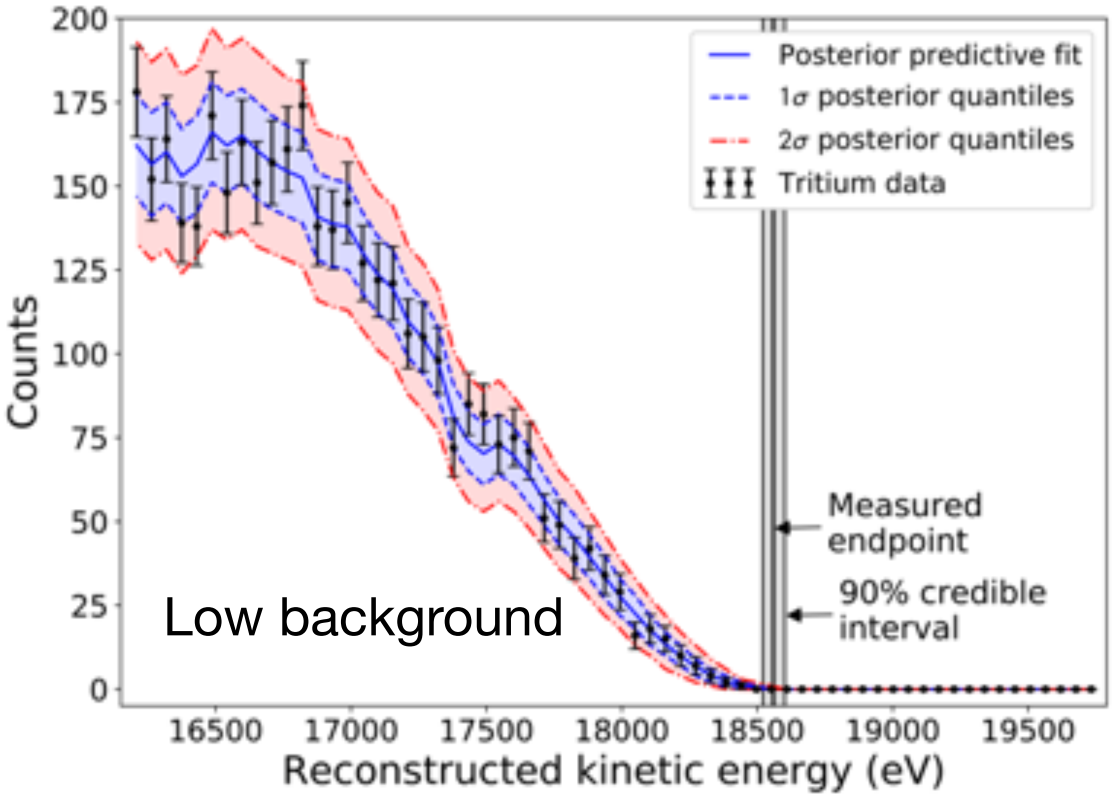
T_2 endpoint result:

$$E_0 = \left(18559.4^{+24.9}_{-24.7}\right)\ \mathrm{eV}$$

Background rate:

$$\leq 3\times10^{-10}\mathrm{eV}^{-1}\mathrm{s}^{-1}\ (90\%\ \mathrm{C.I.})$$

Preliminary



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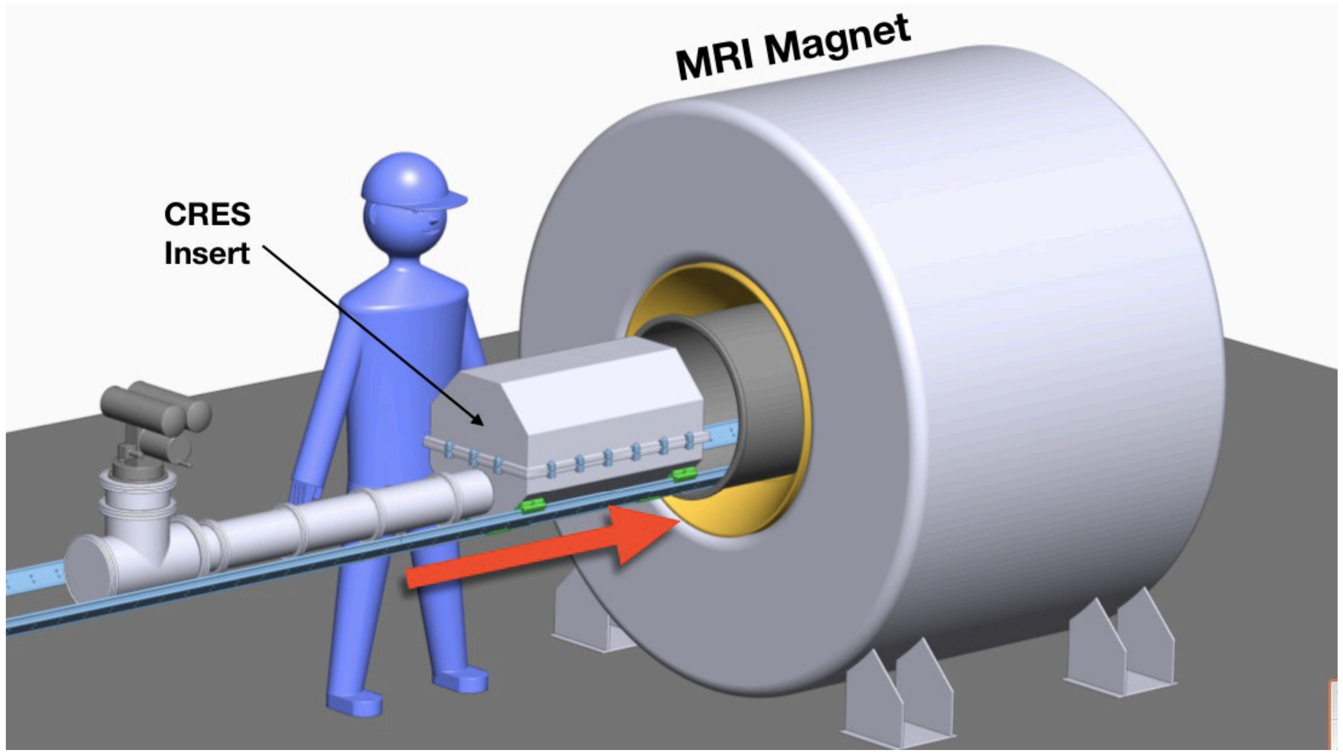
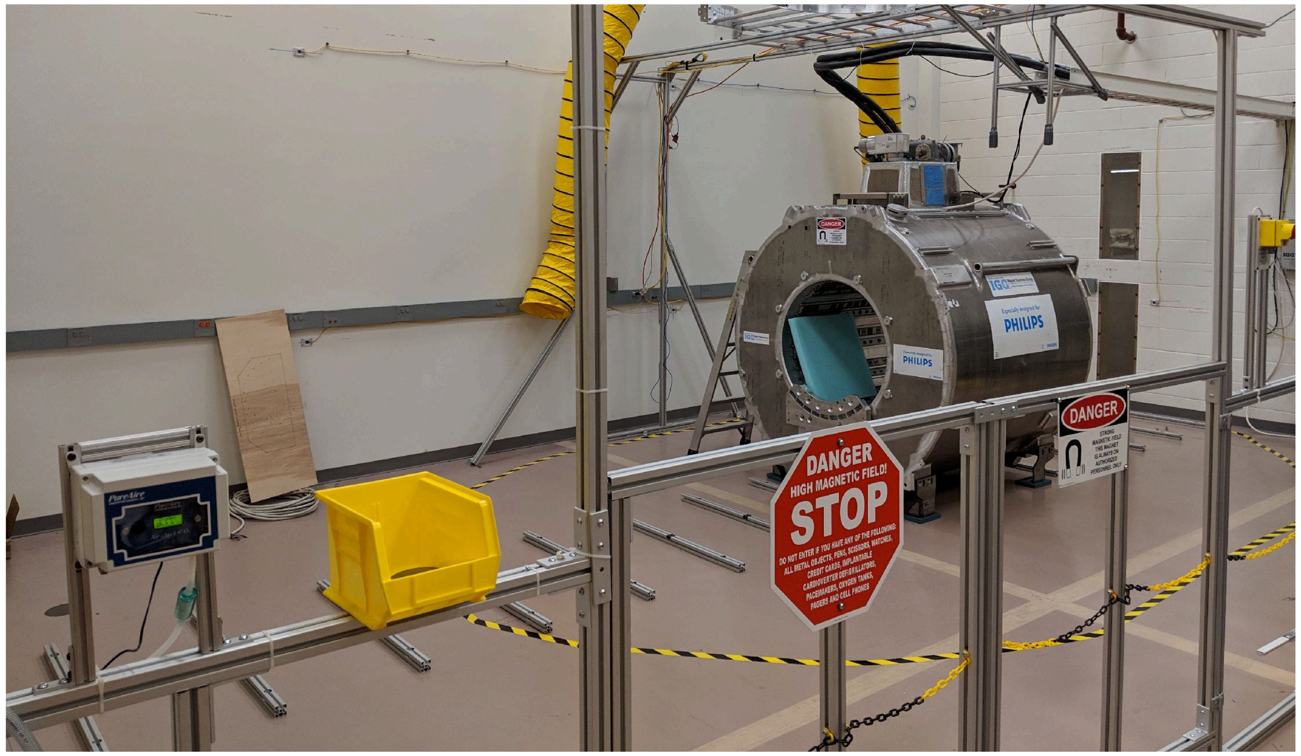
An Open Antenna Array
(Phase III)





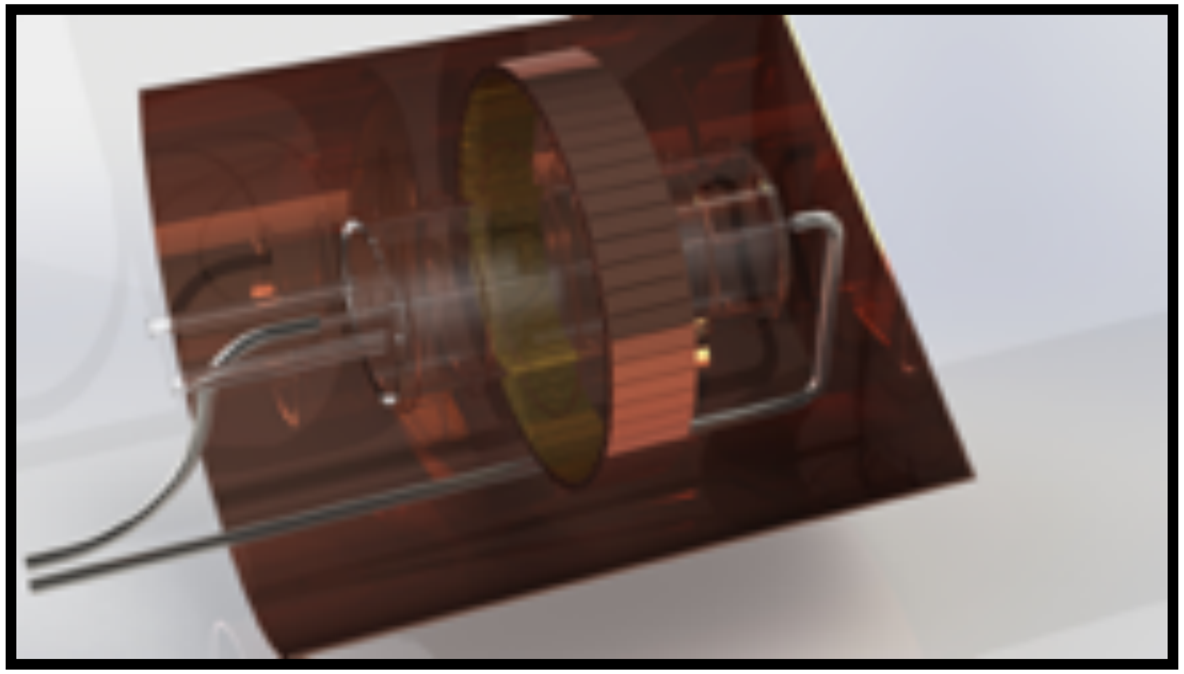
CRES must be scaled to much larger volumes 1 mm^3 → 1 m^3

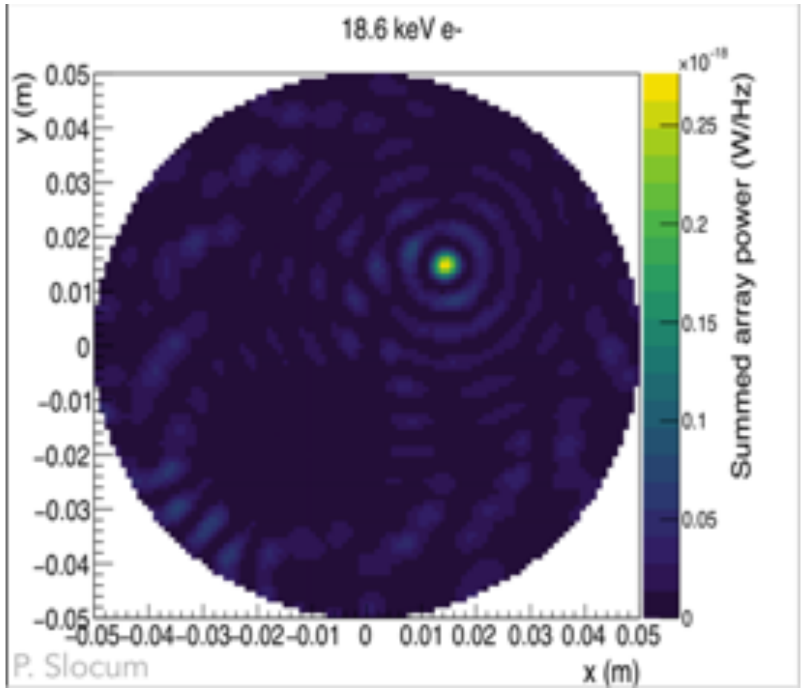
Must leave waveguide for free space observed with antennas

Active signal processing techniques focus and reconstruct source volume:

- Permits simultaneous electron events
- Confines B-field uniformity requirement to single voxels

An Open Antenna Array
(Phase III)





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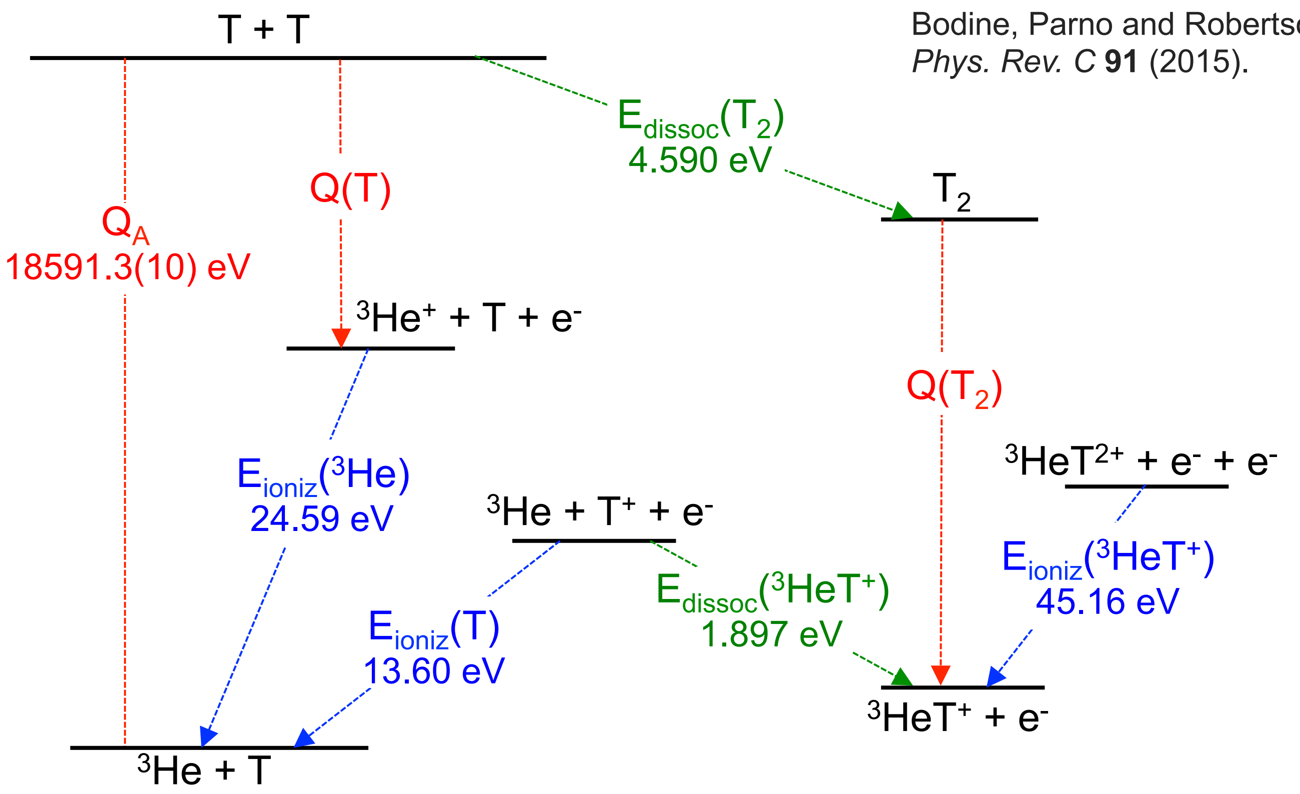
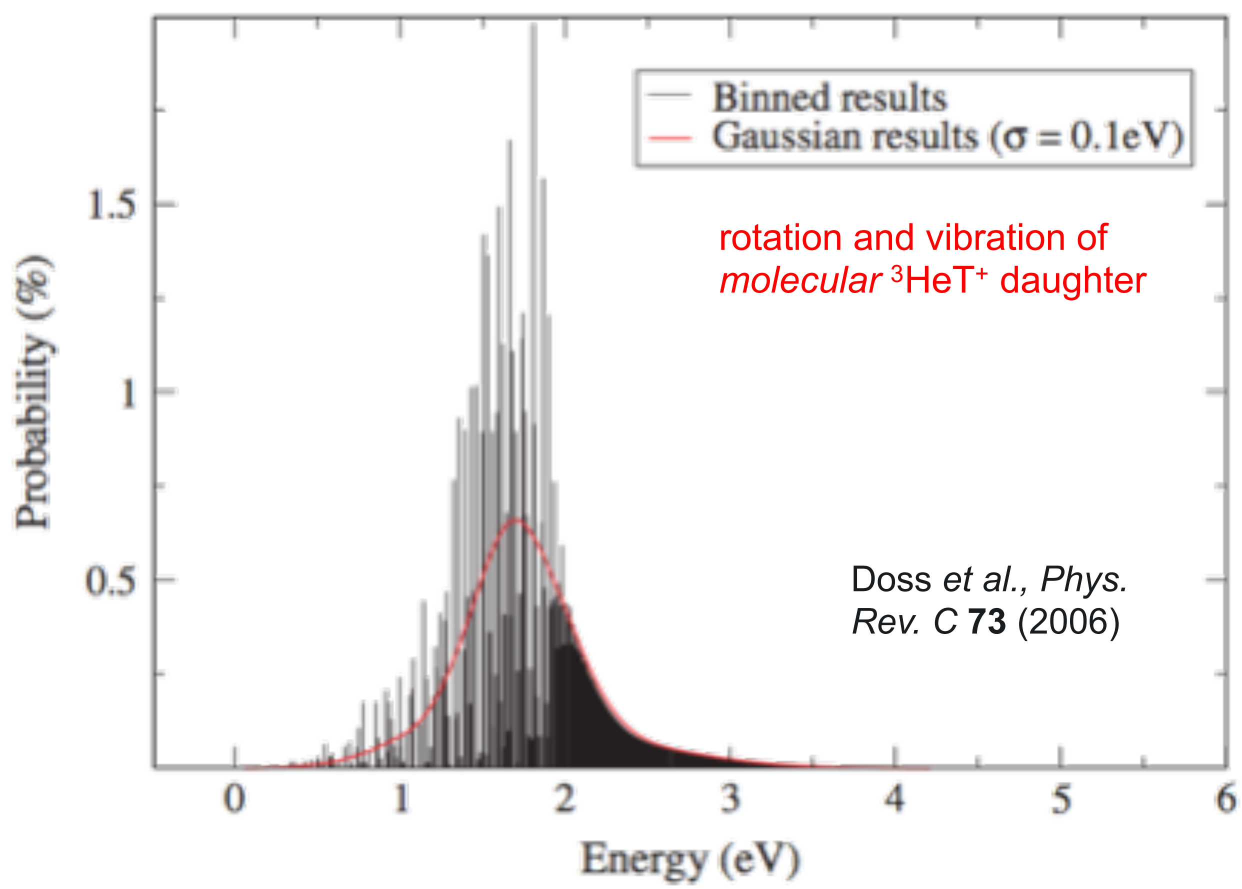
Any experiment with a molecular tritium (T_2) source will have a systematic penalty associated with uncertainty in the width of rotational and vibrational states of the daughter $^3He^+T$ populated in the decay.

In order to push to the next target mass scale (IO), one will need to switch to an *atomic* tritium source.

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



Comparison of T_2 and T decay schemes



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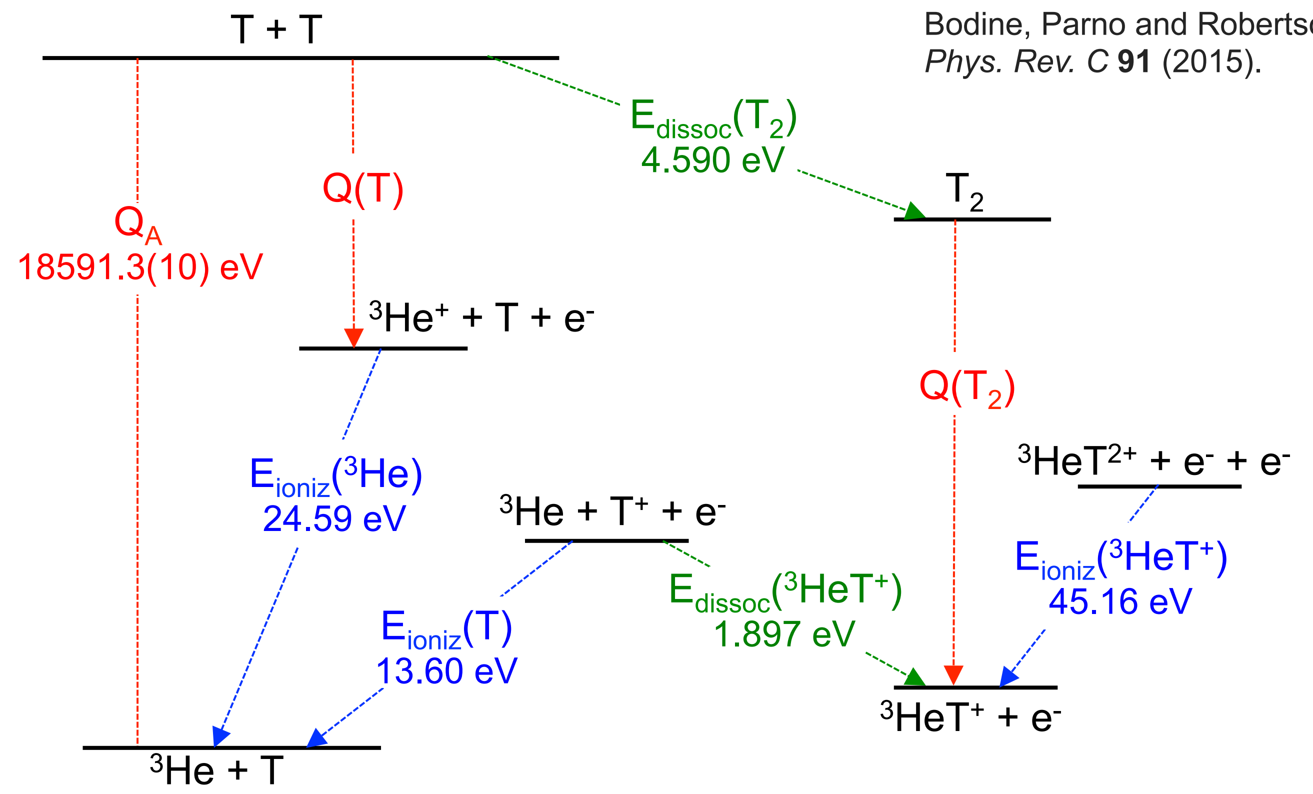

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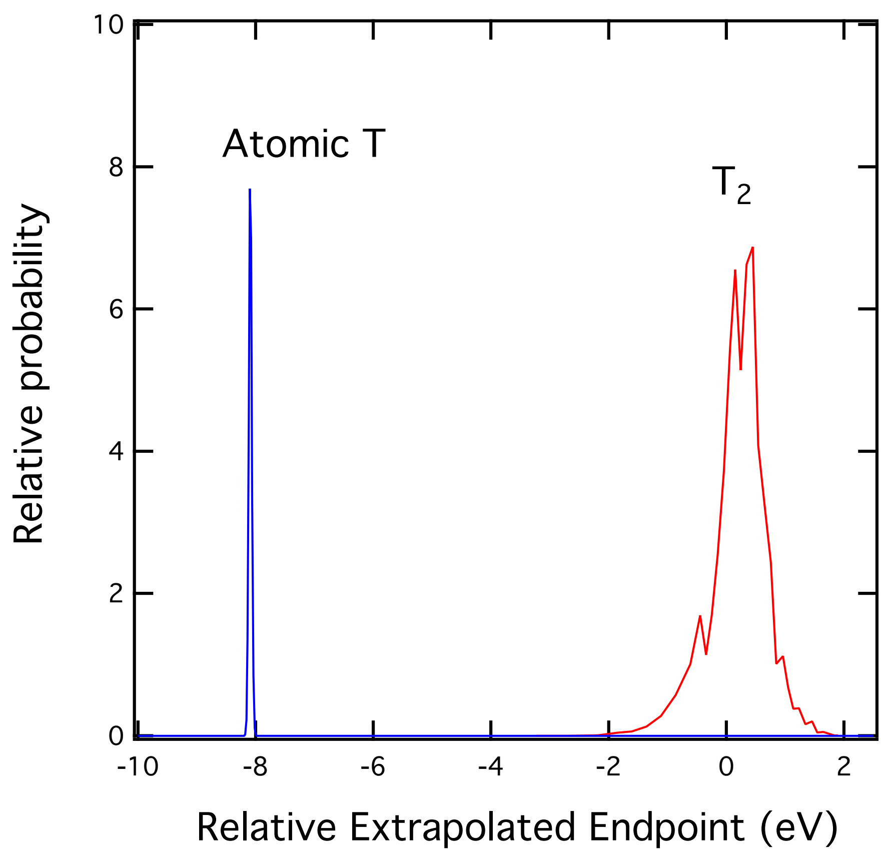
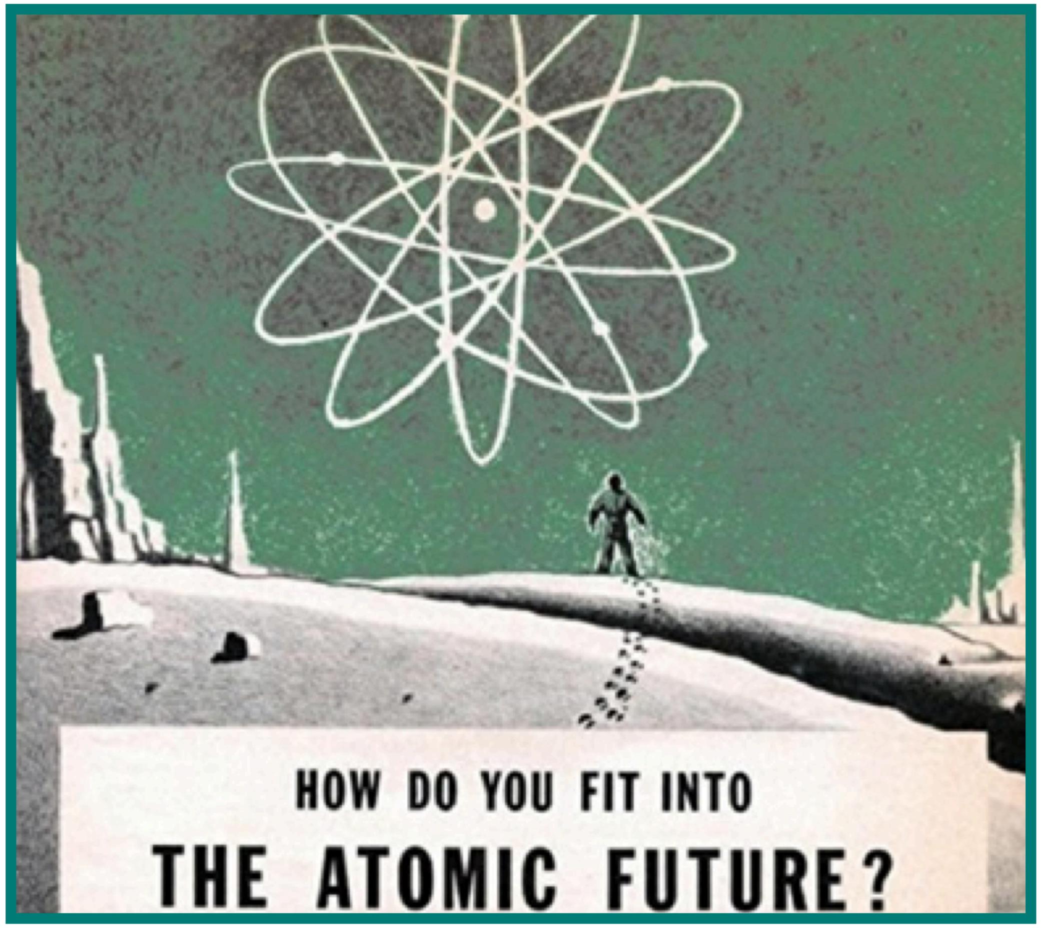
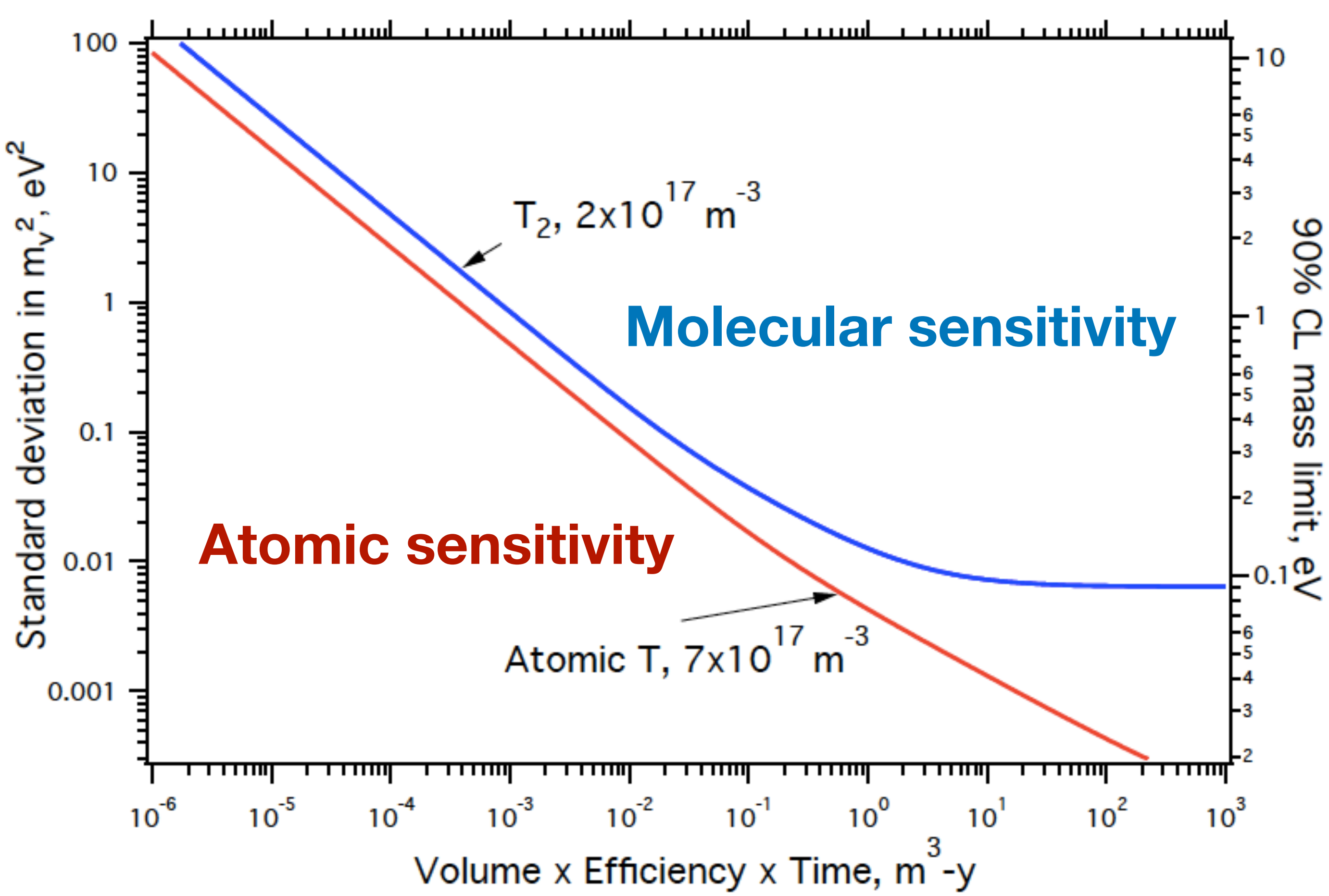


Comparison of T_2 and T ground states

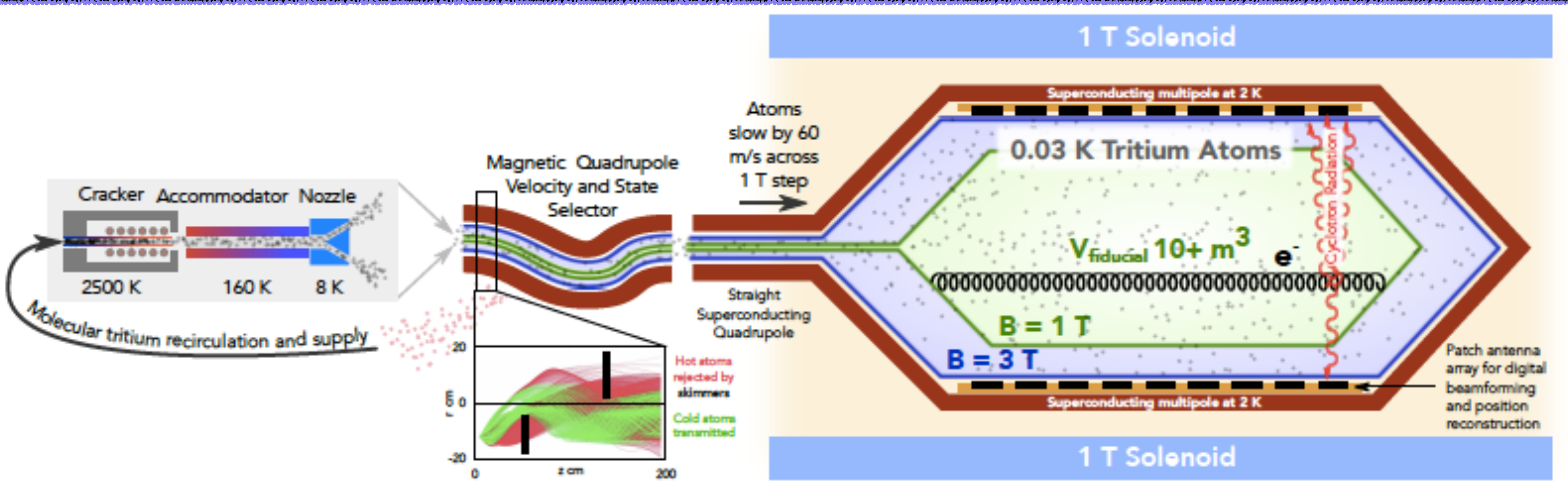
Any experiment with a molecular tritium (T_2) source will have a systematic penalty associated with uncertainty in the width of rotational and vibrational states of the daughter $^3He^+T$ populated in the decay.

In order to push to the next target mass scale (IO), one will need to switch to an *atomic* tritium source.





A large scale atomic experiment to reach the inverted scale.

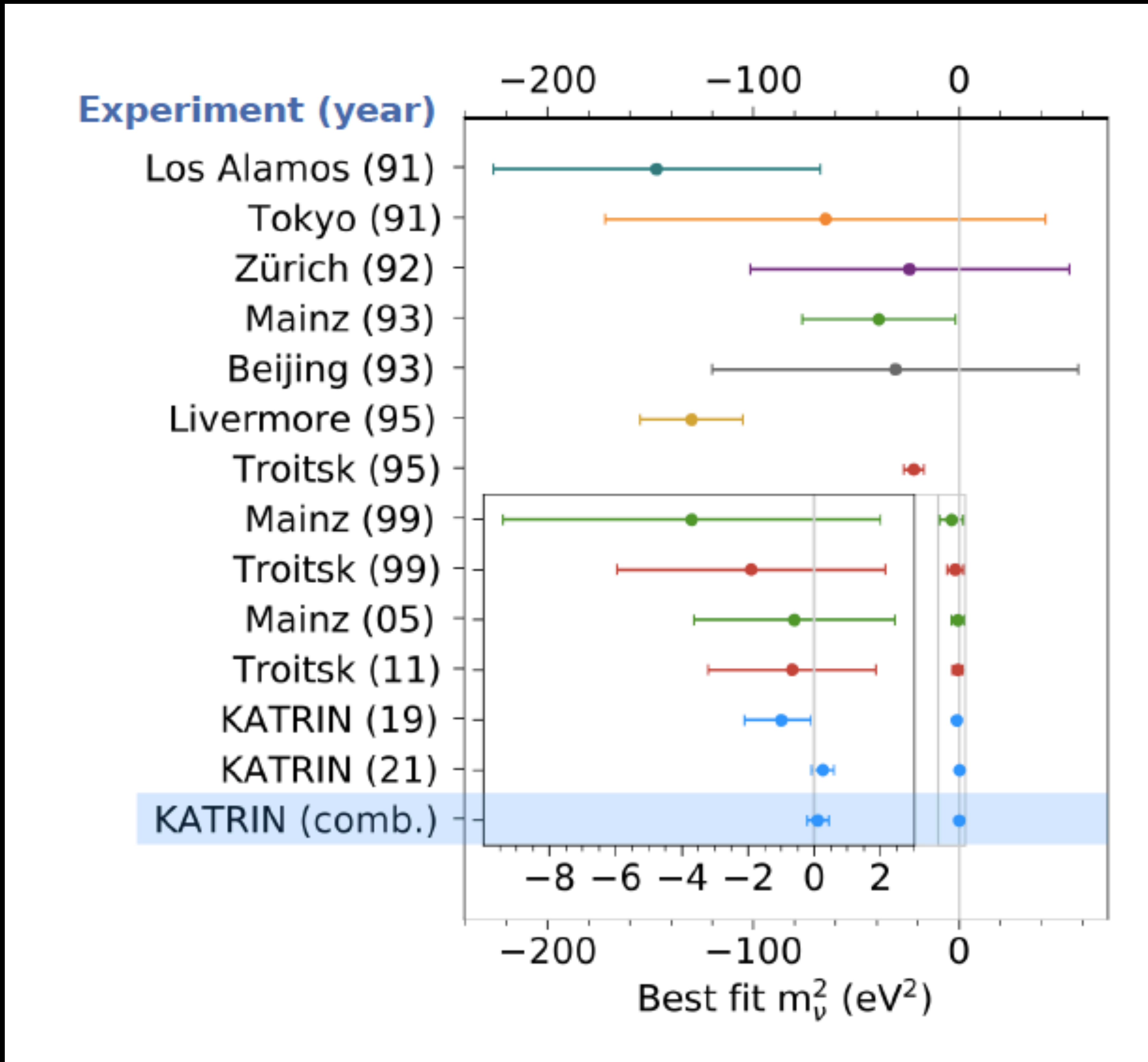


Known as Phase IV, Project 8 hopes to break through the degeneracy scale toward the inverted (40 meV)

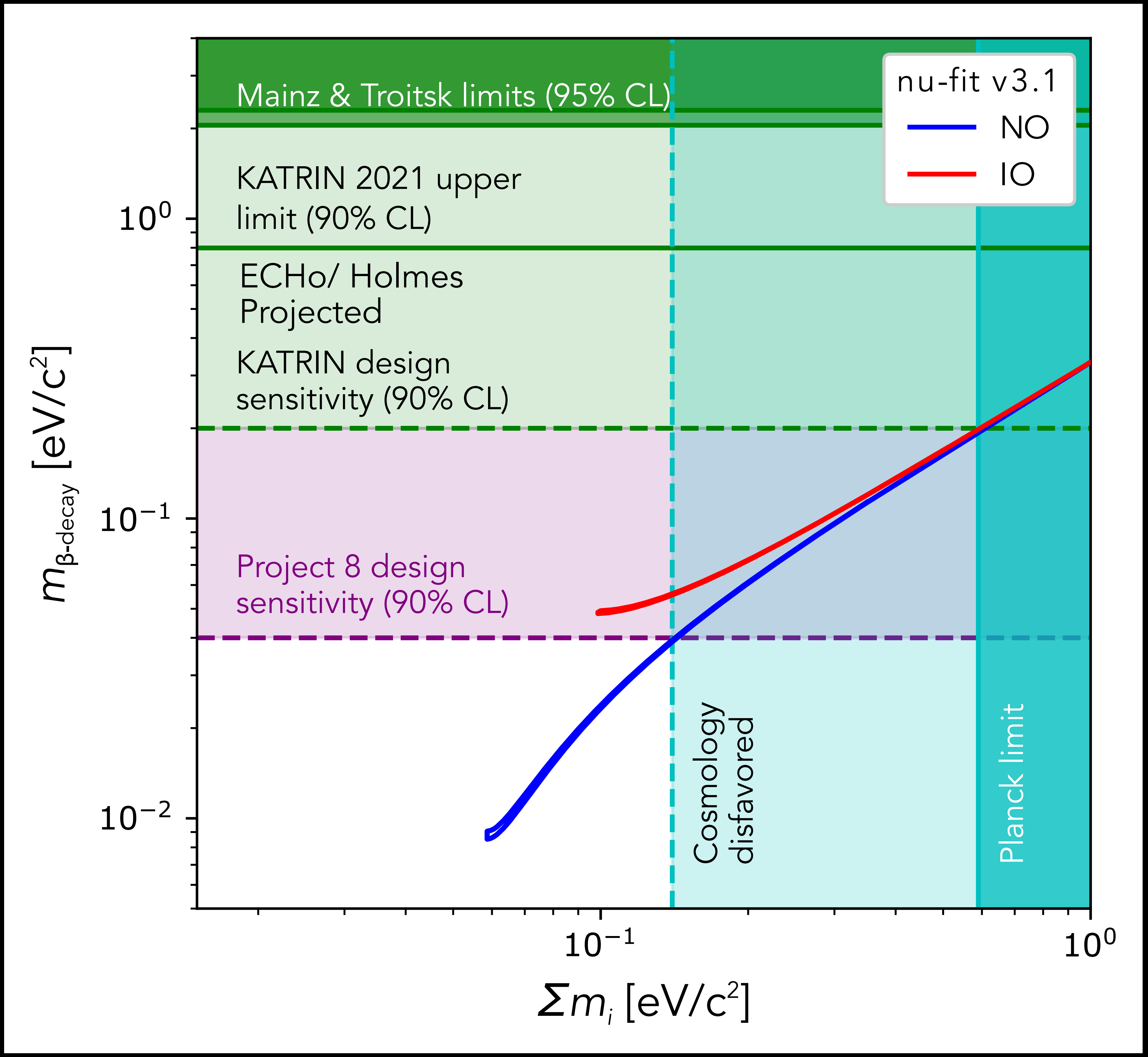
Target Mass Sensitivity

$m_\beta < 40$ meV

Current experiments have broken the eV scale...

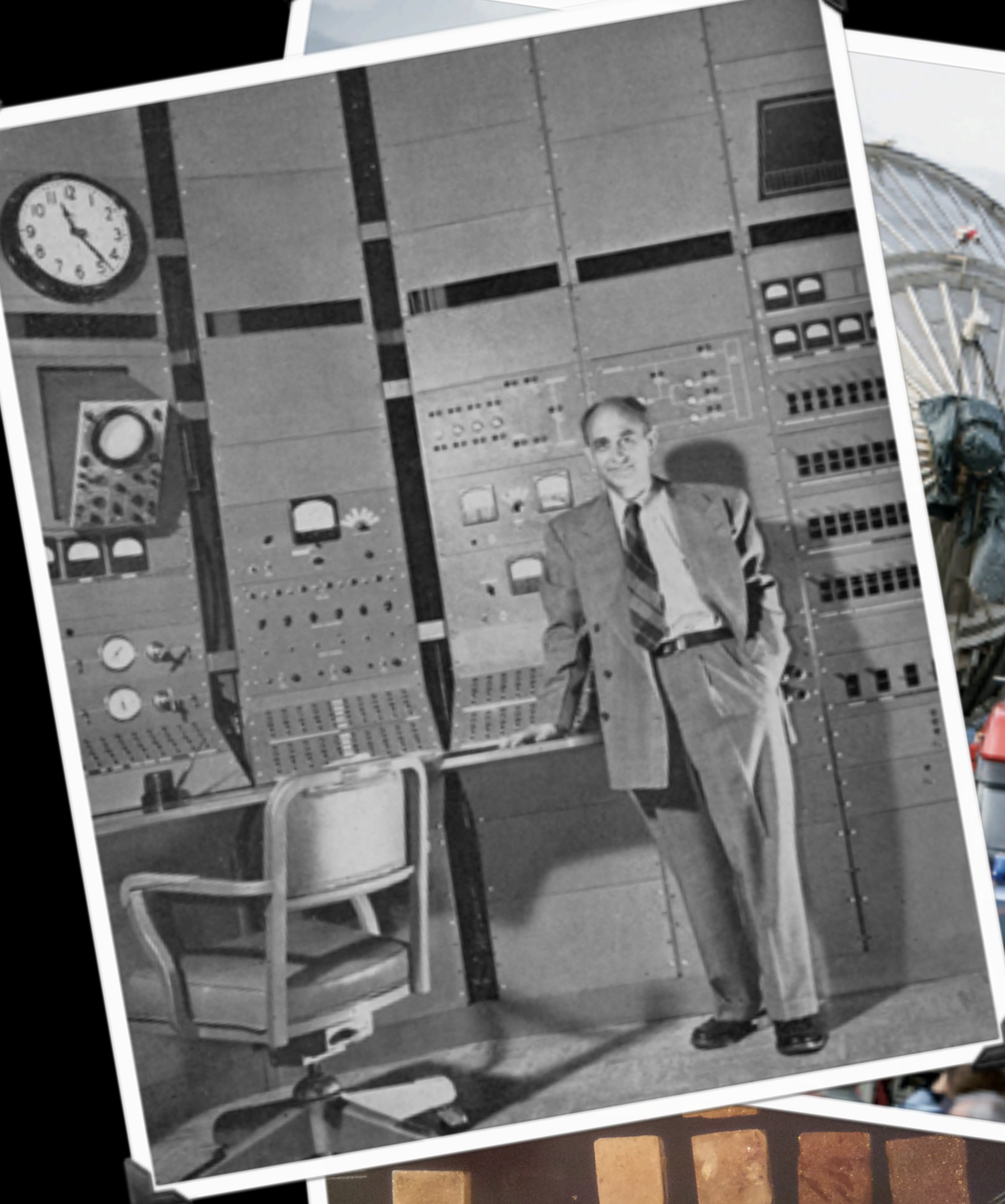


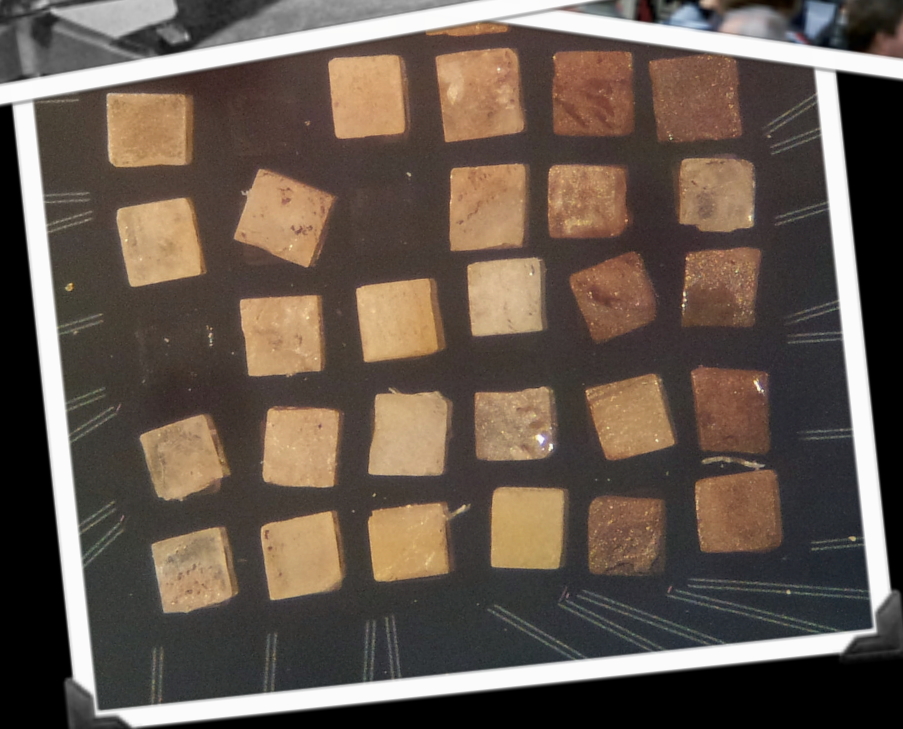
... and a future atomic T experiment could break the inverted scale.



This is a good decade for direct neutrino mass measurements, with several experiments reaching for the sub-eV scale and beyond.

KATRIN, Project 8, ECHo and HOLMES all ramping and taking data in the near future.





Thanks for your attention!

References

(Normally, I would give a full list, but we just finished a huge review, and it has almost 300 references).

Direct measurements of neutrino mass

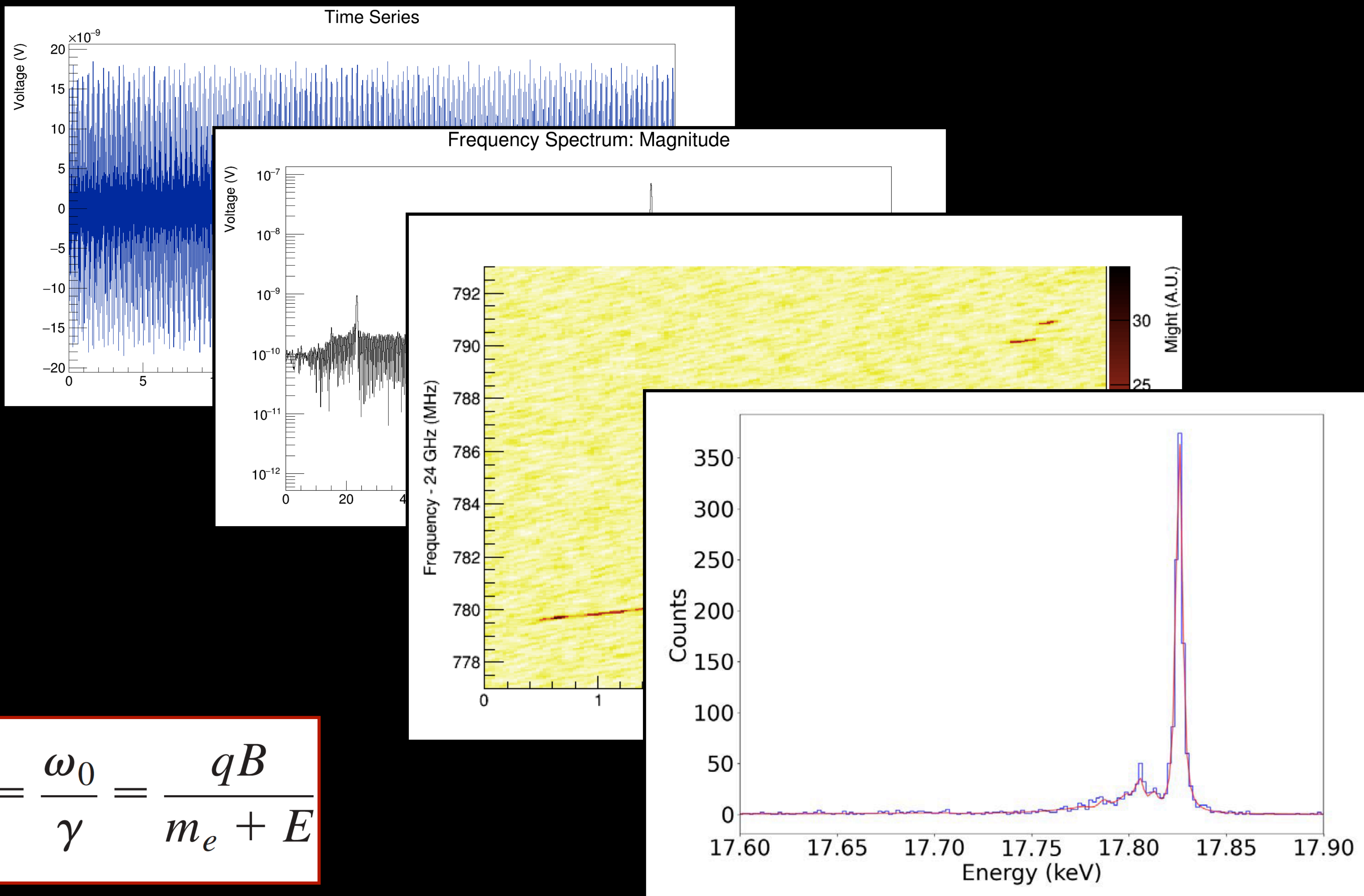
Joseph A. Formaggio[a], André Luiz C. de Gouvêa[b], R.G. Hamish Robertson[c,*]

[a] Laboratory for Nuclear Science and Dept. of Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
[b] Department of Physics and Astronomy, Northwestern University, Evanston, IL 60208, USA
[c] Center for Experimental Nuclear Physics and Astrophysics, and Dept. of Physics, University of Washington, Seattle, WA 98195, USA

That might be more useful.

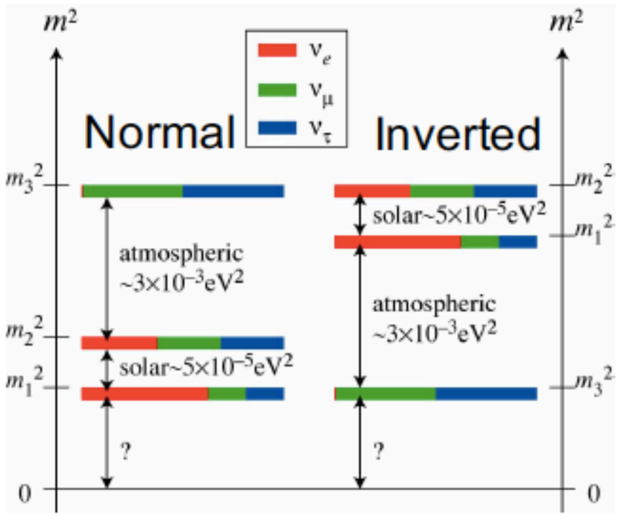
Direct measurements of neutrino mass, Physics Reports, Volume 914, 2021, Pages 1-54, https://doi.org/10.1016/j.physrep.2021.02.002.

Event reconstruction is a bit more complex

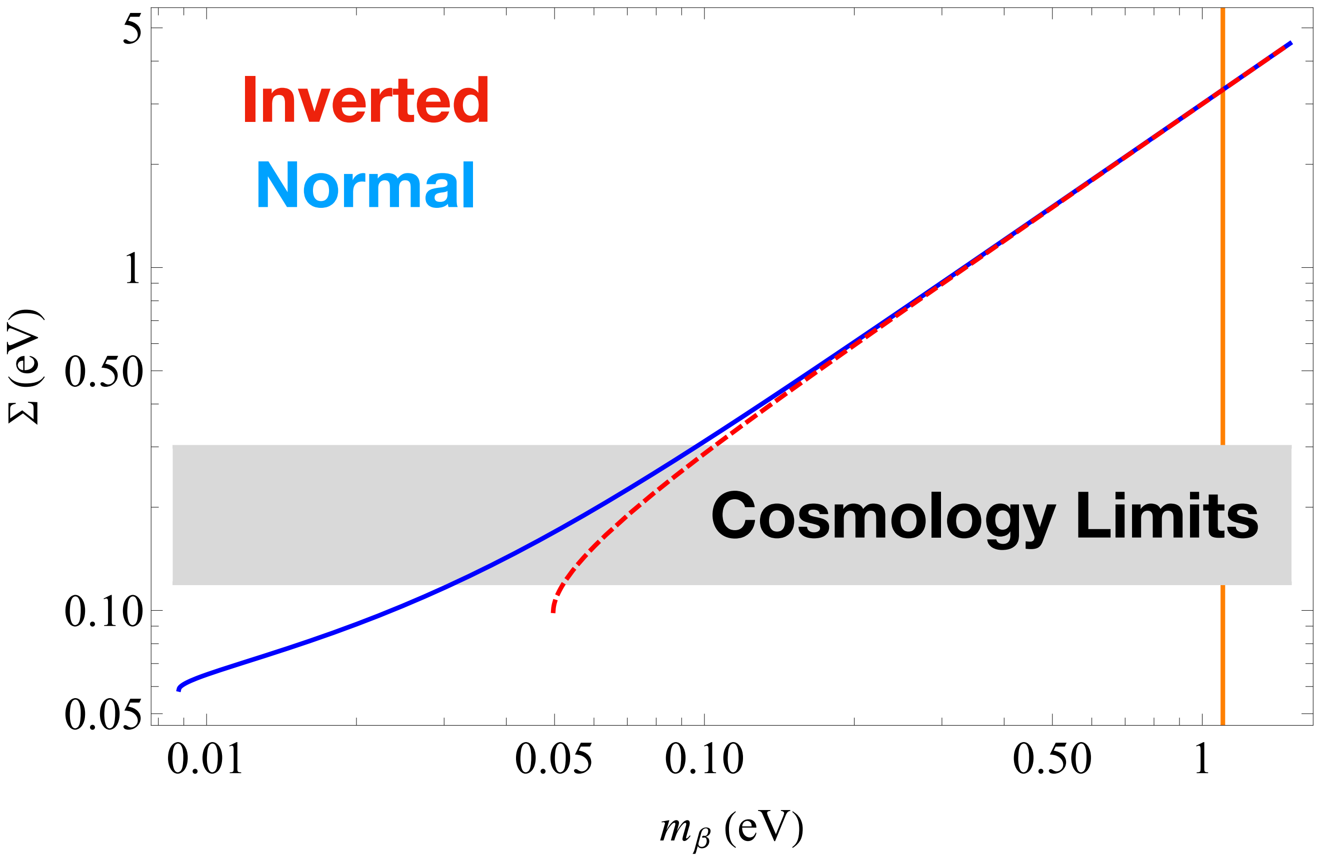


$$\omega = \frac{\omega_0}{\gamma} = \frac{qB}{m_e + E}$$

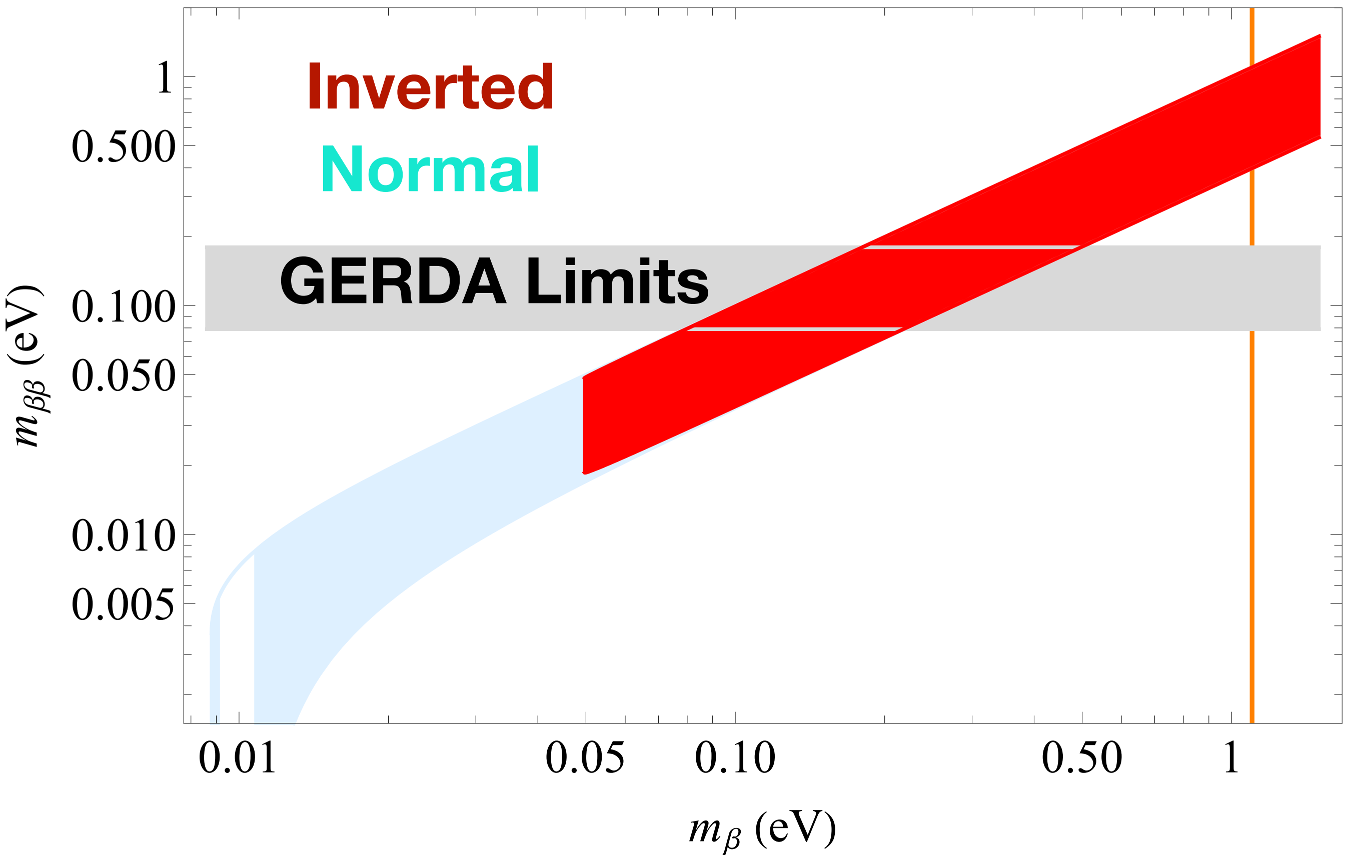
Oscillations



Cosmology



0νββ



Combining all the approaches provides a more complete picture of the neutrino mass scale