The Path to Neutrino Mass

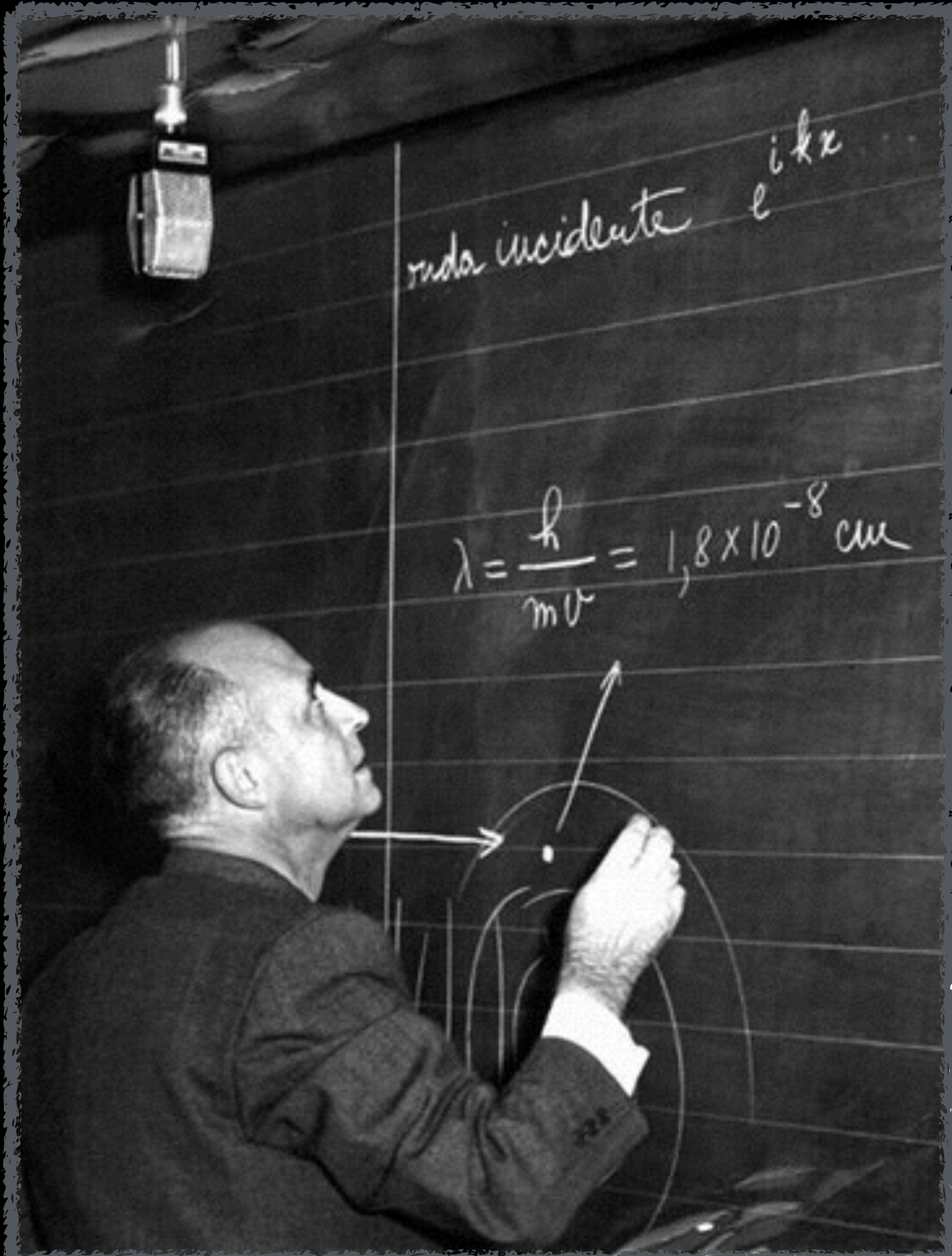
(and maybe relic neutrinos, too)

Institute for Nuclear Theory

Neutrino Astrophysics and Fundamental Properties

June 22nd 2015

Joseph A. Formaggio
MIT



Neutrino mass measurements have a long history in physics, predating the Standard Model itself.

It should therefore be no surprise that our quest to understand this fundamental property continues; both for its own right as well as its theoretical implications.

80 a. – Tentativo di una teoria dei raggi β

LA MASSA DEL NEUTRINO.

probabilità di transizione (32) determina tra l'altro la forma
continuo dei raggi β. Discuteremo qui come la forma di questo
spettro dipende dalla massa di quiete del neutrino, in modo da poter determi-
nare questa massa da un confronto con la forma sperimentale dello spettro
stesso. La massa μ interviene in (32) tra l'altro nel fattore p_σ^2/v_σ. La dipen-
denza della forma della curva di distribuzione dell'energia da μ, è marcata
specialmente in vicinanza della energia massima E_0 dei raggi β. Si riconosce
facilmente che la curva di distribuzione per energie E prossime al valore mas-
simo E_0, si comporta, a meno di un fattore indipendente da E, come

$$\frac{p_\sigma^2}{v_\sigma} = \frac{1}{c^3}(\mu c^2 + E_0 - E)\sqrt{(E_0 - E)^2 + 2\mu c^2 (E_0 - E)}. \quad (36)$$

Nella fig. 1 la fine della curva di distribuzione è rappresentata per μ = 0,
e per un valore piccolo e uno grande di μ. La maggiore somiglianza con le

Fig. 1.

Measuring Neutrino Masses

$$M = \sum_{i}^{n_\nu} m_{\nu,i}$$

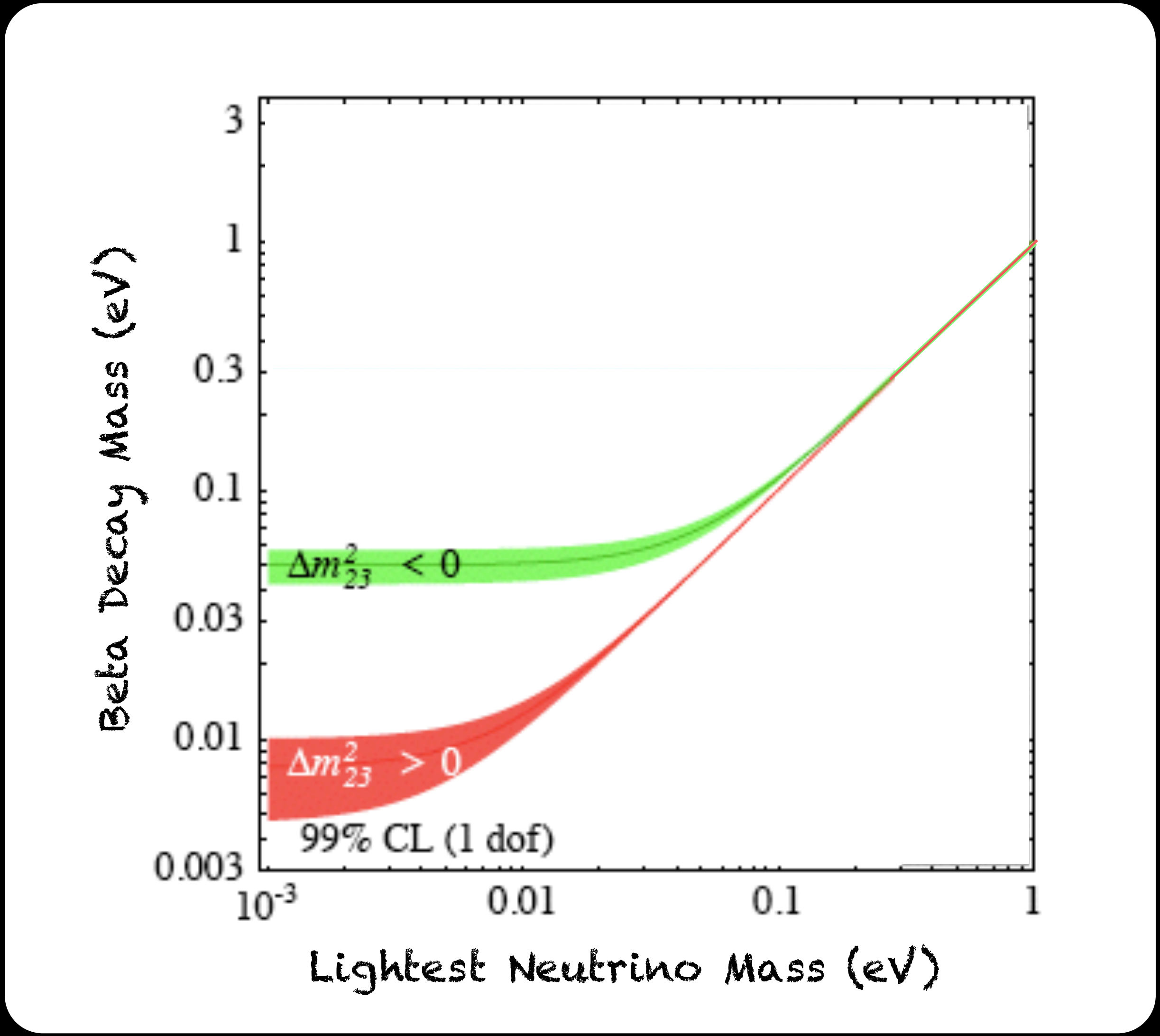
Cosmological Measurements

$$\langle m_{\beta\beta}^2 \rangle = \mid \sum_{i}^{n_\nu} U_{ei}^2 m_{\nu,i} \mid^2$$

0vββ Measurements

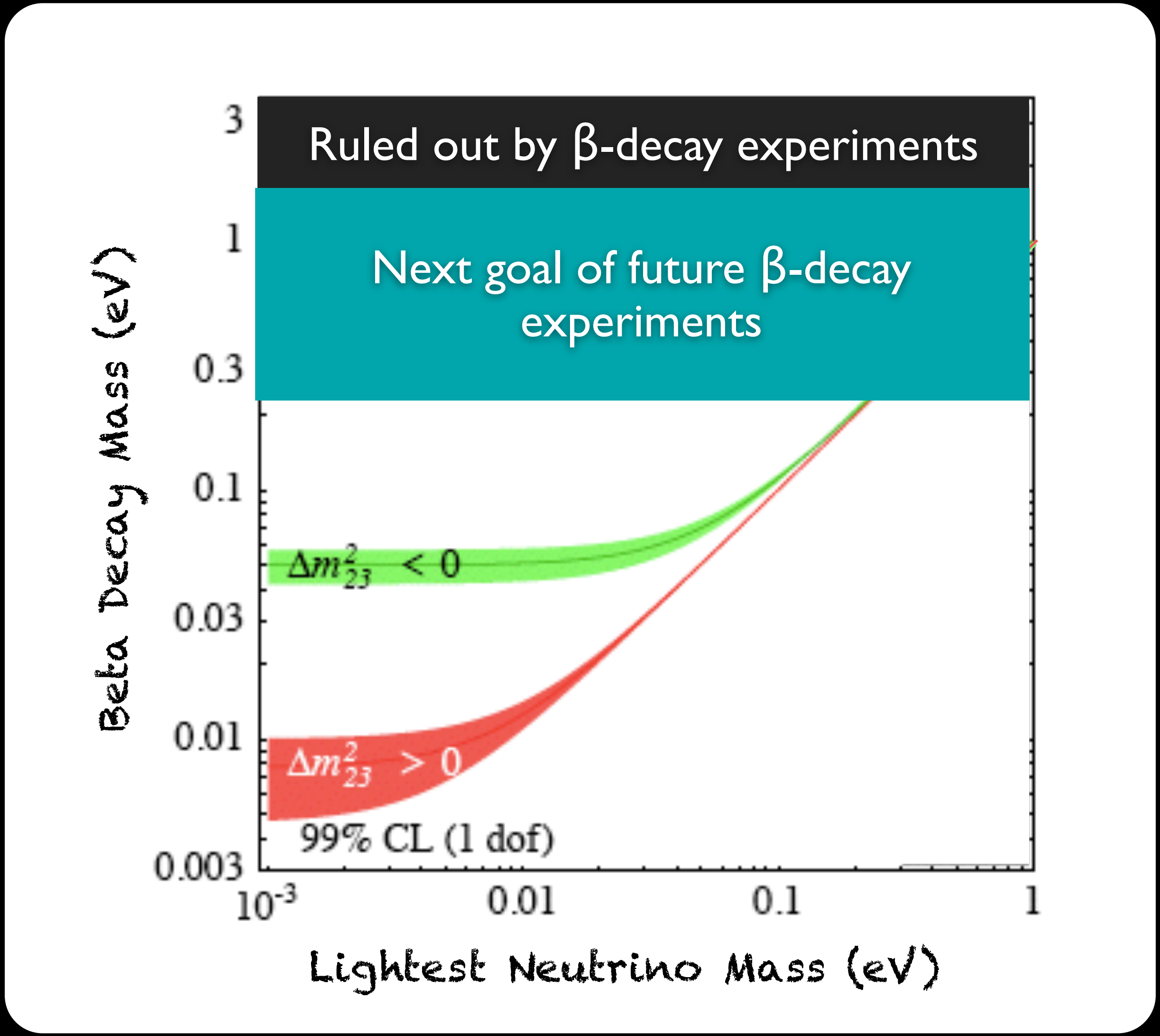
$$\langle m_\beta \rangle^2 = \sum_{i}^{n_\nu} \mid U_{ei} \mid^2 m_{\nu,i}^2$$

Beta Decay Measurements



The Neutrino Mass Scale

- The neutrino mass scale remains one of the essential "unknowns" of the Standard Model.
- Knowledge of neutrino masses can have a significant impact on many different arenas, including cosmology, the mass hierarchy, sterile neutrinos, and even relic neutrino detection.



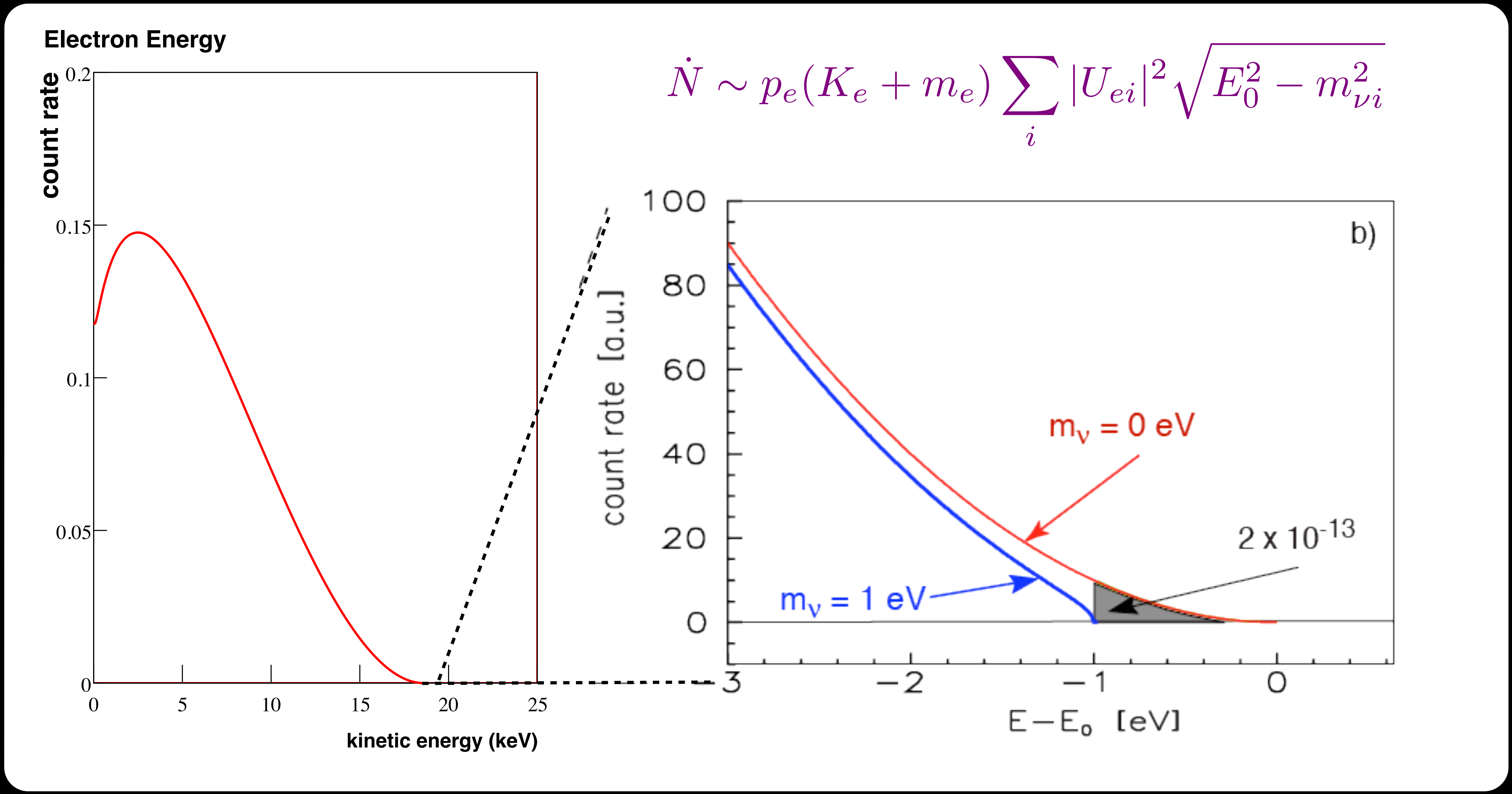
m_ν > 2 eV (eV scale, current)
Neutrinos ruled out as dark matter

m_ν > 0.2 eV (degeneracy scale)
Impact on cosmology and 0νββ reach

m_ν > 0.05 eV (inverted hierarchy)
Resolve hierarchy if null result

m_ν > 0.01 eV (normal hierarchy)
Oscillation limit; possible CνB detection

Direct Probes



Beta Decay

A kinematic determination of the neutrino mass

No model dependence on cosmology or nature of mass

Techniques for the 21^{st} Century

Spectroscopy (KATRIN)

Magnetic Adiabatic Collimation with Electrostatic Filtering

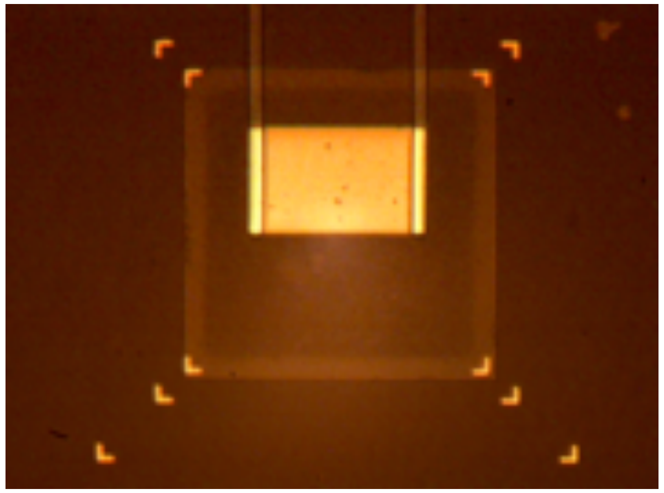
State-of-the-Art technique

$$T_2 \rightarrow (T \cdot {}^3He^+) + e^- + \bar{\nu}_e$$

Calorimetry (HOLMES, ECHO & NUMECS)

Technique highly advanced.

New experiment(s) planned to reach ~eV scale.

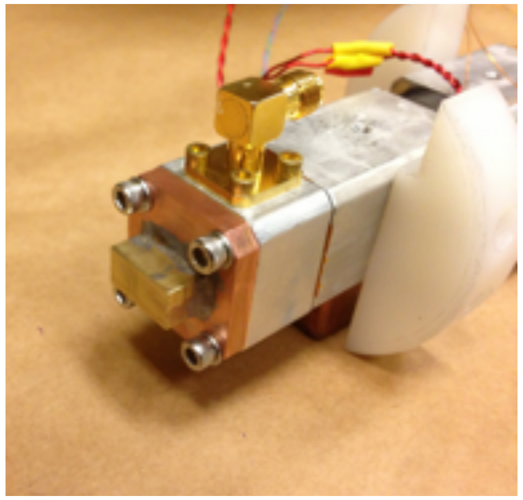


$${}^{163}Ho + e^- \rightarrow {}^{163}Dy^* + \nu_e$$

Frequency (Project 8)

Radio-frequency spectroscopy for beta decay

R&D phase (new results)



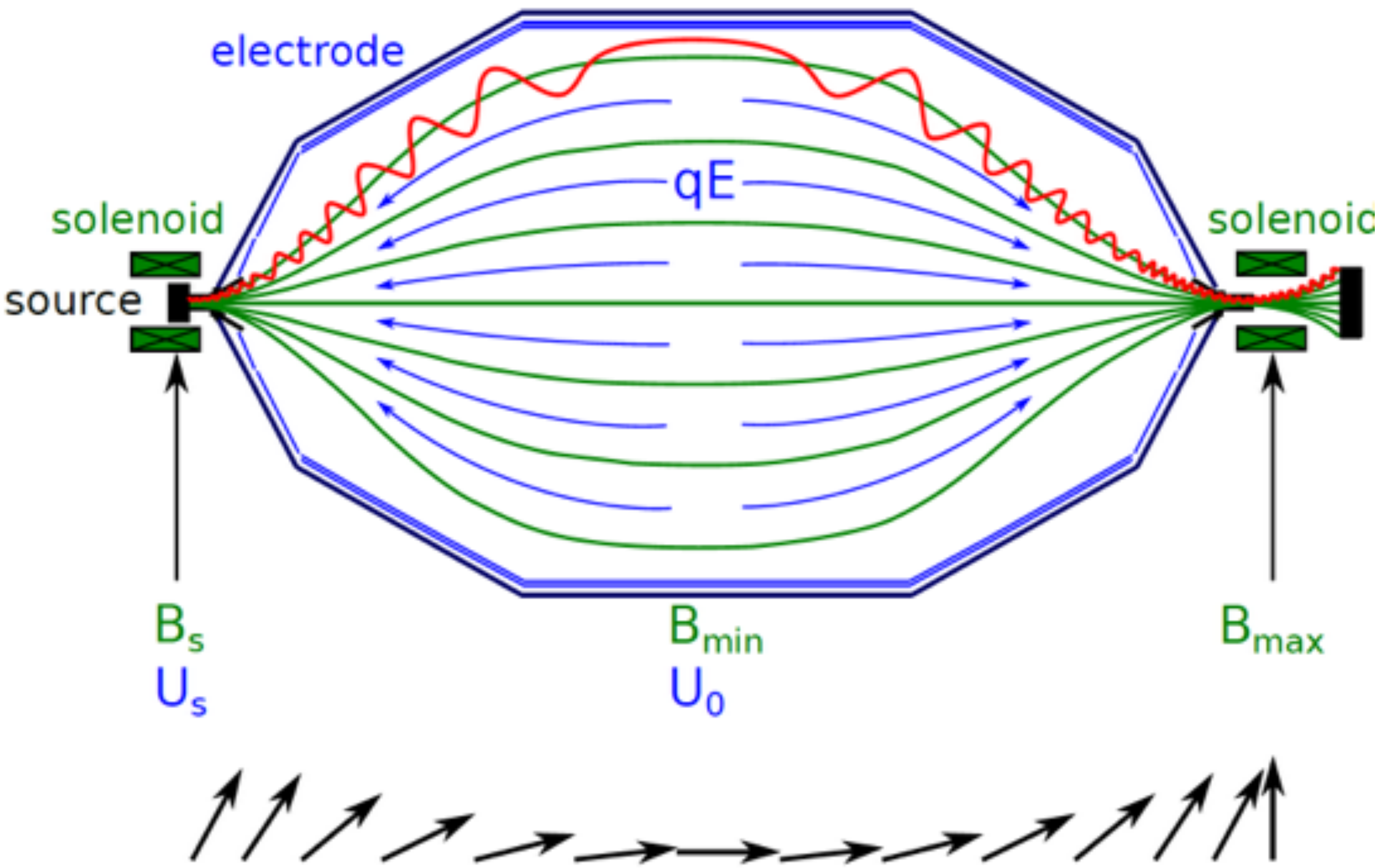
$${}^3H \rightarrow {}^3He^+ + e^- + \bar{\nu}_e$$

MAC-E Filter Technique

KATRIN

$$T_2 \rightarrow (T \cdot {}^3He^+) + e^- + \bar{\nu}_e$$

Spectroscopic: MAC-E Filter



adiabatic transformation of e⁻ momentum

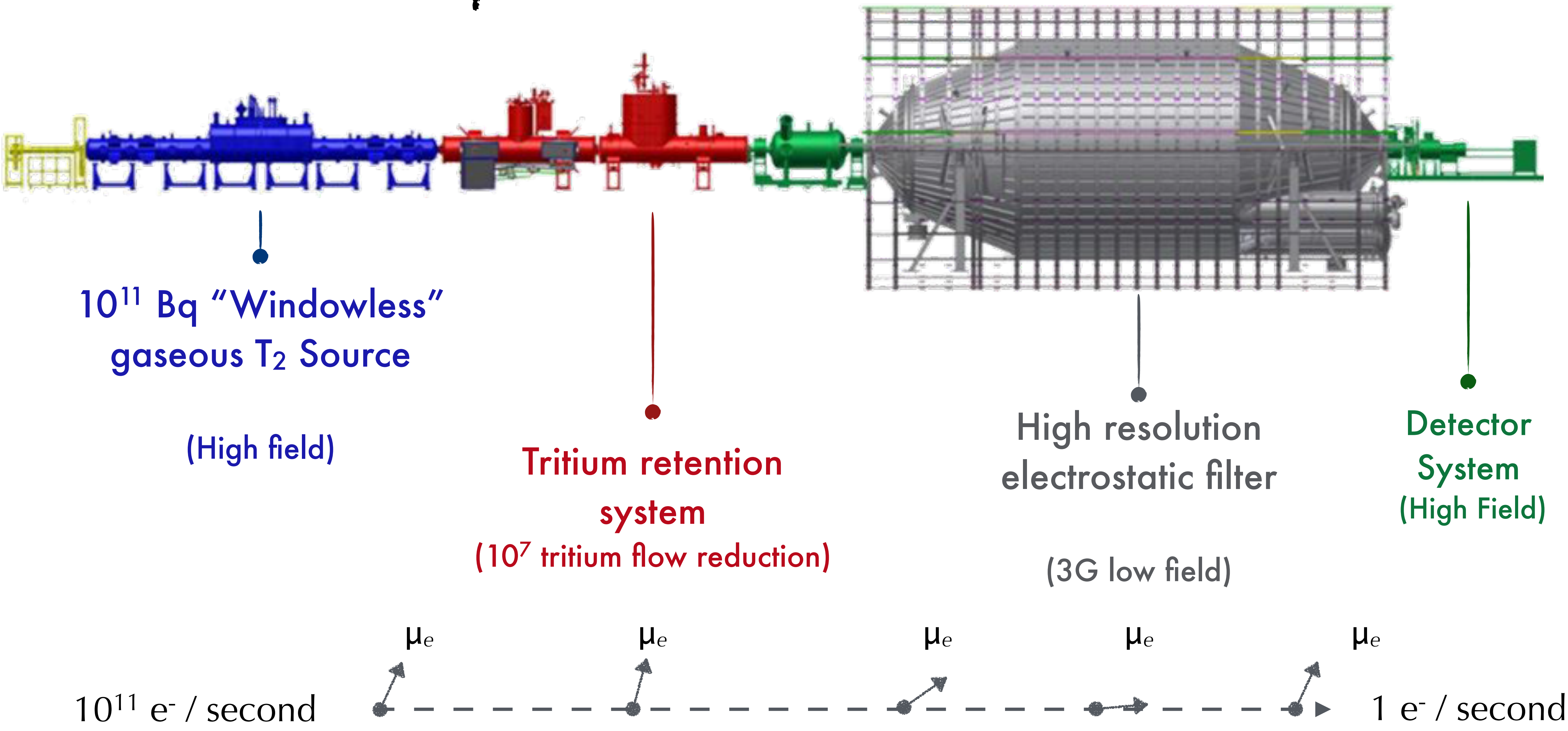
Inhomogeneous magnetic guiding field.

Retarding potential acts as high-pass filter

High energy resolution

($\Delta E/E = B_{min}/B_{max} = 0.93$ eV)

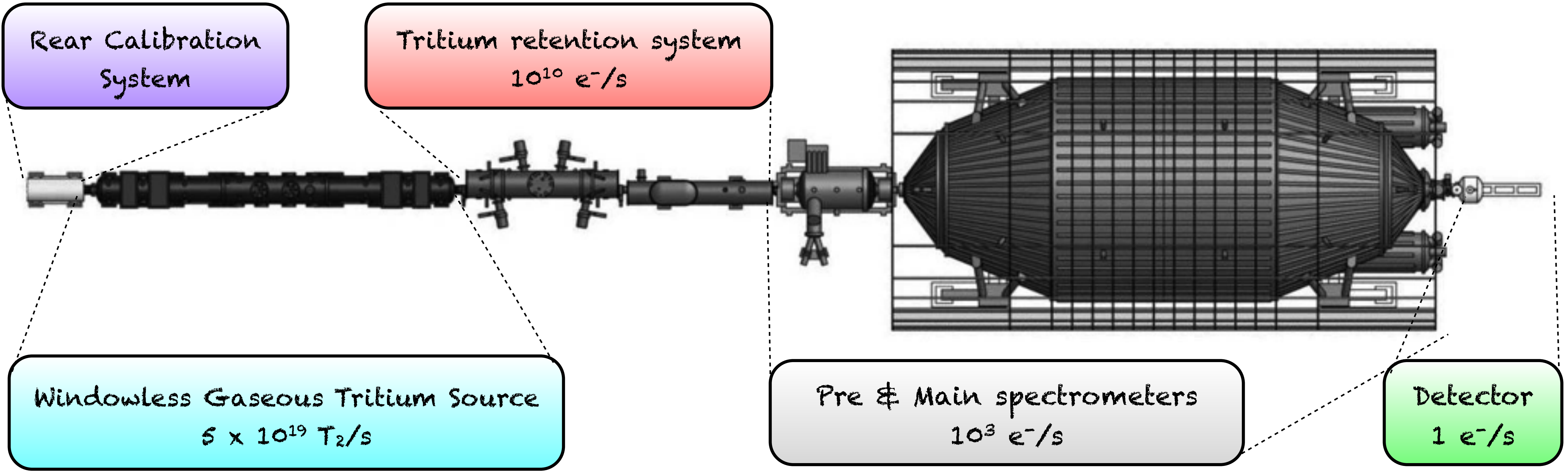
The KATRIN Setup



Adiabatic transport ensures high retention of phase space for decay

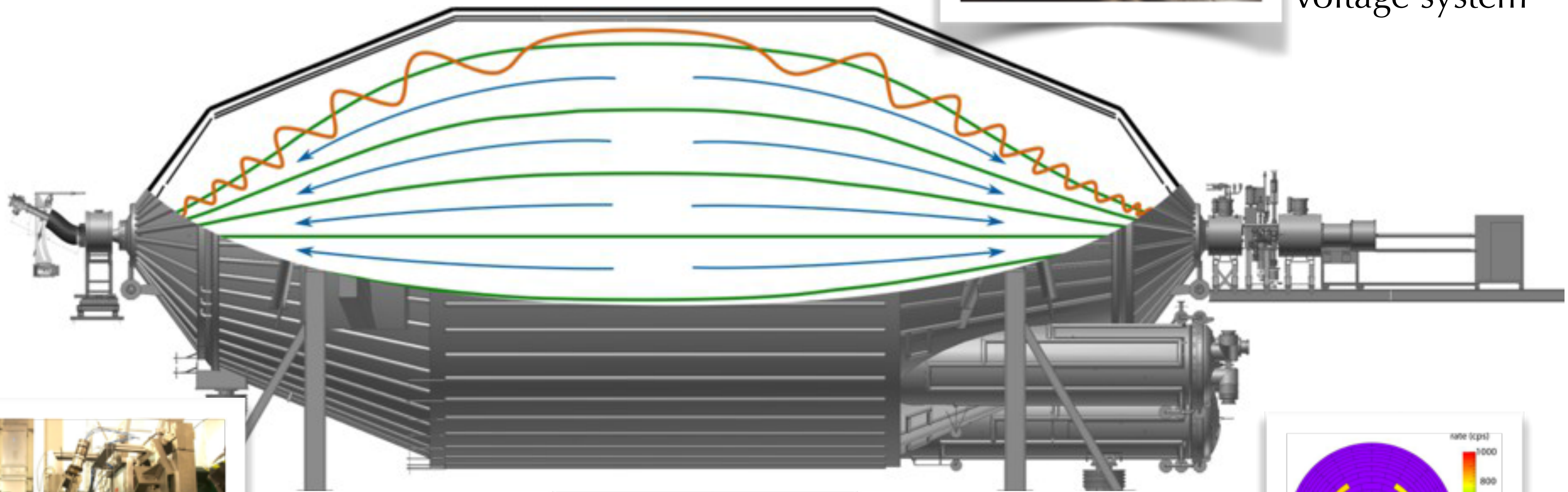
$$\frac{\Delta E}{E} = \frac{B_{\min}}{B_{\max}} \to 0.93 \text{ eV}$$

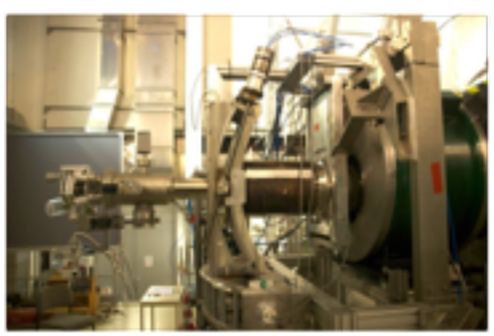
Energy resolution scales as the ratio of minimum / maximum fields


Rear Calibration System
Tritium retention system 10^{10} e^-/s
Windowless Gaseous Tritium Source 5×10^{19} T_2/s
Pre & Main spectrometers 10^3 e^-/s
Detector 1 e^-/s

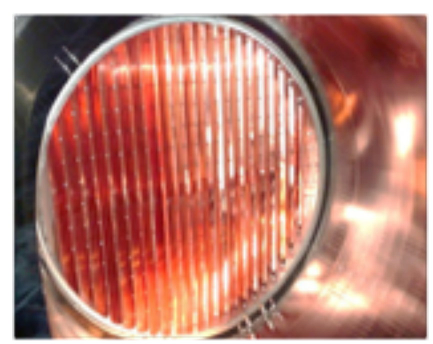
Spectrometer Commissioning

Precision high voltage system

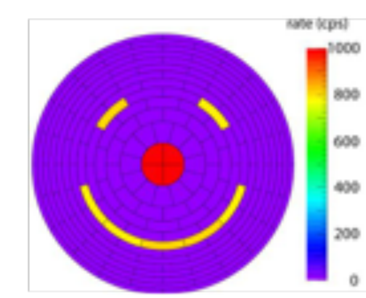




High precision electron gun



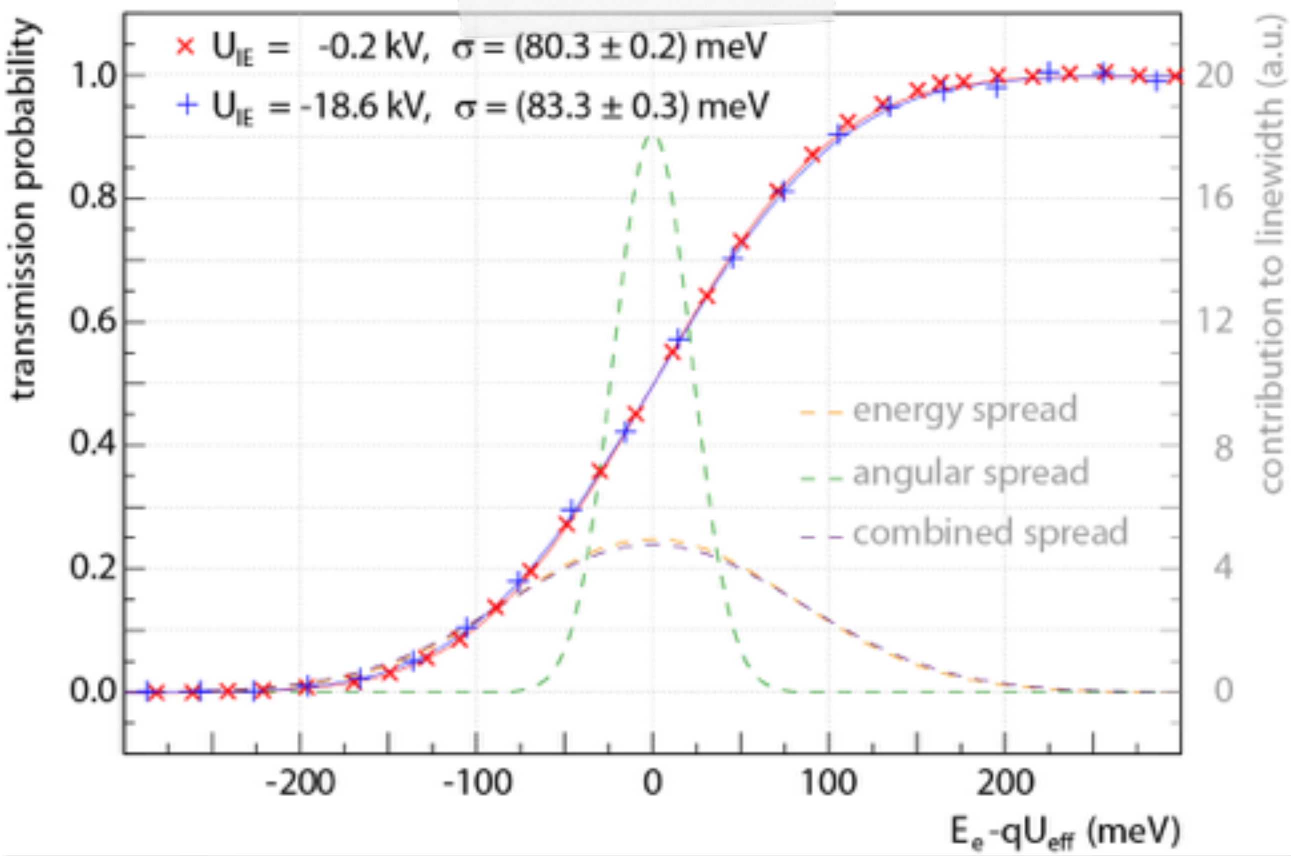
Ultra high vacuum system



Full detector system

Spectrometer and detector system fully integrated.
Allowed for test of transmission function and background levels.

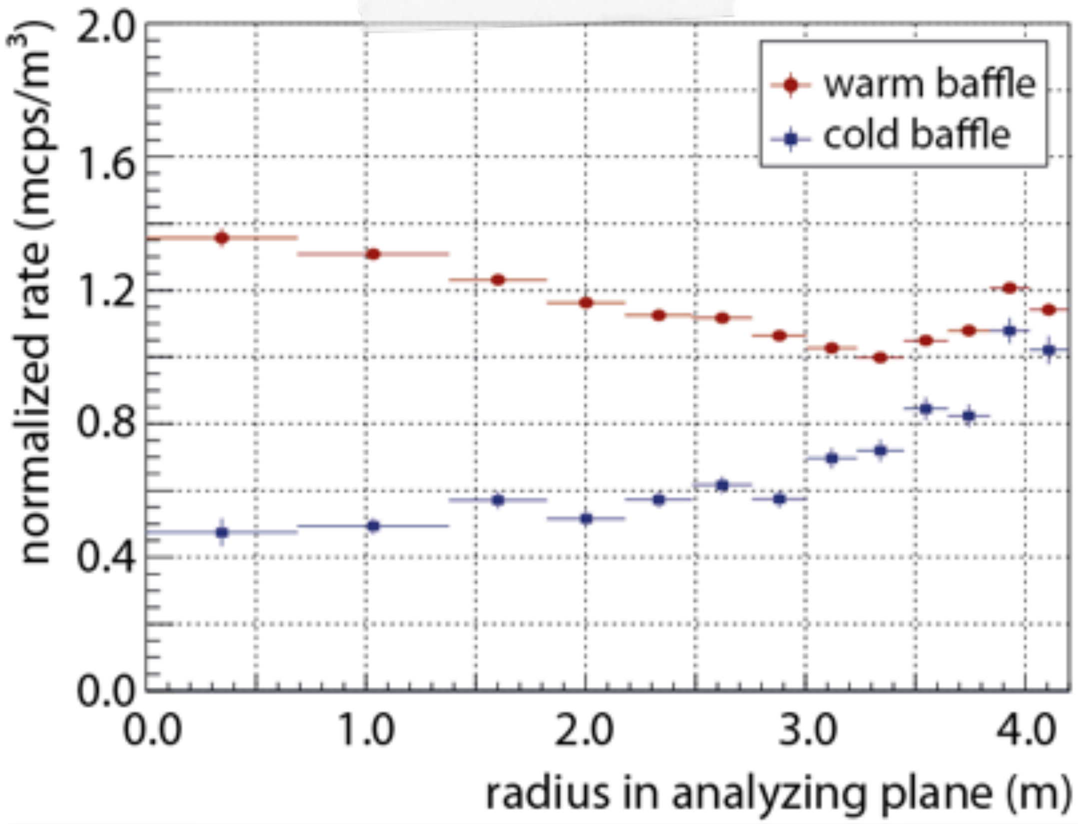
Transmission Function



At -18.6 keV, better than 100 meV resolution

Sharpest transmission function for a MAC-E filter

Background Rates



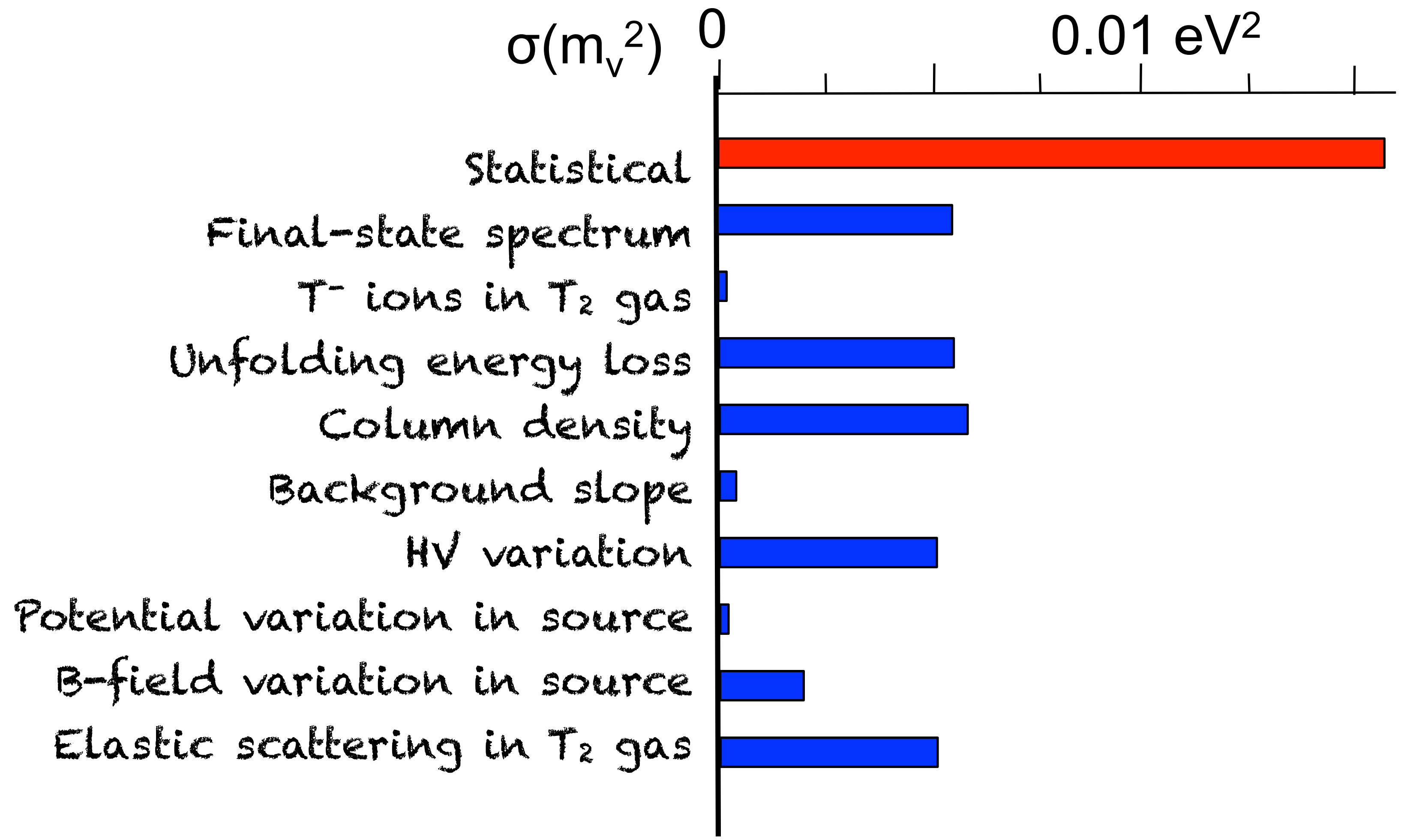
Background rate of order Hz (radon-dominated)

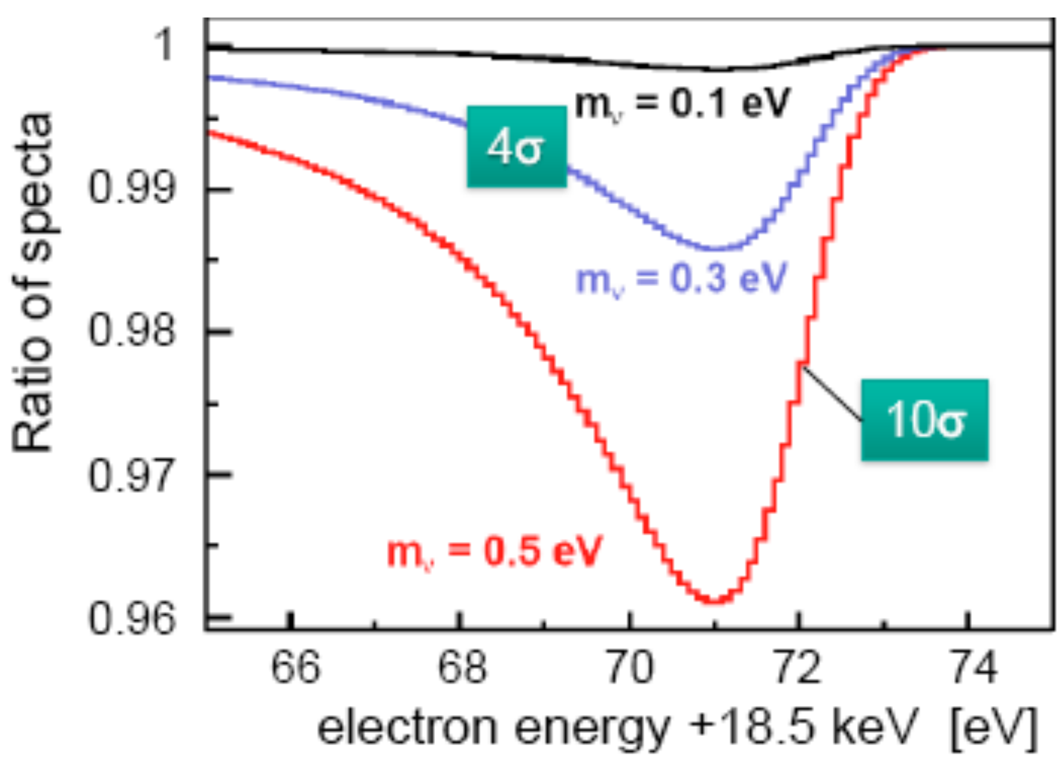
Greater reduction of backgrounds to come

Commissioning showed excellent behavior of MAC-E Filter response.

Next commissioning (now) should show greater background suppression.

Projected Sensitivity

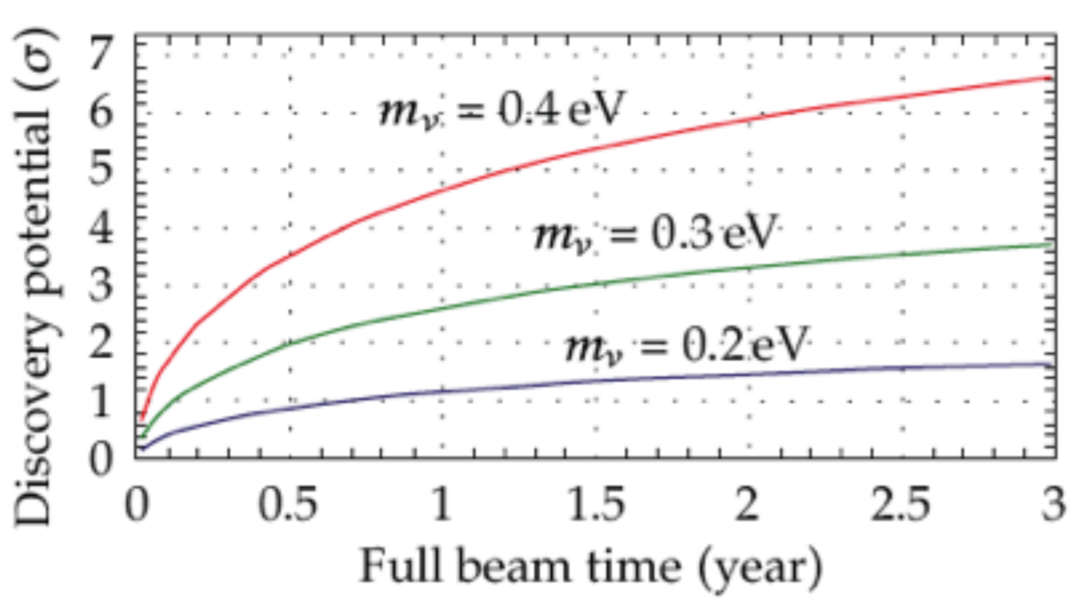




Neutrino Mass Goals

Discovery: 350 meV (at 5σ)

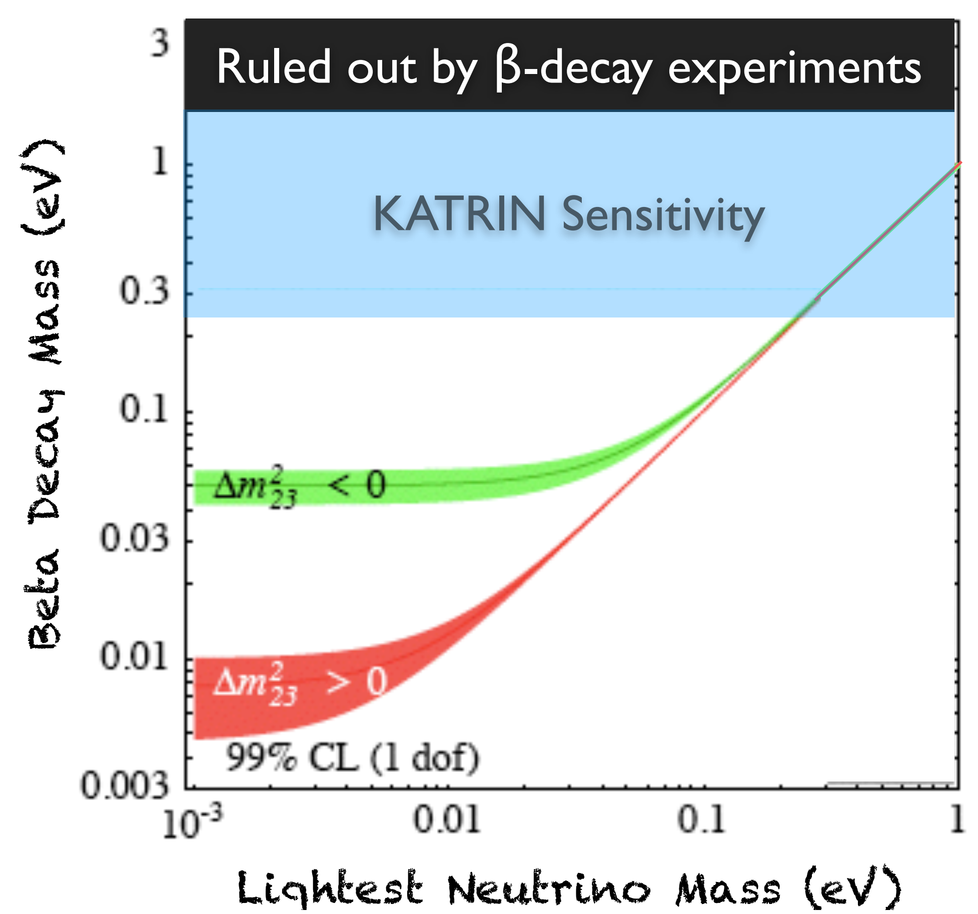
Sensitivity: 200 meV (at 90% C.L.)

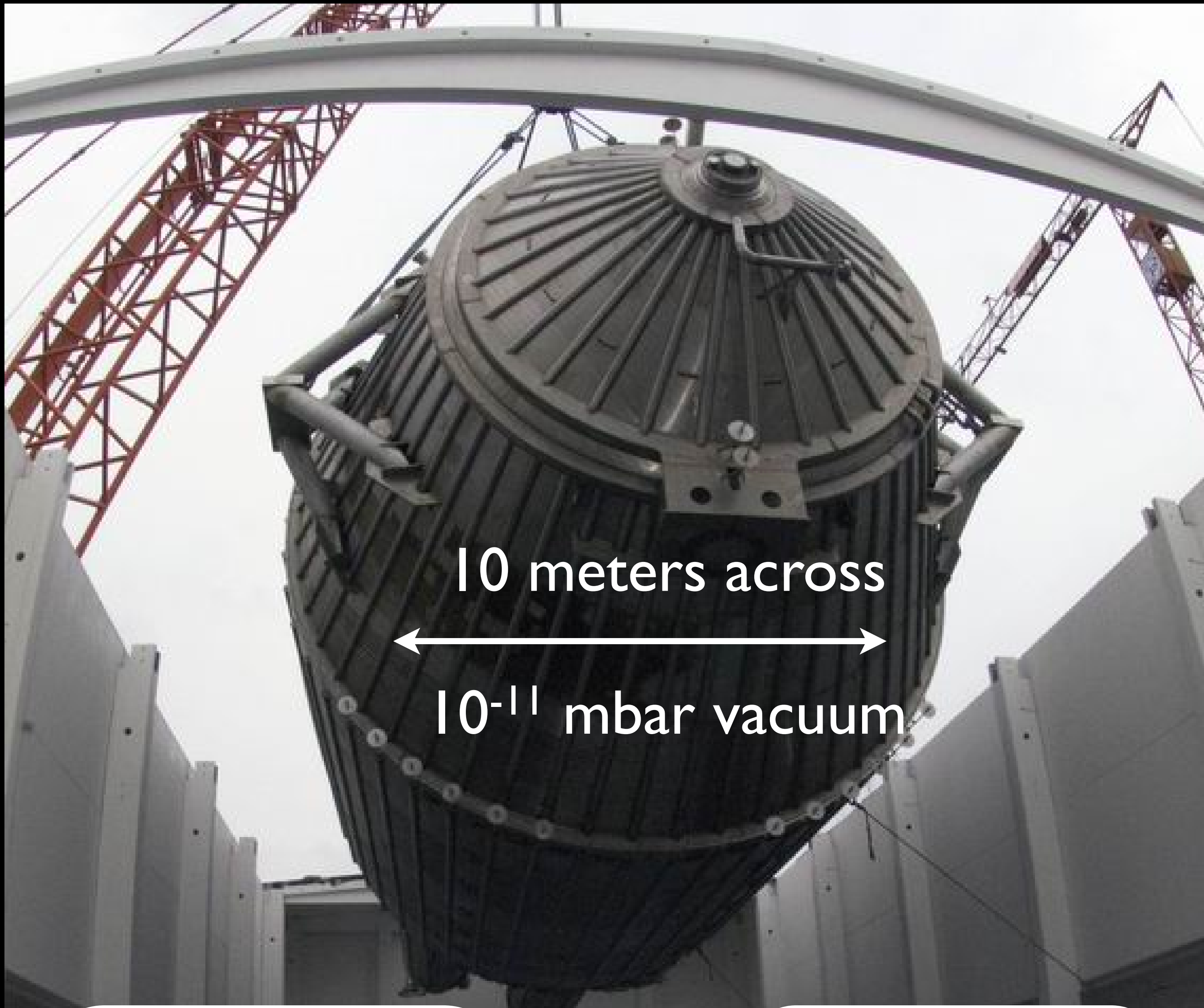


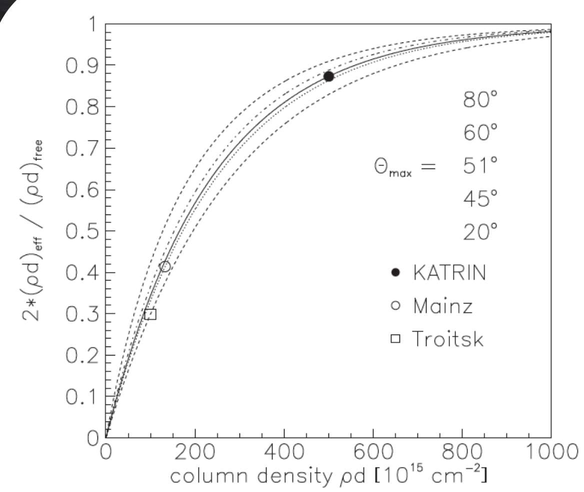
Data taking to commence in 2016.

Can we push further?

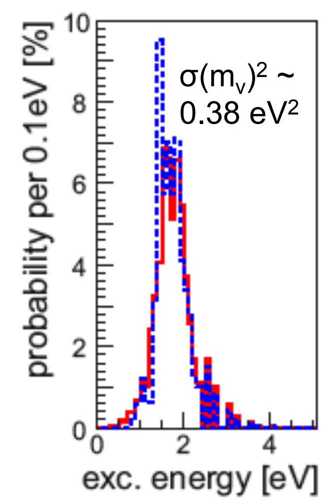
- Can direct measurements push to the inverted hierarchy scale?
- To do so, they must have better scaling law.







Source column density at max



Rovibrational states of THe^+

Time of Flight & KATRIN

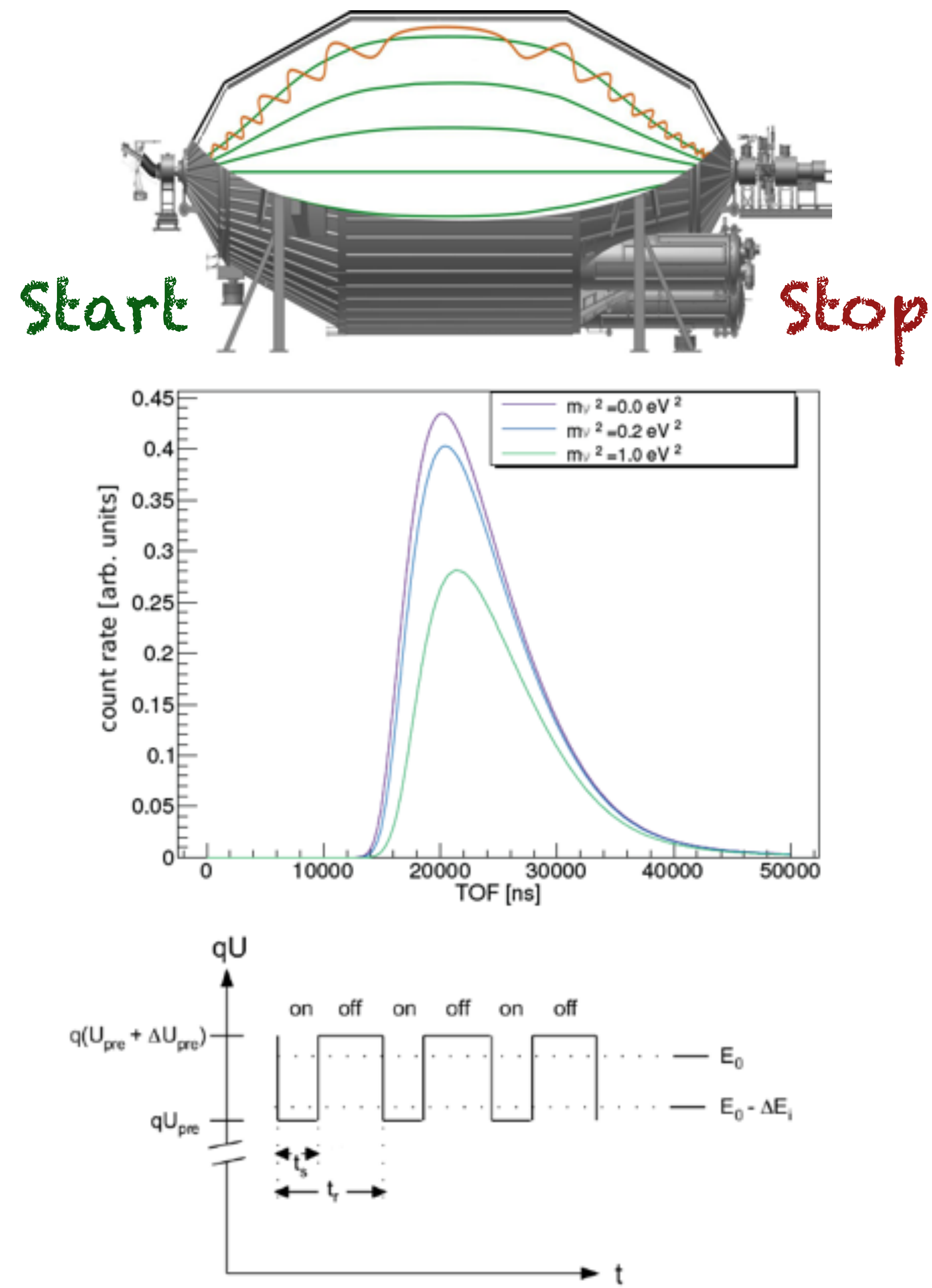
- In principle, it is possible to improve the statistical sensitivity of KATRIN by combining its energy resolution with a time-of-flight measurement.

- By tagging the electron as it travels to the detector.

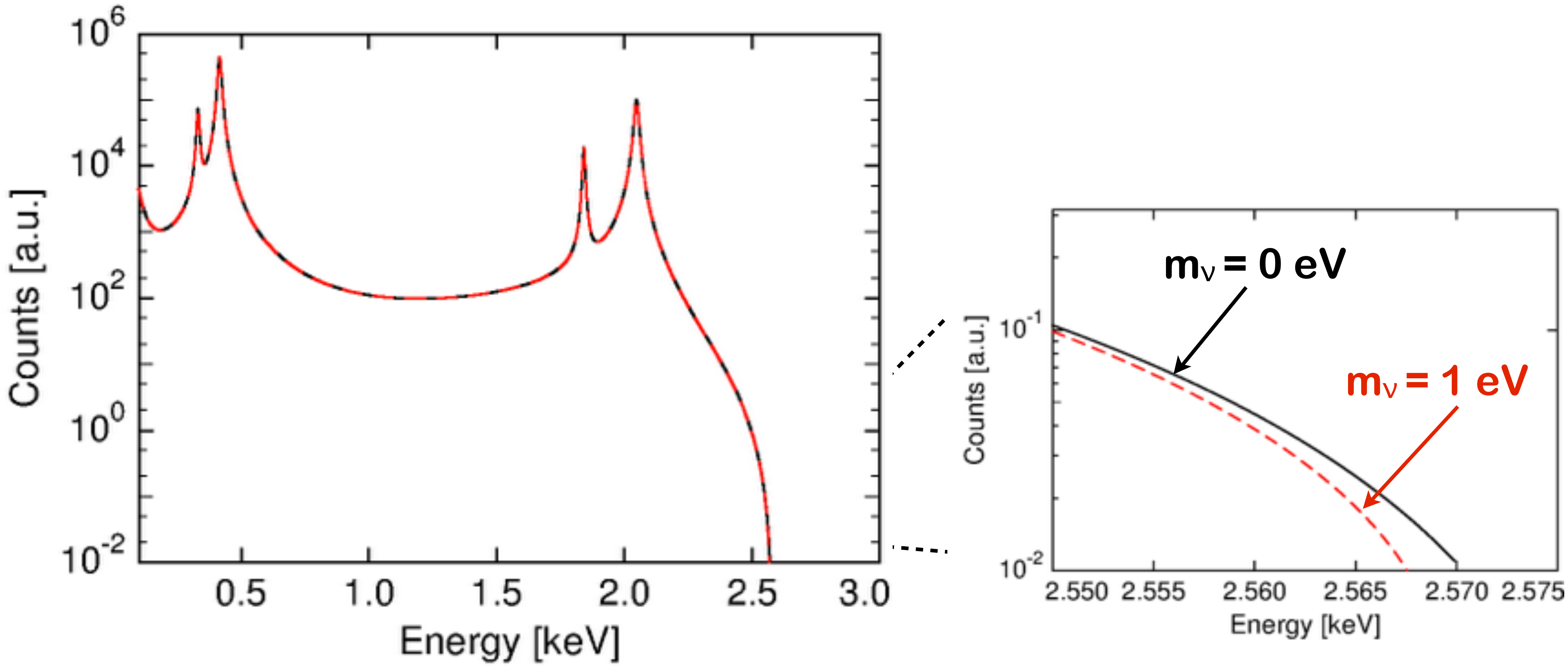
- The improvement is substantial, over a factor of 5-6 in the statistical sensitivity. However, no realistic method to tag the electron in the KATRIN experiment appears possible.

- A gated pulse is possible, but yields equivalent statistical sensitivity.

N. Steinbrink et al. New J.Phys. 15 113020(2013)



$$\dot{N} \sim (Q_{EC} - E_C)^2 \sum_i |U_{ei}|^2 \sqrt{1 - \frac{m_{\nu i}^2}{(Q_{EC} - E_C)^2}} \sum_H B_H \psi_H^2(0) \frac{\frac{\Gamma_H}{2\pi}}{(E_{EC} - E_H)^2 + \frac{\Gamma_H^2}{4}}$$

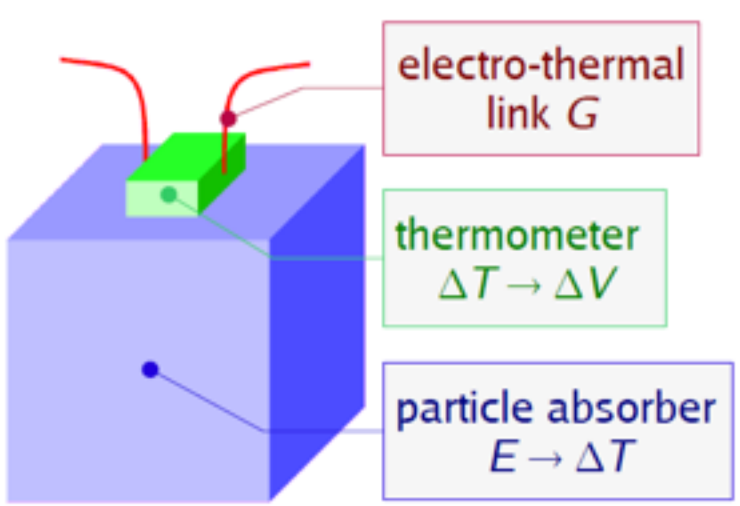


New ~~kid~~ isotope on the block:

Electron Capture

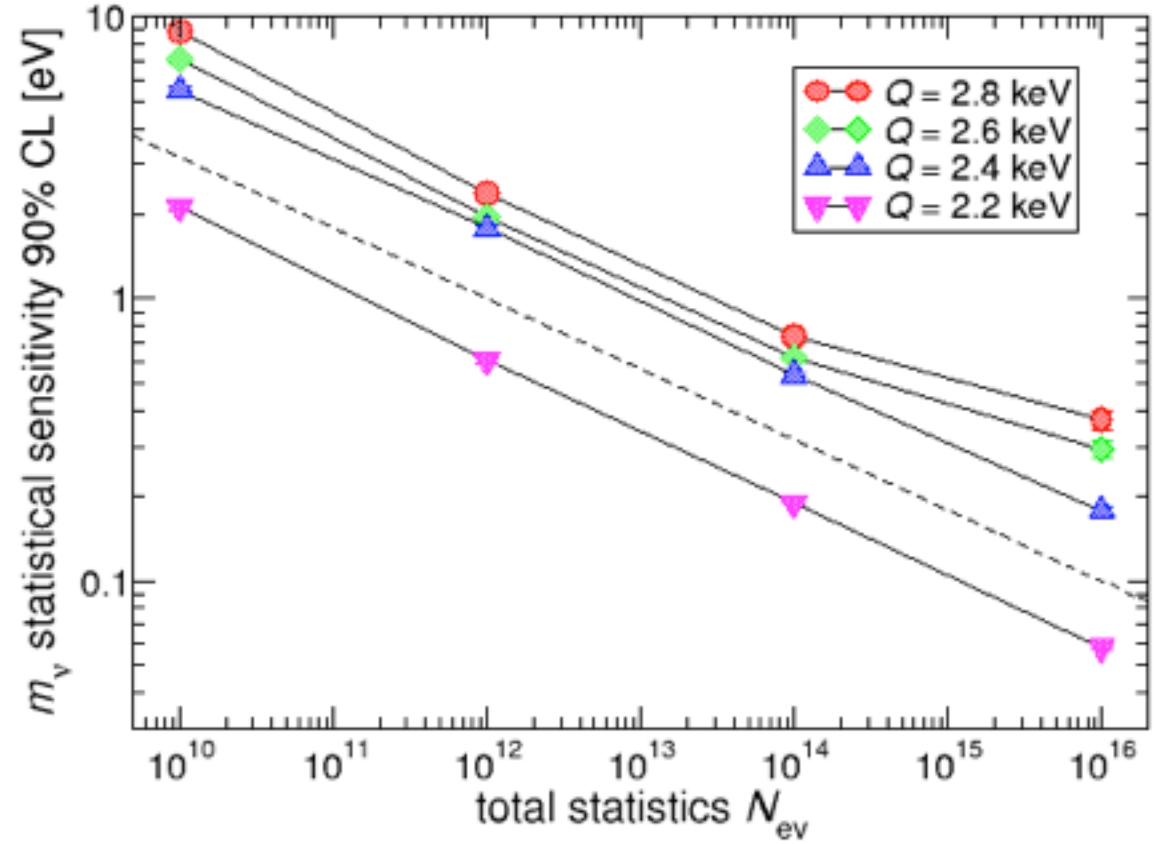
Advantages & Challenges

Calorimetry



$$^{163}\mathrm{Ho} + \mathrm{e}^- \rightarrow {}^{183}\mathrm{Dy}^* + \nu_e$$

Challenges:



Source Activity

$N_{ev} > 10^{14}$ to reach sub-eV level

Detector Response

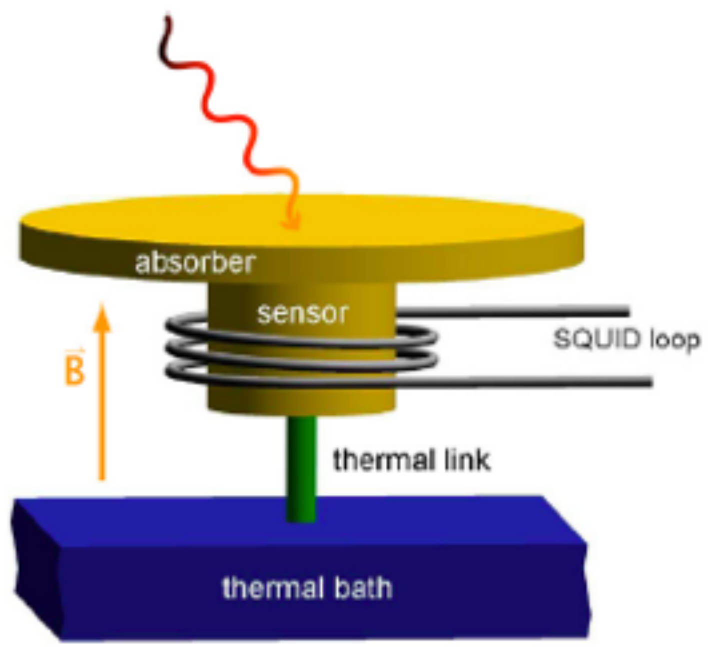
$\Delta E_{FWHM} < 10$ eV
$\tau_{risetime} < 1$ µs

- **Advantages:**
  - Source = detector
  - No backscattering
  - No molecular final state effects.
  - Self-calibrating

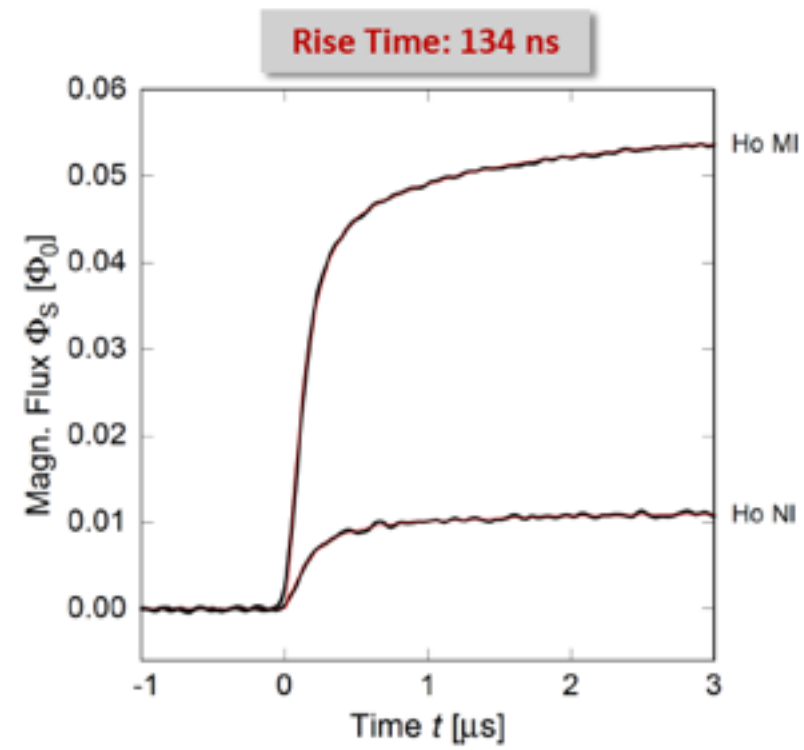
- **Experimental Challenges:**
  - Fast rise times to avoid pile-up effects.
  - Good energy resolution & linearity
  - Sufficient isotope production

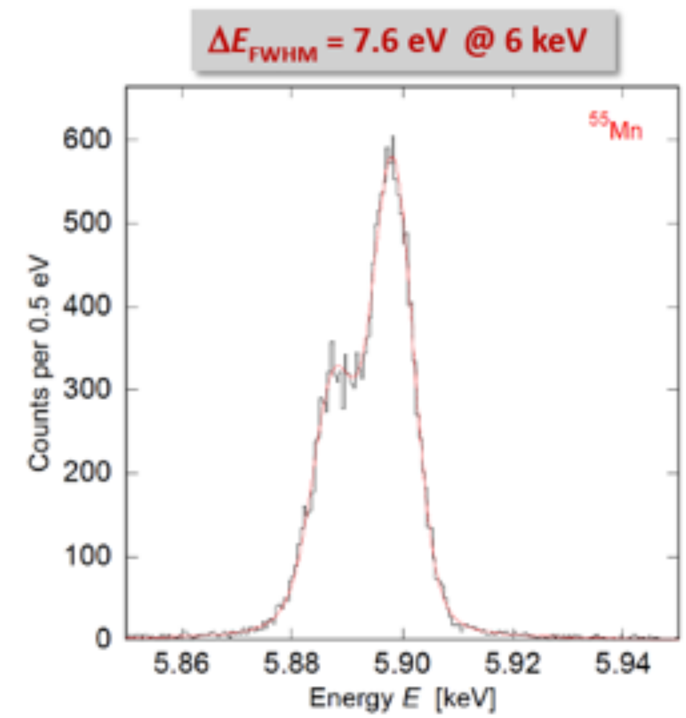
The ECHo Experiment

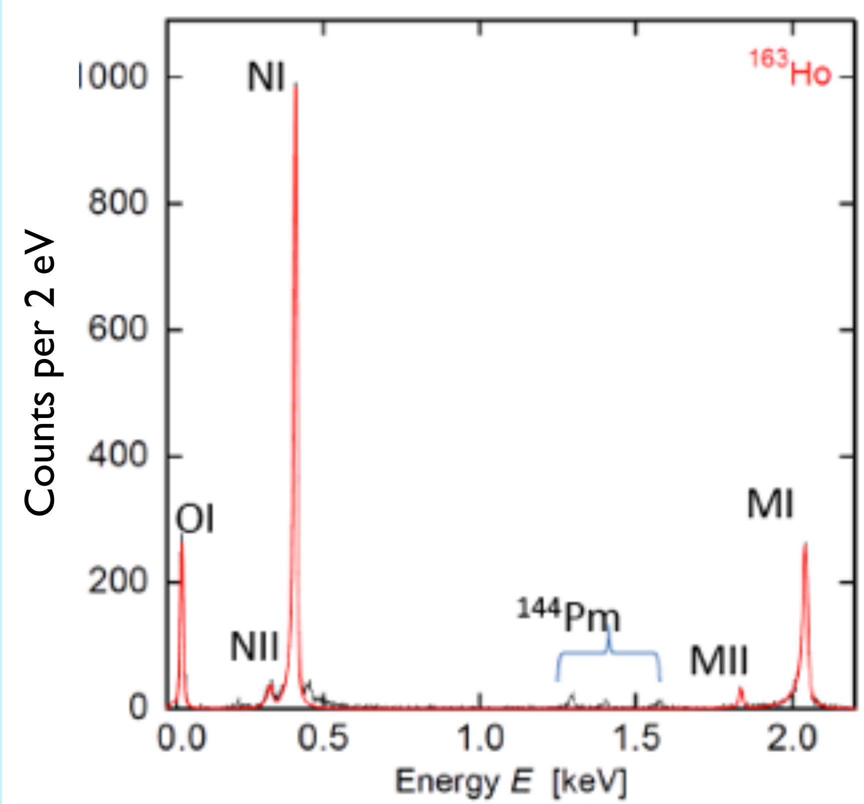
Technology:



Metallic Magnetic Calorimeters







- The ECHo experiment uses metallic magnetic calorimeters to achieve goals.
- Fast rise times and good energy resolutions and linearity demonstrated.
- Endpoint measured at 2.80 ± 0.08 keV.

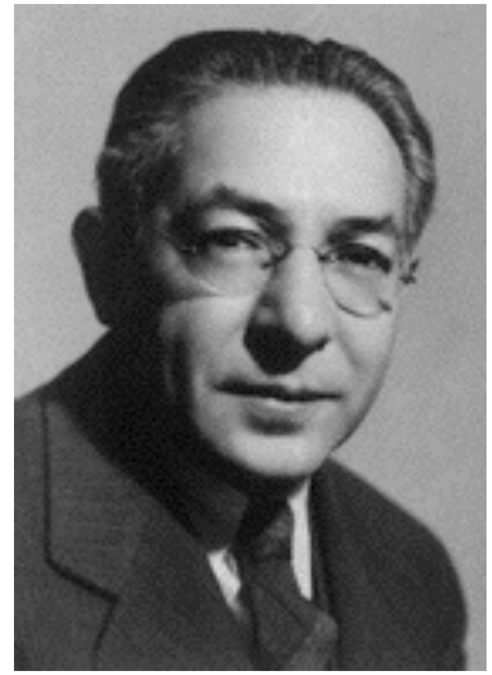
Project 8

Coherent radiation emitted can be collected and used to measure the energy of the electron in non-destructively.

PROJECT 8

Frequency Approach

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



I. I. Rabi

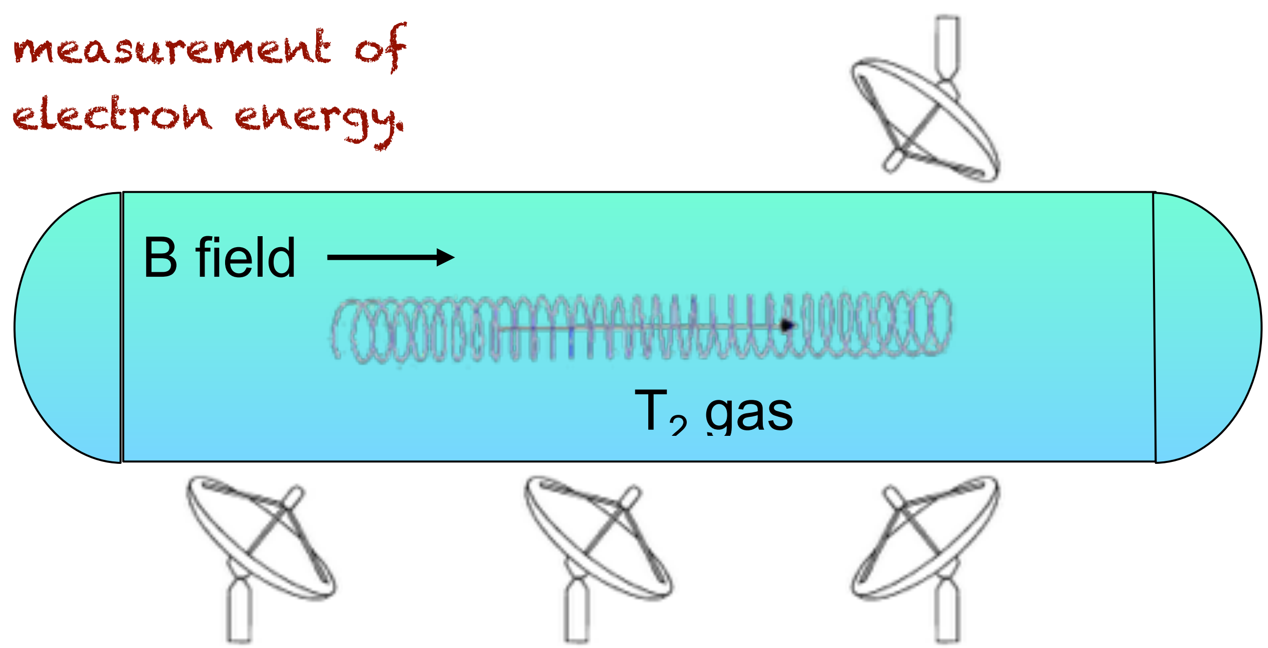
"Never measure anything but frequency."

A. L. Schawlow

- Use cyclotron frequency to extract electron energy.

$$\omega(\gamma) = \frac{\omega_0}{\gamma} = \frac{eB}{K + m_e}$$

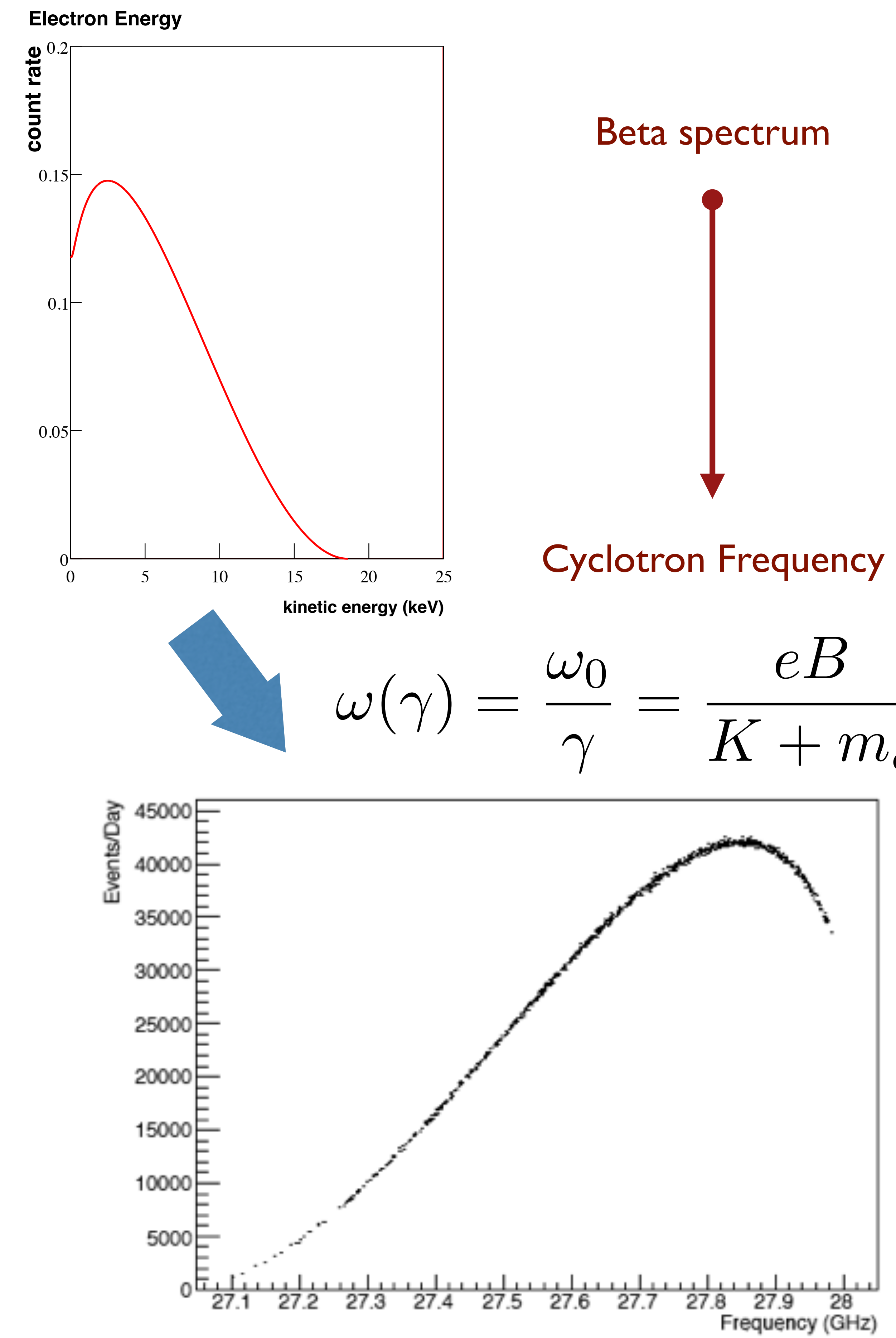
- Non-destructive measurement of electron energy.



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

Unique Advantages

- **Source = Detector**
  (no need to separate the electrons from the tritium)
- **Frequency Measurement**
  (can pin electron energies to well-known frequency standards)
- **Full Spectrum Sampling**
  (full differential spectrum measured at once, large leverage for stability and statistics)



$$\omega(\gamma) = \frac{\omega_0}{\gamma} = \frac{eB}{K + m_e}$$

Beta (frequency) spectrum

…and Challenges

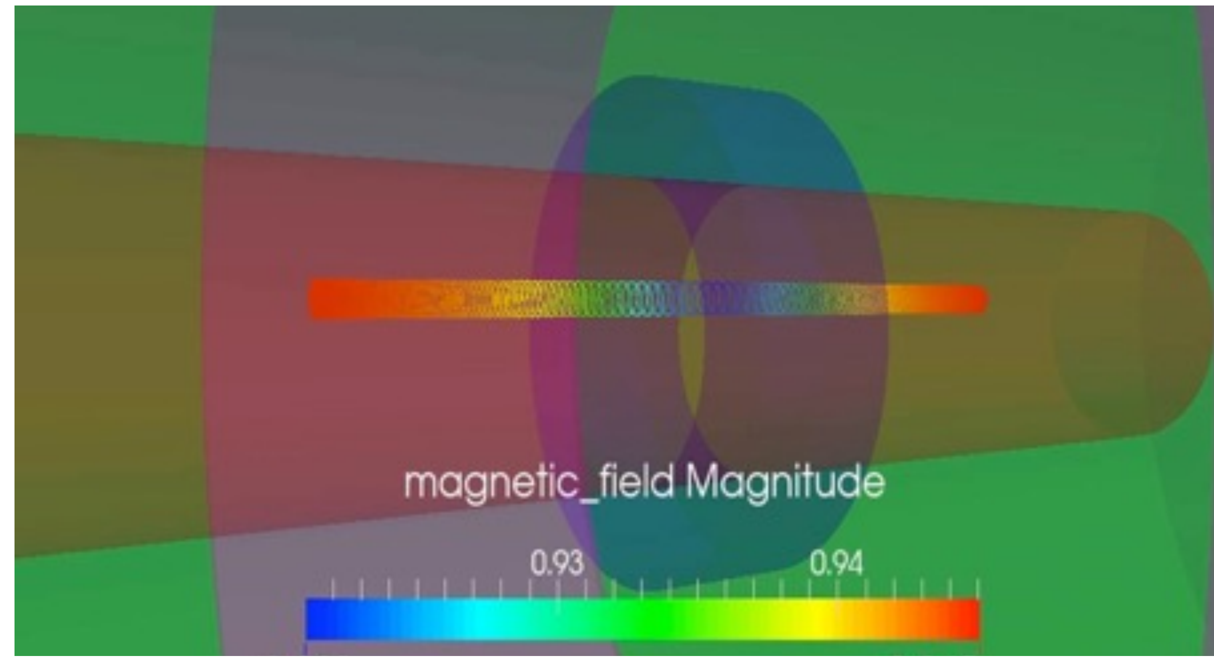
- **Power Emitted**
  Less than 1 fW of power radiated (depends on antenna geometry) is challenging.

- **Confinement Period**
  One needs time to make sufficiently accurate measurement (> 10 μs). Employ magnetic bottle for trapping.

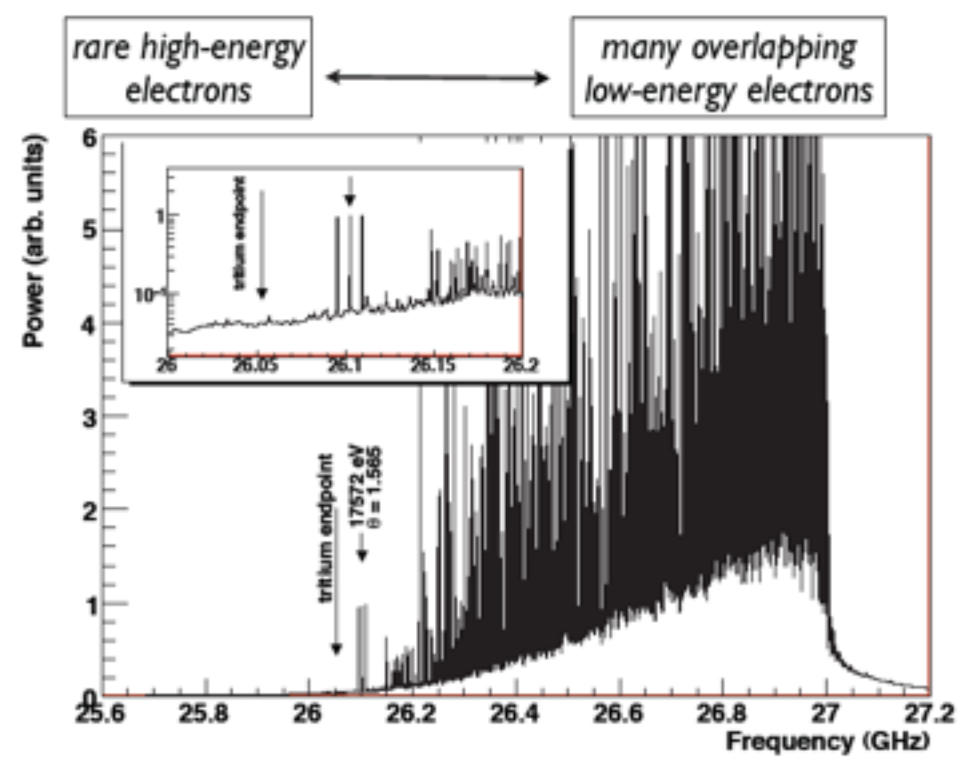
- **Full Spectrum**
  The full spectrum is available. Fortunately, linearity of frequency space helps separate regions of interest.

$$P_{\rm tot}(\beta_\parallel, \beta) = \frac{1}{4\pi\epsilon_0}\frac{2e^2\omega_0^2}{3c}\frac{\beta_\parallel^2}{1-\beta^2}$$

(Free) Radiative Power Emitted



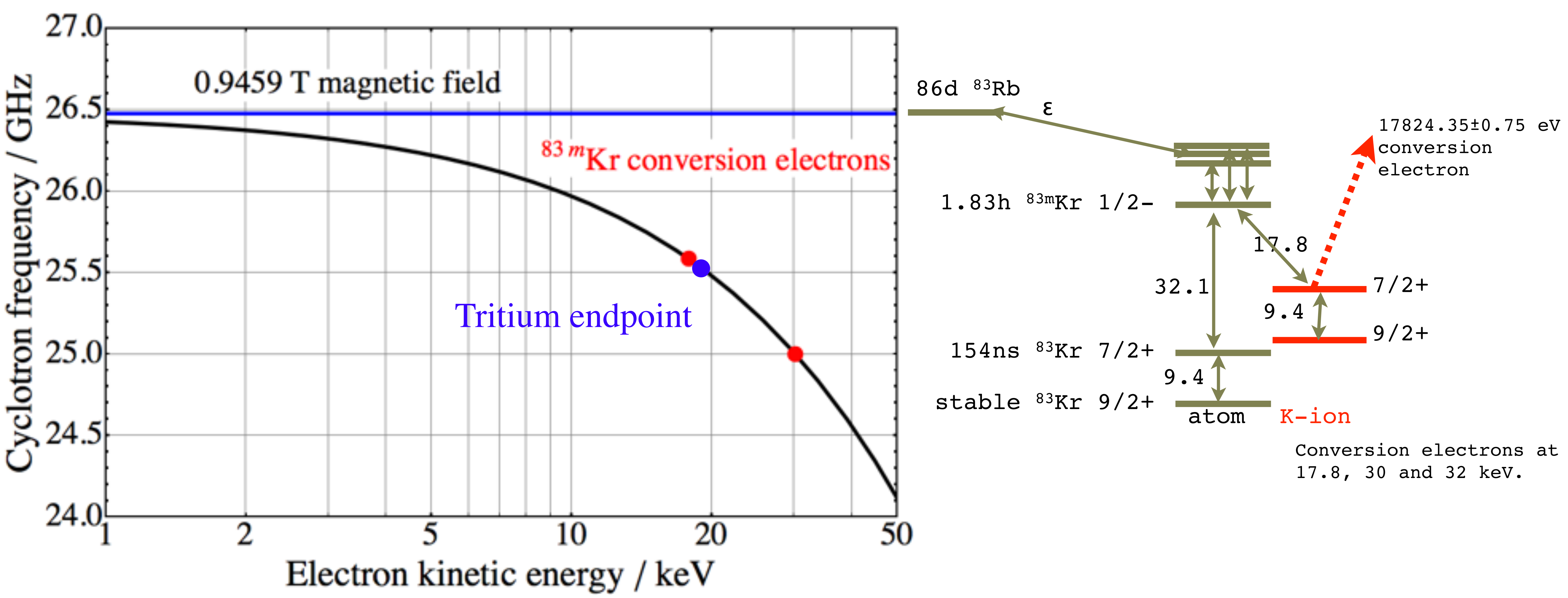
Simulation of electron motion in magnetic bottle



100,000 tritium decays in 30μs

Simulation of beta (frequency) spectrum

Initial Demonstration: ^{83m}Kr



Phase I : Use mono-energetic source to determine single electron detection.

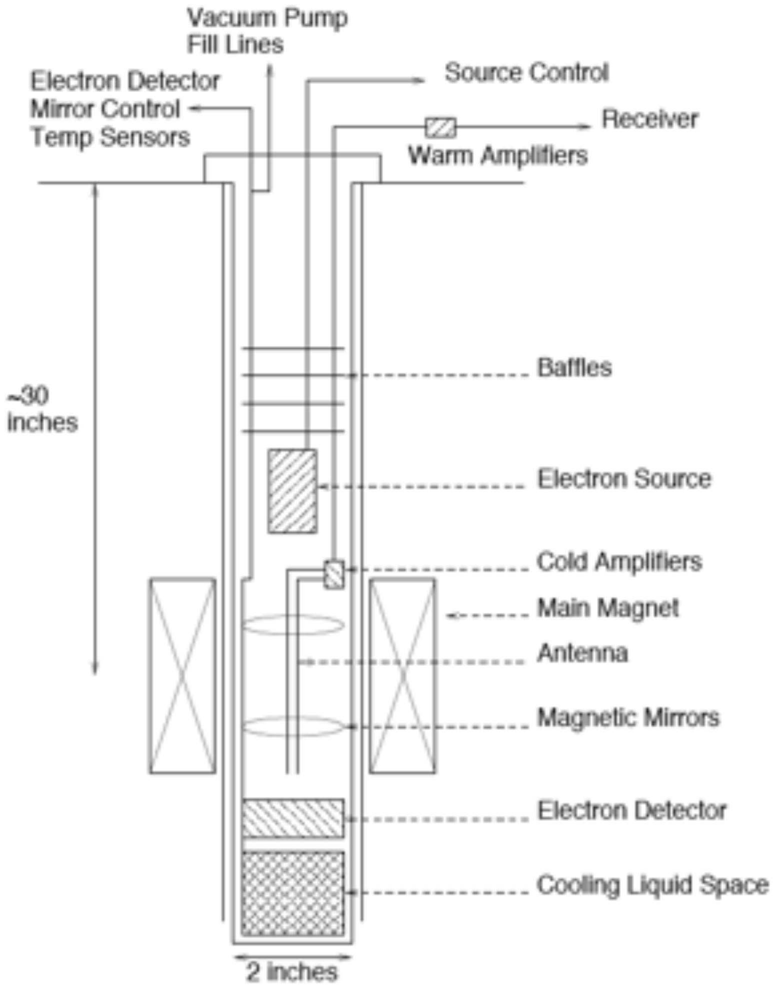
Use of standard gaseous ^{83m}Kr source allows quantification of energy resolution and linearity.

Basic Layout of Phase I

- **Gas/Electron System**
  Provides mono-energetic electrons for signal detection.

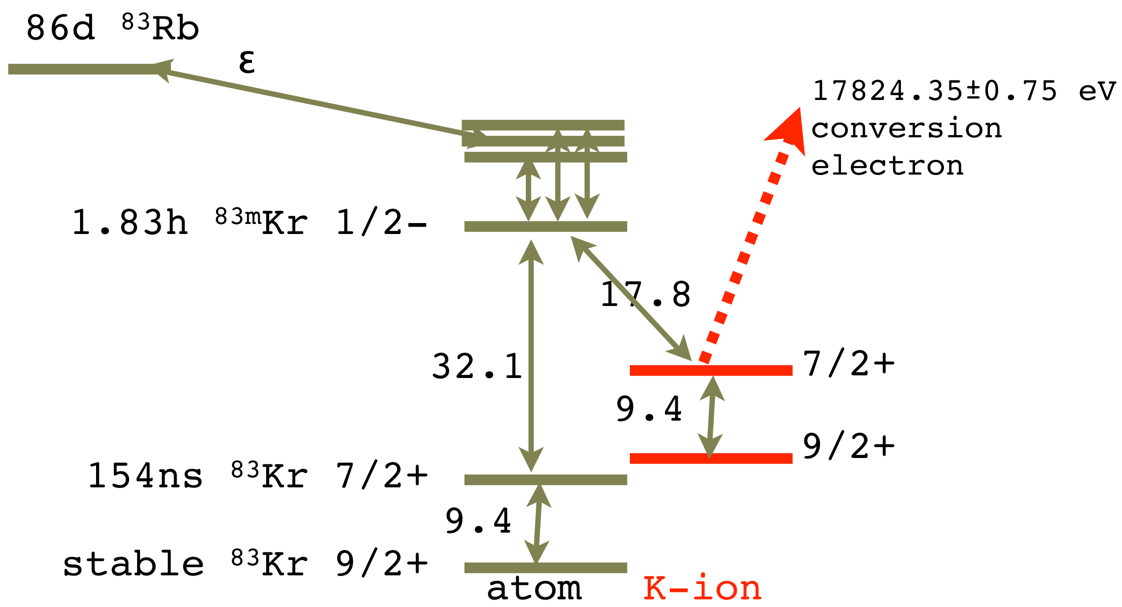
- **Magnet System**
  Provides magnetic field and trapping of electrons.

- **RF Detection/Calibration System**
  Detection of microwave signal.



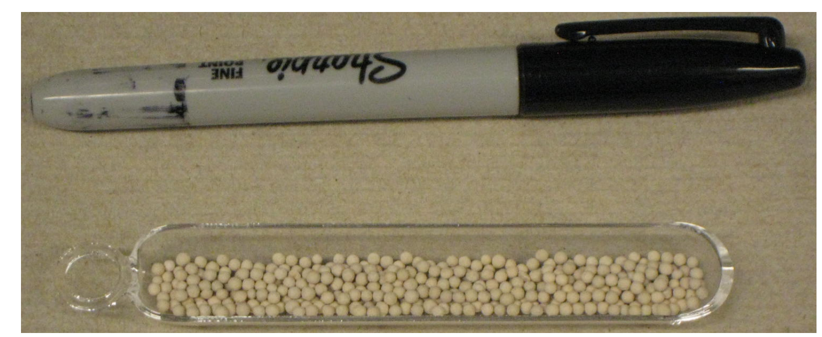
The Electron Source

Initial Demonstration Source: ^{83m}Kr



Conversion electrons at
30 and 32 keV also exist.

Zeolite loading



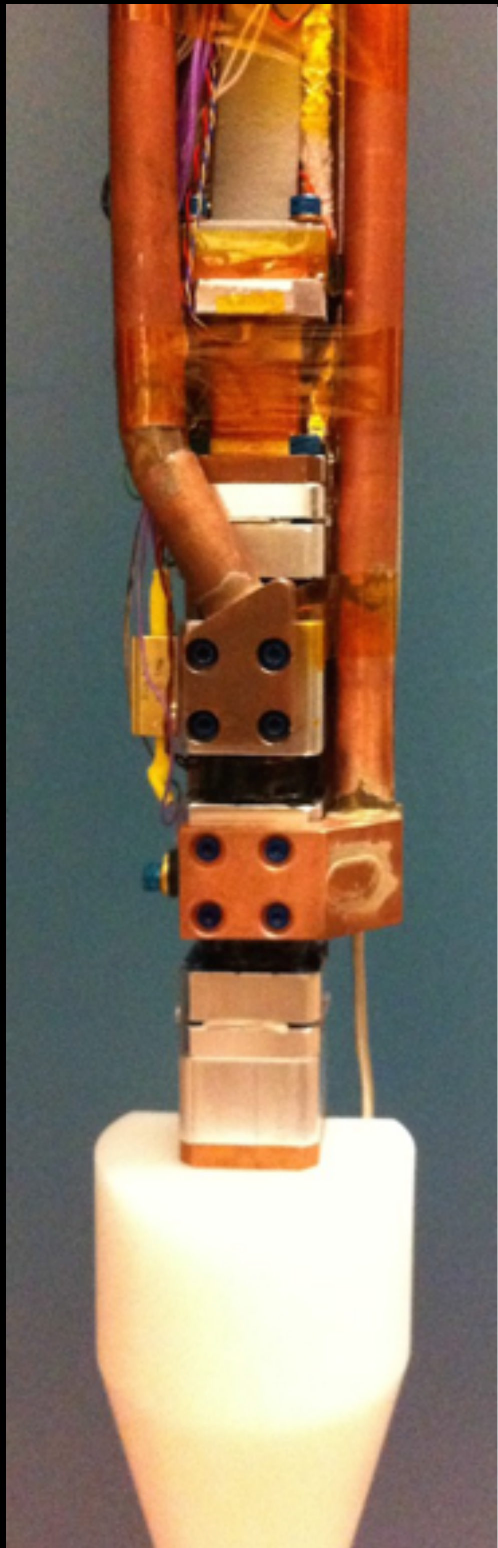
Mono-energetic gaseous electron source

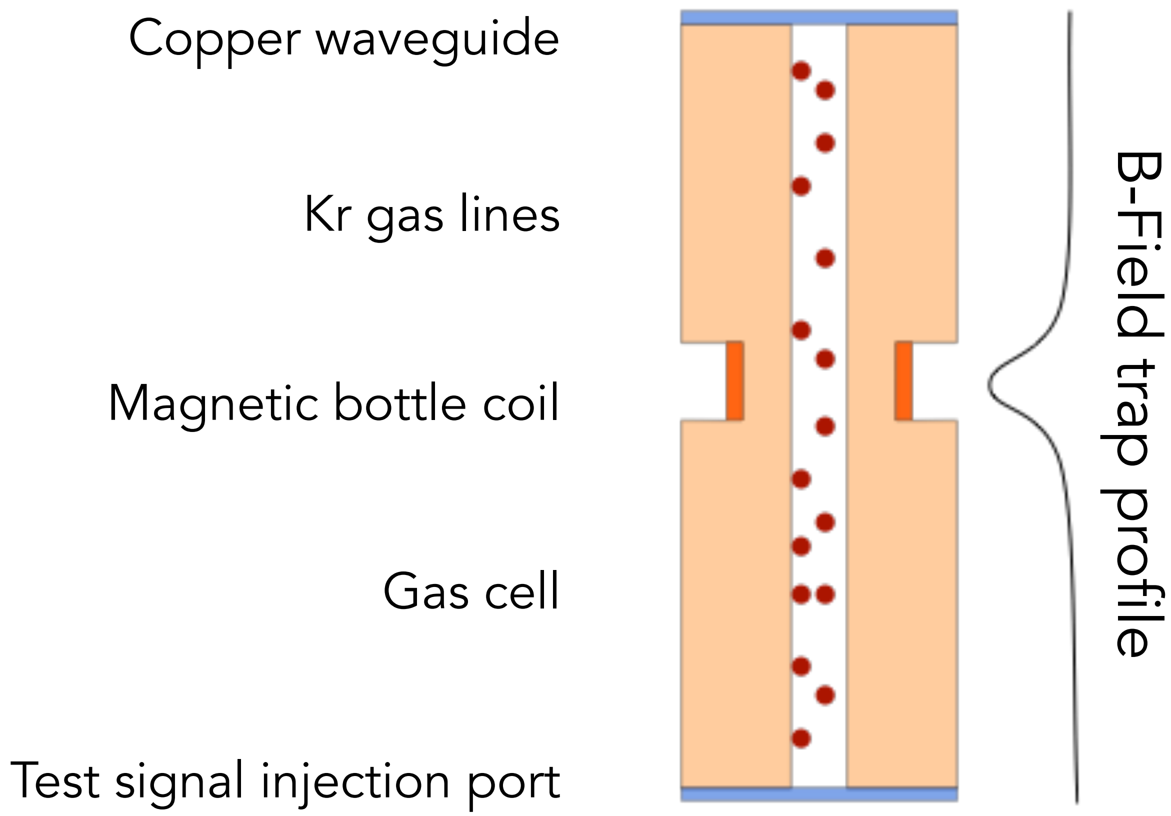
Collaboration taking a phased approach to understand the scaling and systematics of the experiment.

First phase (single electron detection) requires single electron detection.

Using ^{83m}Kr (^{83}Rb implanted in zeolite beads) as source

The Apparatus





Waveguide
Cut-away

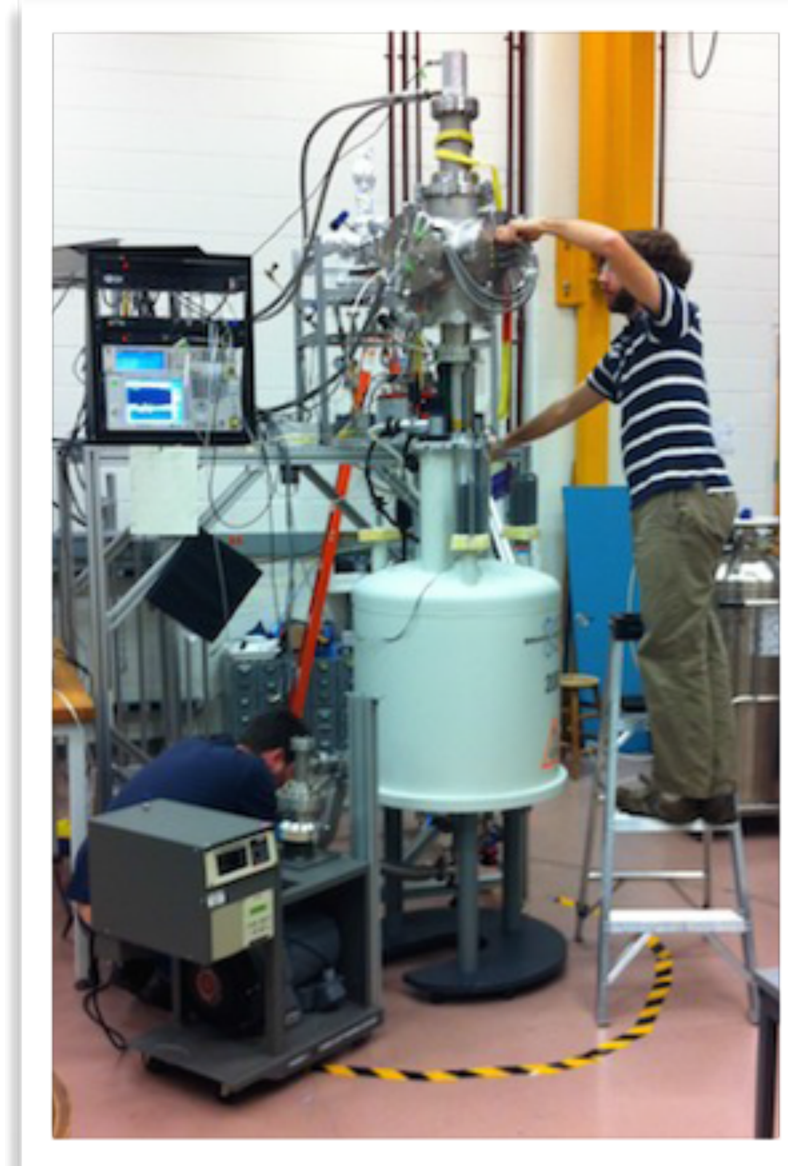
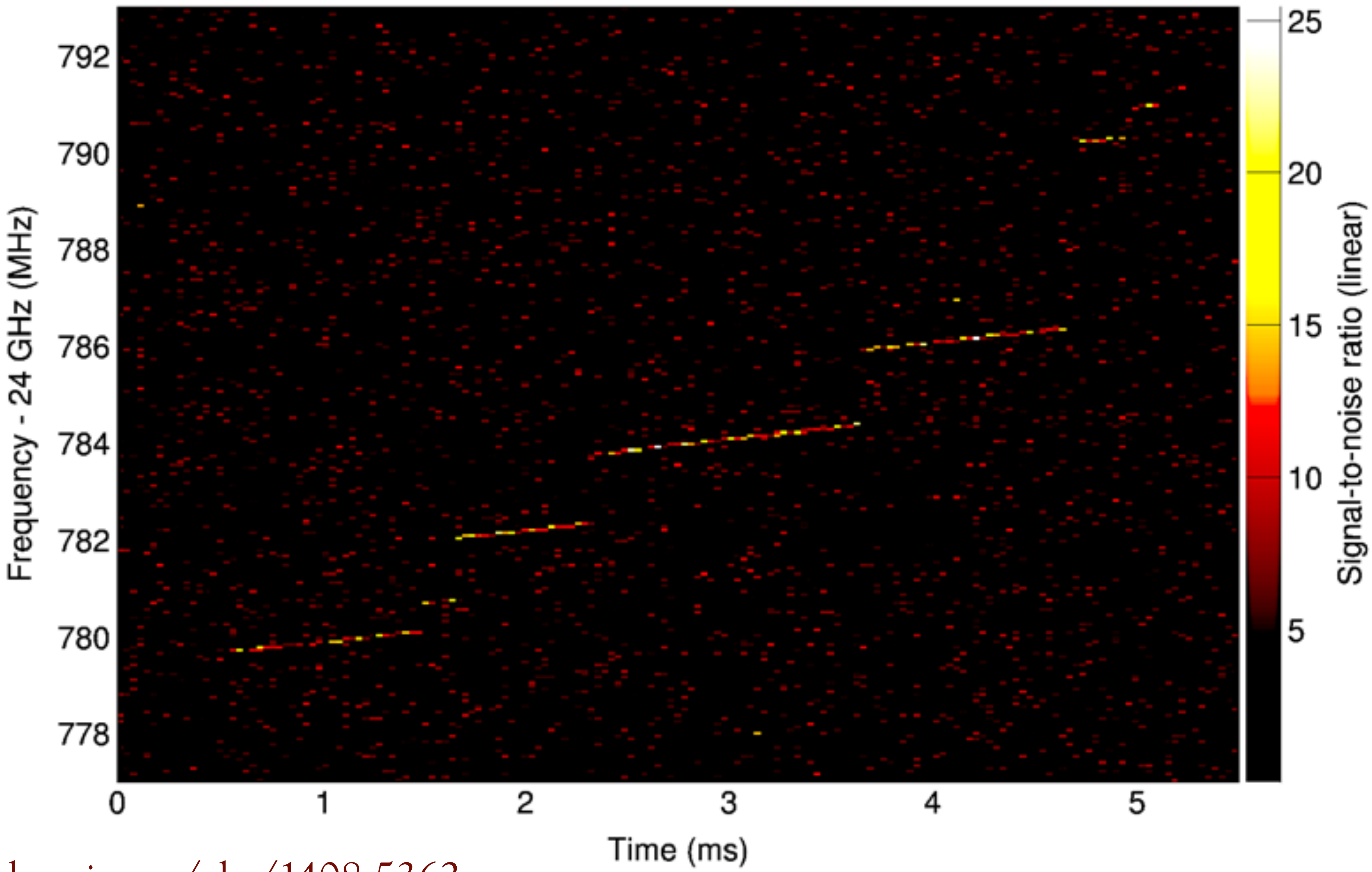


Photo of apparatus

Cyclotron frequency coupled directly to standard waveguide at 26 GHz, located inside bore of NMR 1 Tesla magnet.

Magnetic bottle allows for trapping of electron within cell for measurement.

Project 8 "Event Zero"

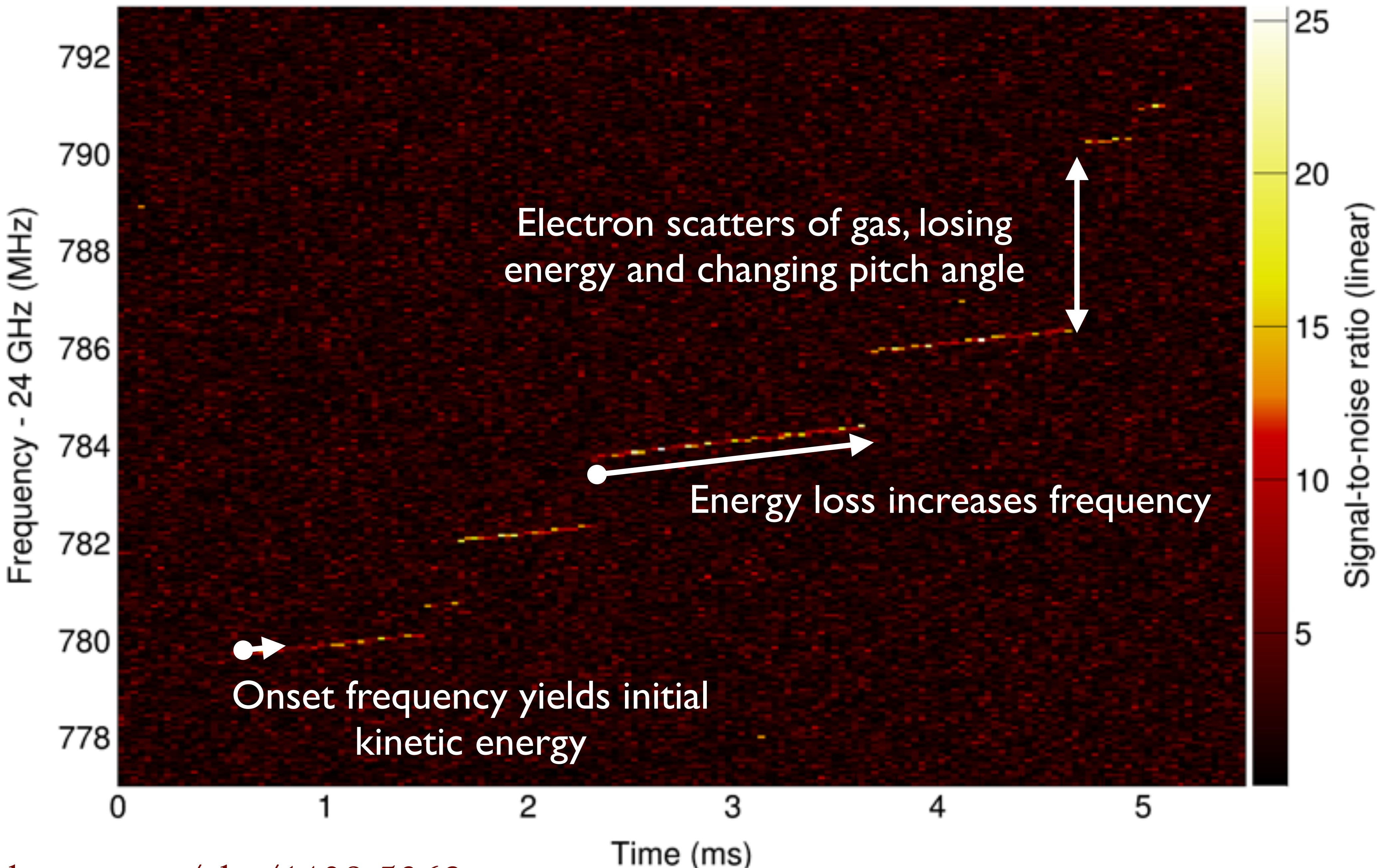


http://lanl.arxiv.org/abs/1408.5362

First detection of single-electron cyclotron radiation.

Data taking on June 6th, 2014 immediately shows trapped electrons.

Project 8 "Event Zero"

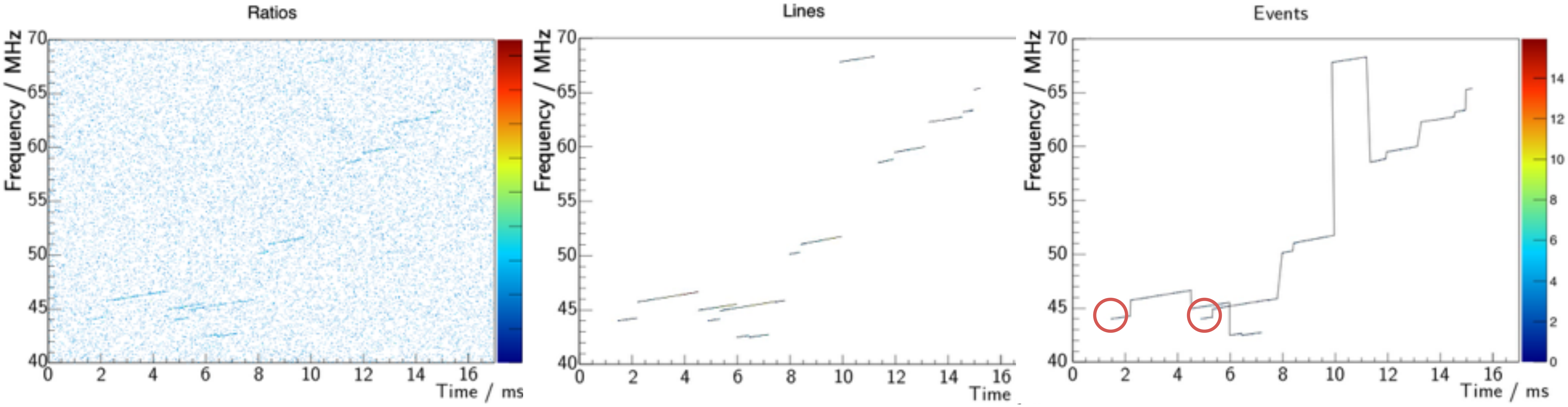


http://lanl.arxiv.org/abs/1408.5362

First detection of single-electron cyclotron radiation.

Data taking on June 6th, 2014 immediately shows trapped electrons.

Image Reconstruction & Energy Resolution

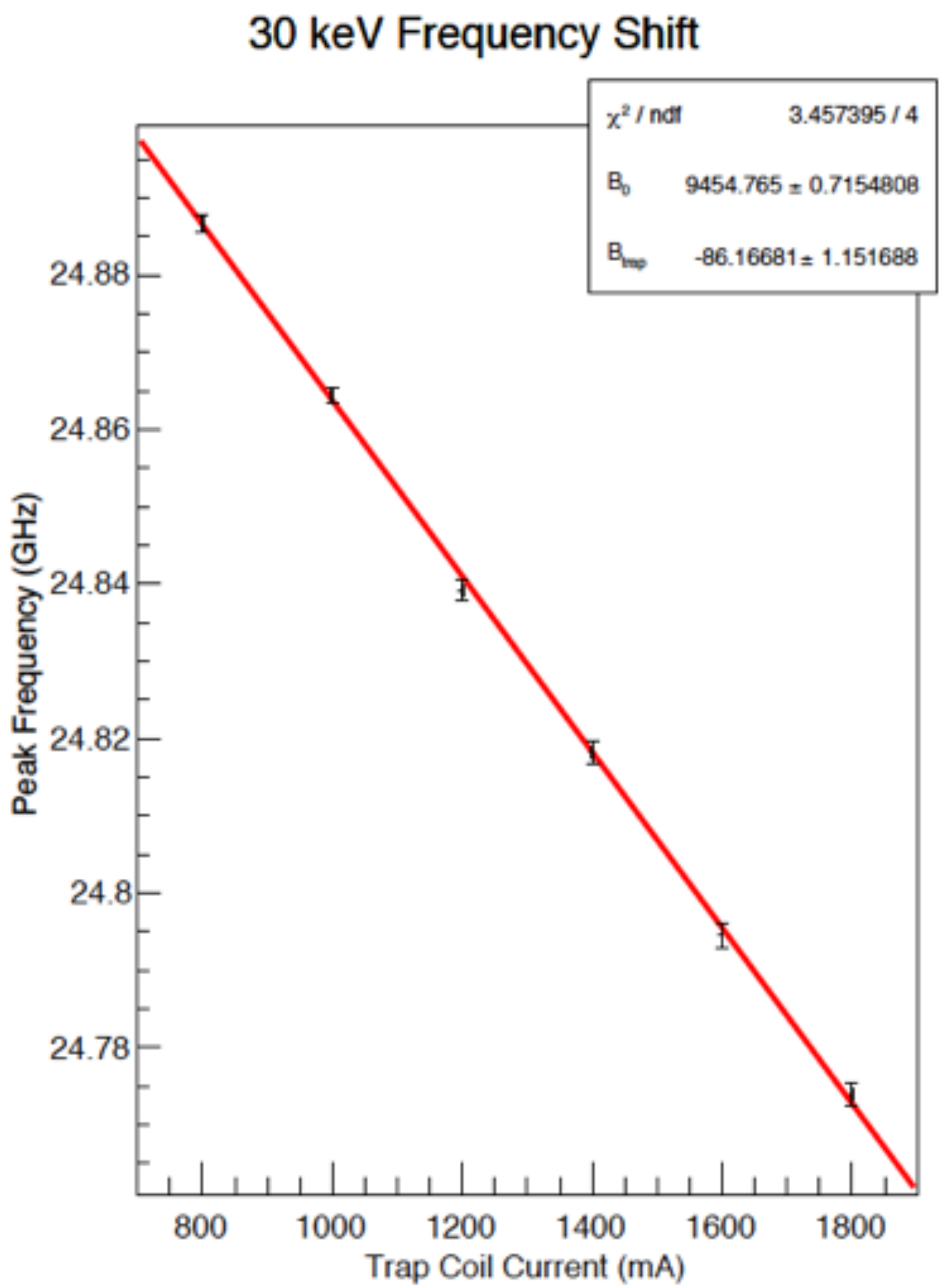


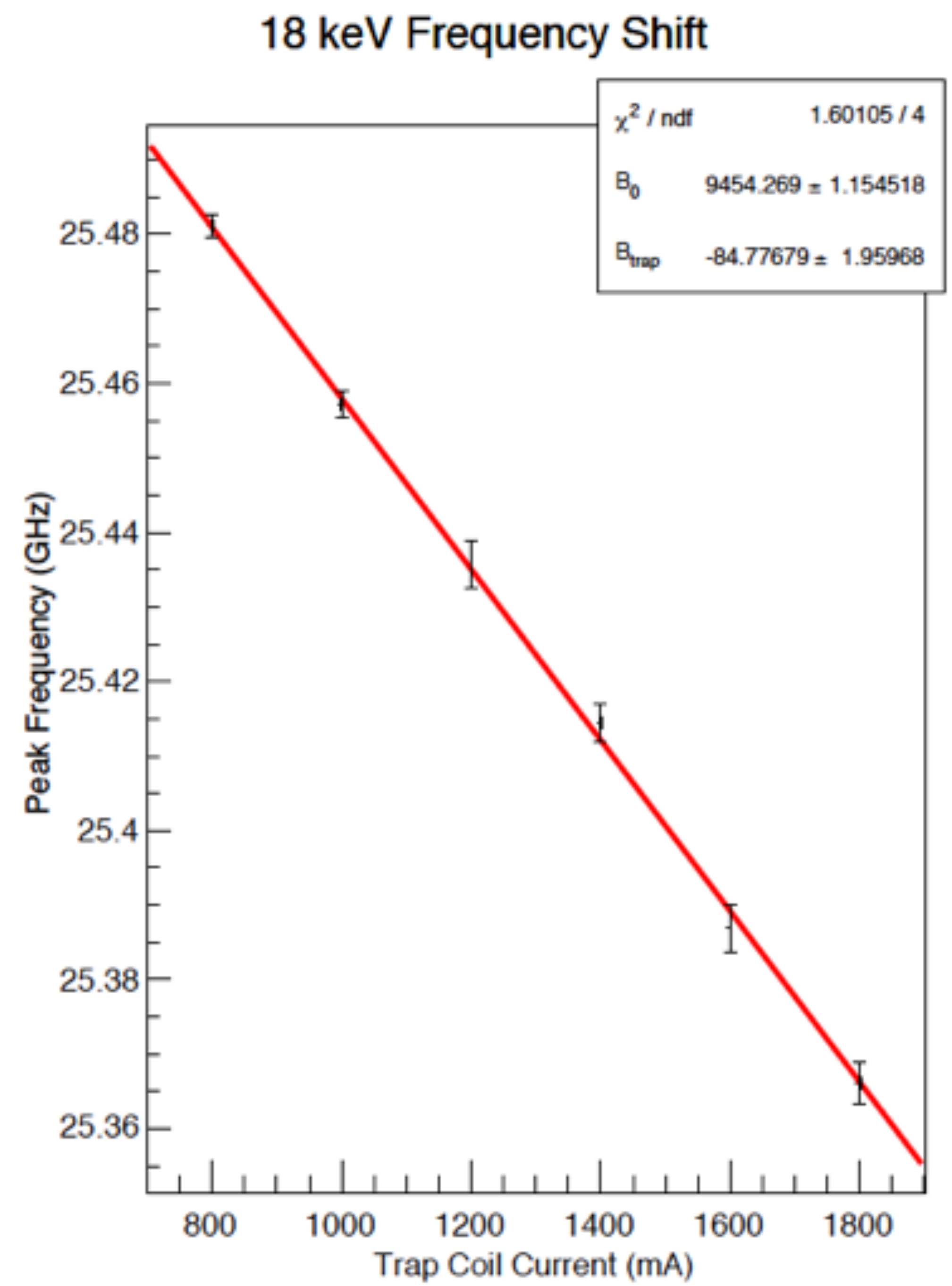
clusters above threshold turn into… tracks, which in turn become… …events

Cyclotron Radiation Emission Spectroscopy (CRES) allows extraction of many details from trapped electrons (energy, resolution, confinement time, etc.)

Reduces to an image analysis for event characterization.

Trap Dependence

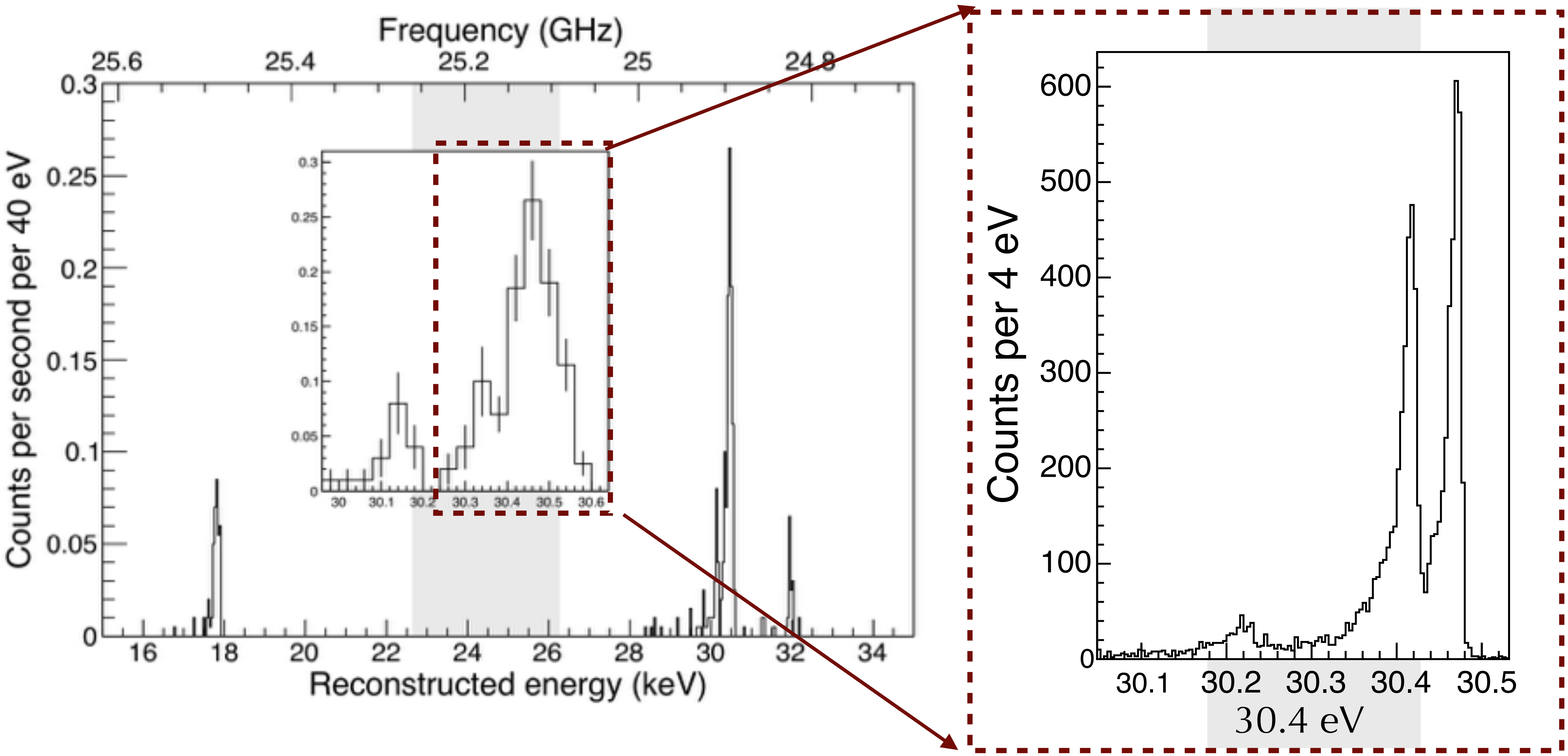




Dependence on trap parameters well understood.

Can be used to determine baseline field strength.

Image Reconstruction & Energy Resolution



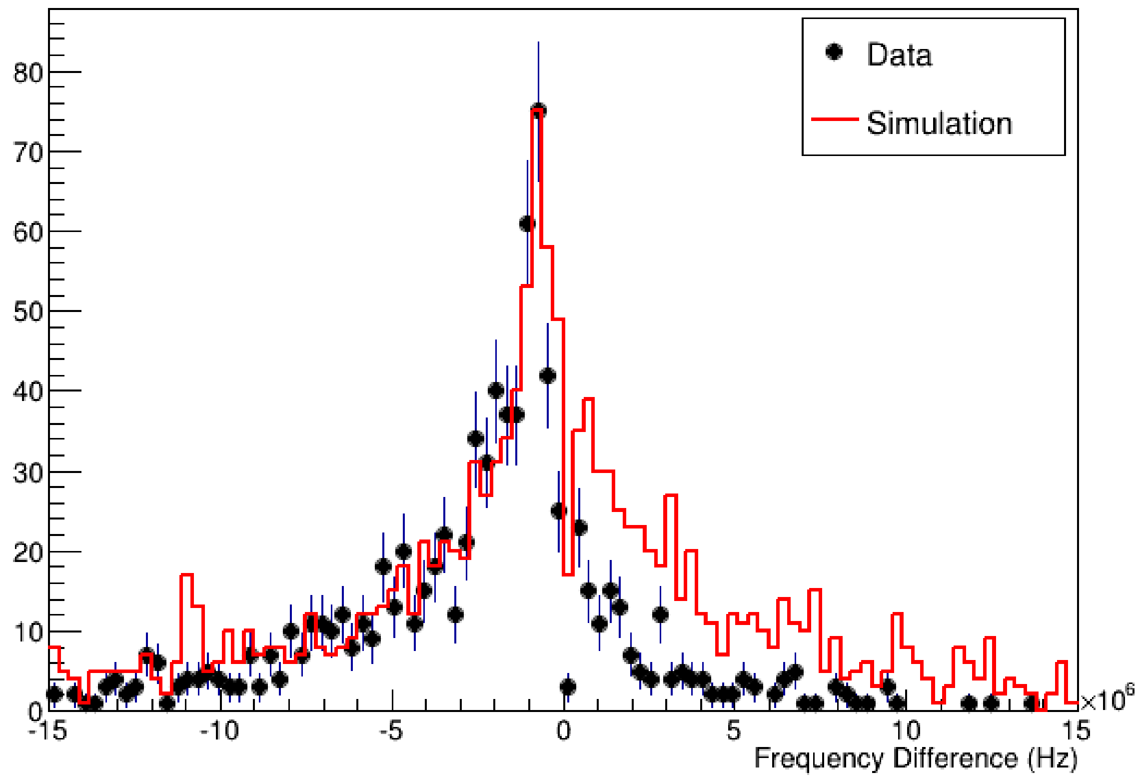
FWHM ~ 140 eV

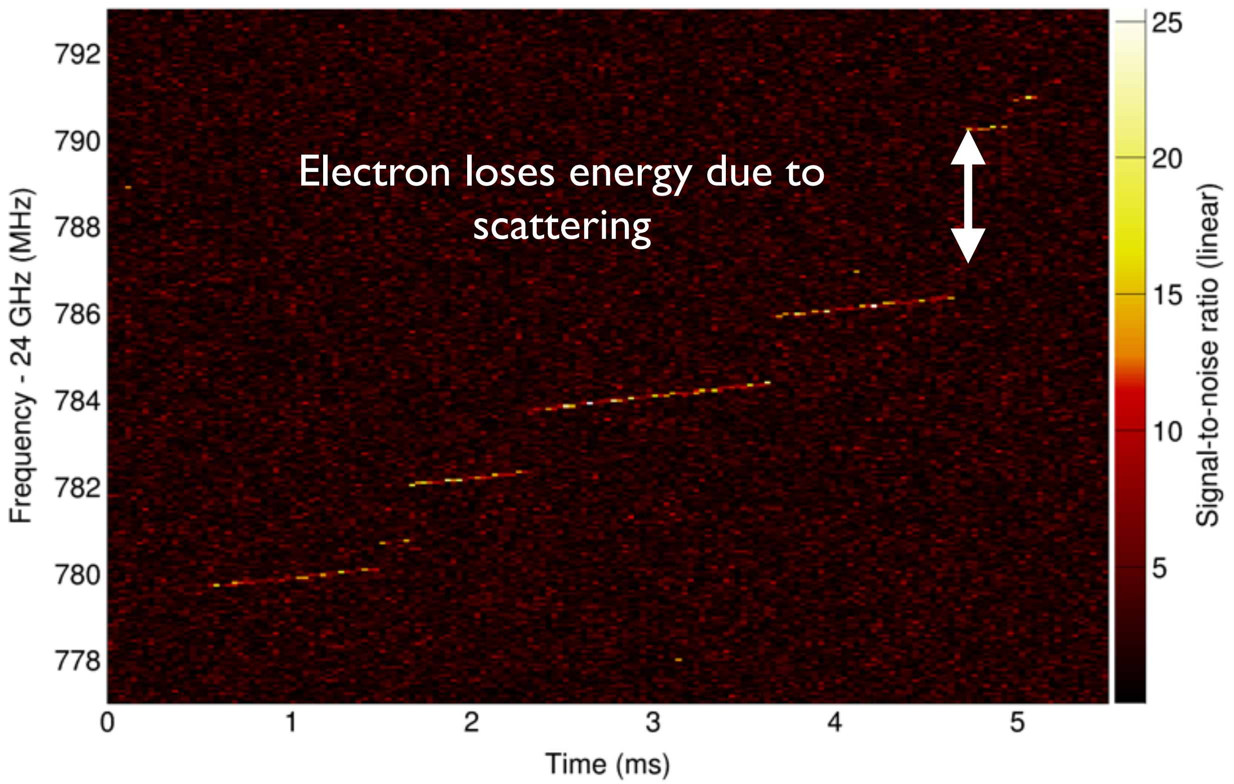
Already improving…
(FWHM ~15 eV)

Event reconstruction from image reconstruction allows detailed analysis

(energy & scattering all extractable)

Image Reconstruction & Energy Resolution





Peak at ~14 eV

consistent with
e^- H_2 scattering

Event reconstruction from image reconstruction allows detailed analysis

(energy & scattering all extractable)

A Phased Approach

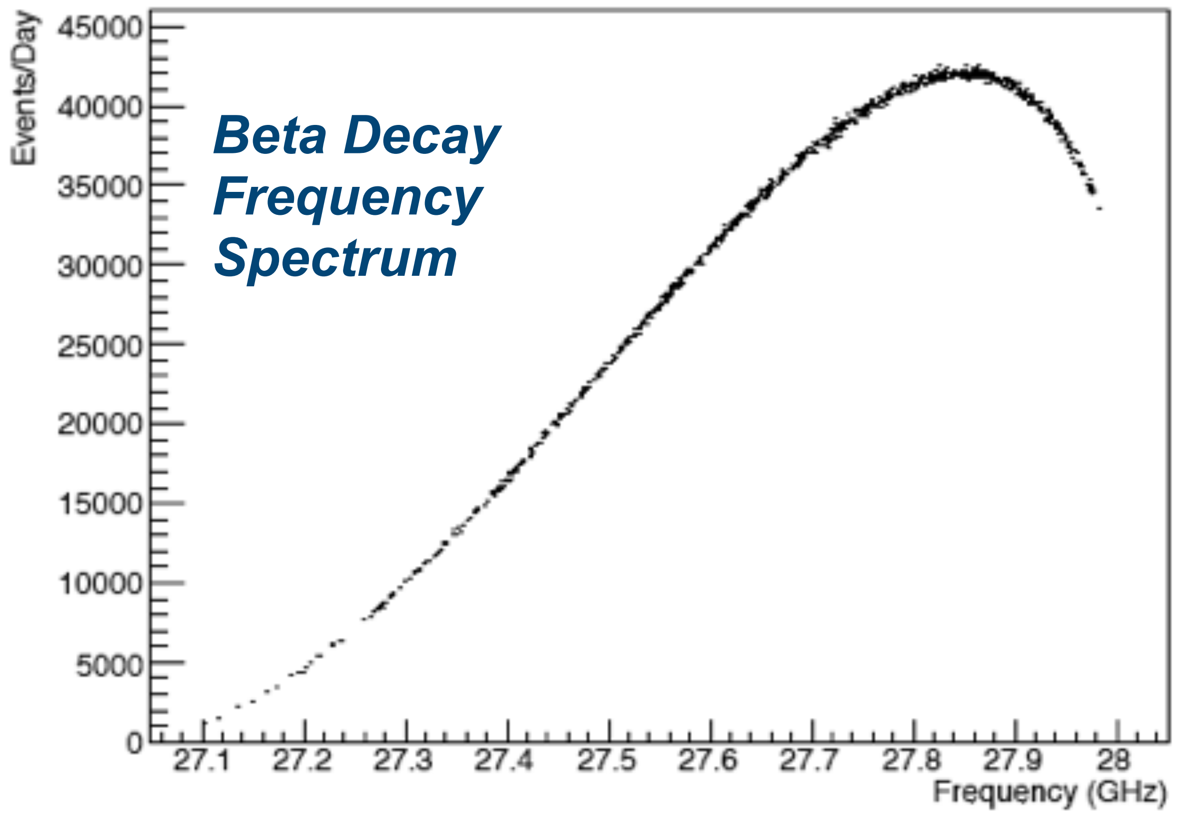
Given the novelty of the project, we are pursuing a phased approach toward neutrino mass measurements:

	Timeline	Scientific Goal	Source	R&D Milestone
Phase I	2010-2014	Proof of principle; Kr spectrum	^{83m}Kr	DONE! Single electron detection
Phase II	2014-2016	T-He mass difference	T_2	Tritium spectrum; calibration and error studies
Phase III	2016-2018	0.2 eV scale	T_2	
Phase IV	2018+	0.05 eV scale	T	High rate sensitivity

We have commenced Phase I, we are designing Phase II

Sensitivity to Neutrino Masses

- There are distinct advantages that are specific to frequency-based measurements:
- You get the entire spectrum (and background) at once.
- The background is extremely small:
  - There is no detector.
  - There might not even be any surfaces.
  - Cosmic ray interactions and radioactive backgrounds are interacting with a gas, very little target material.



$$\frac{dN}{dE_e} = 3rt(E_0 - E_e)[(E_0 - E_e)^2 - m_\nu^2]^{1/2}$$

Mass sensitivity depends on:

Target activity (volume x density)

Background

Field homogeneity

Lifetime of electron in trap (density)

Final states, doppler shifts, temperature

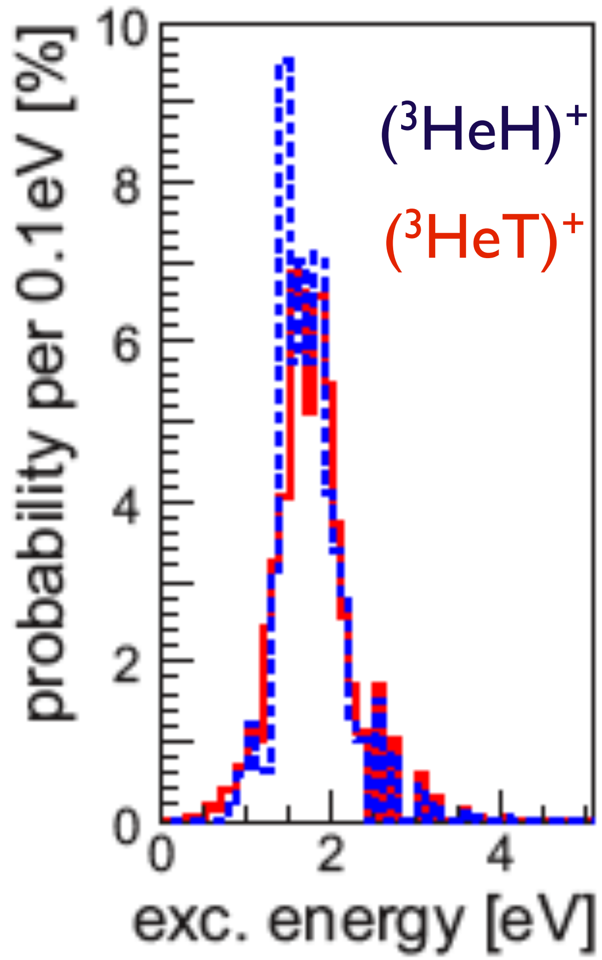
Moving Beyond the Degeneracy Scale

- Most effective tritium source achieved so far involves the use of gaseous molecular tritium.
- Method will eventually hit a resolution "wall" which is dictated by the rotational-vibrational states of T_2. This places a resolution limit of 0.36 eV.
- One needs to either switch to (extremely pure) atomic tritium or other isotope with equivalent yield.
- The trapping conditions necessary for electrons also lends itself for atomic trapping of atomic tritium (R. G. H. Robertson)

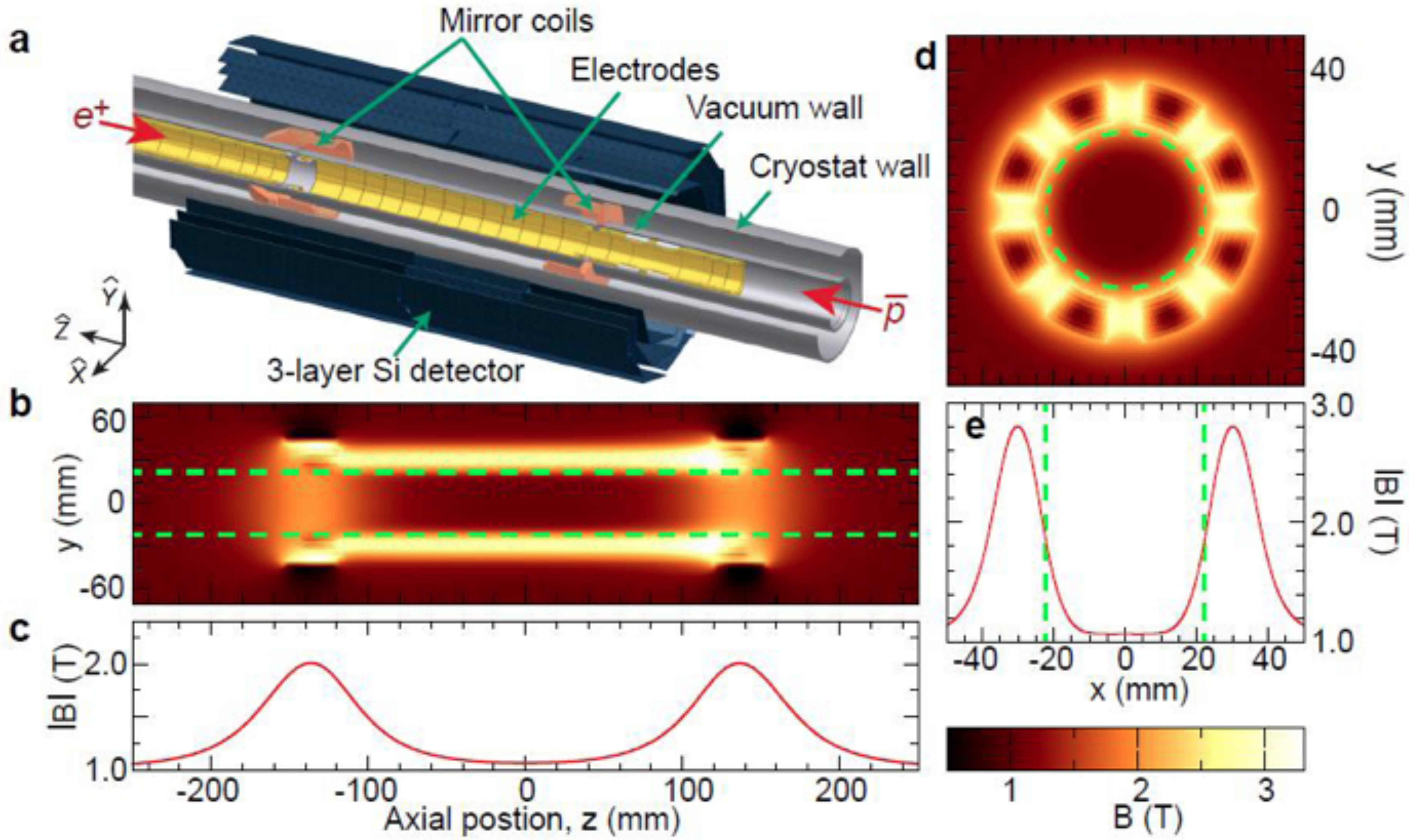
rotational

vibrational

Inherent 0.36 eV final state smearing



Trapping of Atomic Tritium



ALPHA Collaboration: Nature Phys.7:558-564,2011; arXiv 1104.4982

Similar design to anti-hydrogen trapping:

Solenoidal field for uniformity

Pinch coils for axial confinement

Ioffe multipoles for radial confinement

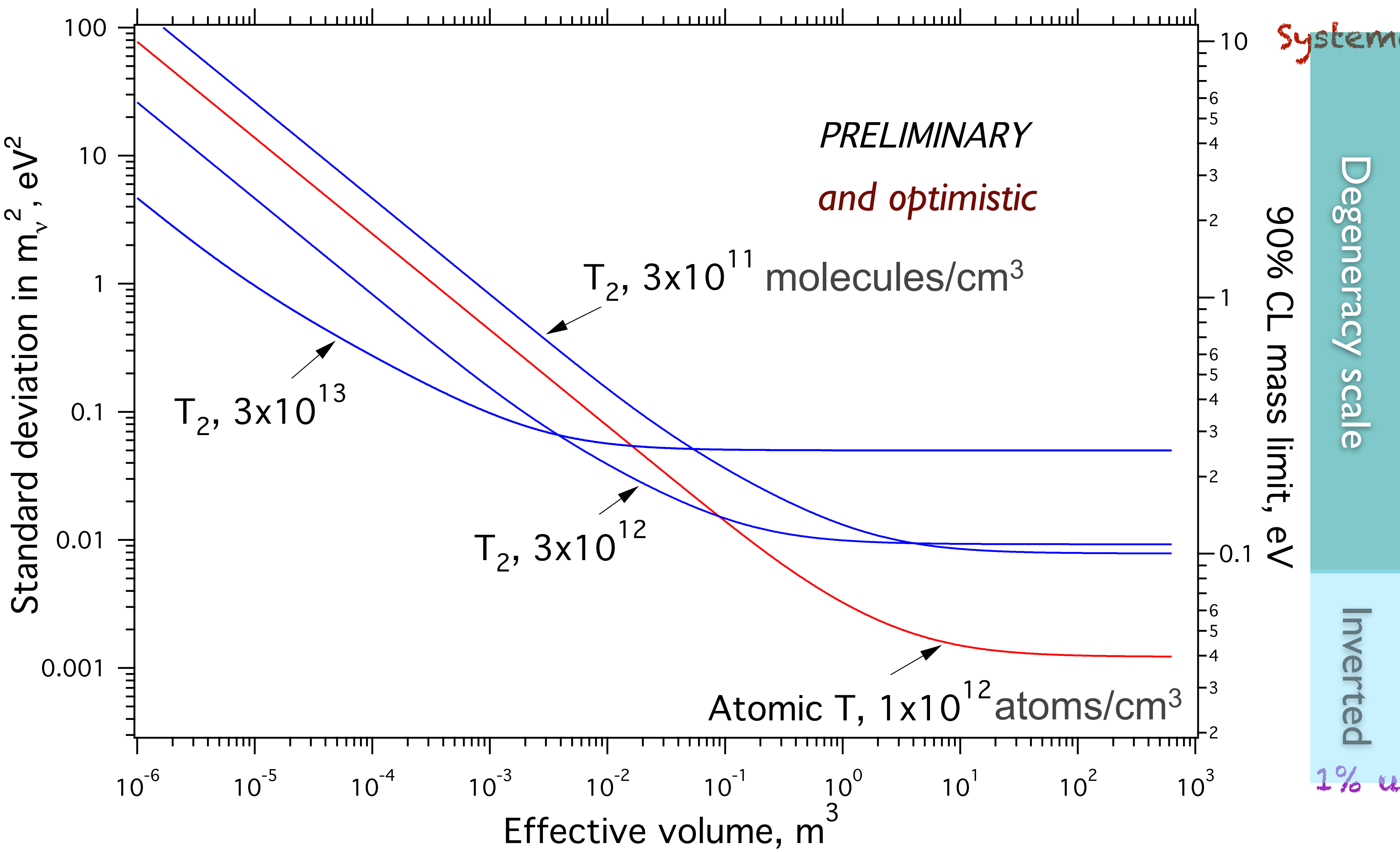
Cooling polarized tritium down to ~ 1K is necessary (and the main challenge)

In order to achieve atomic tritium purity, it is necessary to cool and trap polarized atomic tritium in both a radial and axial magnetic trap (Ioffe-Pritchard traps).

Technique quite similar to hydrogen BEC (MIT) and anti-hydrogen trapping (ALPHA).

Densities low, so recombination is highly suppressed.

Projected Sensitivity (Molecular & Atomic)



Systematics include:

Statistical uncertainties (1 year run)

Final state interactions

Thermal broadening

Volume ≈ 0.05 m^3 (≈ 70 mCi)

Scattering

Background

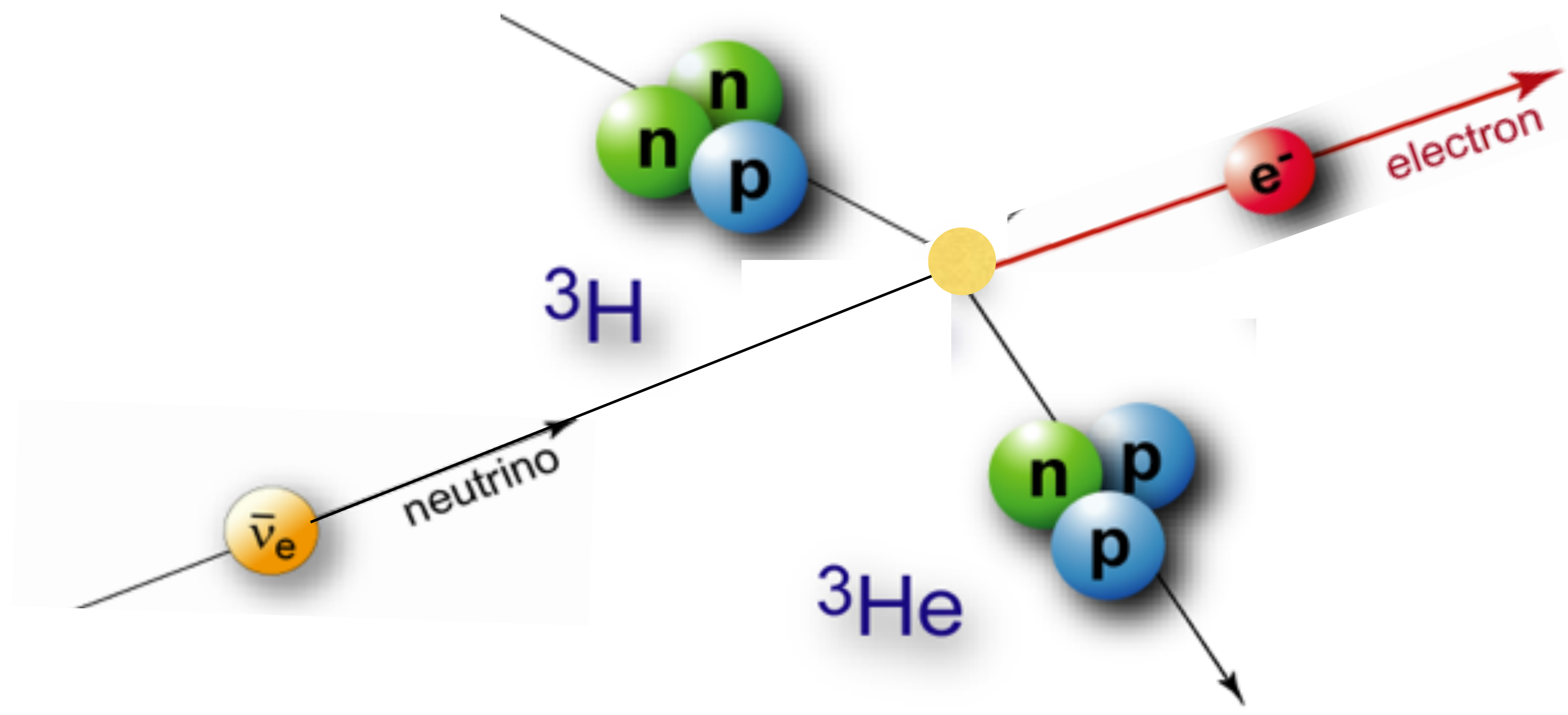
Volume ≈ 5 m^3 (0.25 Ci)

Field inhomogeneity

1% uncertainty in resolution distribution

Systematics include final state interactions, thermal broadening, statistical uncertainties, and scattering.

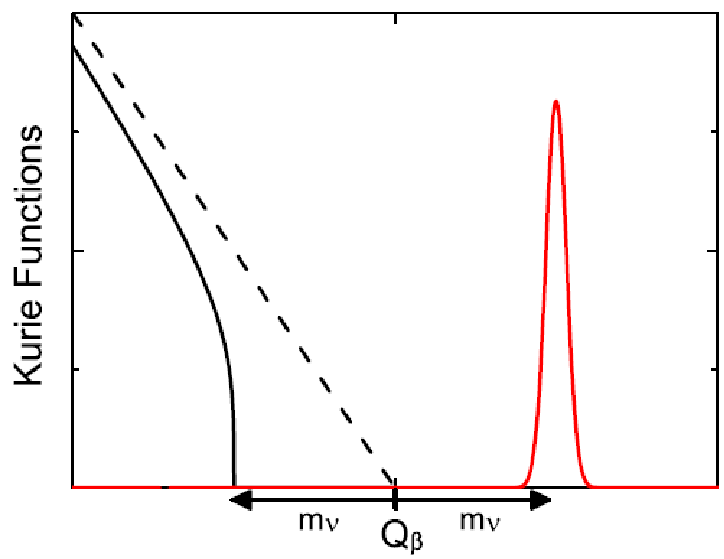
Neutrino Capture



Kinematically allowed

Threshold-less process with beta emission at $2m_\nu$ above threshold

Neutrino Capture



Isotope	Q_β (keV)	Decay type	Half-life (sec)	$\sigma_{\nu_i} \cdot v_{\nu_i}$ (10^{-41} cm^2)
^{3}H	18.591	β^-	3.8878×10^8	7.84×10^{-4}
^{63}Ni	66.945	β^-	3.1588×10^9	1.38×10^{-6}
^{93}Zr	60.63	β^-	4.952×10^{13}	2.39×10^{-10}
^{106}Ru	39.4	β^-	3.2278×10^7	5.88×10^{-4}
^{107}Pd	33	β^-	2.0512×10^{14}	2.58×10^{-10}
^{187}Re	2.64	β^-	1.3727×10^{18}	4.32×10^{-11}

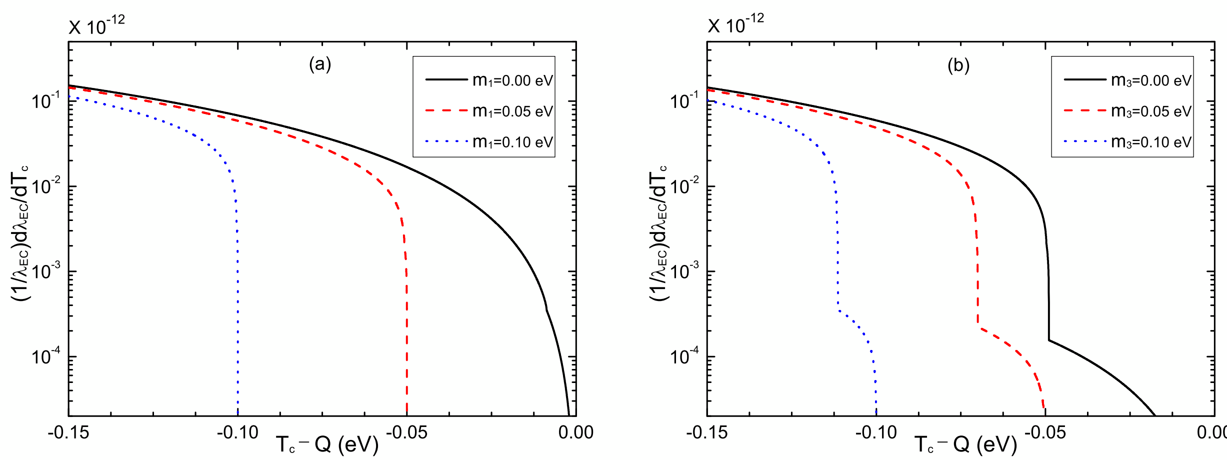


Fig. 5. The fine structure spectrum near the endpoint of the ^{163}Ho EC-decay in the $m_{31}^2 > 0$ (left panel) or $m_{31}^2 < 0$ (right panel) case[17].

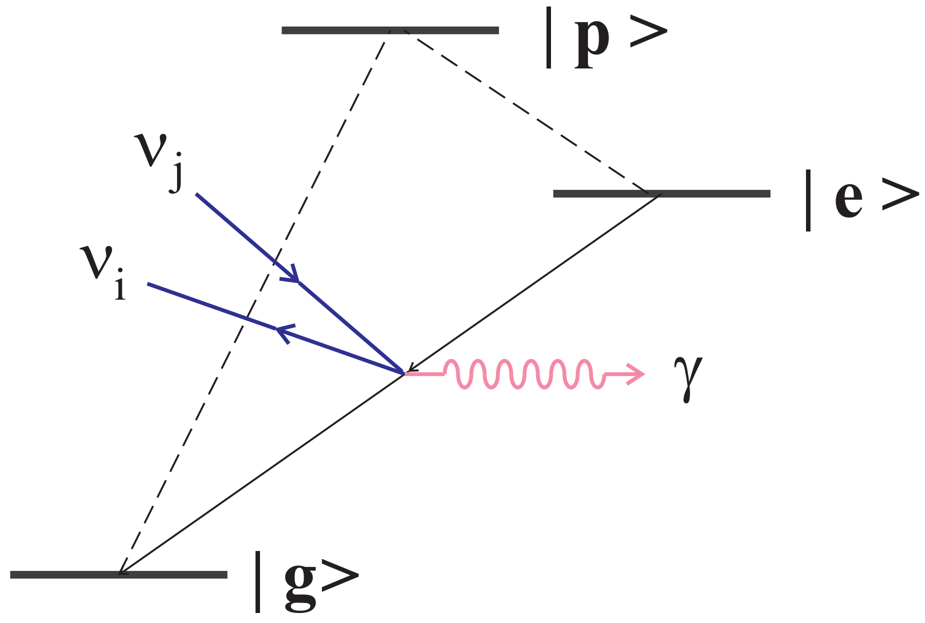
Y. F. Li, arXiv:1504.03966 (2015)

Has been studied for a number of targets (3H, 163Ho, 187Re).

All require vast quantities and superb precision.

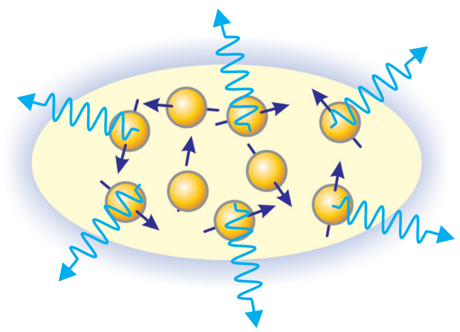
One experimental effort, Ptolemy, specifically aimed at relic neutrino detection.

Radiative Emission of Neutrino Pair (RENP)

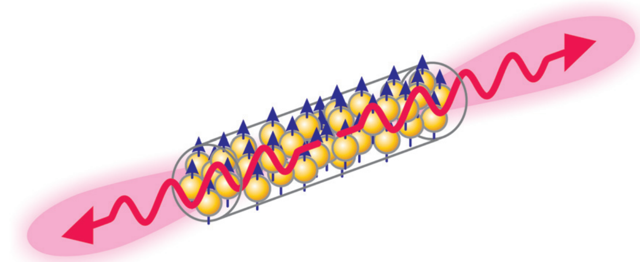


Radiative Pair Emission

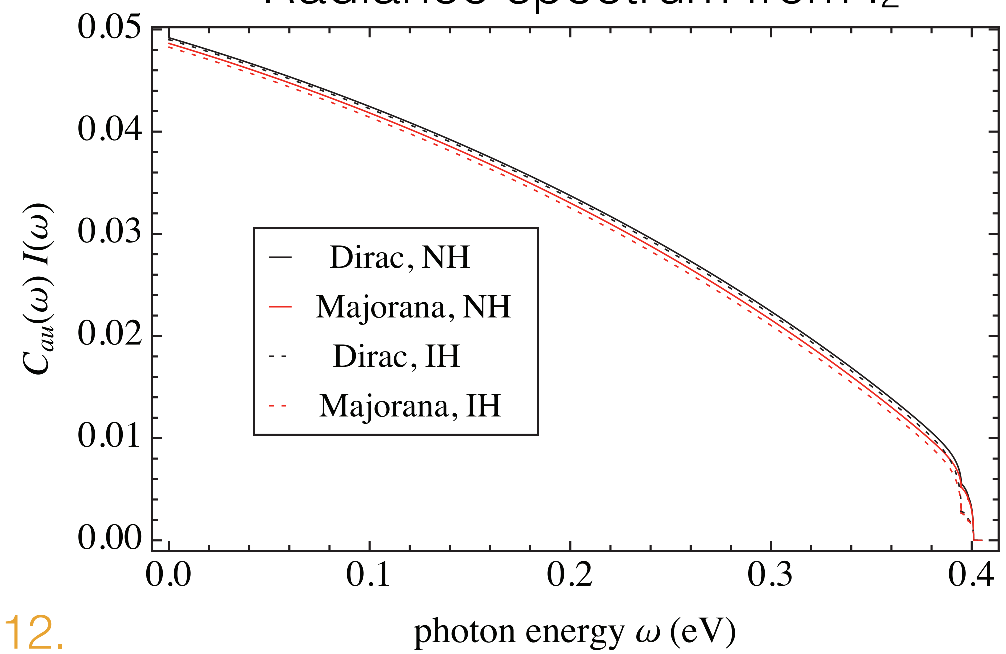
Spontaneous emission (EPR)



Super-radiant emission (EPR)



Radiance spectrum from I_2



M. Yoshimura, N. Sasao, and M. Tanaka, Phys. Rev. A 86 (2012) 013812.

An interesting idea from Yoshimura et al to use atomic de-excitation to look at the neutrino mass spectrum.

Leverage the effect of collective phenomena (super-radiance) to enhance decay rate.

One can use Pauli suppression (from relic neutrinos) of decay to also detect relic neutrinos.

Degeneracy and Beyond...

Spectroscopy (KATRIN)

Technique PROVEN. State-of-the-art.

Experiment soon to commence with 0.2 eV reach.

Integral measurement with TOF possibility.

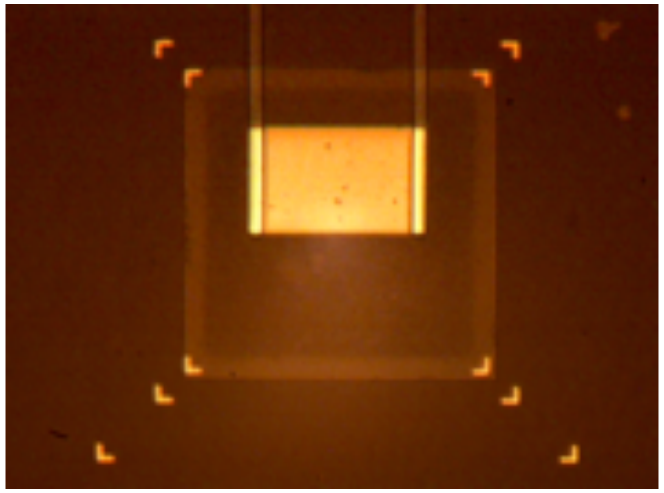
$$T_2 \to (T \cdot {}^3He^+) + e^- + \bar{\nu}_e$$

Calorimetry (HOLMES, ECHO & NuMECS)

Technique advanced.

New experiment(s) planned to reach ~1 eV scale.

Statistics & systematics next hurdle.



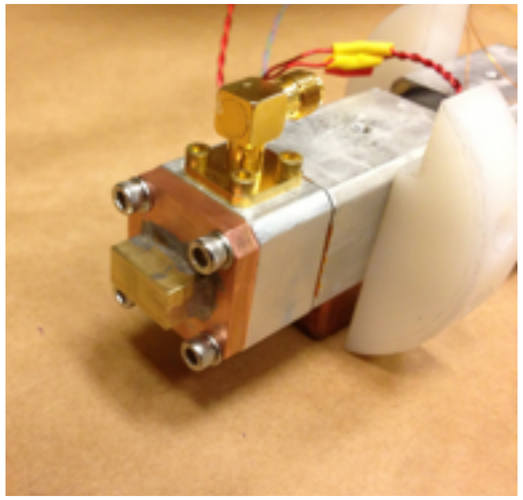
$$^{163}Ho + e^- \to {}^{163}Dy^* + \nu_e$$

Frequency (Project 8)

Technique DEMONSTRATED.

Potential of scalability and exploring atomic sources to inverted scale.

Next to establish the scalability of the technique.



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

Thank you for your attention