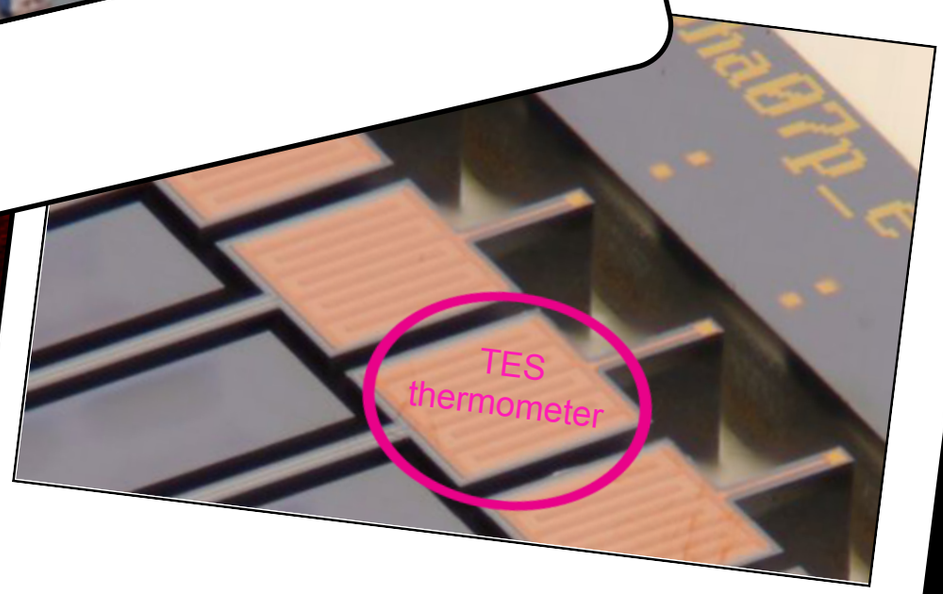
PROJECT

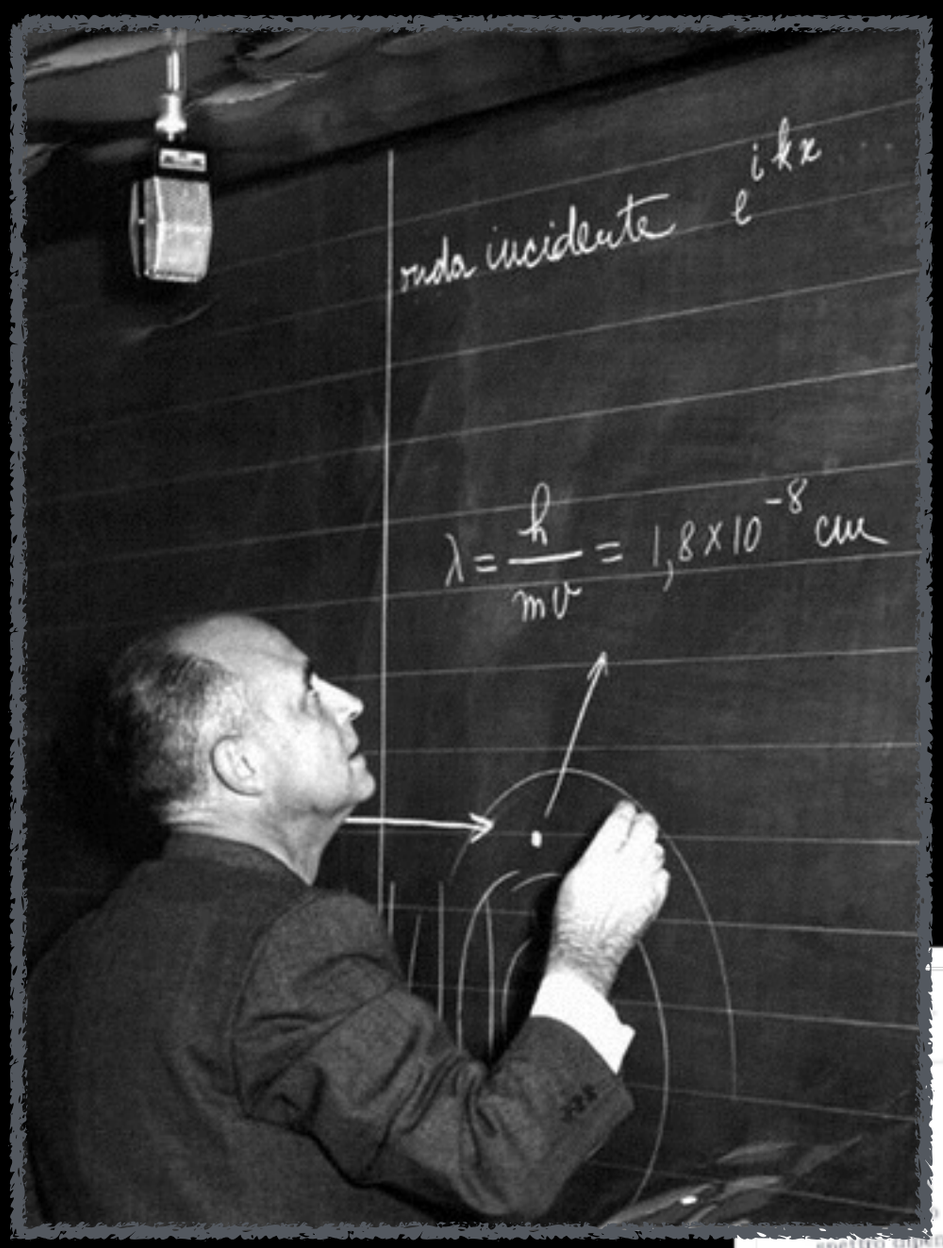

TES
thermometer

Experimental Paths in Neutrino Mass Measurements

Fundamental Symmetries
& Neutrinos
NSAC Chicago Meeting

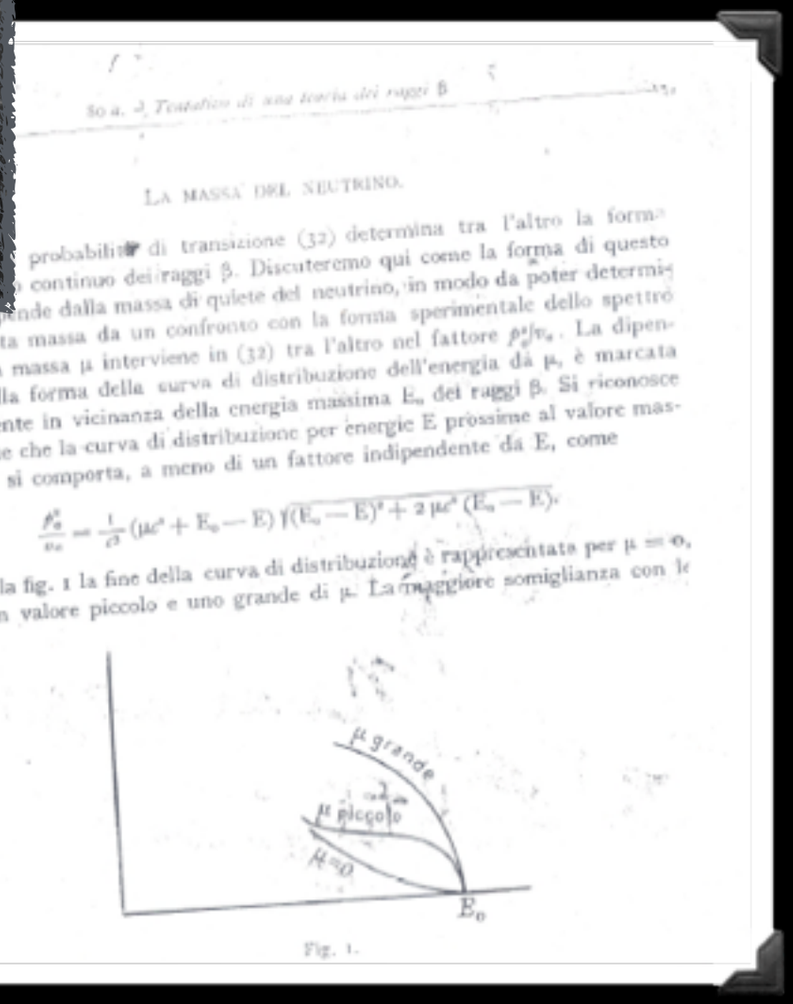
September 29th 2014

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.



so a. 2. Tentativo di una teoria dei raggi β

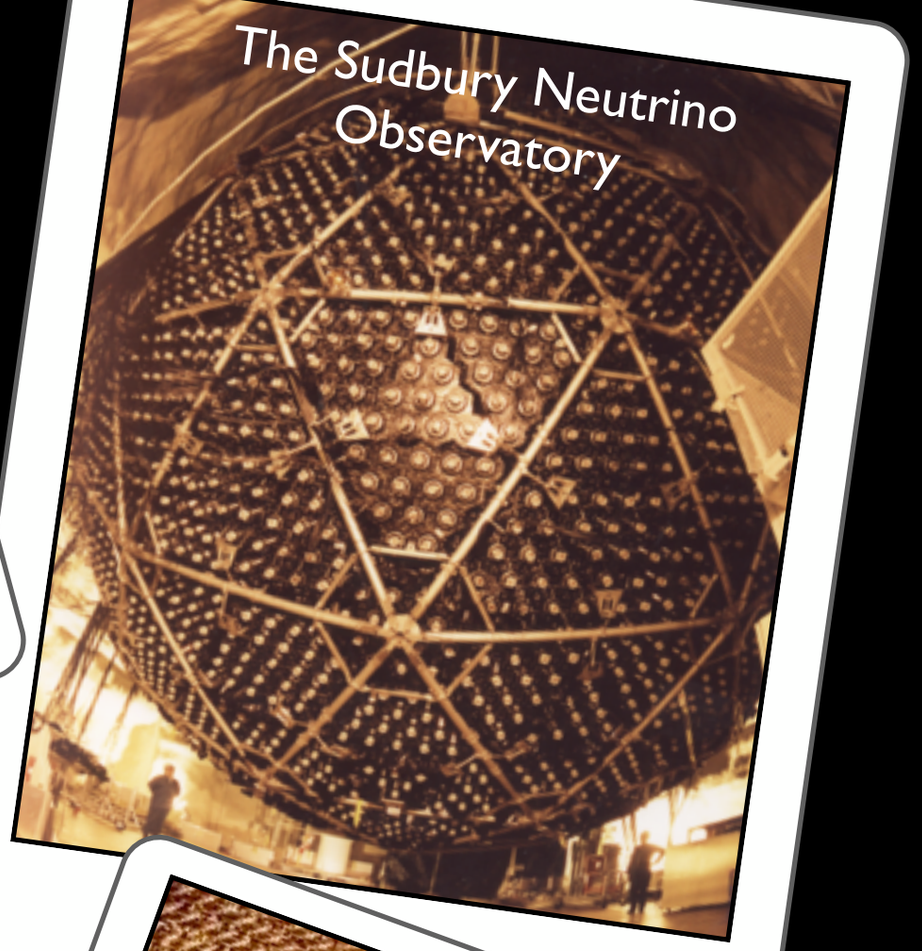
LA MASSA DEL NEUTRINO.

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 determinare questa massa da un confronto con la forma sperimentale dello spettro stesso. La massa μ interviene in (32) tra l'altro nel fattore p_e^2/v_e. La dipendenza della forma della curva di distribuzione dell'energia dà 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 massimo E_0, si comporta, a meno di un fattore indipendente da E, come

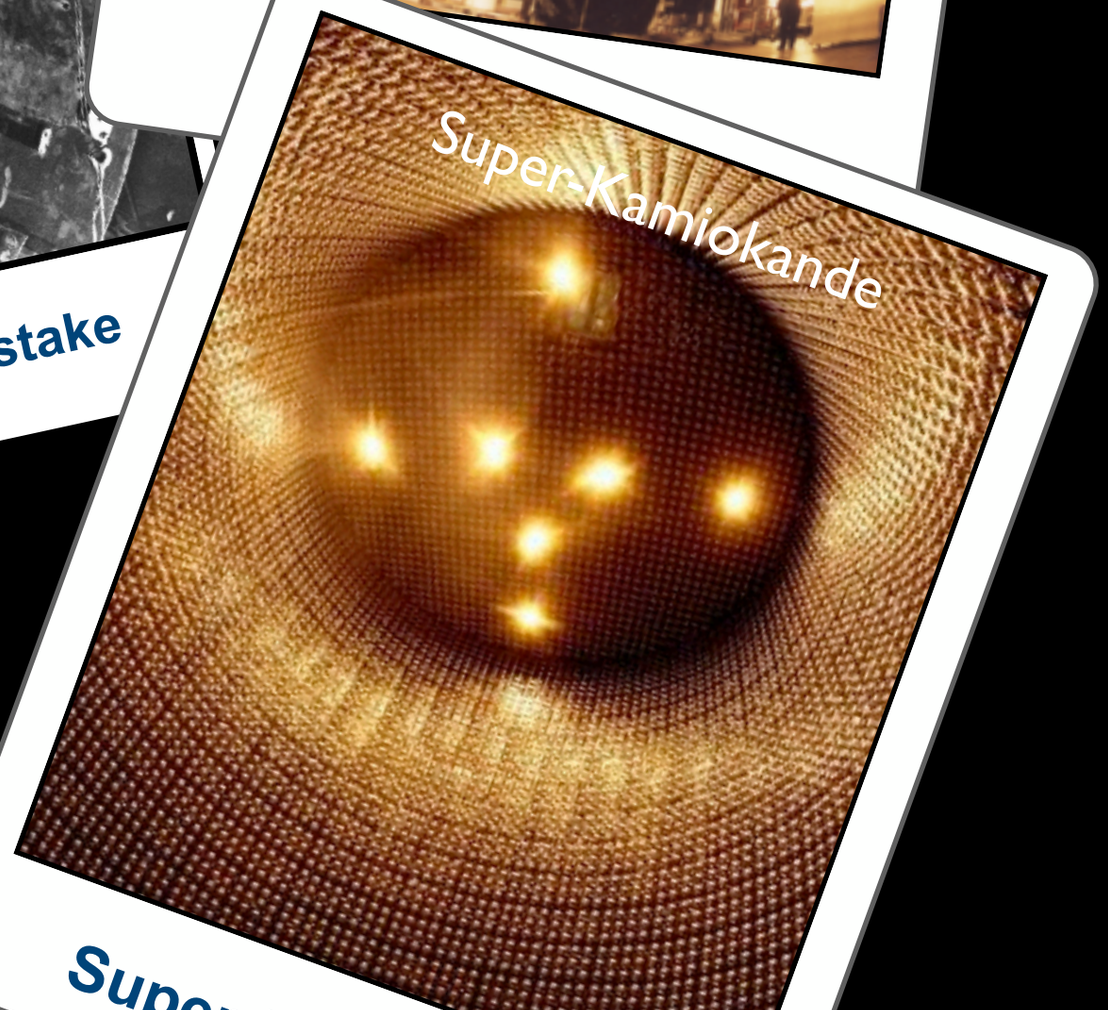
$$\frac{p_e^2}{v_e} = \frac{1}{c^3}(\mu c^2 + E_0 - E)\sqrt{(E_0 - E)^2 + 2\mu c^2 (E_0 - E)}. \tag{16}$$

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

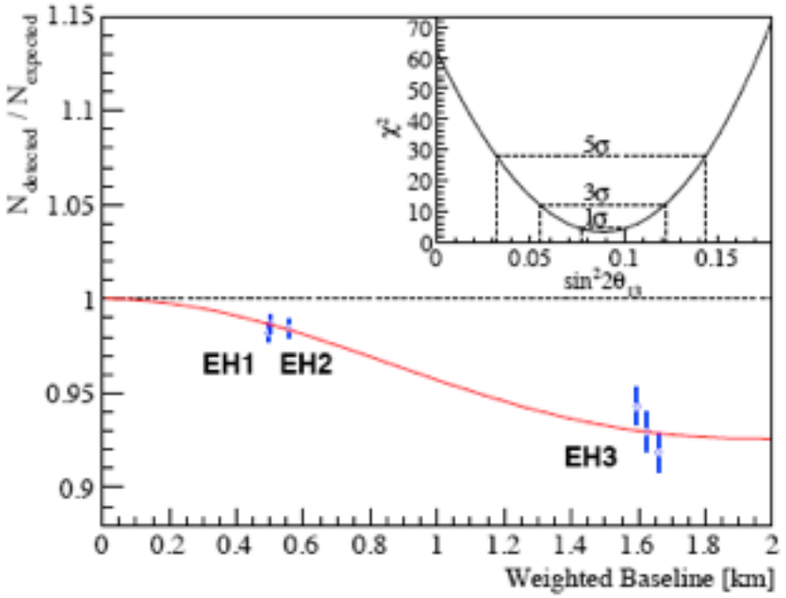
Fig. 1.



With oscillations firmly in place, we at least understand that the neutrino has a mass



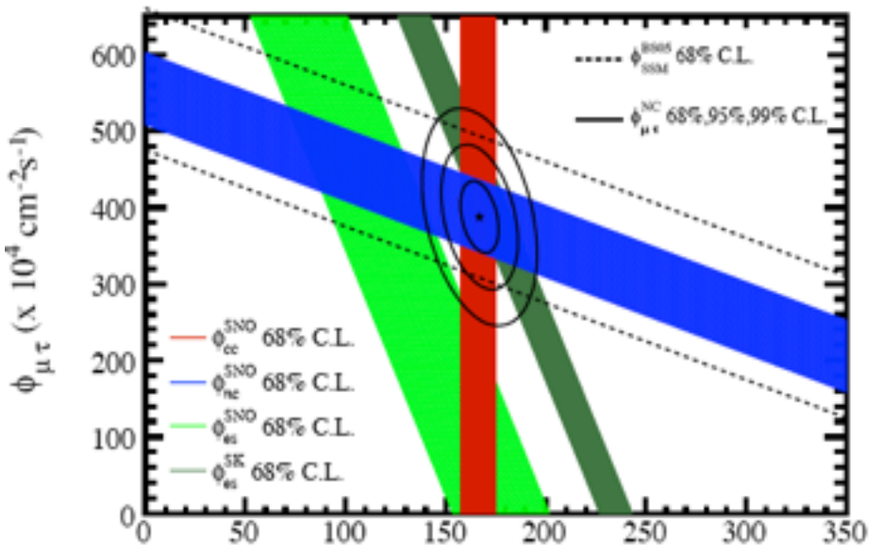
As such, oscillation measurements place a lower limit on the neutrino mass scale.



$$\sin^2(\theta_{13}) = 0.0241 \pm 0.0025$$

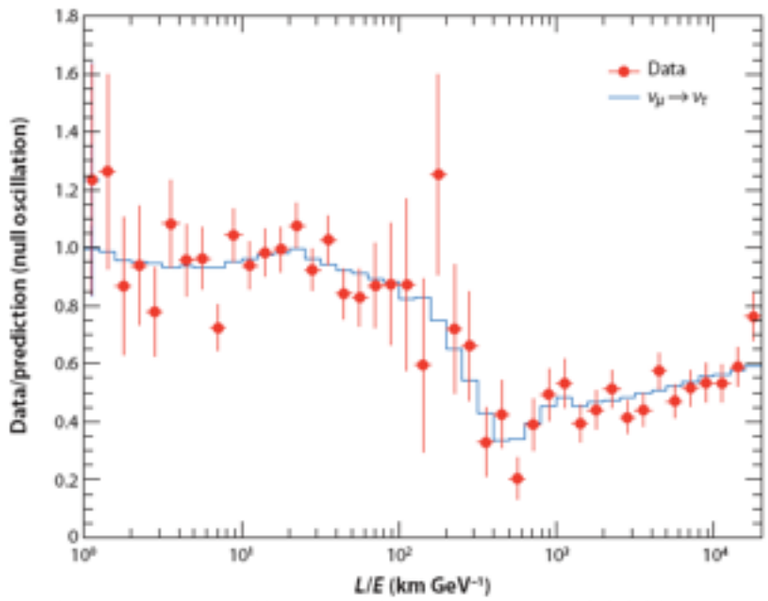
Reactor & Long Baseline

$$\sin^2(\theta_{12}) = 0.307 \pm 0.016$$
$$\Delta m^2_{12} = (7.54 \pm 0.26) \times 10^{-5}\ \mathrm{eV}^2$$



Solar

$$\sin^2(\theta_{23}) = 0.386 \pm 0.022$$
$$\Delta m^2_{23} = (2.43 \pm 0.09) \times 10^{-3}\ \mathrm{eV}^2$$



Atmospheric

Camilieri, Lisi, Wilkerson Ann. Rev. 57 (2008).
Fogli et al, arXiv:1205.5254 (hep-ph)

With oscillations firmly in place, we at least understand that the neutrino has a mass

As such, oscillation measurements place a lower limit on the neutrino mass scale.

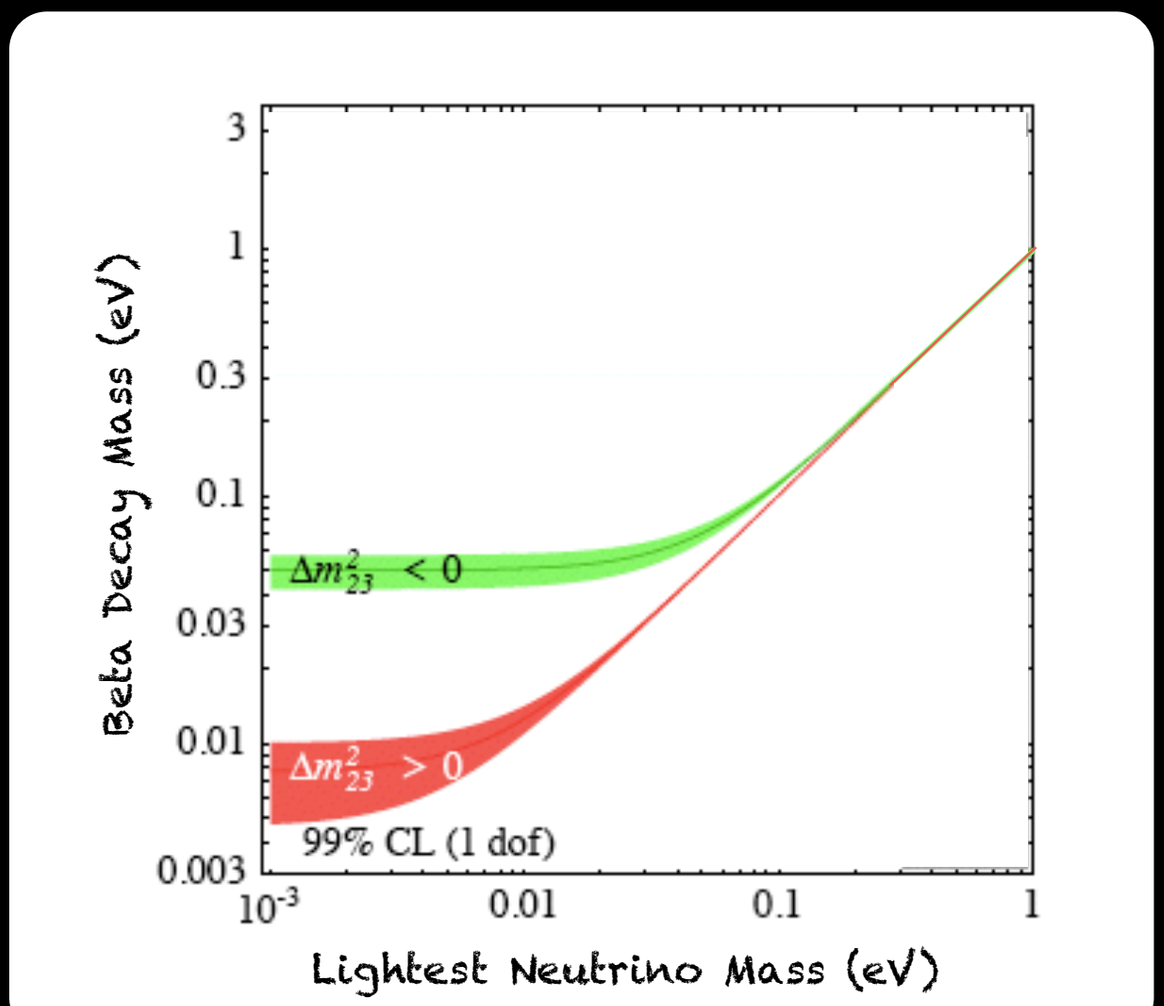
Measuring Neutrino Masses

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

Cosmological Measurements

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

0νββ Measurements



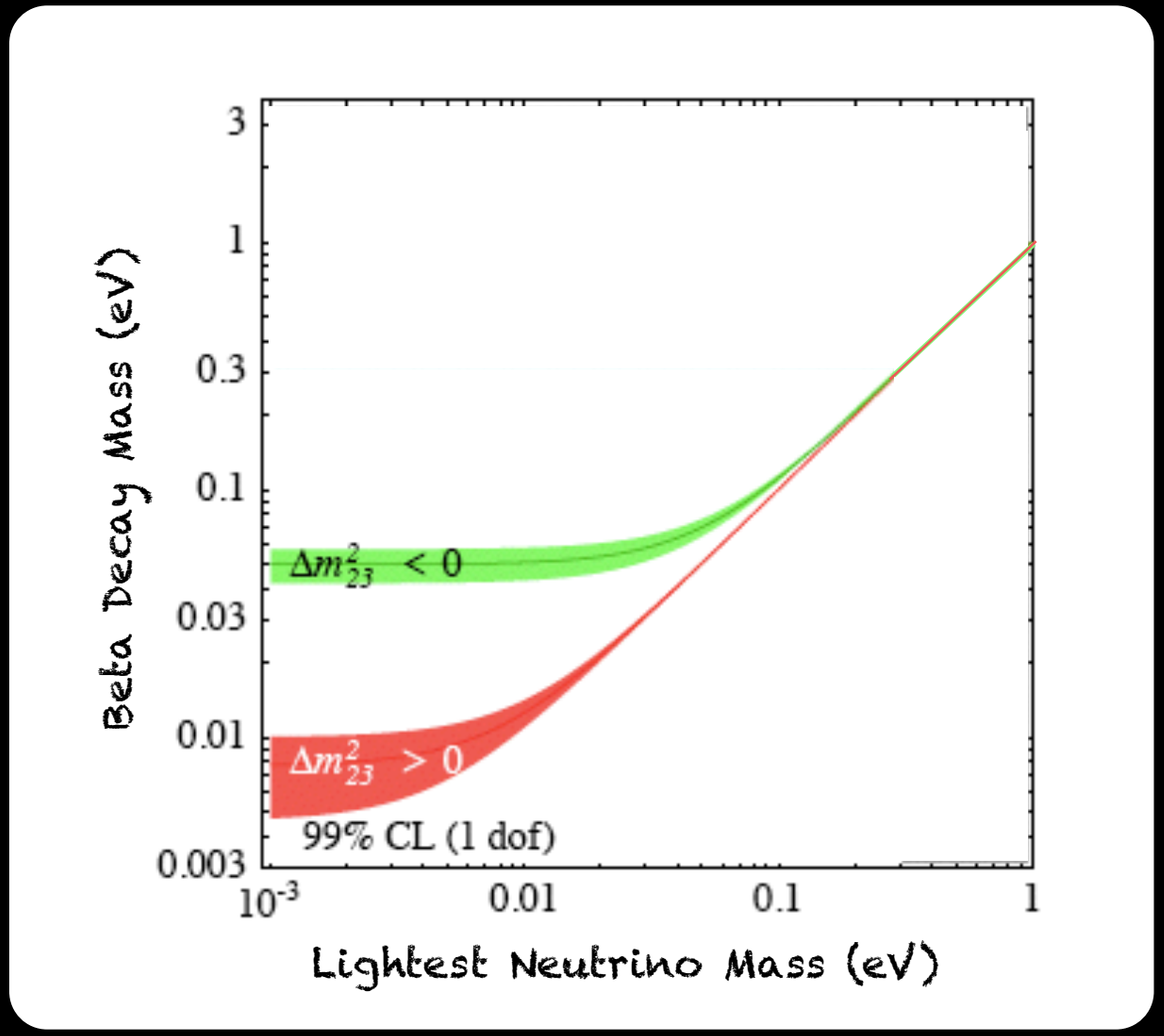
$$\langle m_\beta \rangle^2 = \sum_{i}^{n_\nu} \mid U_{ei} \mid^2 m^2_{\nu,i}$$

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.



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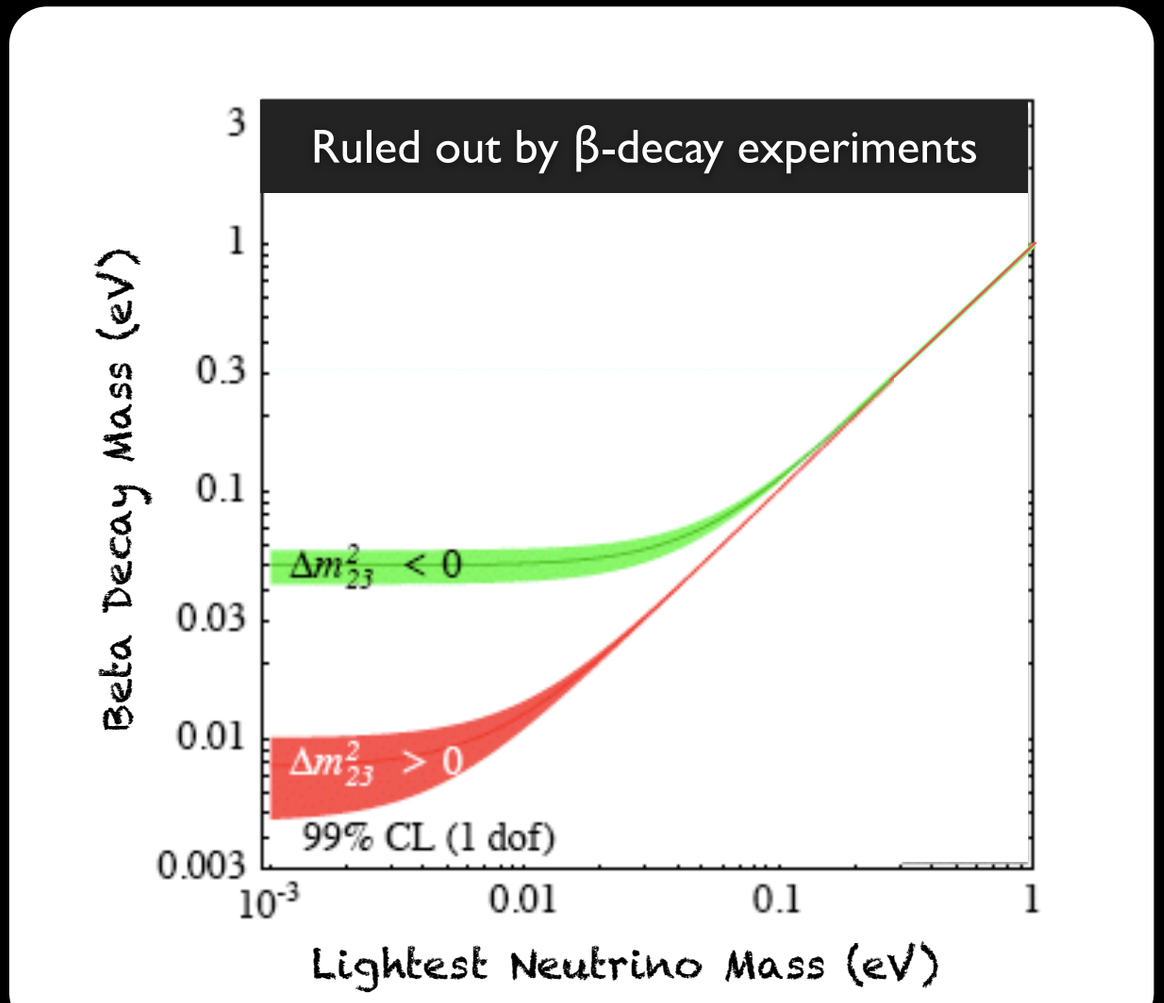

$m_\nu > 2$ eV (eV scale, current)

Neutrinos ruled out as dark matter

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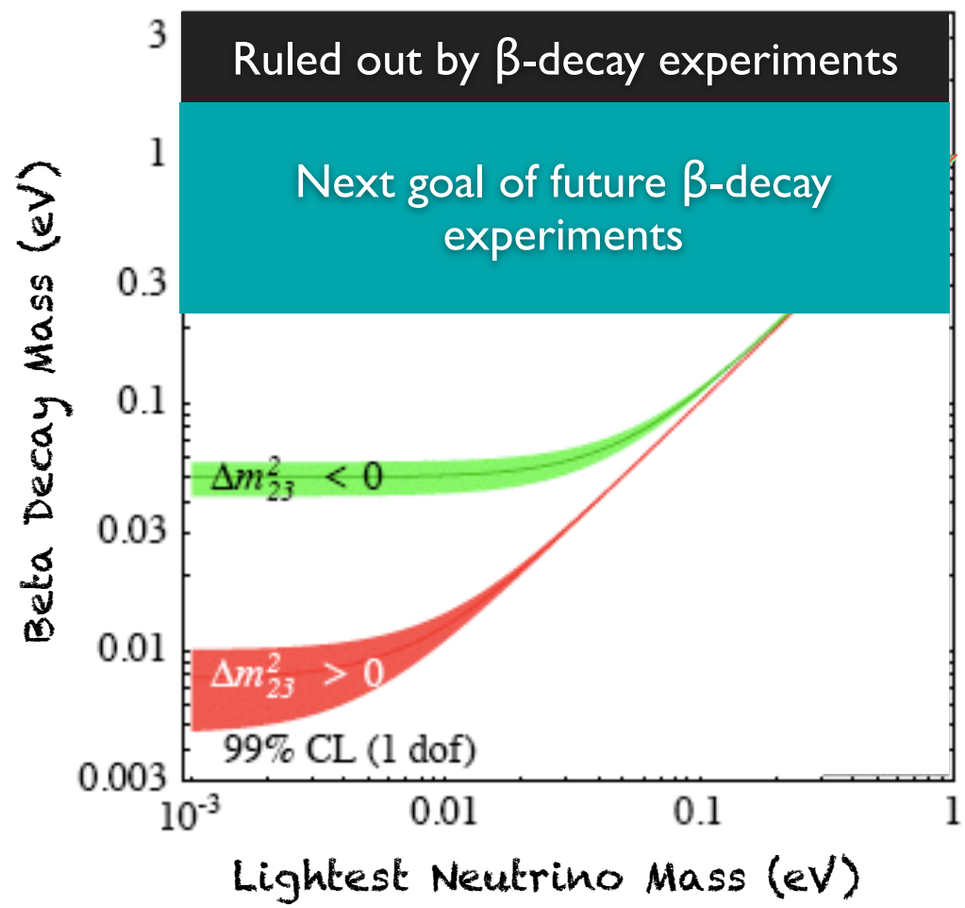

$m_\nu > 2$ eV (eV scale, current)

Neutrinos ruled out as dark matter

$m_\nu > 0.2$ eV (degeneracy scale)

Impact on cosmology and $0\nu\beta\beta$ reach

The Neutrino Mass Scale

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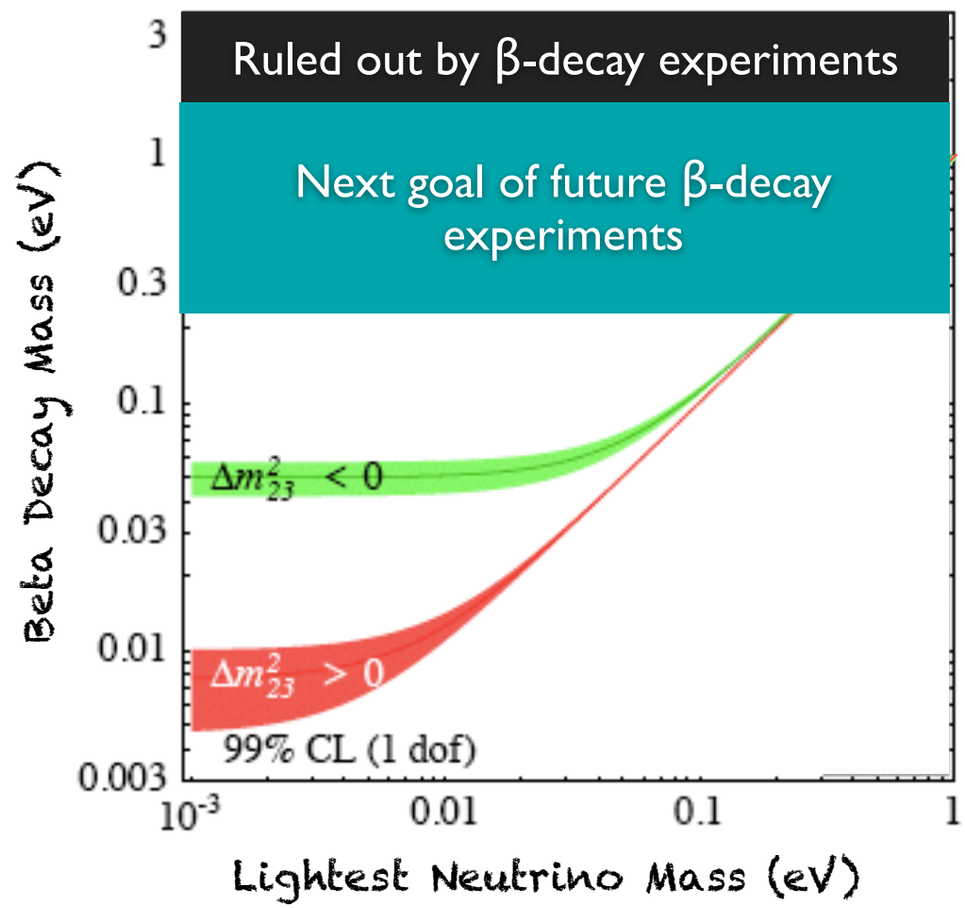

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$m_\nu > 0.2$ eV (degeneracy scale)

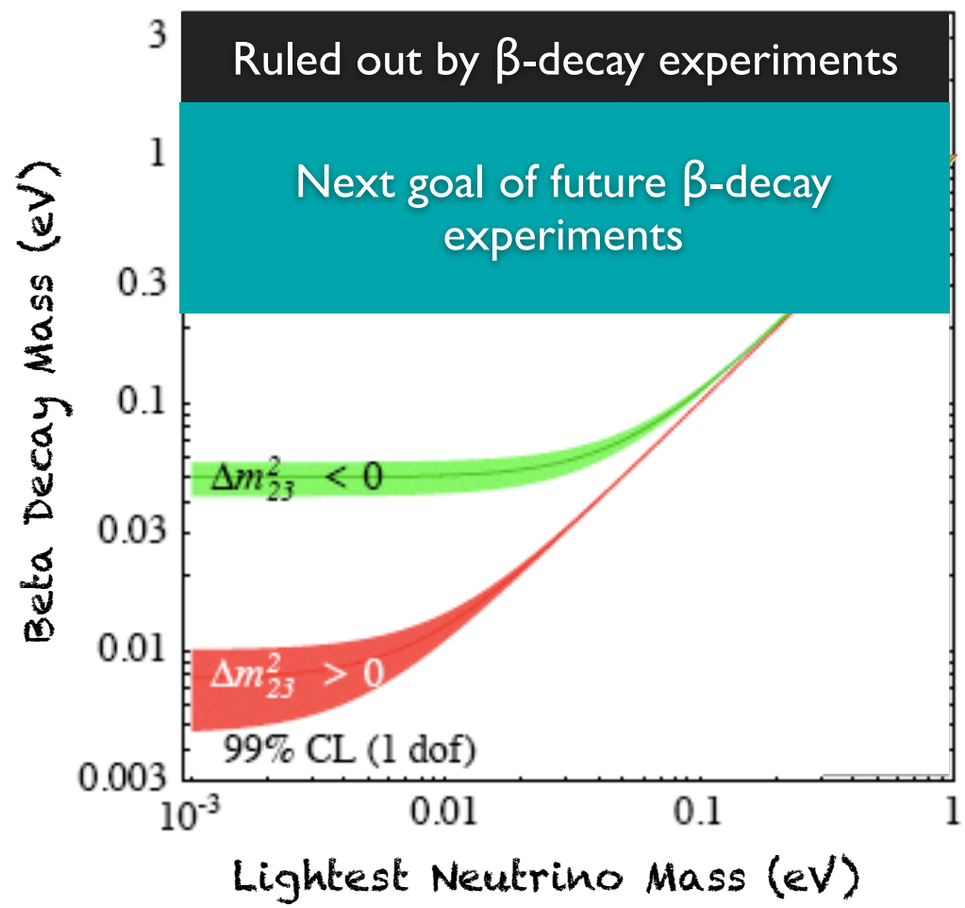
Impact on cosmology and $0\nu\beta\beta$ reach

$m_\nu > 0.05$ eV (inverted hierarchy)

Resolve hierarchy if null result

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.



$m_\nu > 2$ eV (eV scale, current)

Neutrinos ruled out as dark matter

$m_\nu > 0.2$ eV (degeneracy scale)

Impact on cosmology and $0\nu\beta\beta$ reach

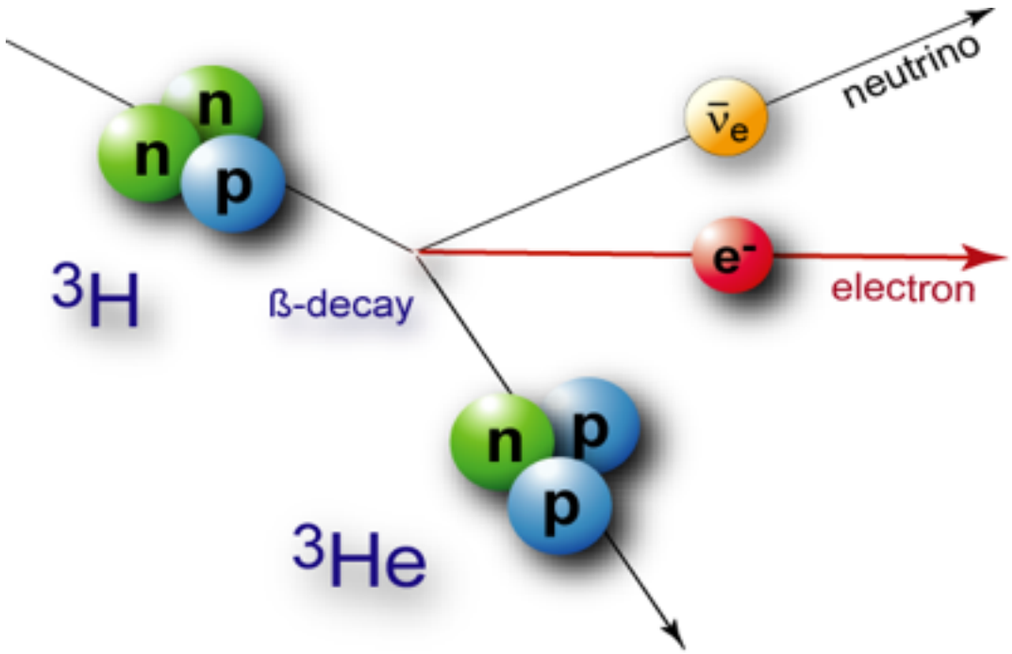
$m_\nu > 0.05$ eV (inverted hierarchy)

Resolve hierarchy if null result

$m_\nu > 0.01$ eV (normal hierarchy)

Oscillation limit; possible $C\nu B$ detection

Direct Probes



$^3H \rightarrow {}^3He^+ + e^- + \nu_e$

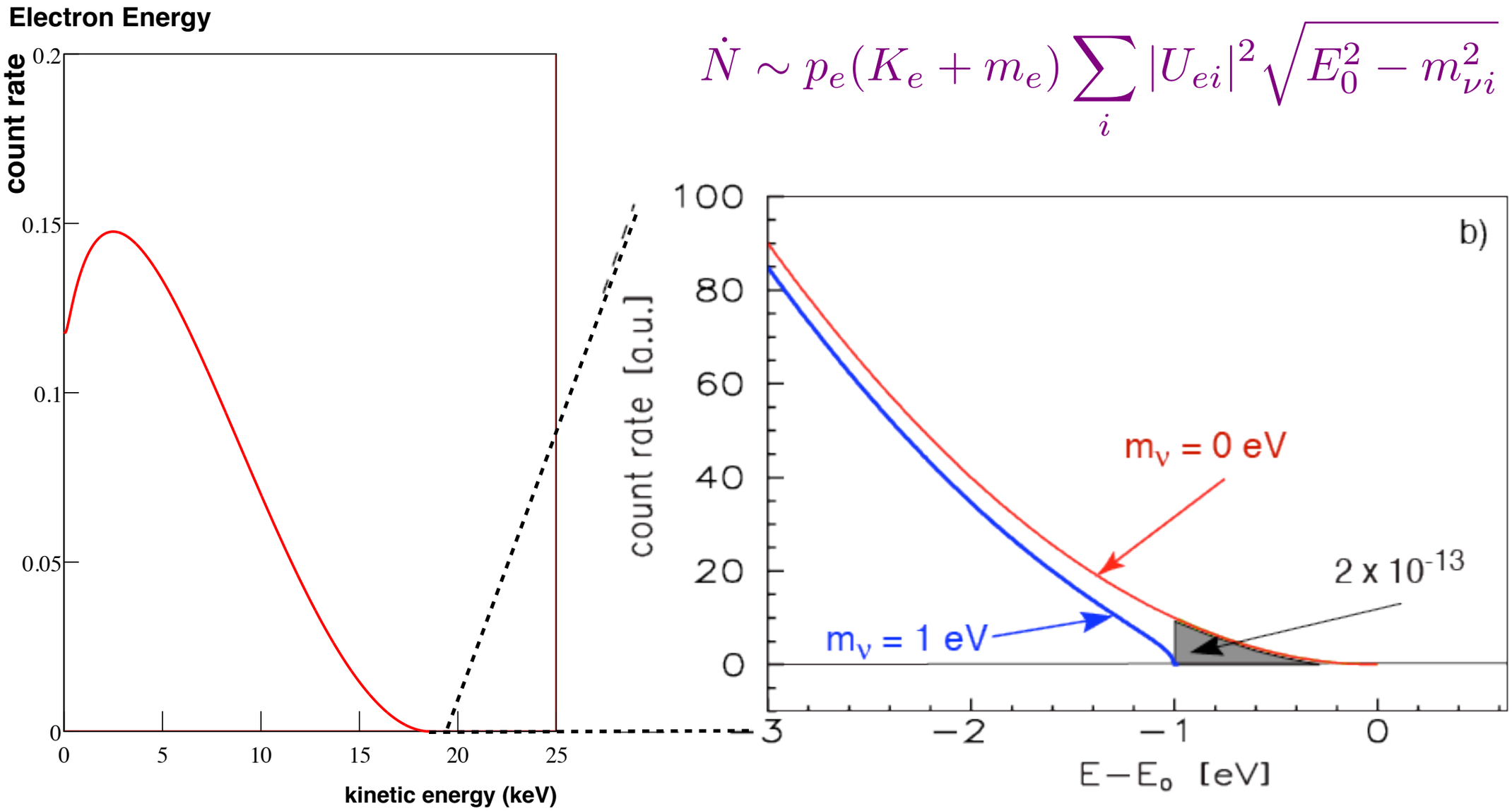
Beta Decay

A kinematic determination of the neutrino mass

No model dependence on cosmology or nature of mass

Direct Probes

$$\dot{N} \sim p_e(K_e + m_e) \sum_i |U_{ei}|^2 \sqrt{E_0^2 - m_{\nu i}^2}$$



Beta Decay

A kinematic determination of the neutrino mass

No model dependence on cosmology or nature of mass

Techniques for the 21st Century

Spectroscopy (KATRIN)

Magnetic Adiabatic Collimation with Electrostatic Filtering

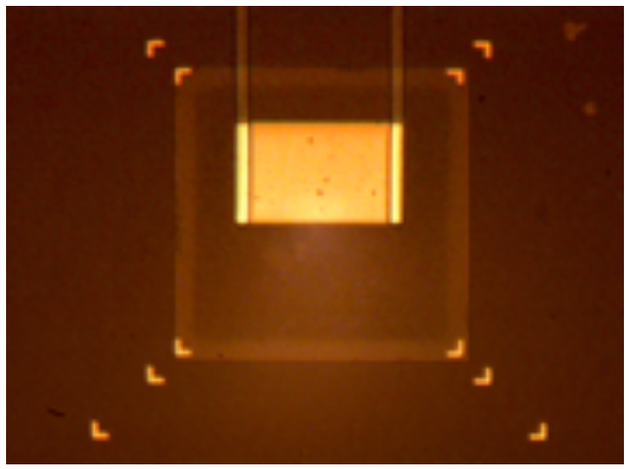
State-of-the-Art technique

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

Calorimetry (HOLMES, ECHO & NUMECS)

Technique highly advanced.

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

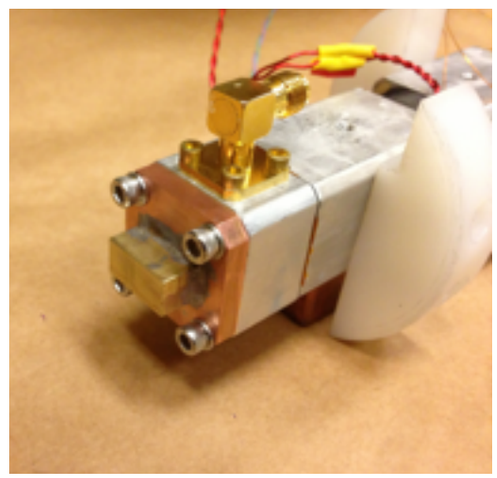


$$^{163}Ho + e^- \rightarrow {}^{163}Dy^* + \nu_e$$

Frequency (Project 8)

Radio-frequency spectroscopy for beta decay

R&D phase (new results)



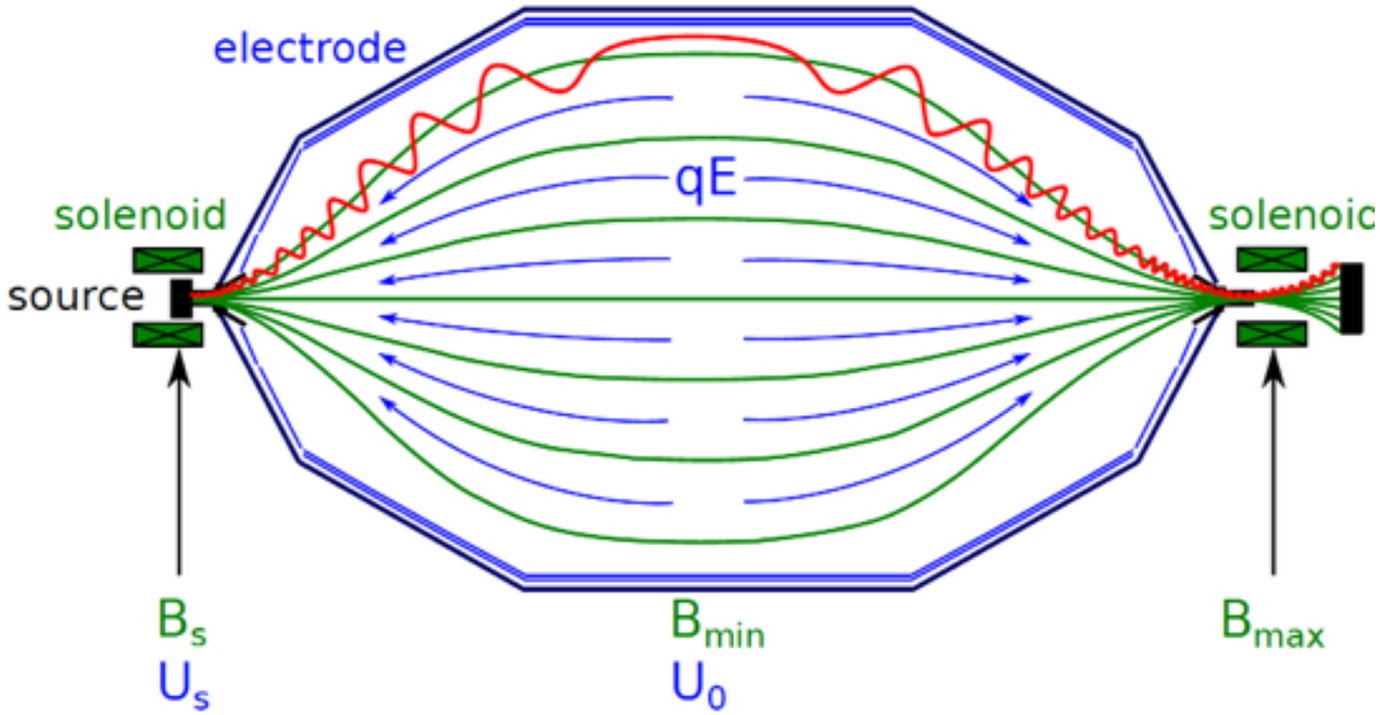
$$^3H \rightarrow {}^3He^+ + e^- + \bar{\nu}_e$$

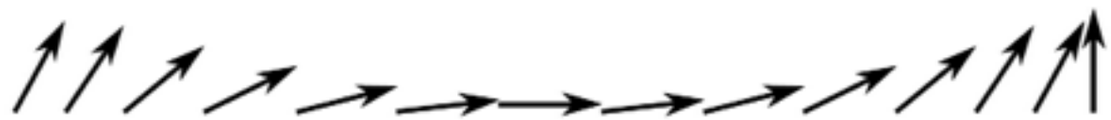
MAC-E Filter Technique

KATRIN

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

Spectroscopic: MAC-E Filter





adiabatic transformation of e⁻ momentum

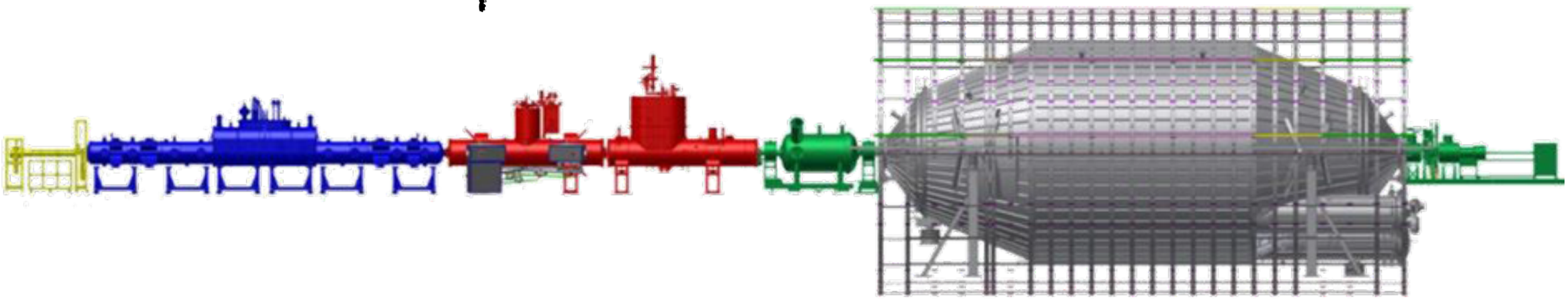
Inhomogeneous magnetic guiding field.

Retarding potential acts as high-pass filter

High energy resolution

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

The KATRIN Setup

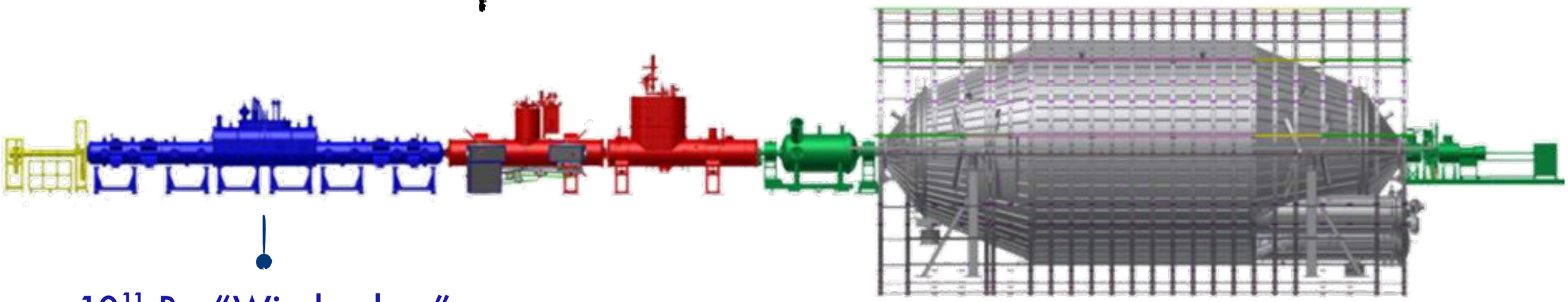


Adiabatic transport ensures high retention of phase space for decay

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

Energy resolution scales as the ratio of minimum / maximum fields

The KATRIN Setup



10^{11} Bq "Windowless" gaseous T_2 Source

(High field)

Adiabatic transport ensures high retention of phase space for decay

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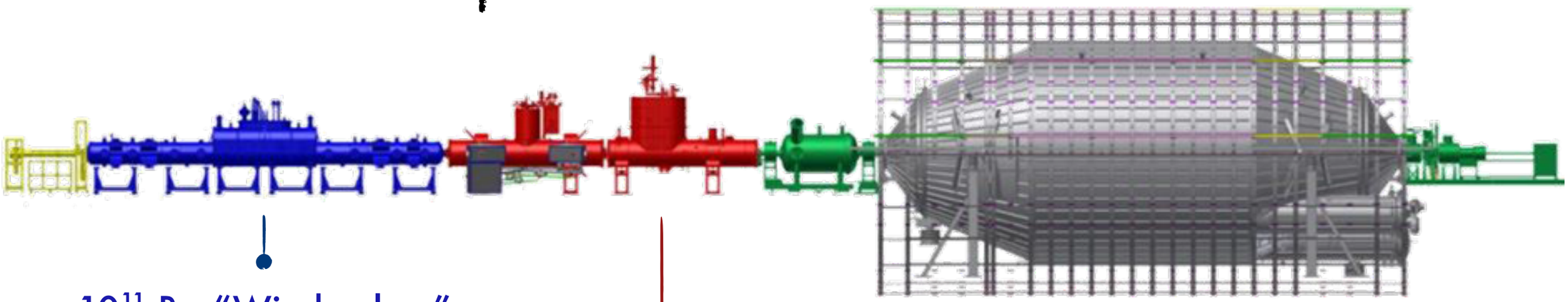

10^{11} Bq "Windowless" gaseous T_2 Source

(High field)

Tritium retention system

(10^7 tritium flow reduction)

Adiabatic transport ensures high retention of phase space for decay

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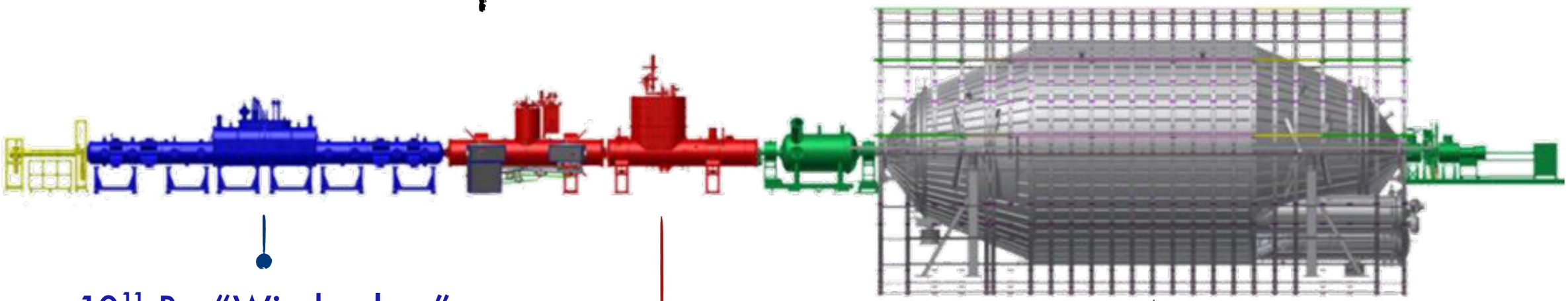

10^{11} Bq "Windowless" gaseous T_2 Source

(High field)

Tritium retention system

(10^7 tritium flow reduction)

High resolution electrostatic filter

(3G low field)

Adiabatic transport ensures high retention of phase space for decay

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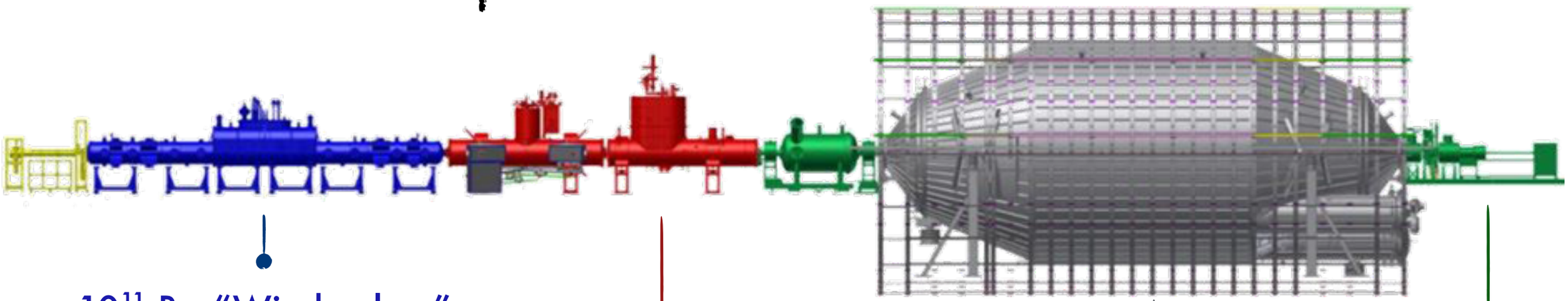


10^{11} Bq "Windowless" gaseous T_2 Source

(High field)

Tritium retention system

(10^7 tritium flow reduction)

High resolution electrostatic filter

(3G low field)

Detector System

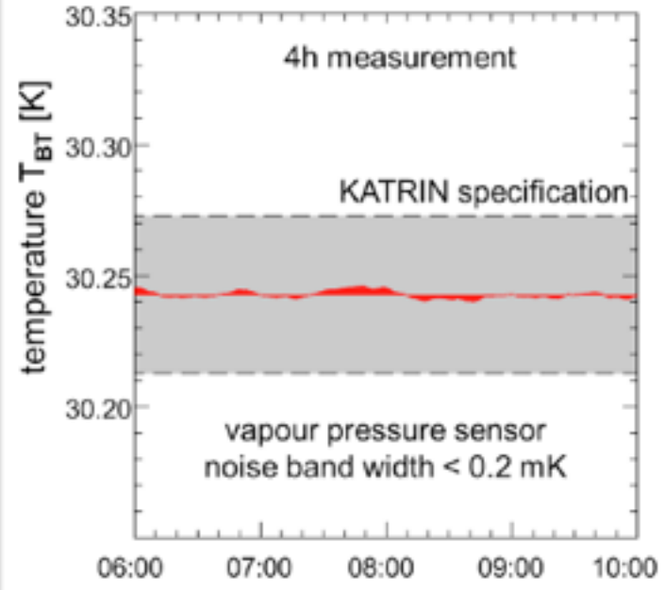
(High Field)

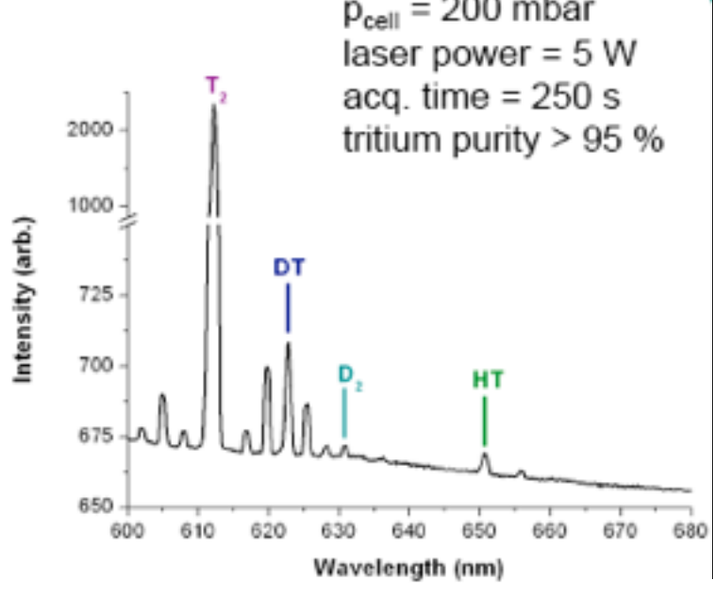
Adiabatic transport ensures high retention of phase space for decay

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

Energy resolution scales as the ratio of minimum / maximum fields

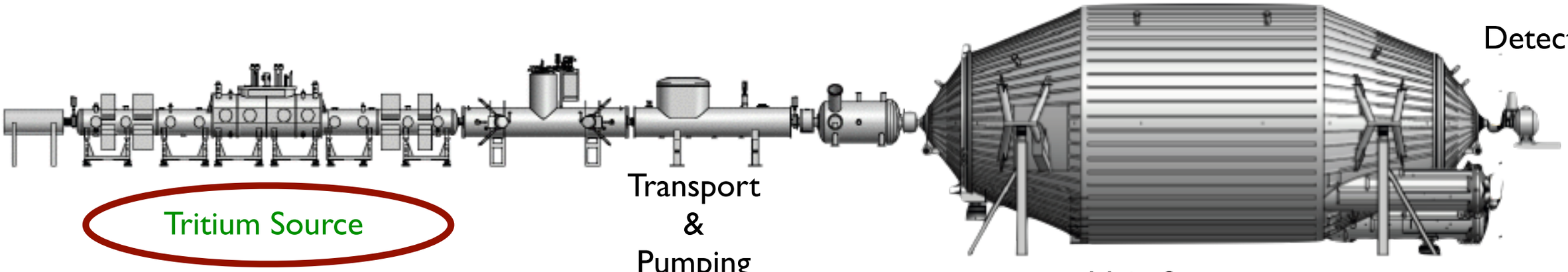
WGTS Demonstrator

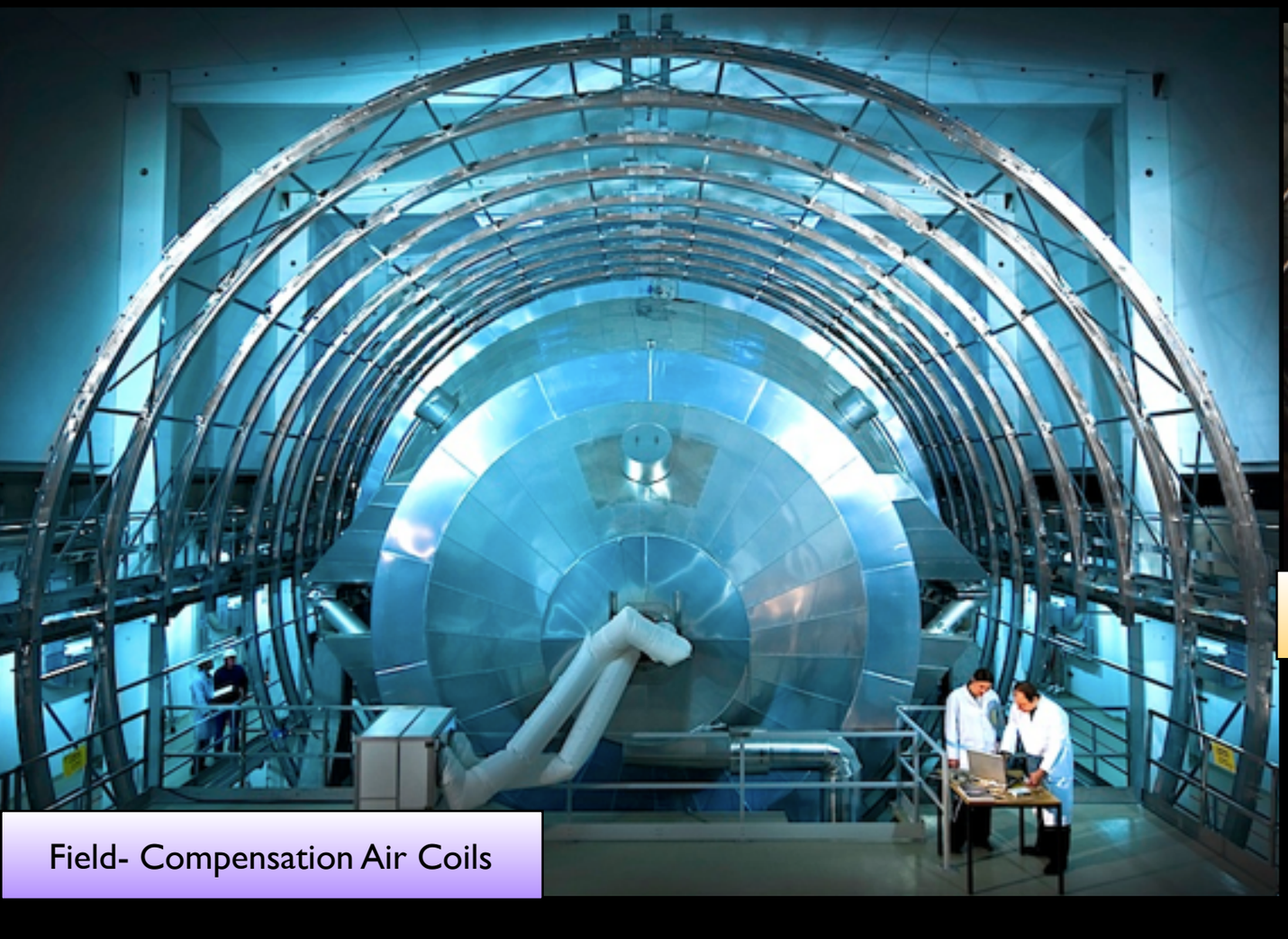




p_{cell} = 200 mbar
laser power = 5 W
acq. time = 250 s
tritium purity > 95 %

- Provides ~ 2 x 10^{11} Bq of activity (with tritium activity extruded from system).
- Monitoring of tritium purity, pressure & temperature.
- Temperature stability of ±3.6 mK recently achieved (x10 better than specification).



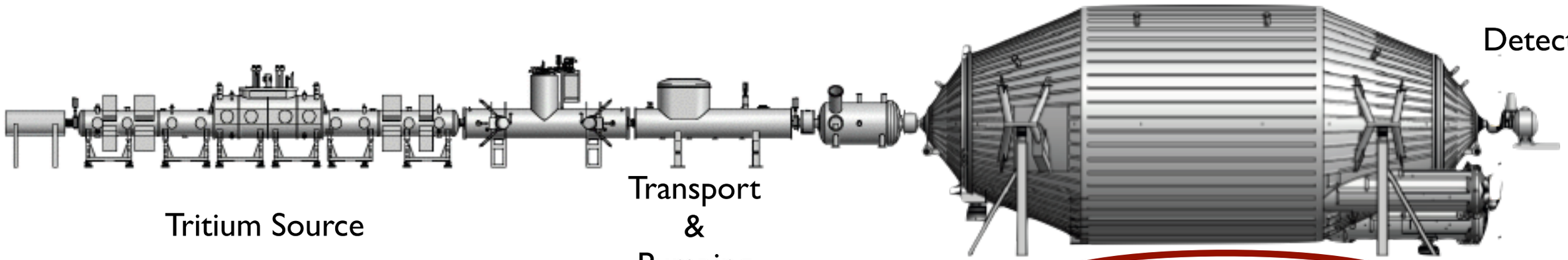


Field- Compensation Air Coils

Inner electrode wire mesh

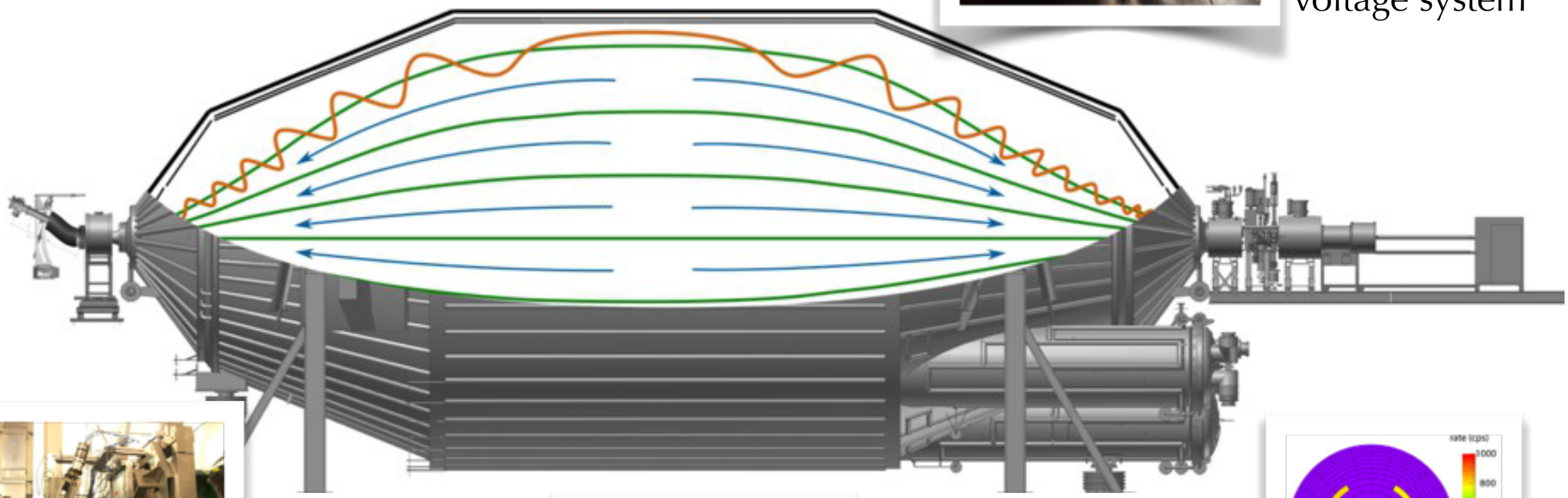
High Voltage Divider

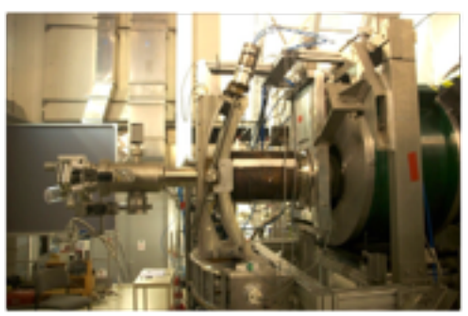
- A 10 m diameter analyzing spectrometer with 1:2000 energy resolution (0.93 eV)
- Extremely stable high voltage of main vessel.
- Few ~ppm precision divider and monitoring spectrometer.



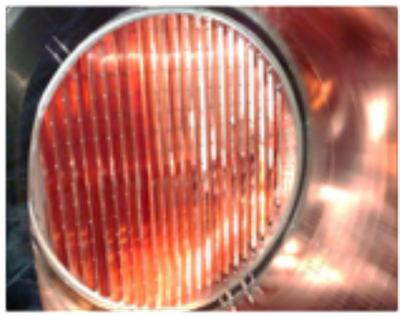
Spectrometer Commissioning

Precision high voltage system

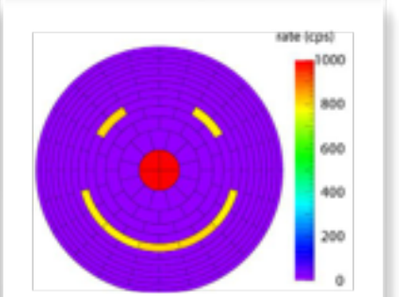




High precision electron gun



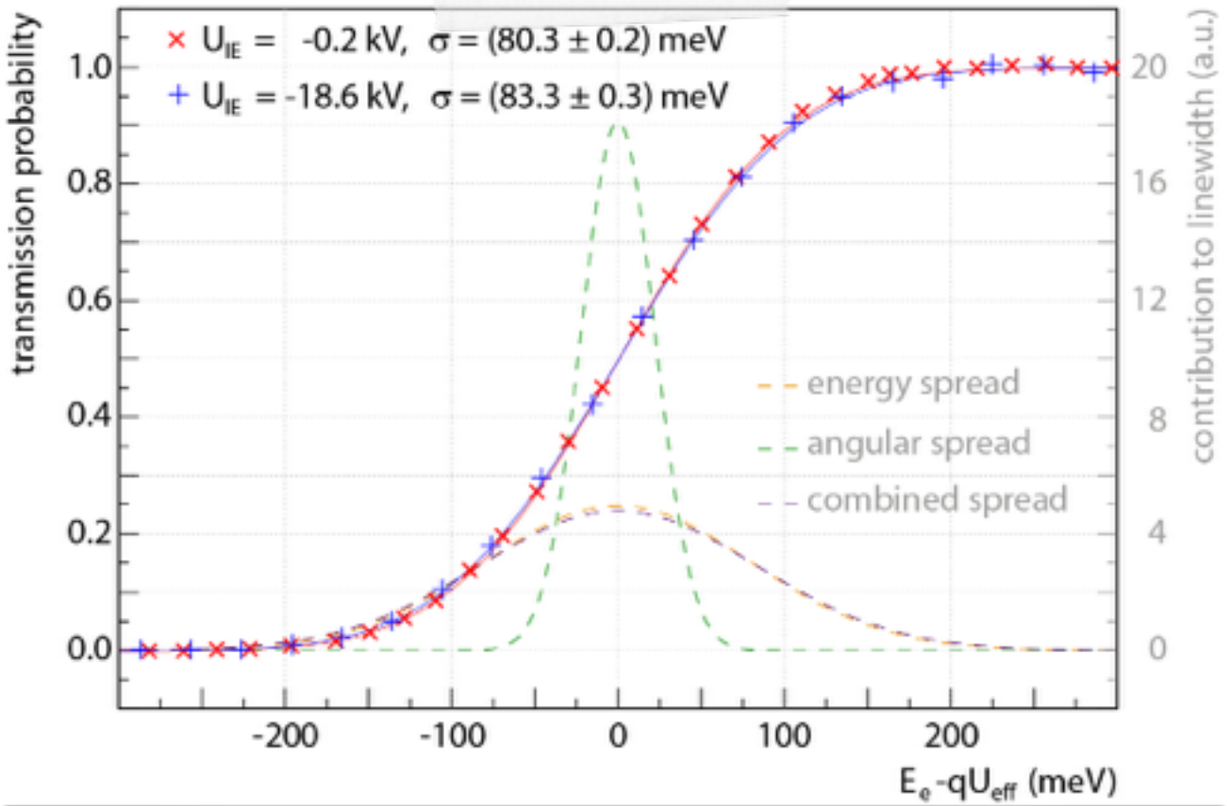
Ultra high vacuum system



Full detector system

Summer 2013 saw "first light" from the KATRIN.
Spectrometer and detector system fully integrated.
Allowed for test of transmission function and background levels.

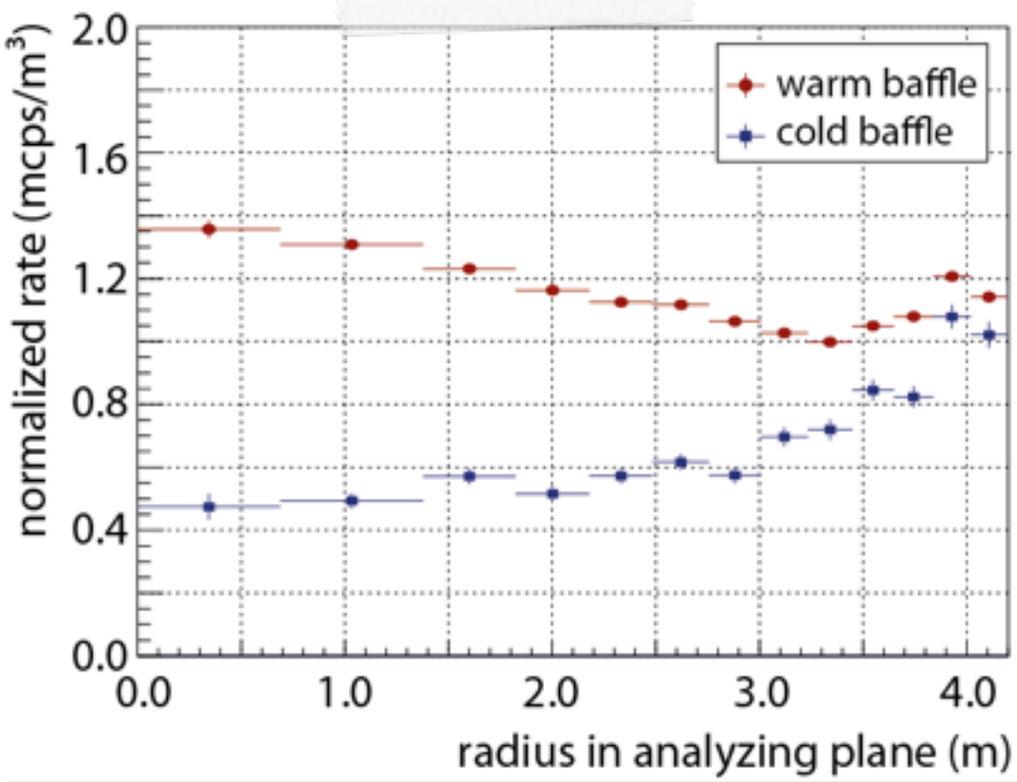
Transmission Function



At -18.6 keV, better than
100 meV resolution

Sharpest transmission function
for a MAC-E filter

Background Rates



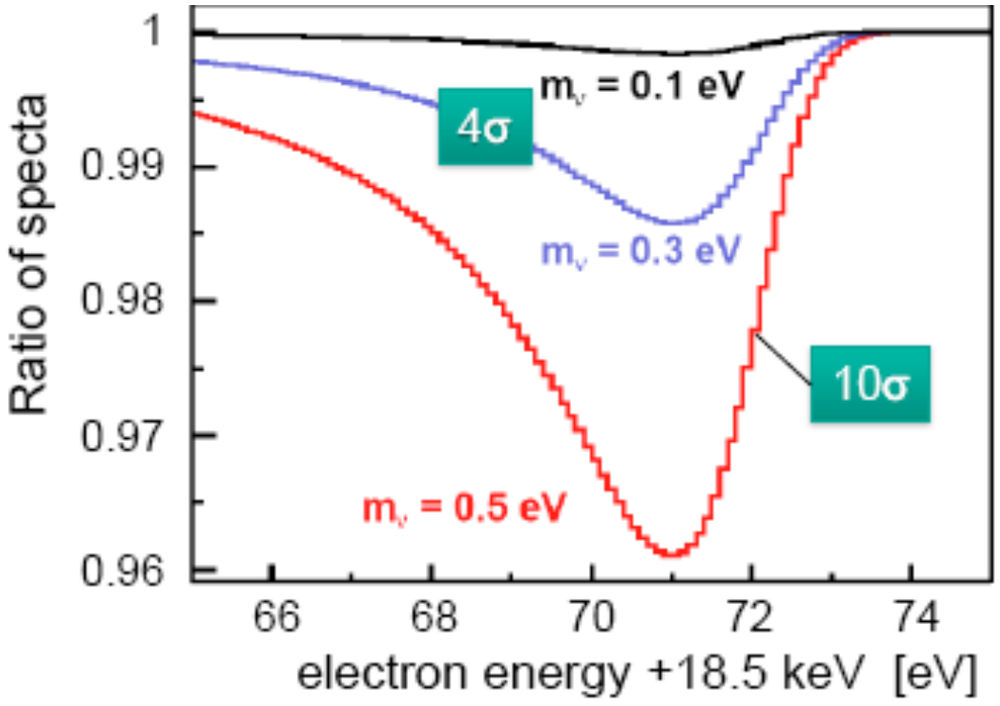
Background rate of order Hz
(radon-dominated)

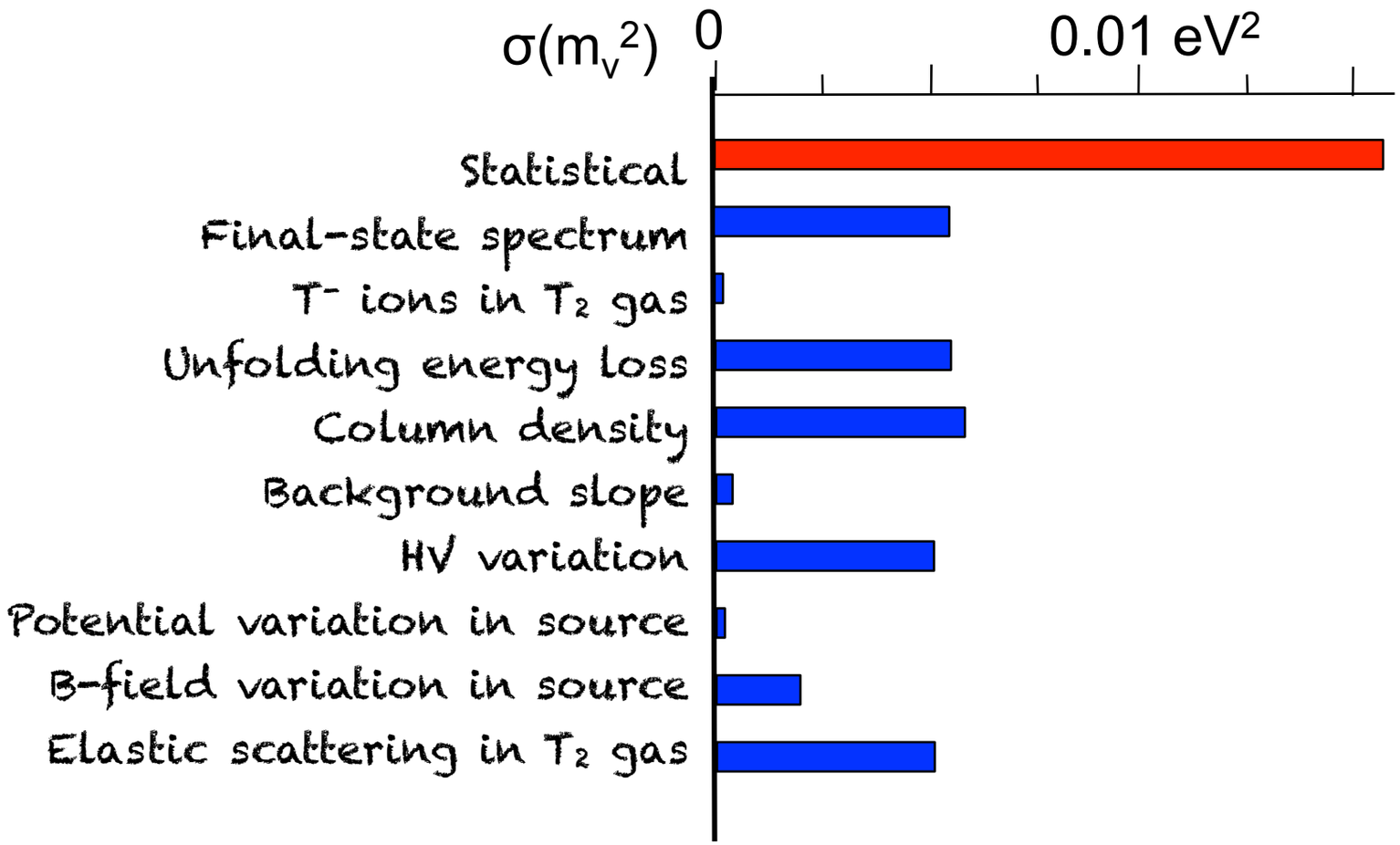
Greater reduction of
backgrounds to come

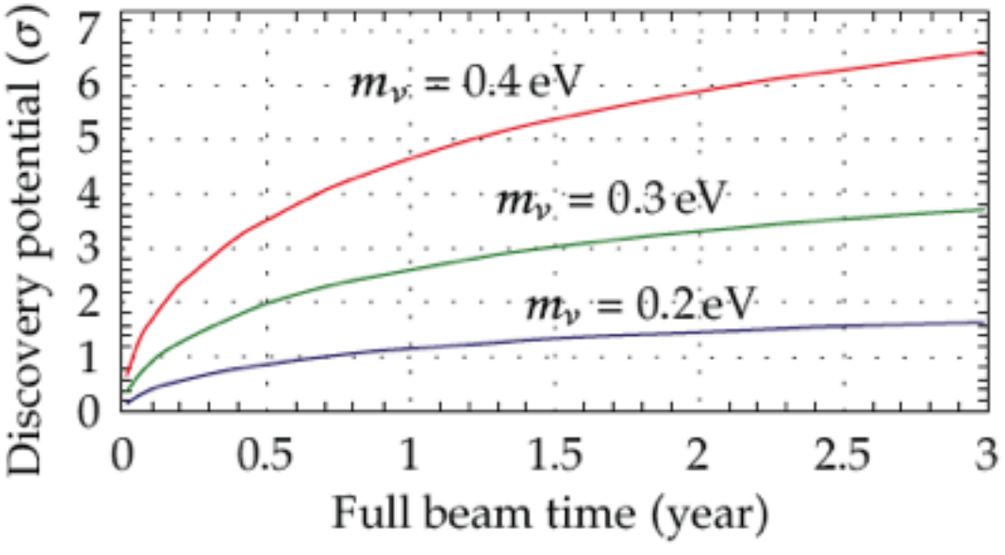
Commissioning showed excellent behavior of MAC-E Filter response.

Next commissioning (now) should show greater background suppression.

Projected Sensitivity







Neutrino Mass Goals

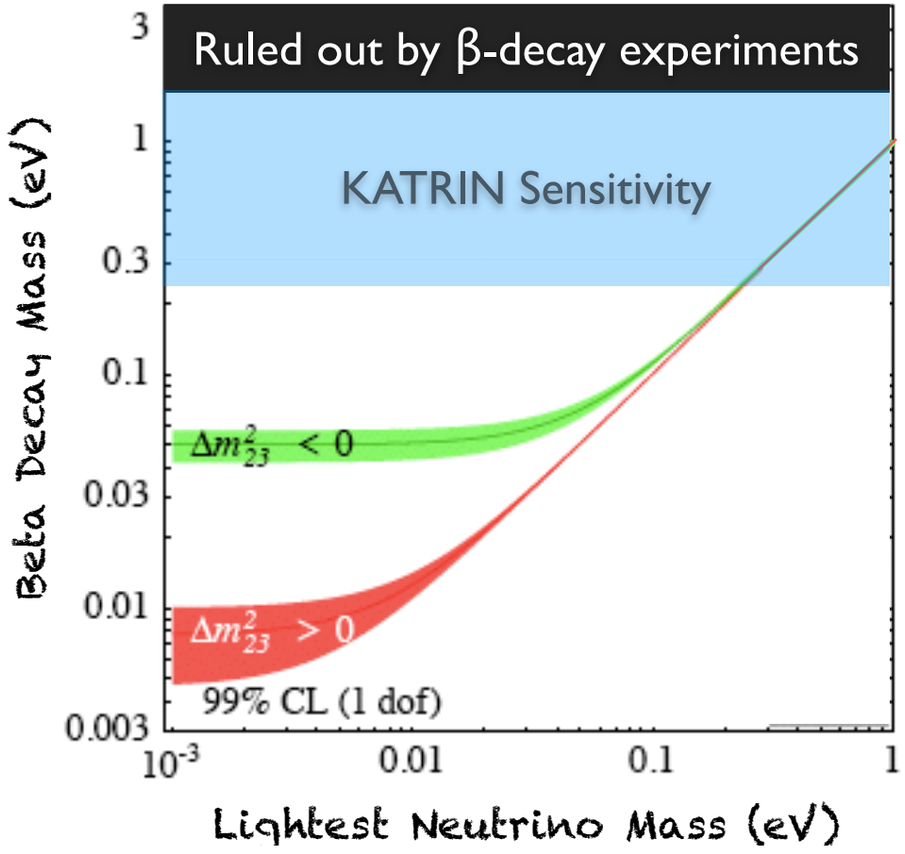
Discovery: 350 meV (at 5 σ)

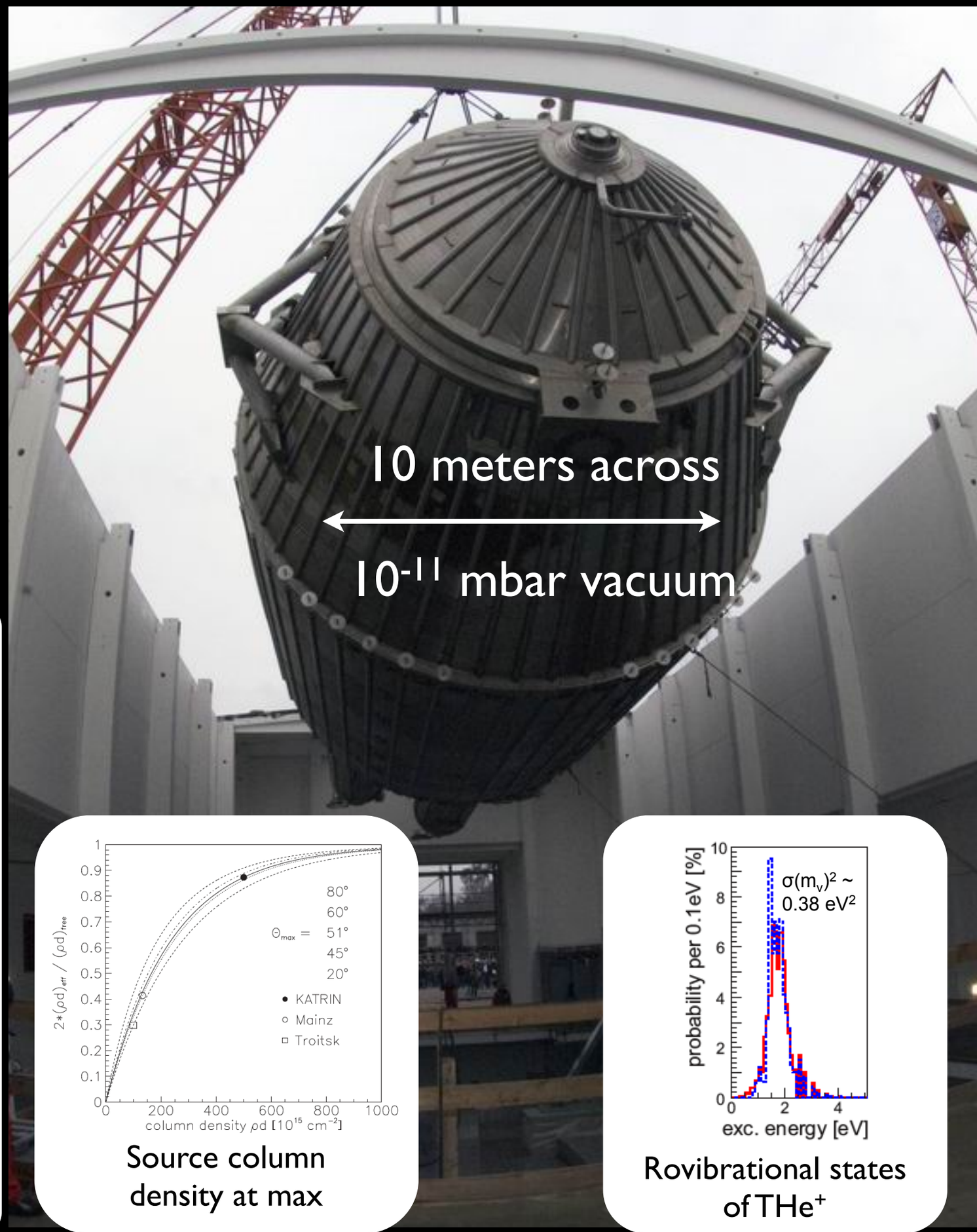
Sensitivity: 200 meV (at 90% C.L.)

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

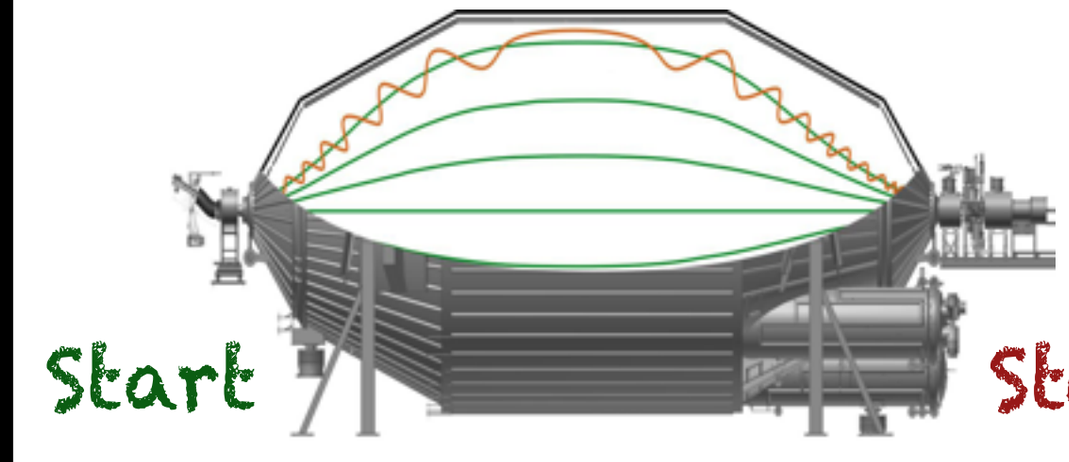
- In principle, it is possible to improve the statistical sensitivity of KATRIN by combining its energy resolution with a time-of-flight measurement.

- 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)



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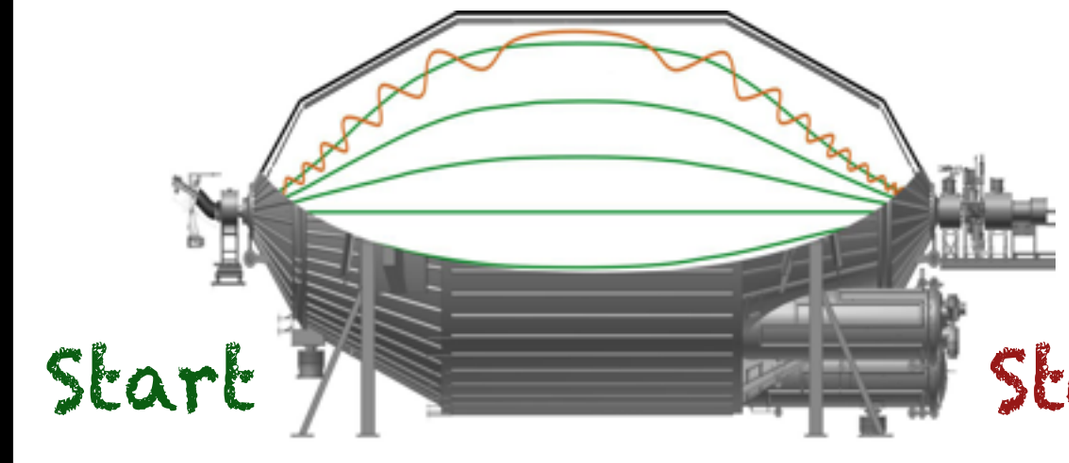
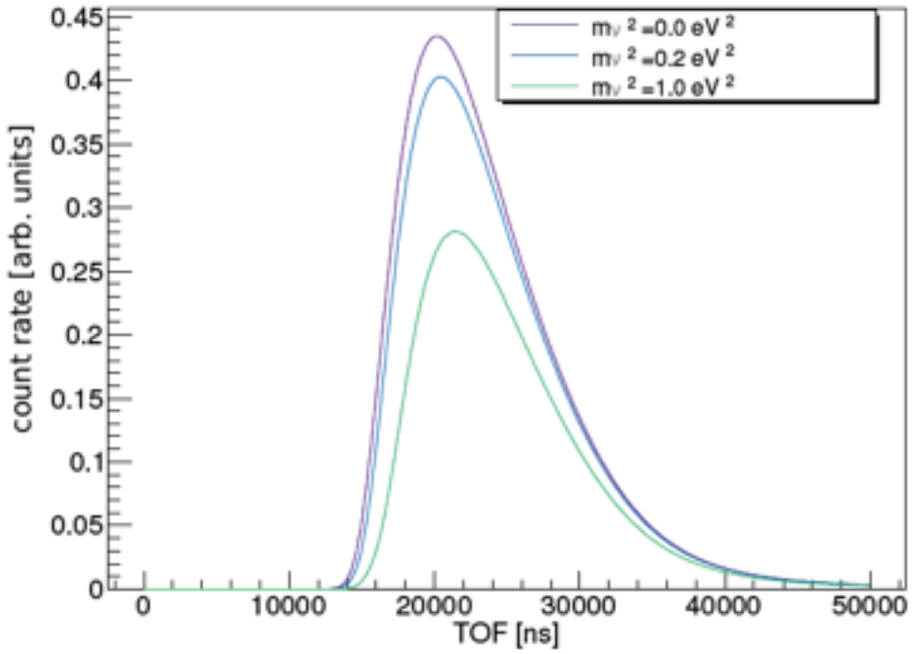
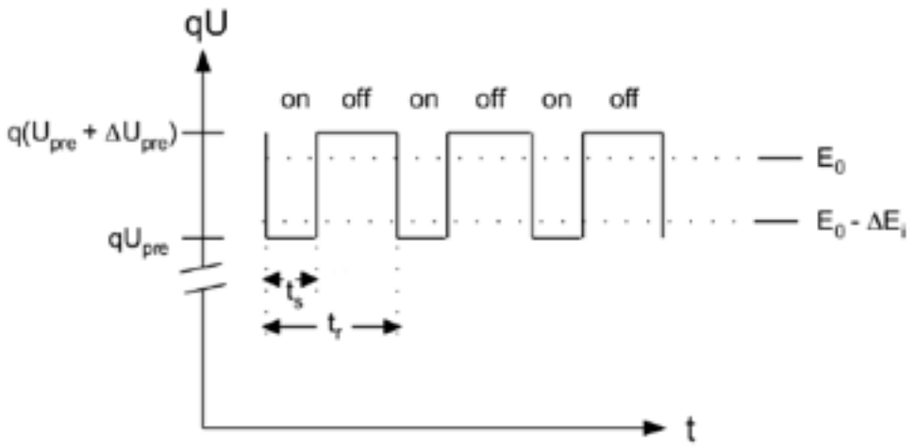
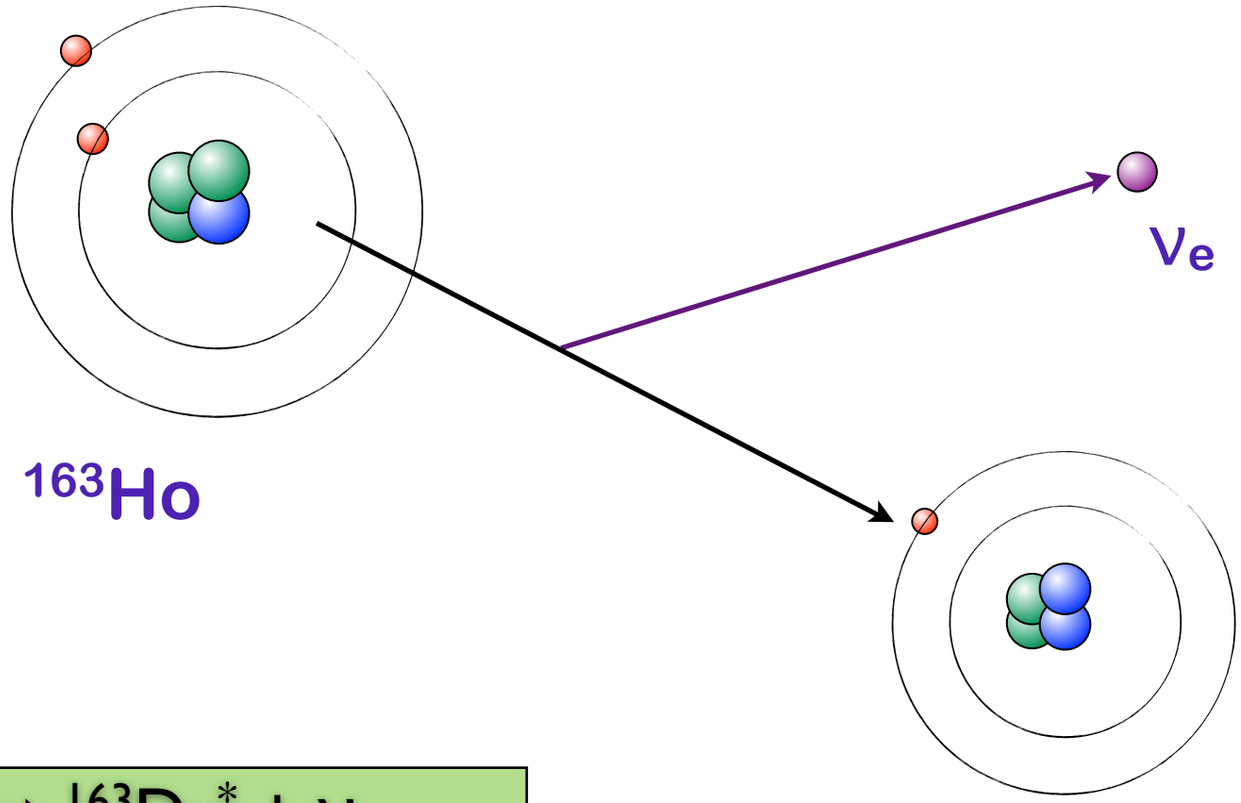




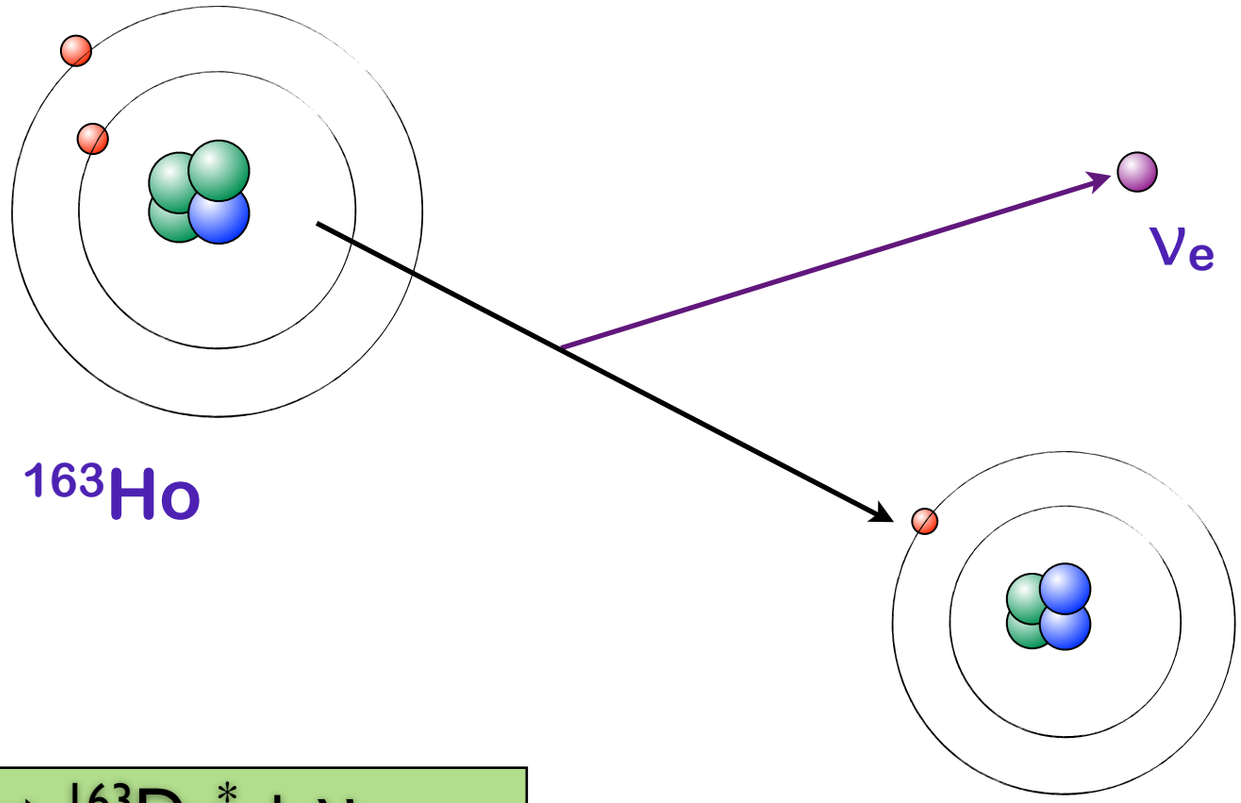




$^{163}Ho + e^- \rightarrow {}^{163}Dy^* + \nu_e$

$^{163}Dy^* \rightarrow {}^{163}Dy + E.C.$

New kid on the block:
Electron Capture



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

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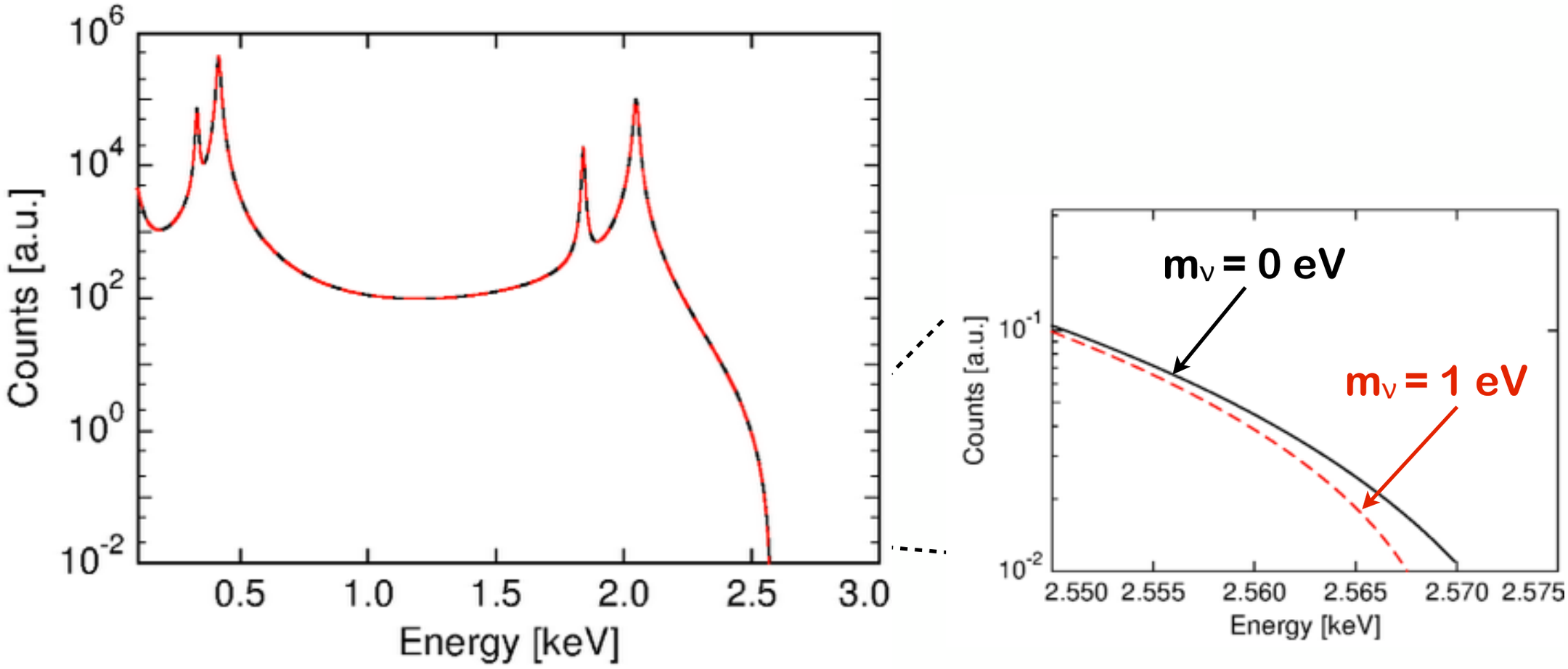
isotope

New ~~kid~~ on the block:

Electron Capture

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



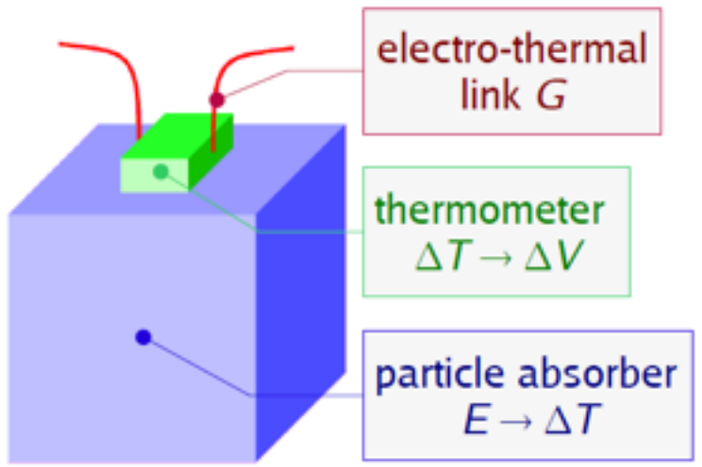
isotope

New ~~kid~~ on the block:

Electron Capture

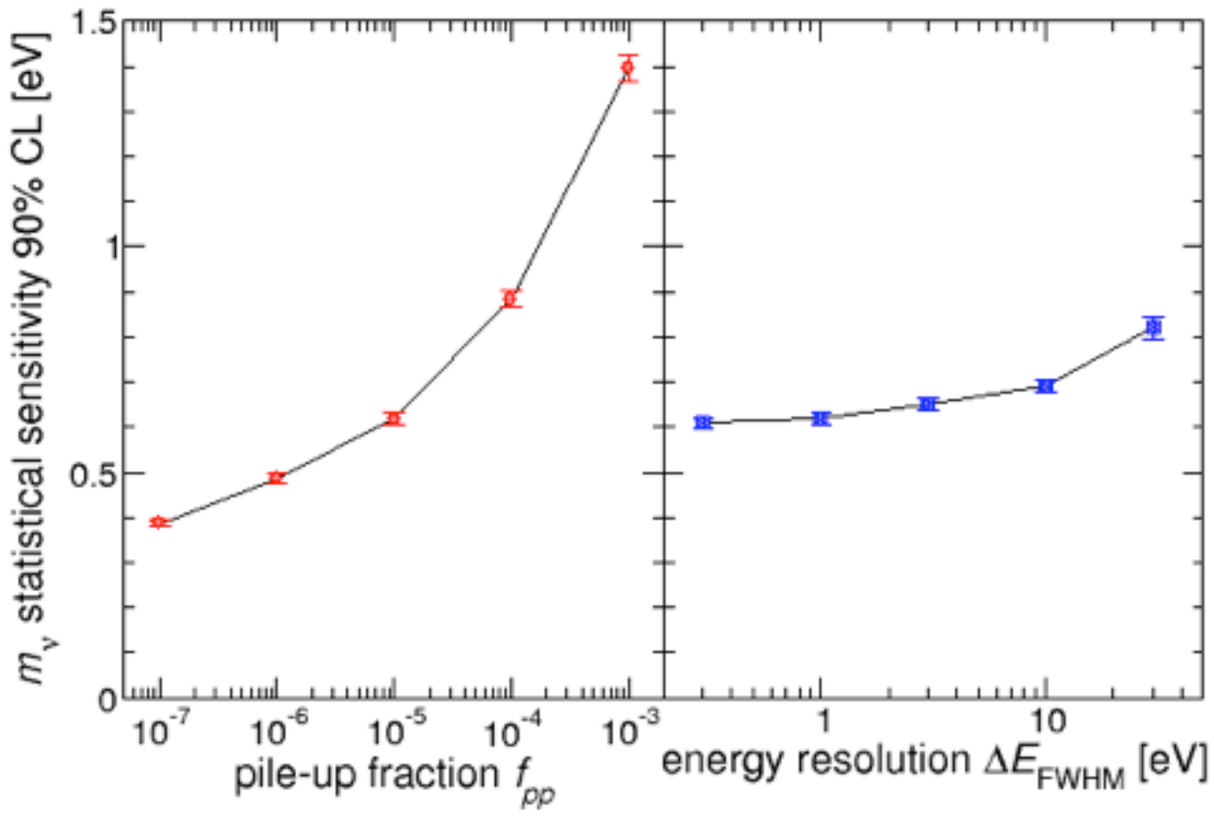
Advantages & Challenges

Calorimetry



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

Challenges:



Source Activity

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

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

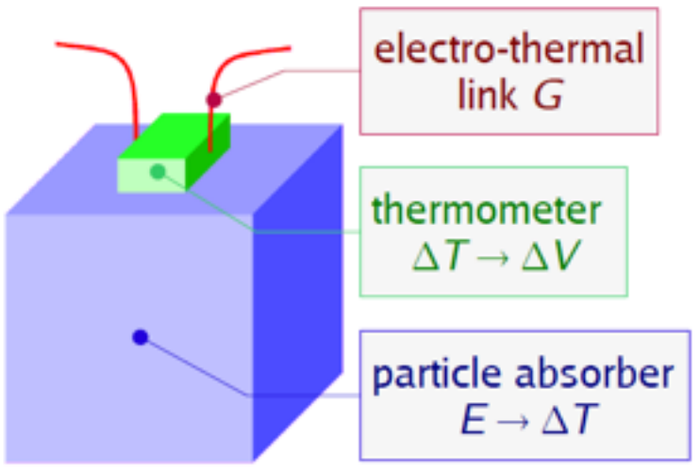
Detector Response

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

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

Advantages & Challenges

Calorimetry



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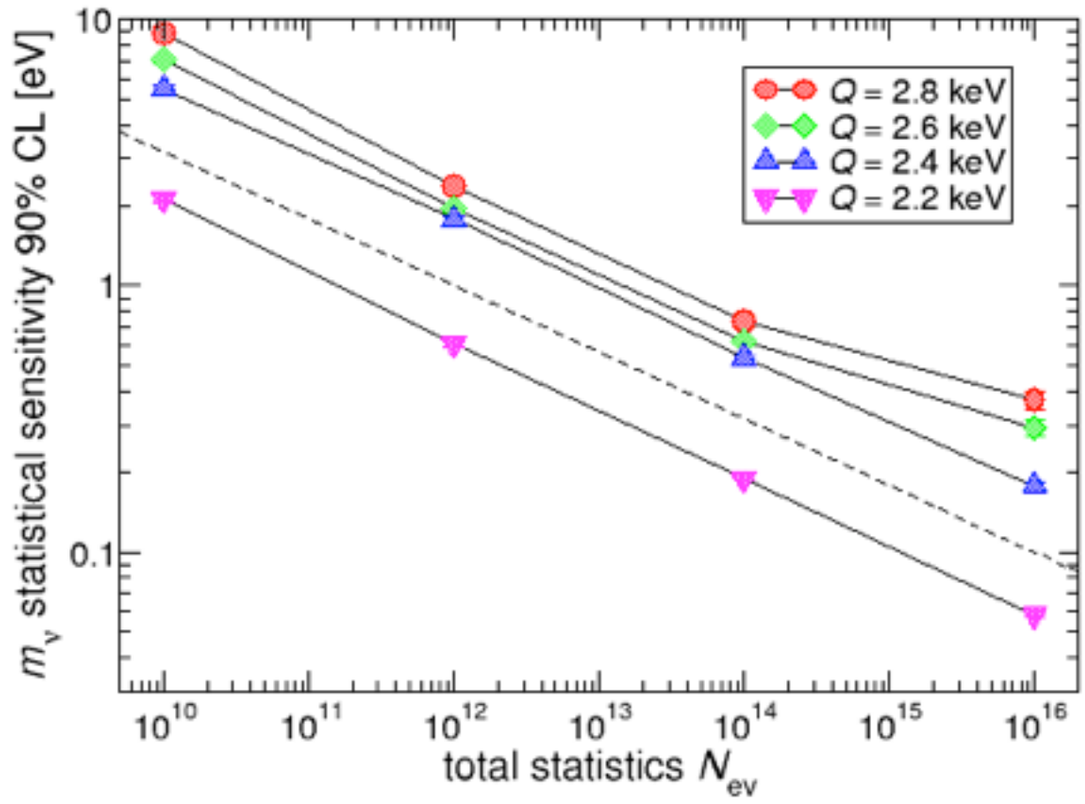

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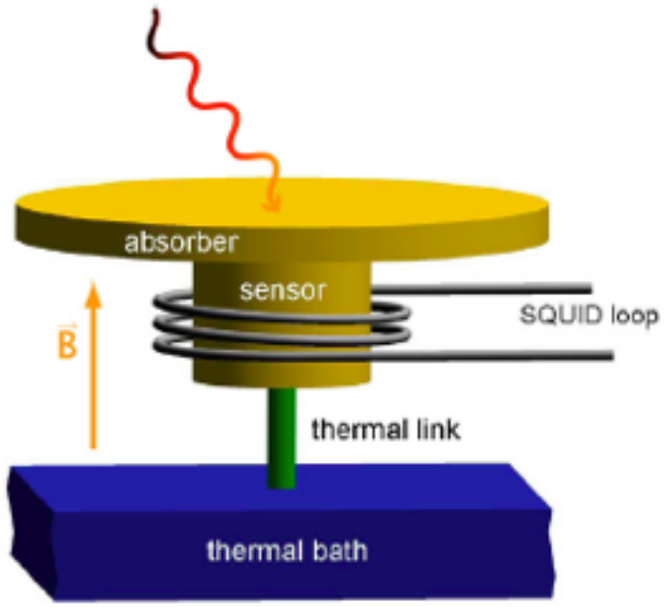
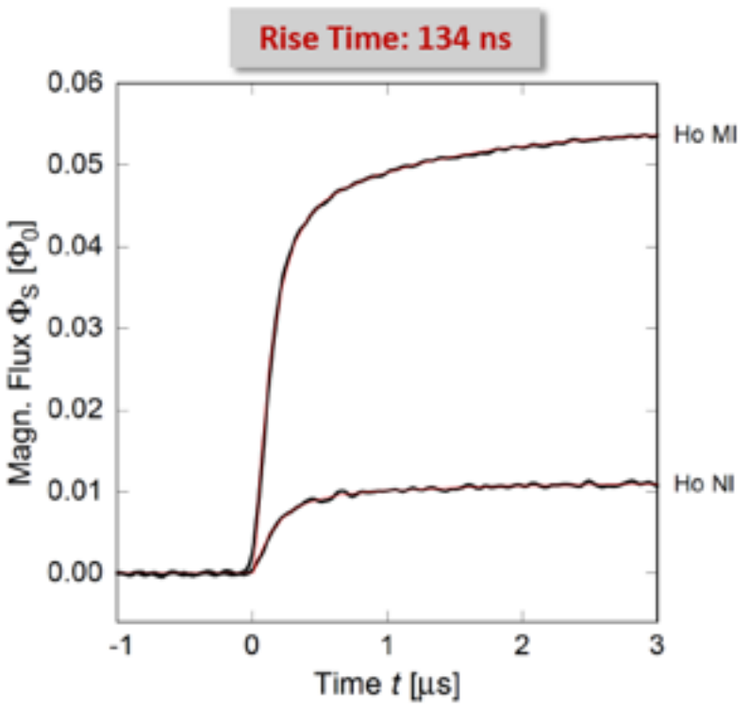
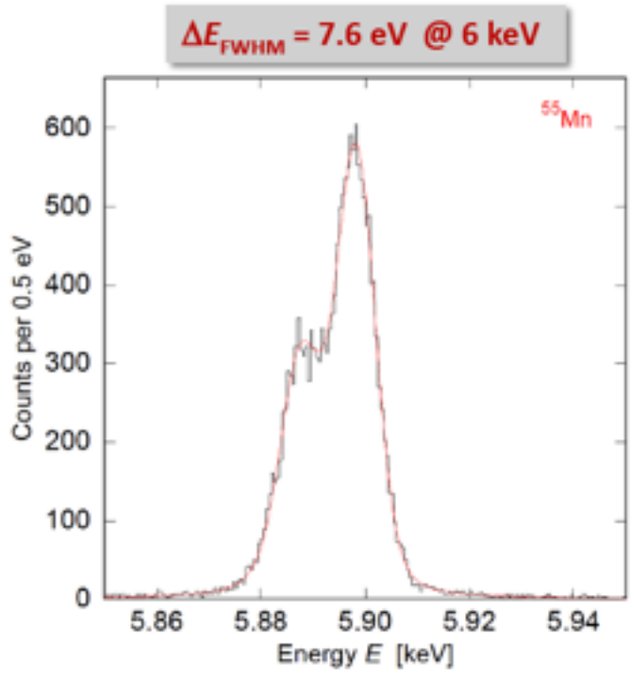
The ECHo Experiment

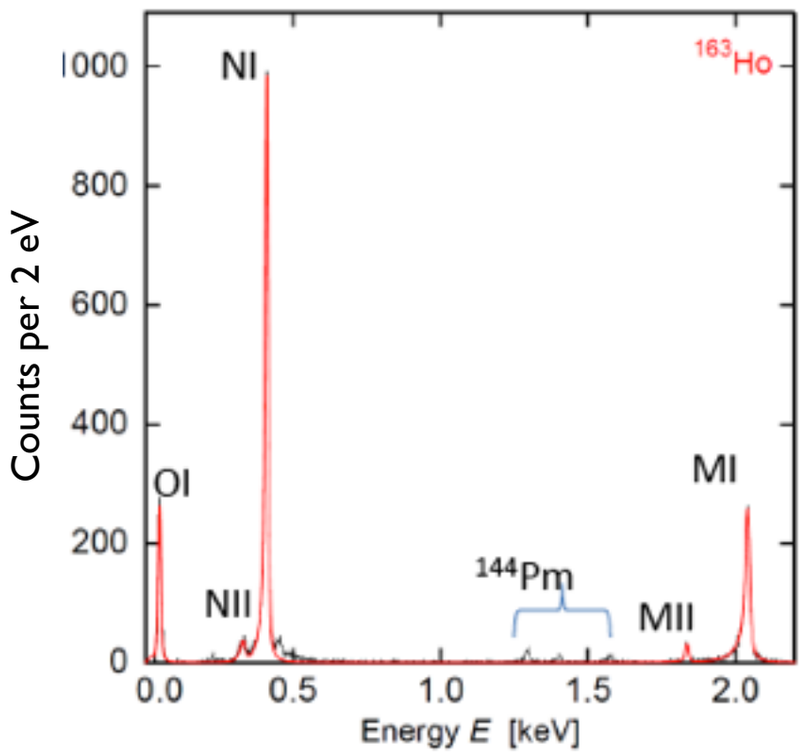
Technology:



Metallic Magnetic Calorimeters



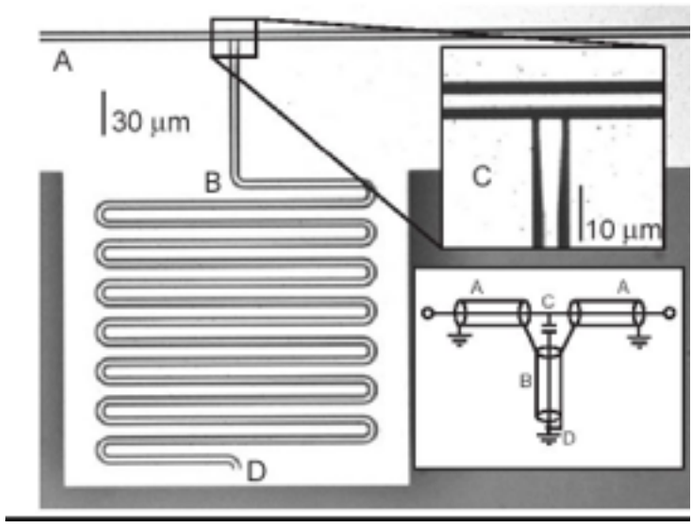




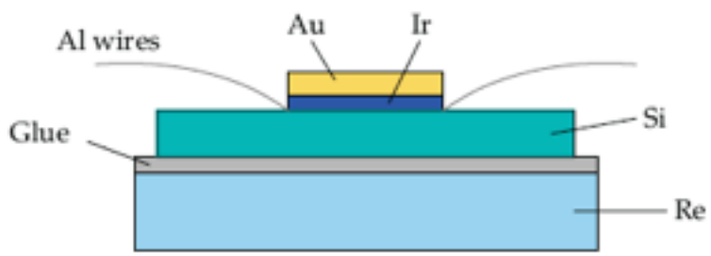
- The ECHo experiment uses metallic magnetic calorimeters to achieve goals.
- Fast rise times and good energy resolutions and linearity demonstrated.
- Endpoint measured at 2.80 ± 0.08 keV.

The HOLMES Experiment

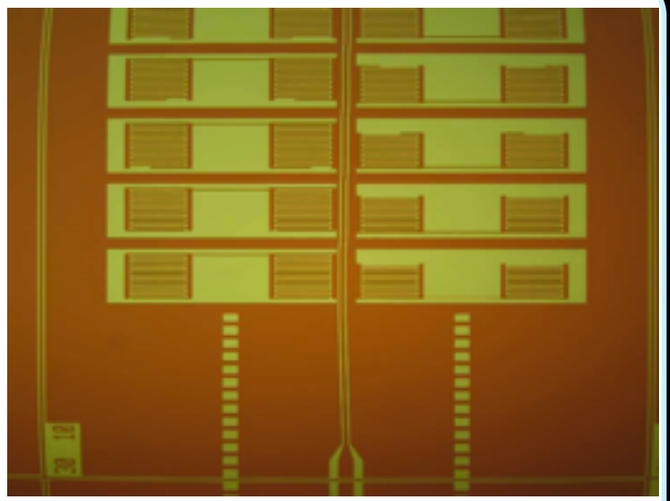
Technologies:

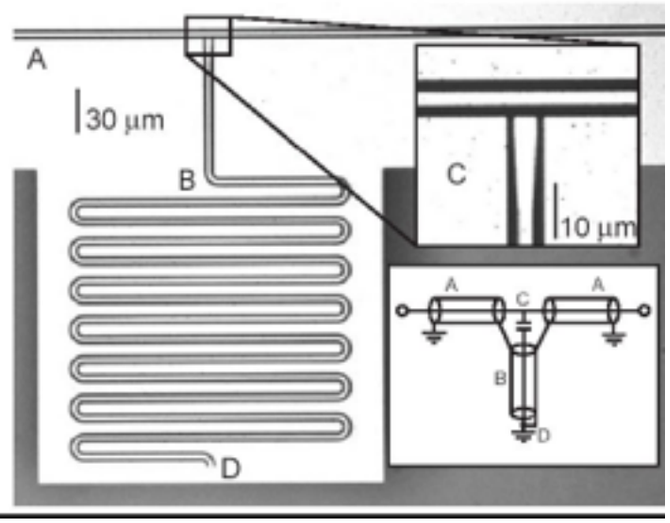


Superconducting Resonators



Transition Edge Sensors



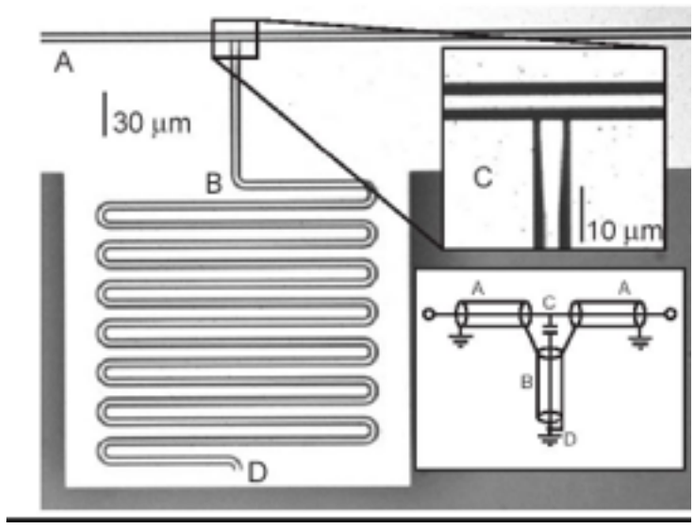


MARE-HOLMES

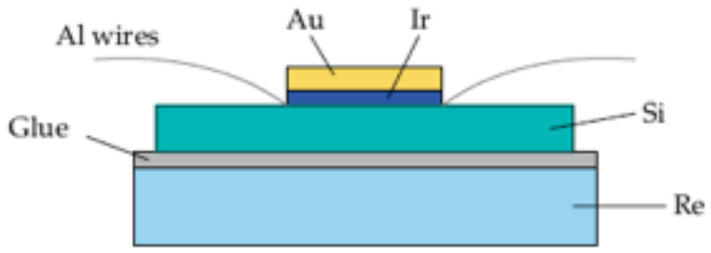
- MARE (Phase I) explored various technology approaches, such as Transition-Edge Sensors (TES) and Microwave Kinetic Inductance Detectors (MKIDs).
- Successful extraction of Ho^{+} ions for metal production and implantation onto detectors.
- Successful funding received for one thousand channel Ho detector experiment (the HOLMES experiment).

The NuMECS Experiment

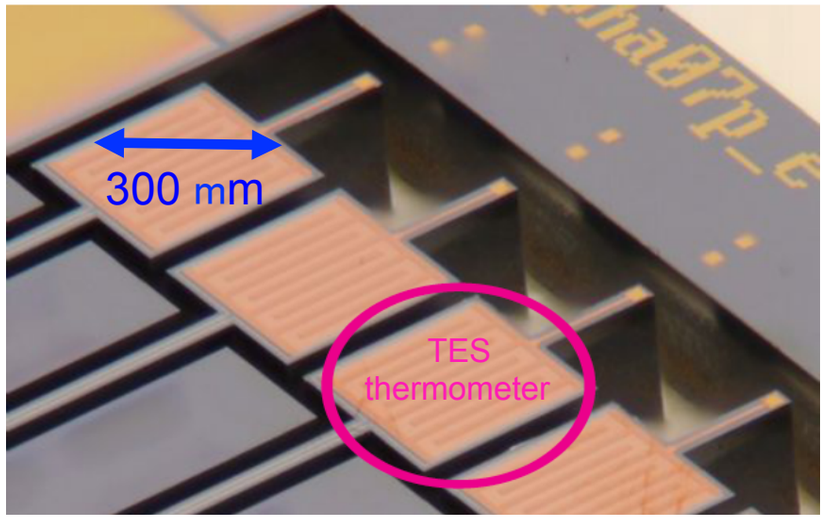
Technologies:



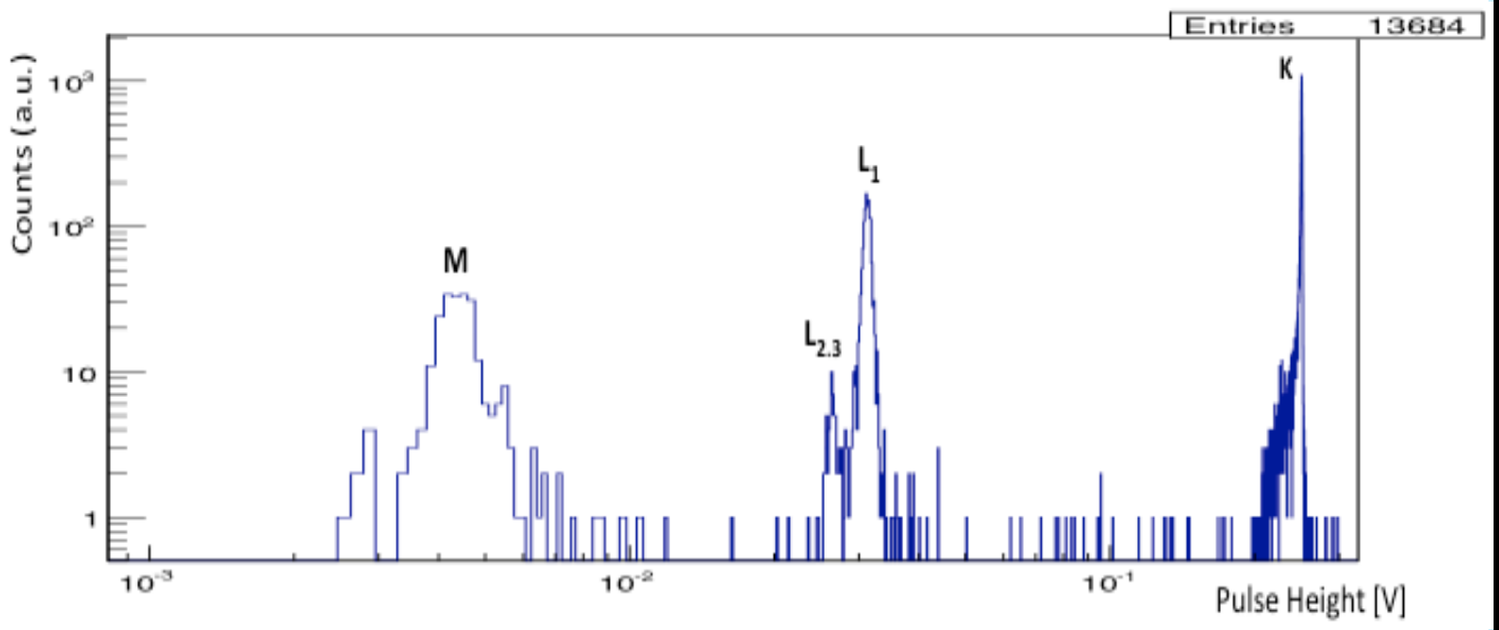
Superconducting Resonators



Transition Edge Sensors



NuMECS (First 2 years)

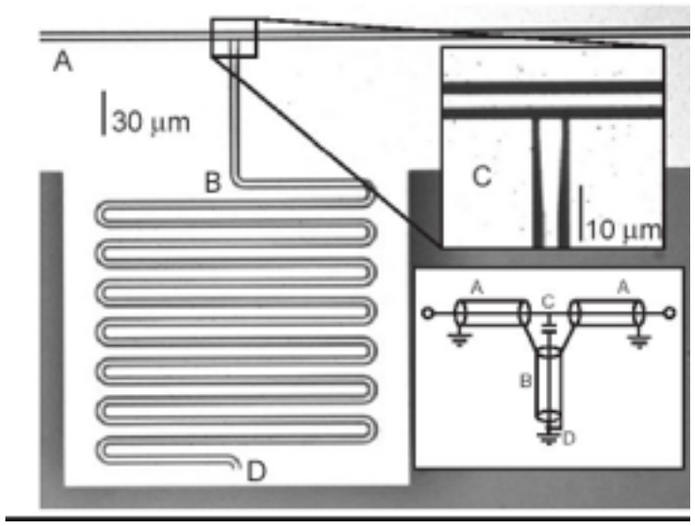


- New effort in the US (Los Alamos) for using transition-edge sensor technology for electron capture characterization.
- Concentration on high purity ^{163}Ho production via FRIB. Recent high purity production at the 0.1 mg level and energy resolution (6 eV @ 6 keV with ^{55}Fe surrogate).

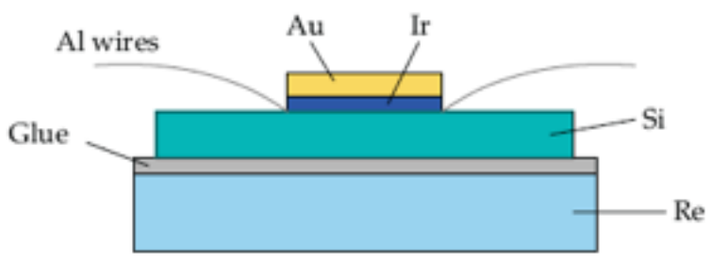
See position paper (link here) for details.

The NuMECS Experiment

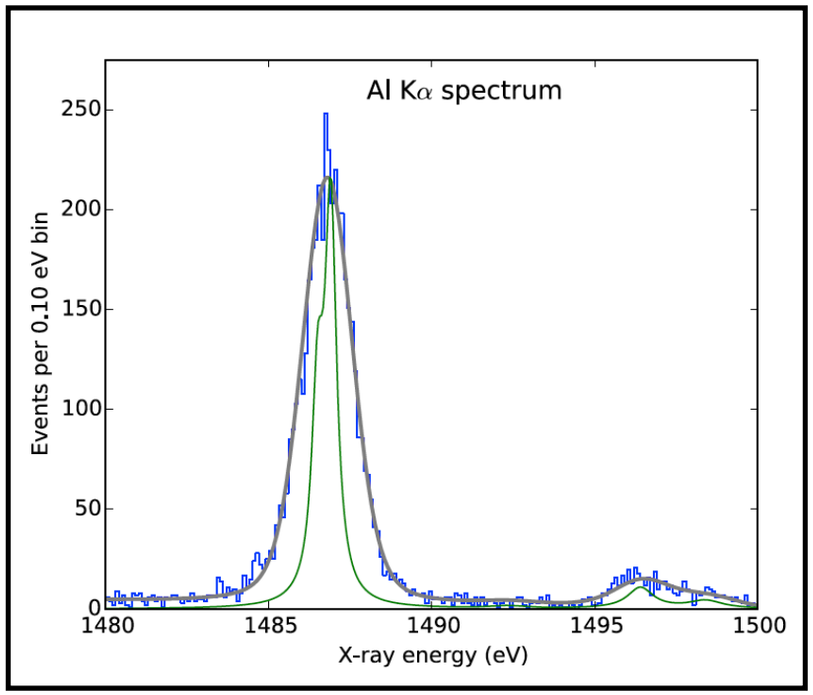
Technologies:



Superconducting Resonators



Transition Edge Sensors



Example spectrum in target energy range for ^{163}Ho ECS

NuMECS (Next 5 years)

Example sensor– segment of LANL-NIST gamma-ray array

- Critically asses entire electron capture method and validate all component technologies.
- Show scalability through a demonstrator experiment with 4 x 1024 TES array of Ho-implanted detectors with RF-SQUID multiplexing.
- Aim mass sensitivity of demonstrator to ~1 eV scale.

See position paper (link here) for details.

Project 8

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

I. I. Rabi

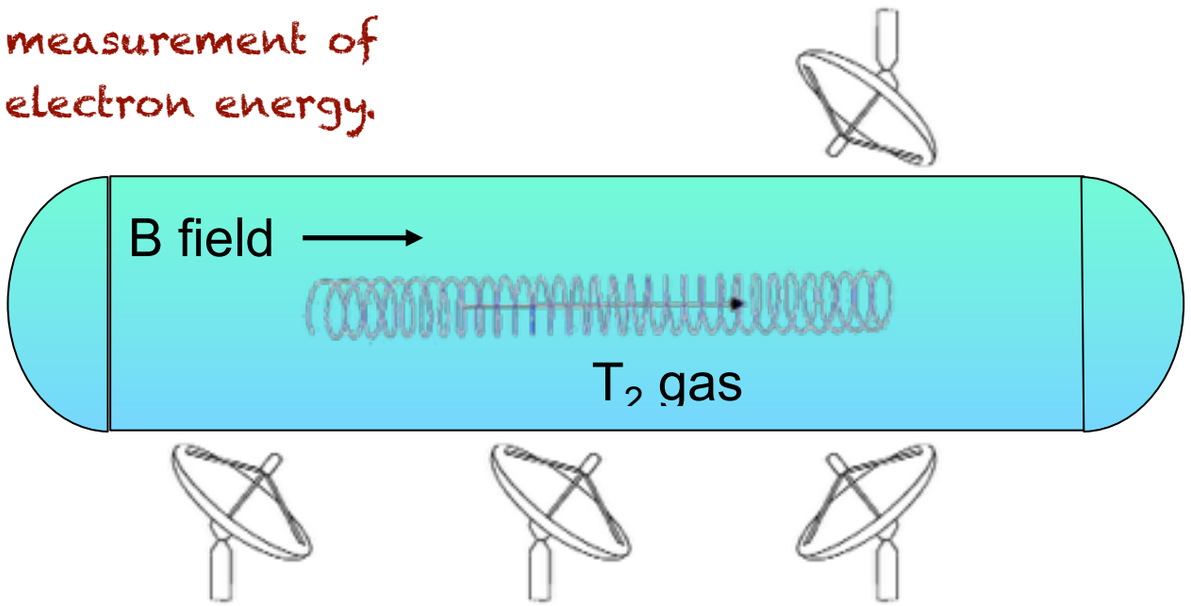
"Never measure anything but frequency."

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

PROJECT 8

Frequency Approach

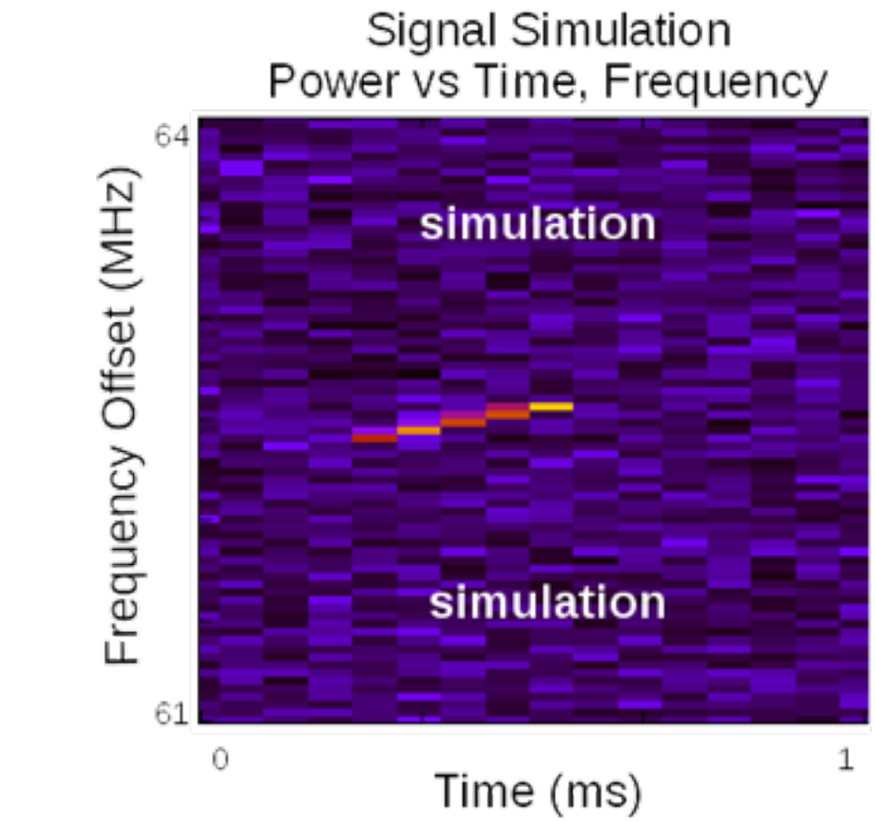
$$^3\mathrm{H} \rightarrow {}^3\mathrm{He}^+ + e^- + \bar{\nu}_e$$

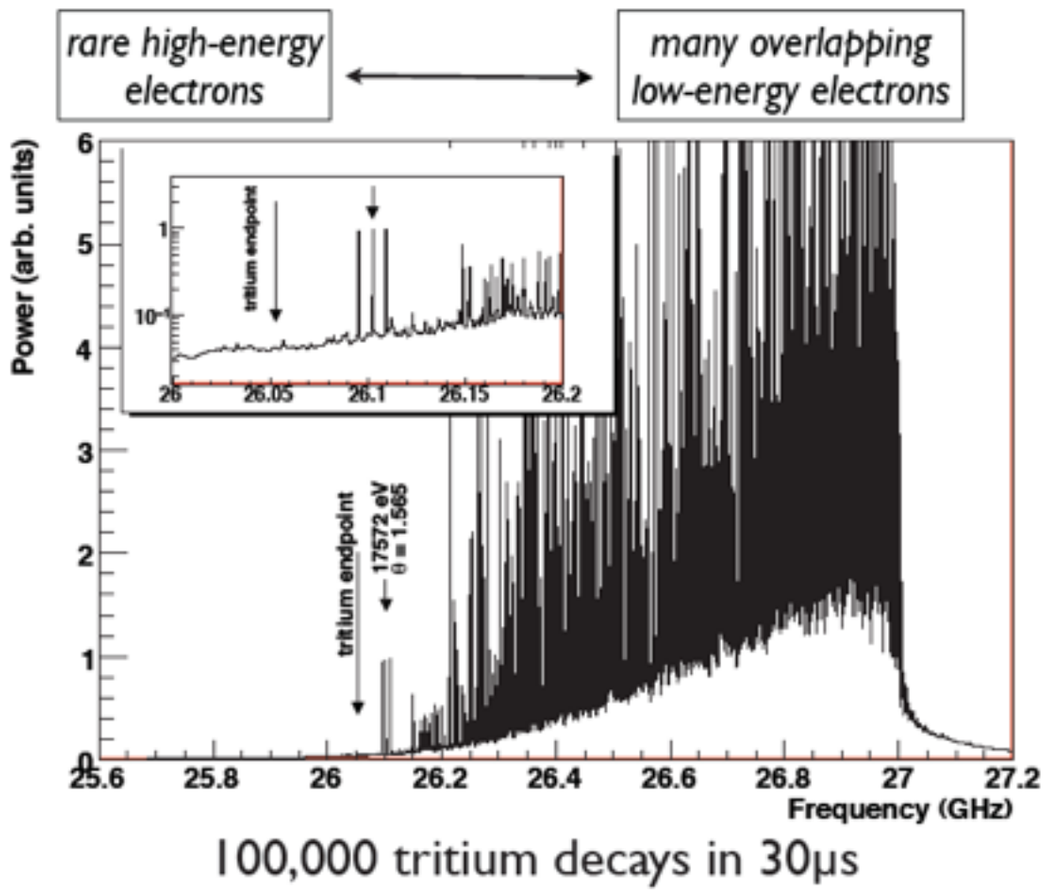
Unique Advantages

- **Source = Detector**
  (no need to extract the electrons from the tritium)

- **Frequency Measurement**
  (can pin electron energies to well-known frequency standards)

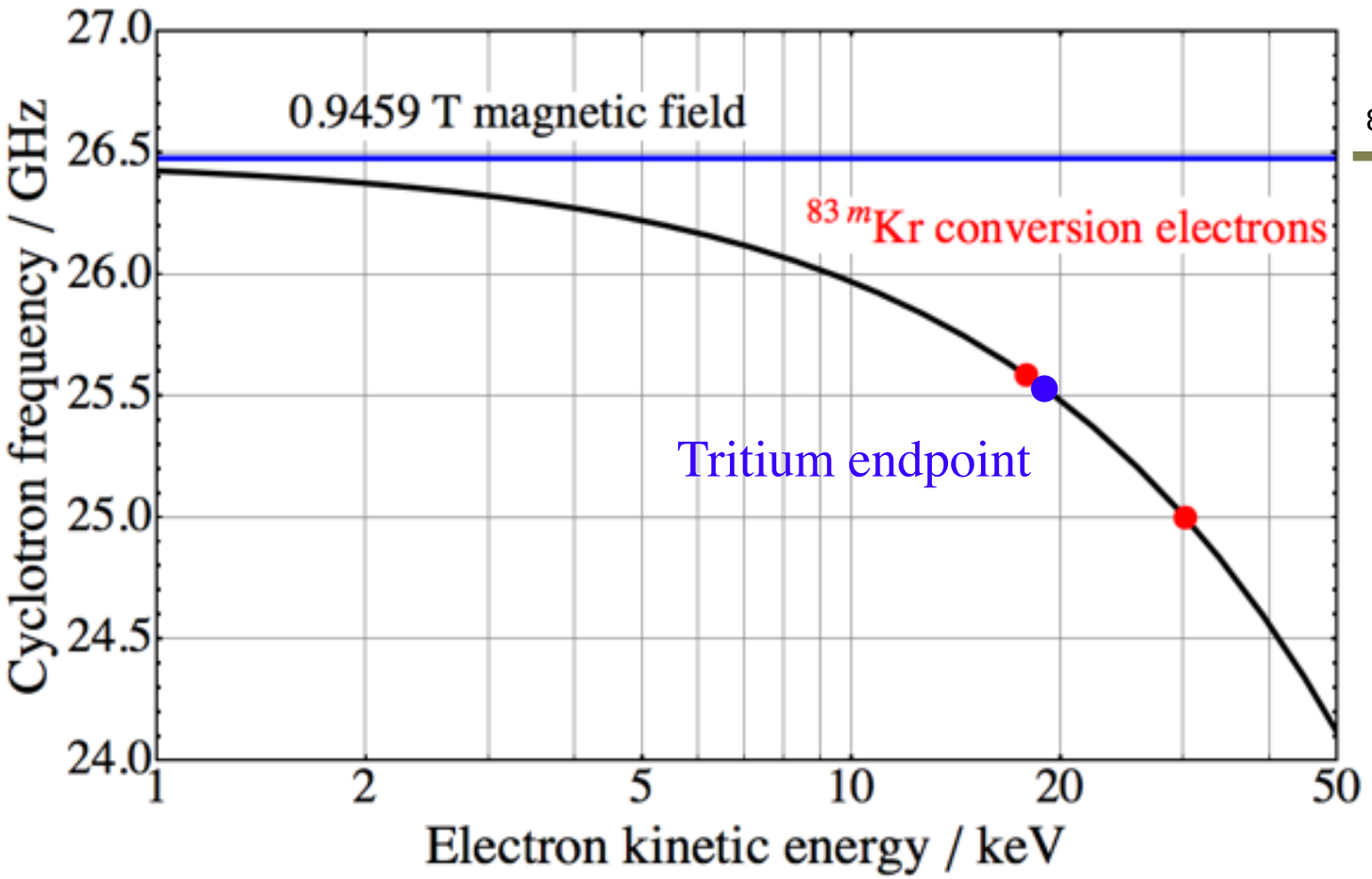
- **Full Spectrum Sampling**
  (full spectrum measured at once, large leverage for stability and statistics)

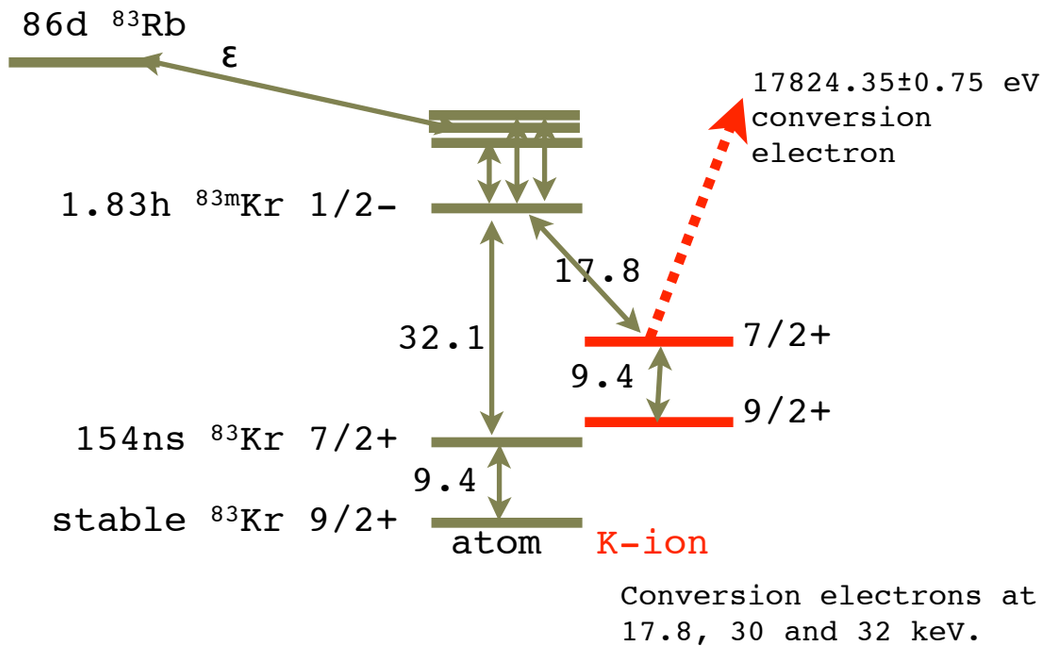




Simulation of beta (frequency) spectrum

Initial Demonstration: ^{83m}Kr



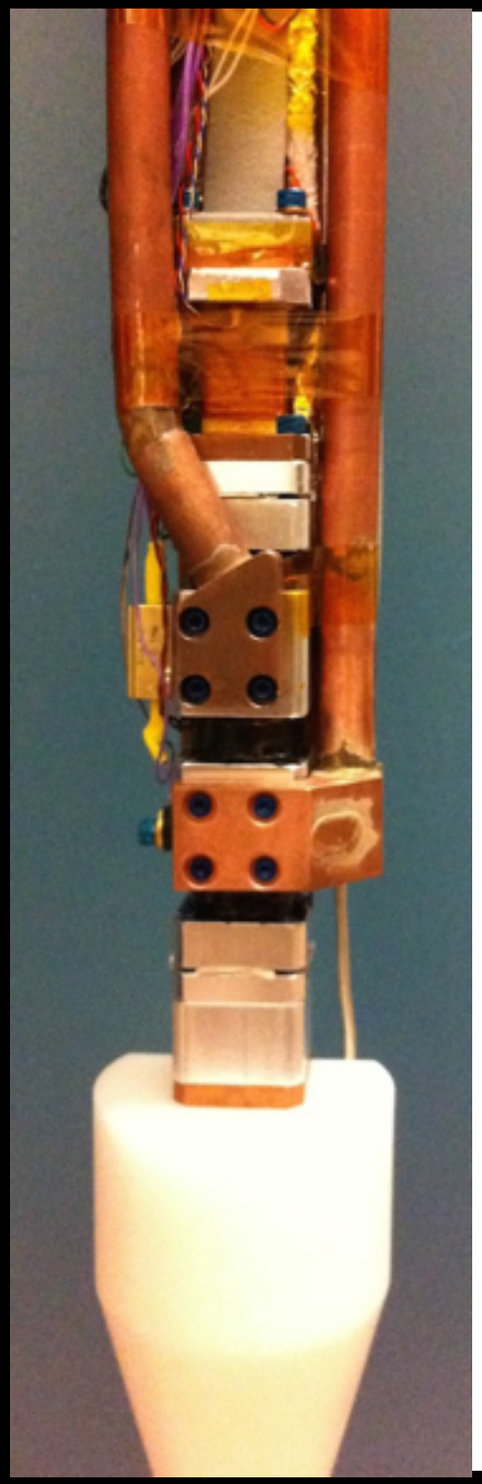


Conversion electrons at 17.8, 30 and 32 keV.

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.

The Apparatus



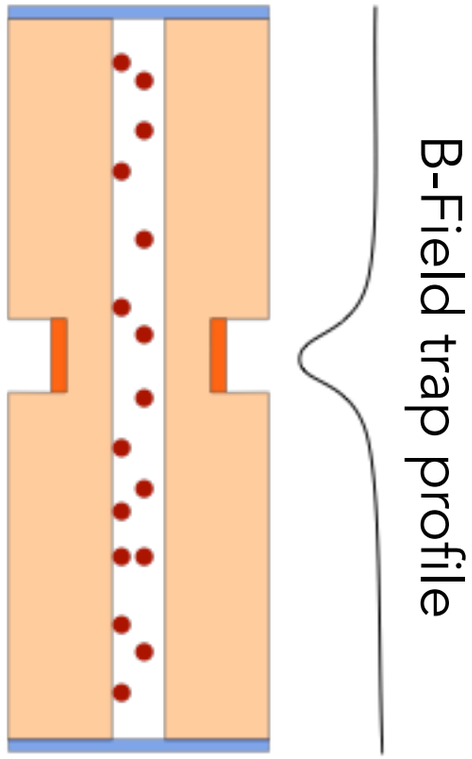
Copper waveguide

Kr gas lines

Magnetic bottle coil

Gas cell

Test signal injection port



Waveguide
Cut-away

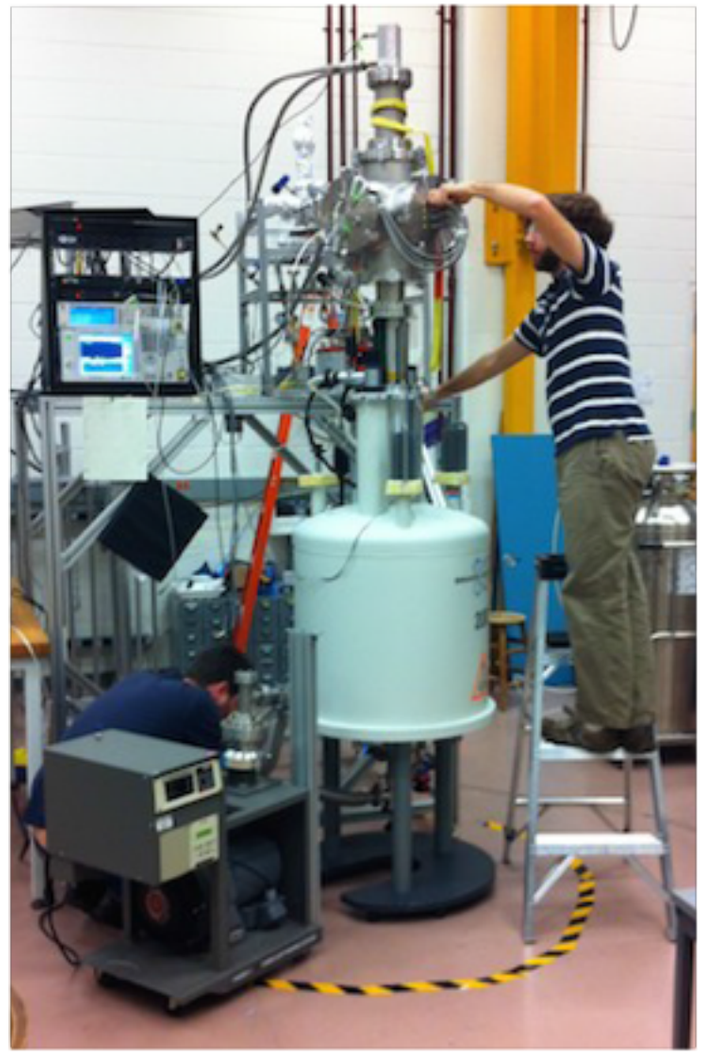
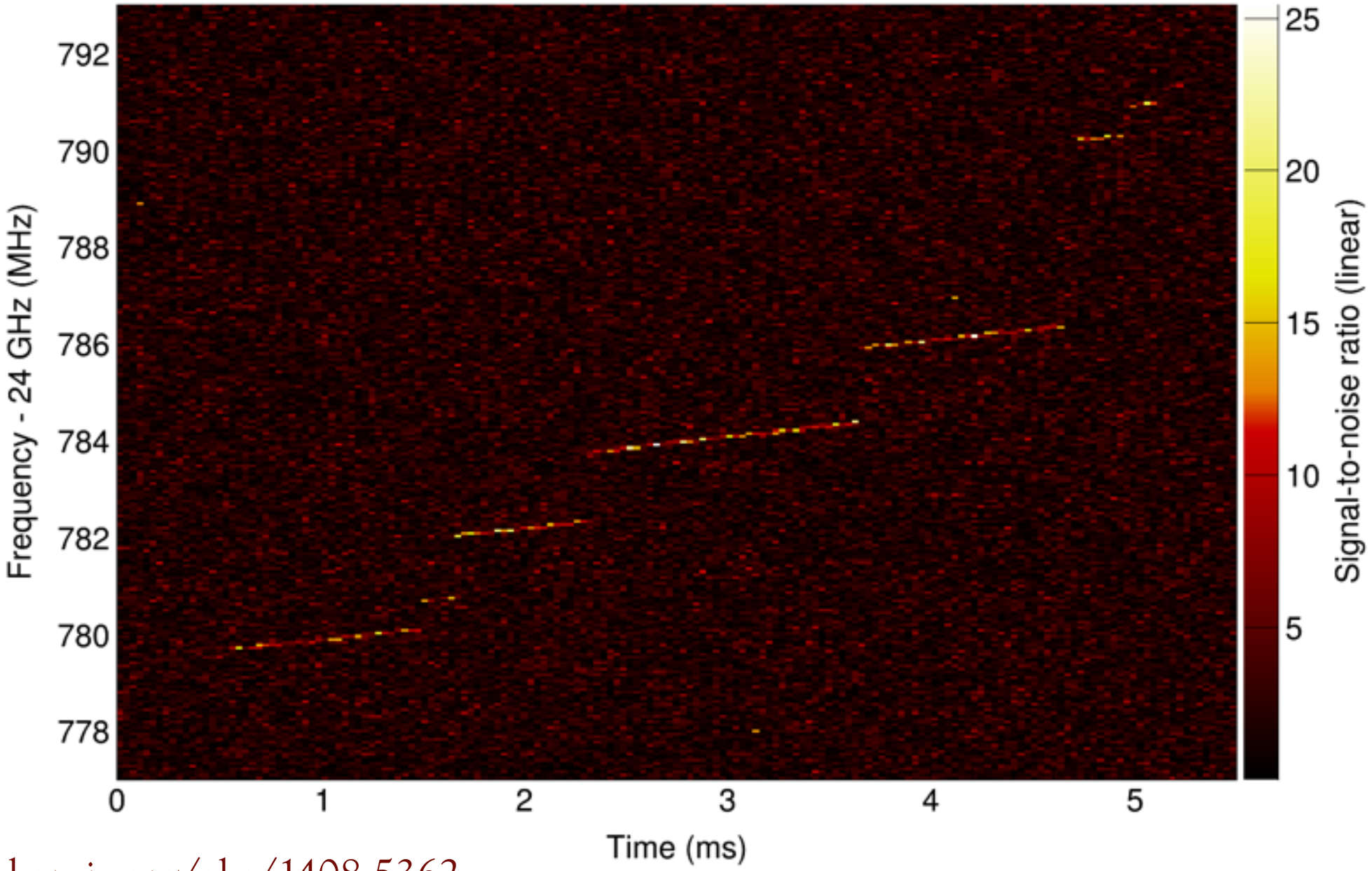


Photo of apparatus

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"

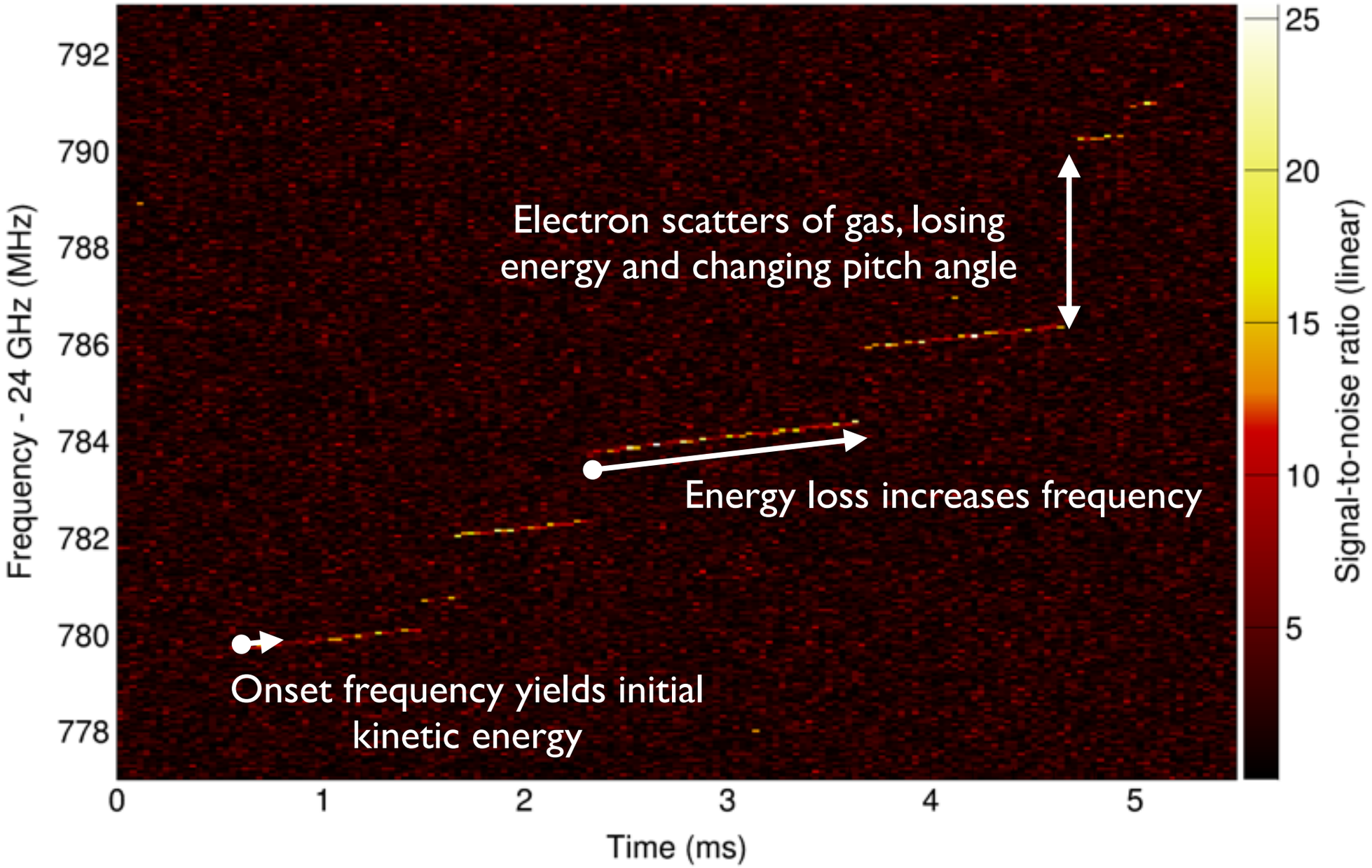


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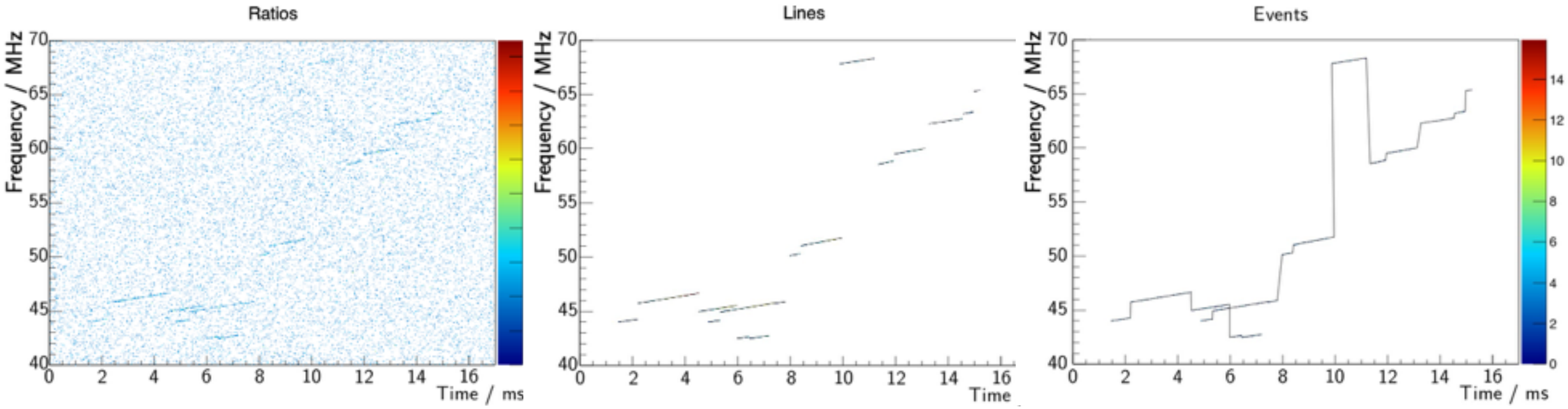
Image Reconstruction & Energy Resolution

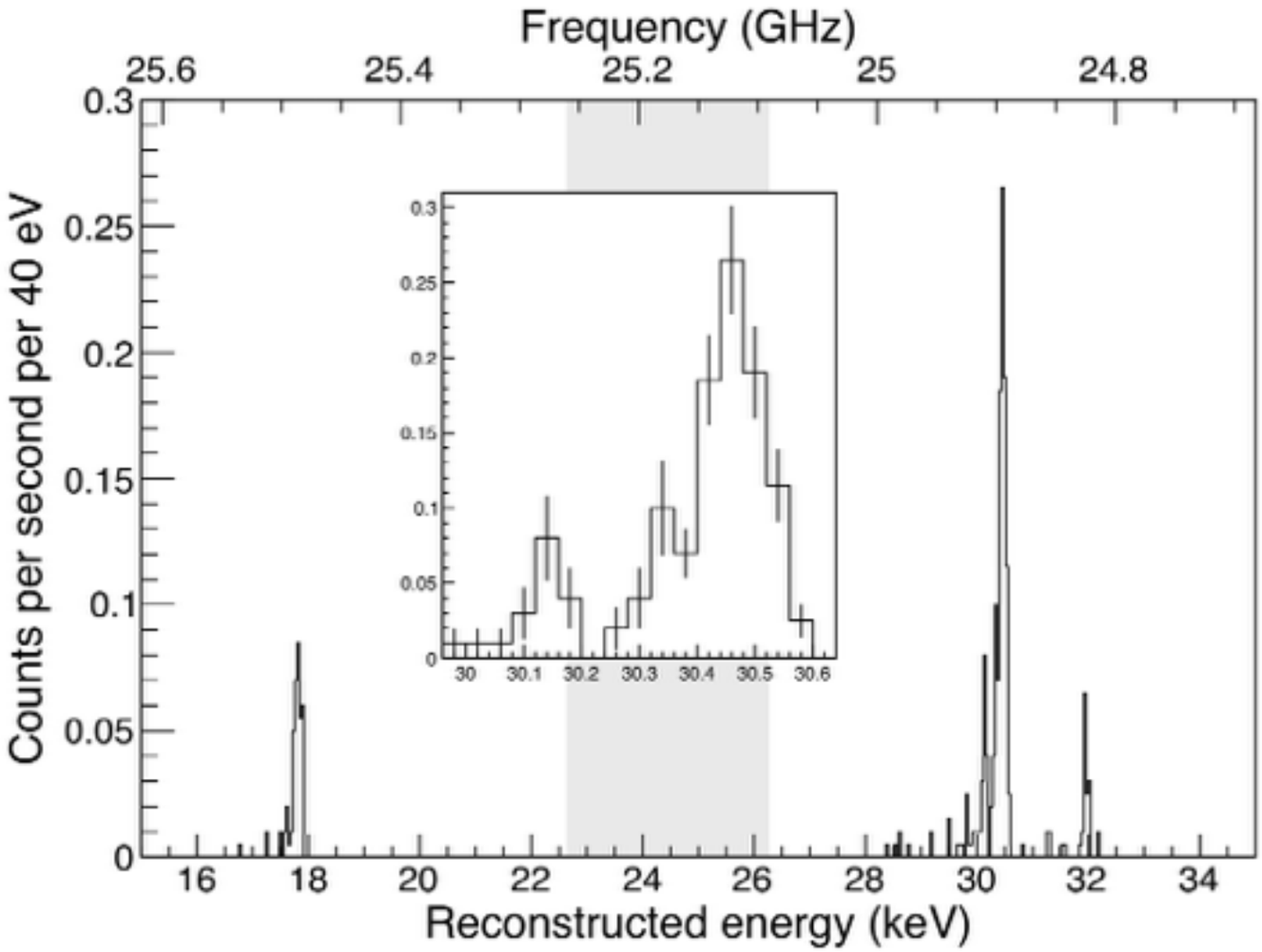


clusters above threshold turn into… tracks, which in turn become… …events

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.

Image Reconstruction & Energy Resolution

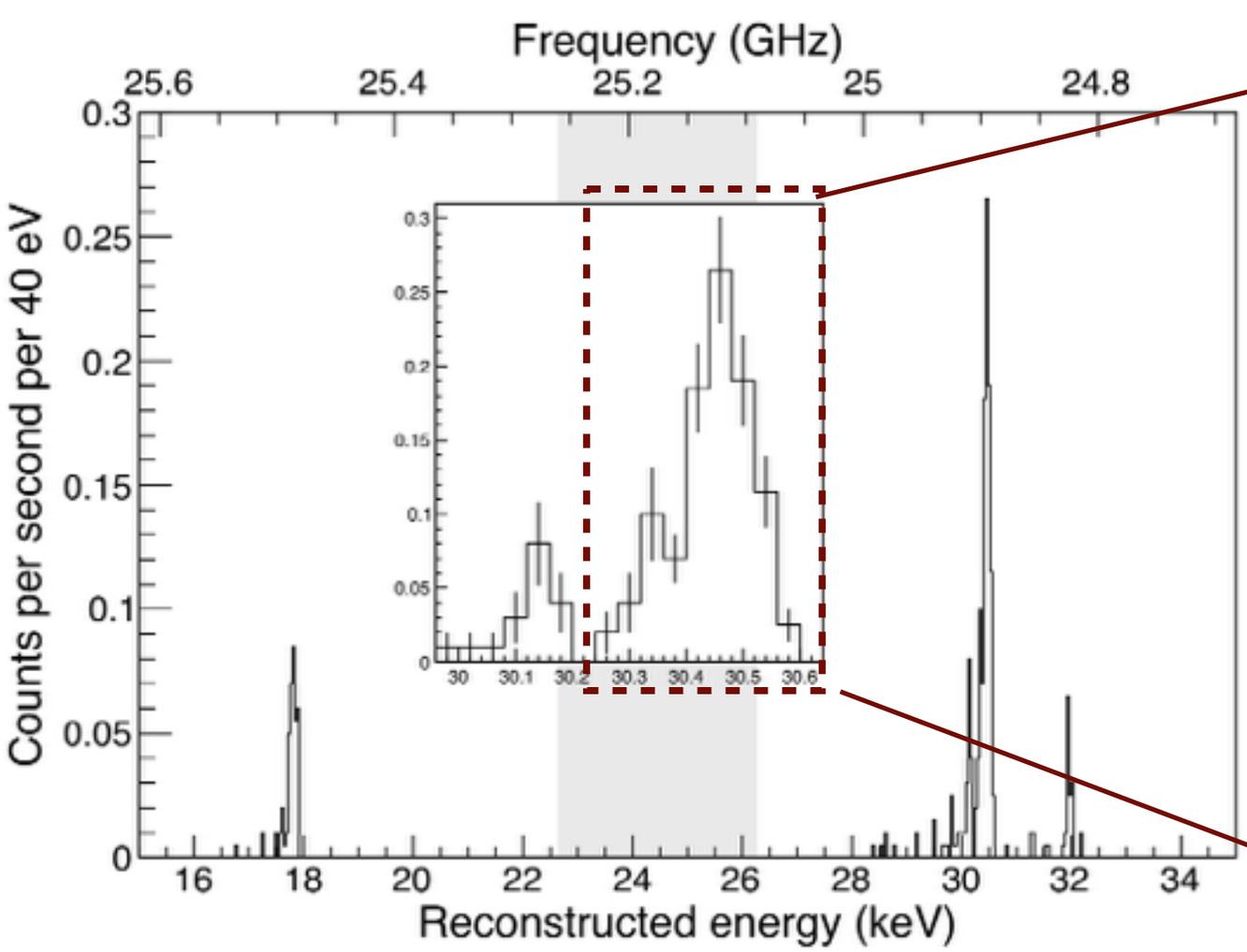


FWHM ~ 140 eV

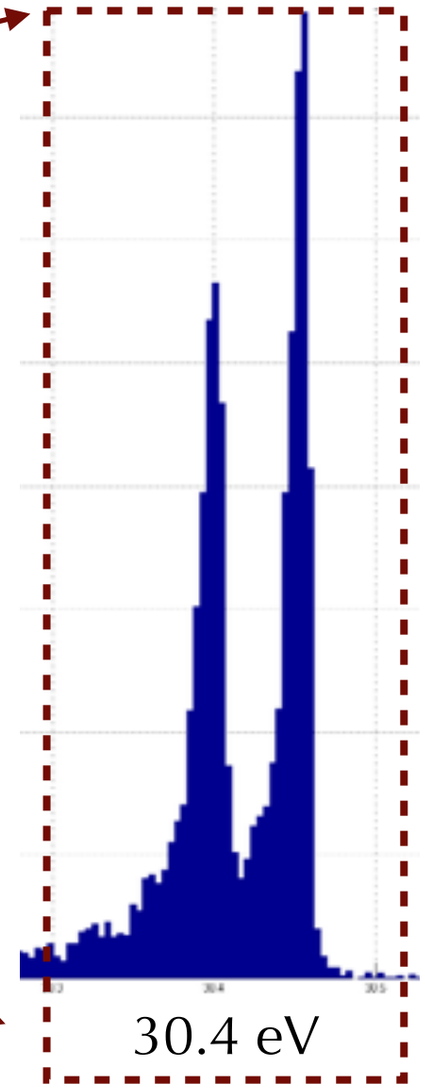
Event reconstruction from image reconstruction allows detailed analysis

(energy & scattering all extractable)

Image Reconstruction & Energy Resolution



FWHM ~ 140 eV



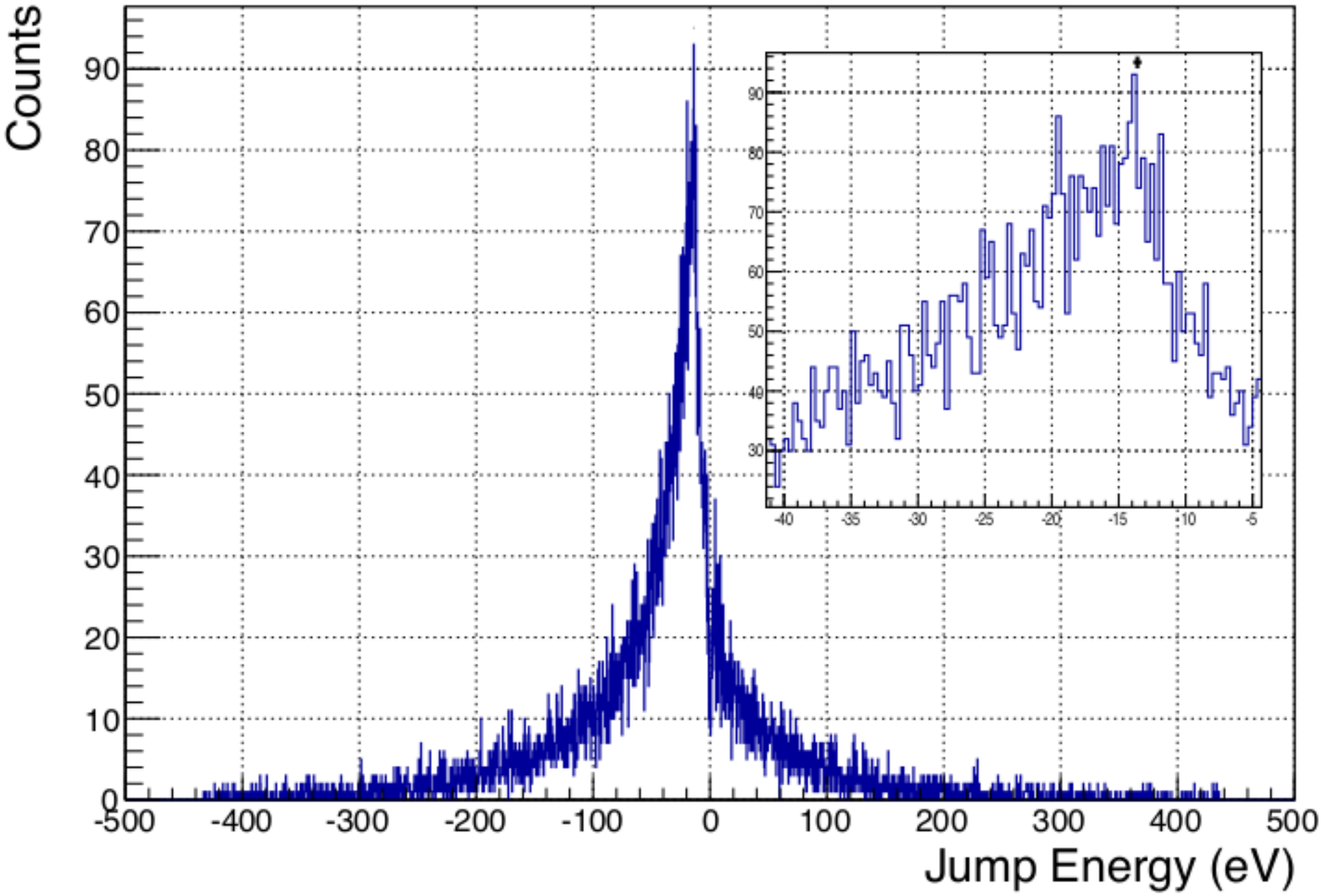
Preliminary

Already improving…

Event reconstruction from image reconstruction allows detailed analysis

(energy & scattering all extractable)

Image Reconstruction & Energy Resolution



Event reconstruction from image reconstruction allows detailed analysis

(energy & scattering all extractable)

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.

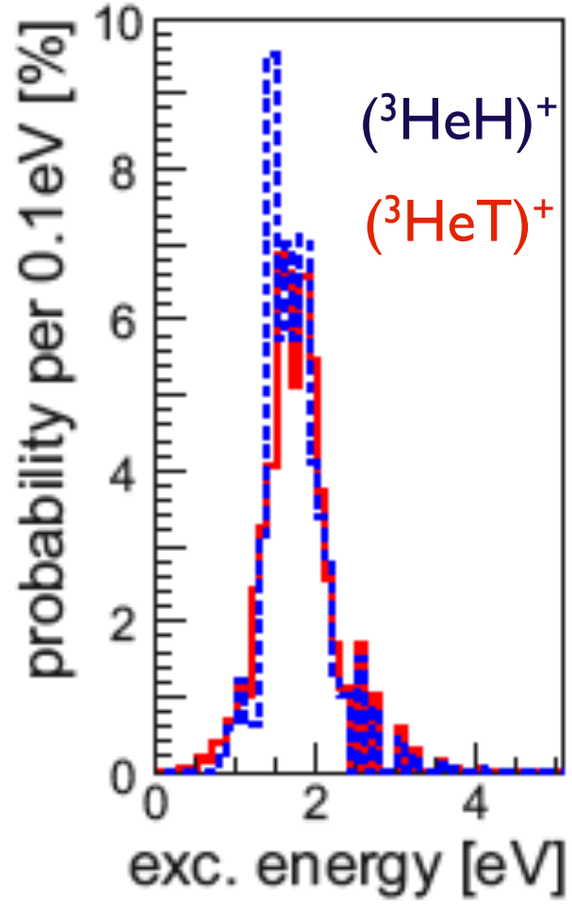
- One needs to either switch to (extremely pure) atomic tritium or other isotope with equivalent yield.

- The trapping conditions necessary for electrons also lends itself for atomic trapping of atomic tritium
(R. G. H. Robertson)

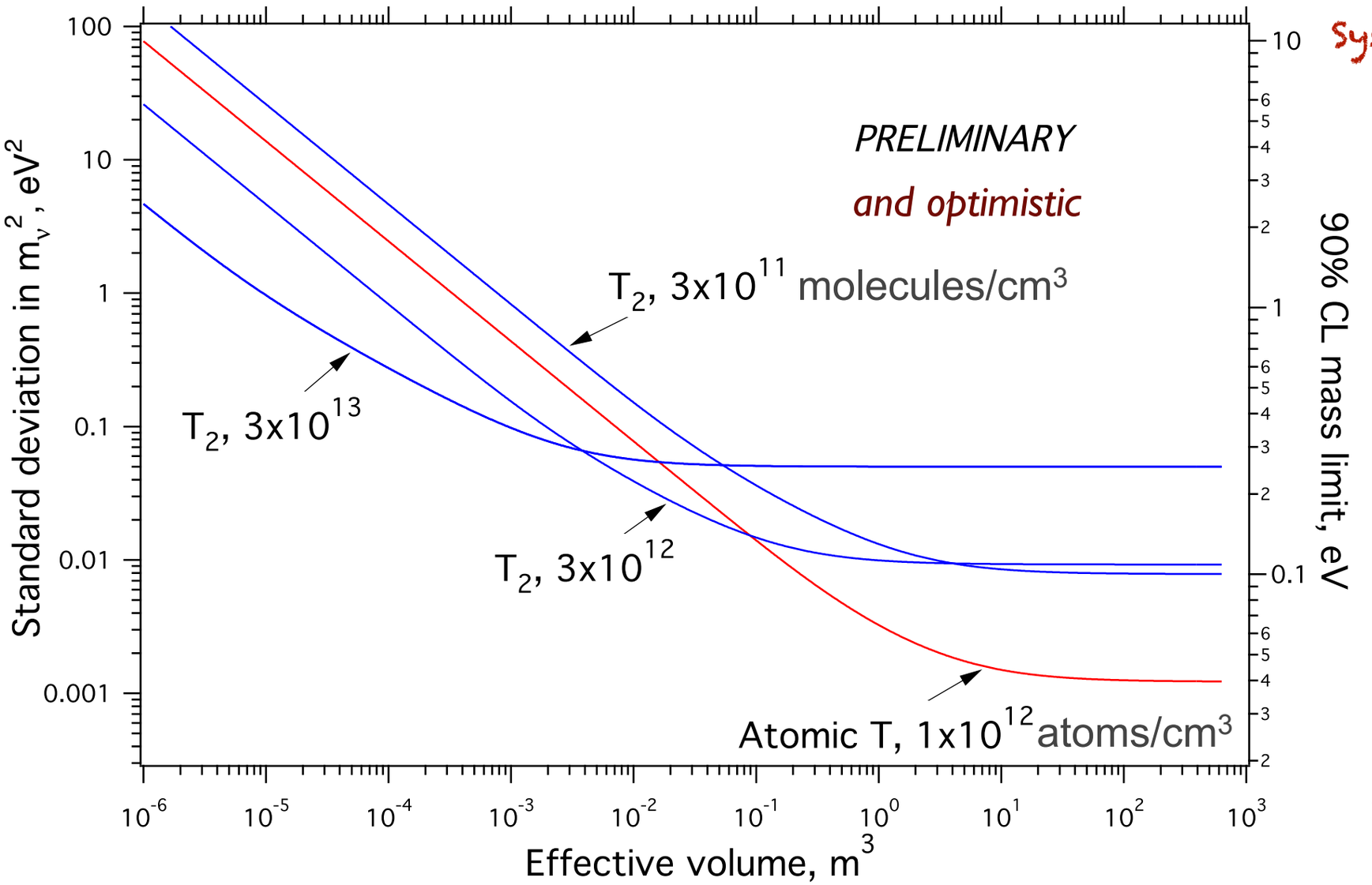
rotational

vibrational

Inherent 0.36 eV final state smearing



Projected Sensitivity (Molecular & Atomic)



Systematics include:

Statistical uncertainties (1 year run)

Final state interactions

Thermal broadening

Scattering

Background

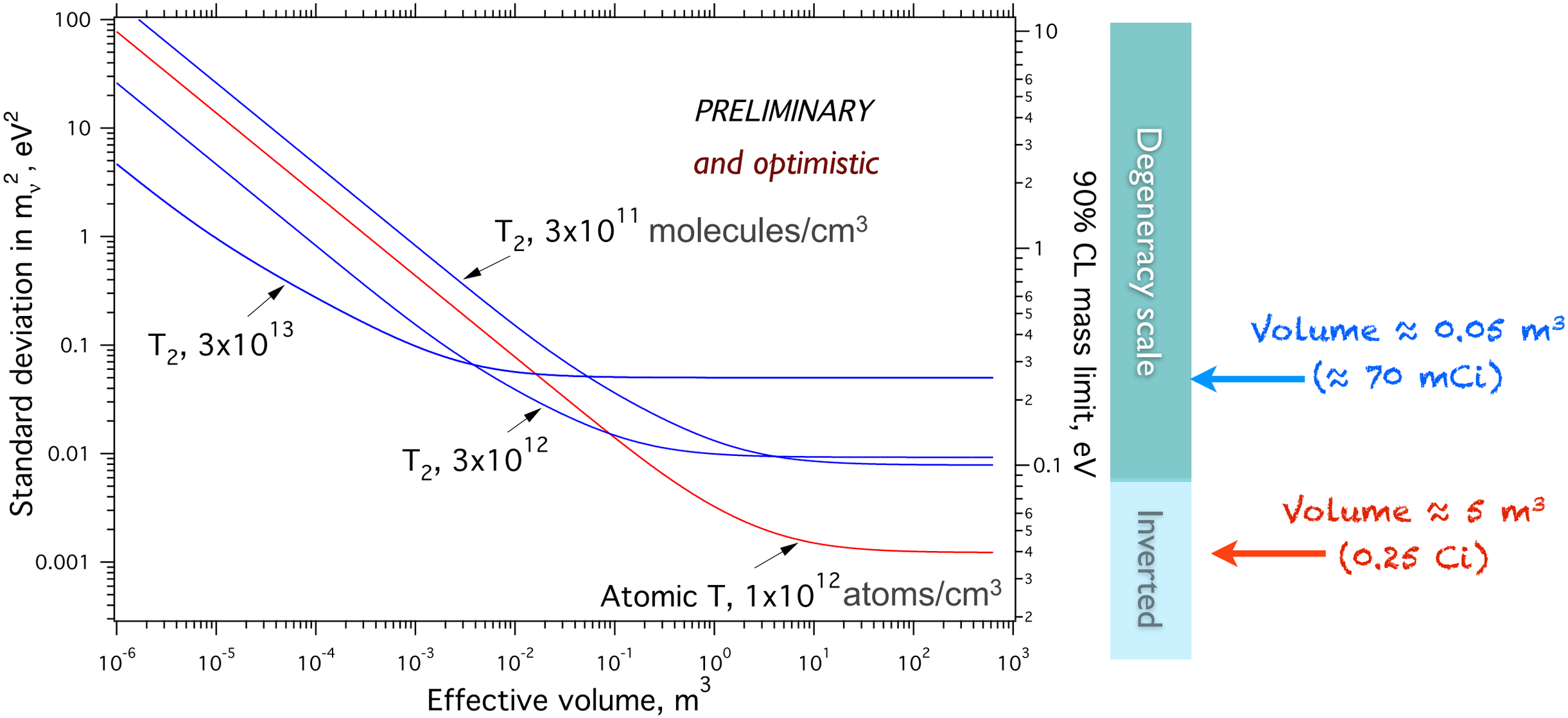
Field inhomogeneity

1% uncertainty in resolution distribution

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

See position paper (link here) for details.

Projected Sensitivity (Molecular & Atomic)



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

See position paper (link here) for details.

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.

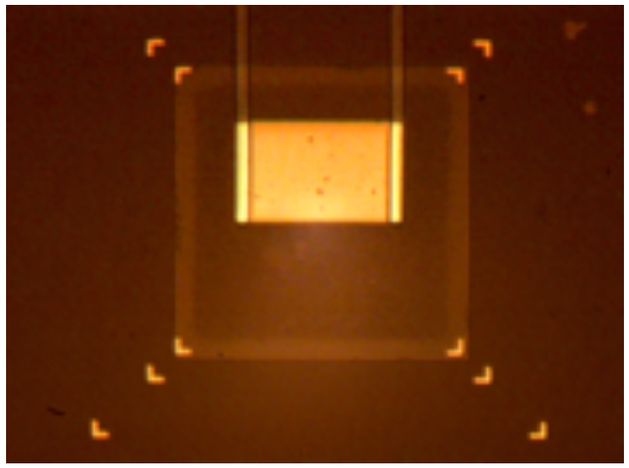
$$T_2 \rightarrow (T \cdot {}^3He^+) + e^- + \bar{\nu}_e$$

Calorimetry (HOLMES, ECHO & NuMECS)

Technique advanced.

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

Statistics & systematics next hurdle.



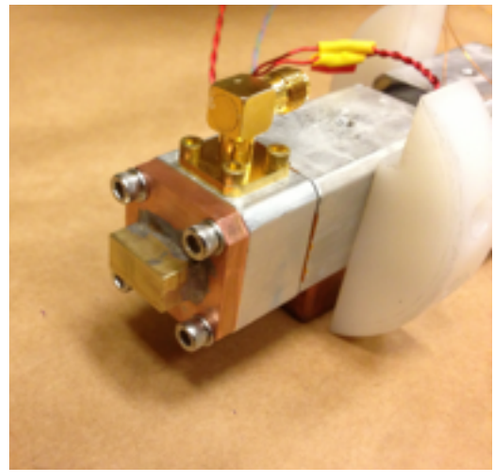
$$^{163}Ho + e^- \rightarrow {}^{163}Dy^* + \nu_e$$

Frequency (Project 8)

Technique DEMONSTRATED.

Potential of scalability and exploring atomic sources to inverted scale.

Next to establish the scalability of the technique.



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