Majorana vs. Dirac Neutrino and Absolute Neutrino Mass Measurements

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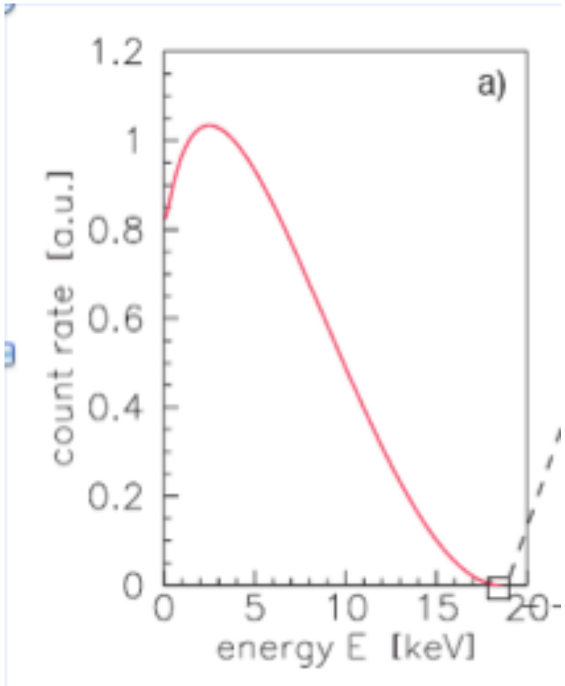
Lecture II, 8/14/2013

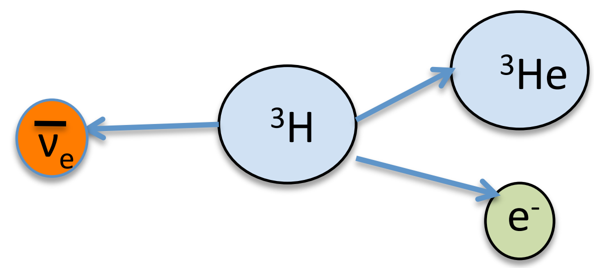
Lecture Outlines

- Lecture 1: Overview
- Lecture 2: Experimental details of weak decay kinematics measurements
  - Experimental considerations
  - Brief review of historical experiments
  - Tritium experiments: KATRIN, Project 8
  - Bolometric experiments: MARE, ECHO
- Lecture 3: Experimental details of double beta decay measurements

Measuring Weak Decay Kinematics

β decay: (A, Z) ➔ (A, Z+1)$^+$ + e^- + ν_e





m_e ~0.5 MeV, $m_{n,p}$ ~ 1GeV

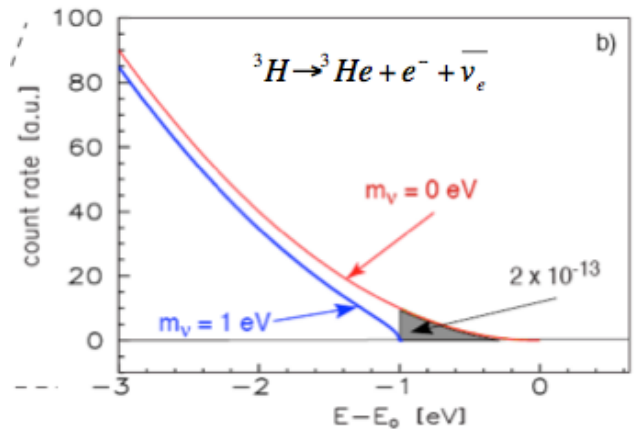
Nuclear recoil is small, but not too small for tritium decay, ~ 3eV, is this a problem?

Your mission, if you choose to accept it, is to measure spectral shape near the end point precisely,

- Choose a system to study
- Choose a detection method
- Background and systematics , etc ….

Choosing a Weak Decay to Study

- Low Q values
- High decay rate
- Simple final states
- Isotope availability
- Well understood spectral shape



$$\frac{n(\Delta E)}{n} \propto \left(\frac{\Delta E}{E_0}\right)^3$$

Choosing a Weak Decay to Study

$$^{3}H \rightarrow {}^{3}He + e^{-} + \overline{\nu}_{e}$$

- E_0 = 18.37 keV
- $t_{1/2}$ = 12.7 y
- Simple final state, though T_2 molecular excitation levels not negligible
- super-allowed decay $0^+ \rightarrow 0^+$, spectral shape well understood

$$^{187}\mathrm{Re} \rightarrow {}^{187}Os + e^{-} + \overline{\nu}_{e}$$

- E_0 = 2.47 keV (lowest among known β decays)
- $t_{1/2}$ = 43.2 Gy
- 63% abundance
- $5/2^+ \rightarrow 1/2^-$ first forbidden transition (shape correction needed)

$$^{163}Ho + e^{-} \rightarrow {}^{163}Dy^{*} + \nu_{e} (E.C.)$$

- $E_{E.C.}$ = 2.3-2.8 keV (electron capture energy)
- $t_{1/2}$ = 4570 y
- Efficient reactor production
- spectral shape not entirely understood

Choosing a Detection Method

- High energy resolution
- Large solid angle
- Short dead time, no pile up
- Low background rate
- Two mature technologies and a few new ideas

Spectrometer	Calorimeter
Source ≠ Detector	Source = Detector

Choosing a Detection Method

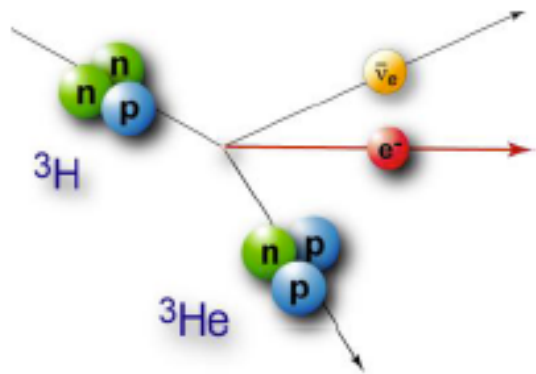
$$^{187}\mathrm{Re} \rightarrow {}^{187}Os + e^- + \overline{\nu_e} \qquad {}^3H \rightarrow {}^3He + e^- + \overline{\nu_e}$$

	calorimeters	spectrometers
source	metallic Re, dielectric $AgReO_4$	high-purity molecular gaseous T_2
ß-energy	arrays of crystal bolometers	MAC-E filter: electrostatic retardation
activity	low: $<10^5$ ß/s	high: $\sim10^{11}$ ß/s
response	entire decay energy	(longitudinal) kinetic energy of electrons
interval	entire ß-decay spectrum	very narrow interval close to E_0
method	differential spectrum	integral spectrum (ToF mode possible)
set-up	modular, size can be upscaled	integral design, spectrometer size limits
resolution	$\Delta E \sim$ few eV (FWHM)	$\Delta E = 0.93$ eV (100%)

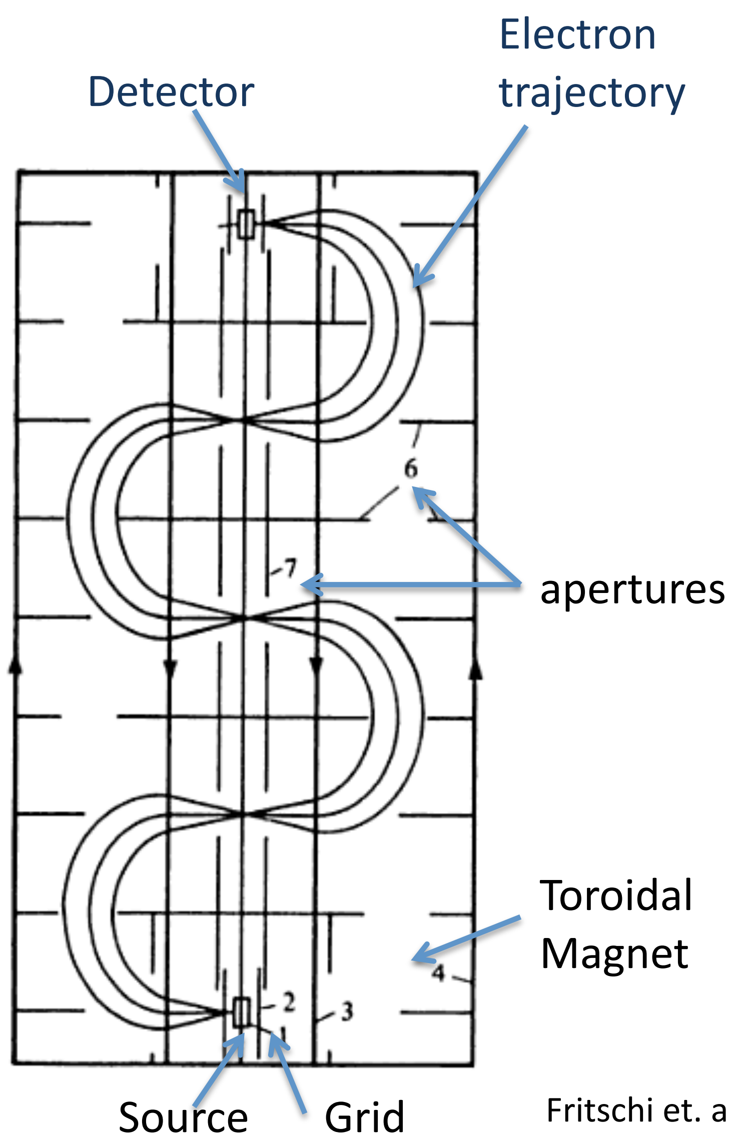
G. Drexlin, NOW 2012

Two methods complementary, different systematics. A few new ideas for ^{3}H will be discussed later. ^{163}Ho will likely need to use calorimeters, why? Can we use spectrometer to measure ^{187}Re, or can we use calorimeter to measure ^{3}H?

Tritium Measurements



Early Days: Magnetic Spectrometer



Zurich Experiment

- Toroidal magnetic spectrometer

- Source biased at HV, electrons slowed down by 15 kV retarding potential at the grid.

- Detector biased also at HV, so electrons passing the spectrometer are reaccelerated.

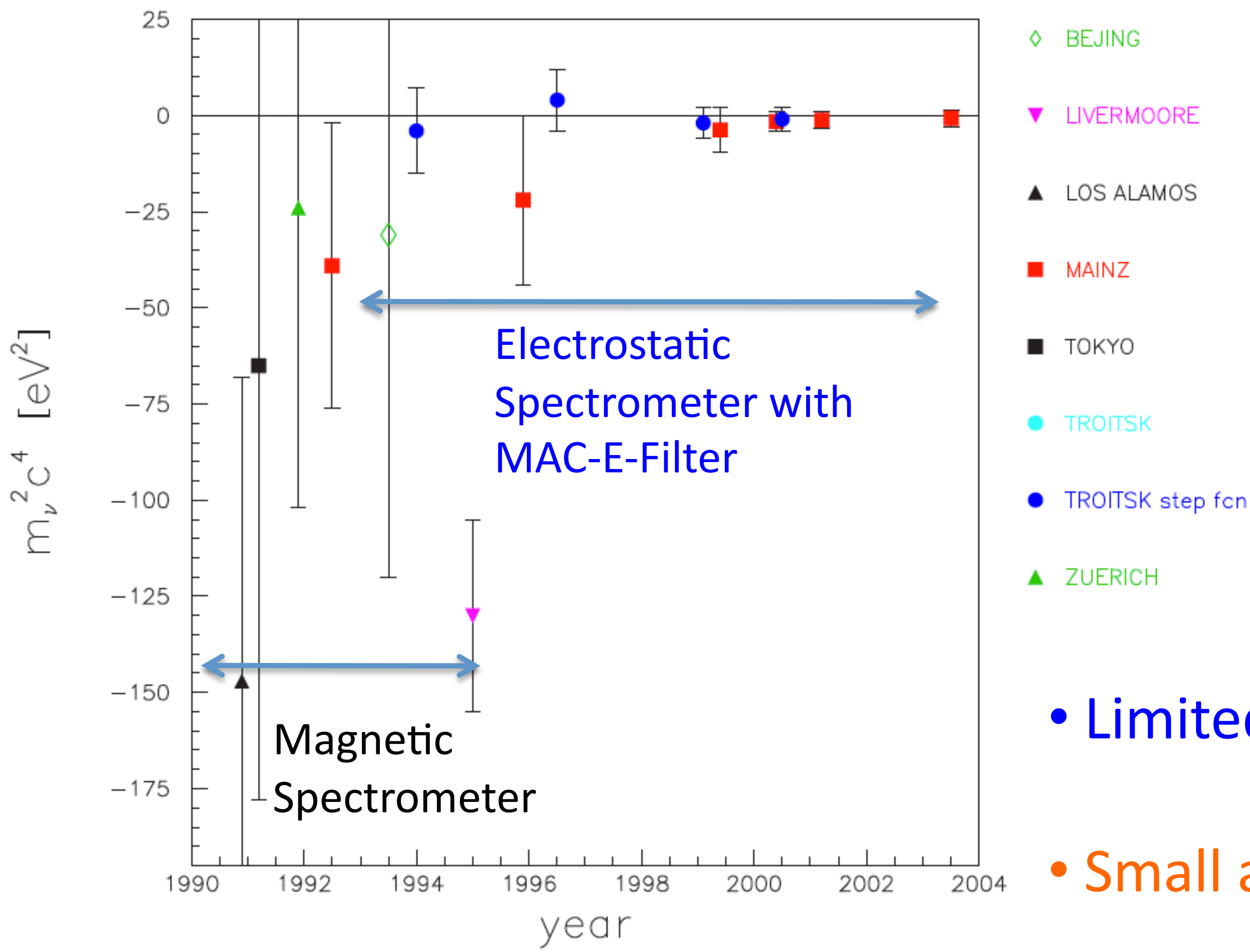
- Moderate resolution at 1% to reach FWHM 27 eV, for 2.2 keV electrons. 0.6% transmission.

Fritschi et. al., in Neutrino 90, *Nucl. Phys*. B19, 205

Discovery or False Signal?

- ITEP Experiments
  - First use of toroidal magnetic spectrometer
  - Tritiated valine source ($C_5H_{11}NO_2$), thin film
  - Claimed discovery of neutrino mass at 30 eV (1980 - 86)
- Zurich Experiment
  - Source: tritiated hydrocarbon chain
  - $m_\nu < 15.4$ eV (86)
- Los Alamos Experiment
  - Novel gaseous source of atomic and molecular tritium
  - $m_\nu < 9.4$ eV (87)

Limitation of Magnetic Spectrometer



- Limited energy resolution
- Small acceptance angle

Why do all measurements show $m_\nu^2 < 0$? Systematic bias?

Need very good understanding of energy resolution!

Principle of MAC-E-Filter

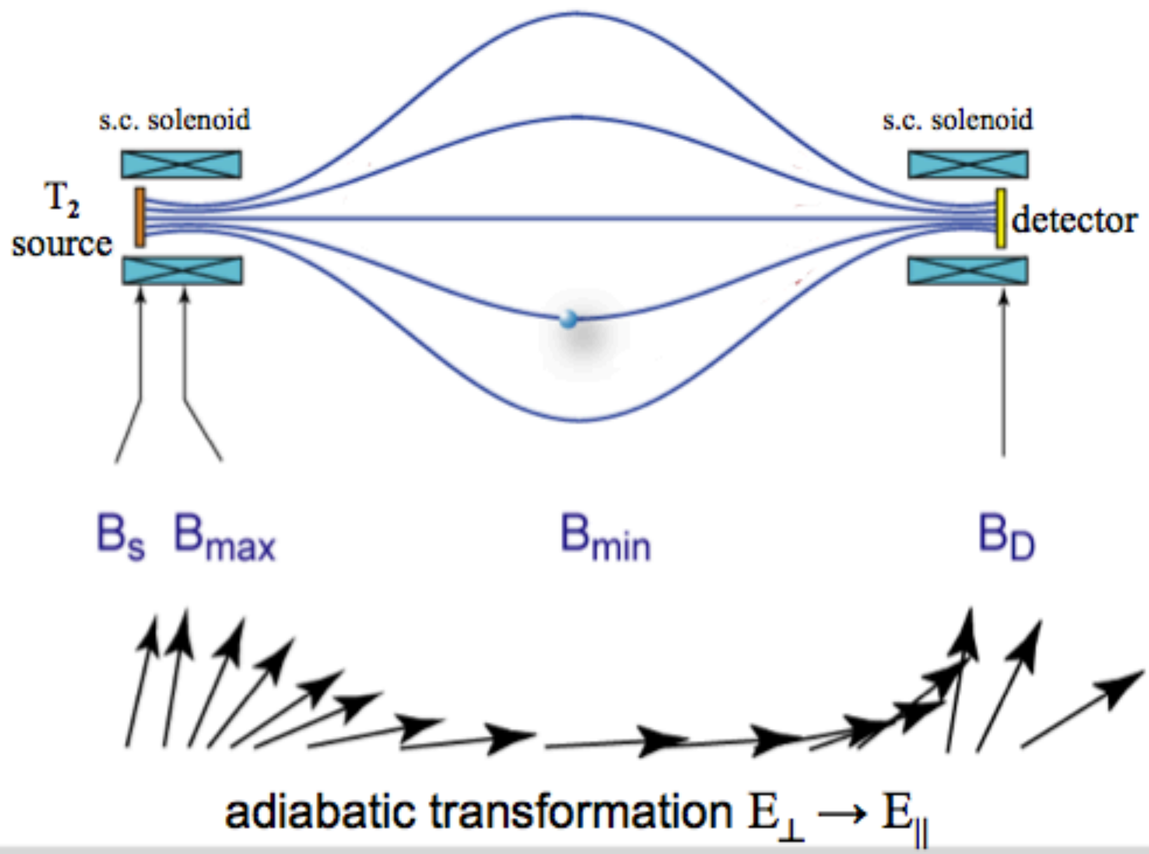
Magnetic Adiabatic Collimation + Electrostatic Filter

A. Picard et. al., Nucl. Instr. Meth. B 63, 345 (1992)

- Two superconducting solenoids with B_{max} = 3-6 T, and B_{min} < 1mT produce the magnetic guiding field.

- T_2 source in the left solenoid.

- Forward going electrons are adiabatically guided along the magnetic field lines



$$\vec{F} = \left(\vec{\mu} \cdot \vec{\nabla}\right)\vec{B} + q \cdot \vec{E}$$

$$\mu = E_\perp / B = const.$$

What is the adiabatic condition?

Principle of MAC-E-Filter

Magnetic Adiabatic Collimation + Electrostatic Filter

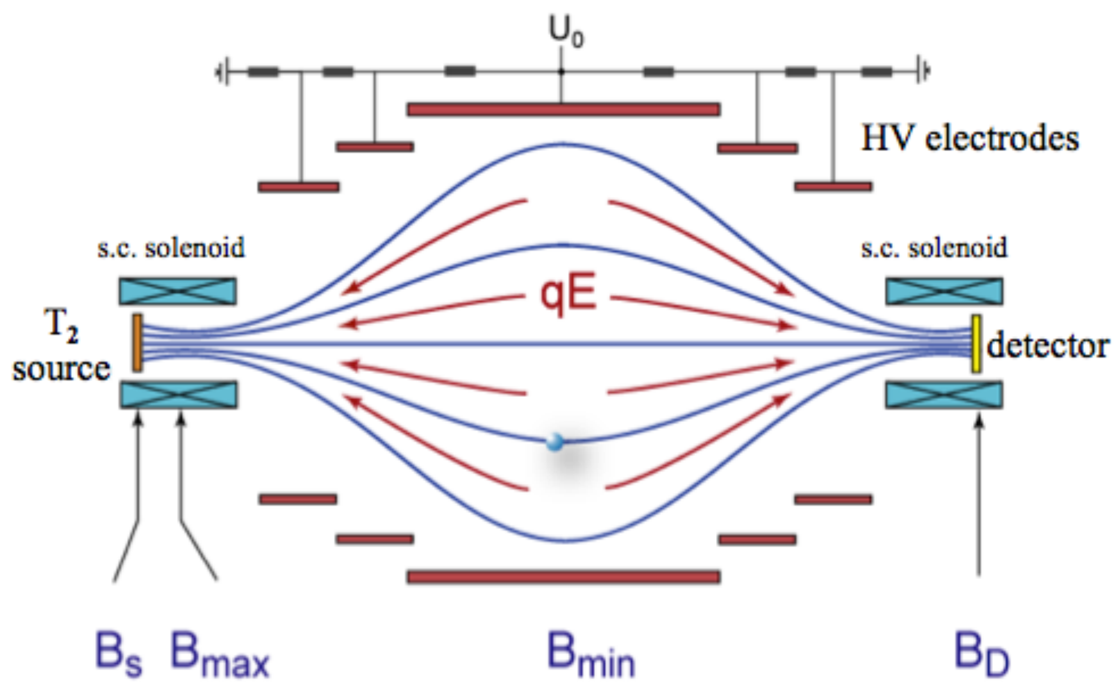
A. Picard et. al., Nucl. Instr. Meth. B 63, 345 (1992)

- Energy analysis by electrostatic retardation

- Measure integrated electron spectrum with $E_e > qU_0$ (High pass filter)

- Source is placed at B_s to restrict the electrons with large starting angle to enter the spectrometer.

$$\sin^2(\theta_s) \leq \frac{B_s}{B_{max}}$$



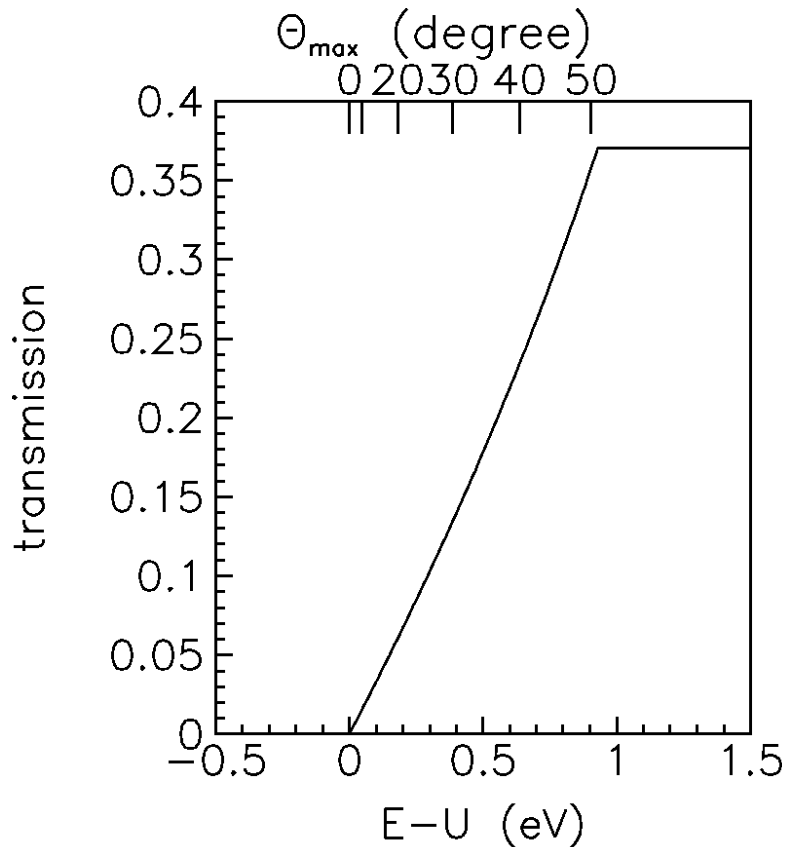
E Feld || B-Feld

$$\Delta E = E \cdot B_{min} / B_{max}$$

~ 4.8 eV (Mainz), 0.93 eV (KATRIN)

Principle of MAC-E-Filter

Magnetic Adiabatic Collimation + Electrostatic Filter

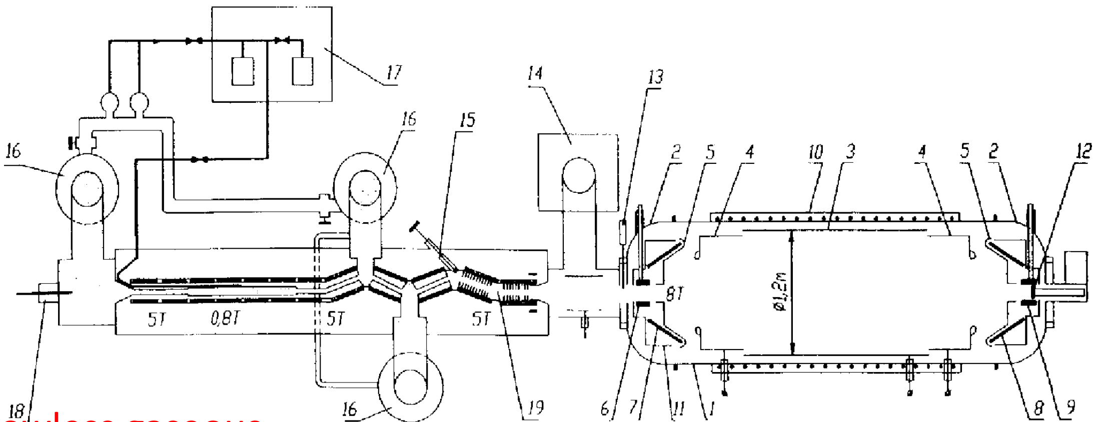


Transmission curve for KATRIN experiment G. Drexlin, arXiv: 1307.0101

Well defined Integrated transmission functions (no tail)

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

The Troitsk Neutrino Mass Experiment

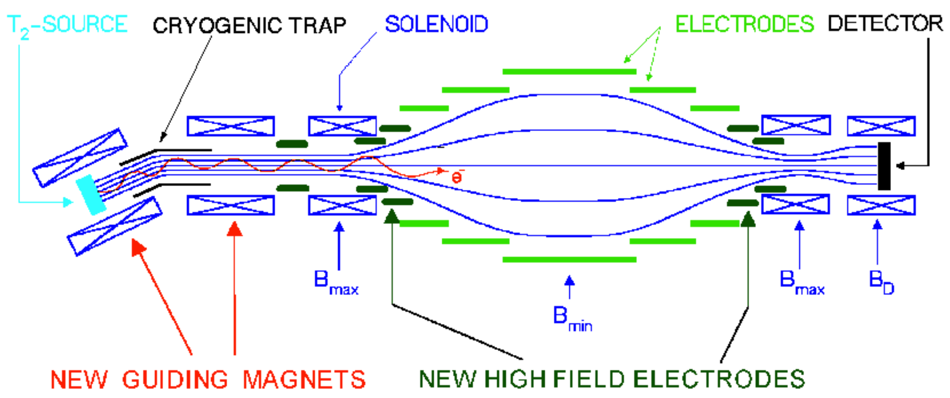


- Spectrometer energy resolution 3.5 eV
- T_2 source column density of 10^{17} cm^{-2}
- Data collection 1994 – 2004.
- Reanalysis of the data in 2011:

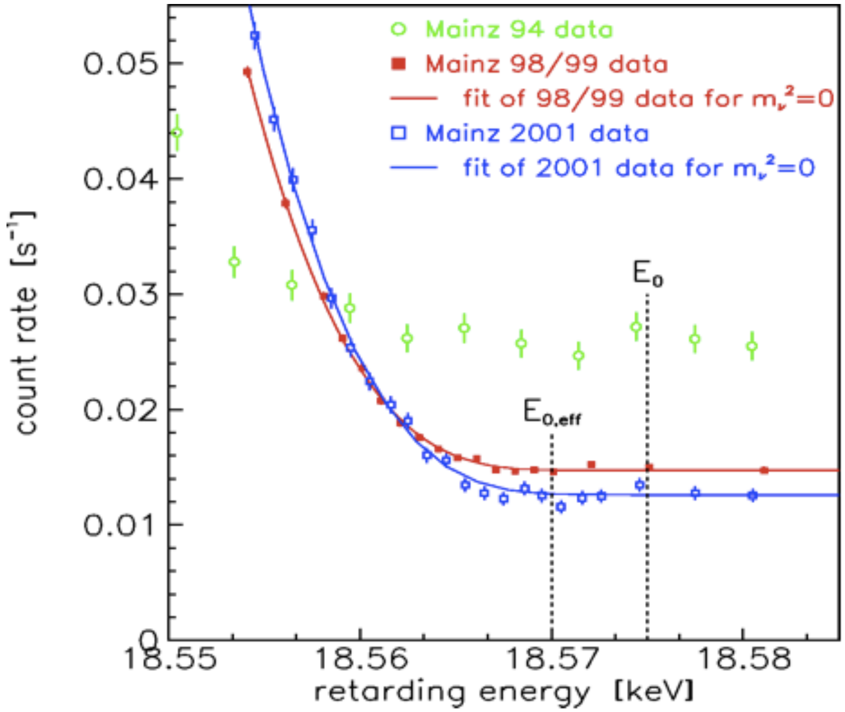
  $m(\nu_e) < 2.05$ eV (95% CL) Aseev et al, Phys. Rev. D 84, 112003, 2011

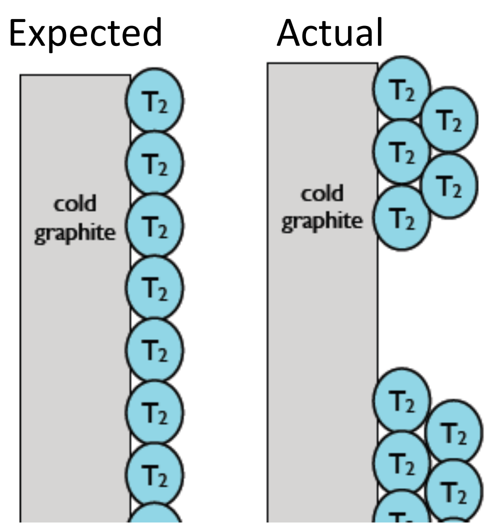
Better source thickness estimates, and data selection, solved spurious peak problem in early analysis.

The Mainz Neutrino Mass Experiment



Phase 2 system (1997 – 2001)





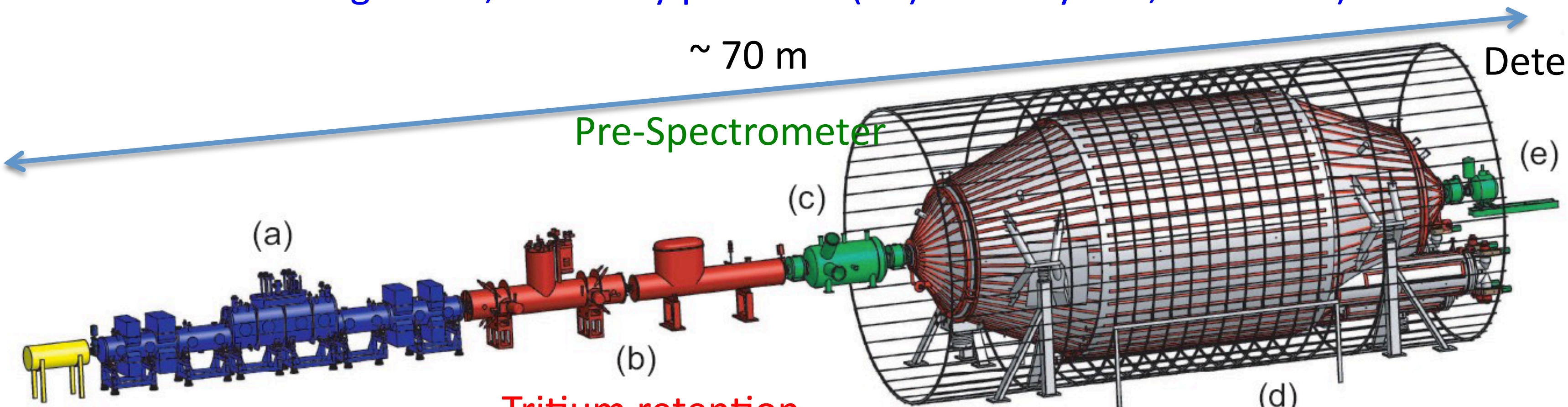
"negative m^2" issue solved

- Novel solid T_2 source.
- Spectrometer energy resolution 4.8 eV
- $m(\nu_e)$ < 2.3 eV (95% CL) C. Klaus et al, Eur. Phys. J. C 40, 2005

KATRIN Overview

(Karlsrushe TRItrium Neutrino Experiment)

Goal: Improve the current tritium neutrino mass limit around 2 eV by an order of magnitude to 200 meV. (Need to improve β spectroscopy by 2 orders of magnitude, discovery potential (5σ) after 3 years, 350 meV)



Tritium retention system

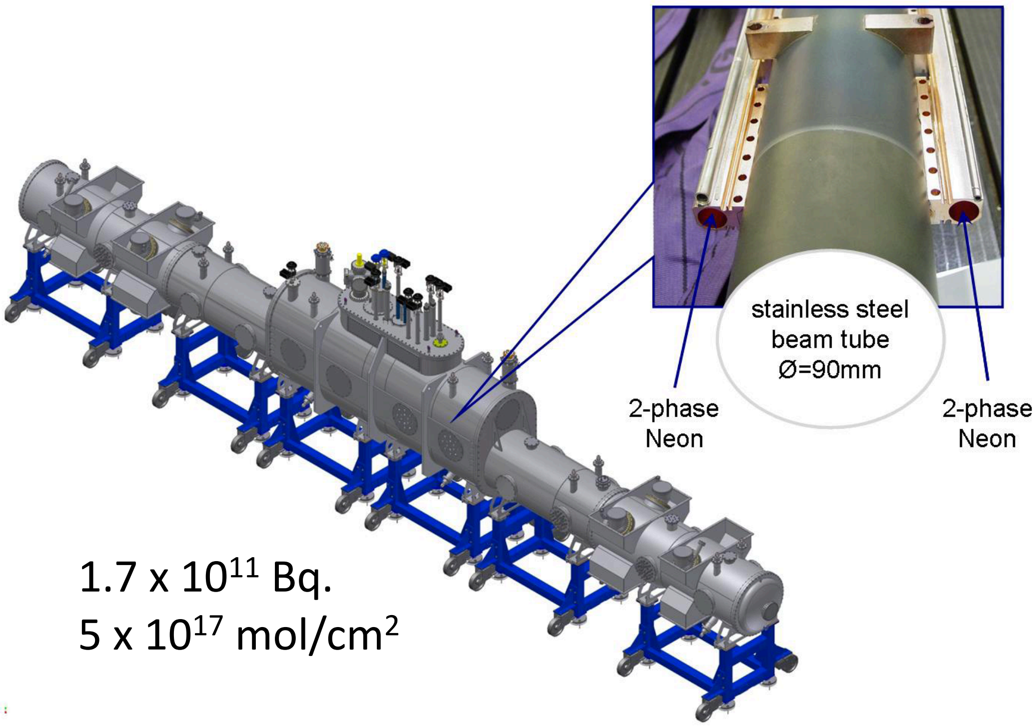
Main Spectrometer

Widowless gaseous T_2 source (WGTS)

- Increase source strength by x 100, measurement time x 10
- Improve energy resolution by x 4
- Background rate < 10^{-2} cps

KATRIN design report

KATRIN: Widowless gaseous T_2 source (WGTS)



1.7 x 10^{11} Bq.
5 x 10^{17} mol/cm^2

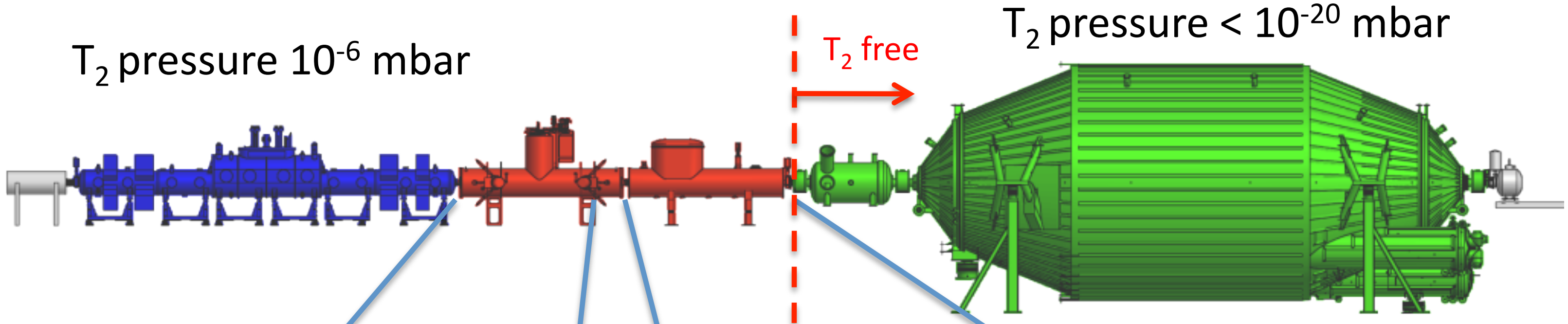
G. Drexlin, arXiv: 1307.0101

- Operated as closed cycle system, throughput of 40 kg/ year.
- Tritium column density stability at 10^{-3}.
- T = 30 K, 2 phase neon used for beam tube cooling. $\Delta T \approx 3$mK achieved over 4 hr during demonstrator test.
- Dedicated Laser Raman system use to monitor Tritiated gas fraction at 0.1% level.

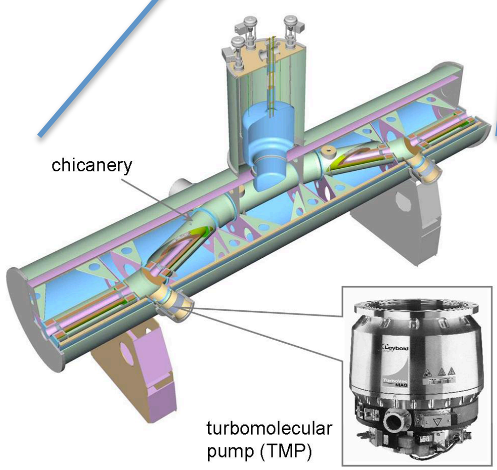
KATRIN: Tritium Retention System

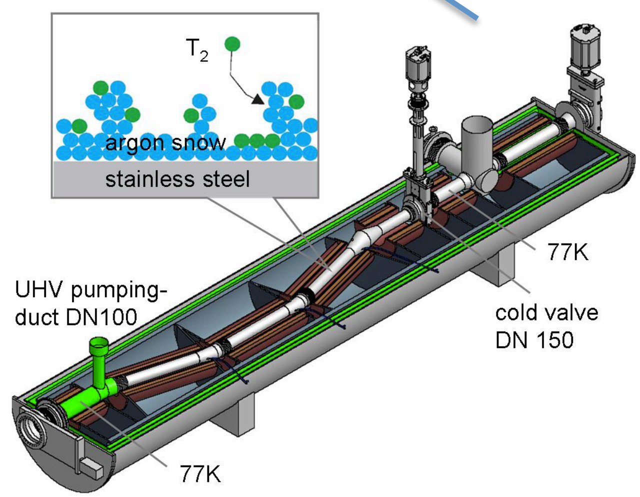
T_2 pressure 10^{-6} mbar

T_2 pressure < 10^{-20} mbar



Bg < 10^{-4} cps





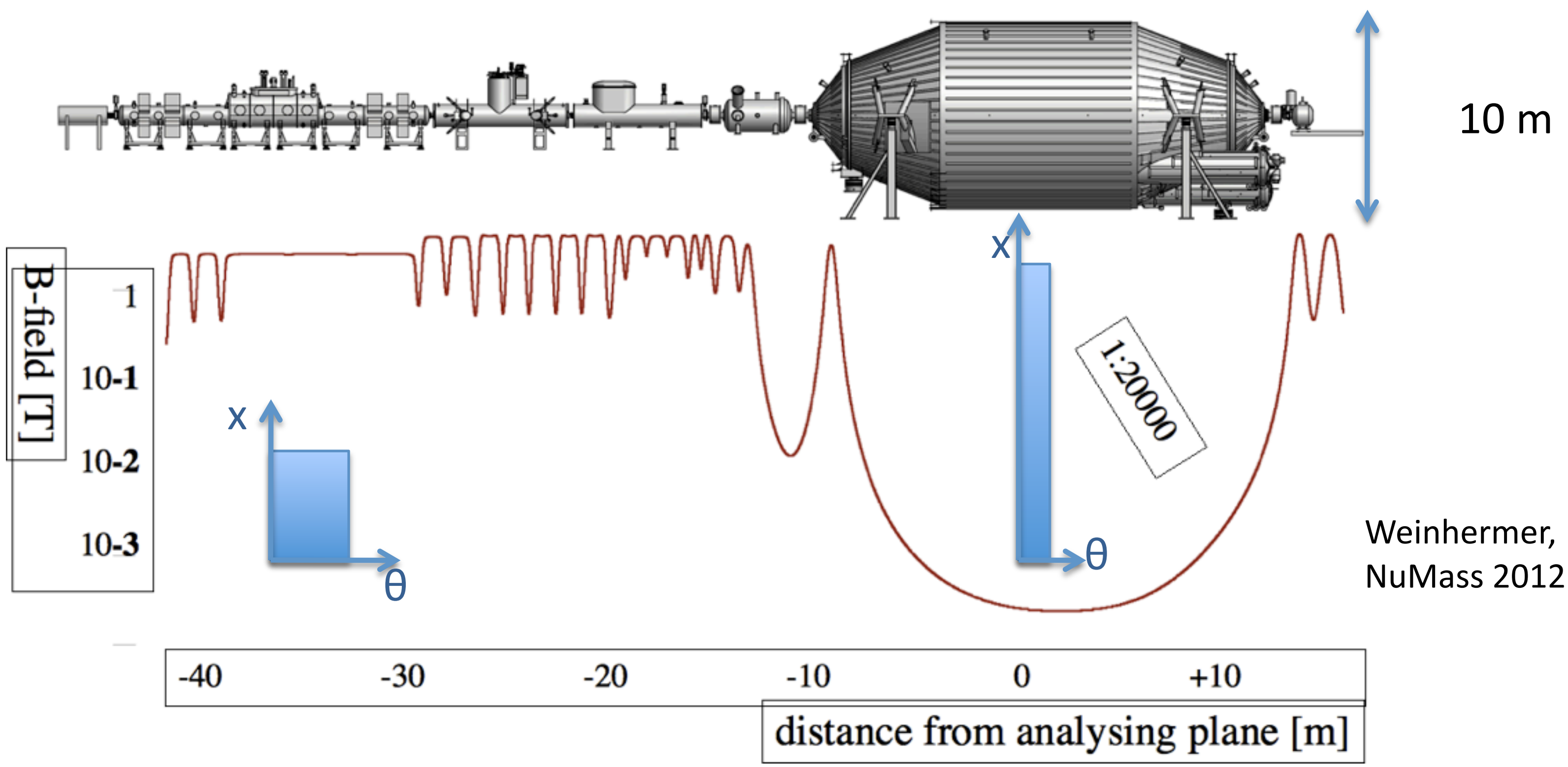
Differential pumping system
10^7 reduction

Need to maintain adiabatic guiding of electrons!

Cryogenic pumping system
3 – 4.5 K, > 3 x 10^7 reduction

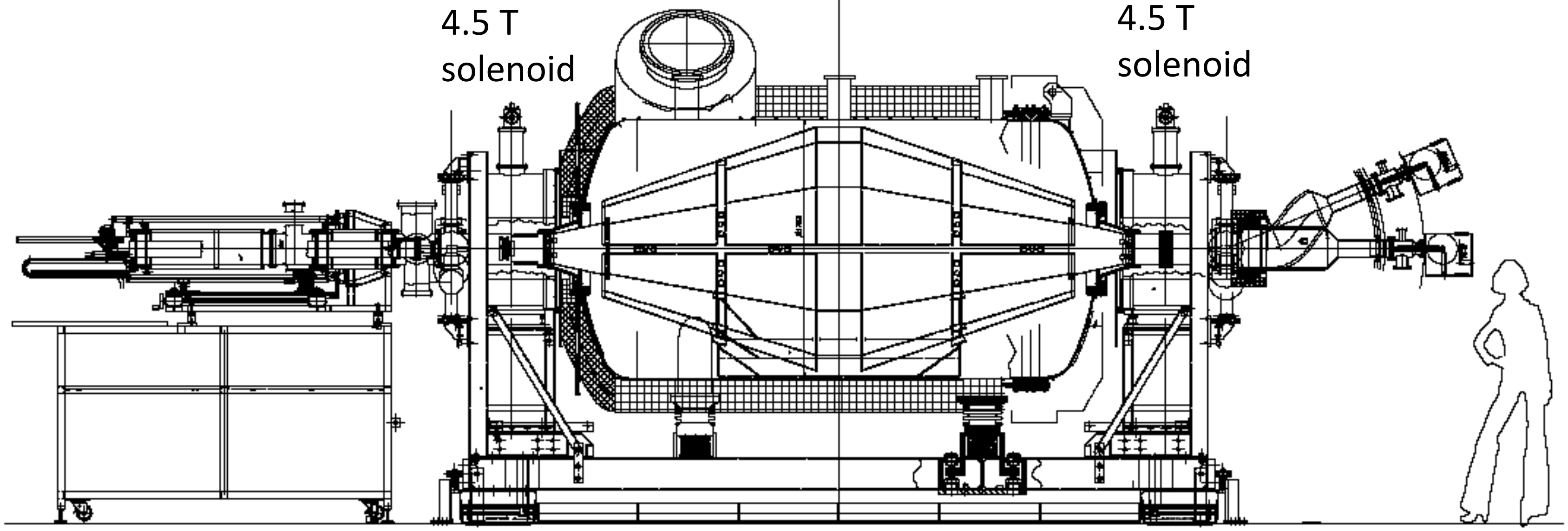
G. Drexlin, arXiv: 1307.0101

KATRIN: Electromagnetic Field Design



- Magnetic flux conservation -> $A_{spec} / A_{source} = B_{source} / B_{spec} = 20000{:}1 = E/\Delta E$
- Maintain adiabatic condition through out 50 m of electron transportation.
- Use pre-spectrometer to reduce electron background and main spectrometer to perform precision measurement.

KATRIN: Pre-spectrometer



Weinhermer, NuMass 2012

- Eliminate all electrons with no $m(\nu_e)$ information, about 300 eV below the end point, 10^{11} e -> 10^{3} e .

- Vessel can can be set at high voltage. ΔE ~ 80 eV

- Serve as a prototype for the main spectrometer for design and background studies. Two new backgrounds: Penning trap and Rn.

KATRIN: Background from Penning Trap

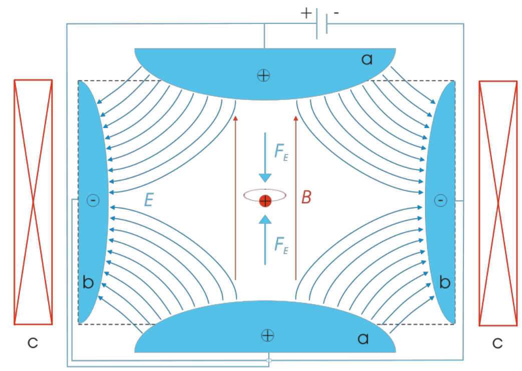
- Penning trap is a great tool for precision measurements, but in this case, accidental penning trapping is not good.

- When an electric field minimum occurs along magnetic field, trapping can occur.

- Detailed electromagnet field simulation (software developed by the collaboration).

- Optimize electrode shape.

- Background reduction by 10^4, 1000 cps to 0.1 cps



Penning trap


New electrode

KATRIN: Background from Rn

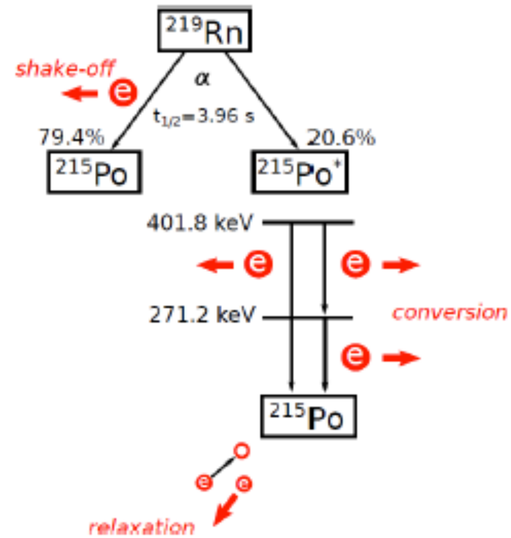
- Non-evaporative getter (NEG) pumps are essential for reaching 10^{-11} mbar.

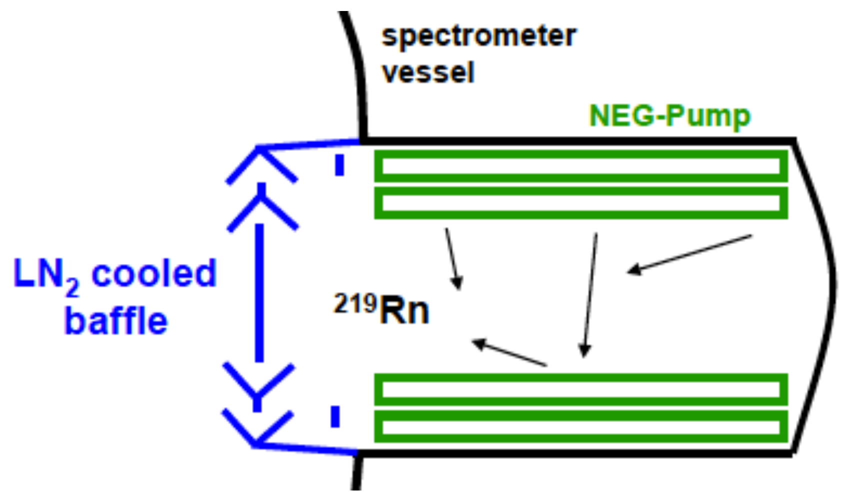
- Radon gas emanated from the getter material can enter the spectrometer and undergo alpha decay.

- Electrons produced by the decay can be stored in the spectrometer and produce secondary electrons.

- Use liquid nitrogen cooled baffle to trap Rn gas.

- Use simulation to understand the effect of stored electrons, and active methods of cleaning stored electrons.





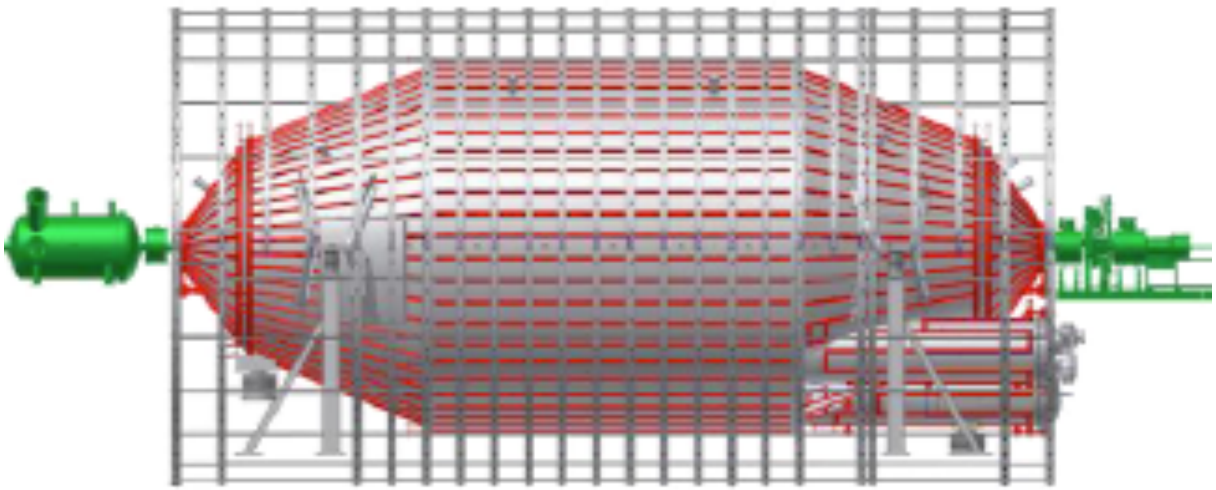
Wandkowsky, NuMass 2013

KATRIN: Main Spectrometer – a long way home

- Main spectrometer, 24 m long, 10 m in diameter, 200 ton
- Too large to be shipped on roads, water comes to rescue.
- 400 km journey turned into an 8000 km odyssey.

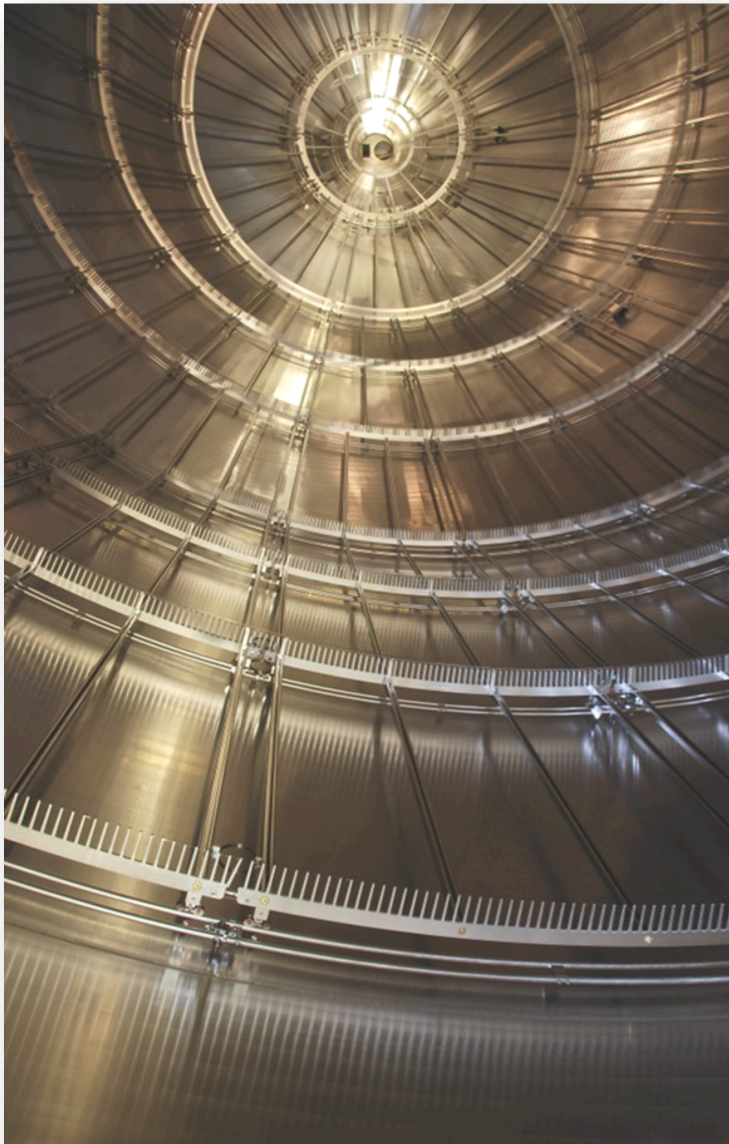
http://www.youtube.com/watch?feature=player_embedded&v=dmmVb779NP4

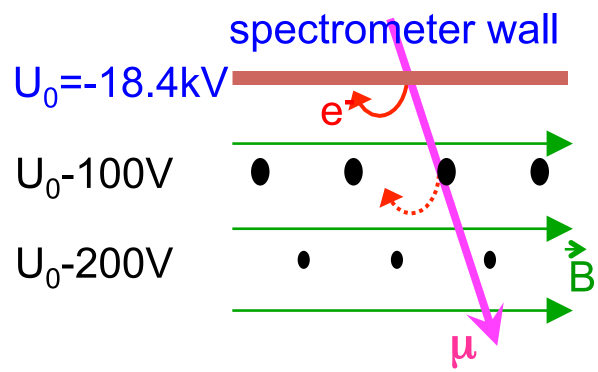
KATRIN: Main Spectrometer



- Superb analyzer power, ΔE = 0.93 eV. Scanning voltage varies in 0.5 – 1 V steps.
- Air coil to compensate for earth magnetic field, central field 3 Gauss.
- HV stability monitored by another spectrometer, using ^{83m}Kr source
- Hugh UHV vessel, (1240 m^3), < 10^{-11} mbar, vacuum baking at 300 C.
- Large surface area, A ~ 650 m^2, source of background electrons?

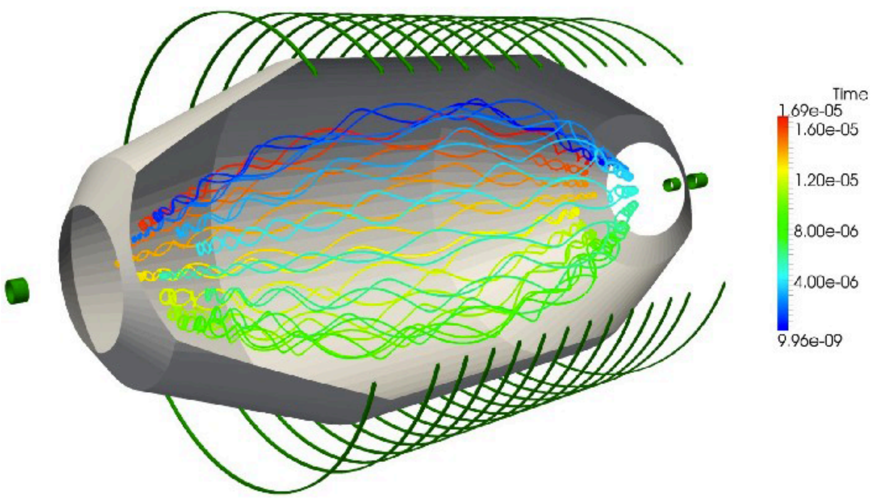
KATRIN: Wire Grid System

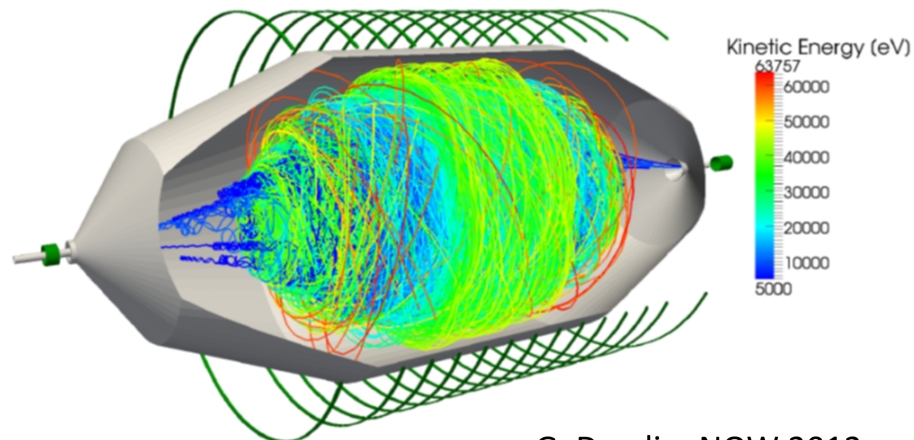




- >23000 wires in 250 frames
- stringent mechanical requirements
- Suppressing background electrons from the chamber wall.
- Fine shaping of the retarding potential
- reduce electrical field fluctuation and active filtering of stored electrons

KATRIN: Removal of Trapped Electrons





G. Drexlin, NOW 2012

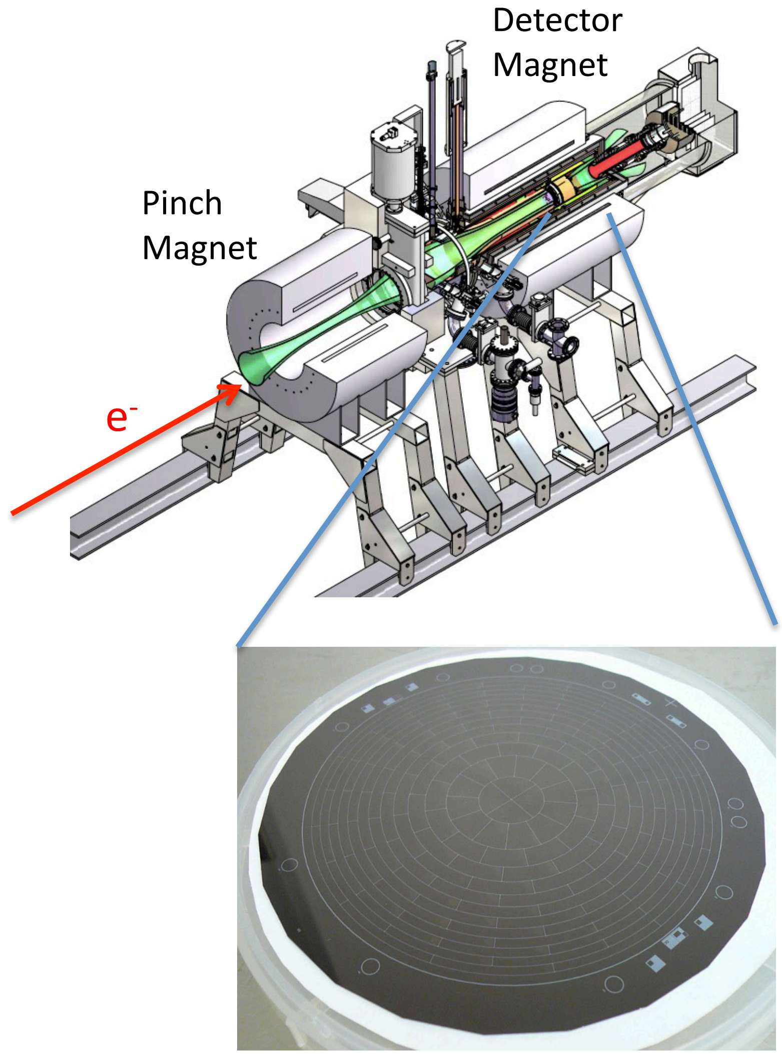
- Trapped electrons constitute a major background source, they can come from cosmic muons, environmental gammas or nuclear decay of detector materials.

- Trapped electrons can be trapped for hours, then ionize residual background gas, which can generate many secondary electrons

- Shown above is an electron removal scheme using RF heating.

KATRIN: Focal Plane Detector

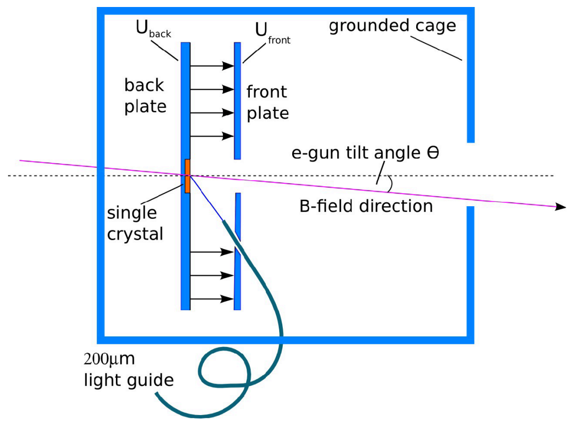
- Silicon PIN diode, > 90% efficiency
- Good energy resolution < 1 keV
- Post-acceleration up to 30 keV possible.
- Passive and active shielding to lower background to < 10^{-2} Hz
- Pinch magnet at 6 T, reflecting all electron with > 51° initial angle in the source.
- Segmented into 148 pixels, each maps to a region of the analyzing plane.



KATRIN: Systematic Uncertainties

Tritium source

- Inelastic scattering of βs inside the source
- fluctuation of source column density (required < 0.1 %)
- source charging due to remaining ions (MC: Φ<20 mV)
- final state distribution



Spectrometer

- transmission function
- High voltage stability 3ppm

2-dim scanning pulsed angular-selective UV laser photoelectron source, an example of tools to study systematics.

Each contributes with $\Delta m_\nu^2 < 0.007 eV^2$

Weinhermer, NuMass 2012

KATRIN: Status and Sensitivity

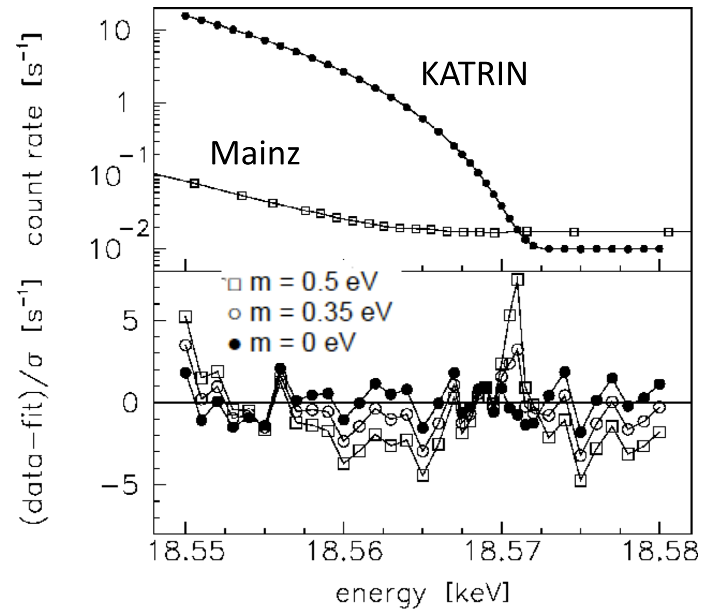
Weinhermer, NuMass 2013

- All major systems under testing or commissioning, data taking expected to take place in the first half of 2015

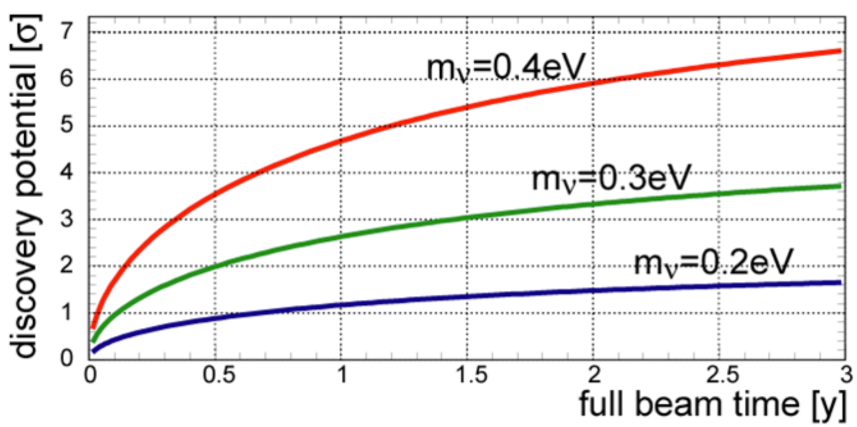
- Three years or running to reach $\sigma_{sys} \sim \sigma_{stat}$

- Sensitivity $m_\nu < 0.2$ eV (90% C.L.)

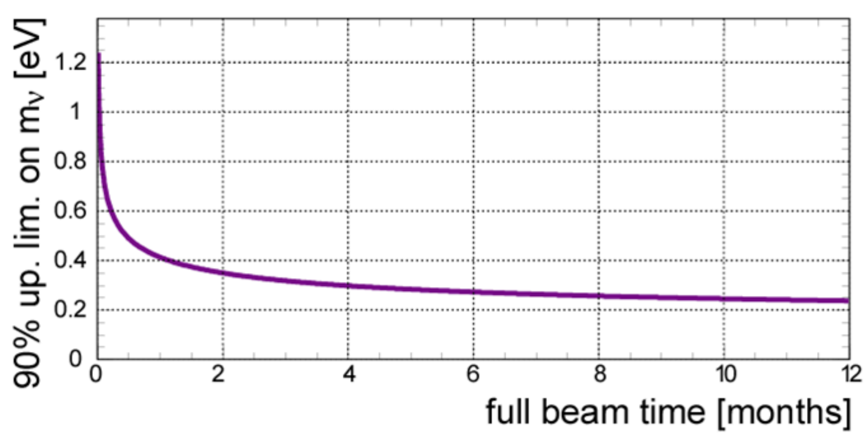
- Discovery potential:
  $m_\nu = 0.3$ eV (3σ)
  $m_\nu = 0.35$ eV (5σ)



KATRIN Simulation and Fits (last 25 eV)



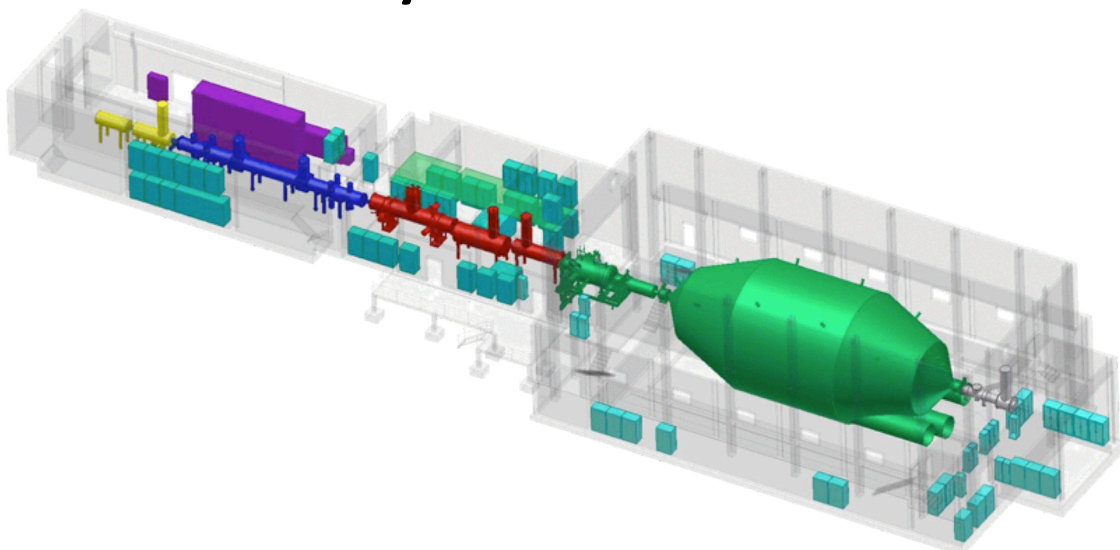
Discovery Potential



90% C.L. Upper Limit

G. Drexlin, arXiv: 1307.0101

Beyond KATRIN



- If the neutrino mass is below 200 meV, is it possible to make direct measurement of them in lab?

- Scaling up KATRIN, possible?
  - Column density near maximal, source activity scales up with area
  - To improve both statistics and energy resolution, main spectrometer size will be O(100m), technically unfeasible.
  - Background dominated by main spectrometer, further reduction difficult

NEW IDEAS NEEDED!

Project 8: Measuring Electron Cyclotron Radiation

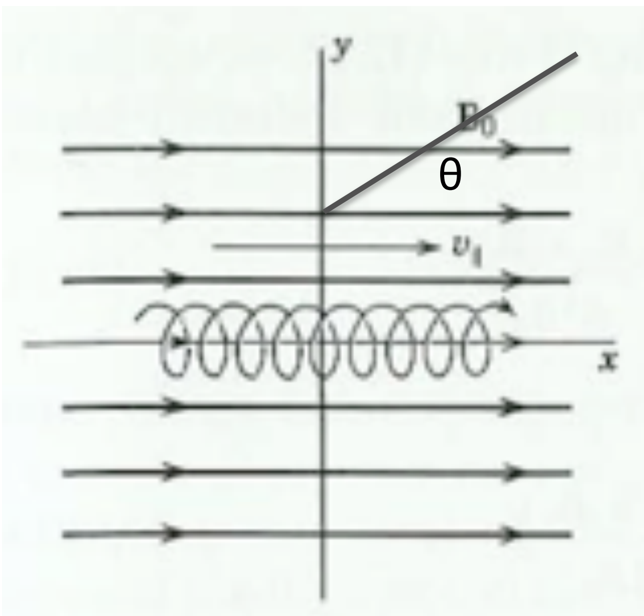
B. Monreal and J. Formaggio, PRD 80:051301, 2009

Electron cyclotron frequency

$$\omega(\gamma) = \frac{eB}{\gamma m_e} = \frac{\omega_c}{\gamma} = \frac{\omega_c m_e}{m_e + E}$$

Power emitted by the electron

$$P(\beta,\theta) = \frac{1}{4\pi\varepsilon_0}\frac{2q^2\omega_0^2}{3c}\frac{\beta^2\sin^2(\theta)}{1-\beta^2}$$



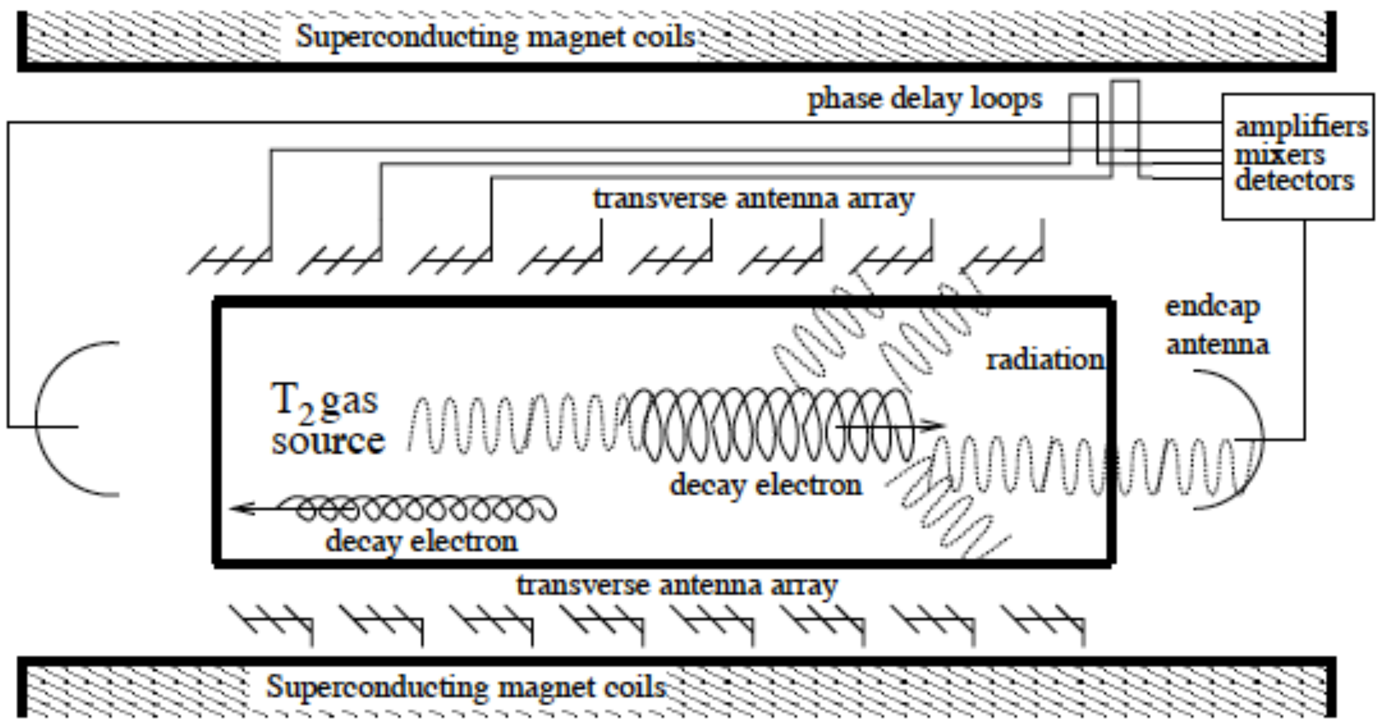
- Relativistic electron in a uniform magnetic field undergoes cyclotron motion.

- The frequency of the cyclotron motion is independent of the pitch angle, only the Lorentz boost factor

- Can the emitted coherent, narrow band microwave be detected and used to determine the electron energy to ΔE<1eV ?

Project 8: Experimental Concept

B. Monreal and J. Formaggio, PRD 80:051301, 2009



Low pressure T_2 gas, in uniform magnetic field. Cyclotron radiation of decay electrons measured by antenna array.

Advantage

- Target mass scales with volume
- High precision achievable with frequency measurements

Disadvantage

- Signal to noise, need long measurement time.
- New technique, need to demonstrate feasibility and control of systematic uncertainties.

Project 8: Frequency Measurement

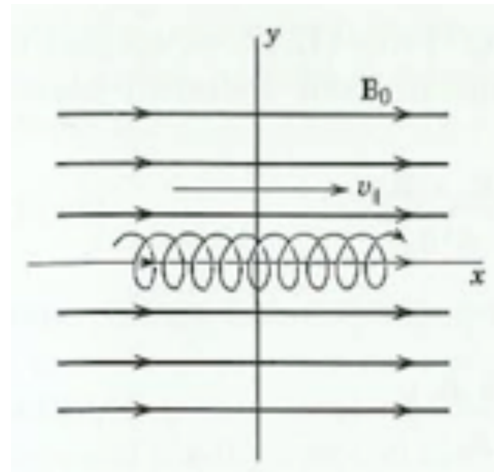
B. Monreal and J. Formaggio, PRD 80:051301, 2009

- For frequency measurements:
  $\Delta\omega \sim 1/T$

- For ΔE = 1 eV ($\sigma = 2\text{x}10^{-6}$), one will need $t_s \sim 40\mu s$ (>2000 m travel before collision). Maximum pressure limited at $10^{11}\ T_2/cm^3$

- Power emitted at 1T field ~ 10^{-15} W, while thermal noise at 20 K, ~ 10^{-19} W.

Parameter	Value	Unit
Electron energy	18.6	keV
β	0.2627	
γ	1.0364	
Field	1	T
ω_c	27.009	GHz



High pitch angles: strong signal, long measuring time

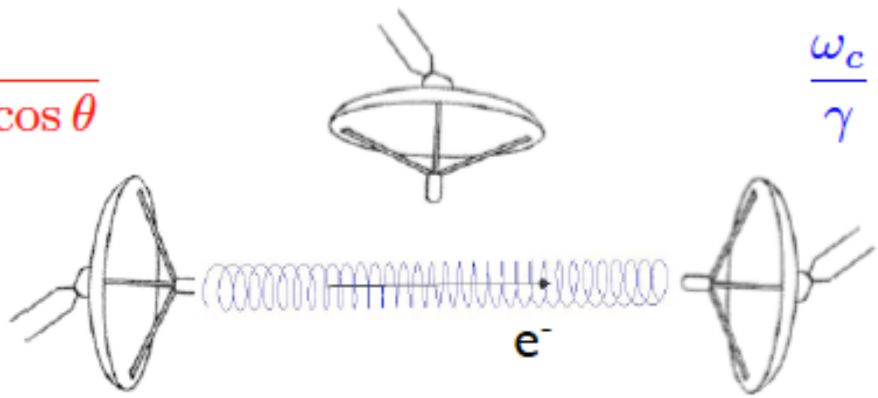
Low pitch angles: weak signal, short measuring time.

Project 8: Doppler Shift

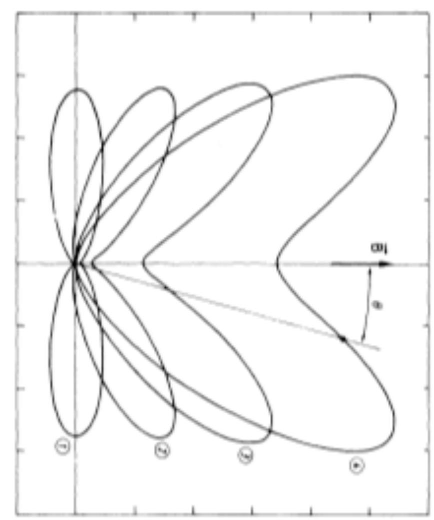
B. Monreal and J. Formaggio, PRD 80:051301, 2009

$$\frac{\omega_c}{\gamma}$$

$$\frac{\omega_c}{\gamma}\frac{1}{1+\beta\cos\theta} \qquad \frac{\omega_c}{\gamma}\frac{1}{1-\beta\cos\theta}$$



J. Formaggio, Neutrino 2010



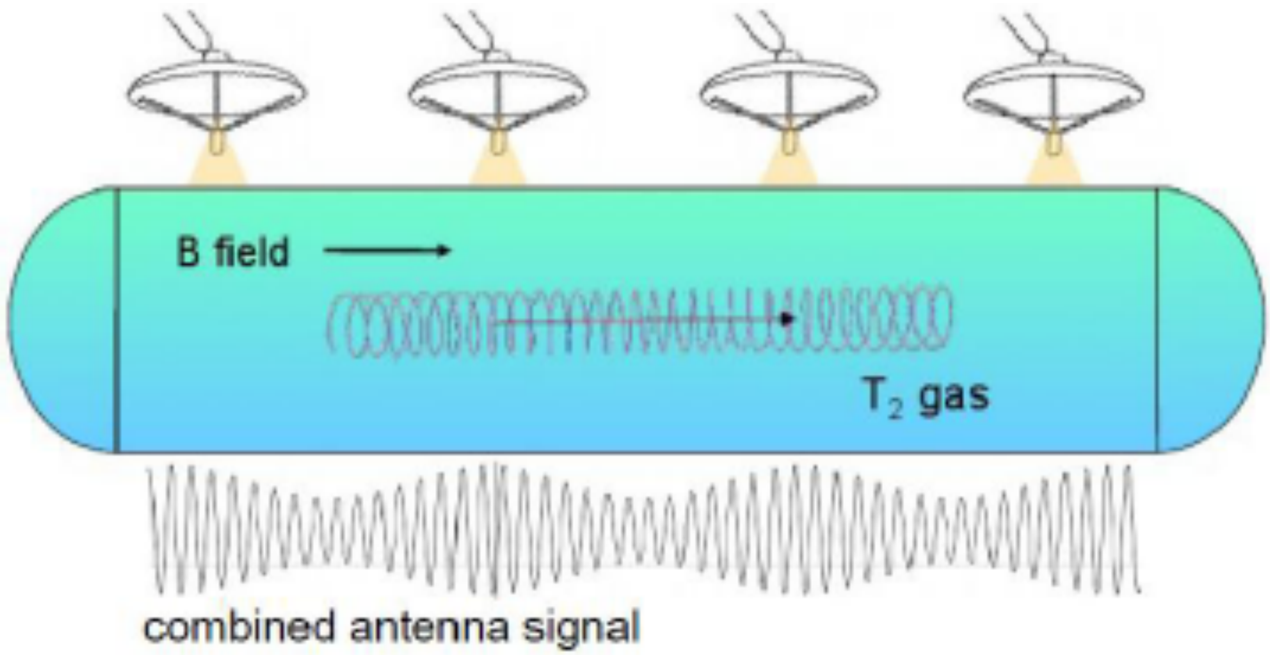
- The axial motion of the electron causes Doppler shift of the measured frequency.

- Antenna on the side of the cell will measure a continuum of frequencies.

- Antennas at the end of cell will measure a fixed frequency, but with very limited power for high pitch electrons.

Project 8: Interferometry of Antenna Array

B. Monreal and J. Formaggio, PRD 80:051301, 2009

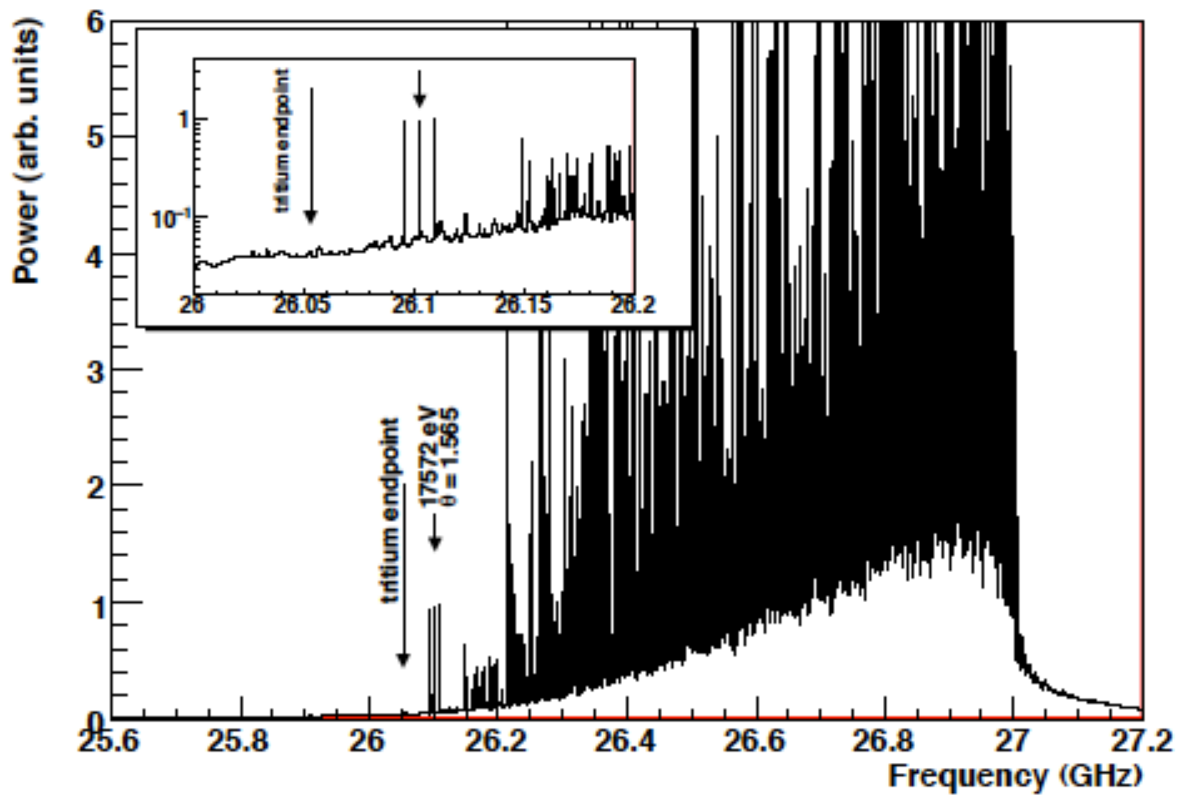


• Use multiple evenly spaced small antenna to observe the signal from a single electron

• Coherent sum of signal results in an amplitude modulated signal, and line splitting in the frequency space.

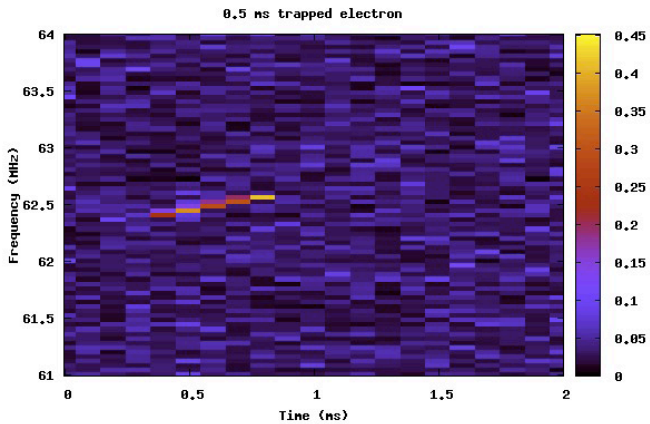
Project 8: Simulated Microwave Spectrum

B. Monreal and J. Formaggio, PRD 80:051301, 2009



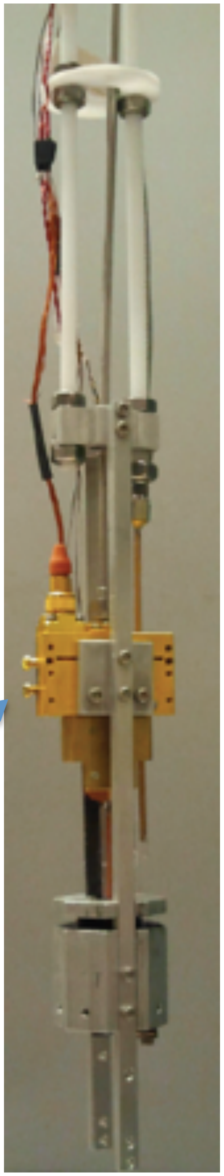
- Simulation of 10^5 T_2 decay: many overlapping low energy events and rare high energy events.
- Many unique signature of the high energy electrons can be used to distinguish them from background. Analysis techniques still need to be developed.

Project 8: Prototype Testing



Simulated signal

Test dewar at UW



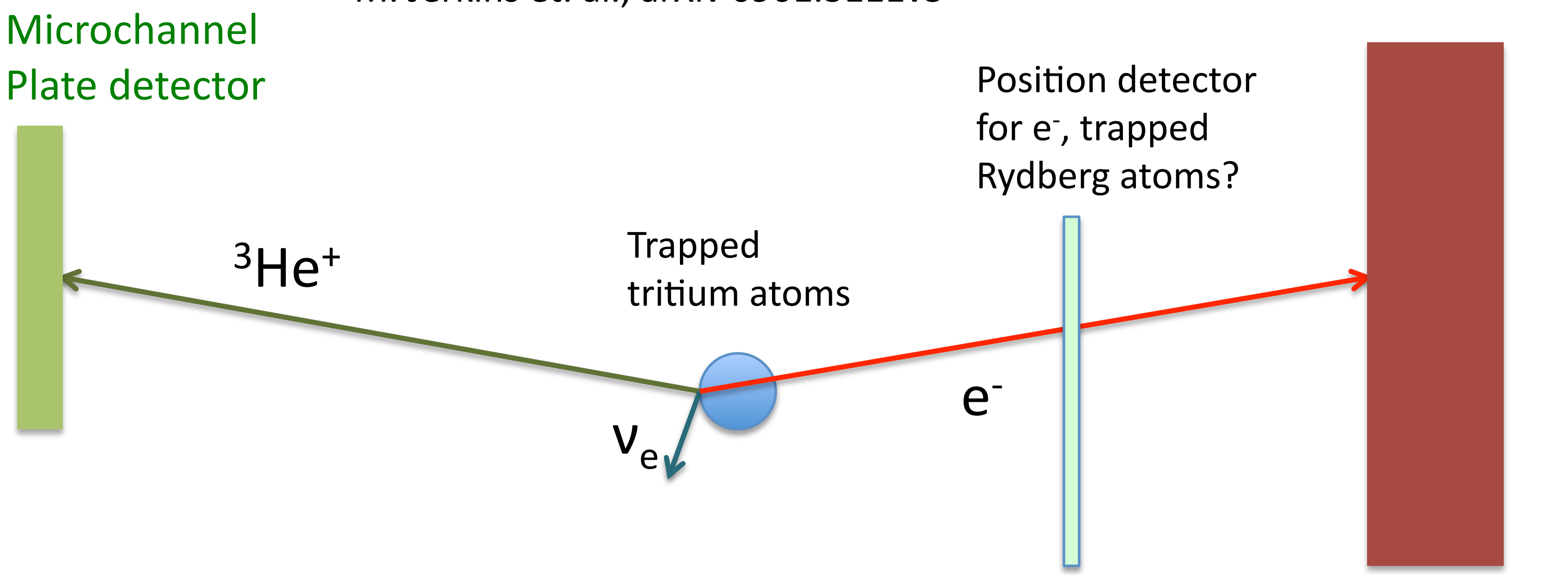
Trap, waveguide, NRAO amplifiers

Proof of principle tests are under way using ^{83m}Kr source to detect microwave signal from a single electron

Monreal, UW, 2011
Wilkerson, Neutrino 2012

Atomic traps: Kinematic Reconstruction

M. Jerkins et. al., arXiv 0901.3111v3



$$m_\nu^2 = \overrightarrow{p_\nu} \cdot \overrightarrow{p_\nu} = (\overrightarrow{p_{^3H}} - \overrightarrow{p_{^3He}} - \overrightarrow{p_\beta}) \cdot (\overrightarrow{p_{^3H}} - \overrightarrow{p_{^3He}} - \overrightarrow{p_\beta})$$

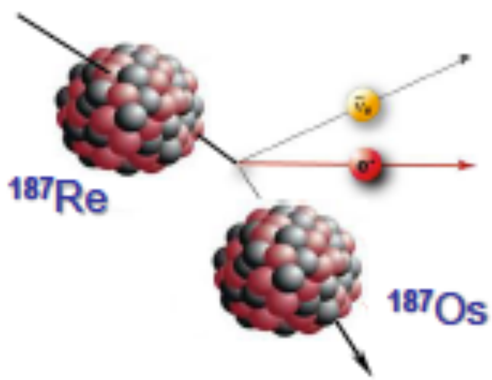
- With full kinematic reconstruction, β decays within 500 eV of the end point can contribute to the measurement. Atomic source with simple final states.

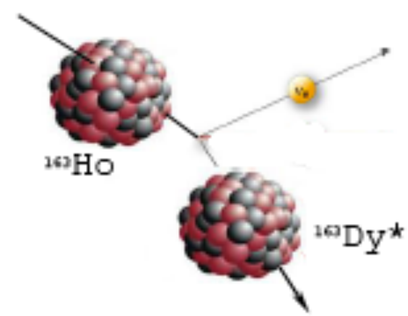
- Many challenges such as β momentum measurements and trapping sufficient amount of tritium atoms

Summary of Tritium Measurements

- β spectrometer techniques have been successfully used to measure the tritium decay, culminating in KATRIN, which will probe $m_\nu \sim 200$ meV region.
- Given the technical challenges, it will be difficult to scale up KATRIN type spectrometer further.
- New ideas needed: can we use cyclotron radiation as Project 8? Or full kinematic reconstruction with atomic traps? What about calorimeters? These new ideas will need time to develop and mature.

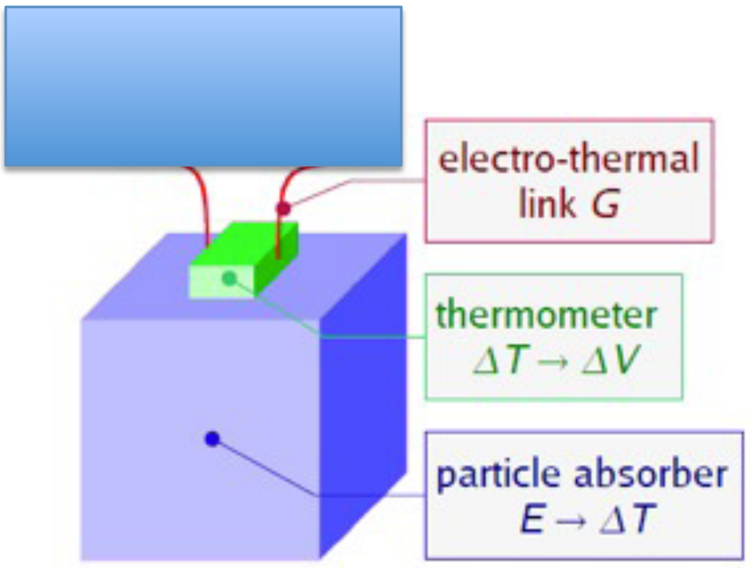
^{187}Rh and ^{163}Ho Measurements

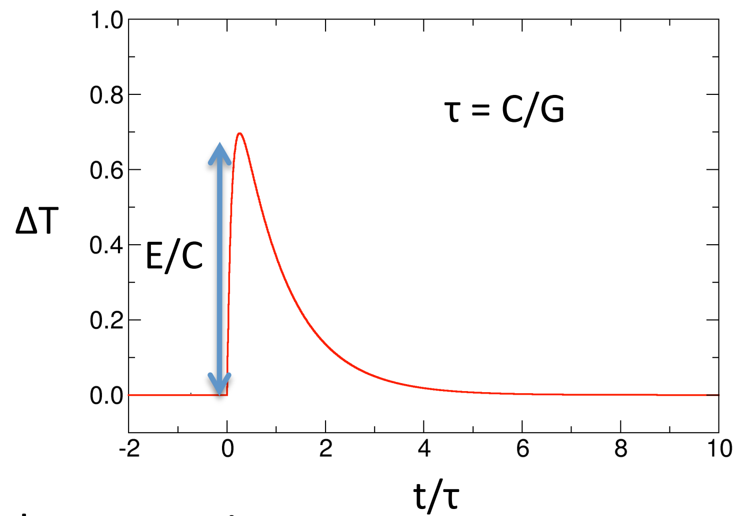




Principle of Calorimetry

Heat sink ~ 100 mK





C: heat capacity

- Measure total deposited energies, no final state or excited states effect, essential for decays with complicated electronics structure.

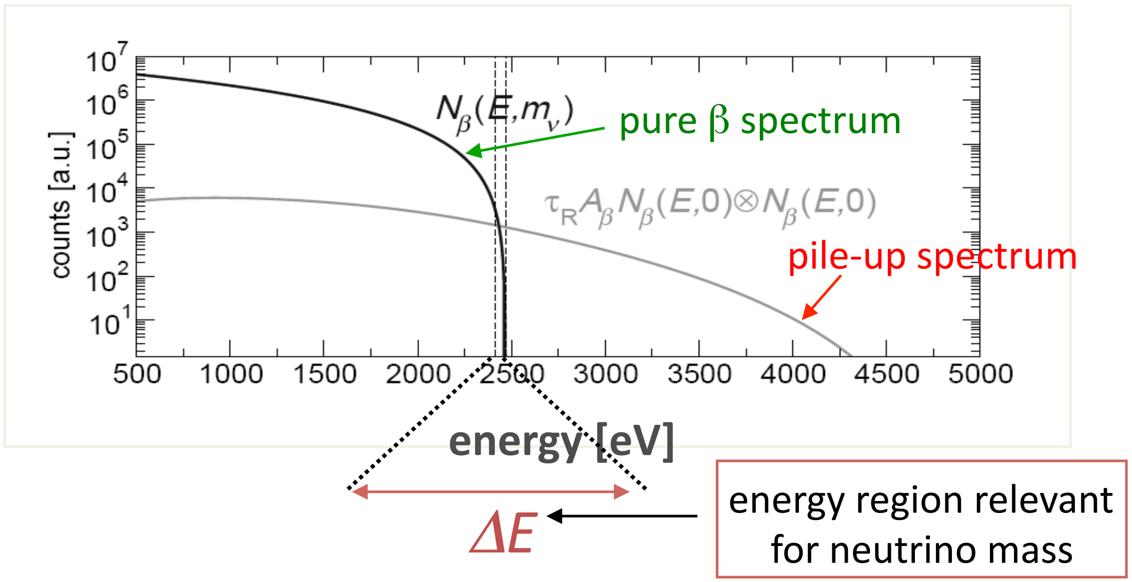
- Measure the entire differential energy spectrum dN/dE

- high energy resolution (< 0.1 %) possible with cryo-micro-bolometers, $C \sim T^3$, phonon energy ~ meV.

Statistics and Pile-up

Event pile-up can result in background near the endpoint

$$(dN/dE)_{exp}=[(dN/dE)_{theo}+ A\tau_r(dN/dE)_{theo}\otimes (dN/dE)_{theo}] \otimes R(E)$$



Giuliani, Pisa meeting, 2006

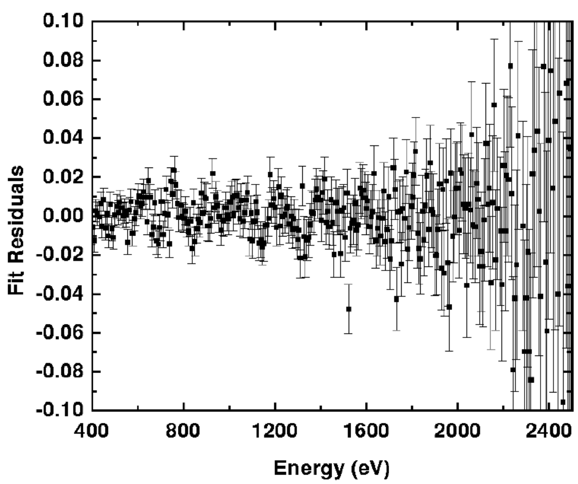
High statistics needed for neutrino mass detection

- Even for Rh (Q~2.47keV), only 10^{-10} fraction of events in the last 1eV.
- Require large number of detector arrays
- 1mg of Re ~ 1 decay per second

Previous ^{187}Rh Experiments

MANU (Genova)

- Single metallic Rh crystal
- Neutron transmutation doped (NTD) Ge thermistor
- Measured beta environmental fine structure (BEFS)
- $\Delta E = 96$ eV FWHM
- $m(\nu_e) < 26$ eV (90% CL)

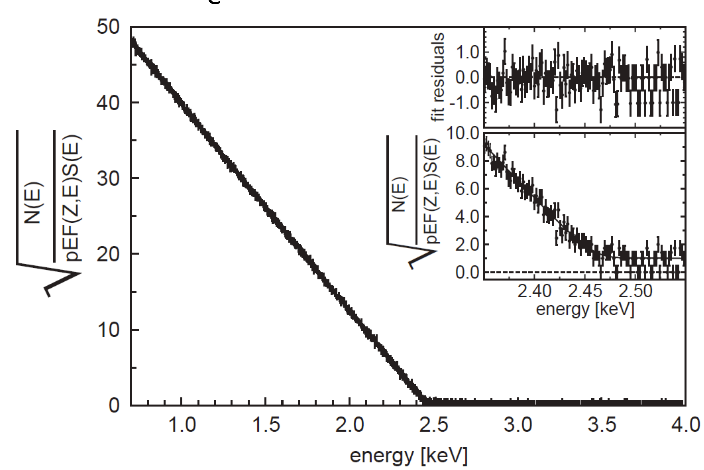


BEFS measured by MANU

M. Galeazzi et. al. Phys. Rev. C, 63, 014302 (2000)

MiBeta (Milan)

- $ReAgO_4$ crystal
- Silicon implanted thermistor
- An array of 10 detectors, total 6 x 10^6 decays
- $\Delta E \sim 28.5$ eV FWHM
- rise time ~ 0.5 ms
- $m(\nu_e) < 15$ eV (90% CL)



Kurie Plot from MiBeta

M. Sisti et. al., Nucl. Inst. and Meth. A 520, 125 (2004)

MARE

Microcalorimeter Arrays for a Rhenium Experiment

Requirement for a neutrino mass calorimeter experiment:

- Large number of parallel channels
- Decrease detector response time to reduce pile up.
- Improvement in energy resolution

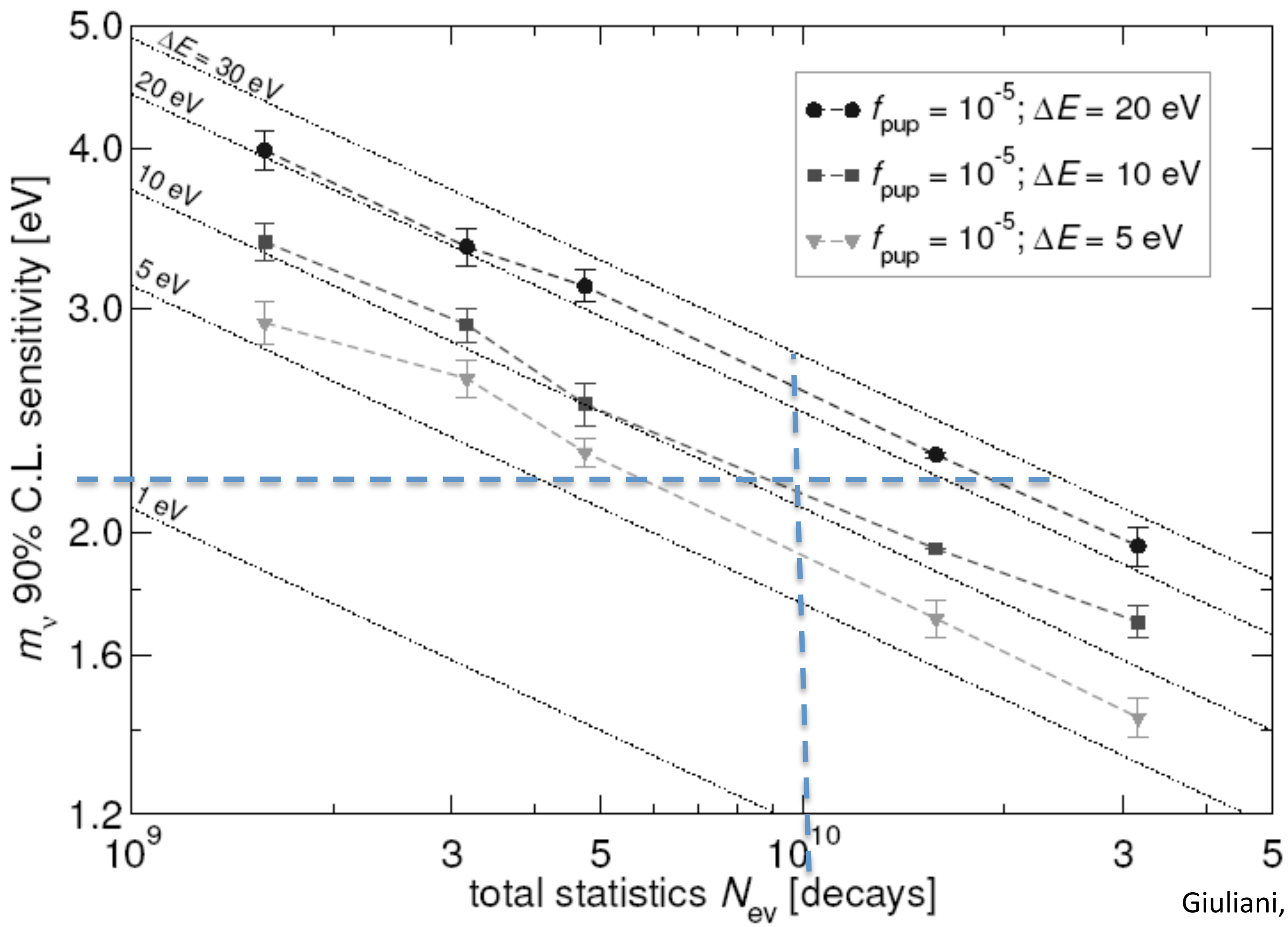
MARE-I (10^9-10^{10} β decays)

- Prototyping to determine optimal technology
- ~ 300 elements
- semiconductor thermistor and transition edge sensors (TES)
- ΔE = 20 eV, T_R = 100-500μs, 0.25 Hz activity/element
- $m(\nu_e)$ sensitivity ~ 2eV

MARE-II (10^{14} β decays)

- ~ 50000 elements
- TES or magnetic calorimeters or kinetic inductance detector
- ΔE = 5 eV, T_R = 100-500μs, 1-10 Hz activity/element
- $m(\nu_e)$ sensitivity ~ 0.2eV

MARE-I Sensitivity



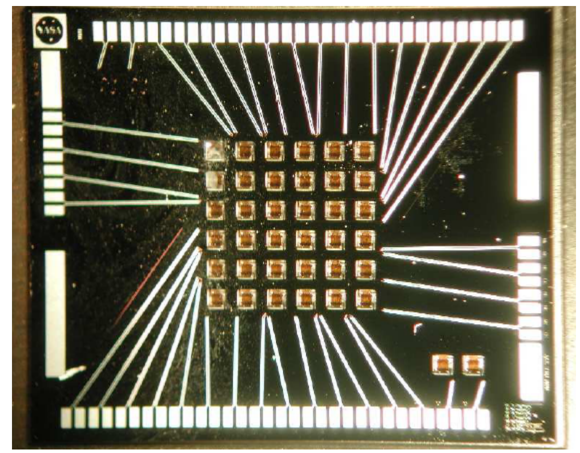
Giuliani, Pisa meeting, 2006

Both energy resolution and statistics are critical, need the best technology.

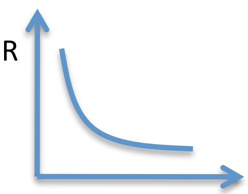
Technology for MARE-I

Semiconductor Thermistors

- $ReAgO_4$ (Milano)
- ΔE ~ 25 eV
- τ_r ~ 250 µs
- m = 0.5 mg, 0.27 Bq
- up to 8x8 array possible

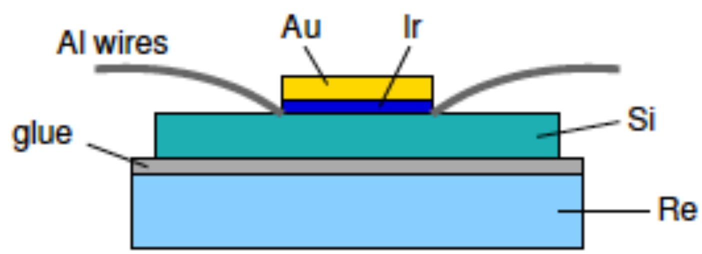


NASA/Wisconsin

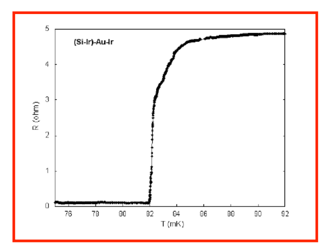


Transition Edge Sensor (TES)

- Metallic Re (Genova)
- ΔE ~ 11 eV
- τ_r ~ 160 µs
- m = 0.2-0.3 mg, 0.25 Bq
- Ir-Au bi-layer configuration
- Multiplexed SQUID readout



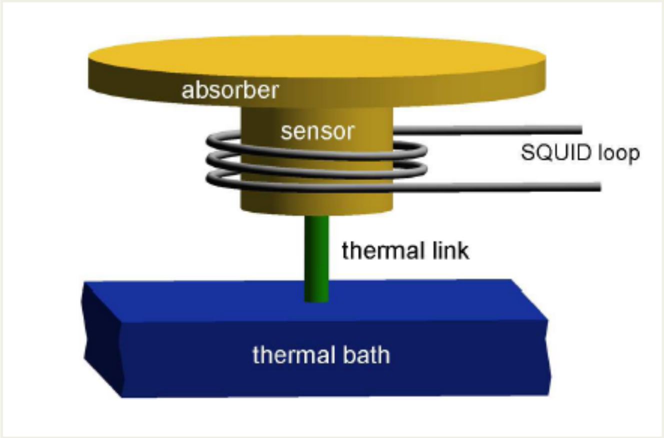
TES Sensor



R&D for MARE-II

Magnetic Micro-Calorimeter (MMC)

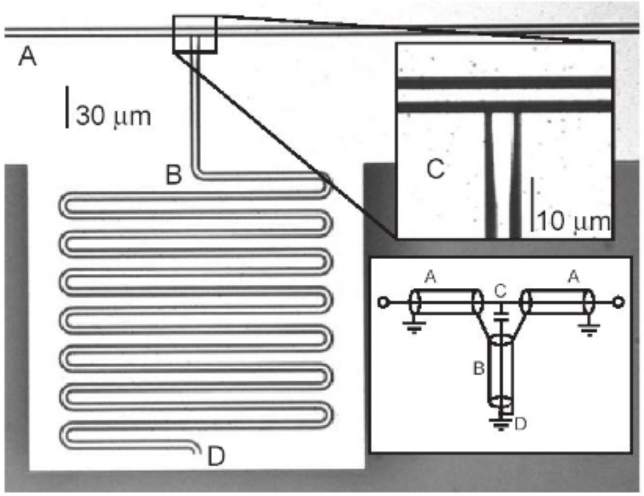
- Measure change in magnetization of a paramagnetic material.
- Gold absorber, $\Delta E \sim 2$ eV, $\tau_r \sim 90$ ns for X ray at 6keV
- Rhenium absorber, $\Delta E \sim 44$ eV, $\tau_r < 10$ µs
- Multiplexed SQUID readout



Kirkhoff Institute of Physics, Heidelberg

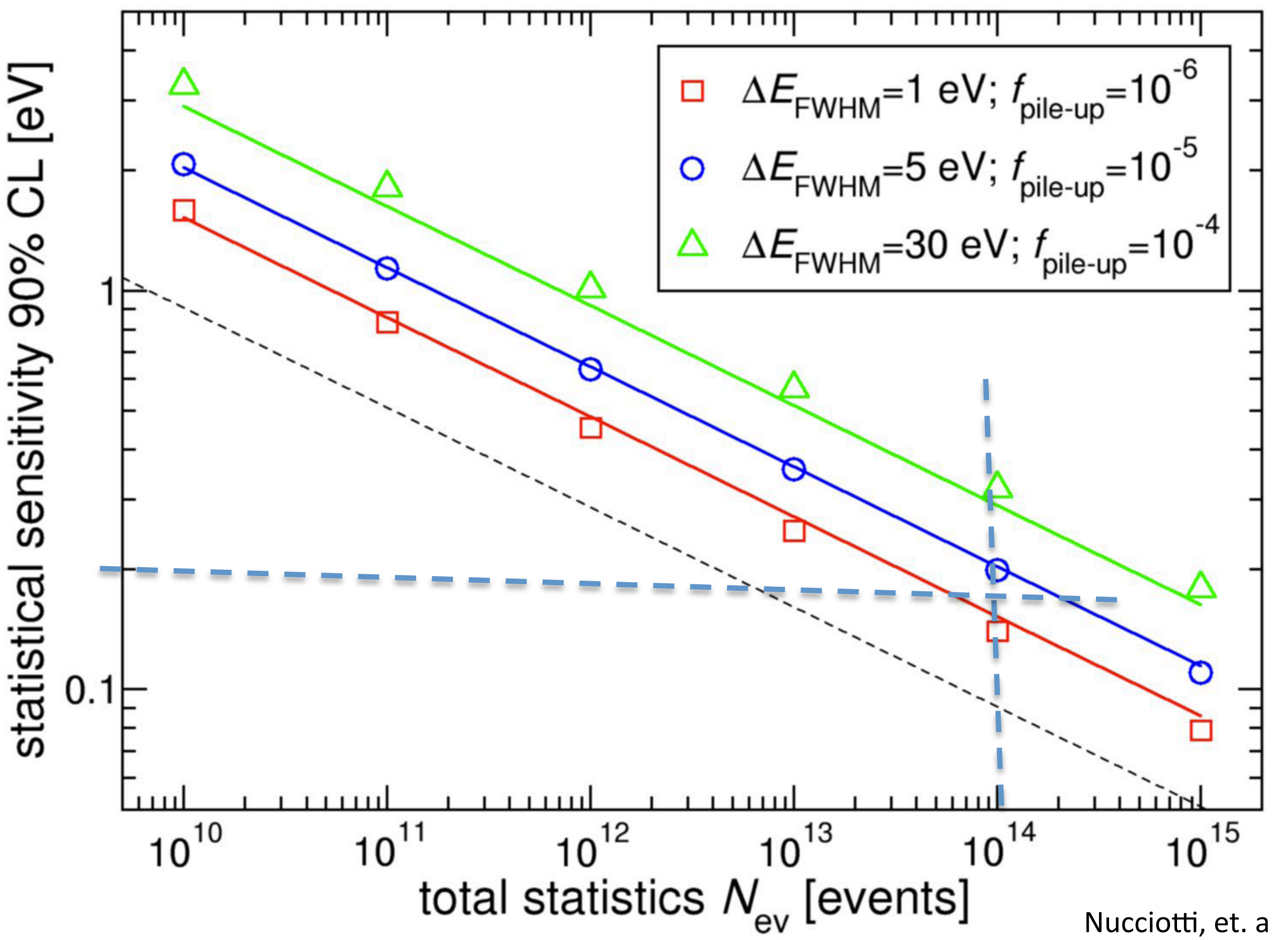
Microwave Kinetic Inductance Detector (MKID)

- Exploit the temperature dependence of a superconducting film
- high energy resolution and fast rise time
- Easy for multiplexing
- R&D underway



Al strip on Si substrate

Sensitivity of MARE-II

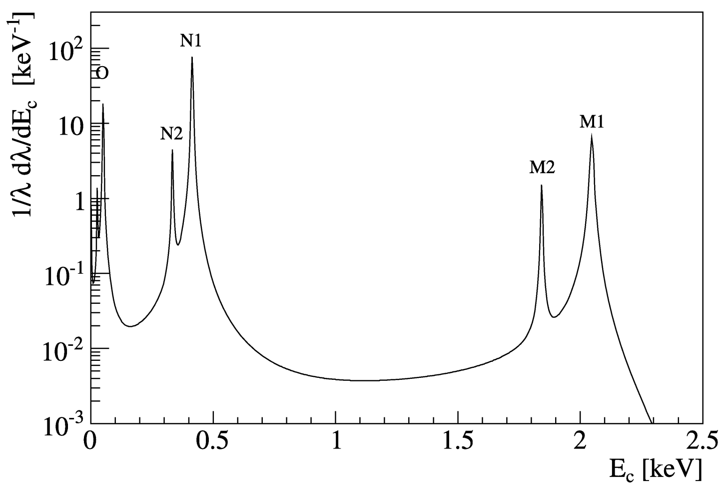


Nucciotti, et. al., arXiv:0912.4638v1

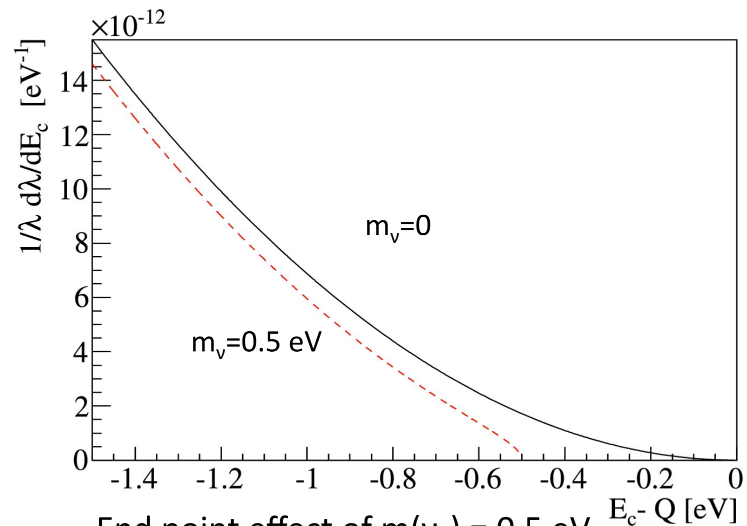
Systematic uncertainties such as BEFS, spectral shape, pile-up, background will need further studies.

^{163}Ho Electron Capture

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



De-excitation spectrum for ^{163}Ho, Q = 2.5 keV



End point effect of $m(\nu_e)$ = 0.5 eV

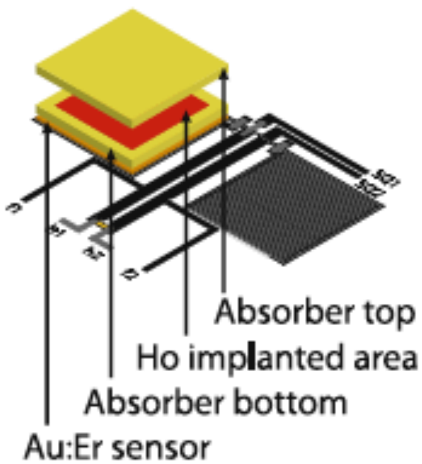
Lusignoli, et. al., Phys. Lett. B, 697, 1114, (2011)

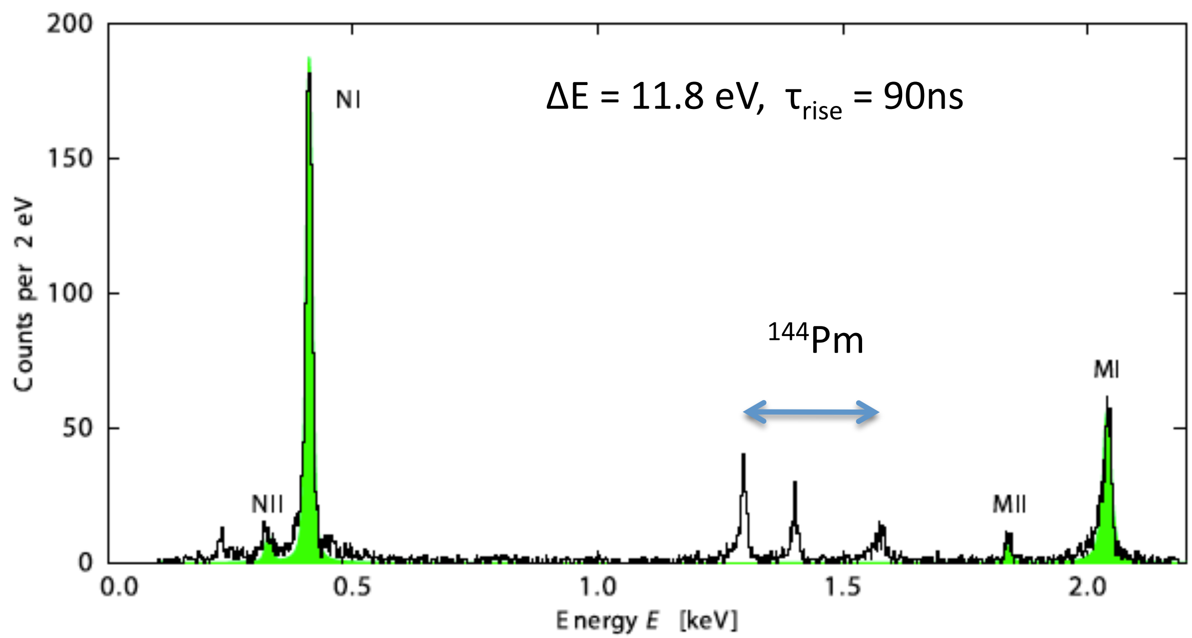
- Only electrons from M_1, M_2, N_1, N_2, O_1, O_2, and P_1 shells can be captured. E_0 = 2.3 – 2.8 keV ?, with recommended value at 2.555 keV.

- Neutrino mass affects the ratio of capture rates, inner Bremsstrahlung, and spectrum shape near end point.

- Calorimeter measurements inspired by good results from R&D with MMC sensor.

Electron Capture on Holmium (ECHO)

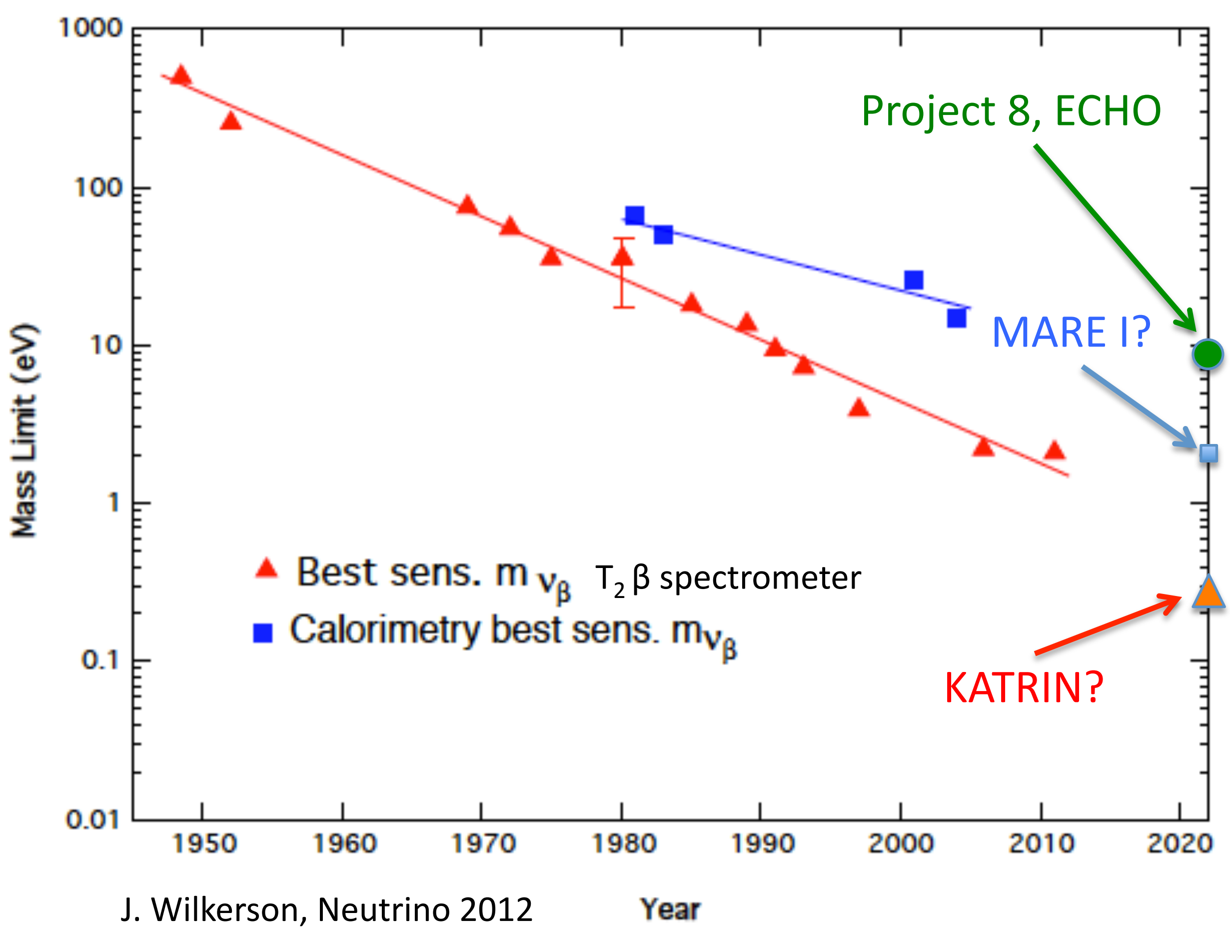




Ranitzsch, et. al., J. Low Temp. Phys. 167, 1004, (2012)

- Develop magnetic micro-calorimeters (MMC) for both ^{187}Re and ^{163}Ho. Ho ions can be implanted in gold absorbers which has good performance, ΔE ~ 2eV possible.
- Extracted end point Q = (2.8 ± 0.1) keV. ^{144}Pm contamination during implantation.
- Systematic uncertainties such as spectral line shapes, background, end-point location need further investigation.

Where we are going?



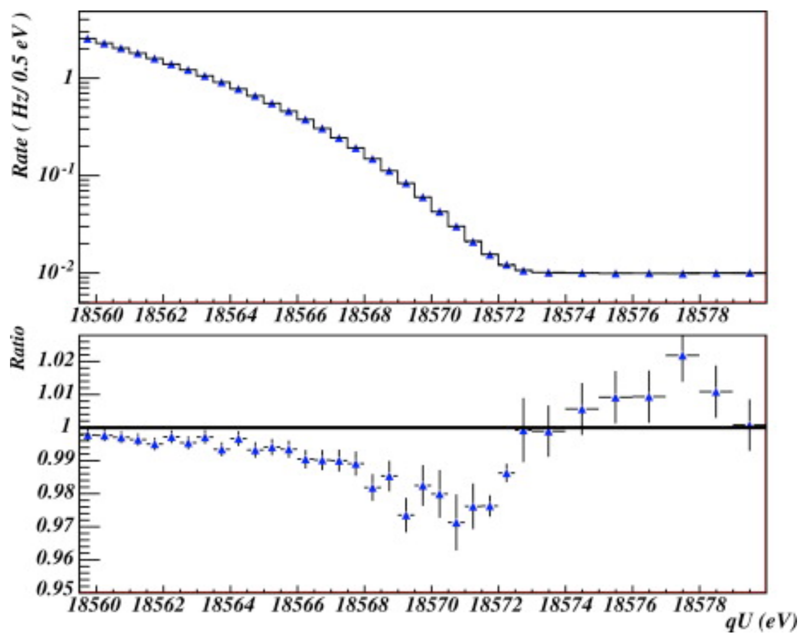
J. Wilkerson, Neutrino 2012

What do we expect to see in the next 5 – 10 years?

- KATRIN reach sensitivity of 0.2 eV
- MARE-I reach sensitivity of 1 eV
- New techniques such as Project 8 and ECHO demonstrate feasibility.

Sterile and Relic Neutrino Detection

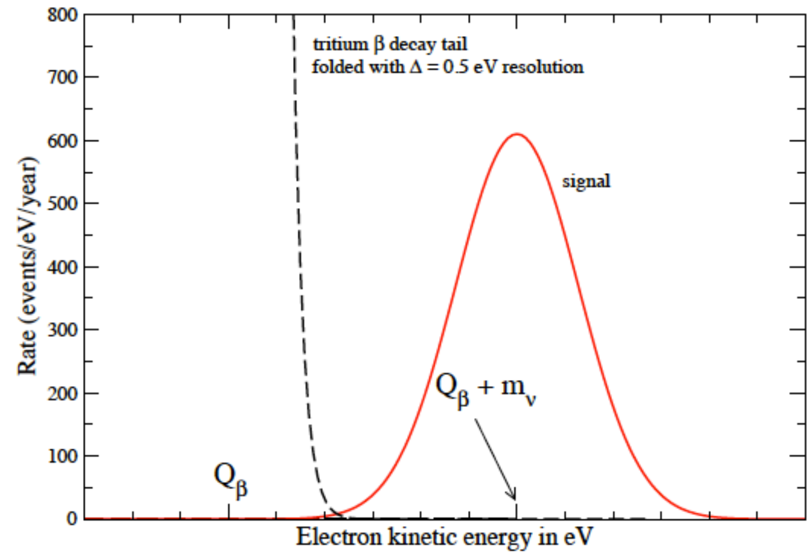
Formaggio, et. al., Phys. Lett. B 706, 68 (2011)



"Kink" in β spectrum from sterile neutrino

KATRIN has sensitivity to low mass sterile neutrino, hypothesized to explain the reactor anomaly

Lazauskas, et. al., J. Phys. G, 35, 025001 (2008)



Relic neutrino capture peak beyond end point

$\nu + n \rightarrow p + e$

Need both large radioactive isotope mass (1 MCi for T), and high energy resolution $\Delta E < m_\nu$

Summary

- Direct neutrino mass measurement using weak decay kinematics is the most sensitive model independent method for neutrino mass determination.

- KATRIN experiment is posed to push the mass sensitivity to 200 meV in the next 5 – 10 years.

- A varieties of new techniques are under development that has the potential to go beyond the limit set by KATRIN.

- All experiments are extremely challenging but exciting. Would welcome young people and fresh ideas.