Measuring the neutrino mass

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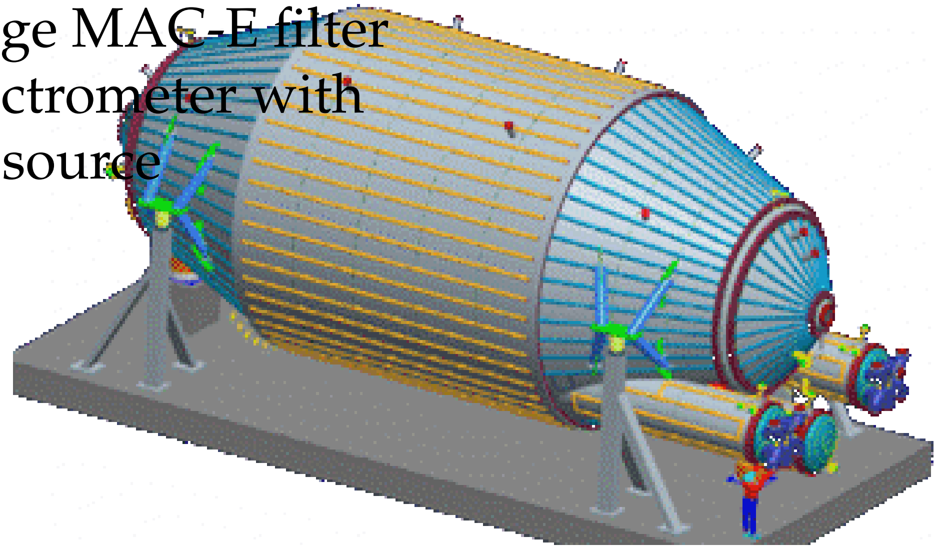
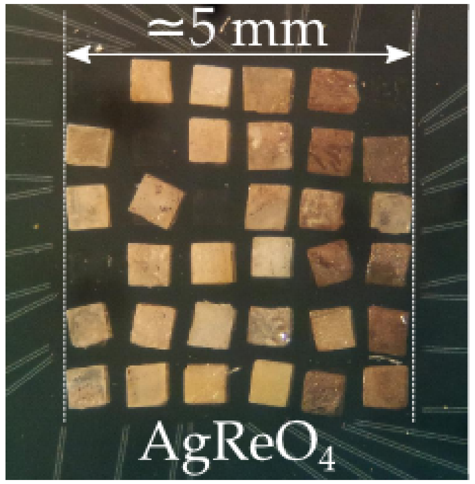
Lecture 7

Spectrometry: KATRIN

Large MAC-E filter spectrometer with ^{3}H source



Calorimetry: Mare, ECHo, Holmes



Array of low temperature microcalorimeters with ^{187}Re or ^{163}Ho

“Direct” measurements of neutrino mass via β decay

β decays and ν mass

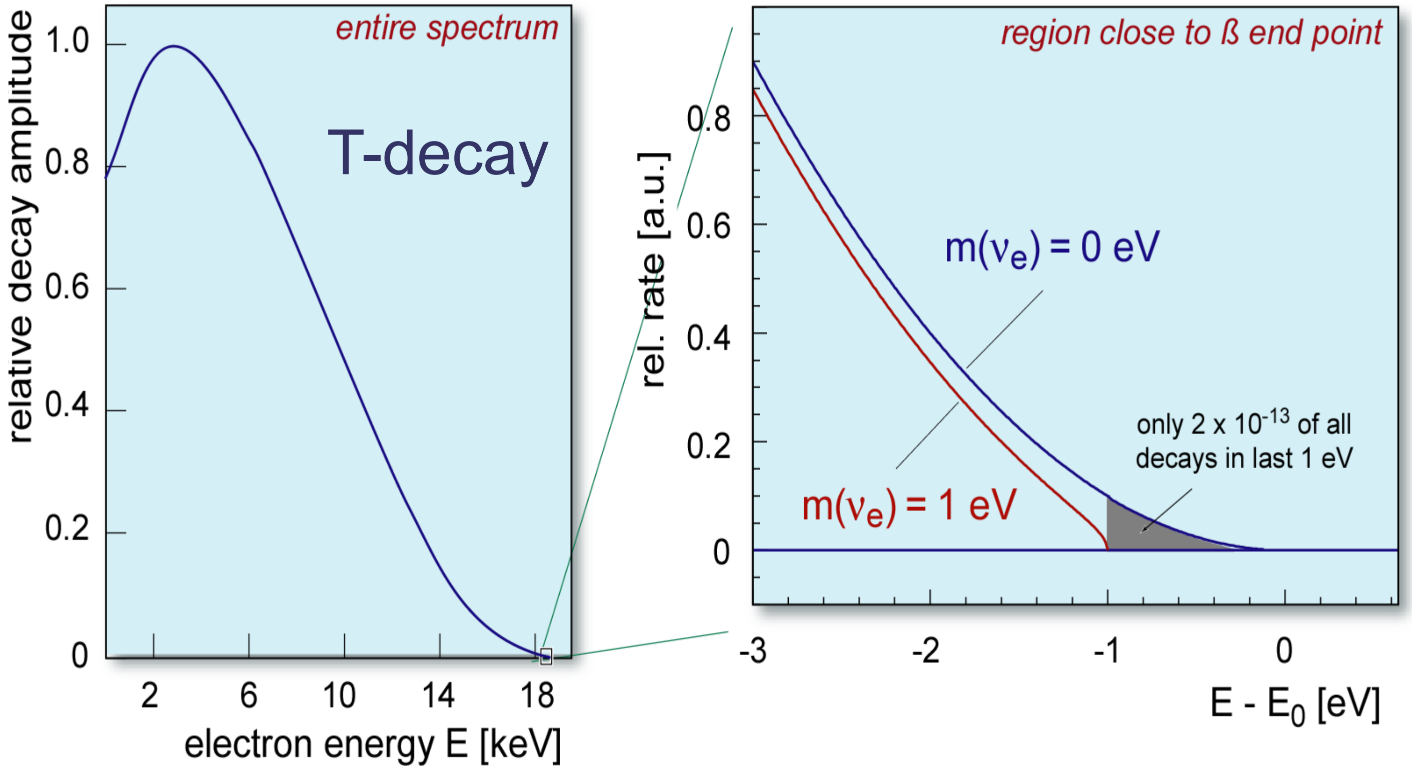
β decay: $(A,Z) \rightarrow (A,Z+1)^{+} + e^{-} + \bar{\nu}_e$

$$\frac{d\Gamma}{dE} = C\, p(E+m_e)(E_0-E)\sqrt{(E_o-E)^2-m_{\nu_e}^2}\, F(Z+1,E)\,\Theta(E_0-E-m_{\nu_e})$$

$$C = \frac{G_F^2}{2\pi^3}\cos^2\theta_C |M|^2$$

$$m_{\nu_e} = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 m_i^2}$$

(modified by final states, recoil corrections, radiative corrections)



Requirements

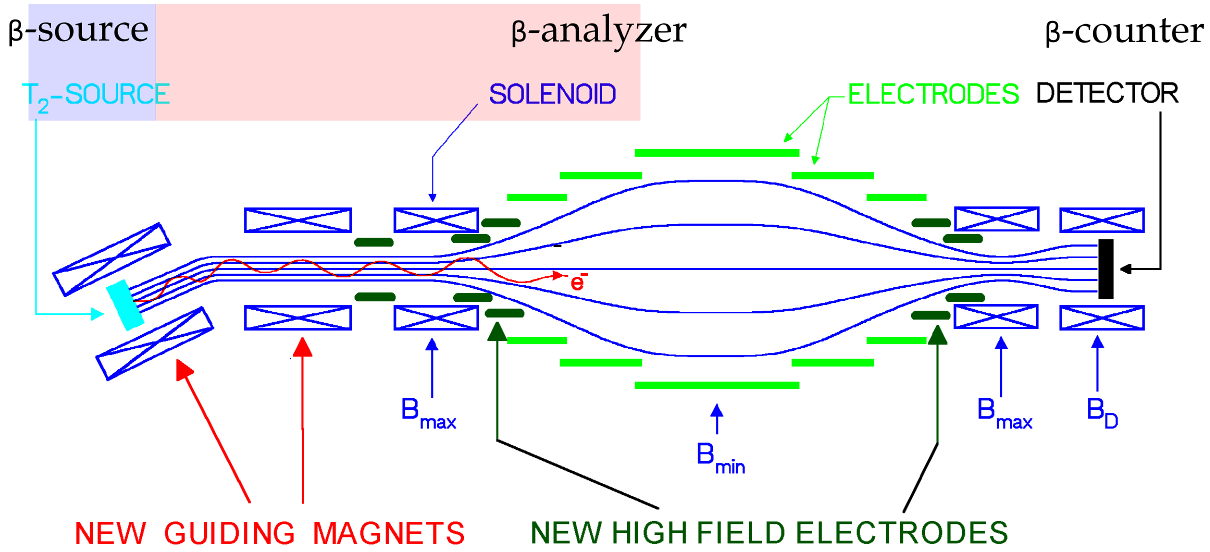
- low endpoint energy
- high count rate
- high energy resolution
- very low background

Tritium

- $E_0 = 18.6$ keV
- $T_{1/2} = 12.3$ a
- superallowed transition
- simple electronic structure

Experimental approaches

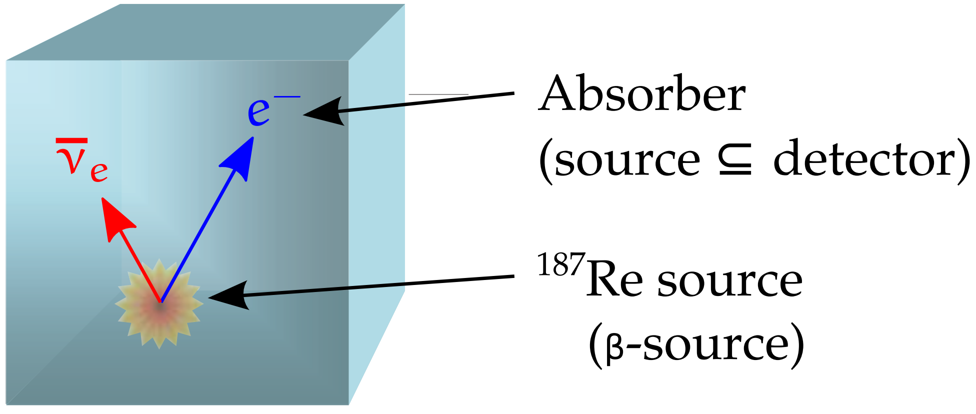
Spectrometers: source ≠ detector



(Mainz spectrometer sketch-up from C. Kraus *et al.* [9])

- Tritium β decay: $^3H \rightarrow ^3He^+ + e^- + \overline{\nu}_e$
- Magnetic spectrometers and MAC-E filter [10];
- The β-electrons with enough energy to pass the MAC-E filter are detected;

Calorimeters: source ⊆ detector



$$^{187}\mathrm{Re} \longrightarrow {}^{187}\mathrm{Os} + e^- + \overline{\nu}_e$$

- The β source is embedded in the detector (absorber);
- Ideally measurement of all the energy E released in the decay except for the ν_e energy;

Calorimeters versus spectrometers

General experimental requirements:

- High statistics at the beta spectrum end-point:
  - Low end-point energy Q: $F(\delta E) \propto (\delta E/Q)^3$
    $\Rightarrow$ where δE is the energy range considered near the end point;
  - High source activity and high efficiency;
- High energy resolution ΔE (same order of magnitude of m_ν sensitivity);
- High signal-to-noise ratio (SNR);
- Small systematic effects.

Spectrometers: source ≠ detector:

☺ high statistics: $\tau_{1/2}(^3H) = 12.3$ y;

☺ high energy resolution: $\delta E \simeq 1$ eV;

☹ systematics due to source effect;

☹ systematics due to decay to excitated states;

☹ background.

Calorimeters: source $\subseteq$ detector:

☺ no backscattering;

☺ no energy losses in the source;

☺ no solid state excitation;

☺ no atomic/molecular final state effect;

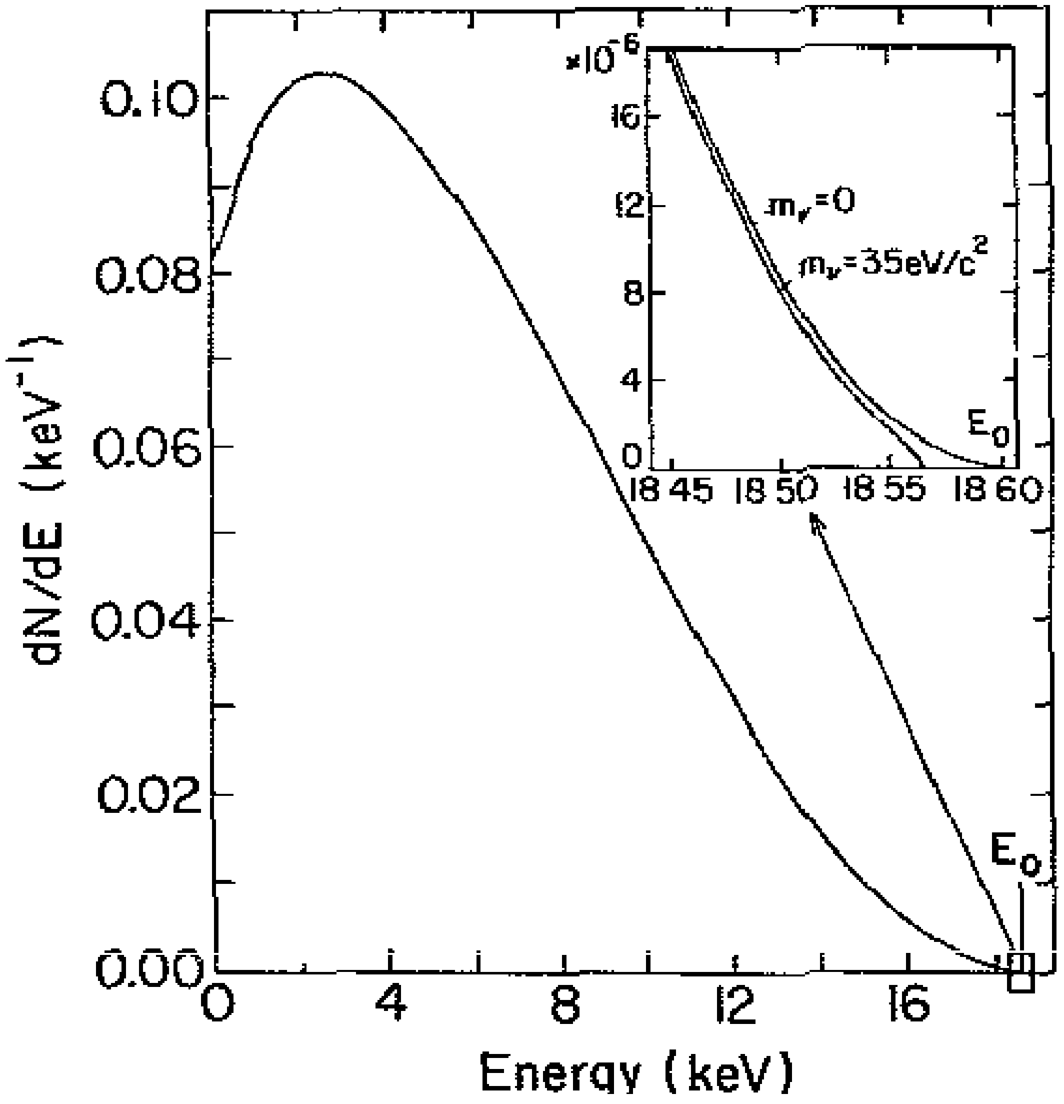
☹ limited statistics: $\tau_{1/2}(^{187}Re) \simeq 4 \cdot 10^{10}$ y;

☹ systematics due to pile-up;

☹ background.

Tritium β decays

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



- Advantages of tritium:
  - Very low end-point energy (E0 = 18.6 keV).
  - “Simple” nuclear structure.
  - “Short” half-life (12.3 y).

$$N(E) = \frac{\mathrm{d}N}{\mathrm{d}E} \sim F(Z,W)pW\epsilon^2\sqrt{1 - m_\nu^2/\epsilon^2}$$

$$\epsilon = E_0 - E$$

- p = momentum of electrons
- E = kinetic energy
- W= Total energy
- F(Z,W) = Fermi function (electrostatic correction to spectrum)

Kurie Plot

$$K(E) = \sqrt{N(E)/(FpW)} \sim \epsilon(1 - m_\nu^2/\epsilon^2)^{1/4}.$$

$$\epsilon = E_0 - E$$

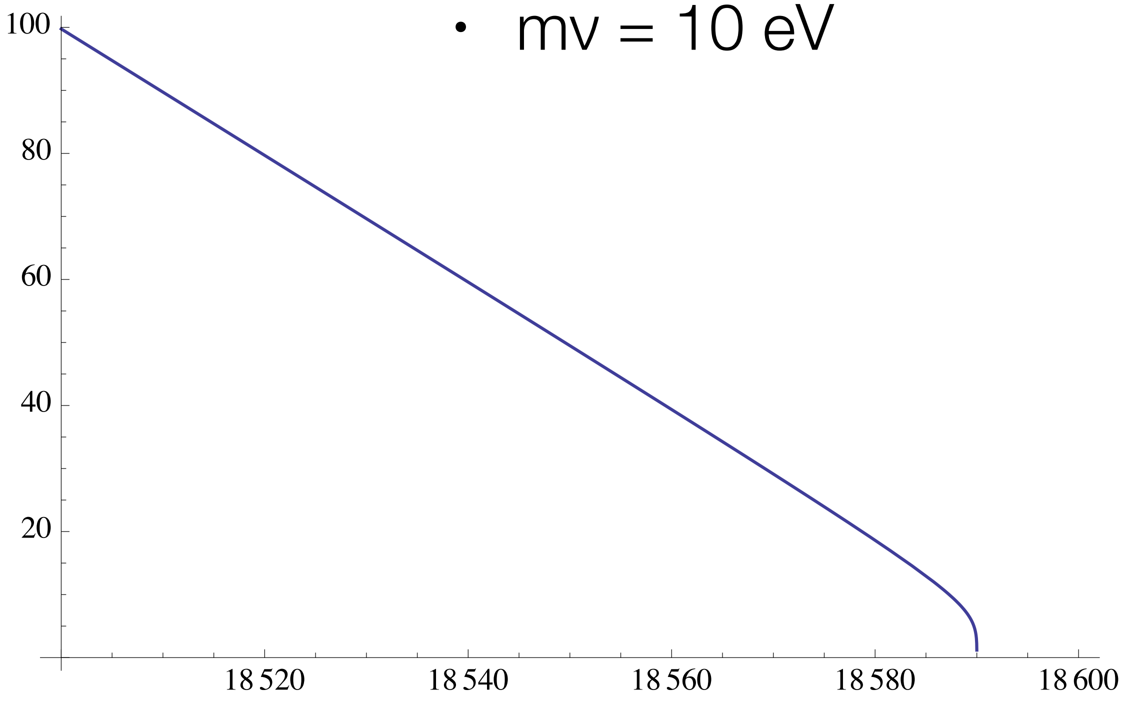
$$\epsilon >> m_\nu \rightarrow K(E) \sim \epsilon$$

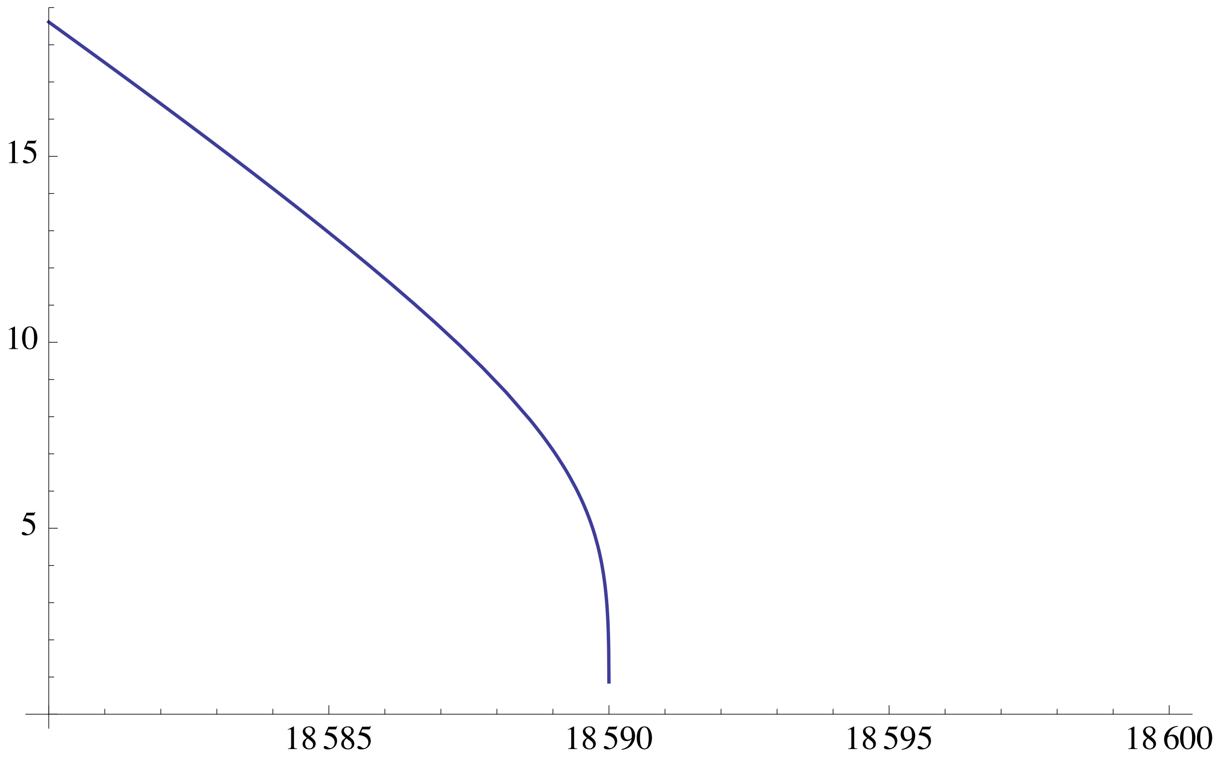
- Linear case:

$$\epsilon \approx m_\nu \rightarrow K(E) \sim \chi\epsilon, \chi \rightarrow 0$$

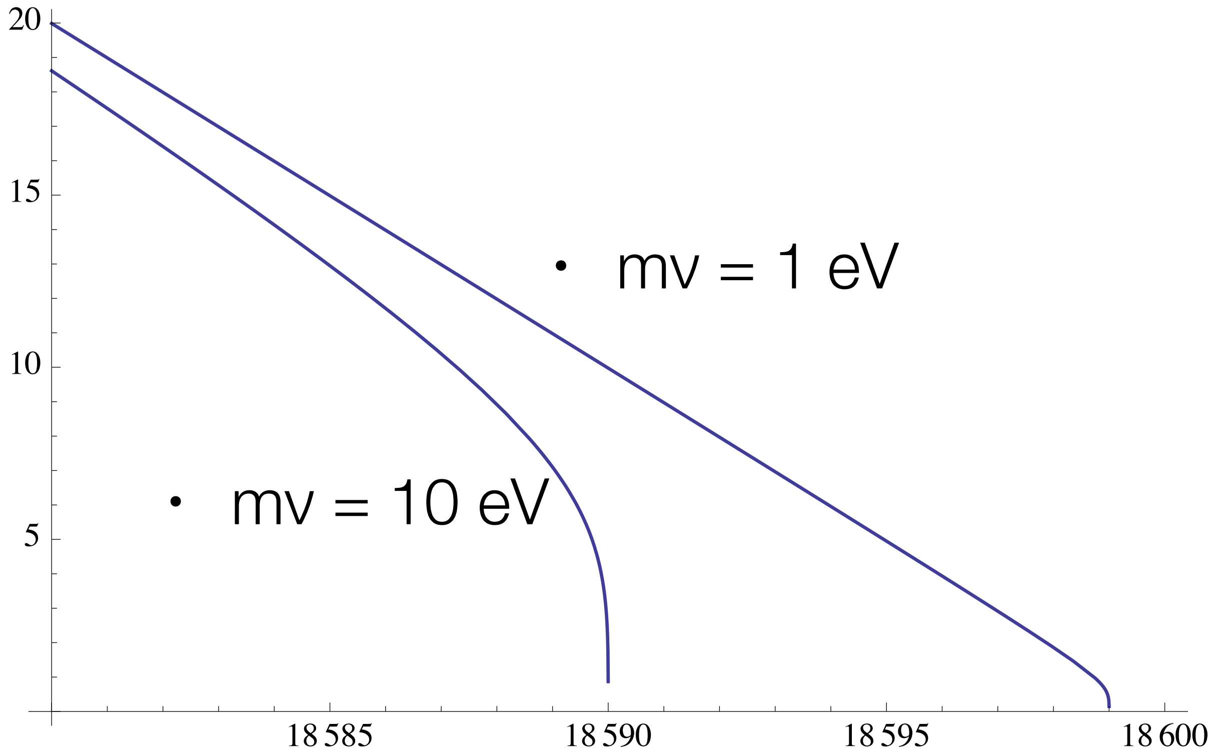
- Steep decrease

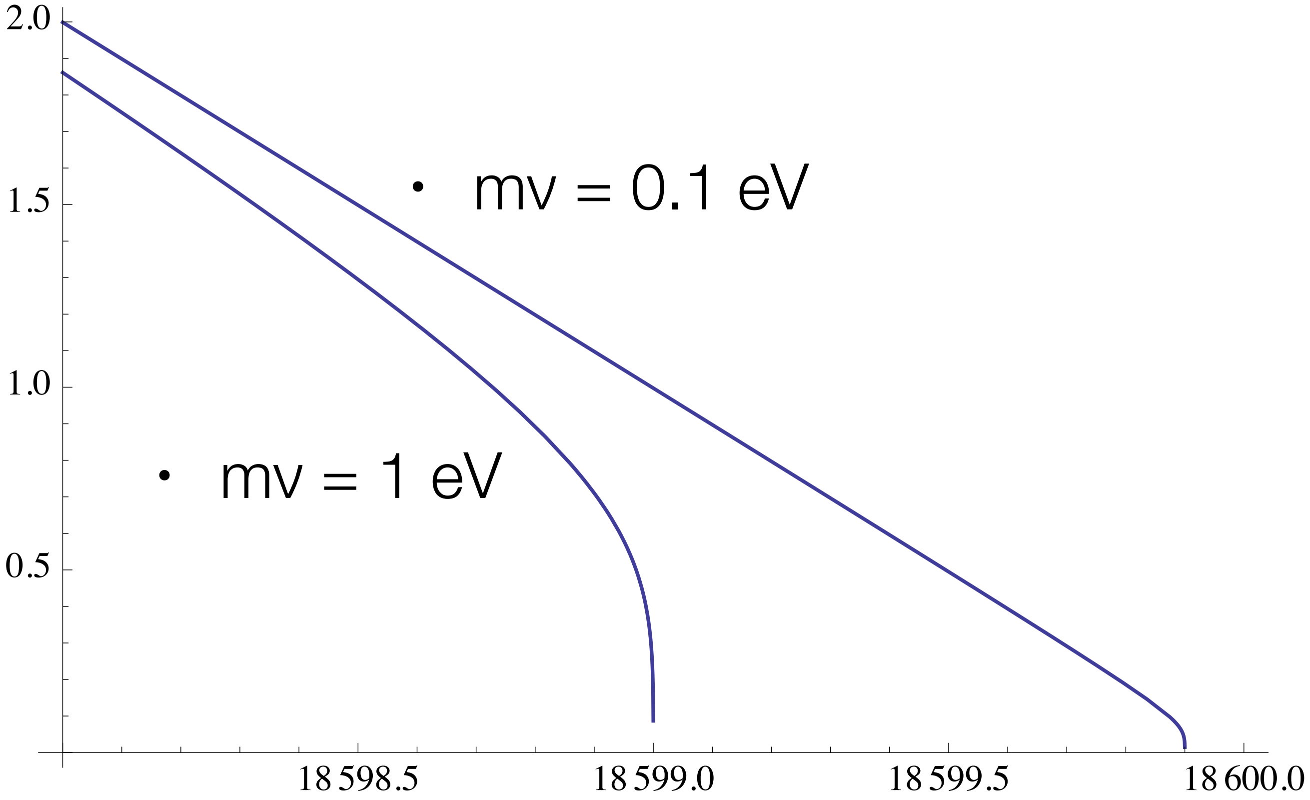
- mv = 10 eV





Kurie's plot



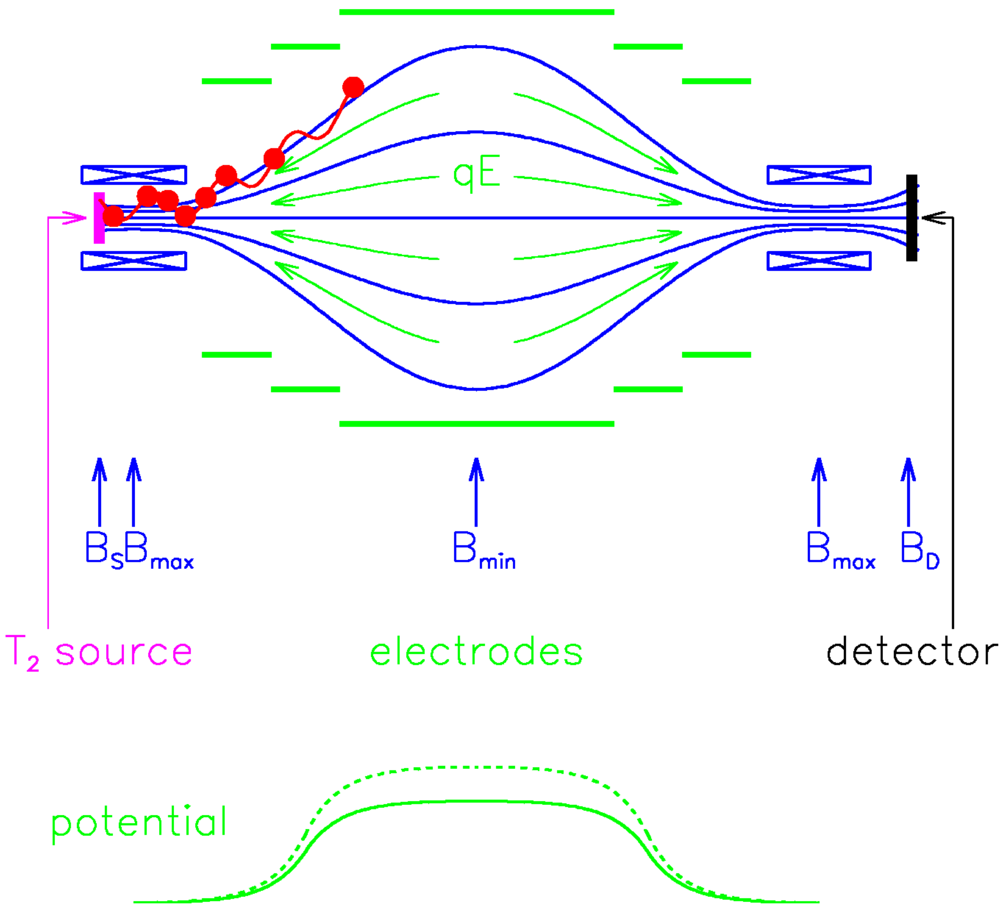


- Experimental difficulties:
  - Rate vanishes as we get closes to E0.
  - Resolution will smear shape near the end.
  - Theoretical corrections to the Kurie plot. Precision in the value of E0, determination of Fermi function, effects of dynamics, etc.

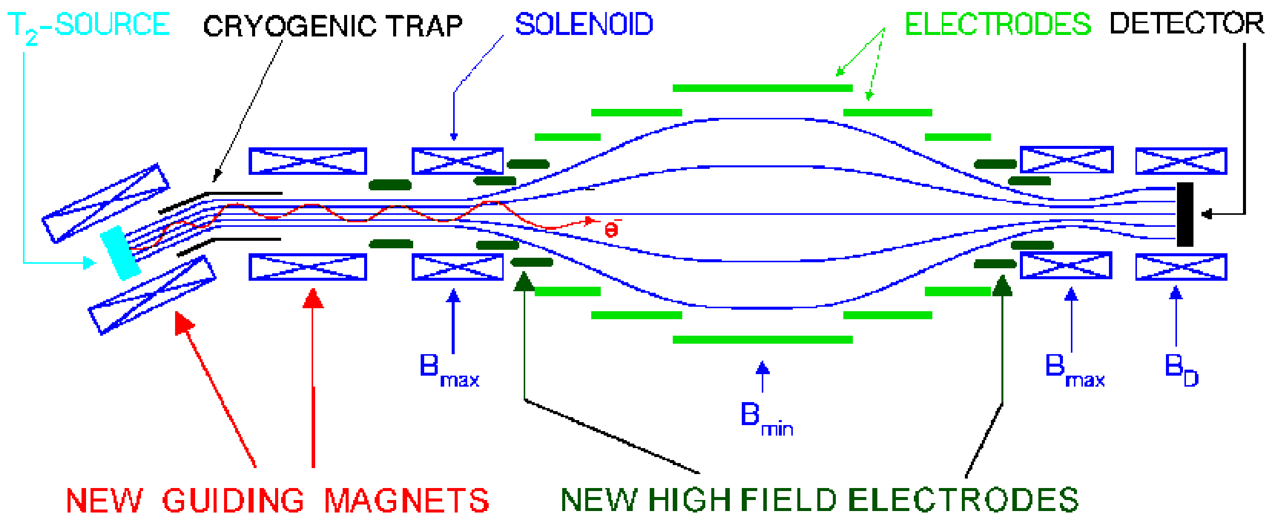
Experimental key concept: MAC-E filter

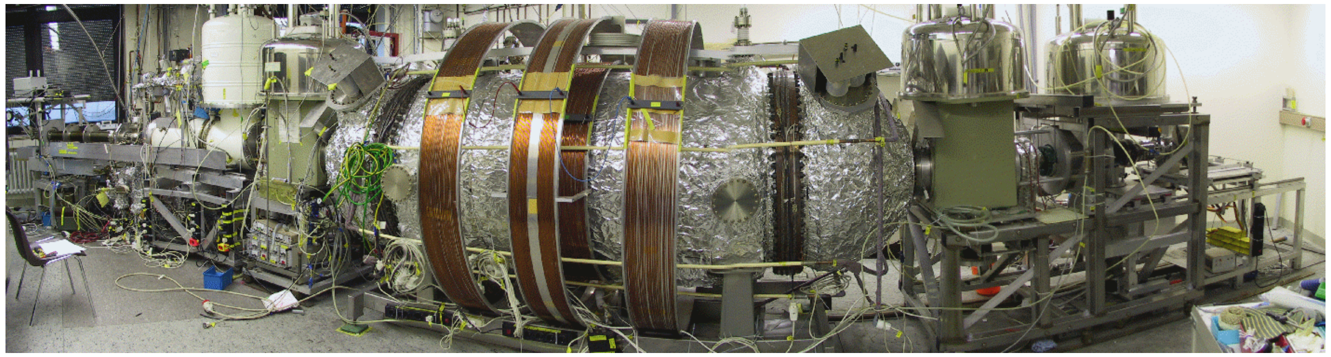
Magnetic Adiabatic Collimation + Electrostatic Filter
(A. Picard et al., Nucl. Instr. Meth. 63 (1992) 345)

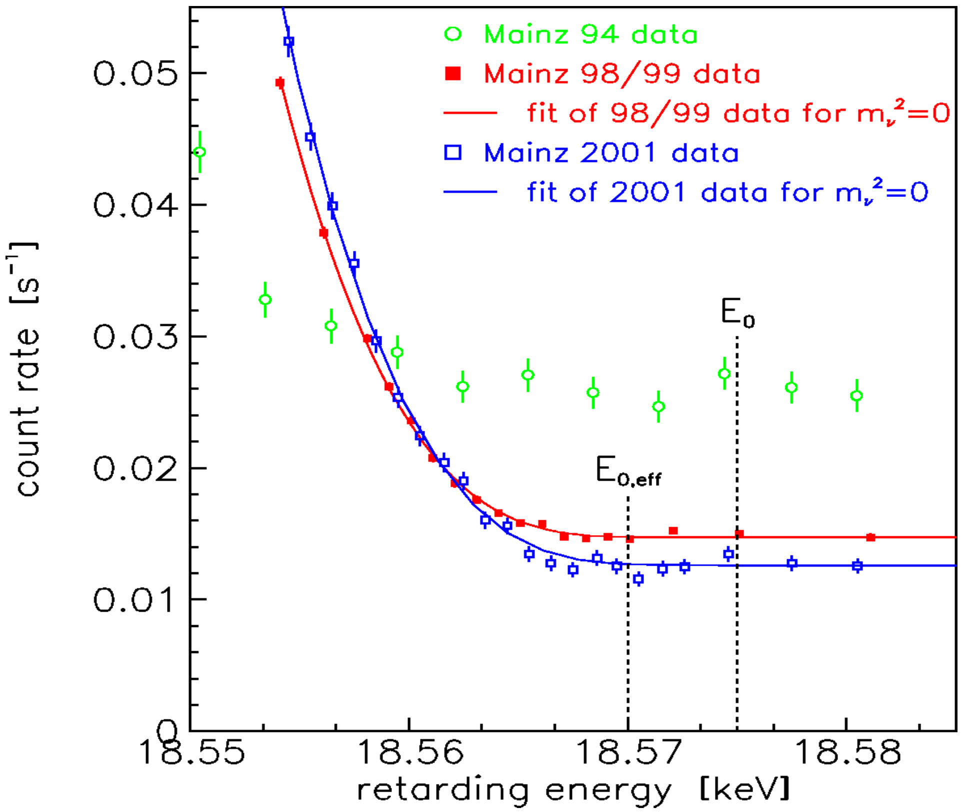
- Two supercond. solenoids compose magnetic guiding field
- Electron source (T_2) in left solenoid
- e^- in forward direction: magnetically guided
- adiabatic transformation: $\mu = E_\perp / B = \text{const.}$
  $\Rightarrow$ parallel e^- beam
- Energy analysis by electrostat. retarding field
  $\Delta E = E \cdot B_{min} / B_{max} = E \cdot A_{s,eff} / A_{analyse}$ ≈ 4.8 eV (Mainz) $= 0.93$ eV (KATRIN)



Mainz result







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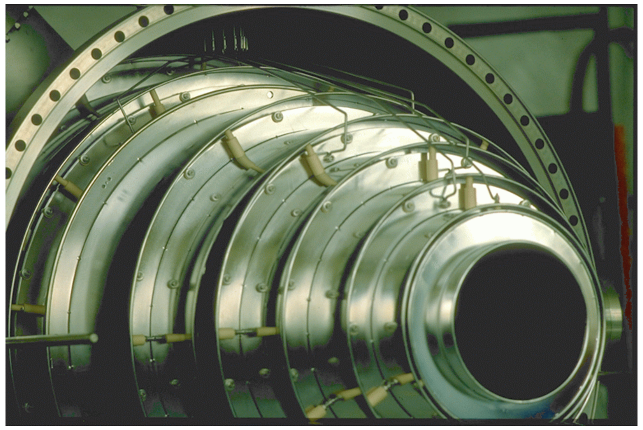


After all critical systematics measured by own experiment (inelastic scattering, self-charging, neighbor excitation):

$m^2(\nu) = -0.6 \pm 2.2 \pm 2.1\ \mathrm{eV}^2 \Rightarrow m(\nu) < 2.3\ \mathrm{eV}$ (95% C.L.)

C. Kraus et al., Eur. Phys. J. C 40 (2005) 447

The next step: Katrin

Westfälische Wilhelms-Universität Münster

The Karlsruhe Tritium Neutrino experiment KATRIN

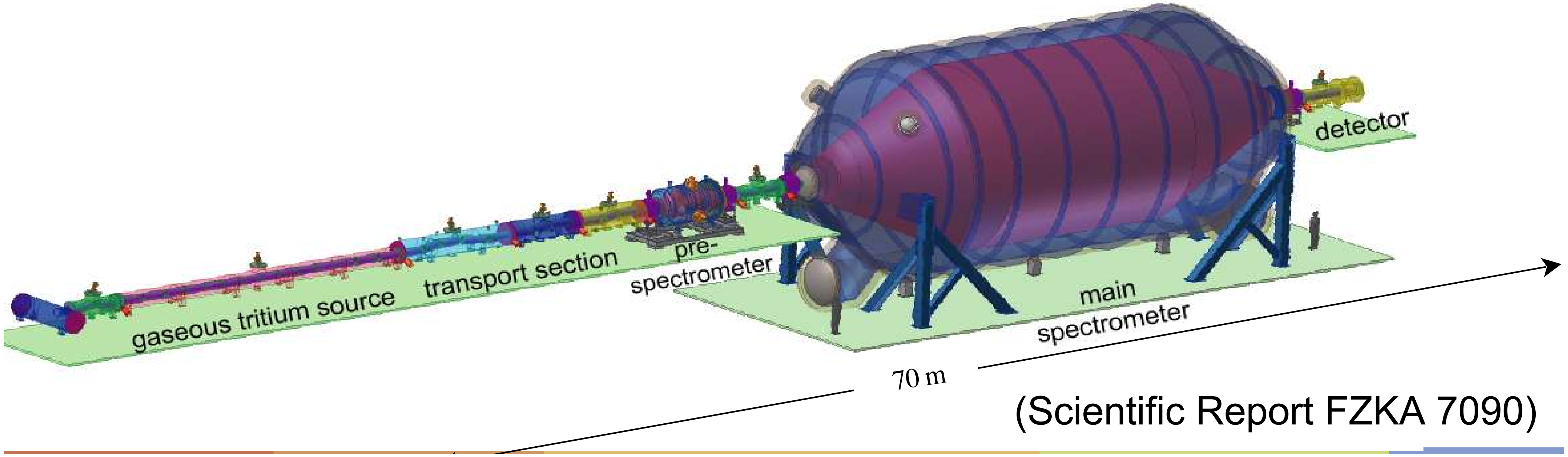
is being set up at the Forschungszentrum Karlsruhe

Physics Aim:

Improvement of sensitivity by 1 order of magnitude: 2.2 eV → 0.2 eV

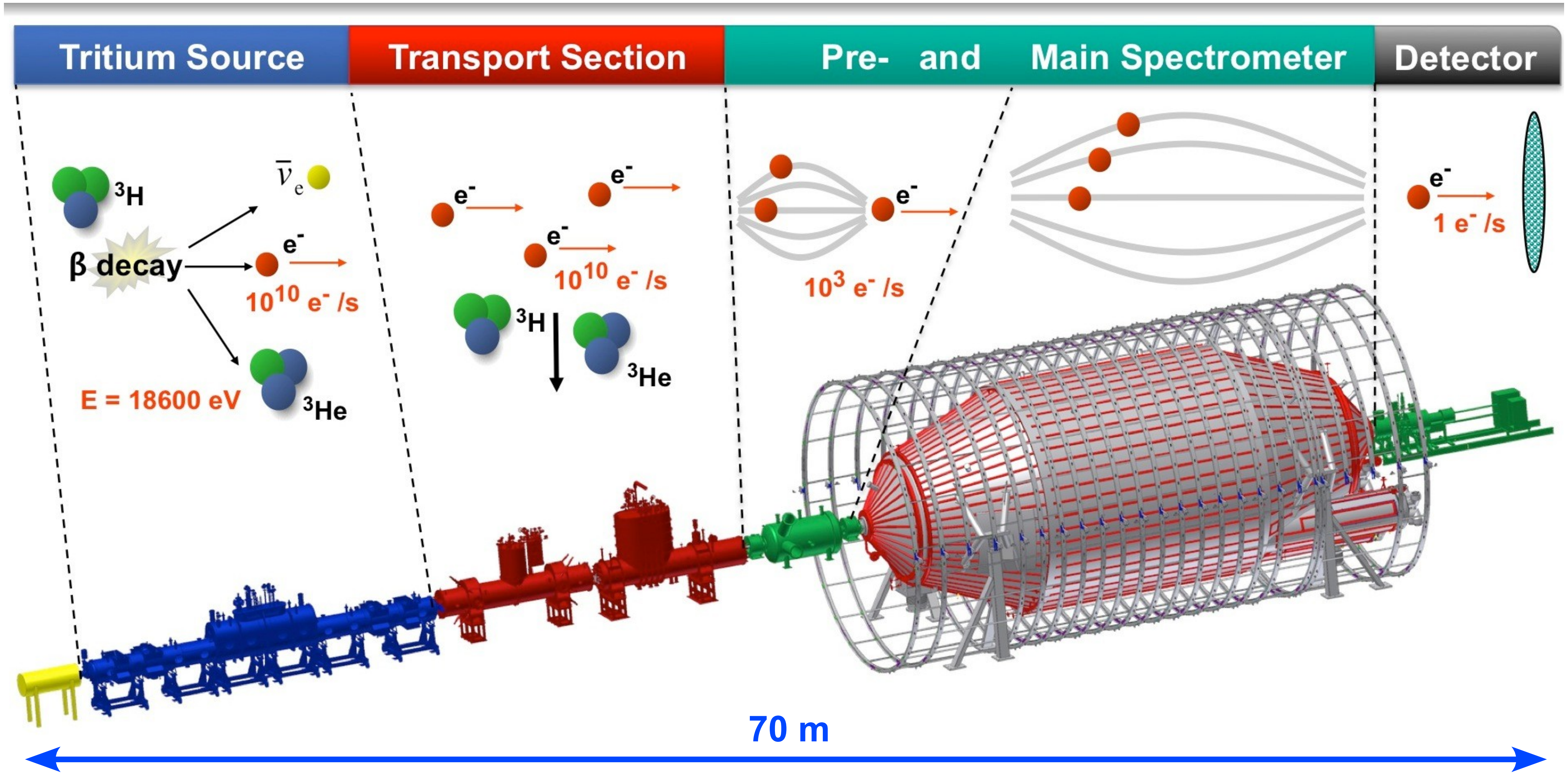
- higher energy resolution: $\Delta E \approx 1\text{eV}$
  since $E/\Delta E \sim A_{\text{spectrometer}}$ ⇒ larger spectrometer
- relevant region below endpoint becomes smaller
  even less count rate $dN/dt \sim A_{\text{spectrometer}}$ ⇒ larger spectrometer
- much longer measurement time: 100 d → 1000 d

} ∅10m



(Scientific Report FZKA 7090)

Katrin overview



Tritium decays, releasing an electron and an anti-electron-neutrino. While the neutrino escapes undetected, the electron starts its journey to the detector.

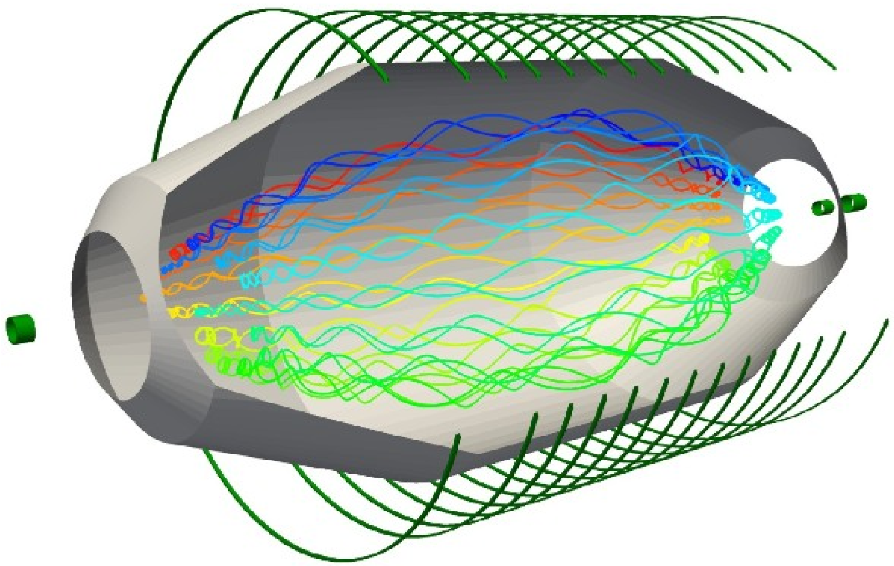
Electrons are guided towards the spectrometer by magnetic fields.
Tritium has to be pumped out to provide tritium free spectrometers.

The electron energy is analyzed by applying an electrostatic retarding potential.
Electrons are only transmitted if their kinetic energy is sufficiently high.

At the end of their journey, the electrons are counted at the detector.
Their rate varies with the spectrometer potential and hence gives an integrated β-spectrum.

Background suppression in Katrin I

Stored electron by magnetic mirrors
F. Fränkle et al., Astropart. Phys. 35 (2011) 128

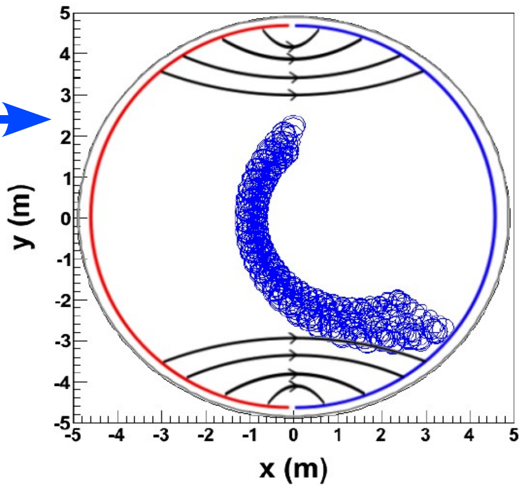


- Trapped particles create background by interactions with rest gas molecules
- Several methods investigated to remove trapped particles:

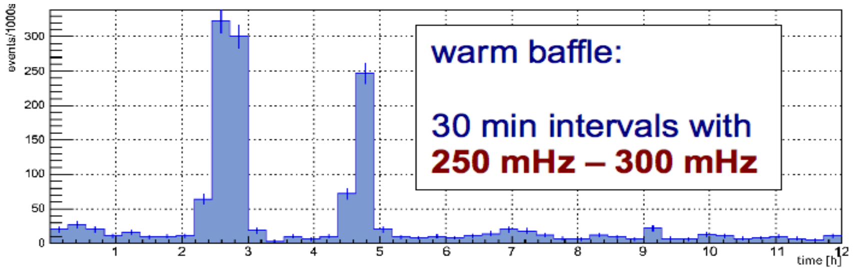
→ Magnetic pulse
→ Electric dipole
→ Electron catcher

M. Beck et al,
Eur. Phys. J.
A44 (2010) 499

→ Electron cyclotron resonance: ECR

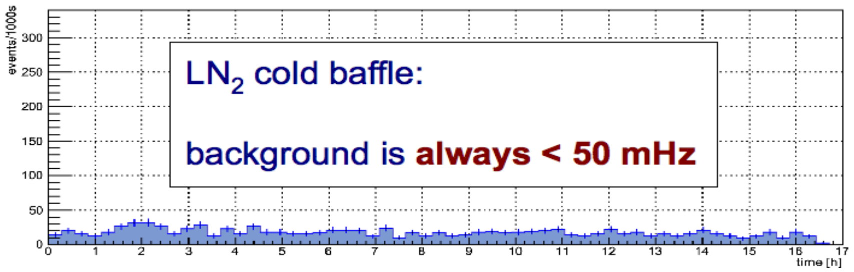


- Radon emission from getter material needs to be suppressed to avoid background from high energy electrons
→ introduction of LN2 cooled baffles
- Proof of principle at pre-spectrometer:



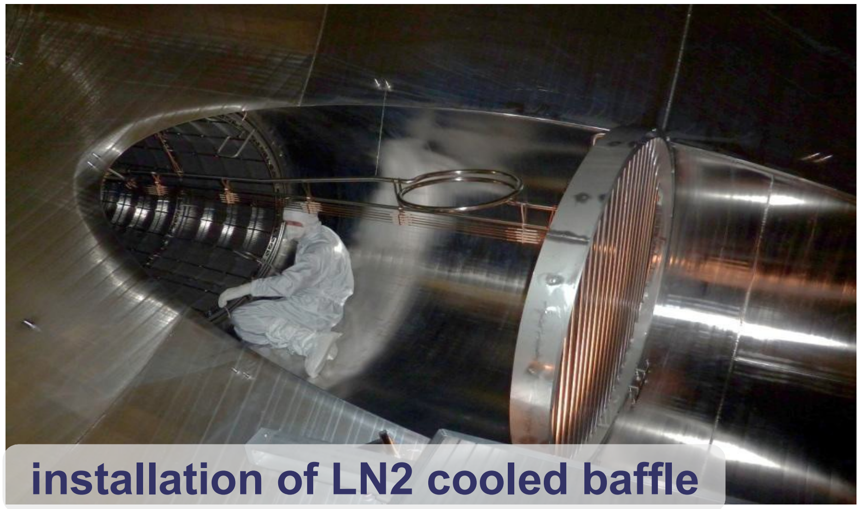
warm baffle:

30 min intervals with
250 mHz – 300 mHz



LN_2 cold baffle:

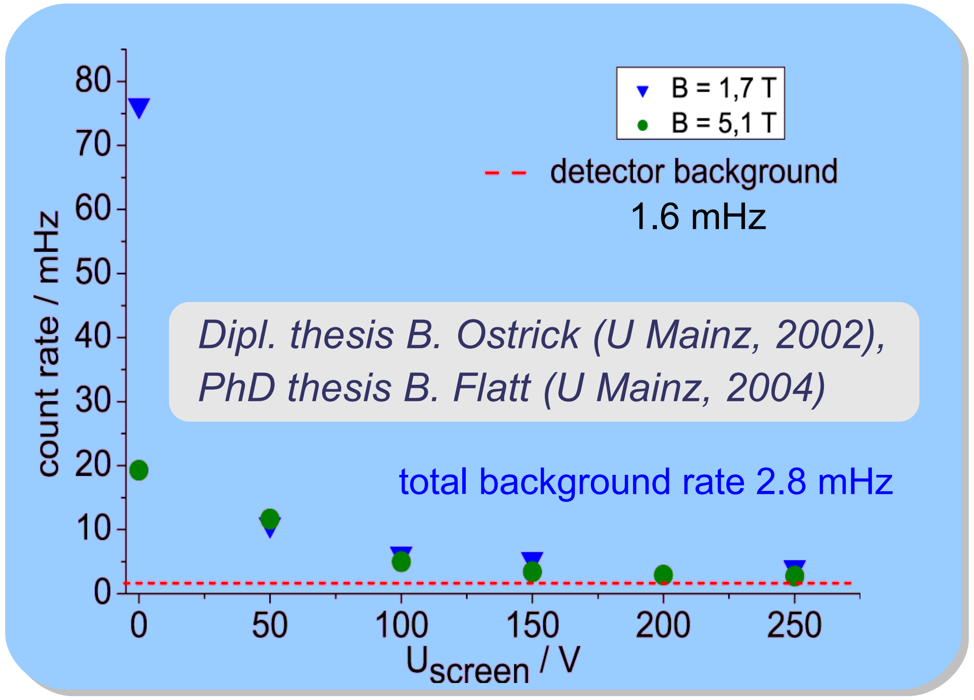
background is **always < 50 mHz**



installation of LN2 cooled baffle

Background suppression in Katrin II

- e^- from cosmics and radioisotopes can mimic e- in endpoint energy region
- 650 m^2 surface of main spectrometer
  → ca. 10^5 µ / s + contamination
- Reduction due to B-field: factor 10^5-10^6
- Real signal rate in the mHz region
- Additional reduction necessary !

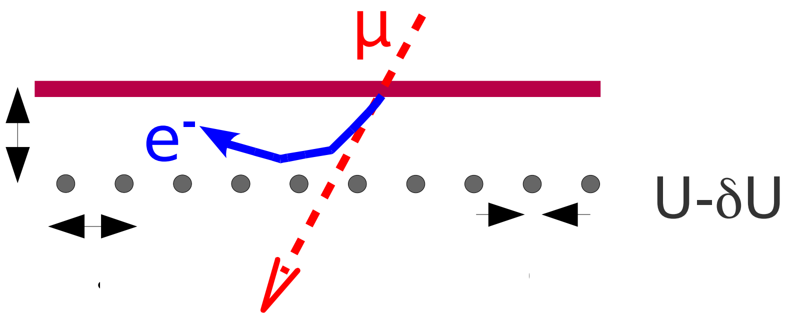


detector background 1.6 mHz

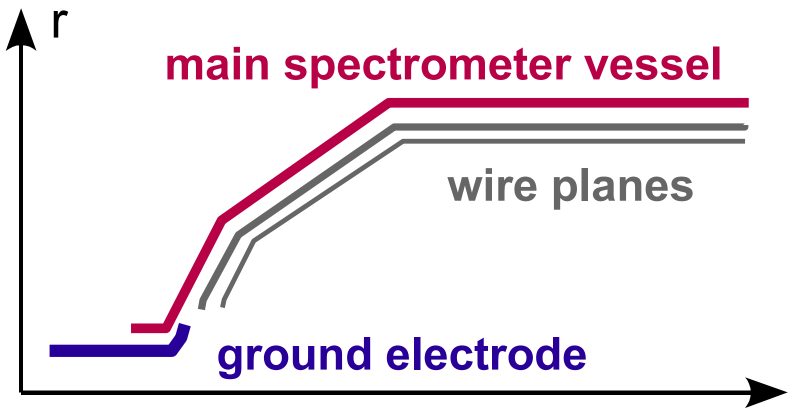
Dipl. thesis B. Ostrick (U Mainz, 2002), PhD thesis B. Flatt (U Mainz, 2004)

total background rate 2.8 mHz

- Screening of background electrons with a wire grid on a negative potential
- The grid has to be 'massless' to avoid background from the grid itself



- Background suppression tested at the former Mainz neutrino mass experiment
  → at 200 V shielding potential background reduction by a factor 10
- KATRIN uses an improved 2 layer design
  → expect reduction by a factor 10-100



Systematic effects and error budget

1. Inelastic scattering of ß´s in the source (WGTS)
   - calibration measurements with e-gun necessary
   - deconvolution of electron energy loss function

2. Fluctuations of WGTS column density (required < 0.1%)
   - rear wall detector, Laser - Raman spectroscopy, T=30K stabilization, e-gun measurements

3. Transmission function
   - spatially resolved e-gun measurements

4. WGTS charging due to decay ions (MC: $\phi < 20$mV)
   - Injection of low energy (meV) electrons from the rear end, diagnostic tools available

5. Final state distribution
   - reliable quantum chem. calculations

6. HV stability of retarding potential on 3ppm level required
   - precise HV-Divider (PTB), monitor spectrometer, calibration sources

fluctuations σ^2 lead to a downward shift in m_ν^2

$$\Delta m_\nu^2 = -2\sigma^2$$

allow only few contributions with $\Delta m_\nu^2 \leq 0.007$ eV²

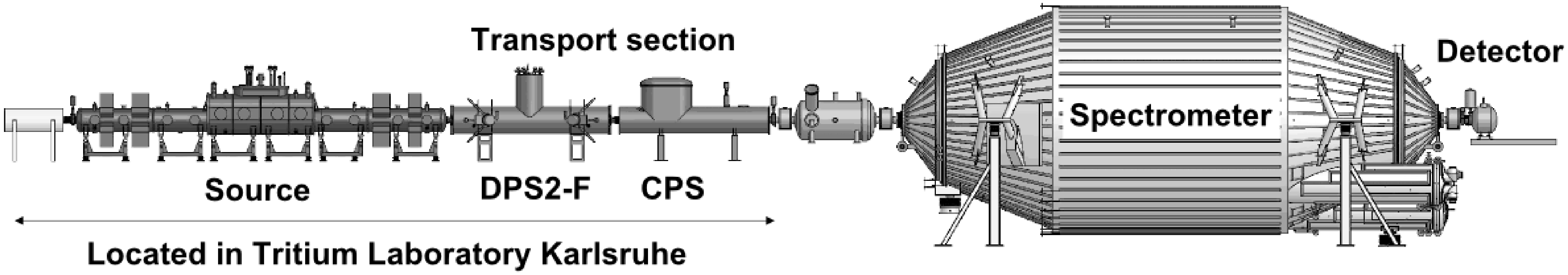
$\Leftrightarrow$ $\sigma < 60$ meV

$$\frac{\Delta U}{U} = \frac{0.06}{18575} \approx 3 \cdot 10^{-6}$$

$\Rightarrow$ 3 ppm long term stability

KATRIN: Summary

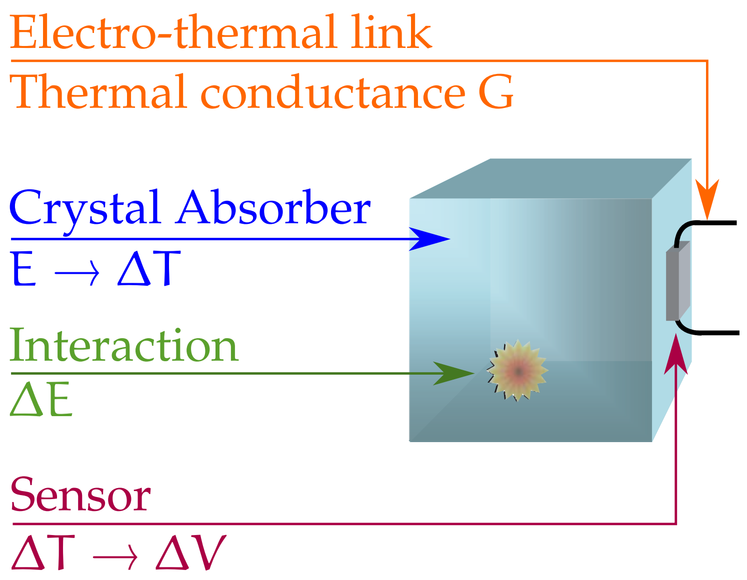
The KArlsruhe TRItium Neutrino Experiment (KATRIN)
@ KIT (Karlsruhe Institute of Technology)



- Larger electrostatic spectrometer ever built (stainless steel vessel, $\varnothing = 10$ m , $L = 22$ m);
- Intense Windowless Gaseous Tritium Source (WGTS): 10^{11} β decay electrons per second;
- Energy resolution: $\Delta E = 0.93$ eV;
- High luminosity: $L = 20\ \text{cm}^2$ (Troitsk: $L = 0.6\ \text{cm}^2$);
- Ultrahigh vacuum requirements: $p < 10^{-11}$ mbar (to reduce the background).

Expected statistical sensitivity: $m_\nu < 0.2$ eV @ 90% C.L. [12, 13]

LTD (Low temperature detectors)


Electro-thermal link

Thermal conductance G

Crystal Absorber

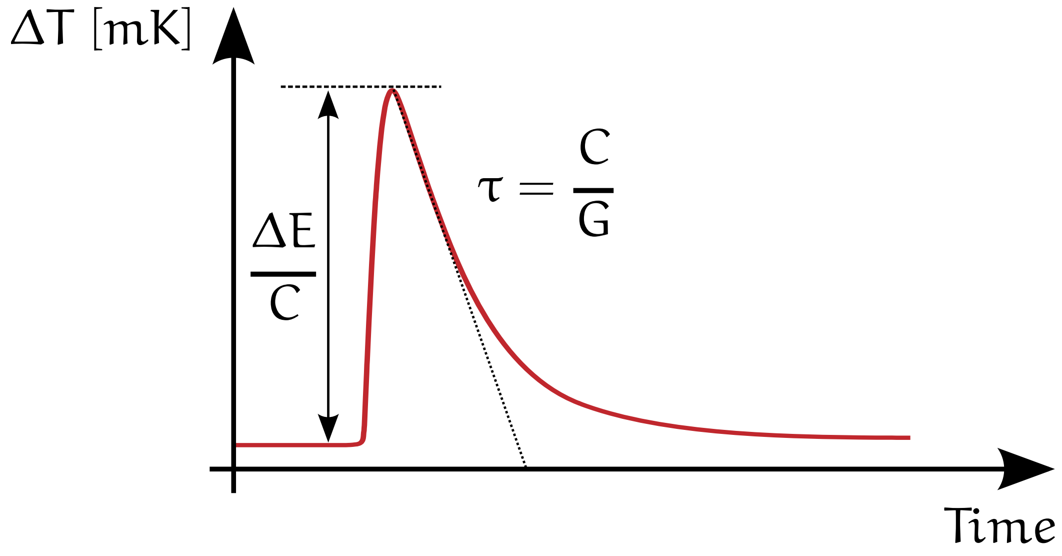
$E \rightarrow \Delta T$

Interaction

ΔE

Sensor

$\Delta T \rightarrow \Delta V$



- Complete energy thermalization: ionization, excitation ⇒ heat⇒calorimetry;
- $\Delta T = \dfrac{\Delta E}{C}$ where ΔE is the released energy and C the total thermal capacity;
  - Absorber with very low thermal capacity: $C \downarrow \quad \Rightarrow \quad \Delta T \uparrow$;
  - Debay low for superconductors below T_C and dielectric: $C \propto \left(\dfrac{T}{\Theta_D}\right)^3$;
  - A very low temperature is needed: $T \downarrow \Rightarrow C \downarrow \Rightarrow \Delta T \uparrow \Rightarrow (T = 10 \div 100 \text{ mK})$;
- Limit to energy resolution: statistical fluctuation of internal energy $\Delta E_{rms} = \sqrt{k_B T^2 C}$;
- $\Delta T(t) = \dfrac{\Delta E}{C} e^{-t/\tau}$ with $\tau = \dfrac{C}{G}$ and G thermal conductance.

Calorimetry with Re-187

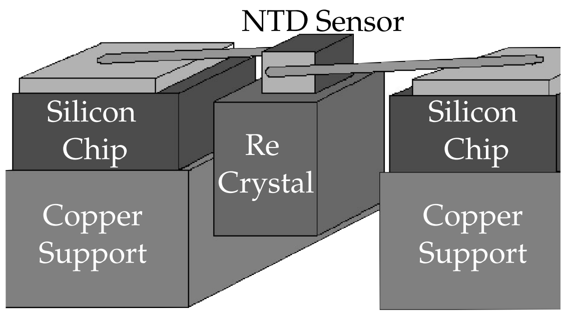
Isotope candidate: $^{187}\mathrm{Re}$ β decay $\Rightarrow$ $^{187}Re \rightarrow {}^{187}Os + e^{-} + \overline{\nu}_e$

Rhenium is perfectly suited for fabricating thermal detectors.

- Dielectric or superconductor behaviour;
- Very low end point: $Q = 2.47$ keV;
- Half-life time: $\tau_{1/2} = 43.2$ Gy;
- High natural abundance: $a.i. = 63\%$;
- Rate of 1 mg metallic Rhenium: $\simeq 1.0$ decay/s.

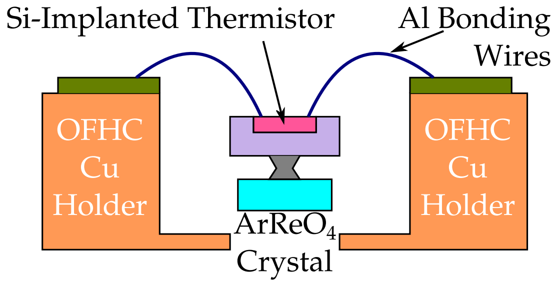
Metallic Rhenium single crystals

- Absorber: Re superconductor with $T_C = 1.6$ K;
- Sensor: NTD thermistors;
- MANU experiment (Genova).



Dielectric Rhenium compound ($AgReO_4$) crystals

- Absorber: $AgReO_4$ crystals (Silver perrhenate);
- Sensor: Silicon implanted thermistors;
- MIBETA experiment (Milano, Como, Trento).



Current results

MANU (1999)

- 1 crystal of metallic Re: 1.6 mg;
- ^{187}Re activity: $\simeq 1.6$ Hz;
- Sensor: Ge NTD thermistor:
- Resolution: $\Delta E = 96$ eV FWHM;
- Live-time: 0.5 years;
- $6.0 \cdot 10^6$ ^{187}Re decays above 420 eV.

MIBETA (2002-2003)

- 10 $AgReO_4$ crystals: 2.71 mg;
- ^{187}Re activity: 0.54 Hz/mg;
- Sensor: Si thermistor (ITC-irst now FBK);
- Resolution: $\Delta E = 28.5$ eV FWHM;
- Live-time: 0.6 years;
- $6.2 \cdot 10^6$ ^{187}Re decays above 700 eV.

$$m_\nu^2 = -462 \pm 579_{(stat)} \pm 679_{(sys)}\ eV^2$$

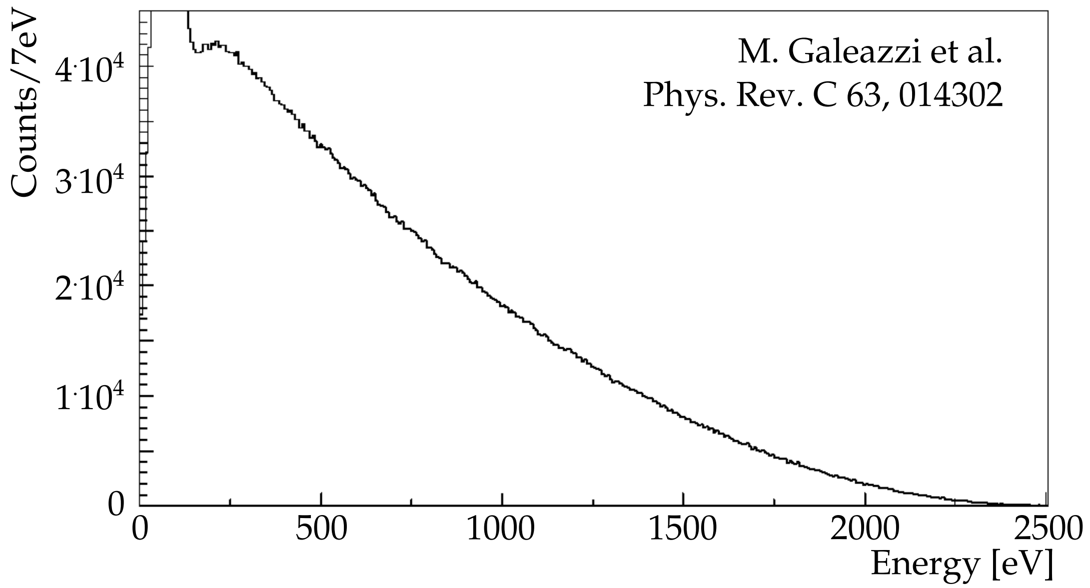
$$\Downarrow$$

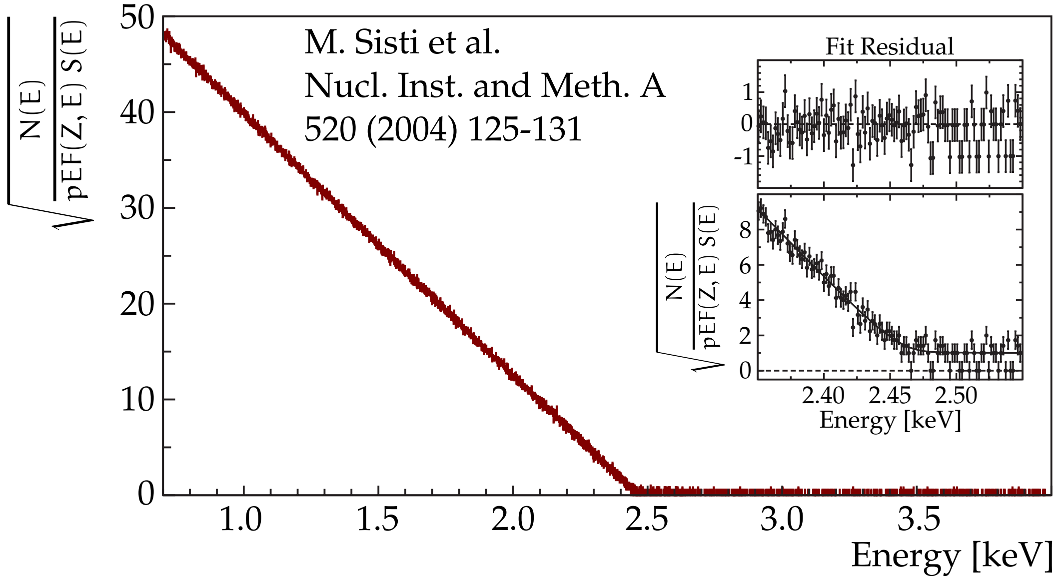
$$m_\nu < 26\ eV\ (95\%\ \mathrm{C.L.})\ [14]$$

$$m_\nu^2 = -112 \pm 207_{(stat)} \pm 90_{(sys)}\ eV^2$$

$$\Downarrow$$

$$m_\nu < 15\ eV\ (90\%\ \mathrm{C.L.})\ [15]$$


M. Galeazzi et al.
Phys. Rev. C 63, 014302


M. Sisti et al.
Nucl. Inst. and Meth. A
520 (2004) 125-131

Improving sensitivity

Exposure required for $m_\nu = 0.2$ eV sensitivity [16]

A_β [Hz]	τ_{rise} [µs]	ΔE [eV]	N_{ev} [counts]	Exposure [det·year]
1	1	1	$0.2 \cdot 10^{14}$	$7.6 \cdot 10^5$
10	1	1	$0.7 \cdot 10^{14}$	$2.1 \cdot 10^5$
10	3	3	$1.3 \cdot 10^{14}$	$4.1 \cdot 10^5$
10	5	5	$1.9 \cdot 10^{14}$	$6.1 \cdot 10^5$
10	10	10	$3.3 \cdot 10^{14}$	$10.5 \cdot 10^5$

Example: *red line in table (background* $b = 0$*)*

- 5000 pixels/array;
- 8 arrays;
- 10 years of live-time;
- 400 g ^{nat}Re.

Exposure required for $m_\nu = 0.1$ eV sensitivity [16]

A_β [Hz]	τ_{rise} [µs]	ΔE [eV]	N_{ev} [counts]	Exposure [det·year]
1	0.1	0.1	$1.7 \cdot 10^{14}$	$5.4 \cdot 10^6$
10	0.1	0.1	$5.3 \cdot 10^{14}$	$1.7 \cdot 10^6$
10	1	1	$10.3 \cdot 10^{14}$	$3.3 \cdot 10^6$
10	3	3	$21.4 \cdot 10^{14}$	$6.8 \cdot 10^6$
10	5	5	$43.6 \cdot 10^{14}$	$13.9 \cdot 10^6$

Example: *green line in table (background* $b = 0$*)*

- 20000 pixels/array;
- 16 arrays;
- 10 years of live-time;
- 3.2 kg ^{nat}Re.

Electron capture in Ho-163

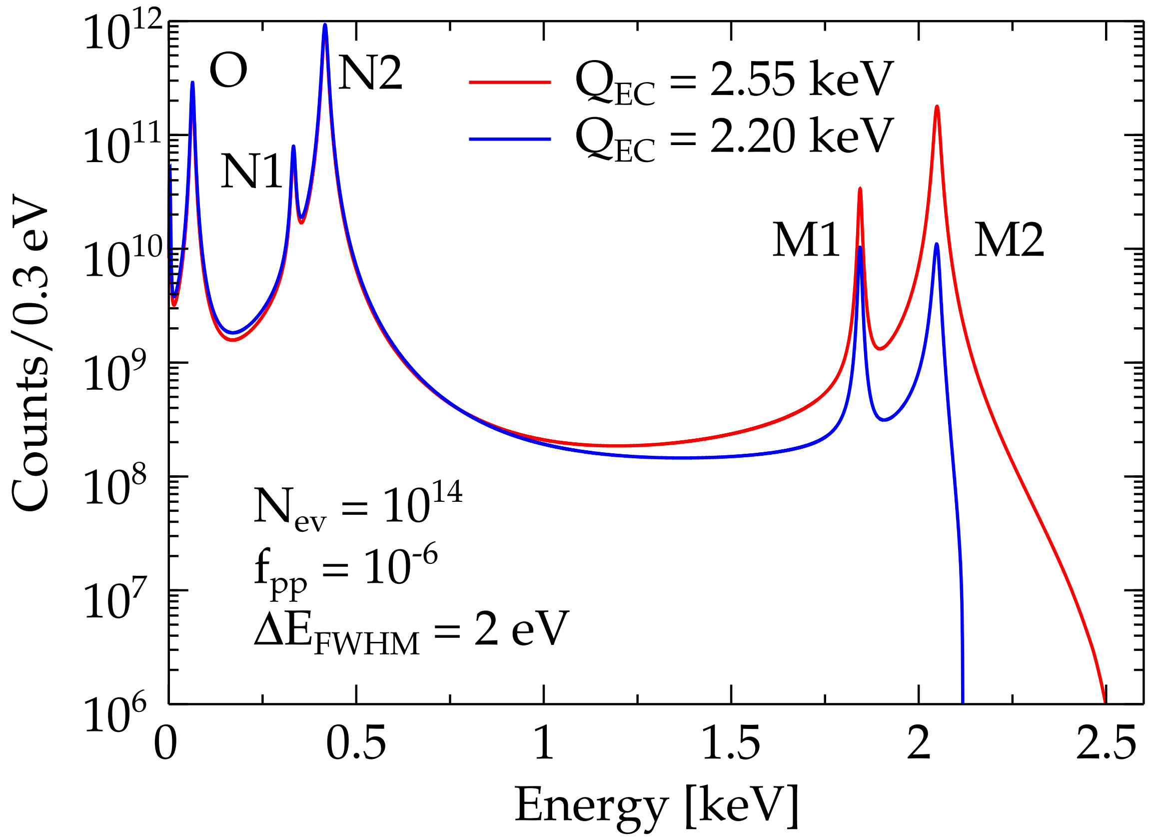
An interesting isotope suitable for the neutrino mass experiment could be the ^{163}Ho.

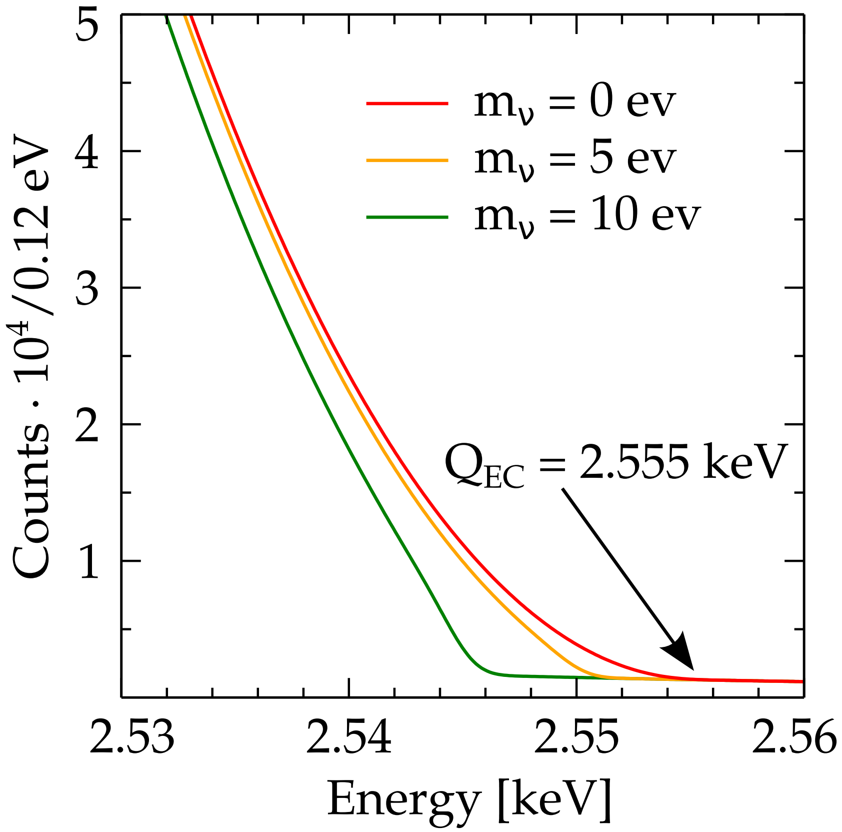
$$^{163}\mathrm{Ho} + e^- \to {}^{163}\mathrm{Dy}^* + \nu_e(E_c) \quad \text{electron capture from shell} > \mathrm{M1}$$

proposed by A. De Rujula e M. Lusignoli in 1982 [17, 18]

- Calorimetric measurement of Dy atomic de-excitations (mostly non-radiative):
  - ⇒ measurement of the entire energy released except the ν energy;
- The rate at end-point may be as high as for ^{187}Re but depends on Q_{EC}:
- Q_{EC} and atomic de-excitation spectrum poorly known:
  - ⇒ Measured: $Q_{EC} = (2.2 \div 2.8)$ keV;
  - ⇒ Recommended: $Q_{EC} = 2.555$ keV [19, 20]);
- $\tau_{1/2} \simeq 4570$ years ⇒ high specific activity:
  - ⇒ Holmium detector not needed;
  - ⇒ ^{163}Ho can be implanted in any suitable microcalorimeter absorber;
- Complex pile-up spectrum;
- No high statistics and clean calorimetric measurement so far;

Ho-163 spectrum





$$\frac{d\lambda_{EC}}{dE_c} = \frac{G_\beta^2}{4\pi^2}(Q_{EC} - E_c)\sqrt{(Q_{EC} - E_c)^2 - m_\nu^2} \times \sum_i n_i C_i \beta_i^2 B_i \frac{\Gamma_i}{2\pi} \frac{1}{(E_c - E_i)^2 + \Gamma_i^2/4}$$

- Continuum with marked peaks with Breit-Wigner shapes lines (width Γ_i of a few eV);
- Series of lines at the ionization energies E_i of the captured electrons;
- End-point shaped by $\sqrt{(Q - E_e)^2 - m_\nu^2}$ (the same of the β-decay);
- Self calibrating spectrum;

Ho-163 expected sensitivity QE =2200 keV

Exposure required for $m_\nu = 0.2$ eV sensitivity [21, 22]

A_β [Hz]	τ_{rise} [μs]	ΔE [eV]	N_{ev} [counts]	Exposure [det·year]
1	1	1	$2.8 \cdot 10^{13}$	$9.0 \cdot 10^{5}$
1	0.1	1	$1.3 \cdot 10^{13}$	$4.3 \cdot 10^{5}$
100	0.1	1	$4.6 \cdot 10^{13}$	$1.5 \cdot 10^{4}$
10	0.1	1	$2.8 \cdot 10^{13}$	$9.0 \cdot 10^{4}$
10	1	1	$4.6 \cdot 10^{13}$	$1.5 \cdot 10^{5}$

Example: *green line in table (background* $b = 0$*)*

- 5000 pixels/array;
- 3 arrays;
- 1 years of live-time;
- $2 \cdot 10^{17}$ nuclei of ^{163}Ho

Exposure required for $m_\nu = 0.1$ eV sensitivity [21, 22]

A_β [Hz]	τ_{rise} [μs]	ΔE [eV]	N_{ev} [counts]	Exposure [det·year]
1	0.1	0.3	$1.2 \cdot 10^{14}$	$3.9 \cdot 10^{6}$
100	0.1	0.3	$6.4 \cdot 10^{14}$	$2.0 \cdot 10^{5}$
100	0.1	1	$7.4 \cdot 10^{14}$	$2.4 \cdot 10^{5}$
10	0.1	1	$4.5 \cdot 10^{14}$	$1.5 \cdot 10^{6}$
10	1	1	$7.4 \cdot 10^{14}$	$2.4 \cdot 10^{6}$

Example: *red line in table (background* $b = 0$*)*

- 5000 pixels/array;
- 4 arrays;
- 10 years of live-time;
- $3 \cdot 10^{17}$ nuclei of ^{163}Ho

Ho-163 expected sensitivity QE =2800 keV

Exposure required for $m_\nu = 0.2$ eV sensitivity [21, 22]

A_β [Hz]	τ_{rise} [µs]	ΔE [eV]	N_{ev} [counts]	Exposure [det·year]
1	1	1	$0.2 \cdot 10^{14}$	$7.6 \cdot 10^{5}$
1	0.1	1	$1.6 \cdot 10^{15}$	$5.3 \cdot 10^{7}$
100	0.1	1	$9.8 \cdot 10^{15}$	$3.1 \cdot 10^{6}$
10	0.1	1	$3.8 \cdot 10^{15}$	$1.2 \cdot 10^{7}$
10	1	1	$9.8 \cdot 10^{15}$	$3.1 \cdot 10^{7}$

Example: *green line in table (background* $b = 0$*)*

- 60000 pixels/array;
- 5 arrays;
- 5 years of live-time;
- $4 \cdot 10^{18}$ nuclei of ^{163}Ho

Exposure required for $m_\nu = 0.1$ eV sensitivity [21, 22]

A_β [Hz]	τ_{rise} [µs]	ΔE [eV]	N_{ev} [counts]	Exposure [det·year]
1	0.1	0.3	$2.6 \cdot 10^{16}$	$8.2 \cdot 10^{8}$
100	0.1	0.3	$1.9 \cdot 10^{17}$	$5.9 \cdot 10^{7}$
100	0.1	1	$1.6 \cdot 10^{17}$	$5.0 \cdot 10^{7}$
10	0.1	1	$6.1 \cdot 10^{16}$	$1.9 \cdot 10^{8}$
10	1	1	$1.6 \cdot 10^{17}$	$5.0 \cdot 10^{8}$

Example: *red line in table (bkg=0*

- 10^{6} pixels/array;
- 6 arrays;
- 10 years of live-time;
- $8 \cdot 10^{19}$ nuclei of ^{163}Ho

Ho-163 vs Re-187

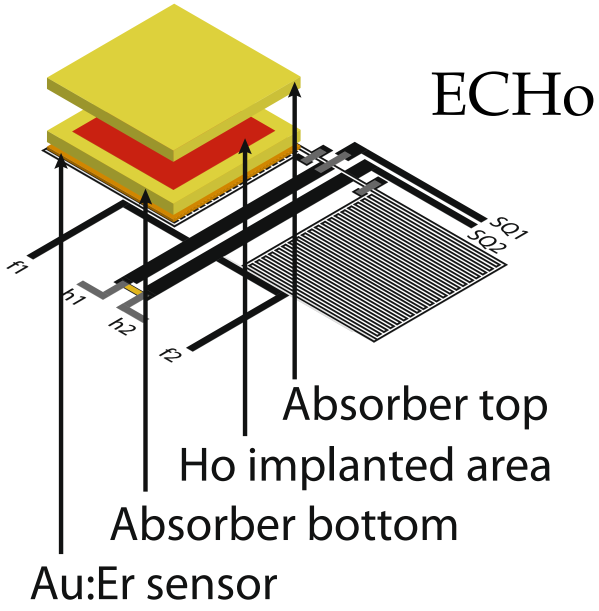
- ☺ higher specific activity ⇒ Holmium detector not needed;
- ☺ self calibrating ⇒ better systematics control;
- ☹ Q_{EC} and atomic de-excitation spectrum poorly known;
- ☹ complex pile-up spectrum;
- ☹ in case of higher Q ⇒ less sensitive;

(At least) two LTD projects with ^{163}Ho:

- ECHo, MMC detectors (Heidelberg)
- HOLMES, TES detectors (Milano, Genova, LNGS, NIST)
- Los Alamos Nat. Lab., Berkeley Univ., ...

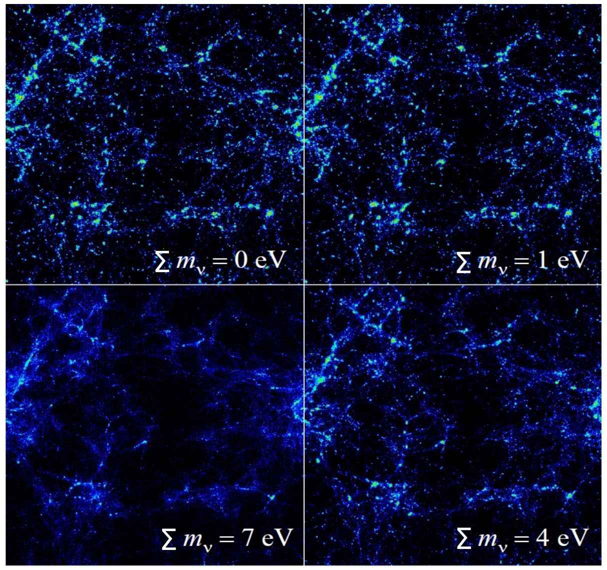
Common technical challenges:

- Clean ^{163}Ho production;
- ^{163}Ho incorporation;
- Large channel number ⇒ high speed MUX;
- Data handling (processing, storage, ...)

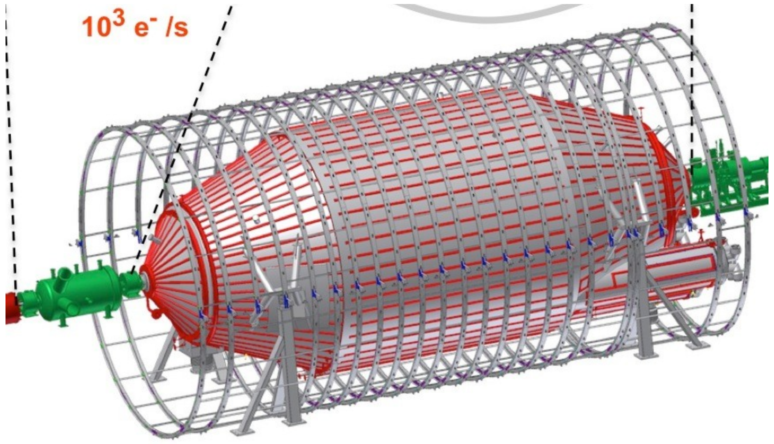


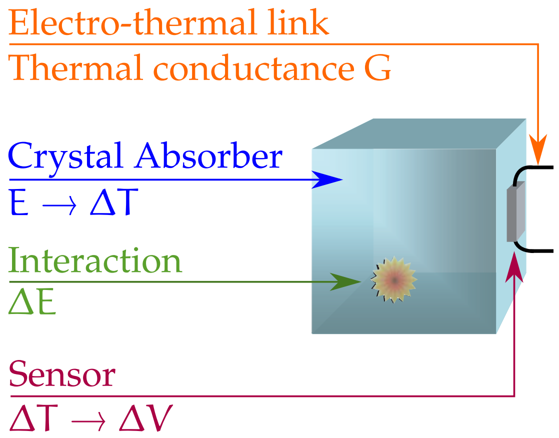
- Transition Edge Sensors (TES) with ^{163}Ho implanted Bi:Au absorbers;
- $6.5 \cdot 10^{13}$ nuclei per detector ⇒ 300 dec/s;
- $\Delta E \simeq 1$ eV and $\tau_{rise} \simeq 1$ s;
- 16 channel demonstrator/1000 channel final array;
- $3 \cdot 10^{13}$ events in 3 years;

Cosmological and β decay measurements



simulation Chung-Pei Ma 1996





Electro-thermal link
Thermal conductance G

Crystal Absorber
E → ΔT

Interaction
ΔE

Sensor
ΔT → ΔV

$$\sum m_i = 0.32 \pm 0.11 eV$$

- **Cosmological measurements may hint an scenario in which neutrino masses may be in the range 0.1-0.2 eV.**
- **Independent experimental techniques (KATRIN, Calorimeters) could be capable of exploring that region in the next few years.**
- **A “direct” measurement of the neutrino mass appears as a tantalising possibility.**