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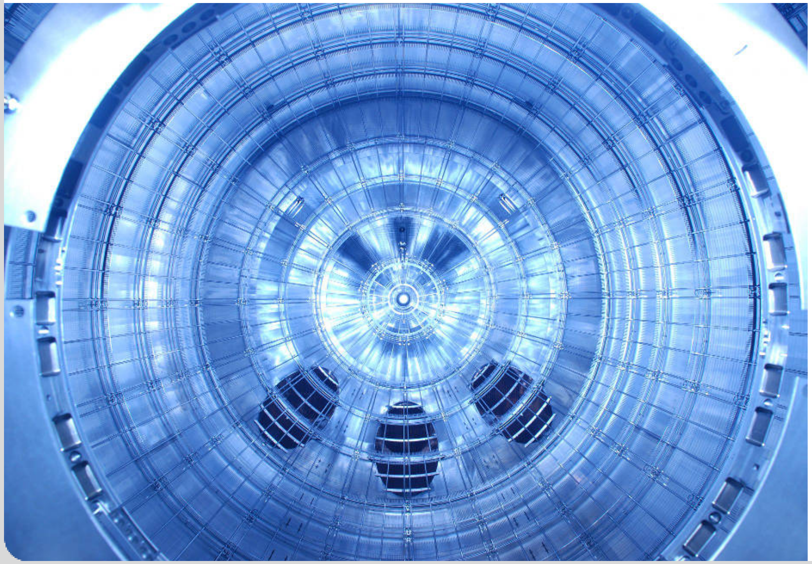
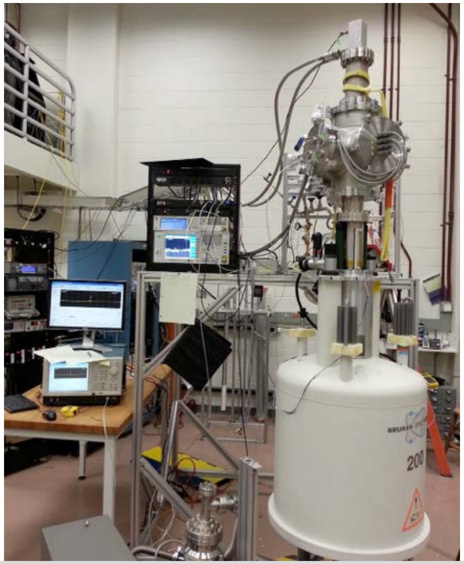
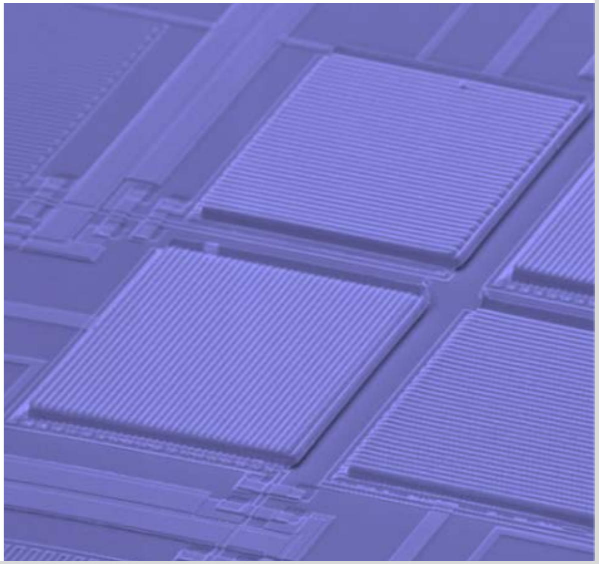
“Status of direct neutrino mass measurements”

Florian Fränkle, Institute for Nuclear Physics (IKP) , Karlsruhe Institute of Technology (KIT)





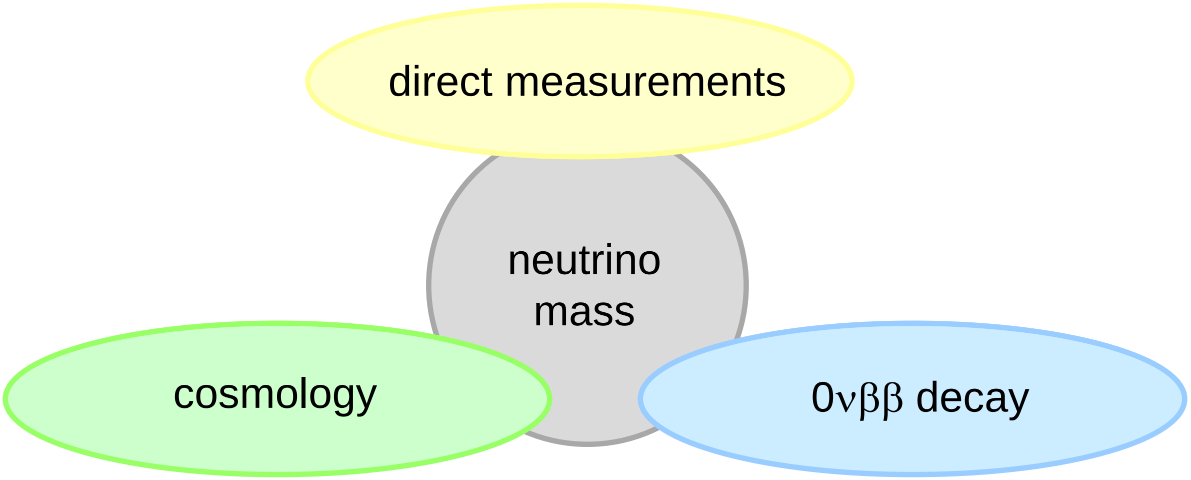


Outline

- Introduction
- Neutrino masses
- Single β-decay experiments
- ^{163}Ho electron capture experiments
- Status and outlook
- Summary

Introduction

- Neutrinos are massive particles, but so far there are only upper (< 2 eV)* and lower limits (> 0.01 eV)
- Absolute neutrino mass scale is one of the big open questions in particle physics, astrophysics and cosmology
- Different approaches to determine neutrino mass:



* J. Beringer et al. (Particle Data Group), Phys. Rev. D86, 010001 (2012) and 2013 partial update for the 2014 edition

Neutrino masses

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- Neutrino flavour eigenstates are related to neutrino mass eigenstates by the lepton mixing matrix (PMNS)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} m_1 \\ m_2 \\ m_3 \end{pmatrix}$$

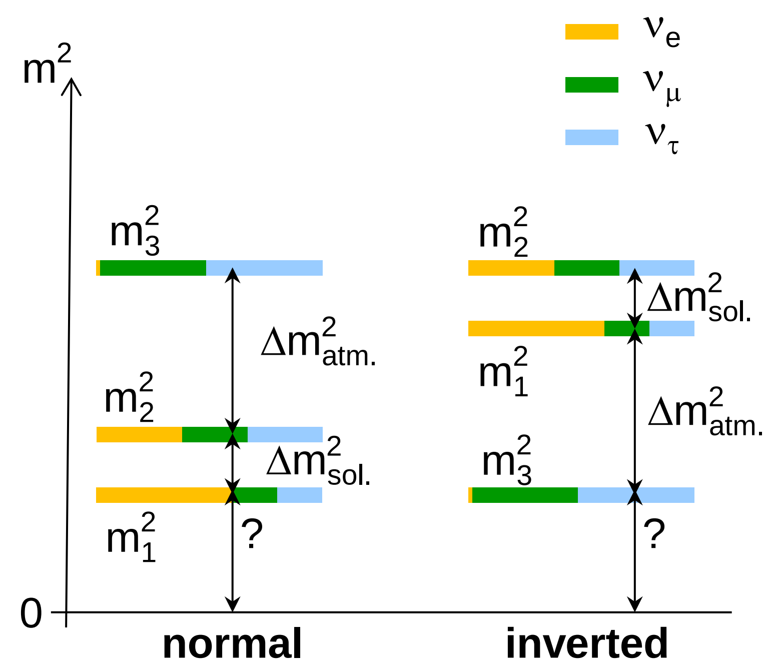
- Neutrino oscillations are sensitive to the differences between the squares of neutrino masses:

$$\Delta m^2_{atm.} = (2.32^{+0.12}_{-0.08}) \times 10^{-3}\ eV^2\ *$$

$$\Delta m^2_{sol.} = (7.5 \pm 0.2) \times 10^{-5}\ eV^2\ *$$

- Two mass ordering scenarios possible
- The value of the lightest neutrino mass is unknown

mass ordering



* J. Beringer et al. (Particle Data Group), Phys. Rev. D86, 010001 (2012) and 2013 partial update for the 2014 edition

Neutrino mass and single β-decay

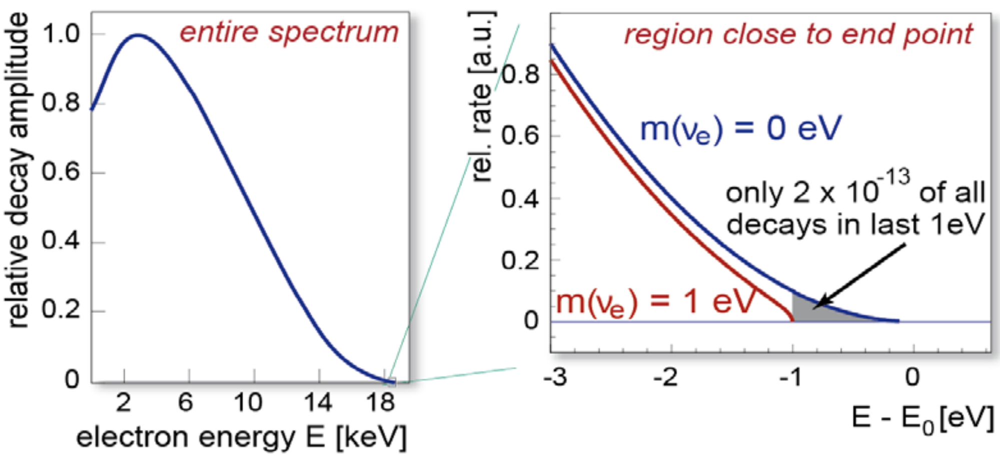
- β-decay: $n \rightarrow p + e^- + \overline{\nu}_e$
- Neutrino mass influences energy spectrum of β-decay electrons
- Neutrino mass determination via precise measurement of the spectral shape close to the endpoint
- Model independent method

Fermi theory of β-decay:

$$\frac{dN}{dE} = C \cdot F(E,Z) \cdot p\,(E + m_e) \cdot (E_0 - E) \cdot \sqrt{(E_0 - E)^2 - m_\nu^2}$$

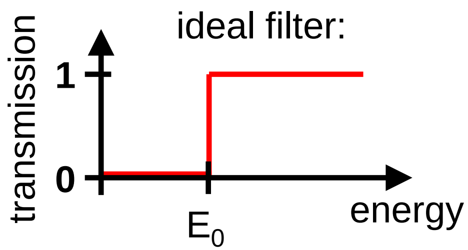
observable: $$m_{\nu_e}^2 = \sum_{i=1}^{3} |U_{ei}|^2 m_i^2$$

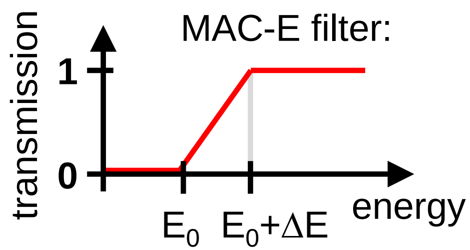
β-spectrum for tritium:



MAC-E filter

- **M**agnetic **A**diabatic **C**ollimation combined with an **E**lectrostatic Filter
- Combines high luminosity with high energy resolution



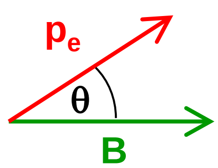


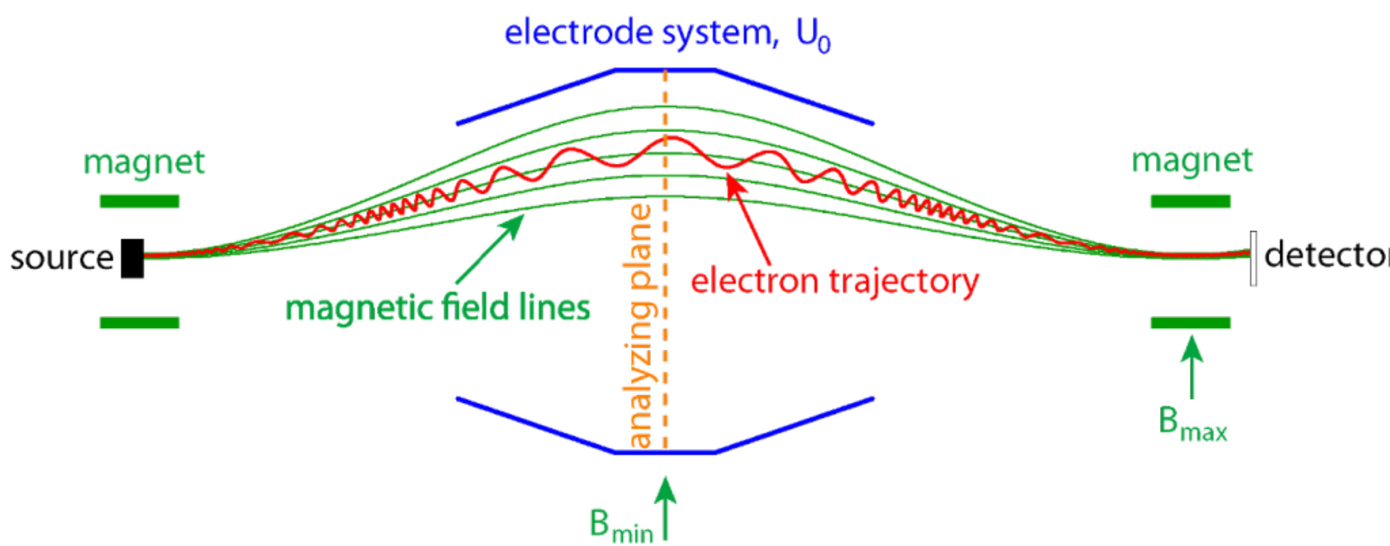
energy resolution:

$$\Delta E = \frac{B_A}{B_{max}} E_t$$

magnetic moment:

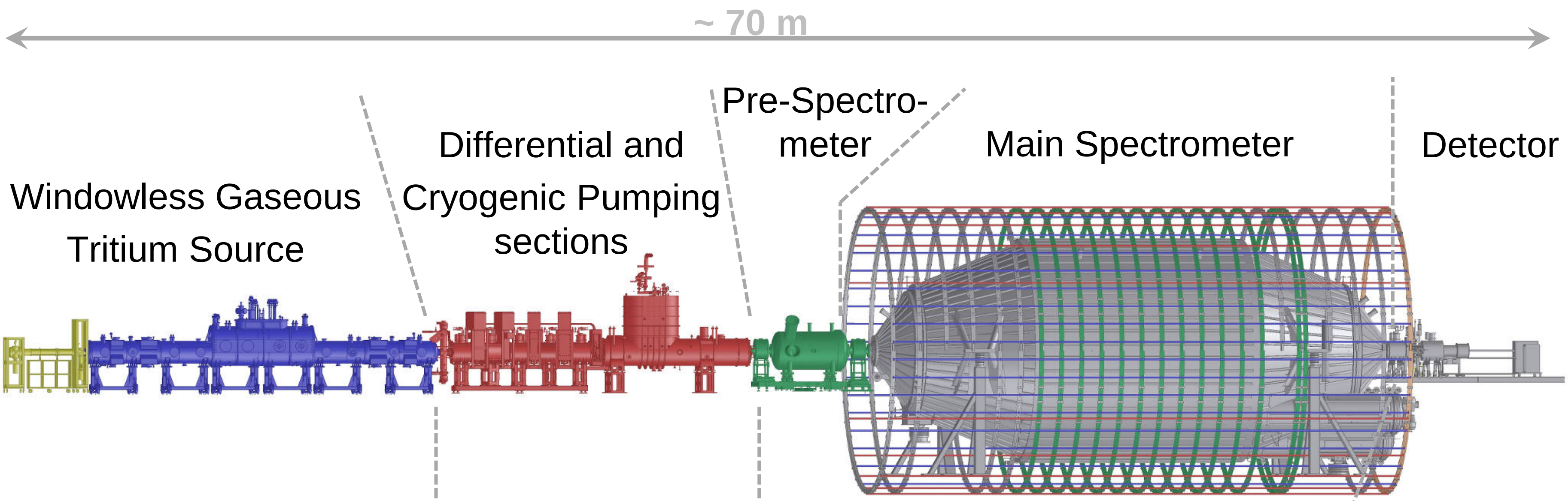
$$\mu = \frac{E_t}{B} = const$$





The KATRIN experiment

- **KA**rlsruhe **TRI**tium **N**eutrino experiment
- goal: measure neutrino mass with a sensitivity of 200 meV



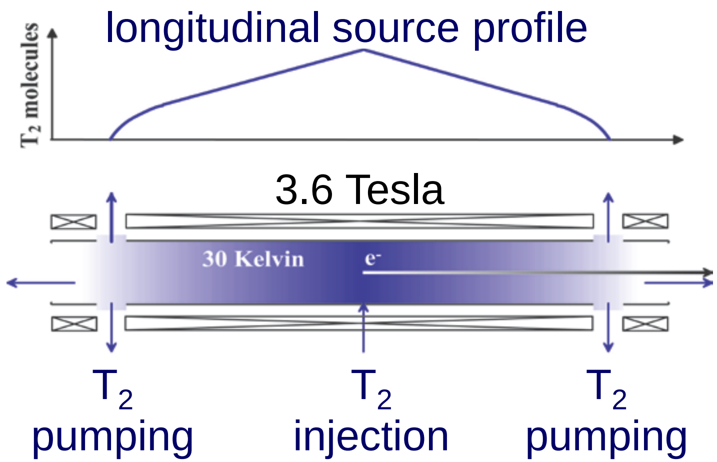
- tritium β-decay
- decay rate: 10^{11} 1/s
- T_2 pressure: 10^{-3} to 10^{-6} mbar

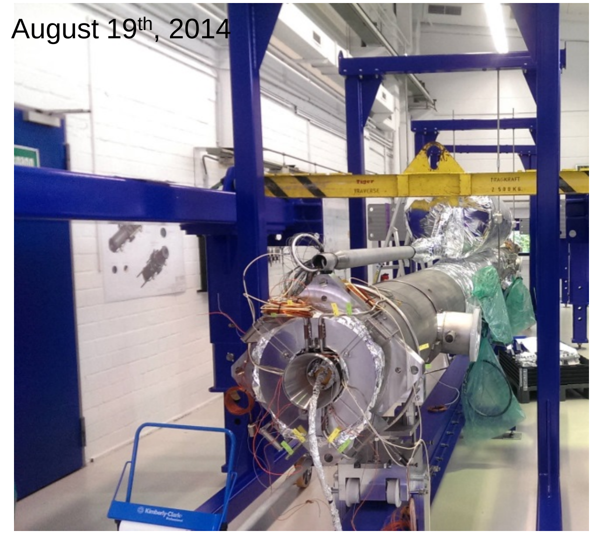
- β-electron transport
- tritium retention (factor > 10^{12})

- energy analysis of β-electrons
- resolution 0.93 eV @ 18.6 keV
- pressure < 10^{-10} mbar

- counting of trans-mitted β-electrons

KATRIN – Windowless Gaseous Tritium Source



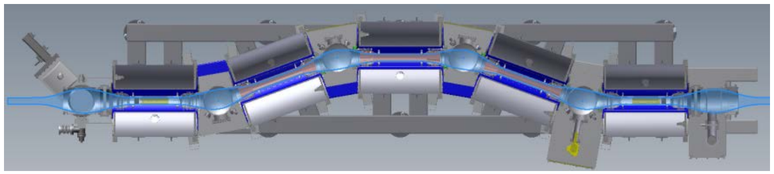


- Stability of T_2 density profile of **10^{-3}** (function of T_2 injection rate, purity, beamtube temperature T_B stability and homogeneity, pump rate)
- T_B stability in prototype experiment 10× better than specified*
- Tritium loop processes 1.4×10^{16} Bq tritium / day (same scale as ITER)
- WGTS currently under construction, delivery to KIT next year (summer)

* S. Grohmann et al. "The thermal behaviour of the tritium source in KATRIN", Cryogenics, V. 55–56, 2013, p. 5–11, DOI: 10.1016/j.cryogenics.2013.01.001

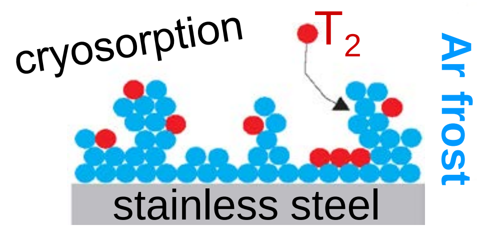
KATRIN – pumping sections

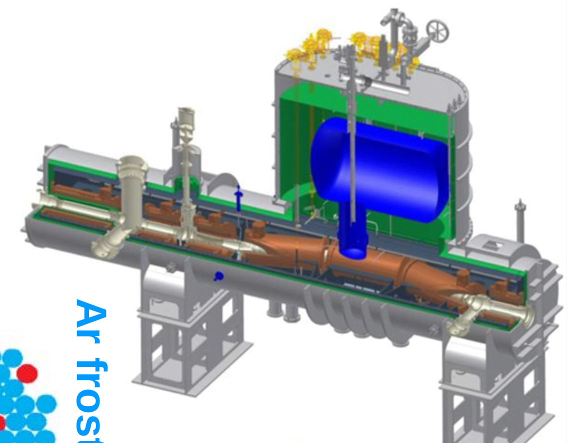
Differential pumping



- T_2 partial pressure reduction (10^5) via differential pumping
- Magnetic guiding of β-electrons
- Removal of positive ions
- Commissioning end of this year

Cryogenic pumping

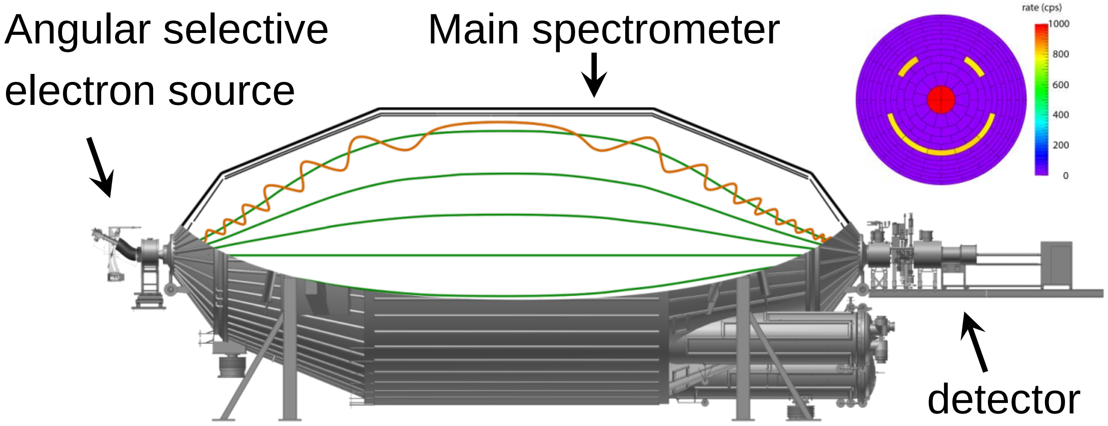


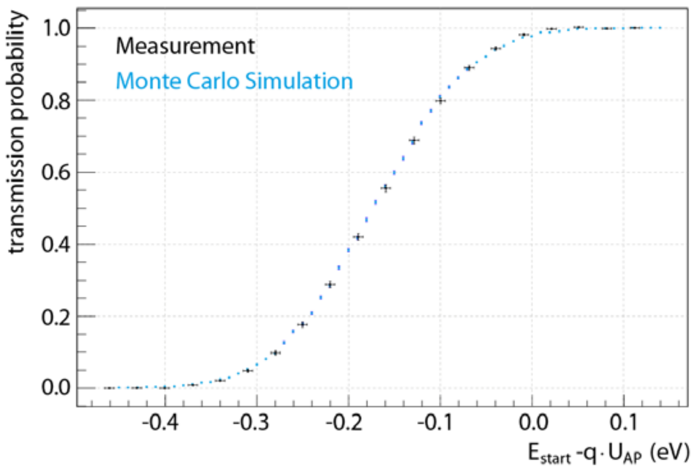


- T_2 partial pressure reduction (10^7) via cryosorption of T_2 on argon frost
- Concept successfully tested*
- Currently under construction, delivery beginning of next year

* F. Eichelhardt et al. "First Tritium Results of the KATRIN Test Experiment Trap" Fusion Science and Technology 54 (2008), Nr. 2, p. 615-618

KATRIN – Spectrometer & Detector Section (SDS)





- First SDS commissioning measurements in autumn 2013
- Main spectrometer successfully operated at -18.6 kV
- Spectrometer pressure ~ 10^{-10} mbar
- Transmission characteristics of main spectrometer as expected
- Initial background rate ~ 1 cps (benchmark 0.01 cps)
- 2nd commissioning phase: test active & passive background reduction

Project 8

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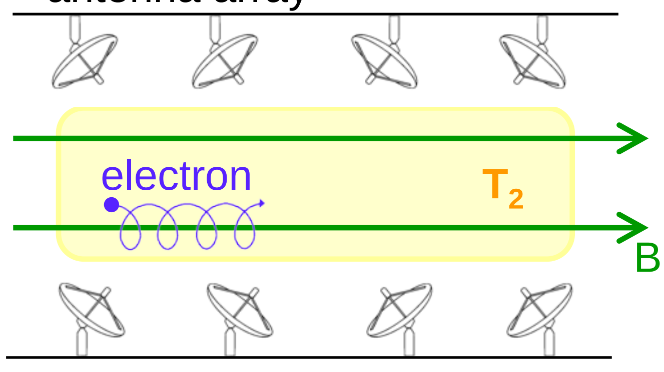
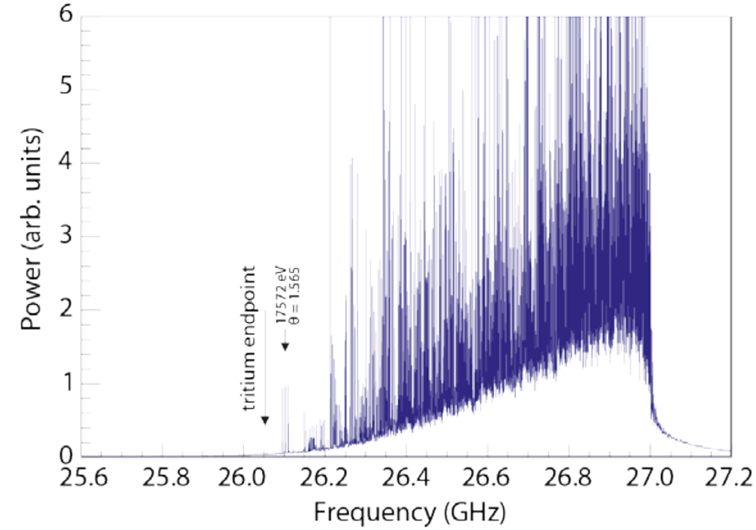


$$\omega(\gamma) = \frac{\omega_0}{\gamma} = \frac{eB}{E + m_e}$$

Simulated spectrum (10^5 T_2 decays)*

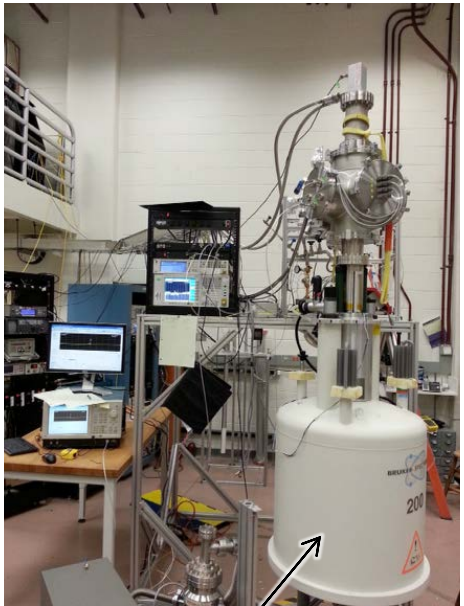


- Idea: Measure β-spectrum via coherent cyclotron radiation emitted by an energetic electron in a magnetic field
- Frequency of emitted radiation independent of electron pitch angle Θ
- New form of nondestructive spectroscopy

* B. Monreal, J.A. Formaggio, PHYSICAL REVIEW D 80, 051301(R) (2009), DOI: 10.1103/PhysRevD.80.051301

Project 8 – phase I

*



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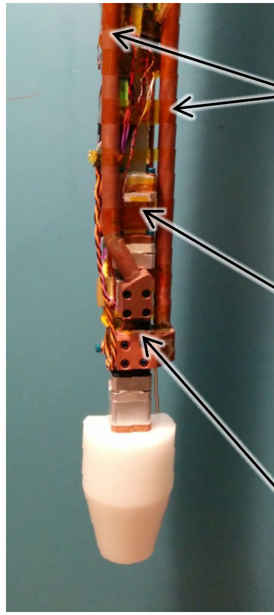
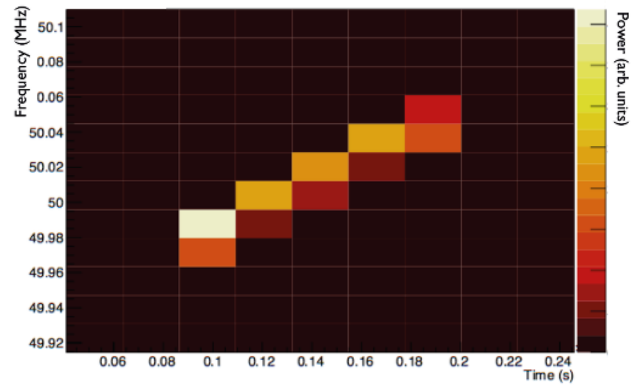


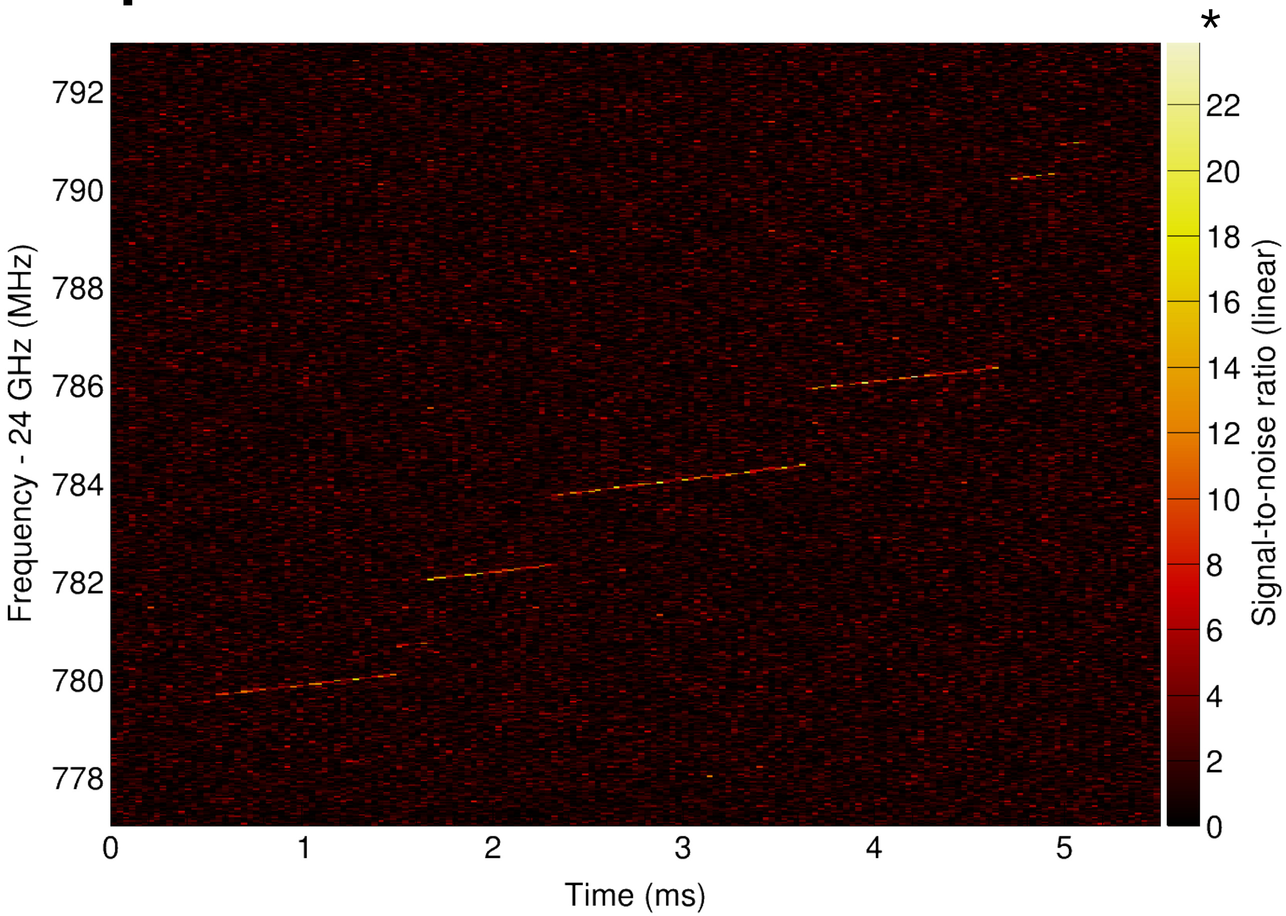
expected signal (simulation) *



- Prototype system for “proof of principle” test
- Goal: detect single electrons from ^{83m}Kr
- Measurement phase finished, data analysis ongoing

* Noah Oblath, „The Project 8 Experiment“, KATRIN Analysis Workshop 2014

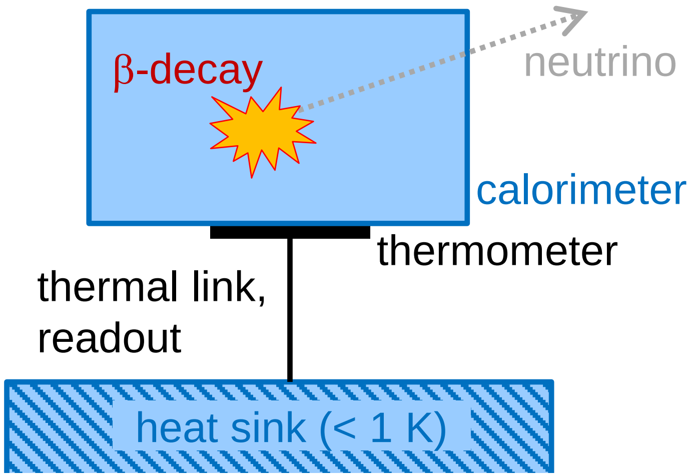
Project 8 – phase I results

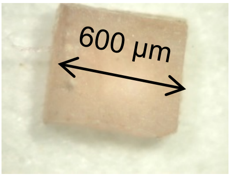


- cyclotron radiation emission from single, mildly relativistic electrons has been observed experimentally for the first time!

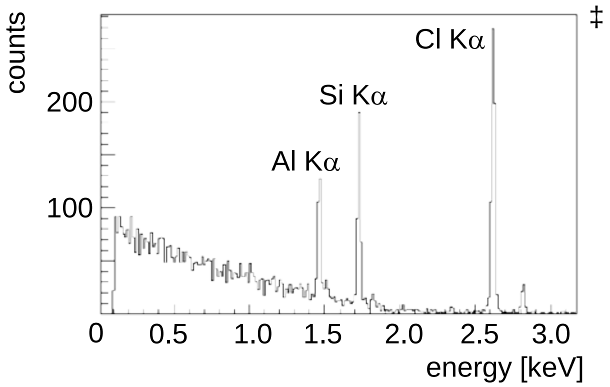
* D.M. Asner et al. „Single electron detection and spectroscopy via relativistic cyclotron radiation " http://arxiv.org/abs/1408.5362

MARE – (Microcalorimeter Arrays for a Rhenium Experiment)





$AgReO_4$ crystal (0.5 mg)
MARE-1 @ Milano-Bicocca*
ΔE = 28 eV @ 1.5 keV‡



- Calorimeter ideally measures all the energy released in the decay (except neutrino energy), source = detector
- ^{187}Re: $T_{1/2} = 4.3 \times 10^{10}$ yr, Q-value = 2.47 keV
- Investigate different techniques: Si thermistors, transition edge sensor, magnetic microcalorimeter, microwave kinetic inductance detector
- MARE also investigates the possibility to use ^{163}Ho electron capture

* A. Nucciotti, Meudon Workshop 2011, 8-10 JUNE 2011, ‡ E. Ferri, "The status of the MARE experiment with ^{187}Re and ^{163}Ho isotopes" TAUP 2013

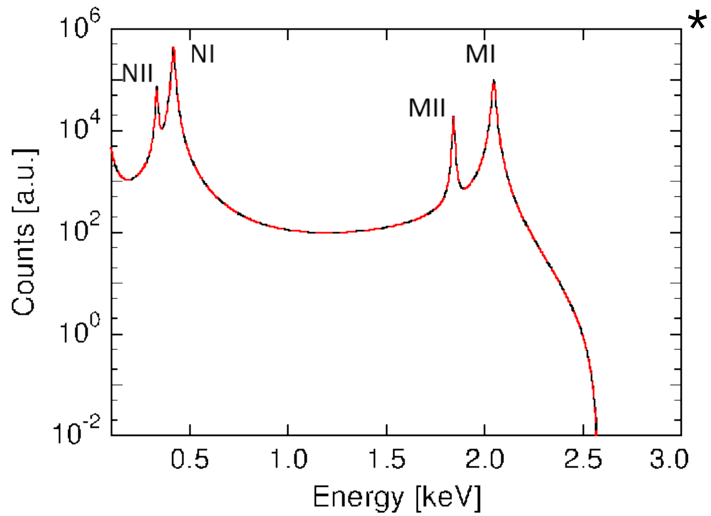
Neutrino mass and electron capture

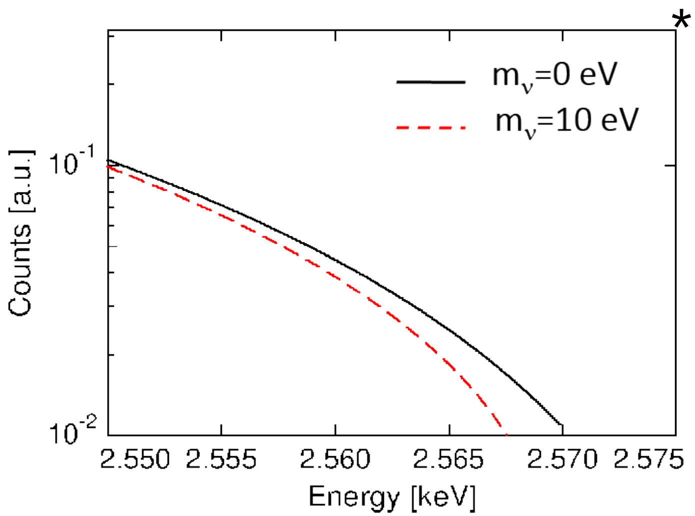
- Electron capture: $p + e^- \rightarrow n + \nu_e$
- Neutrino mass affects the de-excitation energy spectrum

$$\frac{dN}{dE_C} = A(Q_{EC} - E_C)^2 \sqrt{1 - \frac{m_\nu^2}{(Q_{EC} - E_C)^2}} \sum C_H n_H B_H \phi_H^2(0) \frac{\frac{\Gamma_H}{2\pi}}{(E_C - E_H)^2 + \frac{\Gamma_H^2}{4}}$$

- Calorimetric measurement of atomic de-excitation (x-rays, Auger electrons, Coster-Kronig transitions)

^{163}Ho
$T_{1/2}$: 4570 yr
$Q_{(EC)}$: 2.56 keV

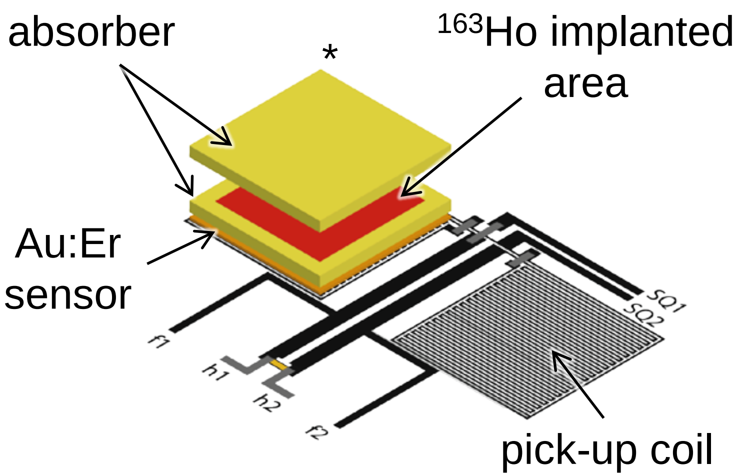


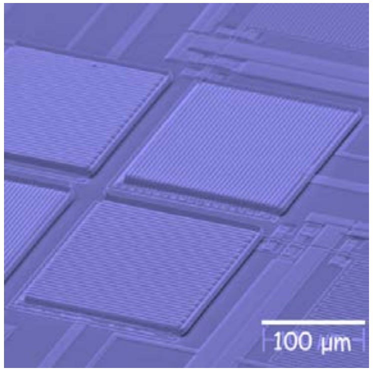


* Loredana Gastaldo, "Status of Holmium-based Neutrino Mass Measurements" Neutrino 2014, Boston

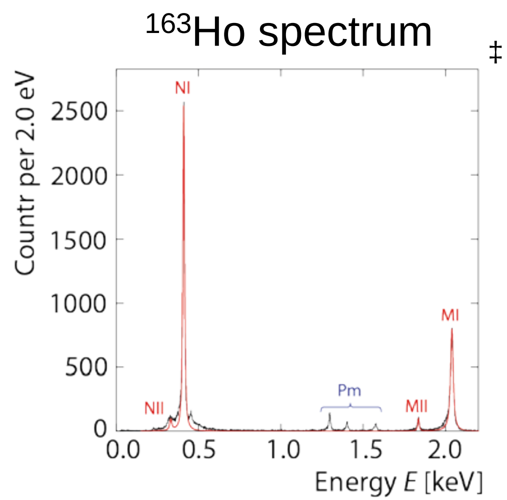
ECHo (Electron Capture ^{163}Holmium)

- Goal: investigate the electron neutrino mass in the energy range < 1eV by calorimetric measurement of ^{163}Ho electron capture using low temperature metallic magnetic colorimeters (MMCs)





http://www.kip.uni-heidelberg.de/echo



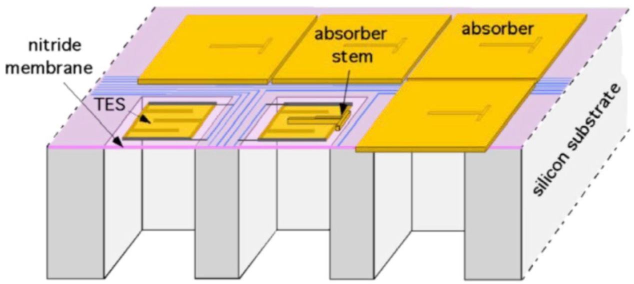
- First detector prototype was tested successfully (ΔE = 7.6 eV @ 6 keV)
- Measurements with 64 detector pixel to prove scalability

* P.C.-O. Ranitzsch et al., J Low Temp Phys (2012) 167:1004–1014 DOI: 10.1007/s10909-012-0556-0 ‡L. Gastaldo et al., J Low Temp Phys (2014) 176:876–884 DOI: 10.1007/s10909-014-1187-4

HOLMES / LANL

- measurement of ^{163}Ho electron capture using transition edge sensors

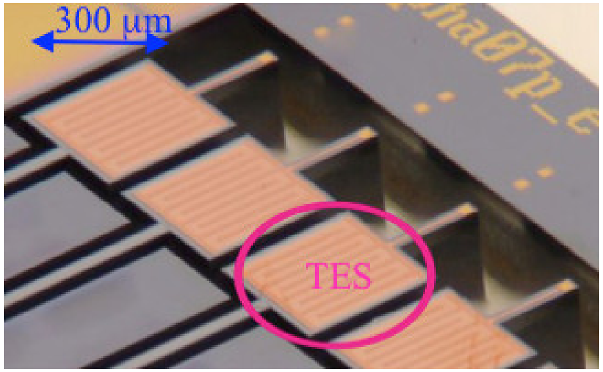
HOLMES



*

- Testing different methods for ^{163}Ho isotope production
- funding received for 1000 channel Ho detector experiment

LANL



*

- Recent experiments show $\Delta E \sim 7.5$ eV
- Testing different methods of incorporating Ho into absorber

* Loredana Gastaldo, "Status of Holmium-based Neutrino Mass Measurements" Neutrino 2014, Boston

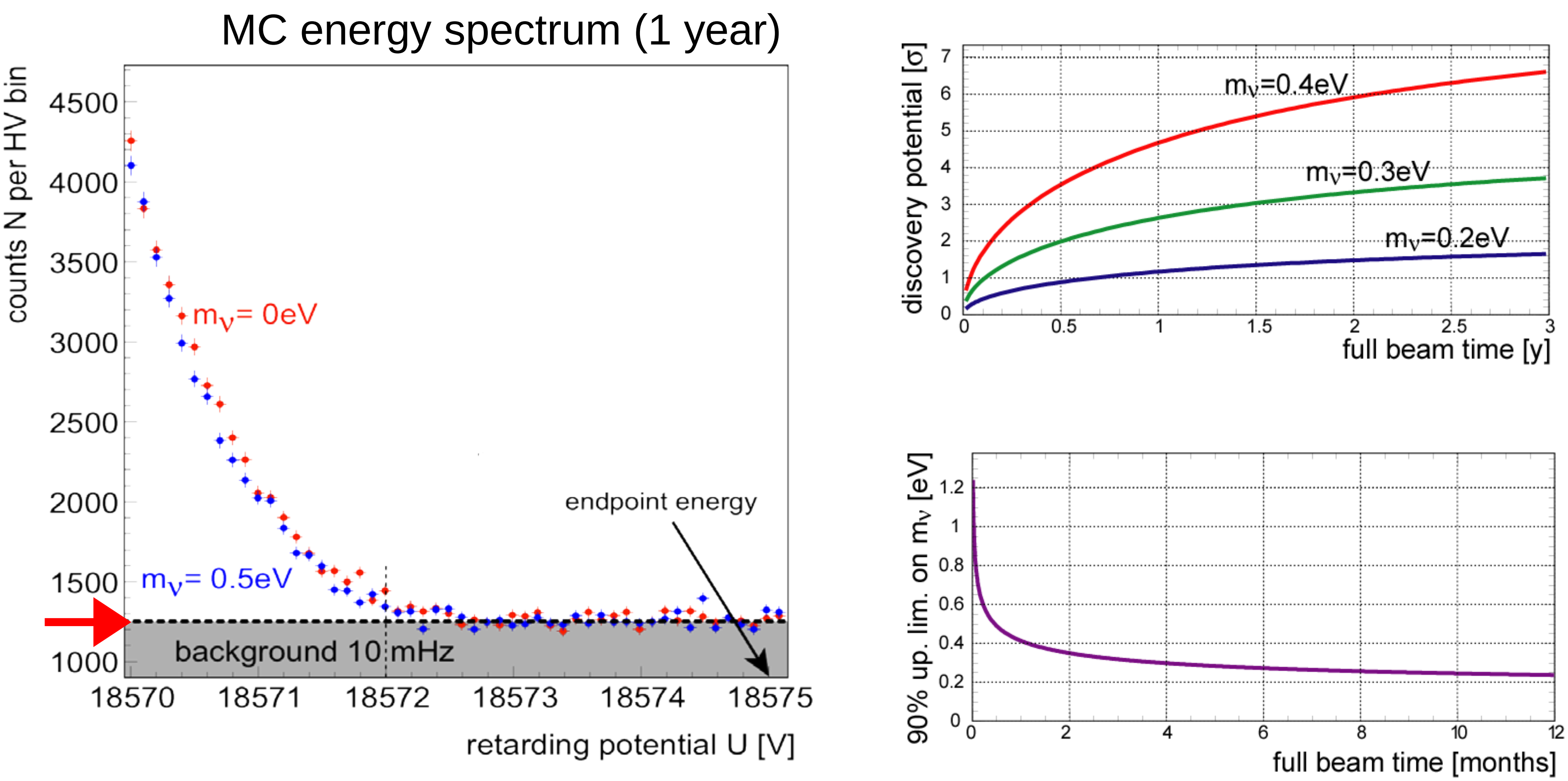
Status and outlook

	“tritium β-decay”	“^{163}Ho electron capture”
status:	KATRIN is in construction and commissioning phase Project 8 phase 1: prototype with ^{83m}Kr, proof of principle successful	Different experiments with R&D on detector performance, scalability and high purity ^{163}Ho source production
outlook:	KATRIN will start neutrino mass measurements 2016 Project 8 phase 2: measure tritium spectrum	^{163}Ho spectra with more than 10^{10} counts $m(\nu_e) < 10$ eV

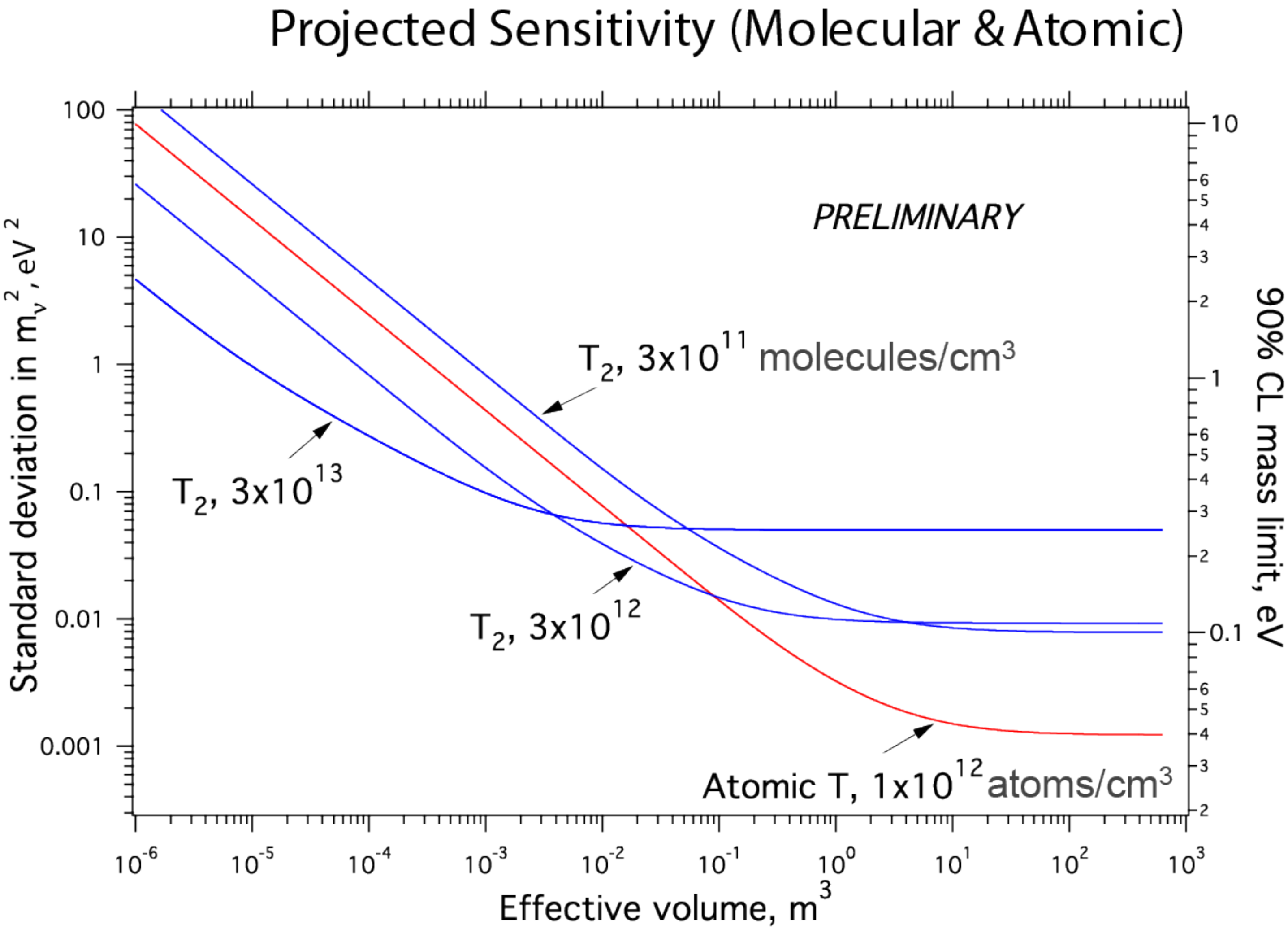
summary

- The absolute neutrino mass scale is one of the big open questions in particle physics, astrophysics and cosmology
- Neutrinos are massive particles, but so far there are only upper < 2 eV and lower limits > 0.01 eV
- The KATRIN experiment aims to measure the neutrino mass with a sensitivity of 0.2 eV. It is currently in a construction and commissioning phase and neutrino mass data taking is expected to start 2016
- Novel techniques to determine the neutrino mass, such as measuring the β-spectrum from coherent cyclotron radiation or measuring the ^{163}Ho electron capture with low temperature microcalorimeters are in development

KATRIN sensitivity

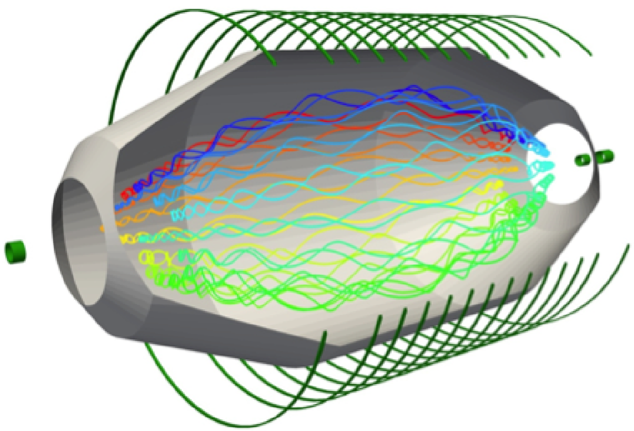


Tritium source: molecular vs. atomic



* J.A. Formaggio, "Project 8 & alternative paths in beta decay experiments" LNGS, May 14th, 2014, https://agenda.infn.it/conferenceDisplay.py?confId=8004

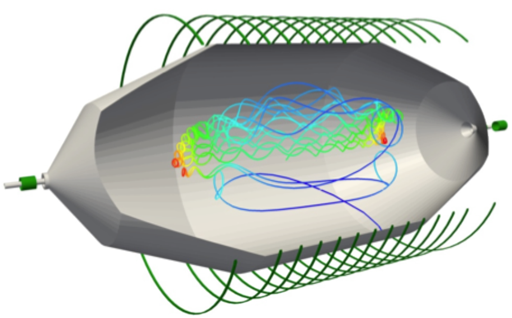
KATRIN background from stored electrons



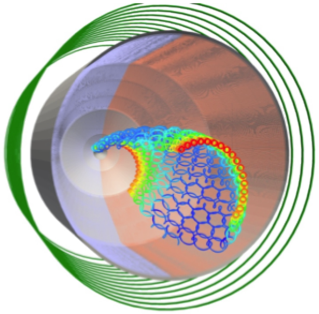
- MAC-E filter works as a magnetic bottle
- high-energy (~10 keV) electrons created in the volume of the spectrometer can be stored for several hours
- stored electrons can create a large number of background electrons via ionization of residual gas molecules

methods to avoid or eliminate stored electrons:

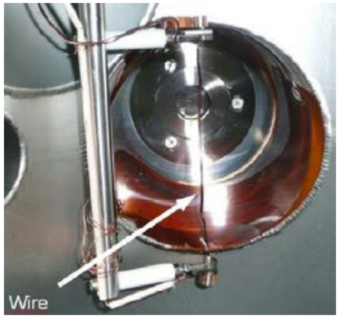
magnetic pulse



electric dipole field



mechanical elimination



LN_2 cooled baffle