“Neutrino mass and nature: status and prospects”

- Florian Fränkle -

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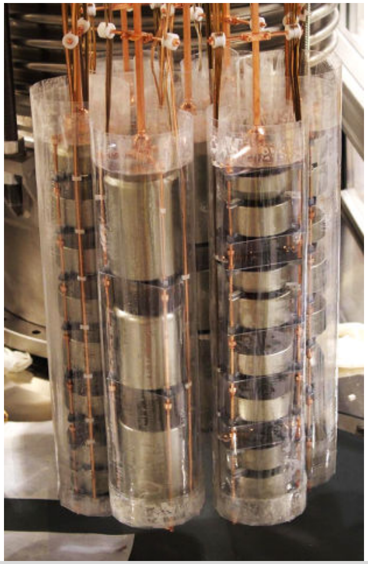
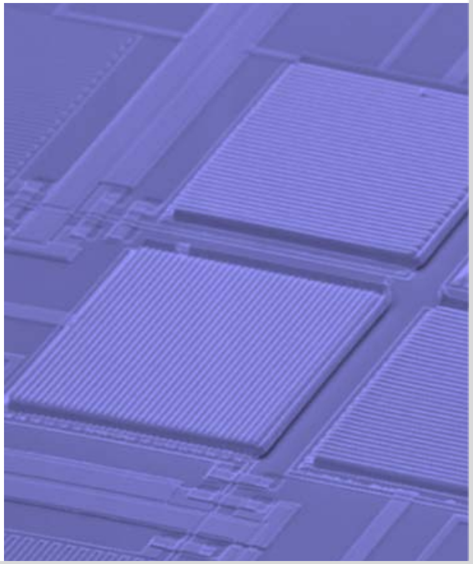




Outline

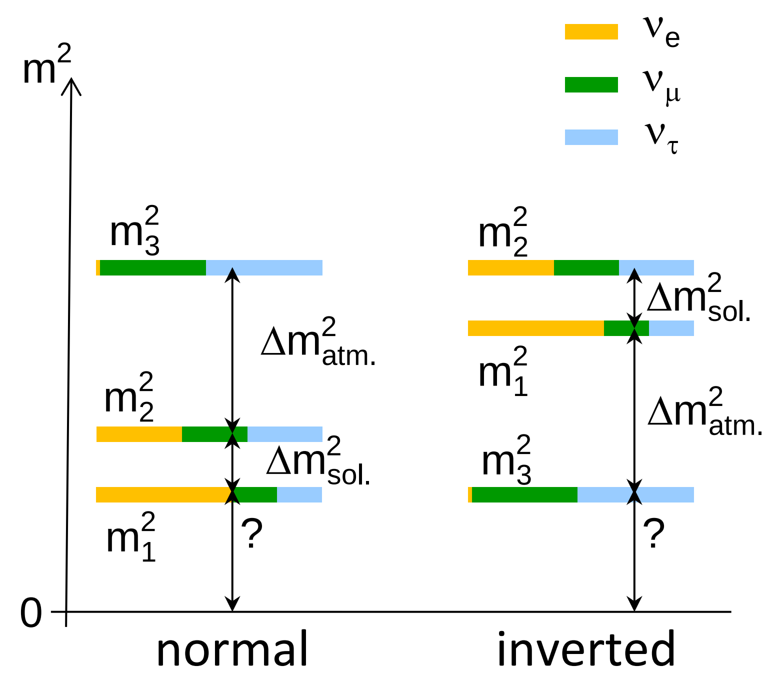
- Neutrino masses
- Single β-decay experiments
- ^{163}Ho electron capture experiments
- $0\nu\beta\beta$-decay experiments
- Summary

Neutrino masses

- Neutrino flavour eigenstates are related to neutrino mass eigenstates by the lepton mixing matrix (PMNS)
- Neutrino oscillations are sensitive to the differences between the squares of neutrino masses
- Two mass ordering scenarios possible
- The value of the lightest neutrino mass is unknown

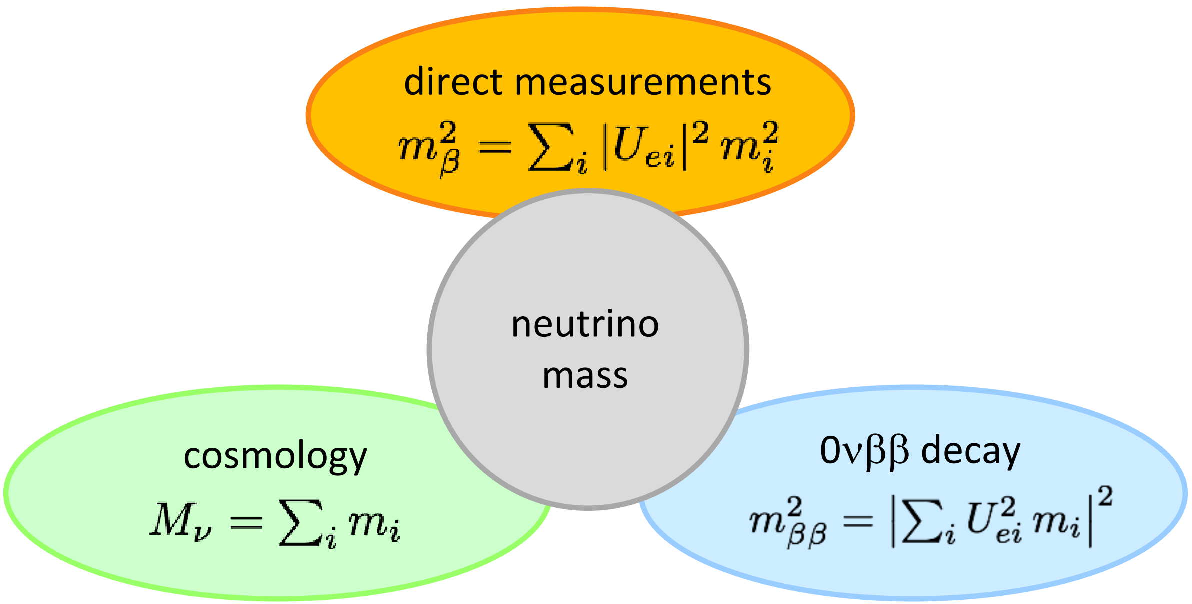
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3}\\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3}\end{pmatrix}\begin{pmatrix}m_1\\ m_2\\ m_3\end{pmatrix}$$

mass ordering



Neutrino masses

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



Neutrino mass and single β-decay

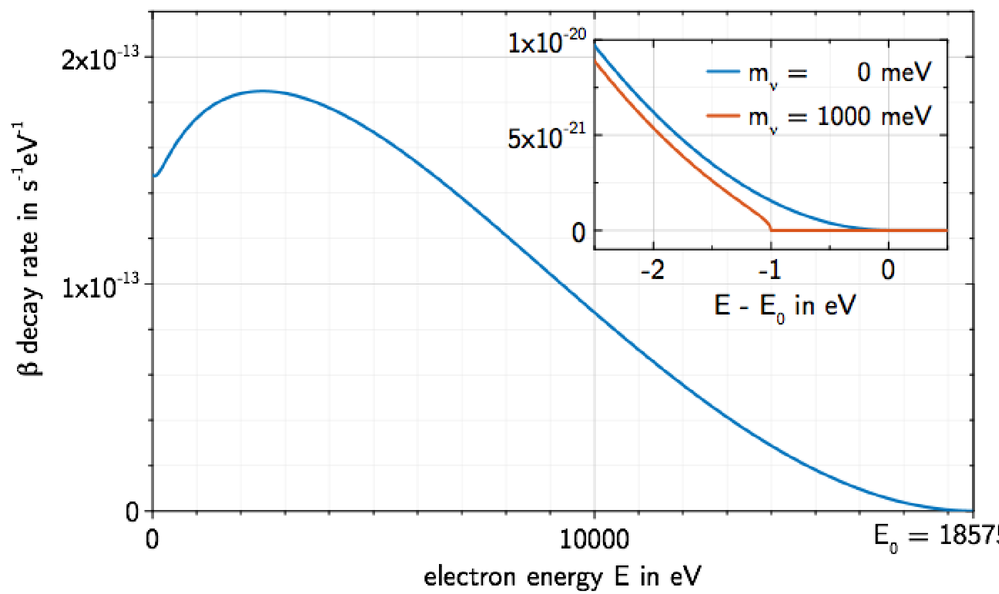
- β-decay: $n \rightarrow p + e^- + \overline{\nu}_e$
- Neutrino mass influences energy spectrum of β-decay electrons
- Neutrino mass determination via precise measurement of the spectral shape close to the endpoint
- Model independent method

Fermi theory of β-decay:

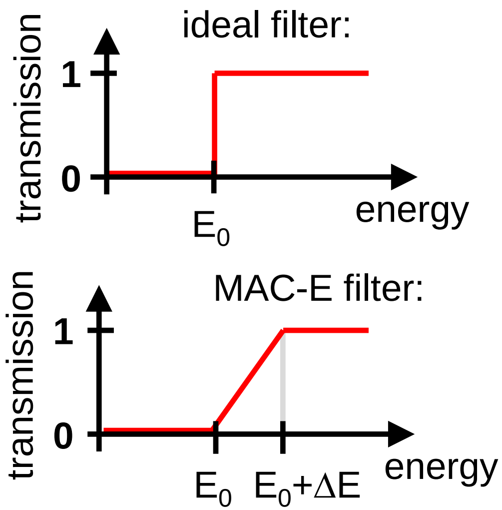
$$\frac{dN}{dE} = C \cdot F(E,Z) \cdot p(E + m_e) \cdot (E_0 - E) \cdot \sqrt{(E_0 - E)^2 - m_\nu^2}$$

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

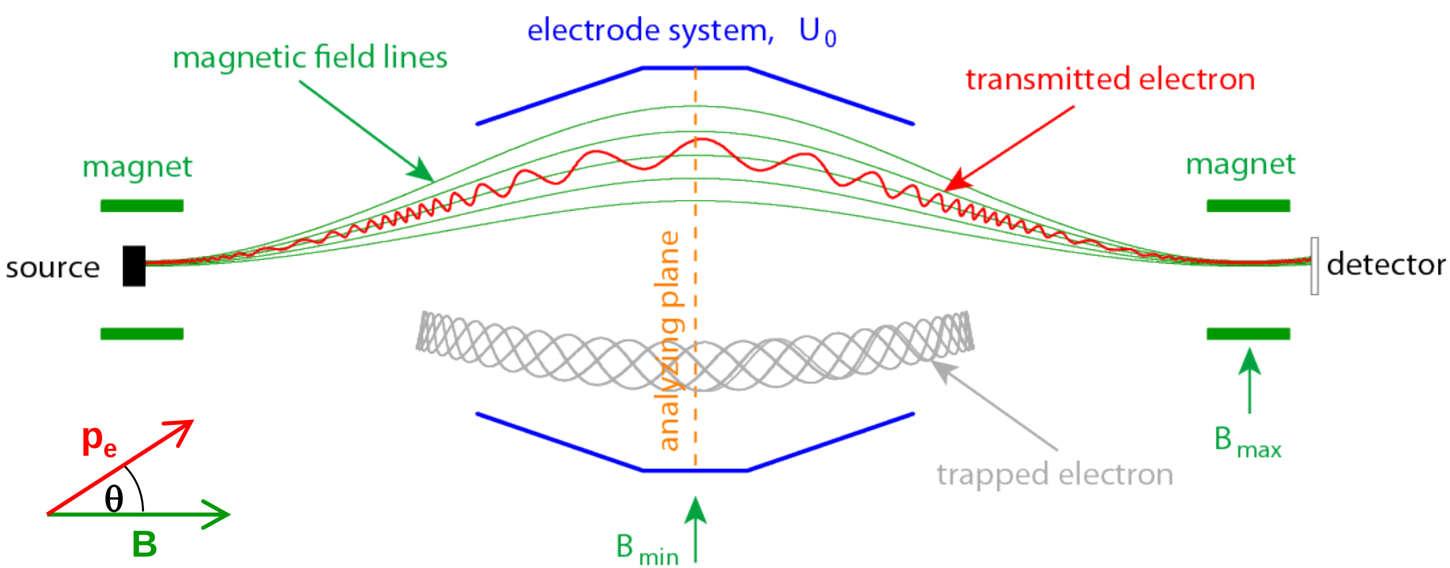
β-spectrum for tritium (E_0 = 18.6 keV, $T_{1/2}$ = 12.3 y):



MAC-E filter



- **M**agnetic **A**diabatic **C**ollimation combined with an **E**lectrostatic Filter
- Technique used by Mainz and Troitsk neutrino mass experiments, current best upper limit $m_\nu < 2$ eV/c²



magnetic moment:

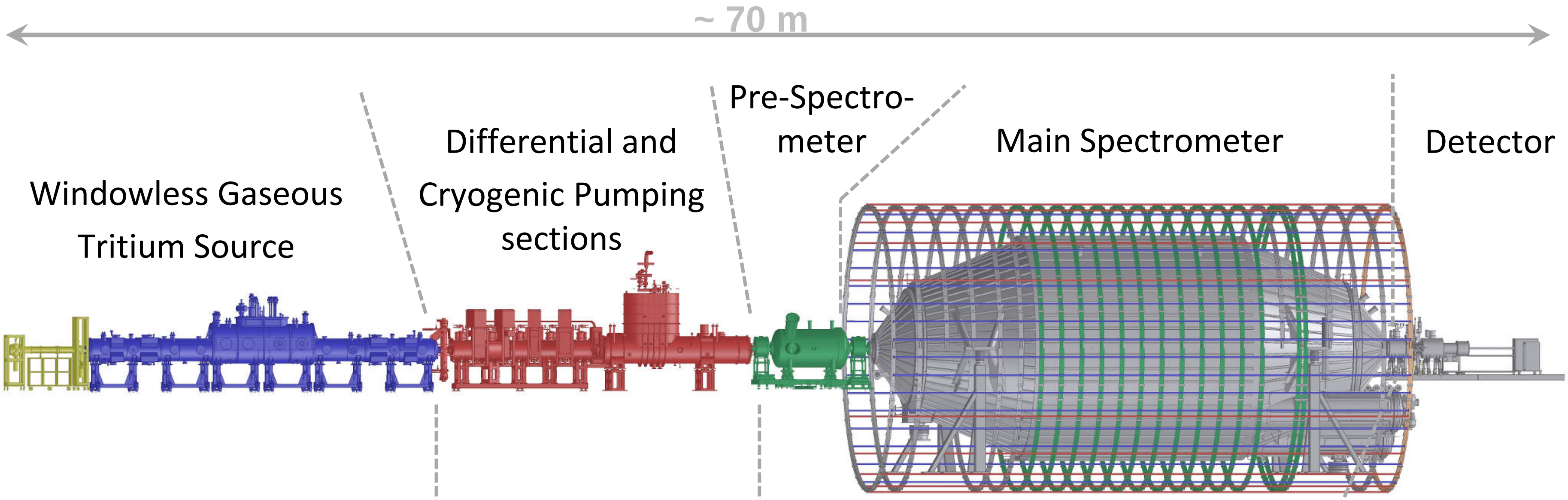
$$\mu = \frac{E_t}{B} = const$$

energy resolution:

$$\Delta E = \frac{B_A}{B_{max}} E_0$$

The KATRIN experiment

- **KA**rlsruhe **TRI**tium **N**eutrino experiment
- Goal: Measure neutrino mass with a sensitivity of **200 meV/c²** (90% C.L.)



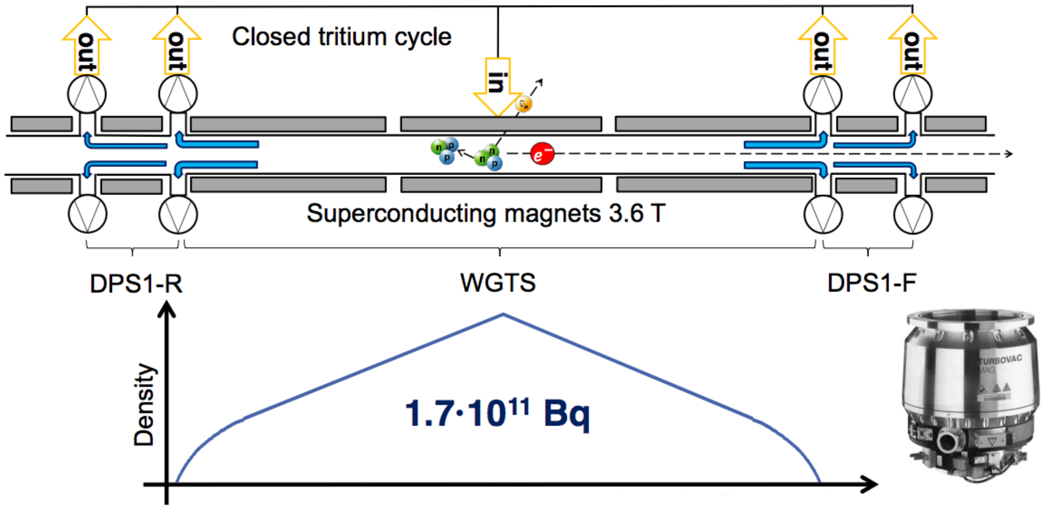
- tritium β-decay
- decay rate: 10^{11} 1/s
- T_2 pressure: 10^{-3} to 10^{-6} mbar

- 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 transmitted β-electrons

KATRIN – Windowless Gaseous Tritium Source

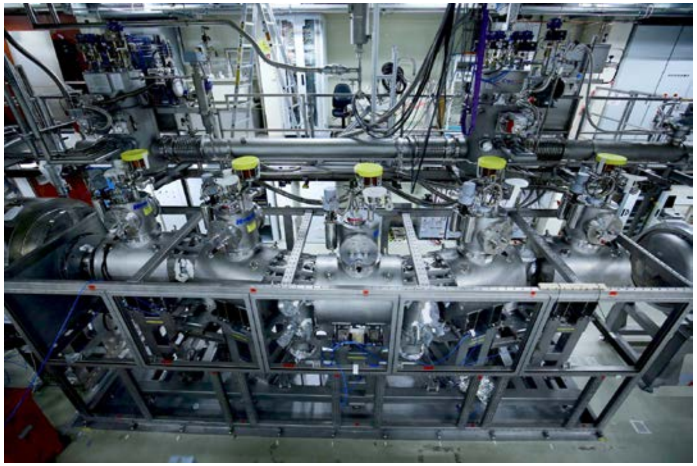


- Stability of T_2 density profile of **10^{-3}** (function of T_2 injection rate, purity, beamtube temperature T_B stability and homogeneity, pump rate)
- T_B stability in prototype experiment 10× better than specified*
- Tritium loop processes 1.4×10^{16} Bq tritium / day (same scale as ITER)
- WGTS currently cooling to operational temperature (30 K)

* 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

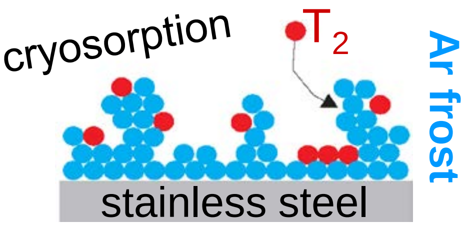
KATRIN – pumping sections

Differential pumping



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

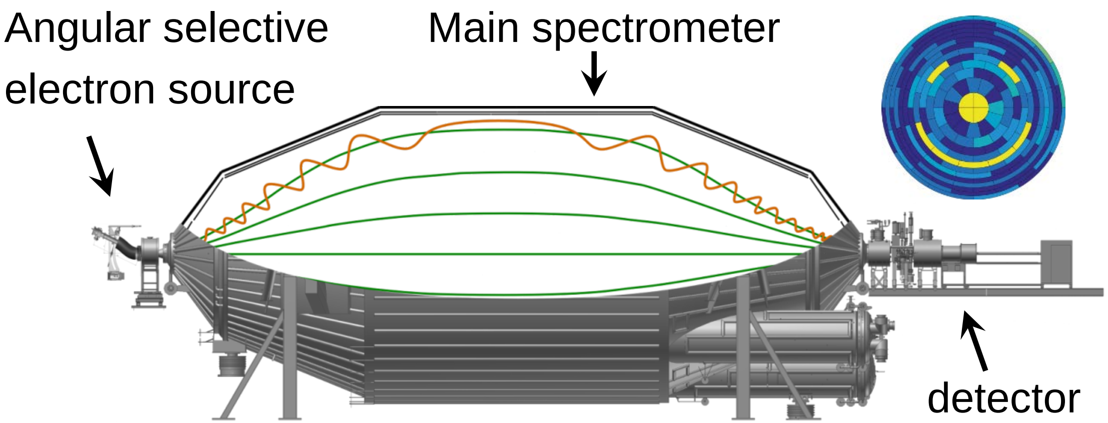
Cryogenic pumping

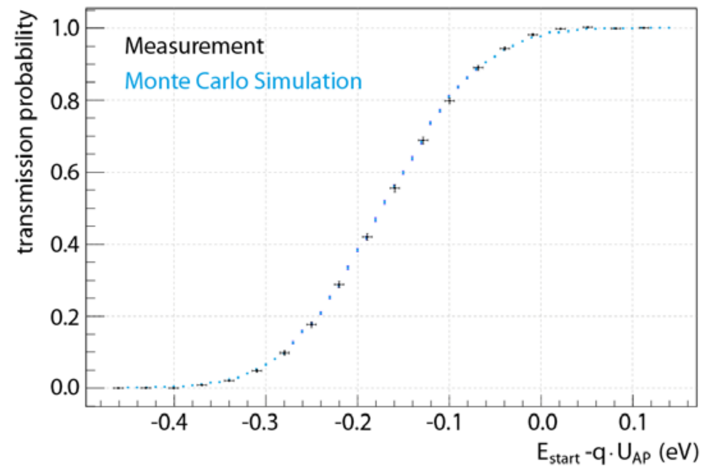


- T_2 partial pressure reduction (10^7) via cryosorption of T_2 on argon frost
- Concept successfully tested*
- Magnet system successfully tested

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

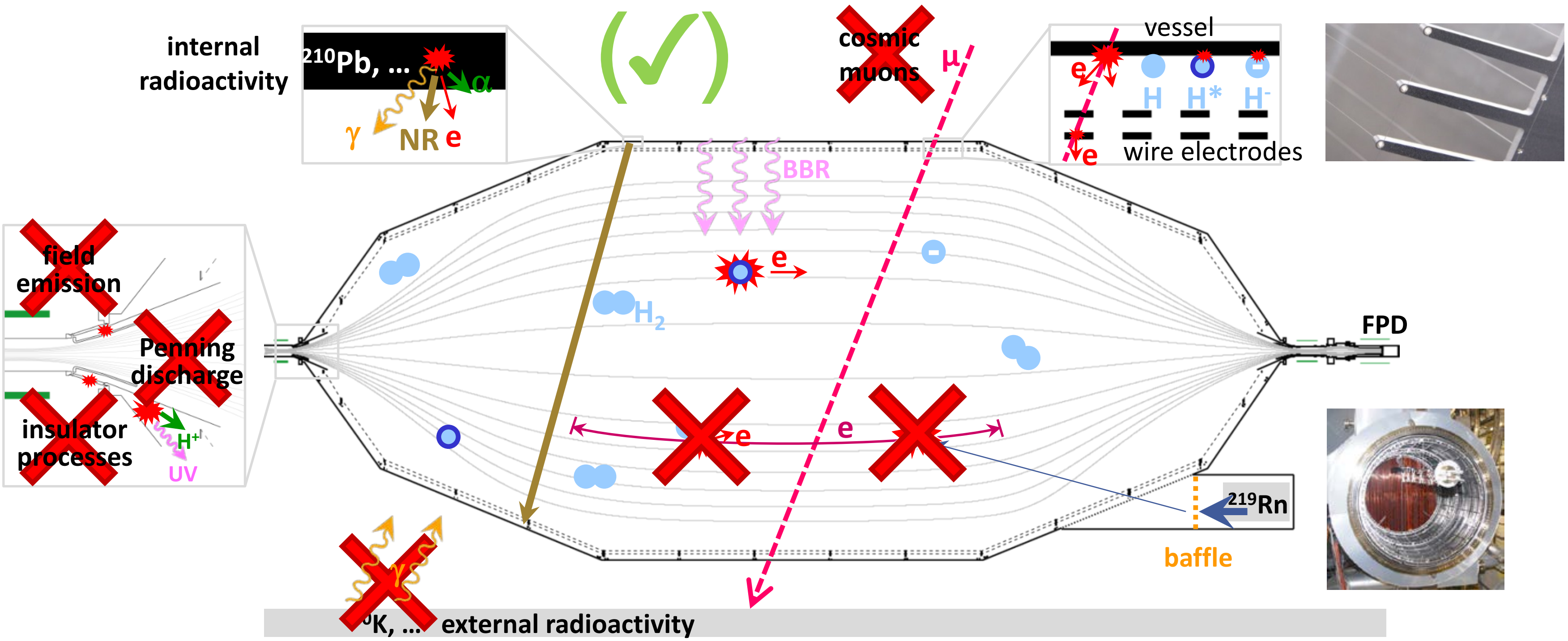
KATRIN – Spectrometer & Detector Section (SDS)





- Two SDS commissioning measurement phases since autumn 2013
- Main spectrometer successfully operated at -18.6 kV
- Spectrometer pressure ~ 10^{-10} mbar
- Transmission characteristics of main spectrometer as expected
- Detailed investigations of spectrometer backgrounds

KATRIN backgrounds

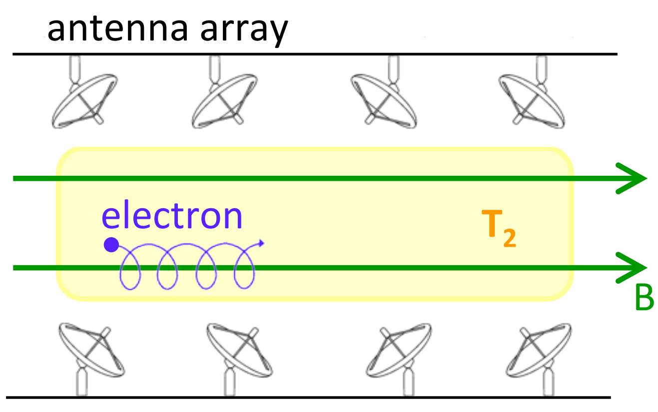


- All previously known background processes are efficiently suppressed
- Background rate about 50 times larger then design value (10 mcps), presumably due to ionization of Rydberg atoms by black body radiation

KATRIN outlook

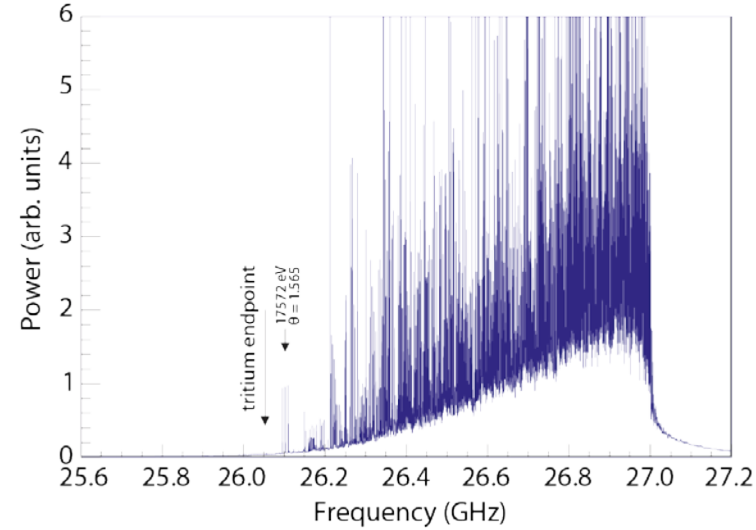
- Elevated background reduces KATRIN sensitivity from 200 to 240 meV/c^2 but further background reduction measures being studied
- Commissioning of complete KATRIN beamline without tritium will start on October 14th (“first light”)
- Test of source beamtube cooling system
- Completion of closed tritium loops
- **First tritium data in 2017**

Cyclotron Resonance Emission Spectroscopy



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

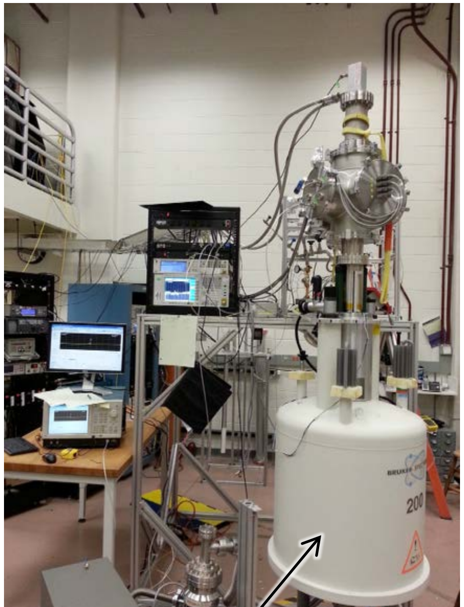
Simulated spectrum (10^5 T_2 decays)*



- Idea: Measure β-spectrum via coherent cyclotron radiation emitted by an energetic electron in a magnetic field (radiated power about 1 fW)
- 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



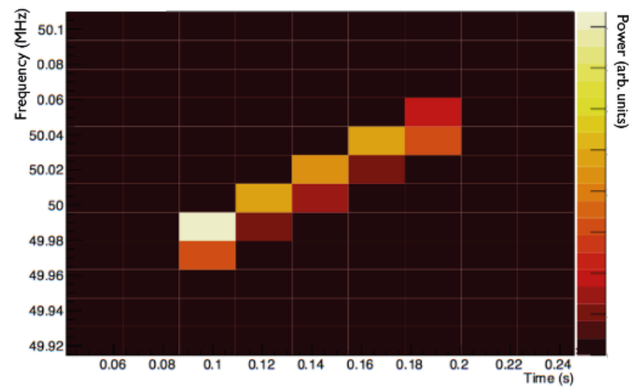
gas lines
(^{83m}Kr)

waveguide

electron
trapping

magnet (~ 1T)

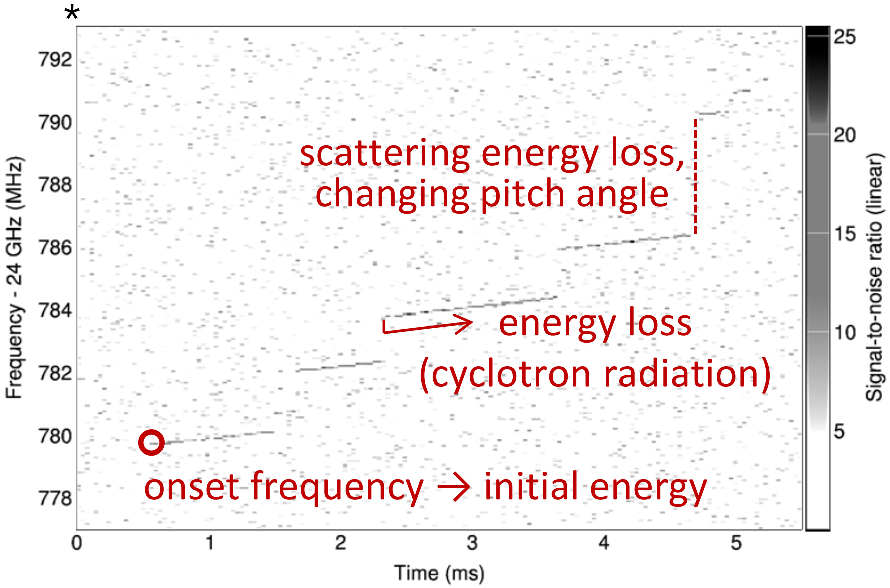
expected signal (simulation) *

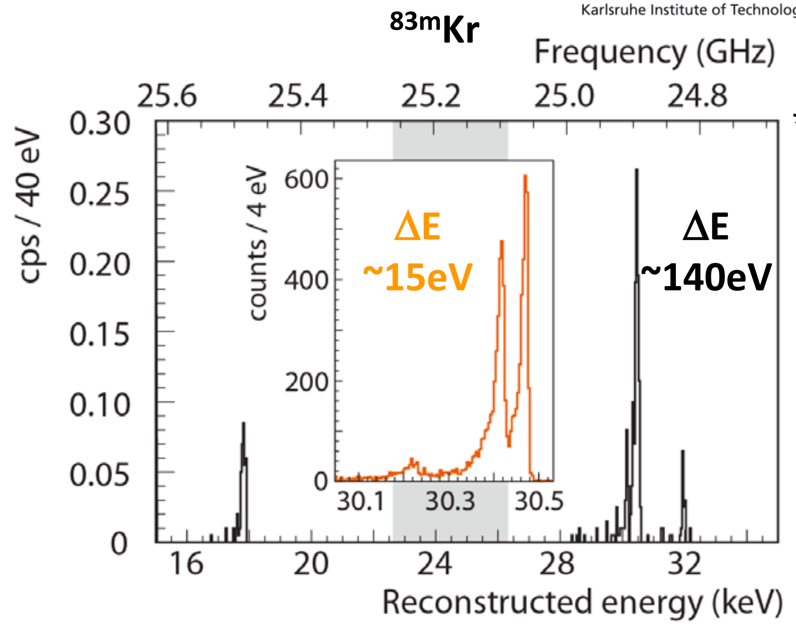


- Prototype system for "proof of principle" test
- Goal: detect single electrons from ^{83m}Kr
- Measurement phase finished

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

Project 8





- First detection of single-electron cyclotron radiation (June 2014)
- Spectrum generation via event reconstruction
- Initial energy resolution could be improved to 15 eV (FWHM)
- Measure first tritium spectrum in 2017
- Long-term goal: large scale experiment with atomic tritium source and sub-eV sensitivity (hierarchy scale)

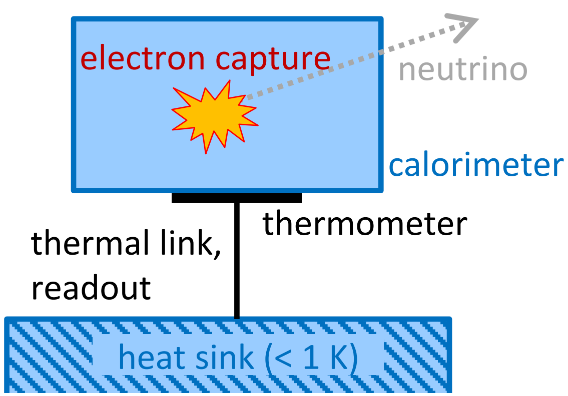
*D.M. Asner et. al. "Single-Electron Detection and Spectroscopy via Relativistic Cyclotron Radiation", Physical Review Letters, 114, 162501 (2015), DOI: 10.1103/PhysRevLett.114.162501

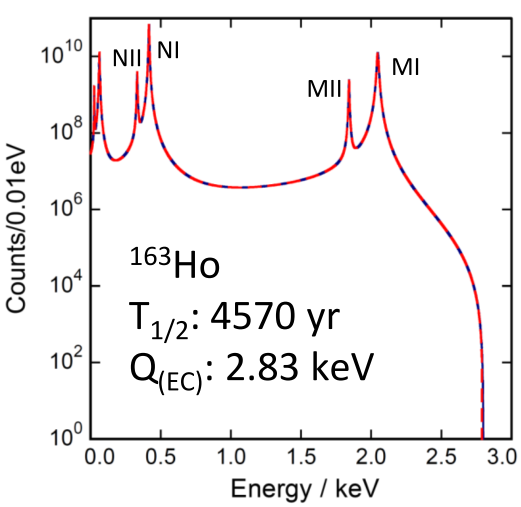
Neutrino mass and electron capture

- 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)





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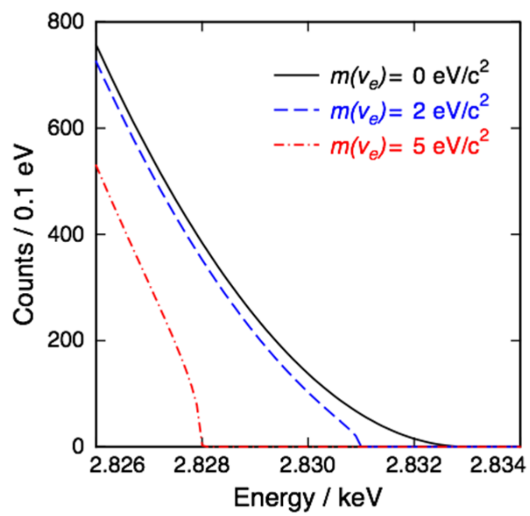
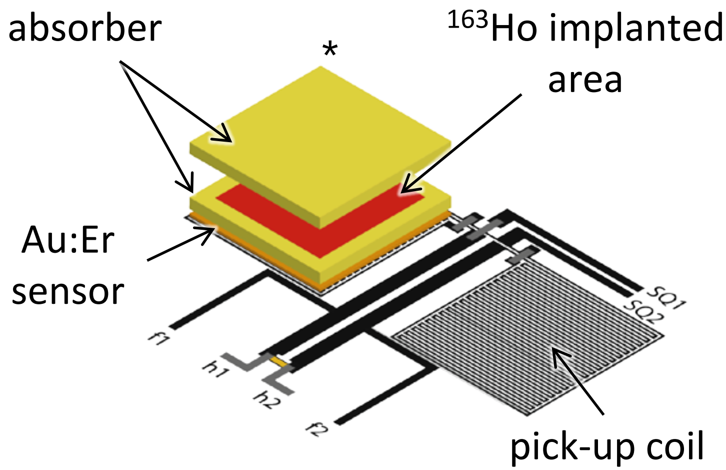
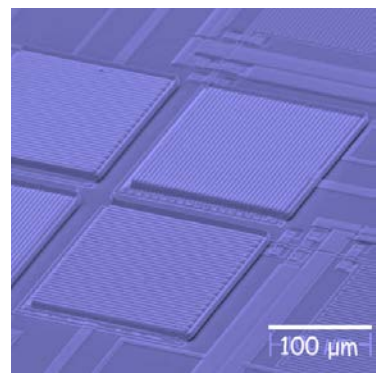


* Christian Enss, "Neutrino Mass Determination by Electron Capture in Holmium-163" ECT workshop Determination of the absolute electron (anti-)neutrino mass, Trento

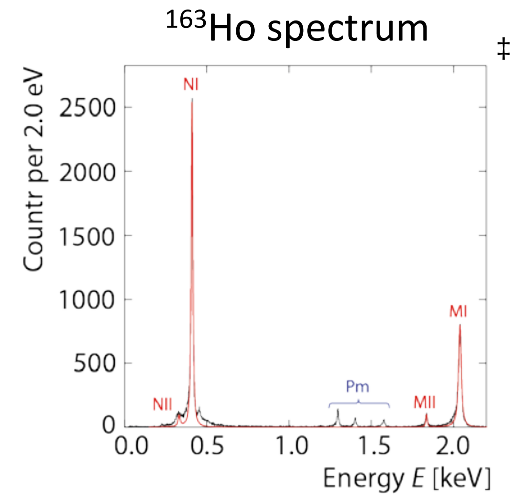
ECHo

- magnetic micro-calorimeter (MMC) arrays with microwave squid multiplexing readout
- fast rise time (~ 130 ns) and excellent linearity & resolution (ΔE ~ 5 eV)





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



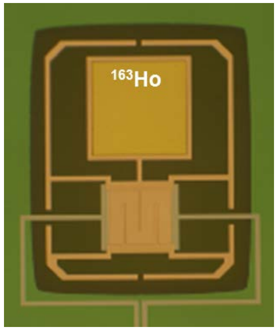
- Phase I: 100 detectors (10 Bq each), $m_\nu < 10$ eV/c² by 2018
- Phase II: 10^5 detectors (10 Bq each), sub-eV sensitivity

* 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 / NuMECS

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

HOLMES



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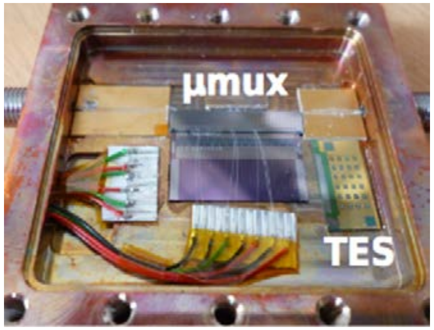
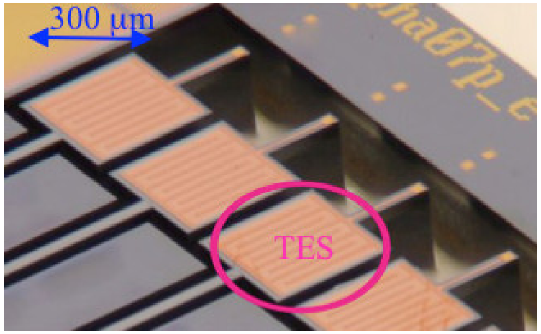


NuMECS



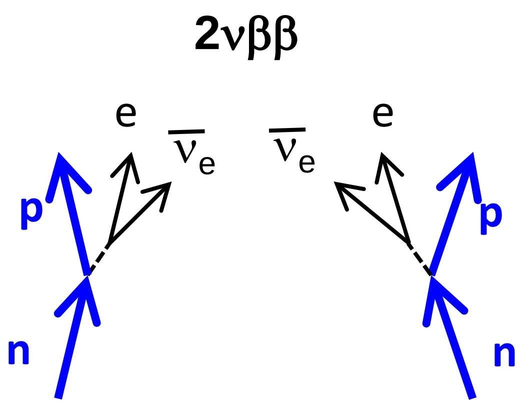
*

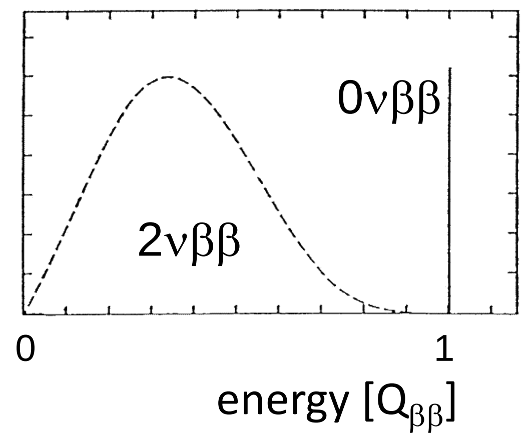
- funding received for 1000 channel Ho detector experiment
- smaller demonstrator array to start data taking 2017

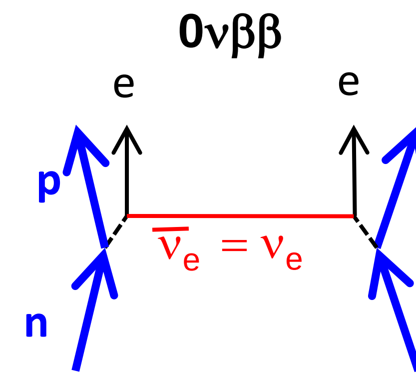
- ^{163}Ho production by proton irradiation of natural dysprosium
- first ^{163}Ho spectrum measured but still limited statistics and resolution

* Kathrin Valerius, "Direct probes of neutrino mass" Neutrino 2016, London

Double β-decay







if 0νββ is discovered:

- lepton number violation
- neutrino is its own antiparticle (Majorana particle)
- measure of effective neutrino mass $m_{\beta\beta}$

$$m_{\beta\beta} = \sum_i U_{ei}^2 \, m_i \qquad \left(T_{1/2}^{0\nu\beta\beta}\right)^{-1} = G^{0\nu} |M|^2 m_{\beta\beta}^2$$

0νββ experiments

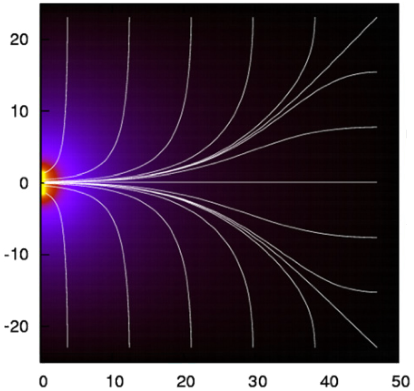
Experiment	Isotope	Technique
AMoRE	^{100}Mo	Low-T MMC
CANDLES	^{48}Ca	CaF_2 scintillator + veto
CDEX	^{76}Ge	Point contact Ge
COBRA	^{116}Cd, etc	CdZnTe
CUORE/CUORE-0	^{130}Te	TeO_2 bolometers
CUPID	^{130}Te, ^{82}Se, ^{100}Mo, ^{116}Cd	Hybrid bolometers
DCBA/MTD	^{100}Mo	Foils + tracker
EXO200	^{136}Xe	LXe TPC
GERDA	^{76}Ge	Semicoax / point contact HPGe
KamLAND-Zen	^{136}Xe	Liquid scintillator
MAJORANA DEMONSTRATOR	^{76}Ge	Point contact HPGe
MOON	^{100}Mo	Foils + scintillator
nEXO	^{136}Xe	LXe TPC
NEXT	^{136}Xe	High-P TPC
NG-Ge76	^{76}Ge	Point contact Ge
PandaX III	^{136}Xe	High-P TPC
SNO+	^{130}Te	Liquid scintillator
SuperNEMO	^{82}Se	Foils + tracker

Germanium detectors

- ^{76}Ge has a relative large Q-value (2.039 MeV), above most backgrounds
- Natural abundance of 7.4 % but enrichment up to > 86 % possible
- Production of high-purity germanium (HPGe) crystals removes unwanted naturally occurring radioactive impurities
- HPGe crystal acts simultaneously as source and detector with excellent energy resolution (4 keV @ 2039 keV)
- Point contact detectors allow for multi-site event identification and background reduction


*

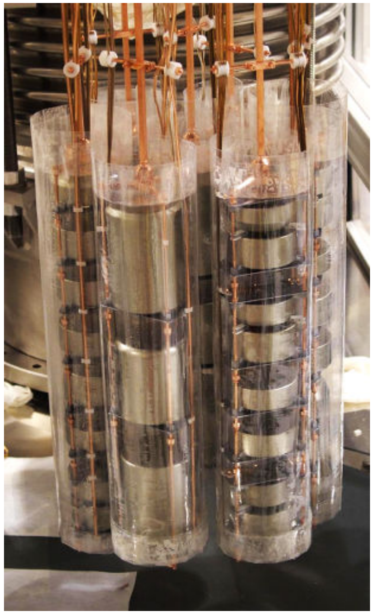
electric potential



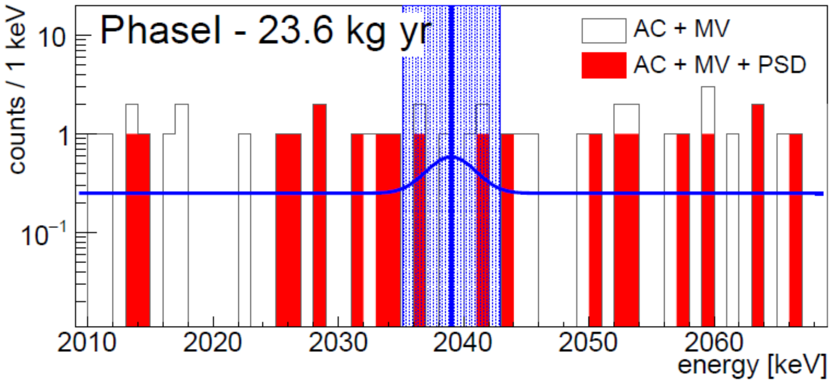
* Steve Elliott, "Initial Results from the MAJORANA DEMONSTRATOR" Neutrino 2016, London

GERDA

‡



- The GERmanium Detector Array (GERDA) searches for neutrinoless double beta decay in ^{76}Ge
- Located underground at Gran Sasso National Laboratory
- Five detector strings with a total target mass of 20 kg are installed in 64 m³ of liquid argon
- Installed LAr scintillation light veto for background suppression after Phase I
- Phase II measurements currently ongoing



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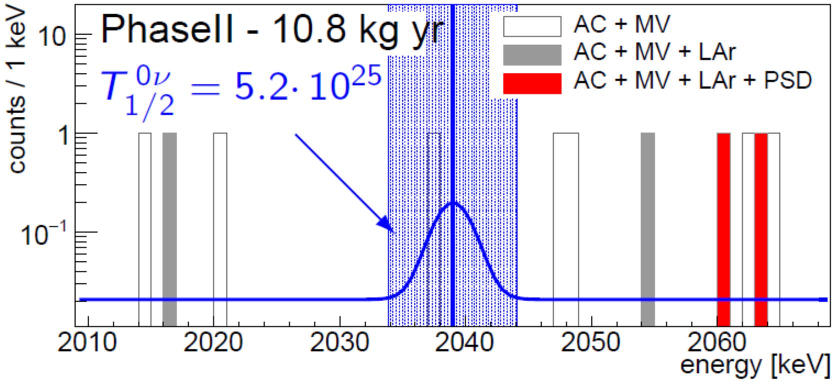

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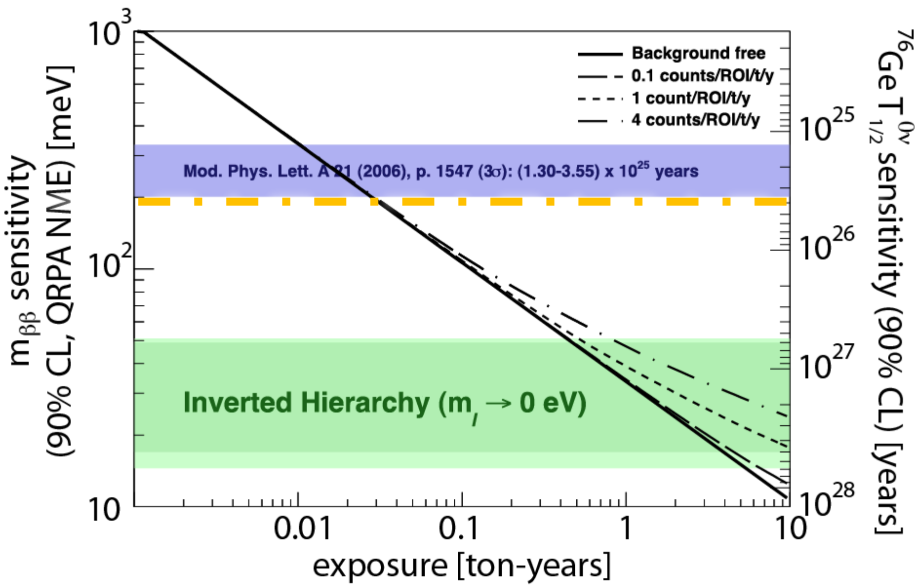
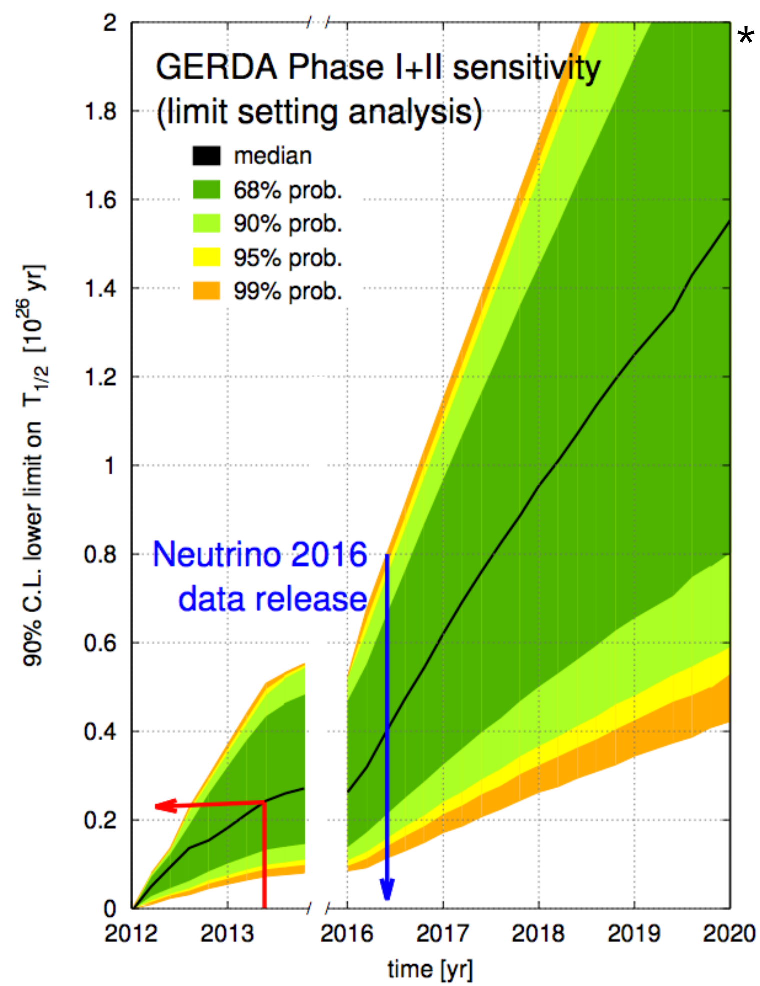
* Matteo Agostini, "First results from Gerda Phase II" Neutrino 2016, London

‡ Christoph Wiesinger, "GERDA meets KATRIN" KATRIN analysis workshop 2016, Munich

GERDA

- GERDA Phase II is a high-resolution and background-free experiment
- Combined Phase I + II sensitivity:
  $T^{0\nu}_{1/2} > 4.0 \times 10^{25}$ yr (90% C.L), preliminary





* Matteo Agostini, "First results from Gerda Phase II" Neutrino 2016, London

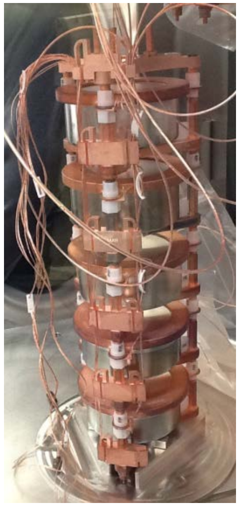
MAJORANA DEMONSTRATOR

- goal: demonstrate backgrounds low enough to justify building a tonne scale experiment
- 44.8 kg of Ge detectors: 29.7 kg enriched (88 %), 15.1 kg natural Ge
- two independent cryostats made from ultra-clean electroformed copper
- located underground at 4850´ Sanford Underground Research Facility

- Cryostat I in operation since January 2016, blind data collection since April 2016
- collected 3 kg yr before blinding:

  $T^{0\nu}_{1/2} > 3.7 \times 10^{24}$ yr

- commissioning of Cryostat II ongoing



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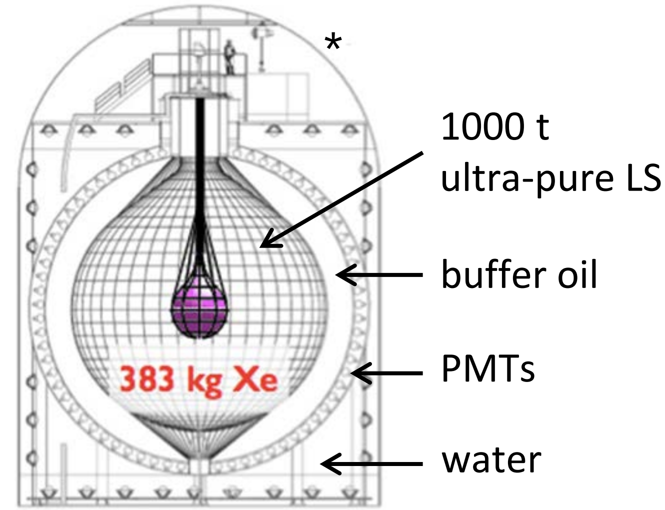
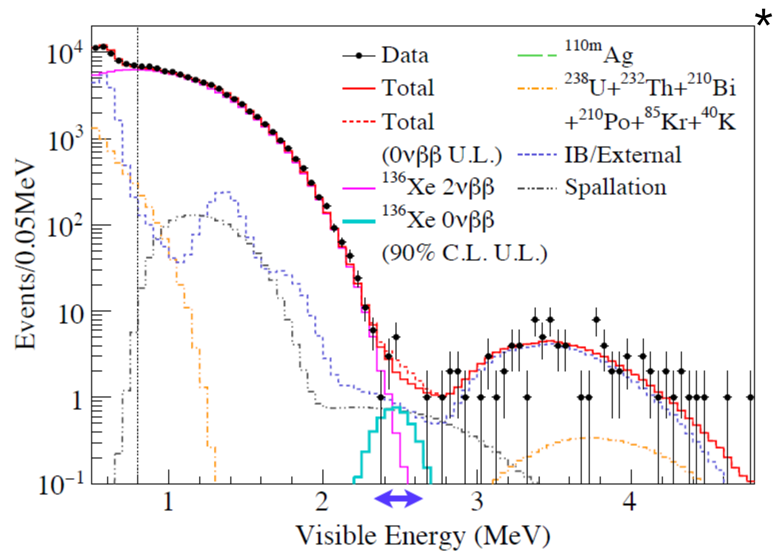
* Steve Elliott, "Initial Results from the MAJORANA DEMONSTRATOR" Neutrino 2016, London

KamLAND-Zen

- KamLAND-Zen repurposed the KamLAND liquid scintillator detector for the search of neutrinoless double beta decay in ^{136}Xe
- Target mass 383 kg Xe (91 % ^{136}Xe)
- Xe purification system
- Combined result phase 1 + 2:

  $T^{0\nu}_{1/2} > 1.07 \times 10^{26}$ yr (90% C.L)
- Detector is currently being upgraded for operation with 750 kg enriched Xe
- R&D for future upgrade to 1000 kg Xe in order to cover the region of inverted mass ordering





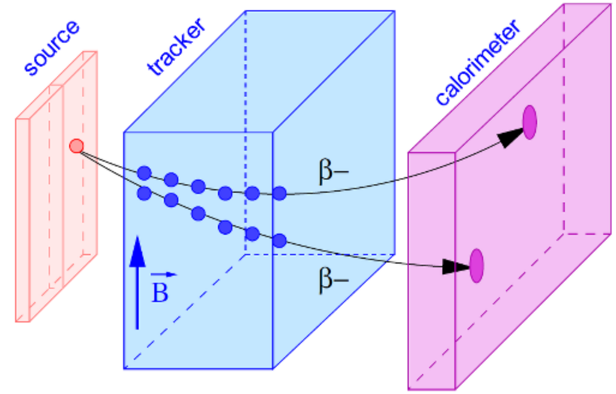
* Junpei Shirai, "Results and future plans for the KamLAND-Zen" Neutrino 2016, London

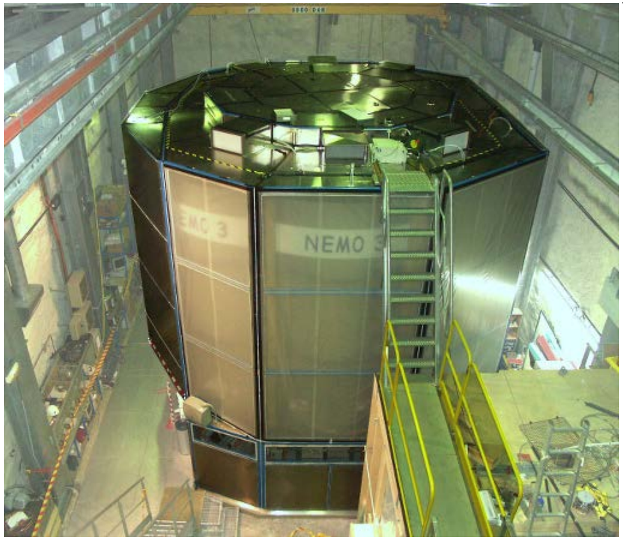
Nemo-3 & SuperNEMO

- Located at 4800 m.w.e. at the Laboratoire Souterrain de Modane (LSM)
- Source separated from detector
- Topological event reconstruction and particle identification allows strong background reduction
- World´s best measurements of $2\nu\beta\beta$ for various isotopes (^{100}Mo, ^{82}Se, ^{96}Zr, ^{48}Ca, ^{116}Cd, ^{130}Te, ^{150}Nd)
- Result for $0\nu\beta\beta$ in ^{100}Mo:

  $T^{0\nu}_{1/2} > 1.1 \times 10^{24}$ yr (90% C.L)

- SuperNEMO Demonstrator Module nearing completion at the LSM





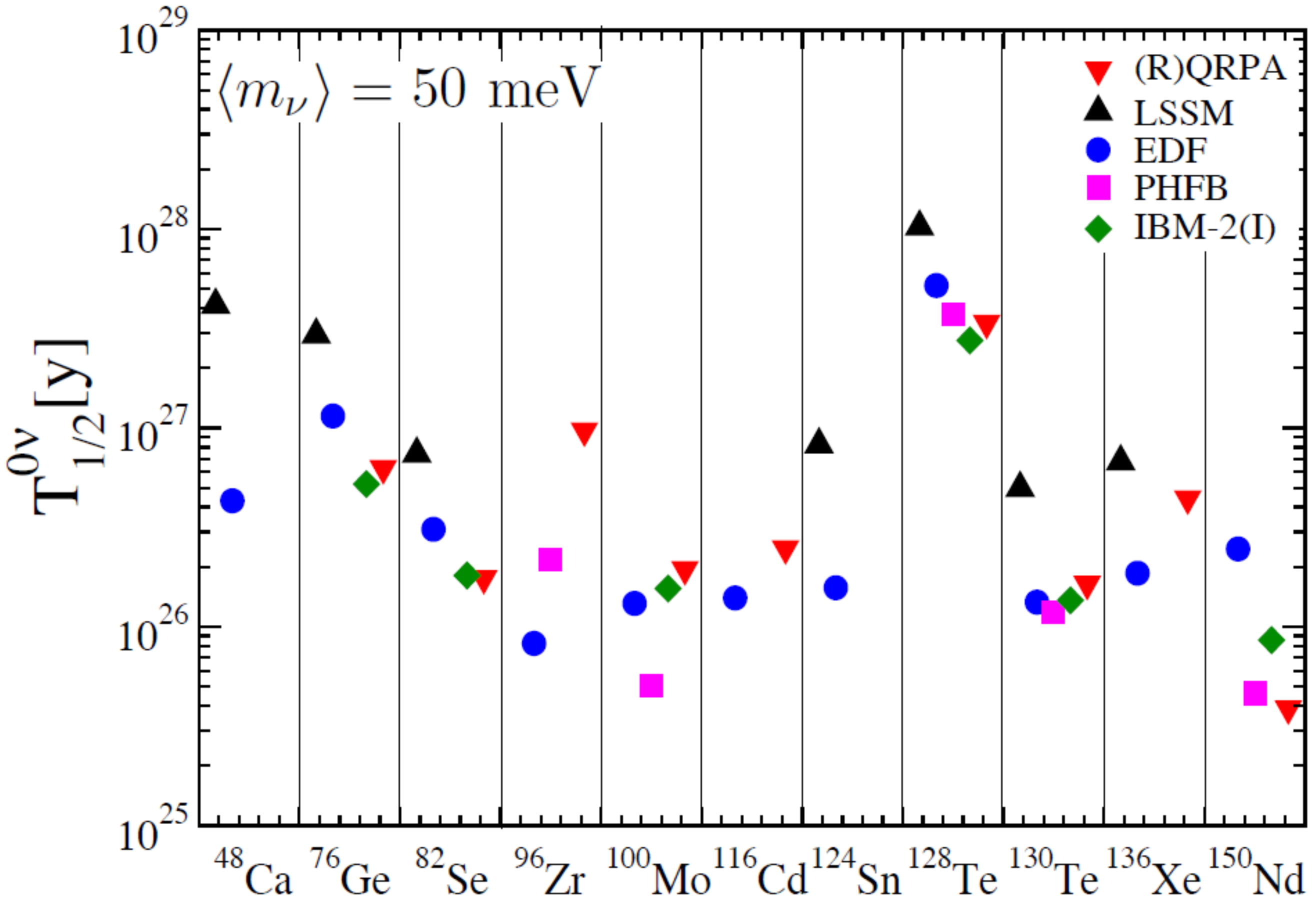
* David Walters, "Latest Results from NEMO-3 & Status of the SuperNEMO Experiment" Neutrino 2016, London

summary

- KATRIN experiment is preparing for first tritium runs in 2017
- R&D for new approaches in direct neutrino mass measurements: electron capture of ^{163}Ho and cyclotron resonance emission spectroscopy
- Several $0\nu\beta\beta$ experiments are currently taking data
- R&D for next-generation $0\nu\beta\beta$ experiments targeting the region of inverted mass ordering

Backup

0νββ nuclear matrix elements



Vergados et al. 2012