Direct neutrino mass determination

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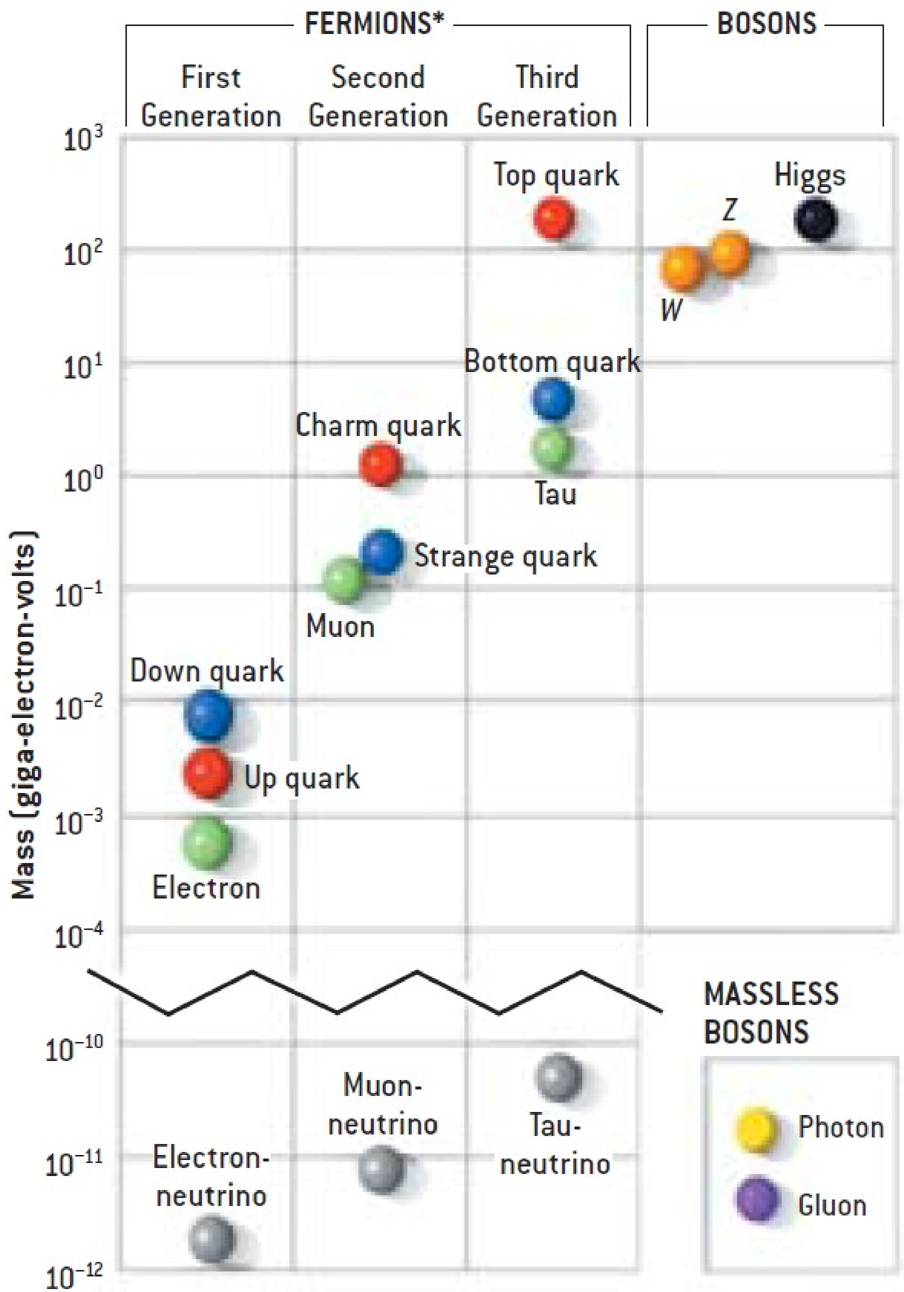
Summary

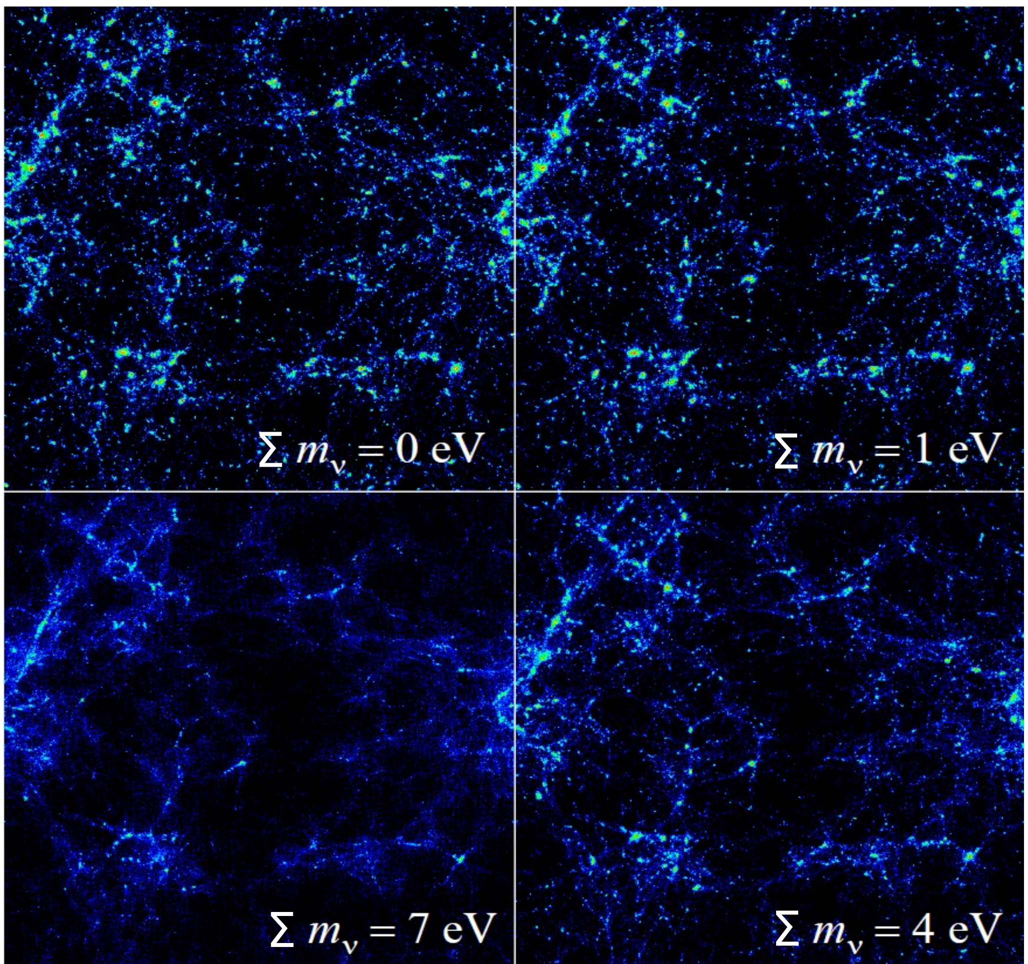
Neutrino mass in particle physics

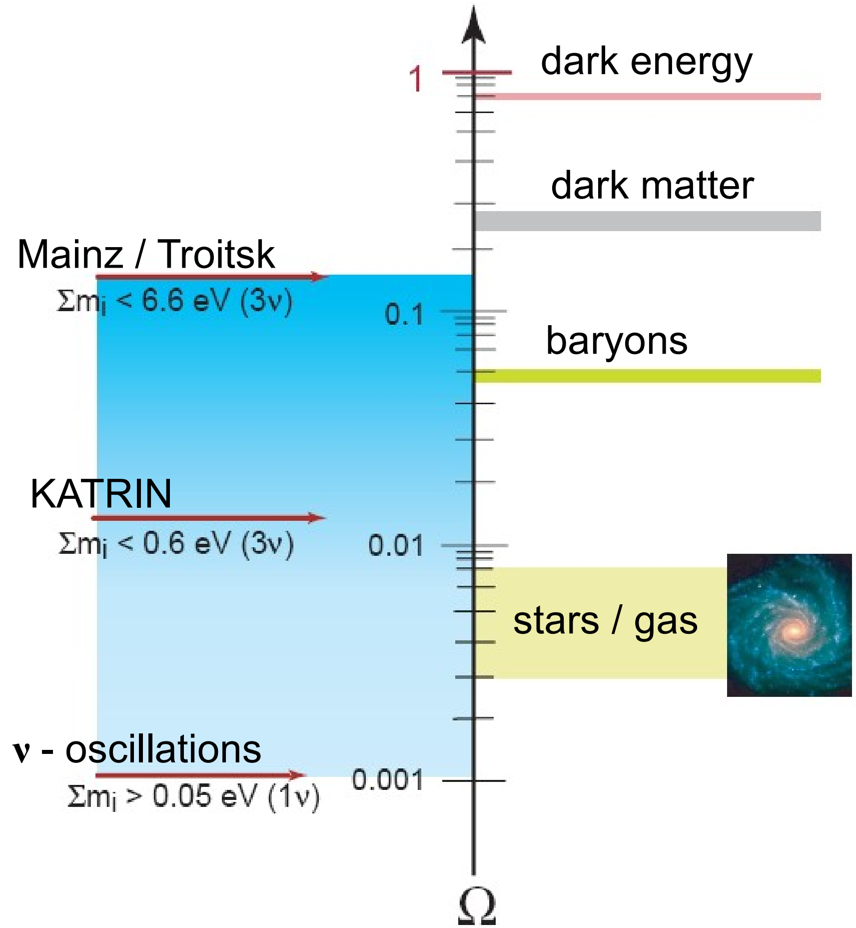
- Nature of the neutrino: Majorana or Dirac particle, i.e. is the neutrino it's own anti-particle ?
- How to explain the many orders of magnitude difference between neutrino mass limits and masses of the charged fermions of the standard model
  → sea-saw type I and type II mechanisms
- Possible connection to the generation of the observed matter - antimatter asymmetry in the universe
  → leptogenesis



Neutrino mass in cosmology

- Neutrinos are (after γ's) the second most abundant particle species in the universe
- As part of the hot dark matter, neutrinos have a significant influence on structure formation





- For large Σm_ν values fine grained structures are washed out by the free streaming neutrinos

Chung-Pei Ma 1996

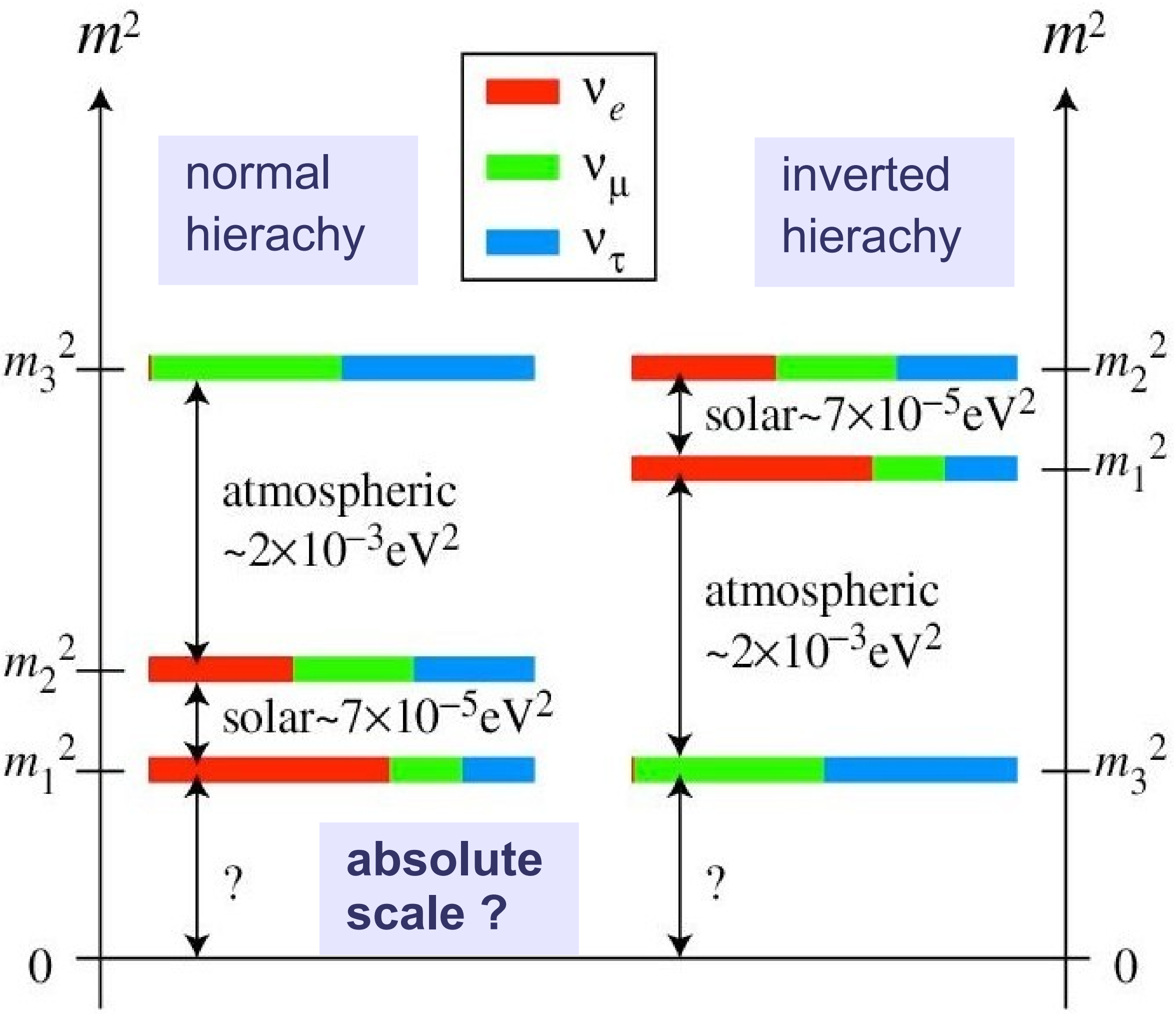
Current knowlegde and open questions

What we know (from ν oscillations):

- Neutrino flavour eigenstates differ from their mass eigenstates
- Neutrinos oscillate, hence they must have mass
- Mixing angles and Δm^2 values known (with varying accuracies)

What we don't know :

- Normal or inverted hierachy ?
- Dirac or Majorana particle ?
- CP violating phases in mixing matrix ?
- **No information about absolute mass scale !** (only upper limits)
- Existence of sterile neutrinos ?



β-decay: absolute ν-mass

model independent, kinematics

status: $m_\nu < 2.3$ eV

potential: $m_\nu \approx 0.2$ eV

e.g.: KATRIN, Project-8, ECHO HOLMES, NuMECS

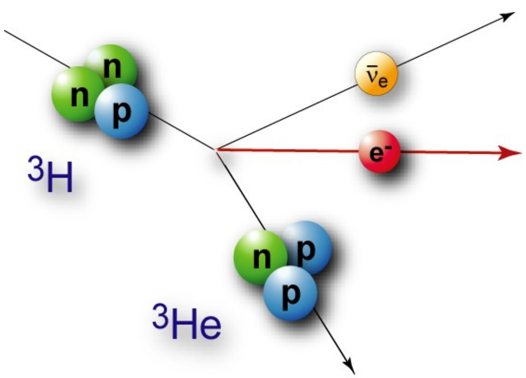
0νββ-decay: eff. Majorana mass

model-dependent (CP-phases)

status: $m_{\beta\beta} < 0.31$ eV

potential: $m_{\beta\beta} \approx 20\text{-}50$ meV

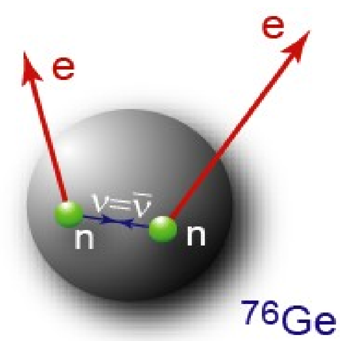
e.g.: GERDA, CUORE, EXO, SNO+, Majorana, Nemo 3, COBRA, KamLAND-Zen



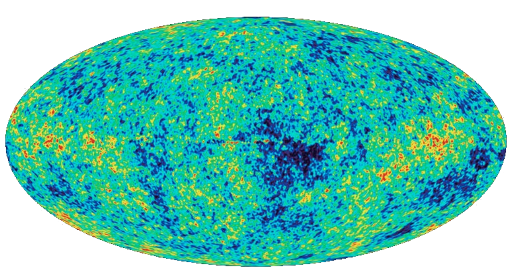
m_ν

neutrino mass measurements

$m_{\beta\beta}$



Σm_i



cosmology: ν hot dark matter Ω_ν

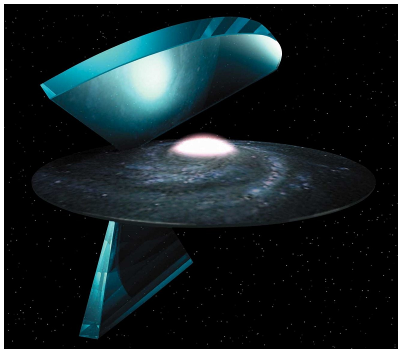
model dependent, analysis of CMB and structure formation data

status: $\Sigma m_\nu < 0.23$ eV

(*Planck Collaboration, A&A 594 (2016) A13*)

possible signal: $\Sigma m_\nu = 0.11 \pm 0.03$eV

(*Emami et al., arXiv:1711.05210*)



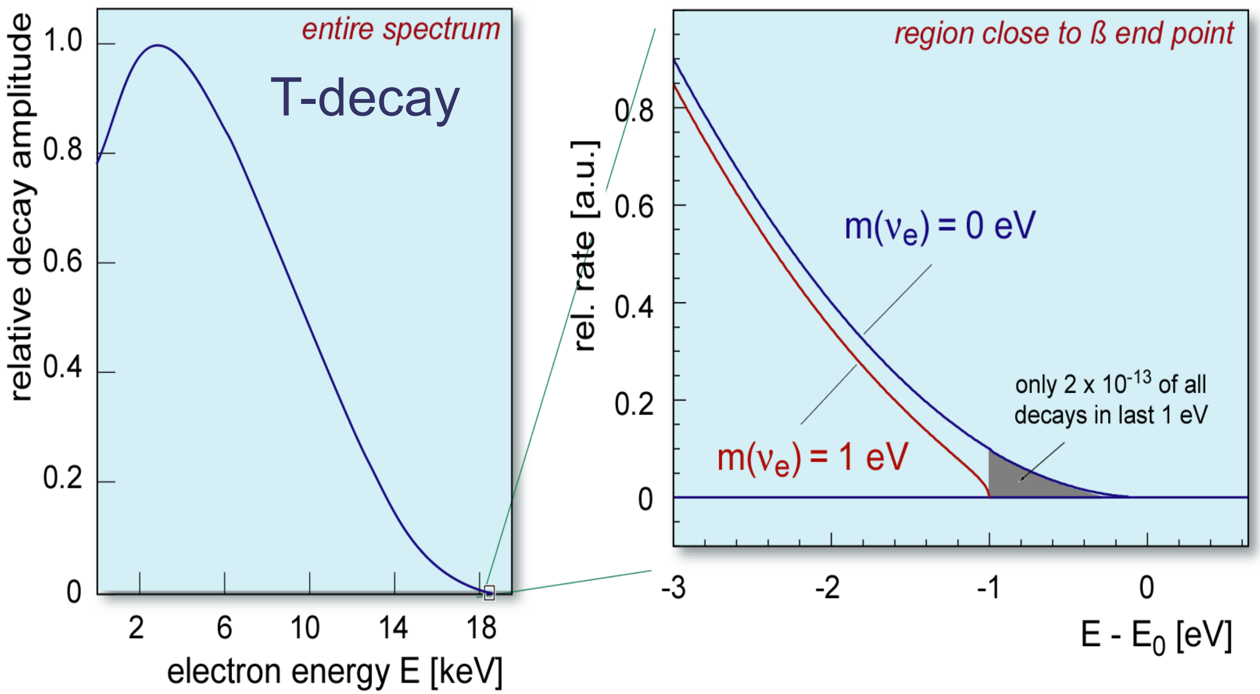
Kinematic determination of $m(\nu_e)$

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

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

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

(modified by final state distribution, recoil corrections, radiative corrections, ...)



Suitable Isotopes:

Tritium
- E_0 = 18.6 keV, $T_{1/2}$ = 12.3 a
- S(E) = 1 (super-allowed)

Rhenium
- E_0 = 2.47 keV, $T_{1/2}$ = 43.2 Gy

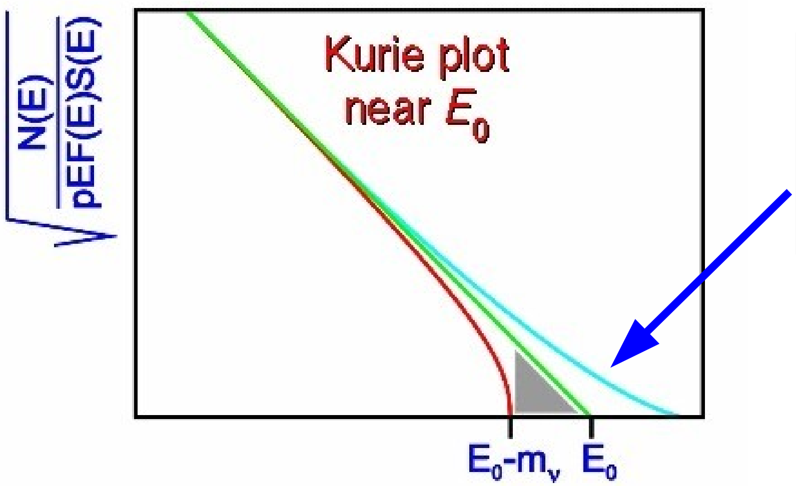
alternative approach:

Holmium (EC decay)
- Q_{EC} ≈ 2.5 keV, $T_{1/2}$ = 4570 y

(Main) experimental approaches

Detector requirements:

- large solid angle or source=detector approach
- high energy resolution
- low background
- low dead time / no pile up



effect of :
- background
- pile up
- fluctuations

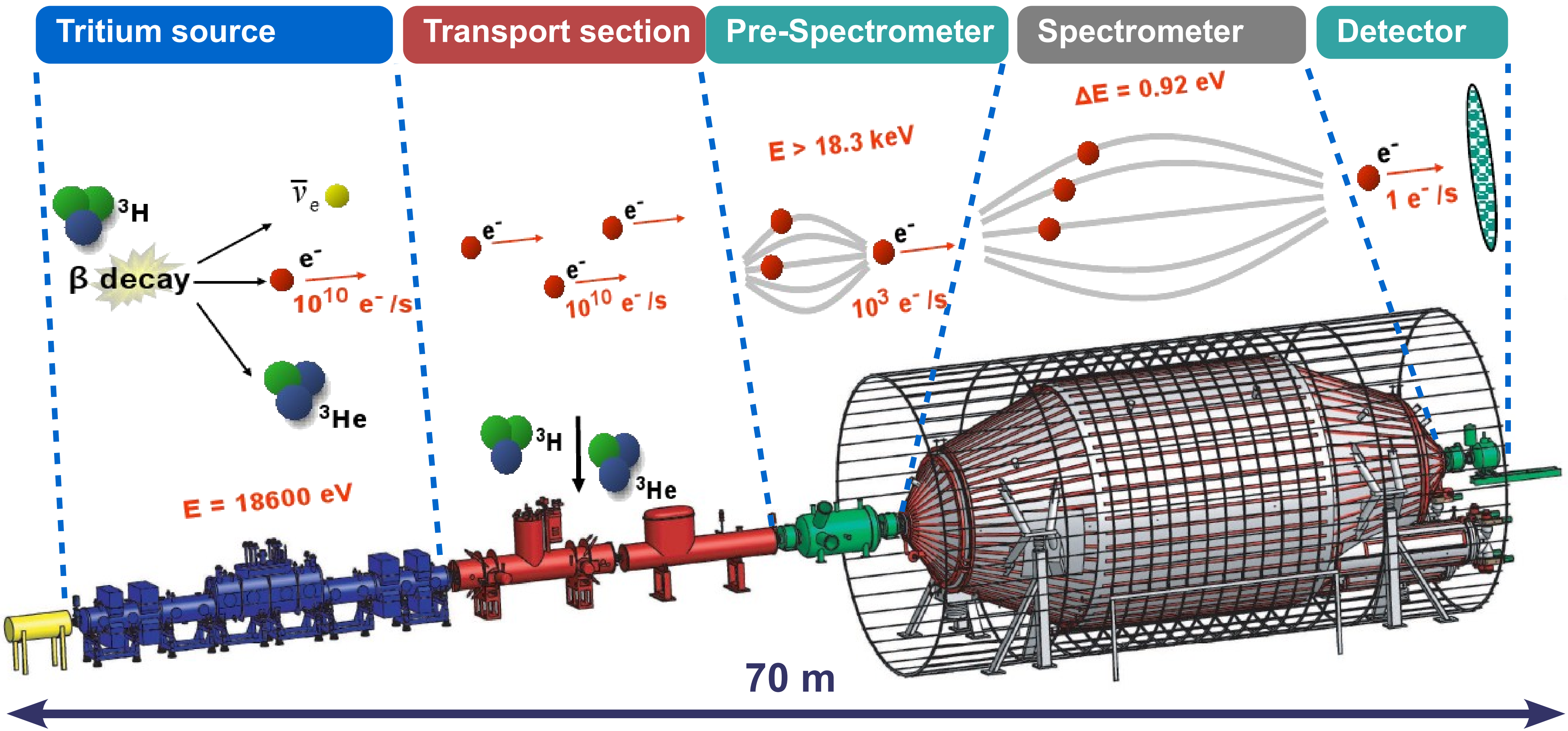
Tritium based experiments

- **KATRIN:** gaseous tritium source with MAC-E type integrating spectrometer determining kinetic energy spectrum of β-decay electrons
- **Project 8:** gaseous tritium source determining kinetic energy spectrum of β-decay electrons by measuring cyclotron radiation emitted in a magnetic field

Holmium based experiments

- **ECHO:** Calorimetric measurement of energy released in EC decay of ^{163}Ho using Metallic Magnetic Calorimeters (MMC)
- **HOLMES:** Calorimetric measurement of energy released in EC decay of ^{163}Ho using Transition Edge Sensors (TES), successor of MARE effort
- **NuMECS:** similar experimental approach as HOLMES

KATRIN experiment at KIT



MAC-E filter concept

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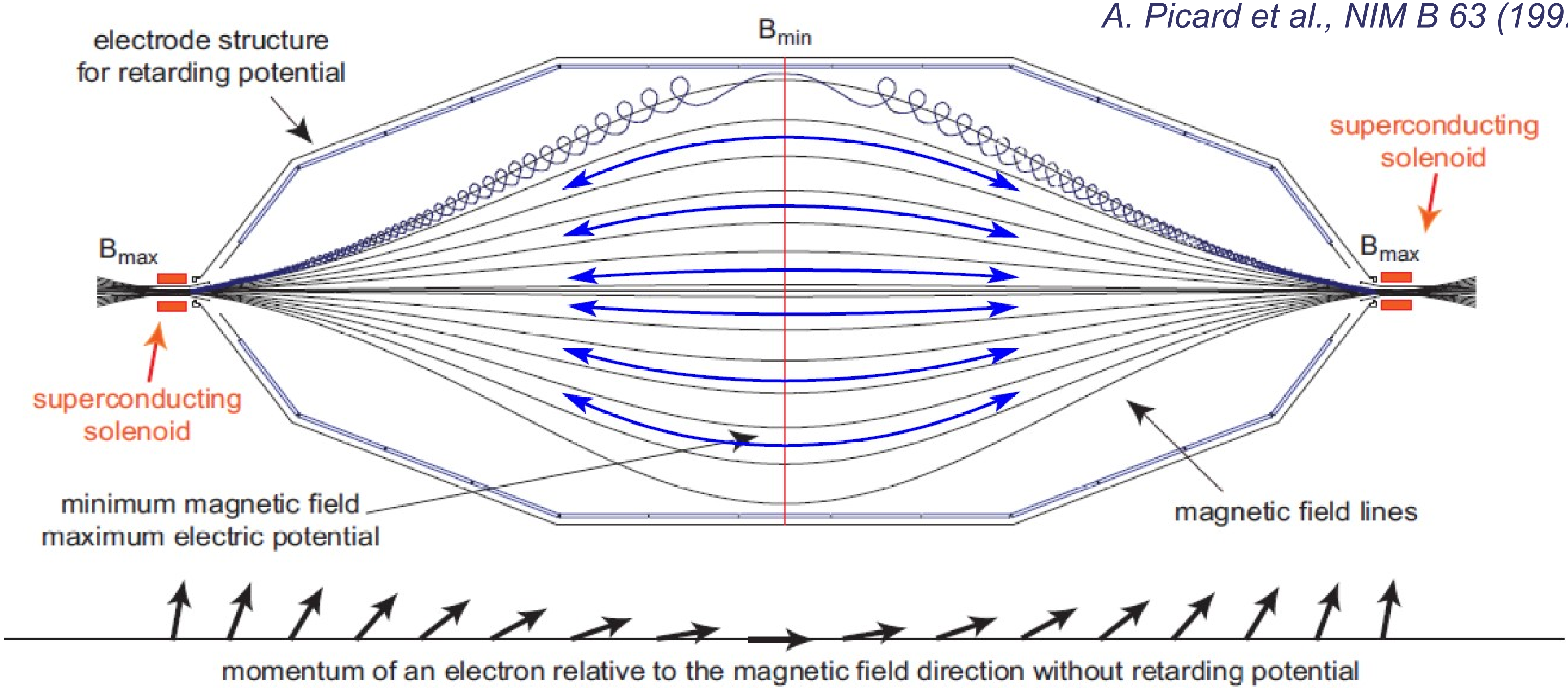
Magnetic Adiabatic Collimation with Electrostatic Filter

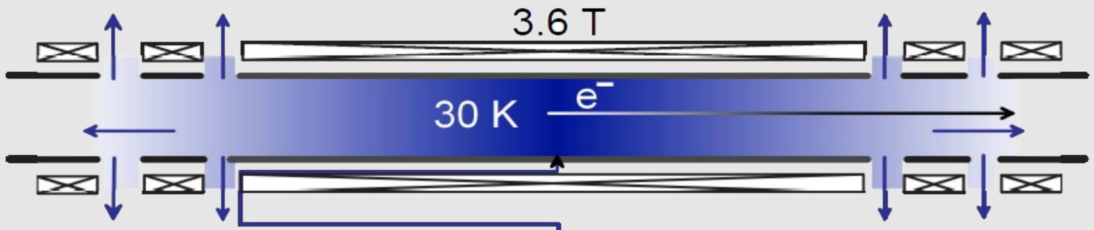
A. Picard et al., NIM B 63 (1992)



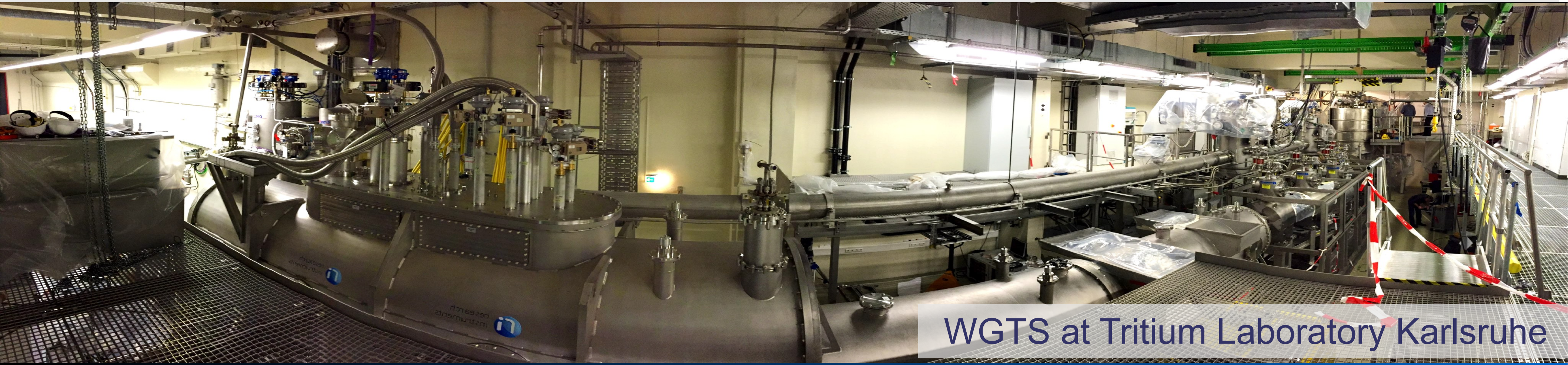
- adiabatic transport → $\mu = E_{\perp} / B = const.$
- B drops by $2 \cdot 10^4$ from solenoid to analyzing plane → $E_{\perp} \rightarrow E_{||}$
- only electrons with $E_{||} > eU_0$ can pass the retardation potential
- Energy resolution $\Delta E = E_{\perp,max,\ start} \cdot B_{min} / B_{max} < 1$ eV

Windowless Gaseous Tritium Source

- beam tube   Ø = 9 cm , L = 10 m
- guiding field   3.6 T
- temperature   T = 30 K ± 30 mK,
- T_2 flow rate $5 \cdot 10^{19}$ molecules/s (40 g of T_2 / day)
- T_2 purity   95% ± 0.1 %
- T_2 inlet pressure 10^{-3} mbar ± 0.1 %



- column density $5 \cdot 10^{17}$ T_2/cm^2
- luminosity $1.7 \cdot 10^{11}$ Bq

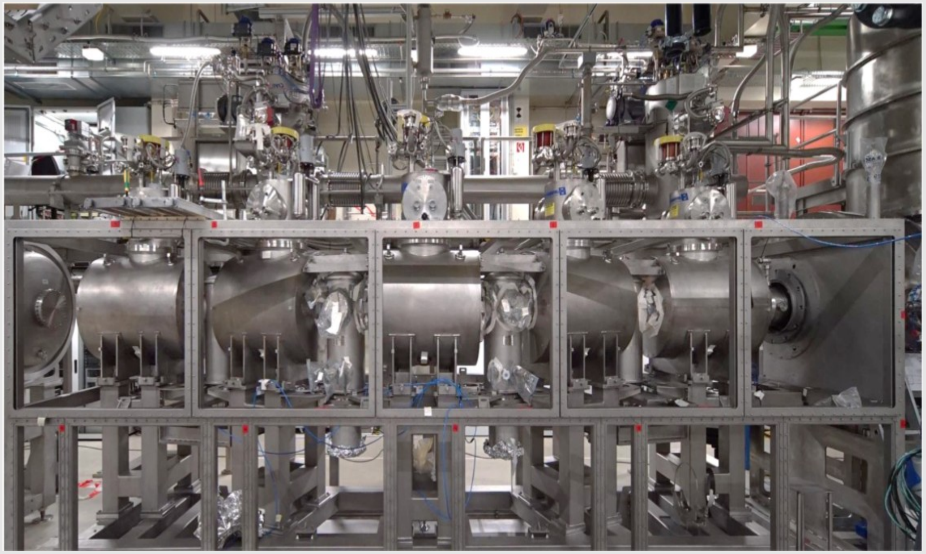


WGTS at Tritium Laboratory Karlsruhe

Pumping sections

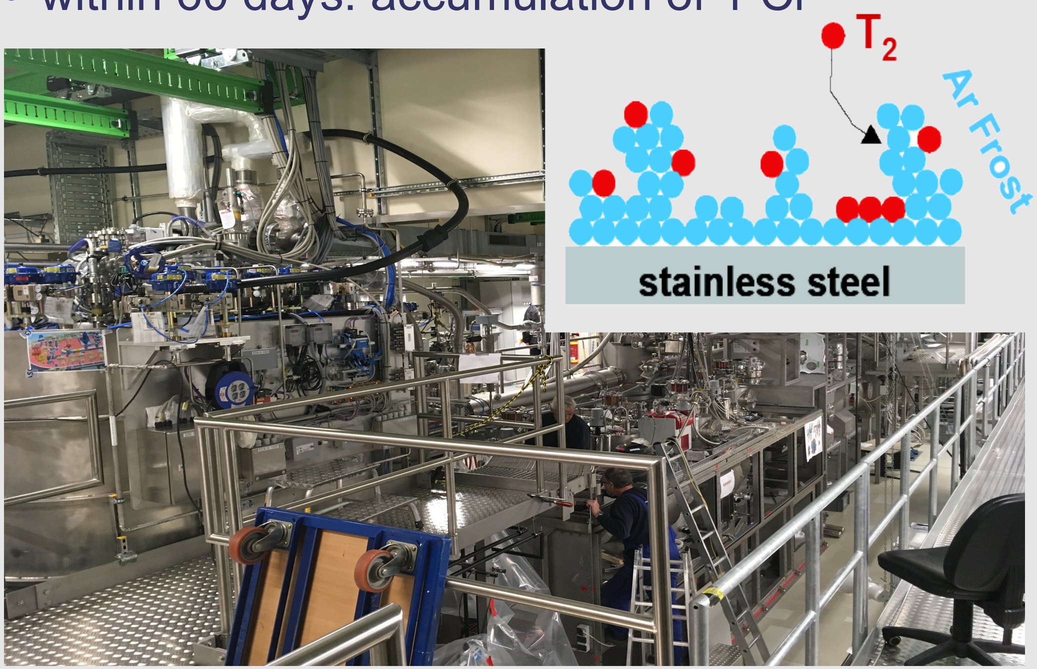
Differential Pumping Section (DPS2-F)

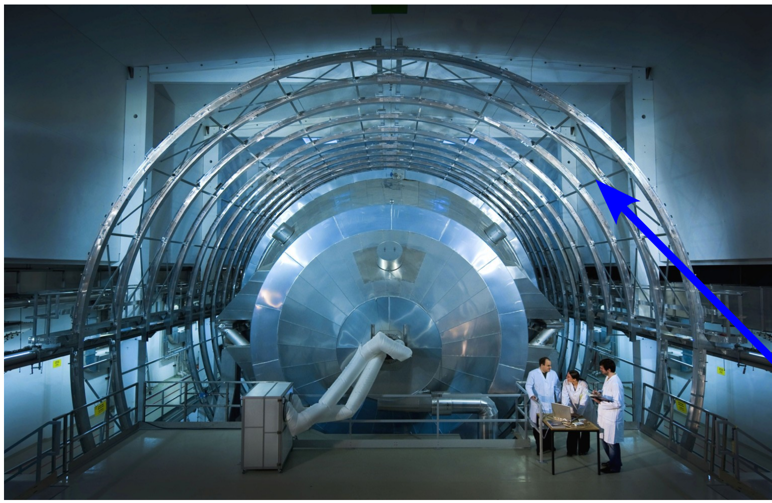
- magnetic guiding field B = 5.6 T
- differential pumping using 2000 l/s TMPs
  → tritium reduction factor: **$1\cdot10^5$**
- ion monitoring by FTICR
- ion manipulation by electrodes



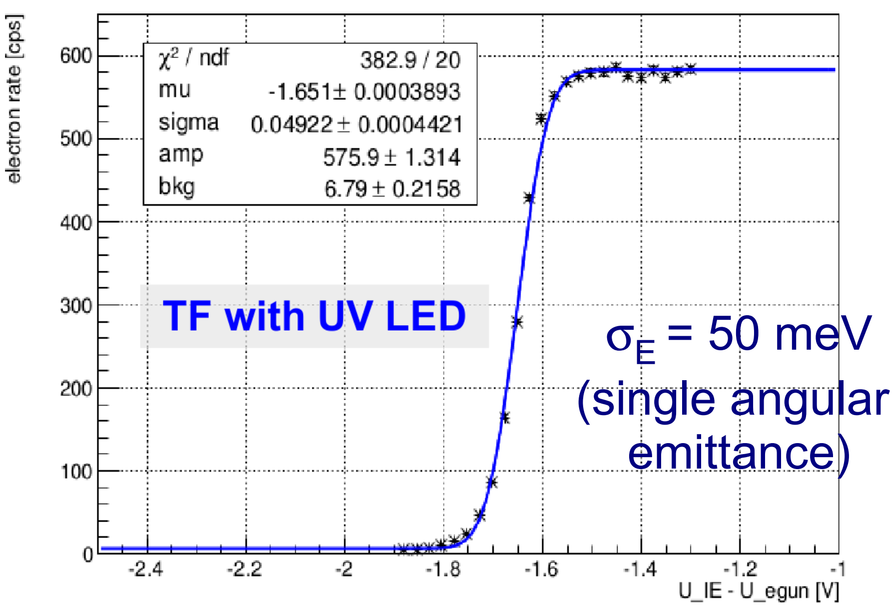
Cryogenic Pumping Section (CPS)

- magnetic guiding field B = 5.6 T
- cryosorption of T_2 on Ar frost at ≈ 3 K
  → tritium reduction factor **$1\cdot10^{-7}$**
- within 60 days: accumulation of 1 Ci





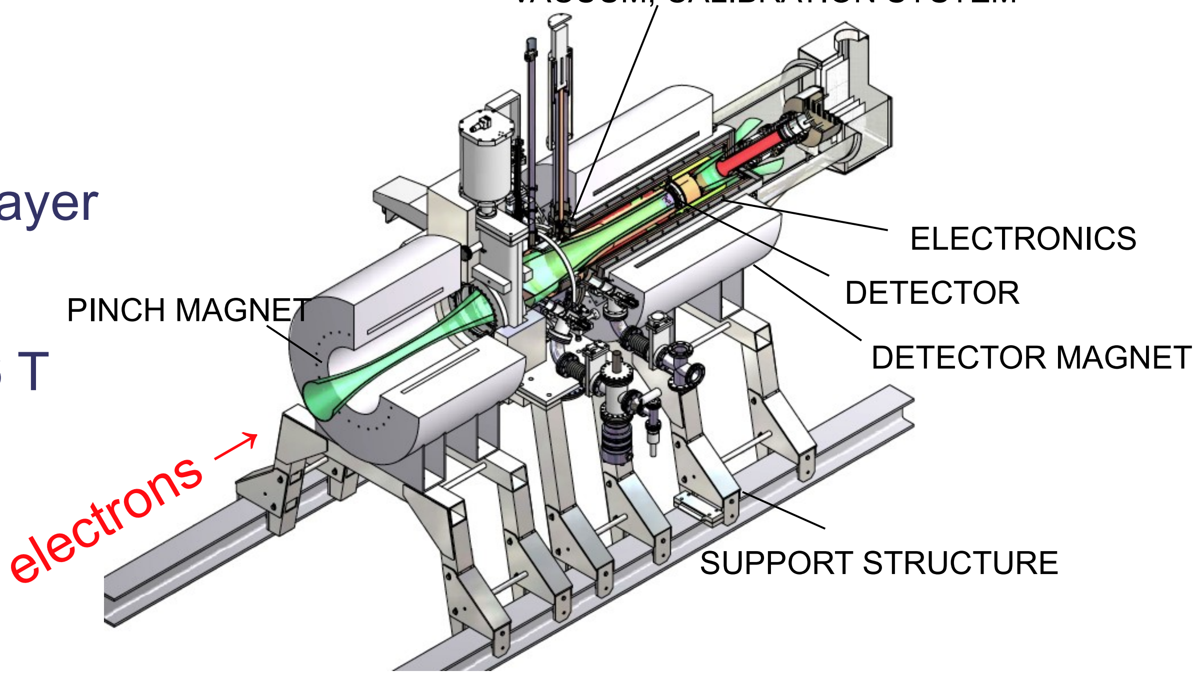
- 18.6 kV retardation voltage, σ < 60 meV
- 0.93 eV resolution
- pressure < 10^{-11} mbar
- Air coils for earth magnetic field compensation
- Double layer wire electrode for background reduction and field shaping



Focal Plane Detector

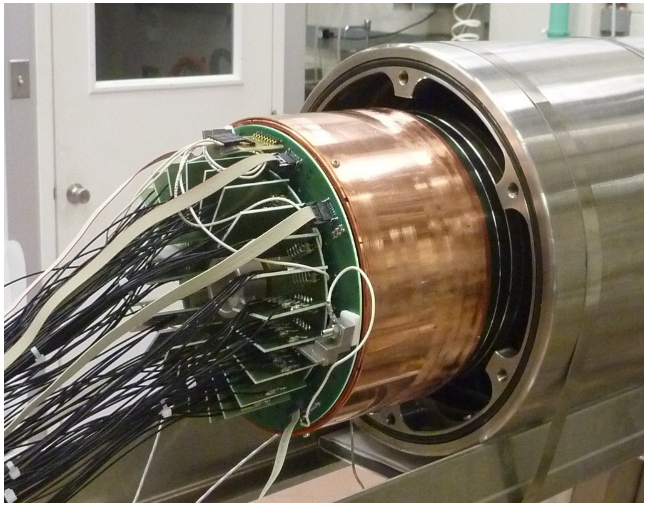
Focal plane detection system

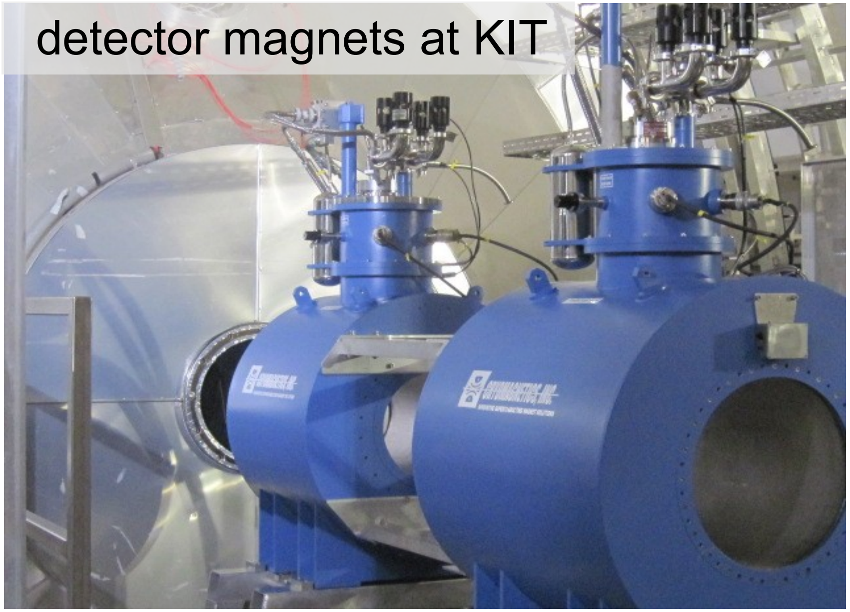
- segmented Si PIN diode:
  90 mm Ø, 148 pixels, 50 nm dead layer
- energy resolution ≈ 1 keV
- pinch and detector magnets up to 6 T
- post acceleration up to 30kV
- active veto shield



segmented Si-PIN wafer

pre-amplifier wheel





Beam line commissioning

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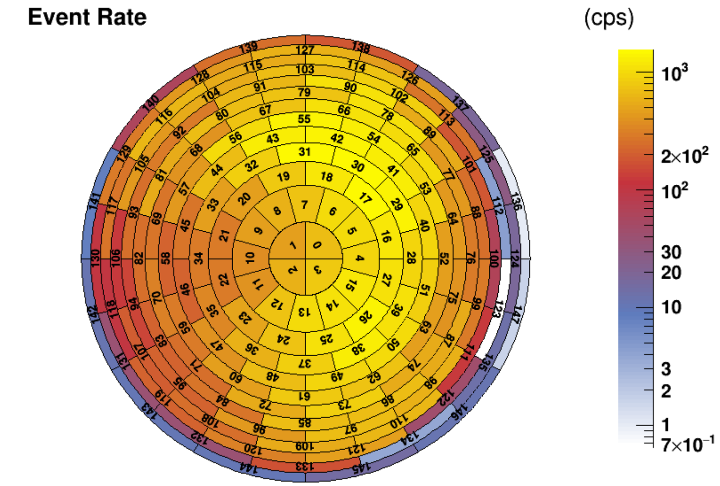
Technical start of KATRIN: „1st light“, photo-electrons from rear wall & and ions



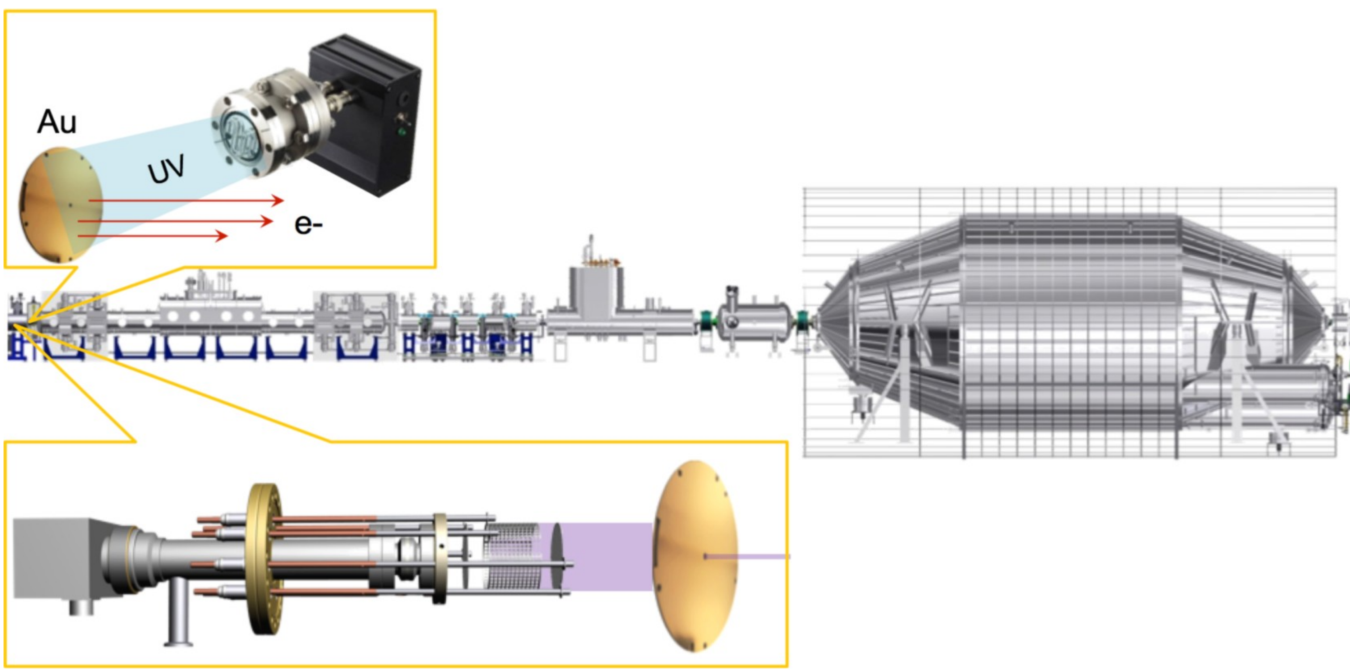
Testing complete 70m long beamline with electrons:

- alignment
- magn. stearing of pencil beam

and with ions:

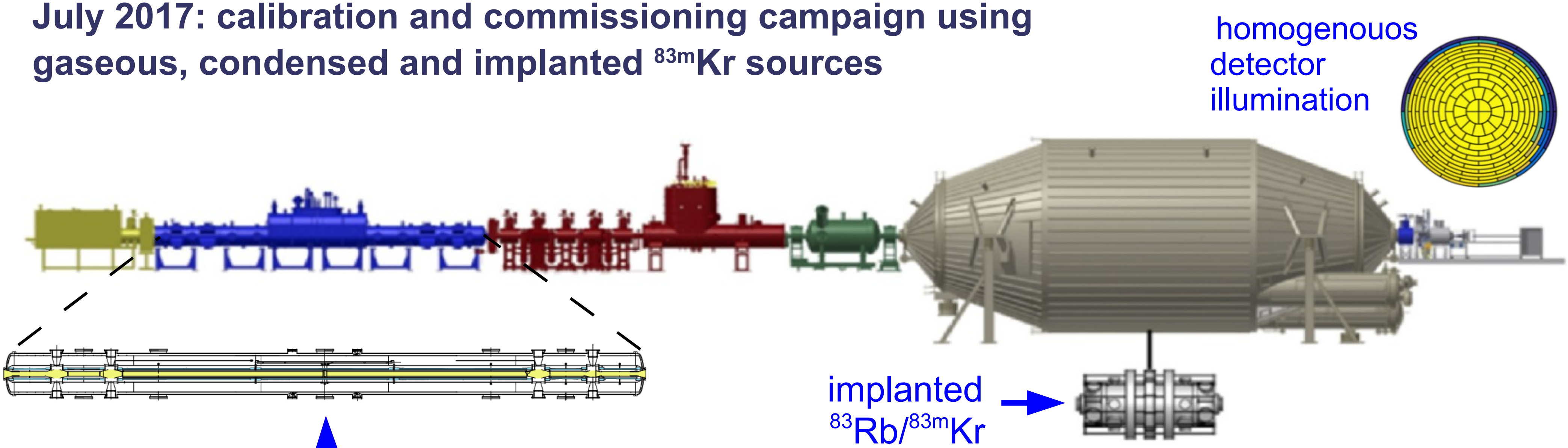
- ion removal

no tritium yet

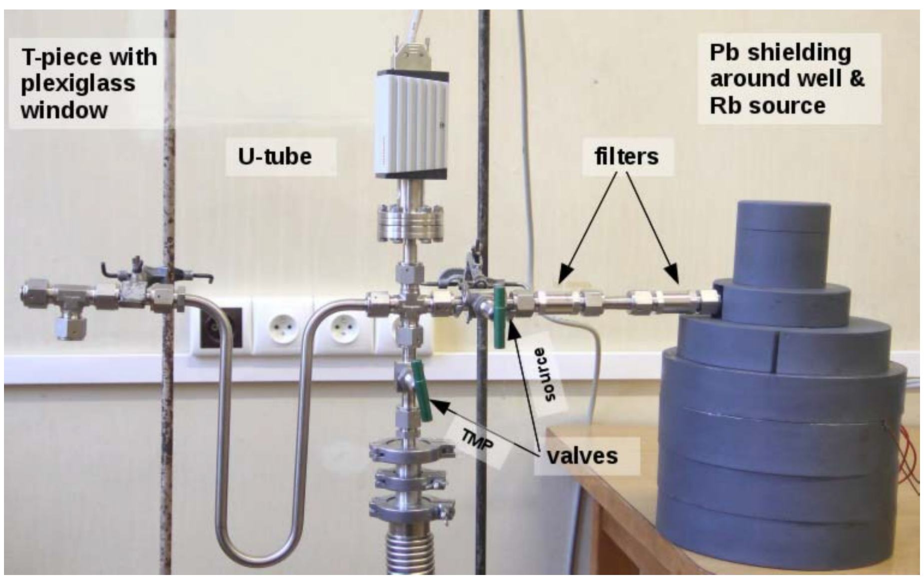


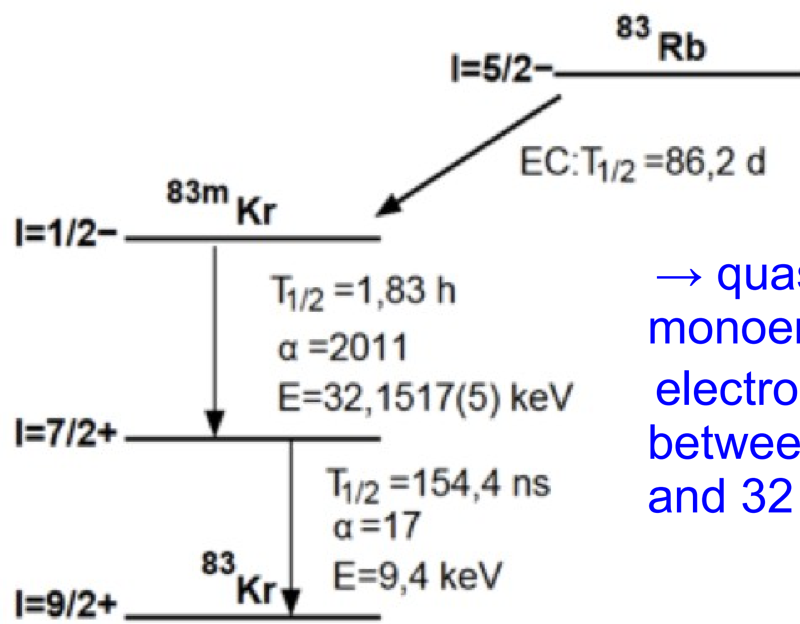
Commissioning campaign with ^{83m}Kr

July 2017: calibration and commissioning campaign using gaseous, condensed and implanted ^{83m}Kr sources



^{83m}Kr from 1 GBq ^{83}Rb source



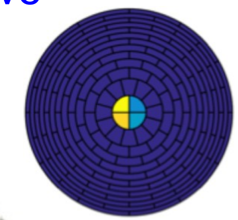


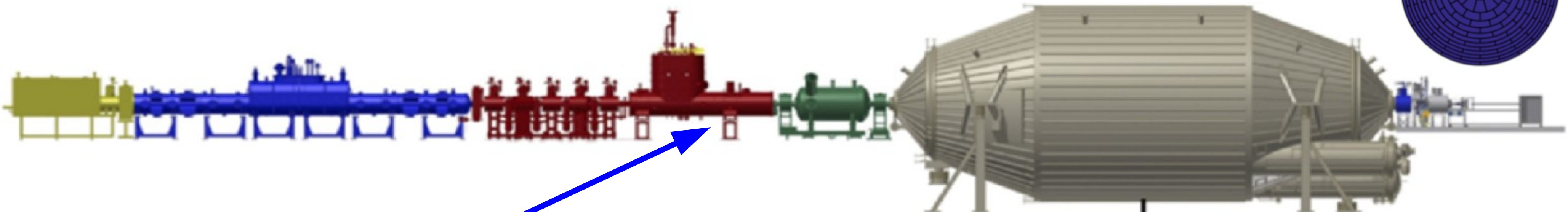
→ quasi-monoenergetic electron lines between 7 keV and 32 keV

Commissioning campaign with ^{83m}Kr

July 2017: calibration and commissioning campaign using gaseous, condensed and implanted ^{83m}Kr sources

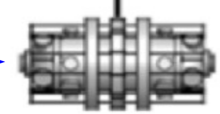
pixel selective detector illumination

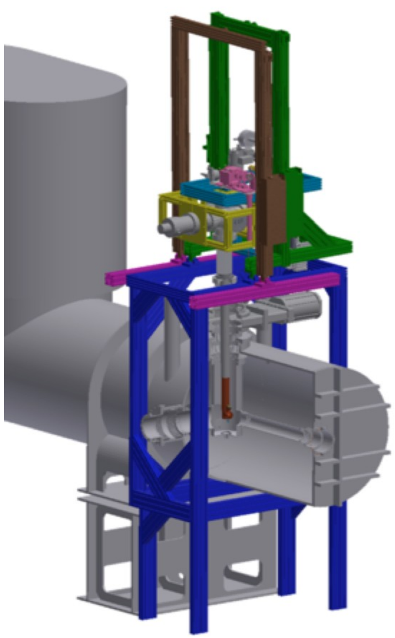


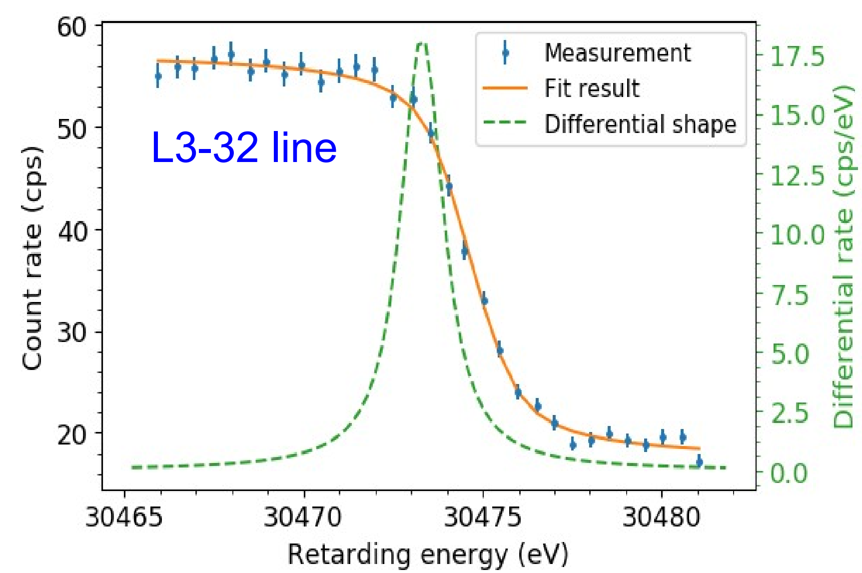


condensed ^{83m}Kr source, point-like, can be scanned over full flux tube

implanted ^{83}Rb/^{83m}Kr







preliminary, small part of statistics only !

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: ϕ < 20mV)
   - 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 $\Delta m_\nu^2 \leq 0.007\ eV^2$

$\Leftrightarrow \sigma < 60$ meV

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

$\Rightarrow$ 3 ppm long term stability

Systematic effects and error budget

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   - calibration measurements with e-gun necessary
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fluctuations σ^2 lead to a downward shift in m_ν^2

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

KATRIN sensitivity:
5 year measurement
(eff. 3 y of data)

statistical uncertainty σ_{stat} ≈ **0.018 eV²**

systematic uncertainty $\sigma_{sys,tot}$ ≈ **0.017 eV²**

→ sensitivity for upper limit: **0.2 eV/c²** (90% C.L.)
$m(\nu_e)$ = 0.35 eV observable with 5σ

5. Final state distribution
   - reliable quantum chem. calculations

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   - precise HV-Divider (PTB), monitor spectrometer, calibration sources

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$\Rightarrow$ 3 ppm long term stability

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Measurement of coherent cyclotron radiation of tritium β electrons

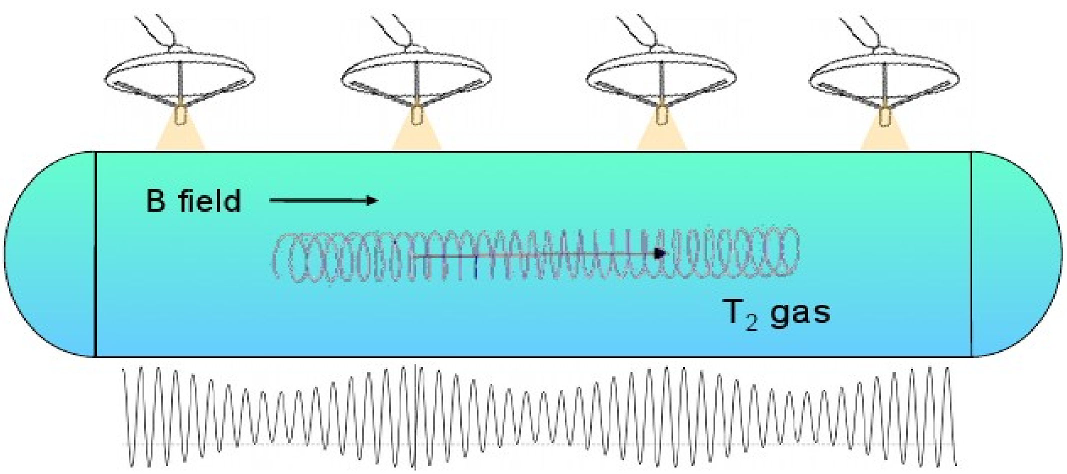
- Source similar to KATRIN: guiding magnetic field + low pressure T_2 gas
- β electrons radiate coherent cyclotron radiation with frequency:

$$\omega(\gamma)=\frac{\omega_0}{\gamma}=\frac{e\,B}{E_k+m_e}$$

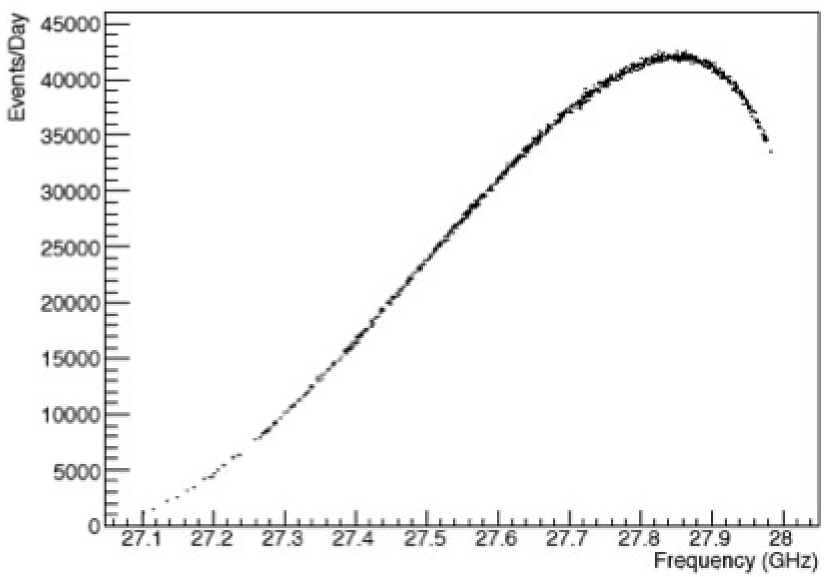
- Antenna array for cyclotron radiation detection

PROJECT 8

UW (Seattle), MIT, UCSB (Santa Barbara), Yale, Pacific NW, Livermore, NRAO, KIT



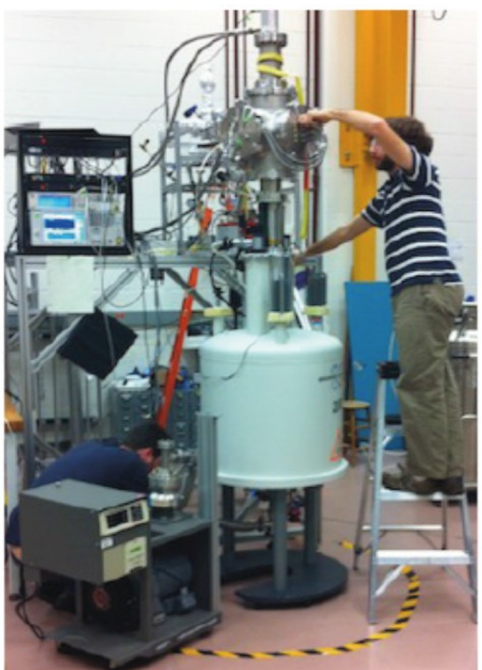
combined antenna signal

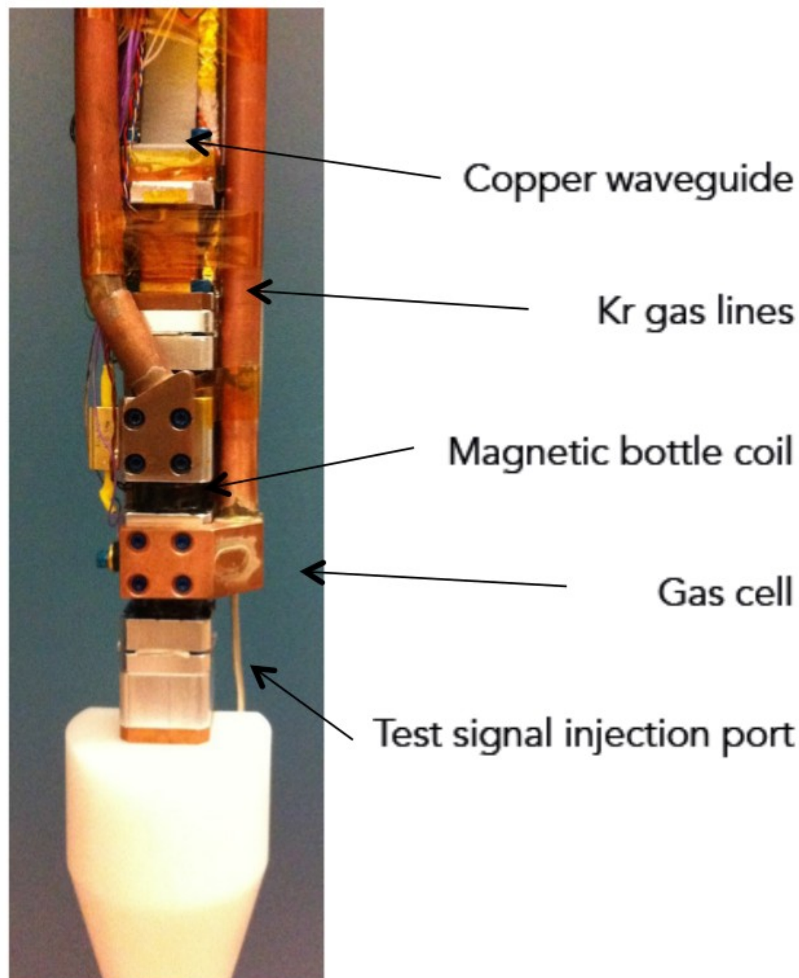


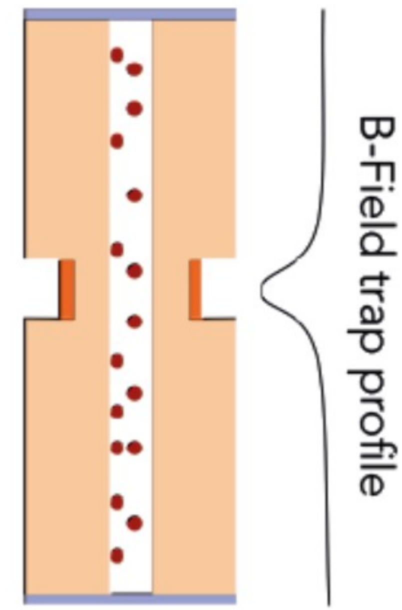
B. Monreal and J. Formaggio, PRD 80:051301, 2009

Prototype for ^{83m}Kr measurements

- ^{83m}Kr moving within a waveguide
- Cyclotron radiation picked up by cascaded cryogenic low noise amplifiers
- B-field: 1 Tesla
- ω(18 keV) ~ 26 GHz
- P(18 keV) = 1.2 fW

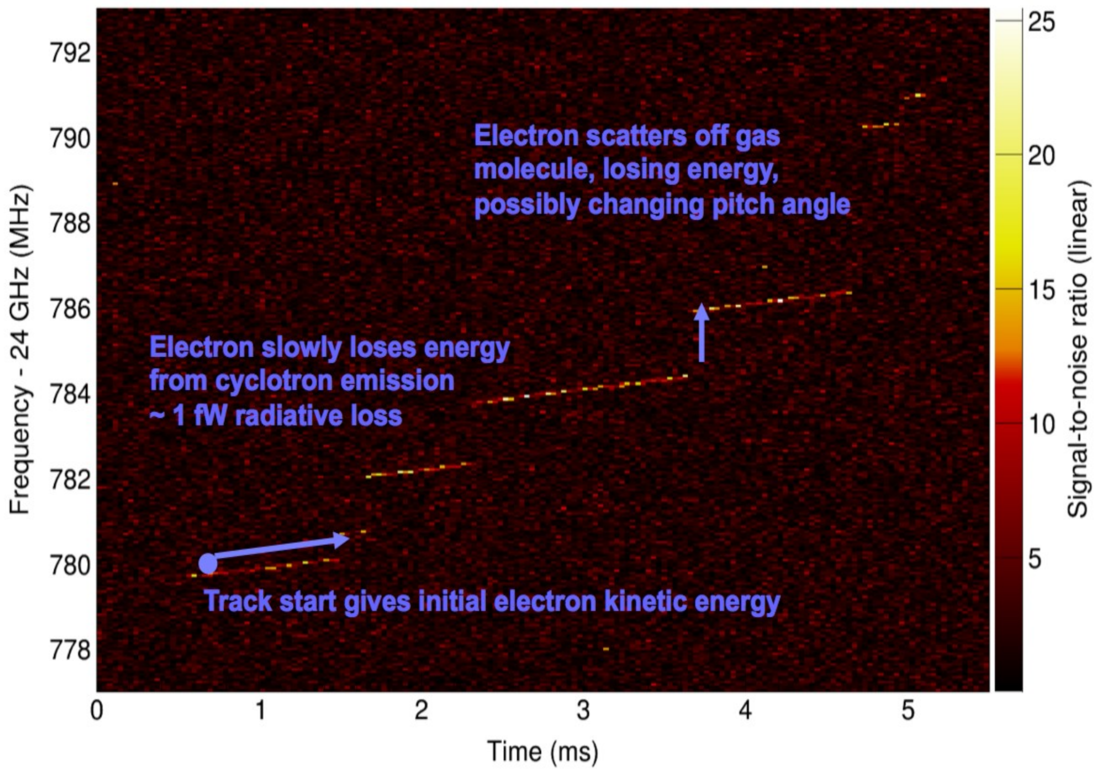




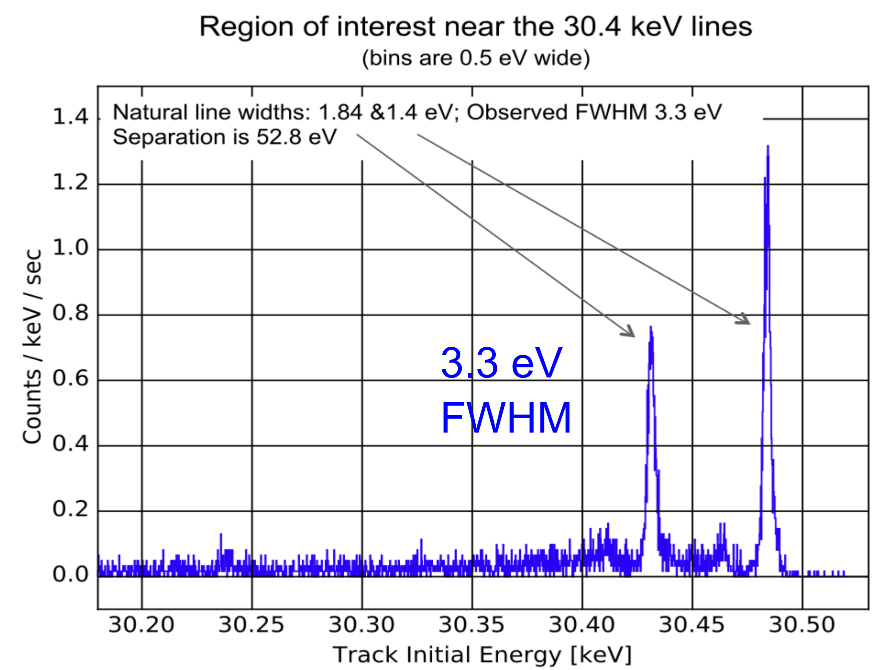


Waveguide Cut-away

First detection of cyclotron radiation from a single trapped electron

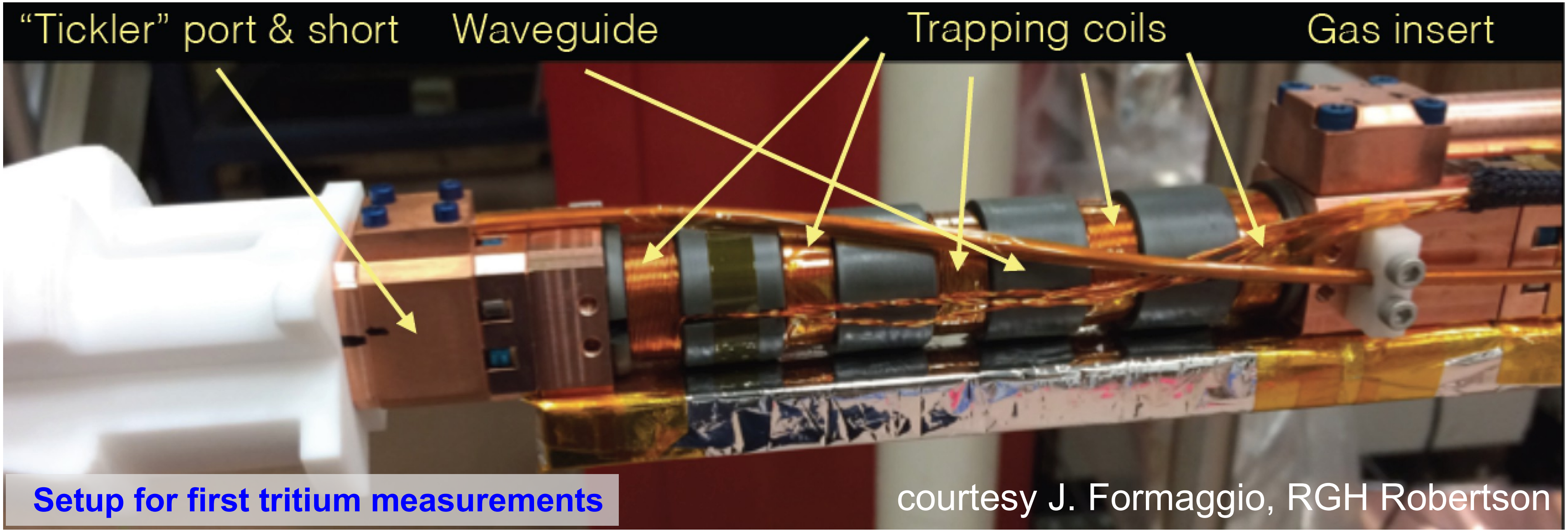


D. M. Asner et al., Phys. Rev. Lett. 114 (2015) 162501



A. A. Esfahani et al., J. Phys. G 44 (2017) 5

Phase 2: start of tritium spectroscopy

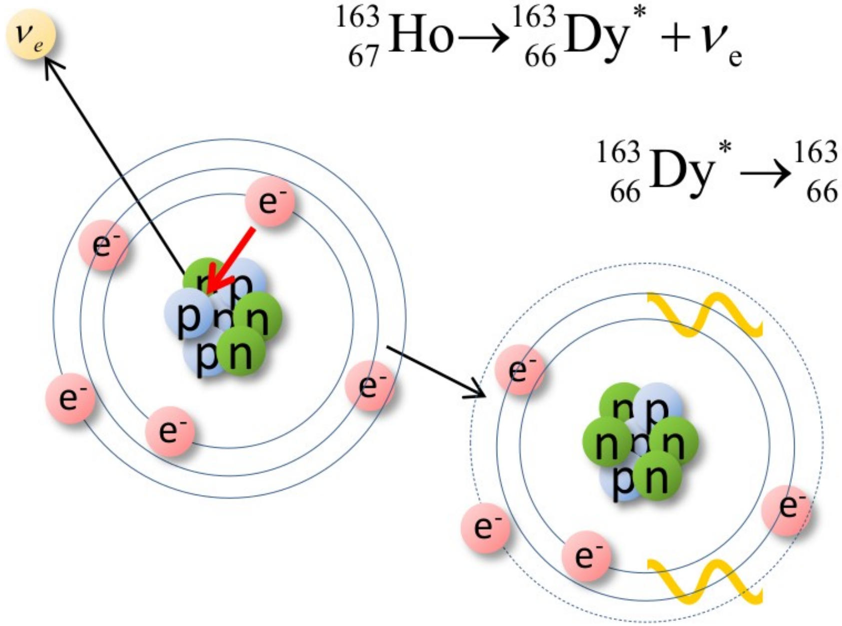


Setup for first tritium measurements

Project 8 outlook:

- T_2 spectroscopy with Project 8 should enable a similar or slightly better sensitivity as with KATRIN (assuming 10^{11} molecules/cm^3, 10 m^3 sensitive volume and 1 year measuring time optimistically 100 meV could be reached)
- Need to consider new systematics (Doppler shift, magnetic field drifts / inhomogeneities, scattering, pile-up, ...) → **lots of R&D work necessary !**
- If a large (100 m^3) atomic tritium source could be realized sensitivities down to 40 meV might be possible *(see A. A. Esfahani et al., J. Phys. G 44 (2017) 5)*

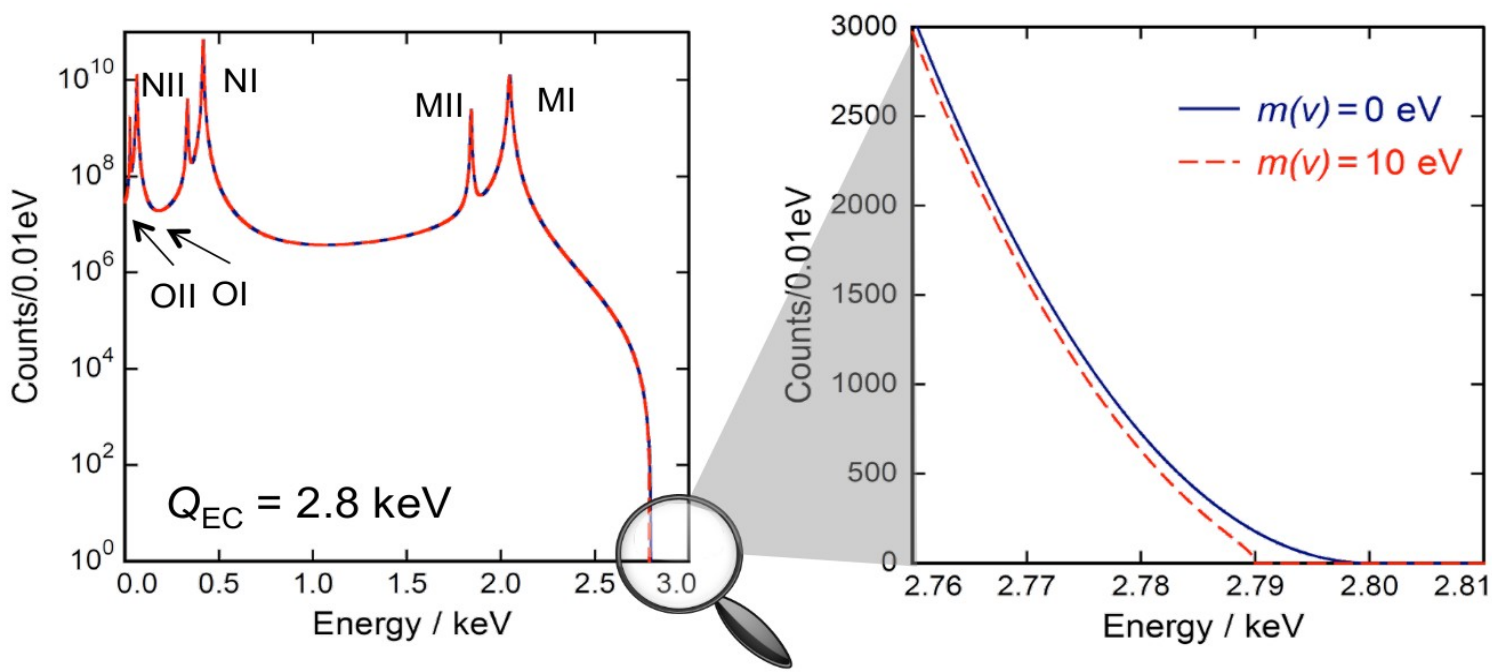
Electron capture in ^{163}Ho



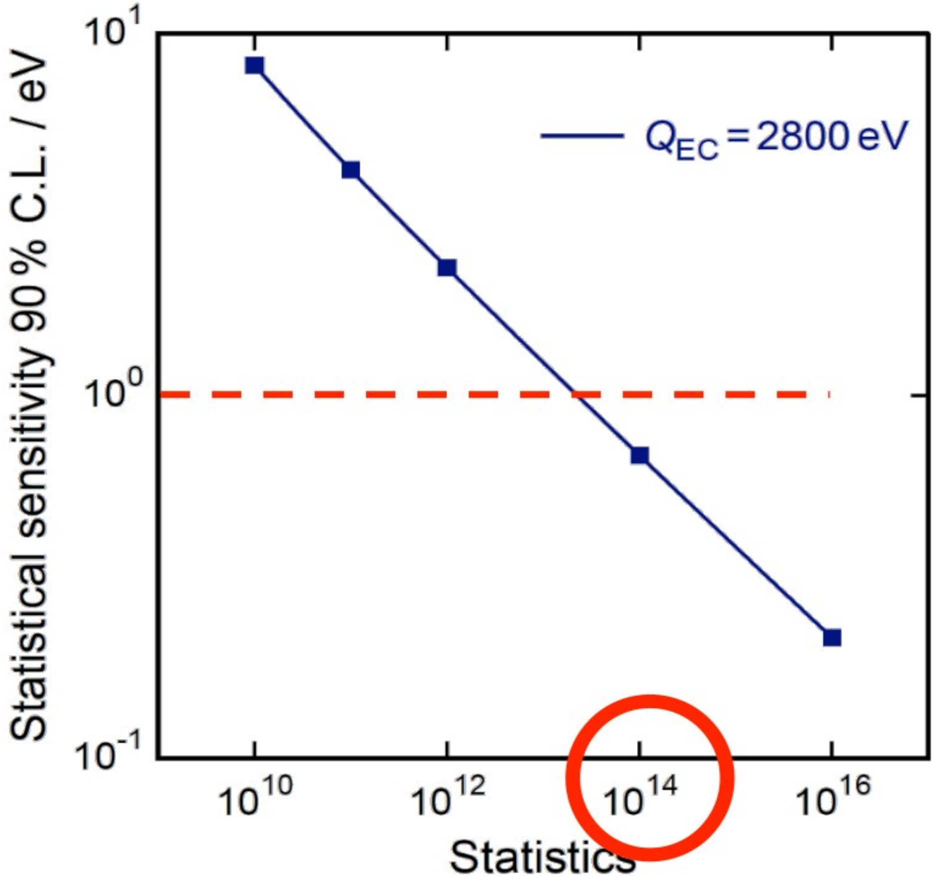
$$^{163}_{67}\mathrm{Ho} \rightarrow ^{163}_{66}\mathrm{Dy}^* + \nu_e$$

$$^{163}_{66}\mathrm{Dy}^* \rightarrow ^{163}_{66}\mathrm{Dy} + E_C$$

- ^{163}Ho decays by electron capture (EC) with $T_{1/2} \approx 4570$ y (2×10^{11} atoms for 1 Bq)
- Atomic de-excitation by:
  - X-ray emission
  - Auger electrons
  - Coster-Kronig transitions
- A non- zero neutrino mass affects the de-excitation energy spectrum



Calorimetric measurements



To reach sub-eV sensitivity:

10^{14} decays in 1 year

10 Bq / detector → 10^5 detectors

- **Calorimetric measurement:**
  All the energy released in the electron capture process minus the one of the electron neutrino is measured by the detector
- **Advantages:**
  - Source = detector
  - All energy is detected
- **Challenges:**
  - Sufficient and clean isotope production
  - ΔE_{FWHM} < 10 eV
  - $\tau_{risetime}$ < 1 µs
  - Muliplexed read-out of a large number of detectors

ECHO: Electron Capture ^{163}Ho Experiment

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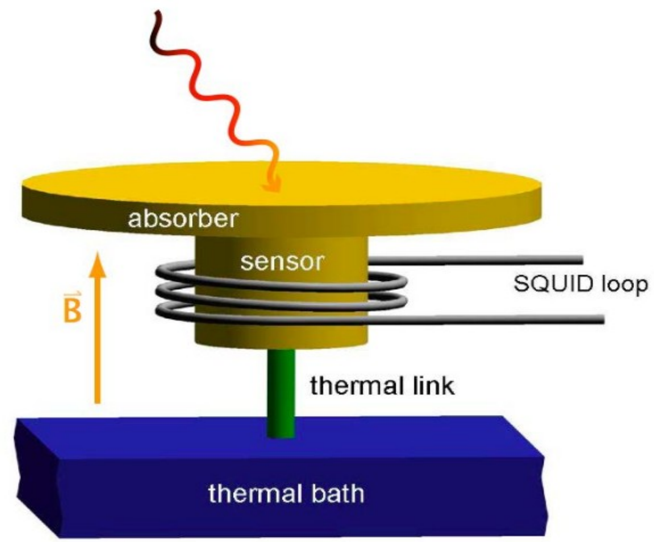
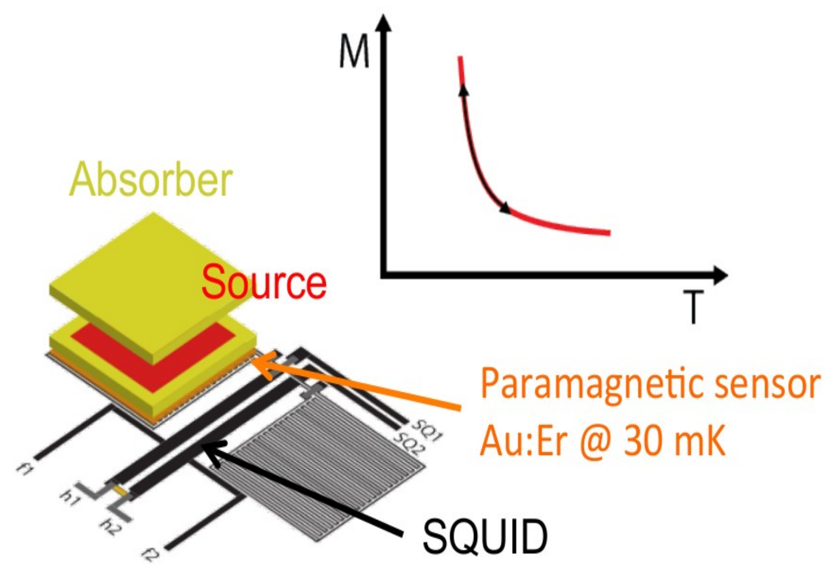
- Measurement of de-excitation energy using Metallic Magnetic Calorimeters (MMC)

  → measure ΔT by determining change in magnetic properties

Heidelberg (Univ., MPI-K), U Mainz, U Tübingen, TU Dresden, U Bratislava, INR Debrecen, ITEP Moscow, PNPI St Petersburg, IIT Roorkee, Saha Inst. Kolkata



$$\Delta\Phi_S \propto \frac{\partial M}{\partial T}\Delta T \rightarrow \Delta\Phi_S \propto \frac{\partial M}{\partial T}\frac{E}{C_{sens}+C_{abs}}$$



- Operated at 30 mK
- Rise Time ~ 130 ns
- E_{FWHM} = 7.6 eV @ 6 keV (2013)
- Non-Linearity < 1% @ 6keV

courtesy L. Gastaldo

Current status of ECHO

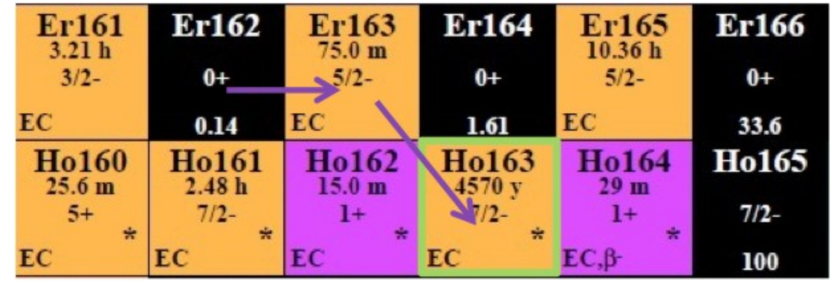
- High purity ^{163}Ho source has been produced
- ^{163}Ho ions have been successfully implanted in offline process

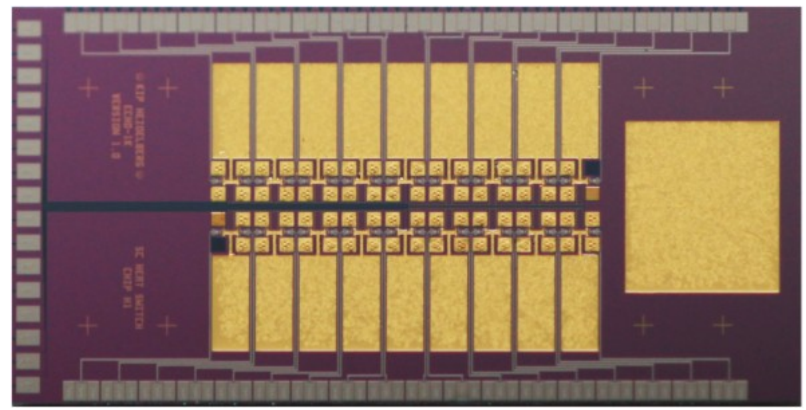
  @ISOLDE-CERN in 32 pixels
  @RISIKO in 8 pixels
  @RISIKO in 64 pixels

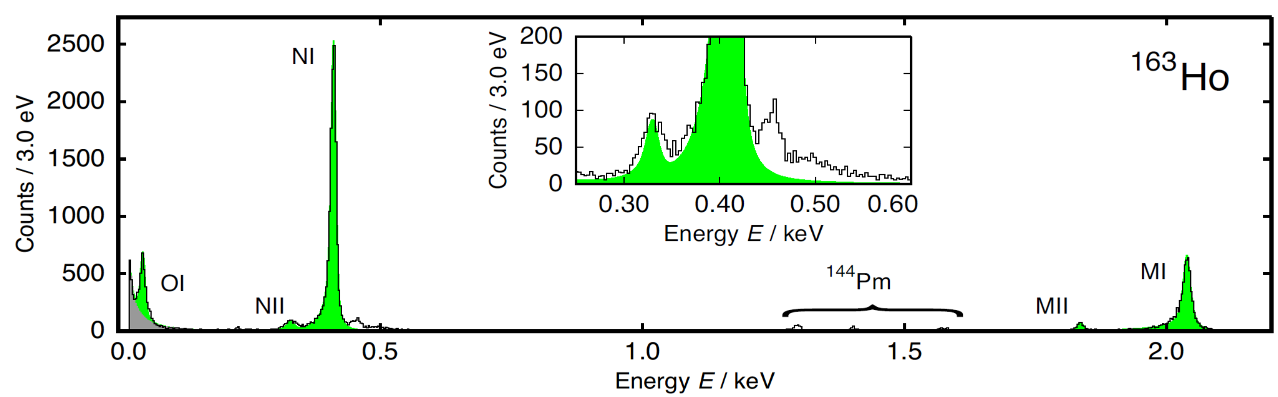
- Large MMC arrays have been tested and microwave SQUID multiplexing has been successfully demonstrated
- Independent Q-value measurement:

$$Q_{EC} = (2.858 \pm 0.010_{stat} \pm 0.05_{syst})\ \text{keV}$$

P. C.-O. Ranitzsch et al., Phys. Rev. Lett. 119 (2017) 122501





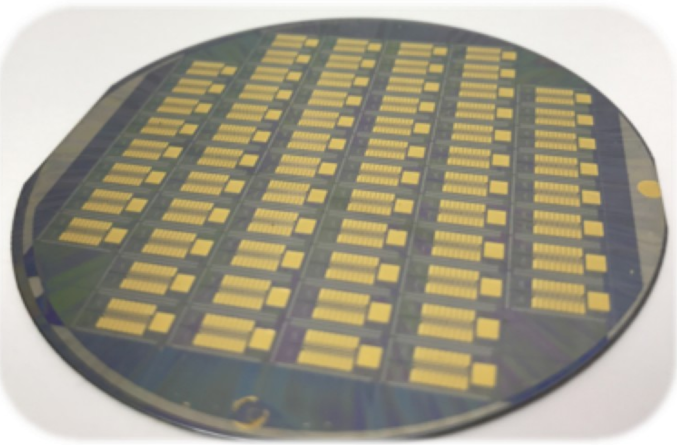


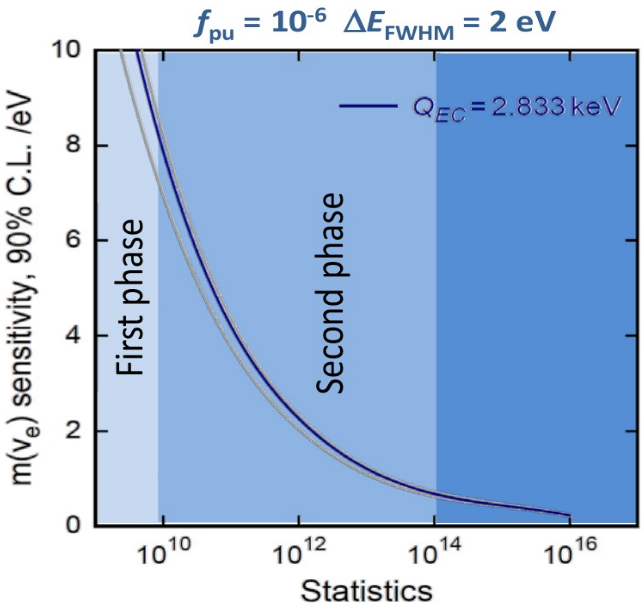
courtesy L. Gastaldo

ECHO timeline

Prove scalability with medium large experiment **ECHo-1K** (2015-2018)

- total activity 1000 Bq, high purity ^{163}Ho source (produced at reactor)
- $\Delta E_{FWHM} < 5$ eV
- $\tau_{rise} < 1$ µs
- multiplexed arrays
  → microwave SQUID multiplexing
- 1 year measuring time
  → 10^{10} counts
  → neutrino mass sensitivity m < 10 eV





Future: ECHo-10M for sub-eV sensitivity

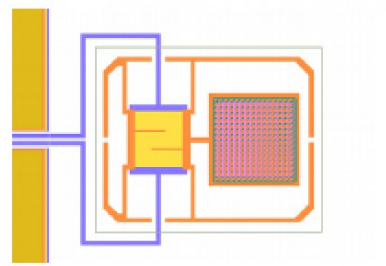
In addition: high energy resolution and high statistics ^{163}Ho spectra allow to investigate the existence of **sterile neutrinos** in the eV-scale and keV-scale

courtesy L. Gastaldo

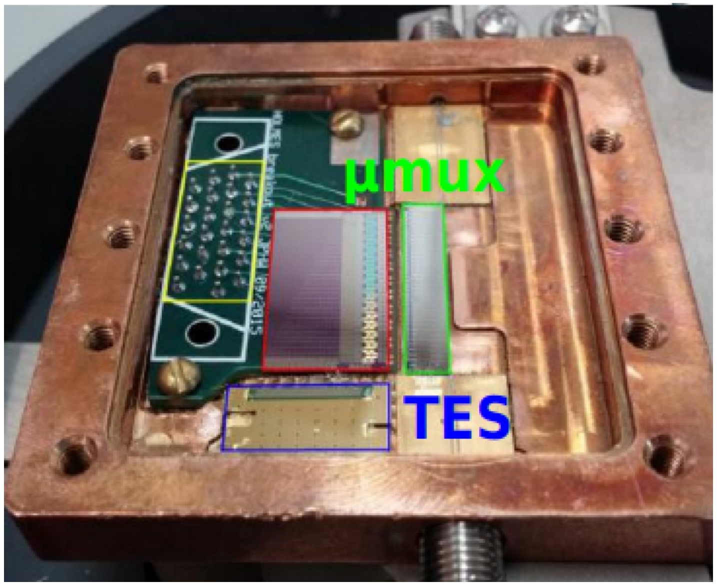
HOLMES: EC experiment with TES readout

HOLMES

- ^{163}Ho implanted in Au absorber with transition edge sensor (TES) readout
- frequency multiplexing approach for readout of multi-pixel detector
  - custom chip μMUX17A
  - 33 resonances in 500 MHz interval with a width of 2 MHz and 14 MHz separation
- sampling frequency 400 kS/s
- energy resolution at endpoint ΔE_0 = 4 eV
- rise time 35 μs, decay time 141 μs

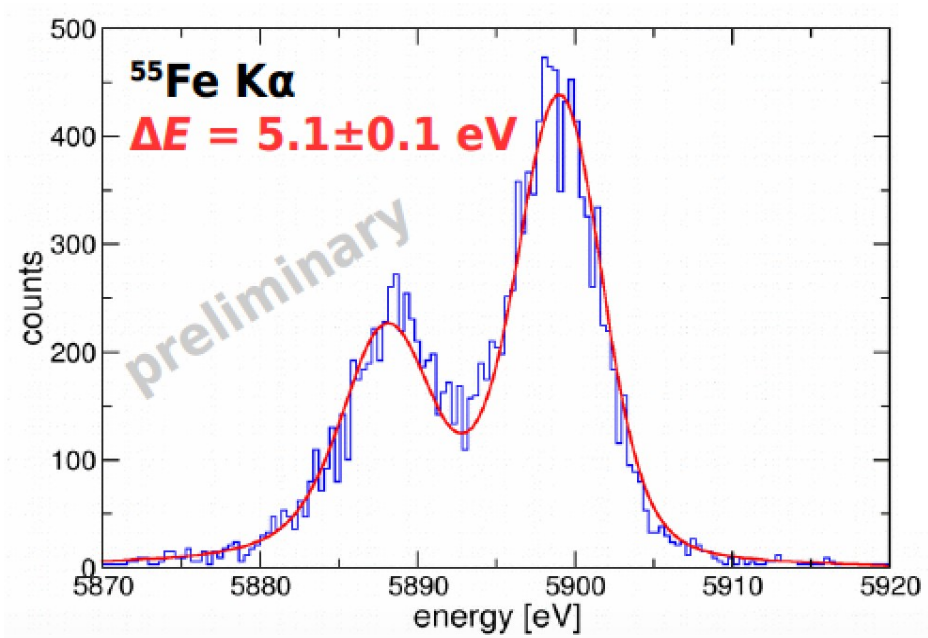


200×200 μm² absorber
C = 0.9 pJ/K
G = 570 pW/K



Project status

- TES array and DAQ ready
- ion implanter setup in progress
- first ^{163}Ho implantation coming shortly
- first spectrum late in 2017
  → 32 pixels for 1 month
  → m_ν sensitivity ≈ 10 eV



courtesy A. Nucciotti

Summary

- Studies of β-decay kinematics offer a model-independent way to determine the neutrino mass, complementary to cosmology and $0\nu\beta\beta$ searches
- Besides neutrino mass the experiments in preparation are also sensitive to sterile neutrinos
- KATRIN will probe the neutrino mass range down to 0.2 eV
- Start of tritium data taking with KATRIN: June 2018
- Calorimetric experiments (ECHO, HOLMES) will provide an independent look at kinematic neutrino mass limits. The scalable approach and further R&D work will allow to reach a competitive level of sensitivity.
- New ideas and a lot of R&D work are required to go beyond 100 meV !