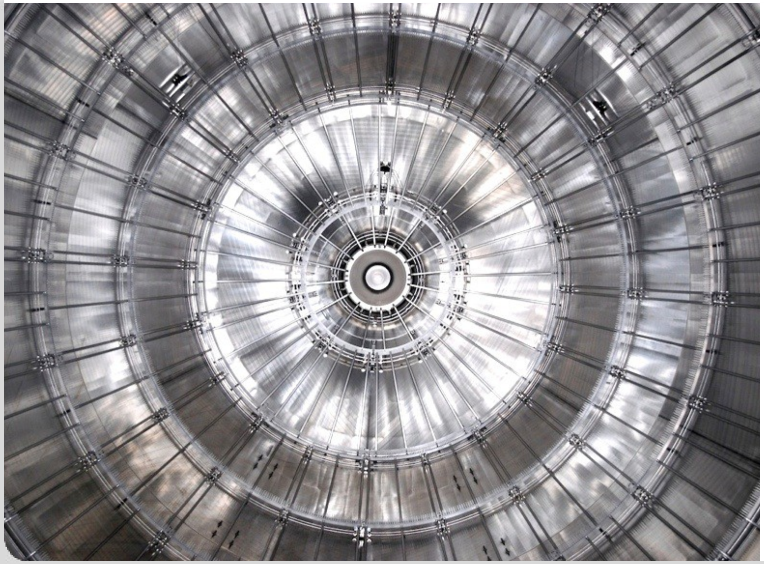
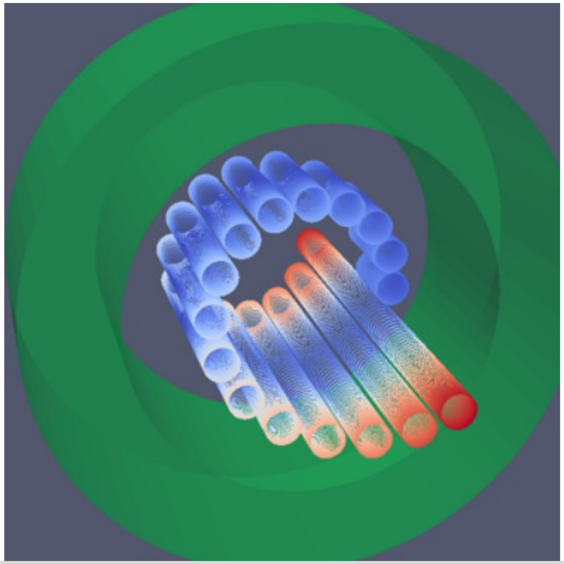
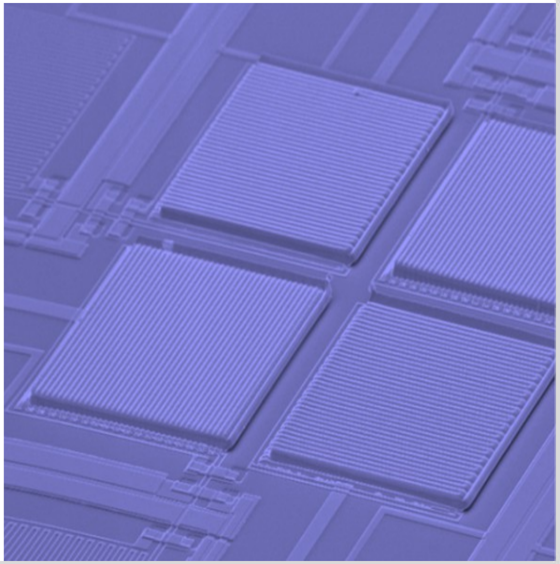
Direct neutrino mass experiments

Kathrin Valerius, KIT Center Elementary Particle and Astroparticle Physics (KCETA)







Karlsruhe Institute of Technology

Direct neutrino mass experiments

Kathrin Valerius, KIT Center Elementary Particle and Astroparticle Physics (KCETA)

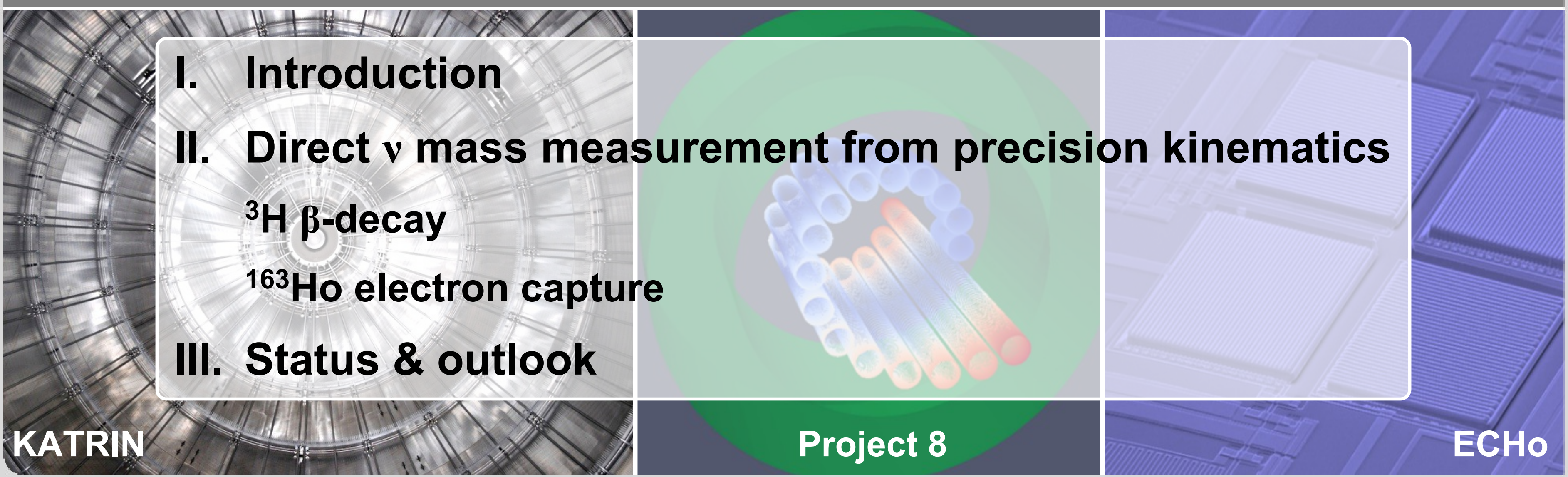
I. Introduction

II. Direct ν mass measurement from precision kinematics

^{3}H β-decay

^{163}Ho electron capture

III. Status & outlook



Neutrino masses

→ **W. Rodejohann, Neutrino properties**

Karlsruhe Institute of Technology

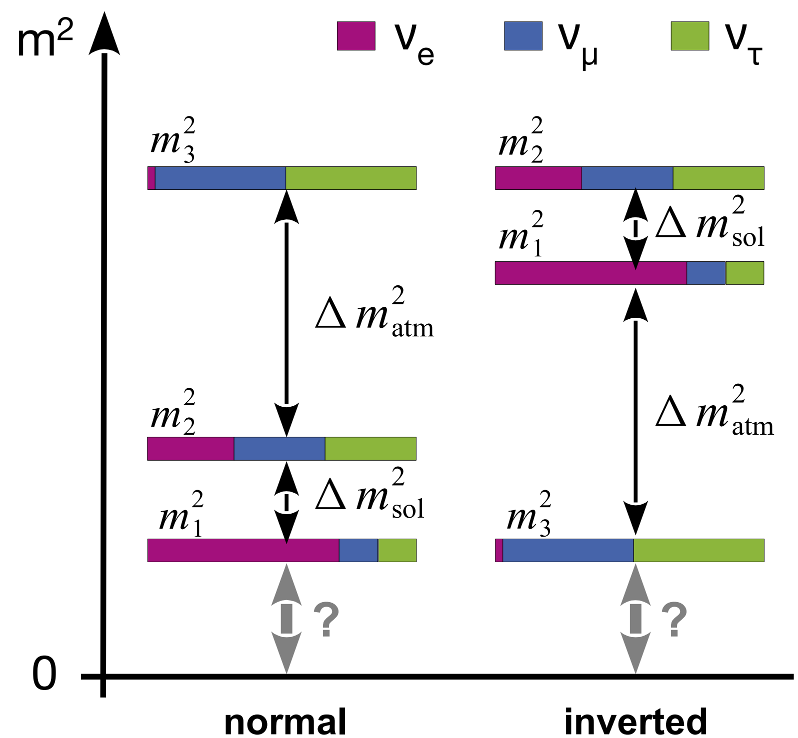
Wealth of ν oscillation data:

- Neutrino mixing & m(ν_i) ≠ 0 established
- Oscillation experiments: tiny mass splittings

$$\Delta m^2_{atm} = \left(2.32^{+0.12}_{-0.08}\right)\times 10^{-3}\,\mathrm{eV}^2$$

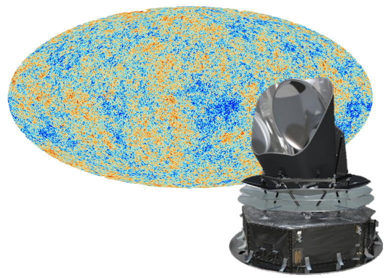
$$\Delta m^2_{sol} = \left(7.5\pm 0.2\right)\times 10^{-5}\,\mathrm{eV}^2 \quad \text{(PDG, 2014)}$$

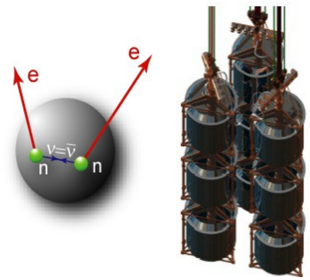
- Which mass ordering (normal, inverted)?
- **What is the absolute ν mass scale?**

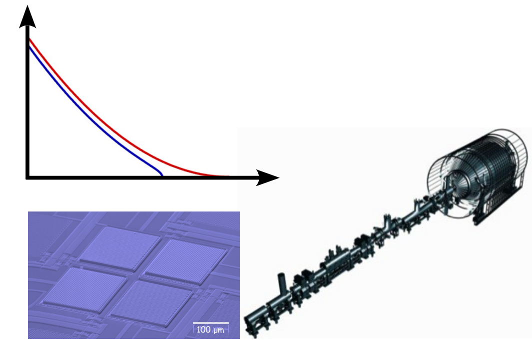


So far: only **upper** (< 2 eV) and **lower bounds** (>0.01 resp. >0.05 eV)

Complementary paths towards the ν mass scale







Tool	**Cosmology** CMB+LSS+...	**Neutrinoless double β-decay**	**β-decay endpoint and EC**
Observable	$m_\Sigma := \sum_i m_i$	$m_{\beta\beta} := \lvert \sum_i U_{ei}^2 m_i \rvert$	$m_\beta := \left(\sum_i \lvert U_{ei} \rvert^2 m_i^2 \right)^{1/2}$
Present upper limit	0.2 – 1 eV	0.2 – 0.4 eV	2 eV
Potential	20 – 50 meV	20 – 50 meV	200 meV
Model dependence	yes	yes	no: **direct meas.** from kinematics

→ **B. Schwingenheuer**

→ **this talk**

Direct neutrino mass measurement

Imprint of m_ν on endpoint region of β spectrum (similar for EC):

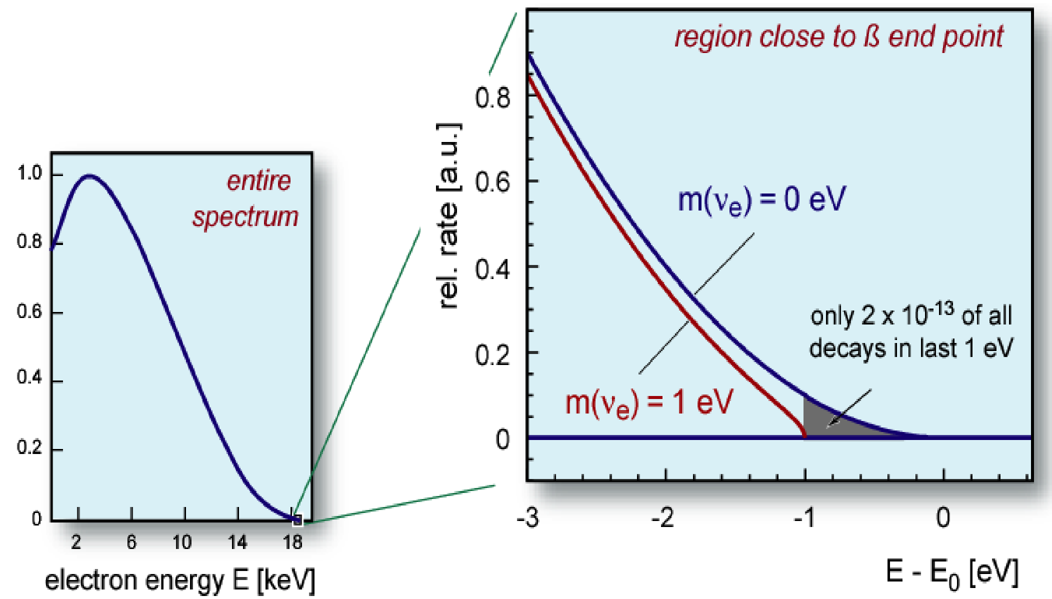
$$\frac{dN}{dE} = C \cdot F(Z,E) \cdot p \cdot (E+m_e) \cdot (E_0 - E) \cdot \sqrt{(E_0-E)^2 - m^2(\nu_e)}$$

$$m^2(\nu_e) = \sum |U_{ei}|^2 m_i^2$$

observable: effective squared mass

Key requirements

- Source isotope:
  - Low spectral endpoint Q
  - Large decay rate (short $T_{1/2}$)
- Instrument:
  - Excellent energy resolution
  - Very low background



Direct neutrino mass measurement

Karlsruhe Institute of Technology

Imprint of m_ν on endpoint region of β spectrum (similar for EC):

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

$$m^2(\nu_e) = \sum |U_{ei}|^2 m_i^2$$

observable: effective squared mass

Key requirements

- Source isotope:
  - Low spectral endpoint Q
  - Large decay rate (short $T_{1/2}$)
- Instrument:
  - Excellent energy resolution
  - Very low background

Experimental options

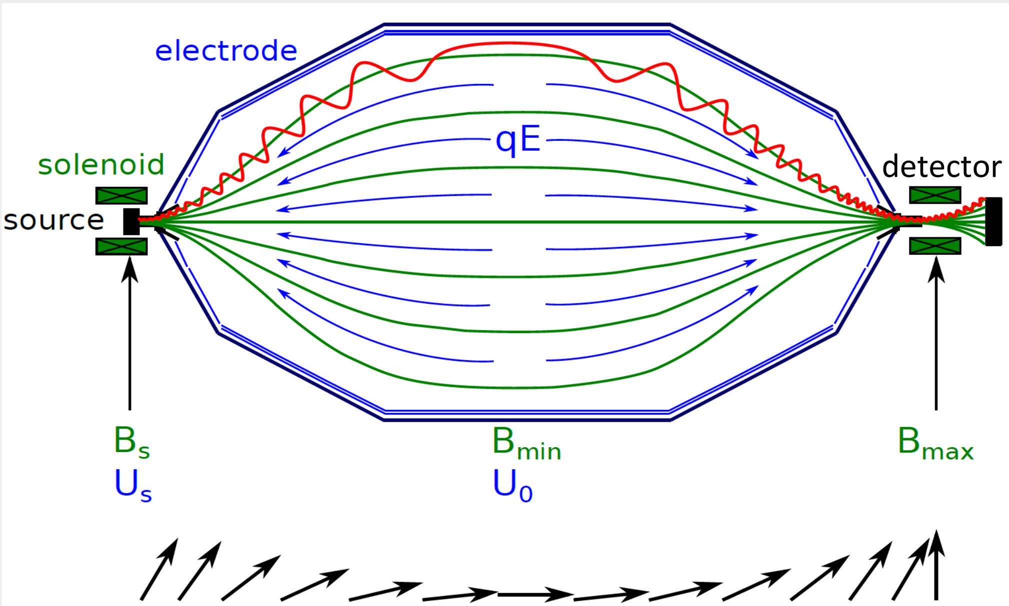
	^{3}H (β)	^{187}Re (β)	^{163}Ho (EC)
Q value	18.6 keV	2.5 keV	~2.5 keV
$T_{1/2}$	12.3 yr	41 Gyr	4.5 kyr
technique	spectrometer	cryogenic micro-calorimeter	
	source ≠ det.	source *within* detector	
present m(ν) sens.	**< 2 eV** **Mainz, Troitsk ~2004**	< 15-30 eV Milan, Genoa ~2004	< 225 eV Livermore 1987
	$\bar{\nu}_e$	$\bar{\nu}_e$	ν_e

Tritium β-decay experiments

Spectroscopic technique for tritium β-decay

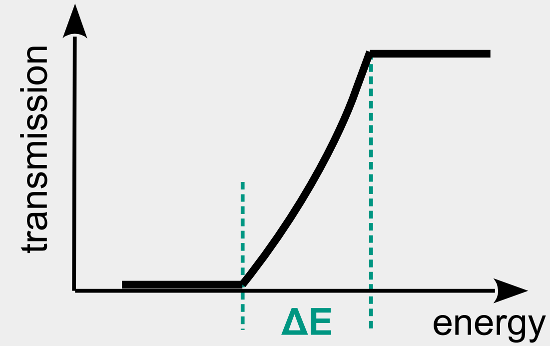
MAC-E filter technique

Magnetic Adiabatic Collimation with Electrostatic filter
Picard et al., NIM B63 (1992) 345



$$\mu = \frac{E_\perp}{B} = \text{const.}$$

Sharp high-pass filter:



Steps of filter potential
→ integrated β spectrum

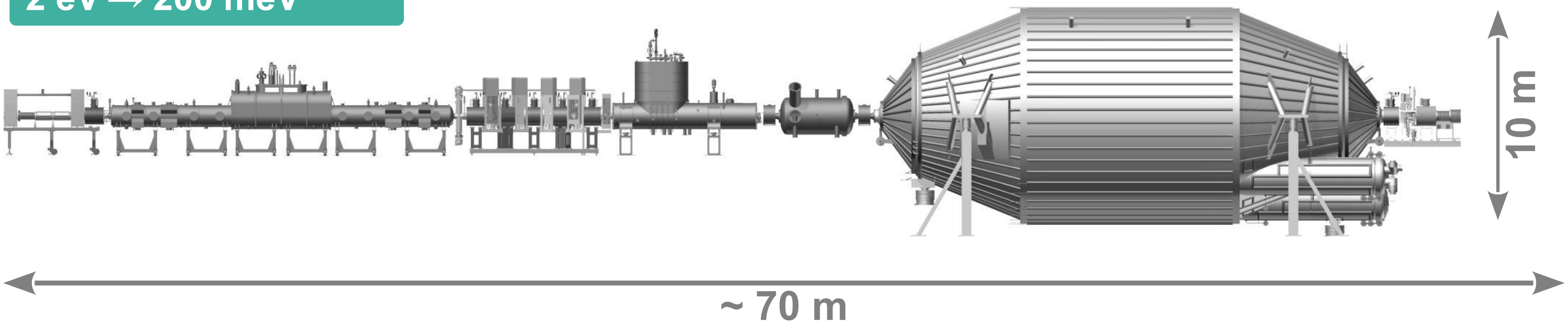
Combination of high luminosity and high energy resolution:

$$\frac{\Delta E}{E} = \frac{B_{min}}{B_{max}} = \frac{1}{20000}$$

(at KATRIN)

KATRIN: overview

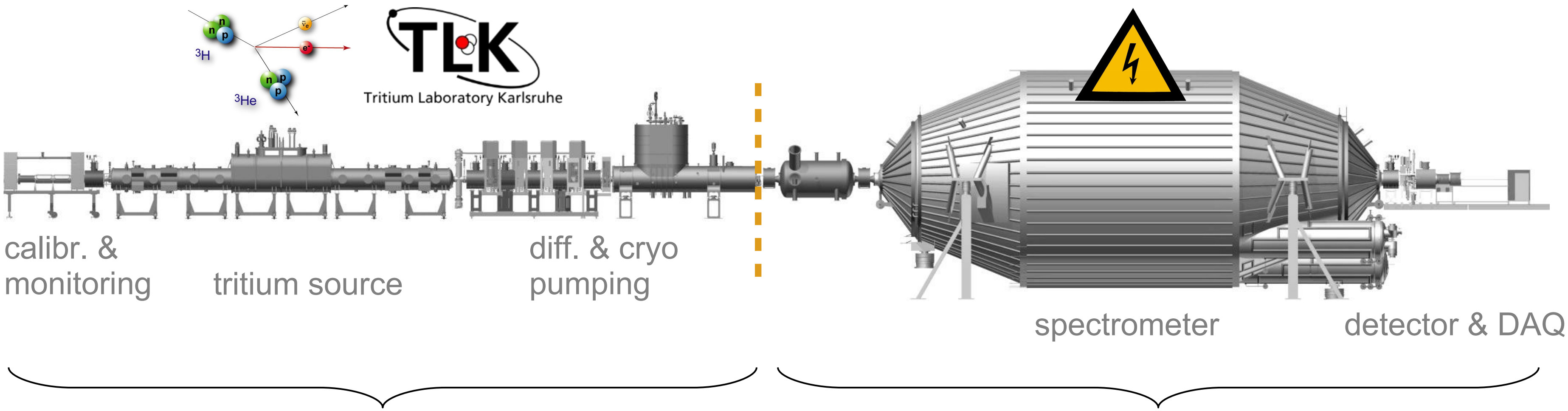
sensitivity on $m(\nu_e)$:
2 eV → 200 meV




KATRIN Collaboration, March 2014

KATRIN: main components

Karlsruhe Institute of Technology



Source & transport section

- Windowless gaseous tritium source
  - Intensity (10^{11} decays/s)
  - Stability (10^{-3} h^{-1})
  - Isotopic purity (> 95%)
- Tritium retention (factor > 10^{14})
- Adiabatic transport of electrons

→ Poster S. Rupp

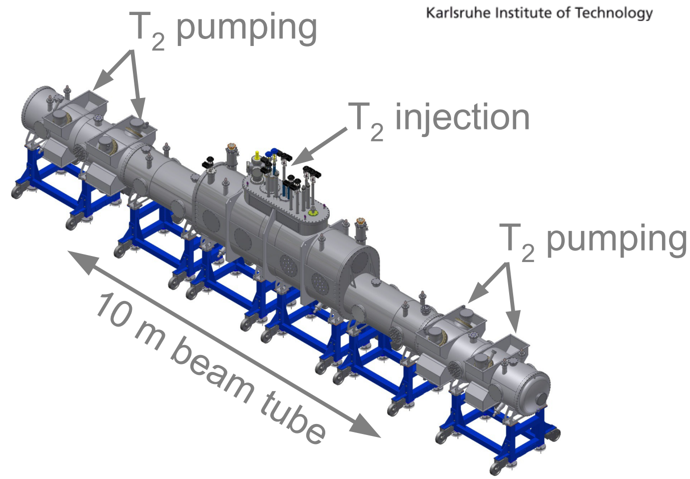
Spectrometer & detector section

- Spectrometer UHV (p < 10^{-11} mbar)
- Energy resolution (<1 eV at 18.6 keV)
- High voltage stability (sub-ppm/month)
- High detection efficiency (10^{-3}…10^{3} cps)
- Low background rate (10^{-2} cps)

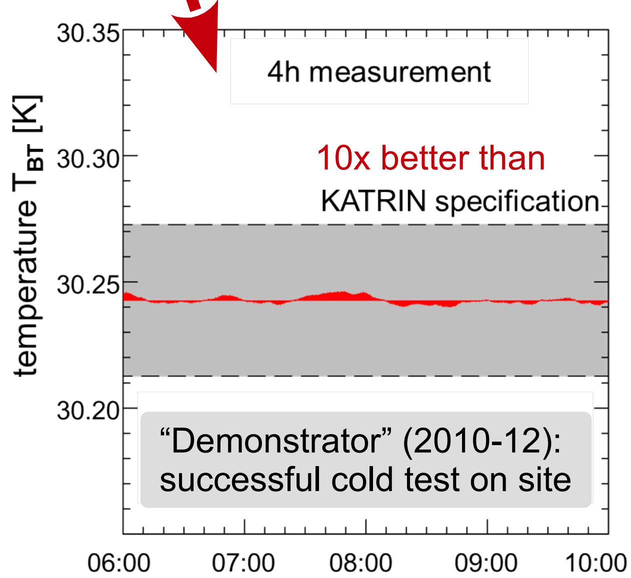
→ Poster F. Harms

Windowless gaseous tritium source

- Closed loop processing ~10^{16} Bq tritium / day
- 10^{-3} relative stability of T_2 column density:
  → injection & pumping rate, isotopic purity,
  temperature stability & homogeneity

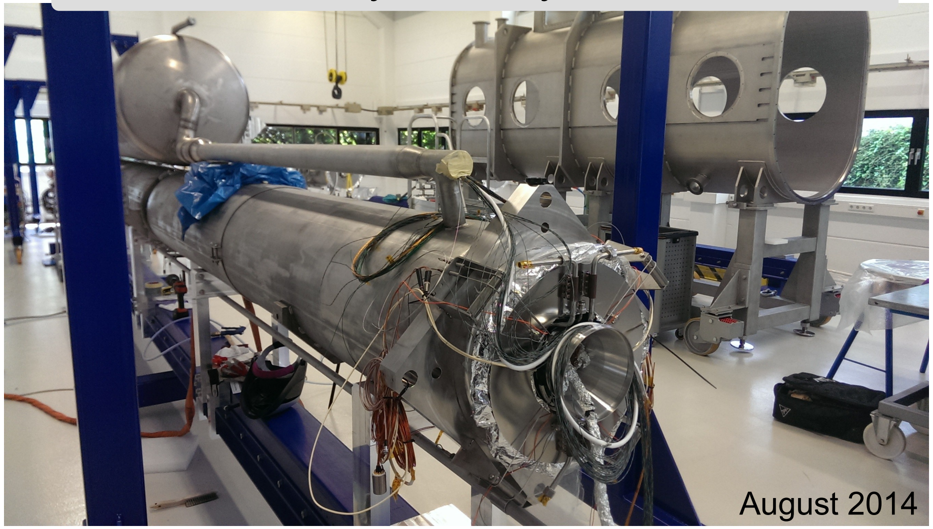


novel 2-phase
neon cooling



S. Grohmann et al., Cryogenics 55–56 (2013) 5

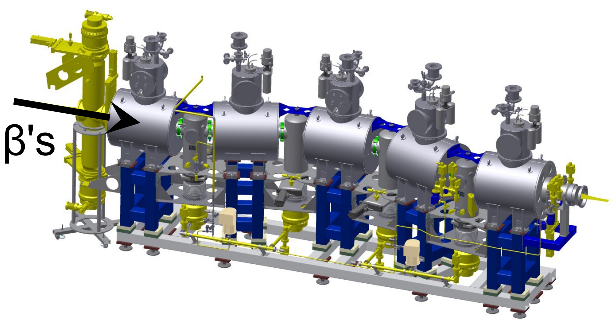
WGTS assembly, delivery to KIT mid-2015



Transport and pumping sections

Differential pumping section (DPS)

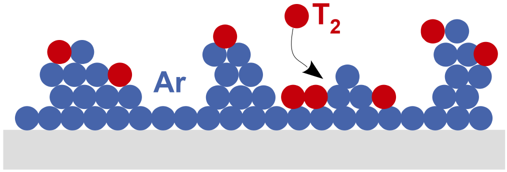
- Turbomolecular pumps
- Tritium retention **~10^5**
- Magnetic guiding of β's (5.6 T)



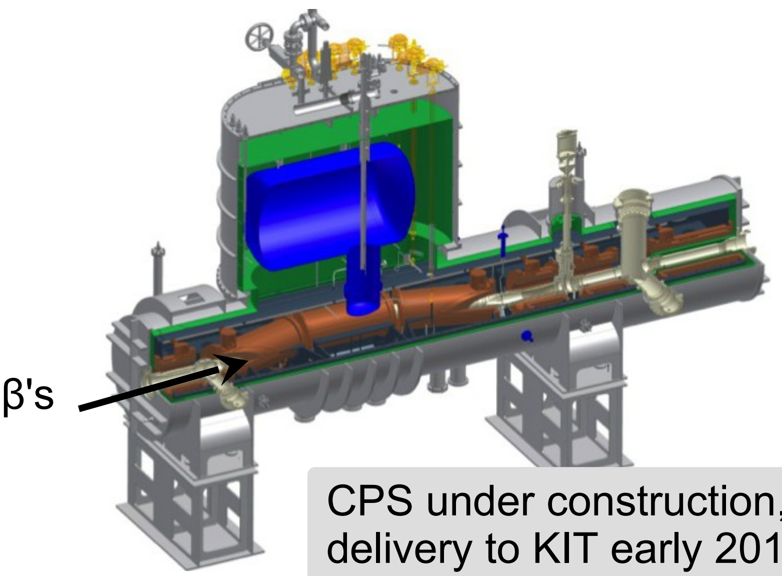
DPS being installed right now

Cryogenic pumping section (CPS)

- Cryo-sorption on 3-4 K argon frost



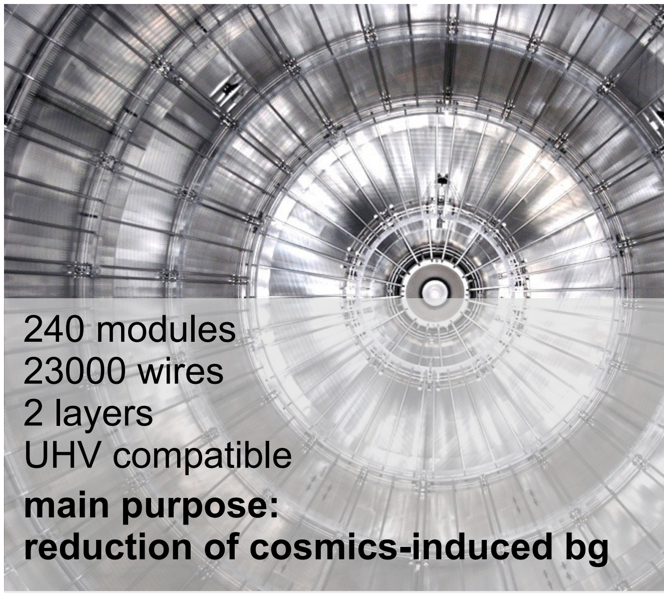
- Tritium retention **>10^7**
- Magnetic guiding of β's (5.6 T)



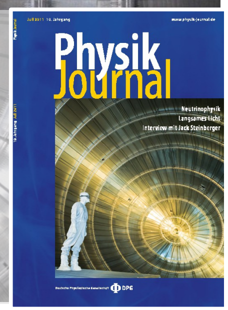
CPS under construction, delivery to KIT early 2015

Spectrometer and detector section

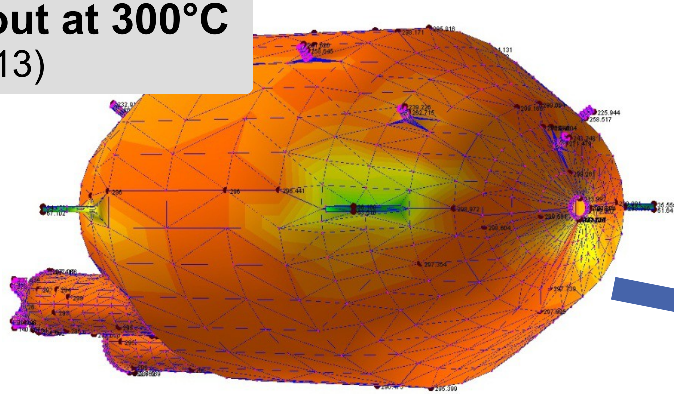
Installation of wire electrodes (~2007-2012)



240 modules
23000 wires
2 layers
UHV compatible
main purpose:
reduction of cosmics-induced bg

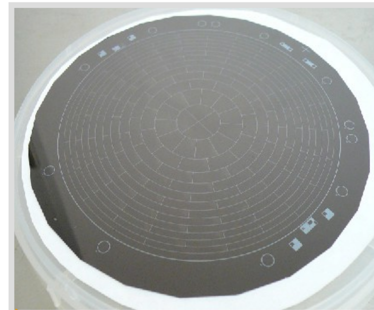


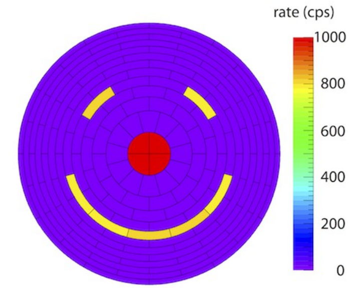
Bake-out at 300°C
(Jan 2013)

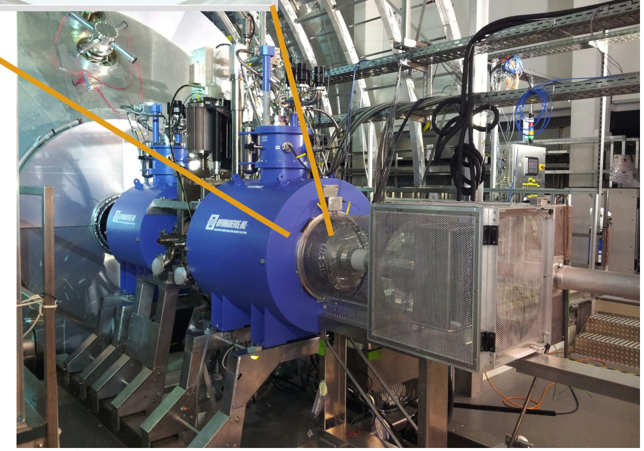


Detector tests (until spring 2013)

148 pix. Si-PIN diode







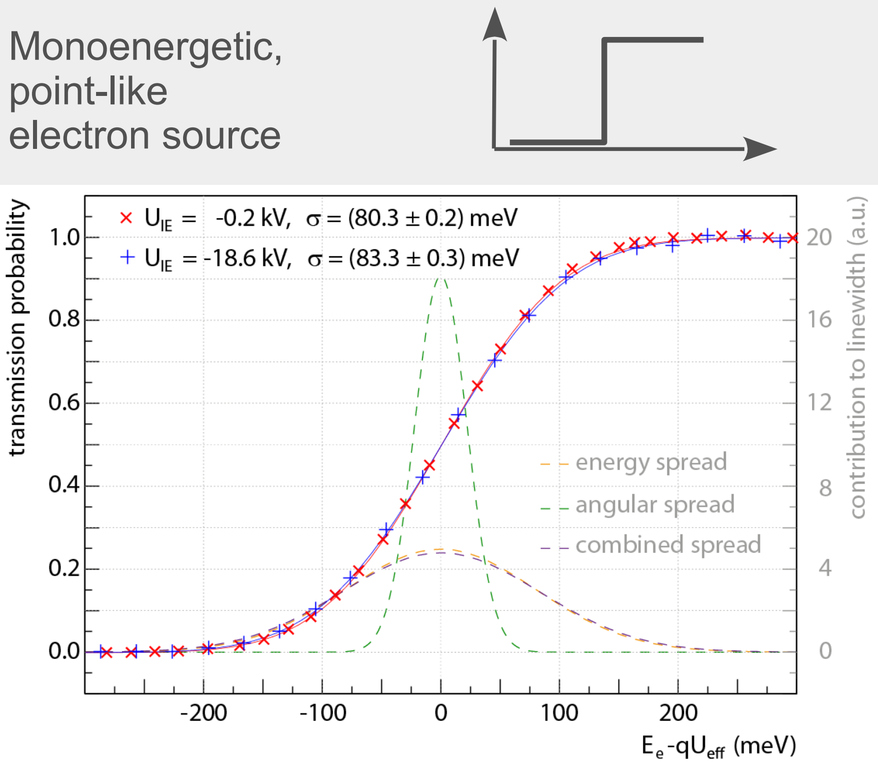
Mid-2013: commissioning phase I of main spectrometer & detector

KATRIN: commissioning measurements

Spectrometer & detector commissioning: **phase I, summer 2013**

Characterisation of transmission

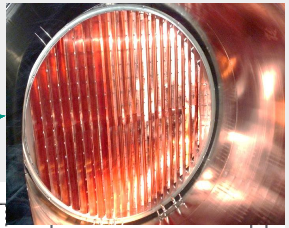
Monoenergetic,
point-like
electron source

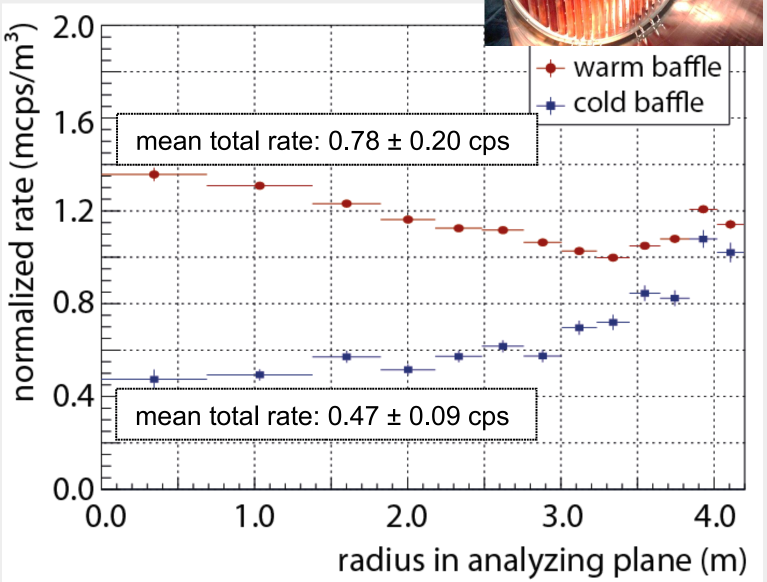


- Transmission characteristics of main spec. as expected (limited by e-gun systematics ...)

Characterisation of backgrounds

First tests of
wire electrode
and cold baffles





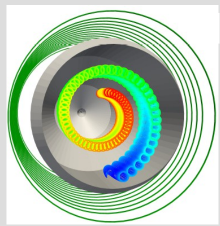
- Discriminate cosmics/Rn-induced bg
- Need to cut down total rate to **~0.01 cps**

Next steps for KATRIN

Spectrometer & detector commissioning: **phase II starting 10/2014**

improved background suppression

- **passive:** double-layer wire electrode, cold baffles
- **active breaking of storage conditions:** electric dipole, magnetic pulses

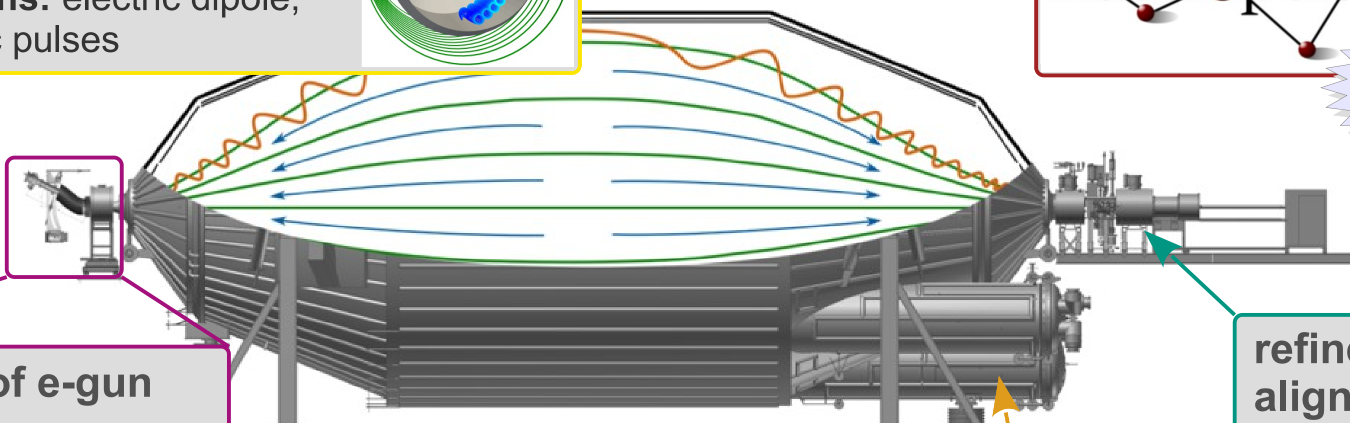


software package

for field calculations & particle trajectories

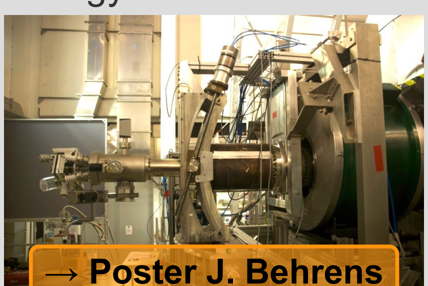
Kassiopeia 3.0

coming soon: public release



upgrade of e-gun

improved angular and energy resolution



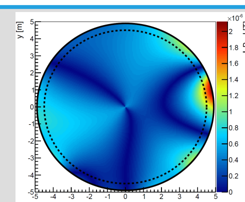
→ **Poster J. Behrens**

refined system alignment

imaging of flux tube onto detector

improved B-field homogeneity

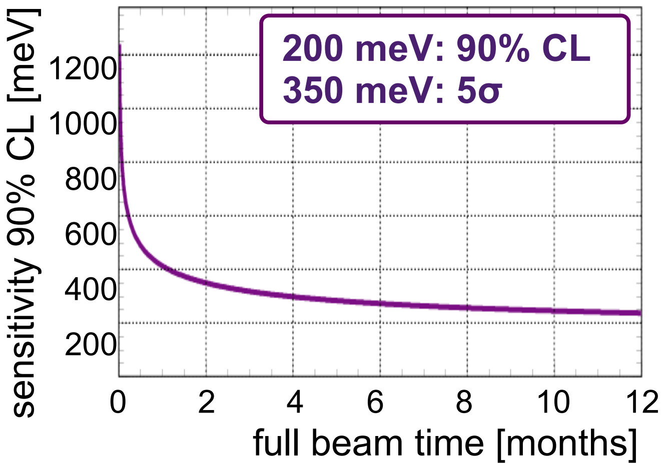
de-magnetization of spectrometer building



upgrade of vacuum system

electrical heating of NEG pumps

KATRIN: ν-mass sensitivity

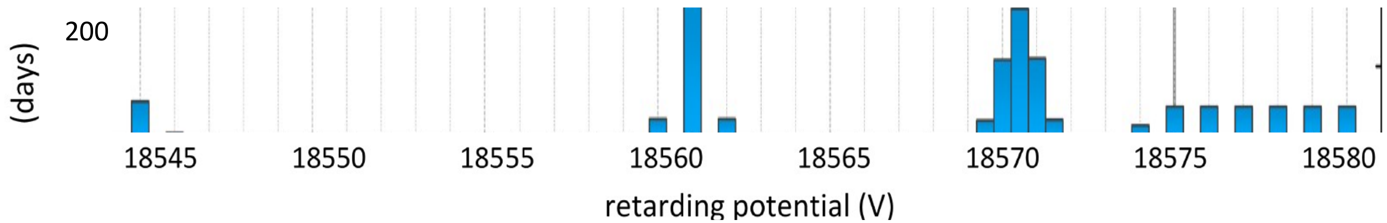


Reference neutrino mass sensitivity

- Start of first tritium measurements: mid-2016
- After **3 yrs** of data (5 calendar yrs): balance of statistics and systematics

→ **Poster M. Kleesiek**

$\sigma_{stat}(m^2_\nu) \leq 0.018\ eV^2$ (even **$0.016\ eV^2$** with optimized measuring time distribution)



$\sigma_{syst}(m^2_\nu) \leq 0.017\ eV^2$ – total systematic uncertainty budget

- Source-related (final states, energy loss, column density, plasma potential, ...)
- Other (HV fluctuations, transmission function, non-Poissonian backgrounds, ...)

KATRIN: ν-mass sensitivity … and more:

Karlsruhe Institute of Technology

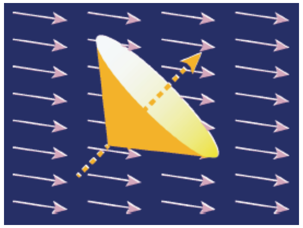
Explore physics potential

- **close to the spectral endpoint E_0:**

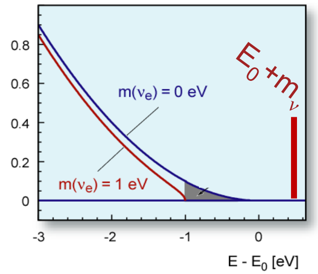
standard operation mode for KATRIN

RH currents
Bonn et al. (2011)

Violation of Lorentz symmetry
Diaz, Kostelecky & Lehnert (2013)

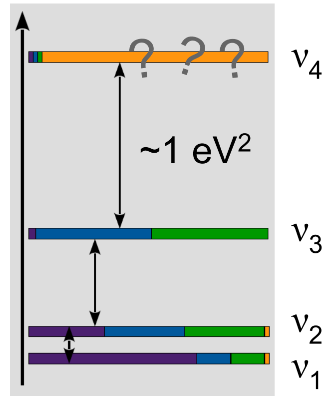


Constraining local CνB overdensities
e.g. Kaboth & Formaggio (2010)
Fässler et al. (2013)



capture of relic ν on β-instable nuclei

Search for eV-scale sterile ν



- **and further away from E_0:**

  search for keV-mass scale sterile ν as DM candidates
  Steinbrink et al. (2013), Mertens et al. (arXiv:1409.0920)

non-standard operation, requires novel concepts

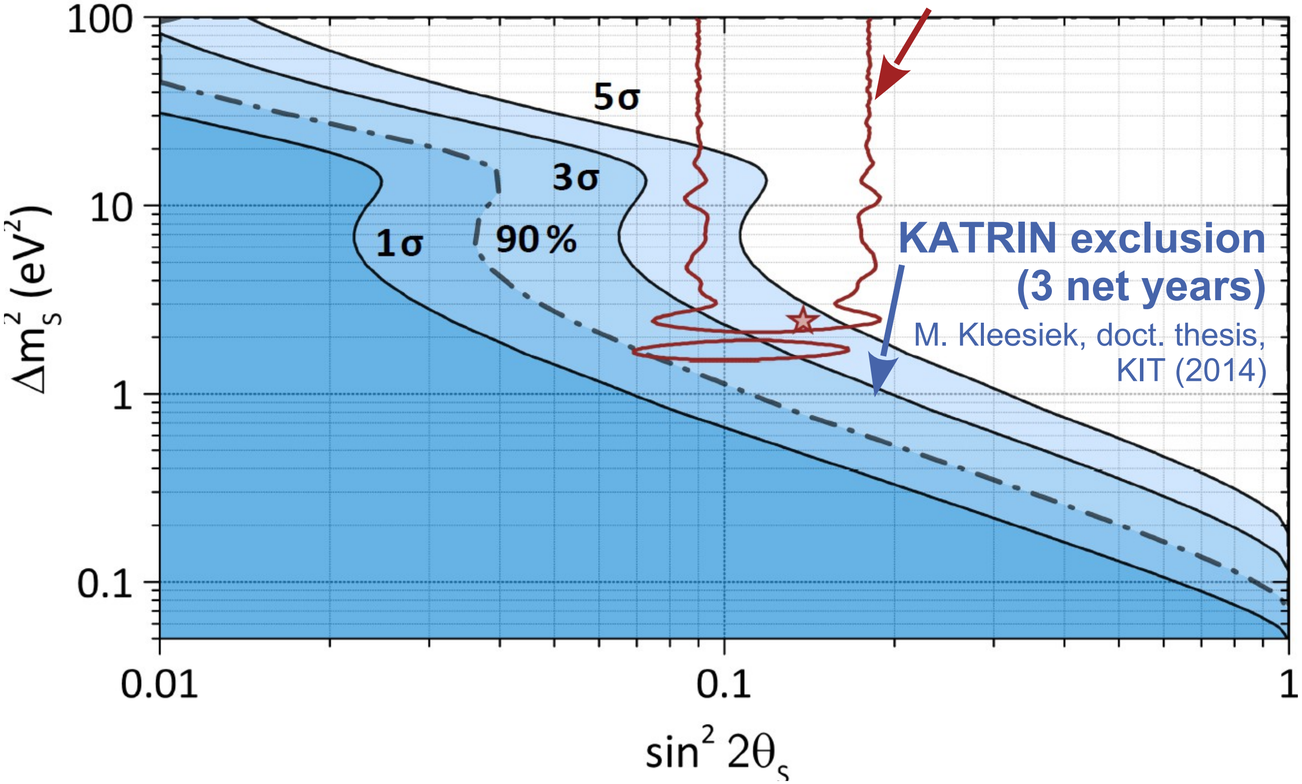
Search for eV-scale sterile neutrinos

Additional kink in β spectrum at $E = E_0 - m_s$:

$$\frac{d\dot{N}}{dE} = \cos^2\theta_s \frac{d\dot{N}}{dE}(m_a^2) + \sin^2\theta_s \frac{d\dot{N}}{dE}(m_s^2)$$

"Reactor anomaly"
Mention et al., PRD 83 (2011) 073006

$\Delta m^2_s \sim 1\ \mathrm{eV}^2$
$\sin^2(2\theta_s) \sim 0.1$



See also:

Formaggio & Barrett (2011)
Sejersen Riis & Hannestad (2011)
Esmaili & Peres (2012)

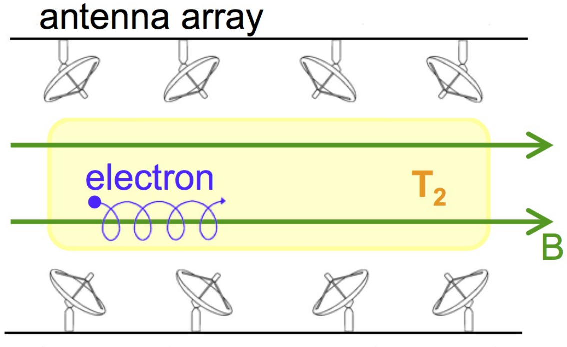
– novel approach to β spectroscopy

Karlsruhe Institute of Technology

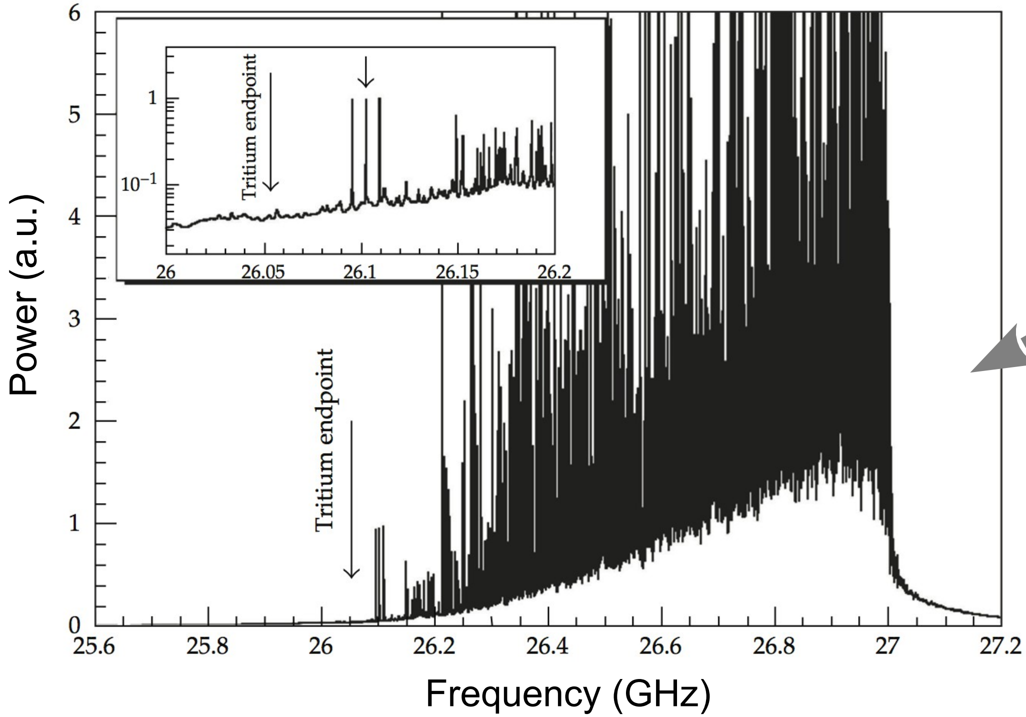
Energy measured via **cyclotron frequency** of electron in magnetic field:

$$\omega_\gamma = \frac{\omega_c}{\gamma} = \frac{eB}{E_{kin}+m_e}$$

UW/Seattle, MIT, UC/Santa Barbara, Yale, Pacific NW, Livermore, NRAO, KIT



single electron
in trapping volume

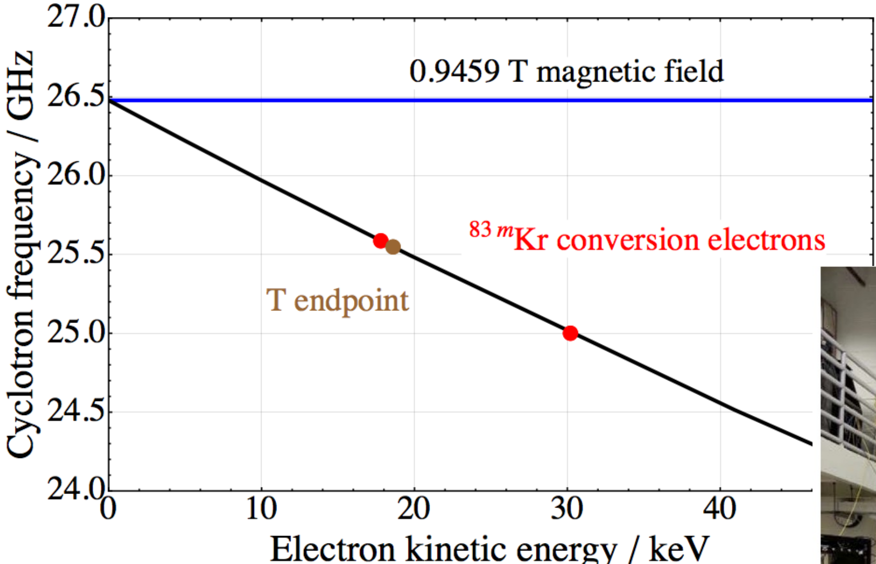


β spectrum
10^5 simulated decays
B = 1 T

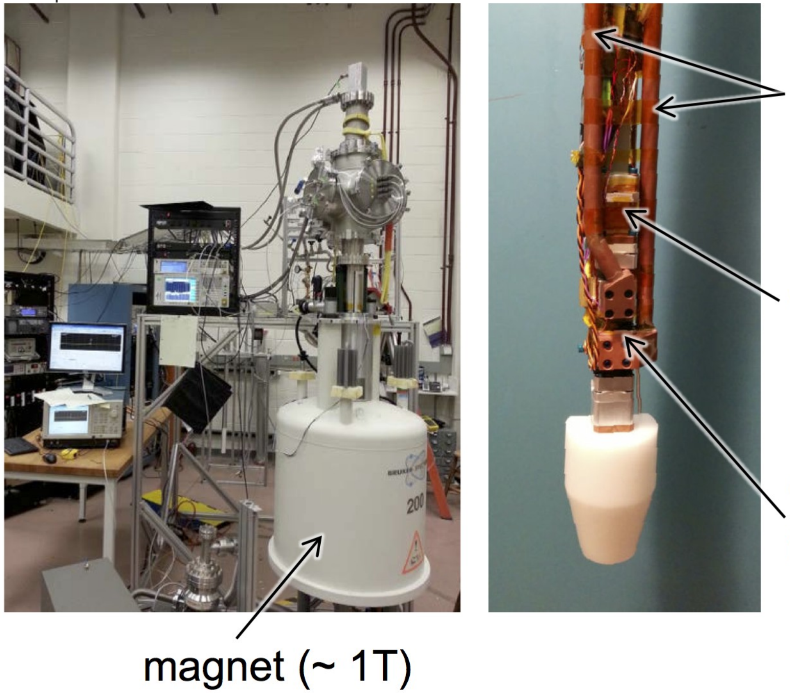
Formaggio & Monreal, Phys. Rev. D80 (2009) 051301(R)

Project 8 – phase I

Proof-of-principle goal:
detect single electrons from ^{83m}Kr

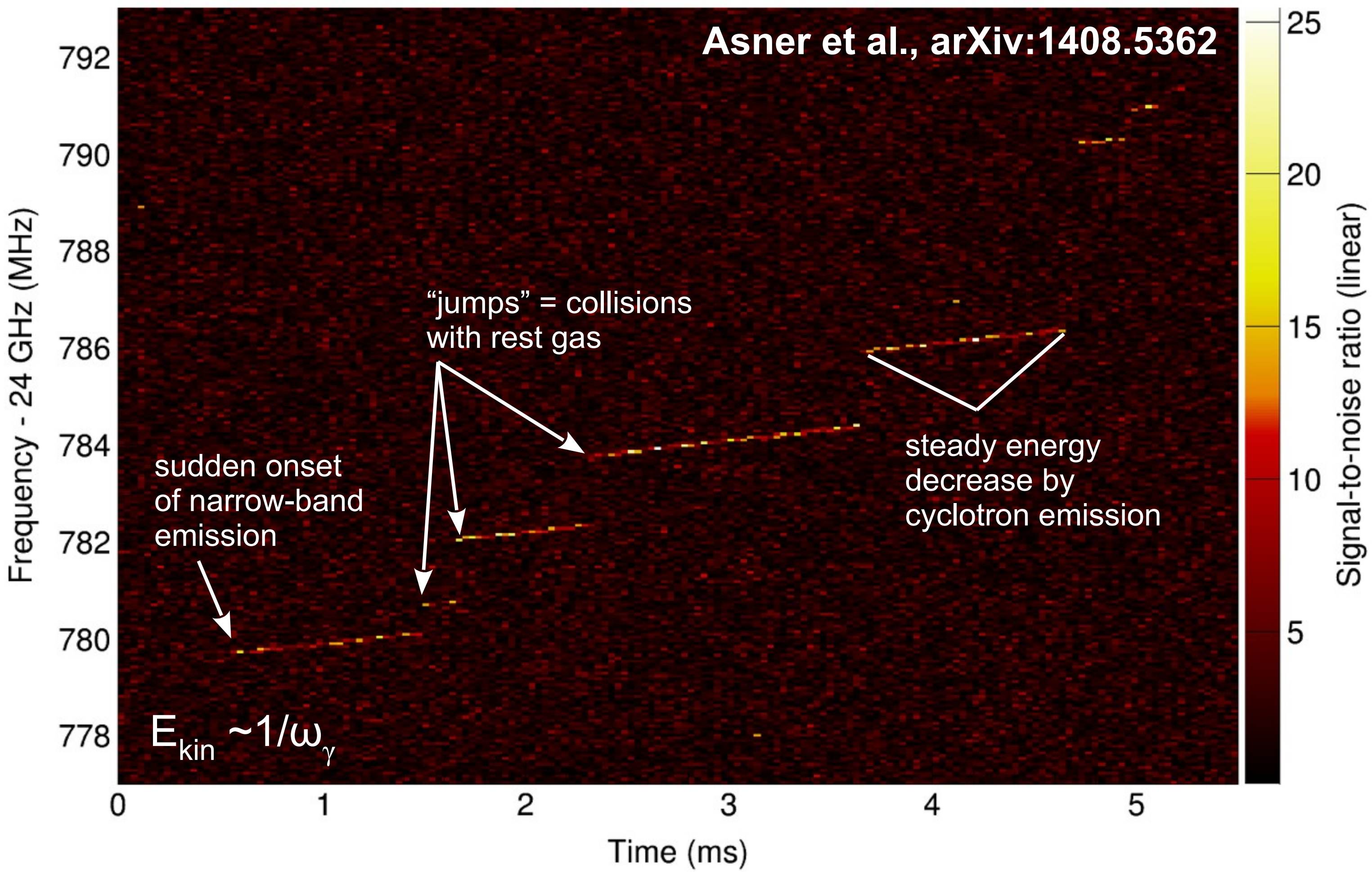


Successful measurements with prototype system at UW/Seattle



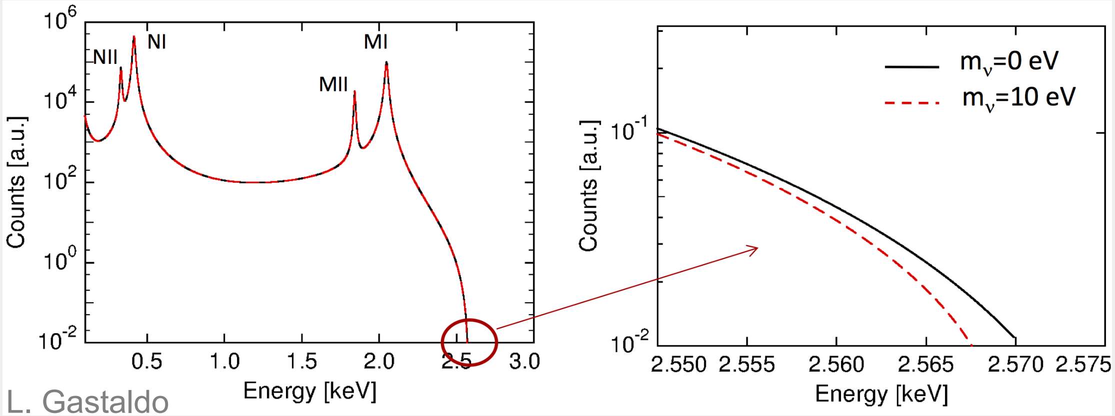
Project 8 – phase I results

First observation of cyclotron radiation from single electrons



Electron capture experiments

^{163}Ho-based experiments: basics



$^{163}Ho \rightarrow ^{163}Dy^* + \nu_e$:

lowest Q_{EC} ~2.5 keV

short $T_{1/2}$ ~ 4570 a

Atomic de-excitation of ^{163}Dy*:

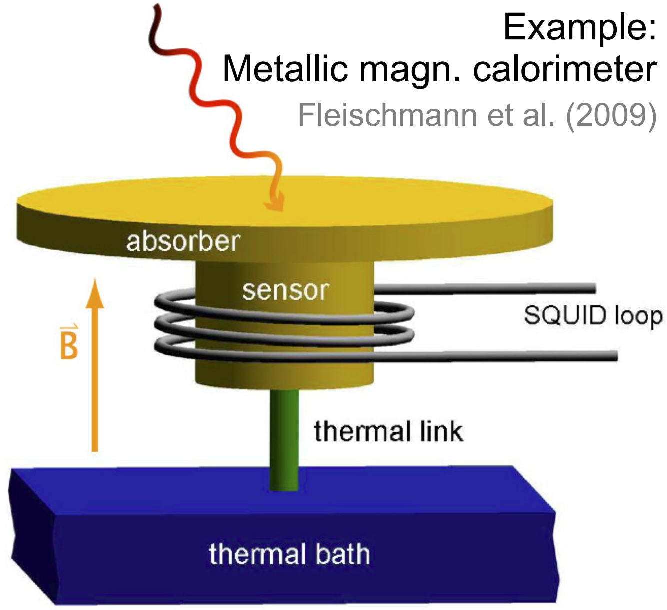
- X-rays
- Electrons (Auger, Coster-Kronig)

→ **Cryogenic calorimetric measurement**

$$\Delta \Phi_s \propto \frac{\partial M}{\partial T} \cdot \underbrace{\frac{E}{C_{sensor} + C_{absorber}}}_{\Delta T}$$

T < 100 mK

Example:
Metallic magn. calorimeter
Fleischmann et al. (2009)



^{163}Ho-based experiments: overview

Karlsruhe Institute of Technology

ECHo

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

- Started R&D in 2011
- **MMC technology**
- Prototype: currently most precise calorimetric ^{163}Ho spectrum

HOLMES

U Milano-Bicocca,
INFN Milano/Genova/Roma,
U Lisboa, U Miami,
NIST, JPL

- Established in 2013 (previous R&D in MARE)
- **TES technology**
- Multi-channel readout

LANL

Los Alamos,
NIST,
U Madison
and others

- Since ~2011
- **TES technology**
- Source production & detector development

Different technological approaches, but common challenges:

- **Detector characteristics:** energy resolution, pile-up
- **Source preparation:** isotopic quantity & purity, implantation process
- **Scalability** for eV (and sub-eV) sensitivity: large arrays

^{163}Ho-based experiments: challenges

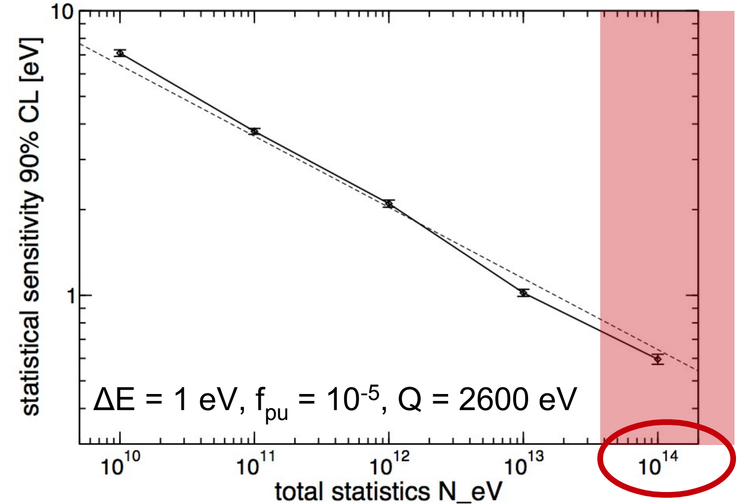
Detector

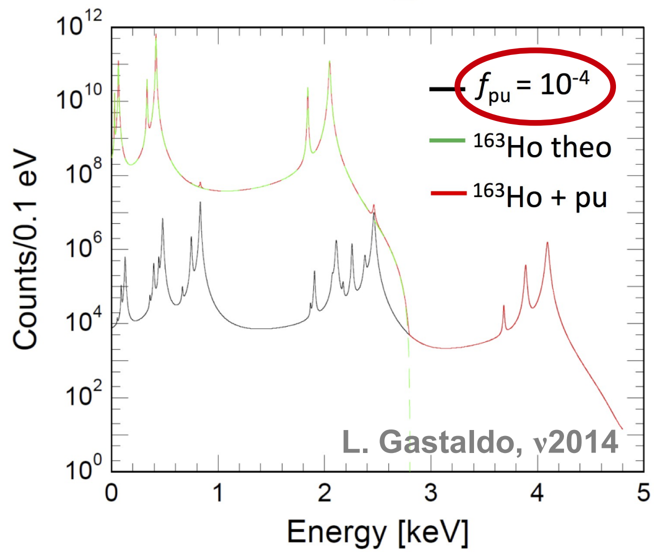
- Statistics: $N_{ev} = N_{det} \cdot A_\beta \cdot t_M$
  $\rightarrow N_{ev} > 10^{14}$ requires $\mathbf{N_{det} \cdot A_\beta \sim 10^6}$ **Bq** for t_M ~ few years
- Pile-up fraction: $f_{pu} \sim A_\beta \cdot \tau_r \ll 10^{-4}$
  → Fast & large number of detectors
- "Moderate" resolution: **ΔE ~ 1–10 eV**

Source implanted into absorber

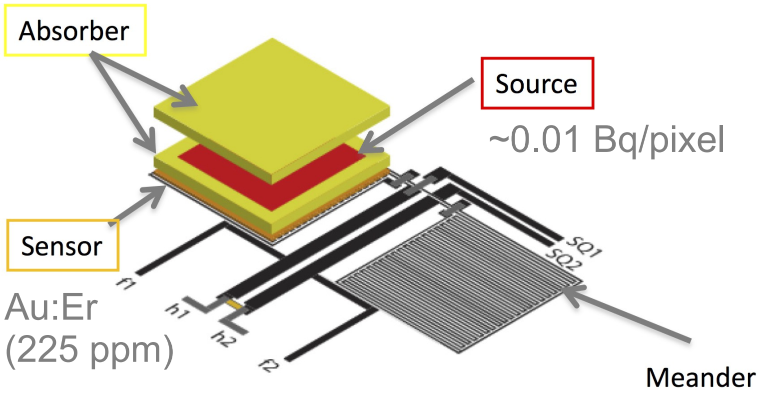
- Production: 10^6 Bq → N(^{163}Ho) = $2\cdot10^{17}$
- Implantation: Preserving detector features
- Background: Radiochemical purity

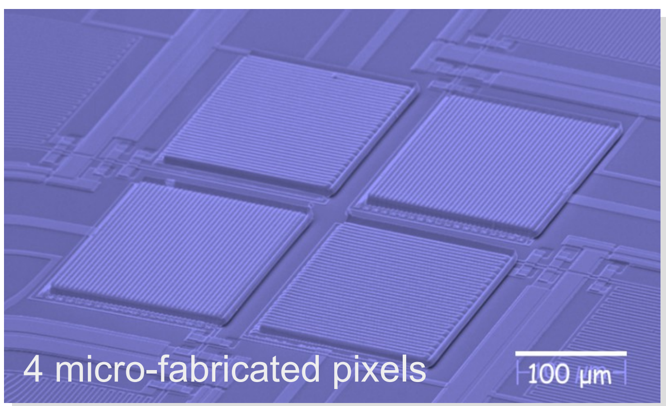
Galeazzi et al., arXiv:1202.4763





ECHo – Metallic Magnetic Calorimeters

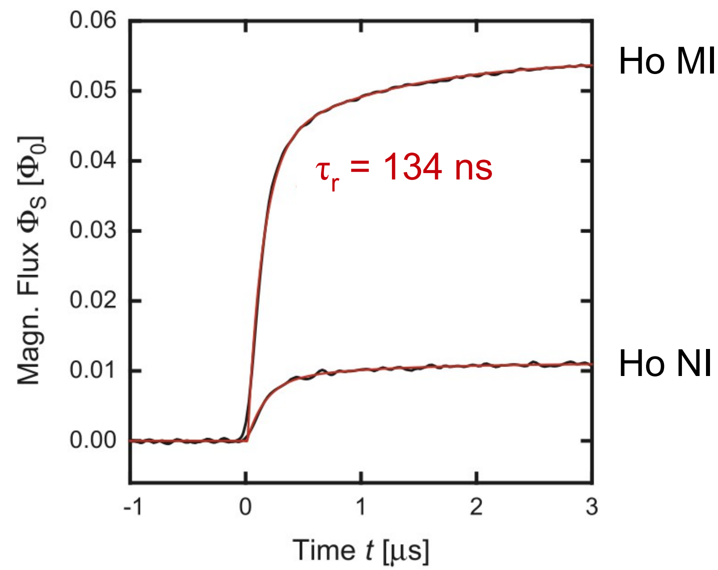




Ranitzsch et al., JLTP 167 (2012) 1004
Gastaldo et al., NIM A711 (2013) 150

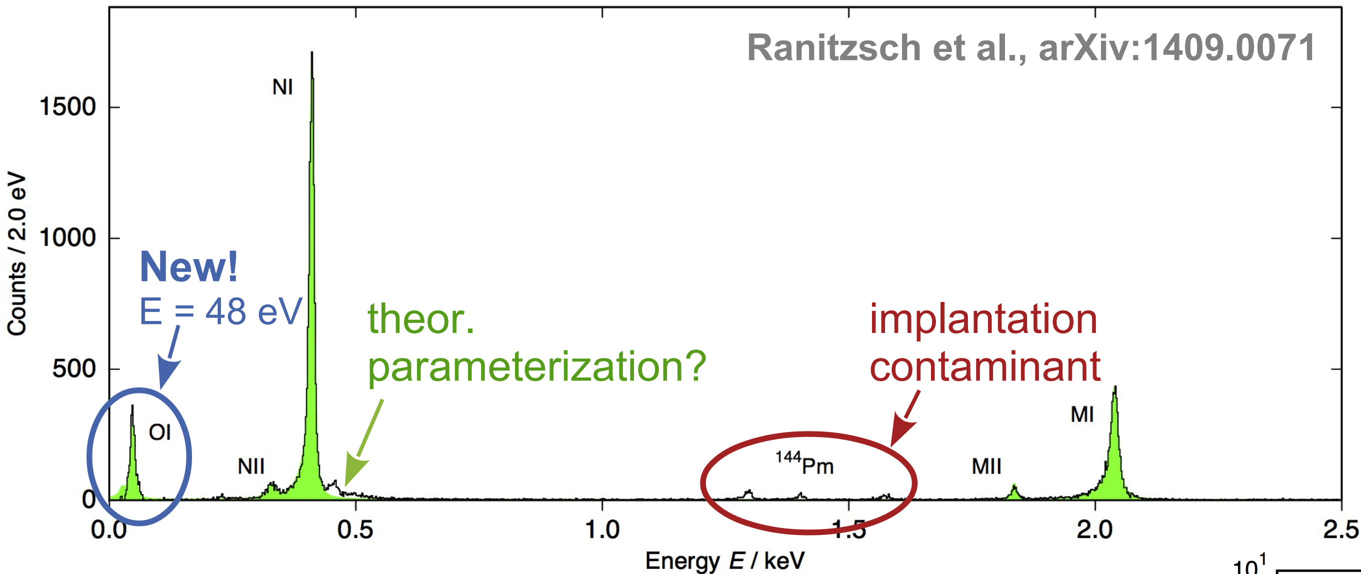
ECHo prototype

- Rise time ~130 ns
- Energy res. ΔE_{fwhm} = 7.6 eV at 6 keV
- Non-linearity < 1% at 6 keV



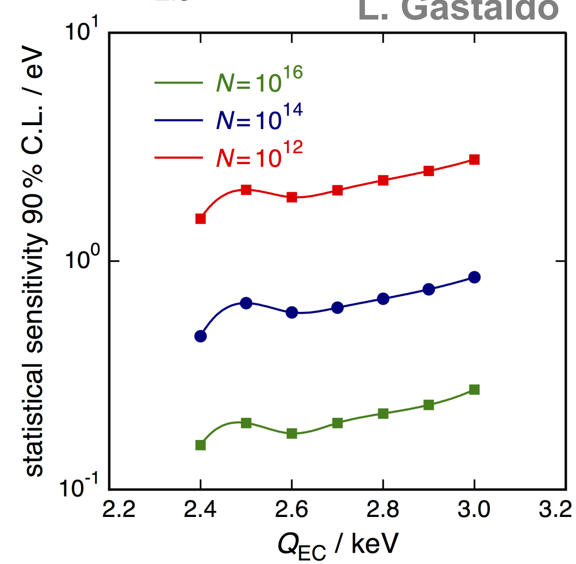
Gastaldo et al., JLTP 176 (2014) 876

ECHo – Metallic Magnetic Calorimeters



High-precision calorimetric ^{163}Ho spectrum recorded with 2 sensors

L. Gastaldo



Spectral fit: **Q_{EC} = 2849 (5) eV**

Recommended value: Q_{EC} = 2555 (16) eV

Other measurements: Q_{EC} = 2300 … 2800 eV

→ Large impact on m(ν) sensitivity

^{163}Ho-based experiments: next steps

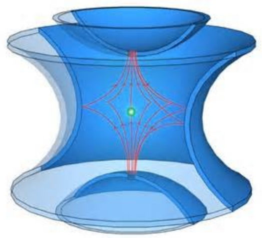
Precision parameterization of the EC spectrum

- Penning trap mass spectrometry to pin down Q_{EC}:

  uncertainty 30-100 eV SHIPTRAP, TRIGA-TRAP – ongoing

  1 eV PENTATRAP – next few years

- Improved description of environmental effects



Source/absorber development

Test various ^{163}Ho **production**, **purification** & **implantation** options

- Thermal neutron activation of ^{162}Er:
  :) high prod. rate
  :(contamination

- Charged-particle activation (e.g. ^{nat}Dy):
  :(low rate, :) little contamination

Array development

- Pile-up: **10-100 Bq**/pixel tolerable
- Still need arrays of **O(10^4–10^5)** pix.
- Read-out: microwave multiplexing
- ECHo: prepare test with **64 pixels**

Aim: < 10 eV sensitivity on m(ν)

Summary

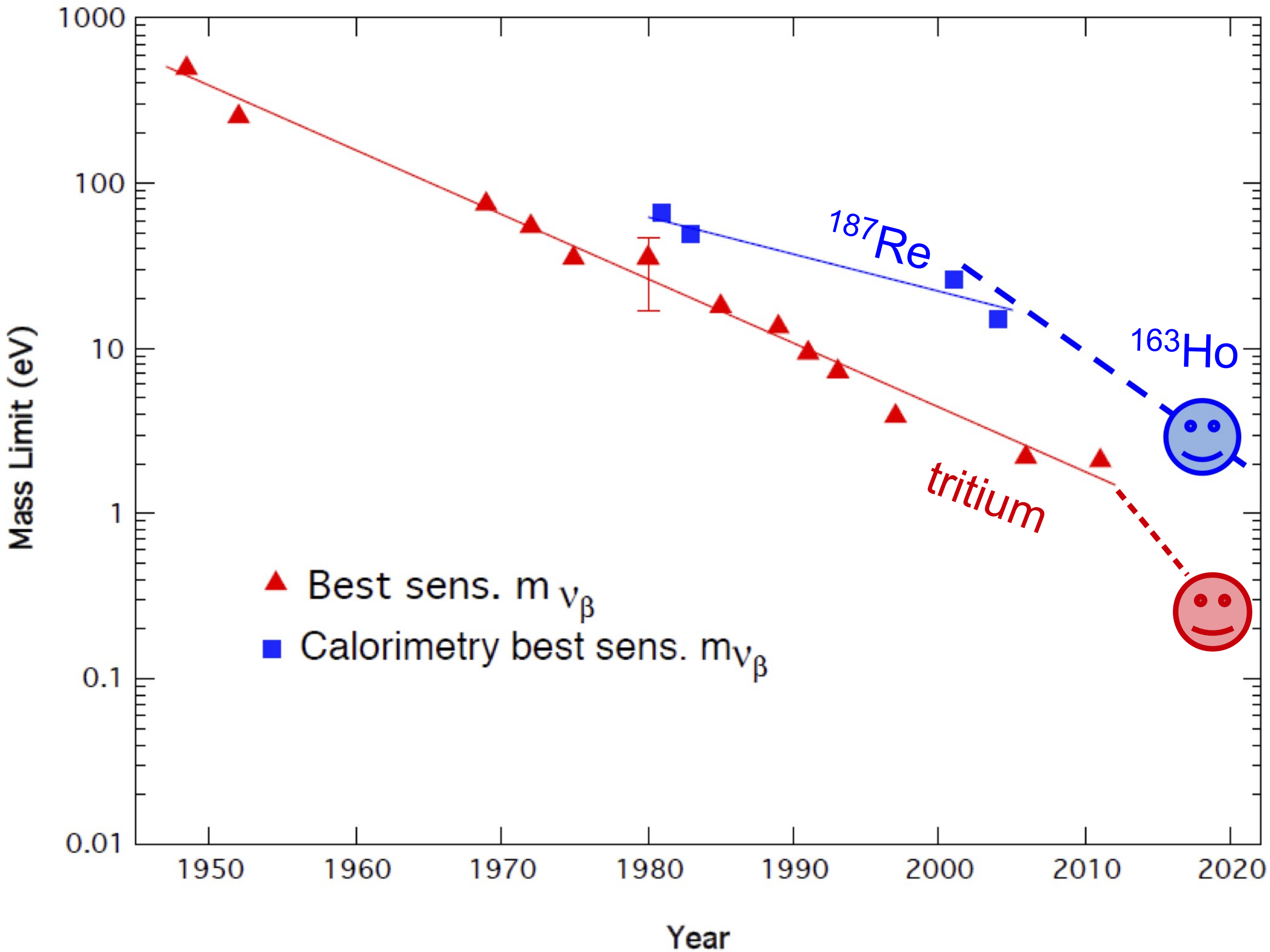
Status and outlook

	tritium β-decay	^{163}Ho electron capture

status	• KATRIN is in construction and commissioning phase
	• Project 8 prototype, proof of principle with ^{83m}Kr
		• 3 experiments in various stages, parallel R&D on
		  • detector technology
		  • high-purity ^{163}Ho production
		  • scalable arrays

outlook	• Reach sensitivity of 200 meV with KATRIN • Develop cyclotron spectroscopy towards a first tritium measurement	• Operate small arrays to collect ~10^{10} counts for a sensitivity of 10 eV • Prepare large-scale experiment for sub-eV range

(Breaking) Moore's law for direct ν-mass measurements



Adapted from J.F. Wilkerson/R.G.H. Robertson, L. Gastaldo