Absolute neutrino mass

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Introduction

The KArlsruhe TRItium Neutrino experiment KATRIN

- overview & commissioning campaigns

Possible improvements and neutrino mass beyond KATRIN

- Electron capture with ^{163}Ho cryo bolometers

- radio-based tritium β-spectroscopy: Project 8

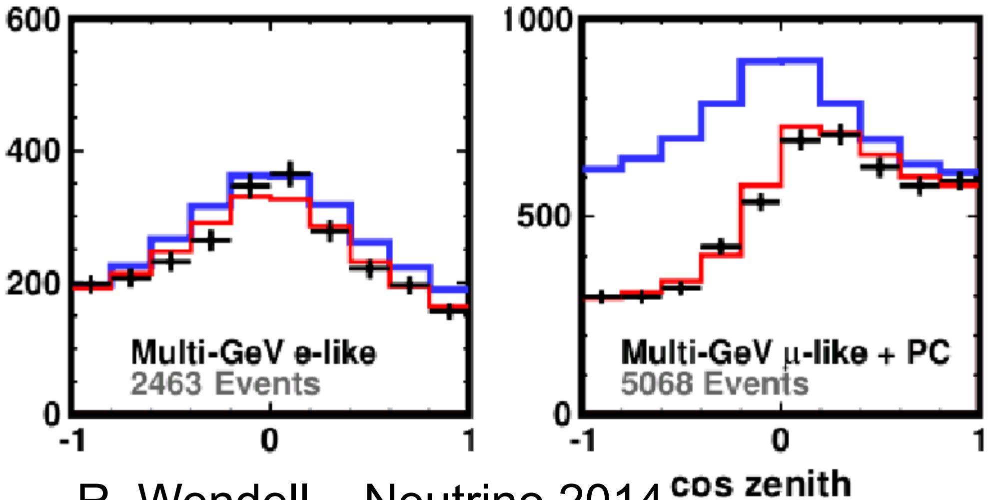
Conclusions

Photo: M. Zacher

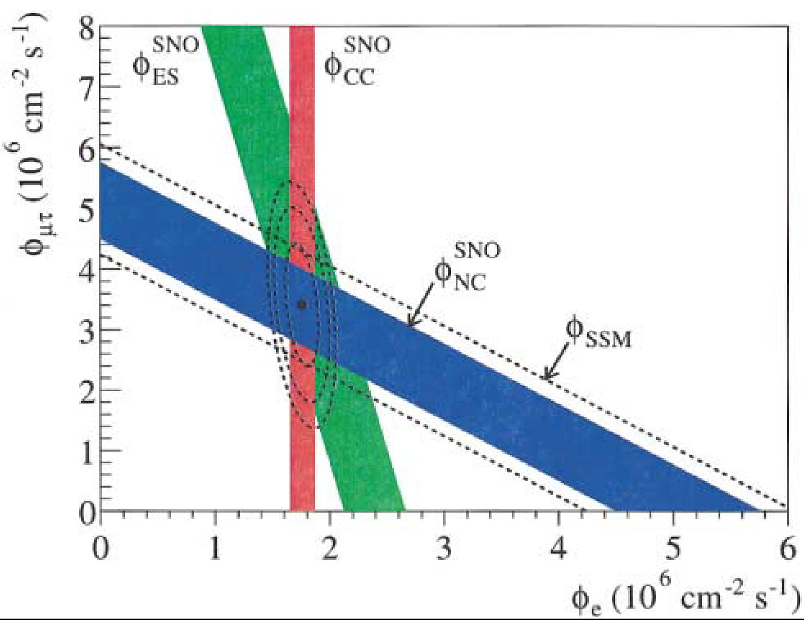
Discovery of atmospheric ($\nu_\mu \rightarrow \nu_\tau$) & solar ($\nu_e \rightarrow \nu_\mu/\nu_\tau$) neutrino oscillations $\rightarrow m(\nu) \neq 0$

Expectation no neutrino oscillation

Fit $\nu_\mu \rightarrow \nu_\tau$ oscillation



R. Wendell – Neutrino 2014



neutrino oscillation $\Rightarrow \Delta m^2_{ij} \Rightarrow m(\nu_j) \neq 0$, but unknown absolute scale

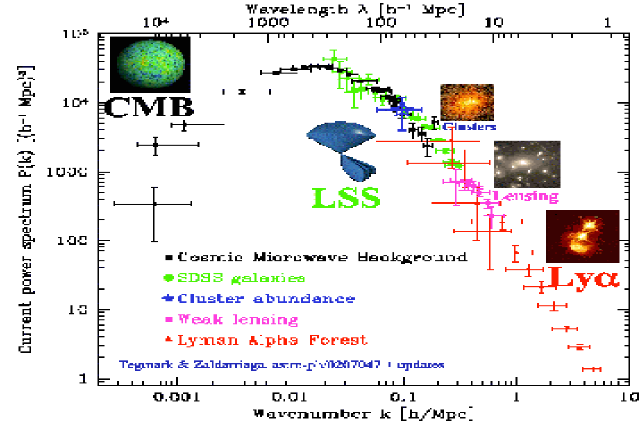
Three complementary routes to the absolute neutrino mass scale

1) Cosmology

very sensitive, but model dependent

compares power at different scales

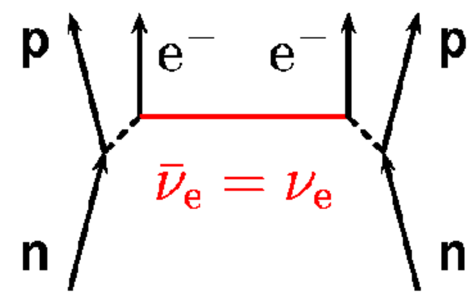
current sensitivity: $\Sigma m(\nu_i) \approx 0.23$ eV



2) Search for $0\nu\beta\beta$

Sensitive to Majorana neutrinos

Limits by EXO-200, KamLAND-Zen, GERDA II, CUORE?



3) Direct neutrino mass determination:

No further assumptions needed, use $E^2 = p^2c^2 + m^2c^4 \Rightarrow m^2(\nu)$ is observable mostly

Time-of-flight measurements (ν from supernova)

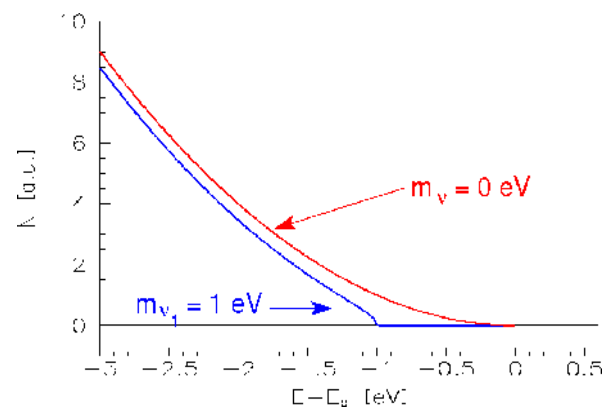
SN1987a (large Magellan cloud) $\Rightarrow m(\nu_e) < 5.7$ eV

Kinematics of weak decays / β-decays

measure charged decay products, E-, p-conservation

β-decay searches for $m(\nu_e)$ - tritium, ^{187}Re β-spectrum

- ^{163}Ho electron capture (EC)



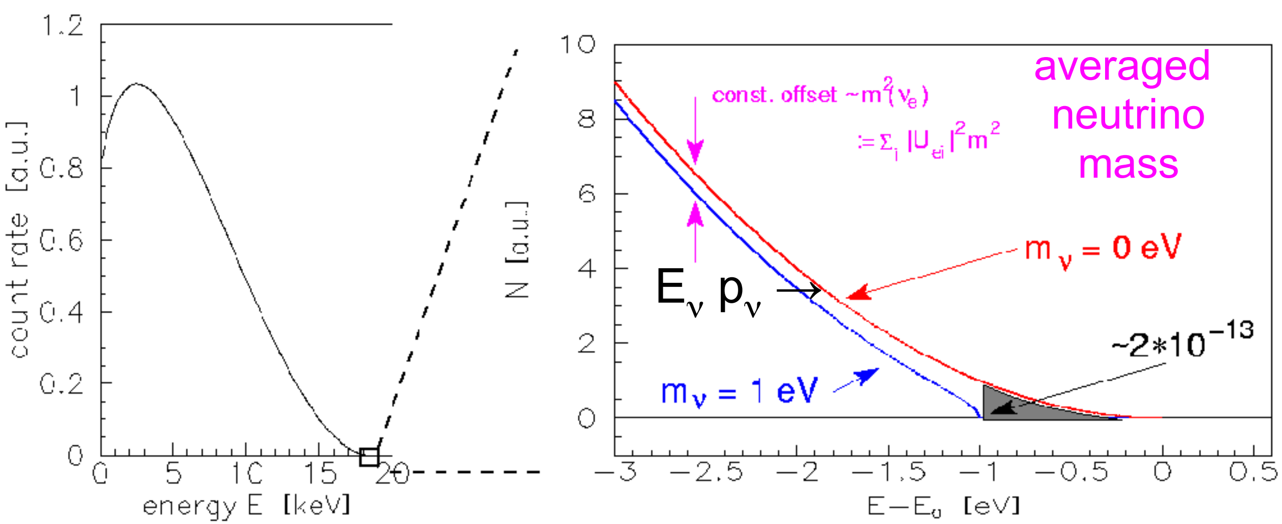
Direct determination of $m(\nu_e)$ from β-decay (and EC)

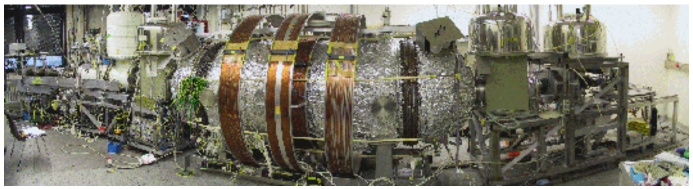
$$\beta:\ dN/dE = K\ F(E,Z)\ \underbrace{p}_{p_e}\ \underbrace{E_{tot}}_{E_e}\ \underbrace{(E_0-E_e)}_{E_\nu}\ \underbrace{\Sigma\,|U_{ei}|^2 \sqrt{(E_0-E_e)^2 - m(\nu_i)^2}}_{p_\nu}$$

essentially phase space: p_e E_e E_ν p_ν **→ EC at upper end is similar**

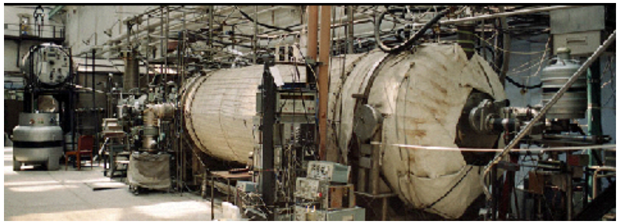
with "electron neutrino mass": $m(\nu_e)^2 := \Sigma\, |U_{ei}|^2\, m(\nu_i)^2$, complementary to $0\nu\beta\beta$ & cosmology

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



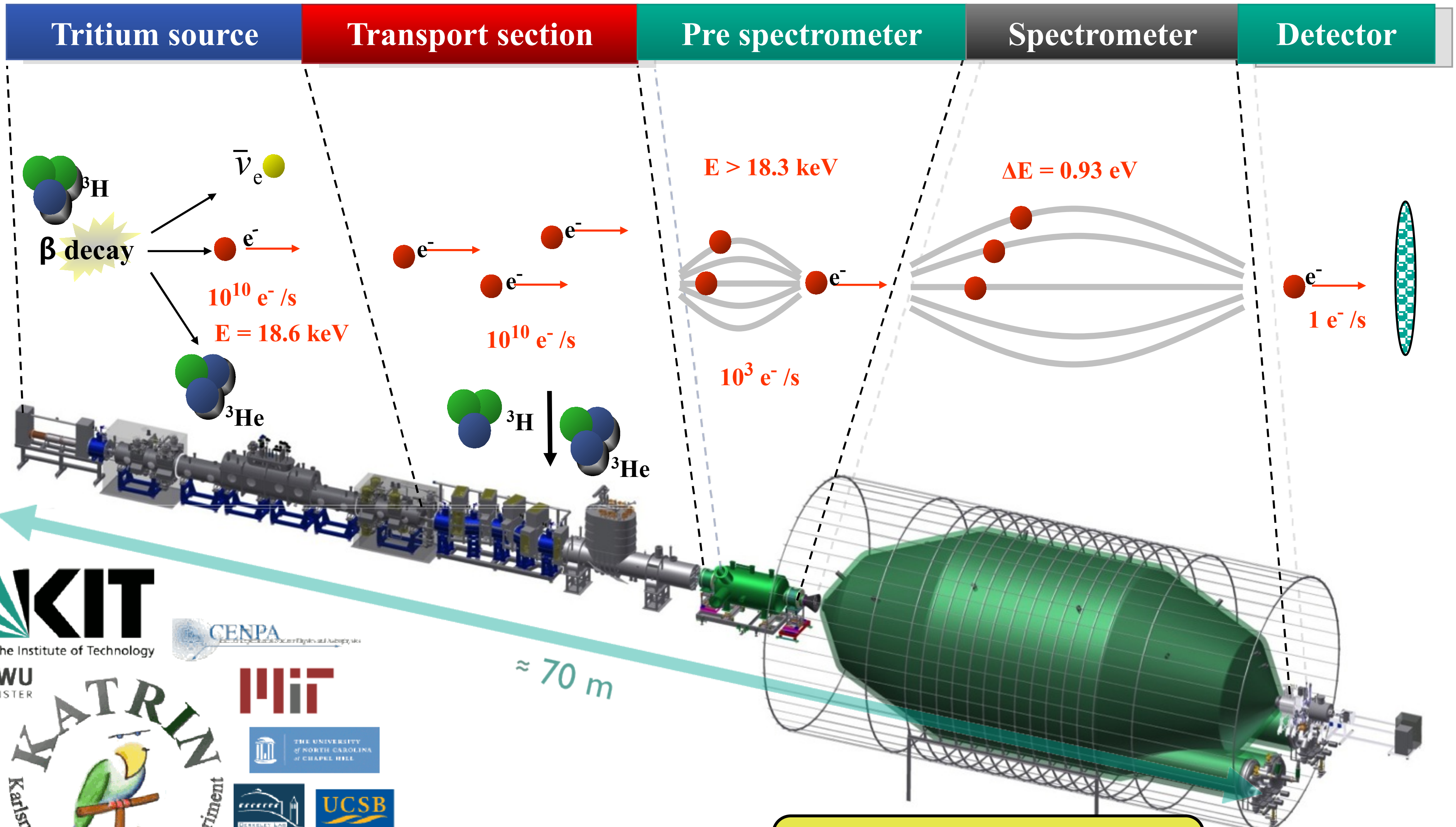


m(ν) < 2 eV (Mainz, Troitsk)



Need:
- **low endpoint energy** ⇒ **Tritium ^{3}H (^{187}Re, ^{163}Ho)**
- **very high energy resolution & very high luminosity & very low background** ⇒ **MAC-E-Filter (or bolometer for ^{187}Re, ^{163}Ho)**

The Karlsruhe Tritium Neutrino Experiment
KATRIN - overview



Sensitivity on $m(\nu_e)$:

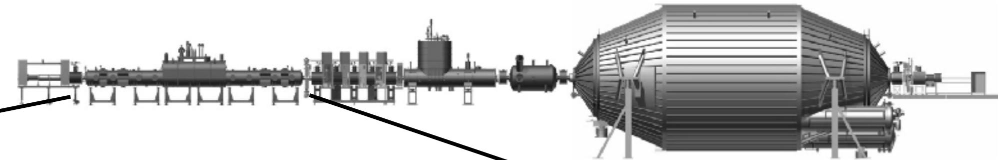
2 eV → 200 meV

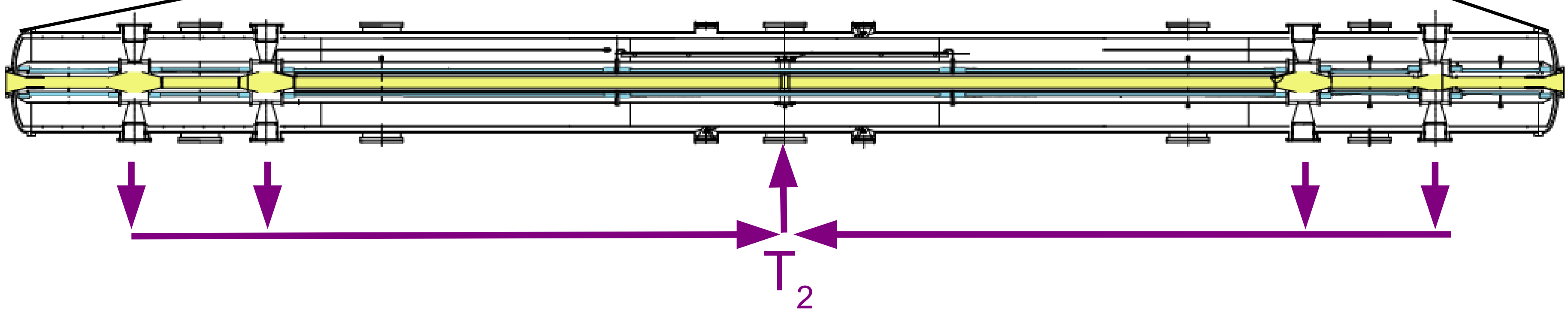
Molecular Windowless Gaseous Tritium Source WGTS

per mill stability source strength request:

$dN/dt \sim f_T \cdot N / \tau \sim n = f_T \cdot p \; V / R \, T$

tritium fraction f_T & ideal gas law

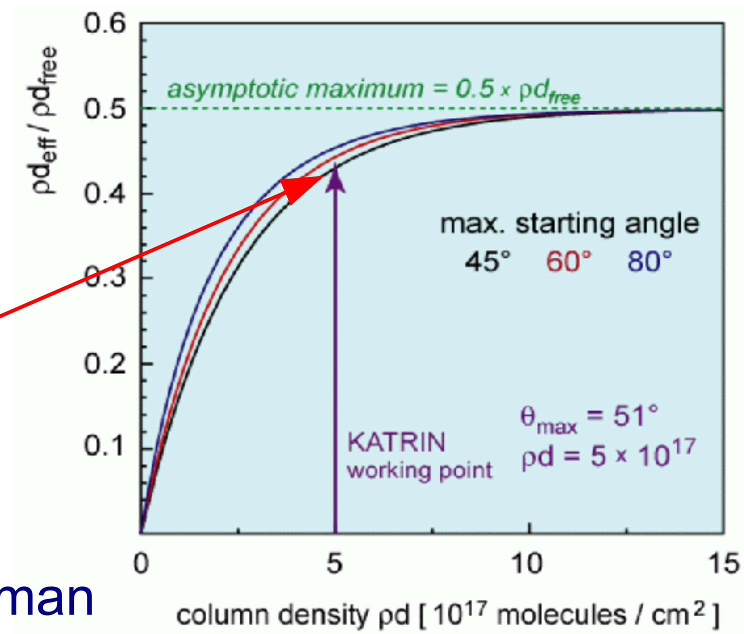




WGTS: tube in long superconducting solenoids
⊘ 9cm, length: 10m, T = 30 K

Tritium recirculation (and purification)
p_{inj} = 0.003 mbar, q_{inj} = 4.7Ci/s

allows to measure with near to maximum count rate using
$\rho d = 5 \cdot 10^{17}/cm^2$
with small systematics

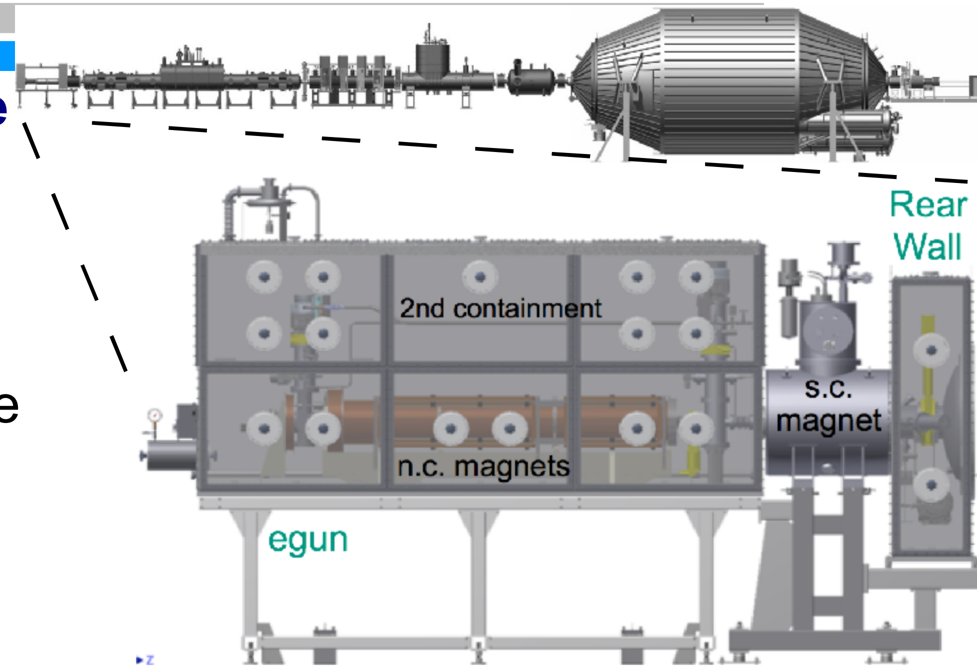


check column density by e-gun, T_2 purity by laser Raman

Molecular Windowless Gaseous Tritium Source WGTS

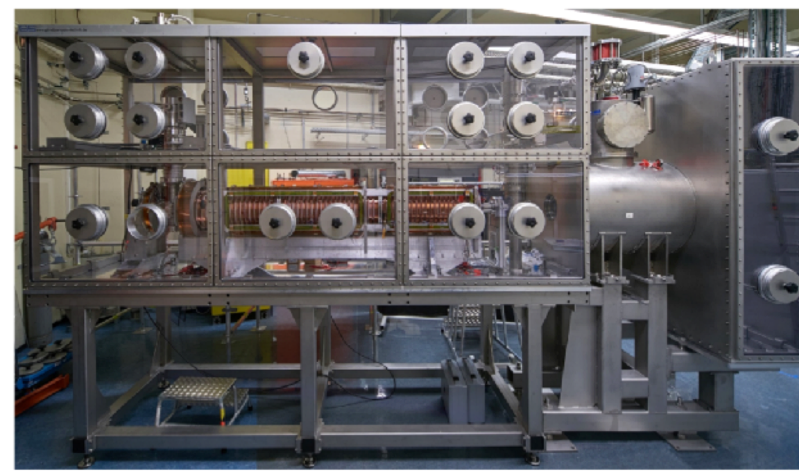

WGTS at Tritium Laboratory Karlsruhe

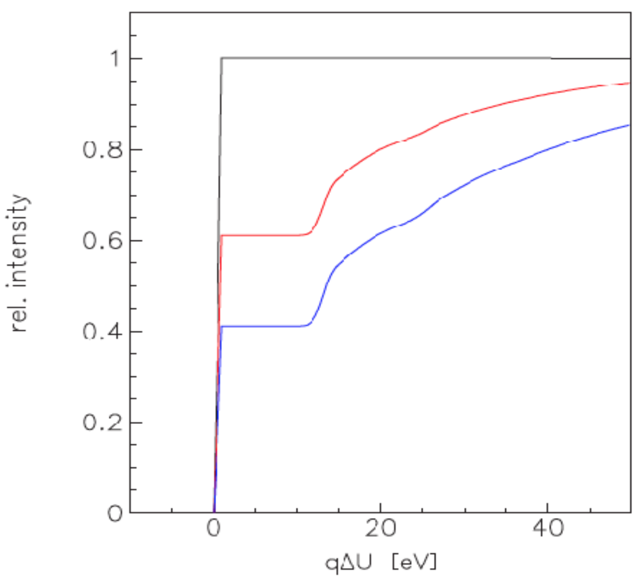
Calibration and monitoring rear system: controling and studying systematics



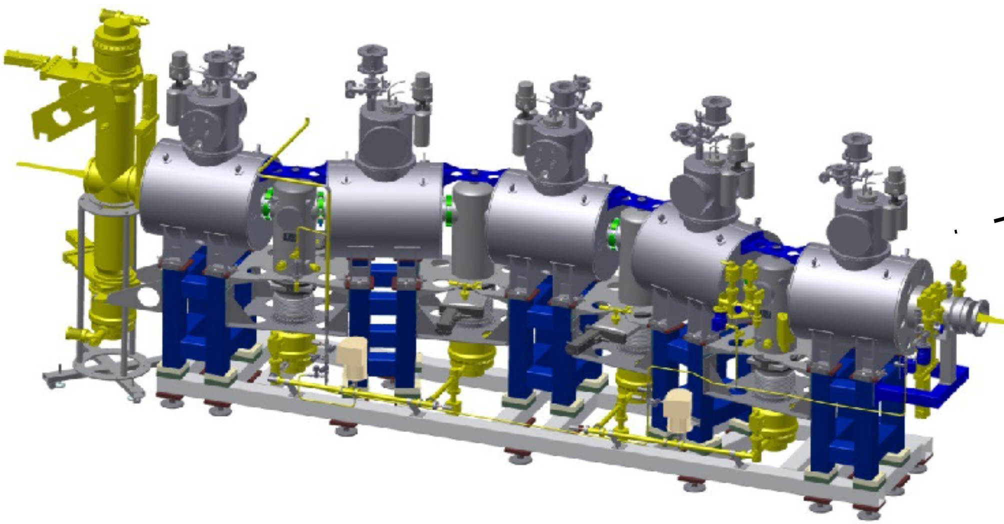
Essential for diagnostics of tritium source & spectrometer transmission

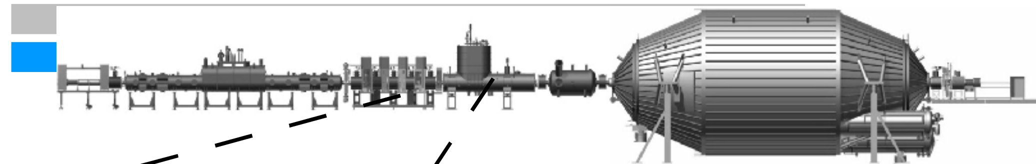
- **photo-electron gun**:
  spectrometer transmission
  column density & energy losses in source
- **rear wall**: definition of source potential,
  neutralization of tritium plasma
- **X-ray detectors:**
  online monitoring of tritium ß-decay
  activity via X-rays (BIXS)

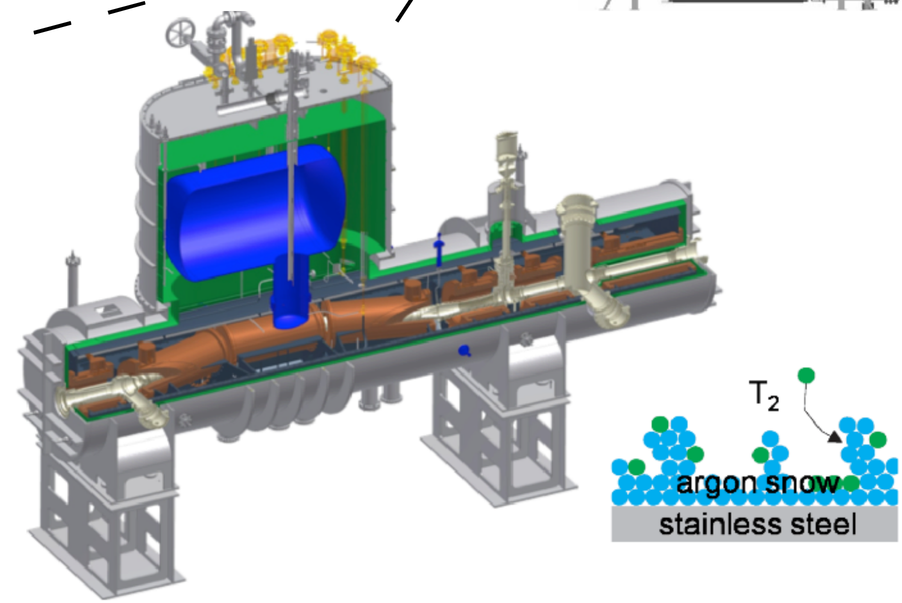


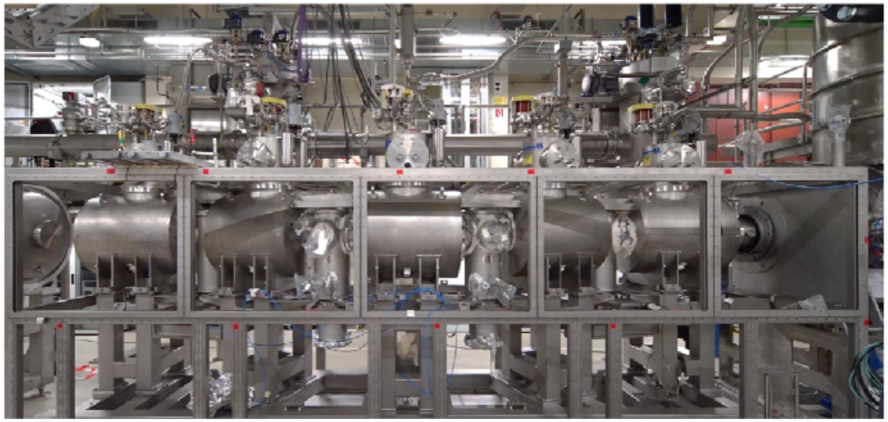


Differential and cryo pumping sections: supression of T_2 by 10^{14} (incl. WGTS)





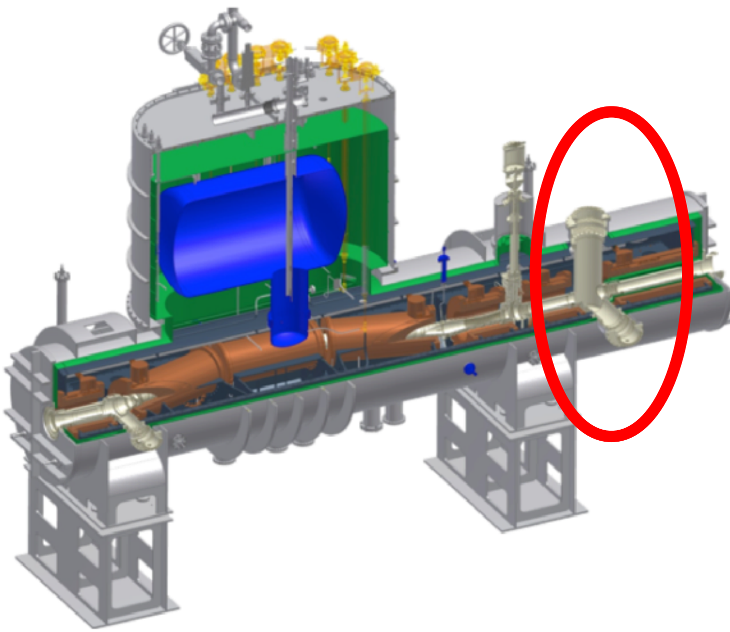




- based on by cryo-sorption at Ar snow at 3-4 K
- Tritium retention: $>10^7$
- magnetic field: 5.6 T

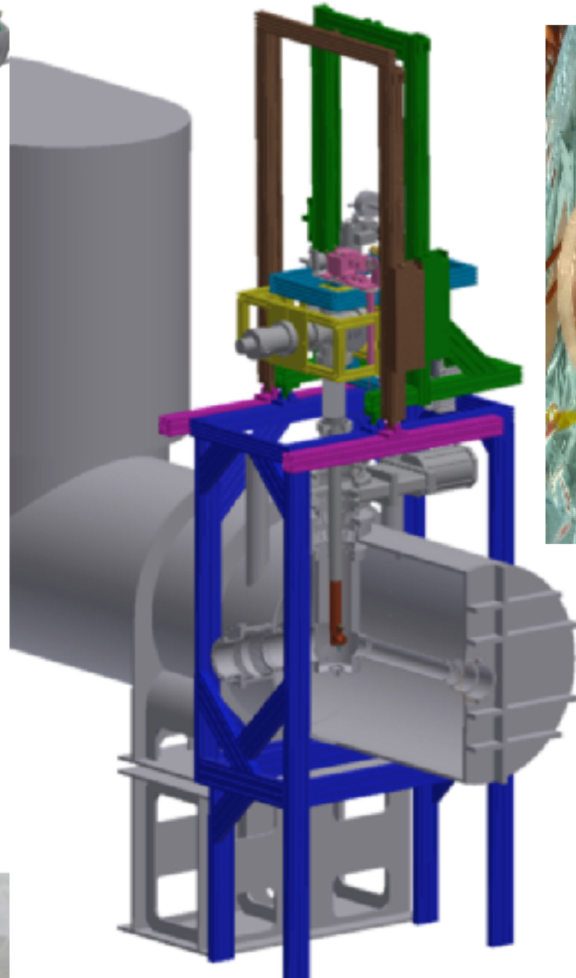
- active pumping: 4 TMPs
- Tritium retention: 10^5
- magnetic field: 5.6 T
- **Ion monitoring by FTICR and ion manipulation by dipole and monopole electrodes inside**

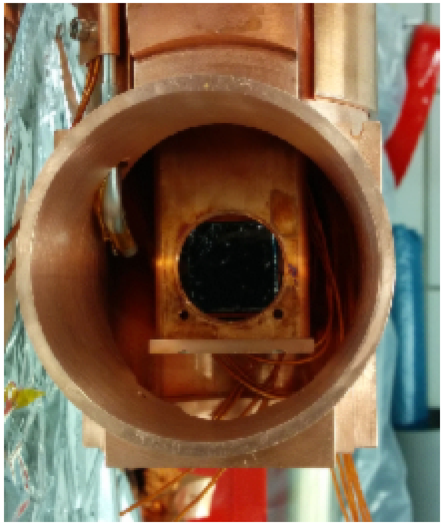
Monitoring and calibration instrumentation of the CPS

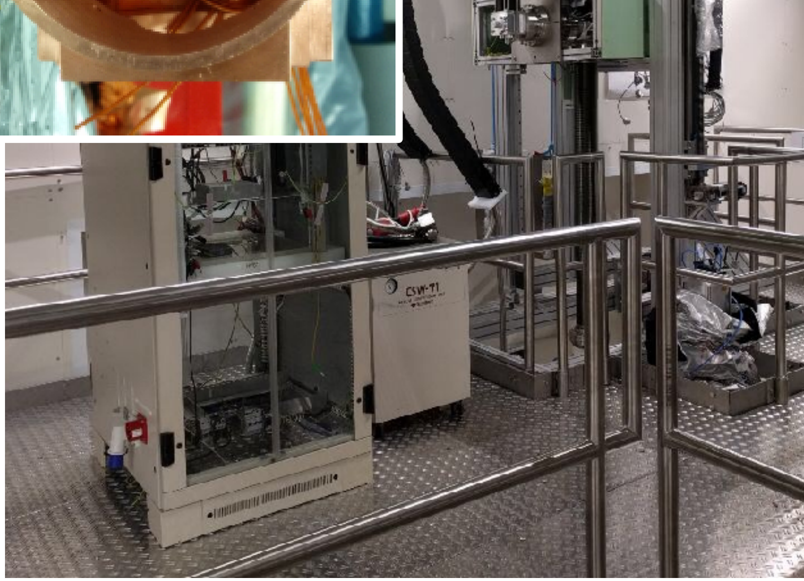


Condensed ^{83m}Kr conversion electron source

for energy calibration and studies of transmission properties
HOPG @T=25K, UHV, on HV, can scan full flux tube
surface control: heating & laser ablation, laser ellipsometry

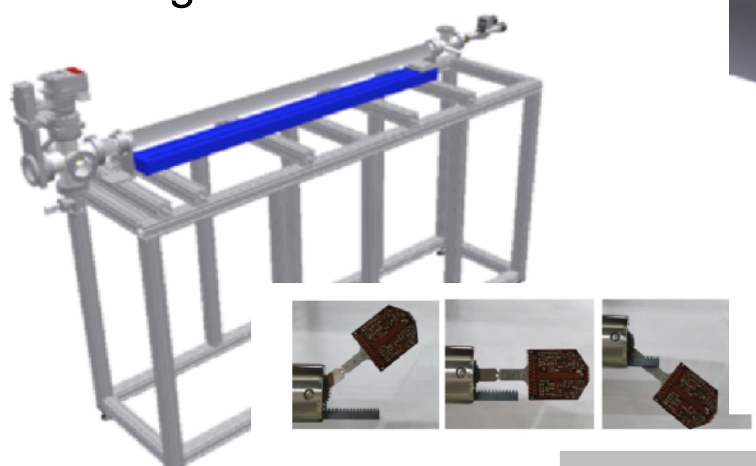




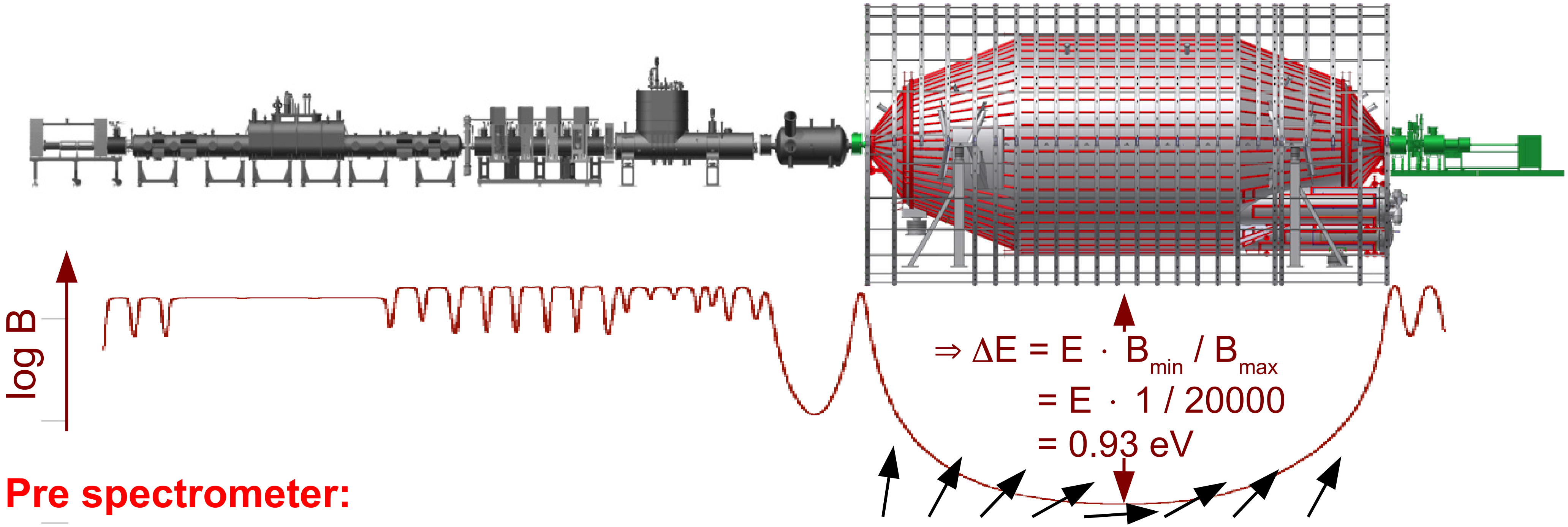


Electron rate monitor

scanning small SD or PIN diode



KATRIN spectrometers of MAC-E-Filter type



$\Rightarrow \Delta E = E \cdot B_{min} / B_{max}$
$= E \cdot 1 / 20000$
$= 0.93$ eV

Pre spectrometer:

- successful tests & developments of new concepts

Main spectrometer:

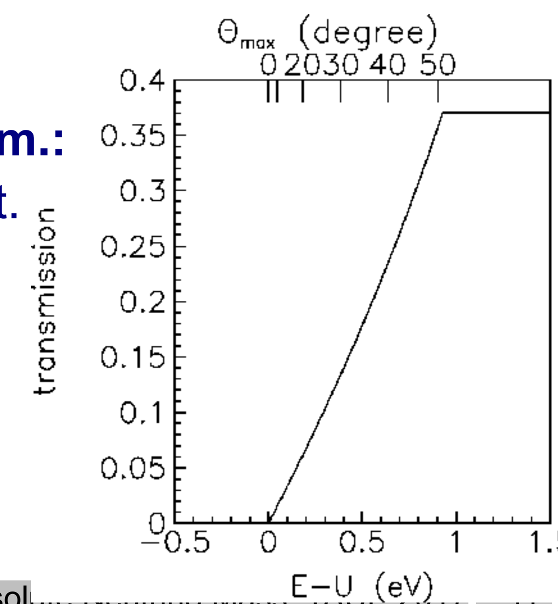
- huge size: 10m diameter, 24m length
  1240 m^3 volume, 690 m^2 inner surface
- ultra-high vacuum: p = $O(10^{-11}$ mbar)
- ultra-high energy resolution: $\Delta E = 0.93$eV
- vacuum vessel on precise high voltage (ppm precision)

adiabatic transform.:

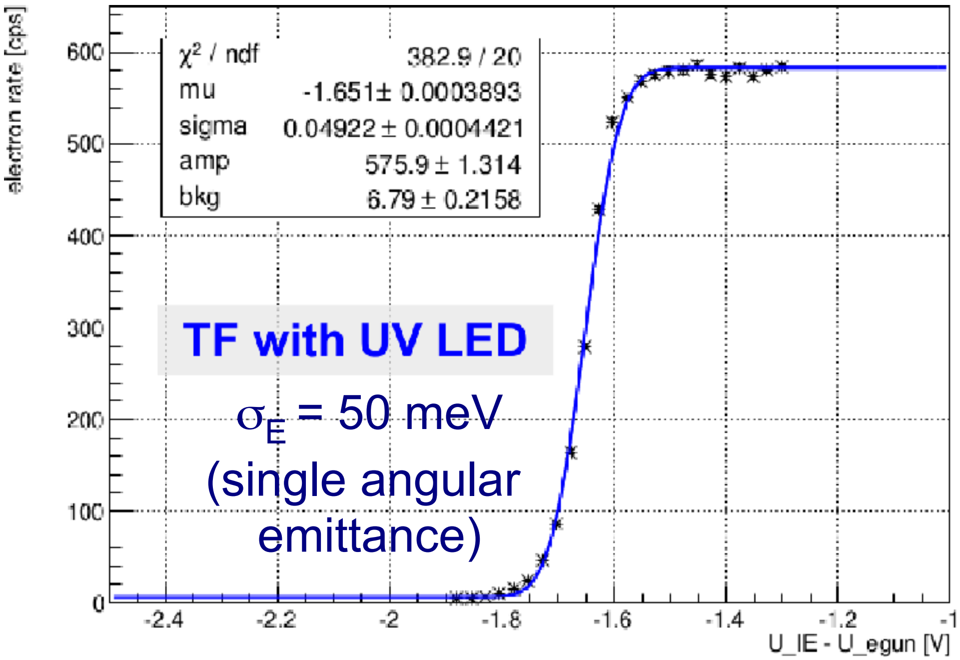
$\mu = E_{\perp} / B = \text{const.}$

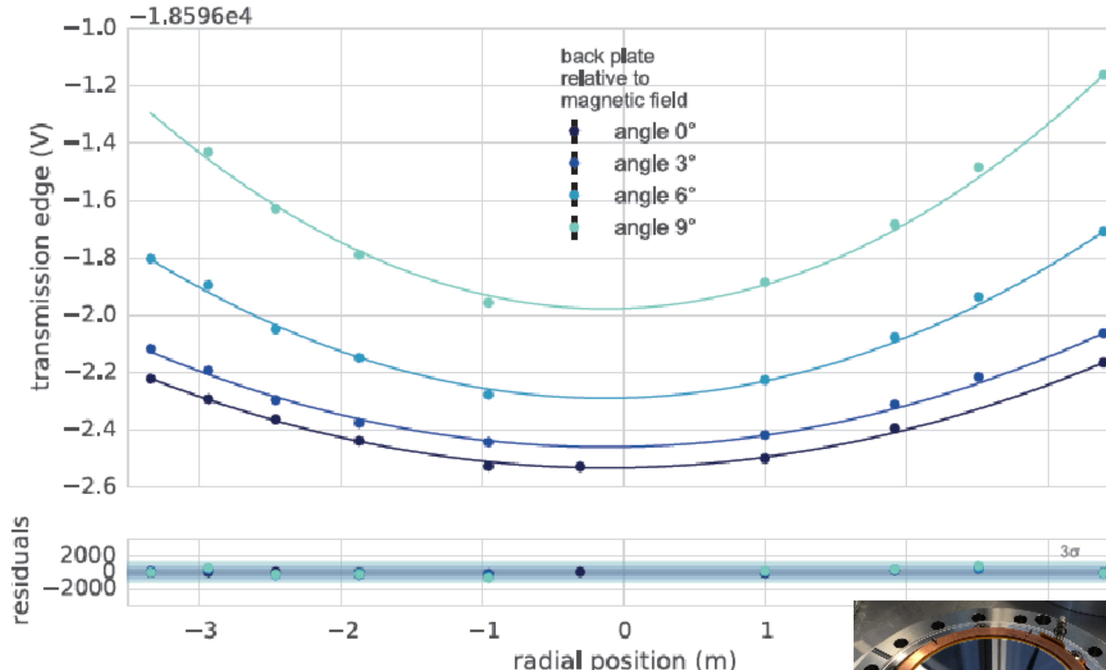
$\Rightarrow$ parallel e^- beam

$\Delta E/E = B_{min}/B_{max}$

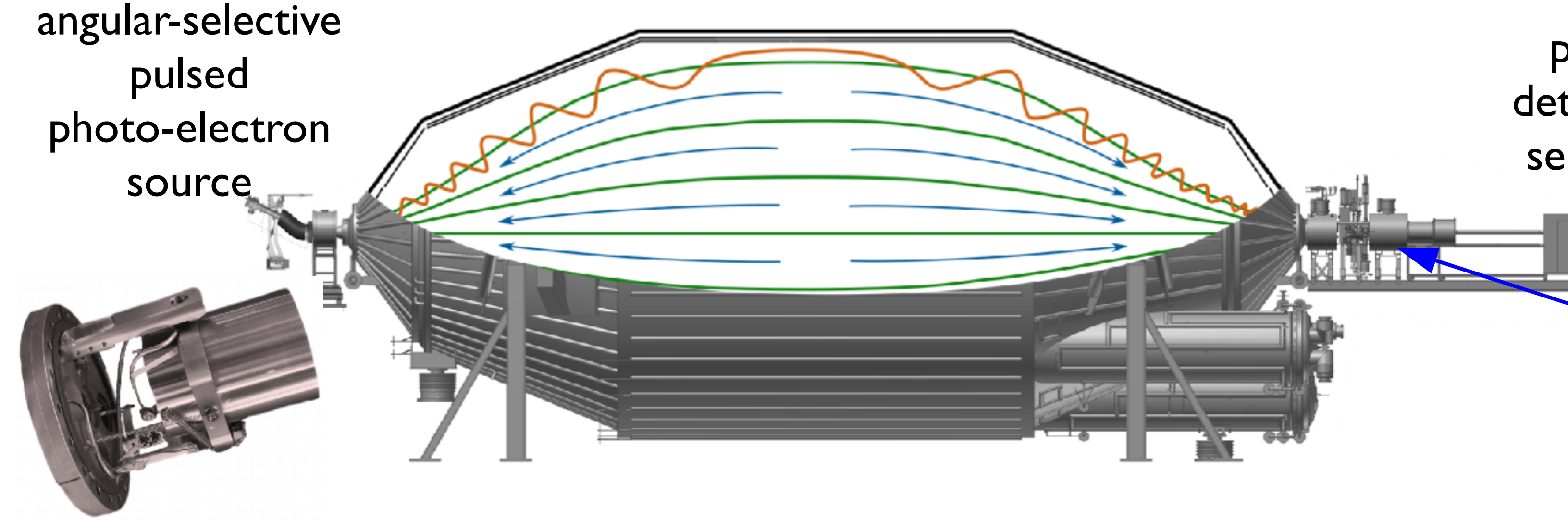


Commissioning of main spectrometer (ΔE = 0.93 eV) and detector

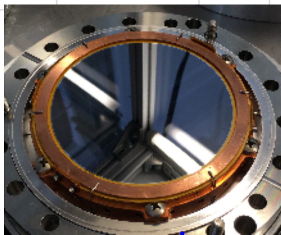


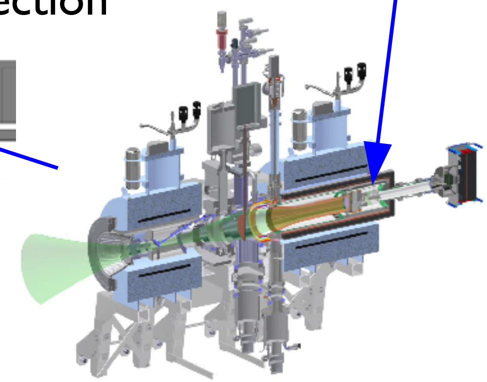


angular-selective pulsed photo-electron source

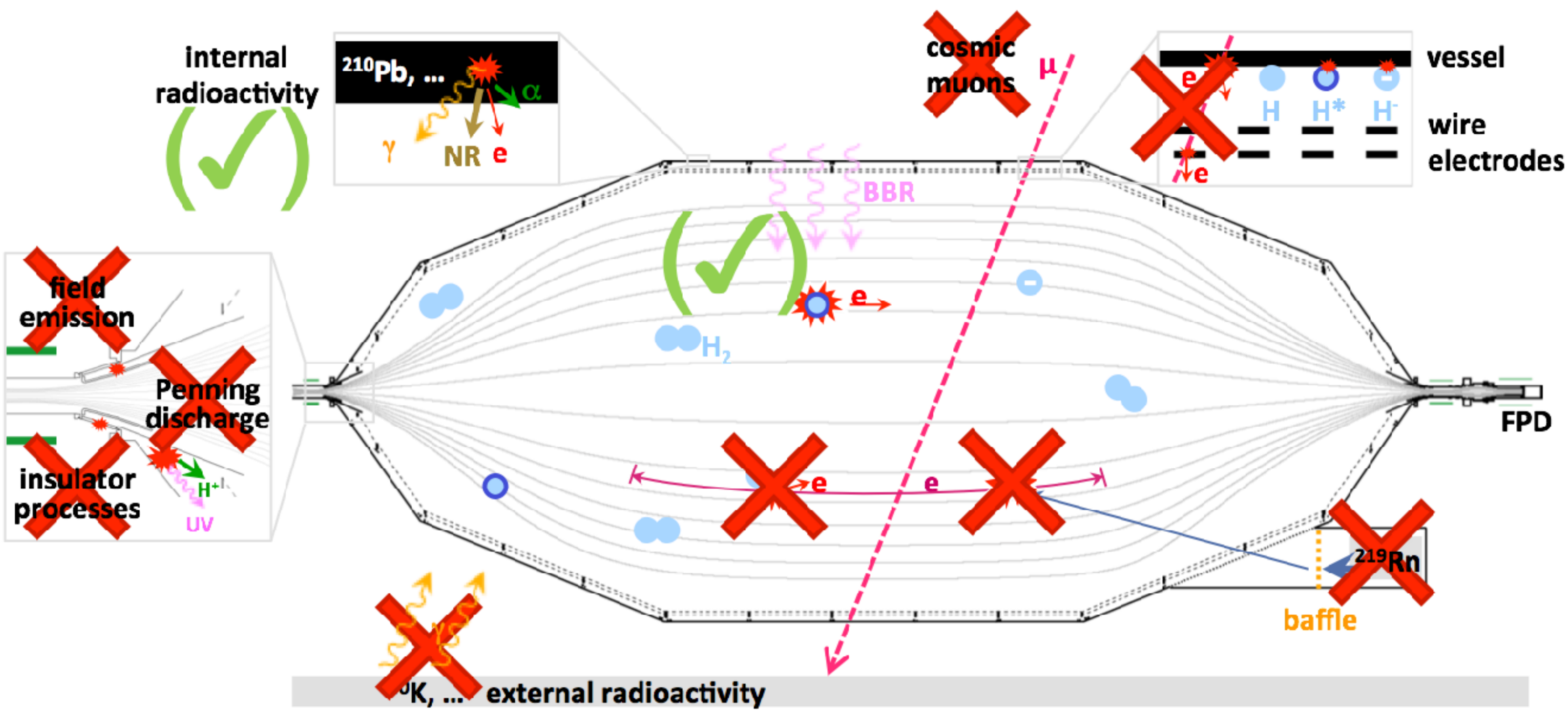


pixel detector section





Background sources at KATRIN: detailed understanding, but ...



- 8 sources of background investigated and understood
- 7 out of 8 avoided or actively eliminated by
  - fine-shaping of special electrodes
  - symmetric magnetic fields
  - LN_2-cooled baffles (cold traps)
  - wire electrode grids

- 1 out of 8 remaining:
  caused by ^{210}Pb on spectrometer walls (neutral H* atoms ionised by black-body radiation in spectrometer)

Background due to ionization of Rydberg atoms sputtered off by α decays

H* Rydberg atoms:

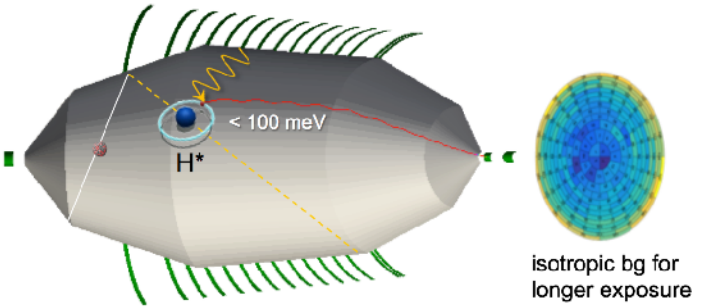
- desorbed from walls due to ^{206}Pb recoil ions from ^{210}Po decays
- non-trapped electrons on meV-scale
- bg-rate: ~0.5 cps

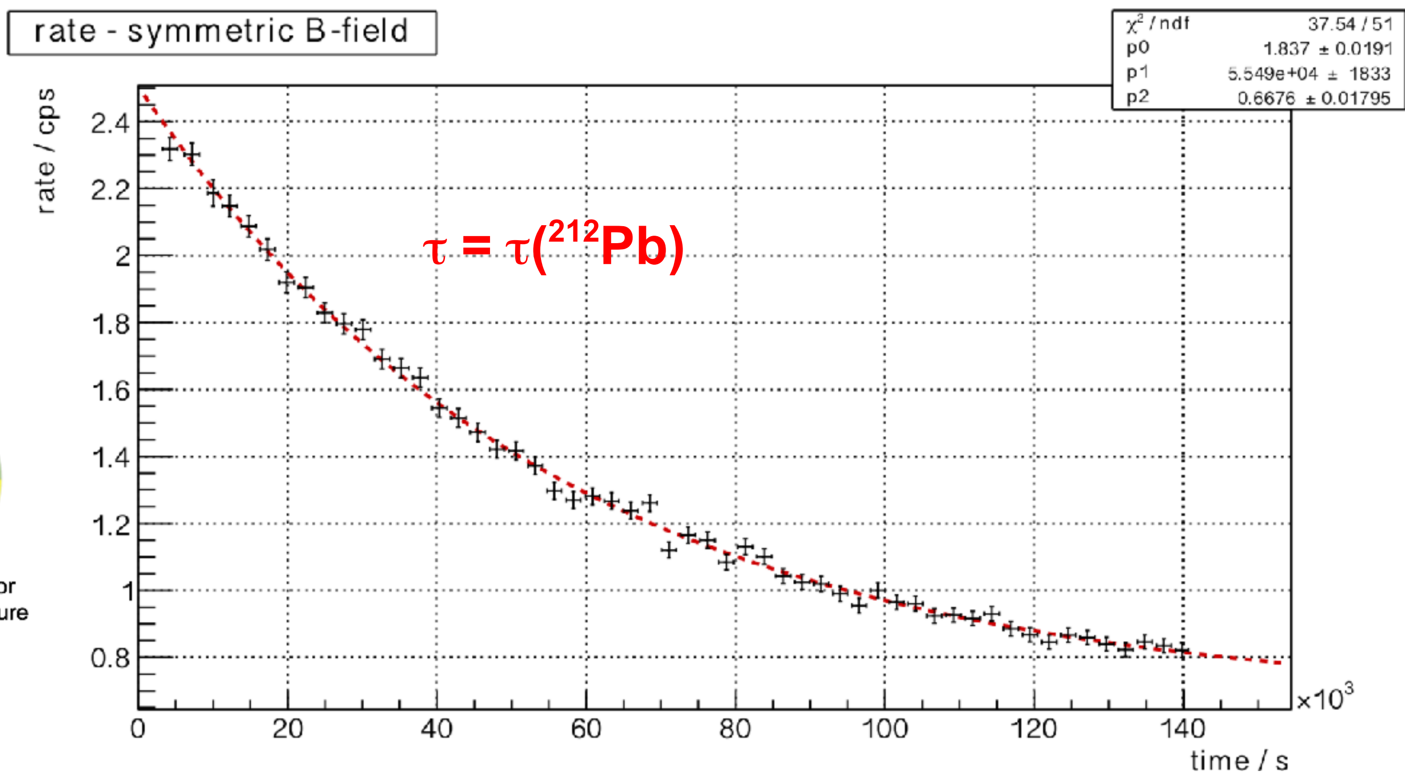
counter measures:

- reduce H-atom surface coverage:
  a) extended bake-out phase: done
  b) strong UV illumination source

Testing this hypothesis:

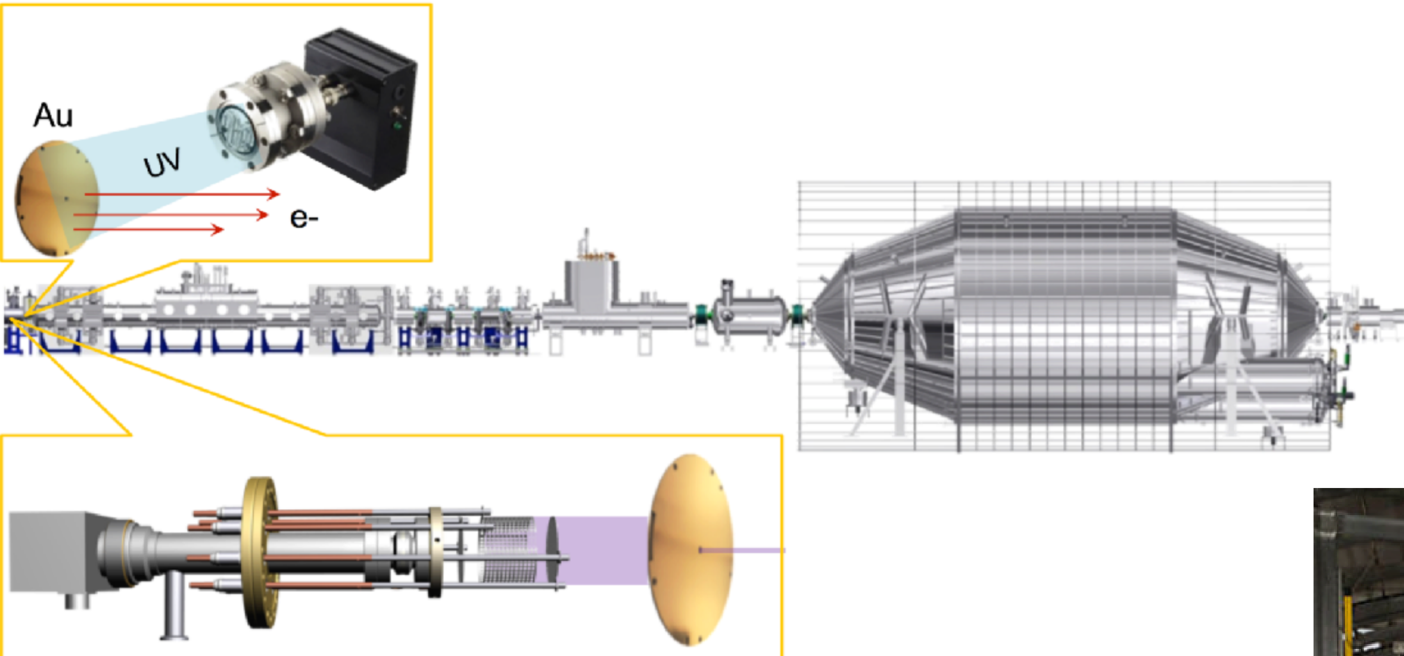
artifically contaminating the spectrometer with implanted short-living daughters of ^{220}Rn





WWU MÜNSTER

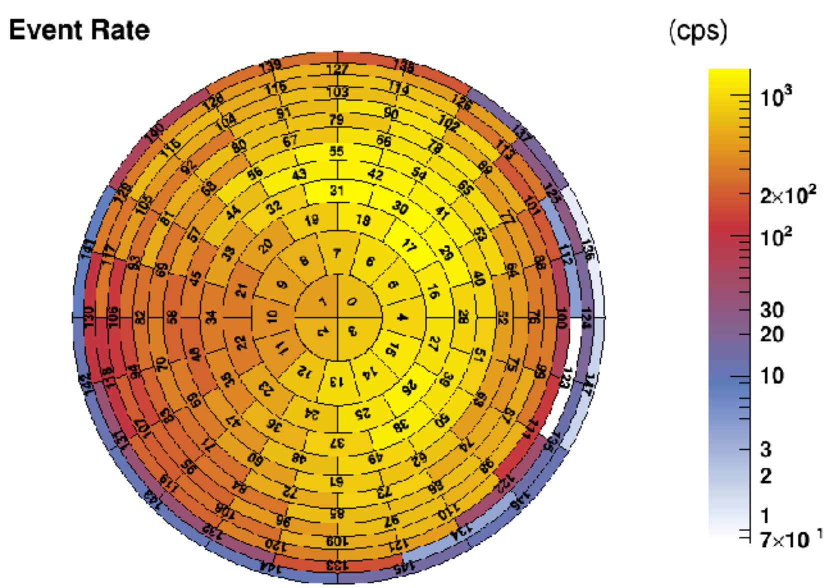
Technical start of KATRIN: „1st light“, photo-electrons from rear wall & and ions



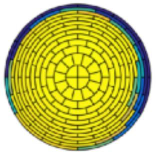
Testing whole 70m long beamline with electrons:
- alignment
- magn. stearing of pencil beam

With ions:
- ion removal

no tritium yet

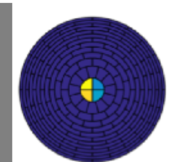


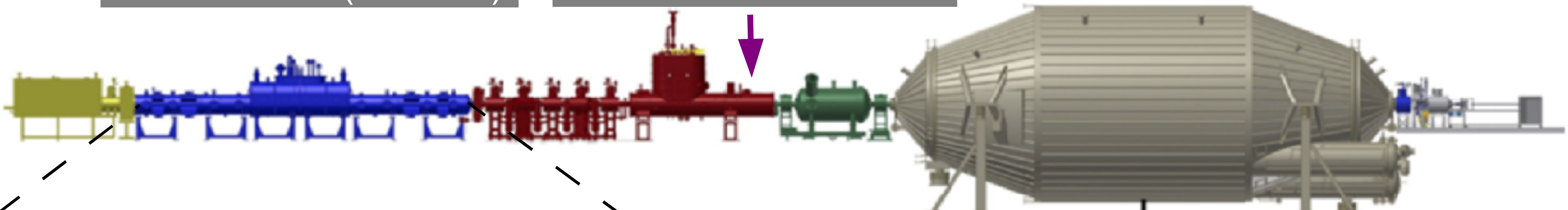
July 2017: calibration and comissioning campaign with all 3 ^{83m}Kr sources

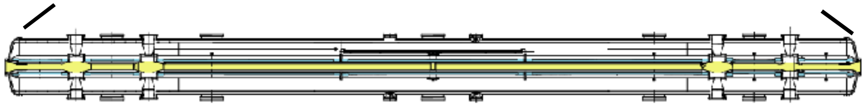


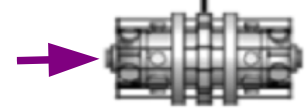
gaseous ^{83m}Kr source
decaying ^{83m}Kr atoms fill whole WGTS (at 100 K)

condensed ^{83m}Kr source
point-like source
full flux tube scanable



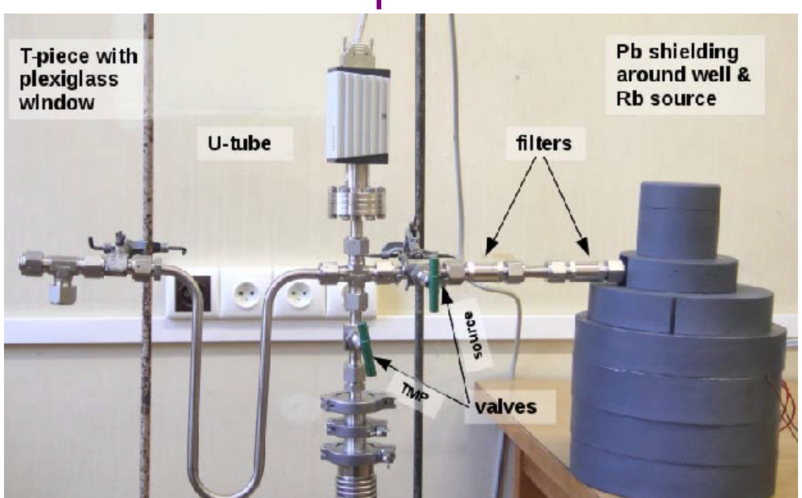


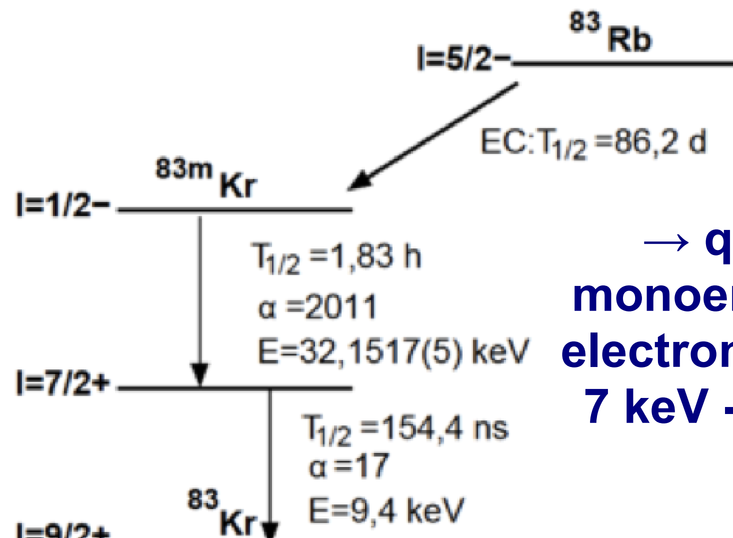




implanted ^{83}Rb/^{83m}Kr source

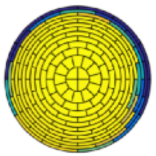
^{83m}Kr
from 1 GBq ^{83}Rb source





→ **quasi-monoenergetic electron lines at 7 keV - 32 keV**

July 2017: calibration and comissioning campaign with all 3 ^{83m}Kr sources



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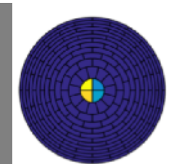
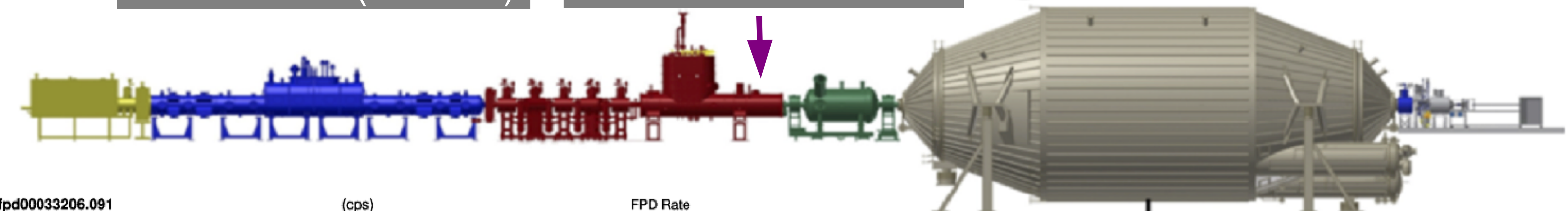
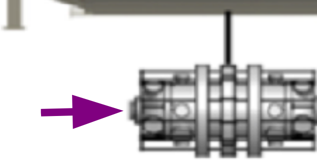
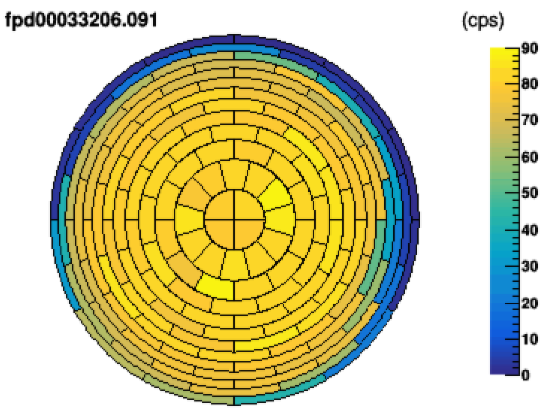
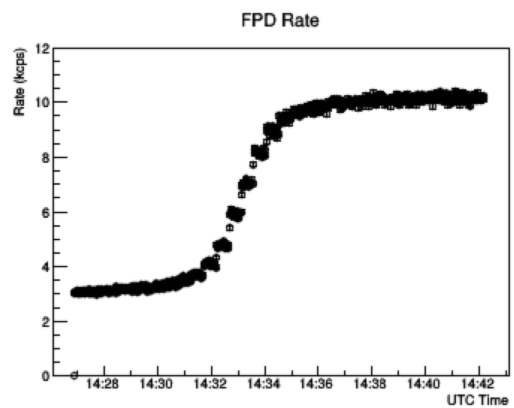


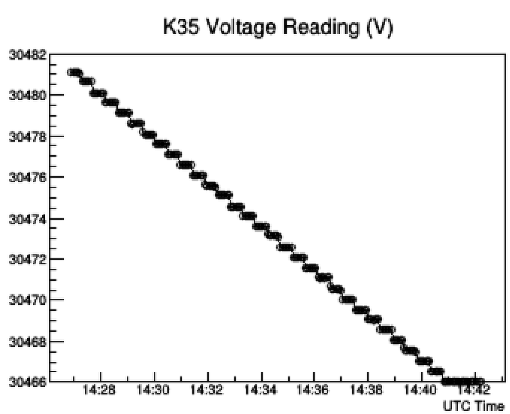


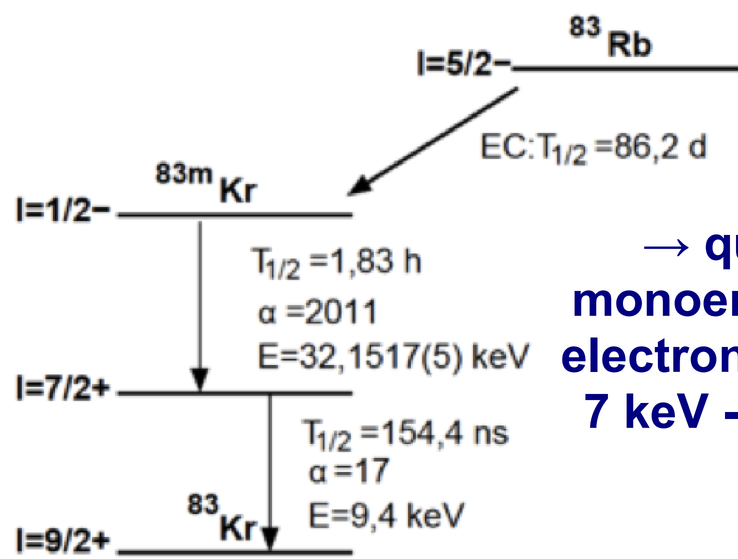


implanted ^{83}Rb/^{83m}Kr source



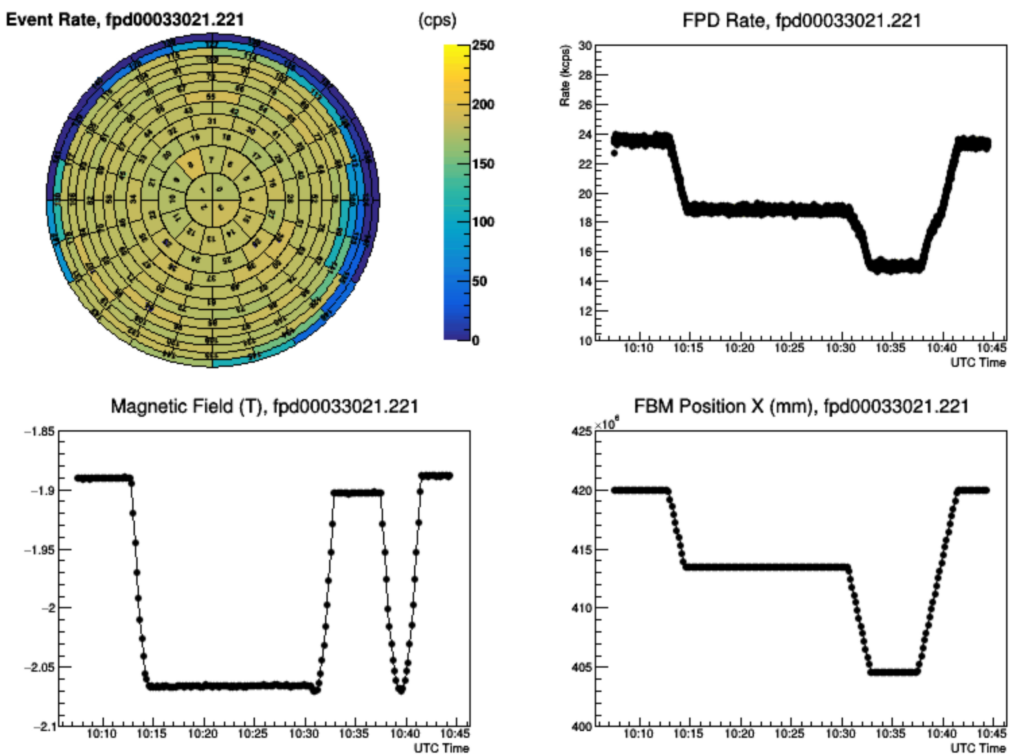


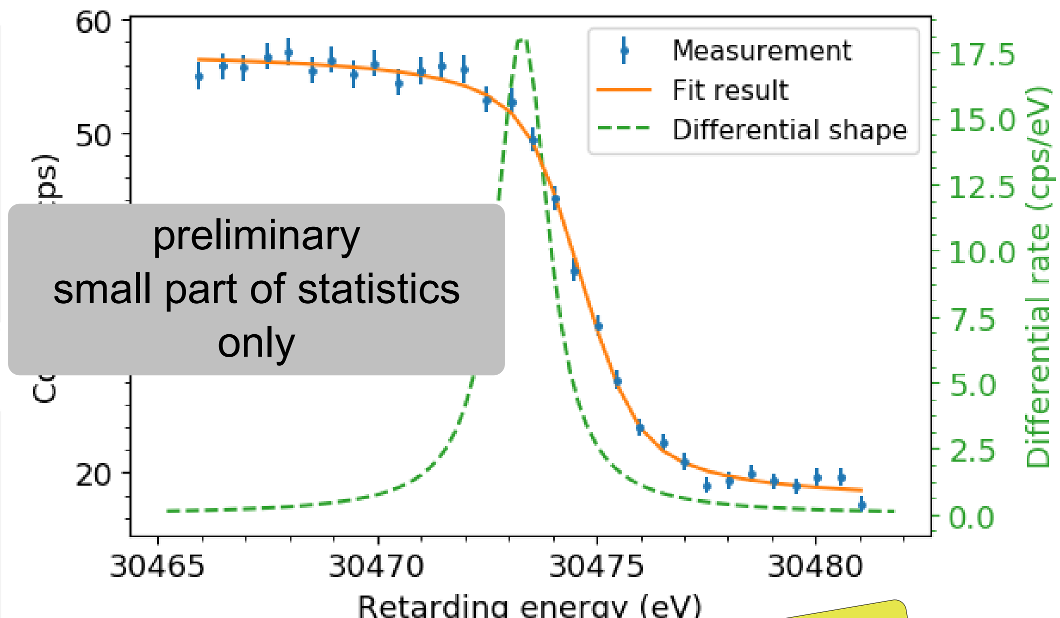




→ quasi-monoenergetic electron lines at 7 keV - 32 keV

Purpose of ^{83m}Kr measurements: calibration, alignment, systematics, HV





see talk by F. Fränkle today
& poster by O. Rest

Systematic uncertainties

As smaller m(ν) as smaller the region of interest below endpoint E_0

→ quantum mechanical thresholds help a lot !

A few contributions with $\Delta m_\nu^2 \leq$ 0.007 eV² each:

1. inelastic scatterings of β´s inside WGTS
- dedicated e-gun measurements, unfolding of response fct.

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

3. WGTS charging due to remaining ions (MC: φ < 20mV)
- monocrystaline rear plate short-cuts potential differences

4. final state distribution
- reliable quantum chem. calculations

(1.–4.: tritium source)

5. transmission function
- detailed simulations, angular-selective e-gun measurements

6. HV stability of retarding potential on ~3ppm level required
- precision HV divider (with PTB), monitor spectrometer beamline

(5.–6.: spectrometer)

Systematic uncertainties

As smaller m(ν) as smaller the region of interest below endpoint E_0

→ quantum mechanical thresholds help a lot !

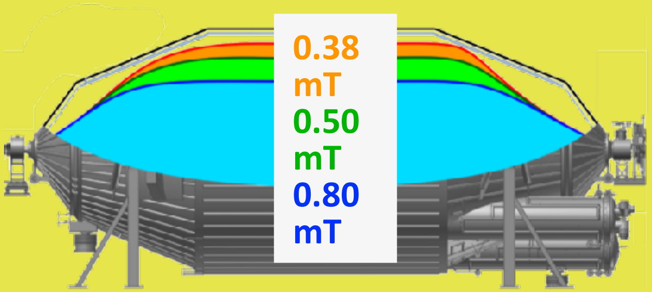
3 yr of data taking

sensitivity on the neutrino mass (stat.+sys. uncertainties):

→ 200 meV (design value)

Higher (Rydberg) background rate

→ using larger data range (E_0-60 eV) and a bit less energy res.:



→ 240 meV (without further mitigation of the Rydberg background)

spectrometer

6. HV stability of retarding potential on ~3ppm level required

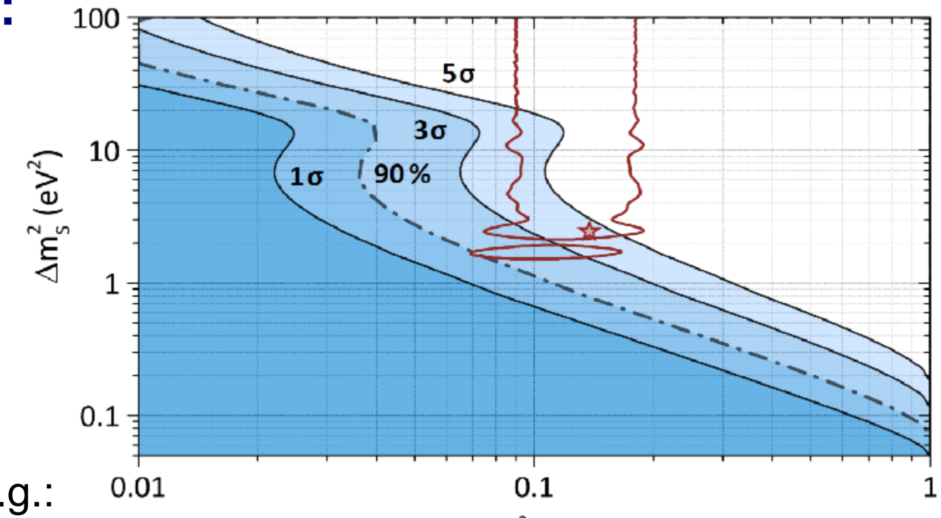
- precision HV divider (with PTB), monitor spectrometer beamline

KATRIN will measure an ultra-precise β-spectrum → search for physics beyond the SM

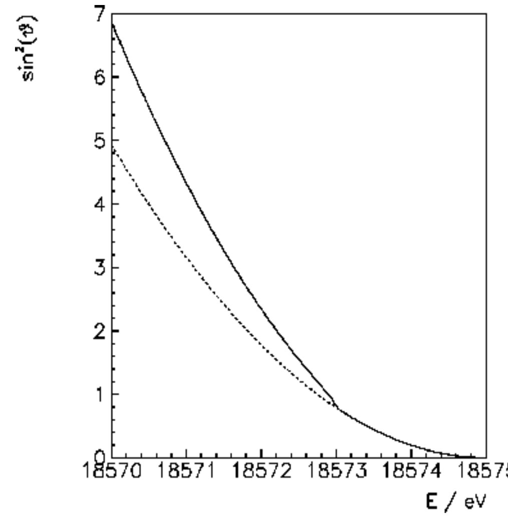
Sterile neutrinos

$$dN/dE = K\ F(E,Z)\ p\ E_{tot}\ (E_0-E_e)\left(\cos^2(\theta)\sqrt{(E_0-E_e)^2 - m(\nu_{1,2,3})^2} + \sin^2(\theta)\sqrt{(E_0-E_e)^2 - m(\nu_4)^2}\right)$$

eV ν:



M.Kleesiek, PhD thesis, KIT (2014)



see e.g.:

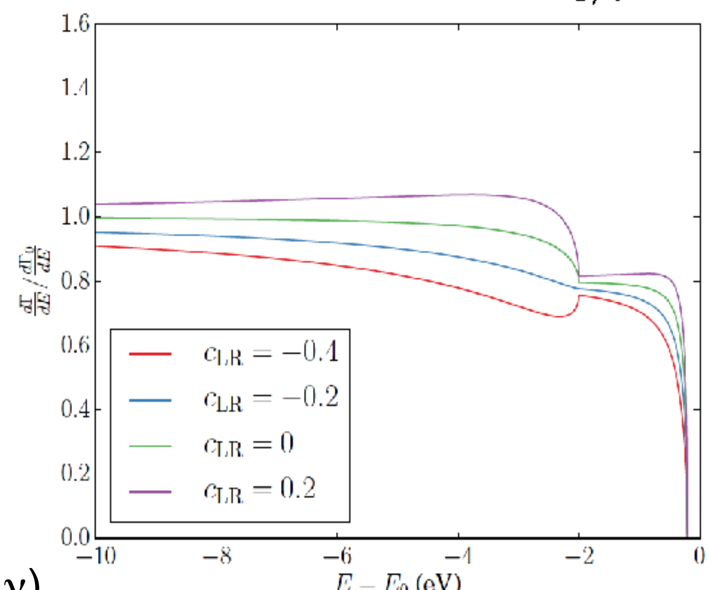
J. A. Formaggio, J. Barret, PLB 706 (2011) 68

A. Sejersen Riis, S. Hannestad, JCAP02 (2011) 011

A. Esmaili, O.L.G. Peres, arXiv:1203.2632

keV ν:

see e.g.
S. Mertens et al., JCAP 02 (2015) 020
M. Drewes et al. JCAP 01 (2017) 025

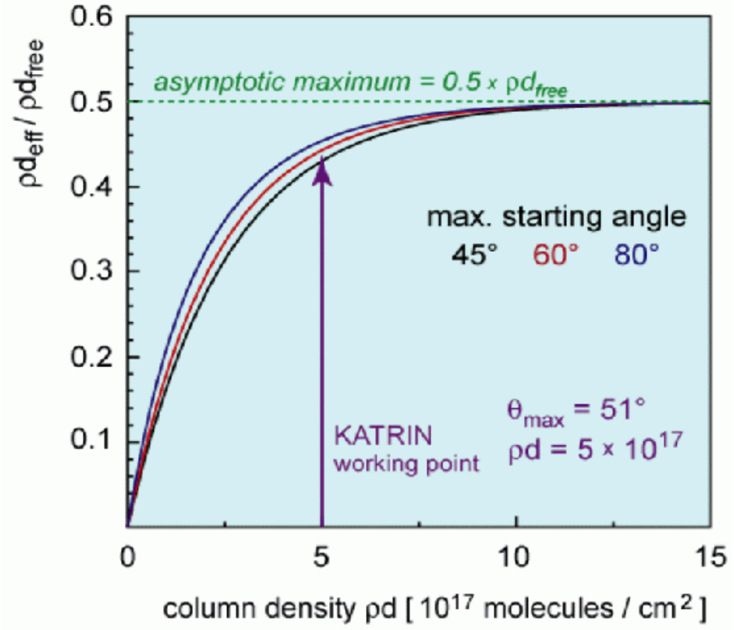


non SM currents, ...

see e.g.: N. Steinbrink et al., JCAP 6 (2017) 15 (RH currents & sterile ν)

Can we go beyond or improve KATRIN ? Problems to be solved

1) The source is already opaque
→ need to increase size transversally
magnetic flux tube conservation
requests larger spectrometer too
but a Ø100m spectrometer is not feasible

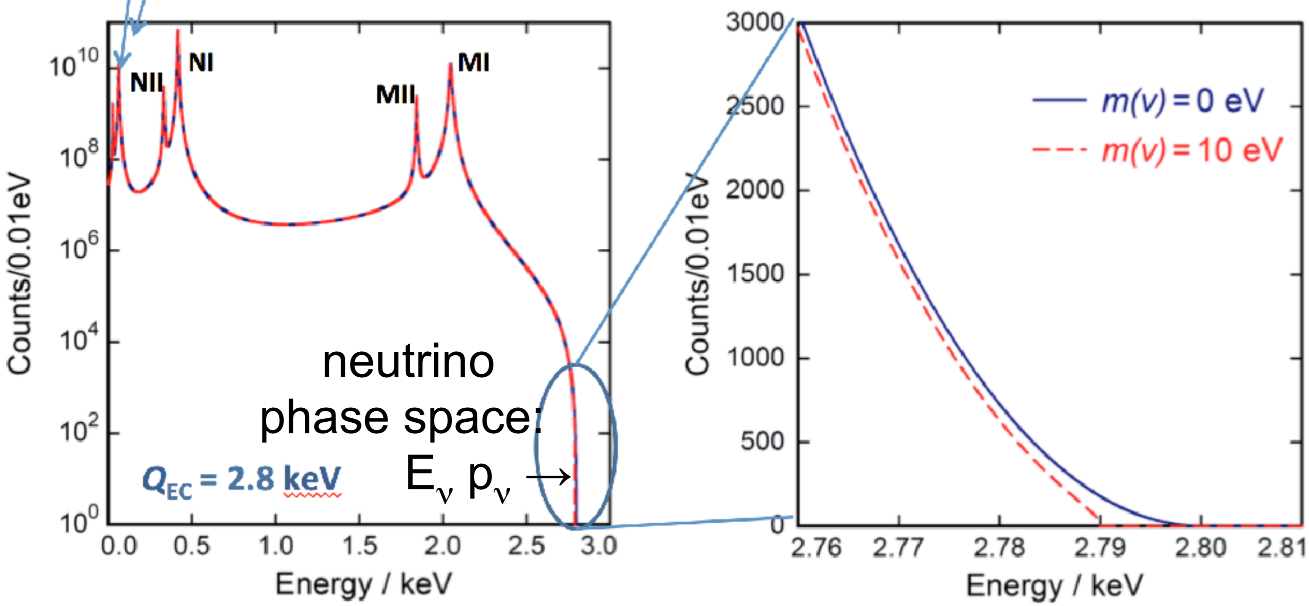


Possible ways out:

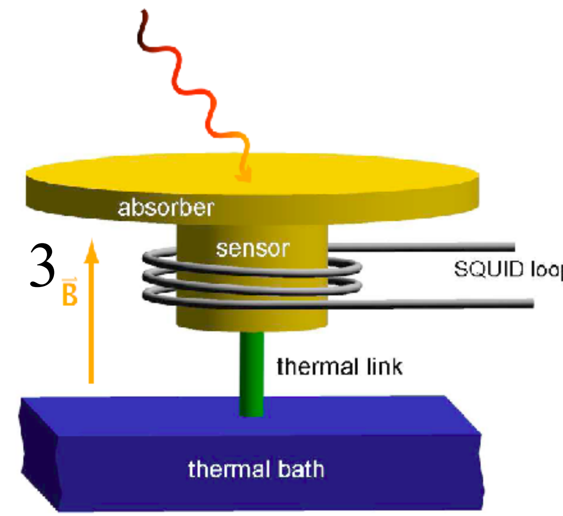
a) source inside detector (compare to $0\nu\beta\beta$) using cryogenic bolometers (ECHo, HOLMES, NuMECS)

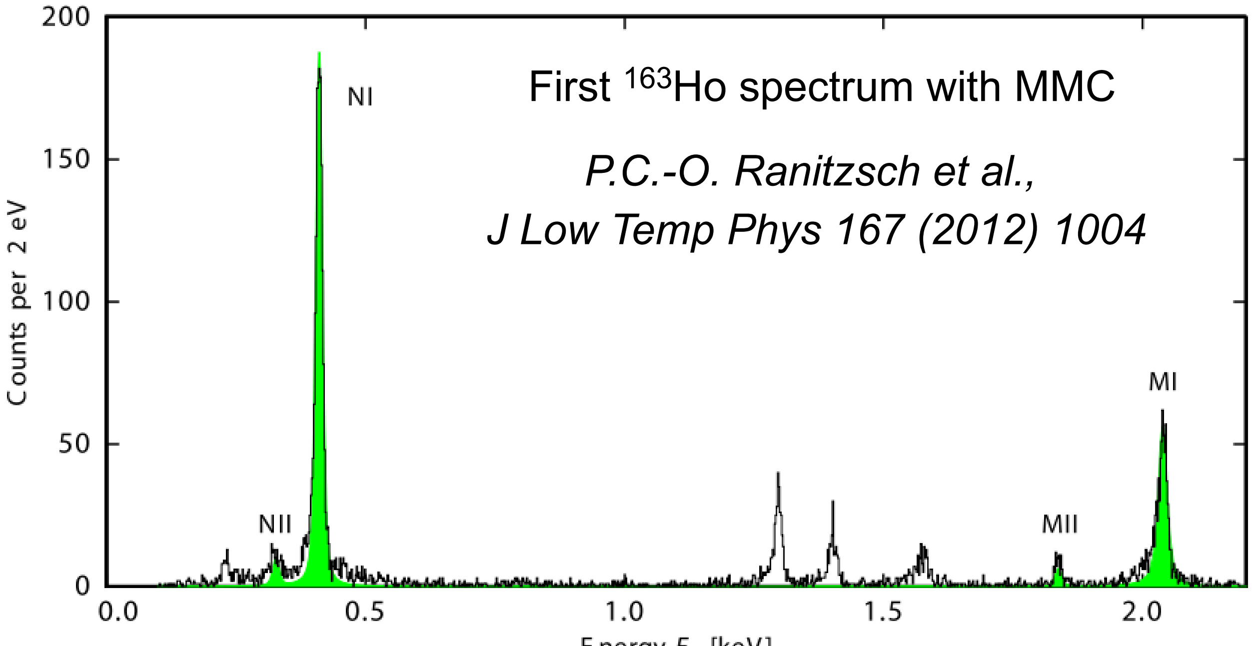
ECHo neutrino mass project: ^{163}Ho electron capture with metallic magnetic calorimeters (MMC)

$$^{163}\mathrm{Ho} + e^- \rightarrow {}^{163}\mathrm{Dy}^* + \nu_e \rightarrow {}^{163}\mathrm{Dy} + \gamma/e^- + \nu_e$$



MMC: determine ΔT by measuring change of magnetic properties
$\Delta T = \Delta E/C$, $C \propto T^3$

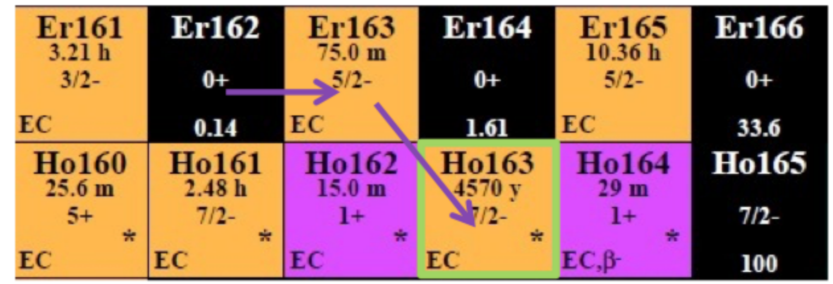




courtesy L. Gastaldo

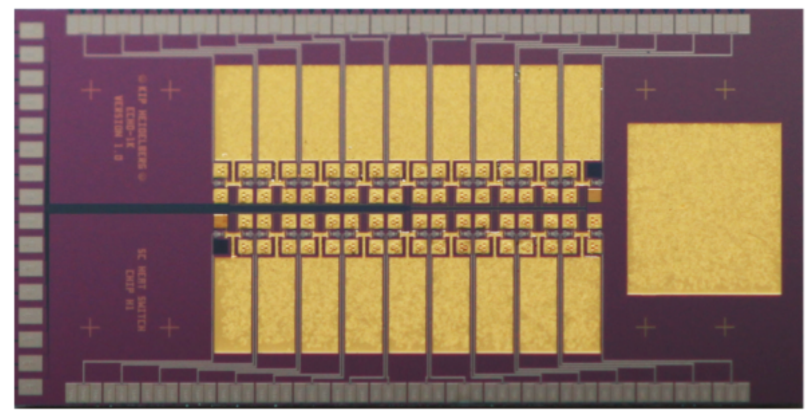
Current status of ECHo

- Independent ^{163}Ho Q_{EC} measurement
  $Q_{EC} = (2.833 \pm 0.030_{stat} \pm 0.015_{sys})$ keV



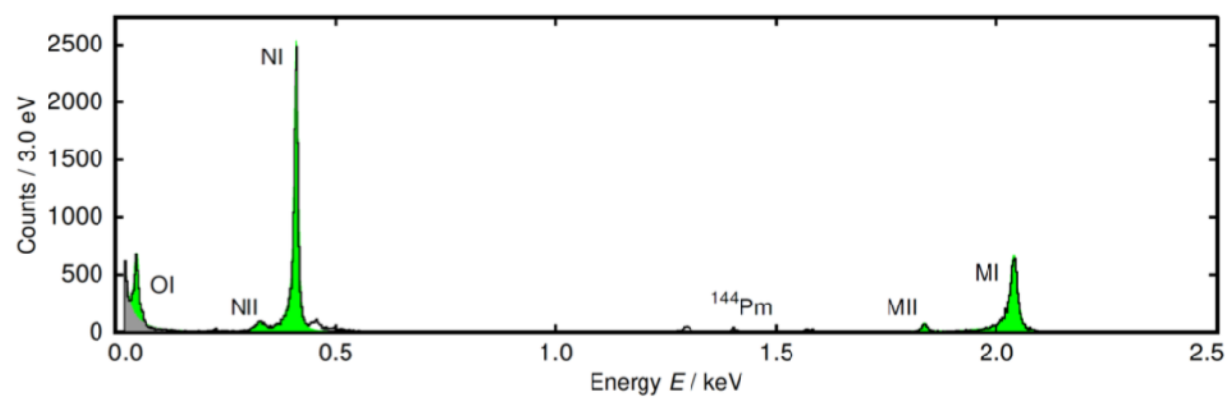
- High purity ^{163}Ho source has been produced

- ^{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 proved

- **New limit on the electron neutrino mass is approaching**



courtesy L. Gastaldo

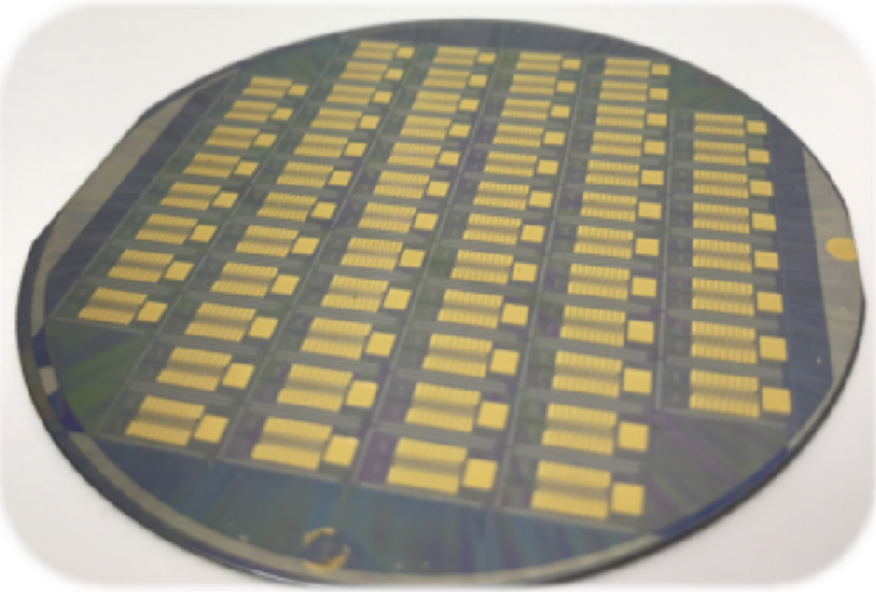
ECHo neutrino mass project: timeline

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
- Data taking will start in August 2017

Future: ECHo-10M sub-eV sensitivity

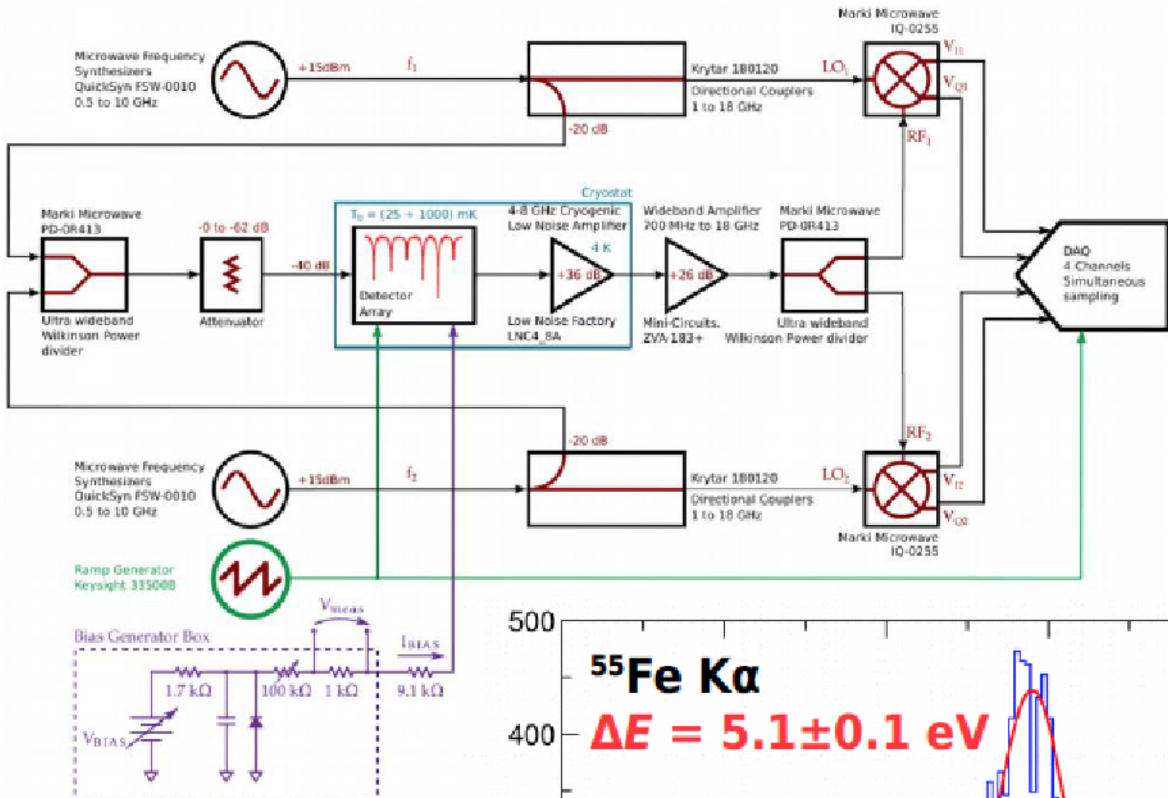
In addition: high energy resolution and high statistics
^{163}Ho spectra allow to investigate
the existence of **sterile neutrinos**
in the eV-scale and keV-scale

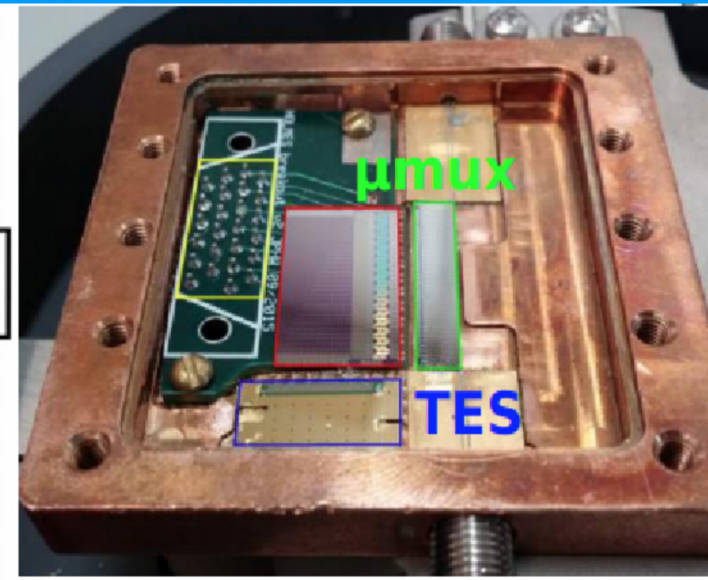


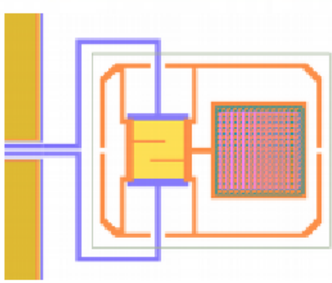
see talk today & poster both by S. Scholl

courtesy L. Gastaldo

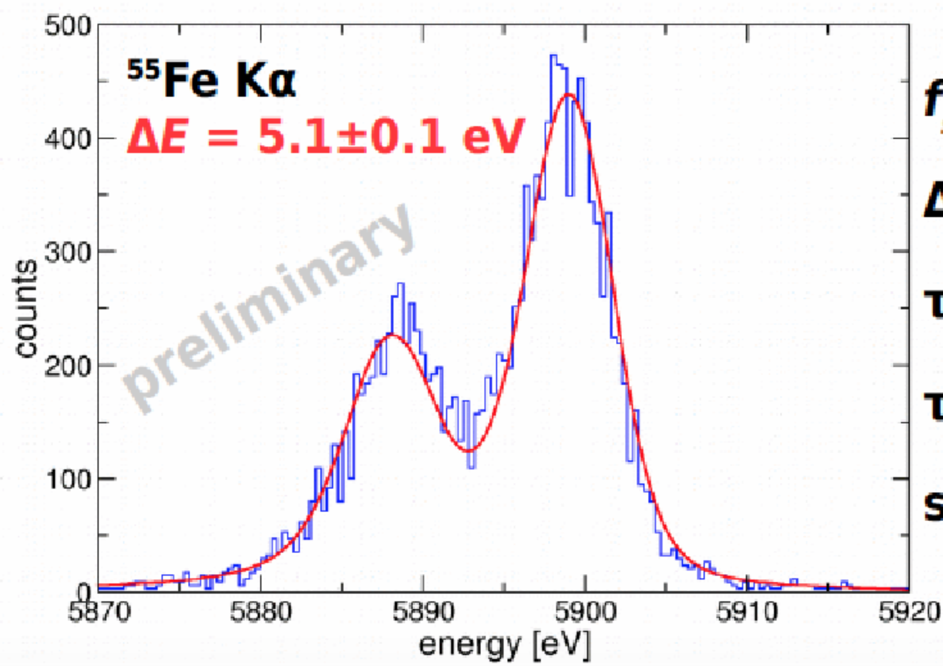
HOLMES: ^{163}Ho implanted in Au absorber with transition edge sensor (TES) readout







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



f_{samp} = 400 kS/s

ΔE_0 = 4.0 eV

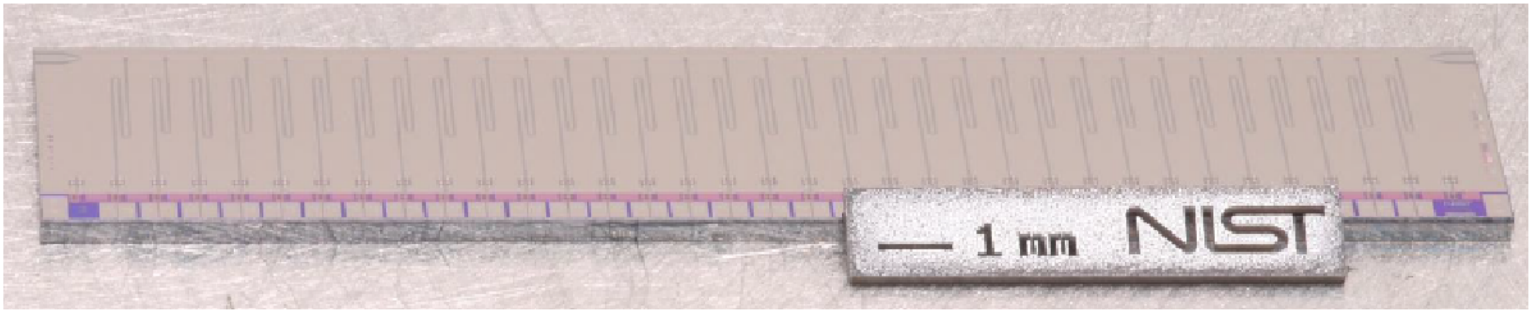
τ_{rise} = 35 µs

τ_{decay} = 141 µs

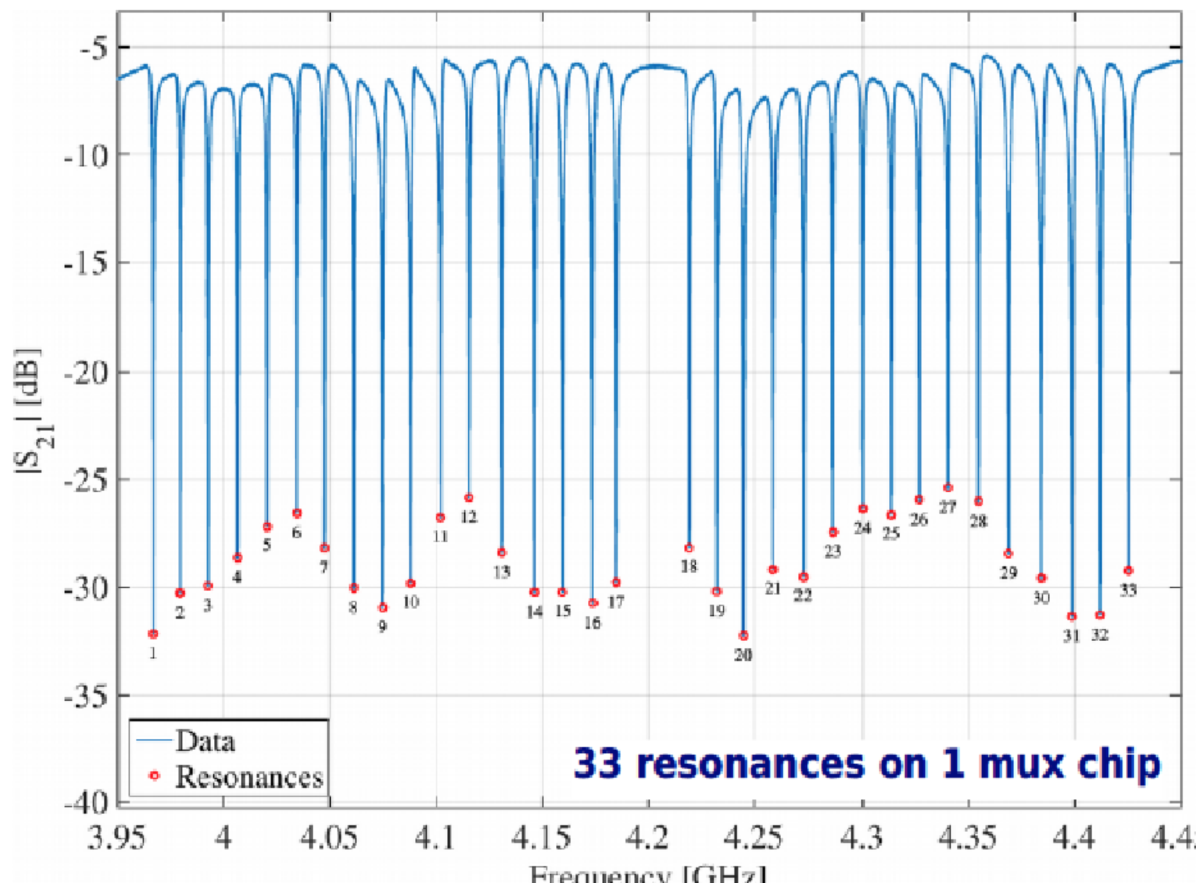
slew rate ≈ 0.2 Φ_0/S

courtesy A. Nucciotti

HOLMES: frequency multiplexing

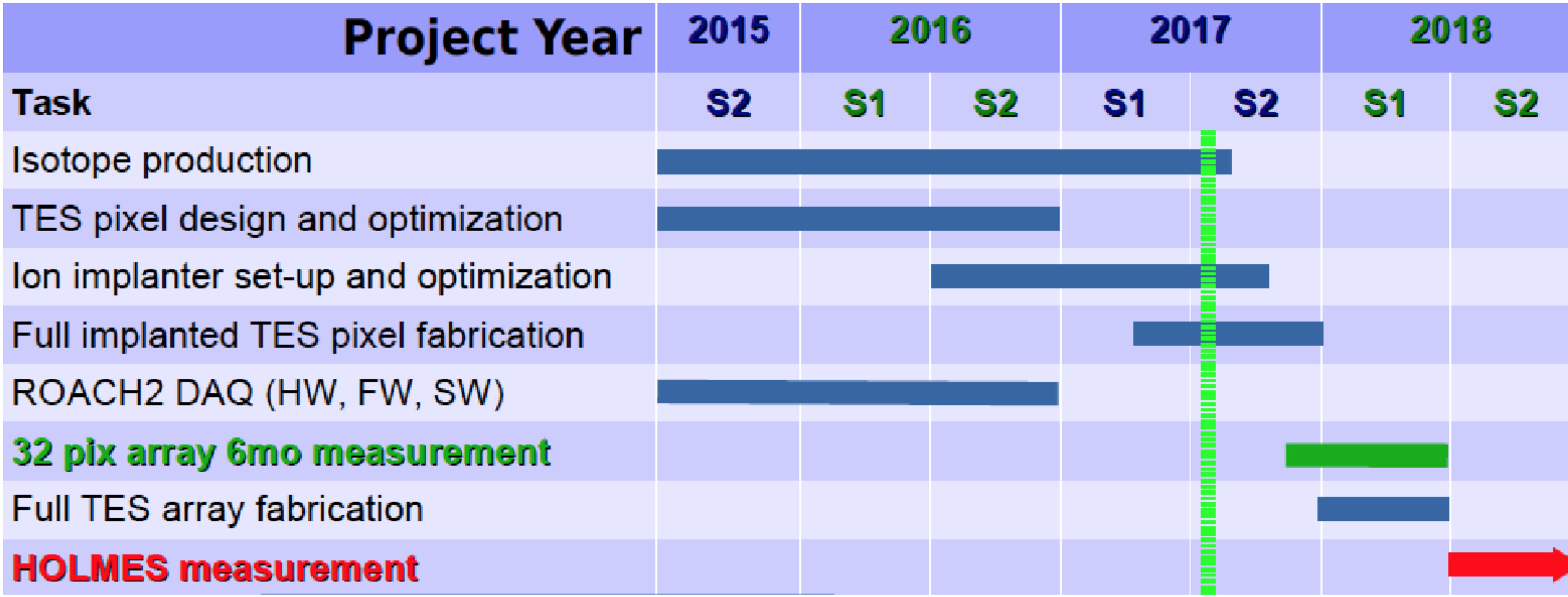


- chip **µMUX17A**
- 33 resonances in 500 MHz
  - width 2 MHz
  - separation 14 MHz
- squid noise <≈2 $\mu\Phi_0/\sqrt{Hz}$



courtesy A. Nucciotti

HOLMES: timeline



HOLMES project status:

- TES array and DAQ ready
- ion implanter setting up is in progress
- first ^{163}Ho implantation coming shortly
- spectrum measurements will begin late in 2017

→ 32 pixels for 1 month → m_ν sensitivity ≈10 eV

see talk by M. De Gerone on Thursday

courtesy A. Nucciotti

HOLMES: timeline

Project Year	2015	2016	2017	2018
Task				S2
Isotope produc				
TES pixel desig				
Ion implanter s				
Full implanted				
ROACH2 DAQ				
32 pix array 6				
Full TES array				
HOLMES mea				

^{163}Ho EC is being investigated by ECHo, HOLMES, NuMECS

Cryo-calorimetric multipixel detectors are a very interesting technology → starts to become scalable

Still many orders of magnitude to go for required statistics and background !

Understand EC de-excitation spectrum ?

Systematics and show stoppers on the way?

→ We should stay tunned !

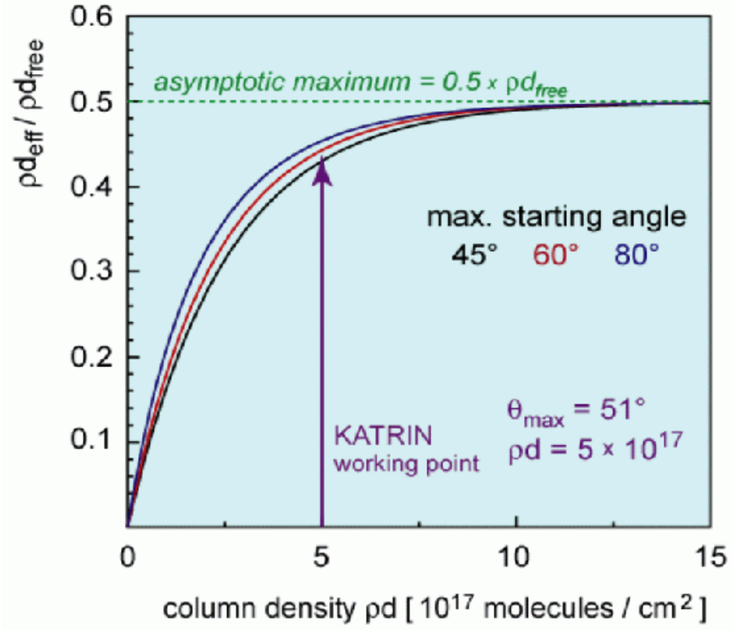
HOL
- TES
- ion
- first
- spe

e Gerone
day

→ 32 pixels for 1 month → m_ν sensitivity ≈10 eV

Can we go beyond or improve KATRIN ? Problems to be solved

1) The source is already opaque
→ need to increase size transversally
magnetic flux tube conservation
requests larger spectrometer too
but a Ø100m spectrometer is not feasible



Possible ways out:

a) source inside detector (compare to $0\nu\beta\beta$) using cryogenic bolometers (ECHo, HOLMES, NuMECS)

b) hand-over energy information of β electron to other particle (radio photon), which can escape tritium source (Project 8)

Project 8's goal: Measure coherent cyclotron radiation of tritium β electrons

General idea: *B. Monreal and J. Formaggio, PRD 80 (2009) 051301*

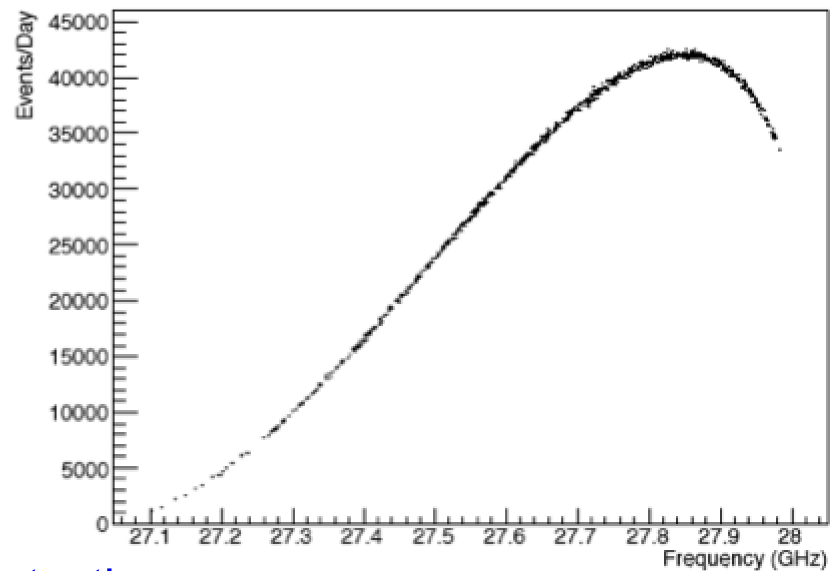
- Source = KATRIN tritium source technology :

  uniform B field + low pressure T_2 gas

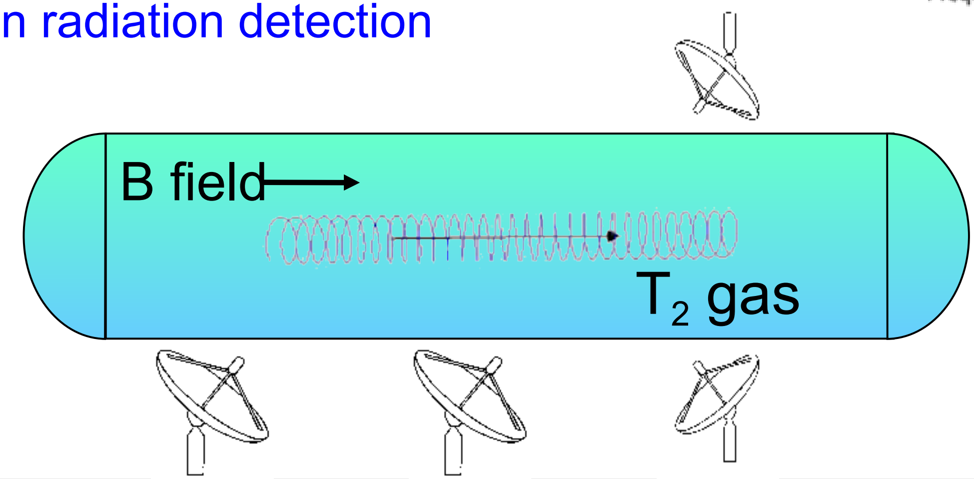
  β electron radiates coherent cyclotron radiation

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

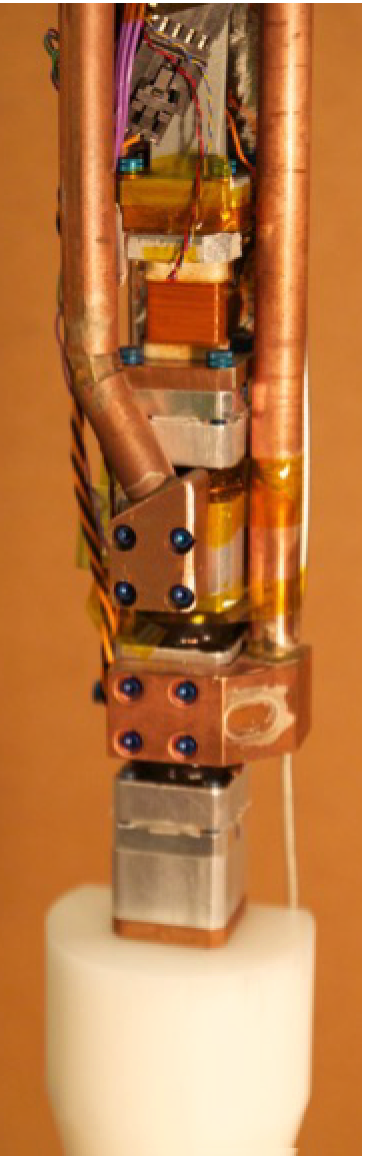
  But tiny signal: P (18 keV, θ=90°, B=1T) = 1 fW

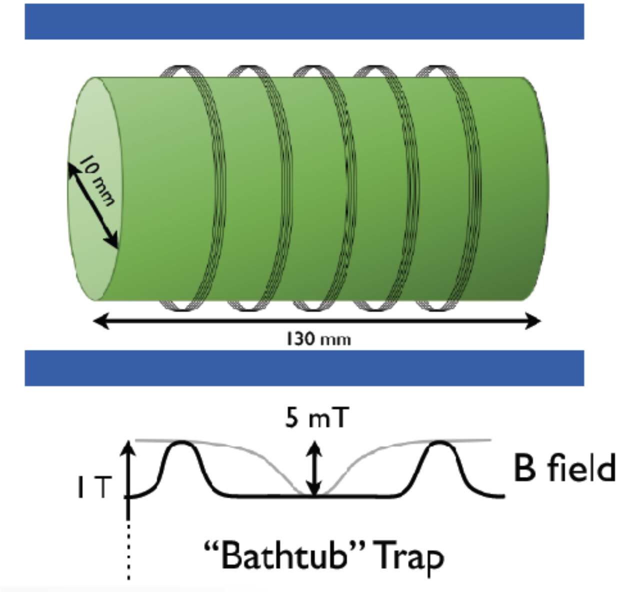


- Antenna array (interferometry) for cyclotron radiation detection
  since cyclotron radiation
  can leave the source and
  carries out the information
  of the β-electron energy

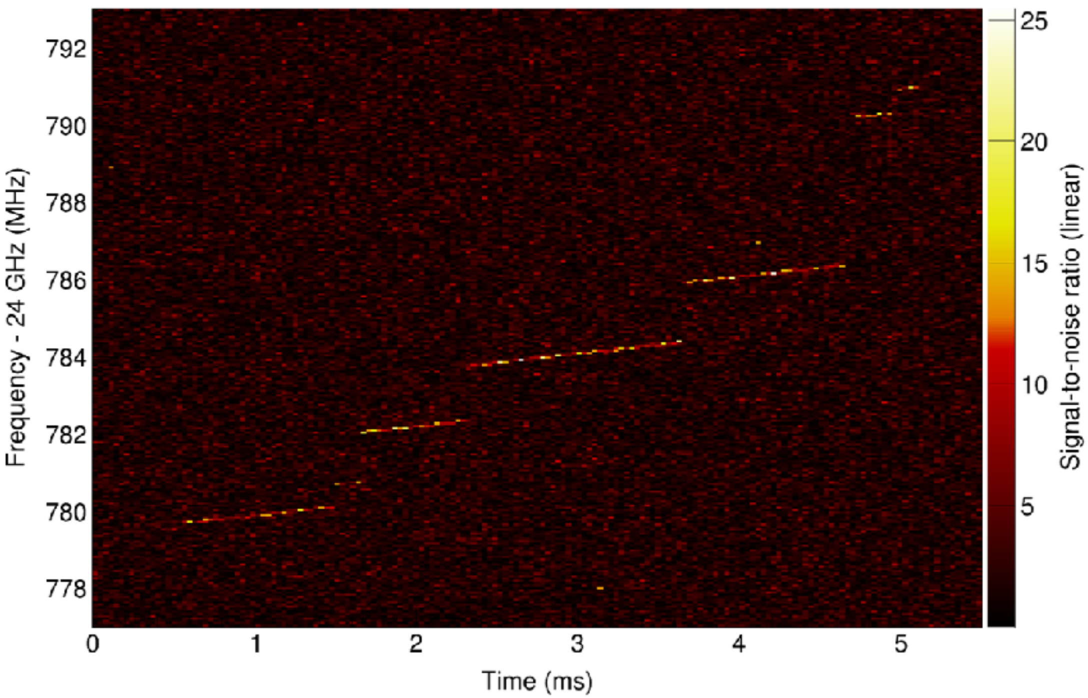


Project 8's phase 1: detection single electrons from ^{83m}Kr





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



courtesy J. Formaggio, RGH Robertson

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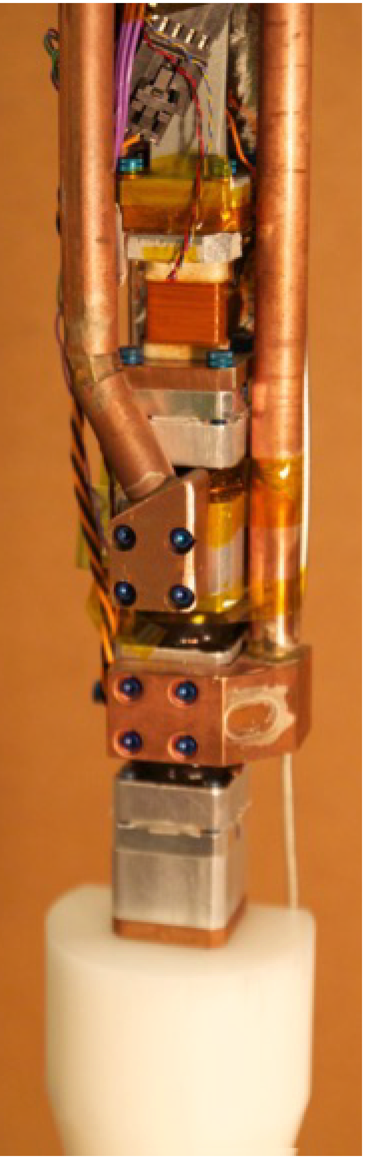
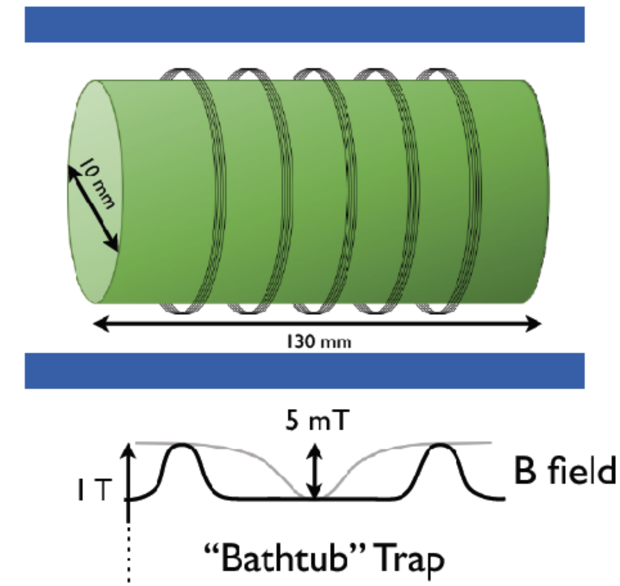
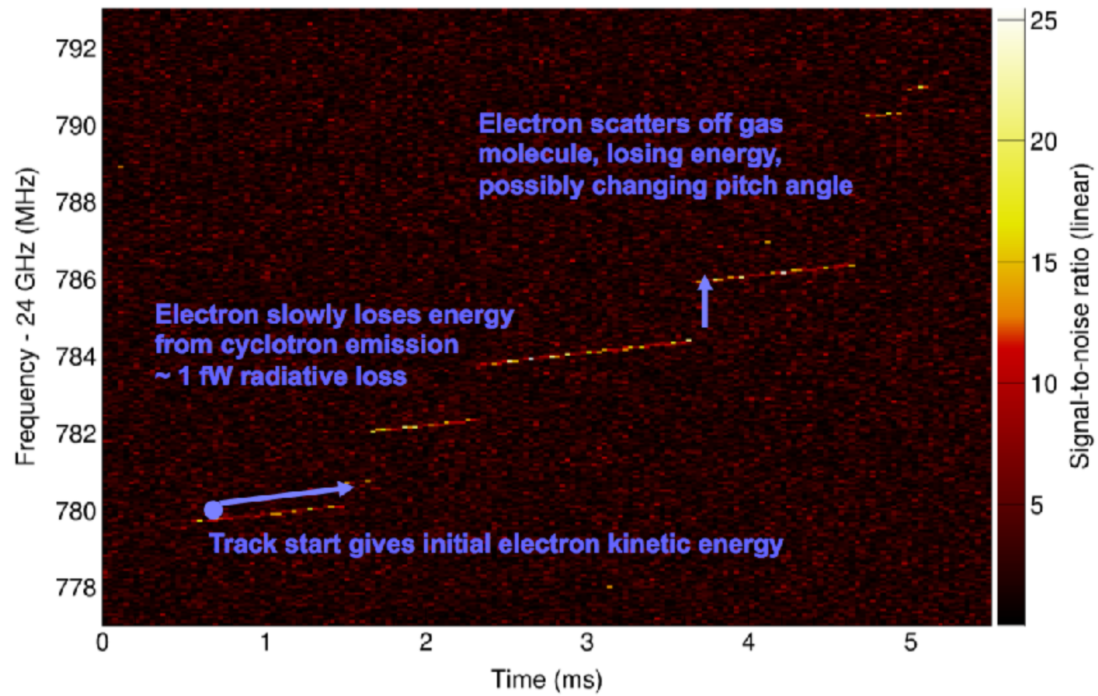
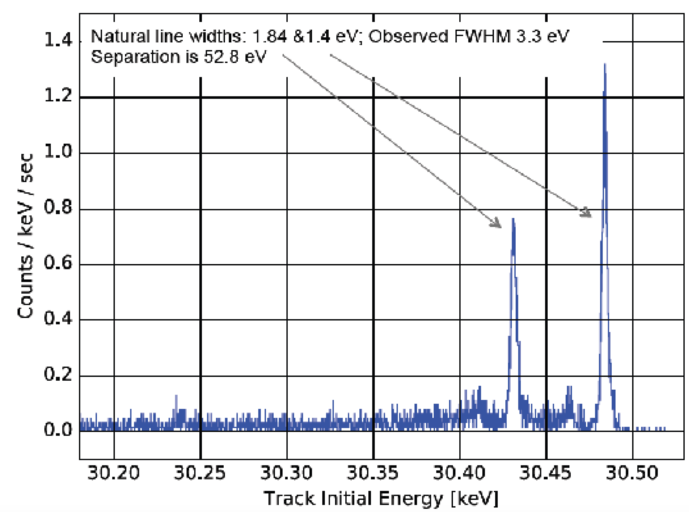




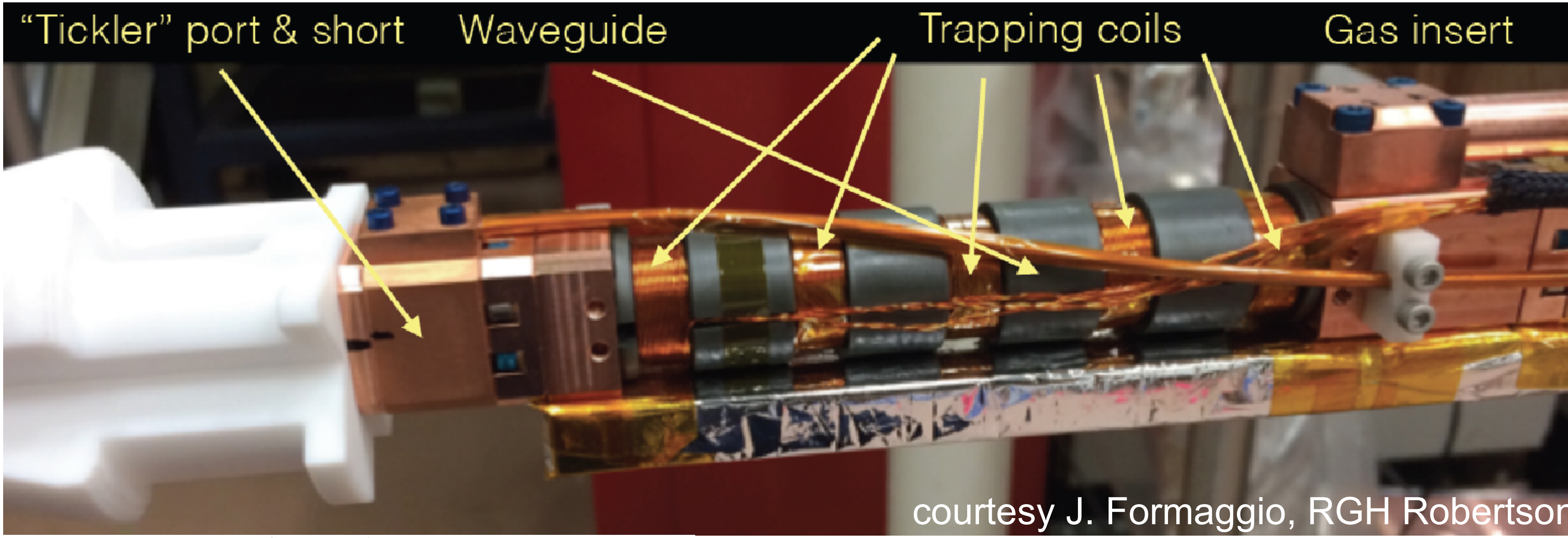
D. M. Asner et al., Phys. Rev. Lett. 114, 162501

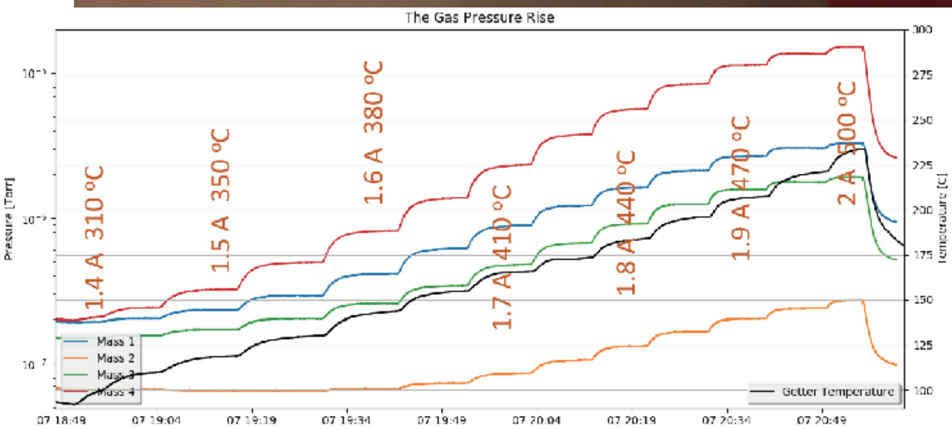




courtesy J. Formaggio, RGH Robertson

Project 8's phase 2: Measure tritium beta spectrum





first tests with deuterium loading

First detection of single electrons successfull – tritium spectroscopy should start in August but still a lot of R&D necessary

- final goal: atomic tritium source

- Is a large scale experiment possible ?

- What are the systematic uncertainties & other limitations?

see talks by W. Pettus (205) today & by M. Guigue (190) on Thursday

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

Can we go beyond or improve KATRIN ?
Problems to be solved

1) The source is already opaque
   → need to increase size transversally
   magnetic flux tube conservation
   requests larger spectrometer too
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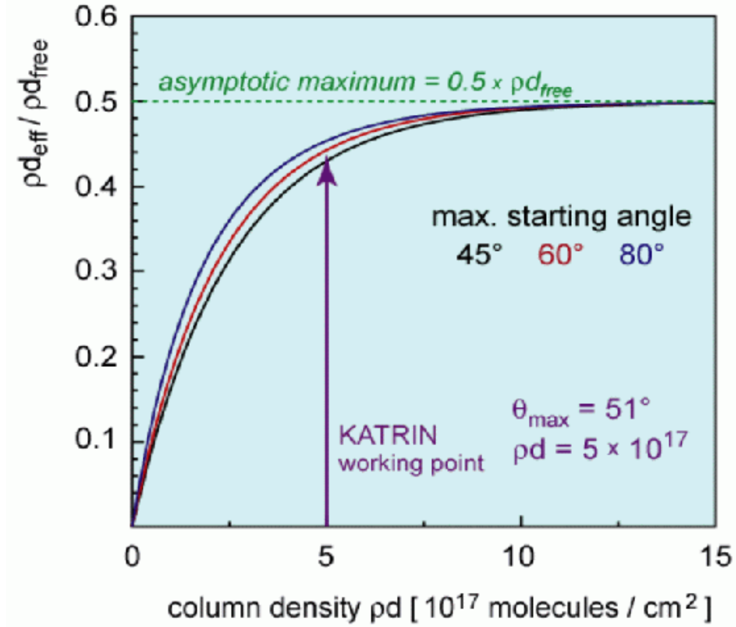

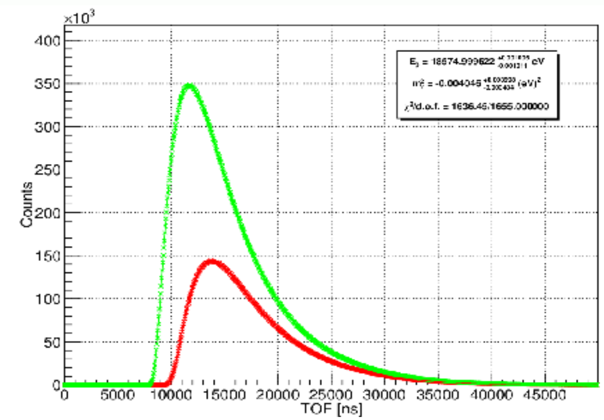

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using cryogenic bolometers (ECHo, HOLMES, ..)

b) hand-over energy information of β electron
to other particle (radio photon),
which can escape tritium source (Project 8)

c) make better use of the electrons
by differential measurement instead of integral
(measure all retarding voltage settings at once)
→ differential detector, e.g. cryobolometer array
(but 90mm diameter and multi Tesla field)
→ time-of-flight spectroscopy,
e.g. by electron tagging

→ Factor 5 improvement in m_ν^2 by TOF
w.r.t. standard KATRIN in ideal case !
N. Steinbrink et al. NJP 15 (2013) 113020

Conclusions

Direct neutrino mass experiments: complementary to cosmological analyses and $0\nu\beta\beta$
can look also for sterile neutrinos (eV, keV) and other BSM

KATRIN: direct neutrino mass experiment with 200 meV sensitivity
- System is complete (except tritium loops and rear wall and calibration system):
  1st light in October 2016, ^{83m}Kr calibration measurements in July 2017 successful
- Tritium data taking: start in 2018

KATRIN inauguration ceremony: June 11, 2018 (after Neutrino 2018 at Heidelberg)

Micro calorimeters experiments for ^{163}Ho EC
ECHo: technology ready, ECHo-1k will start in August 2017, ECHo-10M planned
HOLMES: large progress: start data taking in 2018
NuMECS: similar technology

Project 8:
Spectroscopy of tritium β-deday by radio-detection of cyclotron radiation
^{83m}Kr measurements successful, first tritium R&D run in August 2017

Ptolemy:
R&D combining many leading technologies aiming to detect relic neutrinos:
cryo bolometer, MAC-E-Filter-technology, tritium bound to graphene, ...