Direct neutrino mass search

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Christian Weinheimer

Institut für Kernphysik, Westfälische Wilhelms-Universität Münster
weinheimer@uni-muenster.de

Introduction

The KArlsruhe TRItium Neutrino experiment KATRIN

- overview & commissioning campaigns

Possible improvements and neutrino mass beyond KATRIN

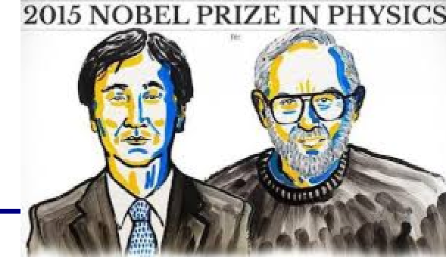
- Electron capture with ^{163}Ho cryo bolometers

- radio-based tritium β-spectroscopy: Project 8

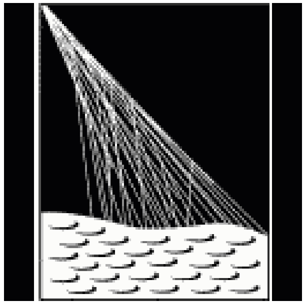
Conclusions

Photo: M. Zacher

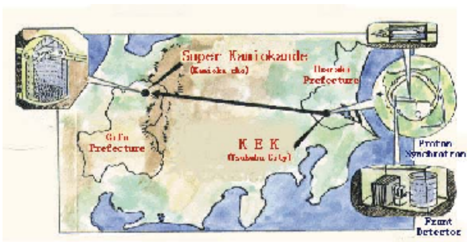
Clear evidence by so many ν oscillation experiments



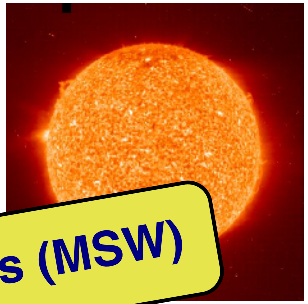
atmospheric neutrinos
(Kamiokande, Super-Kamiokande, IceCube, ANTARES)



accelerator neutrinos
(K2K, T2K, MINOS, OPERA, MiniBoone)

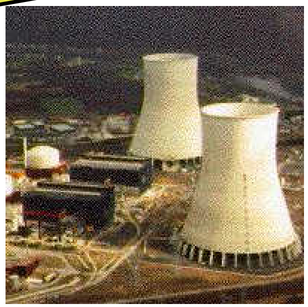


solar neutrinos
(Homestake, Gallex, Sage, Super-Kamiokande, SNO, Borexino)



Matter effects (MSW)

reactor neutrinos
(KamLAND, CHOOZ, Daya Bay, Double CHOOZ, RENO, ...)



$\Rightarrow$ non-trivial ν-mixing

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$|U_{\mathrm{PMNS}}| \sim \begin{pmatrix} 0.8 & 0.5 & 0.1 \\ 0.5 & 0.6 & 0.7 \\ 0.3 & 0.6 & 0.7 \end{pmatrix}$$

$0.37 < \sin^2(\theta_{23}) < 0.63$ maximal!

$0.26 < \sin^2(\theta_{12}) < 0.36$ large !

$0.018 < \sin^2(\theta_{13}) < 0.030$ 8.4°

$7.0\ 10^{-5}\ \mathrm{eV}^2 < \Delta m_{12}^2 < 8.2\ 10^{-5}\ \mathrm{eV}^2$

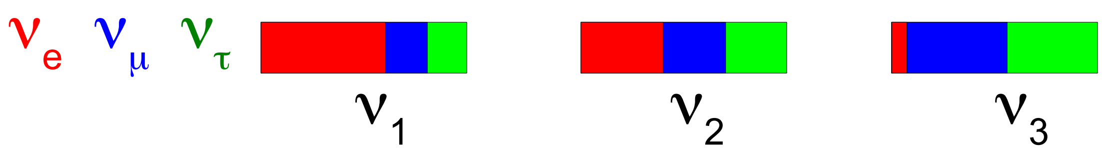
$2.2\ 10^{-3}\ \mathrm{eV}^2 < |\Delta m_{13}^2| < 2.6\ 10^{-3}\ \mathrm{eV}^2$

$\Rightarrow m(\nu_j) \neq 0$, but unknown

additional sterile neutrinos ?

Need for the absolute ν mass determination

Results of recent oscillation experiments: Θ_{23}, Θ_{12}, Θ_{13}, $|\Delta m^2_{13}|$, Δm^2_{12}



degenerated masses

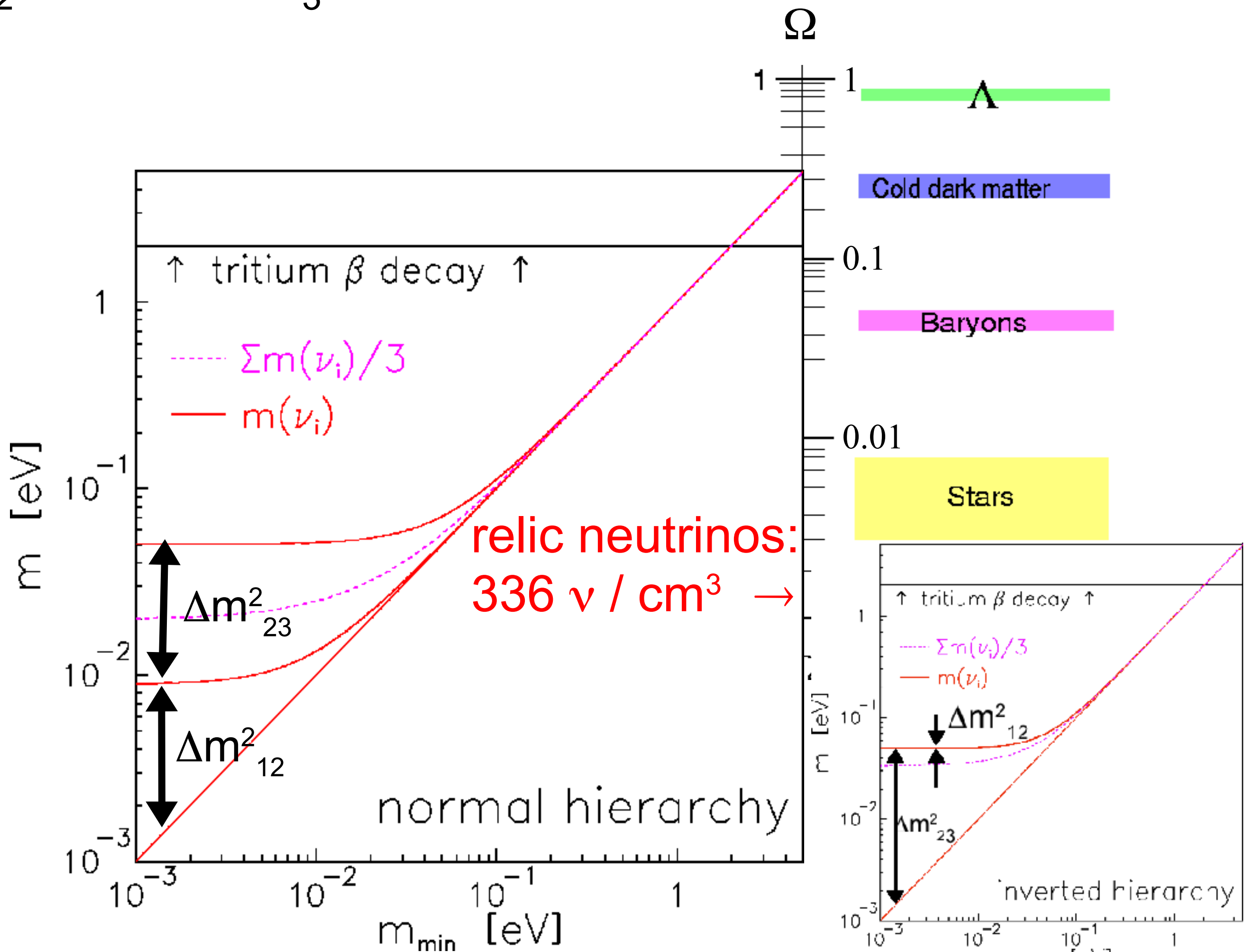
cosmological relevant

e.g. seesaw mechanism type 2

hierarchical masses

e.g. seesaw mechanism type 1

explains smallness of masses, but not large (maximal) mixing



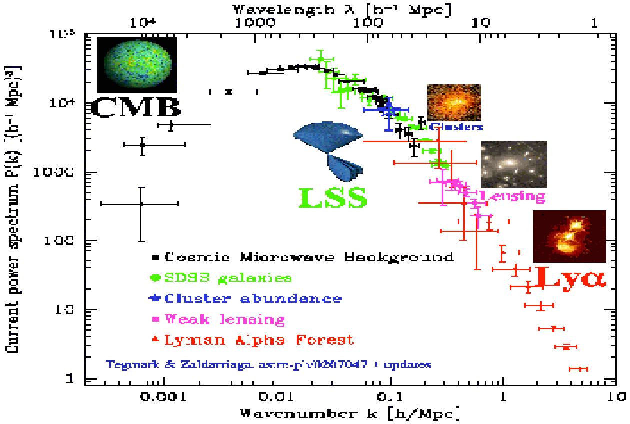
Three complementary ways to the absolute neutrino mass scale

1) Cosmology

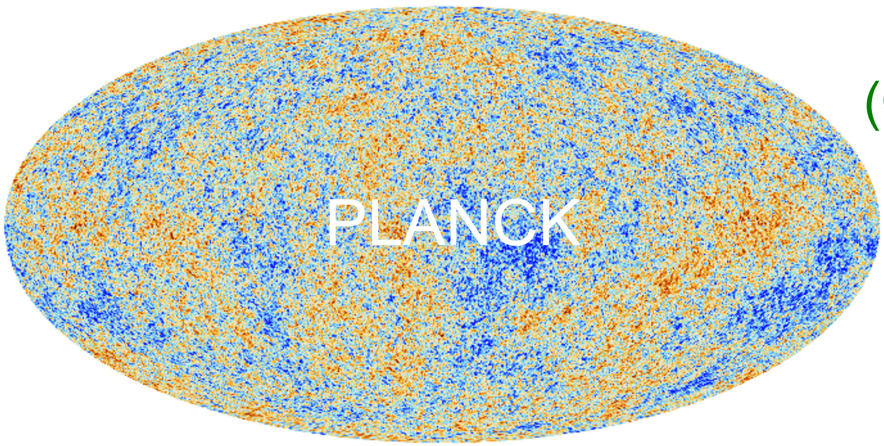
very sensitive, but model dependent

compares power at different scales

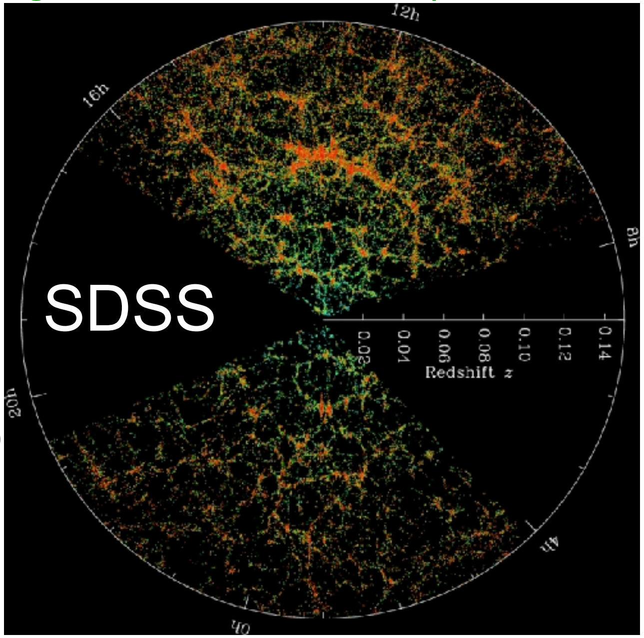
current sensitivity: $\Sigma m(\nu_i) \approx 0.23$ eV



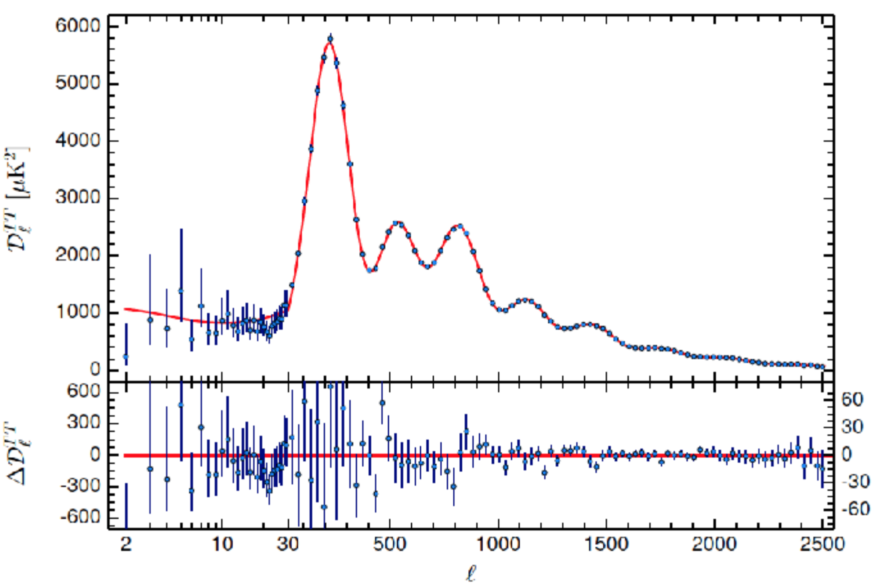
Neutrino mass from cosmology



measurement of CMBR
(Cosmic Microwave Background Radiation)

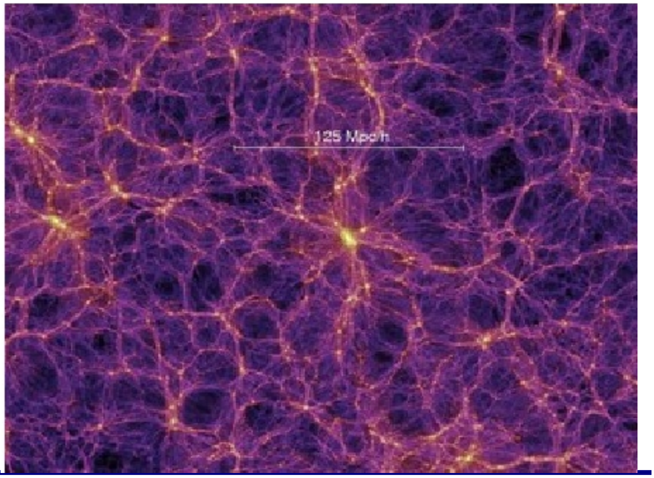


measurement of matter density distribution LSS
(Large Scale Structure)
by 2dF, SDSS, ...



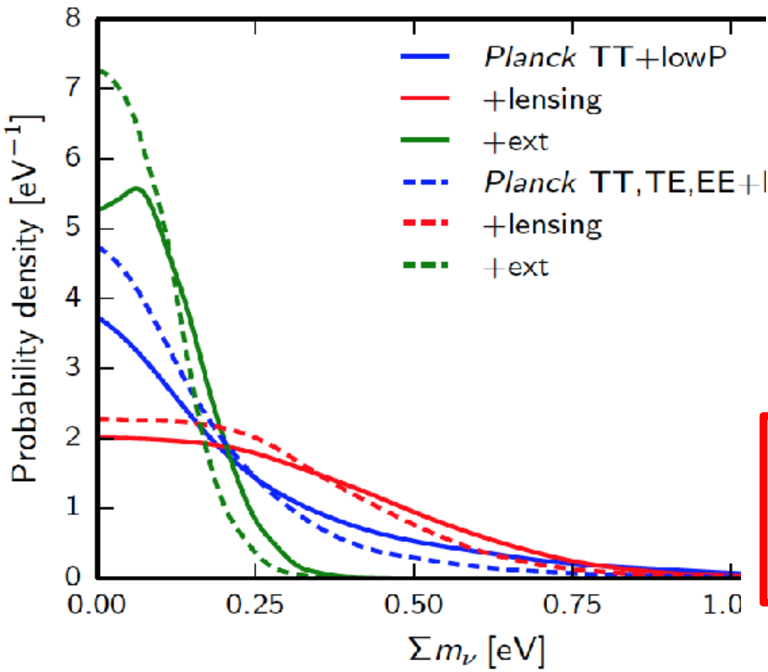
Planck Collaboration:
P. A. R. Ade et al., arXiv:1502.01589

compare to numeric. models including relic neutrino densitiy of 336 cm^{-3}



Millenium simulation →
http://www.mpa-garching.mpg.de/galform/presse/

Neutrino mass from cosmology



$$\sum m_\nu < 0.72 \text{ eV} \quad \textit{Planck} \text{ TT+lowP};$$
$$\sum m_\nu < 0.21 \text{ eV} \quad \textit{Planck} \text{ TT+lowP+BAO};$$
$$\sum m_\nu < 0.49 \text{ eV} \quad \textit{Planck} \text{ TT, TE, EE+lowP};$$
$$\sum m_\nu < 0.17 \text{ eV} \quad \textit{Planck} \text{ TT, TE, EE+lowP+BAO}.$$

$$\left.\begin{array}{l}\sum m_\nu < 0.23 \text{ eV} \\ \Omega_\nu h^2 < 0.0025\end{array}\right\} \quad 95\%, \textit{Planck} \text{ TT+lowP+lensing+ext.}$$

Planck Collaboration: P. A. R. Ade et al., arXiv:1502.01589

Relies on ΛCDM model !

Is this fully correct, there are some discrepancies ?

More than 95% of the energy distribution in the universe is not known (dark energy, dark matter)

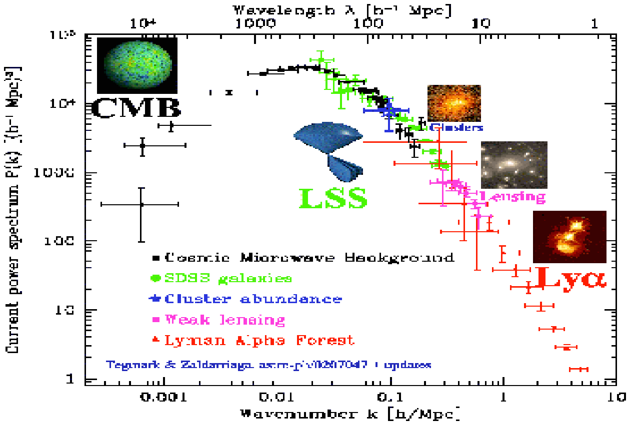
Three complementary ways to the absolute neutrino mass scale

1) Cosmology

very sensitive, but model dependent

compares power at different scales

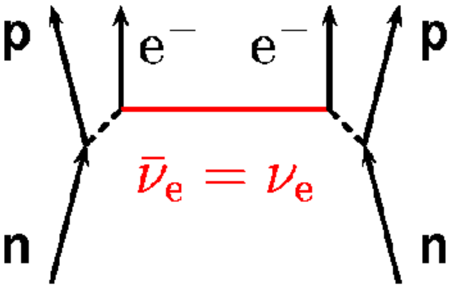
current sensitivity: $\Sigma m(\nu_i) \approx 0.23$ eV



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

Sensitive to Majorana neutrinos

Upper limits by EXO-200, KamLAND-Zen, GERDA, 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)

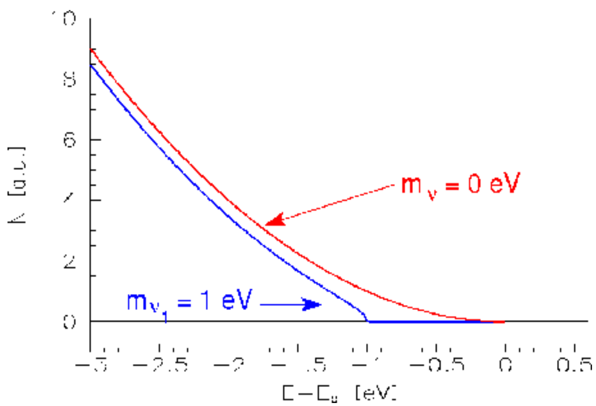
SN1987a (large Magellan cloud) $\Rightarrow m(\nu_e) < 5.7$ eV

Kinematics of weak decays / beta decays

measure charged decay prod., E-, p-conservation

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

- ^{163}Ho electron capture (EC)



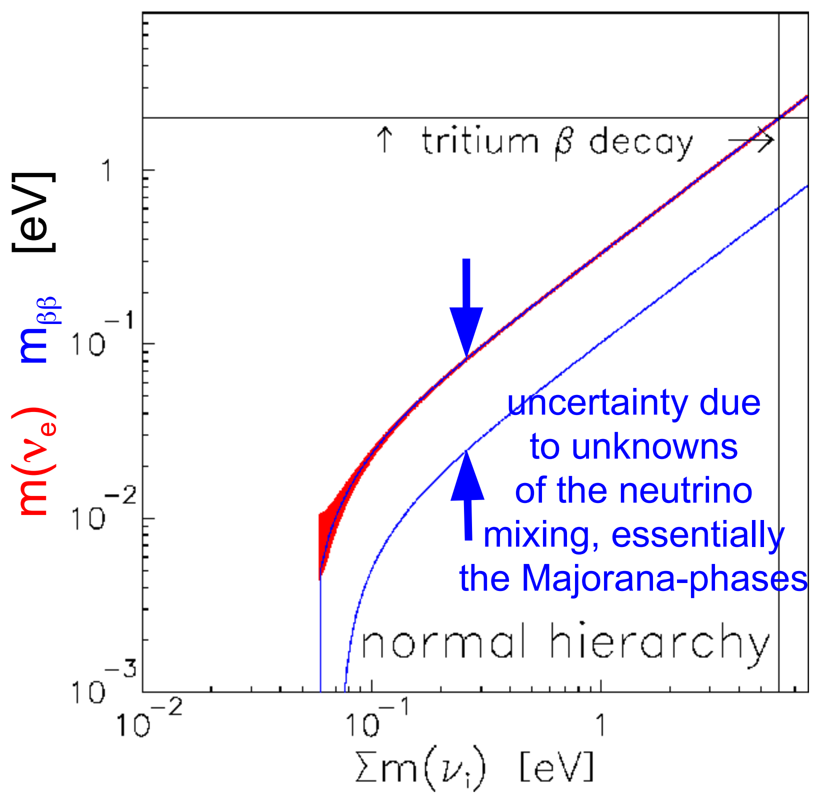
Comparison of the different approaches to the neutrino mass

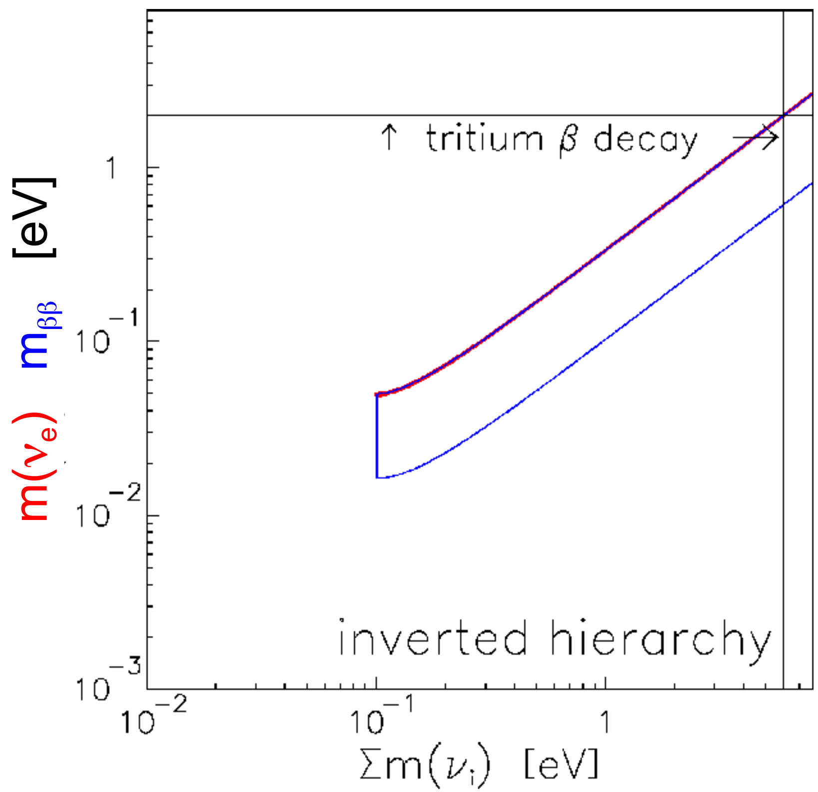
Direct kinematic measurement: $m^2(\nu_e) = \Sigma\, |U_{ei}{}^2|\, m^2(\nu_i)$ (incoherent)

Neutrinolesss double β decay: $m_{\beta\beta}(\nu) = |\, \Sigma\, |U_{ei}{}^2|\, e^{i\alpha(i)}\, m(\nu_i)|$ (coherent)

if no other particle is exchanged (e.g. R-violating SUSY)

without additional uncertainties of nuclear matrix elements *M* and quenching factor g_A





⇒ absolute scale/cosmological relevant neutrino mass in the lab by single β decay

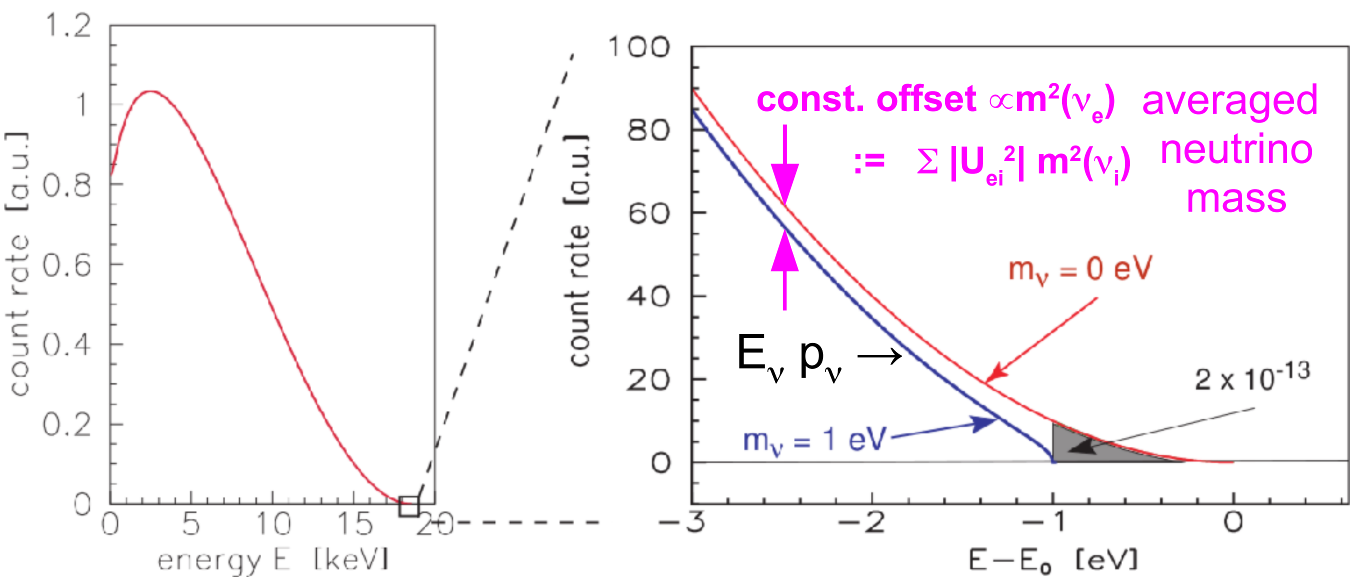
Direct determination of $m(\nu_e)$ from β-decay (and EC)

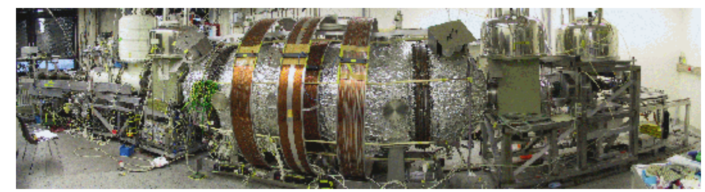
β: $dN/dE = K\ F(E,Z)\ \underbrace{p}_{p_e}\ \underbrace{E_{tot}}_{E_e}\ \underbrace{(E_0-E_e)}_{E_\nu}\ \underbrace{\Sigma |U_{ei}|^2 \sqrt{(E_0-E_e)^2 - m(\nu_i)^2}}_{p_\nu}$

essentially phase space: p_e E_e E_ν p_ν

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

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

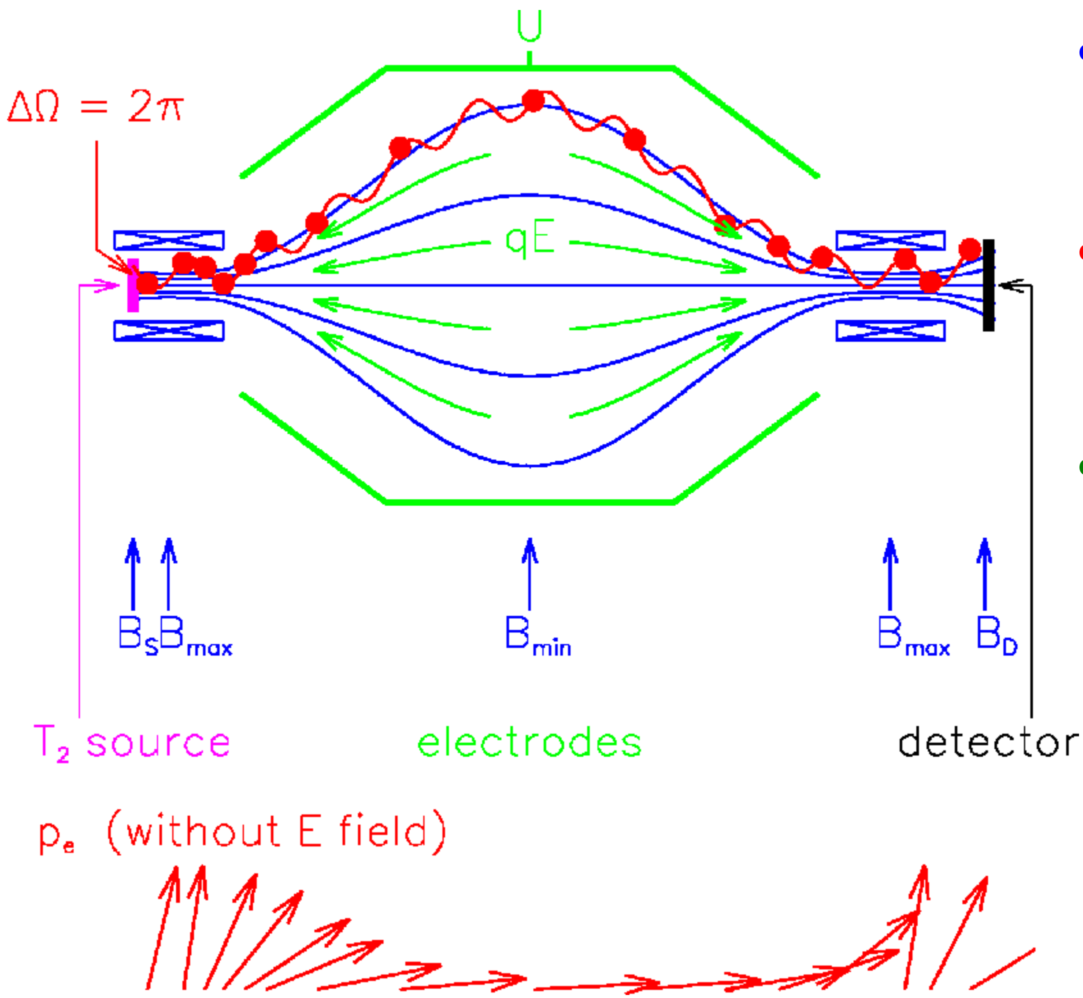




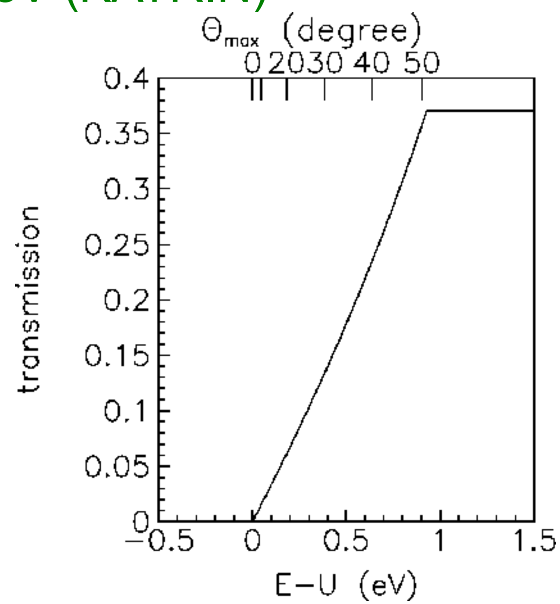
$m(\nu) < 2$ eV (Mainz, Troitsk)
ν do not solve DM problem

Need:	**low endpoint energy**	⇒	**Tritium ^3H (^{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 classical way: Tritium β-spectroscopy with a MAC-E-Filter



- Two supercond. solenoids compose magnetic guiding field
- adiabatic transformation:
  $\mu = E_\perp / B = \text{const.}$
  ⇒ parallel e^- beam
- Energy analysis by electrostat. retarding field
  $\Delta E = E \cdot B_{min}/B_{max}$
  $= 0.93$ eV (KATRIN)



⇒ sharp integrating transmission function without tails →

Magnetic Adiabatic Collimation + Electrostatic Filter
(A. Picard et al., Nucl. Instr. Meth. 63 (1992) 345)

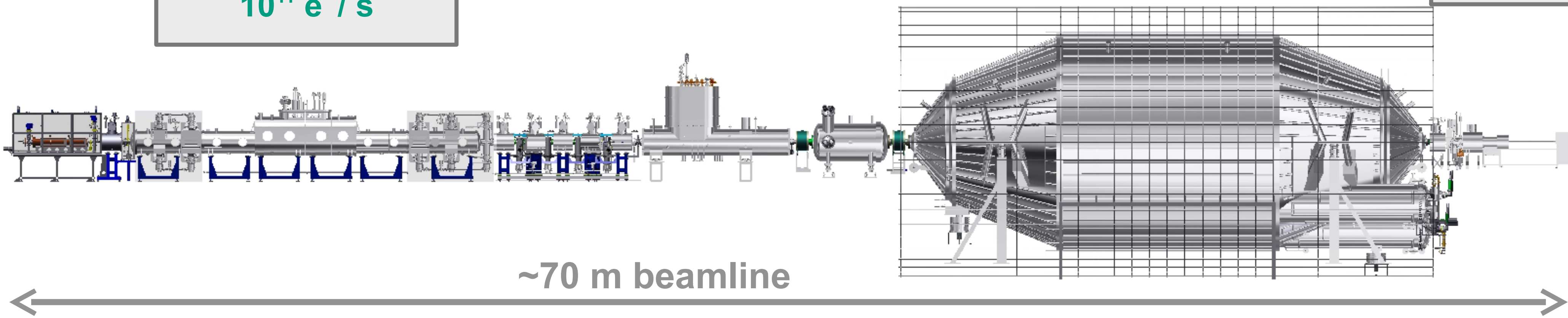
The KATRIN experiment

windowless gaseous T2 source
10^{11} e^- / s

tritium pumping & e^- transport

MAC-E type spectrometer
10 m diameter, 24 m length

electron detector
< 1 e^- / s



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

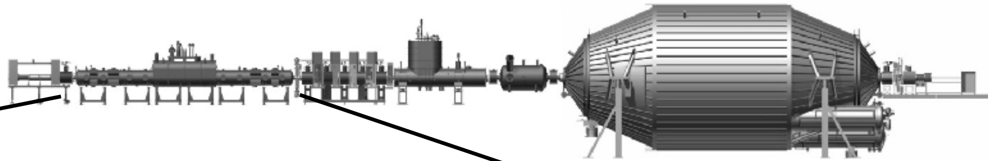
KATRIN at Karlsruhe Institute for Technology
Int. Collaboration: 20 institutions from 6 countries

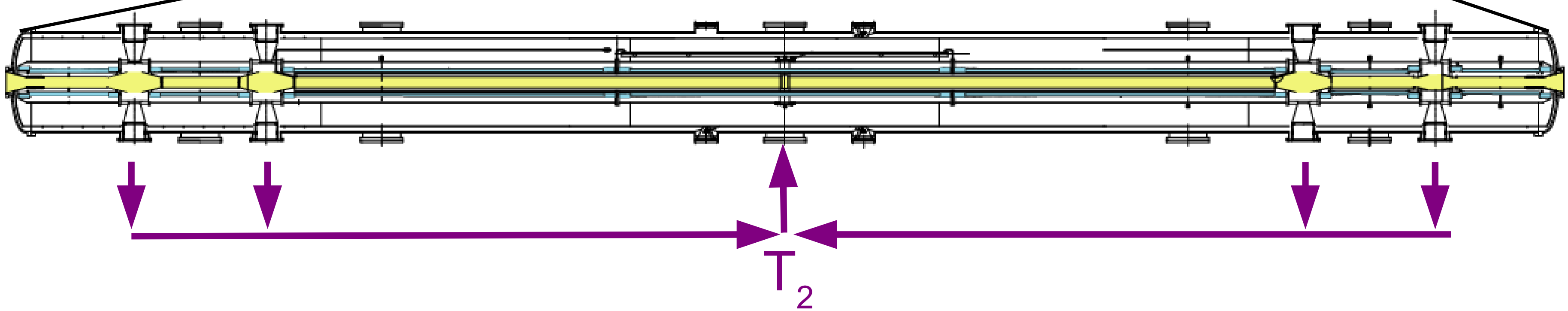
Molecular Windowless Gaseous Tritium Source WGTS

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

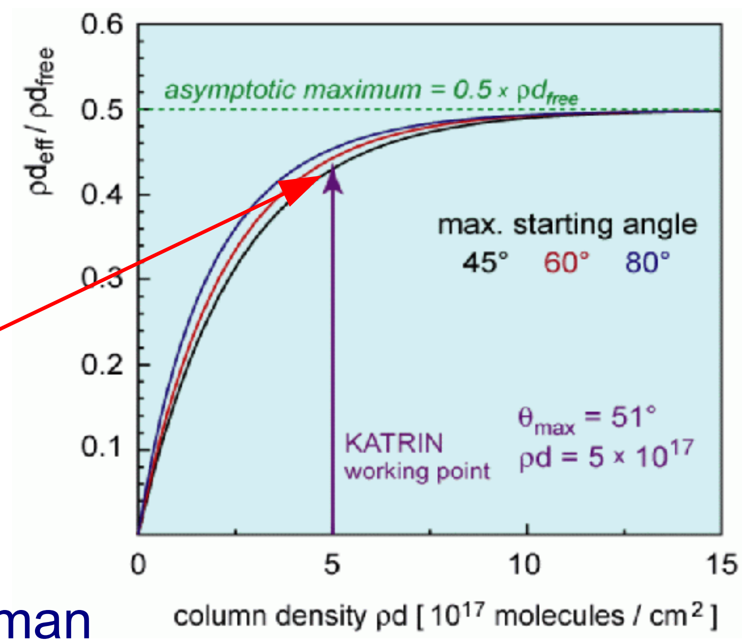




WGTS: tube in long superconducting solenoids
⌀ 9cm, length: 10m, T = 30 K

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

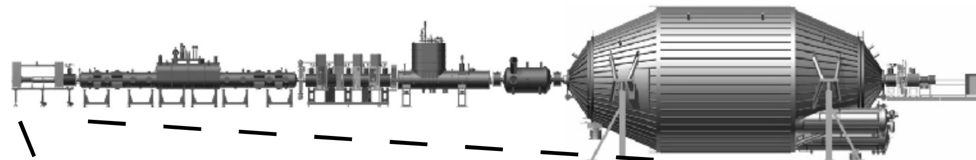
allows to measure with near to maximum count rate using
$\rho d = 5 \cdot 10^{17}/cm^2$
with small systematics

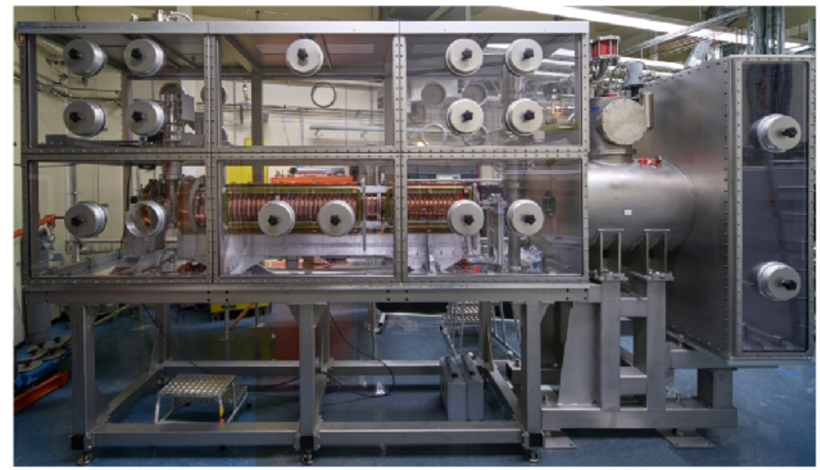


check column density by e-gun, T_2 purity by laser Raman

Molecular Windowless Gaseous Tritium Source WGTS

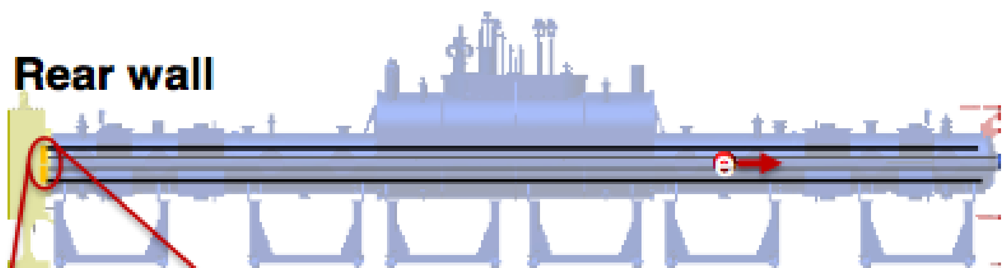
Calibration and monitoring rear system: controling and studying systematics

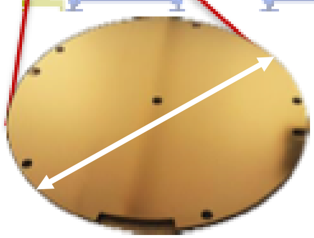




Essential for diagnostics of tritium source & spectrometer transmission

- **photo-electron gun**:
  spectrometer transmission
  column density & energy losses in source
- **rear wall**: definition of source potential,
  neutralization of tritium plasma



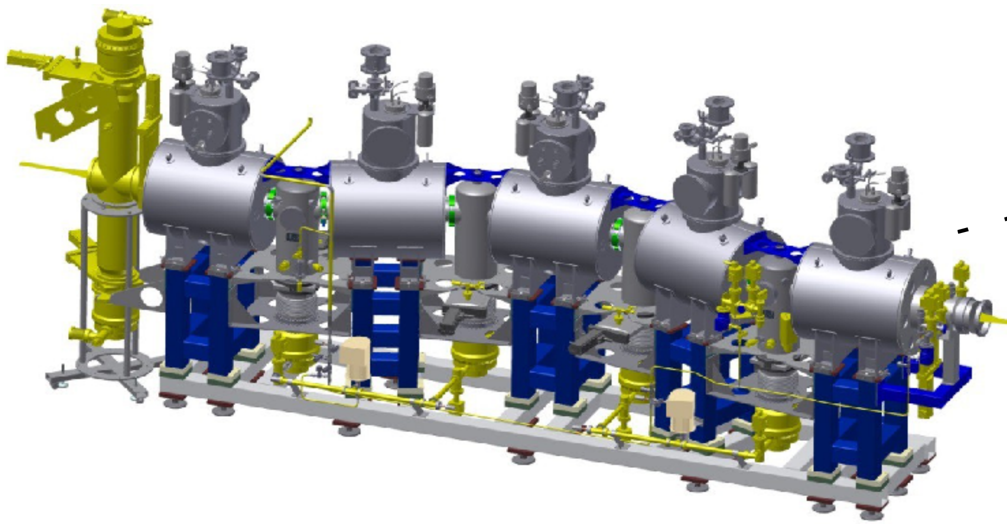


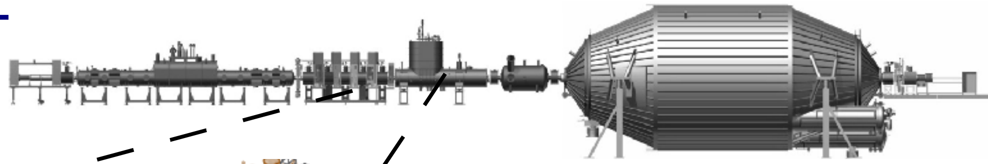
∅ 150 mm

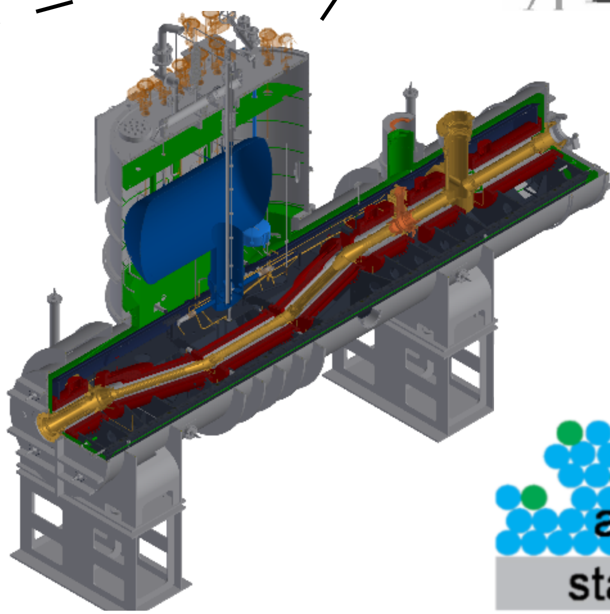
Rear Wall: Au surface creates stable and homogeneous electrostatic potential (~10-20 mV) in the source plasma, can be illuminated by UV light

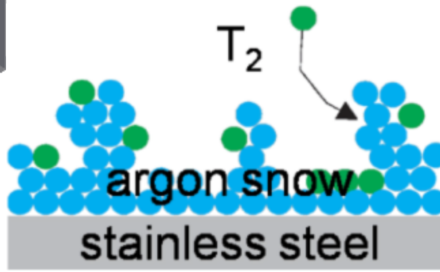
- **X-ray detectors:**
  online monitoring of tritium
  ß-decay activity via X-rays (BIXS)

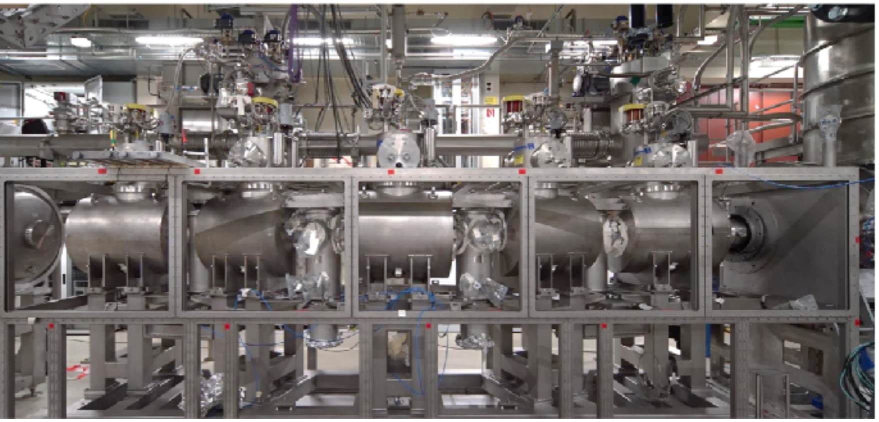
Differential and cryo pumping sections: supression of T_2 by 10^{14} (incl. WGTS)







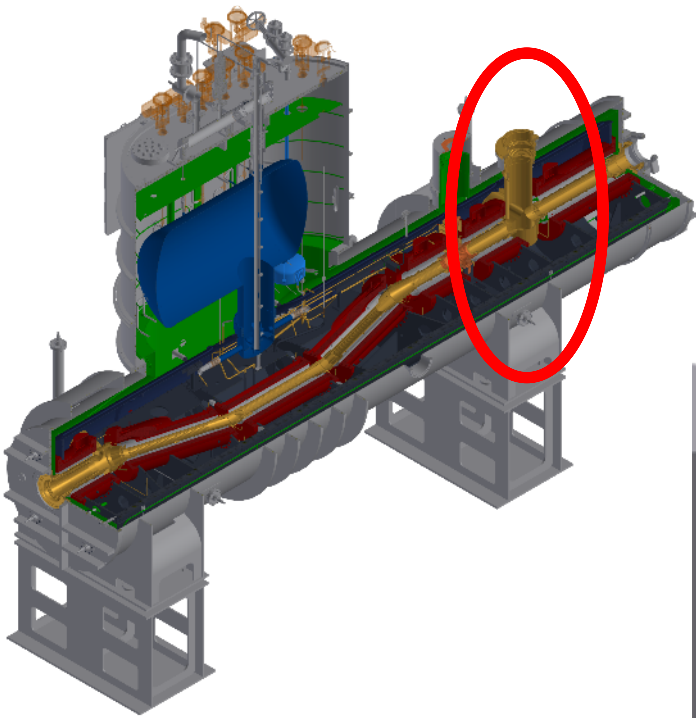




- based on by cryo-sorption at Ar snow at 3-4 K
- Tritium retention: >10^7
- magnetic field: 5.6 T

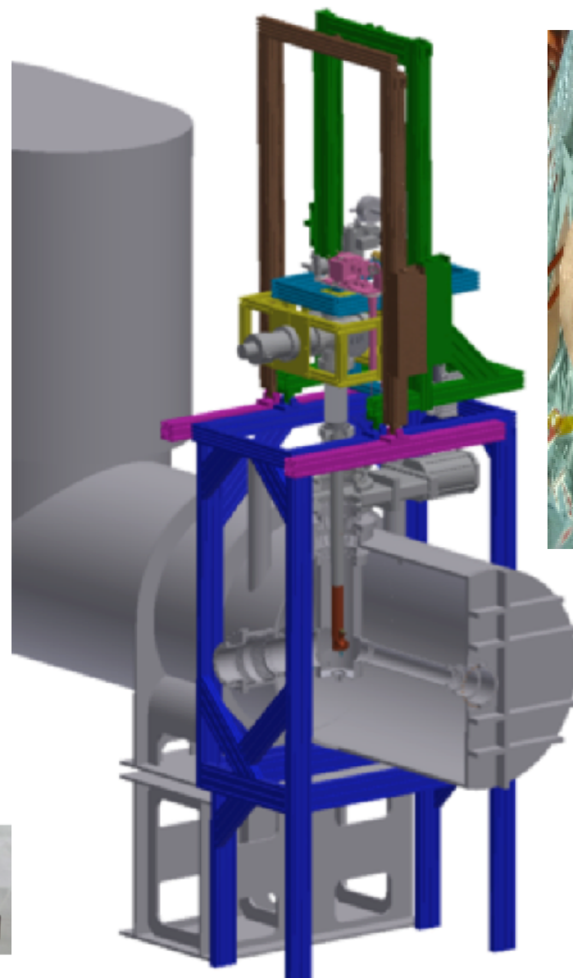
- active pumping: 4 TMPs
- Tritium retention: 10^5
- magnetic field: 5.6 T
- **Ion monitoring by FTICR and ion manipulation by dipole and monopole electrodes inside**

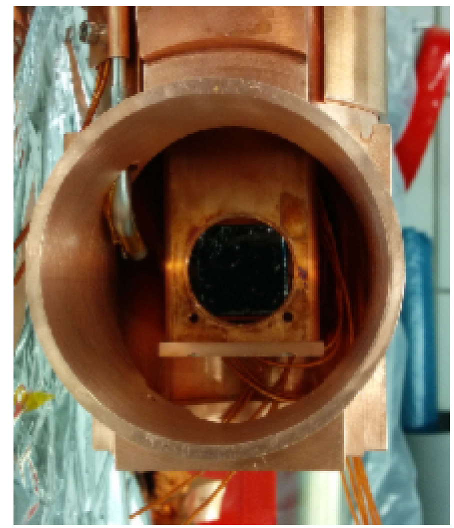
Monitoring and calibration instrumentation of the CPS

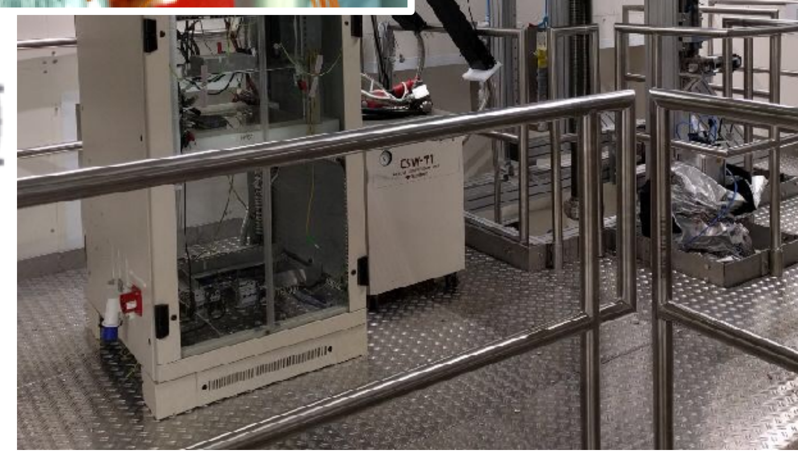


Condensed ^{83m}Kr conversion electron source

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

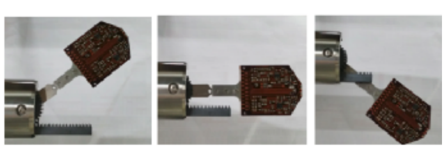




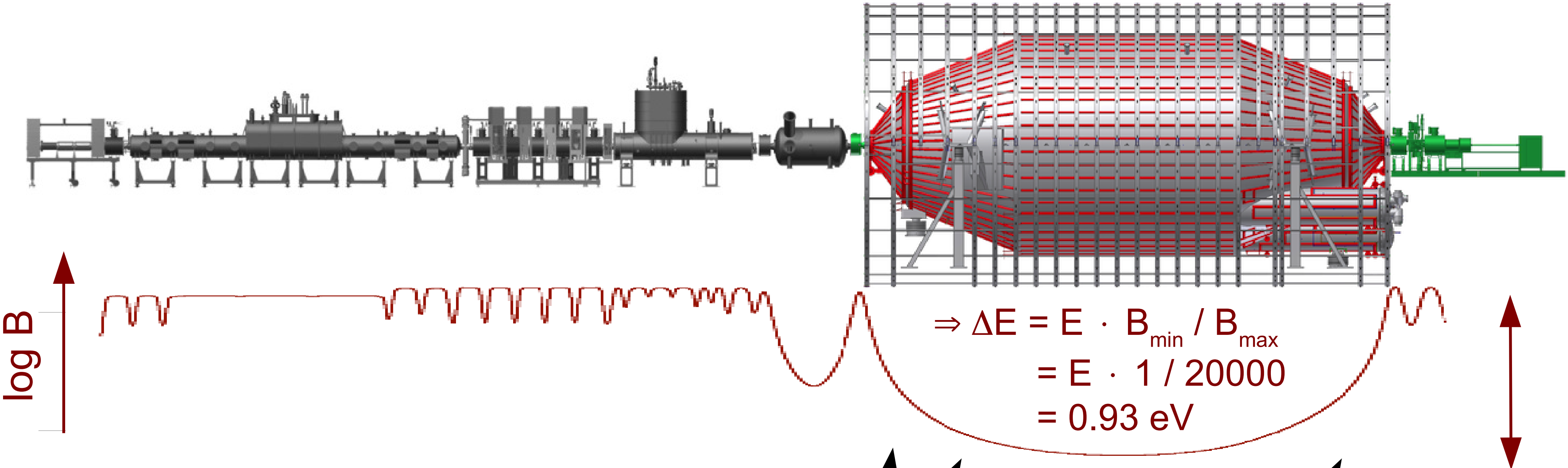


Electron rate monitor

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:

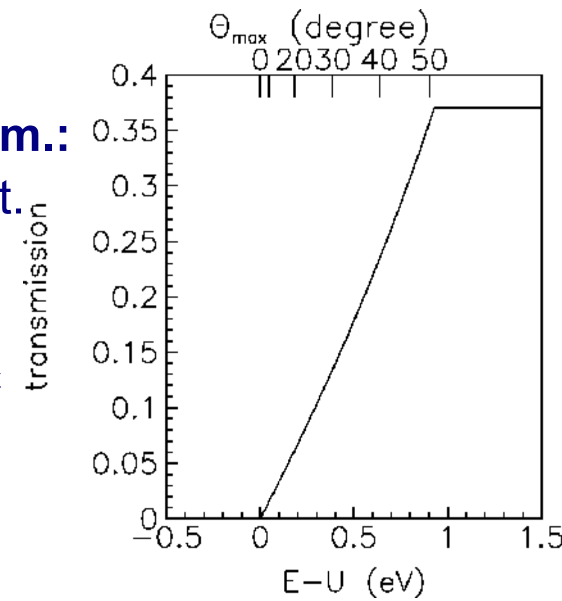
- huge size: 10m diameter, 24m length
  1240 m^3 volume, 690 m^2 inner surface
- ultra-high vacuum: p = $O(10^{-11}$ mbar)
- ultra-high energy resolution: $\Delta E = 0.93$eV
- vacuum vessel on precise high voltage (ppm precision)

adiabatic transform.:

$\mu = E_\perp / B = const.$

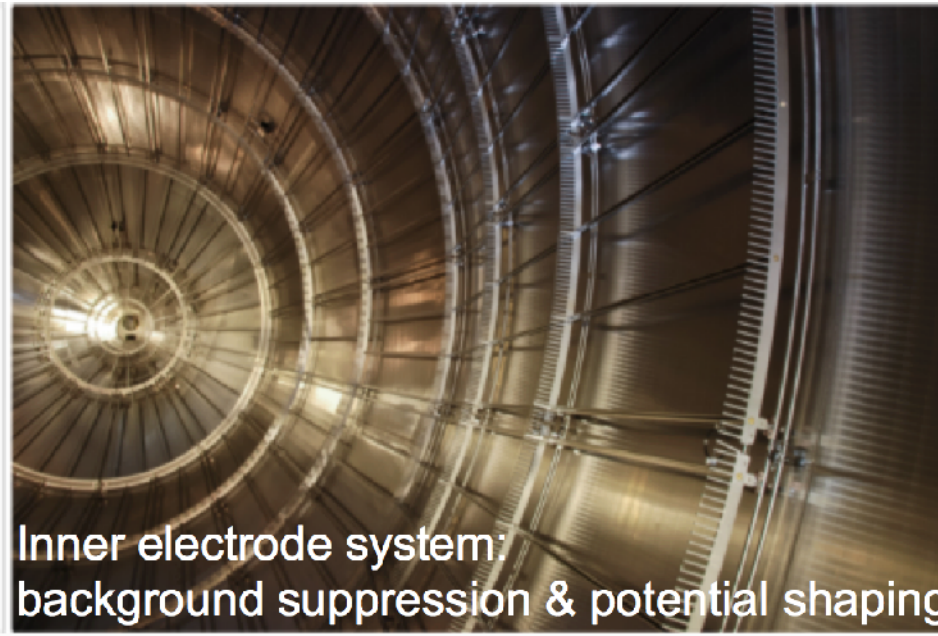
$\Rightarrow$ parallel e^- beam

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

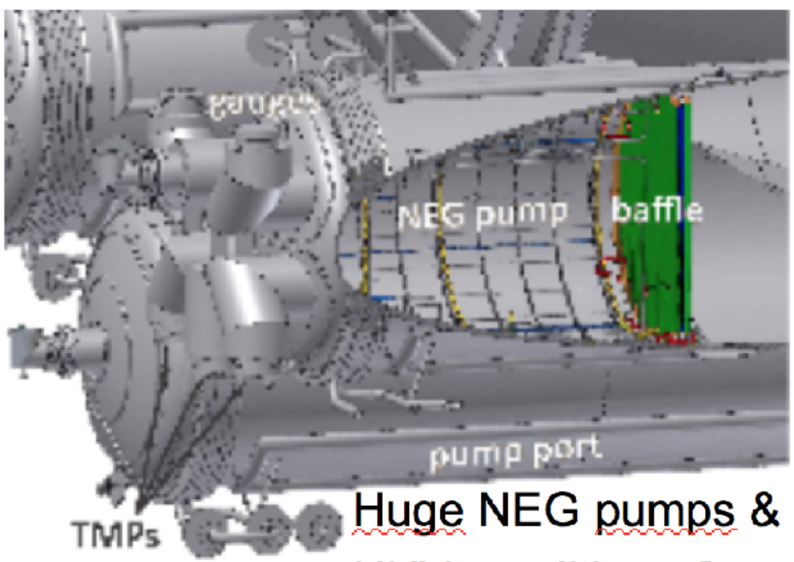


KATRIN main spectrometer

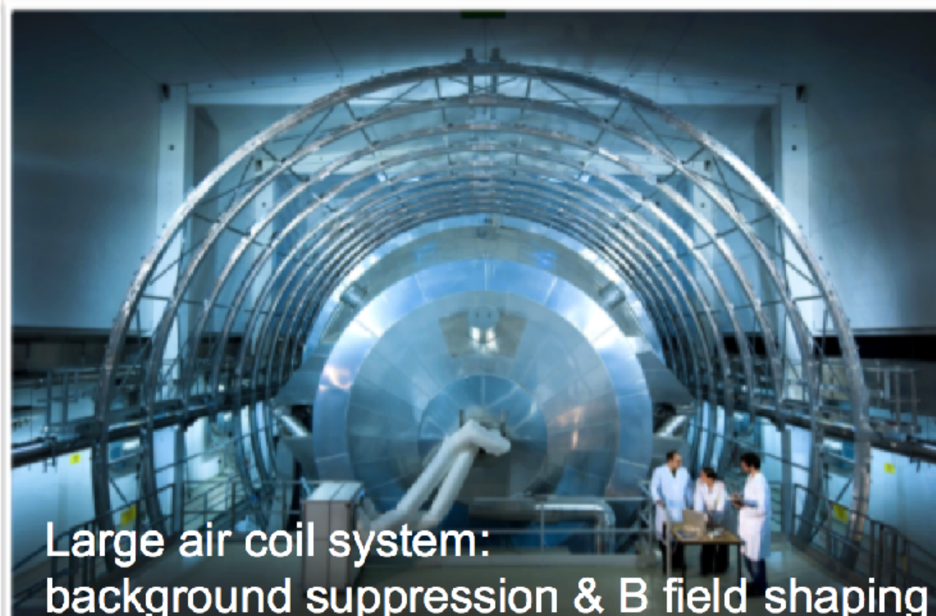
Huge spectrometer:
high energy resolution & huge acceptance



Inner electrode system:
background suppression & potential shaping



Huge NEG pumps & LN_2 baffles:
UHV conditions & radon trapping



Large air coil system:
background suppression & B field shaping

The detector

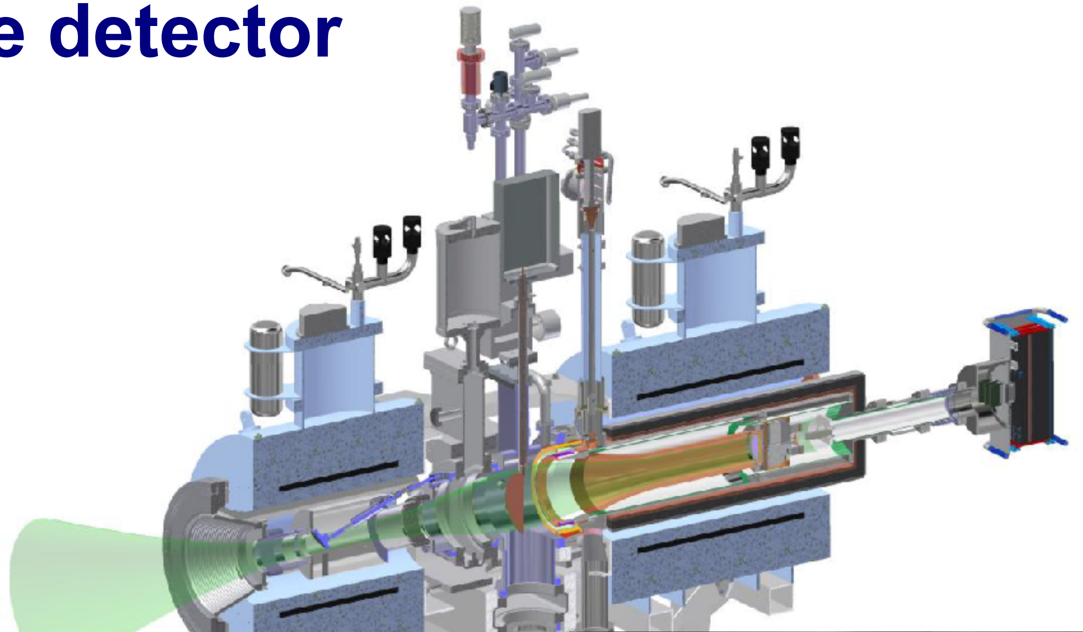
Requirements

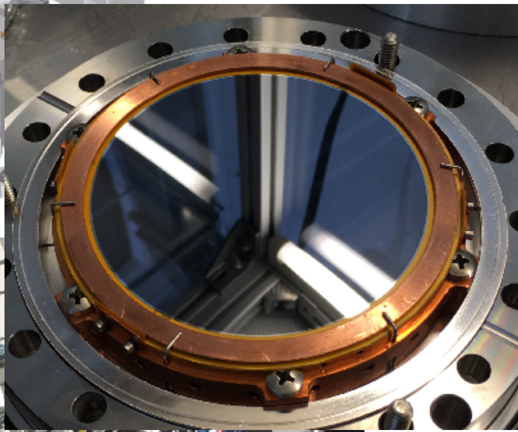
- detection of β-electrons (mHz to kHz)
- high efficiency (> 90%)
- low background (< 1 mHz)
  (passive and active shielding)
- good energy resolution (< 1 keV)

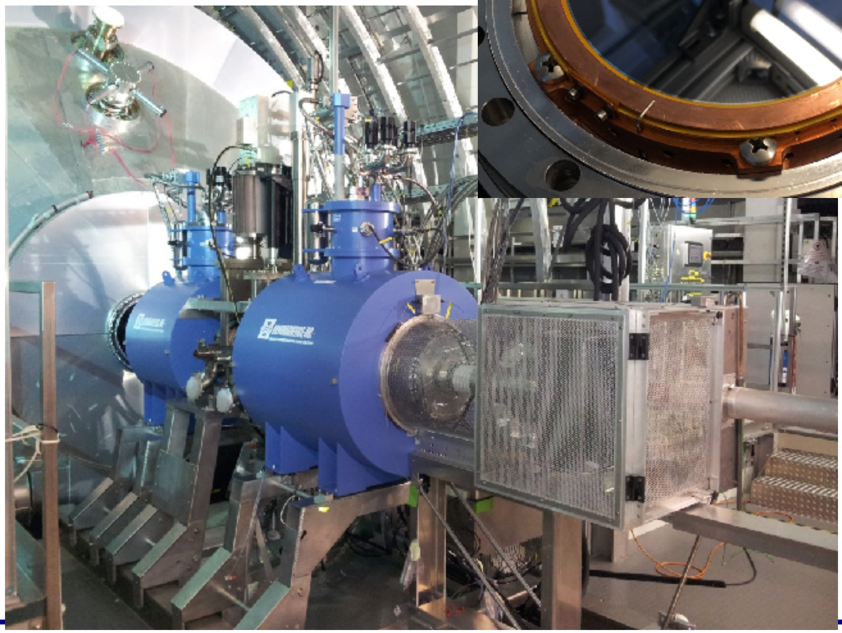
Properties

- 90 mm Ø Si PIN diode
- thin entry window (50nm)
- detector magnet 3 - 6 T
- post acceleration (30kV)
  (to lower background in signal region)
- segmented wafer (148 pixels)

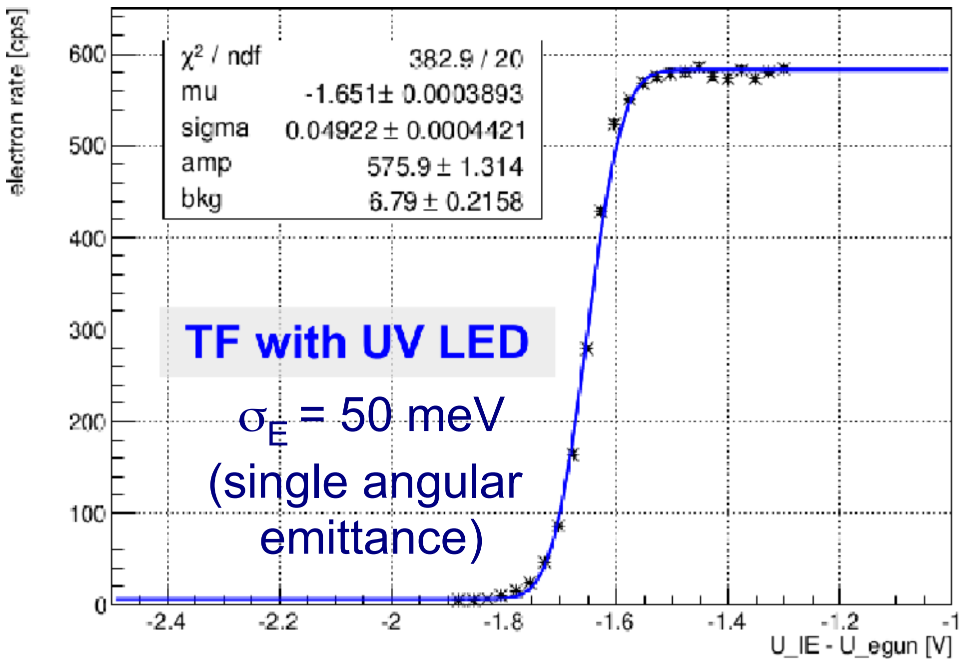
  → record azimuthal and radial profile of the flux tube
  → investigate systematic effects
  → compensate field inhomogeneities

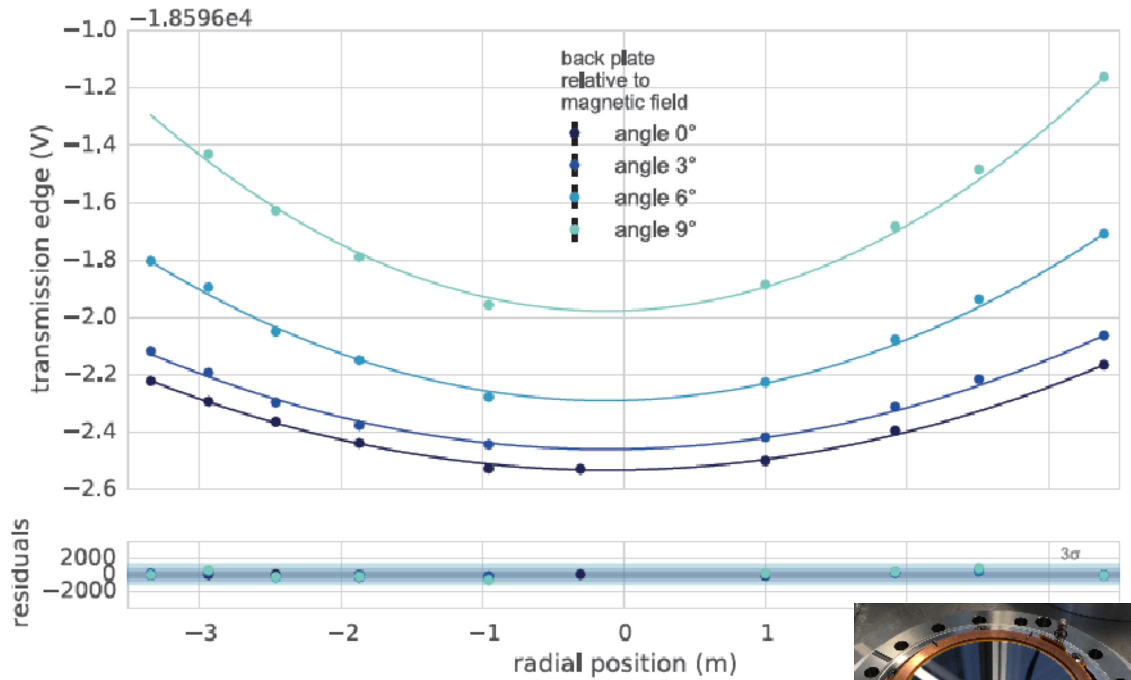


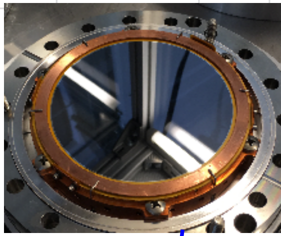


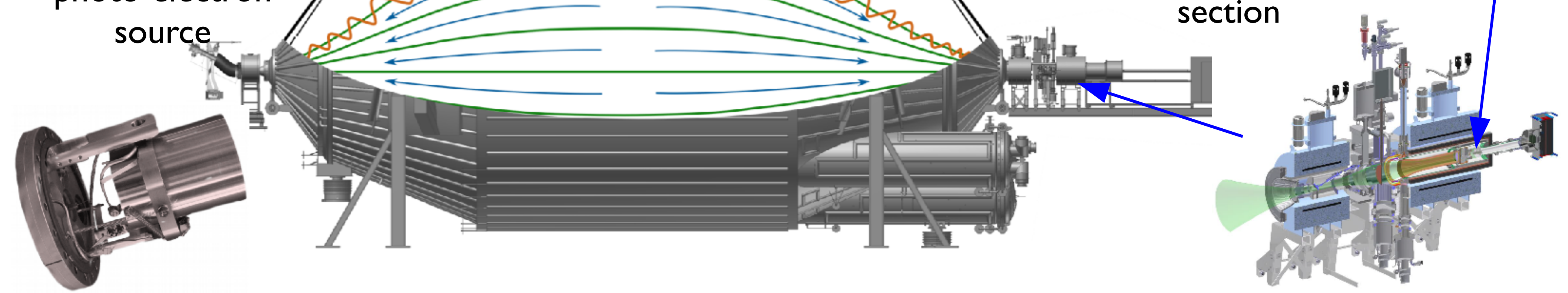


Commissioning of main spectrometer (ΔE = 0.93 eV) and detector

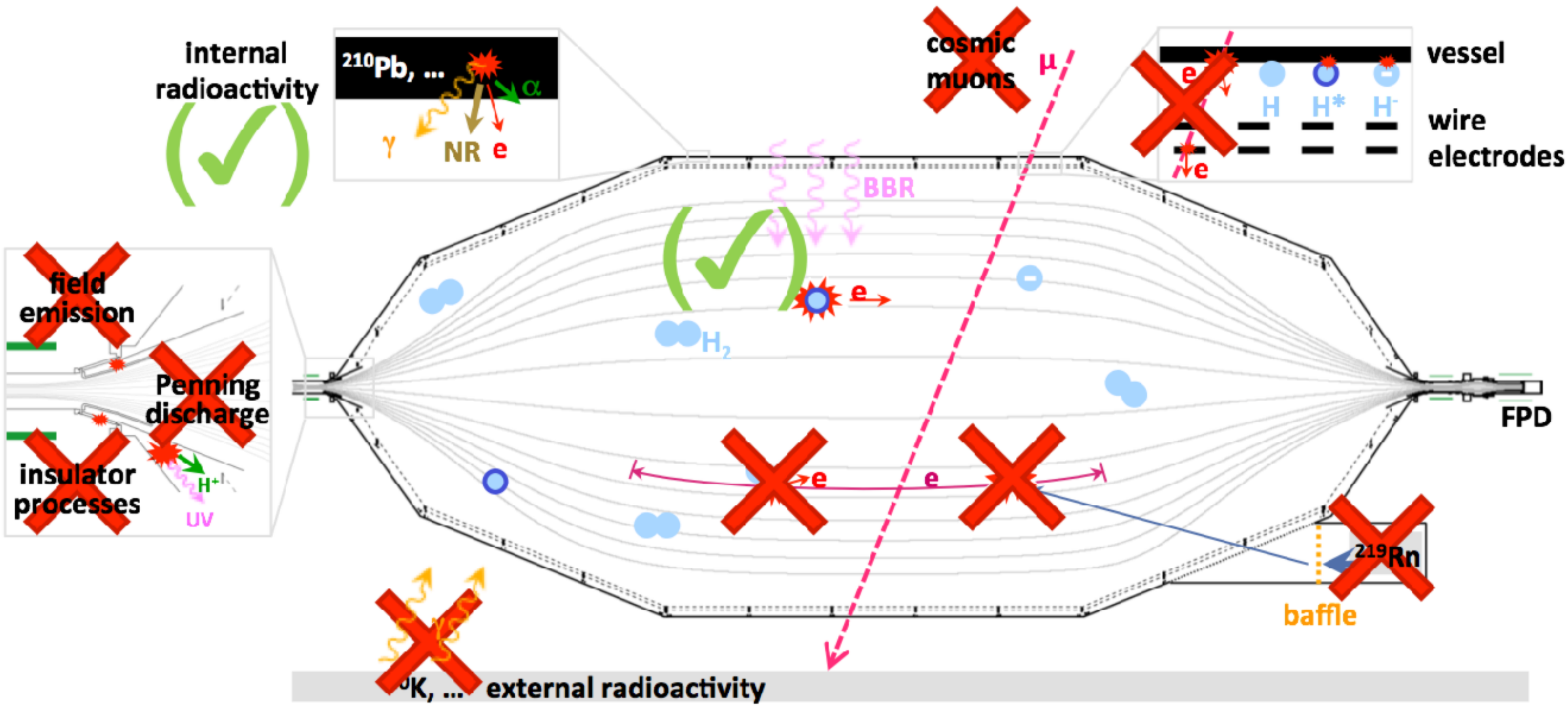








Background sources at KATRIN: detailed understanding, but ...



- 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:

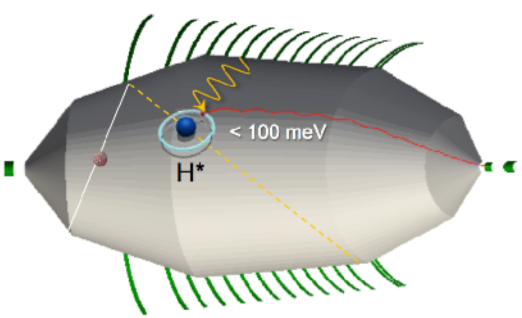
- desorbed from walls due to ^{206}Pb recoil ions from ^{210}Po decays
- non-trapped electrons on meV-scale
- bg-rate: ~0.5 cps

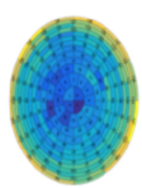
counter measures:

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

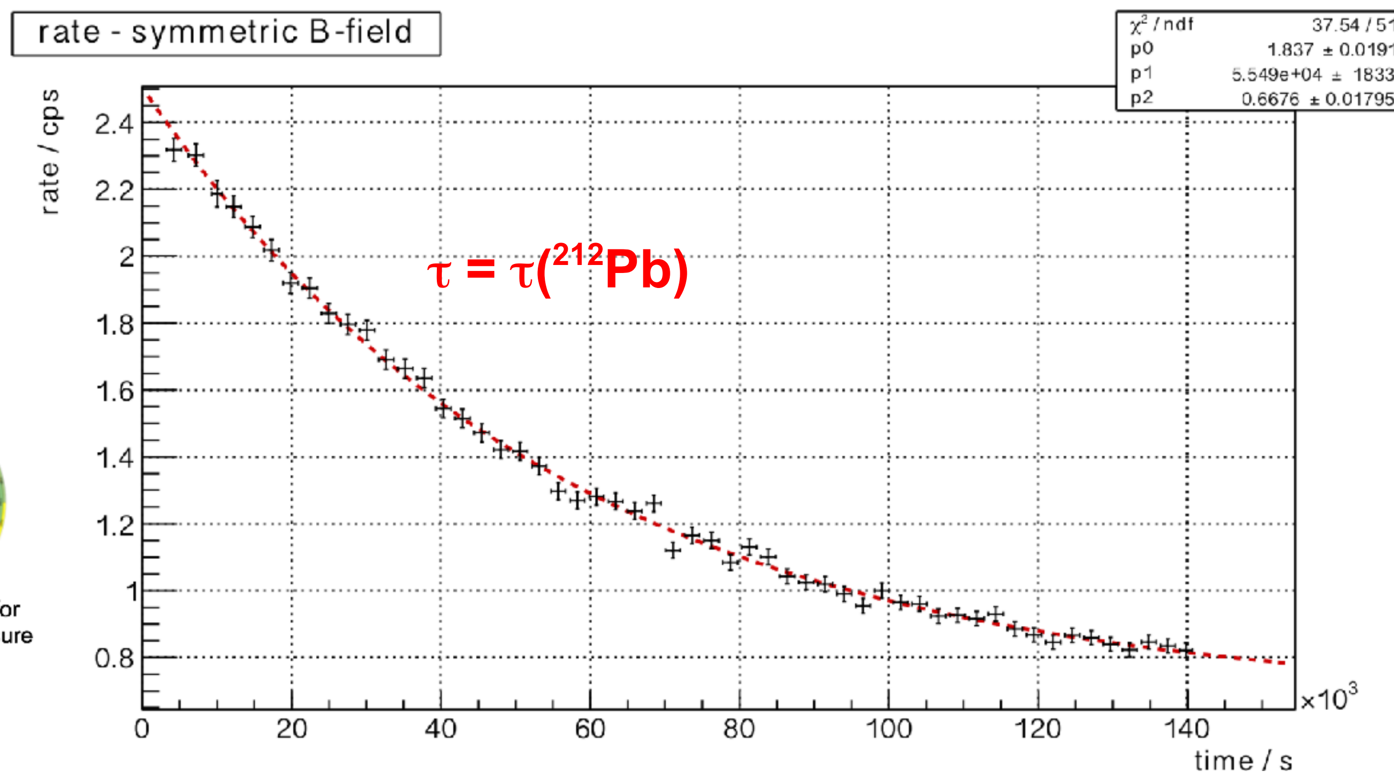
Testing this hypothesis:

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

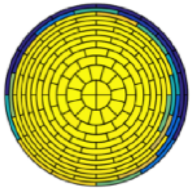




isotropic bg for longer exposure

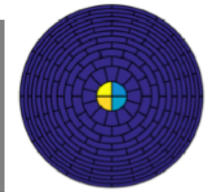


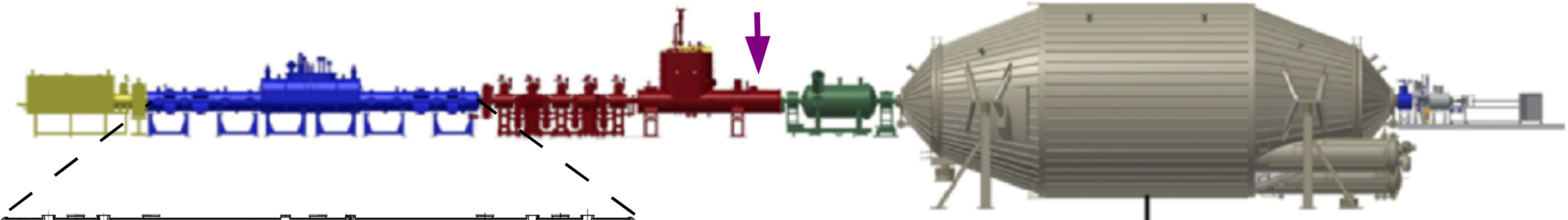
July 2017: calibration and comissioning campaign with all 3 ^{83m}Kr sources

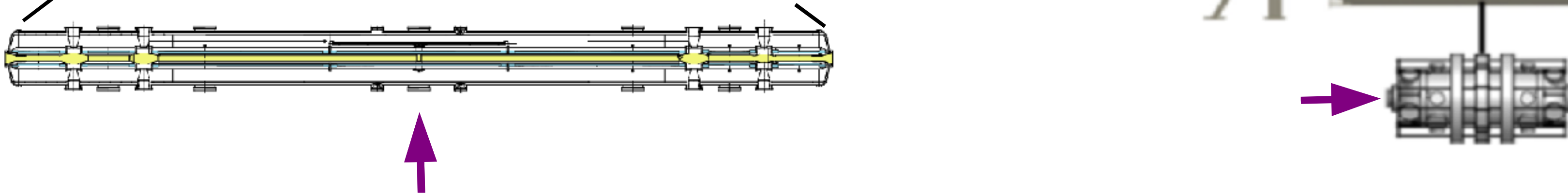


gaseous ^{83m}Kr source
decaying ^{83m}Kr atoms fill
whole WGTS (at 100 K)

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

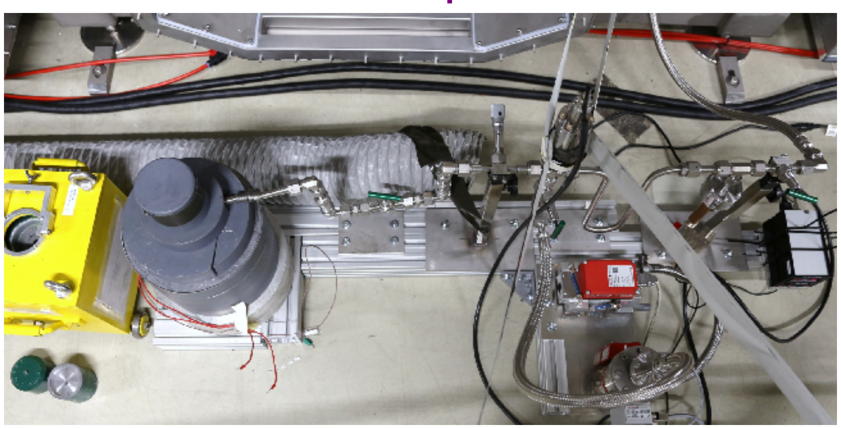


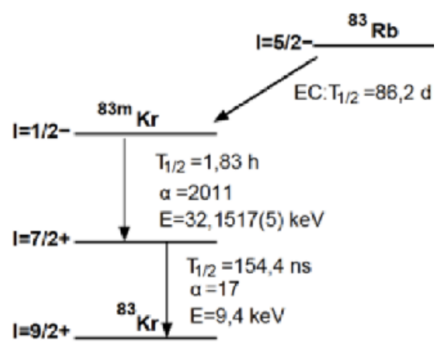


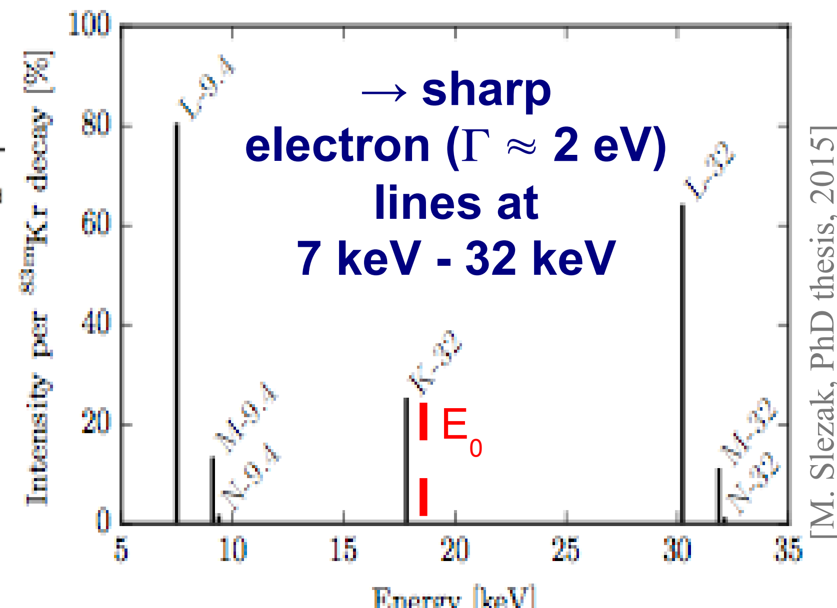


implanted
^{83}Rb/^{83m}Kr source

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

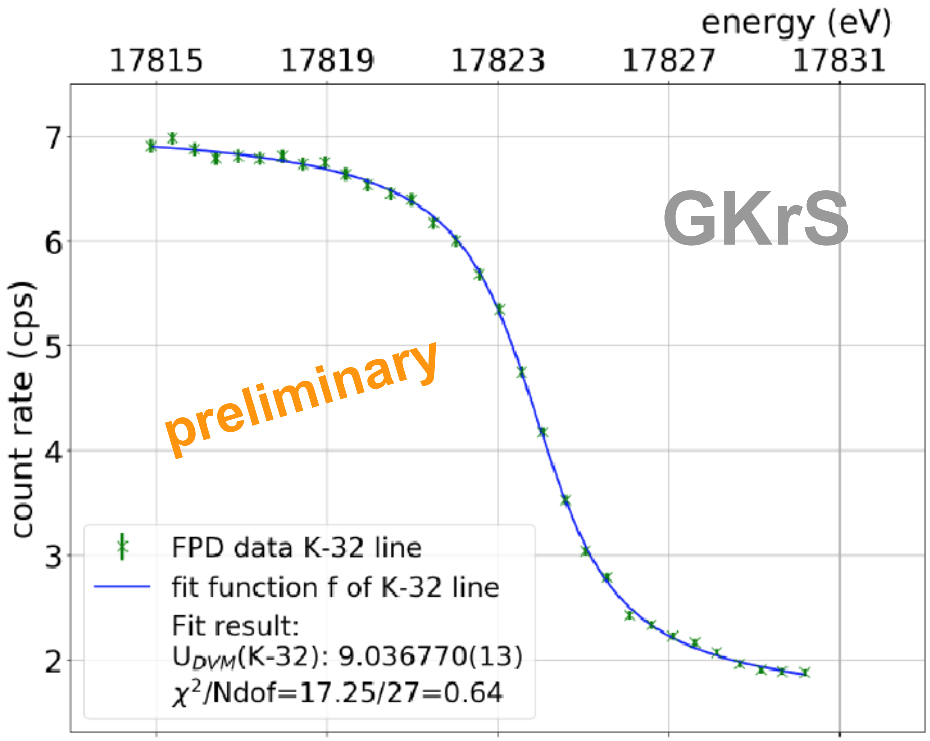






Line scan & stability gaseous (condensed) Kr source GKrS (CKrS)

fitting well, line near tritium endpoint:
K-32 line (17.82 keV, Γ ~2.7 eV)

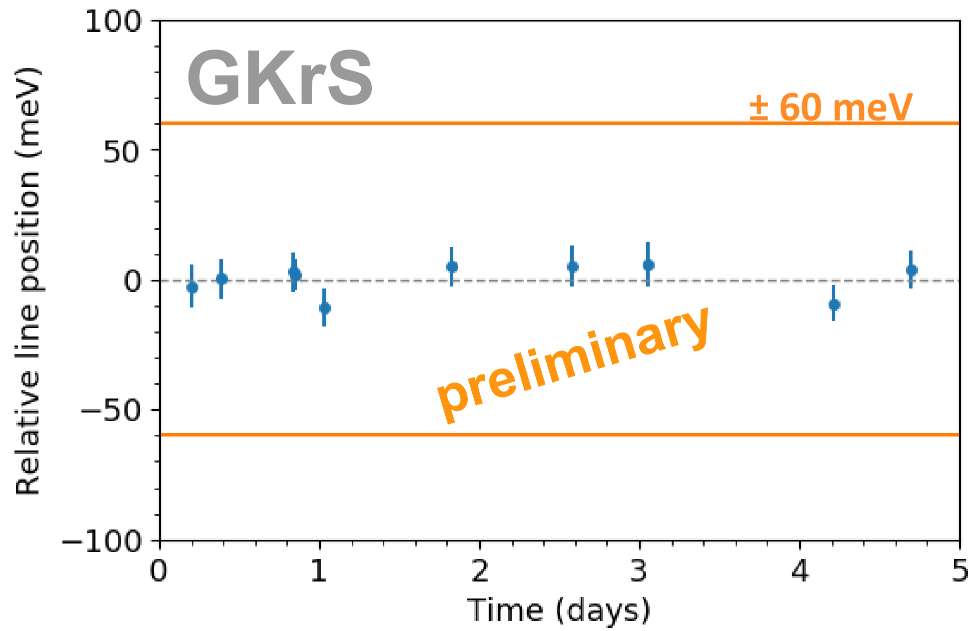


Just one example:

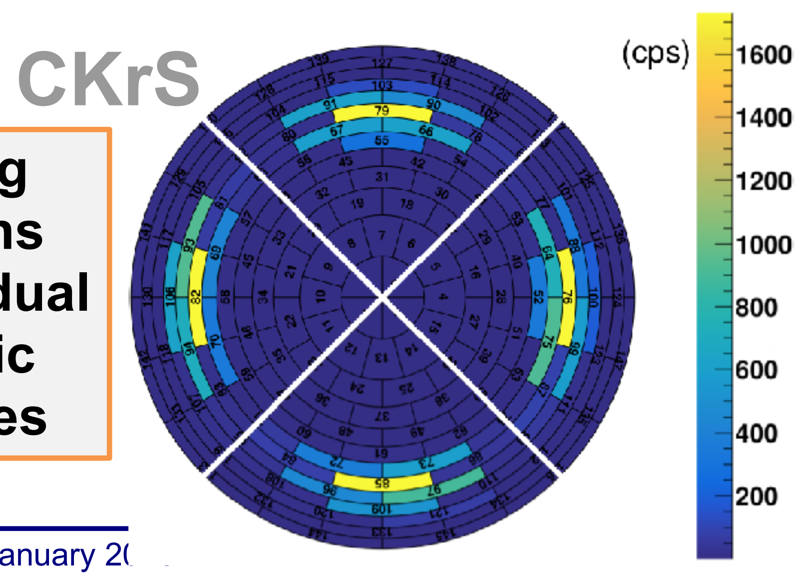
one out of many lines
from 7 keV to 32 keV

much more statistics

stability of L3-32 line position, 30.47 keV:

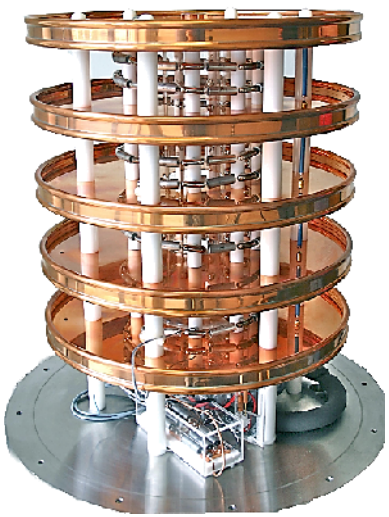


sending electrons on individual magnetic field lines



Absolute energy scale calibration by difference of electron conversion lines

Measure retarding voltage with ultra-high precision HV divider:

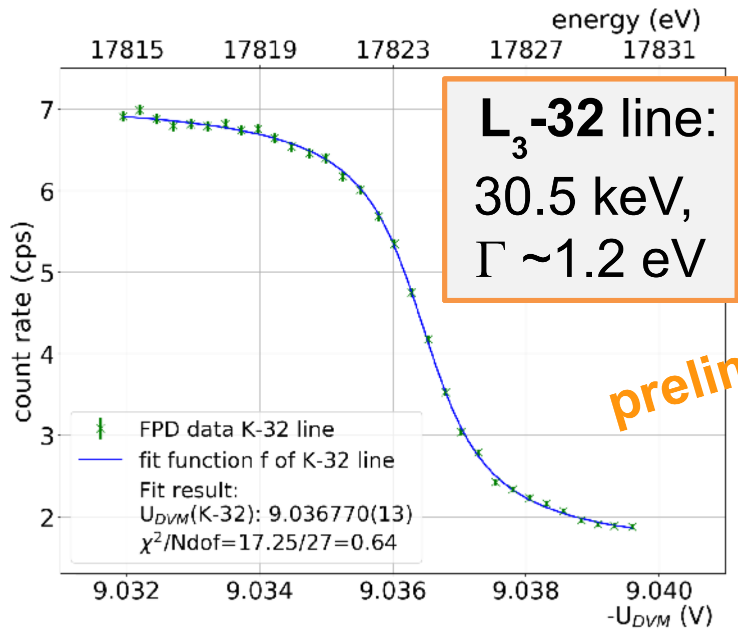


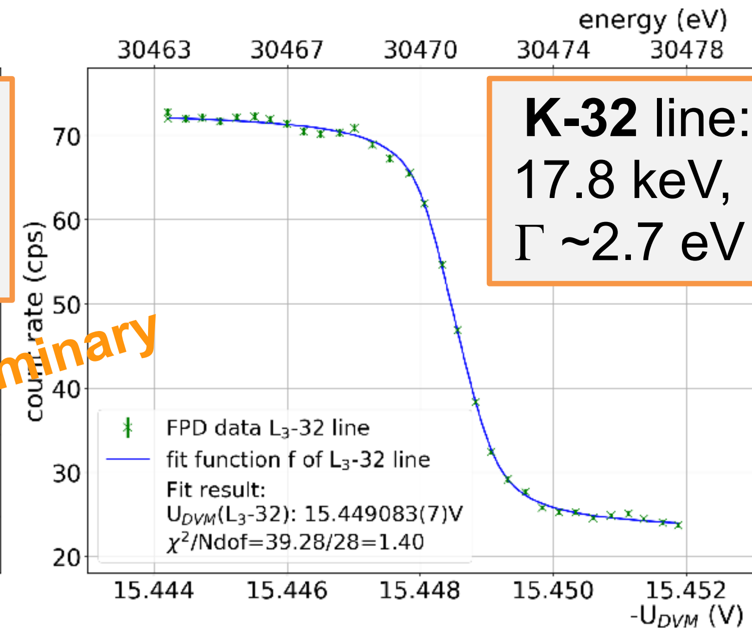
In cooperation with German national metrology institute PTB

Last calibration at PTB in 2013:

M = 1972.4531(20)

Determine difference of conversion electron line positions:





K-32 line
E(ce) = 17824.23(50) eV
$E_{binding}$(ce) = 14327.26(4) eV
E_{recoil}(ce) = 0.120 eV

L3-32 line
E(ce) = 30472.19(50) eV
$E_{binding}$(ce) = 1679.21(3) eV
E_{recoil}(ce) = 0.207 eV

Energy of electrons:

$$E_{kin} = E_\gamma - E_{binding} + E_\gamma^{rec} - E_{ion}^{rec}$$

Energy of γ-transition | Binding energy | Recoil energies

Transmission condition:

$$E_{kin} = -\Delta\Phi - q\Delta U + qU_{spec}$$

Work function difference source - spectrometer | Potential decrease in analyzing plane (≈2V)

considering line difference → systematic effects (ΔΦ, E_γ) cancel out

GKrS 2017: M = 1972.449(10)

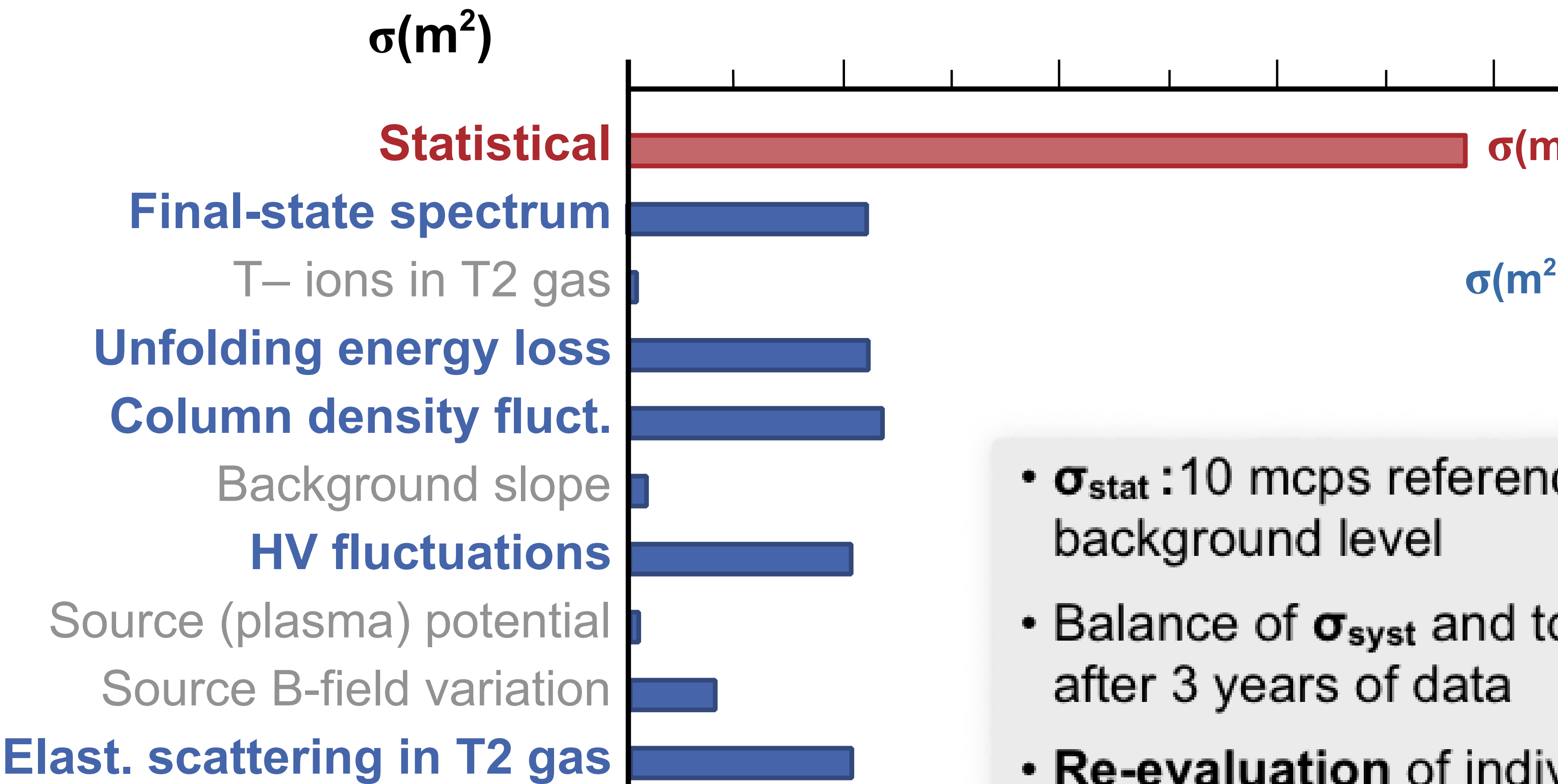
preliminary

→ both values agree very well !

HV divider scale factor changes only by 2 ppm over 4 years (5 ppm uncertainty) !

Statistical & systematic uncertainties

KATRIN's uncertainty budget (design sensitivity, ~2004):



$\sigma(m^2)_{stat} = 0.018\ eV^2$

$\sigma(m^2)_{syst} = 0.017\ eV^2$

- σ_{stat} : 10 mcps reference background level
- Balance of σ_{syst} and total σ_{stat} after 3 years of data
- **Re-evaluation** of individual systematics ongoing during system characterisation

check systematics by comparison of Q-value and $\Delta M(^3He, ^3H)$ from Penning trap measurement

Statistical & systematic uncertainties

KATRIN's uncertainty budget (design sensitivity, ~2004):

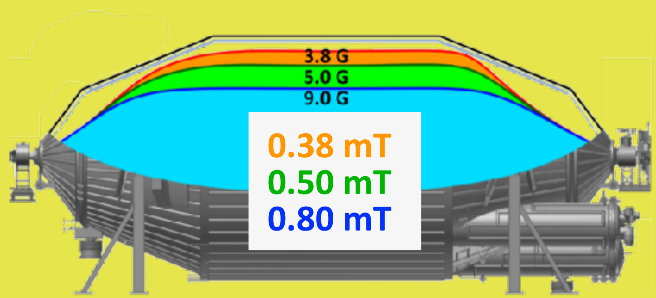
3 yr of data taking

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)

eV^2

eV^2

S

Ela

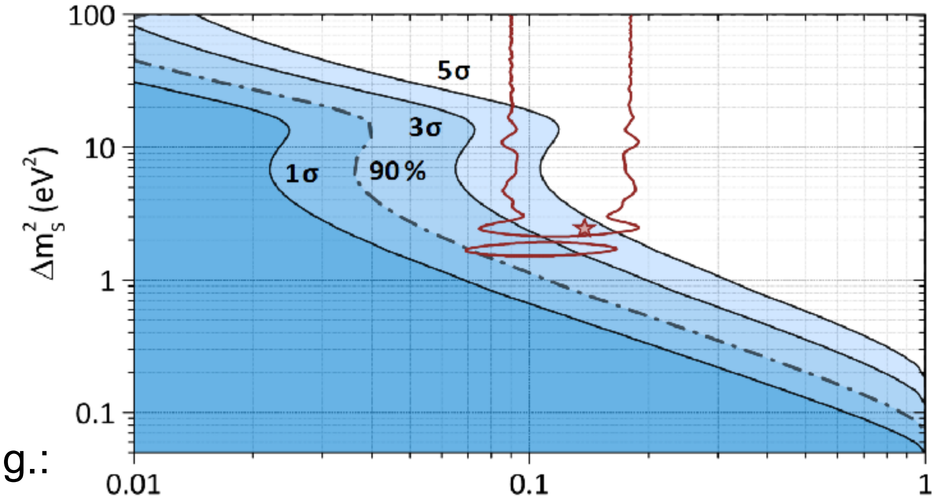
system characterisation

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

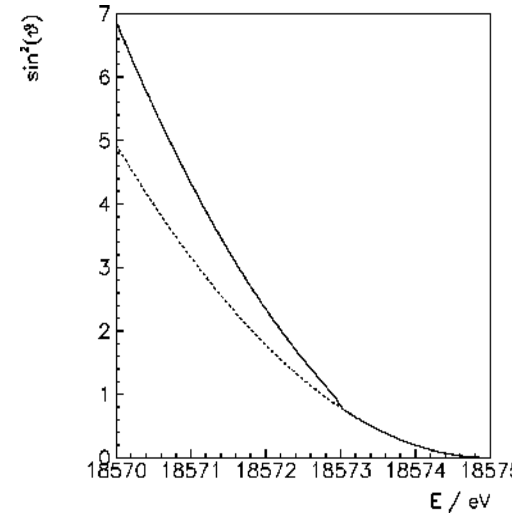
Sterile neutrinos

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

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

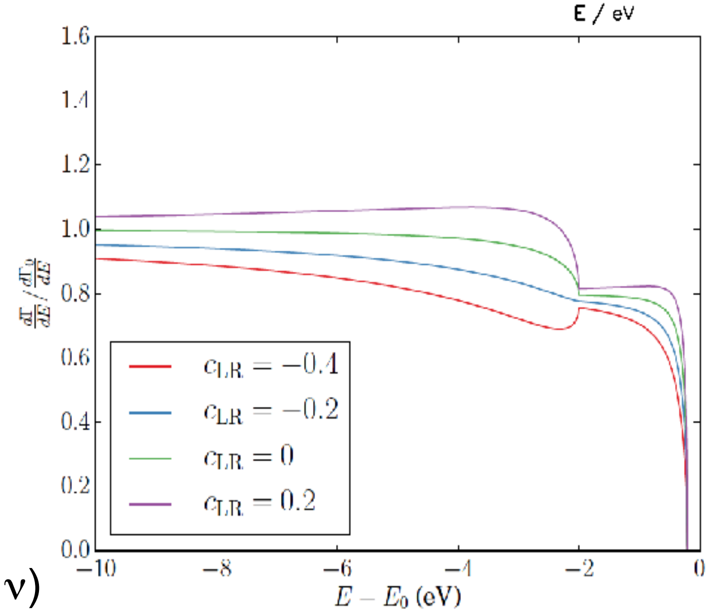
A. Esmaili, O.L.G. Peres, arXiv:1203.2632

keV ν:

see e.g.

S. Mertens et al., JCAP 02 (2015) 020

M. Drewes et al. JCAP 01 (2017) 025



non SM currents, ...

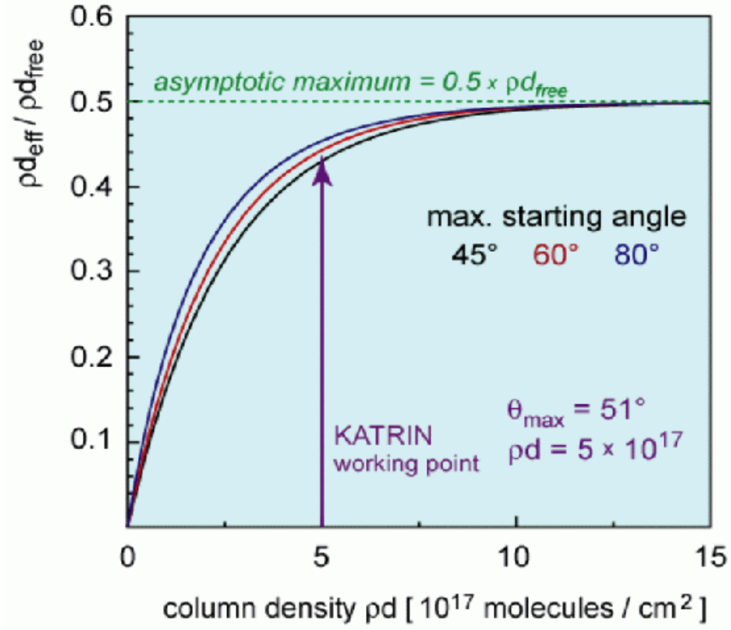
see e.g.: N. Steinbrink et al., JCAP 6 (2017) 15 (RH currents & sterile ν)

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

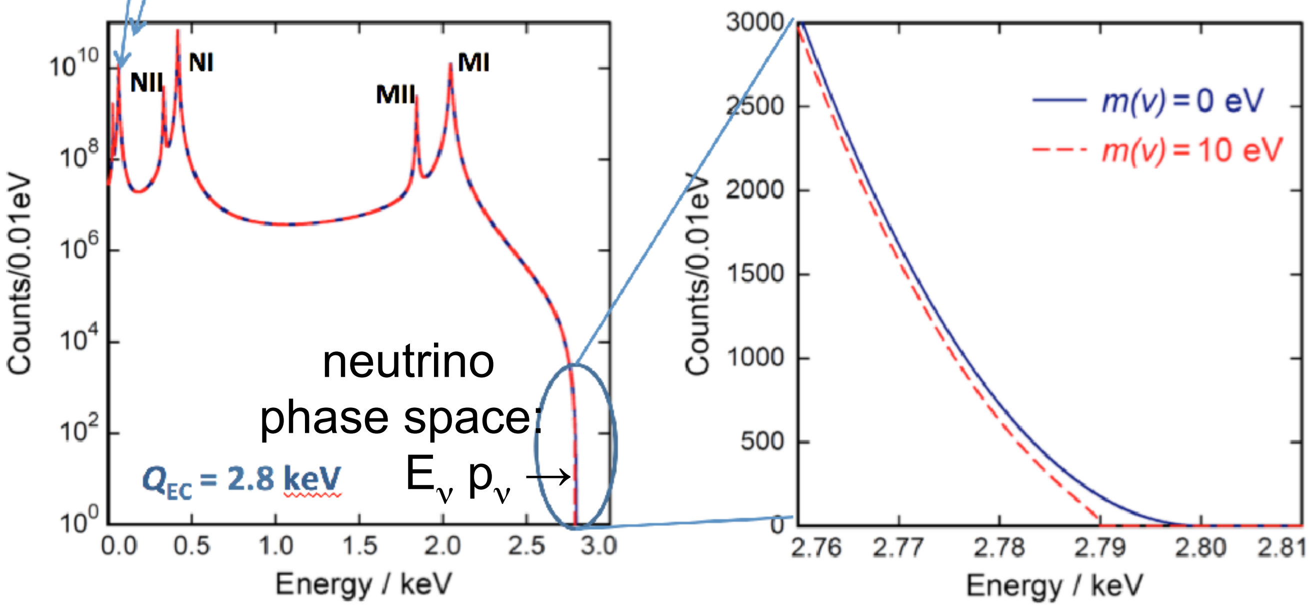
Possible ways out:

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



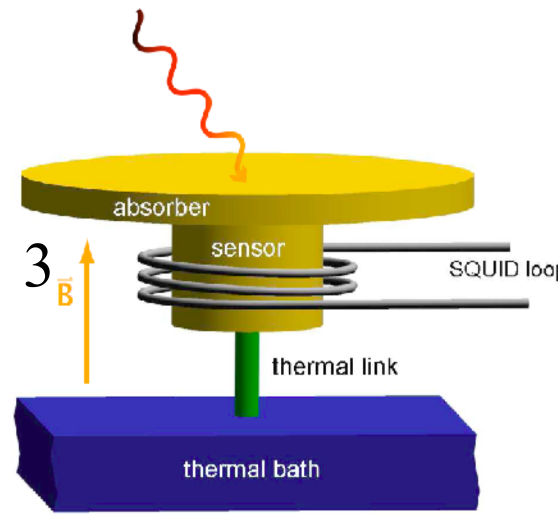
ECHo neutrino mass project: ^{163}Ho electron capture with metallic magnetic calorimeters (MMC)

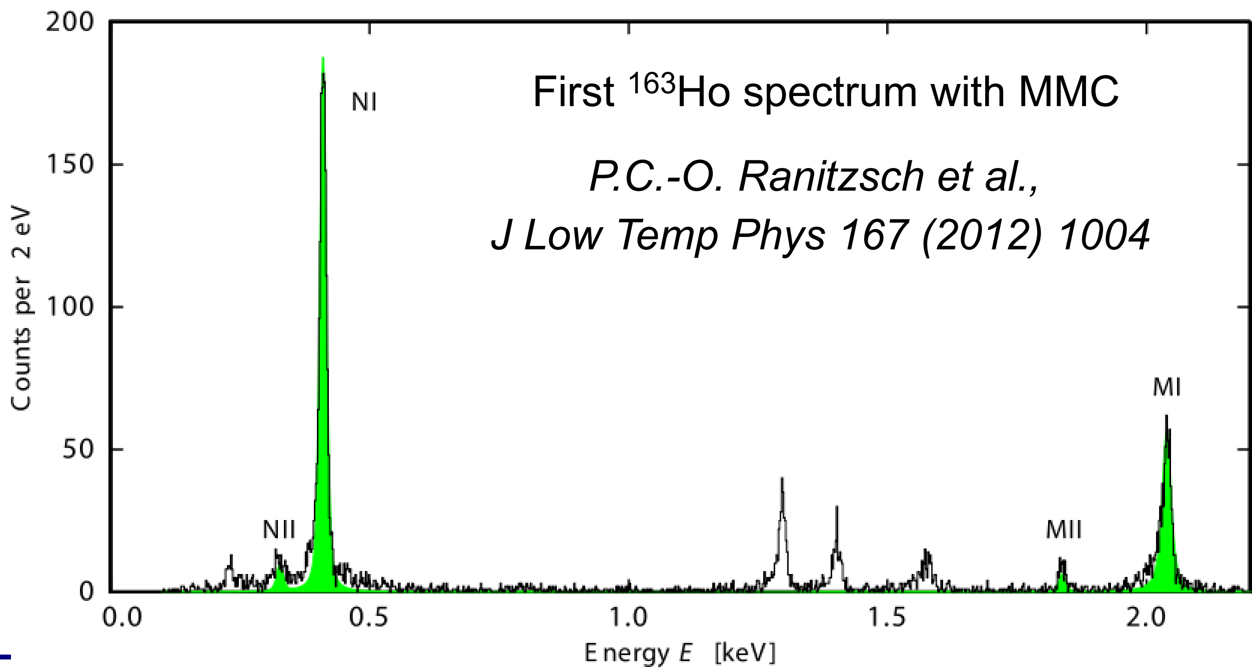
$$^{163}\mathrm{Ho} + e^- \rightarrow {}^{163}\mathrm{Dy}^* + \nu_e \rightarrow {}^{163}\mathrm{Dy} + \gamma/e^- + \nu_e$$



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

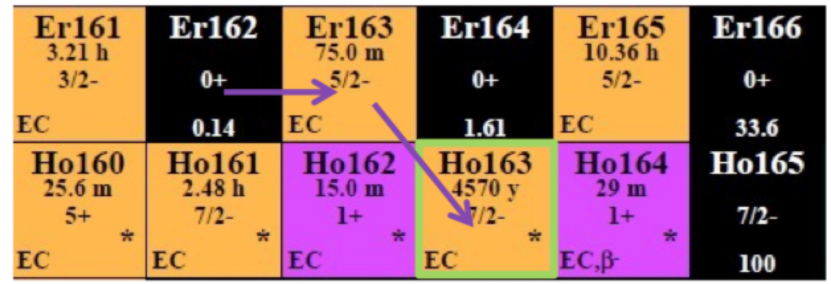
- Independent ^{163}Ho Q_{EC} measurement
  $Q_{EC} = (2.833 \pm 0.030_{stat} \pm 0.015_{sys})$ keV

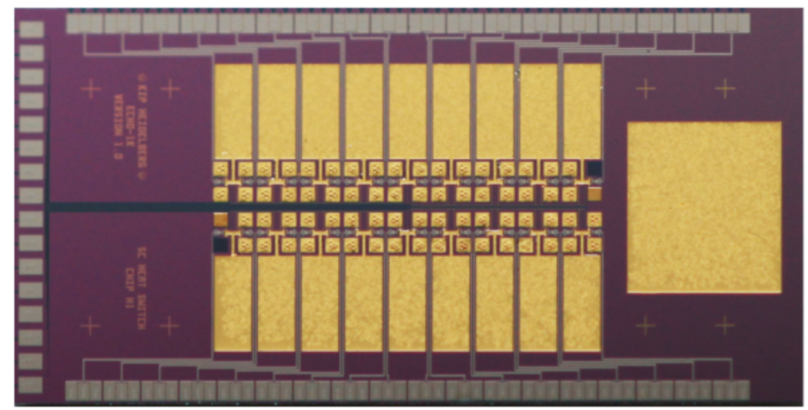
- High purity ^{163}Ho source has been produced

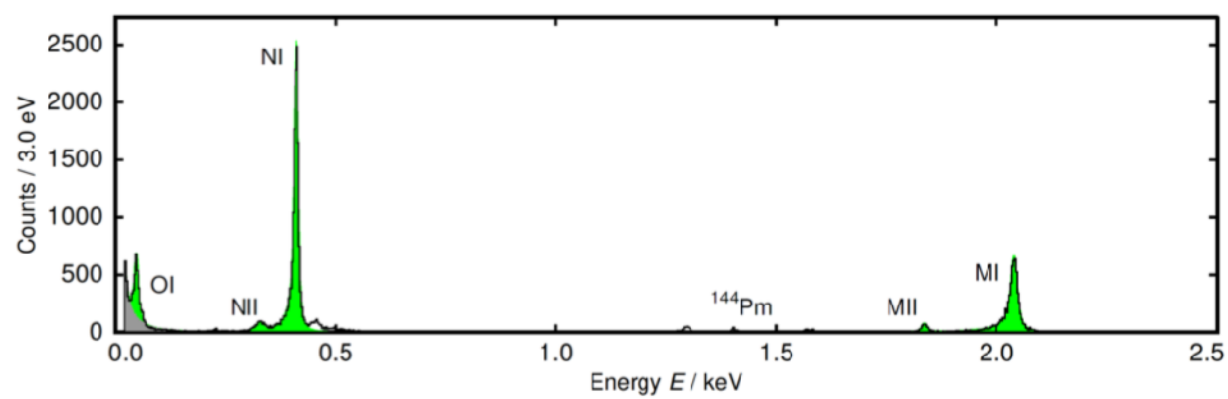
- ^{163}Ho ions have been successfully implanted
  in offline process @ISOLDE-CERN in 32 pixels
  @RISIKO in 8 pixels
  @RISIKO in 64 pixels

- 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

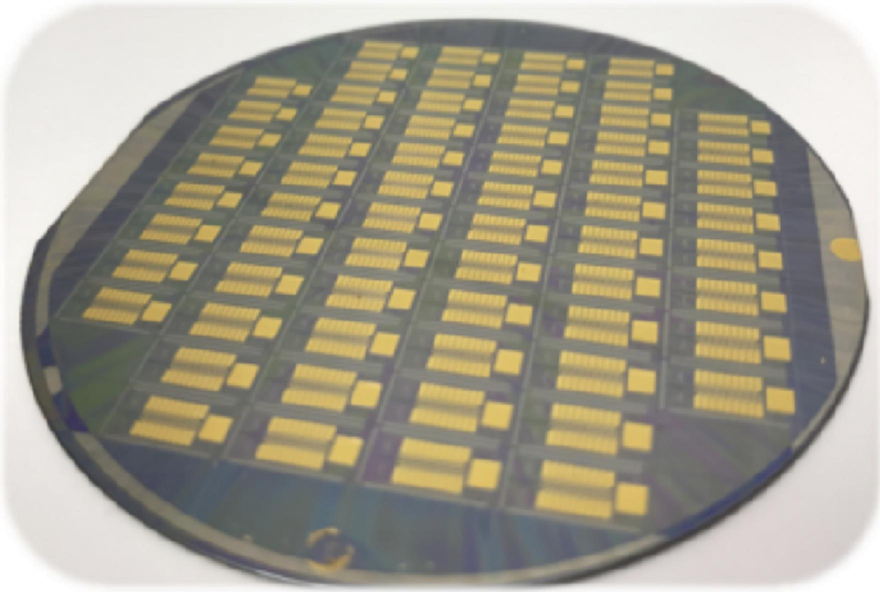
ECHo neutrino mass project: timeline

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
- $\tau_{rise} < 1\ \mu s$
- multiplexed arrays → microwave SQUID multiplexing
- 1 year measuring time 10^{10} counts → neutrino mass sensitivity m < 10 eV
- Data taking will starting early 2018

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



courtesy L. Gastaldo

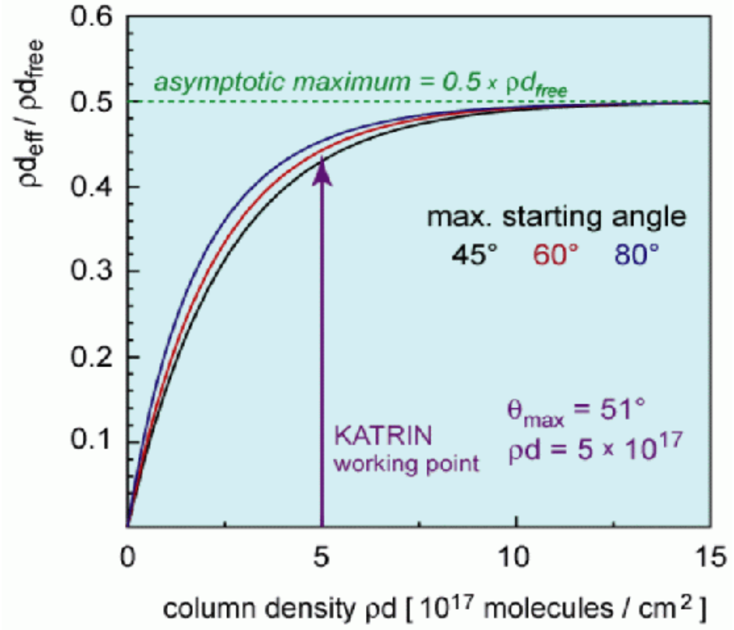
Other ^{163}Ho EC projects:

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

NuMECS

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*

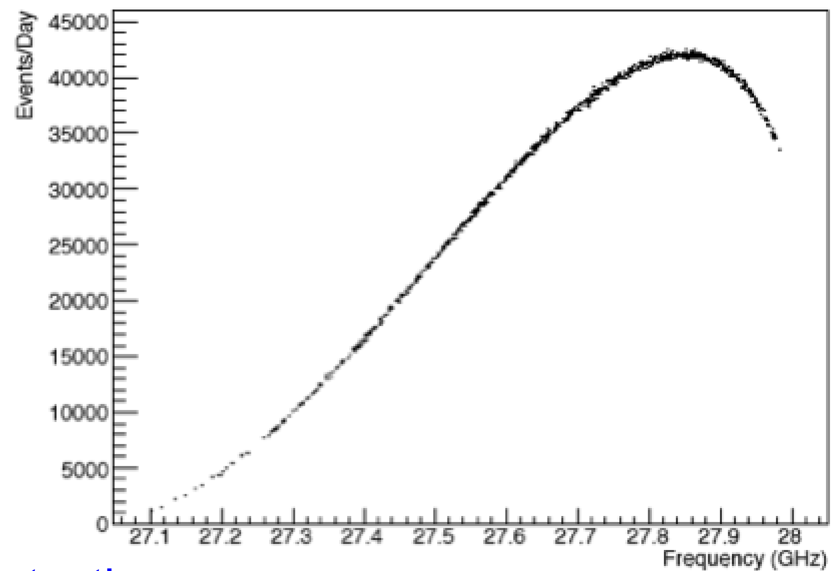
- Source = KATRIN tritium source technology :

  uniform B field + low pressure T_2 gas

  β electron radiates coherent cyclotron radiation

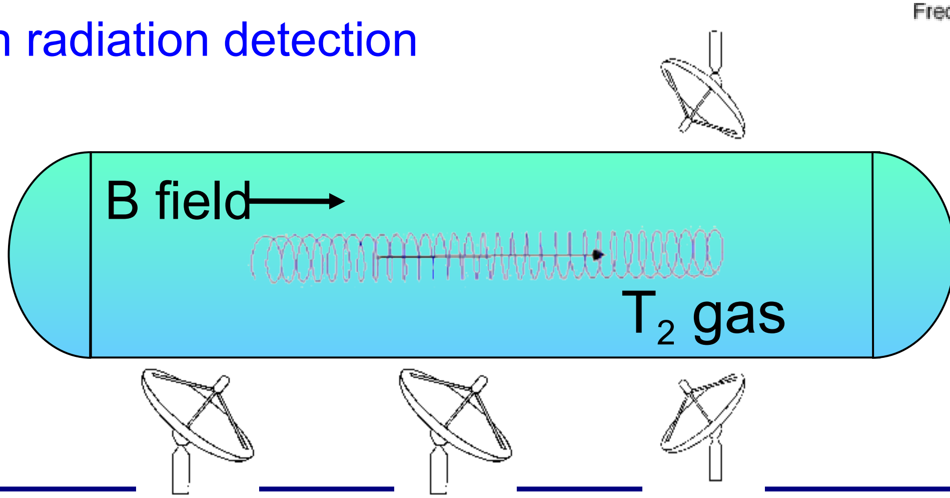
  $$\omega(\gamma) = \frac{\omega_0}{\gamma} = \frac{eB}{K + m_e}$$

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

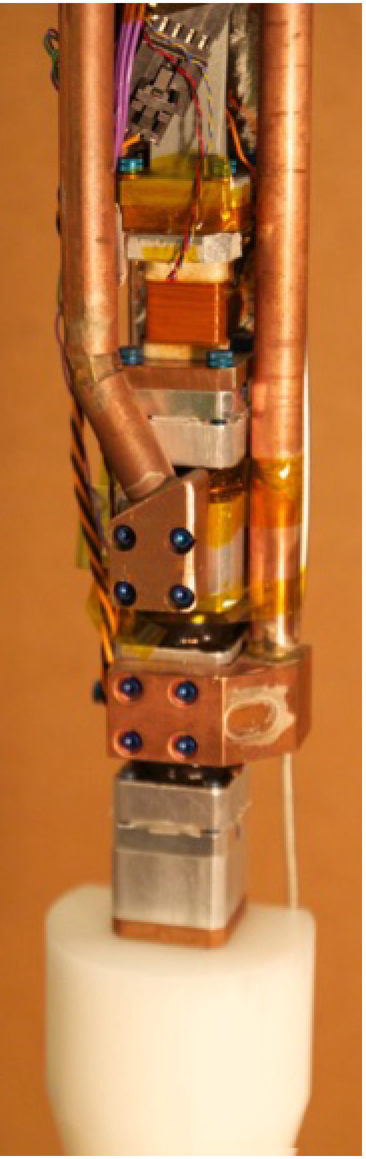


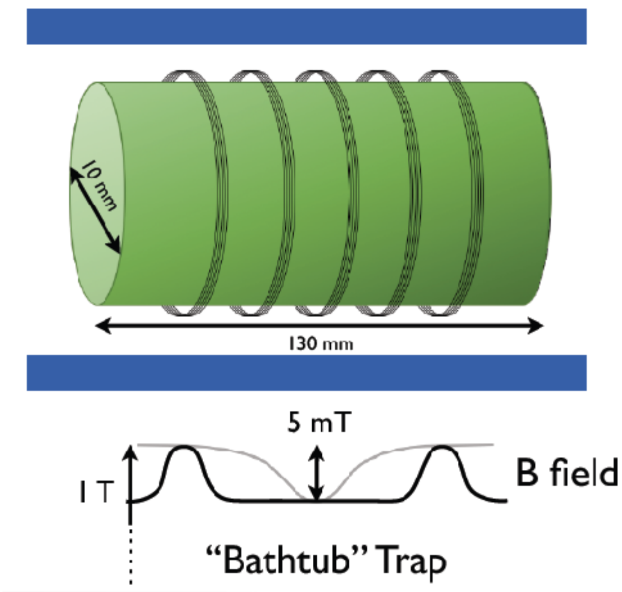
- Antenna array (interferometry) for cyclotron radiation detection

  since cyclotron radiation can leave the source and carries out the information of the β-electron energy

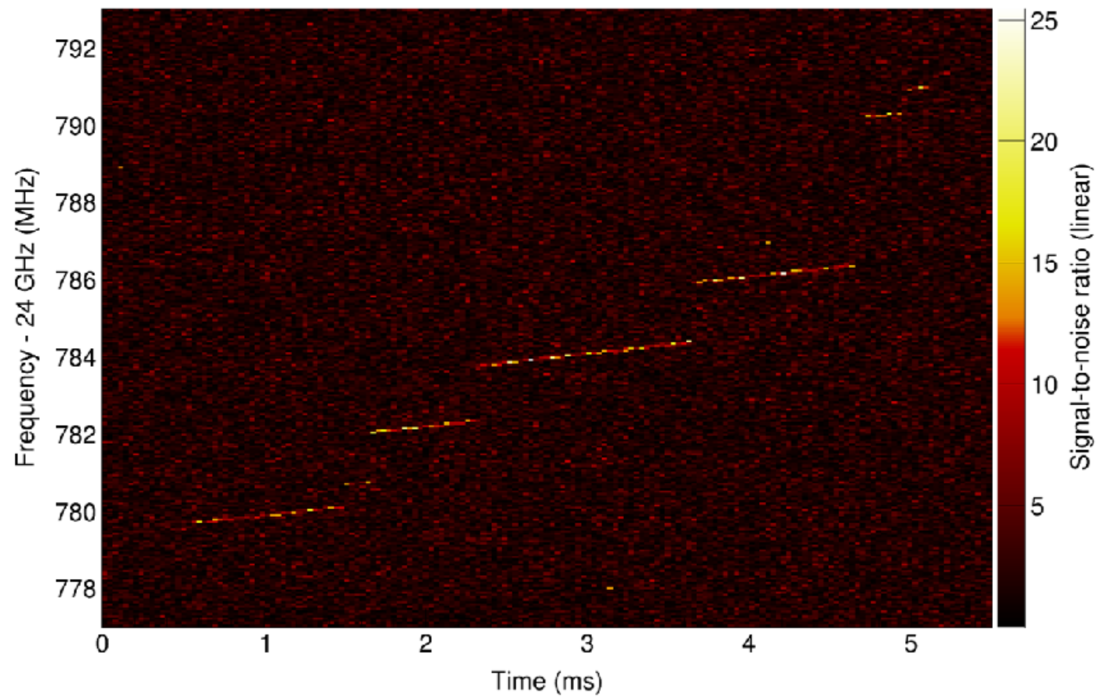


Project 8's phase 1: detection single electrons from ^{83m}Kr



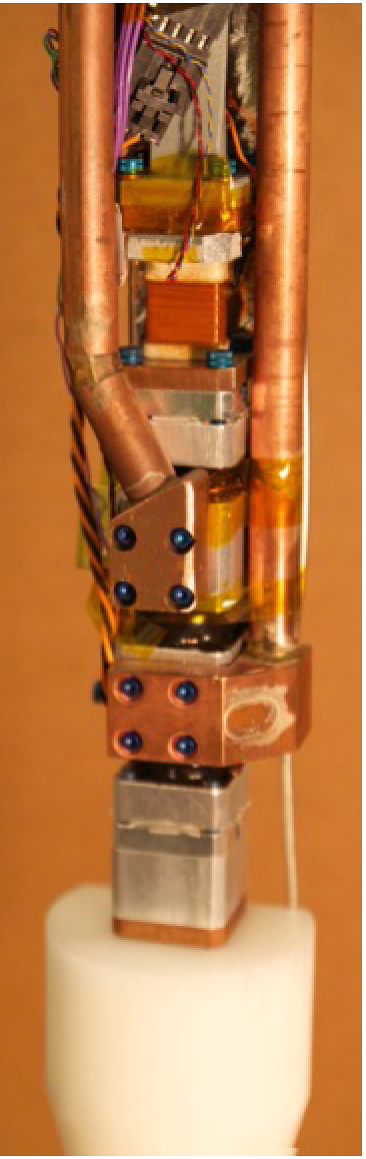


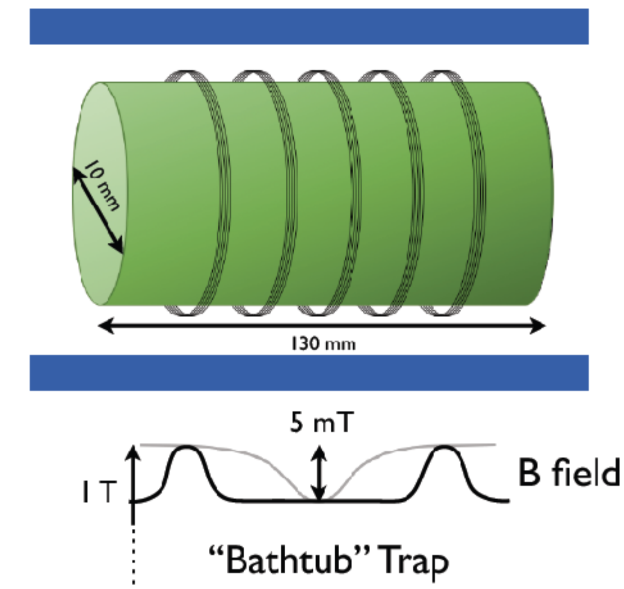
D. M. Asner et al., Phys. Rev. Lett. 114, 162501



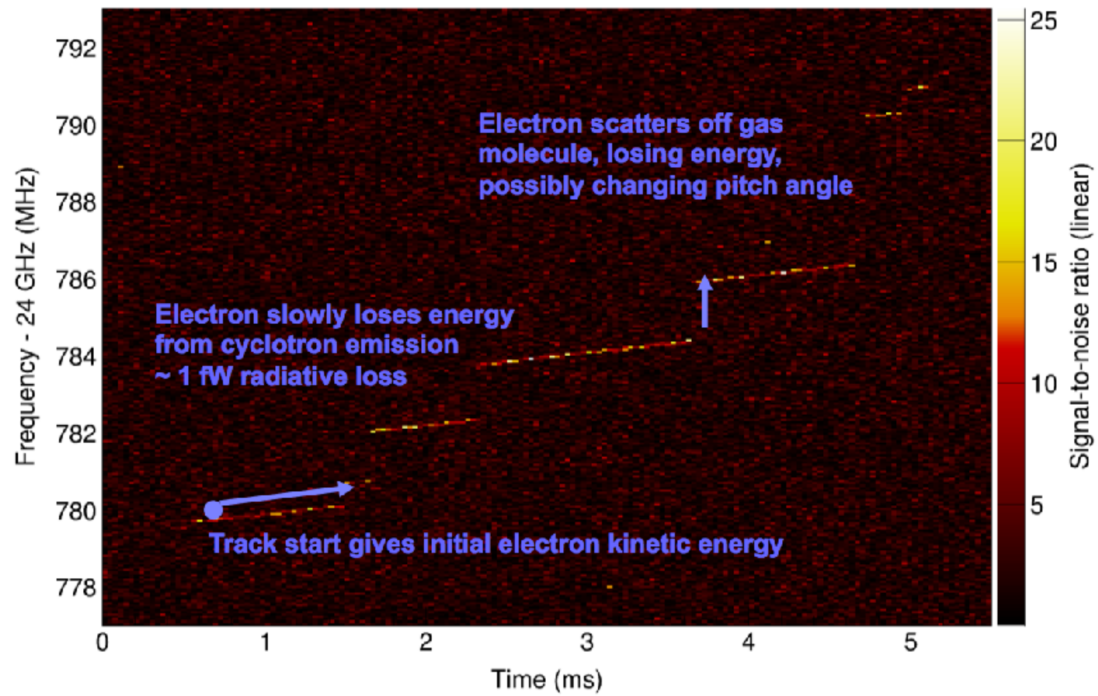
courtesy J. Formaggio, RGH Robertson

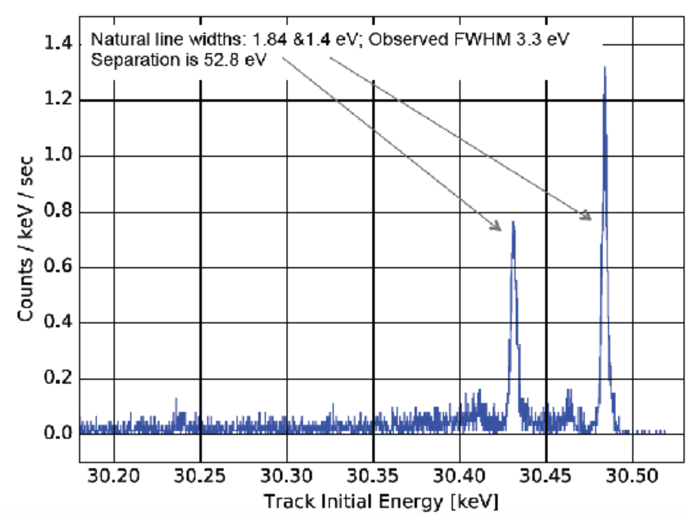
Project 8's phase 1: detection single electrons from ^{83m}Kr





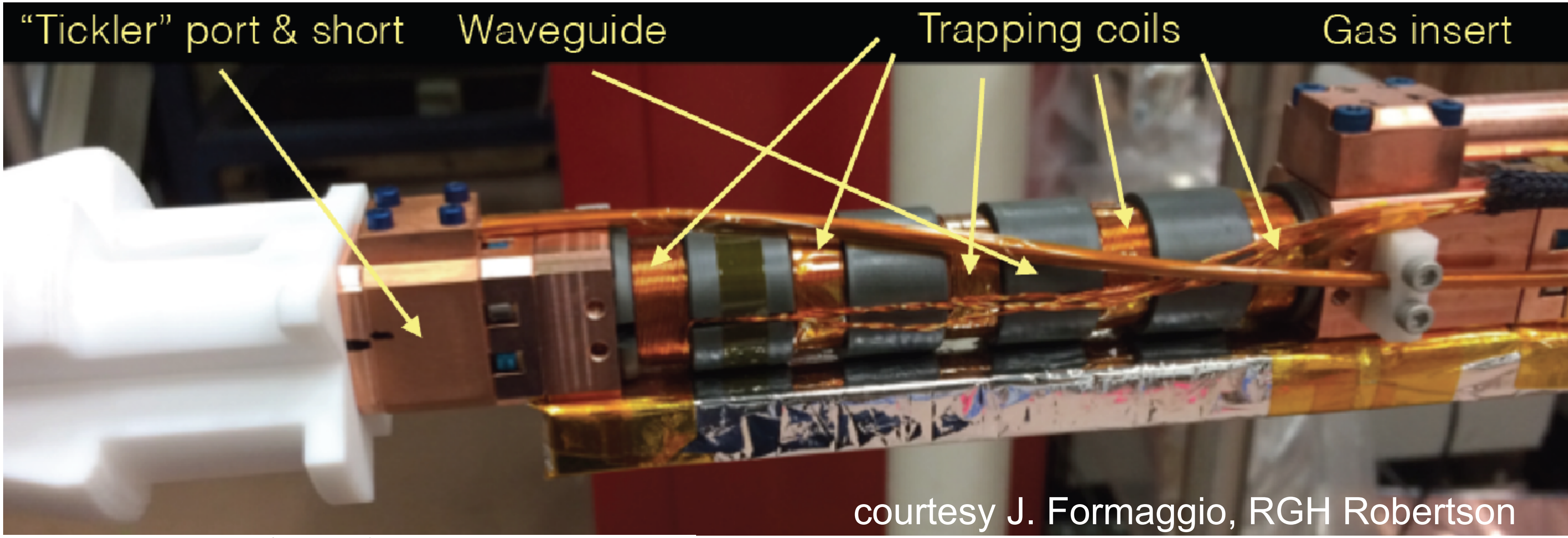
D. M. Asner et al., Phys. Rev. Lett. 114, 162501

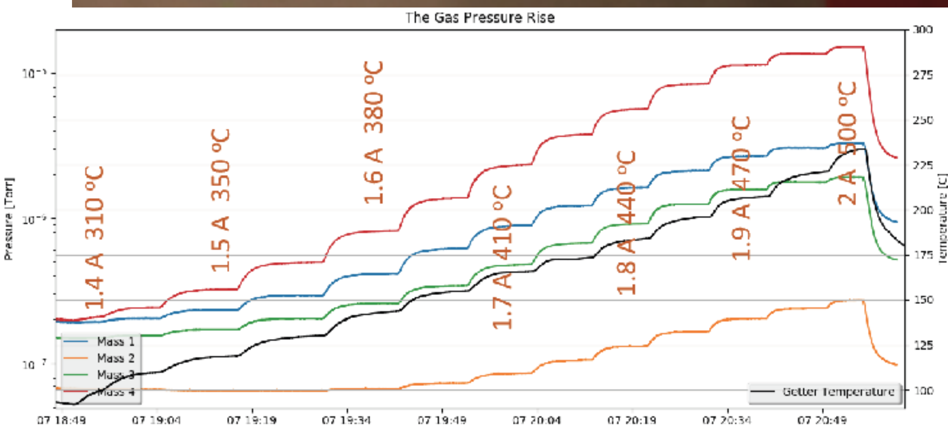




courtesy J. Formaggio, RGH Robertson

Project 8's phase 2: Measure tritium beta spectrum





first tests with deuterium loading

First detection of single electrons successfull
– tritium spectroscopy starting in 2017/18
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?

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
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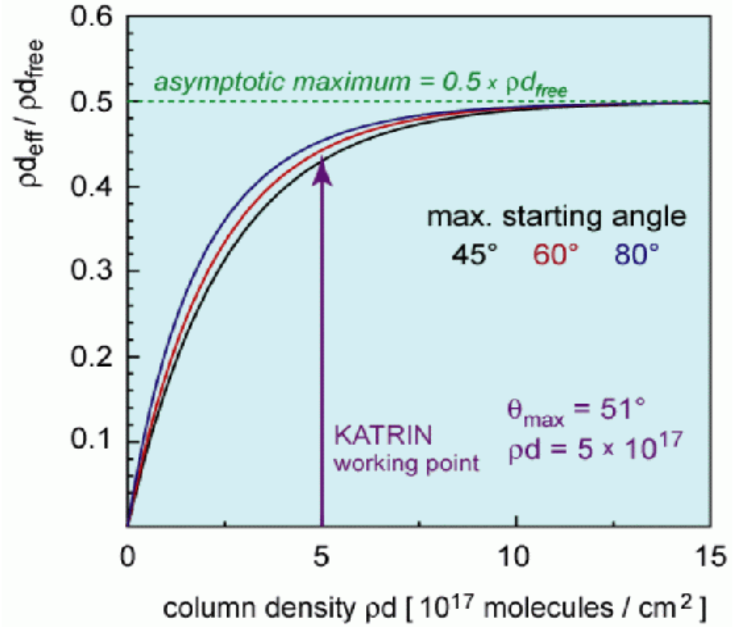

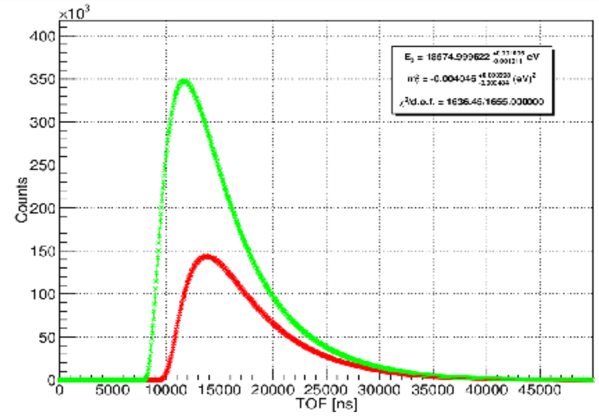

Possible ways out:

a) source inside detector (compare to 0νββ)
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 very 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 early 2018, 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 2017/2018