The KATRIN experiment and next-generation tritium β-decay experiments for keV-scale sterile neutrinos

20th Paris Chalonge de Vega Colloquium 2016, Observatoire de Paris

Christian Weinheimer

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

- Introduction
- The KArlsruhe TRItium Neutrino experiment KATRIN
- Beyond KATRIN and TOF@KATRIN
- Sterile neutrino searches with KATRIN
- Conclusions

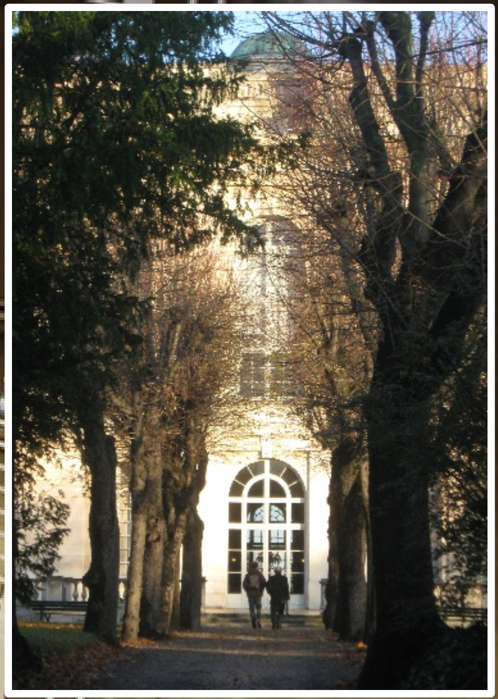
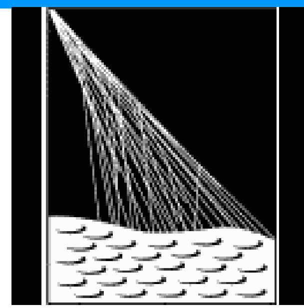


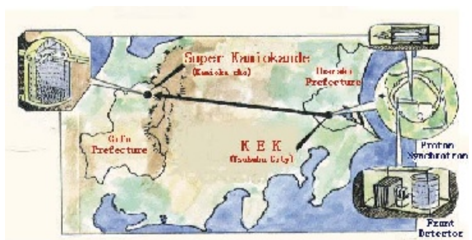
Photo: M. Zacher

Positive results from ν oscillation experiments

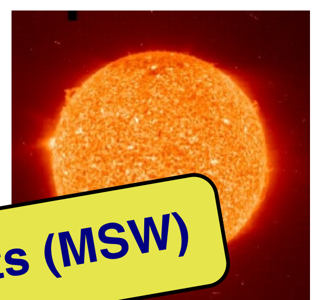
atmospheric neutrinos
(Kamiokande, Super-Kamiokande, ...)



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

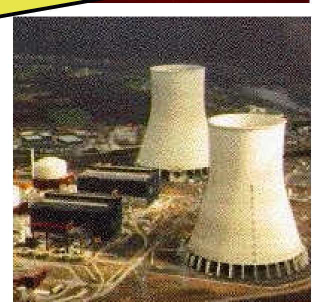


solar neutrinos
(Homestake, Gallex, Sage, Super-Kamiokande, SNO, Borexino)



Matter effects (MSW)

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



⇒ non-trivial ν-mixing

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

with:

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

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

$0.018 < \sin^2(\theta_{13}) < 0.030$ 8.9°

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

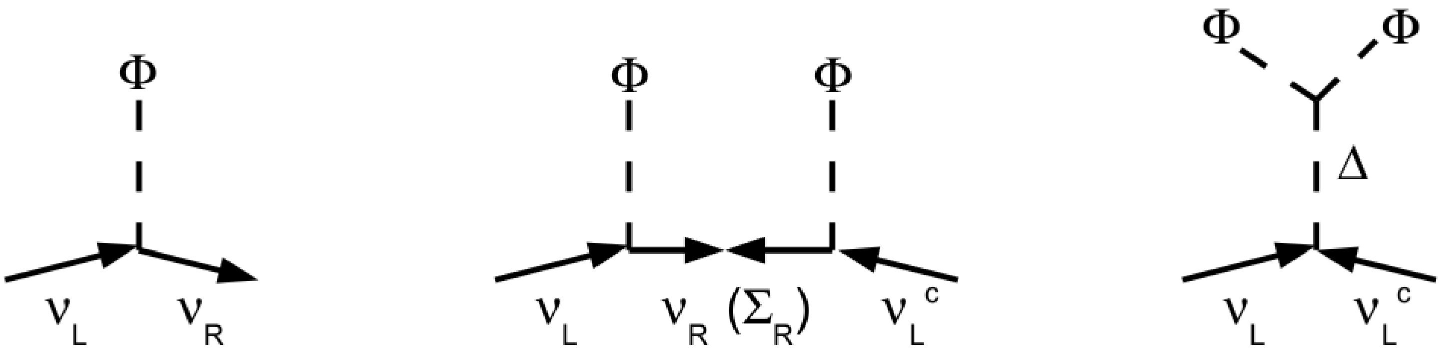
$2.2\ 10^{-3}\ \text{eV}^2 < |\Delta m_{13}^2| < 2.6\ 10^{-3}\ \text{eV}^2$

⇒ $m(\nu_j) \neq 0$, but unknown !

→ direct m(ν) & 0νββ &searches, cosmology

Need for the absolute ν mass determination

Non-zero neutrino masses go beyond the usual Yukawa coupling to the Higgs → Beyond the SM physics



degenerated masses

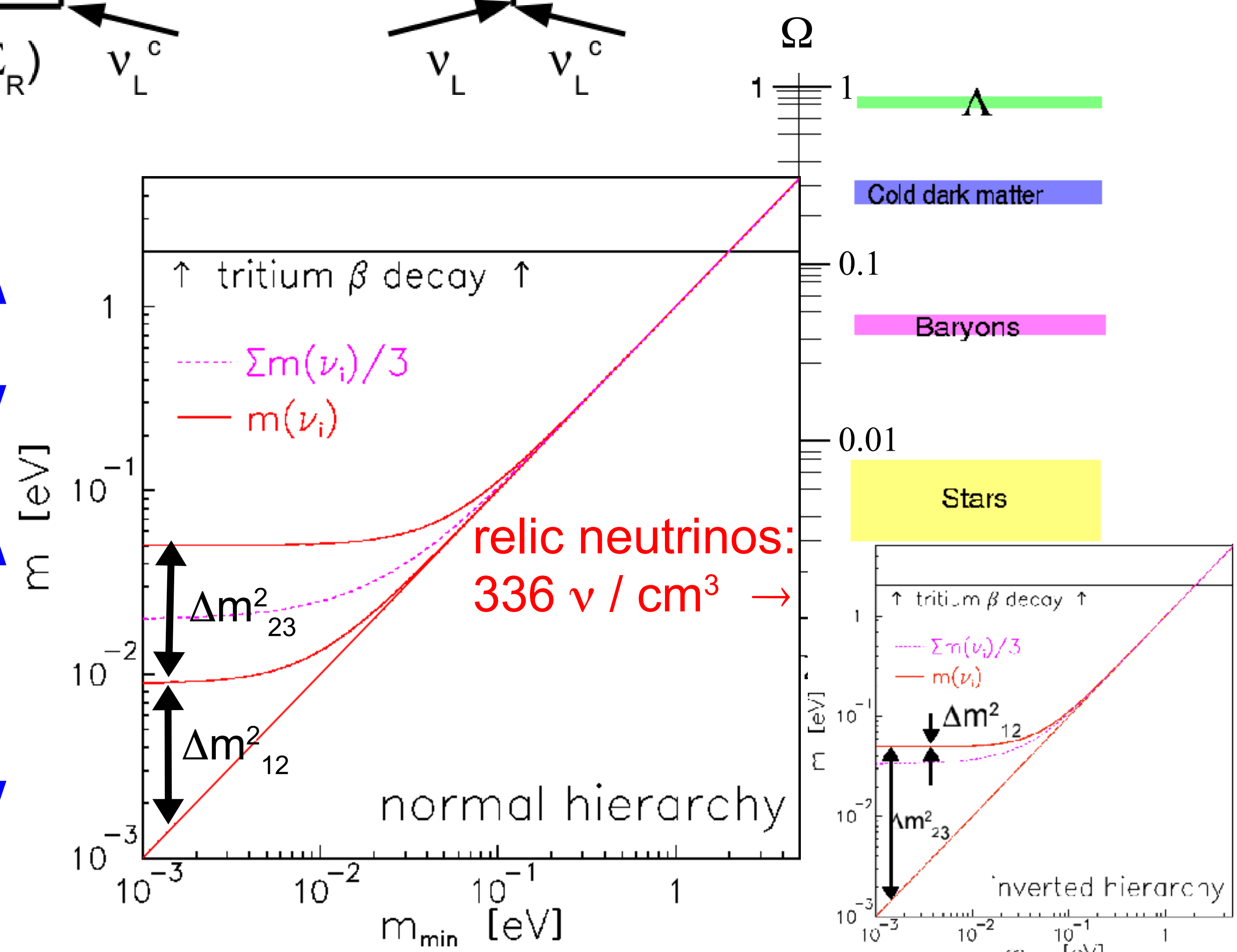
cosmological relevant

e.g. seesaw mechanism type 2

hierarchical masses

e.g. seesaw mechanism type 1

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



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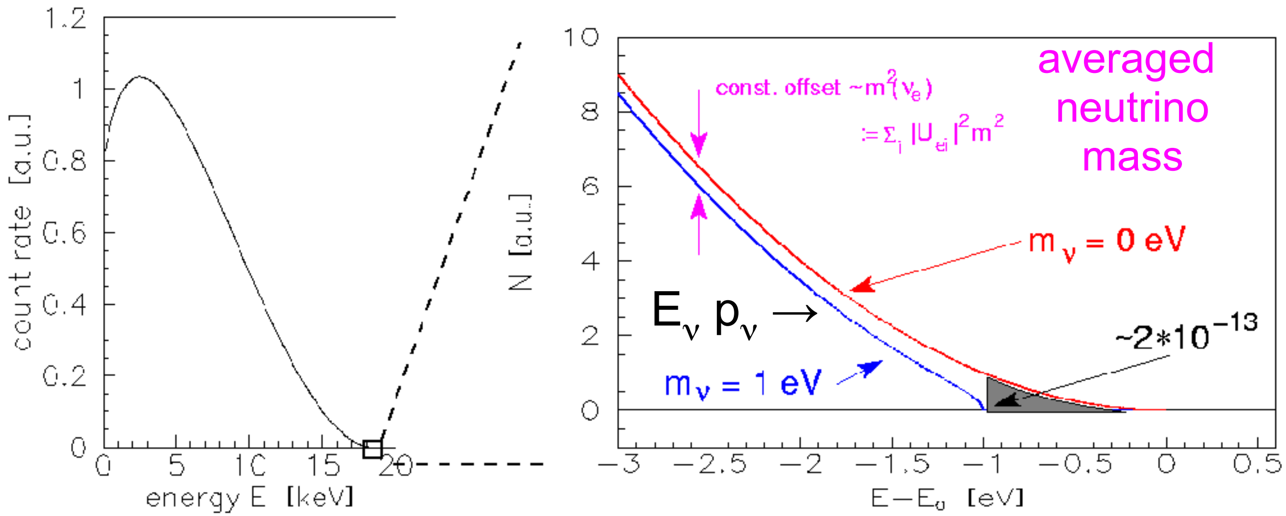
Direct determination of $m(\nu_e)$ from β decay

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

phase space: p_e (p), E_e (E_{tot}), E_ν (E_0-E_e), p_ν ($\Sigma |U_{ei}|^2 \sqrt{(E_0-E_e)^2 - m(\nu_i)^2}$)

with "electron neutrino mass": $m(\nu_e)^2 := \Sigma |U_{ei}|^2\ m(\nu_i)^2$

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



m(ν) < 2 eV (Mainz, Troitsk)

Recent review:
G. Drexlin, V. Hannen, S. Mertens, C. Weinheimer, Adv. High Energy Phys., 2013 (2013) 293986

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)

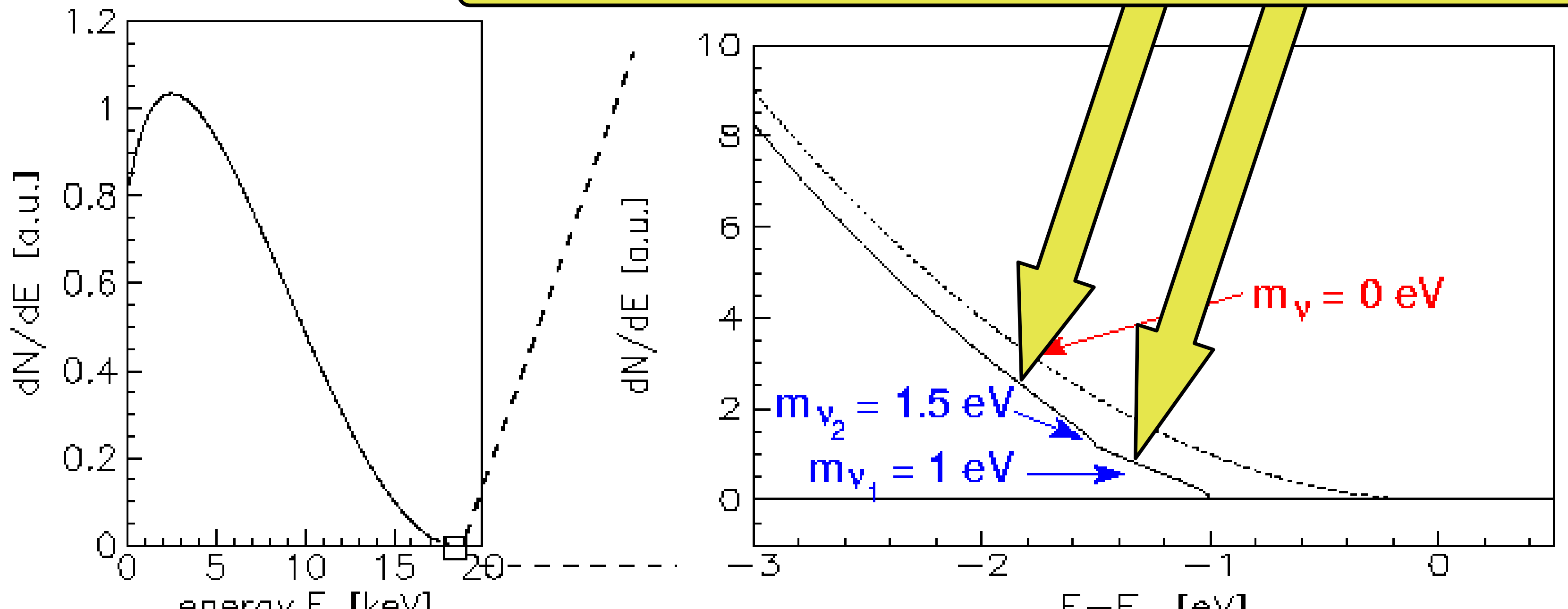
Direct determination of $m(\nu_e)$ from β decay

The neutrino mass eigenstates are observable as kinks in principle
→ amplitudes add incoherently

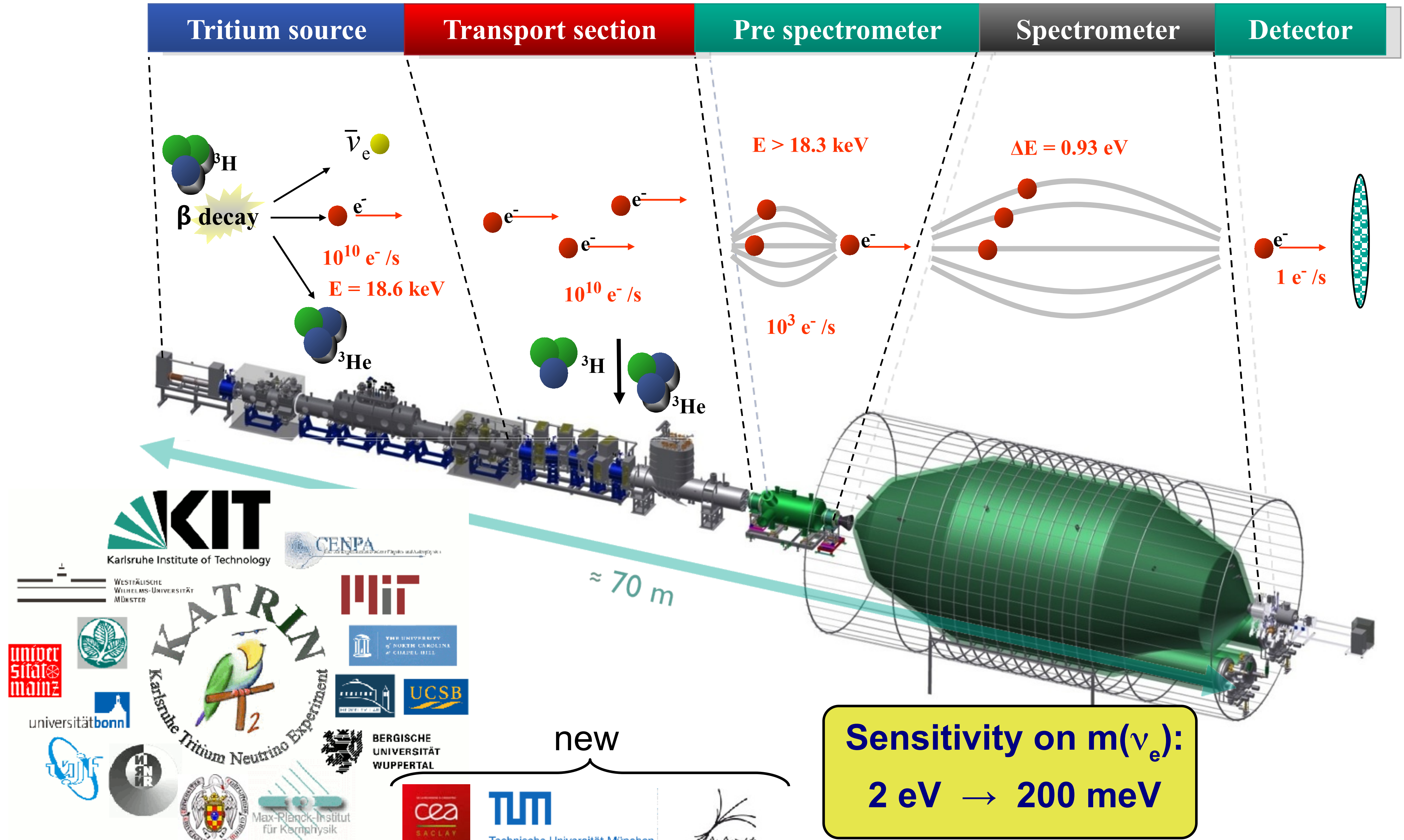
If the resolution is better than the mass splitting then the various mass eigenstate appear

If mass eigenstates are not resolved:

$$m^2(\nu_e) = \Sigma |U_{ei}^2| m^2(\nu_i)$$



The Karlsruhe Tritium Neutrino Experiment KATRIN - overview

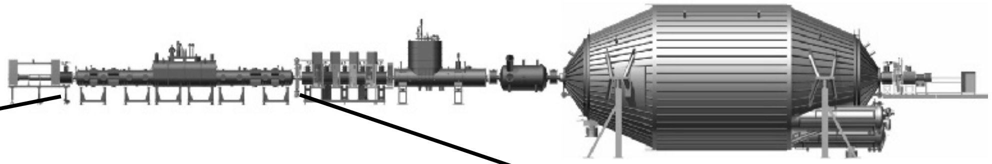


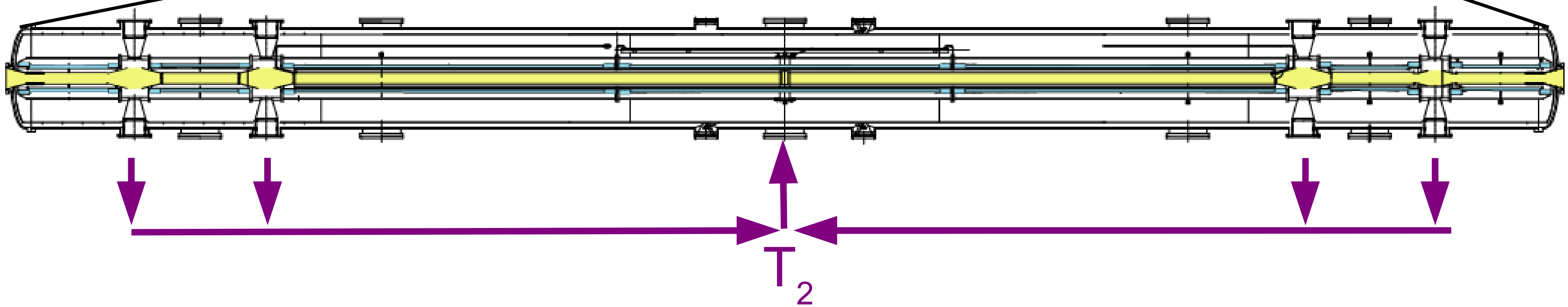
Sensitivity on m(ν_e):

2 eV → 200 meV

Molecular Windowless Gaseous Tritium Source WGTS

per mill stability source strength request:
$dN/dt \sim f_T \cdot N / \tau \sim n = f_T \cdot p \cdot V / R \cdot T$
tritium fraction f_T & ideal gas law

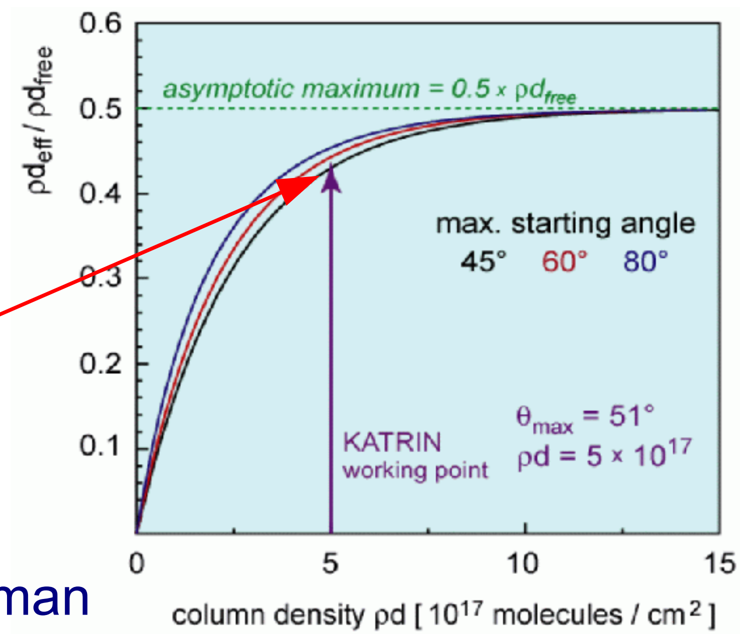




WGTS: tube in long superconducting solenoids
⊘ 9cm, length: 10m, T = 30 K

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

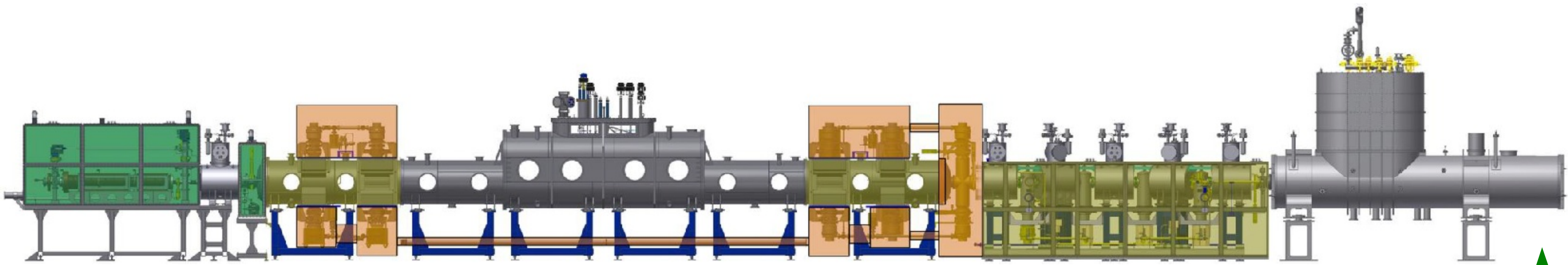
Transport and differential & cryo pumping sections

Monitoring & calibration system

Molecular windowless gaseous tritium source

Differential pumping

Cryogenic pumping with Argon snow at LHe temperatures



T_2-injection 1.8 mbar l/s (STP) = $1.7 \cdot 10^{11}$ Bq/s = 40 g/d

FT-ICR Penning traps to measure ions from WGTS

$\approx 10^{-7}$ mbar l/s

$< 2.5 \cdot 10^{-14}$ mbar l/s

⇒ adiabatic electron guiding & T_2 reduction factor of $\sim 10^{14}$

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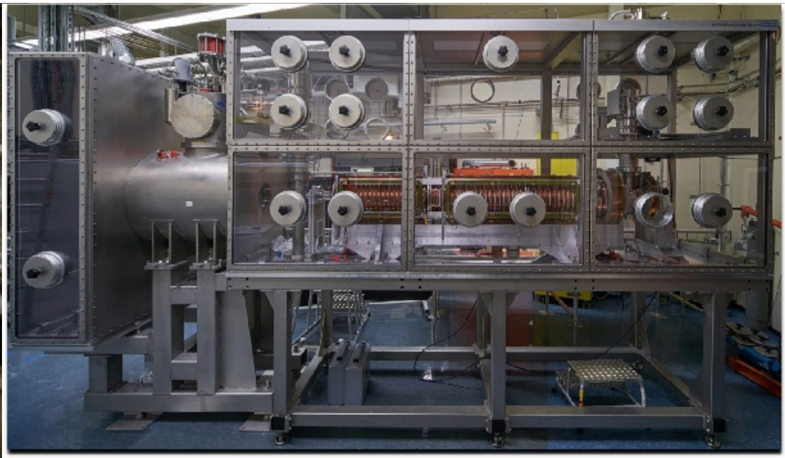
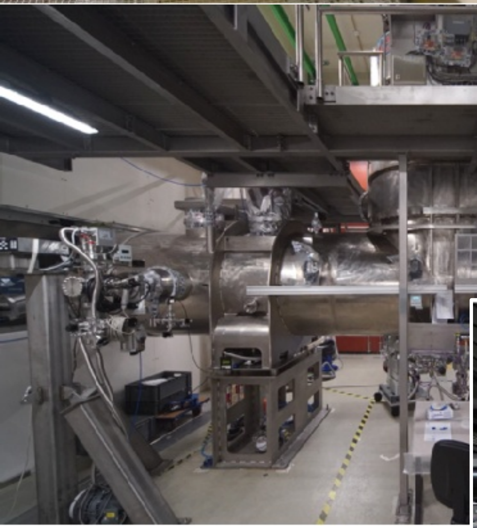
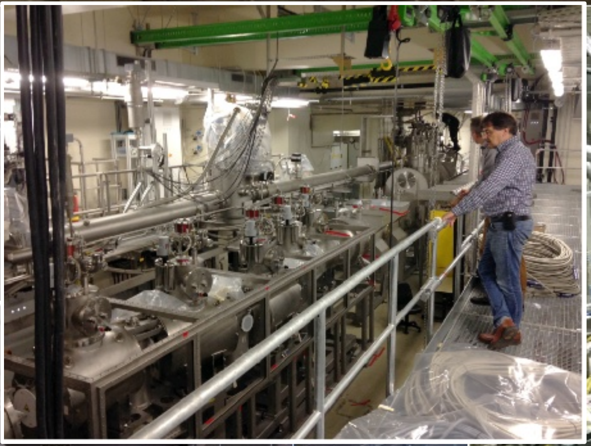
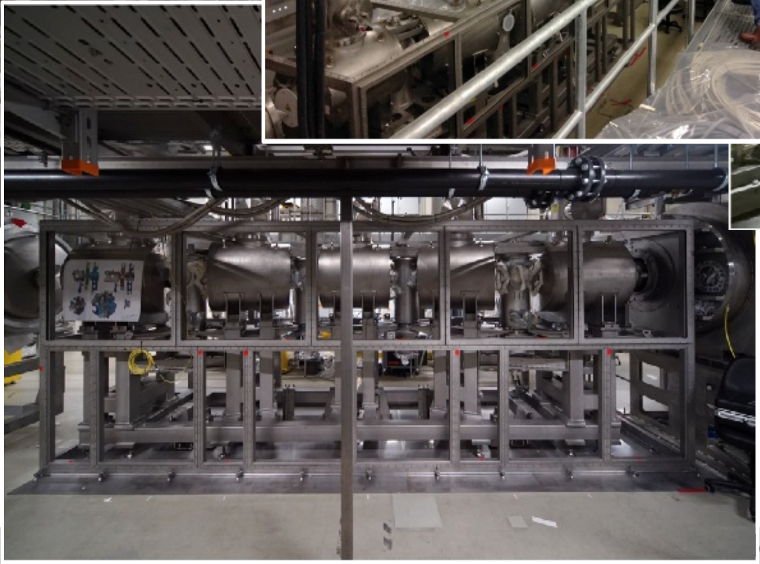
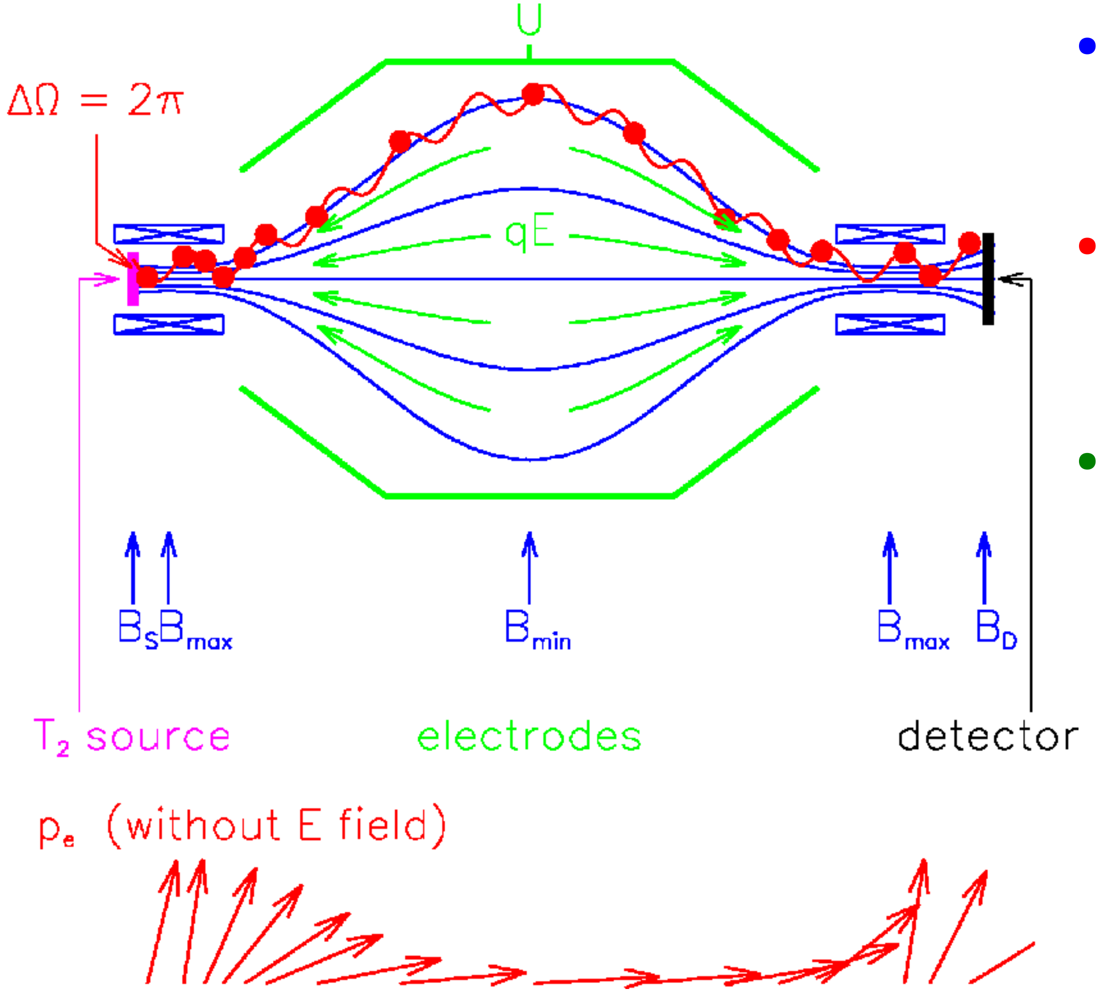
The tritium source and transport section is really there !

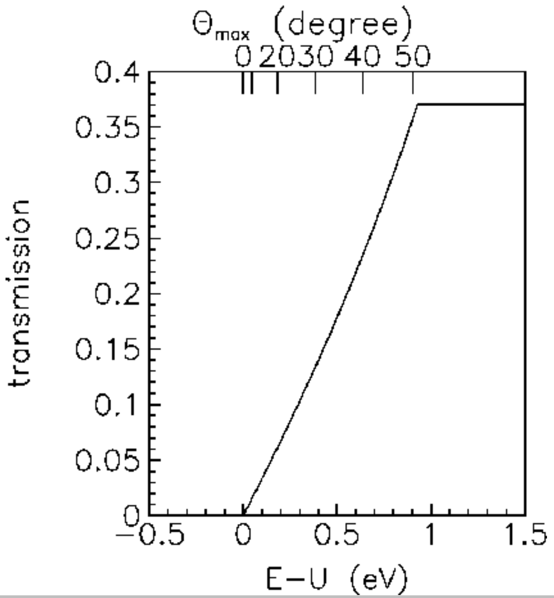


Full commissioning under way start data taking with tritium in 2017

The classical way: Tritium β-spectroscopy with a MAC-E-Filter



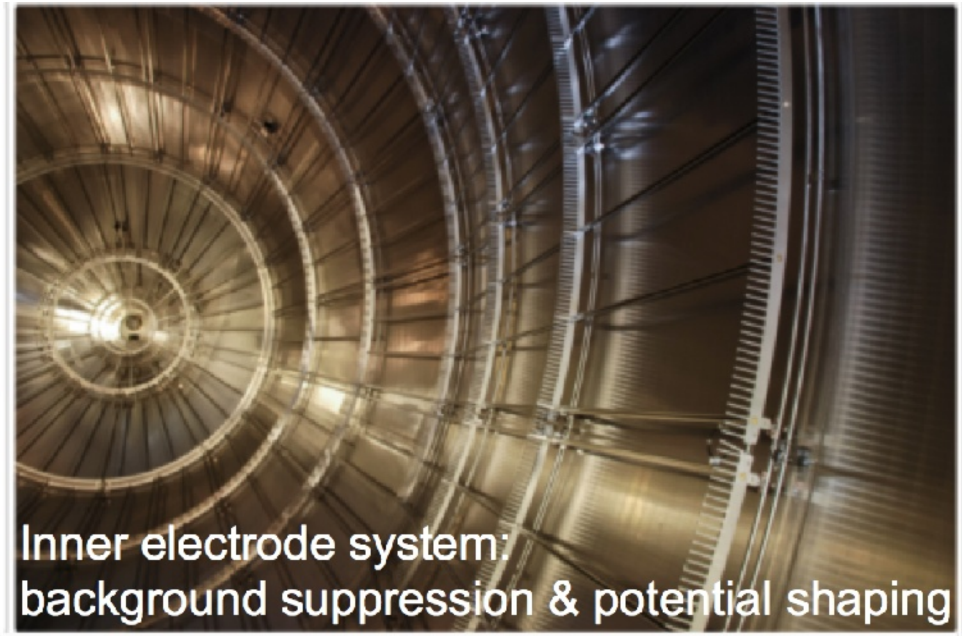
- Two supercond. solenoids compose magnetic guiding field
- adiabatic transformation:
  $\mu = E_\perp / B = \text{const.}$
  ⇒ parallel e^- beam
- Energy analysis by electrostat. retarding field
  $\Delta E = E \cdot B_{min}/B_{max}$
  $= 0.93$ eV (KATRIN)

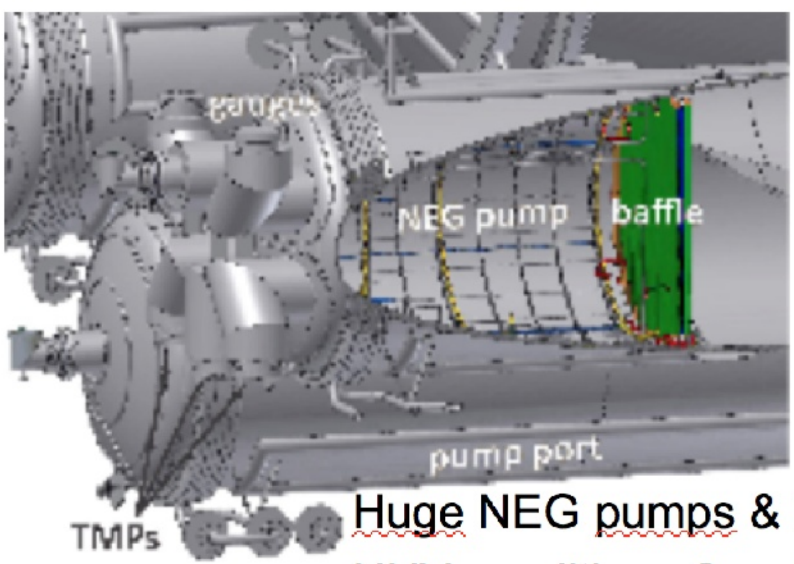


⇒ sharp integrating transmission function without tails →

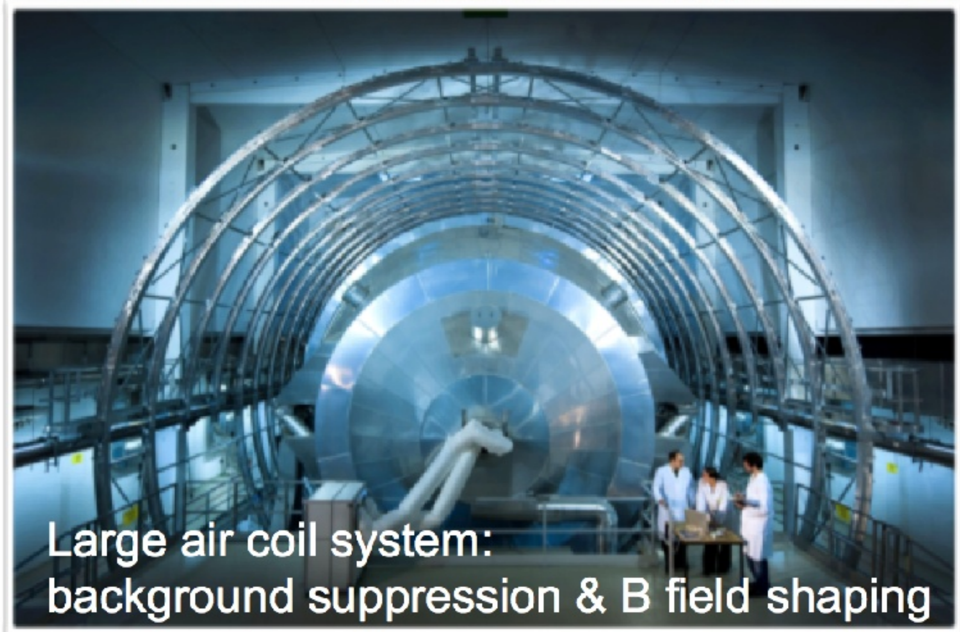
Magnetic Adiabatic Collimation + Electrostatic Filter
(A. Picard et al., Nucl. Instr. Meth. 63 (1992) 345)

KATRIN main spectrometer

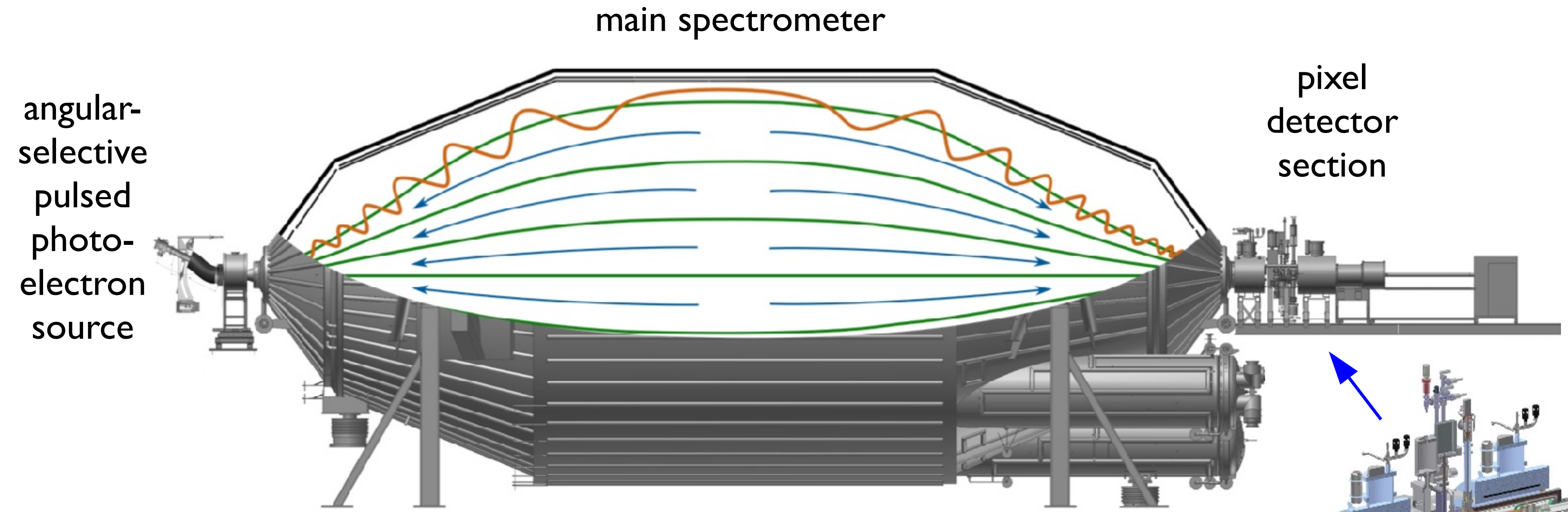


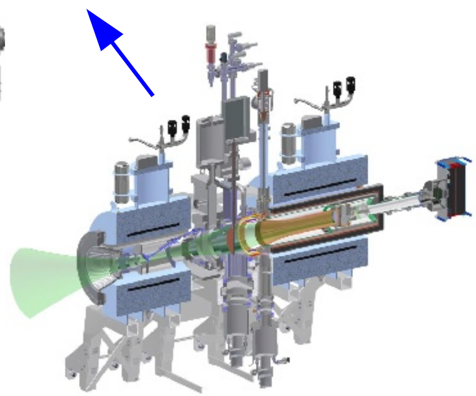


Huge NEG pumps & LN_2 baffles:
UHV conditions & radon trapping



Main spectrometer and detector commissioning – objectives





Primary objectives:

- test of hardware, software and slow control components
- provide ultra high vacuum conditions at the $p \approx 10^{-11}$ mbar level
- detailed understanding of the transmission properties of this MAC-E-Filter ($E = 18.6$ keV with $\Delta E = 0.93$ eV resolution) and compare to simulation with Kasseiopeia
- detailed understanding and passive & active control of background processes

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

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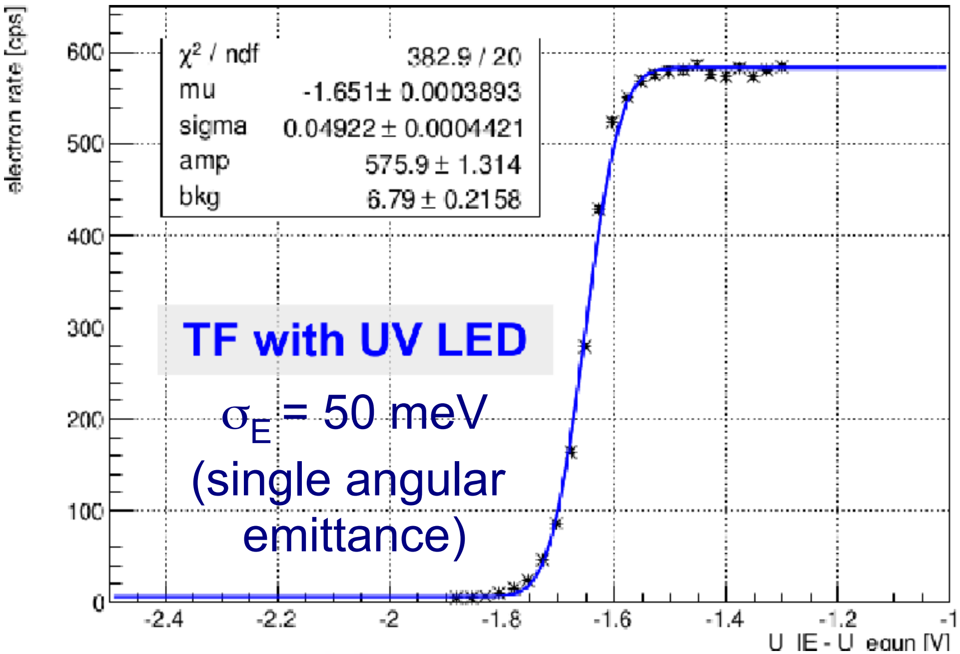
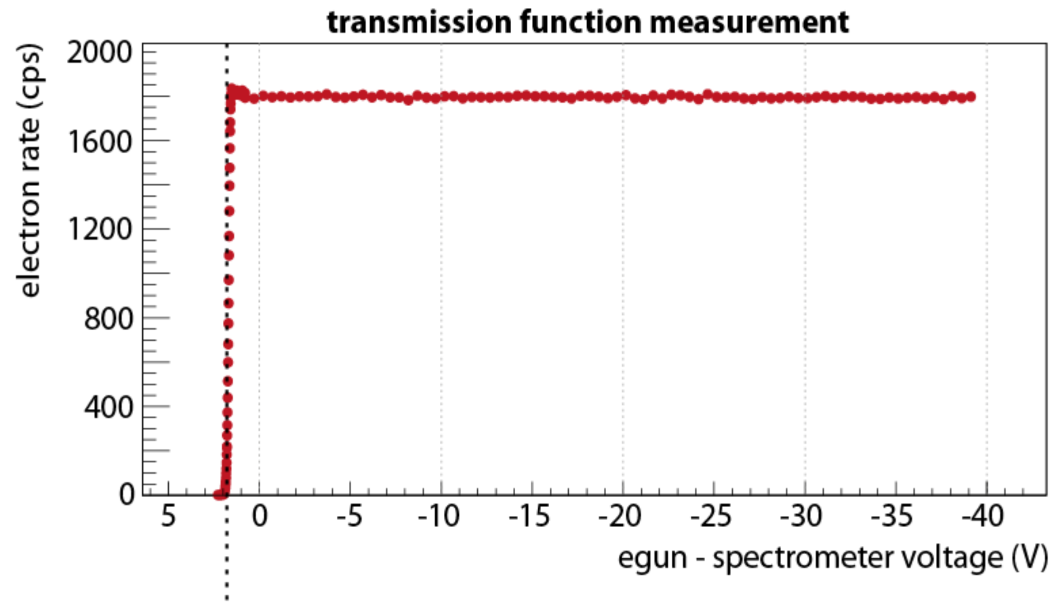
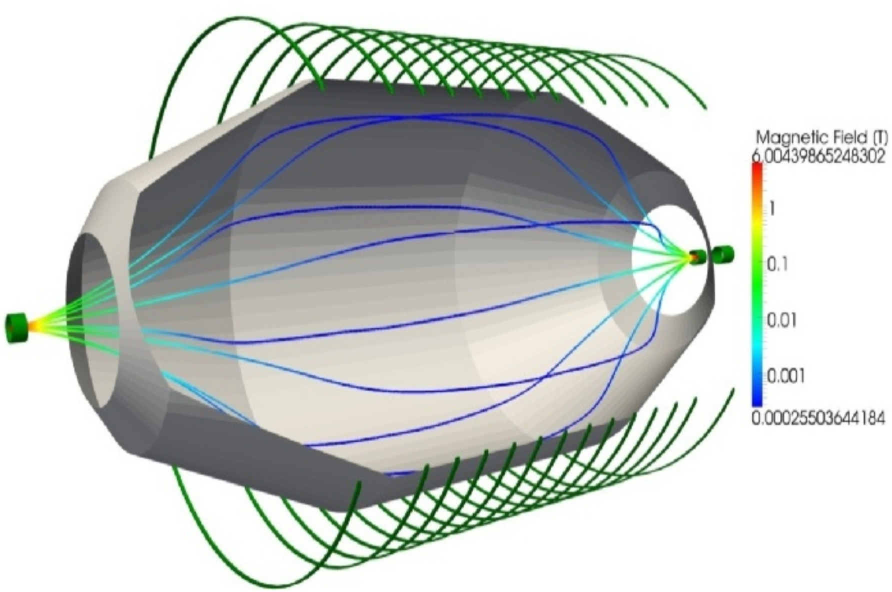
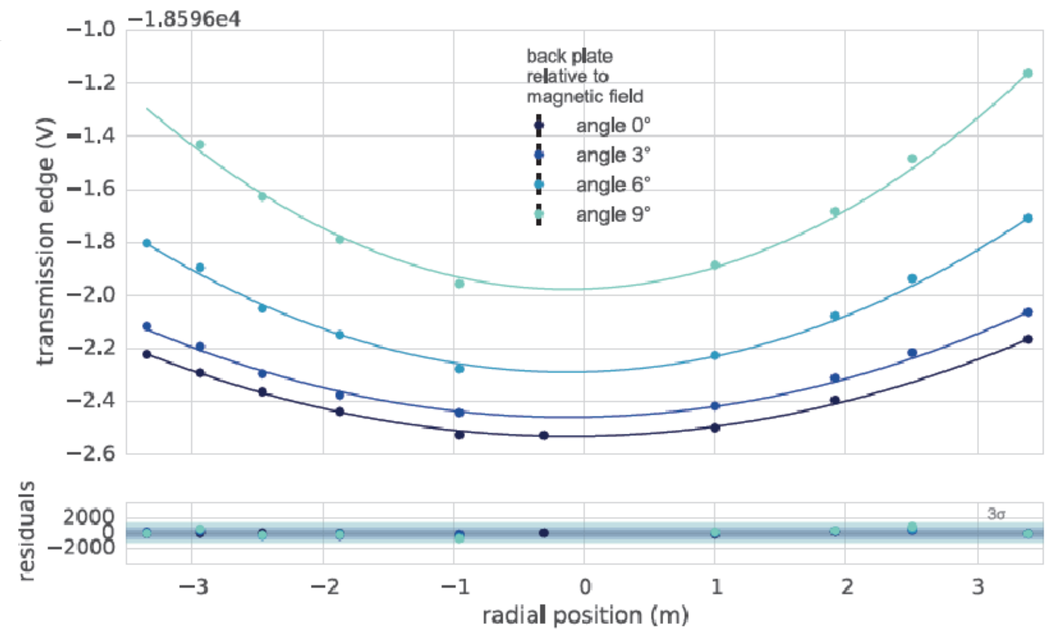
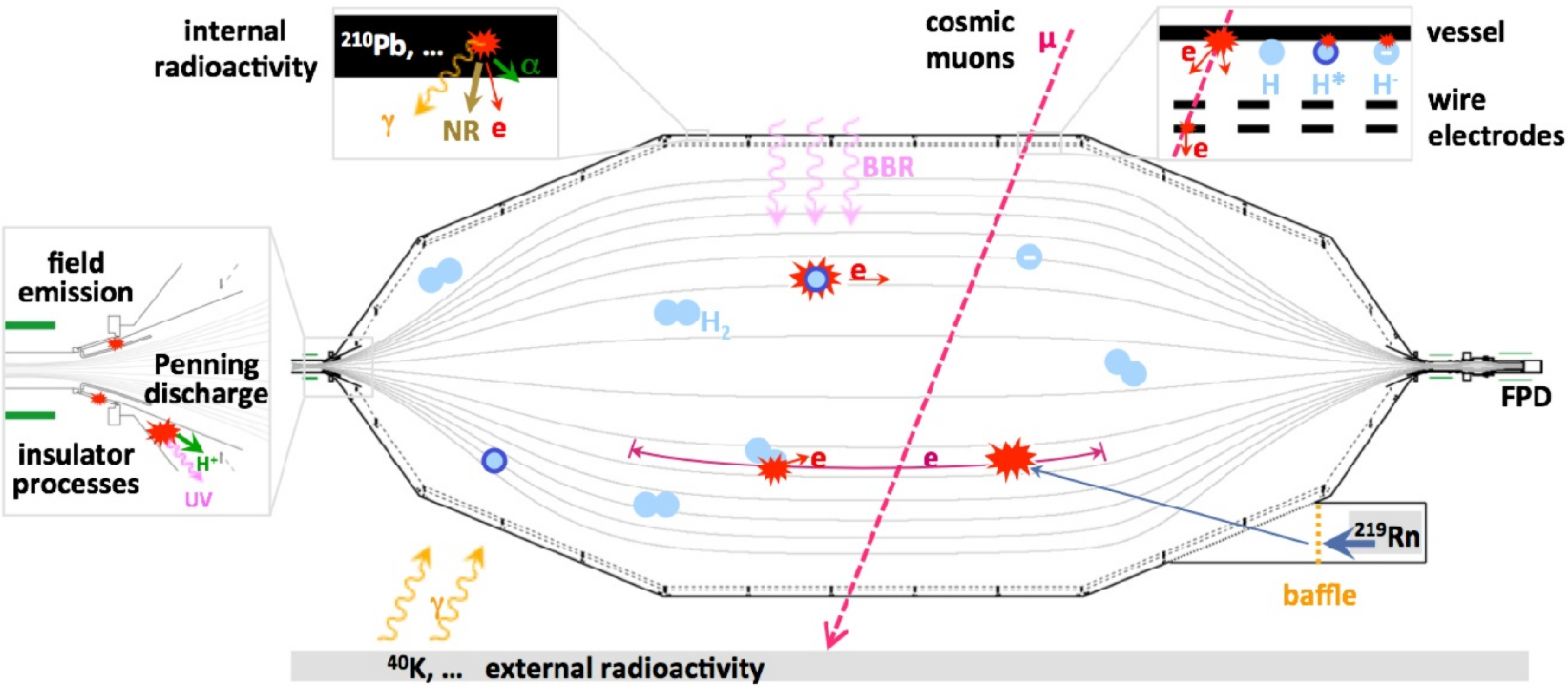








Possible background sources at KATRIN



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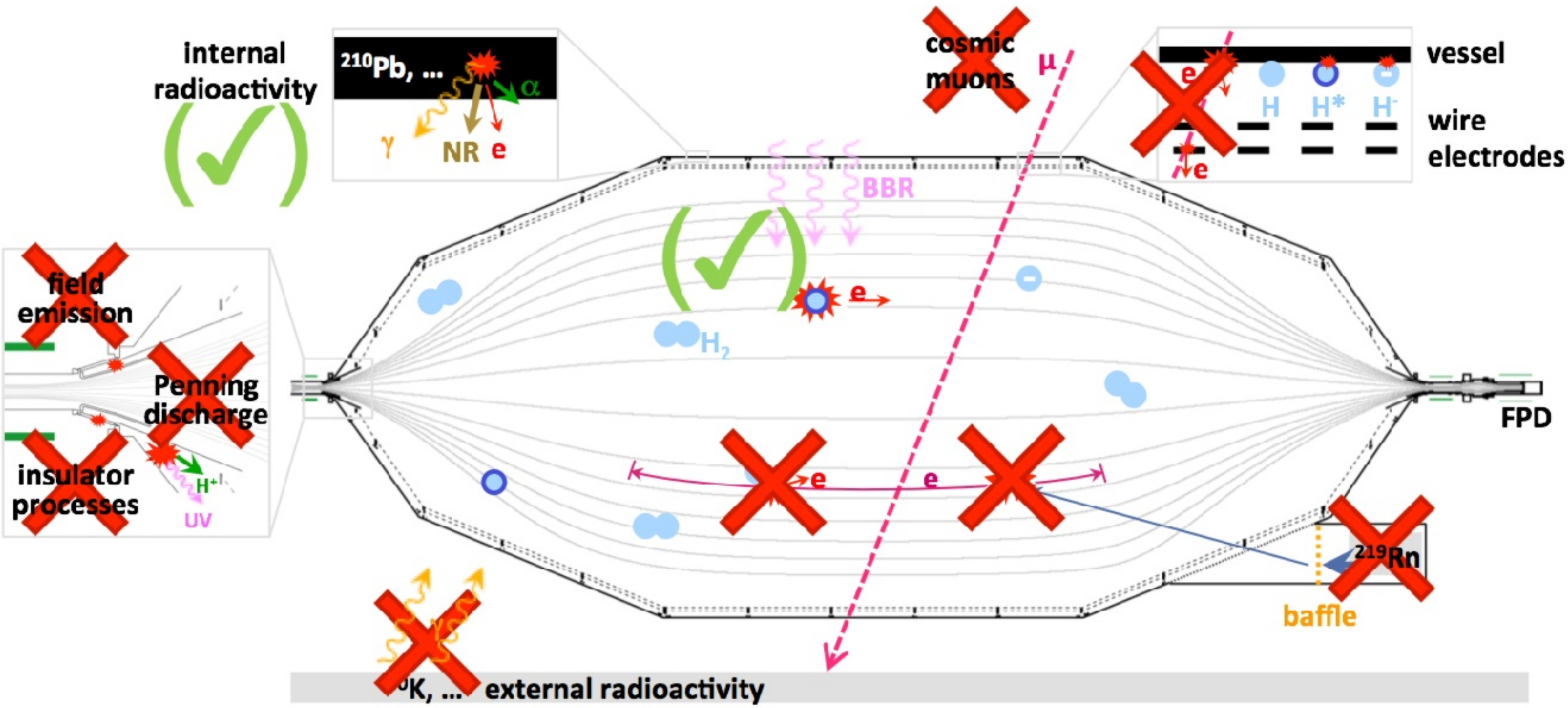
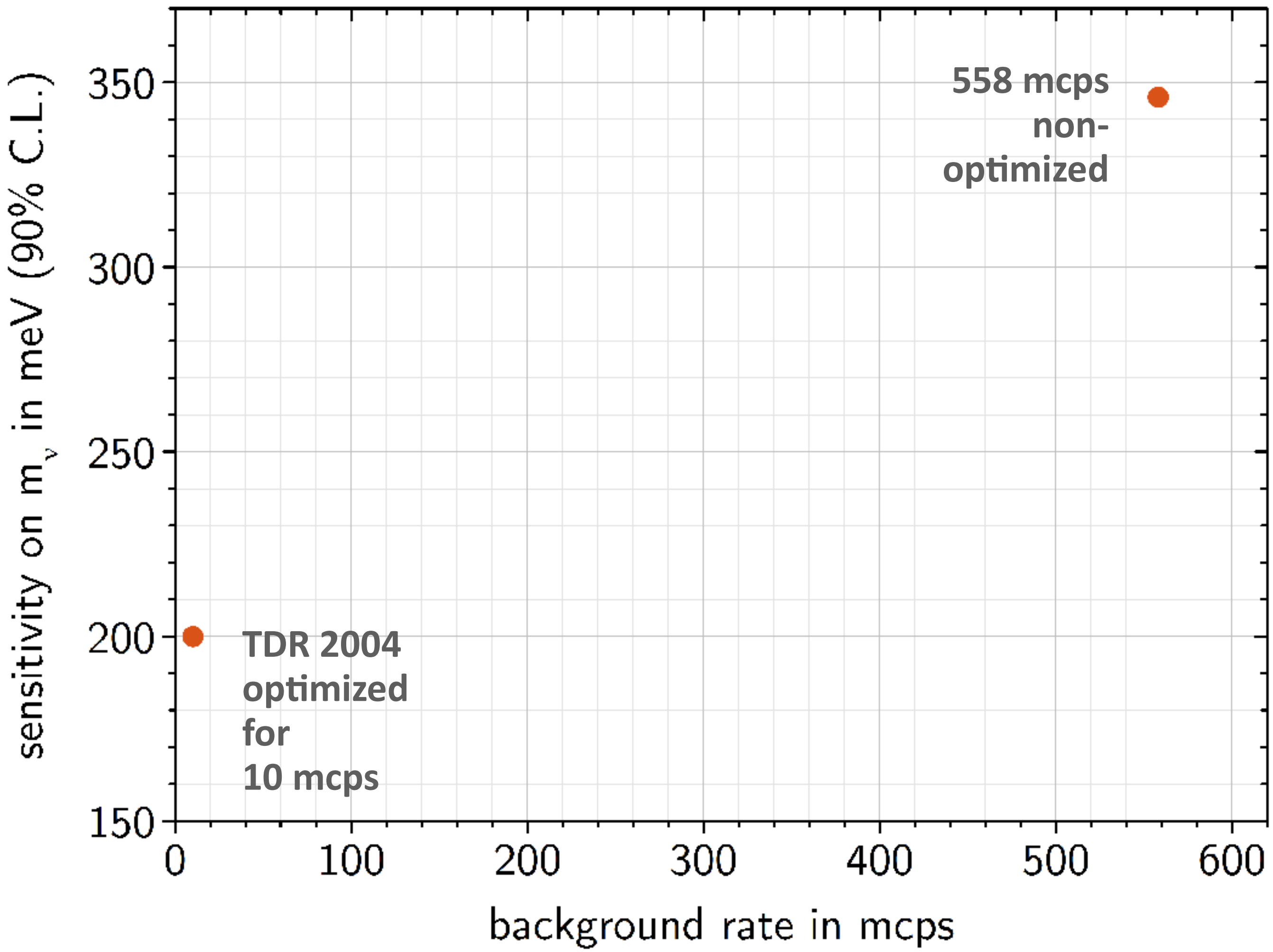
Background sources at KATRIN: detailed understanding, but ...



- 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

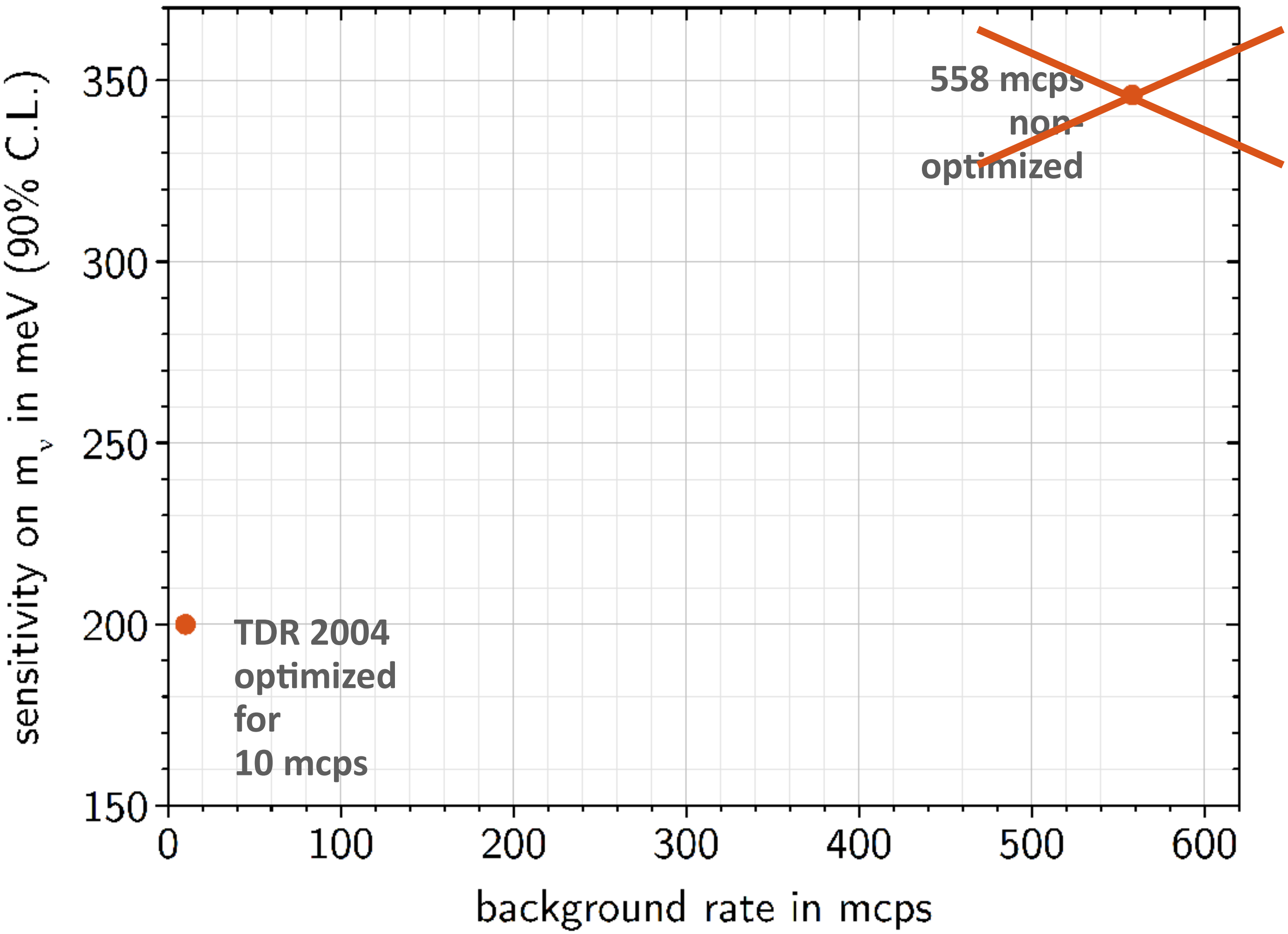
- 1 out of 8 remaining:
  caused by ^{210}Pb on spectrometer walls (neutral H* atoms ionised by black-body radiation in spectrometer)

Sensitivity & background rate



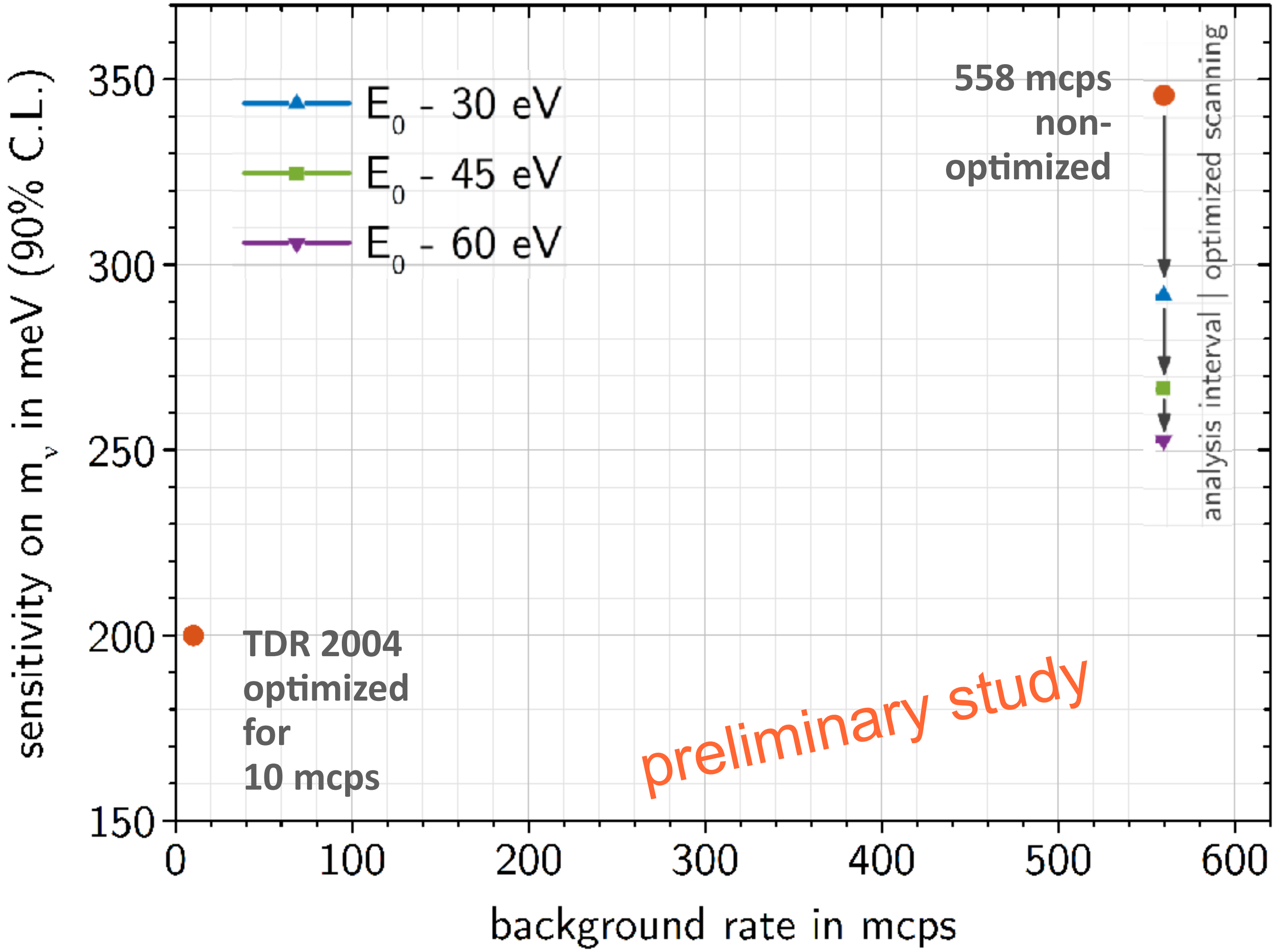
Sensitivity & background rate

- Further **background reduction measures** being studied
- In addition: **several mitigation strategies** currently under investigation:



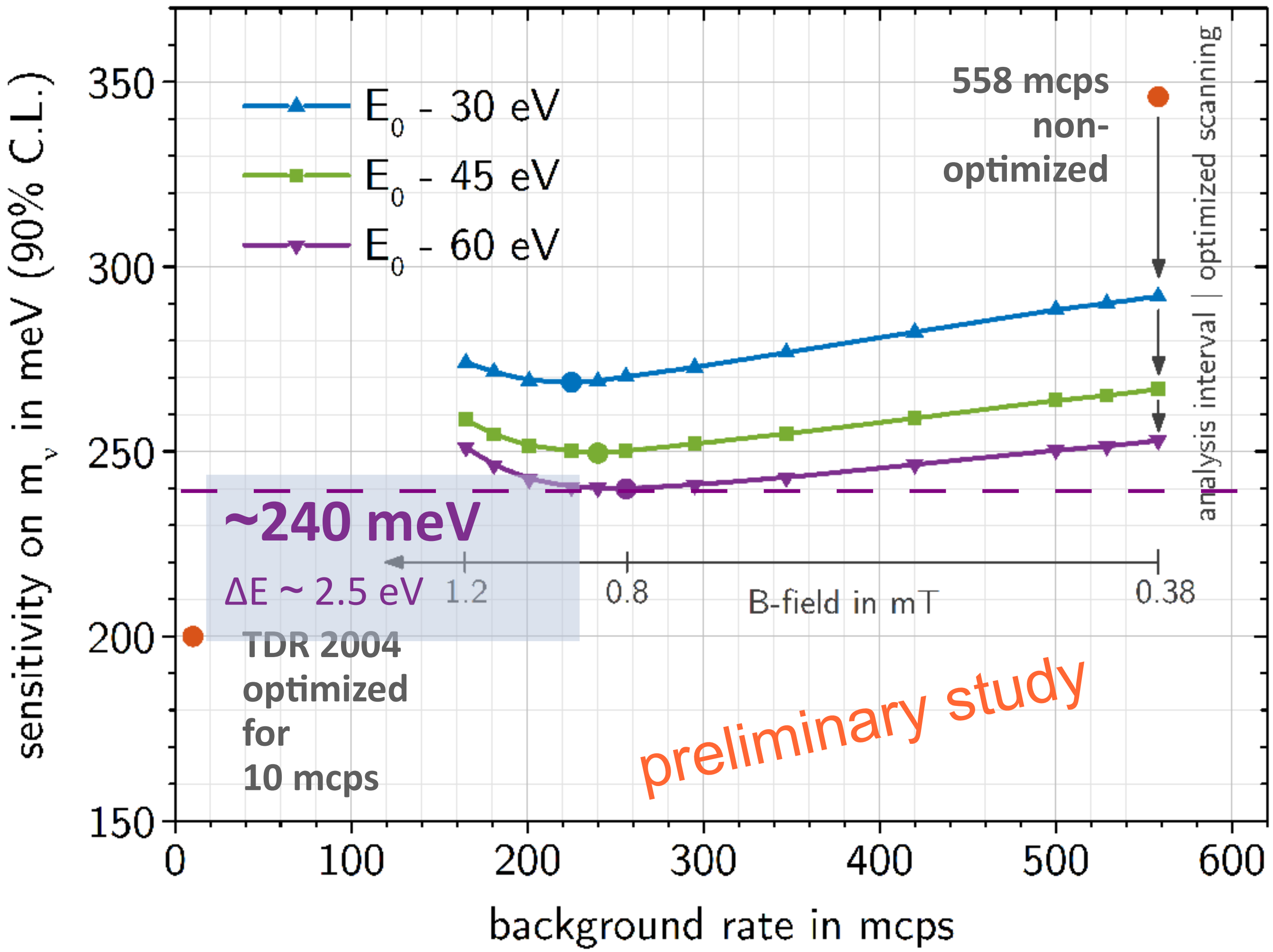
Sensitivity & background rate

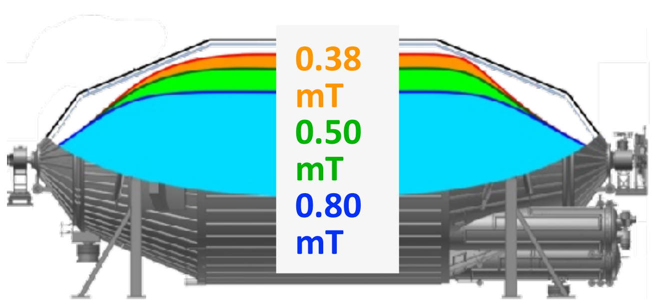
- Further **background reduction measures** being studied
- In addition: **several mitigation strategies** currently under investigation:
  - optimized scanning
  - range of spectral analysis



Sensitivity & background rate

- Further **background reduction measures** being studied
- In addition: **several mitigation strategies** currently under investigation:
  - optimized scanning
  - range of spectral analysis
  - flux tube compression by increasing B





KATRIN timeline

2016: Commissioning of pre and main spectrometer with detector SDS 3

Continue commissioning of KATRIN Source and Transport Section

Sending electrons through the 70m long beamline

2017: Ramping up Windowless Gaseous Tritium Source: D_2, $D_2(T_2)$, T_2

Commissioning of complete KATRIN system

First tritium data

First chance to look for keV sterile neutrinos

Regular neutrino mass measurements

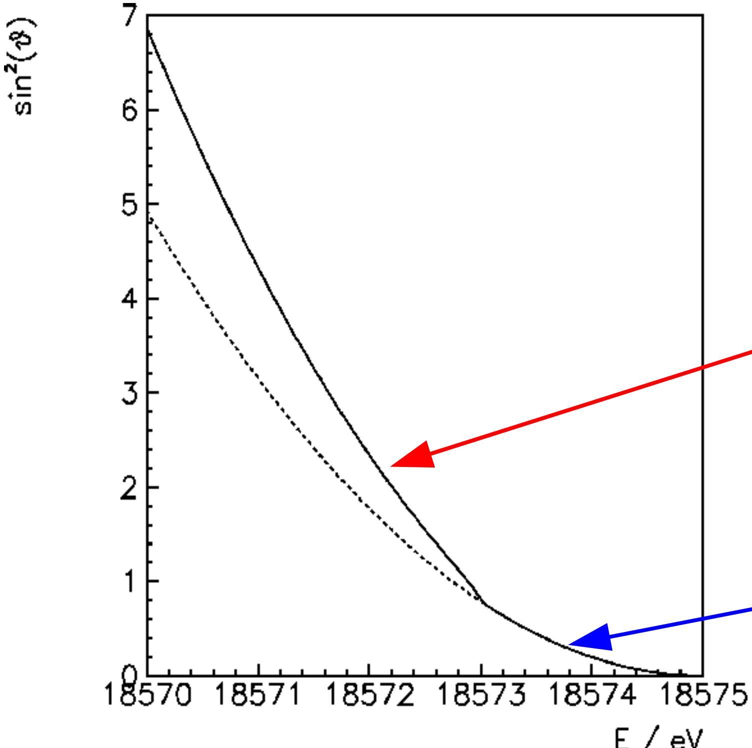
Influence of a 4th sterile neutrino near the endpoint E_0

Weak mixing of a 4th sterile neutrino state:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_{sterile} \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

If **m(ν_1), m(ν_2), m(ν_3)** are similarly light:

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



e.g.

m(ν_4) = 2 eV

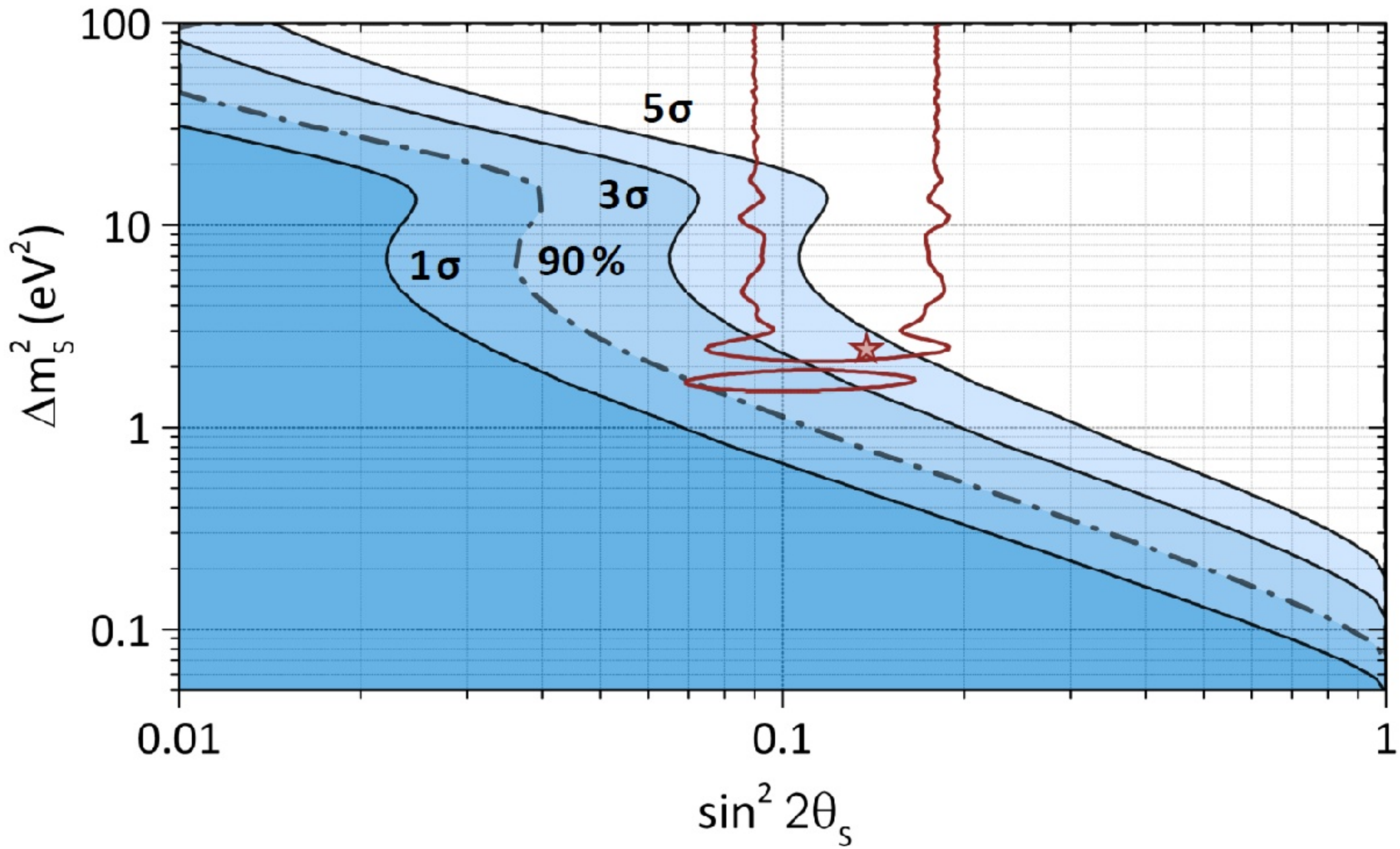
$\sin^2(\theta)$ = 0.3

e.g.

m($\nu_{1,2,3}$) » 0 eV

$\cos^2(\theta)$ = 0.7

Sensivity on sterile eV neutrinos



M.Kleesiek, PhD thesis, KIT (2014)

see also:

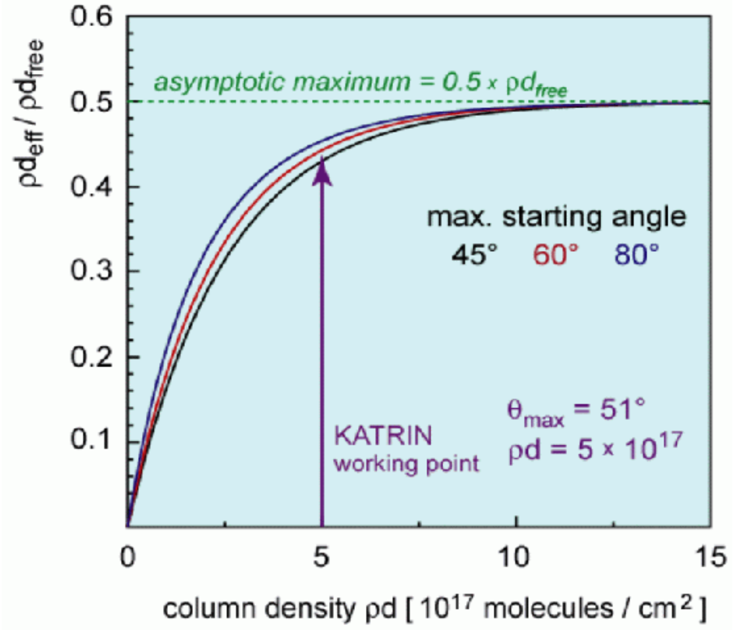
J. A. Formaggio, J. Barret, PLB 706 (2011) 68

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

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

Can KATRIN be largely improved ?
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

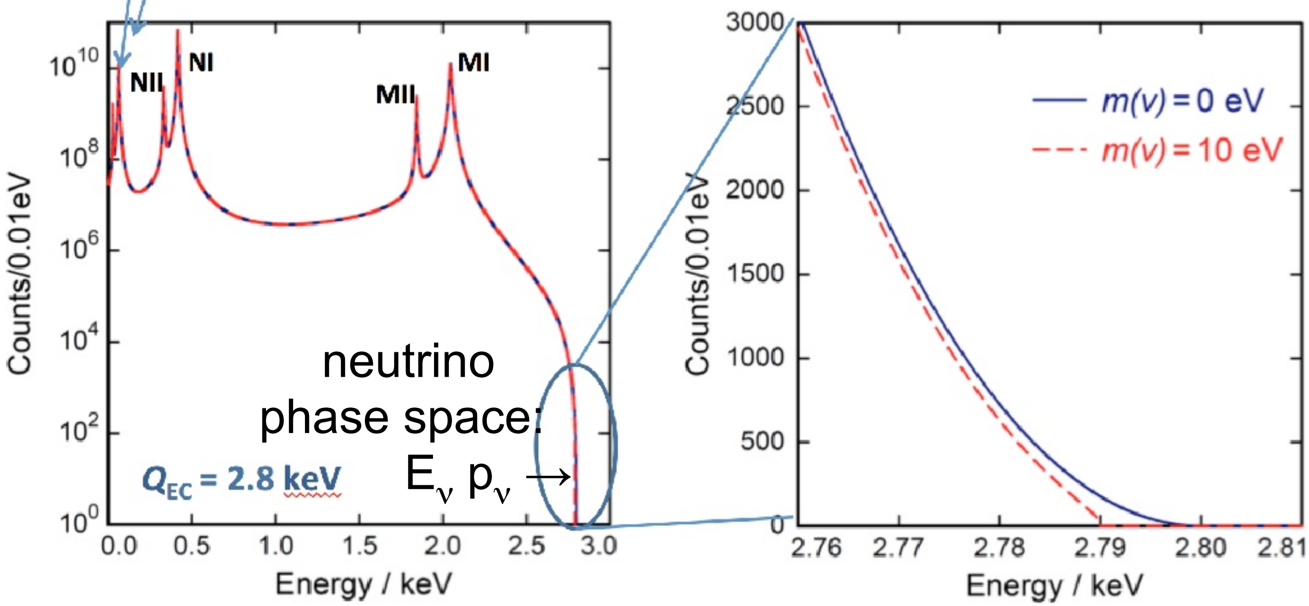


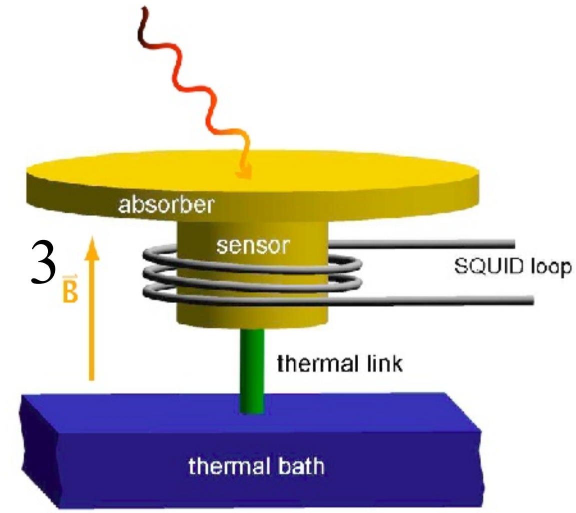
Possible ways out:

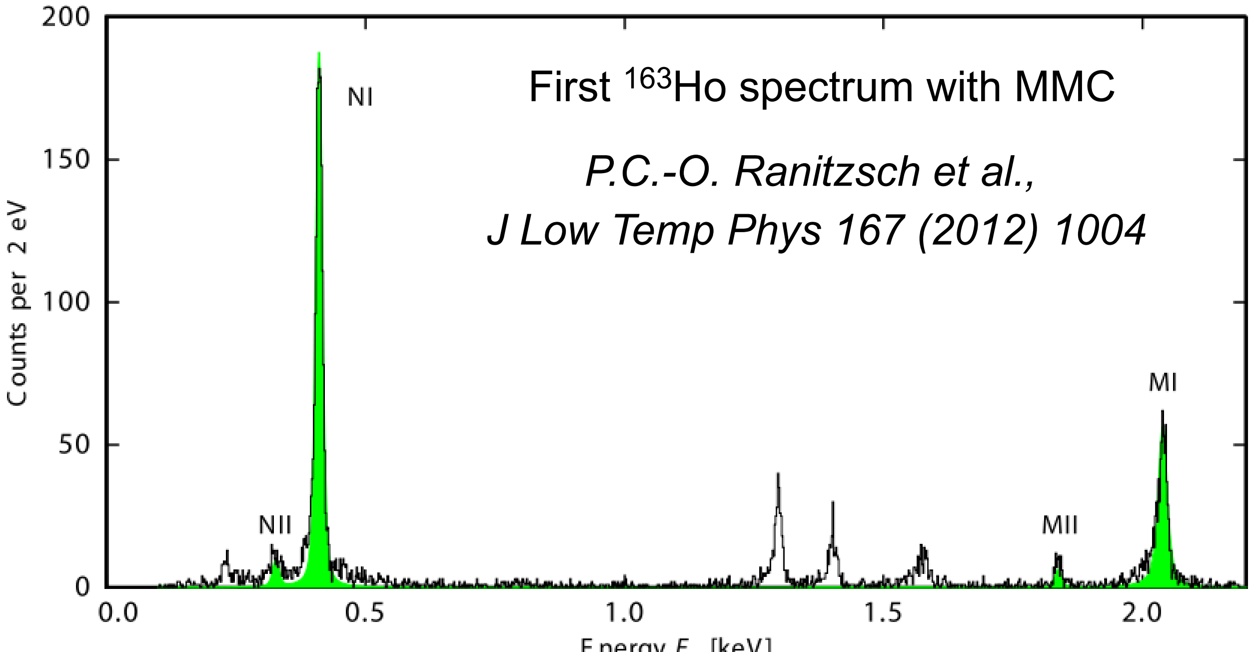
a) source inside detector (compare to $0\nu\beta\beta$) using cryogenic bolometers (ECHo, HOLMES, ..)

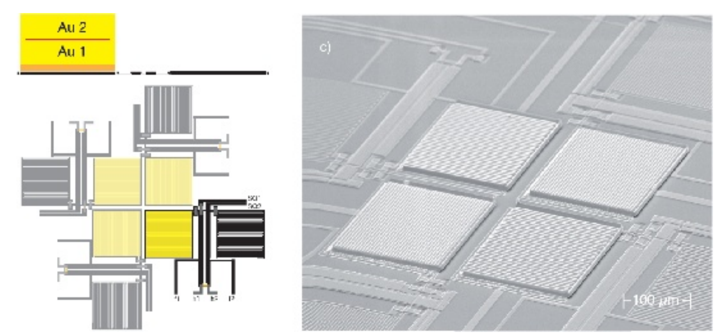
ECHo neutrino mass project: ^{163}Ho electron capture with metallic magnetic calorimeters

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







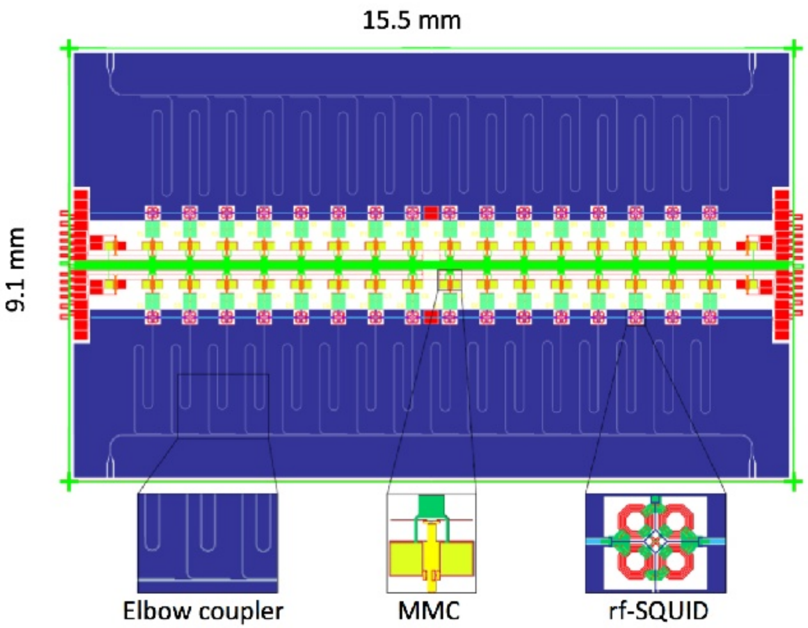


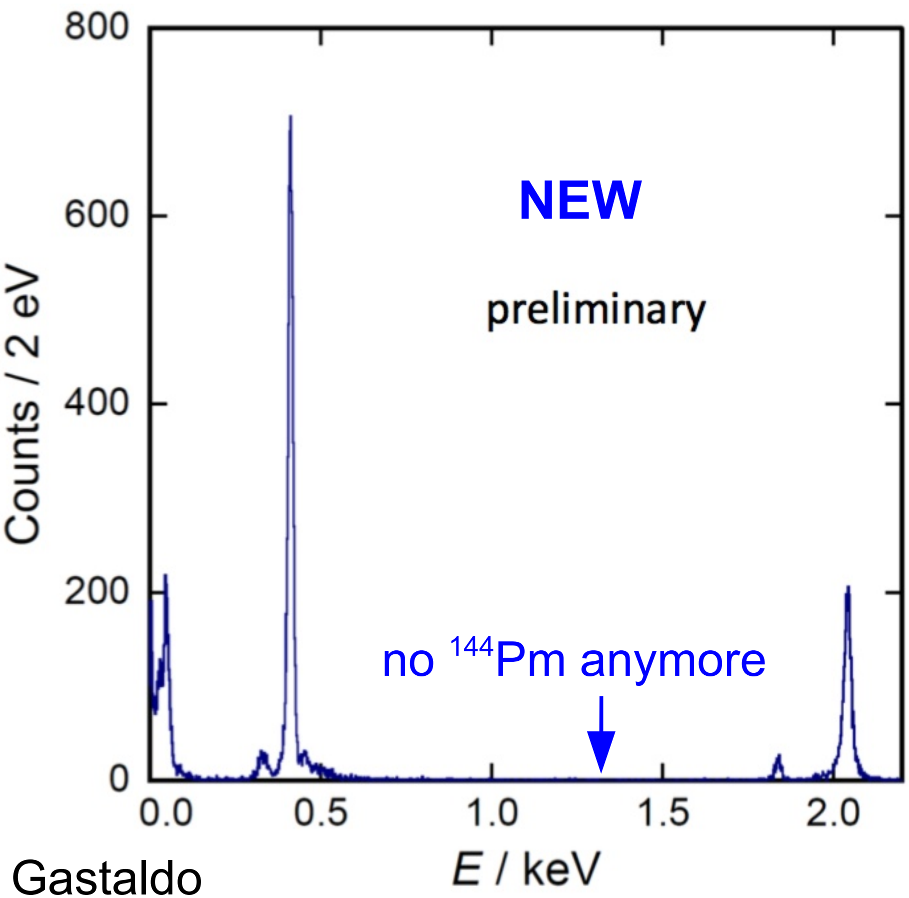
courtesy L. Gastaldo

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

Recent achievements by ECHo:

- new Q-value: 2.8 keV (independently by MMC & Penning trap, was 2.5 keV before!)
- new source production: chemical purification + mass separation → no ^{144}Pm or ^{166m}Ho
- very good energy resolution of this technology (ΔE_{FWHM} = 1.6 eV at 6 keV)
- ultra-short response (pile-up!): risetime 90 ns
- 128 pixels: microwave SQUID multiplexing
- funding for ECHo-1k





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- new Q-value: 2.8 keV (independently by MMC & Penning trap, was 2.5 keV before!)
- new source production: chemical purification + mass separation → no ^{144}Pm or ^{166m}Ho
- very good …)
- ultra-short …
- 128 pixels …
- funding fo…

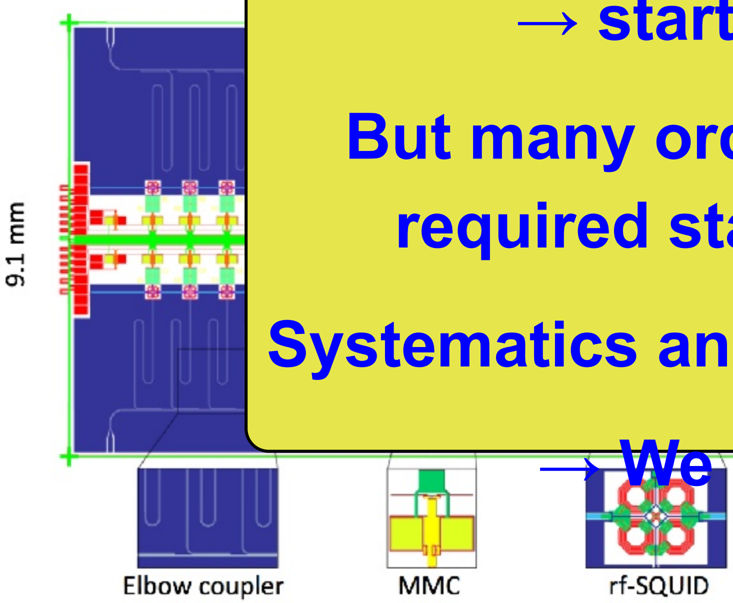
^{163}Ho EC is investigated by 3 collaborations: ECHo, HOLMES, NuMECS

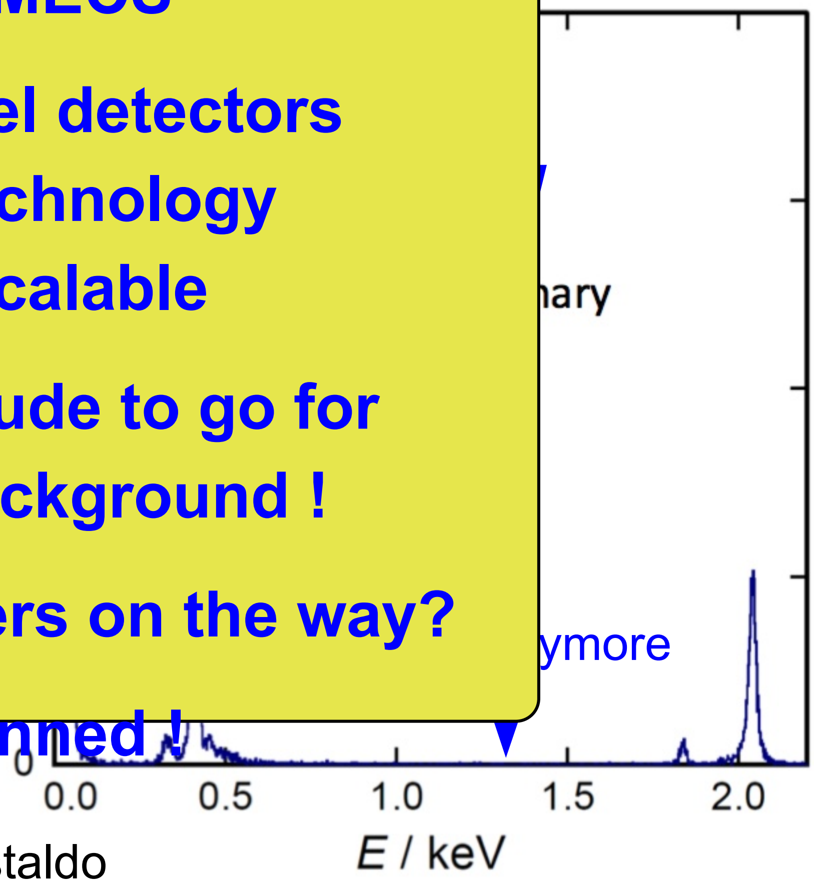
Cryo-calorimetric multipixel detectors are a very interesting technology → starts to become scalable

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

Systematics and show stoppers on the way?

→ We should stay tunned !

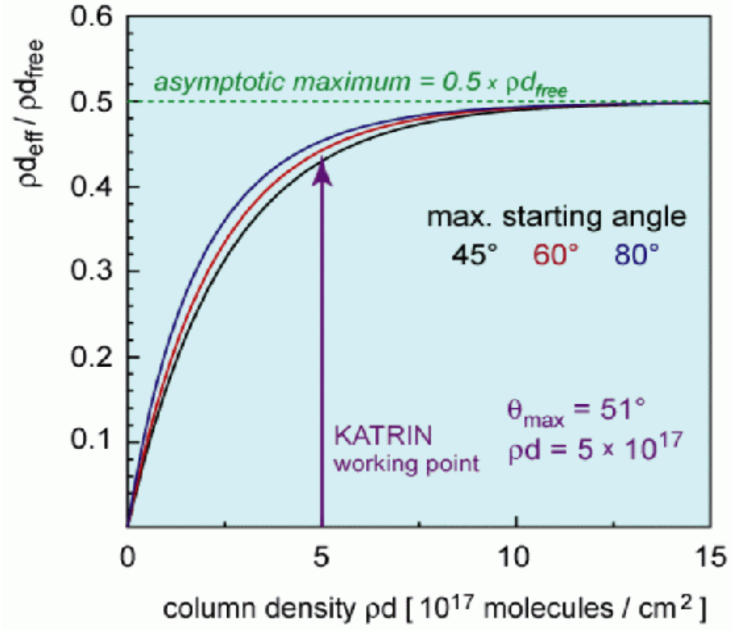




courtesy L. Gastaldo

Can KATRIN be largely improved ? 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 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)

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

Westfälische Wilhelms-Universität Münster

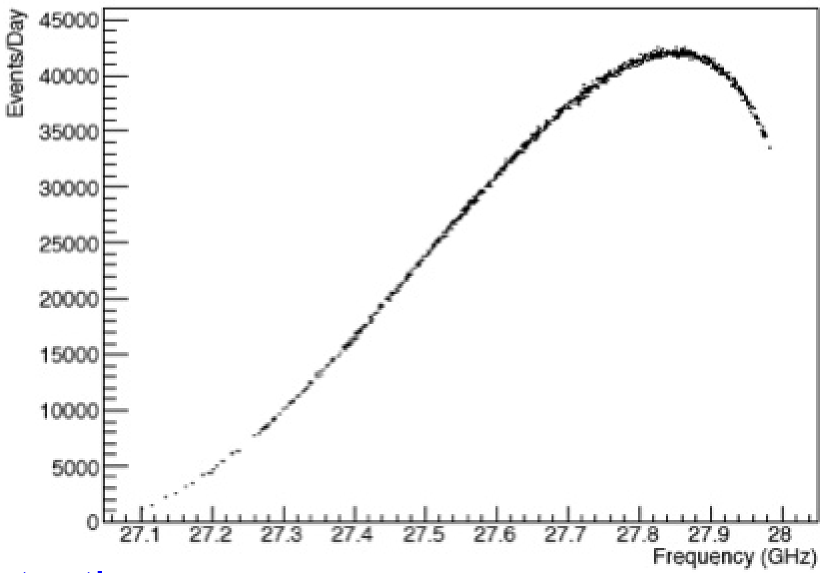
General idea: *B. Monreal and J. Formaggio, PRD 80 (2009) 051301*

- Source = KATRIN tritium source technology :

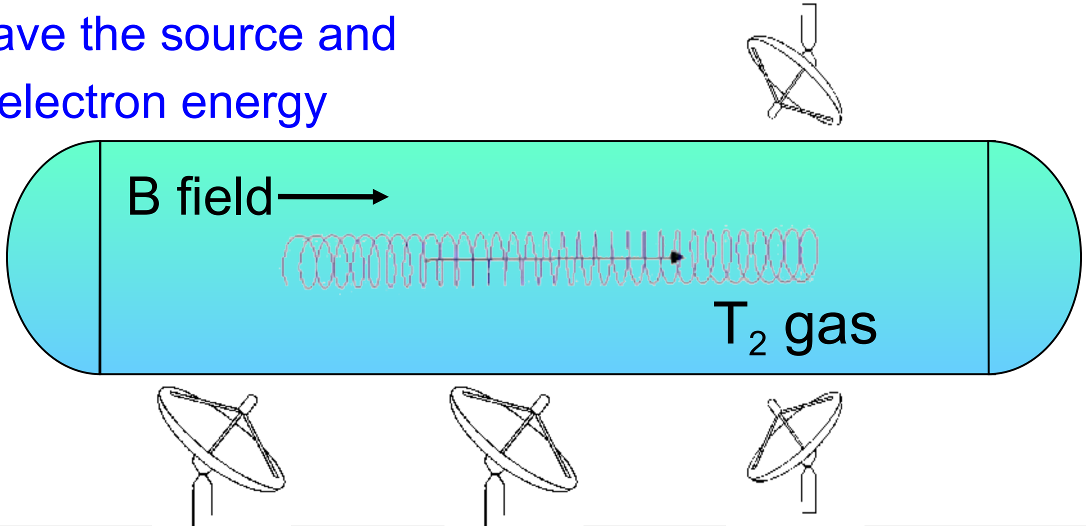
uniform B field + low pressure T_2 gas

β electron radiates coherent cyclotron radiation

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



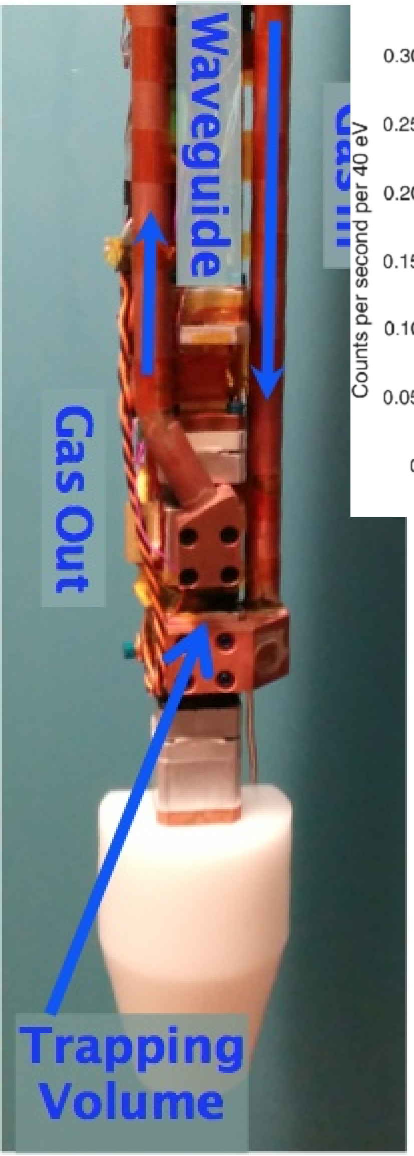
- Antenna array (interferometry) for cyclotron radiation detection
  since cyclotron radiation can leave the source and carries the information of the β-electron energy

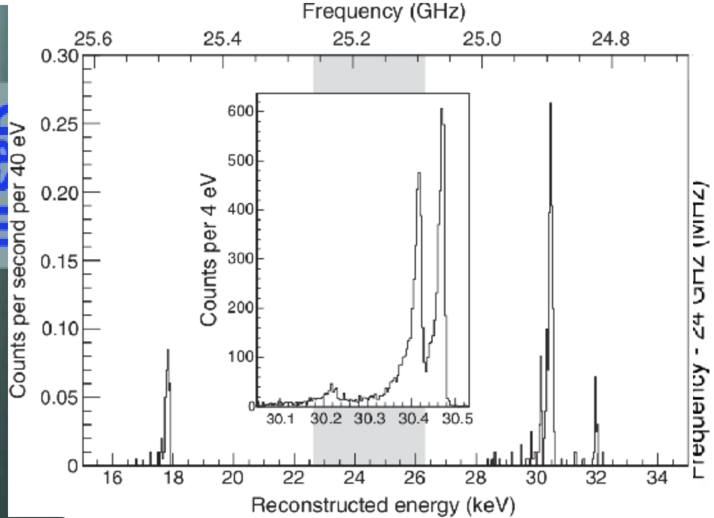


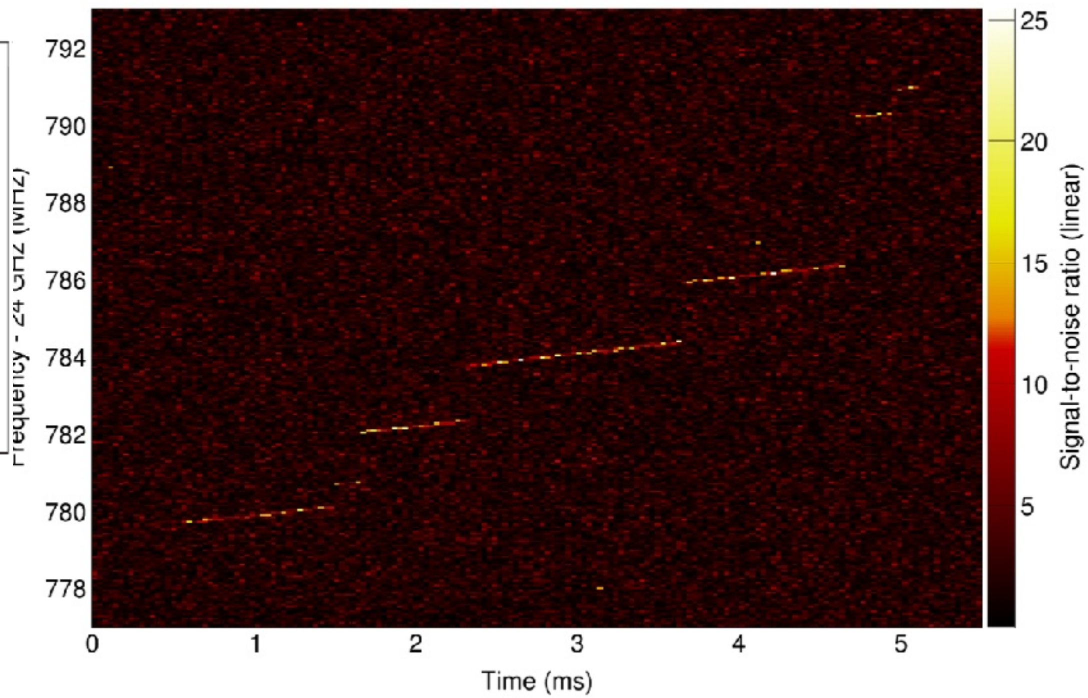
Project 8's phase 1: detection single electrons from ^{83m}Kr

Westfälische Wilhelms-Universität Münster

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



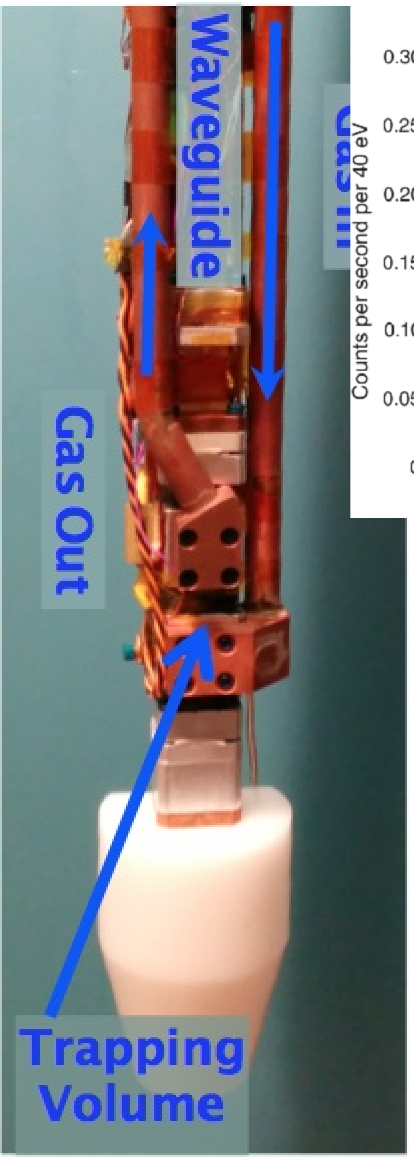


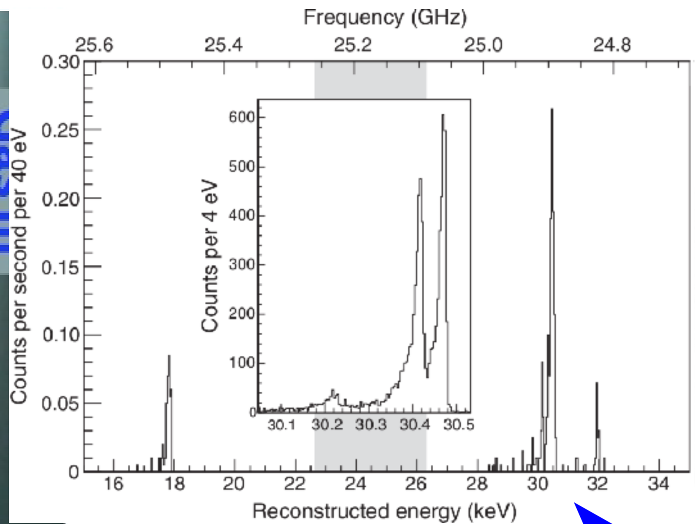


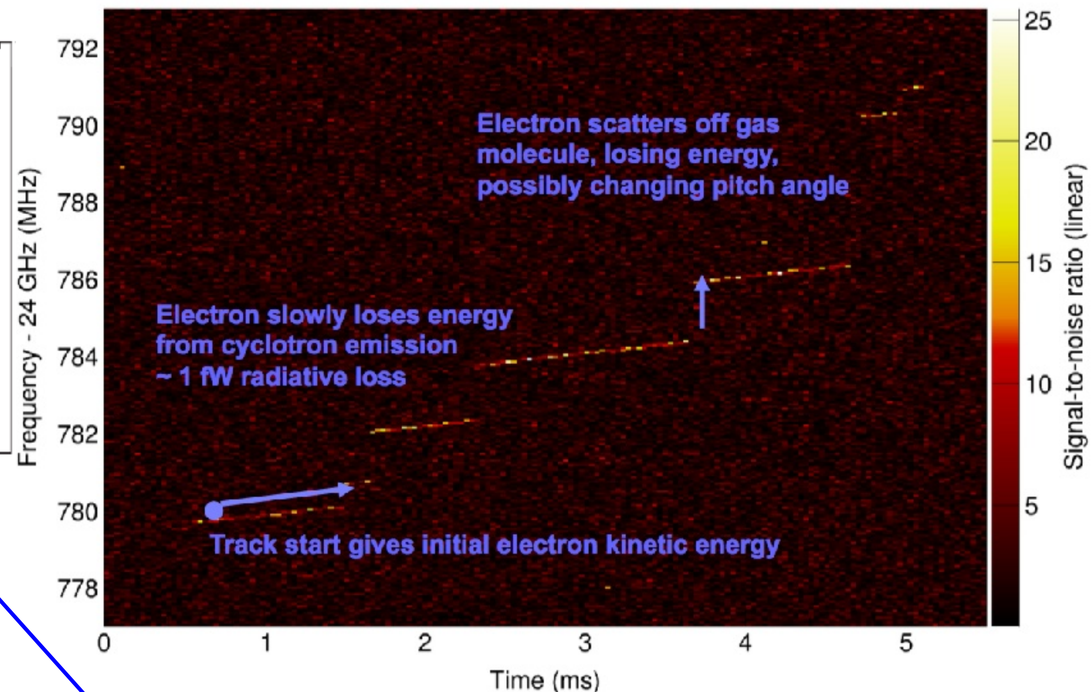
courtesy J. Formaggio, RGH Robertson

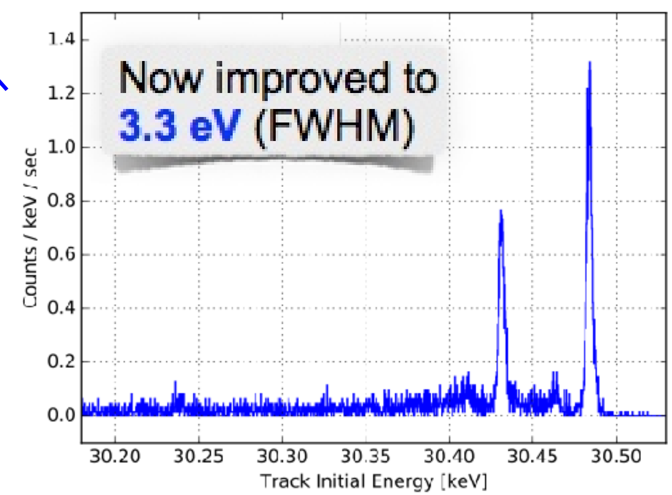
Project 8's phase 1: Detection single electrons from ^{83m}Kr

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









courtesy J. Formaggio, RGH Robertson

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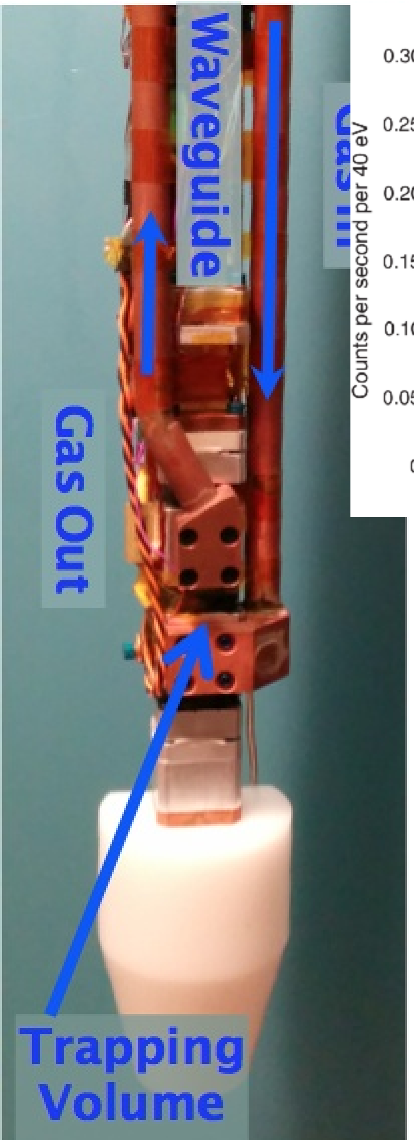
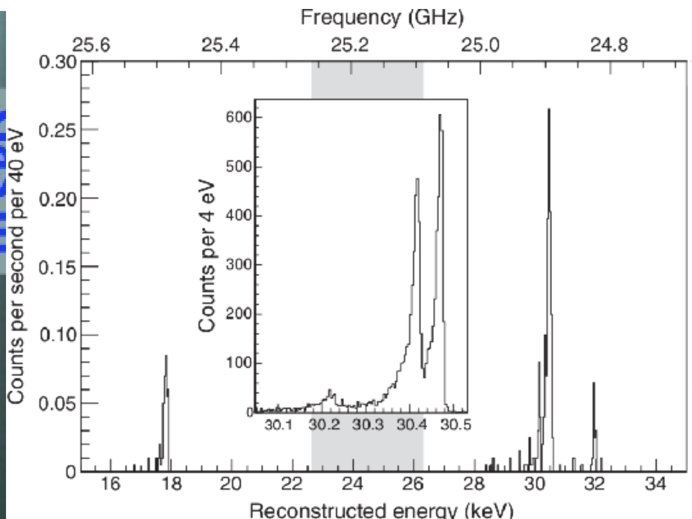
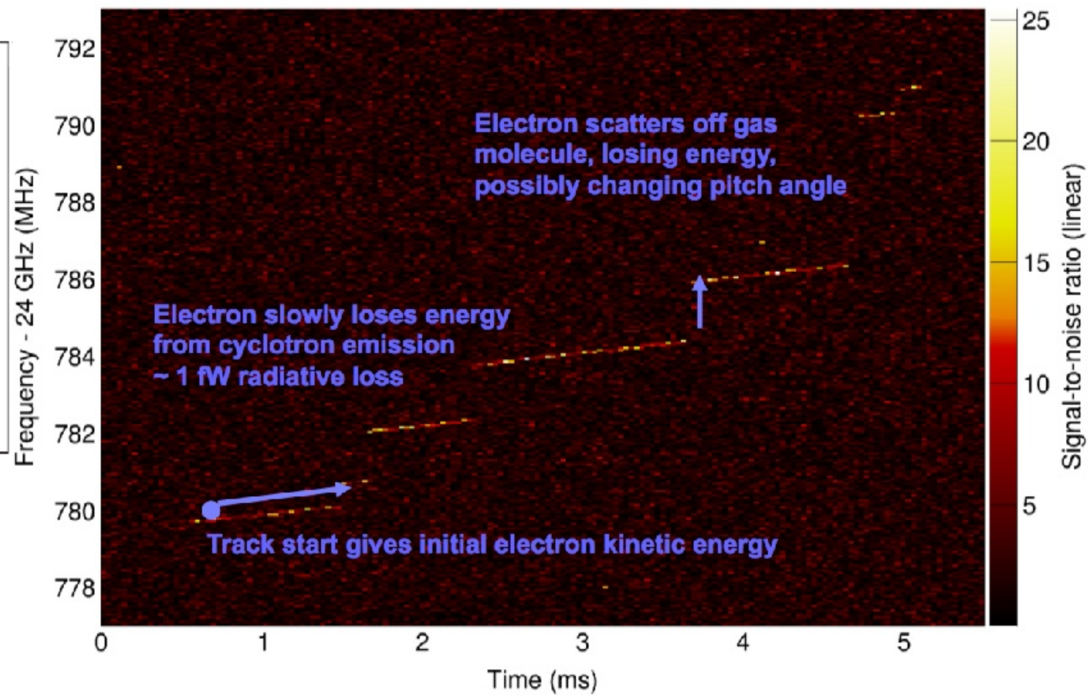
Project 8's phase 1: Detection single electrons from ^{83m}Kr

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





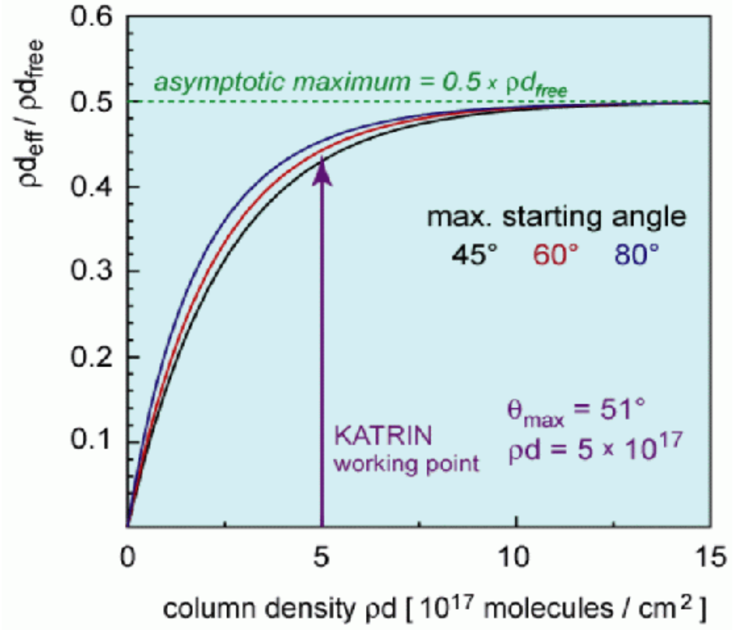


First detection of single electrons successfull but still a lot of R&D necessary
- **Is a large scale experiment possible ?**
- **What are the systematic uncertainties & other limitations?**

courtesy J. Formaggio, RGH Robertson

Can KATRIN be largely improved ?
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



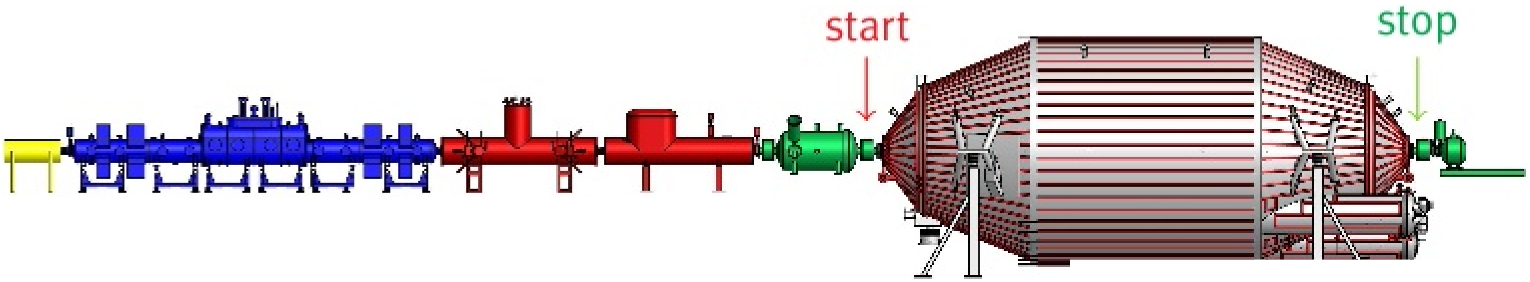
Possible ways out:

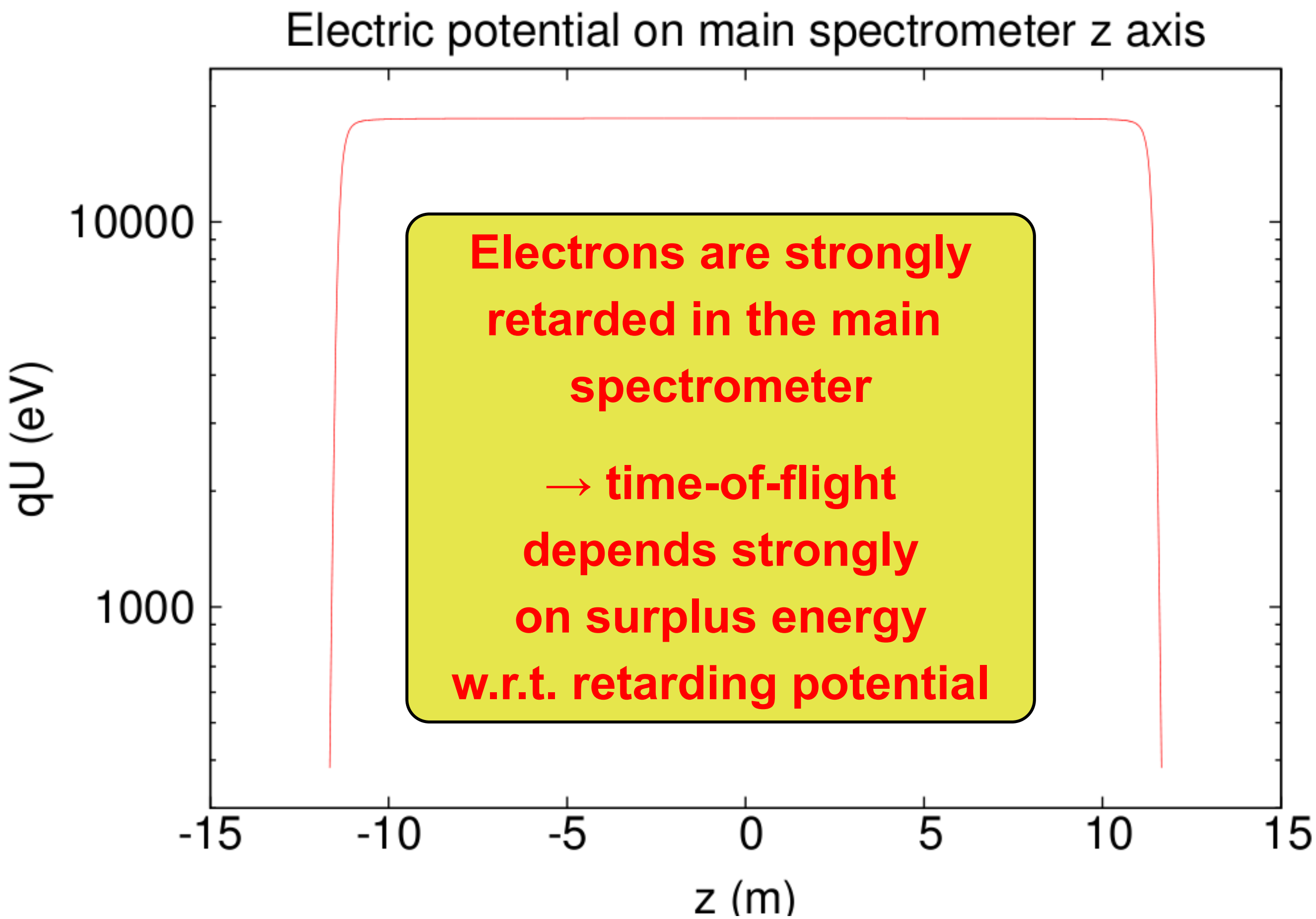
a) source inside detector (compare to 0νββ) using cryogenic bolometers (ECHo, HOLMES, ..)

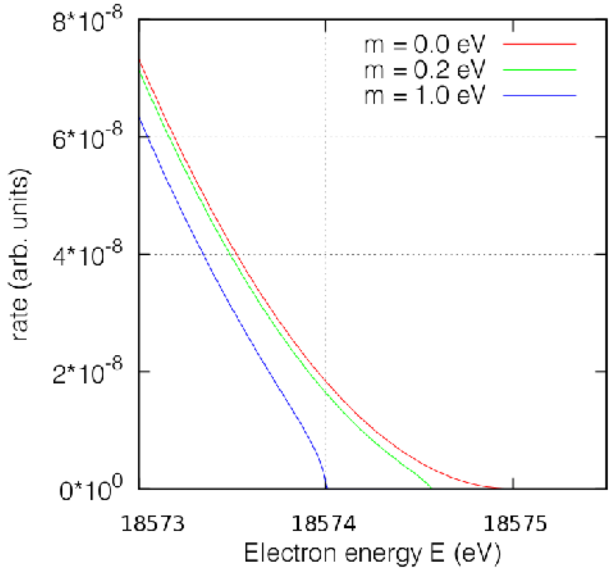
b) hand-over energy information of β electron to other particle (radio photon), which can escape tritium source (Project 8)

c) make better use of the electrons → time-of-flight spectroscopy

Alternative spectroscopy: measure time-of-flight TOF through KATRIN spectrometer







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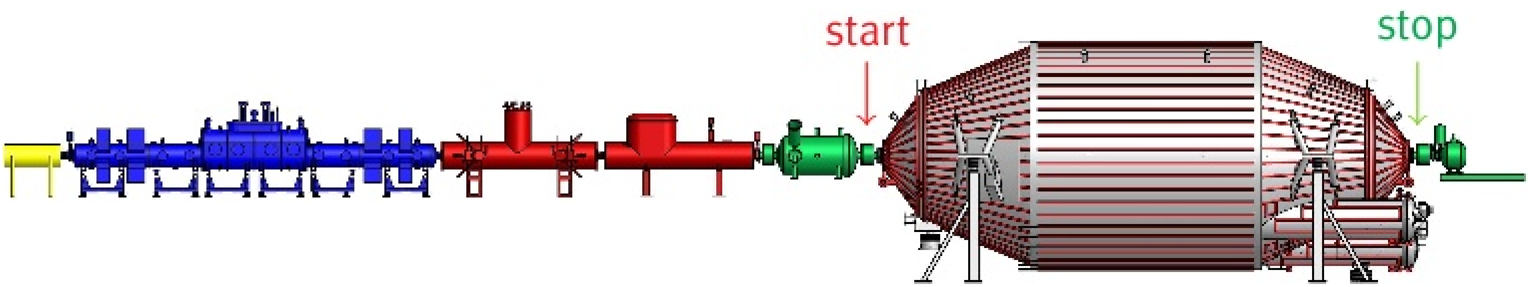
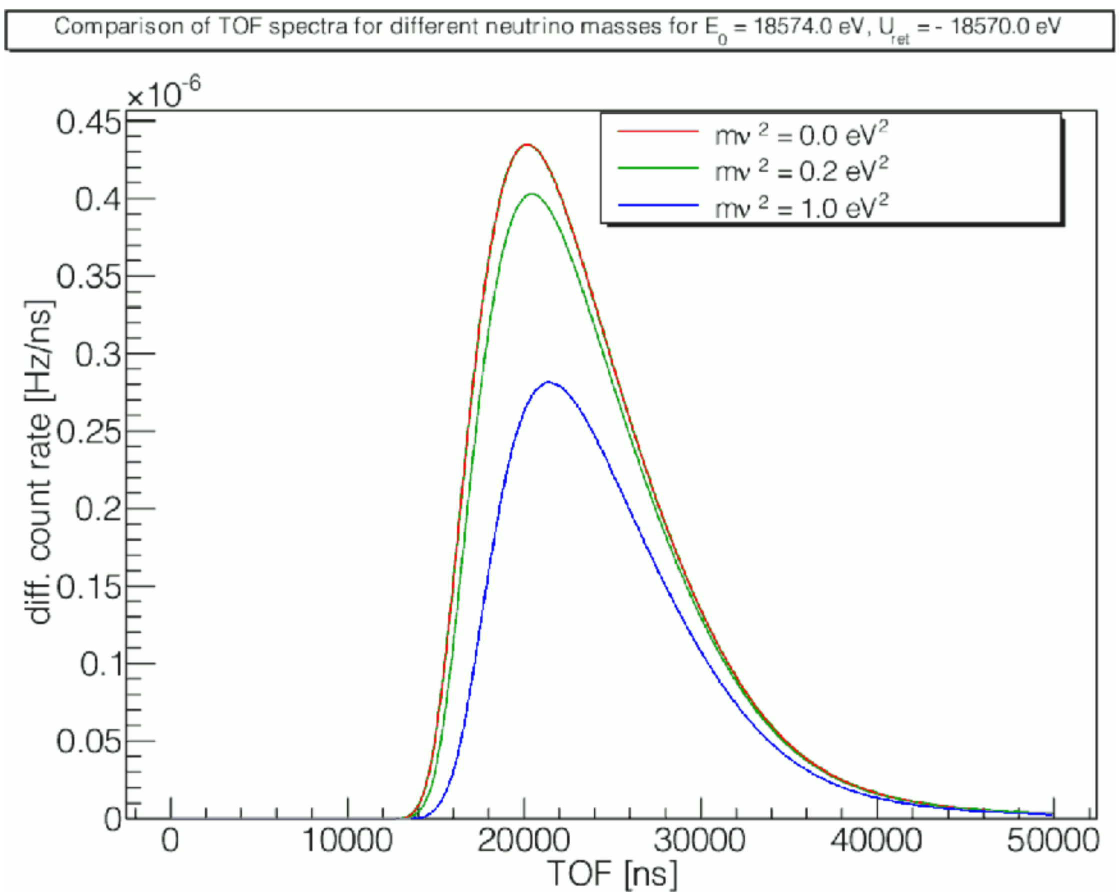
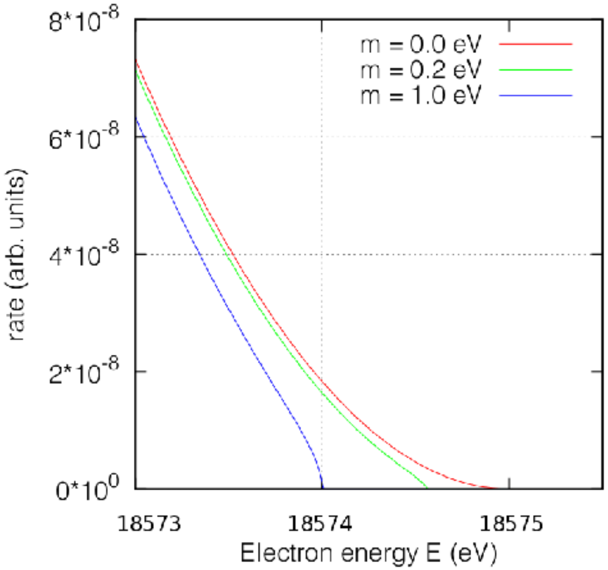






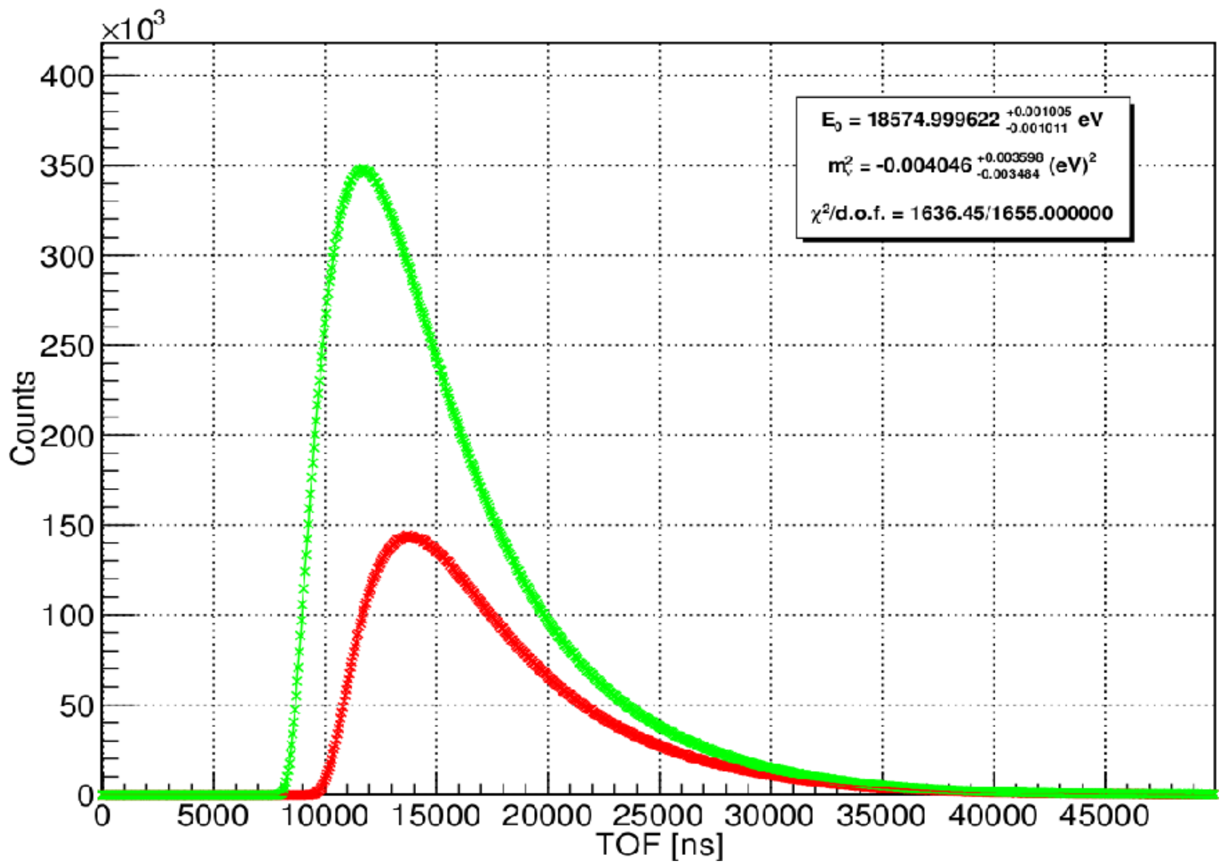
Time-of-flight spectrum corresponds to a full energy spectrum

→ sensitive to the neutrino mass

Sensitvity improvement on $m^2(\nu_e)$ by ideal TOF determination

Measure at 2 (instead of ≈30) different retarding potentials since TOF spectra contain already all the information

→ Factor 5 improvement in m_ν^2 w.r.t. standard KATRIN in ideal case !

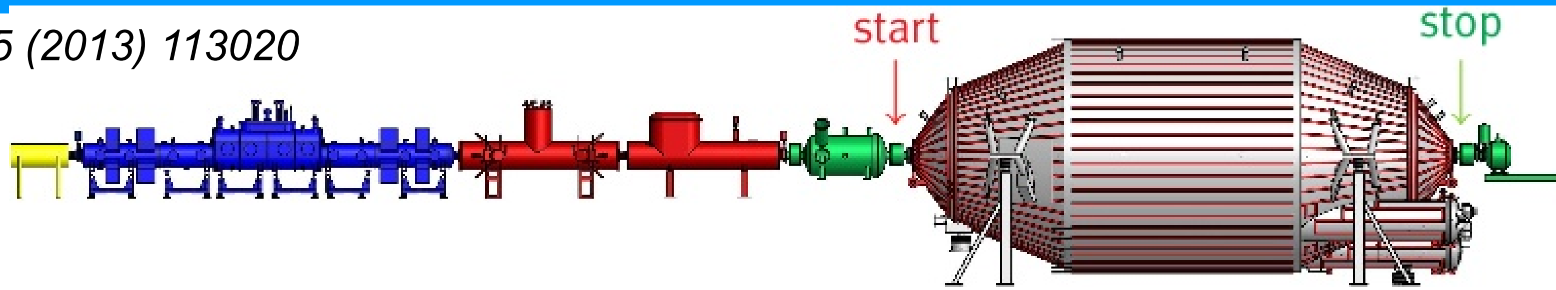


N. Steinbrink et al.
NJP 15 (2013) 113020

Coincidence request between start and stop signal → nice background suppression

How to realize time-of-flight spectroscopy @KATRIN

N. Steinbrink et al., NJP 15 (2013) 113020



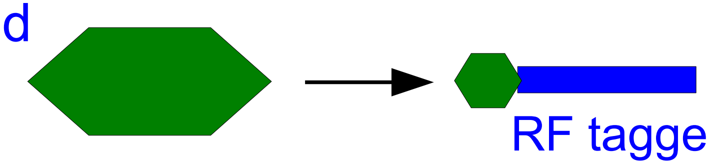
Advantage: measure β-spectrum by TOF at one (a few) retarding potential(s) i.e. as measuring differential β-spectrum

Stop: Can measure time-of-arrival with KATRIN detector with Δt = 50 ns → ok

Start: e^--tagger: Need to determine time-of-passing-by of e^- before main spectrometer without disturbing energy and momentum by more than 10 meV:

> **→ factor 5 in $\Delta m(\nu)^2_{stat}$ under ideal conditions**
> **added value: significant background reduction !**

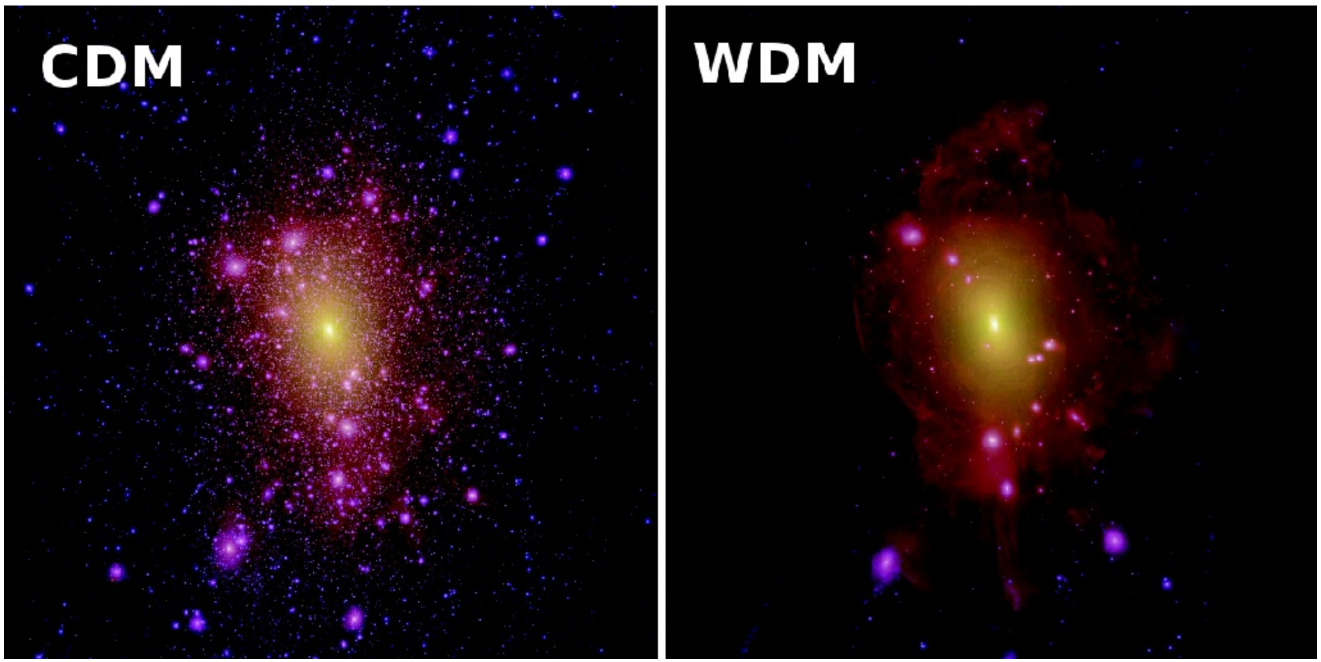
One implementation: reduce pre spectrometer length & add a Project 8-type tagger within a long solenoid or another type of electron tagger



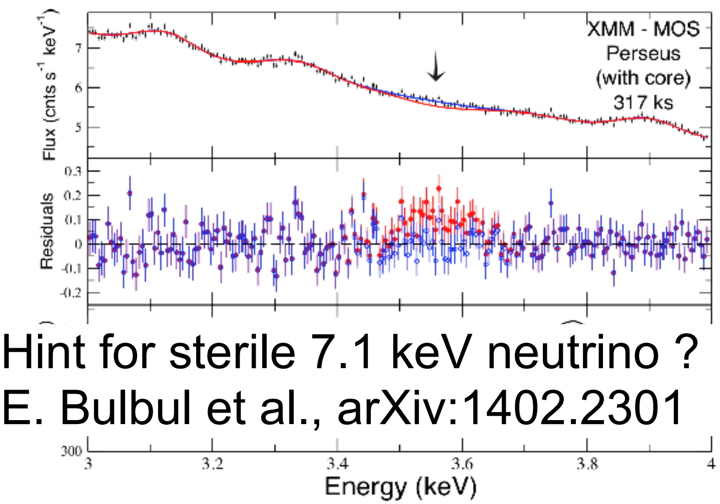
or: Use use tagger-less methods: „gated filter“ or „time-focusing time-of-flight“

Hints for a 2nd sterile neutrino: Warm Dark Matter in the universe

ΛCDM (Cold Dark Matter with cosmological constant) models (masses of about 100 GeV) predict to much structure at galactic scales (too many satellite galaxies)

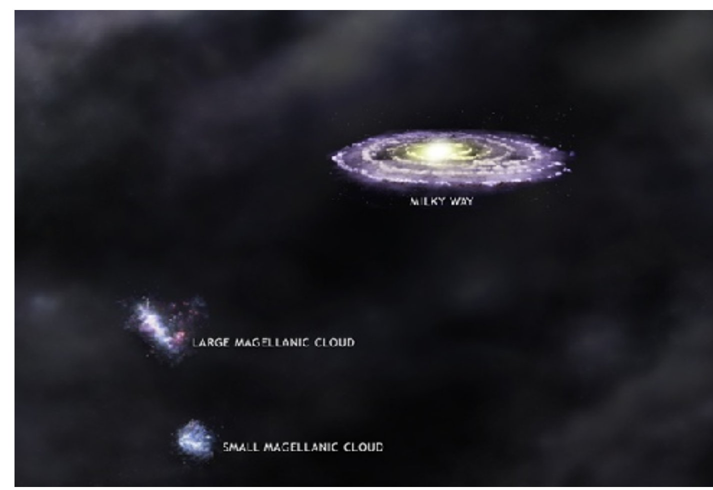


(e.g. Lovell et al. at Meudon Workshop 2012)



Hint for sterile 7.1 keV neutrino ?
E. Bulbul et al., arXiv:1402.2301

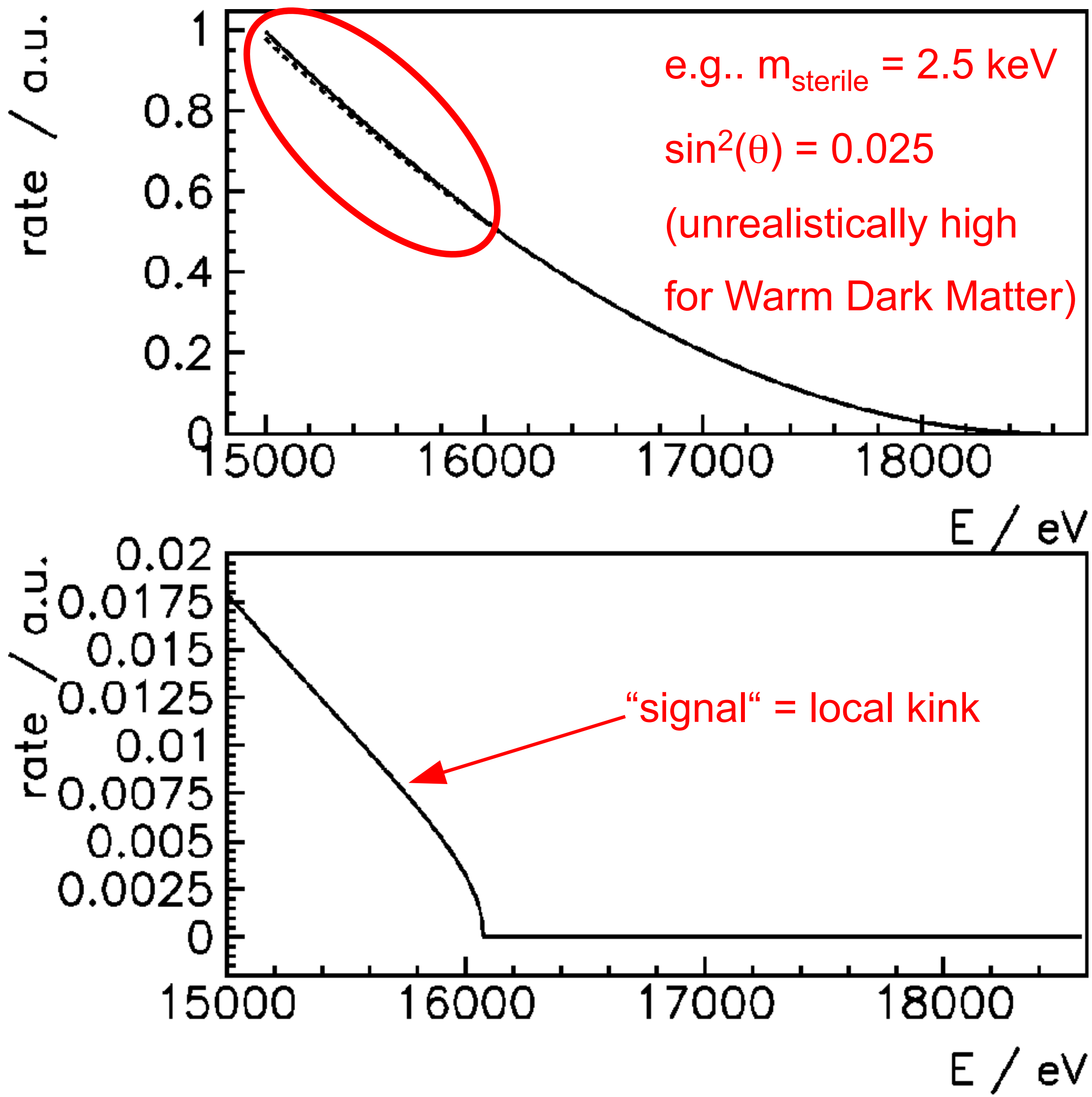
In contrast to observations ! (here only artist view on the right)



Warm Dark Matter (masses of a few keV, e.g. sterile neutrinos) would smear out these structures

http://chandra.harvard.edu/graphics/resources/illustrations/milkyWay/milkyway_magellanic_clouds.jpg

Search for a tiny kink of a keV neutrino



Main questions:

1) How to measure this tiny kink a few keV below the endpoint ?

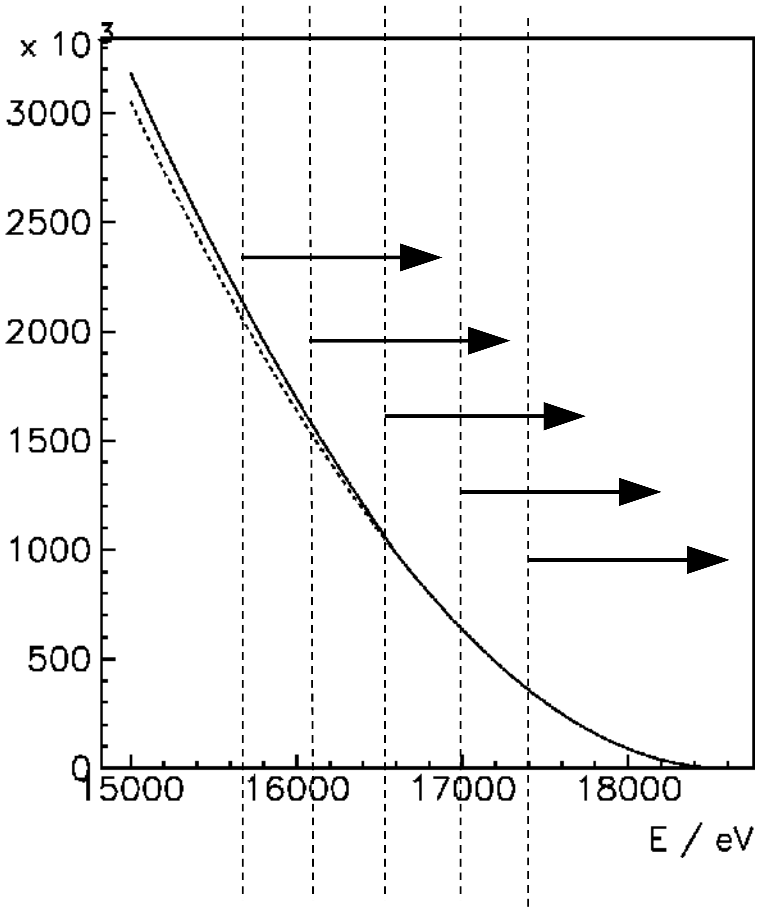
   In parallel, in addition or after KATRIN's $m(\nu_e)$ mission ?

2) How to get enough statistics ?

3) How to fight against the systematics ?

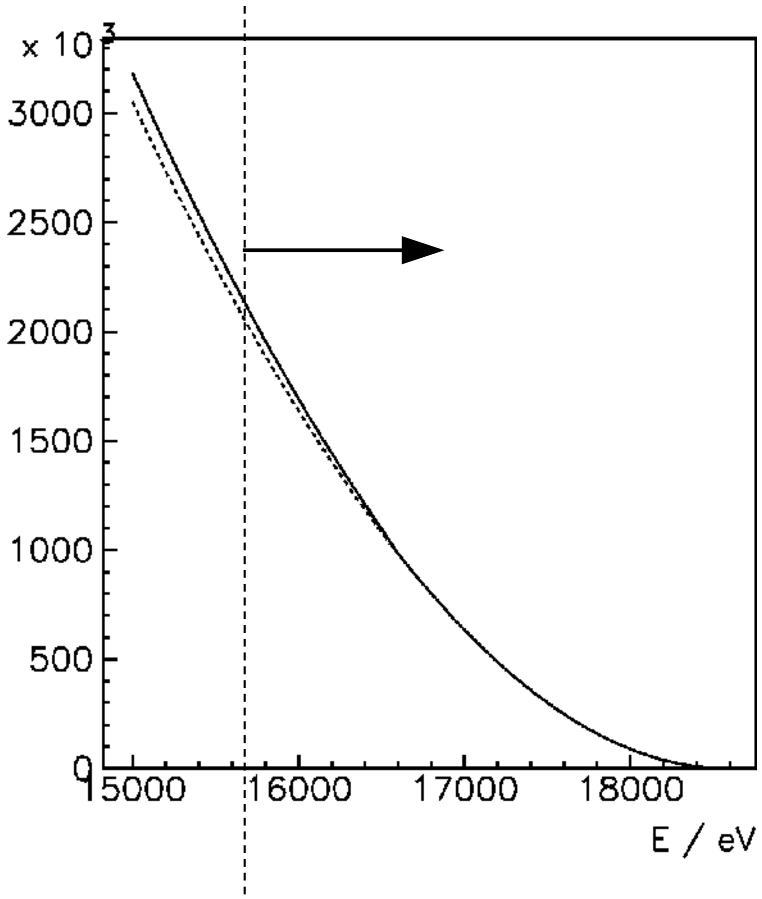
Second gain of integral versus differential: Avoid many steps in MAC-E-Filter mode

Integral – MAC-E-Filter method



need many retardation voltages
to obtain spectral information

Differential measurement



need one retardation voltage
and other means (TRISTAN-detector, TOF)
to obtain spectral information

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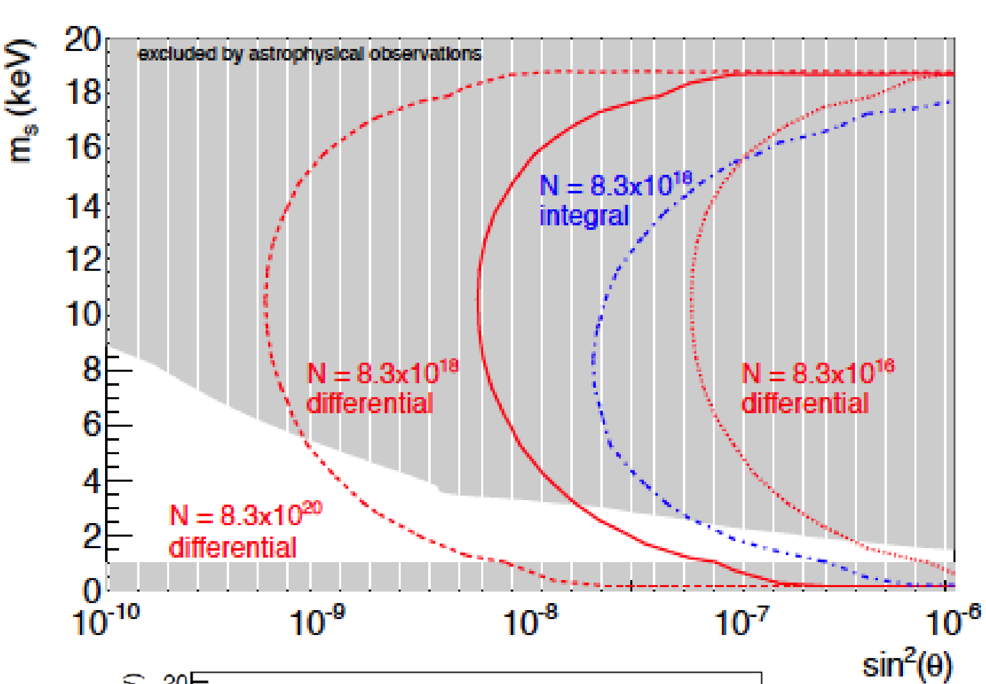
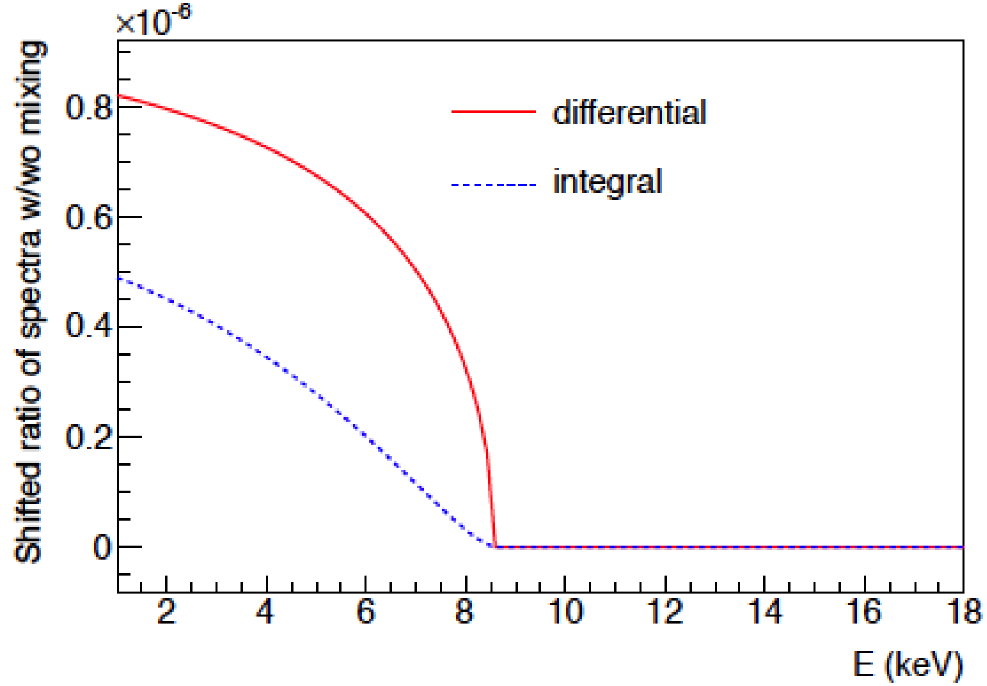
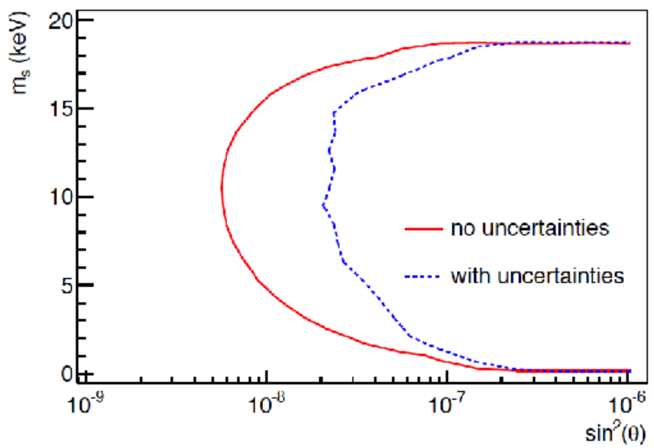
Statistical sensitivity for integral and differential measurement







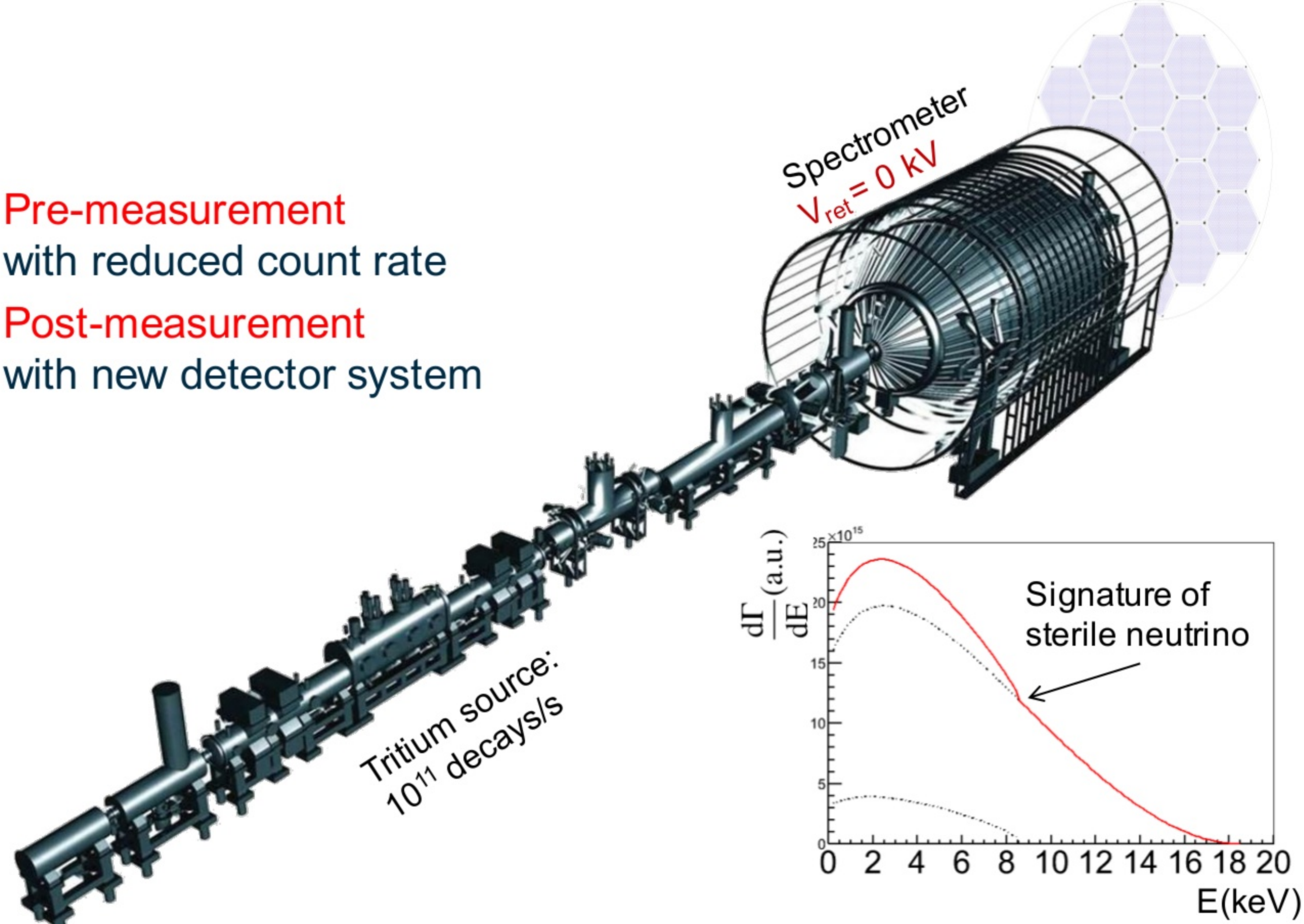
S. Mertens et al., JCAP 02 (2015) 020
„Sensitivity of Next Generation Tritium β-Decay Experiments for keV-Scale Sterile Neutrinos"

→ **Potential statistical uncertainty is not a problem for 10^{-7} even including systematics (1^{st} investigation)!**

but would require different measurement strategy

How to search for keV neutrinos with KATRIN: several options

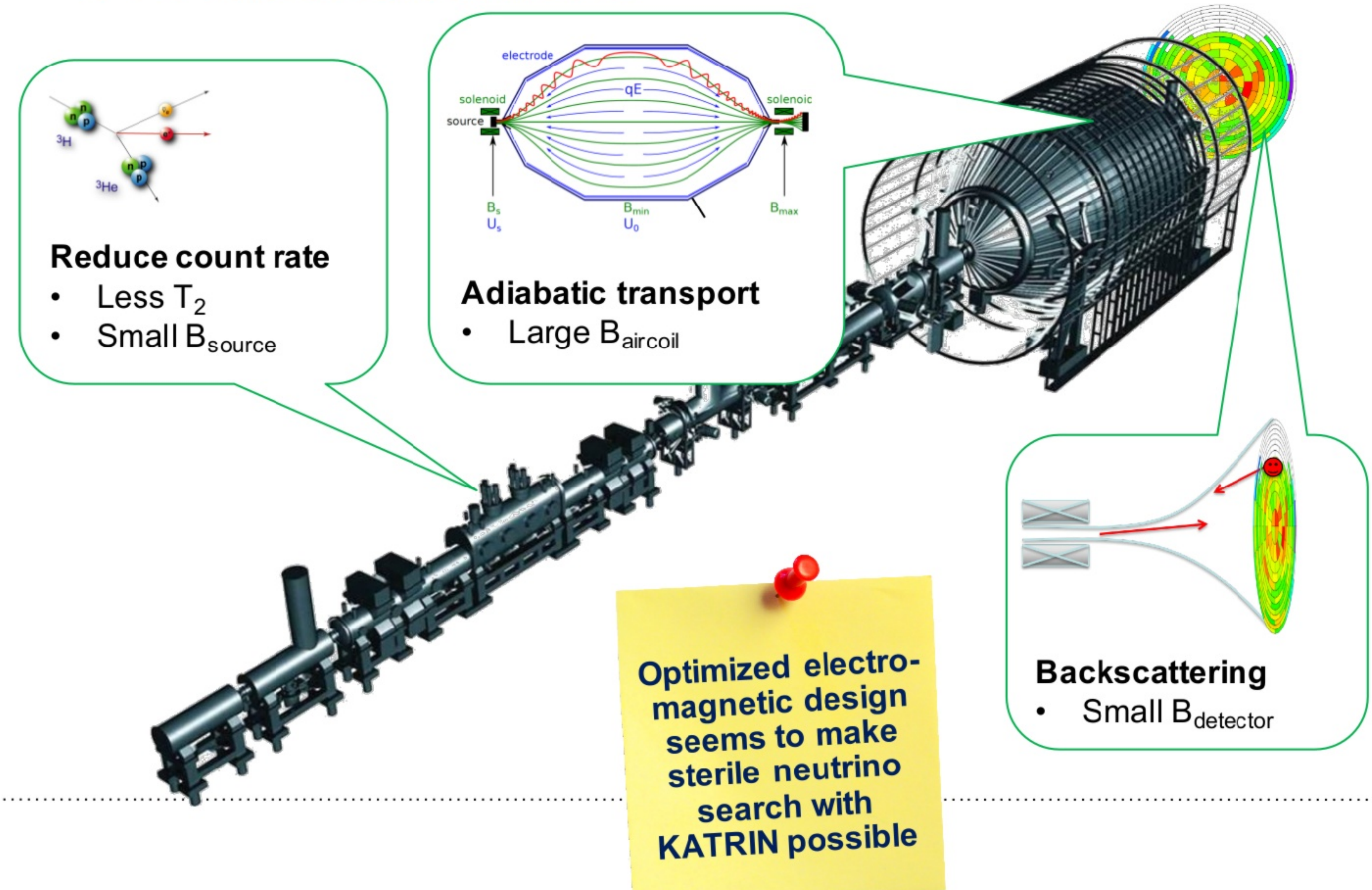
- Pre-measurement
  with reduced count rate
- Post-measurement
  with new detector system



S. Mertens, ECT* workshop, Trento 2016

How to search for keV neutrinos with KATRIN: could be done soon (2017)

Pre-Measurement



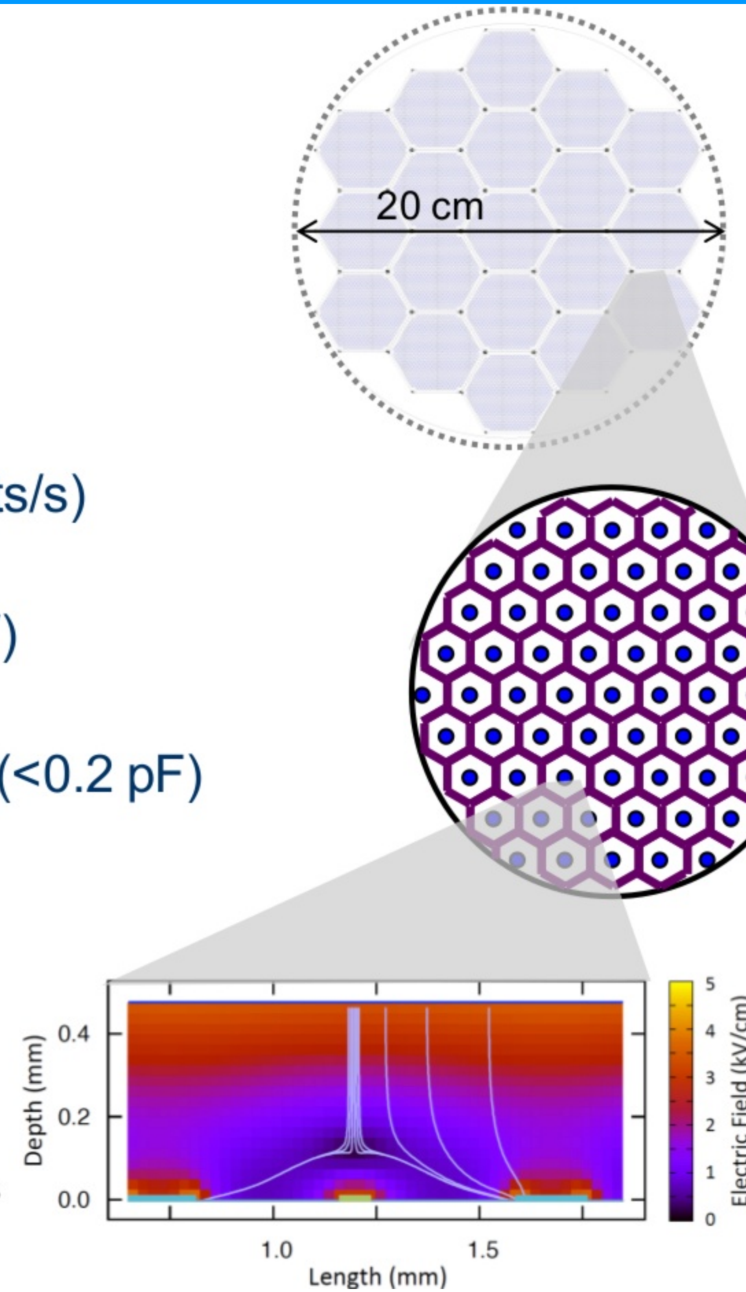
S. Mertens, ECT* workshop, Trento 2016

How to search for keV neutrinos with KATRIN: optimize for keV sterile ν

Post-Measurement

Novel detector design:

- Capability of handling high rates (>10^9 cnts/s)
  - >10 000 pixel
- High energy resolution (300 eV @ 20 keV)
  - Thin deadlayer (~10 nm)
- Large pixels (~1 mm) with small capacity (<0.2 pF)
  - Multi-drift-ring design (SDD)
- Minimize systematics (ppm-level)
  - Sophisticated read-out*



TRISTAN detector design simulations

S. Mertens, ECT* workshop, Trento 2016

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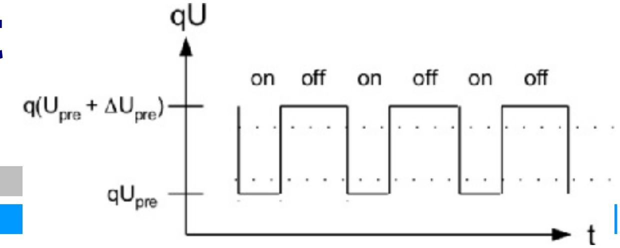
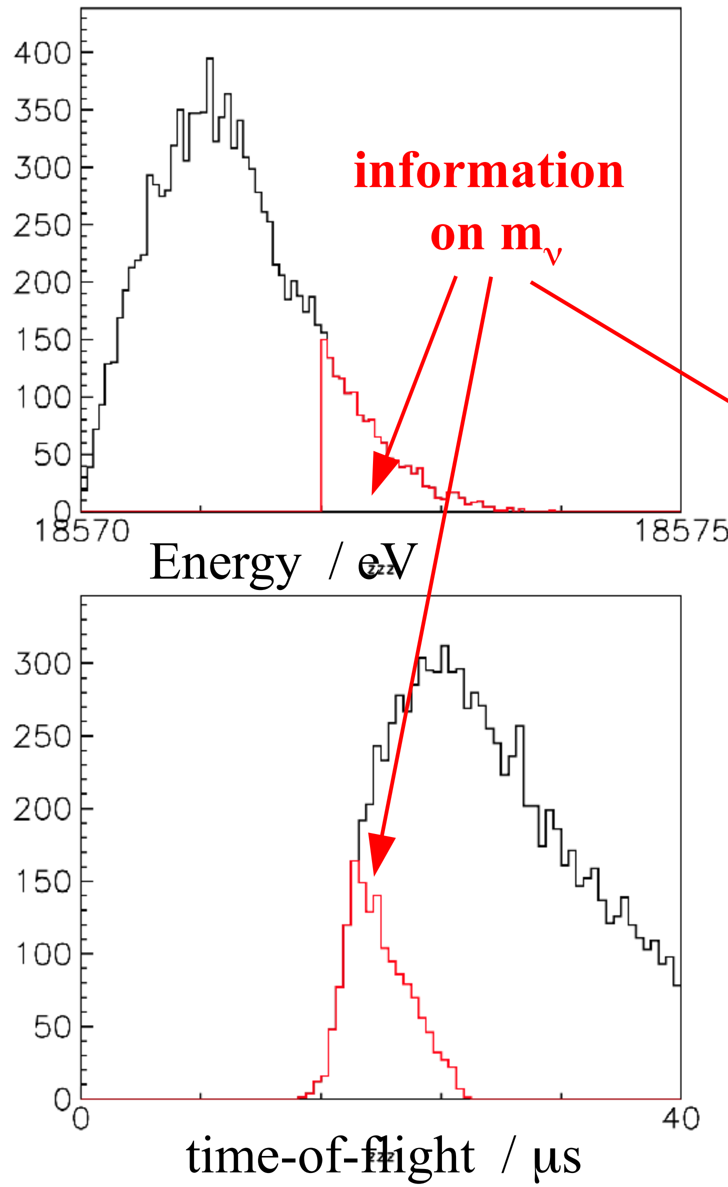
Smearing of time-of-flight in gated-filter mode



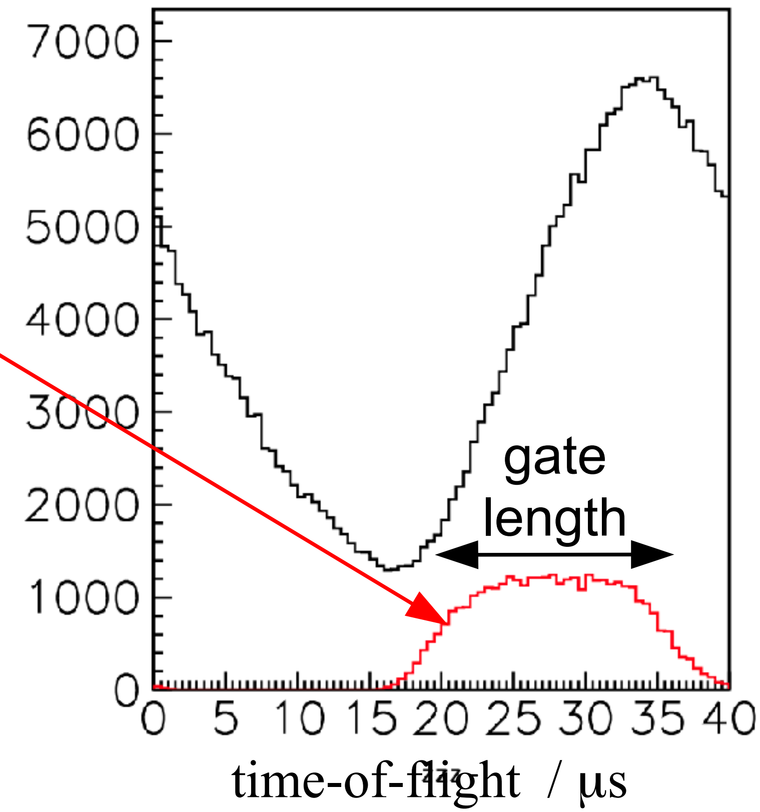
E_0=18.575 eV, U0 =-18570V, last 3 eV



Gated filter:

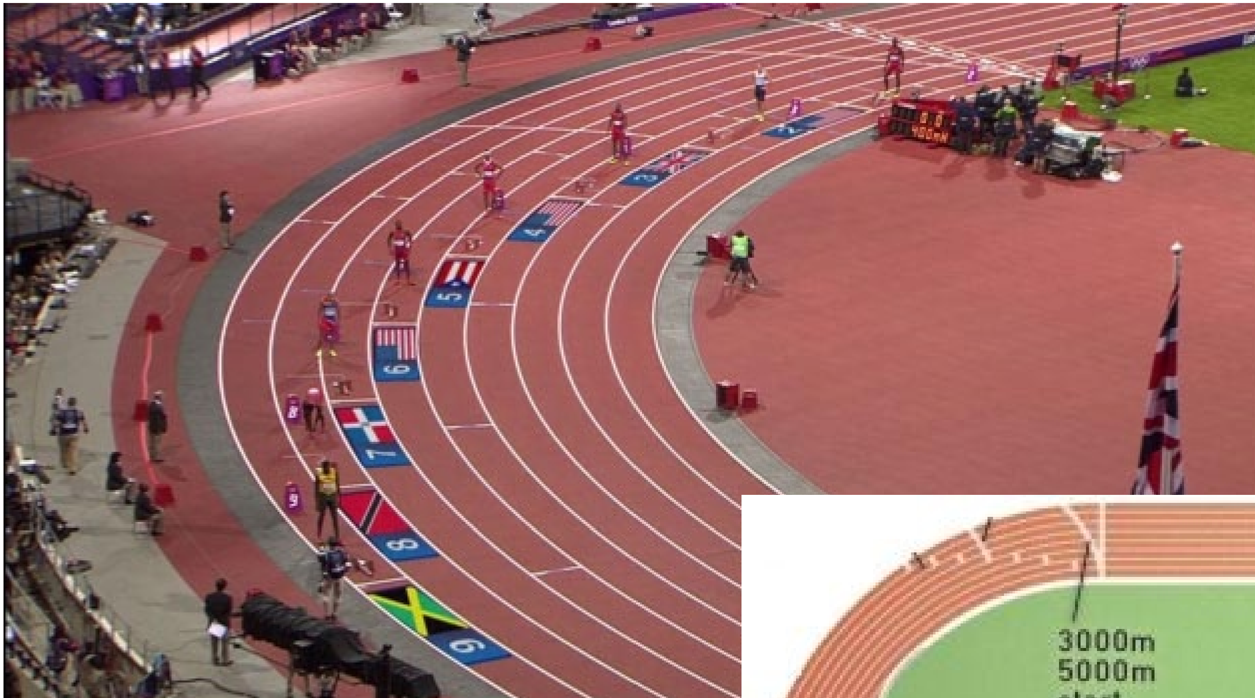
$T = t_{on} + t_{off}$ = 40 µs, t_{on} = 16 µs,

E_0 = 18.575 eV, qU=18.570 eV

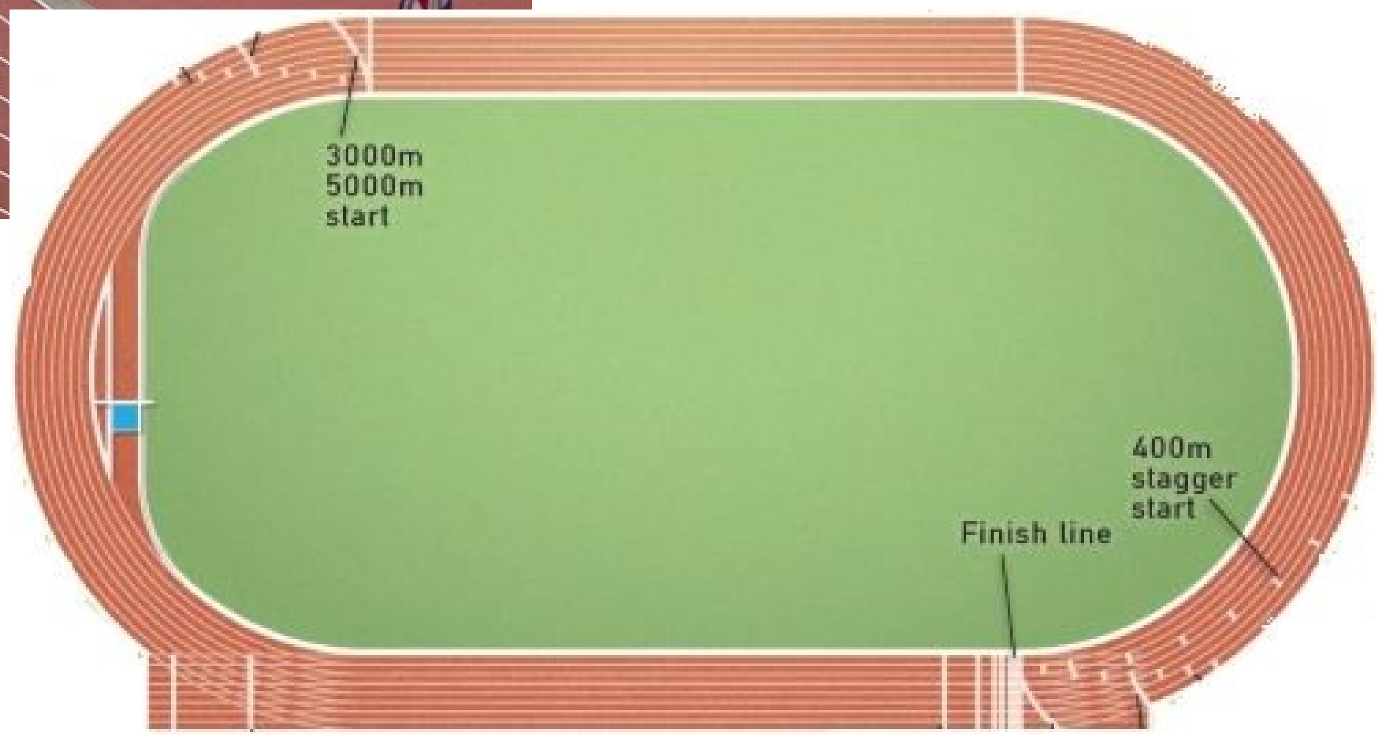


→ **m_ν-sensitive part of tof spectrum is smeared out → loss of sensitivity!**

Avoid smearing by gated-filter: “Time-focusing time-of-flight“



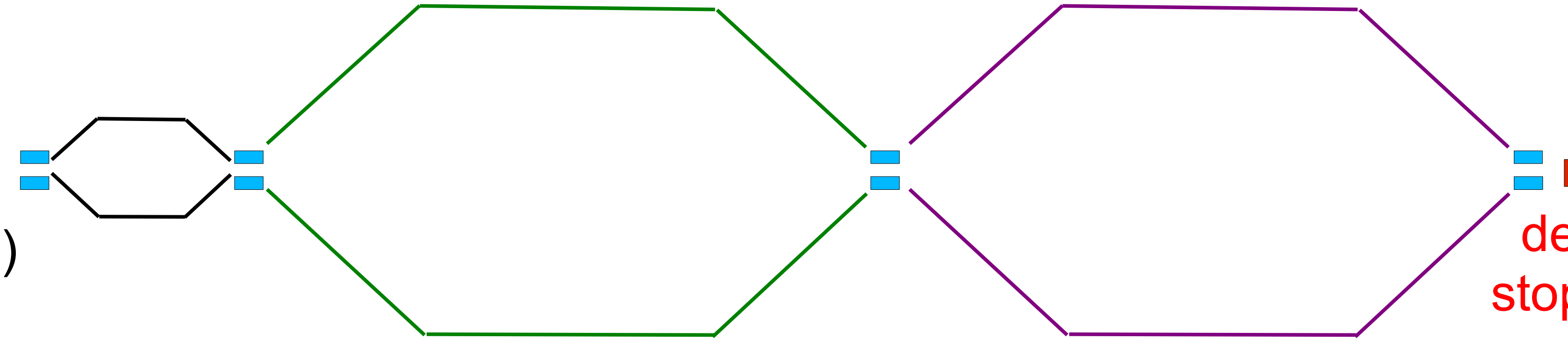
Idea: “Electrons starting behind/later get a shortcut/inner track or get accelerated (shortcut in time) in order to arrive in time“



Pictures:
http://olympic.org
http://100milesisnotthatfar.com

Time-focusing at KATRIN

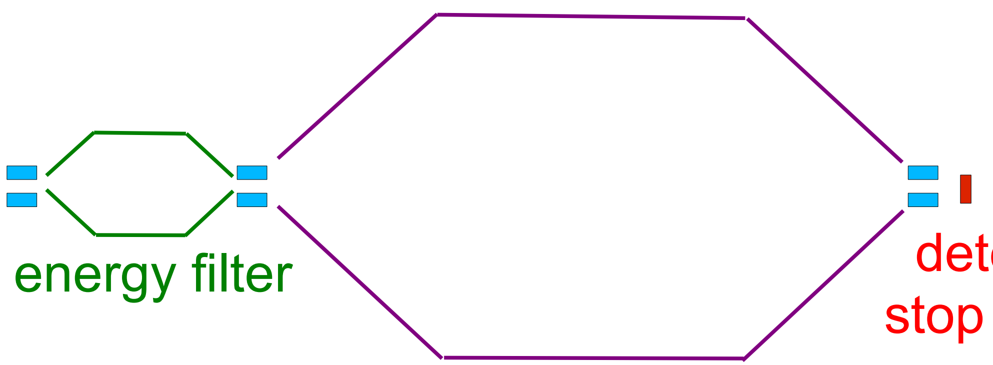
ideal
(but not realistic)



„inner track“: give electron higher energies by periodic acceleration:

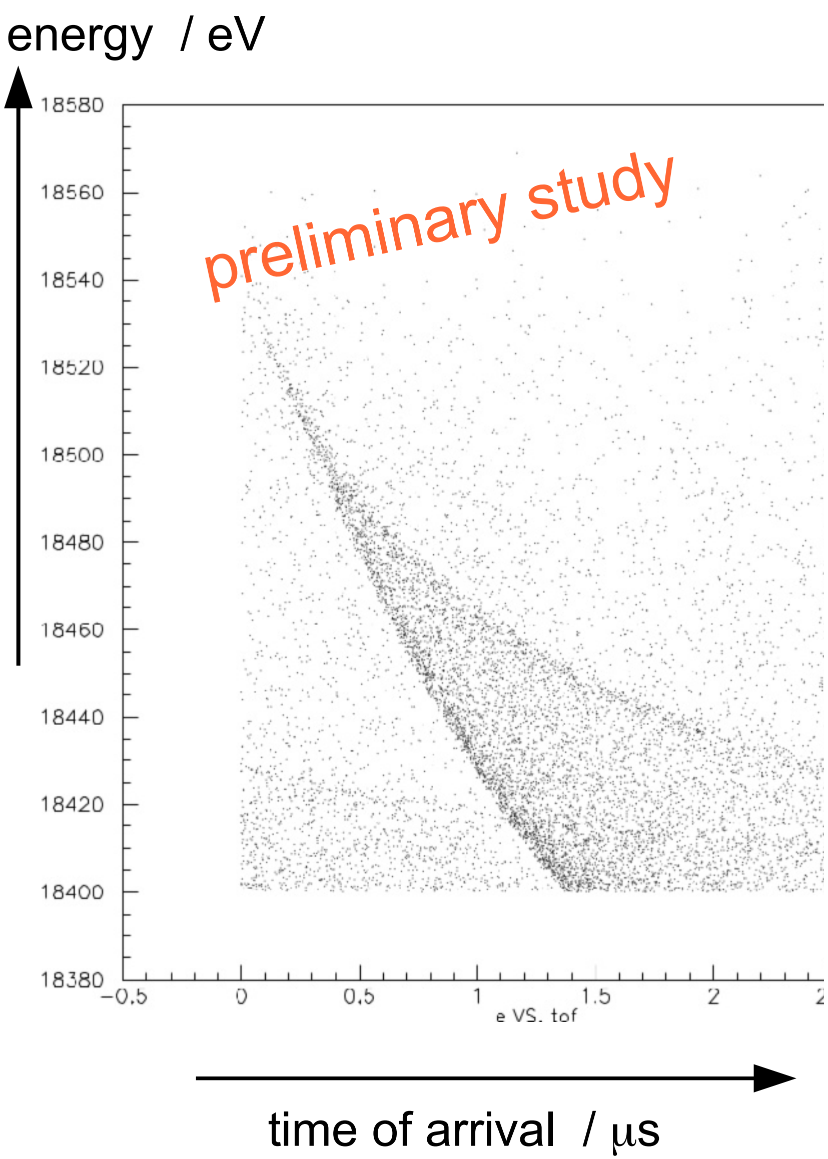
$$U = U_0 + U_1(t) \qquad \text{e.g. } U_1(t) = U_{10} * (1+\sin(\omega t))/2$$

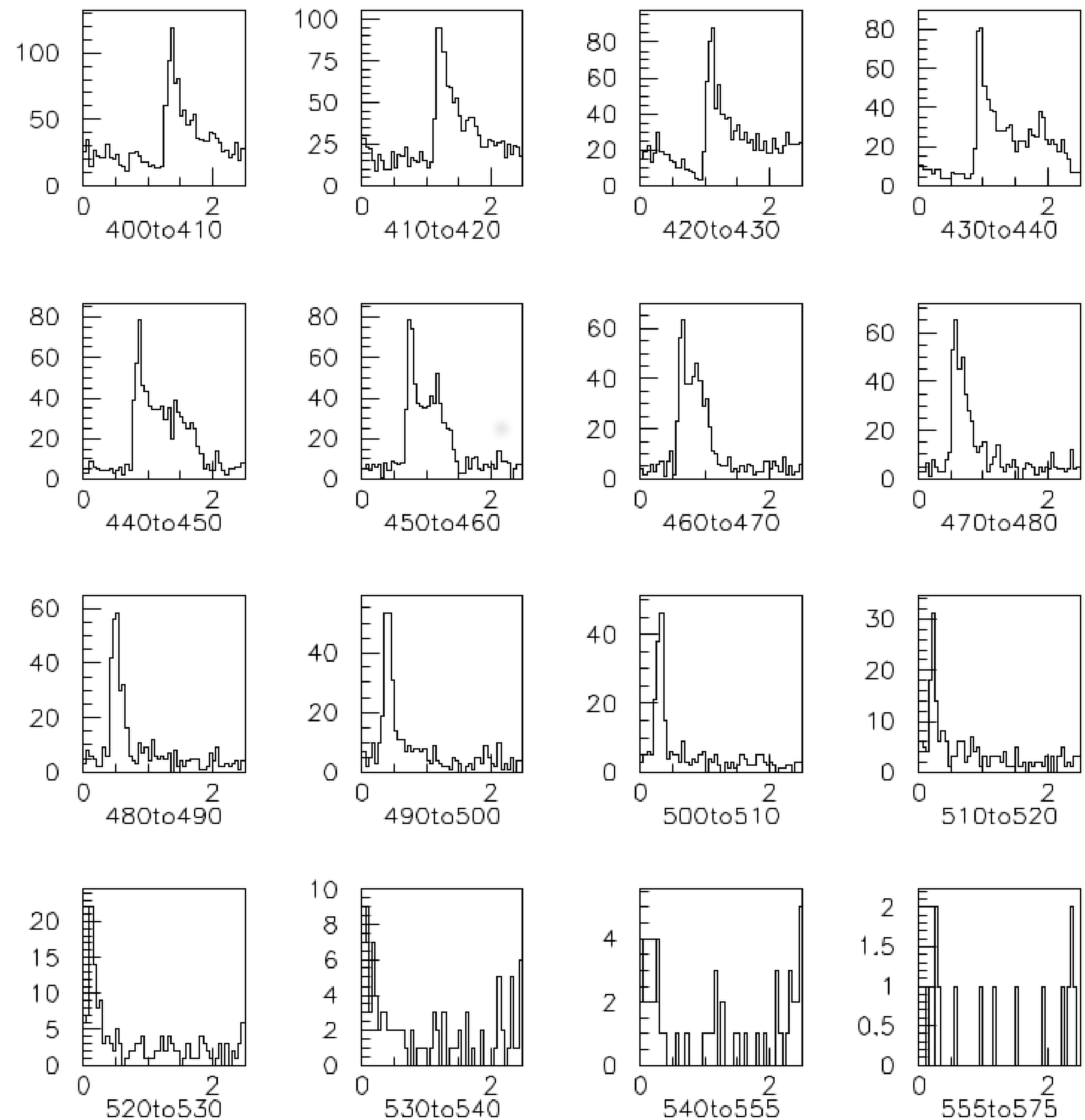
for keV sterile ν search: hardware exists in principle



Time-focusing at main spectrometer sine wave 400 kHz, 100 Vpp, U = -18400 V

Ideal scenario, toy simulations





Time-focusing at main spectrometer sine wave 400 kHz, 100 Vpp, U = -17575 V

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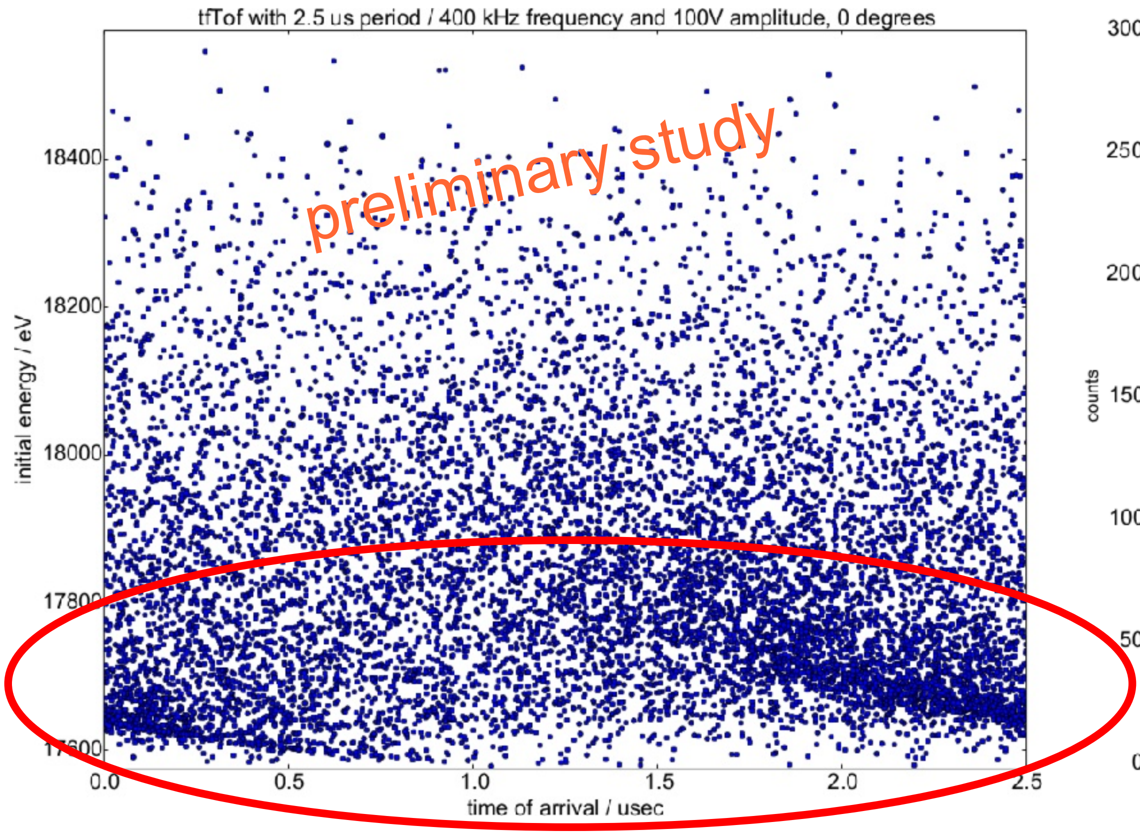
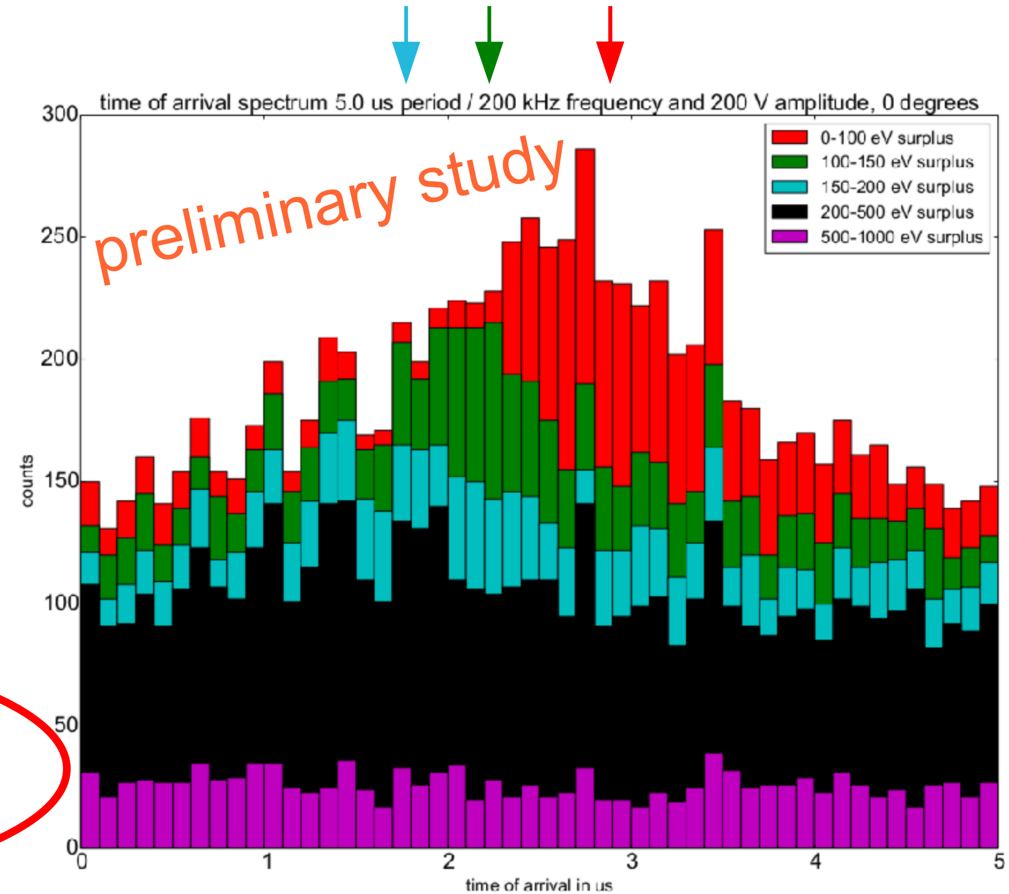
Realistic scenario, modulating HV on central wire electrode system



time-focusing energy band just above energy threshold



Statistical sensitivty of a 163Ho EC experiment (ECHo, HOLMES, NuMECS)

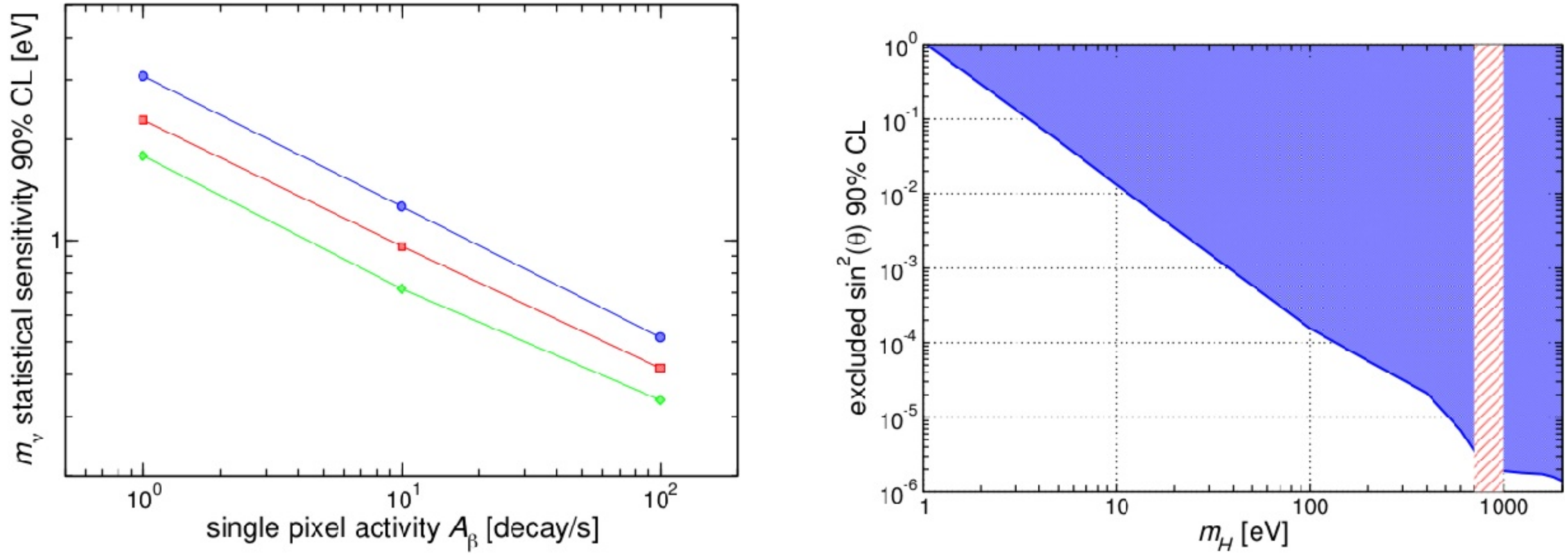
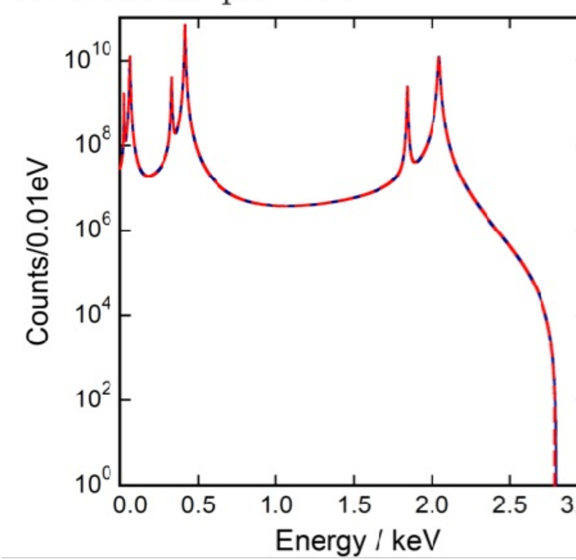


Figure 28: Calculated experimental ^{163}Ho EC calorimetric spectrum for $Q = 2.8\,\text{keV}$, $\Delta E = 1\,\text{eV}$, for a constant exposure of 10^5 detector×year, and for (top to bottom) $\tau_R = 10\,\mu s$, $1\,\mu s$, and $0.1\,\mu s$ (left). Sensitivity to heavy sterile neutrinos detected from kinks in a ^{163}Ho calorimetric spectrum with $Q = 2.8\,\text{keV}$, $N_{ev} = 3 \times 10^{13}$, $\Delta E = 1\,\text{eV}$, and $f_{pp} = 3 \times 10^{-4}$. (right).

A. Nucciotti, arXiv:1511.00968



limited by statistics

shape is non-trivial below the endpoint

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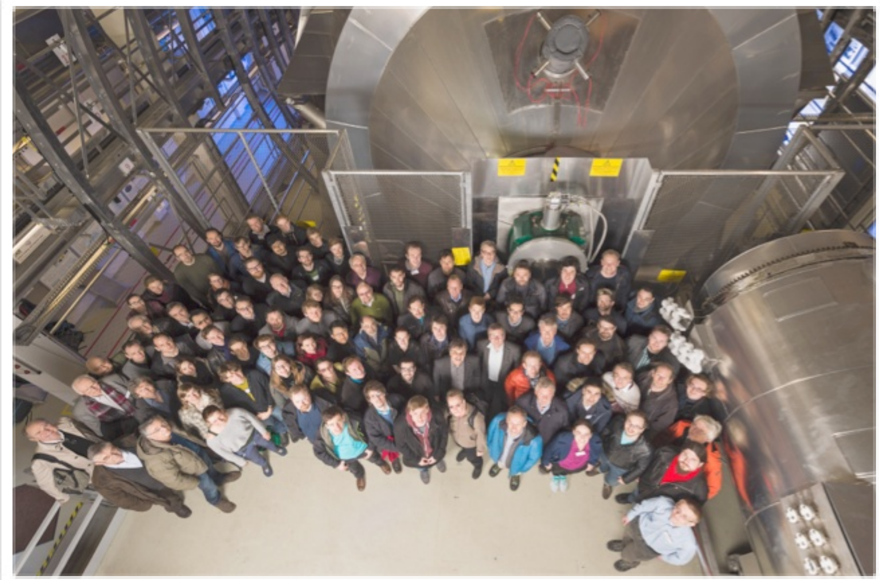
Conclusions

KATRIN is the direct neutrino mass experiment complementary to cosmological analyses and $0\nu\beta\beta$ searches

KATRIN will to start direct neutrino mass measurements in 2017

KATRIN's sensitivity: 200 meV

KATRIN can also look for sterile neutrinos (eV, keV)



Is 200 meV the end of direct neutrino mass searches? No!
- significant developments on ^{163}Ho micro calorimeters (ECHo, HOLMES, NuMECS)
- new ideas like Project 8, …
- addition differential methods to KATRIN by TOF, new detectors, ..

keV neutrino search possible with KATRIN, first search will be done in 2017 !

THANK YOU FOR YOUR ATTENTION !