Westfälische
Wilhelms-Universität
Münster

Absolute scale of the active neutrino mass and the search for sterile neutrinos with KATRIN

Ecole Internationale Daniel Chalonge – The 18th Paris Cosmology Colloquium 2014,
Observatoire de Paris, Paris, July 23-25, 2014

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- Introduction
- The Karlsruhe tritium neutrino experiment
  KATRIN
- Search for sterile neutrinos
- Summary

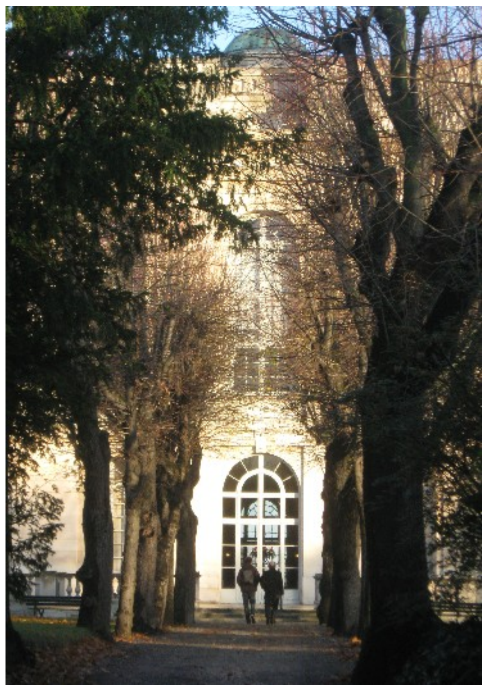
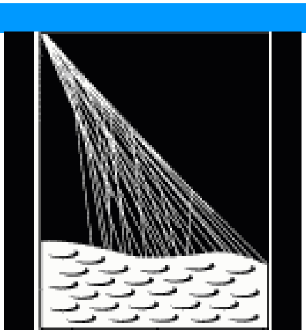


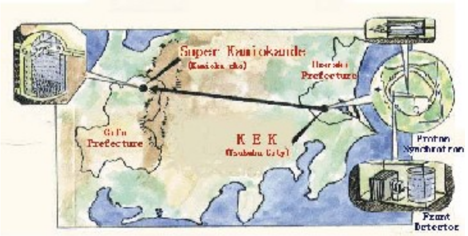
Photo: M. Zacher

Positive results from ν oscillation experiments

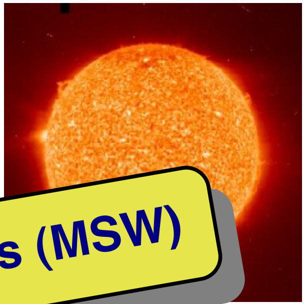
atmospheric neutrinos
(Kamiokande,
Super-Kamiokande, ...)



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

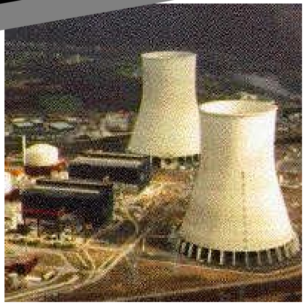


solar neutrinos
(Homestake, Gallex,
Sage, Super-Kamiokande,
SNO, Borexino)



Matter effects (MSW)

reactor neutrinos
(KamLAND, CHOOZ,
DoubleCHOOZ, Daya Bay, 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:

$0.34 < \sin^2(\theta_{23}) < 0.64$ maximal!

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

$\sin^2(\theta_{13}) = 0.084 \pm 0.005$

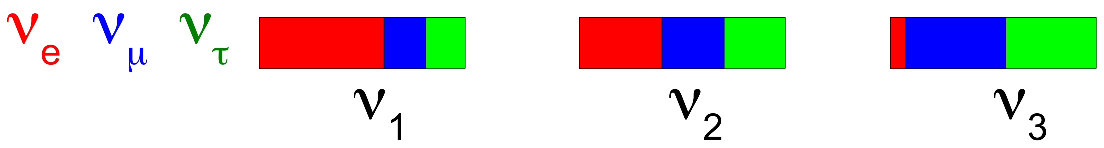
$7.0\ 10^{-5}\ \mathrm{eV}^2 < \Delta m_{12}^2 < 8.2\ 10^{-5}\ \mathrm{eV}^2$

$2.1\ 10^{-3}\ \mathrm{eV}^2 < |\Delta m_{13}^2| < 2.7\ 10^{-3}\ \mathrm{eV}^2$

⇒ $m(\nu_j) \neq 0$, but unknown !

Need for the absolute ν mass determination

Results of recent oscillation experiments: Θ_{23}, Θ_{12}, Θ_{13}, Δm^2_{23}, Δm^2_{12}



degenerated masses

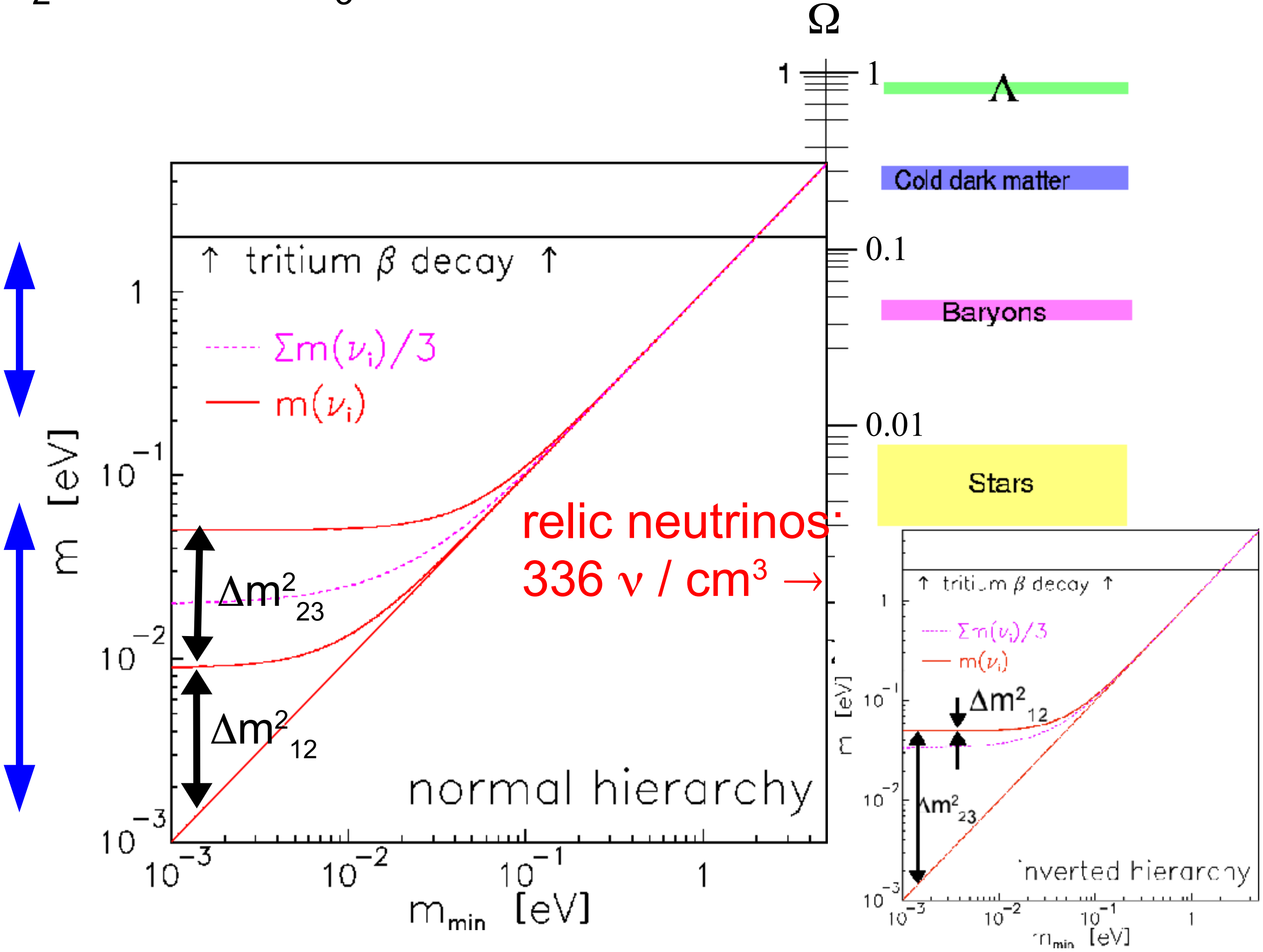
cosmological relevant

e.g. seesaw mechanism type 2

hierarchical masses

e.g. seesaw mechanism type 1

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



relic neutrinos: 336 ν / cm^3 →

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

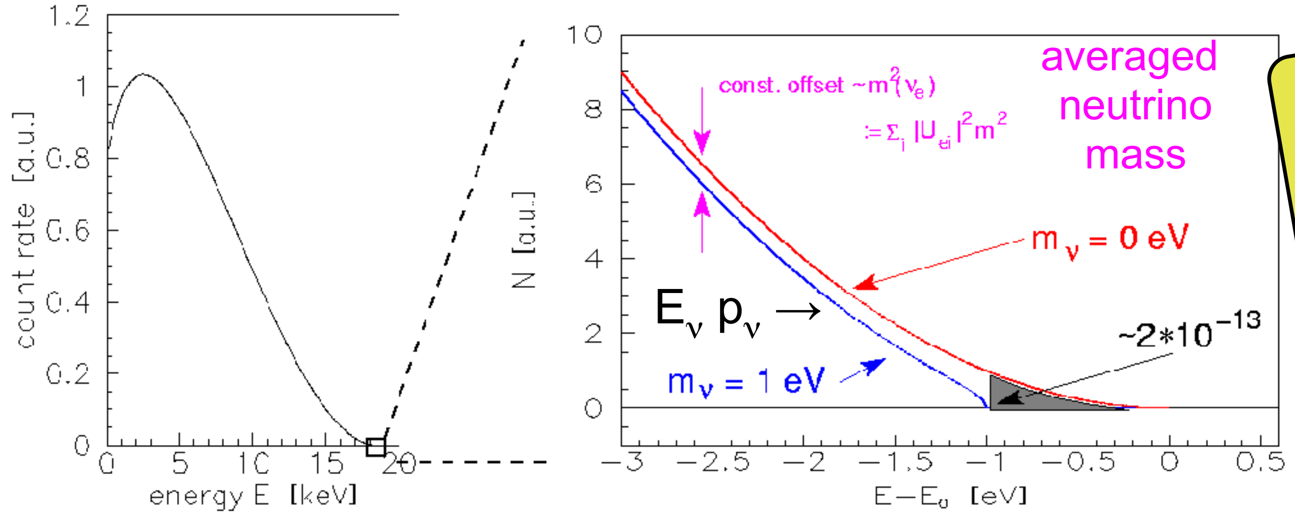
β decay: $(A,Z) \rightarrow (A,Z+1)^+ + \boxed{e^-} + \bar{\nu}_e$

Complementary to $0\nu\beta\beta$ and cosmology

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

phase space: p_e E_e E_ν p_ν

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



E.W. Otten & C. Weinheimer
Rep. Prog. Phys.
71 (2008) 086201

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

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)

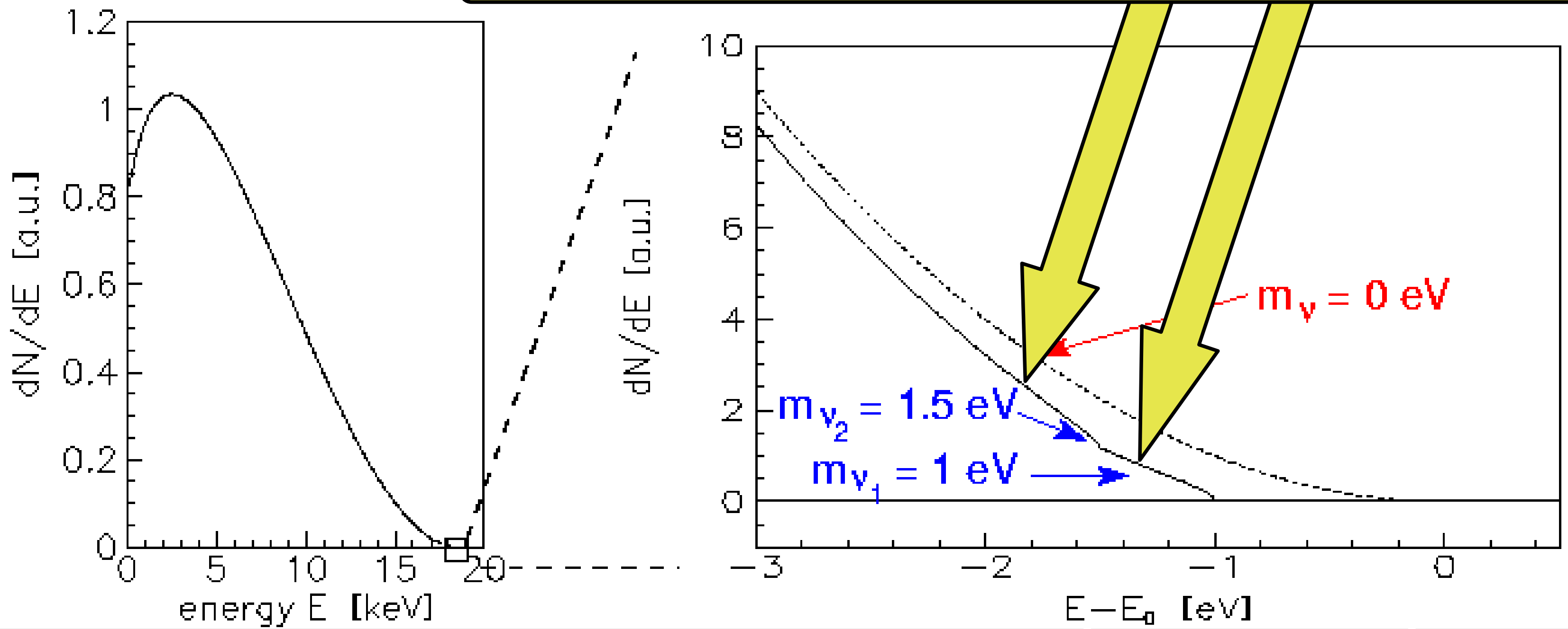
Direct determination of $m(\nu_e)$ from β decay

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

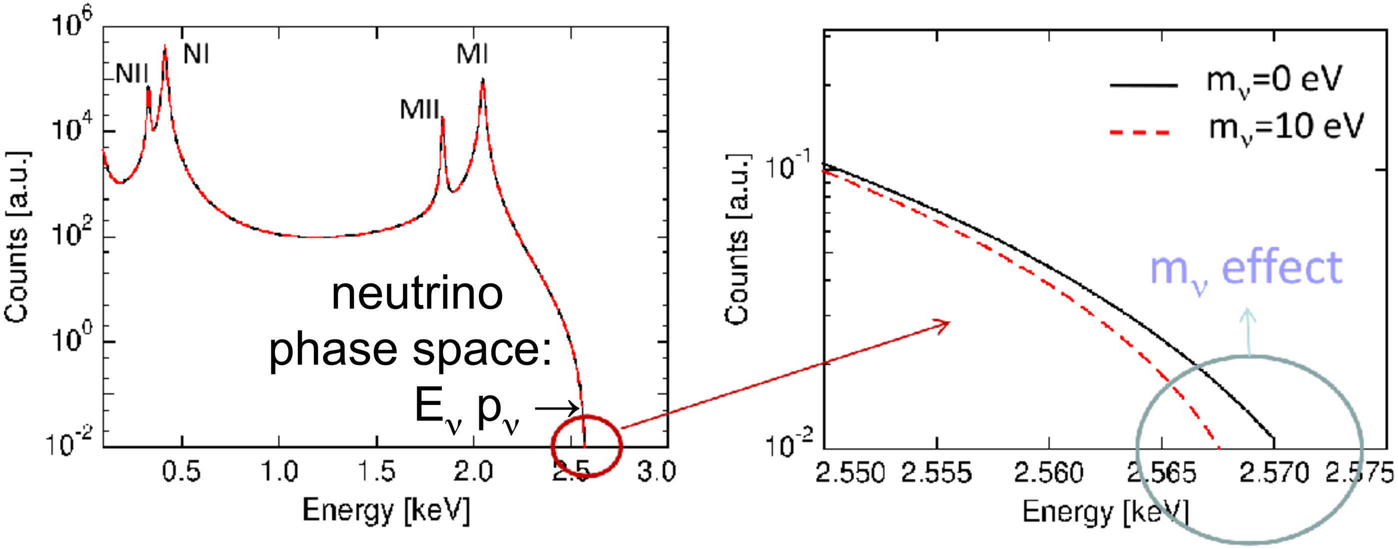
If mass eigenstates are not resolved:

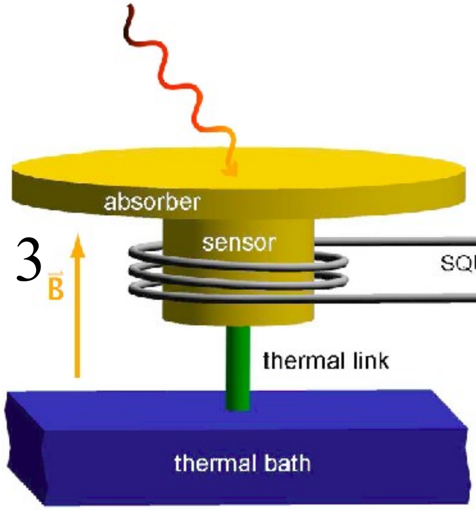
$$m^2(\nu_e) = \sum |U_{ei}^2|\, m^2(\nu_i)$$

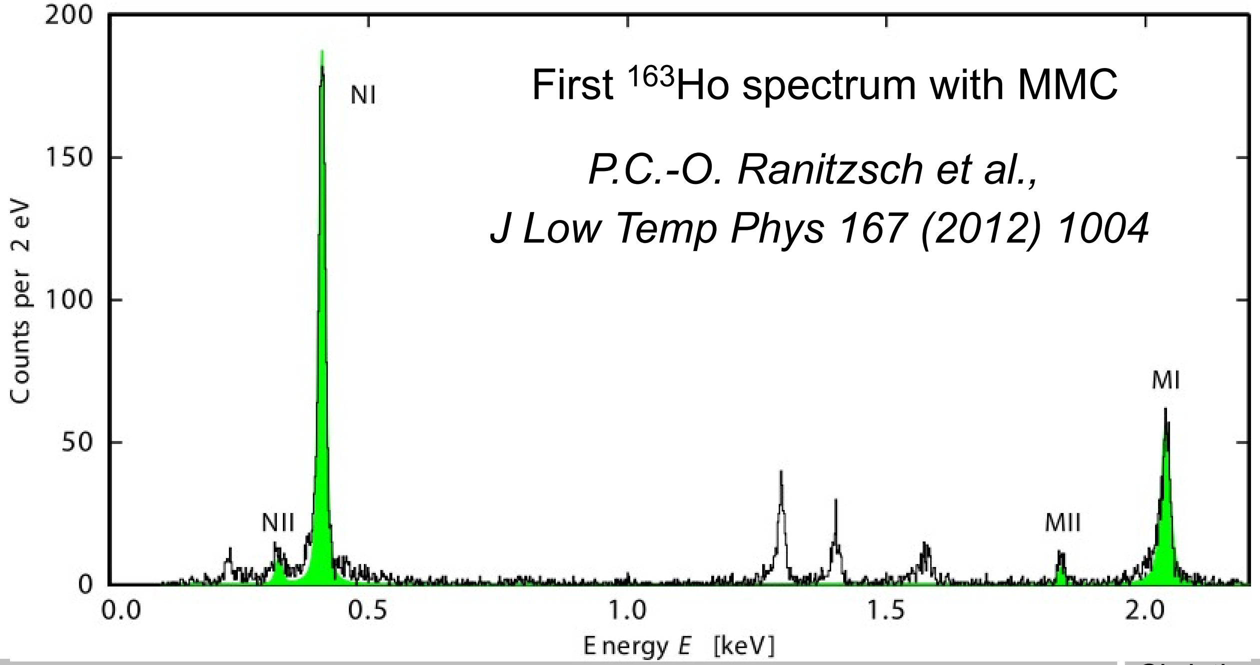


ECHo neutrino mass project: ^{163}Ho electron capture with metallic magnetic calorimeters

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

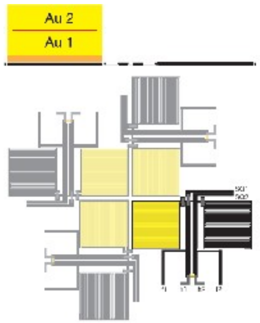


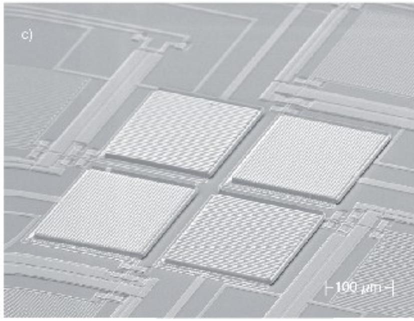




First ^{163}Ho spectrum with MMC

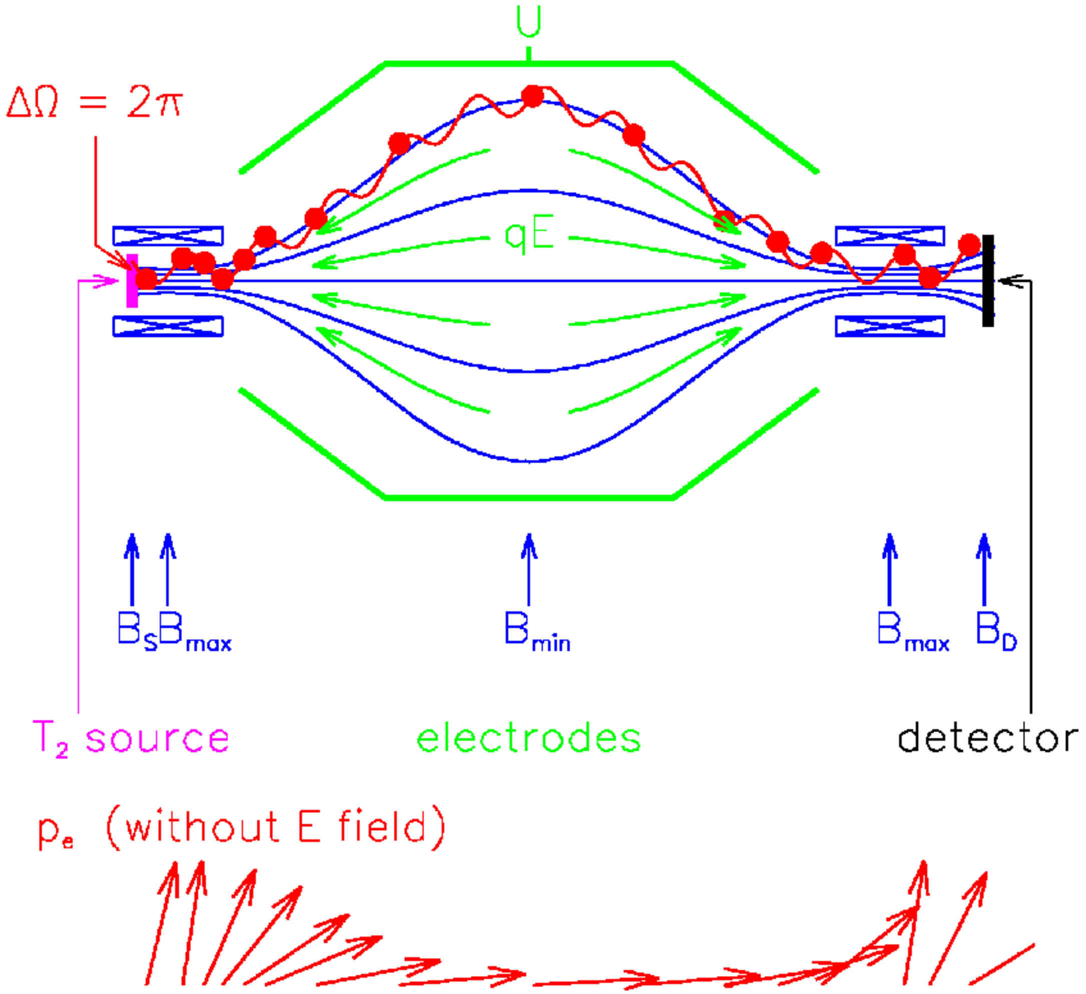
P.C.-O. Ranitzsch et al., J Low Temp Phys 167 (2012) 1004



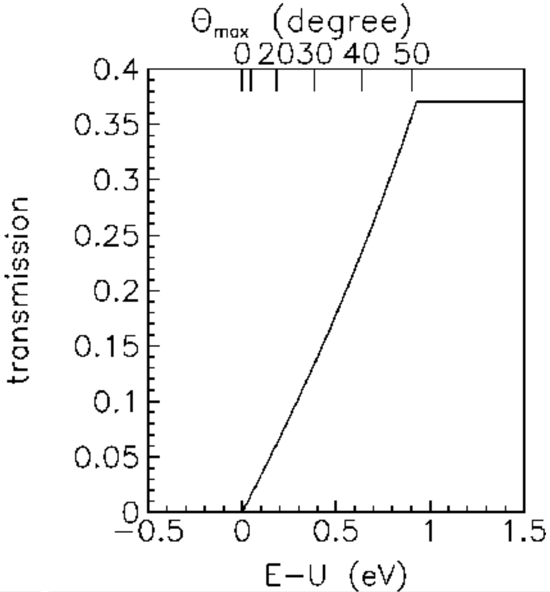


courtesy L. Gastaldo

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



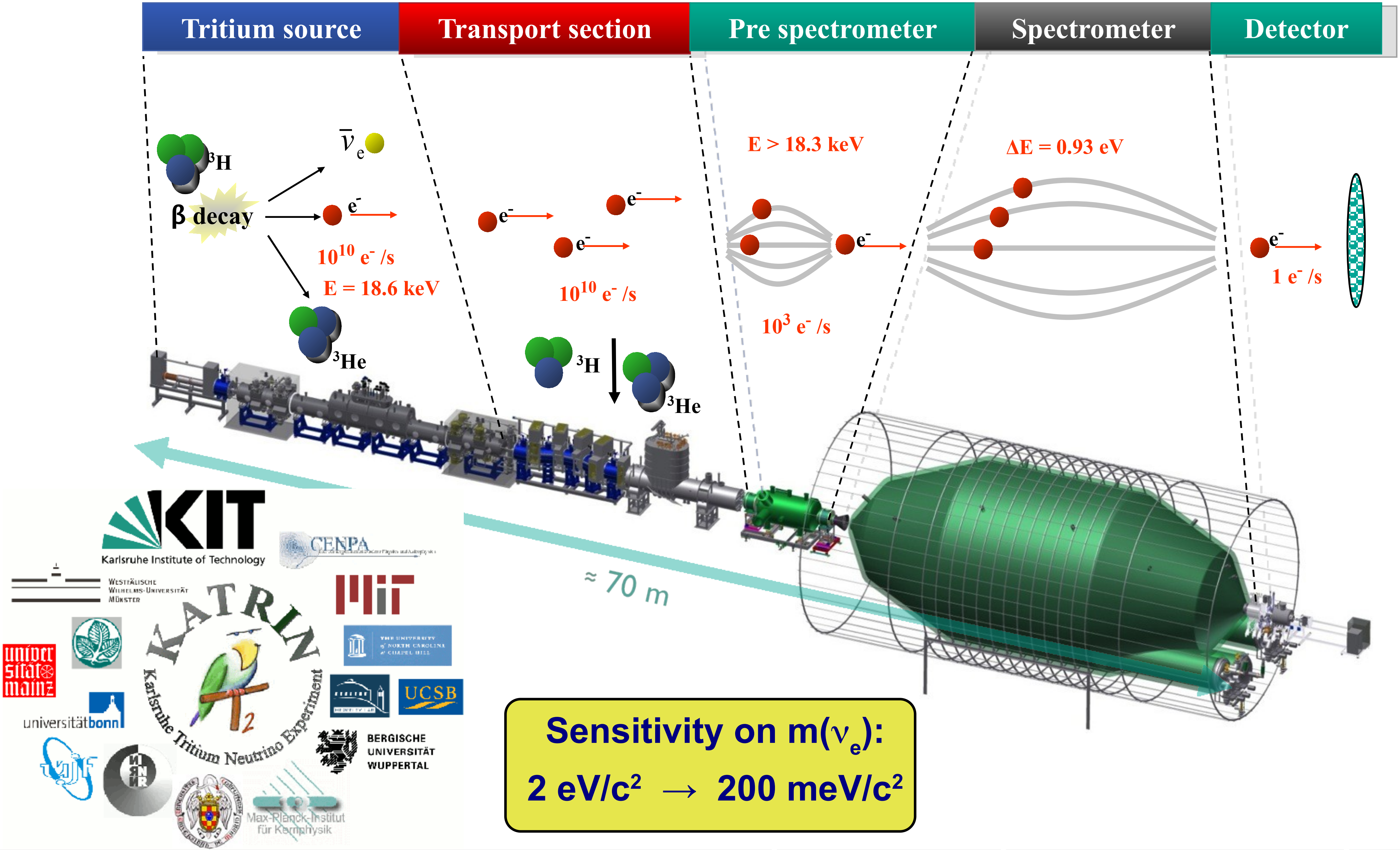
- Two supercond. solenoids compose magnetic guiding field
- adiabatic transformation:
  $\mu = E_\perp / B = \text{const.}$
  ⇒ parallel e^- beam
- Energy analysis by electrostat. retarding field
  $\Delta E = E \cdot B_{min}/B_{max}$
  $= 0.93$ eV (KATRIN)



⇒ sharp integrating transmission function without tails →

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

The Karlsruhe Tritium Neutrino Experiment
KATRIN - overview



Sensitivity on m(ν_e):

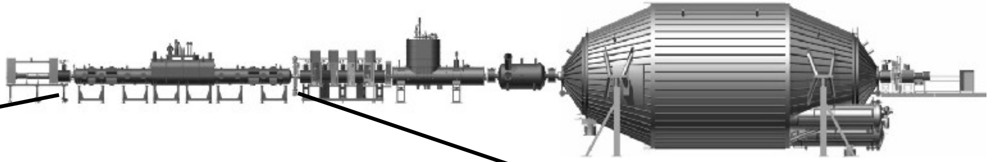
2 eV/c^2 → 200 meV/c^2

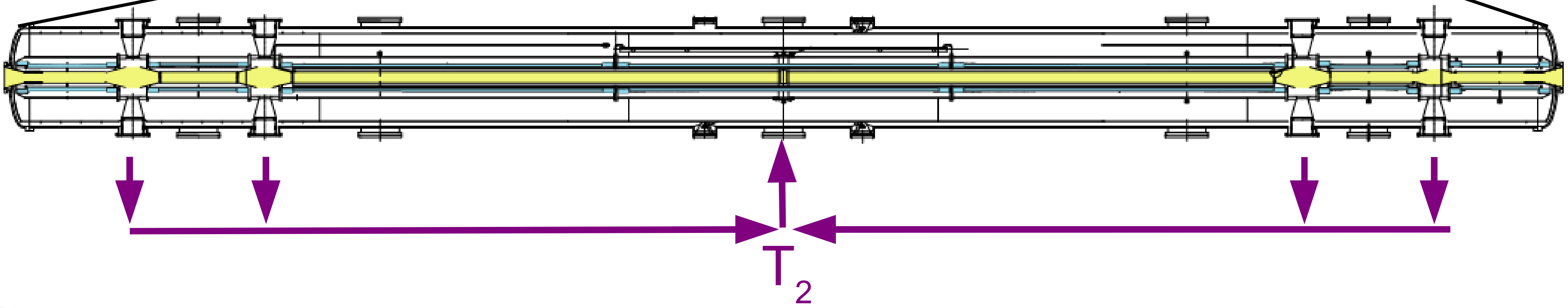
Molecular Windowless Gaseous Tritium Source WGTS

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

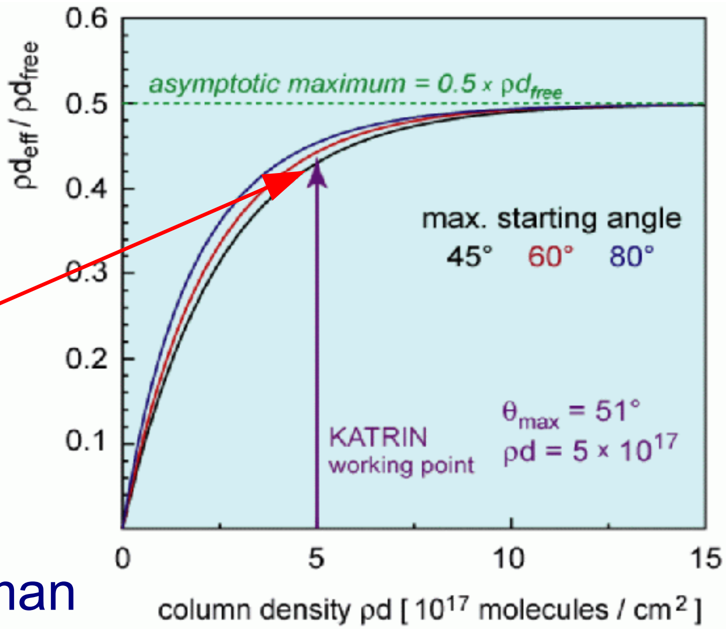




WGTS: tub in long superconducting solenoids
⌀ 9cm, length: 10m, T = 30 K

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

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



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

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Status of Windowless Gaseous molecular Tritium Source WGTS

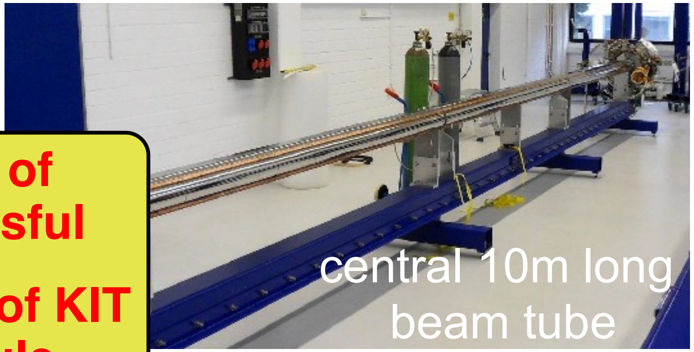
Assembly of beam tube, magnets and cryostat:


magnets and beam tubes
at both ends

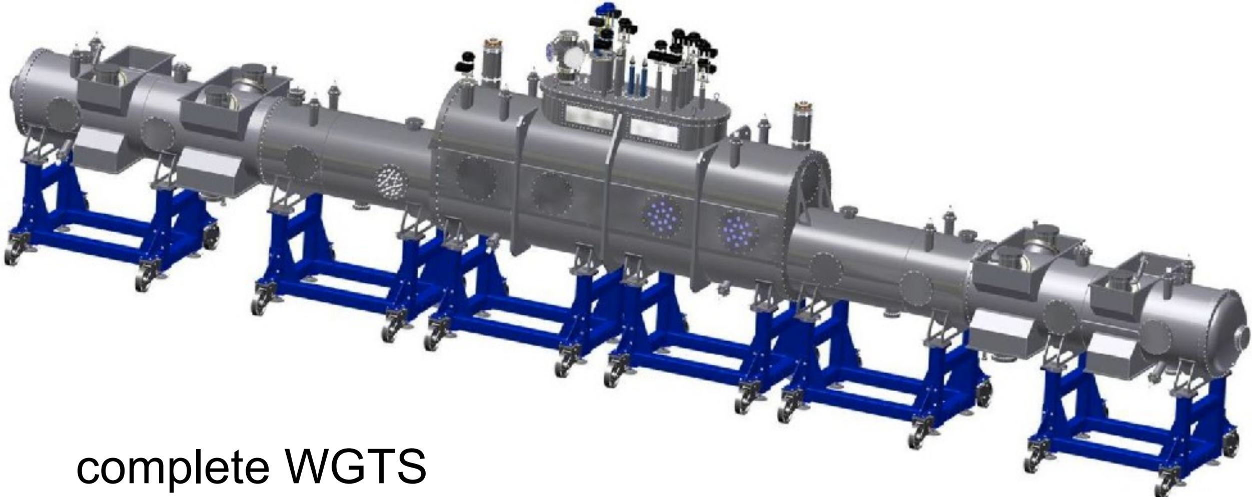
Temperature stability tests of „demonstrator“ very successful

Management now in the hand of KIT progress according schedule

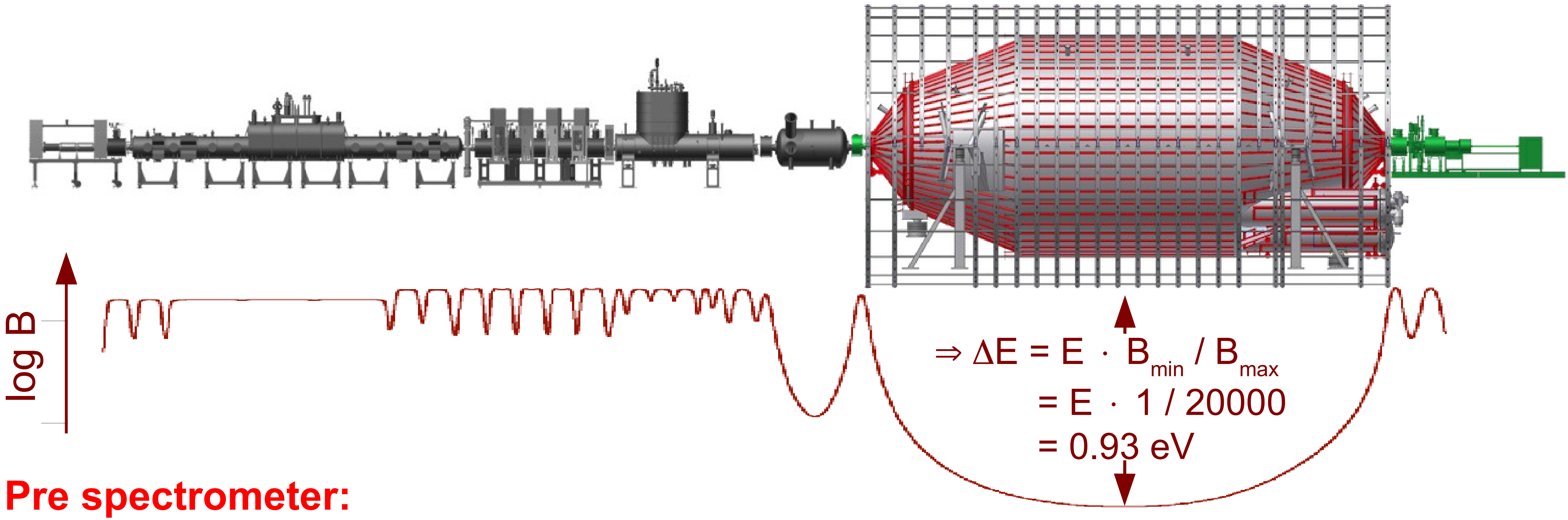
Arrival at KIT in 2015


central 10m long
beam tube


central 10m long beam tube
with superconducting magnets


complete WGTS

KATRIN spectrometers



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

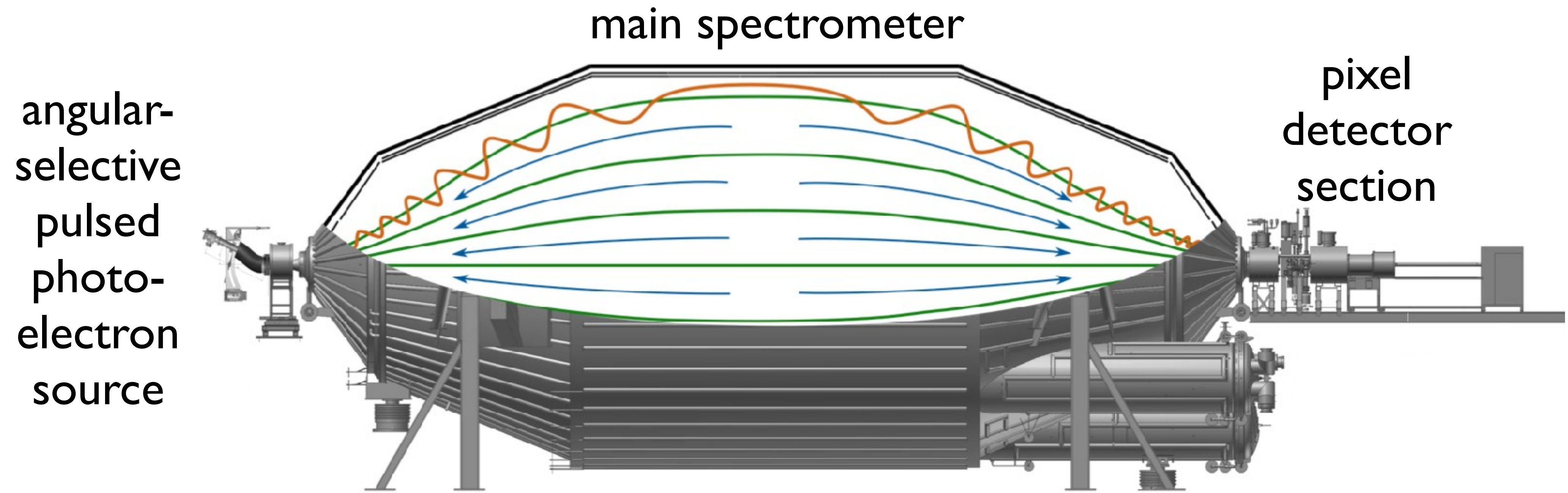
Pre spectrometer:

- 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)

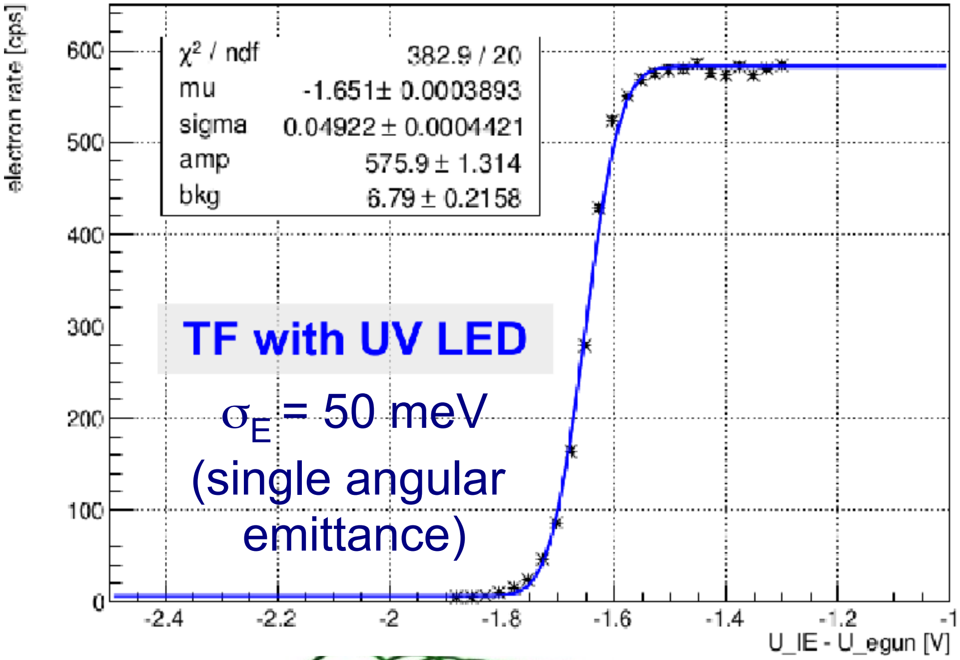
Main spectrometer and detector commissioning – objectives



Primary objectives:

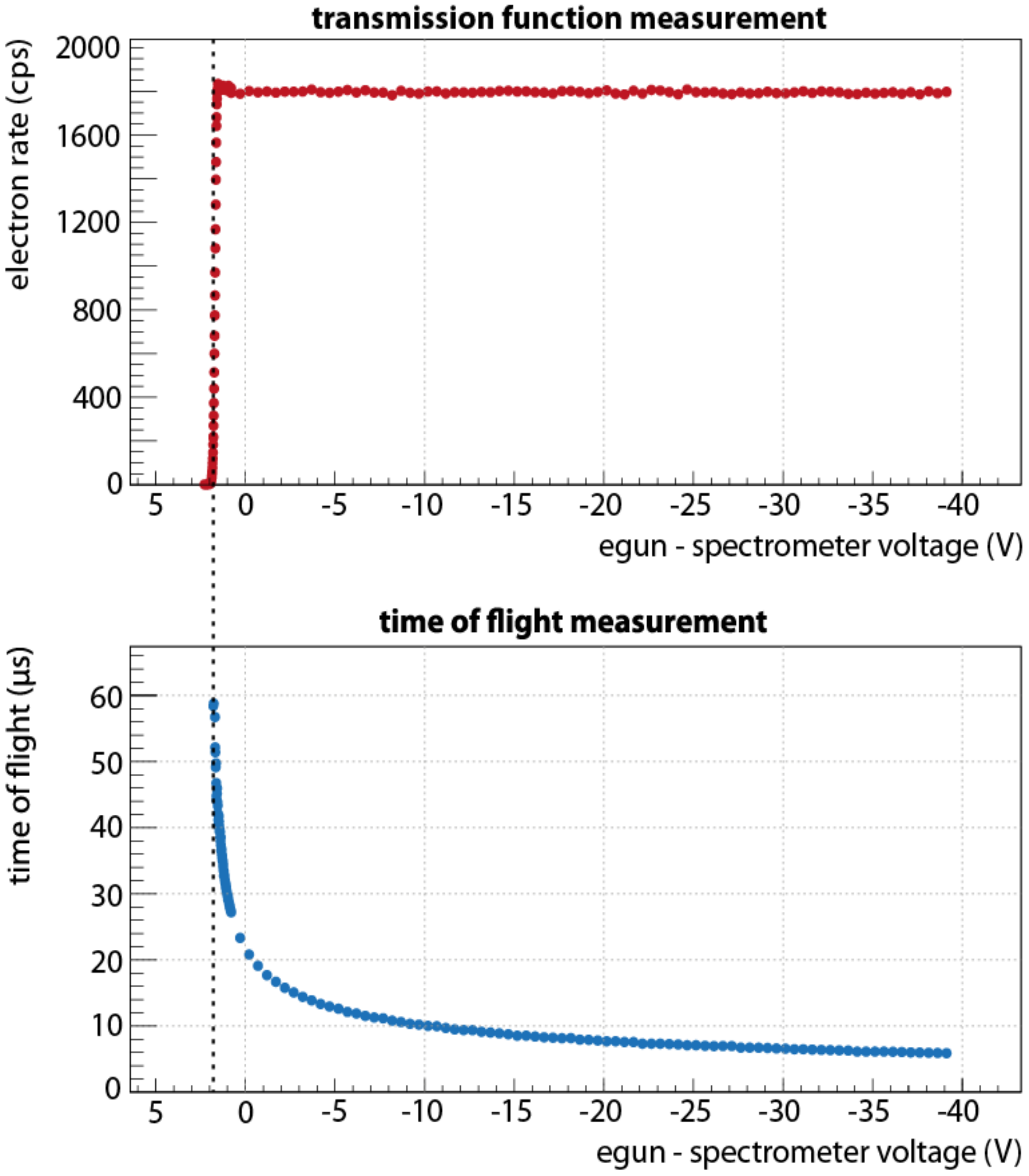
- test of individual hardware, software and slow control components
- provide ultra high vacuum conditions at the $p \approx 10^{-11}$ mbar level
- detailed understanding of the transmission properties of this MAC-E-Filter ($E = 18.6$ keV with $\Delta E = 0.93$ eV resolution) and compare to simulation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

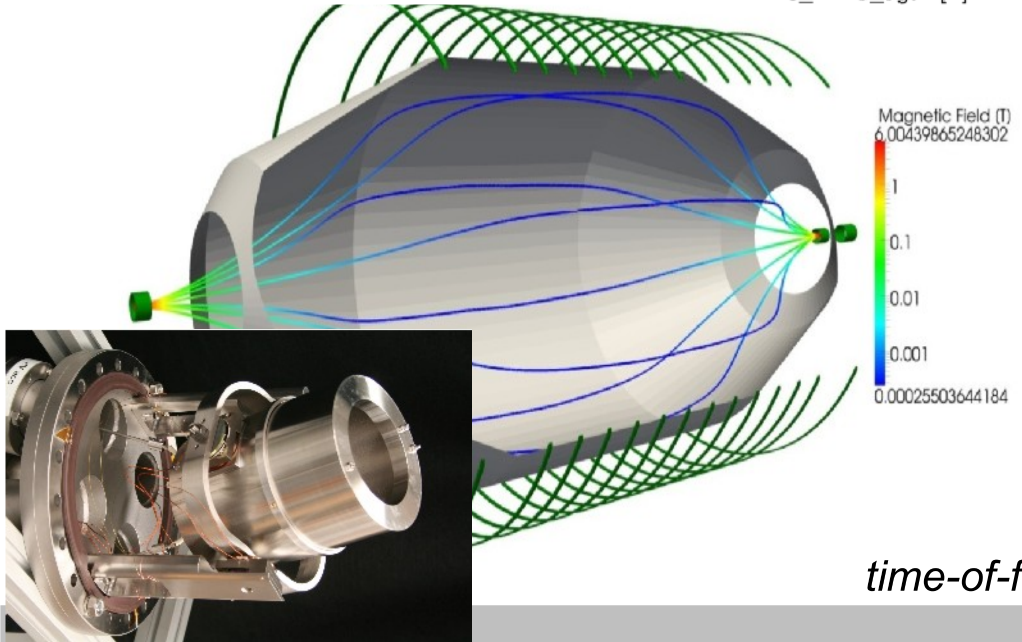
Commissioning of main spectrometer and detector



TF with UV LED

σ_E = 50 meV (single angular emittance)





time-of-flight, see also N. Steinbrink et al., NJP 15 (2013) 113020

Suppress secondary electron background from walls on high potential

Secondary electrons from wall/electrode

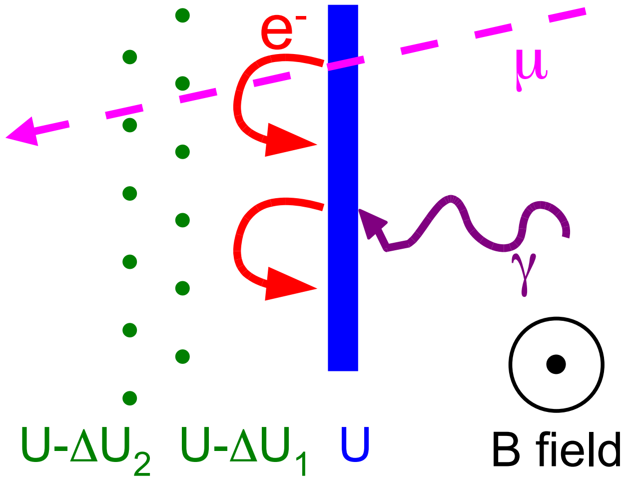
by cosmic rays, environmental radioactivity, ...

Excellent magnetic shielding by nearly perfect axial sym.

Additionally double layer wire electrode

on slightly more negative potential

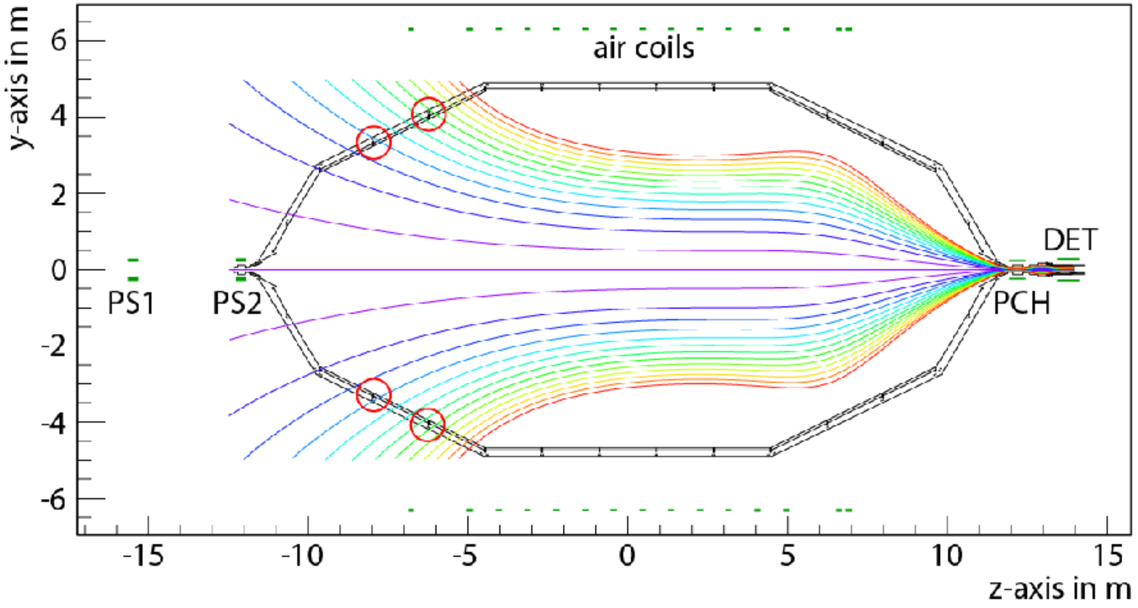
(ca. 23,000 wires, 200 μm precision, UHV compatible)



Background suppression by dual layer wire electrode

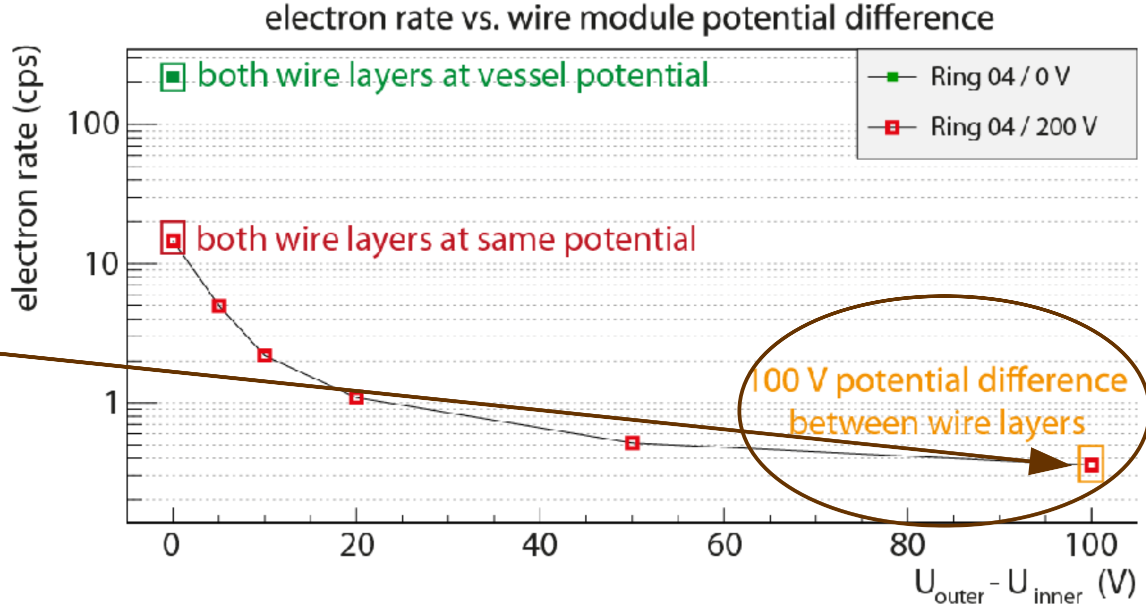
6 electric shorts between layer 1 and layer 2 of electrode system due to out-baking

→ test wire electrode shielding
by applying asymmetric B-fields
switching off magnetic shielding

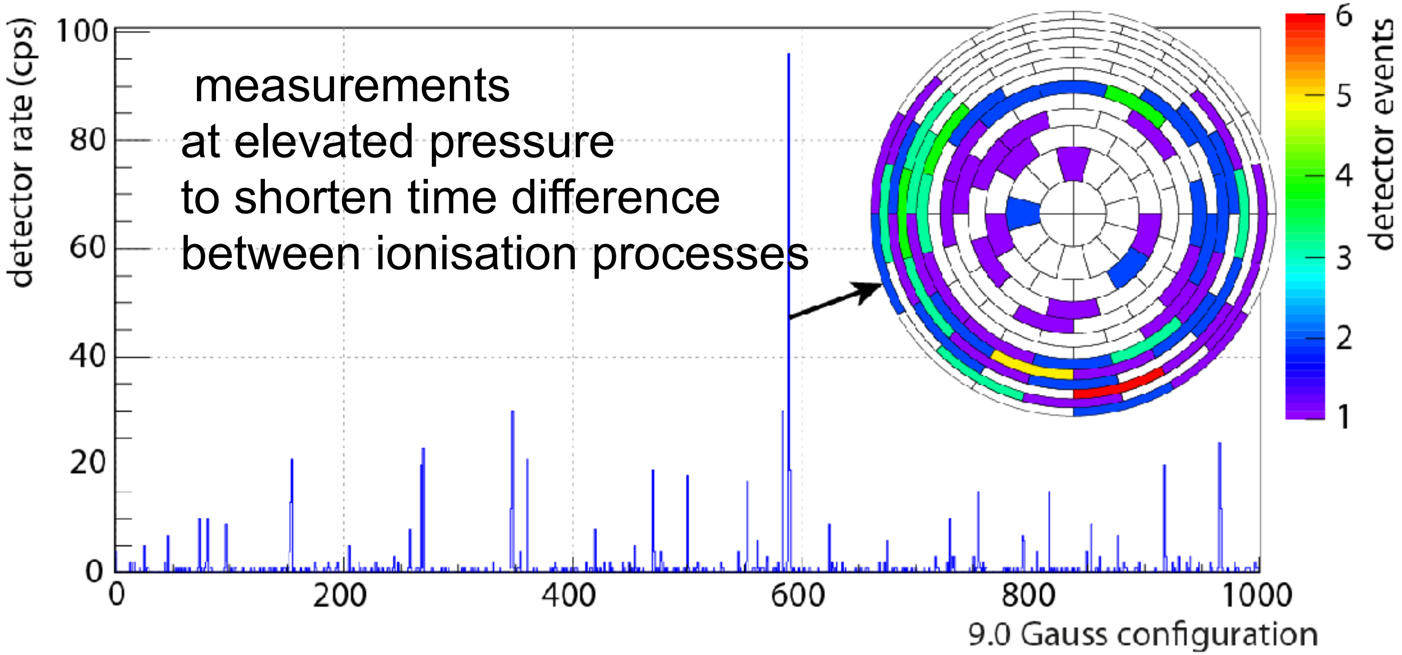


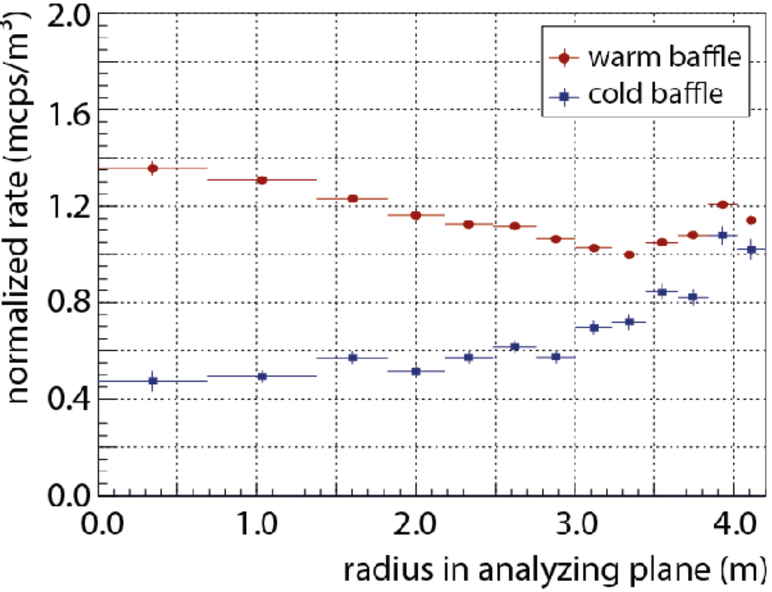
Secondary electrons from wall
- a lot, but screend by wire electrode
- dual wire electrode system is
order of magnitude more efficient

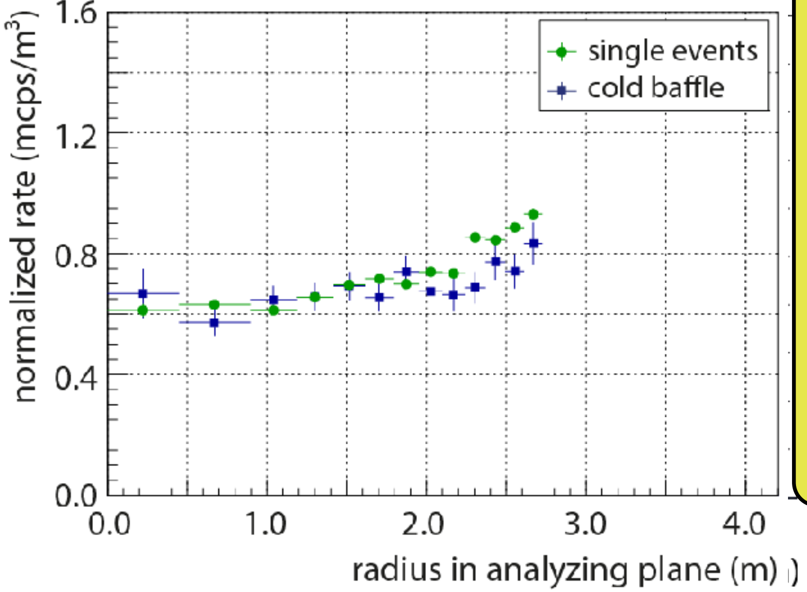
April 2014:
electric shorts in central cylindrical part of wire electrode removed !



Understanding the background: Radon and other background sources


measurements
at elevated pressure
to shorten time difference
between ionisation processes





Very good background understanding:

spike pulses can also be removed by LN2 baffle

→ indeed stored electrons by radon decays

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 eV^2 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**

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**

spectrometer

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 eV^2

Measuring the last 25 or 30 eV only
KATRIN becomes nearly
a „single final state“ experiment
as cryo-bolometers

1. inelastic scatterings of β´s inside WGTS
   - **dedicated e-gun measurements**, unfolding
2. fluctuations of WGTS column density (required <
   - rear detector, Laser-Raman spectroscopy, T=30K stabilisation, **e-gun measurements**
3. WGTS charging due to
   - **monocrystaline rea**
4. final state distribution
   - **reliable quantum ch**
5. transmission function
   - detailed simulations
6. HV stability of retarding
   - **precision HV divider (with PTB), monitor spectrometer beamline**

tritium source

spectrometer

sensitivity:

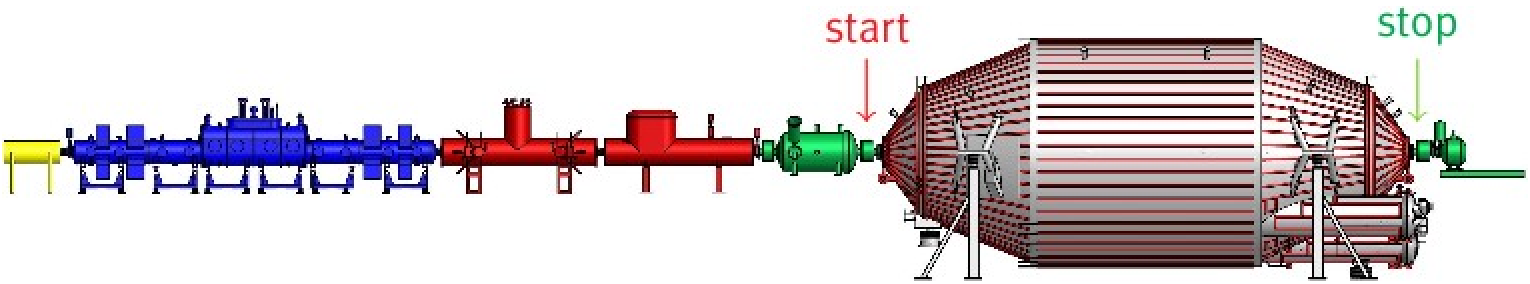
$$m_\nu < 0.2\,\text{eV (90\%CL)}$$

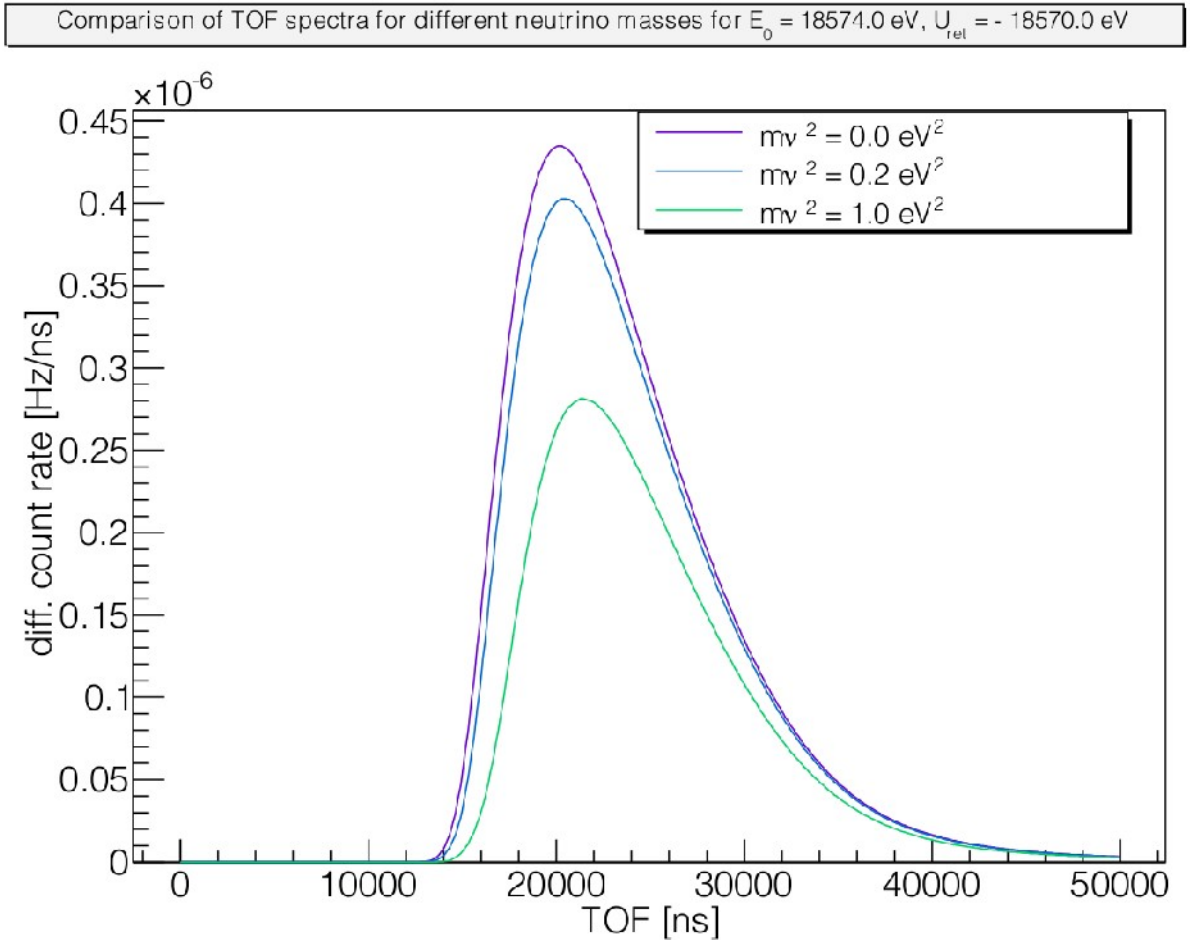
discovery potential:

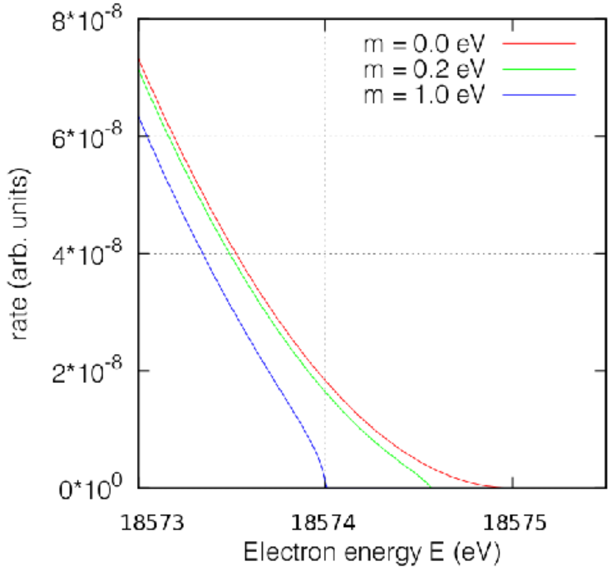
$$m_\nu = 0.3\,\text{eV} \quad (3\sigma)$$

$$m_\nu = 0.35\,\text{eV} \quad (5\sigma)$$

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





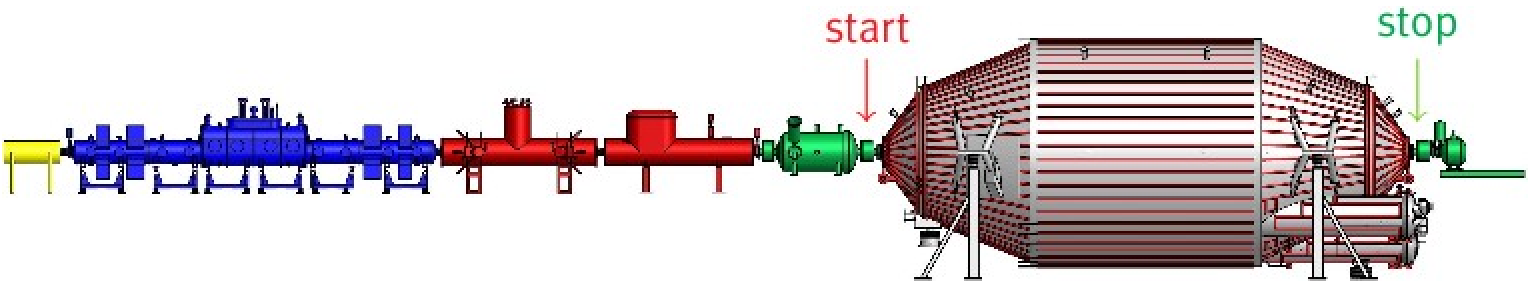


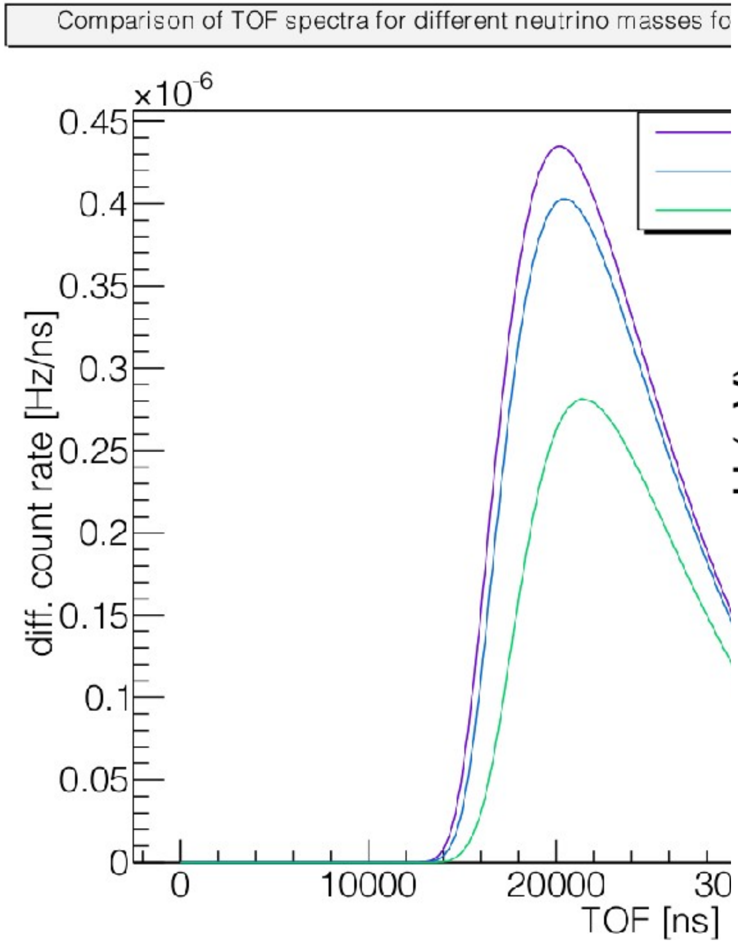
Time-of-flight spectrum is sensitive to the neutrino mass

require one retardation potential only

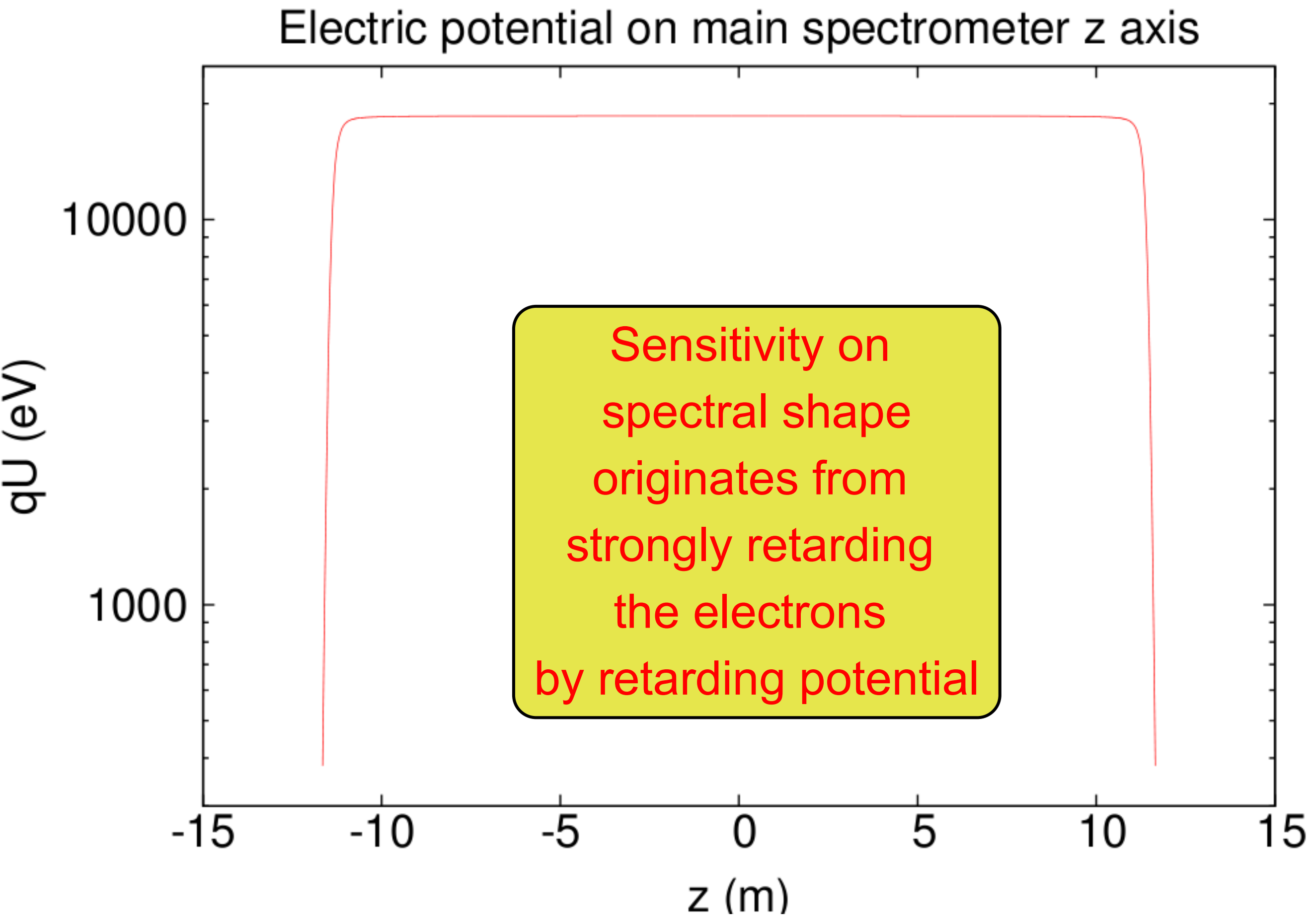
not integral but differential β-spectrum

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





Comparison of TOF spectra for different neutrino masses fo



Electric potential on main spectrometer z axis

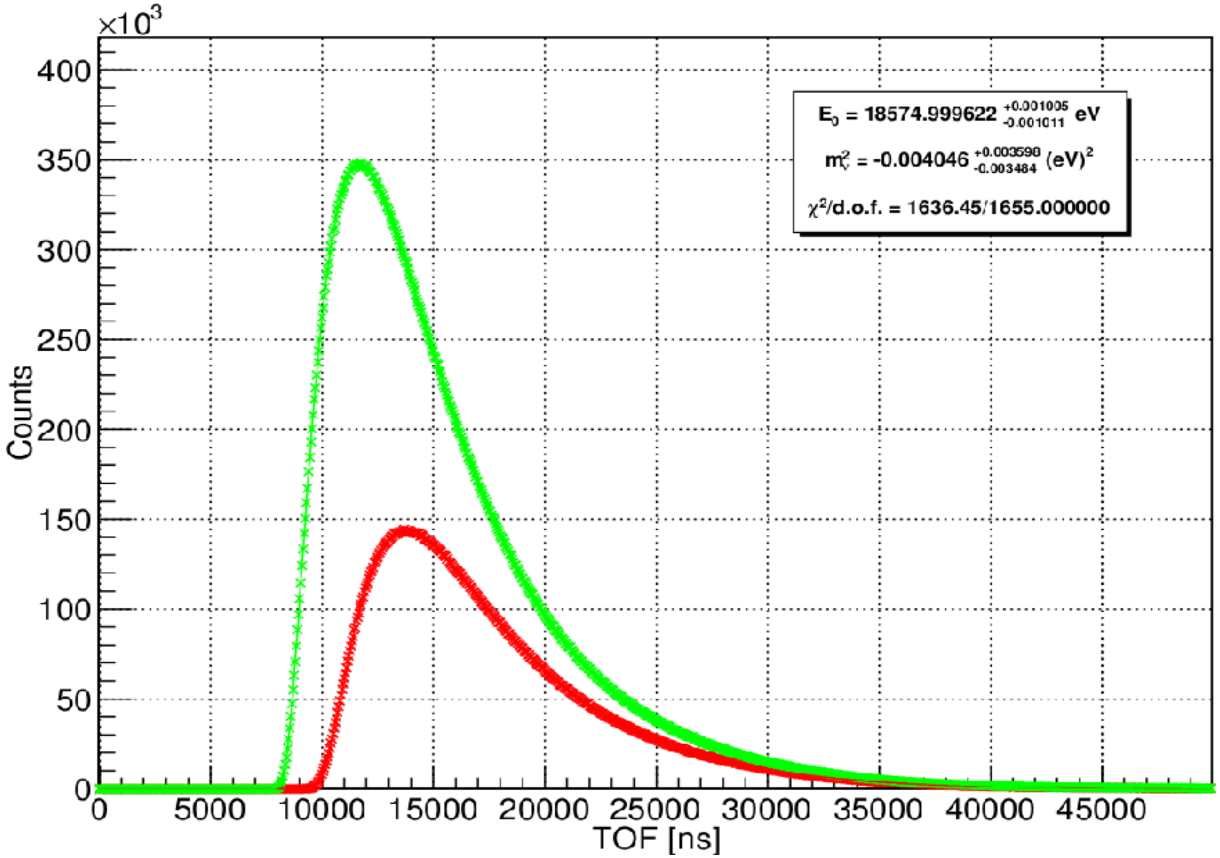
Sensitivity on spectral shape originates from strongly retarding the electrons by retarding potential

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

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

Coincidence request between start and stop signal → nice background suppression

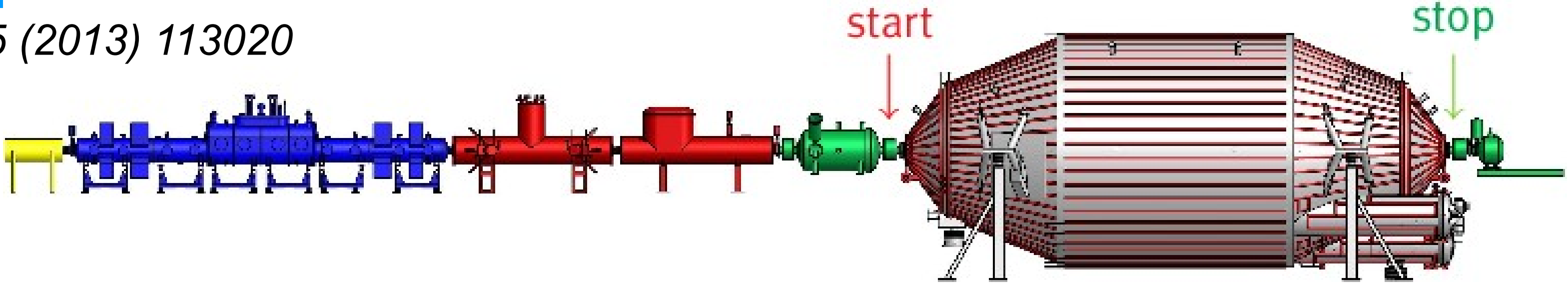
→ Factor 5 improvement in m_ν^2 w.r.t. standard KATRIN, but ideal case !



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

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

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

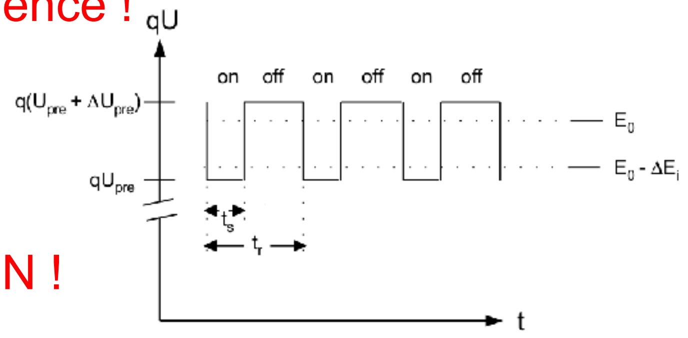


Advantage: measure full β-spectrum by time-of-flight at one (a few) retarding potential

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

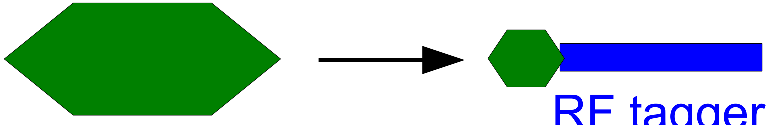
Start: e^--tagger: Need to determine time-of-passing-by of e^- before main spectrometer without disturbing energy and momentum by more than 10 meV:
→ Need „detector“ with 10 meV threshold
seems not to be forbidden but unrealistic for the near future !
Added value: significant background reduction by coincidence !

→ factor 5 in $\Delta m(\nu)^2_{stat}$ under ideal cond.



or: Use pre spectrometer as a „gated-filter“
by switching fast the retarding voltage
→ As sensitive on the neutrino mass as standard KATRIN !

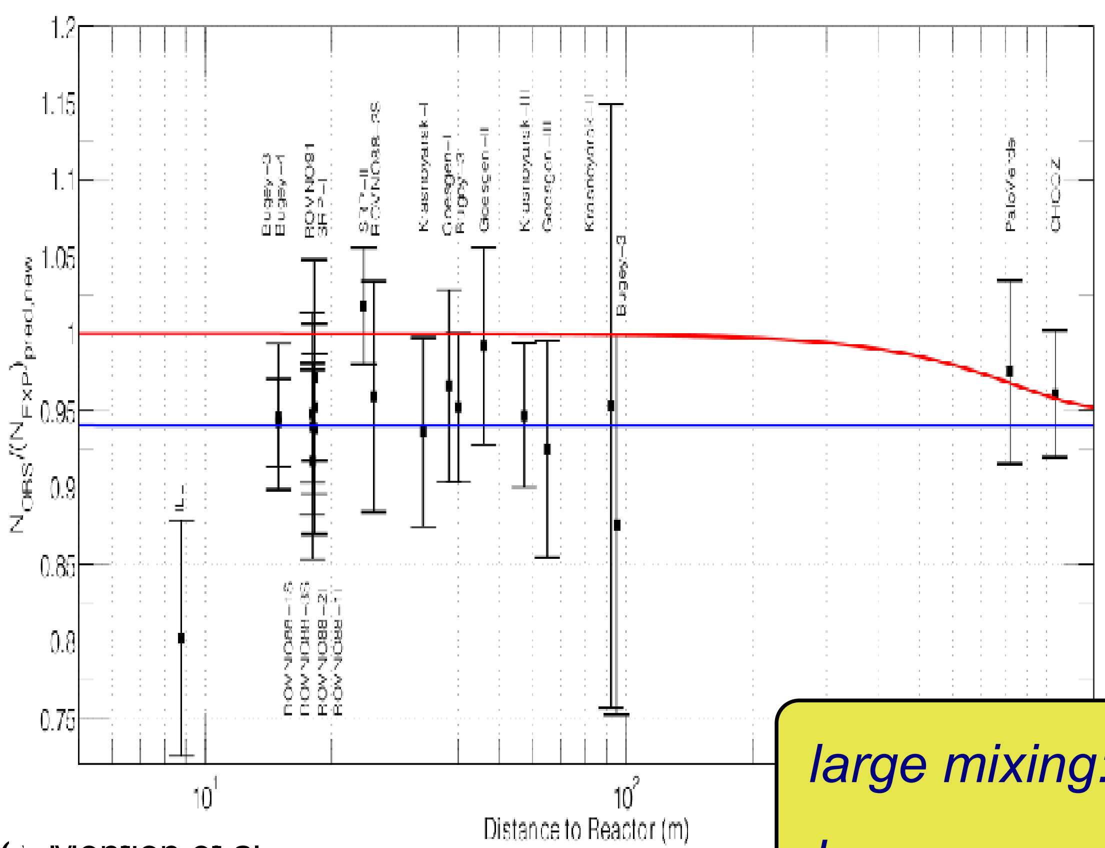
or: Reduce pre spectrometer to a minimal small one,
add a Project 8-type tagger within a long solenoid



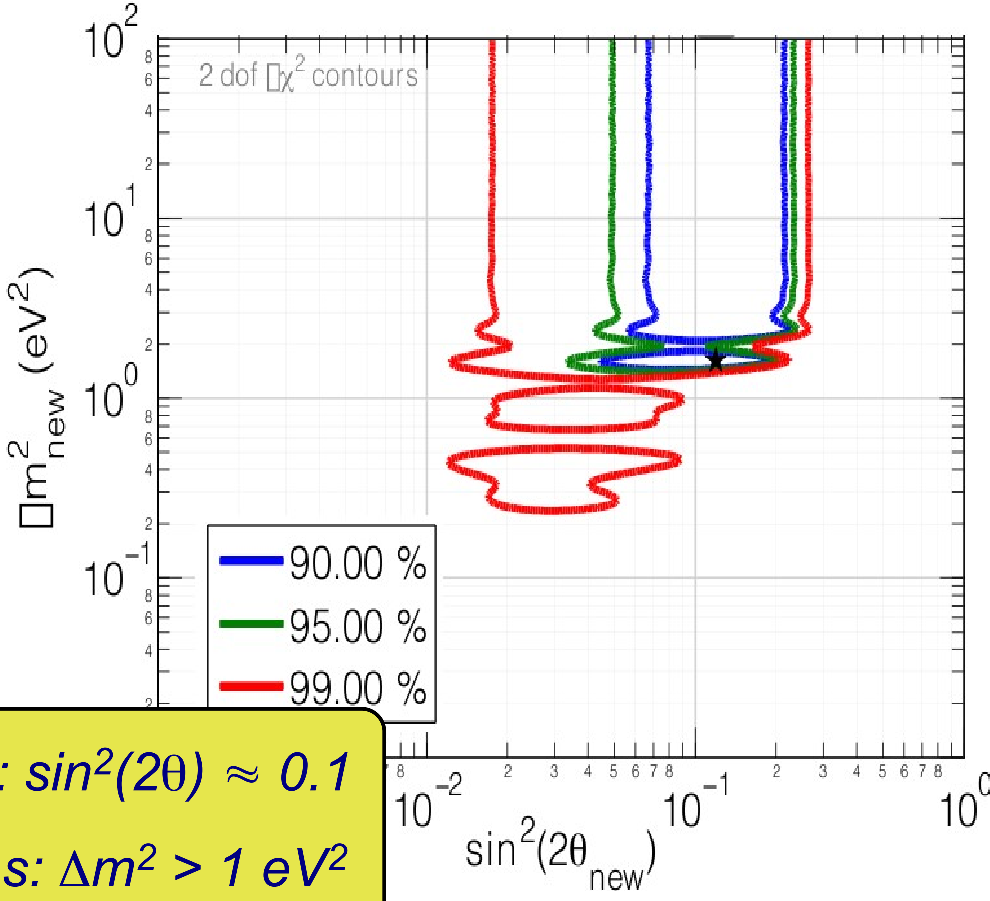
Is there a fourth sterile neutrino state ?

Re-evaluation of reactor neutrinos fluxes and use of GALLEX/SAGE calibration measurements:

"reactor antineutrino anomaly": $P_{ee} = 0.943 \pm 0.023$



G. Mention et al.,
Phys. Rev. D 83 (2011) 073006

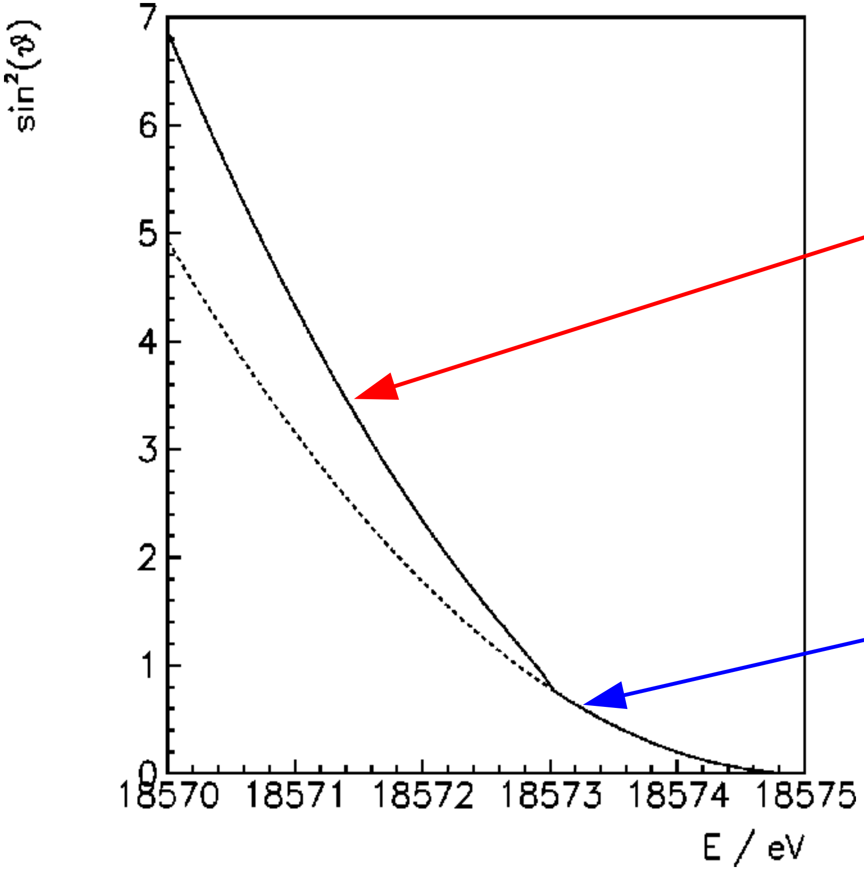


large mixing: $\sin^2(2\theta) \approx 0.1$

large masses: $\Delta m^2 > 1$ eV^2

Influence of a 4th sterile neutrino near the endpoint E_0

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



e.g.

$m(\nu_4) = 2$ eV

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

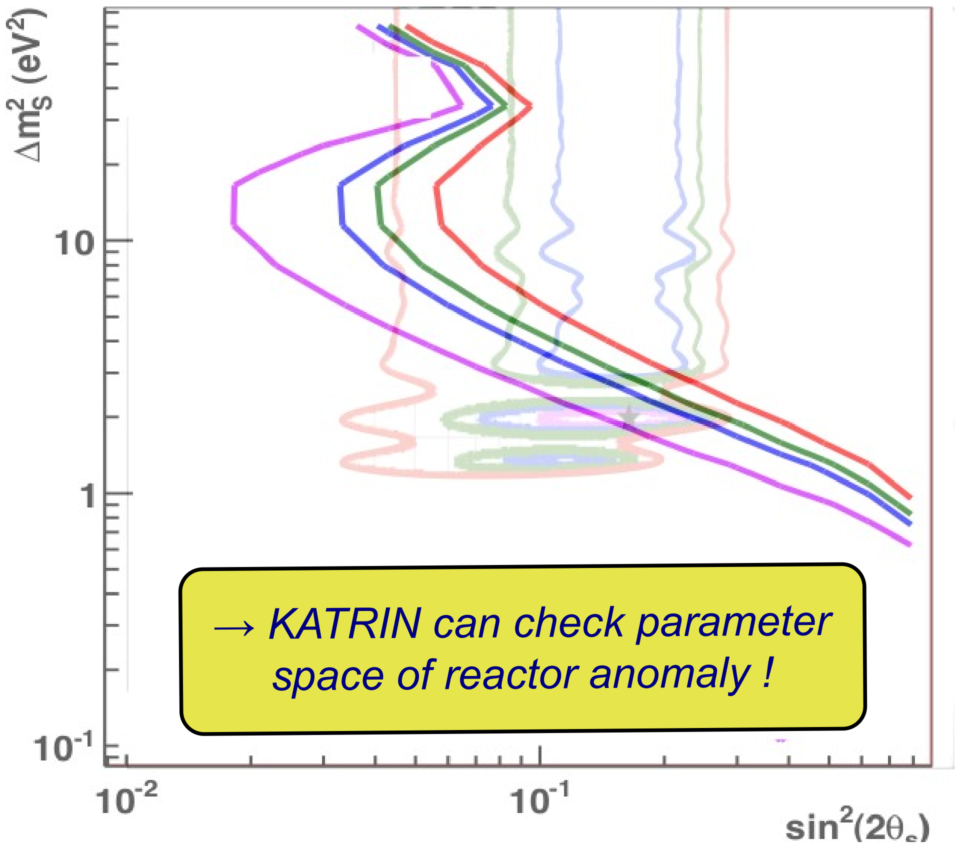
e.g.

$m(\nu_{123}) \approx 0$ eV

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

Sensivity on sterile neutrinos of the next direct neutrino mass experiments

KATRIN



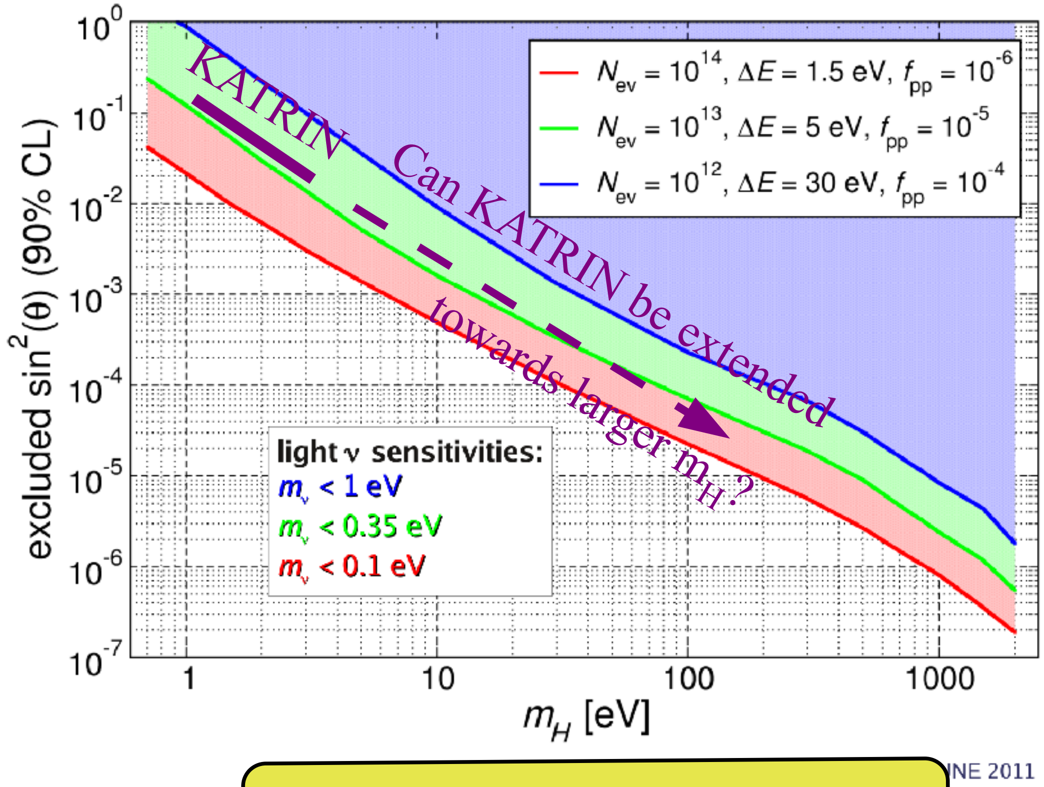
→ *KATRIN can check parameter space of reactor anomaly !*

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

MARE II



KATRIN

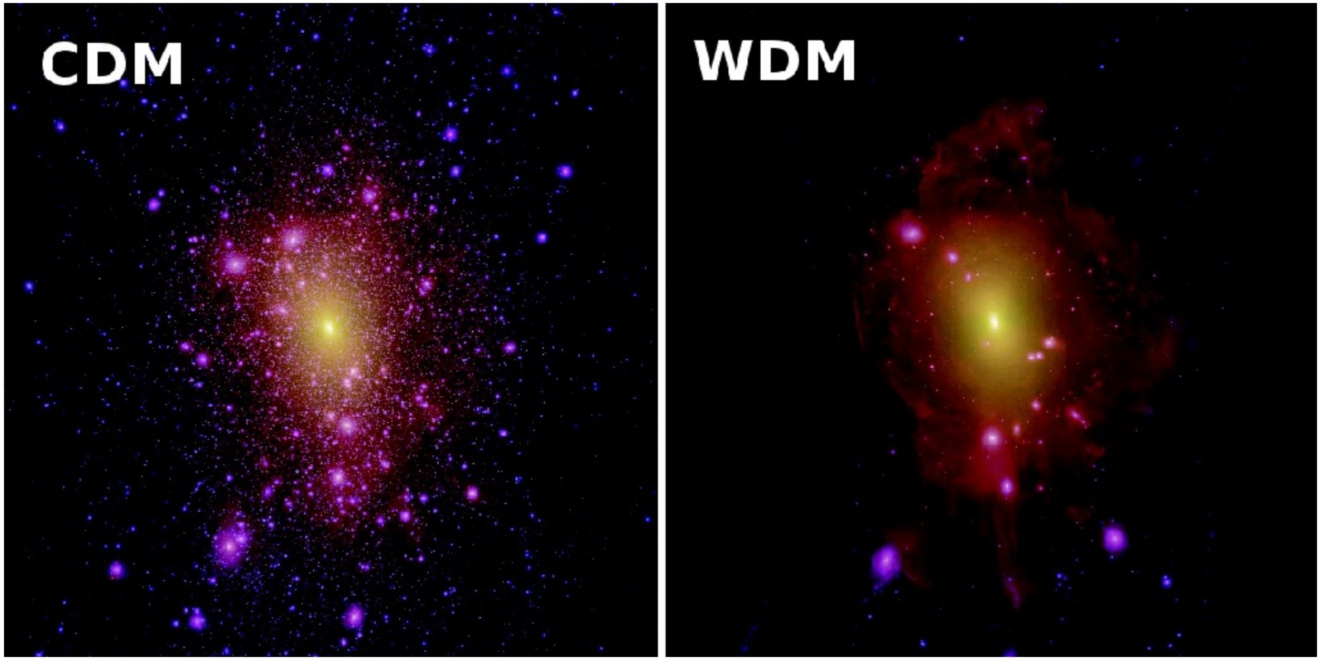
Can KATRIN be extended towards larger m_H?

→ *Need certainly a new strategy !*

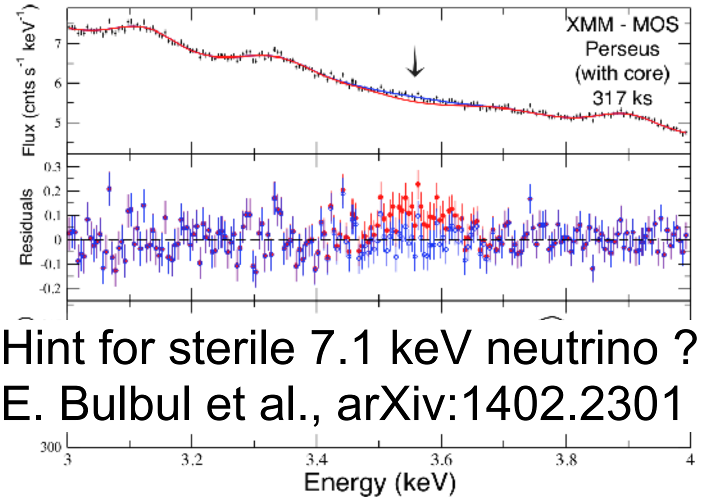
A. Nucciotti, Meudon Workshop, June 2011

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

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

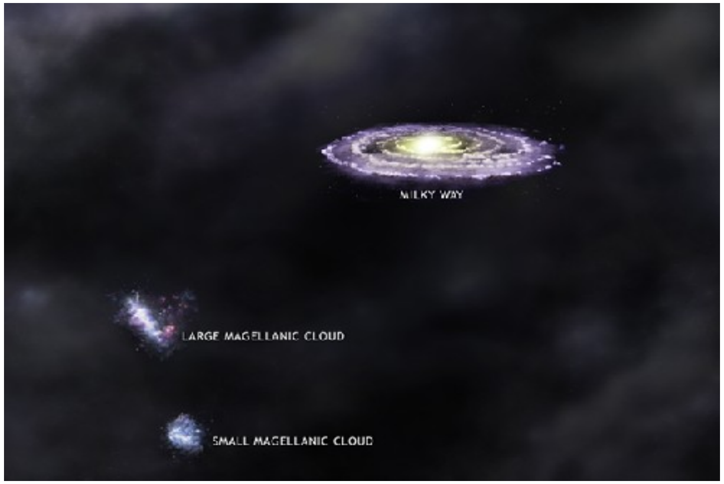


(e.g. Lovell et al. at Meudon Workshop 2012)



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

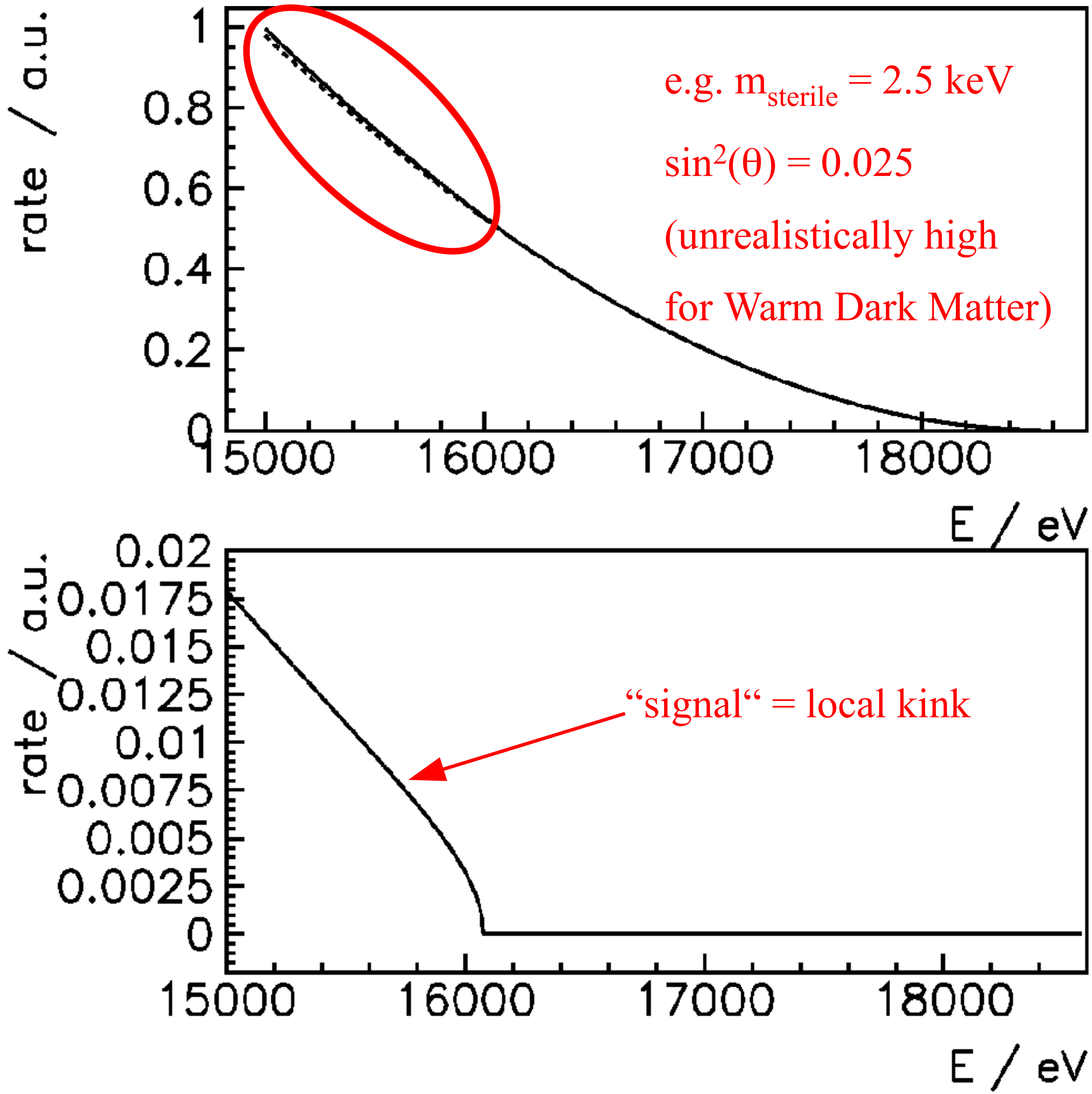
In contrast to observations ! (here only artist view on the right)



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

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

Search for a tiny kink of a keV neutrino



e.g. $m_{\text{sterile}} = 2.5$ keV

$\sin^2(\theta) = 0.025$

(unrealistically high

for Warm Dark Matter)

“signal“ = local kink

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 ?

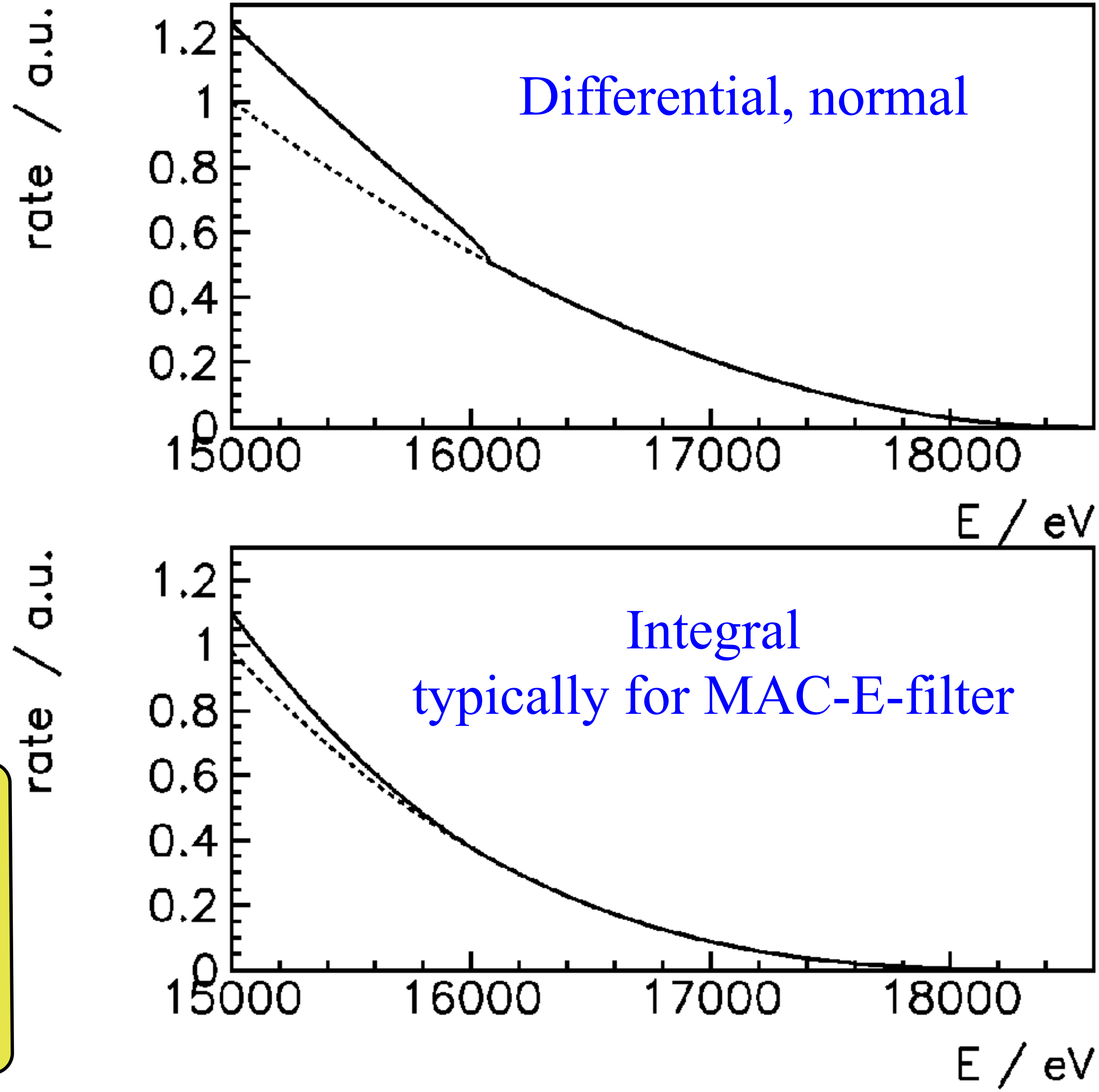
Normal (“differential“) or integral β-spectrum

e.g. $m_{sterile}$ = 2.5 keV

$\sin^2(\theta) = 0.25$

(unrealistically high

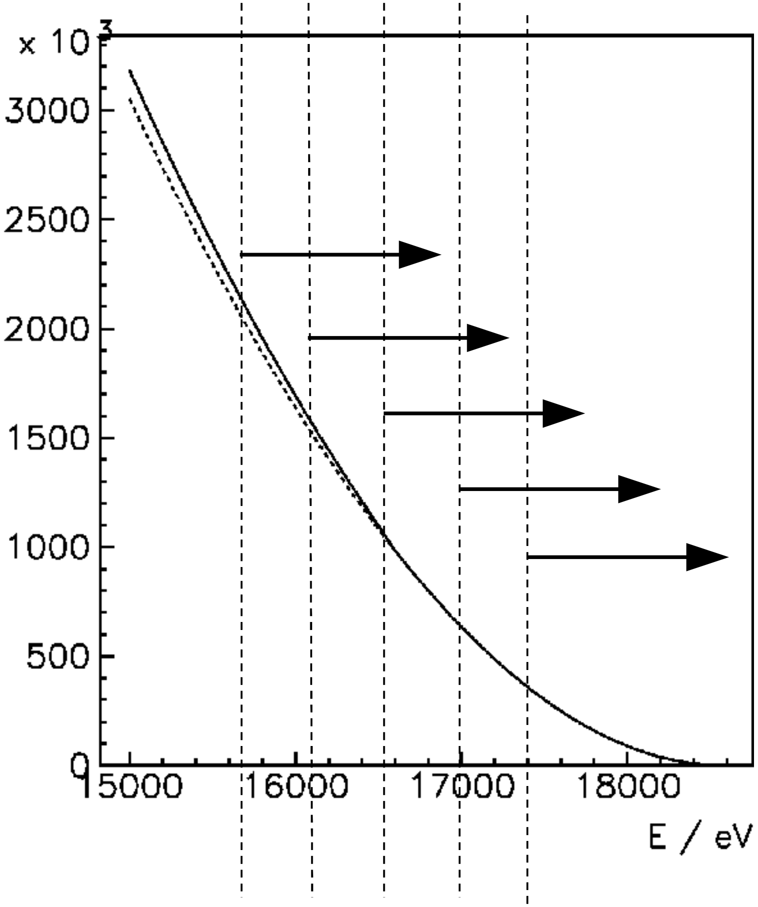
for Warm Dark Matter)



→ obviously much better signal-to-background-ratio for differential β-spectrum w.r.t. integral β-spectrum

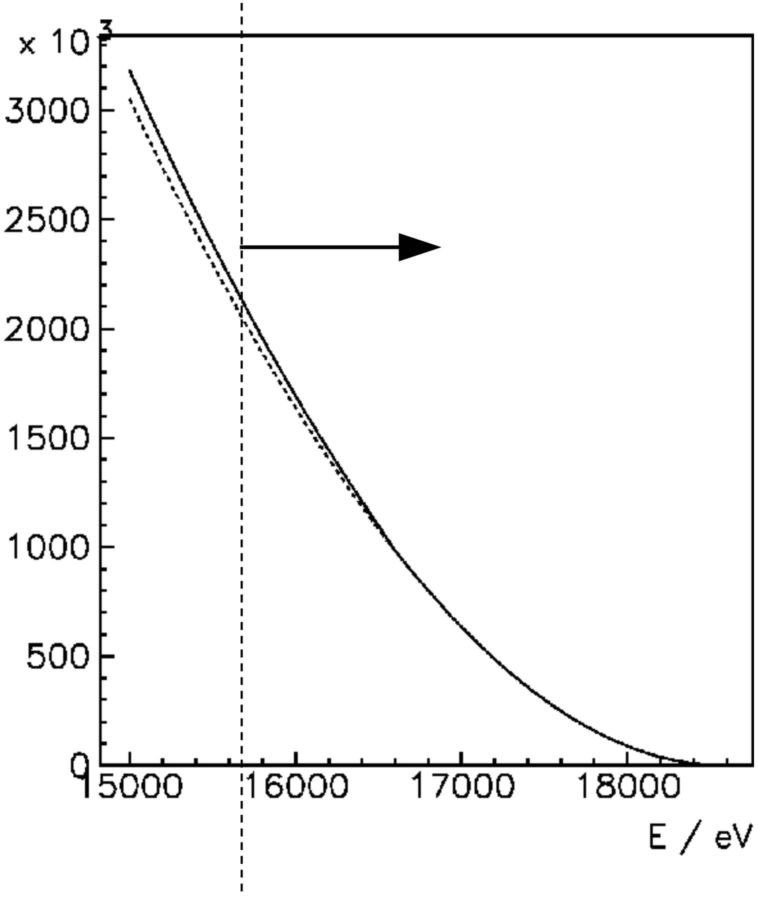
Second gain of integral versus differential: Avoid many steps in MAC-E-Filter mode

Integral – MAC-E-Filter method



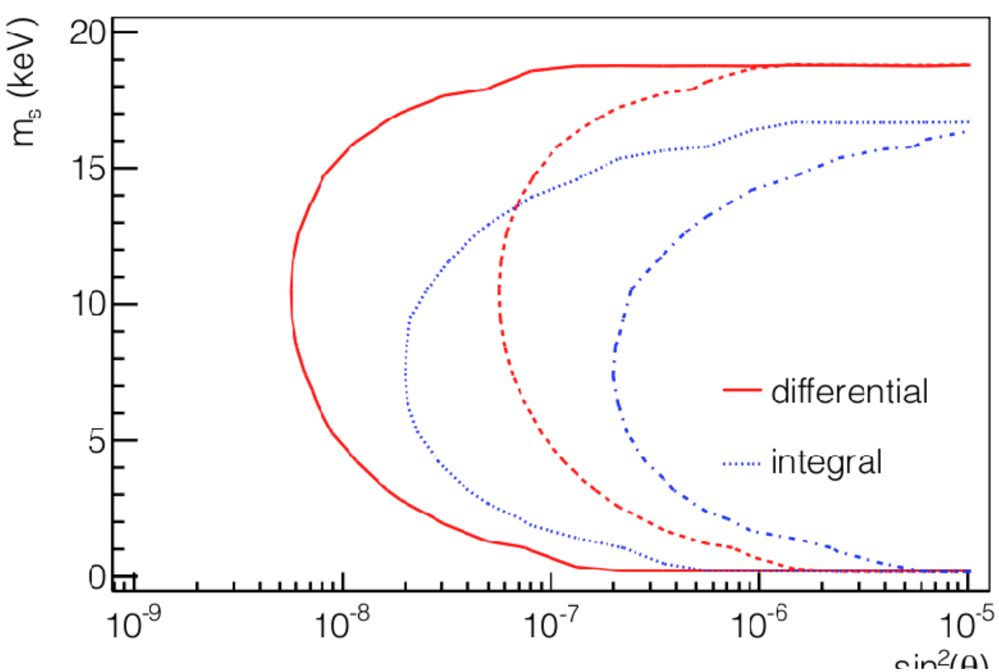
need many retardation voltages
to obtain spectral information

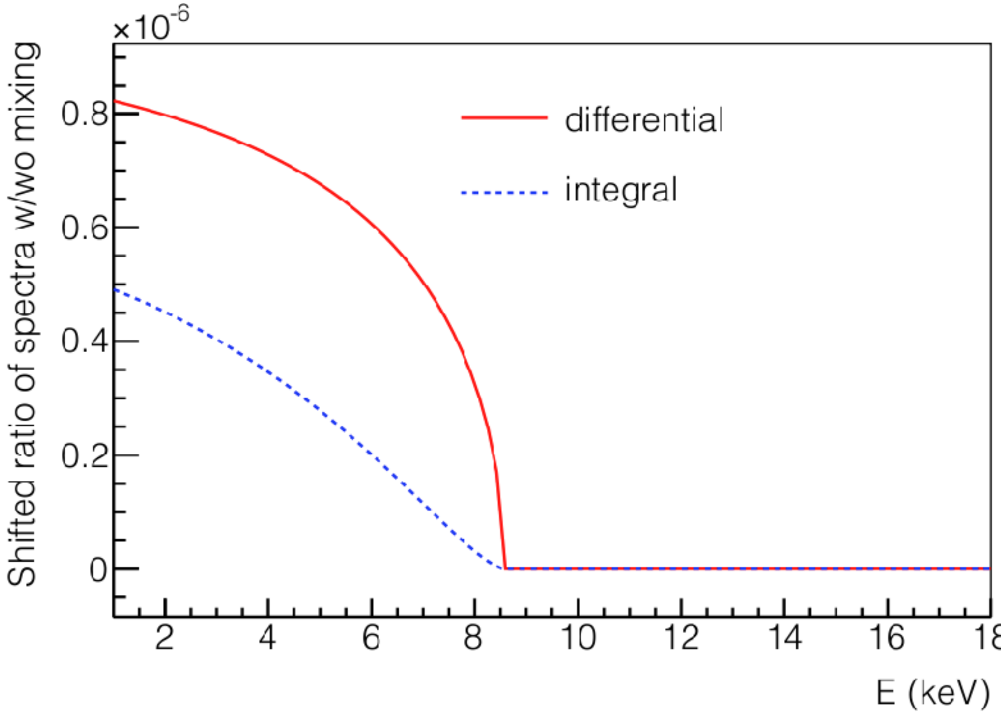
Differential measurement



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

Statistical sensitivity for integral and differential measurement





----- standard KATRIN source

- - - 1% KATRIN source

S. Mertens et al., „Sensitivity of Next Generation Tritium β-Decay Experiments for keV-Scale Sterile Neutrinos", close to submission,
see also S. Mertens, proceedings of TAUP 2013

→ statistical uncertainty is not a problem for 10^{-7} but what about the systematics !

Systematic uncertainties

1. β-decay spectrum:

   a) β-decay and nuclear physics: radiative decays, weak magnetism, size of the nucleus

      recoil corrections: all effects are small, e.g. $\mathcal{O}(10^{-5})$, and follow smooth functions

      S. Mertens et al., checked systematic uncertainties: $\Delta\sin^2(\theta < 10^7$

      (see S. Mertens, talk at Chalonge 2013, Meudon)

   b) β-decay and atomic and molecular physics

      Fermi function: quite well-known, smooth function

      electronic final states of T_2-decay:

         43% of all decays go to excited or ioinized states: $\mathcal{O}(1)$ effect !

2. tritium source:

   a) energy loss by inelastic scattering

   b) stability column density: KATRIN 10^{-3} (10^{-4} reachable)

standard KATRIN:

$\mathcal{O}(1)$ effect !

3. transmission of the spectrometer:

   a) constancy of transmission at large surplus energies $\mathcal{O}$(keV)

      requires full conservation of adiabaticity by larger magnetic fields

works well at pre spectr.
for higher magnetic fields
M. Prall et al.,
NJP 14 (2012) 073054

4) detection system:

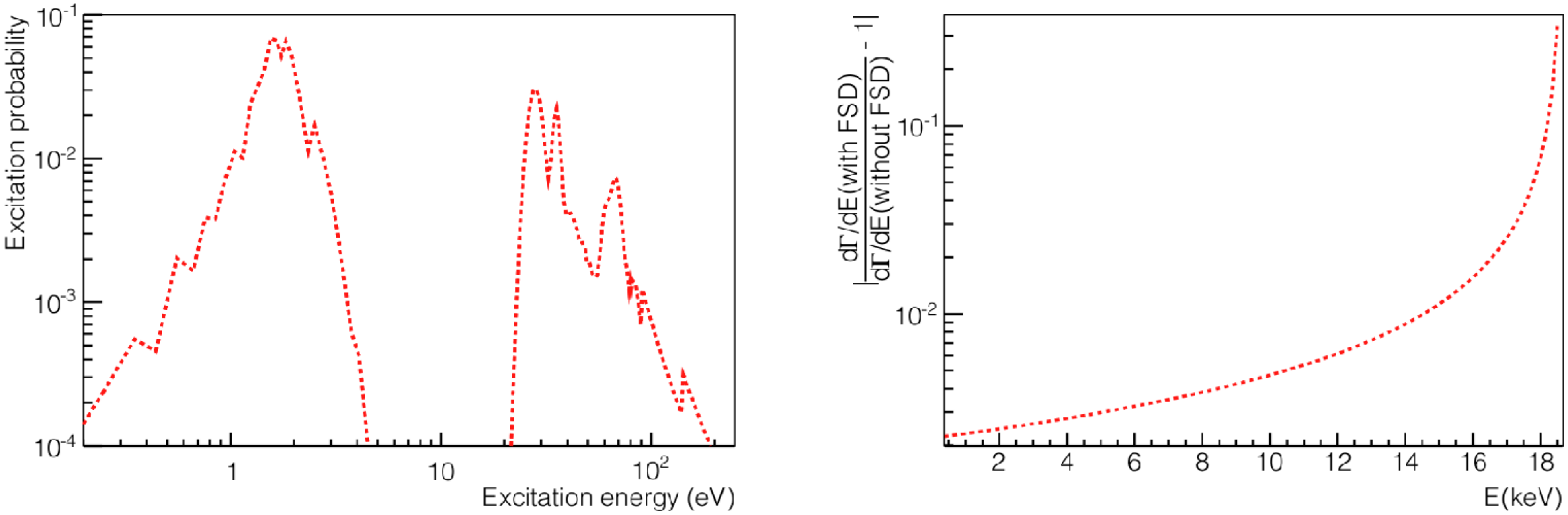
   a) tails of response functions, pile-up, time resolution, stabilities, …

Systematic uncertainties

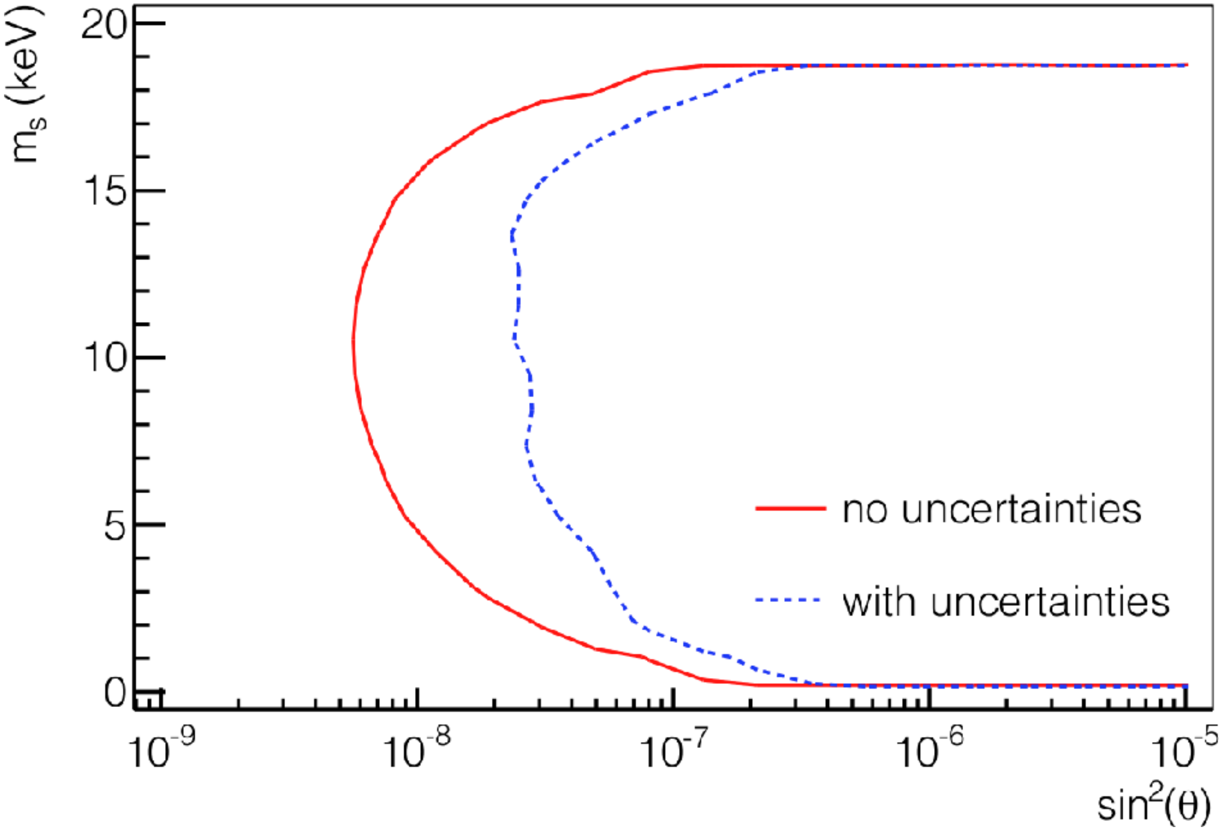
S. Mertens et al.,
„Sensitivity of Next Generation Tritium β-Decay Experiments for keV-Scale Sterile Neutrinos“,close to submission:

Although the systematic effects have clear structures due to quantization they get smoothed by convolution with be β-spectrum,

E.g. vib-rotationally & electronically excited final states of T_2 β-decay:



Systematic uncertainties



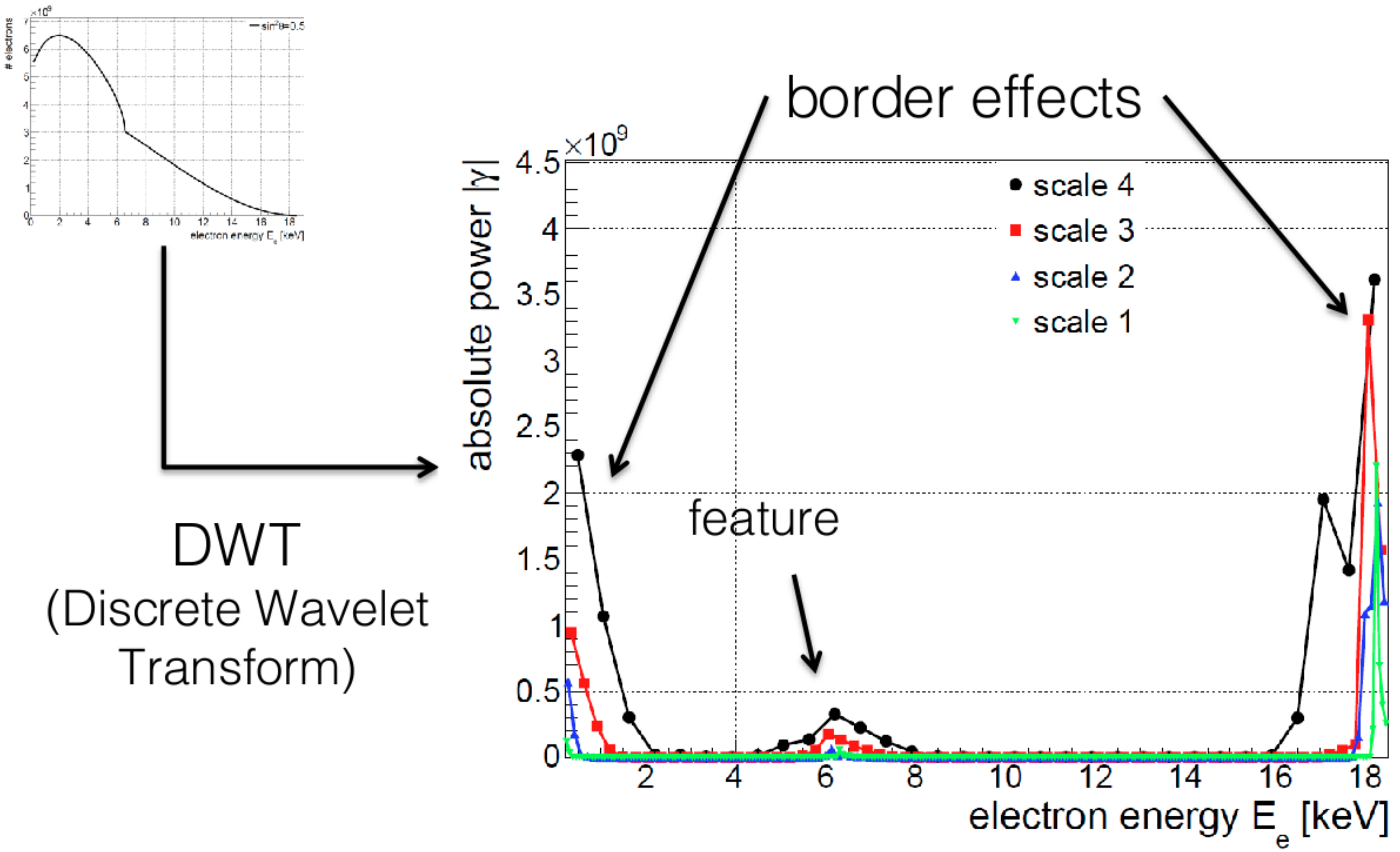
→ Systematics seem not to prohibit a 10^{-7} sensitivity

more detailed studies are necessary

S. Mertens et al., „Sensitivity of Next Generation Tritium β-Decay Experiments for keV-Scale Sterile Neutrinos“, close to submission,

How to find the keV neutrino kink ? very interesting: wavelet analysis

Analysis of the Tritium *β*− **decay spectrum**

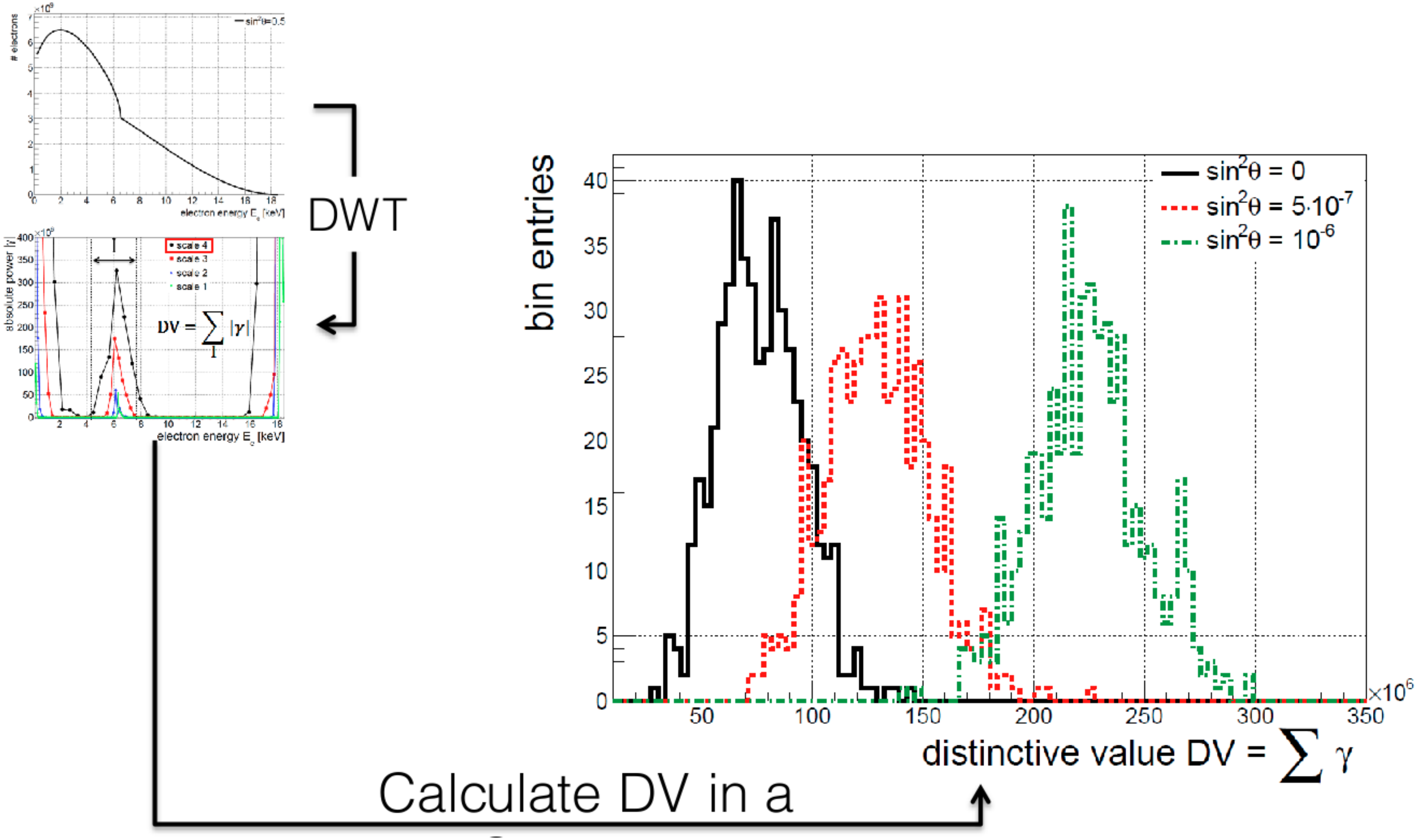


Power Spectrum

M. Korzeczek/KIT, Chalonge Meudon School 2014

How to find the keV neutrino kink ?
very interesting: wavelet analysis

Analysis of the Tritium **$\beta-$ decay spectrum**



DWT

Calculate DV in a

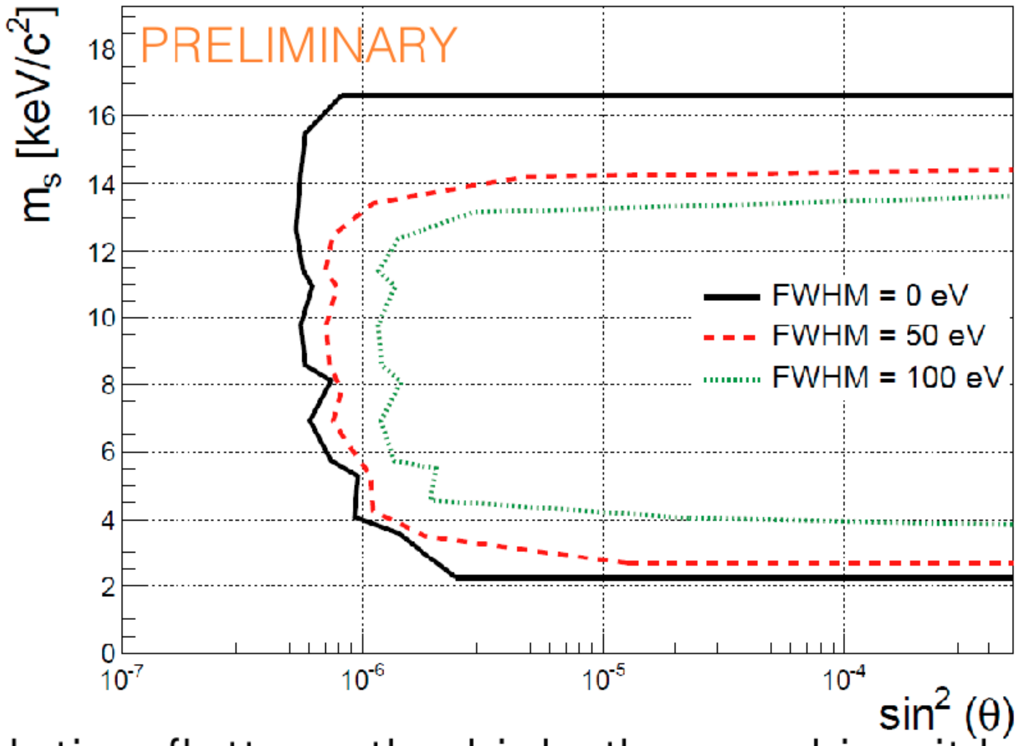
M. Korzeczek/KIT, Chalonge Meudon School 2014

How to find the keV neutrino kink ?
very interesting: wavelet analysis

Results - Impact of systematical uncertainties

Detector resolution:

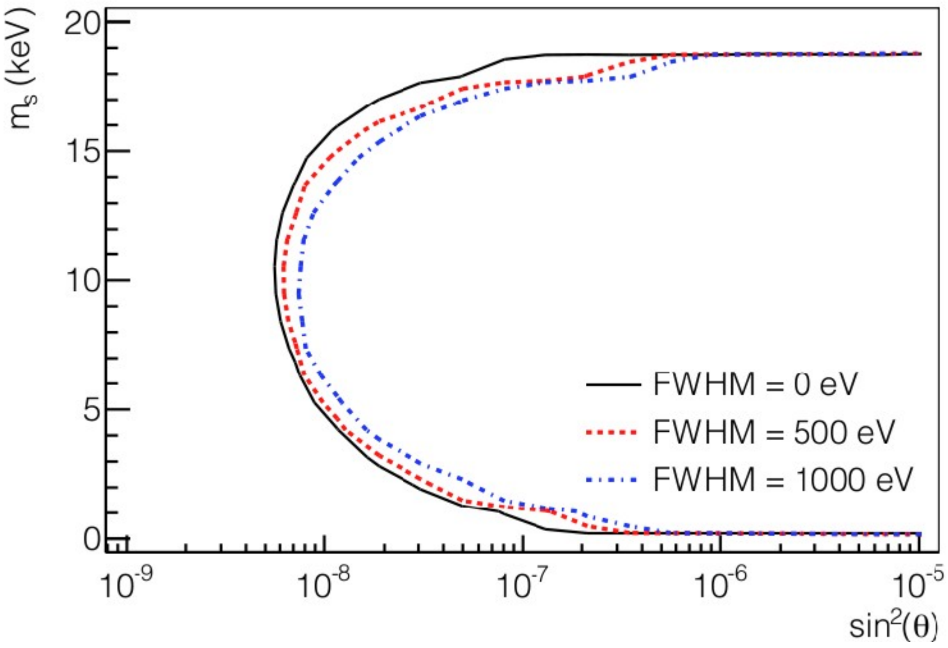
Simulate the detector resolution by convoluting the electron spectrum with a Gaussian curve ($\bar{x} = E$, $\sigma = \mathrm{FWHM}$).

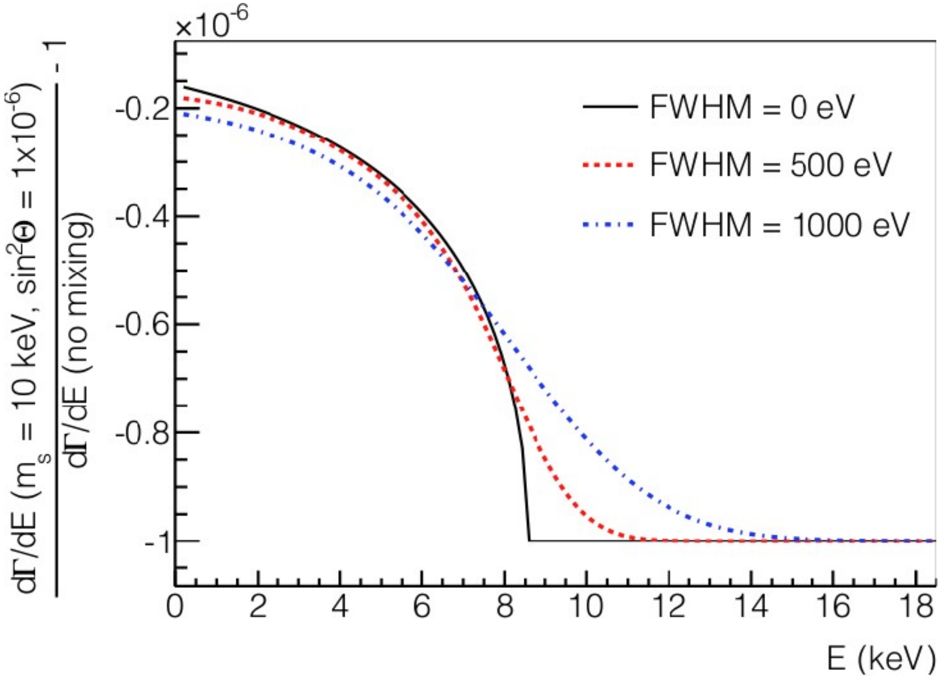


→ The resolution flattens the kink, thus making it harder to detect.

M. Korzeczek/KIT, Chalonge Meudon School 2014

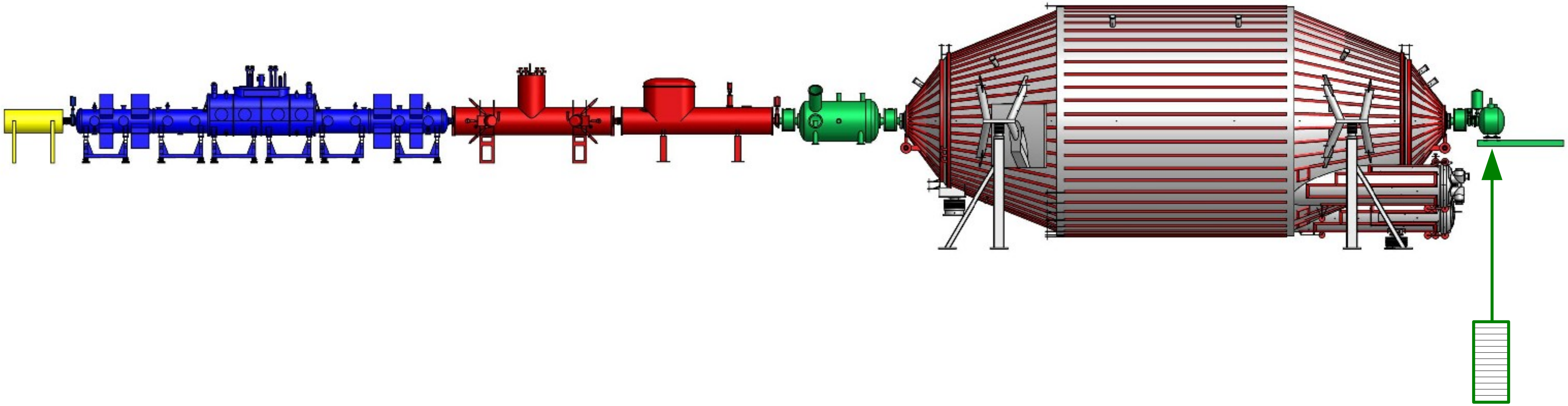
Effect of energy resolution of differential detector in standard fits





S. Mertens et al., „Sensitivity of Next Generation Tritium β-Decay Experiments for keV-Scale Sterile Neutrinos“, close to submission,

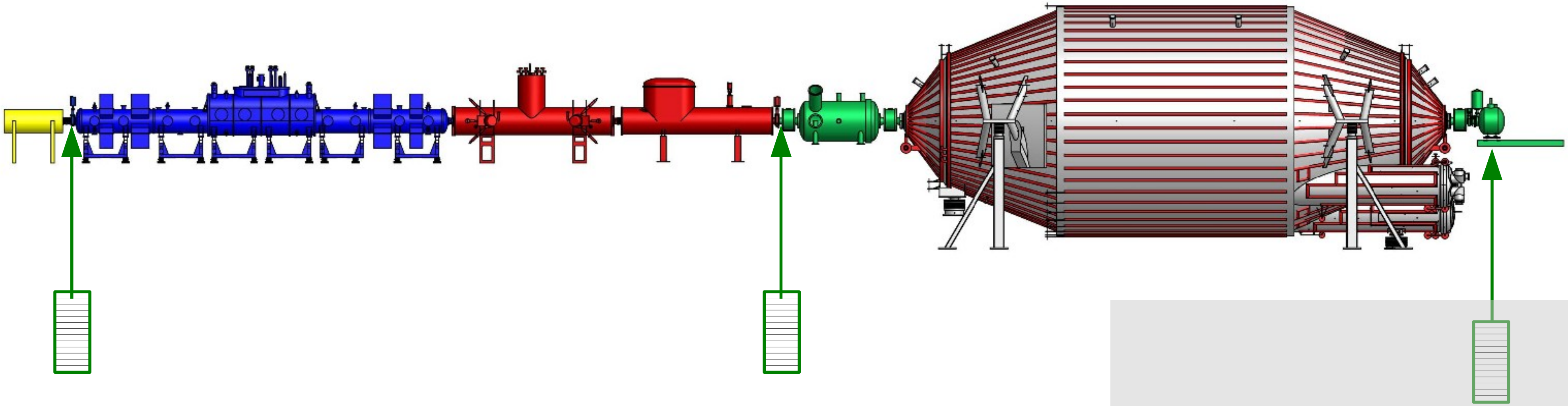
Possible implementations of a differential β-spectrum measurement with KATRIN



Detector
measures β-spectrum
with energy resolution
ΔE ~ 1keV (FWHM)
above a retarding energy
qU_0 = const.

Problems:
tails of resolution function
high count rate capability
(pile-up)

Possible implementations of a differential β-spectrum measurement with KATRIN



“Instrumented rear-wall“ or forward beam detector
measures β-spectrum
with energy resolution
ΔE ~ 1keV (FWHM)
completely and
all the time parasitically

Problems:
tails of resolution function
ultra-high count rate
capability (pile-up, ...)

Detector
measures β-spectrum
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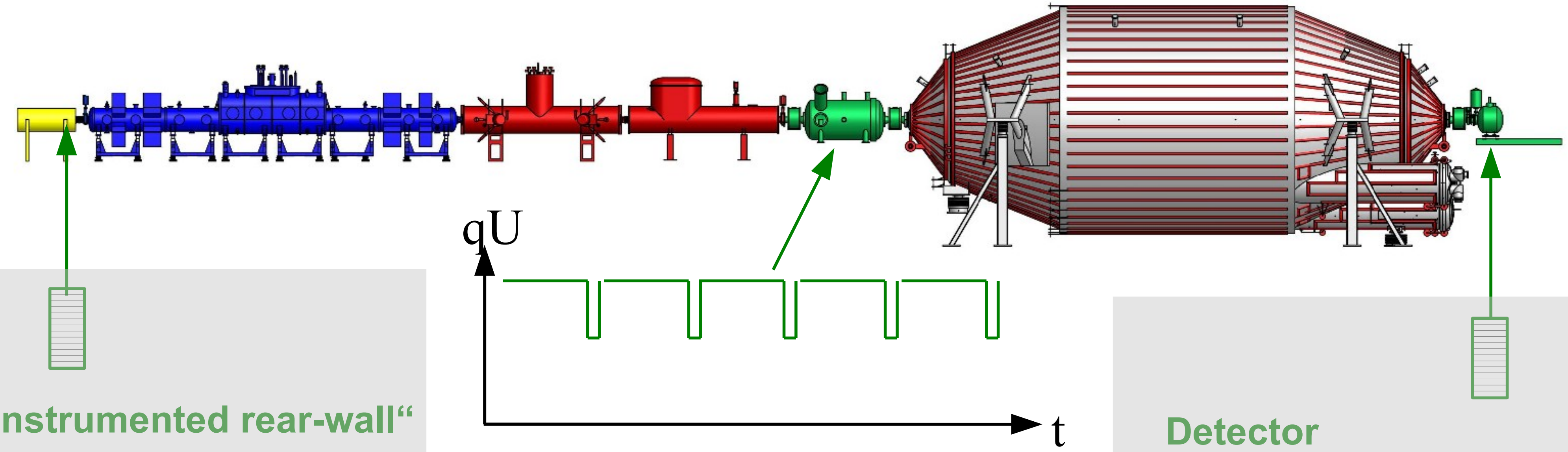
Possible implementations of a differential β-spectrum measurement with KATRIN



"Instrumented rear-wall" or forward beam detector
measures β-spectrum
with energy resolution
ΔE ~ 1keV (FWHM)
completely and
all the time parasitically

Problems:
tails of resolution function
ultra-high count rate
capability (pile-up, ...)

TOF by pulsing retarding
potential of
pre spectrometer applying
short on & long off pulses

Problems:
can we pulse the pre
spectrometer potential
within less than 1 μs
by up to 10 kV ?

Detector
measures β-spectrum
with energy resolution
ΔE ~ 1keV (FWHM)
above a retarding energy
qU_0 = const.

Problems:
tails of resolution function
high count rate capability
(pile-up)

A possible strategy to detect a few keV sterile neutrinos by TOF with KATRIN

Set (a few) retarding potentials below kink position

Use gating filter with short on- and long off-times to have optimal time resolution

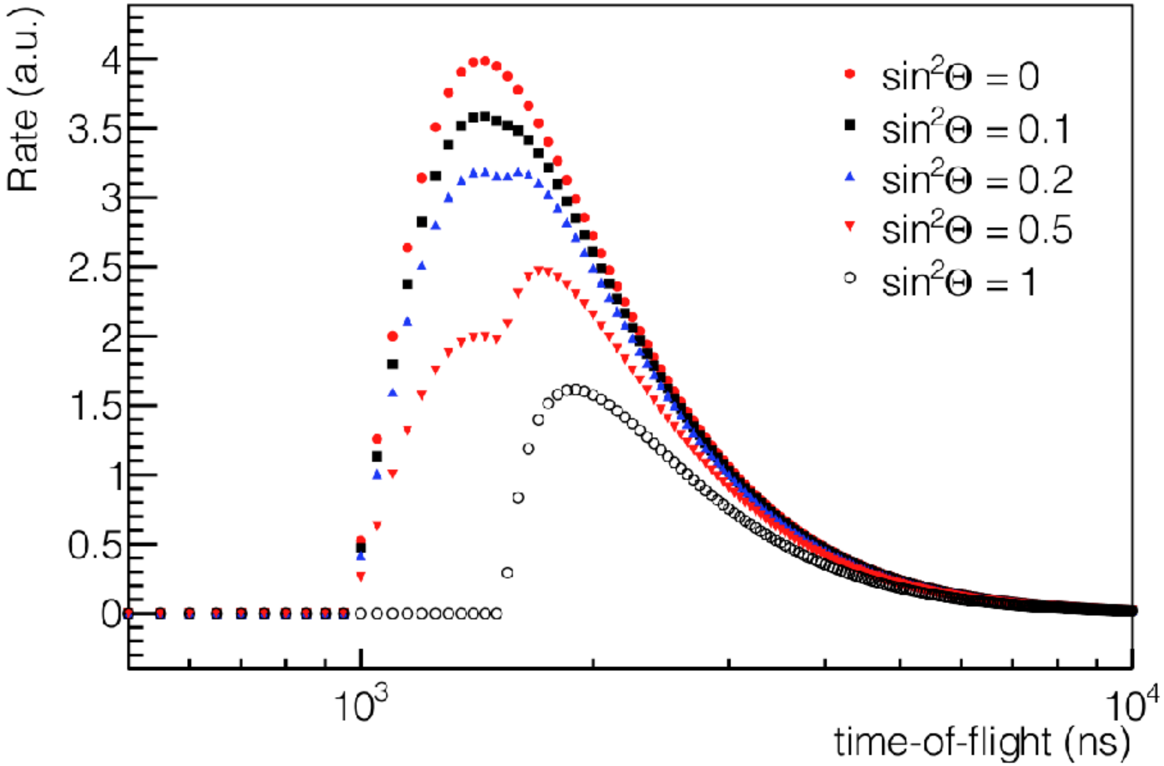
Differentiate spectrum by measuring time-of-flight

Use low column density

Fight final states uncertainties and energy losses by sum rules, parameterisations and extrapolations

e.g. $m(\nu_4)$ = 1 keV, various $\sin^2(\theta)$

(unrealistically high for Warm Dark Matter)



→ ***dedicated study under way***

N. Steinbrink et al., Meuden 2013

Upgraded Troitsk nu mass setup and sterile neutrinos search

Spectrometer inner/outer diameter 2.20/2.75 m, length 8.10 m.
Resolution 1.8 eV (@18 keV)

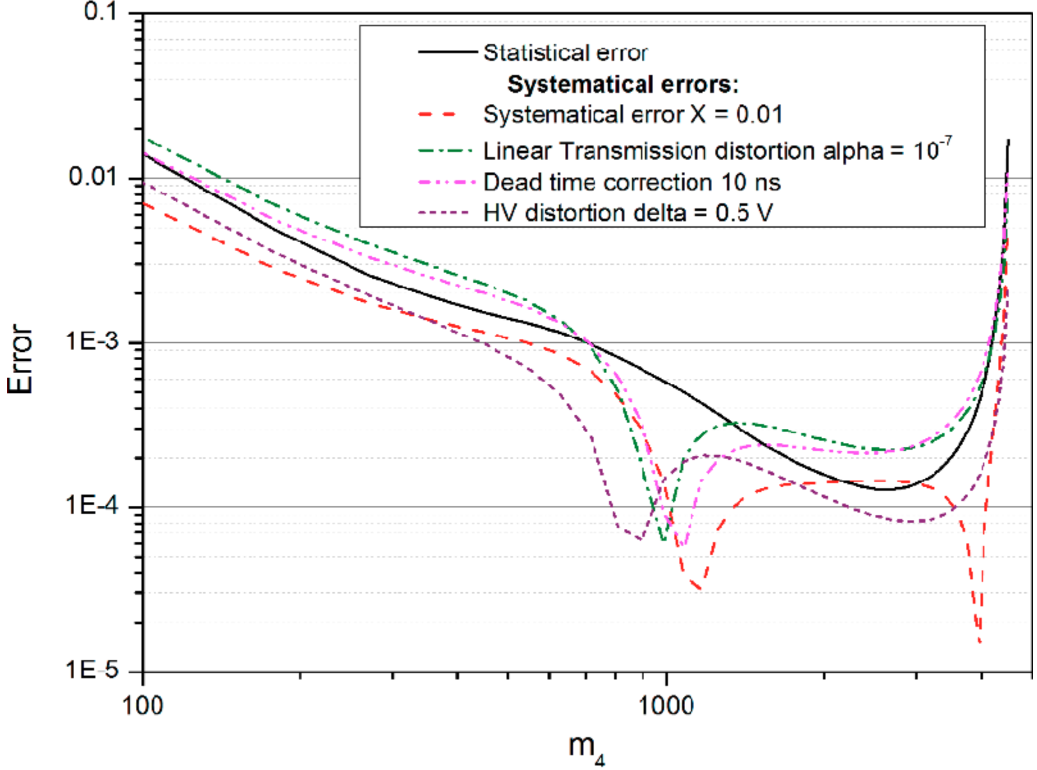
Upgrade of Troitsk exp.

aim to investigate KATRIN systematics and keV neutrinos

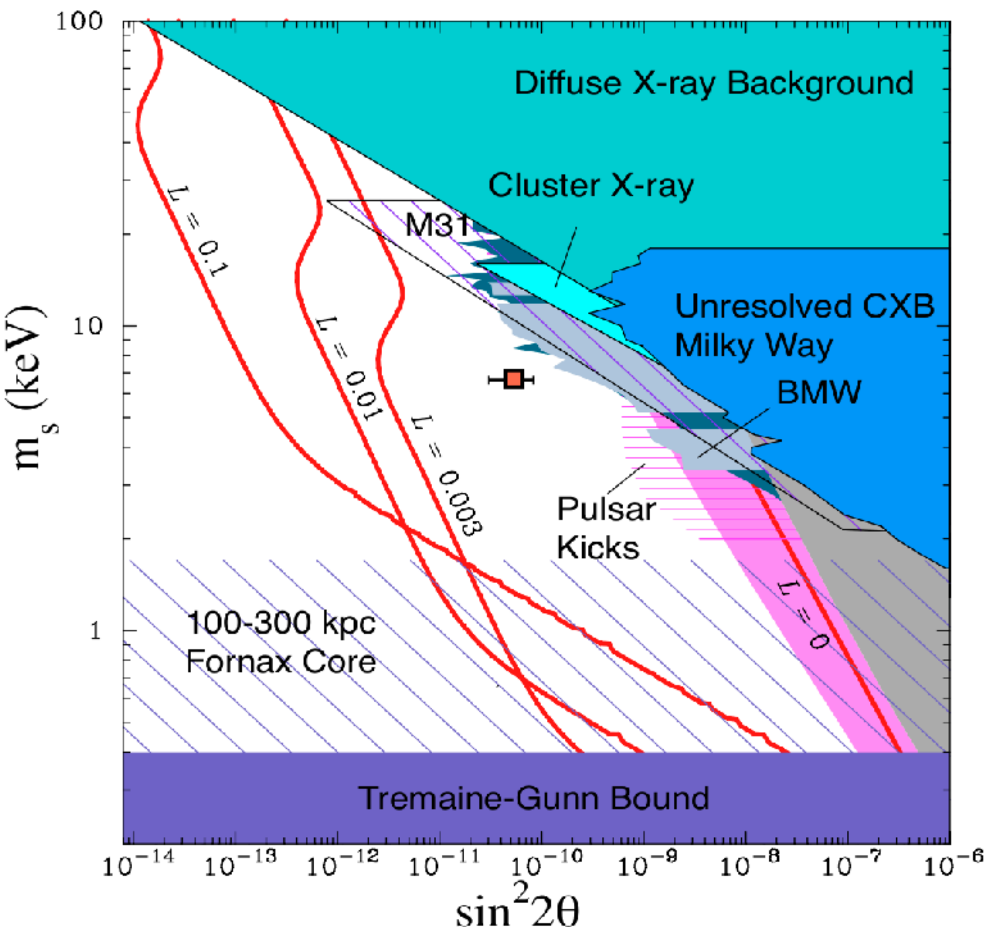
Sterile neutrino search up to m(ν_4) = 5 keV

with 1% of original source strength of 10^{17}cm^{-2}
Troitsk sensitivity

V. Pantuev, Neutrino 2014, Boston, July 2014



Remark on sensitivity in sin$^2\theta$



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

Bulbul et al: sin$^2\theta \approx 10^{-11}$

→ request 10^{22} counts
for detection of kink in β-spectrum !

KATRIN-statistics:
10^{11} β-decays/s of which
10^{10} β-electrons sent to spectrometer
max. measurement time 10^8 s
→ maximal 10^{18} counts

No way to measure with KATRIN

Need to use a method which detects the sterile neutrino with a single or a few events (like in 0νββ for zero background),
e.g. by fully reconstructing the kinematics

E. Otten will discuss at NOW2014
the feasibility of such an experiment

Conclusions

KATRIN is the next generation direct neutrino mass experiment with 200 meV sensitivity

- spectrometer and detector successfully commissioned
- tritium source and electron transport line are coming in 2015
- start of tritium data taking in 2016 !

Sterile neutrinos at the eV- and the keV-scale (warm dark matter) are well motivated

KATRIN will check the reactor anomaly and
- could in principle search for Warm Dark Matter in a dedicated run

- maybe a first test in 2016 is possible, when KATRIN gets started with 5% source intensity

To yield optimal sensitivity, it requires taking
- differential spectra a few keV below E_0,
- e.g. by time-of-flight spectroscopy in gated-filter mode or analysing spectra of a (new?) detector
- detailed studies by S. Mertens, N. Steinbrink et al.