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

Ecole Internationale Daniel Chalonge

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- **Introduction**
- **Direct neutrino mass search**
- **Search for sterile neutrinos in β-endpoint spectra**
- **Time-of-flight method and 1st tests at the KATRIN main spectrometer**
- **Conclusions**

Photo: M. Zacher

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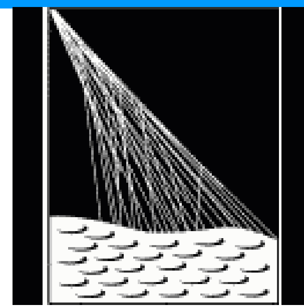
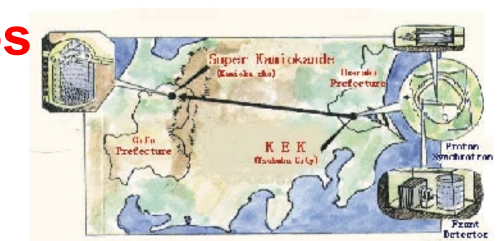
Positive results from ν oscillation experiments

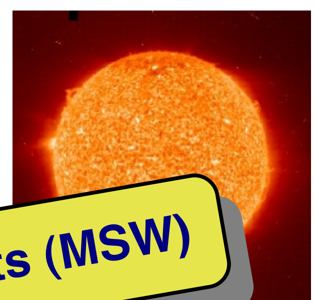
atmospheric neutrinos
(Kamiokande,
Super-Kamiokande, ...)



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

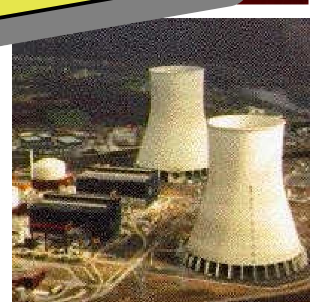


solar neutrinos
(Homestake, Gallex,
Sage, Super-Kamiokande,
SNO, Borexino)



Matter effects (MSW)

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



$\Rightarrow$ non-trivial ν-mixing

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

with:

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

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

$\sin^2(\theta_{13}) = 0.089 \pm 0.010 \pm 0.005$

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

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

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

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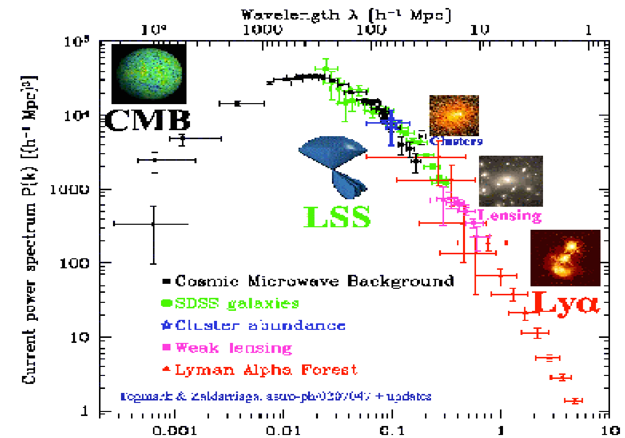
Three complementary ways to the absolute neutrino mass scale

1) Cosmology

very sensitive, but model dependent

compares power at different scales

current sensitivity: $\Sigma m(\nu_i) \approx 0.5$ eV

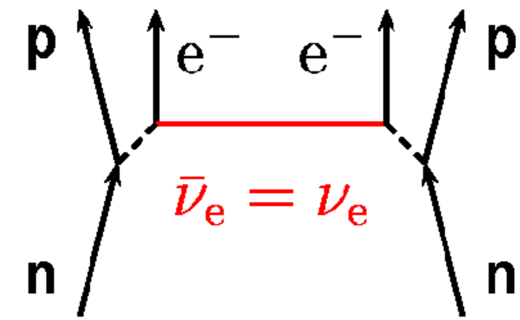


2) Search for $0\nu\beta\beta$

Sensitive to Majorana neutrinos

Evidence for $m_{ee}(\nu) \approx 0.3$ eV ?

GERDA, EXO-200 & KamLAND-ZEN have 1st results !

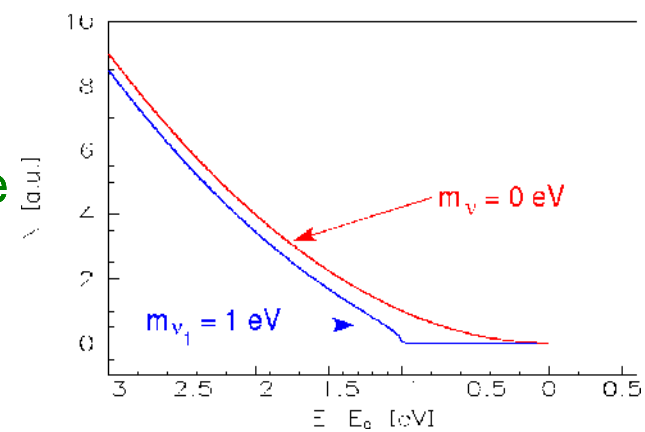


3) Direct neutrino mass determination:

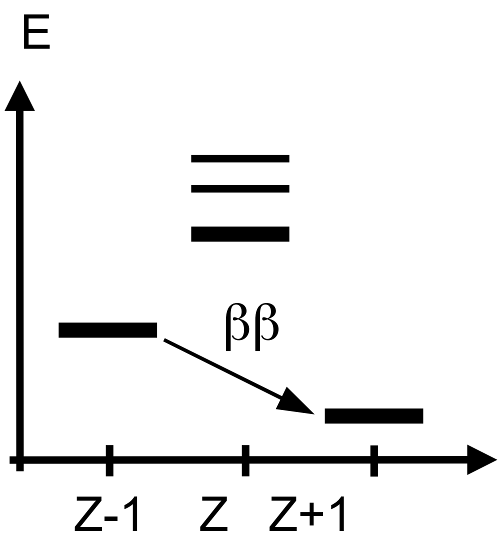
No further assumptions needed. no model dependence

use $E^2 = p^2c^2 + m^2c^4 \Rightarrow m^2(\nu)$ is observable mostly

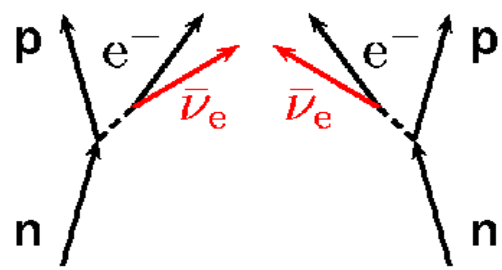
most sensitive methode: endpoint spectrum of β-decay



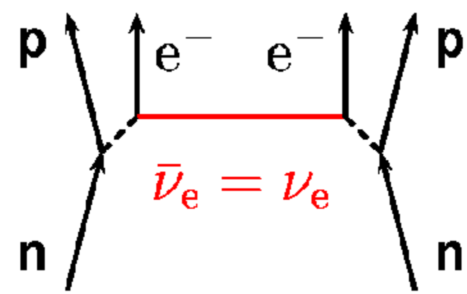
Double β decay



normal (2νββ)



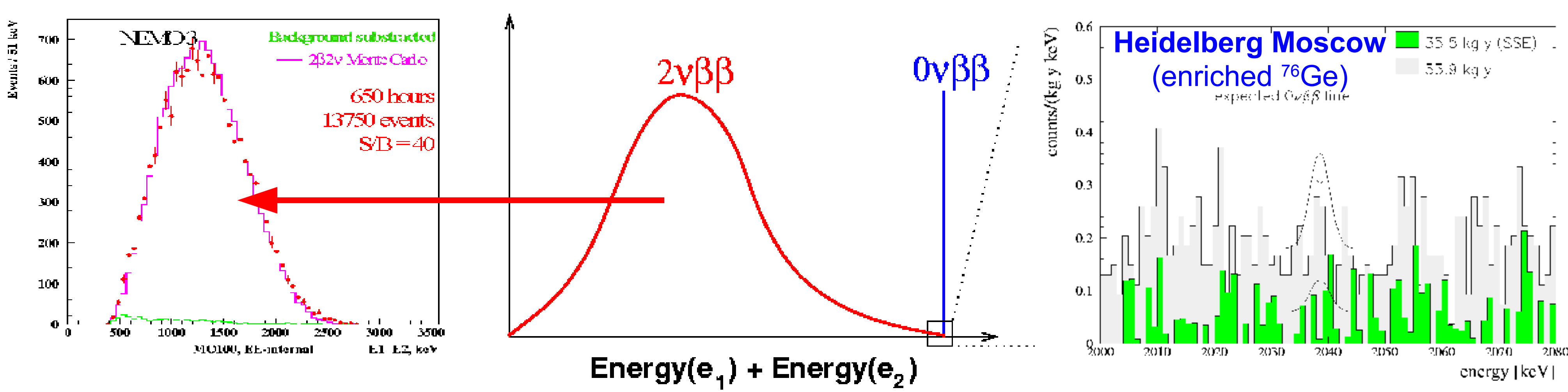
neutrinoless (0νββ)



needed: a) $\bar{\nu} = \nu$ (Majorana)

b) helicity flip: $m(\nu) \neq 0$

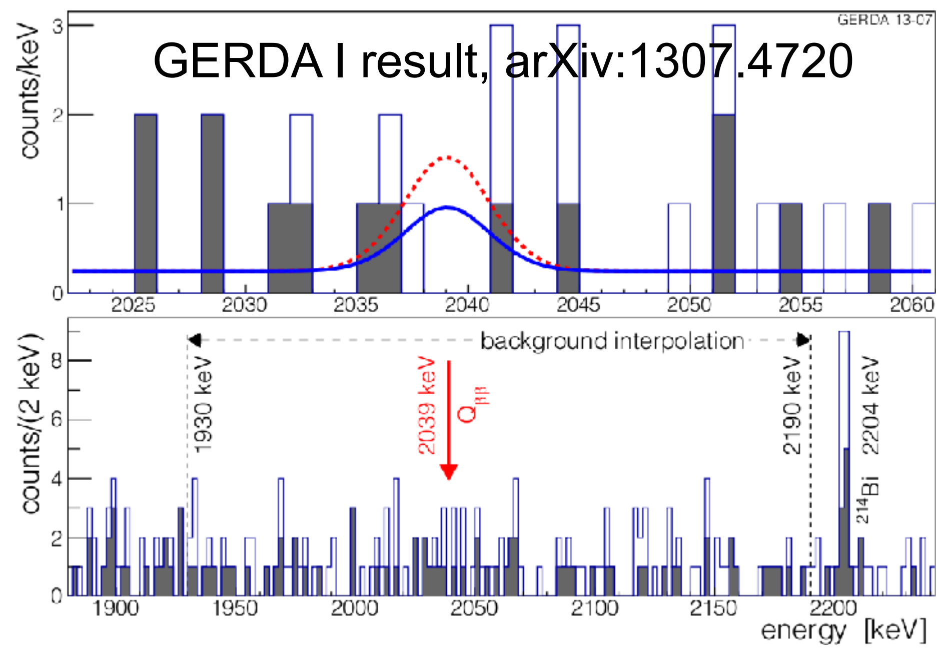
or other new physics

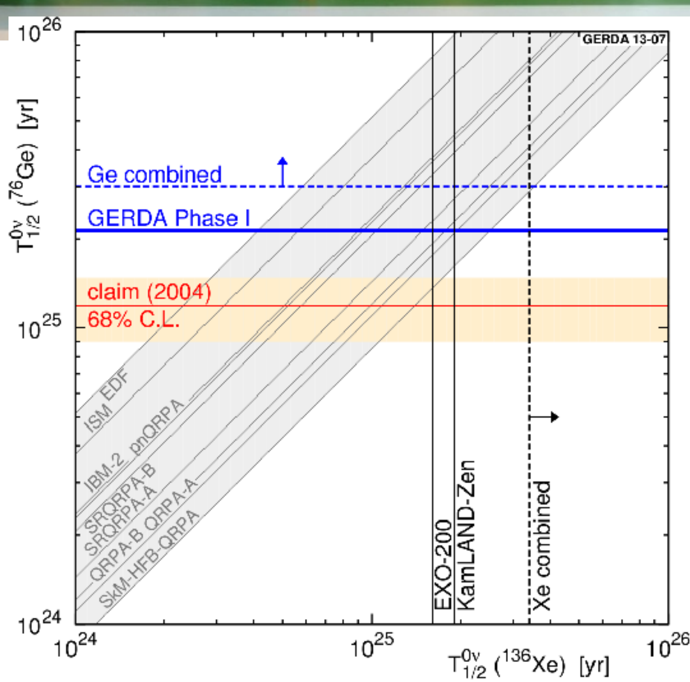


First results from GERDA phase 1

New background reduction methods:

- phase 1: 18 kg enriched Ge detectors in LAr
- phase 2: point contact detectors p-type (BEGe)
  to identify multi-side events and
  use scintillation of LAr shield as veto





$T_{1/2} > 2.1\ 10^{25}$ yr (90% C.L.)

$T_{1/2} > 3.0\ 10^{25}$ yr (90% C.L.) (using all ^{76}Ge experiments)

$m_{\beta\beta} < 0.2 – 0.4$ eV (using all ^{76}Ge experiments)

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

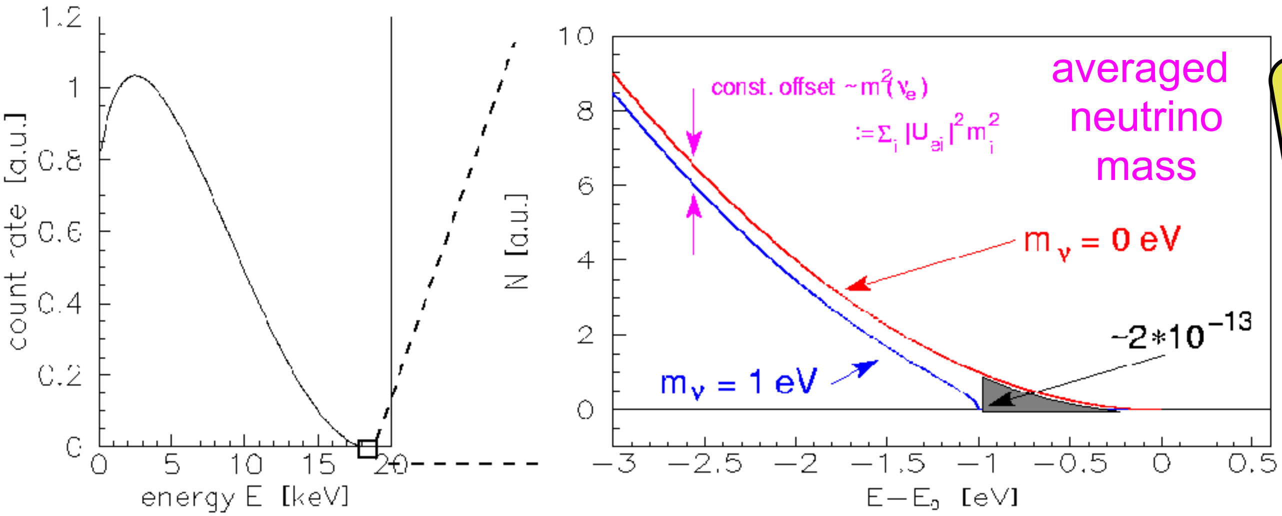
β decay: $(A,Z) \rightarrow (A,Z+1)^+ + e^- + \bar{\nu}_e$

β electron energy spectrum:

$$dN/dE = K\ F(E,Z)\ p\ E_{tot}\ (E_0-E_e)\ \sqrt{(E_0-E_e)^2 - "m(\nu_e)"^2}$$

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

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



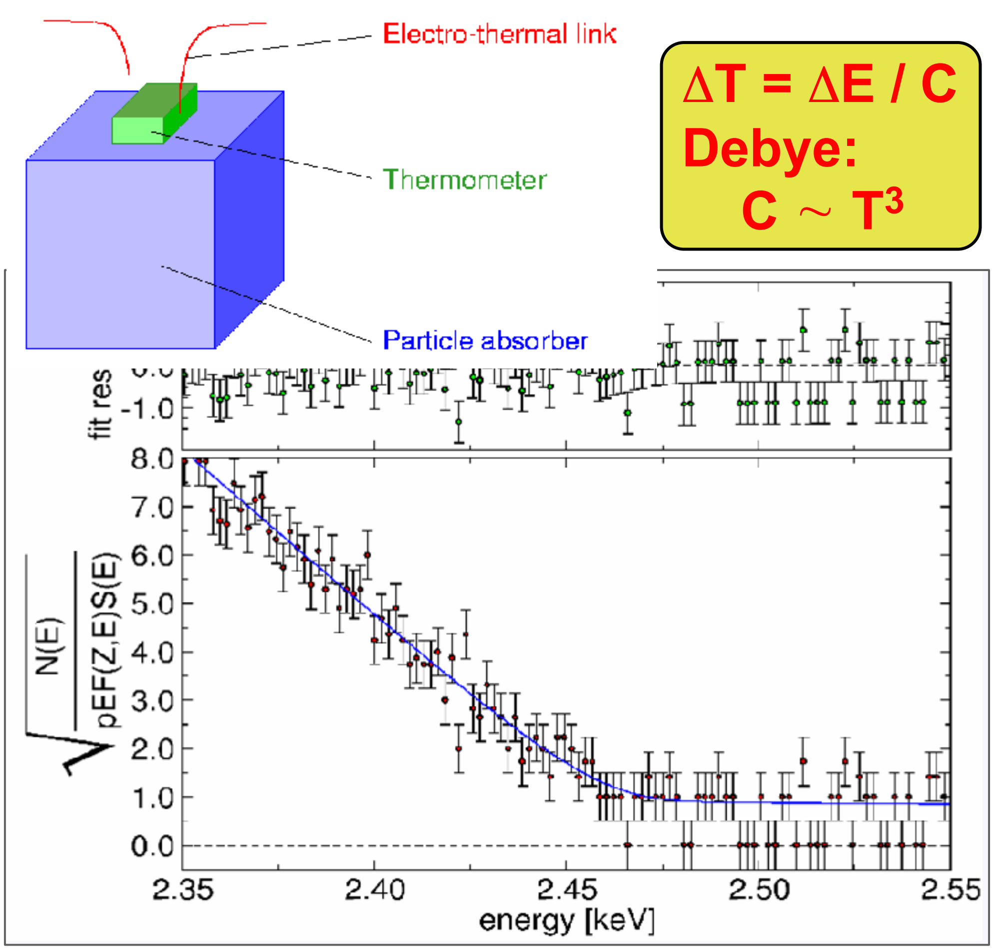
E.W. Otten & C. Weinheimer Rep. Prog. Phys. 71 (2008) 086201

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

Need: **low endpoint energy** $\Rightarrow$ **Tritium ^3H, (^{187}Re)**

very high energy resolution &
very high luminosity &
very low background
} $\Rightarrow$ **MAC-E-Filter (or bolometer for ^{187}Re)**

Cryogenic bolometers with ^{187}Re MIBETA (Milano/Como)



$\Delta T = \Delta E / C$
Debye:
$C \sim T^3$

Measures all energy except that of the neutrino

detectors: 10 ($AgReO_4$)

rate each: 0.13 1/s

energy res.: $\Delta E = 28$ eV

pile-up frac.: $1.7 \; 10^{-4}$

$M_\nu^2 = -141 \pm 211_{stat} \pm 90_{sys}$ eV^2

$M_\nu < 15.6$ eV (90% c.l.)

(M. Sisti et al., NIMA520 (2004) 125)

MANU (Genova)

- Re metalic crystal (1.5 mg)
- BEFS observed (F.Gatti et al., Nature 397 (1999) 137)
- sensitivity: $m(\nu) < 26$ eV (F.Gatti, Nucl. Phys. B91 (2001) 293)

MARE neutrino mass project: ^{187}Re beta decay with cryogenic bolometers

Advantages of cryogenic bolometers:
- measures all released energy except that of the neutrino
- no final atomic/molecular states
- no energy losses
- no back-scattering

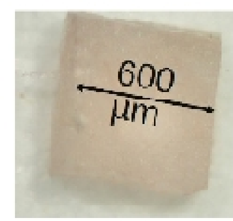
Challenges of cryogenic bolometers:
- measures the full spectrum (pile-up)
- need large arrays to get statistics
- understanding spectrum
- still energy losses or trapping possible
- beta environmental fine structure

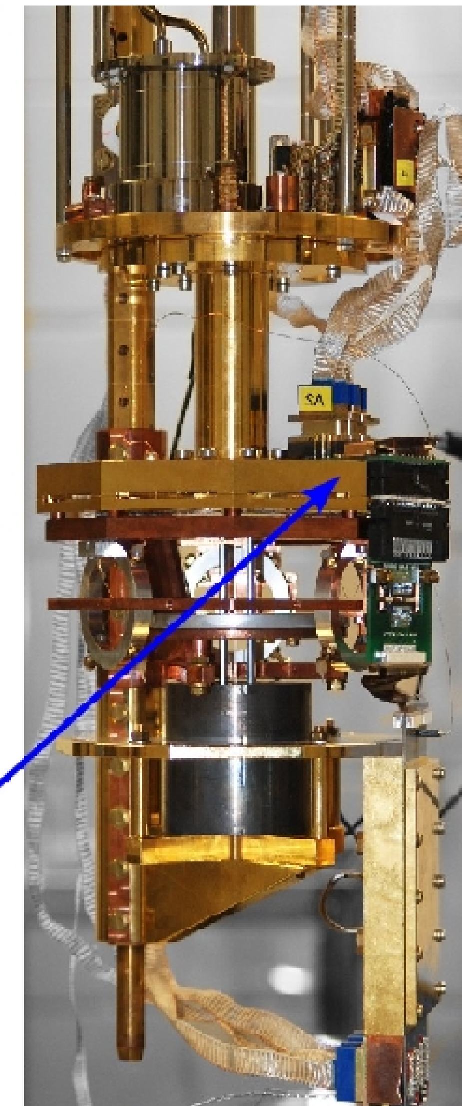
MARE-1 @ Milano-Bicocca

- 6x6 array of Si-implanted thermistors (NASA/GSFC)
- 0.5 mg $AgReO_4$ crystals
- $\Delta E \approx 30$ eV, $\tau_R \approx 250$ μs
- experimental setup for up to 8 arrays completed
- starting with 72 pixels in 2011
- up to 10^{10} events in 4 years → ~ 4 eV sensitivity

MARE-1 @ Genova

- R&D effort for Re single crystals on transition edge sensors (TES) → improve rise time to ~ μs and energy resolution to few eV
- large arrays (≈10^3 pixels) for 10^4-10^5 detector experiment
- high bandwidth, multiplexed SQUID readout
- also used with ^{163}Ho loaded absorbers





Angelo Nucciotti, Meudon 2011

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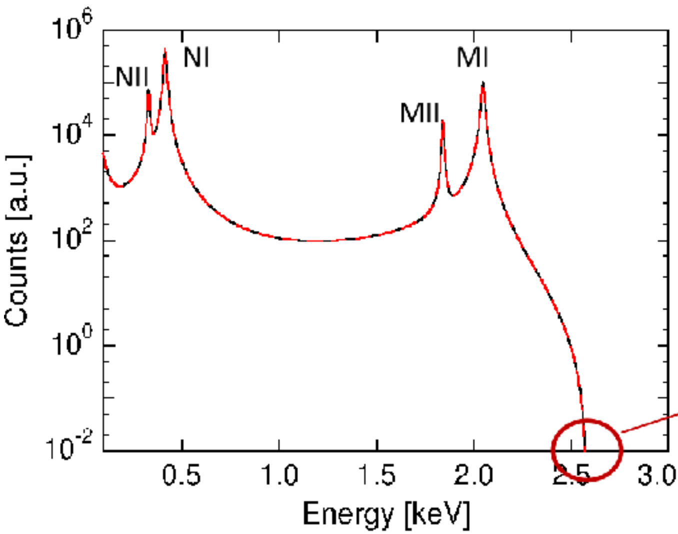
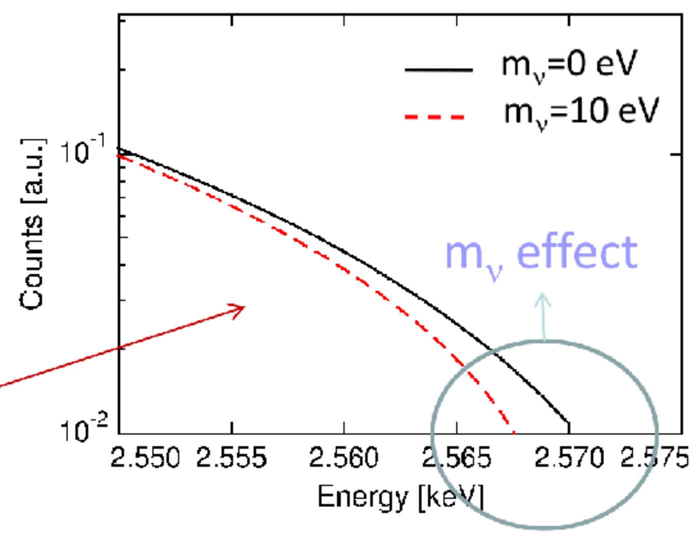
ECHO neutrino mass project: ^{163}Ho electron capture with metallic magnetic calorimeters

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





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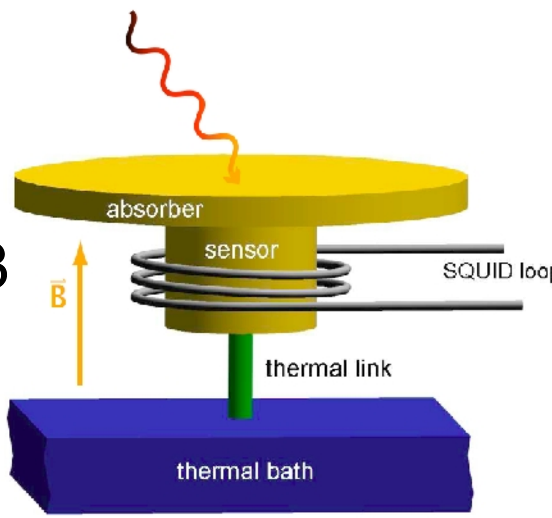

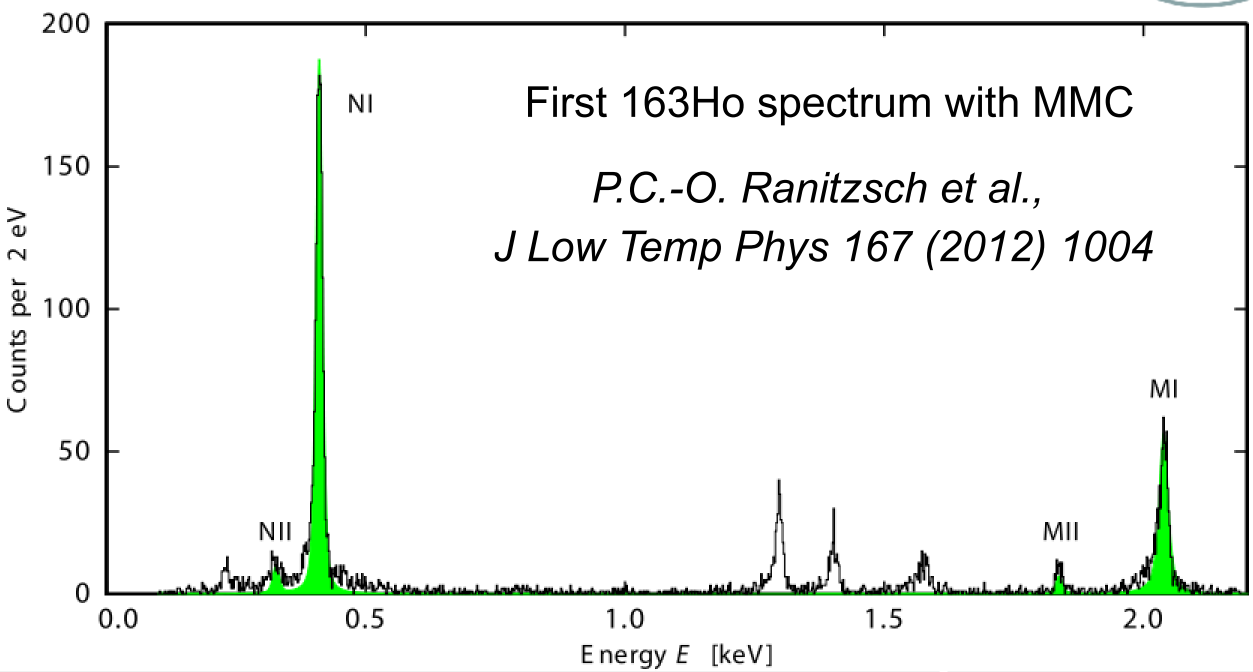

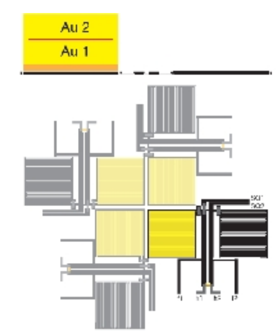

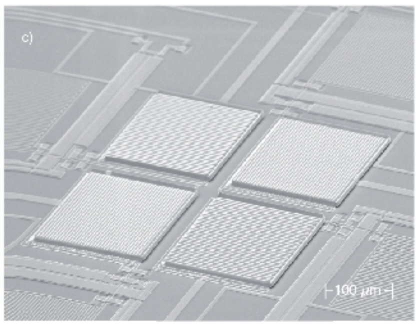

courtesy L. Gastaldo

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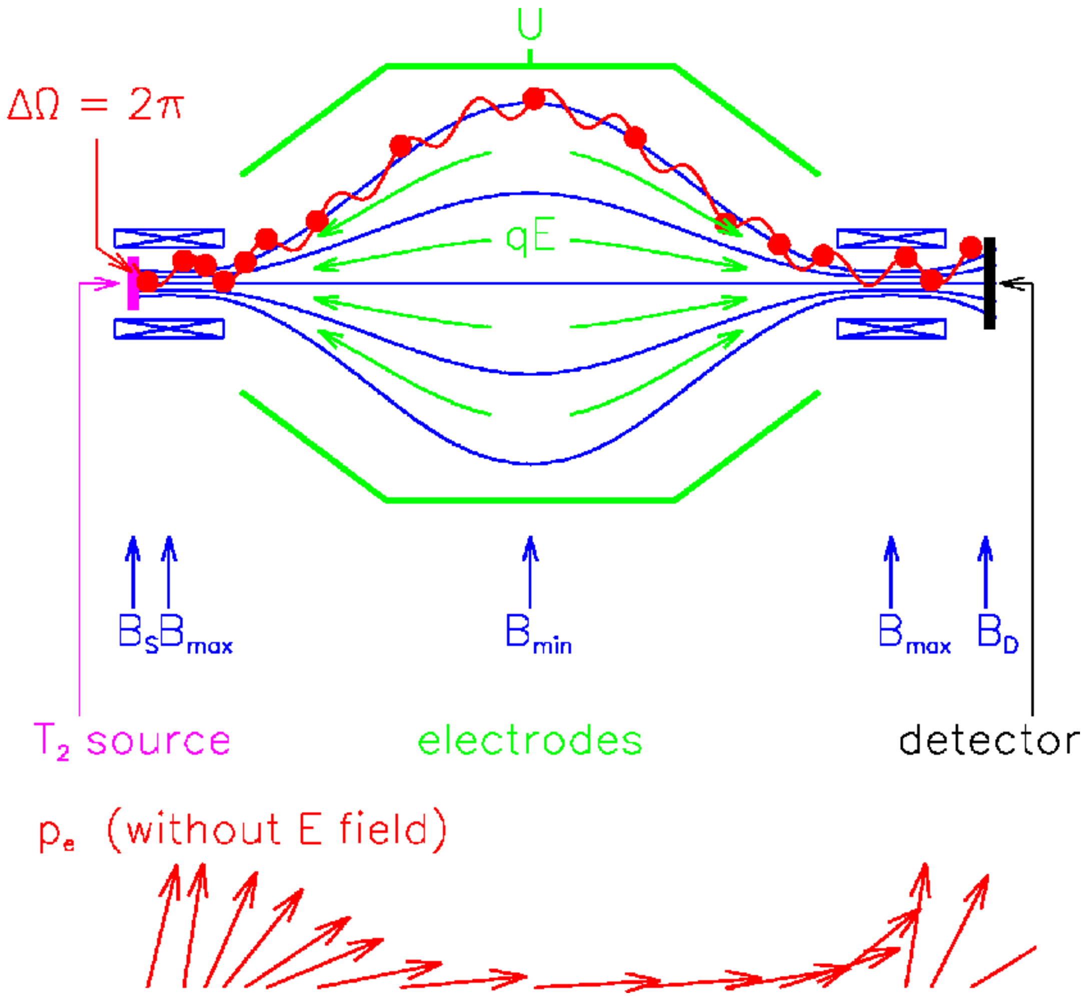
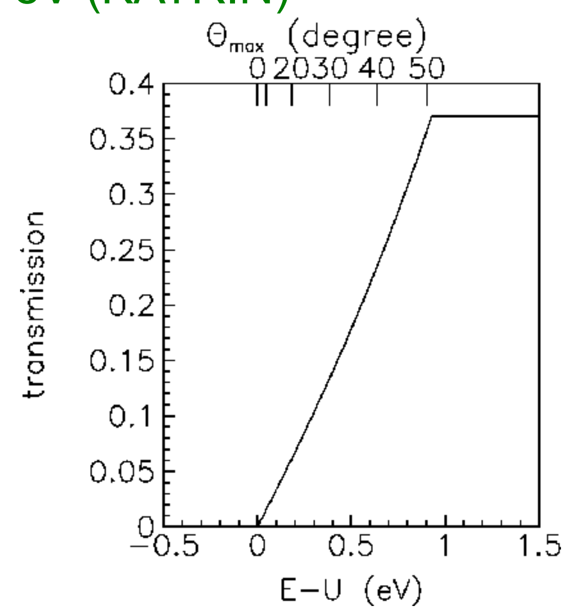
Tritium experiments: source ≠ spectrometer
MAC-E-Filter



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

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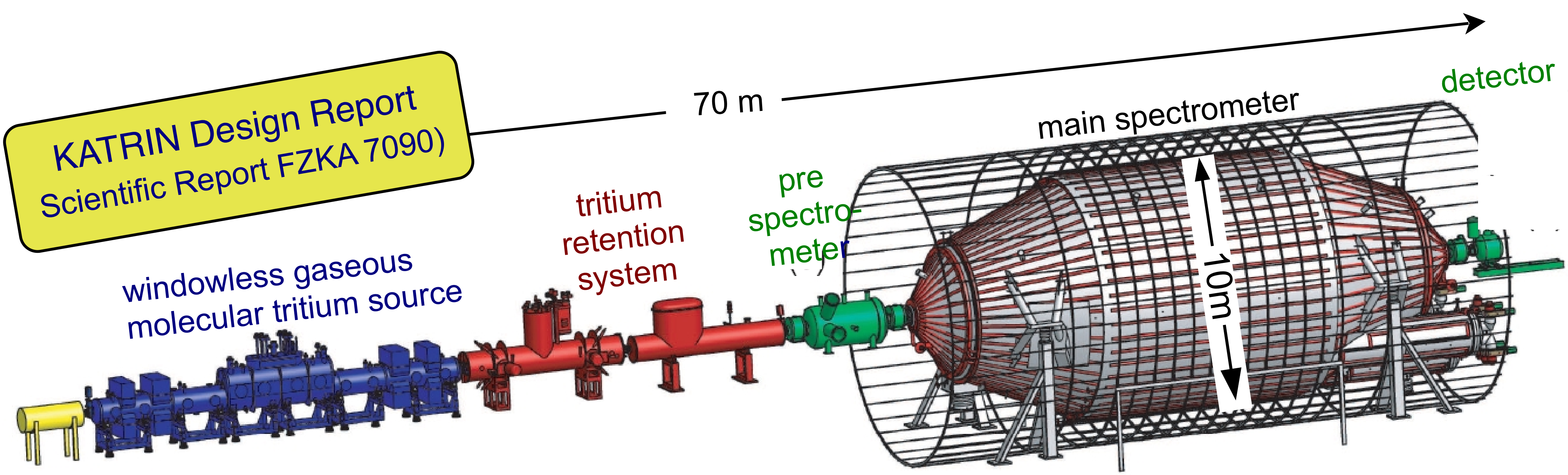
Aim: $m(\nu_e)$ sensitivity of 200 meV (currently 2 eV)

- very high energy resolution ($\Delta E \leq$ 1eV, i.e. σ = 0.3 eV) $\Rightarrow$ source $\neq$ spectrometer concept
- strong, opaque source $\Rightarrow$ $dN/dt \sim A_{source}$
- magnetic flux conservation (Liouville) $\Rightarrow$ scaling law:

$$A_{spectrometer} / A_{source} = B_{source} / B_{spectrometer} = E / \Delta E = 20000 / 1$$

KATRIN Design Report
Scientific Report FZKA 7090)



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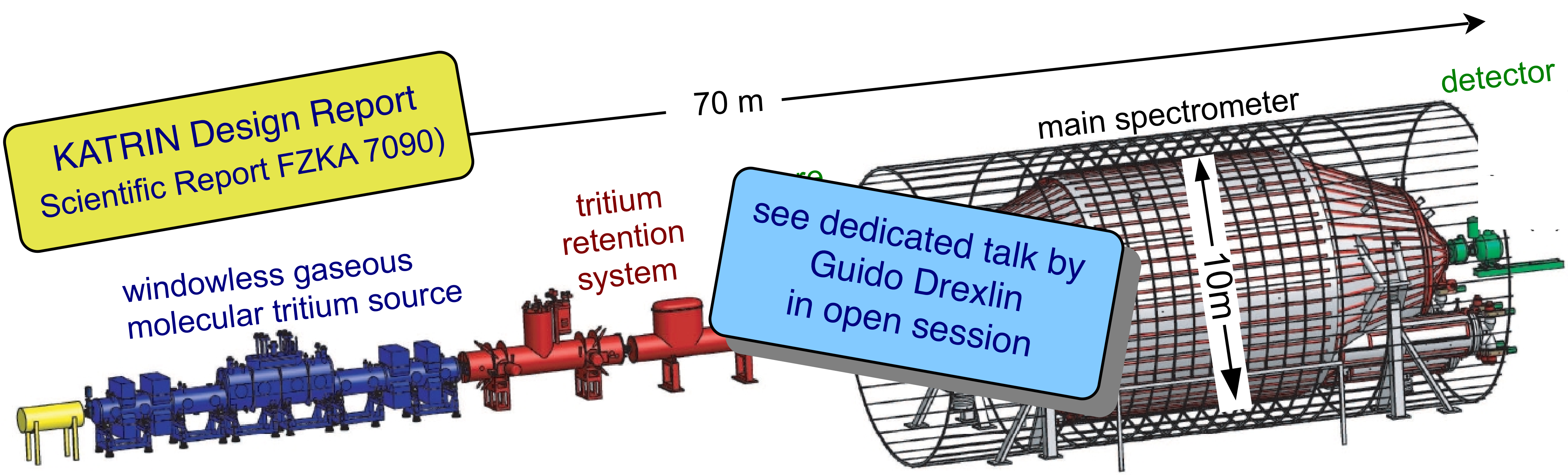
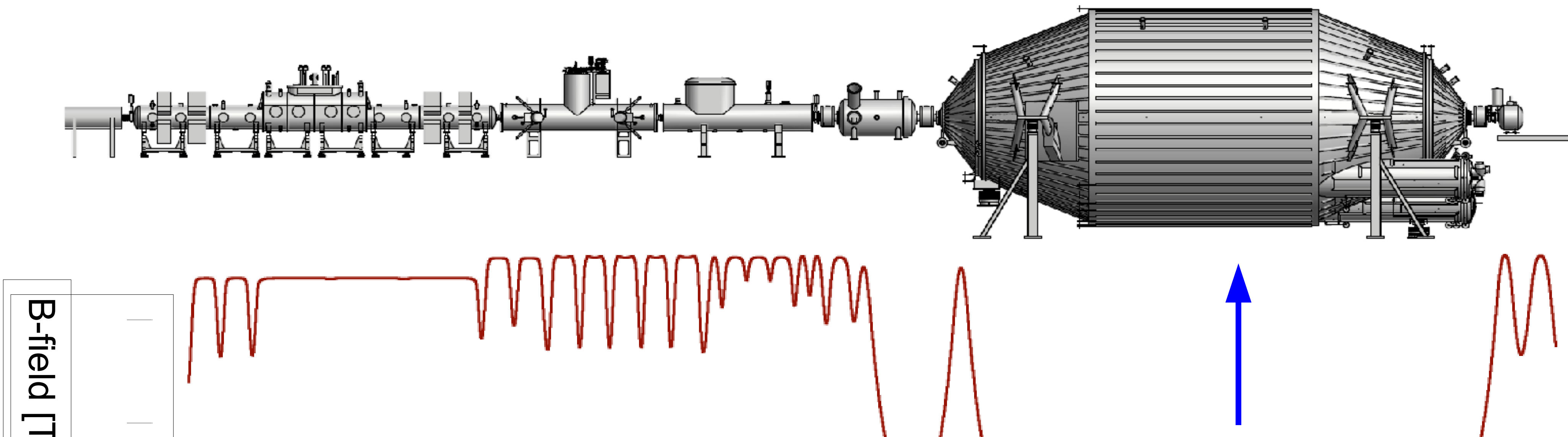
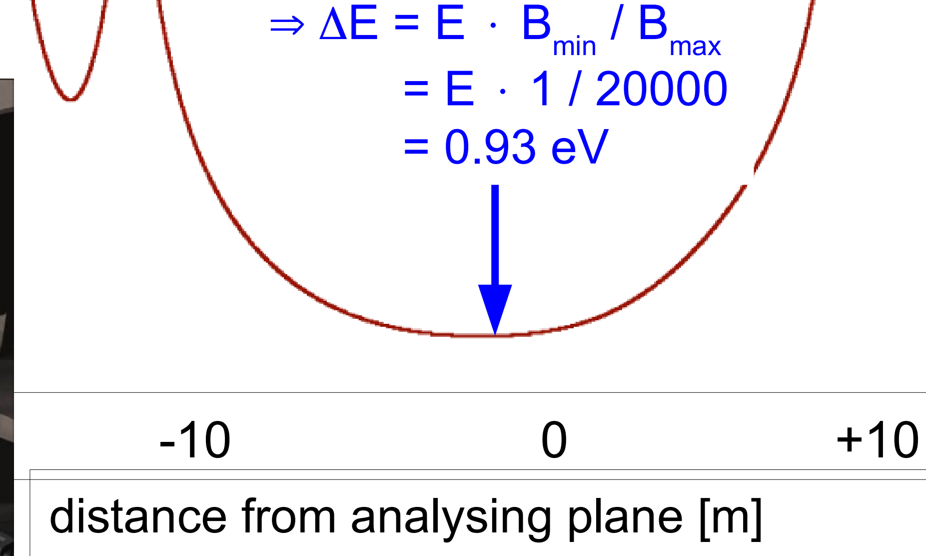
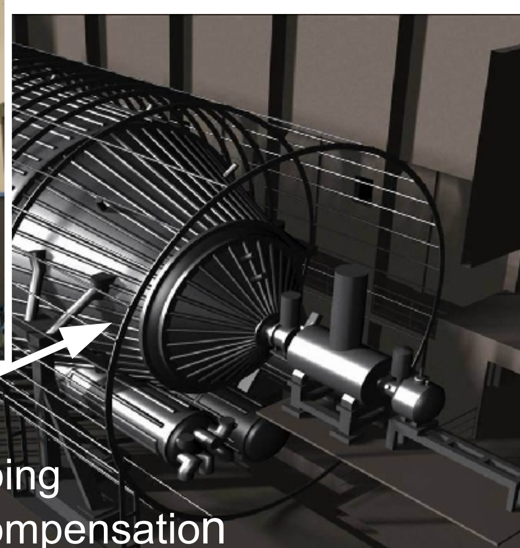


Electromagnetic design: magnetic fields

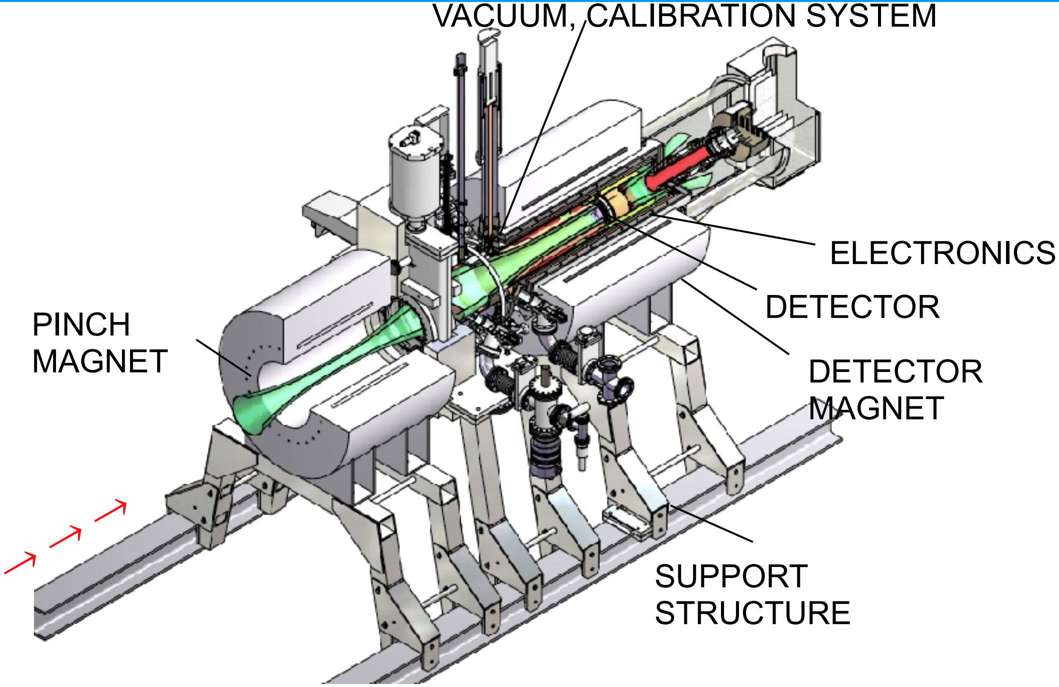





The detector

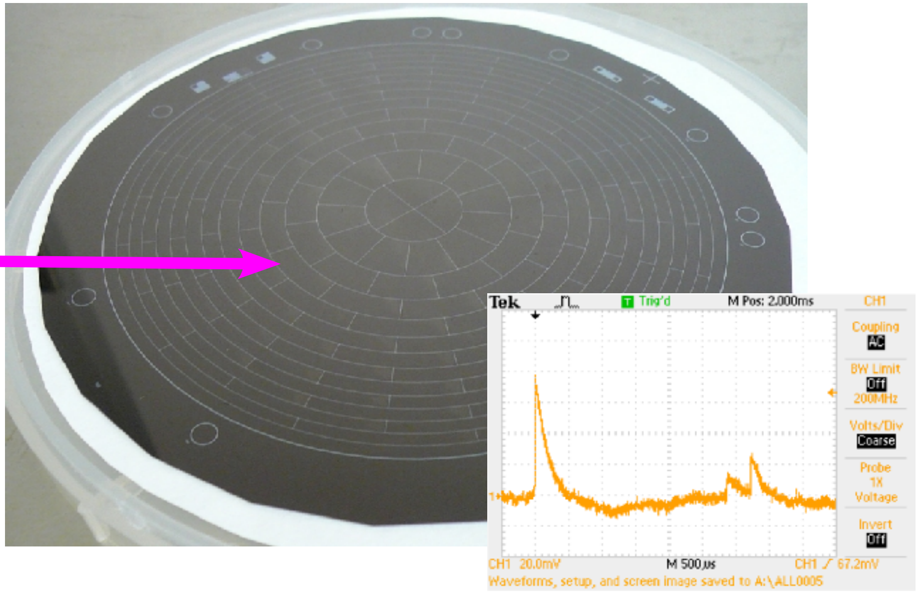
Requirements

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

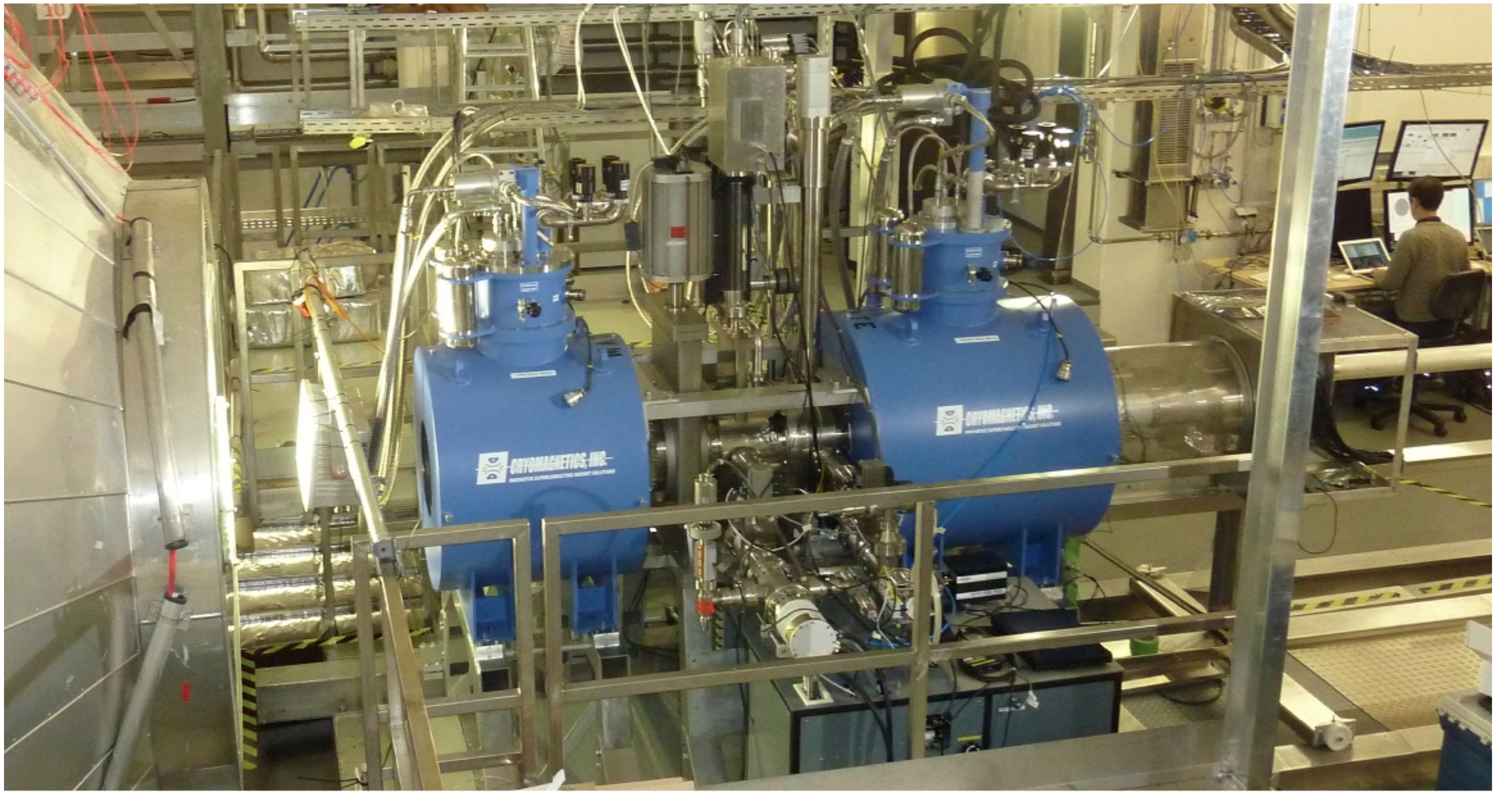


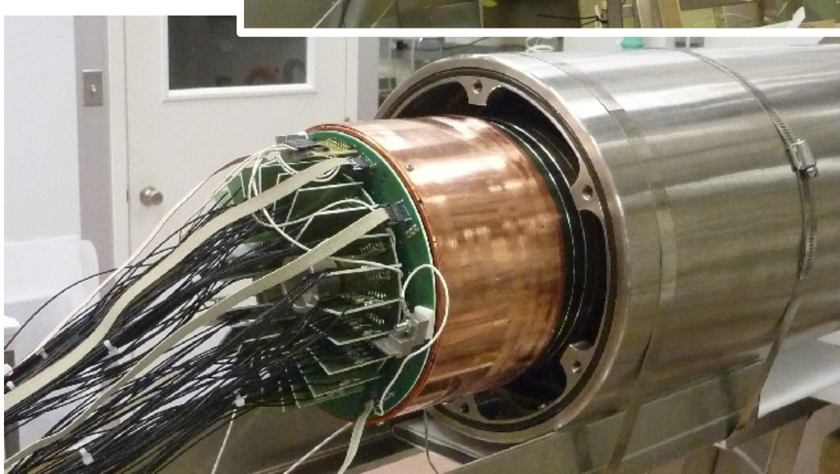
Properties

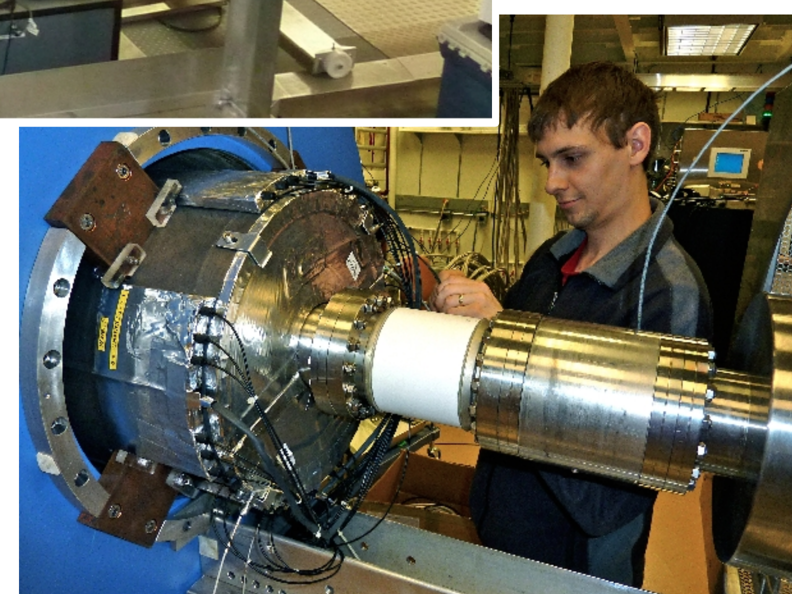
- 90 mm Ø Si PIN diode
- thin entry window (50nm)
- detector magnet 3 - 6 T
- post acceleration (30kV)
  (to lower background in signal region)
- segmented wafer (145 pixels)
  → record azimuthal and radial profile of the flux tube
  → investigate systematic effects
  → compensate field inhomogeneities



KATRIN detector has been commissioned at KIT







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Main spectrometer – transport to Karlsruhe Institute of Technology

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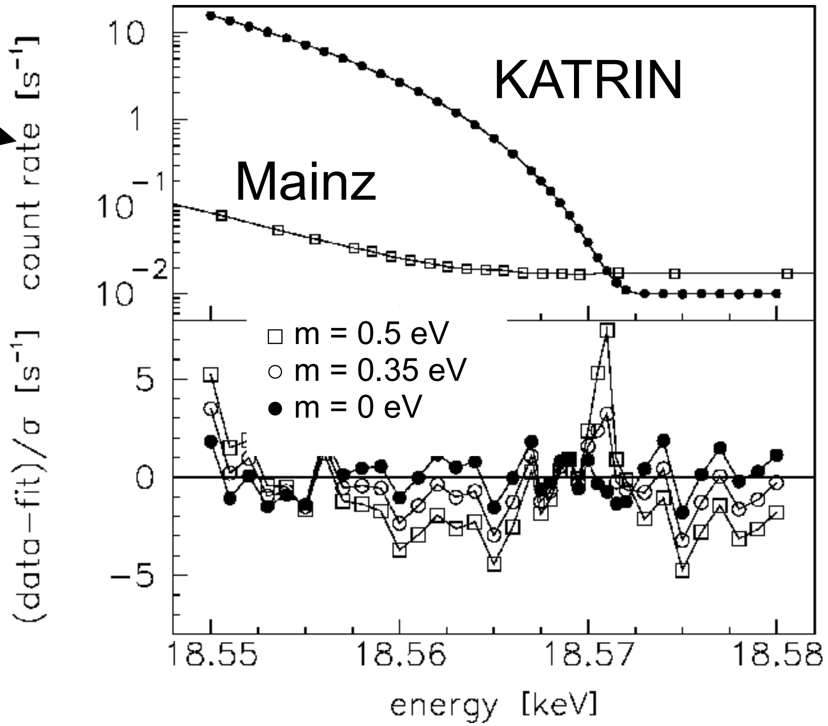
Main spectrometer with air coil system

Wire electrode system inside: bg reduction, field shaping, ...

KATRIN´s sensitivity

Example of KATRIN simulation & fit
(last 25eV below endpoint, reference):



sensitivity:

m_ν < 0.2eV (90%CL)

discovery potential:

m_ν = 0.3eV (3σ)

m_ν = 0.35eV (5σ)

Expectation for 3 full data taking years: $\sigma_{syst} \sim \sigma_{stat}$

Sensitivity is still statistically limited,
because with more statistics would go closer to the endpoint,
where most systematics nearly vanish

Sensitivity still has to proven, but there might be even some more improvements

KATRIN´s sensitivity

Example of KATRIN simulation & fit
(last 25eV below endpoint, ref...

⇒ **KATRIN will improve the sensitivity by 1 order of magnitude**
will check the whole cosmological relevant mass range
will detect degenerate neutrinos (if they are degen.)

KATRIN can also searching sterile neutrinos
by looking for a kink in the decay spectrum:

$$dN/dE = K\ F(E,Z)\ p\ E_{tot}\ (E_0-E_e) \sum_{i=1}^{n_{active}+n_{sterile}} |U_{ei}|^2 \sqrt{(E_0-E_e)^2 - m(\nu_i)^2}$$

eV scale (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

keV scale (dark matter): under study

E...

Se...

Sensitivity still has to proven, but there might be even some more improvements

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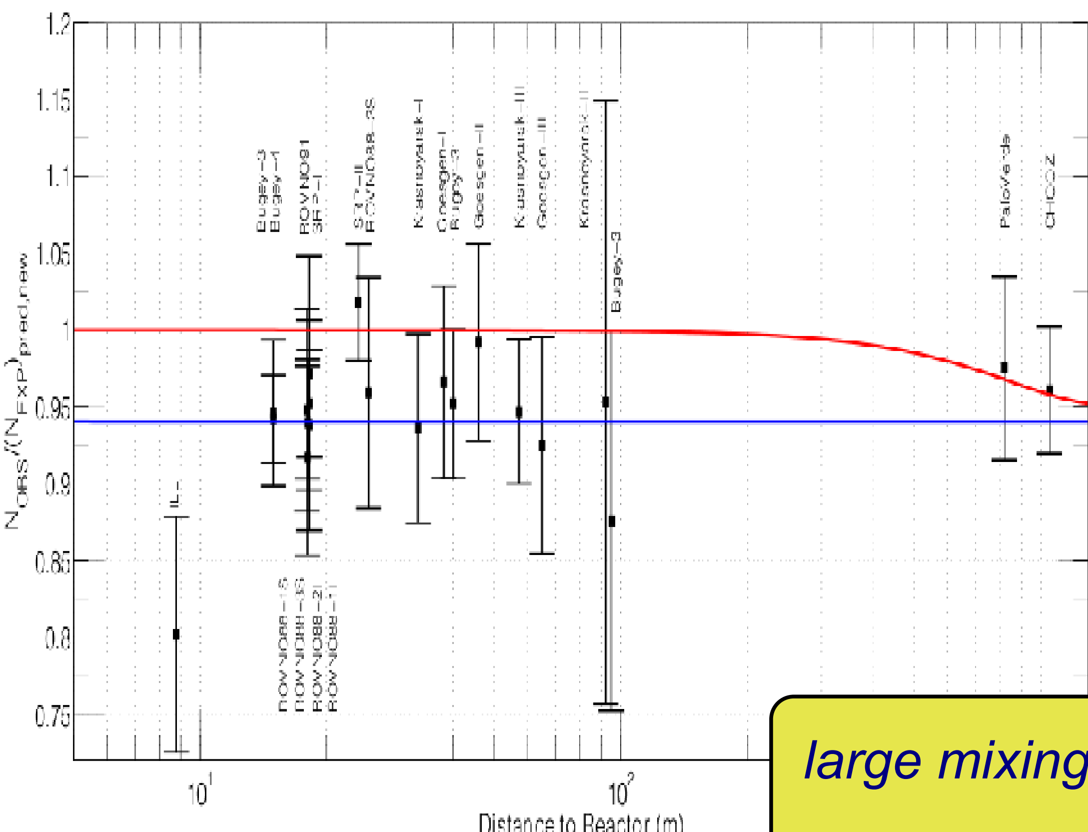
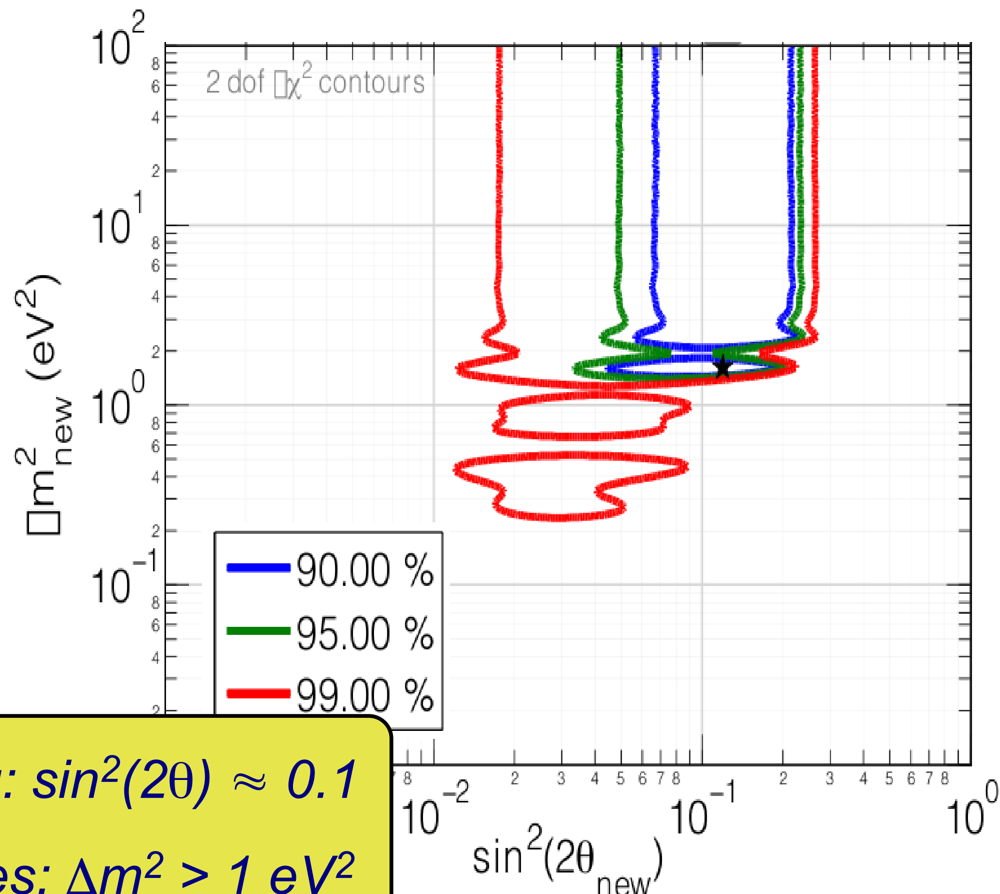
Is there a fourth sterile neutrino state ?

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: $\Delta m^2 > 1$ eV²

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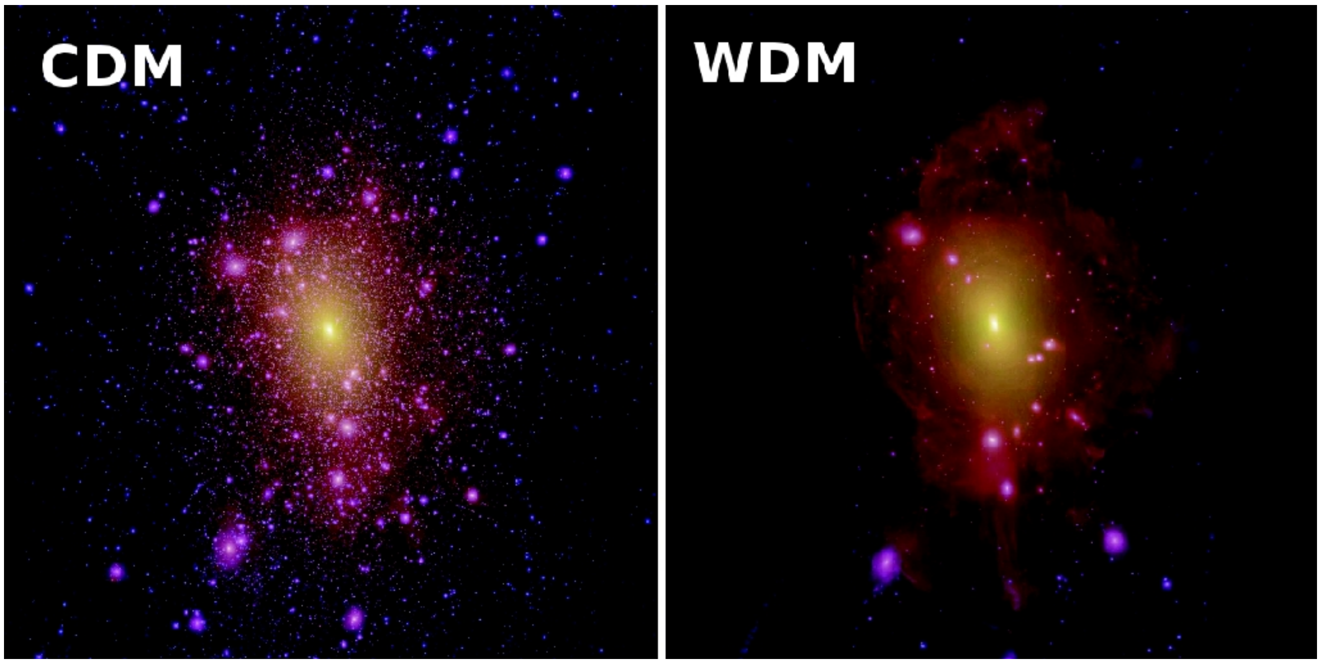
Hints for a 2nd sterile neutrino: Warm Dark Matter in the universe

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)

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

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Neutrino mixing with 3 active neutrinos: active = coupling to Z^0 and $W^{+/-}$

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

U is unitary 3 x 3 matrix

3 active neutrinos plus a sterile neutrino

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_{sterile} \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & 0 \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & 0 \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

$\nu_{sterile}$ does not couple to Z^0 and $W^{+/-}$

Now we have an unitary 4 x 4 matrix, but still the 3 x 3 submatrix is unitary

$\nu_{sterile}$ and ν_4 do not play any physical role (except for gravitation)

3 active neutrinos plus a sterile neutrino with non-vanishing mixing

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_{sterile} \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

$\nu_{sterile}$ **does not couple to Z^0 and $W^{+/-}$**

Now we have an unitary 4 x 4 matrix, but usually $U_{s1}, U_{s2}, U_{s3}, U_{e4}, U_{\mu4}, U_{\tau4} \ll 1$

But the 3 x 3 submatrix is not unitary anymore !

$\nu_{sterile}$ **and ν_4 do play a physical role by their mixing:**

$$\nu_e = \sum_{i=1}^{3} U_{ei}\,\nu_i + U_{e4}\,\nu_4$$

$$m^2(\nu_e) := \sum_{i=1}^{3} |U_{ei}|^2\, m^2(\nu_i) + |U_{e4}|^2\, m^2(\nu_4)$$
$$\approx \cos^2(\theta)\, m(\nu_{1,2,3})^2 + \sin^2(\theta)\, m(\nu_4)^2$$

3 active neutrinos plus a sterile neutrino with non-vanishing mixing

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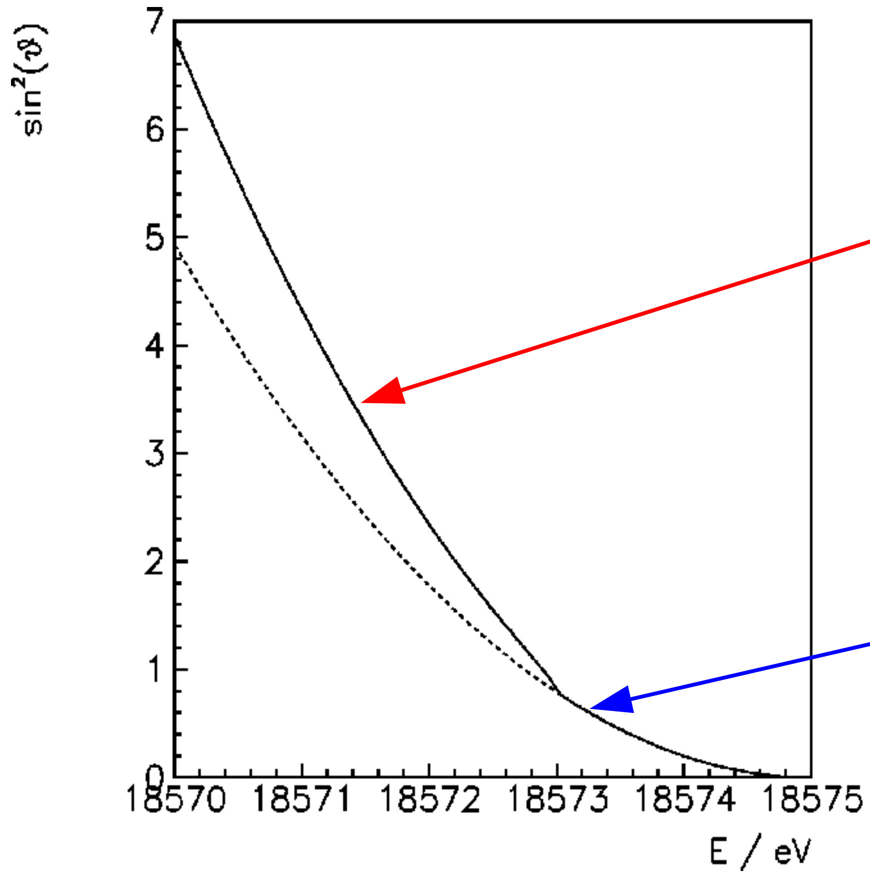
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_{sterile} \end{pmatrix} = \begin{pmatrix} \boldsymbol{U_{e1}} & \boldsymbol{U_{e2}} & \boldsymbol{U_{e3}} & U_{e4} \\ \boldsymbol{U_{\mu 1}} & \boldsymbol{U_{\mu 2}} & \boldsymbol{U_{\mu 3}} & U_{\mu 4} \\ \boldsymbol{U_{\tau 1}} & \boldsymbol{U_{\tau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

Are sterile neutrinos a crazy idea ?
Not a all:
We expect 3 right-handed („sterile“)
neutrinos from the sea-saw mechanism
to create the light neutrino masses $\nu_1, \nu_2\, \nu_3$

The only new thing is, that one (ν_4) *or two neutrinos* (ν_4, ν_5)
do not have masses of 10^x *GeV but are very light*

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

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

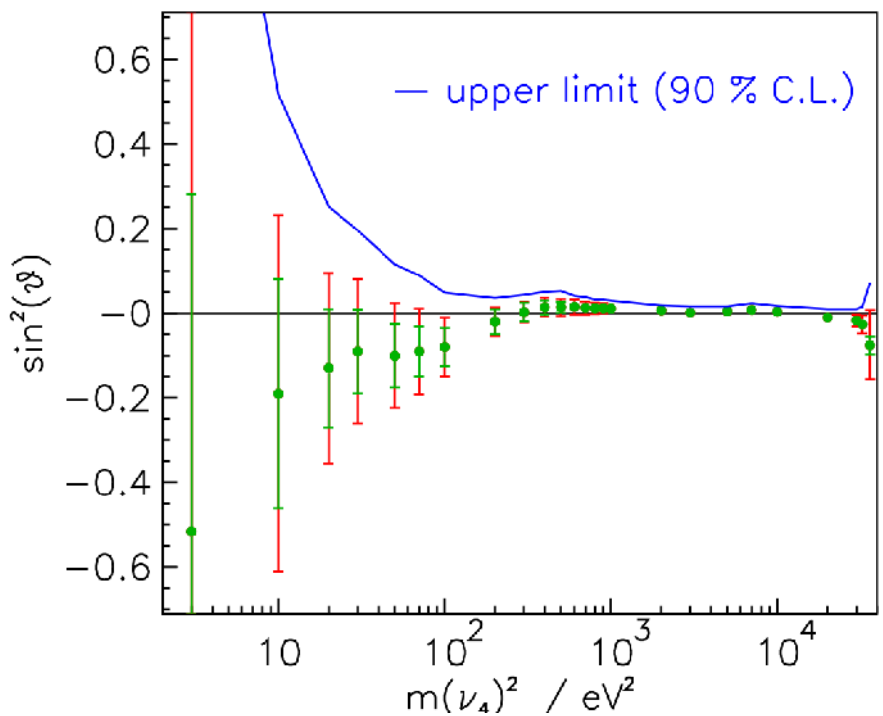
Remark: Neutrinolesss double β decay: $m_{\beta\beta}(\nu) = |\sum_{i=1}^{n_a+n_s} |U_{ei}^2|\, e^{i\alpha(i)}\, m(\nu_i)|$ (coherent)

measures only „one number“ → cannot distinguish sterile neutrinos if U_{ei} is small

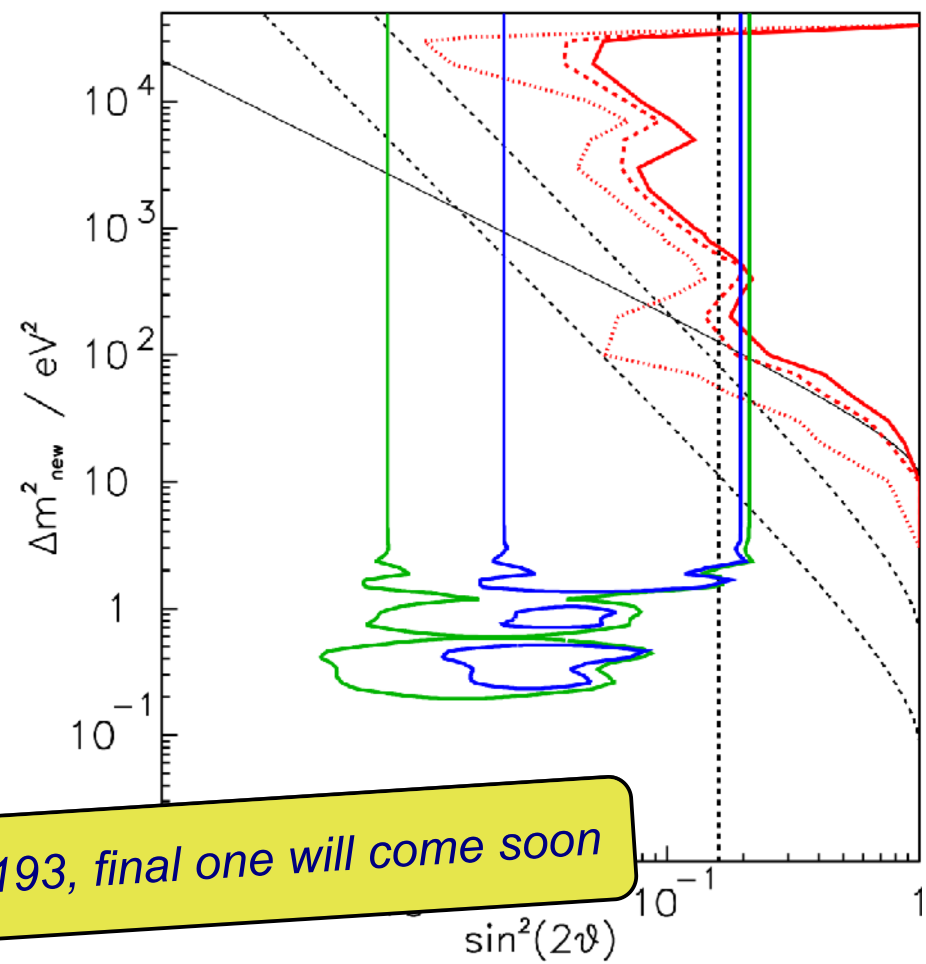
Sterile neutrino limits from the Mainz Neutrino Mass Experiment

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

Do same analysis (same data sets, same programs, same way to treat systematic uncertainties) on Mainz phase 2 data as in *C. Kraus et al., Euro. Phys. J. C40 (2005) 447*



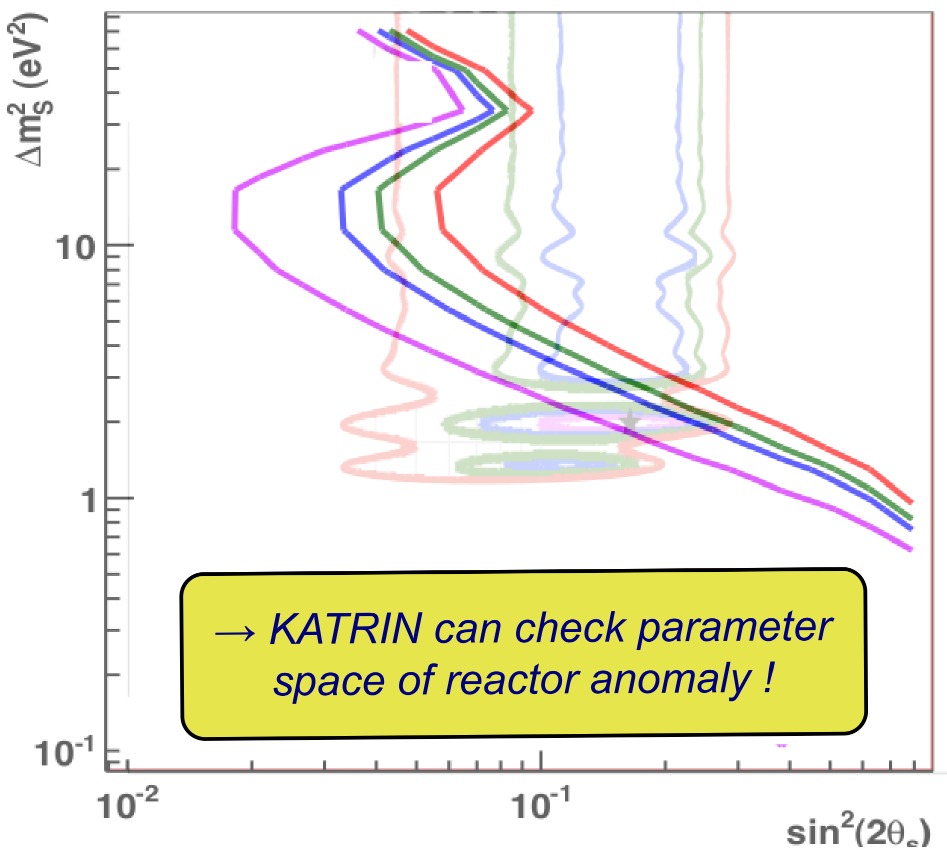
Ch. Kraus, A. Singer, K. Valerius, CW, arXiv.1210.4194, Eur. Phys. J. C73 (2013) 2323



similar analysis by Troitsk: preliminary arXiv:1211.7193, final one will come soon

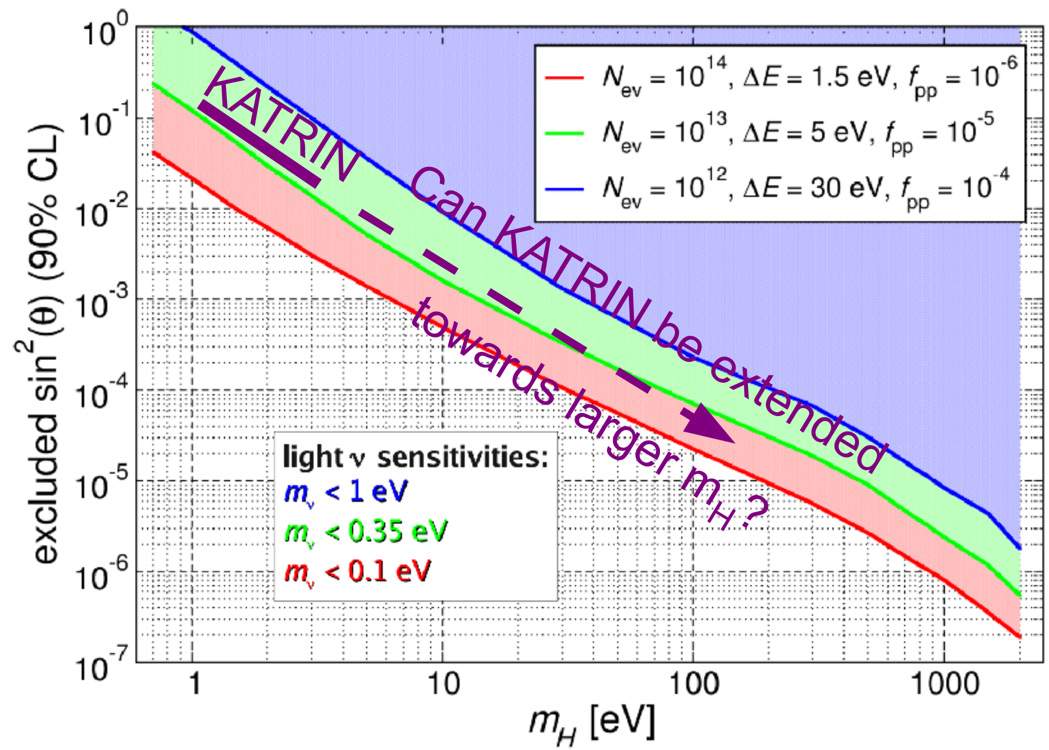
Sensivity on sterile neutrinos of the next direct neutrino mass experiments

KATRIN



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

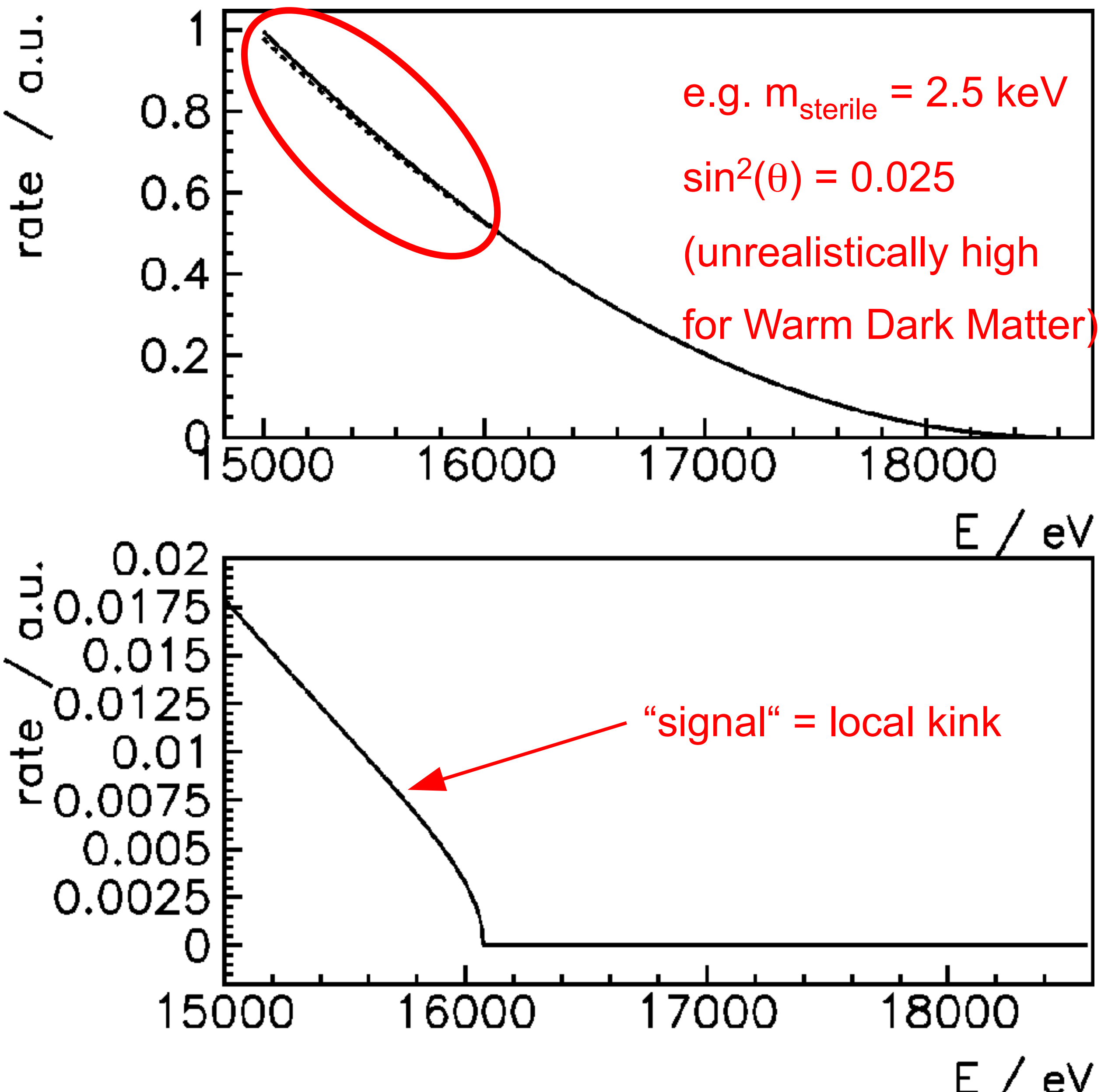
MARE II



→ *Need certainly a new strategy !*

A. Nucciotti, Meudon Workshop, June 2011

Search for a tiny kink of a keV neutrino



Main questions:

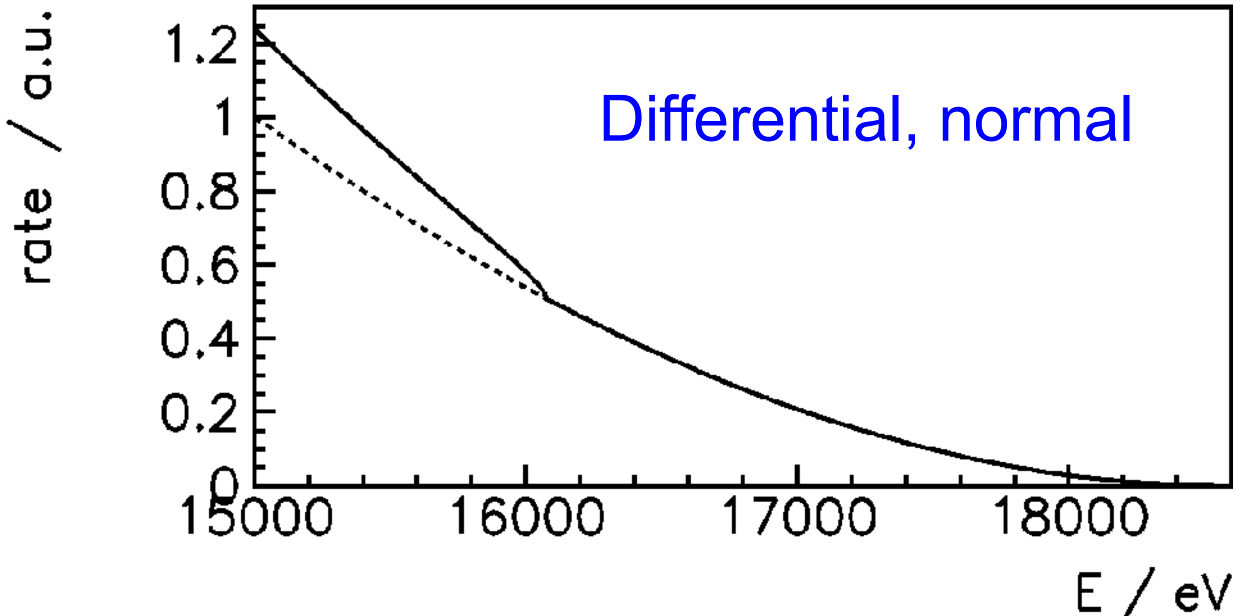
1) How to measure this tiny kink a few keV below the endpoint ?

   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 ?

Normal ("differential") or integral β-spectrum

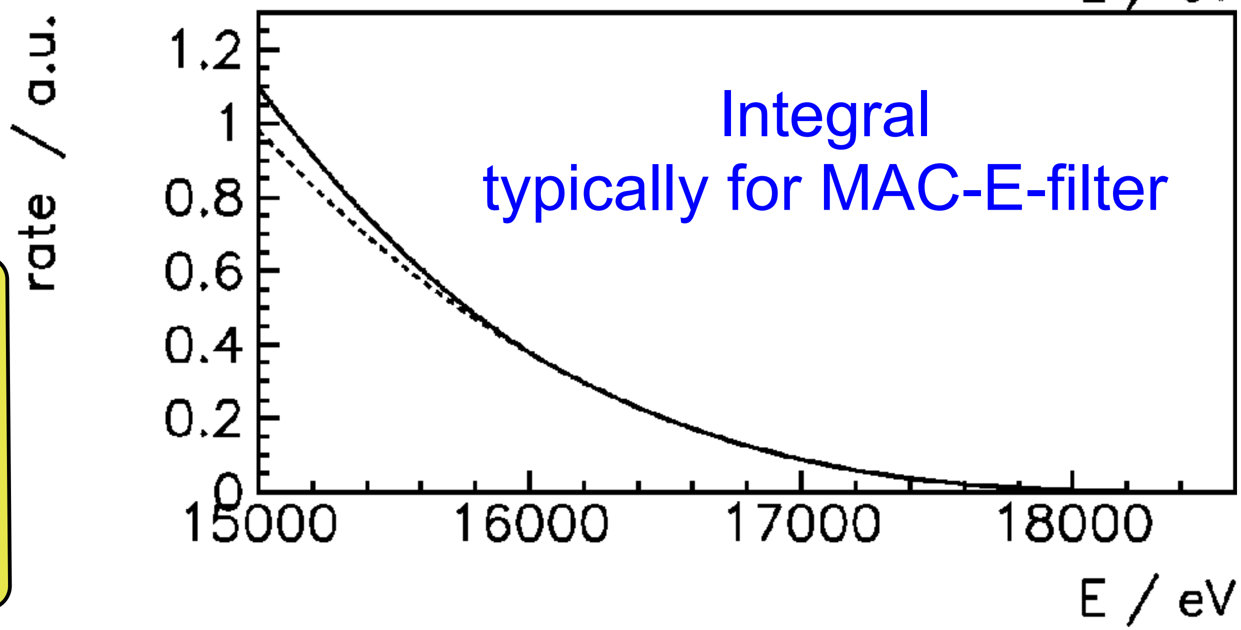


e.g. $m_{sterile}$ = 2.5 keV

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

(unrealistically high

for Warm Dark Matter)



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

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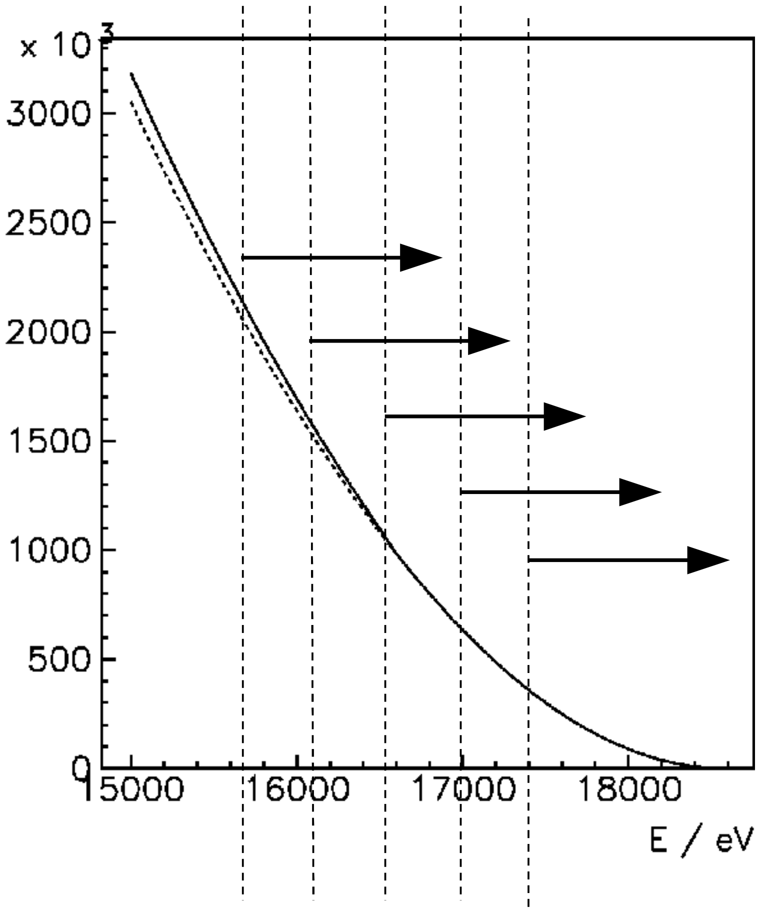
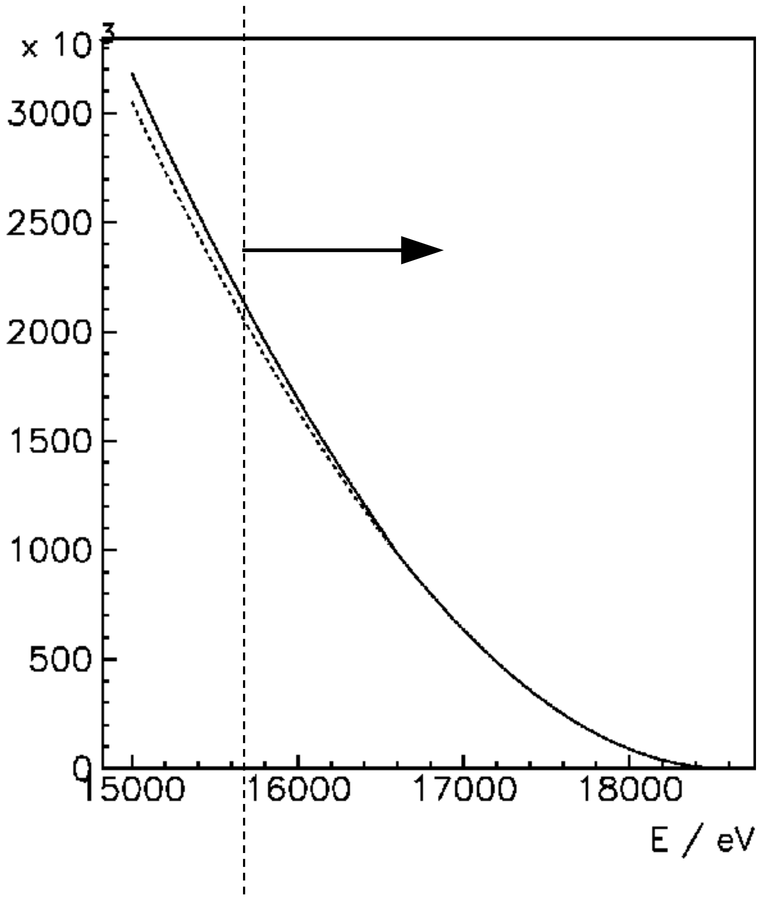
Second gain of integral versus differential: Avoid many steps in MAC-E-Filter mode

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

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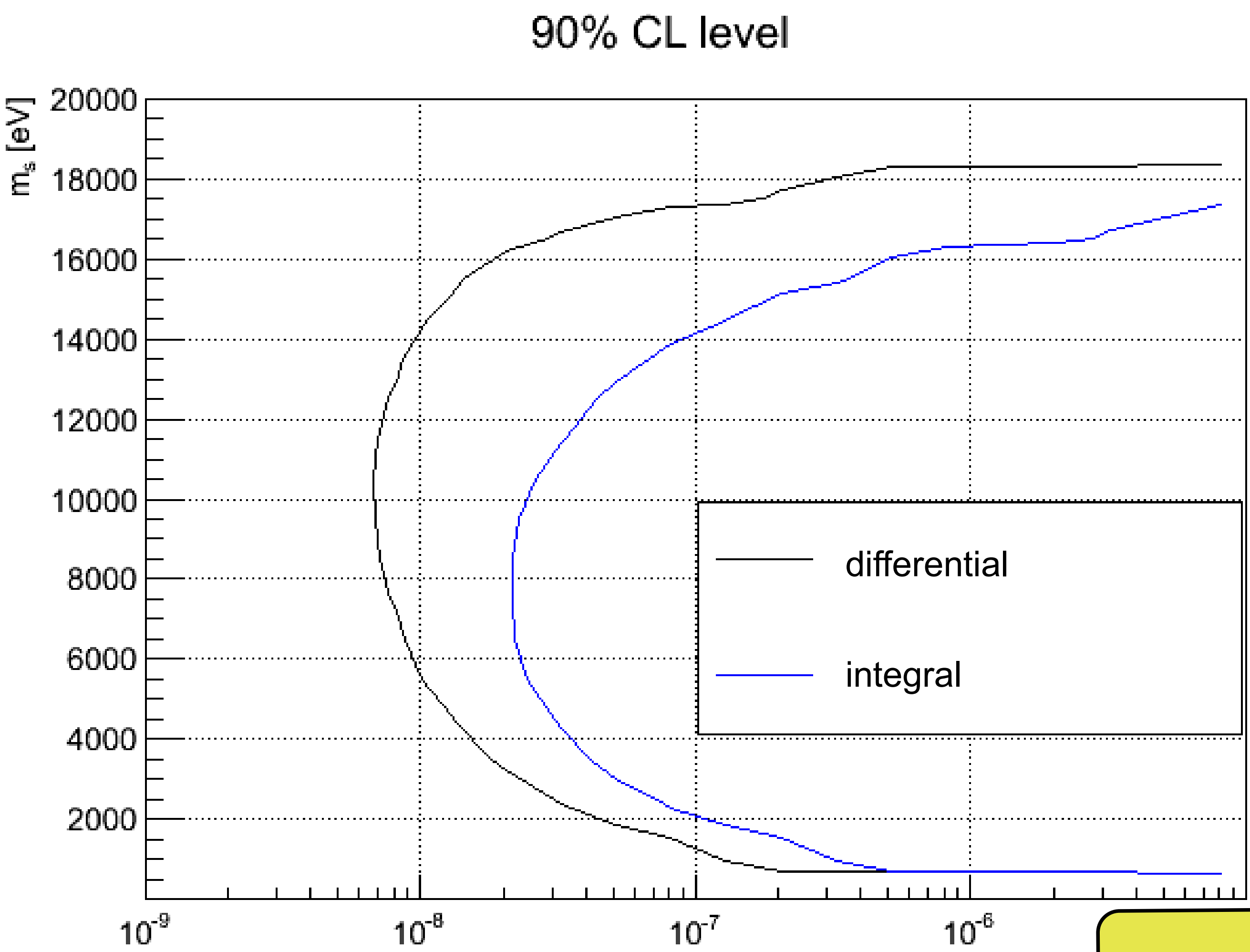
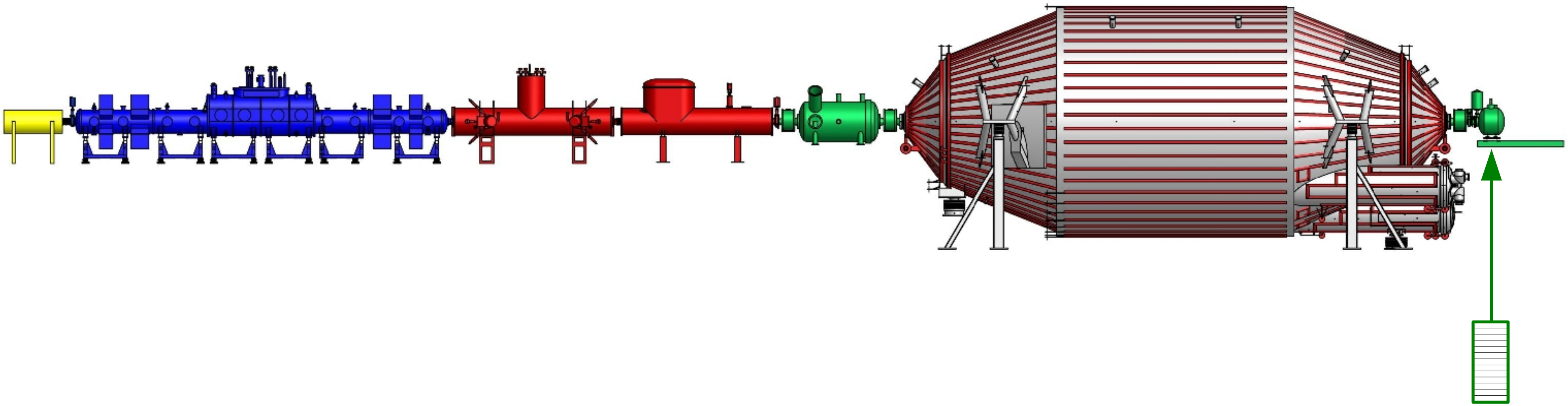
Statistical sensitivity for integral and differential measurement



→ **statistical uncertainty is not a problem but the systematics !**

Susanne Mertens, Chalonge 2013, Meudon

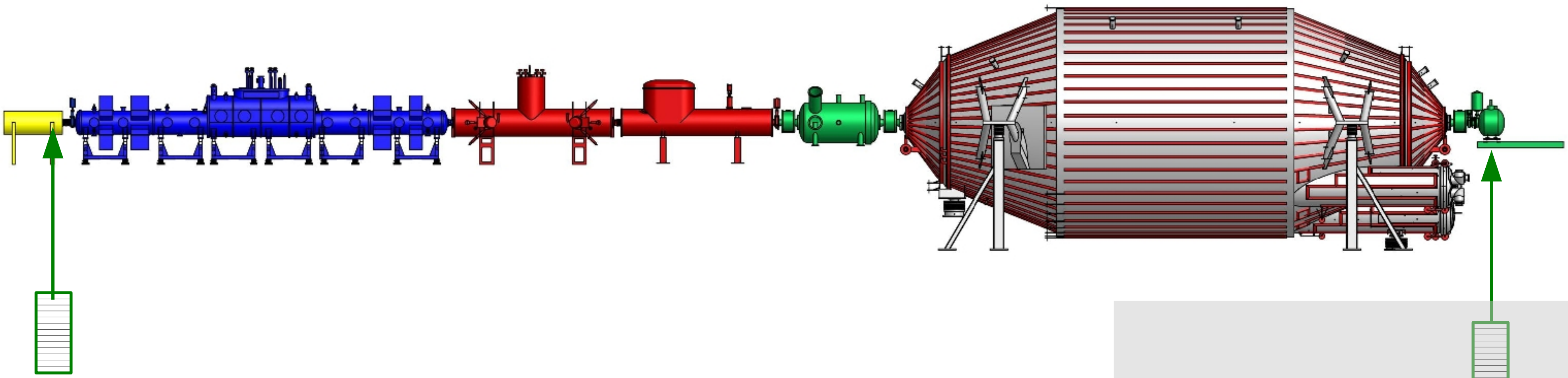
Possible implementations of a differential β-spectrum measurement with KATRIN



Detector
measures β-spectrum with energy resolution $\Delta E \sim 1$keV (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



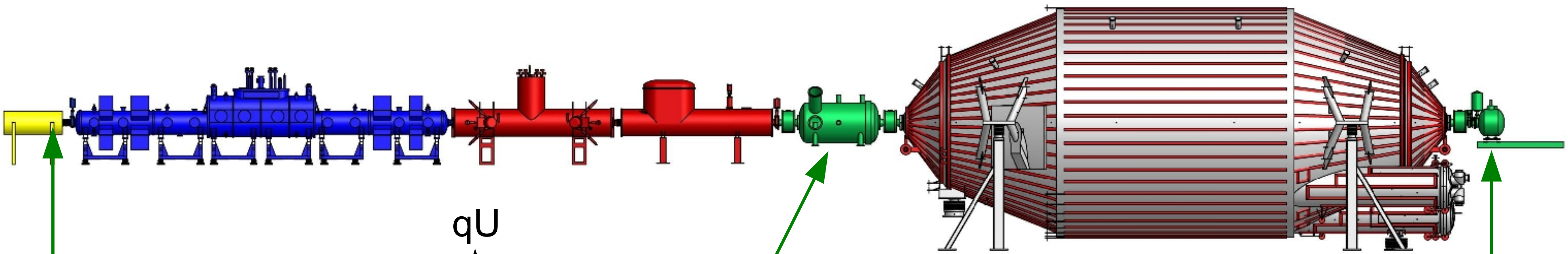
"Instrumented rear-wall" (detector)
measures β-spectrum
with energy resolution
ΔE ~ 1keV (FWHM)
completely and
all the time parasitically

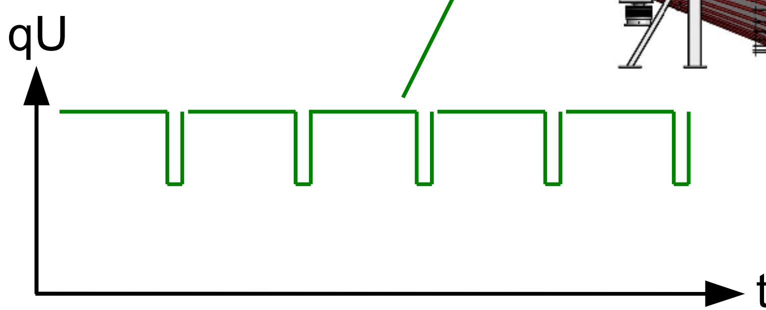
Problems:
tails of resolution function
ultra-high count rate
capability (pile-up, ...)

Detector
measures β-spectrum
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" (detector)
measures β-spectrum
with energy resolution
$\Delta E \sim$ 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 3kV ?

Detector
measures β-spectrum
with energy resolution
$\Delta E \sim$ 1keV (FWHM)
above a retarding energy
qU_0 = const.

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

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, …

Electronic final states of tritium β-decay: $T_2 \rightarrow ({}^3HeT)^+$, ${}^3He + T^+$, ...

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Including electronic excited final states of excitation energy V_j with probability W_j

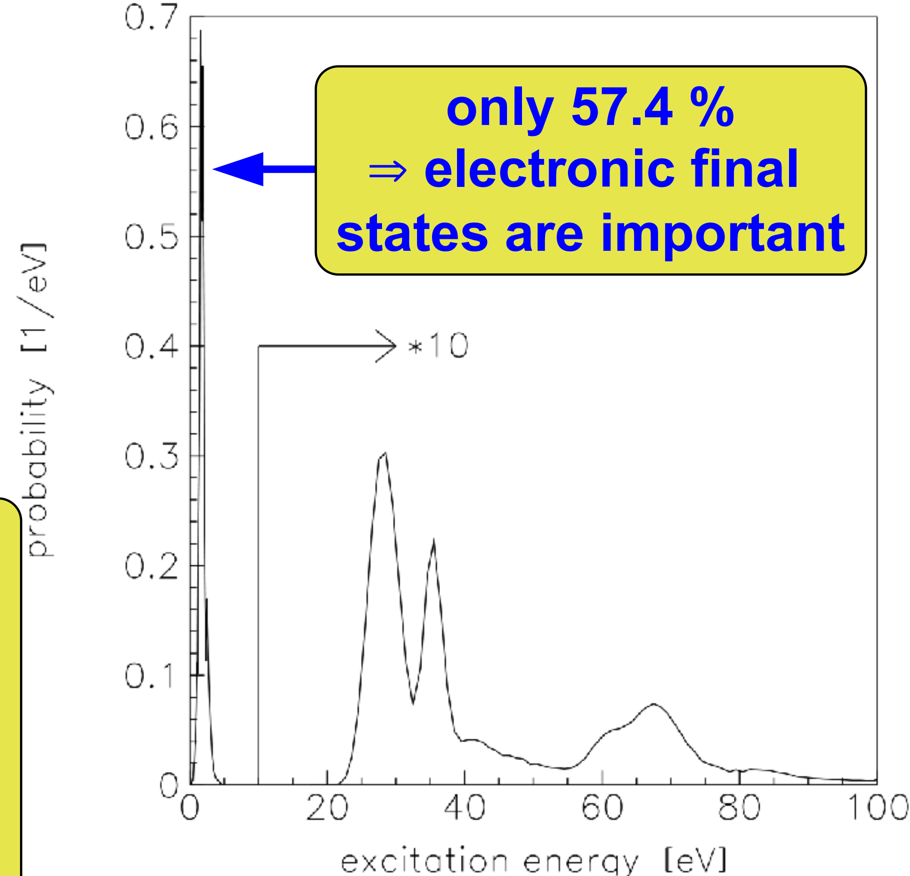
$$W_j = |\langle \Psi_0 | \Psi_{f,j} \rangle|^2$$

Using $\varepsilon_j = E_0 - V_j - E$

$$\frac{d^2N}{dt\,dE} = A \cdot F(E, Z+1) \cdot p \cdot (E+m) \cdot \sum_j W_j \cdot \varepsilon_j \cdot \sqrt{\varepsilon_j{}^2 - m^2(\nu_e)} \cdot \Theta(\varepsilon_j - m(\nu_e))$$

Quantum-chemical calculations of electronic final states of T_2 β-decay:

A. Saenz et al. Phys. Rev. Lett. 84 (2000) 242,
N. Doss et al., Phys. Rev. C73 (2006) 025502
N. Doss and J. Tennyson, J. Phys. B, 41 (2008)

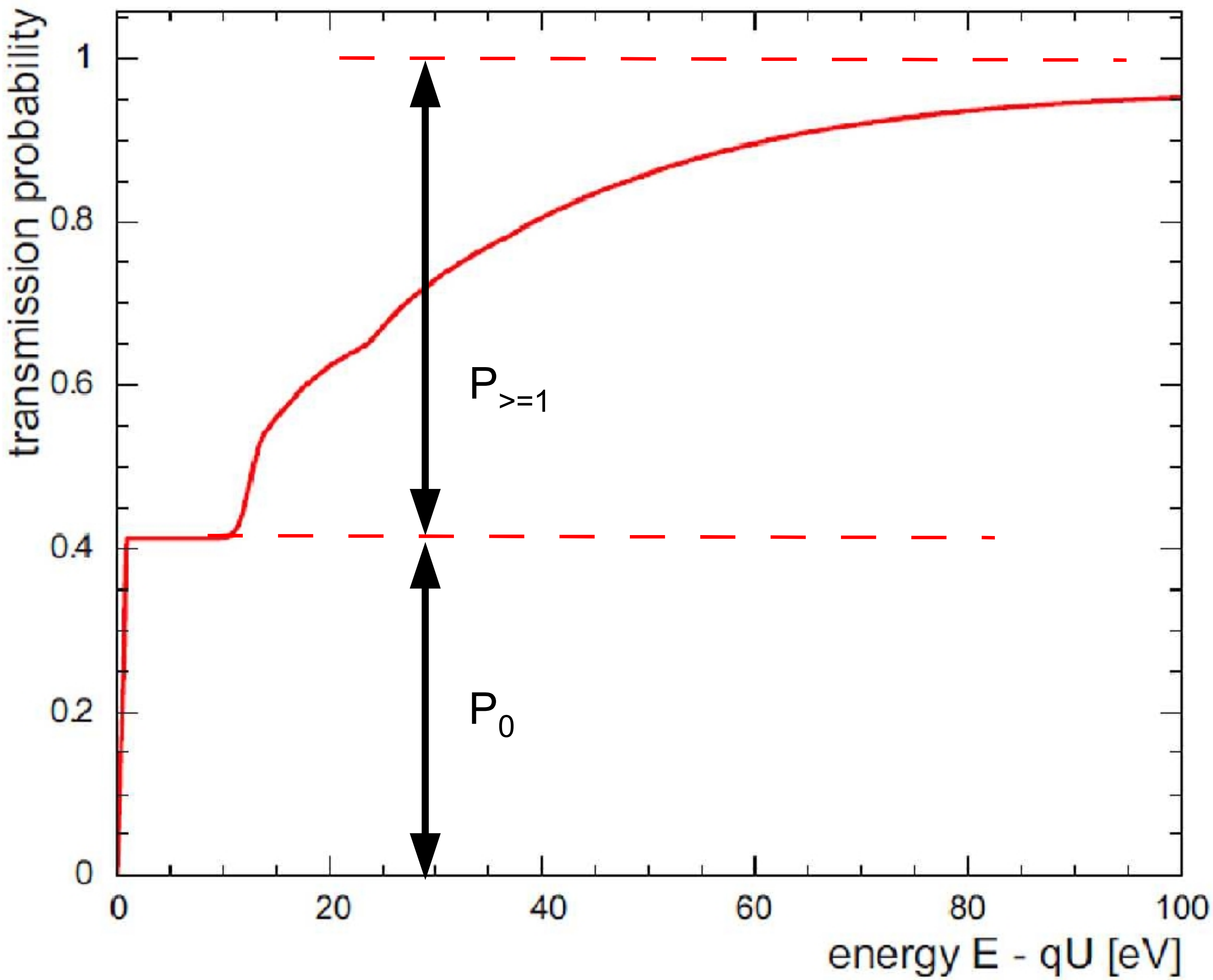


only 57.4 % ⇒ electronic final states are important

Can access the electronic final state spectrum quite accurately by sum rules and at higher excitation energies by the quasi-free electron extension

Precise enough for WDM searches ?

Inelastic scattering x transmission fcn



Standard KATRIN:

P_0 = 41%

→ need to lower tritium column density to get P_0 >> 90%

$\mathcal{O}(1) \rightarrow \mathcal{O}(0.1 - 0.01)$ effect

And there is still enough statistics !

Energy loss function:
apply sum rules and high energy extrapolation by quasi-free electrons measurements @ KATRIN

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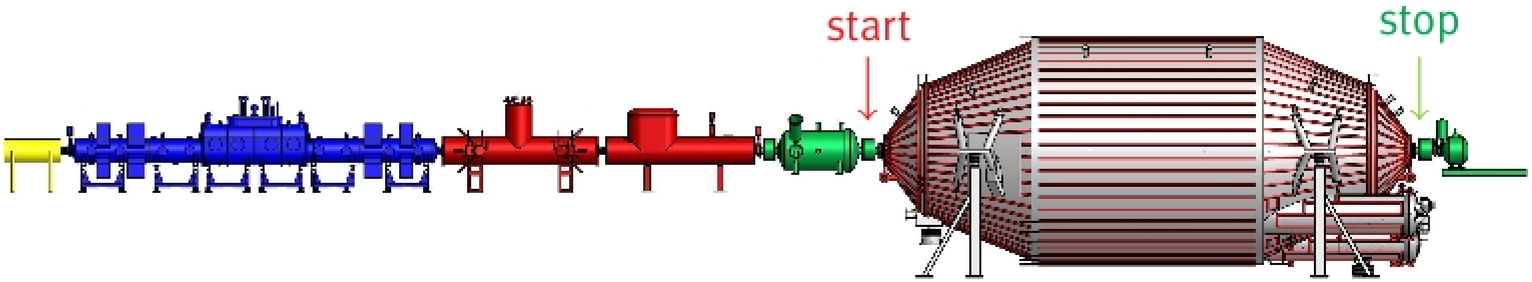
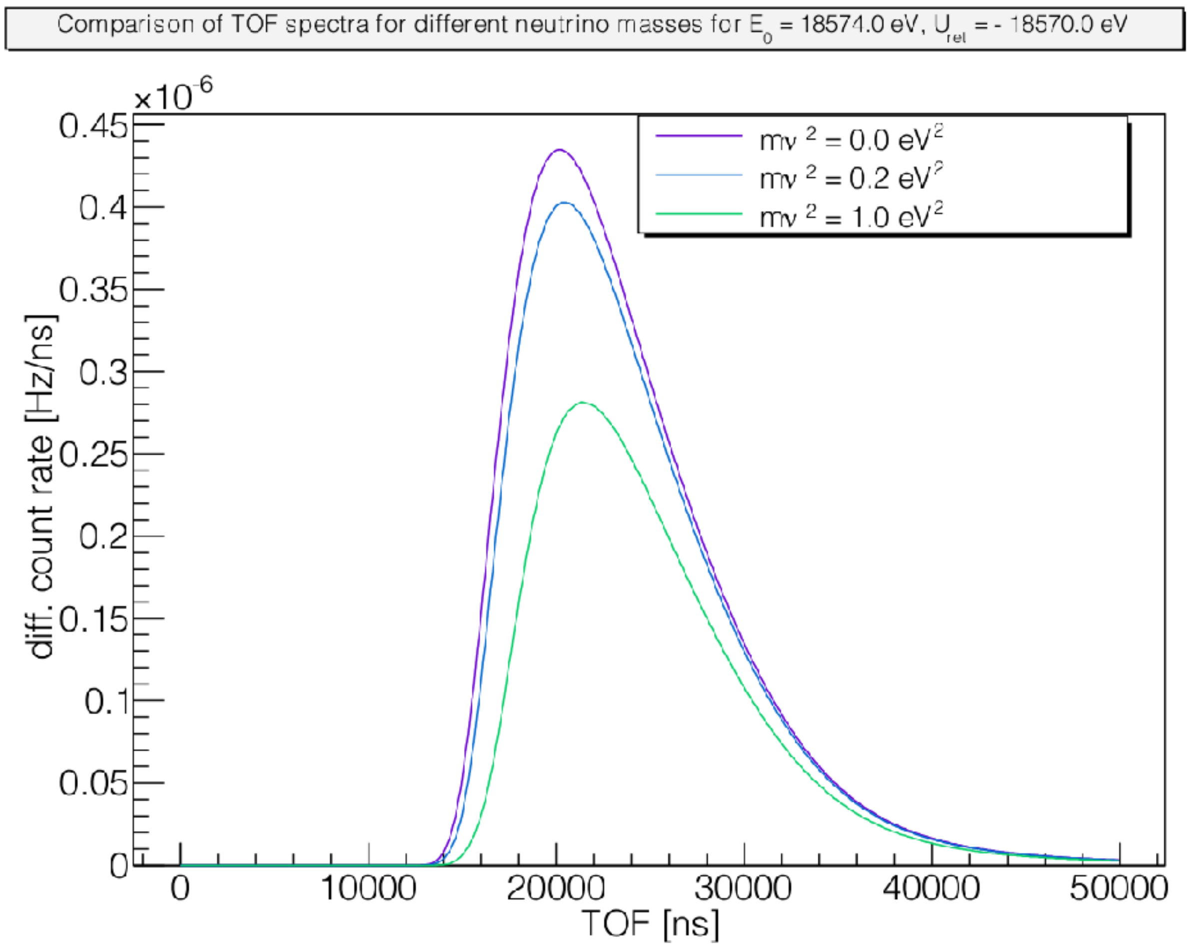
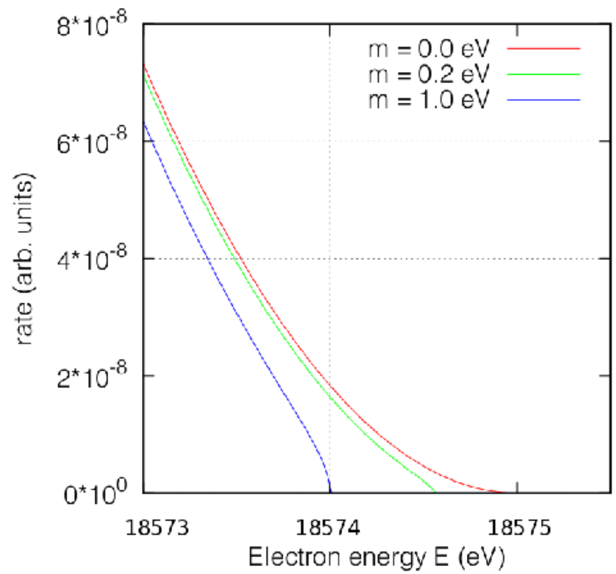
Alternative spectroscopy: measure time-of-flight TOF through KATRIN spectrometer





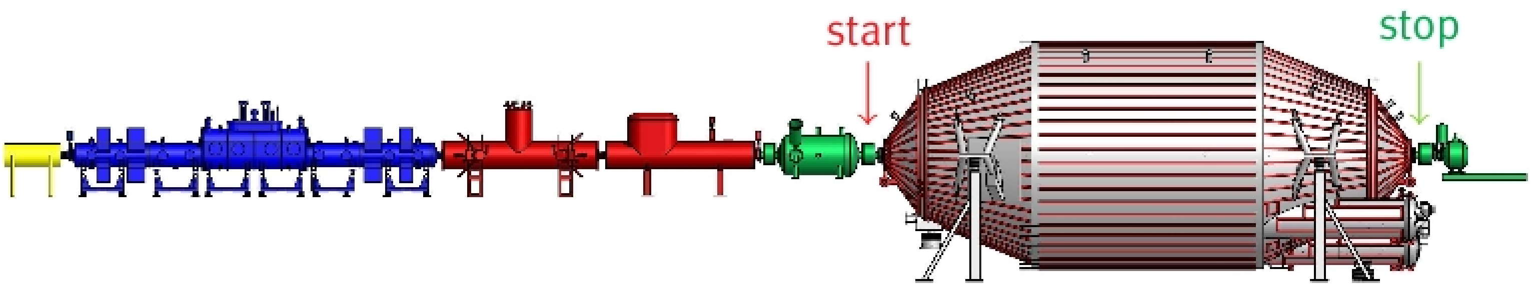


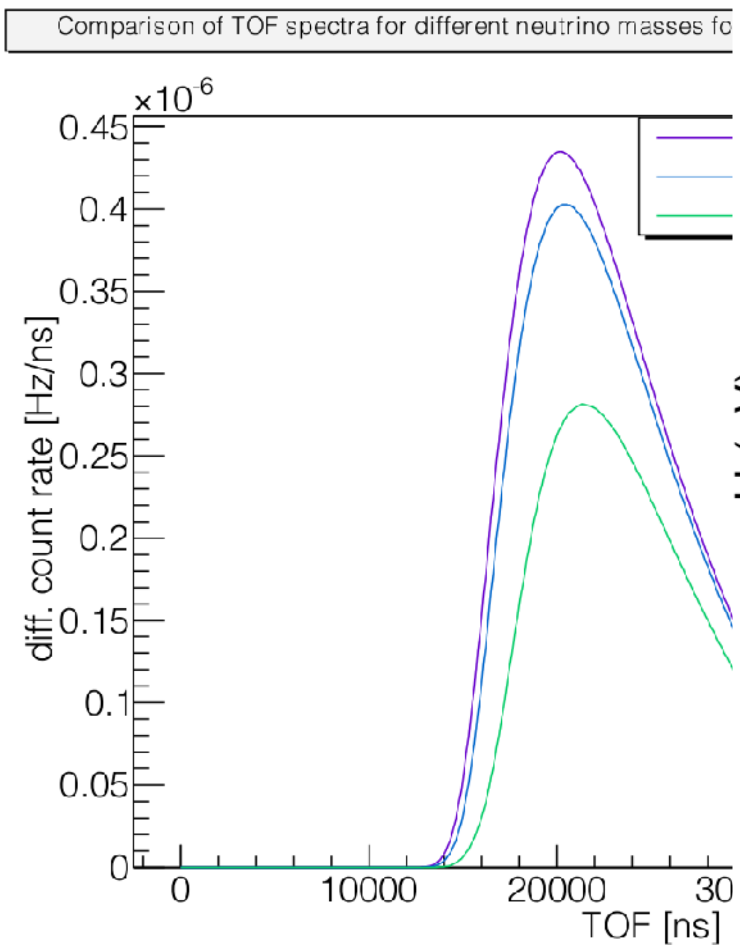
Time-of-flight spectrum is sensitive to the neutrino mass

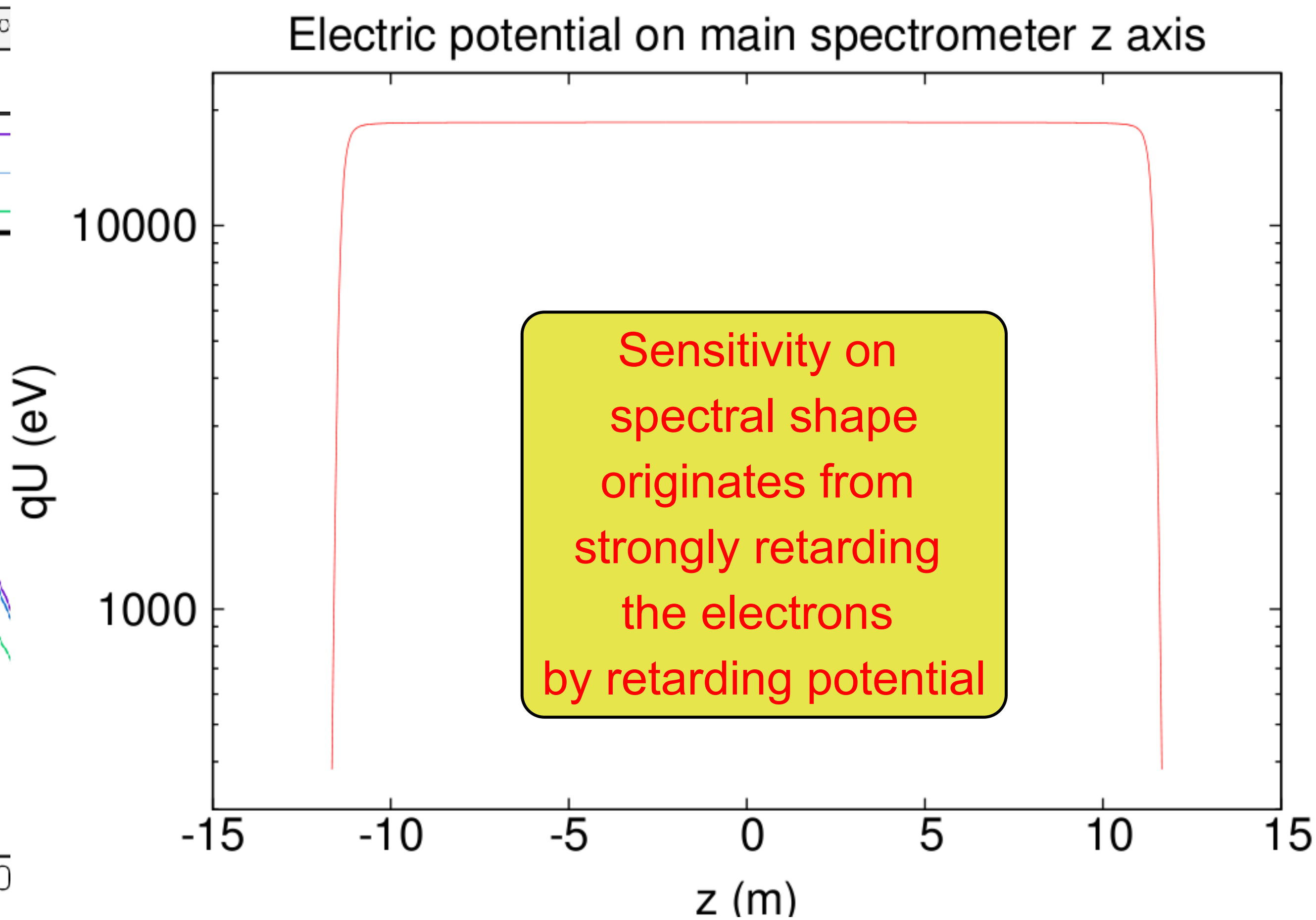
require one retardation potential only

not integral but differential β-spectrum

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





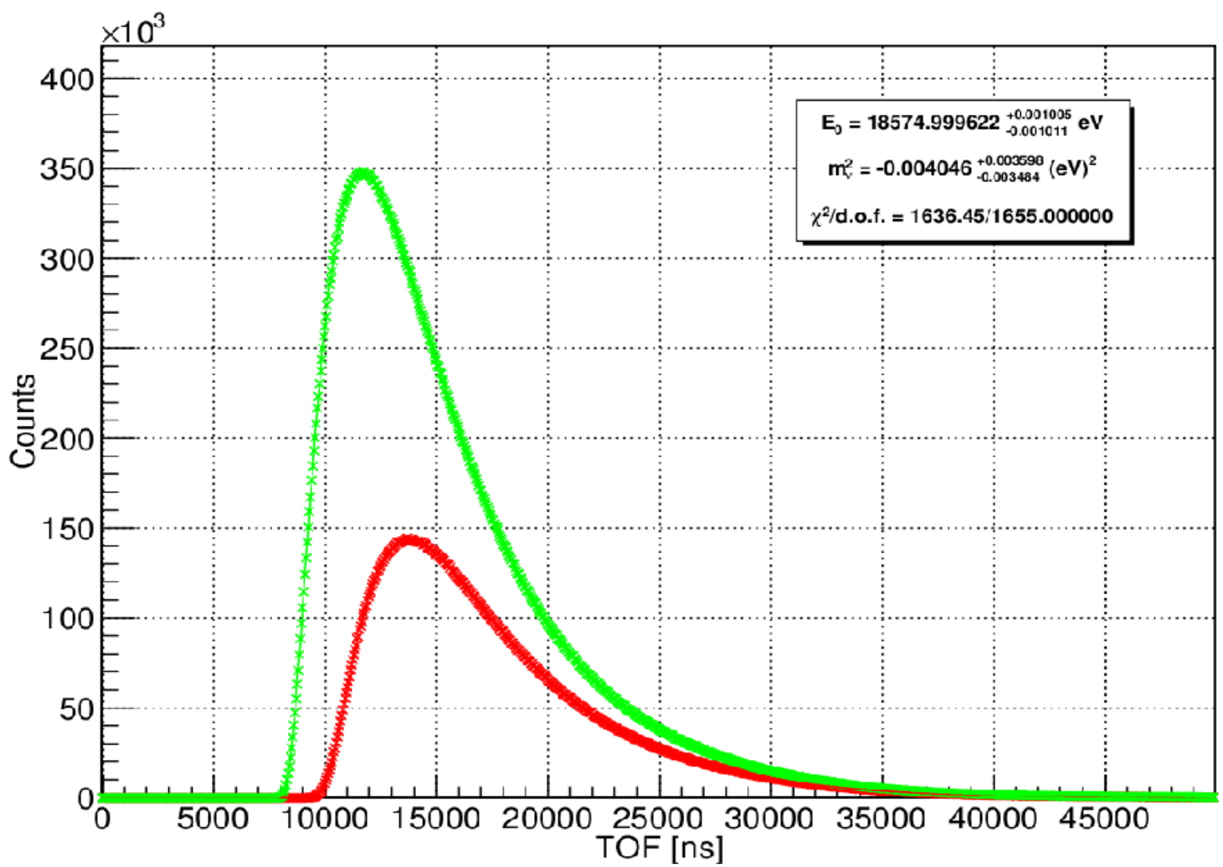


Sensitvity improvement on $m^2(\nu_e)$ by ideal TOF determination

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 !



N. Steinbrink et al., to appear on arXiv within the next days

How to measure time-of-flight at KATRIN ? gated-filter

1) Can measure time-of-arrival with KATRIN detector with Δt = 50 ns → ok

2) Need to determine time-of-passing-by of beta electron before main spectrometer without disturbing energy and momentum by more than 10 meV !

→ Need „detector“ with 10 meV threshold

This seems not to be prohibited in principle but it is unrealistic for the near future !

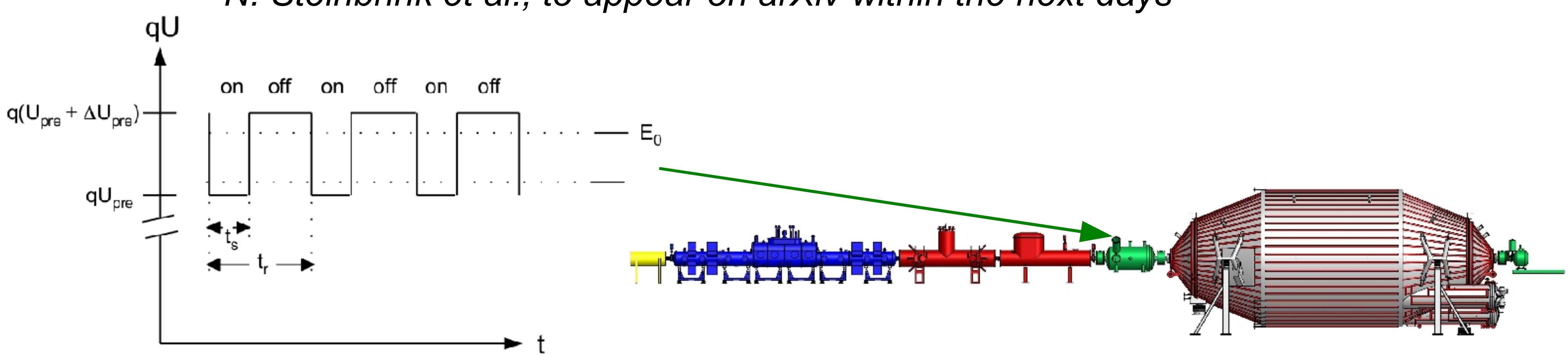
2') Use pre spectrometer as a „gated-filter“ by switching fast the retarding voltage

MAC-E-TOF demonstrated: *J. Bonn et al., Nucl. Instr. Meth. A421 (1999) 256*

no problem with transmission properties: *M. Prall et al., NJP 14 (2012) 073054*

About as sensitive on the neutrino mass as standard KATRIN:

N. Steinbrink et al., to appear on arXiv within the next days



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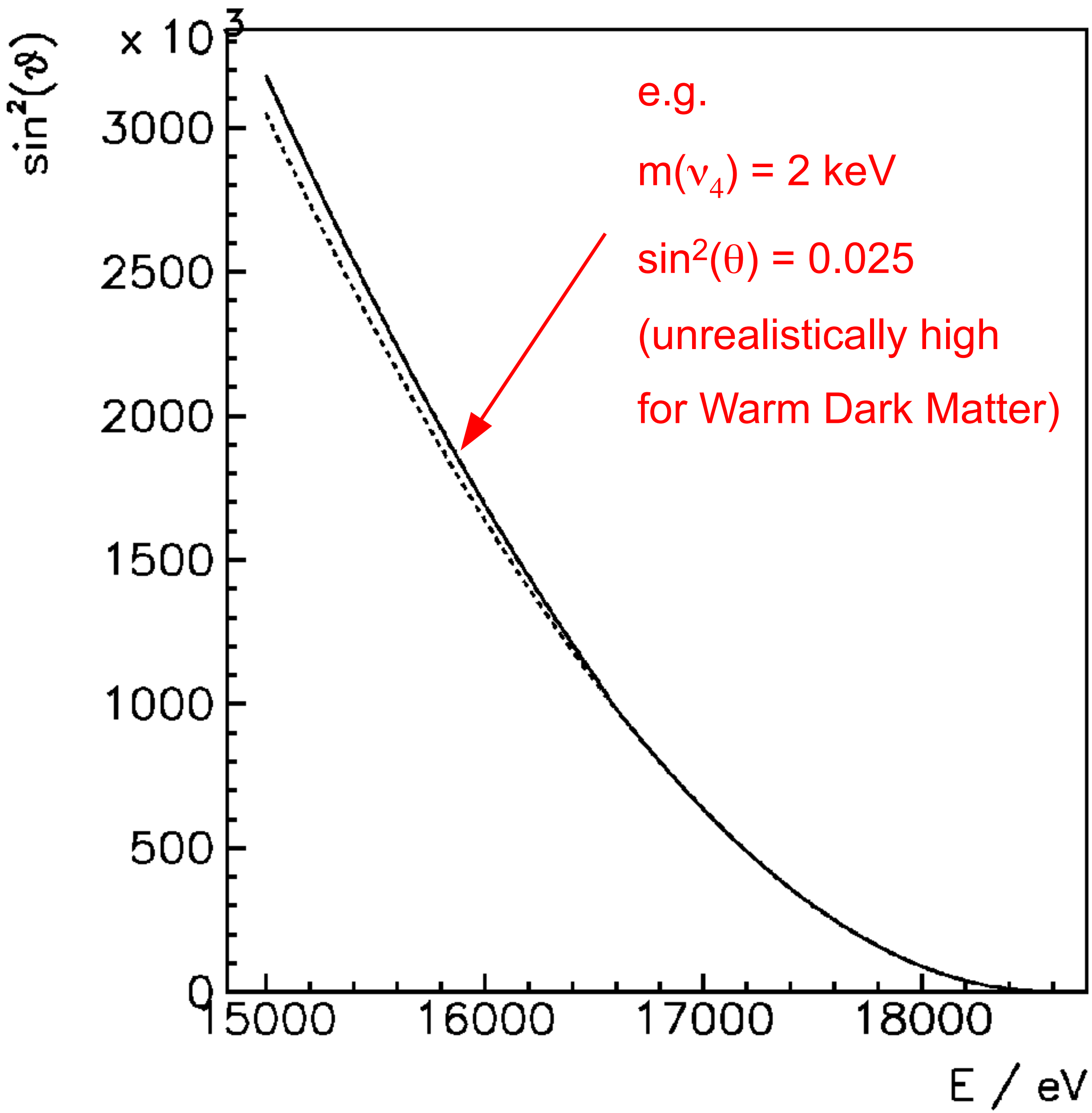
A possible strategy to detect a few keV sterile neutrinos by TOF with KATRIN



Set (a few) retarding potentials below kink position

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

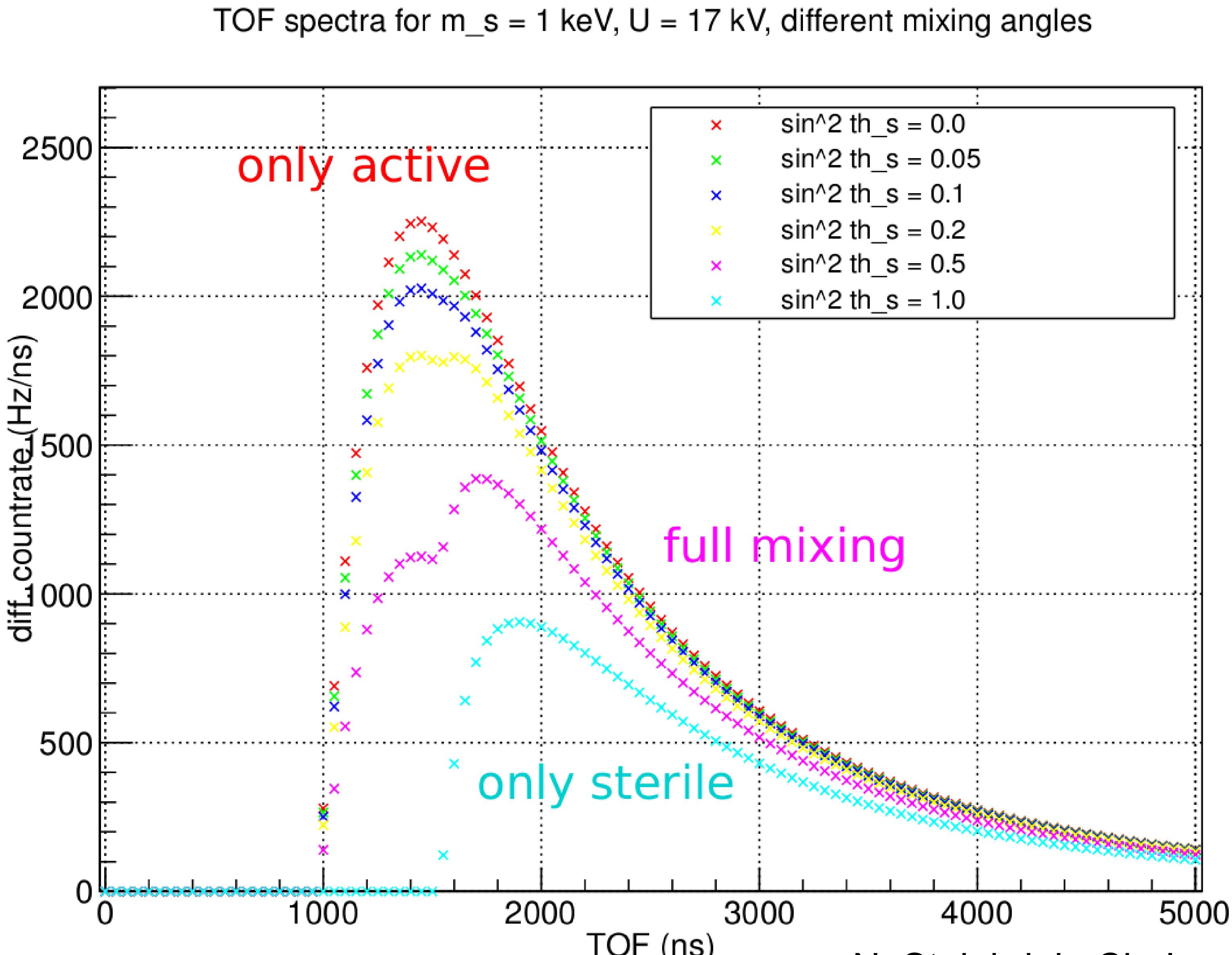
Differentiate spectrum by measuring time-of-flight

Use low column density

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

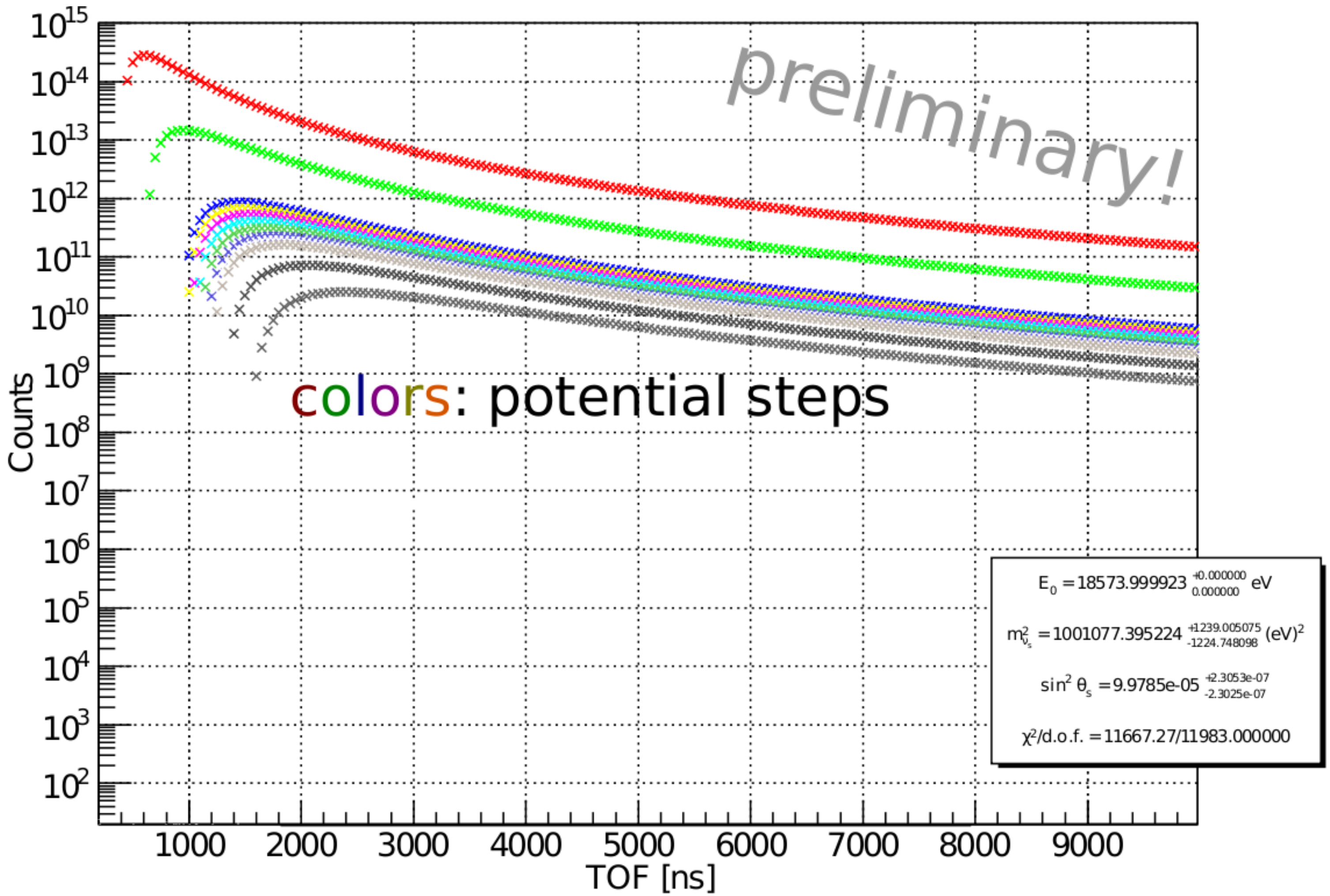
→ dedicated study under way

Preliminary results of a first study



N. Steinbrink, Chalonge 2013, Meudon

Preliminary results

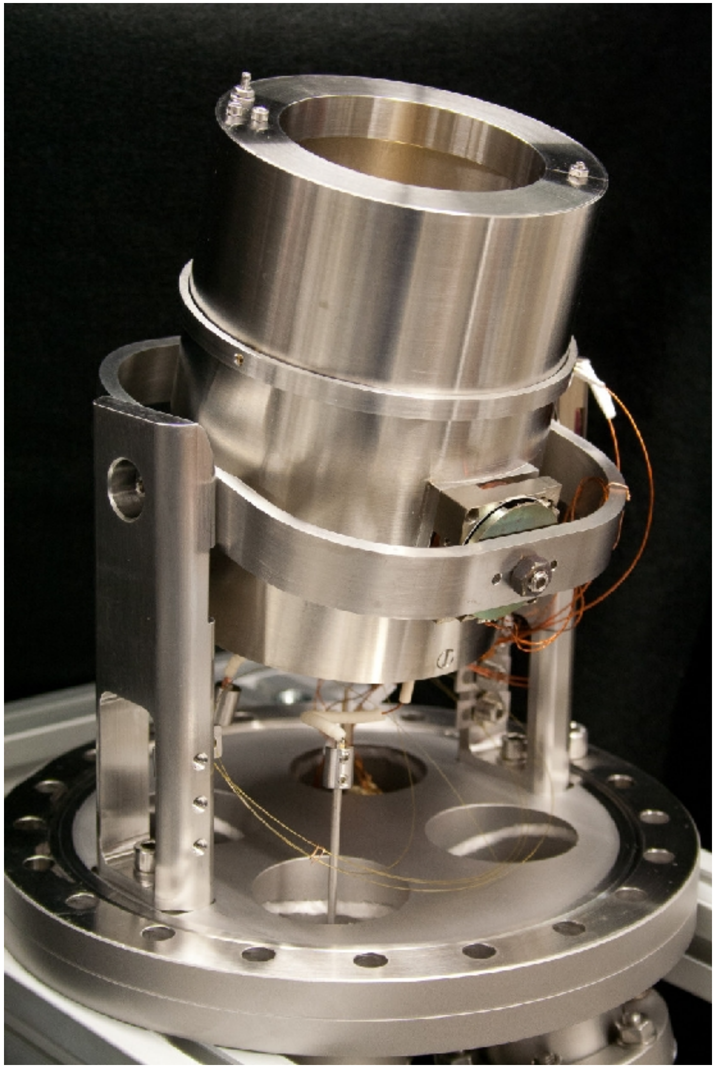


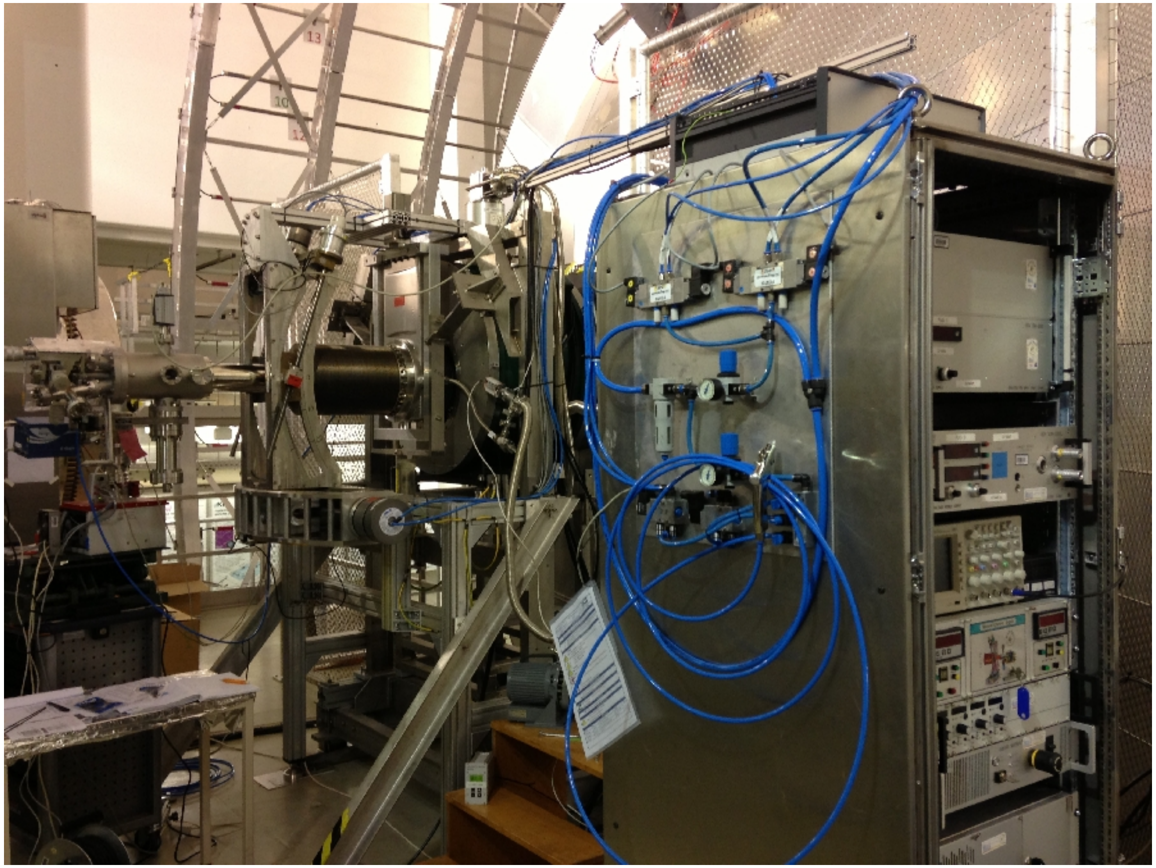
preliminary: statistical sensitivity about 10^{-7}
no sophisticated statistical analysis yet

N. Steinbrink, Chalonge 2013, Meudon

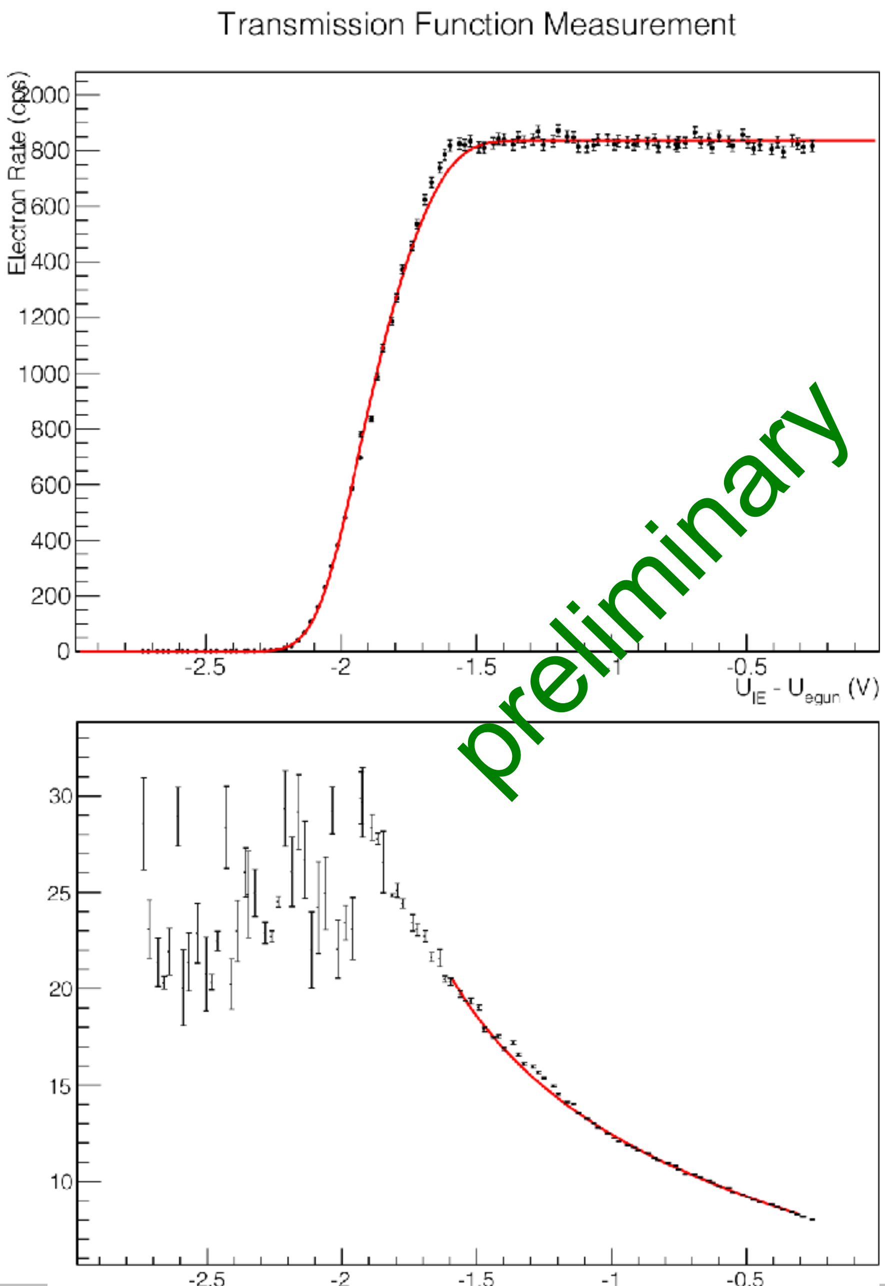
Test of TOR method at KATRIN main spectrometer during SDS commissioning

Angular-selective pulsed UV laser photoelectron source at main spectrometer & detector





Test of tof method at main spectrometer during SDS commissioning



Integral transmission function at -200 V

measured TOF agrees with calculated TOF by N. Steinbrink from electrical potential and magnetic field maps

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Conclusions

Neutrinos do oscillate → non-zero neutrino mass which is very important

- for nuclear & particle physics (which model beyond the Standard Model ?)
- for cosmology & astrophysics (evolution of the universe)

KATRIN is the next generation direct

- neutrino mass experiment with 200 meV sens.
- main spectr. + detector commissioning is running, tritium data from 2015 on

see dedicated talk by Guido Drexlin in open session

MARE, ECHO: cryo-bolometers may achieve similar

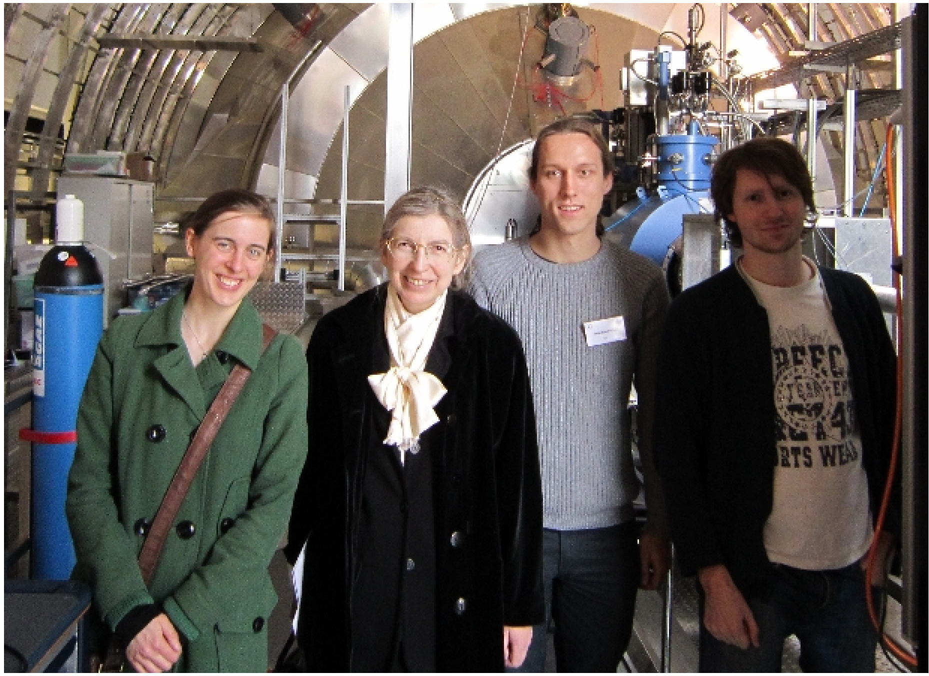
- sensitivity after a lot of successful R&D

Sterile neutrinos are well motivated by the

- "reactor neutrino anomaly" (eV-scale) and
- "Warm Dark Matter" (keV-scale)

KATRIN will check the reactor anomaly and

- could in principle search for Warm Dark Matter in a dedicated run
- 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 detector spectra
- detailed studies by S. Mertens, N. Steinbrink et al.



Conclusions

N ... ry important
Standard Model ?)

K

... data from 2015 on

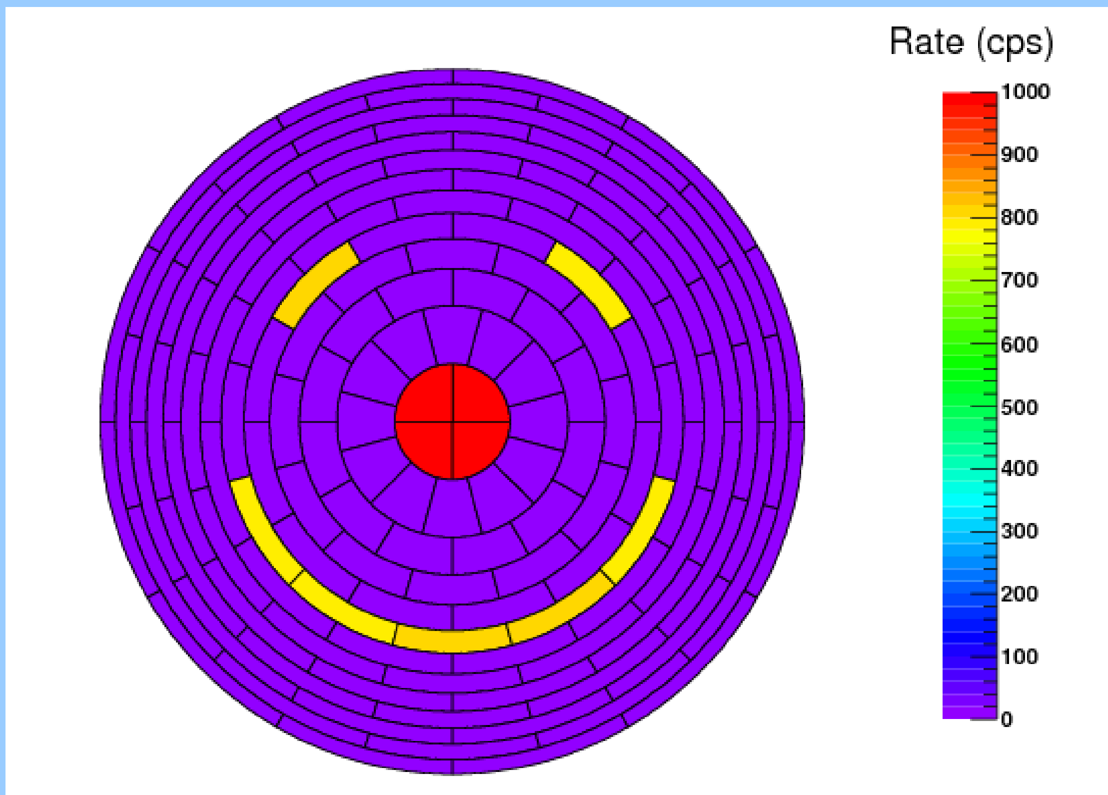
M

S

K

see dedicated talk by Guido Drexlin in open session

The KATRIN 148-pixel detector is smiling



when being hit by electrons
from 11 subsequent positions
of the scanning photoelectron source

detailed studies by S. Mertens, N. Steinbrink et al.

backup slides

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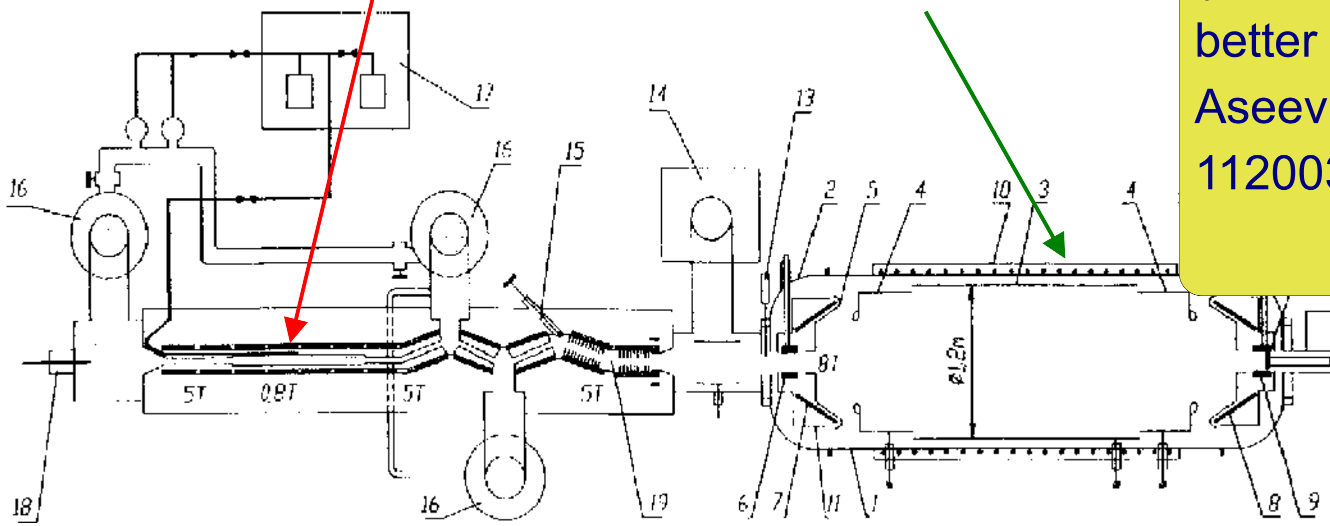
The Troitsk Neutrino Mass Experiment

windowless gaseous T_2 source, similar to LANL

MAC-E-Filter, similar to Mainz



Re-analysis of Troitsk data
(better source thickness,
better run selection)
Aseev et al, Phys. Rev. D 84, 112003 (2011)

m_β < 2.05 eV, 95% CL

Luminosity: L = 0.6cm^2
(L = $\Delta\Omega/2\pi * A_{source}$)

Energy resolution: ΔE = 3.5eV
3 electrode system in 1.5m diameter UHV vessel (p<10^{-9} mbar)

Upgrade of Troitsk exp.
aim to investigate KATRIN systematics and keV neutrinos