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

Ecole Internationale Daniel Chalonge

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- Introduction
- Direct neutrino mass search:
  Cryo-bolometer experiments
  The KATRIN experiment
- Search for sterile neutrinos
  in beta endpoint spectra
- Conclusions

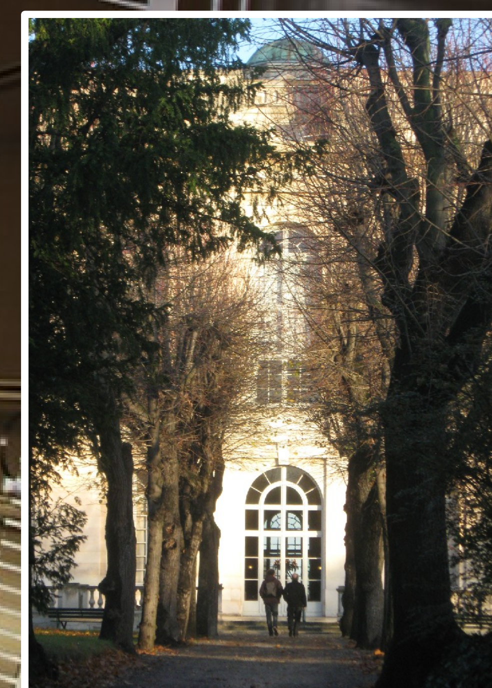
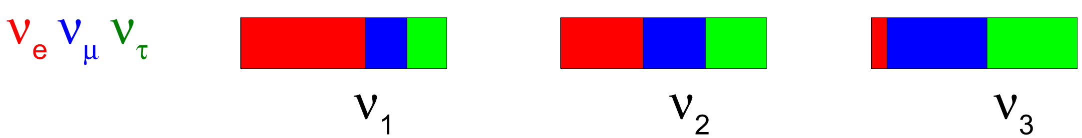
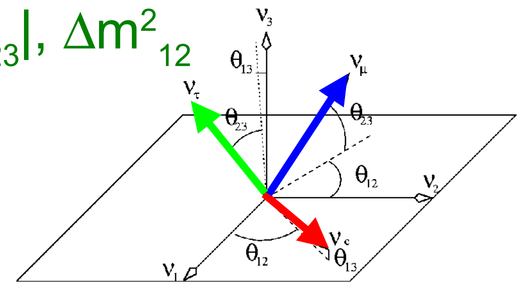


Photo: M. Zacher

Need for the absolute ν mass determination

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





degenerated masses

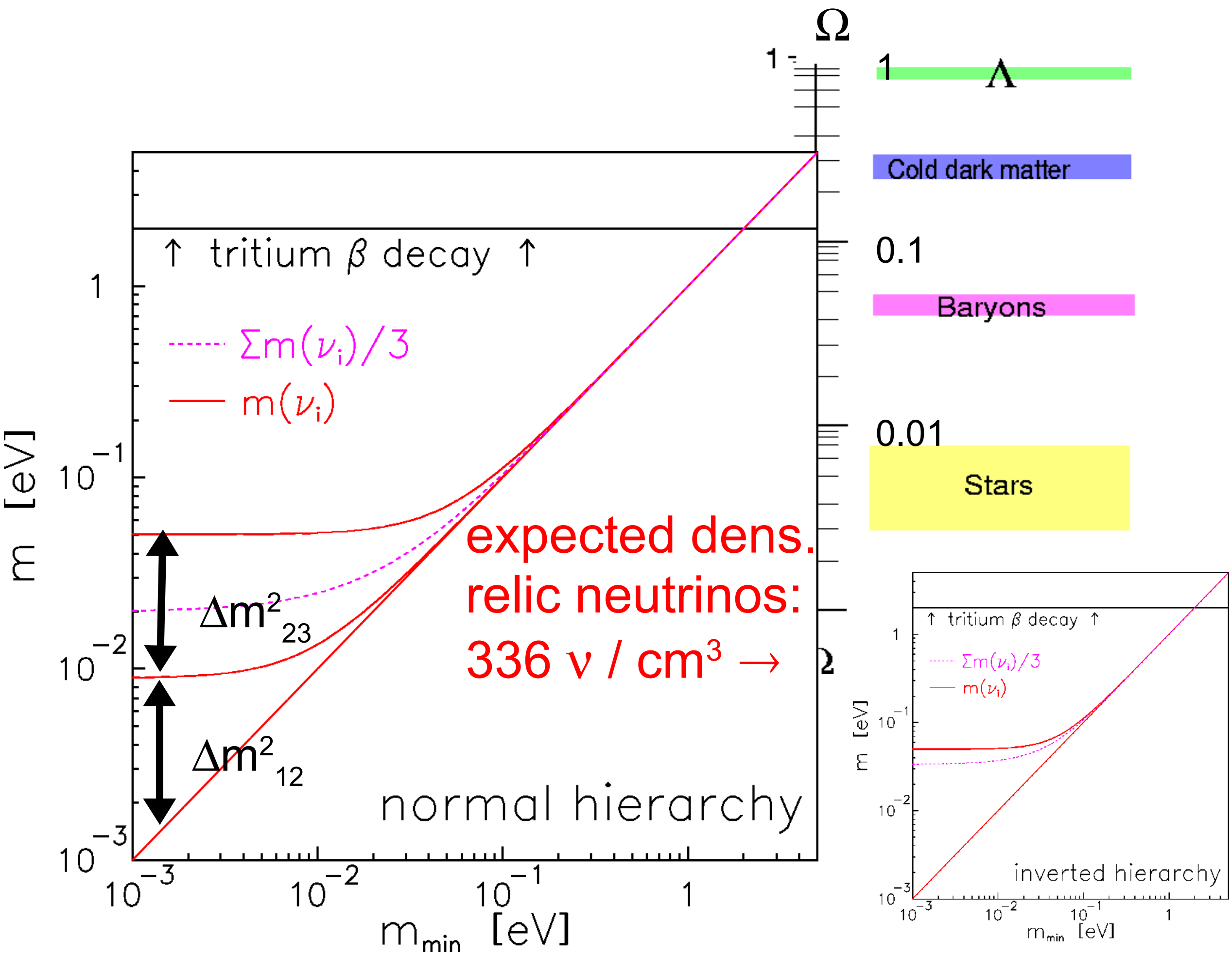
cosmological relevant

e.g. seesaw mechanism type 2

hierarchical masses

e.g. seesaw mechanism type 1

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



Three complementary ways to the absolute neutrino mass scale

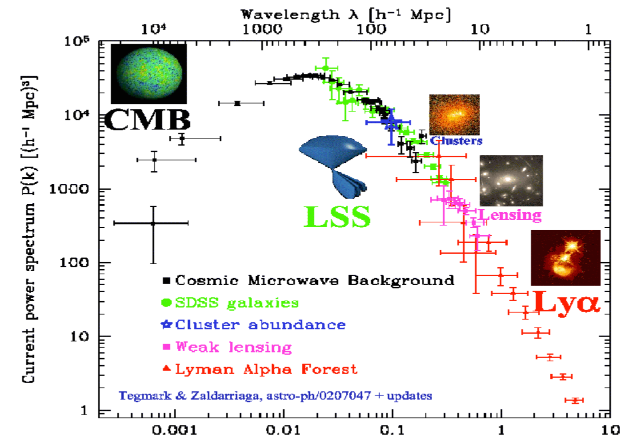
1) Cosmology

very sensitive, but model dependent

compares power at different scales

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

e.g. S. Hannestad, Prog.Part.Nucl.Phys.65 (2010) 185

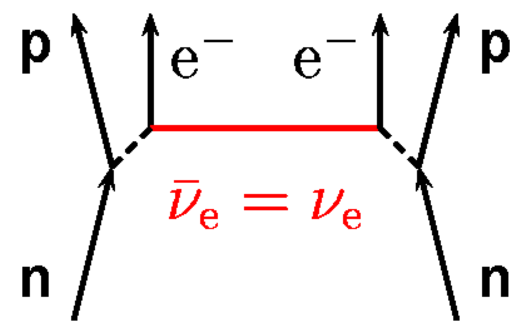


2) Search for $0\nu\beta\beta$

Sensitive to Majorana neutrinos

Evidence for $m_{ee}(\nu) \approx 0.4$ eV ?

GERDA is running, EXO has 1st results !

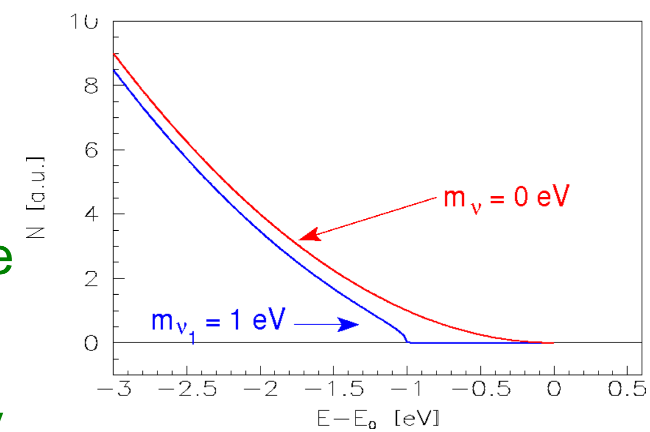


3) Direct neutrino mass determination:

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



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

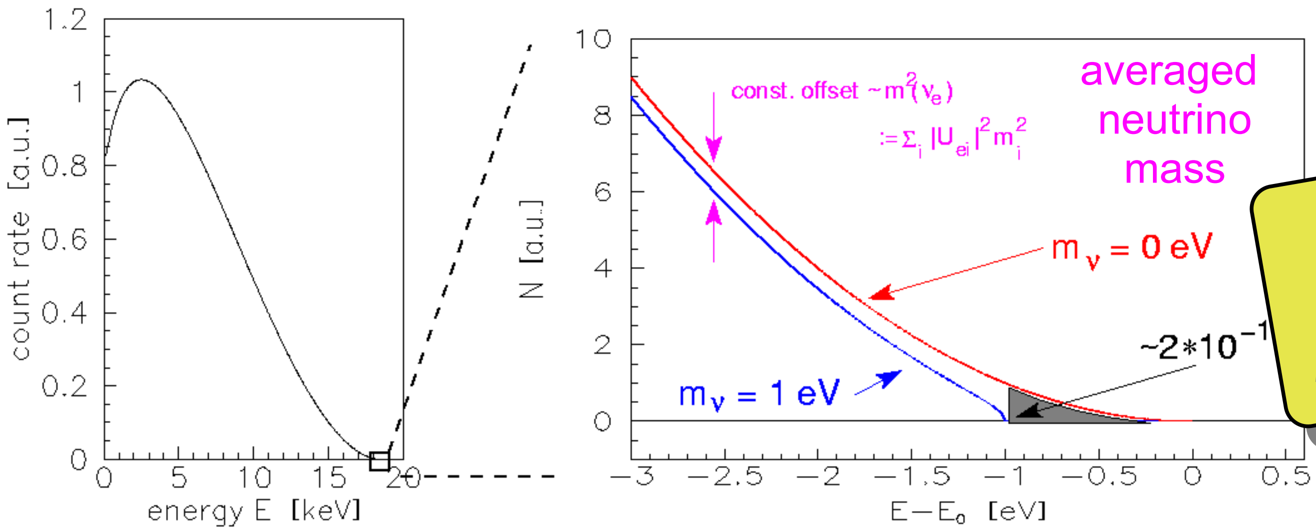
β decay: $(A,Z) \rightarrow (A,Z+1)^+ + e^- + \bar{\nu}_e$

β electron energy spectrum:

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

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

Complementary to 0νββ and cosmology

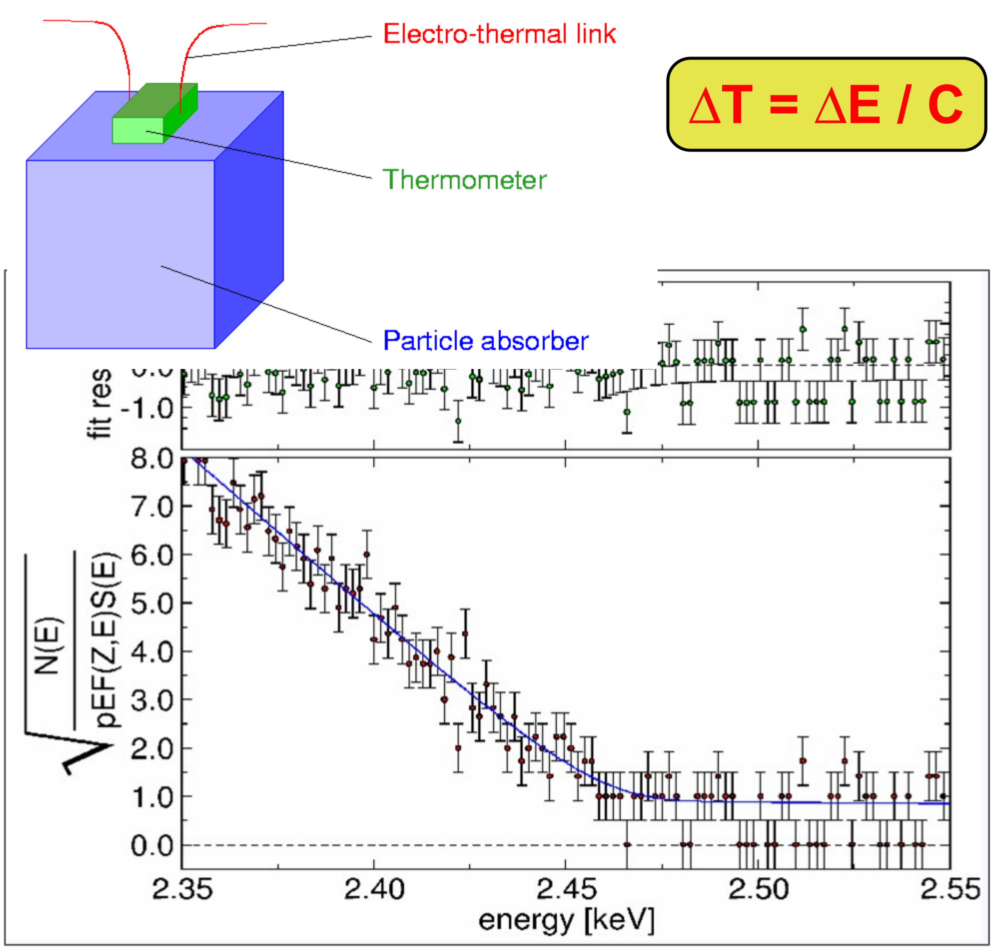


Review: E.W. Otten & C. Weinheimer Rep. Prog. Phys., 71 (2008) 086201

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

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

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



$\Delta T = \Delta E / C$

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)

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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

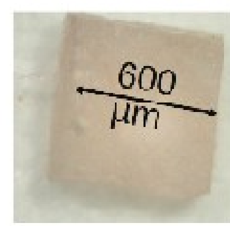
Challenges of cryogenic bolometers:
- measures the full spectrum (pile-up)
- need large arrays to get statistics
- understanding spectrum
- still energy losses or trapping possible

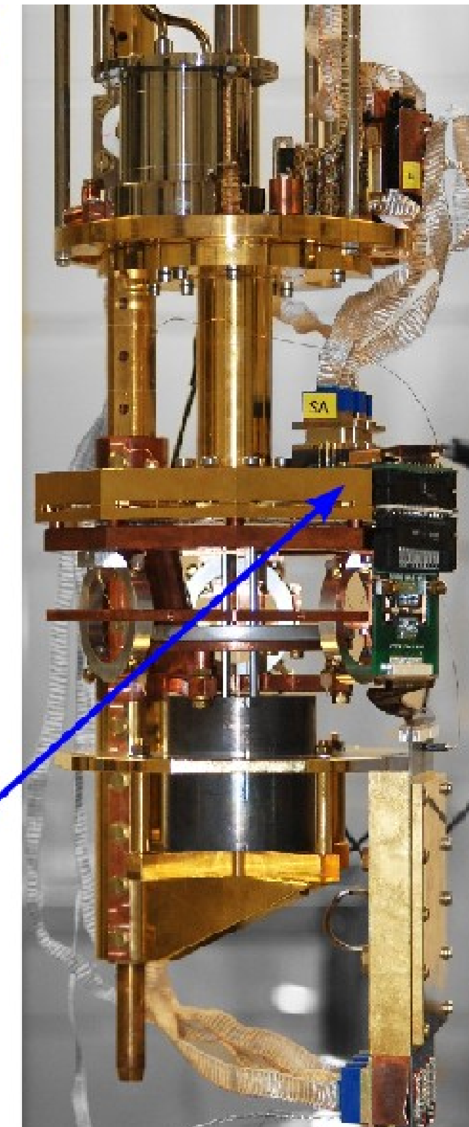
MARE-1 @ Milano-Bicocca

- 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

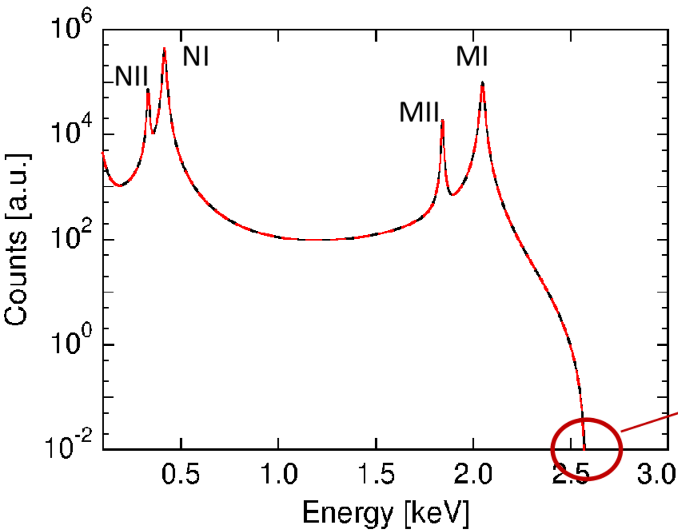


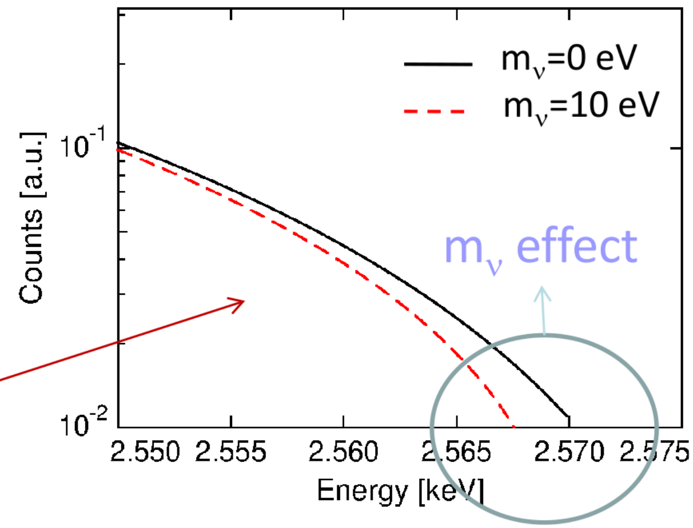


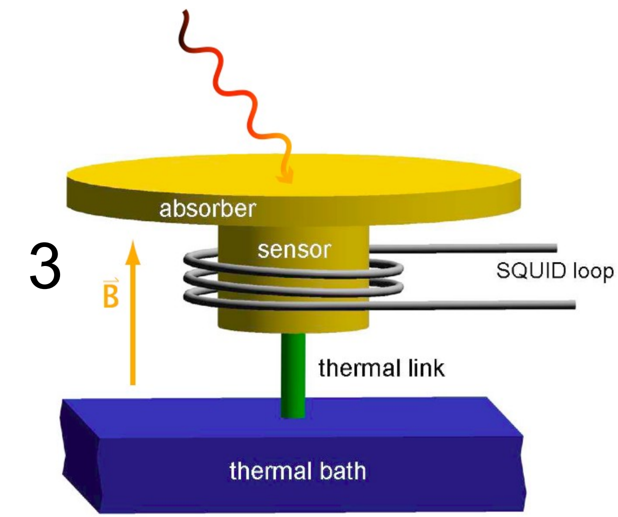
Angelo Nucciotti, Meudon 2011

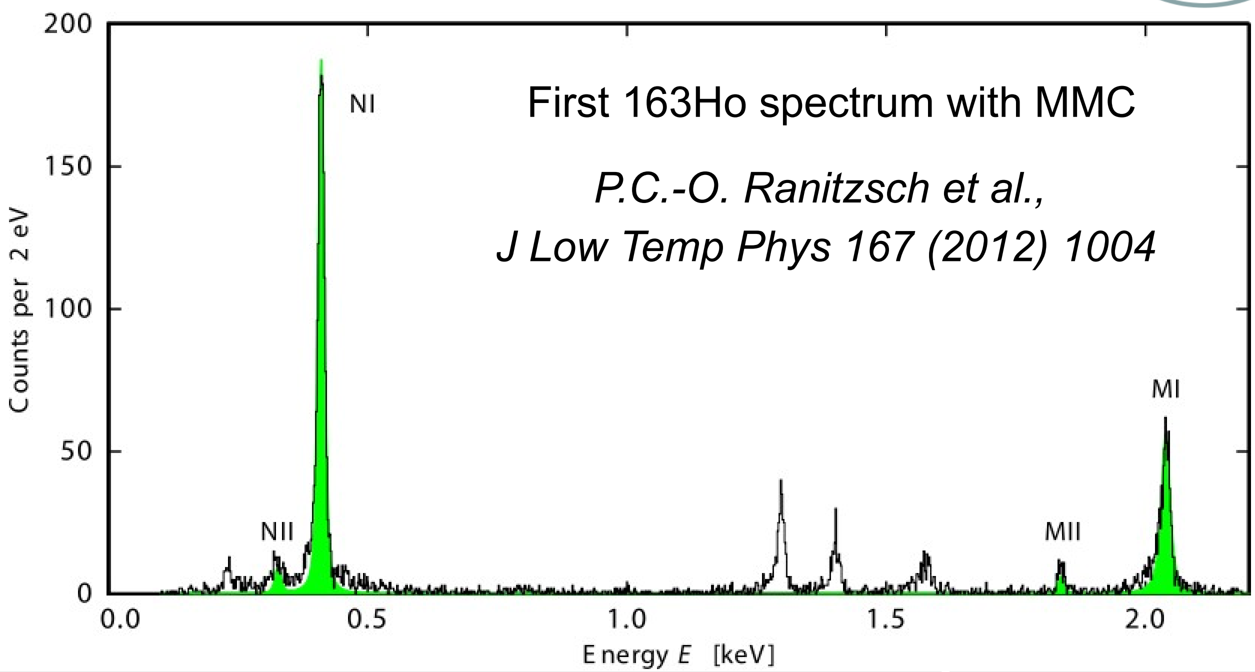
ECHO neutrino mass project: ^{163}Ho electron capture with metallic magnetic calorimeters

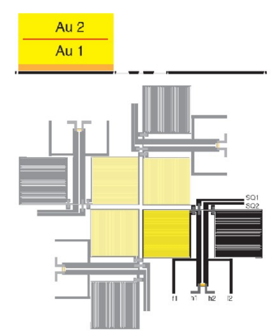
$$^{163}\text{Ho} + e^- \rightarrow {}^{163}\text{Dy}^* + \nu_e \rightarrow {}^{163}\text{Dy} + \gamma/e^- + \nu_e$$

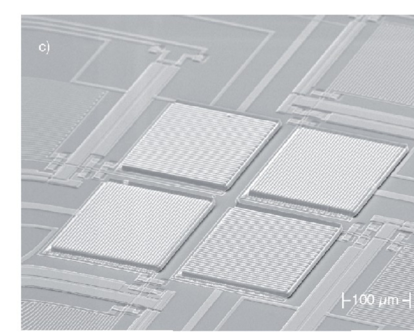






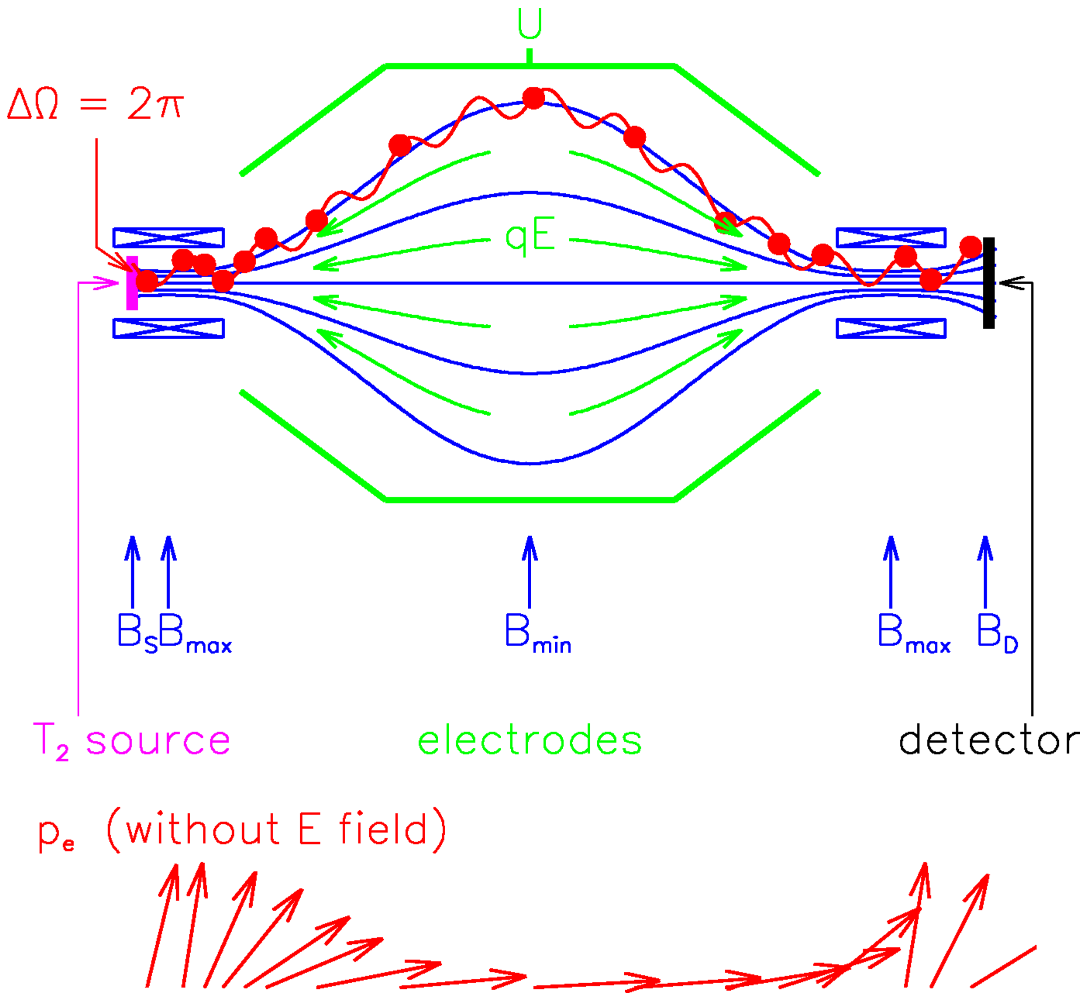




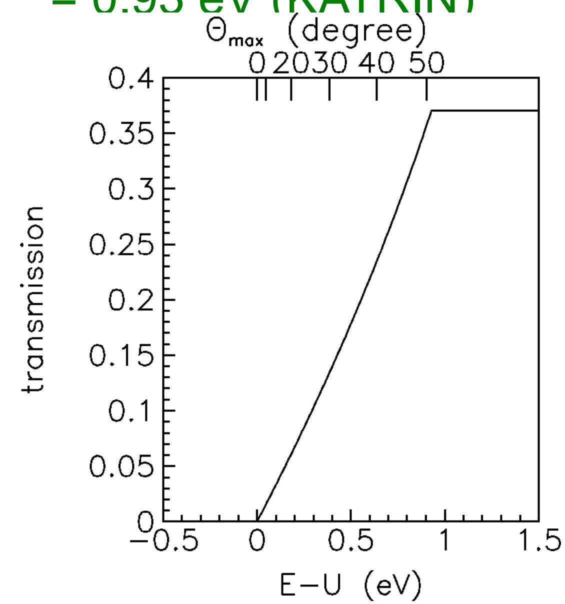


courtesy L. Gastaldo

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)

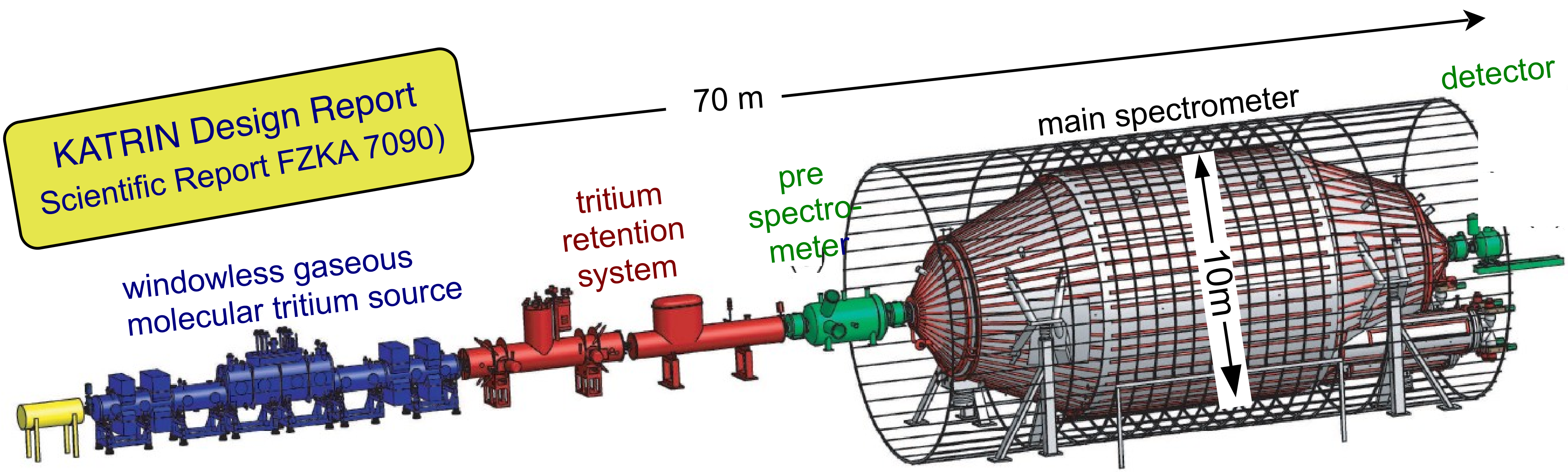
The KATRIN experiment at KIT

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)** ⇒ **source ≠ spectrometer concept**
- **strong, opaque source** ⇒ **$dN/dt \sim A_{source}$**
- **magnetic flux conservation (Liouville)** ⇒ **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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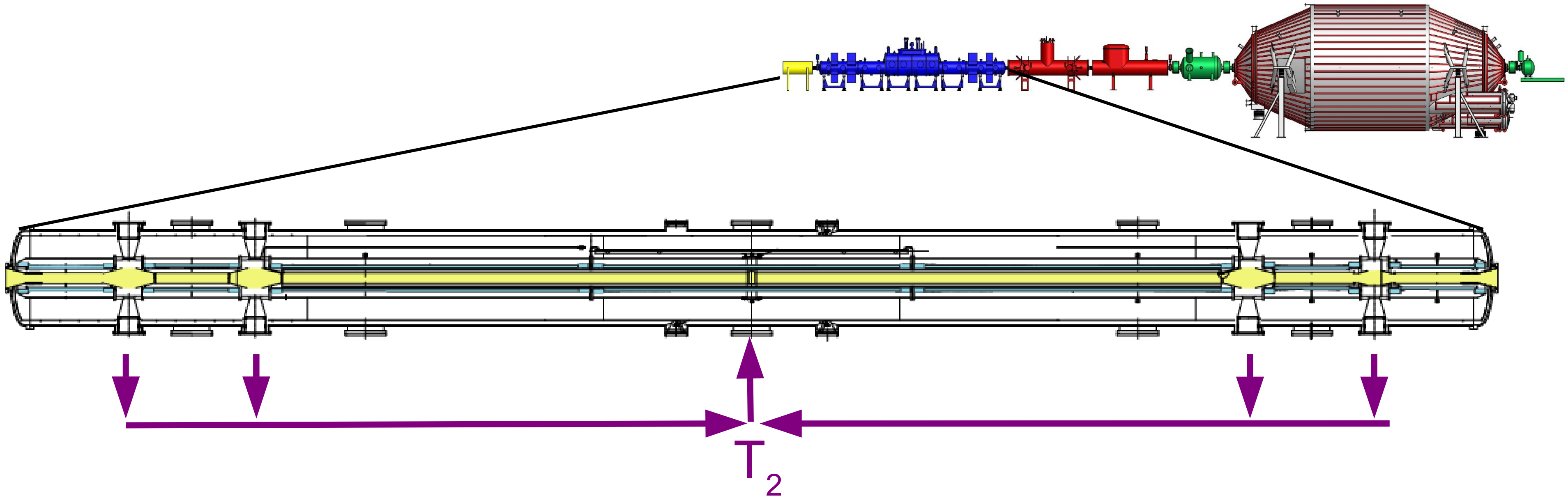
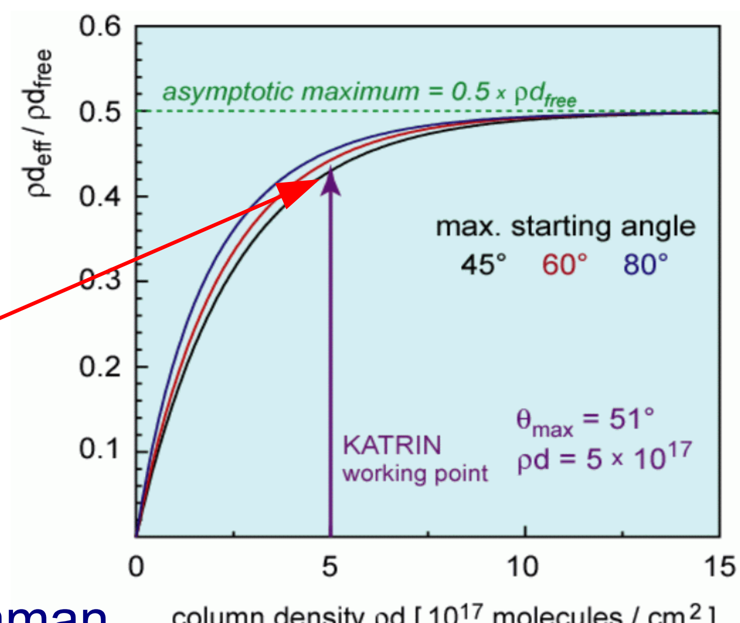
Molecular Windowless Gaseous Tritium Source WGTS



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

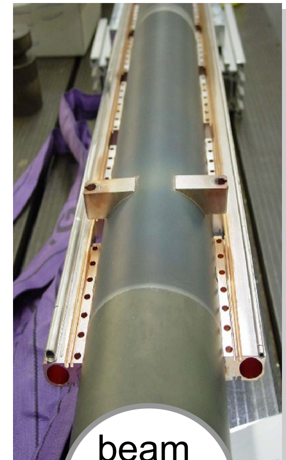
allows to measure with near to maximum count rate using
$\rho d = 5 \cdot 10^{17}/cm^2$
with small systematics



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

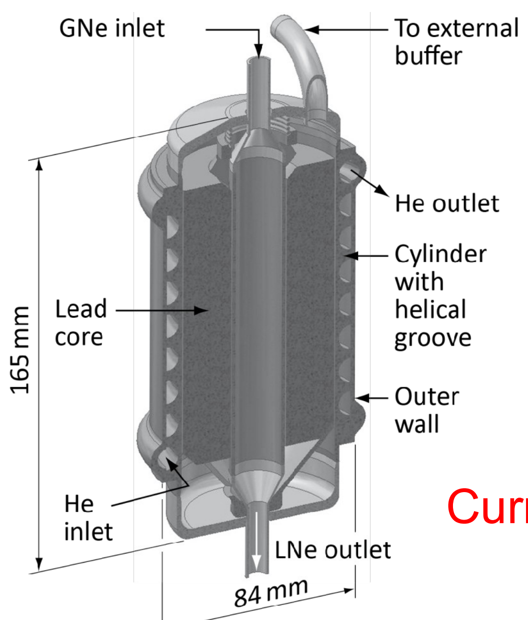
Very successful cool-down and stability tests of the WGTS demonstrator

arrival of WGTS demonstrator at KIT: April 2010

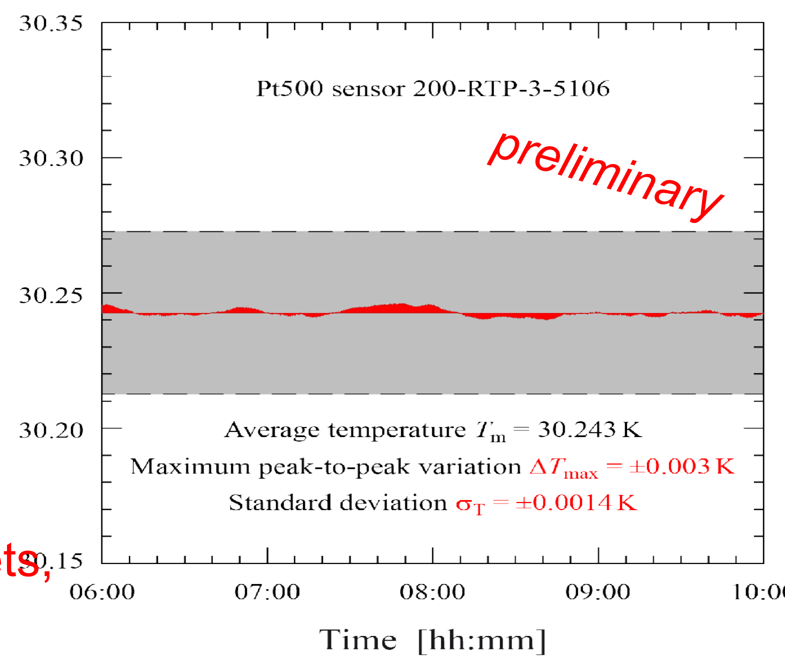


beam tube Ø=90mm

cooling concept of WGTS: pressurized 2-phase Ne



S. Grohmann, Cryogenics 49, No. 8 (2009) 413



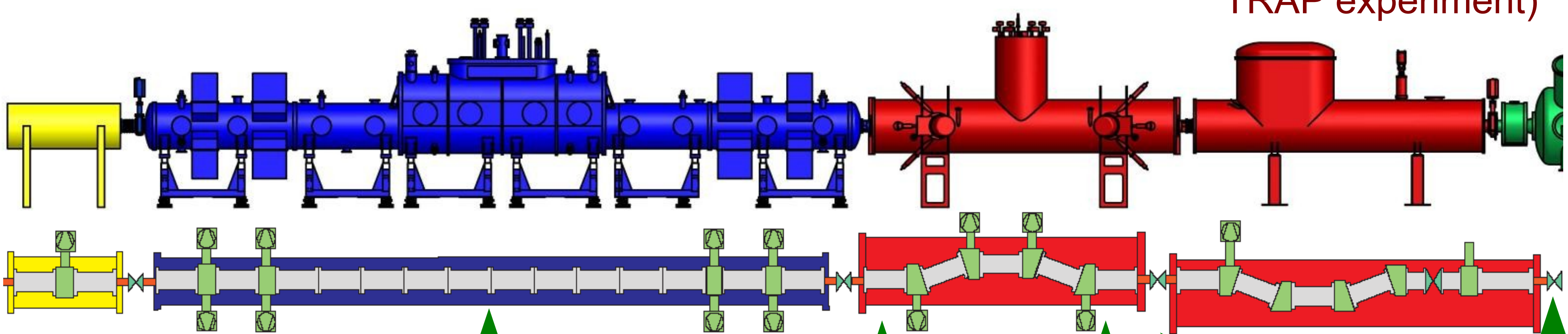
Currently: tests of sc magnets, constructing of WGTS out of demonstrator

Transport and differential & cryo pumping sections

Molecular windowless gaseous tritium source

Differential pumping

Cryogenic pumping
with Argon snow
at LHe temperatures
(successfully tested with the TRAP experiment)



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

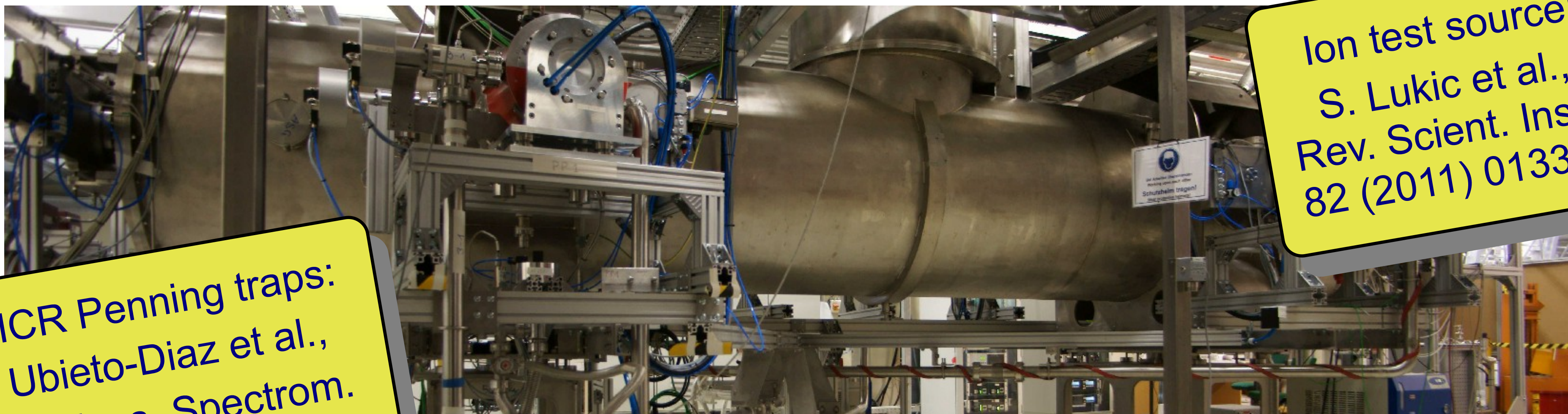
FT-ICR Penning traps to measure ions from WGTS

≈ 10^{-7} mbar l/s

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

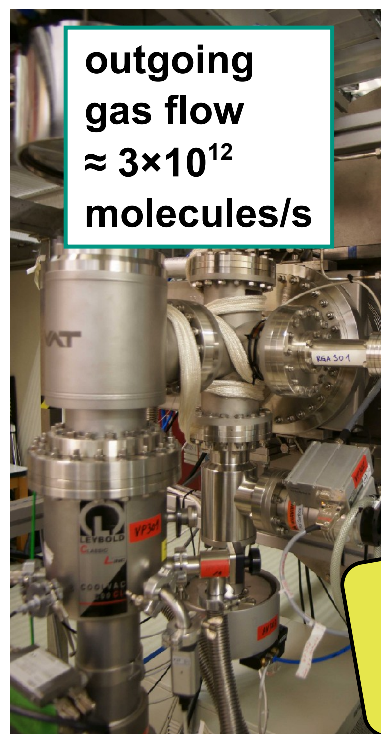
⇒ adiabatic electron guiding & T_2 reduction factor of ~10^{14}

Commissioning of DPS2-F



Ion test source:
S. Lukic et al.,
Rev. Scient. Instr.
82 (2011) 013303

FT-ICR Penning traps:
M. Ubieto-Diaz et al.,
Int. J. Mass. Spectrom.
288 (2009) 1-5



outgoing gas flow
≈ 3×10^{12} molecules/s

First gas flow reduction measurements with Ar

gas inlet
≈ 3×10^{17} molecules/s

S. Lukic et al.,
Vacuum 86 (2012) 1126

Currently:
Problem of a broken diode from the safety system of a superconducting coil

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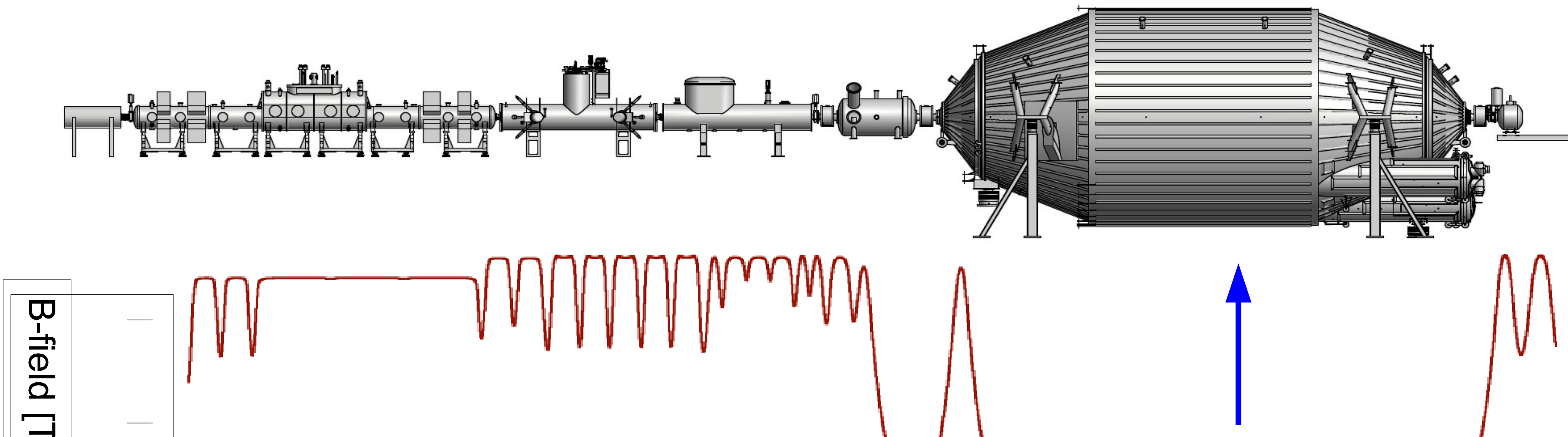
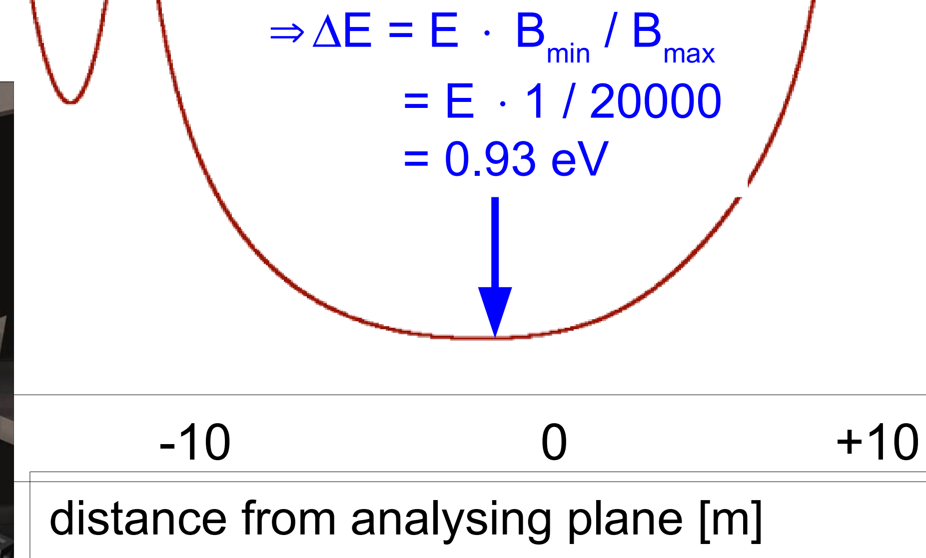
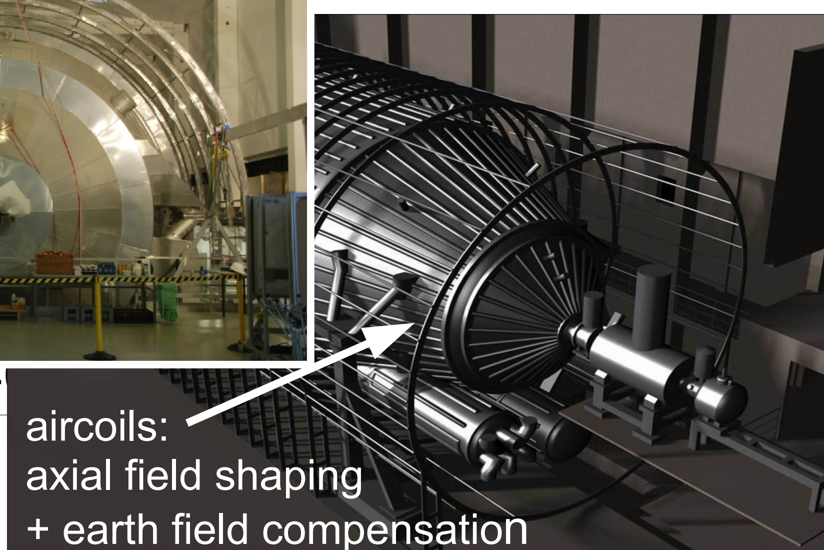
Electromagnetic design: magnetic fields



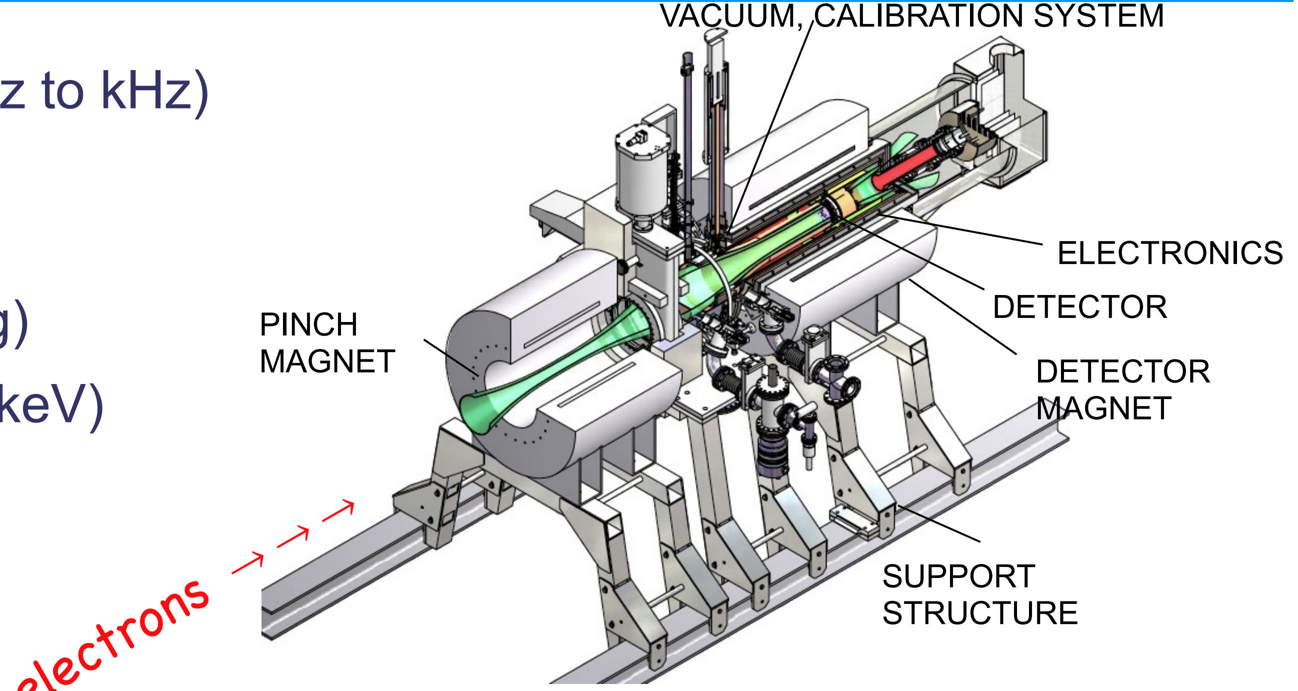




The detector

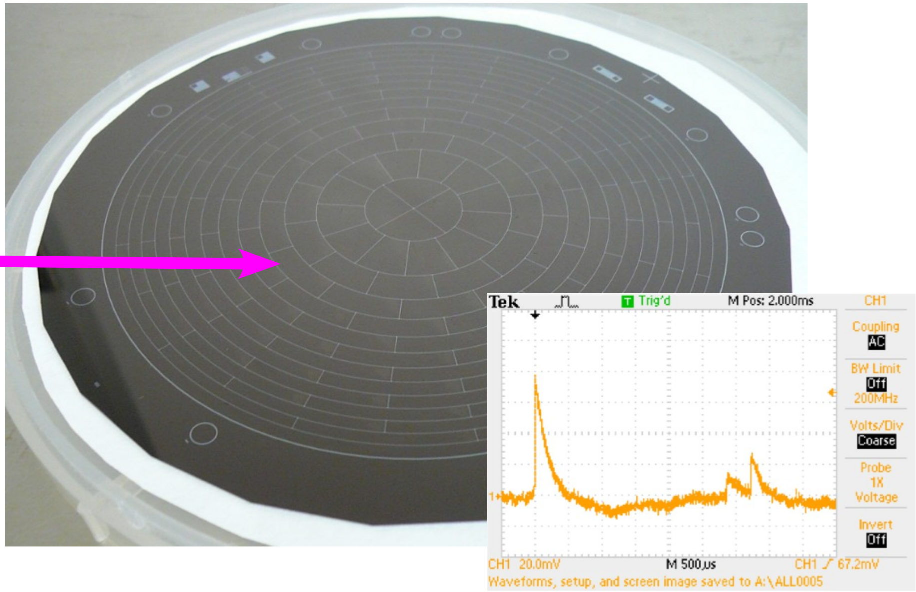
Requirements

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

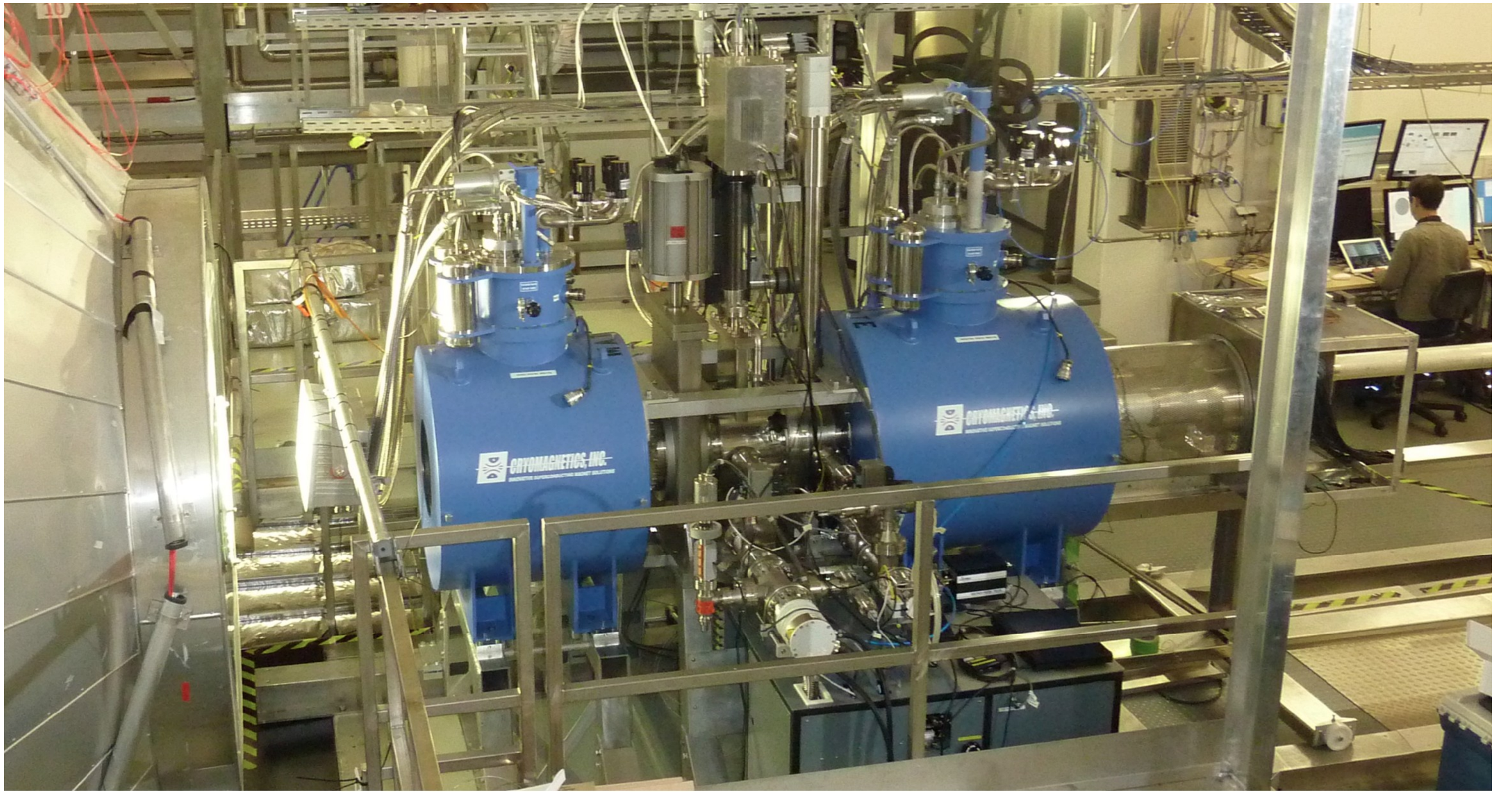


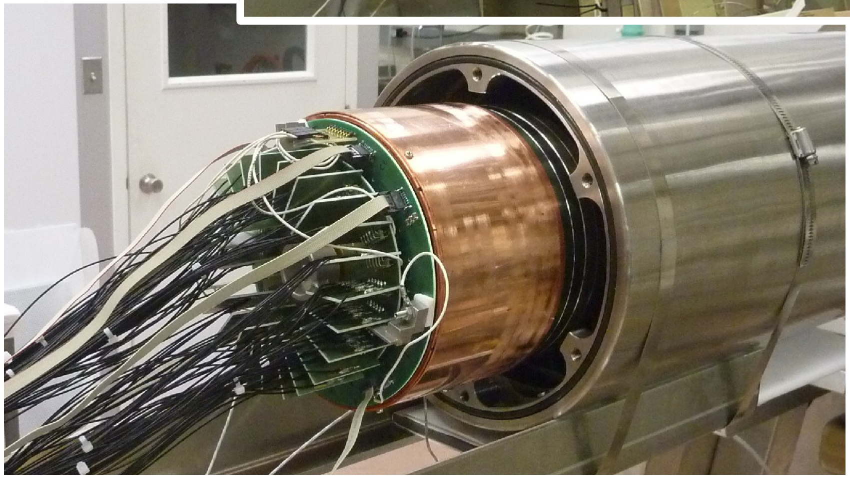
Properties

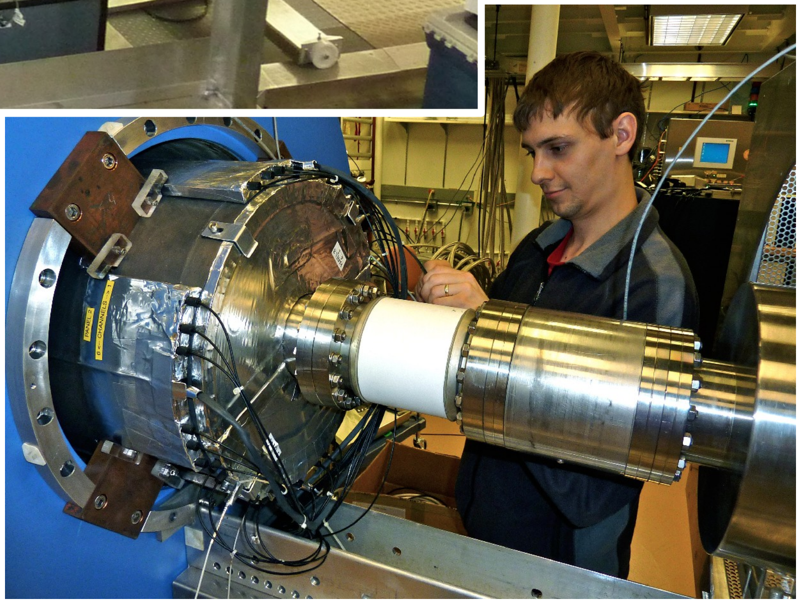
- 90 mm Ø Si PIN diode
- thin entry window (50nm)
- detector magnet 3 - 6 T
- post acceleration (30kV)
  (to lower background in signal region)
- segmented wafer (145 pixels)
  → record azimuthal and radial profile of the flux tube
  → investigate systematic effects
  → compensate field inhomogeneities



KATRIN detector is being commissioned at KIT







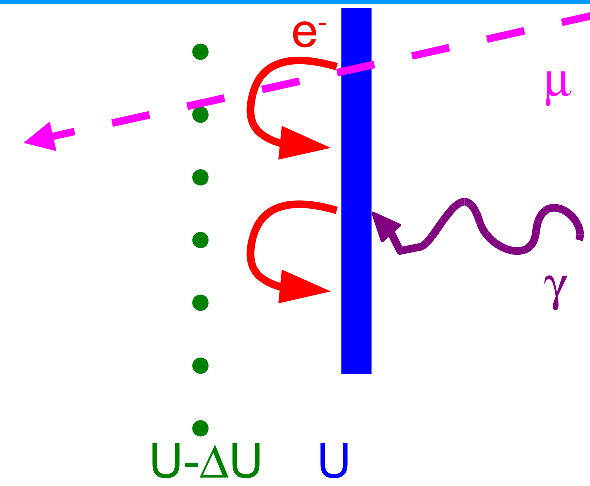
Main Spectrometer – Transport to Karlsruhe Institute of Technology

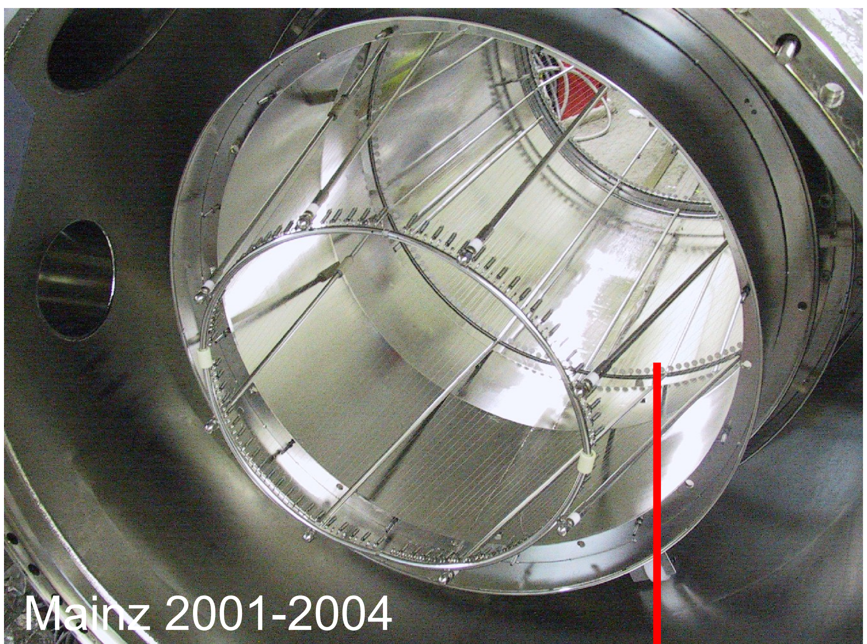
KATRIN has a 100-times larger surface, but requests same bg → something new

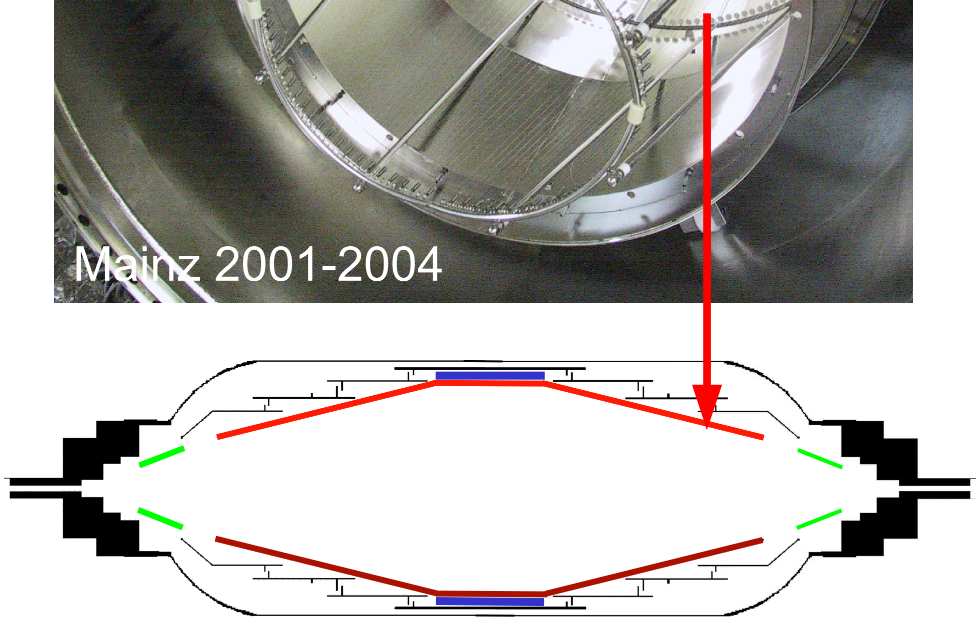
Secondary electrons from wall/electrode

by cosmic rays, environmental radioactivity, ...

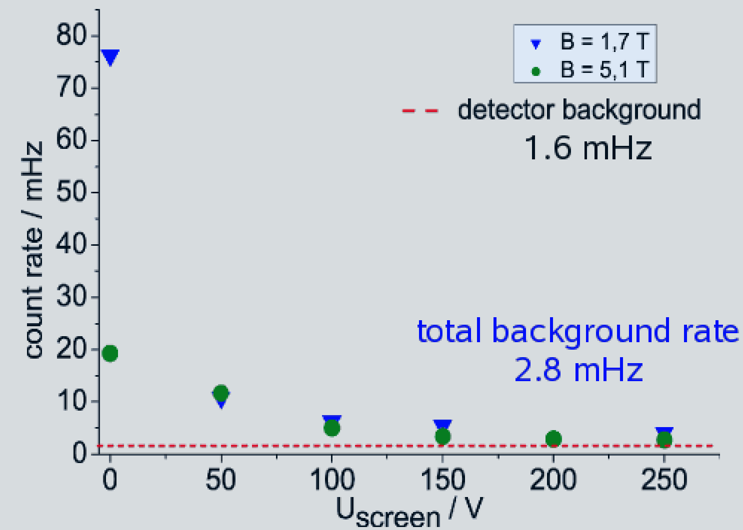
New: wire electrode on slightly more negative potential







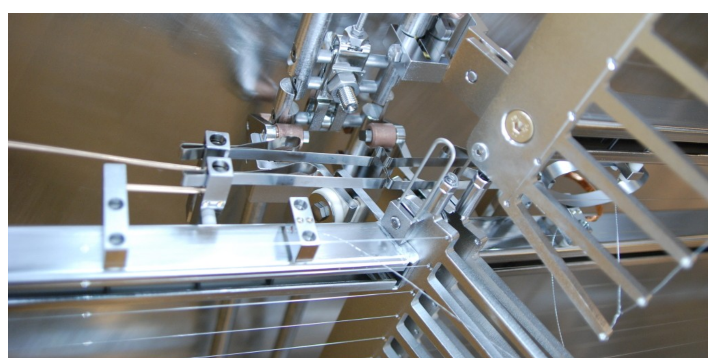
Background suppression successfully tested at the Mainz MAC-E filter:



Dipl. thesis B. Ostrick (U Mainz, 2002), PhD thesis B. Flatt (U Mainz, 2004)

Two-layer wire electrode modules installation inside main spectrometer

All 248 modules are installed, January 31, 2012



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**

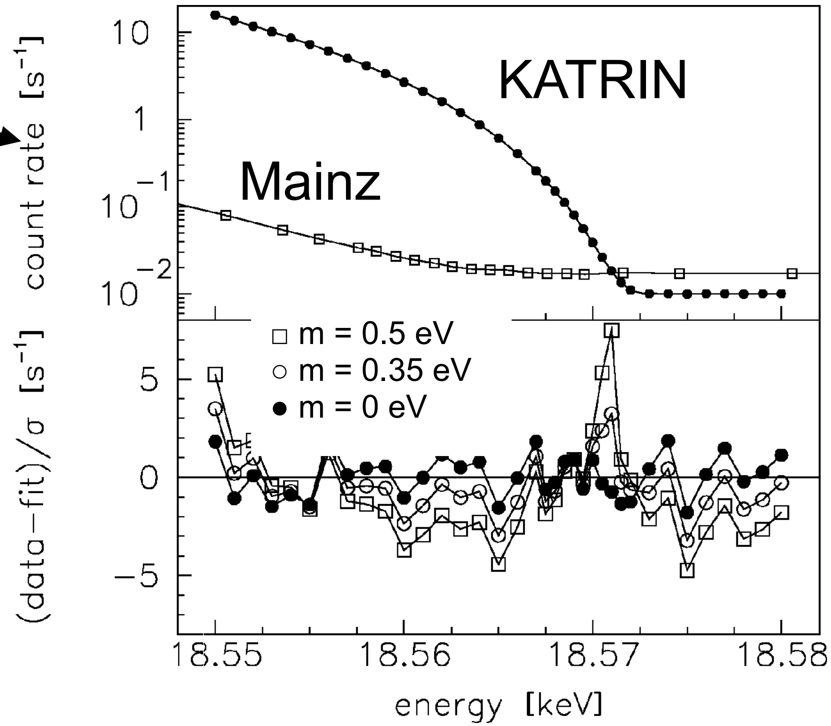
} tritium source

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

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)

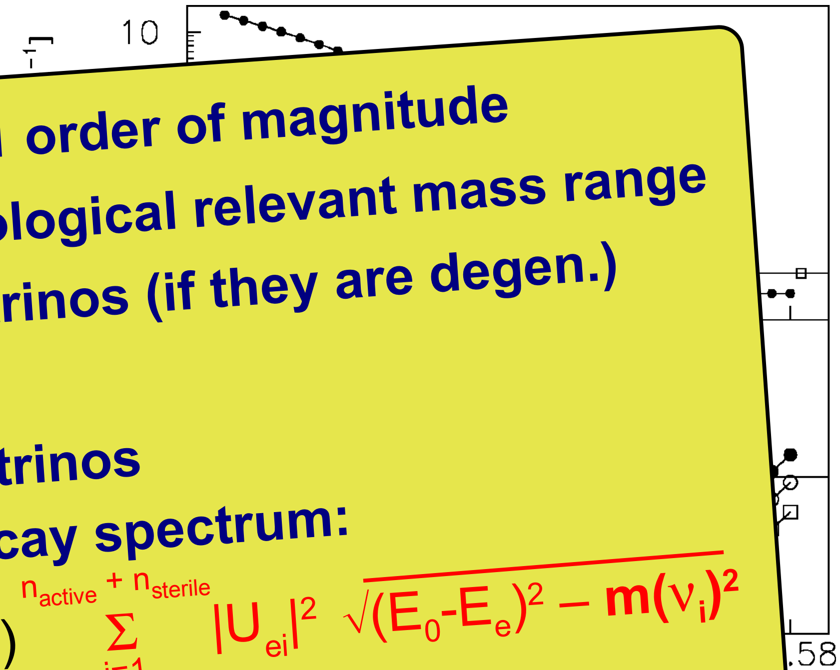
Expectation for 3 full data taking years: $\sigma_{syst} \sim \sigma_{stat}$

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

Ex...

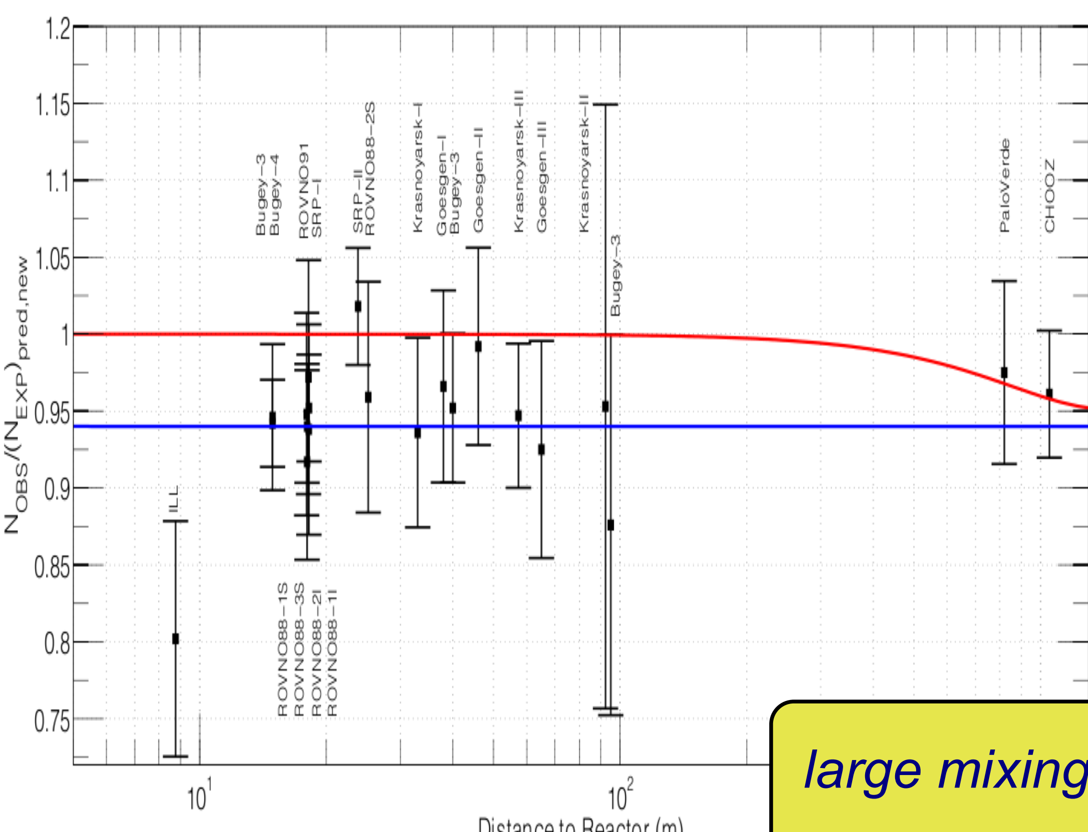
Se...

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

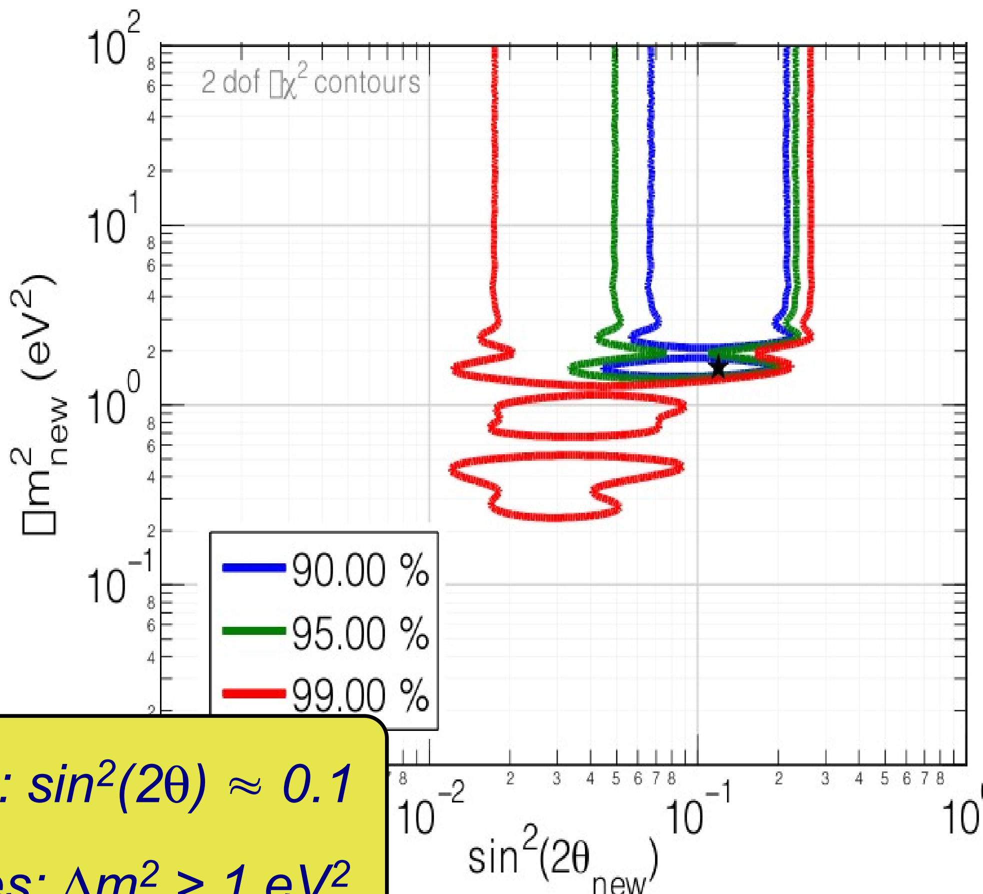
Is there a fourth sterile neutrino state ?

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

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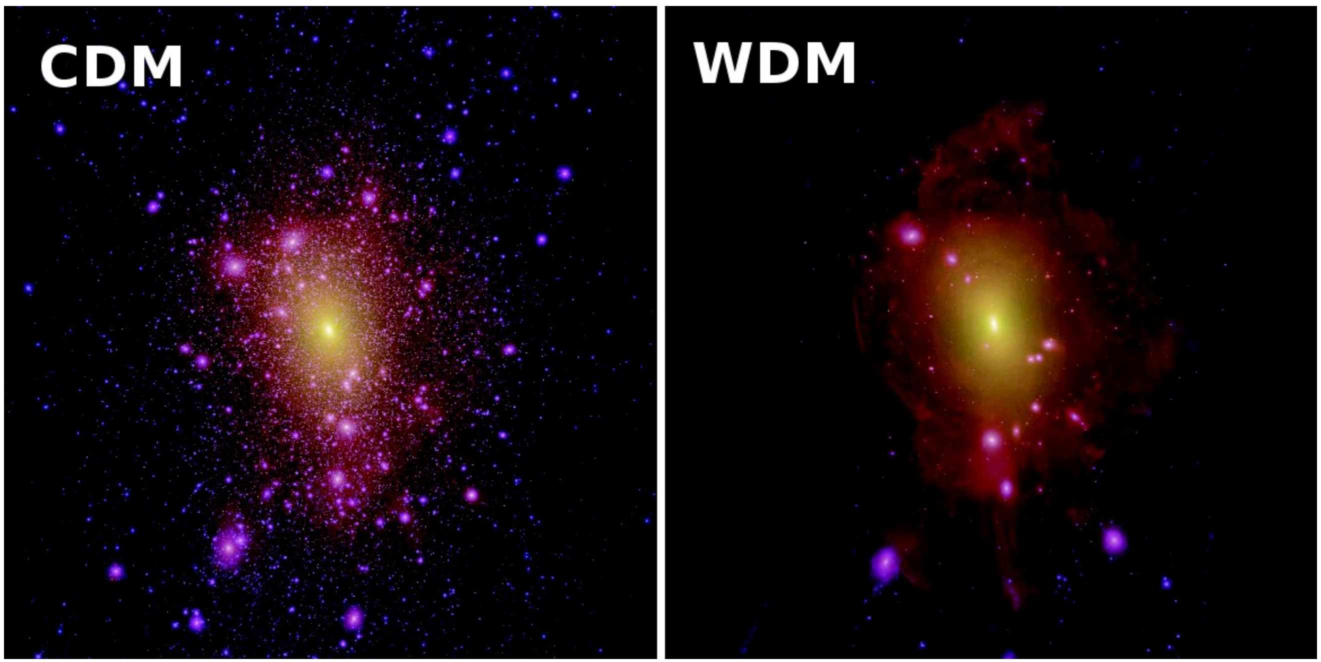
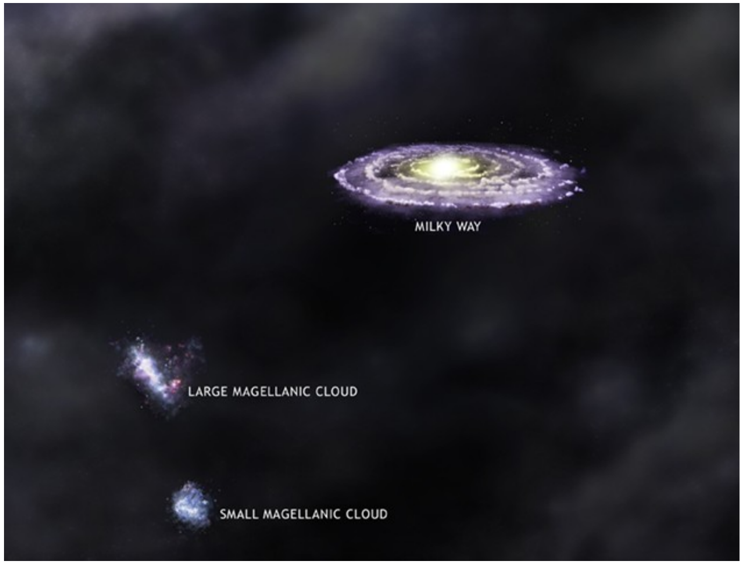
Hints for a 2nd sterile neutrino: Warm Dark Matter in the universe

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

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

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

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

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

But the 3 x 3 submatrix is not unitary anymore !

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

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

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

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

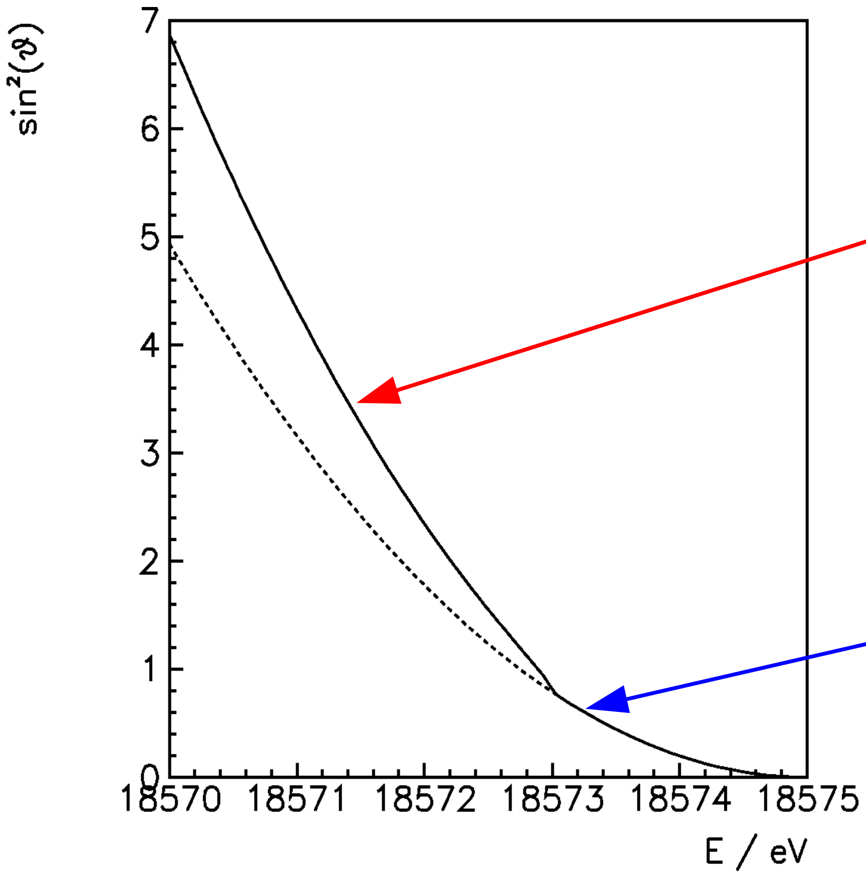
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_{sterile} \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1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

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 ν_1, ν_2 ν_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: $m_{\beta\beta}(\nu) = \left|\sum_{i=1}^{n_a+n_s} |U_{ei}^2|\, e^{i\alpha(i)}\, m(\nu_i)\right|$ (coherent)

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

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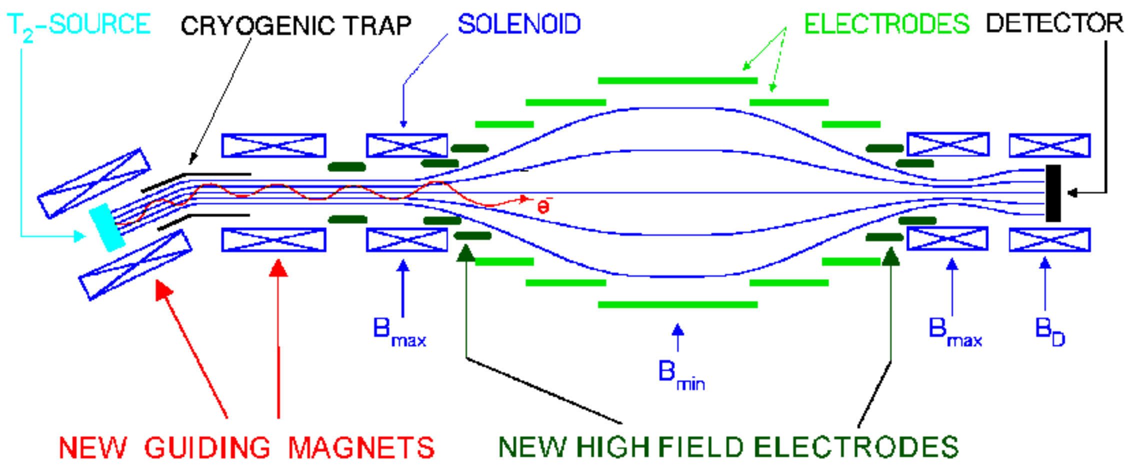
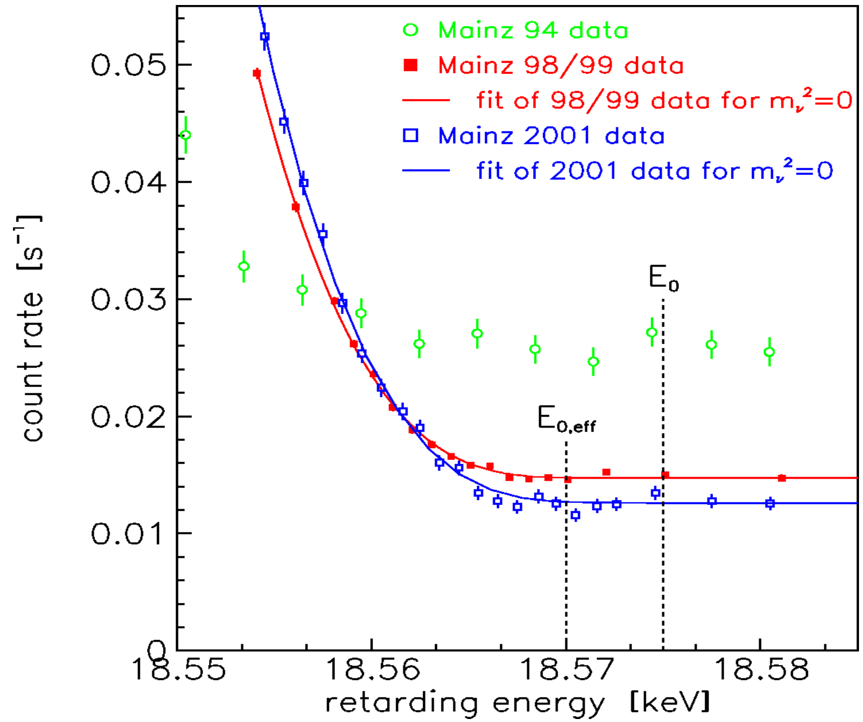
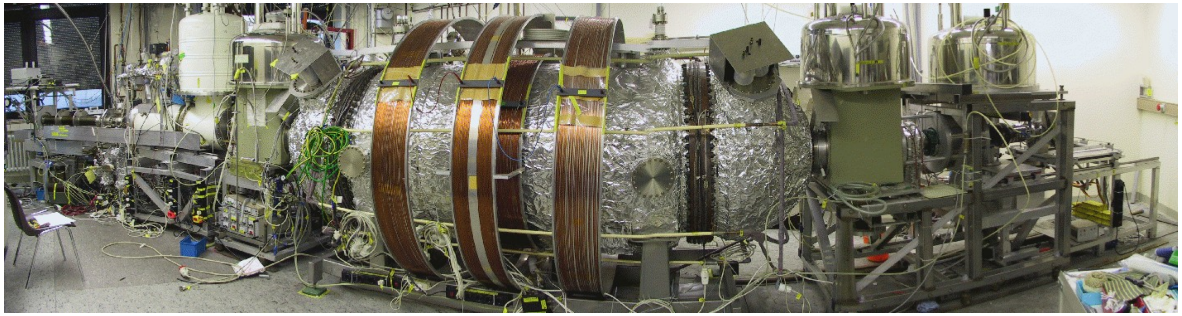
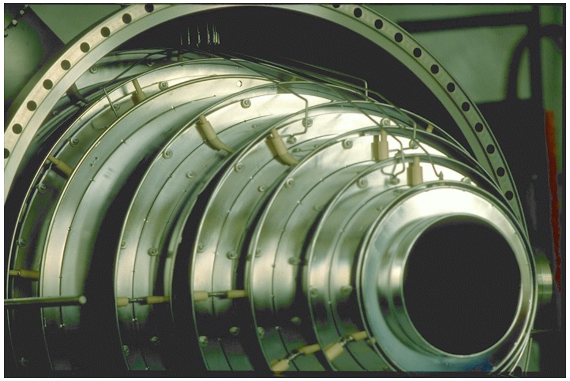
The Mainz Neutrino Mass Experiment
Phase 2: 1997-2001









⇓

After all critical systematics measured by own experiment (atomic physics, surface and solid state physics:
inelastic scattering, self-charging, neighbour excitation):

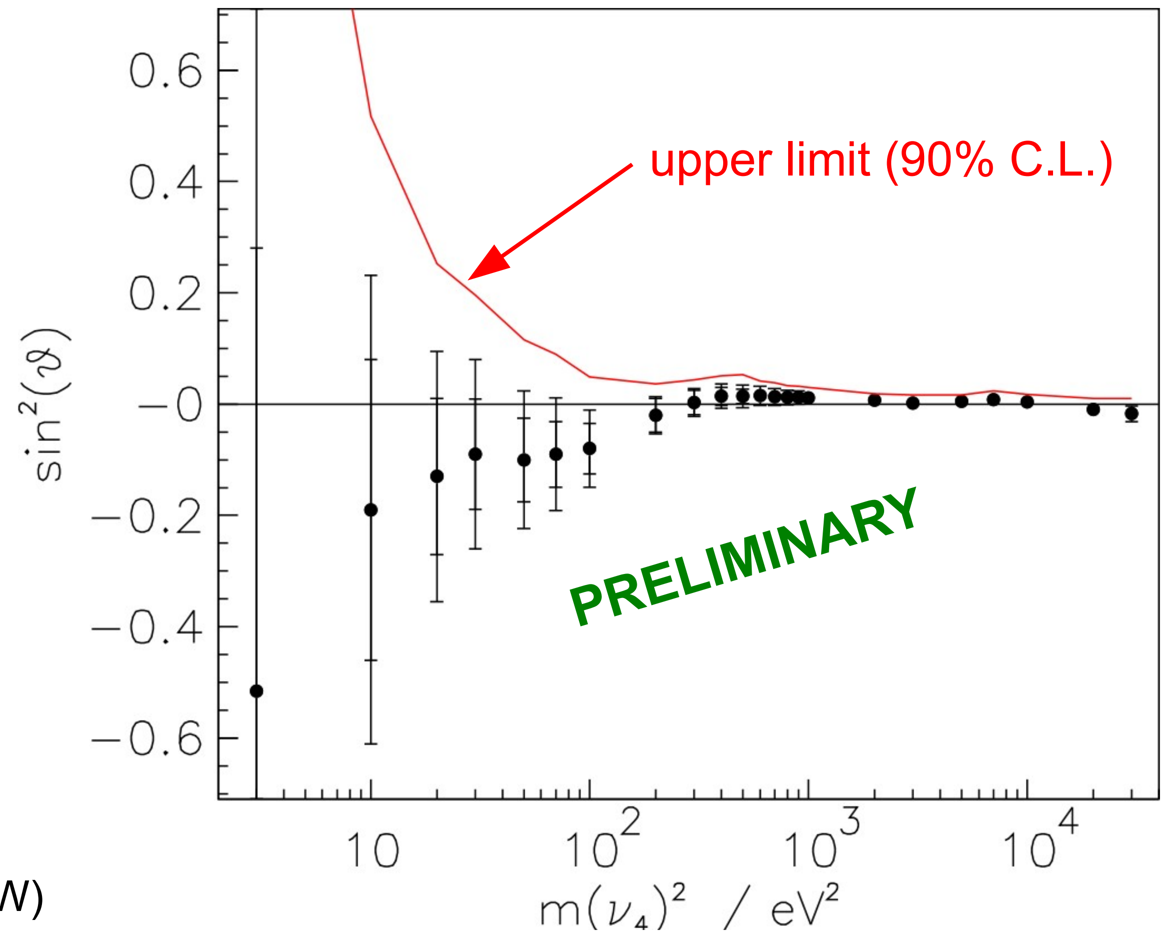
$m^2(\nu) = -0.6 \pm 2.2 \pm 2.1\ eV^2 \Rightarrow m(\nu) < 2.3\ eV$ (95% C.L.)

C. Kraus et al., Eur. Phys. J. C 40 (2005) 447

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*

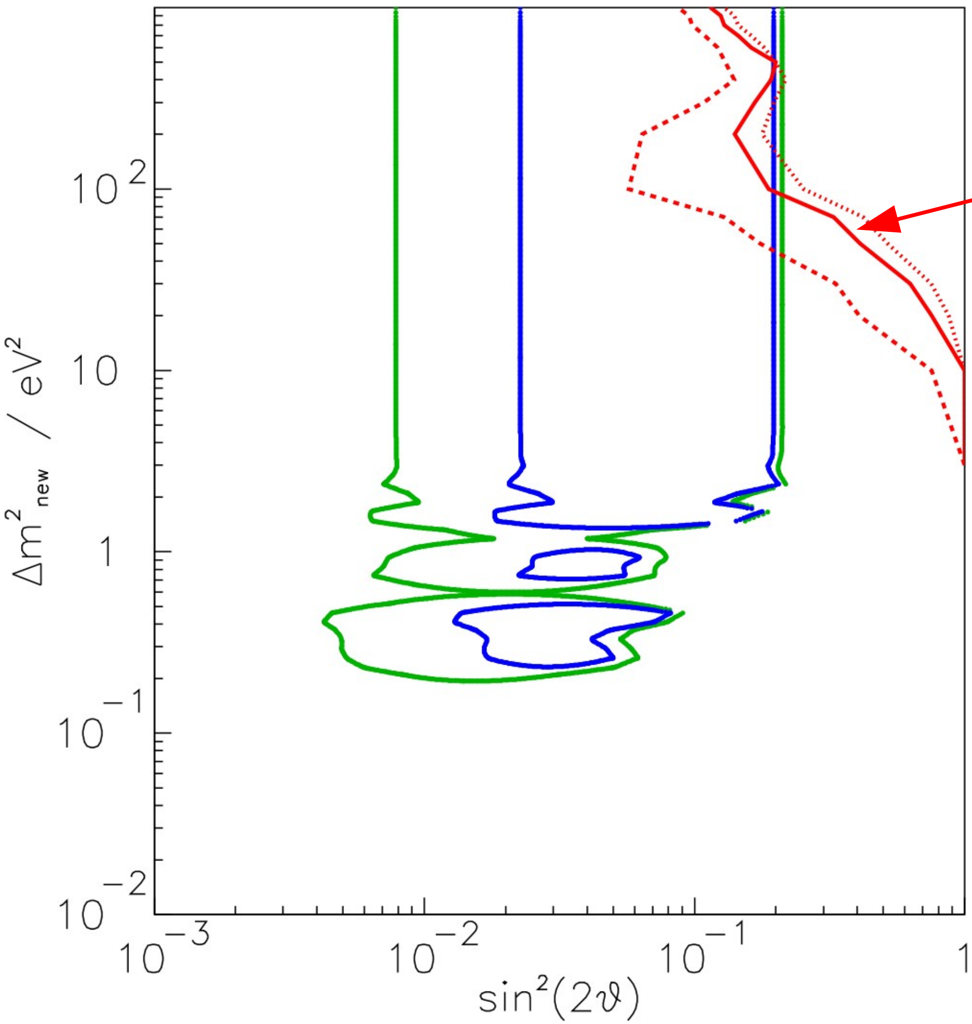


first work on this presented by A. Singer on Heraeus-Seminar on Neutrino Physics, 2006 (work by Ch. Kraus, A. Singer, K. Valerius, ChW) to be published soon

Sterile neutrino limits from the Mainz Neutrino Mass Experiment

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*

now only small mass region with more fits and a bit different evaluation program



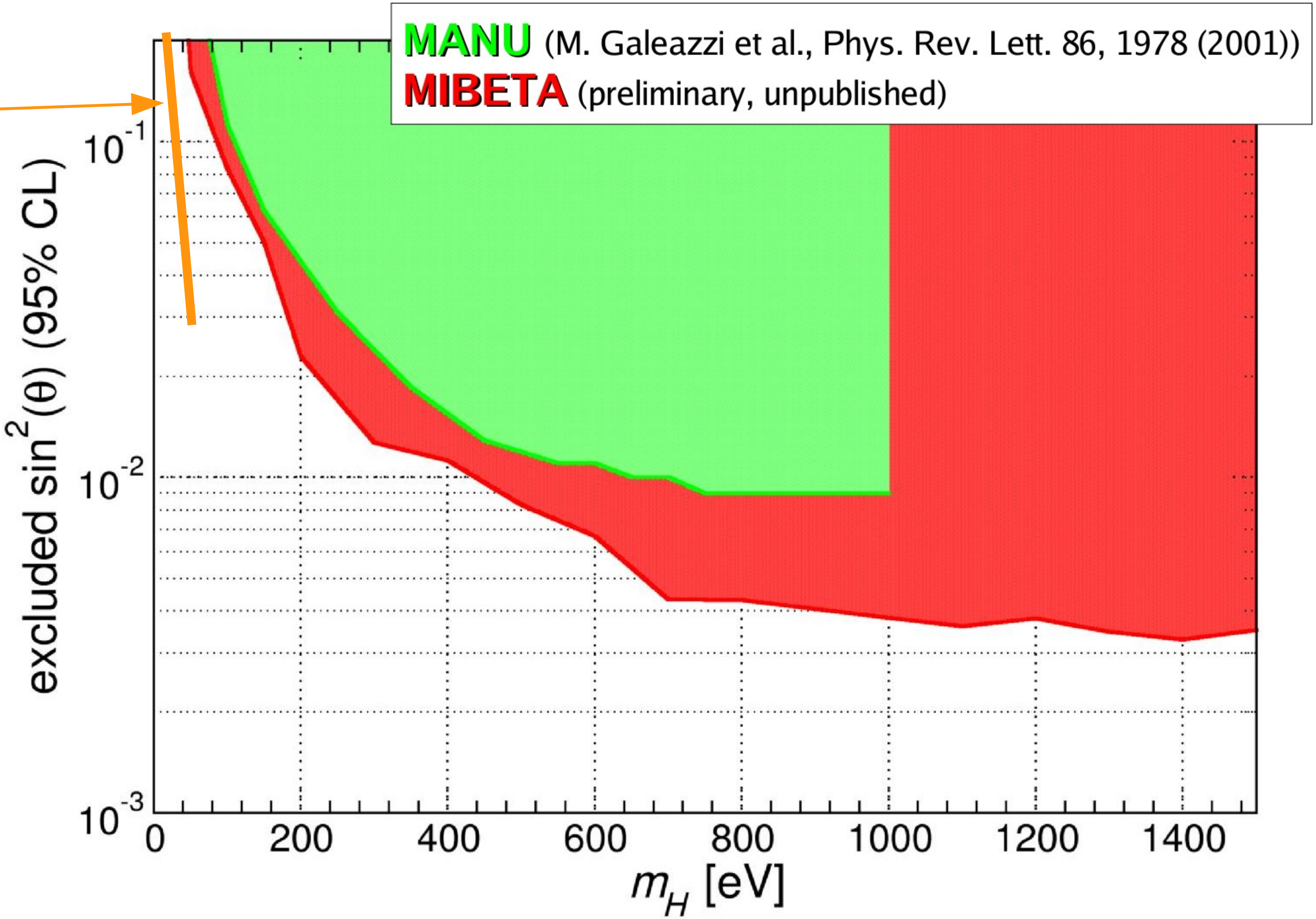
68, 90, 95% C.L. upper limits from Mainz data (preliminary)

(work by C. Kraus, A. Singer, K. Valerius, CW)

reactor + gallium calibration data from G. Mention et al., Phys. Rev. D 83 (2011) 073006 (courtesy Thierry Lassere)

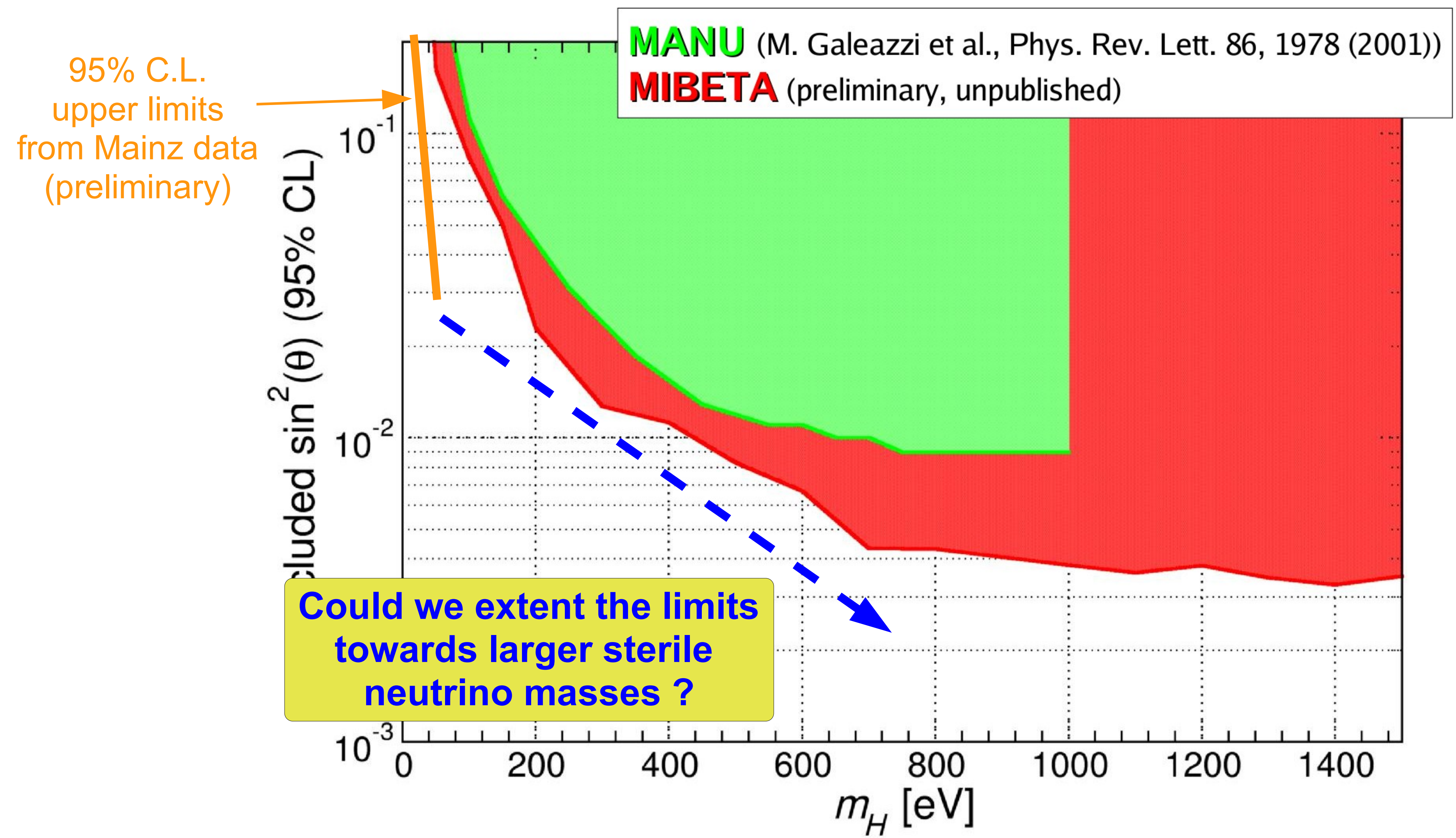
Sensivity on sterile neutrinos of previous direct neutrino mass experiments

95% C.L. upper limits from Mainz data (preliminary)



A. Nucciotti, Meudon Workshop 2011, 8-10 JUNE 2011

Sensivity on sterile neutrinos of previous direct neutrino mass experiments

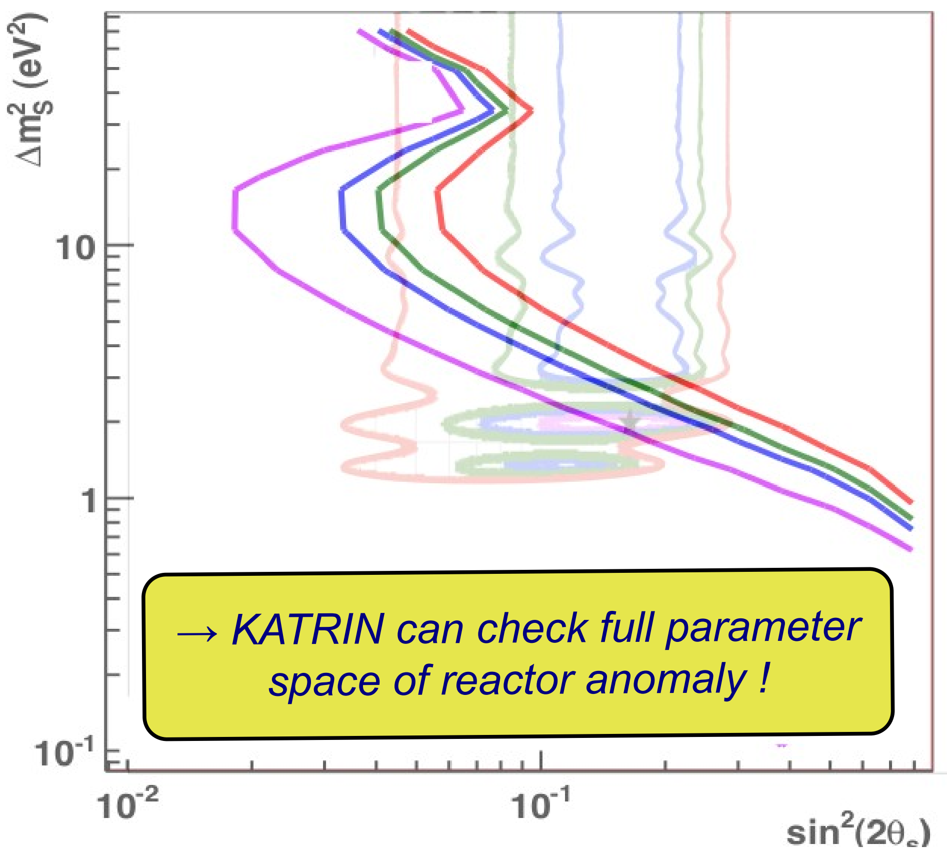


A. Nucciotti, Meudon Workshop 2011, 8-10 JUNE 2011

Sensivity on sterile neutrinos of up-coming direct neutrino mass experiments

Westfälische Wilhelms-Universität Münster

KATRIN

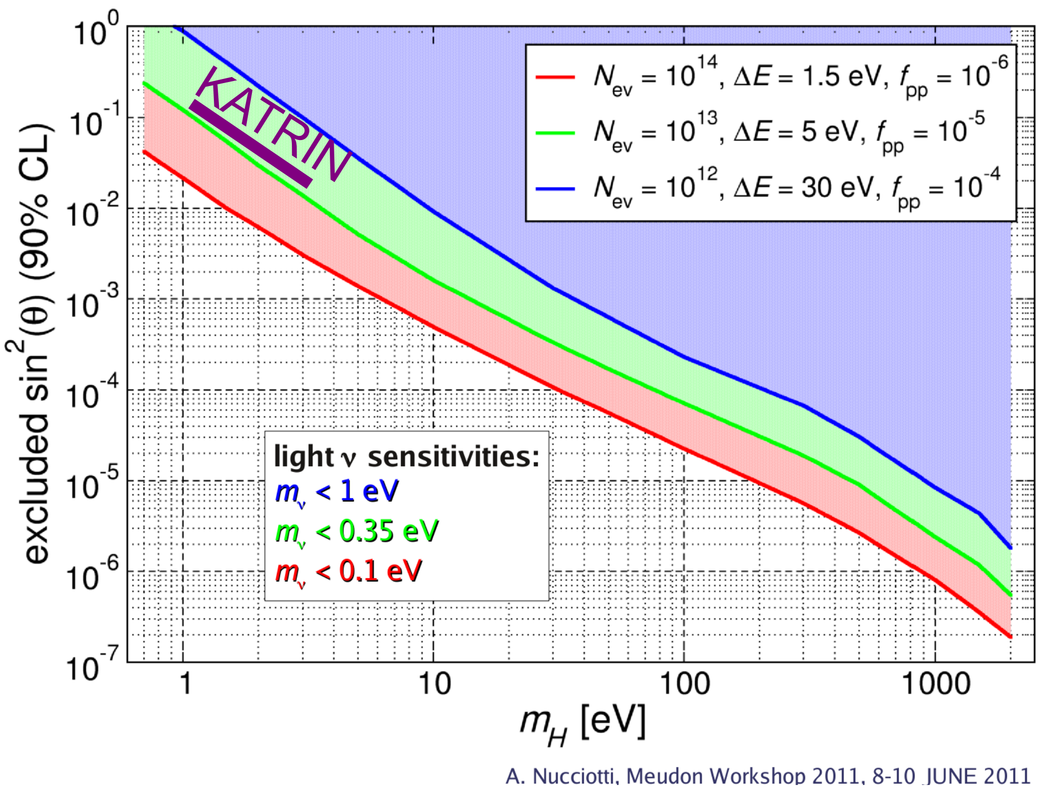


J. A. Formaggio, J. Barret, PLB 706 (2011) 68

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

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

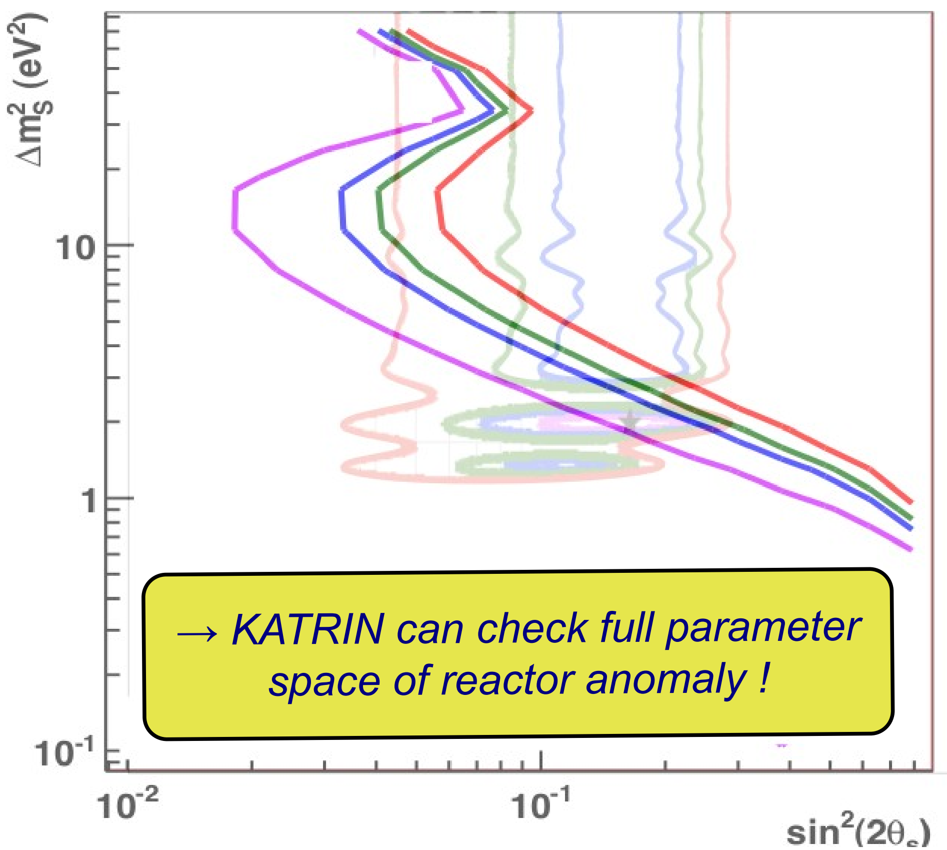
MARE II



A. Nucciotti, Meudon Workshop, June 2011

Sensivity on sterile neutrinos of up-coming direct neutrino mass experiments

KATRIN



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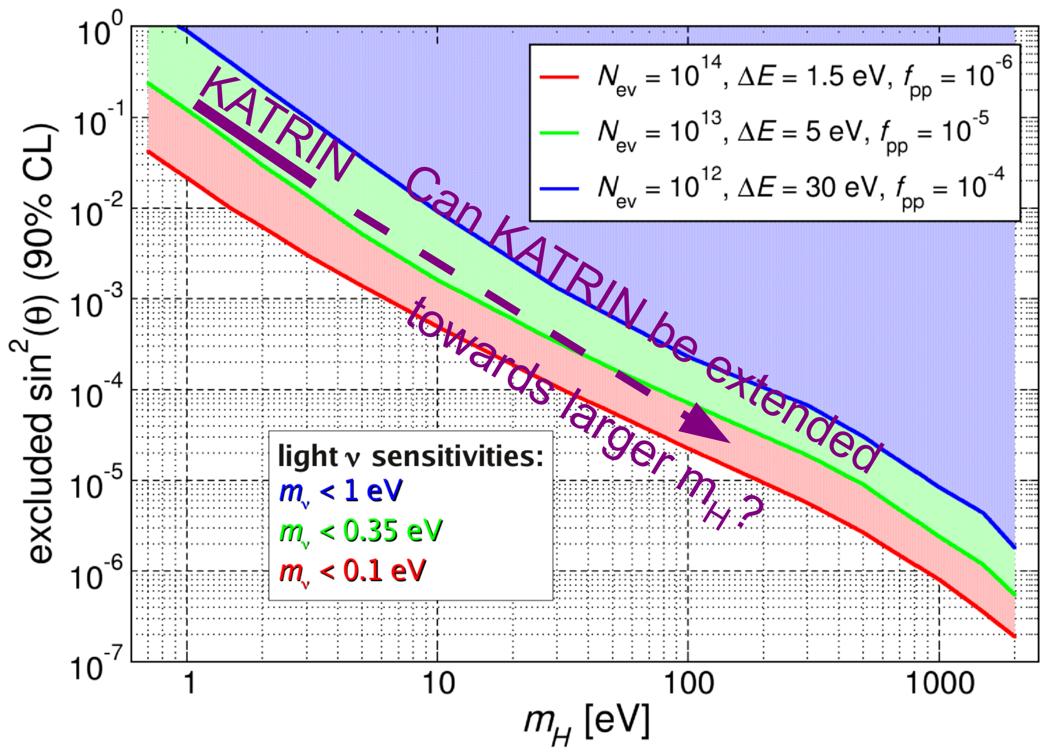
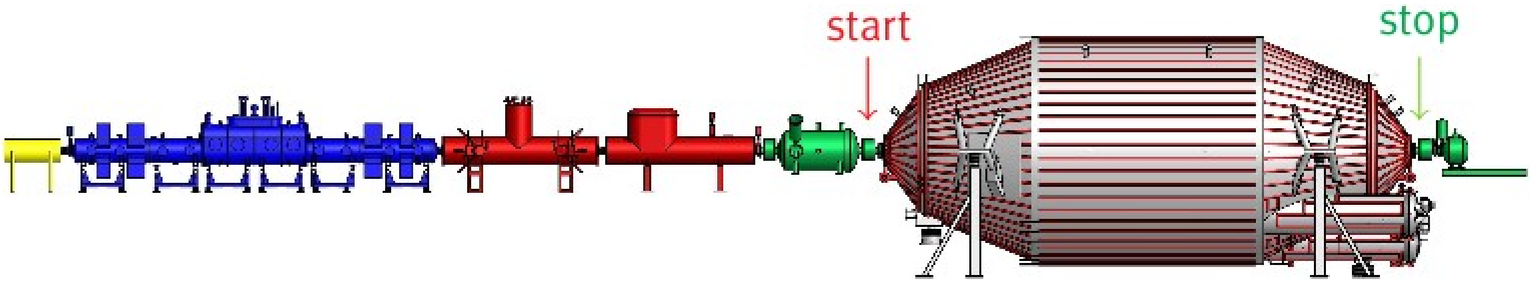
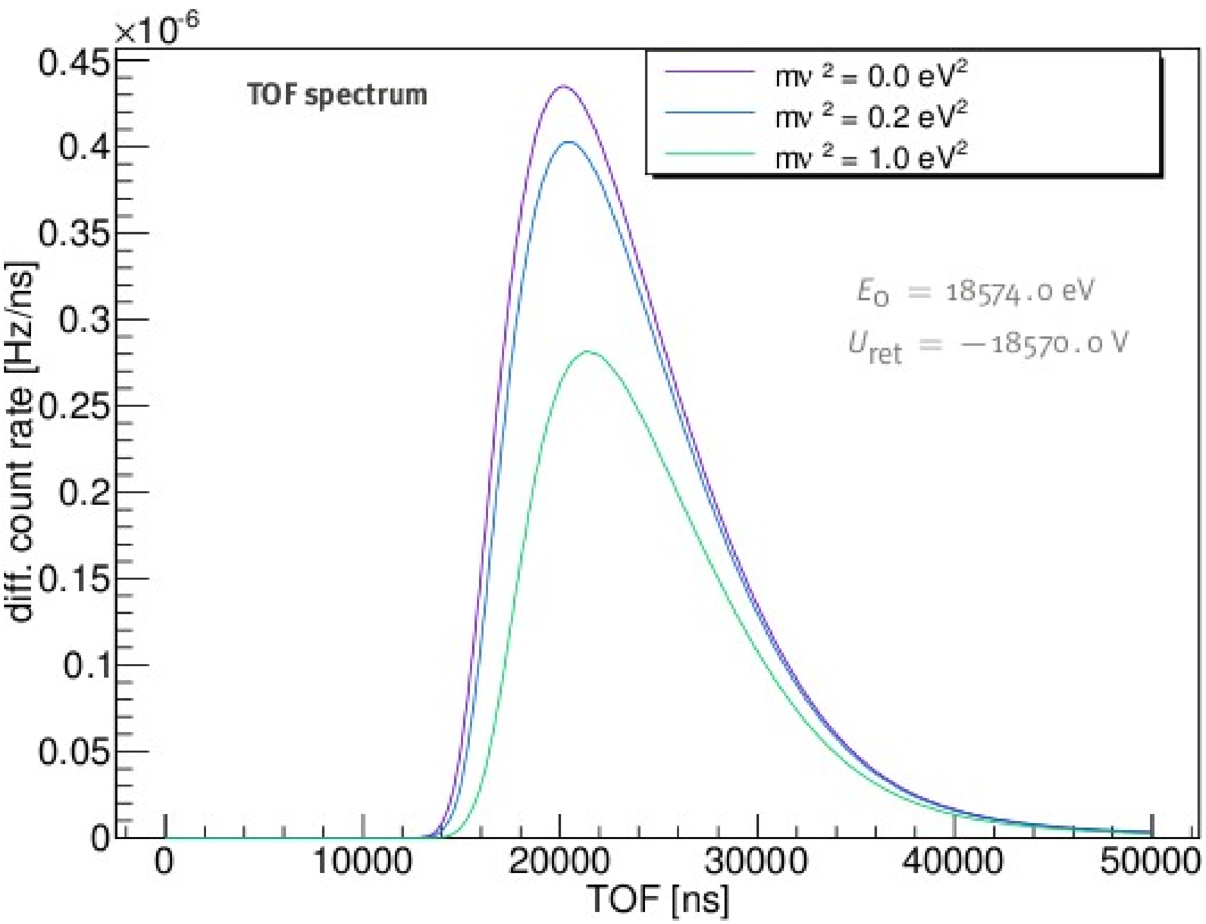


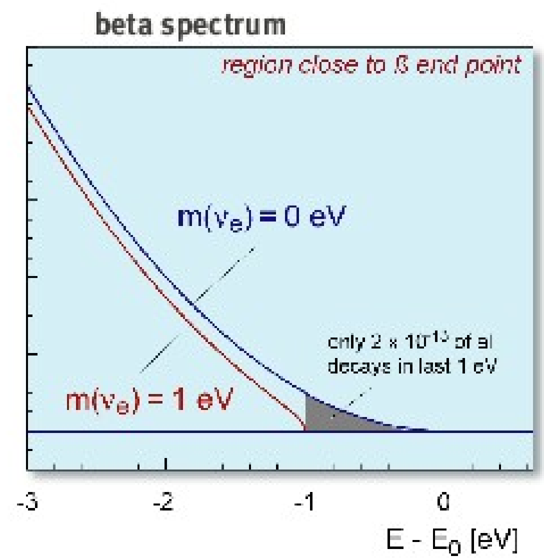
→ Need certainly a new strategy !

A. Nucciotti, Meudon Workshop, June 2011

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

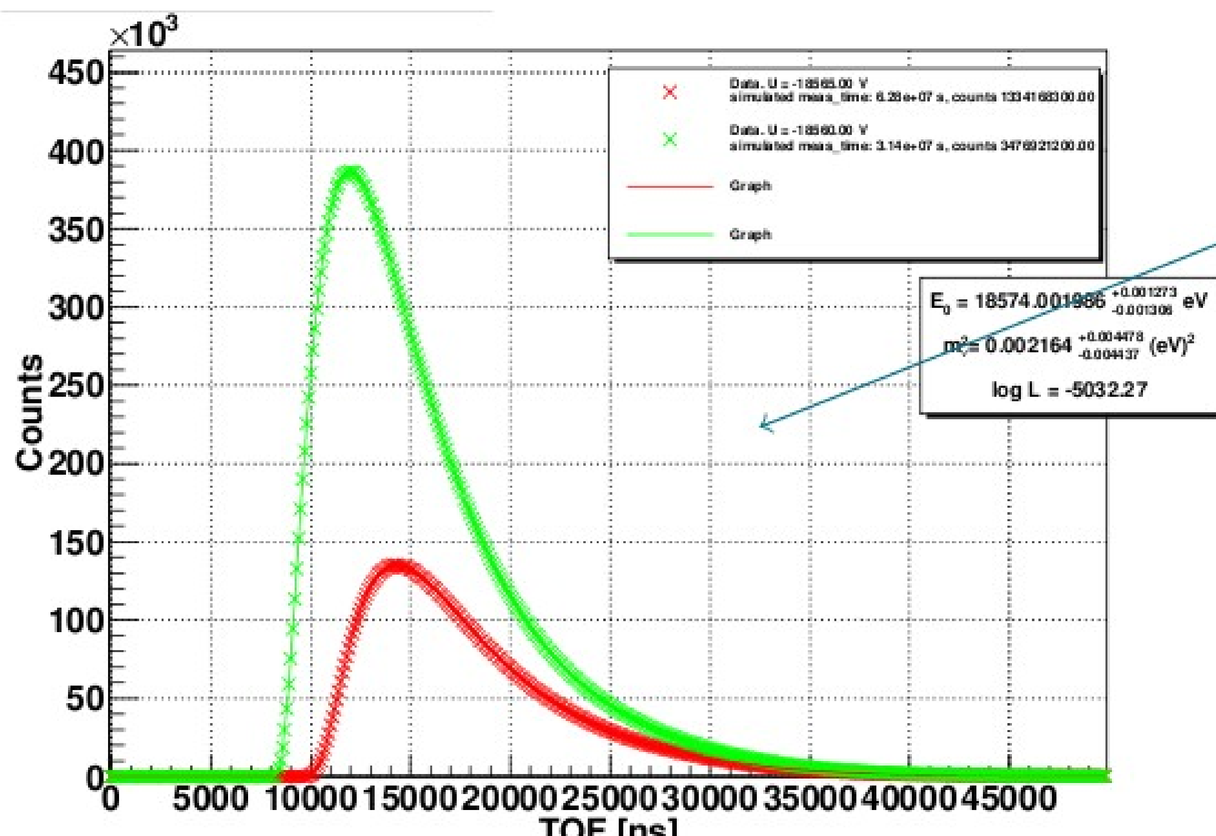
not integral but differential β spectrum

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 4-5 improvement in m_ν^2 w.r.t. standard KATRIN !



mean $\sigma_{stat}(m^2_{\nu_e})$
TOF mode:
0.0043 eV^2

$\sigma_{stat}(m^2_{\nu_e})$
standard mode:
$\mathcal{O}(0.02\ eV^2)$

diploma thesis N. Steinbrink
Münster 2012

How to measure time-of-flight at KATRIN ?

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

Is this possible ?

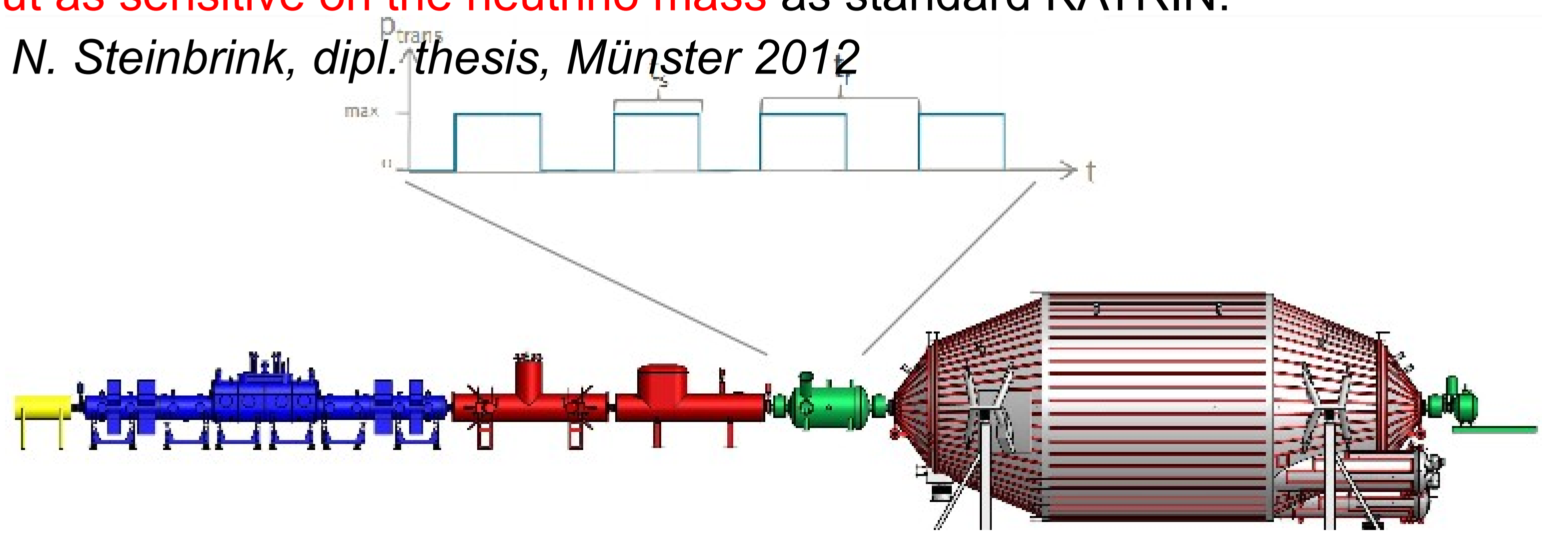
2') Use pre spectrometer as a „gated-filter“ by switching fast the retarding voltage

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

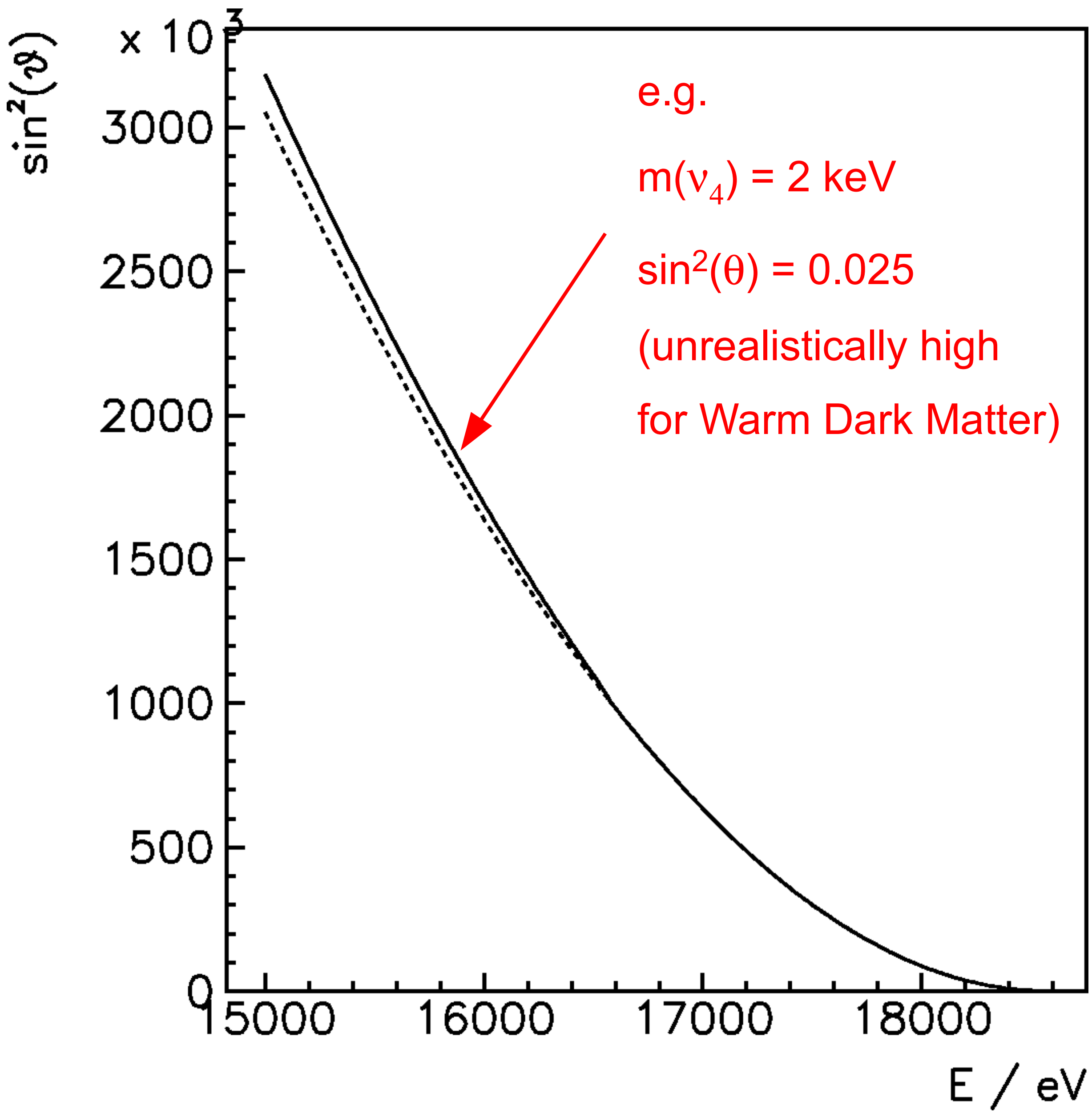
no problem with transmission properties: *M. Prall et al., accept. by NJP, arXiv:1203.2444*

About as sensitive on the neutrino mass as standard KATRIN:

N. Steinbrink, dipl. thesis, Münster 2012



Could we detect a few keV sterile neutrinos with KATRIN ?



The sterile neutrino kink is in a region, which is dominated by inelastically scattered electrons and other systematics.

Could we still see a tiny kink by just extrapolating the unknown systematics i.e. by an effective description

How precise can we become ?

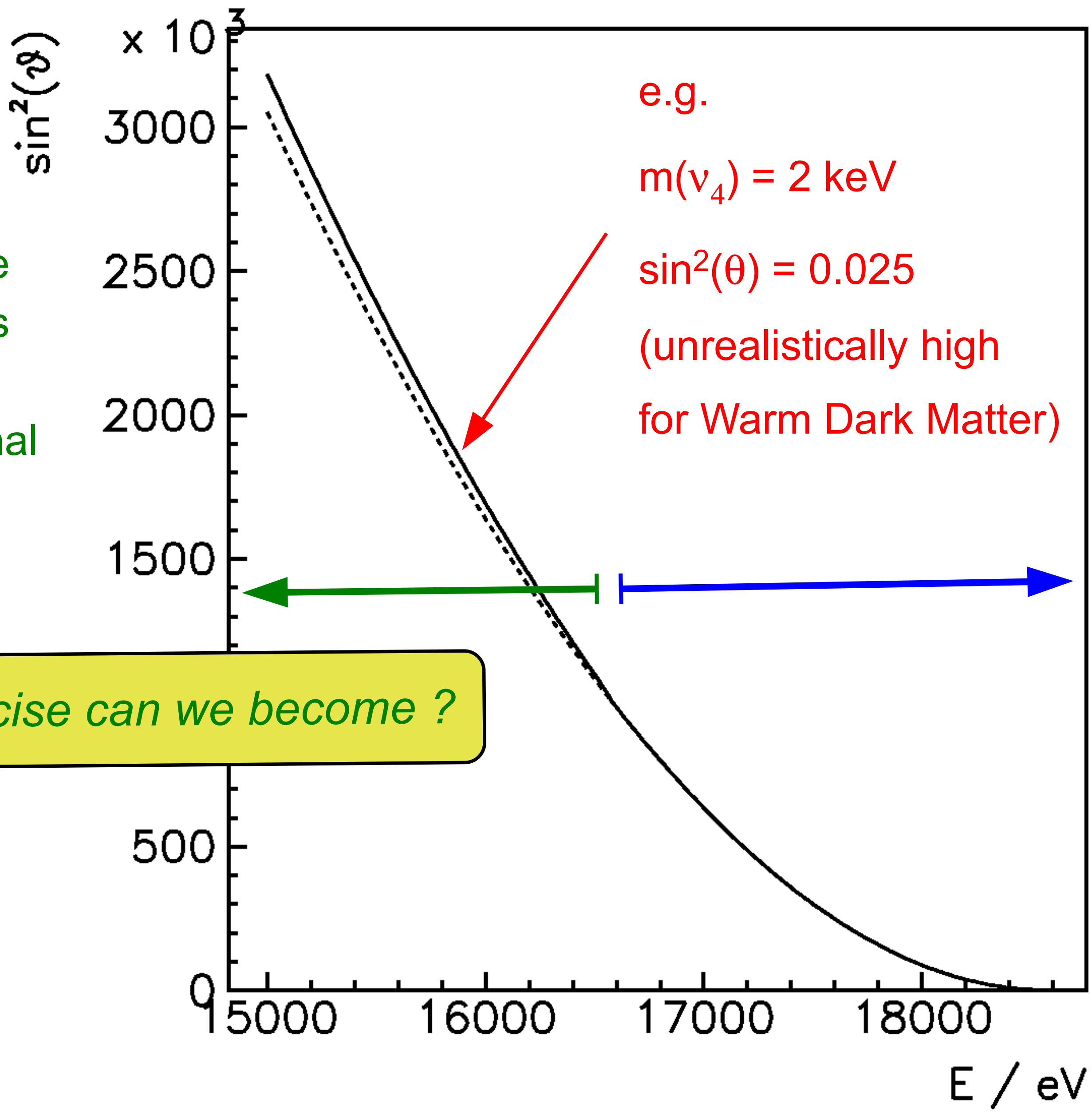
Could we tolerate the rate ?

Need certainly to lower column density in tritium source

→ need a dedicated study (some work has been started)

General idea for KATRIN to try out

Extrapolate downwards and check for additional keV sterile neutrino



How precise can we become ?

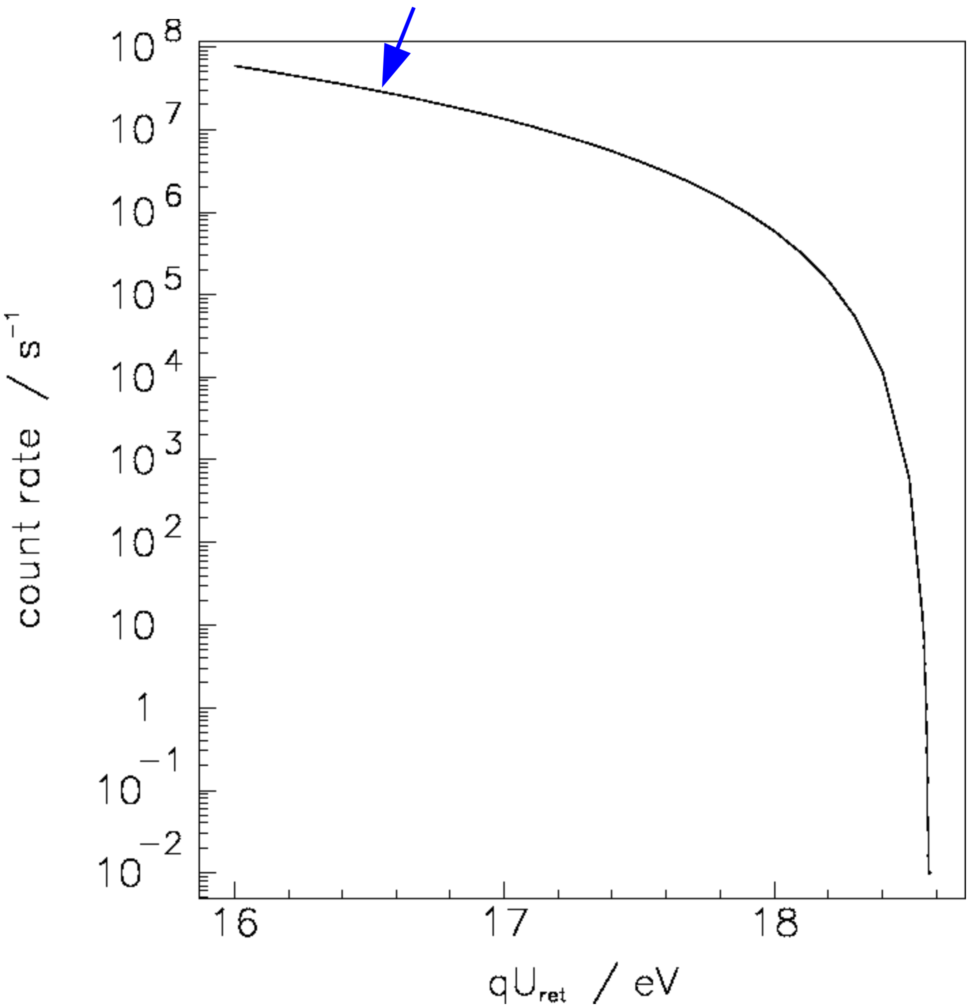
1) Exrapolote systematics
   - by model fitting
   - use atomic „sum rules“

2) Reduce "background“
   - from spectrum above kink
   - by non-integrating TOF modus („gated-filter“ is fine)

3) Low column density windowless gaseous T_2 source (KATRIN-WGTS)

β spectrum to be measured with KATRIN

Statistics is NOT an issue for the sensitivity on even very low values of $\sin^2(\theta)$



Could afford to operate with very short „on phases" in duty cycles in gated filter mode

→ close to ideal TOF measurements

What are the systematic uncertainties ?

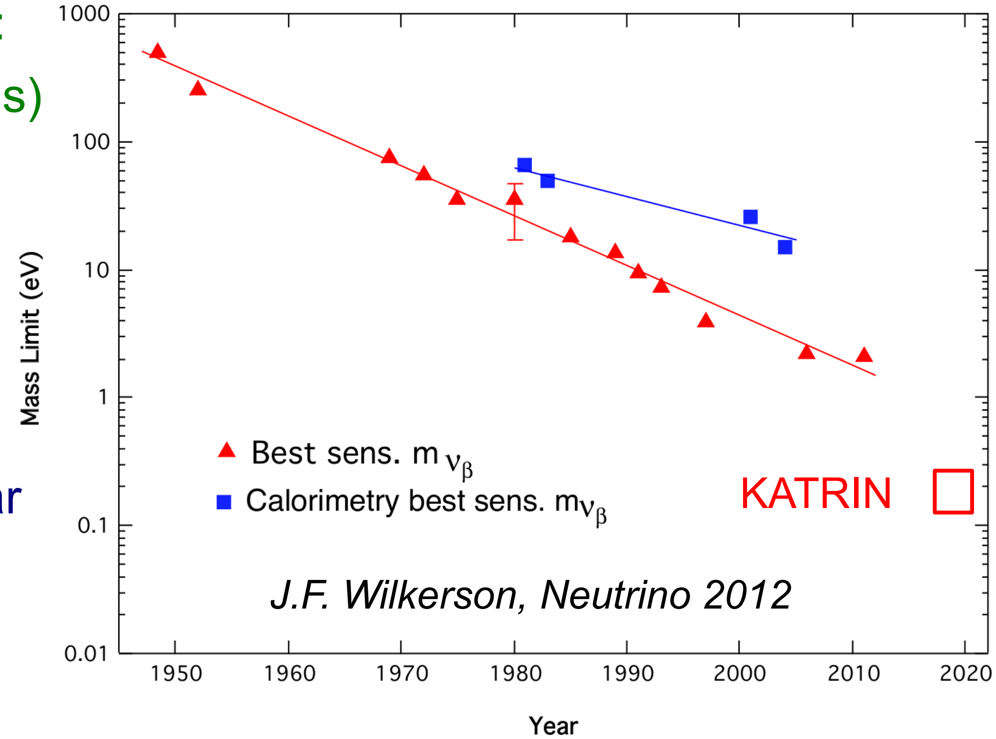
(need a dedicated study)

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)

3 complementary approaches to the neutrino mass:
cosmology, $0\nu\beta\beta$, direct (no further assumptions)

KATRIN is the next generation direct
neutrino mass experiment with 200 meV sens.
starting in 2015 to take tritium data



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 can check the reactor anomaly and has a chance
to search for Warm Dark Matter by time-of-flight spectroscopy in gated-filter mode