Search for Sterile Neutrinos with KATRIN

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Karlsruhe Institute of Technology and
Lawrence Berkeley National Laboratory

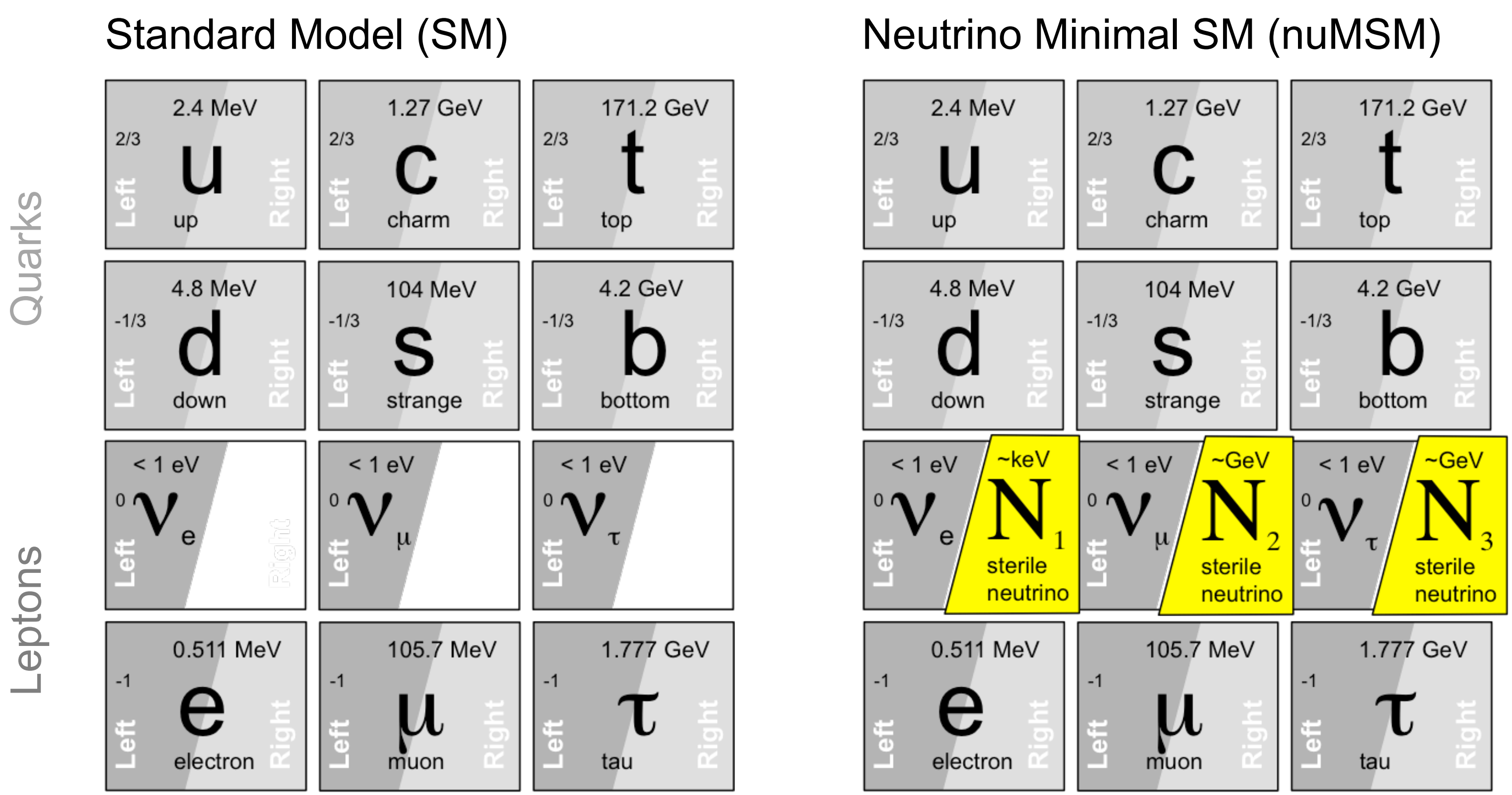
Chalonge Meudon Workshop 2015

Unterstützt von / Supported by
Alexander von Humboldt Stiftung / Foundation

Overview

- Introduction
  - Why sterile neutrinos?
  - How do sterile neutrinos imprint on the tritium decay spectrum?
- The KATRIN Experiment
  - … and the neutrino mass
  - … and sterile neutrinos

Sterile Neutrinos



L. Canetti, M. Drewes, and
M. Shaposhnikov, PRL **110** 061801 (2013)

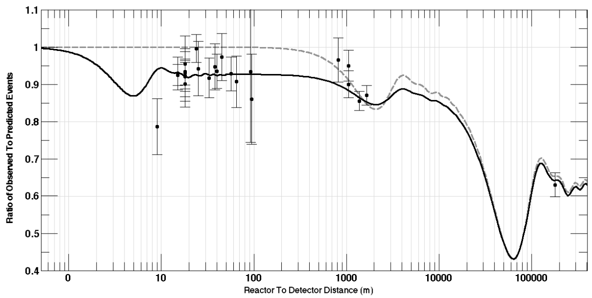
Sterile Neutrinos

Heavy sterile neutrinos (~GeV)

- Lightness of neutrinos via See-saw mechanism

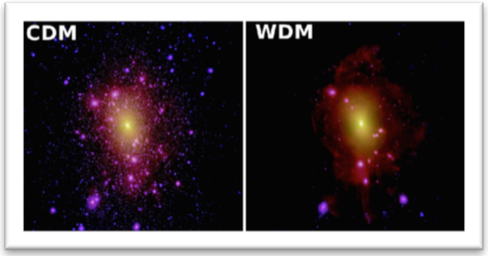
Light sterile neutrinos (~1 eV)

- Reactor anomaly, Gallium anomaly, Short baseline accelerator results



KeV-scale sterile neutrinos (~ 1- 50 keV)

- Warm and cold dark matter candidate



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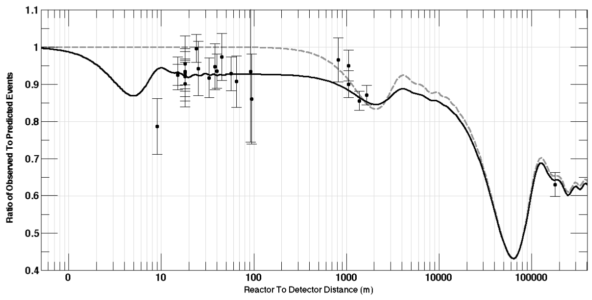

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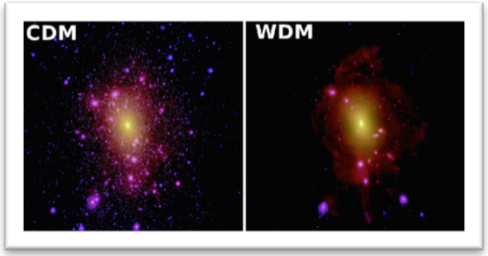
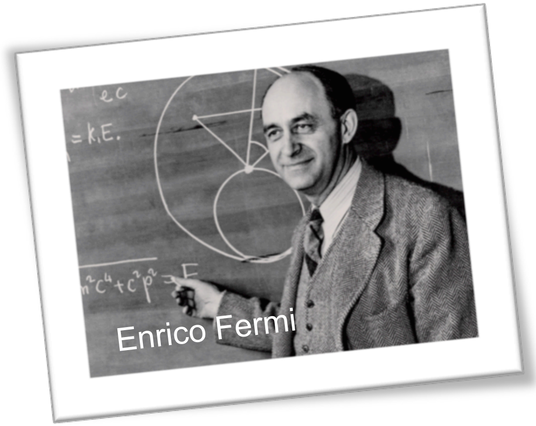
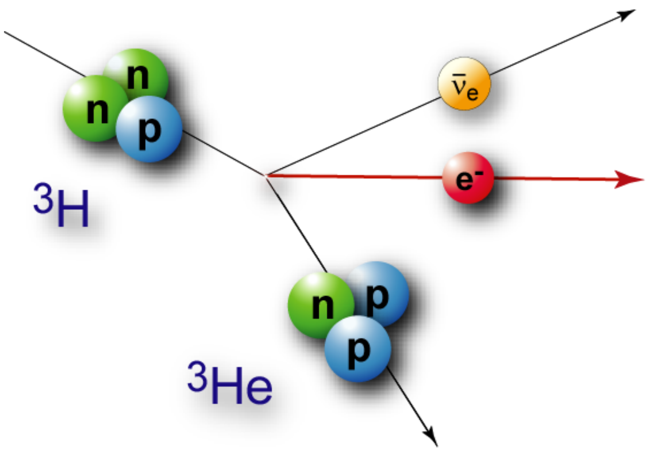


→ Accessible in tritium beta decay

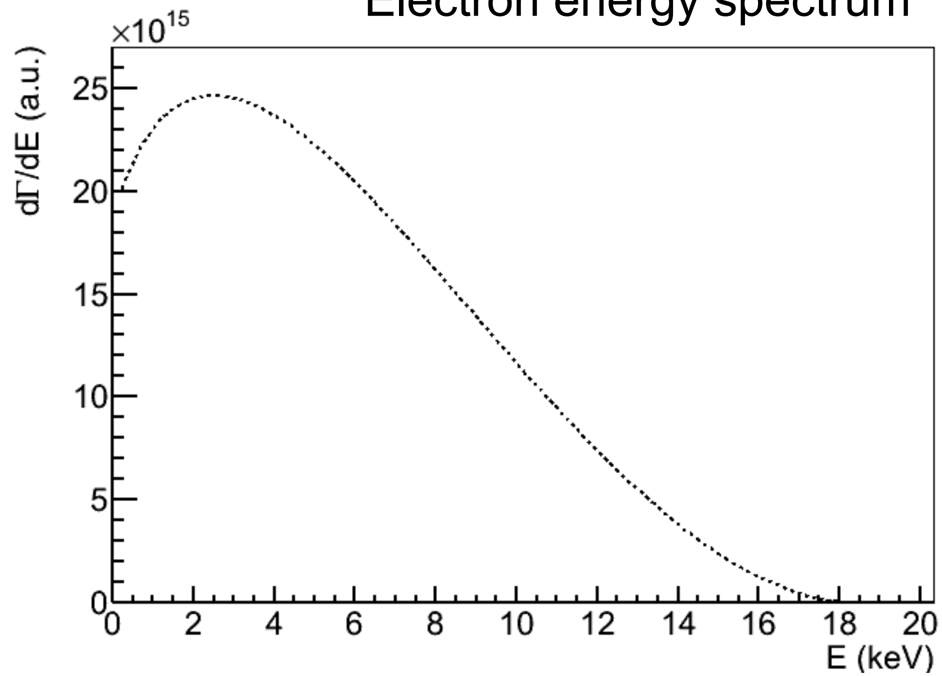
Tritium beta decay



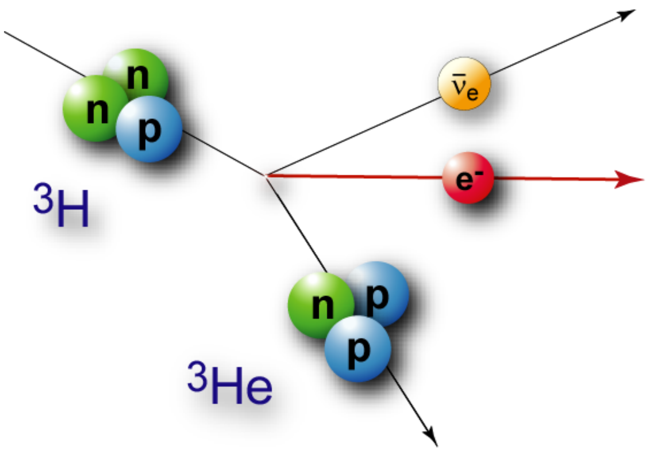


$$\frac{d\Gamma}{dE} = C \cdot F(E,Z) \cdot p \cdot (E + m_e) \cdot (E - E_0) \cdot \sqrt{(E - E_0)^2 - m_\nu^2}$$

Electron energy spectrum

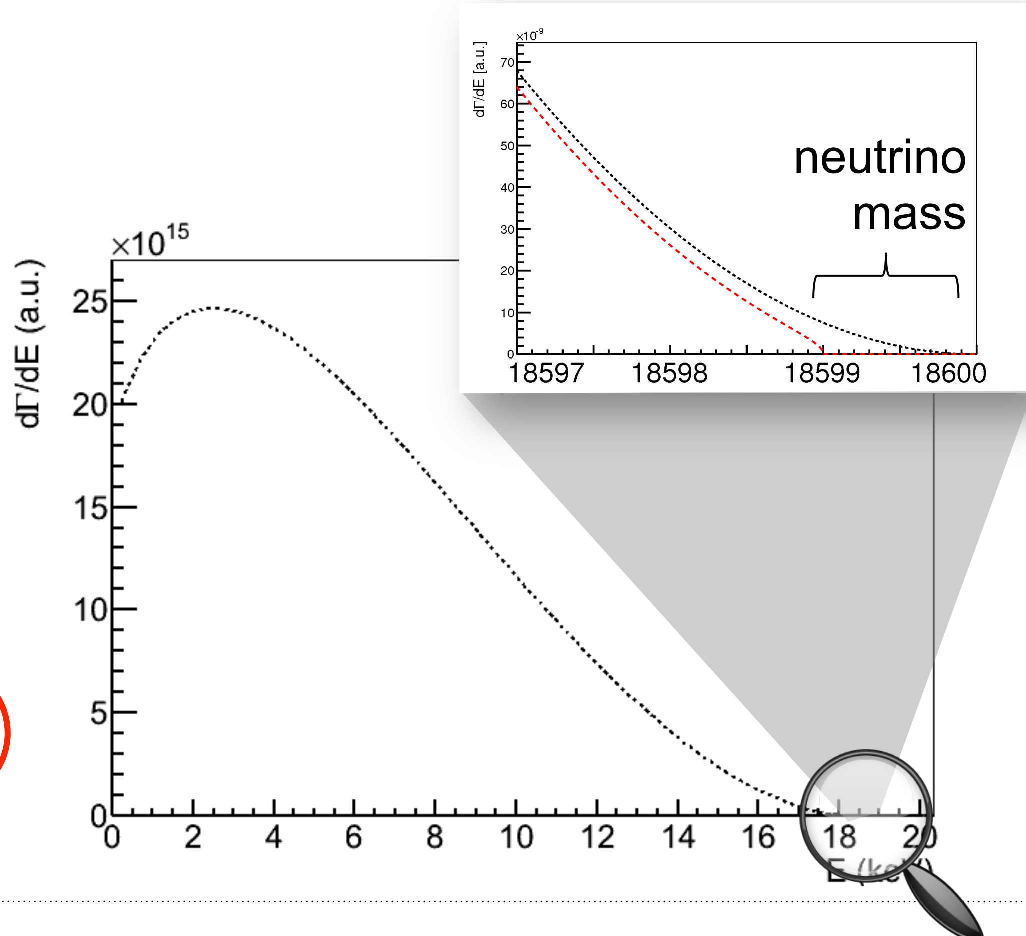


Tritium beta decay



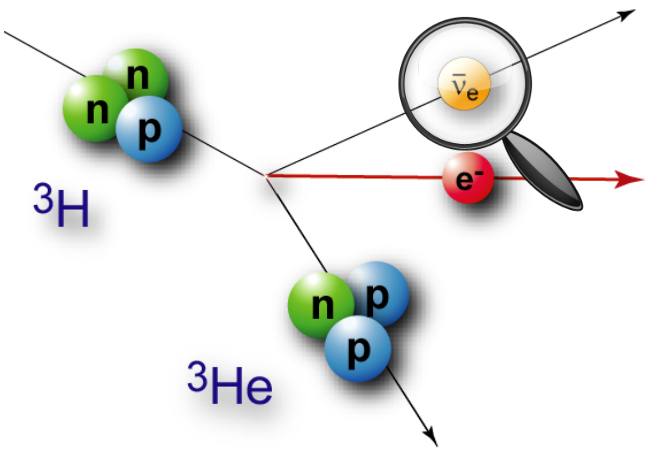
$$\frac{d\Gamma}{dE} = C \cdot F(E,Z) \cdot p \cdot (E + m_e) \cdot (E - E_0) \cdot \sqrt{(E - E_0)^2 - m_\nu^2}$$

10^-13 of all decays in last eV



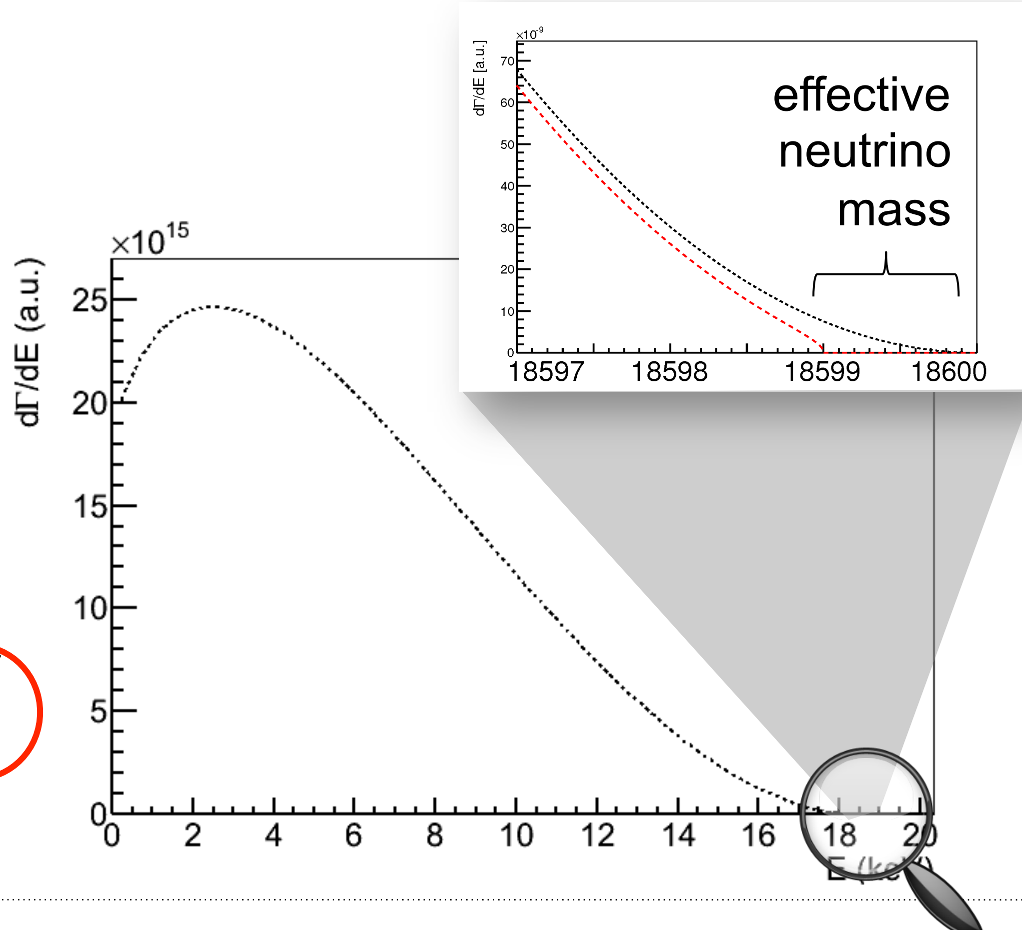
Tritium beta decay

$$m_\beta^2 = \sum_i |U_{ei}|^2 m_{\nu i}^2$$

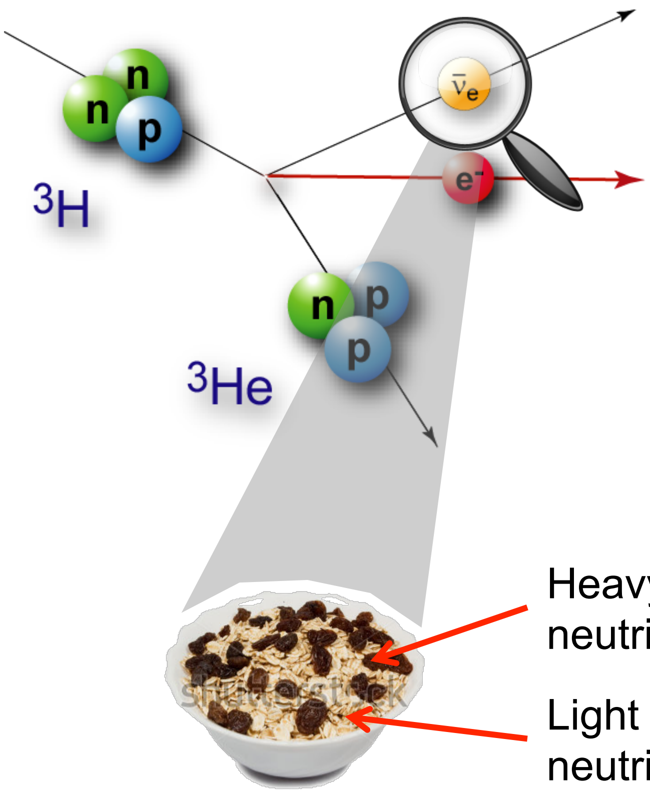


$$\frac{d\Gamma}{dE} = C \cdot F(E,Z) \cdot p \cdot (E + m_e)$$

$$\cdot (E - E_0) \cdot \sum_i |U_{ei}|^2 \sqrt{(E-E_0)^2 - m_{\nu i}^2}$$



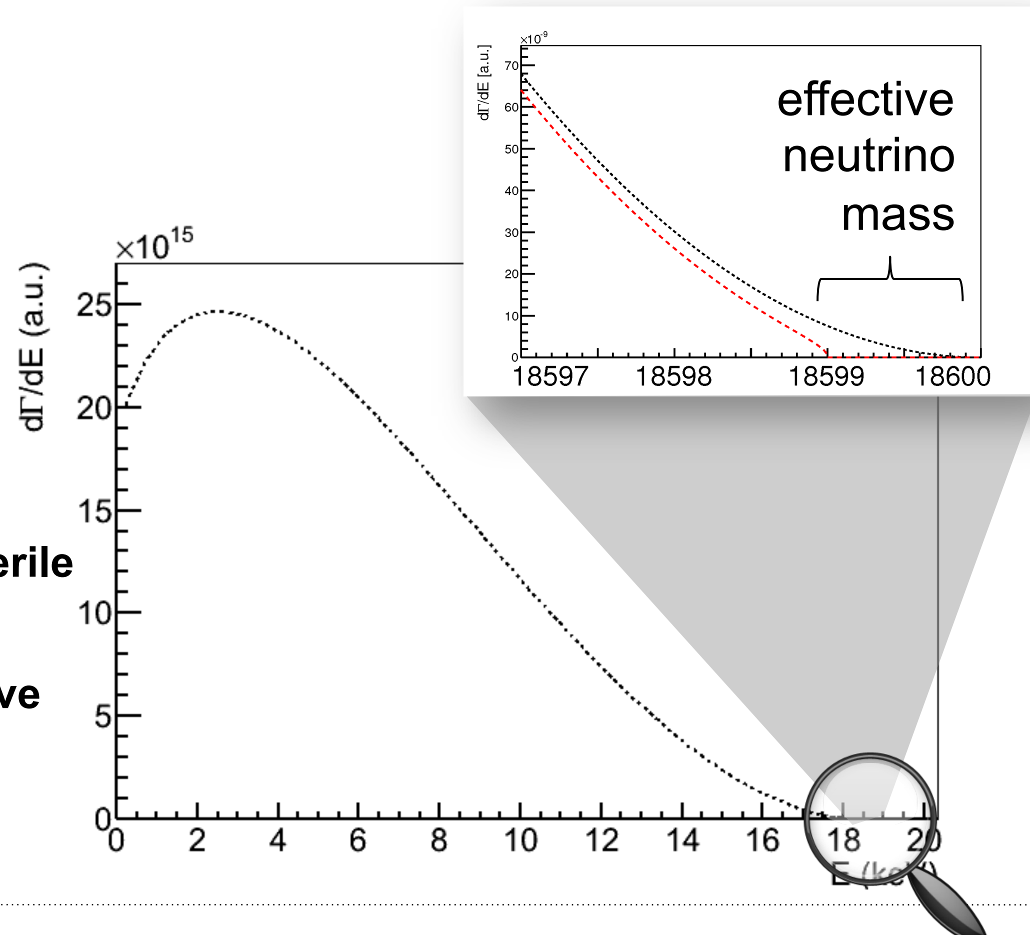
Tritium beta decay



Heavy **sterile** neutrino

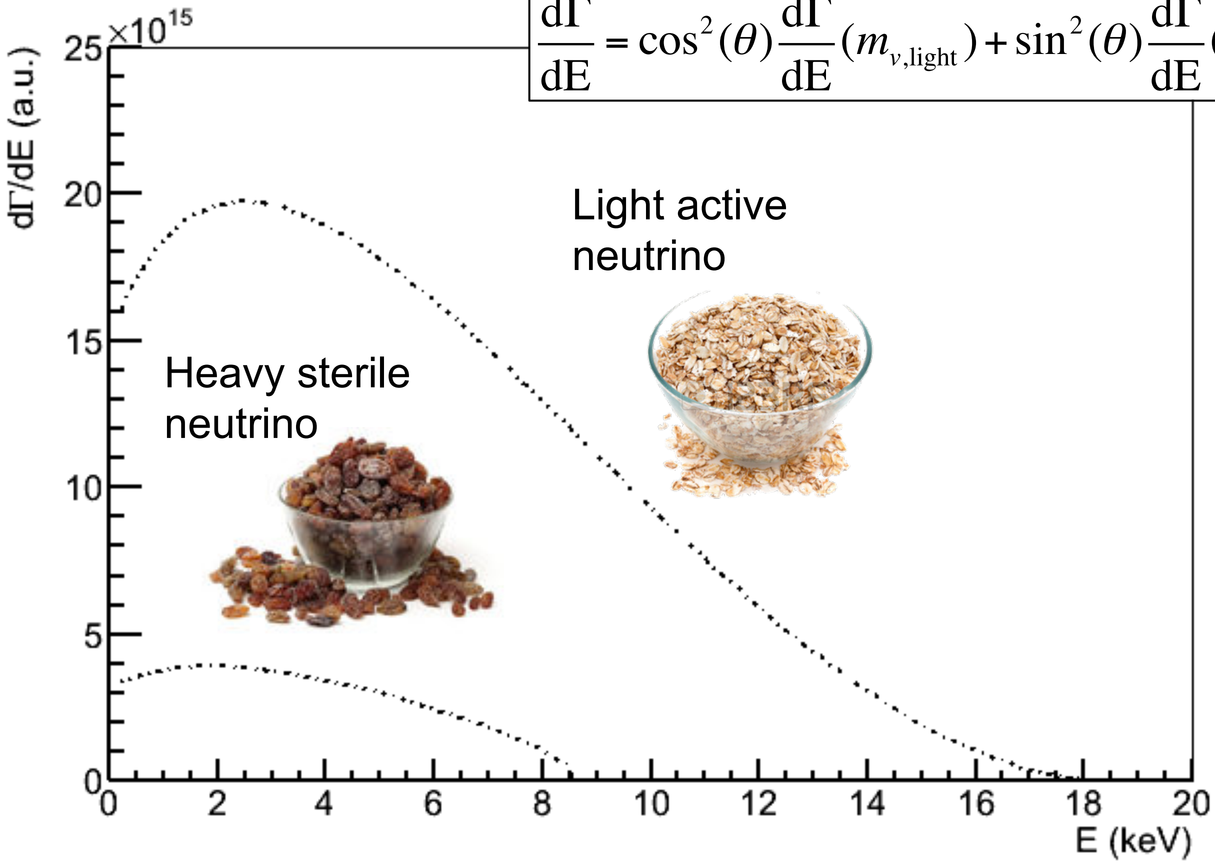
Light **active** neutrinos

Neutrino from tritium β-decay



Imprint of sterile ν's on ß-spectrum

$$\frac{d\Gamma}{dE} = \cos^2(\theta)\frac{d\Gamma}{dE}(m_{\nu,\mathrm{light}}) + \sin^2(\theta)\frac{d\Gamma}{dE}(m_{\nu,\mathrm{heavy}})$$



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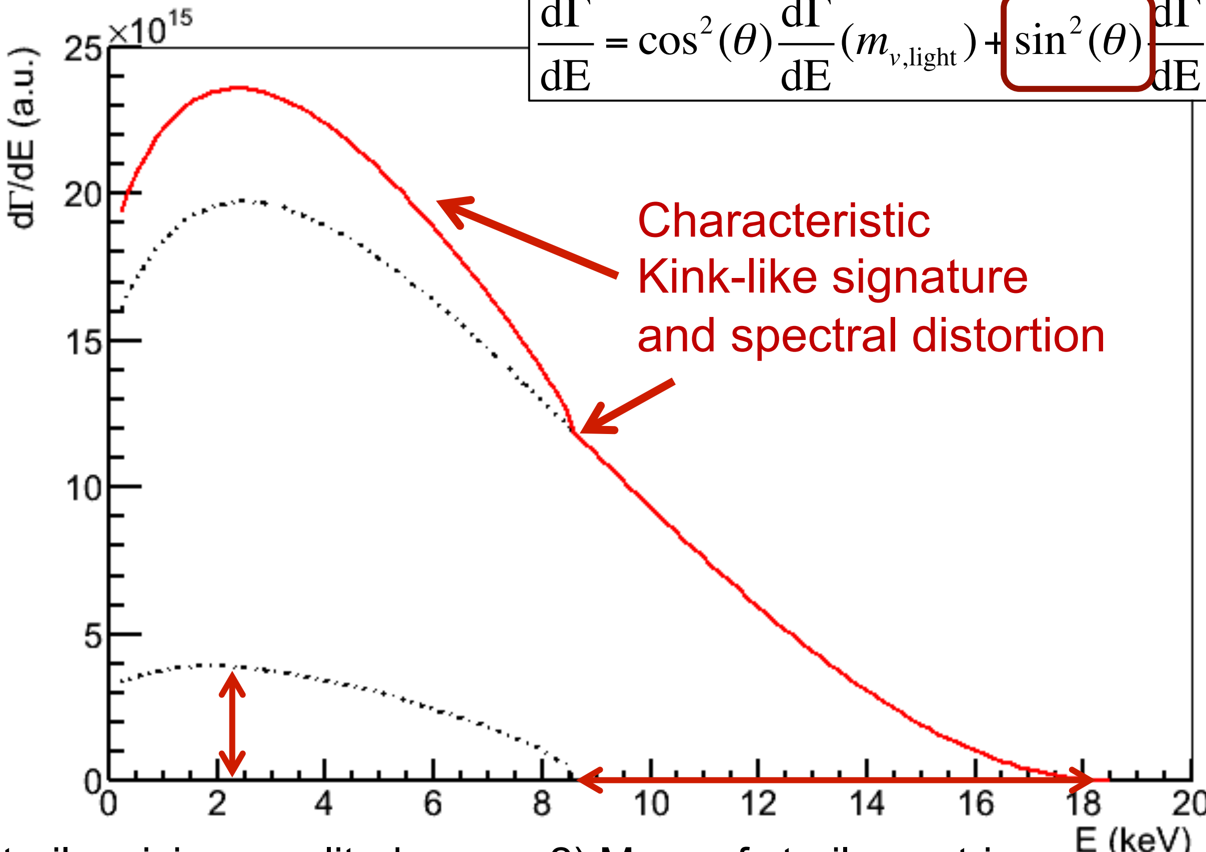


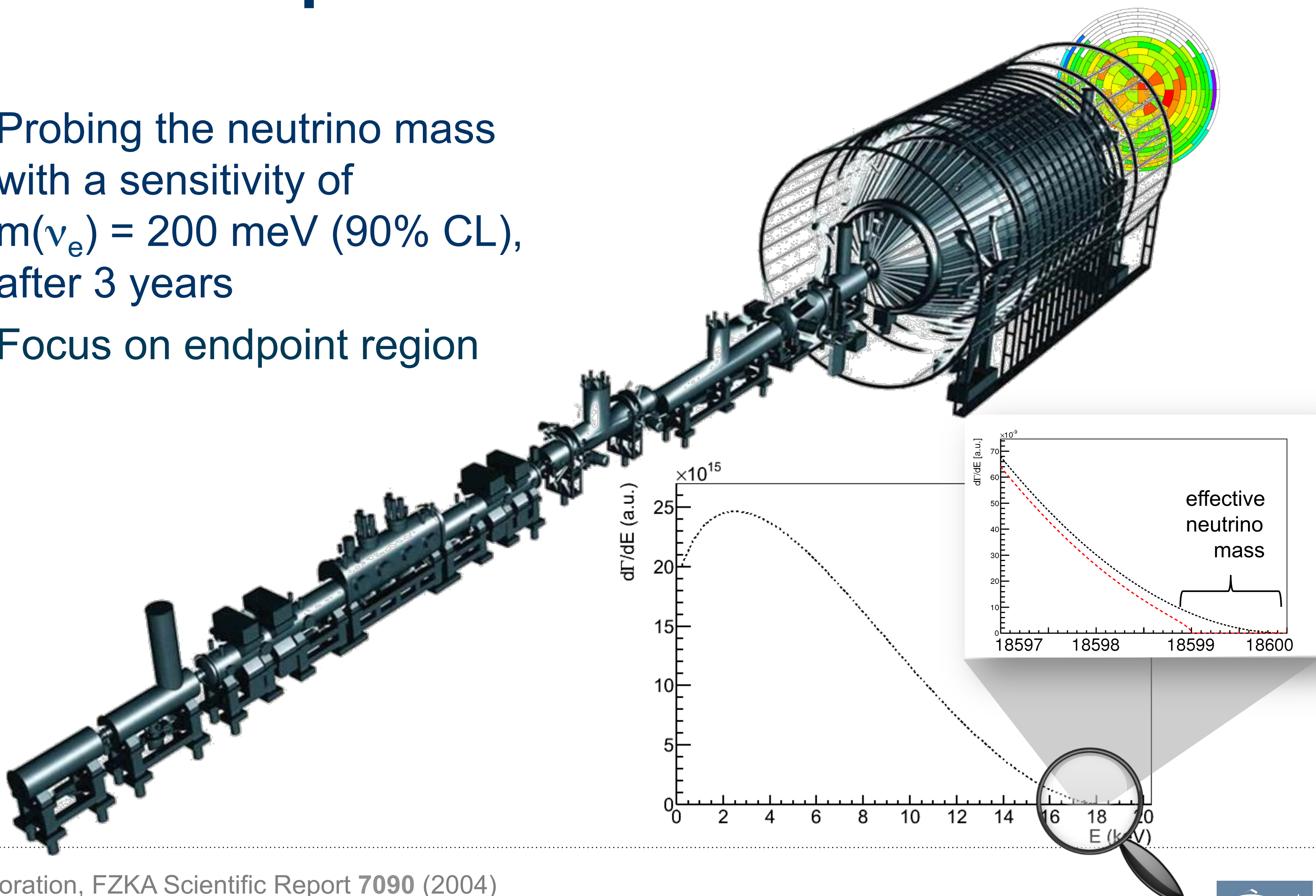
1) Active-to-sterile mixing amplitude

2) Mass of sterile neutrino

Karlsruhe Tritium Neutrino Experiment
KATRIN

KATRIN Experiment

- Probing the neutrino mass with a sensitivity of $m(\nu_e)$ = 200 meV (90% CL), after 3 years
- Focus on endpoint region

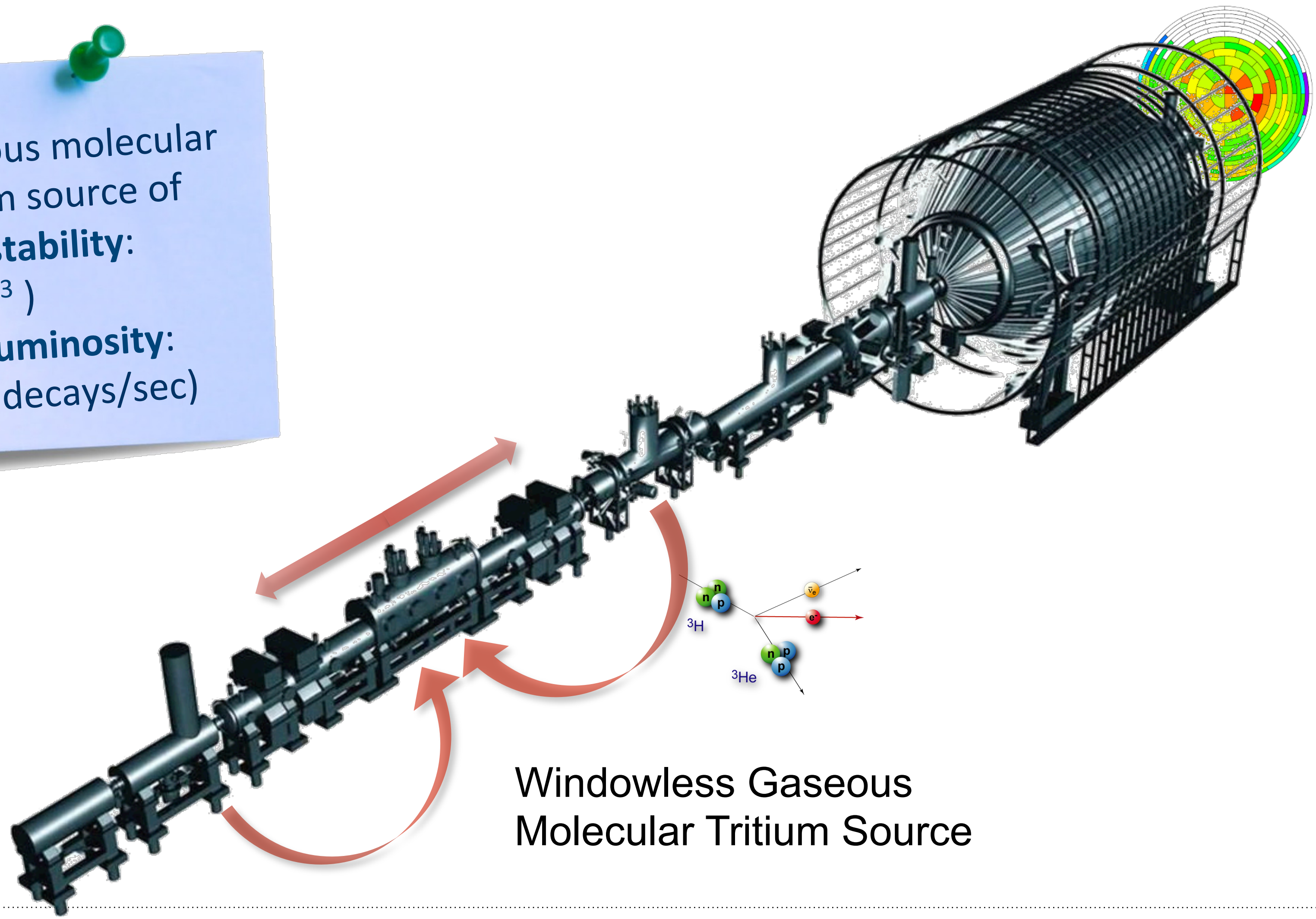


KATRIN Collaboration, FZKA Scientific Report **7090** (2004)

G. Drexlin, V. Hannen, S. M., C. Weinheimer, AdHEP **2013** (2013)

KATRIN Overview

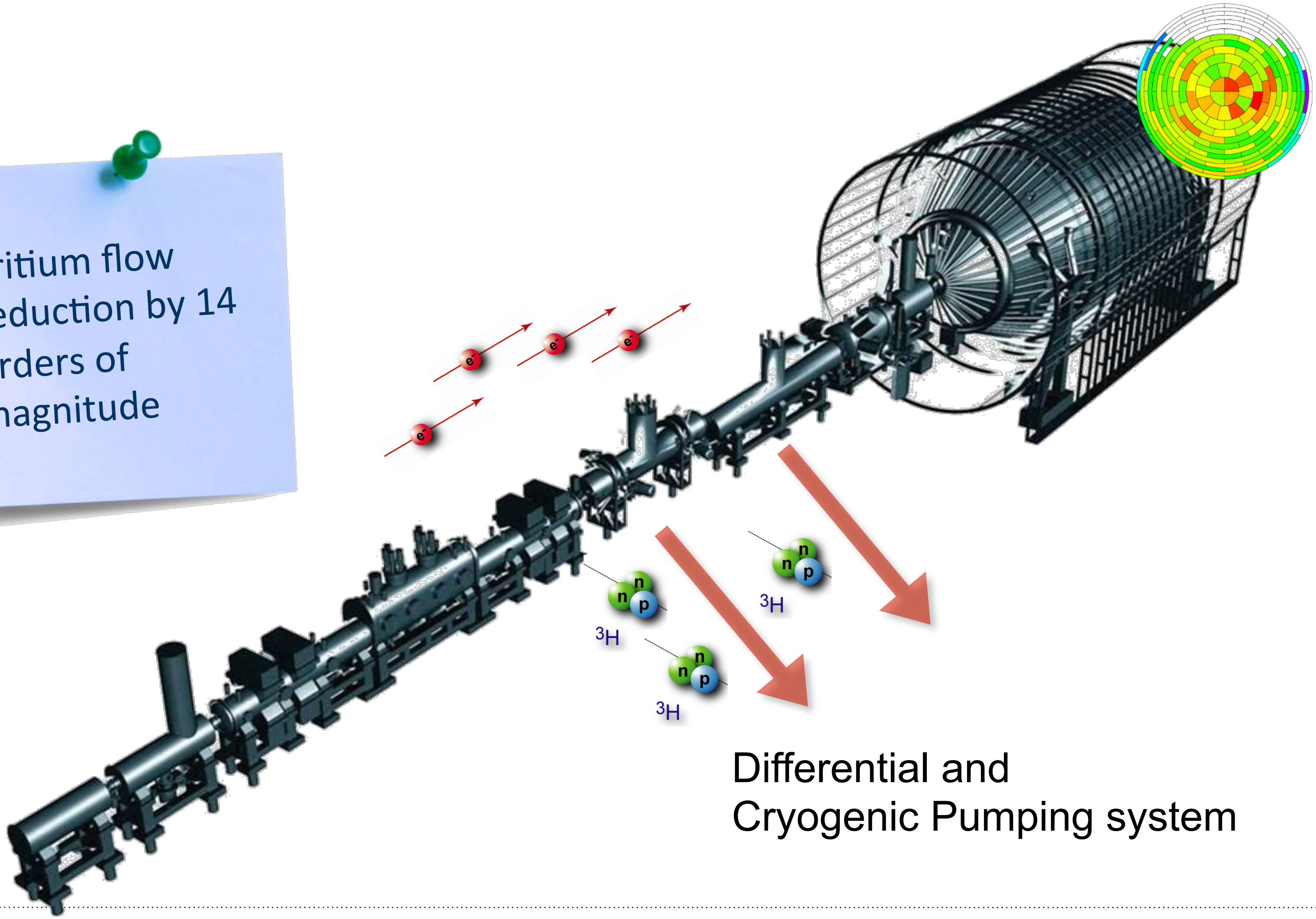
Gaseous molecular tritium source of high **stability**: (< 10^{-3}) and **luminosity**: (10^{11} decays/sec)



Windowless Gaseous Molecular Tritium Source

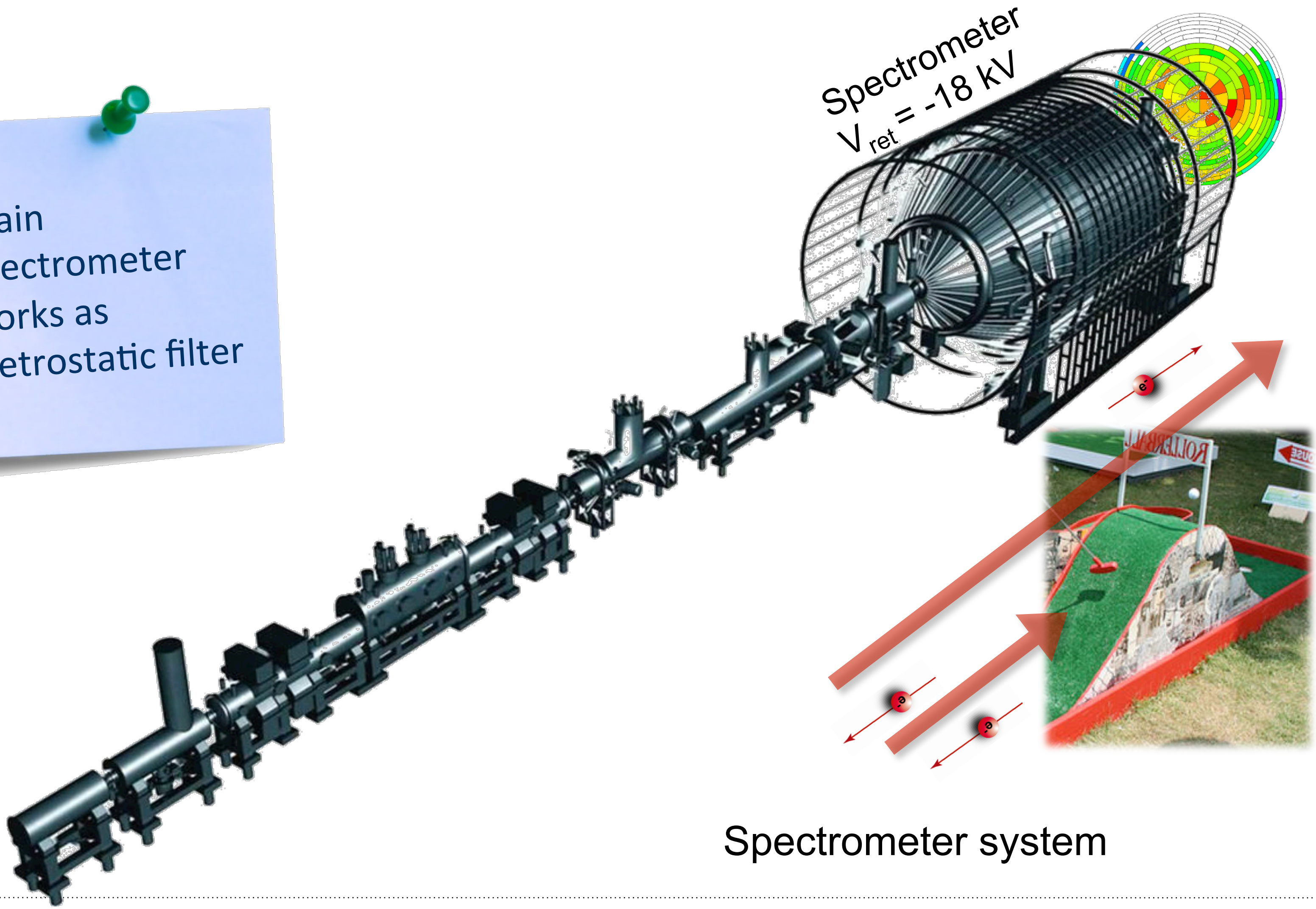
KATRIN Overview

Tritium flow reduction by 14 orders of magnitude



KATRIN Overview

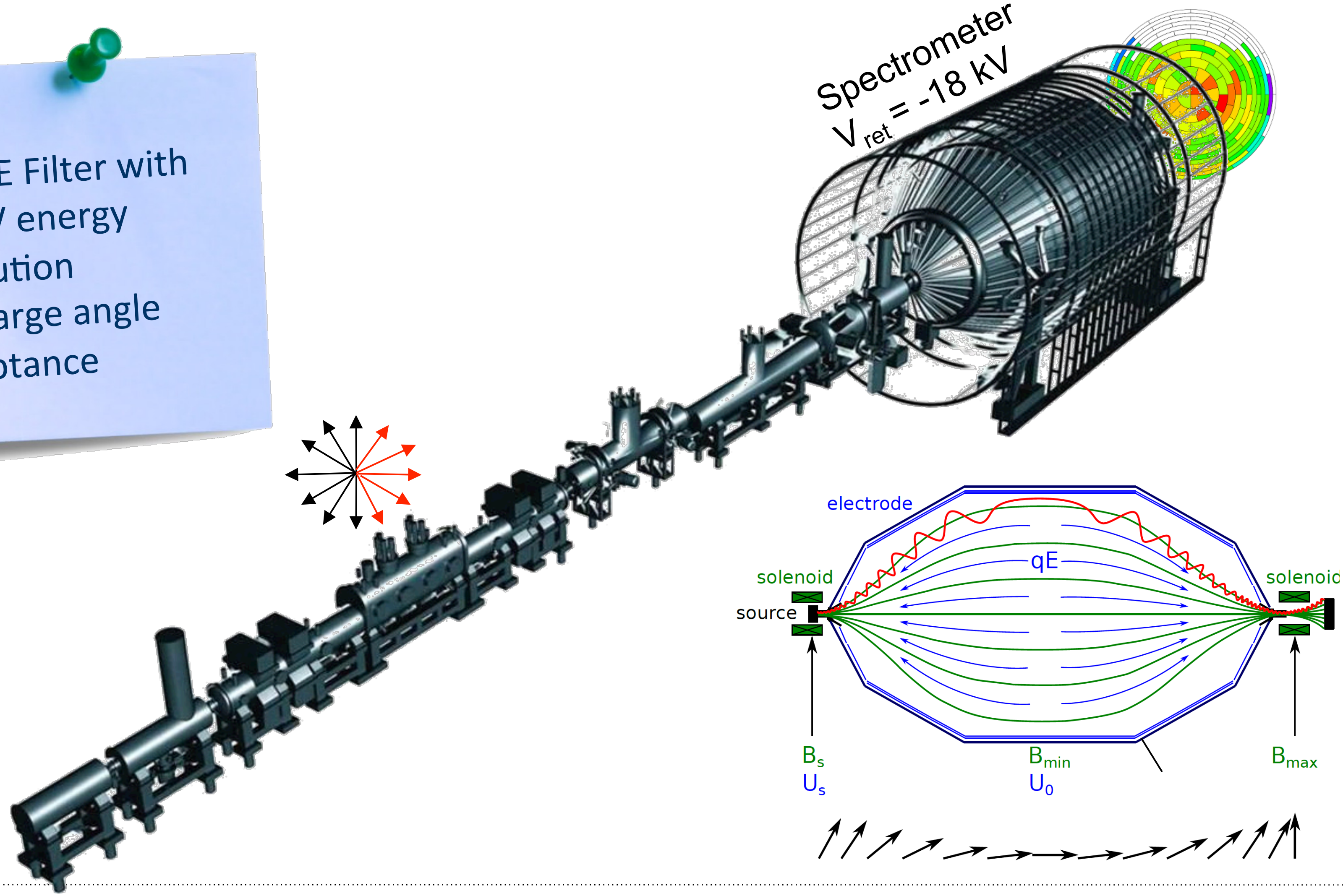
Main spectrometer works as eletrostatic filter



Spectrometer system

KATRIN Overview

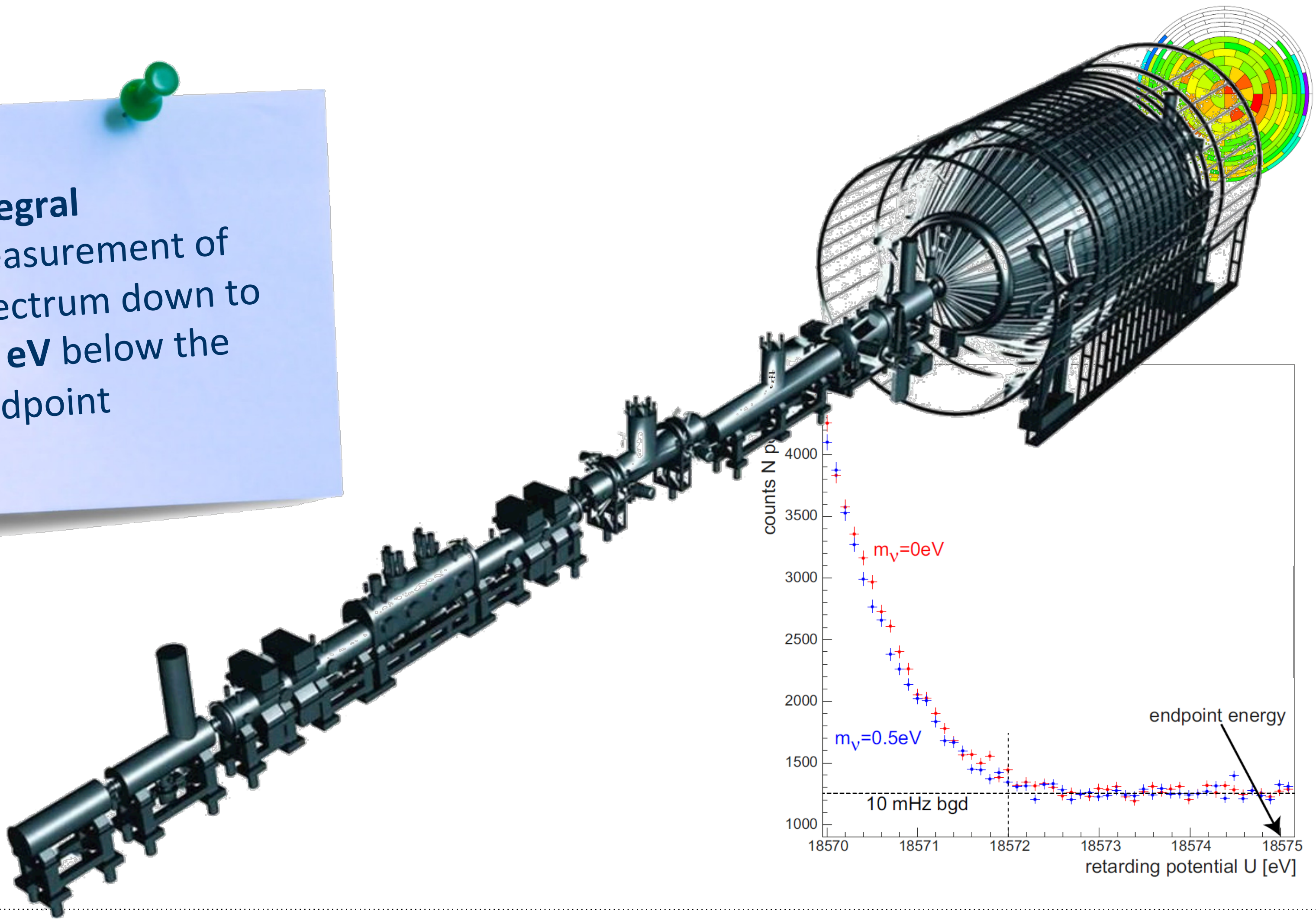
MAC-E Filter with
< 1 eV energy
resolution
and large angle
acceptance



KATRIN Overview

Detector system

Integral measurement of spectrum down to **30 eV** below the endpoint



KATRIN Source Status

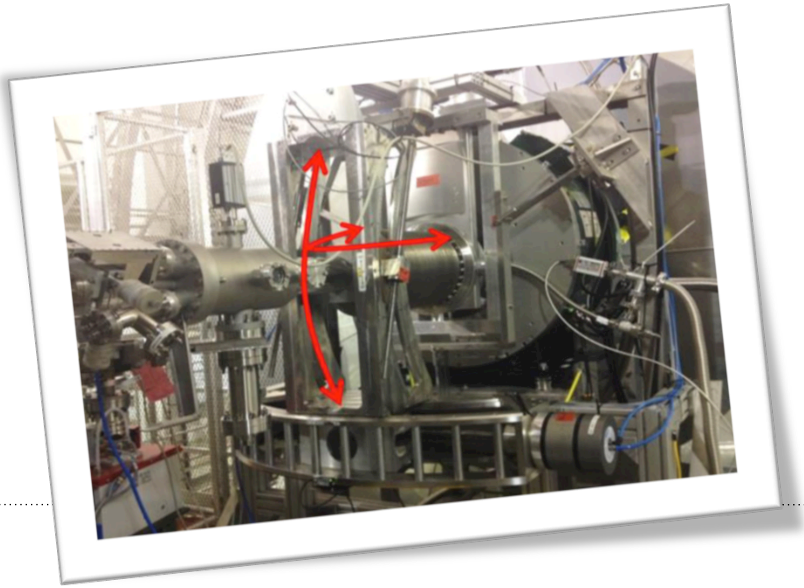

2011:
fully commissioned large
Aircoil system

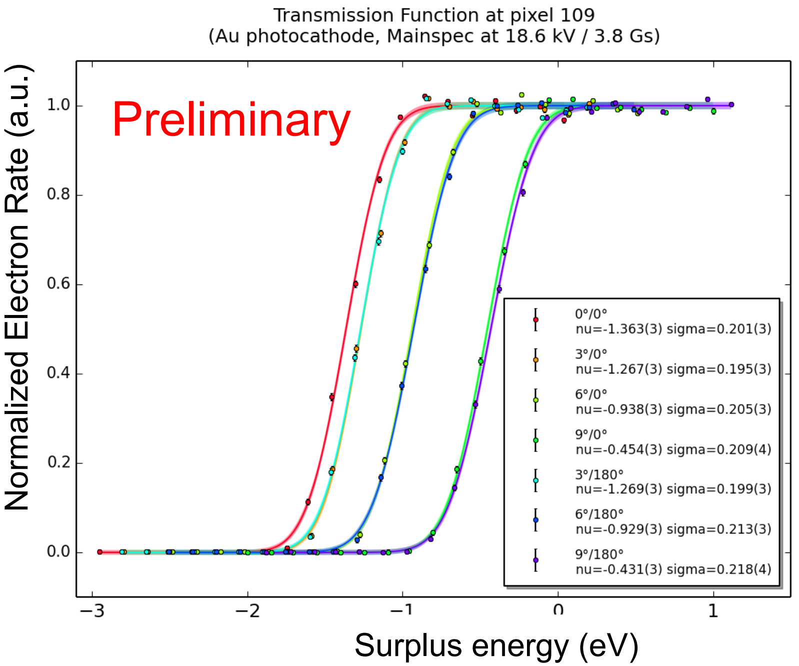

2012:
Inner electrode system
(24.000 wires)
completely mounted
(precision: 200 µm!)

KATRIN Spectrometer Status

2015: 2nd measurement phase completed

- Spectrometer works as MAC-E Filter

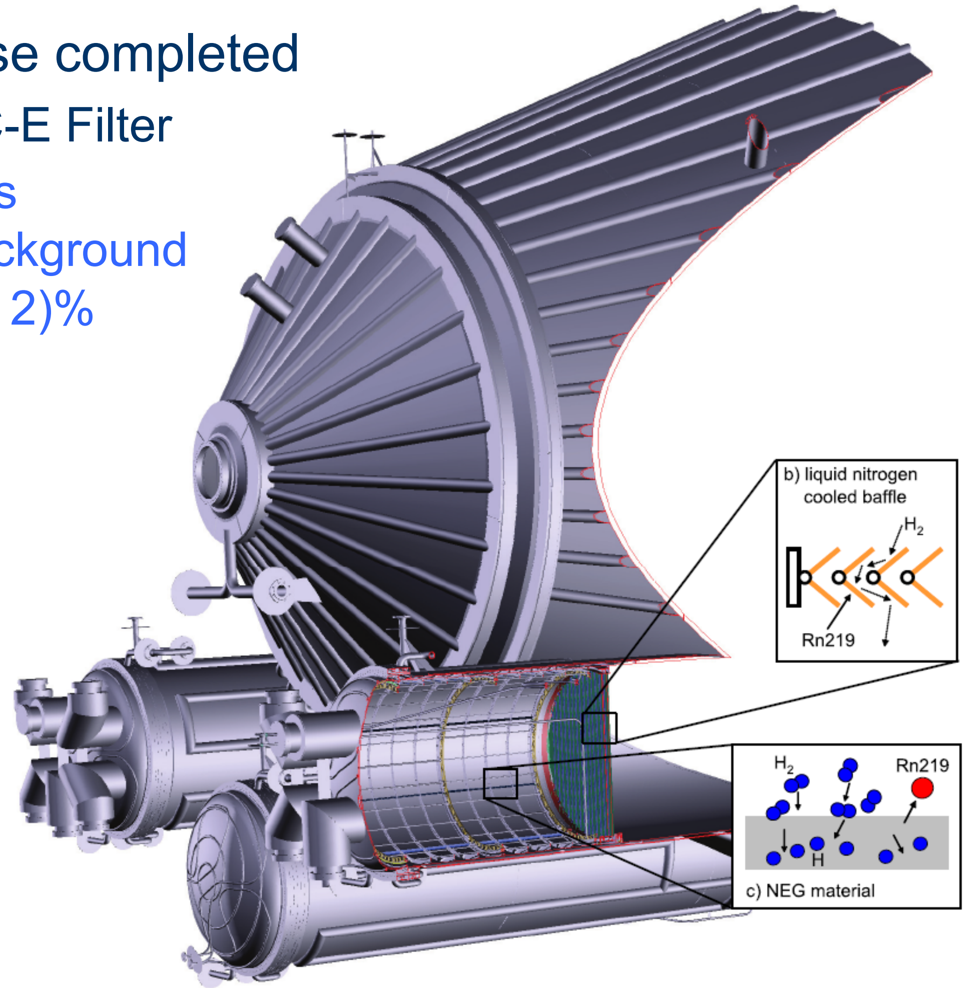




KATRIN Spectrometer Status

2015: 2^{nd} measurement phase completed

- Spectrometer works as MAC-E Filter
- Liquid nitrogen cooled baffles eliminate Radon-induced background with an efficiency of ε = (97± 2)%



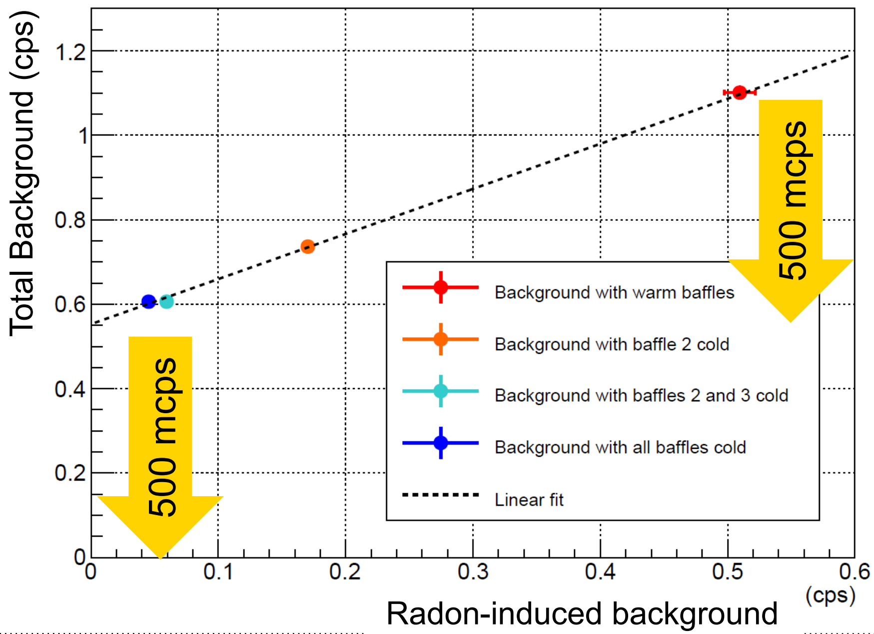
N. Wandkowsky et al., J. Phys. G 40 (2013) 8

S. M. et al., Astropart. Phys. 41 (2013) 52

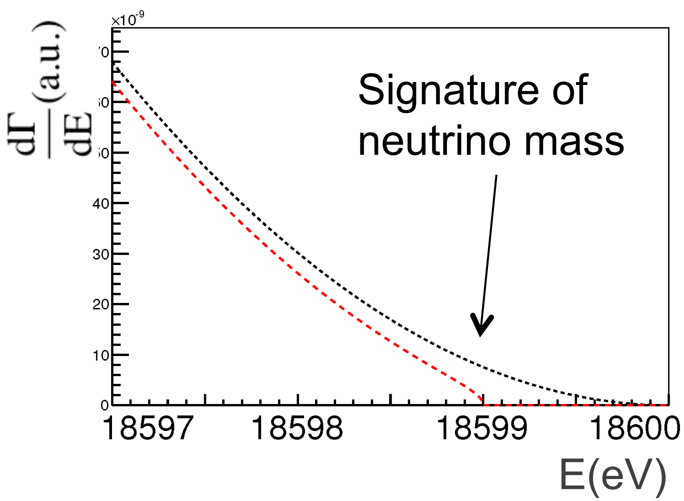
KATRIN Spectrometer Status

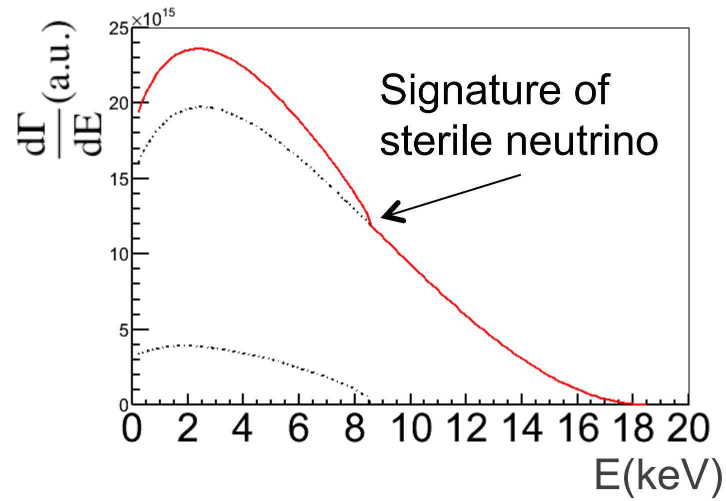
2015: 2nd measurement phase completed

- Spectrometer works as MAC-E Filter
- Liquid nitrogen cooled baffles eliminate Radon-induced background with an efficiency of $\varepsilon = (97 \pm 2)\%$
- Remaining background is still under investigation



KATRIN and sterile neutrinos





keV-Scale Sterile Neutrinos

Sterile Neutrinos in the keV mass range are a prime candidate for both Warm and Cold Dark Matter

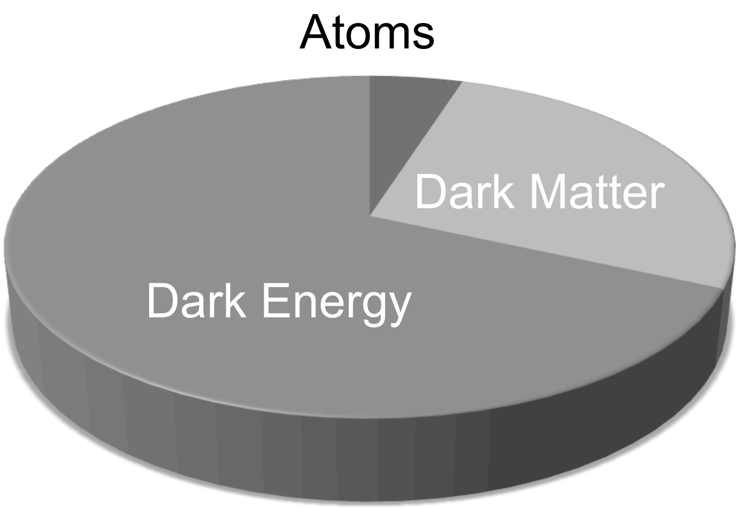
In agreement with cosmological observations from small to large scales

X. Shi, G. M. Fuller 1999 *PRL* **82**

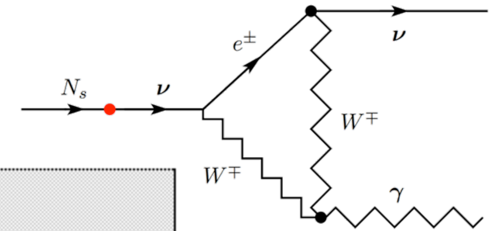
Recent indirect hint from satellite experiments ?

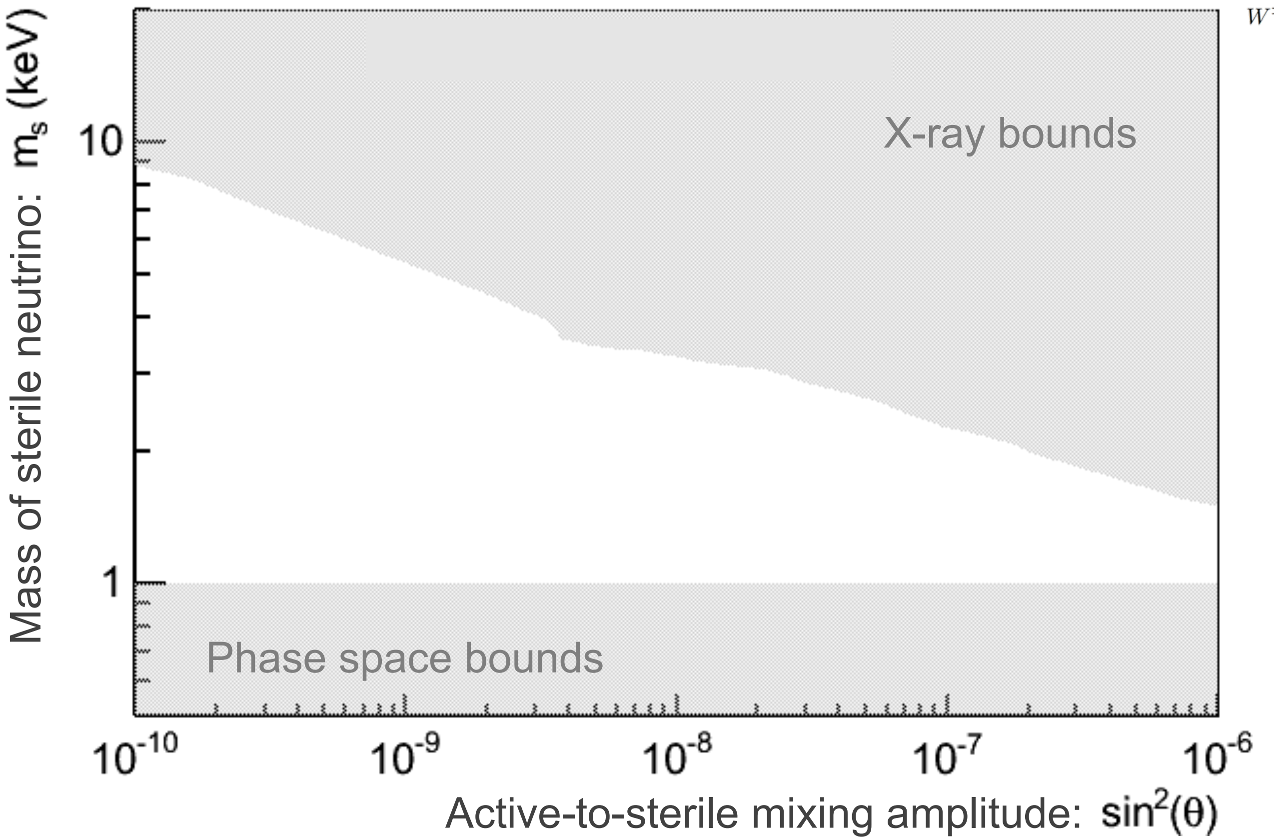
E. Bulbul *et al.* 2014 *ApJ* **789**

Boyarsky *et al.* 2014 *PRL* **113**



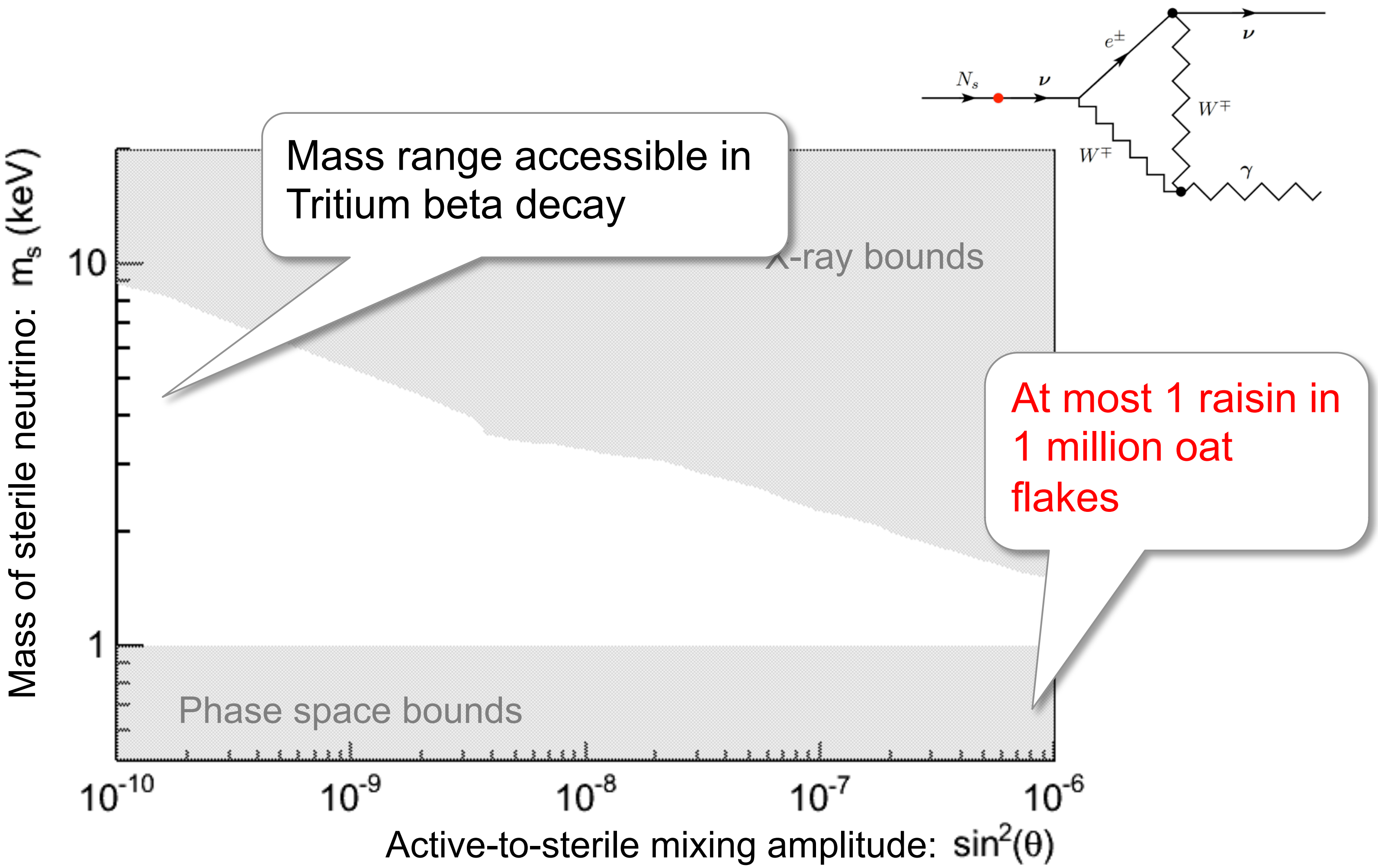
Cosmological constraints





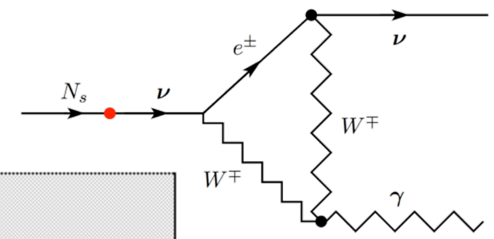
O. Ruchayskiy, A. Ivashko
JHEP **1206** (2012) 100

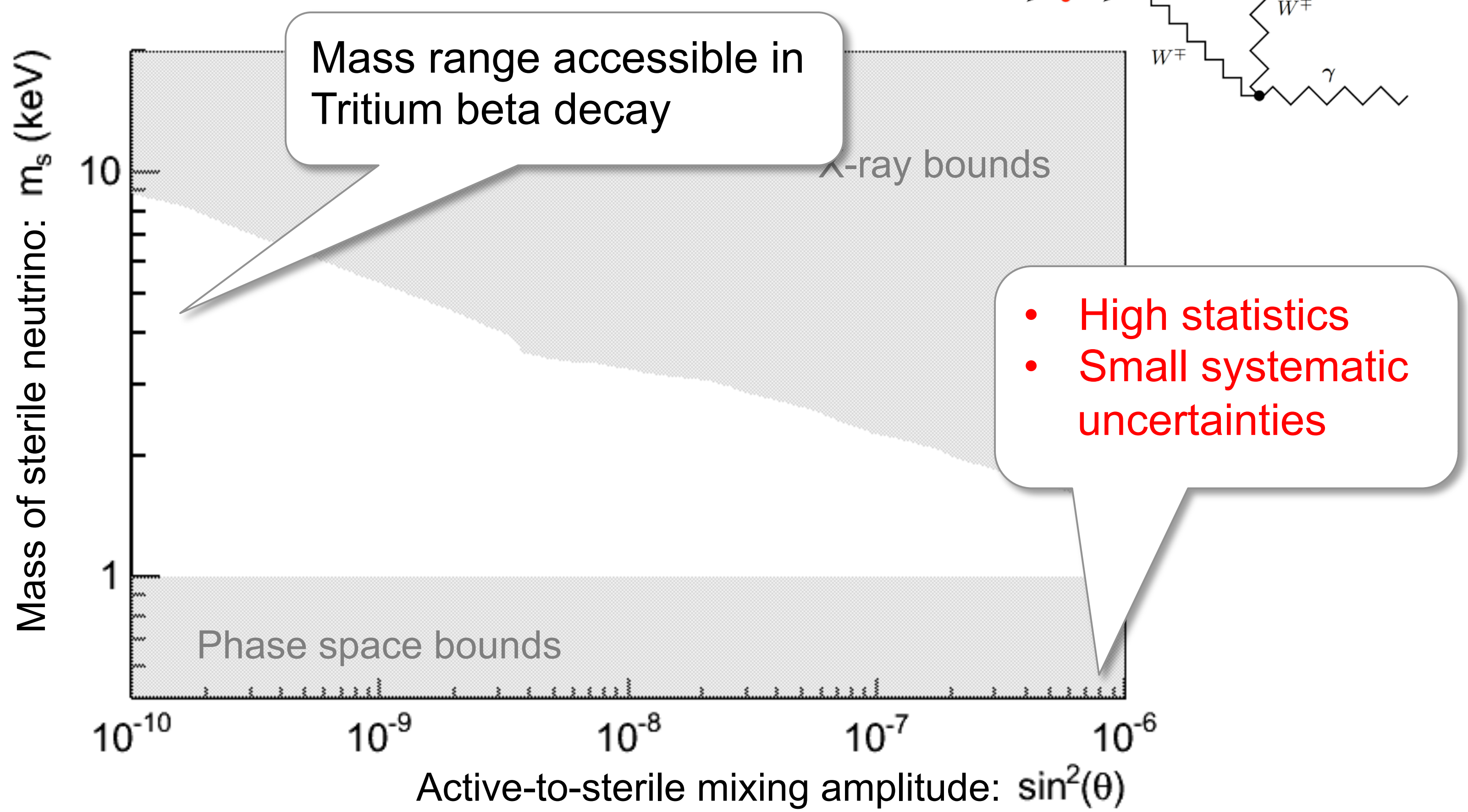
Cosmological constraints



O. Ruchayskiy, A. Ivashko
JHEP **1206** (2012) 100

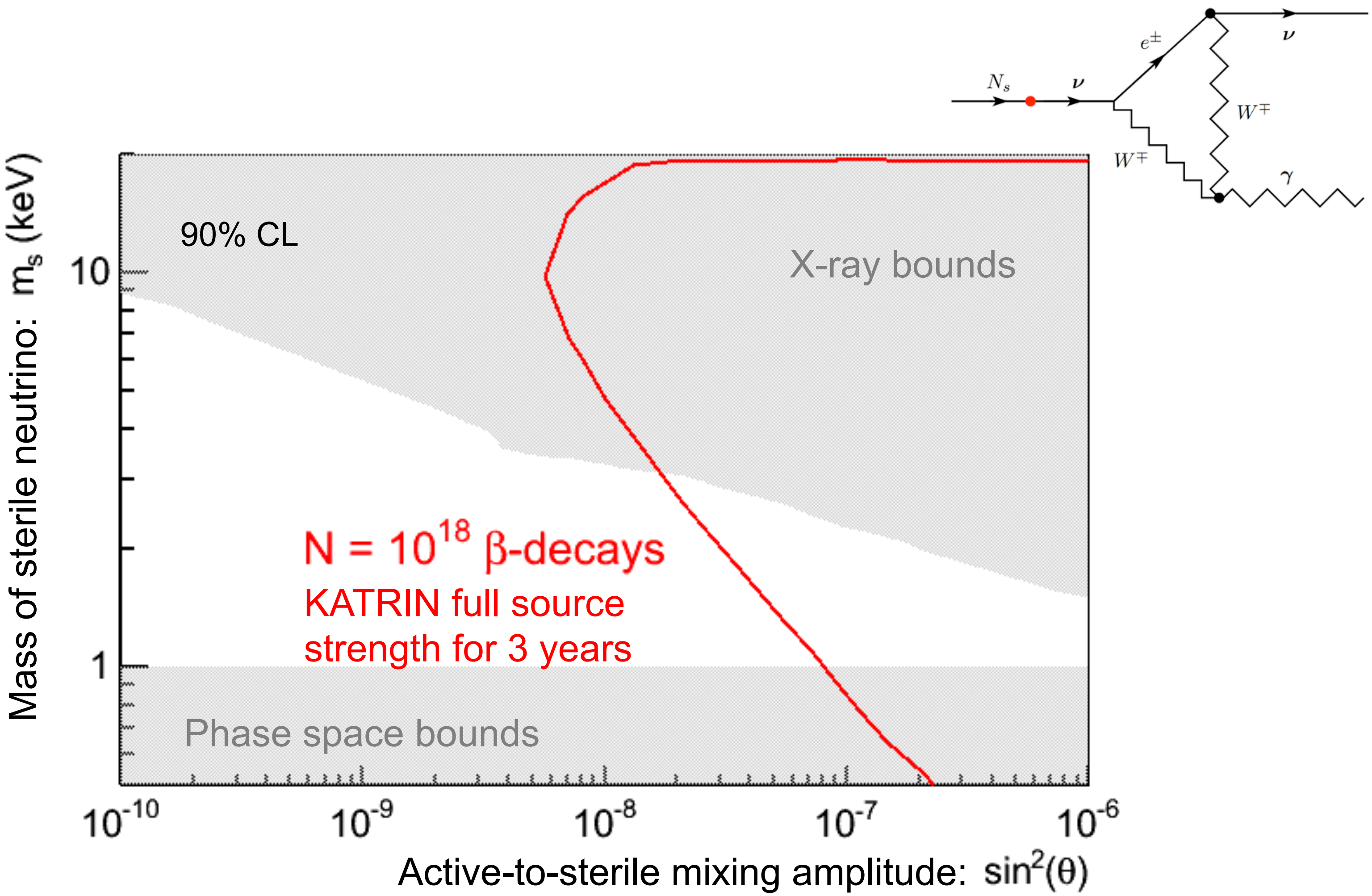
The challenge of sterile ν search





O. Ruchayskiy, A. Ivashko
JHEP **1206** (2012) 100

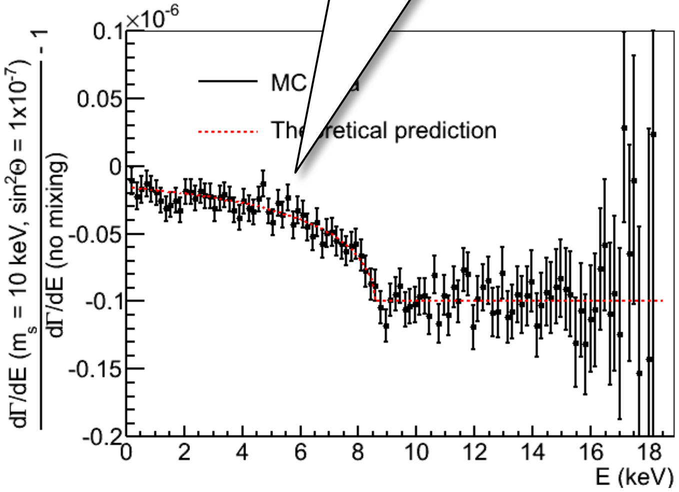
Statistical sensitivity



Systematic uncertainties

1. Spectral Fit Approach
2. Wavelet Approach
3. Covariance Matrix Approach

Idea:
Parametrize uncertainties and let these parameters free in the fit, to allow them to mimic a keV neutrino signature



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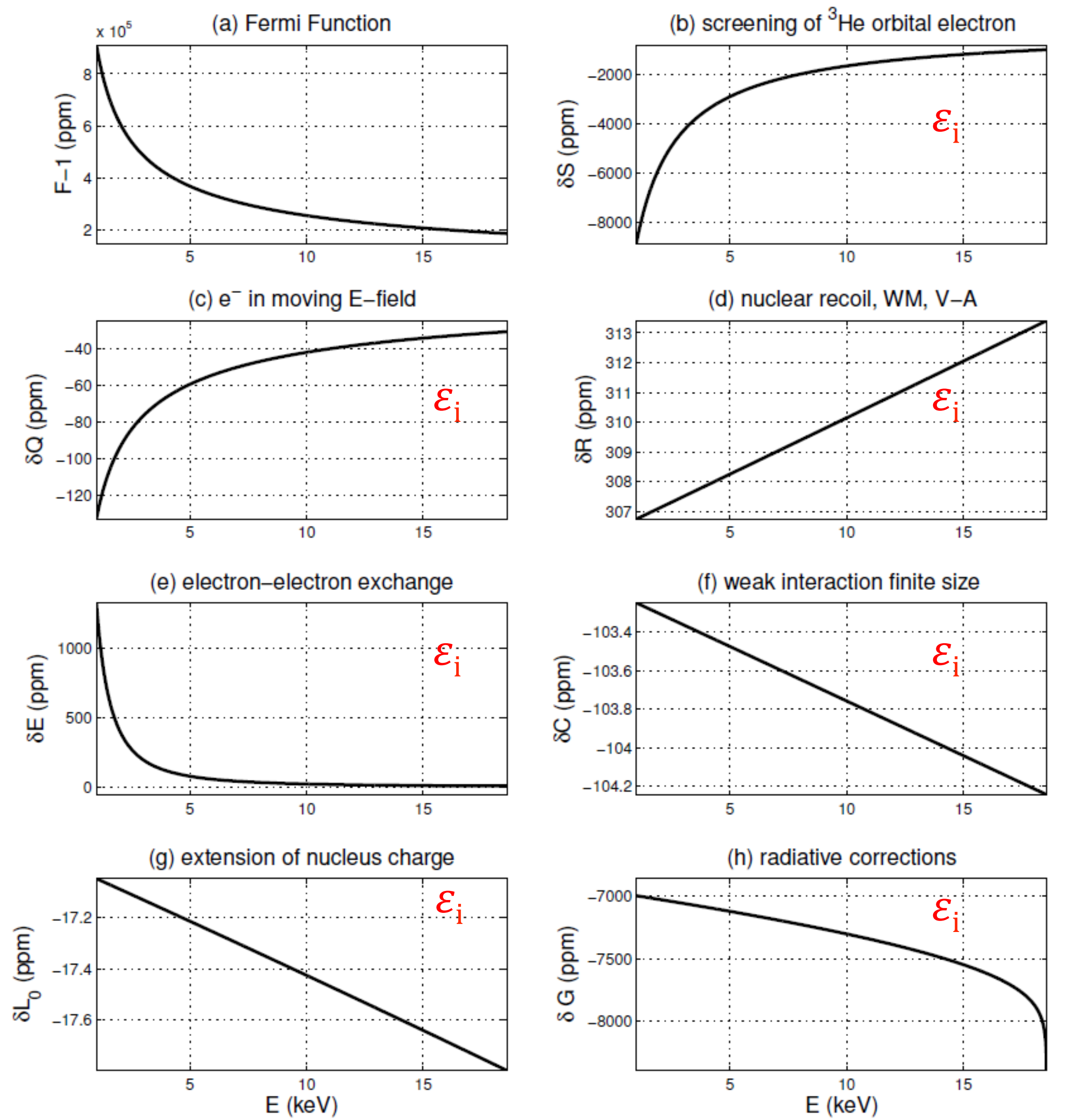
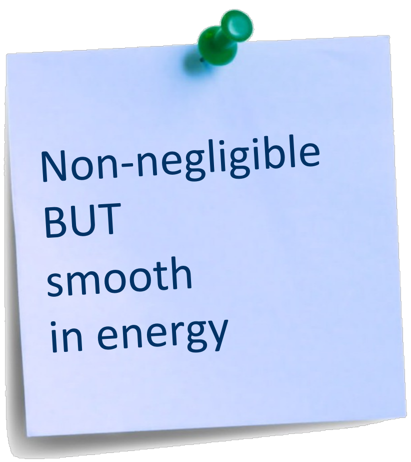
Theoretical corrections to the β-spectrum



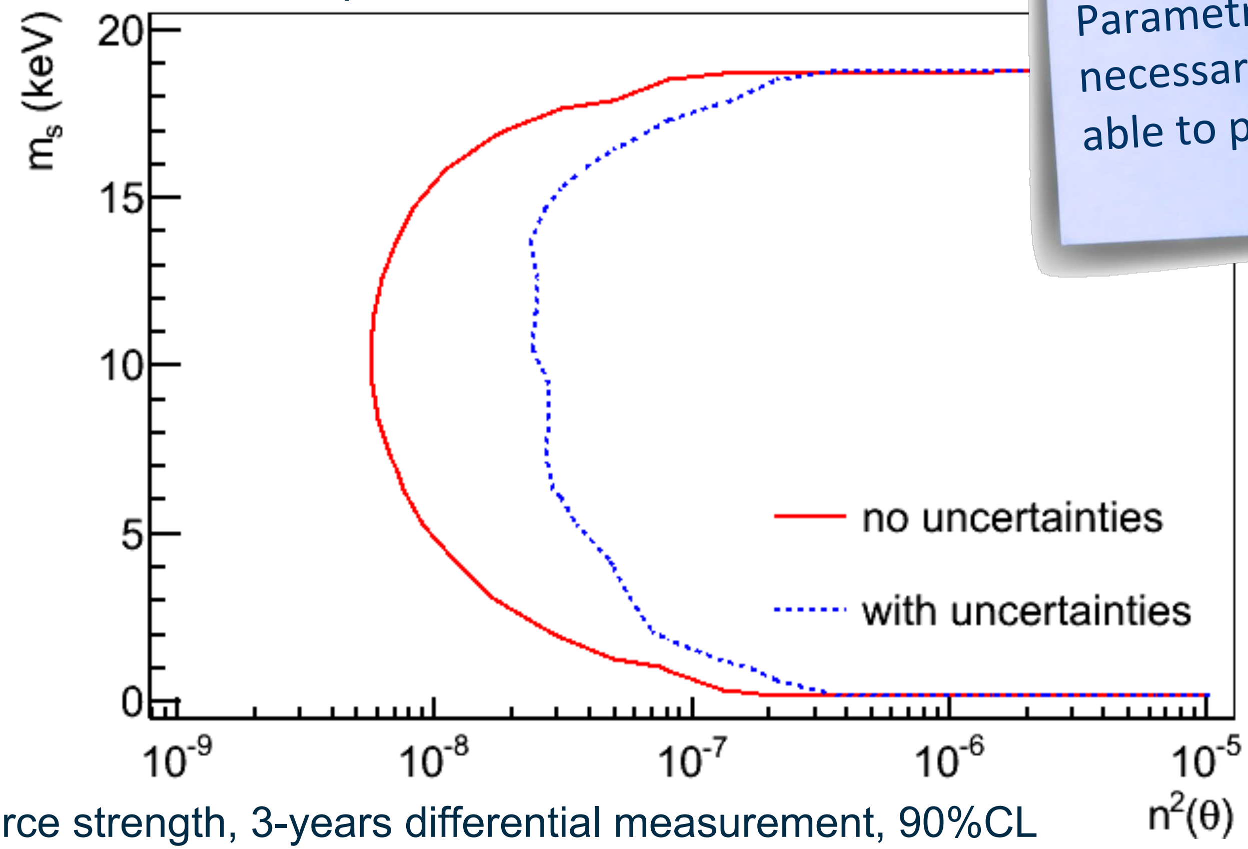


Spectral Fit Approach

Smooth corrections do not fake a kink signal $\sin^2(\theta)>10^{-7}$

Parametrization is necessary in order to be able to perform a fit

12 free parameter fit



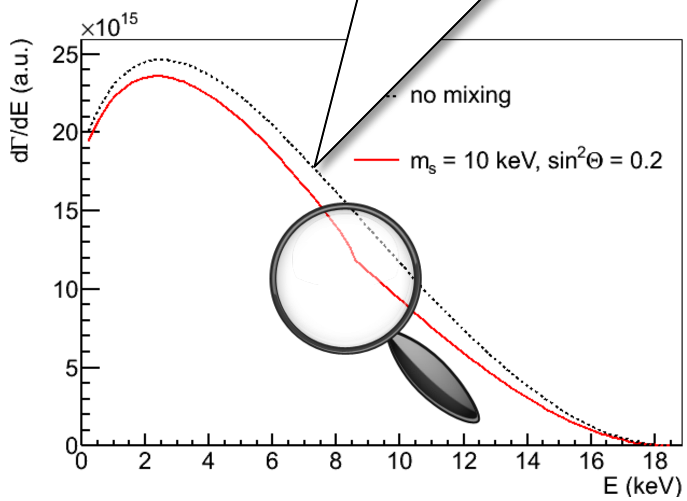
KATRIN source strength, 3-years differential measurement, 90%CL

S. M. *et al.* JCAP 1502 (2015) 02, 020, arXiv:1409.0920

Systematic uncertainties

1. Spectral Fit Approach
2. Wavelet Approach
3. Covariance Matrix Approach

Idea:
Use wavelet transformation to detect „kink“ feature in the spectrum, in order to be be insensitive to the exact knowledge of the true spectrum

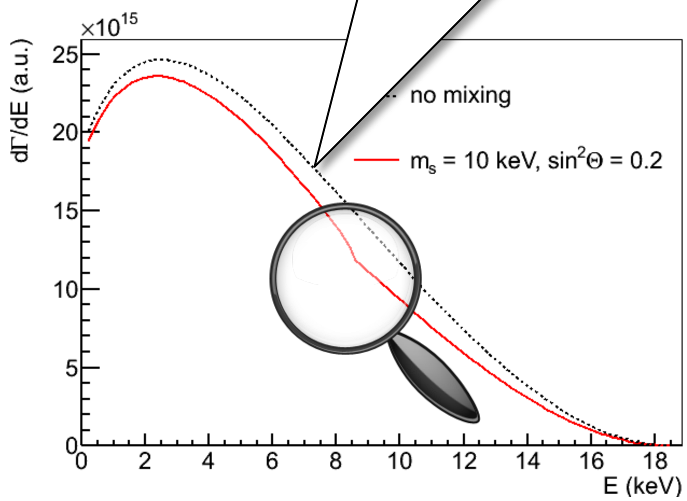


Systematic uncertainties

1. Spectral Fit Approach
2. Wavelet Approach
3. Covariance Matrix Approach

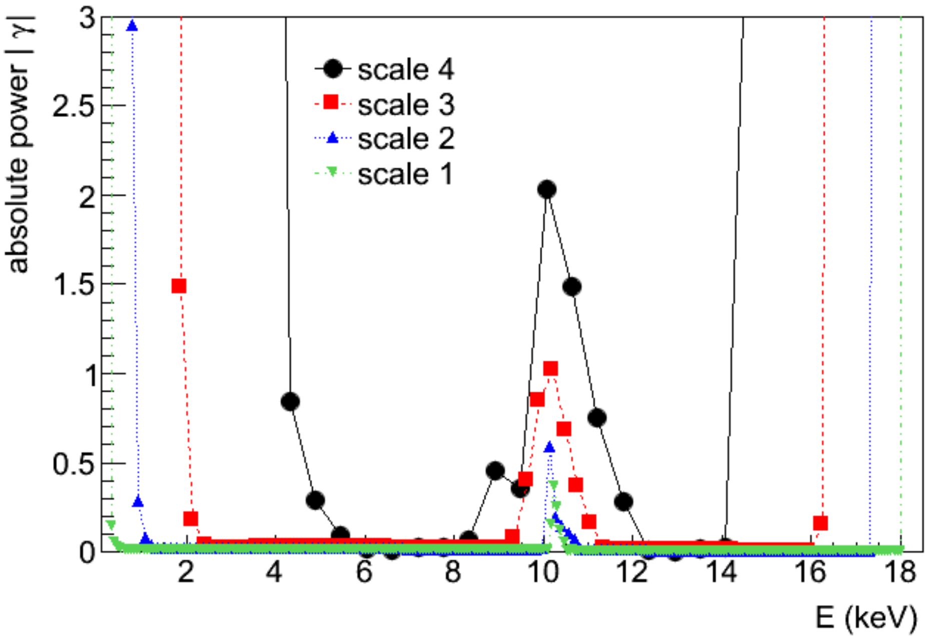
Wavelet Transformation:

Which frequency is present in the signal at which energy?

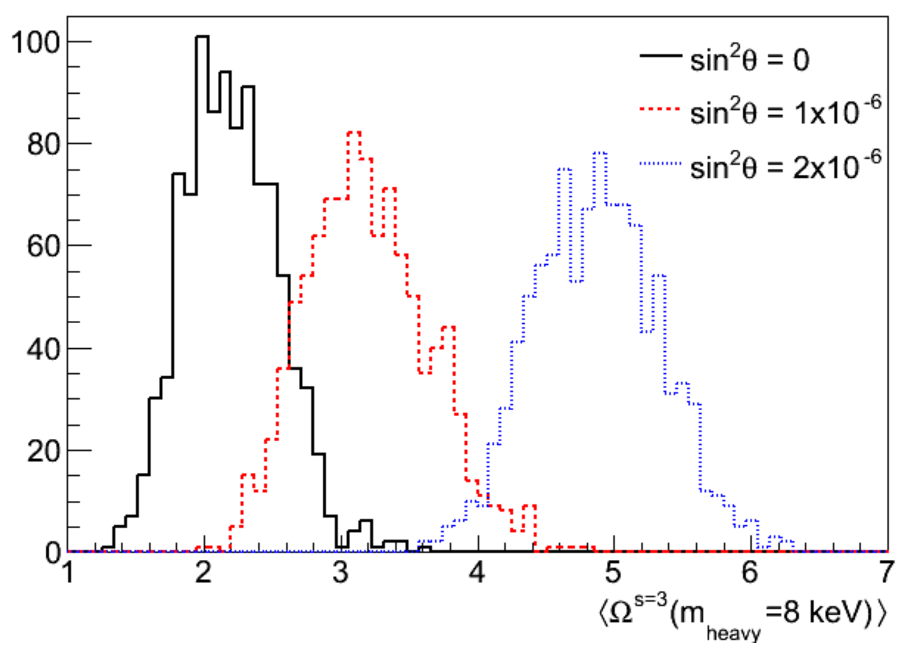


Wavelet Approach

Wavelet transformation of tritium spectrum

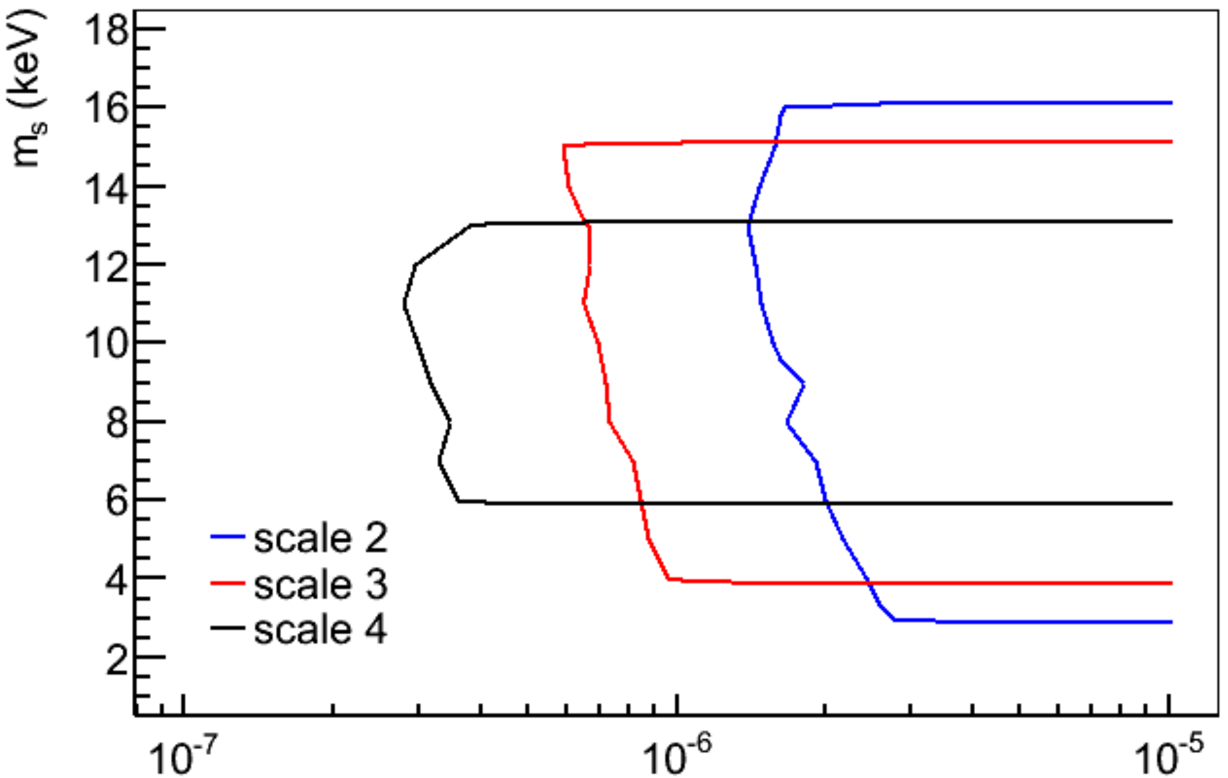


Discrimination power of wavelet technique



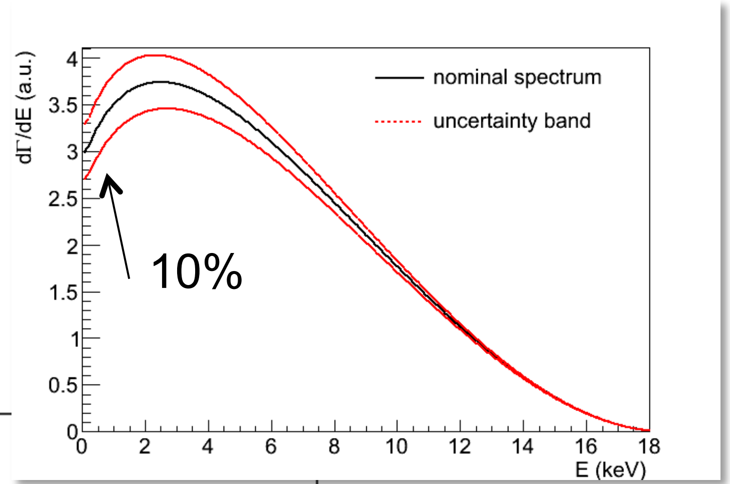
~ Sum of power values in scale 3

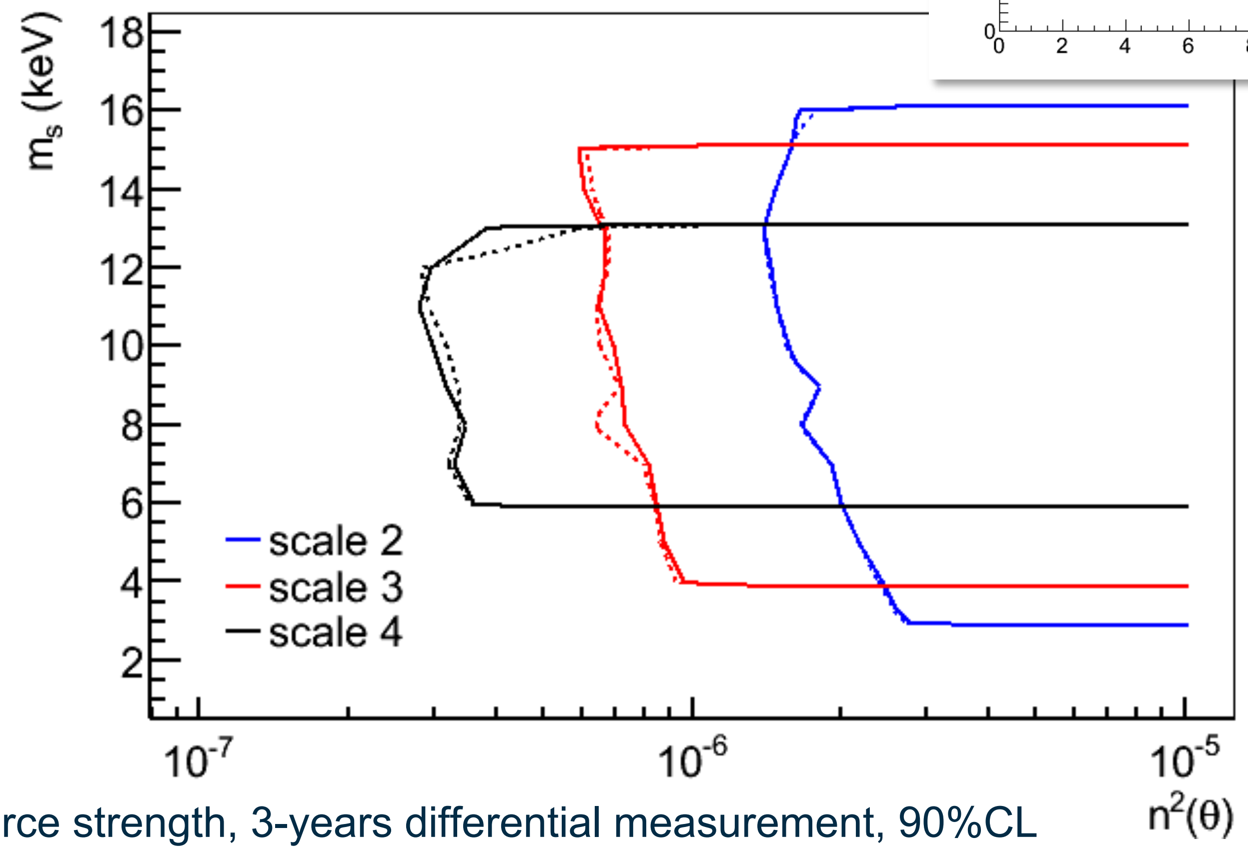
Wavelet Approach



KATRIN source strength, 3-years differential measurement, 90%CL

Wavelet Approach





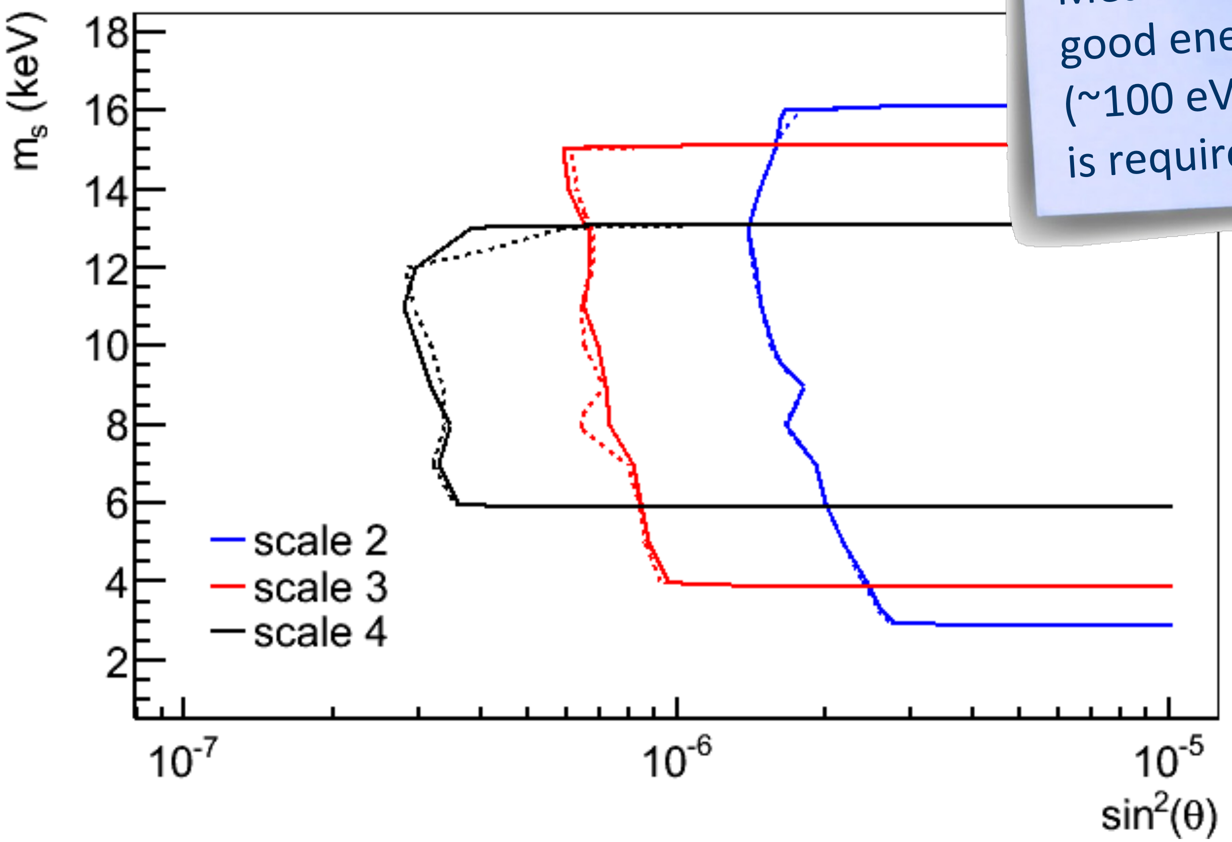
KATRIN source strength, 3-years differential measurement, 90%CL

S. M. *et. al.* Phys.Rev. D91 (2015) 4, 042005,
arXiv:1410.7684

Wavelet Approach

Kink search independent of exact shape

Measurement with good energy resolution (~100 eV FWHM) is required



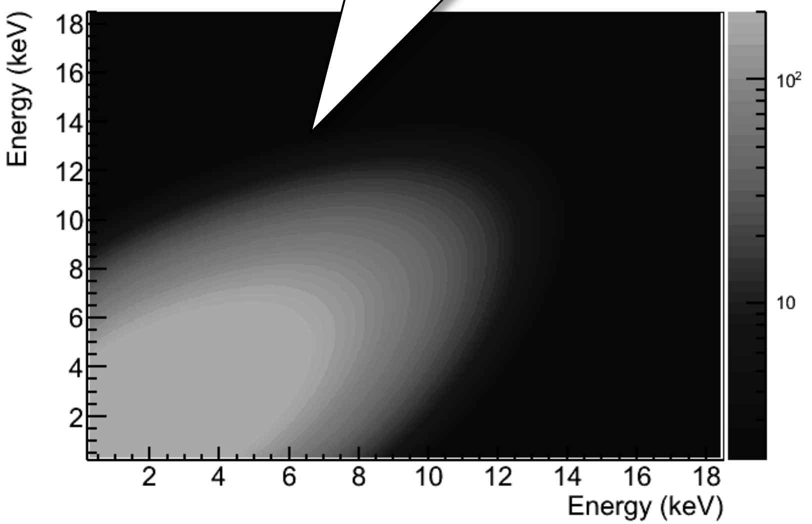
KATRIN source strength, 3-years differential measurement, 90%CL

Systematic uncertainties

1. Spectral Fit Approach
2. Wavelet Approach
3. Covariance Matrix Approach

Idea:

Construct realistic covariance matrix to investigate experimental uncertainties in a conceptual way.



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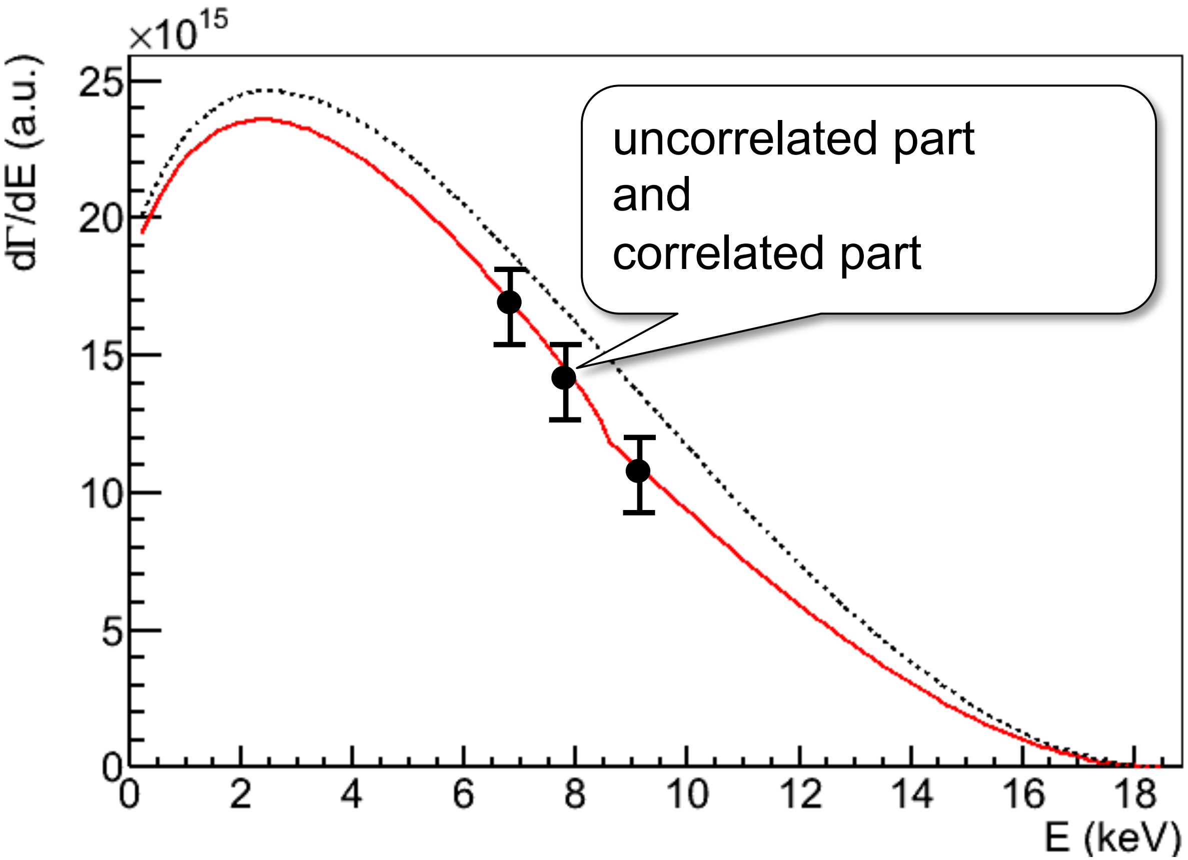
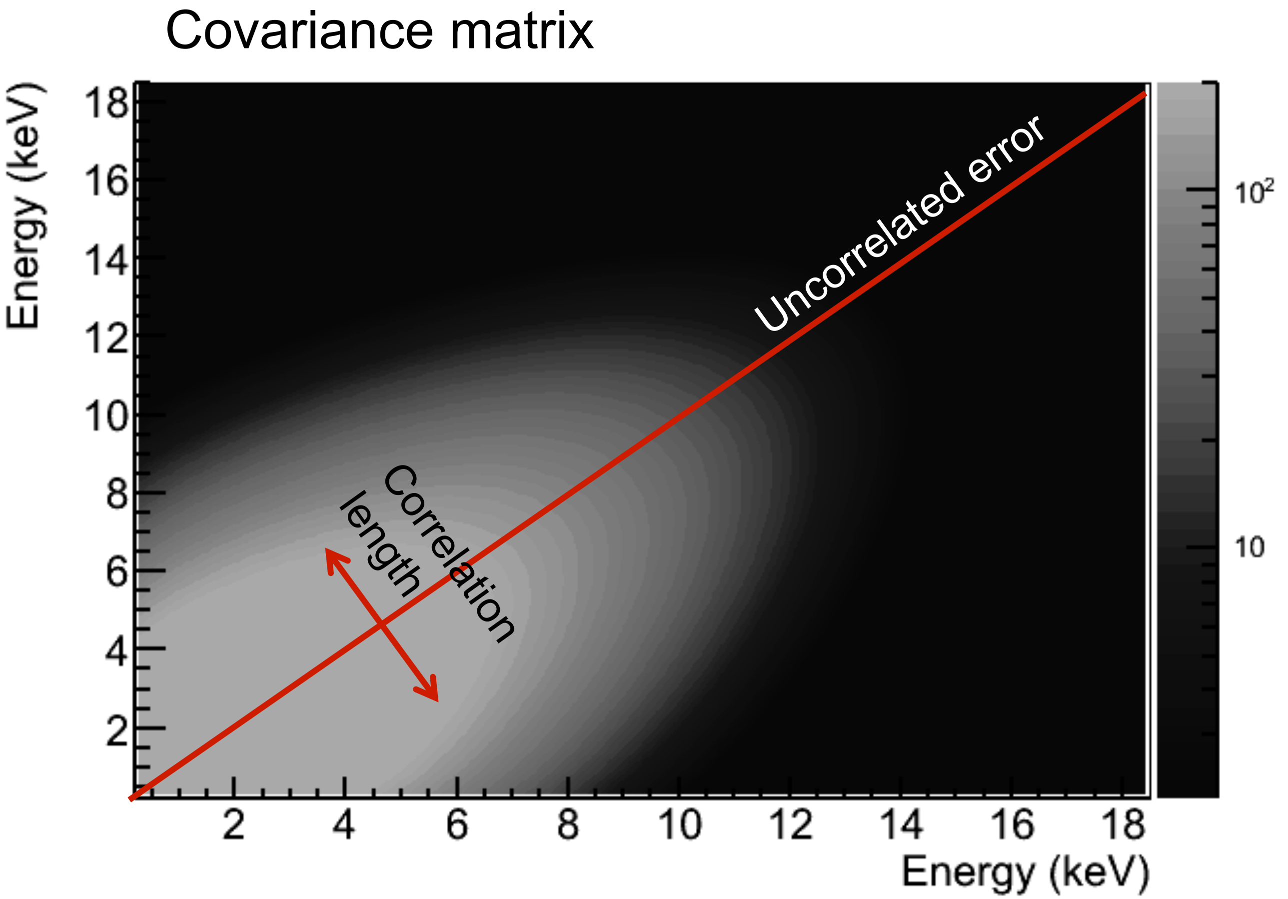
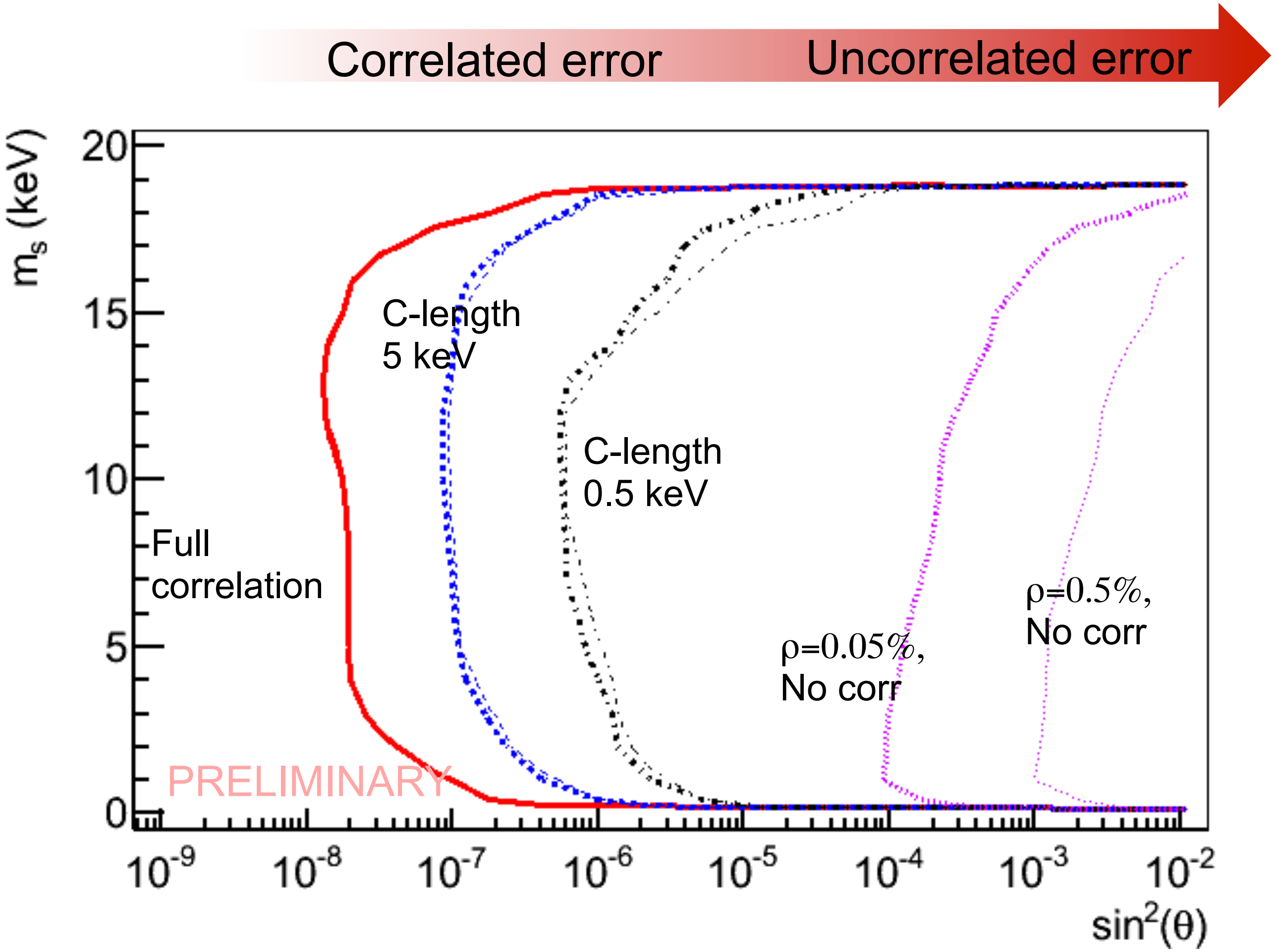
Experimental uncertainties



Experimental uncertainties

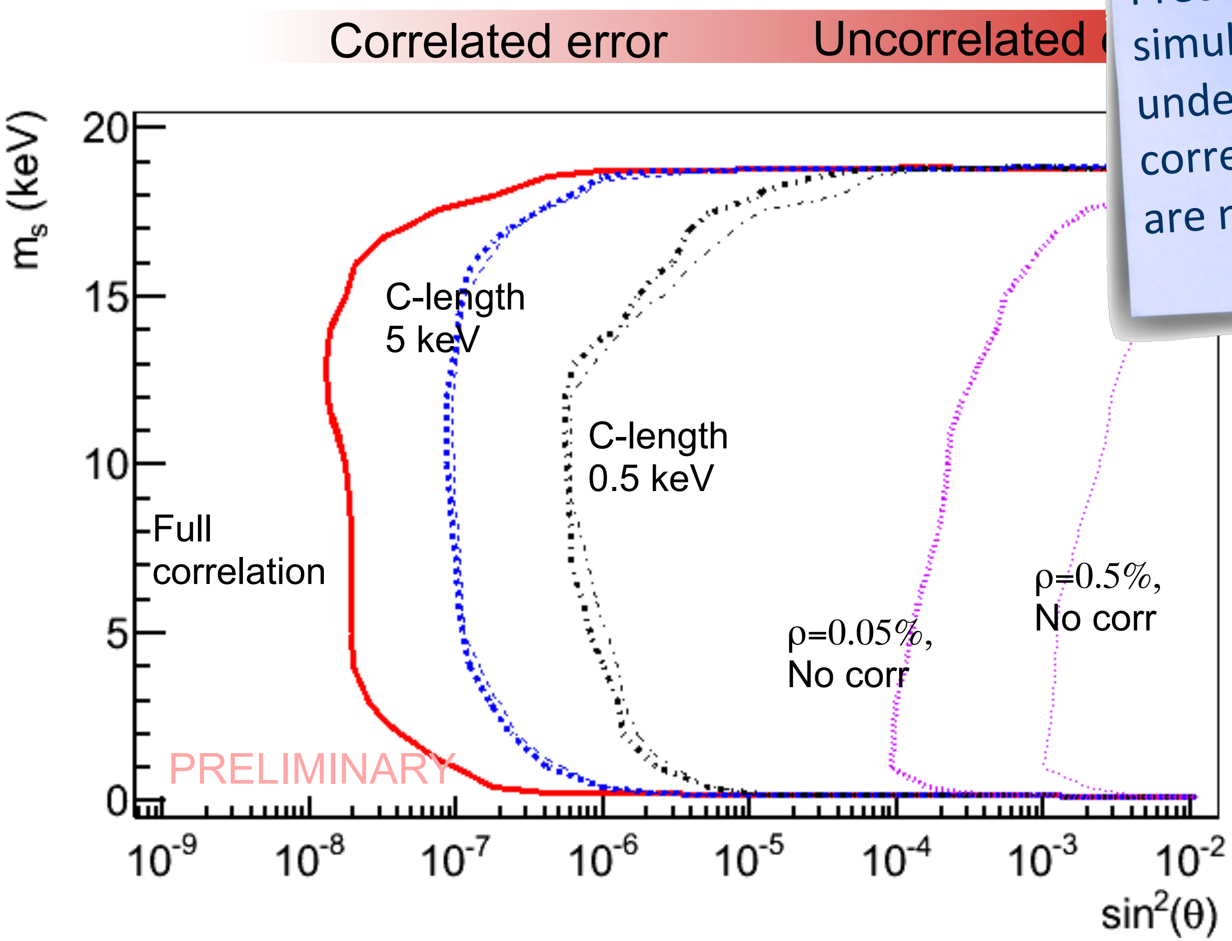


Experimental uncertainties



KATRIN source strength, 3 years differential measurement, 90% CL

Experimental uncertainties



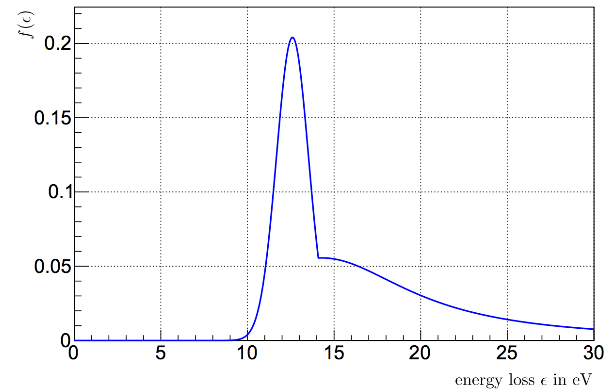
Precise calibrations, simulations, and understanding of correlations are needed

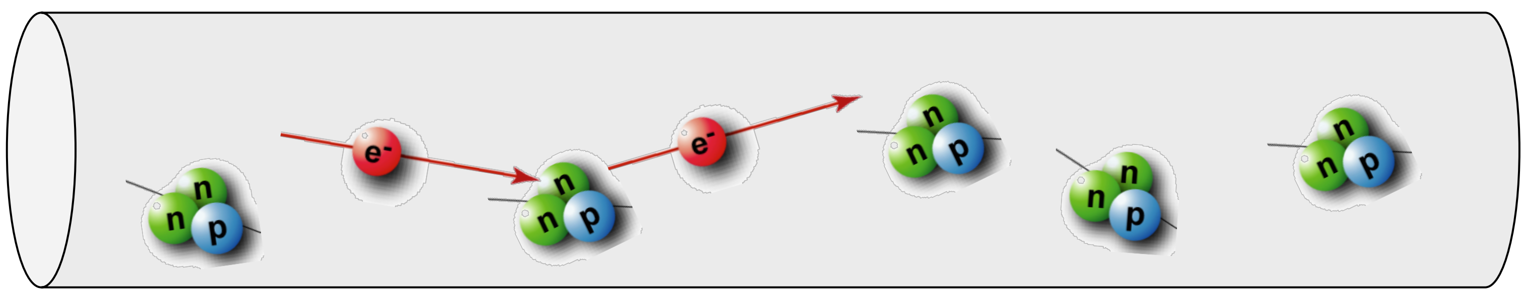
KATRIN source strength, 3 years differential measurement, 90% CL

Ongoing sensitivity studies

Systematic effects related to :

- Source Section
  - scattered electrons arrive at detector

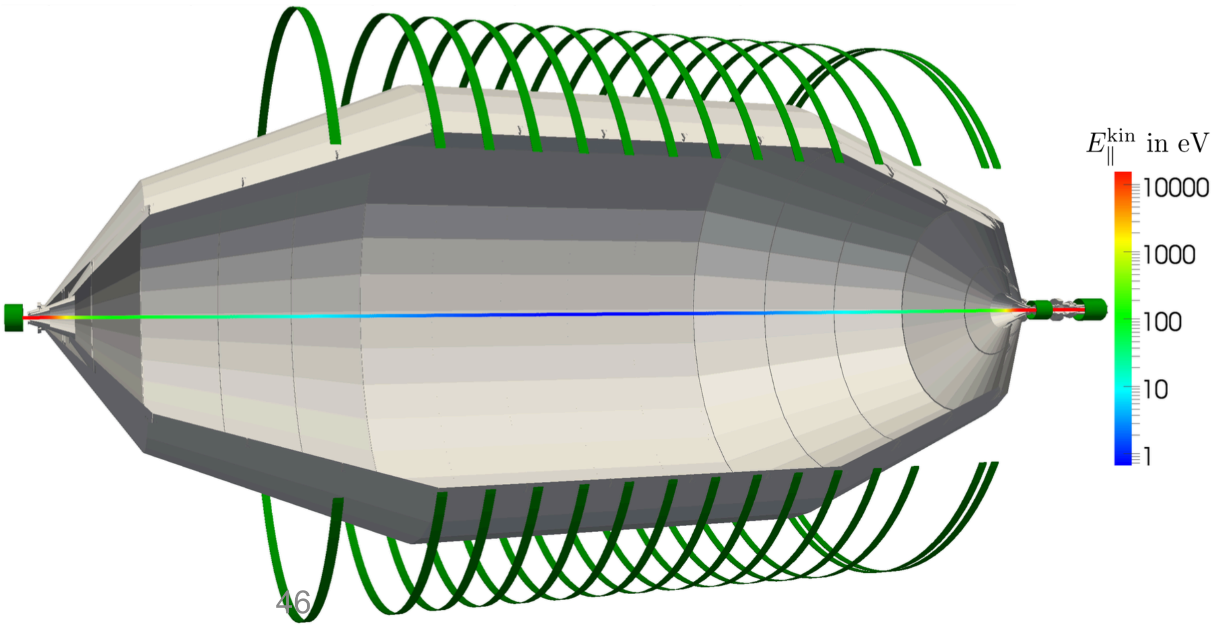




Ongoing sensitivity studies

Systematic effects related to :

- Source Section
  - scattered electrons arrive at detector
- Spectrometer Section
  - electrons pass through spectrometer with high surplus energy



Ongoing sensitivity studies

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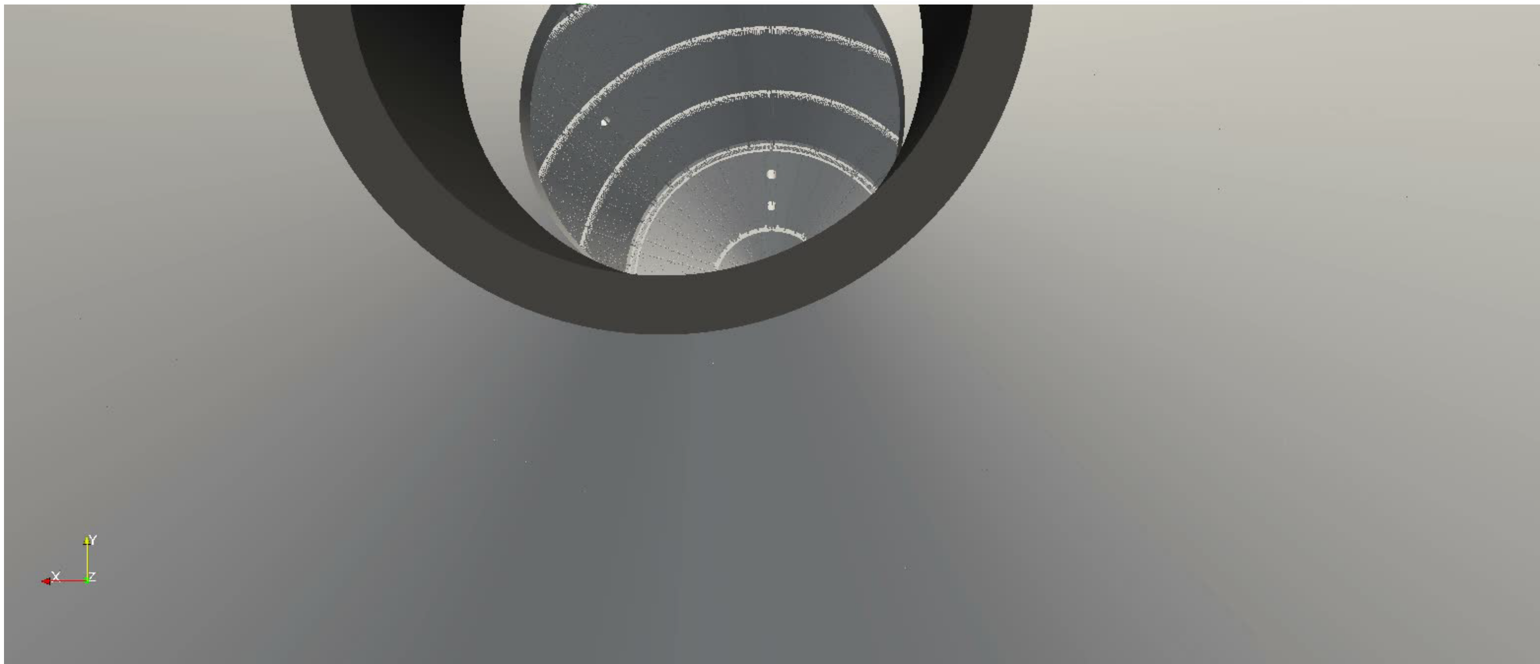
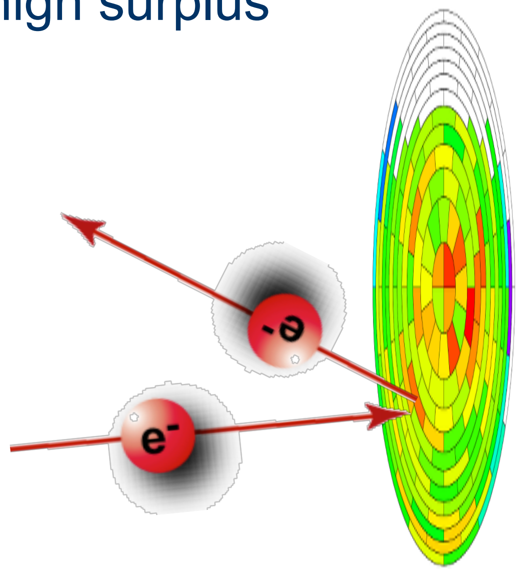


Ongoing sensitivity studies

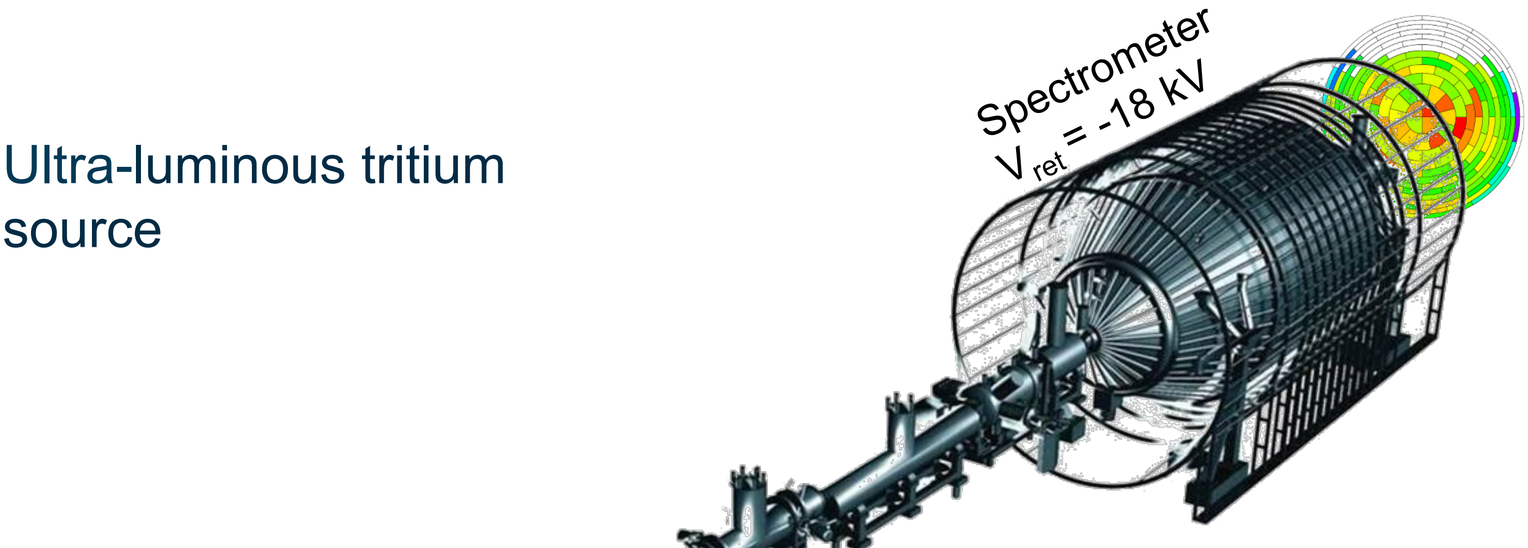
Systematic effects related to :

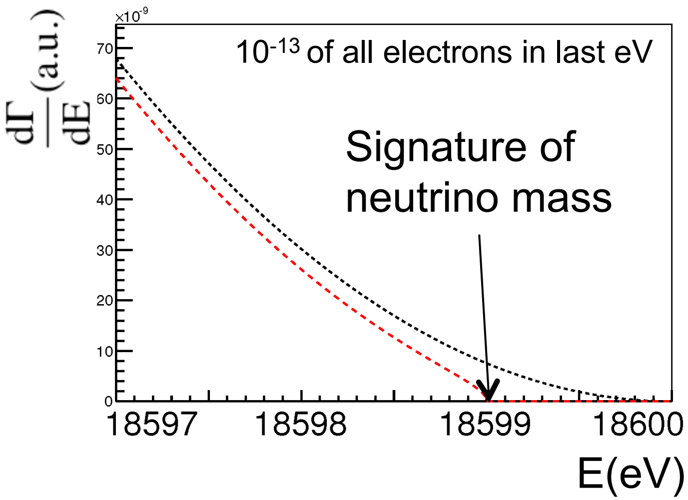
- Source Section
  - scattered electrons arrive at detector
- Spectrometer Section
  - electrons pass through spectrometer with high surplus energy
- Detector Section
  - Backscattering
  - Charge sharing
  - Pile-up
  - Etc.



Technical Realization

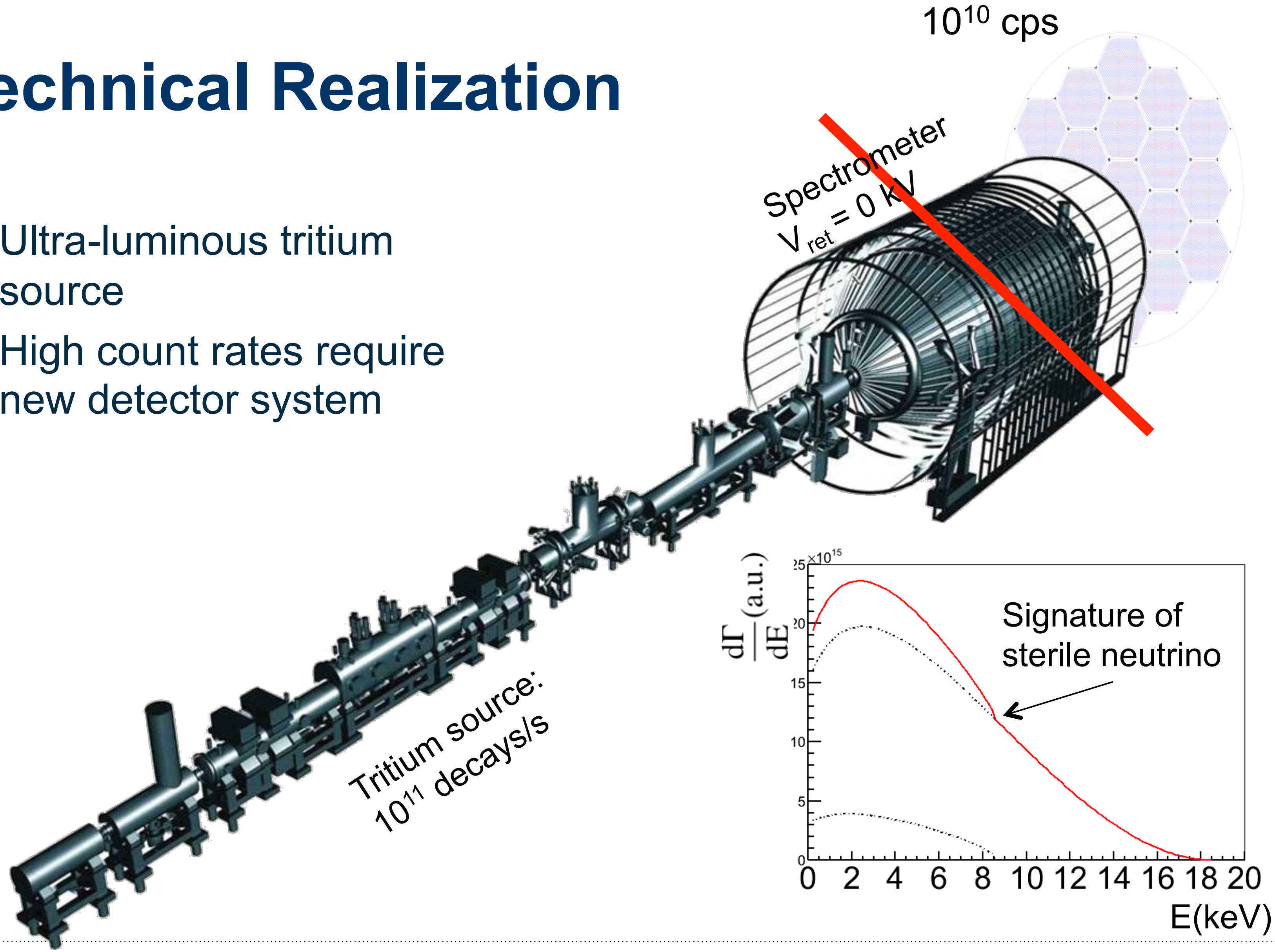
- Ultra-luminous tritium source



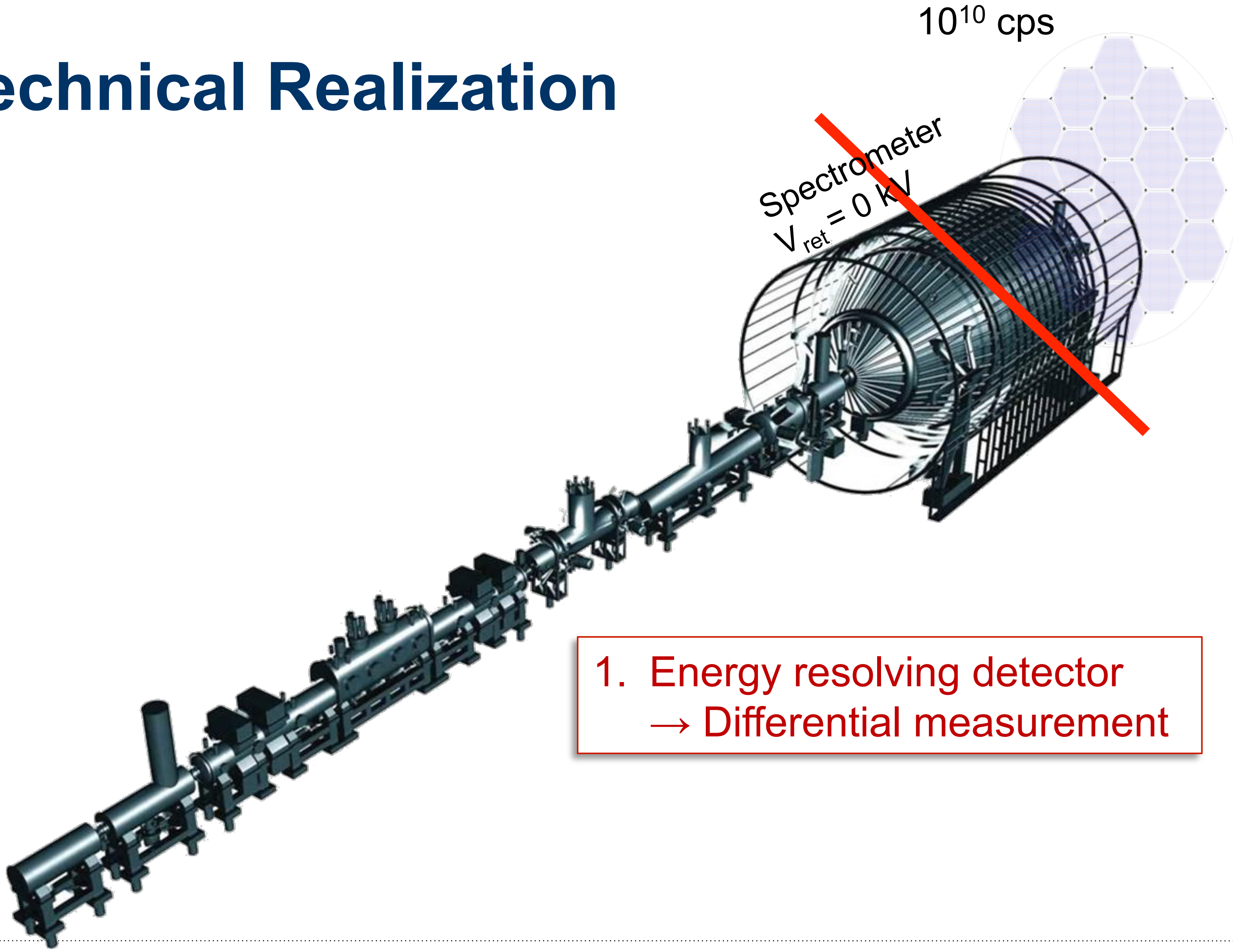


Technical Realization

- Ultra-luminous tritium source
- High count rates require new detector system

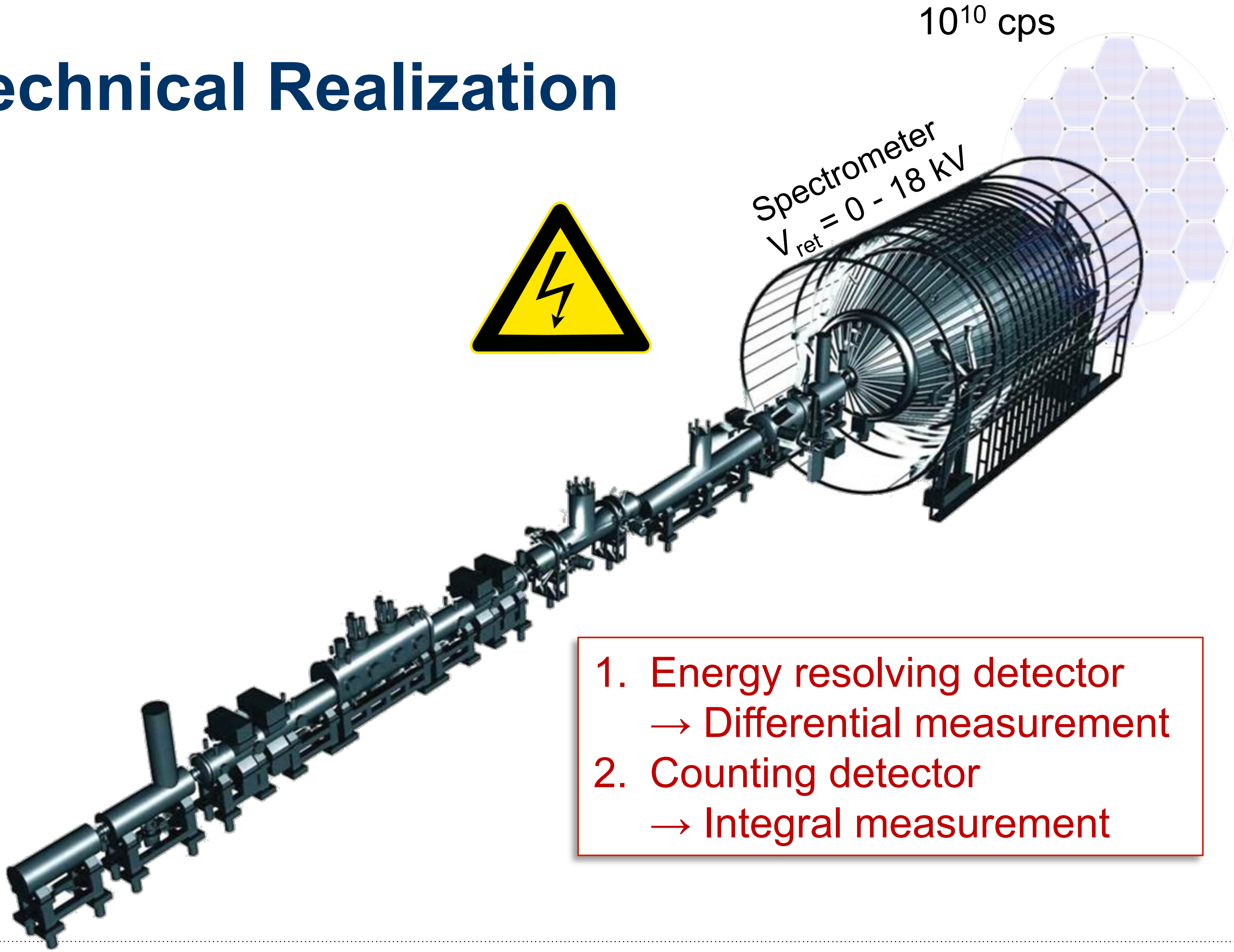


Technical Realization



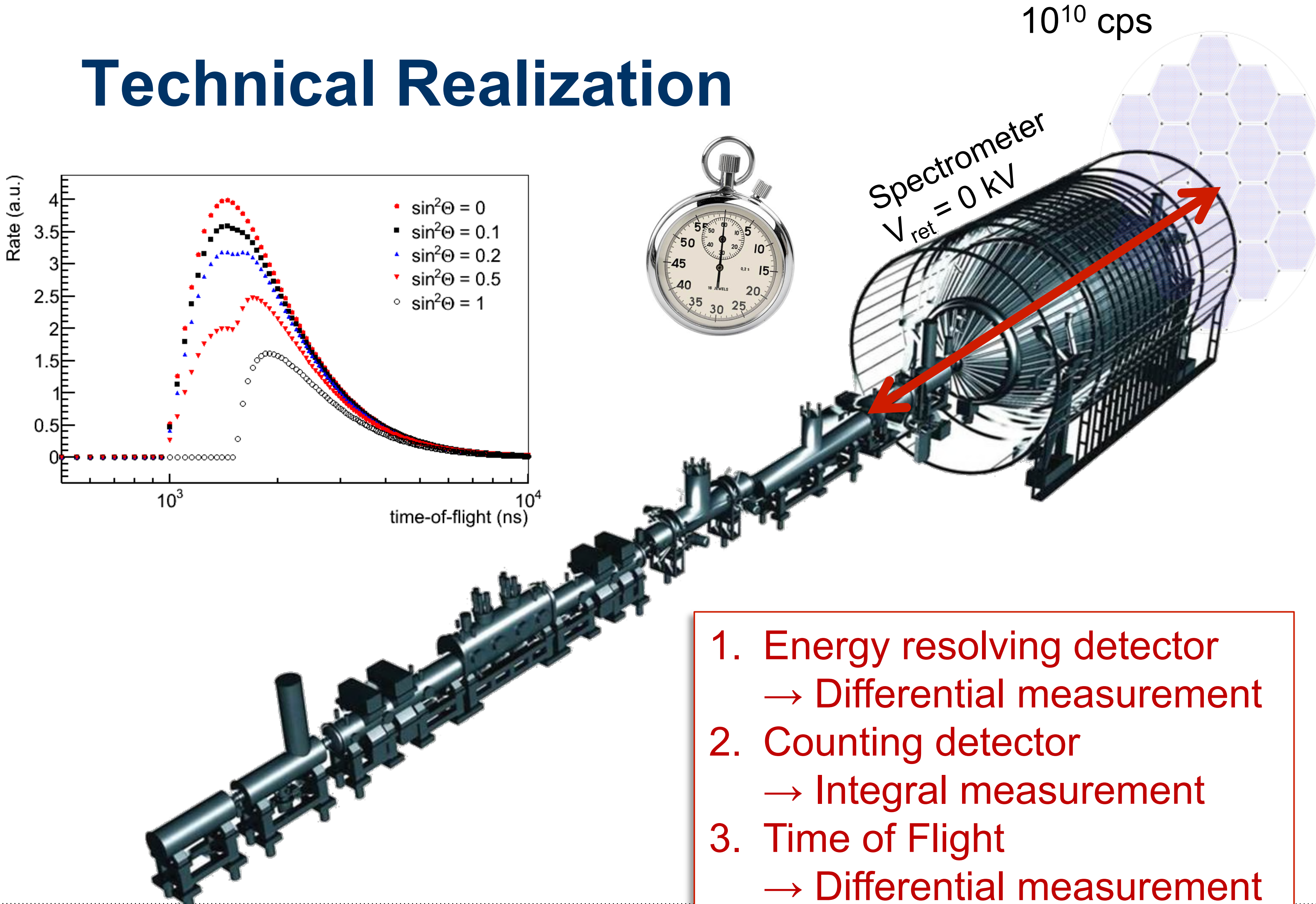
1. Energy resolving detector
   → Differential measurement

Technical Realization



1. Energy resolving detector
   → Differential measurement
2. Counting detector
   → Integral measurement

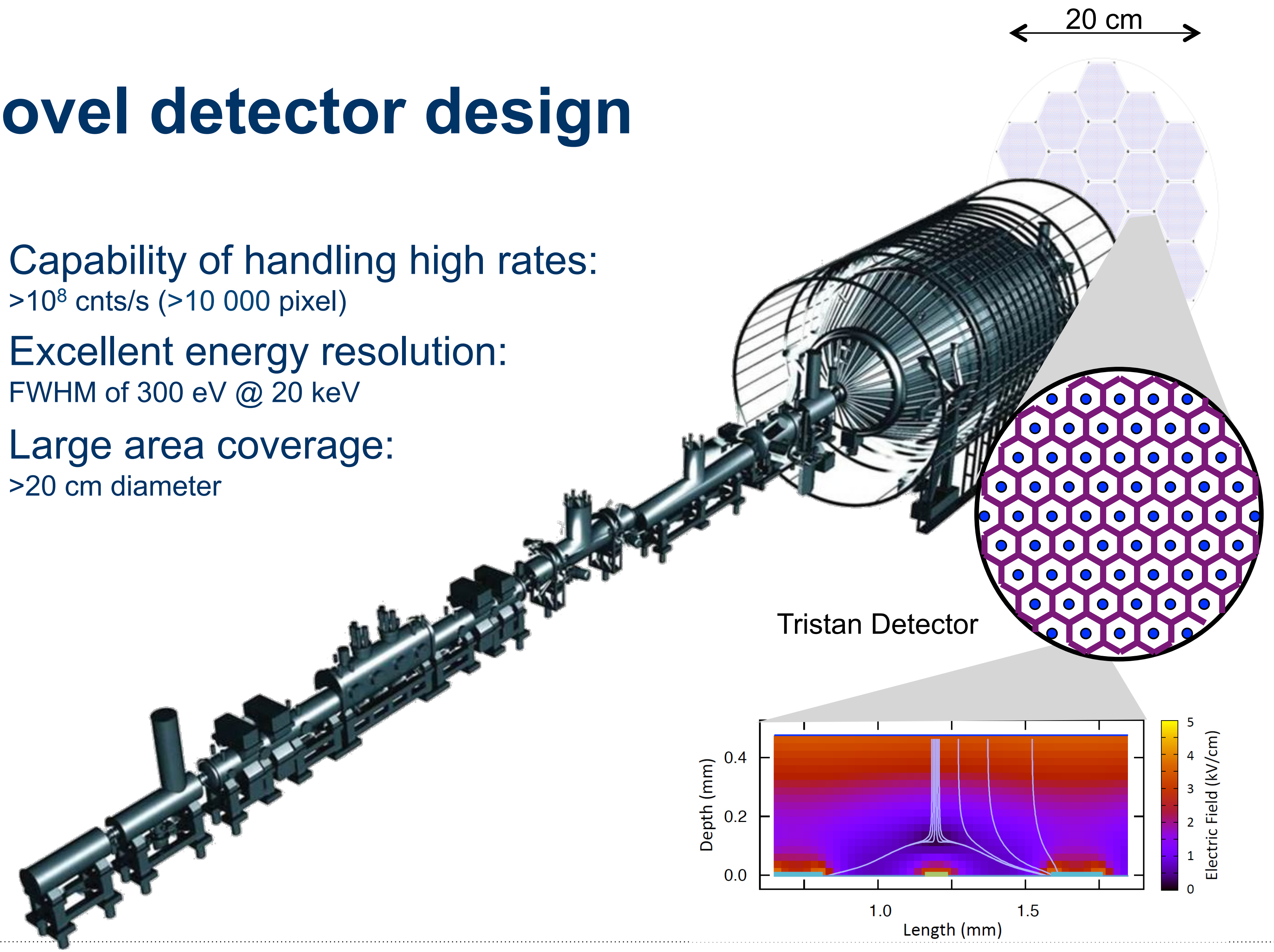
Technical Realization



1. Energy resolving detector
   → Differential measurement
2. Counting detector
   → Integral measurement
3. Time of Flight
   → Differential measurement
   in small energy window

Novel detector design

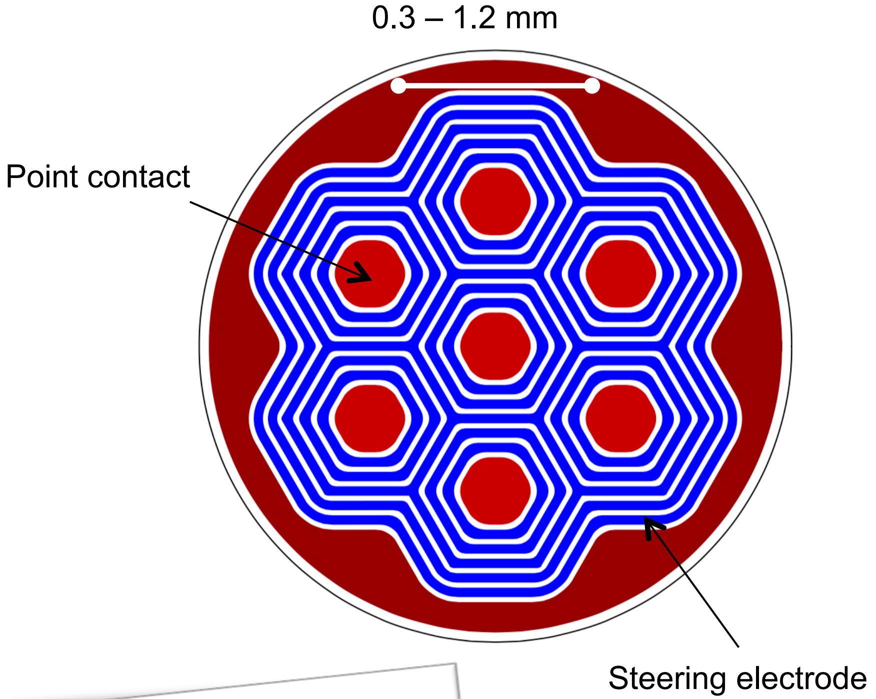
- Capability of handling high rates:
  >10^8 cnts/s (>10 000 pixel)
- Excellent energy resolution:
  FWHM of 300 eV @ 20 keV
- Large area coverage:
  >20 cm diameter



TRISTAN Prototype

- Key design features:
  - Very small point contacts
  - Thin entrance window (~10 nm)
  - Shared steering electrode

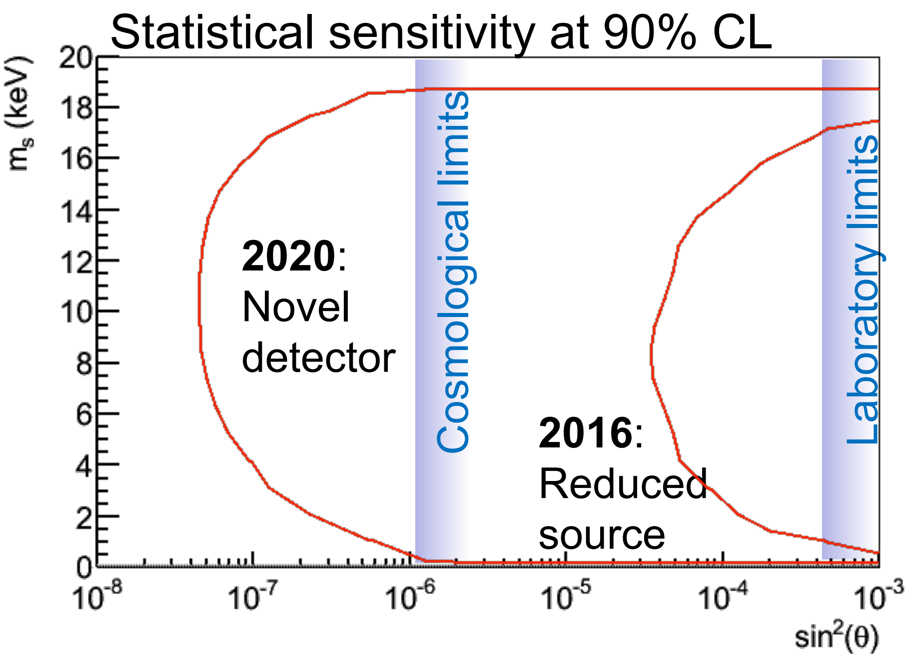
- Cooperations with Max-Planck Halbleiterlabor in Munich and Lawrence Berkeley Lab
- First prototype will be built by October this year
- Characterize pile-up, backscattering, charge-sharing, etc.



Prototype supported by Research Seed Capital funding of MWK Baden Württemberg

Timeline

- First measurements with KATRIN “as is” at reduced source strength
- Sensitivity studies and detector development
- High sensitivity sterile neutrino search after the neutrino mass measurement with new detector system



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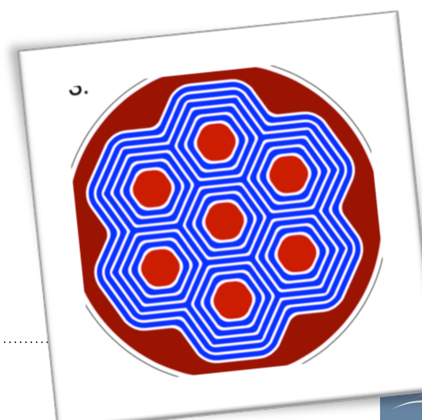
Summary

- KATRIN is moving forward at high speed to start probing the neutrino mass with a sensitivity of 200 meV (90% CL) in 2016

- Sterile neutrinos are a natural extension of the SM
- keV-scale sterile neutrinos are a prime dark matter candidate
- KATRIN provides the statistical sensitivity to probe the cosmologically allowed parameter space for keV-scale sterile neutrinos
- Sensitivity studies and detector prototyping are ongoing to further investigate this new physics case



Thanks for your attention

And special thanks to:

- Thierry Lasserre, CEA Paris
- David Radford, Oak Ridge
- Craig Tindal, LBNL
- Kai Dolde, KIT
- Marc Korzeczek, KIT
- Stefan Groh, KIT
- Anton Huber, KIT
- Guido Drexlin, KIT
- Nicho Steinbrink, Uni Münster
- Christian Weinheimer, Uni Münster
- Jelena Simkovic, HLL

Condolences from the KATRIN Collaboration

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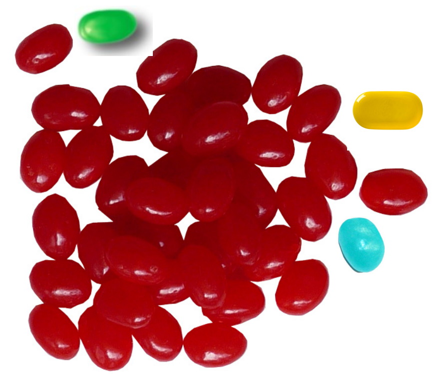
Backup Slides

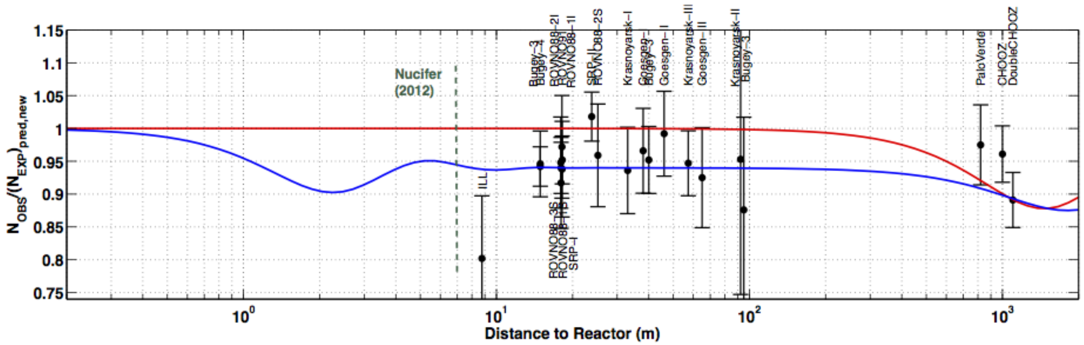
Sterile Neutrino Mass Eigenstates

ν_R

ν_4

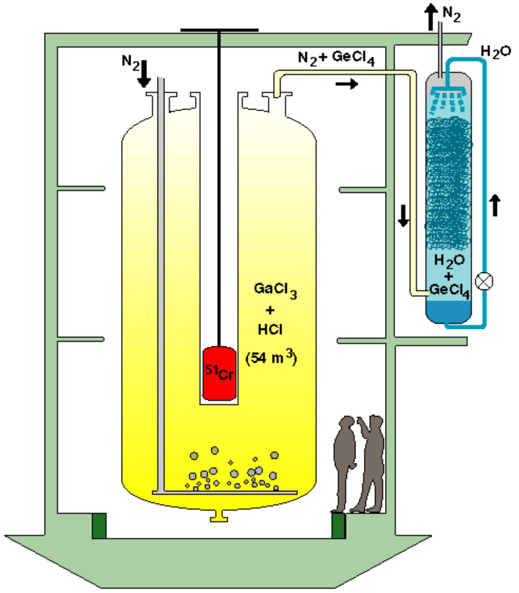


eV-scale sterile neutrinos



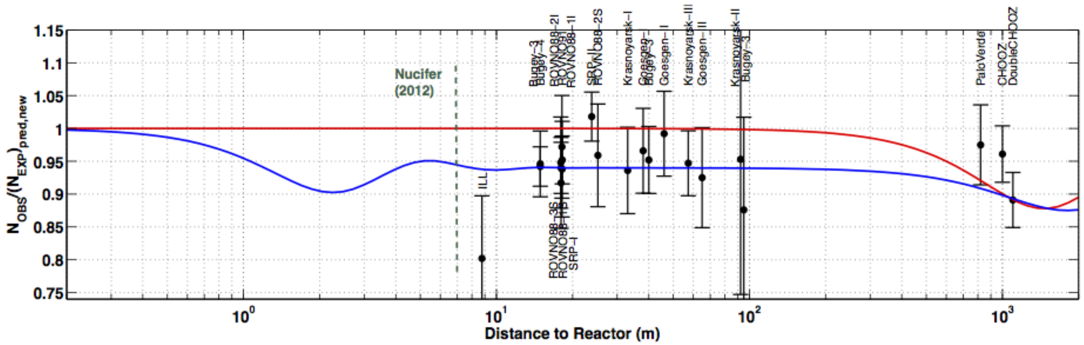
Reactor anomaly:
~2.7σ deficit of measured events compared to prediction

Galium anomaly:
~2.7σ deficit of measured events compared to prediction



G. Mention et al., Phys. Rev. D 83 (2011) 073006
P. Anselmann et al., Phys. Lett. B 357 (1995) 237

eV-scale sterile neutrinos



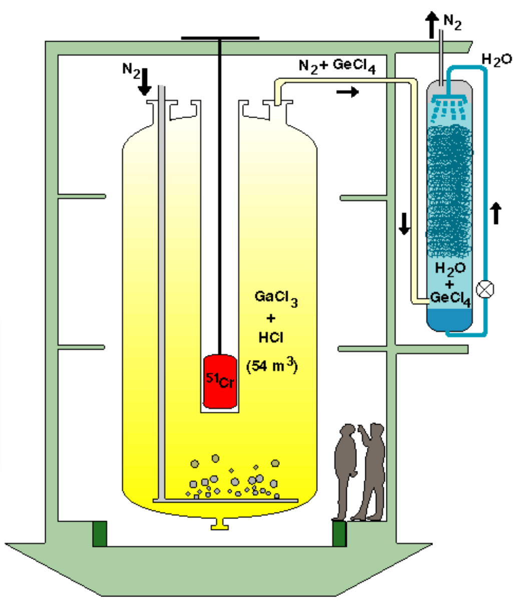
Possible explanation: sterile neutrinos

Best fit:

$\sin^2(2\theta) = 0.17 \pm 0.04$

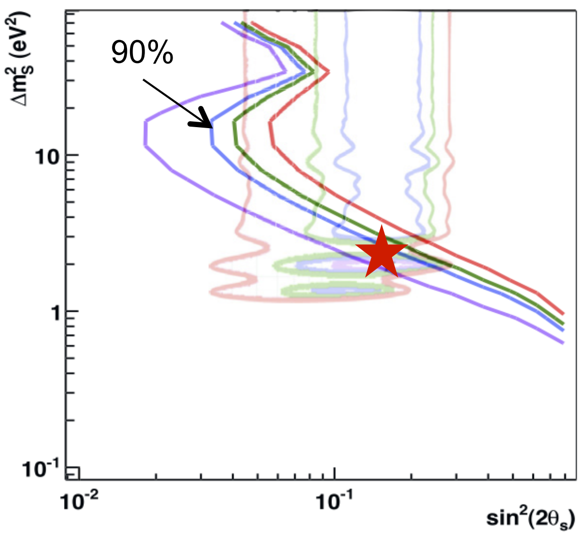
$\Delta m^2 = (2.3 \pm 0.1)\ \mathrm{eV}^2$

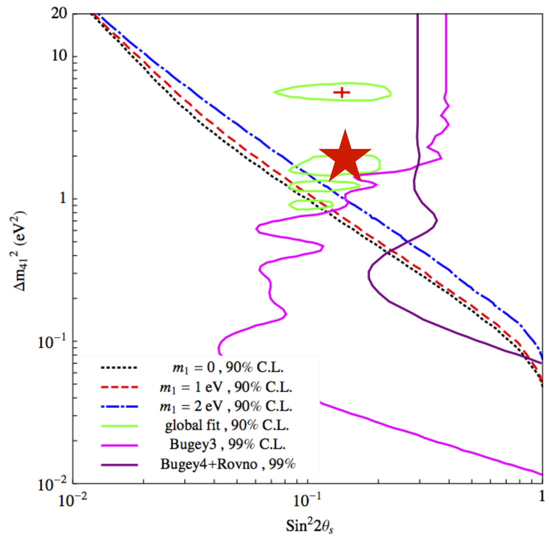
→ This is where KATRIN measures, anyway

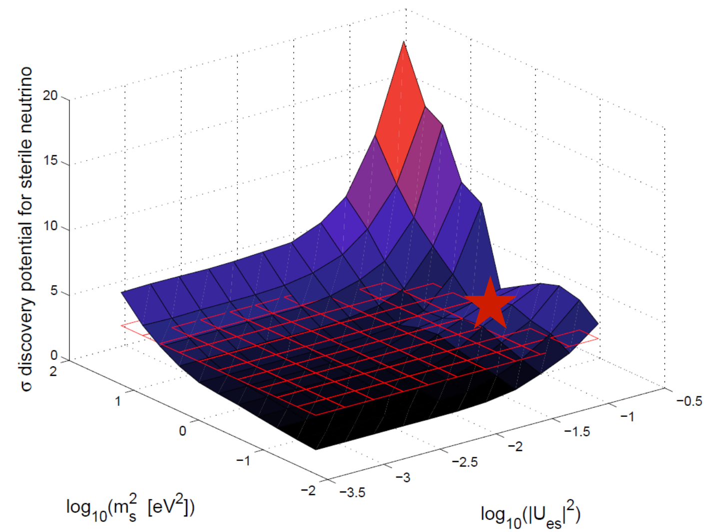


G. Mention et al., Phys. Rev. D 83 (2011) 073006
P. Anselmann et al., Phys. Lett. B 357 (1995) 237

KATRIN's sensitivity for eV ν's





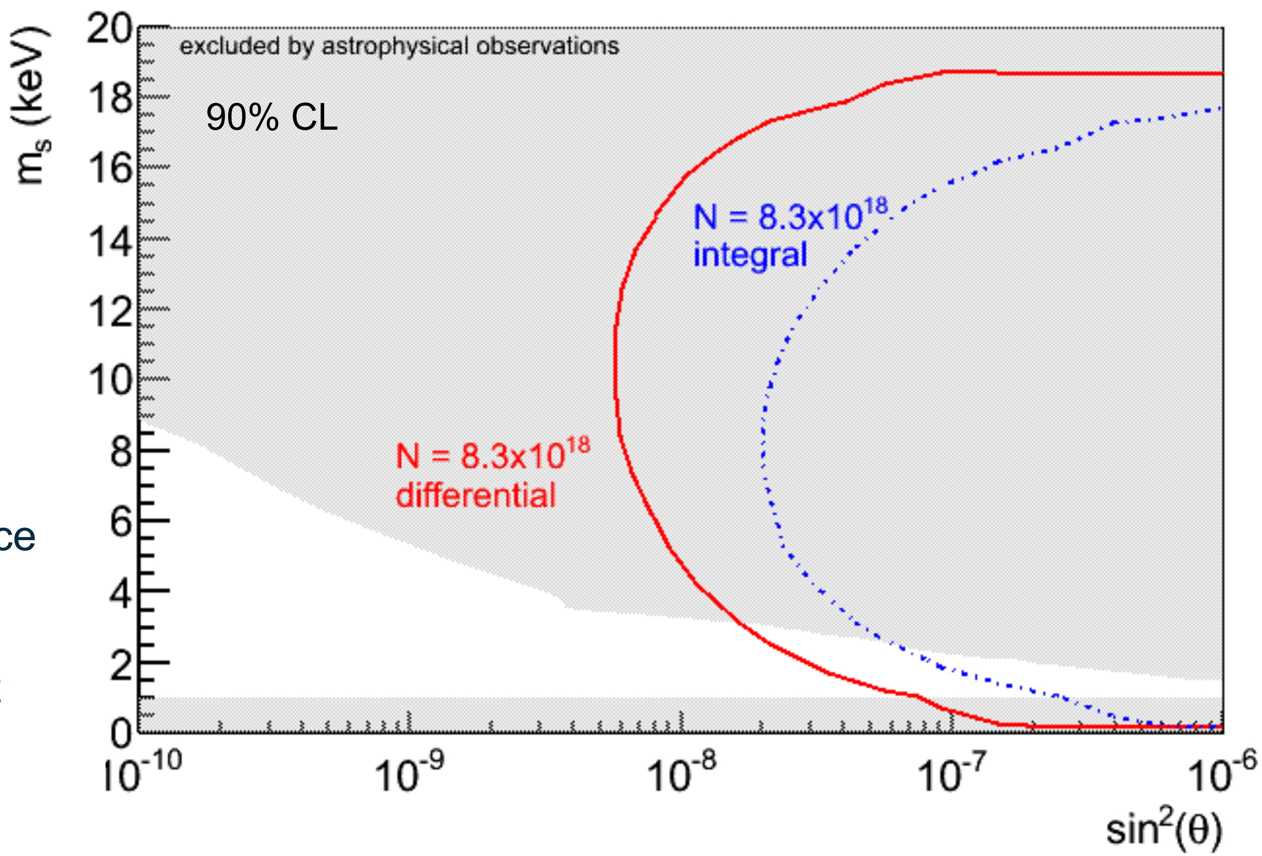


J. A. Formaggio, J. Barret, PLB 706 (2011) 68
A. Esmaili, O.L.G. Peres, Phys. Rev. D 85, 117301
A. Sejersen Riis, S. Hannestad, JCAP02 (2011) 011
M. Kleesiek, PhD Thesis (2014)

KATRIN probes the favored parameter space

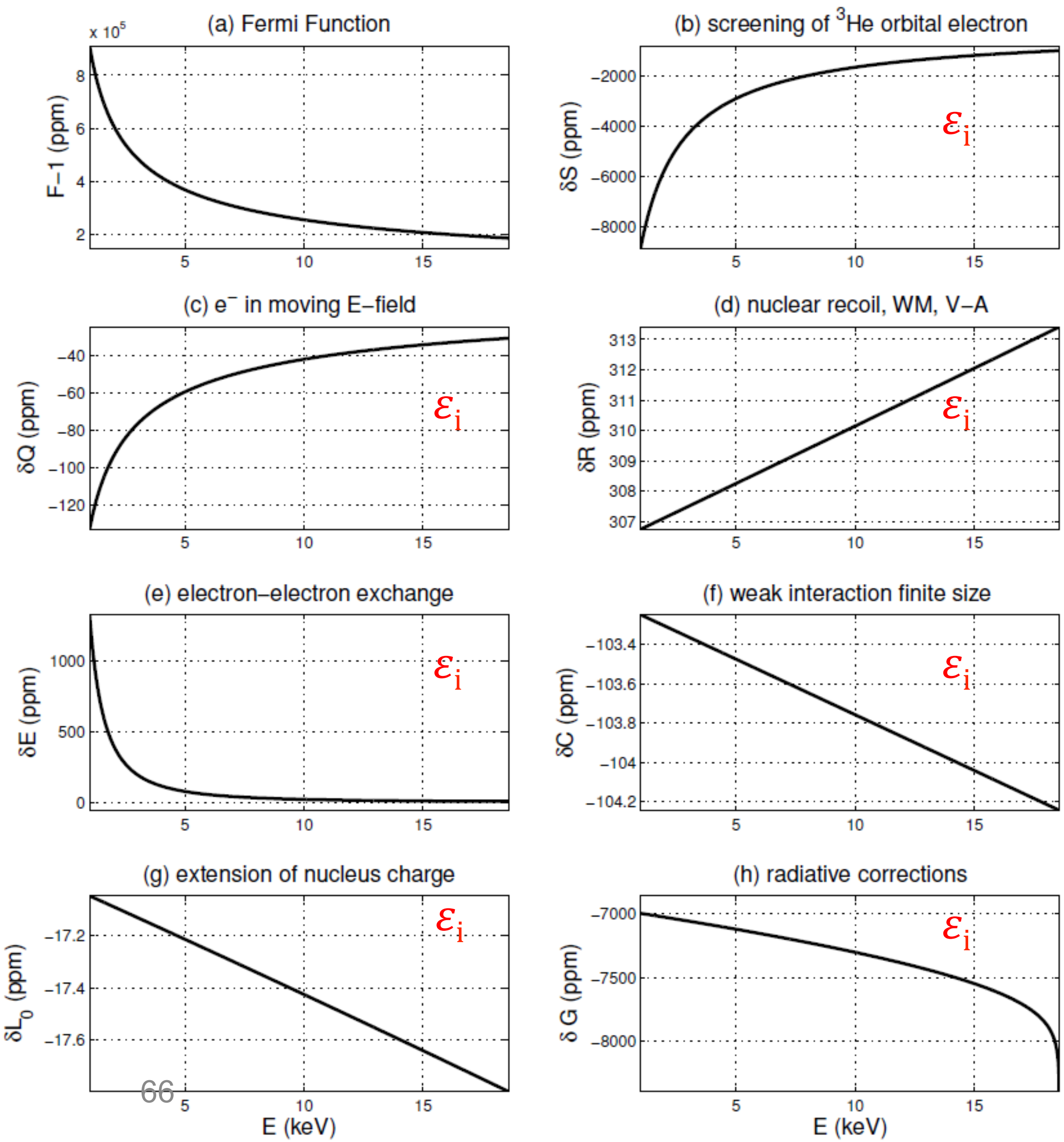
Different measurement modes

KATRIN source strength, 3-years measurement time



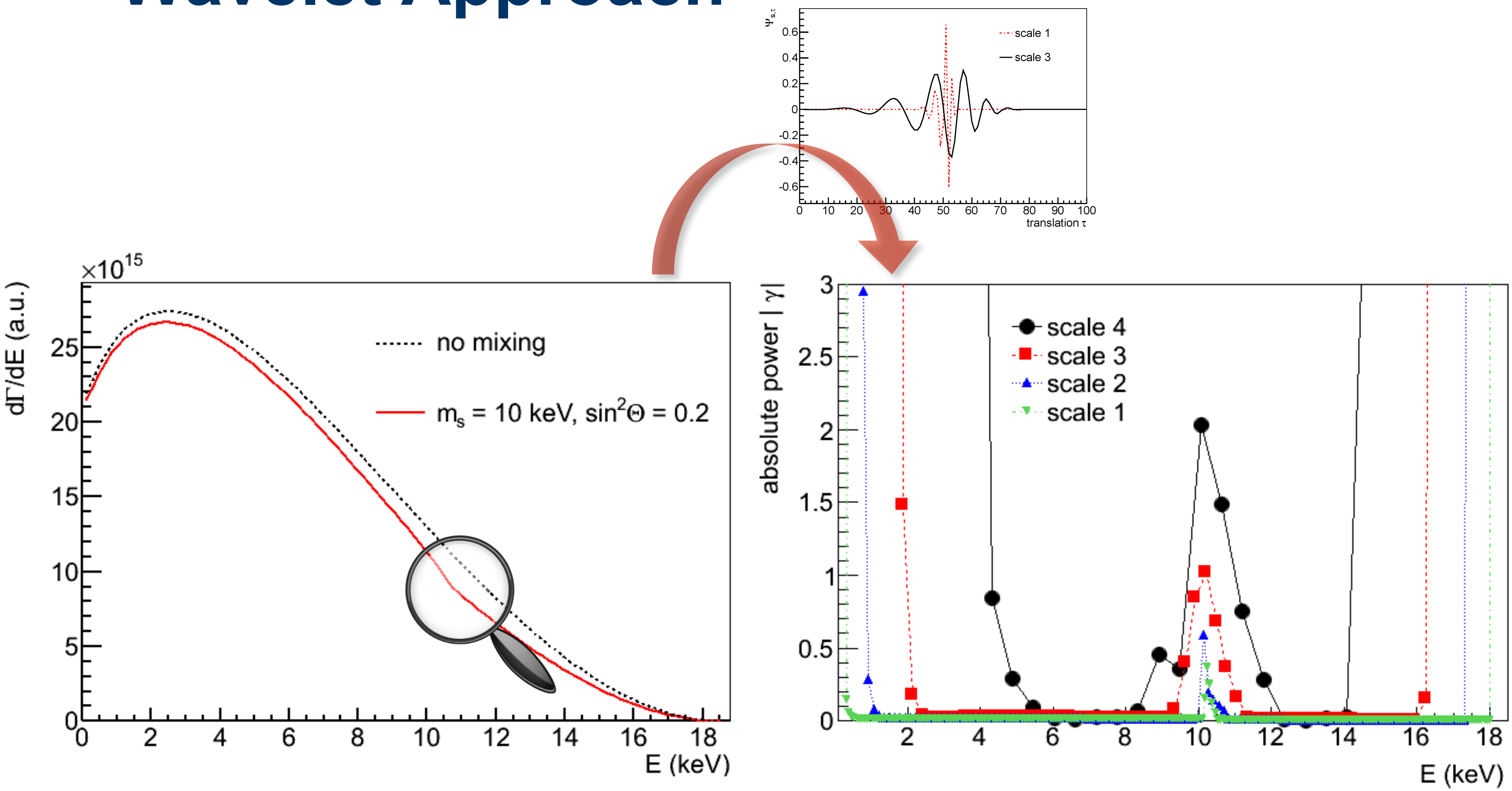
S. Mertens et. al. arXiv:1409.0920

Spectral Fit Approach



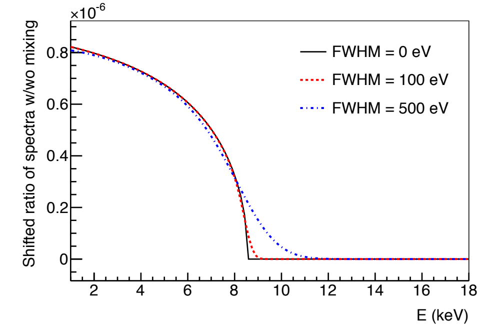
„State-of-the -Art" Tritium Spectrum: Non-negligible but smooth corrections

Wavelet Approach



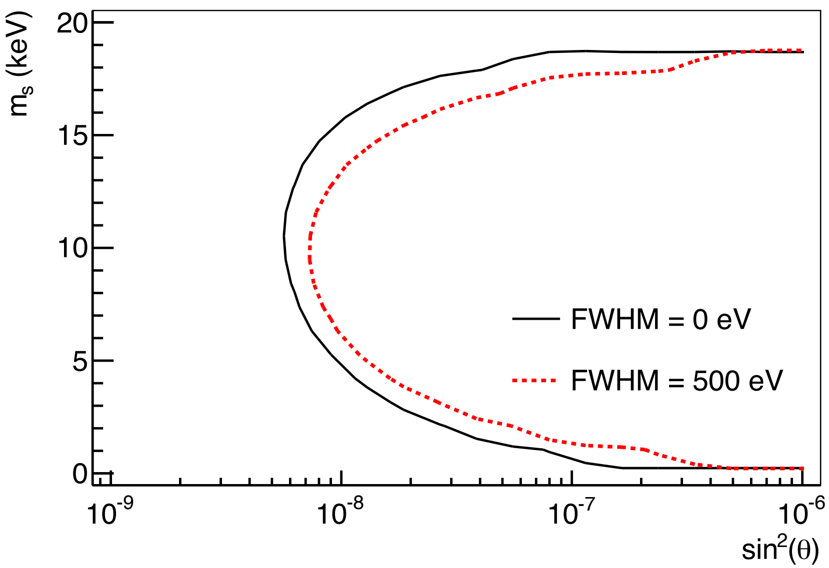
S. Mertens et. al.
arXiv:1410.7684

Detailed sensitivity studies



Spectral fit approach:

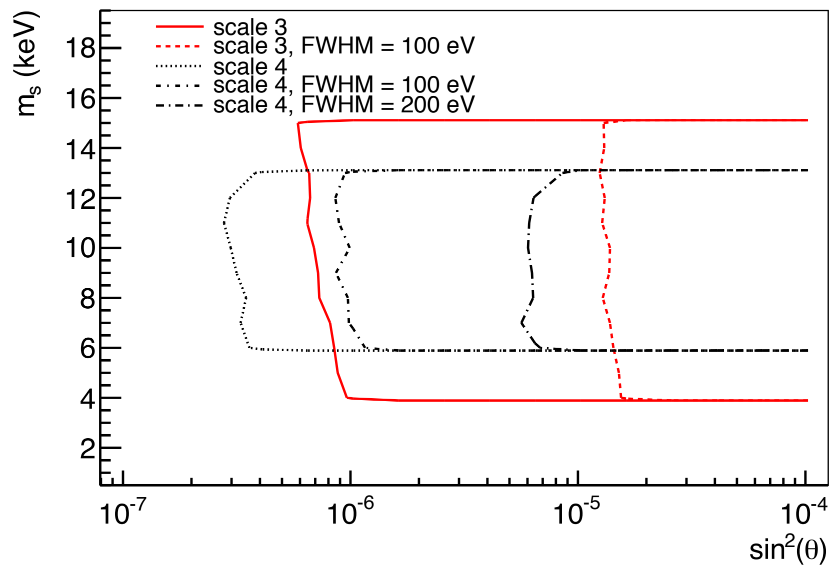
Detector resolution



S. Mertens et. al.
Accepted for publication in Journal of cosmology and astroparticle physics

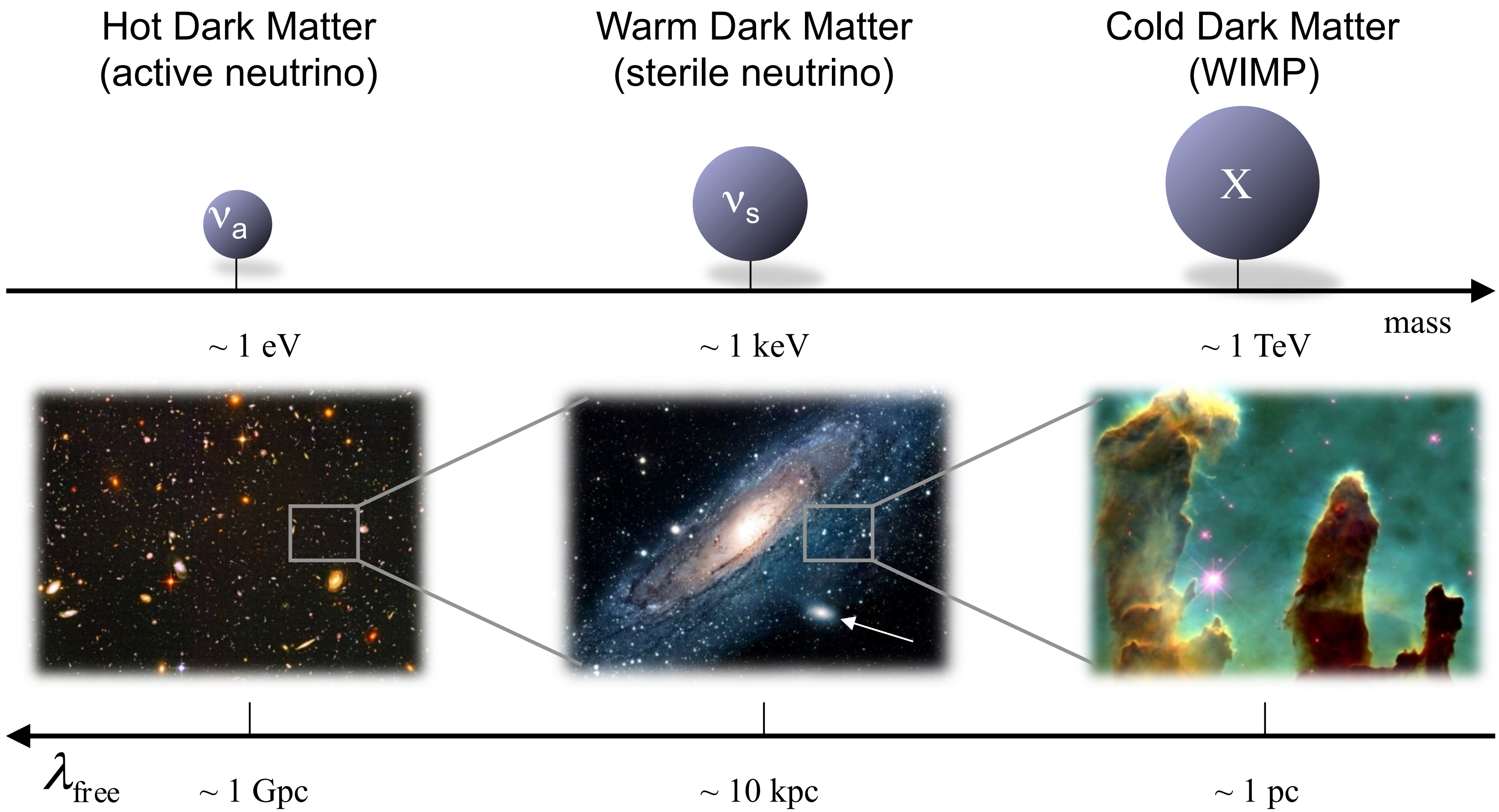
Wavelet approach:

Detector resolution



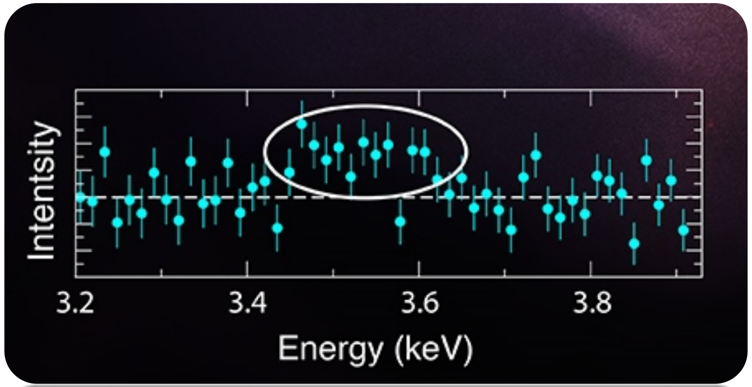
S. Mertens et. al.
Accepted for publication in Phys Rev D

Sterile Neutrinos and Dark Matter

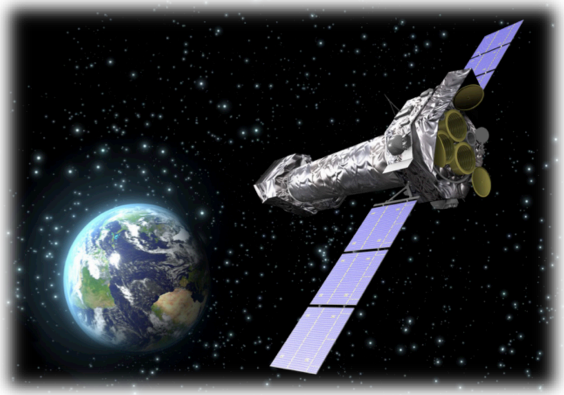


Possible hints for sterile ν DM ?

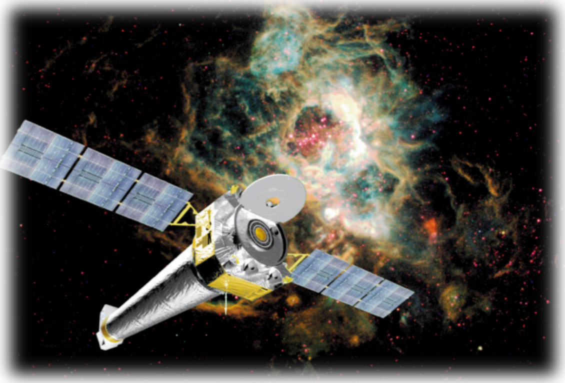
- Unidentified X-ray line observed in Perseus cluster and stacked galaxy clusters
- Could be interpreted signature of decay of sterile neutrino decay ?
- Results are not conclusive at the moment



XMM Newton Telescope

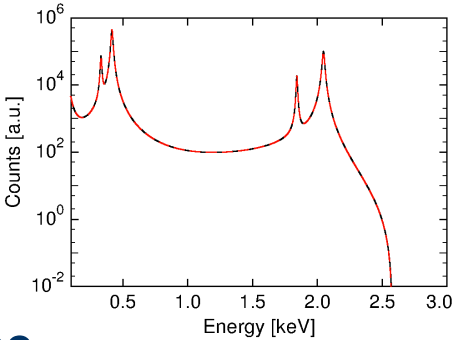


Chandra Telescope



E. Bulbul *et al.* 2014 *ApJ* **789**
Boyarsky *et al.* 2014 *PRL* **113**

Other efforts



The case of Tritium:

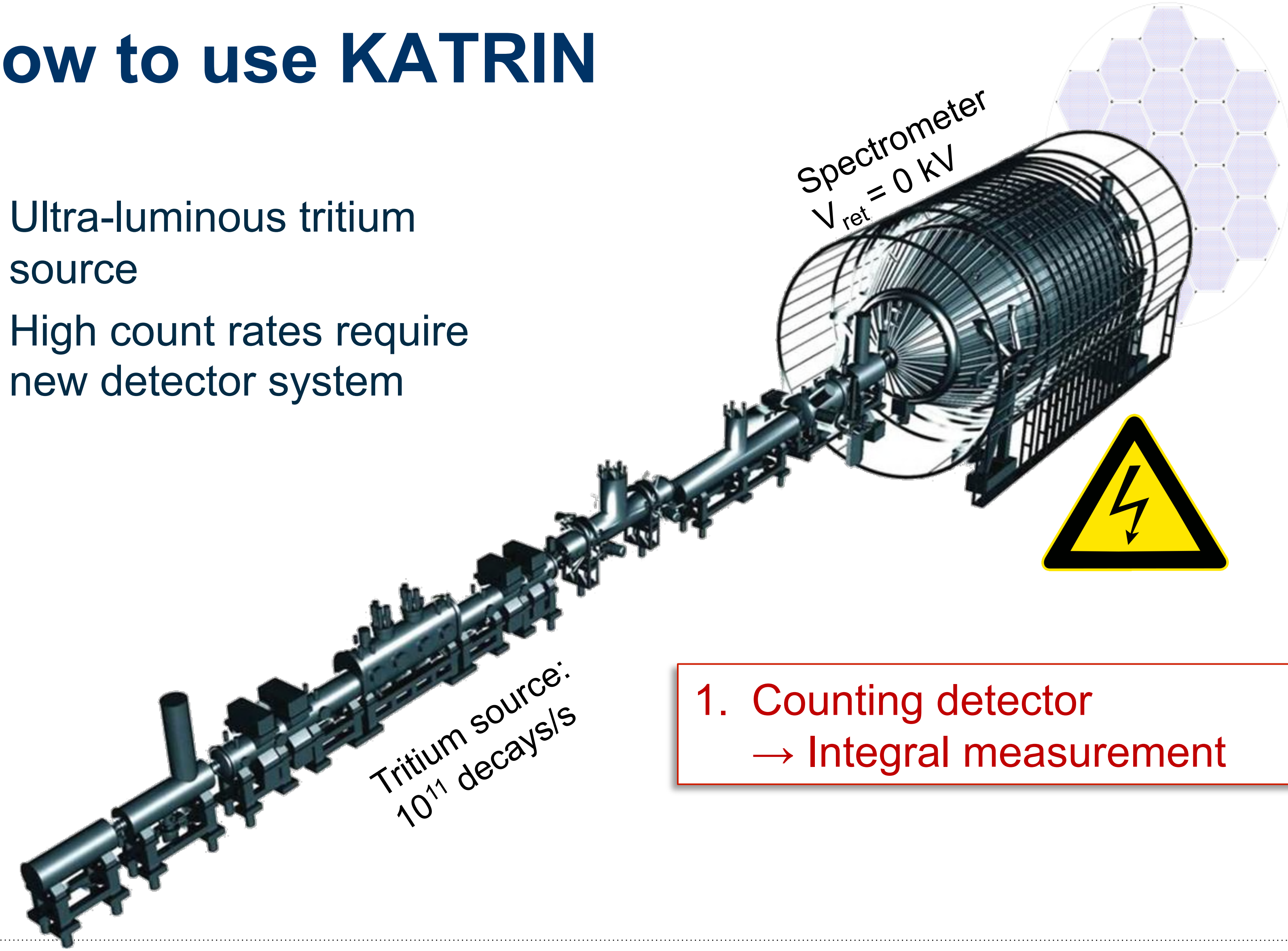
- Endpoint: 18.6 keV
- Super-allowed decay
- Short half life of 12.3 years
- Projects:
  - KATRIN
    S. M. *et al.* (arXiv:1409.0920) Accepted for publication in JCAP
  - Project8
    B. Monreal and Joe Formaggio, Phys. Rev D80:051301
  - Full kinematic reconstruction
    F. Bezrukov and M. Shaposhnikov PRD 75, 053005200

The case of Ho-163:

- Endpoint: 2.3 – 2.8 keV
- Complicated spectral shape
- Half life of 4500 years
- Projects:
  - ECHo
    L. Gastaldo et al., Nucl. Inst. Meth. A, 711, 150-159 (2013)
  - HOLMES
    M. Ribeiro Gomes et al., IEEE ToAS, VOL. 23, NO. 3, JUNE 2013
  - NuMECS
    J.W. Engle et al. NIM B 311 (2013) 131–138

How to use KATRIN

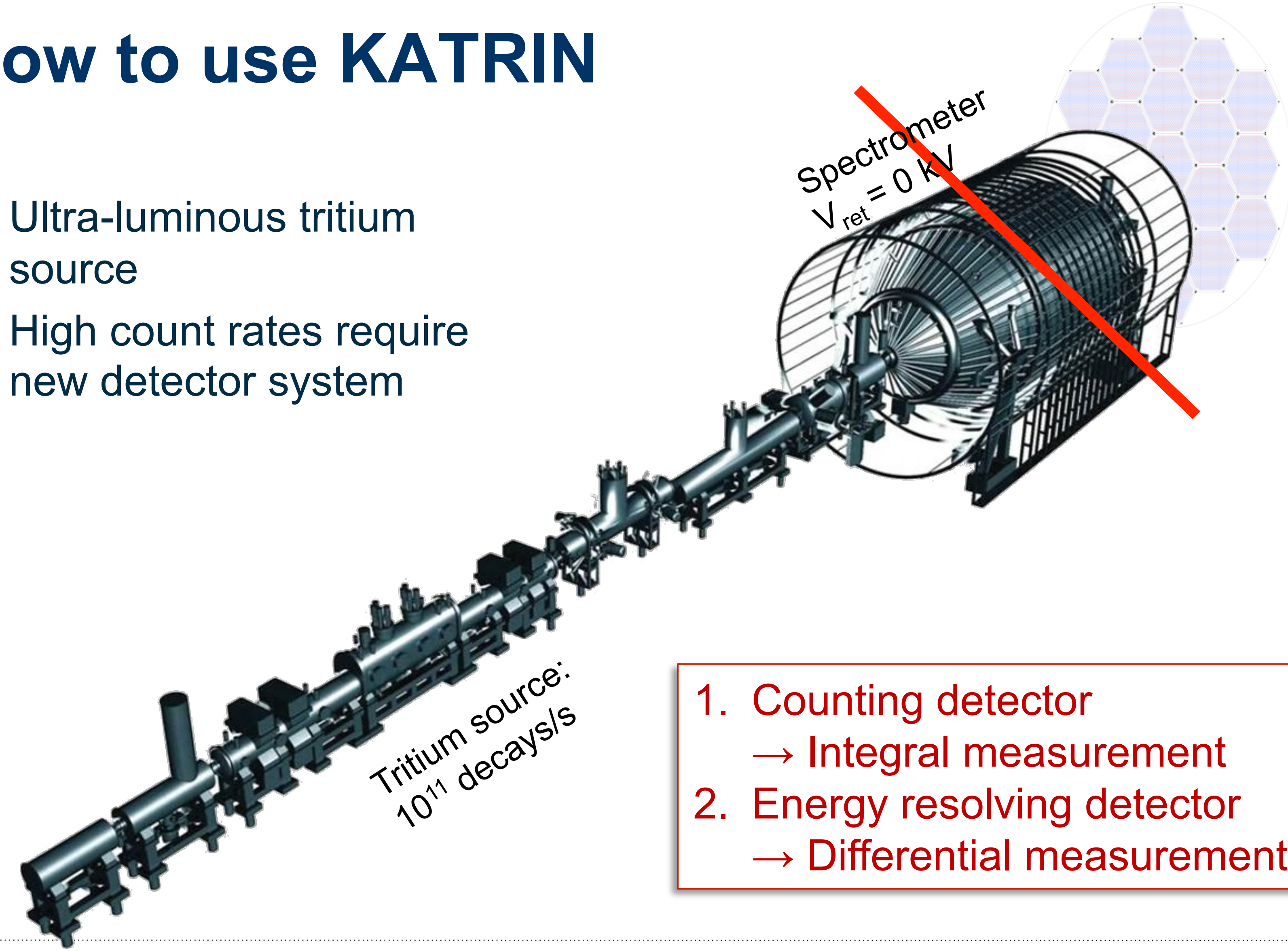
- Ultra-luminous tritium source
- High count rates require new detector system



1. Counting detector
   → Integral measurement

How to use KATRIN

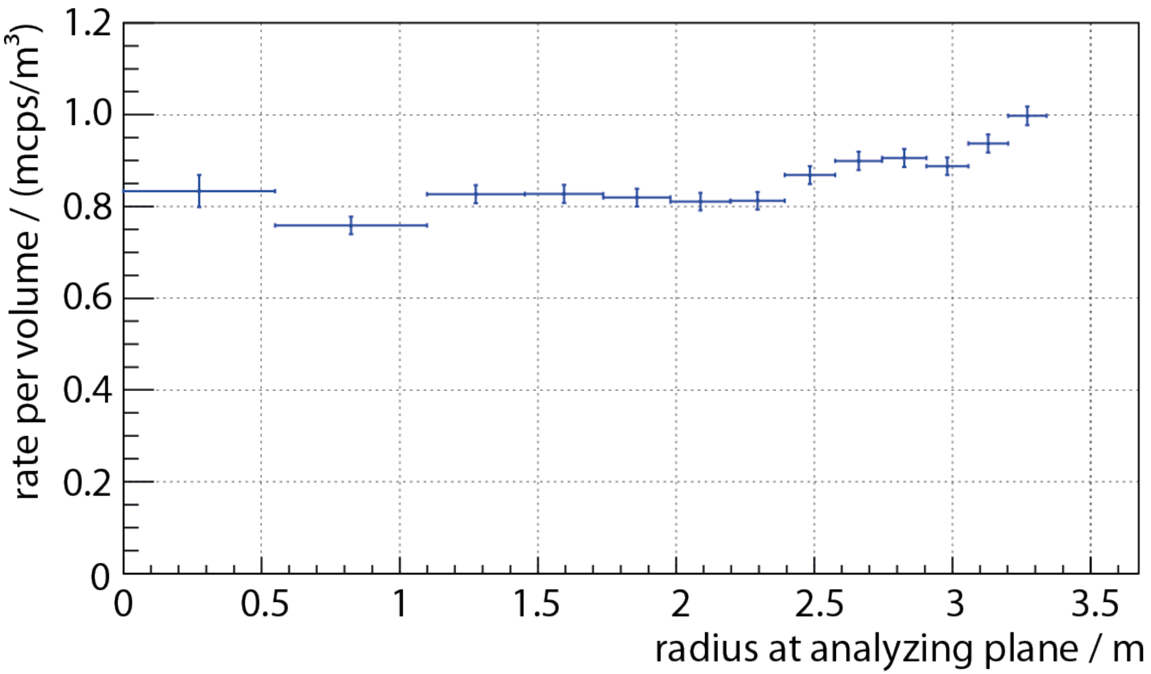
- Ultra-luminous tritium source
- High count rates require new detector system



1. Counting detector
   → Integral measurement
2. Energy resolving detector
   → Differential measurement

KATRIN Background

- Background rate in ROI **477 +/- 3 mcps** (10 mcps required)
- Settings: vessel = -18.5kV, IE = -100V, PAE = +10 kV and "5G" magnetic field setting



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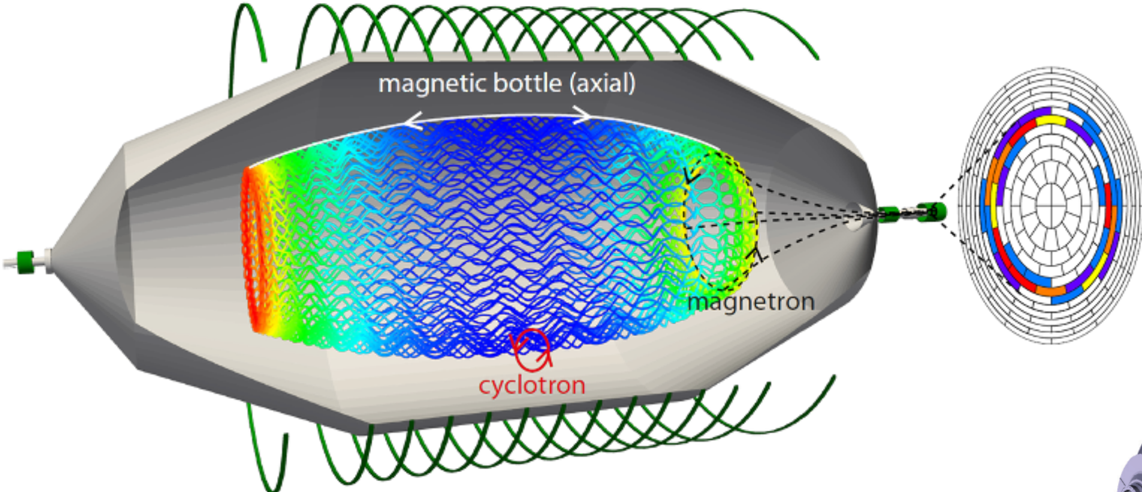
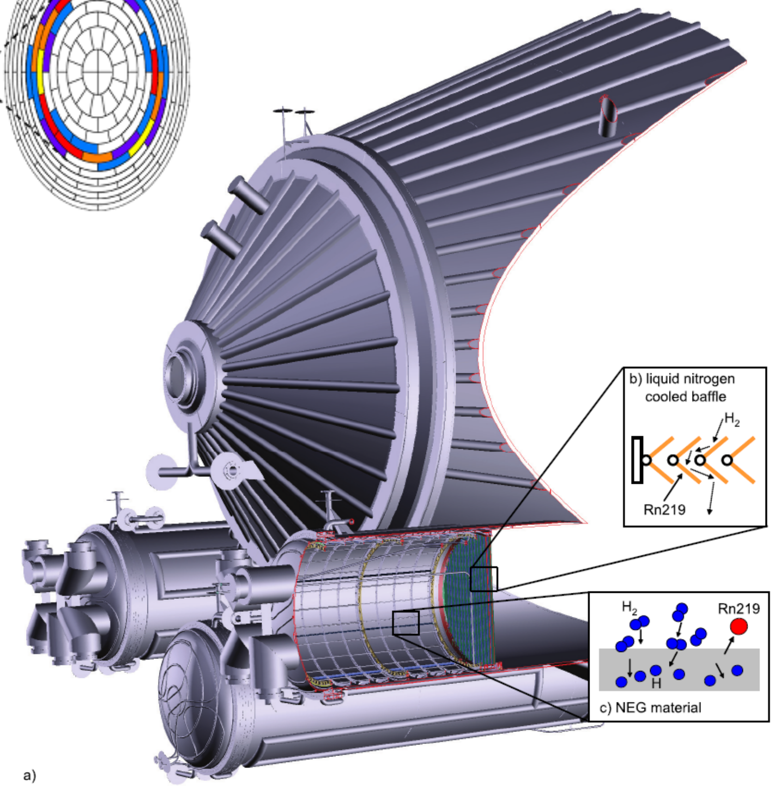
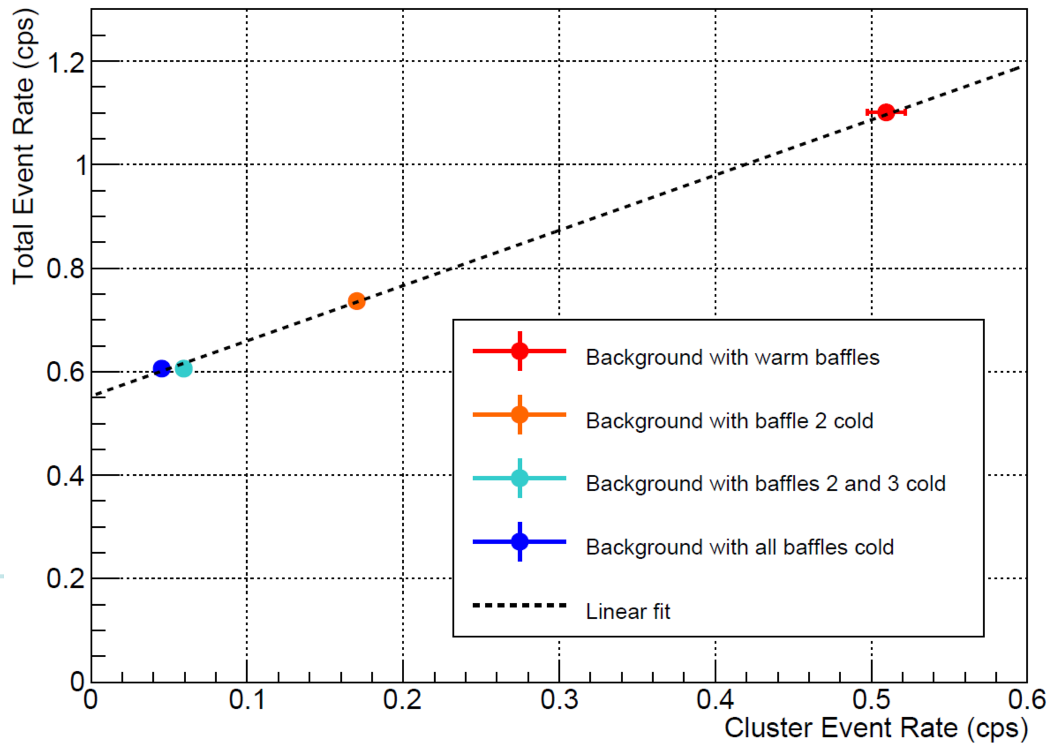
Radon induced background





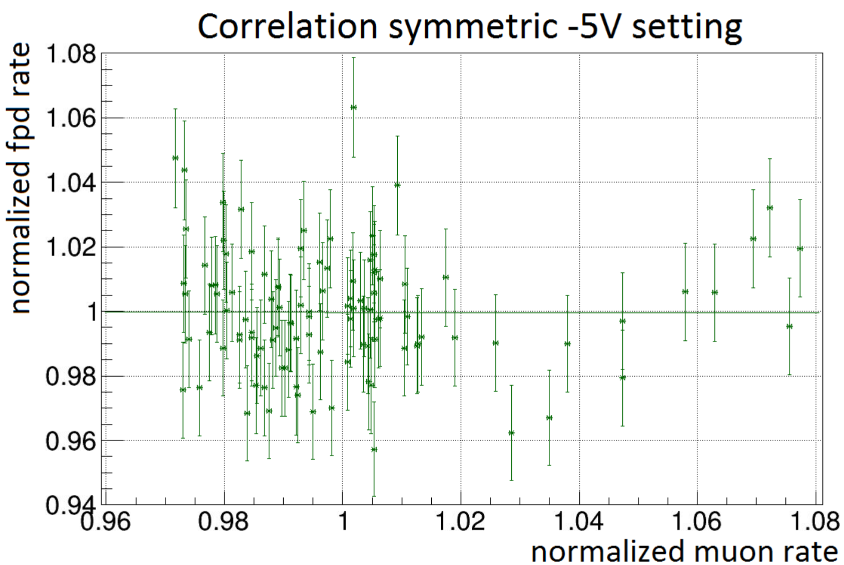
Effect of cold baffle on Radon background

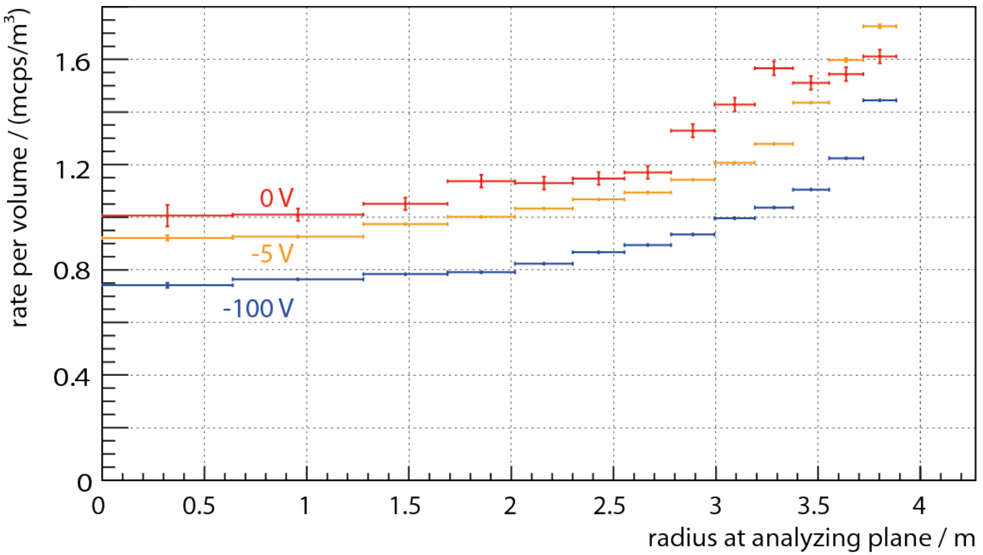


$B_{total} = S_{Rn} + C_{Rn} + R$
$S_{Rn} = \alpha \cdot C_{Rn}$
$B_{total} = (\alpha + 1) \cdot C_{Rn} + R$

B_{total} : Total background rate.
S_{Rn} : Radon-induced single event rate.
C_{Rn} : Event rate in Radon-induced clusters.
R : Non-Radon-induced background rate.

Cosmic induced backgrounds





slope α: -0.001 ± 0.064

correlation factor: -0.01 ± 0.1

KATRIN Spectrometer Status

Beginning of 2015 measurement phase completed

- ➢ Spectrometer works as MAC-E Filter
- ➢ Liquid nitrogen cooled baffles eliminate Radon-induced background with an efficiency of ε = (97± 2)%
- ➢ Remaining background is still under investigation
- ➢ Excellent HV stability