Karlsruhe Institute of Technology

The Status of the keV-scale sterile neutrino search with KATRIN

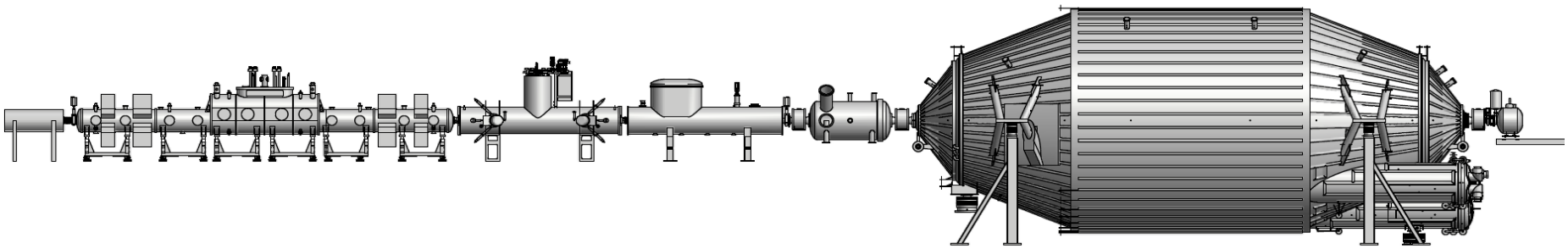
Anton Huber for the KATRIN Collaboration

Chalonge-de Vega Meudon Workshop 2016 - Paris

Overview

- The KATRIN Experiment and the neutrino mass
  - Main goal
  - Measurement principle
  - Status
- The KATRIN Experiment and sterile neutrinos
  - Imprint of a sterile neutrino
  - How to use KATRIN
  - Two main planned measurements
- Conclusion and time to discuss

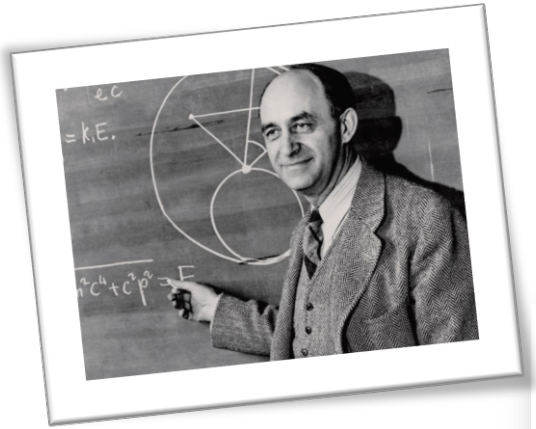
KATRIN Experiment

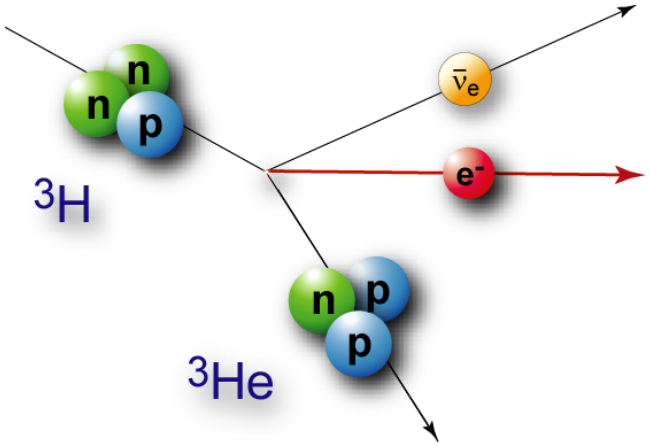


- Probing the neutrino mass with a sensitivity of $m(\nu_e)$ = 200 meV (90% CL), after 3 years
- Improvement of a factor of 10

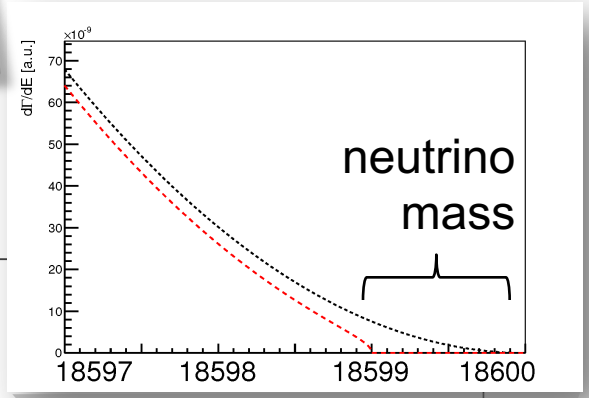
KATRIN Collaboration, FZKA Scientific Report **7090** (2004)

Tritium beta decay



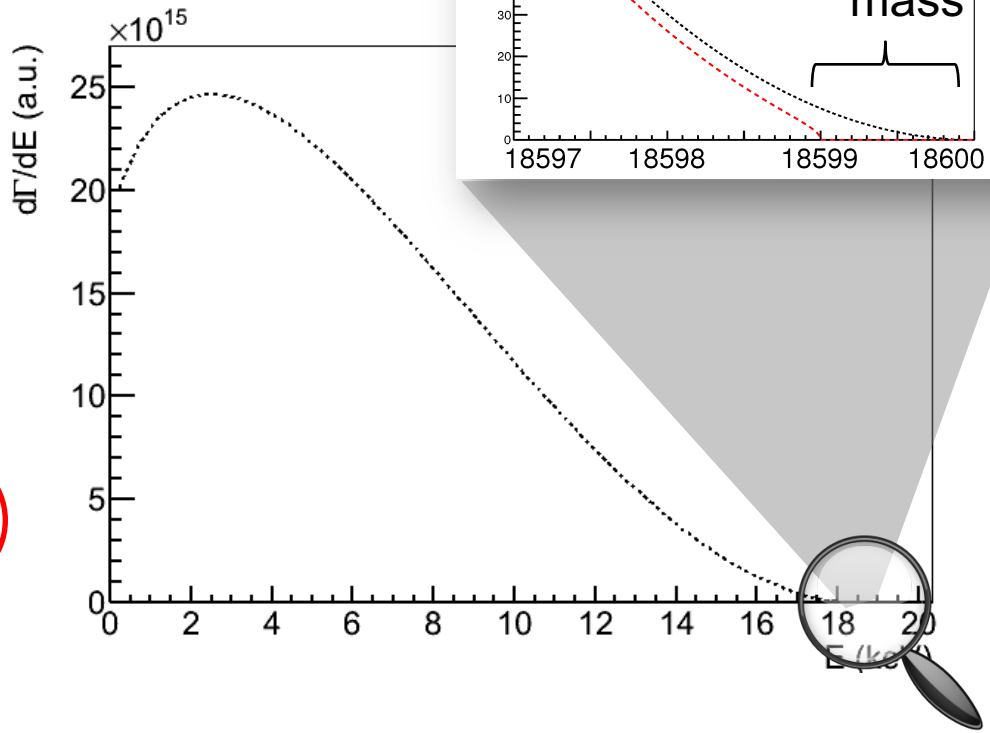


10^{-13} of all decays in last eV



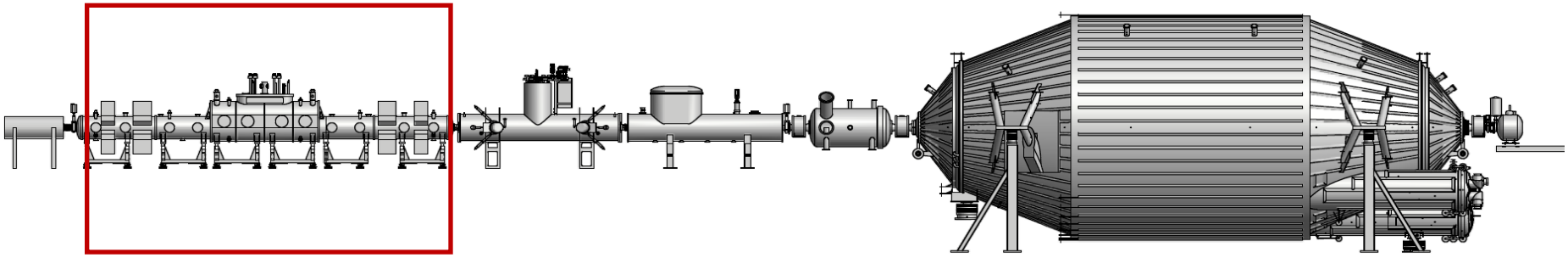
$$\frac{d\Gamma}{dE} = C \cdot F(E,Z) \cdot p \cdot (E + m_e)$$

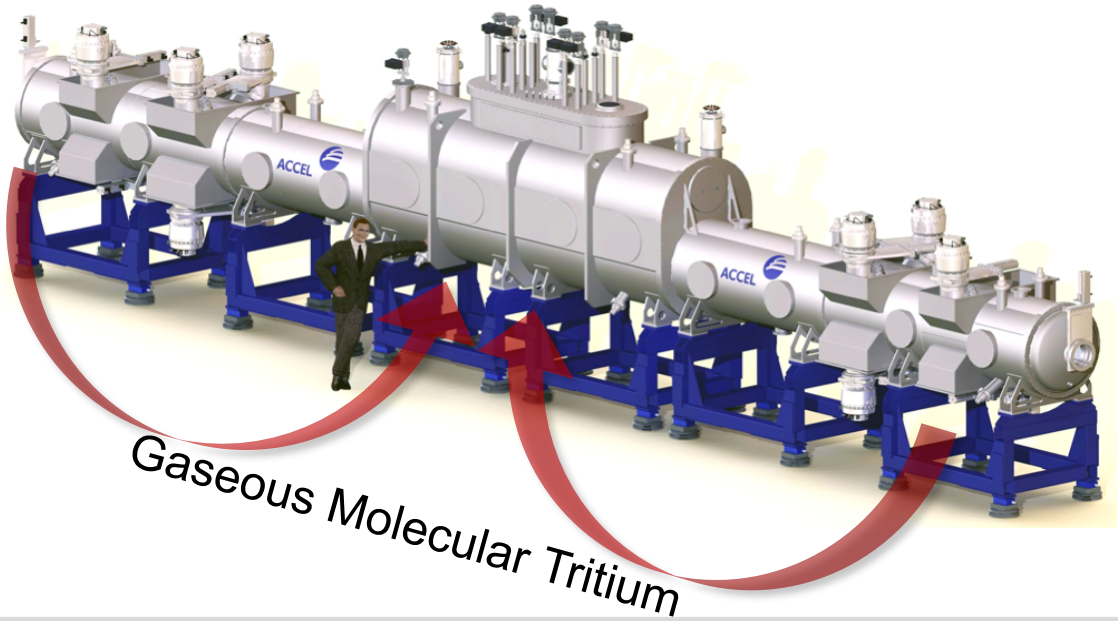
$$\cdot (E - E_0) \cdot \sqrt{(E - E_0)^2 - m_\nu^2}$$



KATRIN Overview

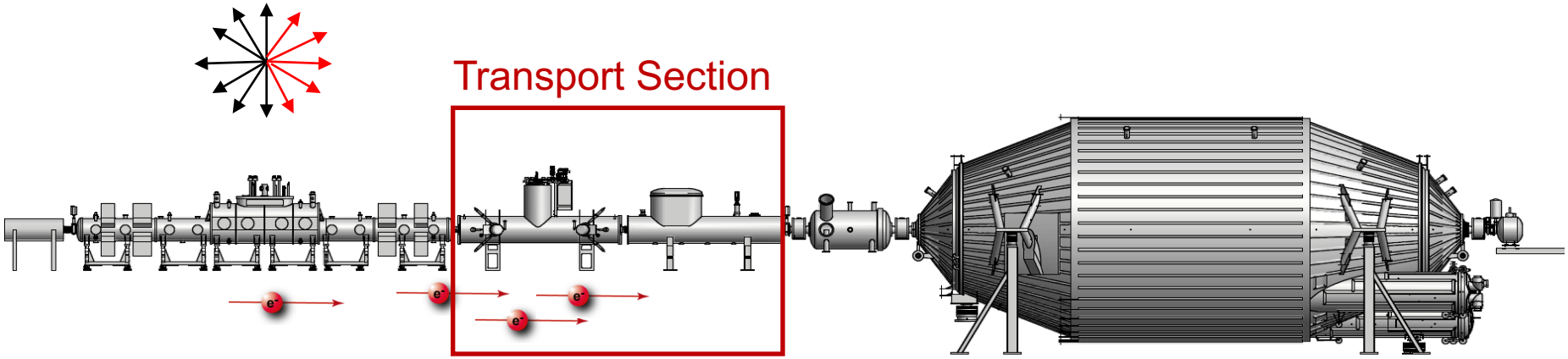
(windowless) Source Section





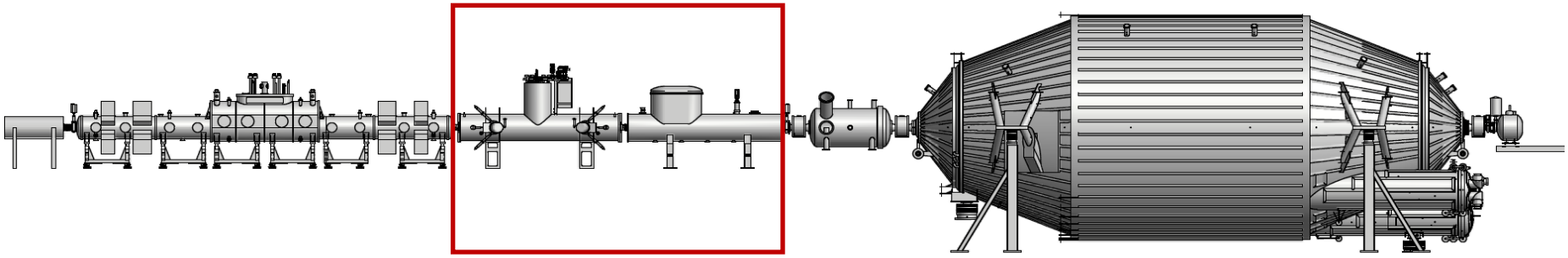
Gaseous molecular tritium source of high **stability**: ($< 10^{-3}$) and **luminosity**: (10^{11} decays/sec)

The KATRIN experiment



Adiabatic guidance of beta electrons

The KATRIN experiment



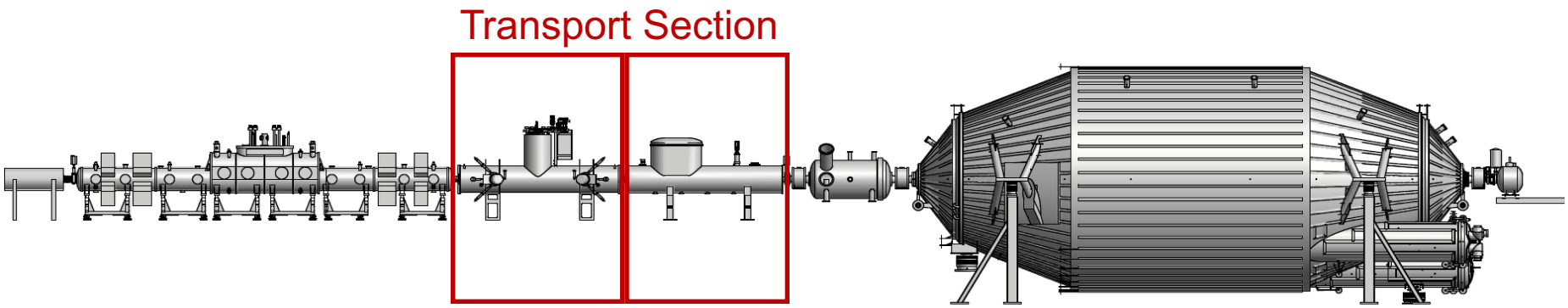
R>10^7 **R>10^7**

Reduction of tritium flow by 14 orders of magnitude

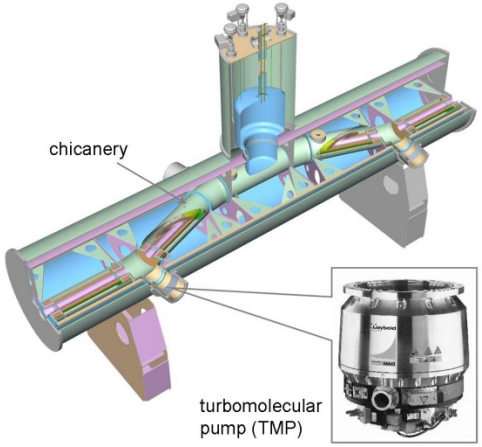
$p(T_2) < 10^{-20}$ mbar

$p = 10^{-11}$ mbar

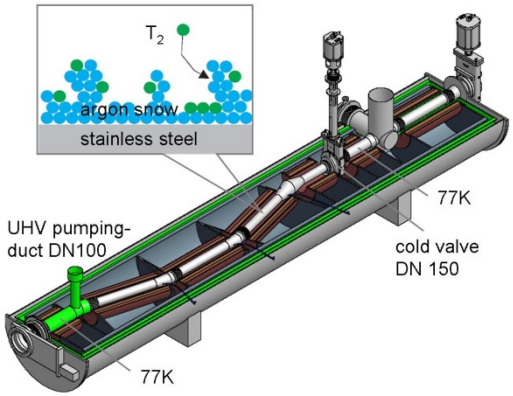
KATRIN Overview



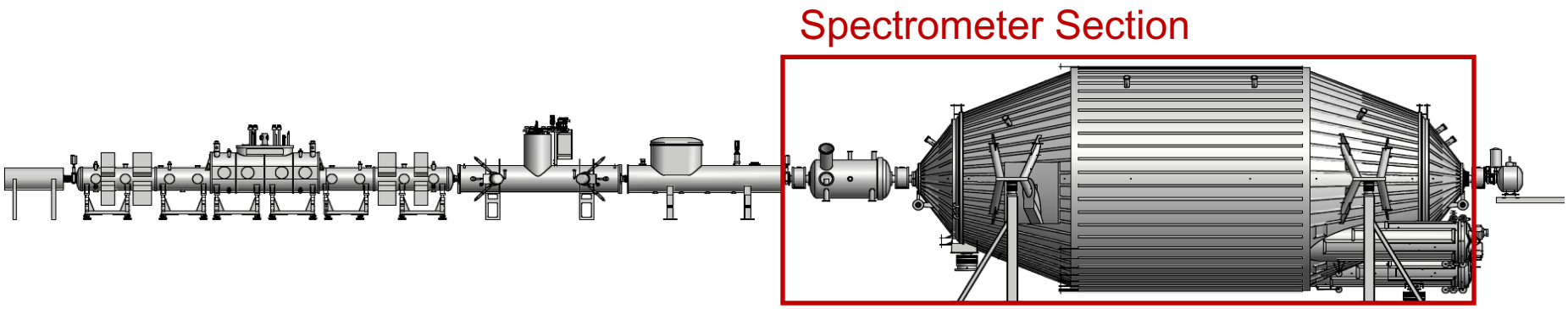
Differential pumping section

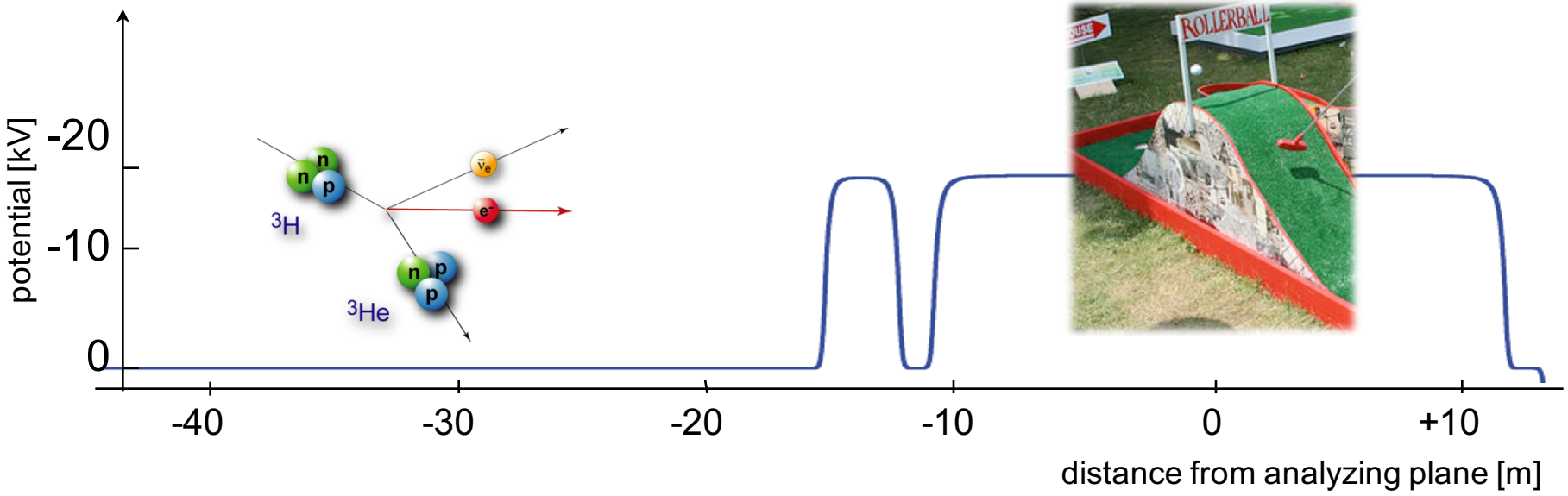


Cryogenic pumping section



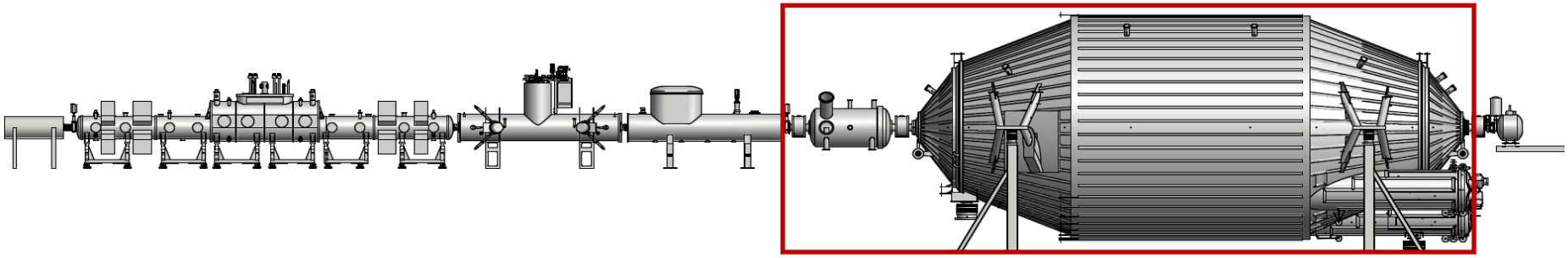
KATRIN Overview

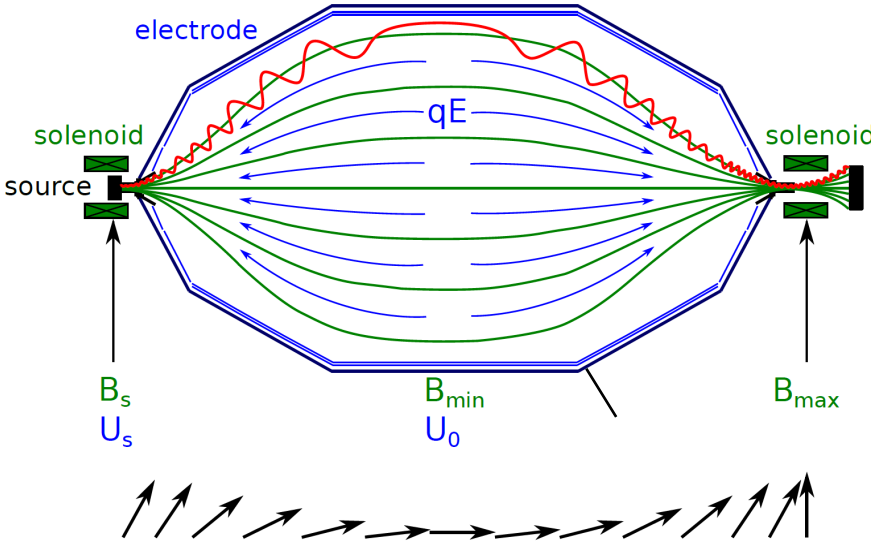




KATRIN Overview

Spectrometer Section





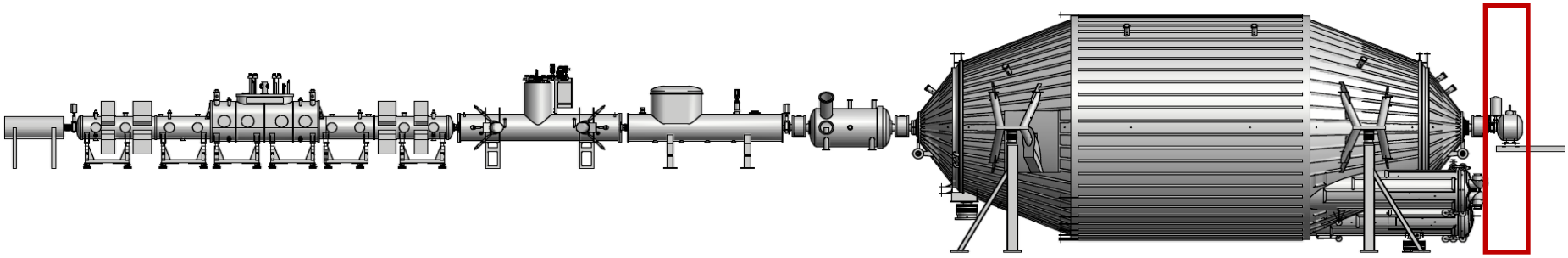
MAC-E Principle:

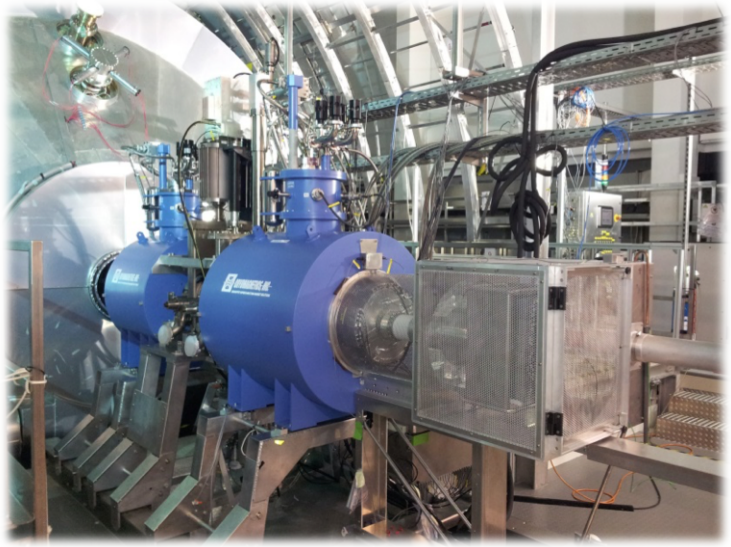
Large angle acceptance

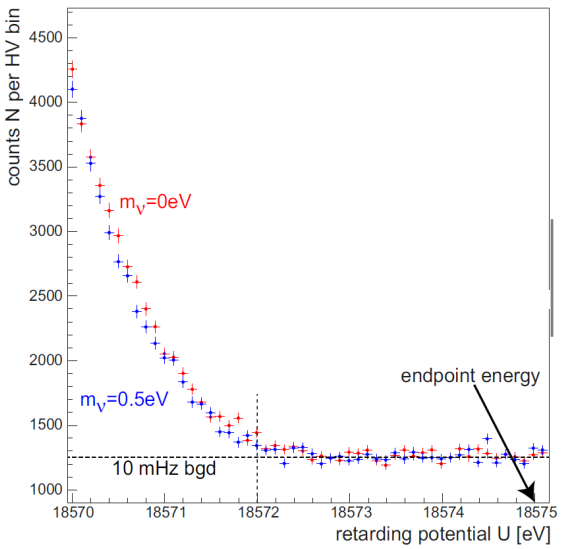
High energy resolution (0.93 eV)

KATRIN Overview

Detector Section

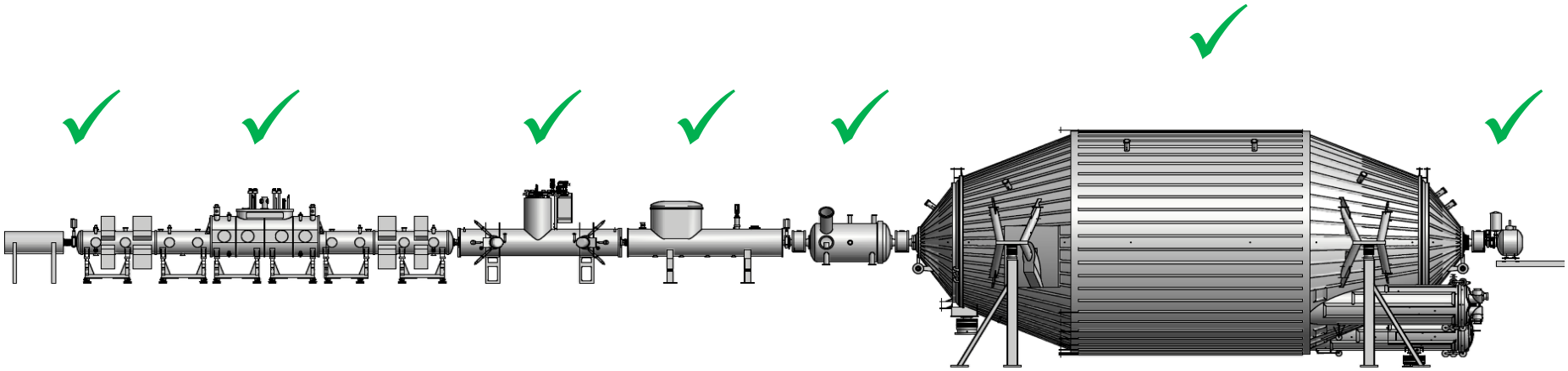






Integral measurement of spectrum down to **30 eV** below the endpoint

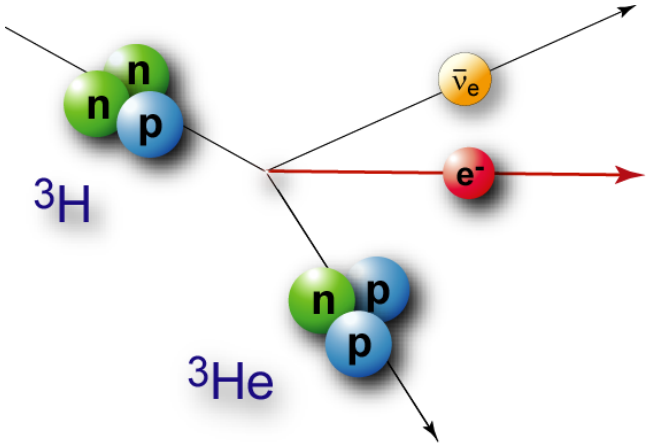
KATRIN Overview



- All Components are on the site
- Alignment and connection are prepared at the moment
- First Light measurement with e-gun in October this year

KATRIN and the keV-scale sterile neutrino

Tritium beta decay



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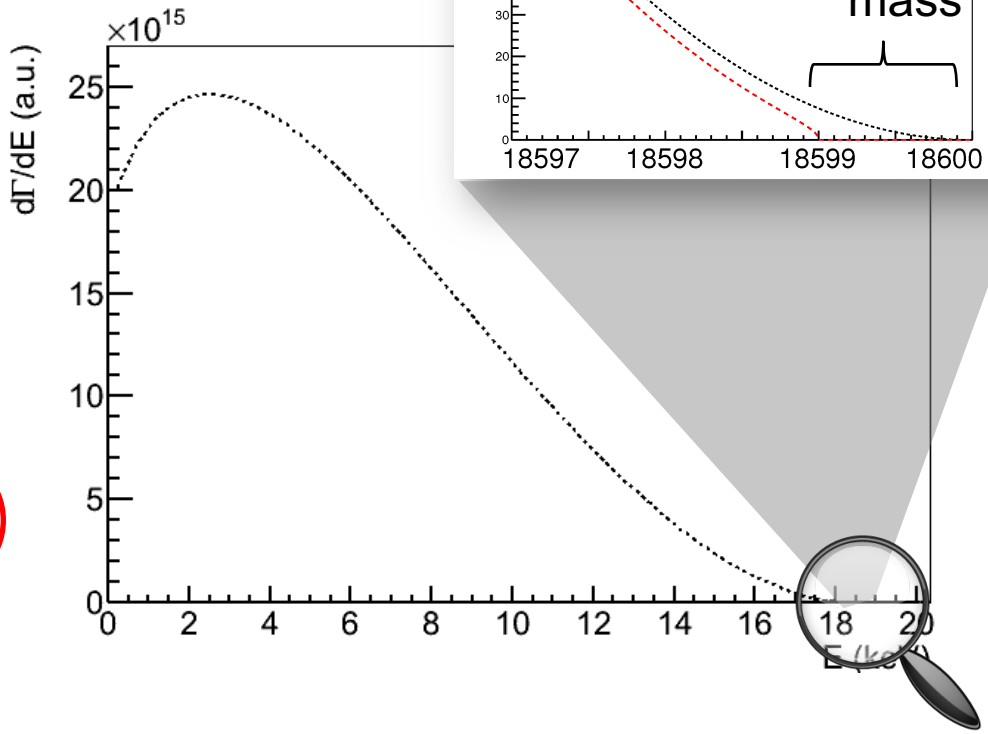
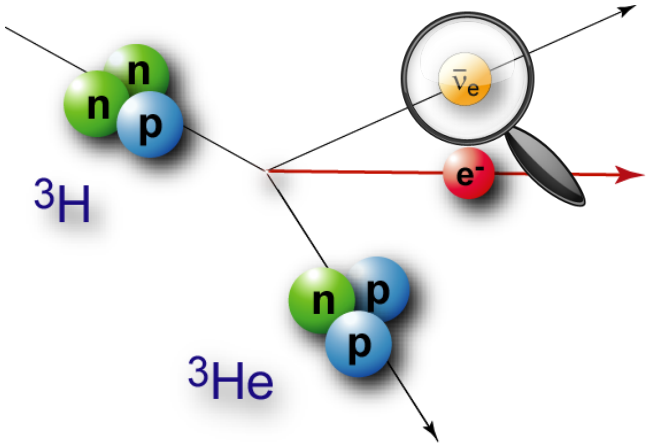
$$\cdot (E - E_0) \cdot \sqrt{(E - E_0)^2 - m_\nu^2}$$

10^{-13} of all decays in last eV



Tritium beta decay

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



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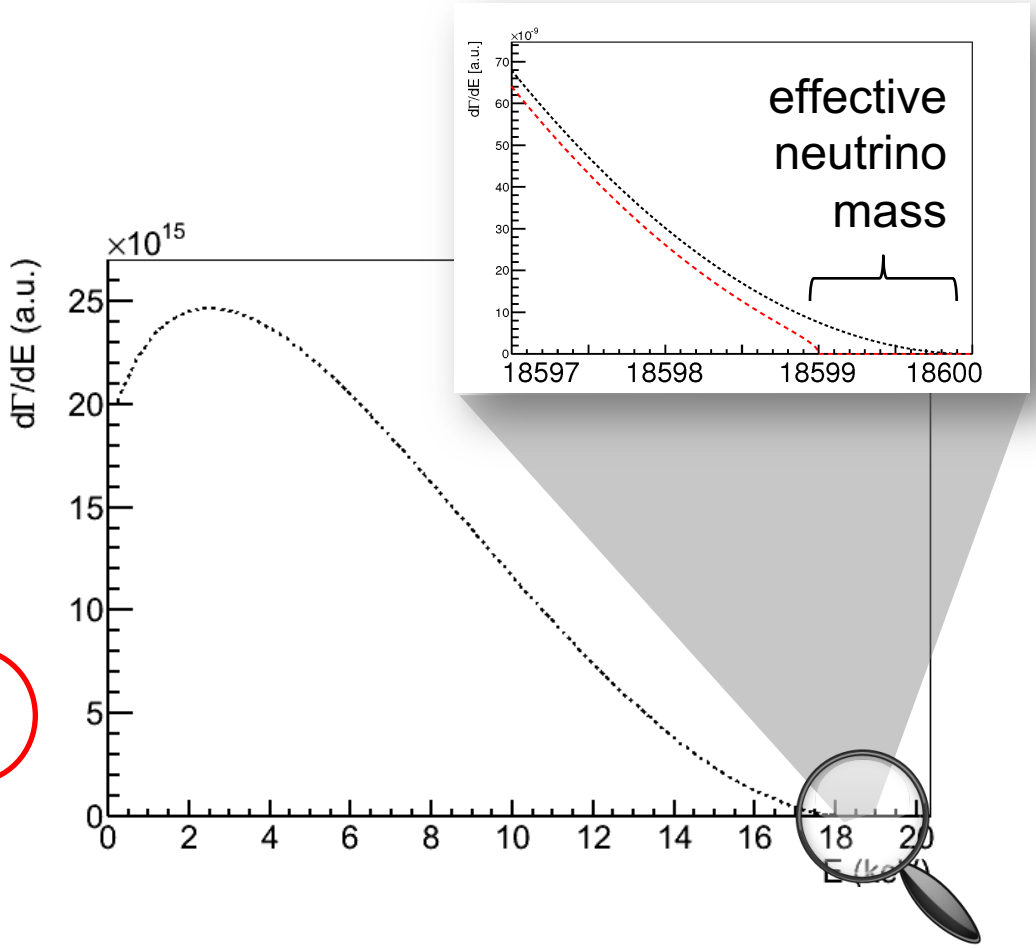
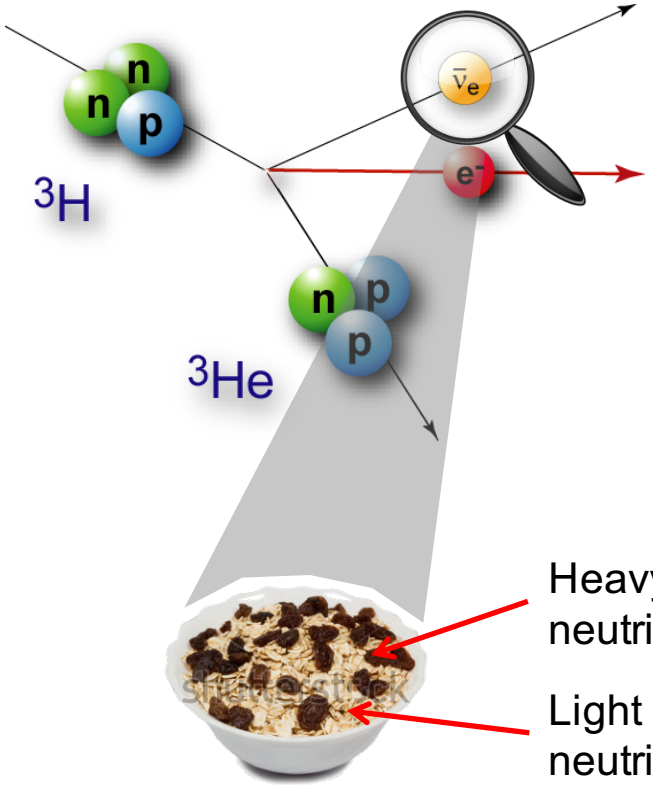


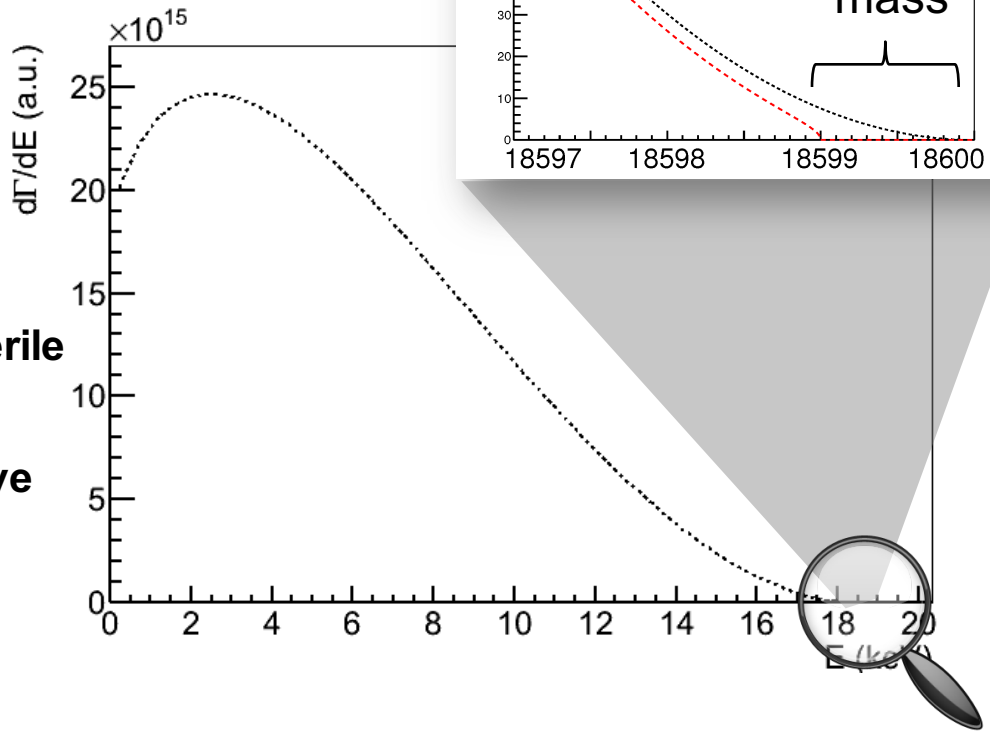
Tritium beta decay



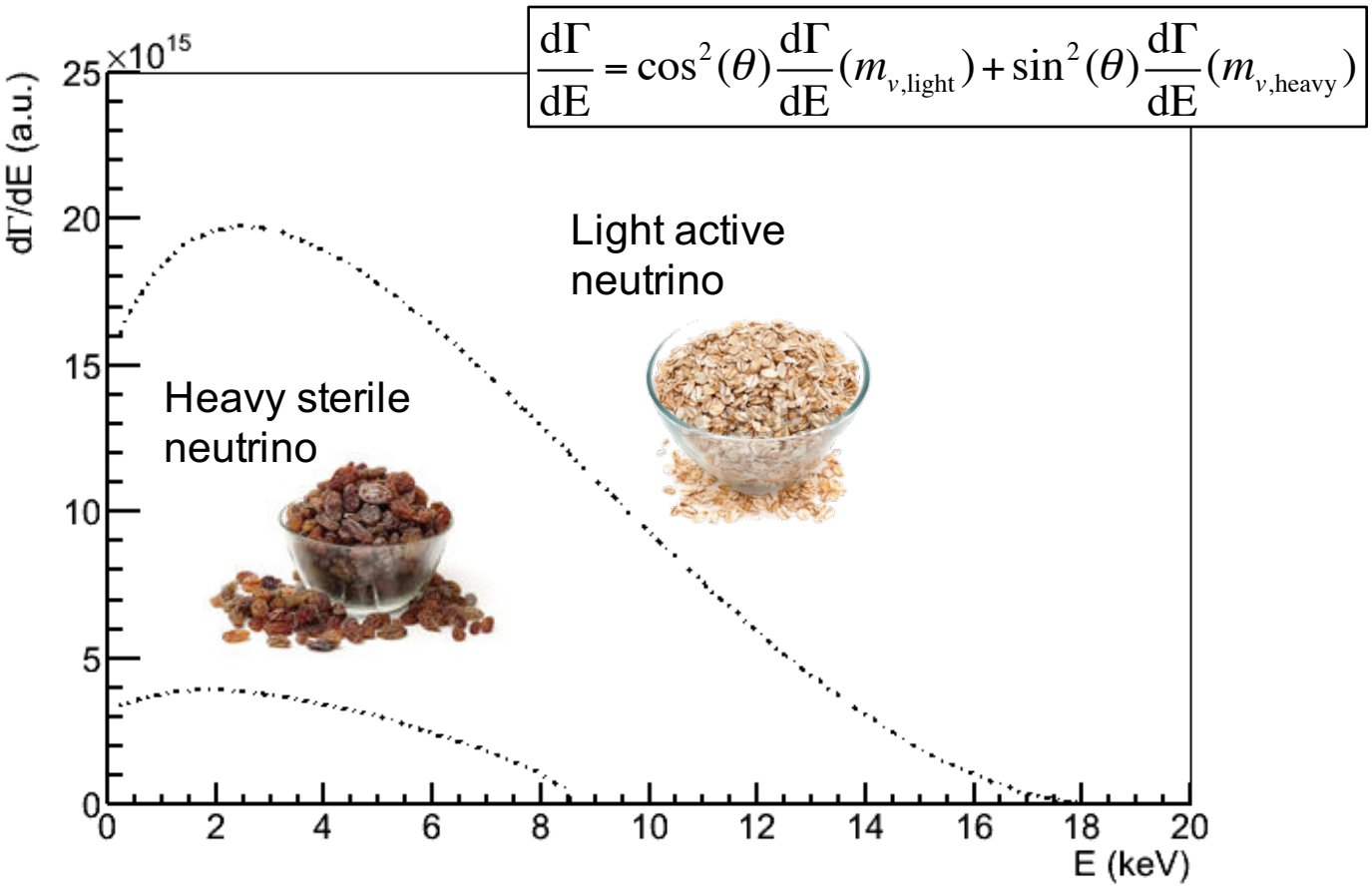
Heavy **sterile** neutrino

Light **active** neutrinos

Neutrino from tritium β-decay



Imprint of sterile ν's on ß-spectrum



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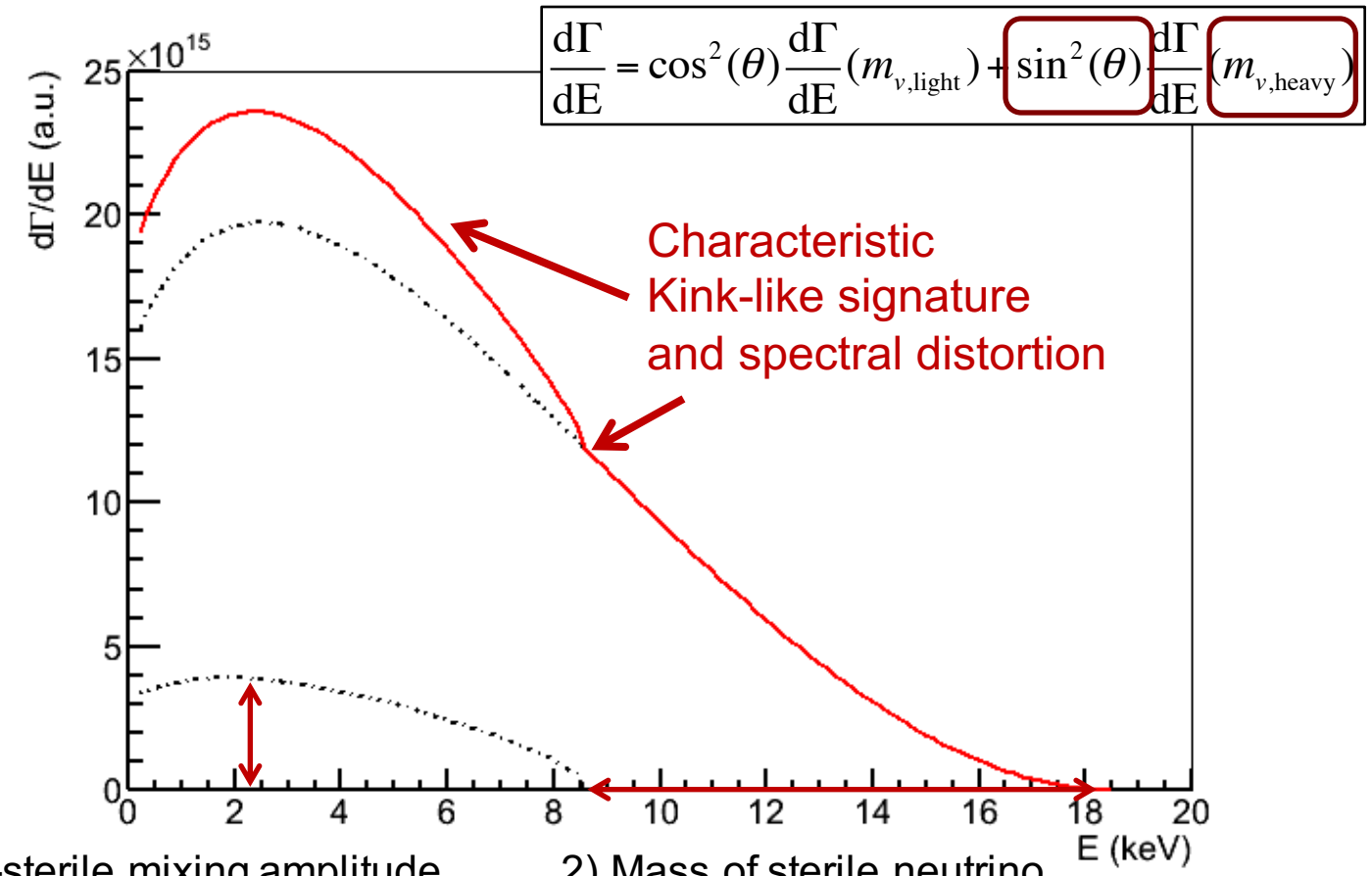
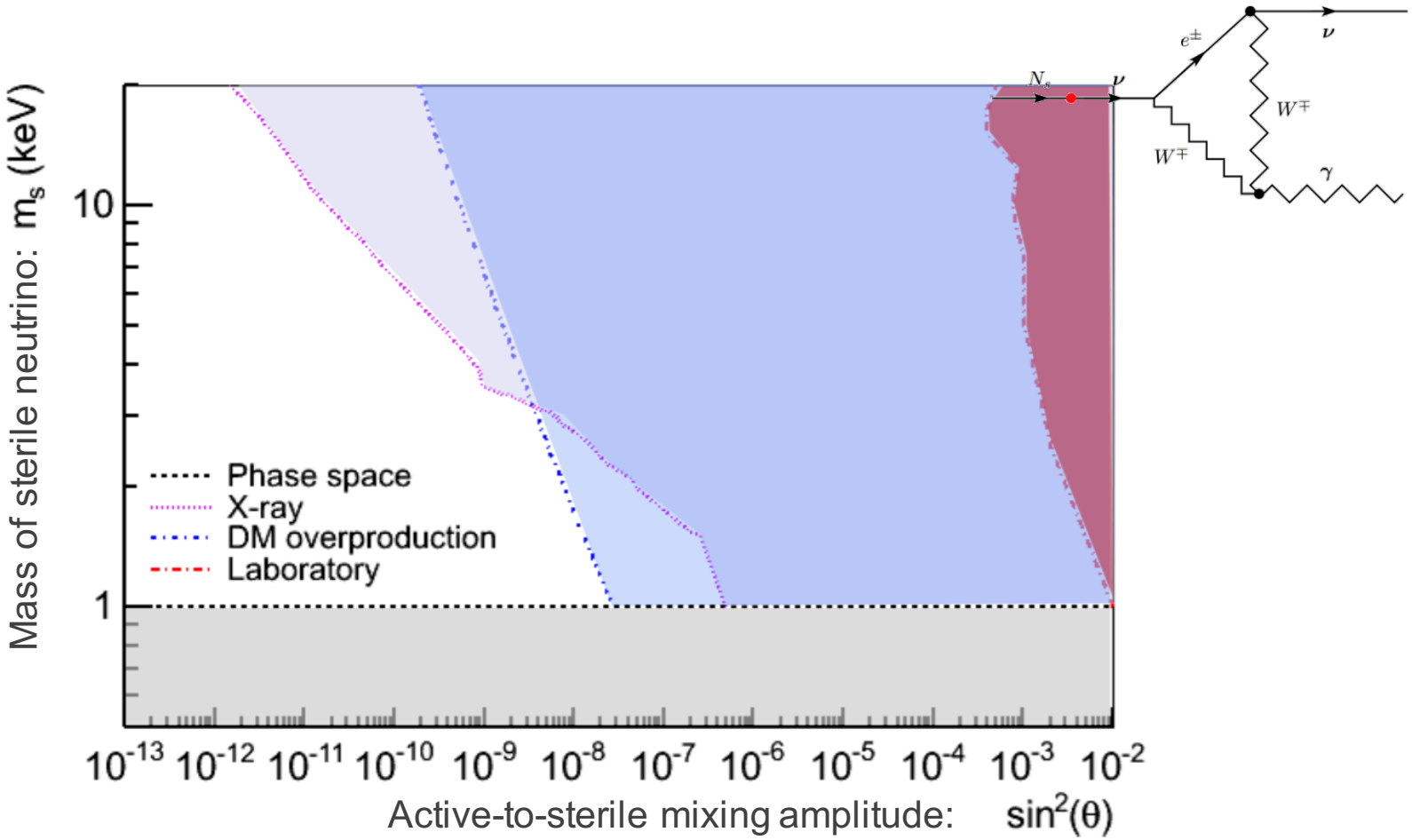


1) Active-to-sterile mixing amplitude

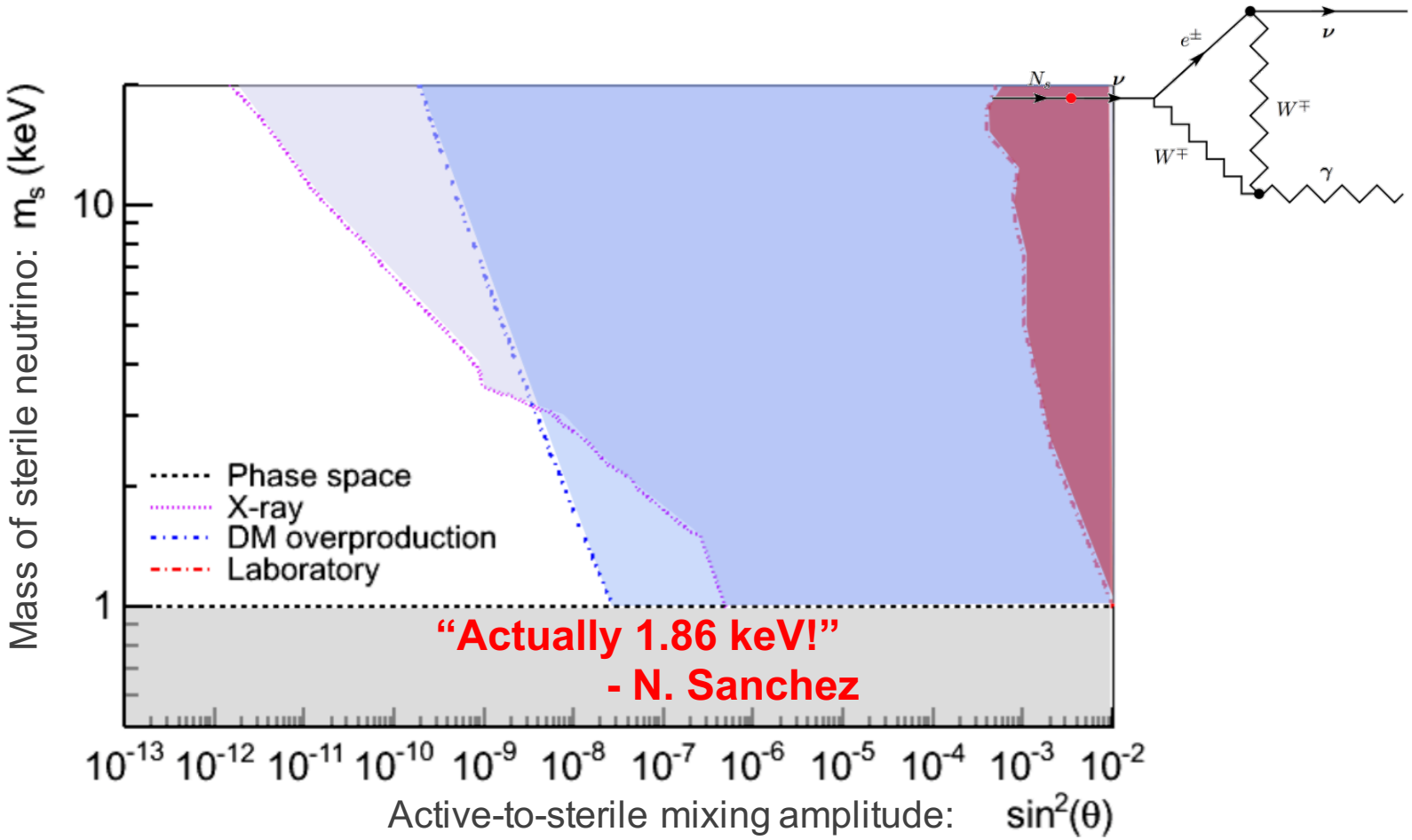
2) Mass of sterile neutrino

Cosmological constraints



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

Cosmological constraints



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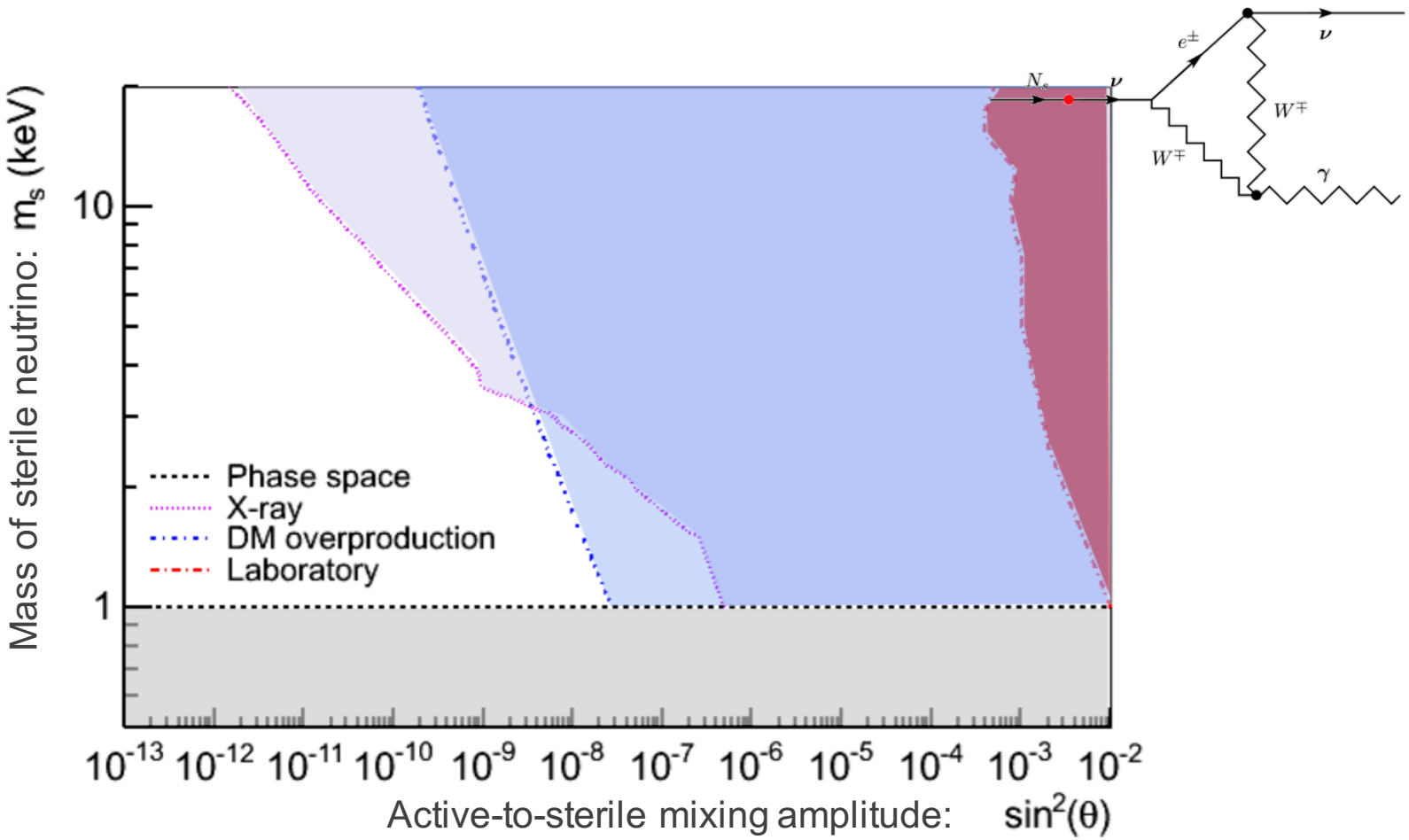

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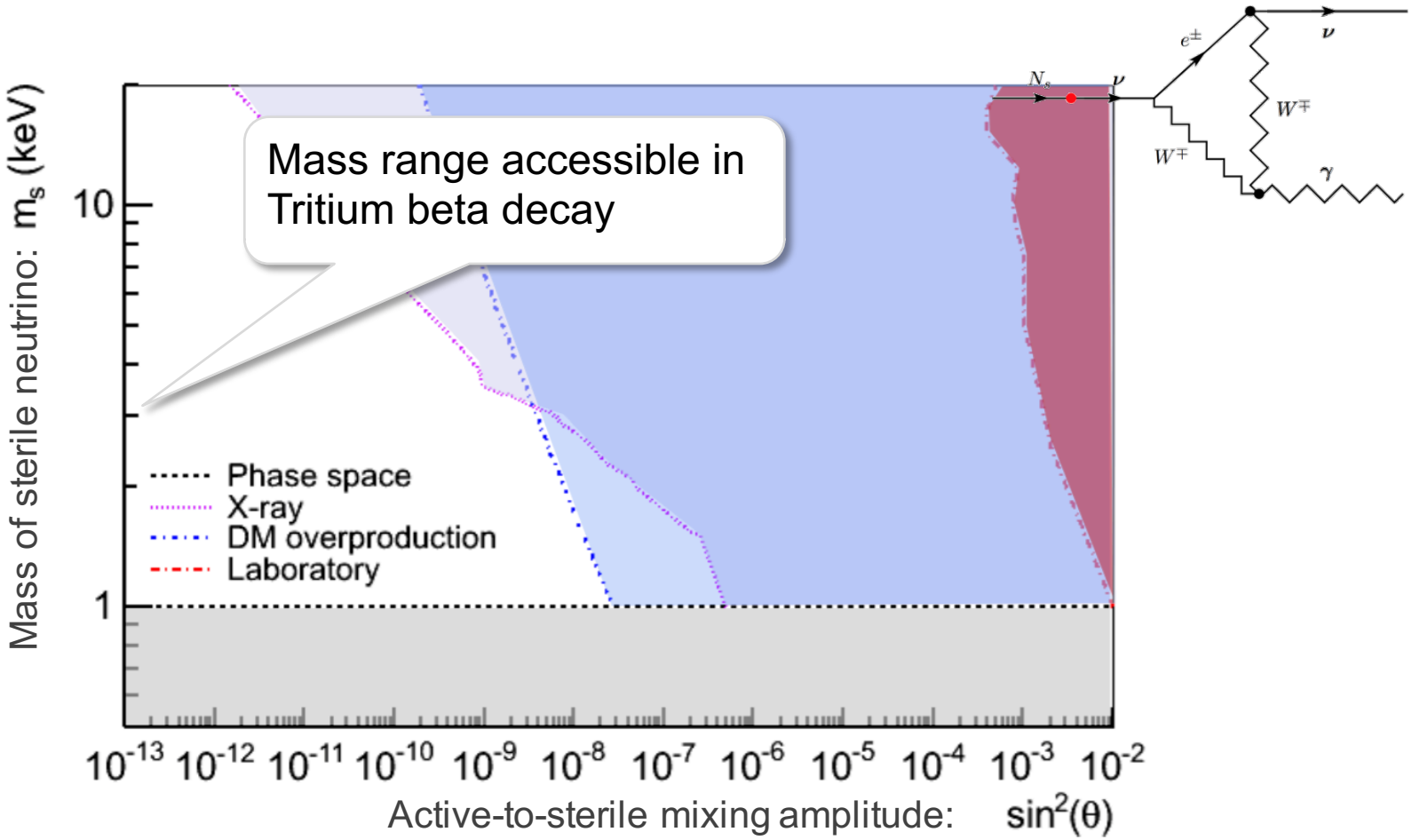

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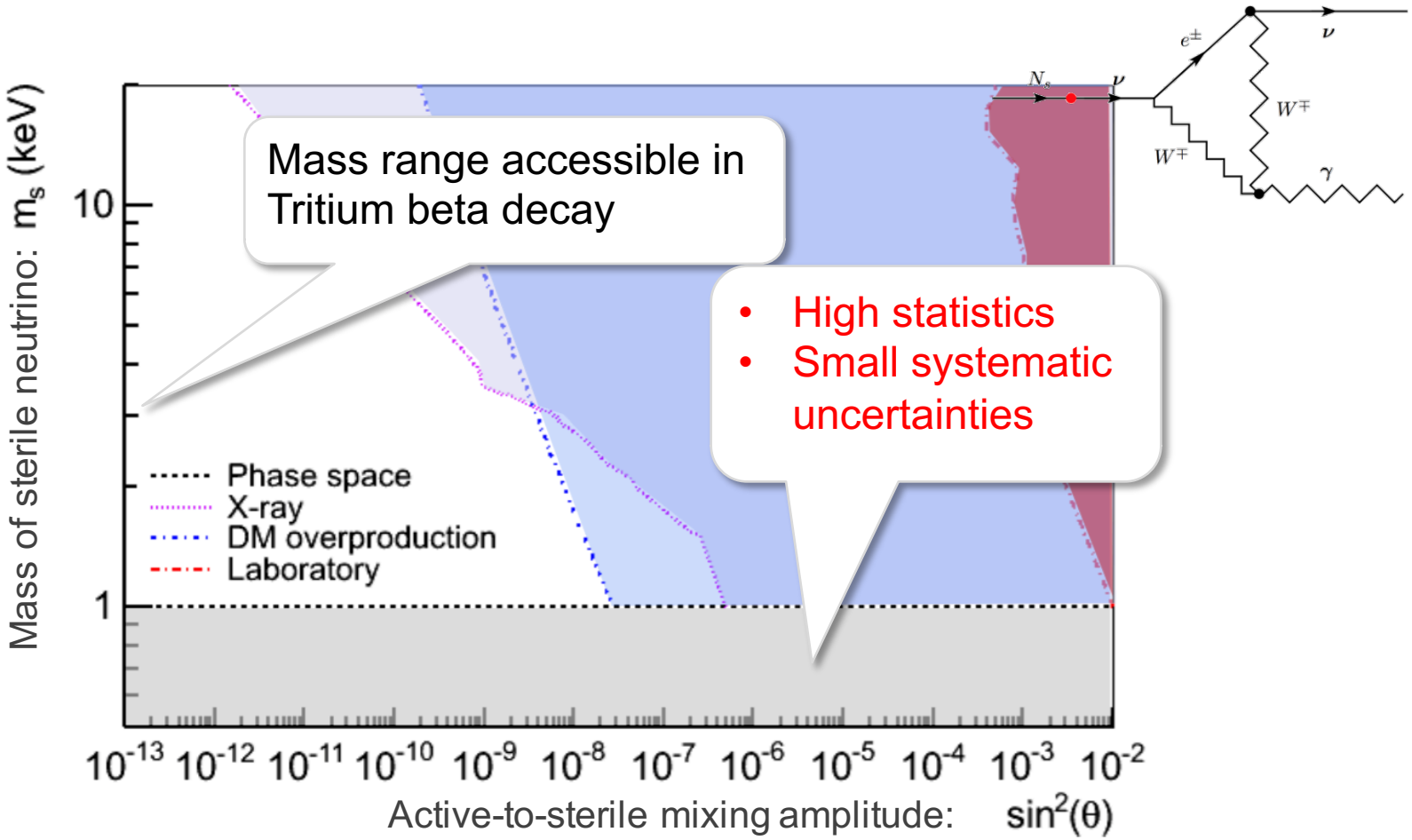
JHEP **1206** (2012) 100

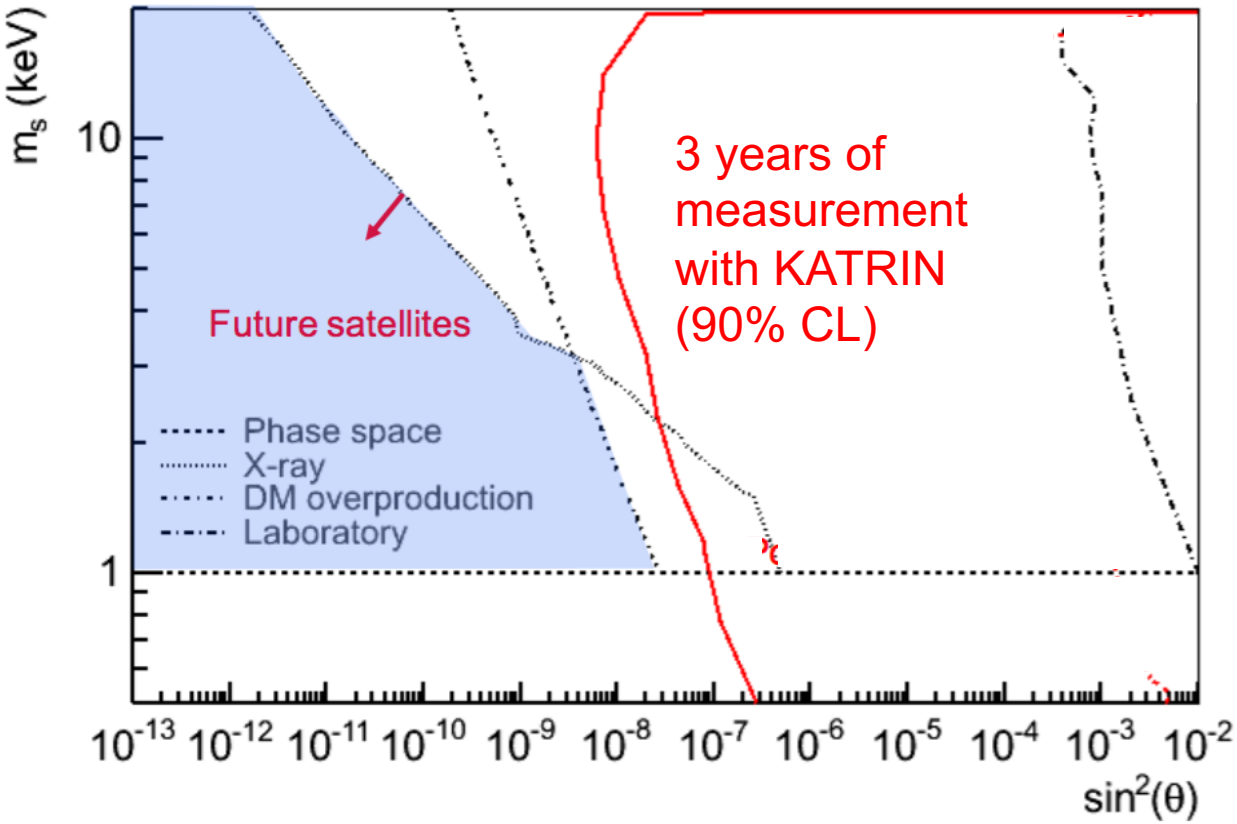
The challenge of sterile ν search



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

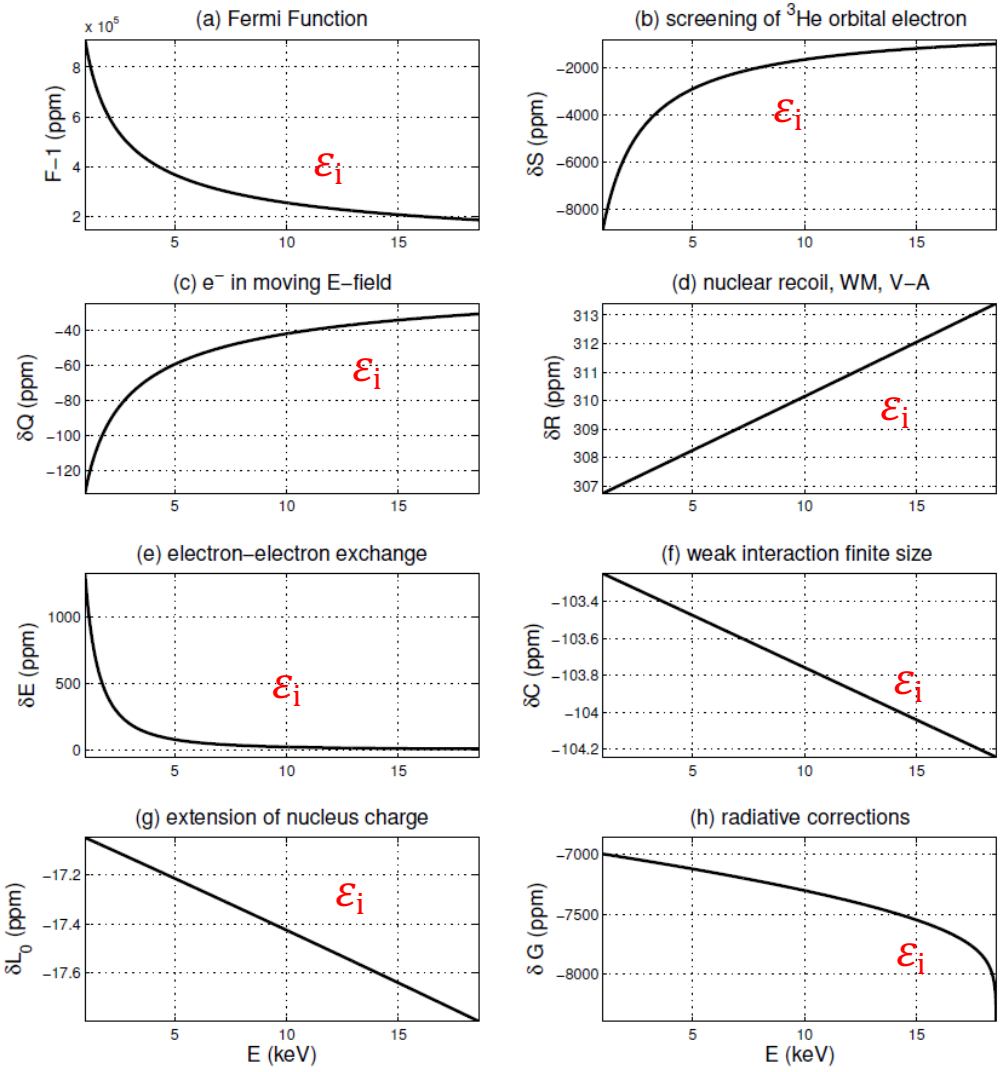
Statistical sensitivity

PRELIMINARY



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

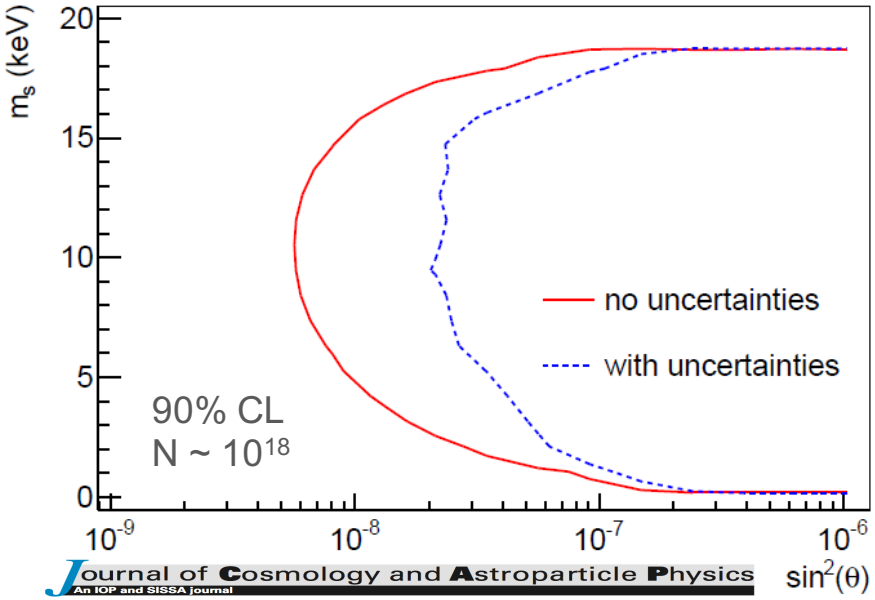
Theoretical corrections to the β-spectrum



Detailed sensitivity studies

Spectral fit approach:

„How do theoretical uncertainties impact the sensitivity to find the signature of a sterile neutrino ?“



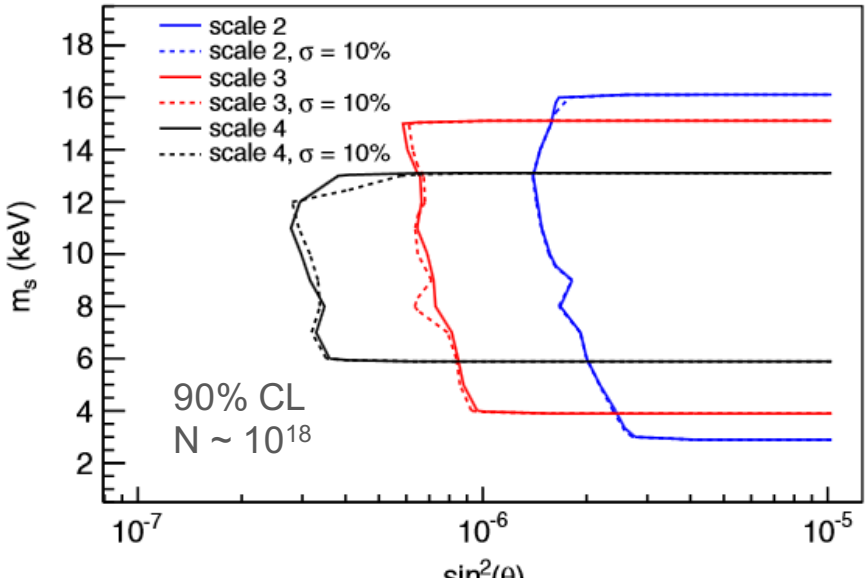
Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

Sensitivity of next-generation tritium beta-decay experiments for keV-scale sterile neutrinos

S. Mertens,[a,d] T. Lasserre,[b,c] S. Groh,[d] G. Drexlin,[d] F. Glück,[d,f] A. Huber,[d] A.W.P. Poon,[a] M. Steidl,[d] N. Steinbrink[e] and C. Weinheimer[e]

Wavelet approach:

„Is a precise knowledge of the spectrum necessary to find the signature of a sterile neutrino ?“



Wavelet Approach to Search for Sterile Neutrinos in Tritium β-Decay Spectra

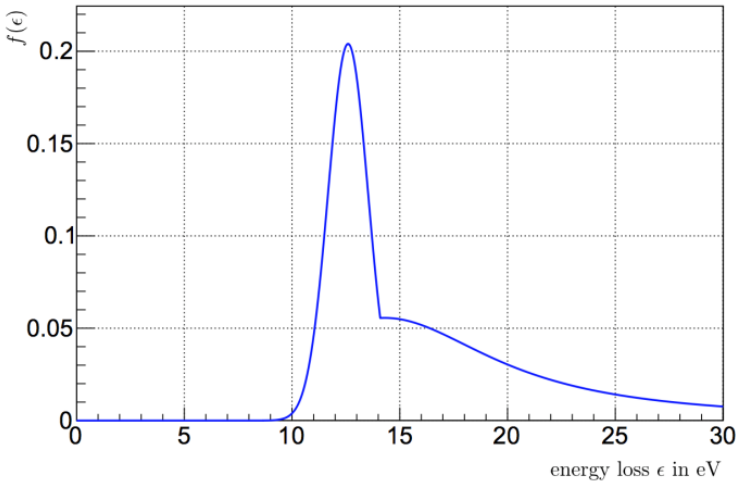
S. Mertens,[1,2] K. Dolde,[2] M. Korzeczek,[2] F. Glueck,[2,3] S. Groh,[2] R. D. Martin,[1,*] A. W. P. Poon,[1] and M. Steidl[2]

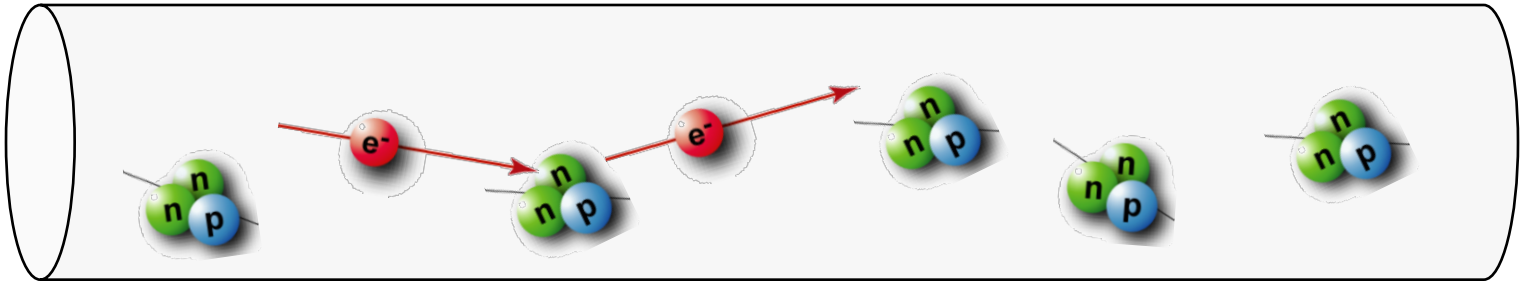
[1] *Institute for Nuclear and Particle Astrophysics, Nuclear Science Division, Lawrence Berkeley National Laboratory, USA*
[2] *Institute for Nuclear Physics (IKP), Karlsruhe Institute of Technology, Germany*
[3] *Wigner Research Institute for Physics, P. O. B. 49, H-1525 Budapest, Hungary*

Ongoing sensitivity studies

Systematic effects related to :

- Source Section
  - scattered electrons arrive at detector





Ongoing sensitivity studies

Systematic effects related to :

- Source Section
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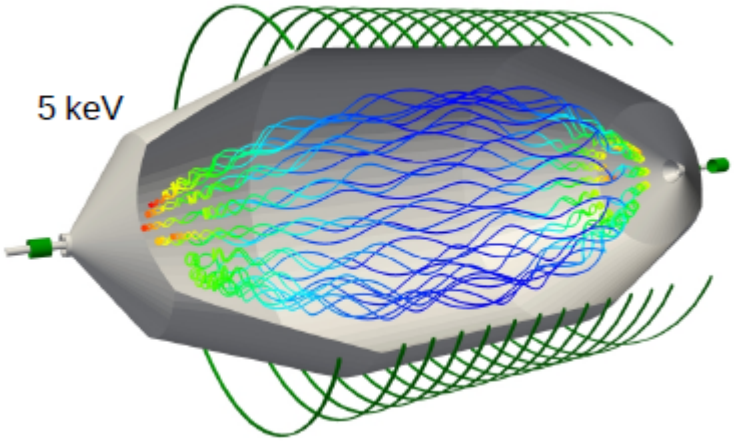
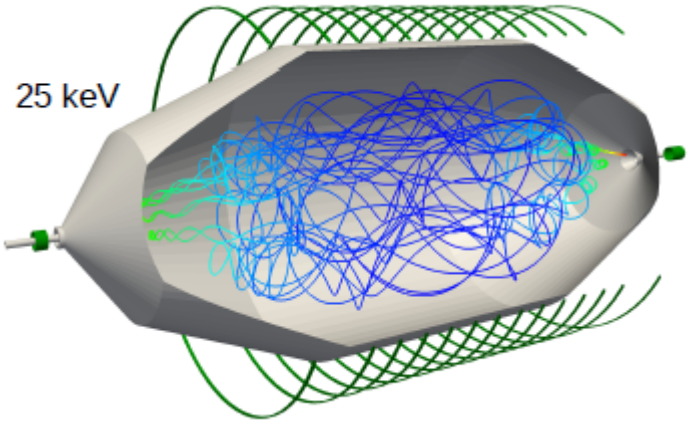
- Spectrometer Section
  - electrons pass through spectrometer with high surplus energy





Ongoing sensitivity studies

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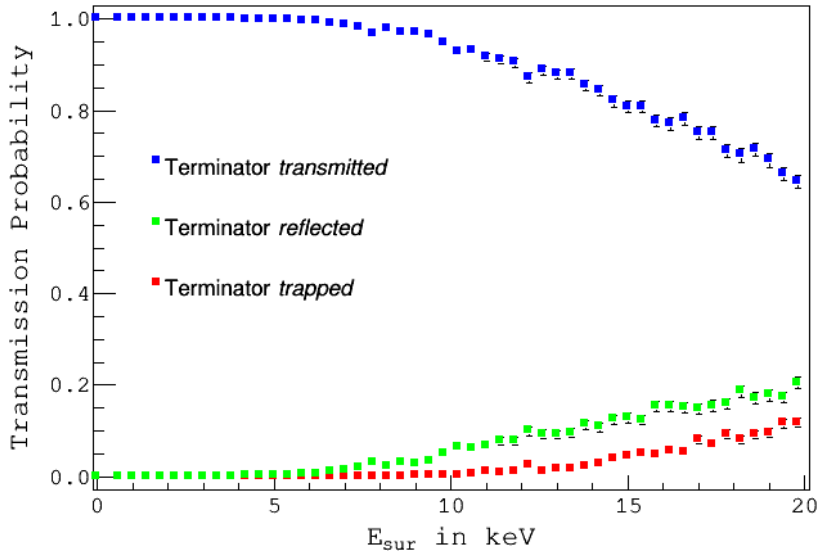

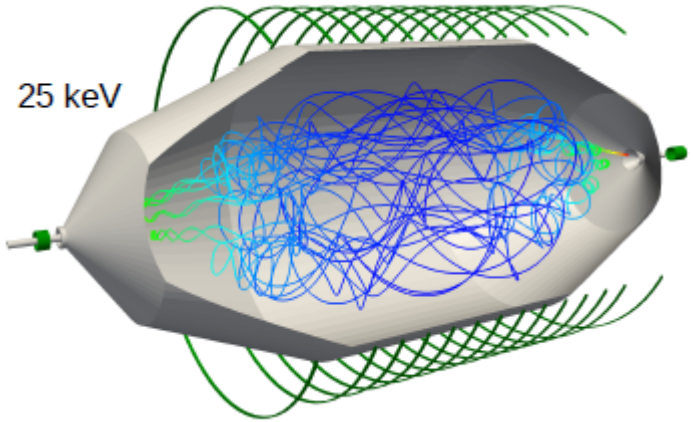

Ongoing sensitivity studies

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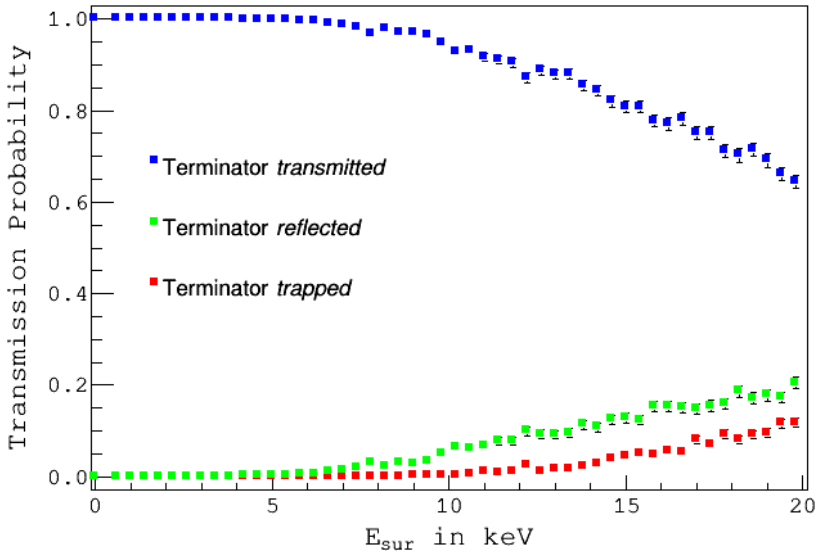
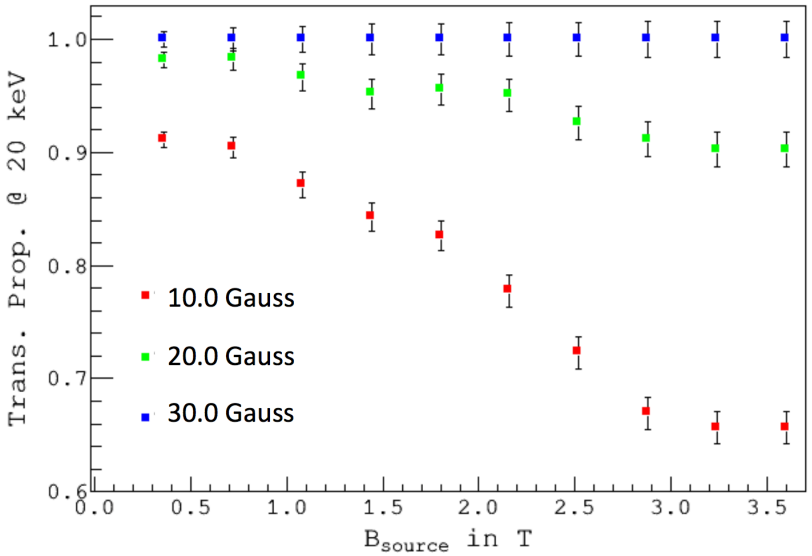




Ongoing sensitivity studies

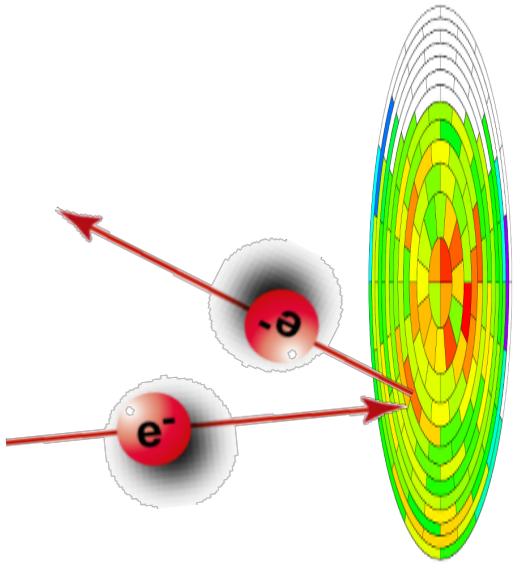
Systematic effects related to :

- 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.

completed Anton Huber Masters Thesis

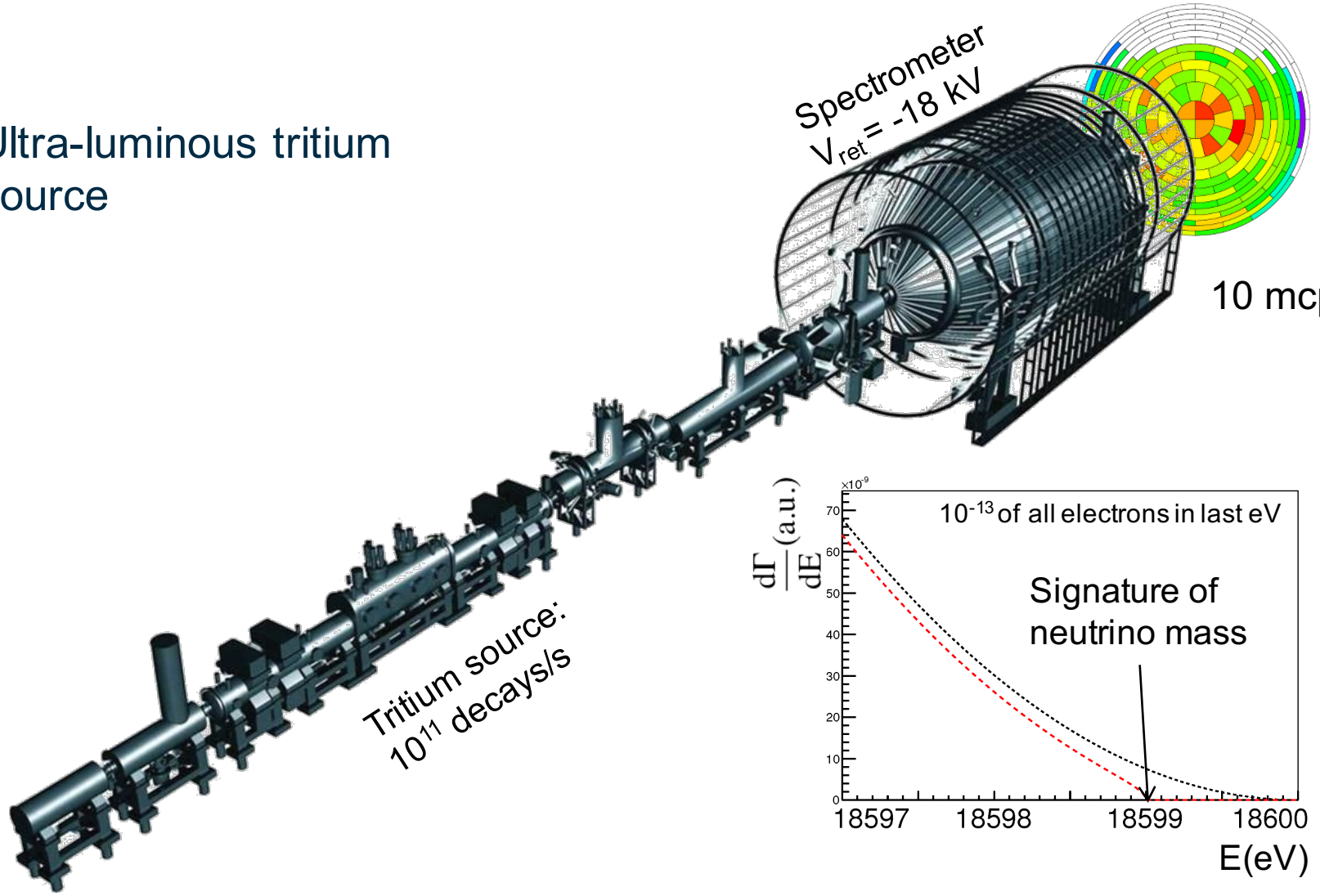
completed Kai Dolde Masters Thesis

… to be published soon



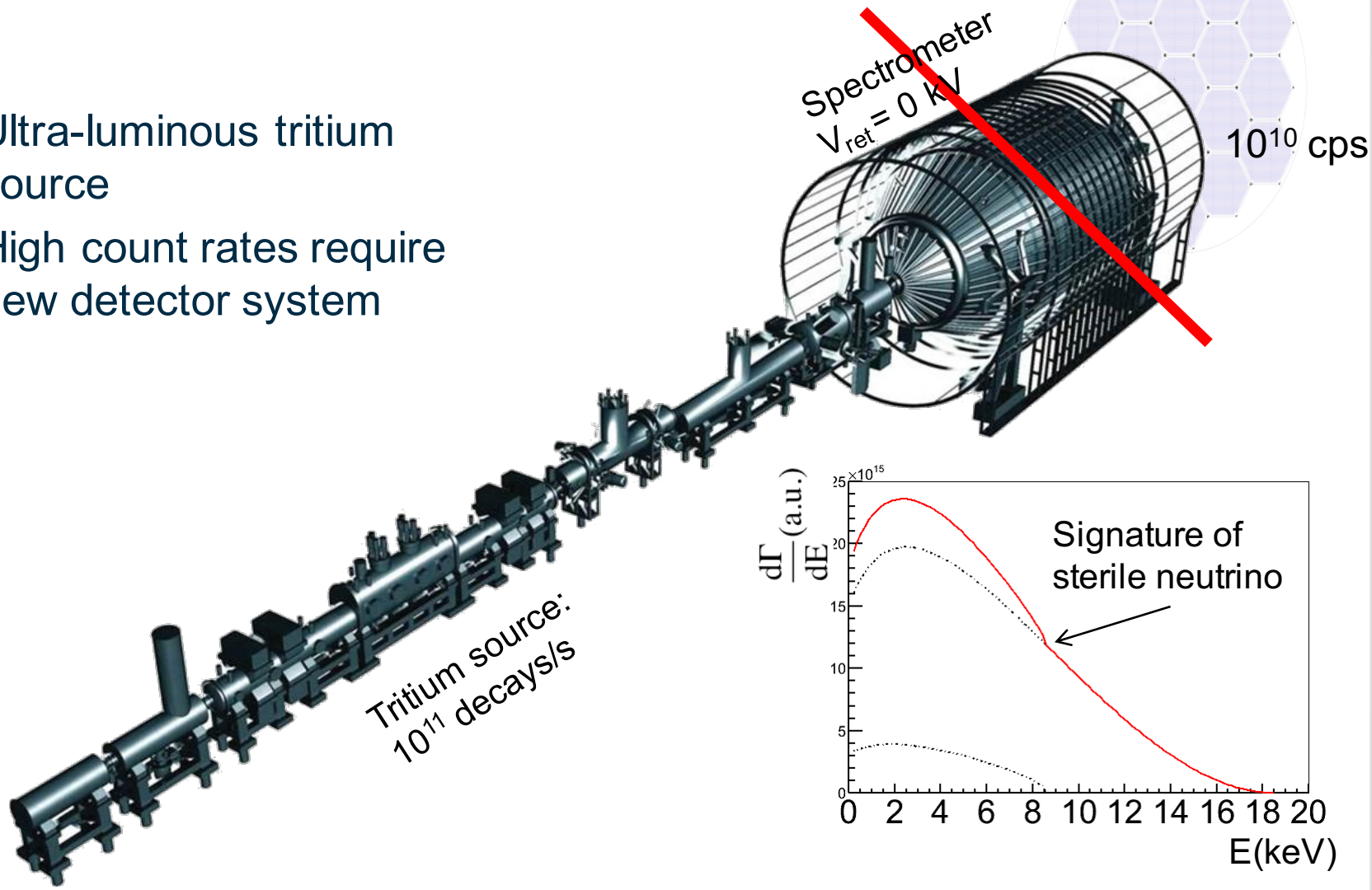
How to use KATRIN

- Ultra-luminous tritium source



How to use KATRIN

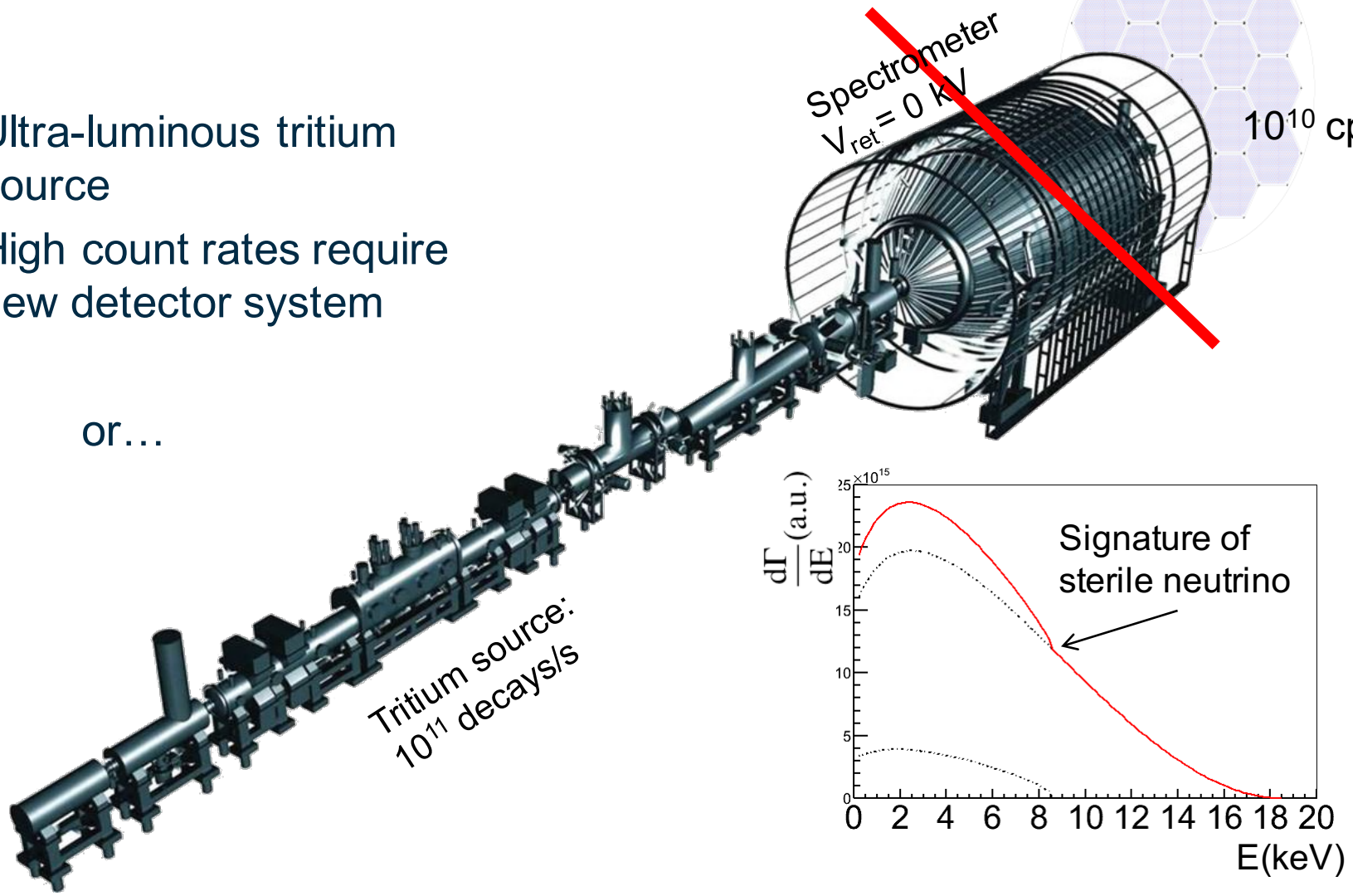
- Ultra-luminous tritium source
- High count rates require new detector system



How to use KATRIN

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

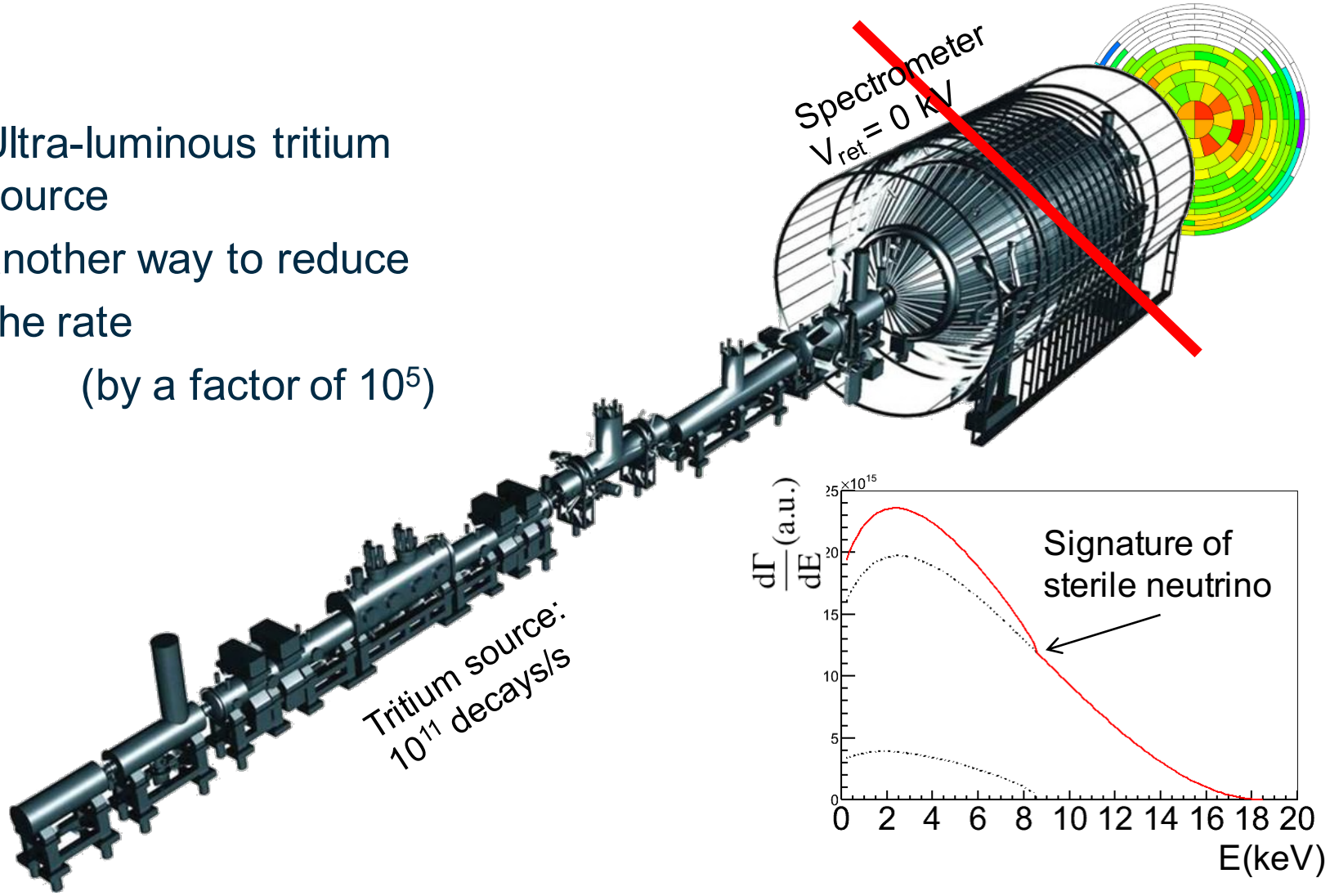
or…



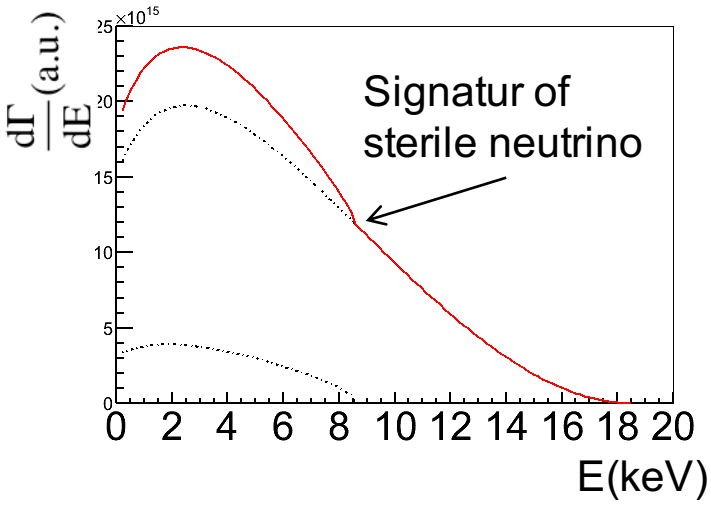
How to use KATRIN

- Ultra-luminous tritium source
- another way to reduce the rate

  (by a factor of 10^5)



How to use KATRIN



A **Pre** KATRIN Measurement

> will be performed very soon
> requiers a 'improvised' rate reduction

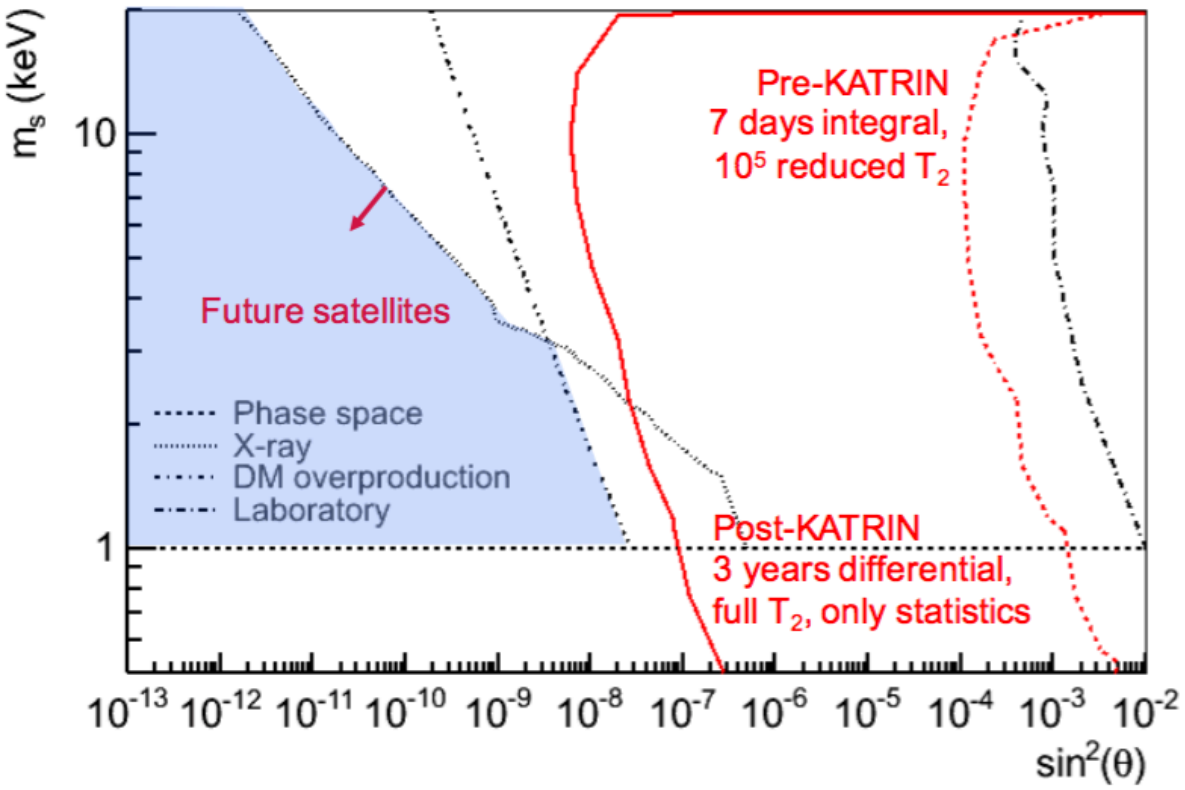
A **Post** KATRIN Measurement

> requiers a new detector system
> will be performed after KATRIN determined the neutrino mass

Preliminary Sensitivty

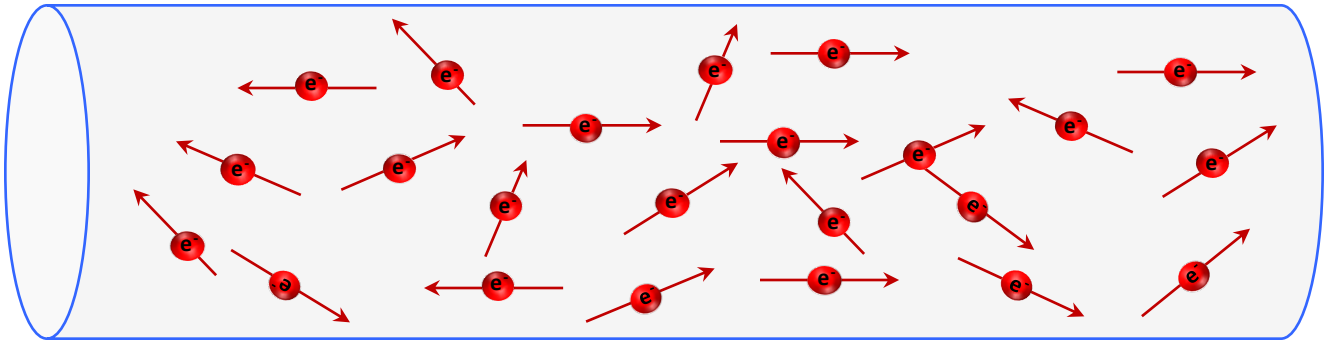
A **Pre** KATRIN Measurement

A **Post** KATRIN Measurement

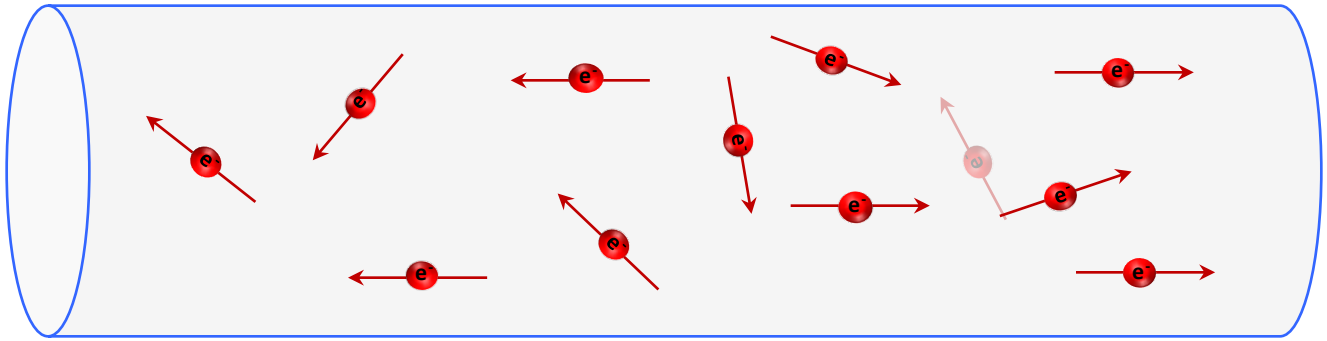


How to reduce the Rate – Pre-Measurement

Standard KATRIN source



modified source

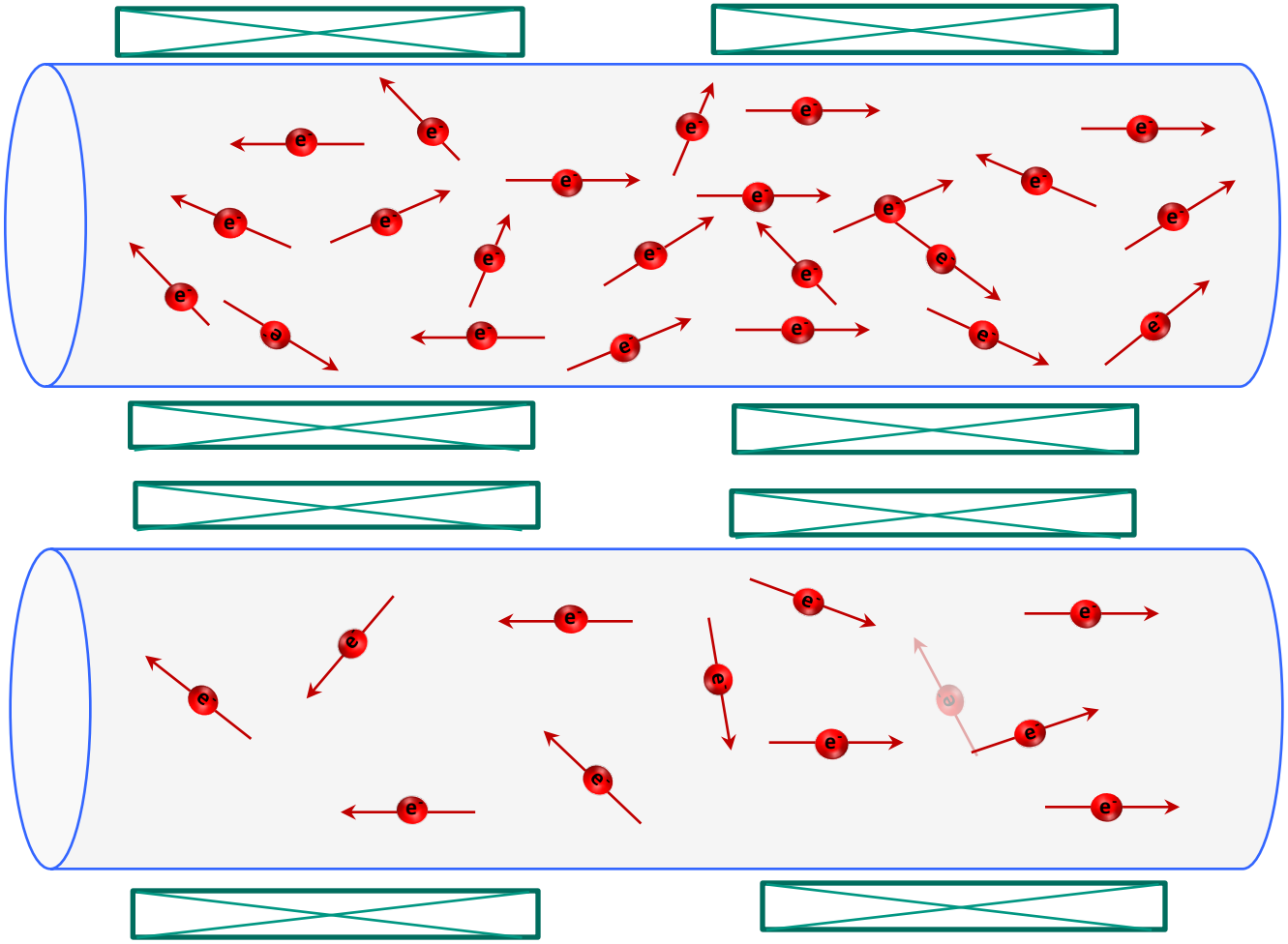


less tritium in source

How to reduce the Rate – Pre-Measurement

Standard KATRIN

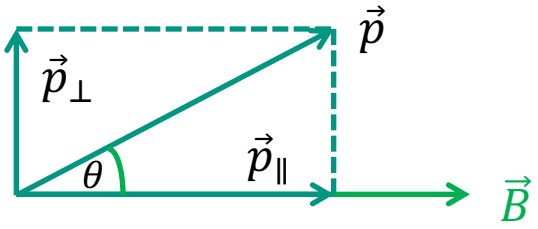
$B_{source} = 3.6\ T$



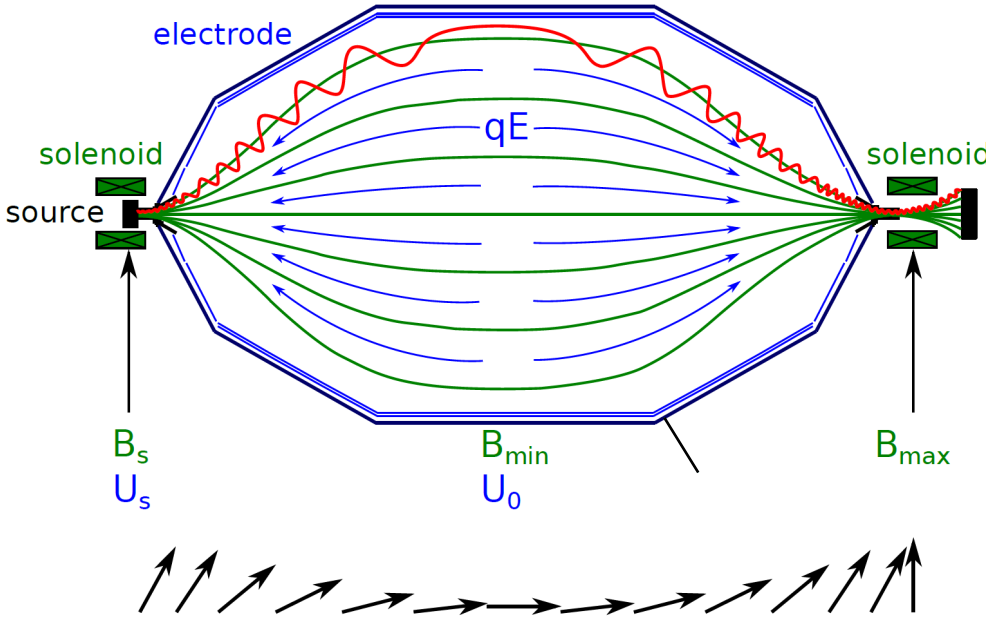
Modified source

$B_{source} = 0.03\ T$

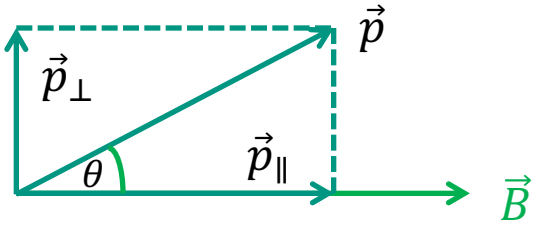
How to reduce the Rate – Pre-Measurement

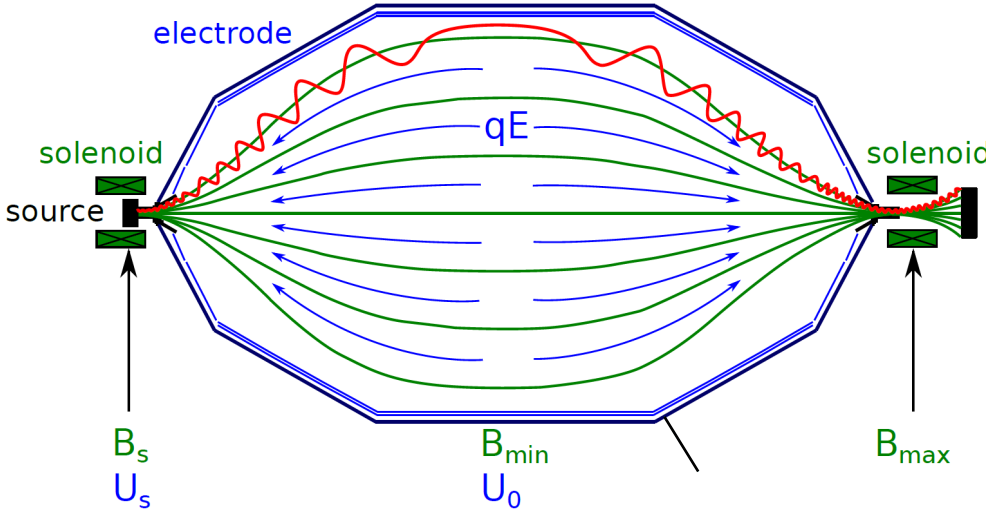


$$\theta_{max} = \sin^{-1}\sqrt{\frac{B_{ini}}{B_{max}}}$$

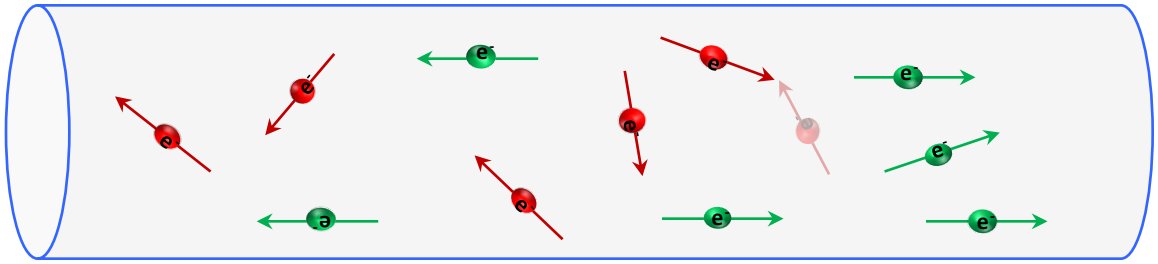


How to reduce the Rate – Pre-Measurement



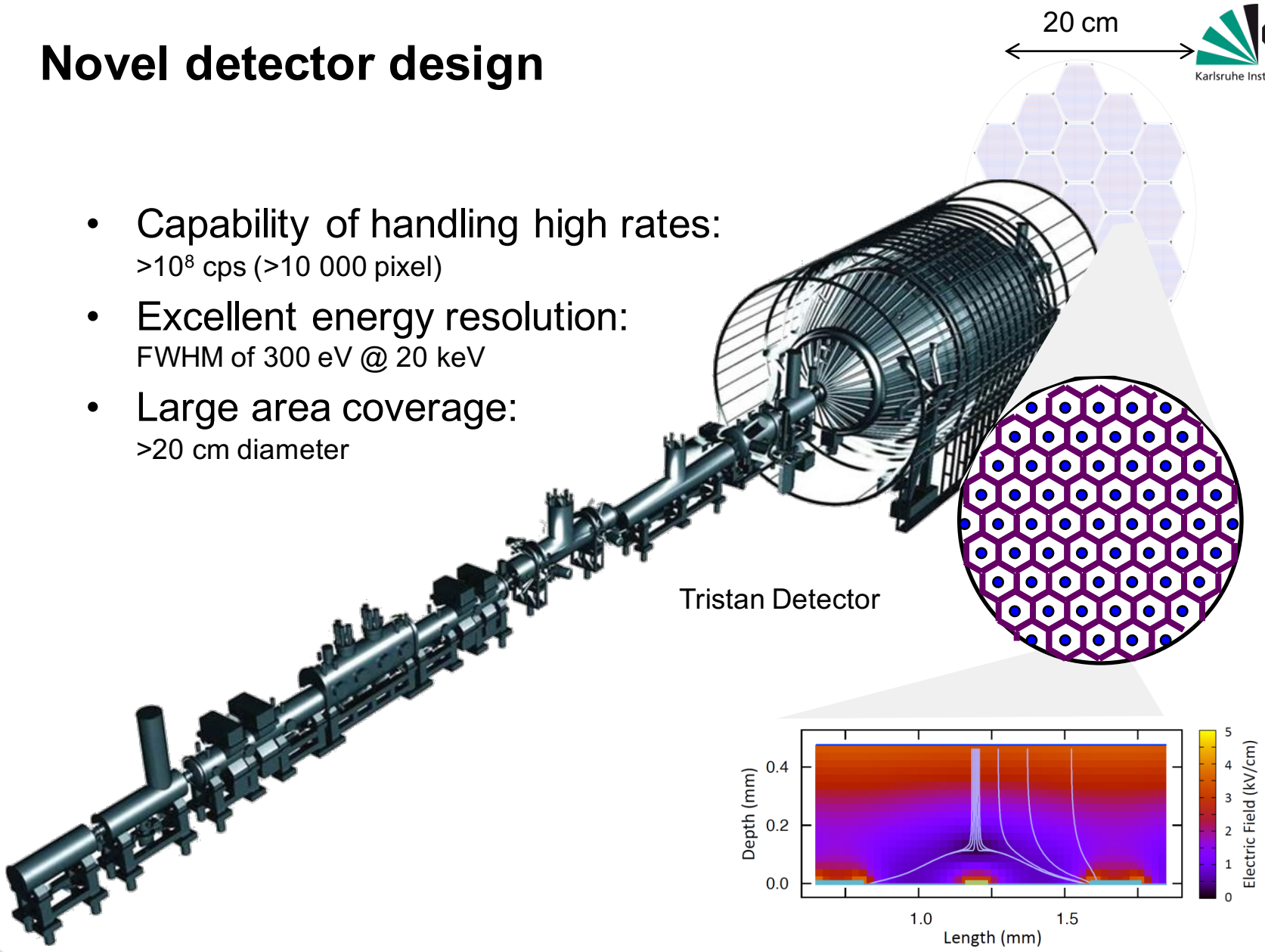


$$\theta_{max} = \sin^{-1}\sqrt{\frac{B_{ini}}{B_{max}}}$$



Novel detector design

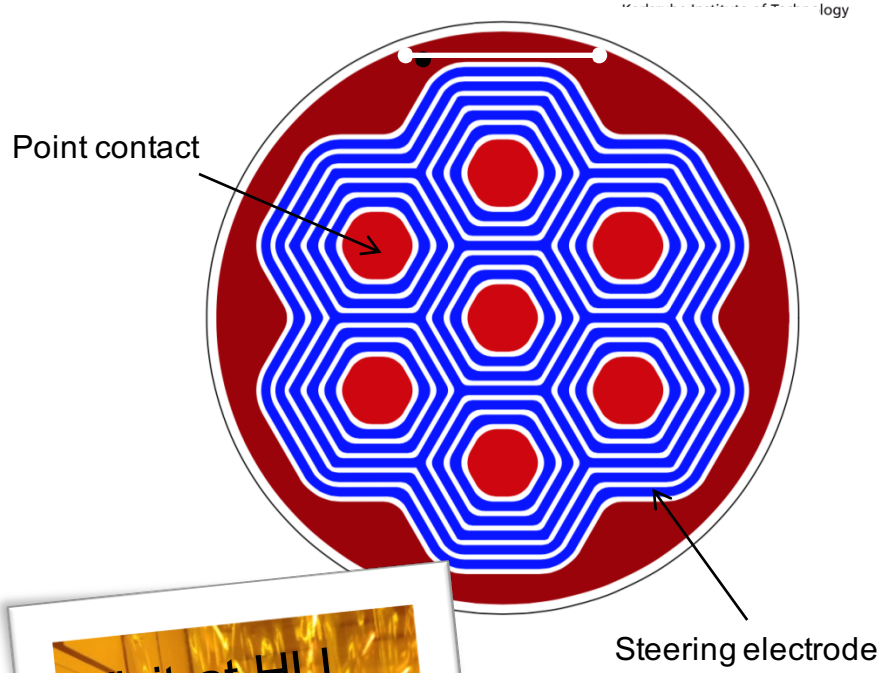
- Capability of handling high rates:
  >10^8 cps (>10 000 pixel)
- Excellent energy resolution:
  FWHM of 300 eV @ 20 keV
- Large area coverage:
  >20 cm diameter



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 was built in October last year
- Characterize pile-up, backscattering, charge-sharing, etc.

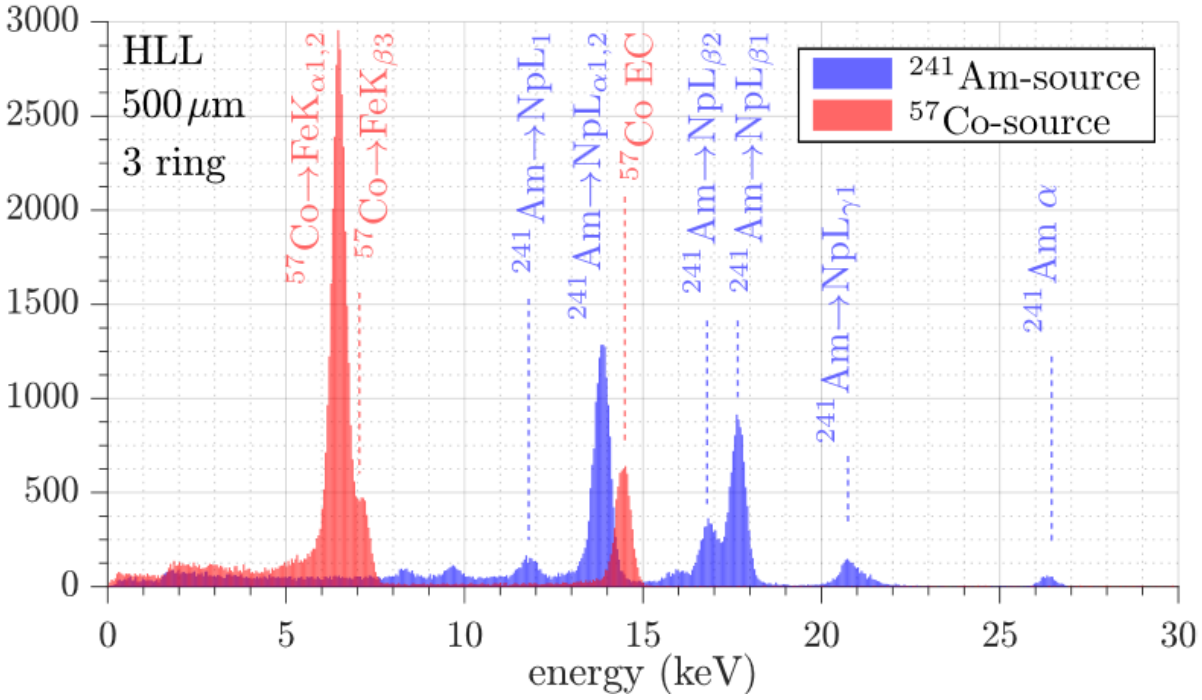


Prototype supported by Research Seed Capital funding of MWK Baden Württemberg

TRISTAN Prototype

> test setups at KIT & CEA

FWHM of 400 eV @ 6 keV

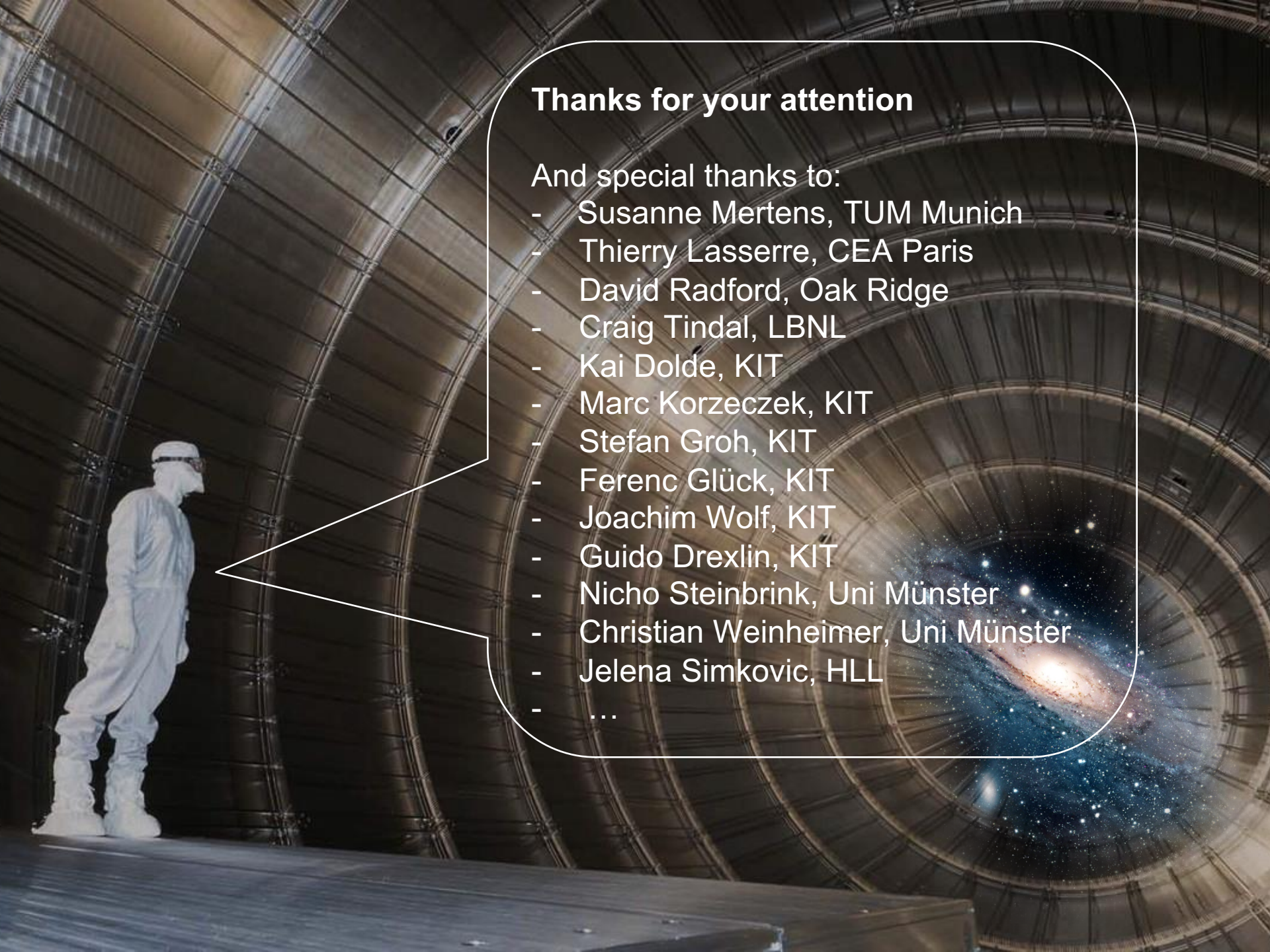


‚First Light' of TRISTAN Prototype measured at CEA

Summary & Conclusion

- The KATRIN Experiment Status
  - All components on-site
  - Alignment and final comissioning at the moment
  - Detailed calibration measurements sheduled for end of this year

- The KATRIN Experiment and sterile neutrinos
  - with the KATRIN source: statistical sensitivity $\sin^2\theta < 10^{-8}$
  - Study of systematic uncertainties is ongoing (goal is to optimize the experiment to reach a sensitivity of $\sin^2\theta < 10^{-6}$
  - Two measurement ideas: a Pre- and a Post-measurement
  - Pre-Measurement will take place mid 2017 (preliminary: $\sin^2\theta < 10^{-4}$)
  - A new detector system (TRISTAN) is currently developed at KIT, CEA and Munich



Thanks for your attention

And special thanks to:

- Susanne Mertens, TUM Munich
- Thierry Lasserre, CEA Paris
- David Radford, Oak Ridge
- Craig Tindal, LBNL
- Kai Dolde, KIT
- Marc Korzeczek, KIT
- Stefan Groh, KIT
- Ferenc Glück, KIT
- Joachim Wolf, KIT
- Guido Drexlin, KIT
- Nicho Steinbrink, Uni Münster
- Christian Weinheimer, Uni Münster
- Jelena Simkovic, HLL
- …

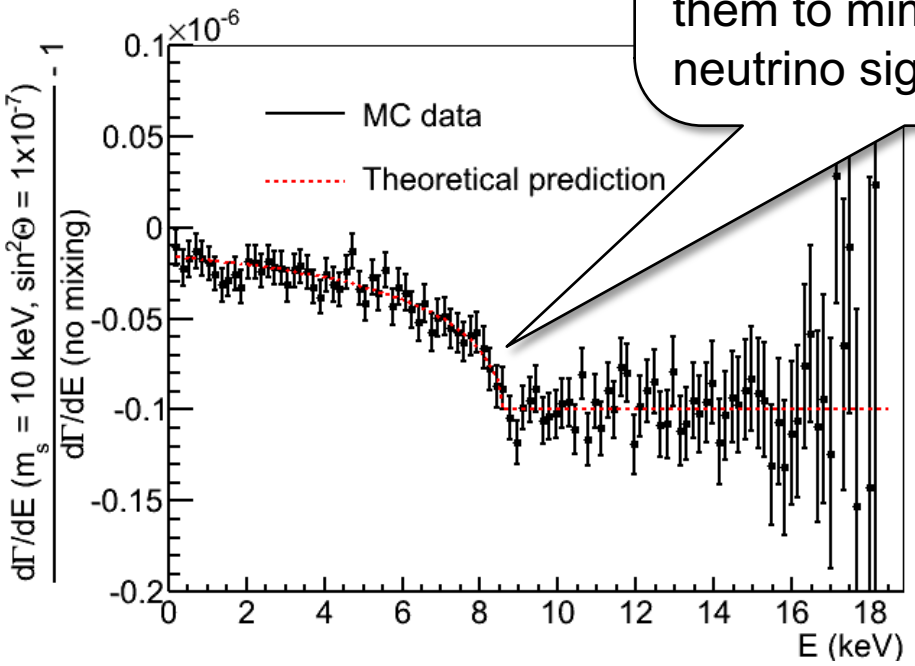
The entire KATRIN Collaboration

Back up Slides

Systematic uncertainties

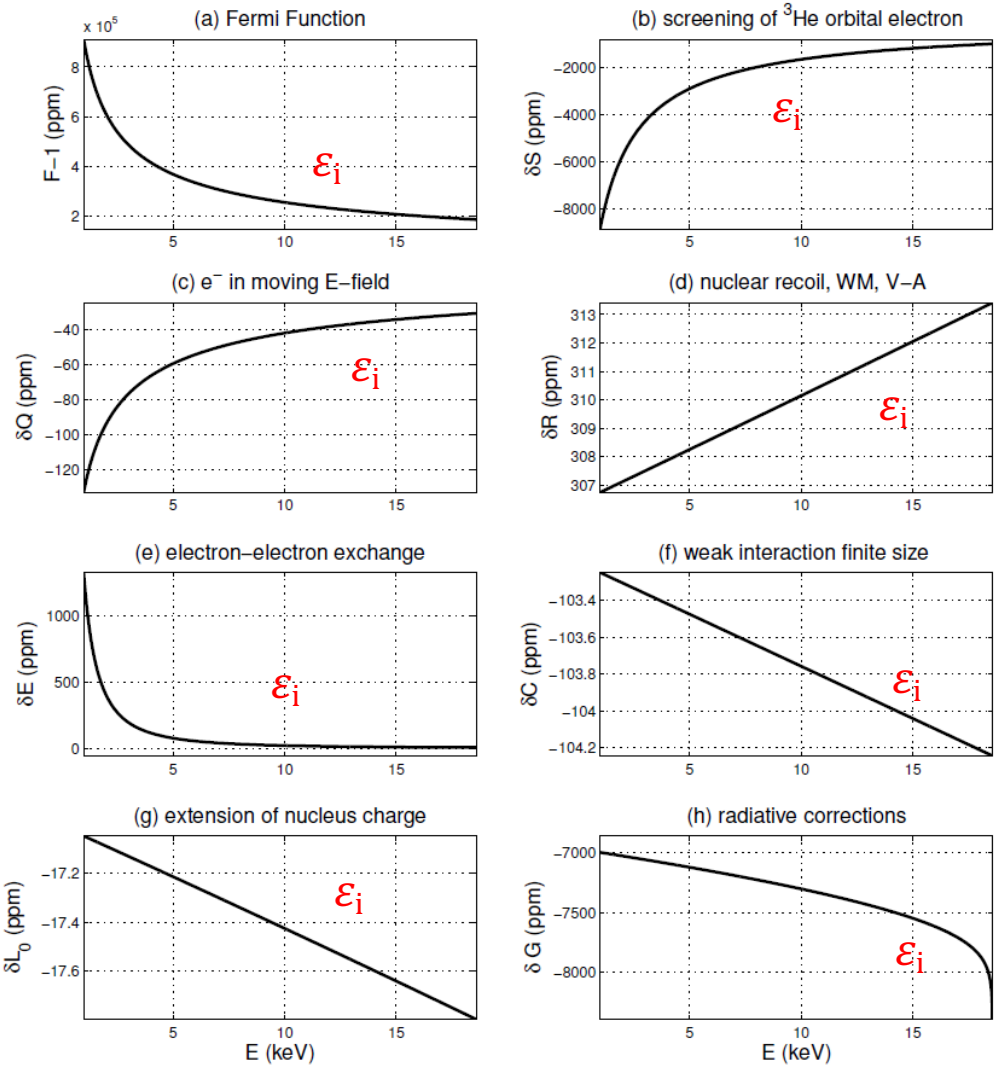
1. Knowledge of the theoretical spectrum?

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

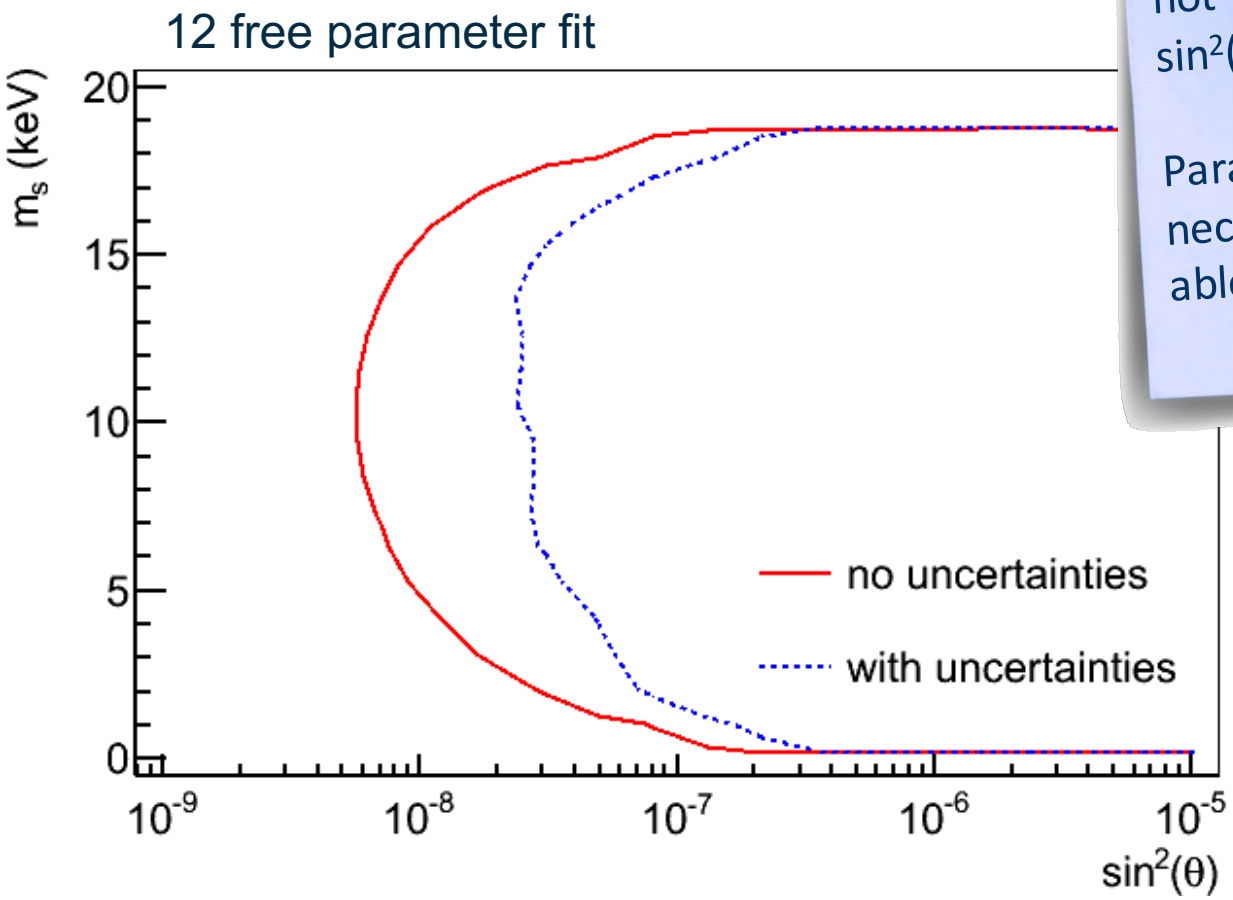


Theoretical corrections to the β-spectrum

Non-negligible
BUT
smooth
in energy



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

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

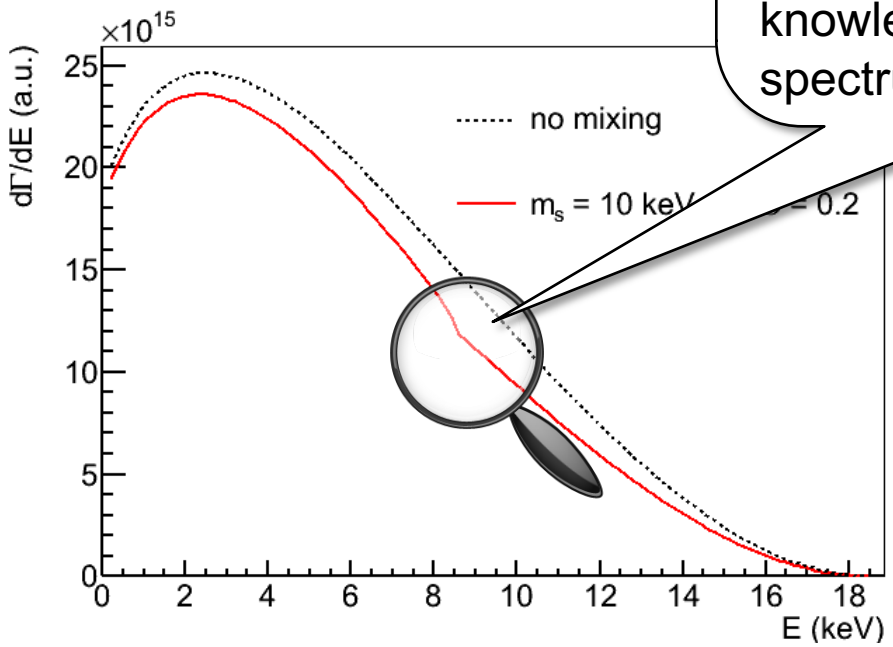
S. M. *et al.* JCAP 1502 (2015) 02, 020, arXiv:1409.0920

Systematic uncertainties

1. Knowledge of the theoretical spectrum?

2. Is this knowledge necessary at all?

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



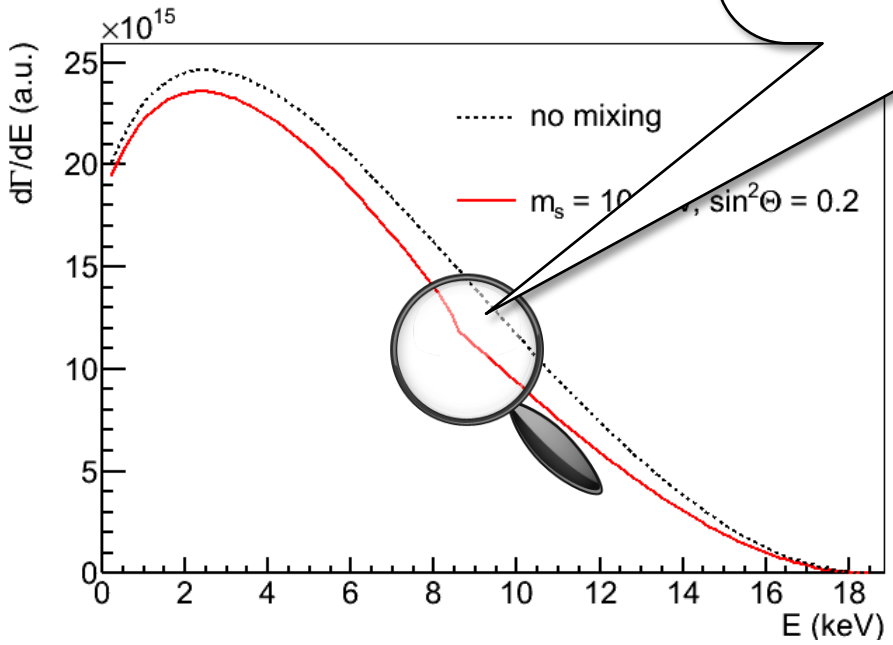
Systematic uncertainties

1. Knowledge of the theoretical spectrum?

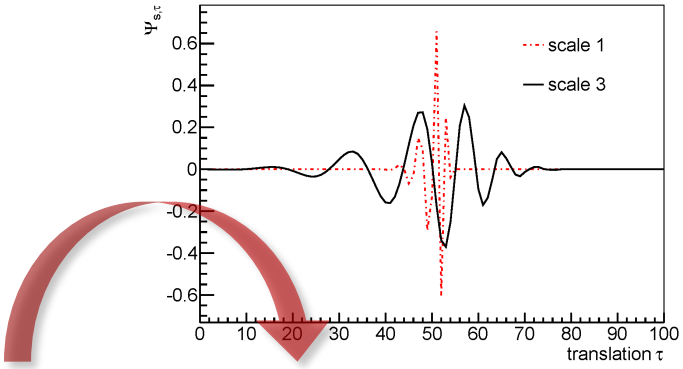
2. Is this knowledge necessary at all?

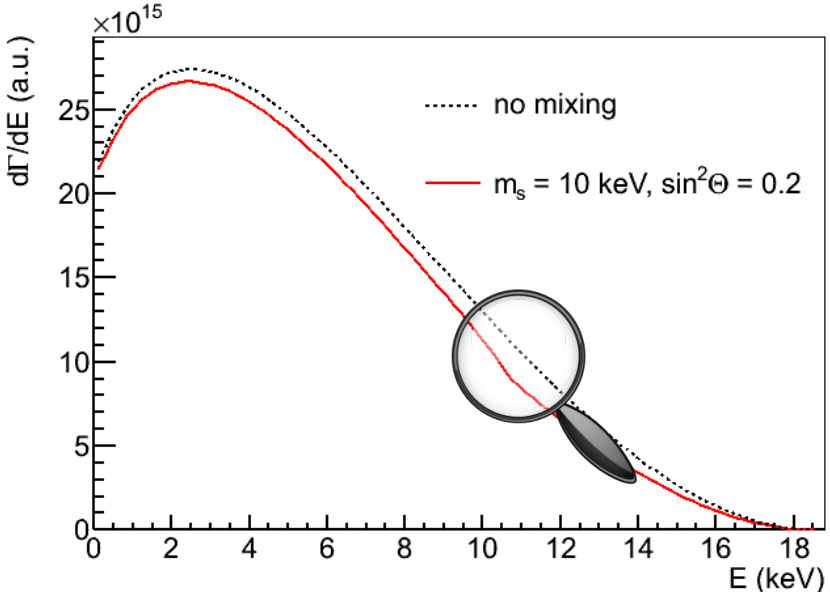
Wavelet Transformation:

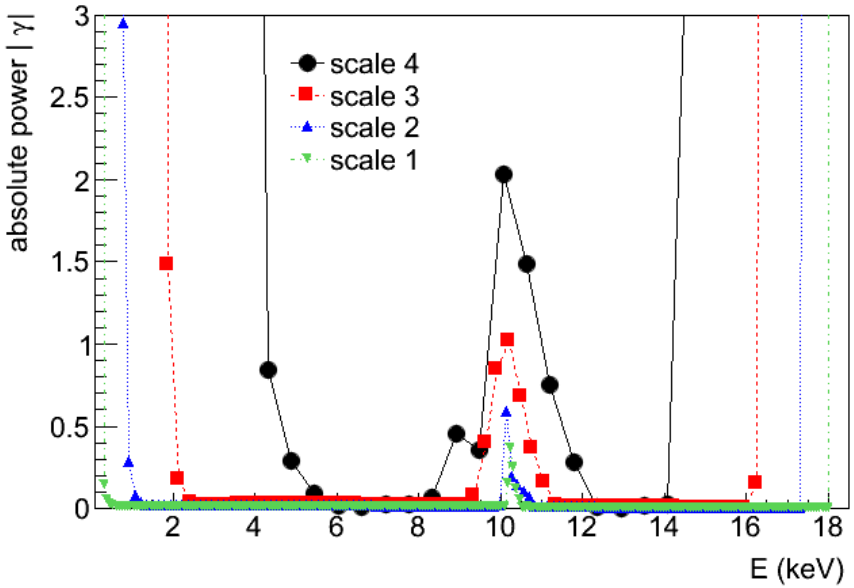
Which frequency is present in the signal at which energy?



Wavelet Approach



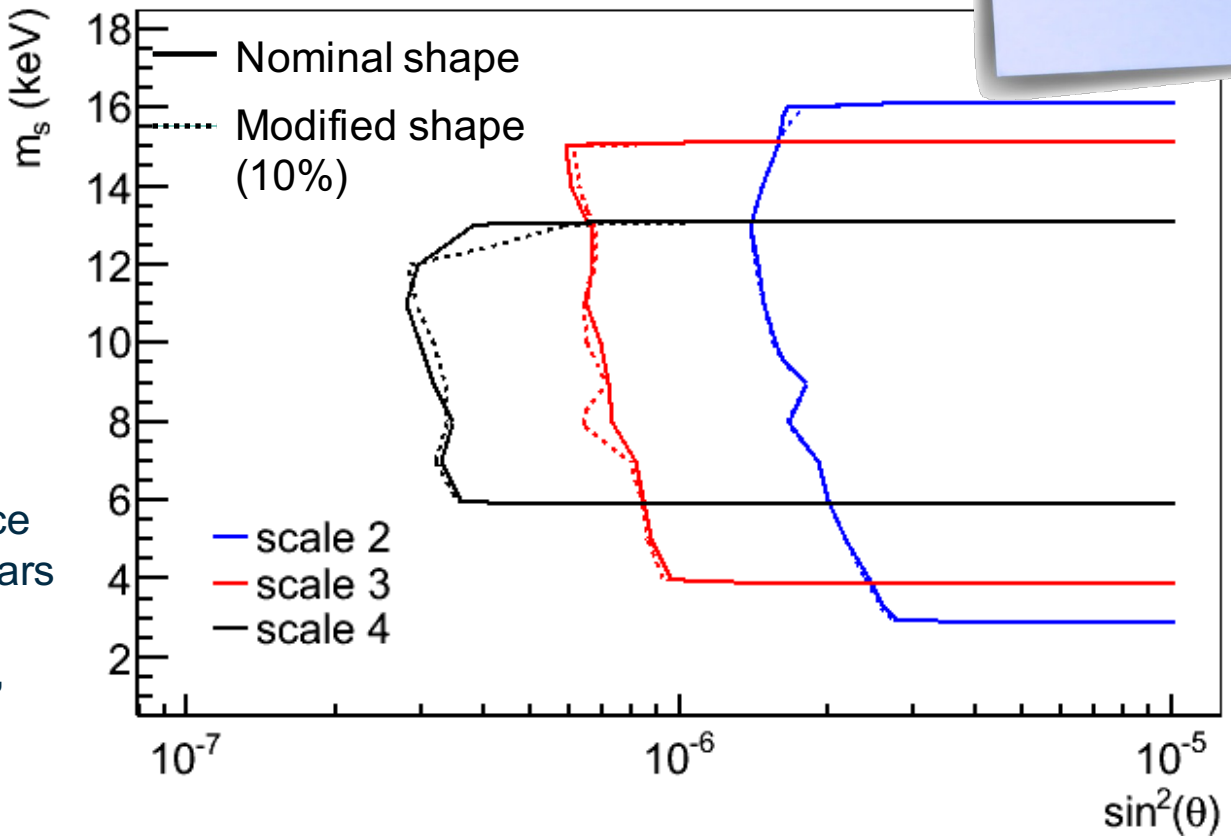




S. Mertens et. al.
arXiv:1410.7684

Wavelet Approach

Wavelet approach is independent of exact shape of tritium spectrum



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

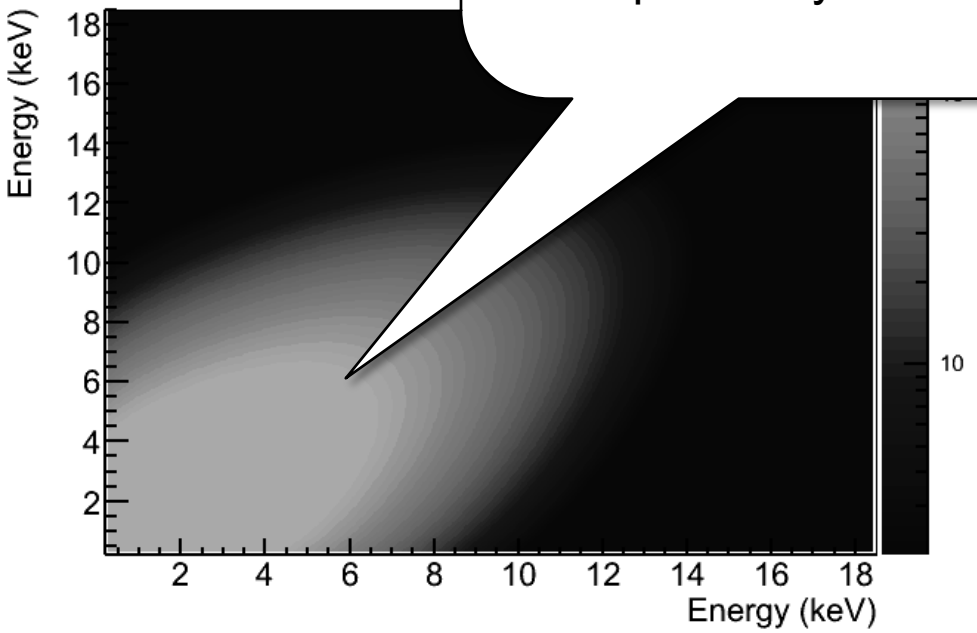
S. Mertens et. al. arXiv:1410.7684

Systematic uncertainties

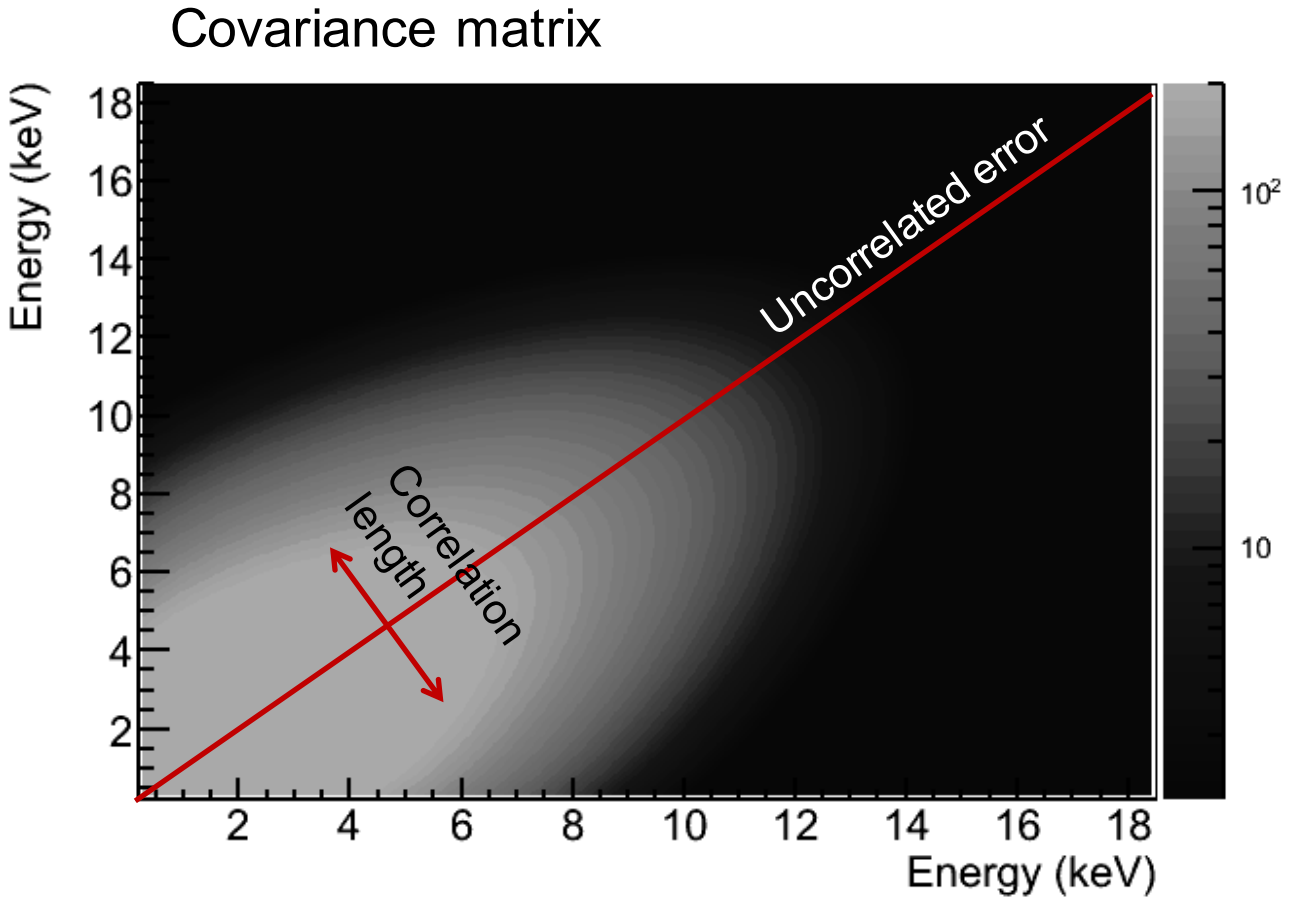
1. Knowledge of the theoretical spectrum?
2. Is this knowledge necessary at all?
3. How to deal with Systematics?

Idea:

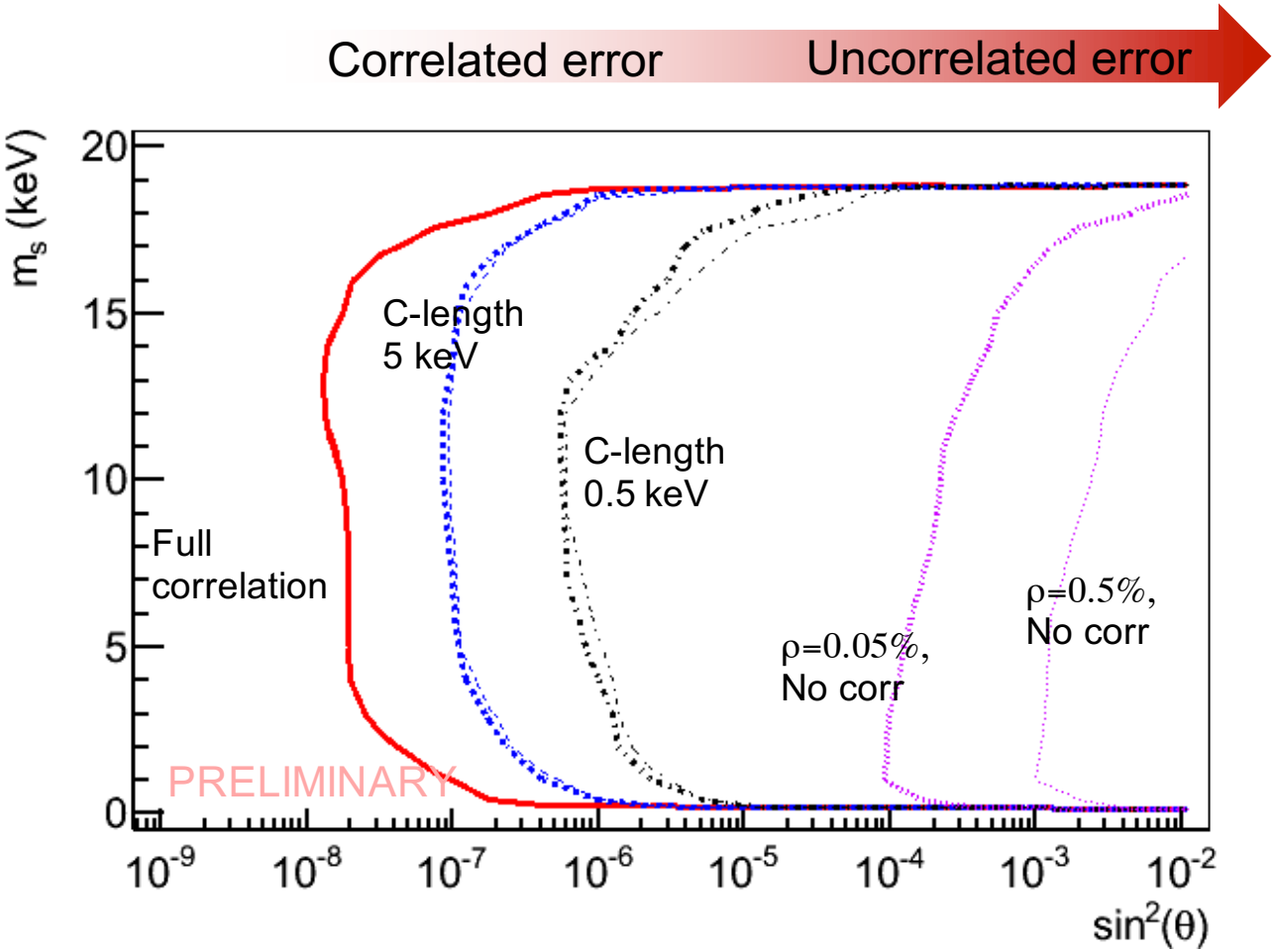
Construct realistic covariance matrix to investigate experimental uncertainties in a conceptual way.



Experimental uncertainties



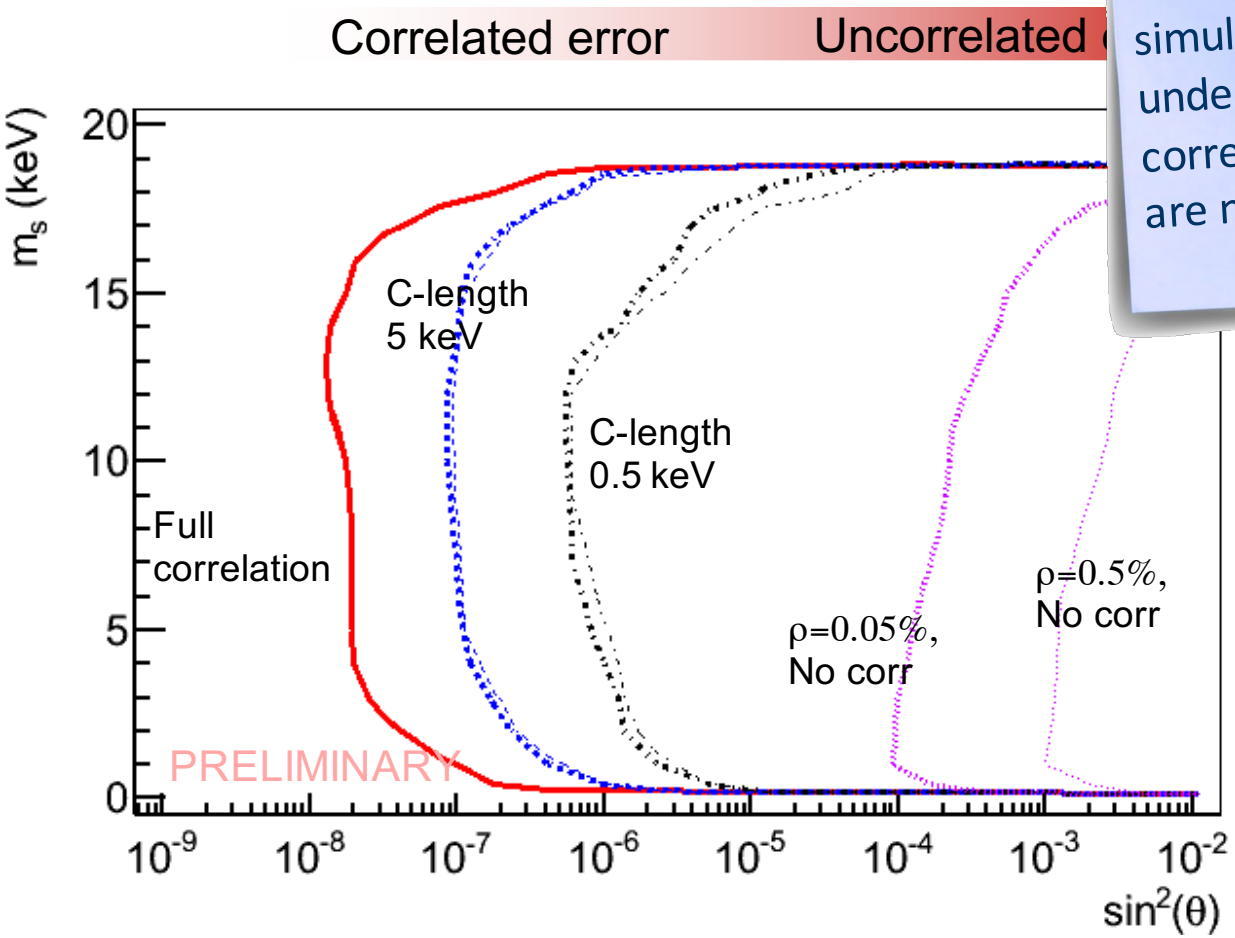
Experimental uncertainties



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

Experimental uncertainties

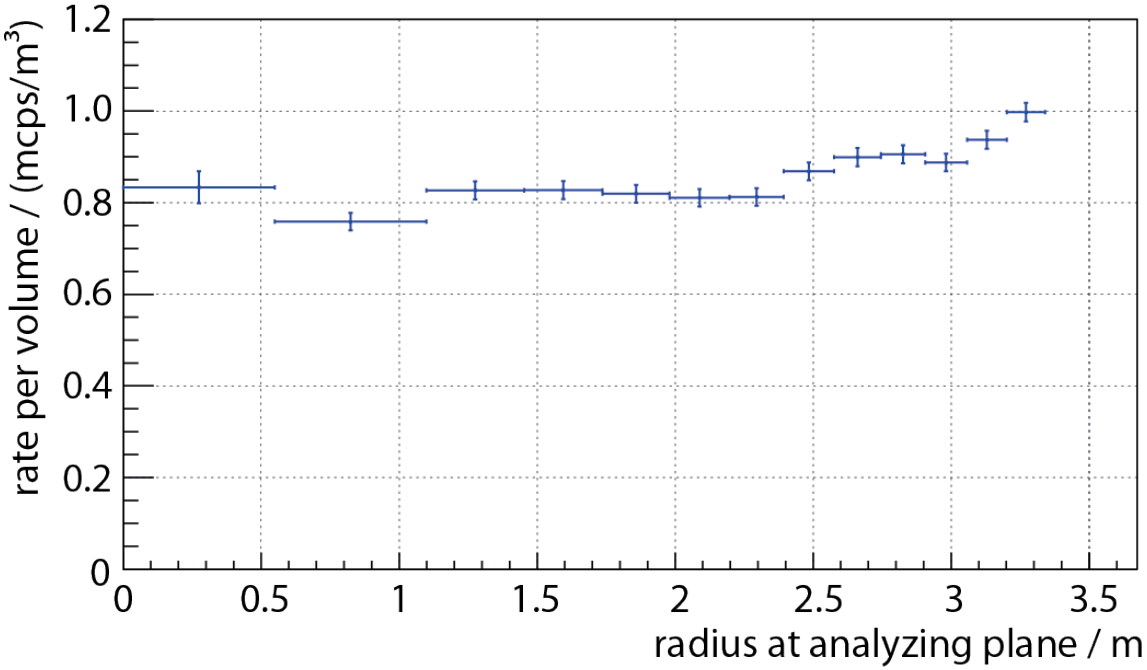
Precise calibrations, simulations, and understanding of correlations are needed



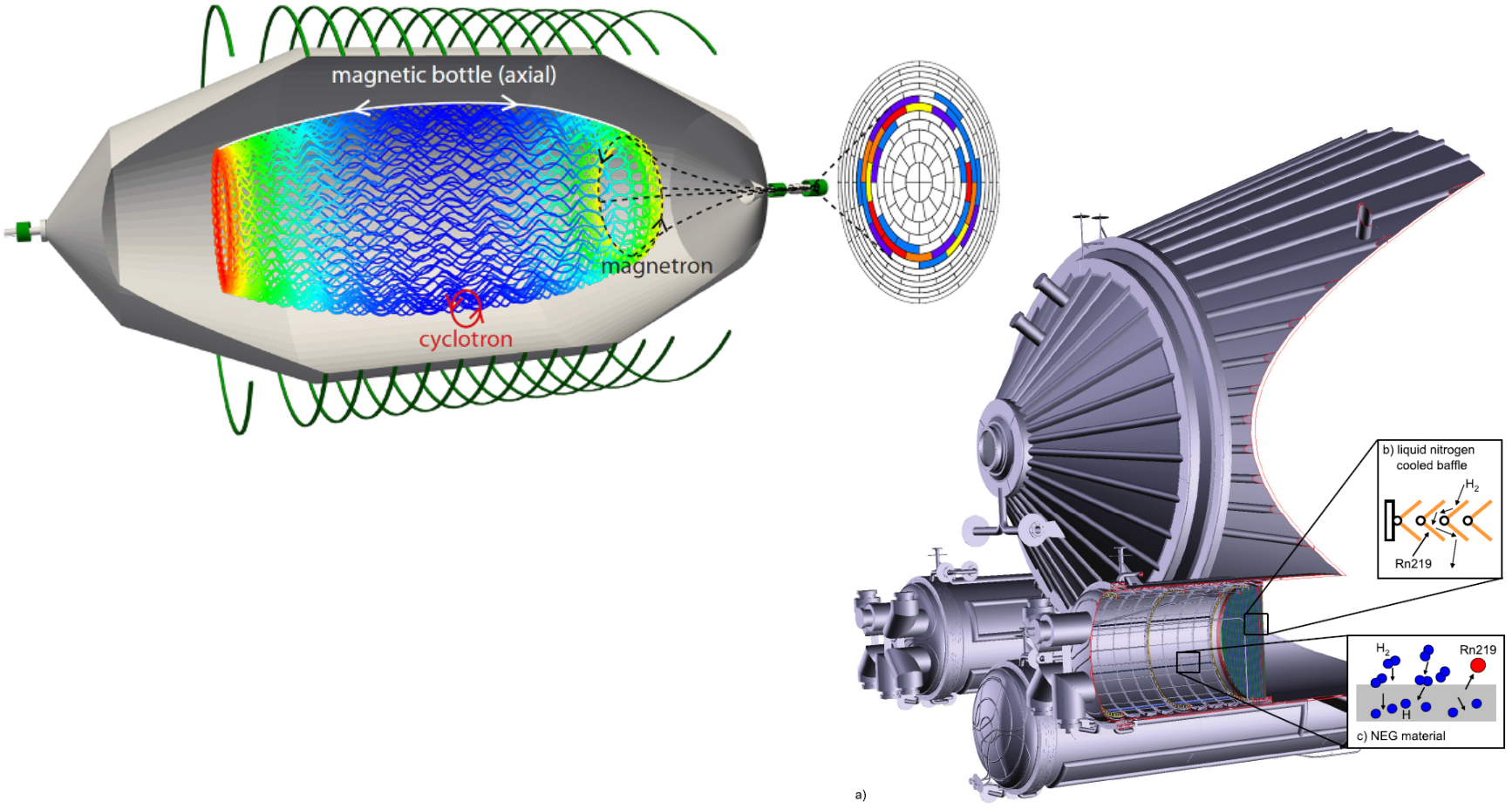
KATRIN source strength, 3 years differential measurement, 90% CL

KATRIN Background

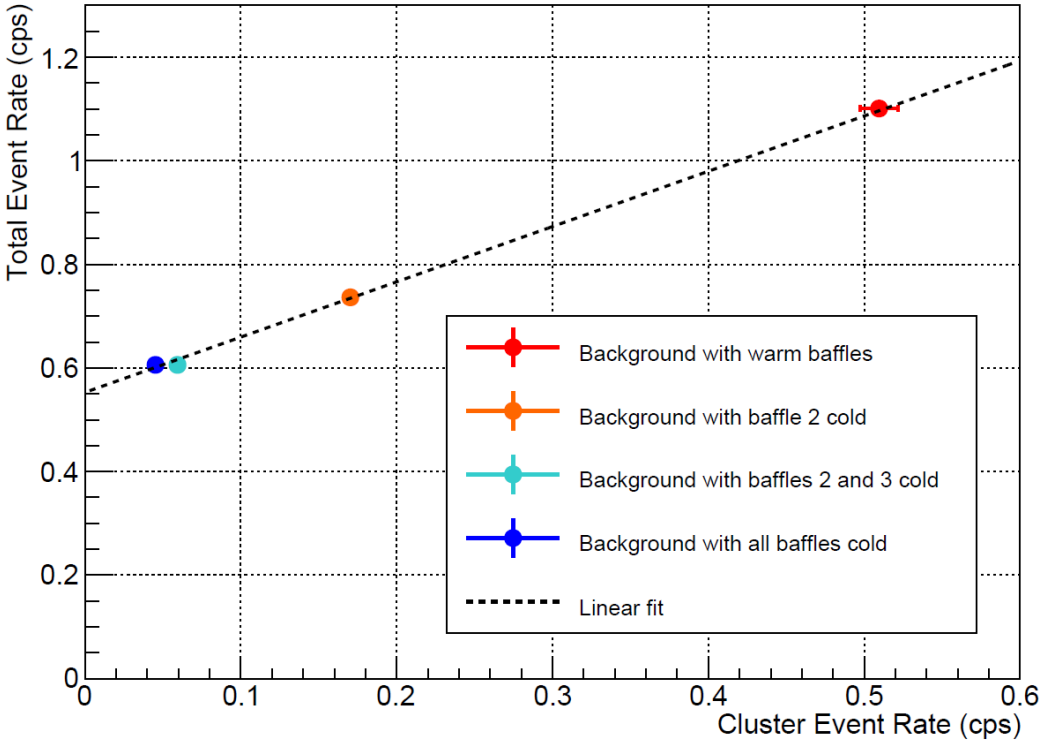
- Background rate in ROI **477 +/- 3 mcps** (10 mcps required)
- Settings: vessel = -18.5kV, IE = -100V, PAE = +10 kV and “5G” magnetic field setting



Radon induced background



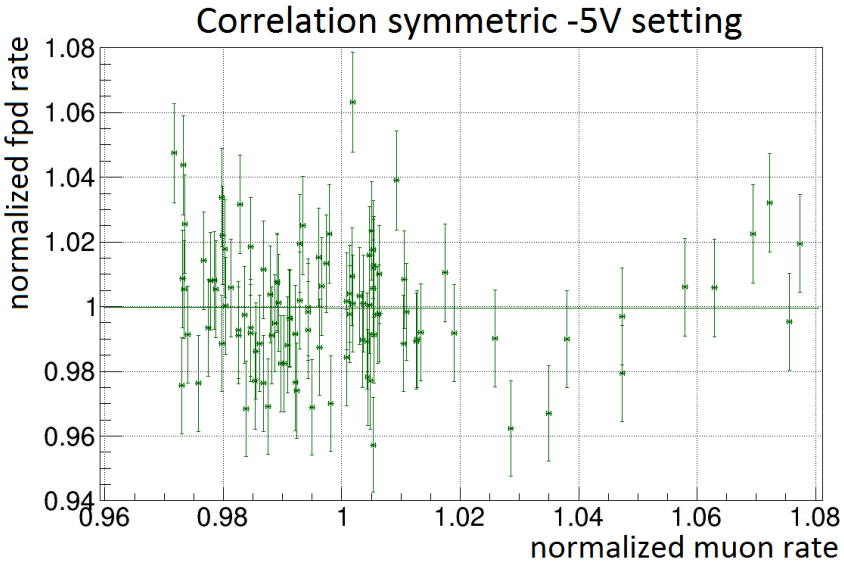
Effect of cold baffle on Radon background



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

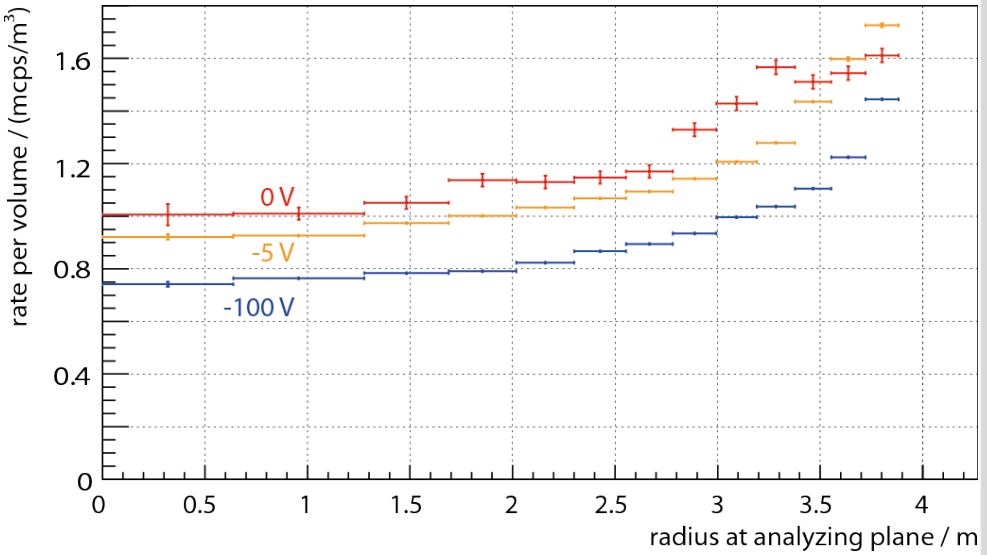
B_{total} : Total background rate.
S_{Rn} : Radon-induced single event rate.
C_{Rn} : Event rate in Radon-induced clusters.
R : Non-Radon-induced background rate.

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