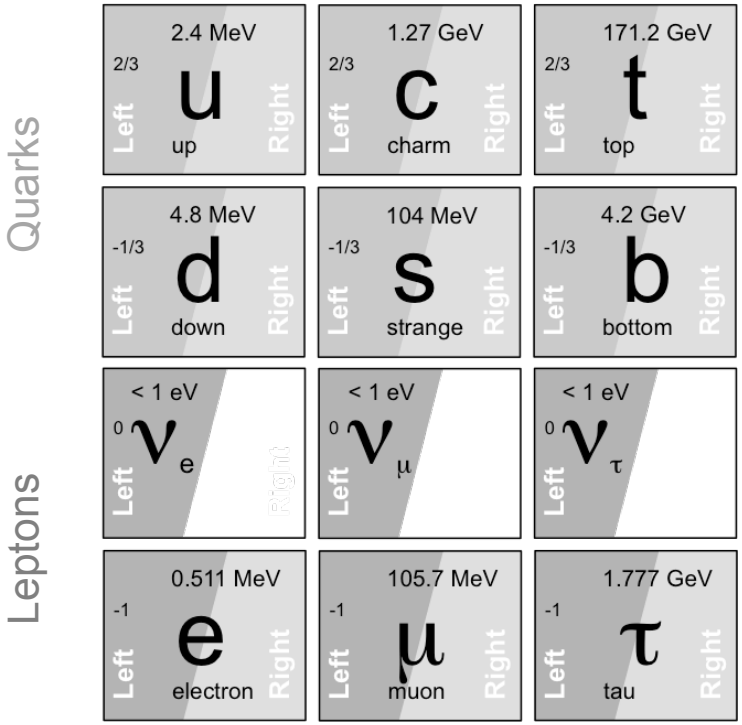
Probing the Neutrino Mass and Search for Sterile Neutrinos with KATRIN

Susanne Mertens for the KATRIN Collaboration
Karlsruhe Institute of Technology and
Lawrence Berkeley National Laboratory

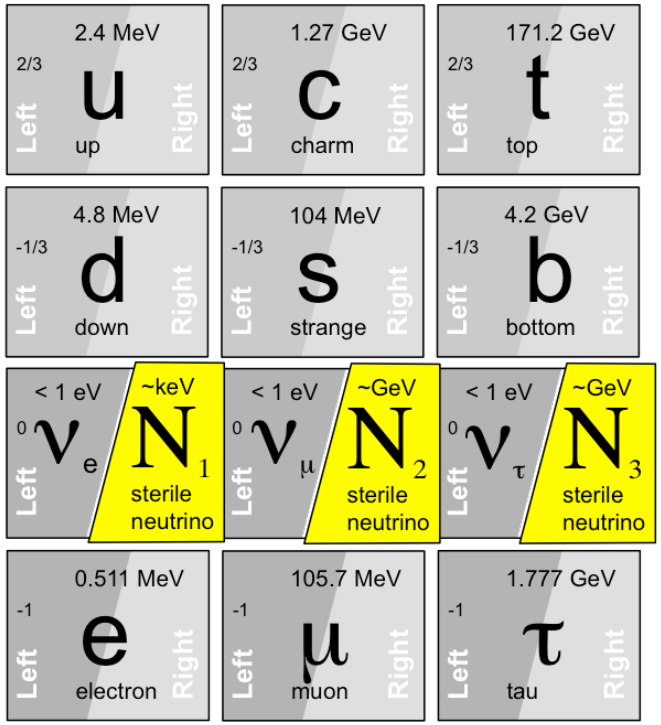
NDM 2015

Sterile Neutrinos

Standard Model (SM)



Neutrino Minimal SM (nuMSM)



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

Sterile Neutrinos

Heavy sterile neutrinos (~GeV)

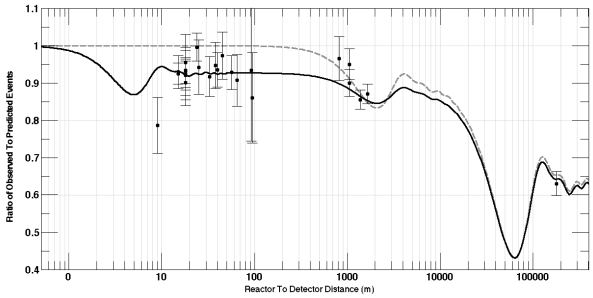
- Lightness of neutrinos via See-saw mechanism

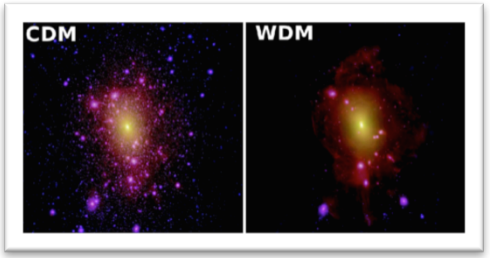
Light sterile neutrinos (~1 eV)

- Reactor anomaly, Gallium anomaly, Short baseline accelerator results

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

- Warm and cold dark matter candidate





Sterile Neutrinos

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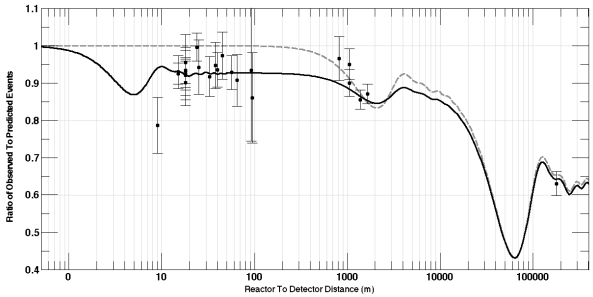
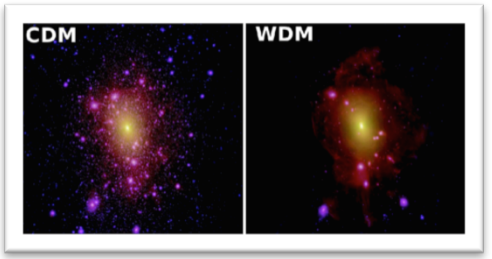
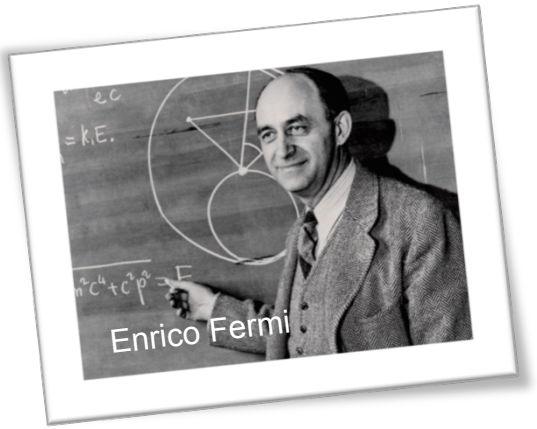
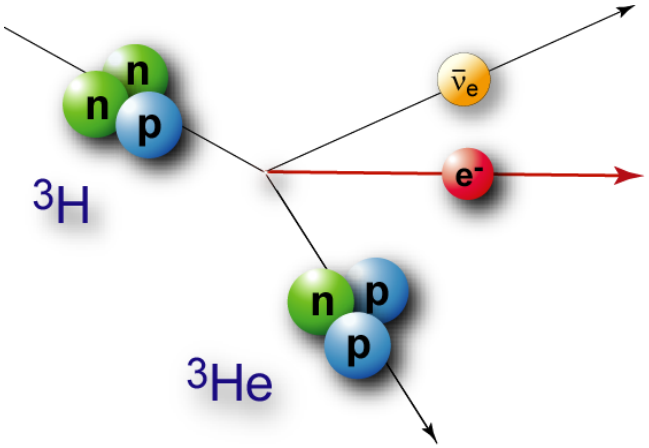
→ **Accessible in tritium beta decay**





Tritium beta decay

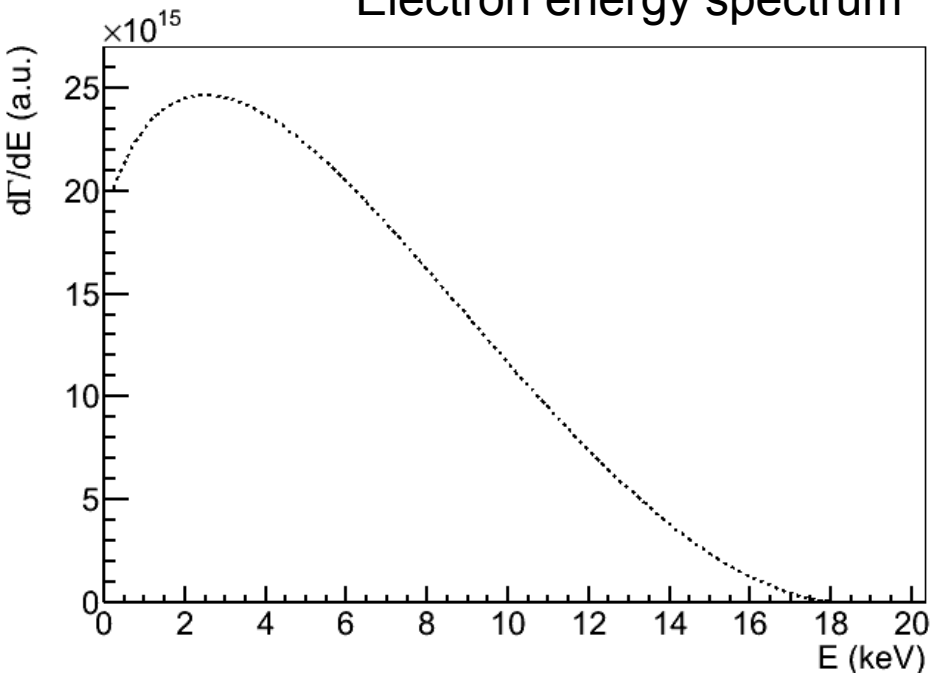




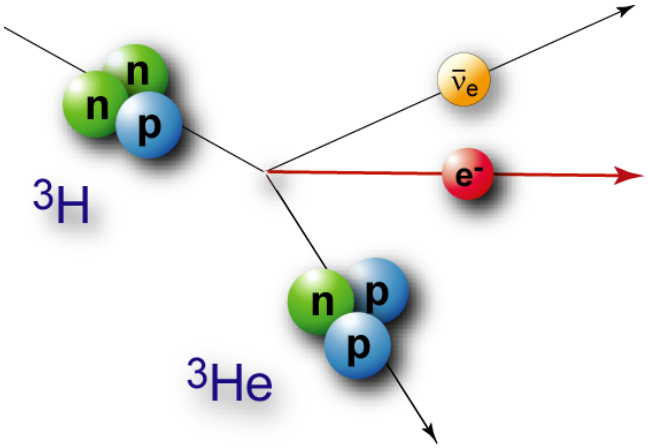
$$\frac{d\Gamma}{dE} = C \cdot F(E,Z) \cdot p \cdot (E + m_e)$$

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

Electron energy spectrum



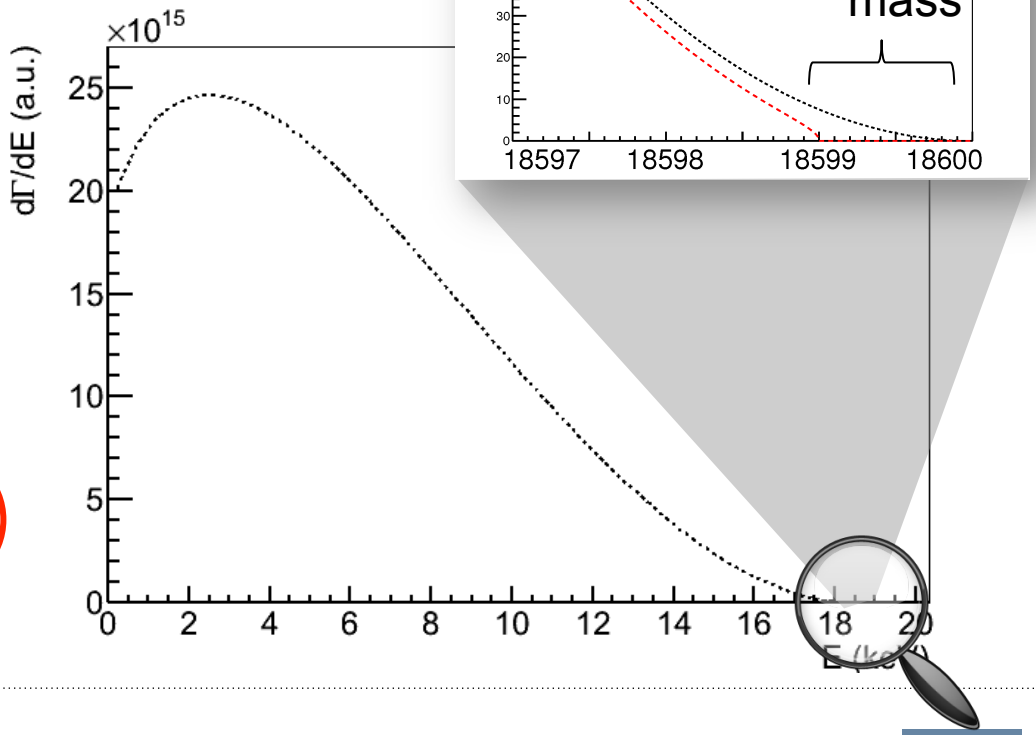
Tritium beta decay



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

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

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



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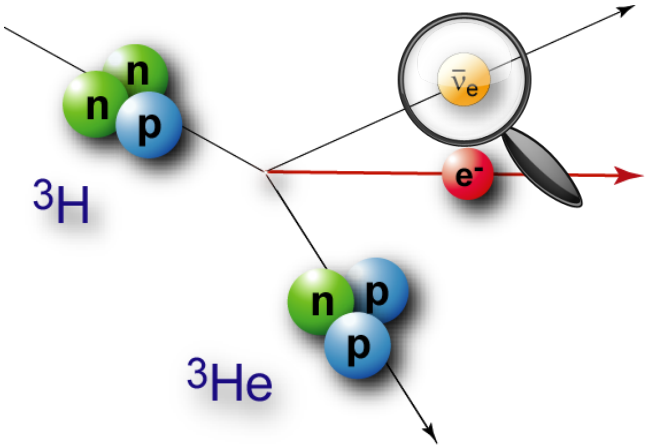
Tritium beta decay

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



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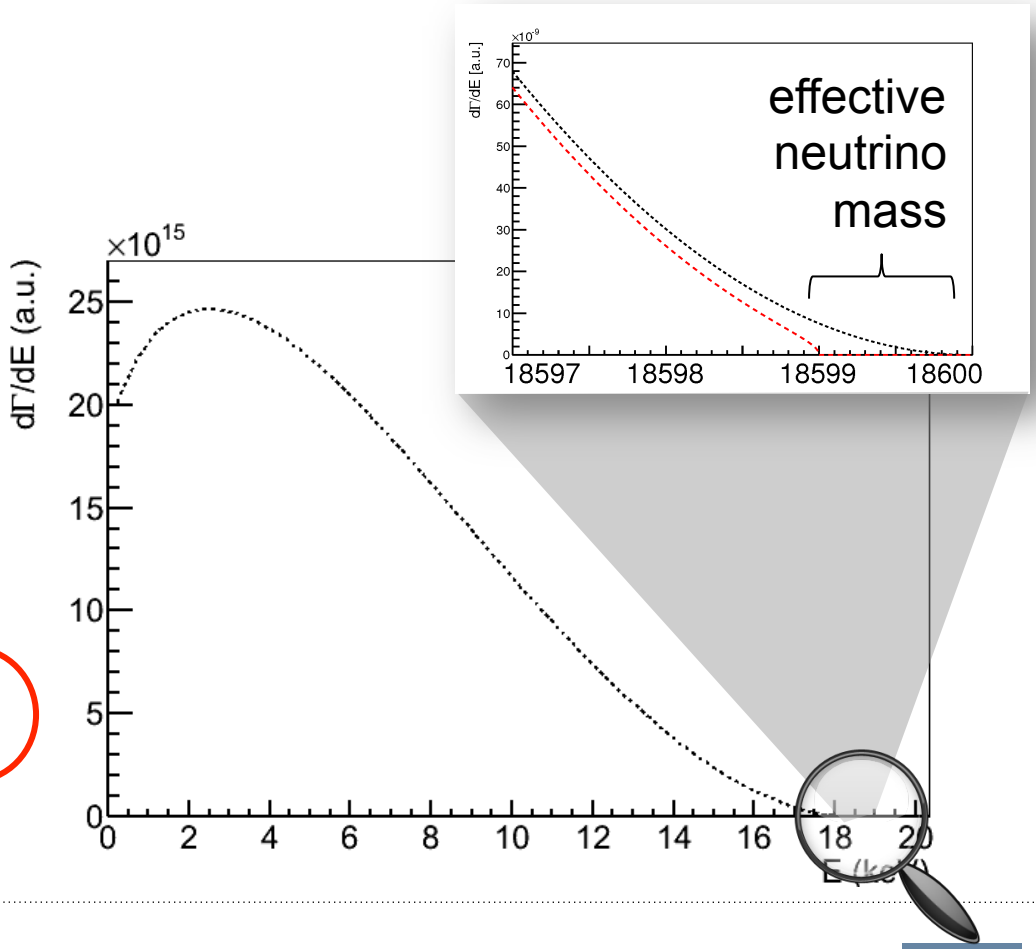

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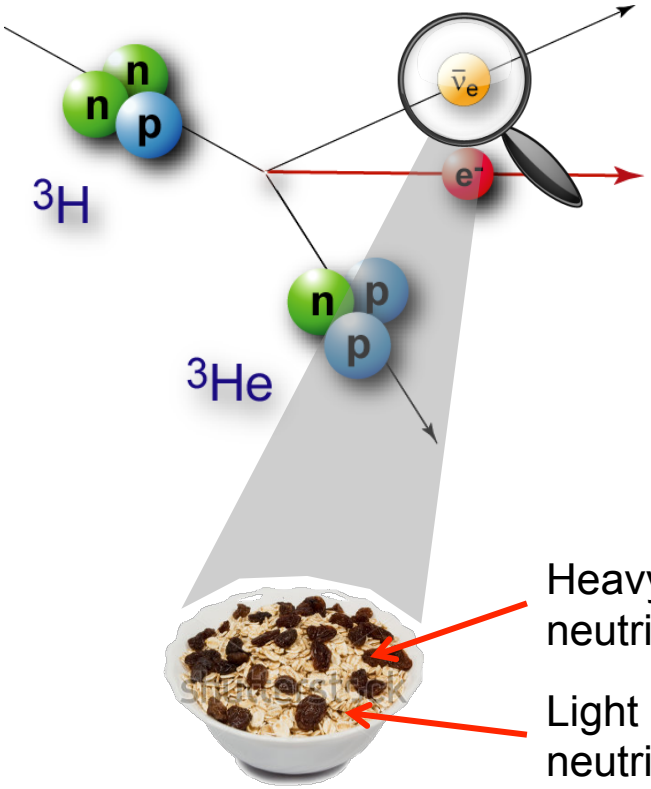
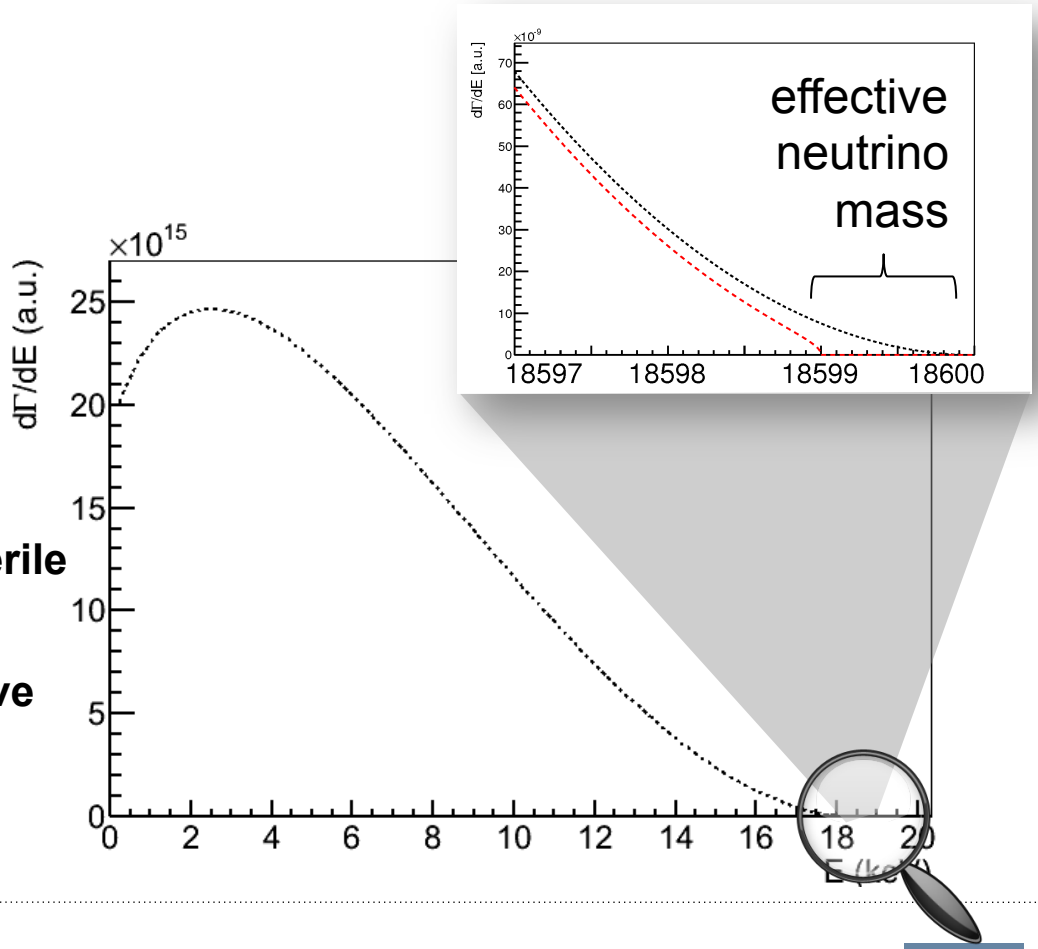
Tritium beta decay



Heavy **sterile** neutrino

Light **active** neutrinos

Neutrino from tritium β-decay



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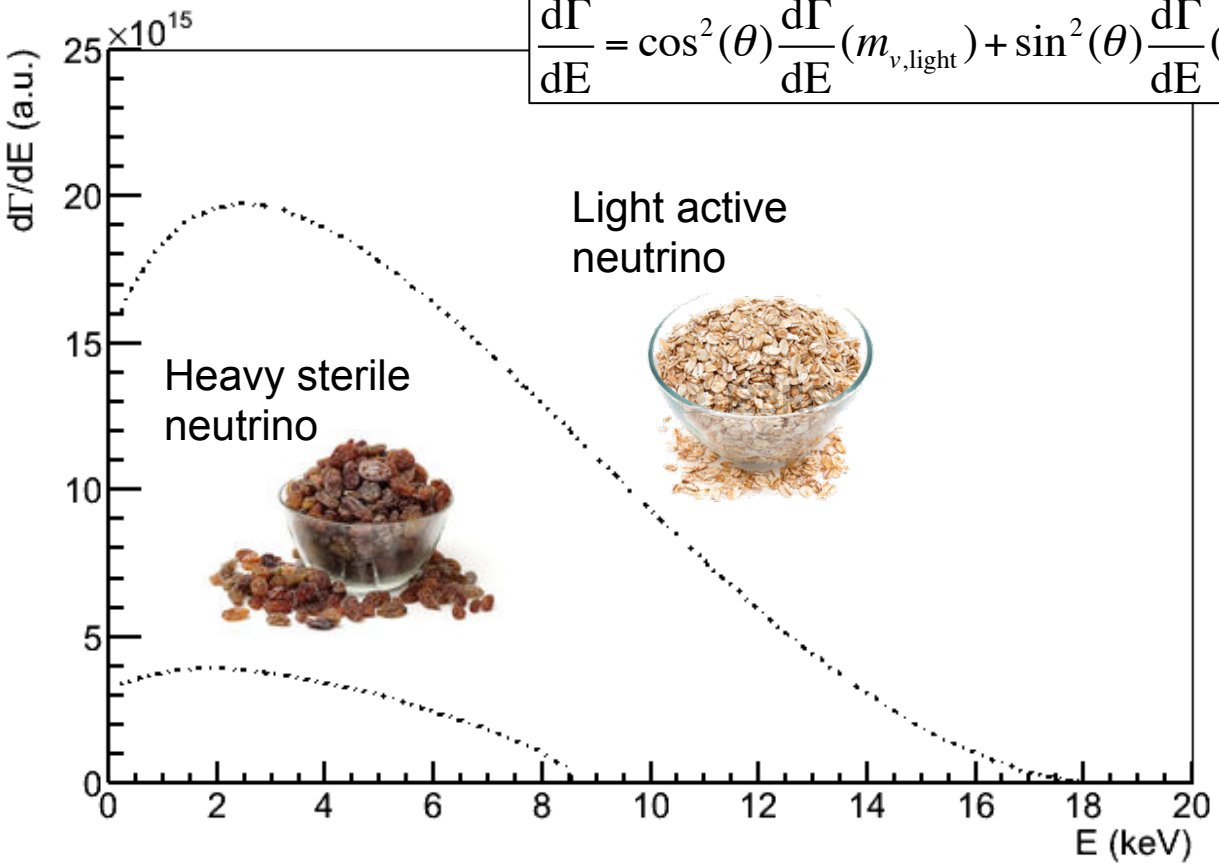
Imprint of sterile ν‘s on ß-spectrum

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



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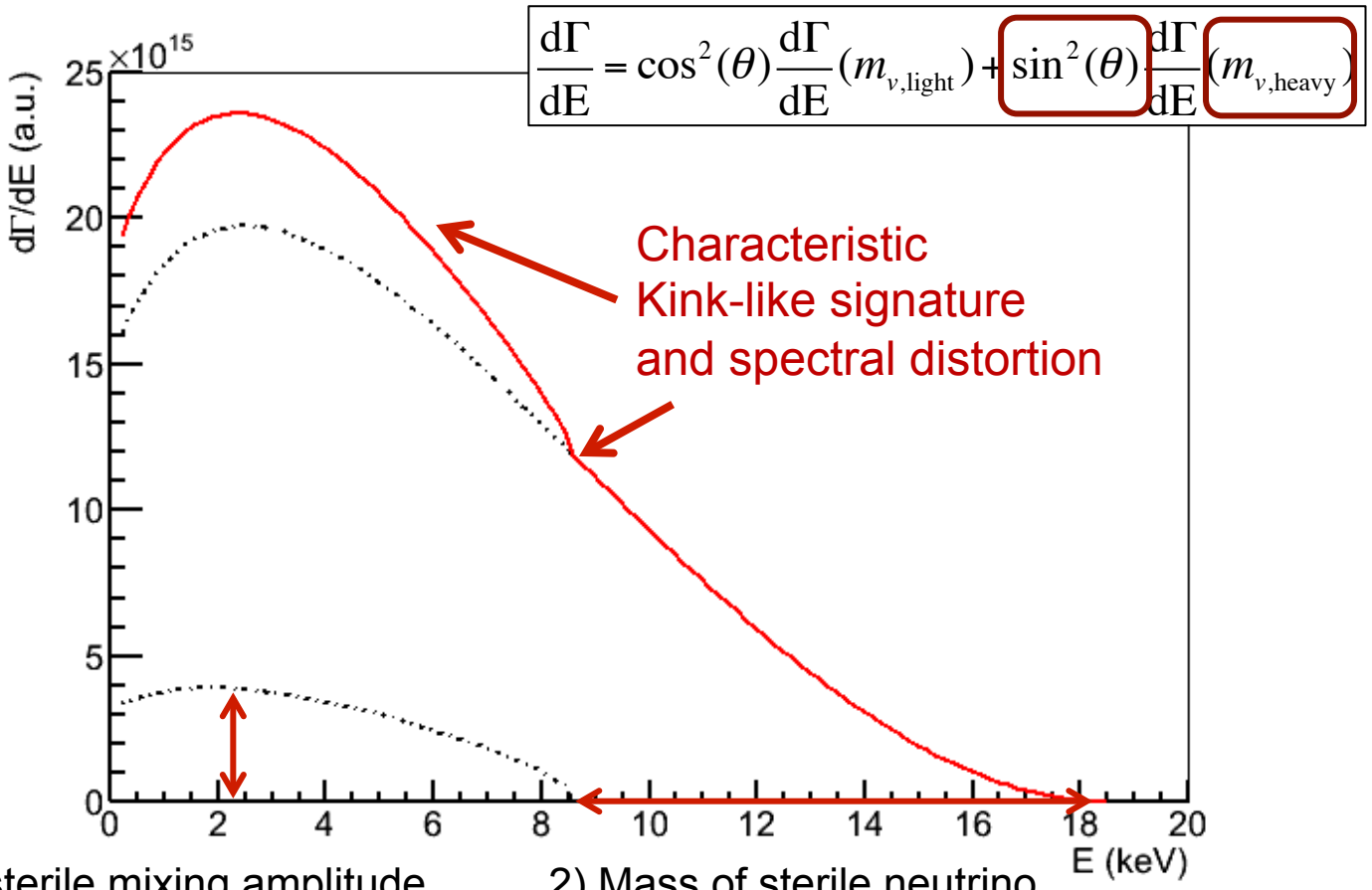

1) Active-to-sterile mixing amplitude

2) Mass of sterile neutrino

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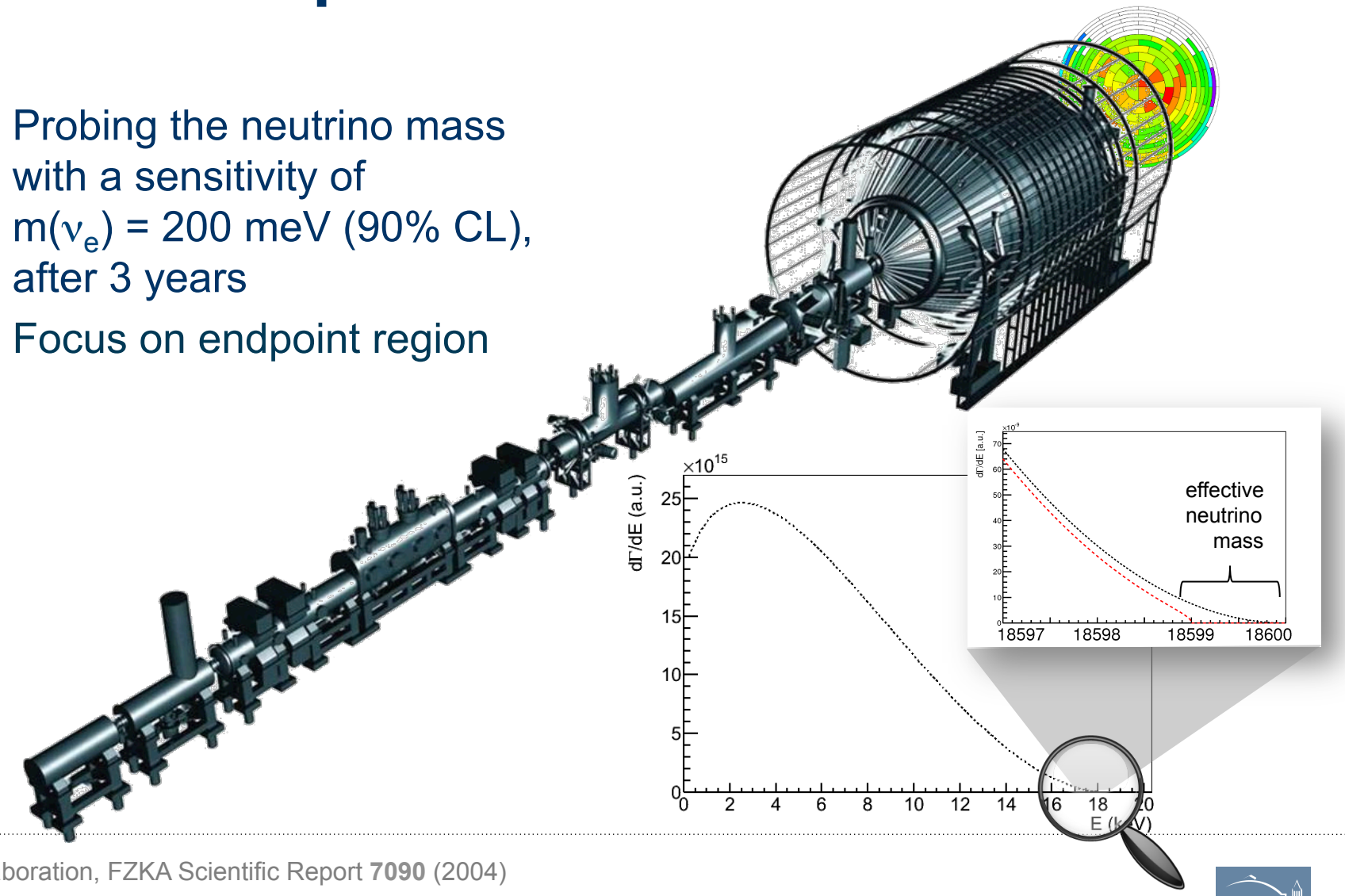
Karlsruhe Tritium Neutrino Experiment KATRIN

KATRIN Experiment

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

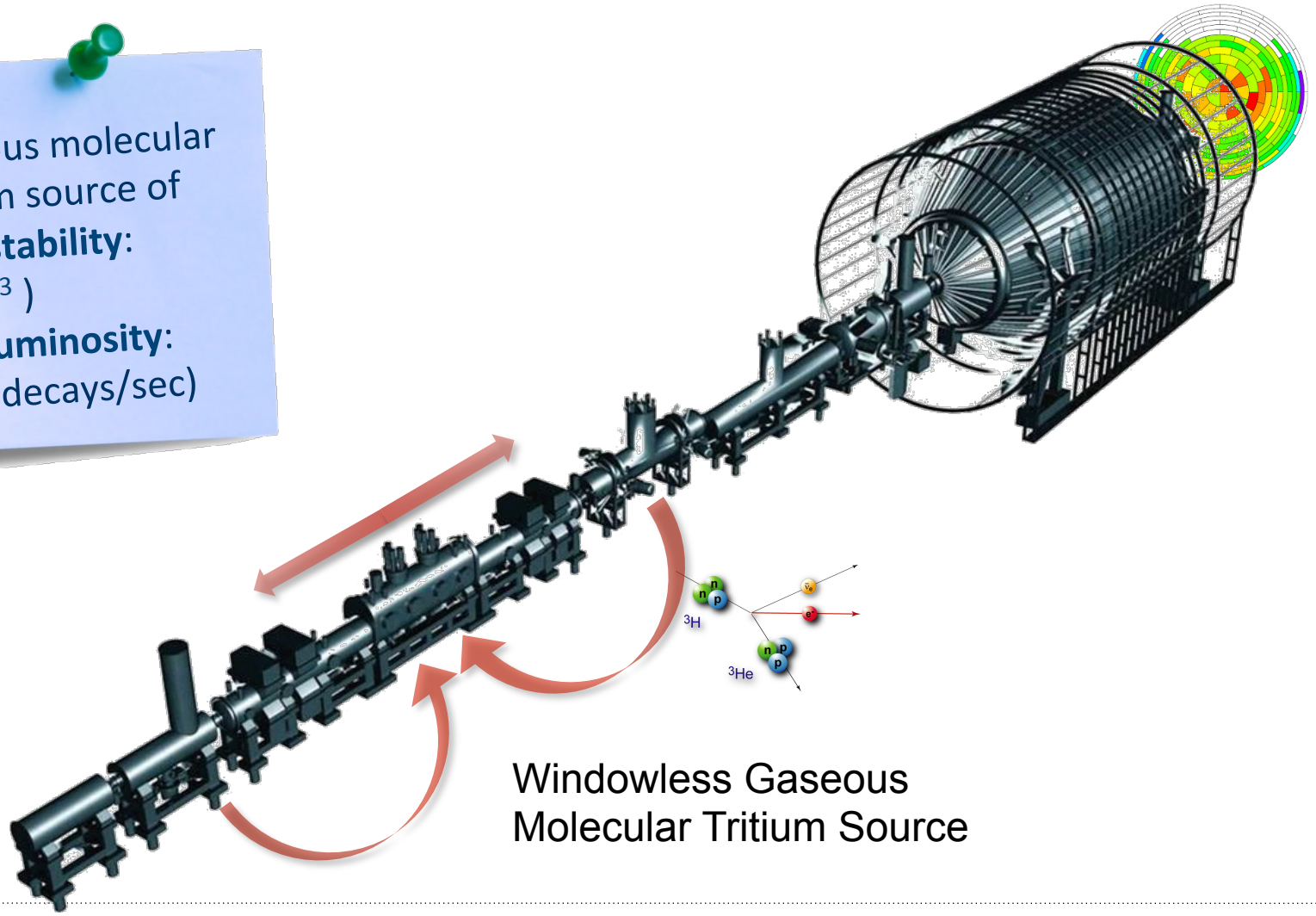


KATRIN Collaboration, FZKA Scientific Report **7090** (2004)

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

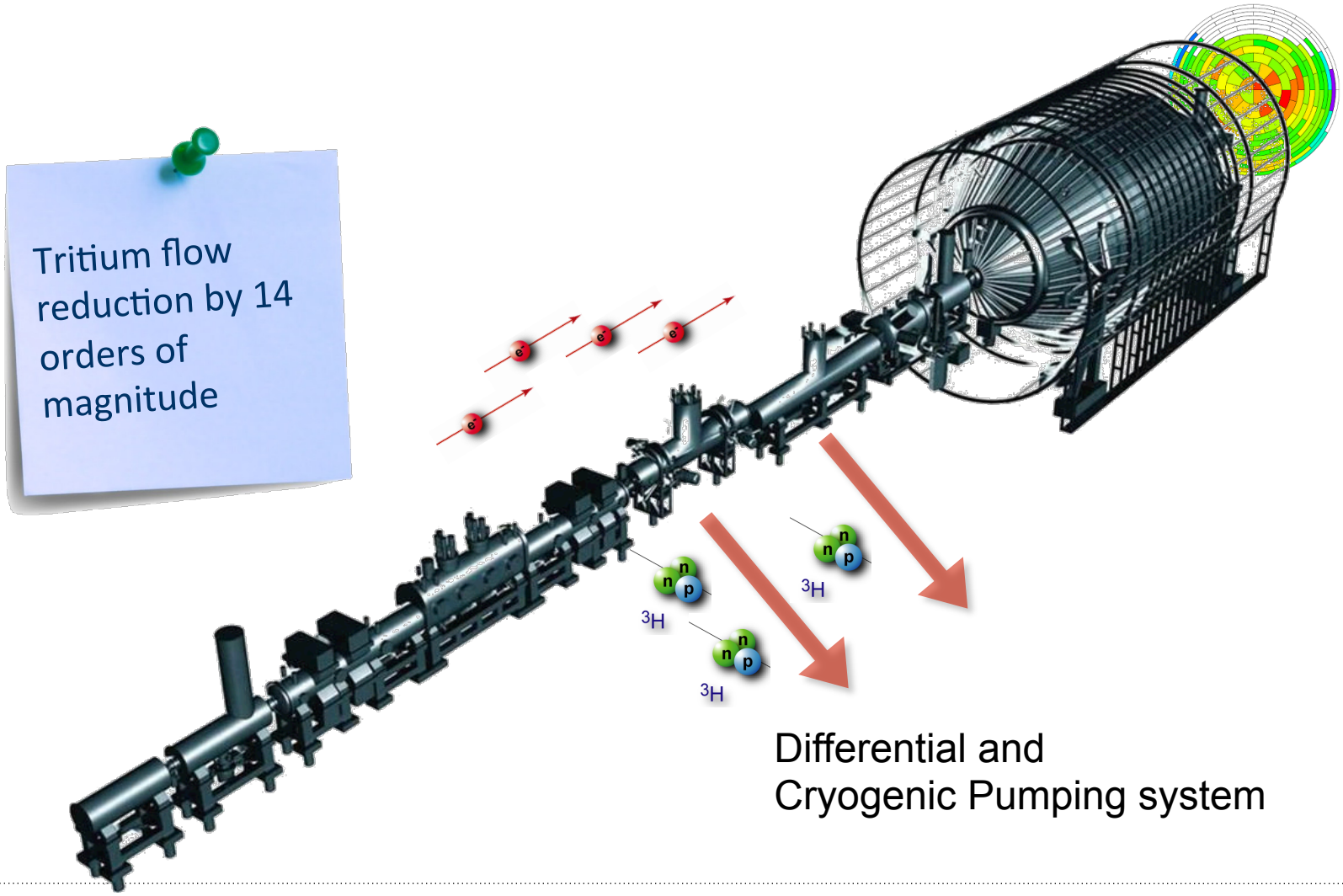
KATRIN Overview

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



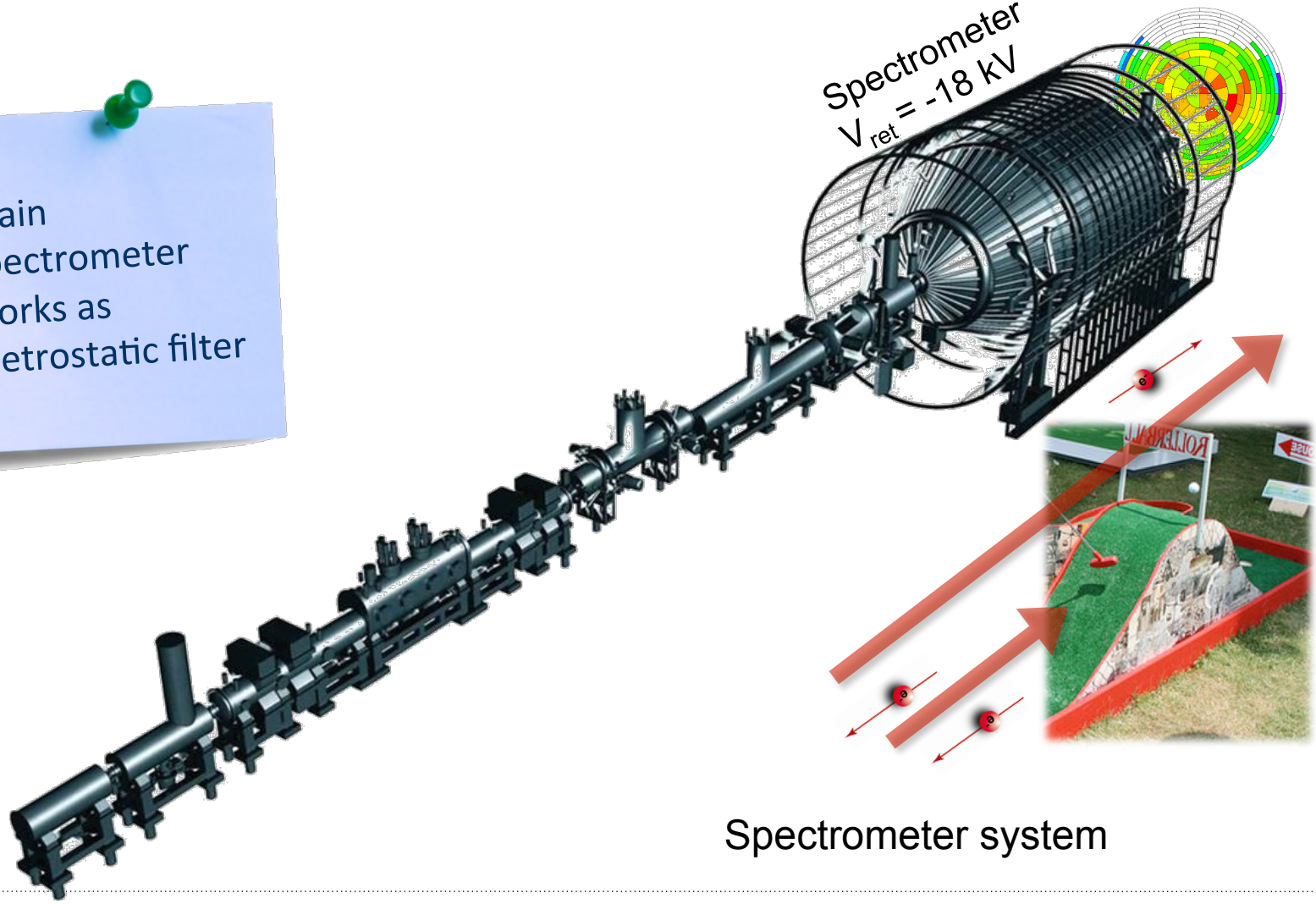
Windowless Gaseous Molecular Tritium Source

KATRIN Overview



KATRIN Overview

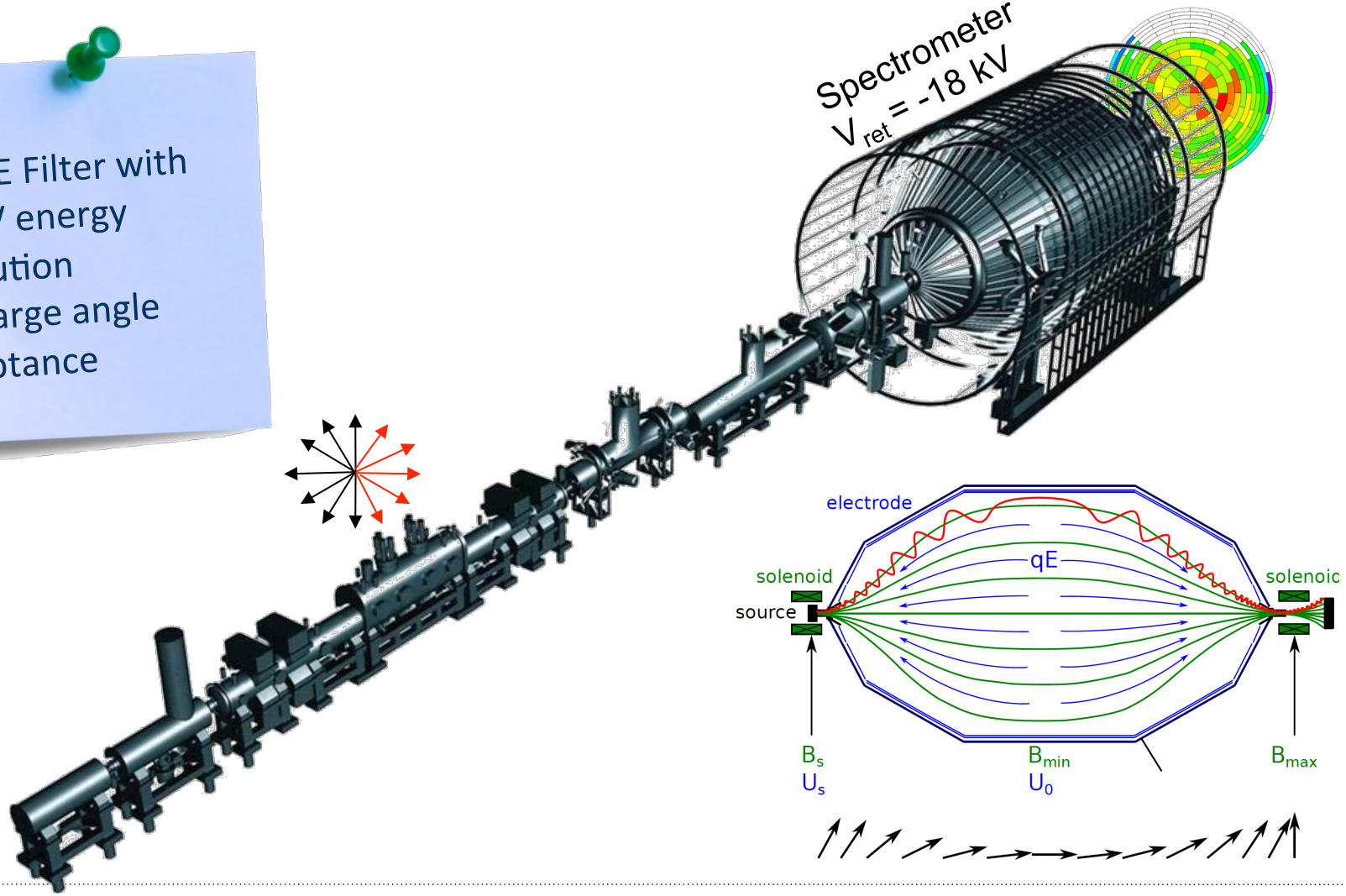
Main spectrometer works as eletrostatic filter



Spectrometer system

KATRIN Overview

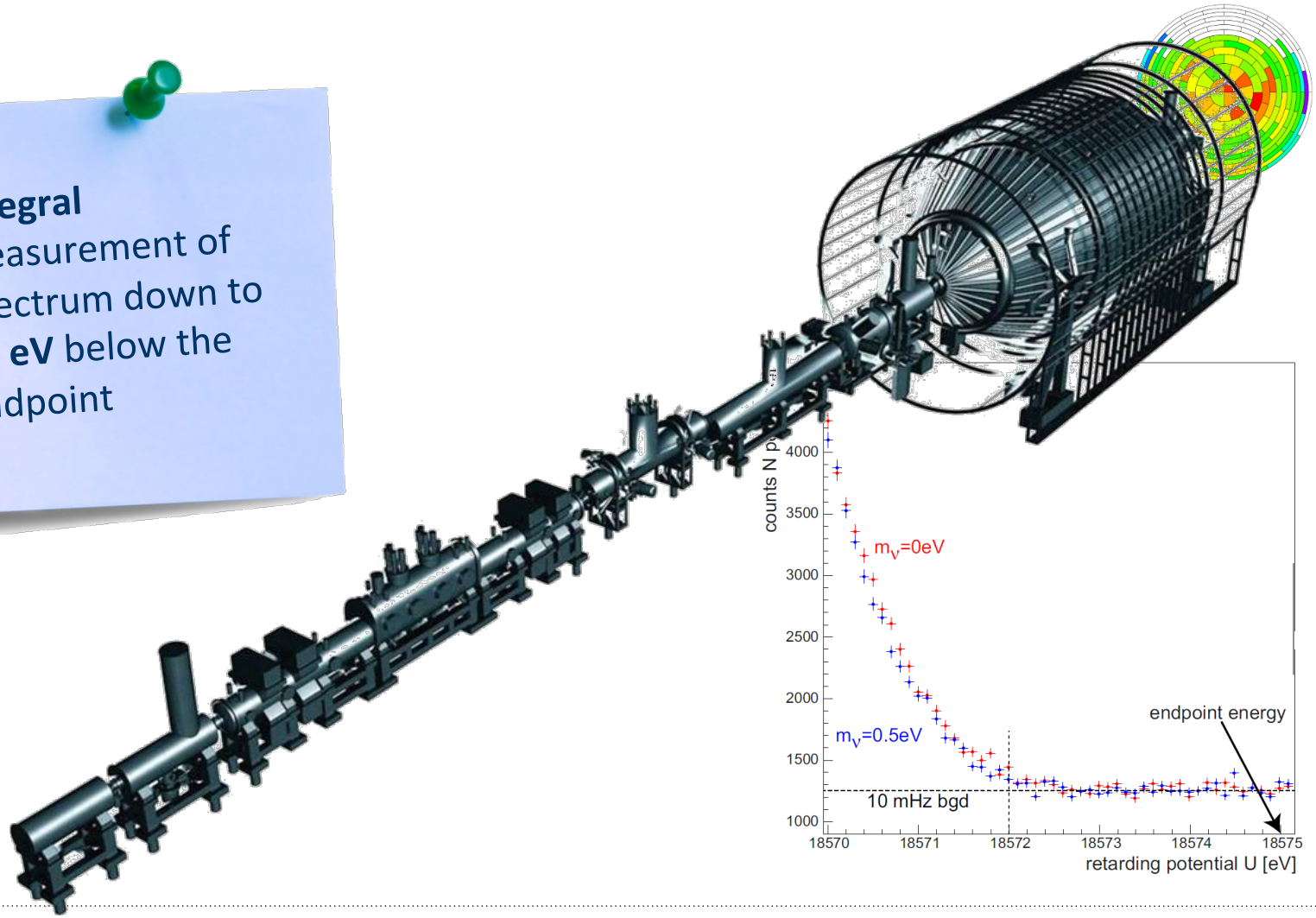
MAC-E Filter with
< 1 eV energy
resolution
and large angle
acceptance



KATRIN Overview

Detector system

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



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KATRIN Source Status

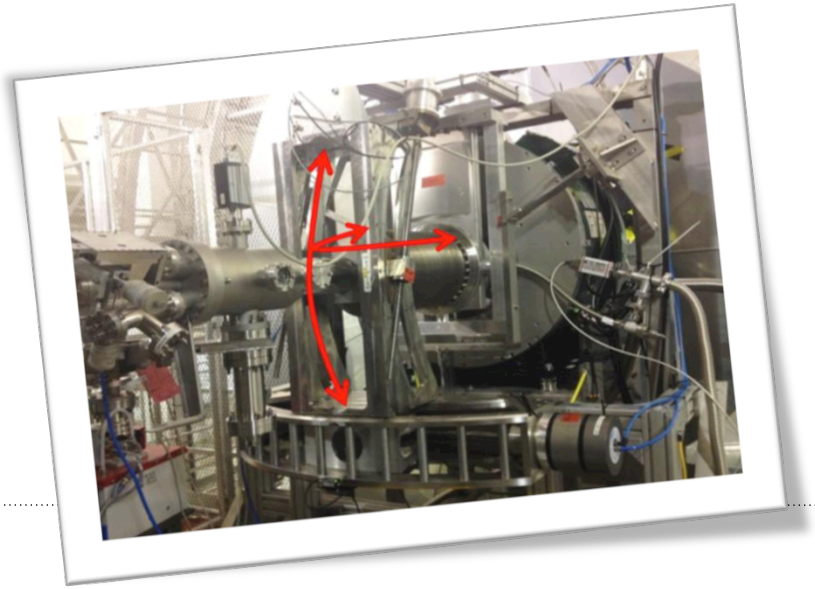

2011:
fully commissioned large
Aircoil system

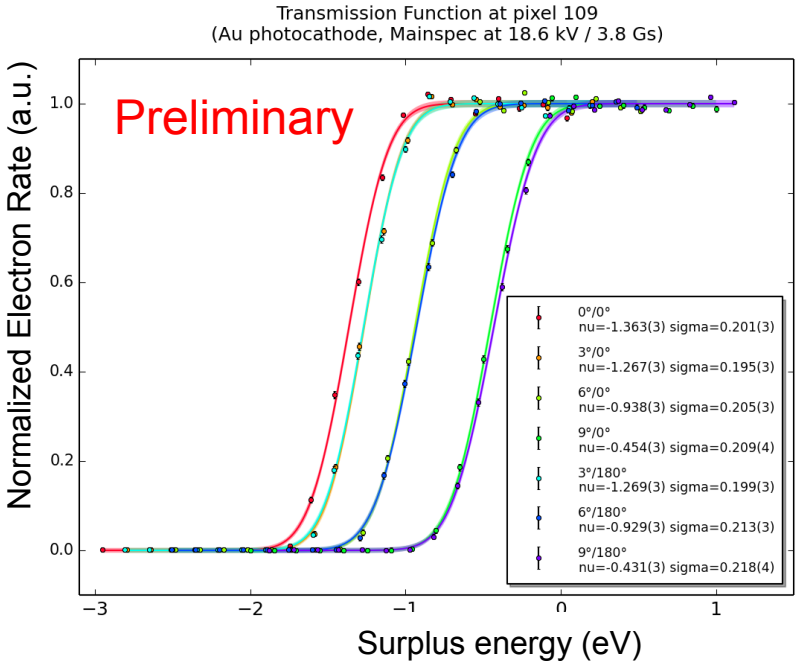

2012:
Inner electrode system
(24.000 wires)
completely mounted
(precision: 200 µm!)

KATRIN Spectrometer Status

2015: 2nd measurement phase completed

- Spectrometer works as MAC-E Filter

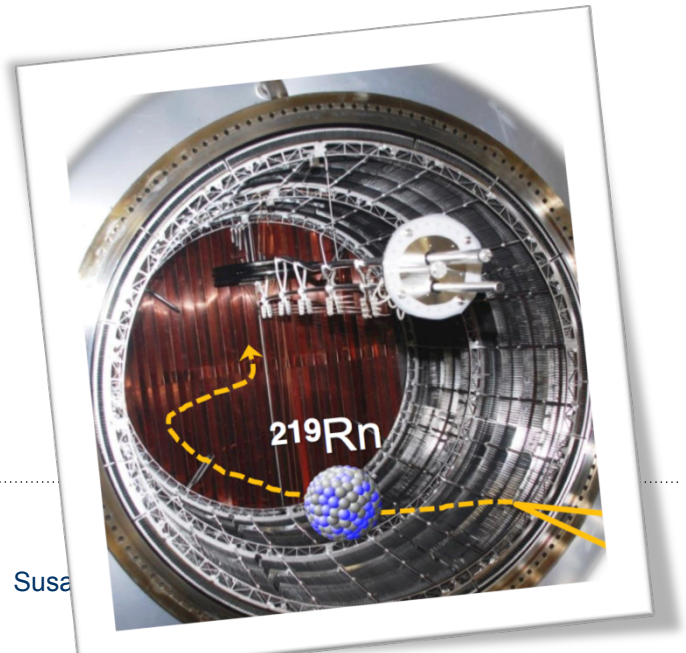


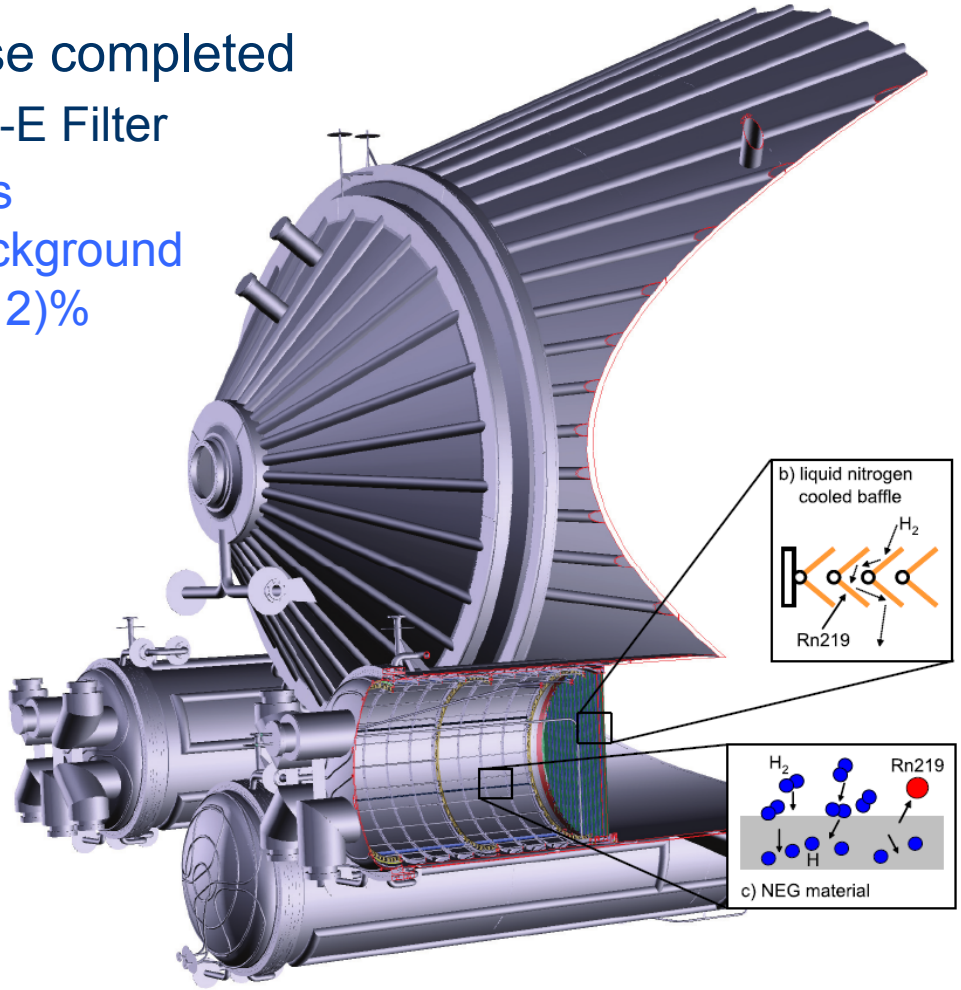


KATRIN Spectrometer Status

2015: 2nd 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

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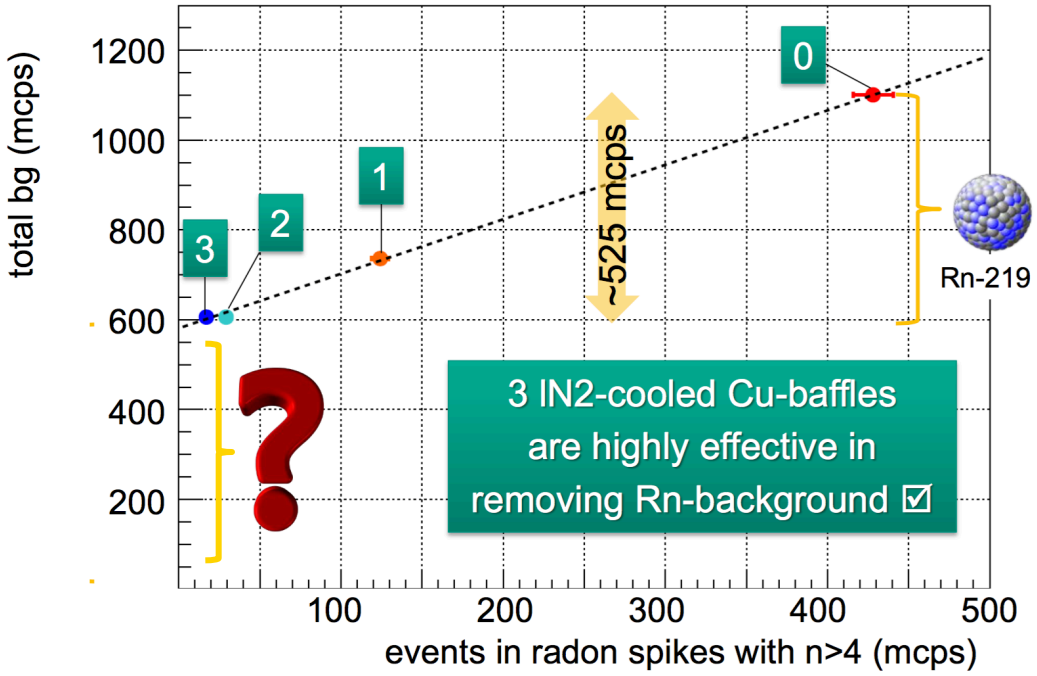
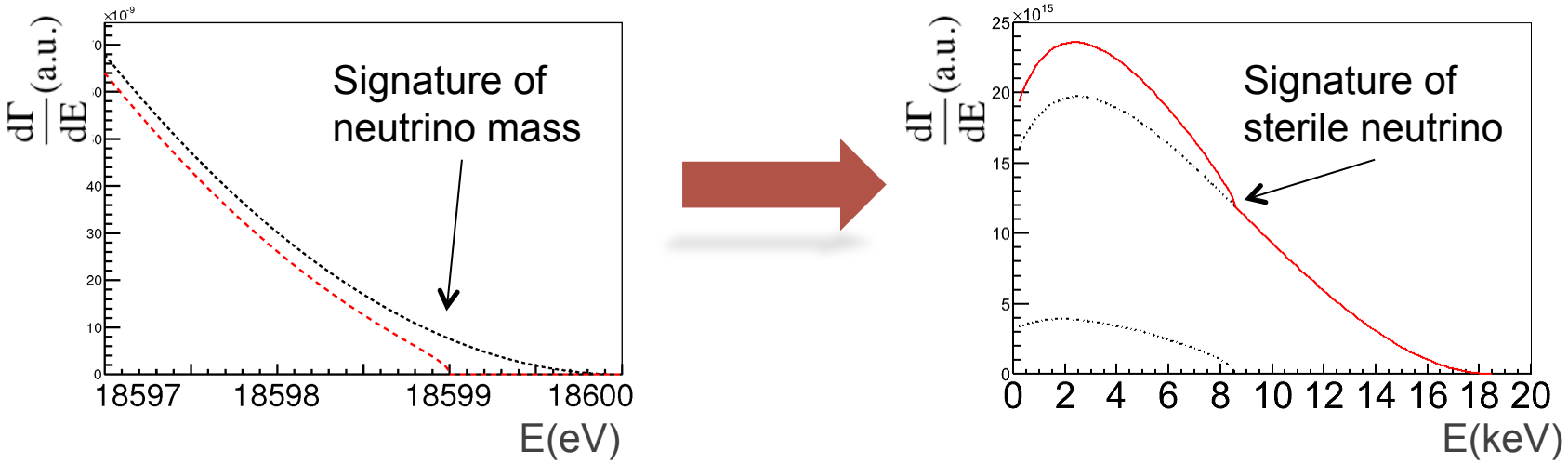
KATRIN Spectrometer Status

2015: 2nd measurement phase completed

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



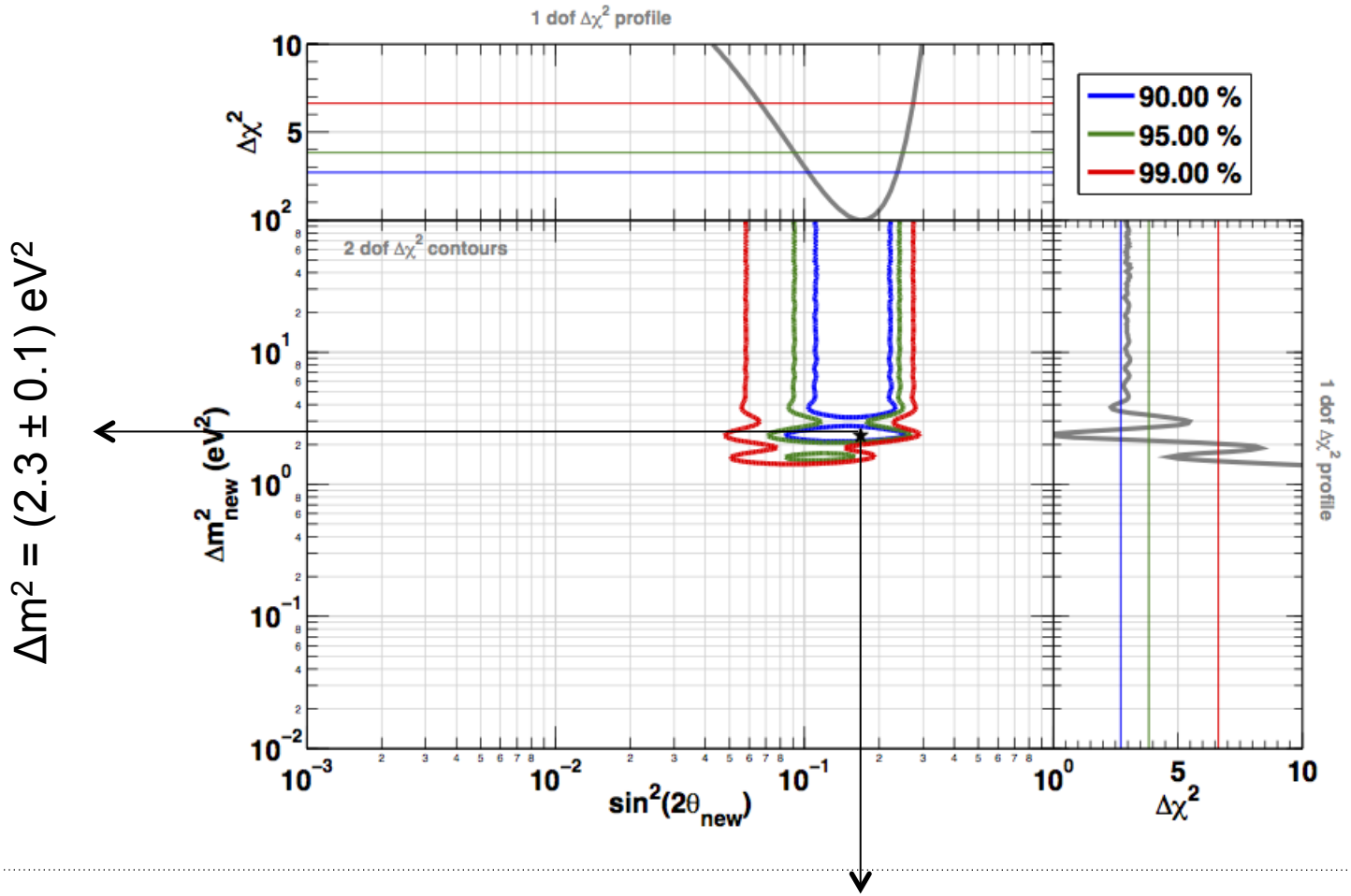
KATRIN and sterile neutrinos



eV-Scale Sterile Neutrinos

...this is where KATRIN measures anyway

Reactor + Gallium anomaly



Reactor + Gallium combined analysis
"White Paper", arXiv:1204.5379

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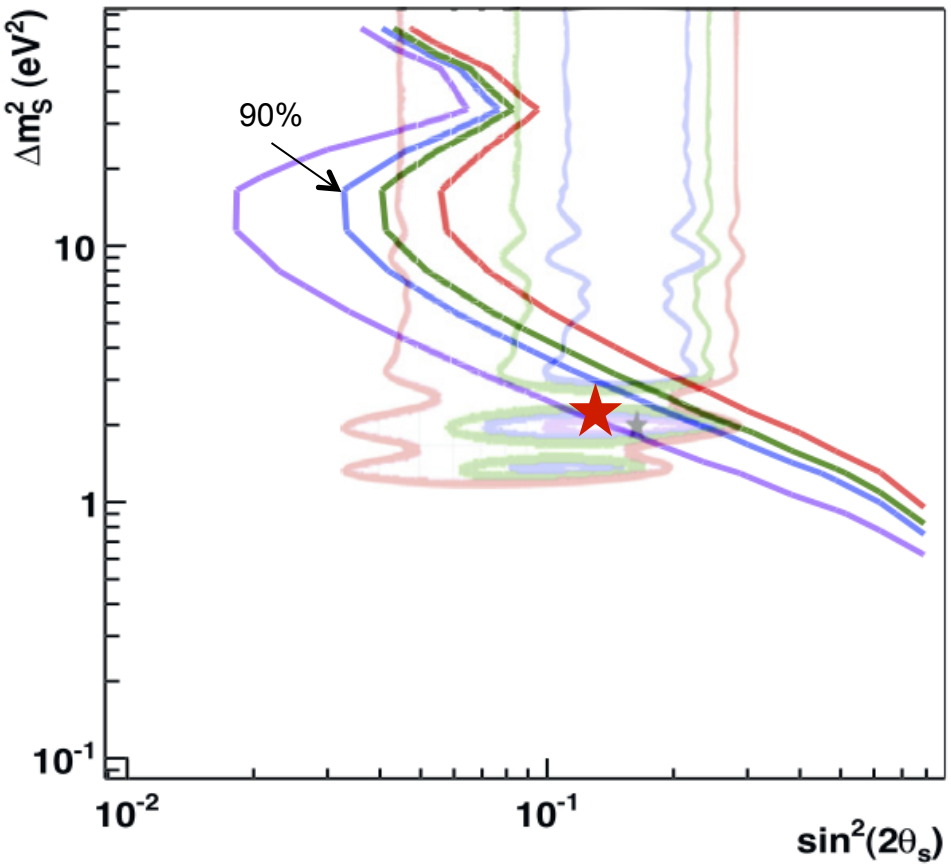
eV-Scale Sterile Neutrinos



KATRIN probes the favored parameter space, without any hardware modification

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

keV-Scale Sterile Neutrinos

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

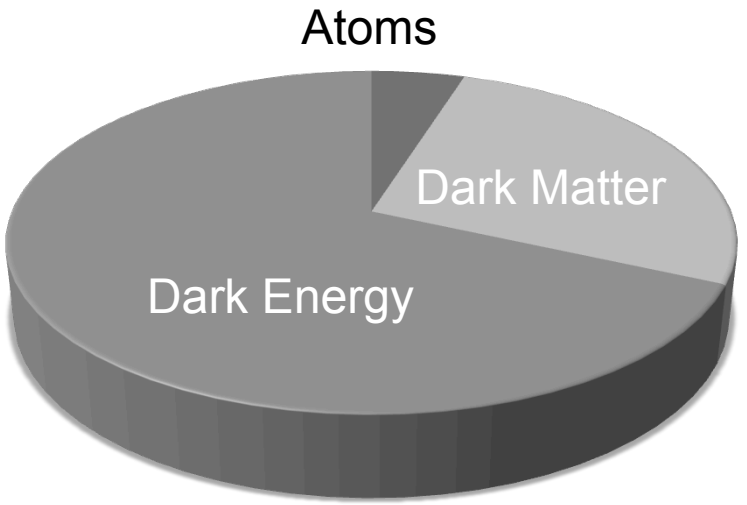
In agreement with cosmological observations from small to large scales

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

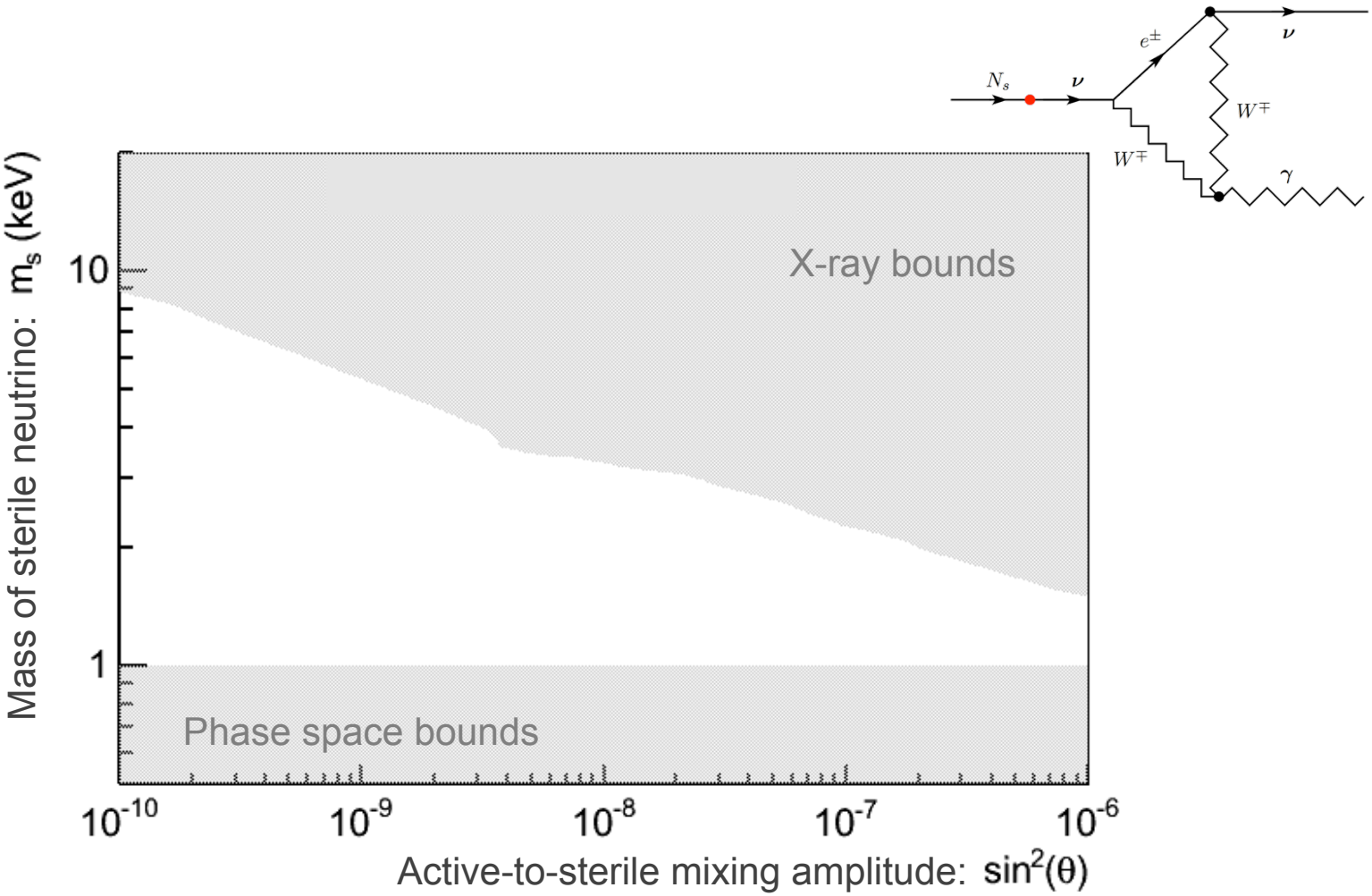
Recent indirect hint from satellite experiments ?

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

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

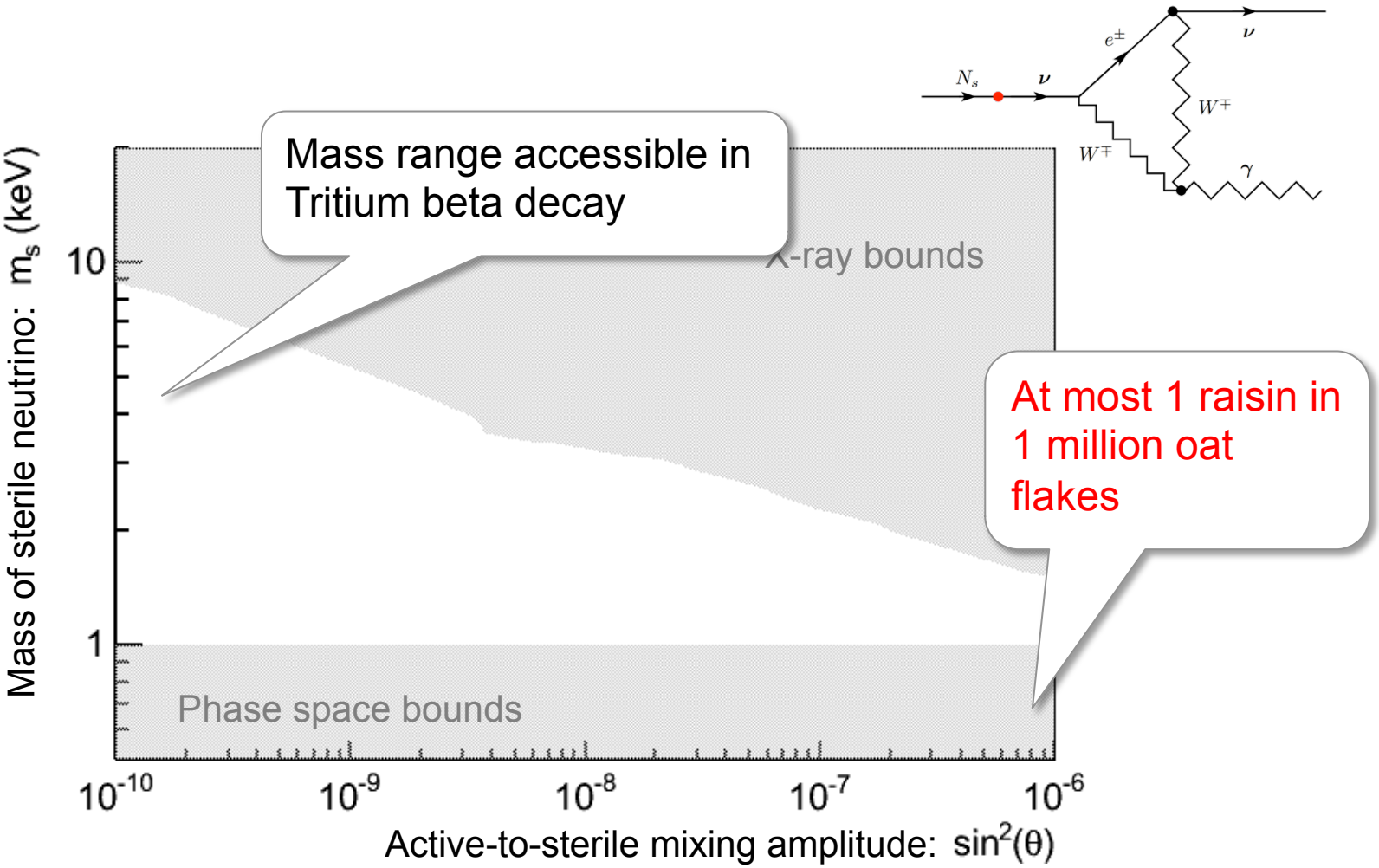


Cosmological constraints



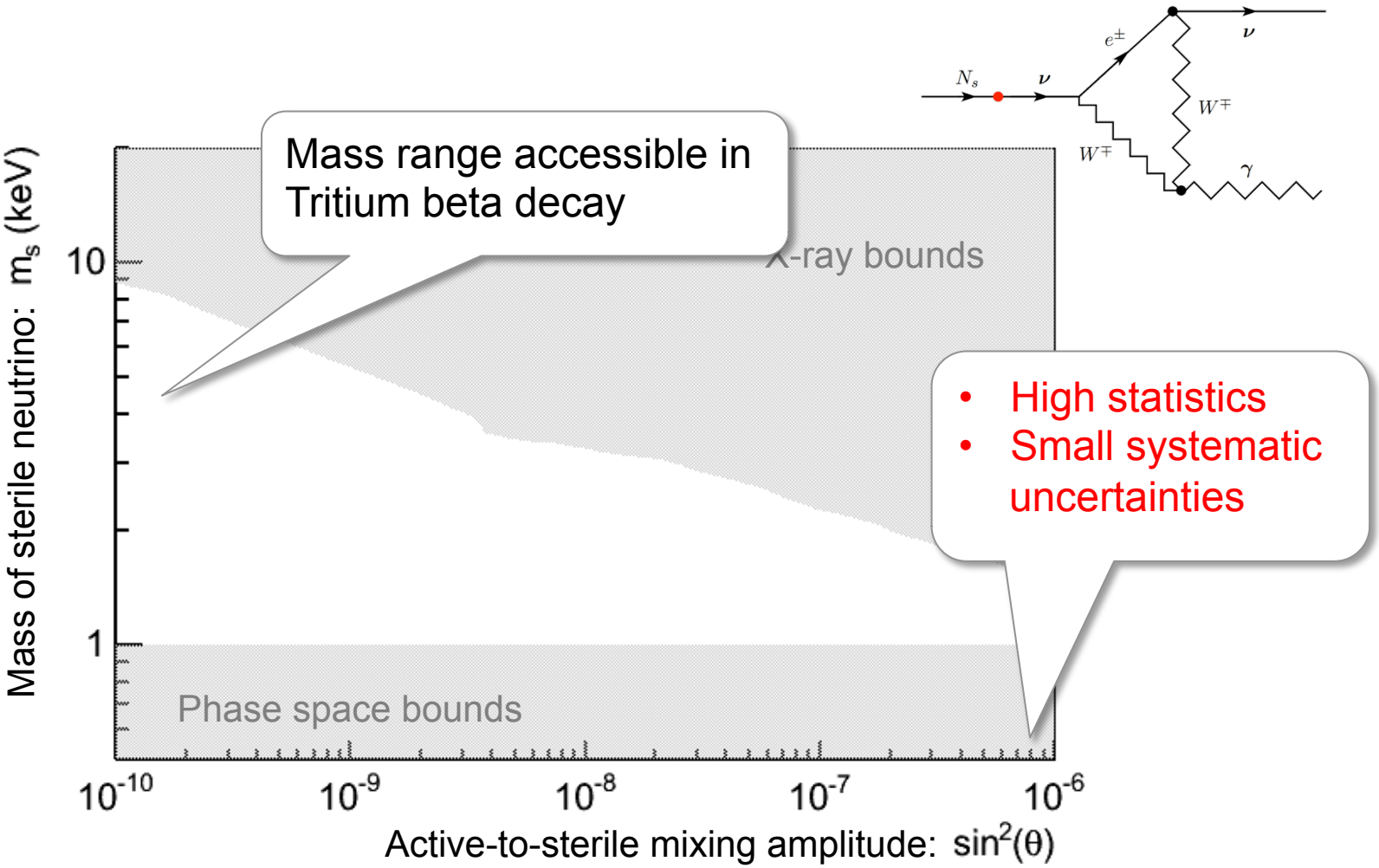
O. Ruchayskiy, A. Ivashko
JHEP **1206** (2012) 100

Cosmological constraints



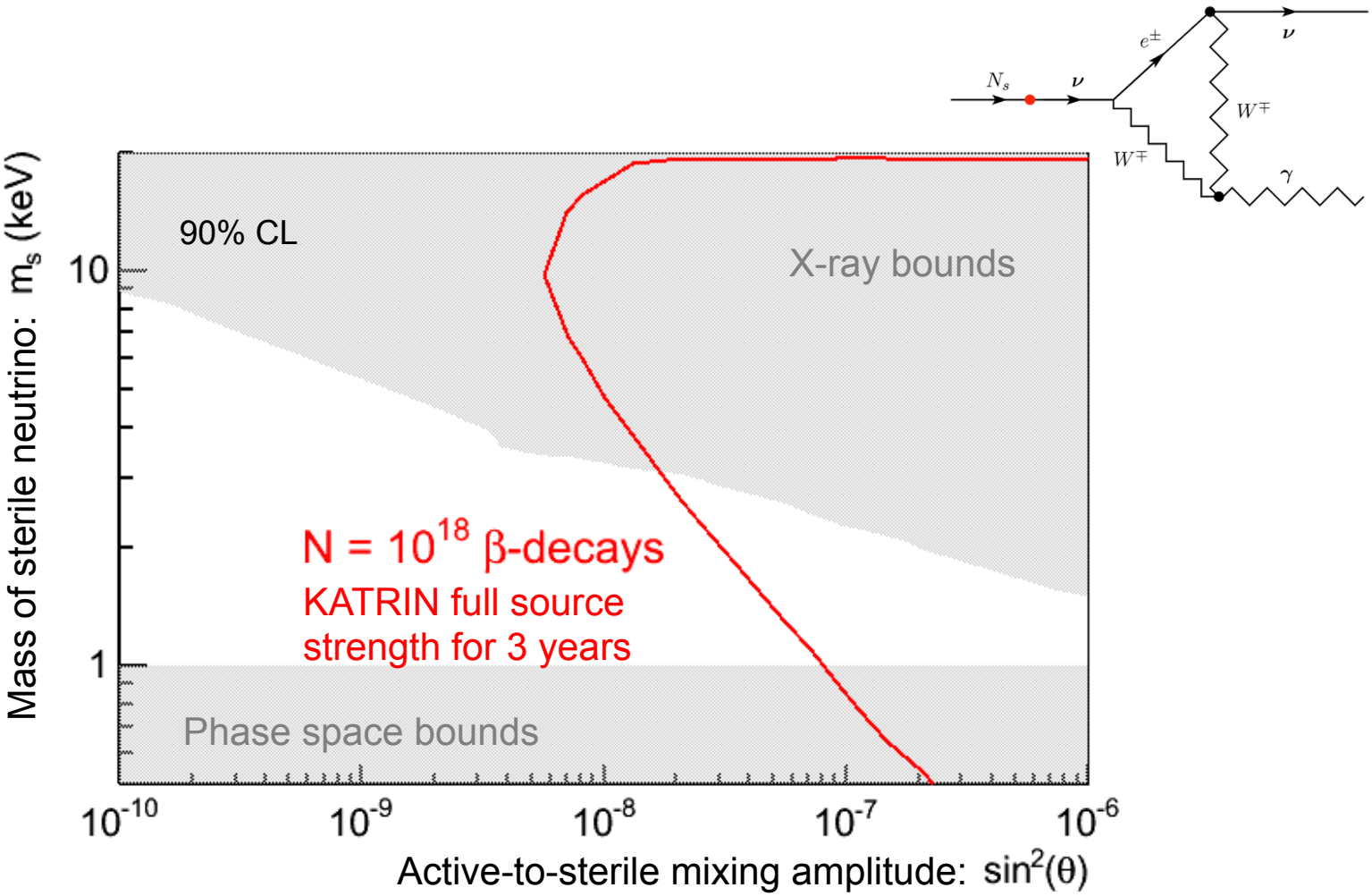
O. Ruchayskiy, A. Ivashko
JHEP **1206** (2012) 100

The challenge of sterile ν search



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

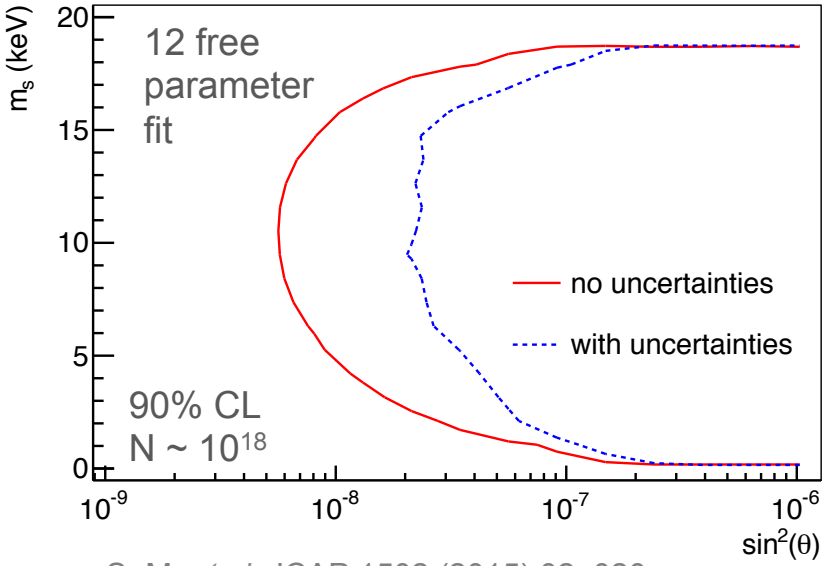
Statistical sensitivity



Detailed sensitivity studies

Spectral fit approach:

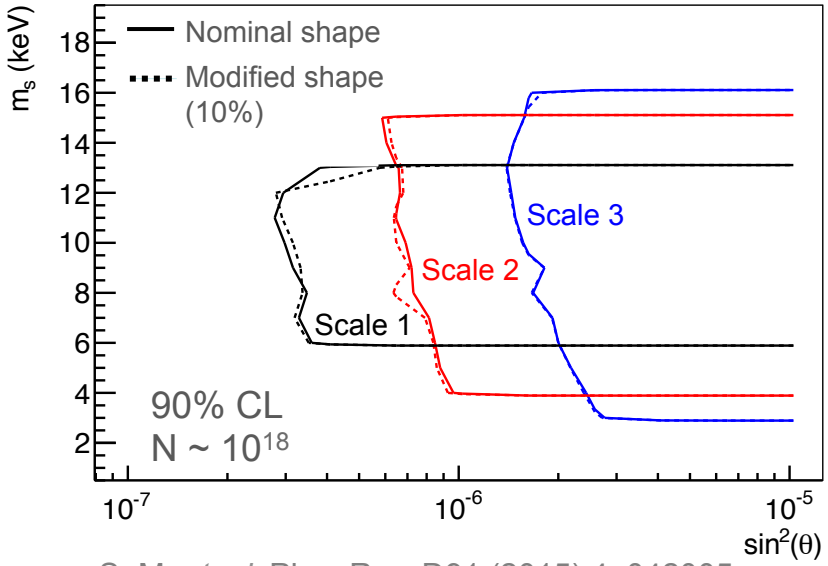
„How do theoretical uncertainties impact the sensitivity to find the signature of a sterile neutrino ?“



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

Wavelet approach:

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



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

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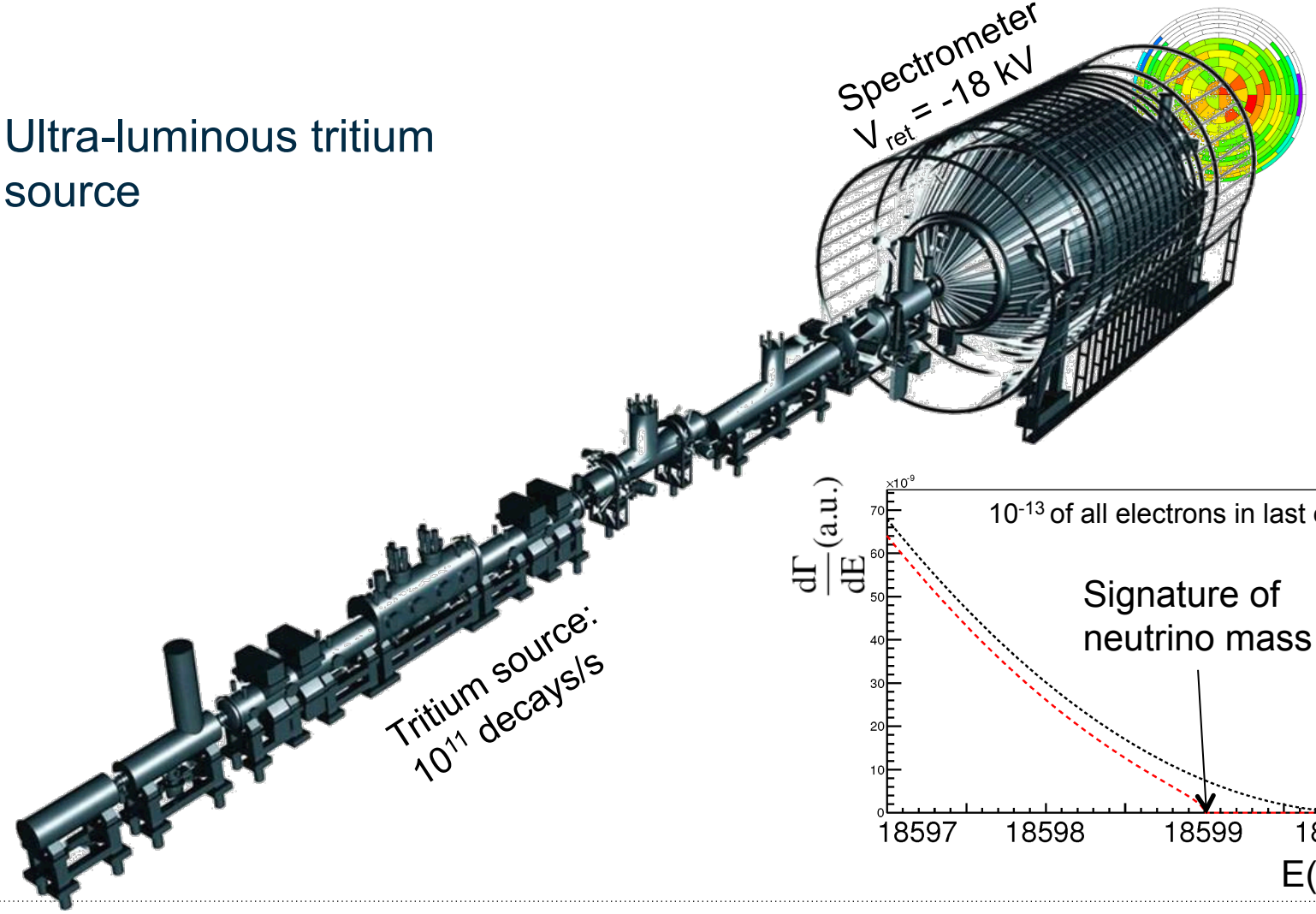
10 mcps

How to use KATRIN

- Ultra-luminous tritium source



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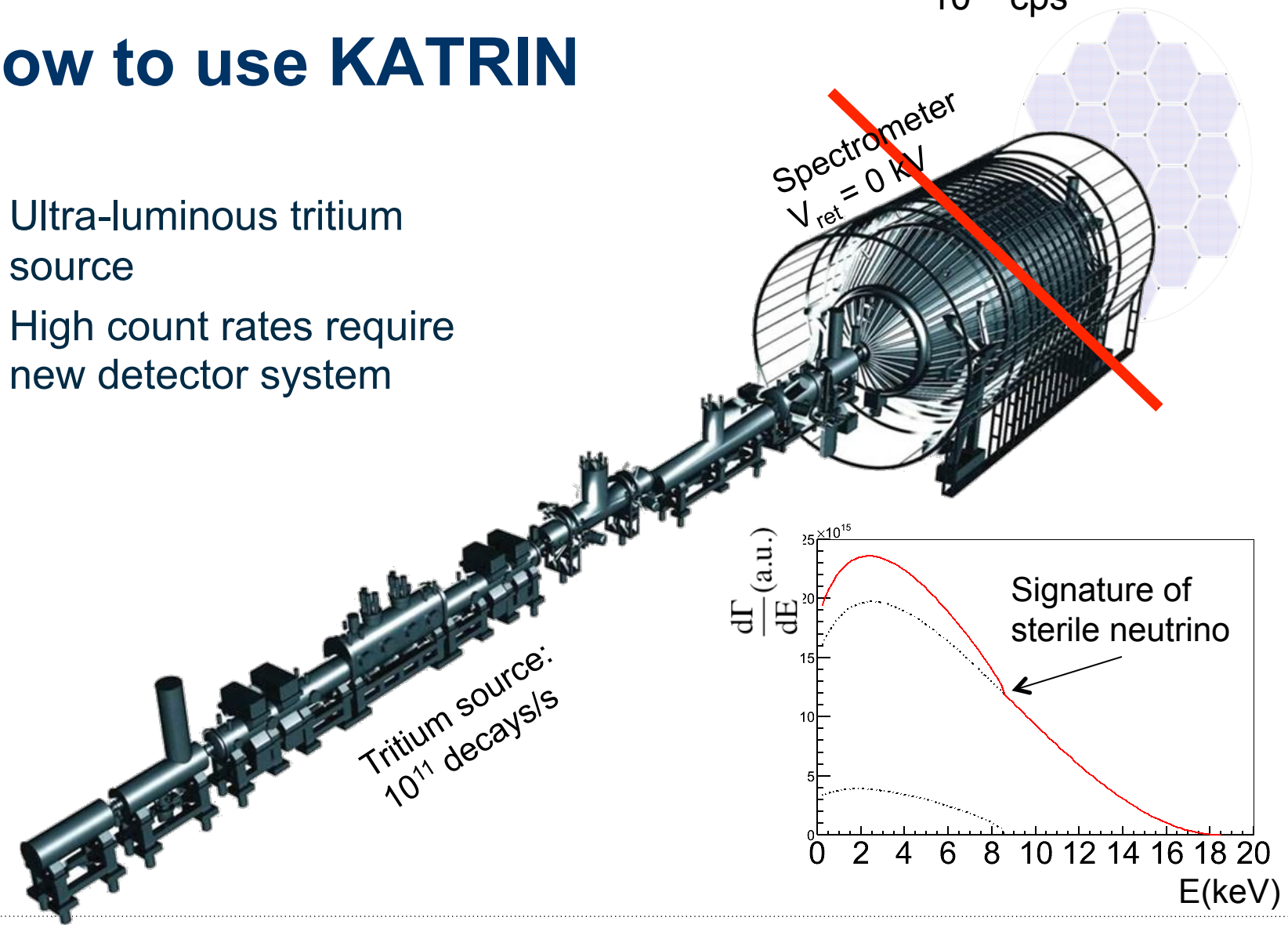
How to use KATRIN

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



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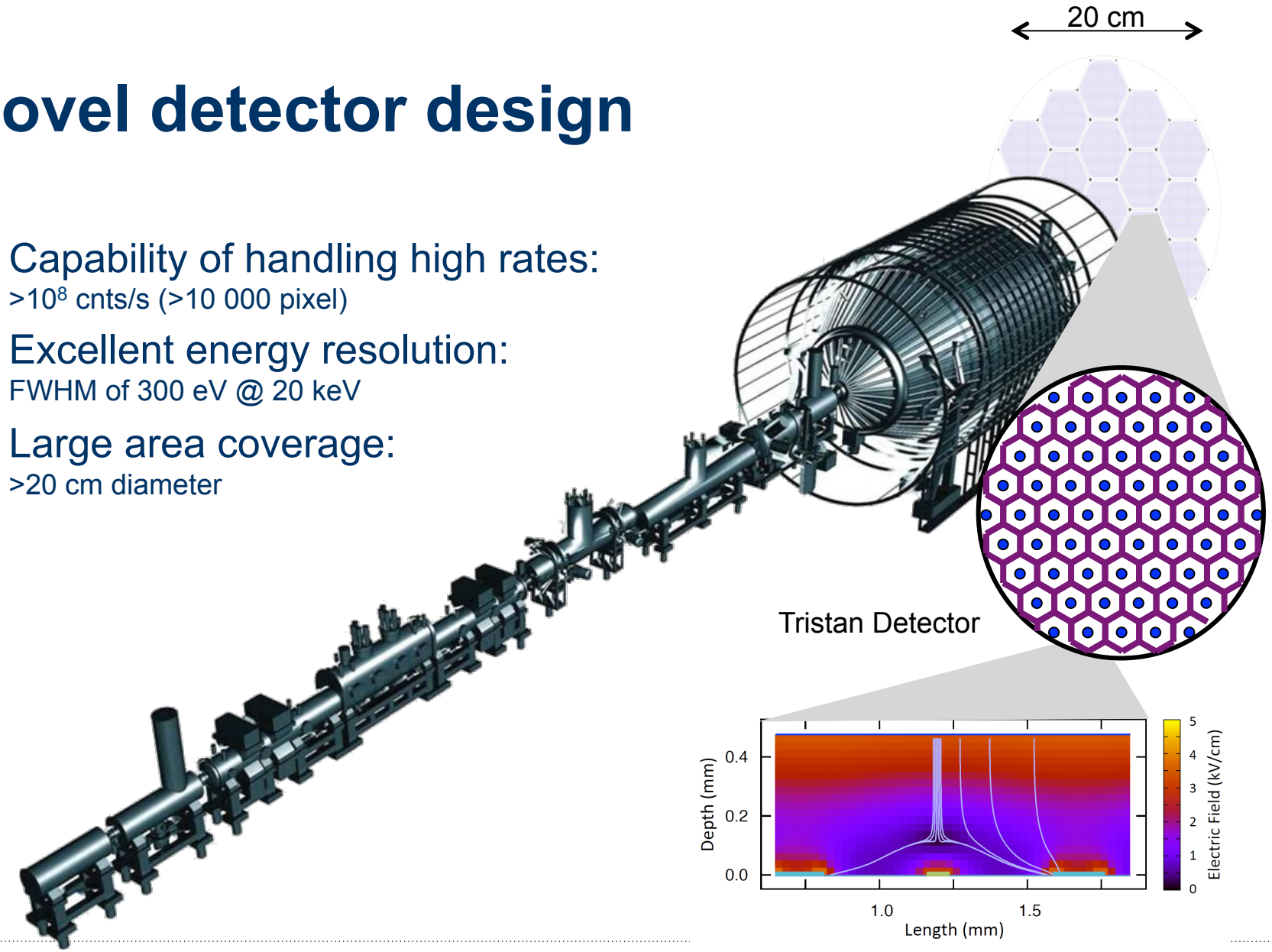
Novel detector design

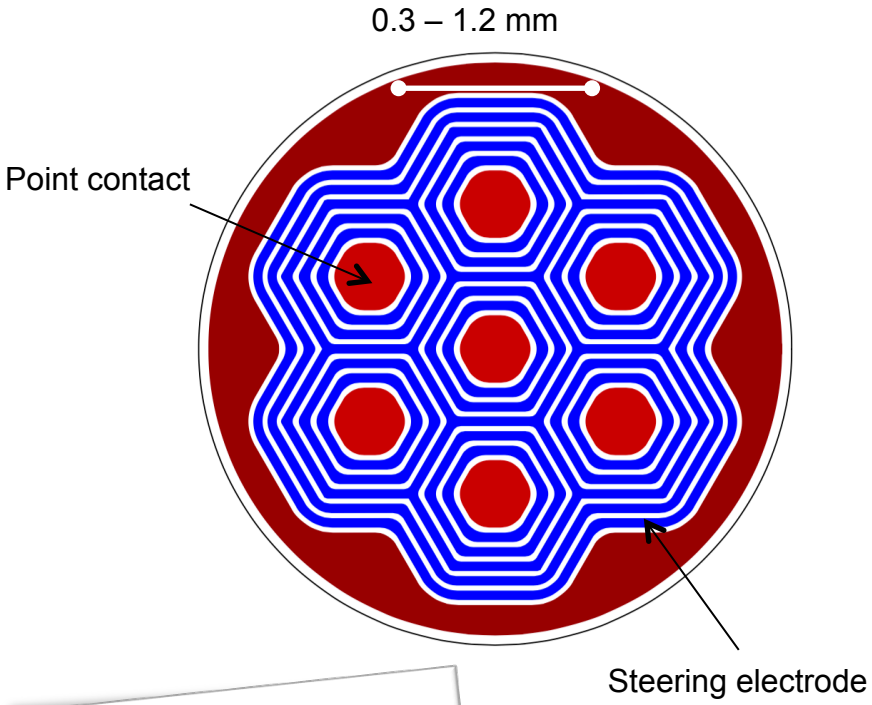
- Capability of handling high rates:
  >10^8 cnts/s (>10 000 pixel)
- Excellent energy resolution:
  FWHM of 300 eV @ 20 keV
- Large area coverage:
  >20 cm diameter



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.

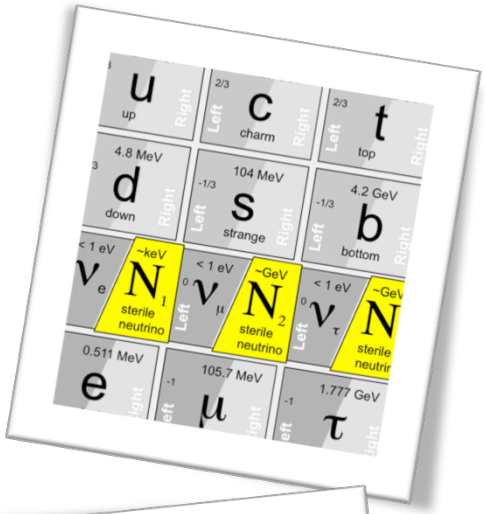


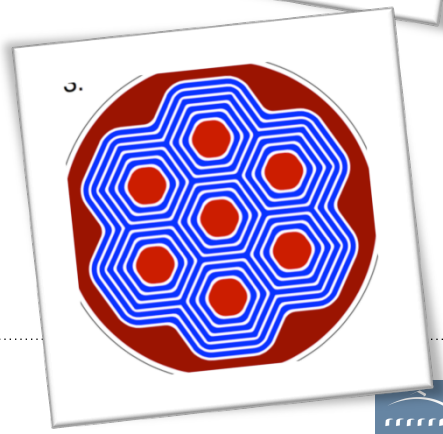
Prototype supported by Research Seed Capital funding of MWK Baden Württemberg

Summary

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

- KATRIN “as-is” provides great sensitivity for eV-scale sterile neutrinos
- Extended 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





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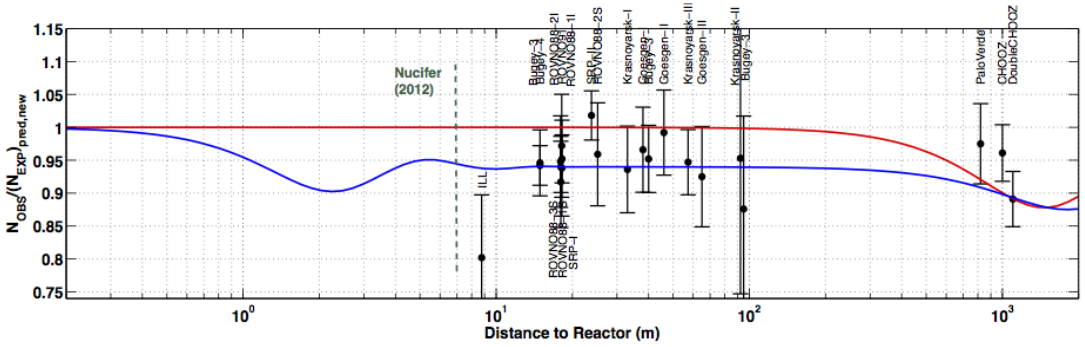
Thanks for your attention

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

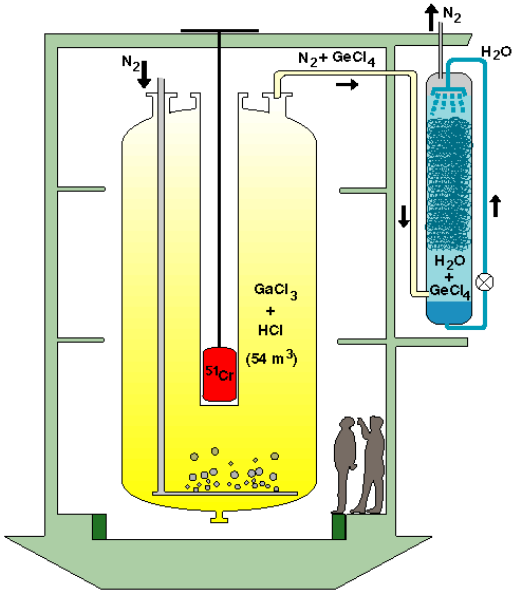
Backup Slides

Sterile Neutrino Mass Eigenstates

eV-scale sterile neutrinos



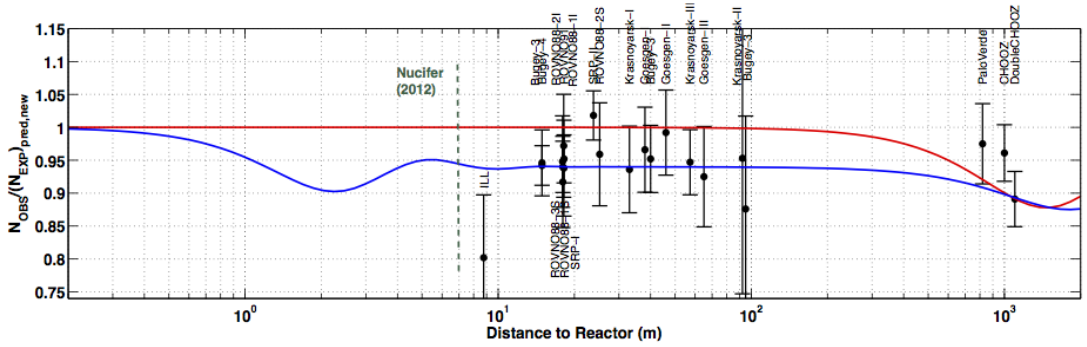
Reactor anomaly:
~2.7σ deficit of measured events compared to prediction



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



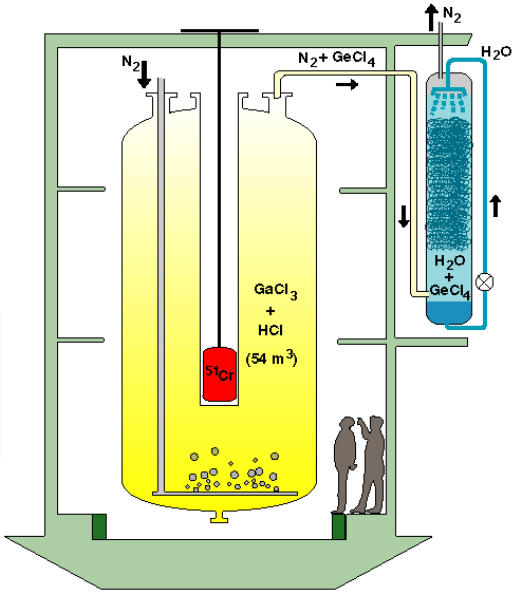
Possible explanation: sterile neutrinos

Best fit:

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

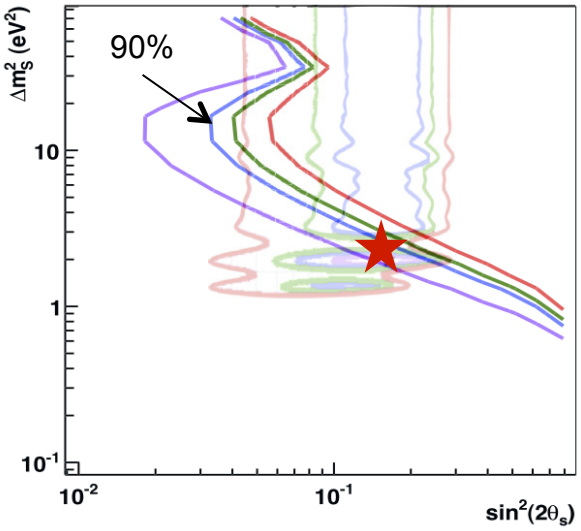
$\Delta m^2 = (2.3 \pm 0.1)\ eV^2$

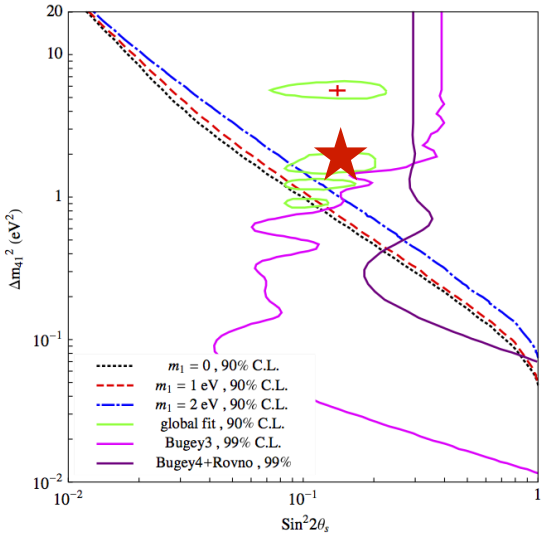
→ This is where KATRIN measures, anyway

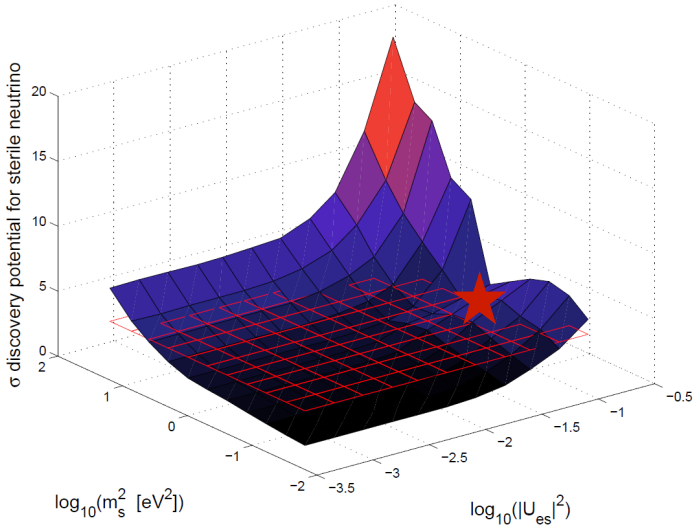


G. Mention et al., Phys. Rev. D 83 (2011) 073006
P. Anselmann et al., Phys. Lett. B 357 (1995) 237

KATRIN‘s sensitivity for eV ν‘s





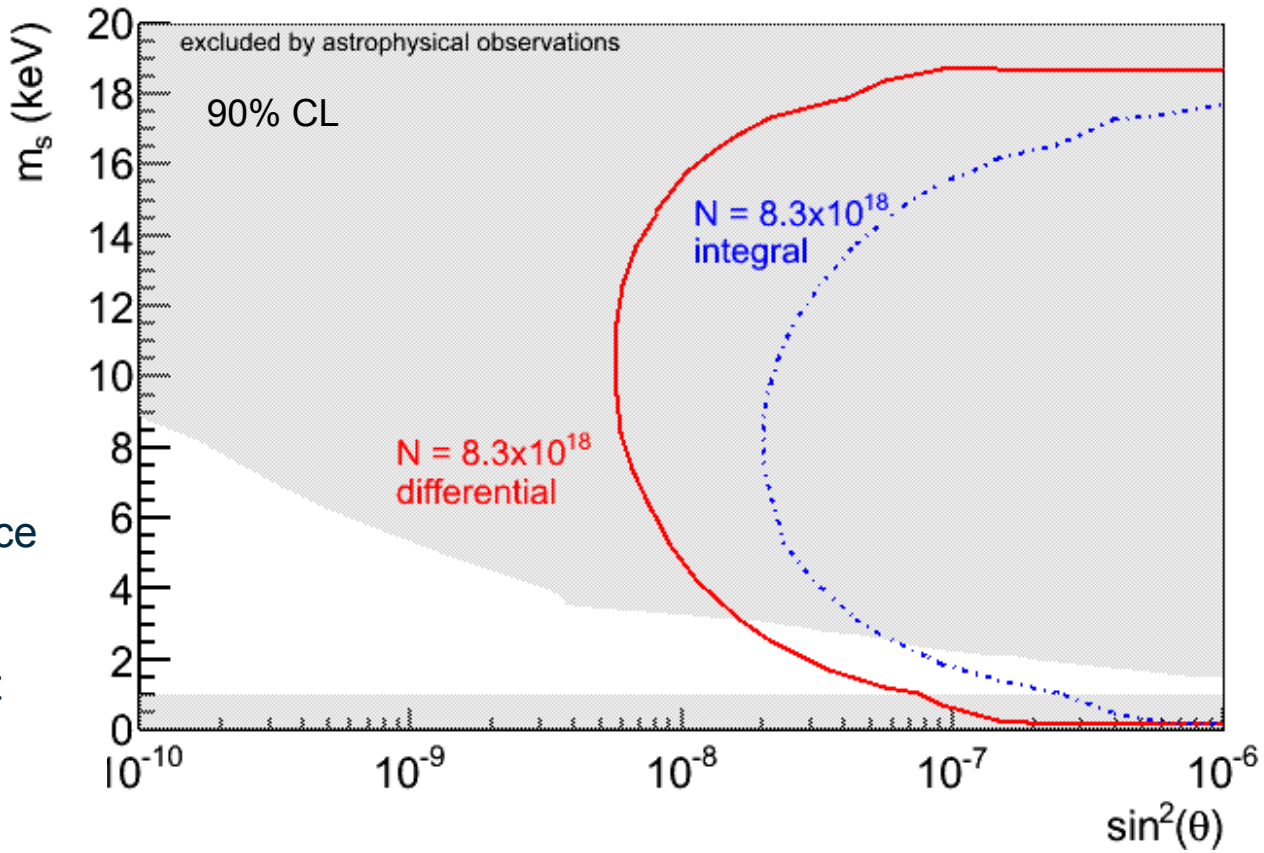


J. A. Formaggio, J. Barret, PLB 706 (2011) 68
A. Esmaili, O.L.G. Peres, Phys. Rev. D 85, 117301
A. Sejersen Riis, S. Hannestad, JCAP02 (2011) 011
M. Kleesiek, PhD Thesis (2014)

KATRIN probes the favored parameter space

Different measurement modes

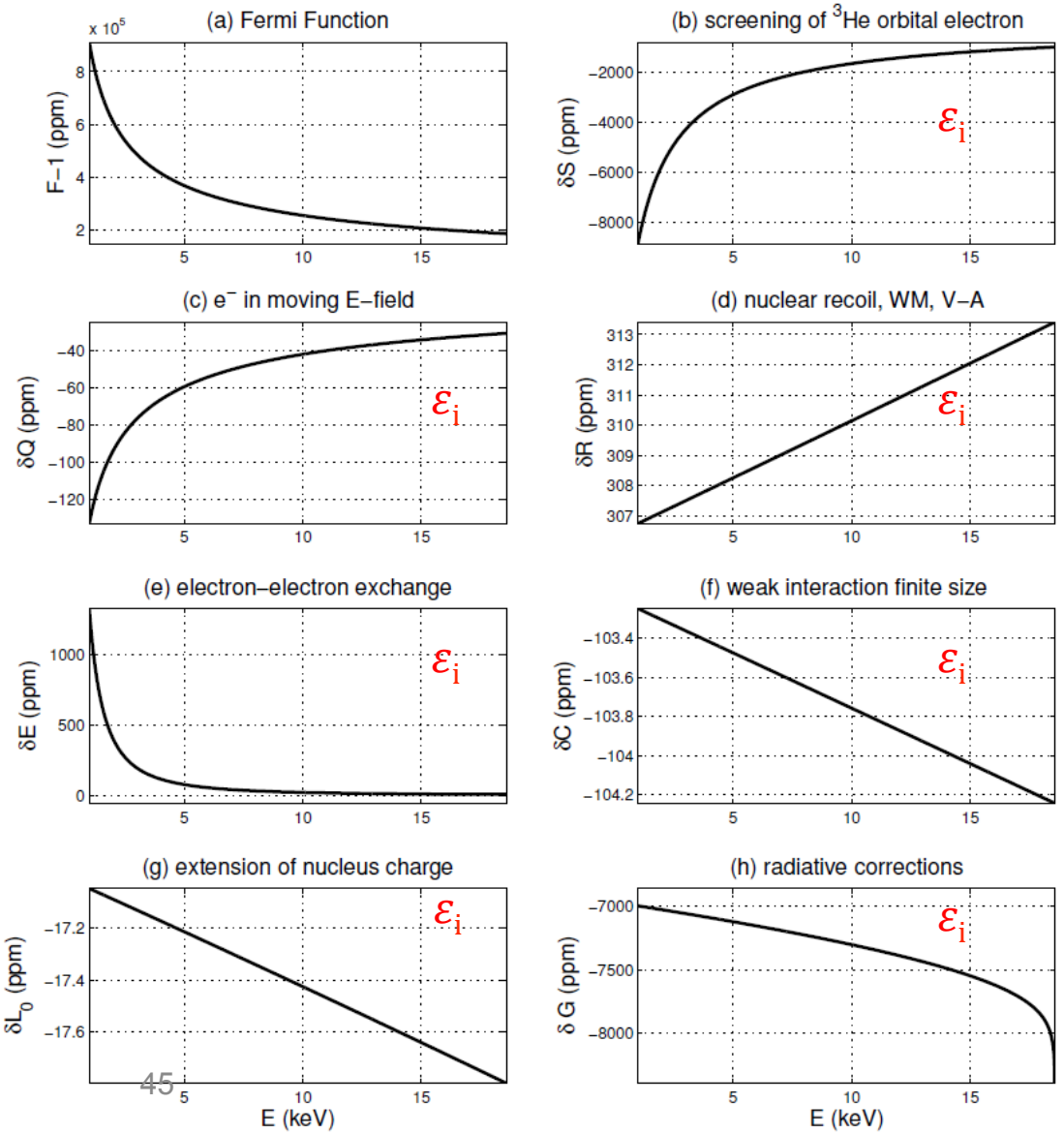
KATRIN source strength, 3-years measurement time



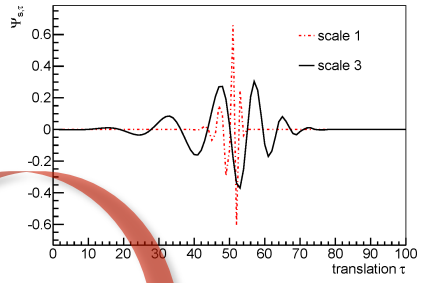
S. Mertens et. al. arXiv:1409.0920

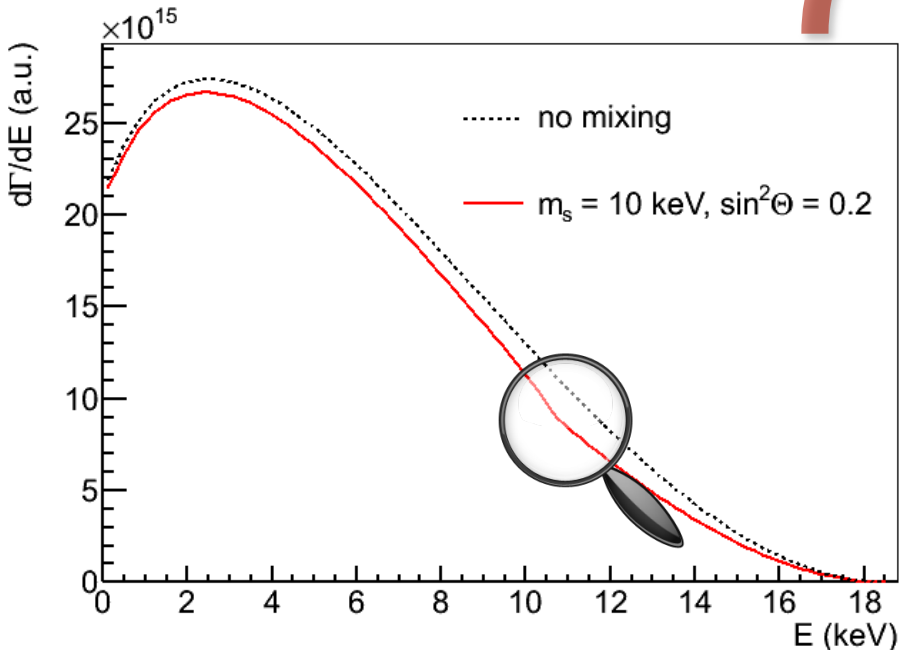
Spectral Fit Approach

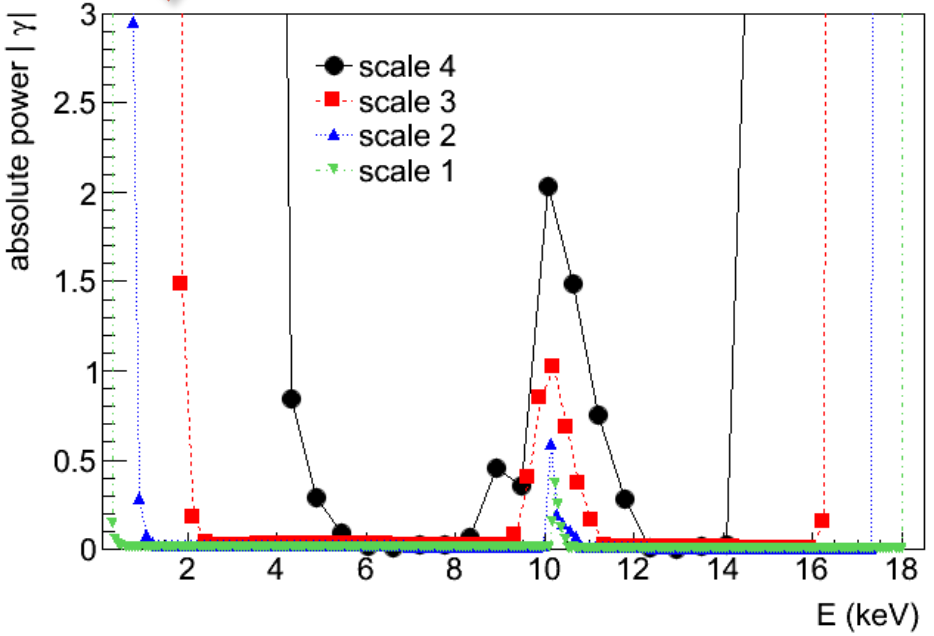
„State-of-the -Art“ Tritium Spectrum: Non-negligible but smooth corrections



Wavelet Approach

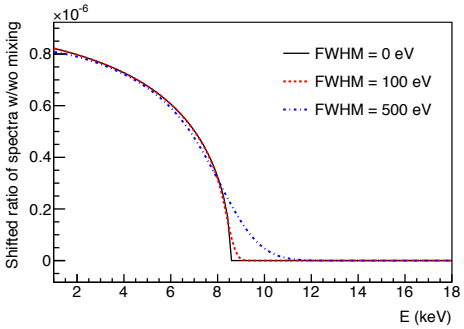




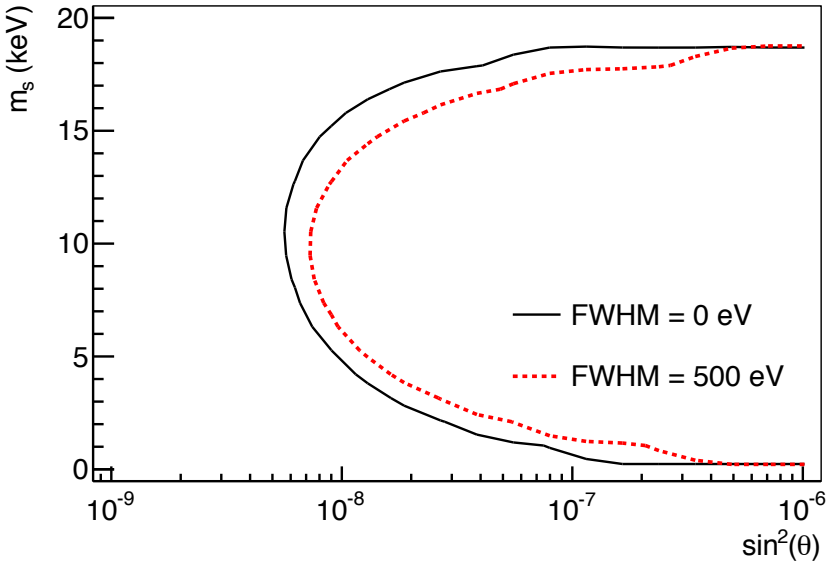


S. Mertens et. al.
arXiv:1410.7684

Detailed sensitivity studies

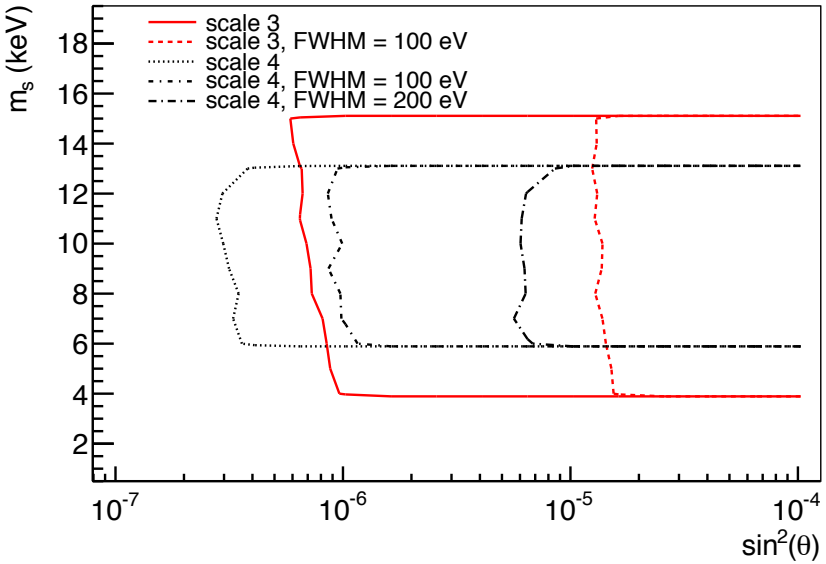


Spectral fit approach: Detector resolution



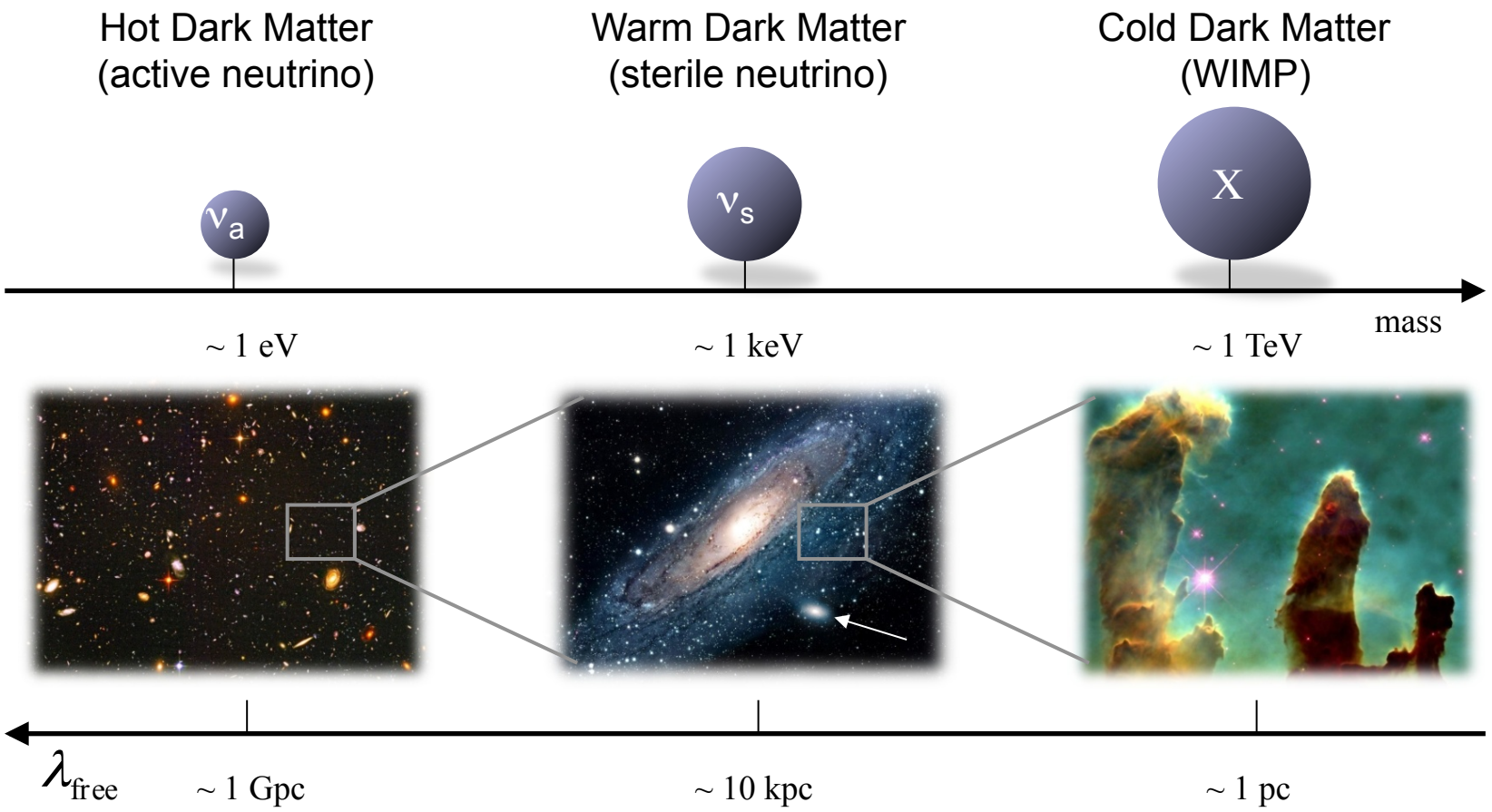
S. Mertens et. al.
Accepted for publication in Journal of cosmology and astroparticle physics

Wavelet approach: Detector resolution



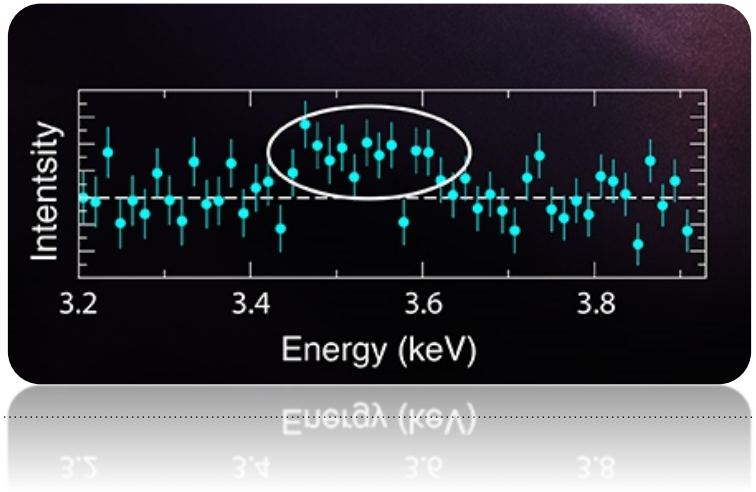
S. Mertens et. al.
Accepted for publication in Phys Rev D

Sterile Neutrinos and Dark Matter

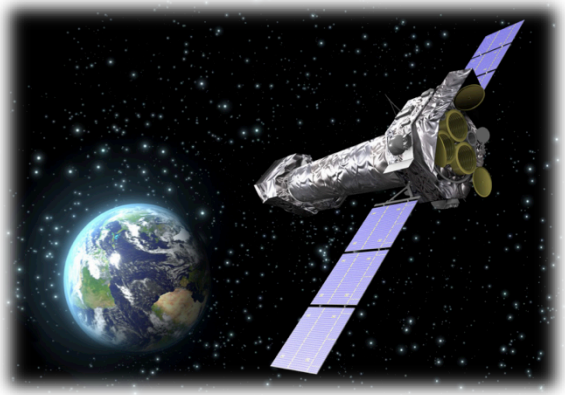


Possible hints for sterile ν DM ?

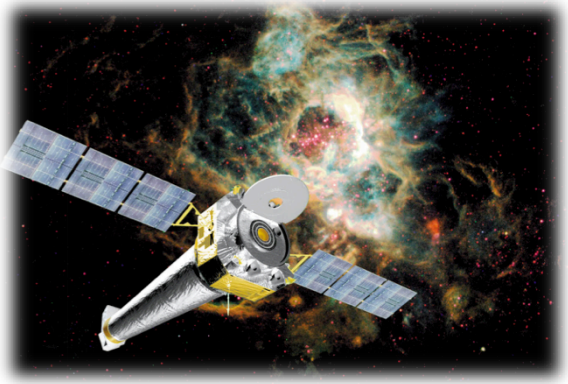
- Unidentified X-ray line observed in Perseus cluster and stacked galaxy clusters
- Could be interpreted signature of decay of sterile neutrino decay ?
- Results are not conclusive at the moment



XMM Newton Telescope

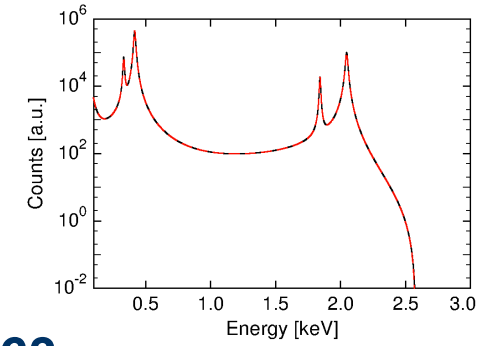


Chandra Telescope



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

Other efforts



The case of Tritium:

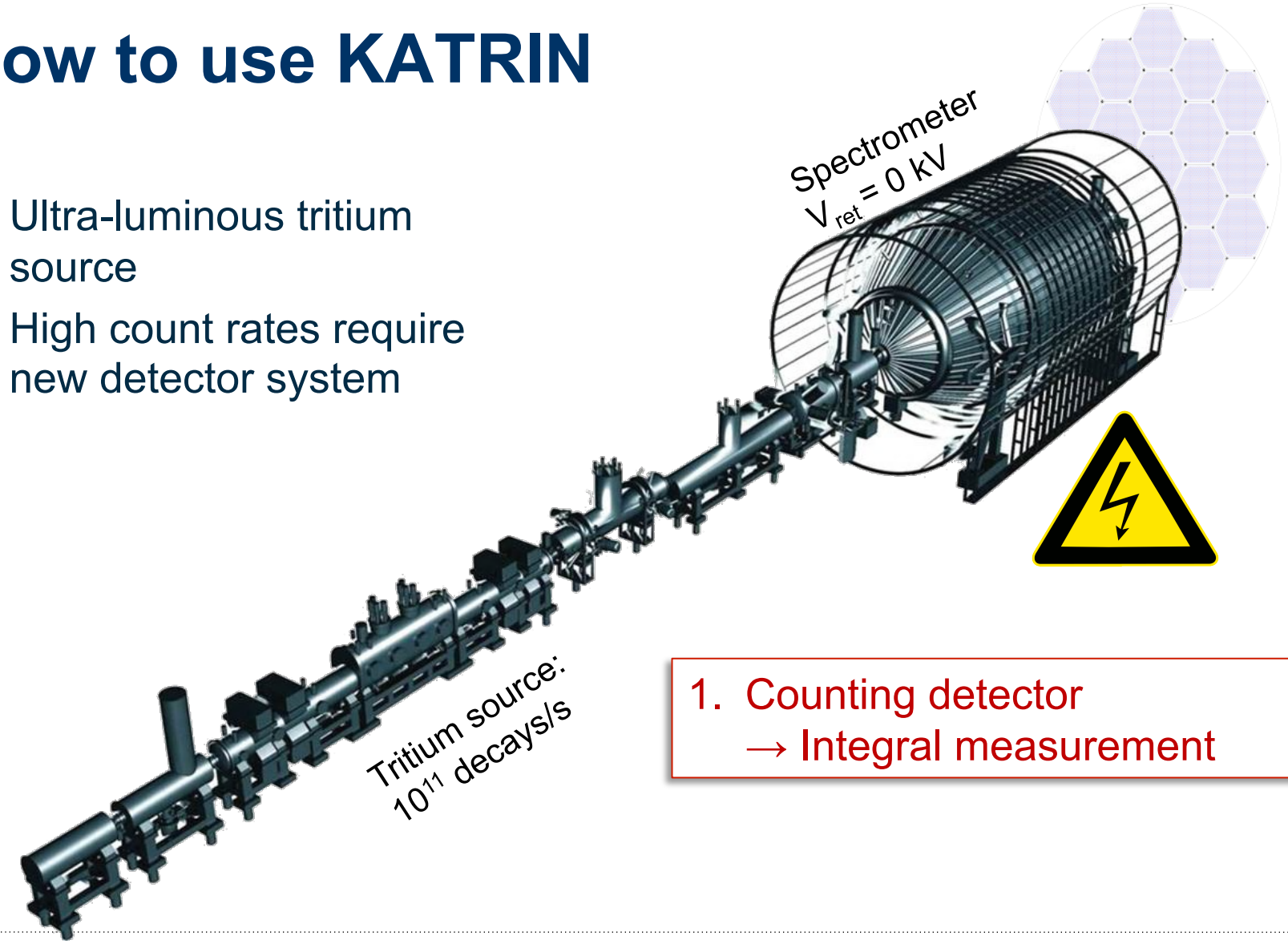
- Endpoint: 18.6 keV
- Super-allowed decay
- Short half life of 12.3 years
- Projects:
  - KATRIN
    S. M. *et al.* (arXiv:1409.0920) Accepted for publication in JCAP
  - Project8
    B. Monreal and Joe Formaggio, Phys. Rev D80:051301
  - Full kinematic reconstruction
    F. Bezrukov and M. Shaposhnikov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

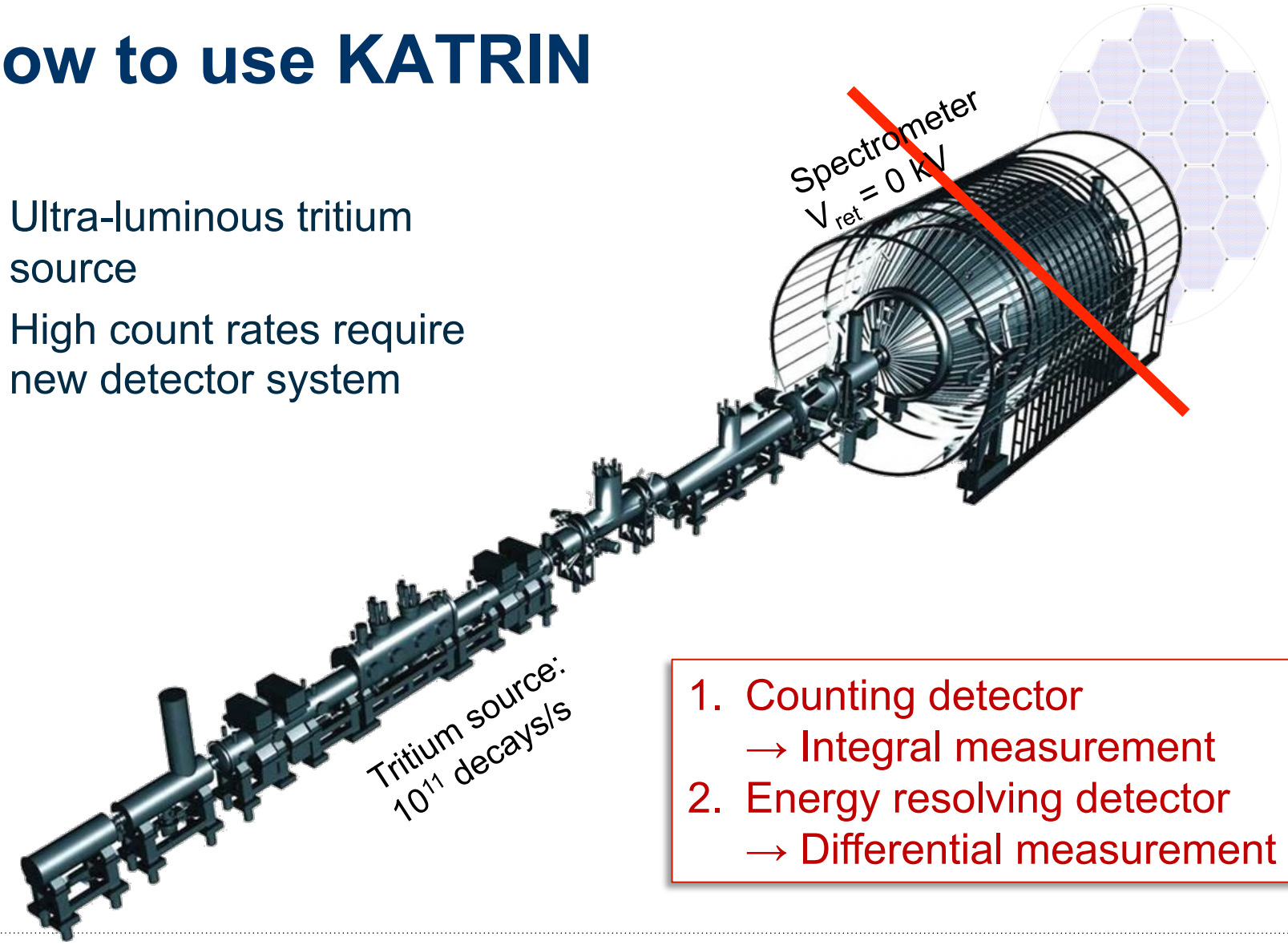
- Ultra-luminous tritium source
- High count rates require new detector system



1. Counting detector
   → Integral measurement

How to use KATRIN

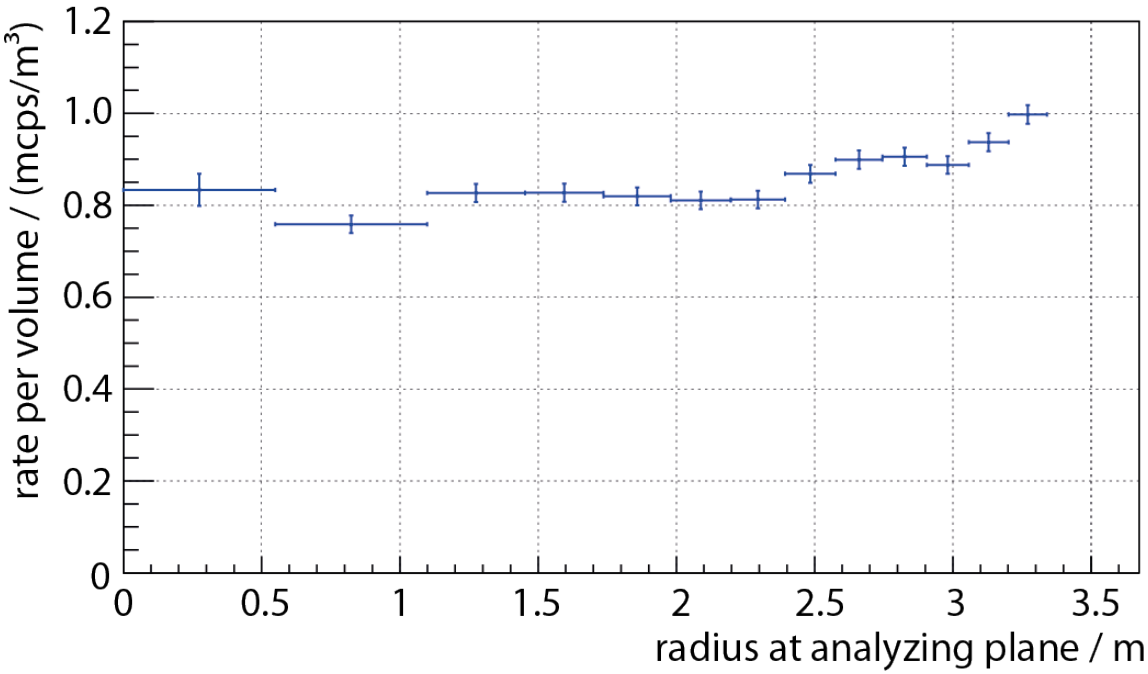
- Ultra-luminous tritium source
- High count rates require new detector system



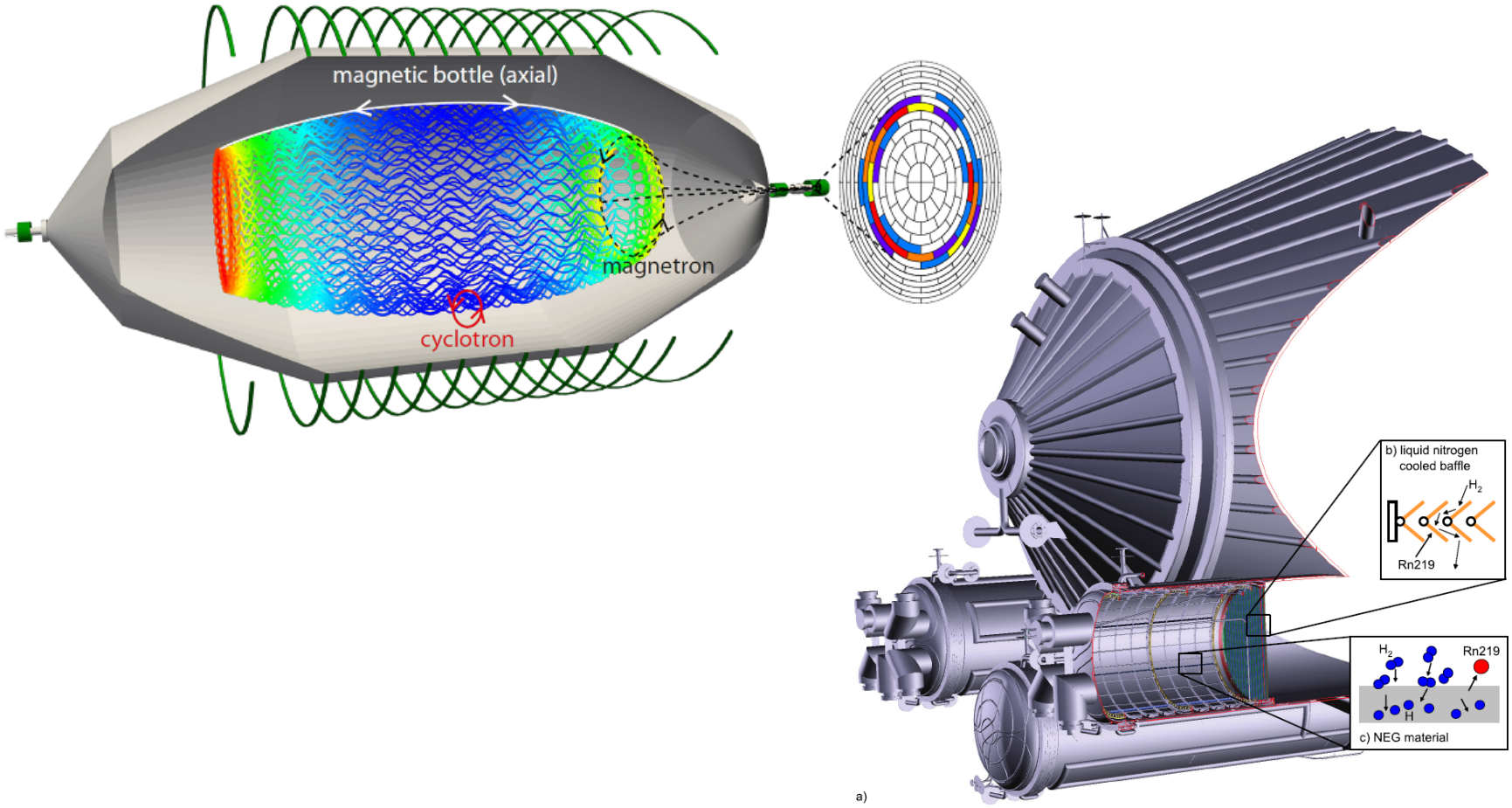
1. Counting detector
   → Integral measurement
2. Energy resolving detector
   → Differential measurement

KATRIN Background

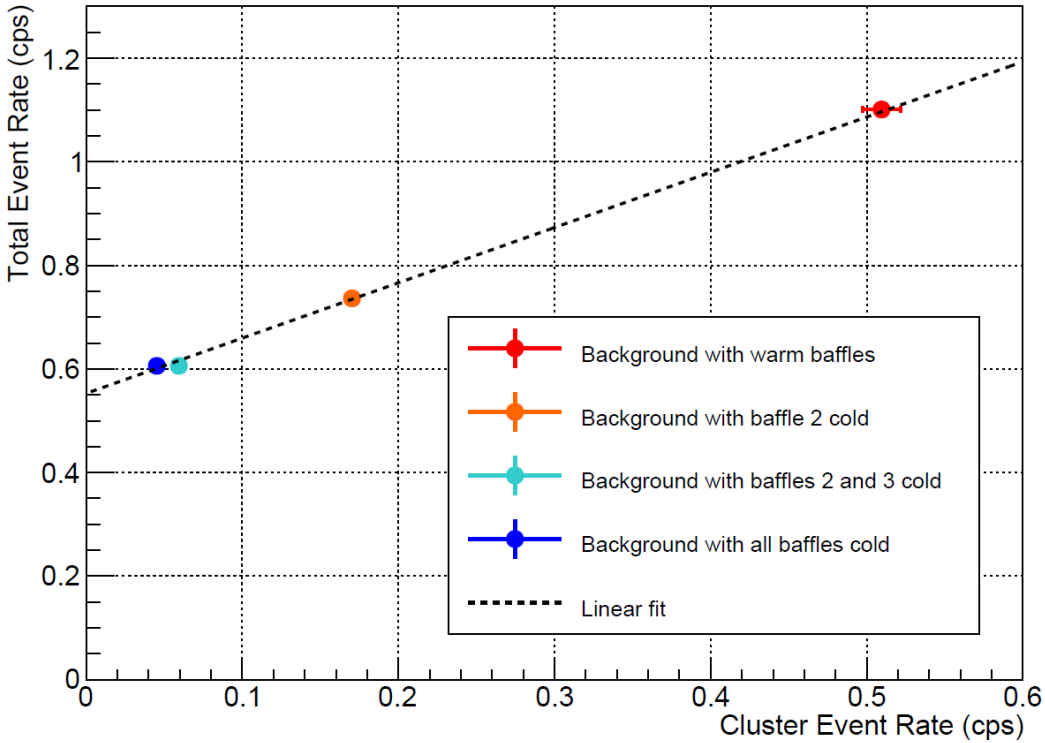
- Background rate in ROI **477 +/- 3 mcps** (10 mcps required)
- Settings: vessel = -18.5kV, IE = -100V, PAE = +10 kV and “5G” magnetic field setting



Radon induced background



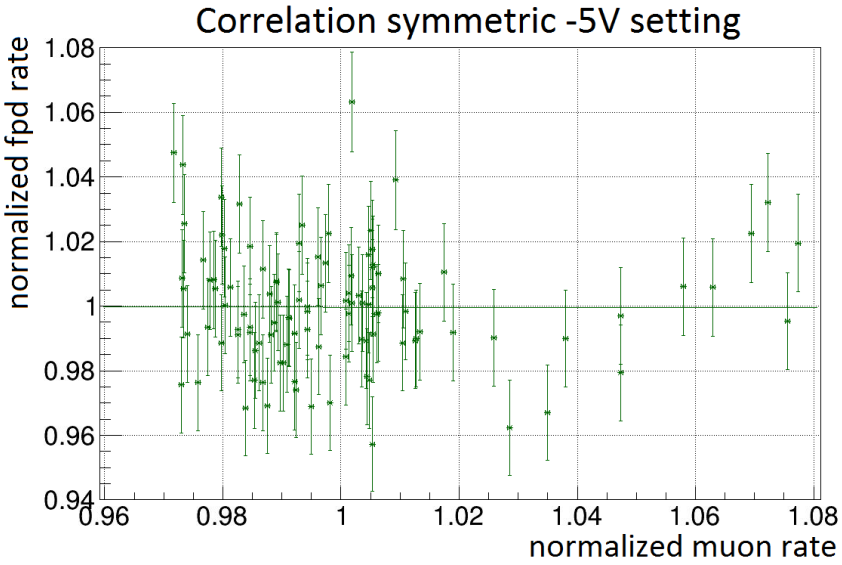
Effect of cold baffle on Radon background



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

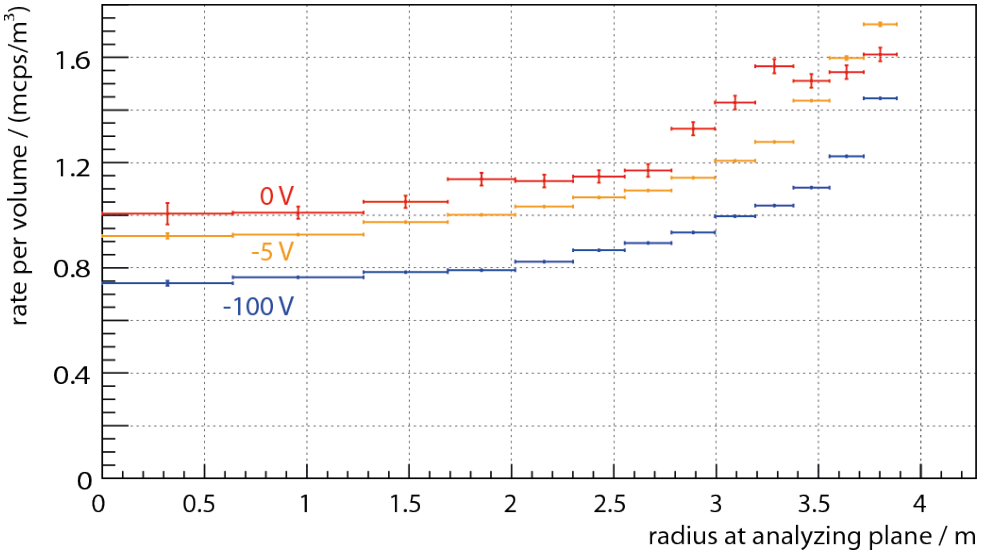
B_{total} : Total background rate.
S_{Rn} : Radon-induced single event rate.
C_{Rn} : Event rate in Radon-induced clusters.
R : Non-Radon-induced background rate.

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