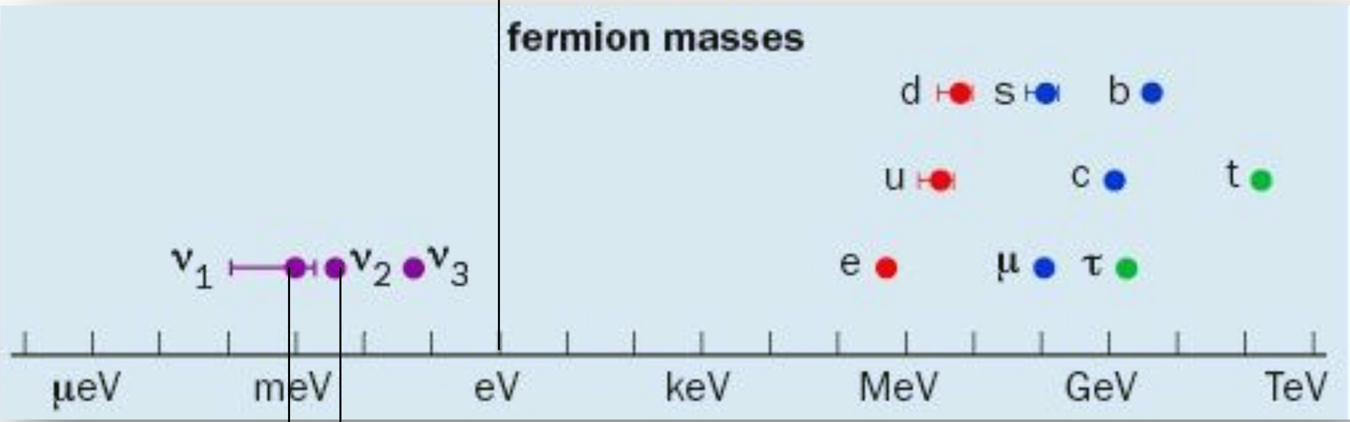
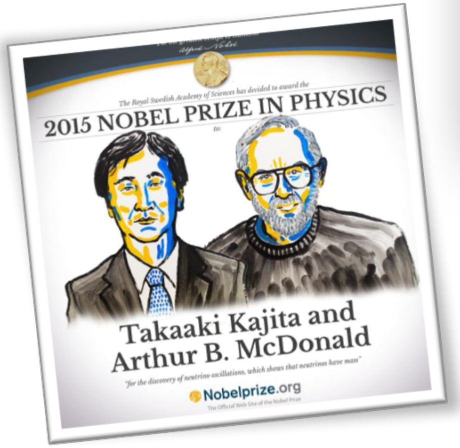
Probing neutrino mass and searching for sterile neutrinos with KATRIN

Susanne Mertens
Max Planck Institute for Physics & Technical University Munich
11th Terascale Detector Workshop, March 1, 2018

Neutrino mass

Upper bound
from direct measurements

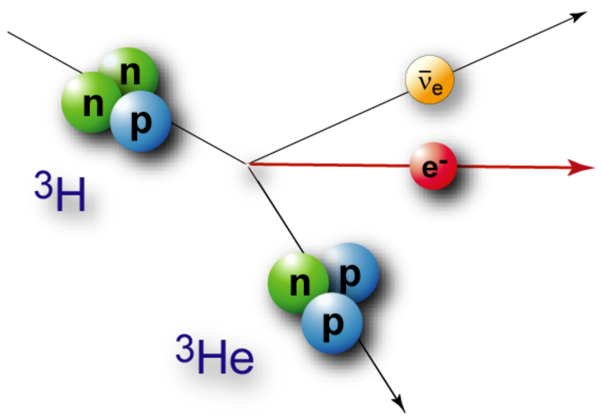


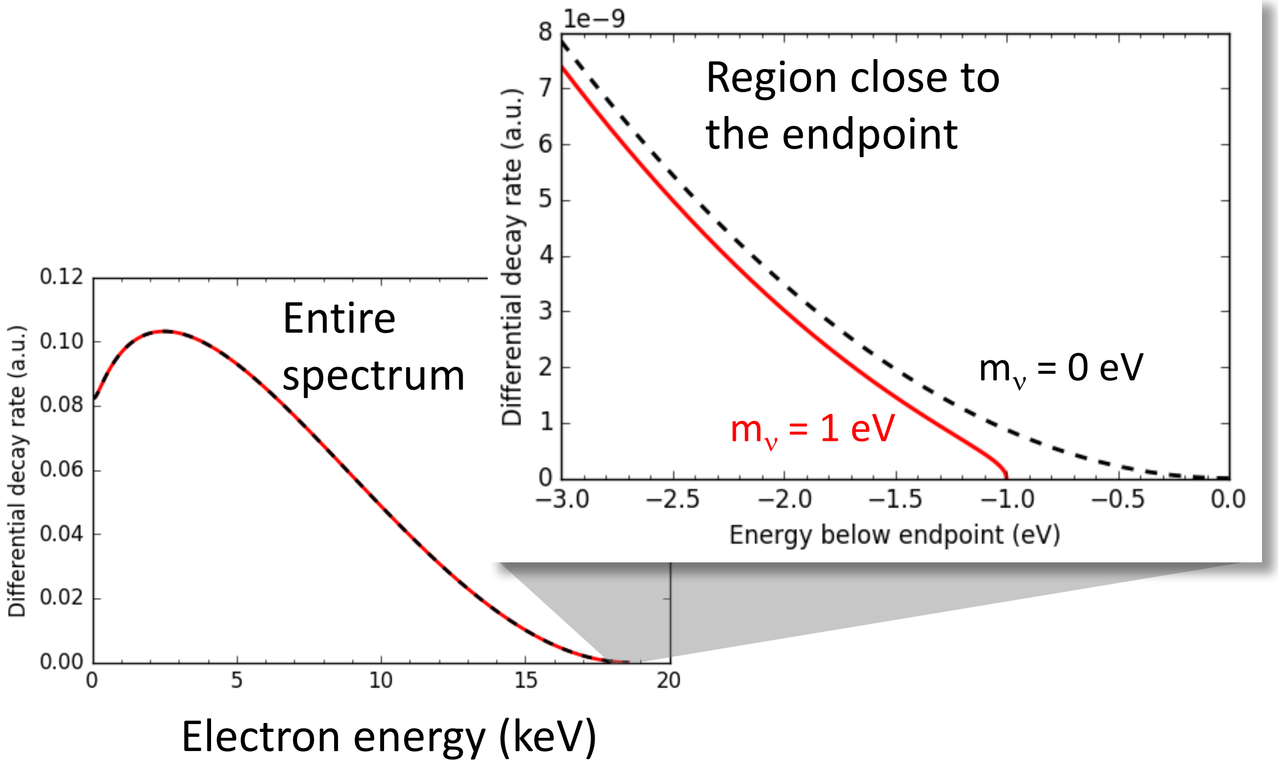


Lower bound
from oscillation experiments

General idea

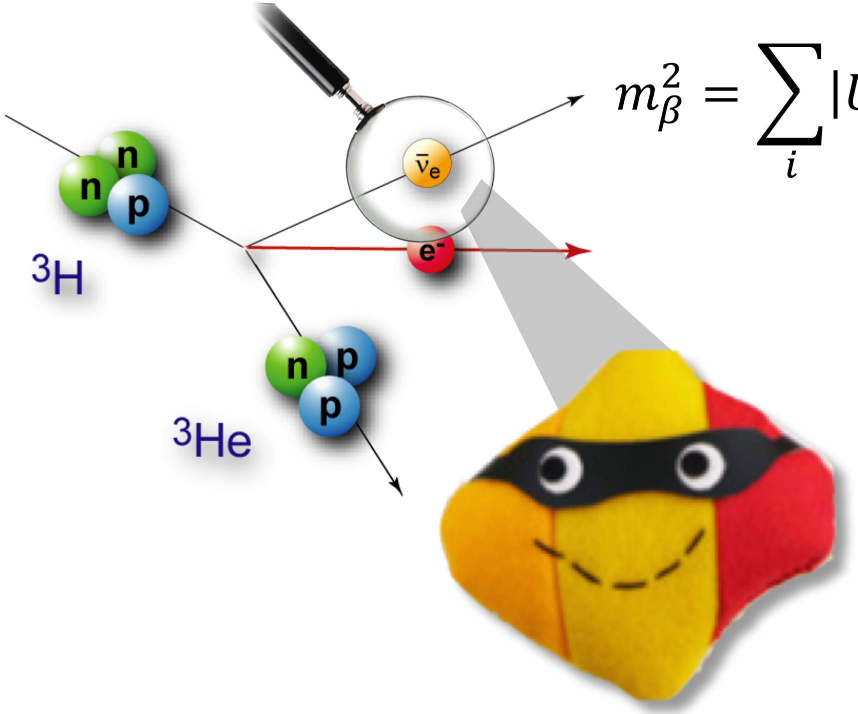
- Kinematic determination of the neutrino mass
- Non-zero neutrino mass reduces the endpoint and distorts the spectrum



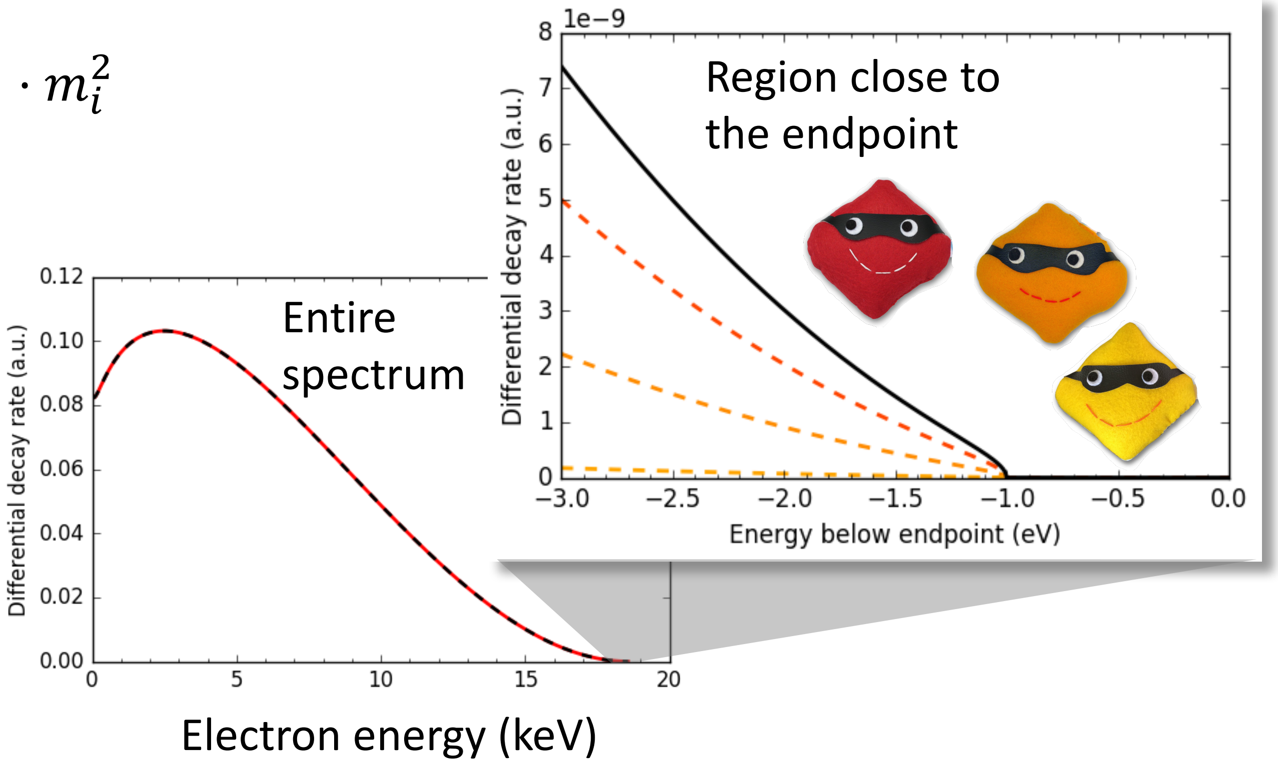


General idea

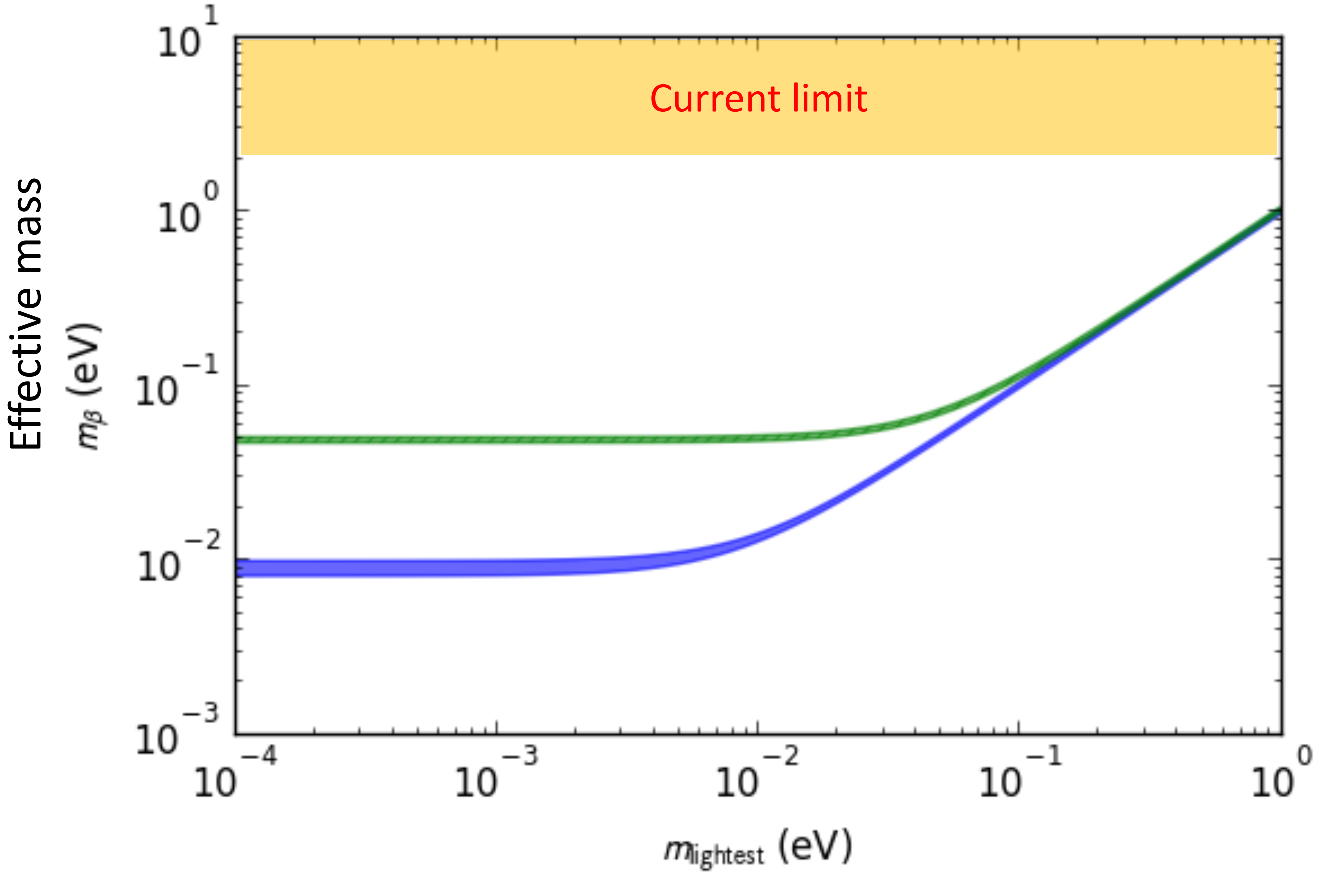
- The tritium spectrum is a superposition of spectra with slightly different endpoints
- Current experiment measure an effective electron anti-neutrino mass



$$m_\beta^2 = \sum_i |U_{ei}|^2 \cdot m_i^2$$



Where do we stand?



- Current limit:
  Mainz and Troitsk Experiment
  V. N. Aseev et al., Phys. Rev. D 84 (2011) 112003
  Kraus, C., Bornschein, B., Bornschein, L. et al. Eur. Phys. J. C (2005)

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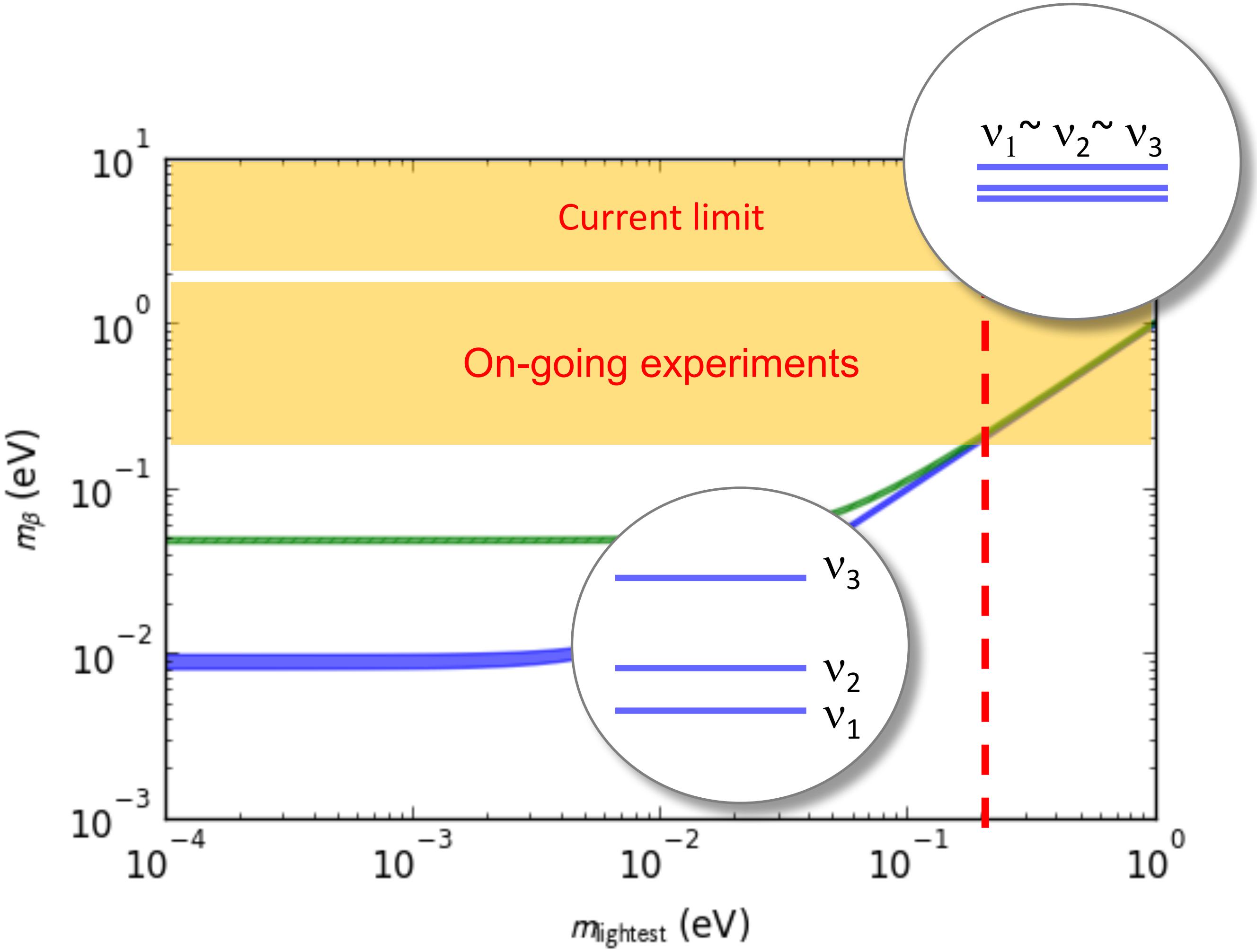

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- Ongoing experiments:
  Distinguish between **degenerate** and **hierarchical** scenario

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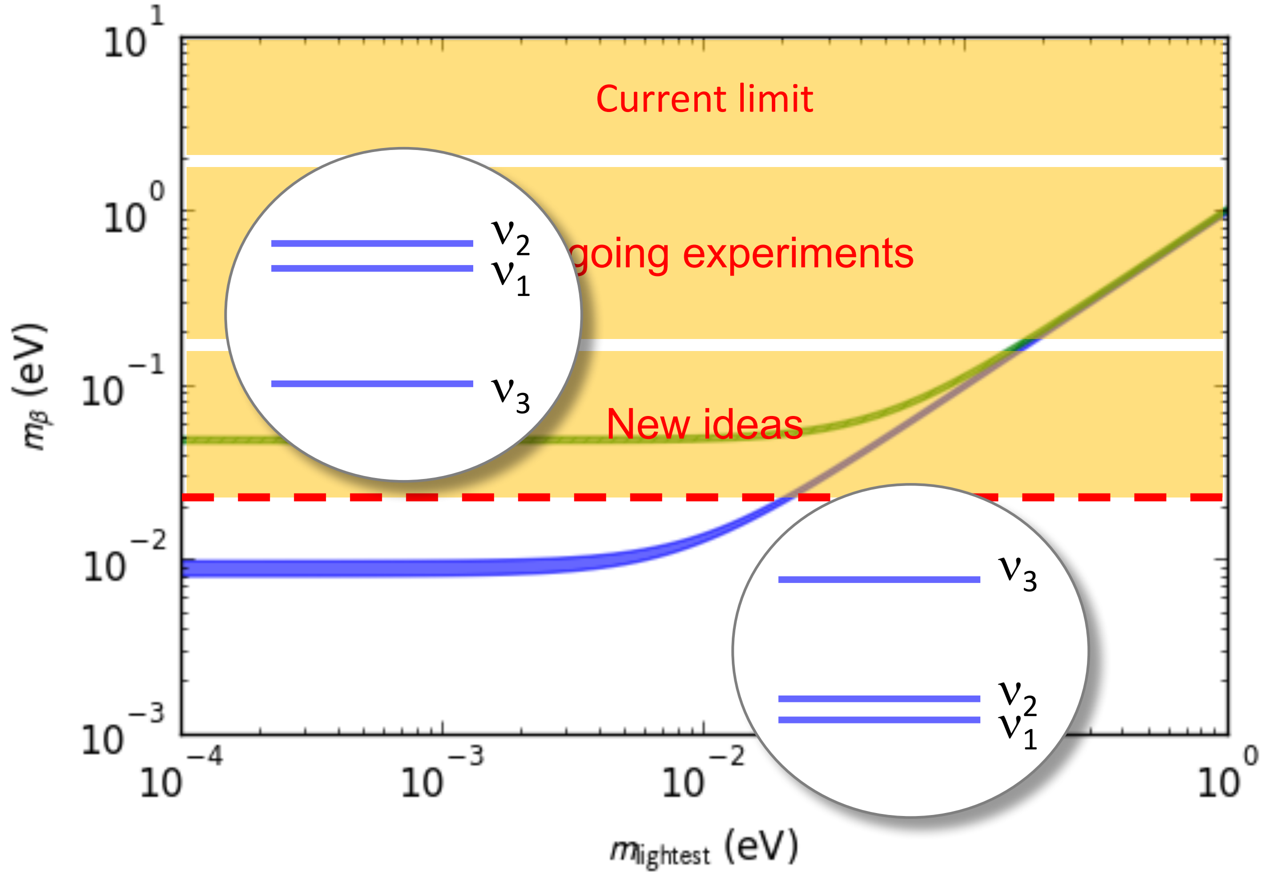

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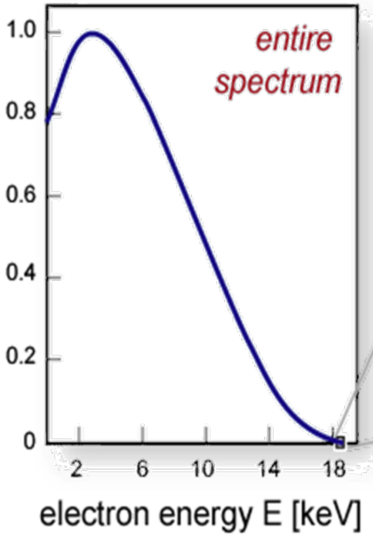
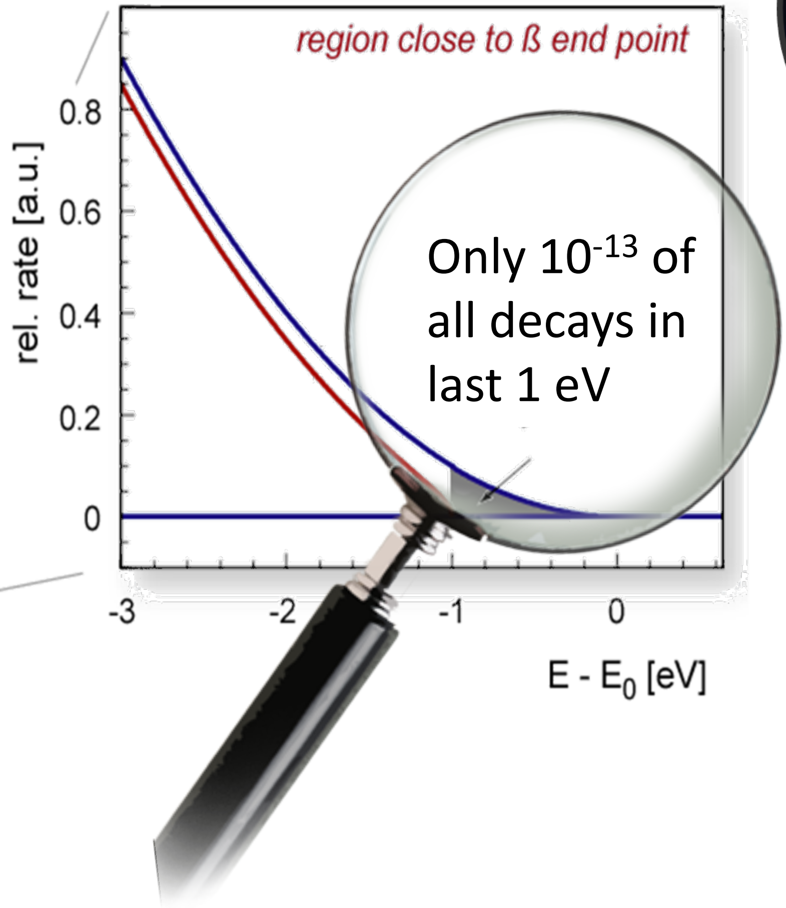
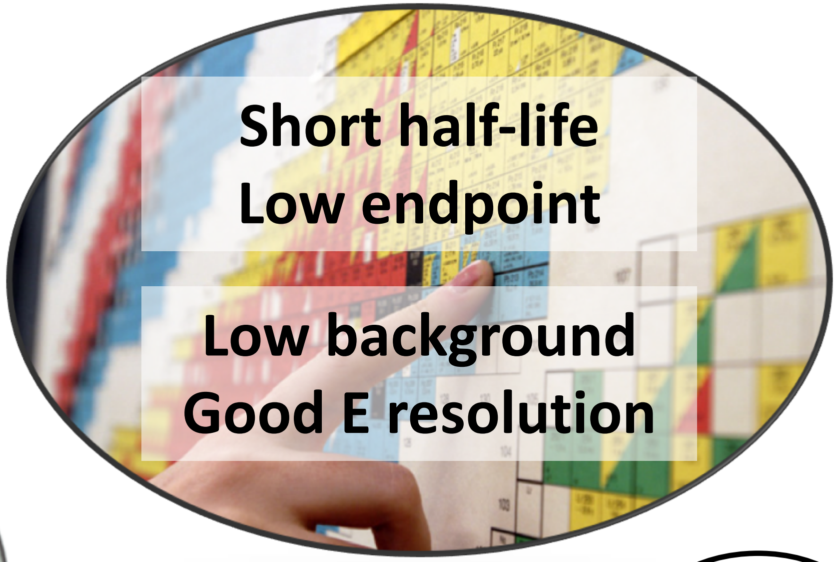
  Kraus, C., Bornschein, B., Bornschein, L. et al. Eur. Phys. J. C (2005)
- Ongoing experiments:
  Distinguish between **degenerate** and **hierarchical** scenario
- New ideas:
  Resolve **normal** vs **inverted** neutrino mass hierarchy

The challenge

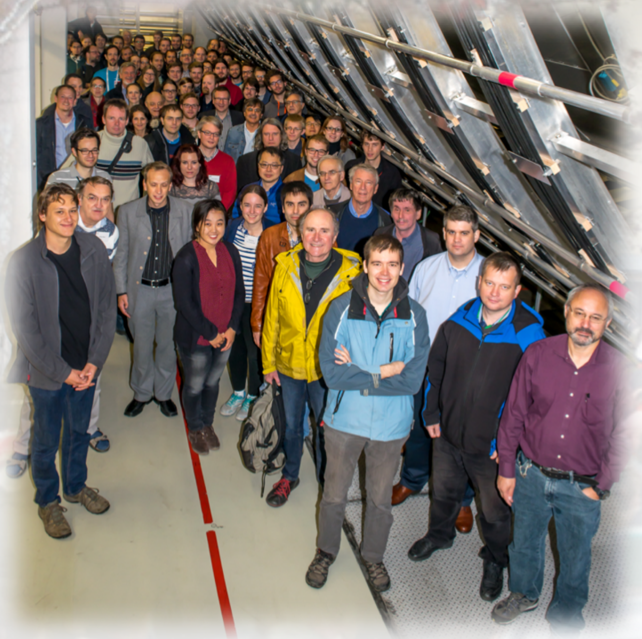






Karlsruhe
Tritium
Neutrino
Experiment

Karlsruhe Tritium Neutrino Experiment



- Experimental site: Karlsruhe Institute of Technology (KIT)
- International Collaboration (150 members)
- Sensitivity m_ν = 200 meV (90% CL) after 3 net-years

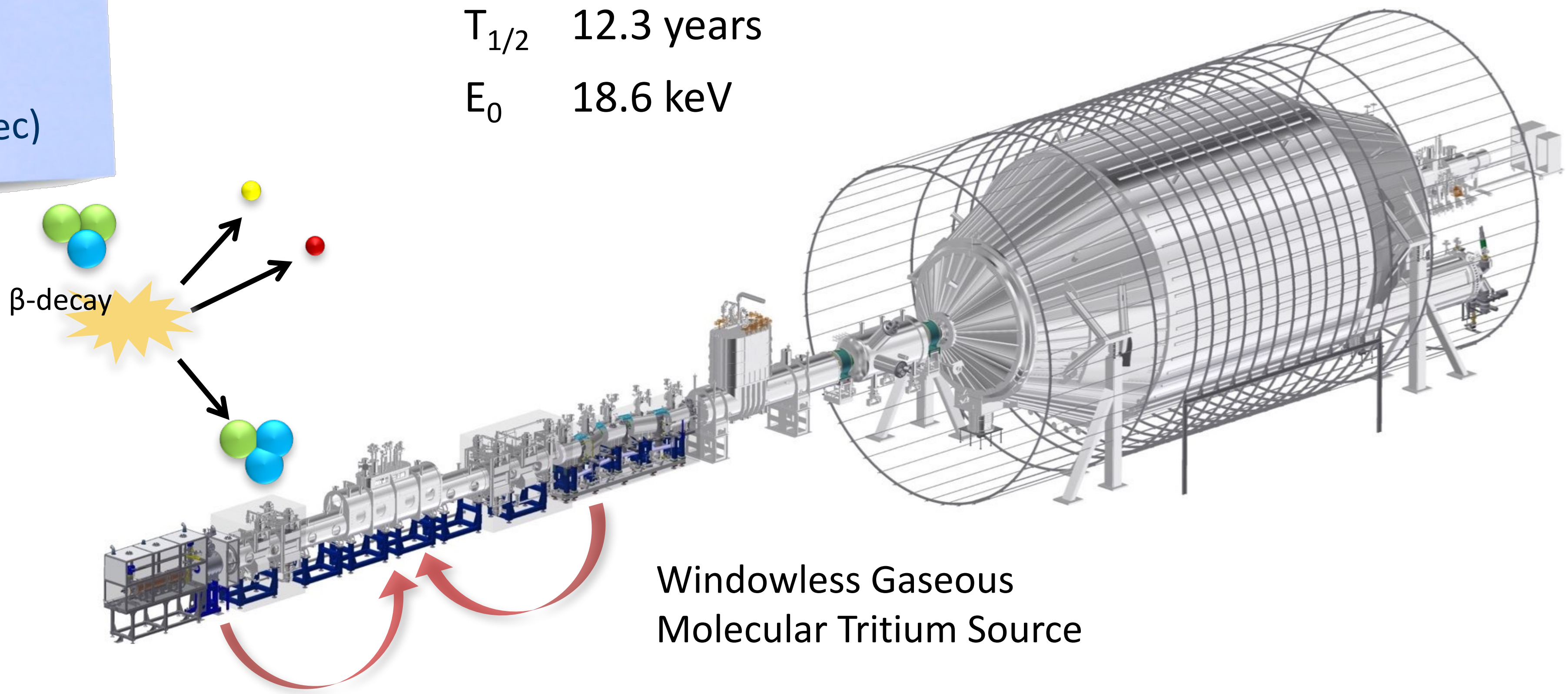
KIT Karlsruher Institut für Technologie
Max-Planck-Institut für Kernphysik Heidelberg
University of Washington
Case Western Reserve University EST. 1826 think beyond the possible
Westfälische Wilhelms-Universität Münster
Massachusetts Institute of Technology
The University of North Carolina at Chapel Hill
The Czech Academy of Sciences
Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)
cea
Carnegie Mellon University Pittsburgh Pennsylvania 1900
Universidad Complutense Madrid
Russian Academy of Sciences
JG|U Johannes Gutenberg Universität Mainz
TUM Technische Universität München
universitätbonn
Hochschule Fulda University of Applied Sciences
Bergische Universität Wuppertal
Berkeley Lab

KATRIN Working Principle

Gaseous molecular tritium source of high stability and luminosity

(10^{11} decays/sec)

	^3H
	super-allowed β-decay
$T_{1/2}$	12.3 years
E_0	18.6 keV

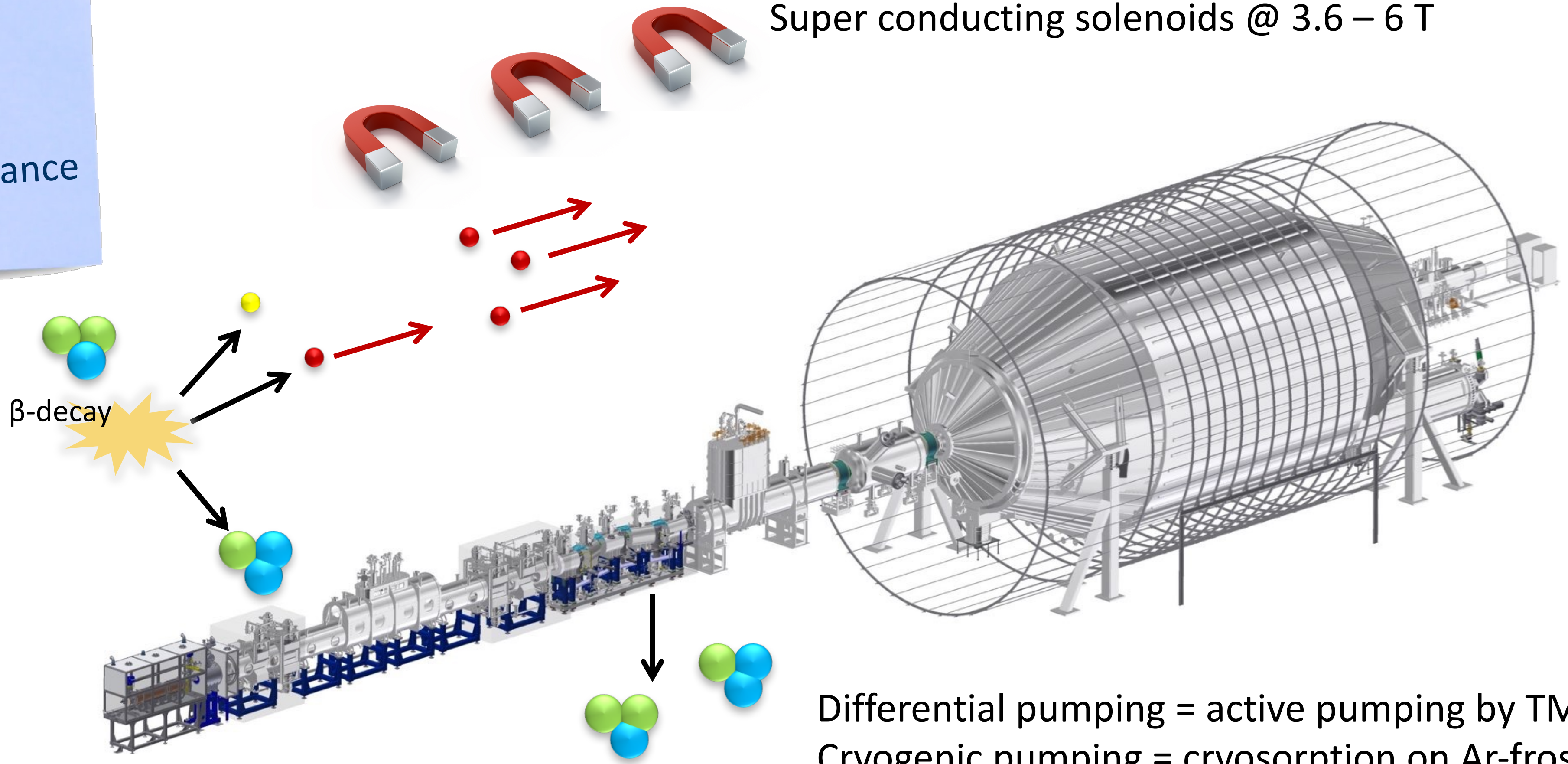


Windowless Gaseous Molecular Tritium Source

KATRIN Working Principle

Tritium flow reduction by 14 orders of magnitude, adiabatic guidance of electrons

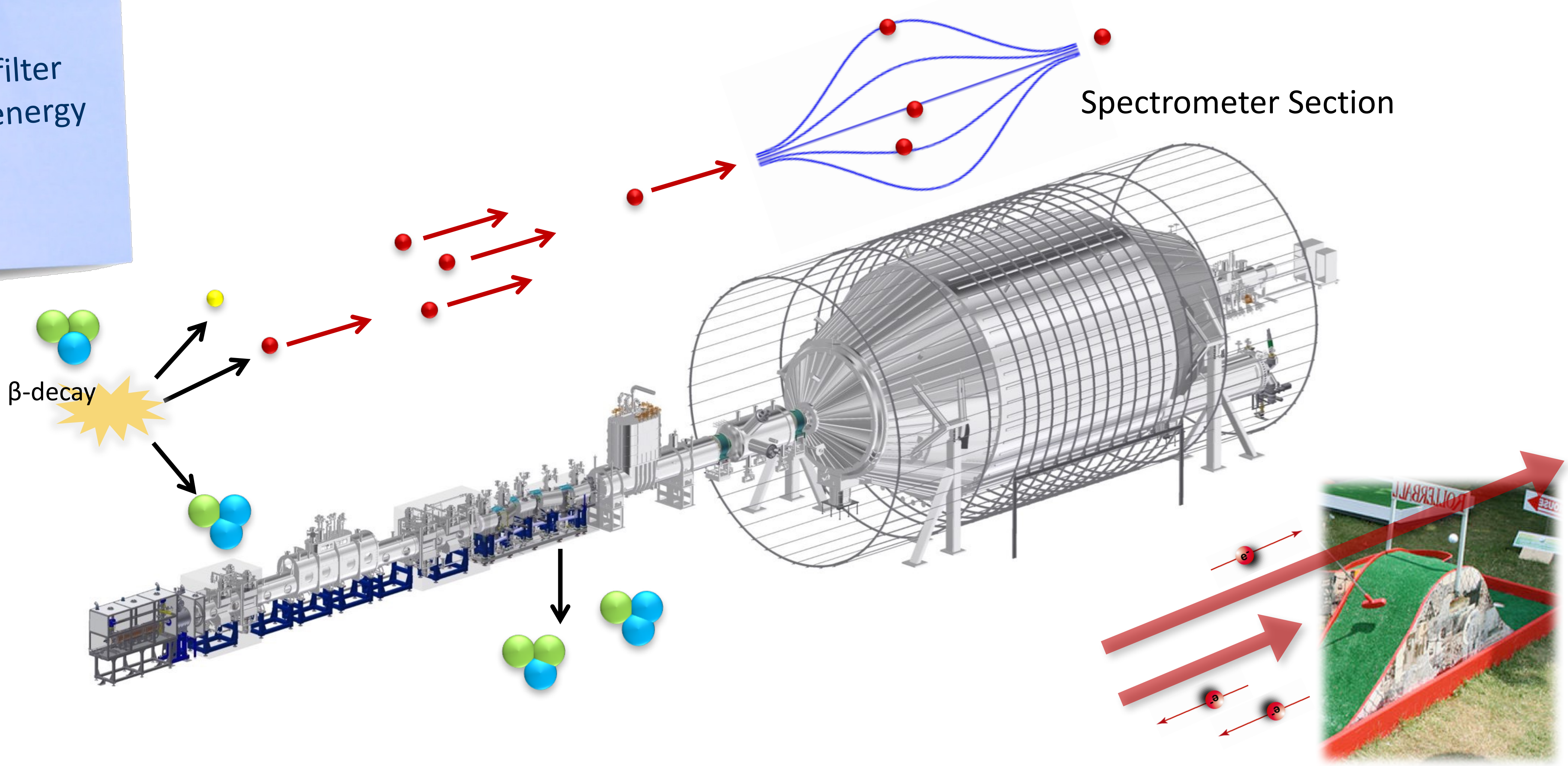
Super conducting solenoids @ 3.6 – 6 T



Differential pumping = active pumping by TMPs
Cryogenic pumping = cryosorption on Ar-frost

KATRIN Working Principle

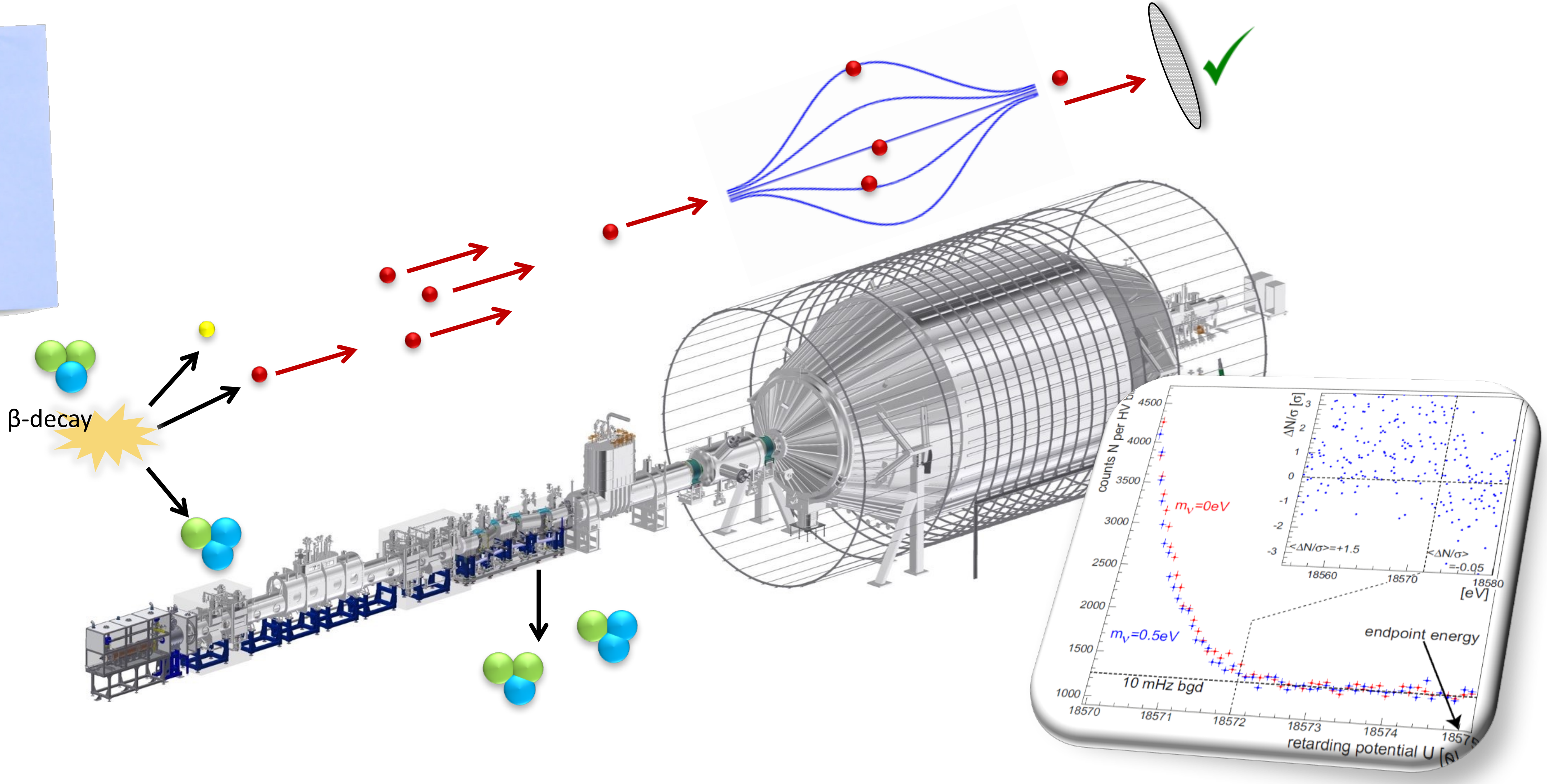
Electrostatic filter selects high energy electrons



KATRIN Working Principle

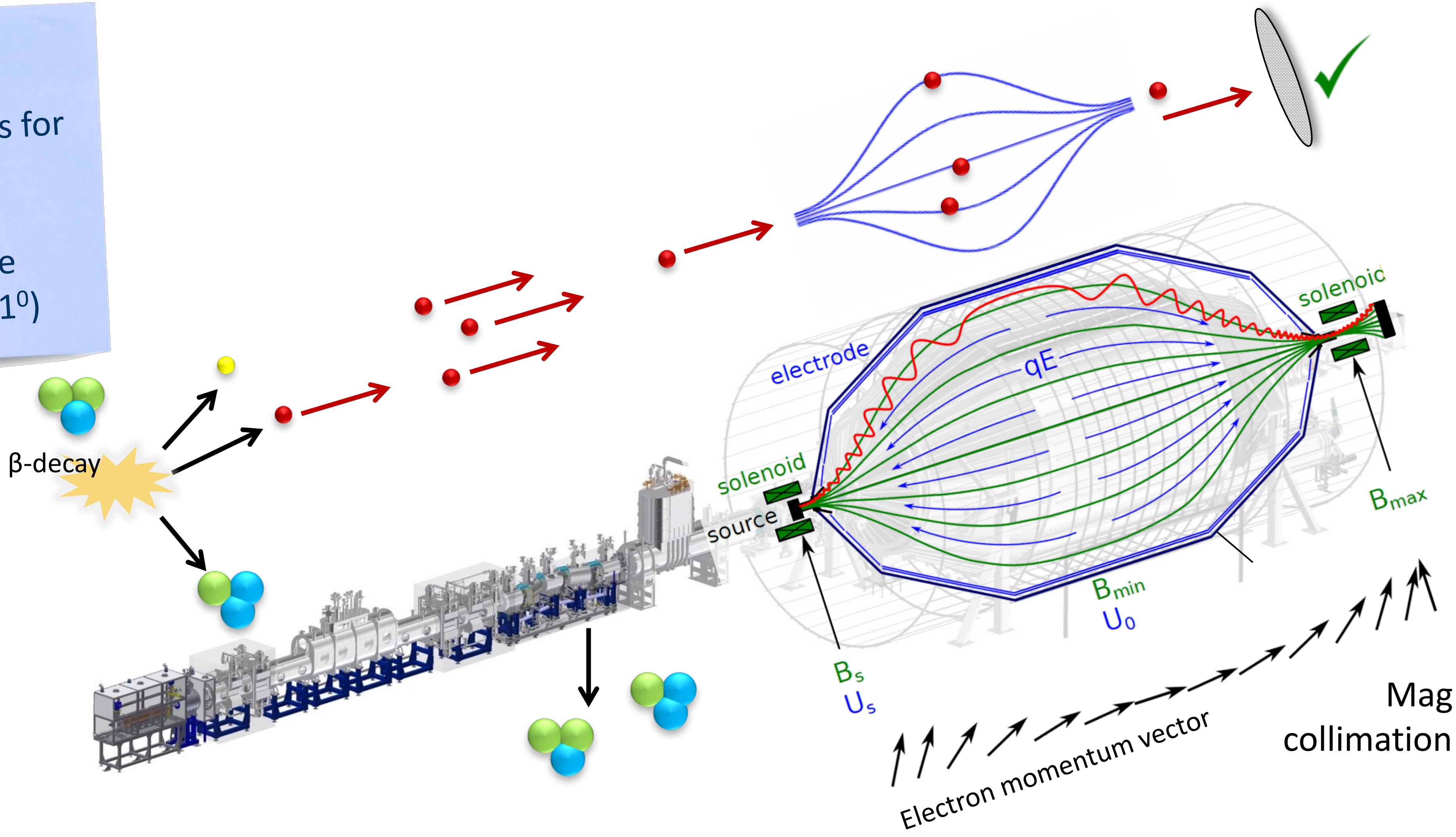
Integral measurement down to 30 eV below the endpoint

148 Pixel Si-pin diode detector system



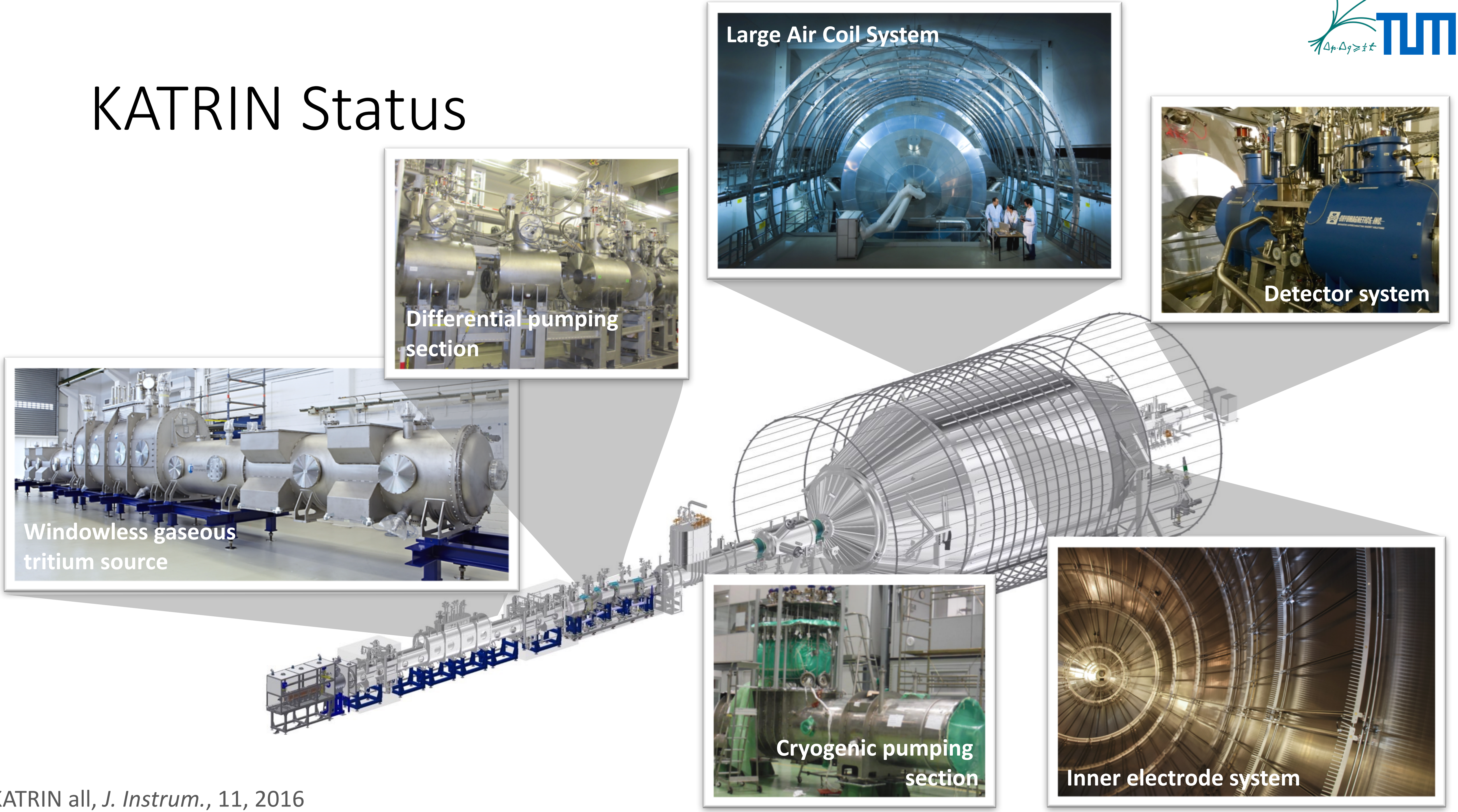
KATRIN Working Principle

MAC-E Filter
principle allows for
< 1 eV energy
resolution
and large angle
acceptance (51^0)



Magnetic adiabatic
collimation + electrostatic
filter (MAC-E)

KATRIN Status



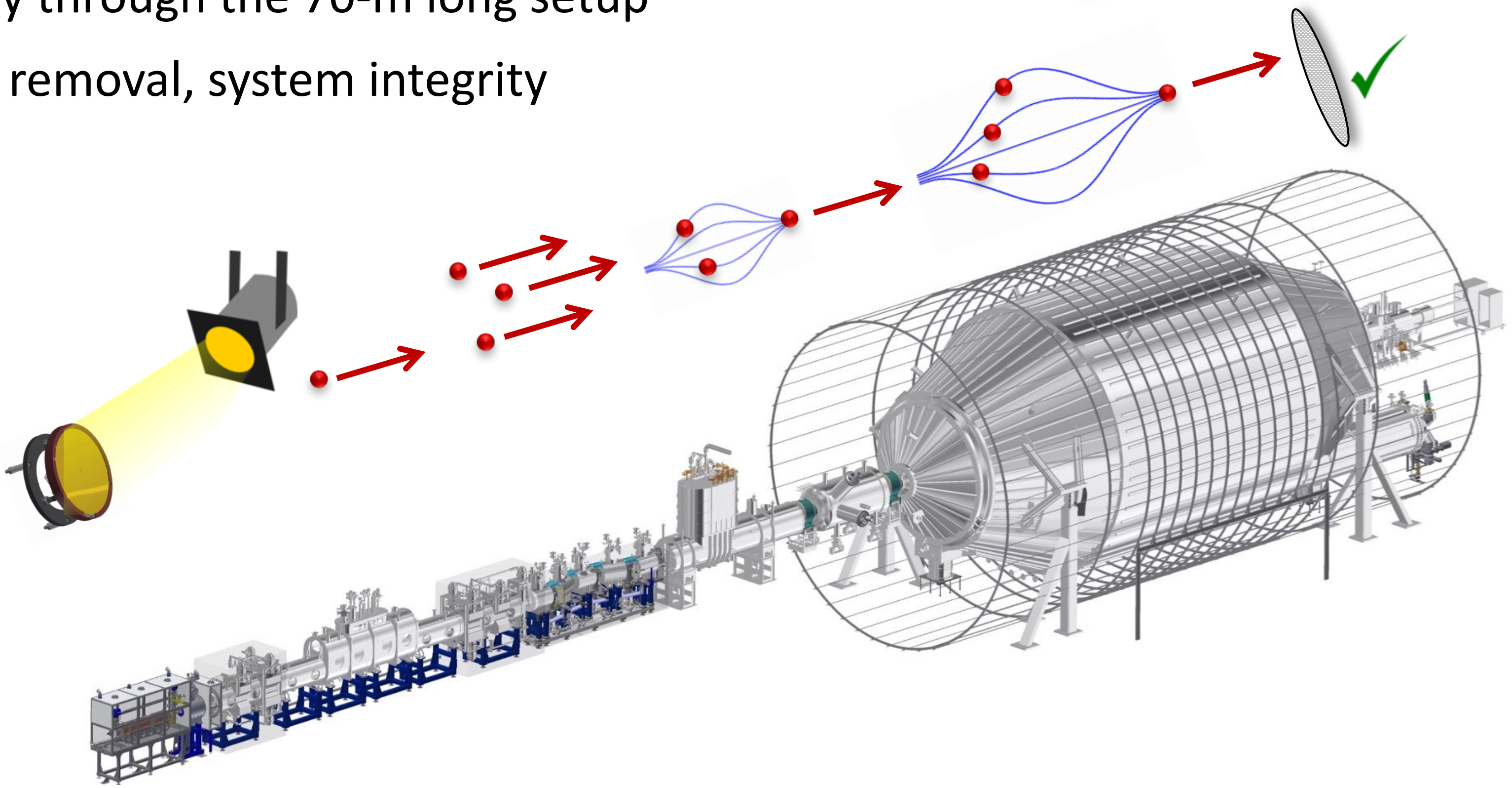
KATRIN all, *J. Instrum.*, 11, 2016

KATRIN Spectrometer Status

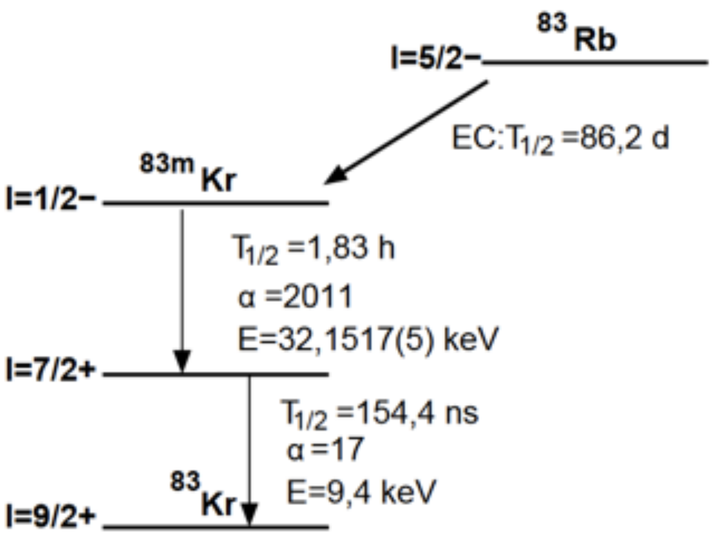
KATRIN Spectrometer Status

KATRIN's first light: October, 2016

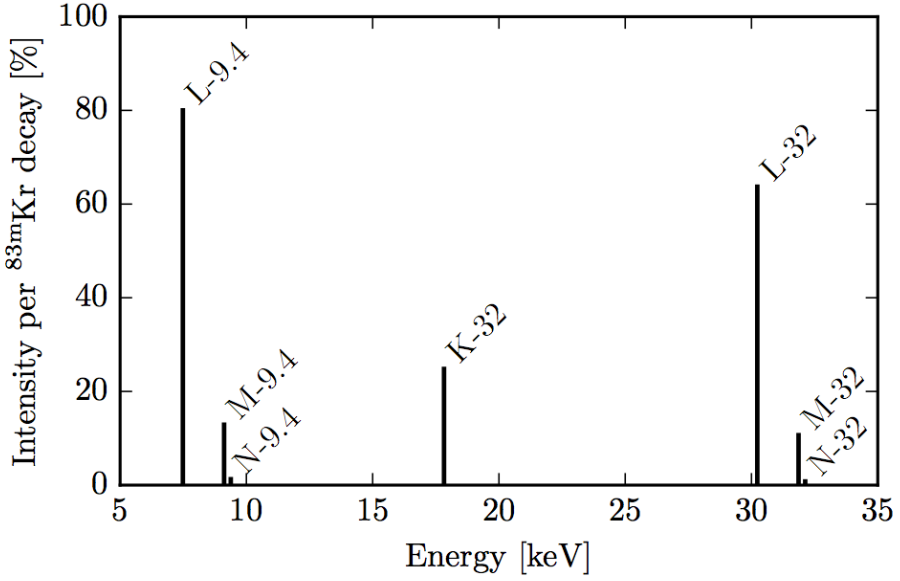
- The first electrons found their way through the 70-m long setup
- Promising results: Alignment, ion removal, system integrity

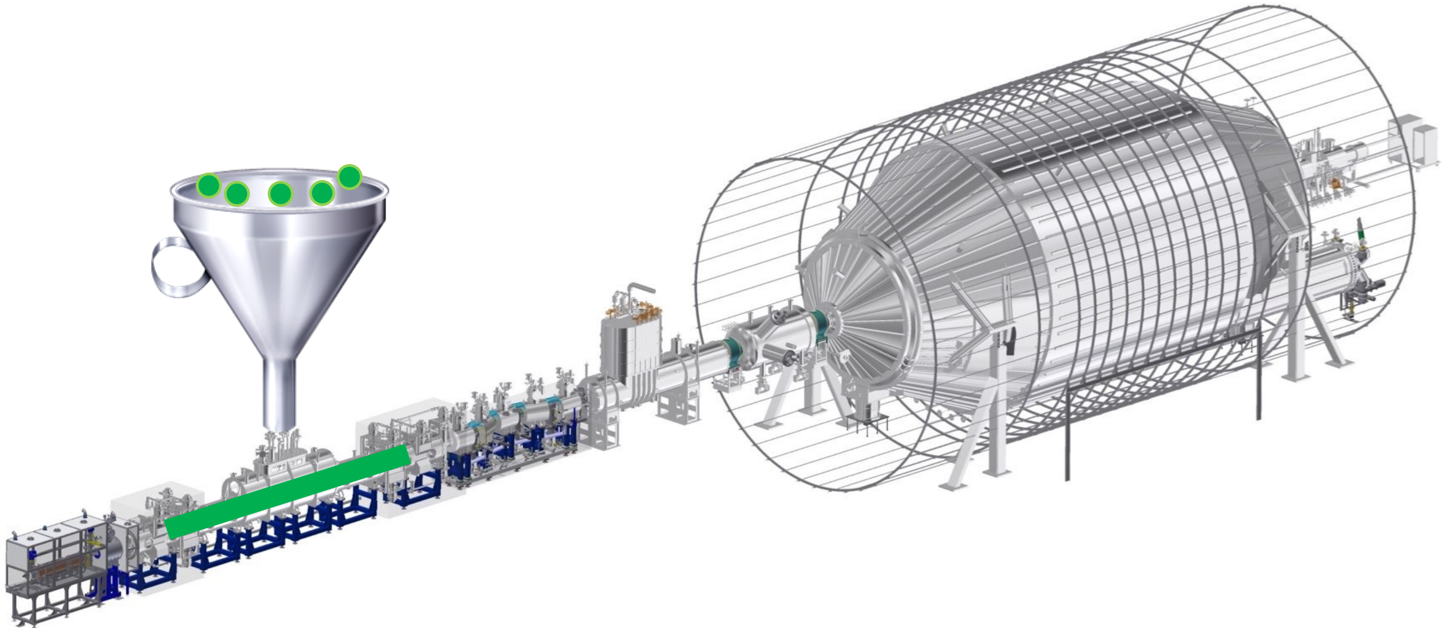


KATRIN’s first run: July 2017



- Calibration with gaseous and condensed krypton sources





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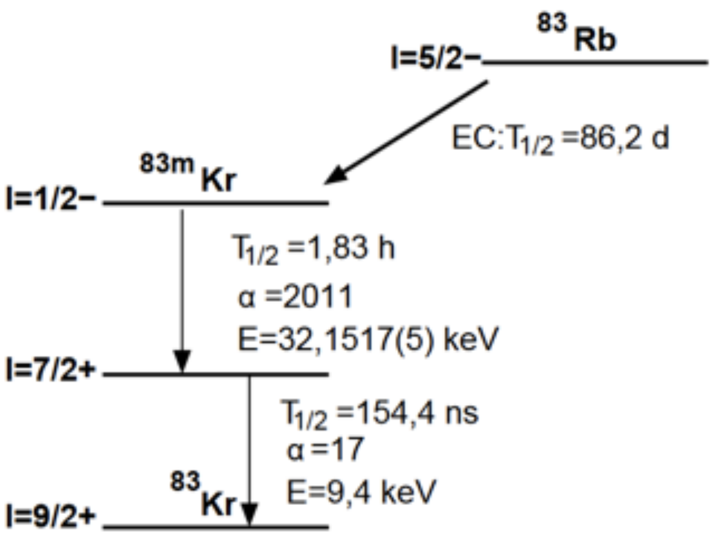
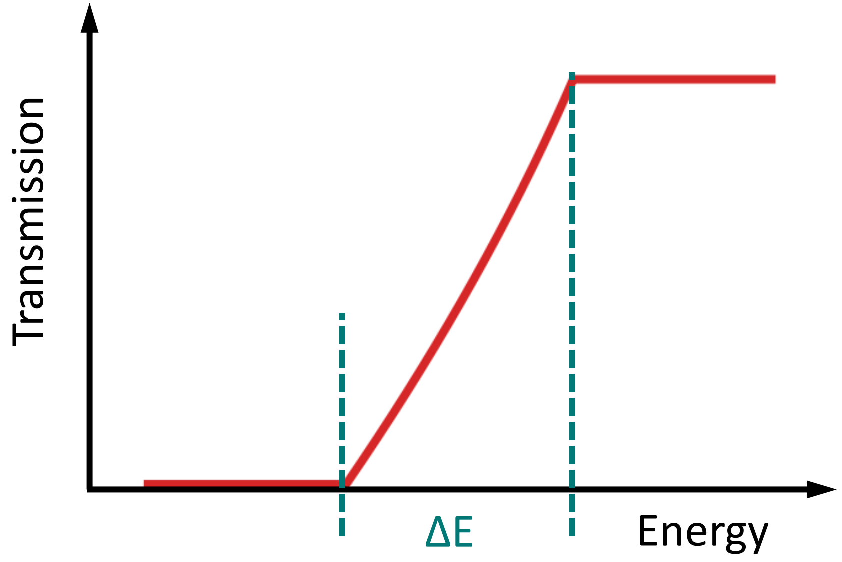
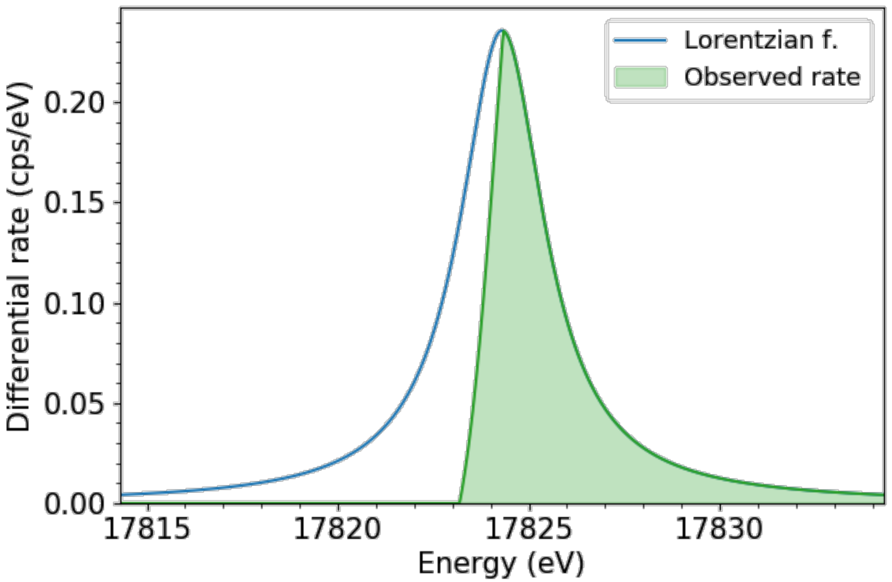


- Calibration with gaseous and condensed krypton sources
- First spectroscopic measurements + test of KATRIN apparatus





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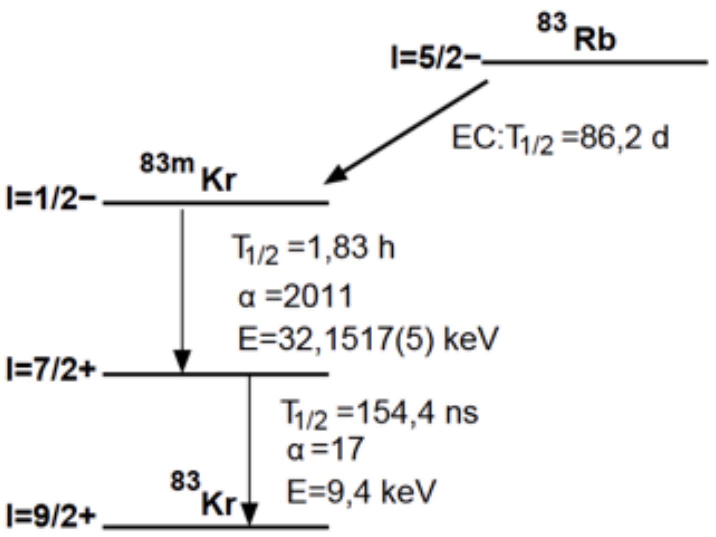

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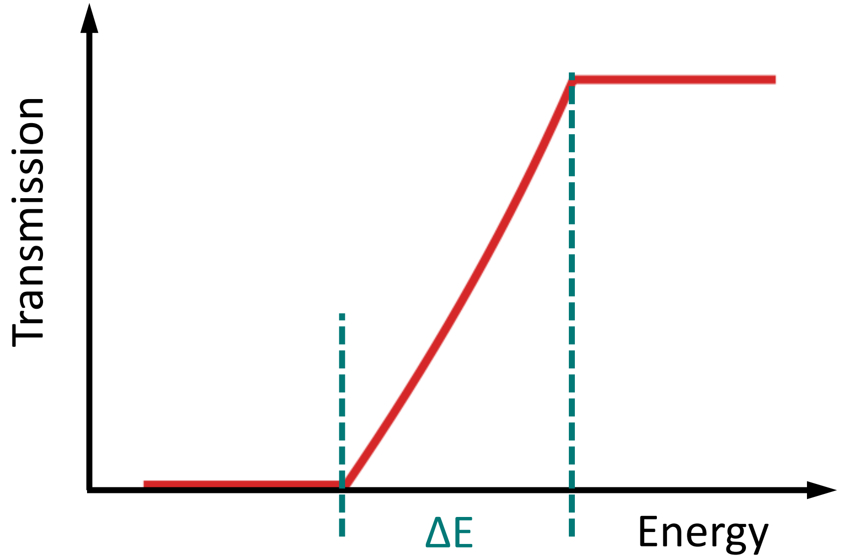
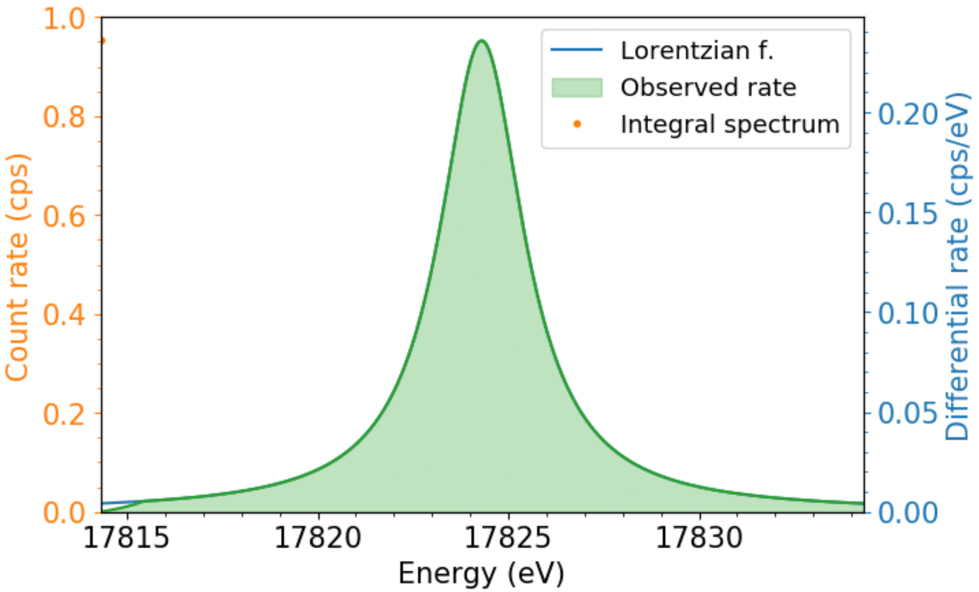


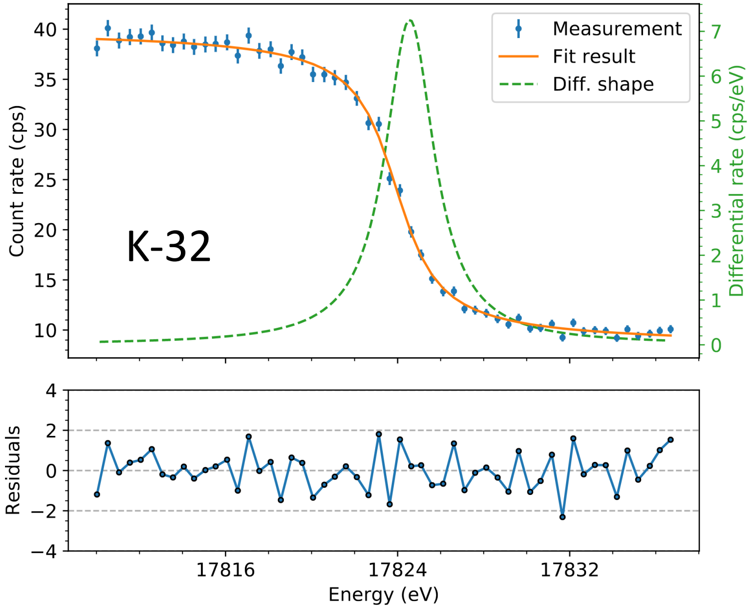


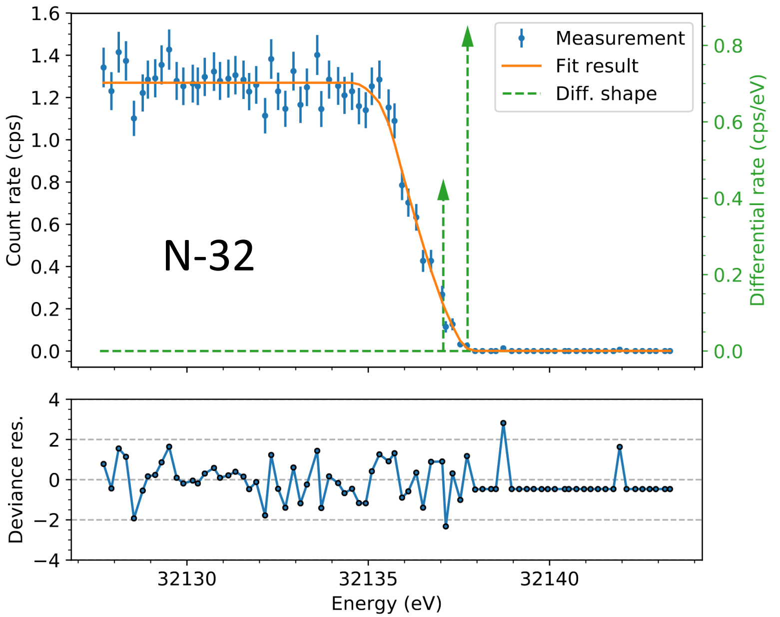
KATRIN’s first run: July 2017

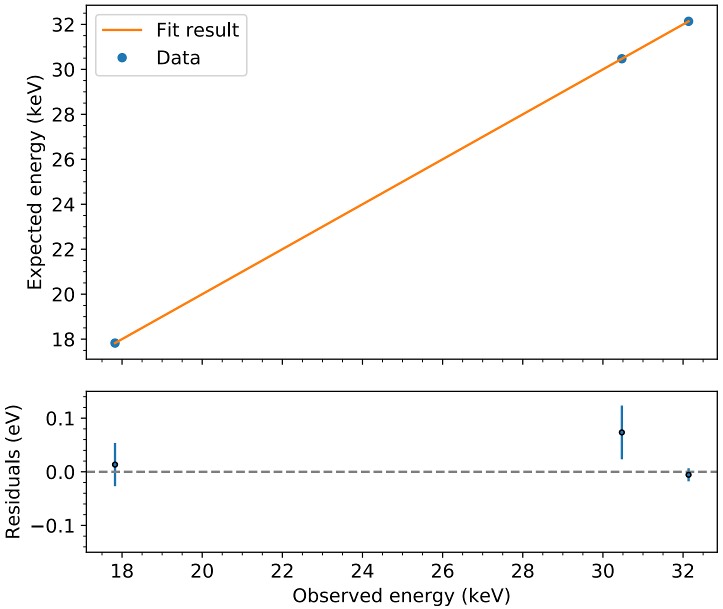
- Calibration with gaseous and condensed krypton sources
- First spectroscopic measurements + test of KATRIN apparatus

- HV calibration on the calibration on the ppm level
- Spectrometer resolution of 1 eV
- Analysis tools techniques improved

Preliminary

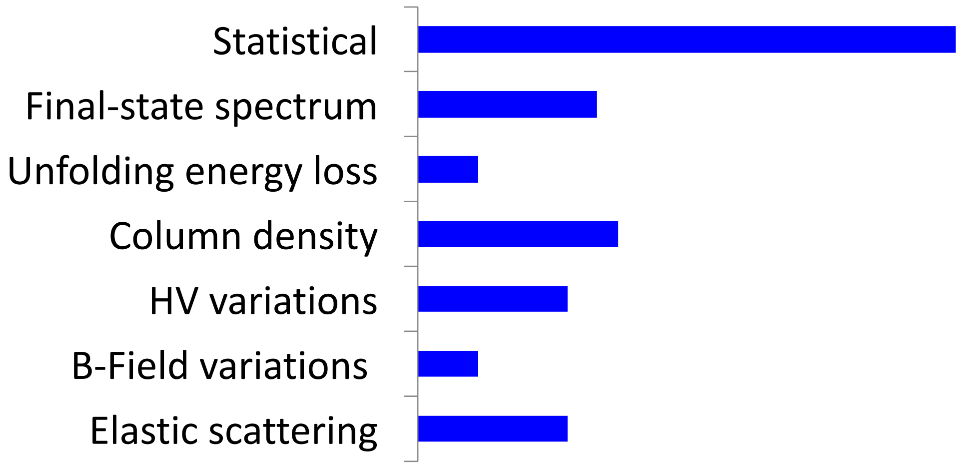


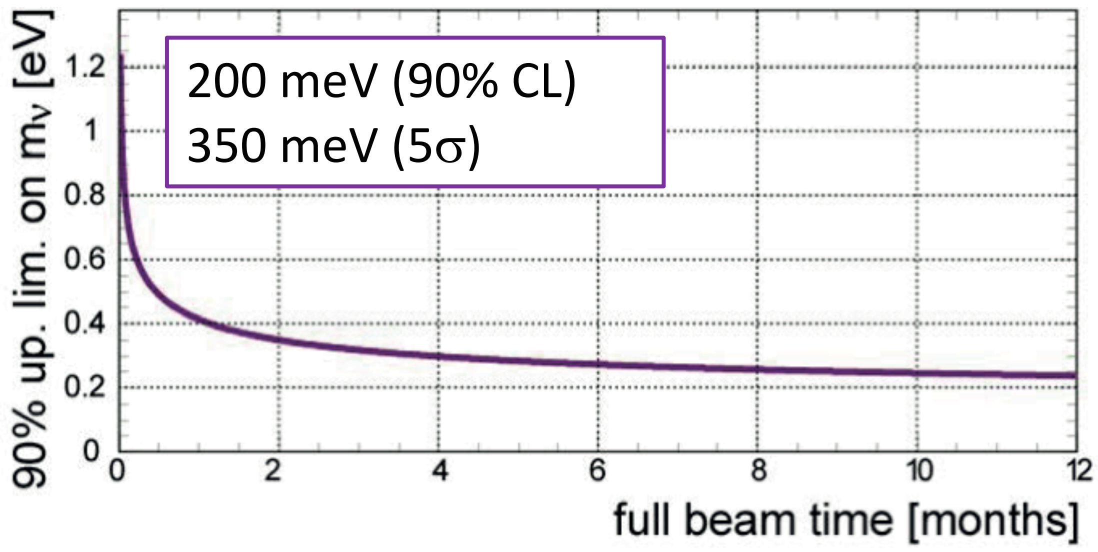




KATRIN's first Boot Camp… (last week)

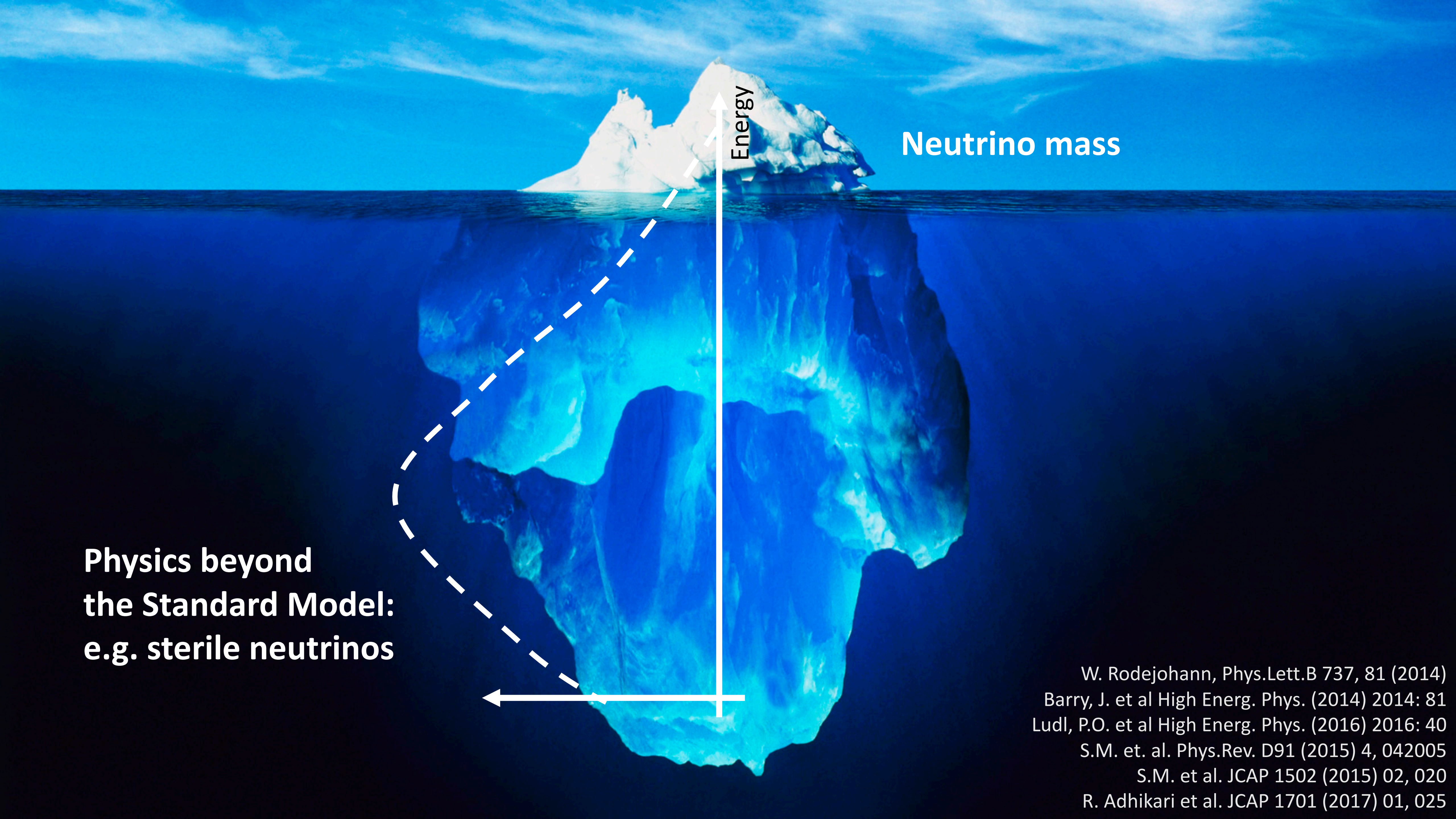
KATRIN's first tritium: May 2018





- First tritium in May this year (first nu-mass shortly after…)
- After 3 yrs of data (5 calendar yrs): balance of statistics and systematics

New Project: TRISTAN



W. Rodejohann, Phys.Lett.B 737, 81 (2014)
Barry, J. et al High Energ. Phys. (2014) 2014: 81
Ludl, P.O. et al High Energ. Phys. (2016) 2016: 40
S.M. et. al. Phys.Rev. D91 (2015) 4, 042005
S.M. et al. JCAP 1502 (2015) 02, 020
R. Adhikari et al. JCAP 1701 (2017) 01, 025

Active neutrinos

Sterile neutrinos

ν_s

ν_4

Sterile Neutrinos

Heavy sterile neutrinos (> GeV)

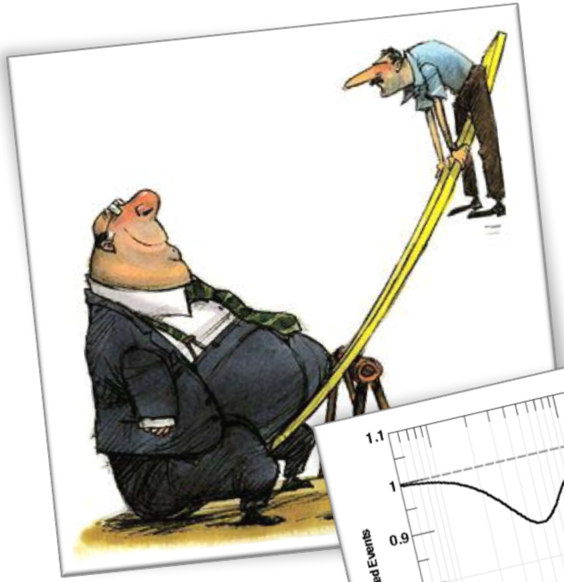
- Lightness of neutrinos
  + Matter/Anti-matter asymmetry

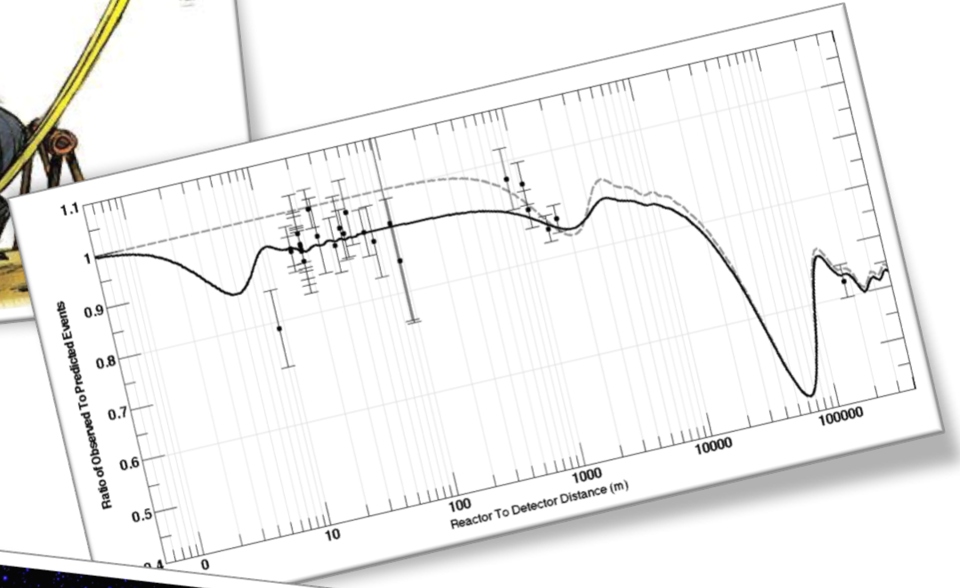
Light sterile neutrinos (~1 eV)

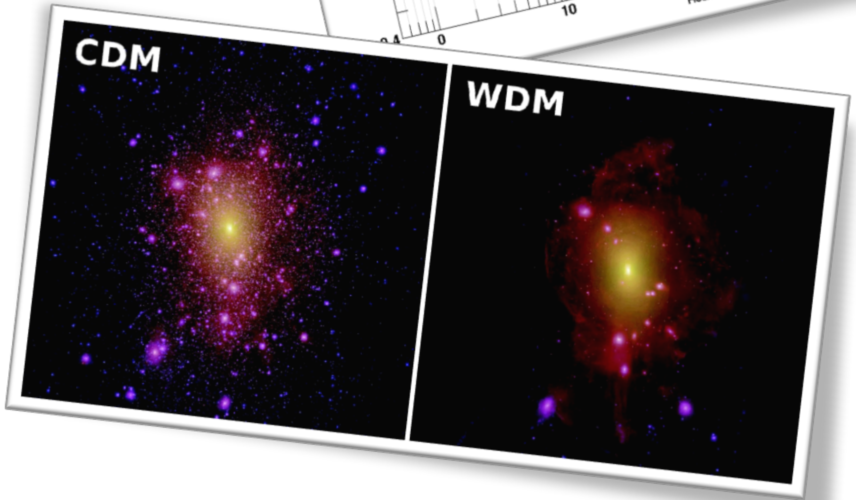
- Short-baseline neutrino oscillation anomalies

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

- Dark matter candidate







Sterile Neutrinos

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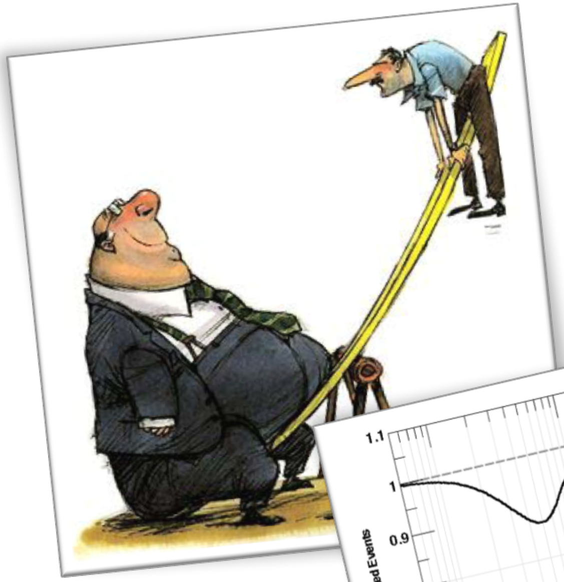
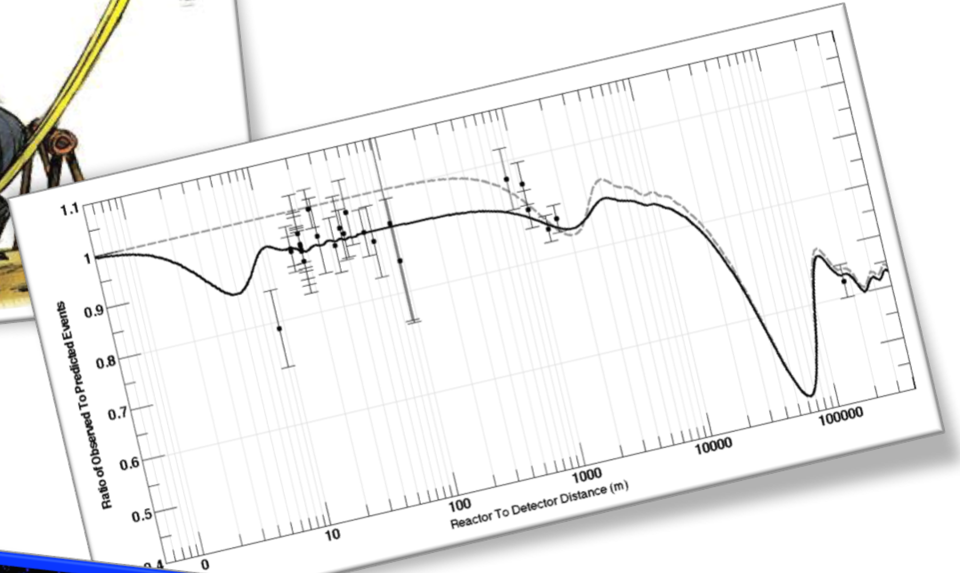
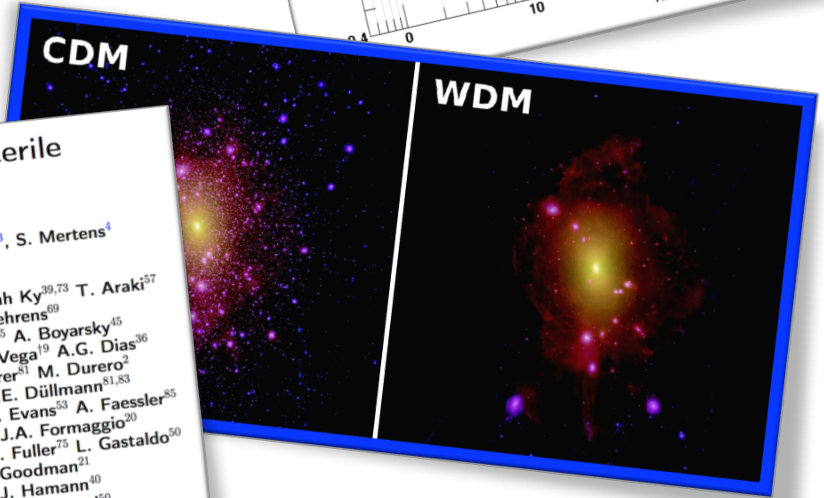
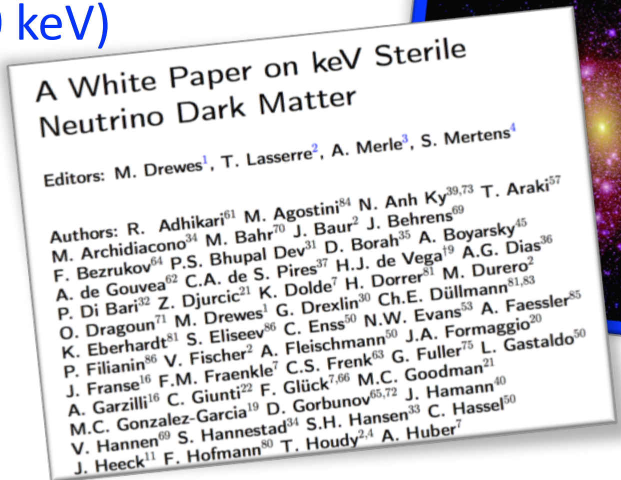
➢ Goal of TRISTAN









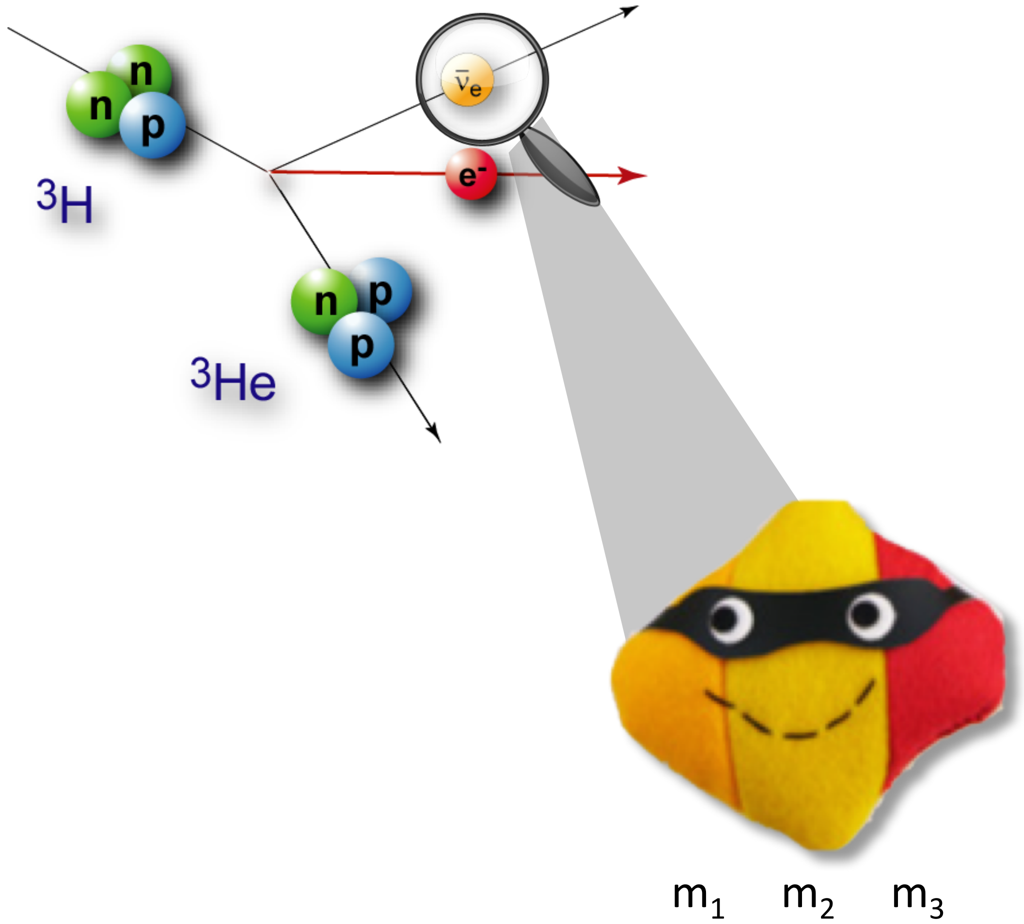
A White Paper on keV Sterile Neutrino Dark Matter

Editors: M. Drewes[1], T. Lasserre[2], A. Merle[3], S. Mertens[4]

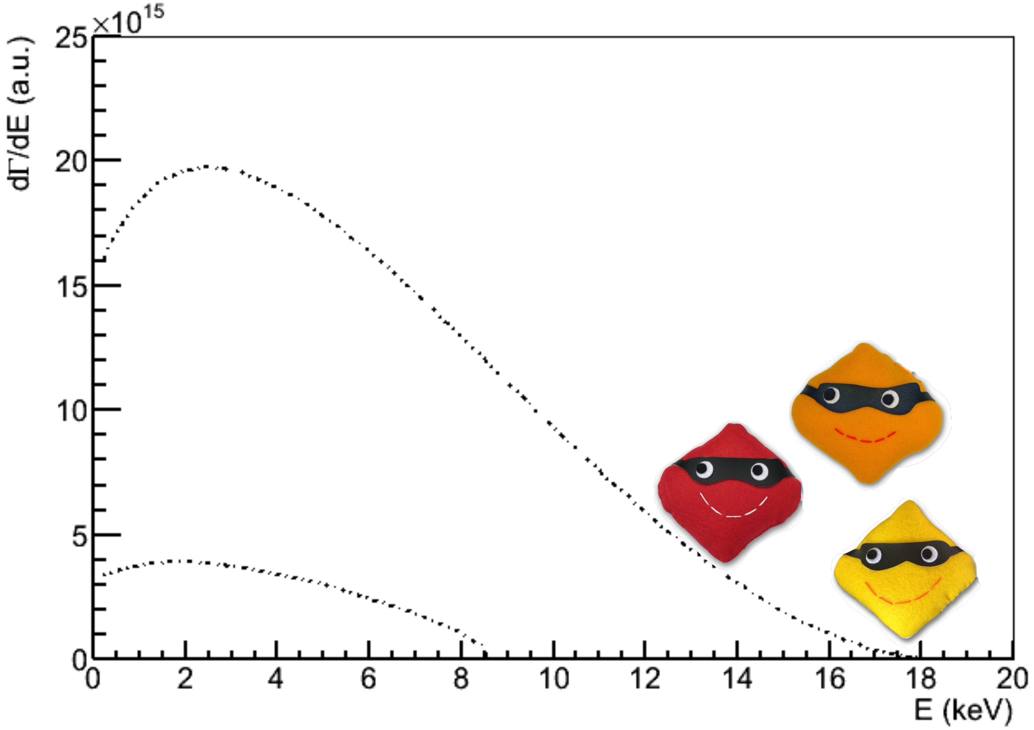
Authors: R. Adhikari[61] M. Agostini[84] N. Anh Ky[39,73] T. Araki[57] M. Archidiacono[34] M. Bahr[70] J. Baur[2] J. Behrens[69] F. Bezrukov[64] P.S. Bhupal Dev[31] D. Borah[35] A. Boyarsky[45] A. de Gouvea[62] C.A. de S. Pires[37] H.J. de Vega[19] A.G. Dias[36] P. Di Bari[32] Z. Djurcic[21] K. Dolde[7] H. Dorrer[81] M. Durero[2] O. Dragoun[71] M. Drewes[1] G. Drexlin[30] Ch.E. Düllmann[81,83] K. Eberhardt[81] S. Eliseev[86] C. Enss[50] N.W. Evans[53] A. Faessler[85] P. Filianin[86] V. Fischer[2] A. Fleischmann[50] J.A. Formaggio[20] J. Franse[16] F.M. Fraenkle[7] C.S. Frenk[63] G. Fuller[75] L. Gastaldo[50] A. Garzilli[16] C. Giunti[22] F. Glück[7,66] M.C. Goodman[21] M.C. Gonzalez-Garcia[19] D. Gorbunov[65,72] J. Hamann[40] V. Hannen[69] S. Hannestad[34] S.H. Hansen[33] C. Hassel[50] J. Heeck[11] F. Hofmann[80] T. Houdy[2,4] A. Huber[7]

(JCAP 2017, 10.1088/1475-7516/2017/01/025)

Imprint of sterile ν's on ß-spectrum



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



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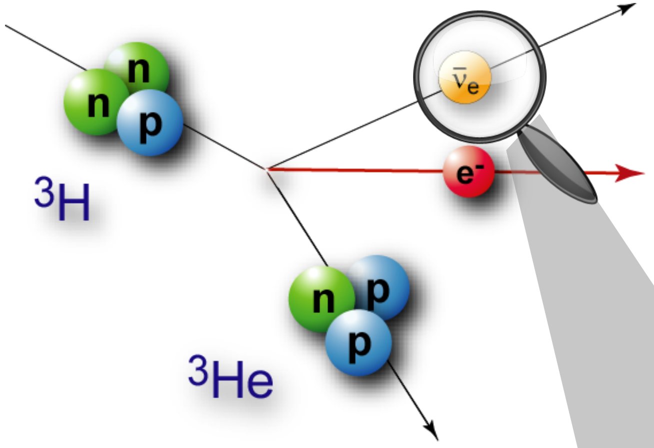
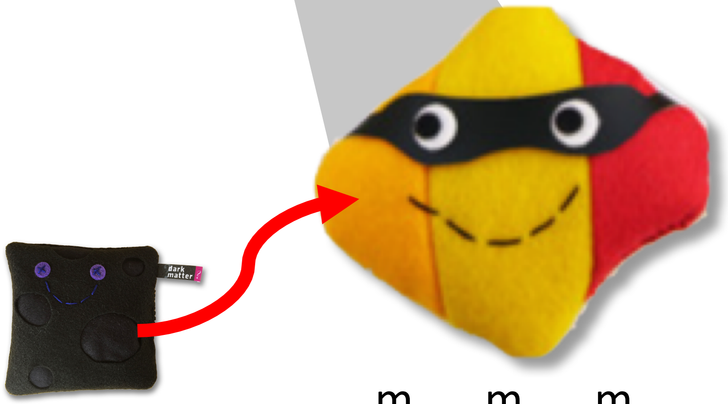
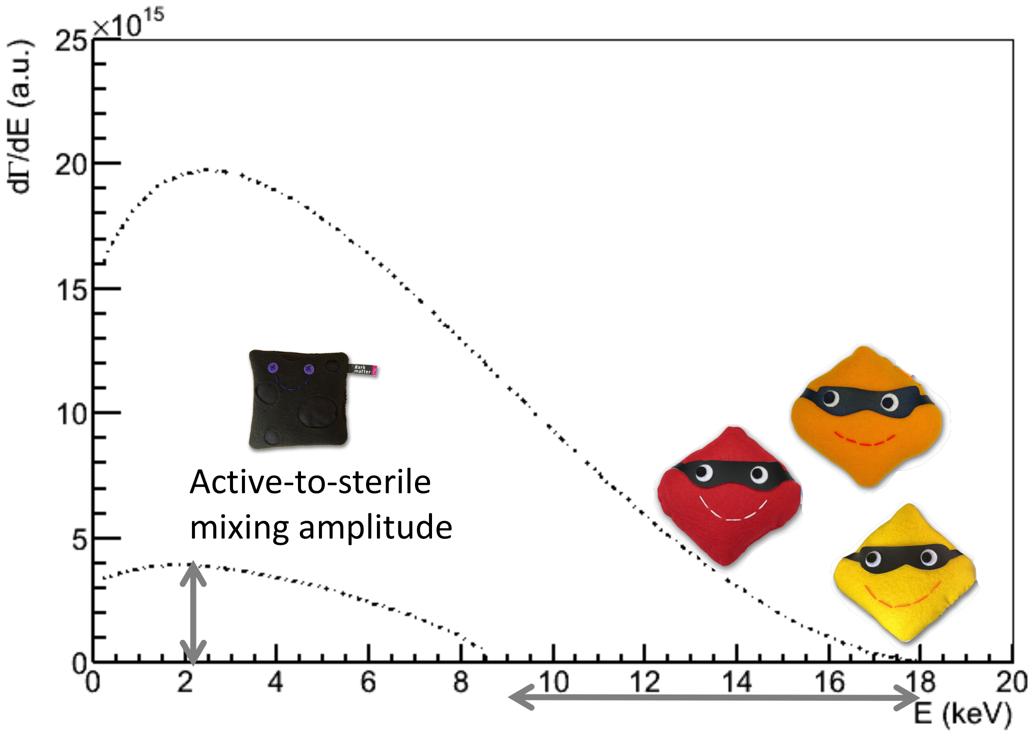


New mass eigenstate



m_1 m_2 m_3

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



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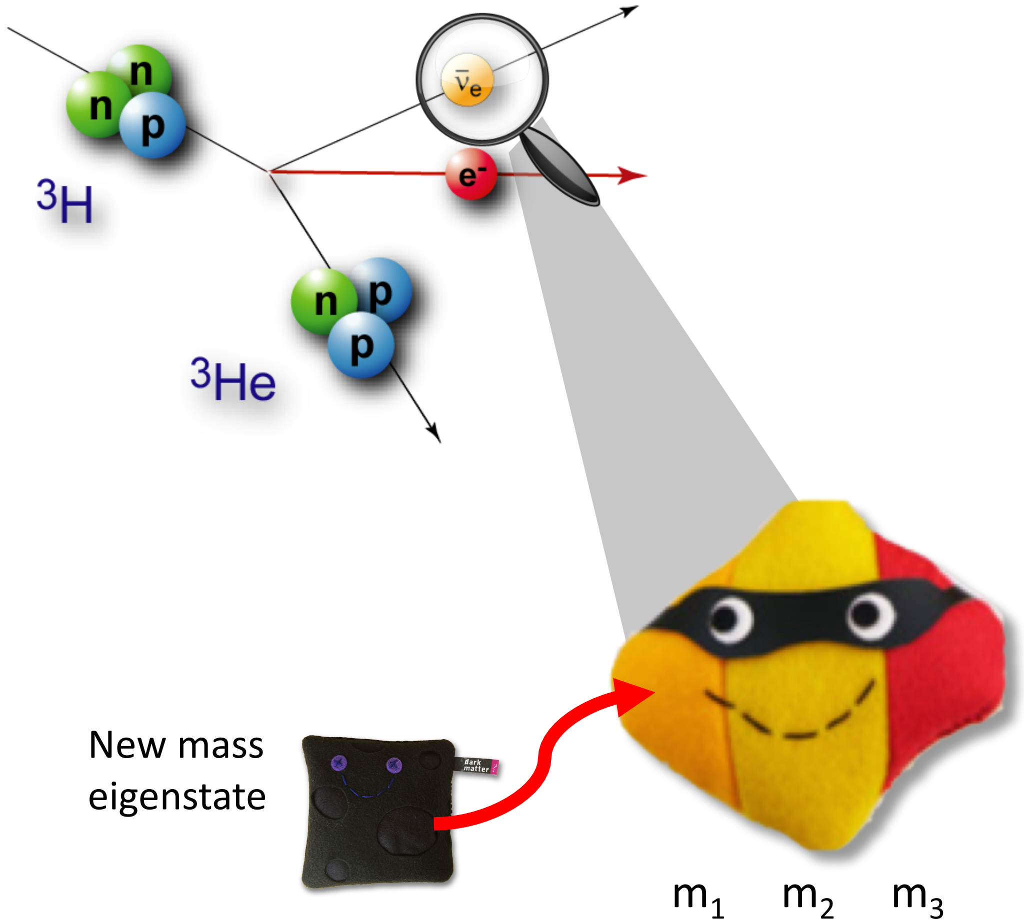
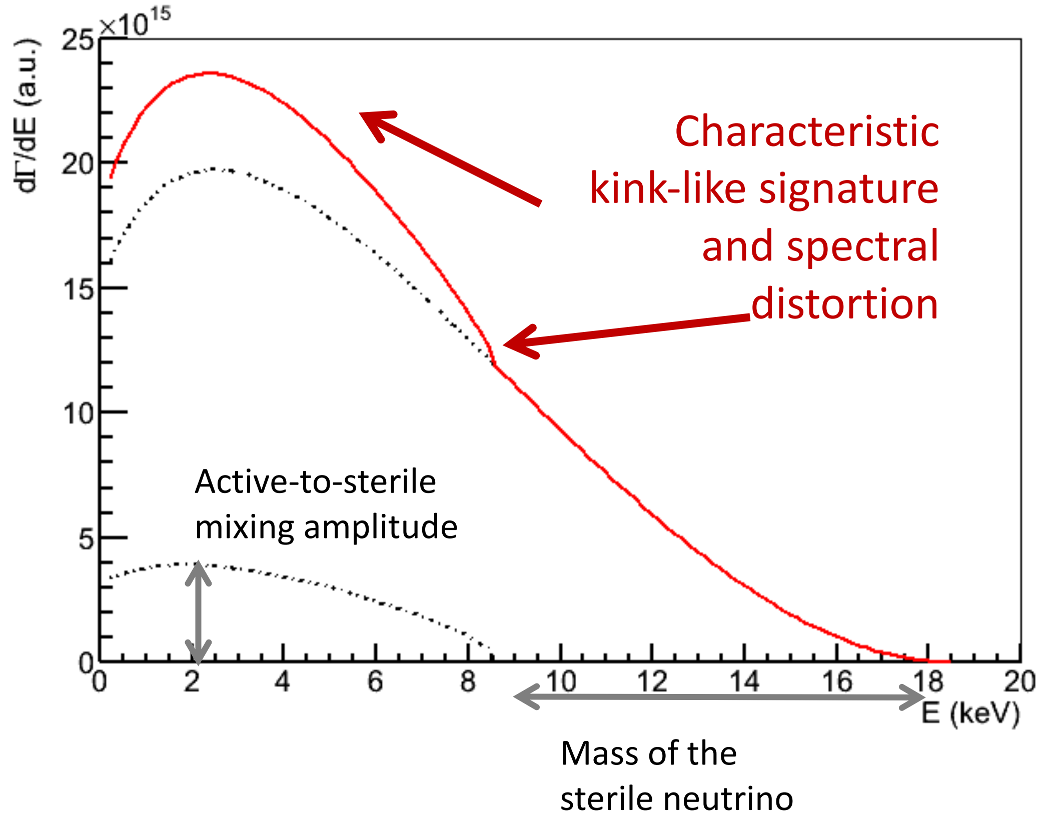
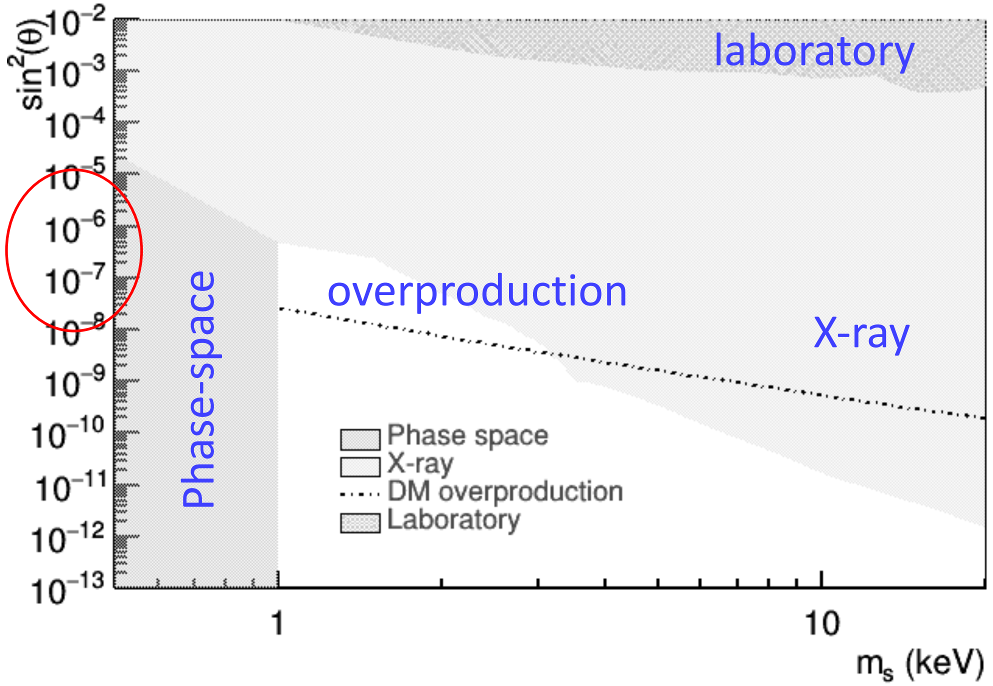
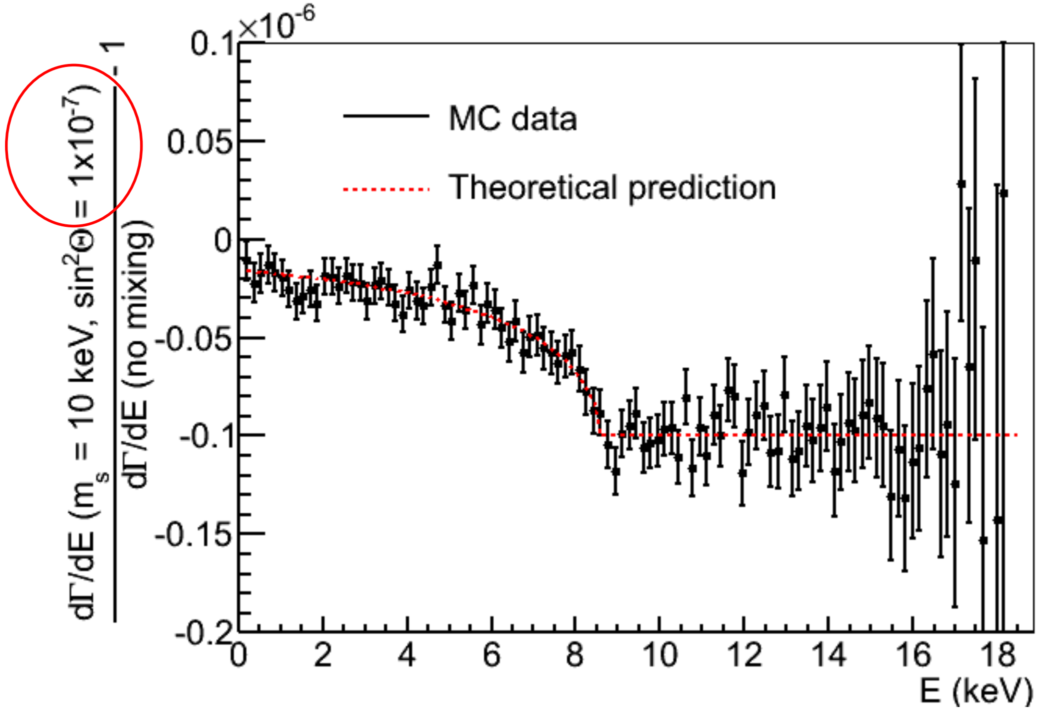


$$\frac{d\Gamma}{dE} = \cos^2\theta \frac{d\Gamma}{dE}(m_\beta) + \sin^2\theta \frac{d\Gamma}{dE}(m_s)$$



Challenge (1)

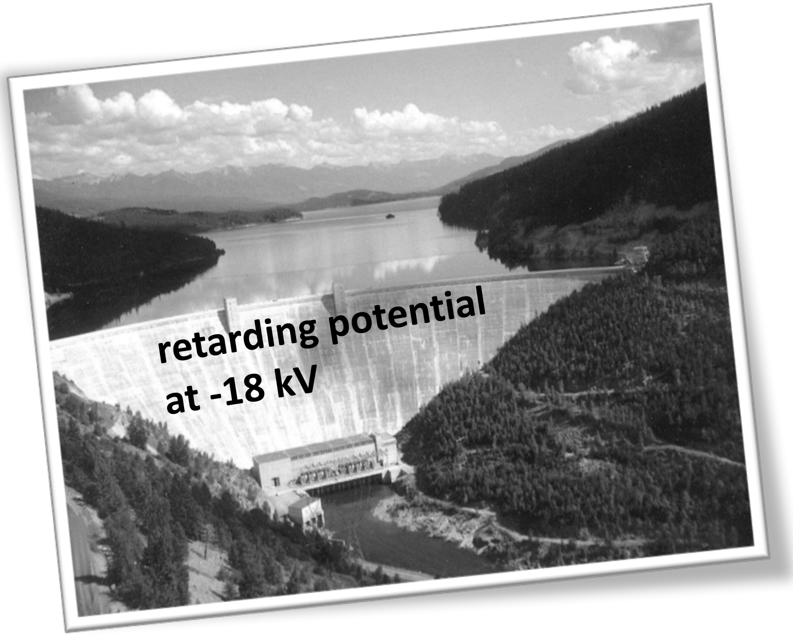


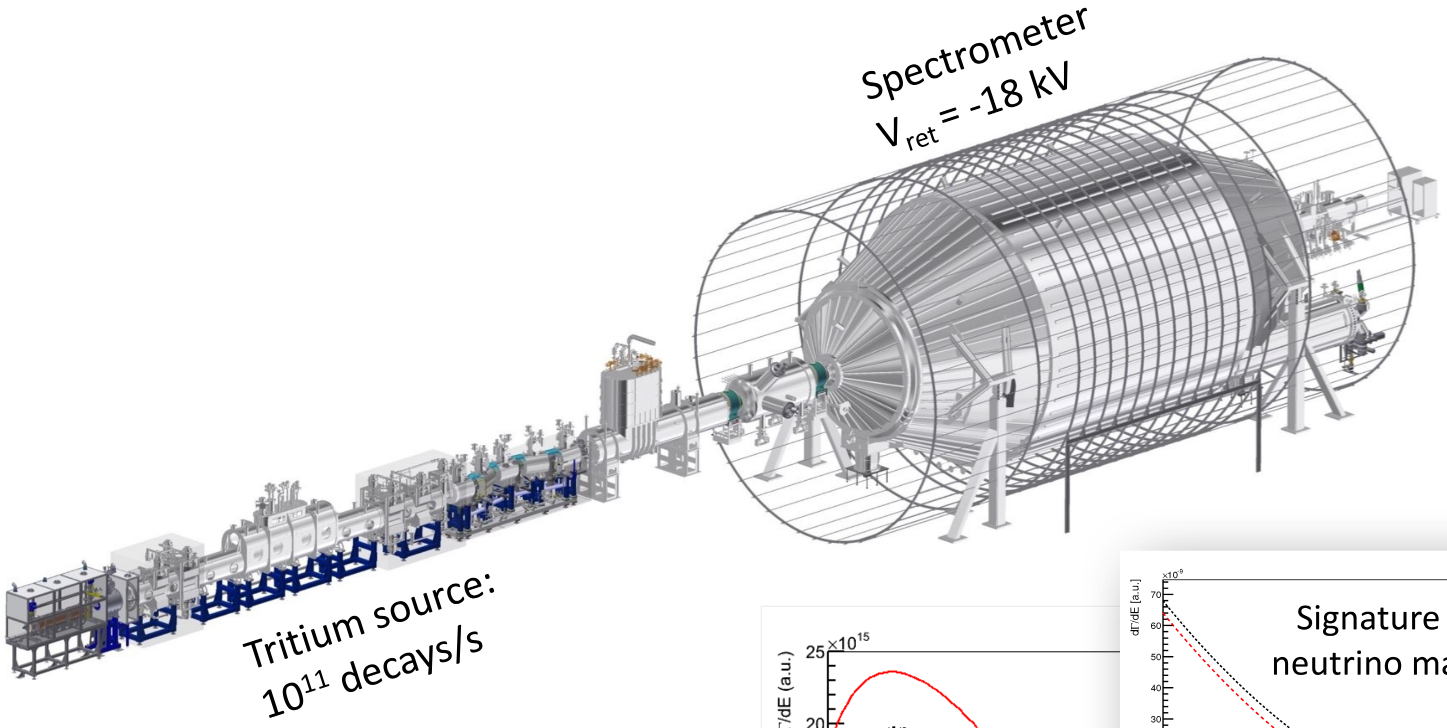


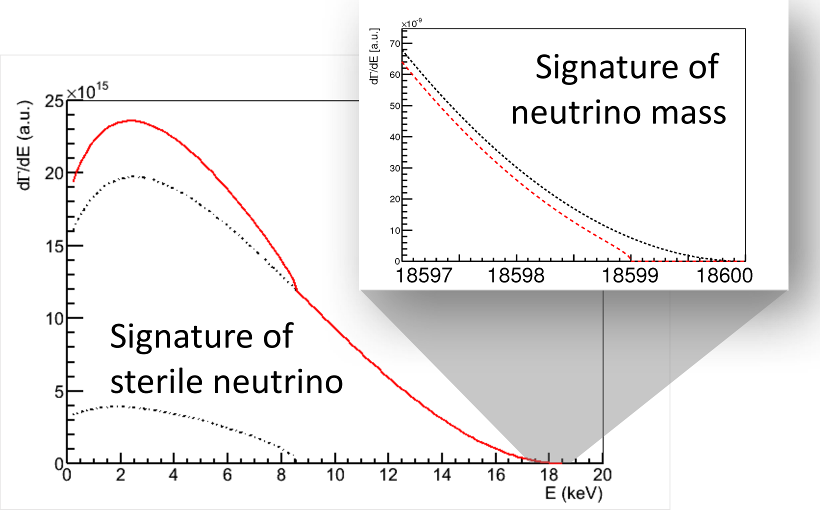
- Strong constrains from astrophysics (model-dependent)
- Laboratory limits are only in the per-mil level

- Expected signal after 3-years with full KATRIN source strength

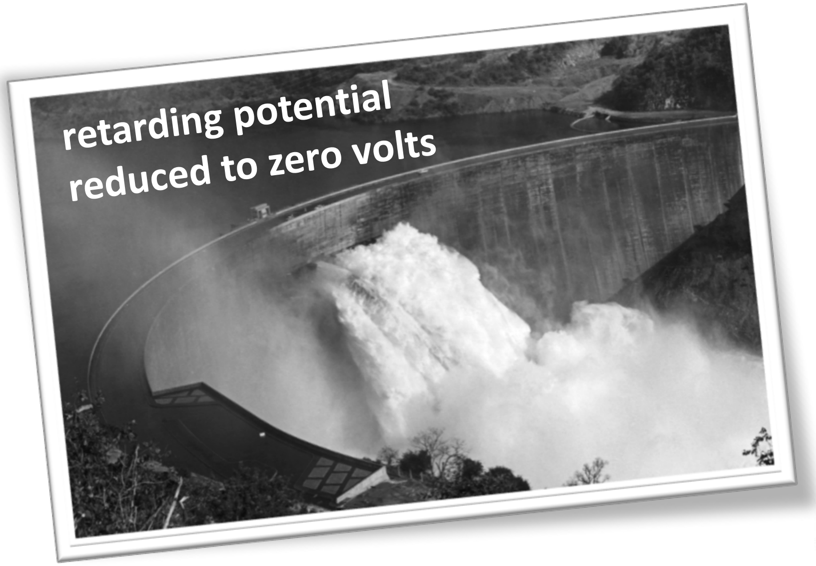
Challenge (2)

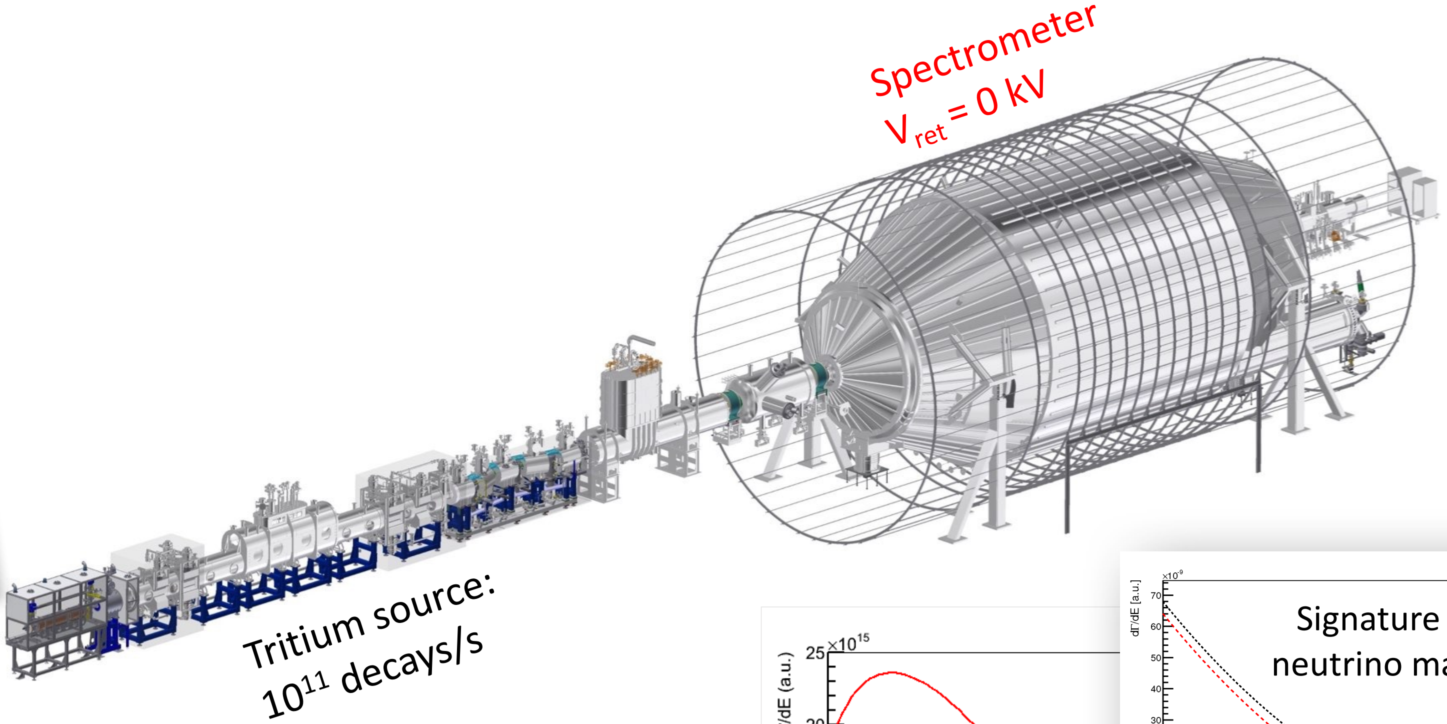

retarding potential
at -18 kV

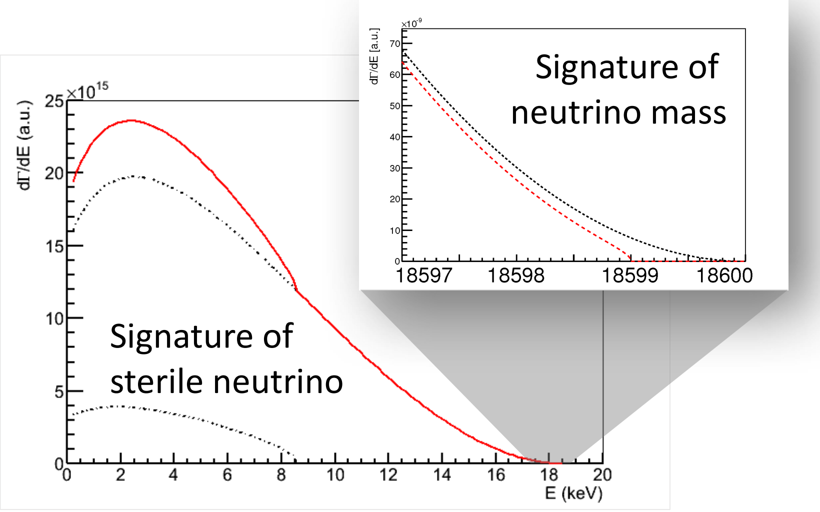

Spectrometer
V_{ret} = -18 kV
Tritium source:
10^{11} decays/s


Signature of
sterile neutrino
Signature of
neutrino mass
dΓ/dE (a.u.)
E (keV)
$\times 10^{15}$
18597
18598
18599
18600

Challenge (2)



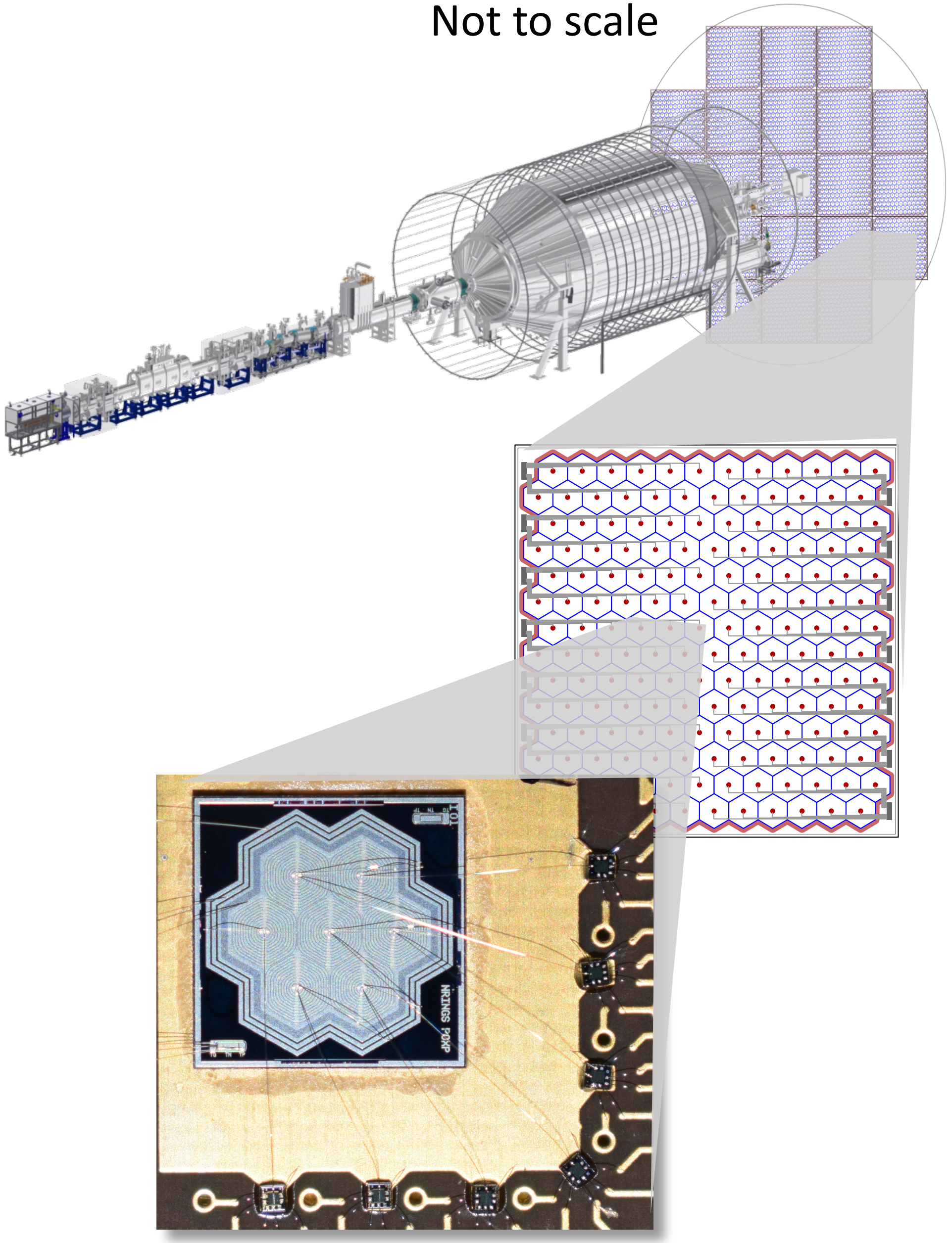




- ➢ Develop a new detector

TRISTAN Detector R&D

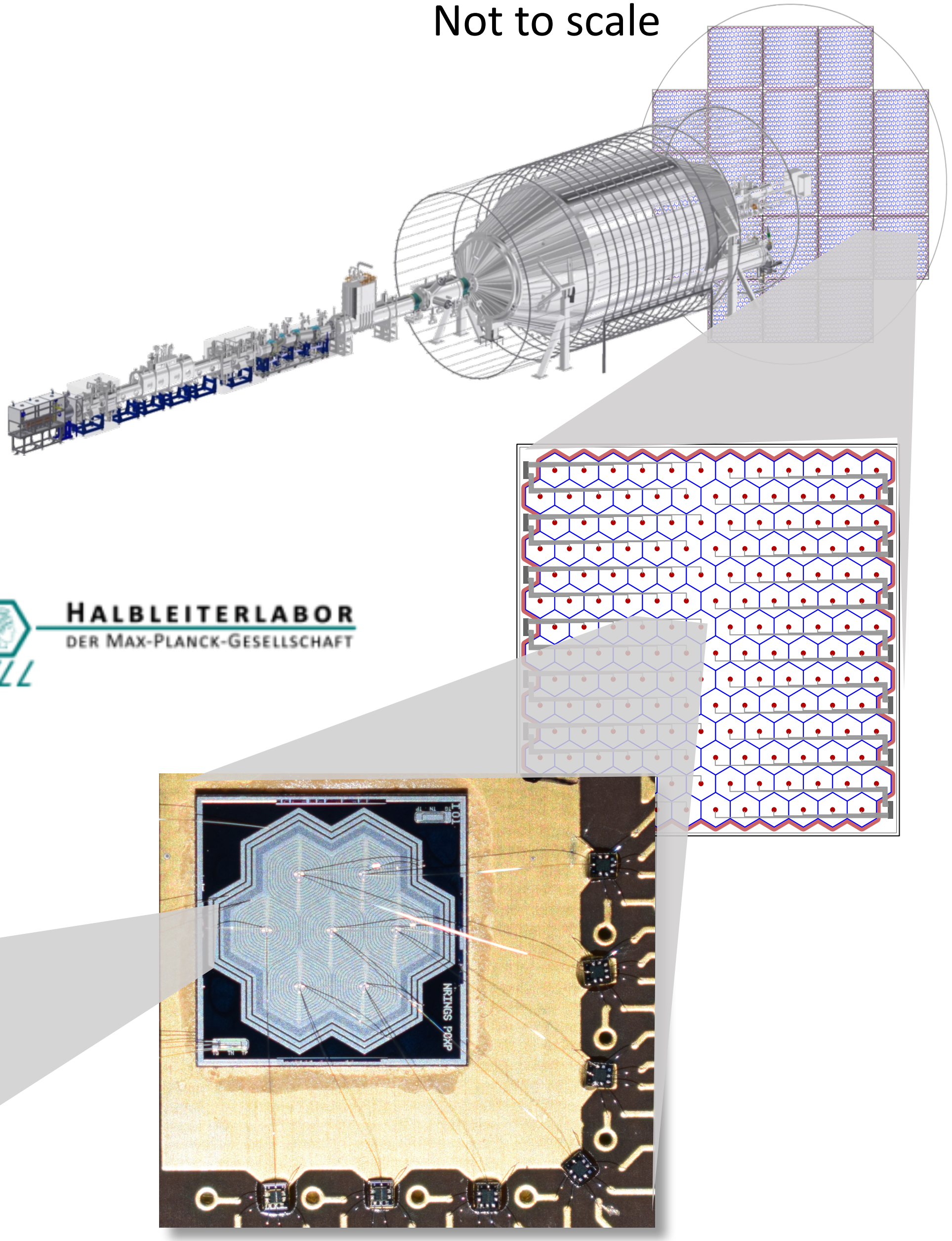
- Capability of handling high rates (>3 x 10^8 cps)
    - O(3000) pixels, 100 kcps per pixel
- Excellent energy resolution (300 eV @ 20 keV)
  Low energy threshold (1 keV)
    - Thin deadlayer (~10 nm)
- Large pixels + low noise at high rate
  (cell size ~ 3mm)
    - Capacity < 0.05 pF
- Minimal non-linearities
    - Sophisticated readout system*

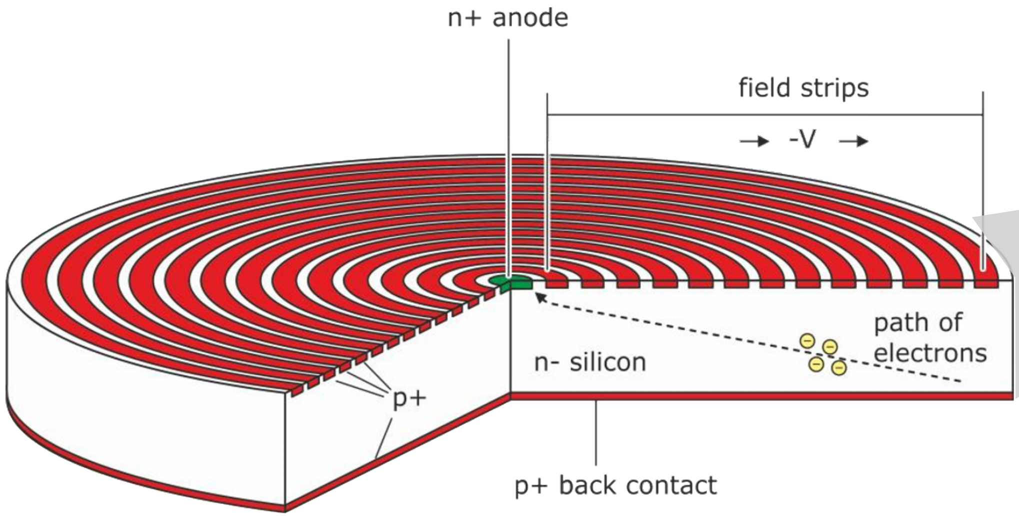


K. Dolde, S.M., D. Radford et. al. NIM-A 848 (2017)

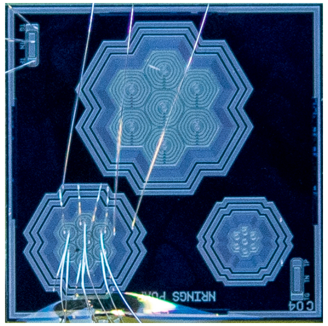
TRISTAN Detector R&D

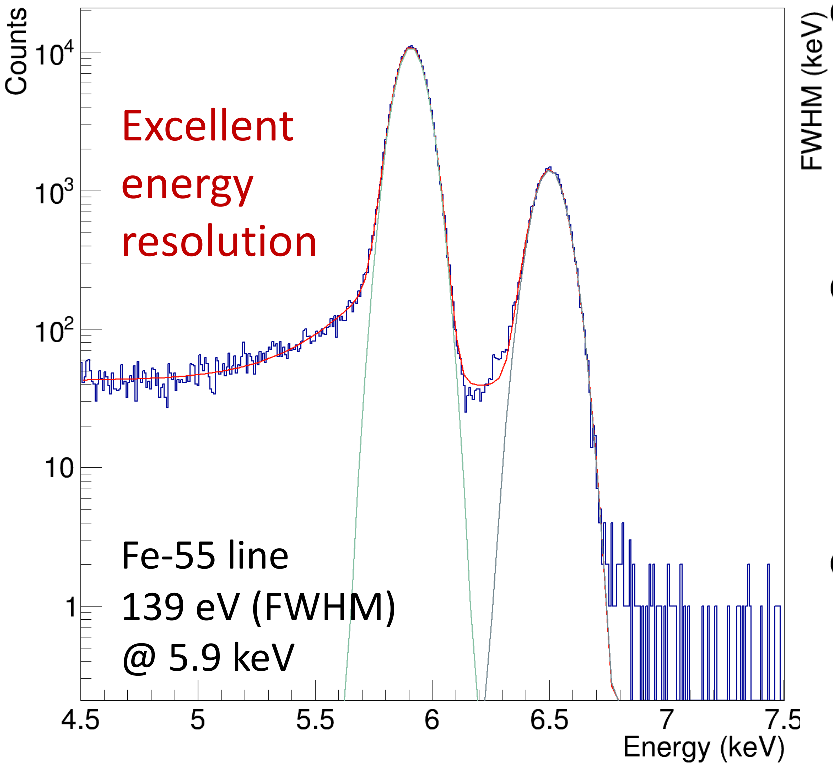
- Silicon drift detector design
- Novelty: extremely thin entrance window (< 100 nm)
- 7-pixel prototype detector produced at the Semiconductor Lab of the Max Planck Society
- Read-out developed at XGLab, KIT, and CEA

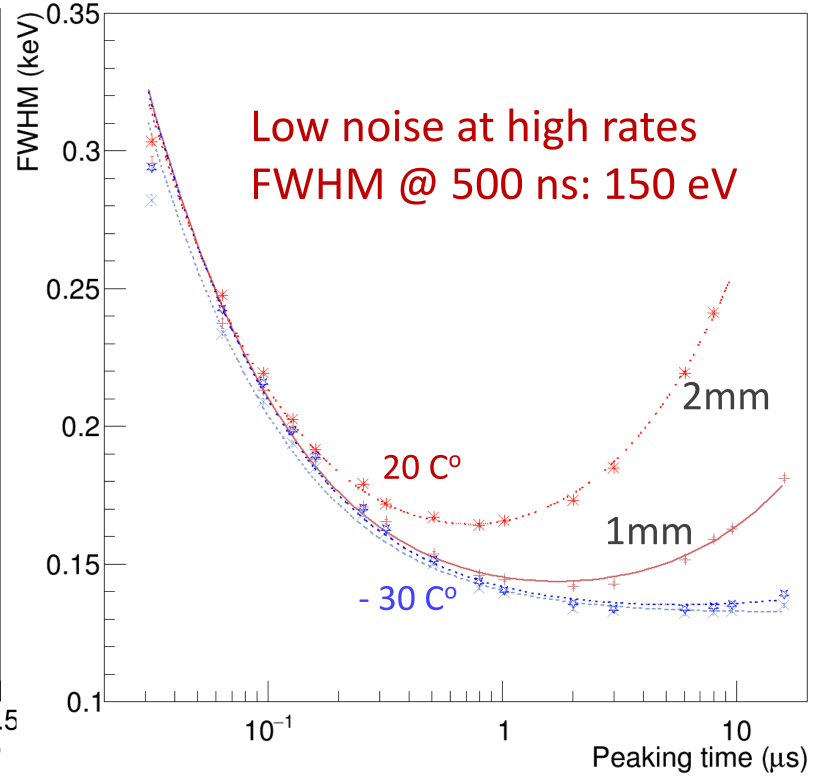


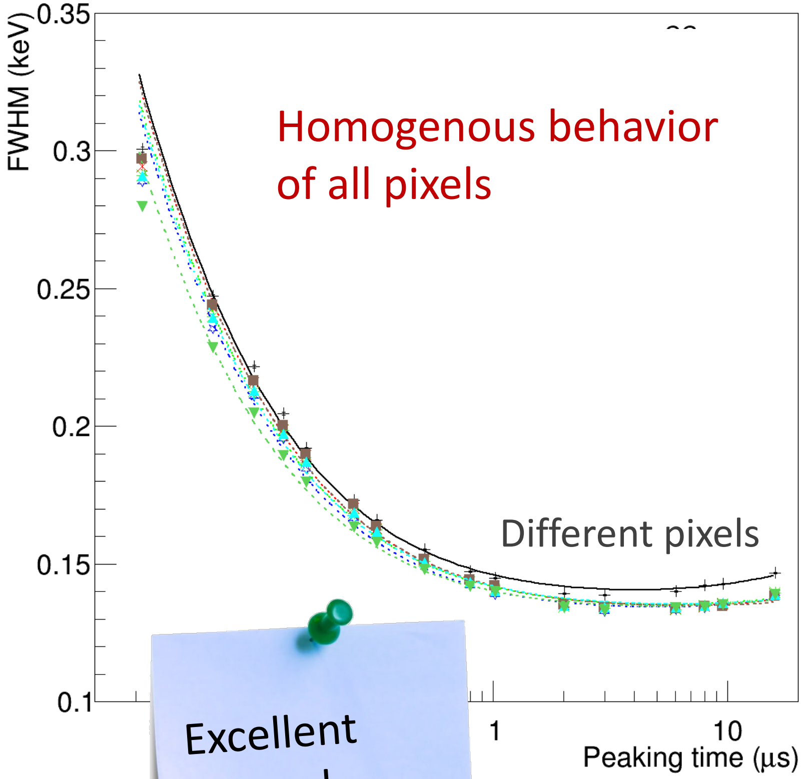


General performance (XGLab system, X-ray sources)









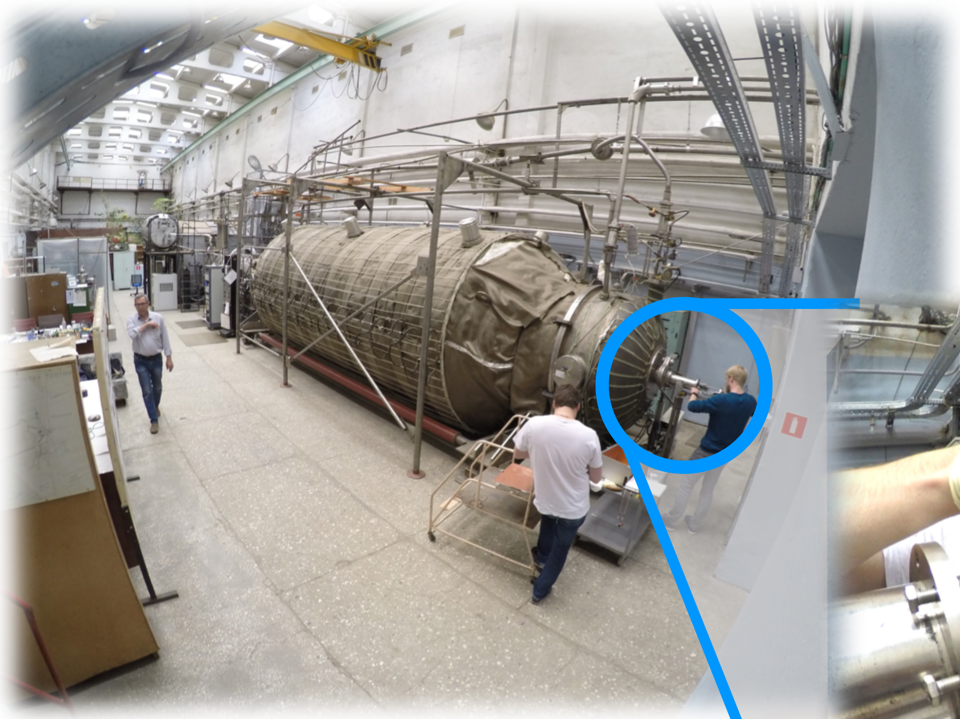
Excellent general performance

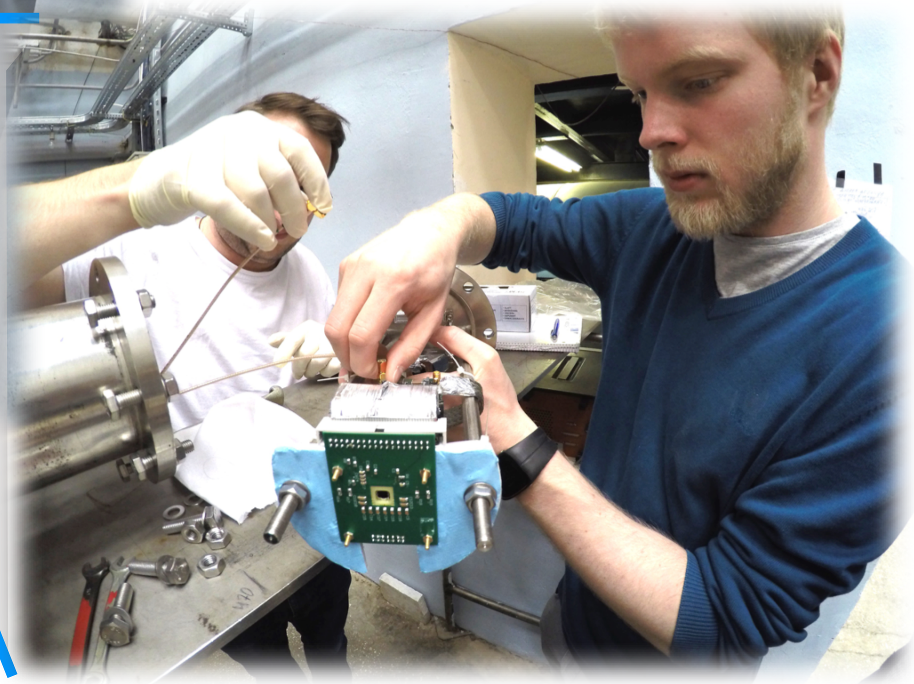
TRISTAN in TROITSK

Application of the TRISTAN detector

at Troitsk nu-mass experiment

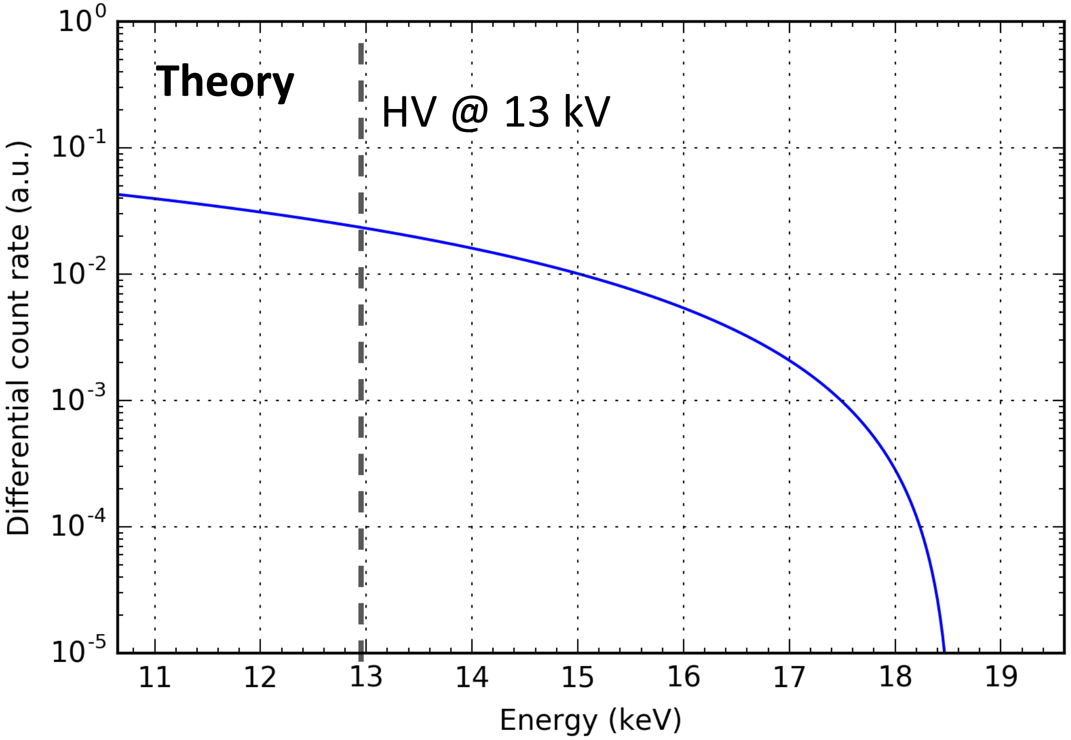
(26.5. – 4.6.2017 and 20.11. – 2.12.2017)

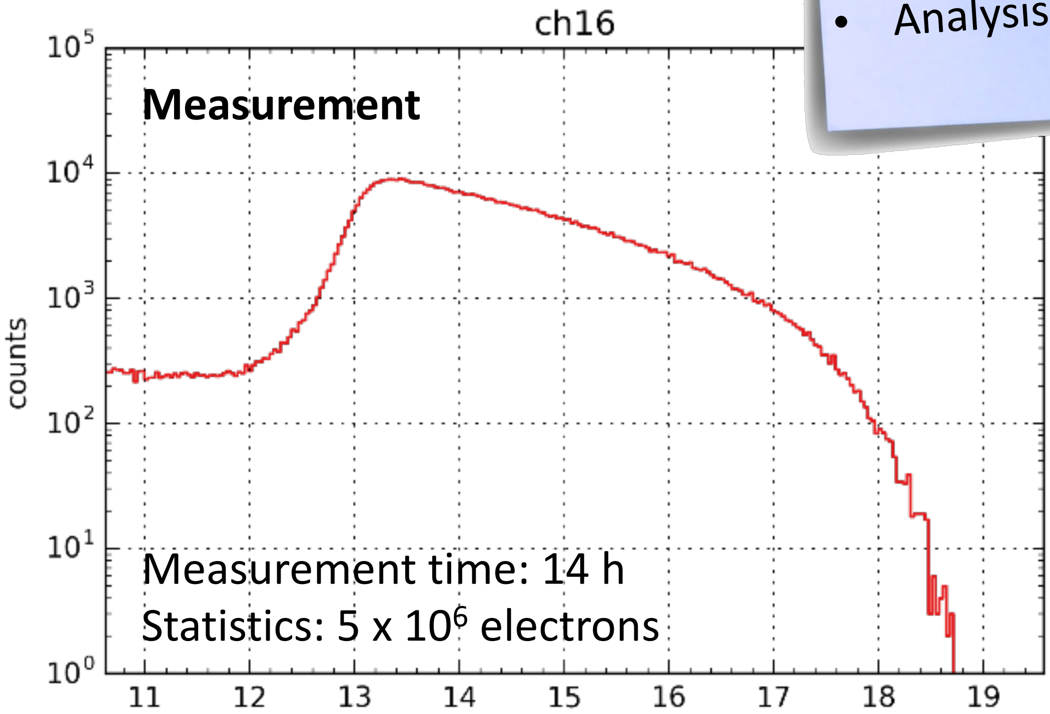




Our first tritium spectrum

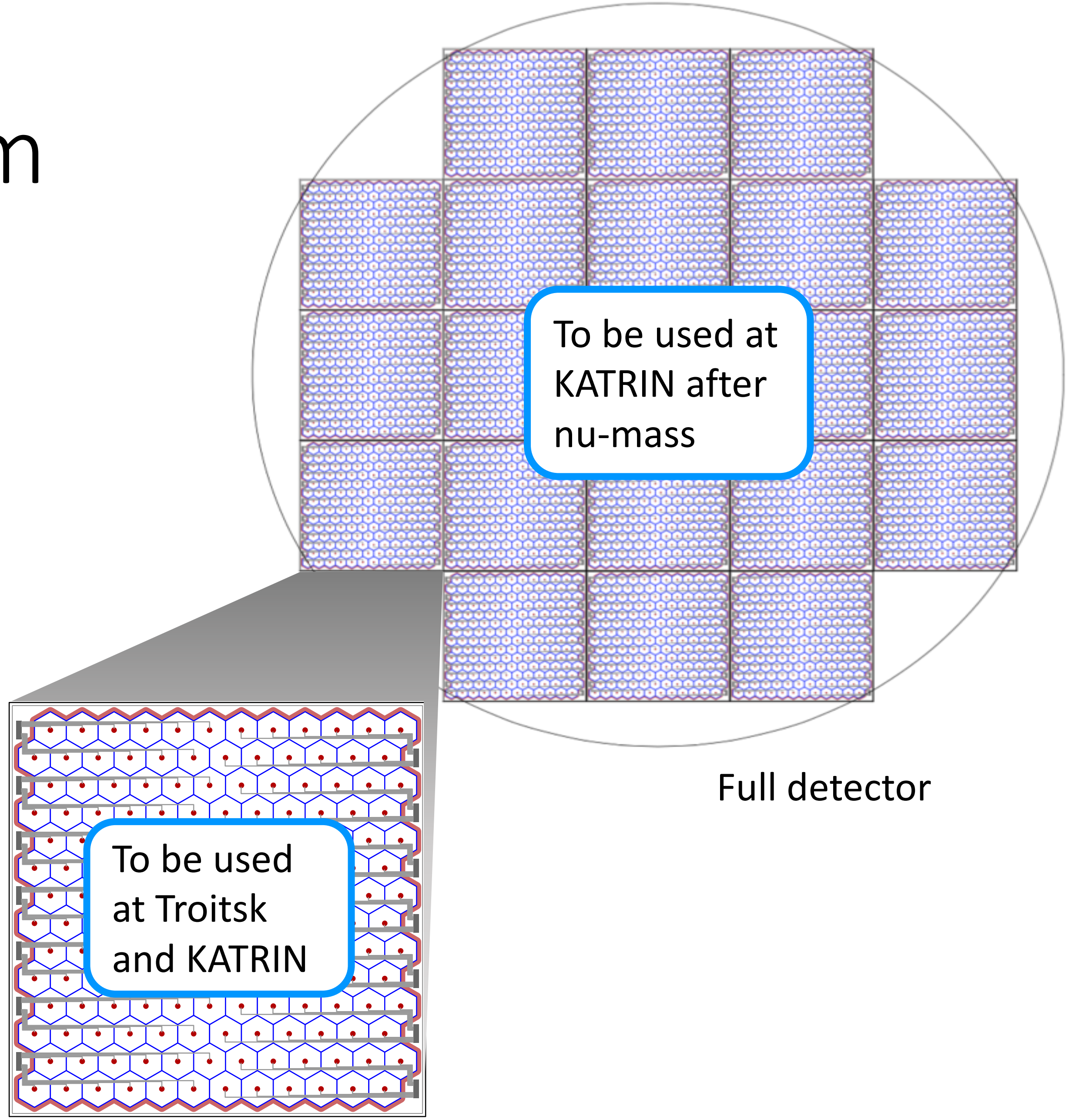
- Good performance in "real conditions"
- Analysis ongoing





Towards the final system

- **Pixel design:**
  - SDD with integrated nJFET
  - Pixel size: ~3 mm diameter
- **Module design:**
  - 168 pixels
  - Module size: ~4 cm diameter
- **Final detector design:**
  - 21 modules → 3500 pixels
  - Detector size: ~20 cm diameter

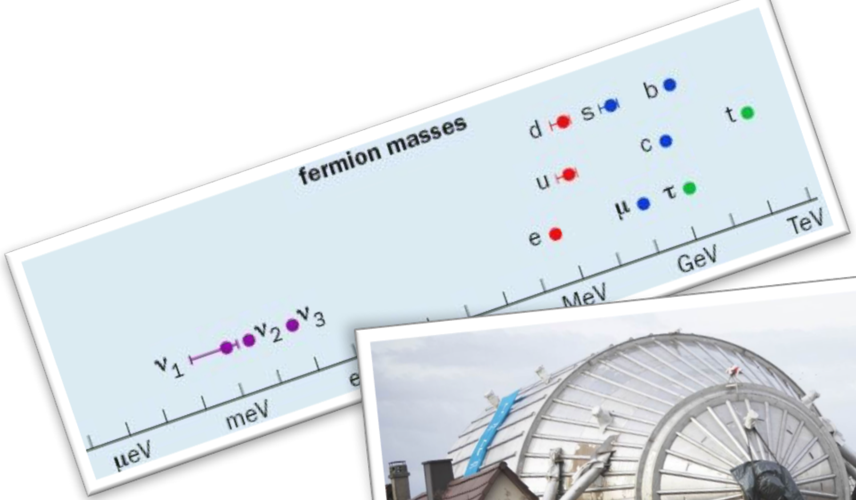


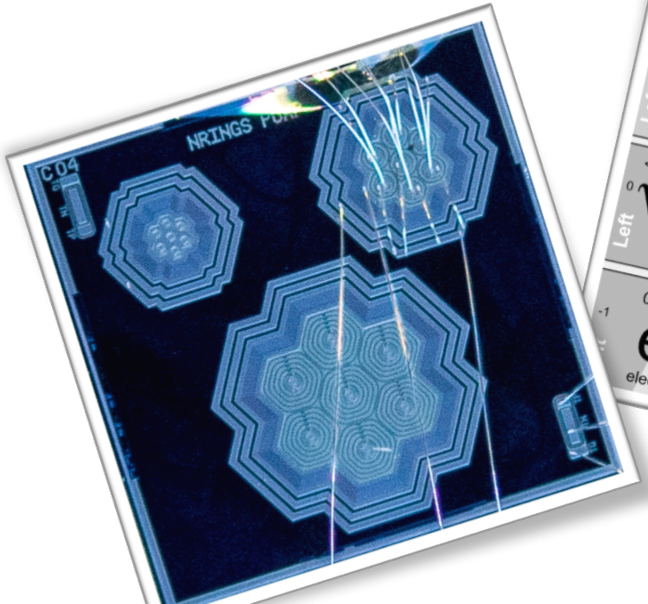
Full detector

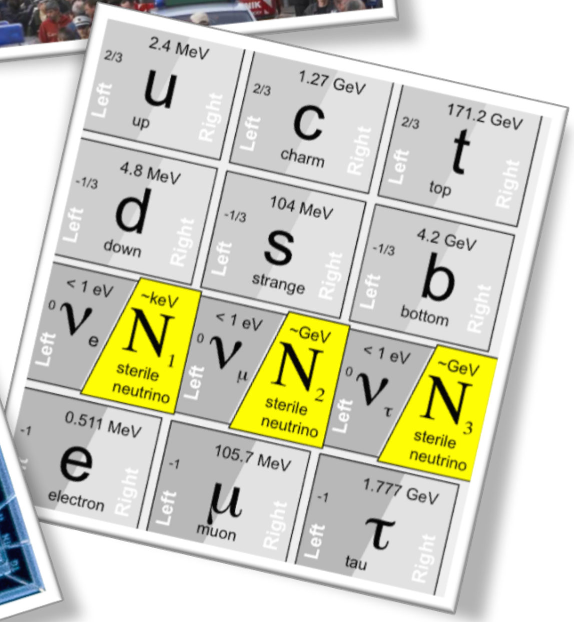
Detector module

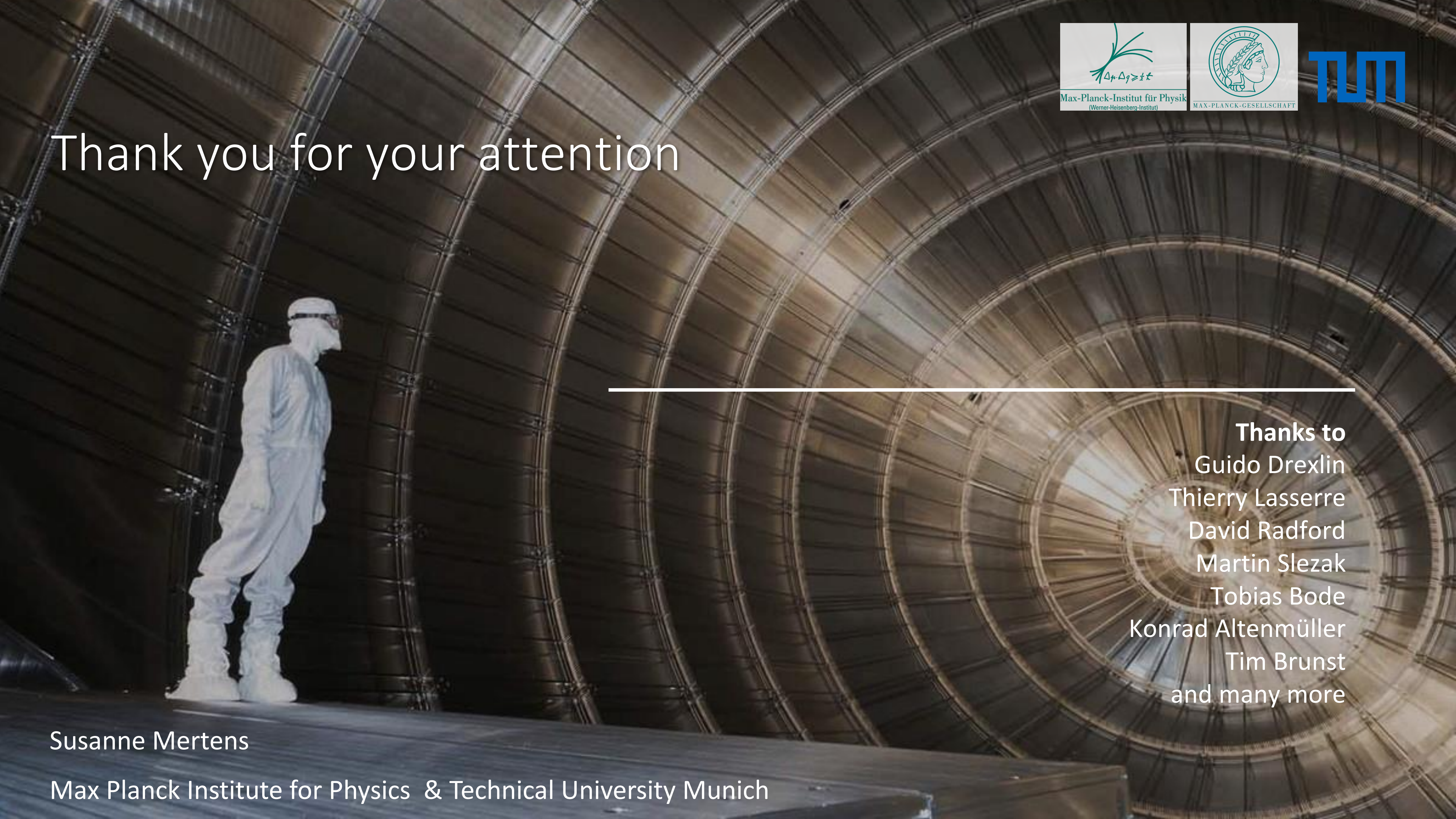
Summary

- Neutrinos provide us with exciting open questions…
- First tritium run with KATRIN is scheduled for May 2018
- KATRIN has to potential to extend its physics reach to search for eV- keV sterile neutrinos
- R&D is ongoing to develop new detector system to allow KATRIN to search for keV sterile neutrinos









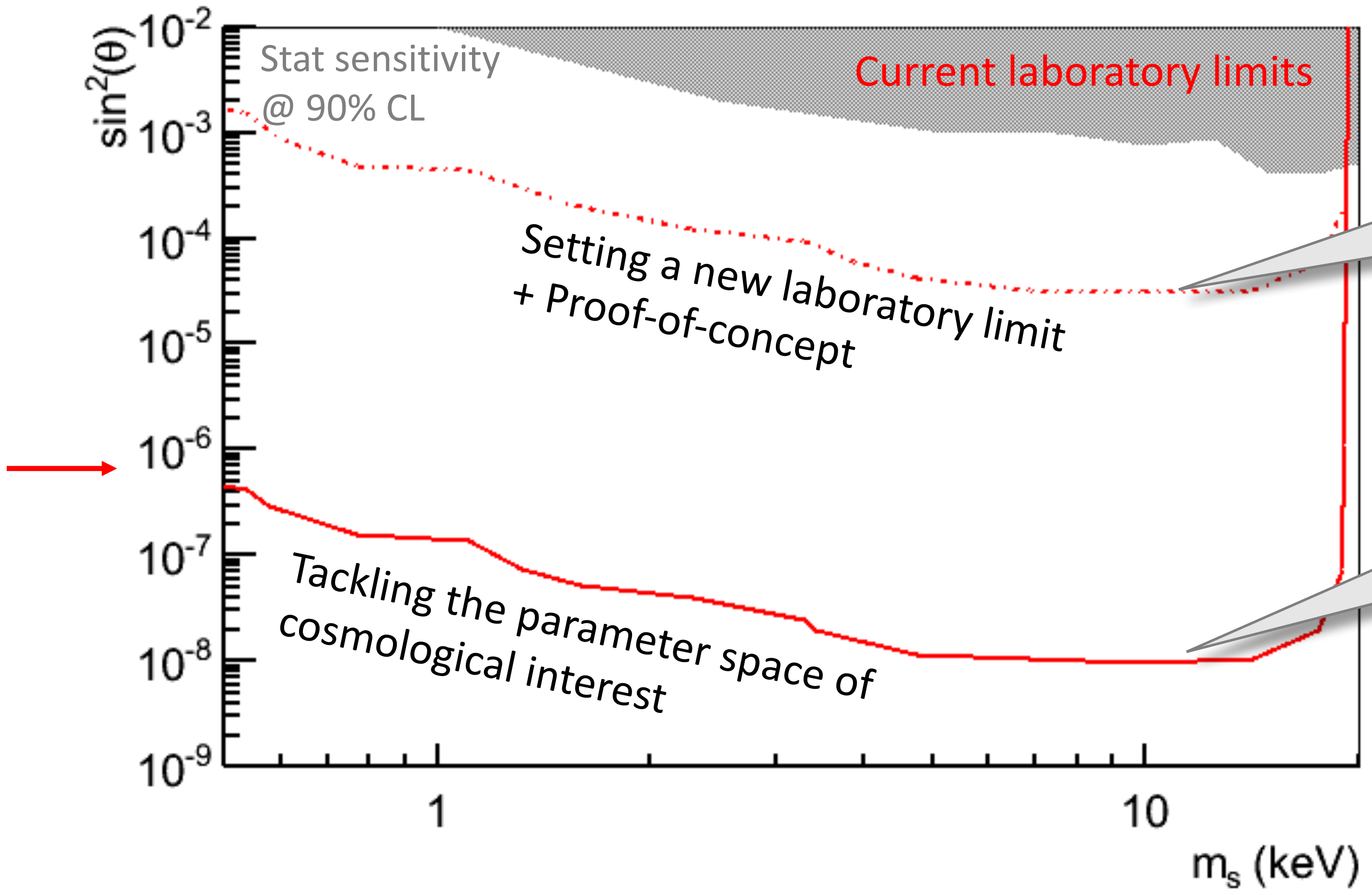
Thank you for your attention

Thanks to
Guido Drexlin
Thierry Lasserre
David Radford
Martin Slezak
Tobias Bode
Konrad Altenmüller
Tim Brunst
and many more

Susanne Mertens

Max Planck Institute for Physics & Technical University Munich

Staged Approach

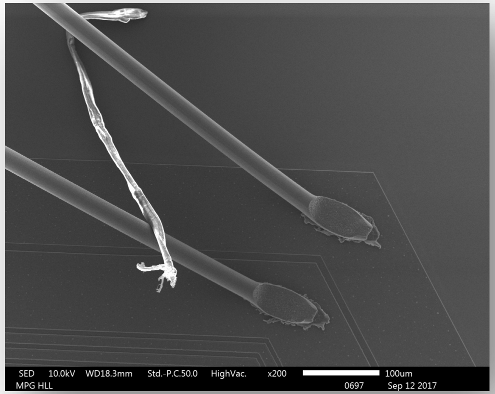


10^{11} electrons:
Reduced source strength and
7 days of measurement time
With KATRIN "as is"

10^{18} electrons:
Full source strength and
3 years of measurement time
With TRISTAN

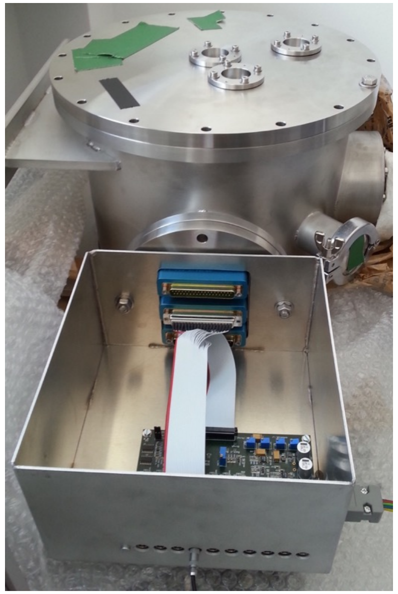
Characterization with electrons

- Electron microscope



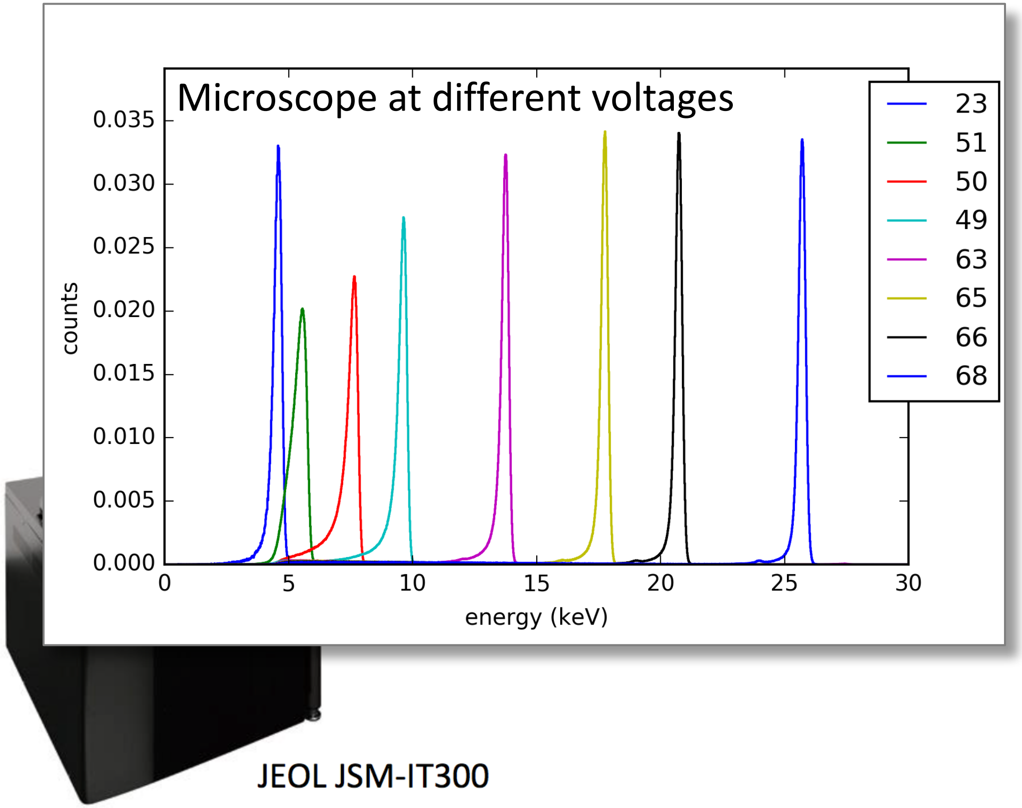

JEOL JSM-IT300

- Evaporated Kr source



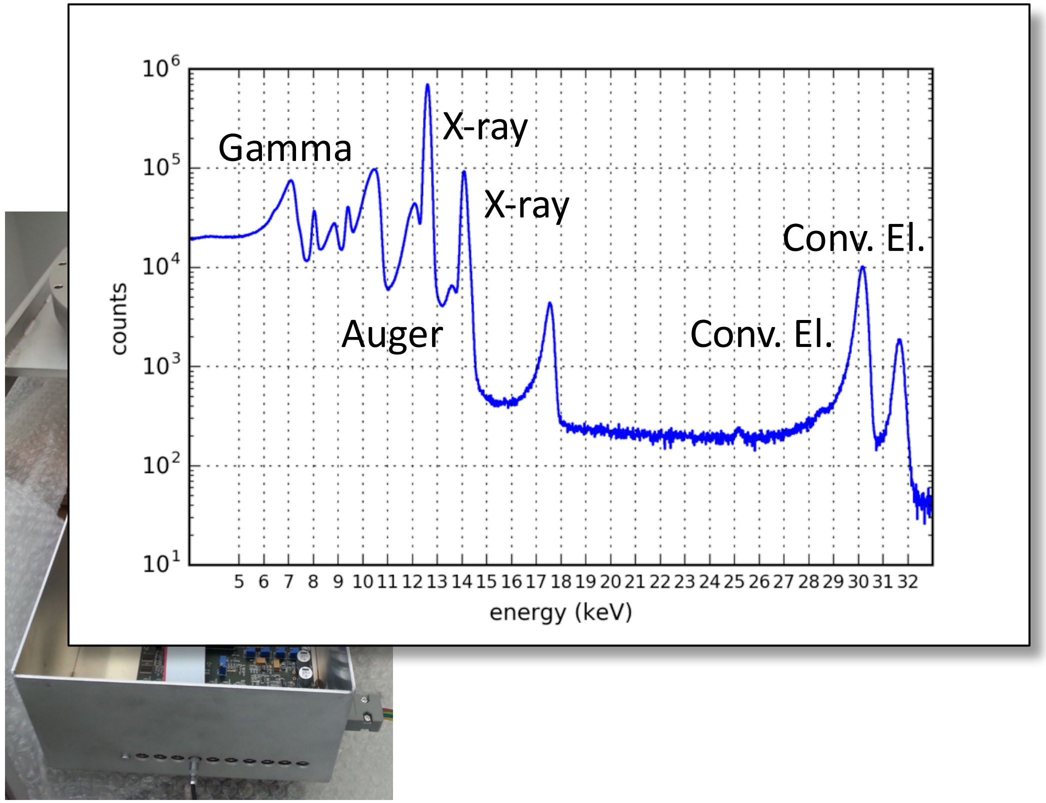
Characterization with electrons

- Electron microscope

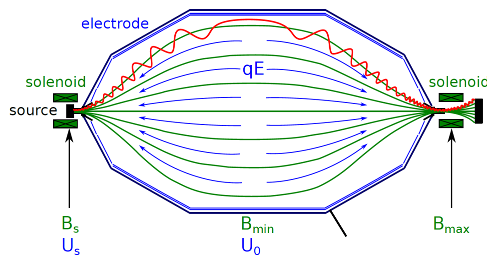


JEOL JSM-IT300

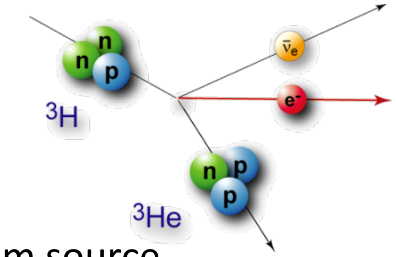
- Evaporated Kr source



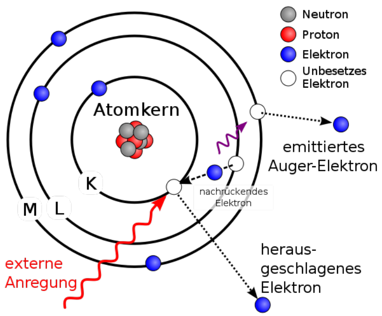
Other Challenges



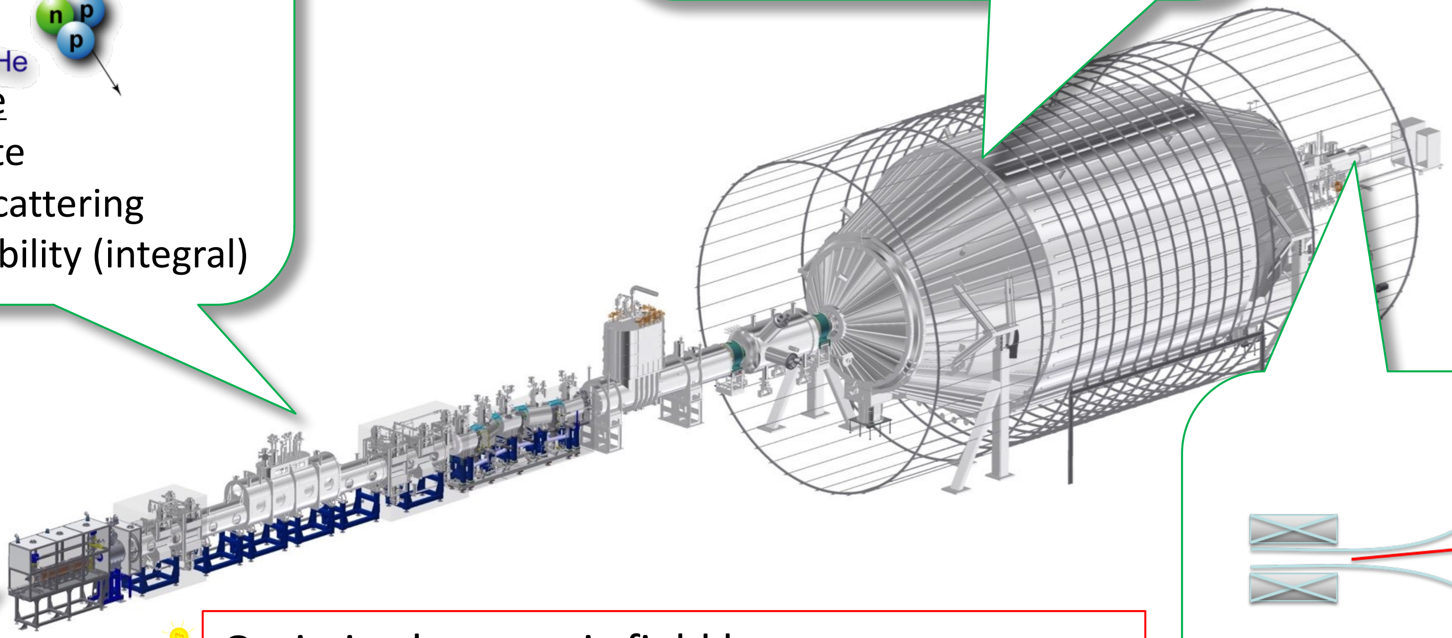
Spectrometer
- ➢ Adiabatic transport

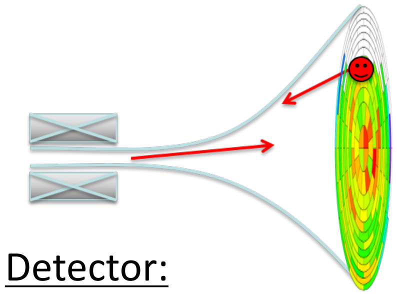


Tritium source
- ➢ Reduce rate
- ➢ Multiple scattering
- ➢ Source stability (integral)

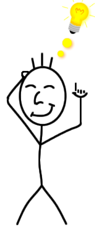


Gold Rear Wall
- ➢ Auger e emission
- ➢ Backscattering



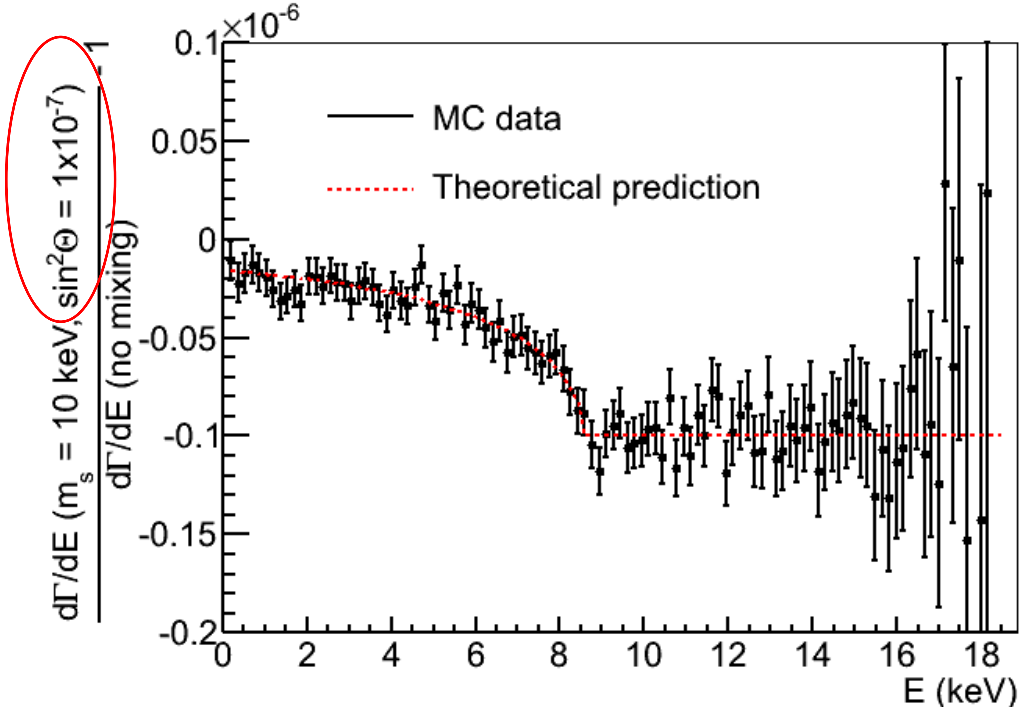


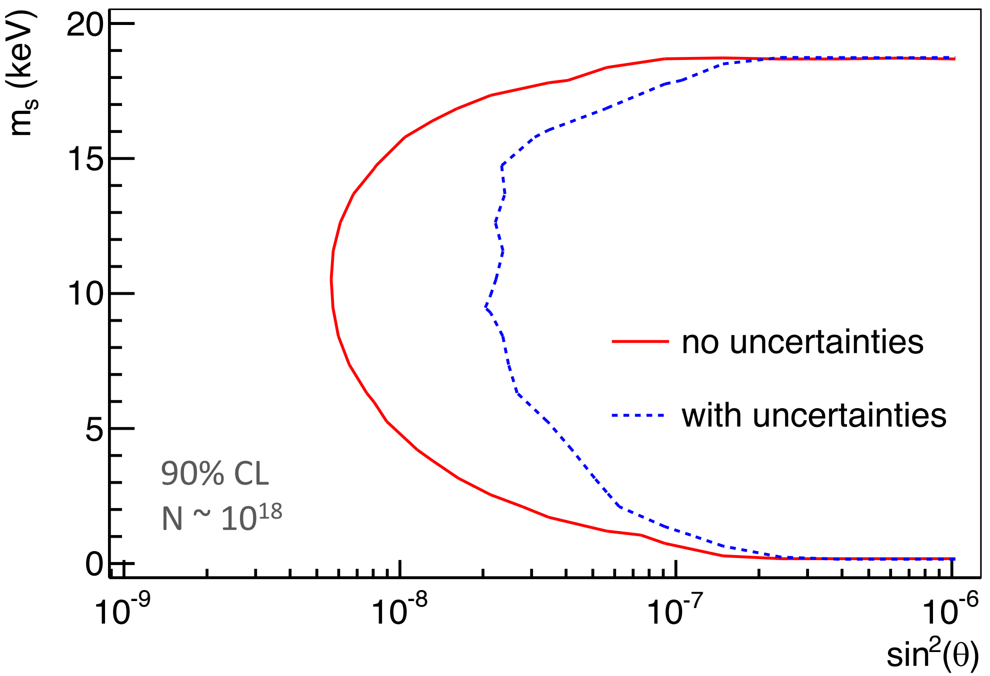
Detector:
- ➢ Backscattering
- ➢ Energy response (differential)



Optimized magnetic field layout
Improved modelling
Combination of integral and differential mode

Sensitivity

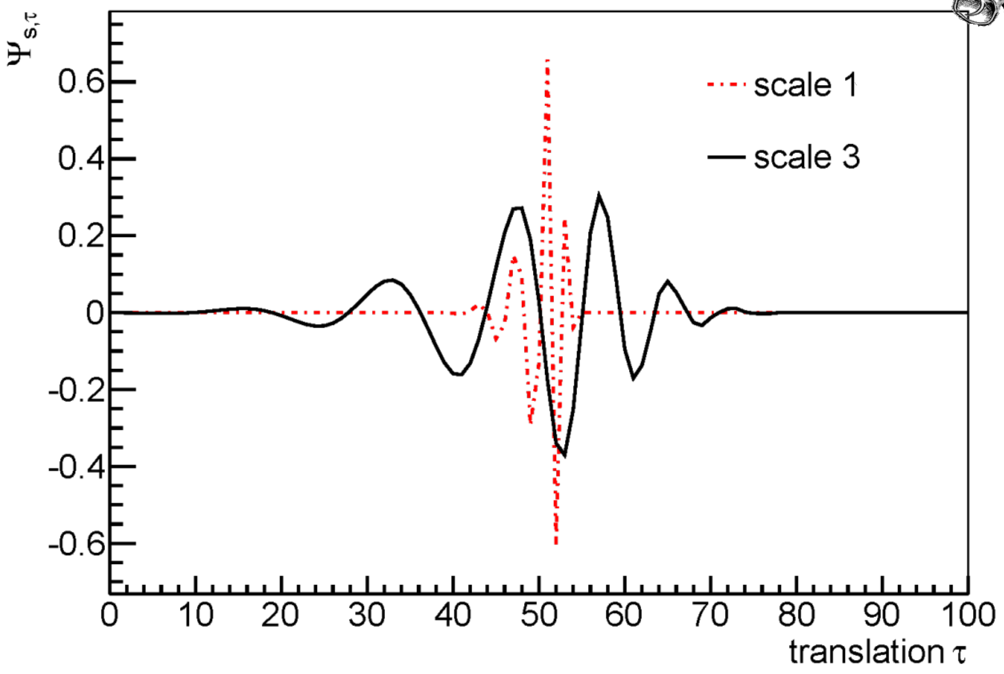


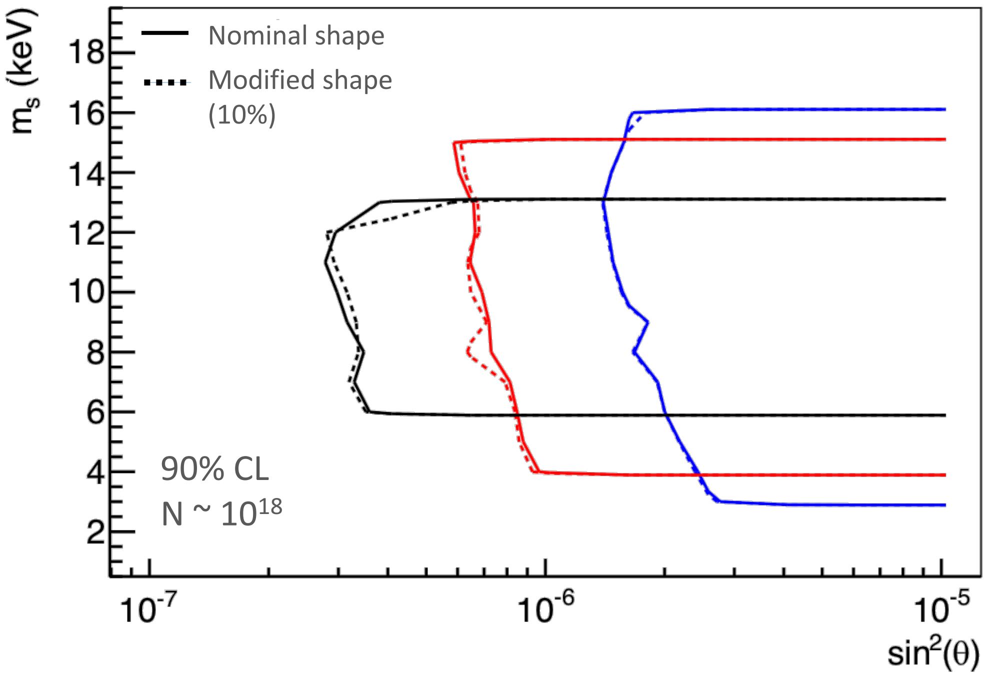


- Expected signal after 3-years with full KATRIN source strength
- Theoretical uncertainties do not destroy the sensitivity

S.M. *et. al.* Phys.Rev. D91 (2015) 4, 042005
S.M. *et al.* JCAP 1502 (2015) 02, 020

Sensitivity



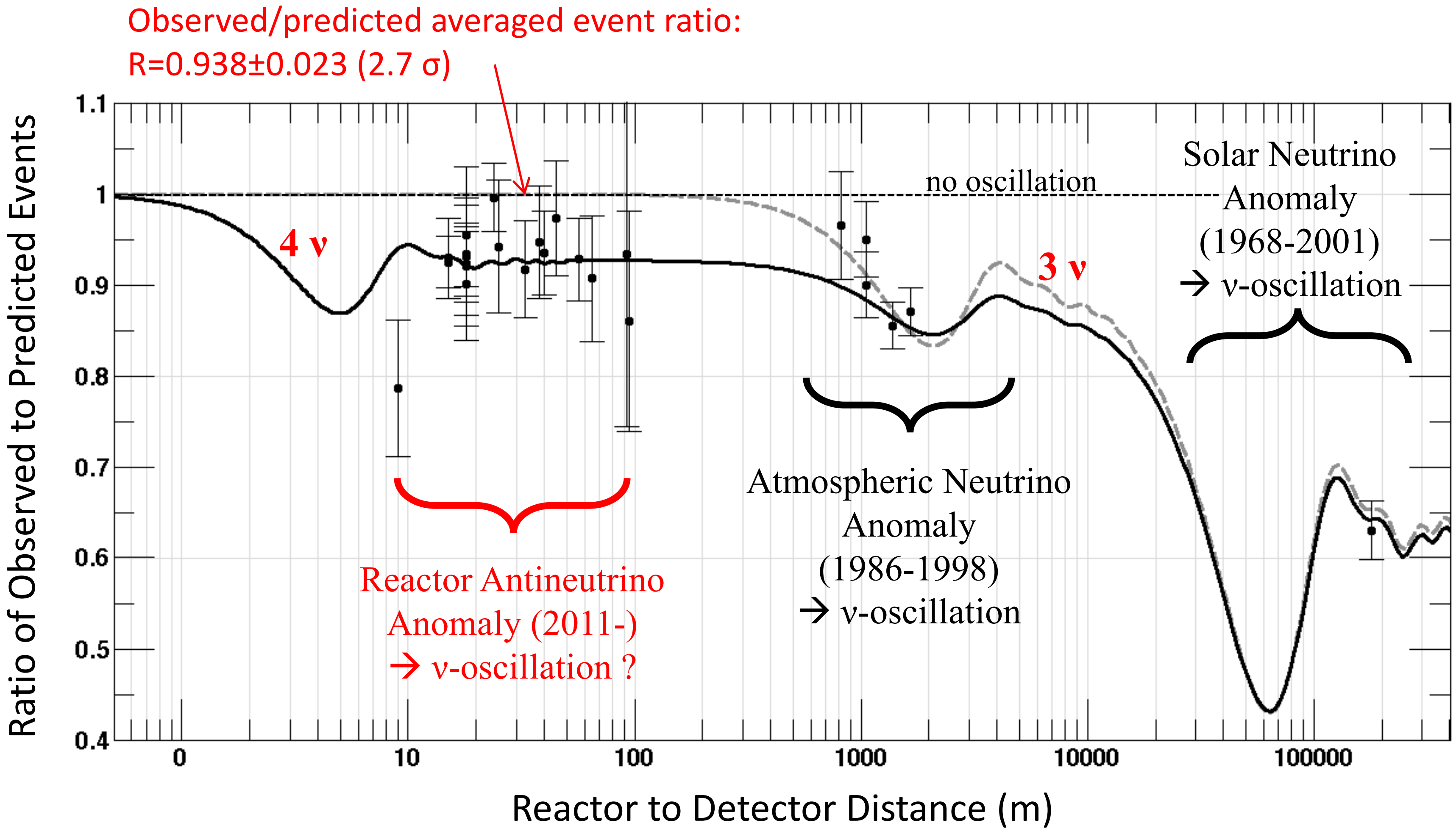


- Wavelet transformation to detect characteristic kink-like signature

- Result largely independent of exact shape
- But good energy resolution required (200 eV)

S.M. *et. al.* Phys.Rev. D91 (2015) 4, 042005
S.M. *et al.* JCAP 1502 (2015) 02, 020

The Reactor Anomaly

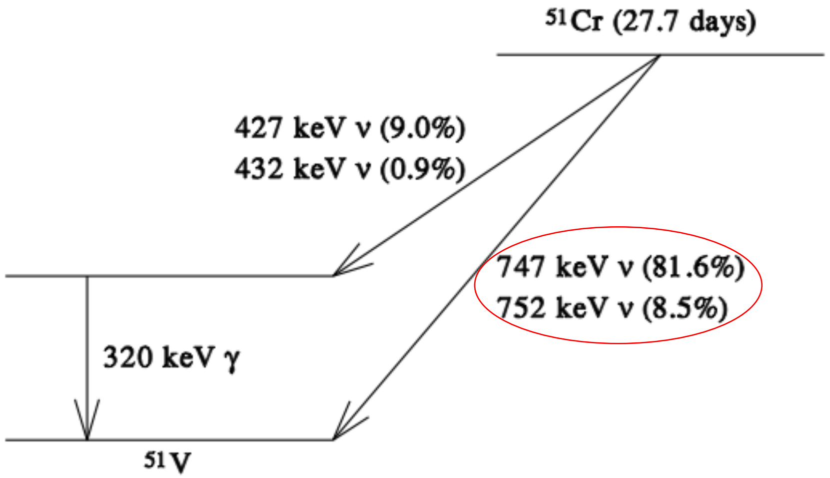


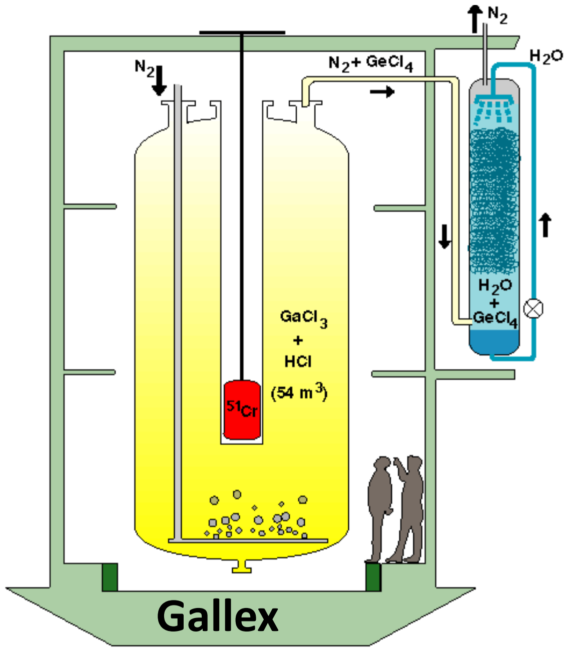
G. Mention, Phys. Rev. D 83, 073006 (2011)

The Gallium Anomaly

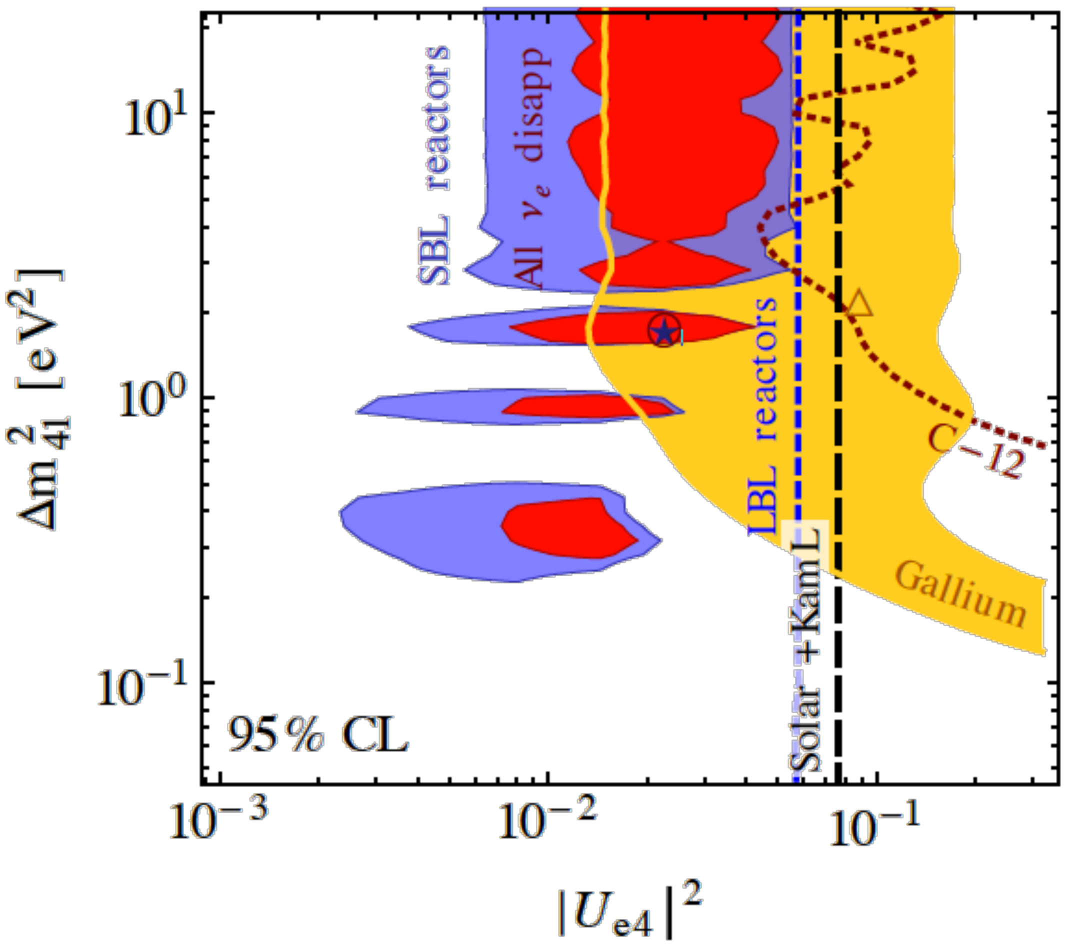
- Test of solar neutrino radiochemical detectors GALLEX and SAGE
  - $^{71}Ga + \nu_e \rightarrow {}^{71}Ge + e^-$
- 4 calibration runs with 20-60 PBq Electron Capture ν_e emitters
  - **GALLEX:**
    $\langle L \rangle = 1.9$ m
    $E_\nu = 750$ keV (^{51}Cr)
  - **SAGE:**
    $\langle L \rangle = 0.6$ m
    $E_\nu = 810$ keV (^{51}Cr, ^{37}Ar)

➢ 3σ deficit observed





ν_e disappearance (3+1)

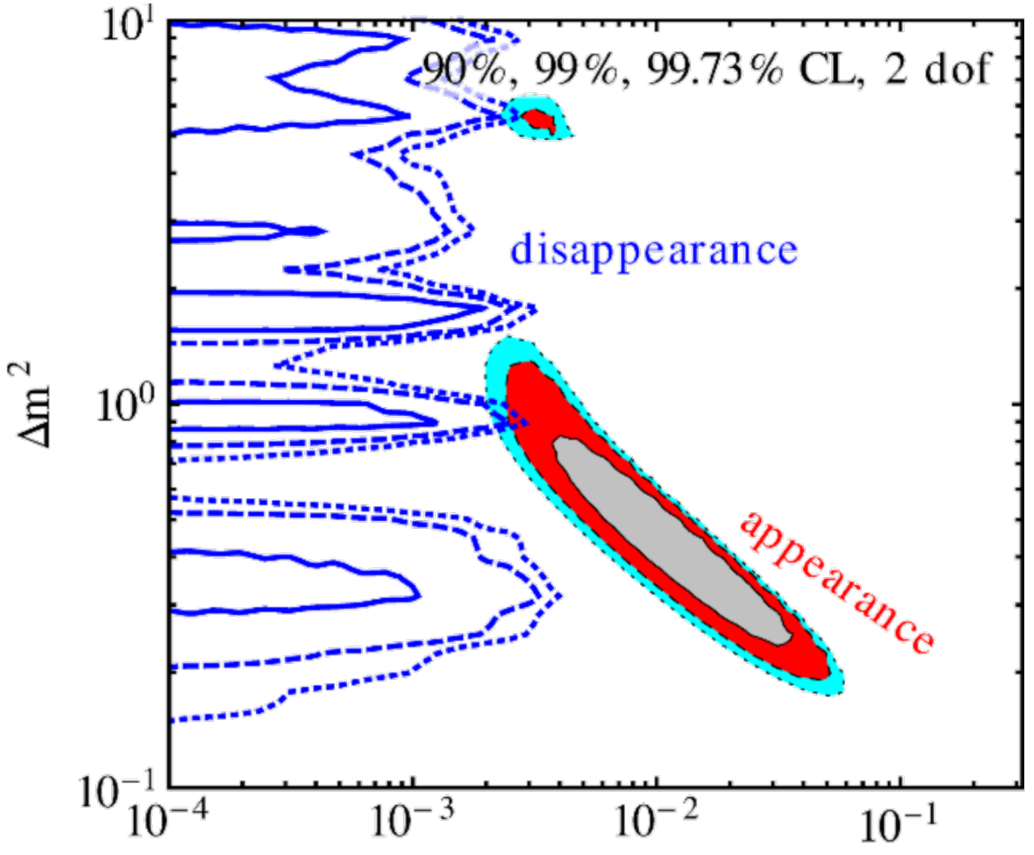


Data consistent with ν_e disappearance at L/E≈1 m/MeV

J. Kopp et al, JHEP 2013, 5, 1 – 52 (2013)

ν_e appearance vs disappearance (3+1)

Appearance anomalies (LSND) hardly consistent with disappearance experiments



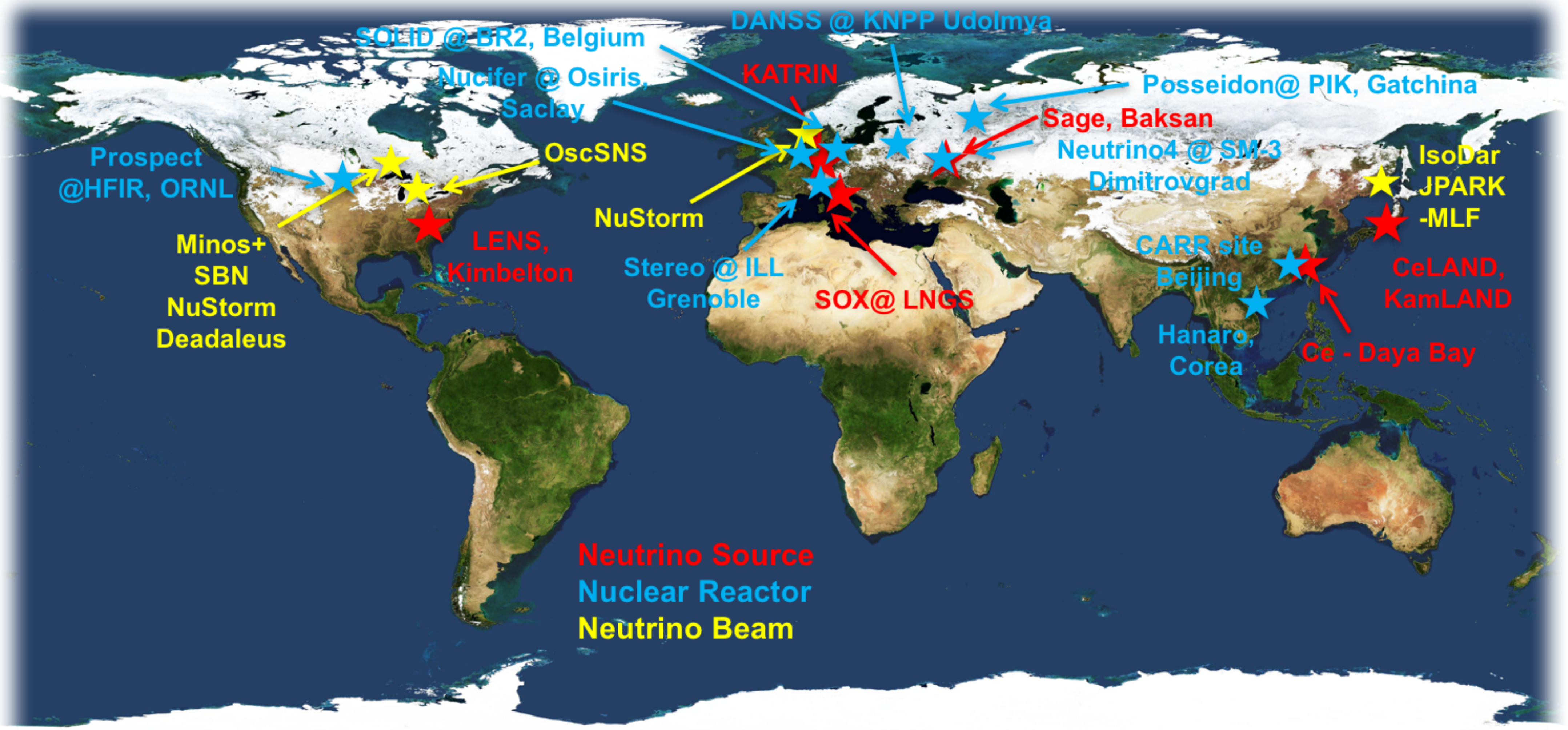
$\sin^2(2\theta_{\mu e})$

ν_e – disappearance
→ observed

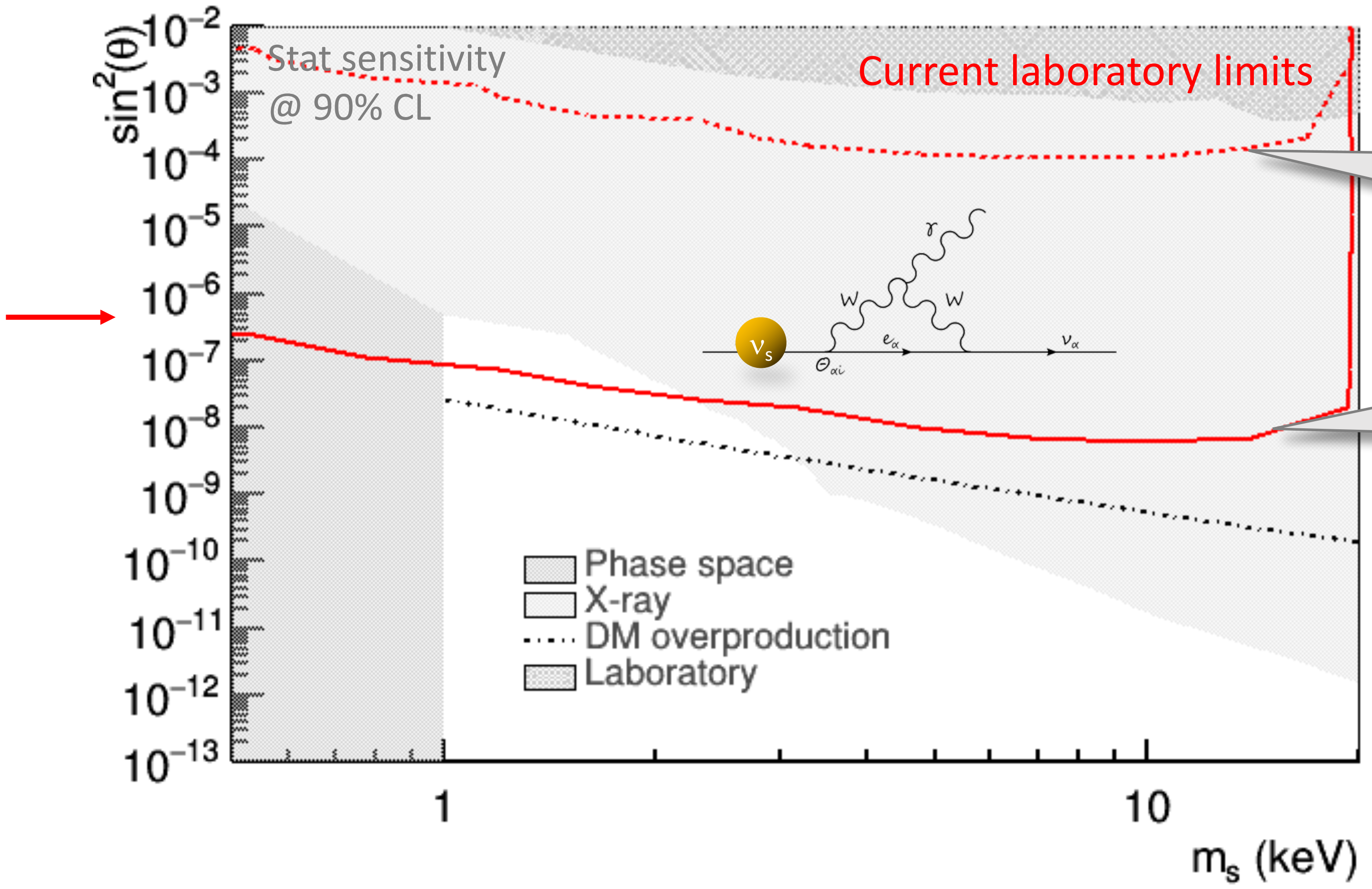
ν_μ – disappearance
→ not observed

$= \sin^2(2\theta_{\mu\mu}) \sin^2(2\theta_{ee})$

World-wide Hunt for Steriles



Staged Approach



10^{11} electrons:
Reduced source strength and
7 days of measurement time
With KATRIN "as is"

10^{18} electrons:
Full source strength and
3 years of measurement time
With TRISTAN

Neutrinos

- Elementary particle, that only interacts weakly
- Appears in 3 flavors and with 3 masses
- Was assumed to be massless…
  … but neutrino oscillation proofed that the neutrinos have mass