Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Sterile neutrinos as dark matter candidate and the TRISTAN project

Tim Brunst, IMPRS Particle Physics School Colloquium, July 12th 2018

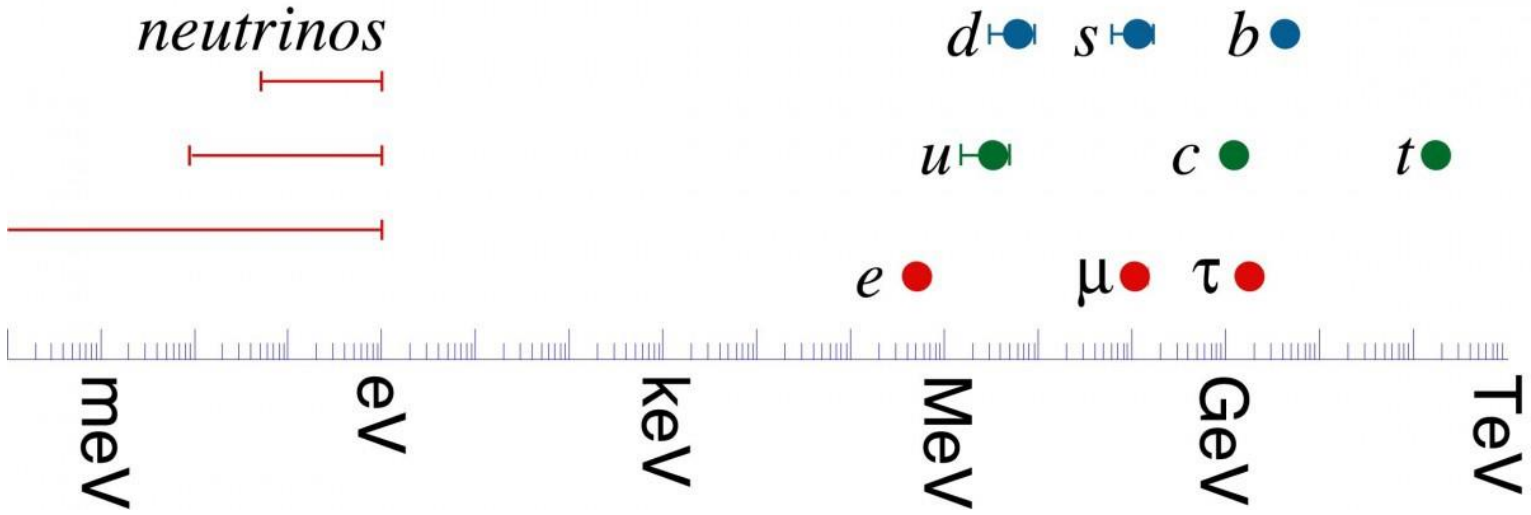
Max Planck Institute for Physics, Munich
KATRIN Collaboration – TRISTAN Group

What is a neutrino?

- 3 flavor, spin ½, neutral, left handed, $\sigma(1\ \mathrm{MeV}) \approx 10^{-44}\ \mathrm{cm}^2$

What is a neutrino?

- 3 flavor, spin ½, neutral, left handed, $\sigma(1\ \mathrm{MeV}) \approx 10^{-44}\ \mathrm{cm}^2$
- Lightest particle in the standard model: $0.04\ \mathrm{eV} < m_\nu < 2\ \mathrm{eV}$



What is a neutrino?

- 3 flavor, spin ½, neutral, left handed, $\sigma(1\ \text{MeV}) \approx 10^{-44}\ \text{cm}^2$
- Lightest particle in the standard model: $0.04\ \text{eV} < m_\nu < 2\ \text{eV}$
- Leptonic mixing & neutrino oscillations

$$P(\bar{\nu}_x \rightarrow \bar{\nu}_x) = 1 - \sin^2(2\theta_i)\sin\left(1.27\frac{\Delta m_i^2\ (\text{eV}^2) L\ (\text{m})}{E\ (\text{MeV})}\right)$$

Atmospheric | Cross-Mixing | Solar

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \times \begin{bmatrix} c_{13} & 0 & c_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \times \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} e^{i\frac{\alpha_1}{2}} & 0 & 0 \\ 0 & e^{i\frac{\alpha_2}{2}} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

θ_{23}: "atm." angle

θ_{13}

δ dirac CP phase

θ_{12} : "solar" angle

Majorana CP phases
(L violating processes)

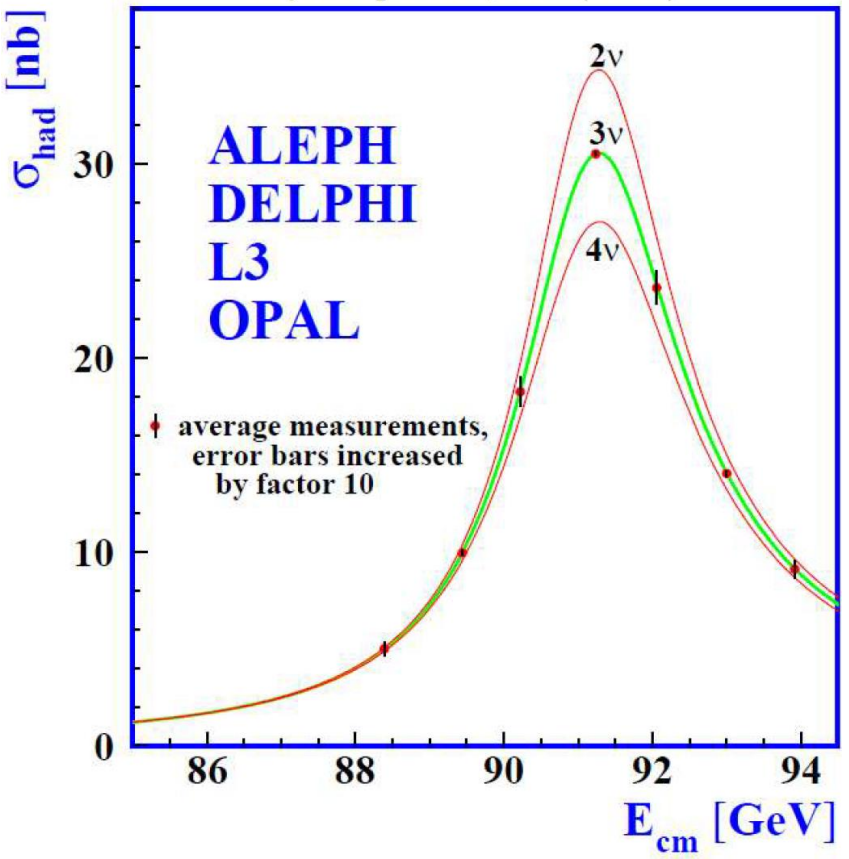
What is a neutrino?

- 3 flavor, spin ½, neutral, left handed, $\sigma(1\ \text{MeV}) \approx 10^{-44}\ \text{cm}^2$
- Lightest particle in the standard model: $0.04\ \text{eV} < m_\nu < 2\ \text{eV}$
- Leptonic mixing & neutrino oscillations
- Open questions:
  - Masses of the mass eigenstates ν_i?
  - Normal or inverted hierarchy?
  - Lepton Number conservation (Dirac or Majorana)?
  - Is CP violated in the neutrino sector?
  - **Are there additional (sterile) neutrino states**

What is a sterile neutrino?

- Z^0 decay width is consistent with only three light active neutrinos

Phys.Rept. 427, 257 (2006)



What is a sterile neutrino?

- Z^0 decay width is consistent with only three light active neutrinos

- A sterile neutrino is a lepton with no ordinary electroweak interaction except those induced by mixing

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

3+1 scenario

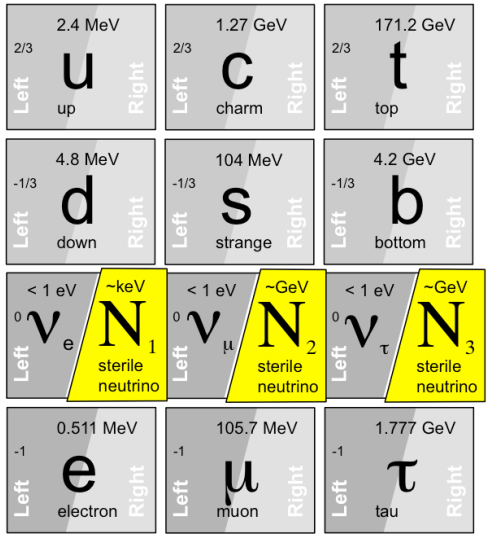
$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{bmatrix}$$

What is a sterile neutrino?

- Z^0 decay width is consistent with only three light active neutrinos

- A sterile neutrino is a lepton with no ordinary electroweak interaction except those induced by mixing

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

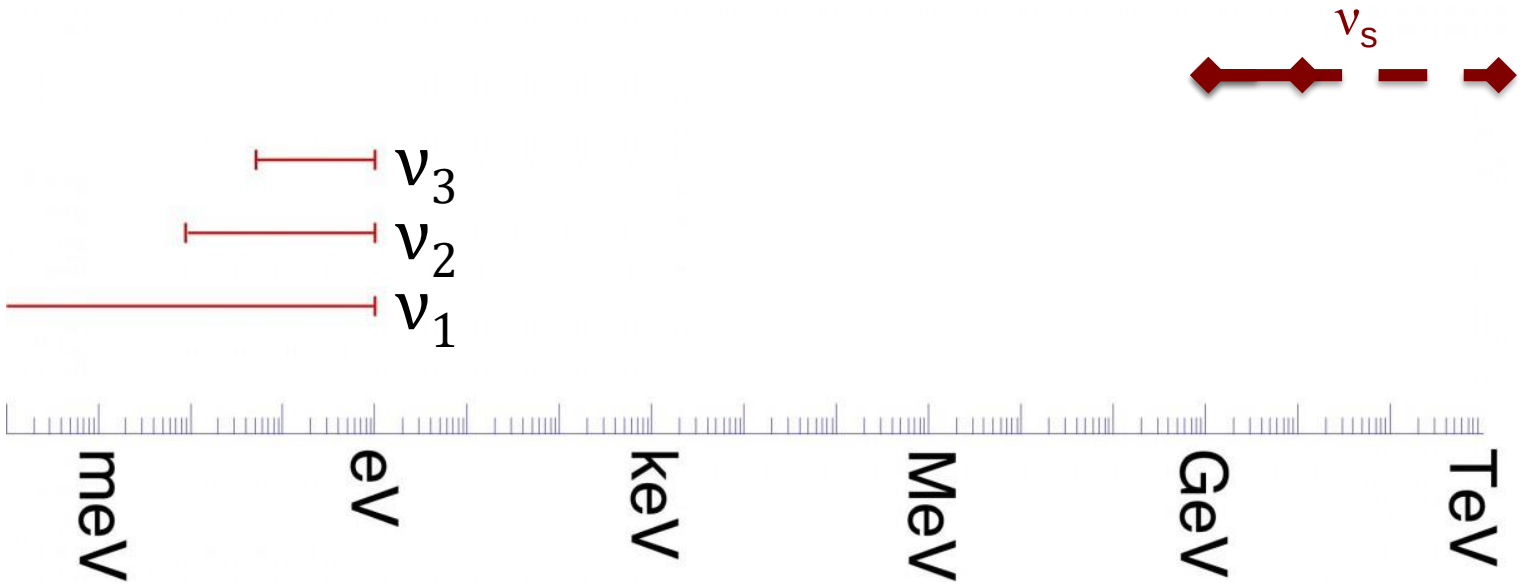


3+3 scenario

$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & U_{e5} & U_{e6} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} & U_{\mu 5} & U_{\mu 6} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} & U_{\tau 5} & U_{\tau 6} \\ U_{s1 1} & U_{s1 2} & U_{s1 3} & U_{s1 4} & U_{s1 5} & U_{s1 6} \\ U_{s2 1} & U_{s2 2} & U_{s2 3} & U_{s2 4} & U_{s2 5} & U_{s2 6} \\ U_{s3 1} & U_{s3 2} & U_{s3 3} & U_{s3 4} & U_{s3 5} & U_{s3 6} \end{bmatrix}$$

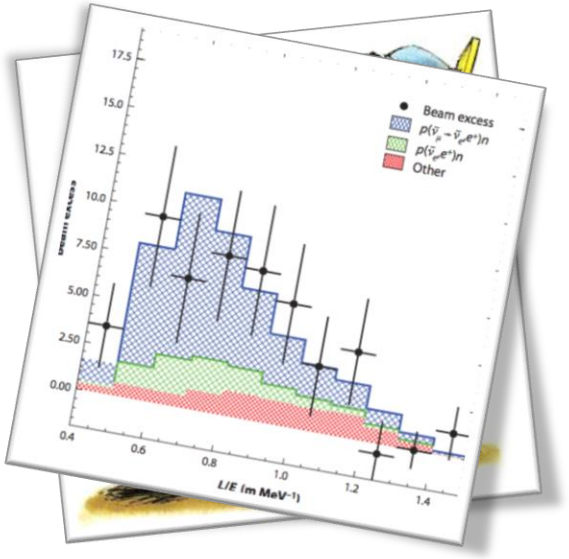
Sterile neutrinos mass ranges

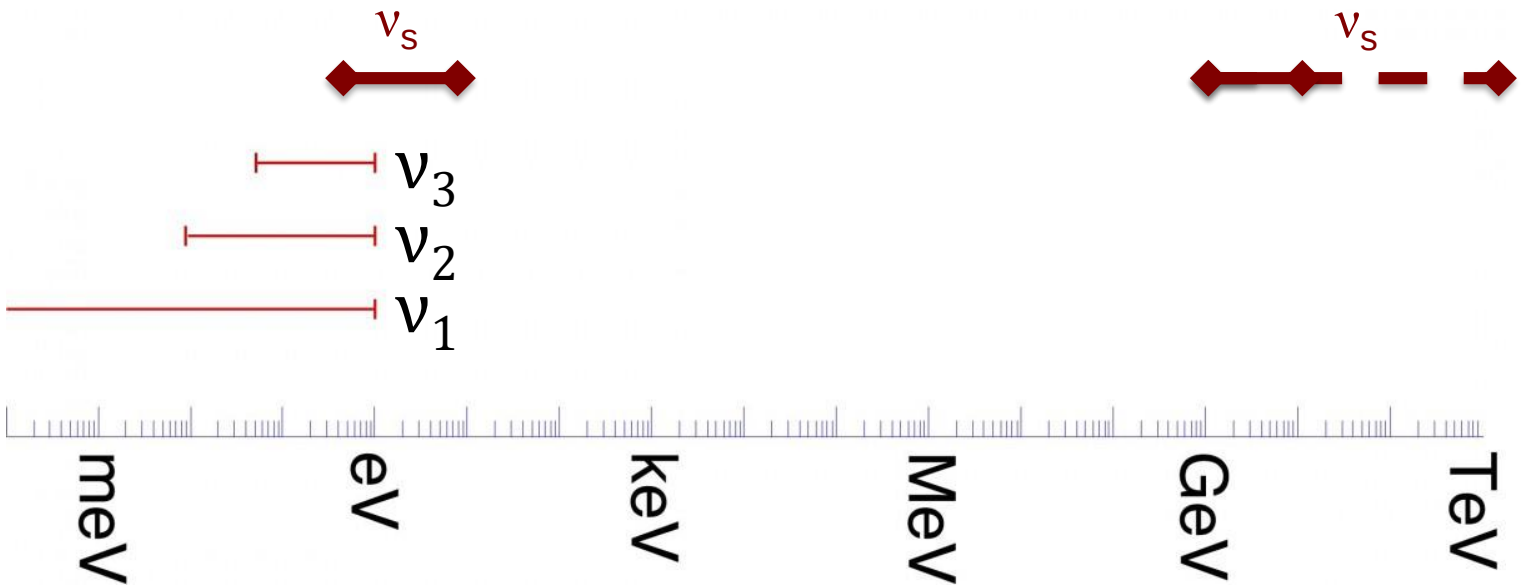
- Heavy sterile neutrinos (> GeV)
  - Matter-antimatter asymmetry through Leptogenesis, lightness of active neutrinos



Sterile neutrinos mass ranges

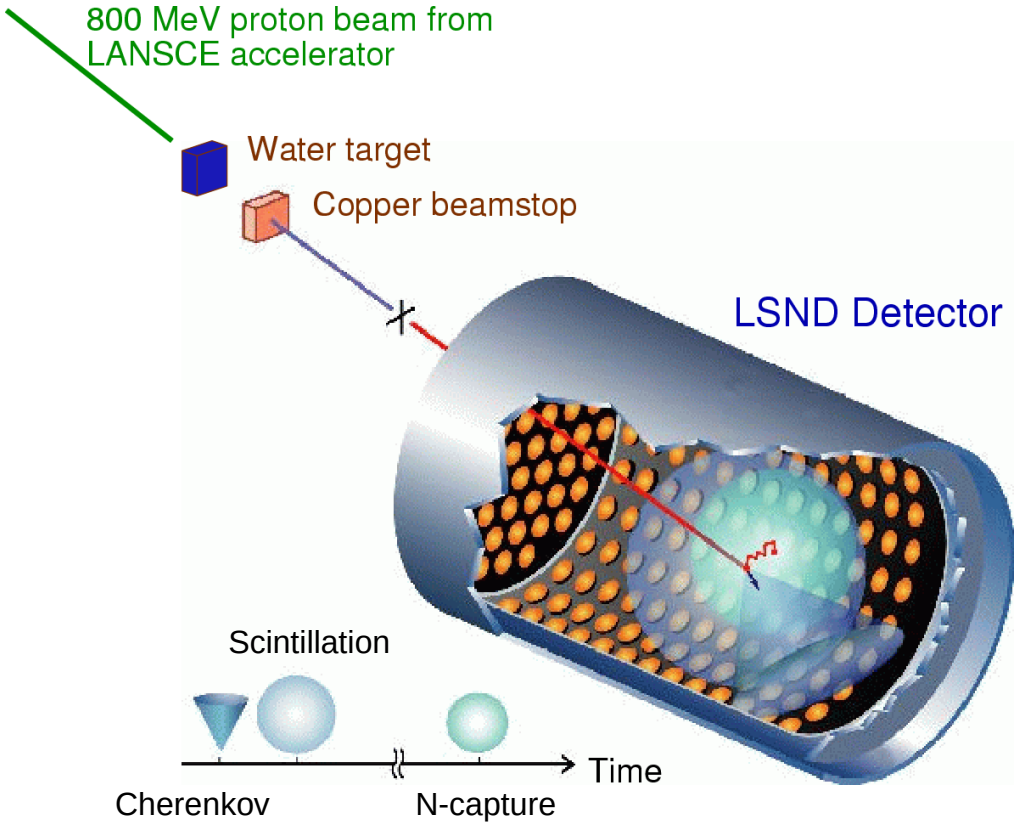
- Heavy sterile neutrinos (> GeV)
  - Matter-antimatter asymmetry through Leptogenesis, lightness of active neutrinos
- Light sterile neutrinos (~ 1 eV)
  - Not understood set of experimental data accumulated for 20 years



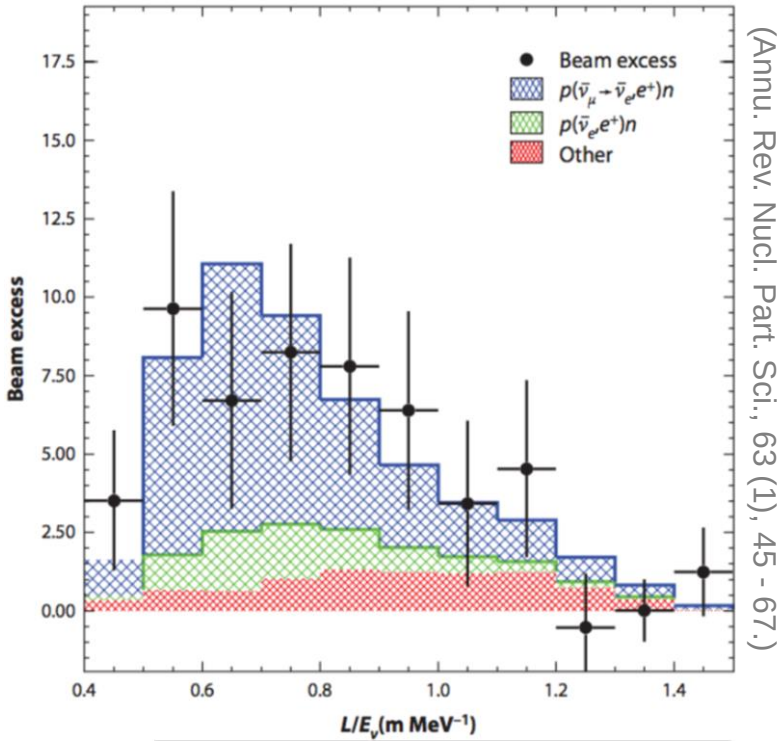


LSND anomaly

- Short baseline ν-beam experiment in Los-Alamos, New Mexico, 1993-1998
- Baseline = 30m, E = 20-50 MeV → L/E ≈ 1 m/MeV



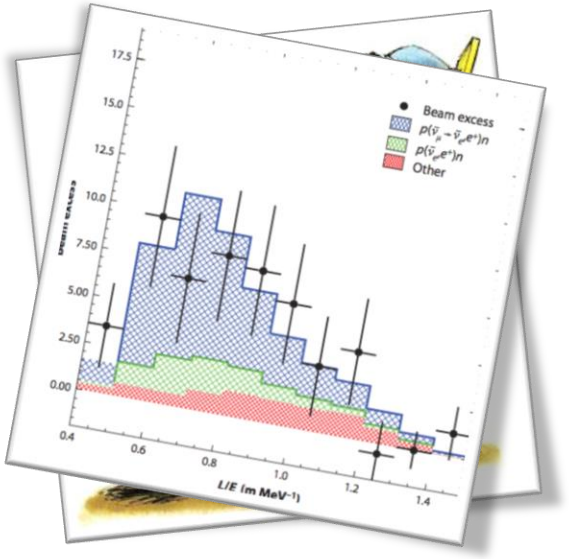
LSND observed a 3.8 σ excess in electron-antineutrinos

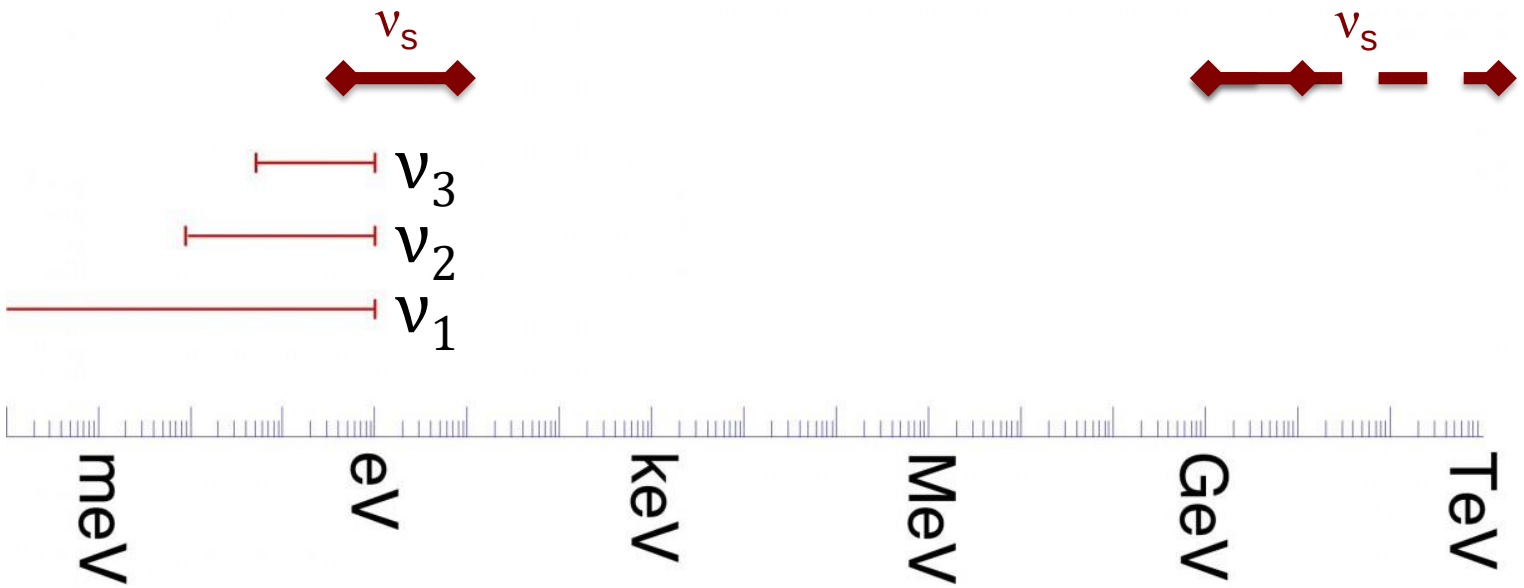


(Annu. Rev. Nucl. Part. Sci., 63 (1), 45 - 67.)

Sterile neutrinos mass ranges

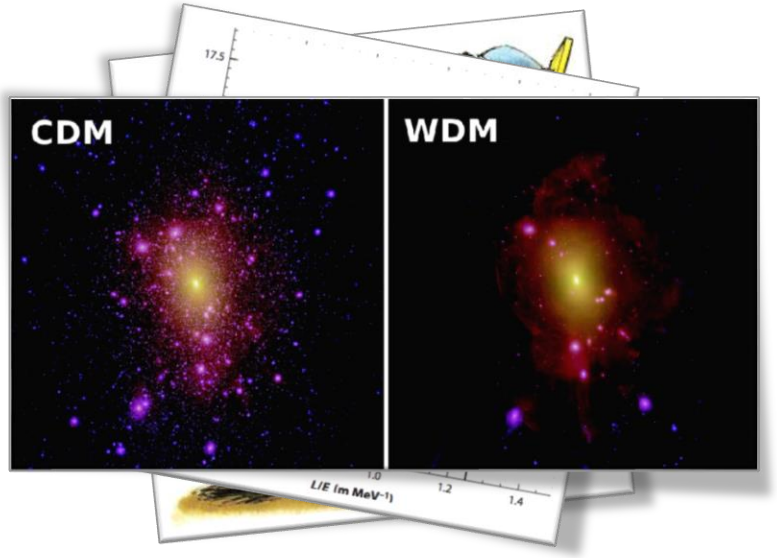
- Heavy sterile neutrinos (> GeV)
  - Matter-antimatter asymmetry through Leptogenesis, lightness of active neutrinos
- Light sterile neutrinos (~ 1 eV)
  - Not understood set of experimental data accumulated for 20 years

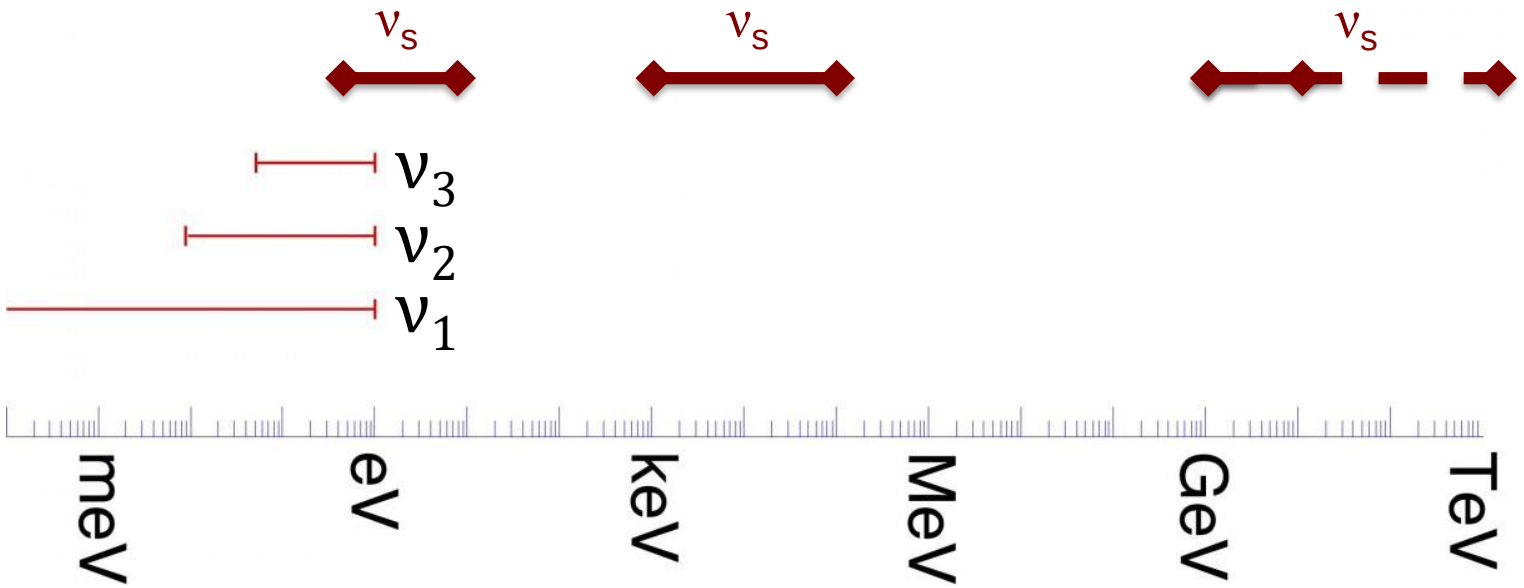




Sterile neutrinos mass ranges

- Heavy sterile neutrinos (> GeV)
  - Matter-antimatter asymmetry through Leptogenesis, lightness of active neutrinos
- Light sterile neutrinos (~ 1 eV)
  - Not understood set of experimental data accumulated for 20 years
- keV-scale sterile neutrinos (~ 1 - 50 keV)
  - Suitable dark matter candidate

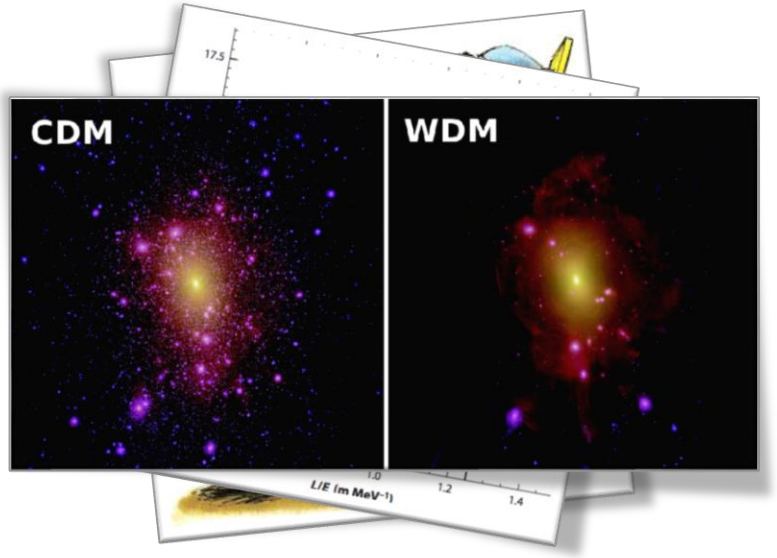


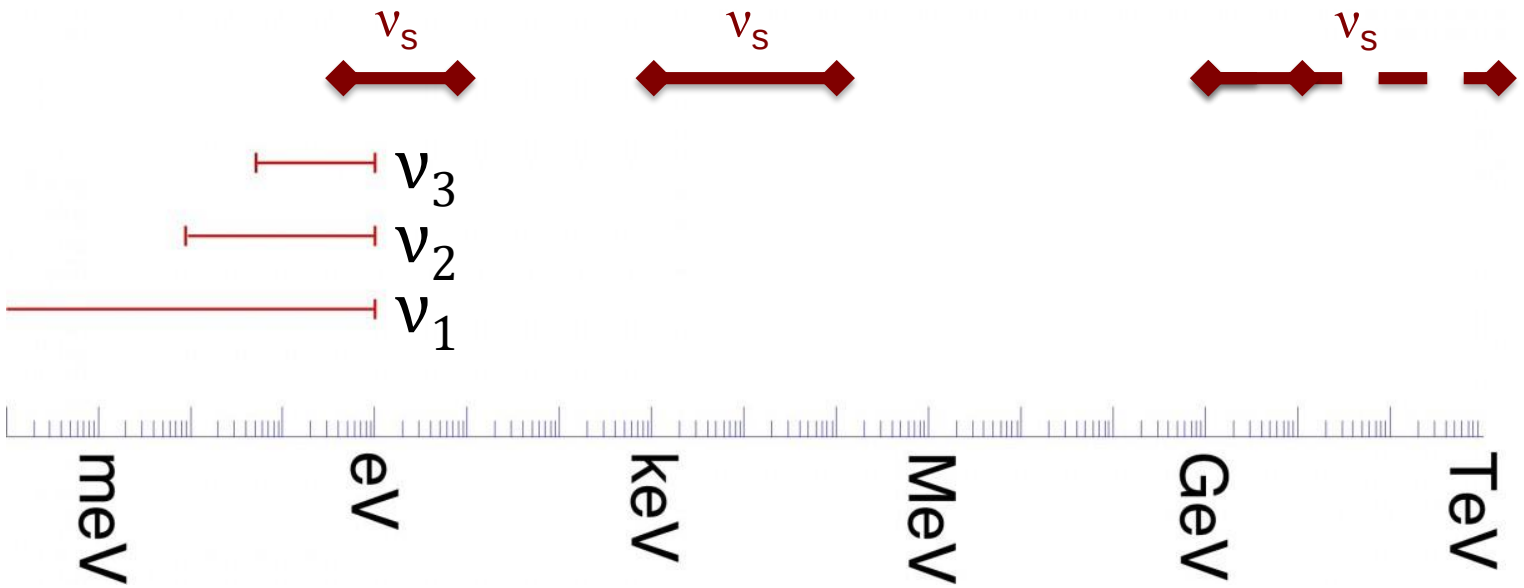


Sterile neutrinos mass ranges

- Heavy sterile neutrinos (> GeV)
  - Matter-antimatter asymmetry through Leptogenesis, lightness of active neutrinos
- Light sterile neutrinos (~ 1 eV)
  - Not understood set of experimental data accumulated for 20 years
- keV-scale sterile neutrinos (~ 1 - 50 keV)
  - Suitable dark matter candidate

Only one sterile neutrino can not solve all open questions at once

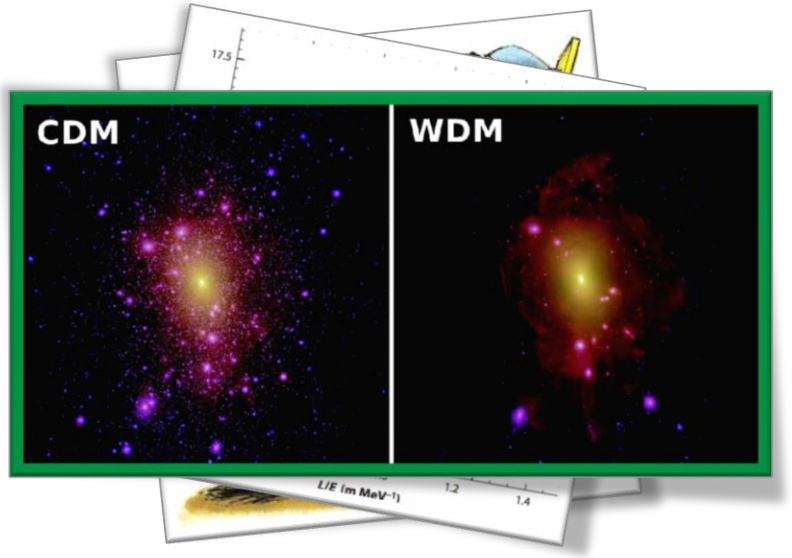


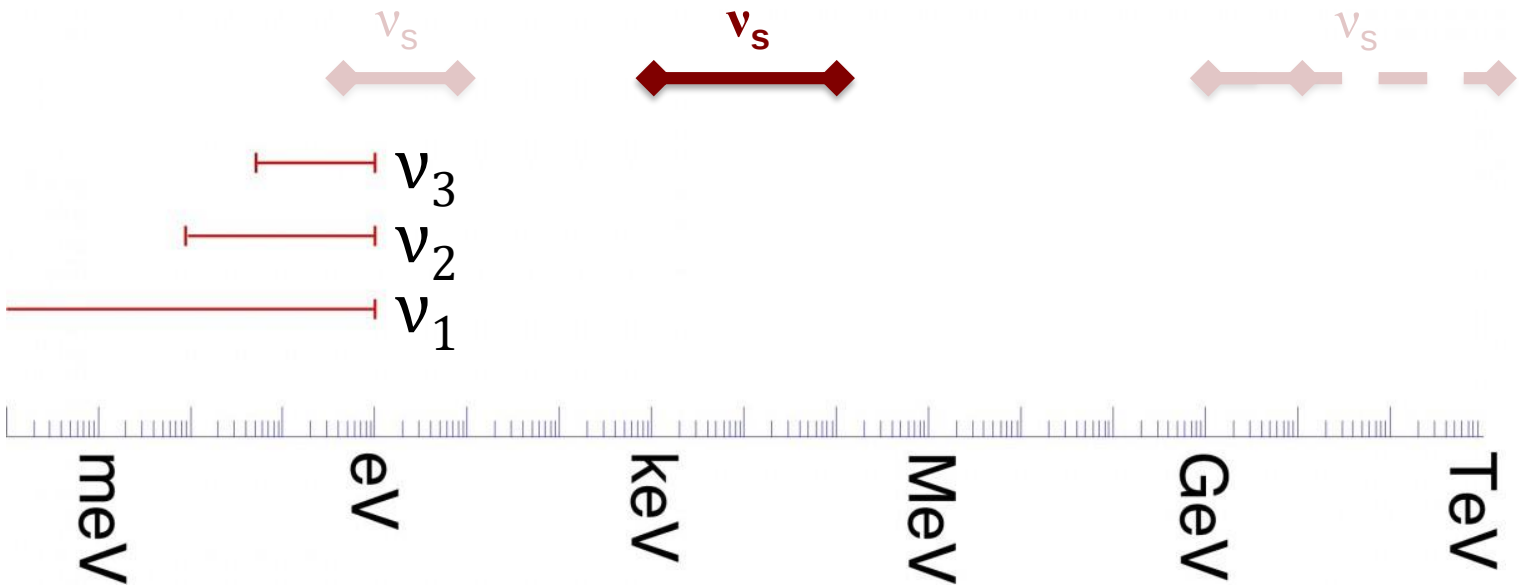


Sterile neutrinos mass ranges

- Heavy sterile neutrinos (> GeV)
  - Matter-antimatter asymmetry through Leptogenesis, lightness of active neutrinos
- Light sterile neutrinos (~ 1 eV)
  - Not understood set of experimental data accumulated for 20 years
- **keV-scale sterile neutrinos (~ 1 - 50 keV)**
  - **Suitable dark matter candidate**

Only one sterile neutrino can not solve all open questions at once





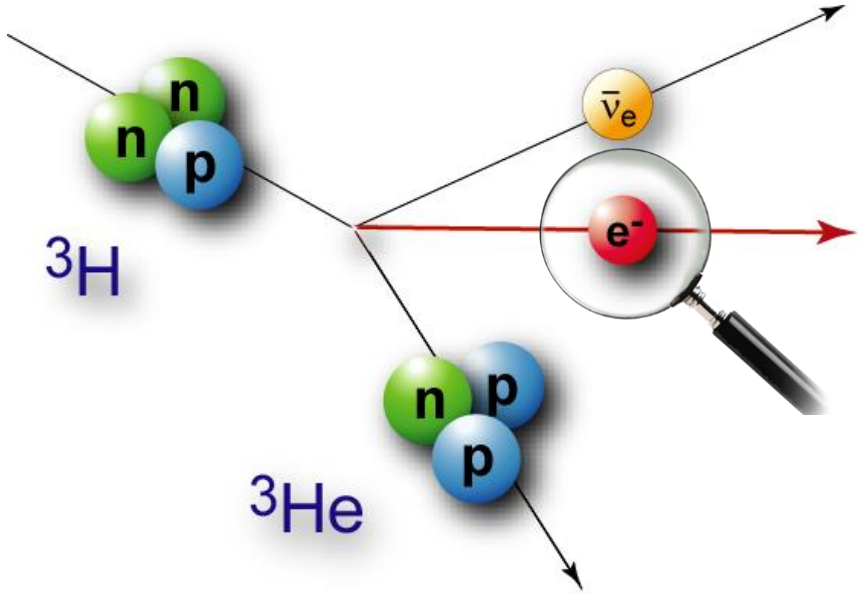
First: KATRIN

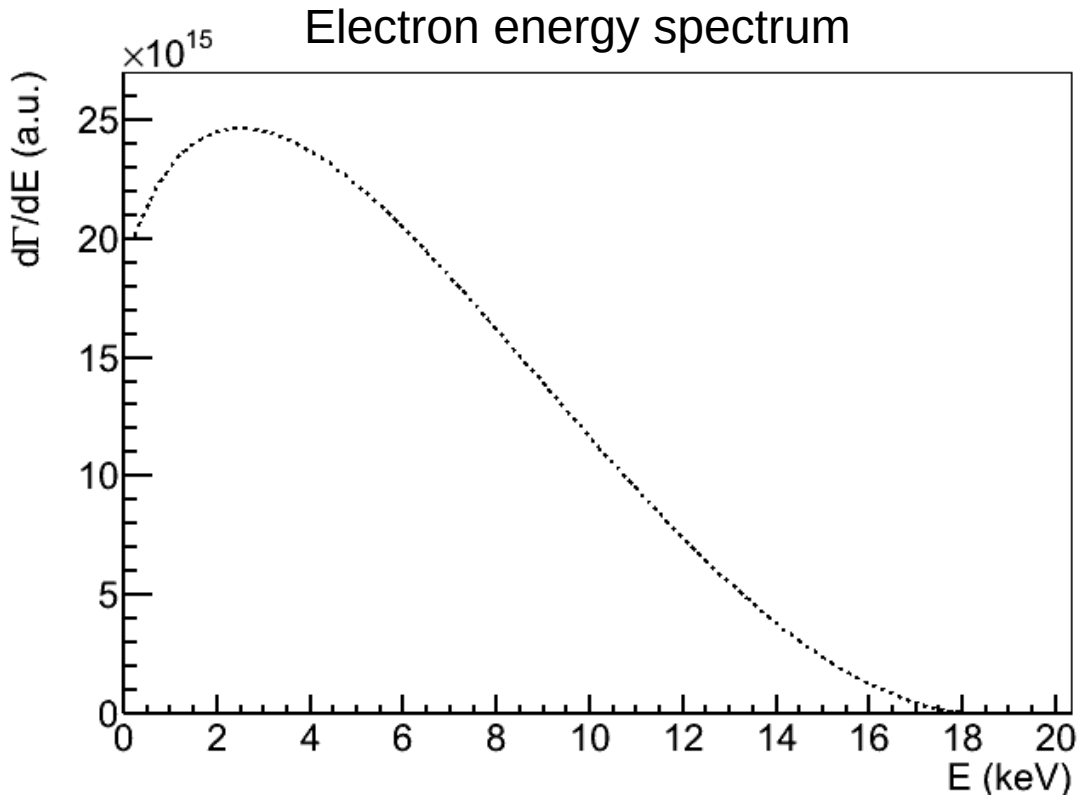
- **Ka**rlsruhe **Tri**tium **N**eutrino Experiment
- Inauguration: June 11th 2018
- KATRIN measures the neutrino mass
  - in a model-independent way
  - via ultrahigh precision measurements of the kinematics of electrons from beta-decay

INSTITUTE OF TECHNICAL PHYSICS, TRITIUM LABORATORY KARLSRUHE

Imprint of ν‘s on tritium ß-spectrum

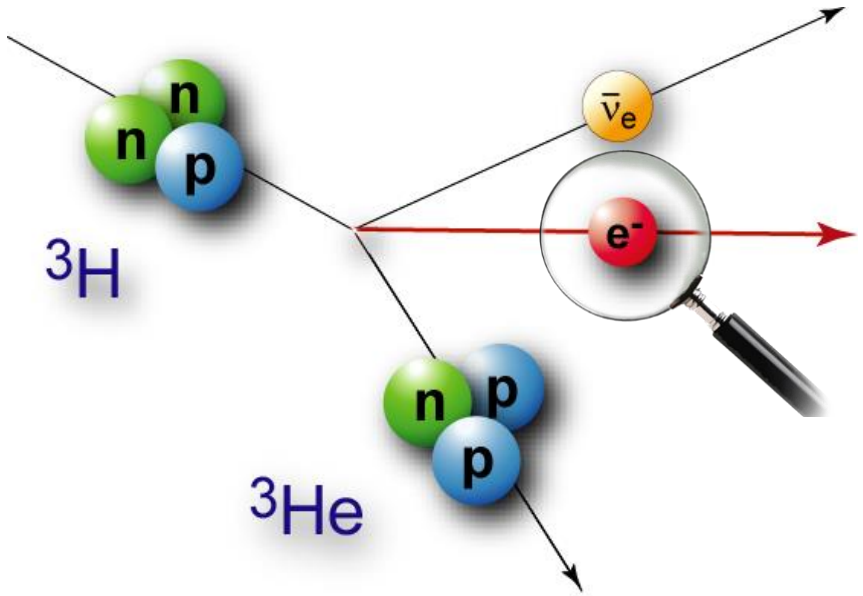
$$\frac{\mathrm{d}\Gamma}{\mathrm{d}E} \propto C\ F(Z,E)\ p(E+m_e)(E_0-E)\ \sqrt{(E_0-E)^2-m_\beta^2(\nu_e)}$$

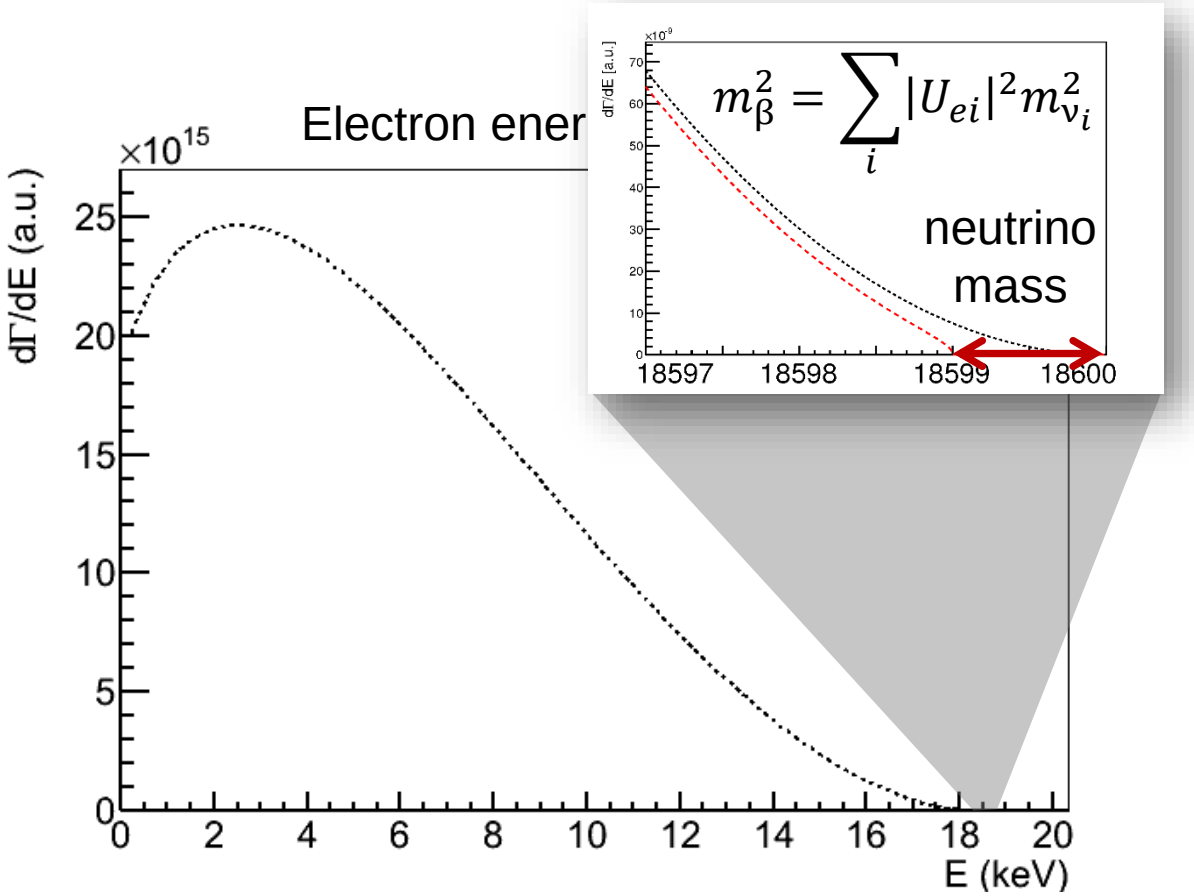




Imprint of ν‘s on tritium ß-spectrum

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}E} \propto C\ F(Z,E)\ p(E+m_e)(E_0-E)\ \sqrt{(E_0-E)^2 - m_\beta^2(\nu_e)}$$



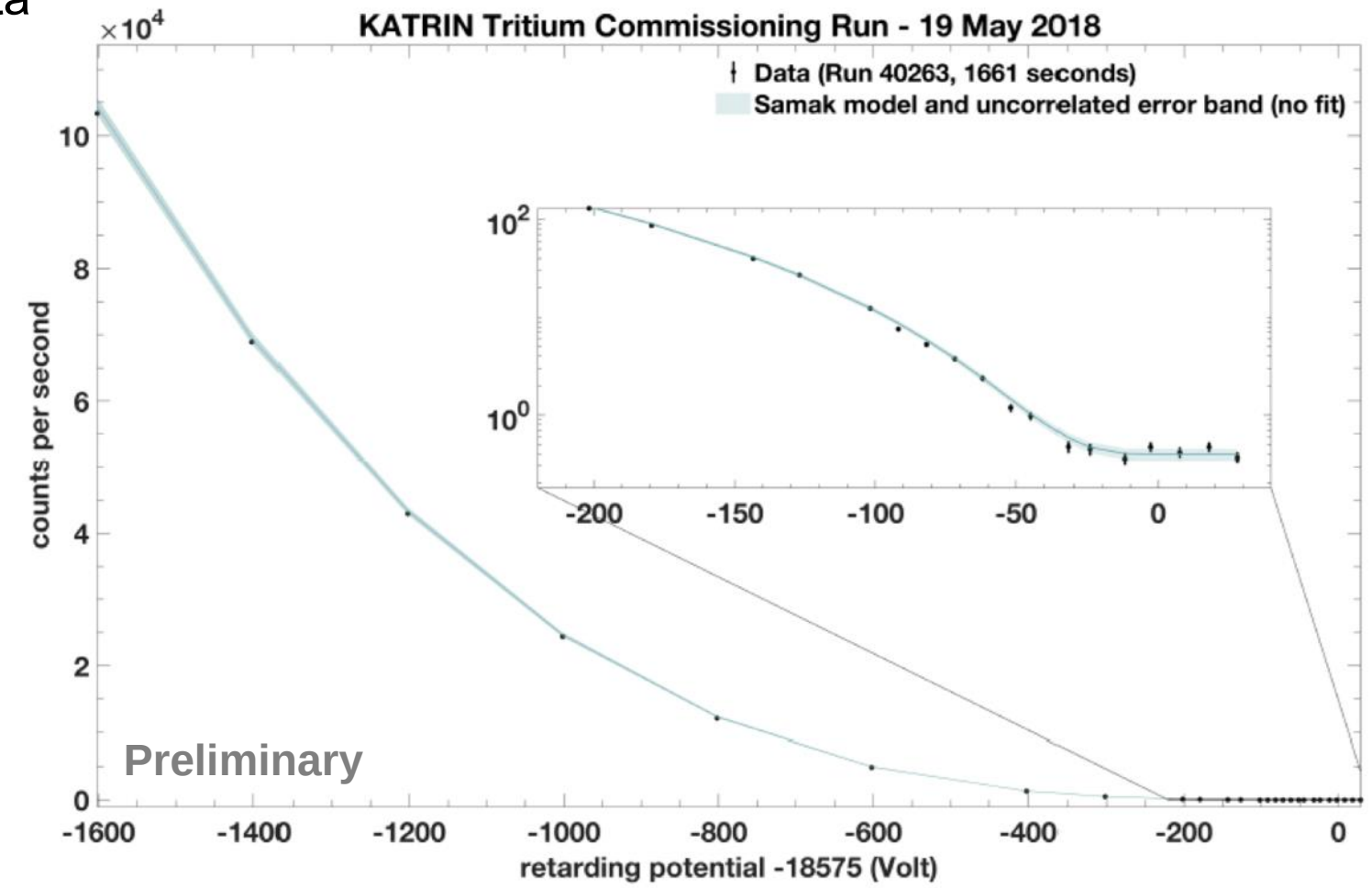


KATRIN‘s first results

- Model input parameters directly taken from experimental “slow control” data
- No further tuning

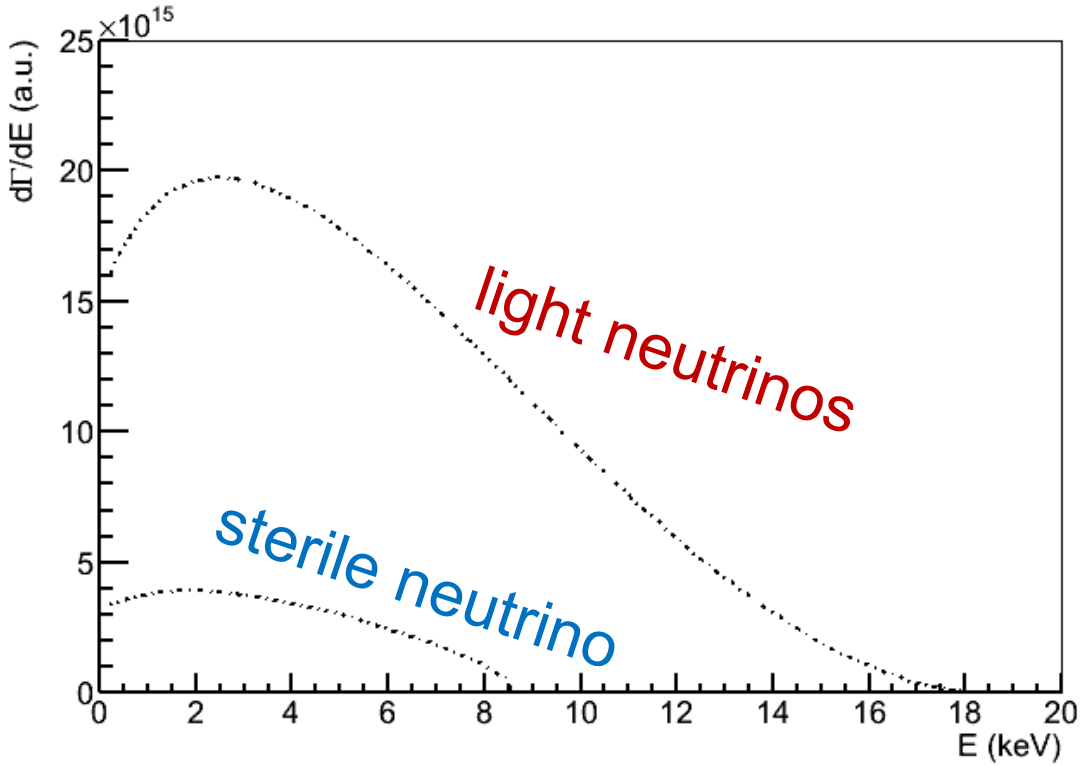
Very good agreement of model with data (shape and absolute rate)

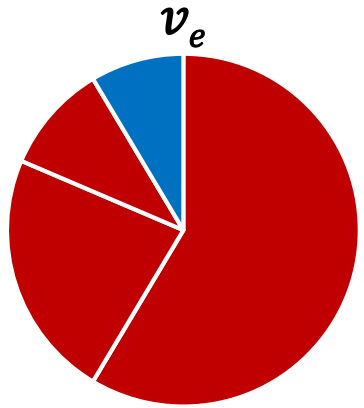
- No official m_ν-fit yet



Imprint of sterile ν‘s on ß-spectrum

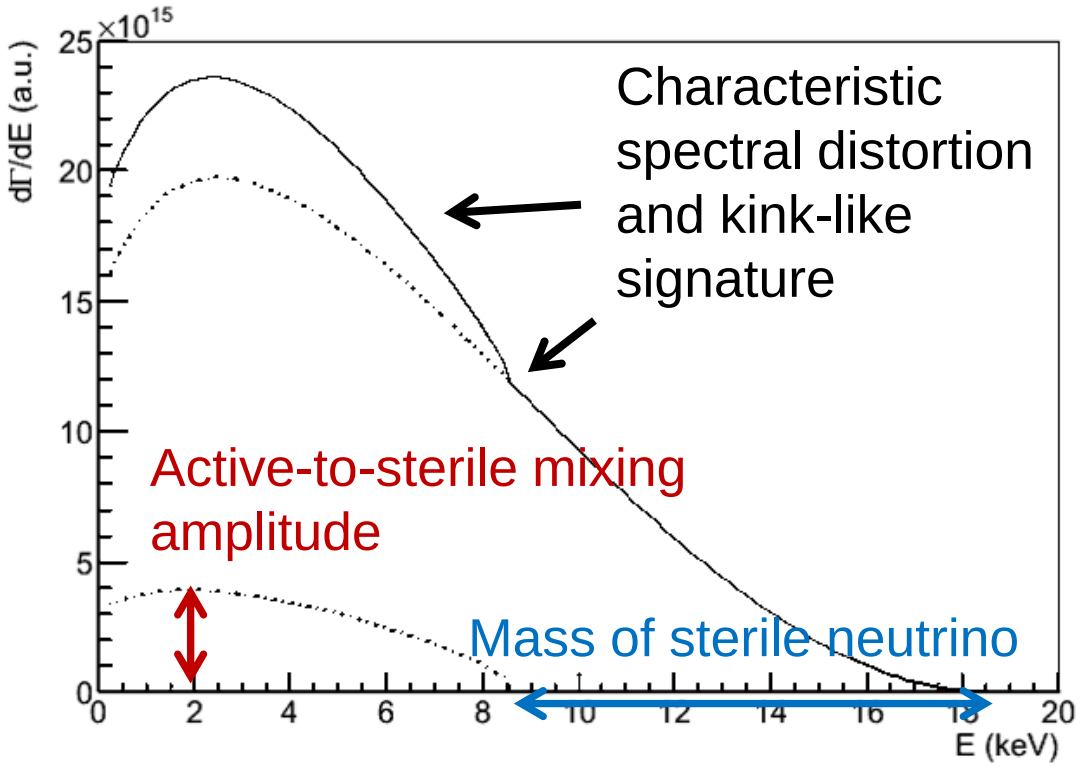
$$\frac{d\Gamma}{dE} = \cos^2(\theta)\frac{d\Gamma}{dE}(m_\beta) + \sin^2(\theta)\frac{d\Gamma}{dE}(m_s)$$

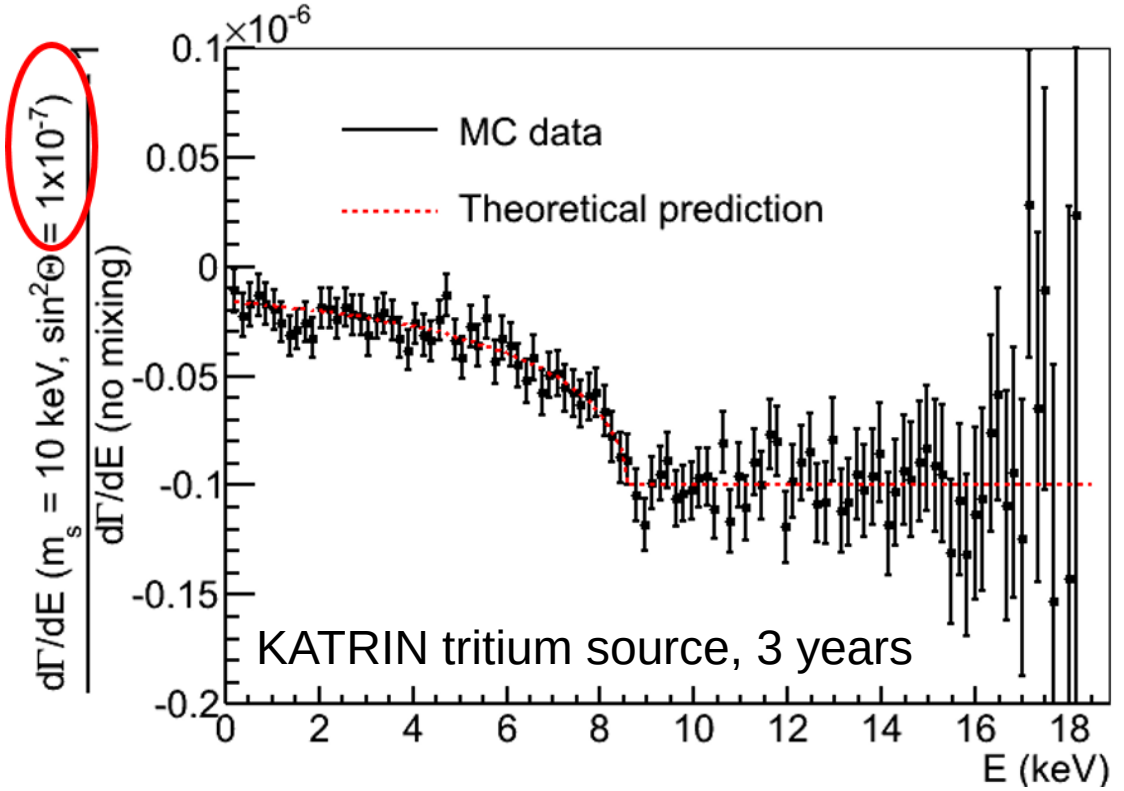




Imprint of sterile ν‘s on ß-spectrum

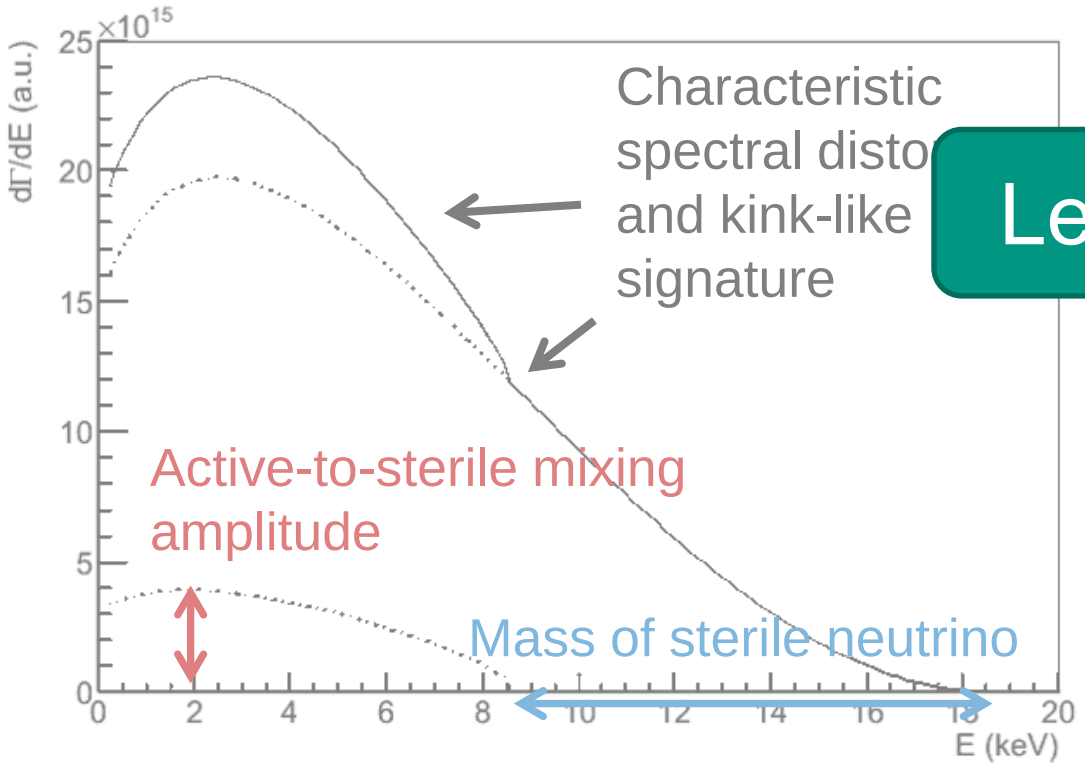
$$\frac{d\Gamma}{dE} = \cos^2(\theta)\frac{d\Gamma}{dE}(m_\beta) + \sin^2(\theta)\frac{d\Gamma}{dE}(m_s)$$



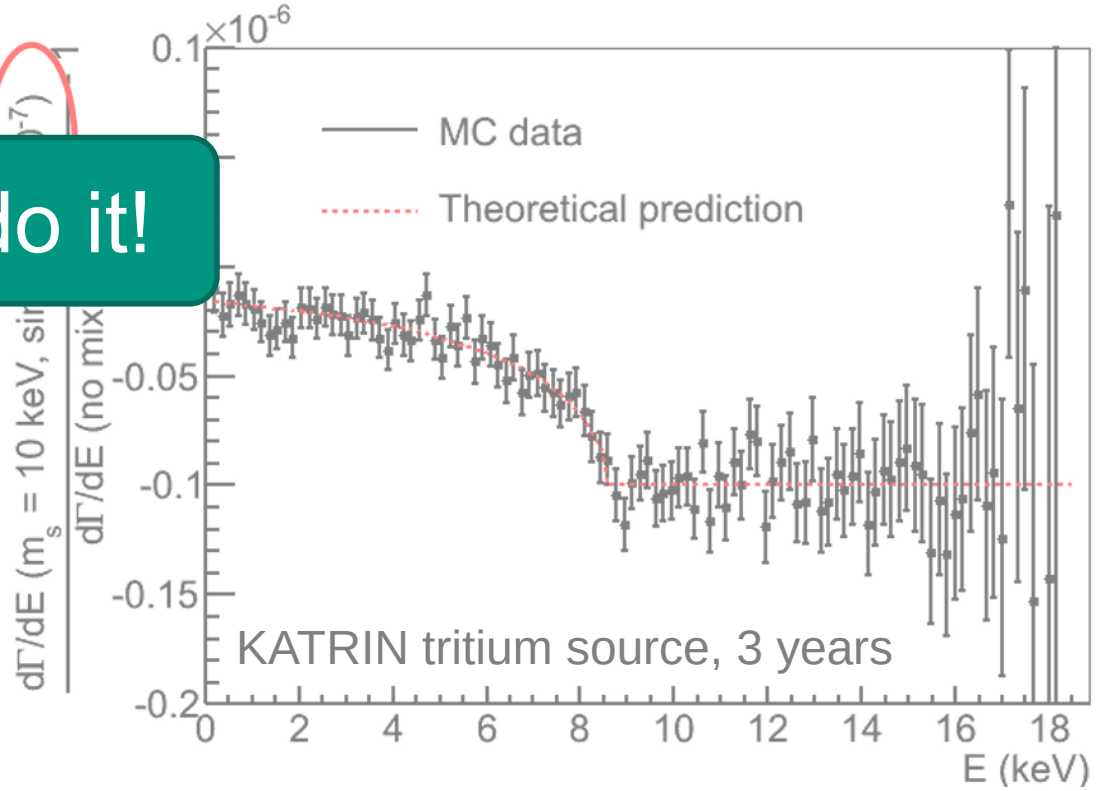


Imprint of sterile ν‘s on ß-spectrum

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

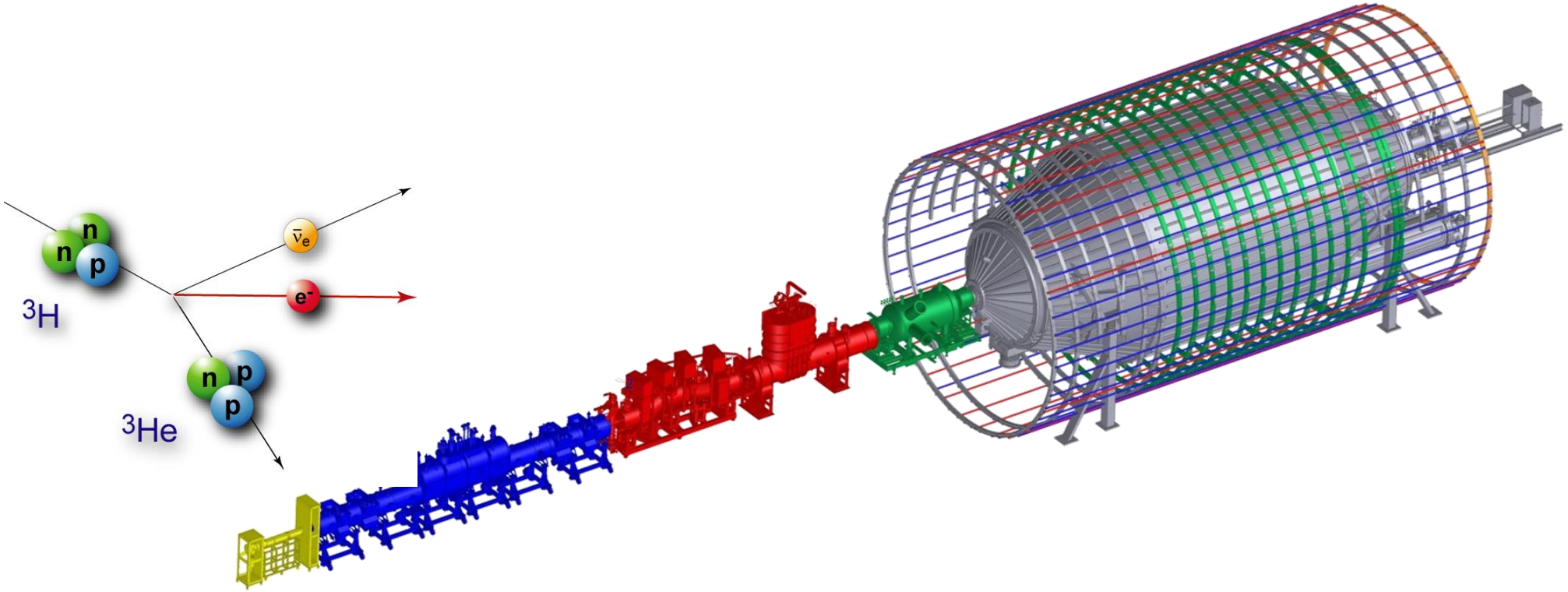


Let‘s do it!



The challenge for TRISTAN

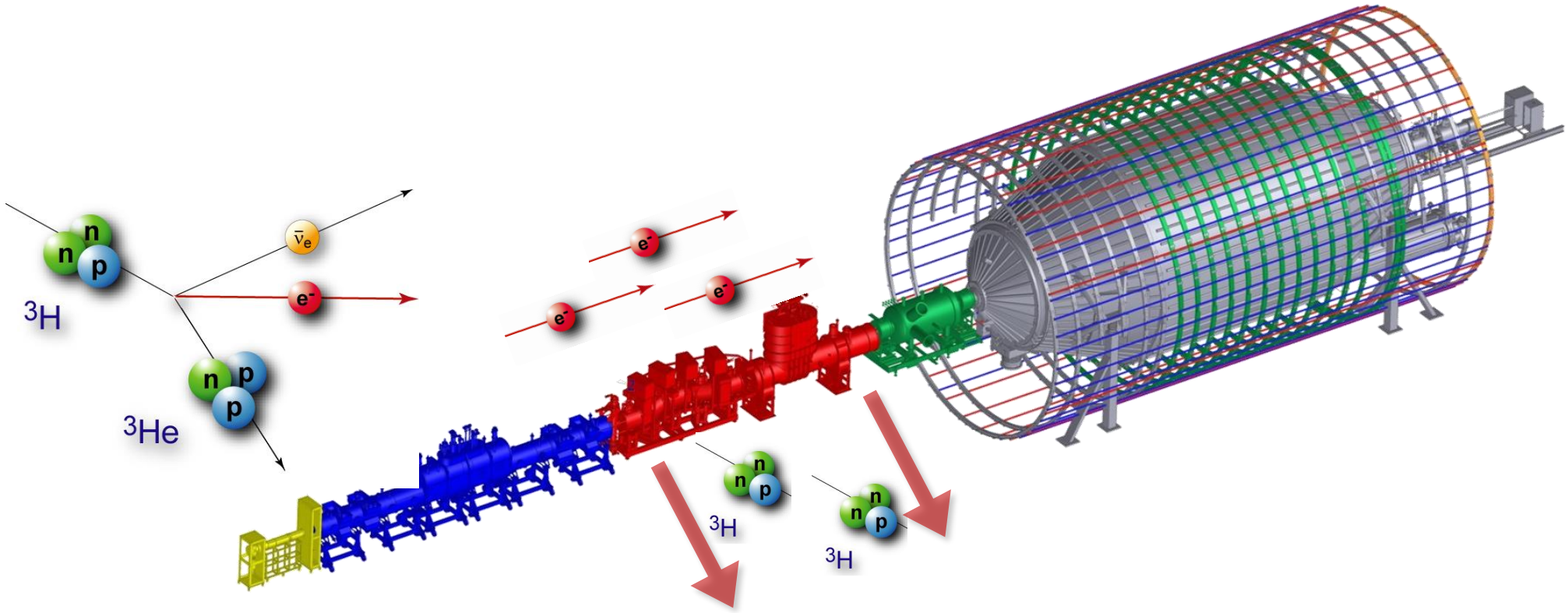
Windowless Gaseous Tritium Source



The challenge for TRISTAN

Windowless Gaseous Tritium Source

Transport and Pumping Section



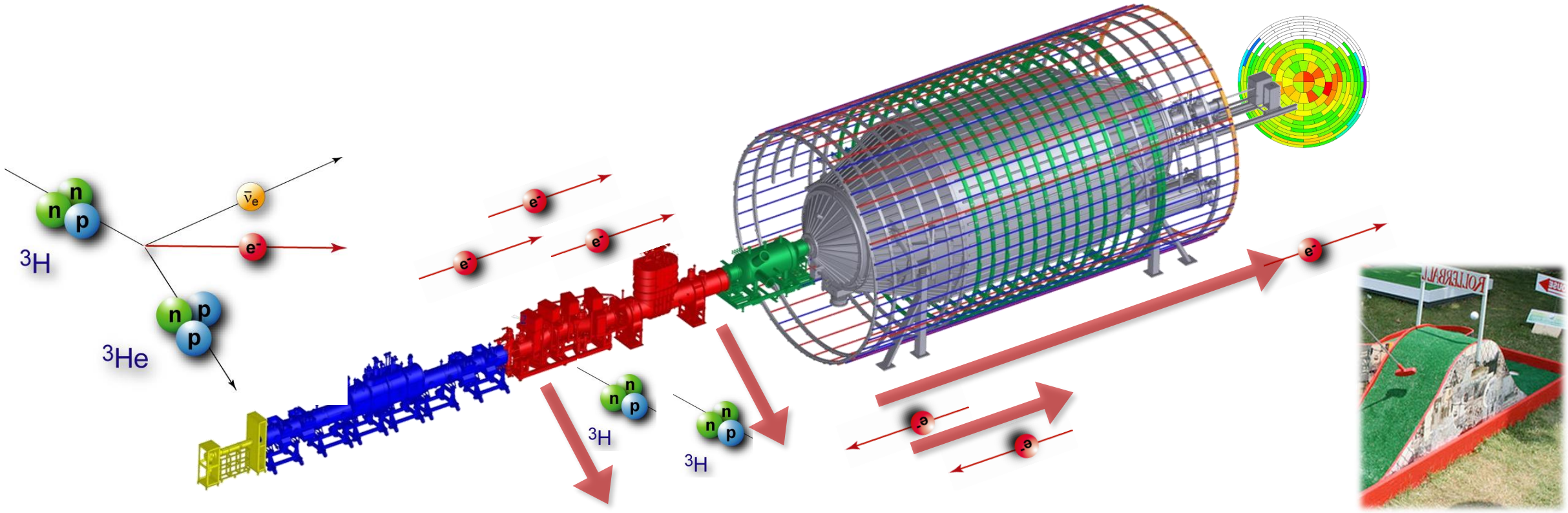
The challenge for TRISTAN

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

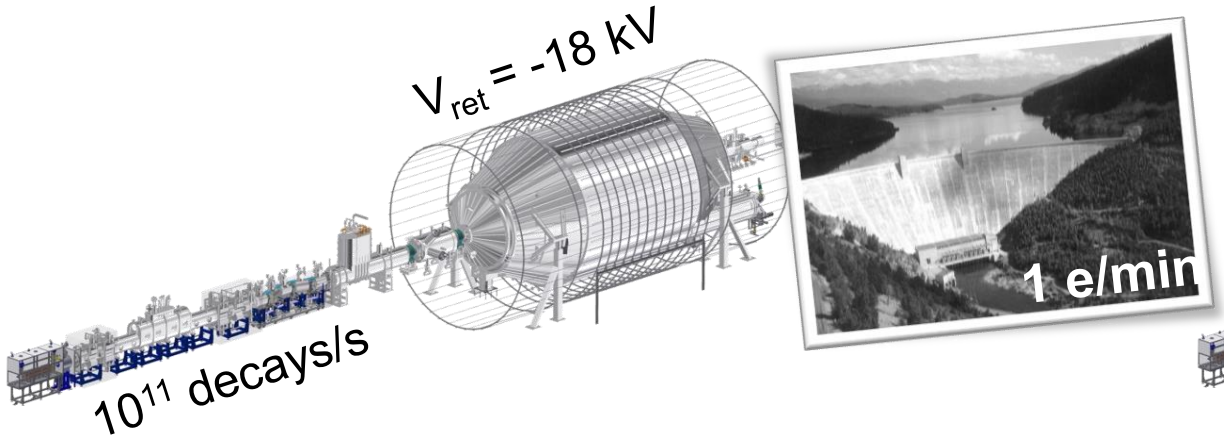
Windowless Gaseous Tritium Source

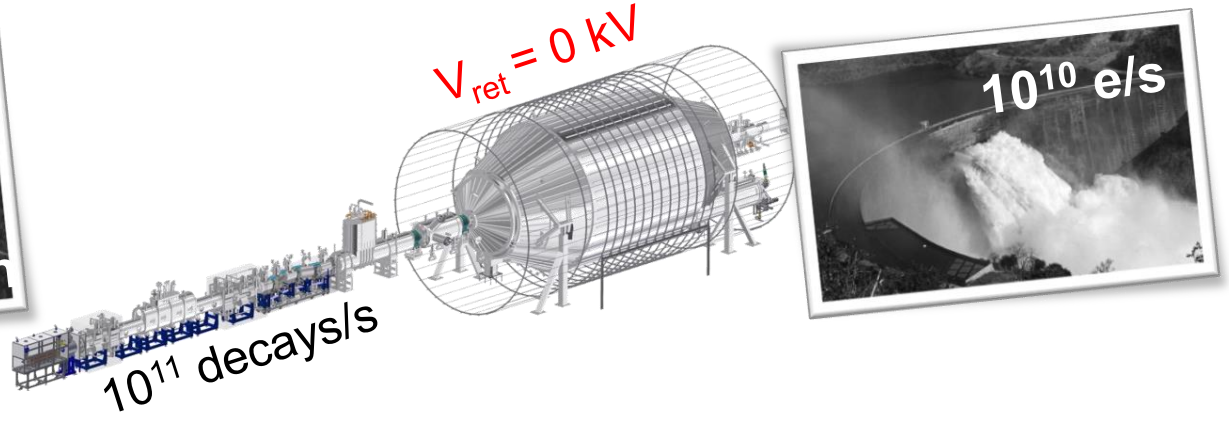
Transport and Pumping Section

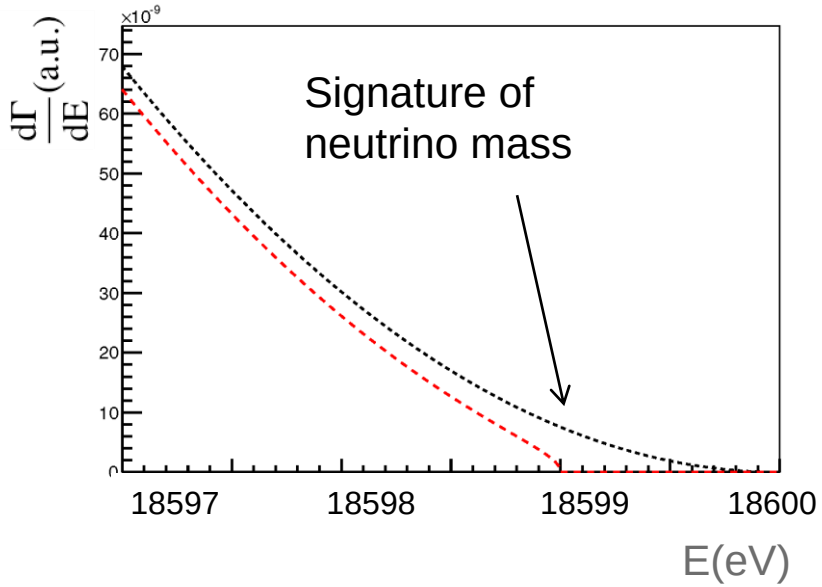
Spectrometer and Detector Section

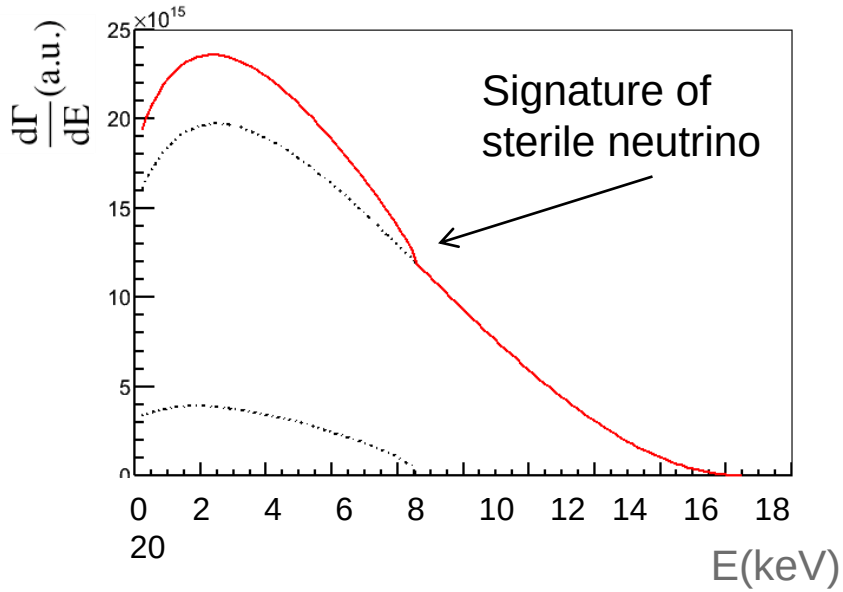


The challenge for TRISTAN



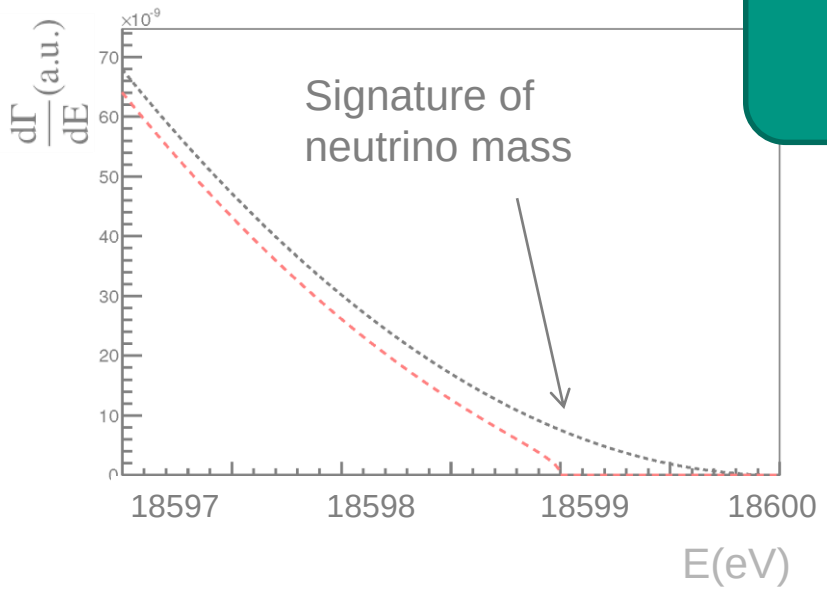


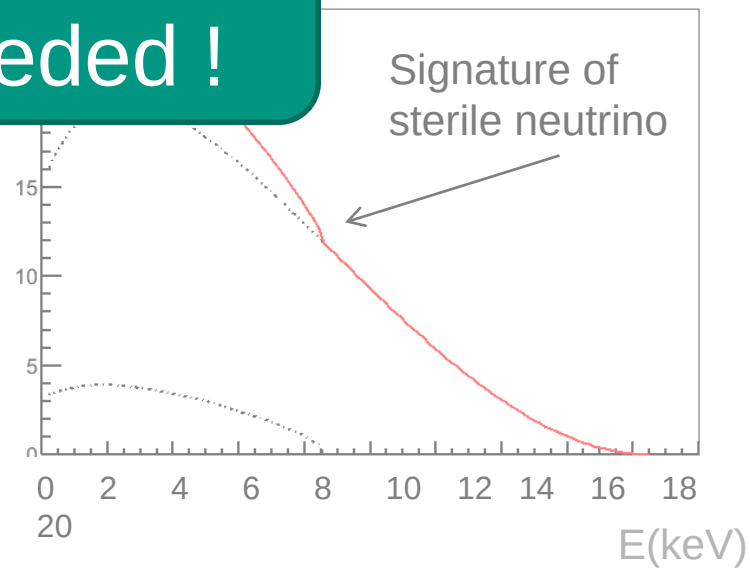




The challenge for TRISTAN

New detector system needed !

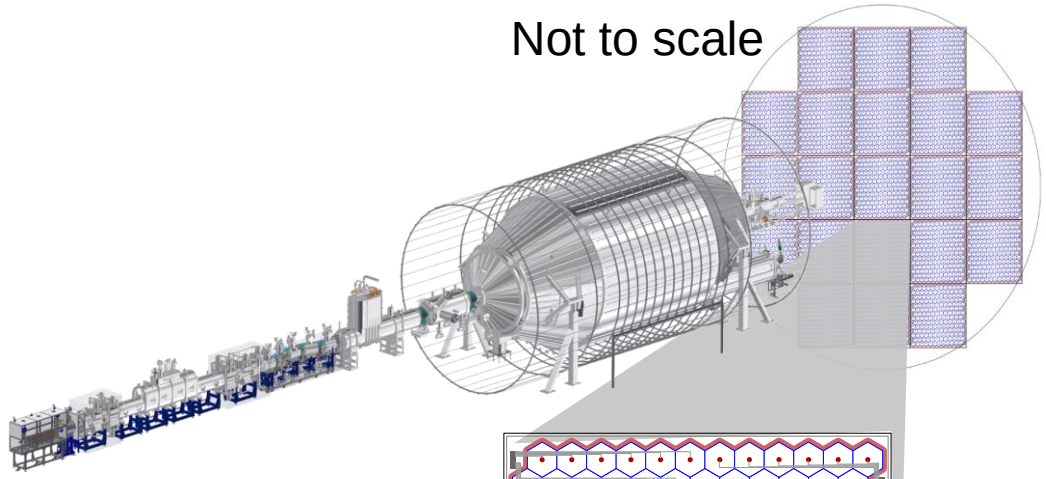


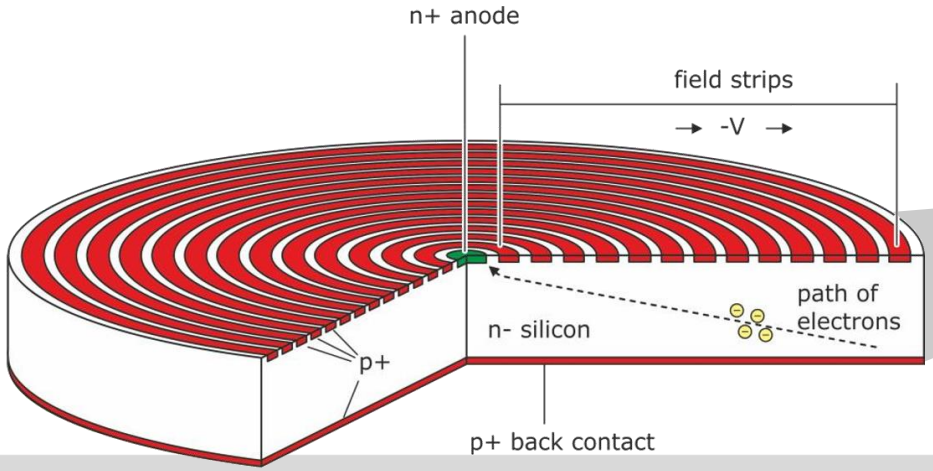


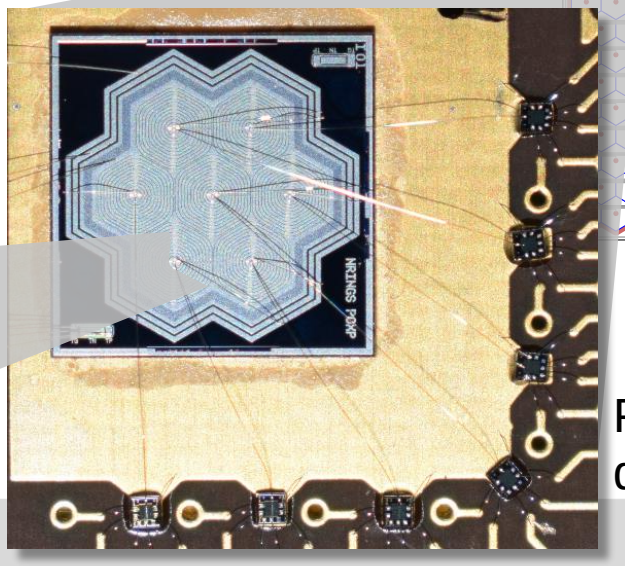
Detector requirements

- Handling of high rates (>10^9 Hz)
  - ➢ ~ 3500 pixels
- Good energy resolution (300 eV @ 20 keV), low threshold (1 keV)
  - ➢ Thin dead layer (< 100 nm)
- Large area coverage (20 cm diameter), small capacitance (low noise)
  - ➢ Silicon drift detector (SDD) design

Not to scale

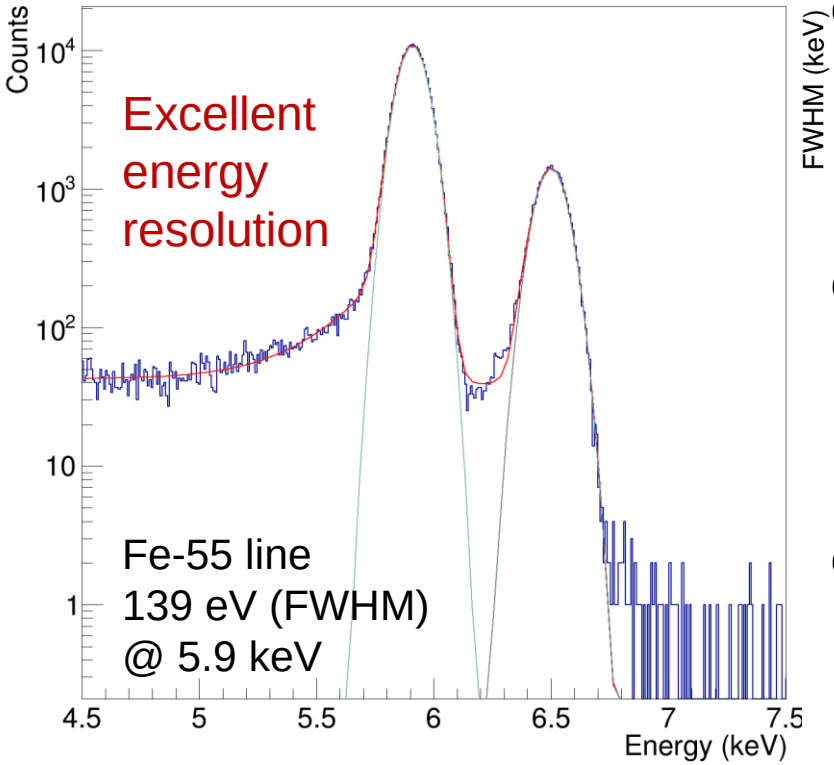


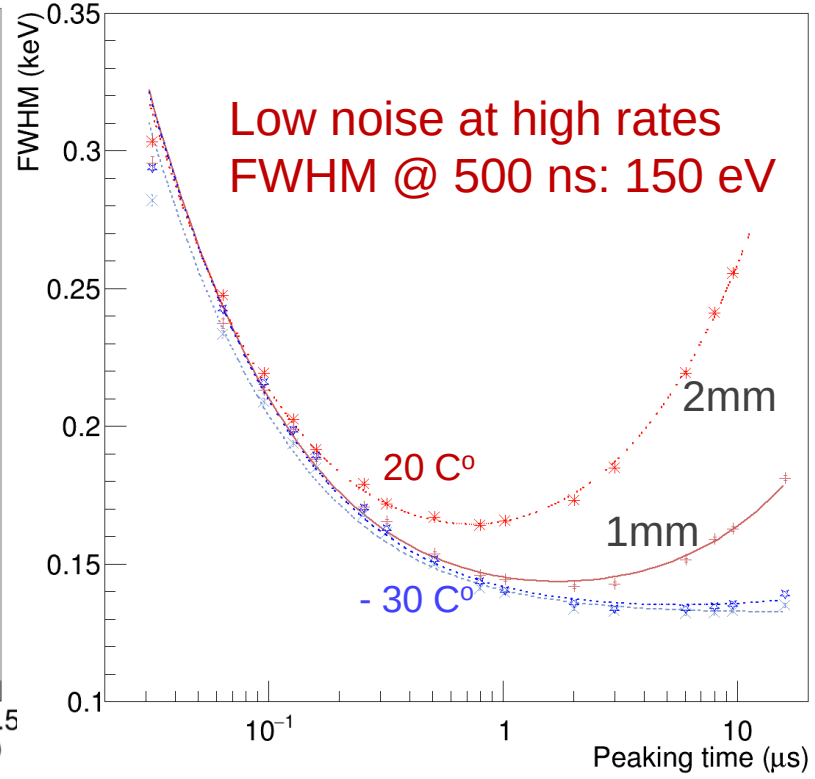


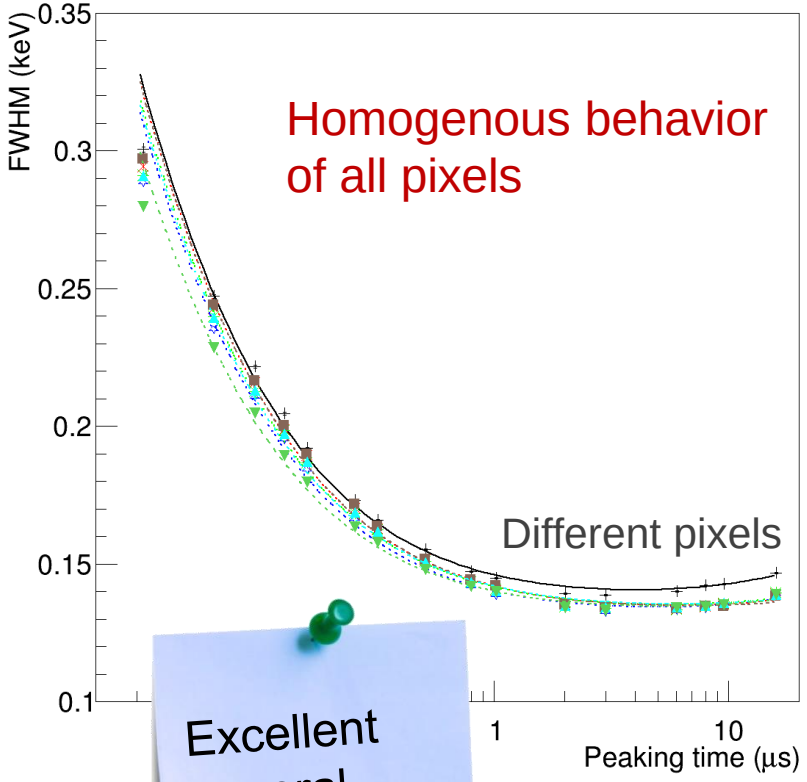


Prototype detector

General performance on x-rays



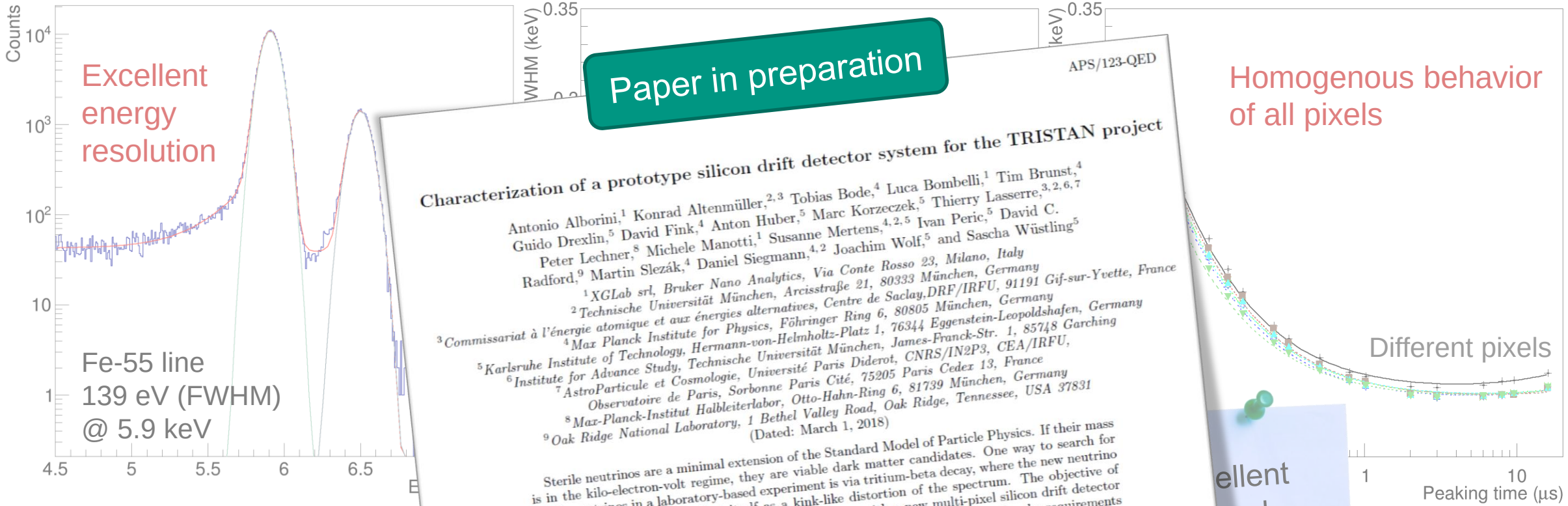




Excellent general performance

General performance on x-rays

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)



Paper in preparation

APS/123-QED

Characterization of a prototype silicon drift detector system for the TRISTAN project

Antonio Alborini,[1] Konrad Altenmüller,[2,3] Tobias Bode,[4] Luca Bombelli,[1] Tim Brunst,[4] Guido Drexlin,[5] David Fink,[4] Anton Huber,[5] Marc Korzeczek,[5] Thierry Lasserre,[3,2,6,7] Peter Lechner,[8] Michele Manotti,[1] Susanne Mertens,[4,2,5] Ivan Peric,[5] David C. Radford,[9] Martin Slezák,[4] Daniel Siegmann,[4,2] Joachim Wolf,[5] and Sascha Wüstling[5]

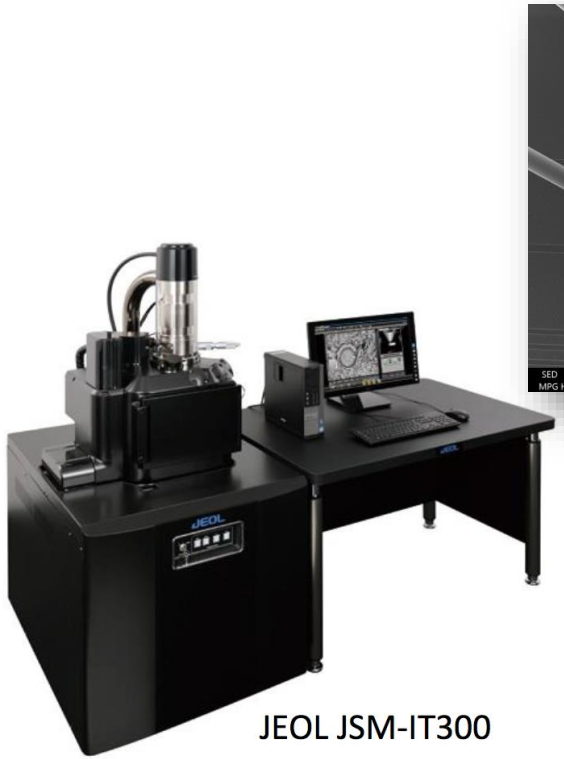
[1] *XGLab srl, Bruker Nano Analytics, Via Conte Rosso 23, Milano, Italy*
[2] *Technische Universität München, Arcisstraße 21, 80333 München, Germany*
[3] *Commissariat à l'énergie atomique et aux énergies alternatives, Centre de Saclay,DRF/IRFU, 91191 Gif-sur-Yvette, France*
[4] *Max Planck Institute for Physics, Föhringer Ring 6, 80805 München, Germany*
[5] *Karlsruhe Institute of Technology, Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany*
[6] *Institute for Advance Study, Technische Universität München, James-Franck-Str. 1, 85748 Garching*
[7] *AstroParticule et Cosmologie, Université Paris Diderot, CNRS/IN2P3, CEA/IRFU, Observatoire de Paris, Sorbonne Paris Cité, 75205 Paris Cedex 13, France*
[8] *Max-Planck-Institut Halbleiterlabor, Otto-Hahn-Ring 6, 81739 München, Germany*
[9] *Oak Ridge National Laboratory, 1 Bethel Valley Road, Oak Ridge, Tennessee, USA 37831*

(Dated: March 1, 2018)

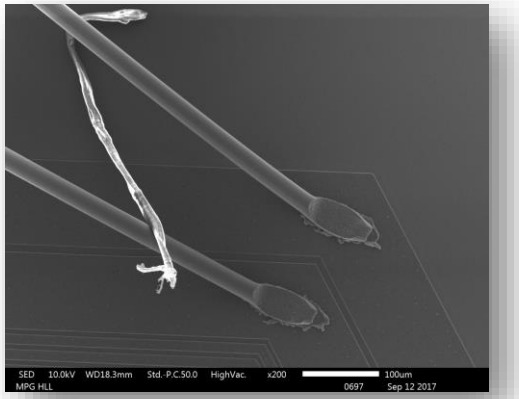
Sterile neutrinos are a minimal extension of the Standard Model of Particle Physics. If their mass is in the kilo-electron-volt regime, they are viable dark matter candidates. One way to search for sterile neutrinos in a laboratory-based experiment is via tritium-beta decay, where the new neutrino mass eigenstate would manifest itself as a kink-like distortion of the spectrum. The objective of the TRISTAN project is to extend the KATRIN setup with a new multi-pixel silicon drift detector system to search for a keV-scale sterile neutrino signal. In this paper we describe the requirements of such a new detector, and present first measurement results obtained with a 7-pixel prototype system.

Characterization with electrons

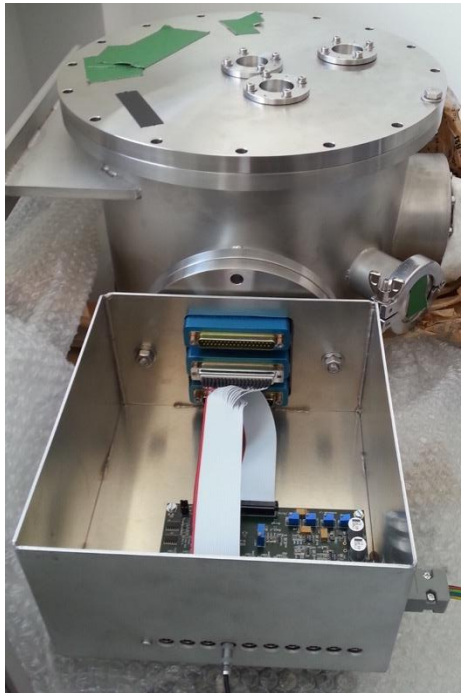
- Electron microscope



JEOL JSM-IT300



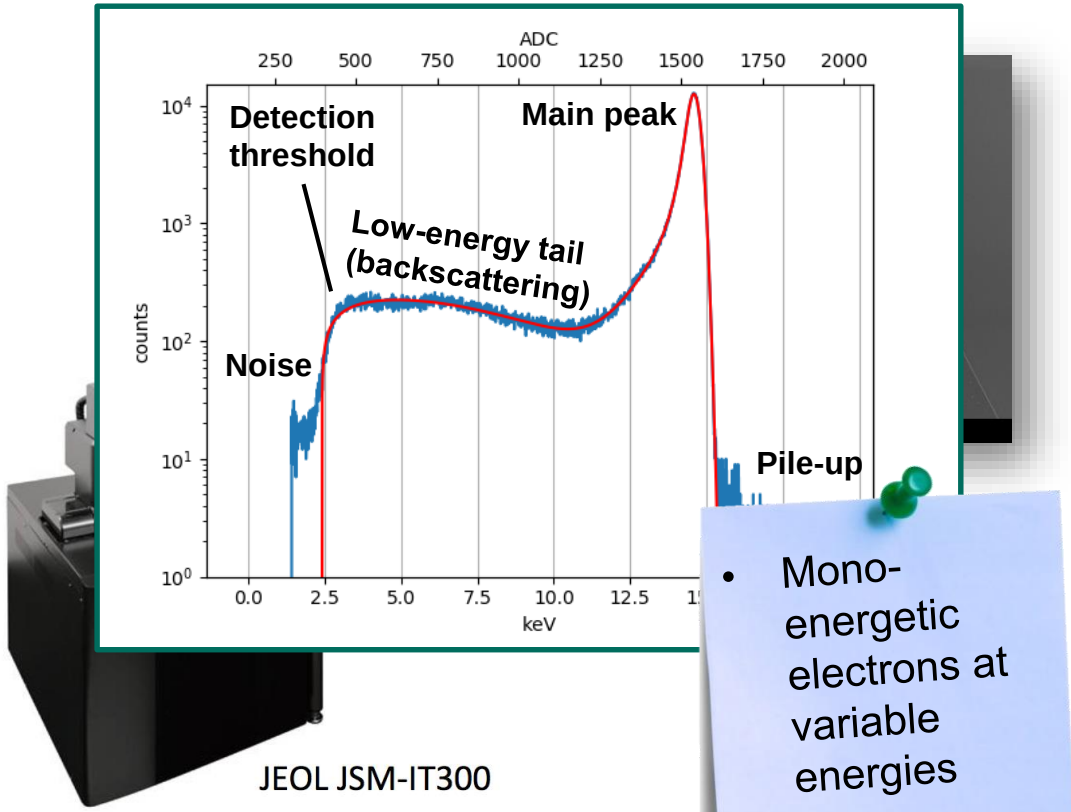
- Evaporated Krypton source



Characterization with electrons

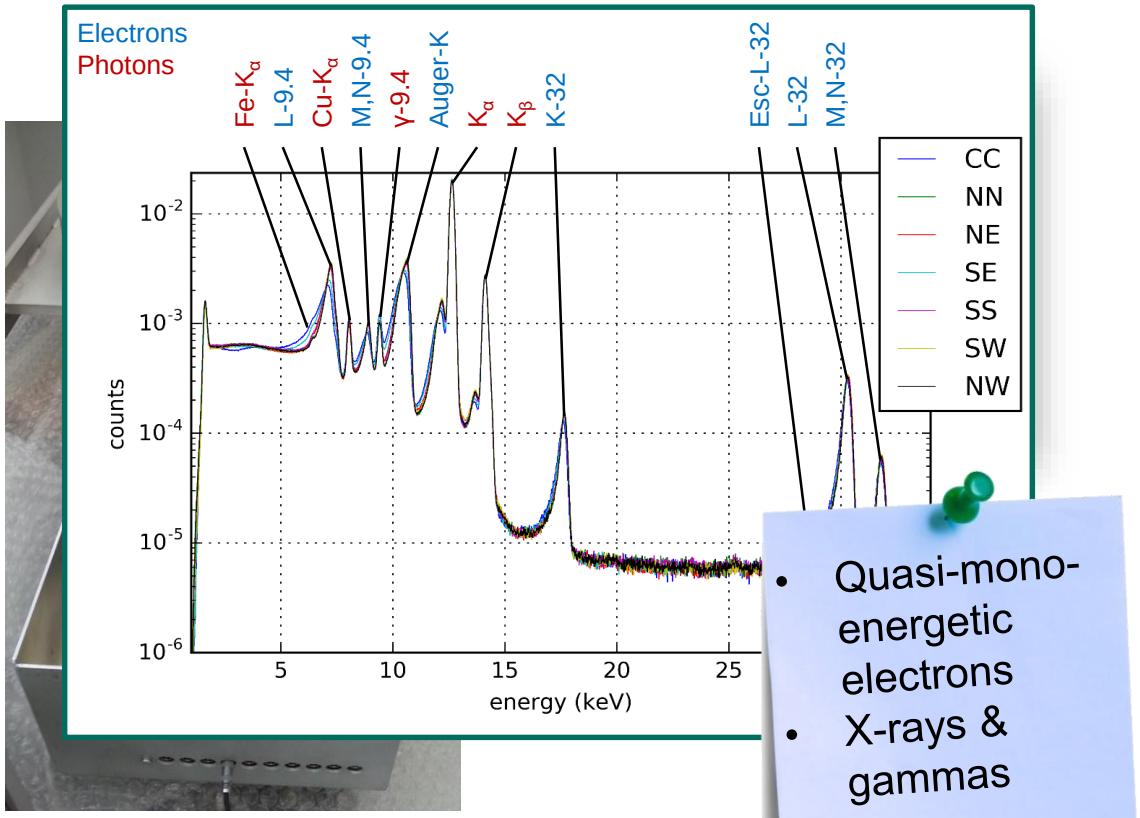
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

- Electron microscope



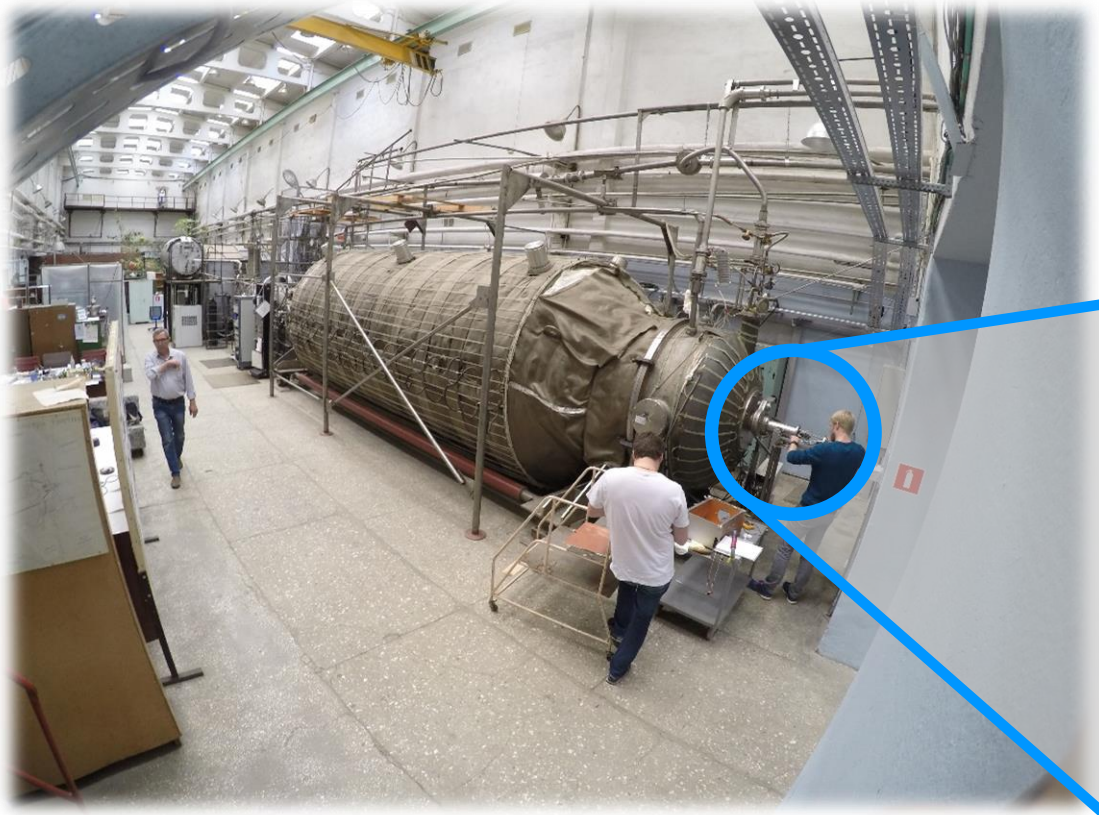
- Mono-energetic electrons at variable energies

- Evaporated Krypton source



- Quasi-mono-energetic electrons
- X-rays & gammas

TRISTAN in Troitsk

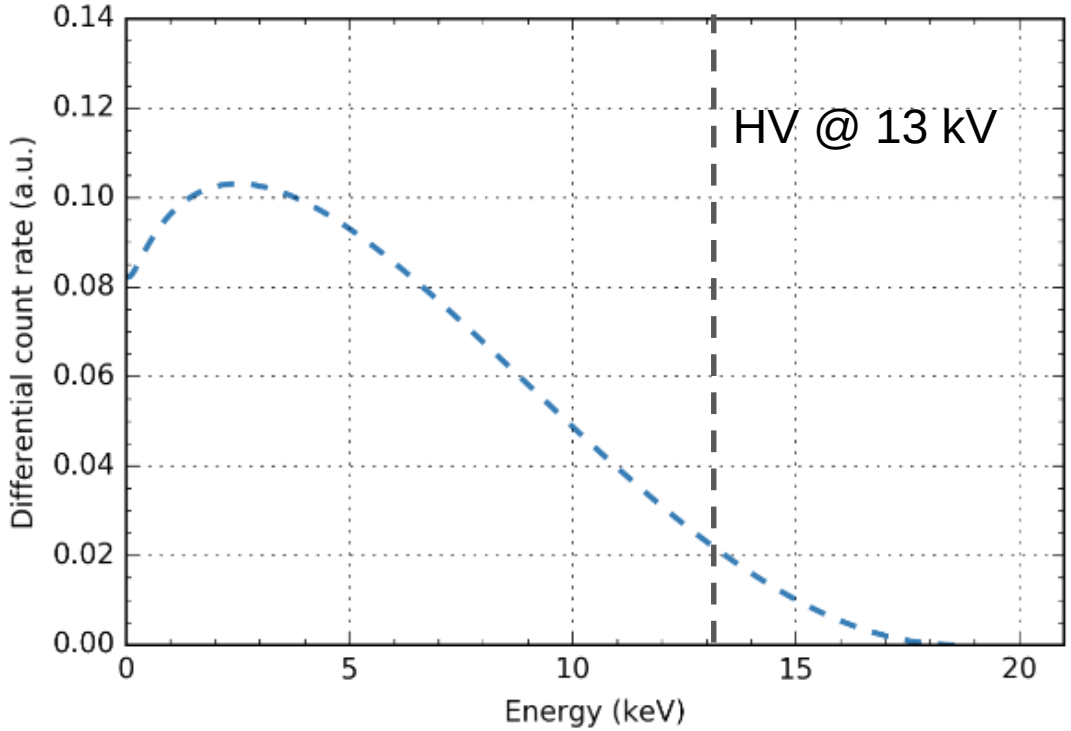


Application of the TRISTAN detector
at Troitsk nu-mass experiment

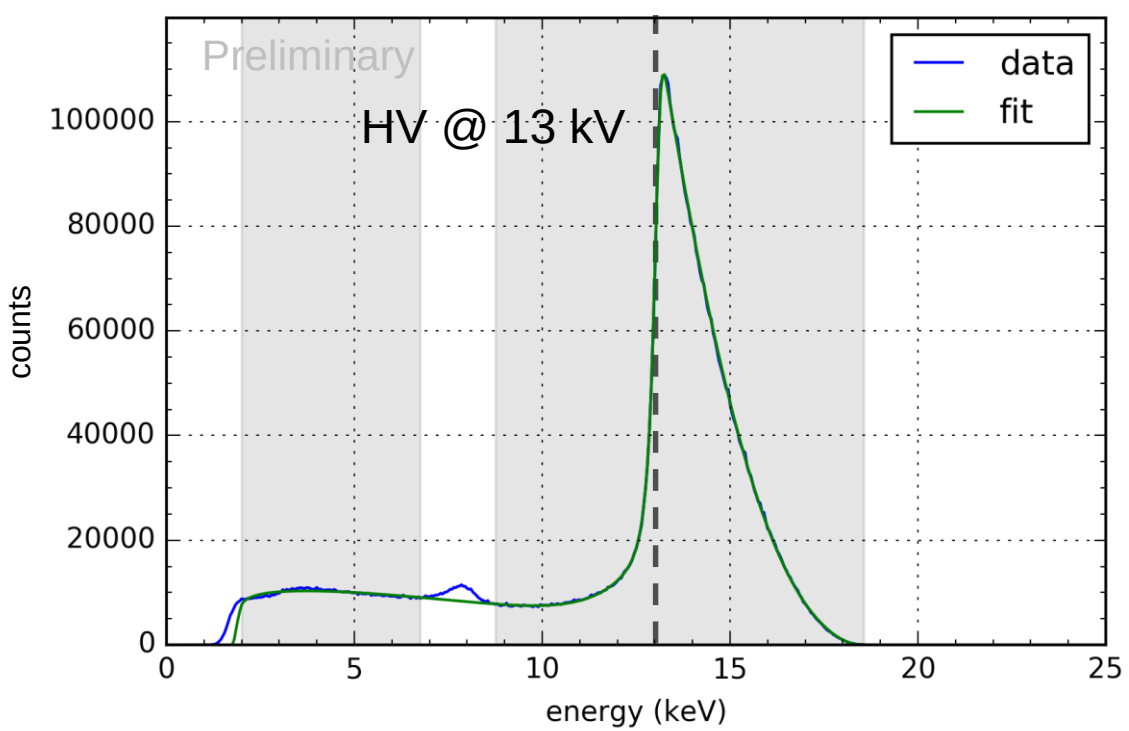
TRISTAN in Troitsk

- Successful operation of two TRISTAN prototype detector systems in „real experimental conditions“
- Good progress in analysis strategy development

Theory



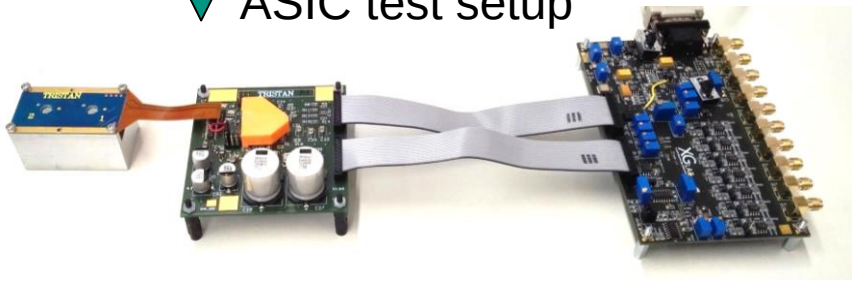
Measurement

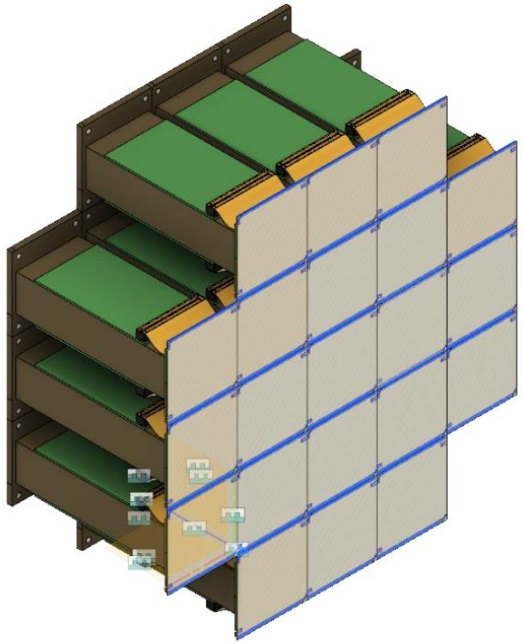


Towards the final system

- Pixel design:
  - SDD with integrated nJFET
  - Pixel size: ~ 3 mm diameter
- Module design:
  - 166 pixels
  - Module size: ~ 4x4 cm^2
  - Completion: Feb 2019
- Final detector design:
  - 21 modules → 3500 pixels
  - Detector size: ~ 20 cm diameter
  - Completion: 2023

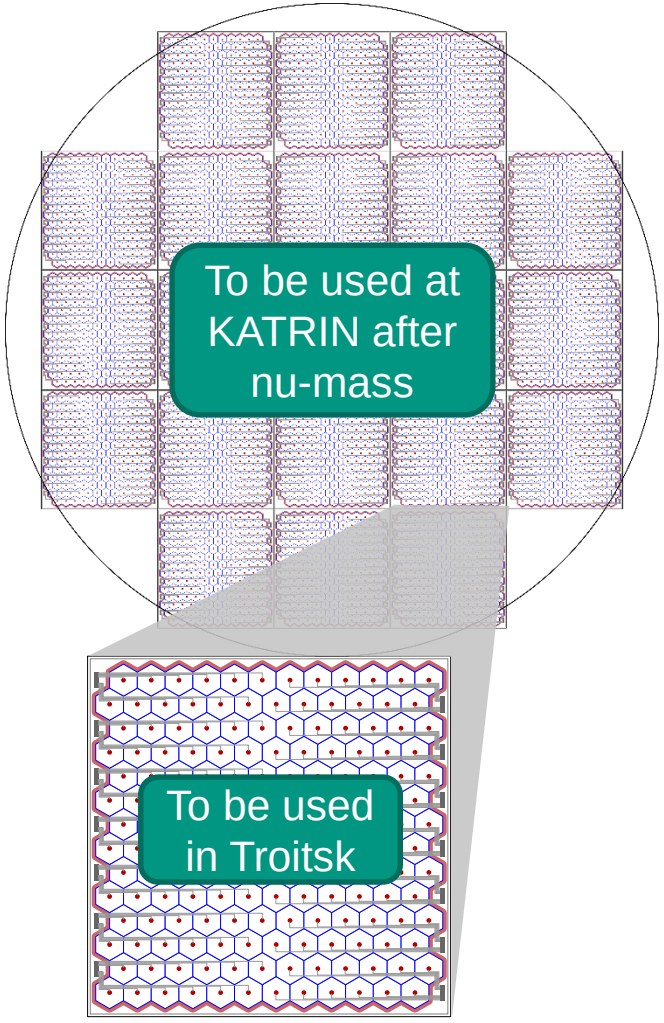
ASIC test setup





Detector with holding structure

Full detector



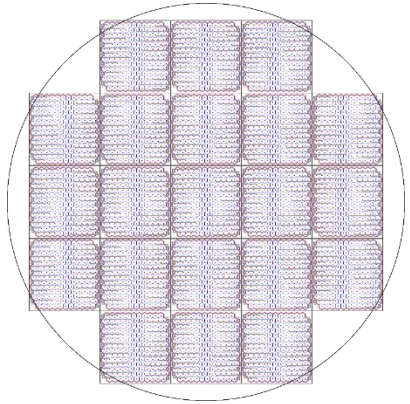
Detector module

Summary

- Neutrinos are key to unraveling some of the most compelling mysteries of the universe
- They are the only particles that show clear evidence for BSM physics

- Sterile neutrinos are a natural extension of the SM
- Controversial experimental results, no clear evidence yet

- TRISTAN aims at detecting a sterile neutrino in tritium beta decay with KATRIN
- A new detector system is being developed in order to handle the high rates



Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Thank you for your attention!