



electron  
neutrino



muon  
neutrino



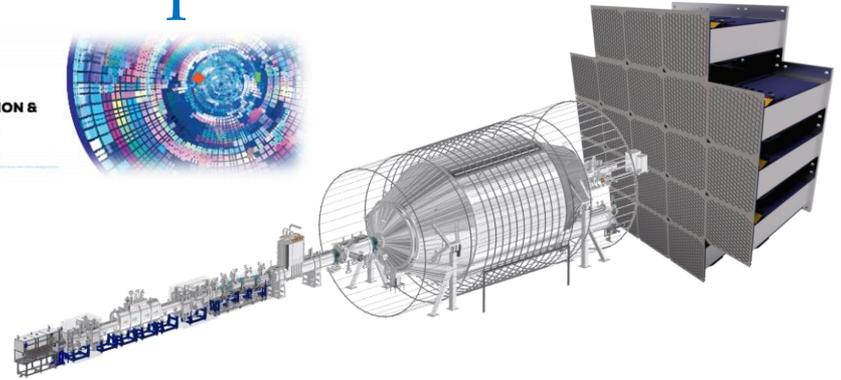
tau  
neutrino



sterile  
neutrino



# Sterile Neutrino Dark Matter Searches with the KATRIN Experiment



**Frank Edzards**

Technical University of Munich  
September 2023



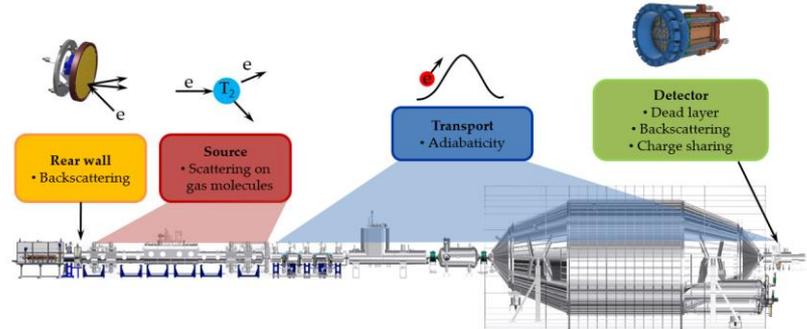
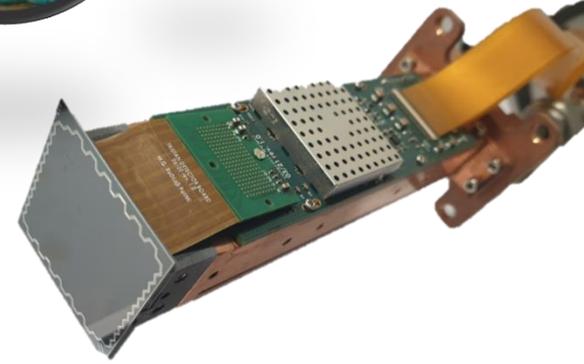
POLITECNICO  
MILANO 1863

DIPARTIMENTO DI ELETTRONICA  
INFORMAZIONE E BIOINGEGNERIA



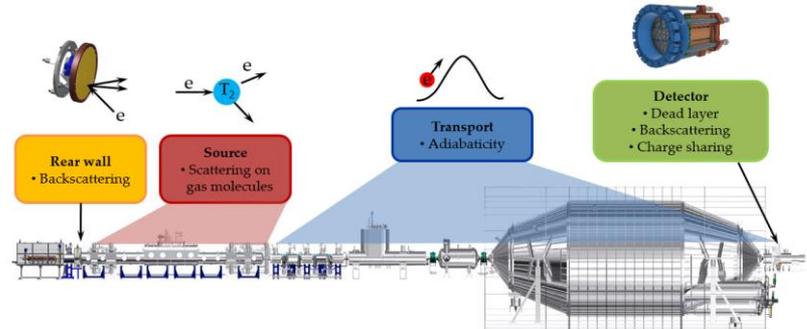
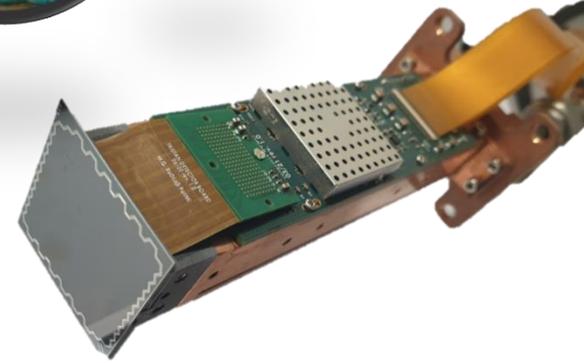
# Agenda

1. Motivation
2. TRISTAN detector system
3. Beamline model



# Agenda

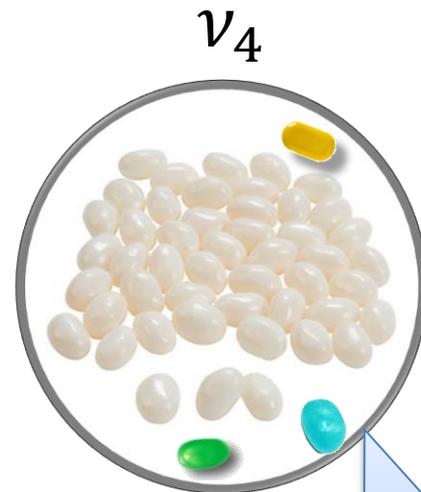
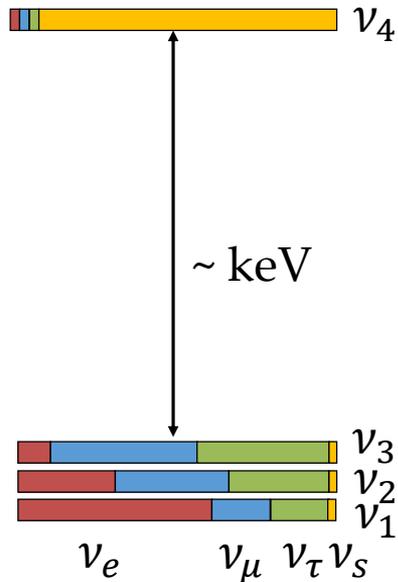
1. Motivation
2. TRISTAN detector system
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# *Active neutrinos*



# Sterile neutrinos



Mass eigenstate not purely sterile, can have any mass

Sterile neutrino:  
lepton that does not  
carry any charge

# Sterile neutrinos

## Light sterile neutrinos ( $\sim 1$ eV)

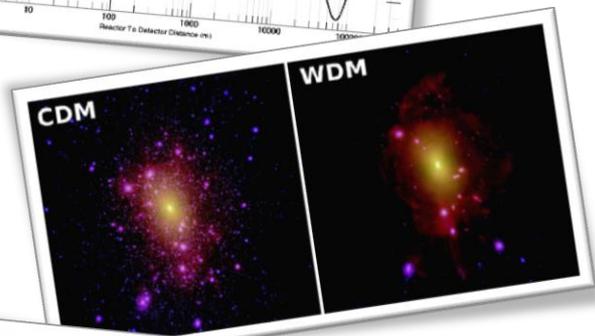
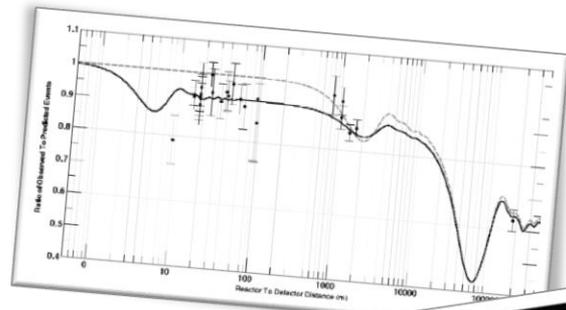
- Short-baseline neutrino oscillation anomalies

## KeV-scale sterile neutrinos ( $\sim 1$ -50 keV)

- Dark matter candidate

## Heavy sterile neutrinos ( $> \text{GeV}$ )

- Lightness of neutrinos  
+ Matter/anti-matter asymmetry



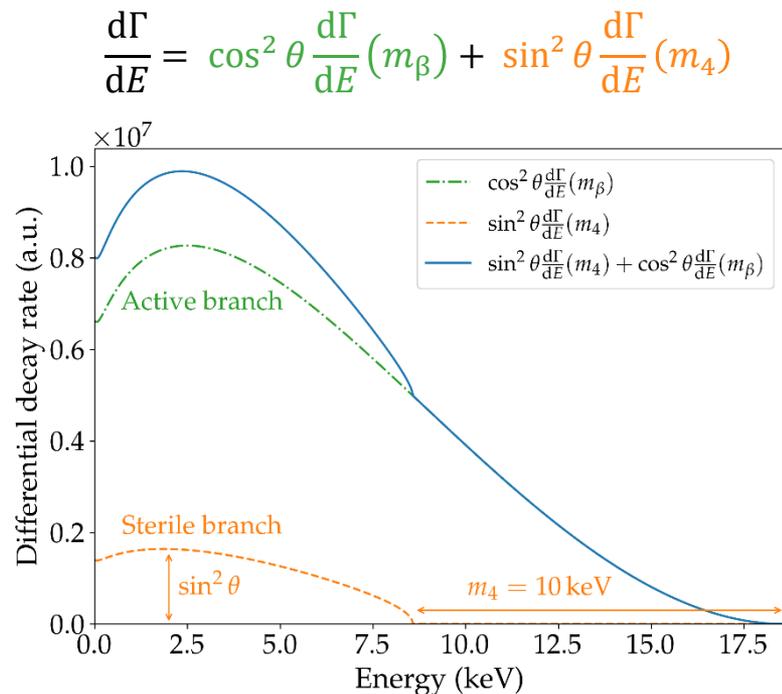
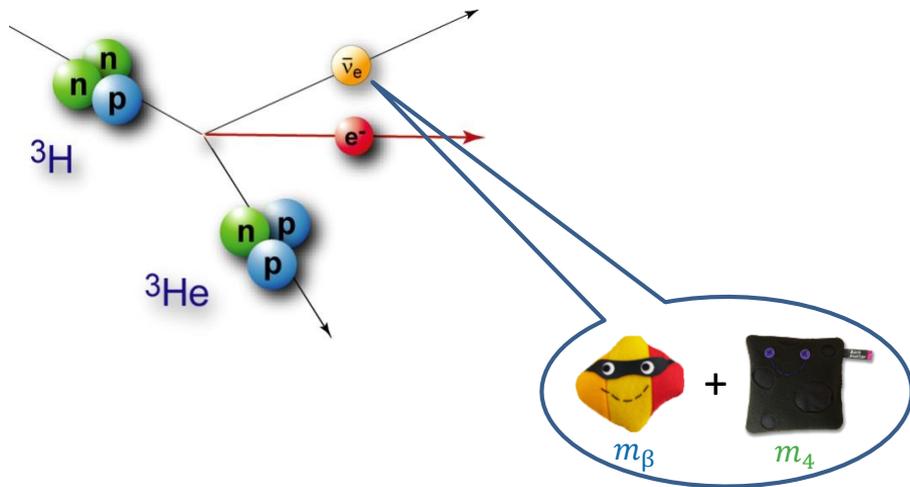
arXiv:1901.08330 (2019): C. Giunti and T. Lasserre

arXiv:1906.01739 (2019): S. Böser, C. Buck, C. Giunti, J. Lesgourgues, L. Ludhova, S. Mertens, A. Schukraft, M. Wurm

Prog. Part. Nucl. Phys. 104 (2019): A. Boyarsky, M. Drewes, T. Lasserre, S. Mertens, O. Ruchayskiy

# Sterile neutrinos in single $\beta$ -decay

- Characteristic **kink-like** signature and spectral distortion



# KATRIN - Working principle



**Tritium source**

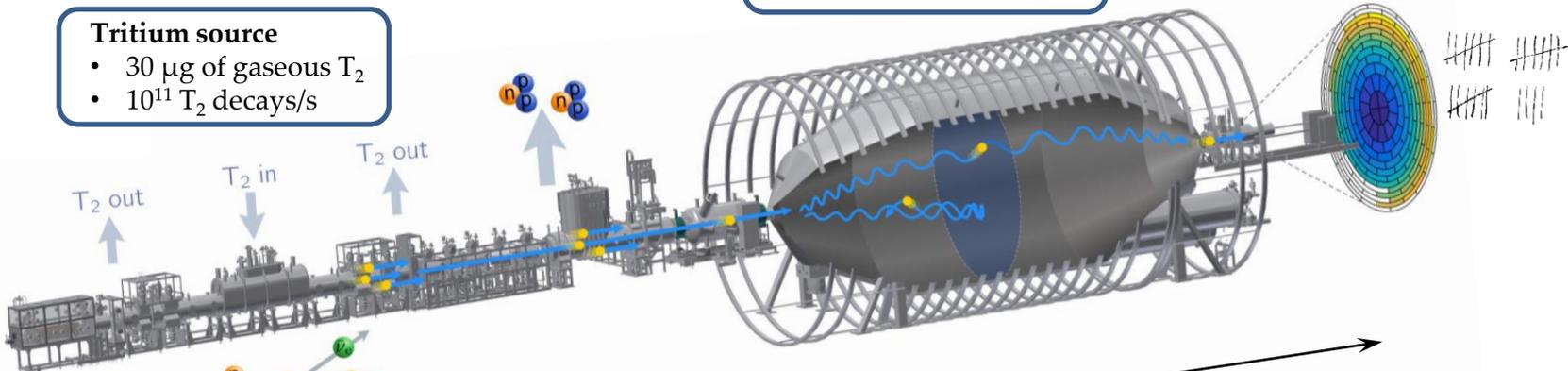
- 30  $\mu\text{g}$  of gaseous  $\text{T}_2$
- $10^{11}$   $\text{T}_2$  decays/s

**Spectrometer**

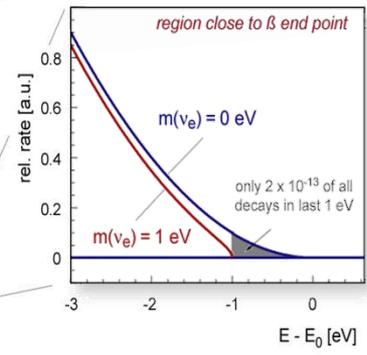
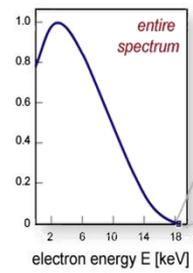
- Electrostatic filter
- MAC-E filter principle

**Detector**

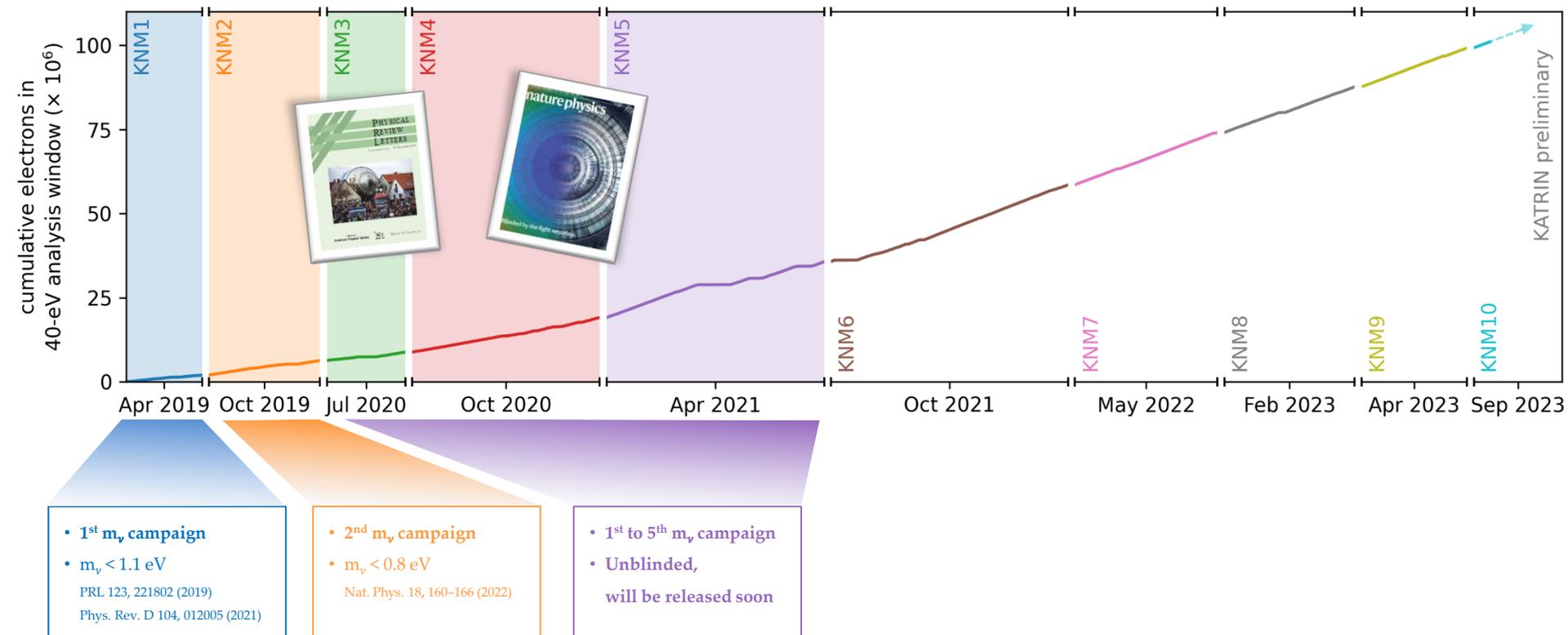
- Counts electrons
- Rate vs HV



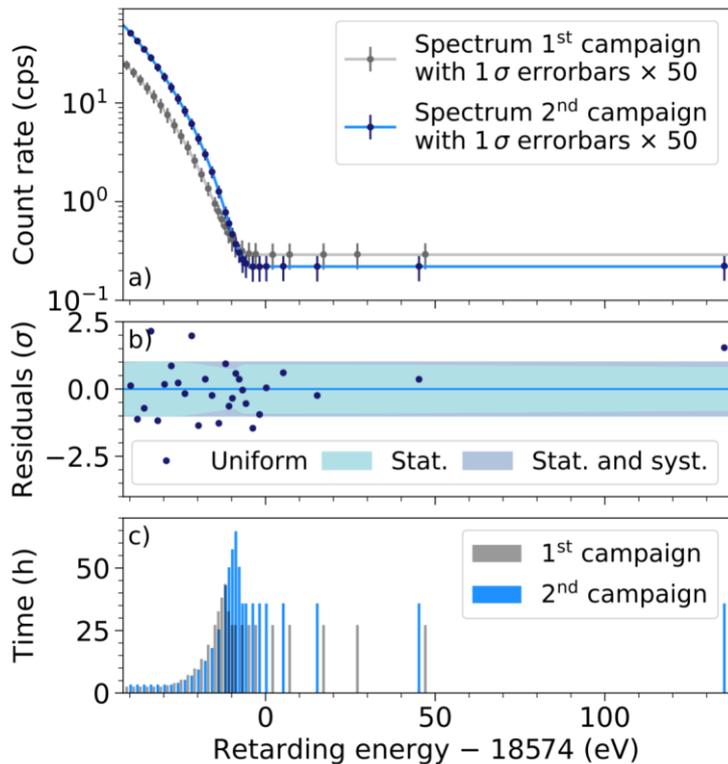
70 m long



# KATRIN - Data taking overview



# KATRIN - Latest results



- *First campaign*

- Total statistics: 2 million events
- Best fit:  $m_\nu^2 = (-1.0_{-1.1}^{+0.9}) \text{ eV}^2$  (stat. dom.)
- Limit:  $m_\nu < 1.1 \text{ eV}$  (90% CL)



- *Second campaign*

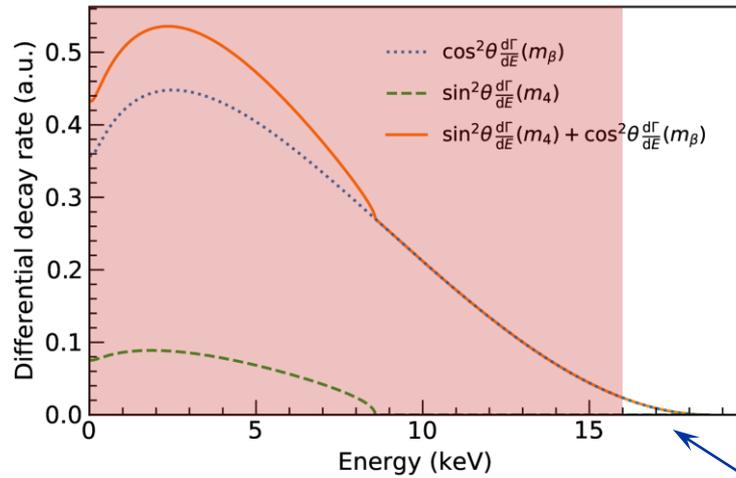
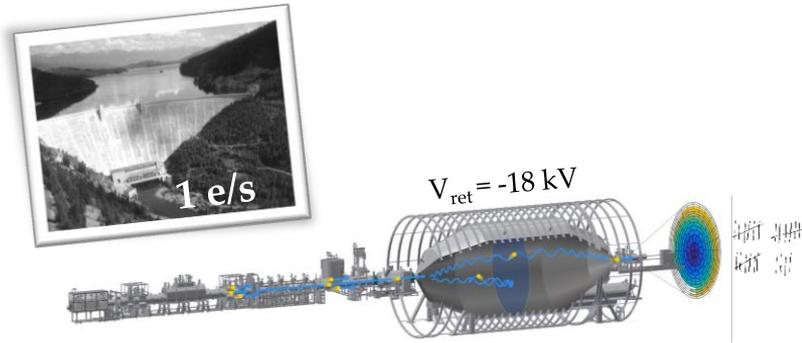
- Total statistics: 4 million events
- Best fit:  $m_\nu^2 = (0.26_{-0.34}^{+0.34}) \text{ eV}^2$  (stat. dom.)
- Limit:  $m_\nu < 0.9 \text{ eV}$  (90% CL)



- *Combined result*

- $m_\nu < 0.8 \text{ eV}$  (90% CL)

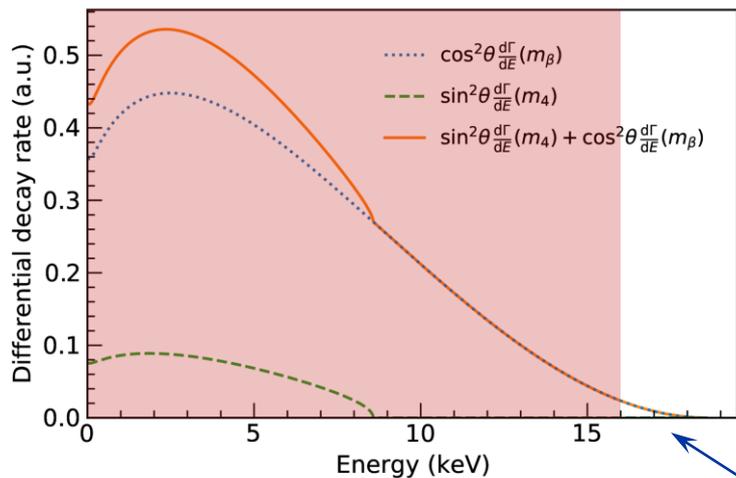
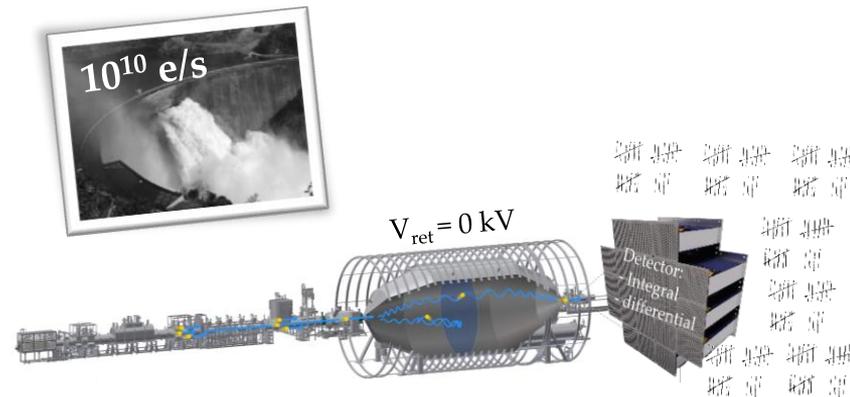
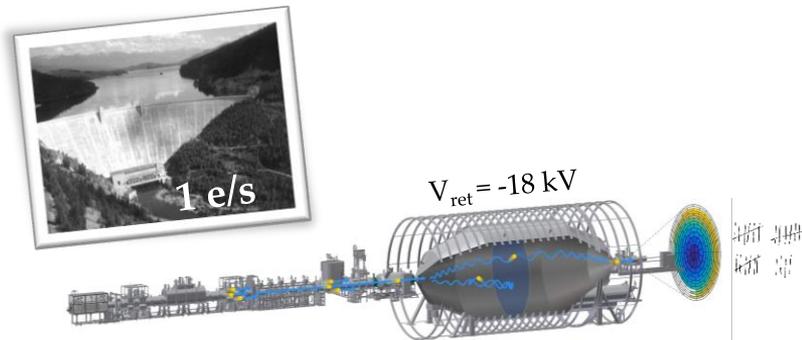
# KATRIN - Challenge



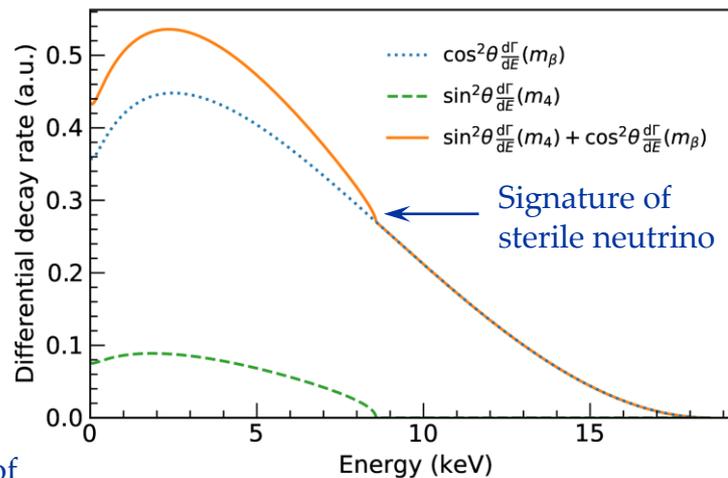
Signature of  
neutrino mass



# KATRIN - Challenge

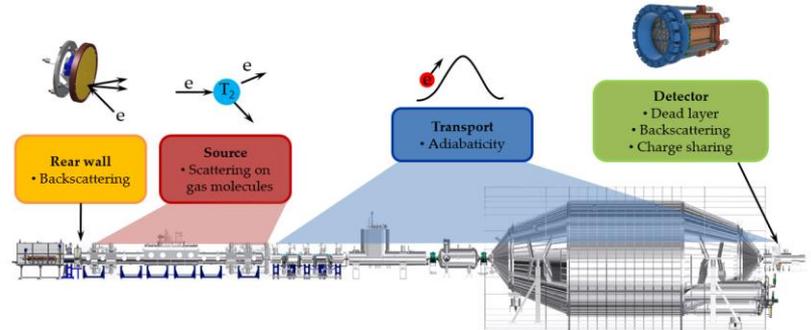
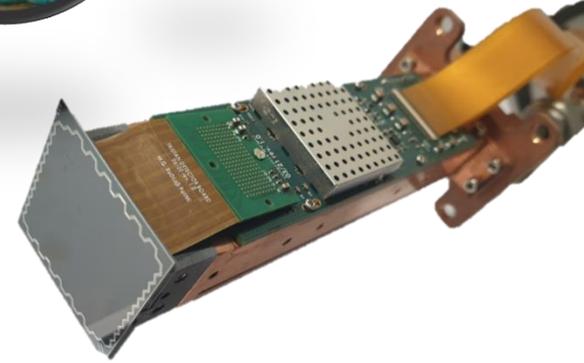


Signature of neutrino mass



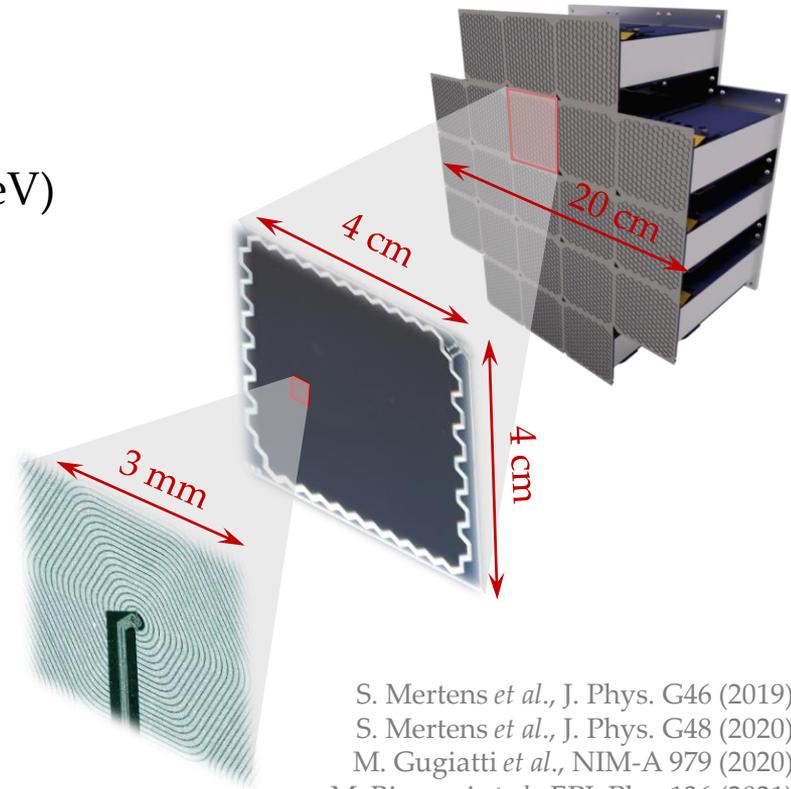
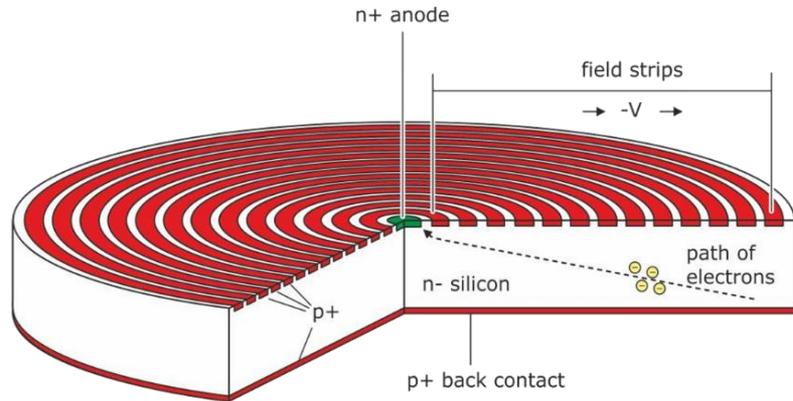
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1. Motivation
2. TRISTAN detector system
3. Beamline model



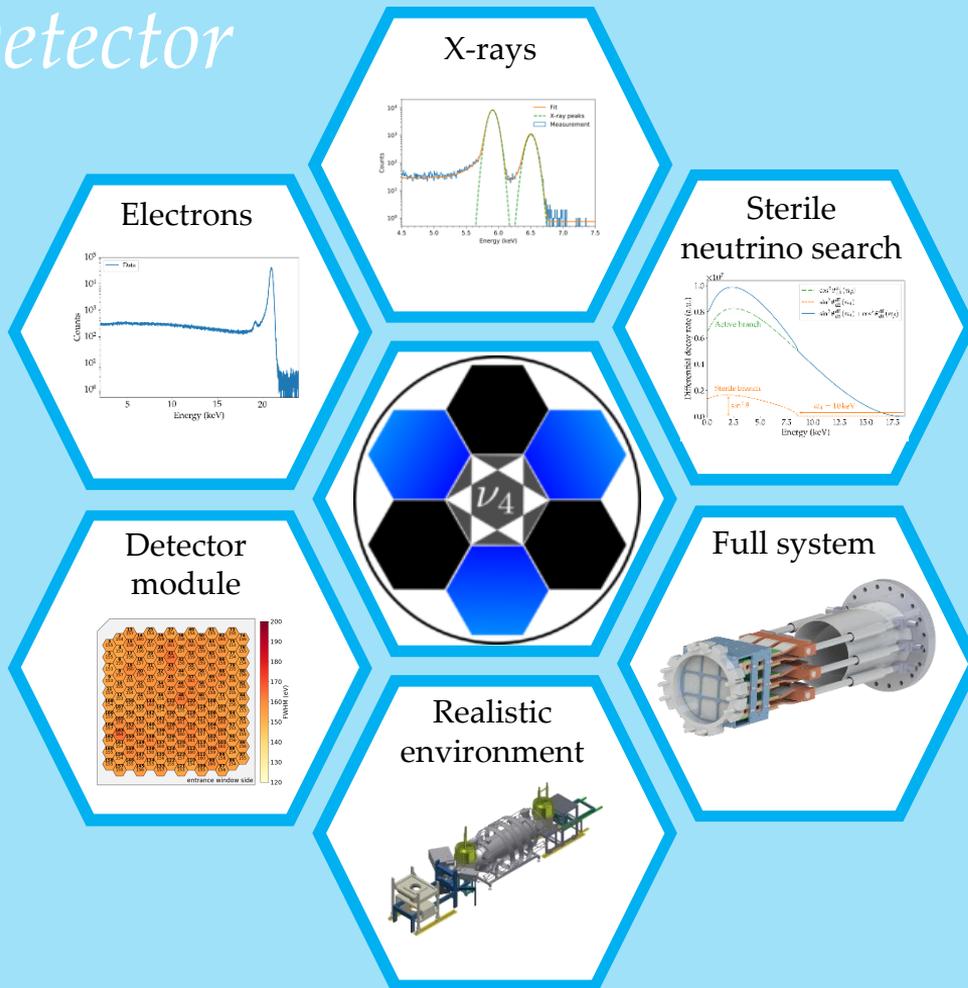
# KATRIN - New Detector (TRISTAN)

- Silicon drift detector (SDD) technology
  - ✓ Handling of high rates (100 kcps/pixel)
  - ✓ Excellent energy resolution (300 eV at 20 keV)
  - ✓ Integrated readout
- Novelty: application to  $\beta$ -spectroscopy



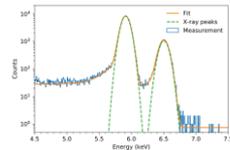
S. Mertens *et al.*, J. Phys. G46 (2019)  
S. Mertens *et al.*, J. Phys. G48 (2020)  
M. Gugiatti *et al.*, NIM-A 979 (2020)  
M. Biassoni *et al.*, EPJ. Plus 136 (2021)  
P. King *et al.*, JINST 16 T07007 (2021)

# TRISTAN Detector

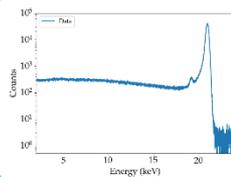


# TRISTAN Detector

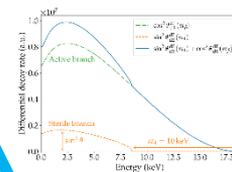
X-rays



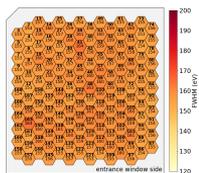
Electrons



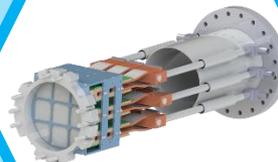
Sterile neutrino search



Detector module



Full system

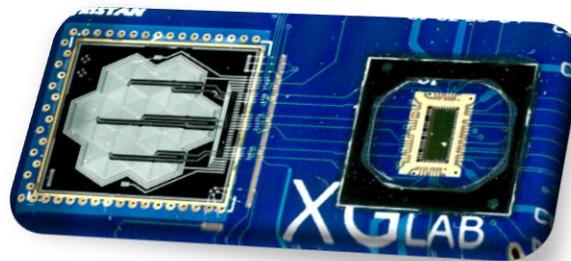


Realistic environment

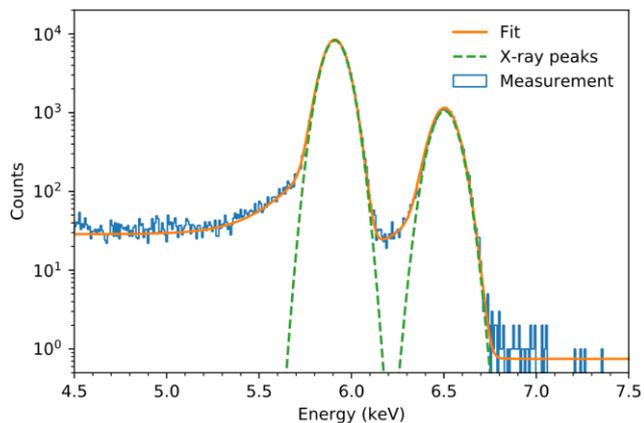


# Performance with X-rays

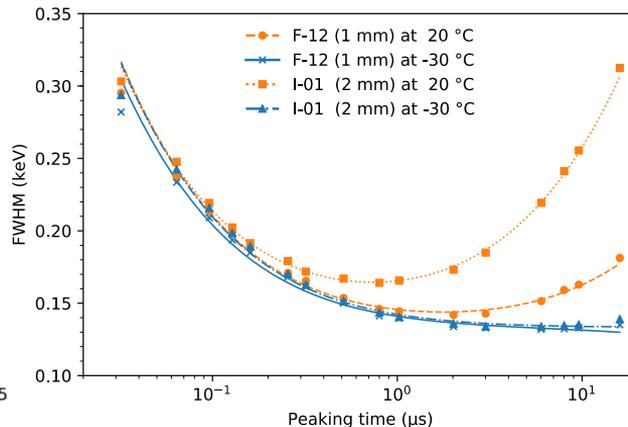
- ✓ Test of multiple prototype designs
- ✓ Excellent performance demonstrated
  - Energy resolution
  - Noise characteristics
  - Linearity



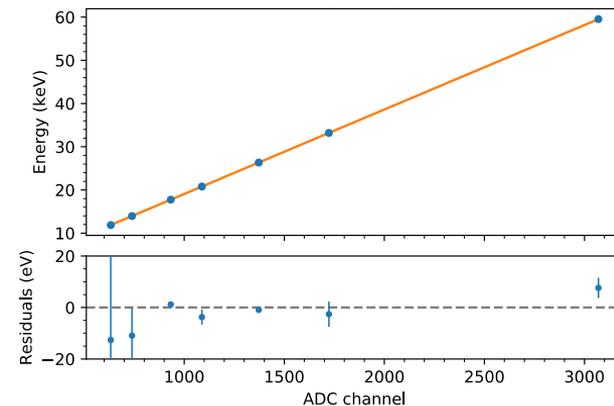
140 eV FWHM at 6 keV (1  $\mu$ s shaping)



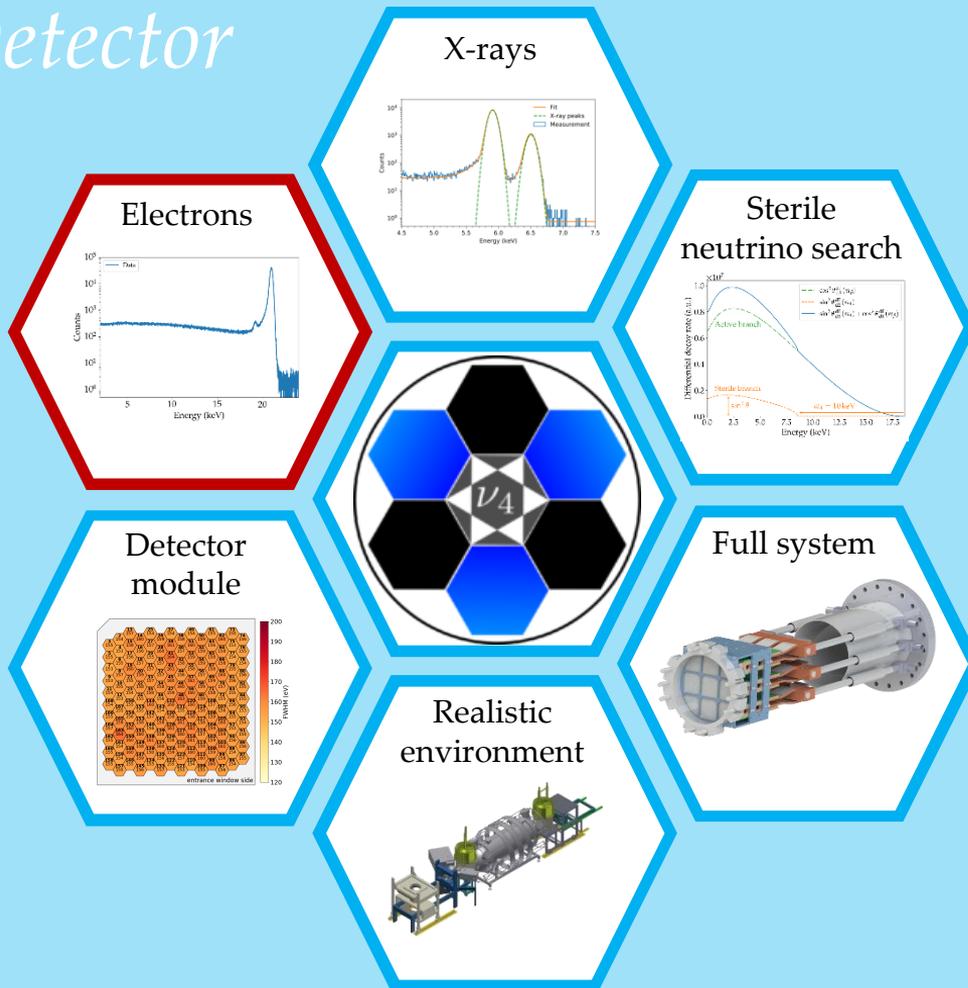
< 150 eV FWHM



0.1% linearity (up to 60 keV)

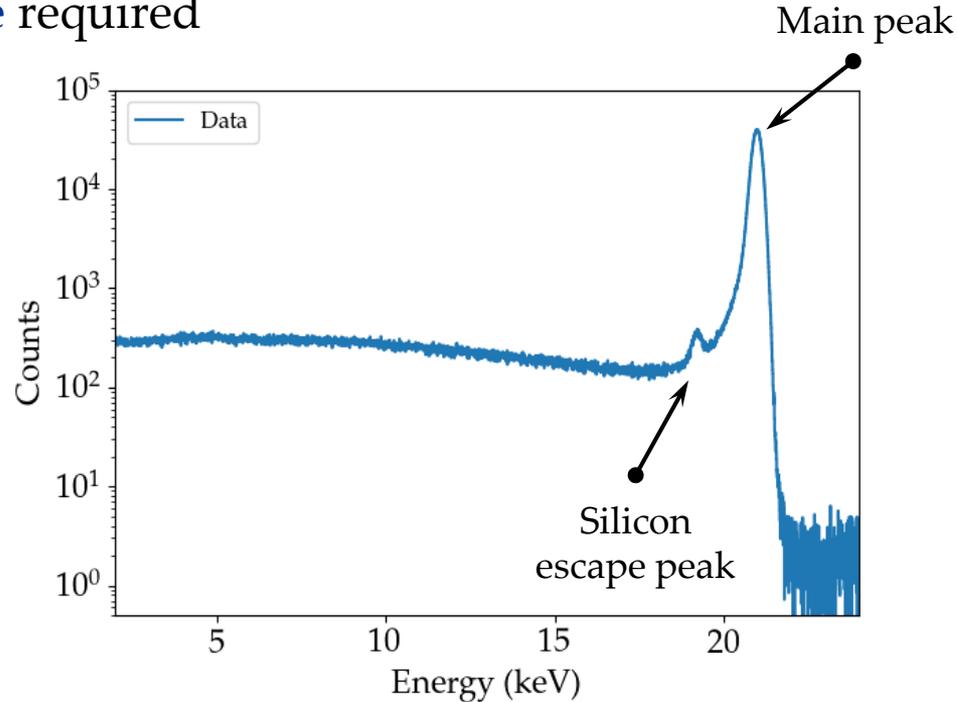


# TRISTAN Detector



# Detector Response to Electrons

- Precise understanding and modeling of detector electron response required



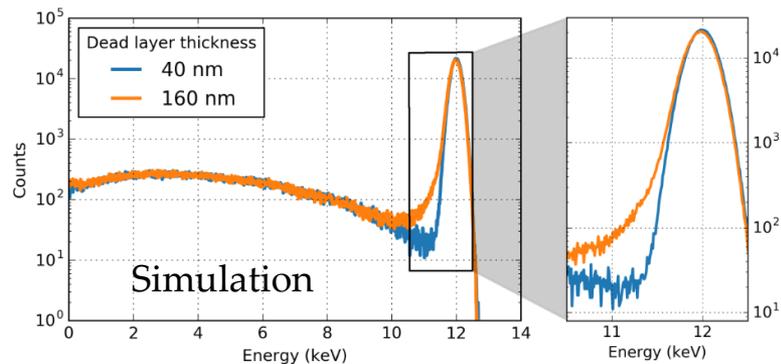
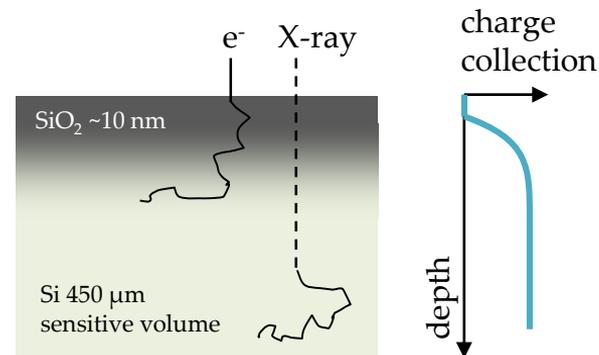
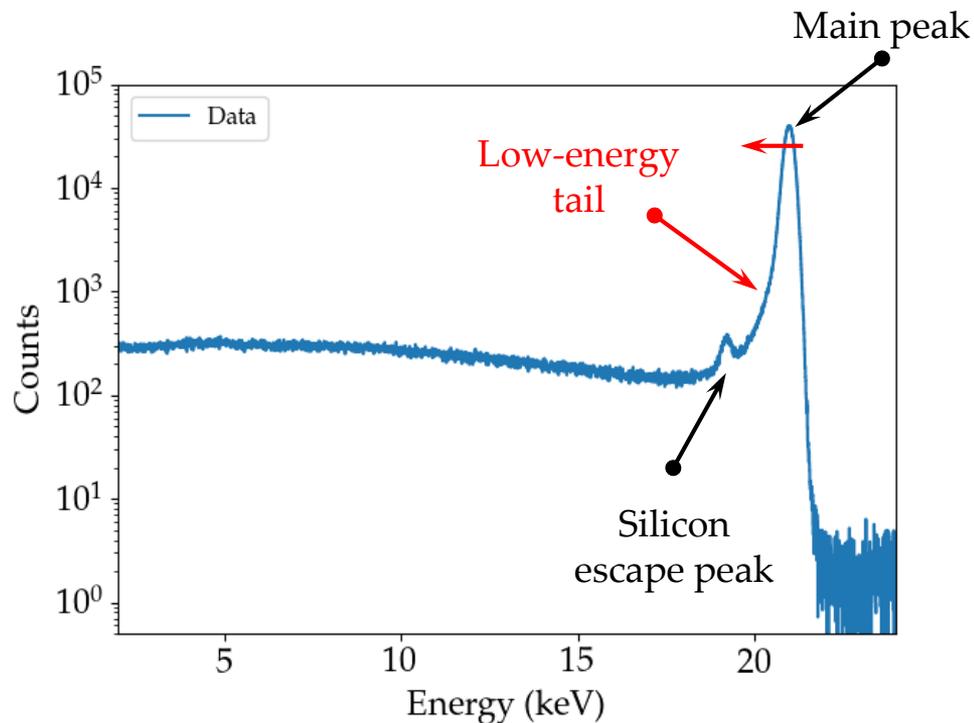
1. Dead layer

2. Charge sharing

3. Backscattering

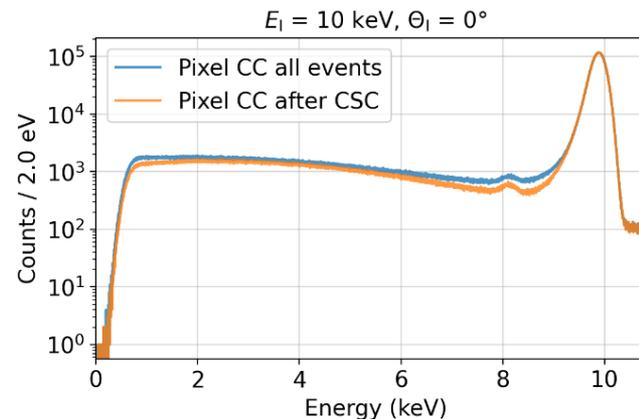
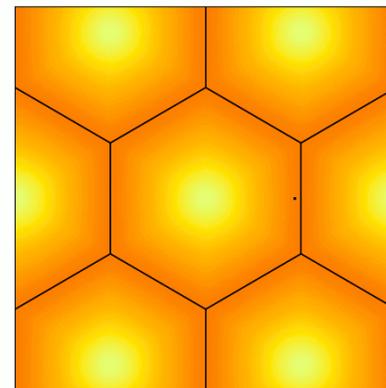
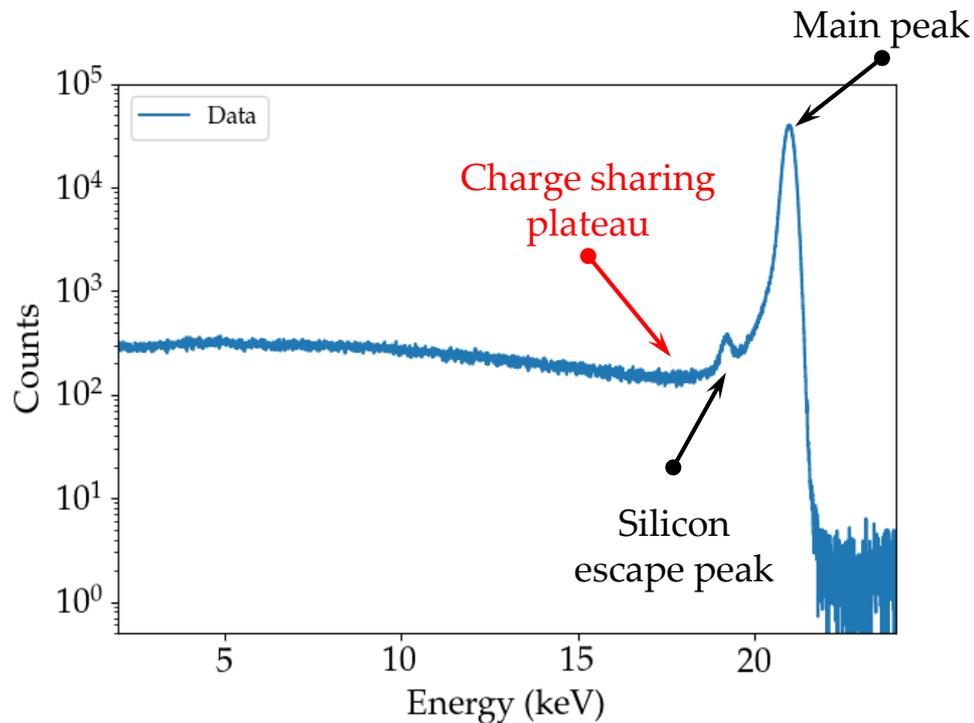
# Detector Response to Electrons

- 1<sup>st</sup> effect: Dead layer



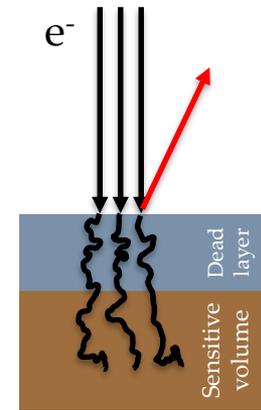
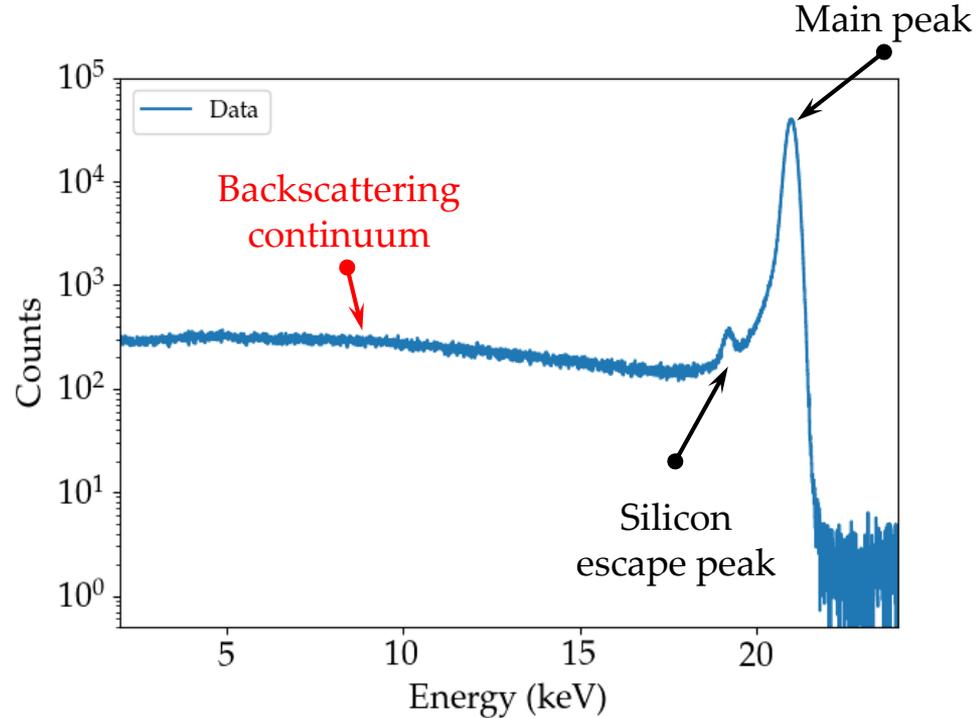
# Detector Response to Electrons

- 2<sup>nd</sup> effect: Charge sharing of pixels



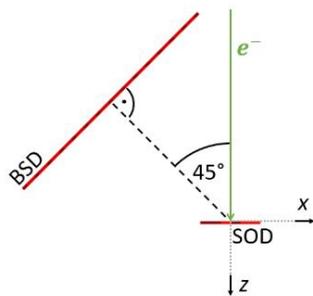
# Detector Response to Electrons

- 3<sup>rd</sup> effect: Backscattering

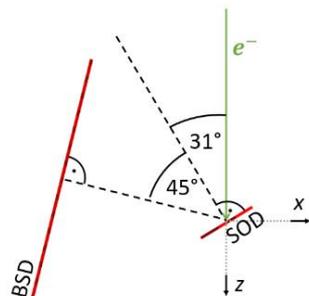


# Detector Backscattering

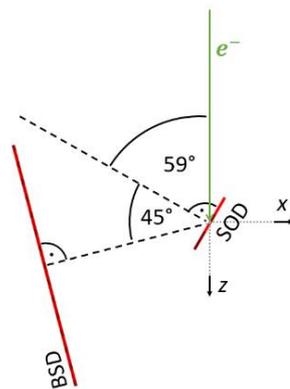
- **Measurements** with two TRISTAN SDDs in dedicated test setup
  - At different electron energies
  - At different incident angles



(a)  $\theta_I = 0^\circ$



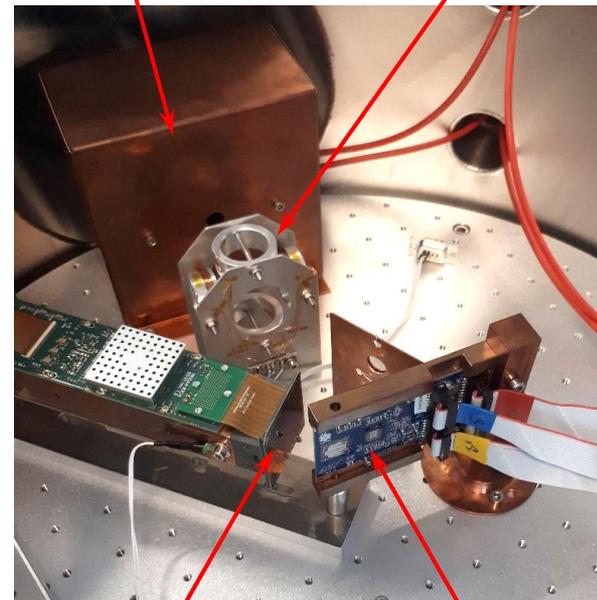
(b)  $\theta_I = 31^\circ$



(c)  $\theta_I = 59^\circ$

Custom e-gun

Steering coils

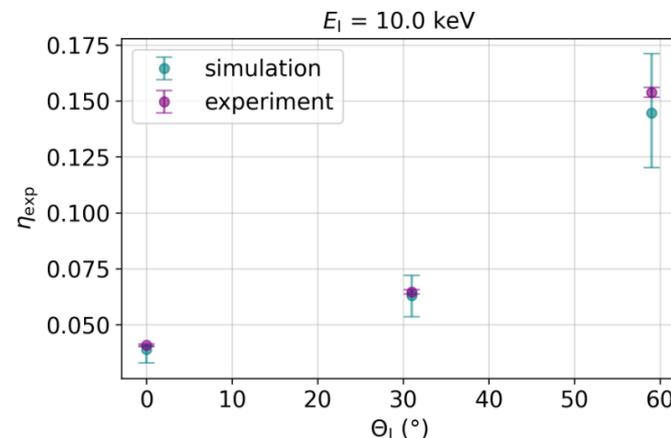
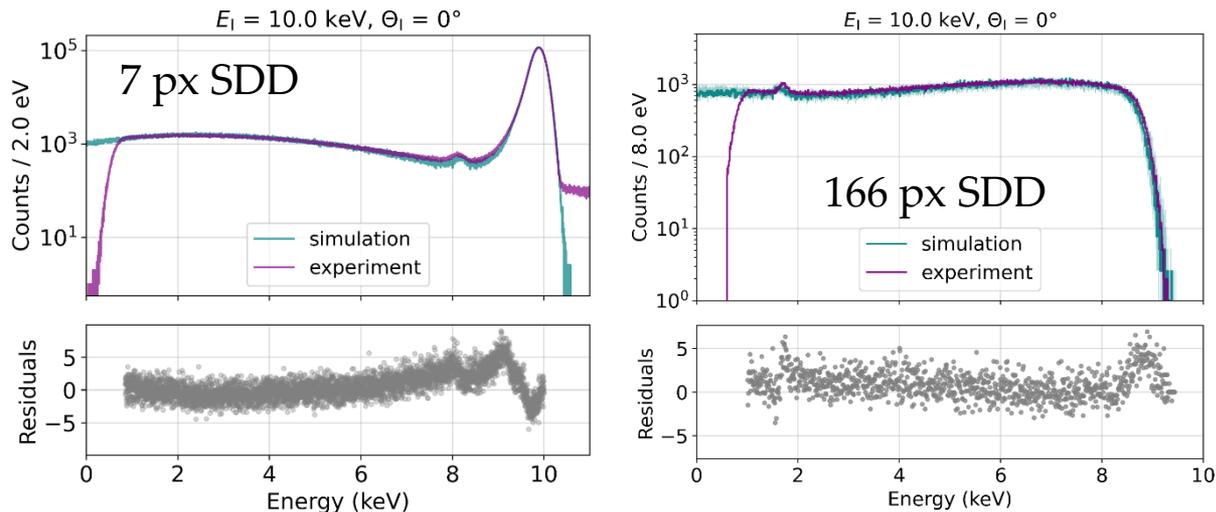
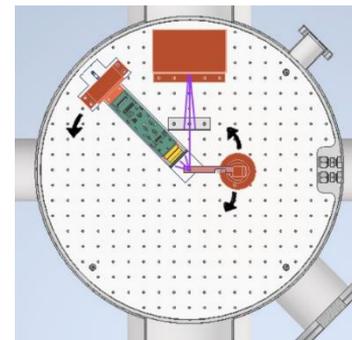


166 px SDD

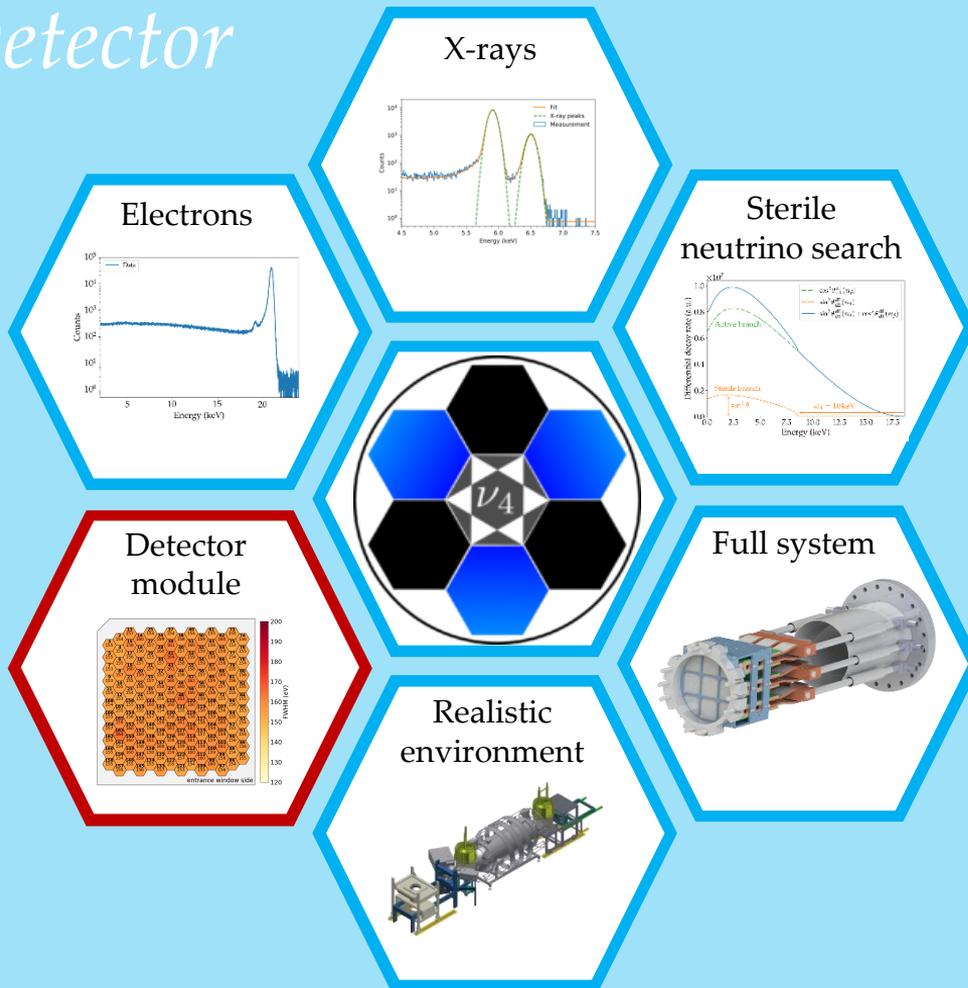
7 px SDD

# Detector Backscattering

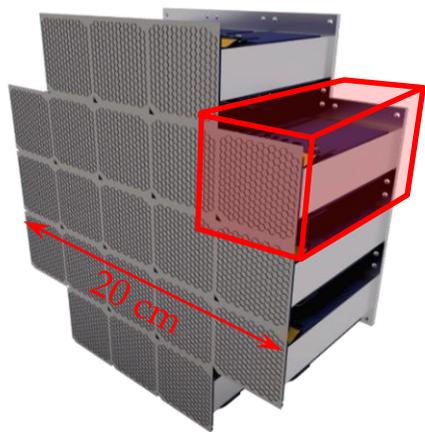
- Measurements agree very well with simulations
- Backscattering
  - decreases with energy
  - increases with incident angle



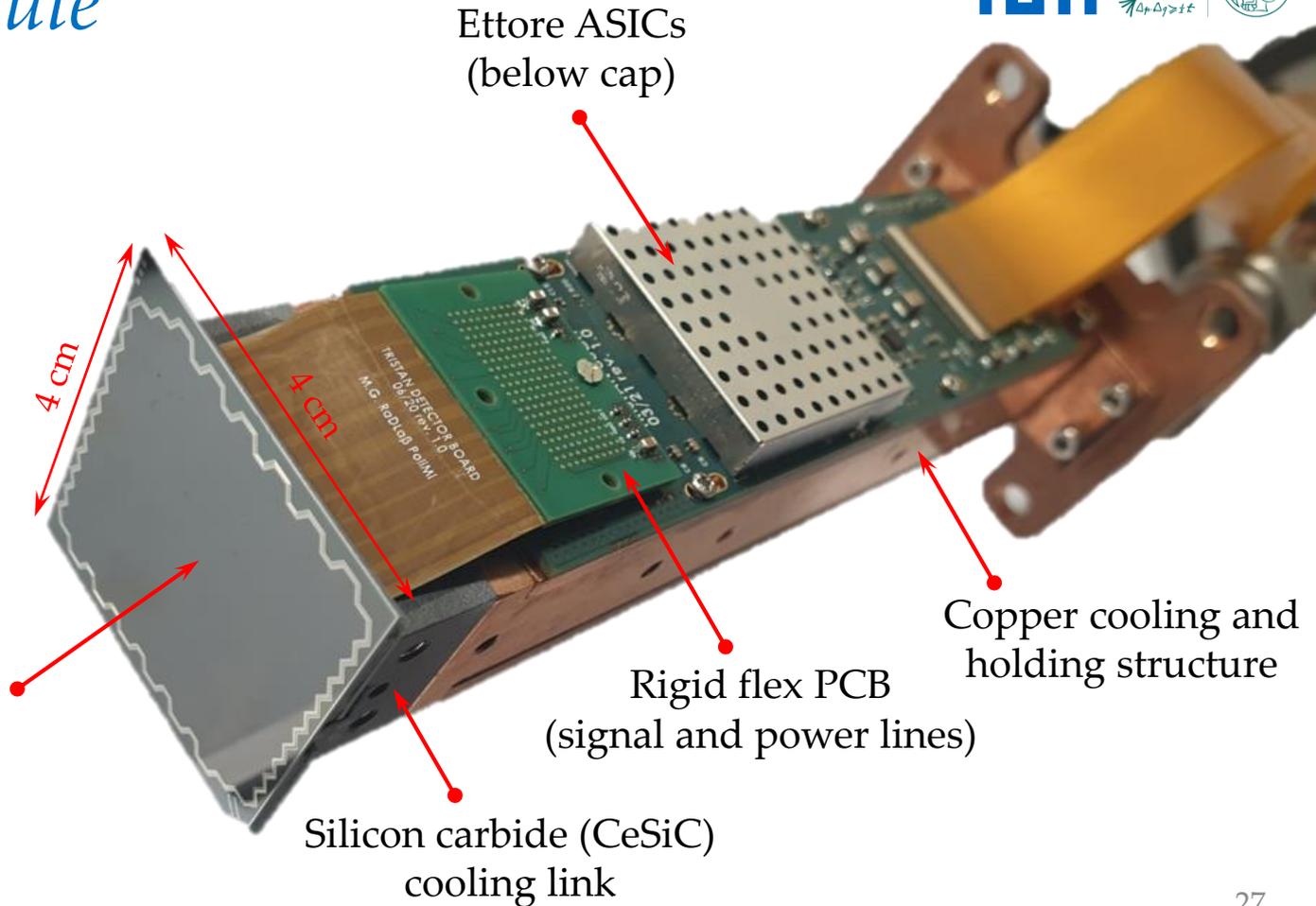
# TRISTAN Detector



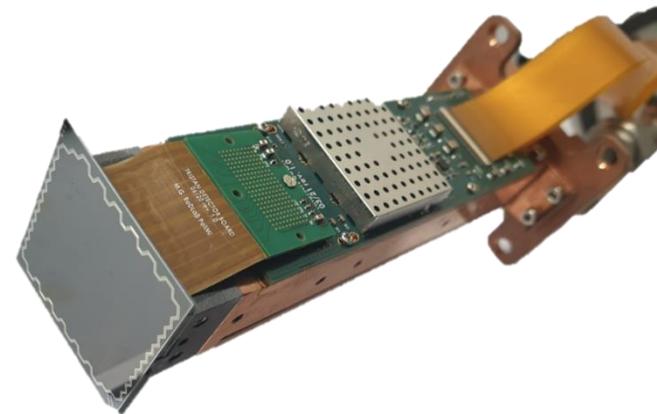
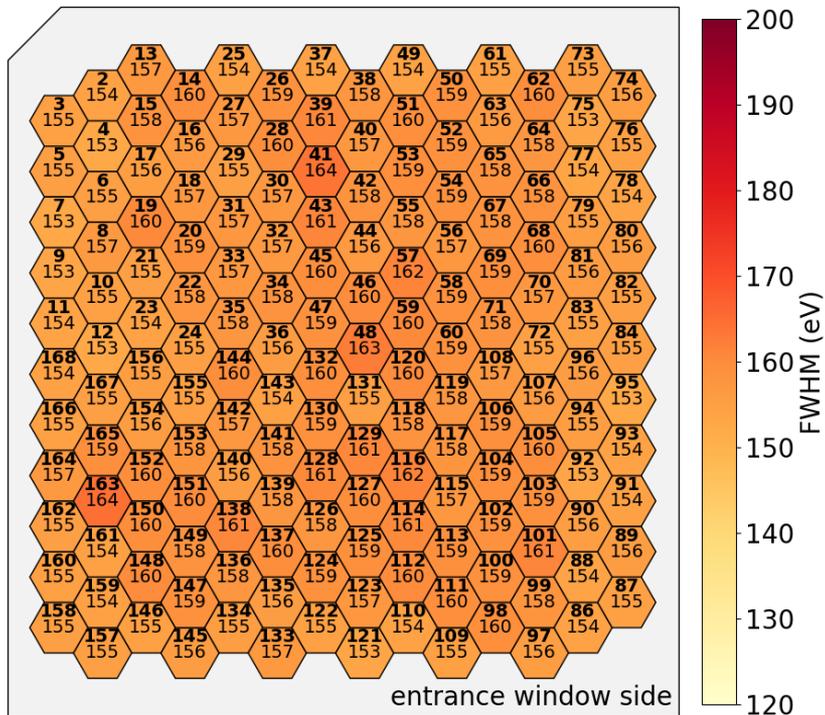
# Detector Module



166 px SDD with integrated JFET

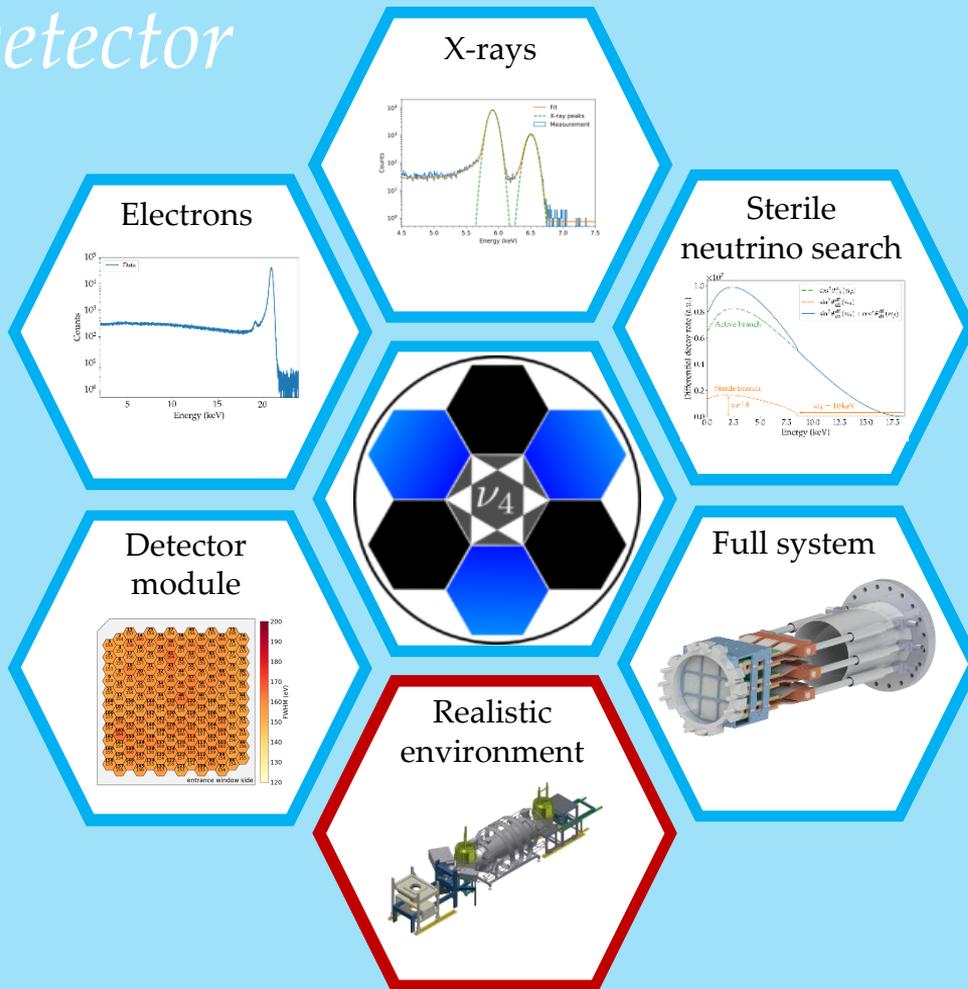


# Detector Module



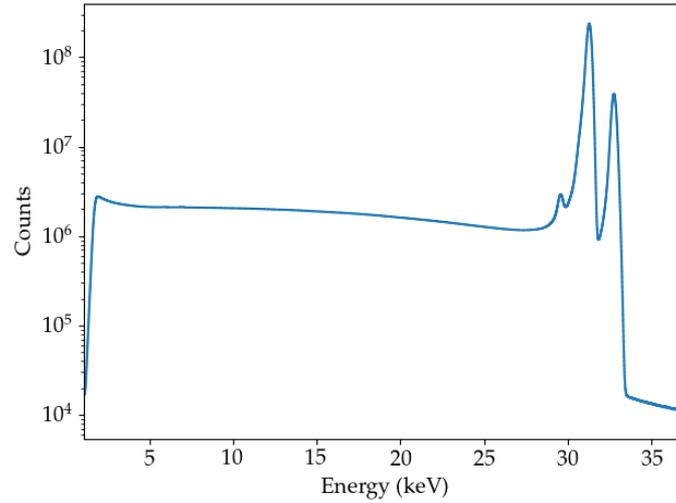
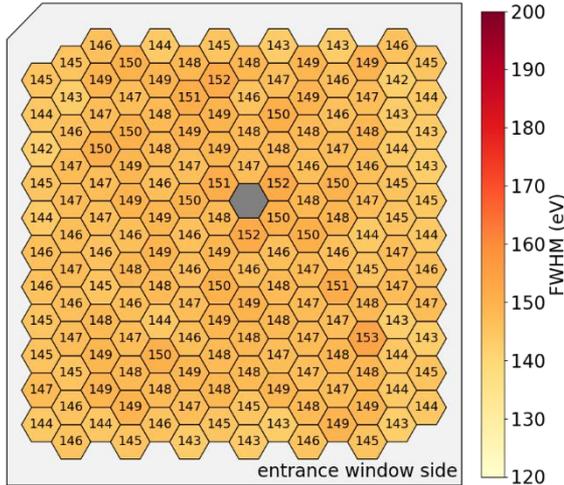
- ✓ Largest SDD array operated ever!
- ✓ All pixels working
- ✓ Homogeneous performance
- ✓ Average energy resolution at  $-35^{\circ}\text{C}$ :  
~160 eV FWHM at 5.9 keV
- ✓ Integration of 9 modules in KATRIN in 2025

# TRISTAN Detector

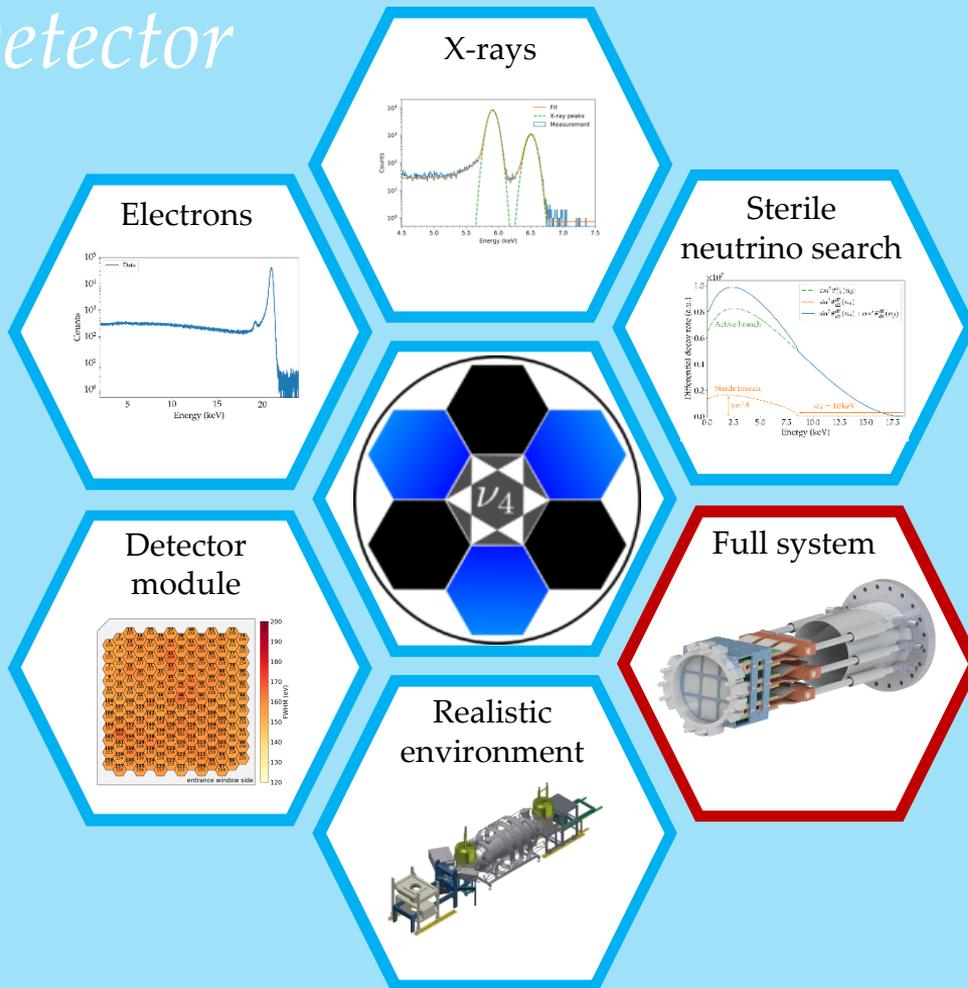


# Installation in KATRIN MoS

- Test in realistic environment (B-field, vacuum, etc.) w/ X-rays and electrons
- Excellent energy resolution: 147 eV FWHM at 6 keV
- Stable long-term operation

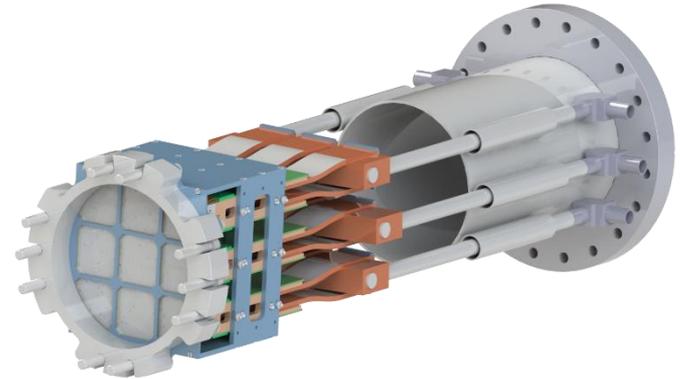
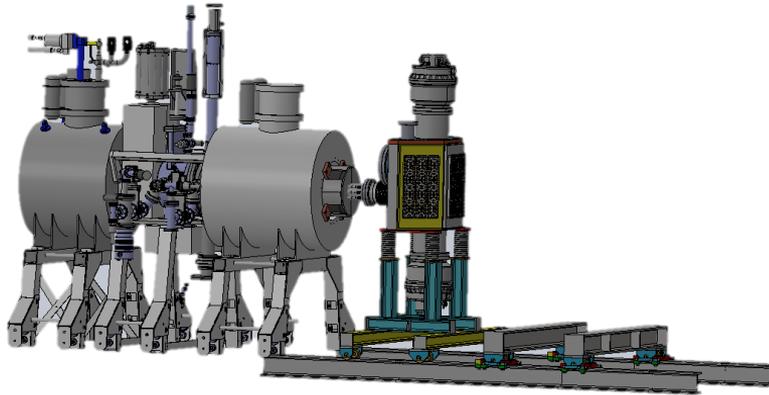
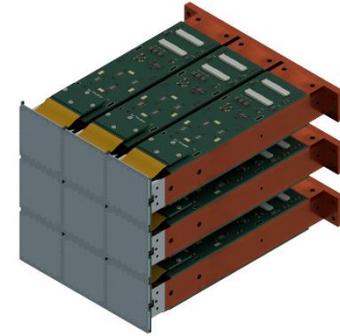


# TRISTAN Detector



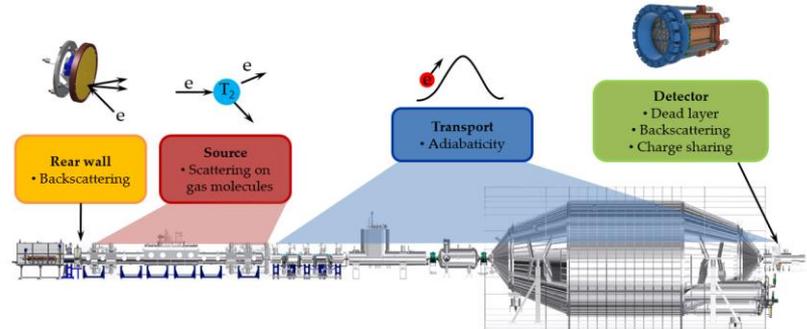
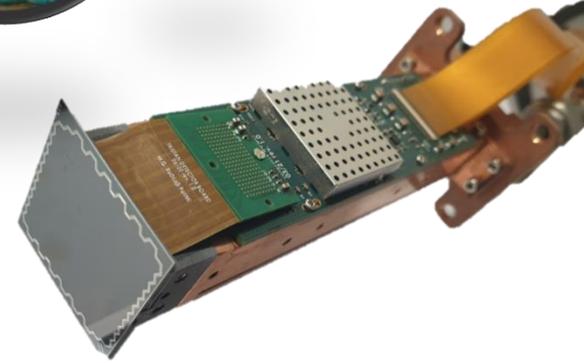
# 9 Modules in KATRIN Beamline

- Preparations for integration in beamline ongoing
  - Detectors and readout electronics currently in production
  - Replica setup currently being built
- Installation in KATRIN beamline planned for 2025

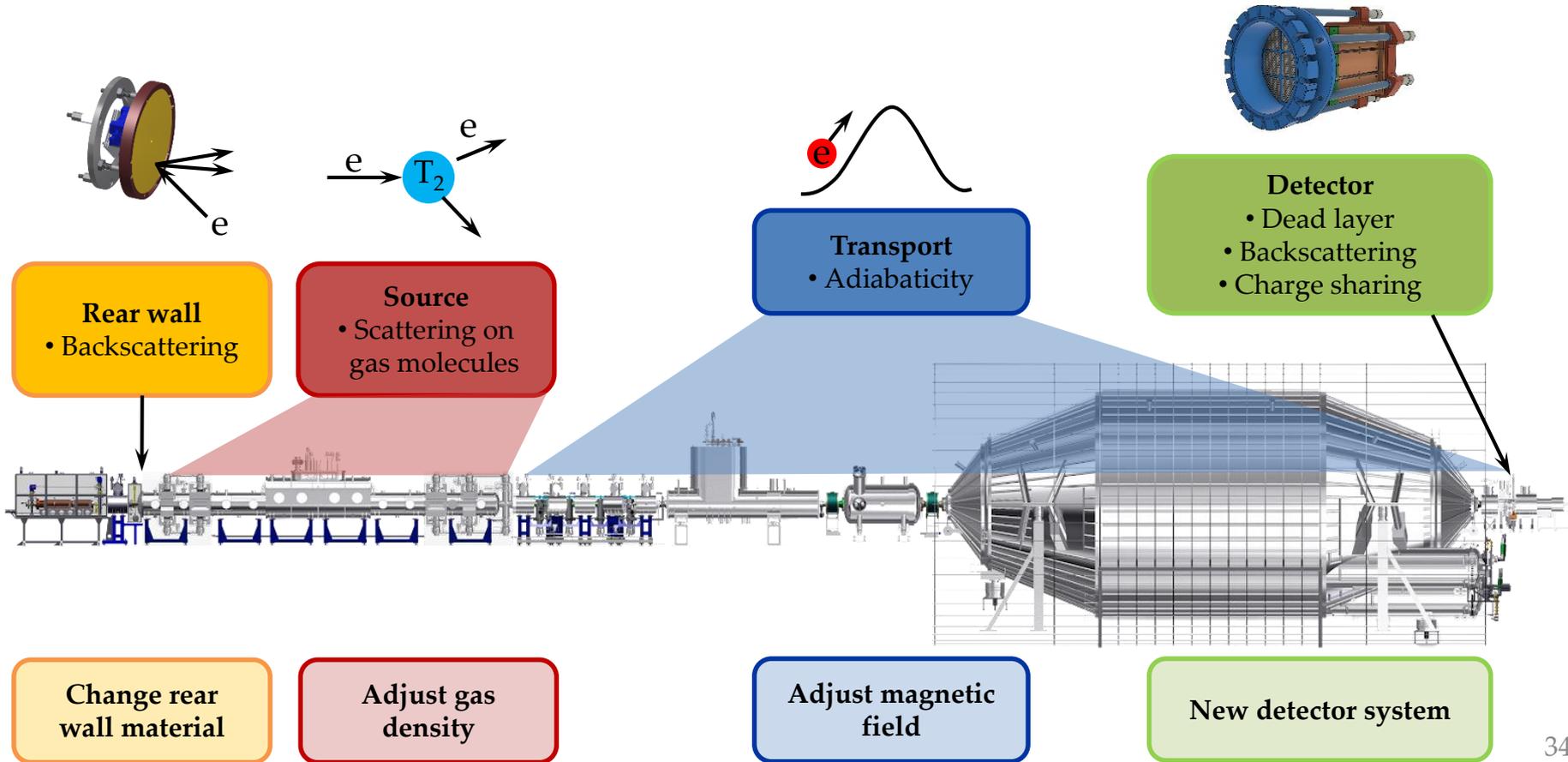


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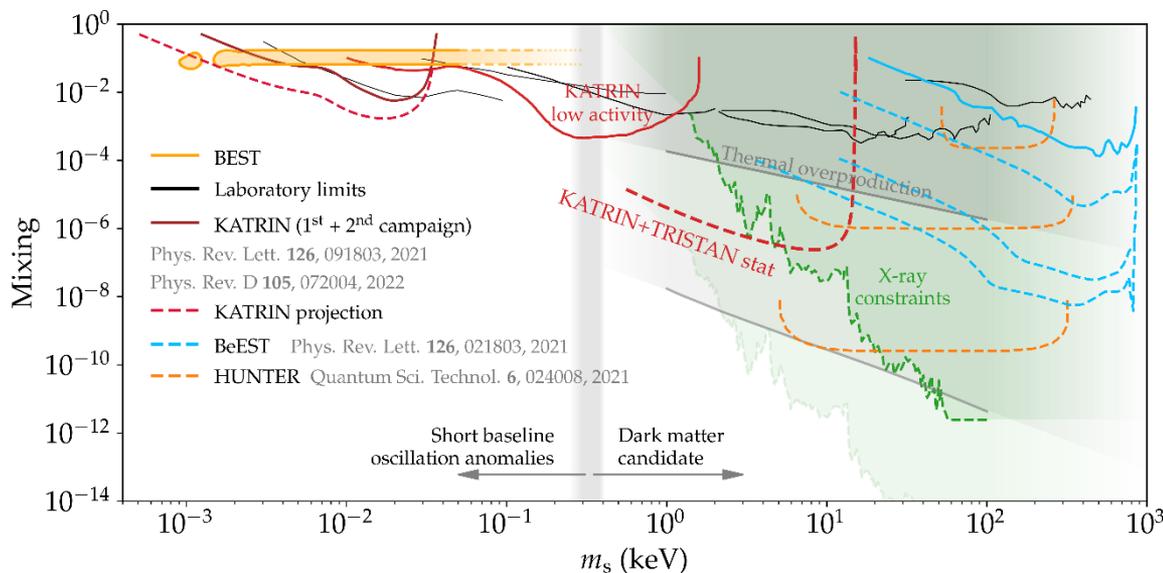
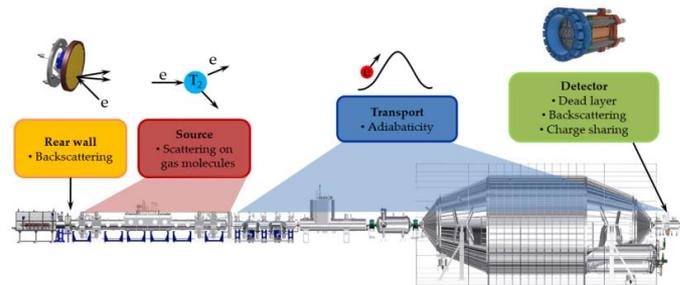


# KATRIN - Sterile Neutrino Model



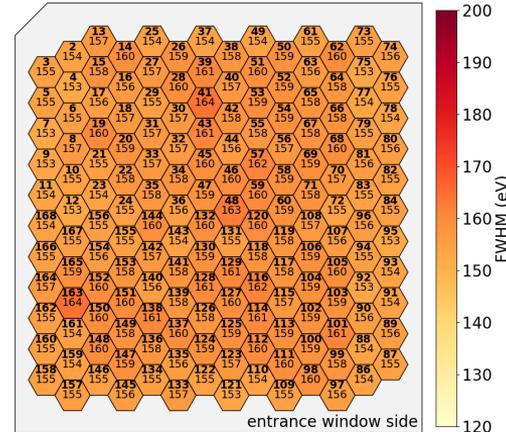
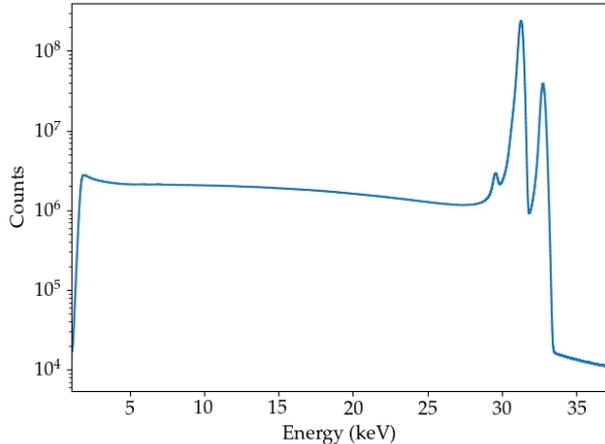
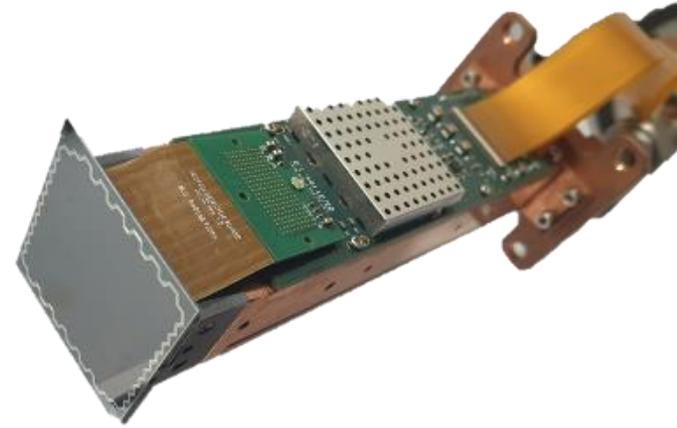
# Spectrum Modeling

- Systematics have to be well understood
- Complete model has been developed to model all relevant effects



# Summary

- ✓ TRISTAN will search for **sterile neutrinos** in the **keV mass range** with the KATRIN experiment
- ✓ Excellent spectroscopic performance (electrons and photons) demonstrated in various test stands
- ✓ Largest SDD array operated ever



*Thanks for your attention!*

