Technical University of Munich
Department for Physics

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# Characterization and First Integration of the TRISTAN Detector

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For the KATRIN collaboration

DPG Spring Meeting, Dortmund

# Content

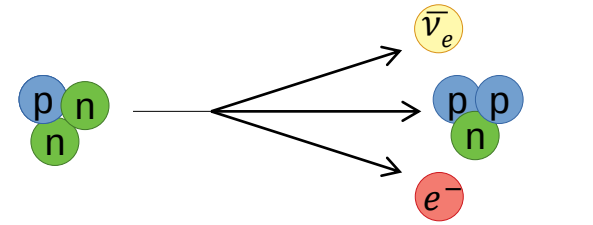
- Introduction to KATRIN and TRISTAN
- X-ray performance
- First integration at the KATRIN site
- Summary

# Idea of TRISAN

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \\ |\nu_S\rangle \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{S1} & U_{S2} & U_{S3} & U_{S4} \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \\ |\nu_4\rangle \end{pmatrix}$$

Idea: Search for a keV sterile neutrino with the KATRIN experiment

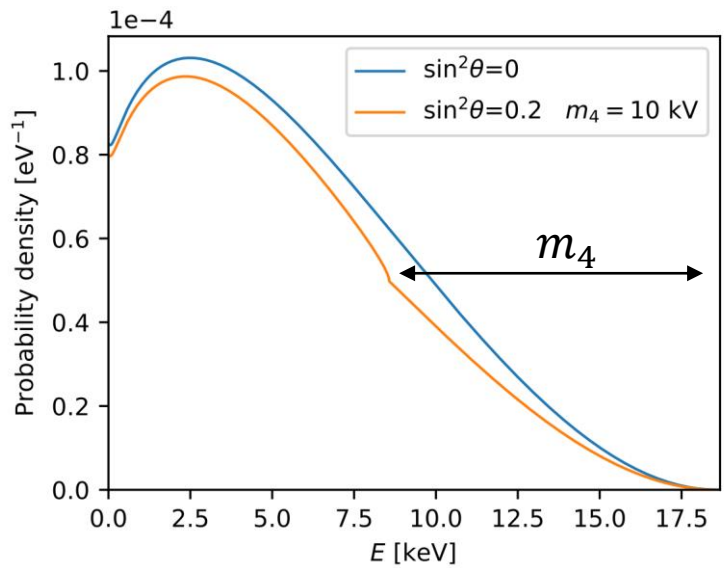
- **Sterile neutrino**:
  - Hypothetical heavy mass eigenstate mixed into the $\overline{\nu}_e$
  - Several theoretical motivations:
    - Warm dark matter candidate
    - ...




$$^3\mathrm{H} \longrightarrow {}^3\mathrm{He} + e^- + \overline{\nu}_e$$

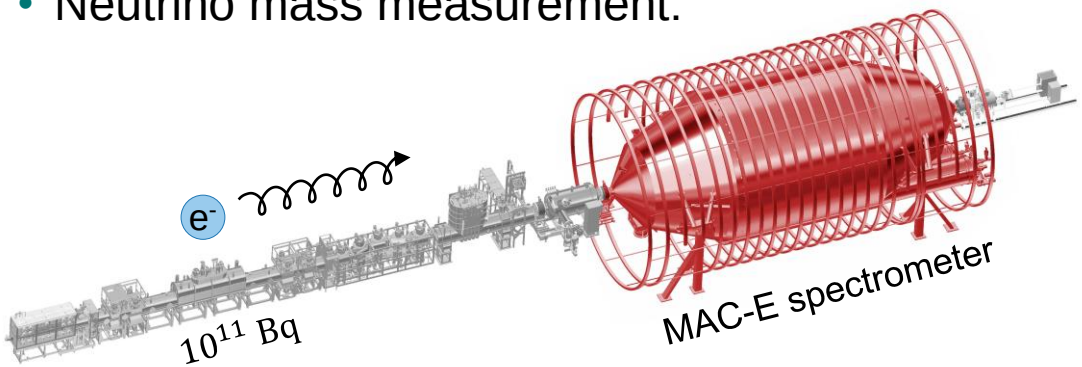
- Imprint of a sterile neutrino on tritium β-decay:
  - If mass is in the keV regime: Kink-like signature in electron spectrum of tritium β-decay

- What do we need to measure this kink with KATRIN?

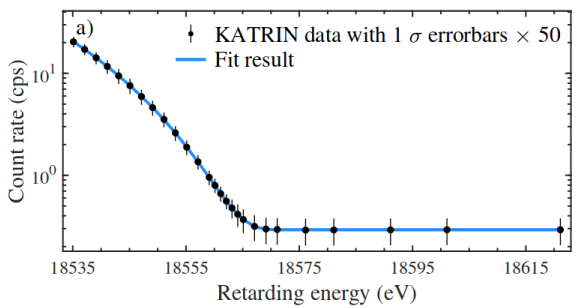


# The KATRIN experiment and TRISTAN

- Neutrino mass measurement:

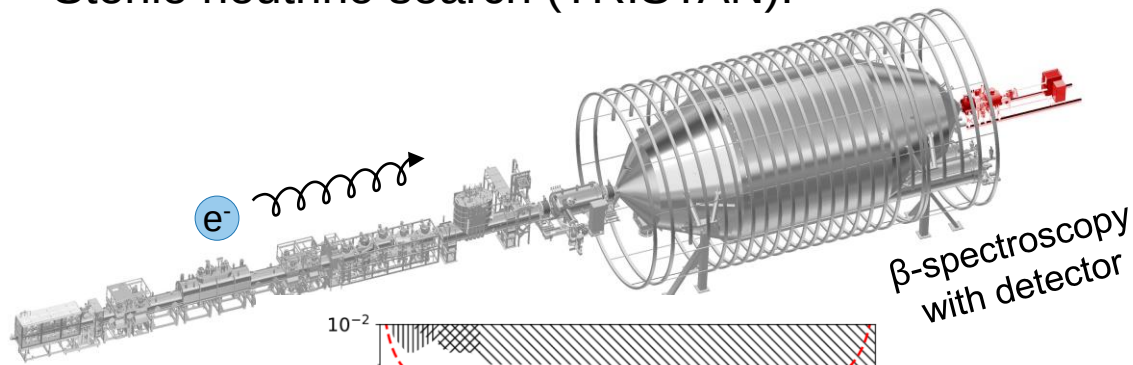


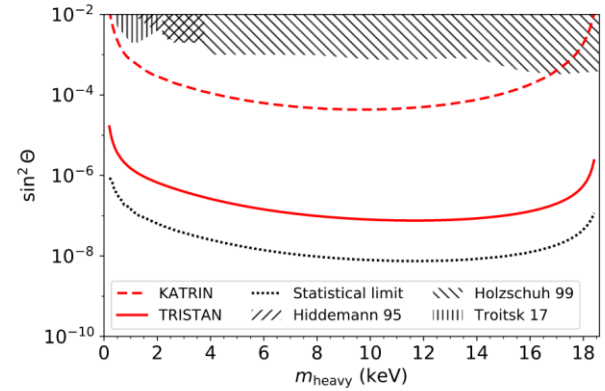

- **Integral** measurement, near endpoint




2020: Aker et al.: Improved Upper Limit on the Neutrino Mass from a Direct Kinematic Method by KATRIN, DOI: 10.1103/PhysRevLett.123.221802

- Sterile neutrino search (TRISTAN):




- **Differential** measurement, deep in the spectrum
  - High rate at detector ($\sim 10^8$ cps)
  - Excellent detector resolution ($\sim 300$ eV)

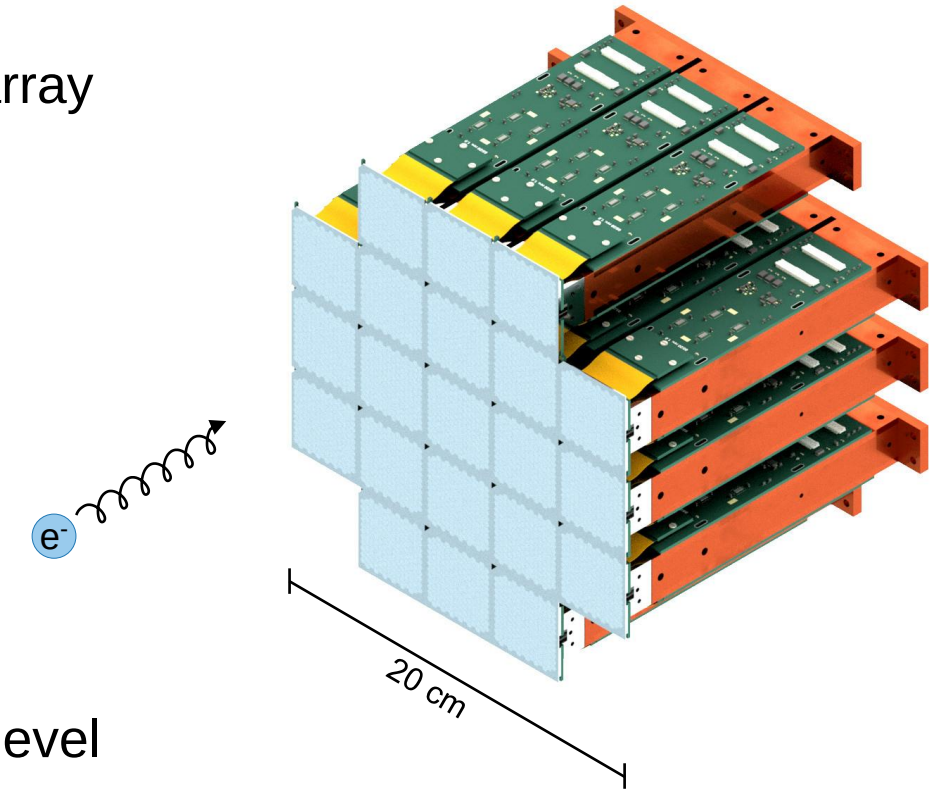
→ New detector being developed

2019: Mertens et al: A novel detector system for KATRIN to search for keV-scale sterile neutrinos, DOI: 10.1088/1361-6471/ab12fe

# About the TRISTAN Detector

New detector for high rate, high resolution β-spectroscopy:

- Multi-pixel Silicon Drift Detector (SDD) focal plane array
- ~3000 pixels, grouped into 166-pixel modules
- 3 mm pixel diameter
- Aimed count rate: $10^5$ cps per pixel
- More challenges:
  - Environmental constrains, mechanics, etc ...
  - Understand detector response to a very precise level



# Available Devices

- Until 2020: “Prototype-0” devices, test of β-spectroscopy with SDDs
  - X-ray and electron characterisation (https://doi.org/10.1088/1361-6471/abc2dc)
  - Sterile neutrino search at Troitsk spectrometer (https://doi.org/10.1088/1748-0221/14/11/P11013)
  - Application as Beam Monitor in KATRIN

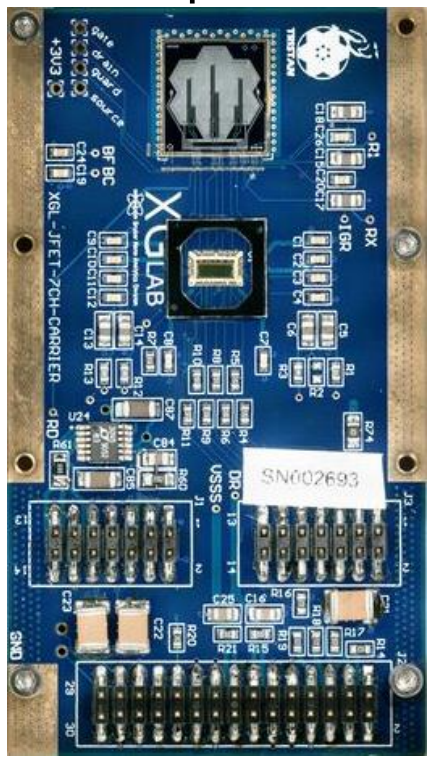
- Early 2020: First “final” TRISTAN SDD production ready by HLL
  - Now: JFET integrated into anode
  - Enables larger devices, 40x40 mm

- Devices with 7, 12, 47 and 166 pixels available

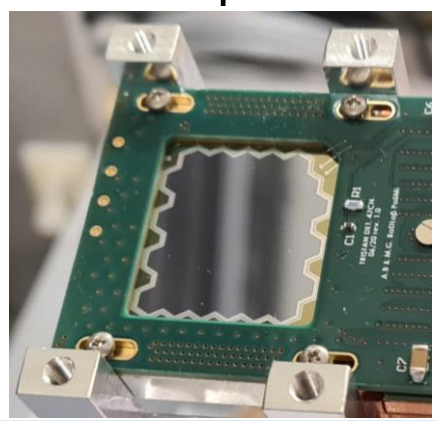
- Readout by ASIC “Ettore”

- In this talk: Characteristics of new 7-pixel devices
- Motivation: Very good understanding of detector is required for TRISTAN

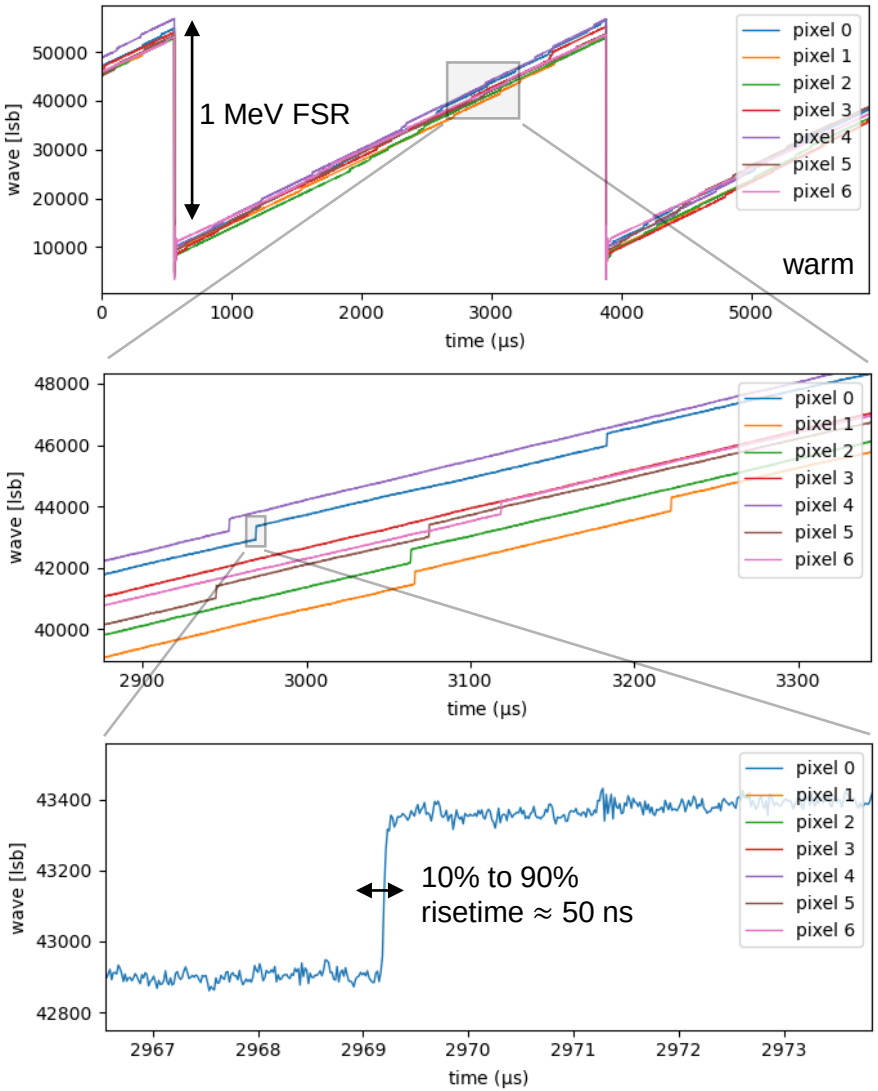
7-pixel

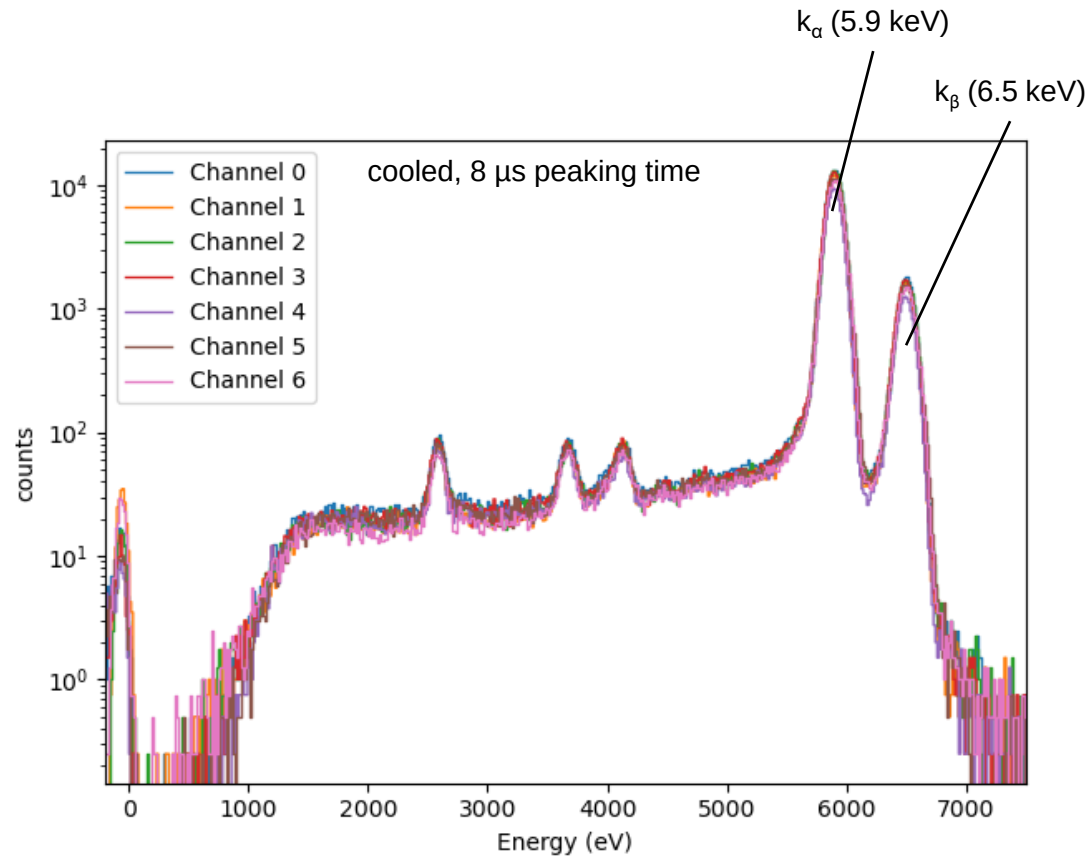



47-pixel



# $^{55}$Fe X-ray Performance

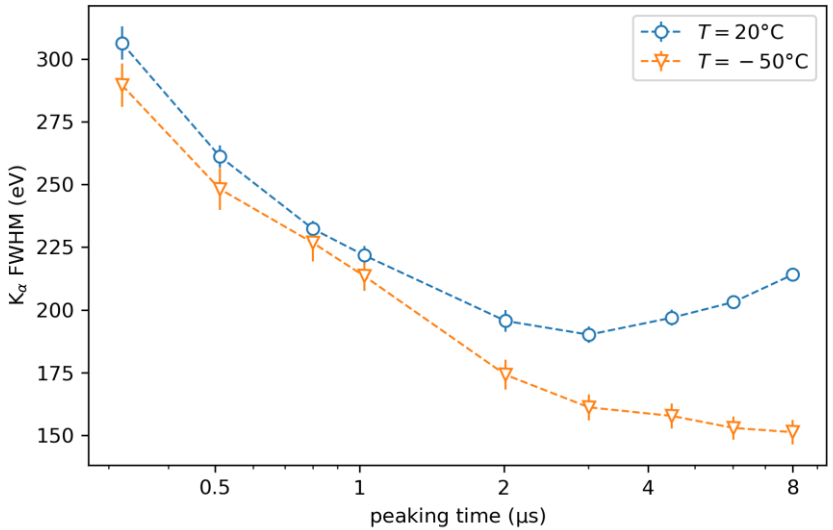


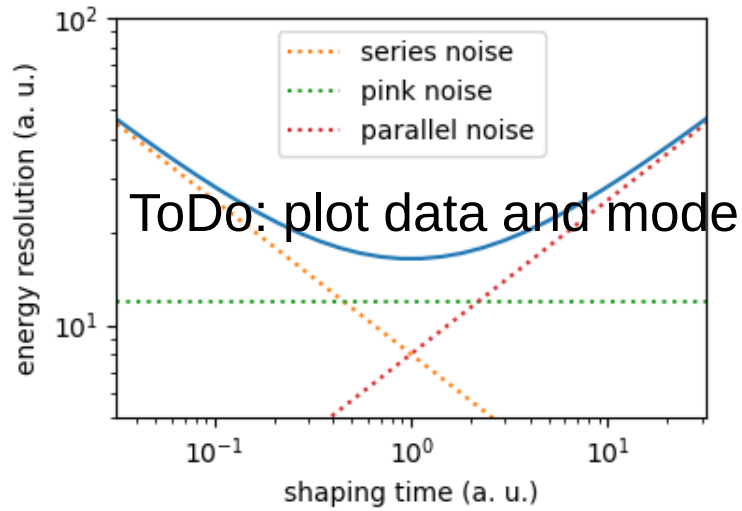
# Energy Resolution for 5.9 keV X-rays

- Energy resolution @ 8 µs peaking time: 150 eV FWHM
- Energy resolution @ 1 µs peaking time: 220 eV FWHM
- Simplified model for the electronics noise:

$$\mathrm{ENC}^2 = \underbrace{\frac{C^2 8 k_B T}{3 g_m} A_1 \frac{1}{\tau}}_{\text{series noise}} + \underbrace{C^2 H A_2}_{\text{pink noise}} + \underbrace{\frac{2eI}{(2\pi)^2} A_3 \tau}_{\text{parallel noise}}$$




| | | |
|---|---|---|
| $I$: | Leakage current to the anode | $\sim 11$ pA at room temperature |
| $C$: | Anode capacitance | $\sim 150$ fF |
| H: | 1/f coefficient | $\sim 10^{-11}\mathrm{V}^2$ |
| $T$: | Temperature | $\sim 300$ K |
| $g_m$: | Transconductance of the JFET | $\sim 150$ µA/V |
| $A_1, A_2, A_3$: | Constants for trapezoidal filter | |



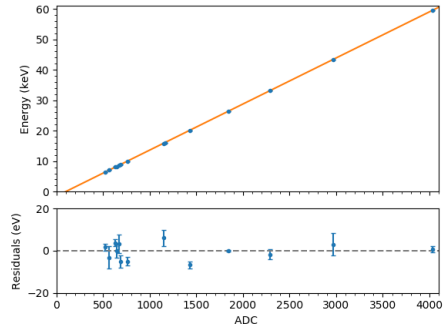

➢ Series noise is higher than expected, reason found in increased contact resistance in this specific wafer production

➢ Hope for even better performance in next production

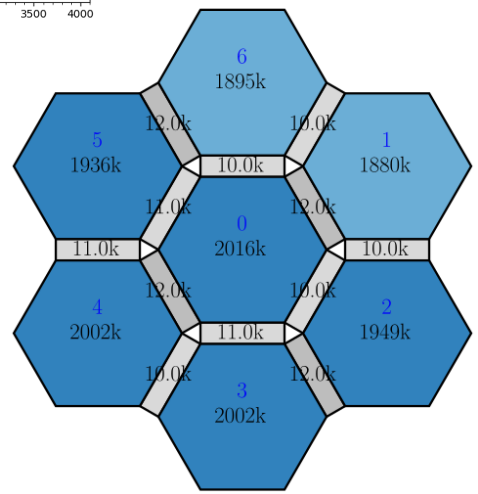
See for example: E. Pinotti el. al. (1993) The pn-CCD on-chip electronics https://doi.org/10.1016/0168-9002(93)90337-H

# Other characterization

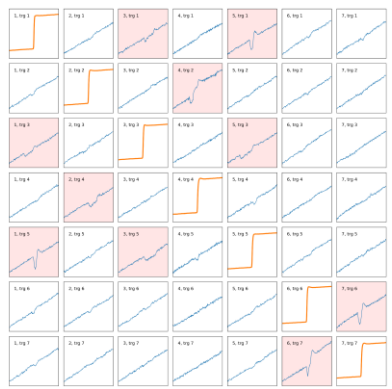
- Good linearity **<0.1%**




- Pixel border effects characterized



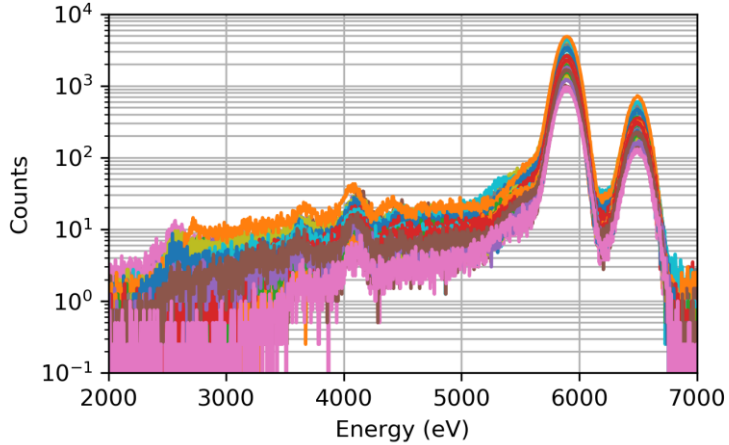

- Work in progress:
  - Response to electrons
  - Crosstalk is investigated

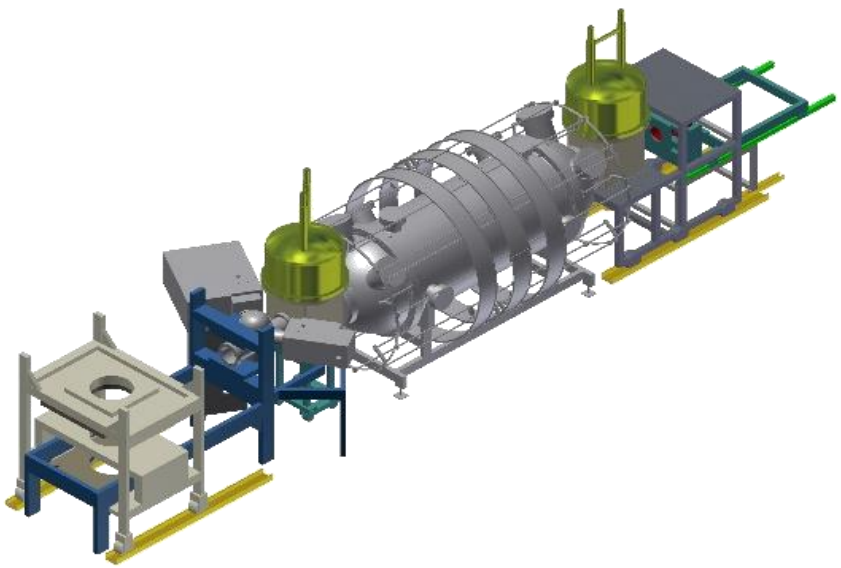


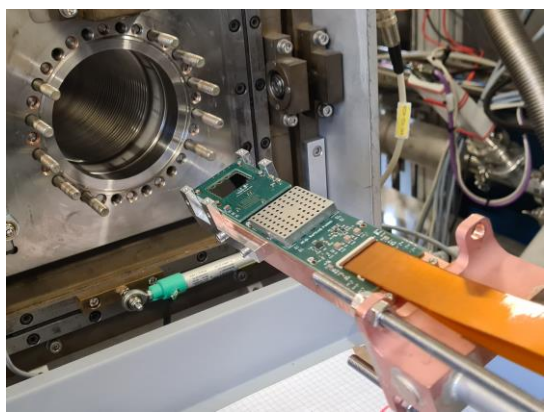
In parallel:
- Commissioning of the final TRISTAN detector module

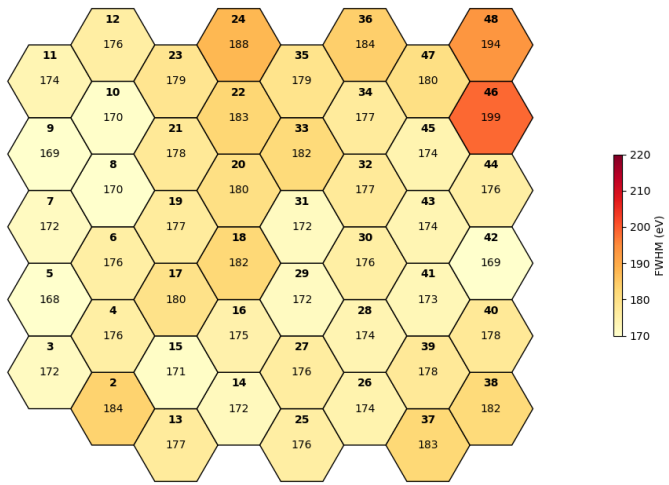
# First 47-pixel TRISTAN SDD integration at KATRIN site

- Since November: First successful integration of a planar 47-pixel TRISTAN detector in a realistic environment
- Location: Monitor Spectrometer at KATRIN site
- More details in Talk by Daniel Siegmann (Thursday, **T 94.9**)







# Conclusion and Outlook

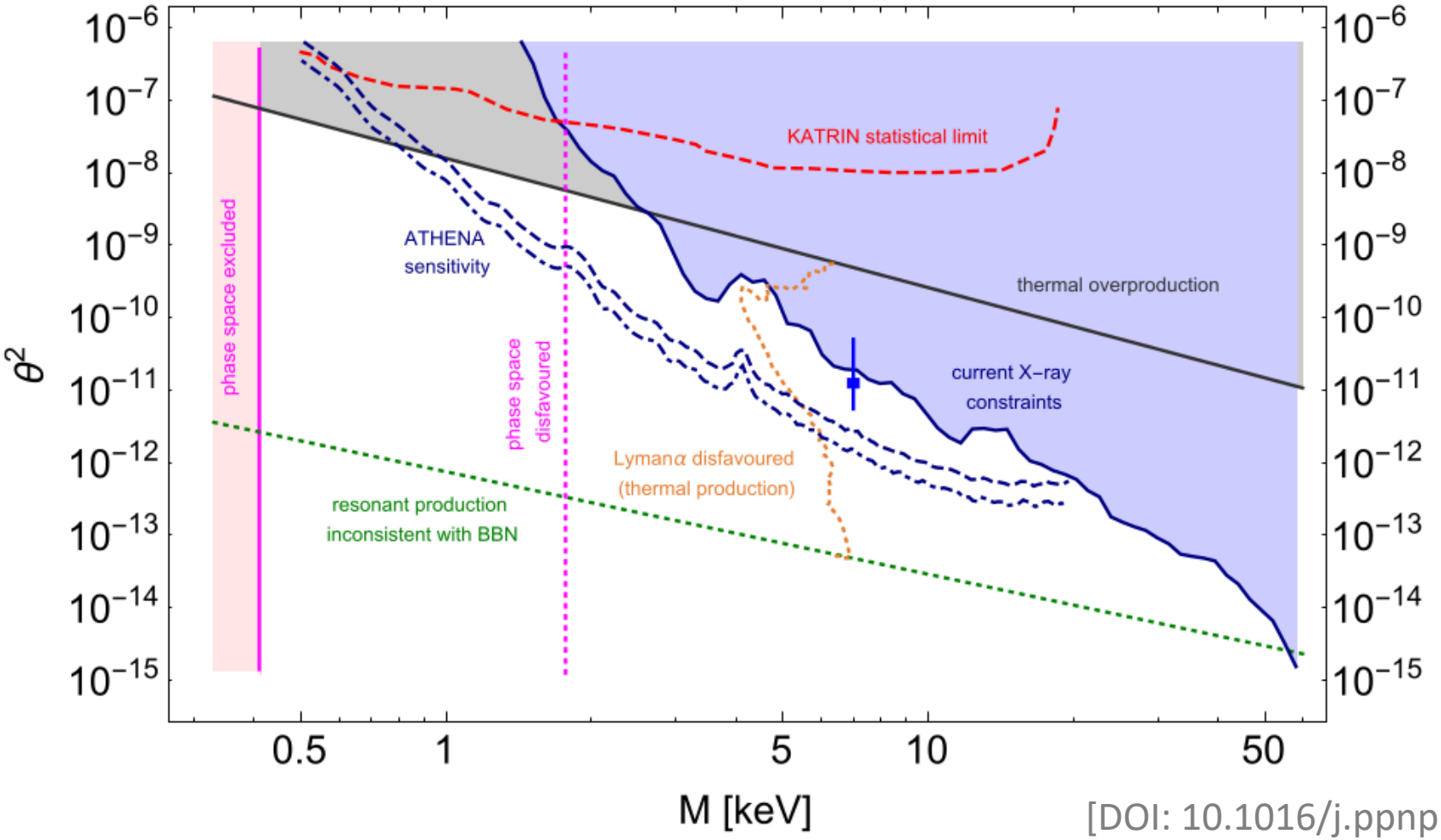
- New Generation of TRISTAN detectors shows good performance
- Successful first 47-pixel tests in a realistic environment

**Next steps:**

- Now (March 2020): First assembly and installation of a 47-pixel 3D module
- This year: First assembly of a 166-pixel 3D module

**Thanks for your attention!**

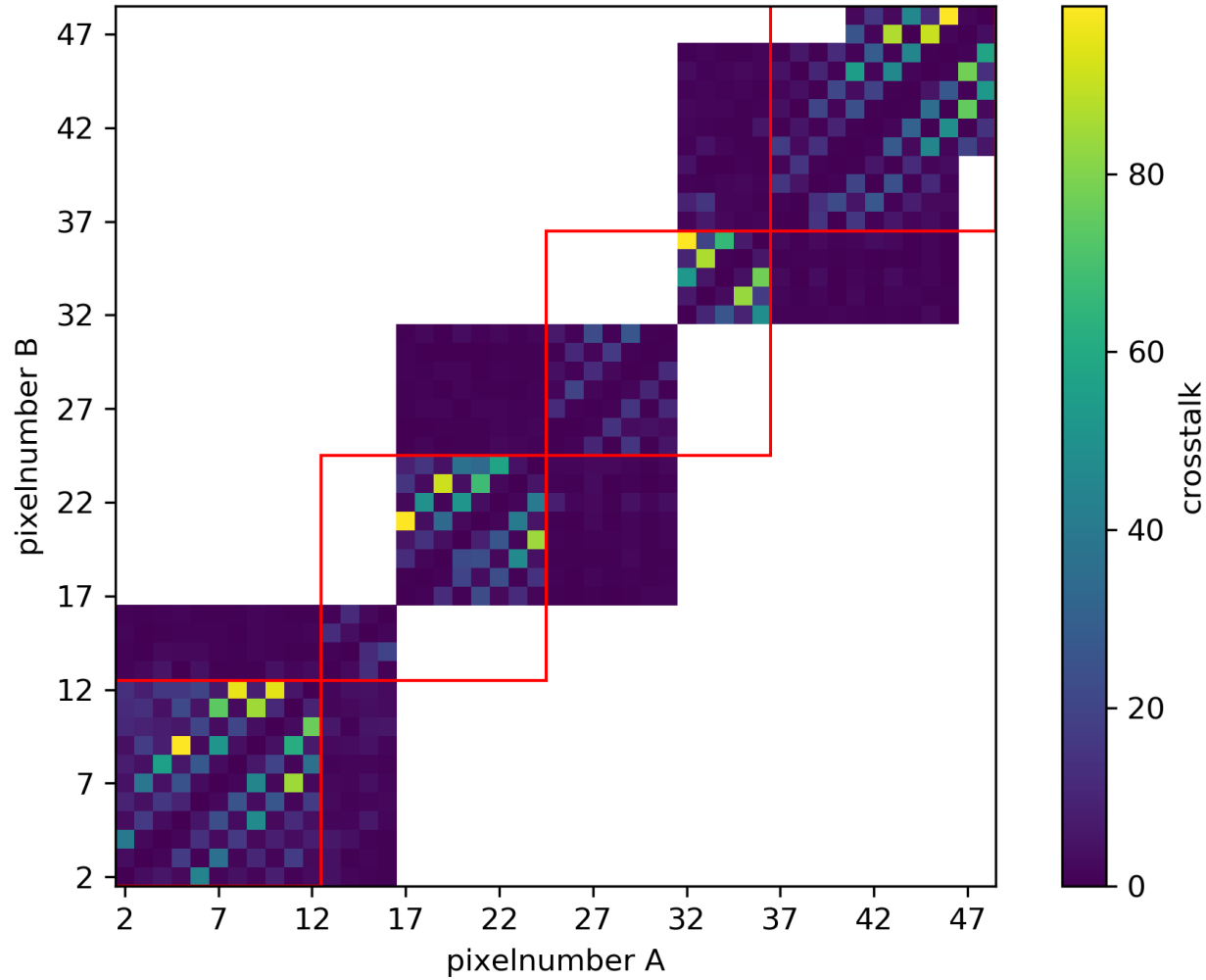
# Sterile Neutrinos as Dark Matter



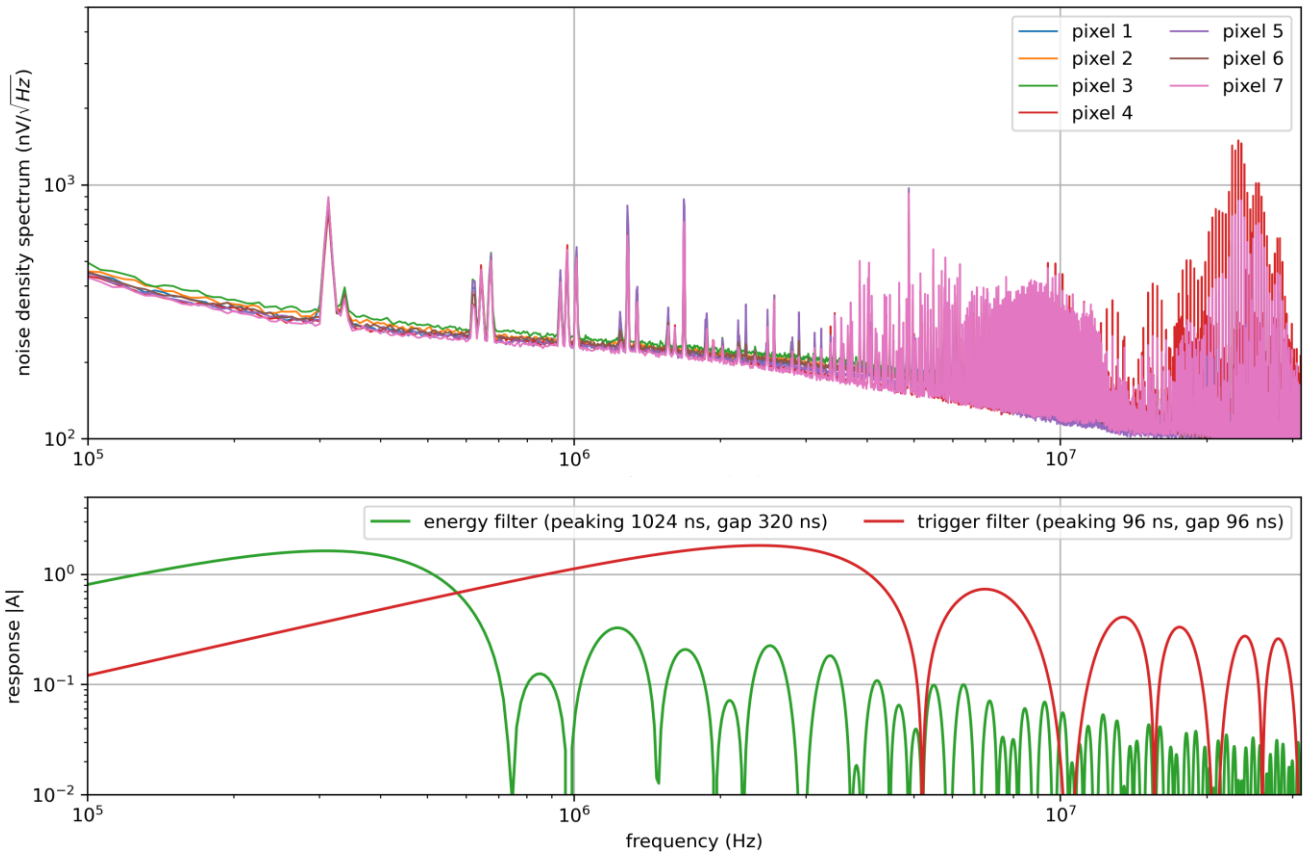

[DOI: 10.1016/j.ppnp.2018.07.004]

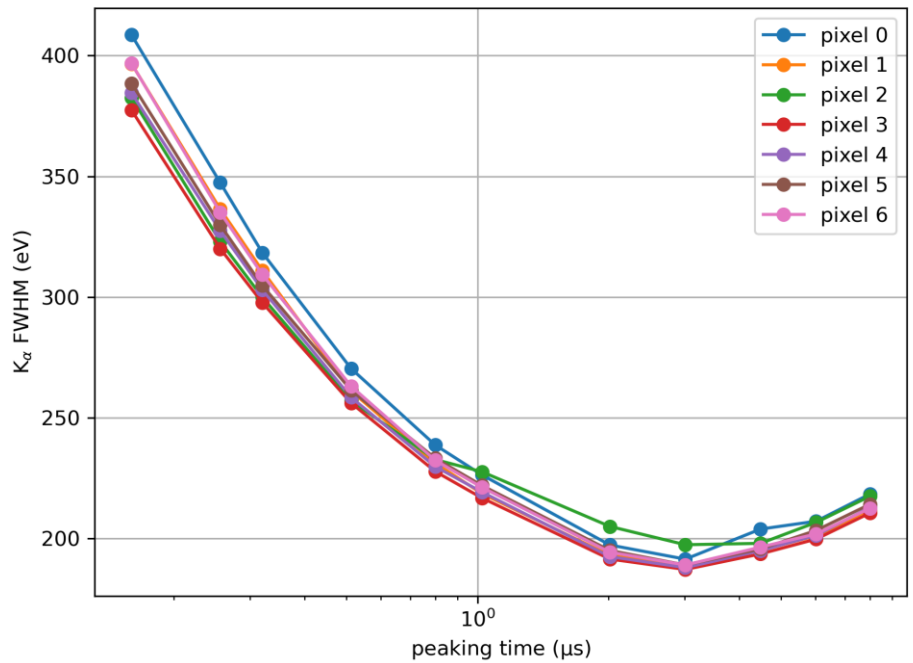
# Backup

- Crosstalk in 47 pixel setup
- Missing: Image of readout

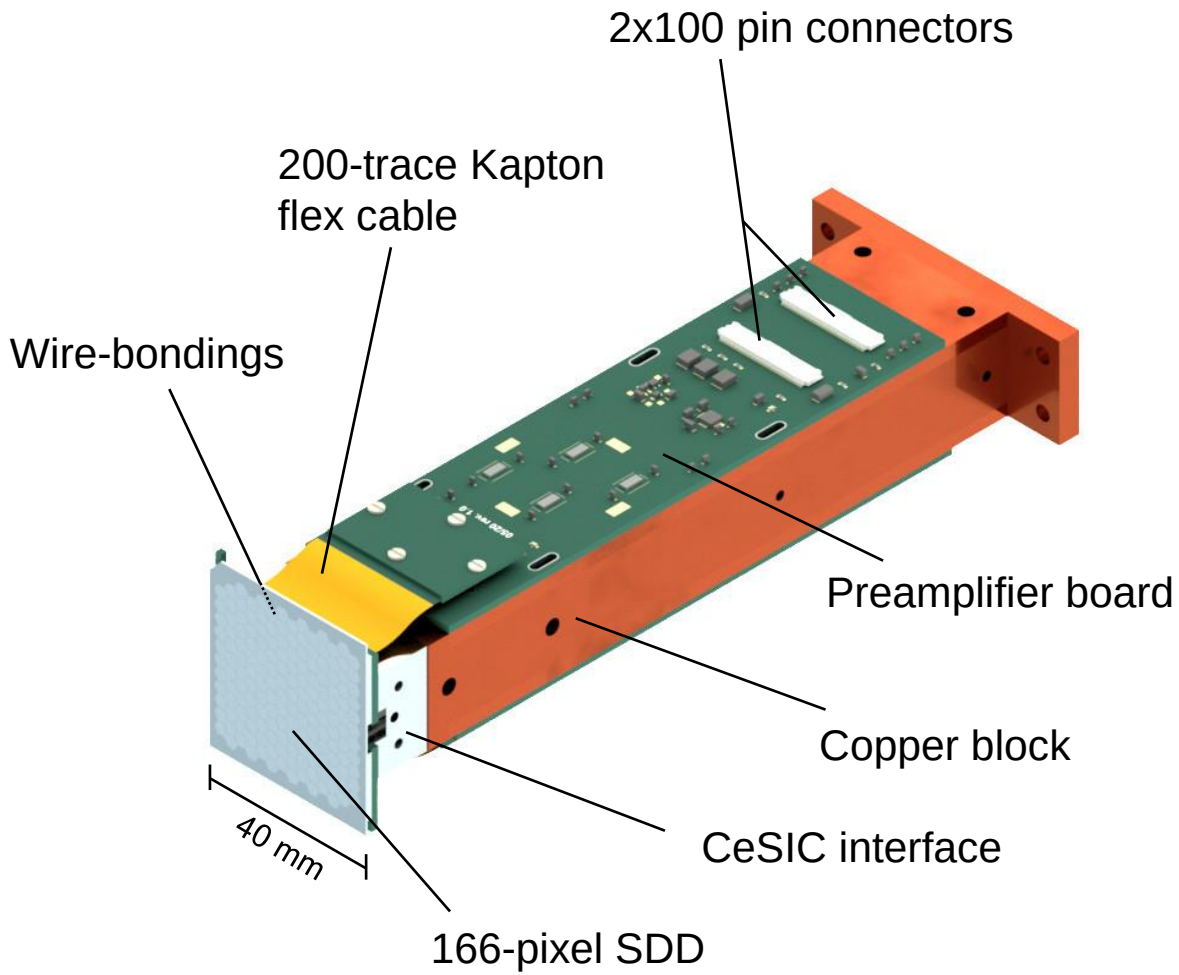


# Backup: Noise Density Spectrum



# The 3D-detector module and Integration

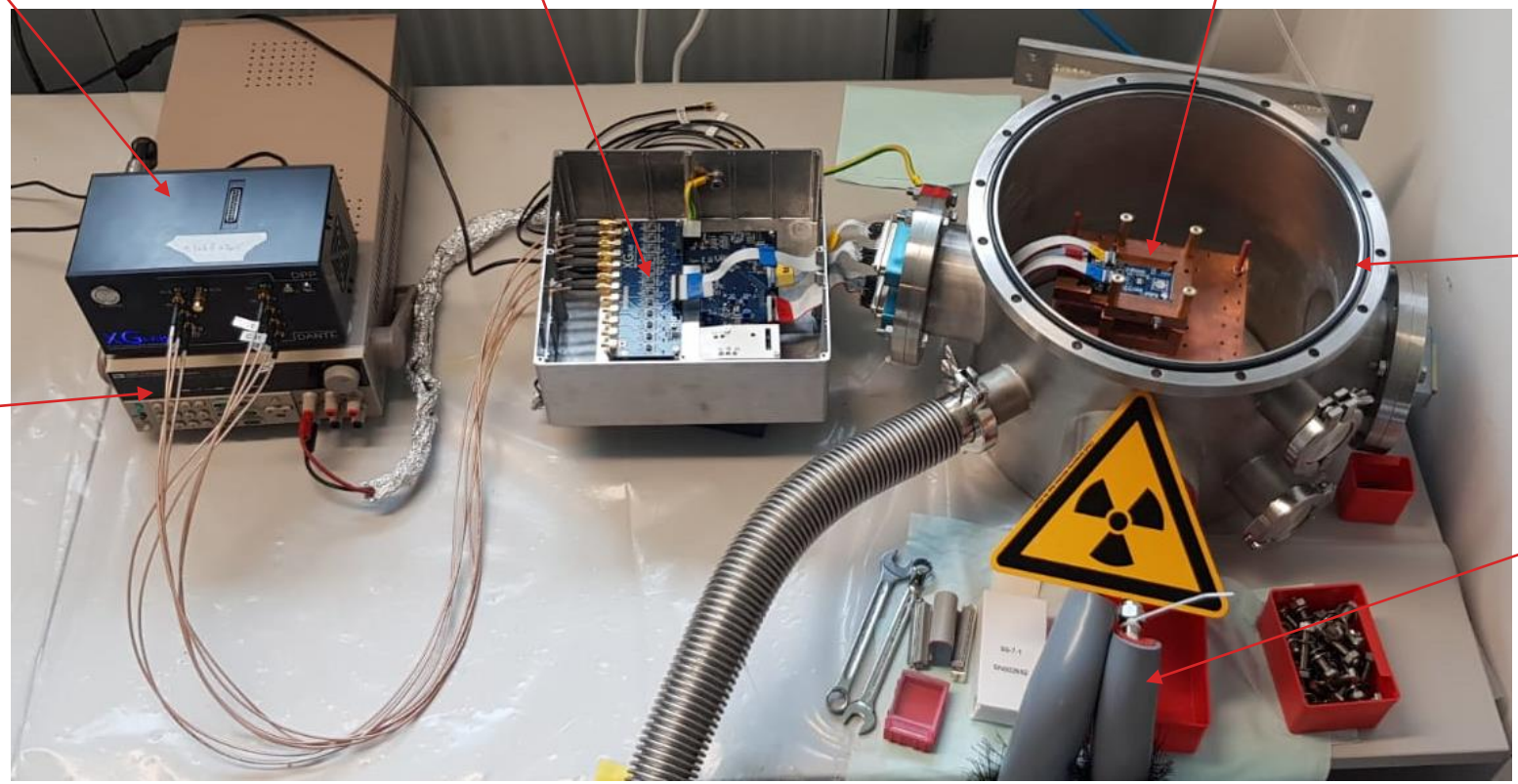


# Test Setup

**DAQ**:
- DANTE 8-pixel pulse processor
- full waveform digitization

**bias board,** provides:
- supply voltages
- reset logic
- signal buffers

**detector board**, contains:
- 7-pixel TRISTAN detector, integrated JFET
- ETTORE preamplifier ASIC



**power supply**

**vacuum chamber**
- multiple sources: $^{55}$Fe, $^{241}$Am, Kr, …

**optional cooling**

# About the TRISTAN Detector