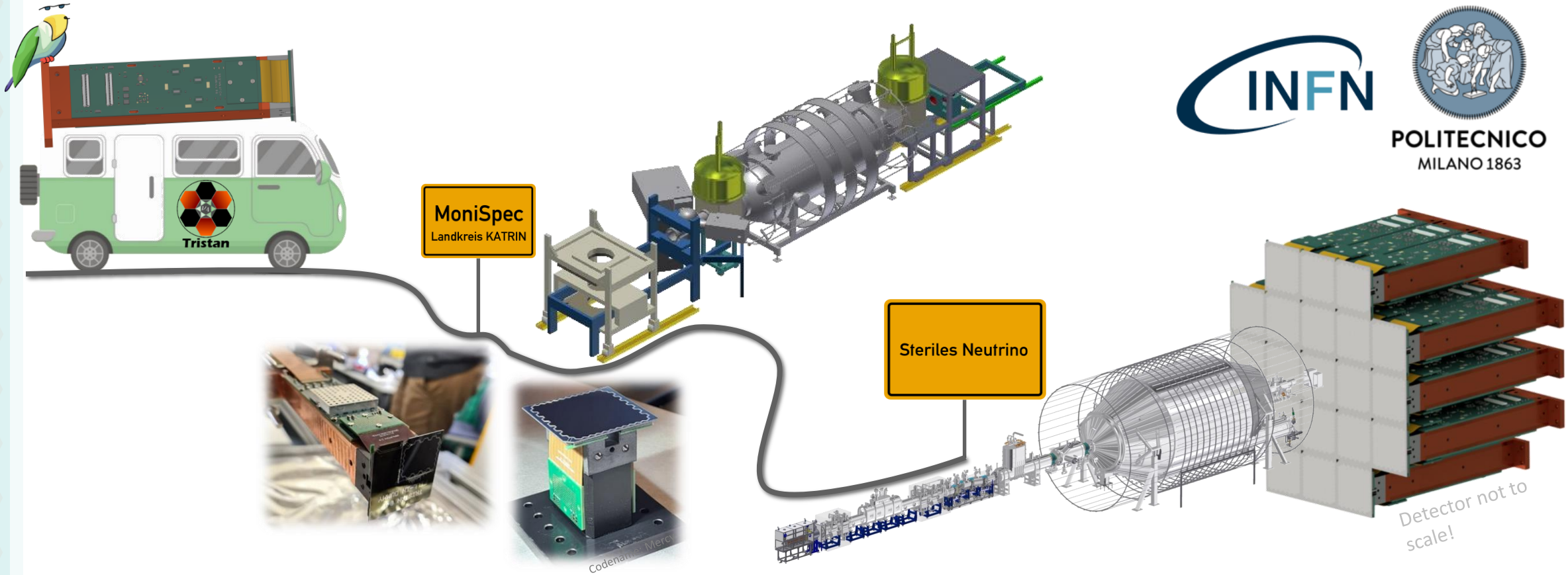
Imaging X-Ray Photons and Electrons with the Spectroscopic 166-Pixel Monolithic TRISTAN SDD

A KEV STERILE NEUTRINO SEARCH WITH KATRIN

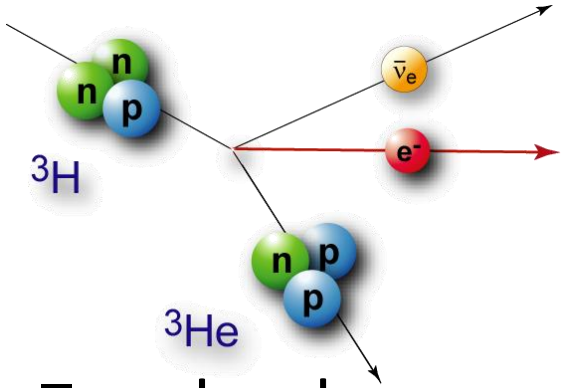


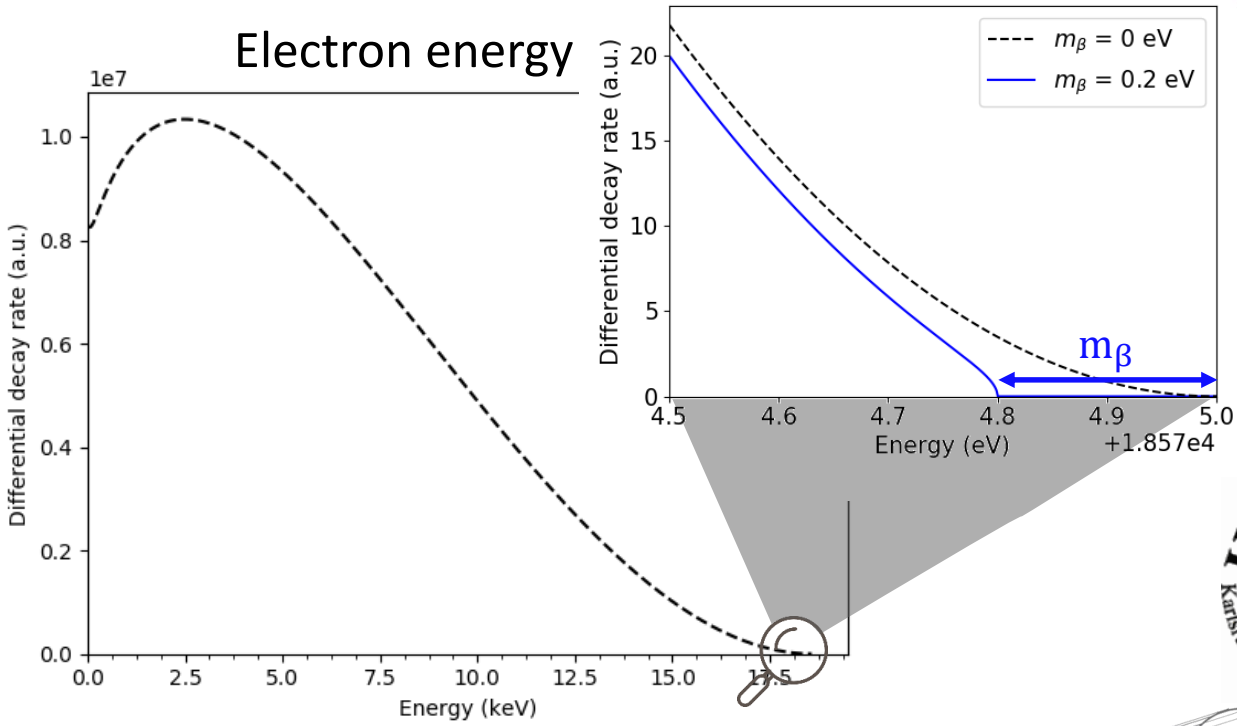
Max Planck Institute for Physics, Munich
KATRIN Collaboration – TRISTAN Group

Daniel Siegmann and Prof. Marco Carminati

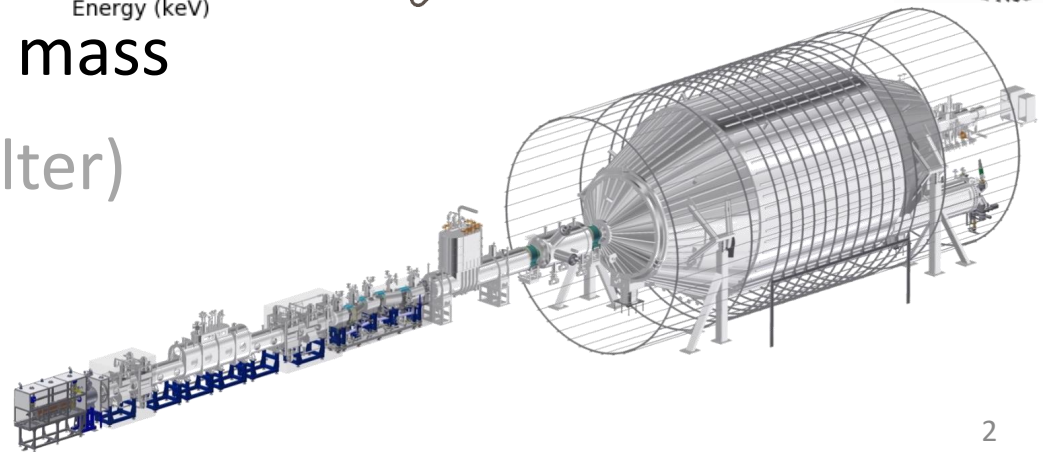
Neutrinos and the KATRIN Experiment

- β-decay of tritium





- e^- and ν share energy
- $E_{e^-} = E_{Total} - E_\nu$
- Measurement of effective neutrino mass
- MAC-E filter principle (~high pass filter)
- $m_\nu < 0.9$ eV (90% CL)

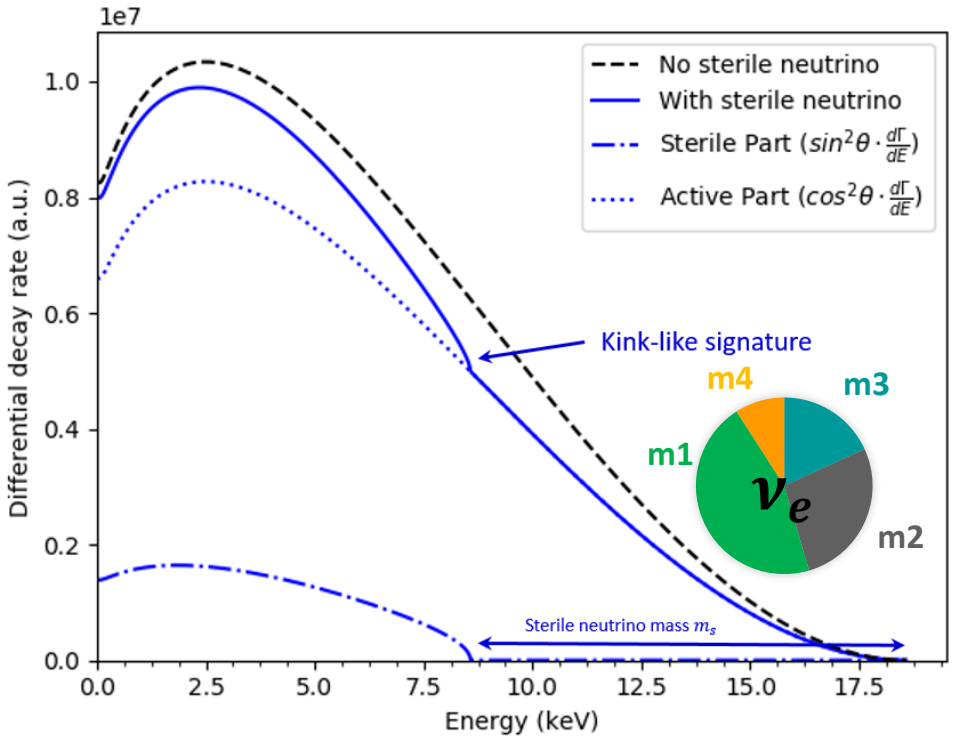


KATRIN Collab. Nat. Phys. 18, 160–166 (2022)

TRISTAN Project – Detector Upgrade for KATRIN

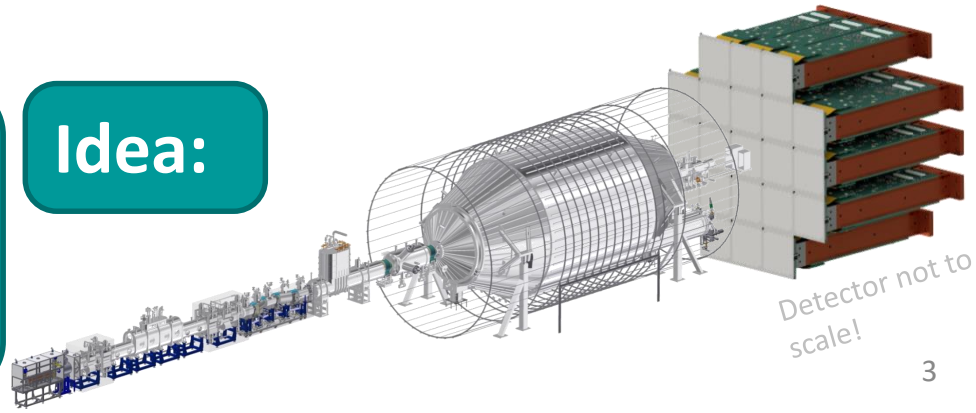
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

- **keV sterile neutrino** search
- **Dark matter** candidate
- Minimal extension to SM
- Tiny **kink**-like imprint in β-decay
- Target sensitivity $|U_{e4}|^2 = 10^{-6}$
  - High rates required $\mathcal{O}(10^8$ e/s)
- After ν-mass campaign completed



➢ **TRISTAN** Project = **high precision electron spectroscopy detector upgrade** for the KATRIN experiment

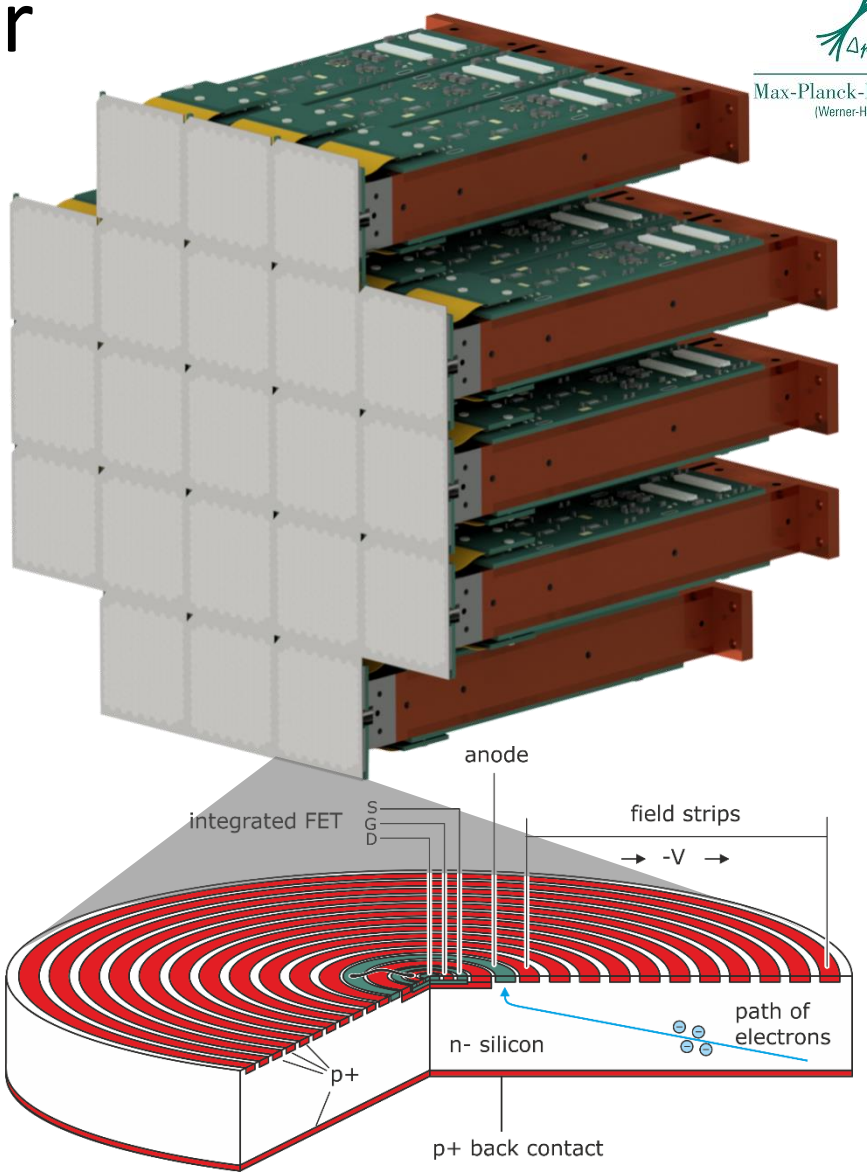
Idea:



Challenges for TRISTAN Detector

- High electron rates $\mathcal{O}(10^8$ e/s)
  - 3500 Pixel (100 kcps per pixel)
  - Flux-tube Ø 20 cm -> Ø 3mm pixels
- Energy resolution < 300 eV (@20 keV)
  - Small anode (Ø90 µm)
- Low energy threshold < 2 keV
  - Thin entrance window (< 100 nm)

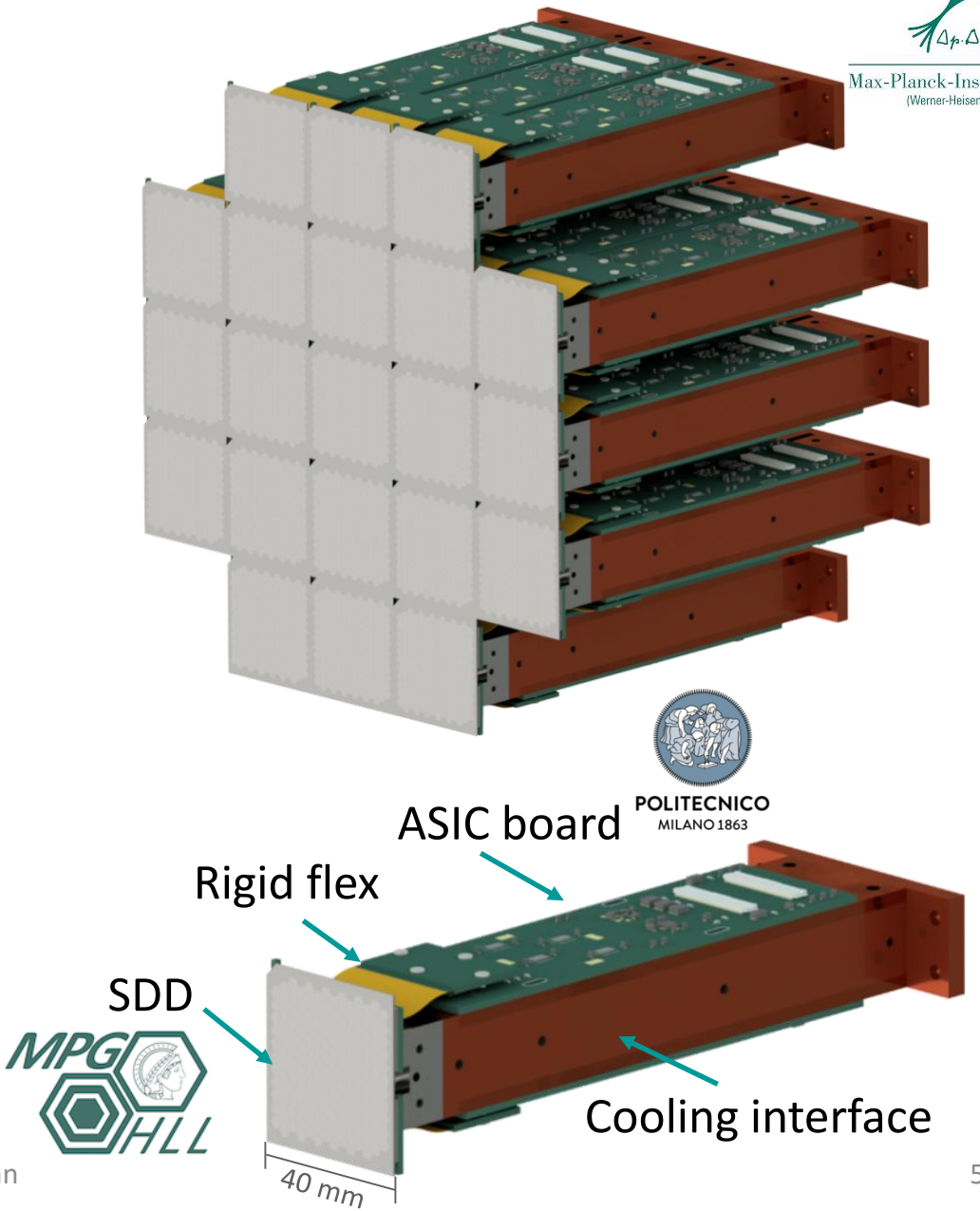
➢ **Silicon Drift Detector**



Design Considerations

- Maximize detection area
  - Hide electronics behind SDD
- Good energy resolution
  - Short distance to amplifier
  - Operate detectors at -50 °C
- Modularity
  - Manufacturing & repair
  - Easier to upscale

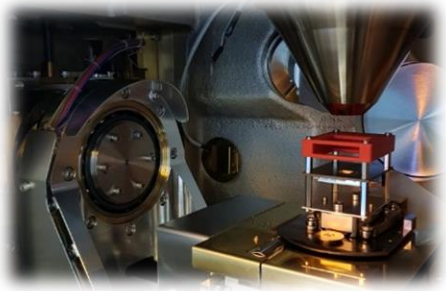
➢ 21 Modules with each 166 pixel



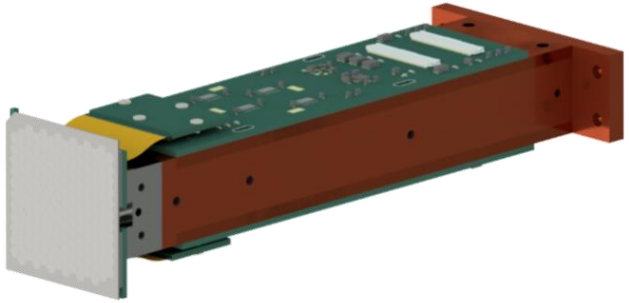
Staged Approach

Proof of concept

Understanding the SDD technology (7 pix)



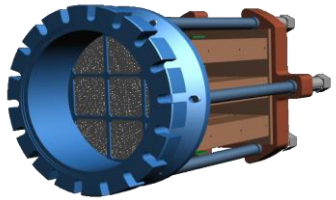
Module (166 pix)



Apply and test detector in realistic environment

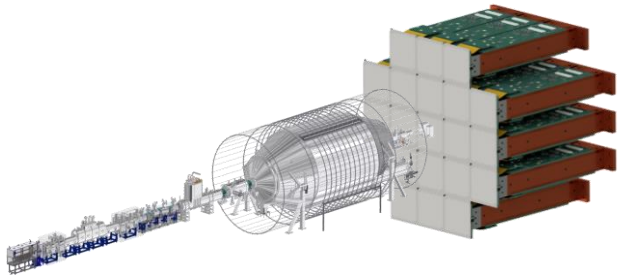
- Monitor spectrometer

Phase 1 (1500 pix)



Sterile search with 9 modules

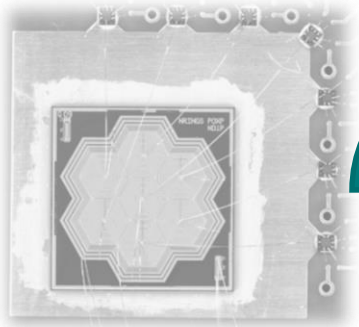
Phase 2 (3500 pix)



Sterile neutrino search with KATRIN (21 modules)

Staged Approach

Proof of concept

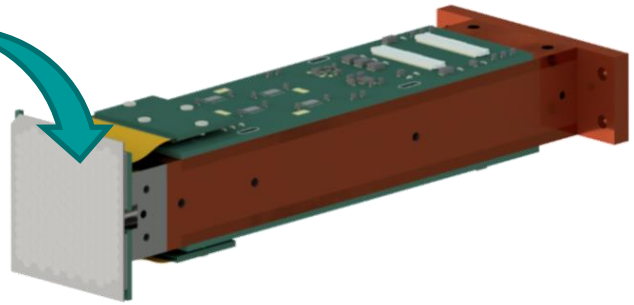


Understanding the SDD technology (7 pix)

(2019, Mertens et al.), Astropart. Phys. 108, 40

(S. Mertens et al 2021) J. Phys. G: Nucl. Part. Phys. 48 015008

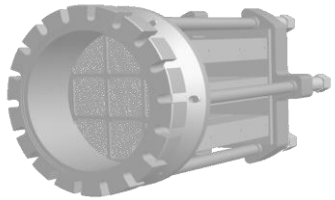
Module (166 pix)



Apply and test detector in realistic environment

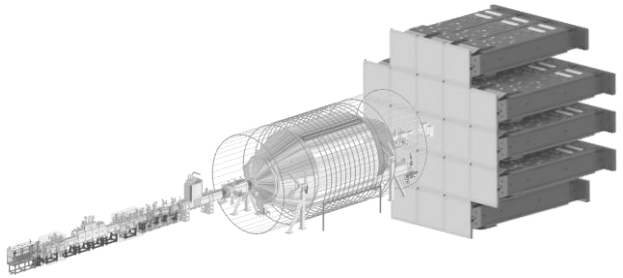
- Monitor spectrometer

Phase 1 (1500 pix)



Sterile search with 9 modules

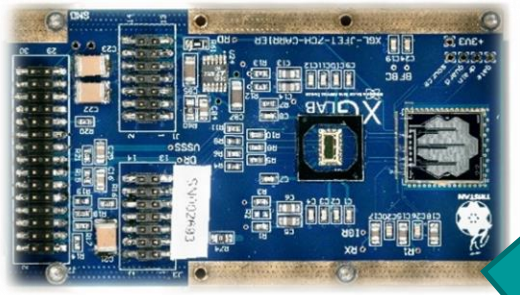
Phase 2 (3500 pix)

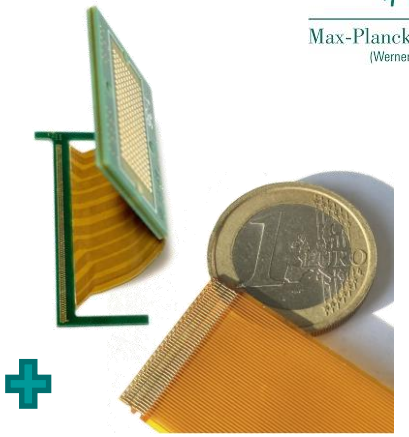


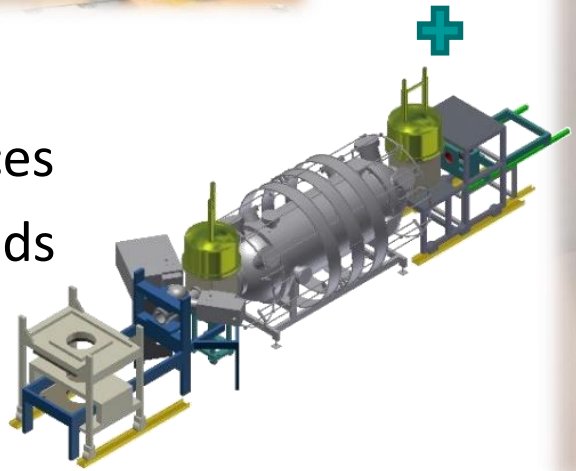
Sterile neutrino search with KATRIN (21 modules)

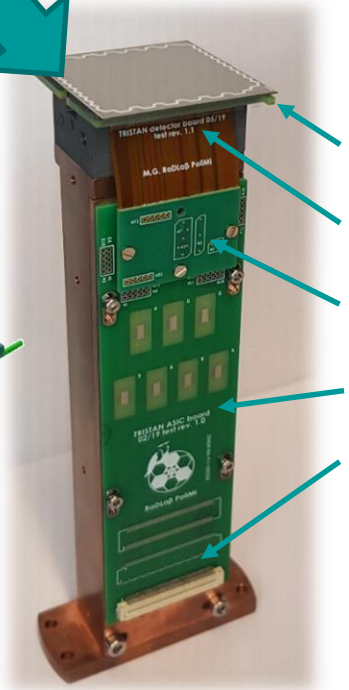
Key challenges towards the 166 pixel module

- 166 independent pixel
  - 400 connections required
  - High density PCB
  - ➢ **Upscaling of electronics**
- Maximize detection area
  - Hide electronics behind SDD
  - ➢ **Assembly/gluing of 3D design**
- Detector performance
  - Resistance against external noise sources
  - Compatibility with vacuum and EM-fields
  - ➢ **Performance in real environment**









SDD

Bonds 2x 200

C-Shape Flex

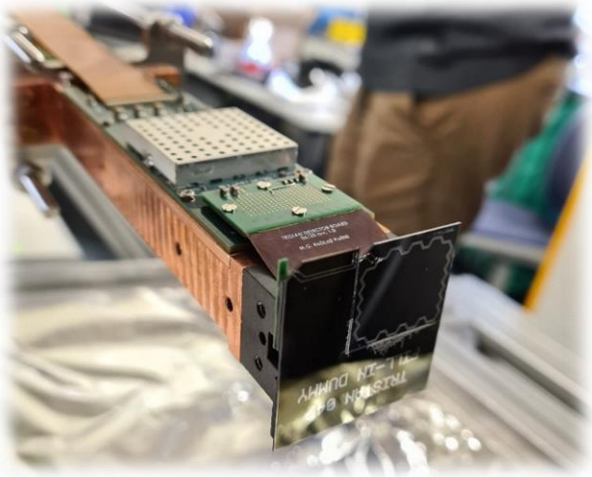
ASIC Board

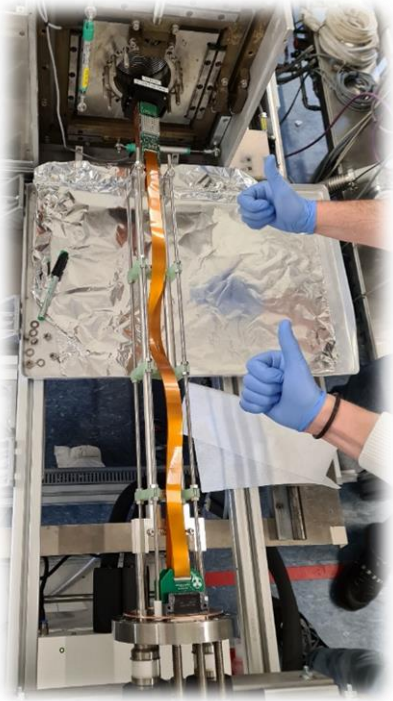
4x 100 Lines

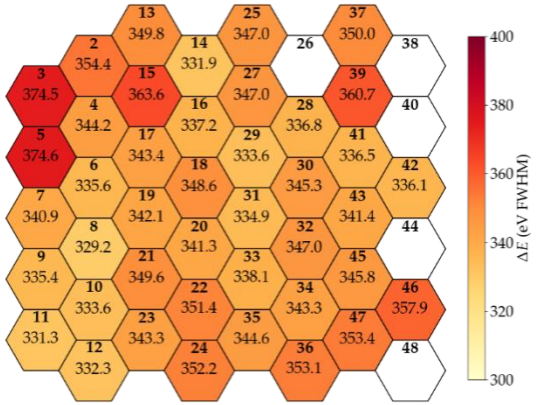
First step - 47 Pixel Detector (March 2021)

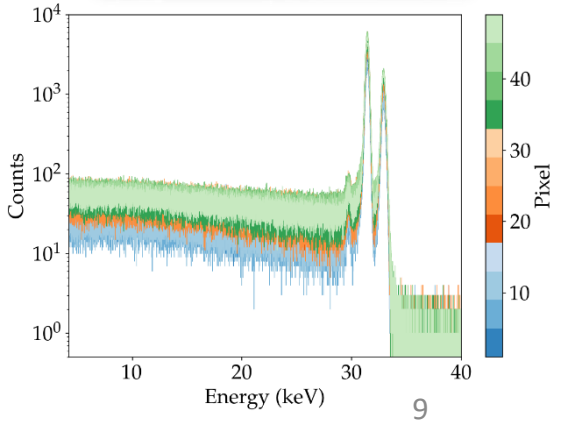
- Assembly of 3D 47 Pixel detector
- Successful installation in MoS
  - Electrons visible in detector
  - $\overline{\mathrm{FWHM}}_{31keV,4\mu s}$ = 345 eV (cold)
    - FWHM(@ 20 keV) ≈ 290 eV
  - Compatible with magnetic fields
  - Vacuum acceptable (Main vessel 2.4e-9 mbar)
- Good check for teething problems
  - Assembly and vacuum shield
  - Slow control and calibration

➢ **Used materials/geometry suitable**



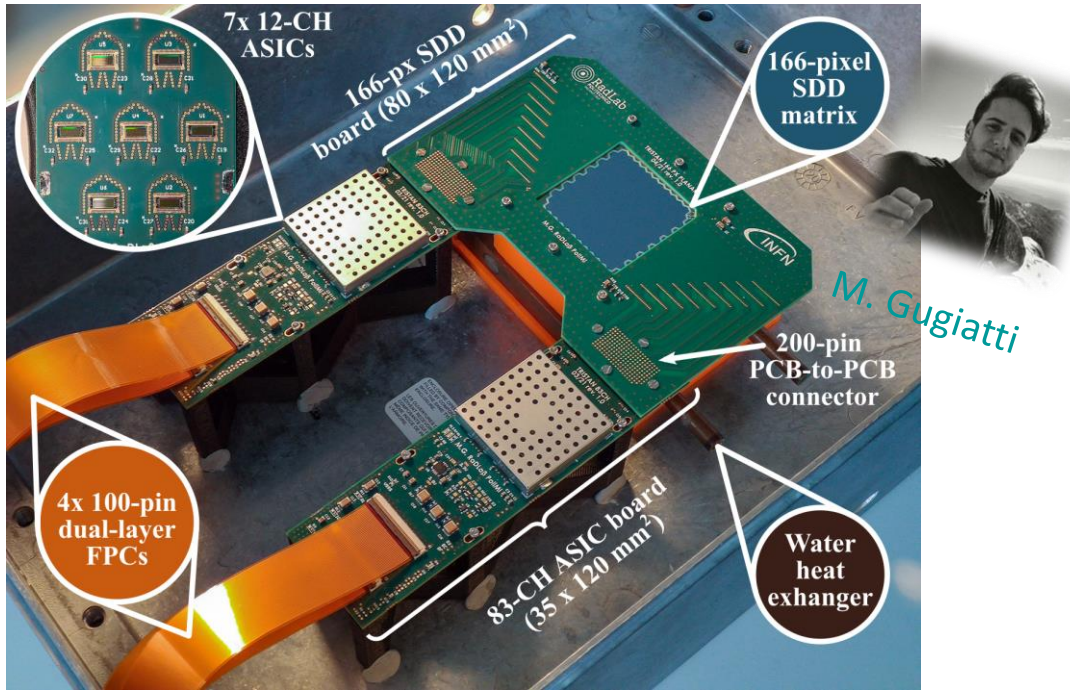




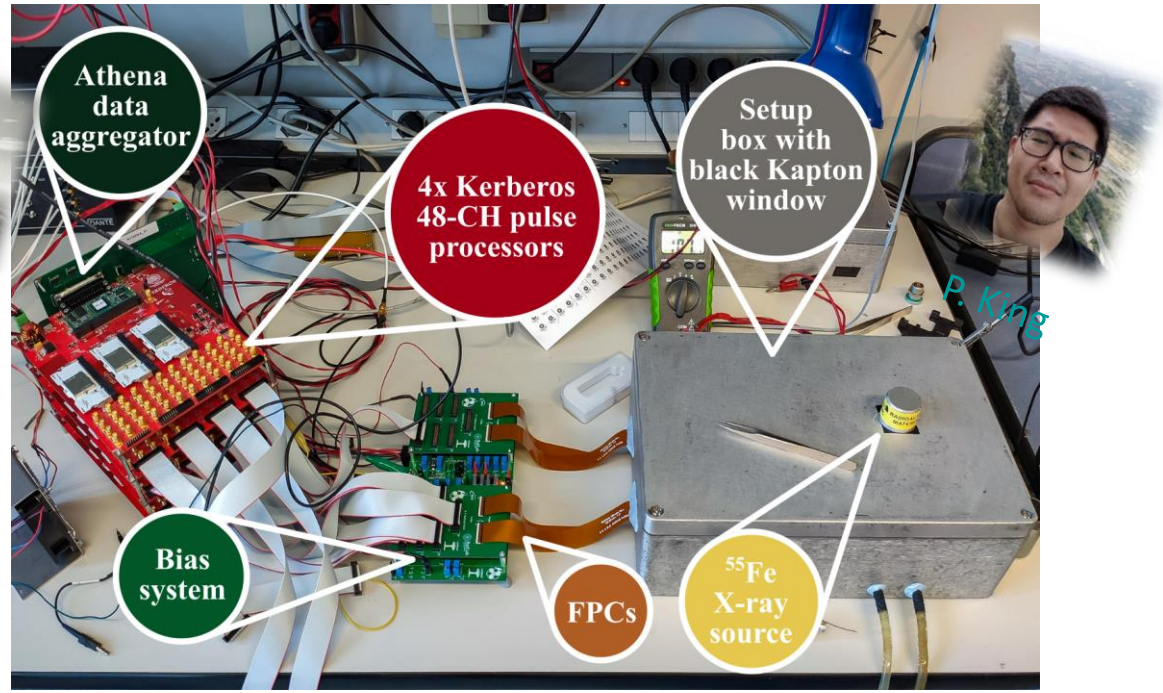


Upscaling Electronics to 166 Pixel

166-PIXEL SDD DETECTION MODULE:



EXPERIMENTAL SETUP FOR X-RAY CHARACTERIZATION:

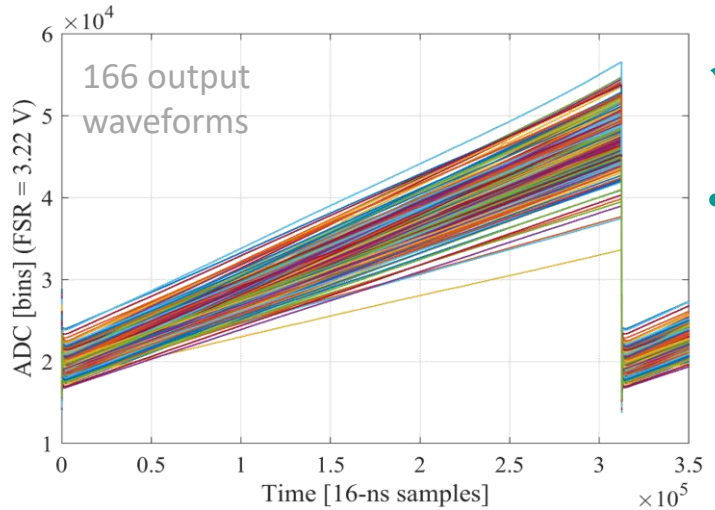


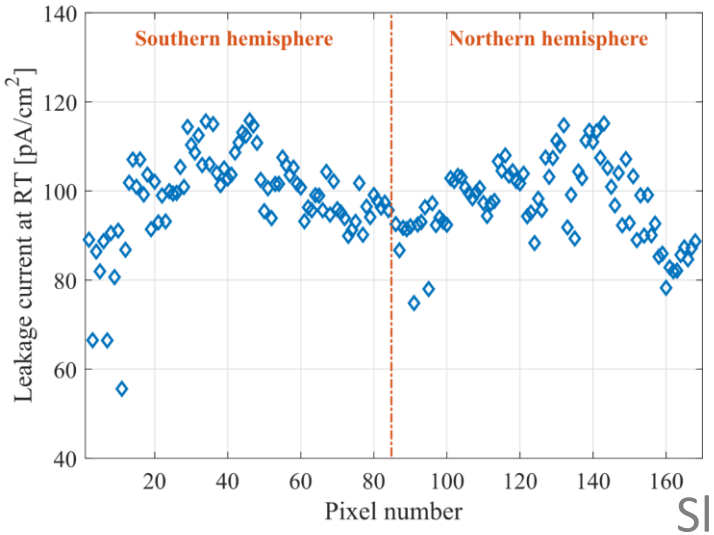
- Development of a new 166-pixel SDD board
- Compact 166-channel bias board
- Athena 192-channel pulse processing platform

Planar 166 Pixel Detector Characterization

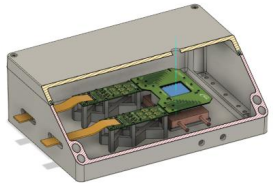
POLITECNICO MILANO 1863

CHARGE PREAMPLIFIER WAVEFORMS AND LEAKAGE CURRENT

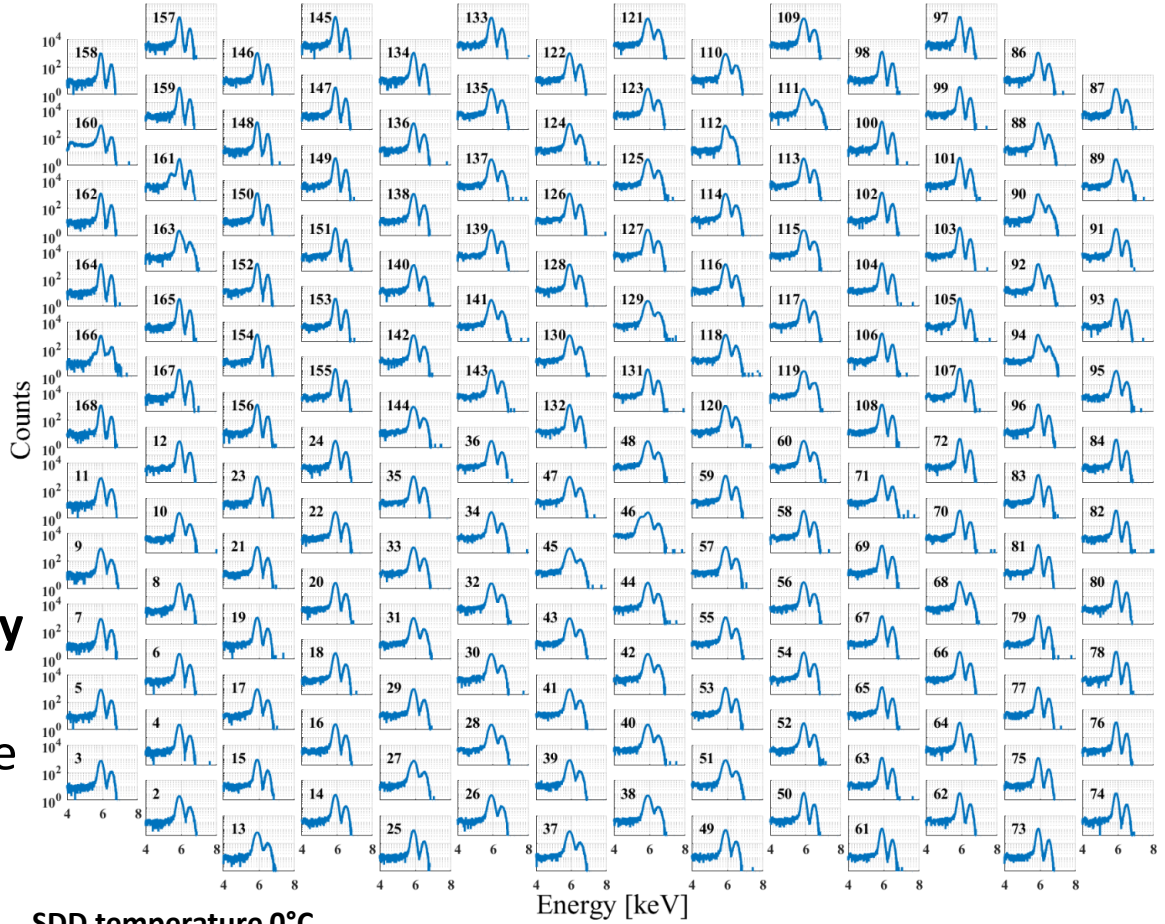




- ✓ **166 out of 166** channels **working**
- Works only with **reduced JFET current** (100 µA)
- ✓ **Good leakage current uniformity** avg. 98 pA/cm² at room temperature



SIMULTANEOUS ^{55}FE X-RAY SPECTROSCOPY WITH 166 SDD PIXELS

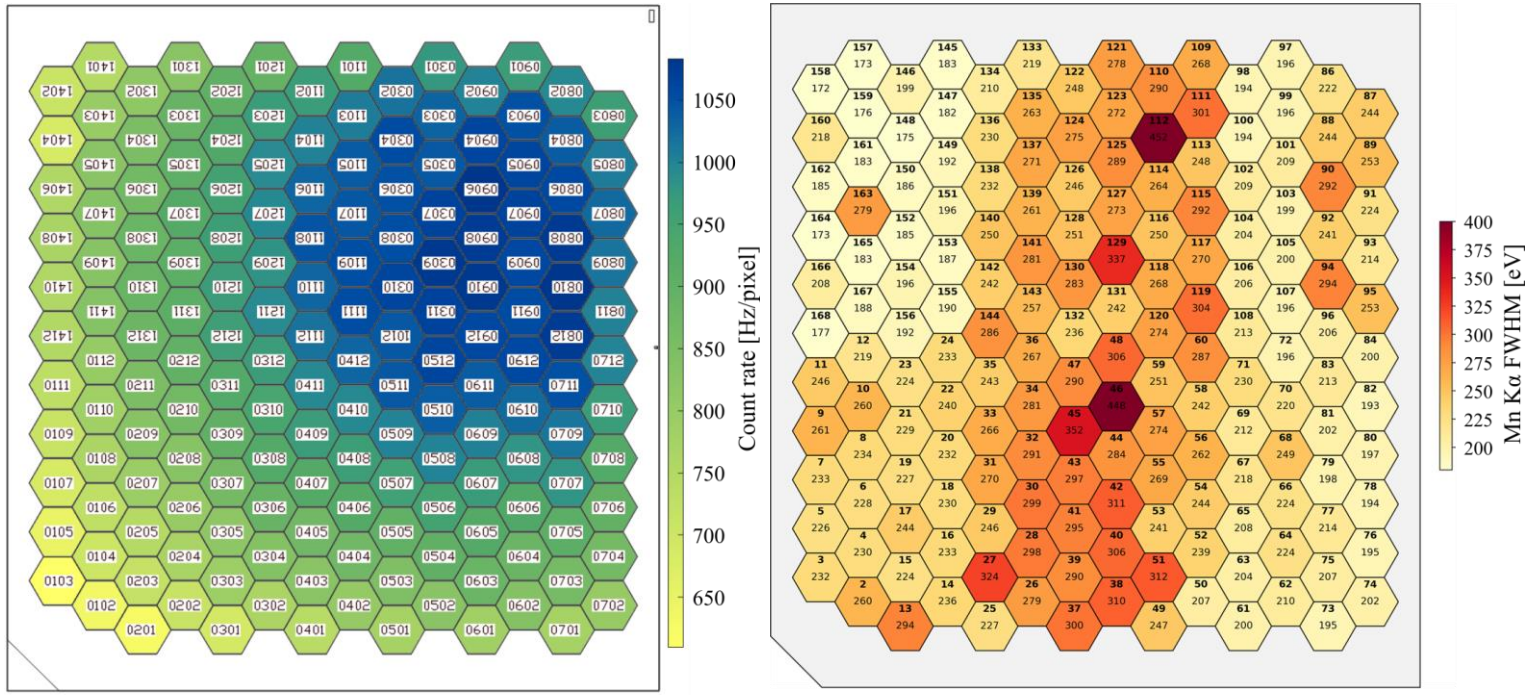


SDD temperature 0°C
Acquired Athena at 6 µs filter shaping time

Slide Adopted from M. Gugiatti

Planar 166 Pixel Detector Characterization

Count rate map
(> 5 keV ^{55}Fe events):

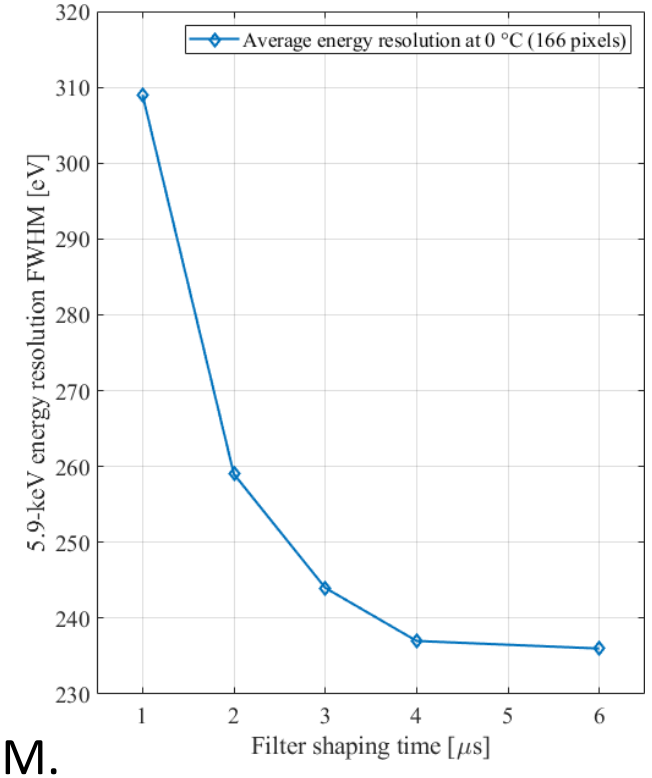


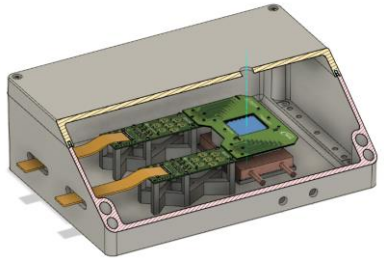
Regular gradient compatible with the position of the radioactive source

Energy resolution at 5.9 keV
(6 µs filter shaping time, 0°C SDD):

Energy resolution = 170-300 eV FWHM.
Worsening is observed in the middle of the SDD (known problem on wafer)

Energy resolution vs filter shaping time:

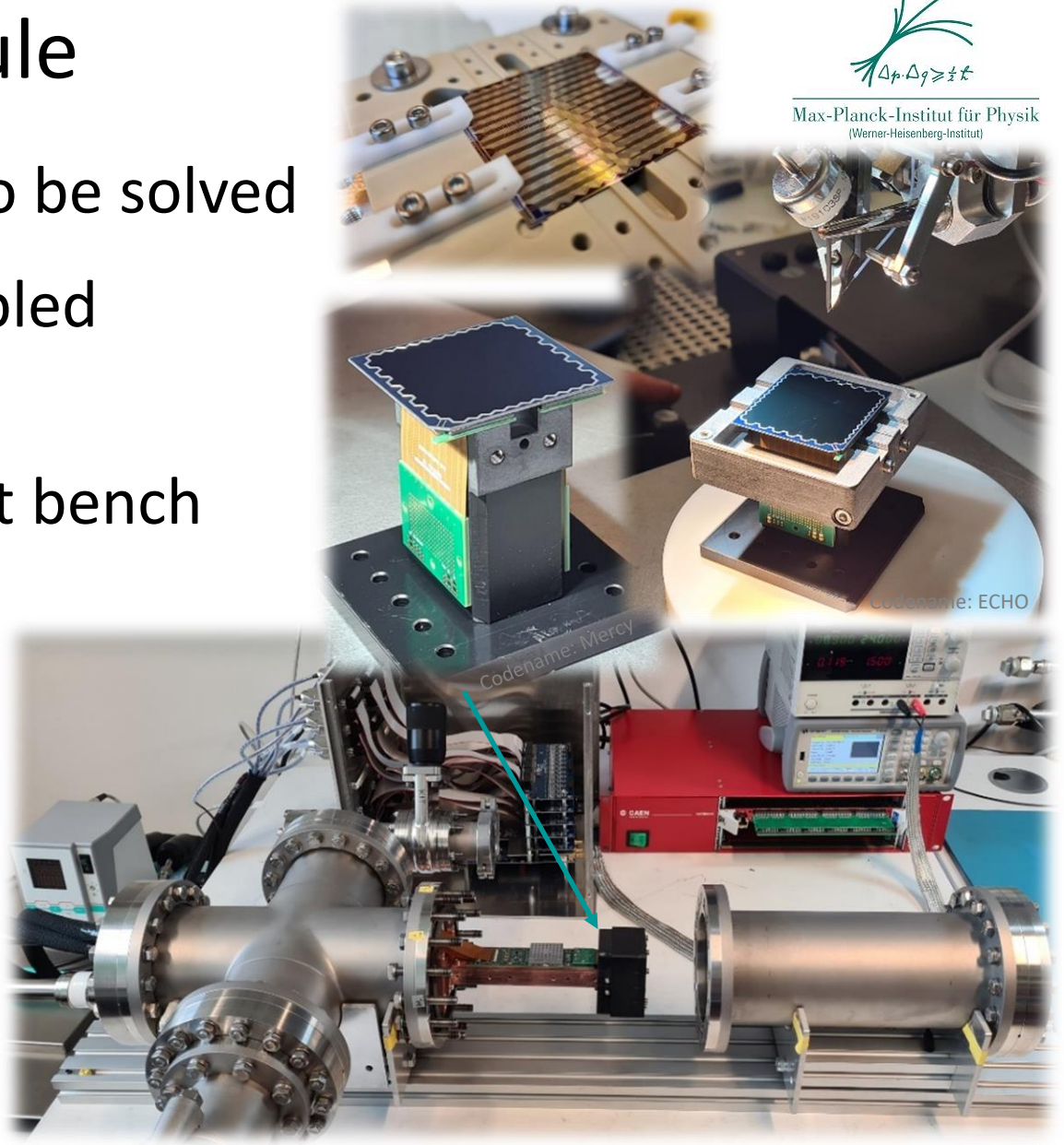




Slide Adopted from M. Gugiatti

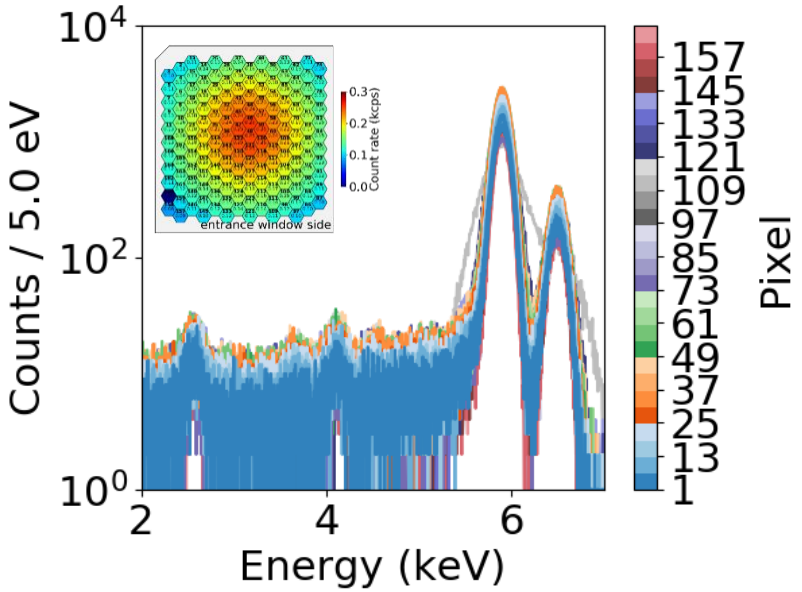
Building a 166 Pixel 3D Module

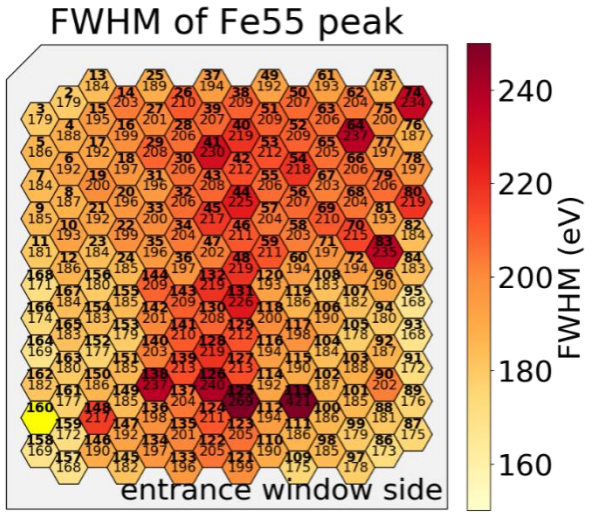
- Difficulties during glue step likely to be solved
- Firsts 3D 166 Pixel detector assembled
  - Two functional modules produced
- Detector installed in laboratory test bench
  - Source: ^{55}Fe (γ @ $\approx$ 5.9keV)
  - Vacuum down to 1e-6 mbar
  - Detector cooled down to -50°C
  - Only minor optimizations preformed



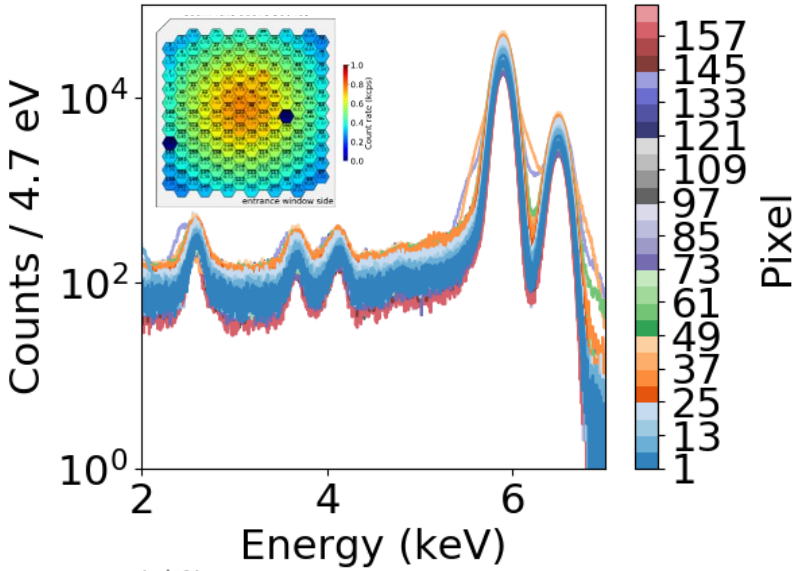
166 Pixel Detector Performance

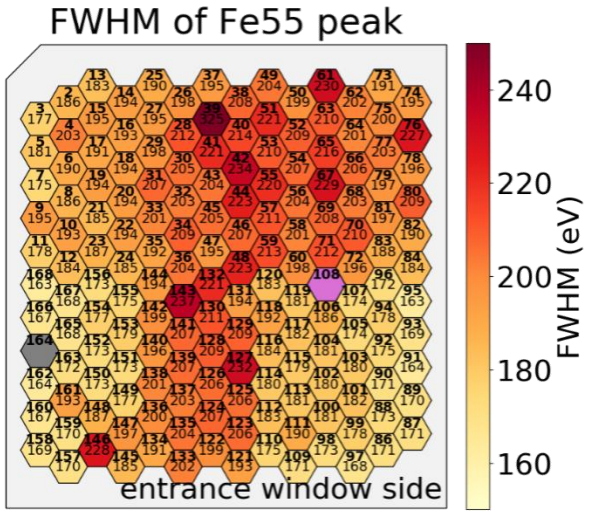
- Detector S0-166-02
  - All 166 pixels show Fe55
  - RTS noise on Pixel 160
  - $\overline{FWHM}_{2us} = \mathbf{195\ eV}$ (γ @ $\approx$ 5.9keV)
- Detector S0-166-03
  - 165 pixels show Fe55
  - Pixel 108 / Pixel 164 connection problems
  - $\overline{FWHM}_{2us} = \mathbf{194\ eV}$ (γ @ $\approx$ 5.9keV)





Chiller @ -50°C

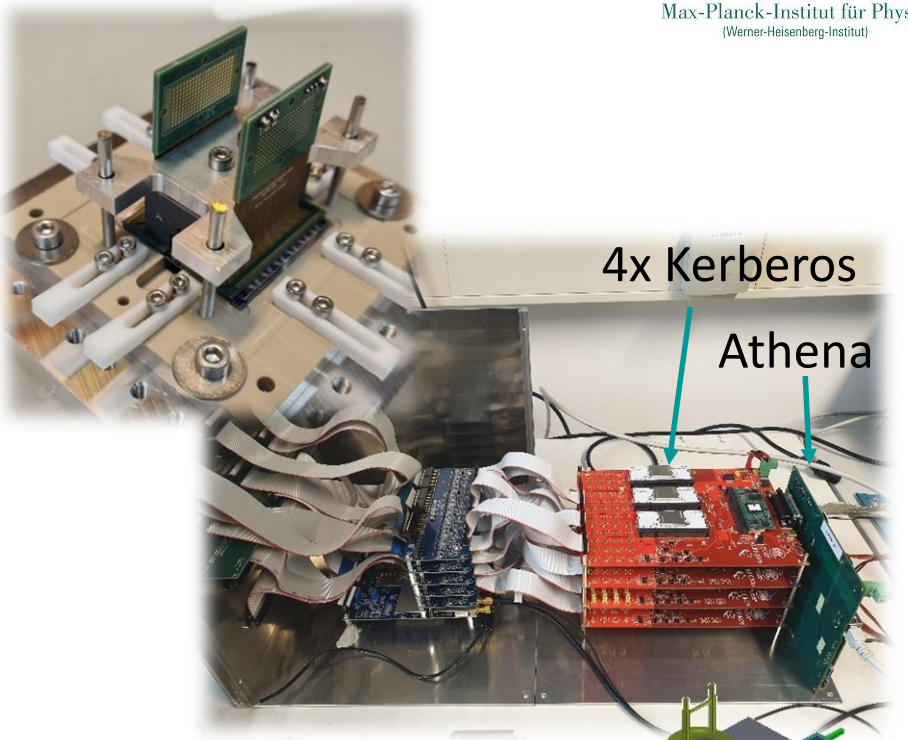


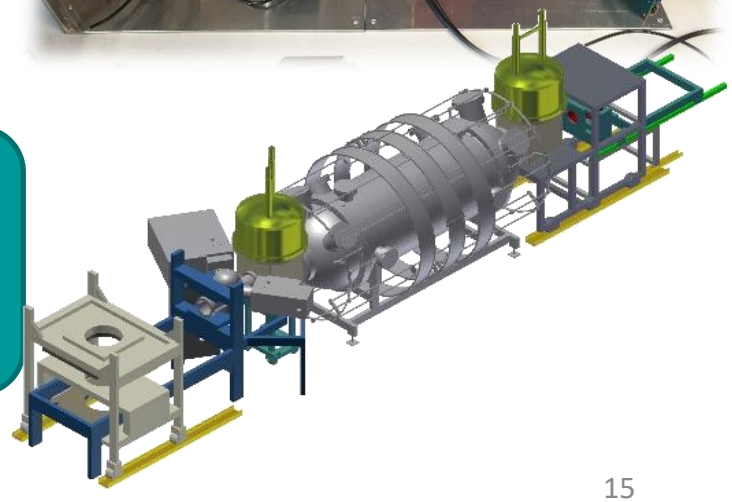


Chiller @ -50°C

Preparation of Monitor Spectrometer Integration

- New detector currently under assembly
  - Next batch of waver -> FWHM will be better
- Characterization measurements stated
  - Optimizing detector bias voltages
  - Understanding long time stability of system
- Upgrading MoS with additional γ souce
  - Comparison of e^- and γ detector response

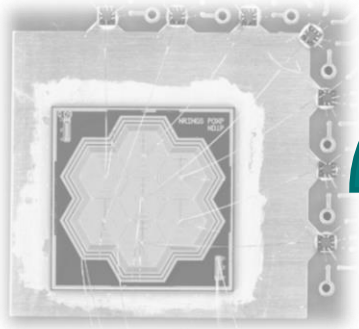




➢ Detector requirements likely to be fulfilled
➢ MoS integration expected in the next months to test in real world environment

Staged Approach

Proof of concept



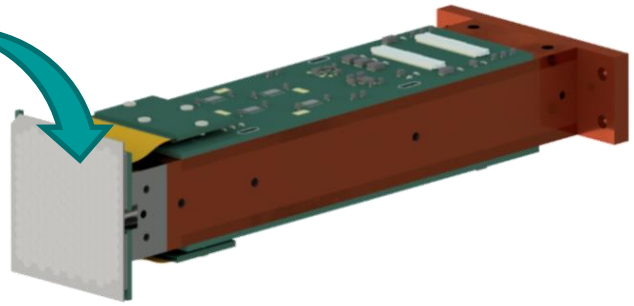
Understanding the SDD technology (7 pix)

(2019, Mertens et al.), Astropart. Phys. 108, 40

(S. Mertens et al 2021) J. Phys. G: Nucl. Part. Phys. 48 015008

Module (166 pix)

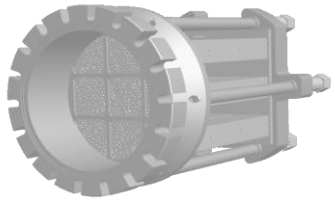
UNDER CONSTRUCTION COMING SOON



Apply and test detector in realistic environment

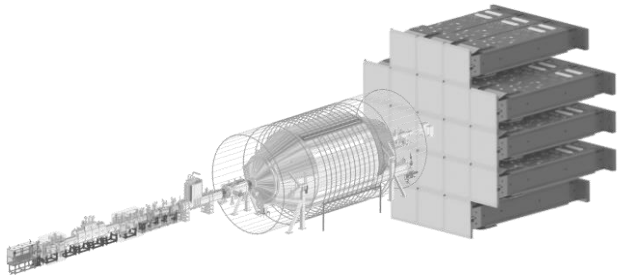
- Monitor spectrometer

Phase 1 (1500 pix)



Sterile search with 9 modules

Phase 2 (3500 pix)



Sterile neutrino search with KATRIN (21 modules)

Towards the Final TRISTAN Detector

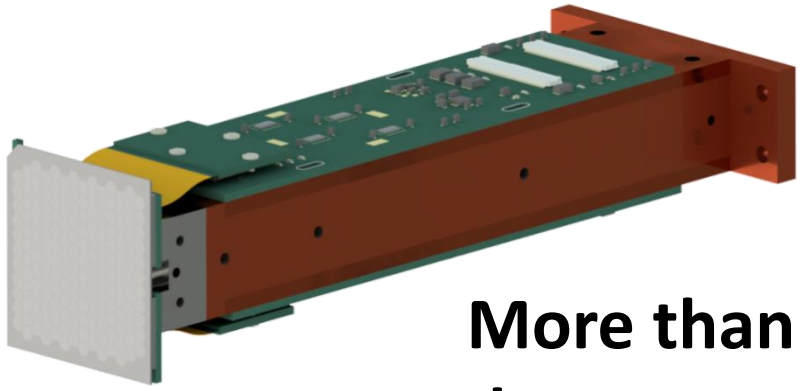
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

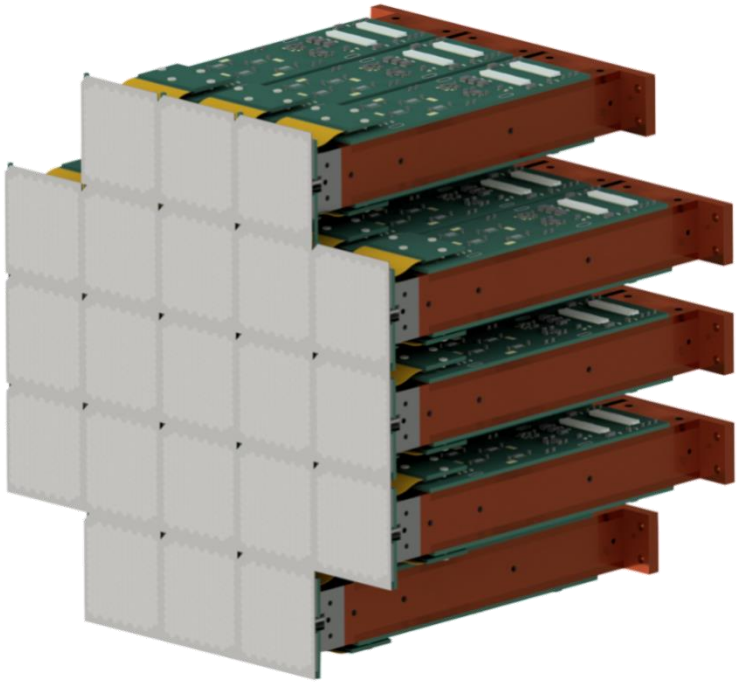
TRISTAN Module

- 166 Pixels Detector
- Commissioning 2022

Full TRISTAN Detector

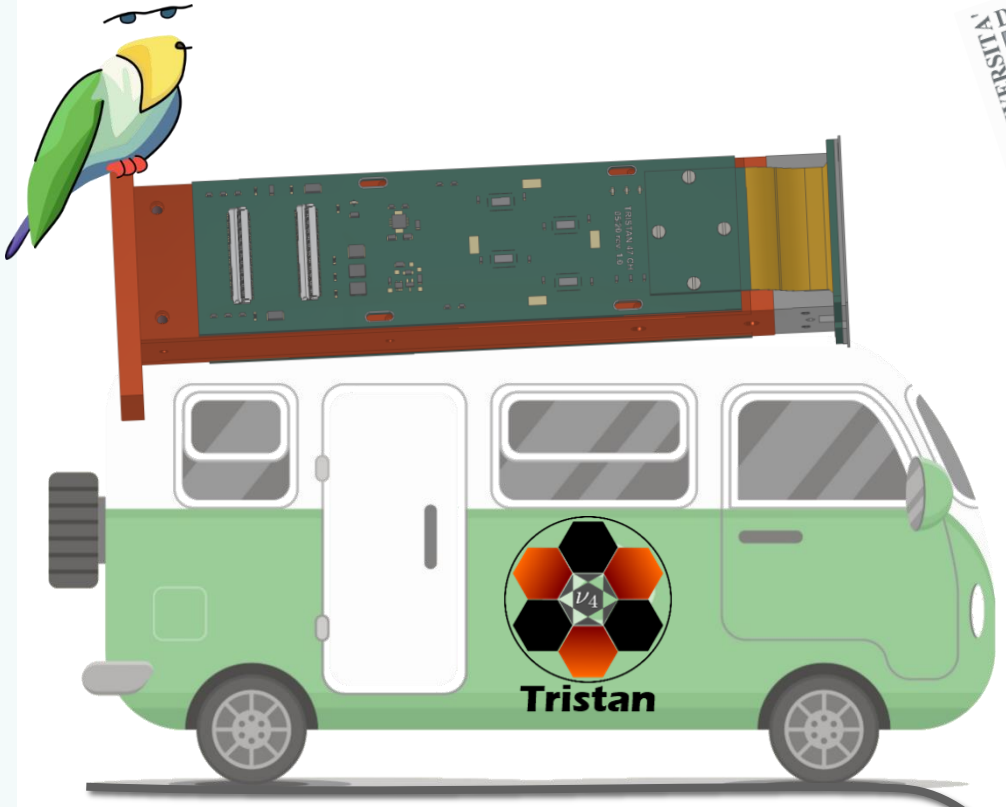
- 21 x 166 Pixels ≈ 3500 Pixels
- Integration after completion of ν-mass measurement





More than scaling up the detector

- Detector chamber
- Outgassing
- High density electronics
- …



... and many more!

Steriles Neutrino

MoniSpec
Landkreis KATRIN

M. Descher
M. Carminati
C. Bruch
D. Hinz
M. Steidl
S. Mertens
C. Forstner
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M. Gugiatti
D. Siegmann
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L. Wunderl
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S. Lichter