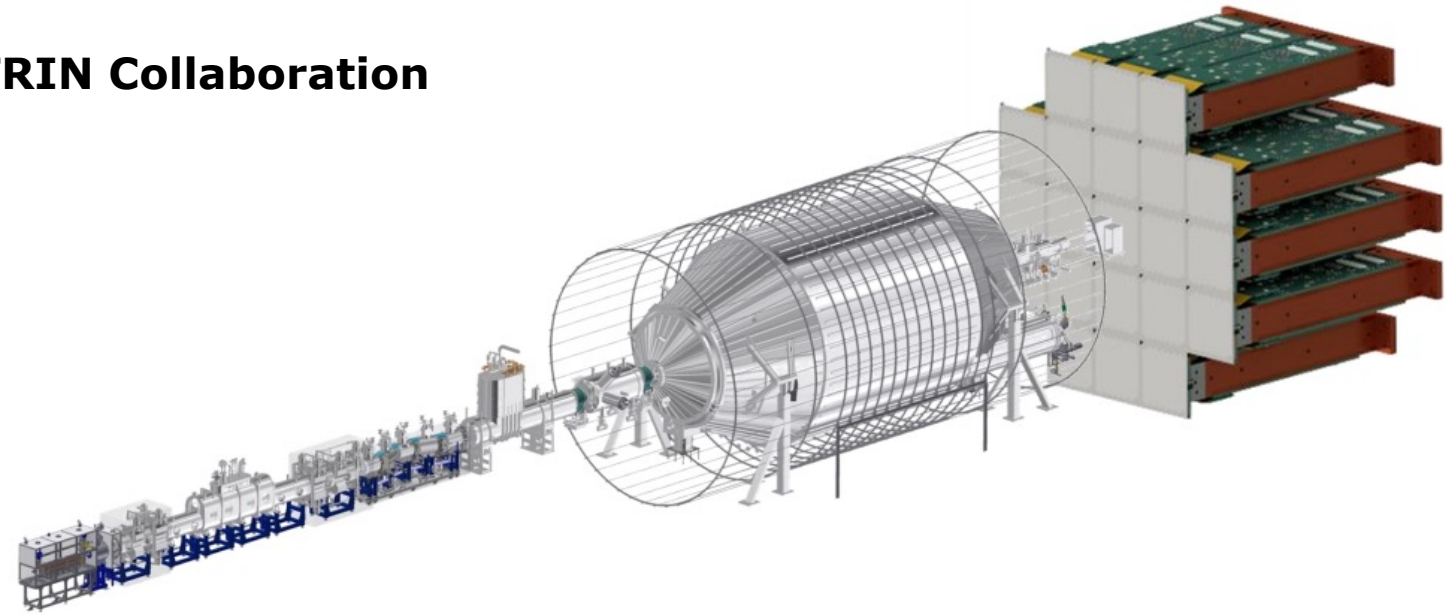
THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

# Search for keV-scale sterile neutrinos with KATRIN/TRISTAN

**Andrew Gavin, on behalf of the KATRIN Collaboration**

**UCLA Dark Matter 2023**

**March 30th, 2023**



TUNL Triangle Universities Nuclear Laboratory · Karlsruhe Institute of Technology · Halbleiterlabor der Max-Planck-Gesellschaft · Politecnico Milano 1863, Dipartimento di Elettronica, Informazione e Bioingegneria · Università degli Studi di Milano Bicocca · XGLab, Bruker Nano Analytics Division · Carnegie Mellon University · INFN

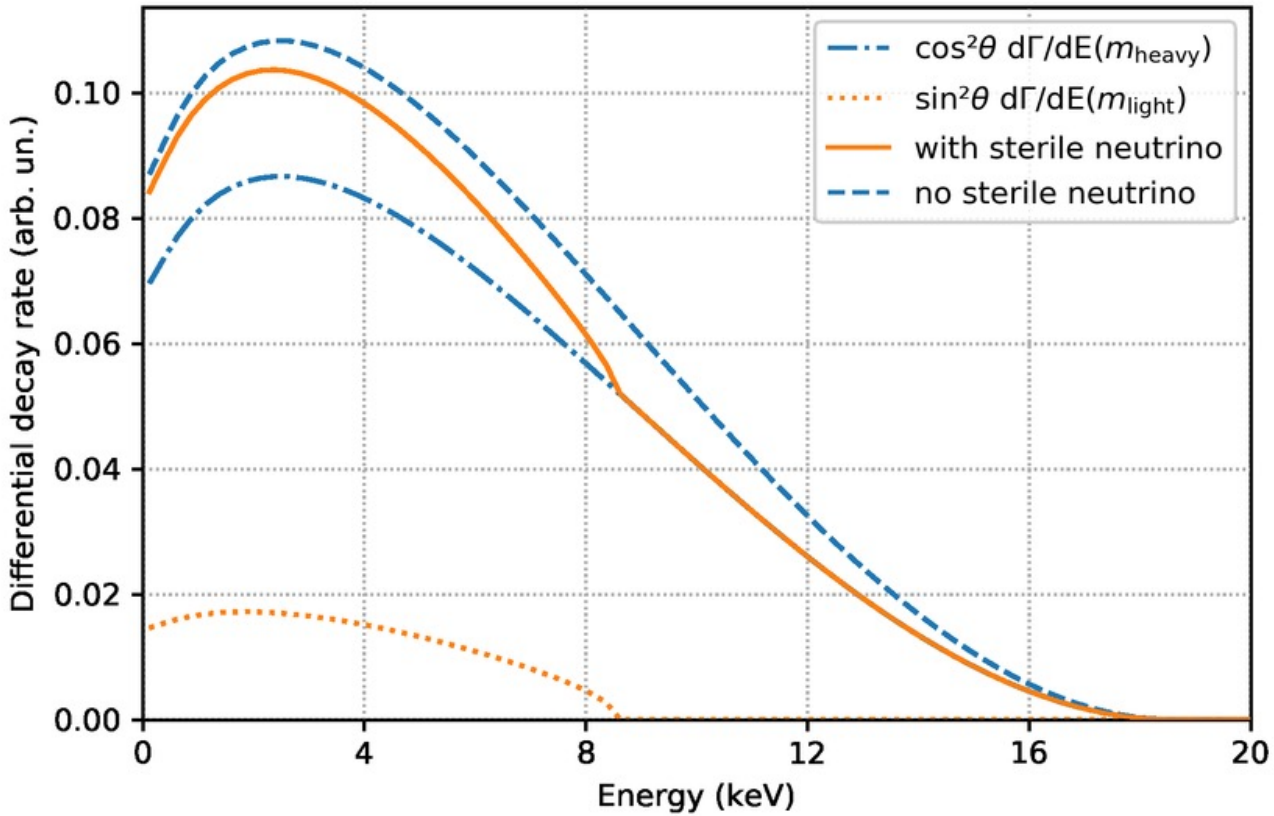
# Sterile Neutrinos

- Right-handed neutrinos are 'natural' extensions to the standard model

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \\ |\nu_s\rangle \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \cdot \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \\ |\nu_4\rangle \end{pmatrix}$$

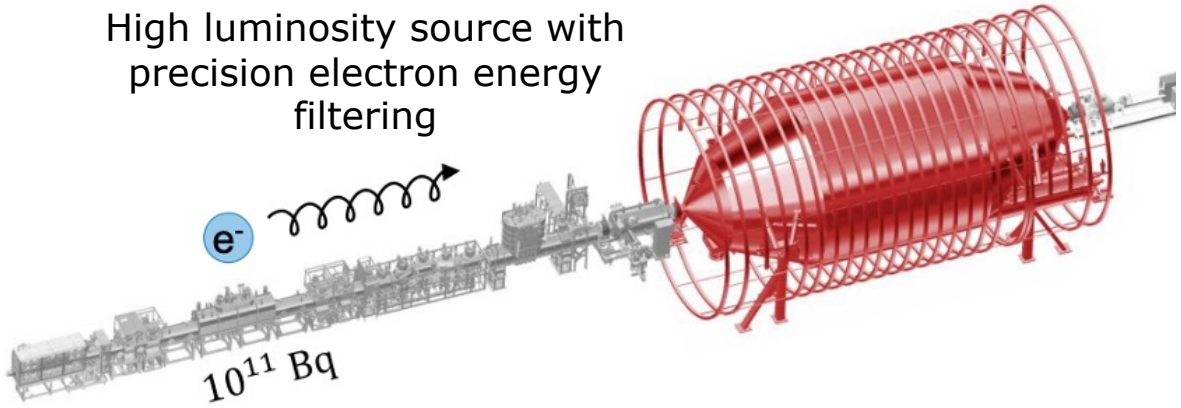
- Mixing with active neutrino branch small but offers experimental signatures

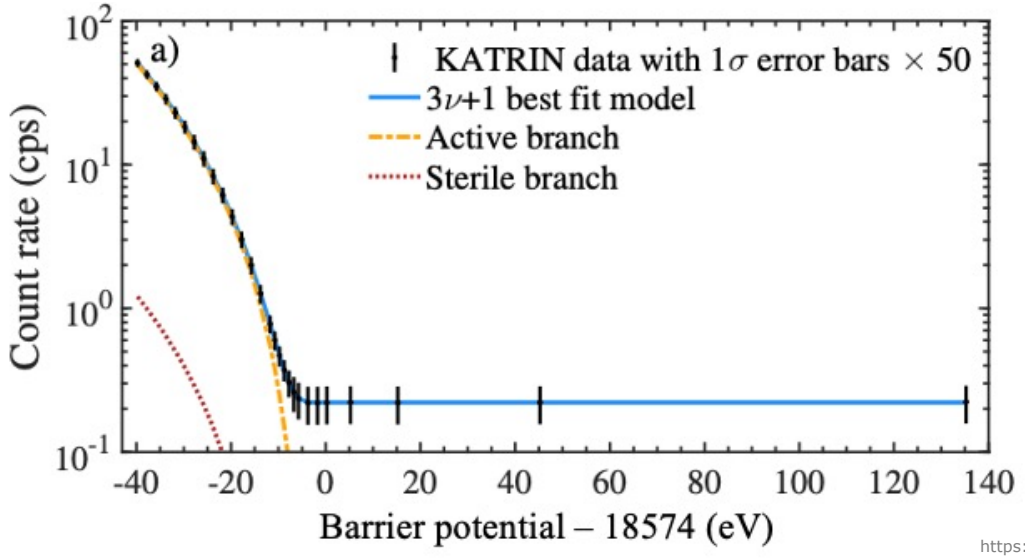
$$T \rightarrow He + e^- + \bar{\nu}_e$$

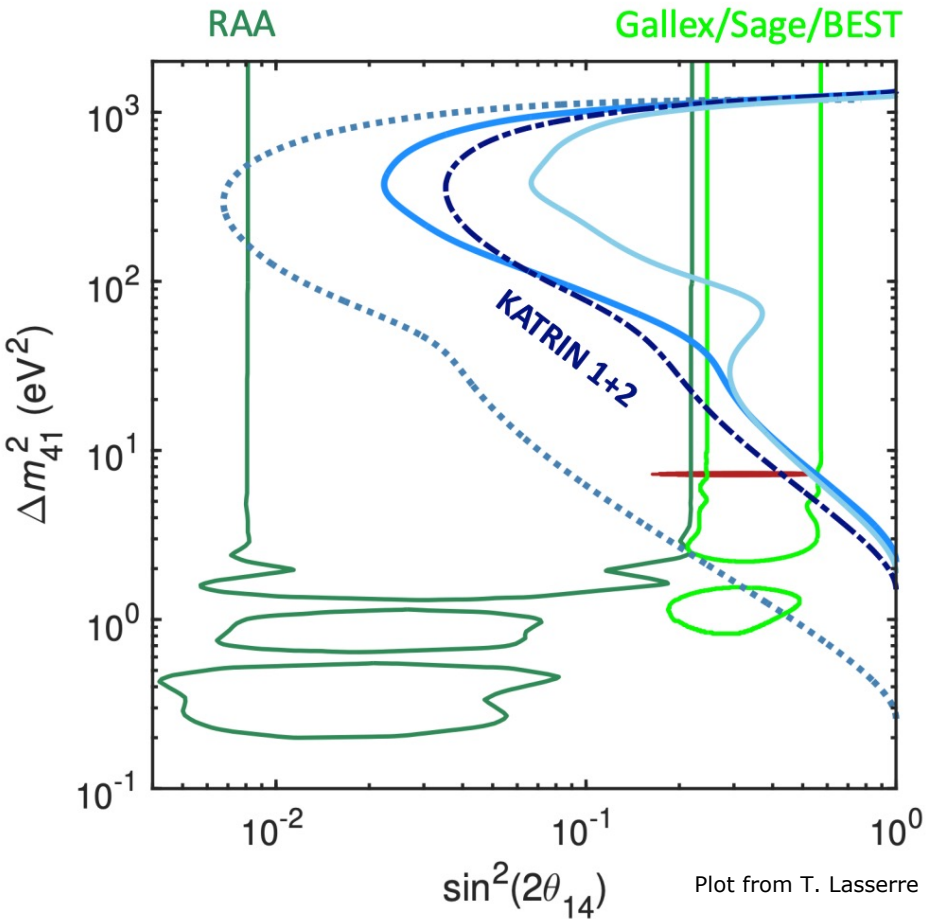


# eV Sterile Neutrinos with KATRIN

High luminosity source with precision electron energy filtering




Plot from T. Lasserre

https://doi.org/10.1038/s41567-021-01463-1
https://doi.org/10.48550/arXiv.2103.04755

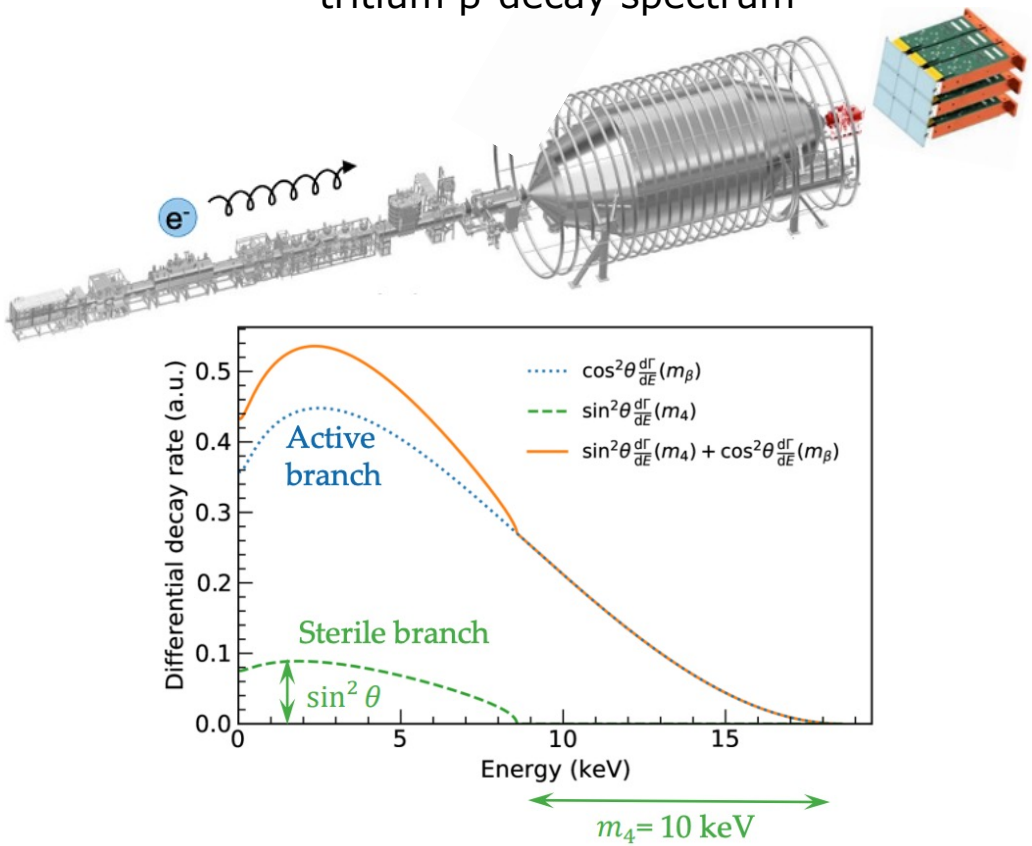
M. Aker *et al.* (KATRIN Collaboration) Phys. Rev. D **105**

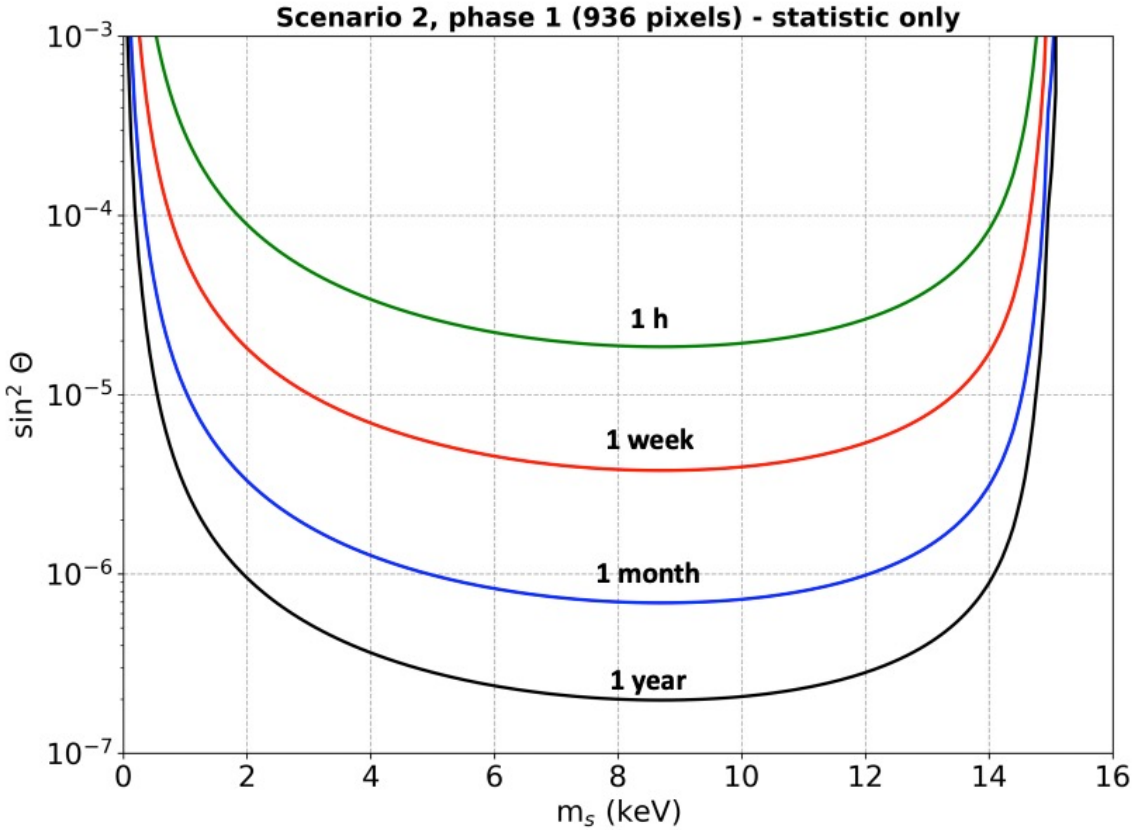
# keV Sterile Neutrinos with KATRIN

**TRISTAN**

"**TR**itium **I**nvestigation on **ST**erile to **A**ctive **N**eutrino Mixing"

- Detector upgrade to perform a differential measurement of the tritium β-decay spectrum

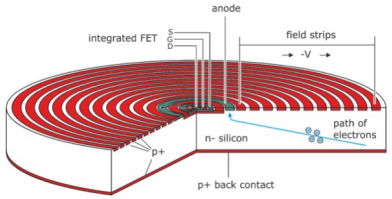


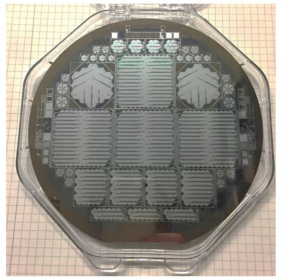



# TRISTAN Project Development

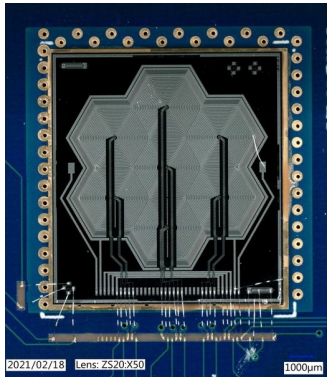
## Detector Development

- 300 eV FWHM at 20 keV
  - $10^8$ counts per second
  - $\mathcal{O}$(mm) pixel diameter
- Minimize deadlayer ($\mathcal{O}(100\ \text{nm})$)

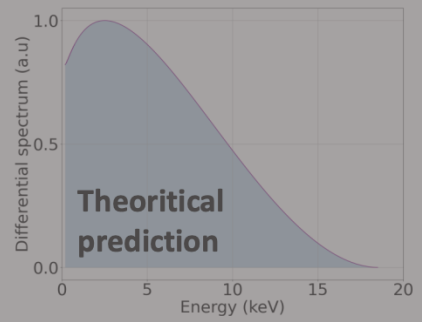


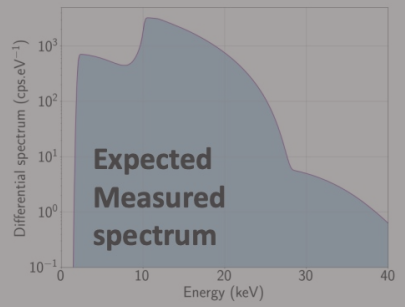



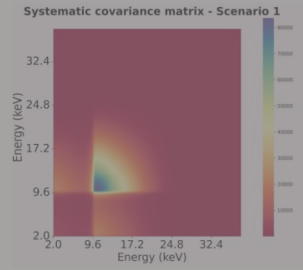
Silicon drift detector




## Spectrum Modeling



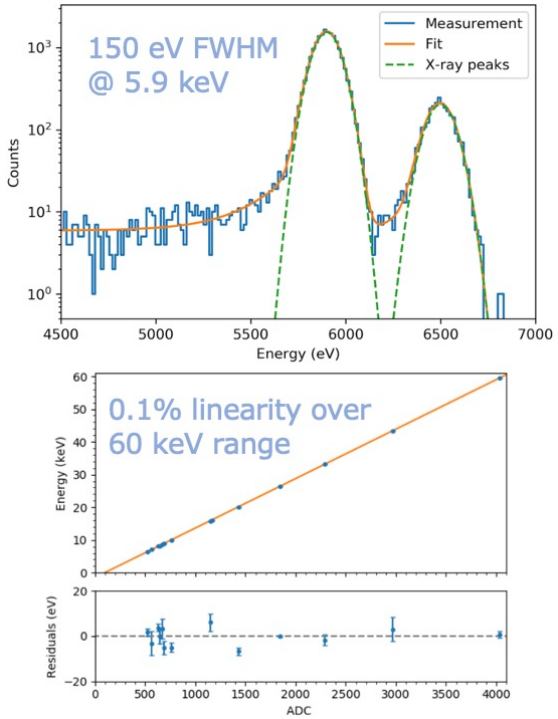




- Full spectrum modeling with included systematics
- Sensitivity studies and data fitting

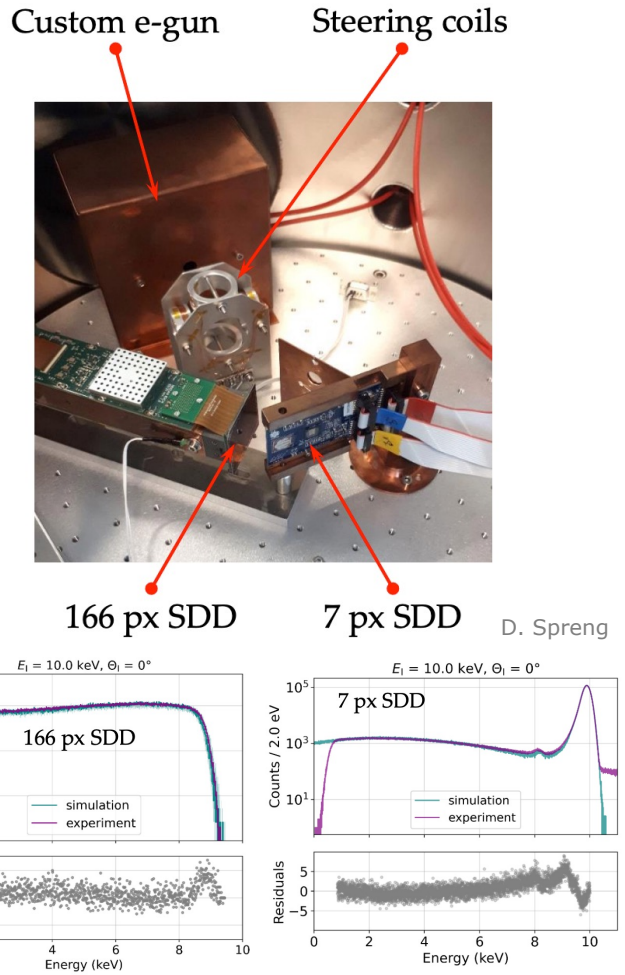
# Detector Characterization

## Overview

- Characterization at MPP/TUM/Polimi
- $^{55}$Fe, $^{231}$Am, electron gun, pulsed laser, etc.
  - Tests of detector performance, radiation damage, and DAQ readout

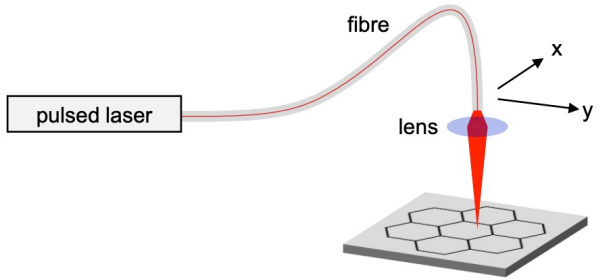


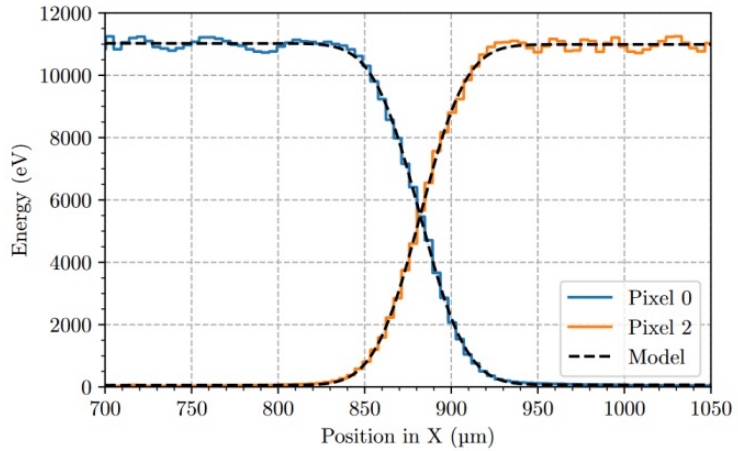

## Backscattering




D. Spreng

## Laser/Light Tests



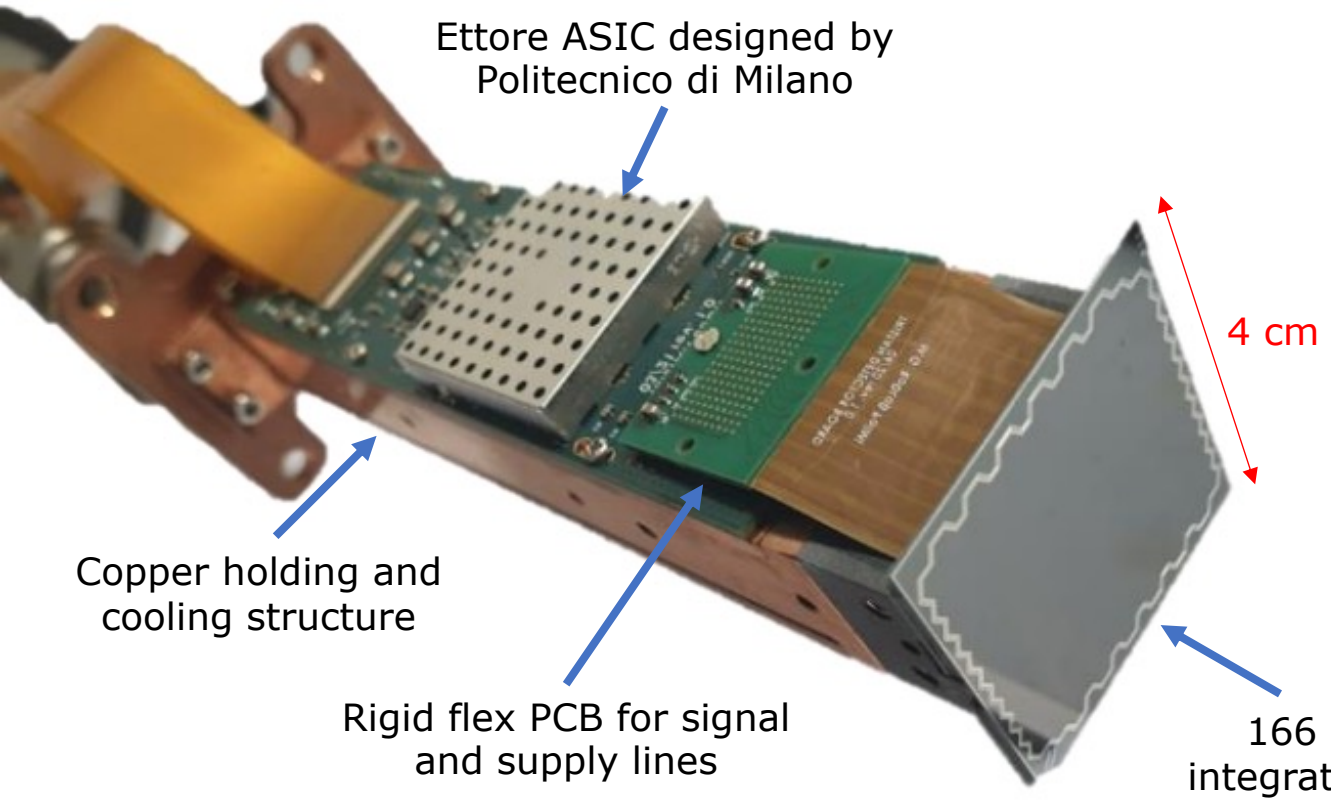



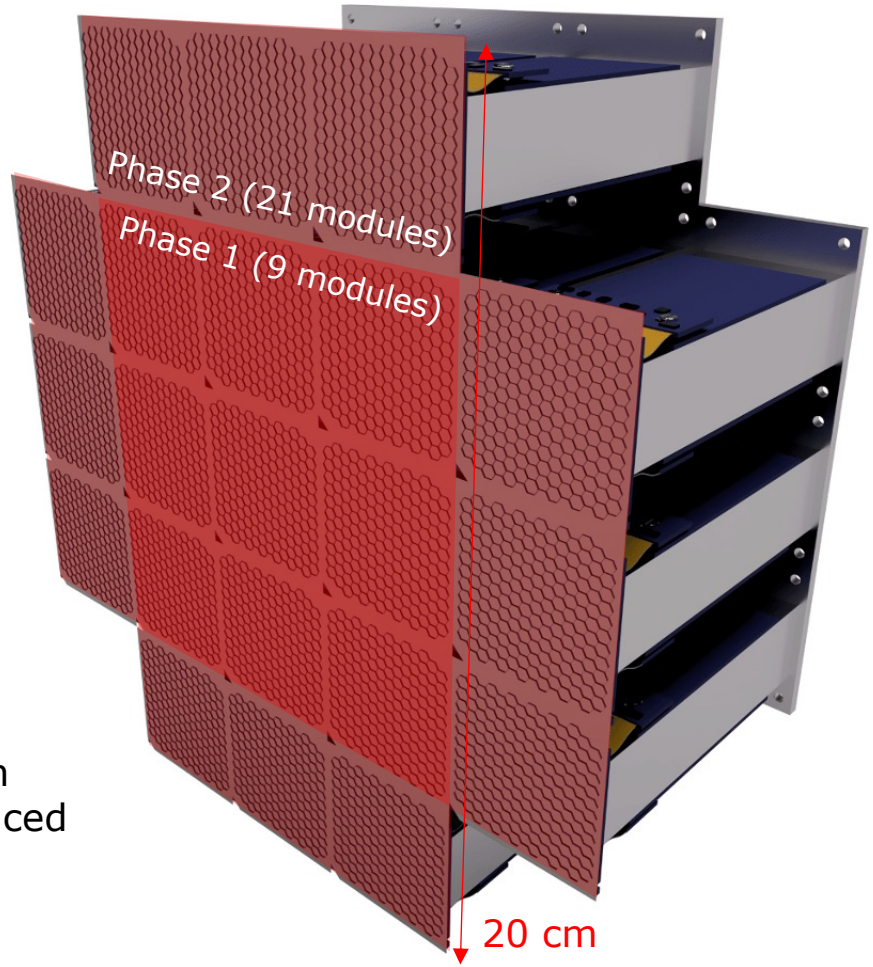

- Fine spatial resolution probing of detector response
- Investigation of charge sharing on boundaries

C. Forstner

# TRISTAN Detector Geometry

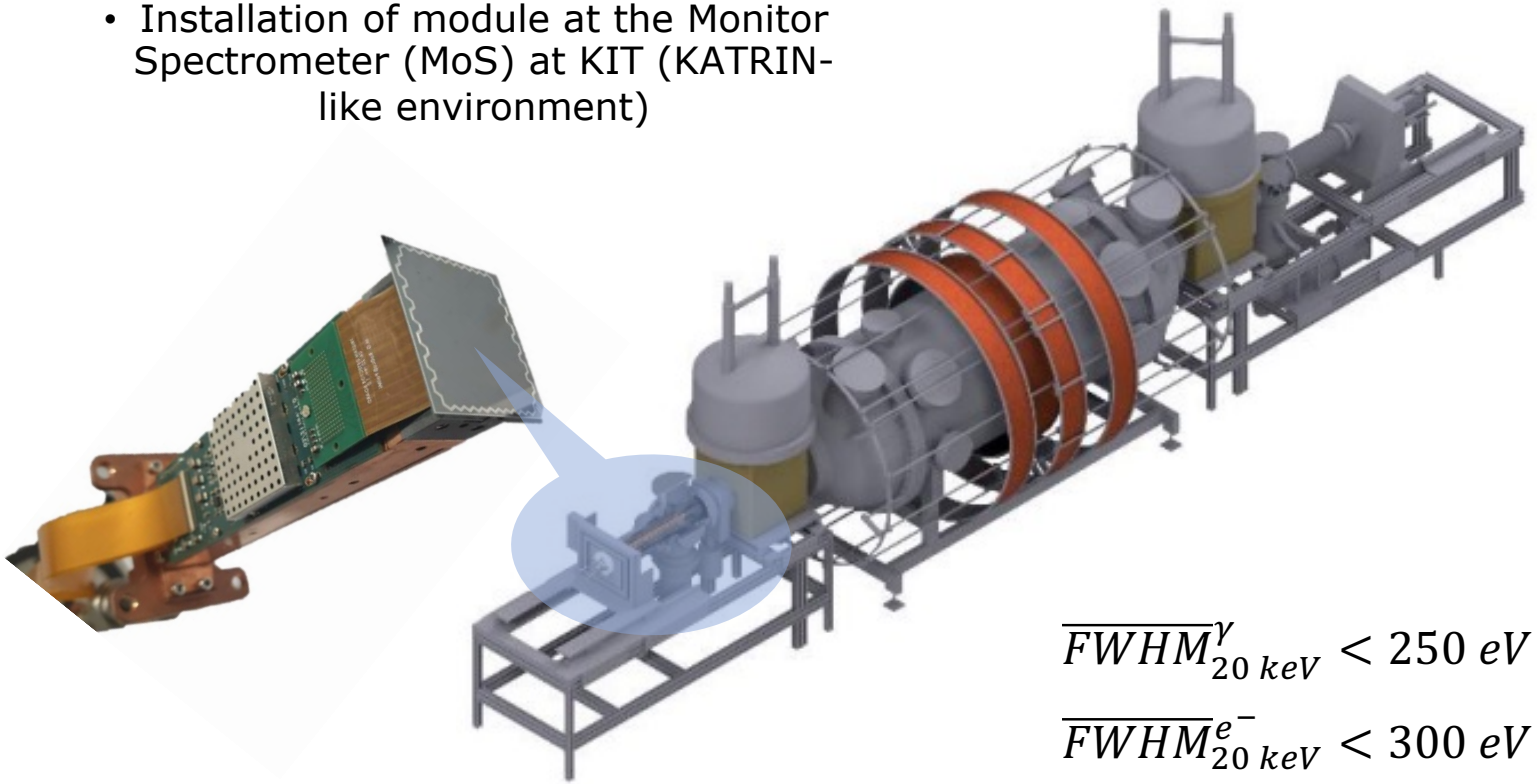
**TRISTAN Module**



# TRISTAN Module Testing

- Reliable production and gluing procedure of 166-pixel modules
- Installation of module at the Monitor Spectrometer (MoS) at KIT (KATRIN-like environment)

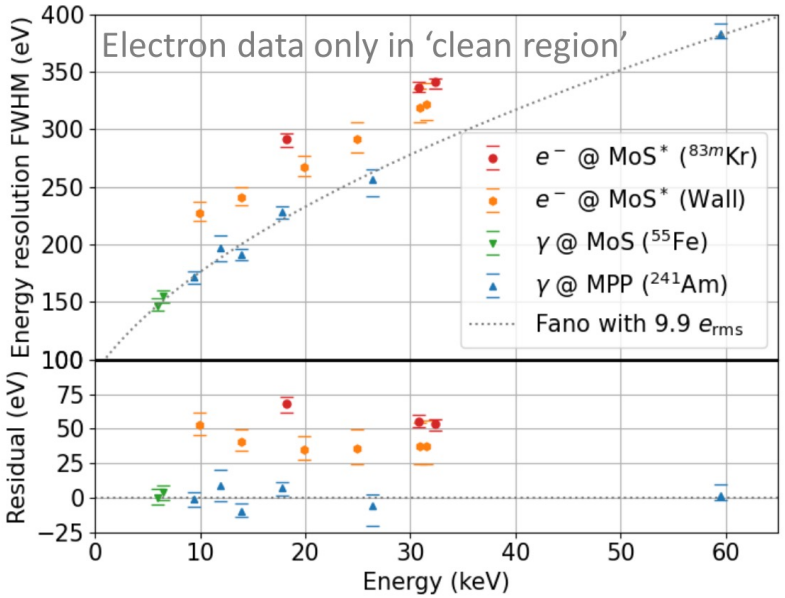


$$\overline{FWHM}^{\gamma}_{20\ keV} < 250\ eV$$

$$\overline{FWHM}^{e^-}_{20\ keV} < 300\ eV$$

Primary Findings

- Detector resolution nicely described by Fano statistics for X-ray sources
- Additional entrance window effect observed for electron sources




courtesy of D. Siegmann and C. Bruch

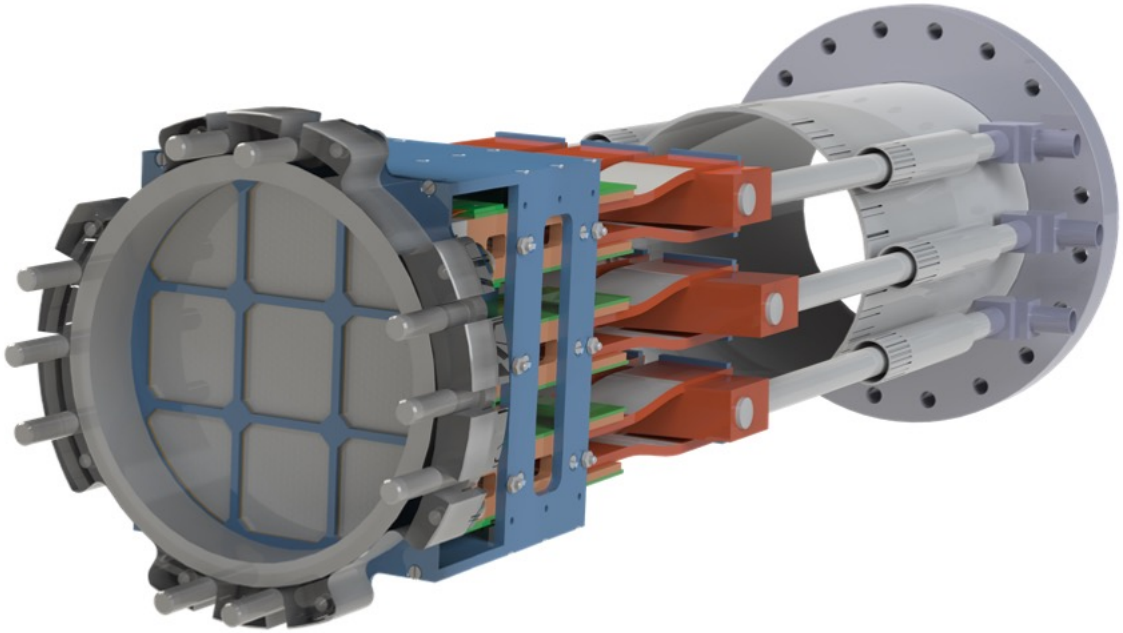
# TRISTAN Integration

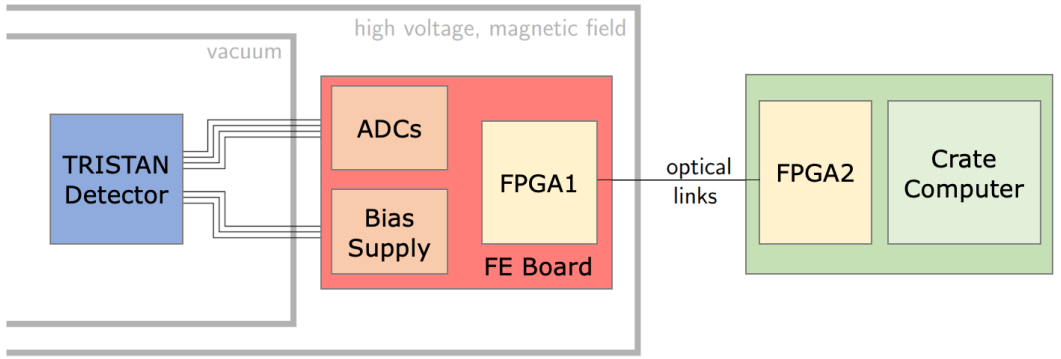
Ongoing detector development tasks:

- Testing of new production of SDD wafers from HLL
- Production of additional 166-pixel modules

- Module mounting and vacuum design
- Testing of 9 modules at KATRIN Focal Plane Detector replica test setup

- Production and commissioning of remote-ADC data acquisition system

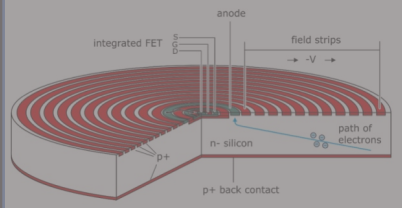


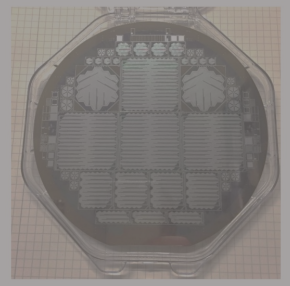


# TRISTAN Project Development

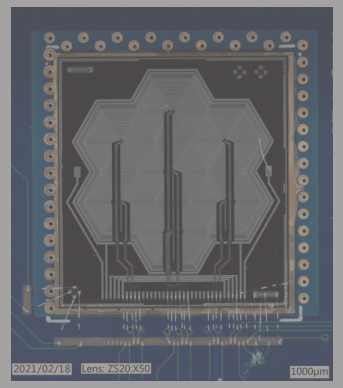
## Detector Development

- 300 eV FWHM at 20 keV
- $10^8$ counts per second
- $\mathcal{O}$(mm) pixel diameter
- Minimize deadlayer ($\mathcal{O}$(100 nm))

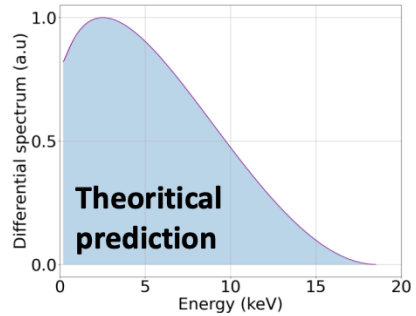


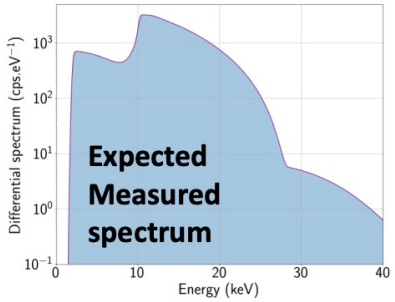



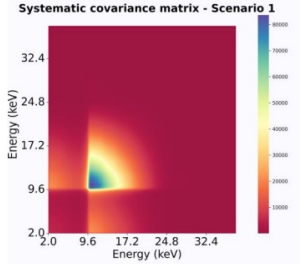
Silicon drift detector




## Spectrum Modeling




- Full spectrum modeling with included systematics
- Sensitivity studies and data fitting

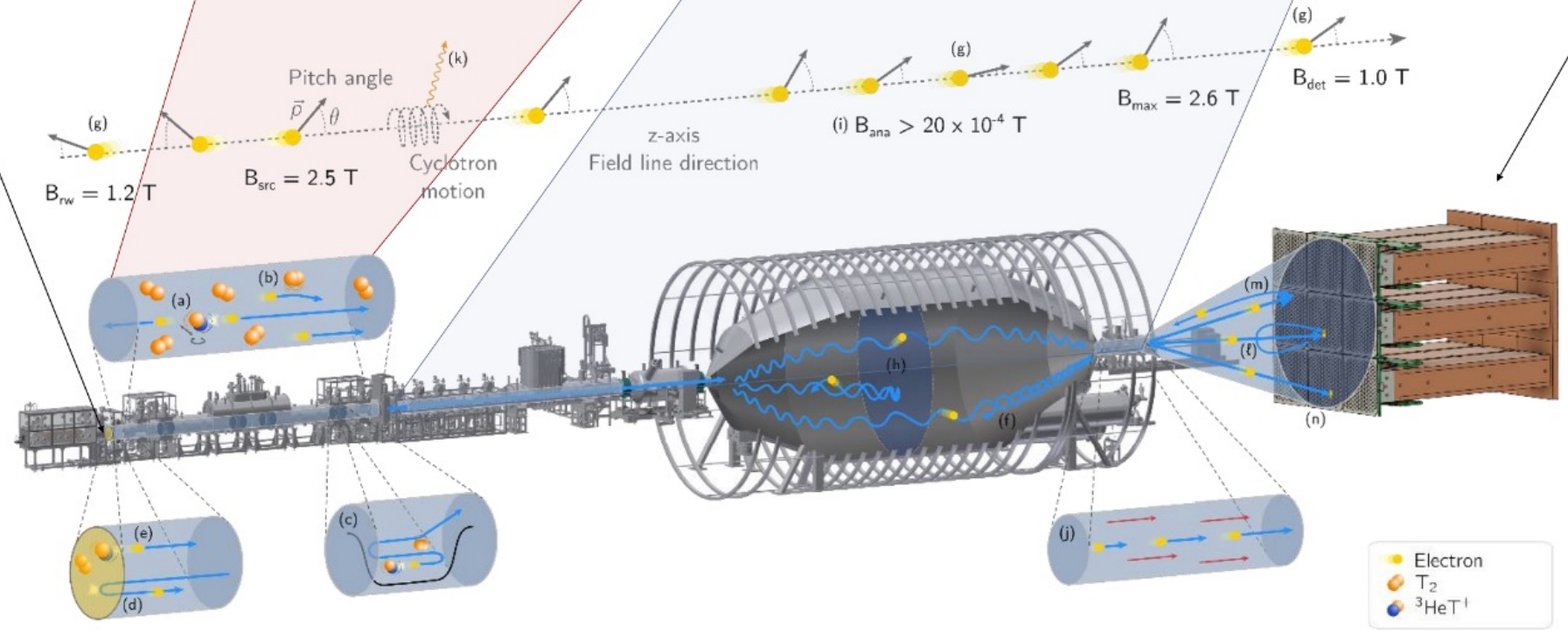
# TRISTAN Systematics

**Rear Wall**
- Source Activity
- Scattering

**Source**
- Scattering
- Magnetic trapping
- Final state distribution

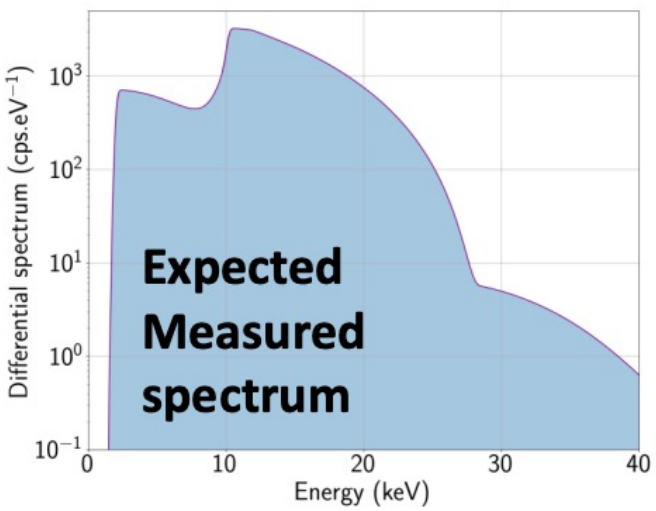
**Transport**
- Spectrometer potential
- Transport adiabaticity
- Post acceleration

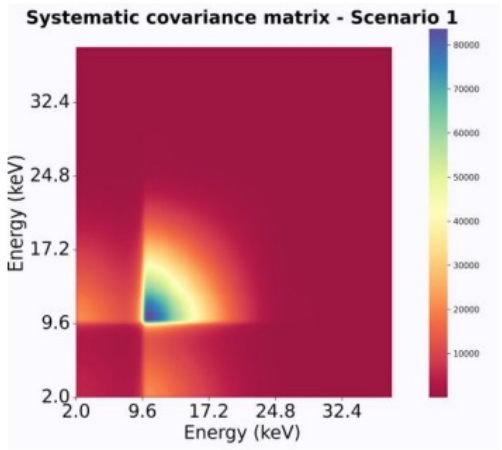
**Detector and DAQ**
- Backscattering and reflection
- Partial charge collection
- Pileup
- DAQ non-linearities



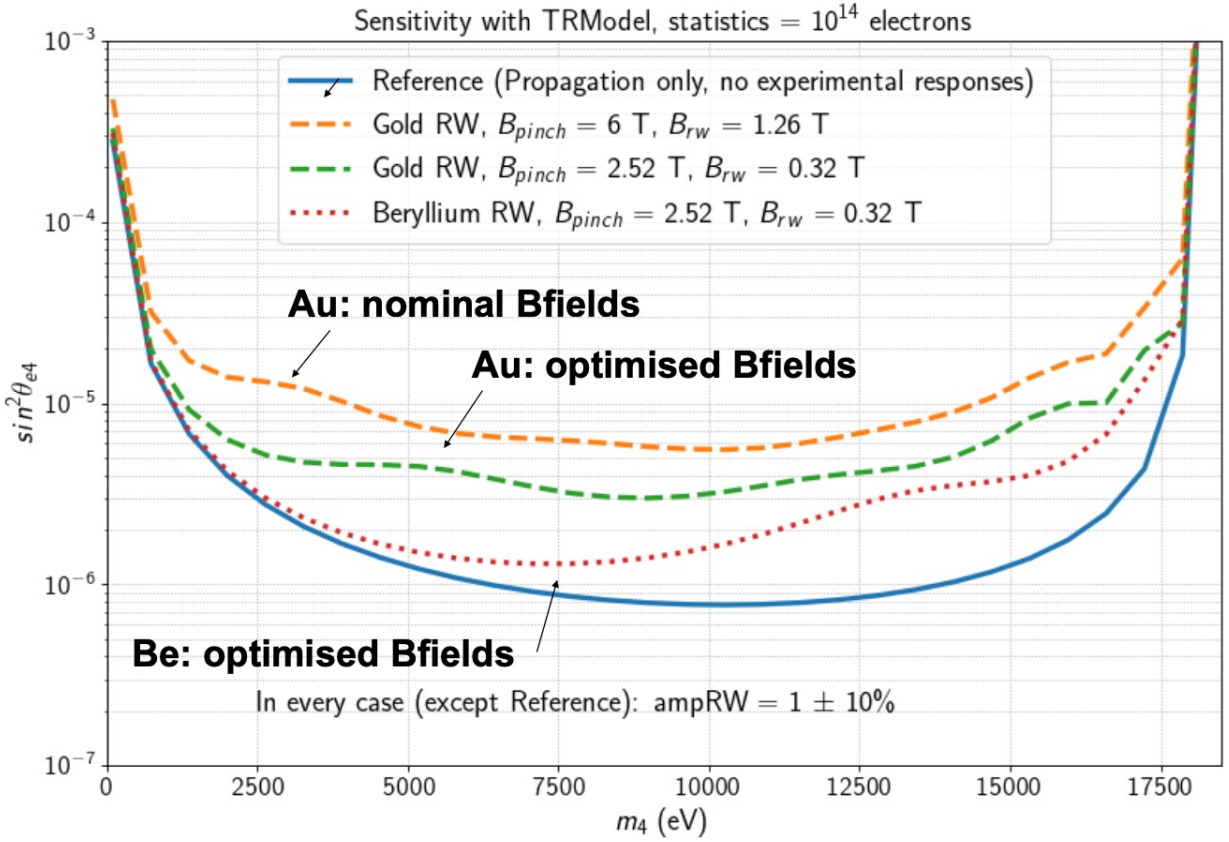
# TRISTAN Sensitivity Projections

Spectrum and systematic covariance matrices simulated through **TRmodel** (dev: M. Descher) framework

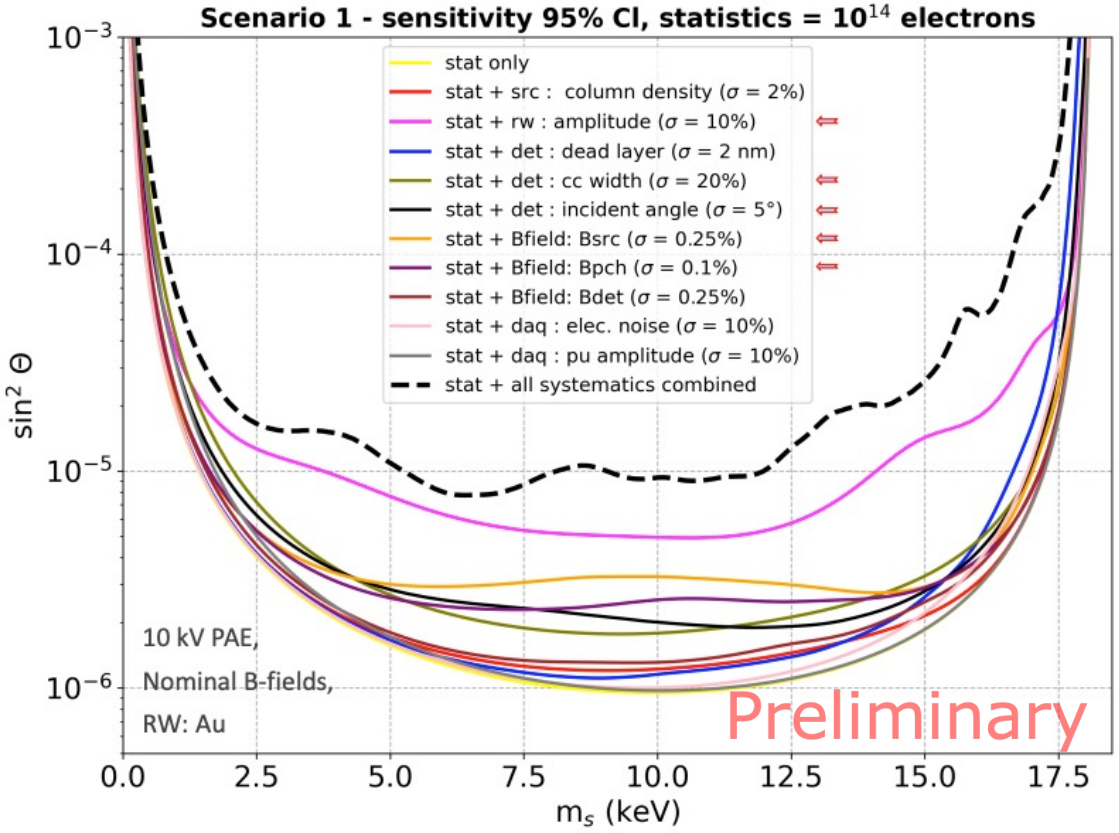


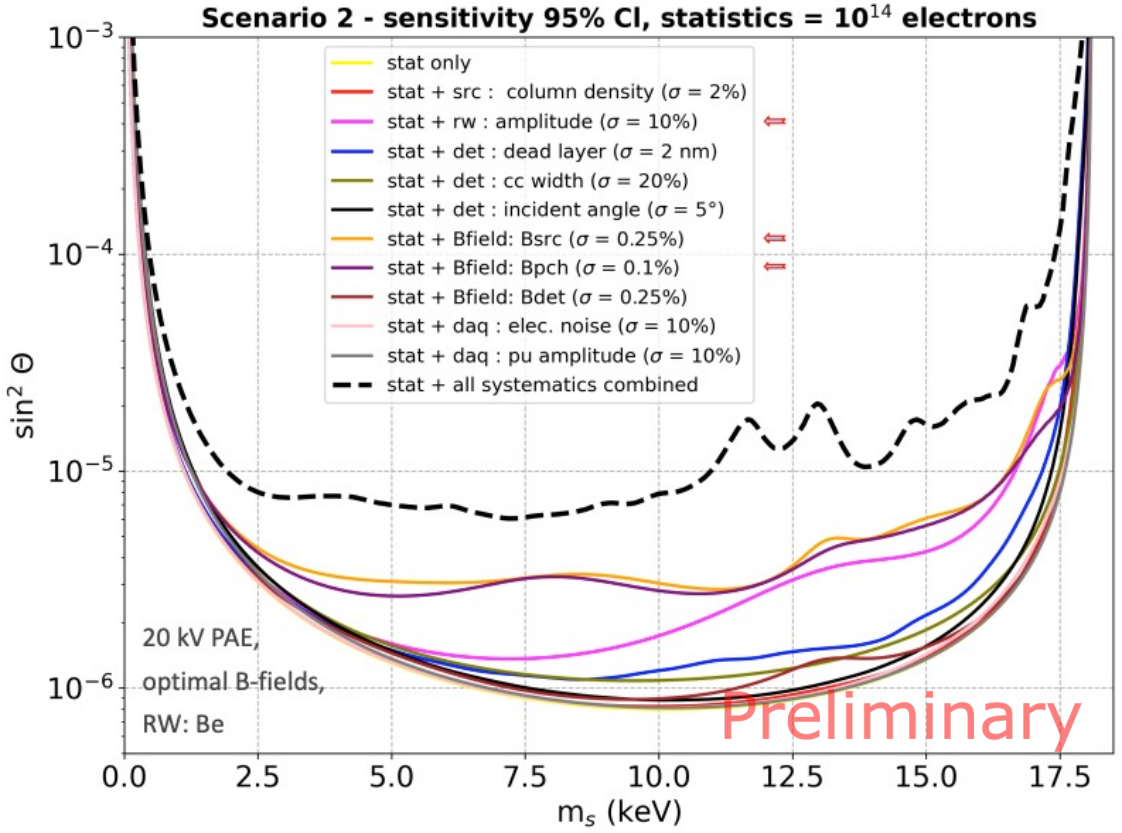




- Grid scan performed over $m_s$ and $\sin^2\theta$, with $\chi^2$ calculated at each point
- Optimization of individual experimental parameters



# TRISTAN Sensitivity



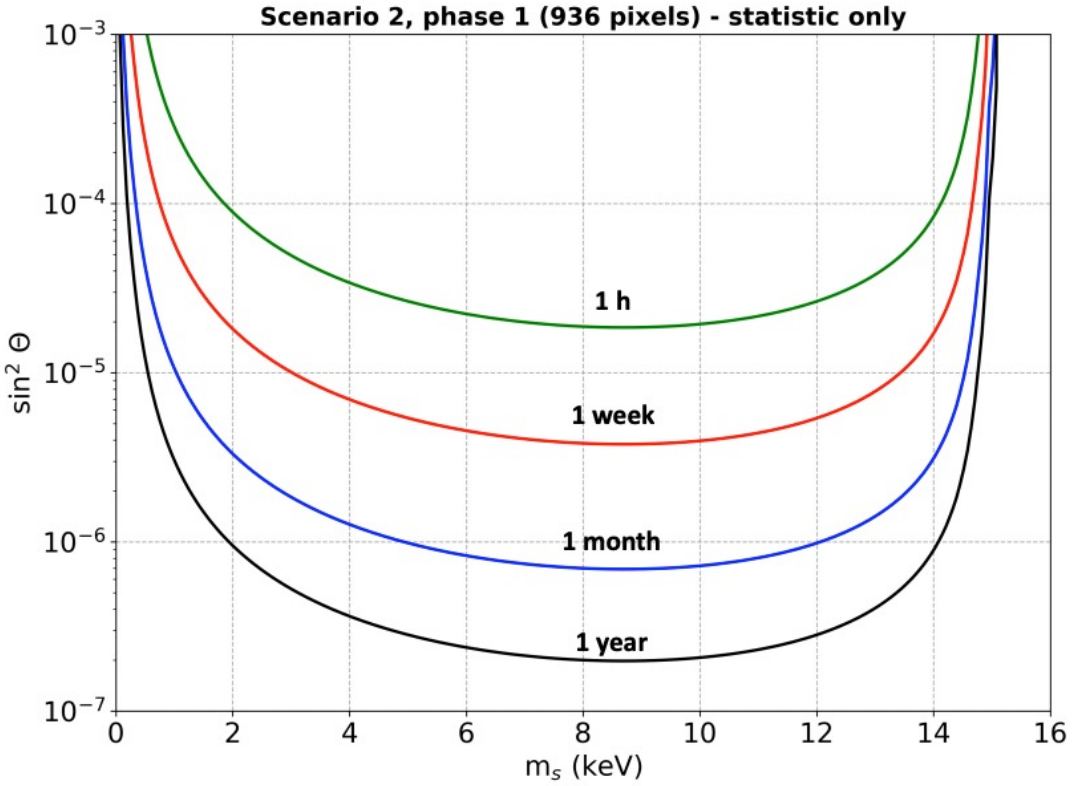

- Systematic effects decrease sensitivity over the mass range by (approximately) an order of magnitude
- Different experimental design considerations alter the breakdown of systematic contributions

# TRISTAN Sensitivity

Statistics
- Data taking for under a week necessary to probe $10^{-5}$ mixing
- 1 year measurement campaign to reach $2 \cdot 10^{-7}$

Systematics
- Majority of major systematic effects implemented in TRmodel
- Approximately order of magnitude decrease in sensitivity
- Ongoing investigations

| Effect | Status |
|---|---|
| T-decays on the RW<br>Shape uncertainties of RW backscattering spectrum | In progress |
| Plasma | Not started |
| Magnetic trapping in the WGTS | In progress |
| Uncertainties of cross-section and energy loss function | Not started |
| Detector backscattering + backreflection | In progress |
| FSD uncertainty and energy dependence | Collaboration with Saenz started |
| Theoretical uncertainties | Considered in publication, has to be reevaluated (arXiv:1409.0920) |
| DAQ: non linearity - cross-talk | In progress |

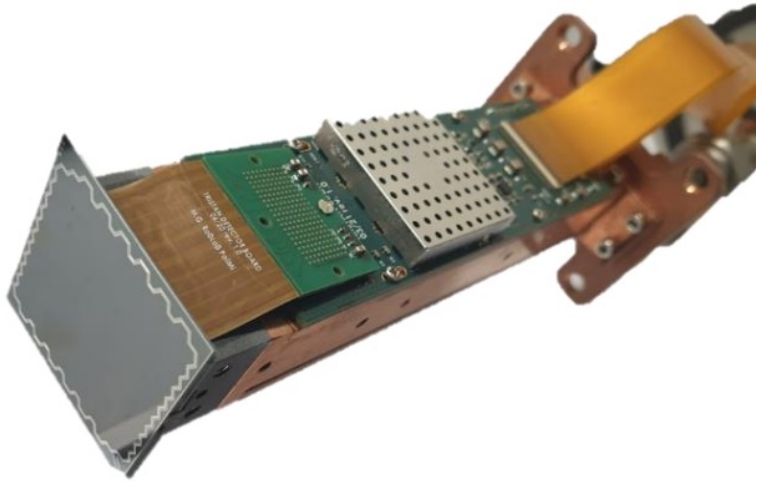


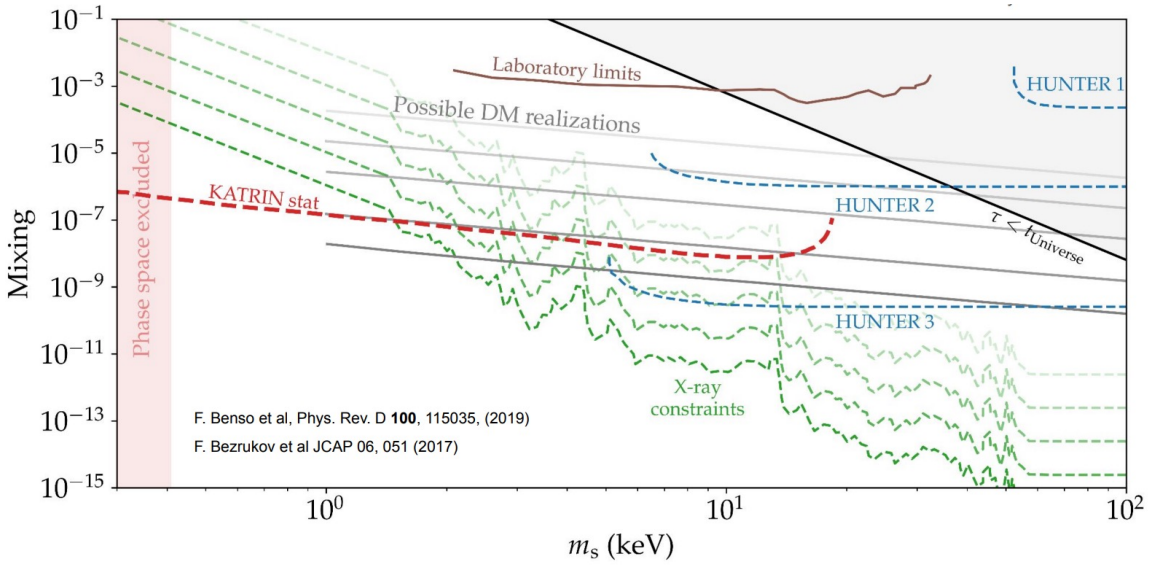
# TRISTAN Summary

Detector Development
- Production of 166-pixel detector modules meeting design requirements
- Continued characterization
- Development of final infrastructure needed for integration as the KATRIN detector

Sensitivity
- Ongoing effort to accurately model tritium spectrum for sensitivity and data fitting
- 1 year measurement campaign to reach $2 \cdot 10^{-7}$ statistical sensitivity

Installation
- Scheduled for installation in the KATRIN beamline following the end of the neutrino mass measurement (2025+)





# Thanks for your time!


TRISTAN Workshop, Summer 2022

This material is based upon work supported by the U.S. Department of Energy, Office of Science,
Office of Nuclear Physics under Award Numbers DE-FG02-97ER41041, DE-FG02-97ER41033

This material is based upon work supported by the National Science Foundation under Grant No. NSF OISE 1743790

This project has received funding from the European Research Council (ERC) under the European Union Horizon 2020 research and innovation programme (grant agreement No. 852845)

# Differential vs Integral