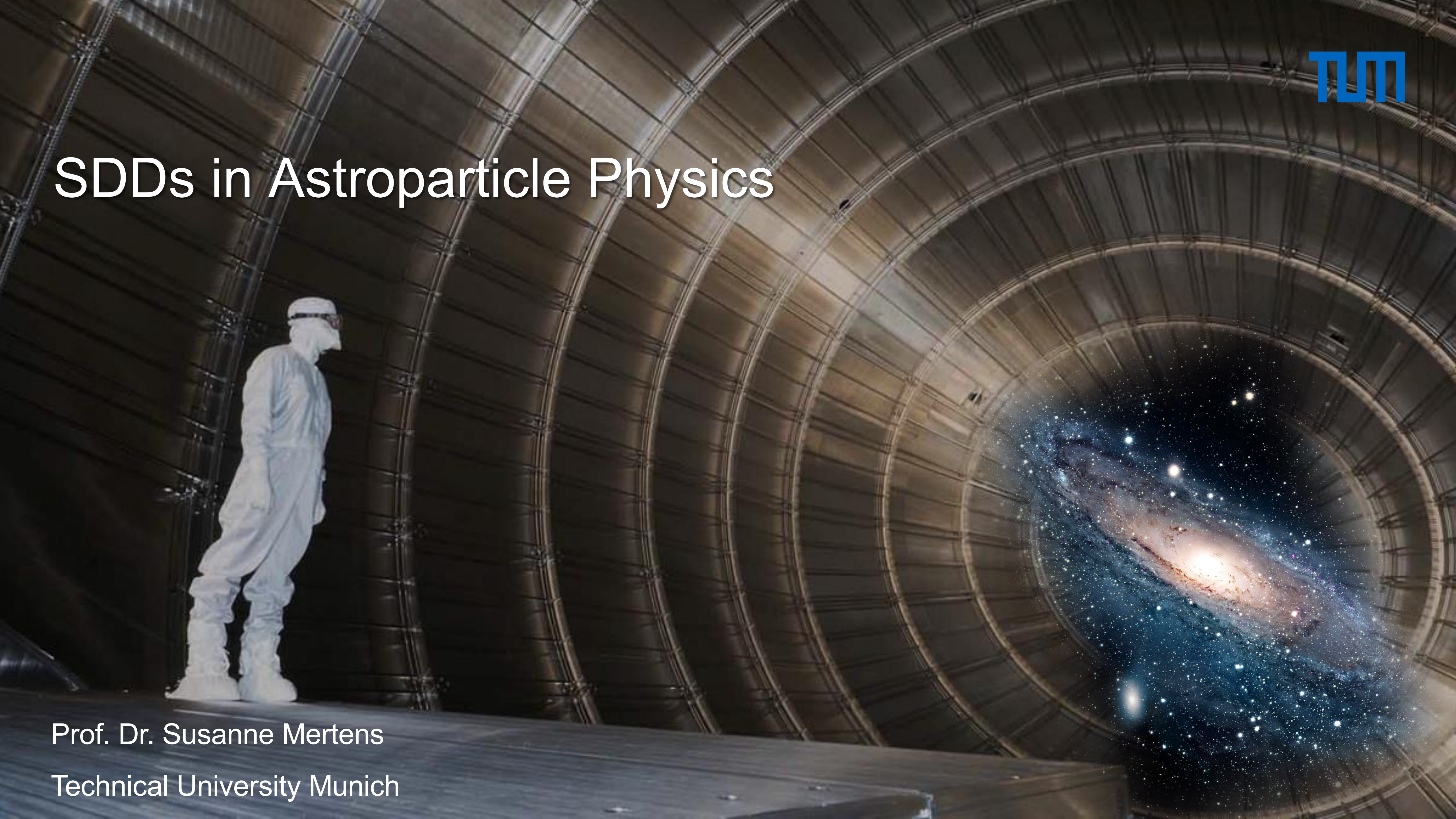
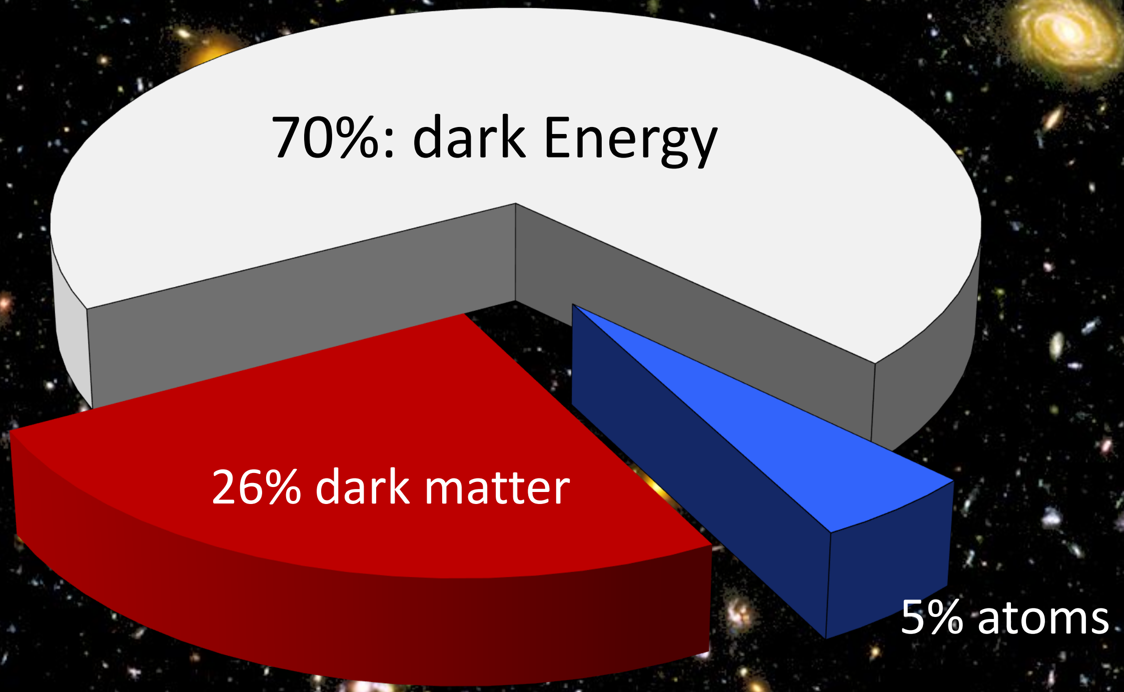
# SDDs in Astroparticle Physics



Prof. Dr. Susanne Mertens

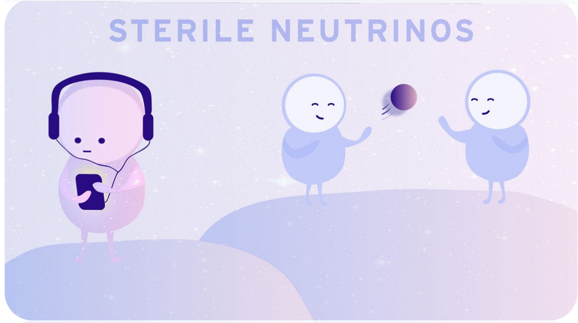
Technical University Munich

# What is our universe made of ?



# Dark Matter Candidates

μeV meV eV keV MeV GeV TeV

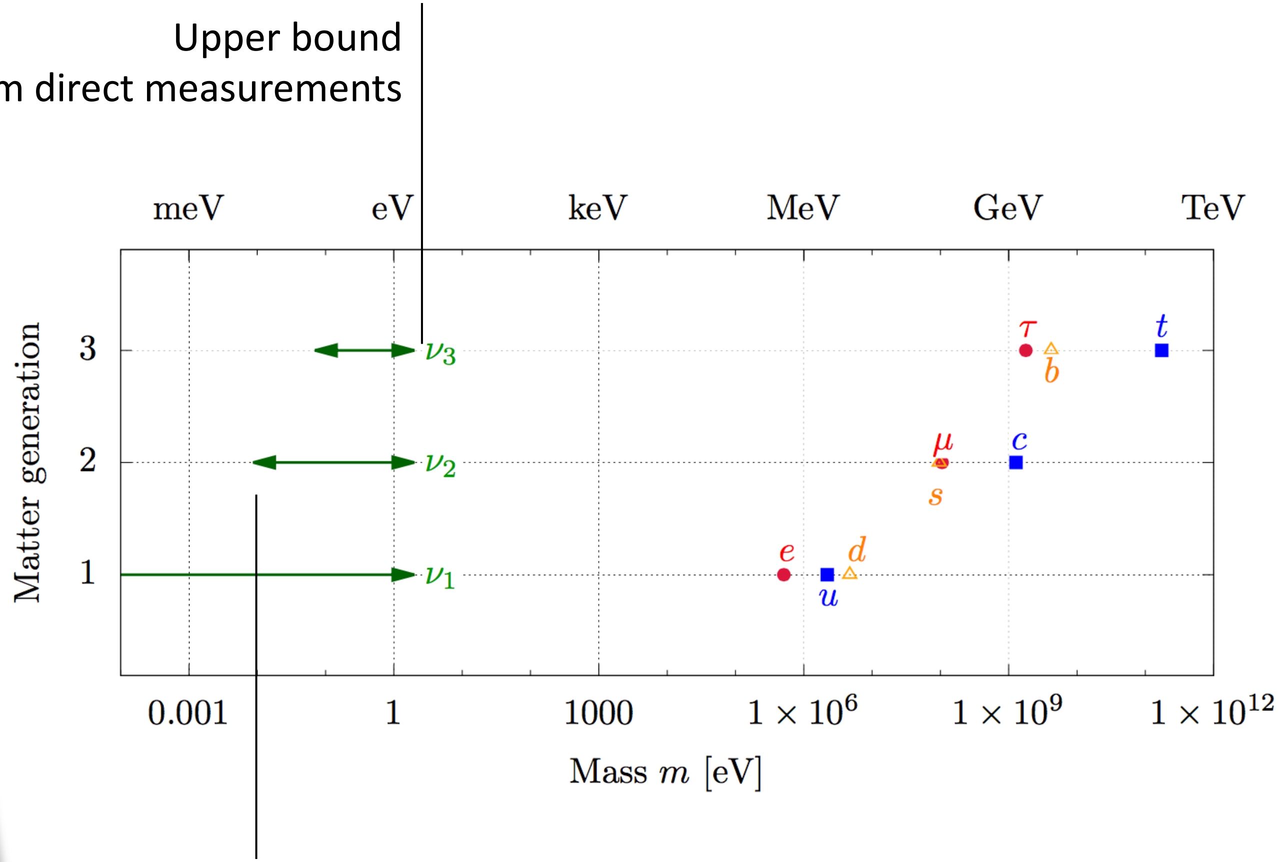



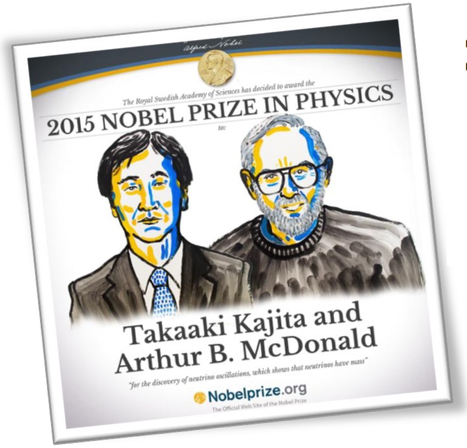


→ Talk by Jochen Schieck

# Neutrinos

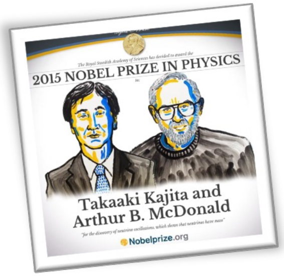
Upper bound
from direct measurements



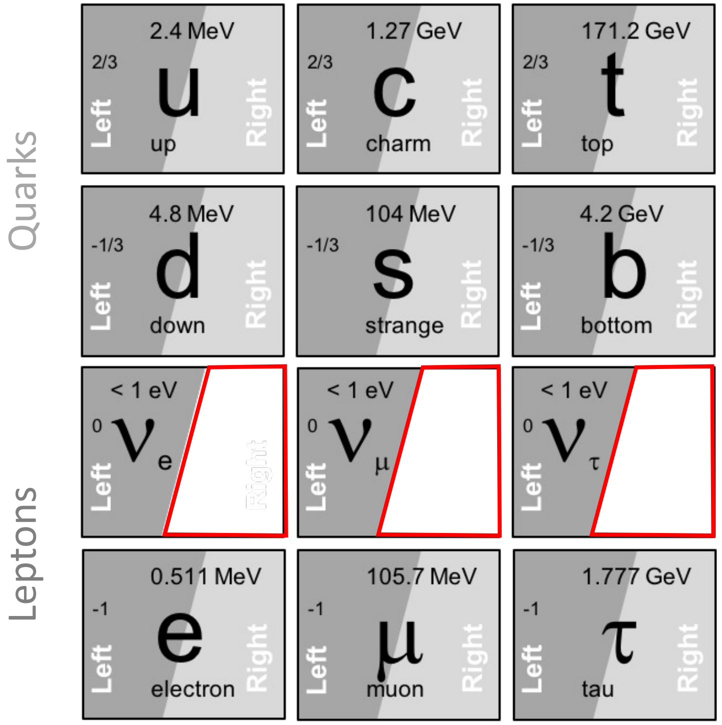




Lower bound
from oscillation experiments

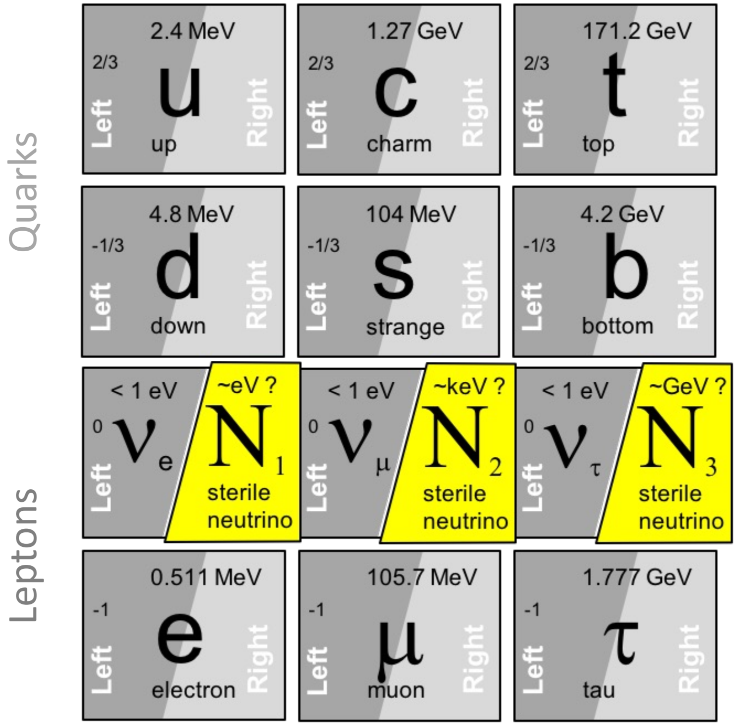
# Sterile Neutrinos




## Standard Model (SM)

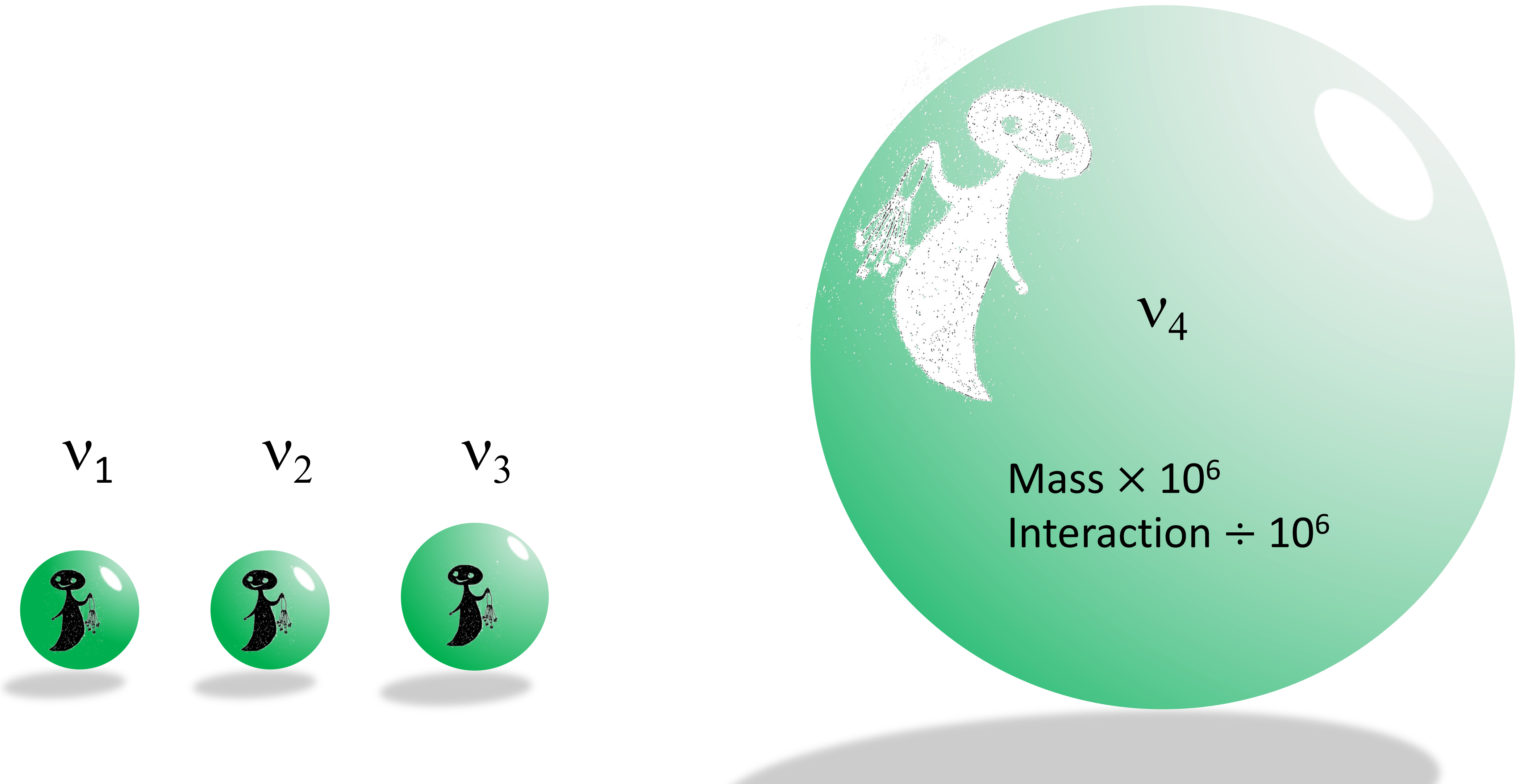



## ν–Minimal Standard Model

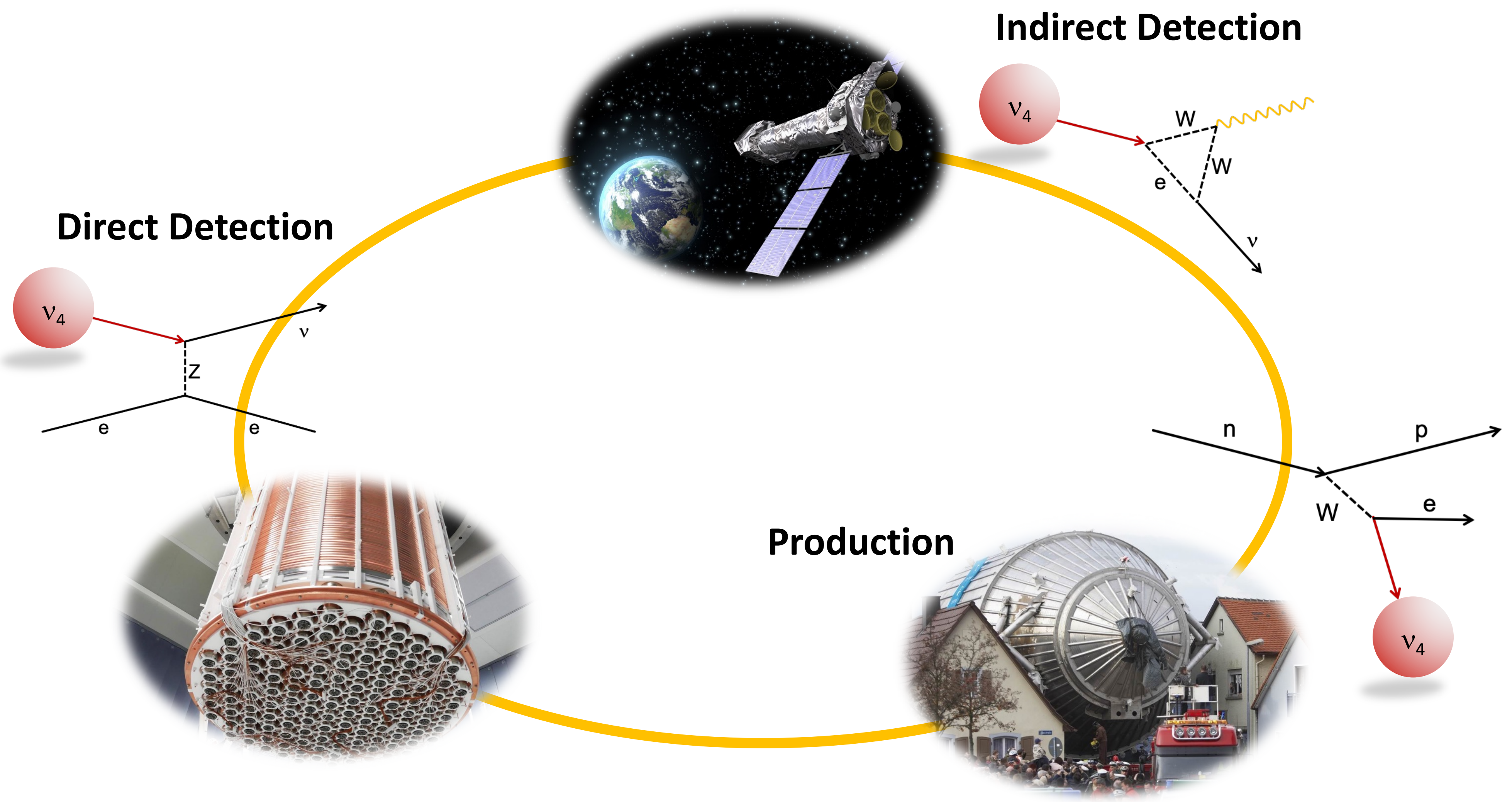



L. Canetti, M. Drewes, and M. Shaposhnikov,
PRL **110** 061801 (2013)

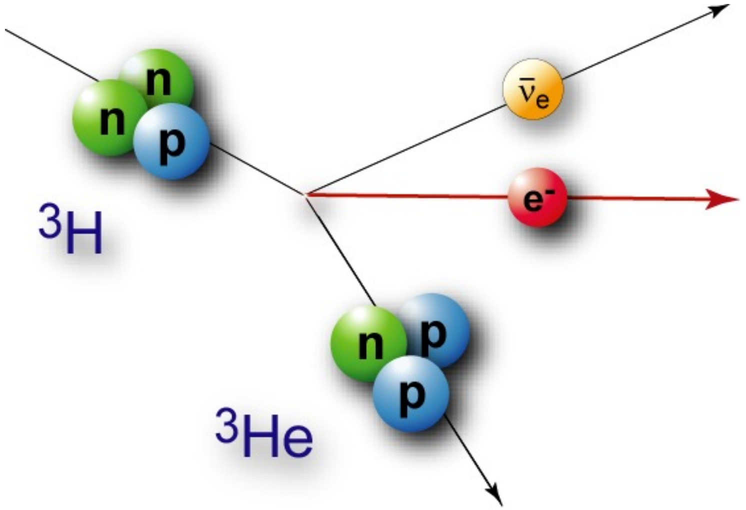
# Dark Matter Sterile Neutrinos



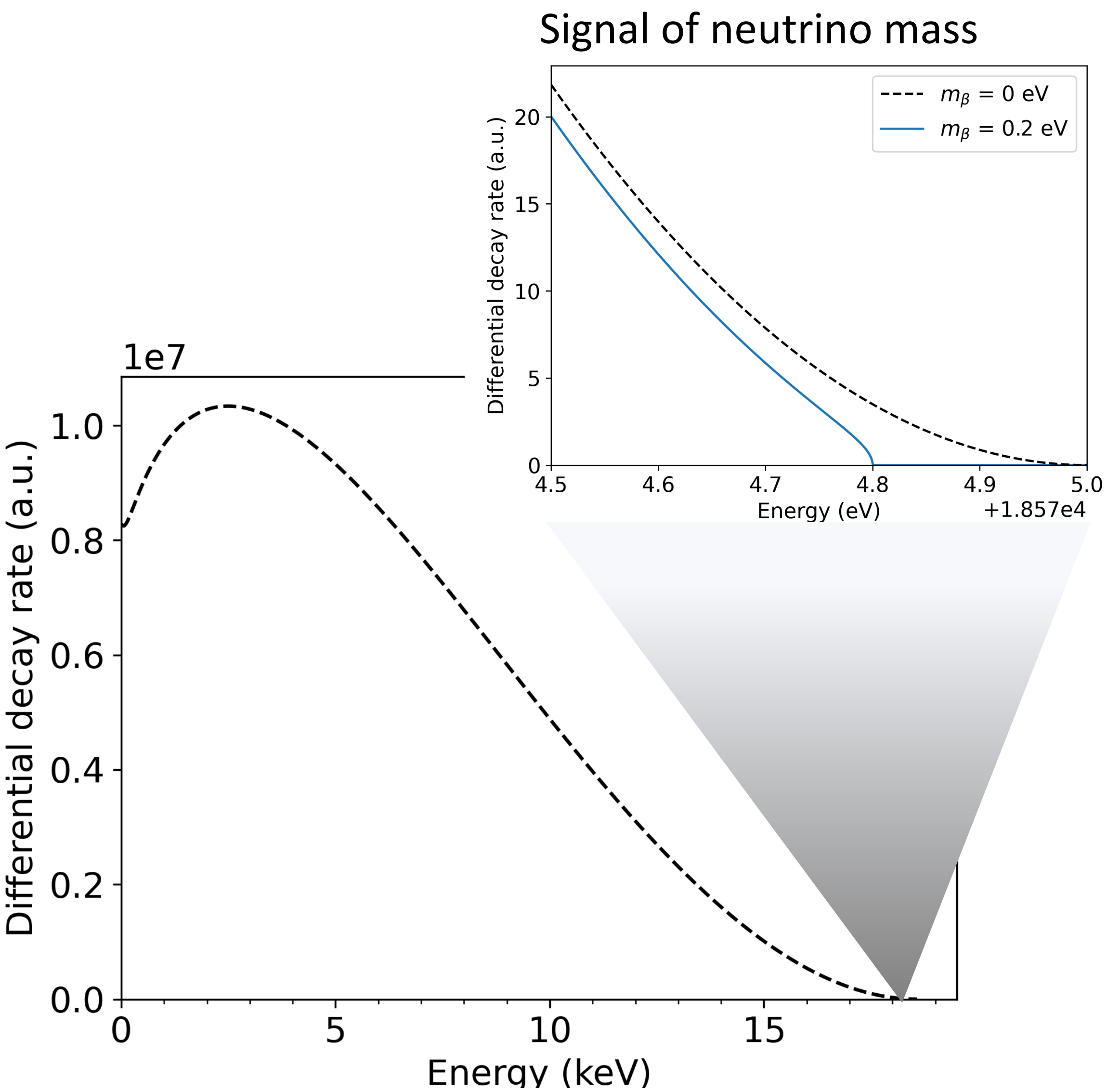
# Experimental searches



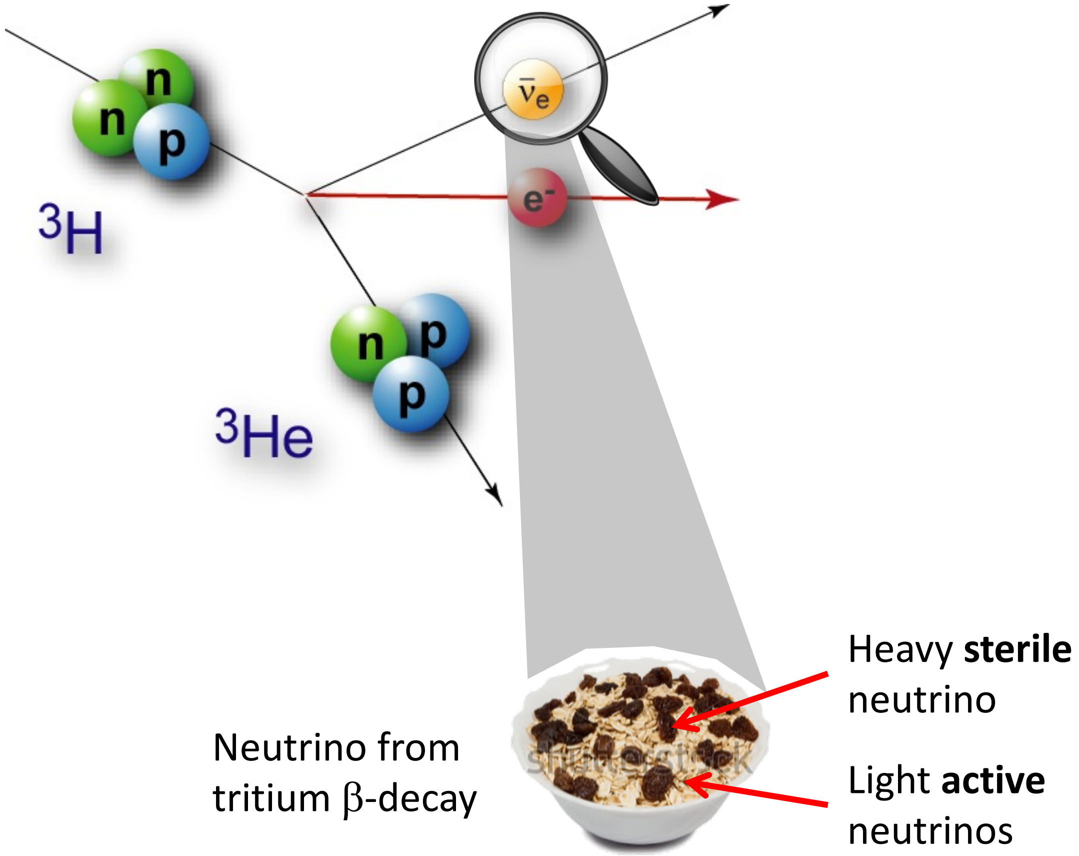
# Tritium ß-decay

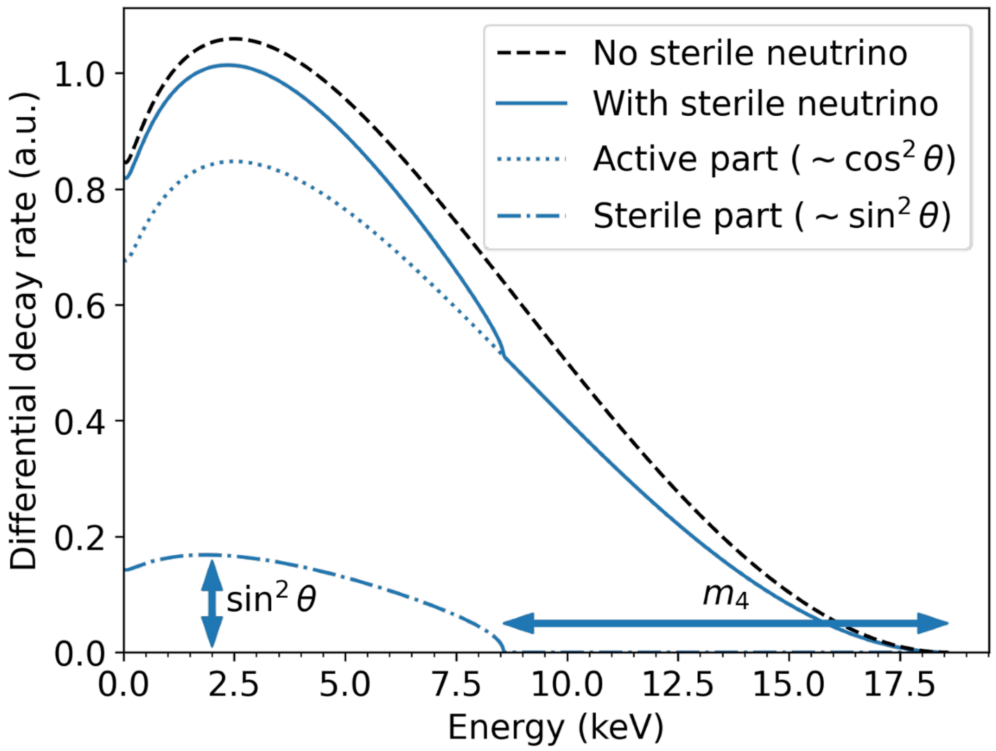



$$\frac{d\Gamma}{dE} = C \cdot F(E,Z) \cdot p \cdot (E + m_e) \cdot (E_0 - E) \cdot \sqrt{(E_0 - E)^2 - \boldsymbol{m_\nu^2}}$$



# Imprint of sterile ν's on ß-spectrum



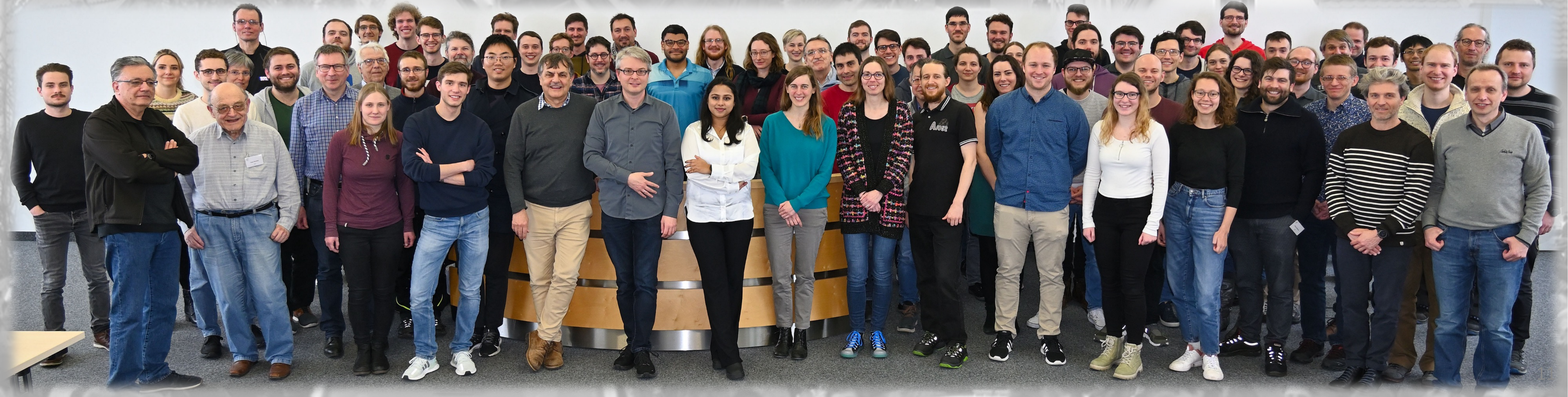



# The world’s strongest tritium source @ KATRIN

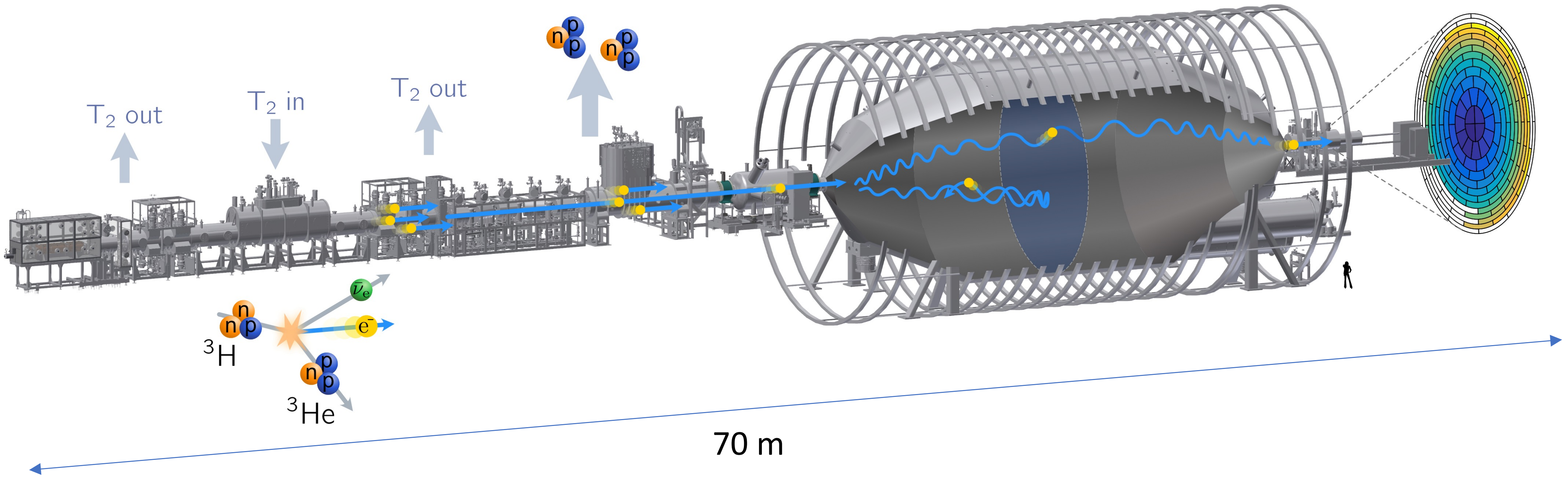
# KATRIN

- **Experimental site: Karlsruhe Institute of Technology (KIT)**
- **International Collaboration (150 members)**
- **Main goal: direct measurement of the neutrino mass with 0.3 eV sensitivity**

KIT Karlsruher Institut für Technologie
Max-Planck-Institut für Kernphysik Heidelberg
University of Washington
Case Western Reserve University EST. 1826 think beyond the possible
Westfälische Wilhelms-Universität Münster
Massachusetts Institute of Technology
Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)
The University of North Carolina at Chapel Hill
The Czech Academy of Sciences
Carnegie Mellon University
Hochschule Fulda University of Applied Sciences
Universidad Complutense Madrid
Università degli Studi di Milano Bicocca
cea
JGU Johannes Gutenberg Universität Mainz
TUM Technische Universität München
universitätbonn
Politecnico Milano 1863
Humboldt-Universität zu Berlin
Bergische Universität Wuppertal
Berkeley Lab
Russian Academy of Sciences



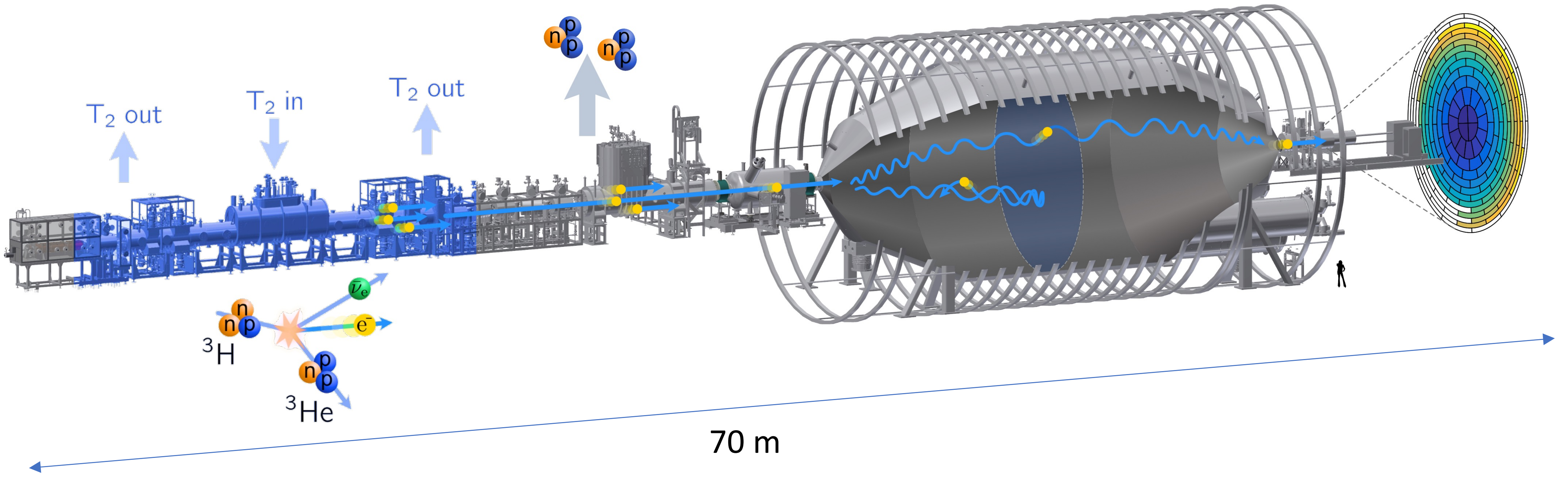
# Working Principle



# Working Principle

**Tritium source**

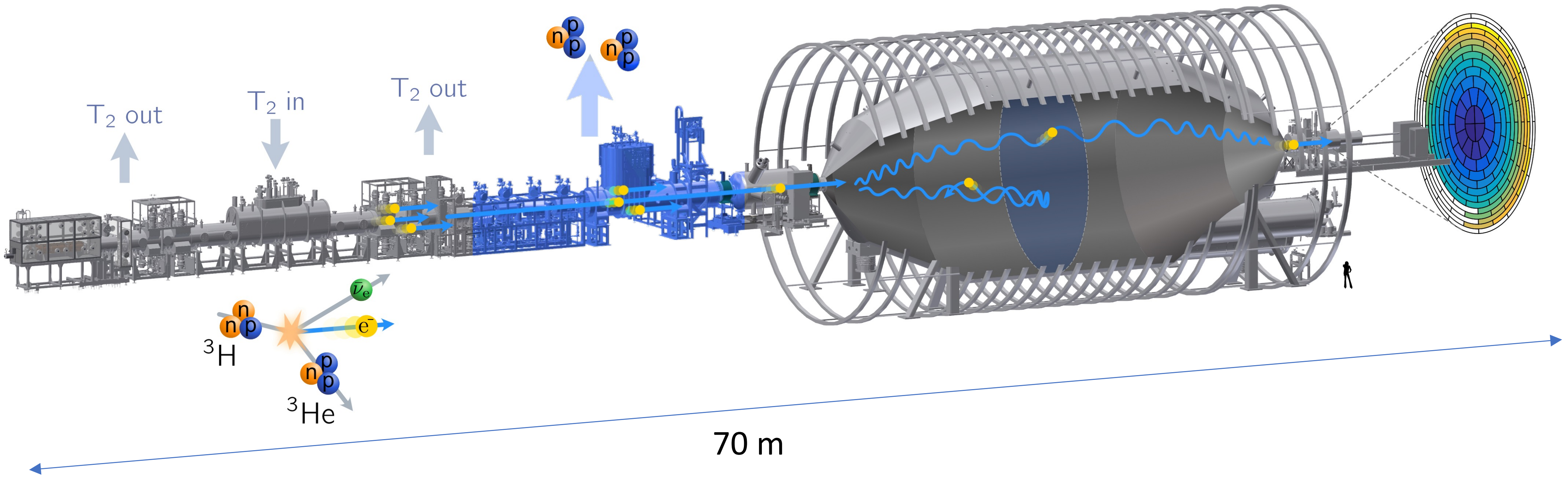
- 100 μg of gaseous $T_2$
- $10^{11}$ $T_2$ decays/s



# Working Principle

**Tritium source**
- 100 µg of gaseous $T_2$
- $10^{11}$ $T_2$ decays/s

**Transport section**
- Guidance of electrons
- Removal of tritium



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**Tritium source**
- 100 µg of gaseous $T_2$
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**Transport section**
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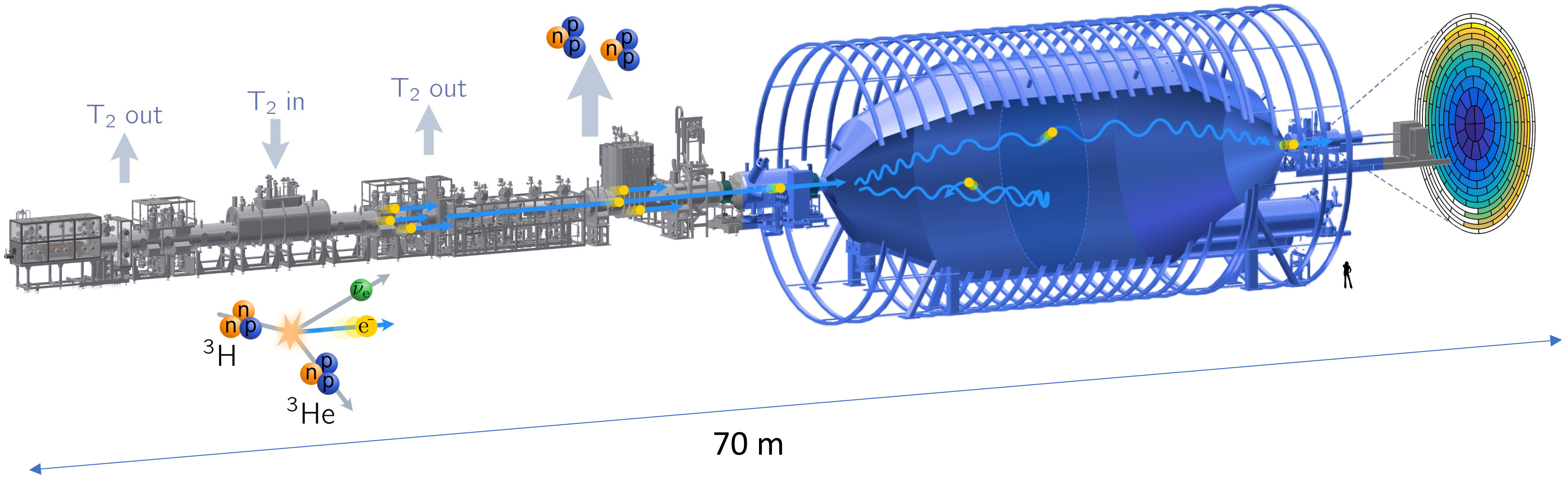
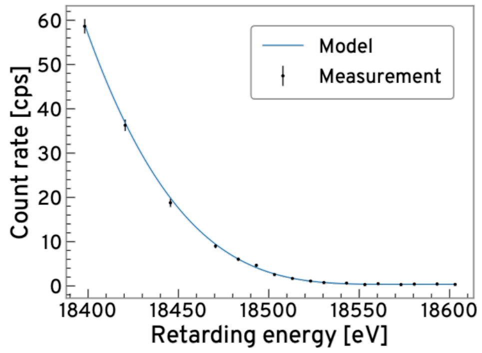
**Spectrometer**
- Electrostatic filter
- MAC-E filter principle



# Working Principle

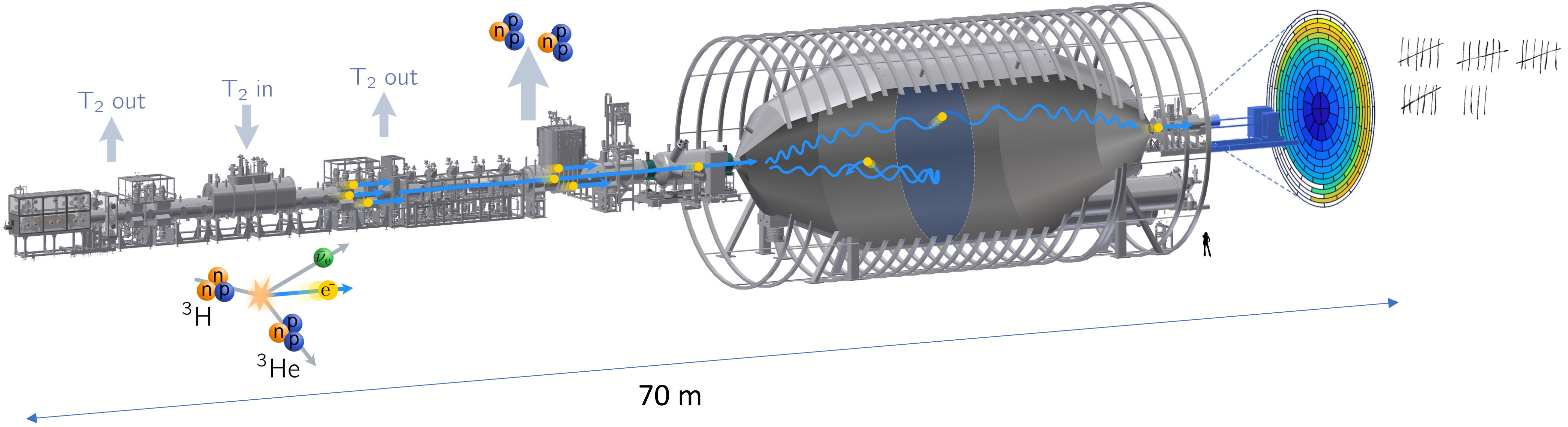



**Tritium source**
- 100 µg of gaseous $T_2$
- $10^{11}$ $T_2$ decays/s

**Transport section**
- Guidance of electrons
- Removal of tritium

**Spectrometer**
- Electrostatic filter
- MAC-E filter principle

**Detector**
- Counts electrons
- Rate vs potential



# New KATRIN result

**Data set:**

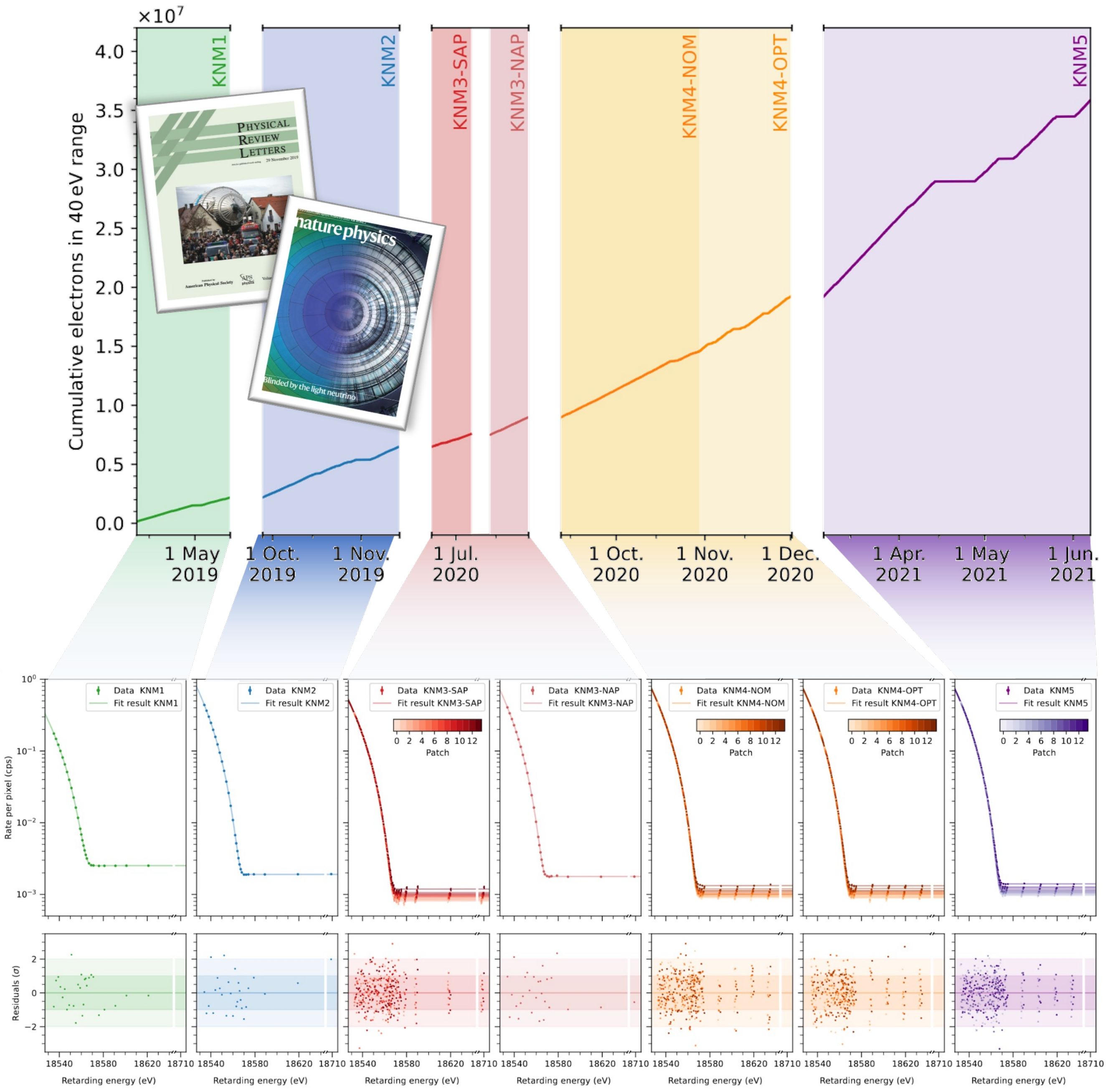
- 250 days of data (5 campaigns)
- 63 Mio electrons

**Result:**

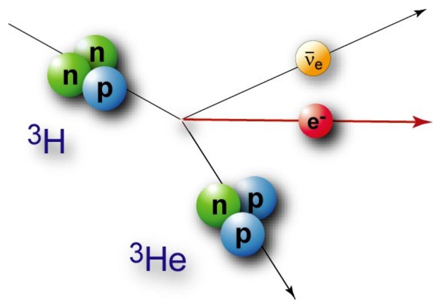
- Best fit:
  $m_\nu^2 = \left(-0.14^{+0.13}_{-0.15}\right)\text{eV}^2$ **(stat. dom.)**
- New limit:
  $m_\nu < 0.45$ **eV (90% CL)** Neutrino-24 (2024)
  arXiv:2406.13516 (2024)

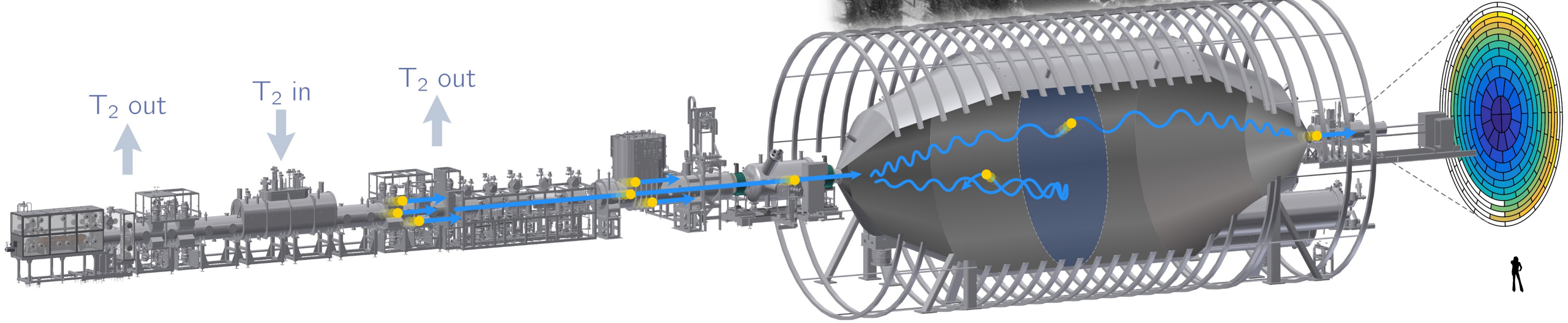
**Final goal (in 2026):**

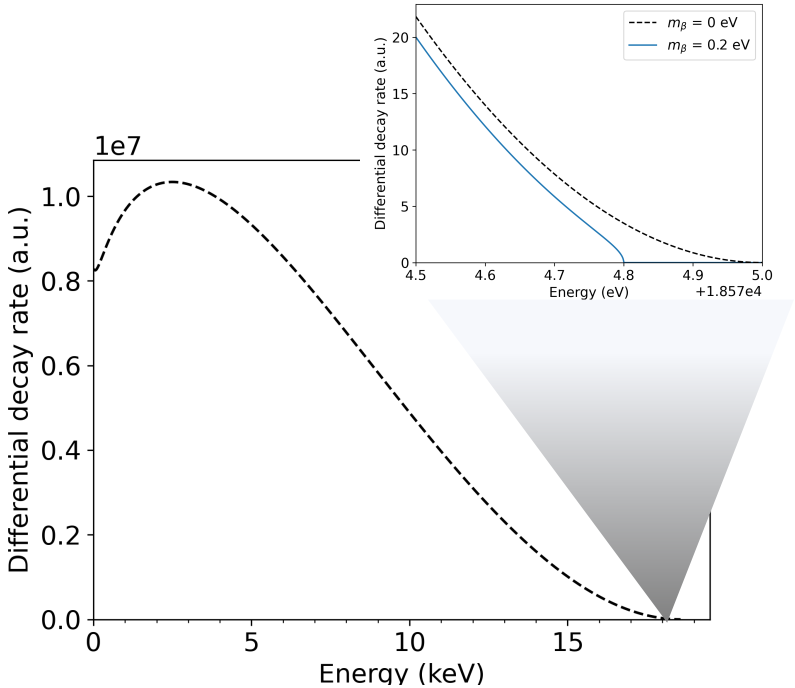
- $m_\nu < 0.3$ **eV (90% CL)**



# Extending KATRIN

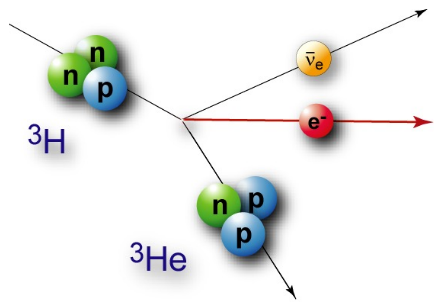


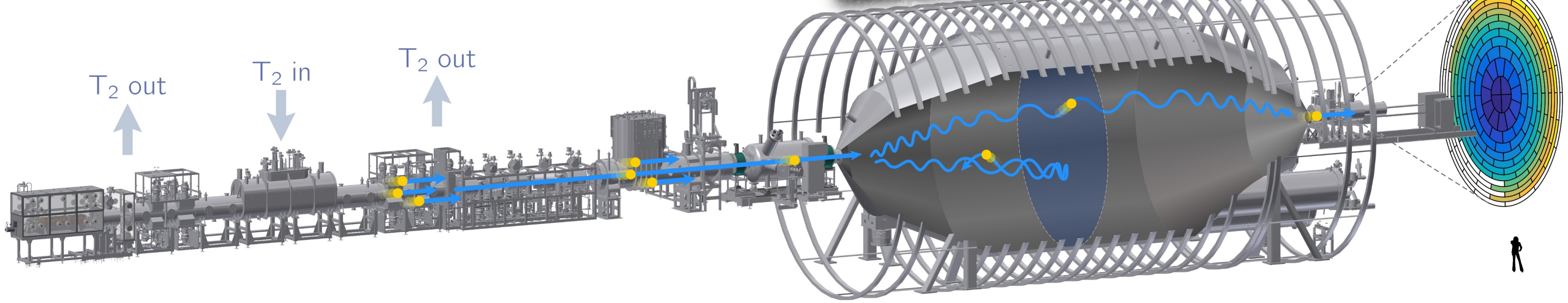



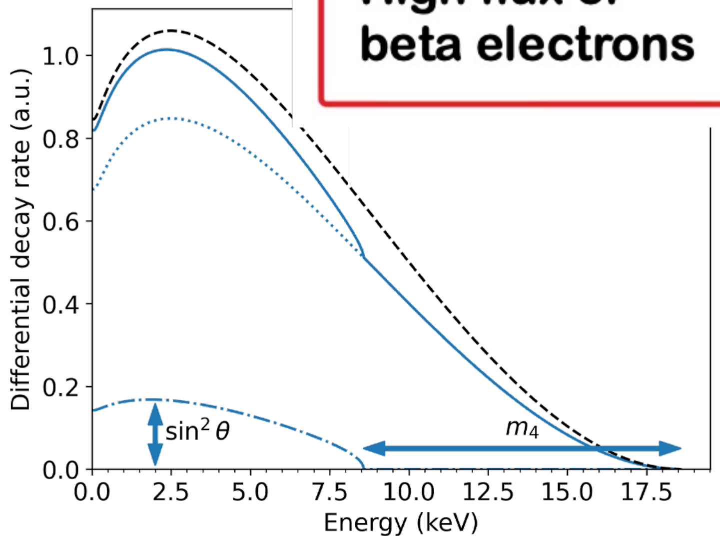




$10^{11}$ decays/s

# Extending KATRIN



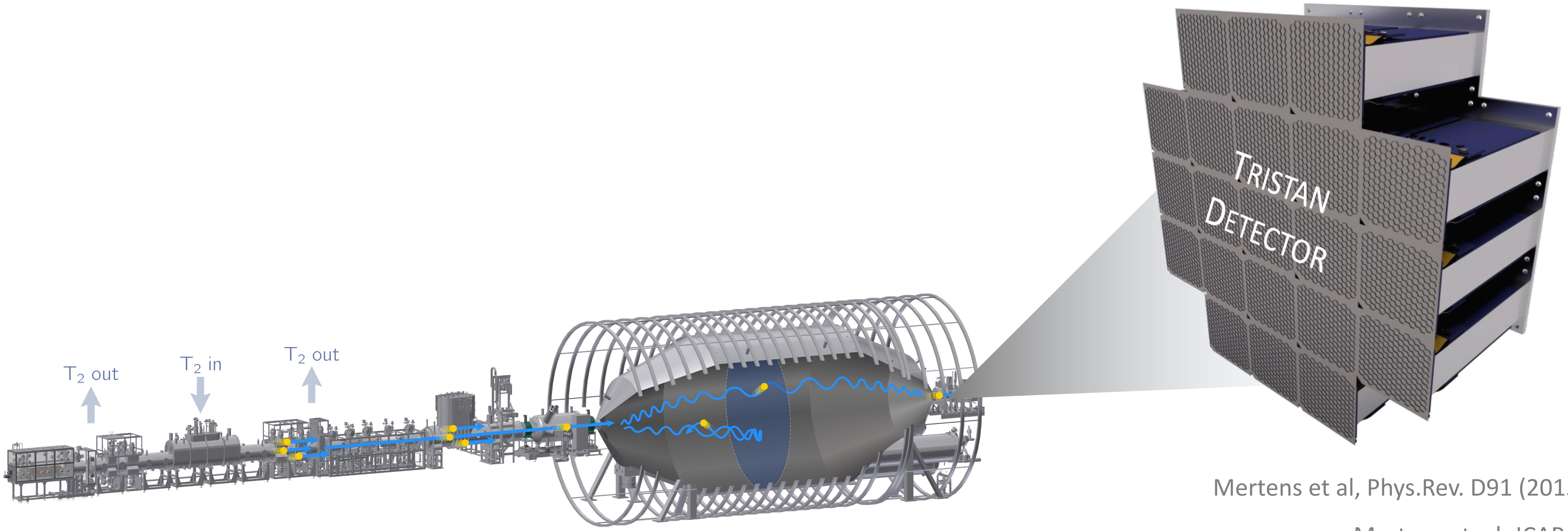





$10^{11}$ decays/s

# A novel detector system




Mertens et al, Phys.Rev. D91 (2015) 4, 042005

Mertens et. al. JCAP 1502 (2015)

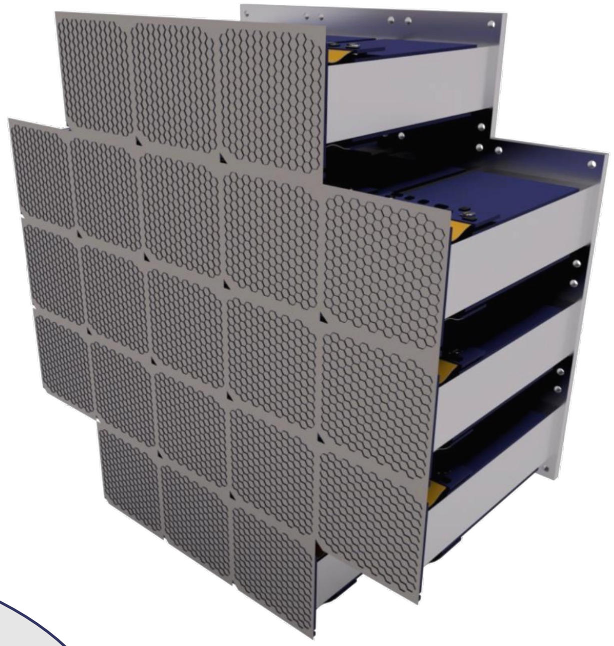
# Detector Requirements

Our first visit to HLL in 2015


The detector needs to handle high rates

We need a good energy resolution, to resolve the kink

The detector needs to cover the full electron beam, without much dead area



# Detector Requirements

Our first visit to HLL in 2015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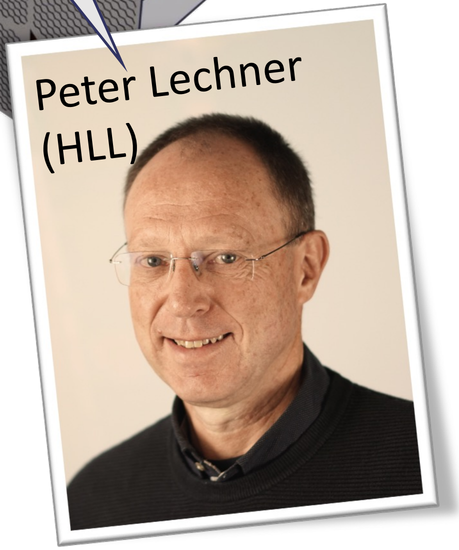
We need a good energy resolution, to resolve the kink

The detector needs to cover the full electron beam, without much dead area

No problem…

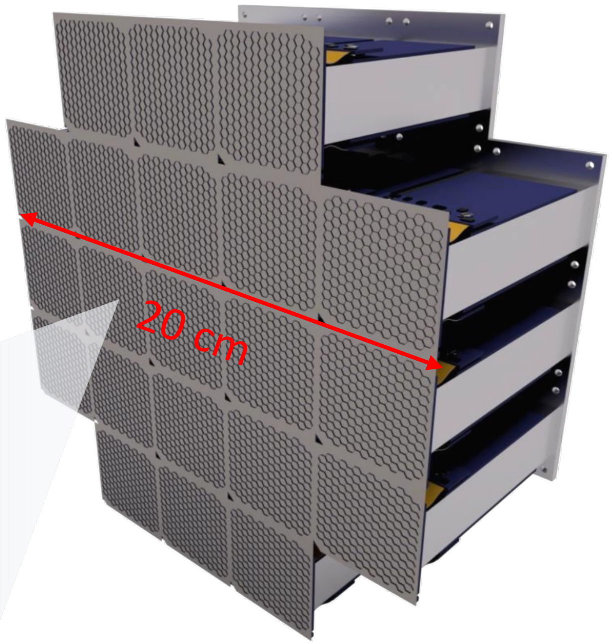


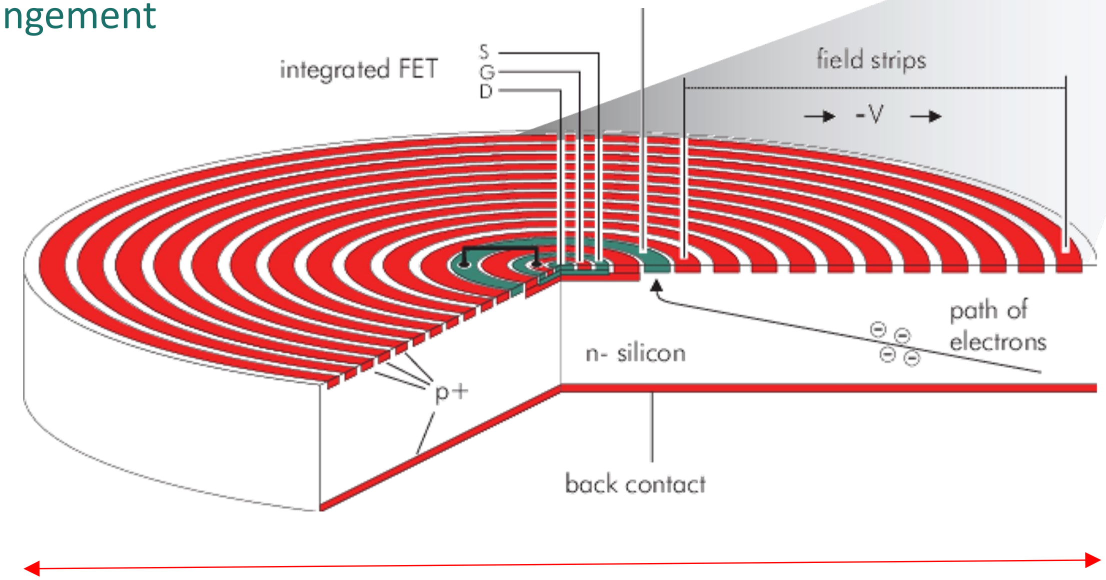
# Silicon Drift Detector (SDD)

✓ Small readout contact
  - ➢ Small detector capacitance → Low noise (good resolution) for high rates

✓ Large detector area
  - ➢ Large area coverage, not too many pixels

✓ Integrated amplification (nJFET)
  - ➢ Focal plane arrangement

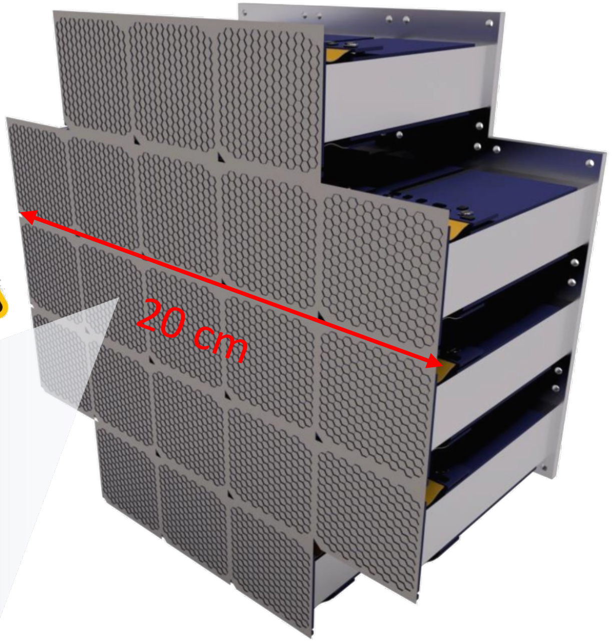


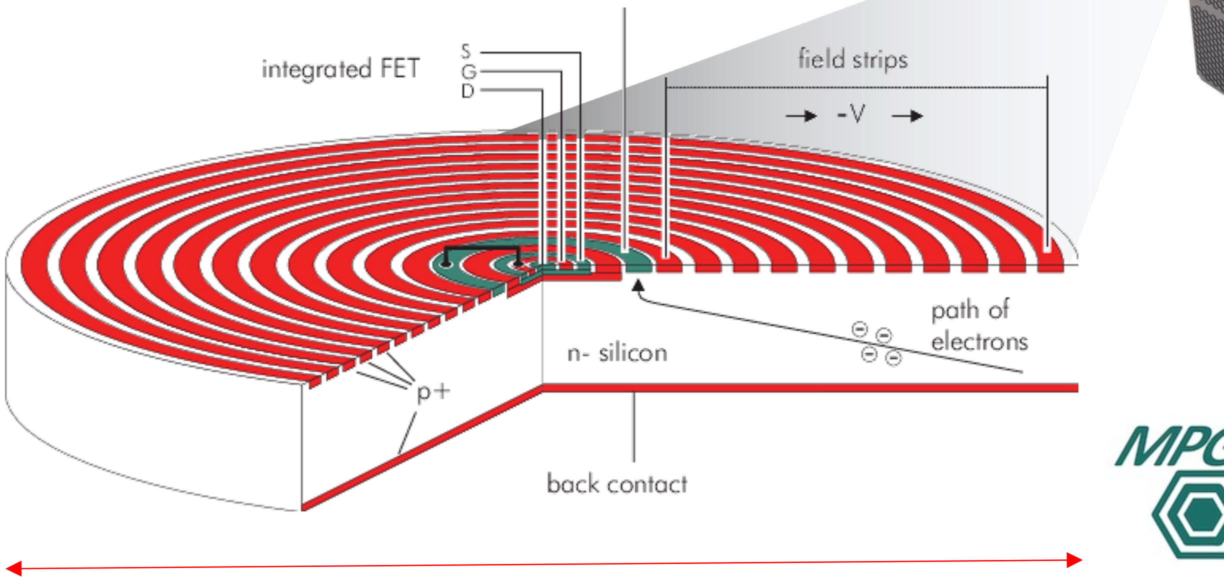



# Challenges

> 1000 pixel SDD
9 - 21 modules (each 166 pixel)

- Large pixel number
- Focal plane configuration
- Operation at high magnetic field and high vacuum
- Ultra-precise beta spectroscopy

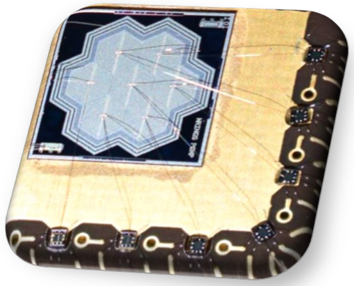



3 mm, 220 fF

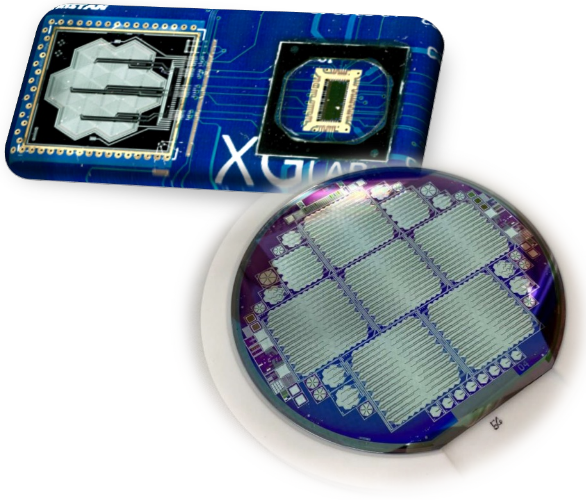
# A long SDD journey…

2017



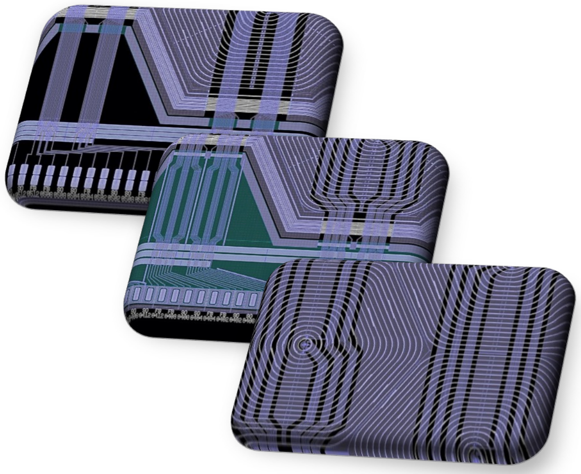
7-pixel
prototype SDDs

2020



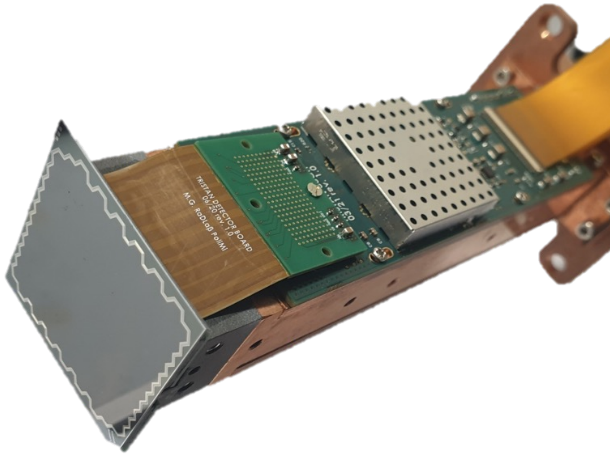
SDDs with integrated nJFET
166-pixel devices

2022



Layout
optimizations

2023



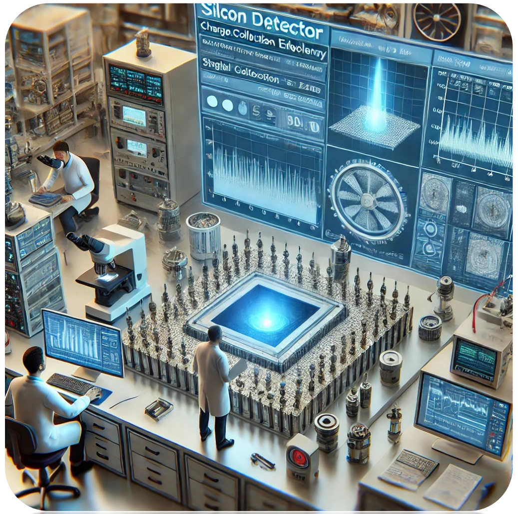
Final production
Our first modules

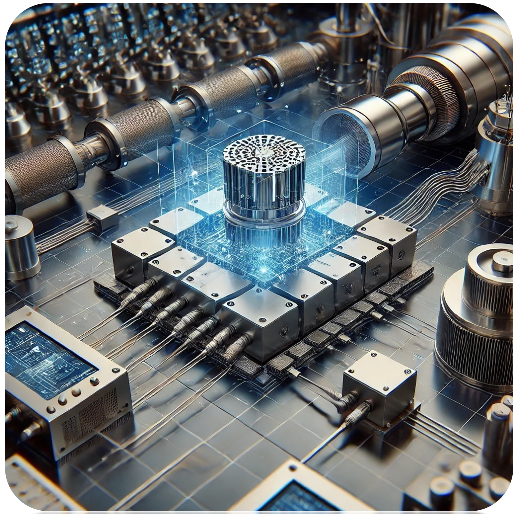
# A long SDD journey…

Characterization

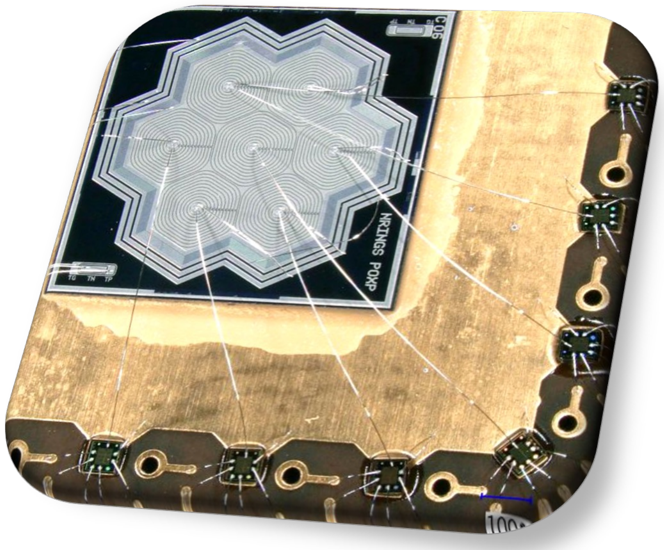
Optimization

Integration





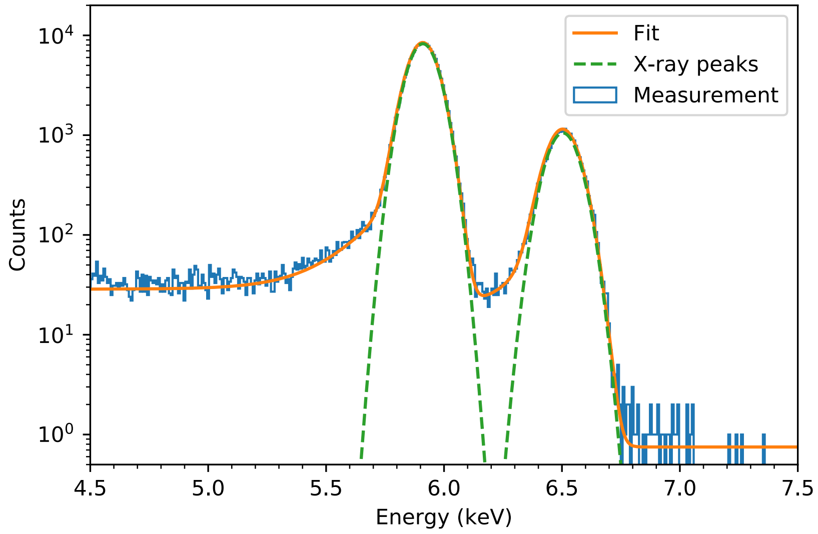
# X-ray characterization



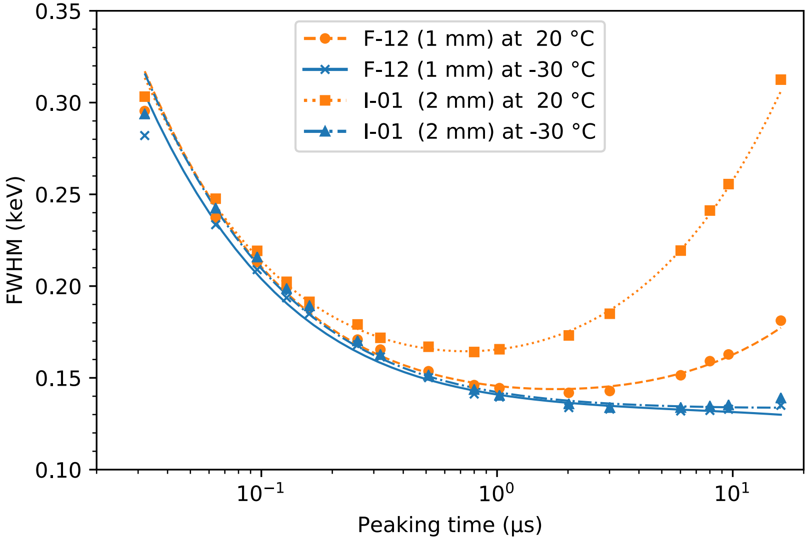

Excellent performance demonstrated J. Phys. G46 (2019)

- ✓ energy resolution
- ✓ noise characteristics
- ✓ linearity

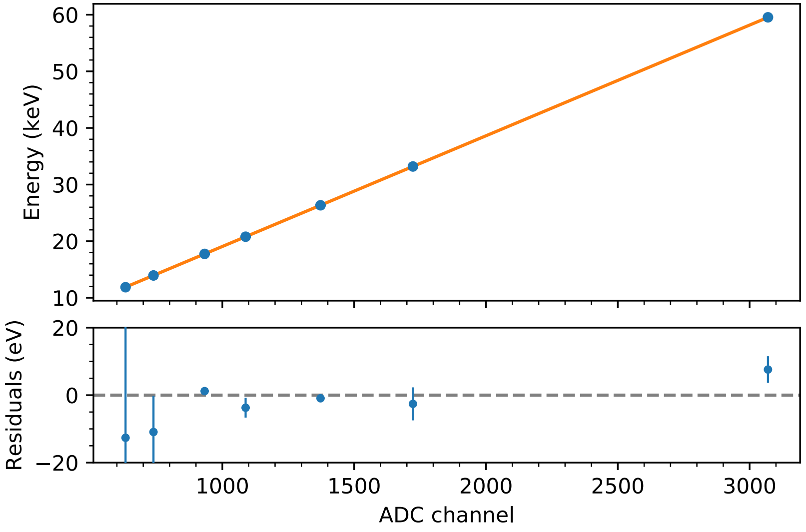
130 eV (FWHM) @ 6 keV



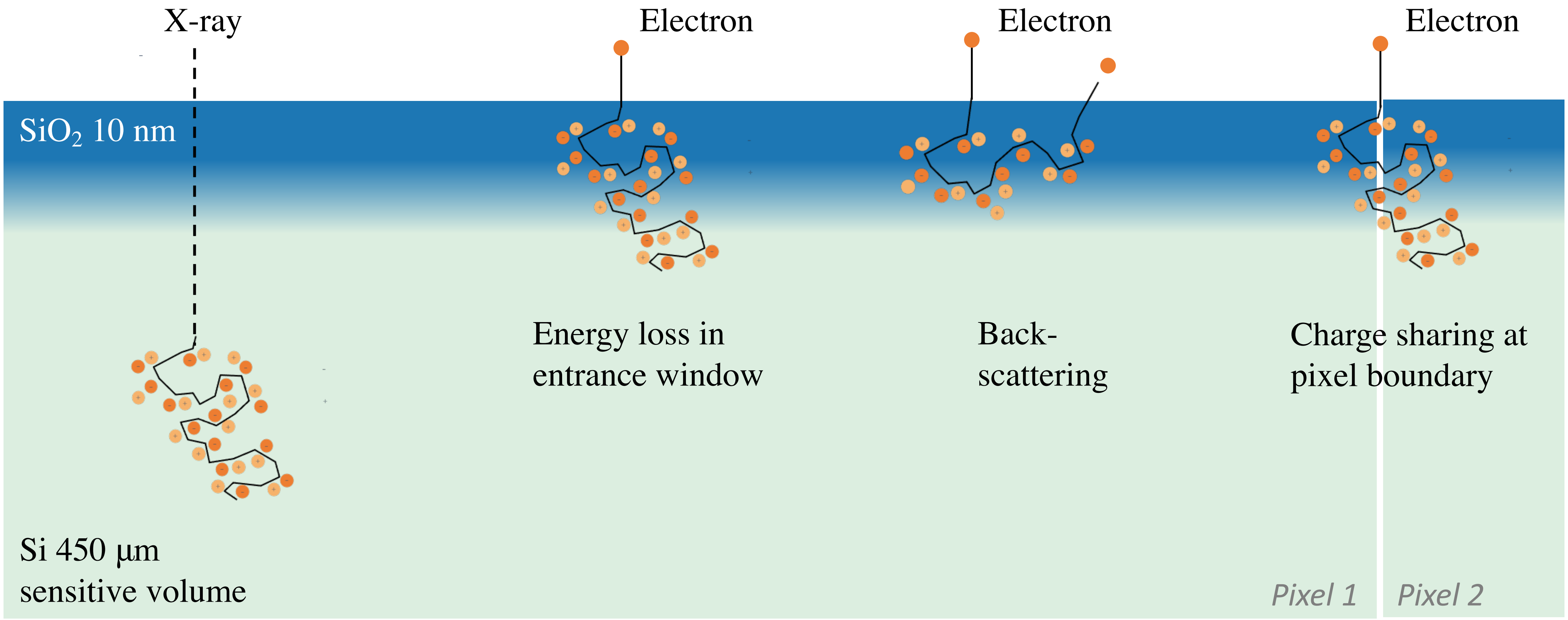

< 150 eV (FWHM), < 1µs shaping time




0.1% linearity over 60 keV range



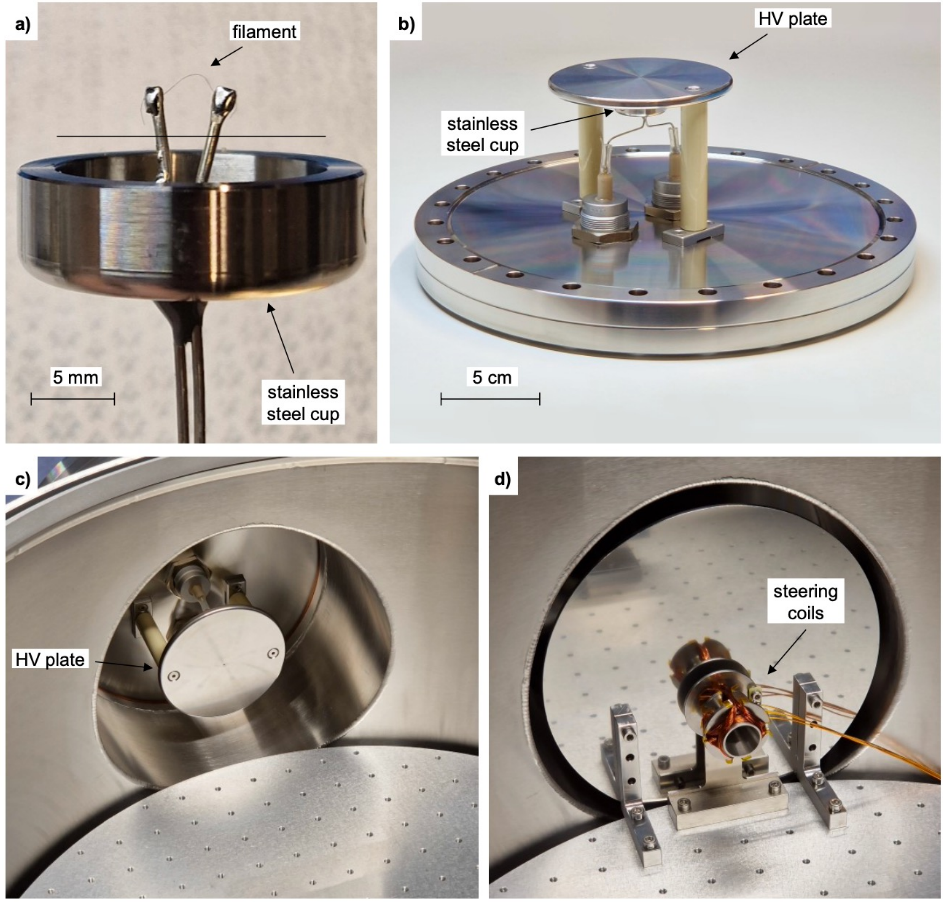
# Electron spectroscopy

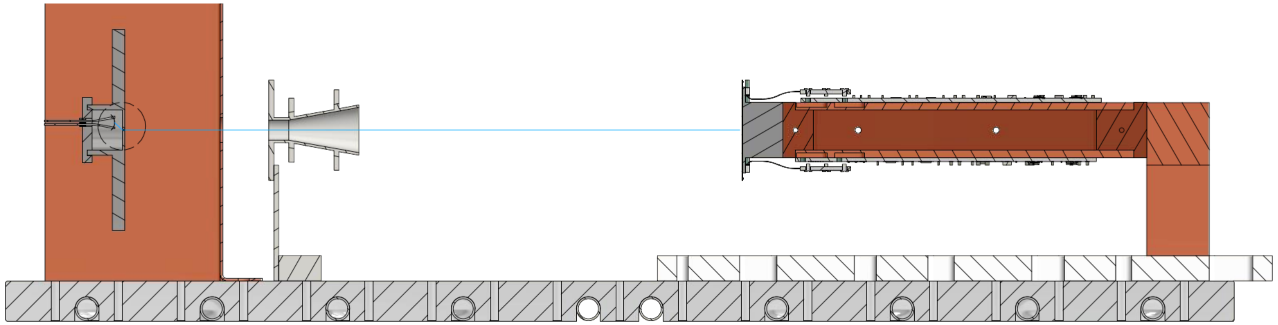


# TRISTAN Hot Cathode (THC) E-gun


- ✓ mono-energetic electrons with kinetic energy up to 30 keV
- ✓ electron rates up to 100 kcps per pixel
- ✓ illumination of the area of one TRISTAN detector module (40 × 38 mm²).

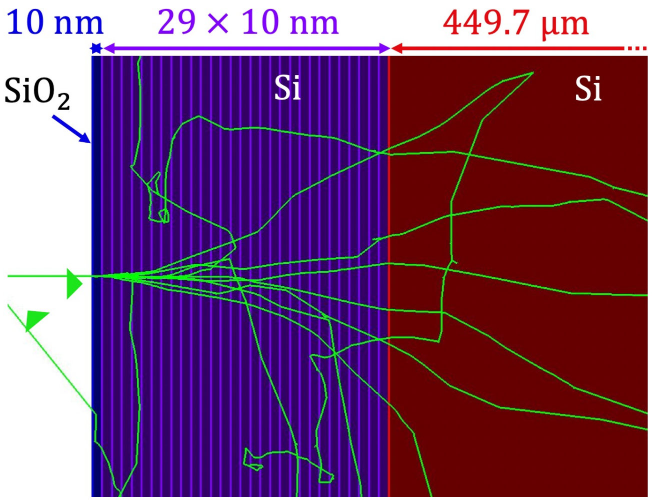
*K. Urban et al, JINST* **19** P06004 (2024)

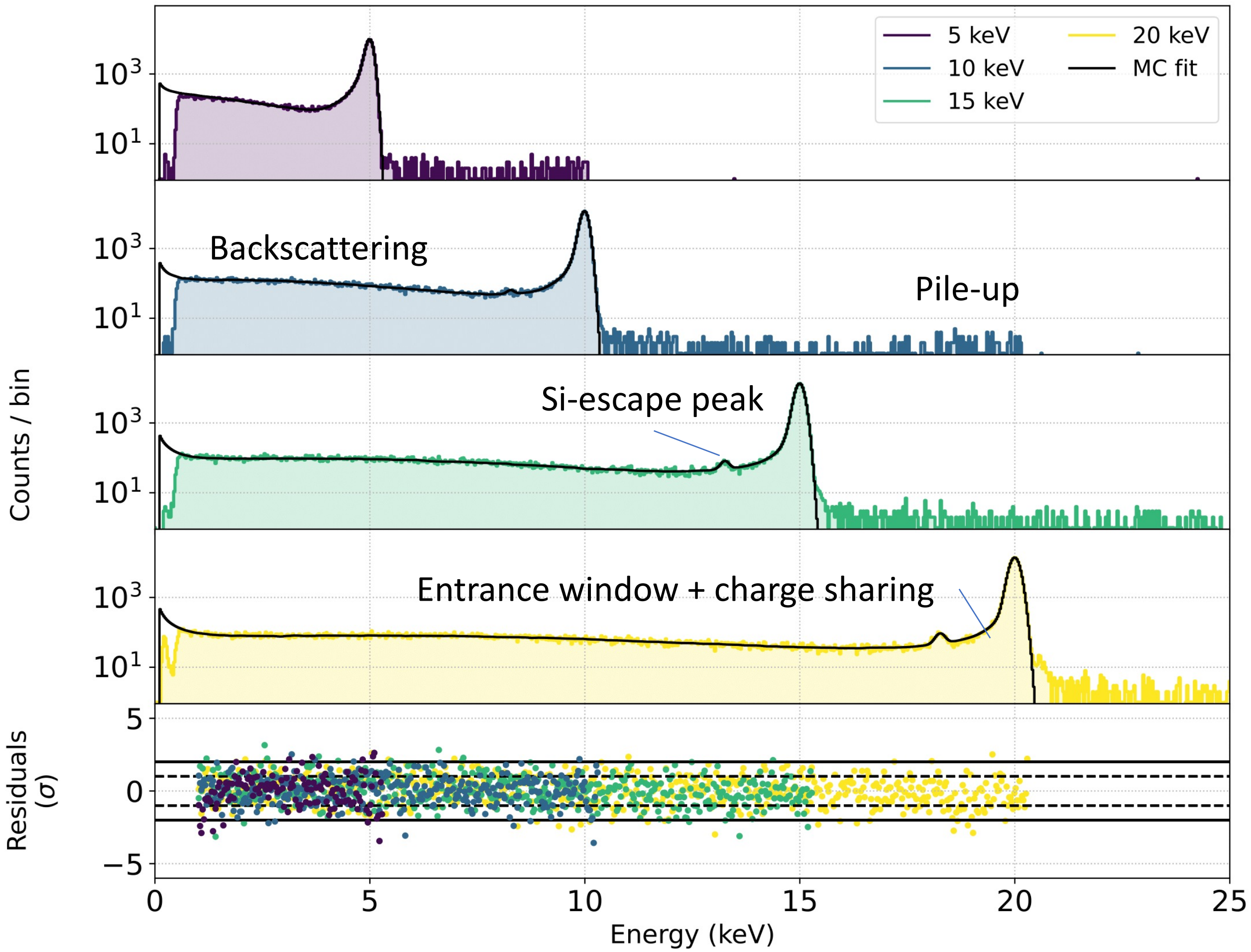


# Electron spectra

- ✓ High statistic electron spectra
- ✓ Good agreement of model with data



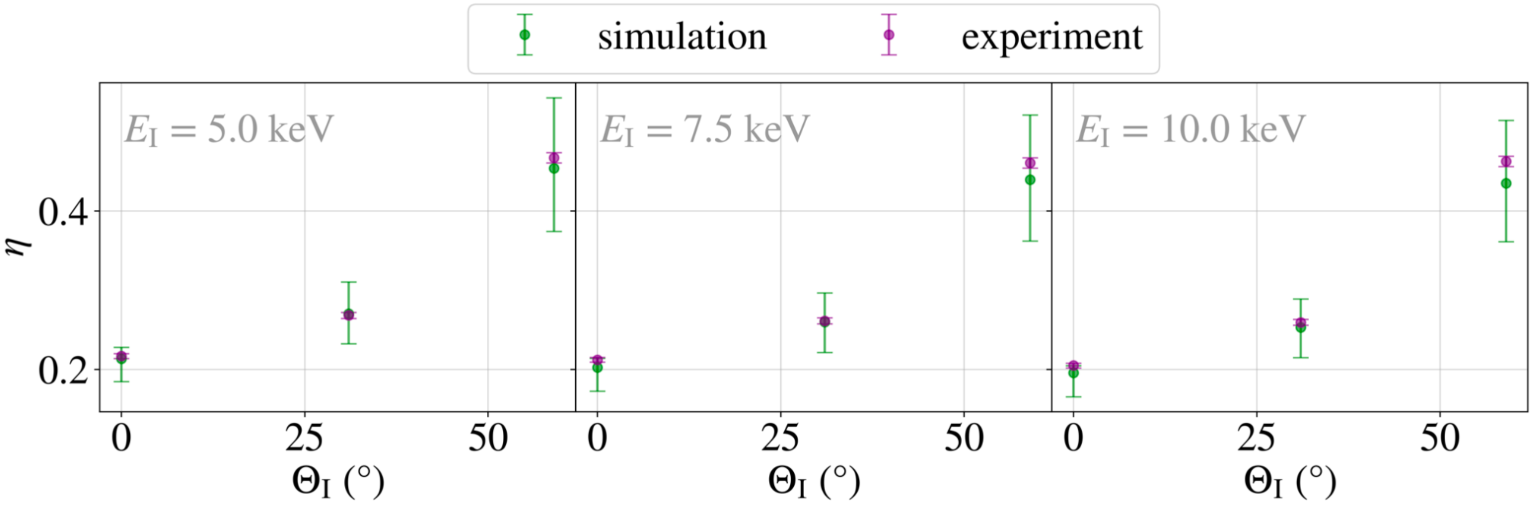



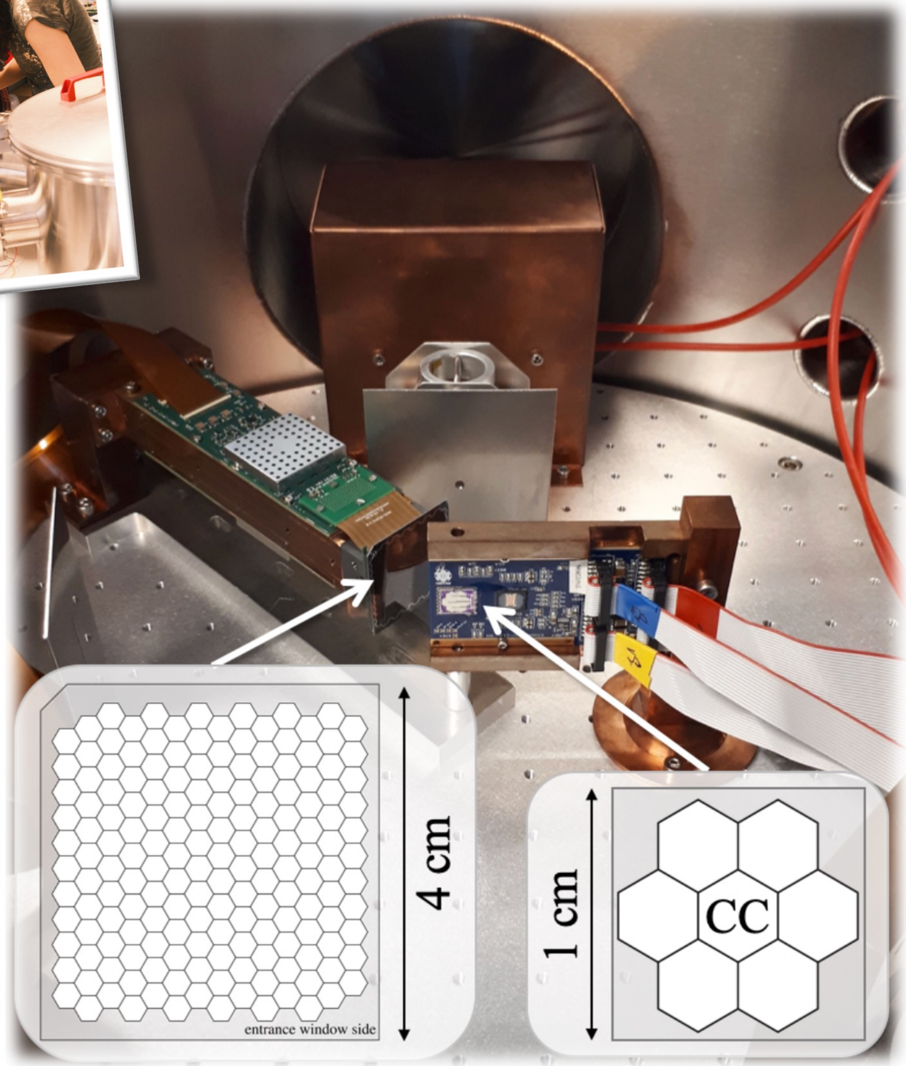

*K. Urban et al 2022 JINST 17 C09020*
*A. Nava et al, NIM-A 1046, 167812 (2023)*

# Backscattering

- ✓ Measurement of backscattering coefficient with two detectors
- ✓ Good agreement with simulations

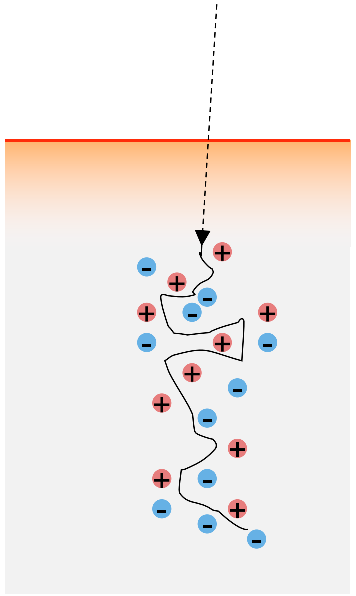
*D. Spreng et al. arXiv:2405.12776 (2024)*



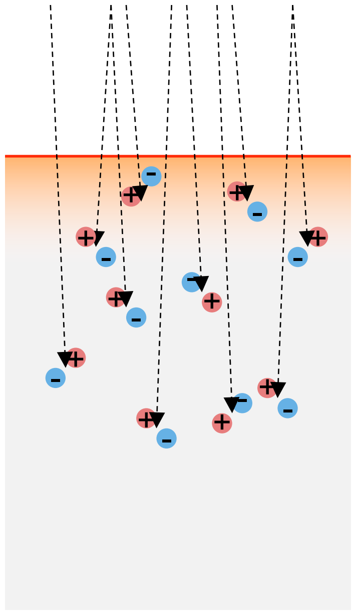



# Pulsed light source

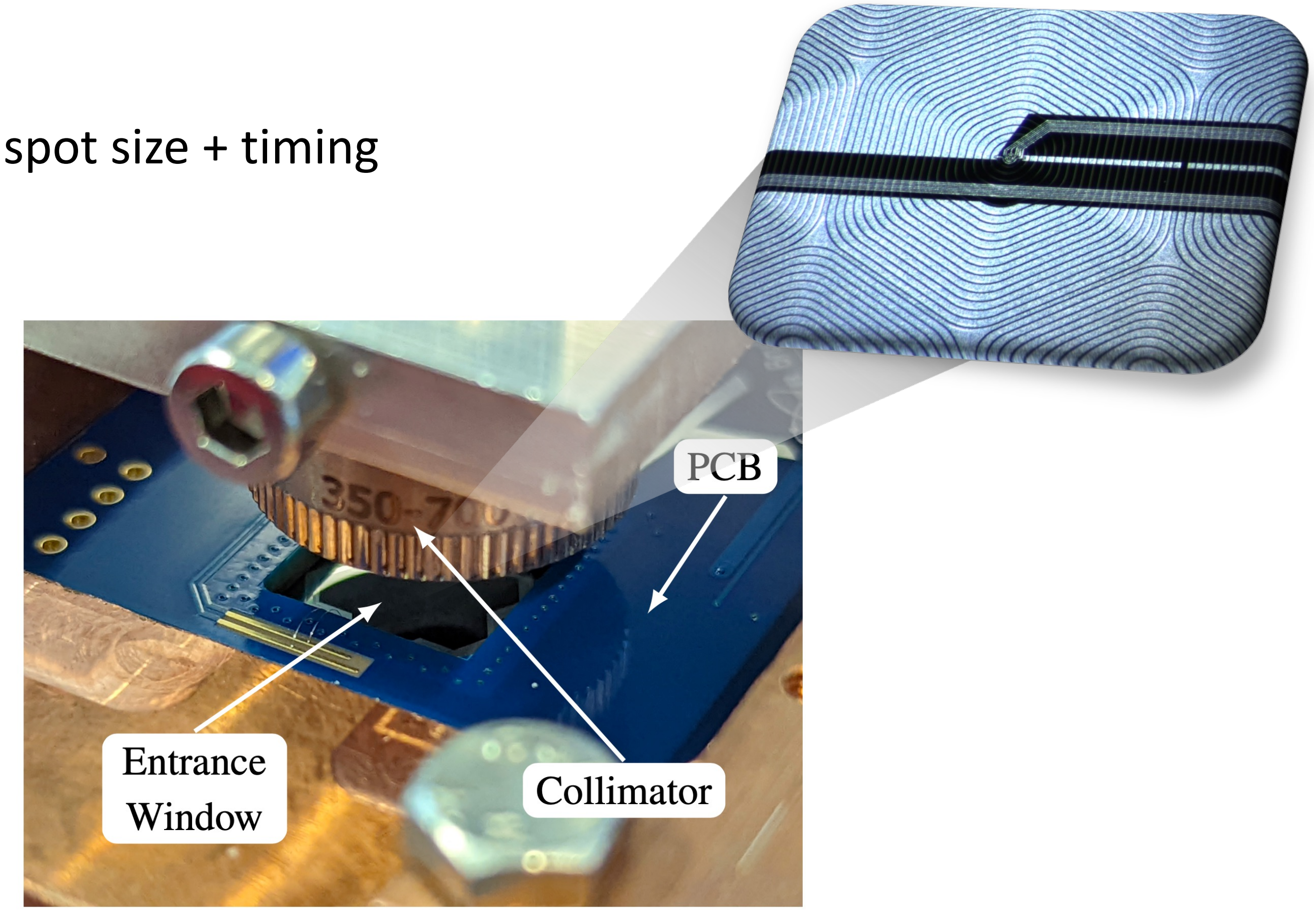
- Laser or LED ($\lambda$ = 630 nm)
- Interaction in entrance window + small spot size + timing



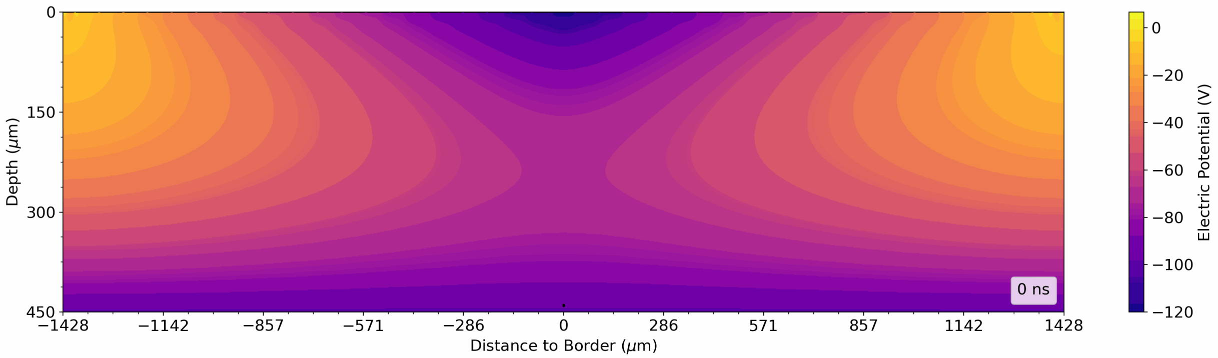
X-ray detection



light detection



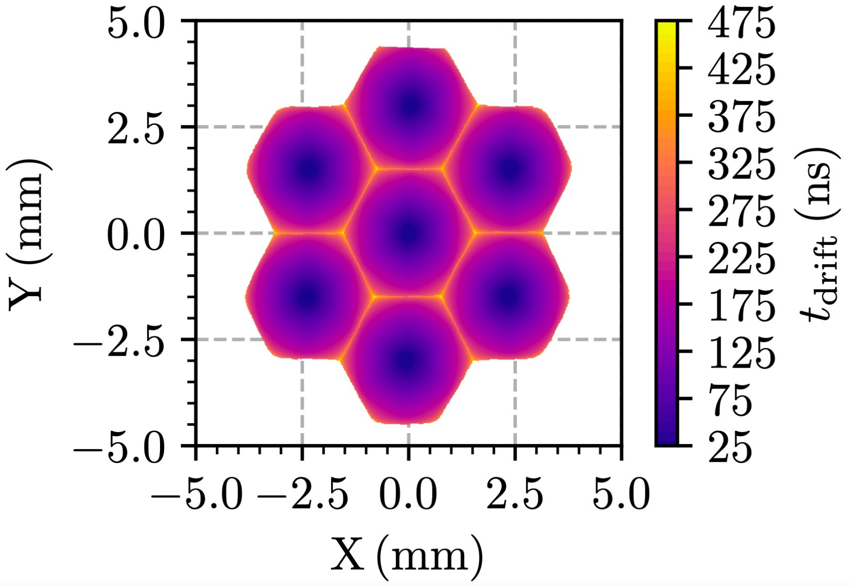
# Pulsed light source

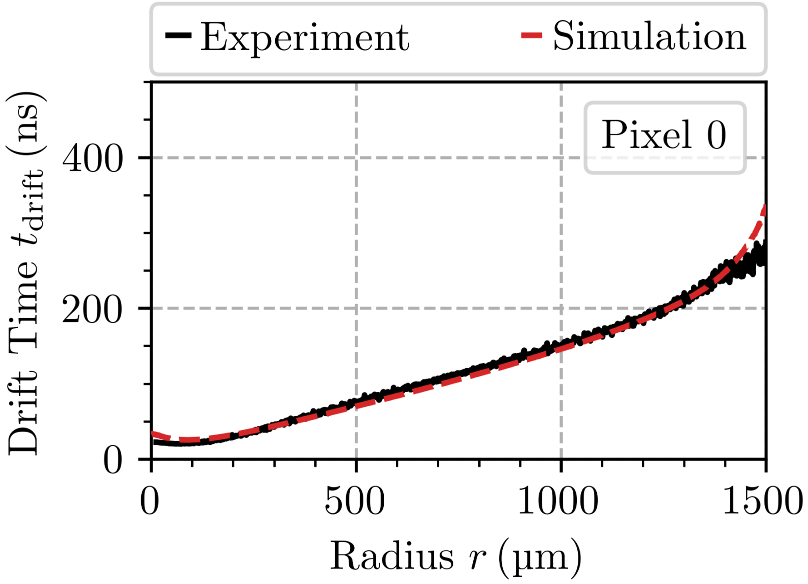


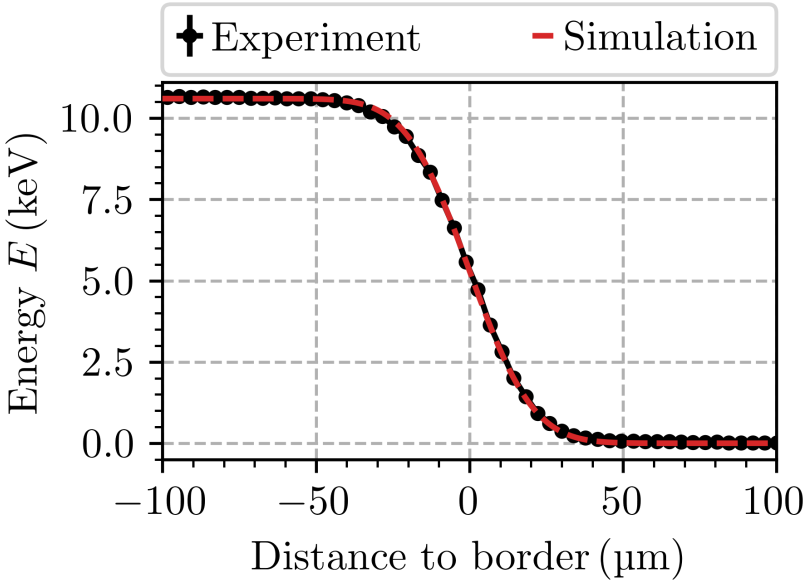

✓ Good understanding of drift times (incl. diffusion and repulsion)

✓ Good description of charge sharing

*C Forstner et al, ArXiv:2409.08901 (2024)*



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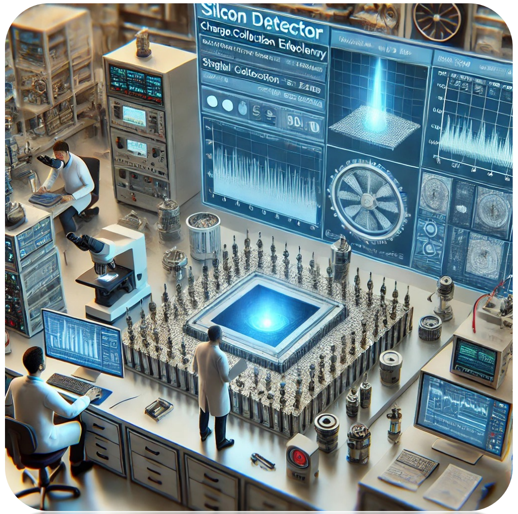
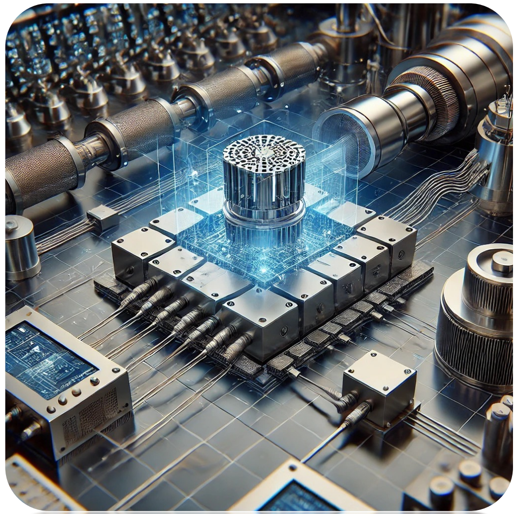
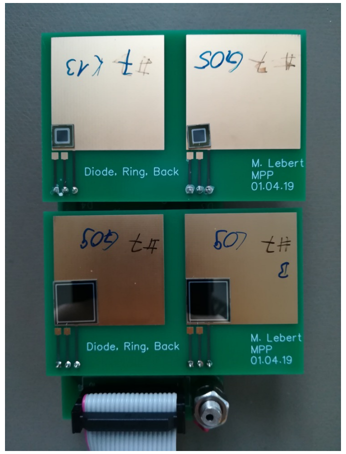
Integration

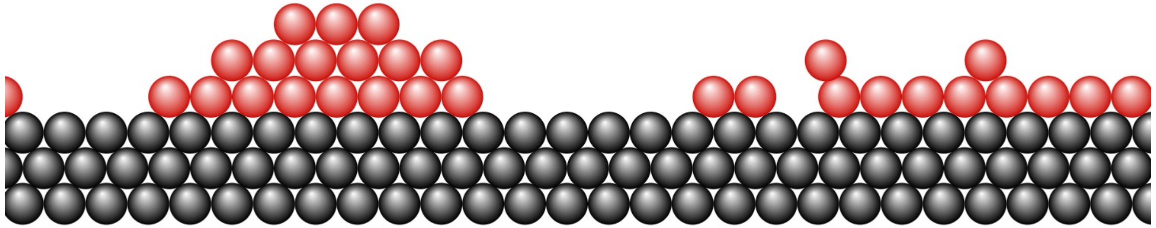


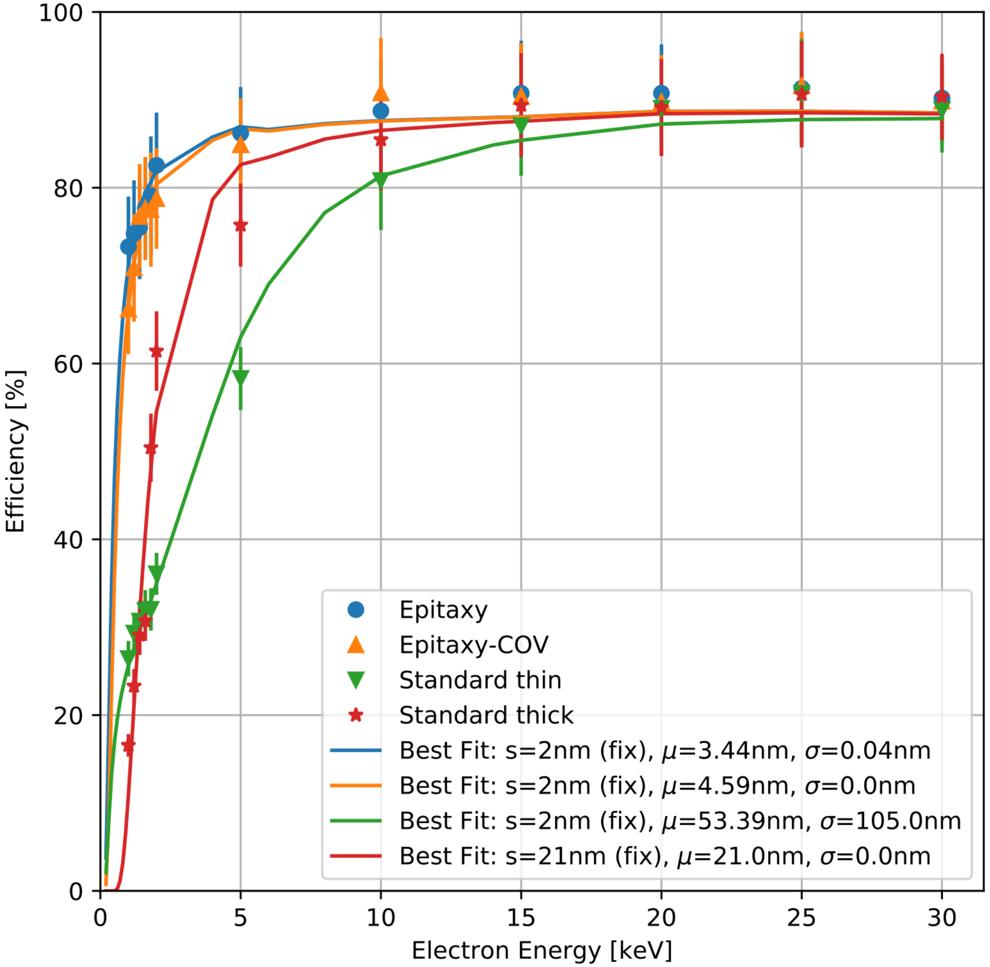



# Science pushing technology

1. Epitaxial growth to reduce deadlayer
   - ✓ First tests look promising

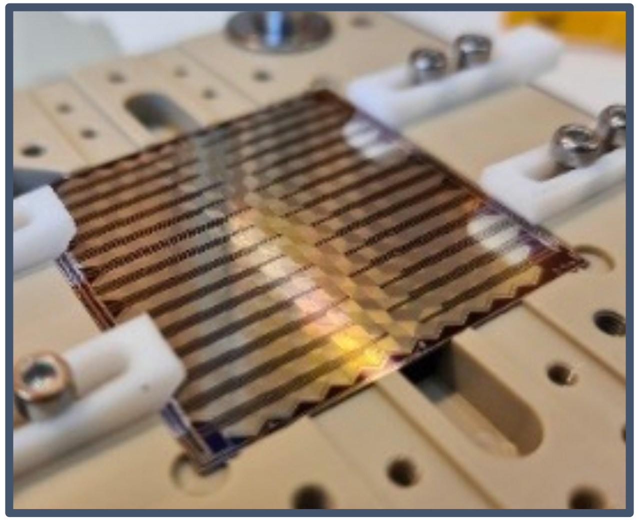


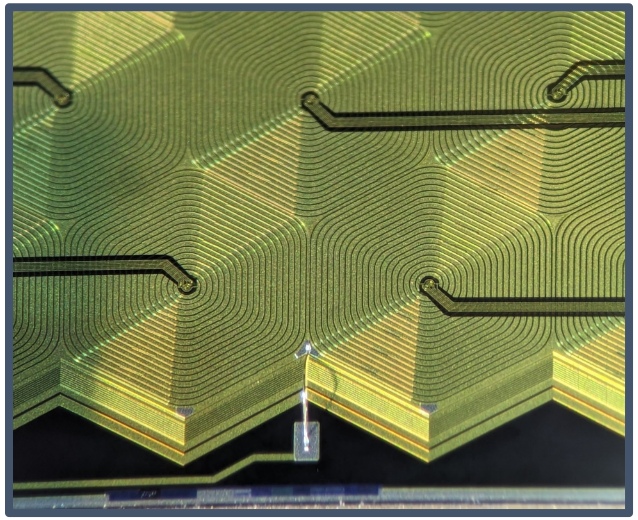



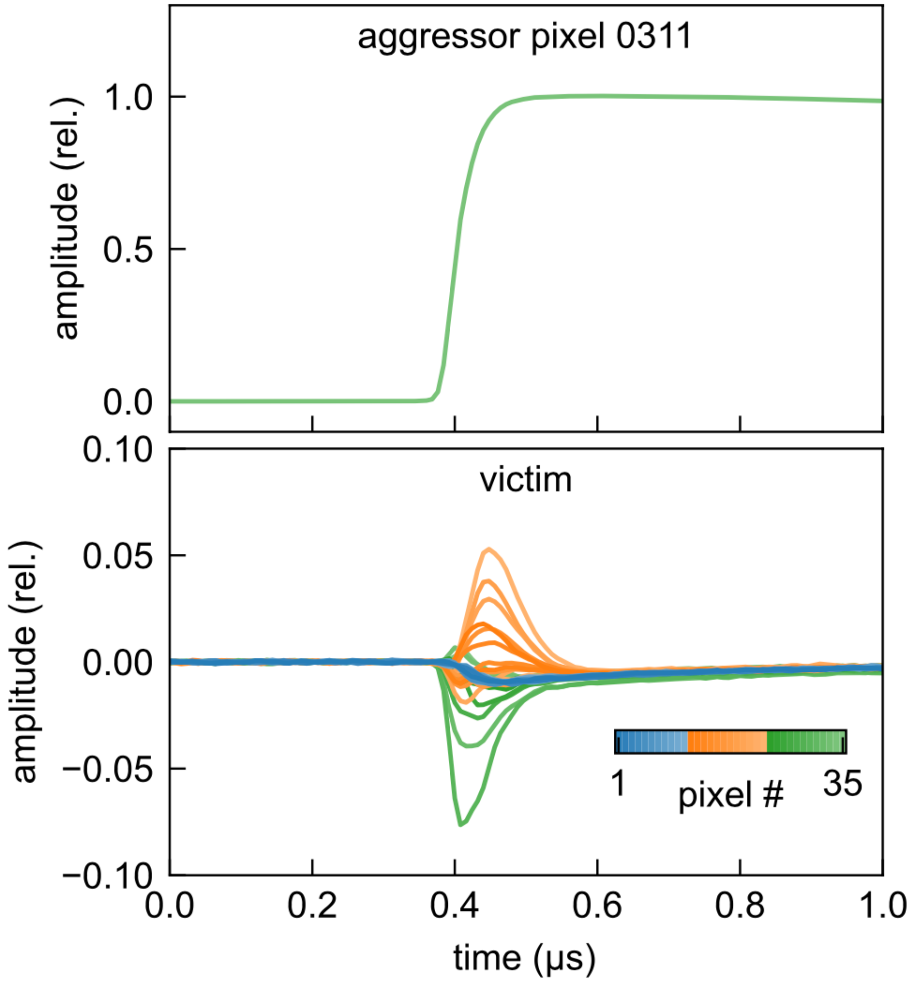


# Science pushing technology

1. Epitaxial growth to reduce deadlayer
   - ✓ First tests look promising
2. Optimized trace layout to reduce x-talk between pixels
   - ✓ Significant reduction of cross-talk in final production



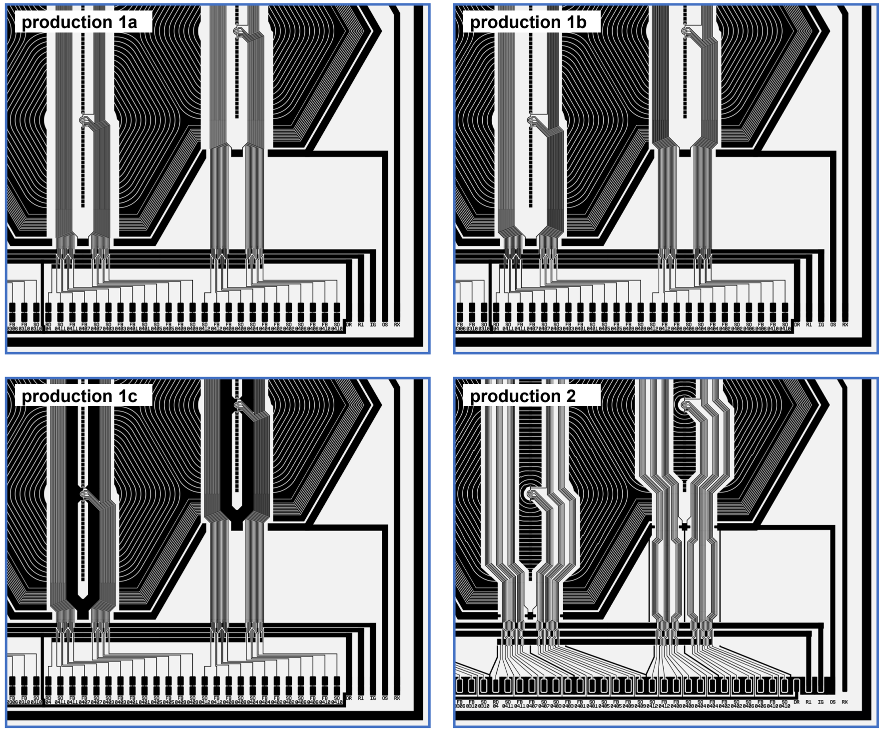


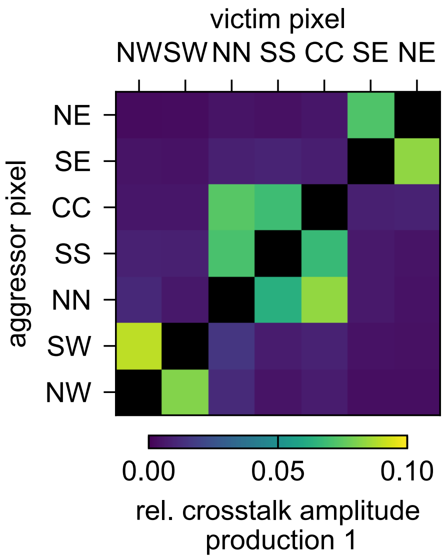


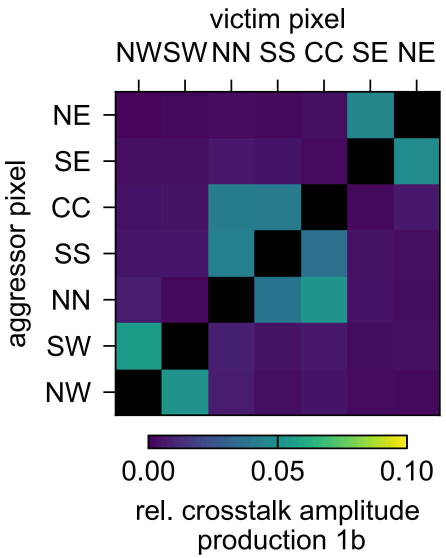
# Science pushing technology

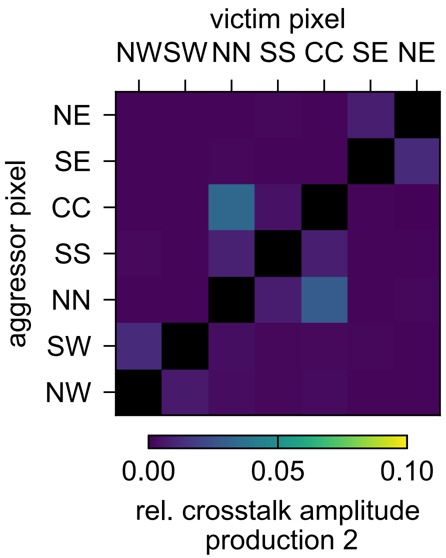
1. Epitaxial growth to reduce deadlayer
   - ✓ First tests look promising
2. Optimized trace layout to reduce x-talk between pixels
   - ✓ Significant reduction of cross-talk in final production

*Lines more narrow and shifted, additional grounding, improved bond pad design*



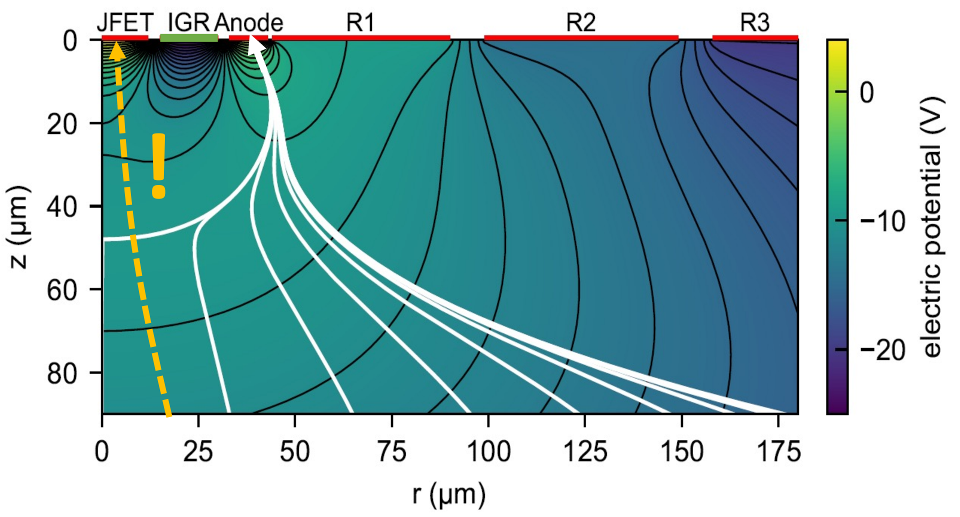



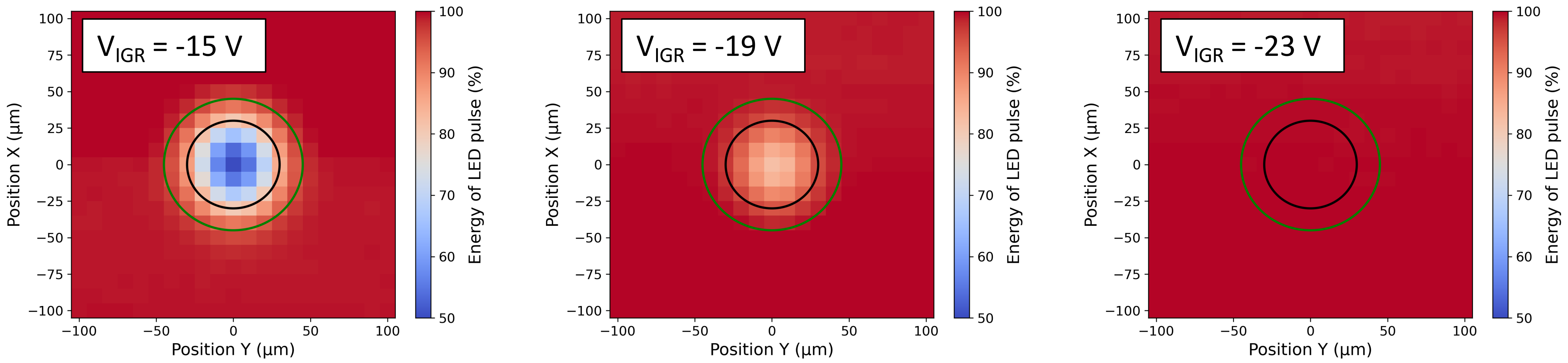



# Science pushing technology

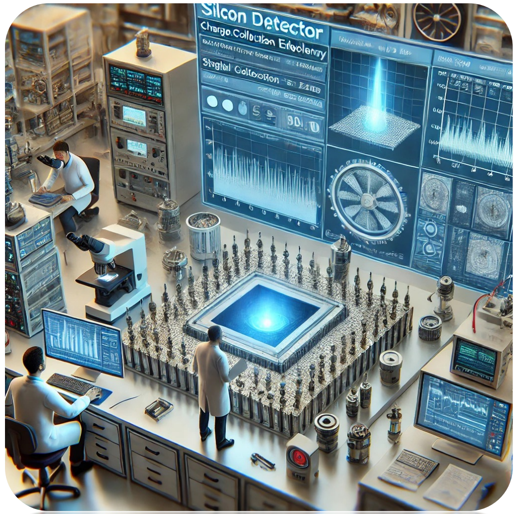
1. Epitaxial growth to reduce deadlayer
   - ✓ First tests look promising
2. Optimized trace layout to reduce x-talk between pixels
   - ✓ Significant reduction of cross-talk in final production
3. Improved nJFET layout to eliminate charge loss
   - ✓ No more charge-losses observed



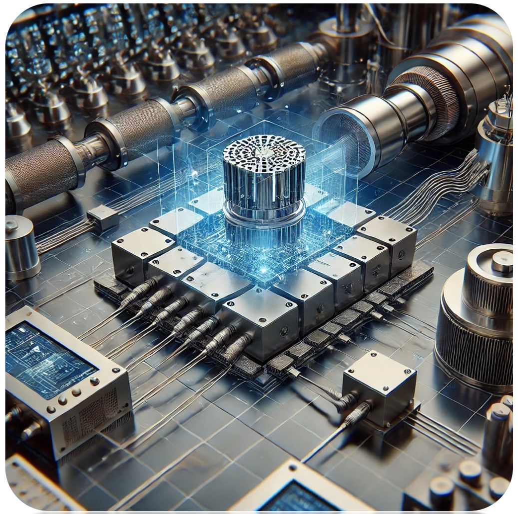
# A long SDD journey…

Characterization

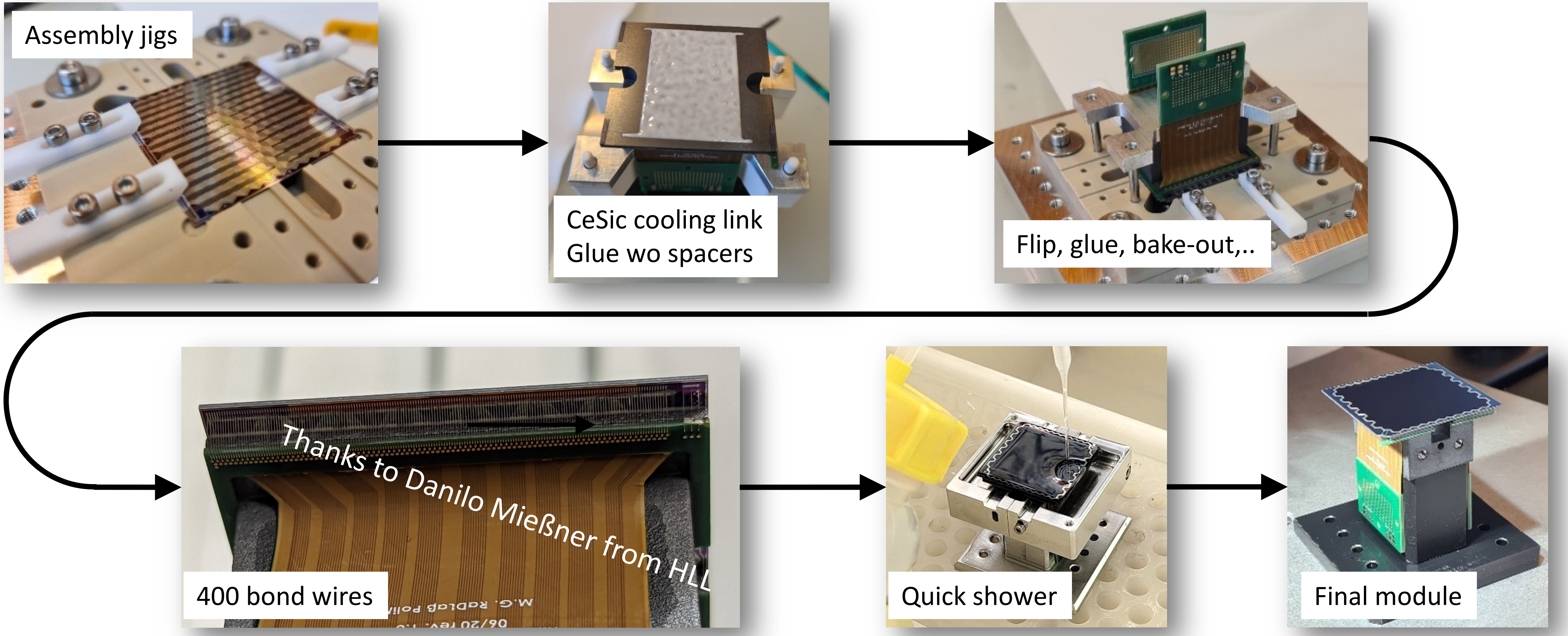



Optimization

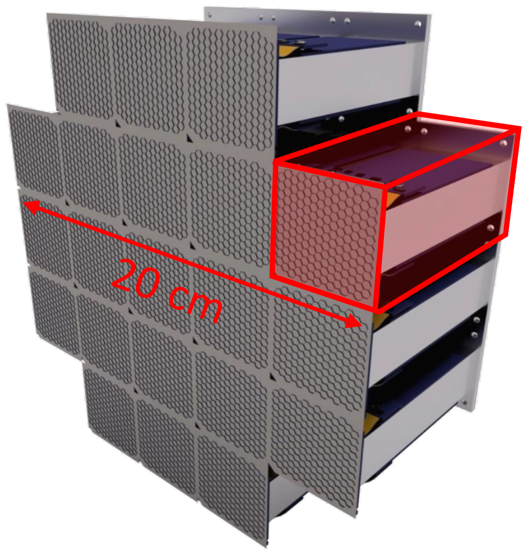
Integration

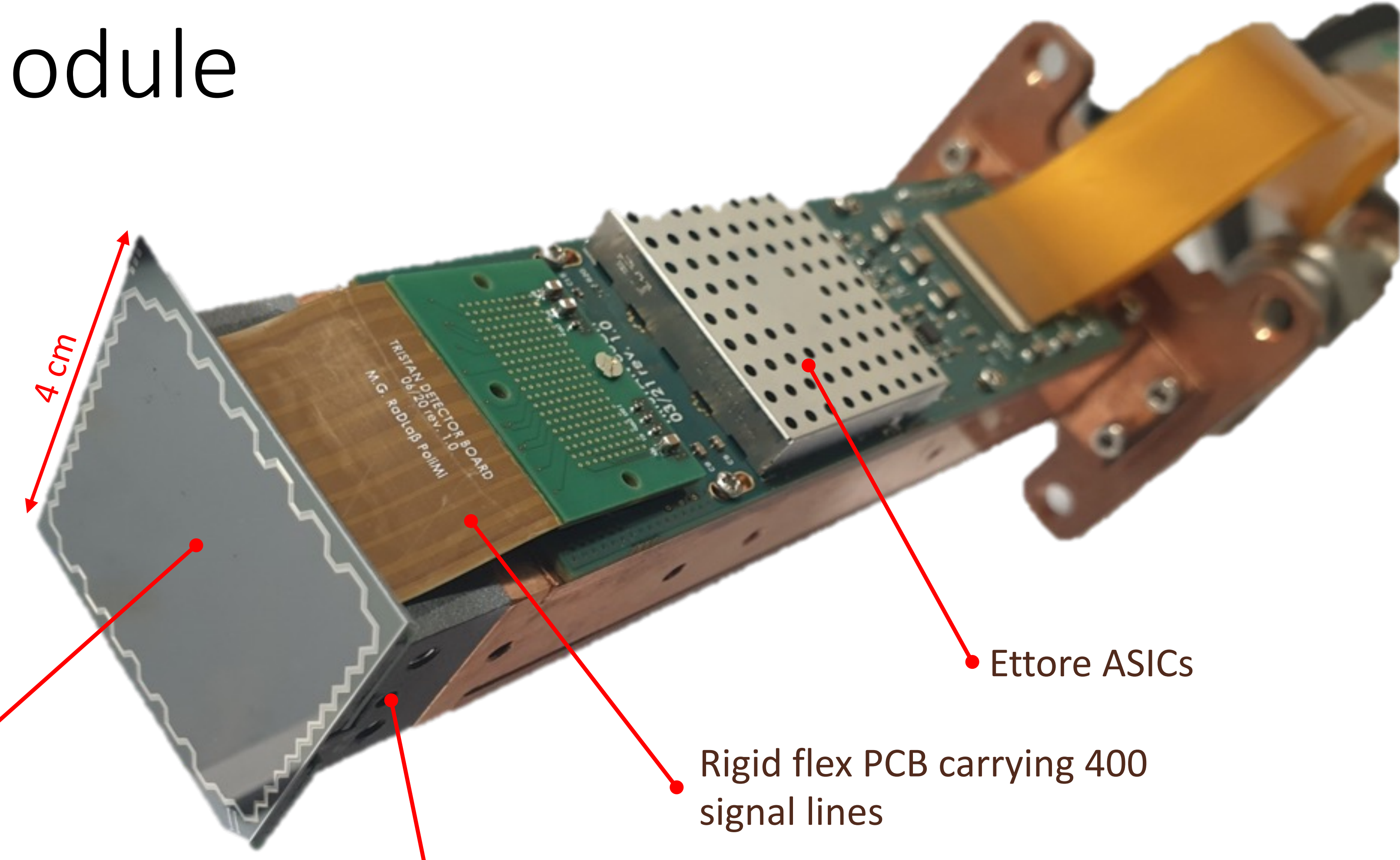


# Assembly procedure

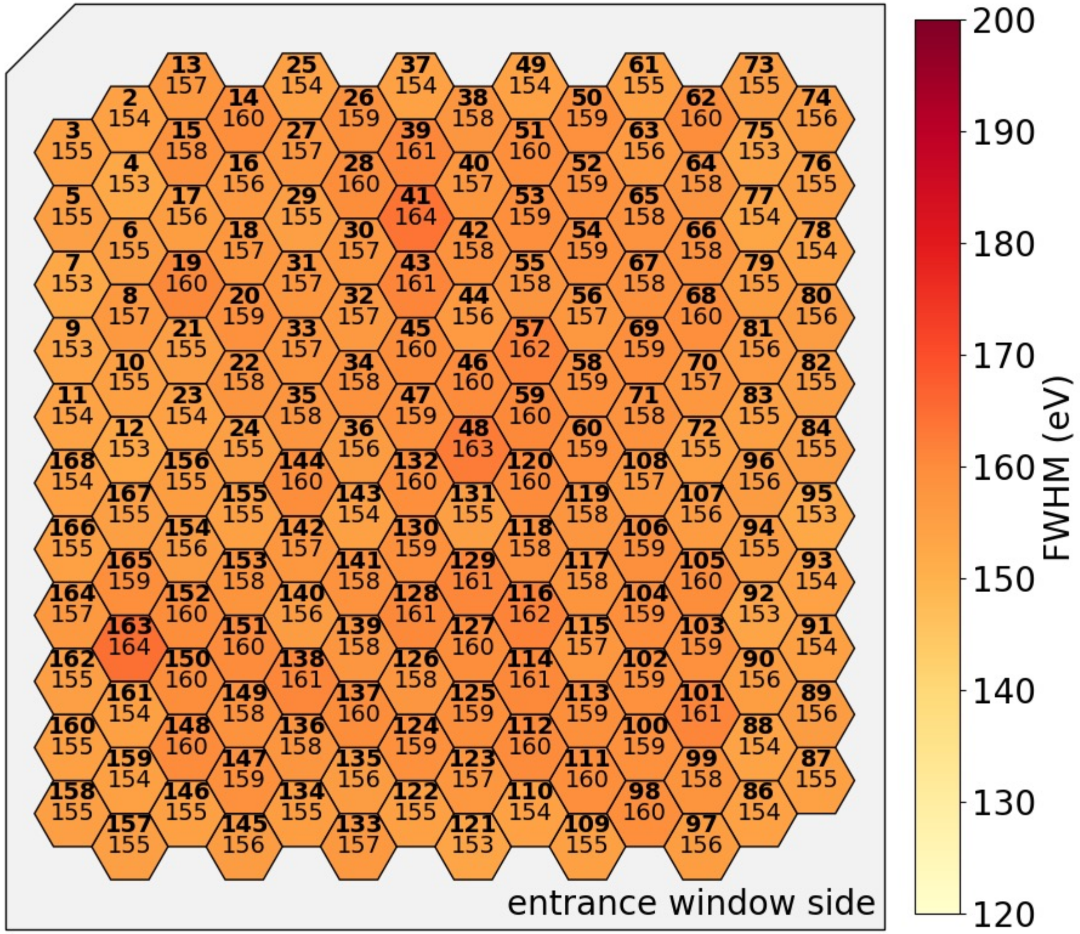


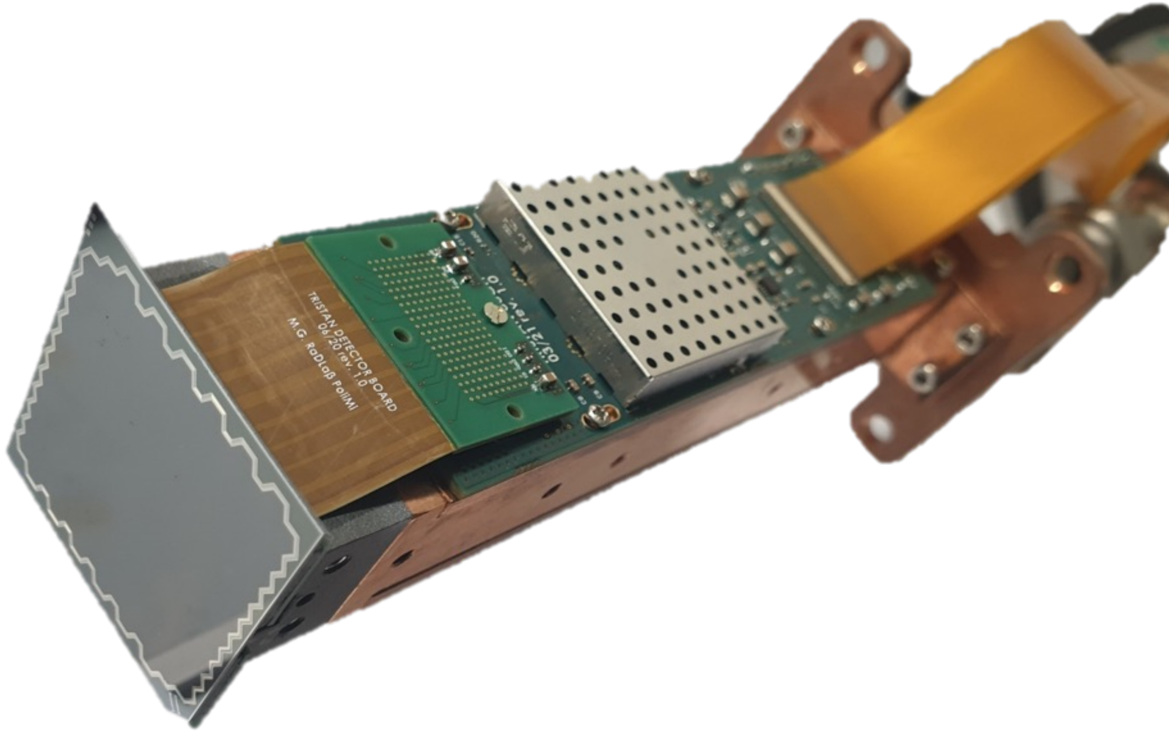
# Final TRISTAN Module



# Final TRISTAN Module

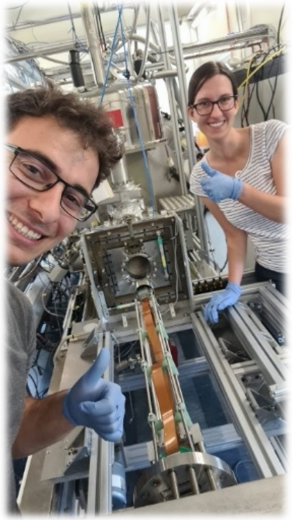


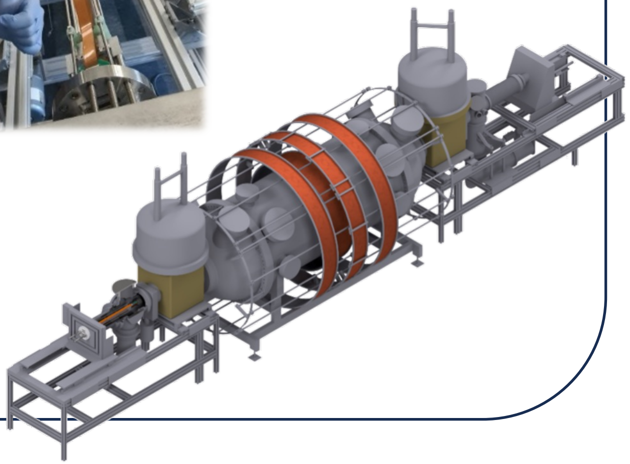
- ✓ Among the largest monolithic SDD ever operated ☺
- ✓ All pixels working (not always…)
- ✓ Average resolution of 160 eV (FWHM) at 6 keV
- ✓ Homogeneous performance

# Integration

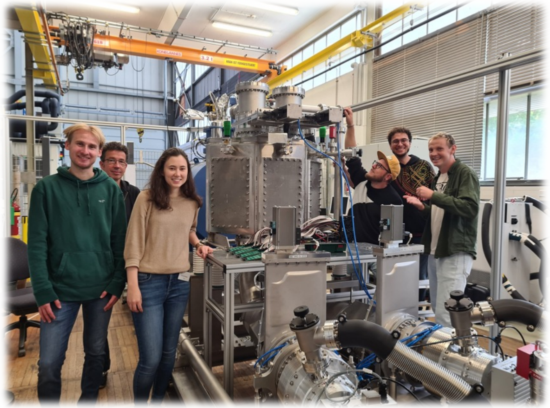
**2020: Monitor spectrometer**

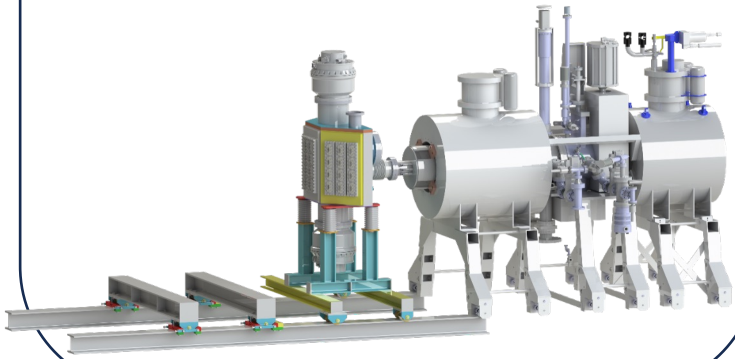


*„good performance demonstrated under realistic conditions“*

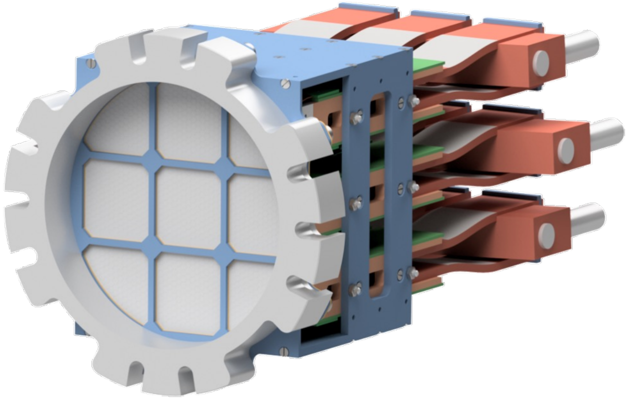


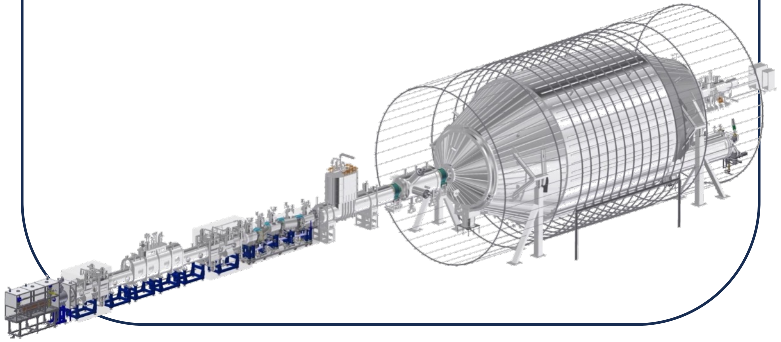
**2024: Replica of KATRIN**



**2026: KATRIN beamline**

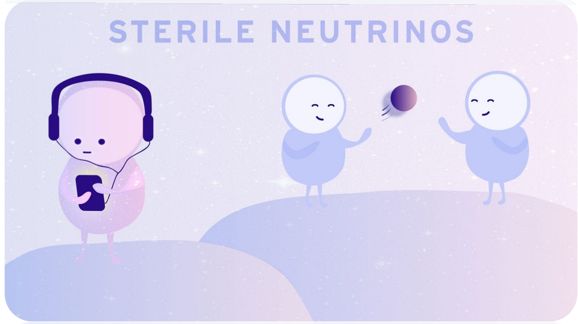




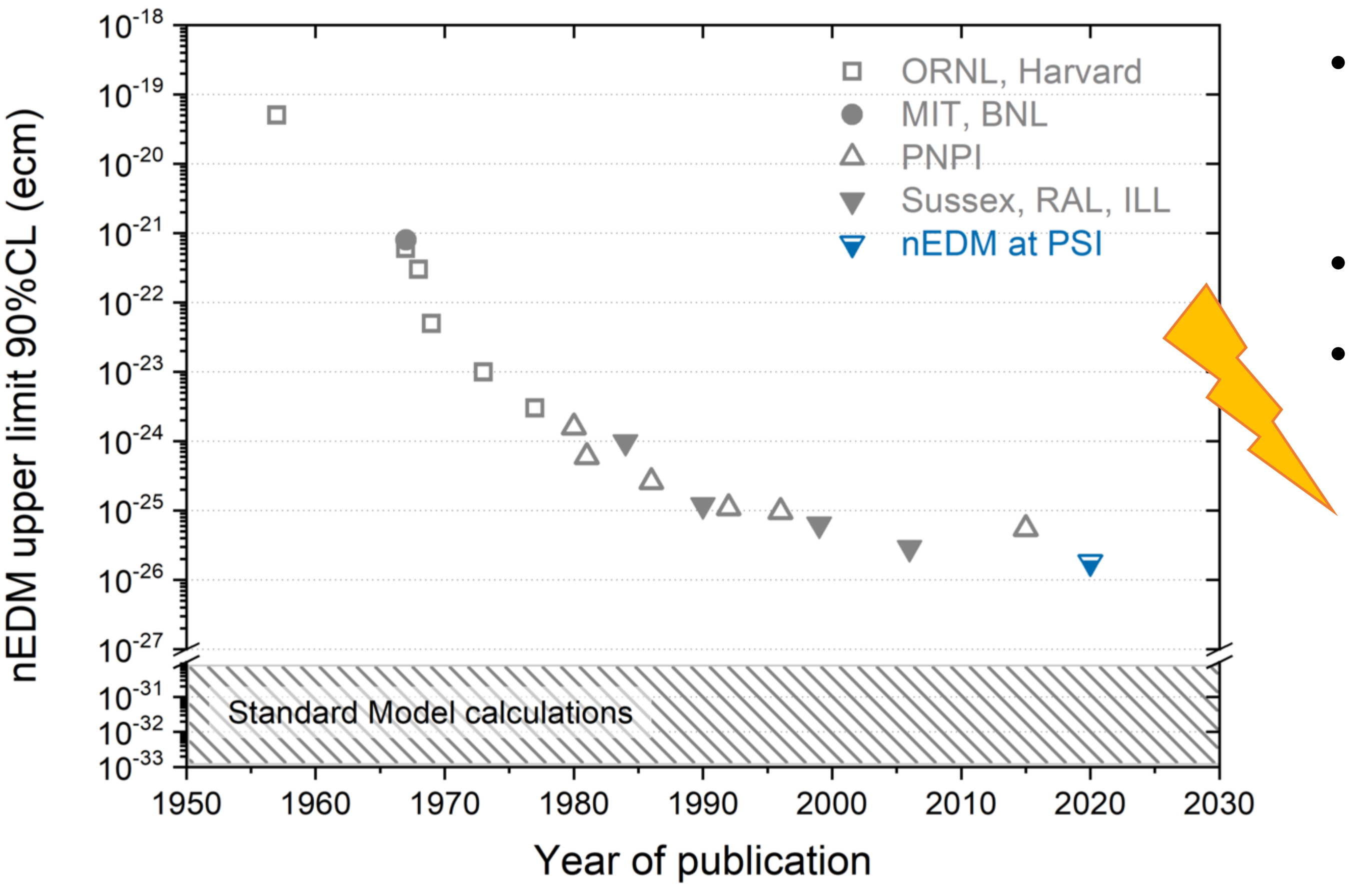
D. Siegmann *et al* 2024 *J. Phys. G: Nucl. Part. Phys.* **51** 085202

# Dark Matter Candidates

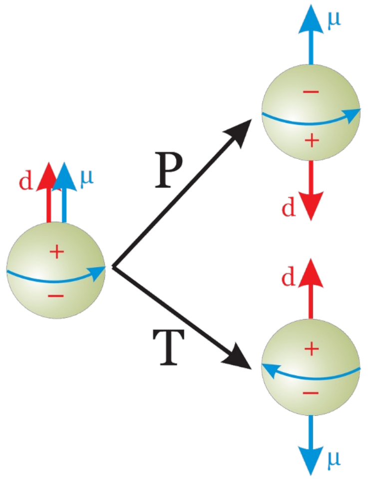
μeV meV eV keV MeV GeV TeV

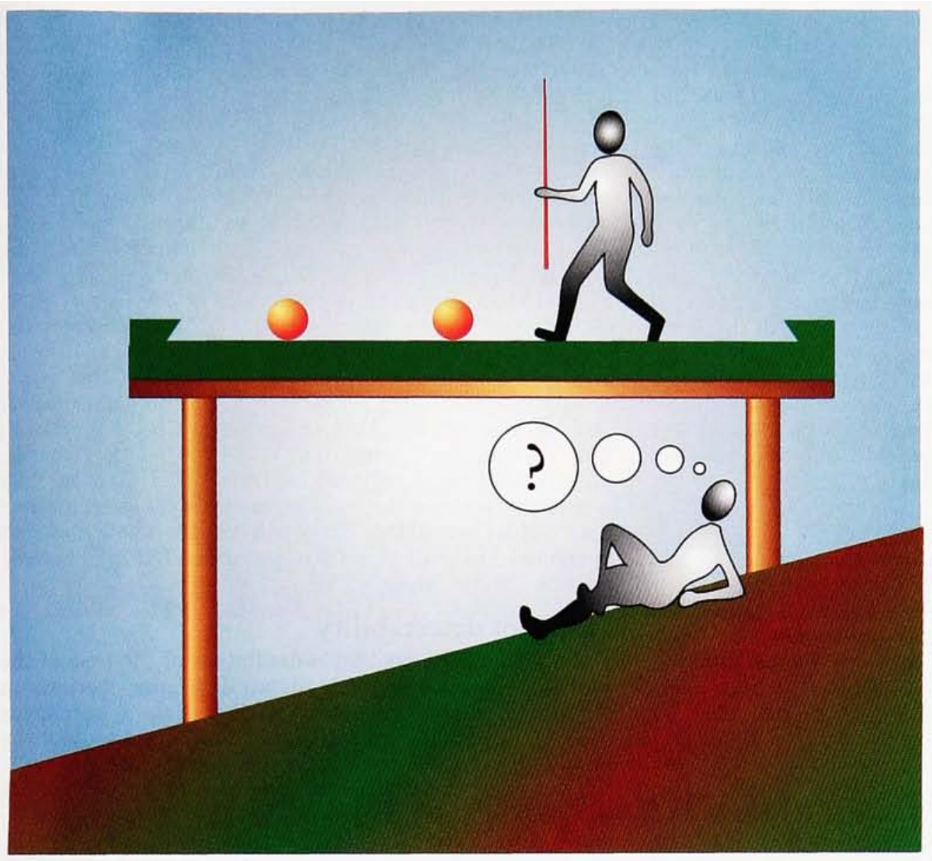

# The strong CP (charge parity) problem

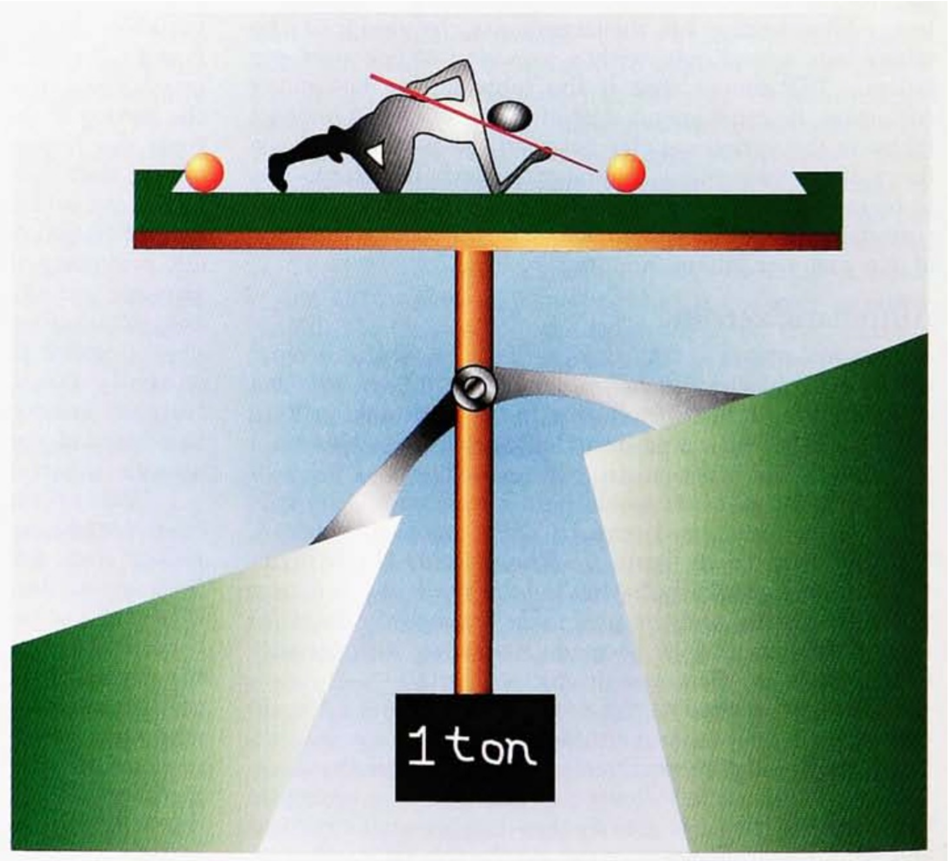



- Quantum Chromodynamics (QCD) predicts an electric dipole moment of the neutron (nEDM)
- Experiments do not observe any nEDM
- Responsibe term $\theta_{QCD}\ \tilde{G}^{\mu\nu} G_{\mu\nu}$ must be set to zero



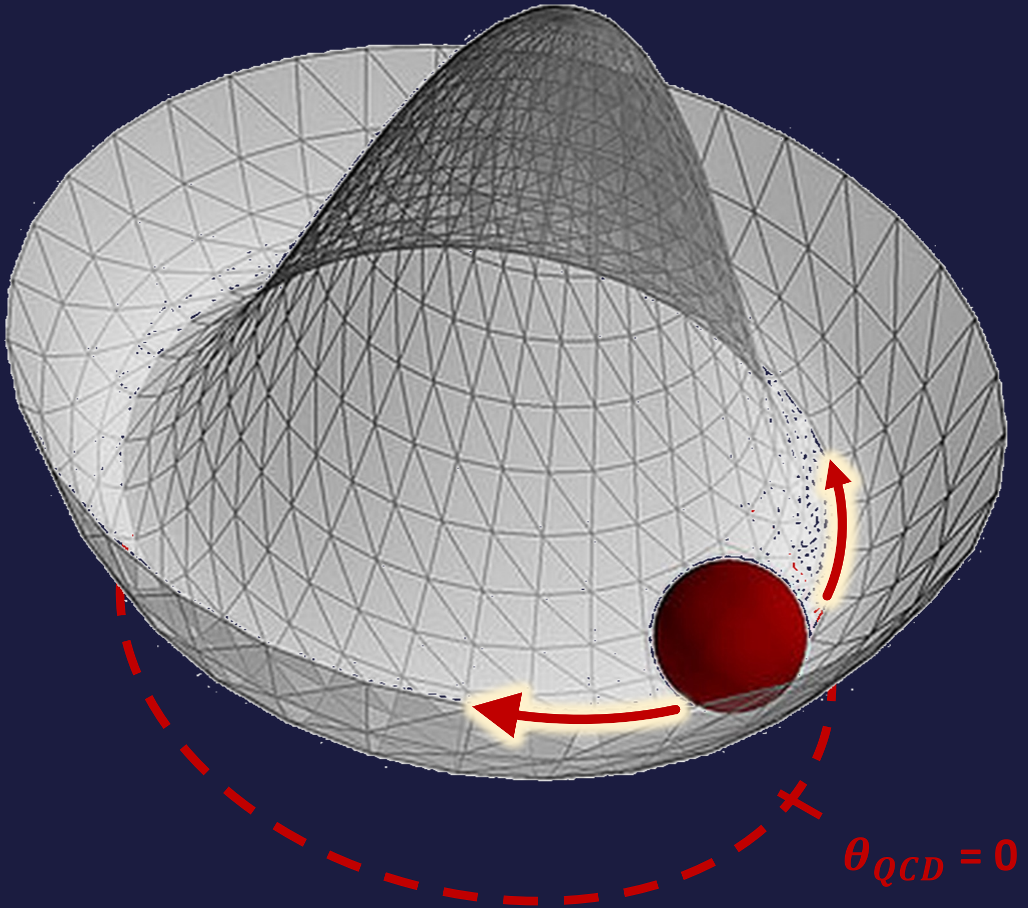
# The pool table analogy



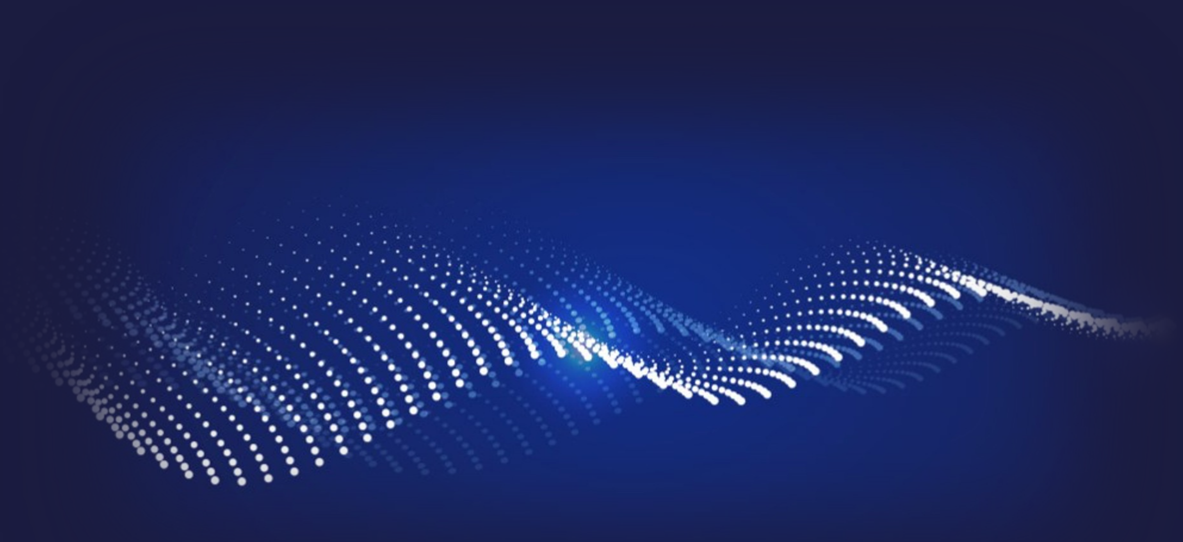



# Axions

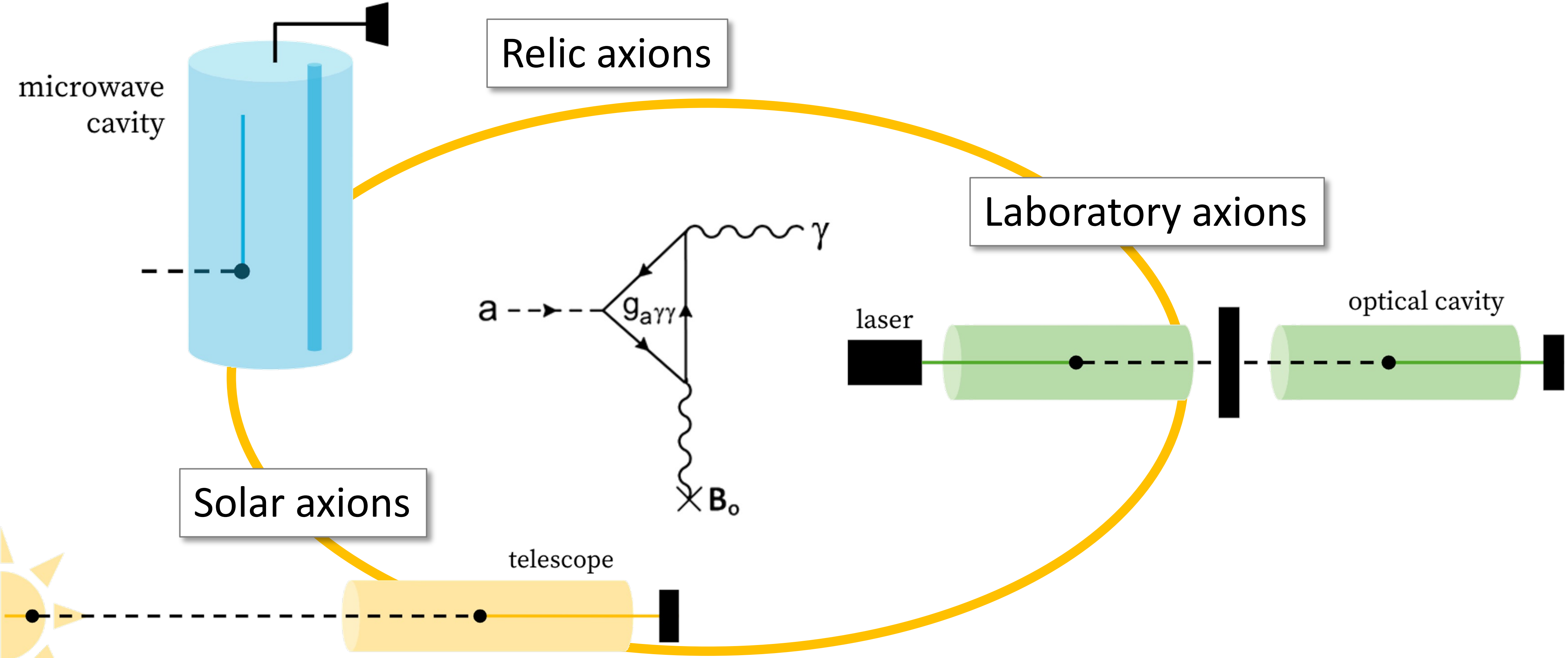

QCD vacuum potential




Axion is like a photon with a small mass

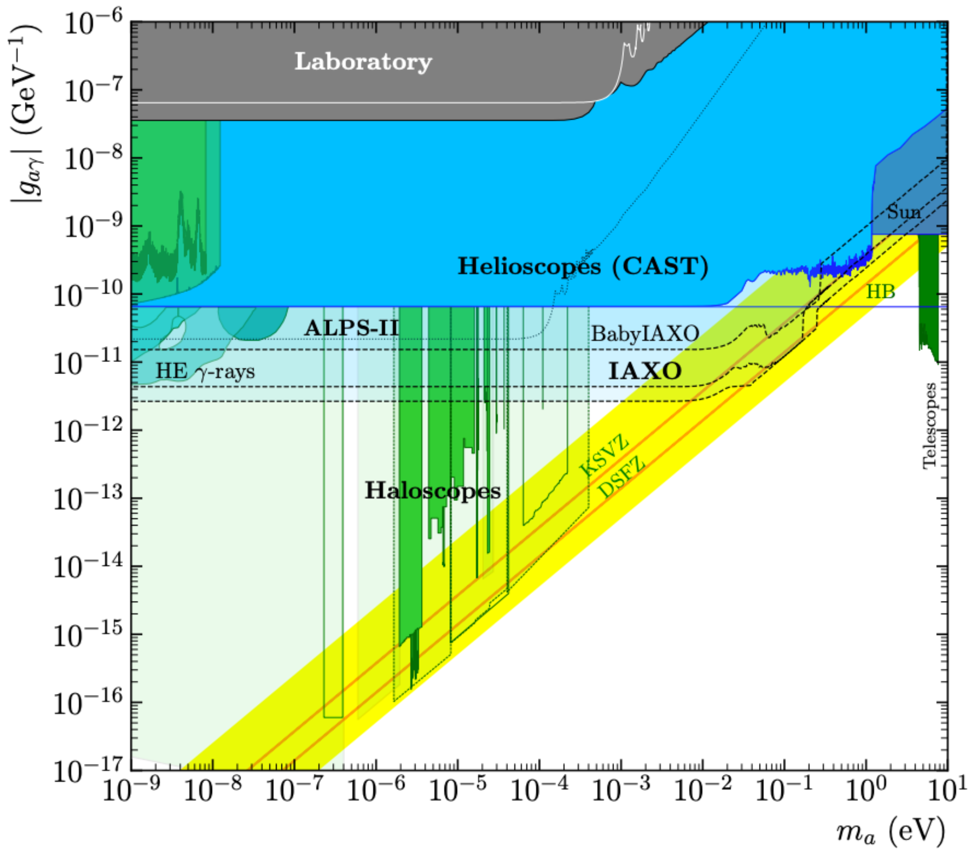


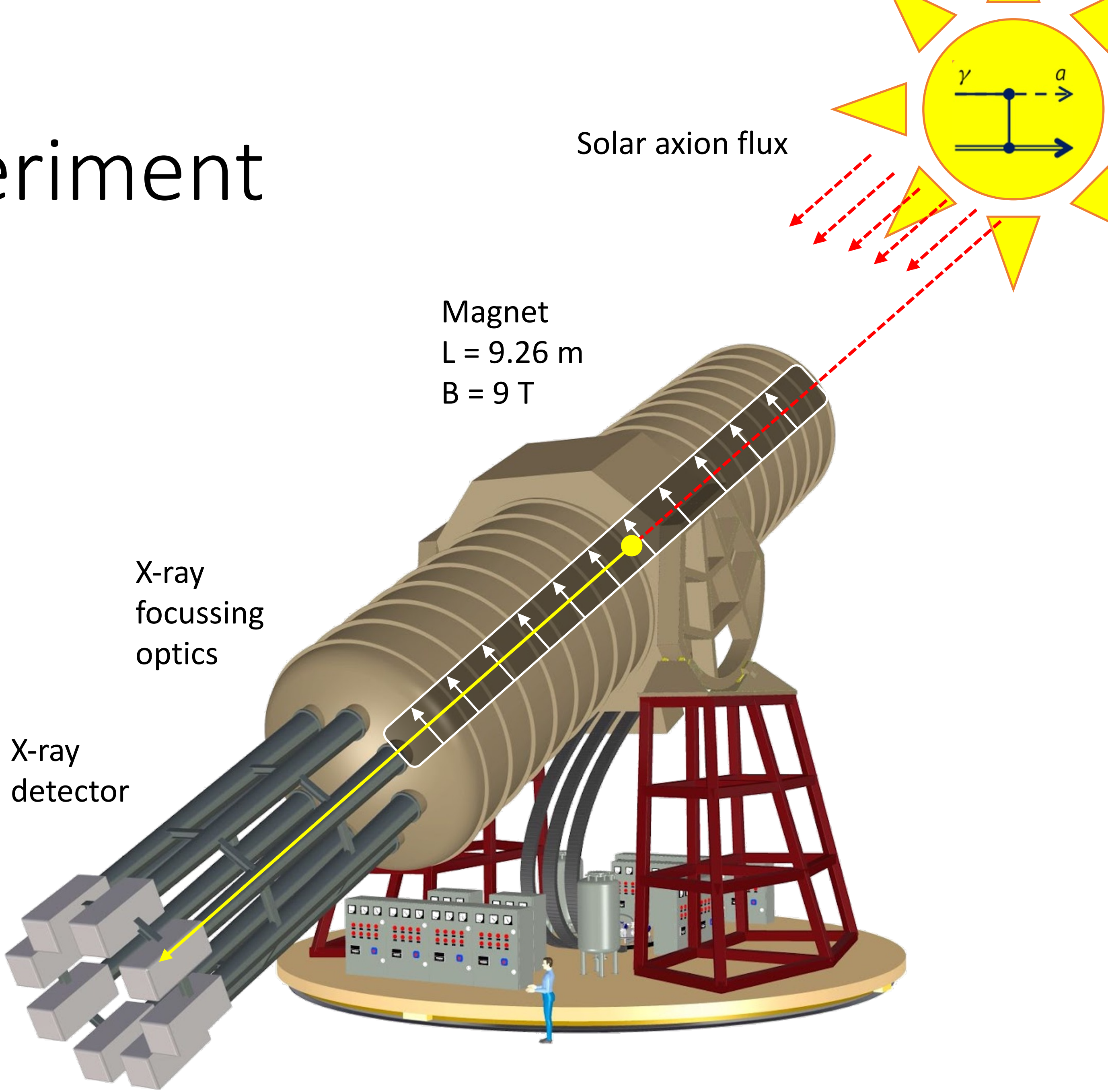
# Experimental searches




[Sikivie, PRL 51 (1983) 1415-1417]

# The IAXO Experiment

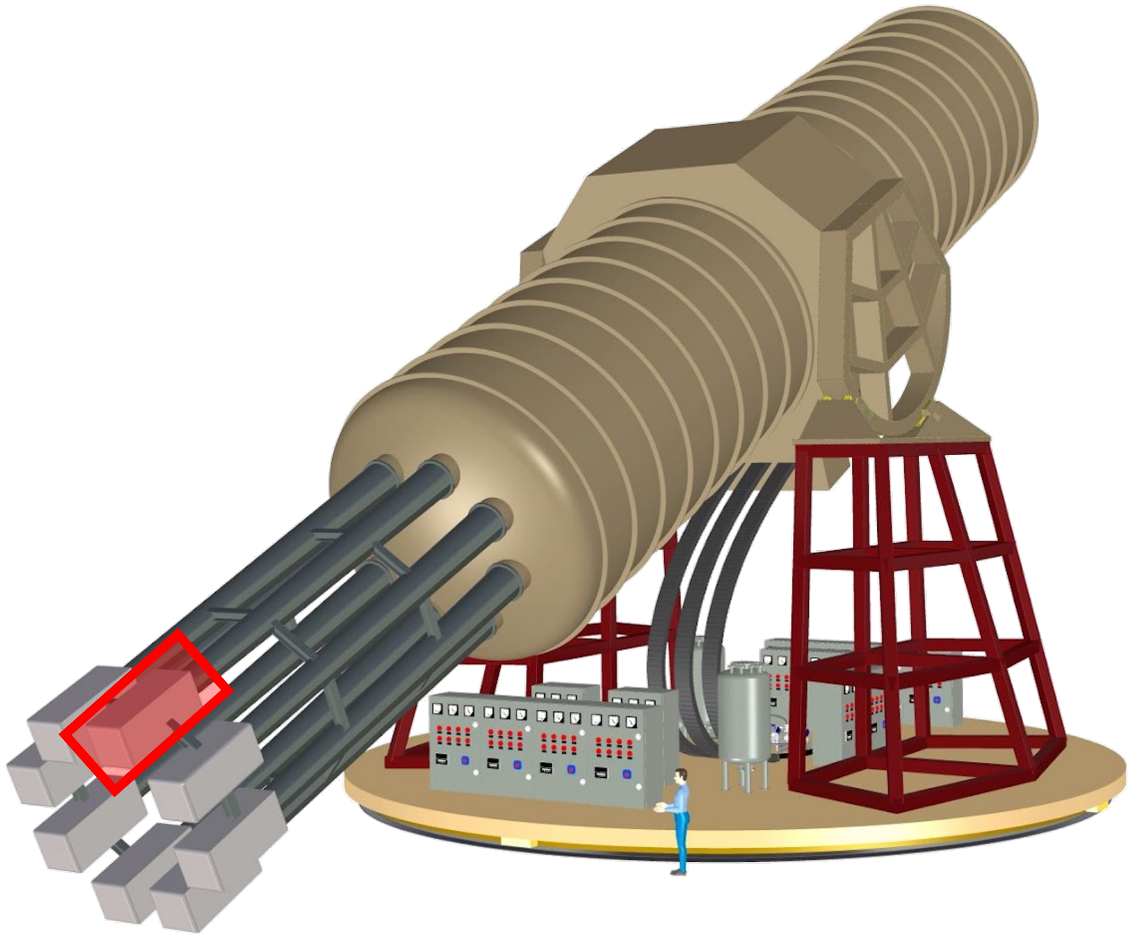


# IAXO X-ray detector

**Requirements:**

- High efficiency for 1 – 10 keV x-rays
- Good energy resolution
- No/little cooling, flexible footprint



# IAXO X-ray detector

**Requirements:**

- High efficiency for 1 – 10 keV x-rays
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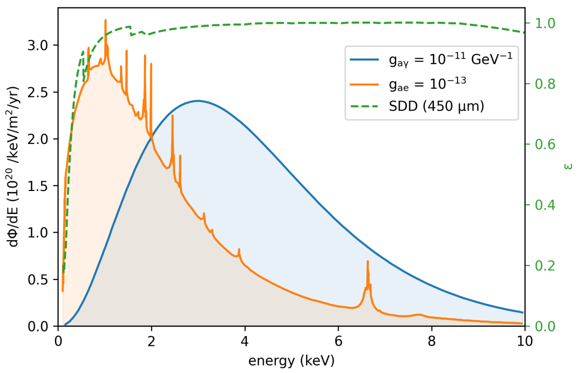
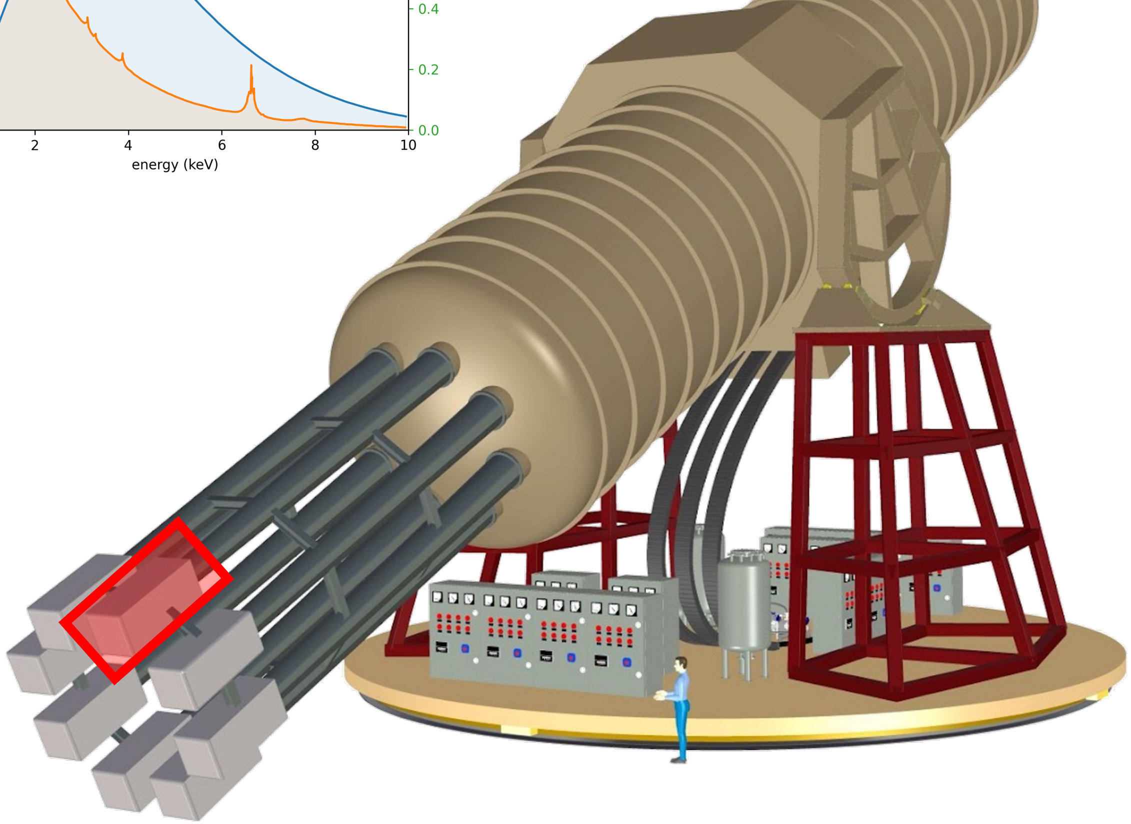



No problem...

# IAXO X-ray detector

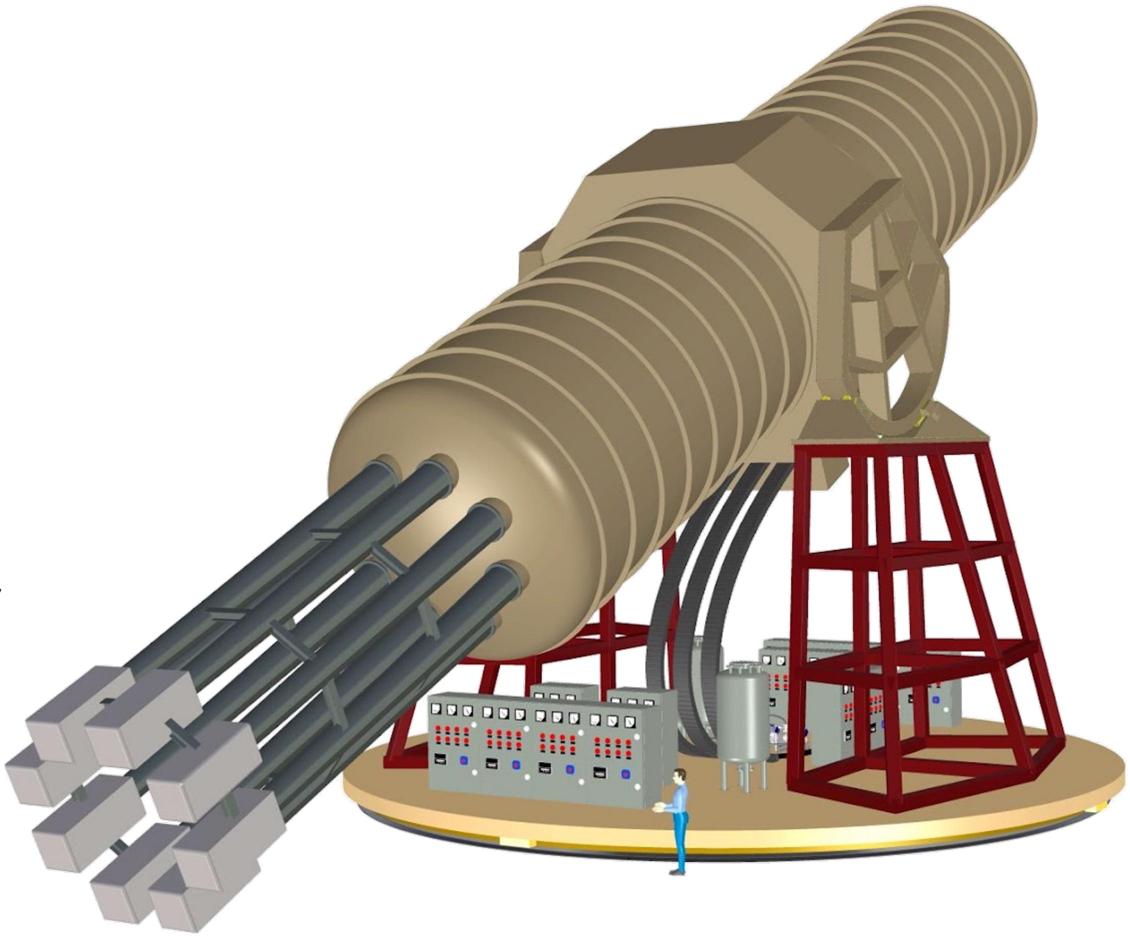
**Requirements:**

- High efficiency for 1 – 10 keV x-rays
- Good energy resolution
- No/little cooling, flexible footprint

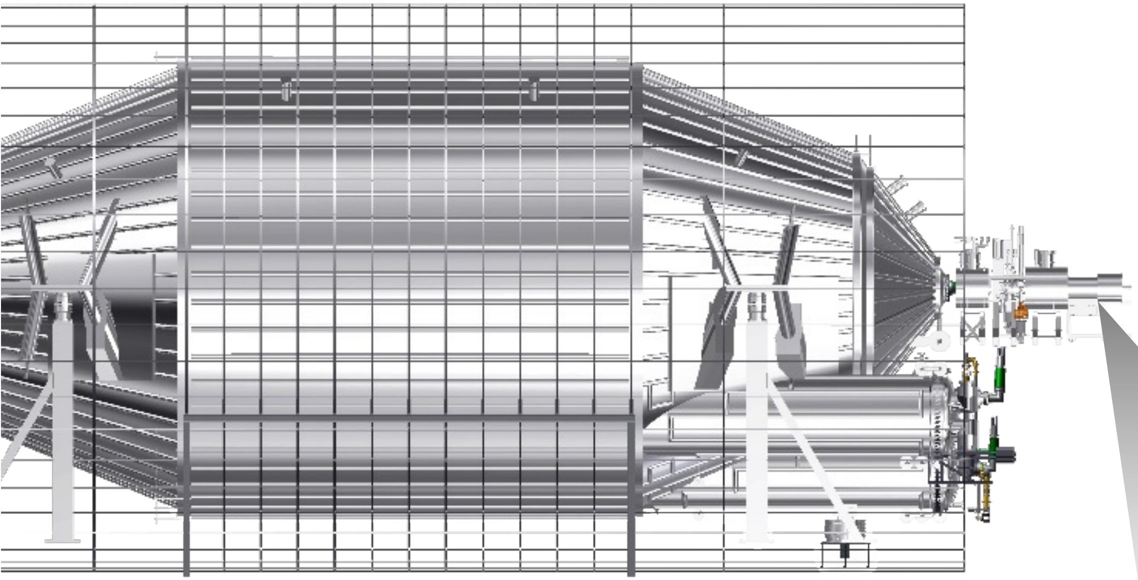
**Challenge:**

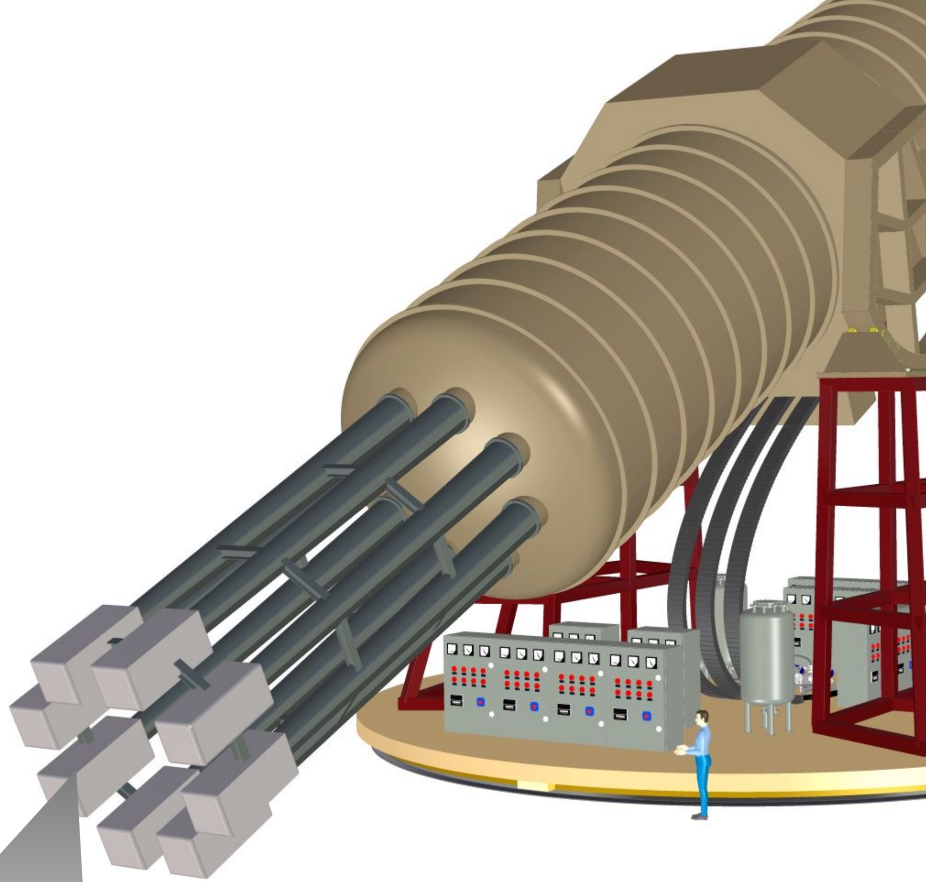
○ Background level of **$10^{-7}$ cts/keV/cm$^2$/s**

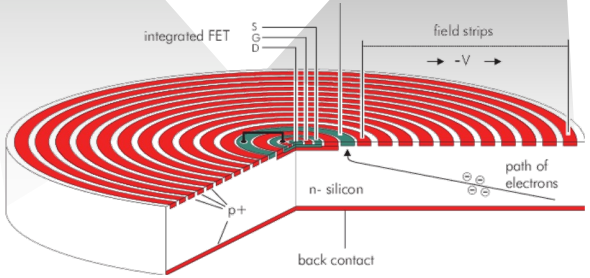
➢ Never achieved in above-ground laboratory



# TRISTAN + IAXO = TAXO

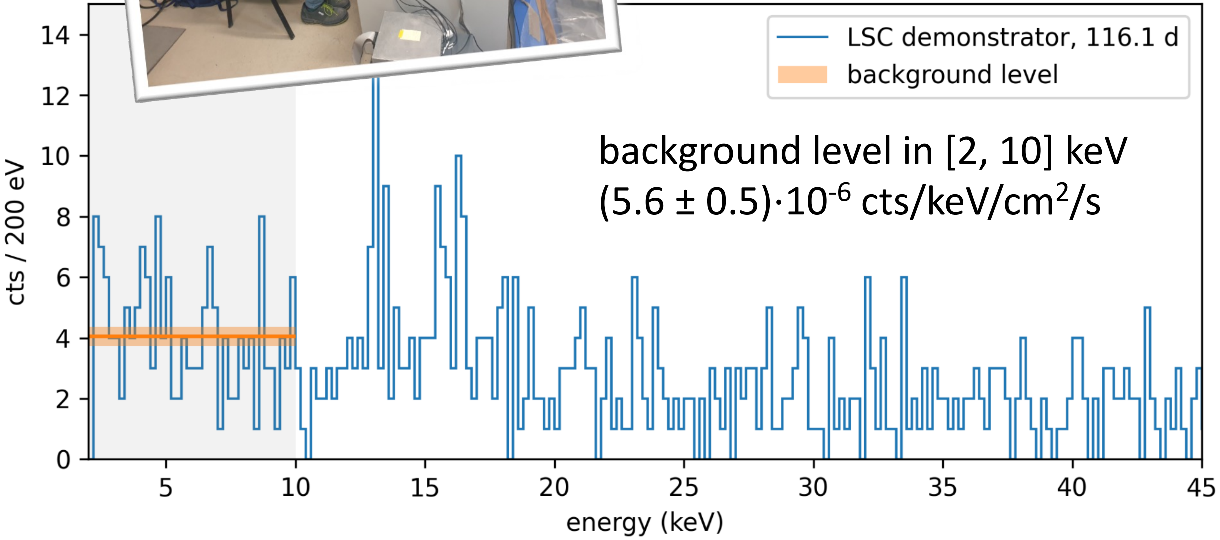


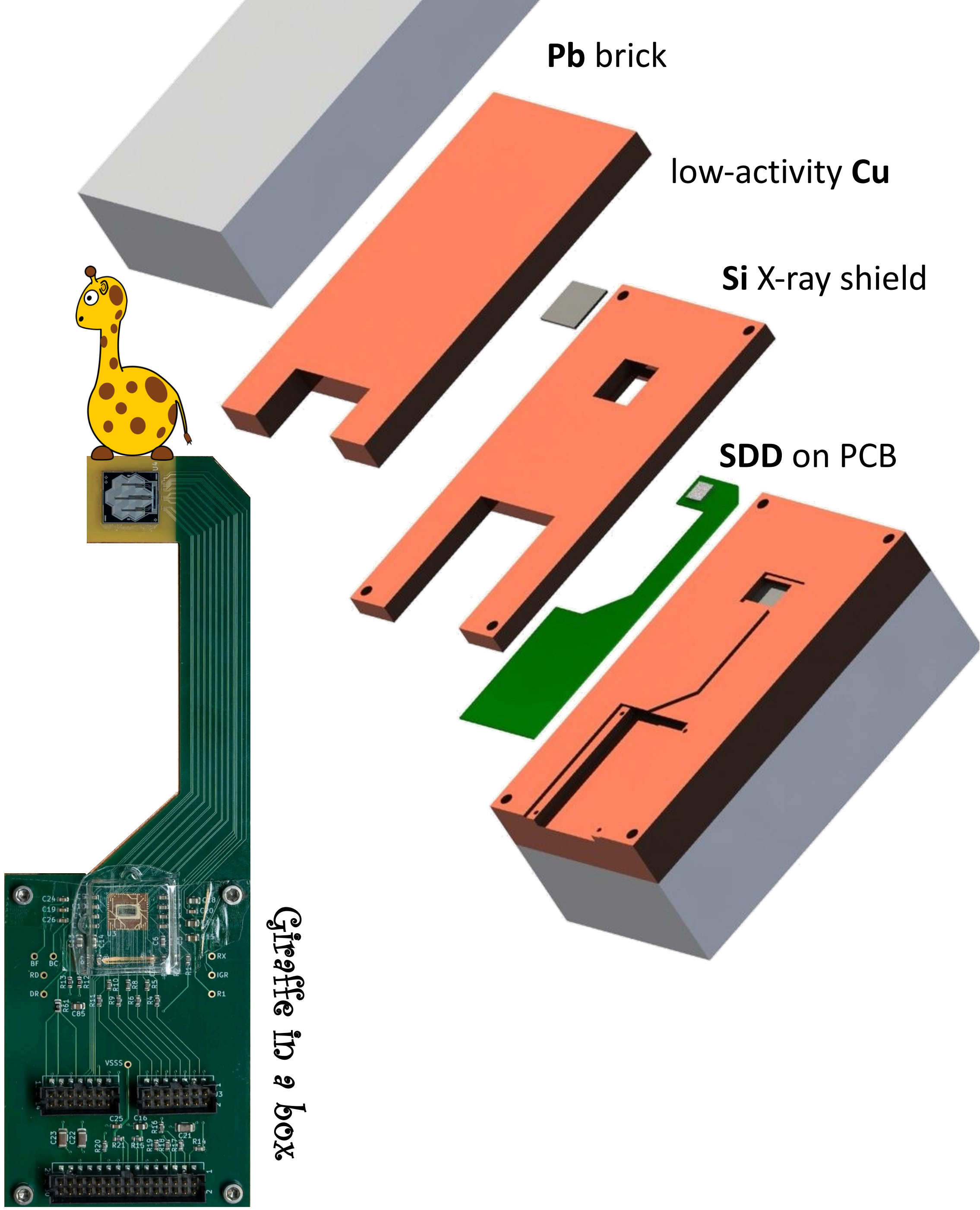




# IAXO demonstrator

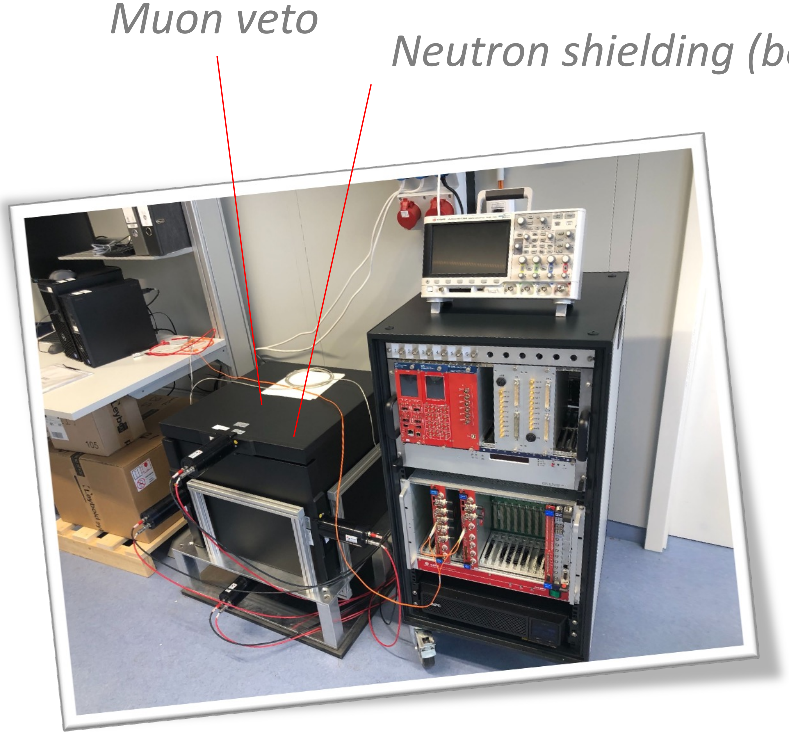
✓ Measurements at Can Franc underground lab

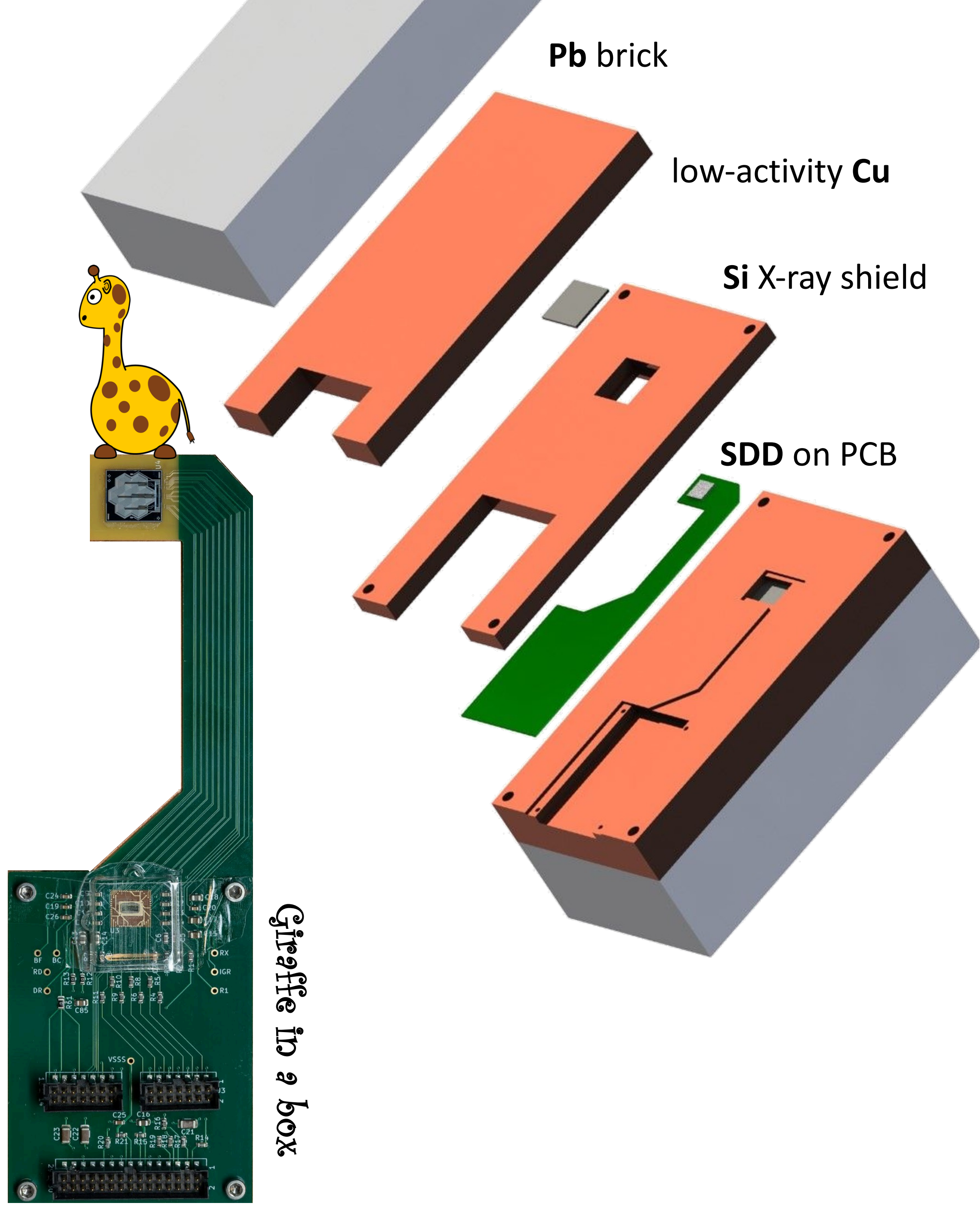


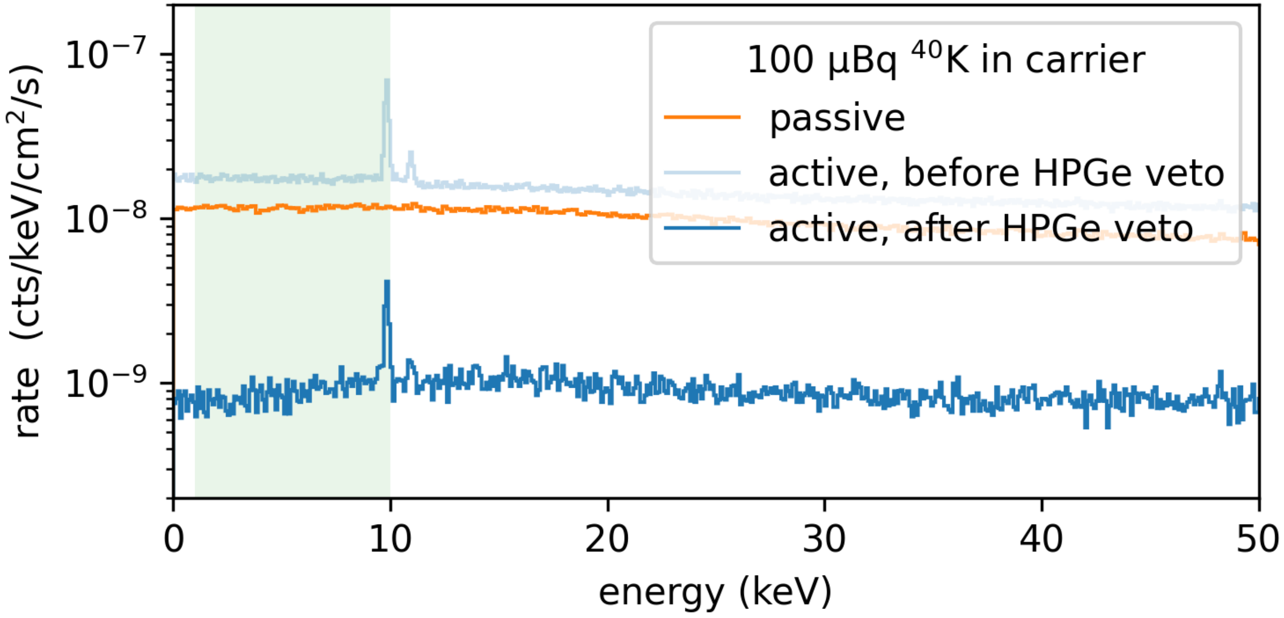
# IAXO demonstrator

- ✓ Measurements at Can Franc underground lab
- ✓ Above-ground measurements in preparation

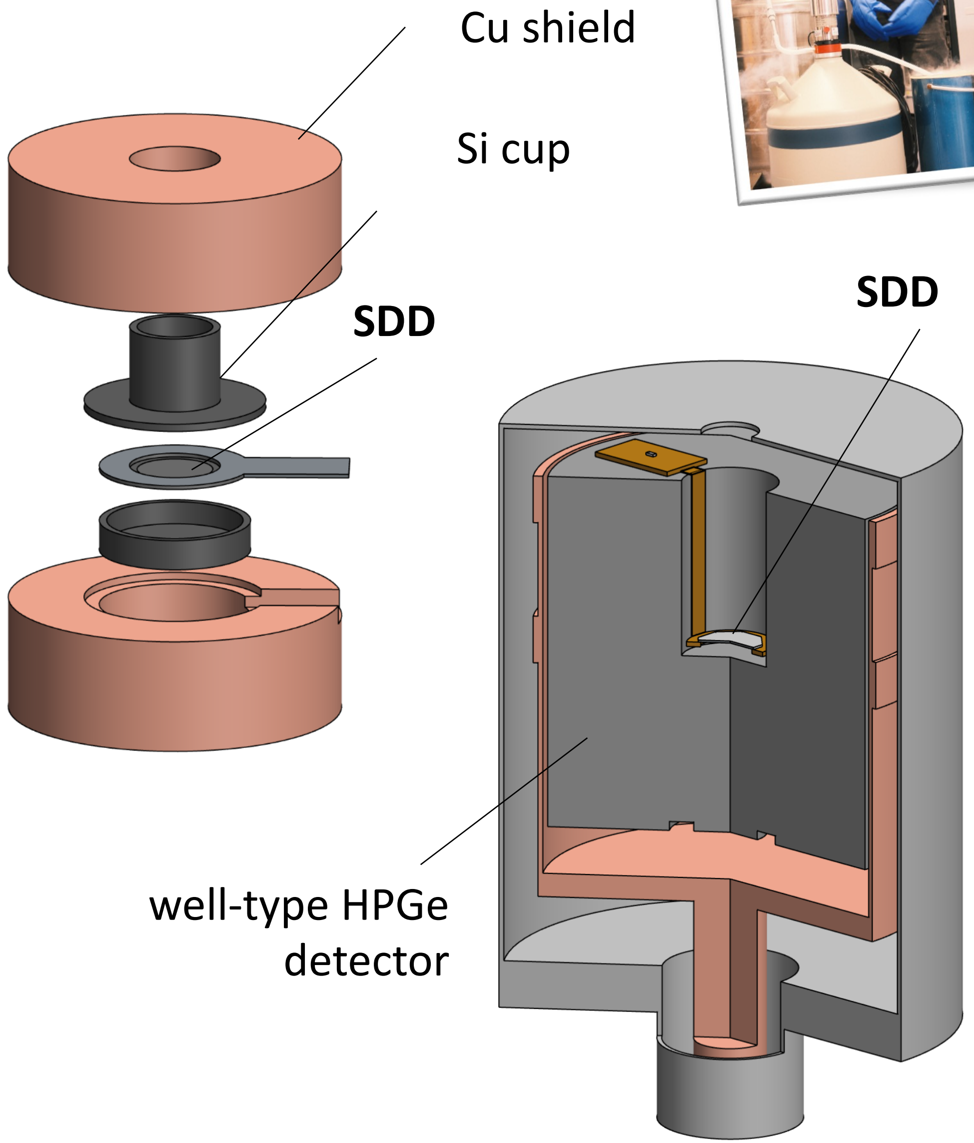


# TAXO – background projections




- *Radioactivity in surrounding material*
- *Cosmogenic activation (tritium, $^{32}Si$)*
- *Cosmic radiation (muons and neutrons)*

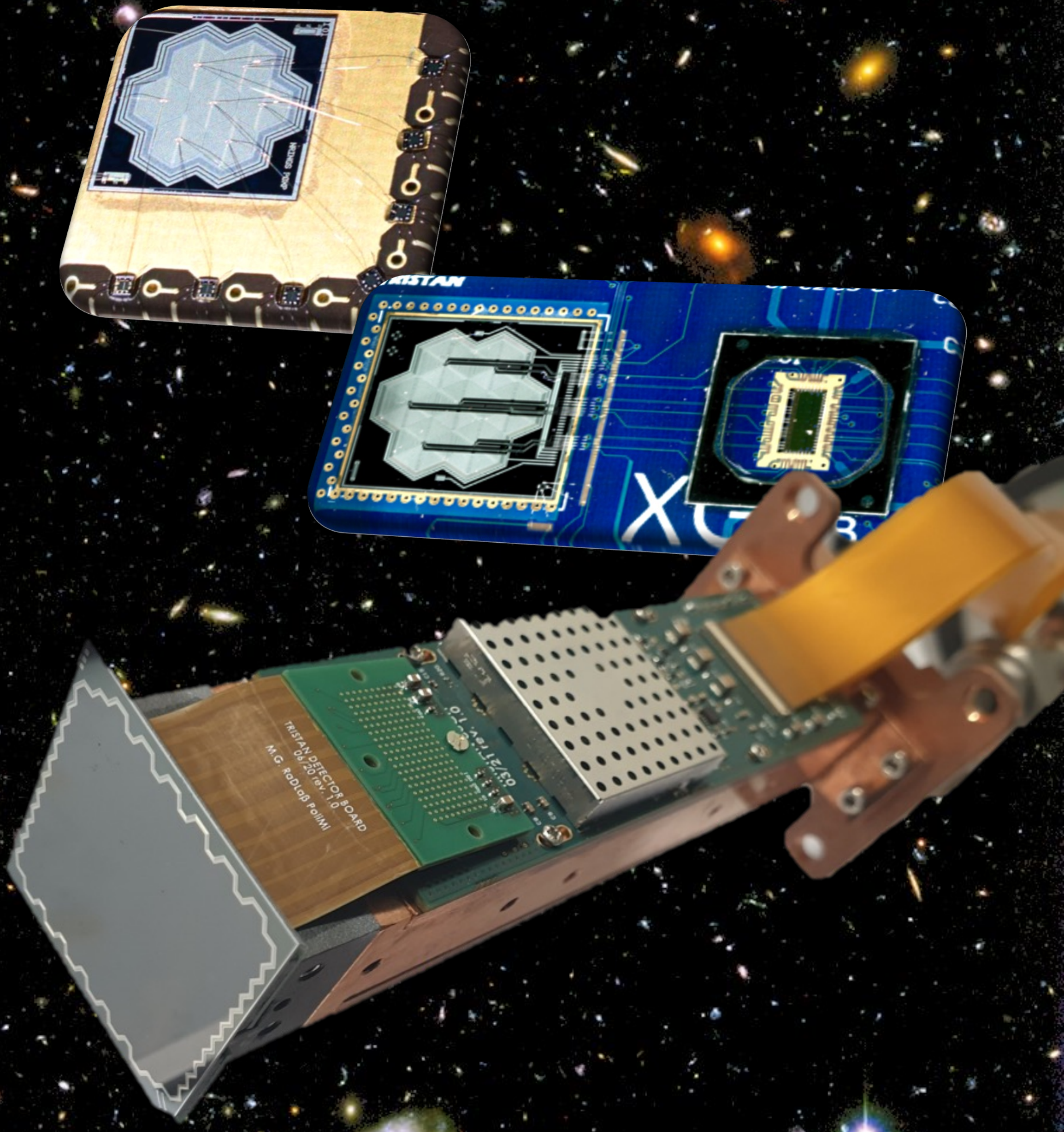



# Summary

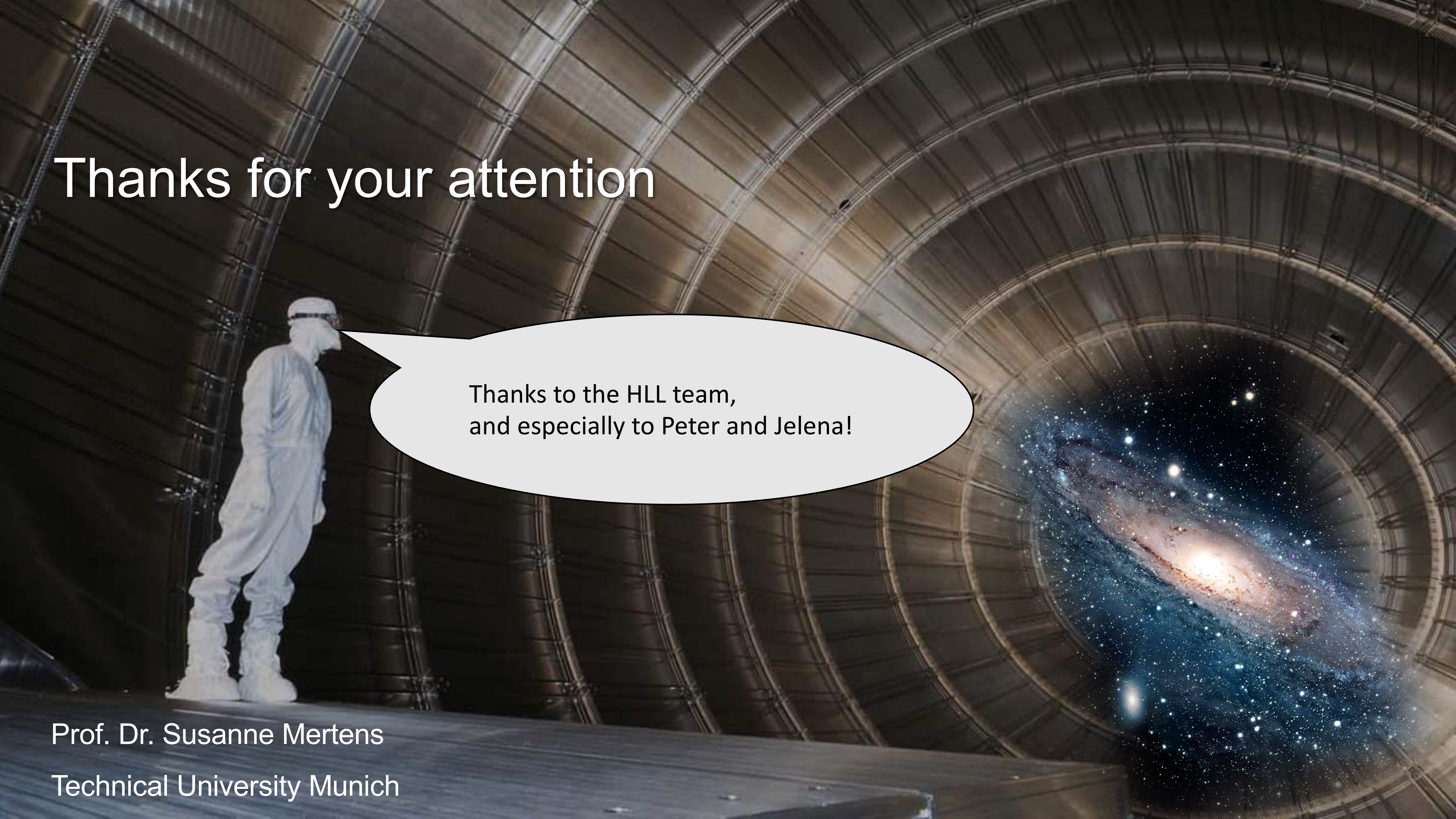
SDDs are highly useful to Astroparticle physics

- ✓ TRISTAN:
  High-precision β-spectroscopy with SDDs enables new physics searches, e.g. dark matter sterile neutrino

- ✓ IAXO:
  Ultra-low background SDDs enable rare event searches, e.g. for solar axions



# Thanks for your attention




Prof. Dr. Susanne Mertens

Technical University Munich