SFB 1258 Neutrinos Dark Matter Messengers

ORIGINS Excellence Cluster

BAdW Bayerische Akademie der Wissenschaften

Towards low-background silicon drift detectors for LUXO

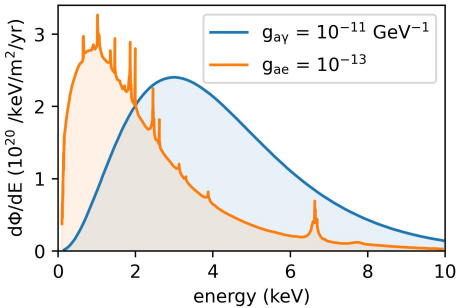
Joanna Bilicki, Patrick Bongratz, Frank Edzards, Susanne Mertens, Lucinda Schönfeld, Juan Pablo Ulloa Beteta, Korbinian Urban, Christoph Wiesinger, Michael Willers (TUM), XDEP conference, 05.02.2024

detector requirements

- search for **solar-axion induced X-rays**

1) sufficient **energy threshold** and **resolution**

[Dafni et al., PRD 99 (2019) 3, 035037]



➔ **sensitivity** scales with $g_{aγ}^{-4} \propto \varepsilon / b^{1/2} \cdot t^{1/2}$ *(square-root)*

2) high X-ray **detection efficiency** *(**ε**)*

3) **ultra-low background** *(**b**)*

   - goal **10^{-8} cts/keV/cm^2/s** *(single events per year)*

Background challenge

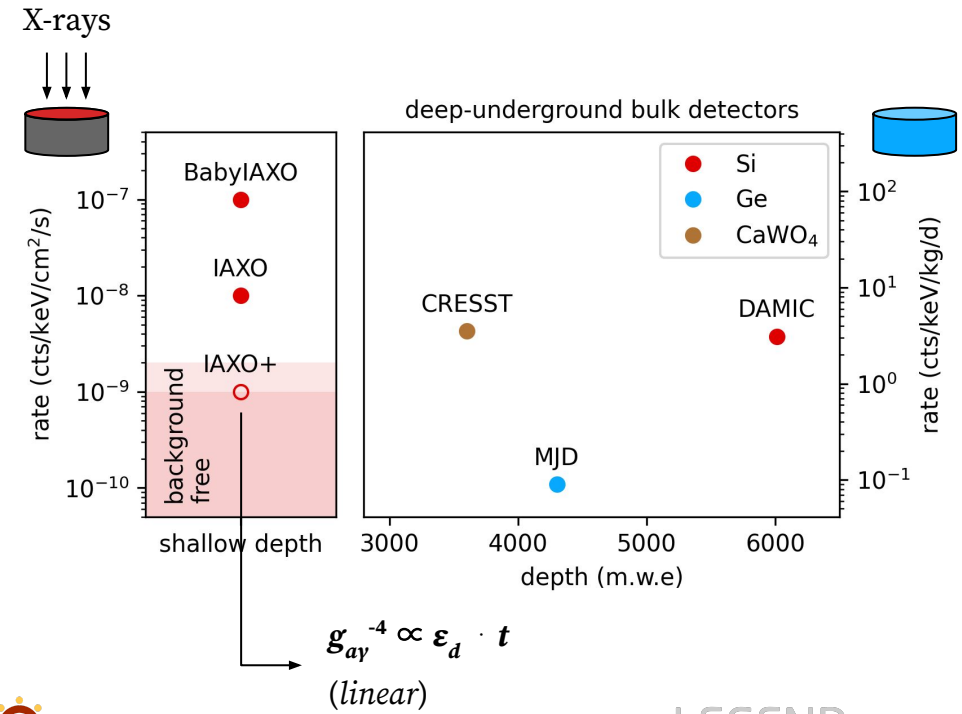
- **similar to** other rare-event searches, e.g. **CEνNS**, **WIMP**, **0νββ decay** searches

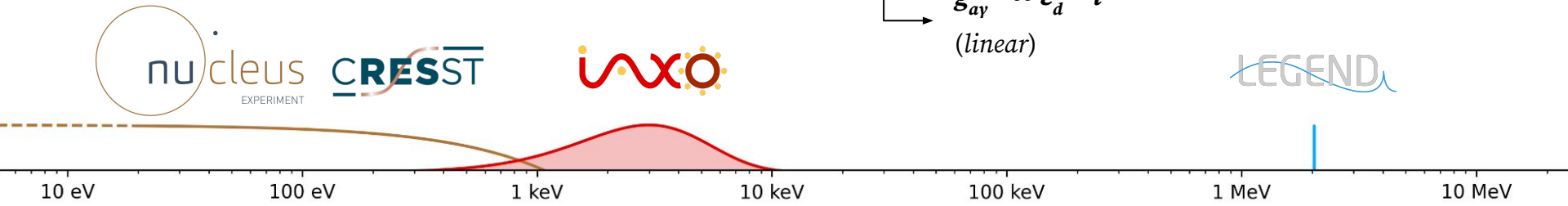
➔ radiopurity, **background mitigation**

but

- deep-underground like performance **at shallow depth**

➔ **cosmic-ray** induced backgrounds





Silicon drift detectors (SDDs)

- tiny read-out electrode, **low capacitance**

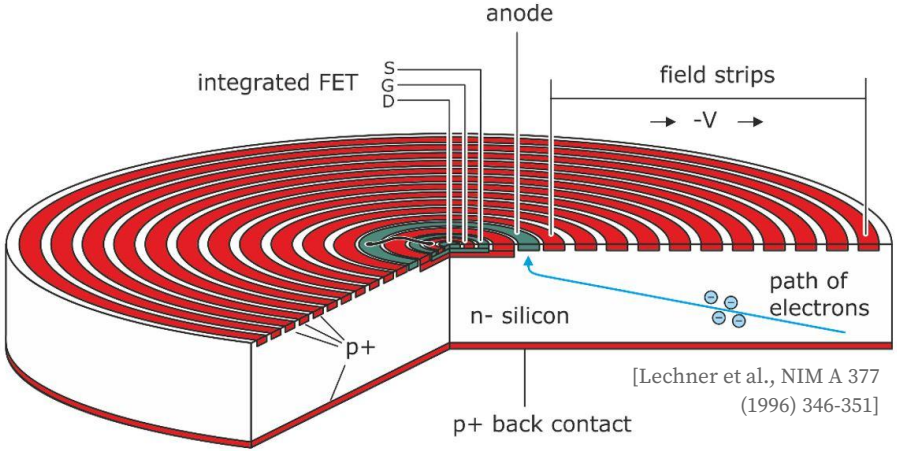
➔ low **energy threshold** (< 1 keV) ✔
and good **resolution** (< 200 eV FWHM at 6 keV) ✔

- thin deadlayer (< 100 nm), **no entrance window**

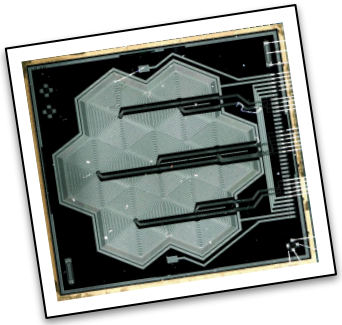
➔ high X-ray **detection efficiency** in [1, 10] keV ✔

- **semiconductor-grade materials**, little auxiliaries

➔ great potential for **low-background** operations ☐



[Lechner et al., NIM A 377 (1996) 346-351]



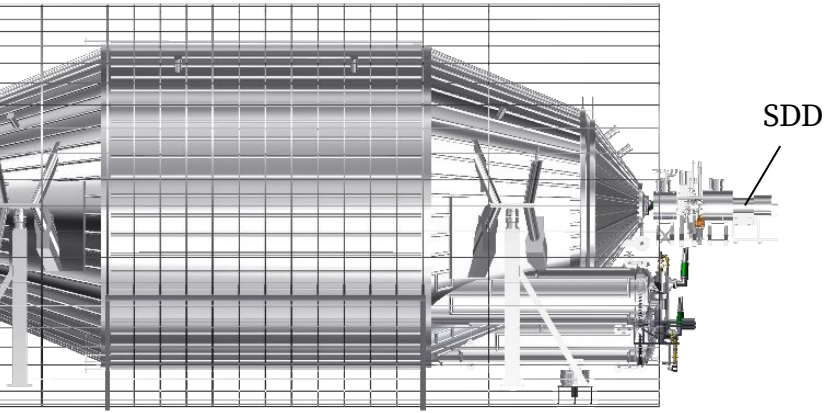
7x3-mm pixel **TRISTAN** prototype
SDD array with integrated JFET

TRISTAN

poster by Christian Forstner

keV-sterile neutrino search with KATRIN

[Mertens et al., J.Phays.G 46 (2019) 6, 065203]



- **high-rate electron spectroscopy**
- ultra-high vacuum compliance, calibration

TRISTAN

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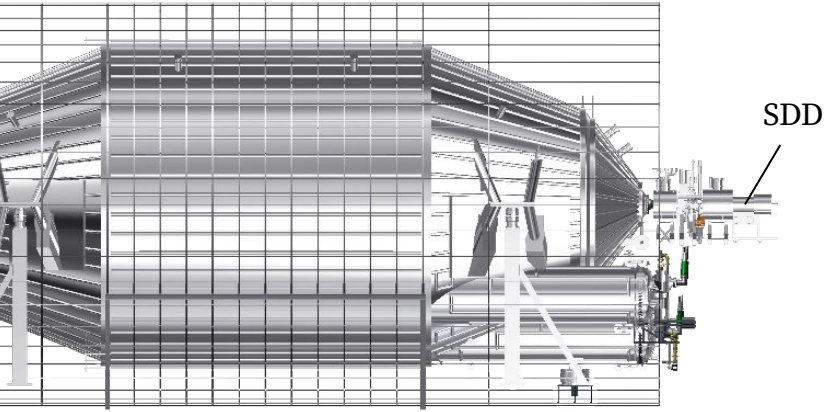


- **high-rate electron spectroscopy**
- ultra-high vacuum compliance, calibration

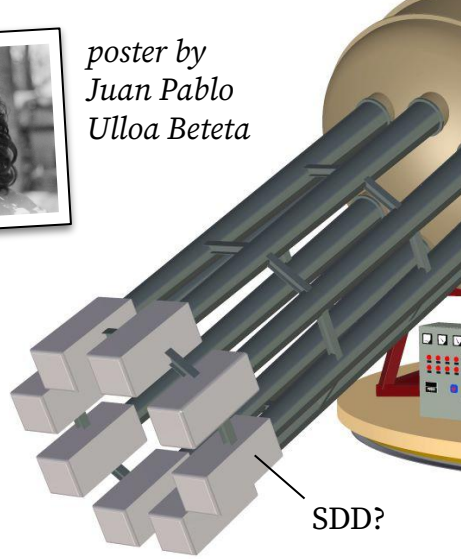
IAXO

poster by Juan Pablo Ulloa Beteta

solar axion search

[Armengaud et al., JINST 9 (2014) T05002]

- **rare-event X-ray detection**
- ultra-low background, high-efficiency



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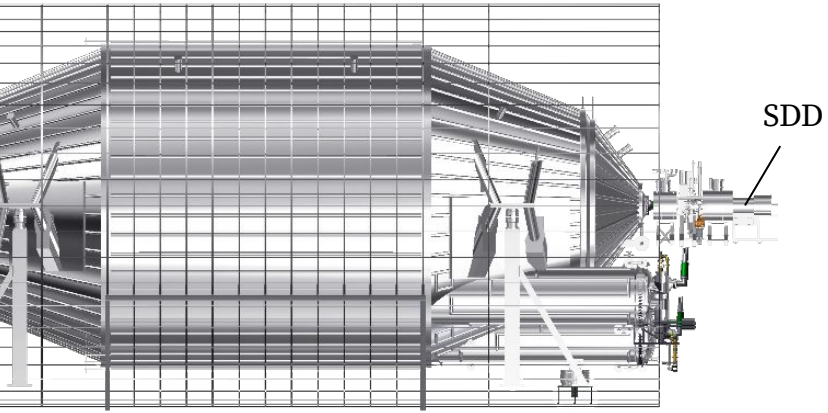

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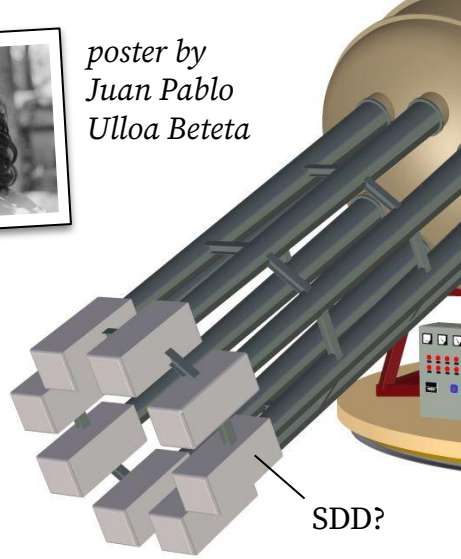
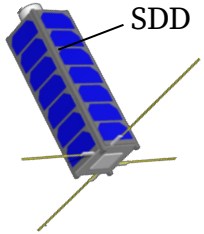


ComPol

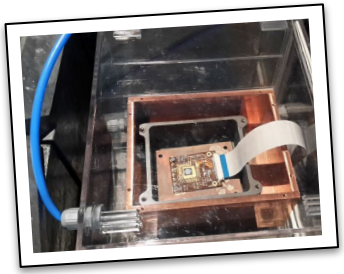


poster by Jonas Schlegel

X-ray polarization measurement of Cygnus X-1

- compact **Compton telescope**, CubeSat mission
- space environment, radiation hardness, remote operation

TAXO *development steps*

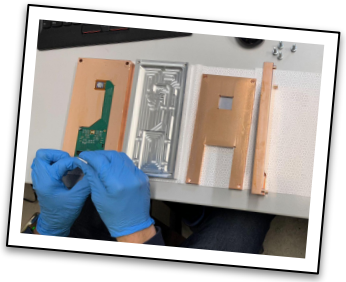


SDD **pathfinder**

material insufficiencies, close-by electronics

➔ **$(1.9 \pm 0.2) \cdot 10^{-5}$ cts/keV/cm^2/s** at shallow depth

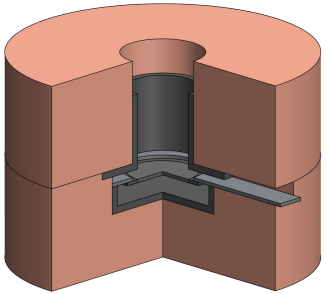
[Houdy et al., 2019]



TAXO **demonstrator**

consequent **low-background** approach, **far electronics**

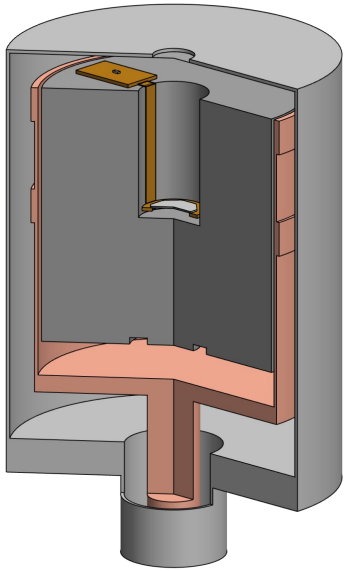
➔ demonstrate **O(10^{-7}) cts/keV/cm^2/s**



BabyTAXO

dedicated SDD production, improved **passive shield**

➔ target **< 10^{-7} cts/keV/cm^2/s** at shallow depth



TAXO

all-semiconductor **active shield** SDD-in-HPGe detector

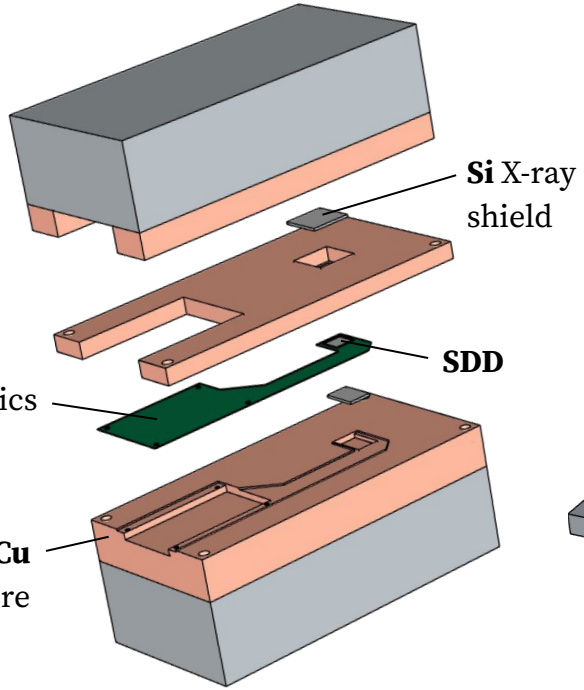
➔ target **< 10^{-8} cts/keV/cm^2/s** at shallow depth

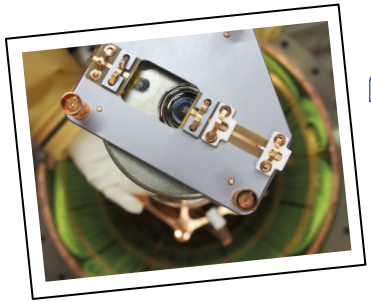
TAXO *demonstrator*

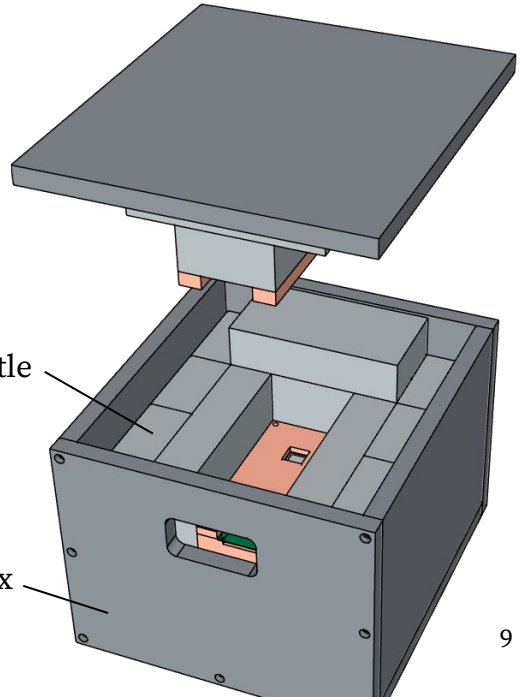
- **passive shield** setup with
  - prototype **SDD** on polyimide board, far electronics
  - **Si** X-ray shield, radiopure **Cu** enclosure
  - compact **Pb** castle, flush box

➔ demonstrate **O(10^{-7}) cts/keV/cm^2/s**

1) **deep underground** at Canfranc
2) at **shallow depth** with muon veto and neutron shield







COSINUS

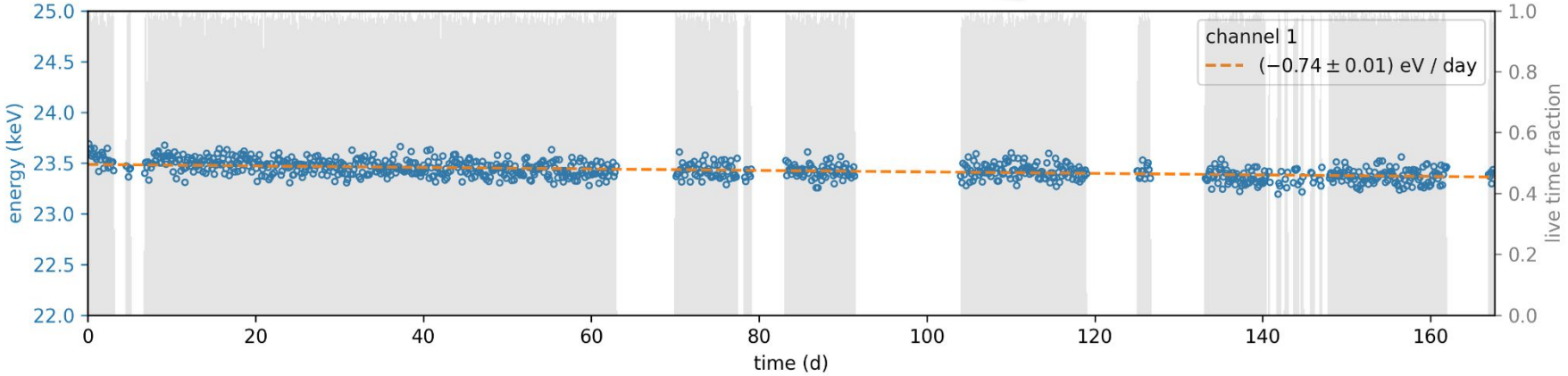
TAXO *demonstrator at Canfranc*

- installed in Lab2500 (**2450 m.w.e.**)

➔ determination of intrinsic **non-cosmic background**

- stable **long-term operation**, **gain monitoring**

➔ **> 100 d** live time, **< 1 eV/d** gain drift



TAXO *demonstrator at Canfranc*

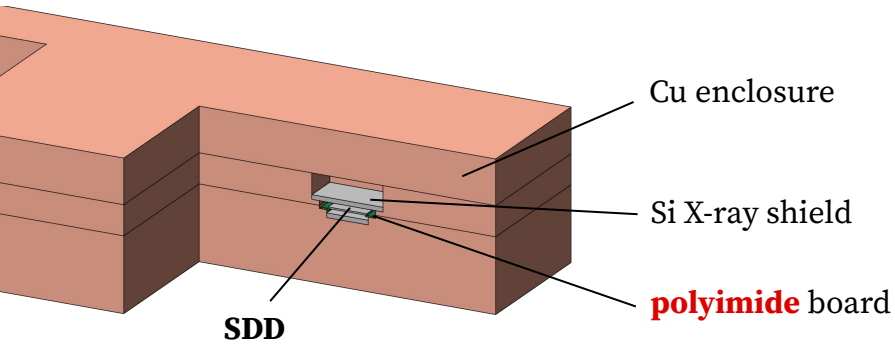
- noise situation suboptimal

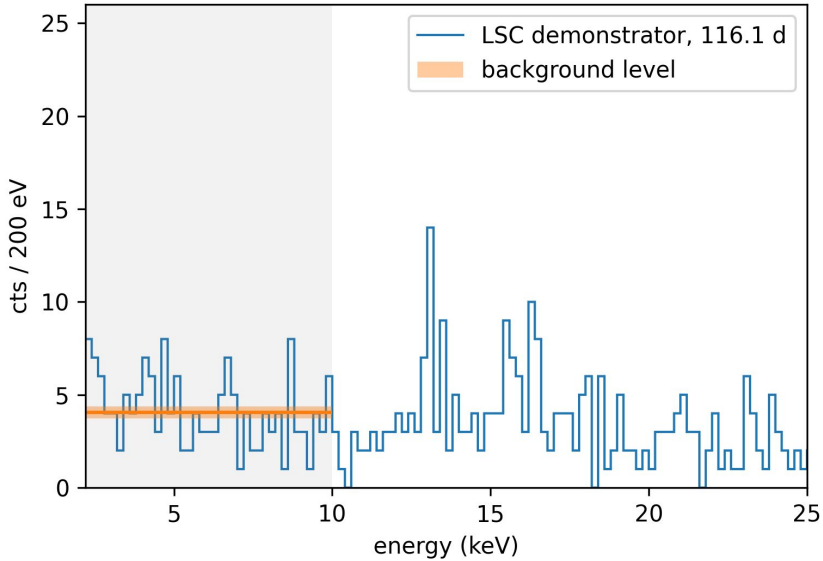
➔ **2 keV** (online) **threshold,** 300 eV FWHM at 10 keV

- **background** level **higher than anticipated**

➔ **$(5.6 \pm 0.5) \cdot 10^{-6}$ cts/keV/cm^2/s** in [2, 10] keV

- **X-ray lines** from close-by contaminants
- **polyimide** assay, **activity** 10-100x **above expectations**





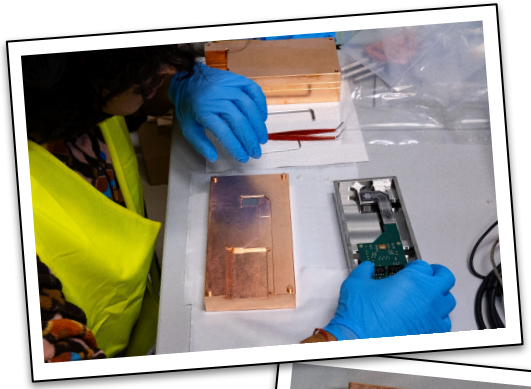
TAXO *demonstrator upgrade*

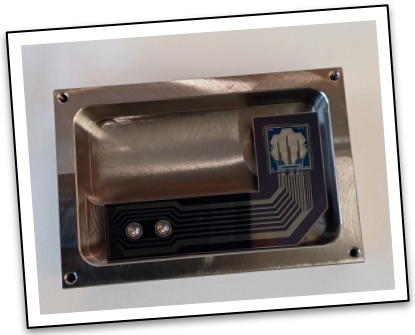
- polyimide board **head area dominates** background budget

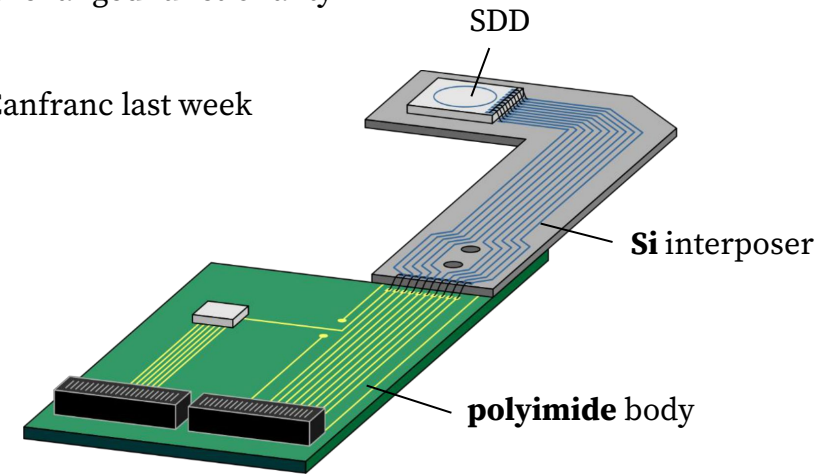
➔ split detector board into

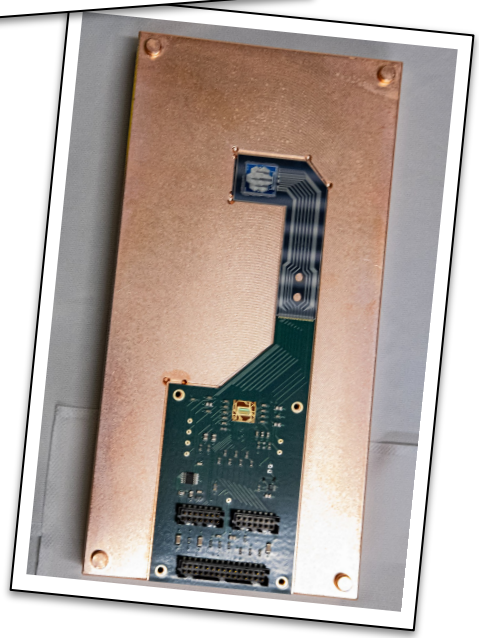
  - **Si** interposer **head**, improved radiopurity in SDD vicinity
  - **polyimide body**, unchanged functionality

- first upgrade attempt at Canfranc last week





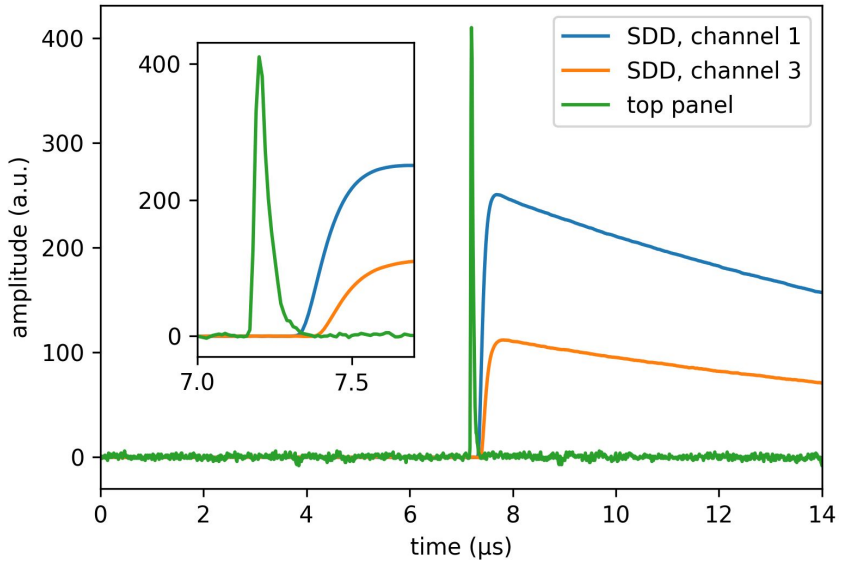




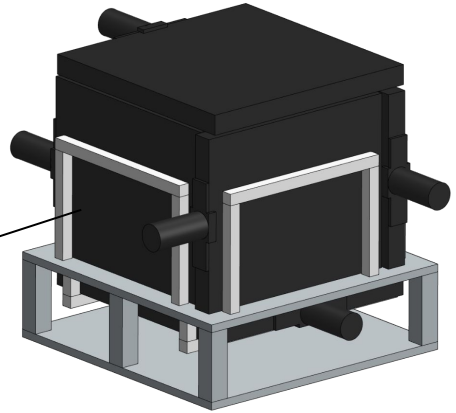
TAXO *demonstrator at* TUM

- **twin** of Canfranc demonstrator with
  - **muon veto**, 6 plastic scintillator panels
  - **neutron shield**, borated polyethylene

➔ disentangle **cosmic-ray induced background**



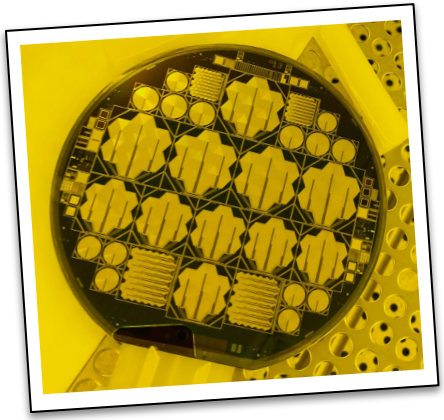
- background measurements in preparation
  - **above ground** at TUM
  - **at shallow-depth** at DESY. HERA south hall

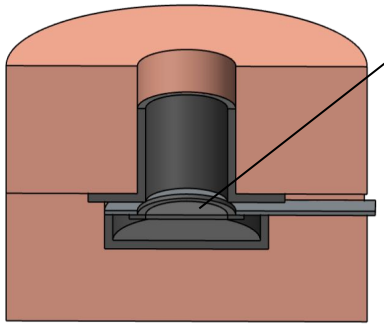


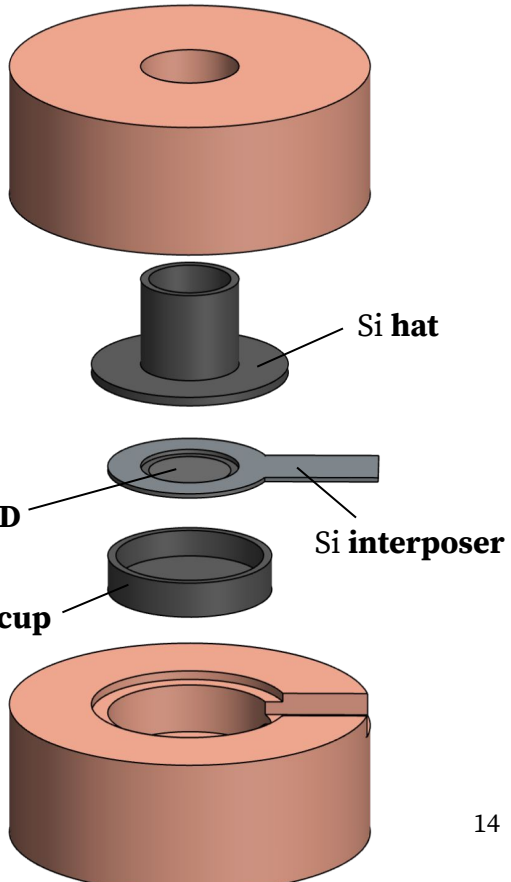
Baby TAXO

- **passive shield** setup, based on demonstrator experience
  - maximal **X-ray shield coverage**
  - radiopure **interposer**
  - optimized **neutron shield**
- dedicated **large-are SDDs**
- beam tube, **vacuum** interface

➔ target **< 10^{-7} cts/keV/cm^2/s,** potential detector for **Baby** TAXO

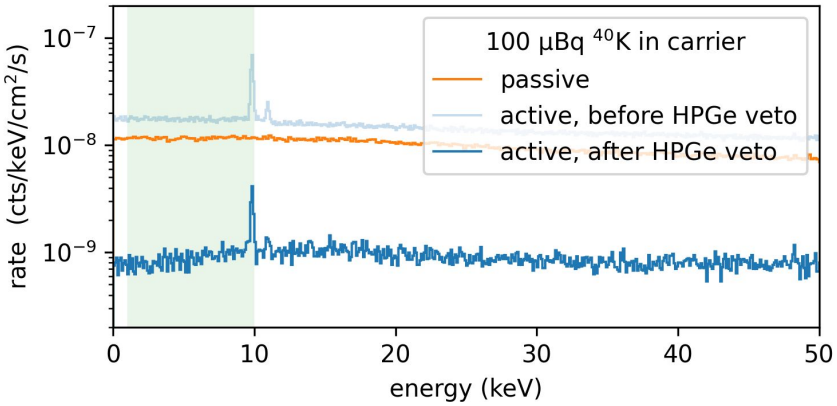






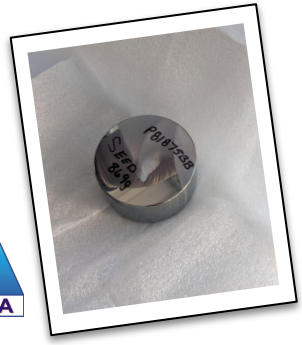
T-LXO - *SDD-in-HPGe detector*

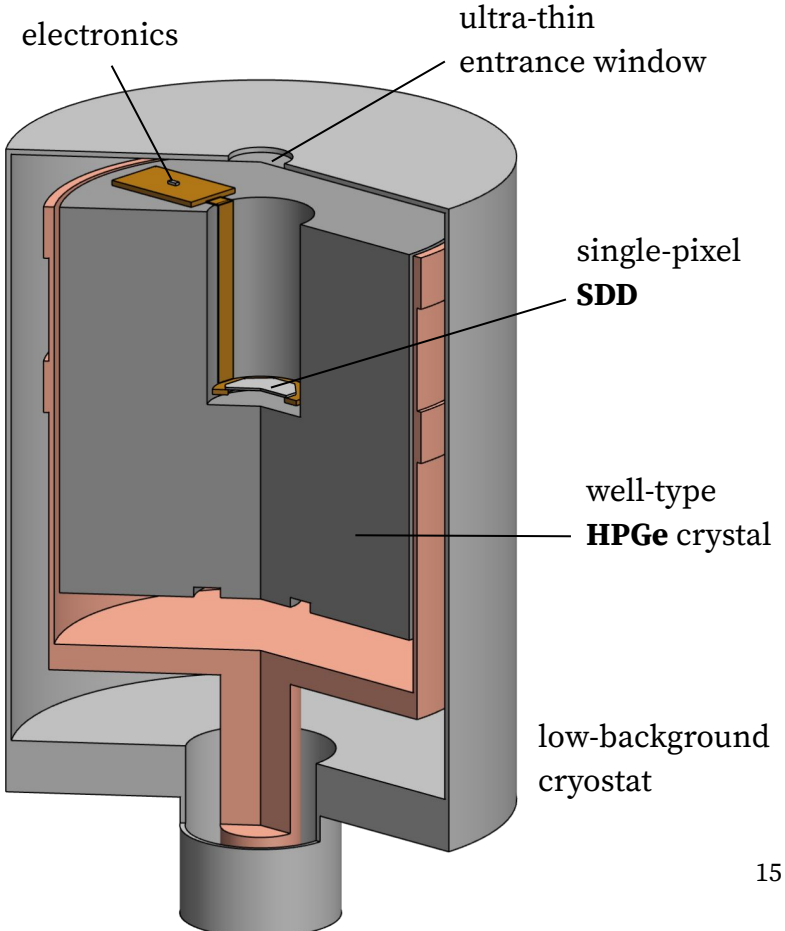
- all-semiconductor **active-shield design**, ultra-pure ~**4π veto**



- well-type HPGe detector **prototype, proof-of-principle** planned for this year

➔ target **< 10^{-8} cts/keV/cm²/s,** potential detector for LXO



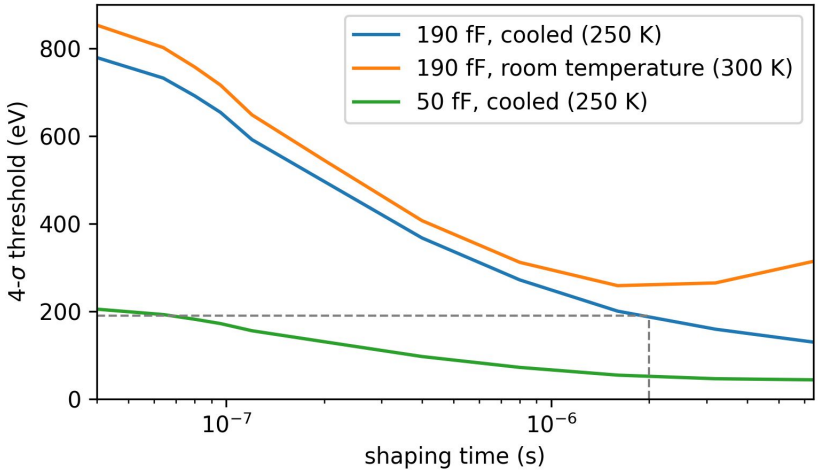


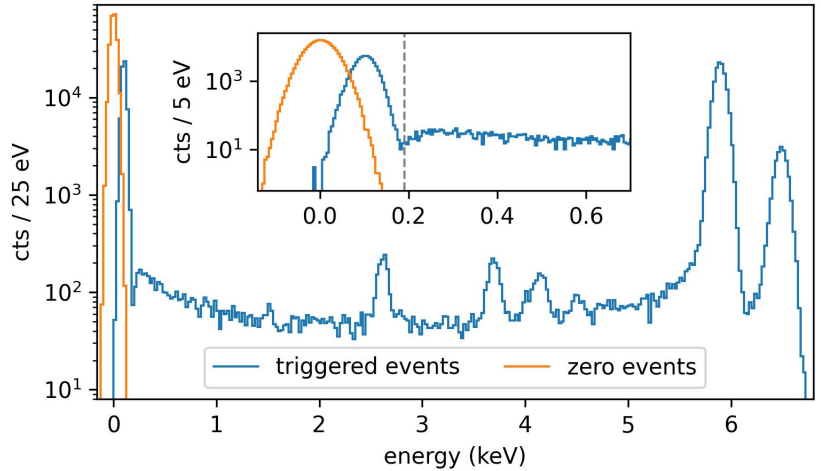
Energy threshold

- depends on **noise performance**
  - read-out capacitance
  - temperature
  - trigger filter (shaping time)

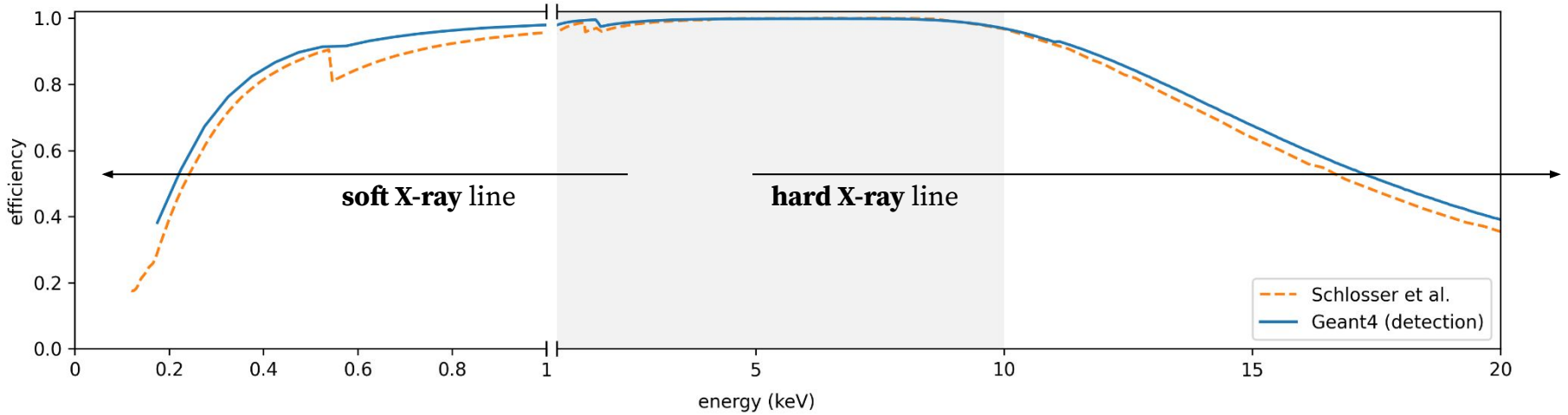
- **200 eV** achieved with TRISTAN SDD (cooled, 2 µs shaping time)
- **25 eV** reported in literature, droplet SDD
  [Strüder et al., Microscopy Today 28 (2020)]

➔ **sub-keV threshold** feasible, but cooling/close-by electronics could alter background performance





Detection efficiency



- **450-µm SDD** with **50 nm dead layer**, no entrance window
- **> 95%** in [1, 10] keV, but also substantial for exotic axion models, **> 50%** above **250 eV**, **> 65%** at **14.4 kev**

➔ efficiency measurement at SOLEIL SYNCHROTRON **metrology beamline** in preparation

Conclusions

- **TAXO** SDD development to meet challenging IAXO X-ray detector requirements with a
  - conventional **passive shield** setup
  - novel all-semiconductor **SDD-in-HPGe active-shield** design
- **background exploration** deep-underground at Canfranc and at shallow depth **ongoing**
- efficiency measurement at SOLEIL SYNCHROTRON **metrology beamline** in preparation

- application in **other particle physics projects**
  - keV-sterile neutrino search with **TRISTAN** in KATRIN
  - X-ray polarization measurement with **ComPol**

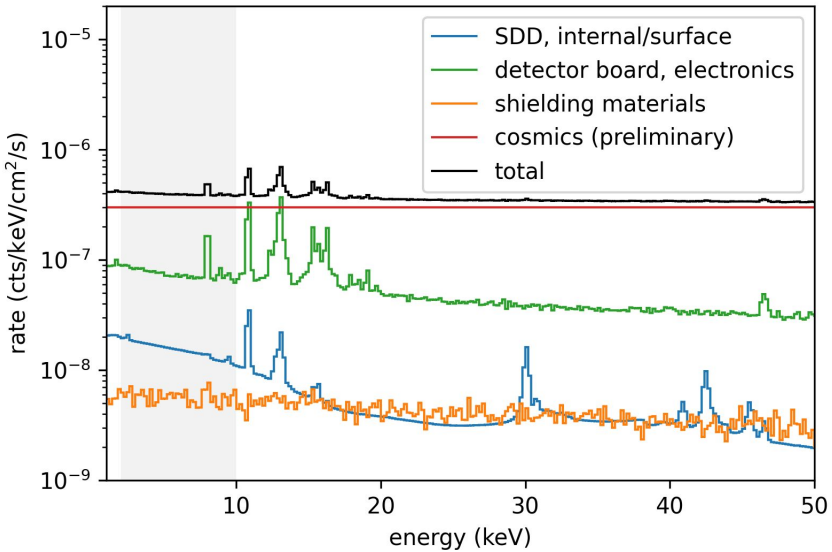
Backup

Background projections

- stand-alone **Geant4** application, demonstrator and different shielding geometries implemented

- **radiogenic** backgrounds
  - **assay** results, radiopurity **estimates**
  - cosmogenic **activation** (^{3}H, ^{32}Si)
    [Saldanha et al., PRD (2020) 10, 102006;
    Orrell et al., Astropart.Phys. 99 (2018) 9-20]

- **cosmic** backgrounds
  - full (correlated) above ground **cosmic ray flux**, cosmic ray library (**CRY**)
    [https://nuclear.llnl.gov/simulation/doc_cry_v1.7/cry.pdf]



➔ significant **reduction of neutron-induced background** with borated polyethylene