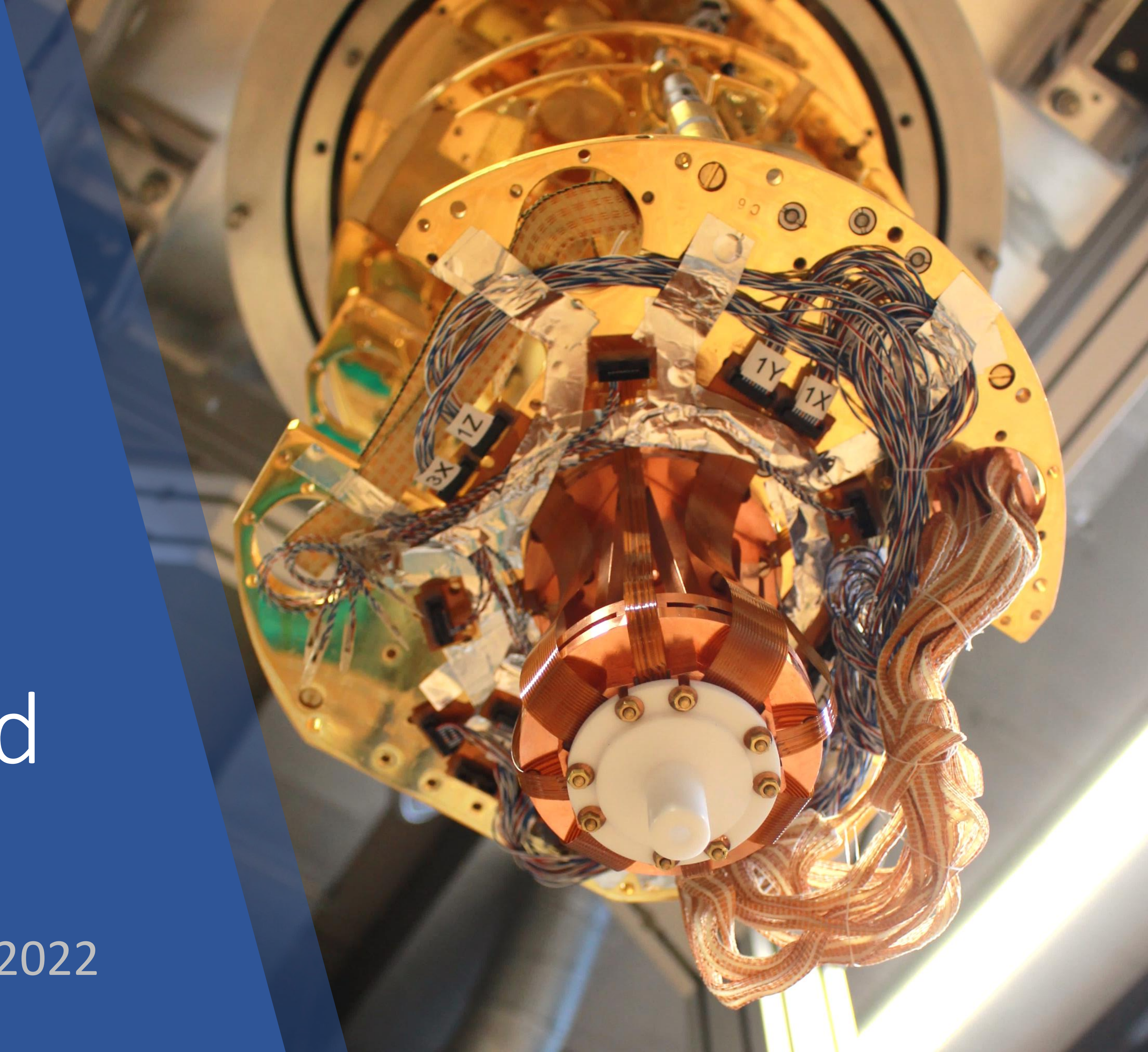
HighRR · BiWeekly-Seminar

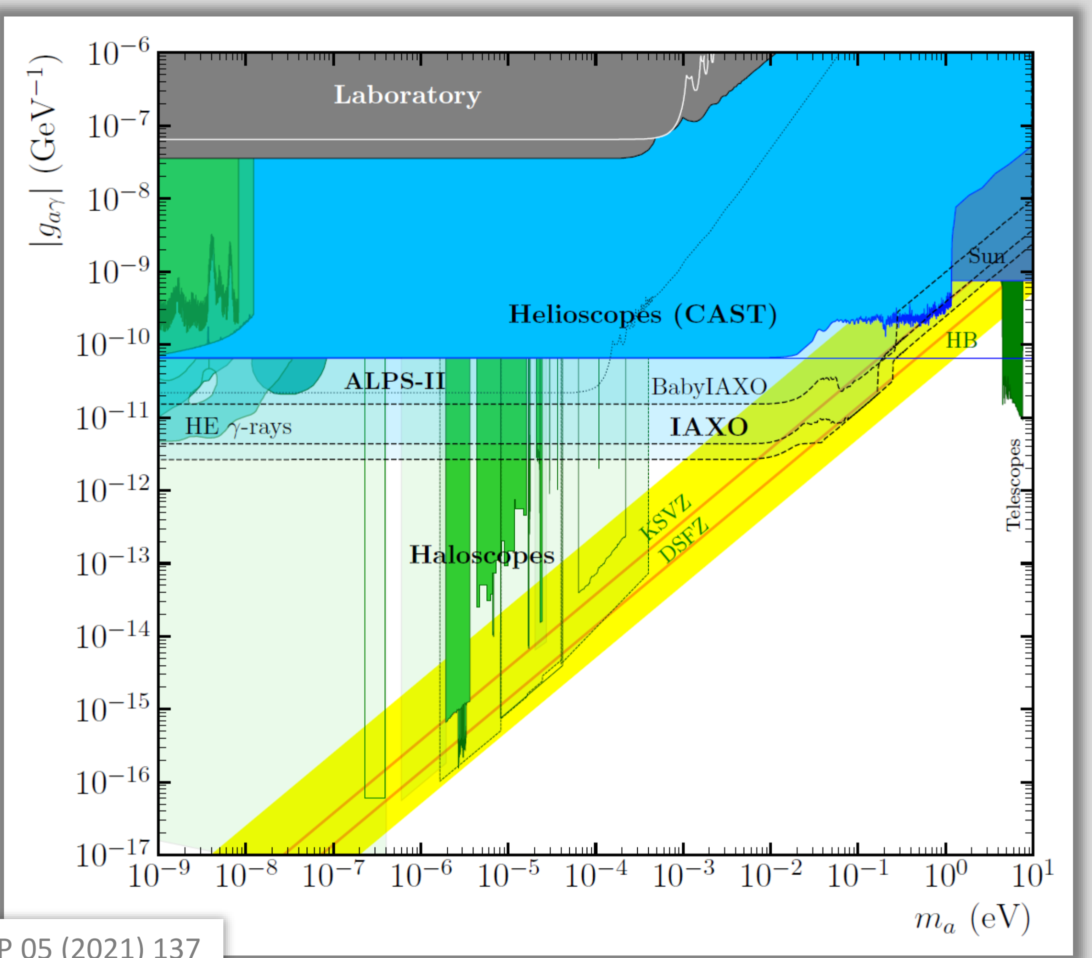
Low Background MMCs for IAXO

Daniel Unger · 2nd November 2022



Axion & ALP Search

- Axion: possible solution to strong CP problem
- Axion-like particles (ALPs):
  - generic photon coupling like axions
  - very light
  - barely interacting
- ALPs could explain several observations, e.g.:
  - dark matter
  - stellar cooling anomalies
  - ɣ-ray transparency of the universe



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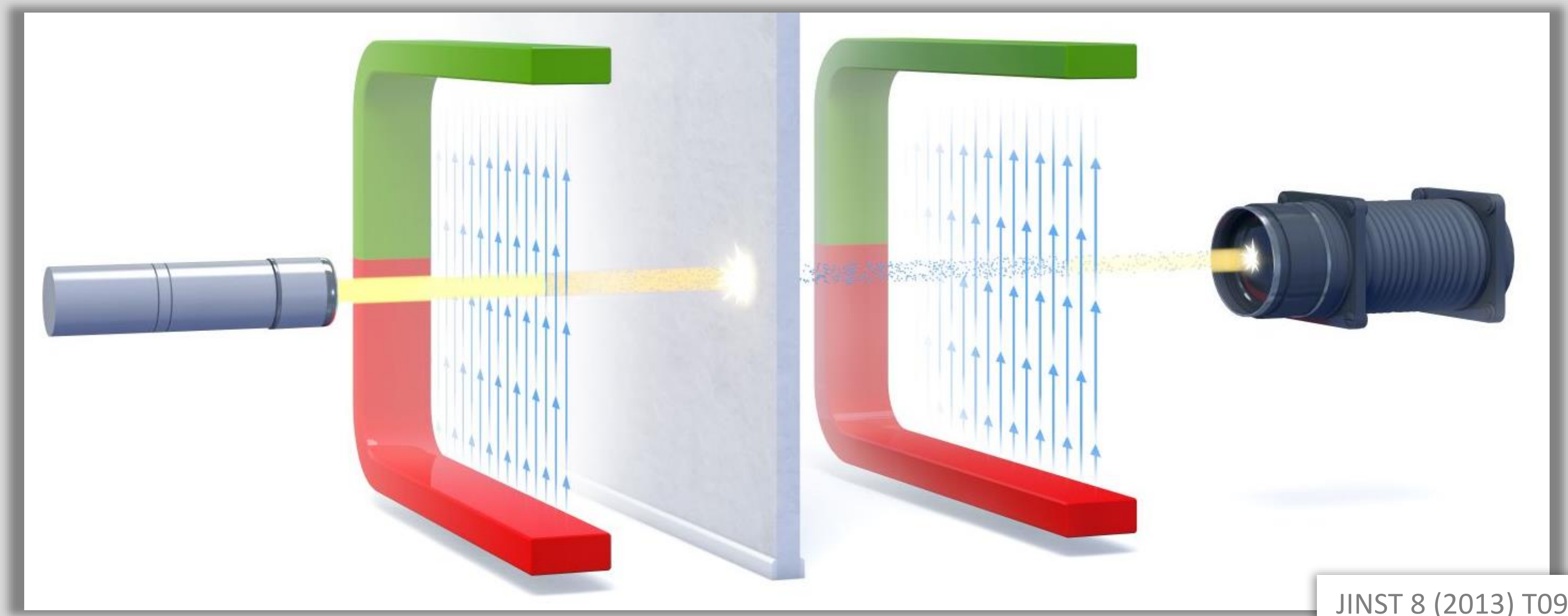
Detection Methods



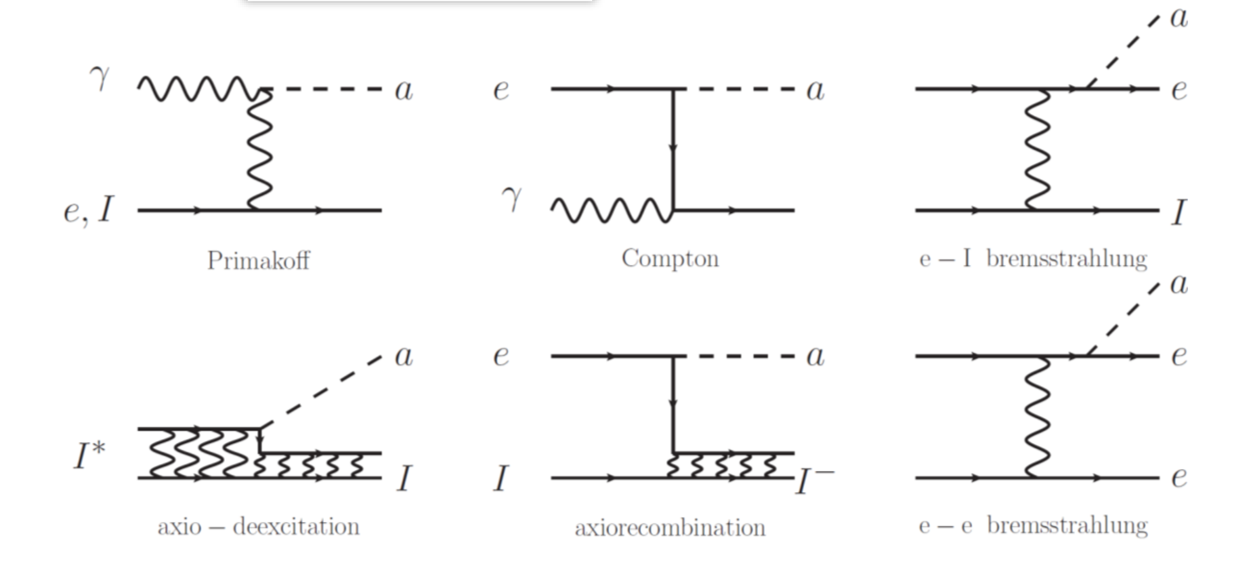
JINST 8 (2013) T09001

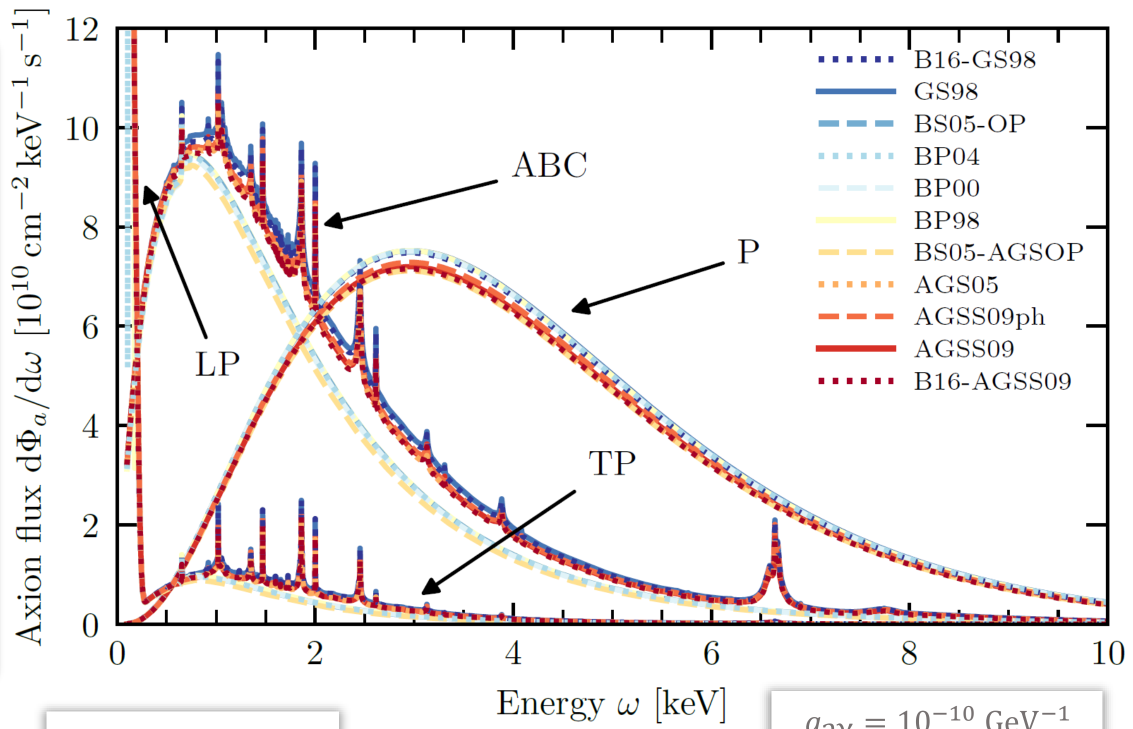
- Light-shining-through-a-wall: axions produced in the laboratory
- Haloscopes: axions as part of the dark matter halo of our galaxy
- Helioscopes: axions produced in the interior of the Sun

natural source of axions

Solar Axion Flux

JCAP 1312 (2013) 008





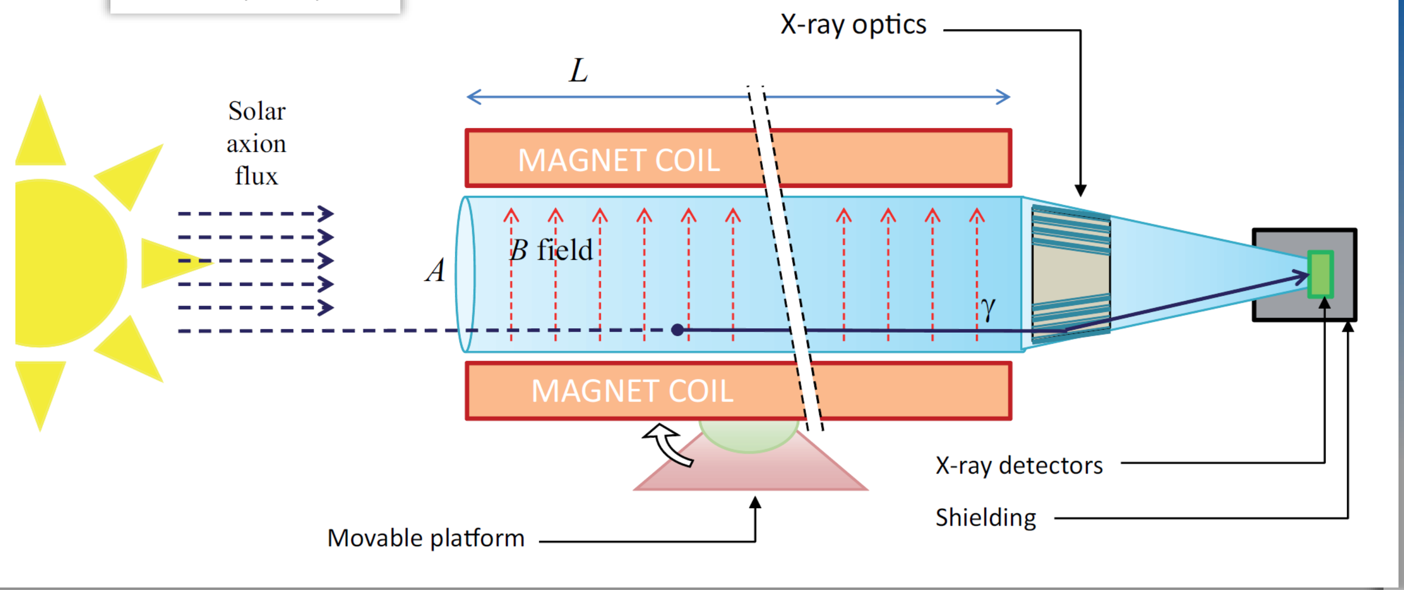
JCAP 09 (2021) 006

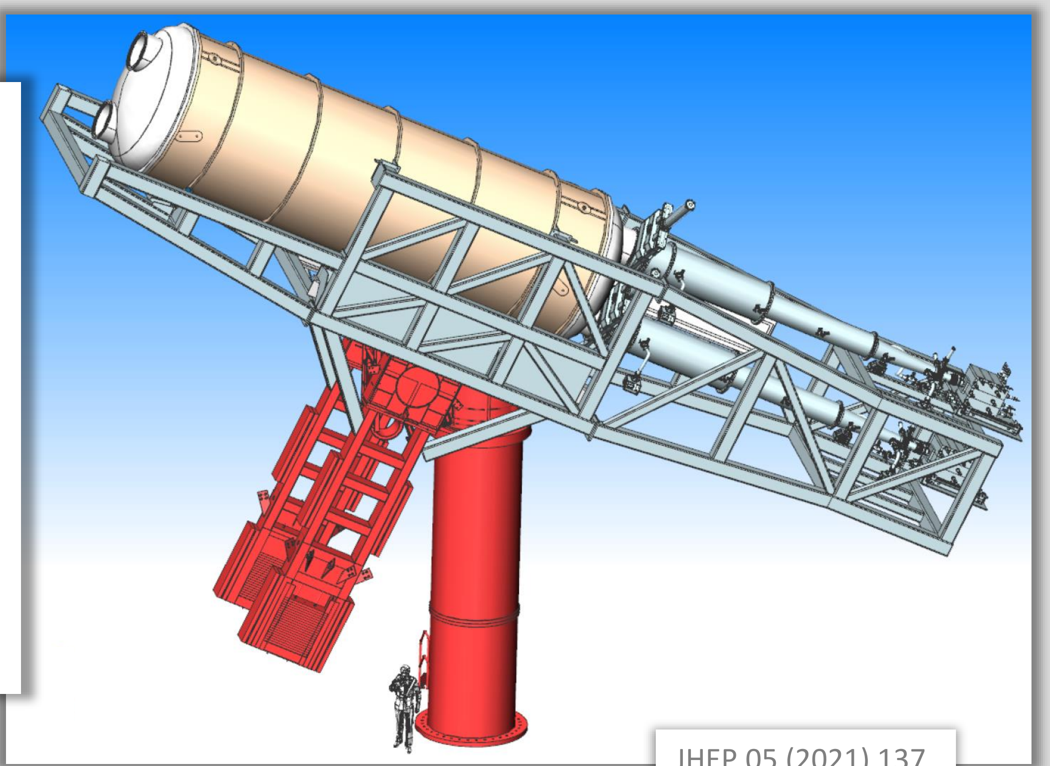
$g_{a\gamma} = 10^{-10}\ \mathrm{GeV}^{-1}$
$g_{ae} = 10^{-12}$

Resolving the spectrum allows to extract axion properties and information about the Sun

Helioscopes

JCAP 06 (2019) 047





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- Helioscopes search for axions from the Sun
- Axions would be converted to X-rays via their generic photon coupling

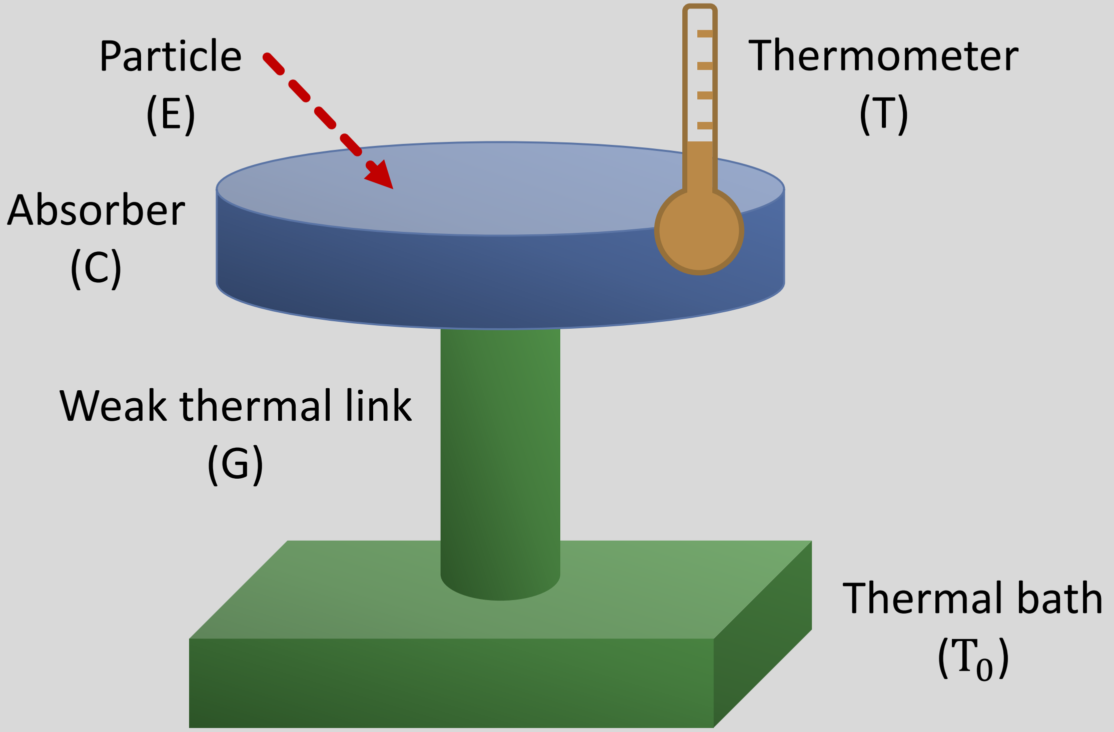
Detector Requirements

- Photon energy of roughly 100 eV – 14.4 keV: **X-ray detector**
- Small coupling: **high efficiency** and **low background**, below $10^{-6}\ \mathrm{keV^{-1}cm^{-2}s^{-1}}$
- Focal spot of X-ray optics: roughly $\mathbf{20\ mm^2}$ **active area**
- Rotating and tilting helioscope: **stable long-term operation** while moving

Additionally favored beyond discovery:

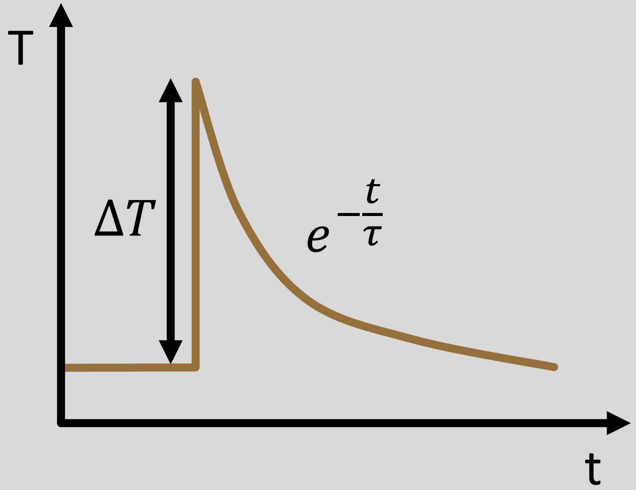
- Study axion spectrum: good energy resolution and low energy threshold

Micro-Calorimeters



$$\Delta T = \frac{E}{C}$$

$$\tau = \frac{C}{G}$$



Required for good energy resolution:

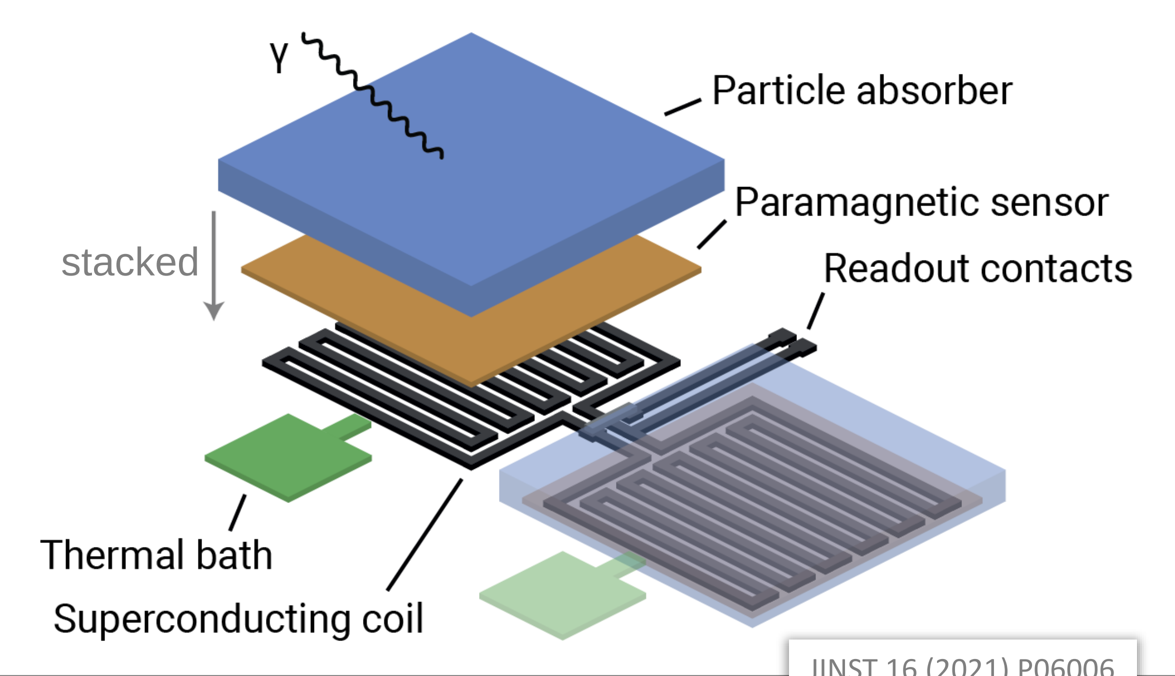
- Small volume at low temperature
- Very sensitive temperature sensor

Metallic Magnetic Calorimeter

- Cryogenic micro-calorimeter
- Paramagnetic temperature sensor
- Operated at around 20 mK

Advantages for IAXO:

- Good energy resolution
- Large bandwidth with high linearity
- Low energy threshold



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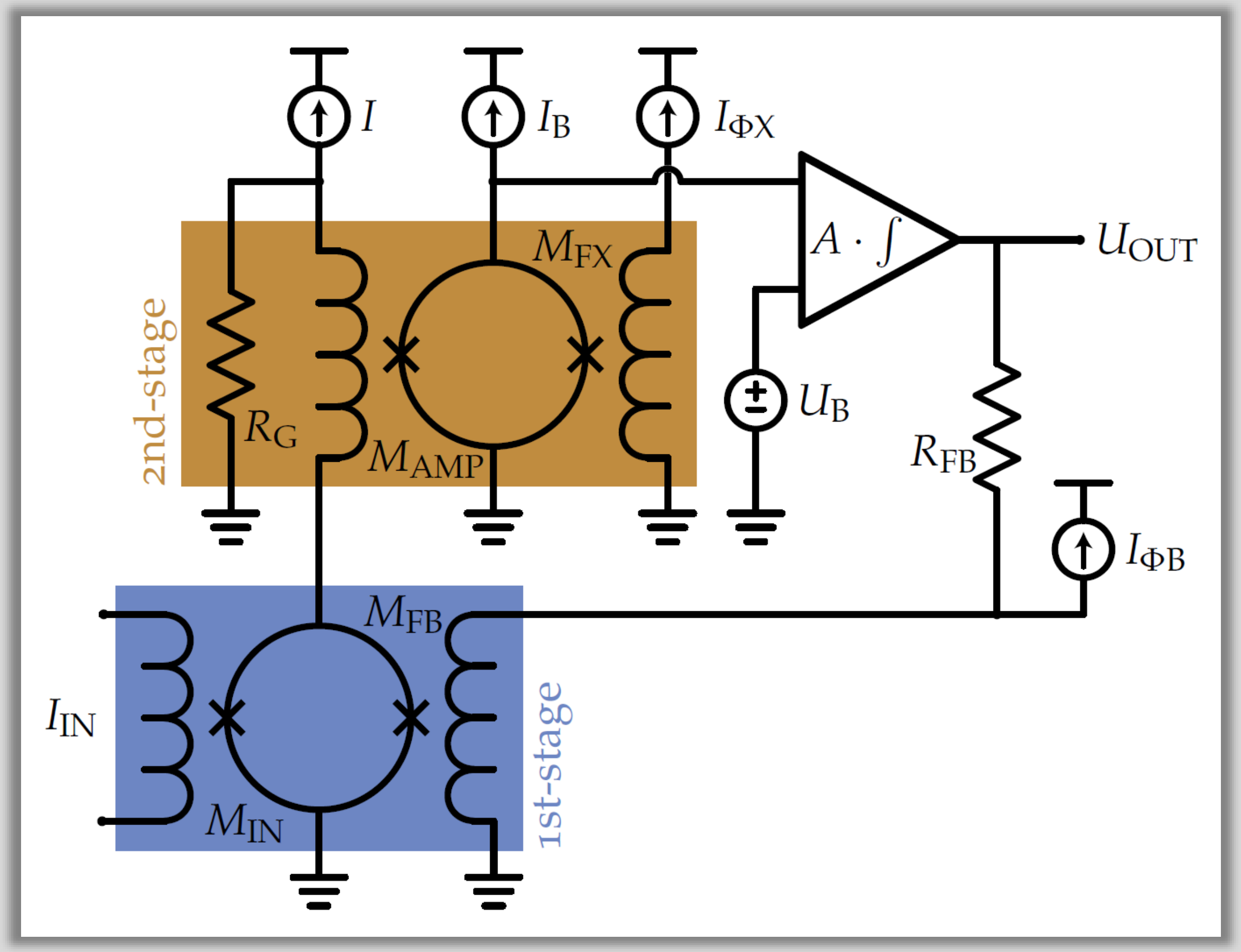
$$\delta E \longrightarrow \delta T = \frac{\delta E}{C} \longrightarrow \delta M = \frac{\partial M}{\partial T}\delta T \longrightarrow \delta \Phi \propto \delta M$$

Energy deposition → Temperature increase → Magnetization decrease → Change of magnetic flux

Two-Stage SQUID Readout



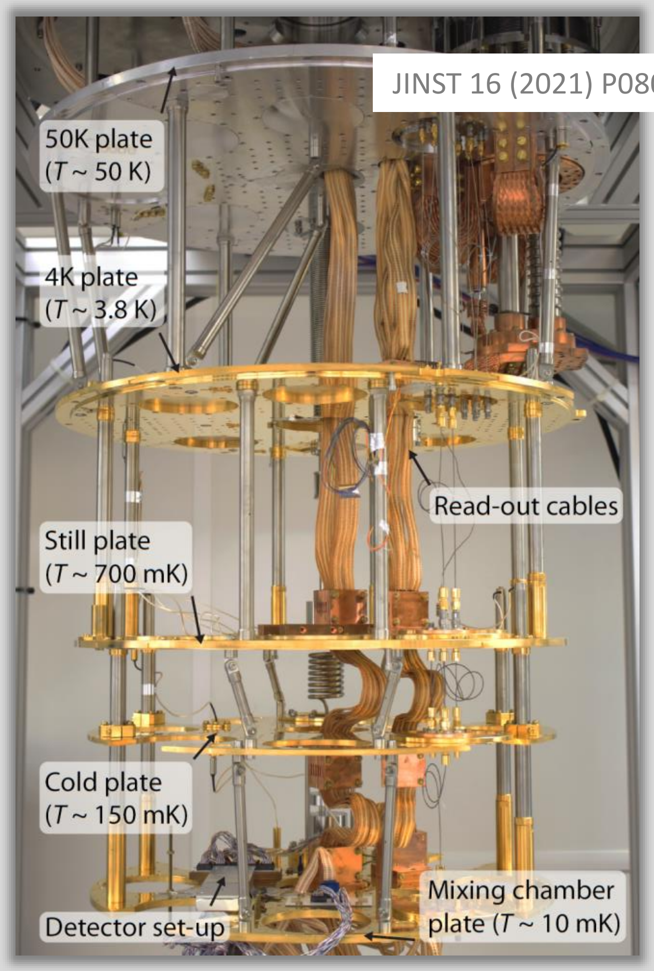
- SQUIDs: sensitive magnetometer
- Flux-locked-loop circuit to linearize SQUID voltage response
- Low noise and large bandwidth amplifier with small power dissipation

$$u_{OUT} = -\frac{M_{IN}}{M_{FB}} R_{FB}\, i_{IN}$$

$$u_{OUT} \propto i_{IN}$$

Dilution Refrigerator

- Continuous cooling to to a few mK
- Cooling provided by using a mixture of ^{3}He and ^{4}He
- MMCs and SQUIDs are mounted on the mixing chamber plate
- Ribbon cables connect the setup to room temperature electronics



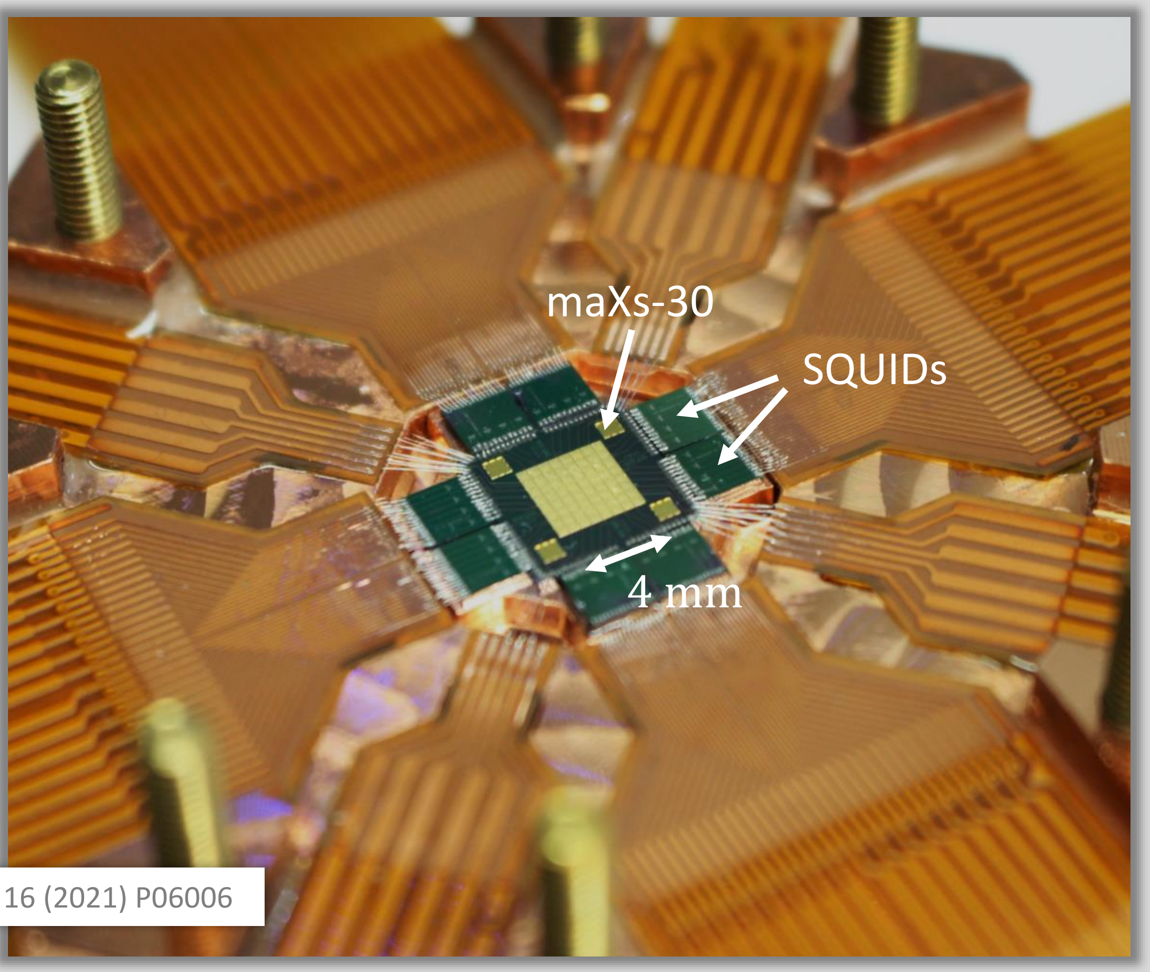
JINST 16 (2021) P08003

First Setup for IAXO

- Based on a maXs30 detector
- Made out of radiopure materials

maXs30 detector:

- For X-ray spectroscopy up to 30 keV
- 64-pixel detector, 16 mm^2 active area



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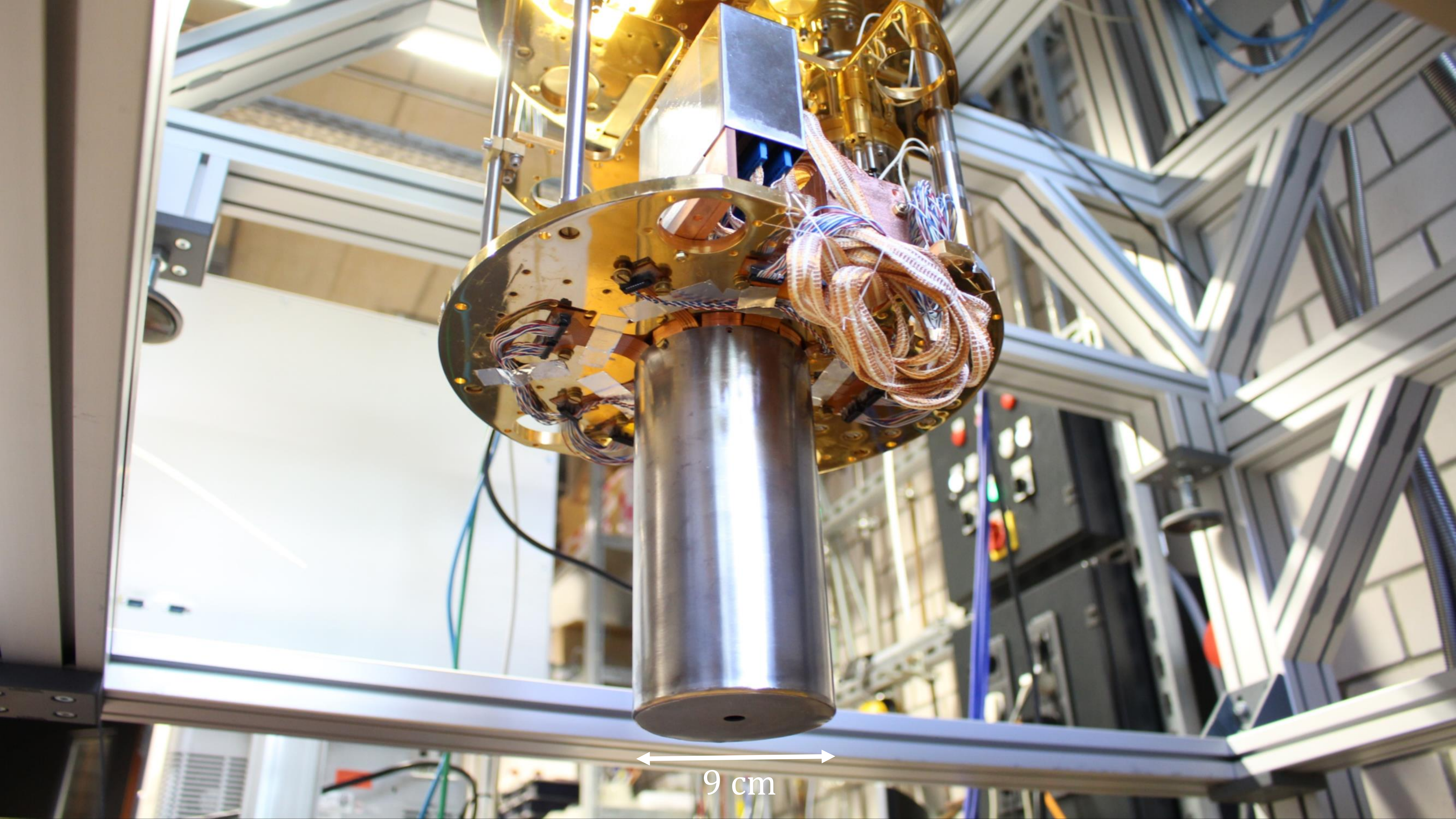
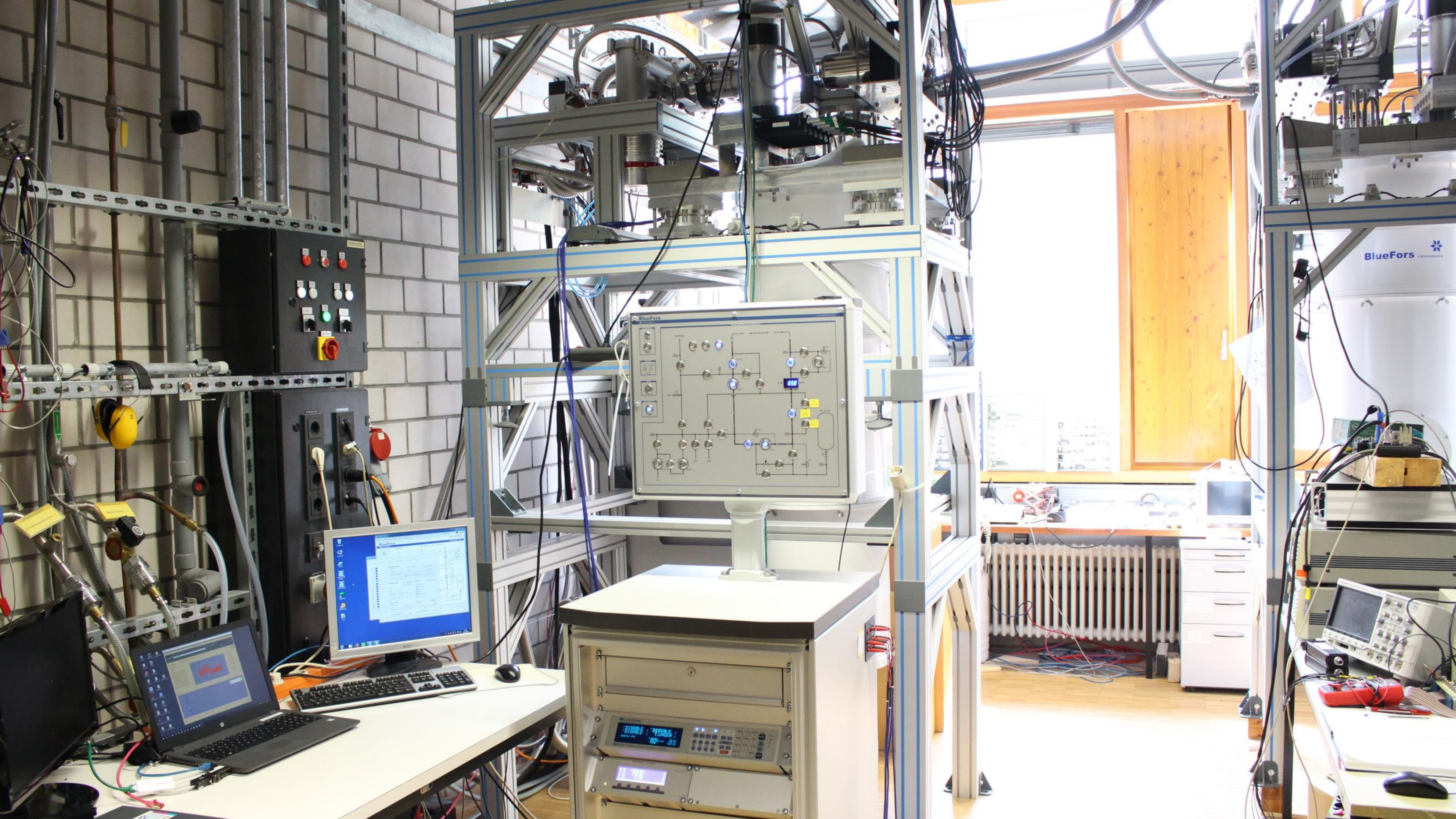

9 cm

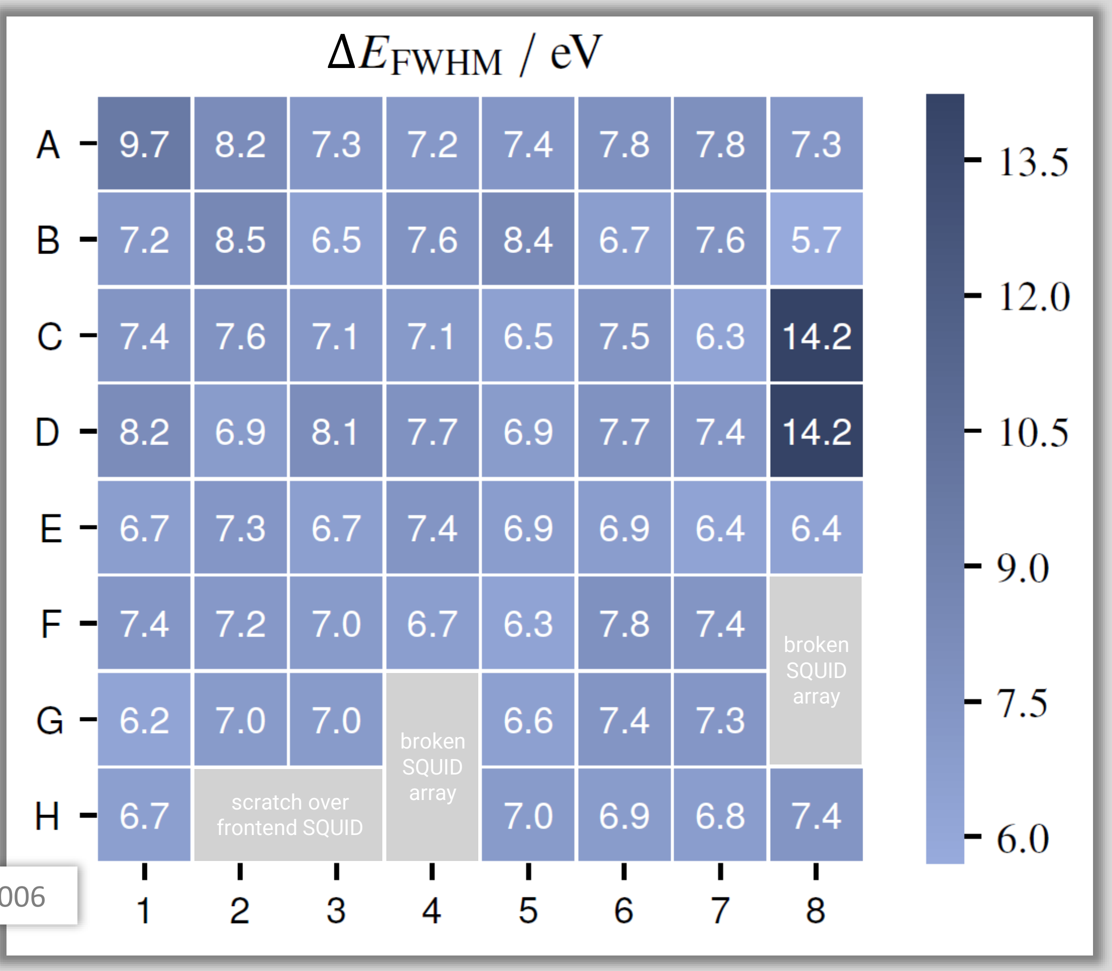

BlueFors CRYOGENICS
BlueFors

Detector Performance

- Operated at 15 mK in a dilution refrigerator
- Average energy resolution:

$$\Delta E_{\mathrm{FWHM}} = 7.2\ \mathrm{eV}\ \text{ at } 5.9\ \mathrm{keV}$$

- 31 out of 32 operational channels
- Threshold below 100 eV
- Nonlinearity of 0.1 % at 5.9 keV



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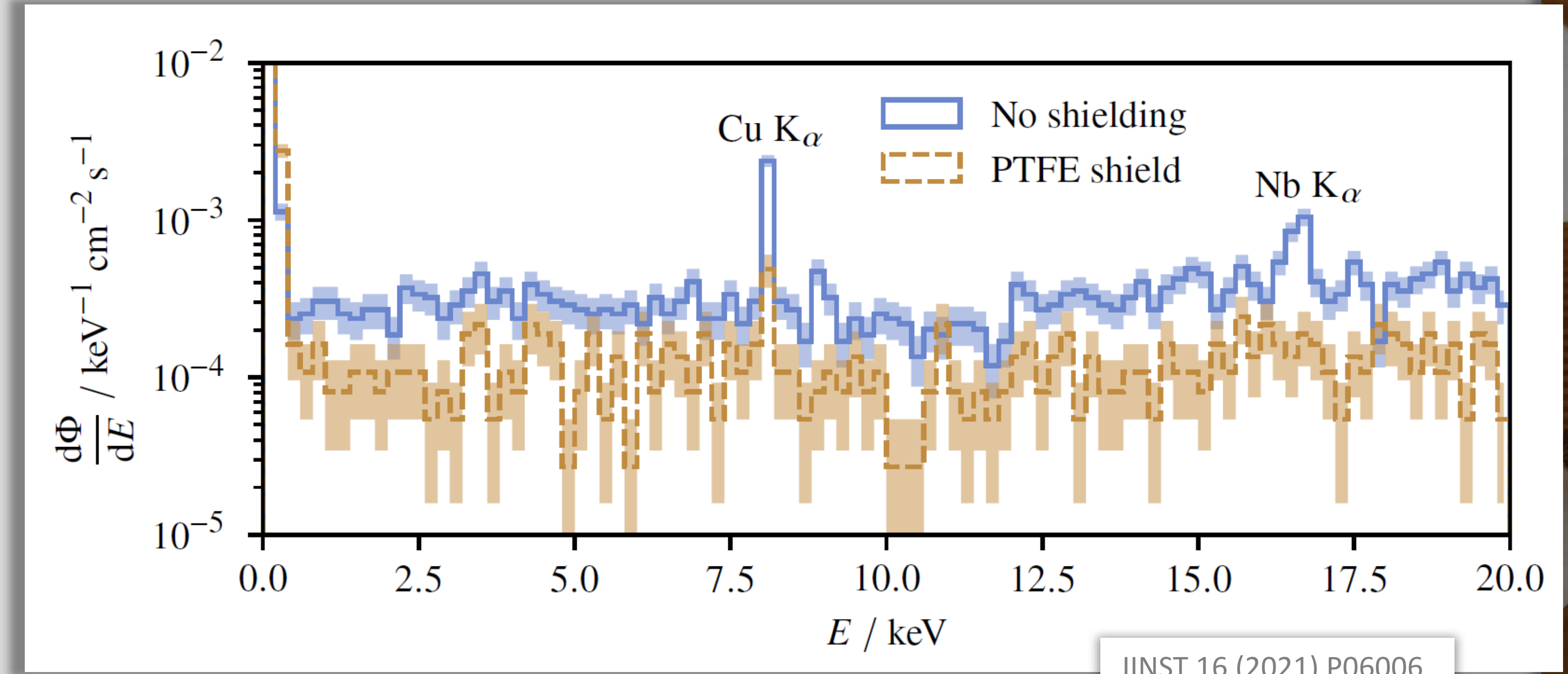
Background Measurements



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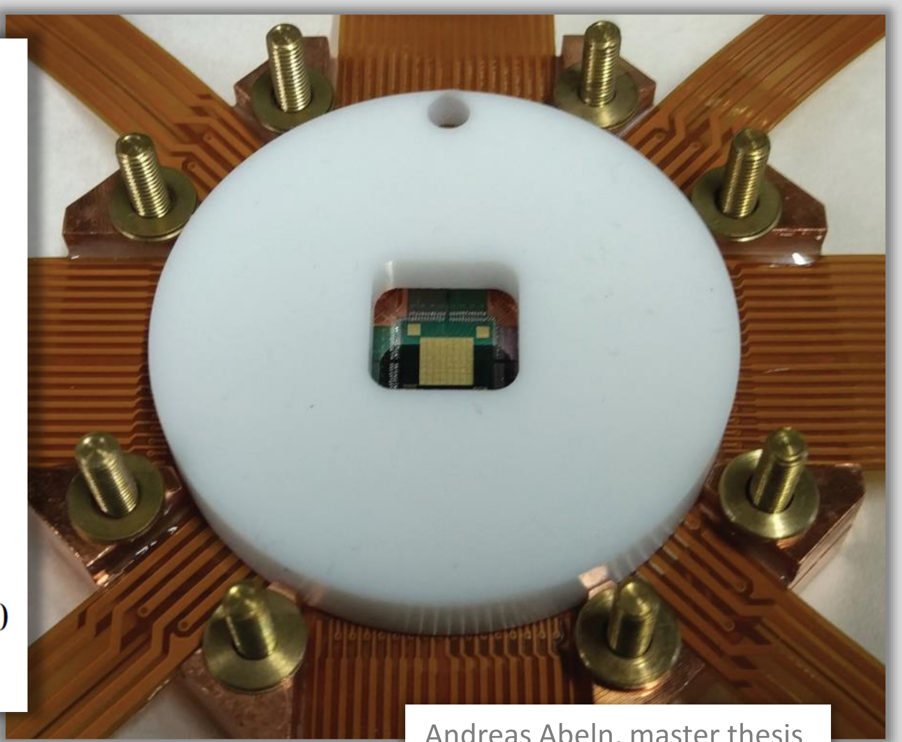


Andreas Abeln, master thesis

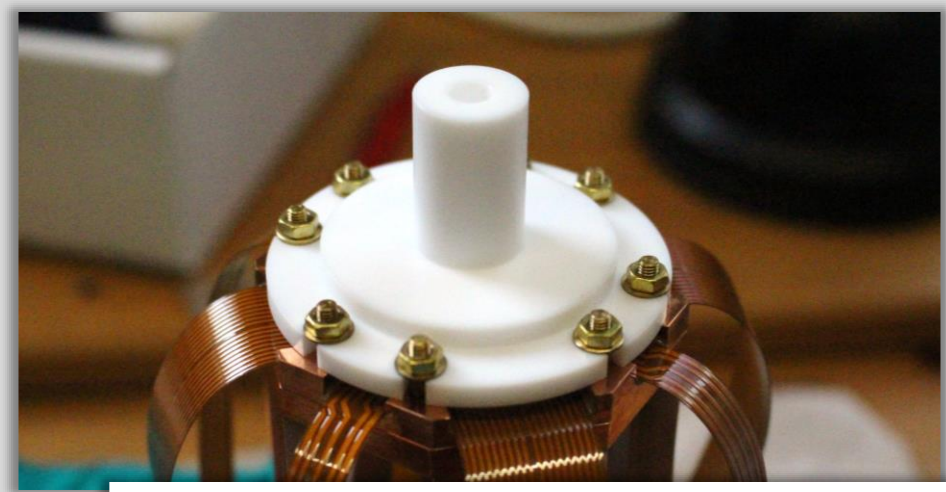
- Background reduction with a preliminary PTFE shield, covering a small solid angle
- Fluorescence lines damped with shield

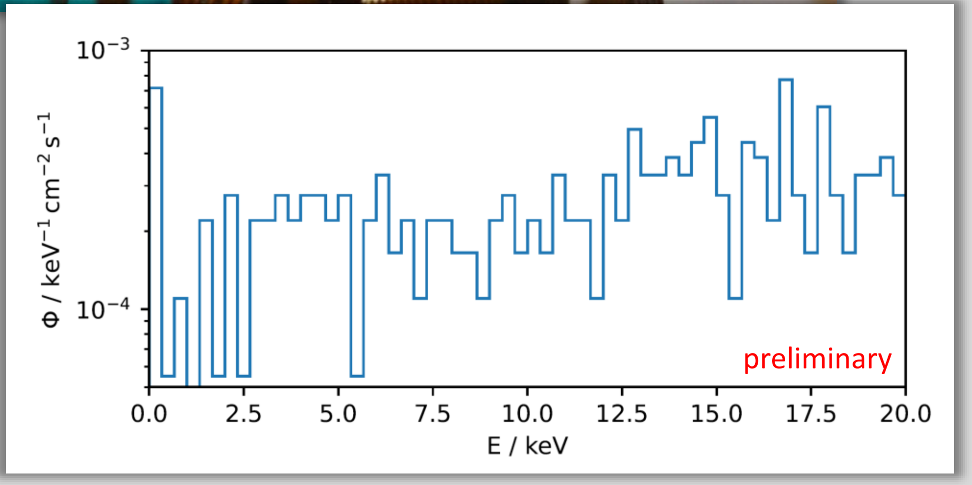
Optimized PTFE Shield

- Enhanced screening factor
- 10 mm PTFE shield, many times the attenuation length of 0.7 mm at 10 keV
- Chimney opening of 5° for calibration

Result after two weeks of measurement:

- No further background reduction
- White background possibly from muons





Background Reduction

- Background between 1 and 10 keV: roughly $2 \cdot 10^{-4}$ $\mathrm{keV^{-1}cm^{-2}s^{-1}}$
- Maintaining high efficiency: only 1 % of calibration events removed with applied cuts

Background Reduction:

- Additional cuts need to be investigated
- Active muon veto required
- Multiple passive shields
- Geant4 simulations to study background

Expected Muon Background

Rate of muons at sea level:

- $10{,}000\ \mathrm{m^{-2}min^{-1}} = 0.017\ \mathrm{cm^{-2}s^{-1}}$

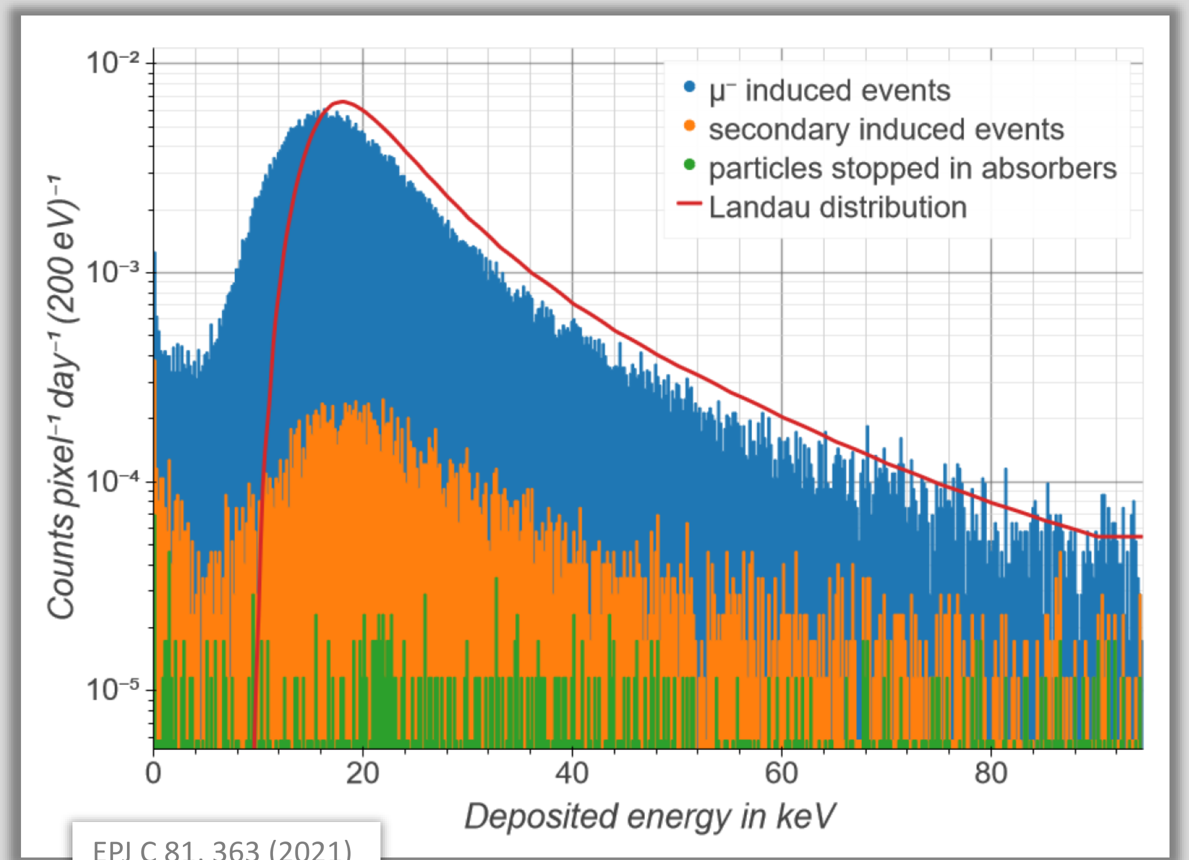
ECHo background from simulations:

- Muon induced white background:

  $0.7 \cdot 10^{-4}\ \mathrm{keV^{-1}cm^{-2}s^{-1}}$

- Natural occurring radionuclides:

  $0.2 \cdot 10^{-4}\ \mathrm{keV^{-1}cm^{-2}s^{-1}}$



EPJ C 81, 363 (2021)

Muon Veto: Requirements

- Close to detector: **cryogenic muon veto**
- Inner passive shielding: **wafer size active area**, vetoed volume around detector
- Presumably muon dominated background: **very high efficiency**, above $99.5\ \%$
- 4π coverage: **replicable fabrication** of multiple detectors
- Looking for coincidences: **sufficient time resolution**
- Inside a helioscope: reliable **long-term operation** while moving

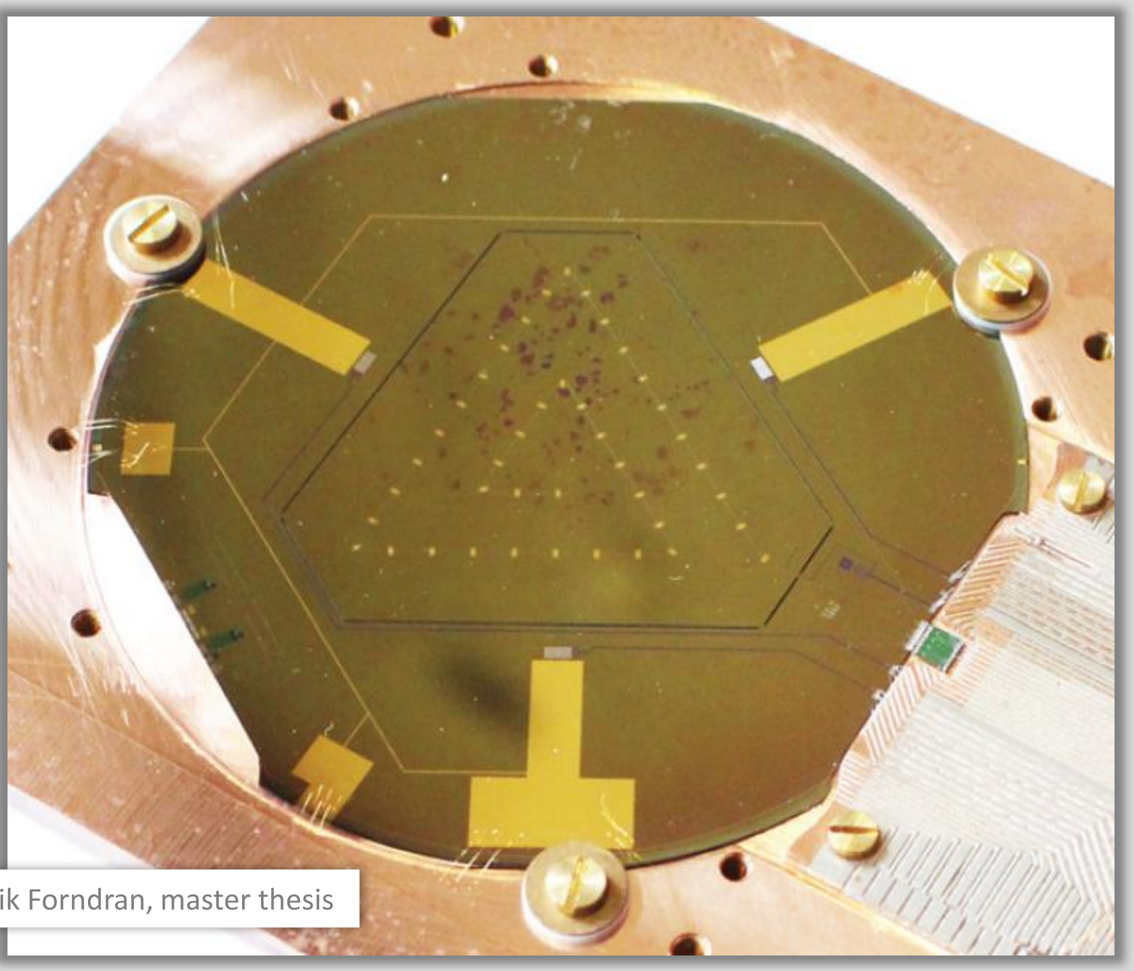
Can be used in coincidence with a room temperature muon veto around the cryostat

P2: Photon-Phonon Detector

- Developed for the AMoRE experiment
- Designed to seach for $0\nu\beta\beta$ in ^{100}Mo
- Measures heat and emitted light upon particle interaction in a scintillating crystal

Features a large photon detector:

- Silicon absorber with 12 cm^2
- 41 distributed sensors over the absorber



Freerik Forndran, master thesis

P2 as a Muon Veto

- Mean energy loss in silicon for a minimum ionizing particle:

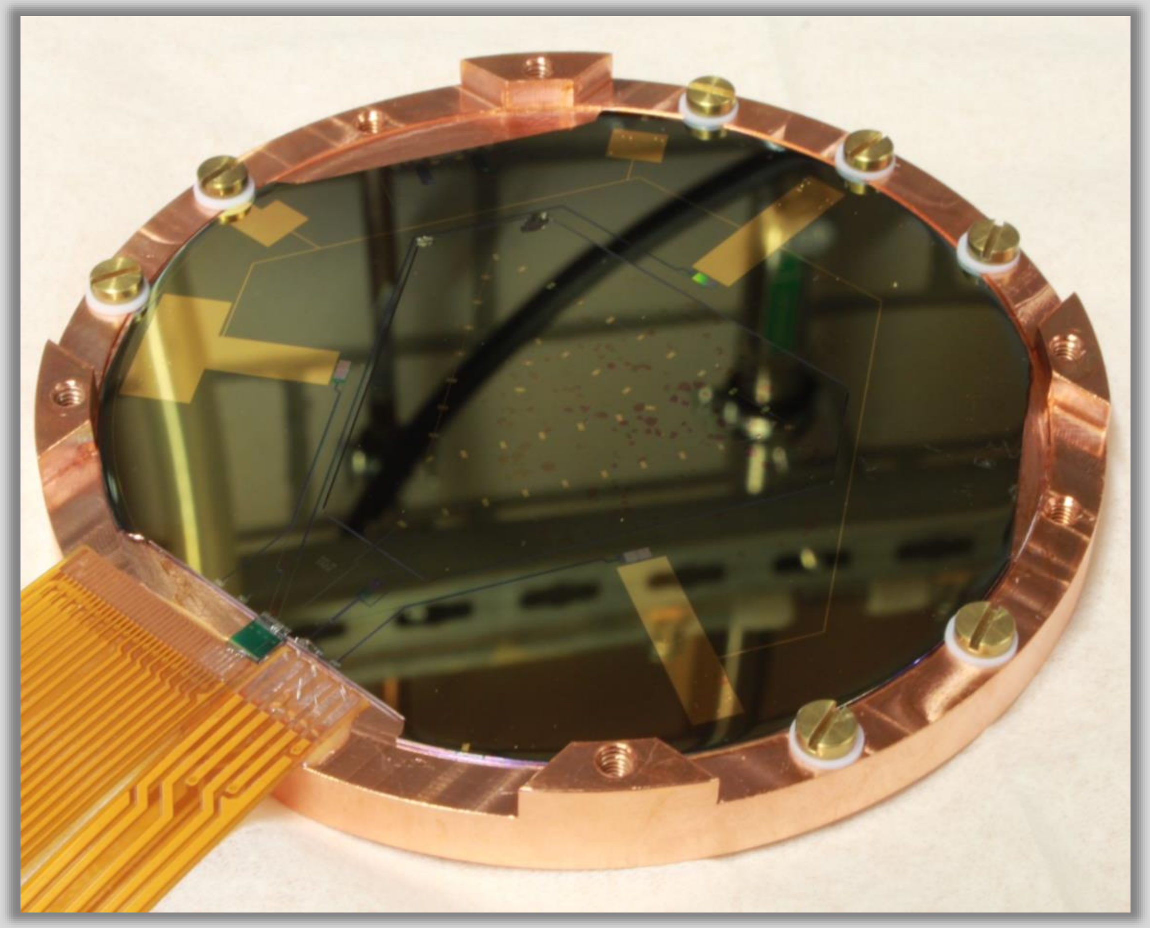
$$3.9\ \mathrm{MeV\ cm^{-1}}$$

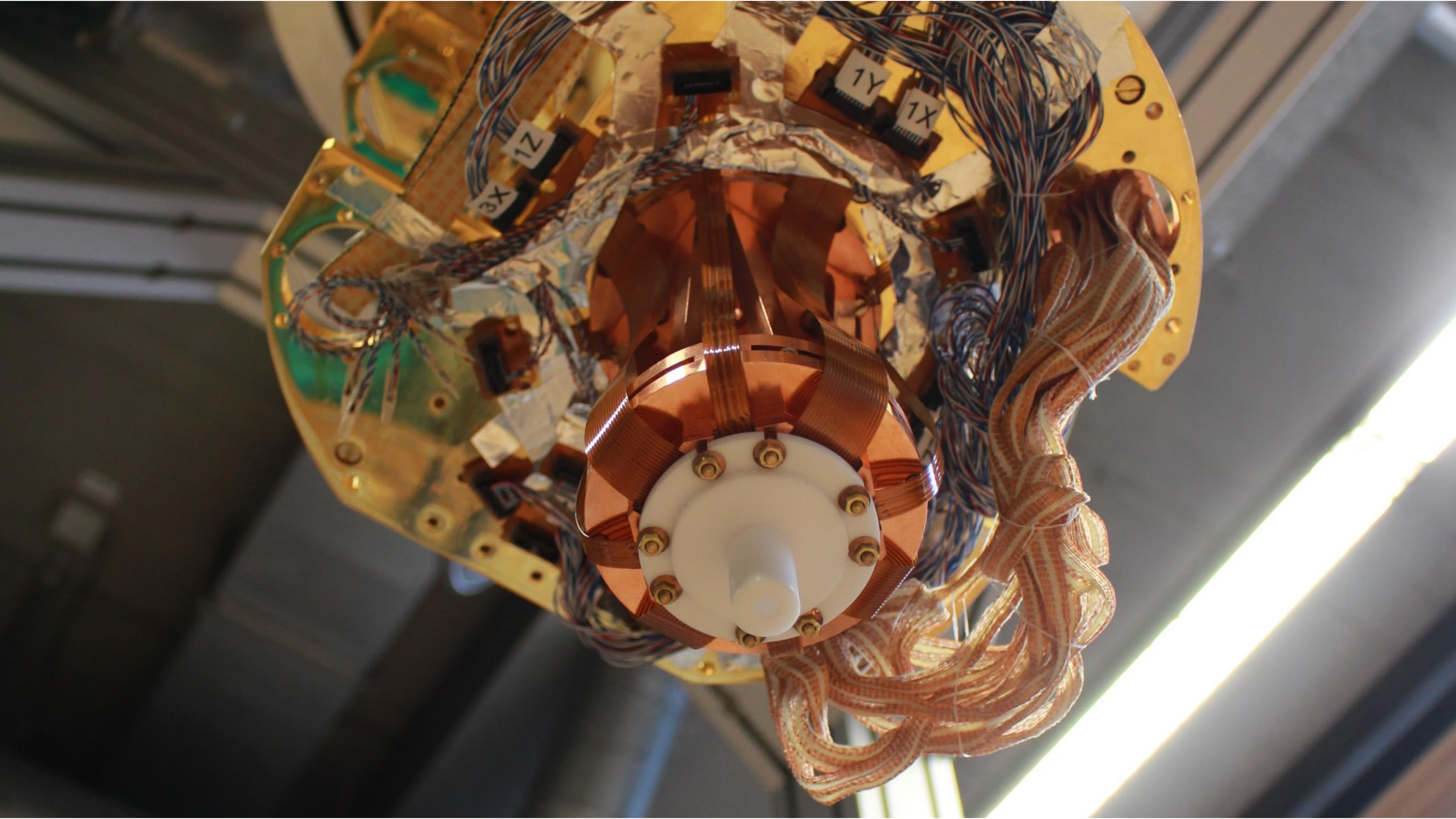
- For the $350\ \mu\mathrm{m}$ wafer (perpendicular trace):

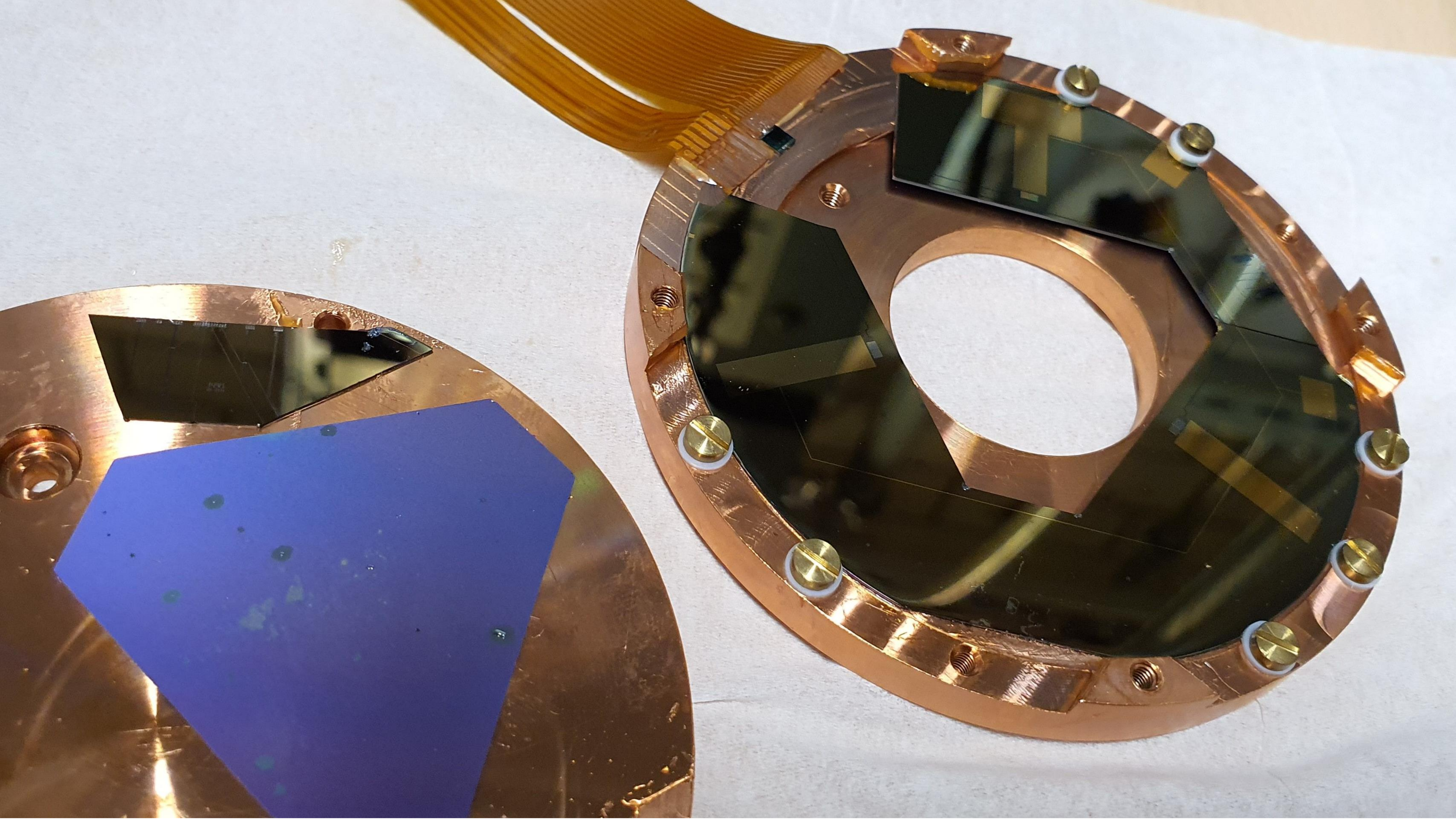
roughly $140\ \mathrm{keV}$

- Expected energy resolution: below $100\ \mathrm{eV}$

⇒ suitable preliminary muon veto




1Y
1X
1Z
3X



Muon Veto: Challenges

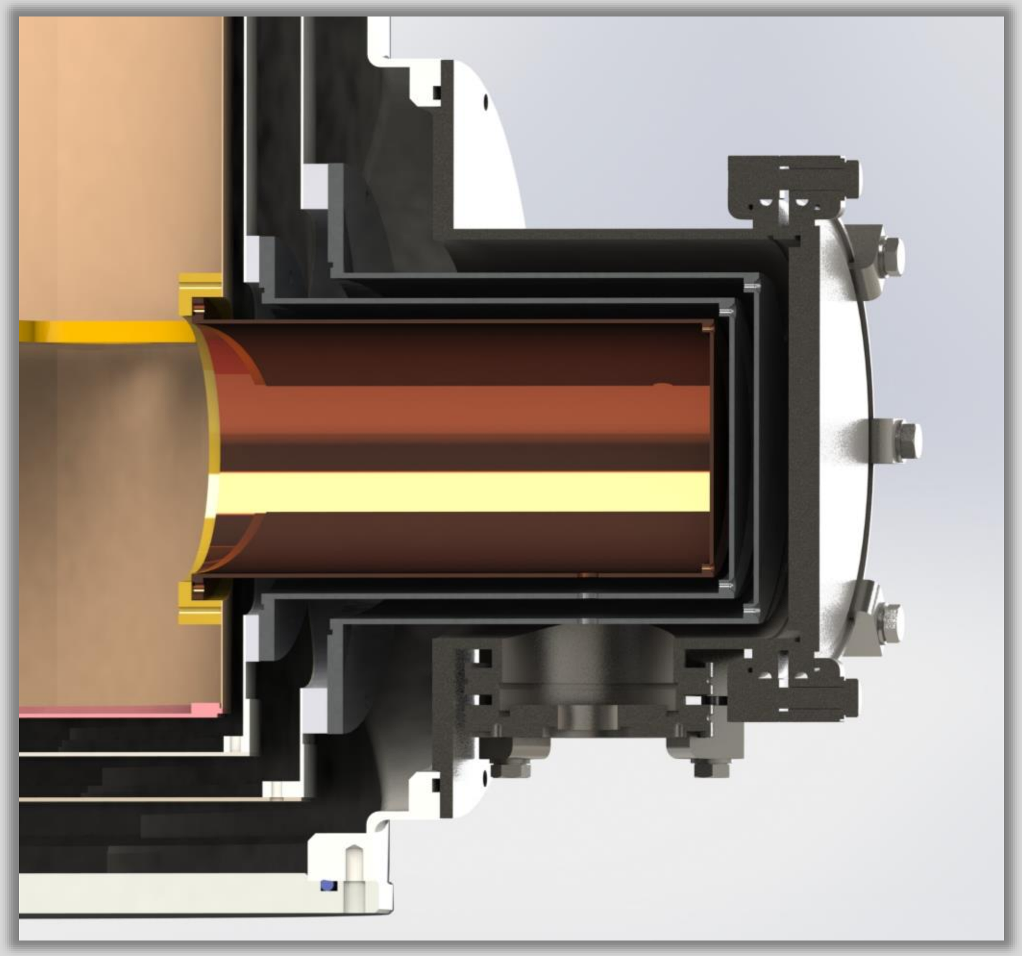
- Thermalisation:
  - Deposited energy propagates though silicon as ballistic phonons
  - Energy transfer from wafer to sensor limited by the Kapitza resistance
  - Distributed sensors and phonon collectors to improve energy transfer
  - Thermal link to the heat bath via silicon
- Fabrication:
  - Pickup coil needs to cover the wafer but the inductance should match to the SQUID
  - Structuring multiple stacked layers while maintaining a high critical current for superconductors
  - Etching to provide a thermally separated but sturdy active area

Cryostat Sidearm

- X-ray windows allow external calibrations
- Sidearm can be rotated from vertical to horizontal
- Allows connections to other vacuum systems

For the background analysis:

- Measuring with two muon veto systems: scintillating panels at room temperature and a cryogenic muon veto
- Comparing the background for a vertical and a horizontal mounted detector

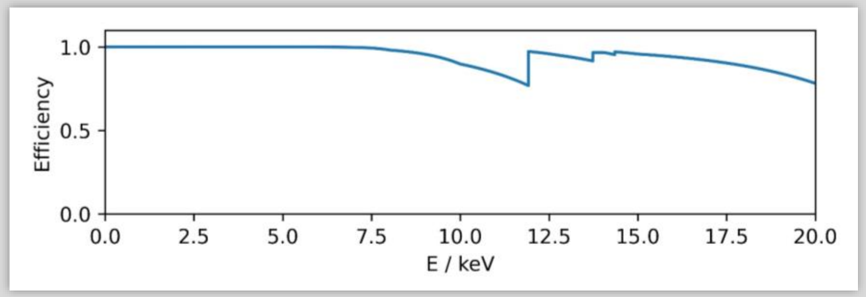


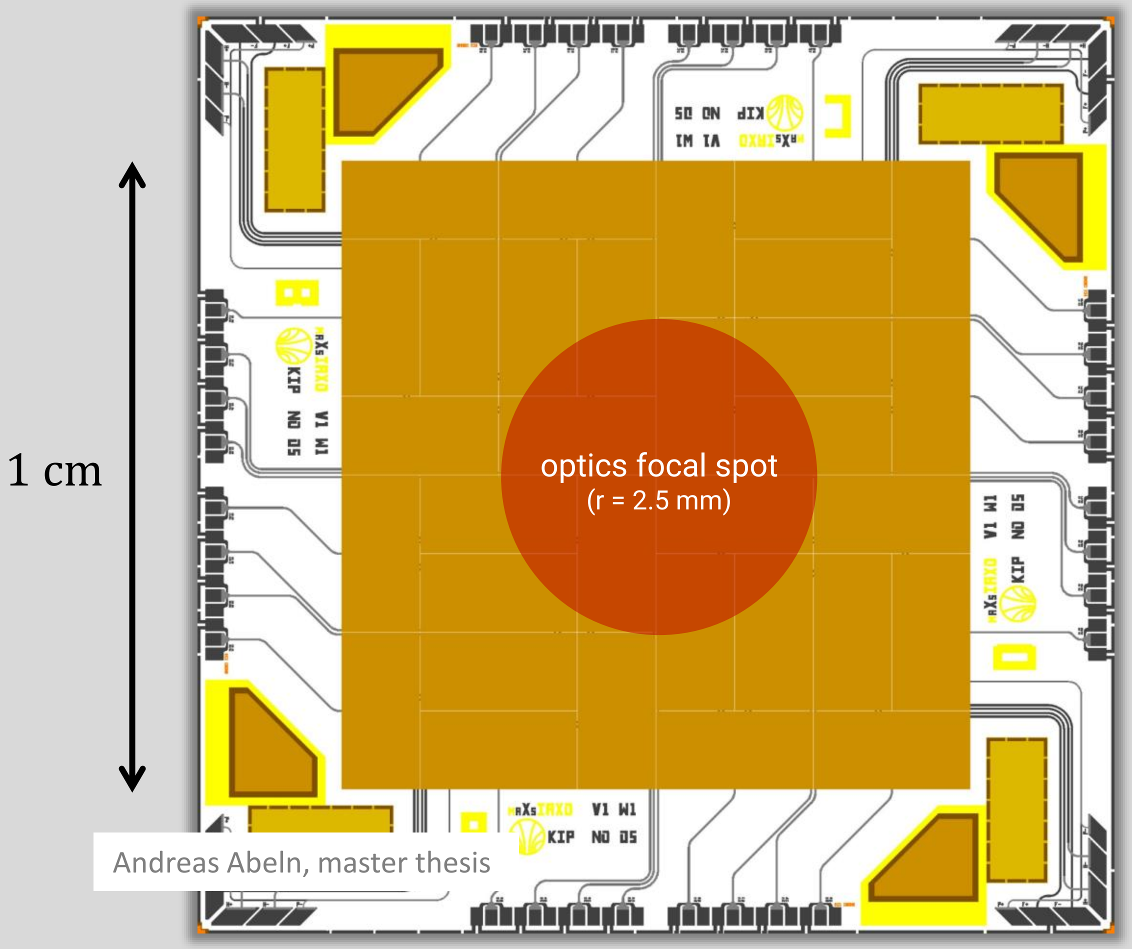
maXs-IAXO

- New detector with 64 pixels
- Large active area of 100 mm²
  - Larger than focal area of X-ray optics
  - In-situ background measurements
- Expected energy resolution:

$$\Delta E_{\mathrm{FWHM}} = 11\ \mathrm{eV}$$

- Efficiency optimized for IAXO:





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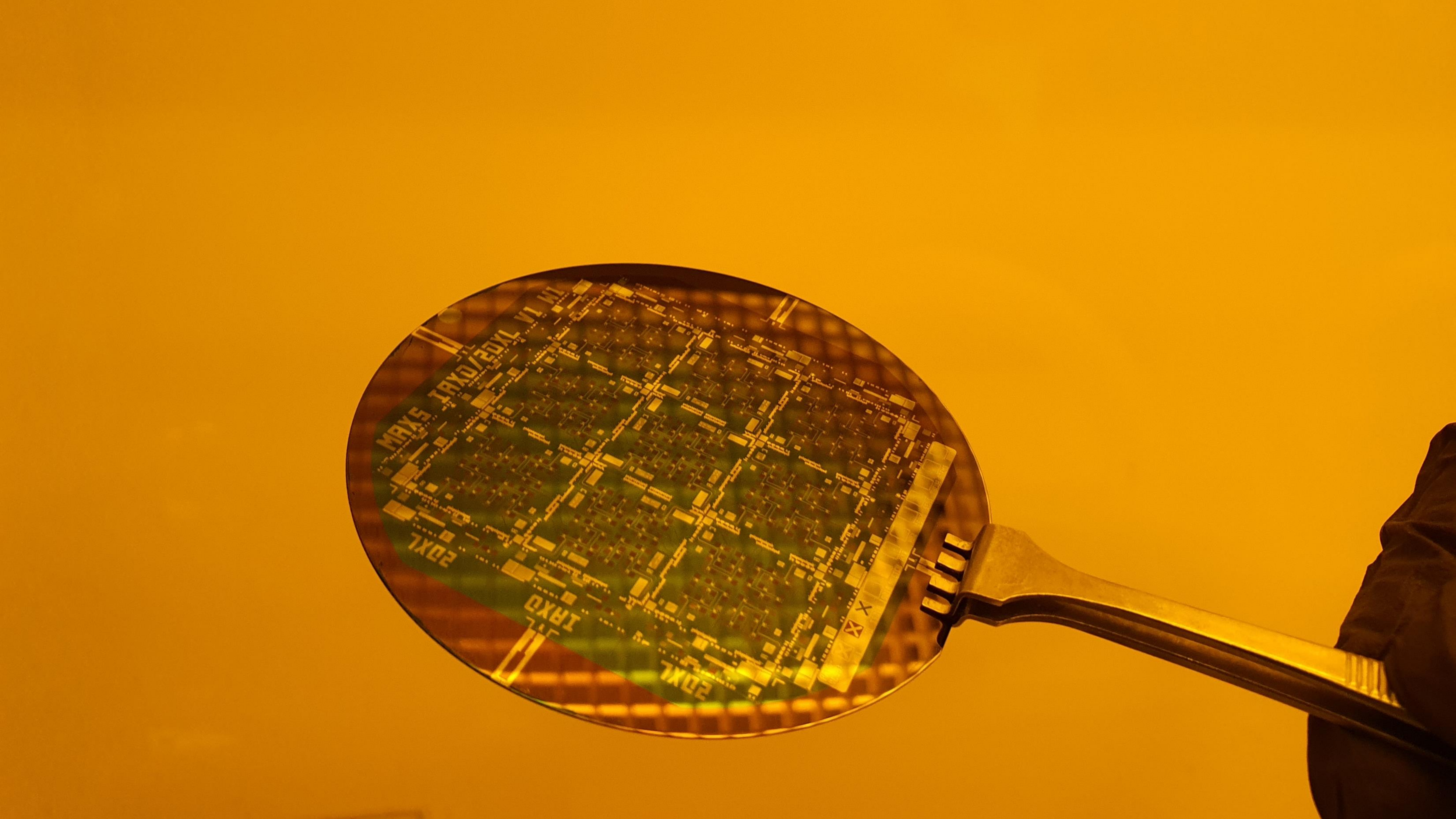
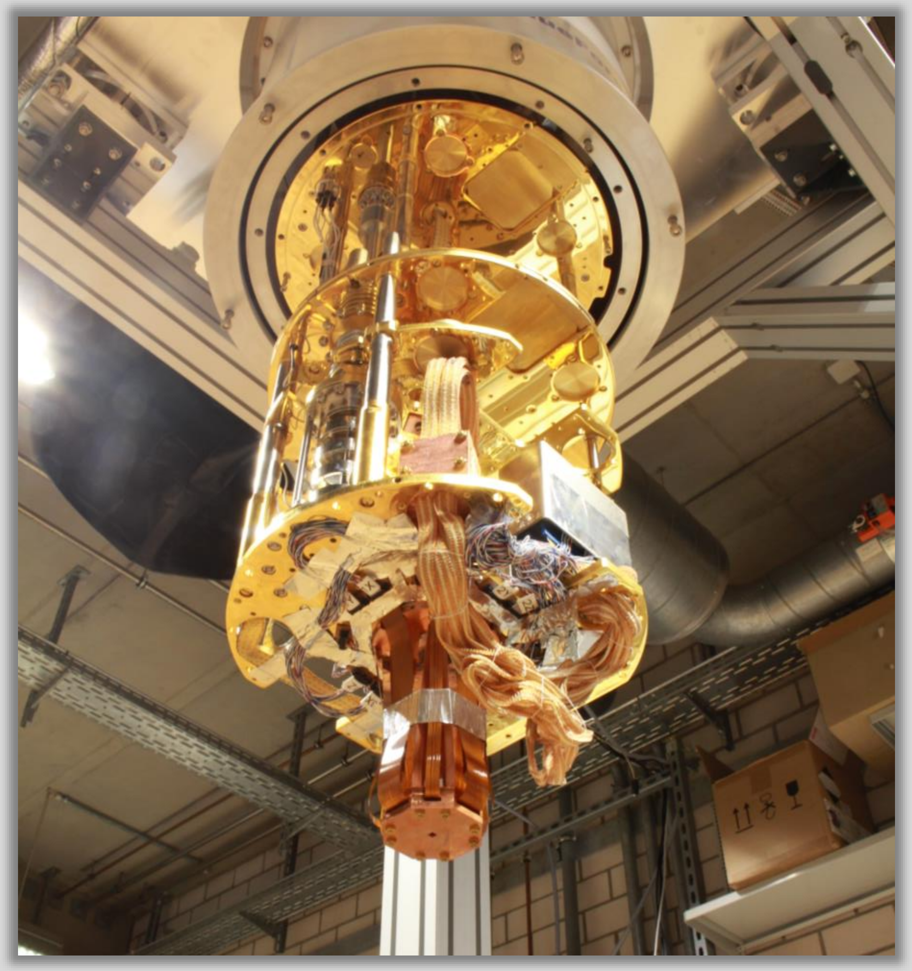

MAXS IAXO/2DXL V1 W1
2DXL
IAXO
2DXL

EBIT Preparation

- Current setup perfectly suitable for low-rate high-resolution EBIT measurements
- Preparations were finished, but breakdown of the EBIT
- Measurement with the repaired EBIT is planned for this winter



Outlook

- Novel cryogenic muon veto based on MMCs will be developed
- Background measurements with two muon veto systems and two detector orientations
- Further background reduction with passive shields later
- EBIT measurement as the first application of the setup prepared for IAXO