High energy resolution x-ray detectors for IAXO: advantages in pre- and post-discovery phases

Loredana Gastaldo

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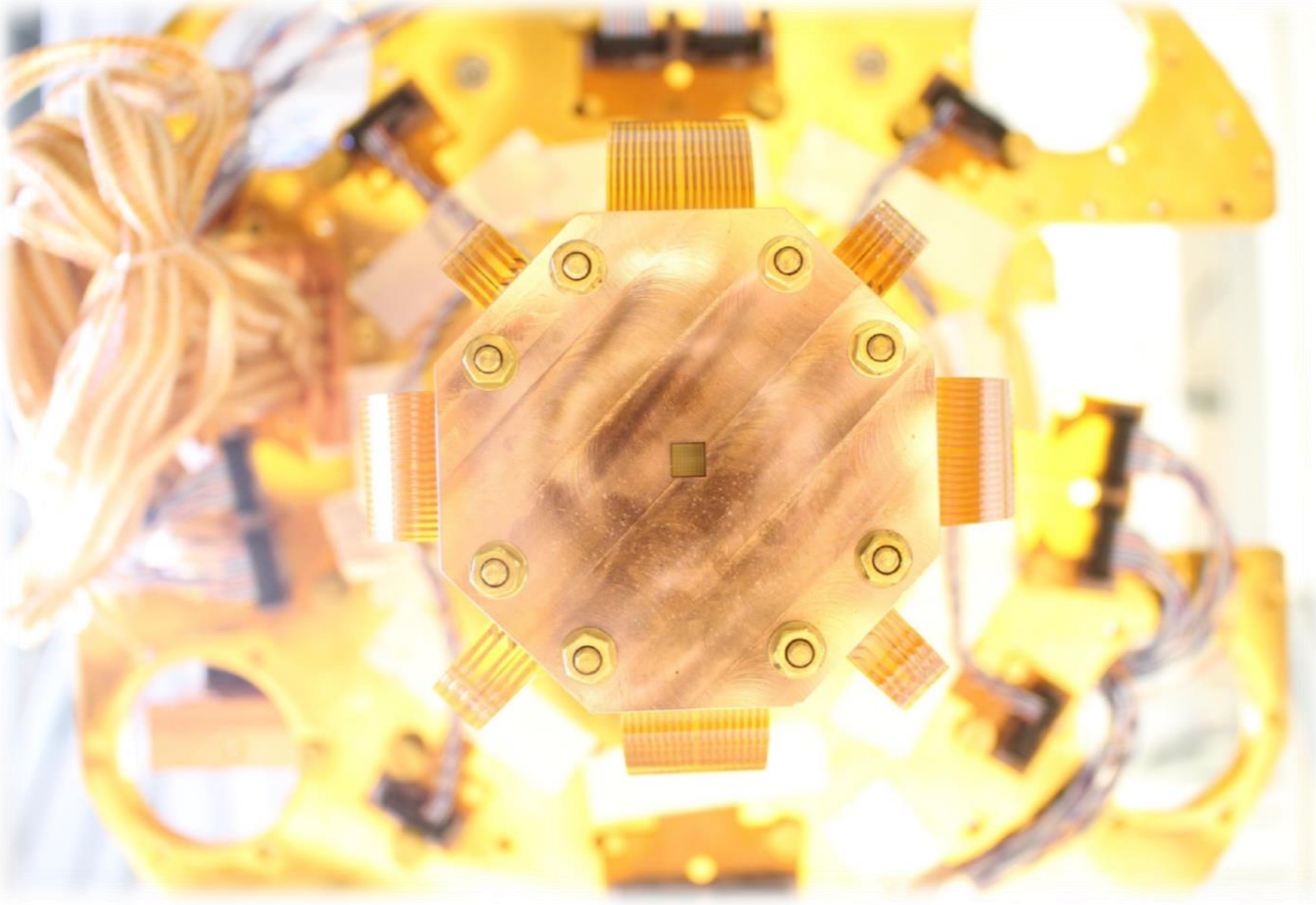
Heidelberg University



UNIVERSITÄT
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Outline

- Helioscope

    Overview

    IAXO

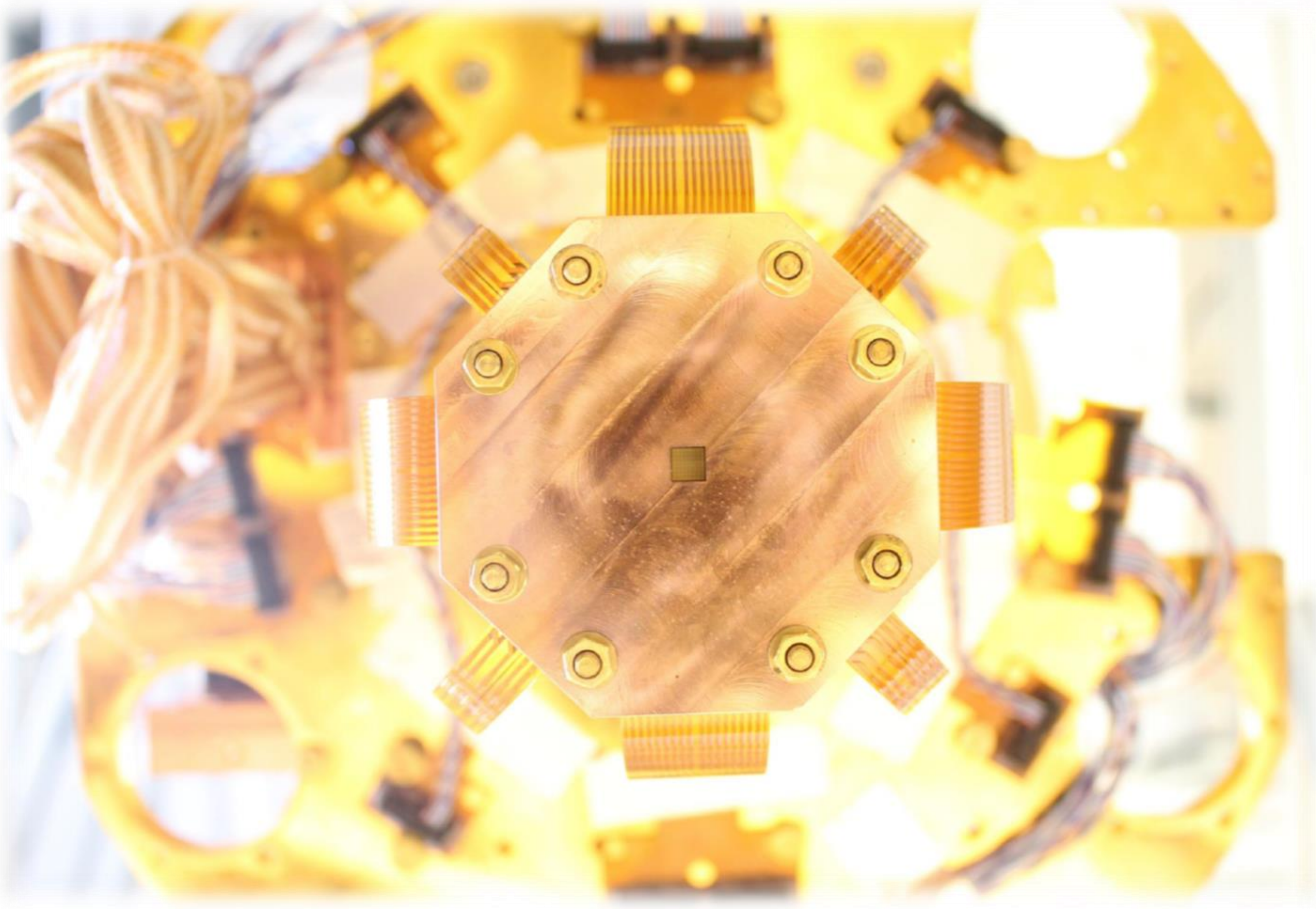
    Post detection

- Metallic magnetic calorimeter for IAXO

    Basic concepts

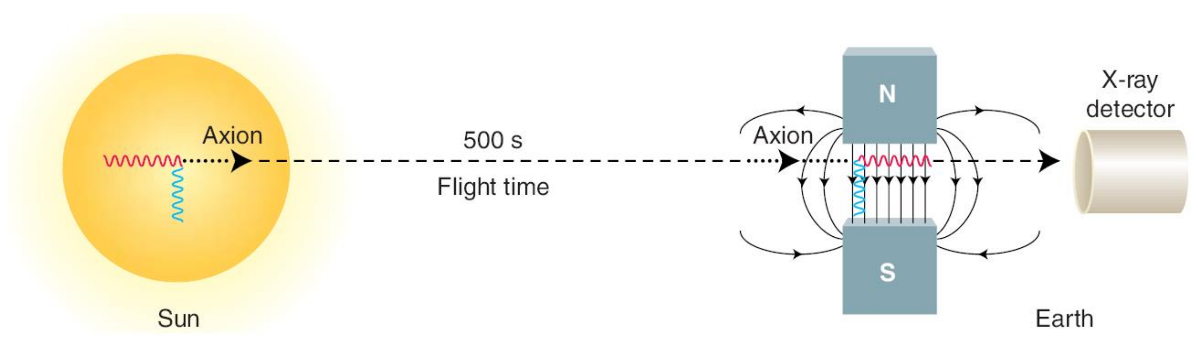
    First results

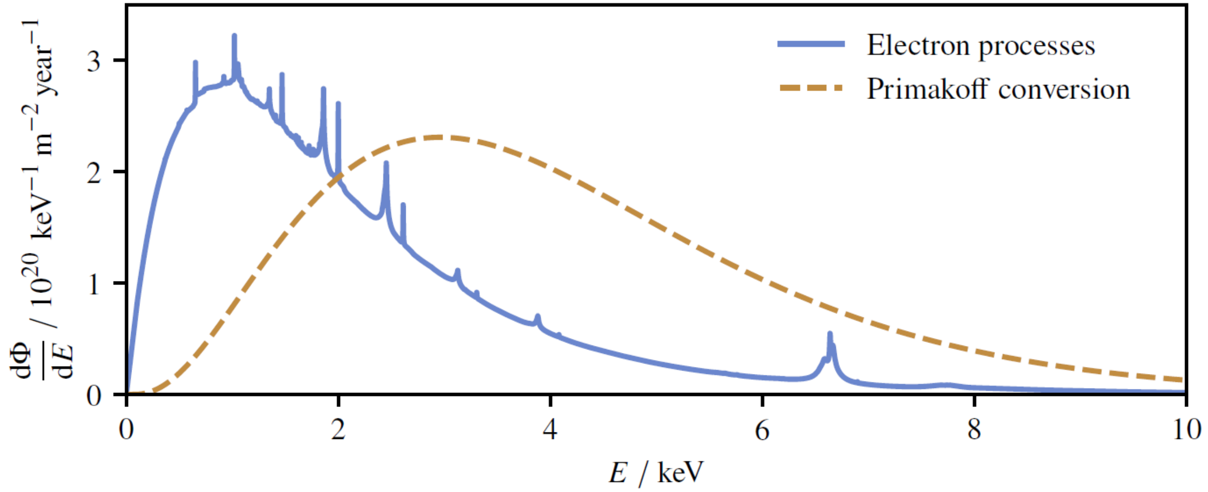
- Conclusions



Solar Axions in Helioscope

Search for an evidence for solar axions





$$g_{a\gamma}^4 \propto \underbrace{b^{1/2}\epsilon^{-1}}_{\text{detectors}} \times \underbrace{a^{1/2}\epsilon_o^{-1}}_{\text{optics}} \times \underbrace{(BL)^{-2}A^{-1}}_{\text{magnet}} \times \underbrace{t^{-1/2}}_{\text{exposure}}$$

Low background and high efficiency x-ray detectors

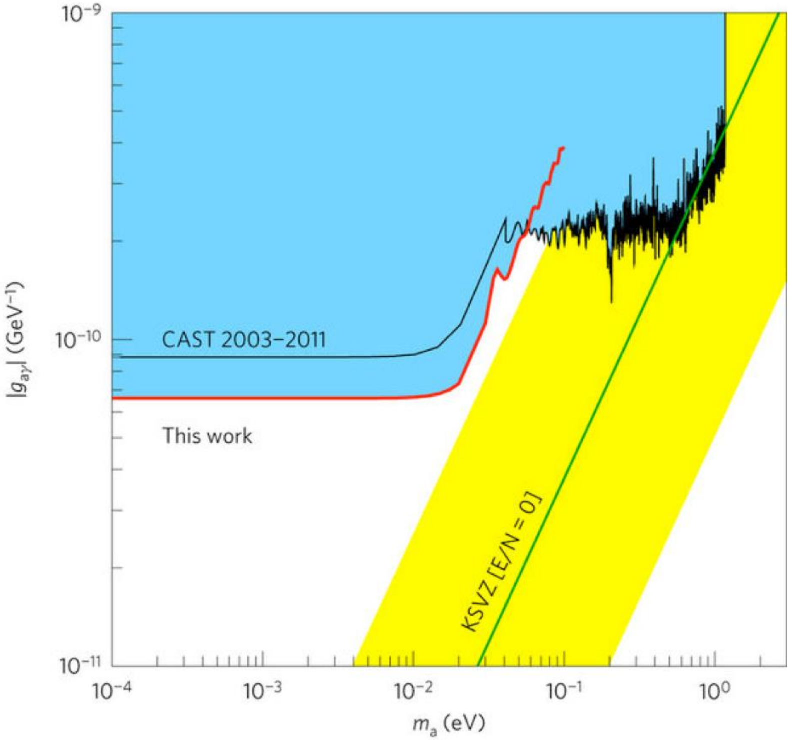
E. Armengaud et al., JCAP 06 (2019) 047

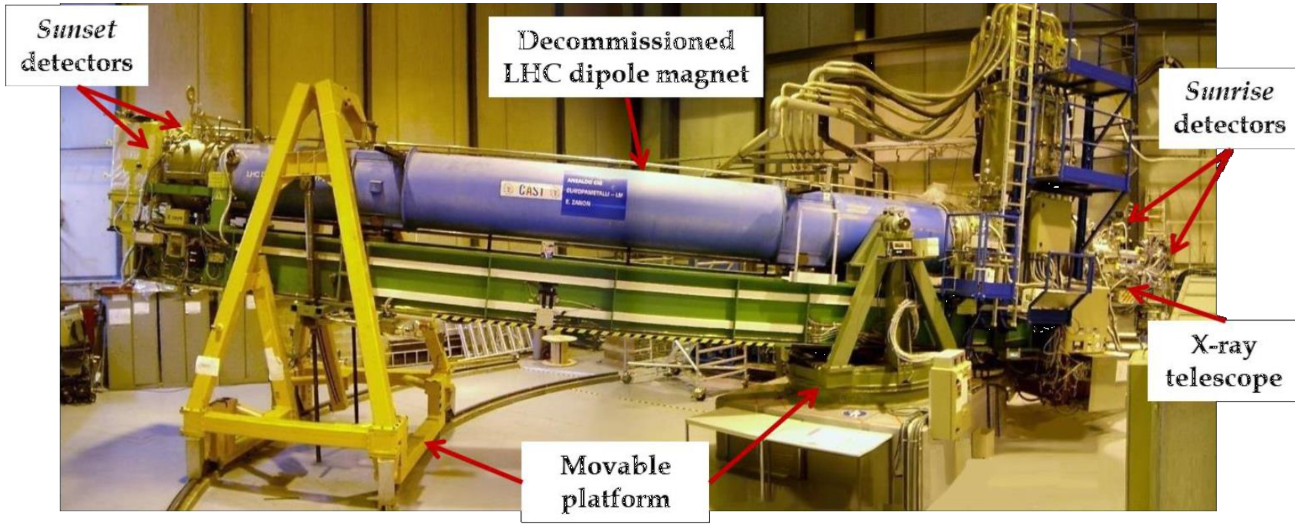
CAST

3rd generation: CERN Axion Solar Telescope (CAST)

- Most sensitive axion helioscope to date (10m, 9T)
- Best experimental limit on axion-photon coupling over broad axion mass range

$$g_{a\gamma} < 0.66 \times 10^{-10}\ \mathrm{GeV}^{-1}\ (95\%\ \mathrm{C.L.})$$





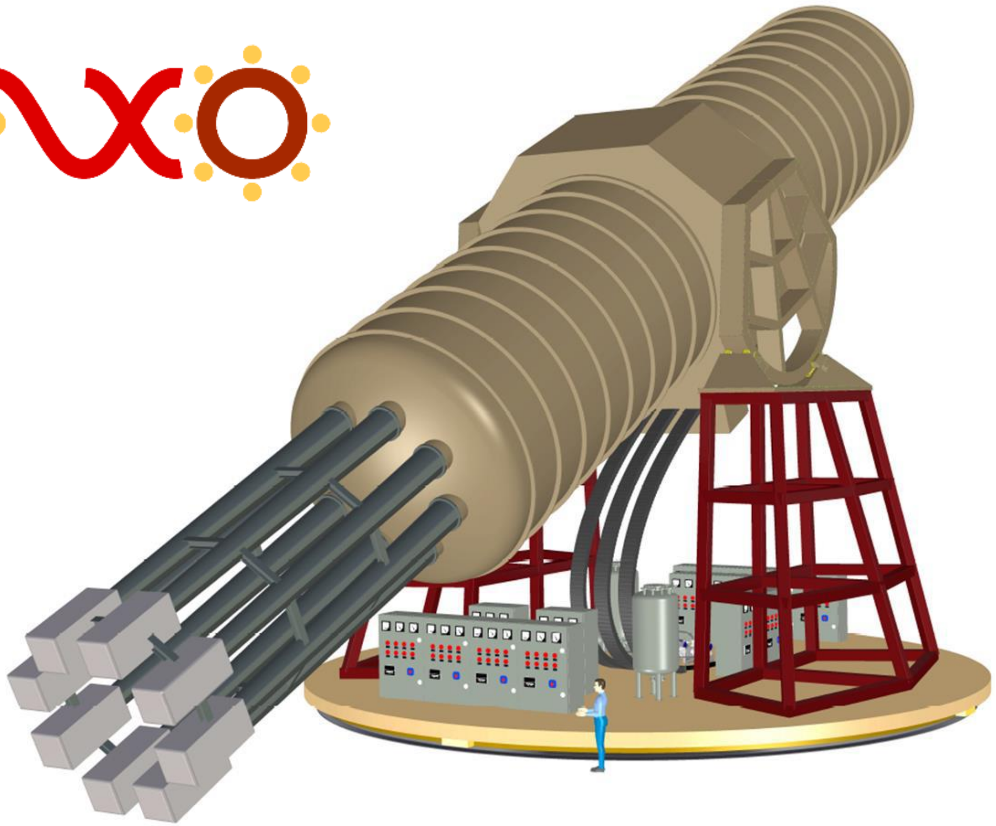
More tomorrow by Serkant Cetin's talk "CAST and more than CAST; A Dark Sector Probe for 20+ Years"

CAST Collaboration *Nature Phys.* 13 (2017) 584

IAXO

IAXO-The International Axion Observatory

IAXO aims to improve CAST sensitivity to solar axions in 1 order of magnitude!



IAXO LoI CERN-SPSC-2013-022

Super toroidal magnet

- 20 meters long
- Magnetic field up to 5.4 T
- 8 bores of 60 cm Ø

Dedicated X-ray optics

- 0.2 cm^2 focal spot

Tracking system

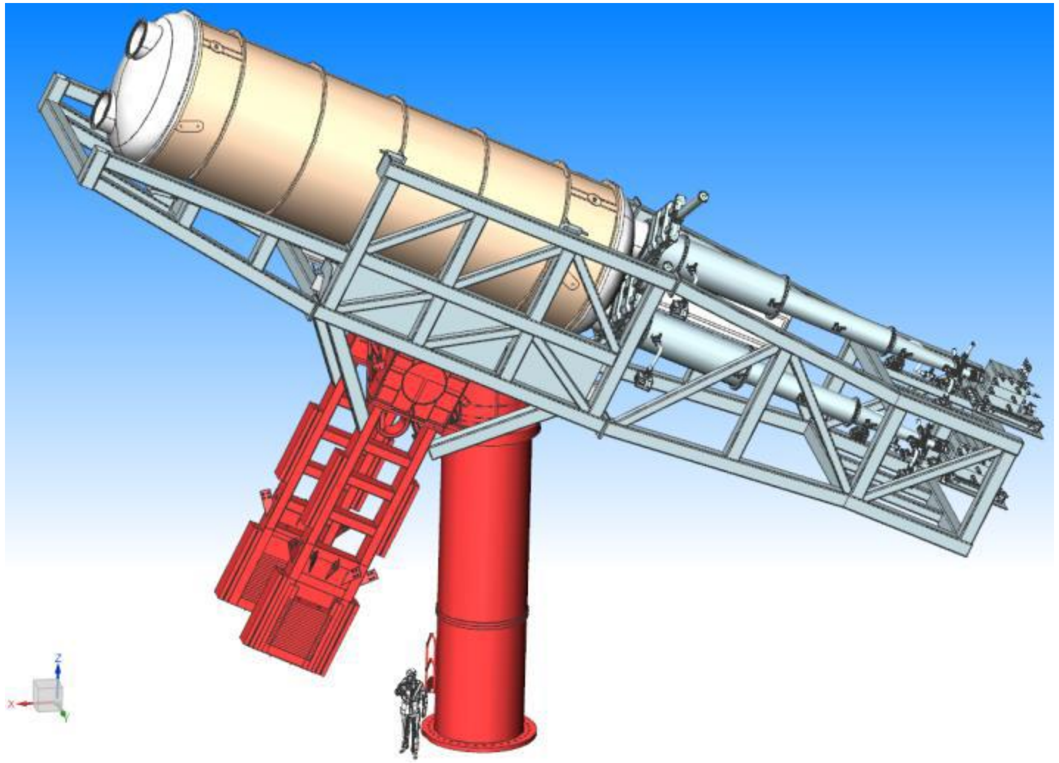
- Based on gamma ray telescopes
- 50% of Sun-tracking time

X-ray detector technologies

- Micromegas
- GridPix
- Metallic Magnetic Calorimeters (MMC)
- Transition Edge Sensors (TES)
- Silicon Drift Detectors (SDD)

Baby-IAXO

Baby-IAXO is currently under construction at DESY!



Conceptual Design Report
10.1007/JHEP05(2021)137

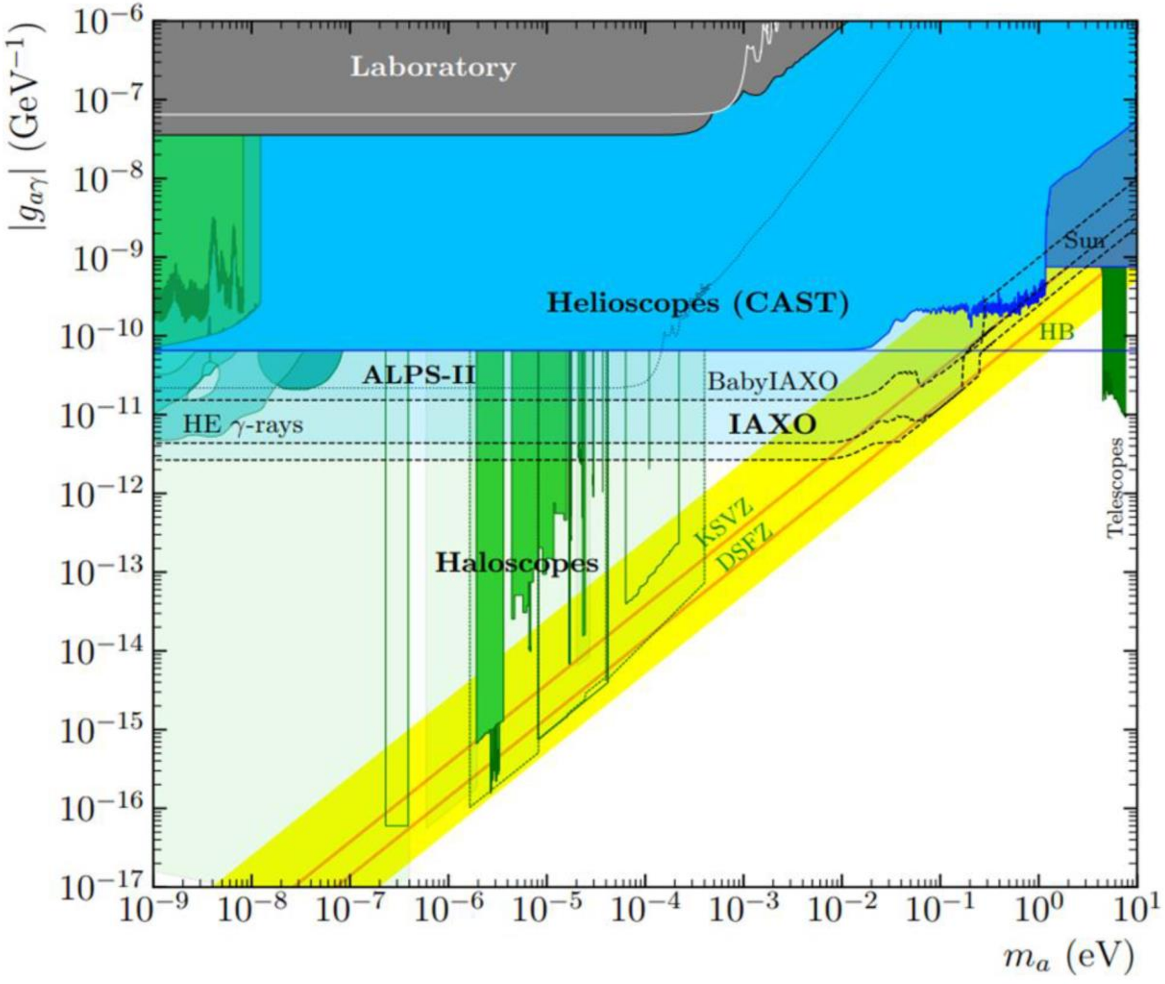
Dipole magnet
- 10 meters long
- Magnetic field ~2 T
- 2 bores of 70 cm Ø

Dedicated X-ray optics
- 0.2 cm² focal spot

Tracking system
- Based on gamma ray telescopes

X-ray detector technologies
- Micromegas (baseline)

IAXO & baby-IAXO: Sensitivity Perspectives



BabyIAXO will be sensitive to realistic QCD axion models!

IAXO will improve CAST sensitivity in more than a factor 10

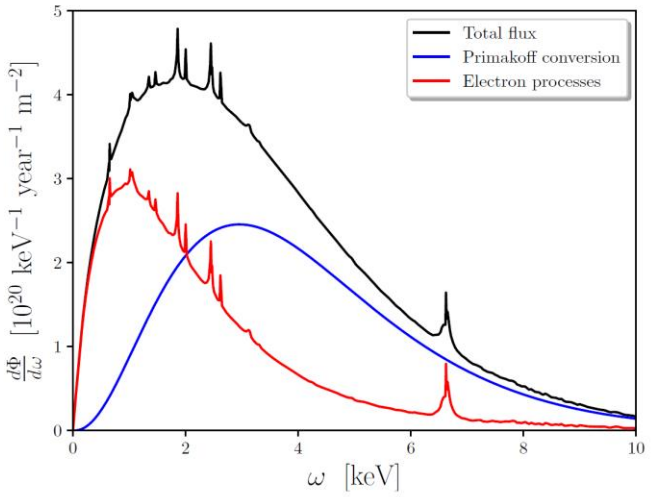
Further physics potential of (Baby)IAXO:

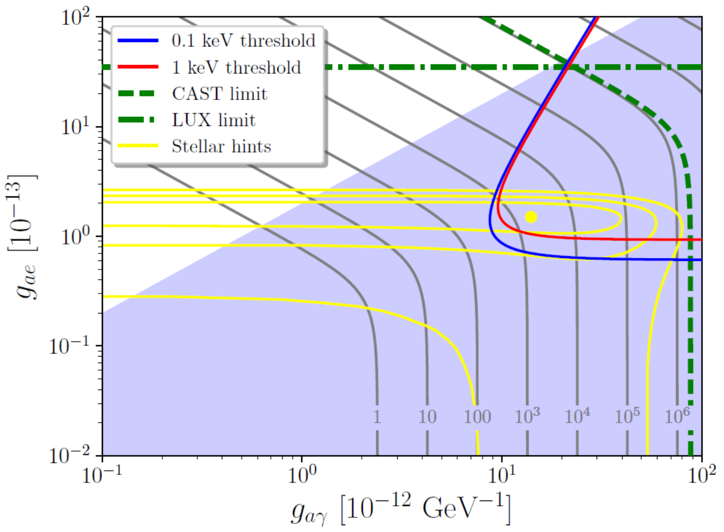
- Axion-electron coupling
- Interesting ALPs parameter space
- Cold Dark Matter axions using the haloscope technique

Post-discovery investigation

Distinguishing Axion Models with IAXO

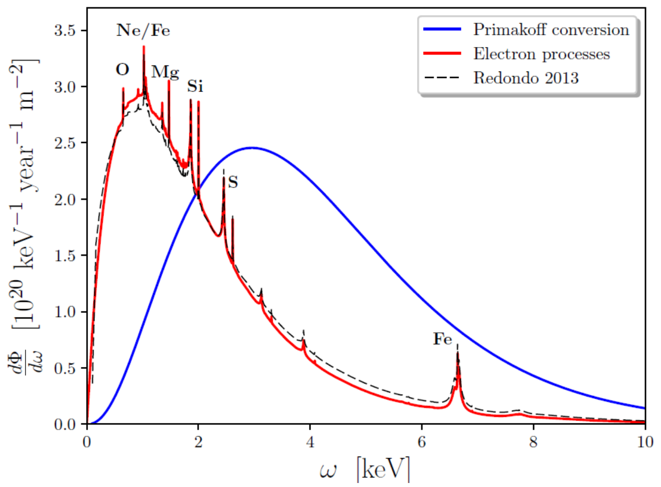
J. Jaeckel and L. J. Thormaehlen,
JCAP 03 (2019) 039

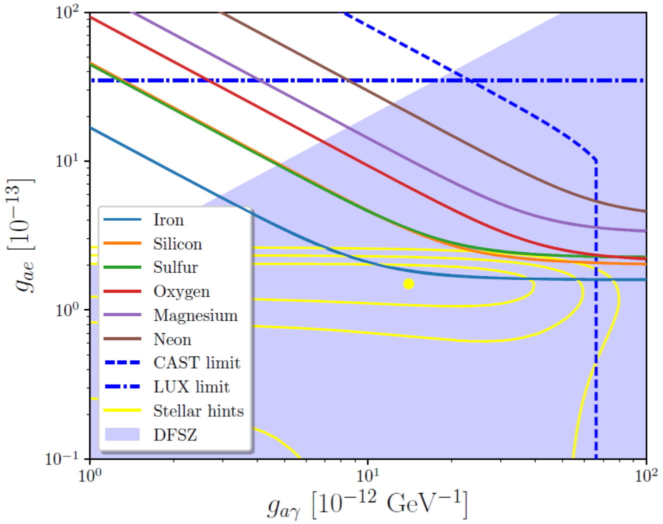




Solar metallicity

J. Jaeckel and L. J. Thormaehlen,
Phys. Rev. D 100, 123020 (2019)

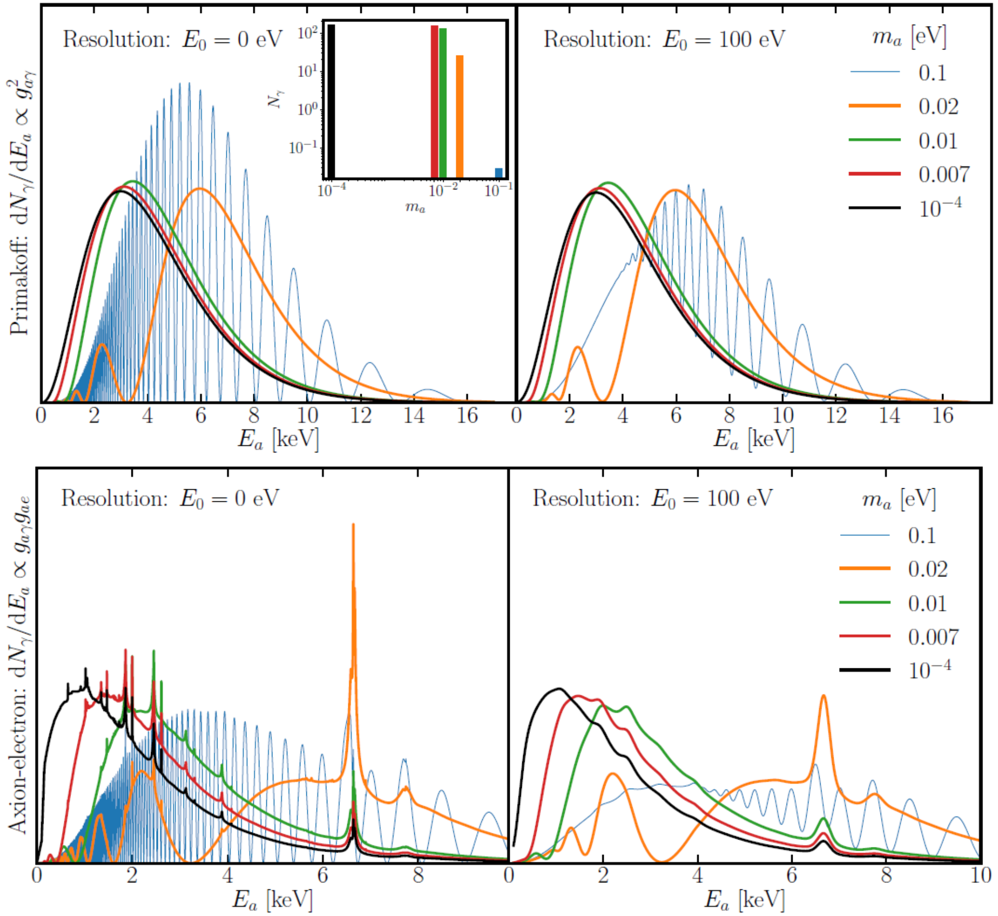




Post-discovery investigation

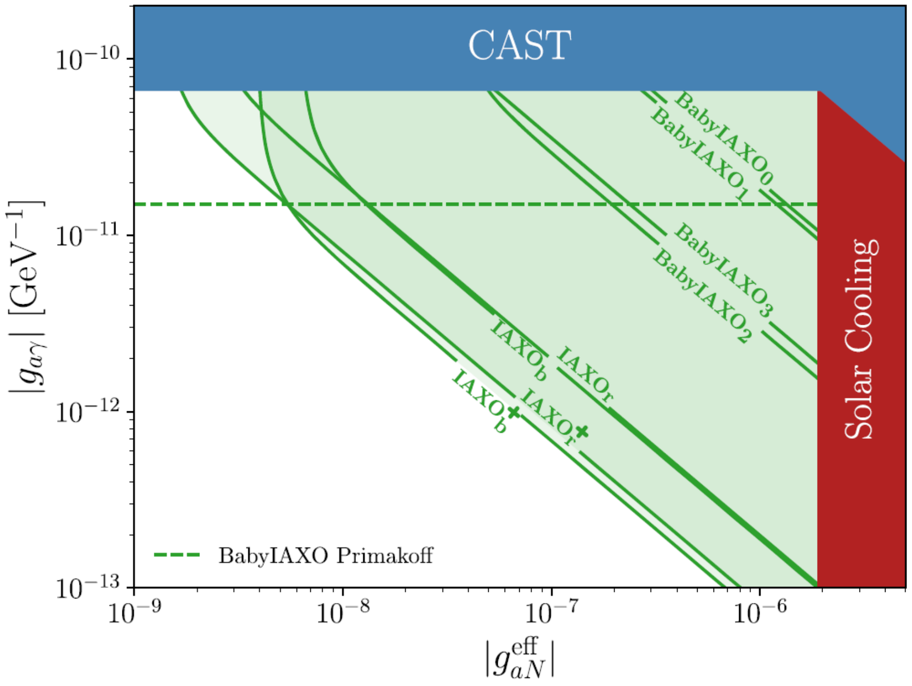
Weighing the Solar Axion

T. Dafni et al., Phys. Rev. D 99, 035037 (2019)

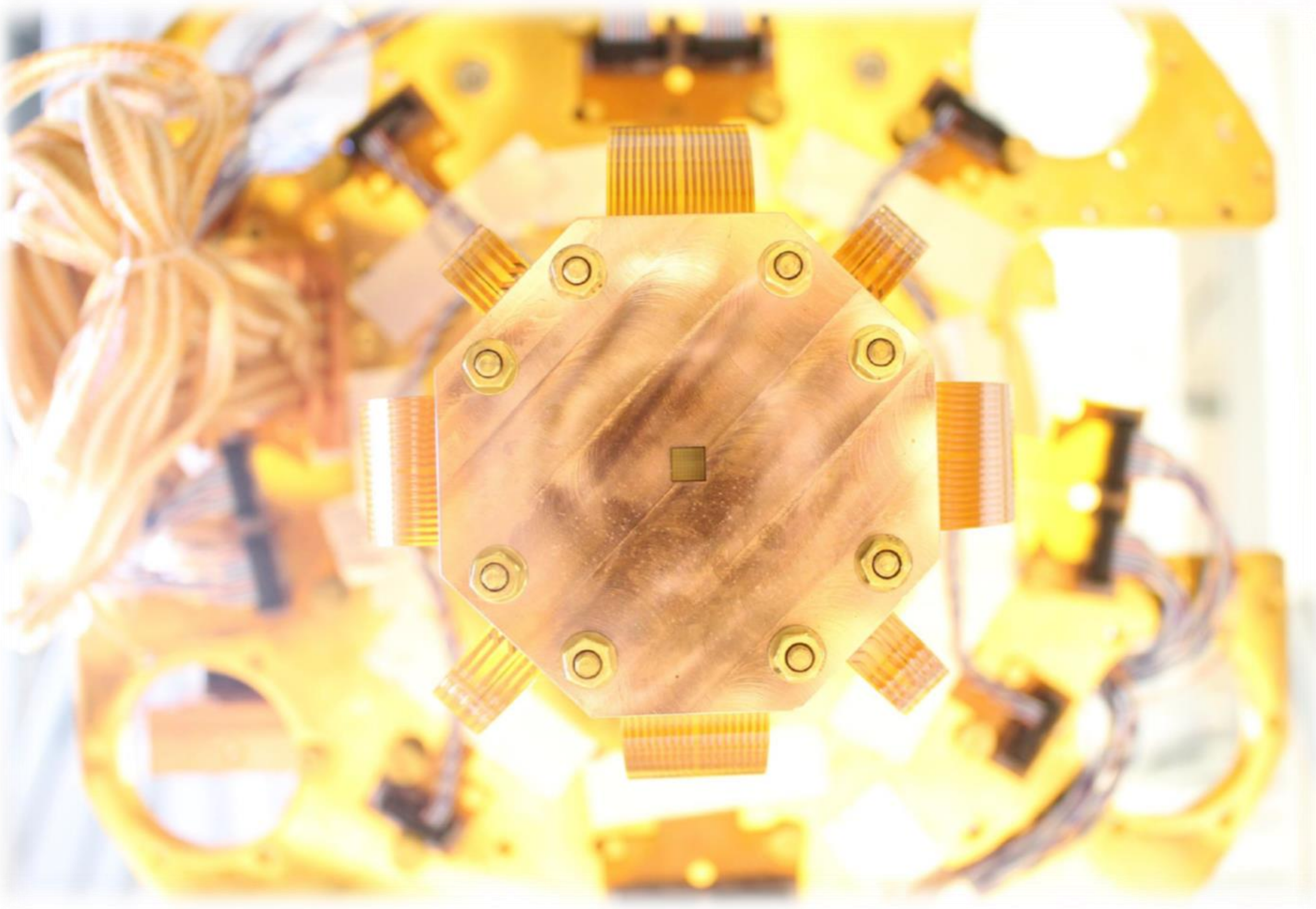


Probing the axion–nucleon coupling with the next generation of axion helioscopes

L. Di Luzio et al., EPJC 82 (2022) 120



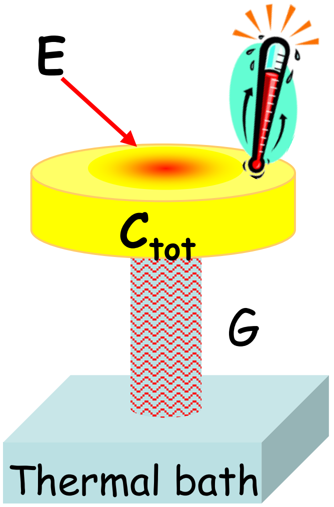
MMC for IAXO



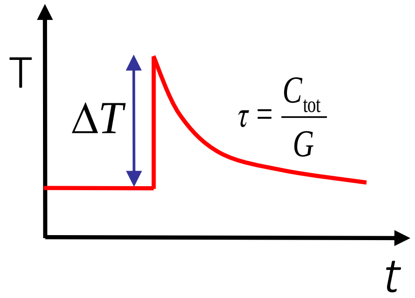
Low Temperature Calorimeters

Near equilibrium detectors

Energy deposition induces increase of temperature



$$\Delta T \cong \frac{E}{C_{tot}}$$



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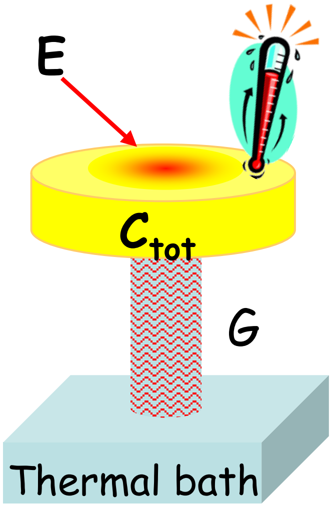

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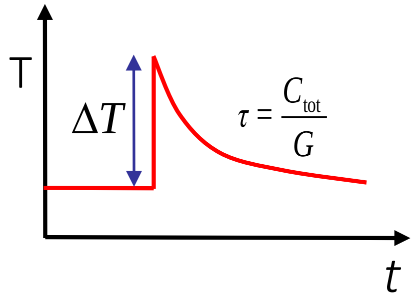
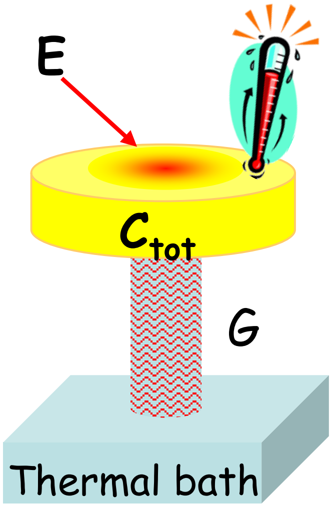


- Very small volume
- Working temperature below 100 mK
  small specific heat
  small thermal noise
- **Very sensitive temperature sensors**

Low Temperature Calorimeters

Near equilibrium detectors

Energy deposition induces increase of temperature



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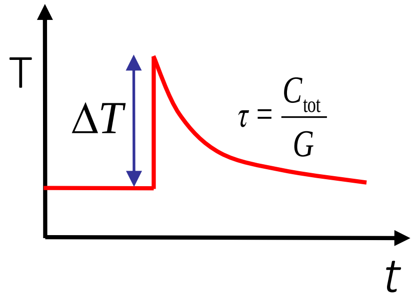

- Very small volume
- Working temperature below 100 mK
  - small specific heat
  - small thermal noise
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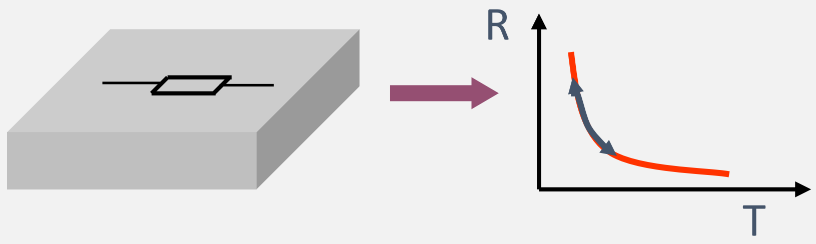
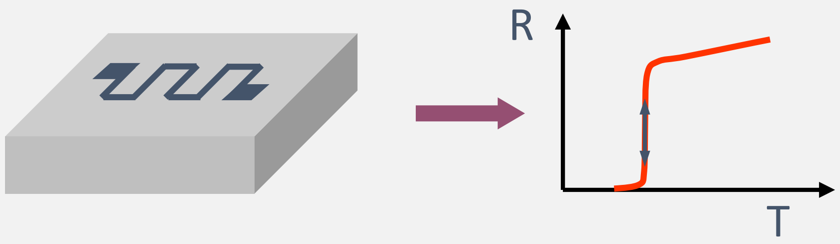
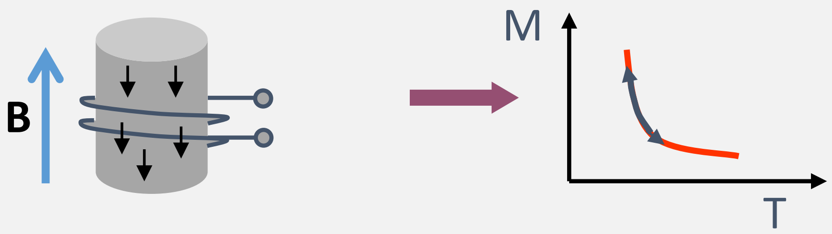
Resistance of highly doped semiconductors



Resistance at superconducting transition,TES



Magnetization of paramagnetic material, MMC



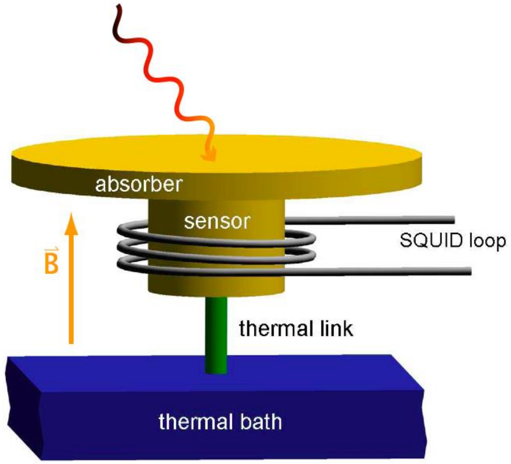
Metallic Magnetic Calorimeters

A.Fleischmann, C. Enss and G. M. Seidel, Topics in Applied Physics **99** (2005) 63

A.Fleischmann et al., *AIP Conf. Proc.* **1185** (2009) 571

Paramagnetic temperature sensor

Dilute alloy Au:Er or Ag:Er (Er concentration: a few hundred ppm)



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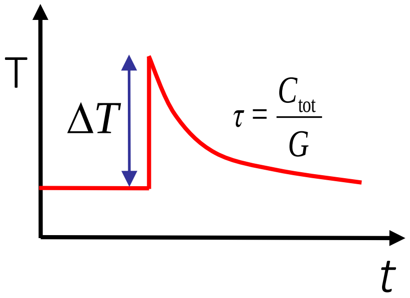

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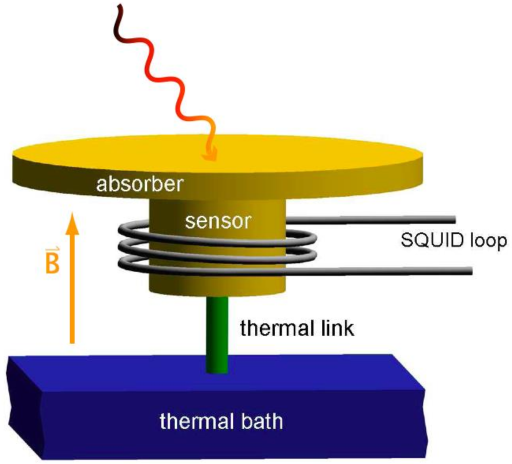
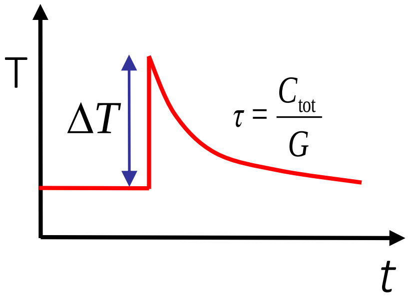


$$\Delta T \cong \frac{E}{C_{\mathrm{tot}}} \xrightarrow{\text{MMC}} \Delta\Phi_S \propto \frac{\partial M}{\partial T}\Delta T \rightarrow \Delta\Phi_S \propto \frac{\partial M}{\partial T}\frac{E}{C_{\mathrm{tot}}}$$



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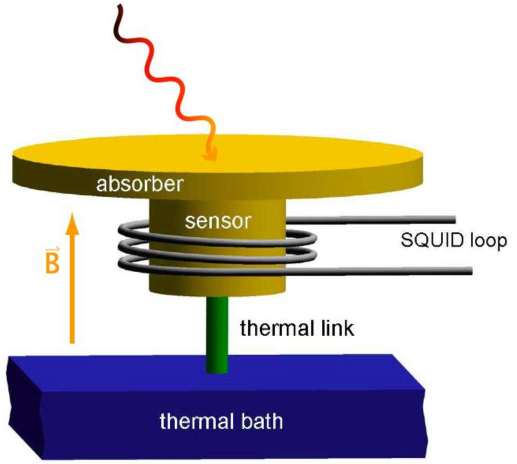

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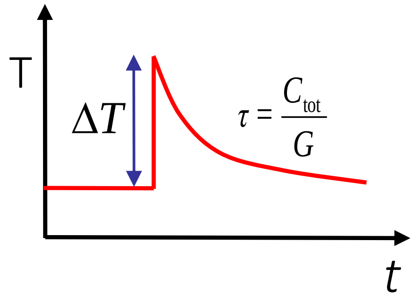
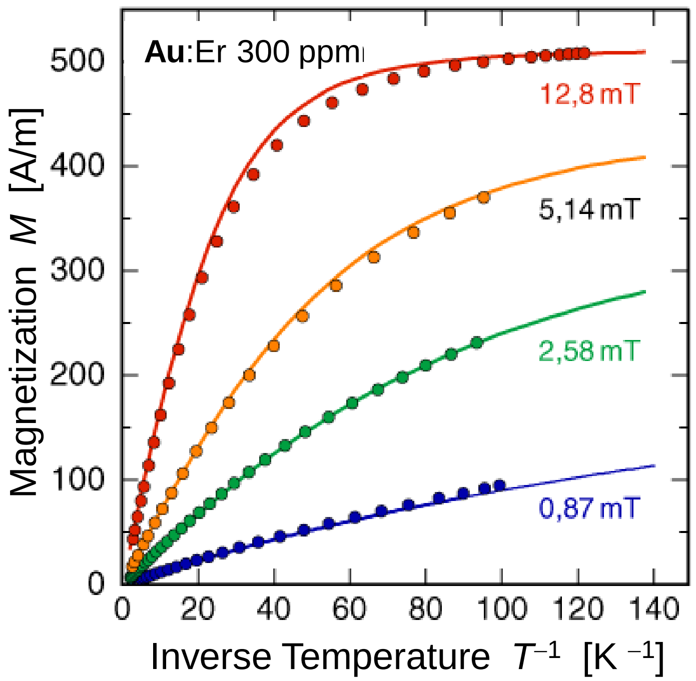
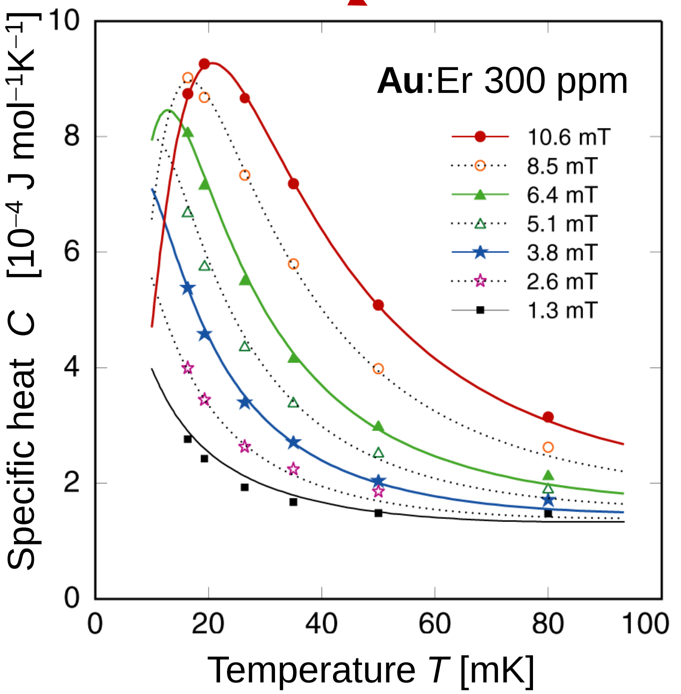






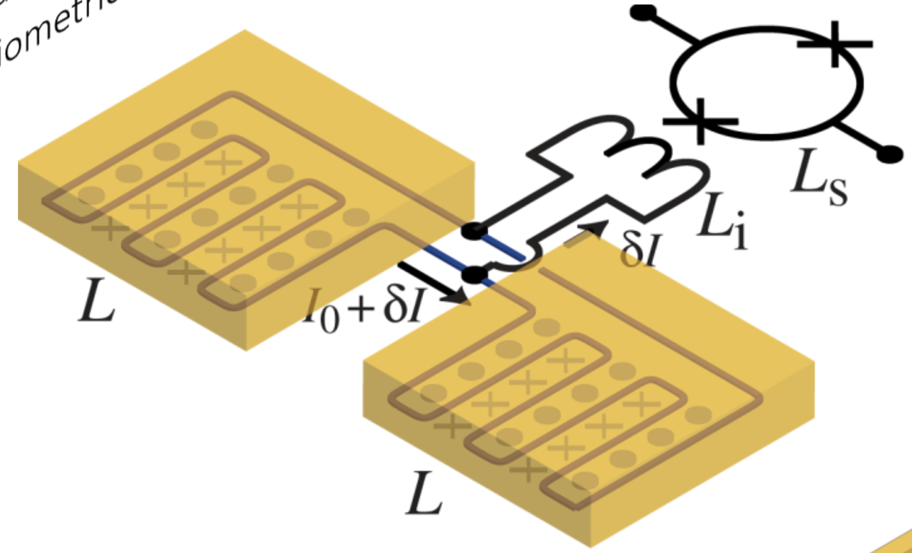
Very good agreement between data and theoretical expectation for interacting spin system

Optimization of detector geometries for wished applications

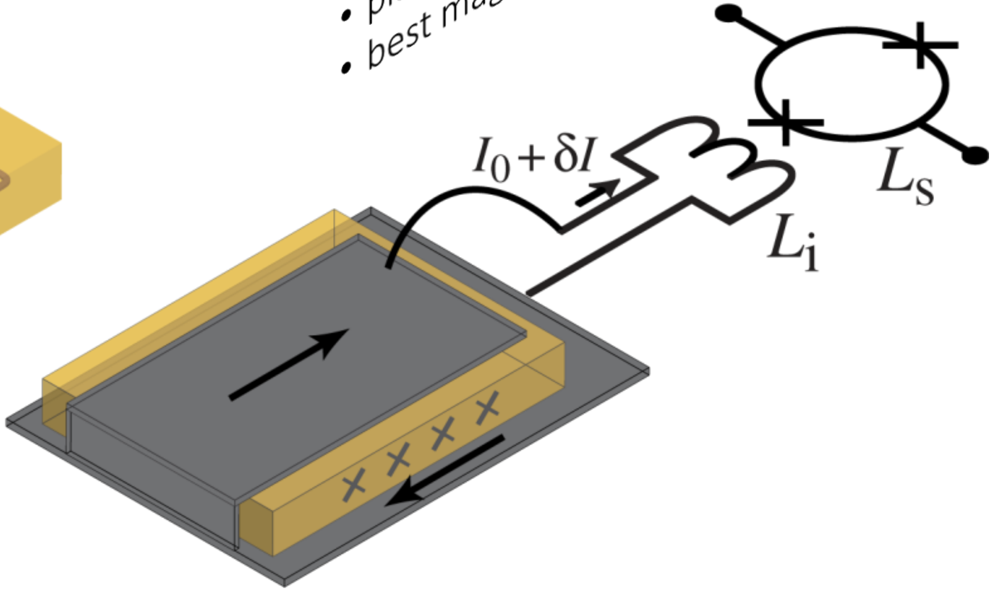
Detector geometries

- planar paramagnetic sensor
- superconducting coil
- transformed coupled to a dc SQUID

Well established:
- *superconducting meander shaped pickup loop*
- *planar sensor on top of meander-shaped coil*
- *gradiometric design*



Sandwich geometry:
- *planar sensor sandwiched between stripline*
- *best magnetic flux coupling*

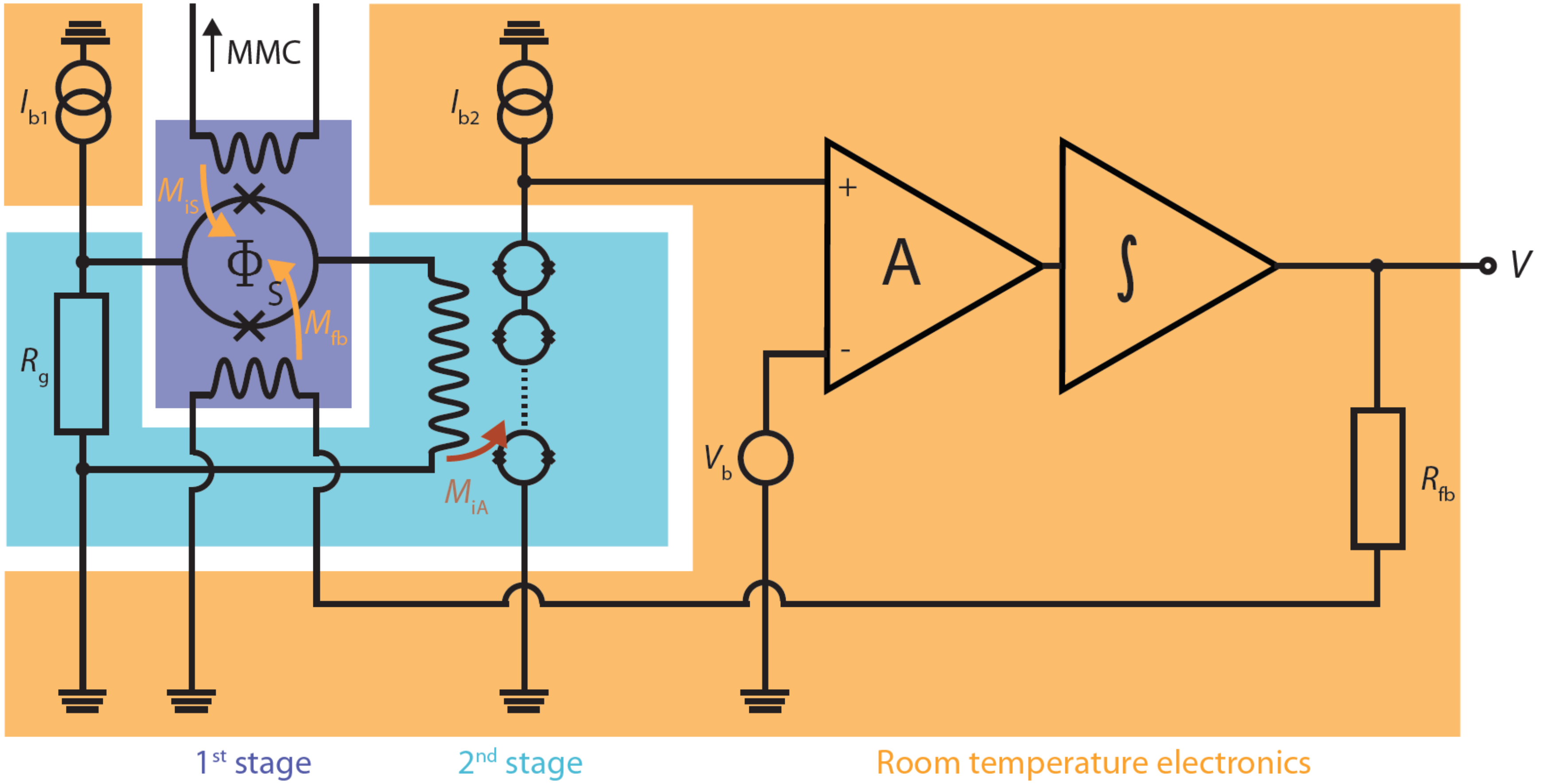


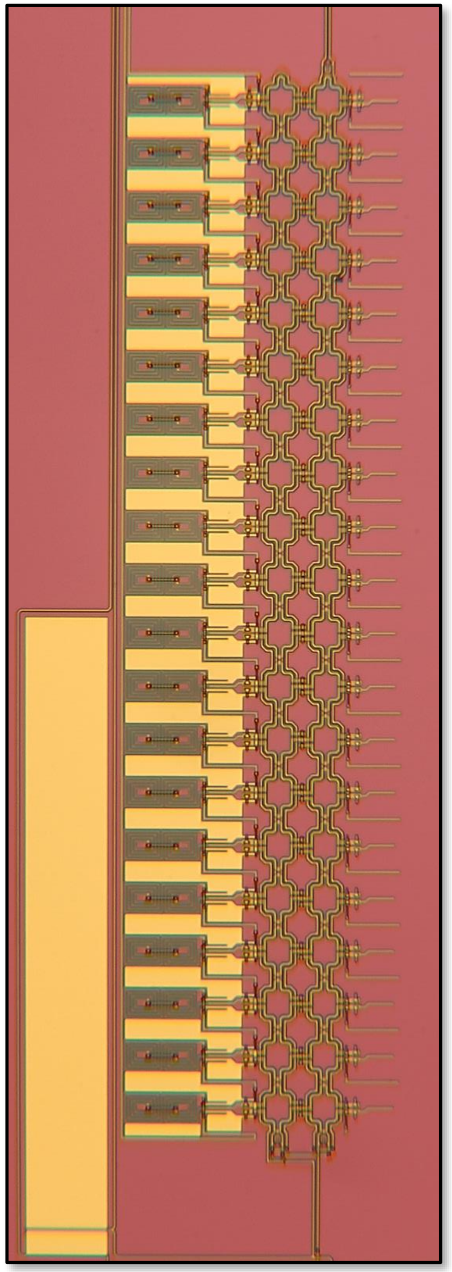
MMC readout

Two-stage dc-SQUID readout with flux-locked loop

low noise

small power dissipation on detector SQUID chip (voltage bias 1st stage)

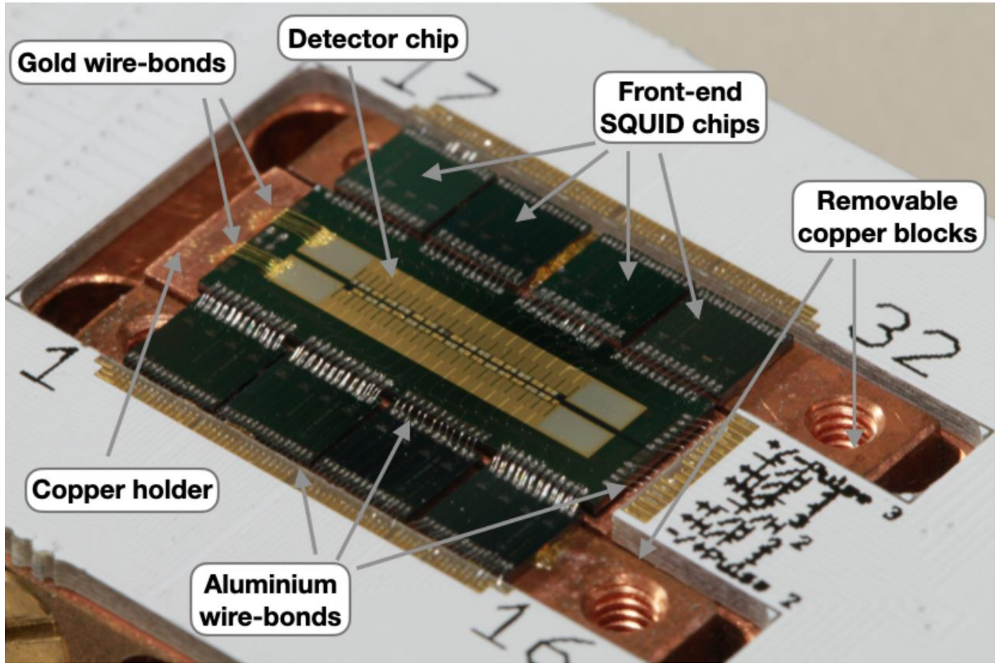




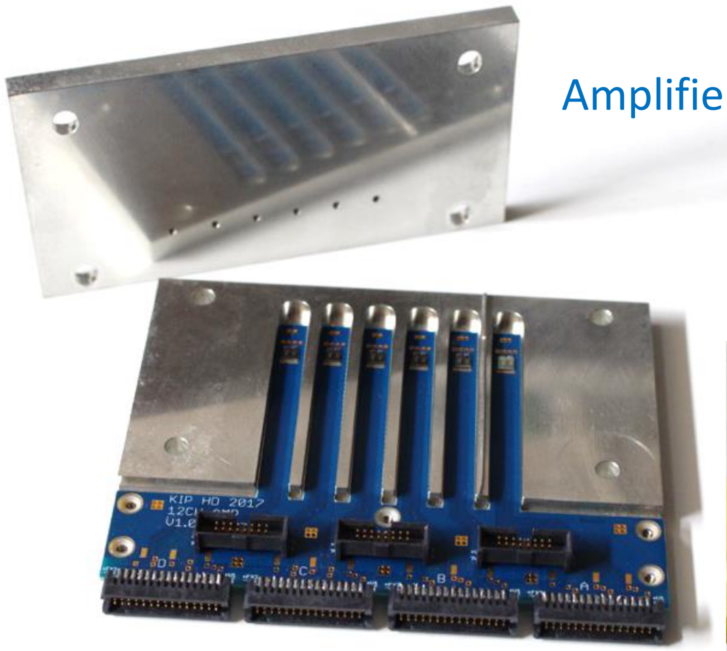
In house produced SQUID array

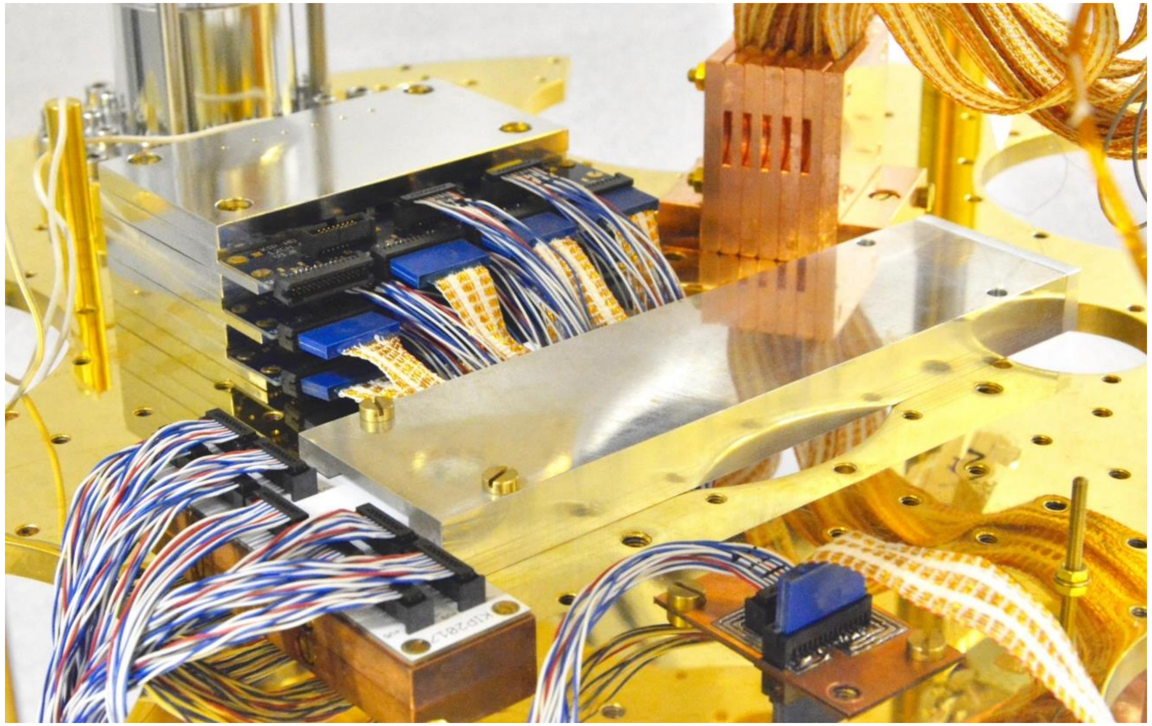
MMC readout

Detector module



Amplifier module

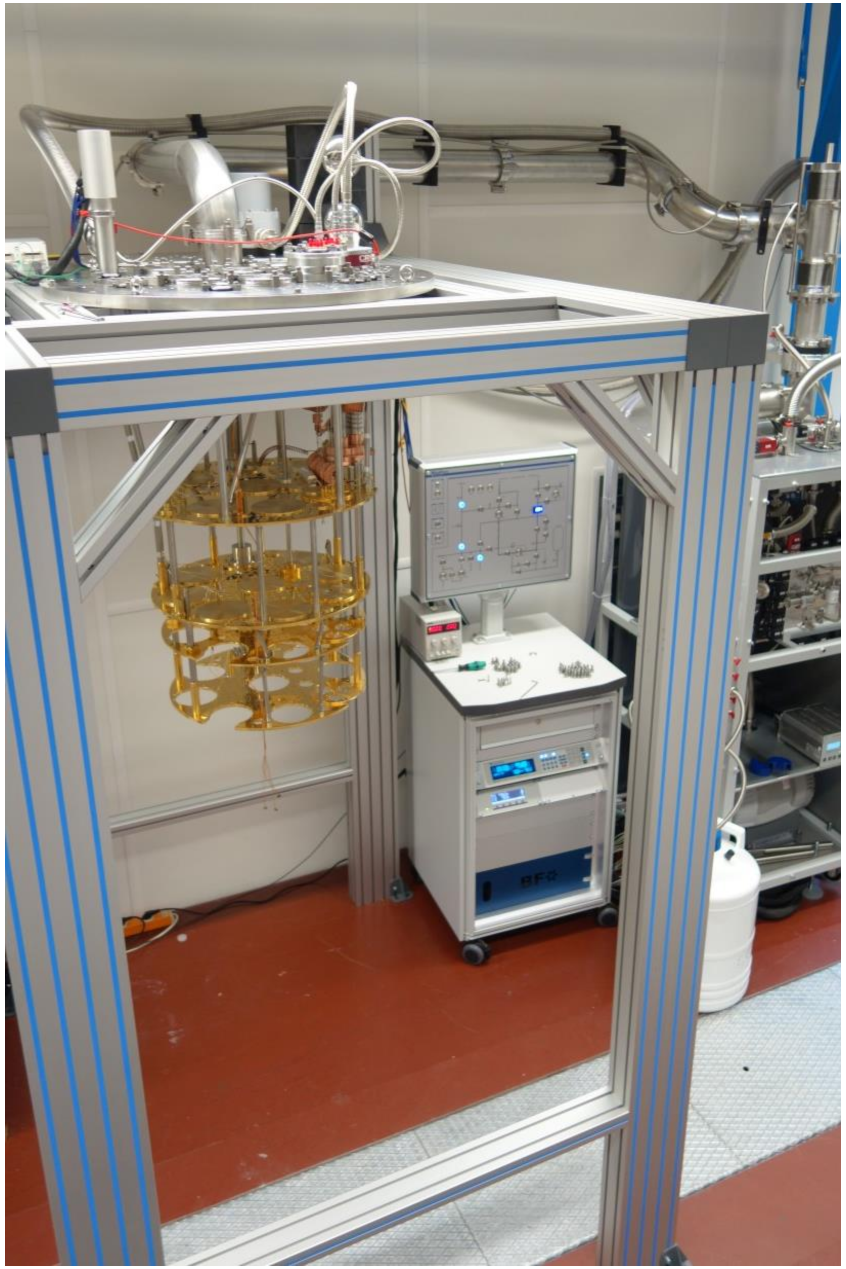


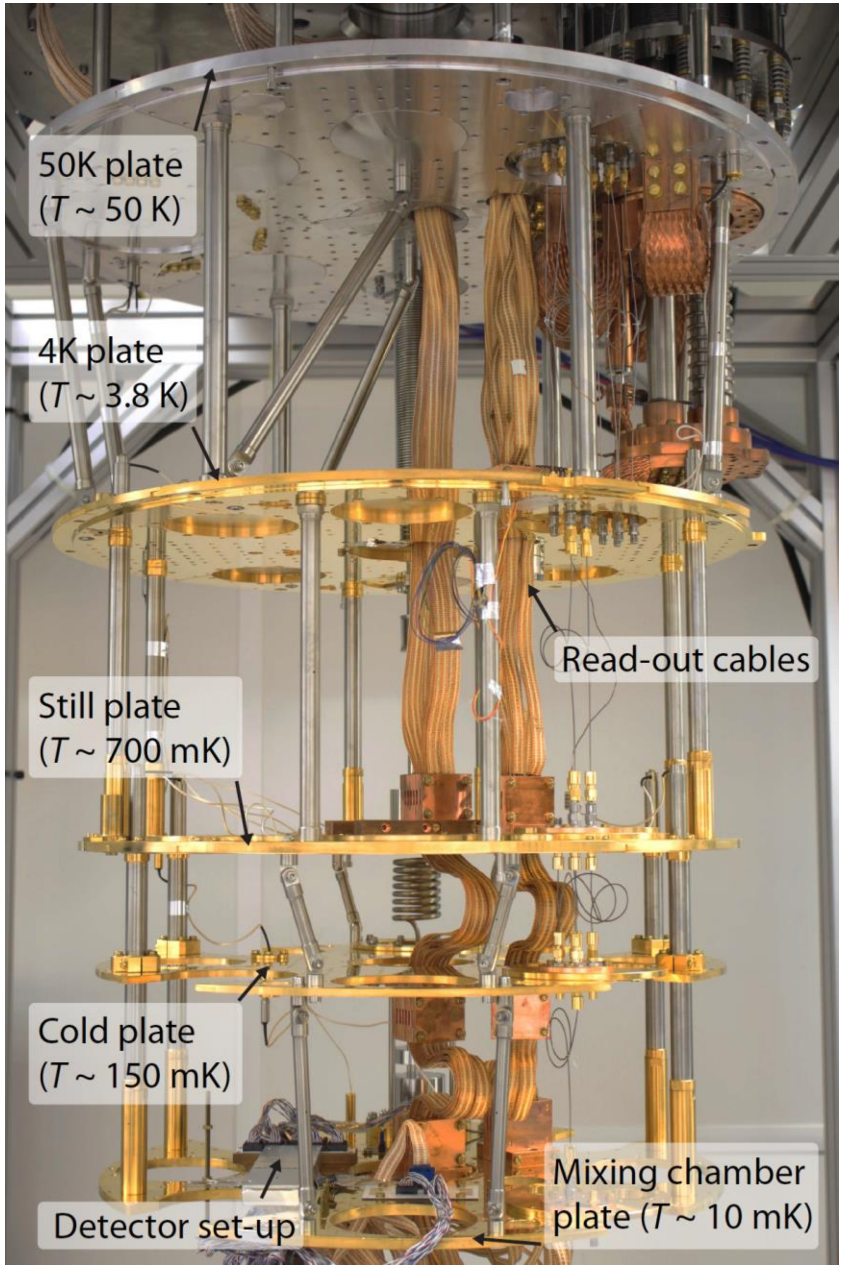


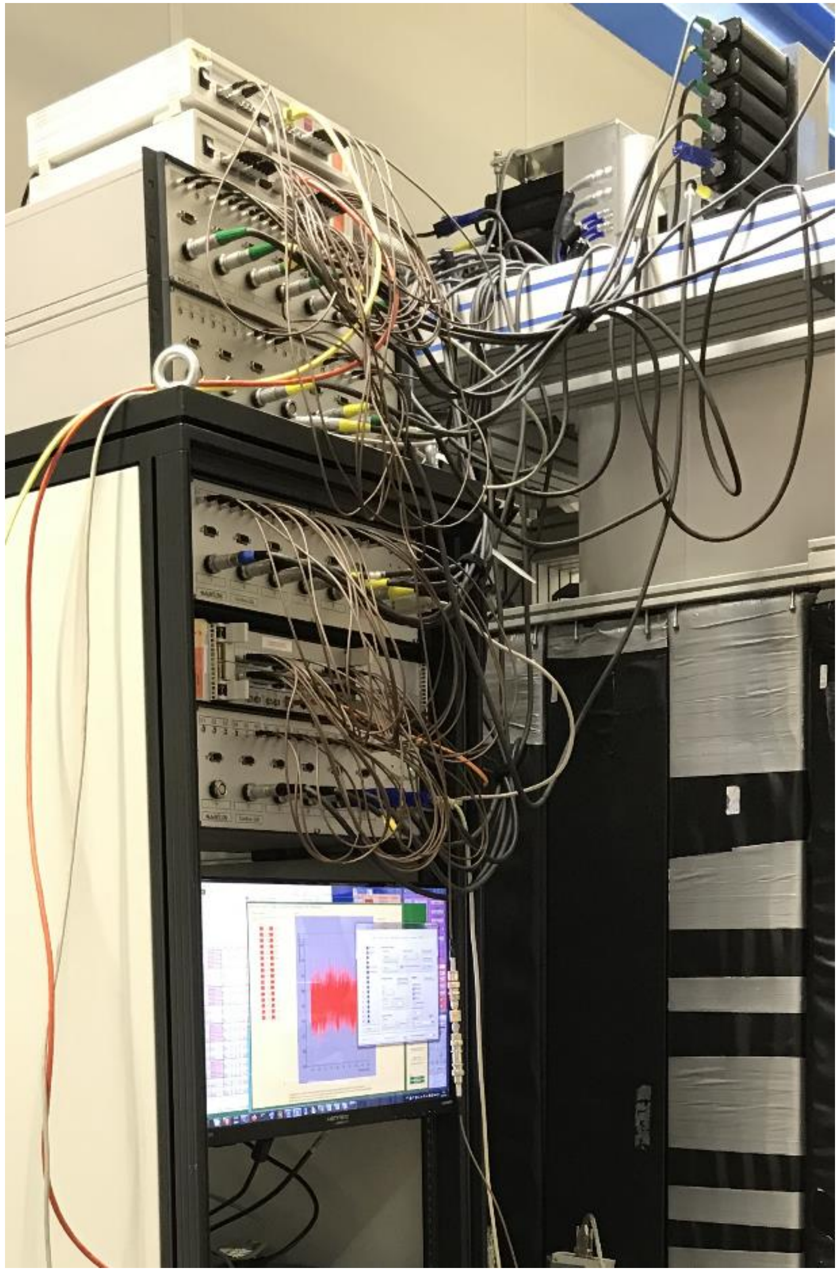
Detector and amplifier module mounted on the [mixing chamber plate]

F. Mantegazzini et al., *JINST* **16** (2021) P08003, [arXiv:2102.11100] [physics.ins-det]

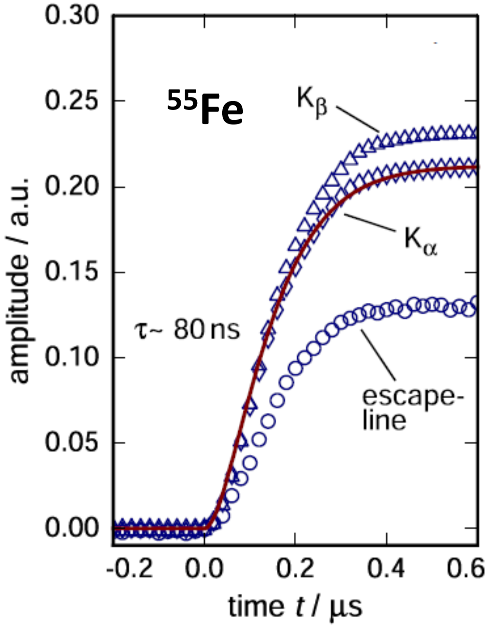
MMC readout

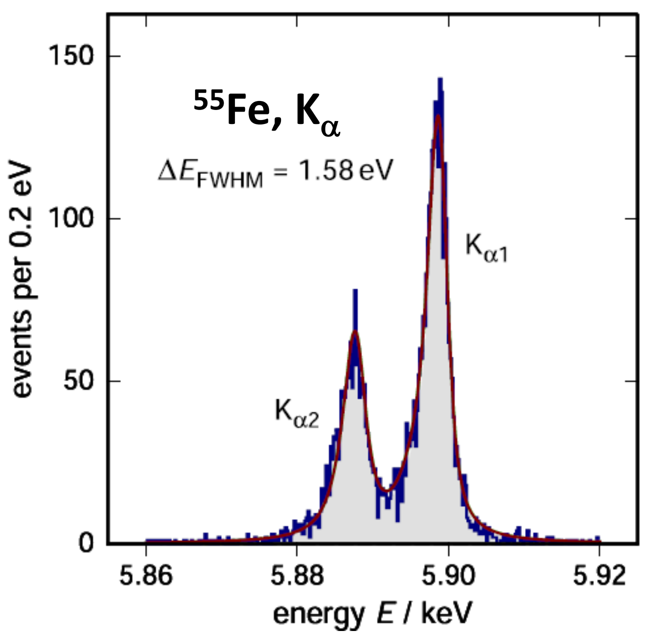


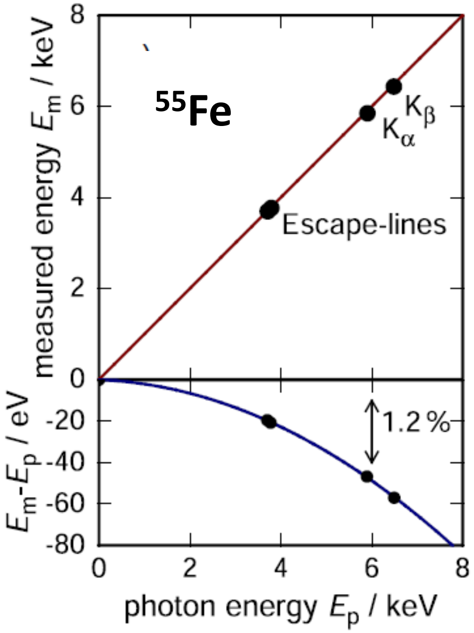

50K plate
($T \sim 50$ K)
4K plate
($T \sim 3.8$ K)
Read-out cables
Still plate
($T \sim 700$ mK)
Cold plate
($T \sim 150$ mK)
Mixing chamber
plate ($T \sim 10$ mK)
Detector set-up



Performance







Fast risetime

→ Reduction un-resolved pile-up

→ coincidence study

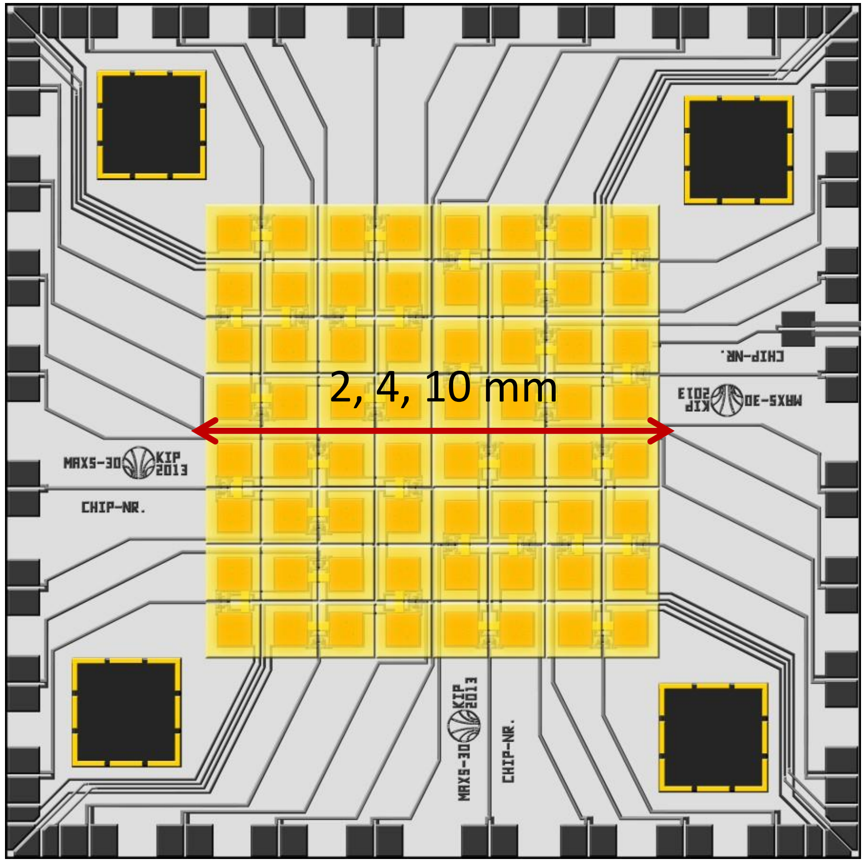
Extremely good energy resolution

→ identification of small structures

Excellent linearity

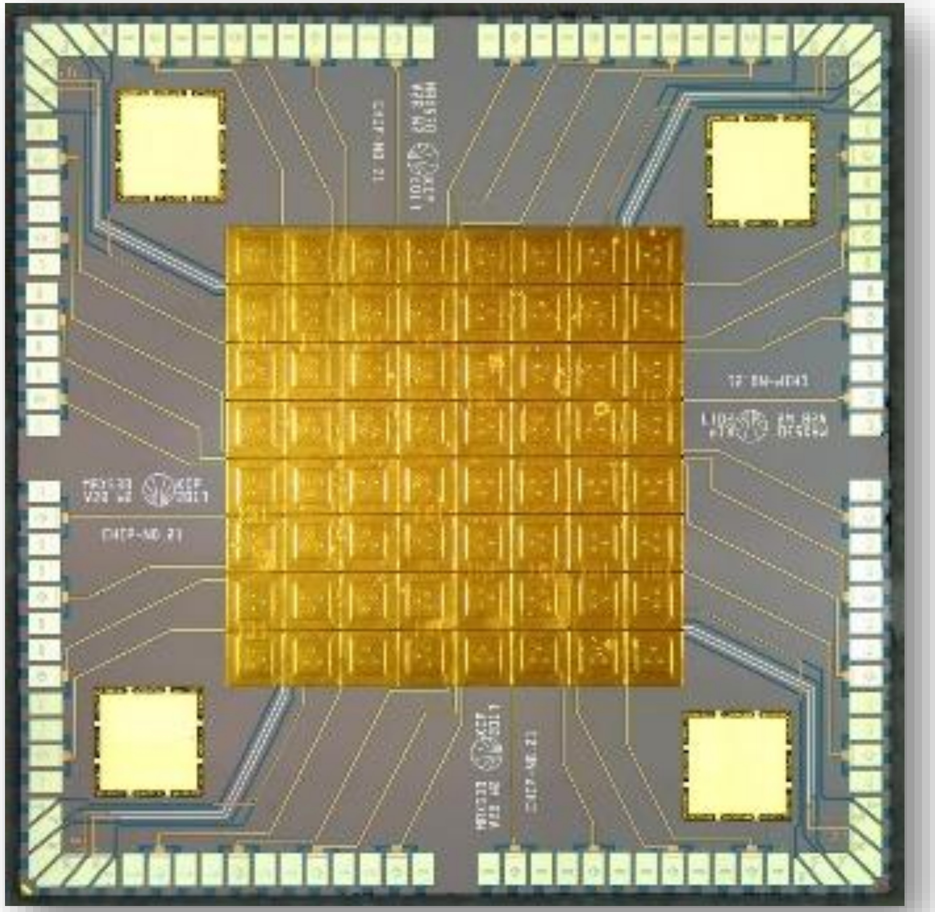
→ precise definition of the energy scale

Microcalorimeter arrays for X-rays spectroscopy - maXs



maXs-20/30/100:

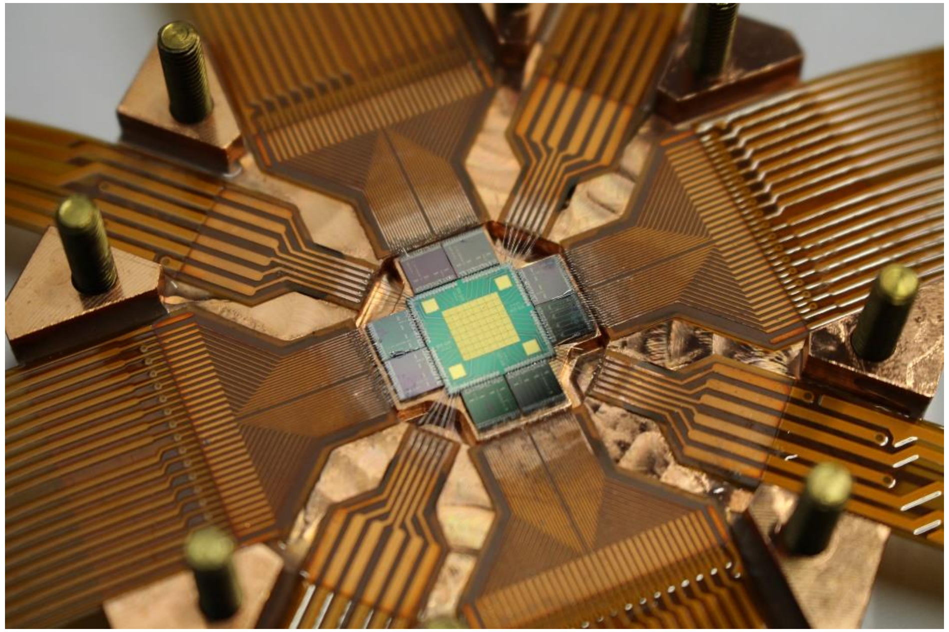
- 8×8 pixels for photons up to 20/30/100 keV
- with ΔE_{FWHM} = 2/5/30 eV
- 32 two-stage dc-SQUIDs

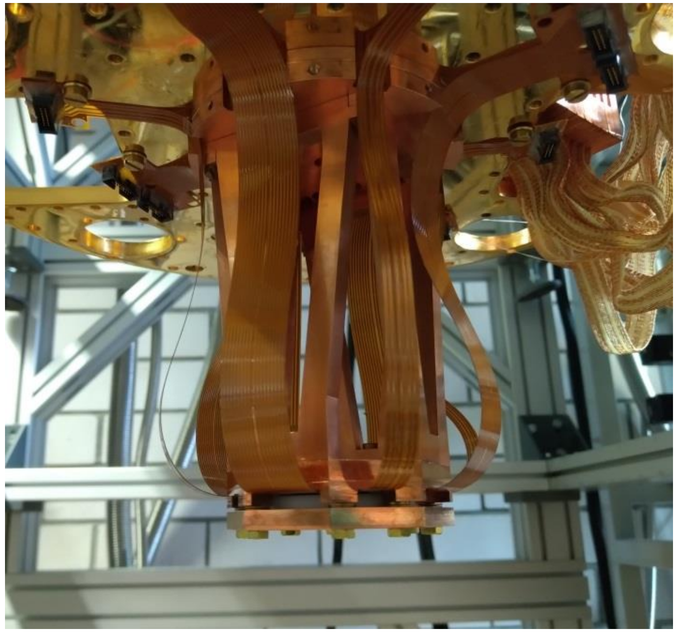


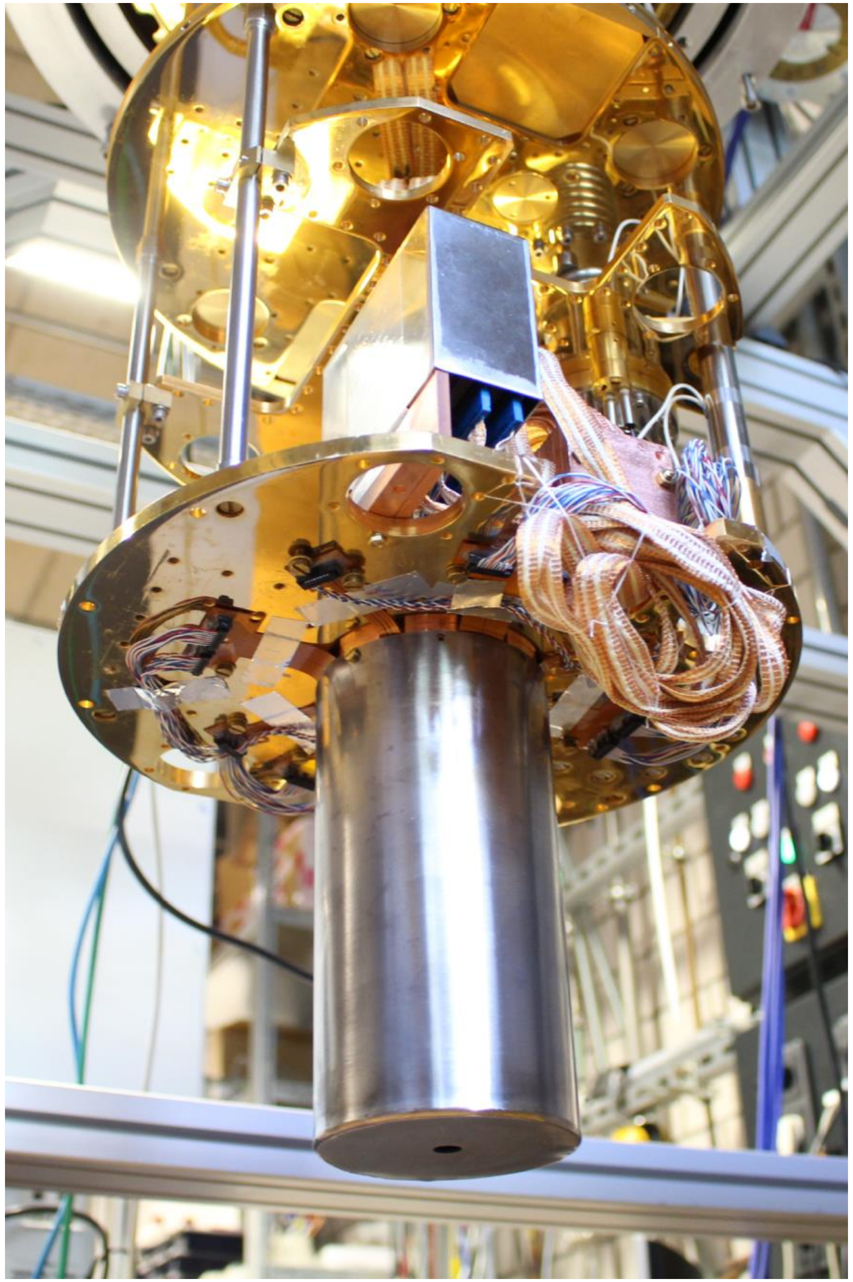
8 mm

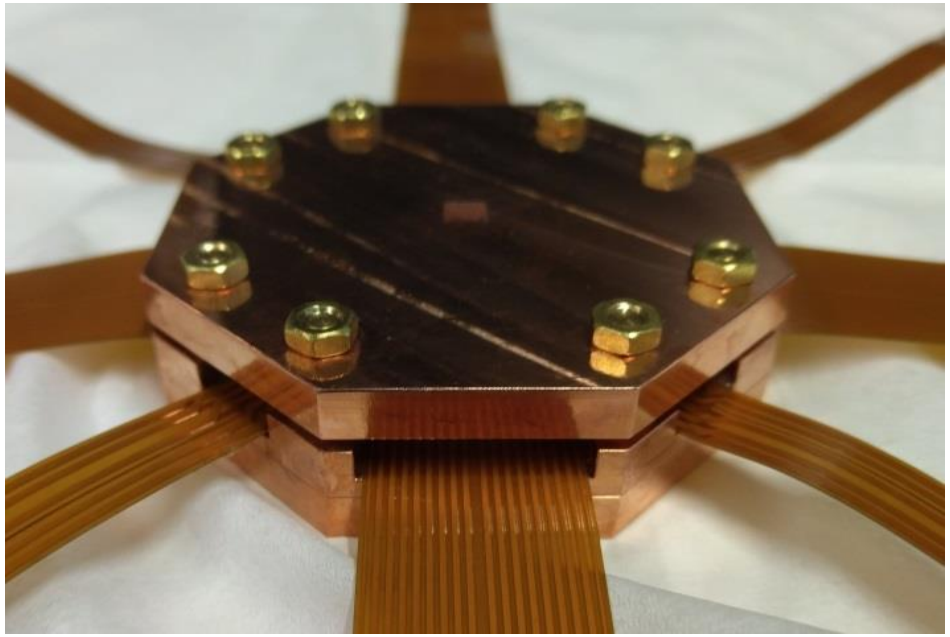
maXs-30
Absorber size: 500 × 500 × 30 µm^3

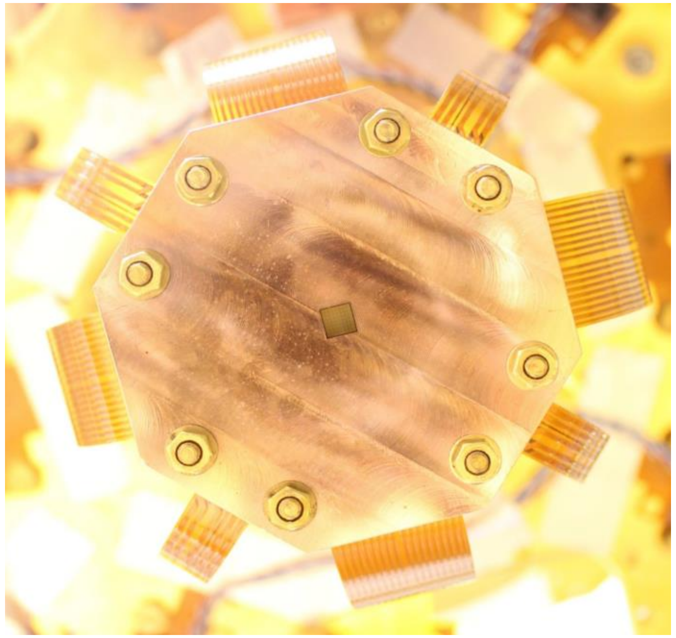
maXs-30 set-up for IAXO



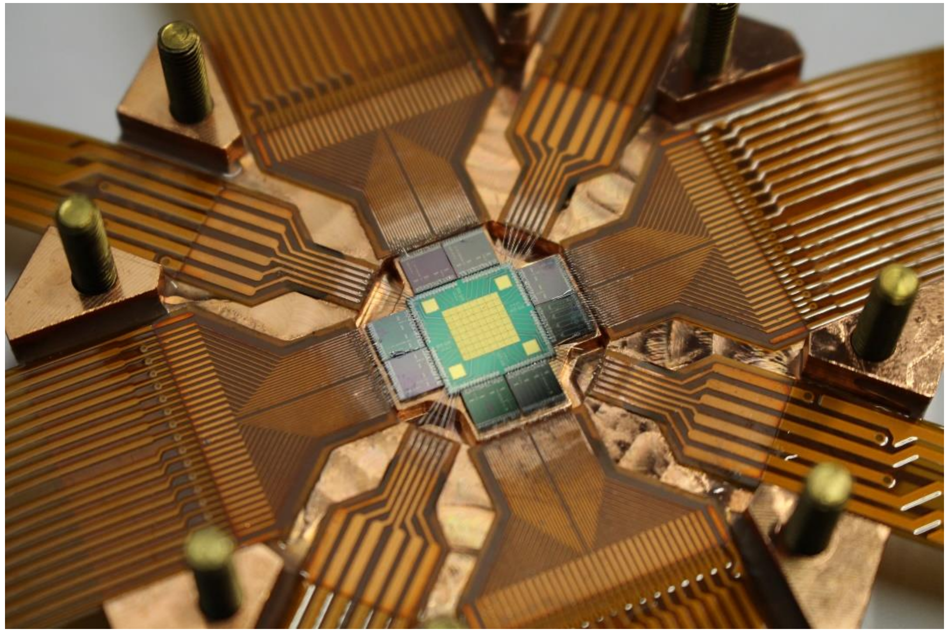


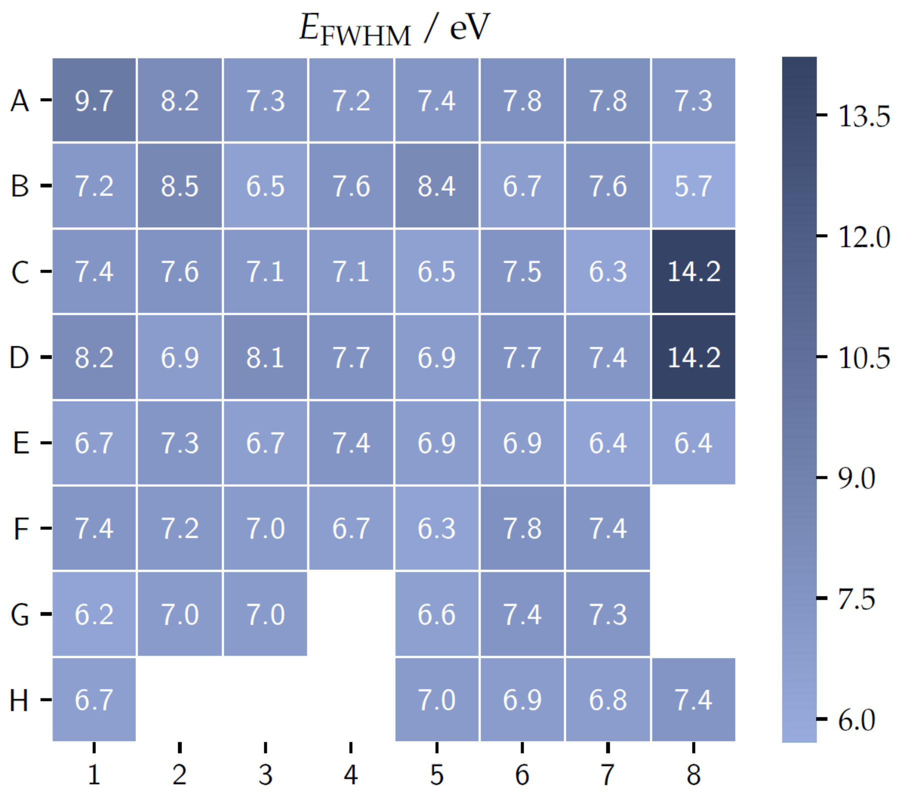






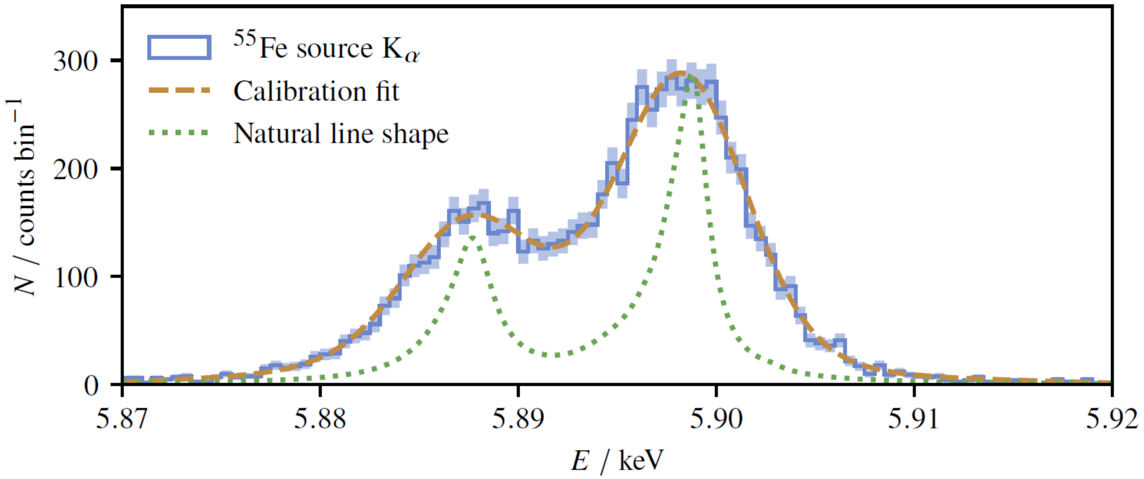
maXs-30 set-up for IAXO





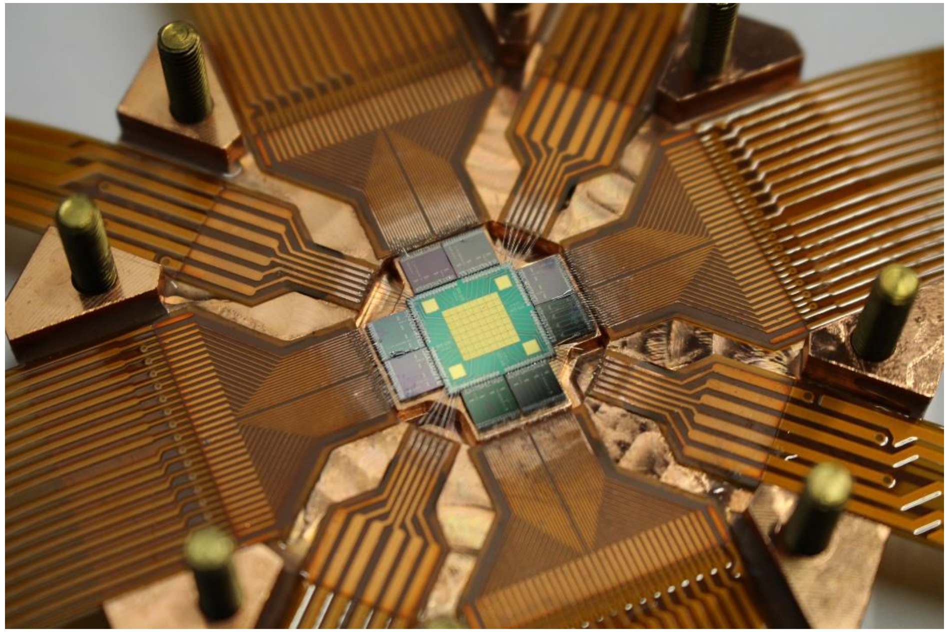
^{55}Fe calibration source
Stopping power @10 keV ~100%

- Homogeneous performance over the array
- Stable operation over 1 month

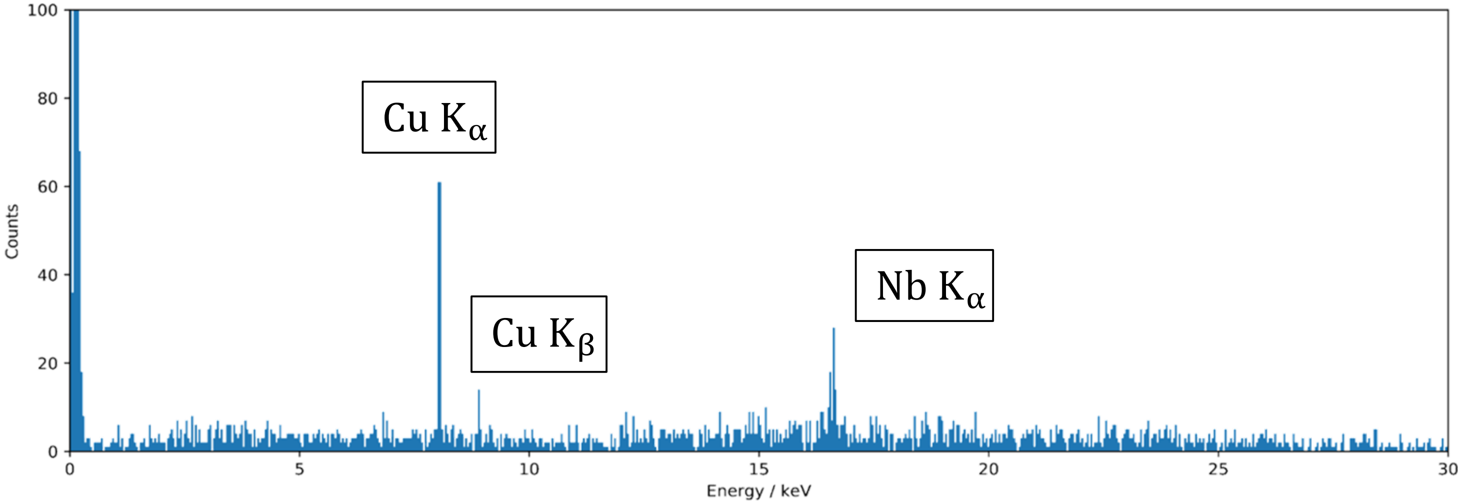


D. Unger et al., *JINST* **16** (2021) P06006,
arXiv:2010.15348 [physics.ins-det]

maXs-30 set-up for IAXO



Background spectrum (one month, no special shielding, no muon veto)



^{55}Fe calibration source

Stopping power @10 keV ~100%

- Homogeneous performance over the array
- Stable operation over 1 month

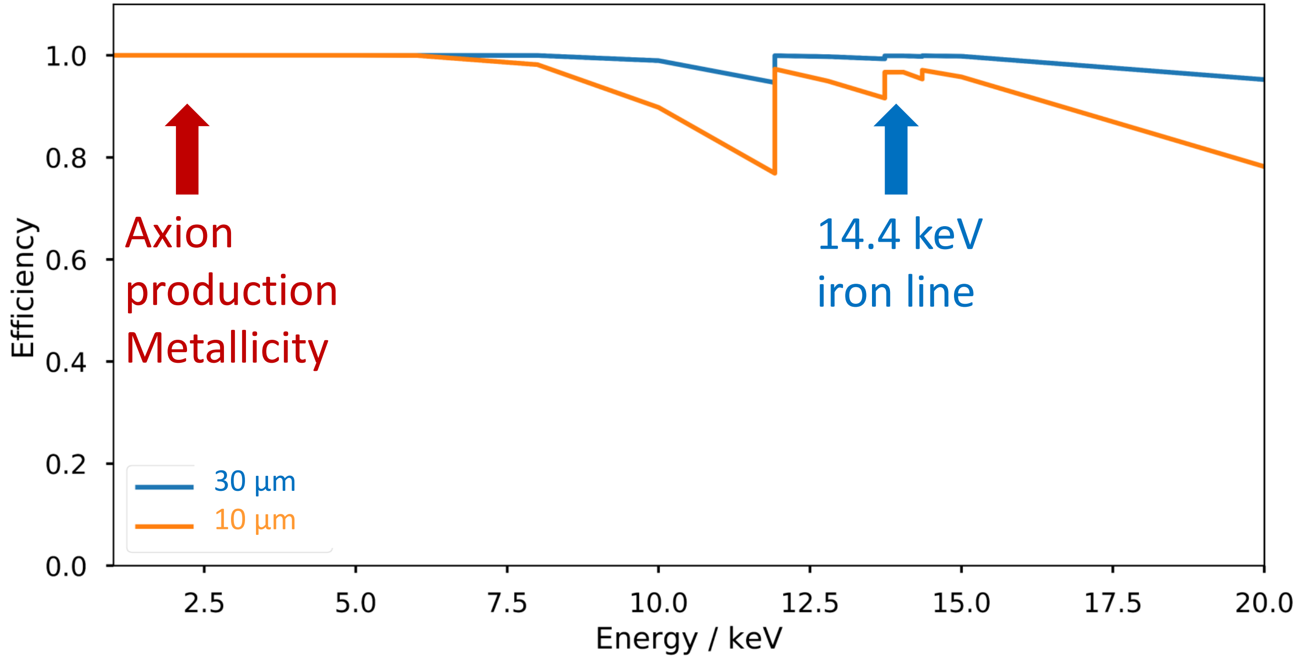
D. Unger et al., *JINST* **16** (2021) P06006,
arXiv:2010.15348 [physics.ins-det]

Cut efficiency > 90% (based on calibration lines)

Background estimation: $2 \cdot 10^{-4} \frac{\text{counts}}{\text{keV cm}^2\text{ s}}$
(from 1 to 10 keV)

Still too high
→ development of a cryogenic veto

From maXs-30 to maXs-100

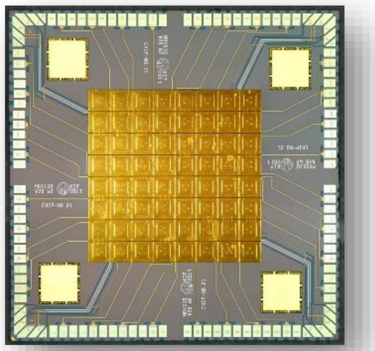


Au absorber volume can be adjusted for the particles to be detected

Sensor volume is optimized to match the heat capacity of the absorber at the working temperature

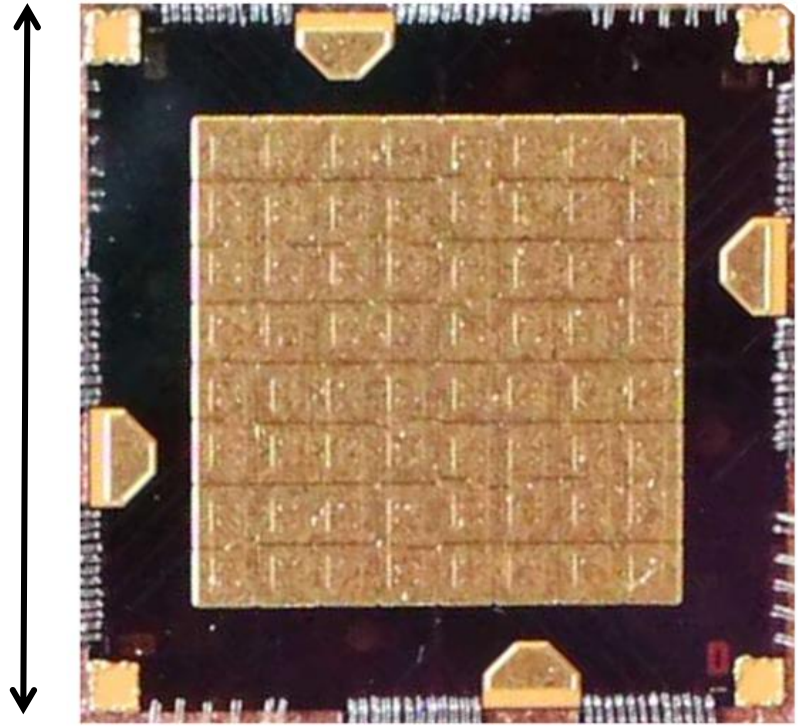
maXs-30

8 mm



maXs-100

15 mm



Same design, but scaled up!

MMCs in IAXO: Challenges

Detector challenges:

- ☑ High efficiency in energy range $0 \ldots 10\ \mathrm{keV}$
- ☑ High energy resolution
- ☑ Active area matching IAXO optics focal spot size

Setup challenges:

- ❑ Extremely low background of $10^{-8}\ \frac{\mathrm{counts}}{\mathrm{keV\ cm^2\ s}}$
- ❑ Good mechanical stability for operating while moving/vibrating
- ❑ Good magnetic shielding

Cryostat challenges:

- ❑ Reliable operation @ $20\ \mathrm{mK}$
- ❑ Tiltable to 30°

} existing technology

Conclusions

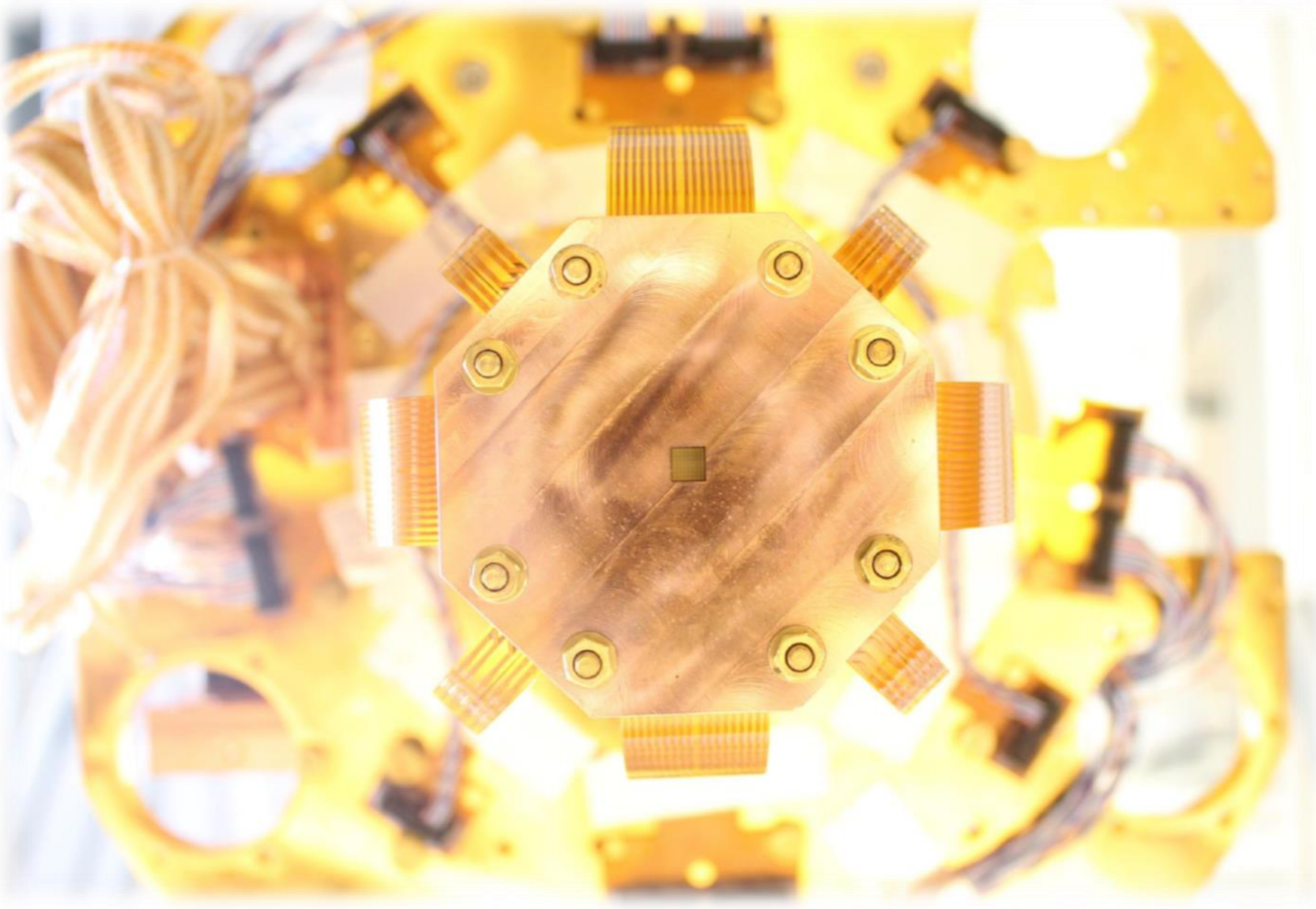
Metallic magnetic calorimeters for IAXO

- high resolution
- wide range of energies
- impressive resolving power

To demonstrate:

- suitable background
- stable operation while tracking the Sun

Achieved MMC performance motivates the efforts !



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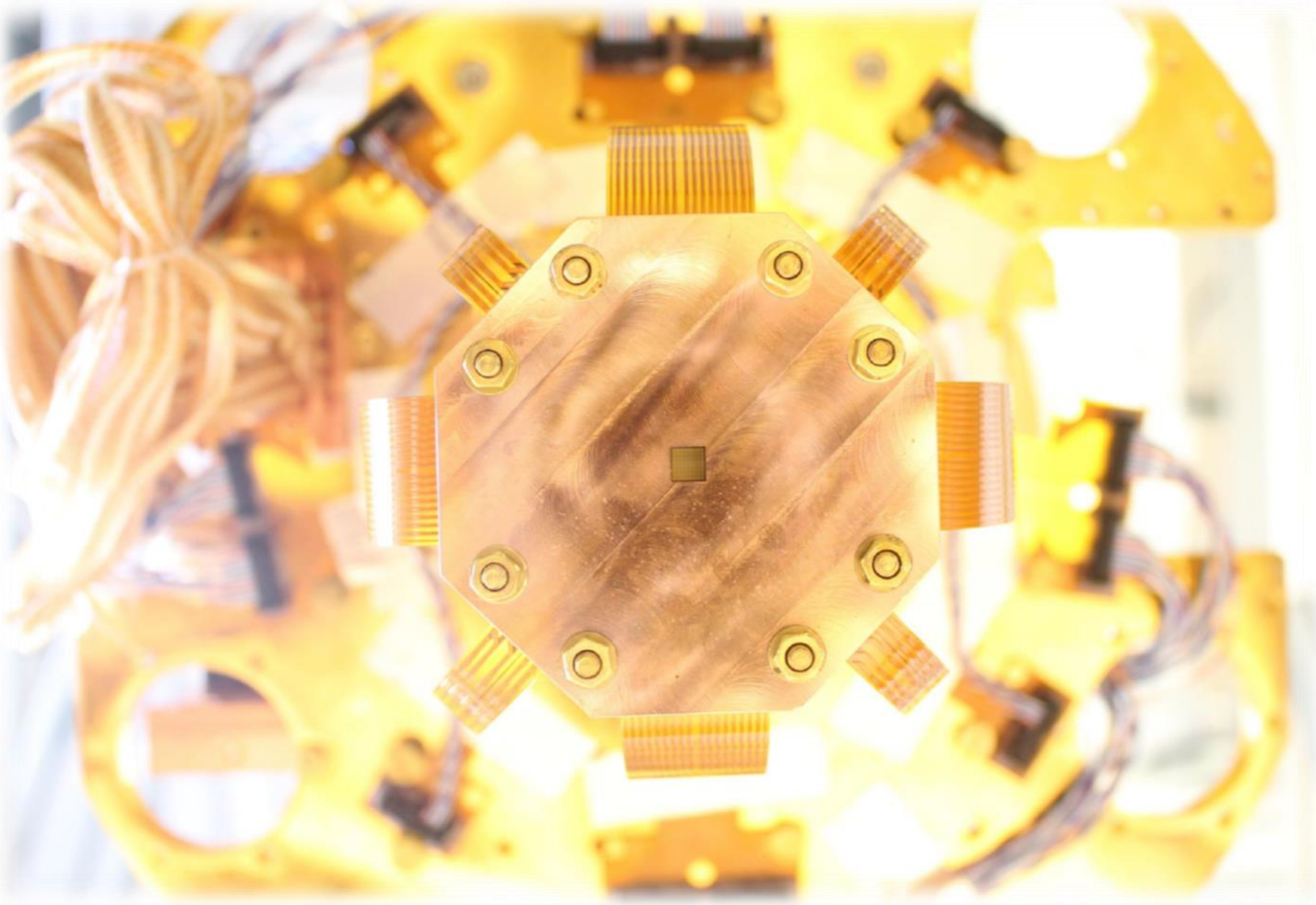


Thank you for the attention!

MMC fabrication

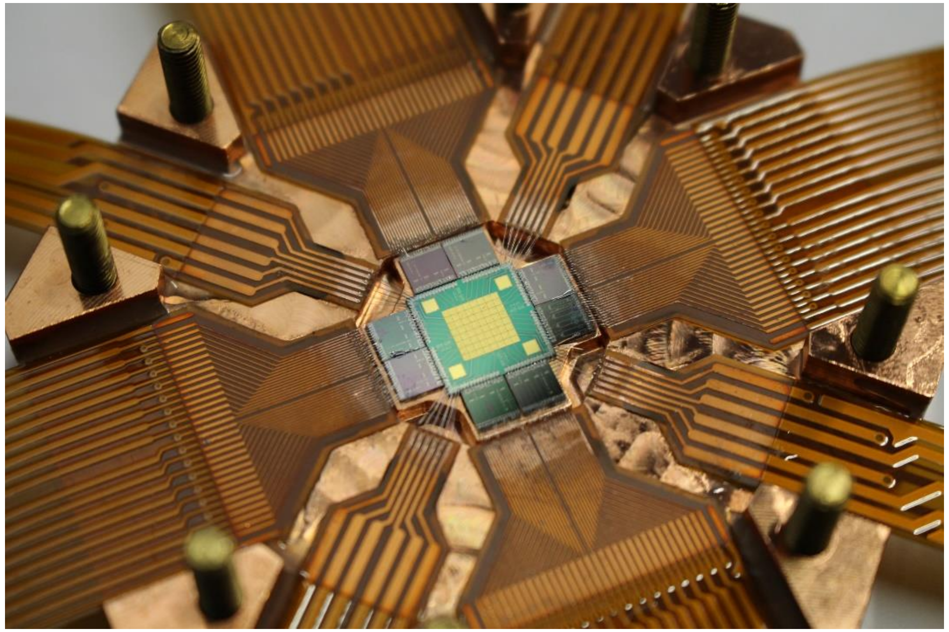
40 m^2 Cleanroom class 100
at Kirchhoff Institute for Physics

Wet bench
Chemistry bench
Maskless aligner
UHV sputtering system
Dry etching system

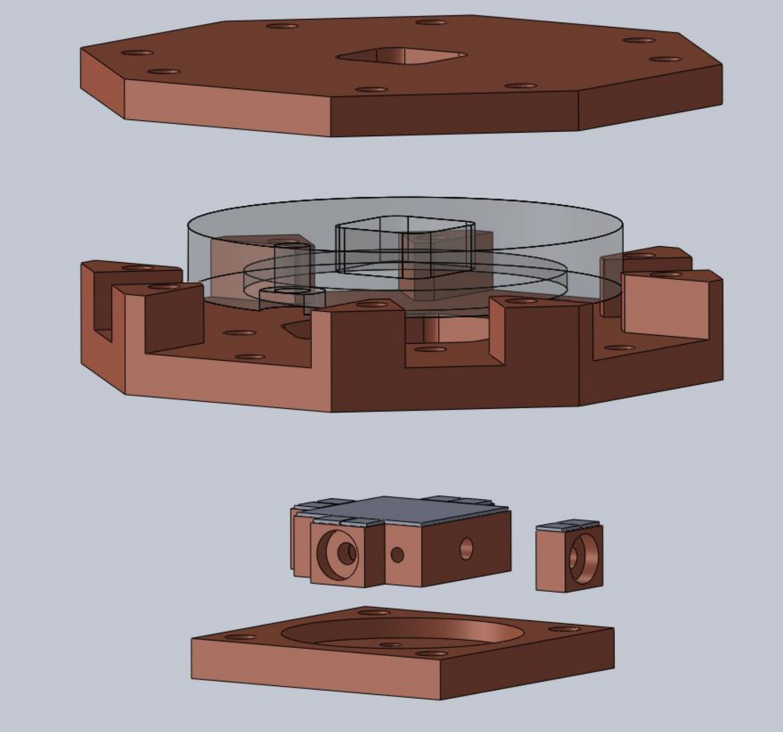
- Flexibility in design and fabrication
- Reliable processes for thin films
- Production of MMC array and superconducting electronics

Detector setup V1

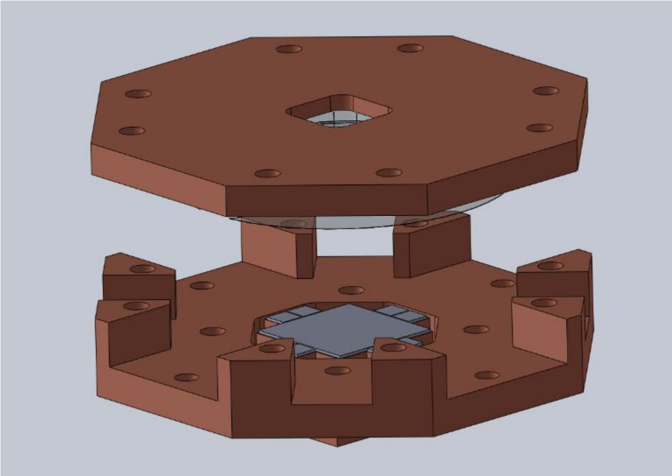
- First IAXO detector setup
- Designed for and equipped with *maXs*30 detector
- Only used radiopure materials (copper and Kapton)
- Magnetic shielding (Nb shield)
- Measured and characterized within last half year



Detector setup V2



New features:
- Modularized detector and SQUID holder → easy repair
- Optimized for new detector *maXs*IAXO
- Additional inner teflon shield to reduce background



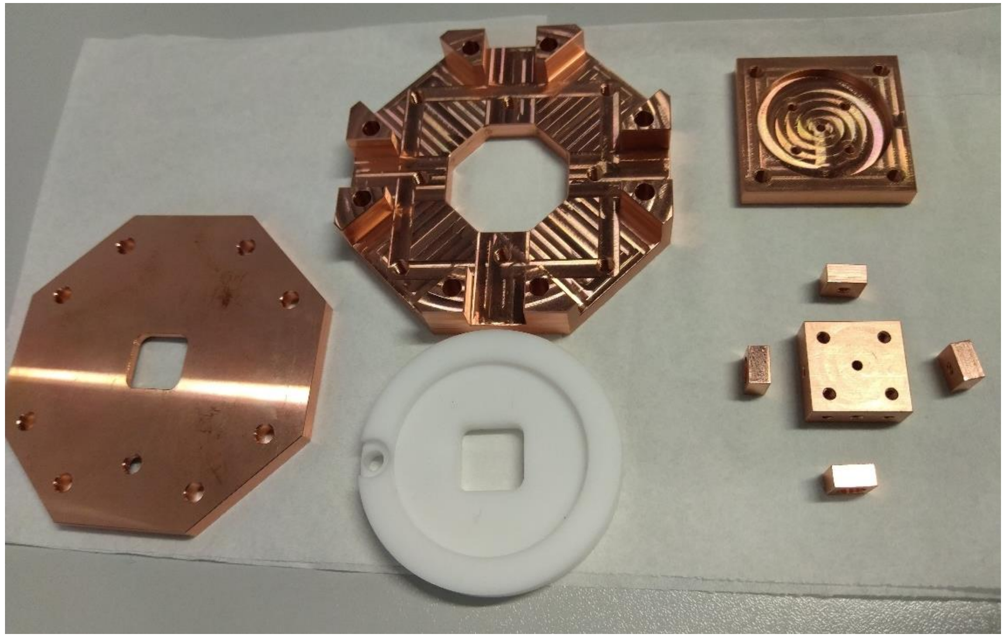
Detector setup V2

Current state:

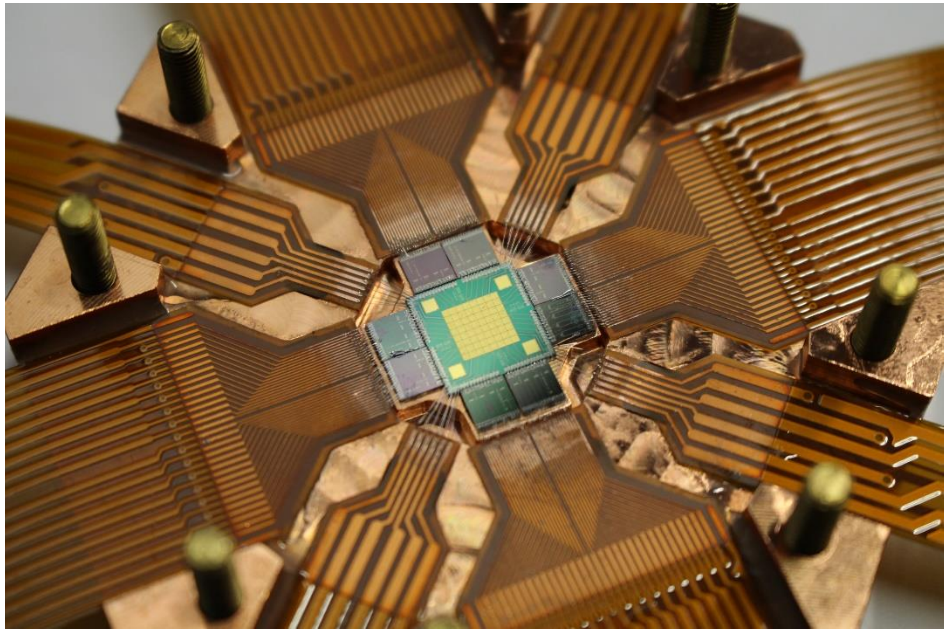
- Copper parts are produced,
  ready to be assembled
- *maXs*IAXO is prepared to be produced
  in cleanroom

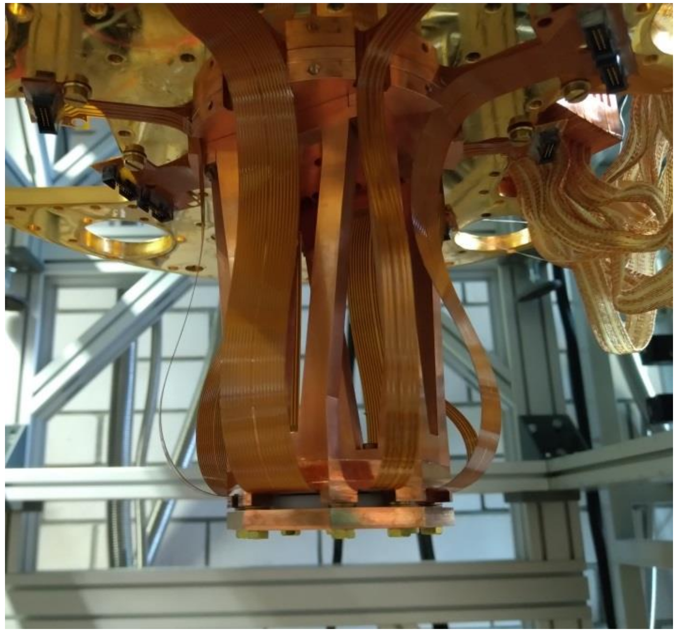
Next steps:

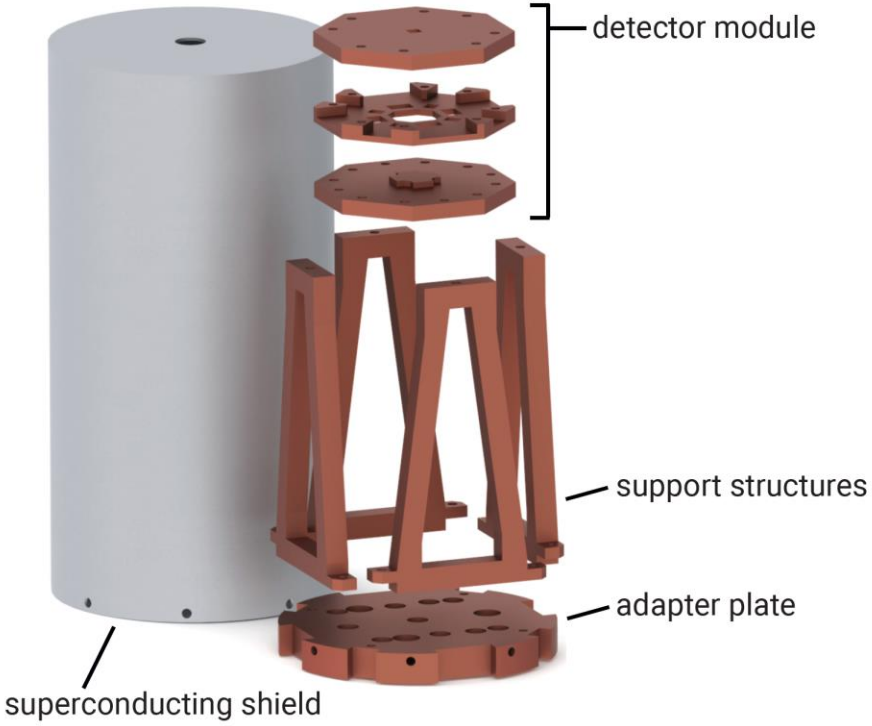
- *maXs*IAXO wafer production in cleanroom
- Assembling and characterization of *maXs*IAXO V2 setup
- Background measurements

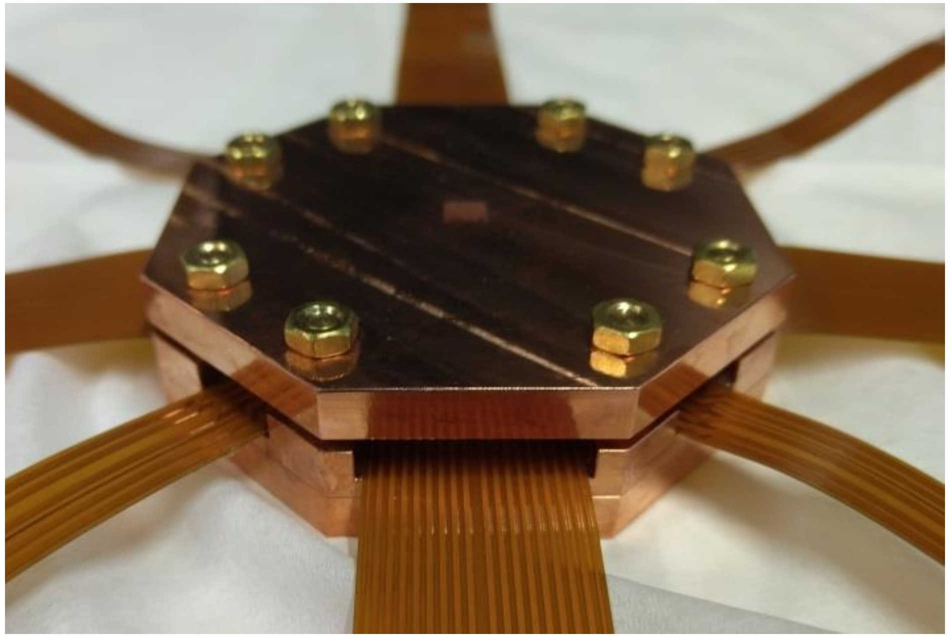


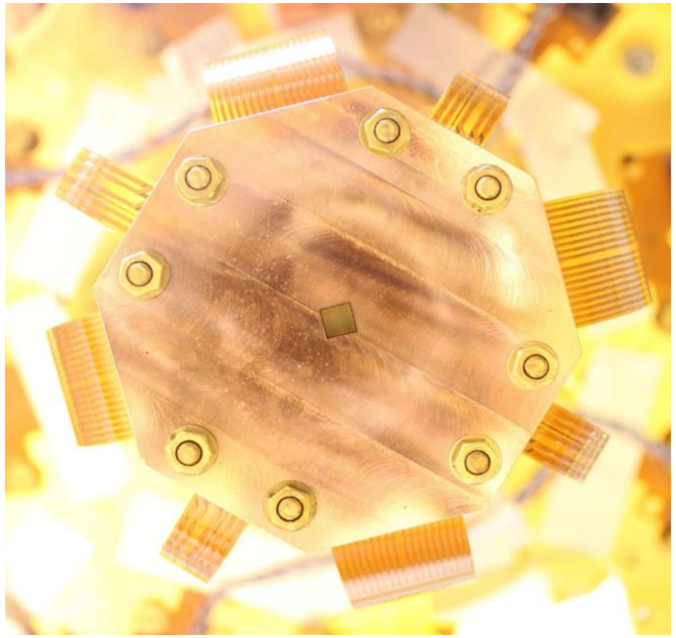
maXs-30 set-up for IAXO











Design suitable for IAXO telescope

High purity materials for background reduction

D. Unger et al., *JINST* **16** (2021) P06006, arXiv:2010.15348 [physics.ins-det]

Tiltable cryostat: BlueFors ASM-LH250