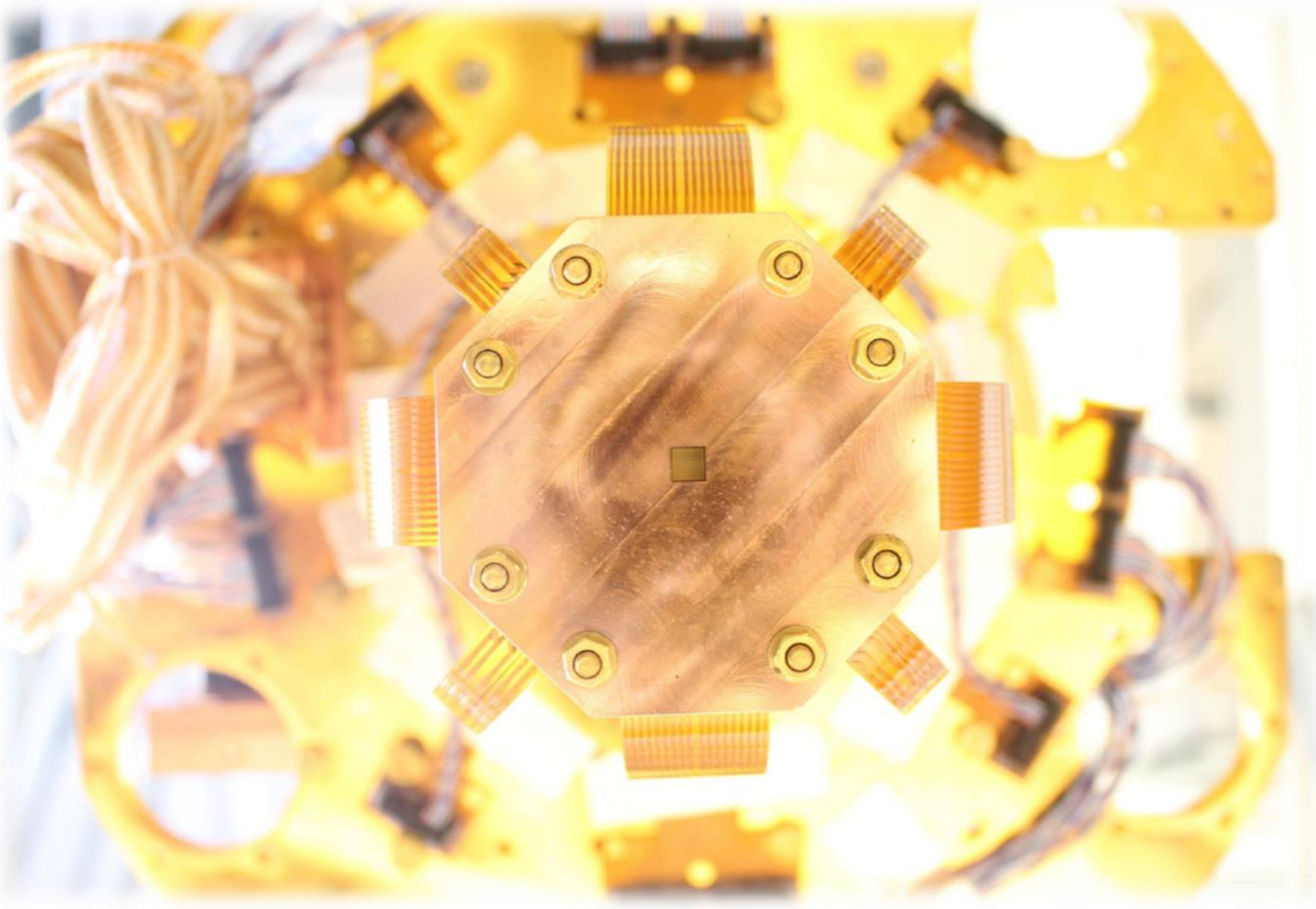
Metallic Magnetic Calorimeters for Axion and Light Dark Matter Searches

Loredana Gastaldo

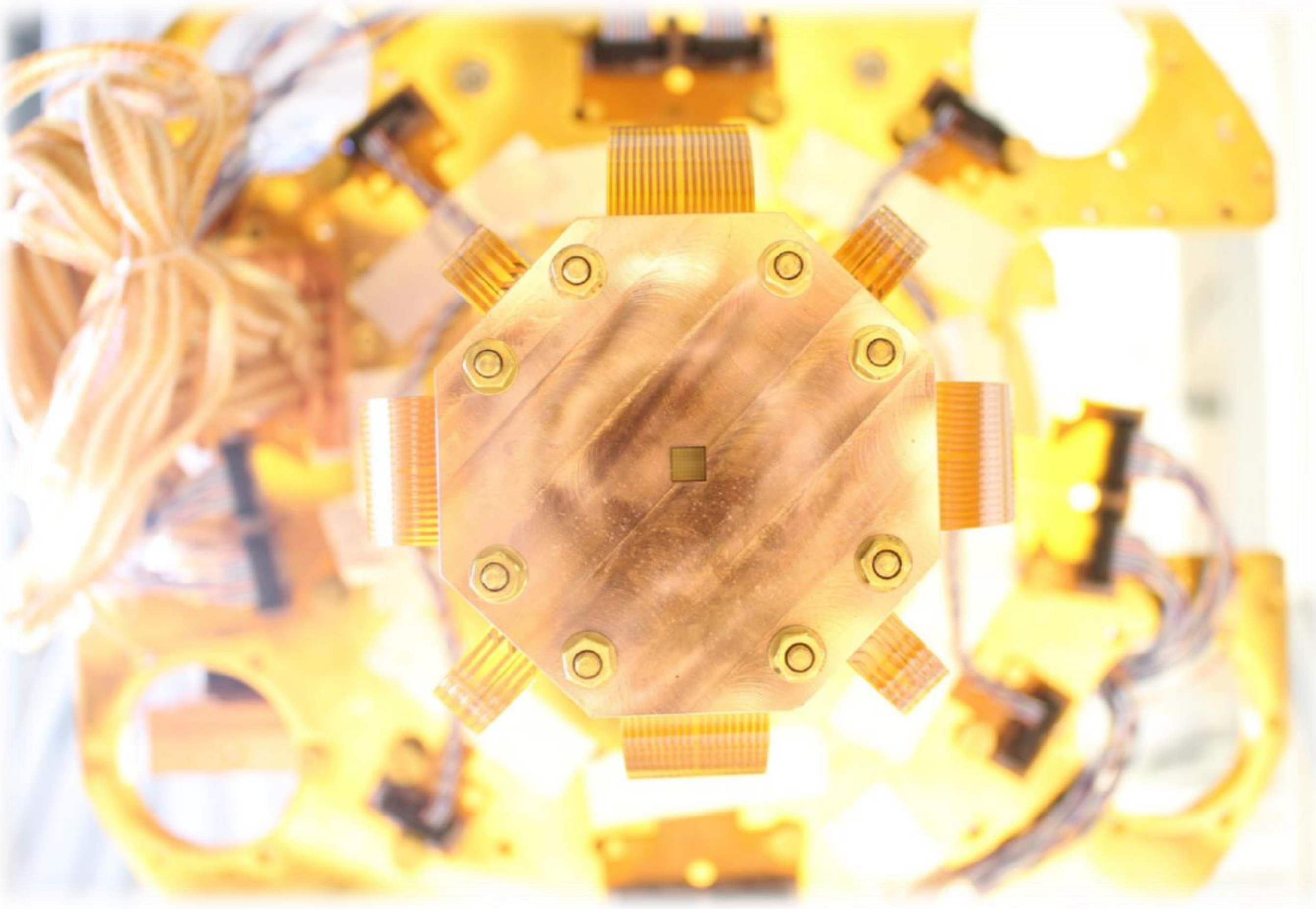
Kirchhoff Institute for Physics
Heidelberg University



UNIVERSITÄT
HEIDELBERG
ZUKUNFT
SEIT 1386

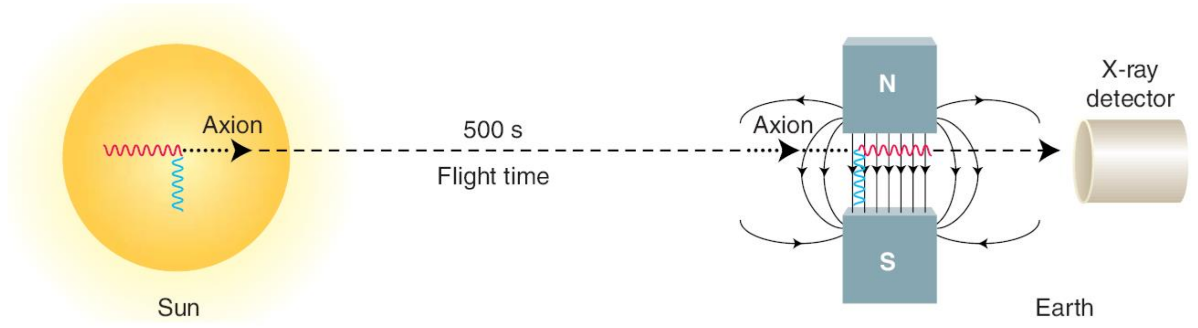
Outline

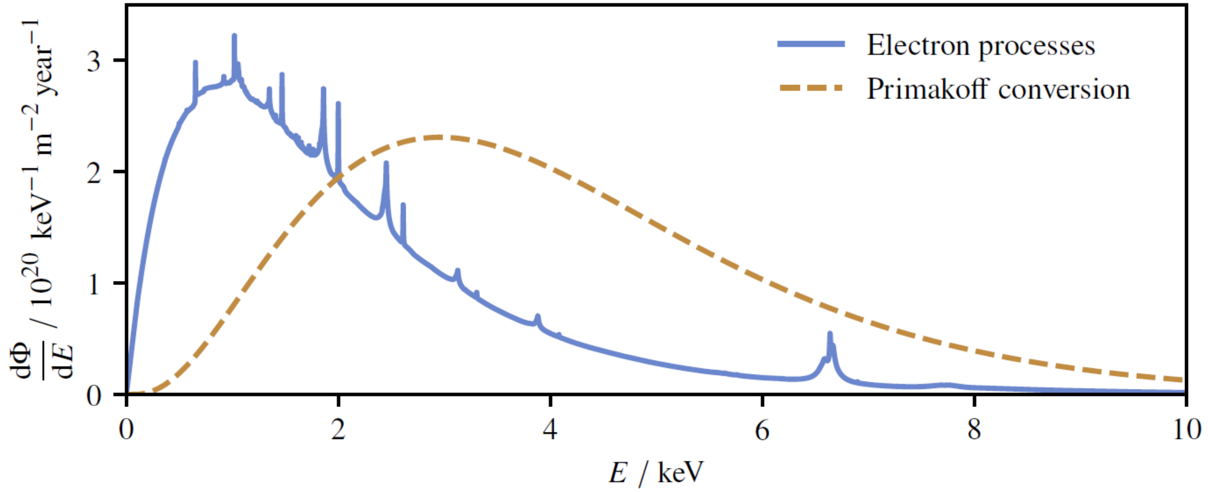
- Helioscope
- Metallic magnetic calorimeter for IAXO
- Post Axion-Detection searches
- Light Dark Matter Searches
- Conclusions



Solar Axions in Helioscope

Search for an evidence for solar axions





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

More details in Julia Vogel's lecture

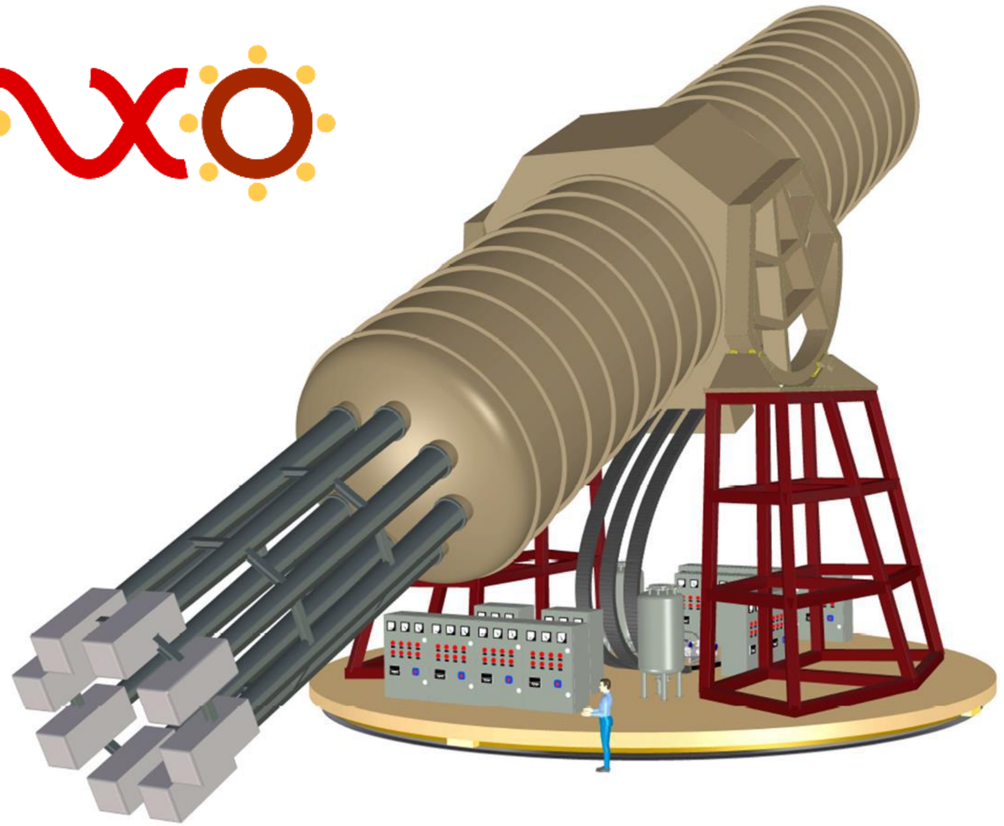
Low background and high efficiency x-ray detectors

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

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

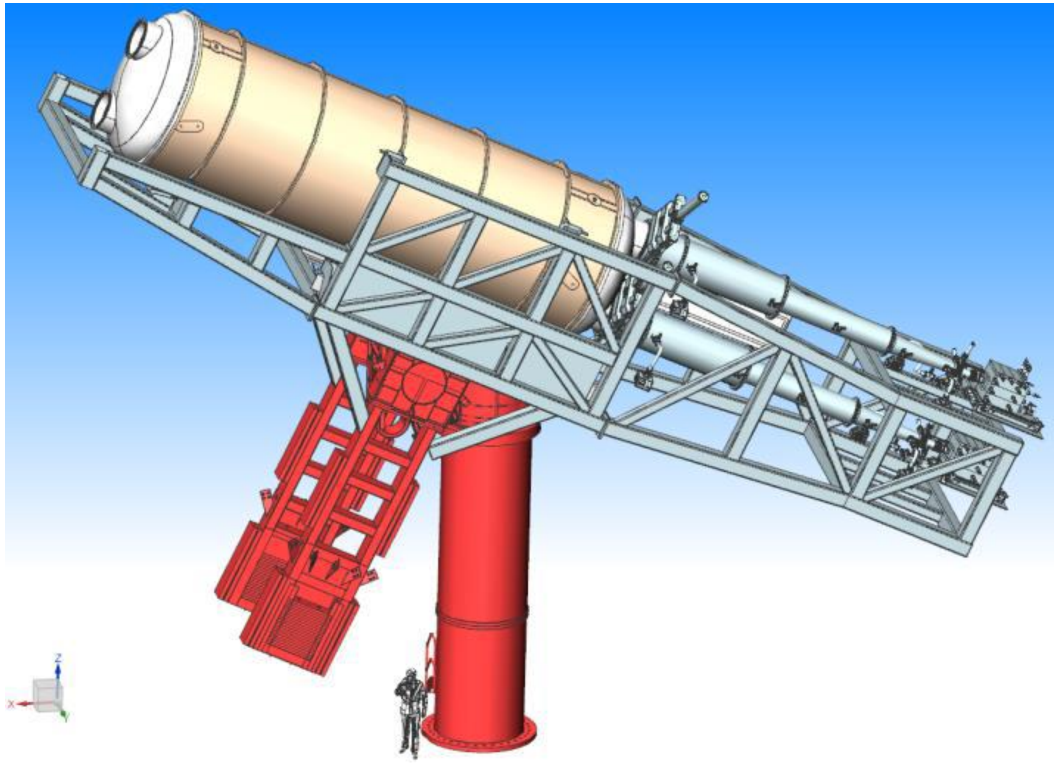
- Based on gamma ray telescopes
- 50% of Sun-tracking time

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!



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

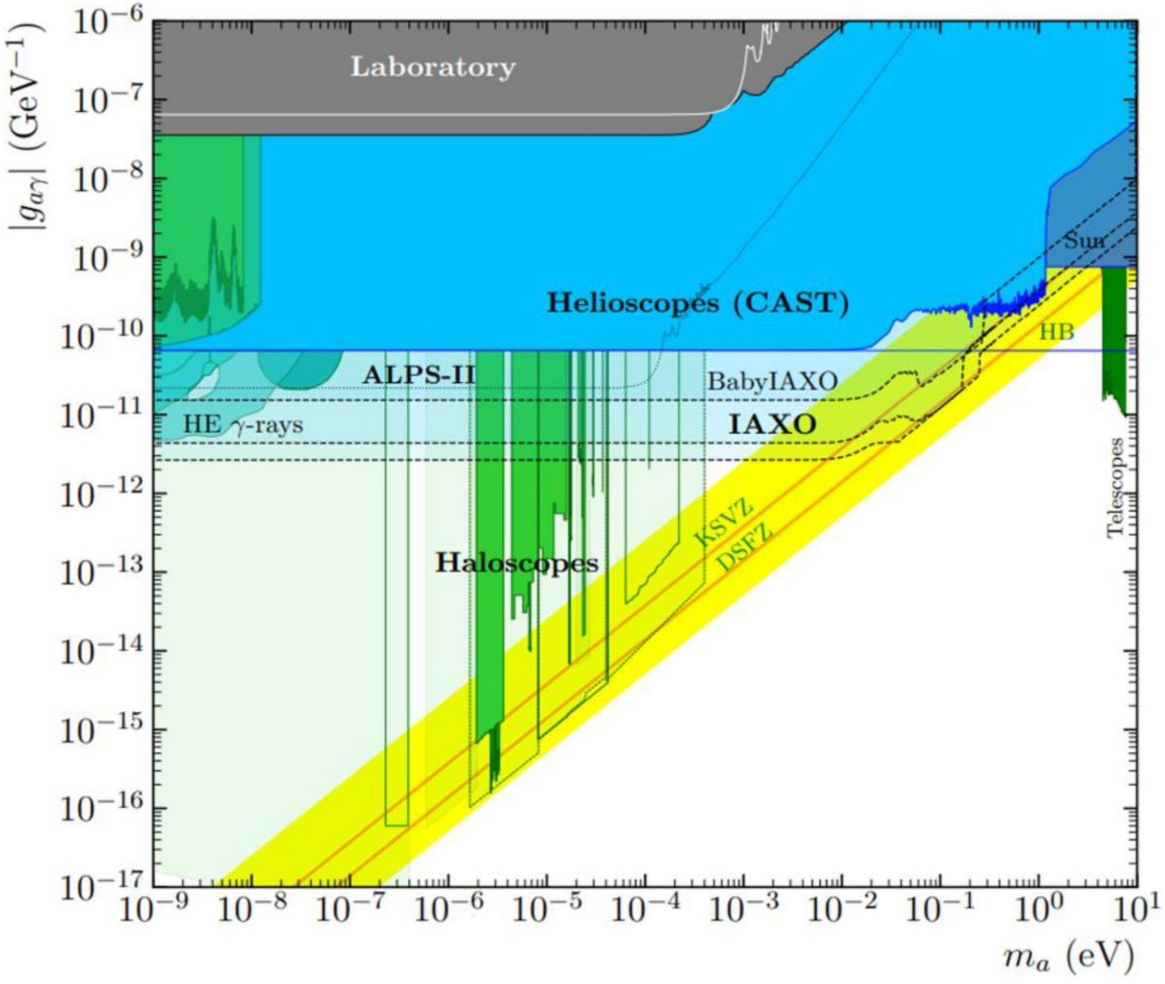
Dedicated X-ray optics
- 0.2 cm² focal spot

Tracking system
- Based on gamma ray telescopes

X-ray detector technologies
- Micromegas (baseline)

Conceptual Design Report
10.1007/JHEP05(2021)137

IAXO & baby-IAXO: Sensitivity Perspectives



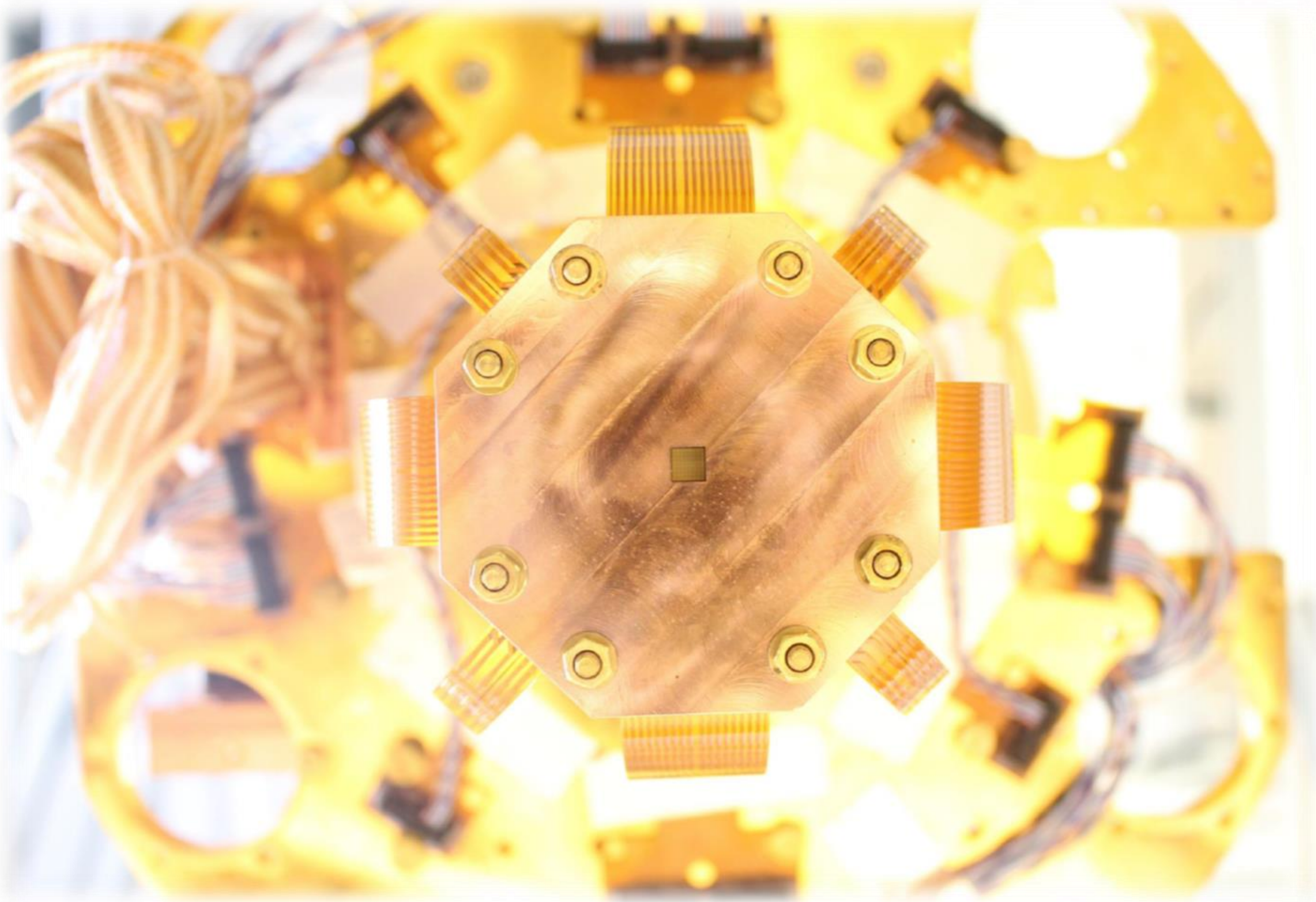
BabyIAXO will be sensitive to realistic QCD axion models!

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

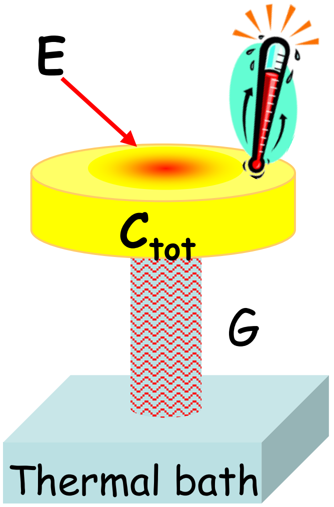
MMC for IAXO



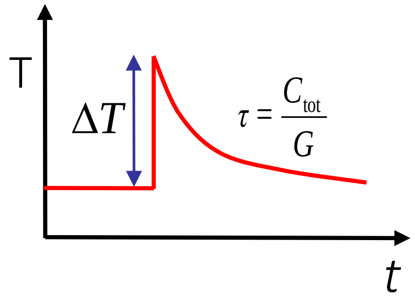
Low Temperature Calorimeters

Near equilibrium detectors

Energy deposition induces increase of temperature



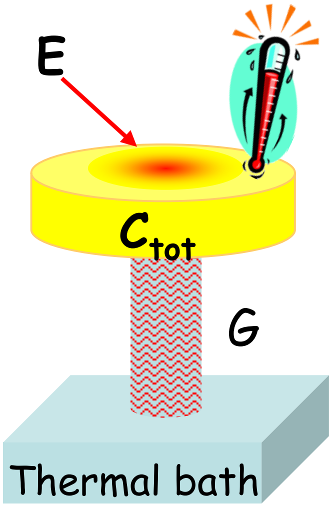
$$\Delta T \cong \frac{E}{C_{tot}}$$



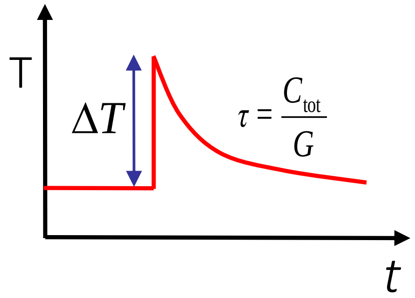
Low Temperature Calorimeters

Near equilibrium detectors

Energy deposition induces increase of temperature



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

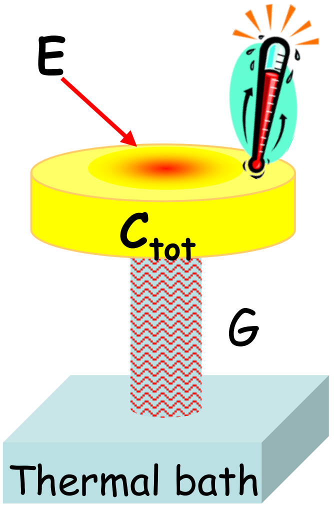


- Very small volume
- Working temperature below 100 mK
  - small specific heat
  - small thermal noise
- **Very sensitive temperature sensors**

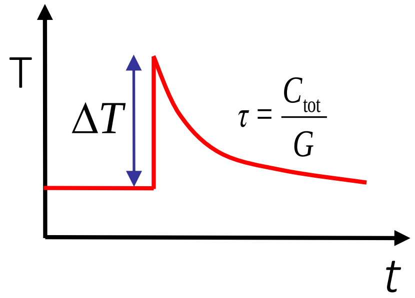
Low Temperature Calorimeters

Near equilibrium detectors

Energy deposition induces increase of temperature

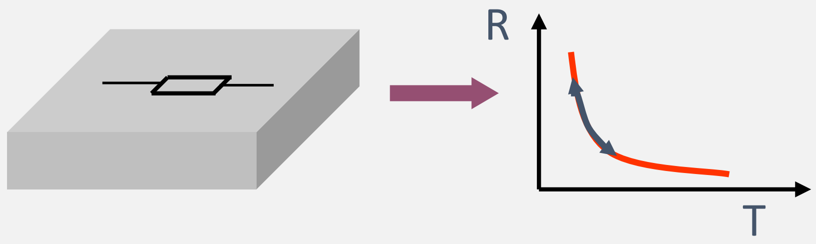


$$\Delta T \cong \frac{E}{C_{tot}}$$

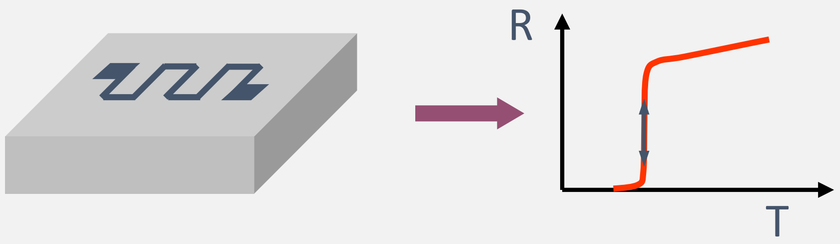


- Very small volume
- Working temperature below 100 mK
  small specific heat
  small thermal noise
- **Very sensitive temperature sensors**

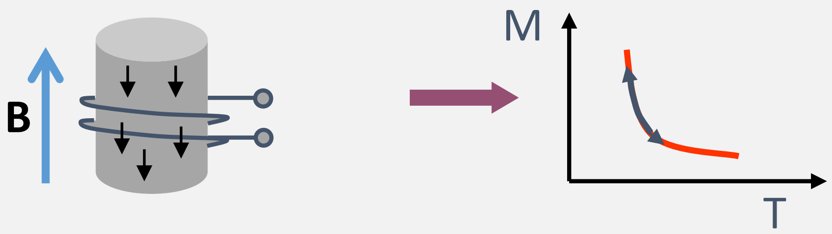
Resistance of highly doped semiconductors



Resistance at superconducting transition,TES



Magnetization of paramagnetic material, MMC



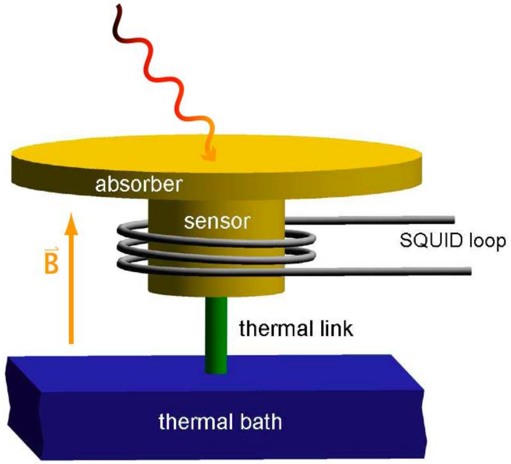
Metallic Magnetic Calorimeters

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

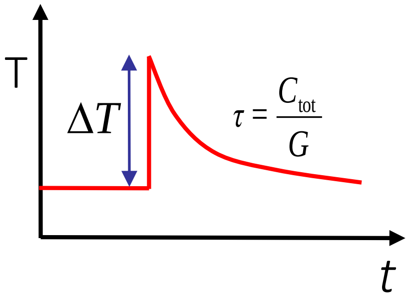
A.Fleischmann et al.,
AIP Conf. Proc. **1185** (2009) 571

Paramagnetic temperature sensor

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



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



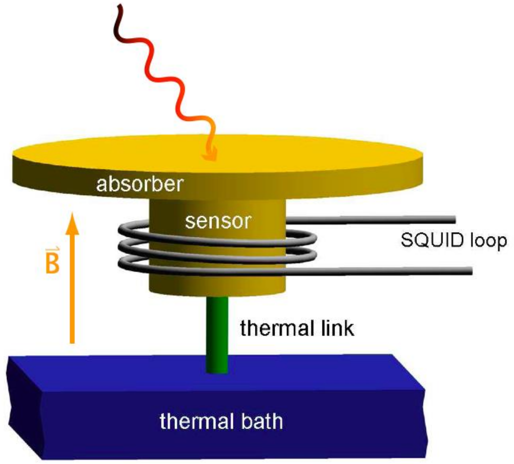
Metallic Magnetic Calorimeters

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

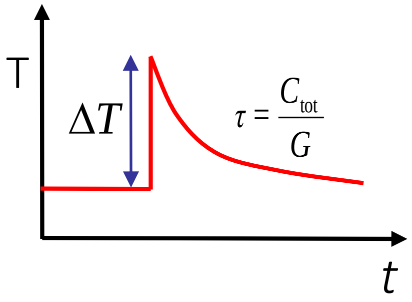
A.Fleischmann et al.,
AIP Conf. Proc. **1185** (2009) 571

Paramagnetic temperature sensor

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



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



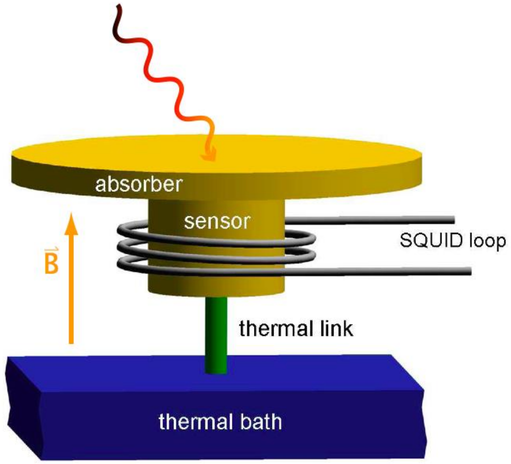
Metallic Magnetic Calorimeters

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

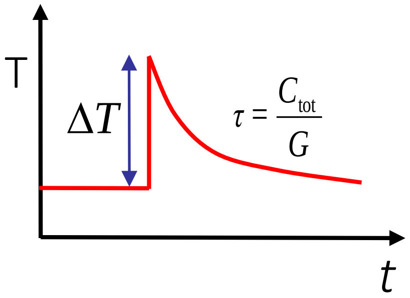
A.Fleischmann et al., *AIP Conf. Proc.* **1185** (2009) 571

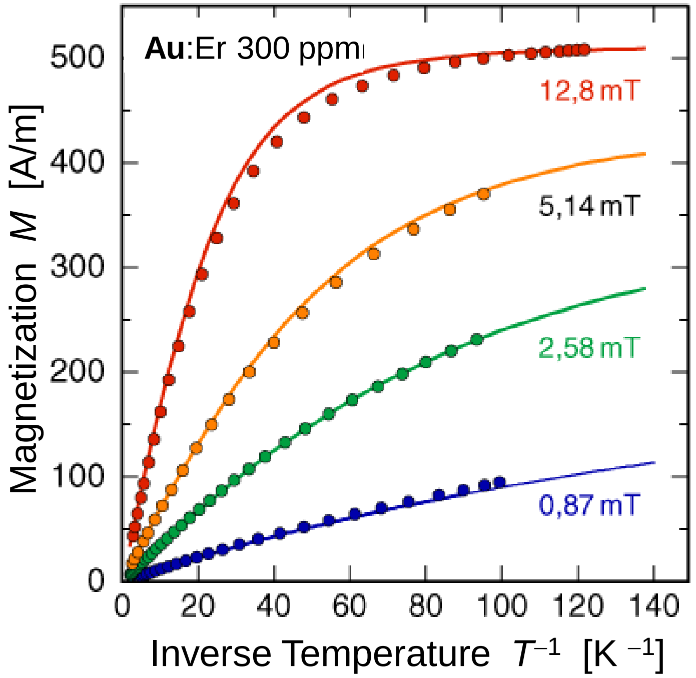
Paramagnetic temperature sensor

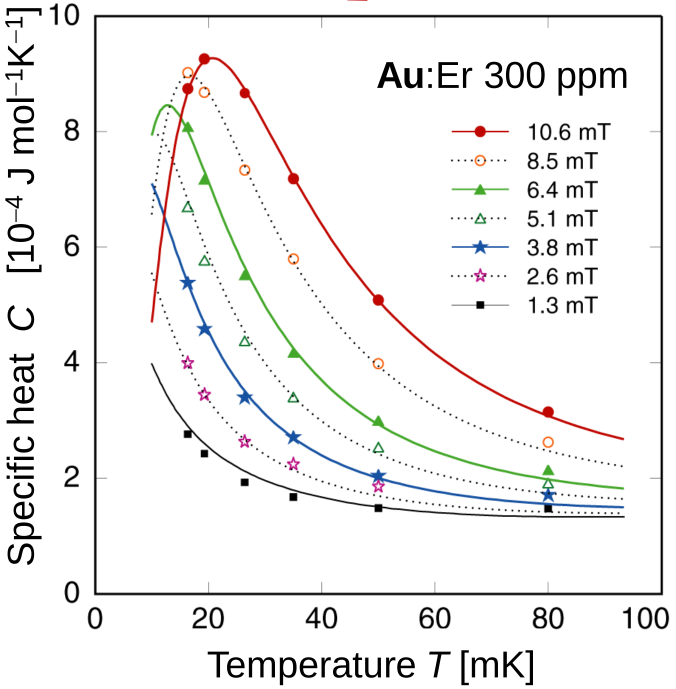
Dilute alloy Au:Er or Ag:Er (Er concentration: a few hundred ppm)



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





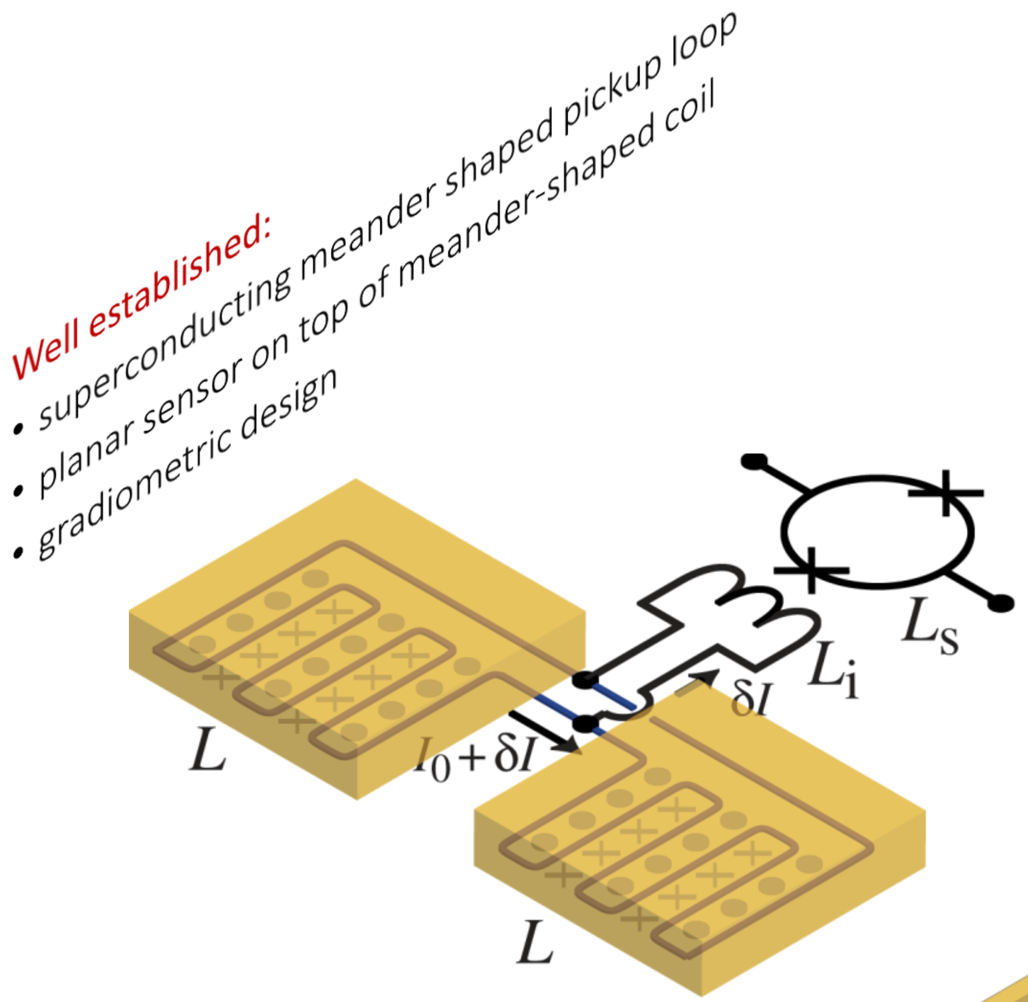


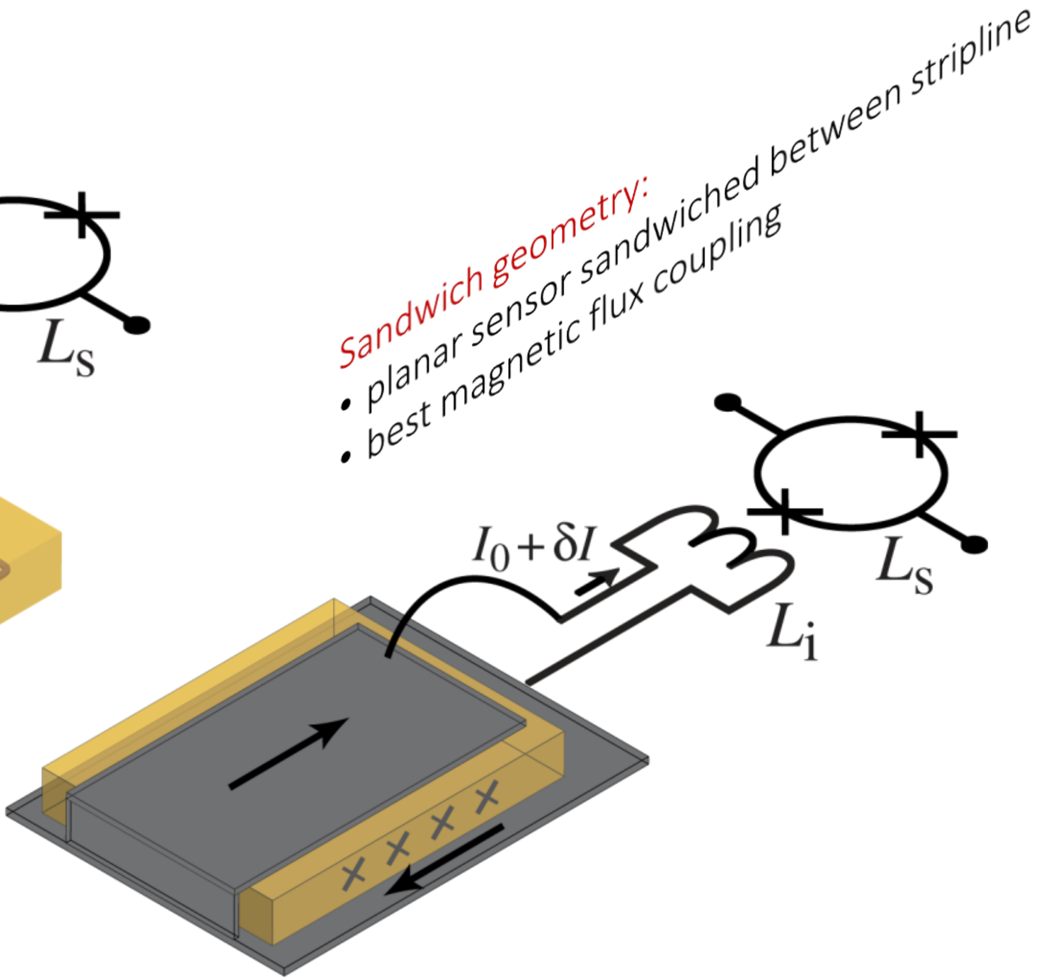
Very good agreement between data and theoretical expectation for interacting spin system

Optimization of detector geometries for wished applications

Detector geometries

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



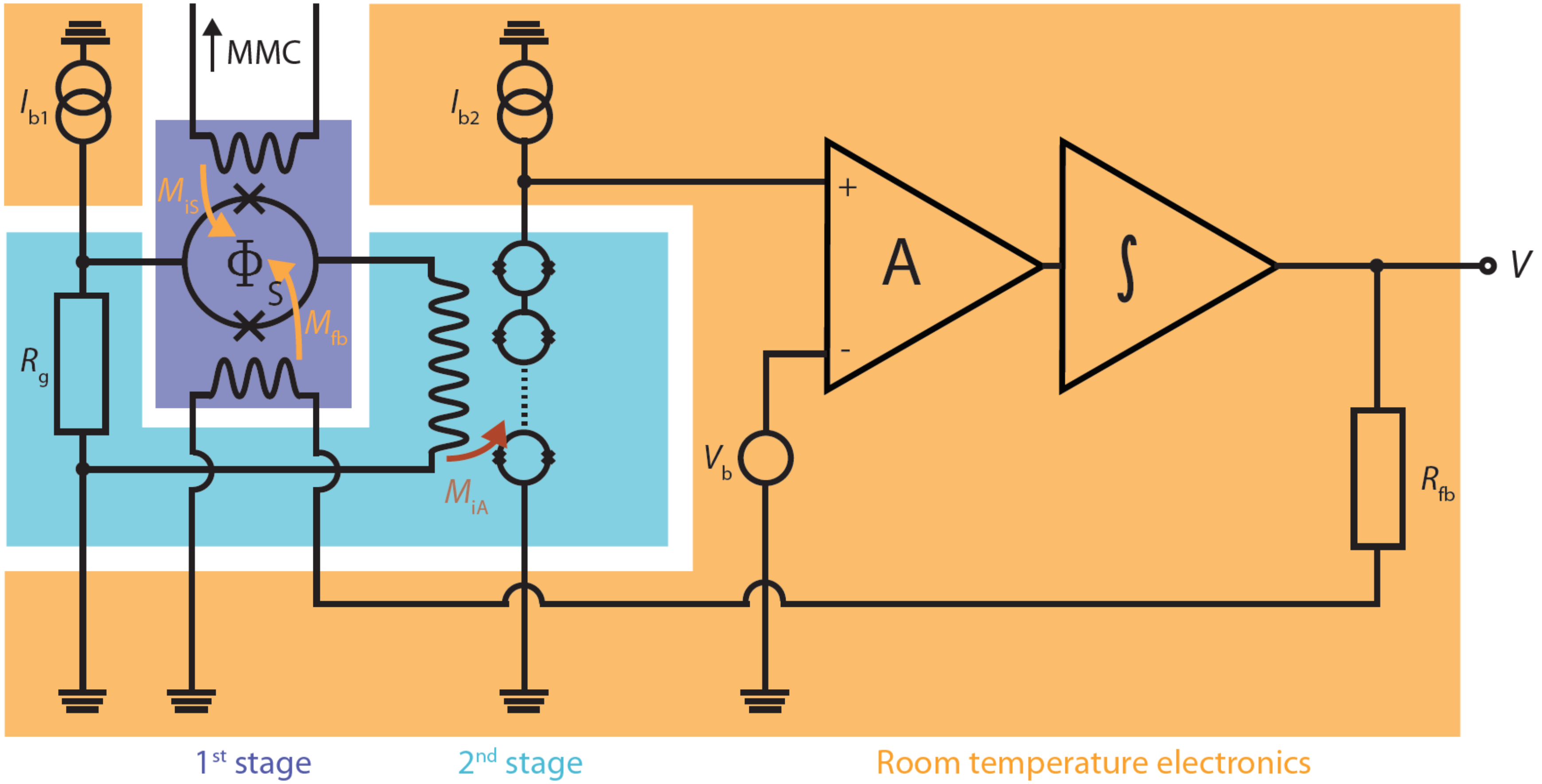


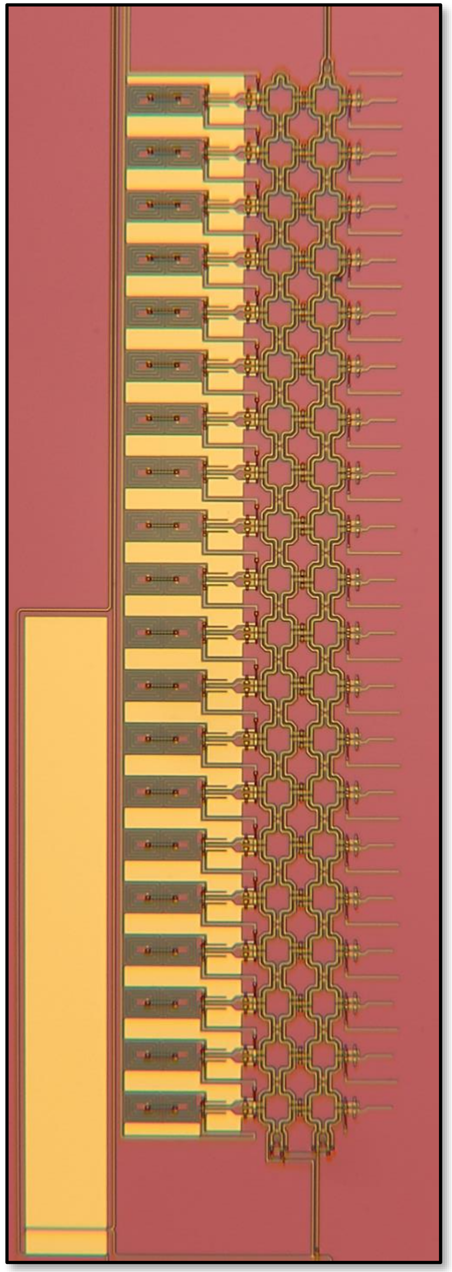
MMC readout

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

low noise

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

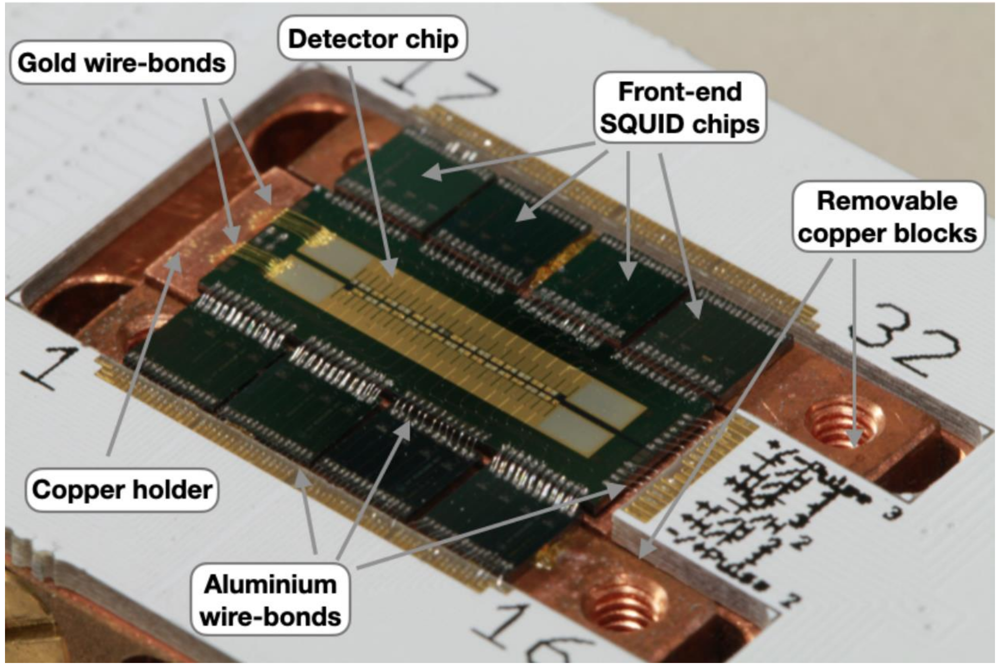




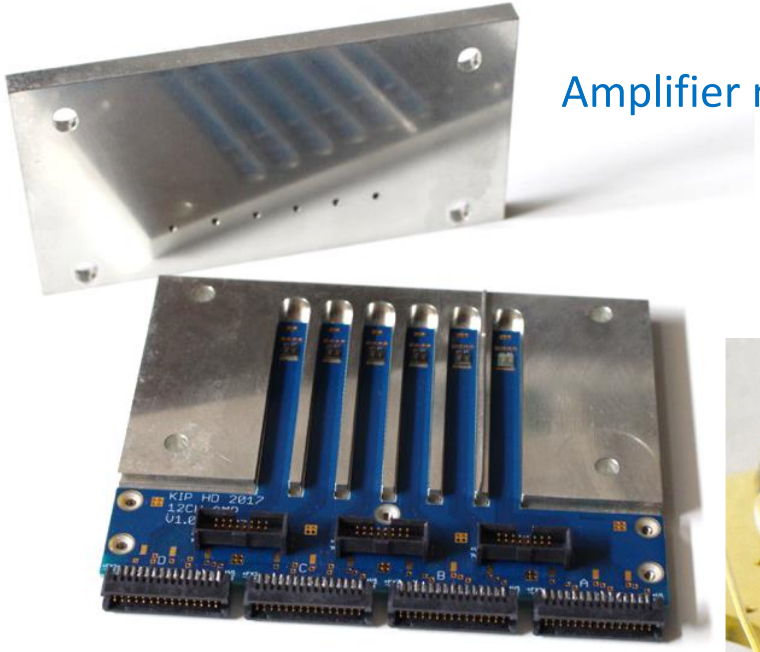
In house produced SQUID array

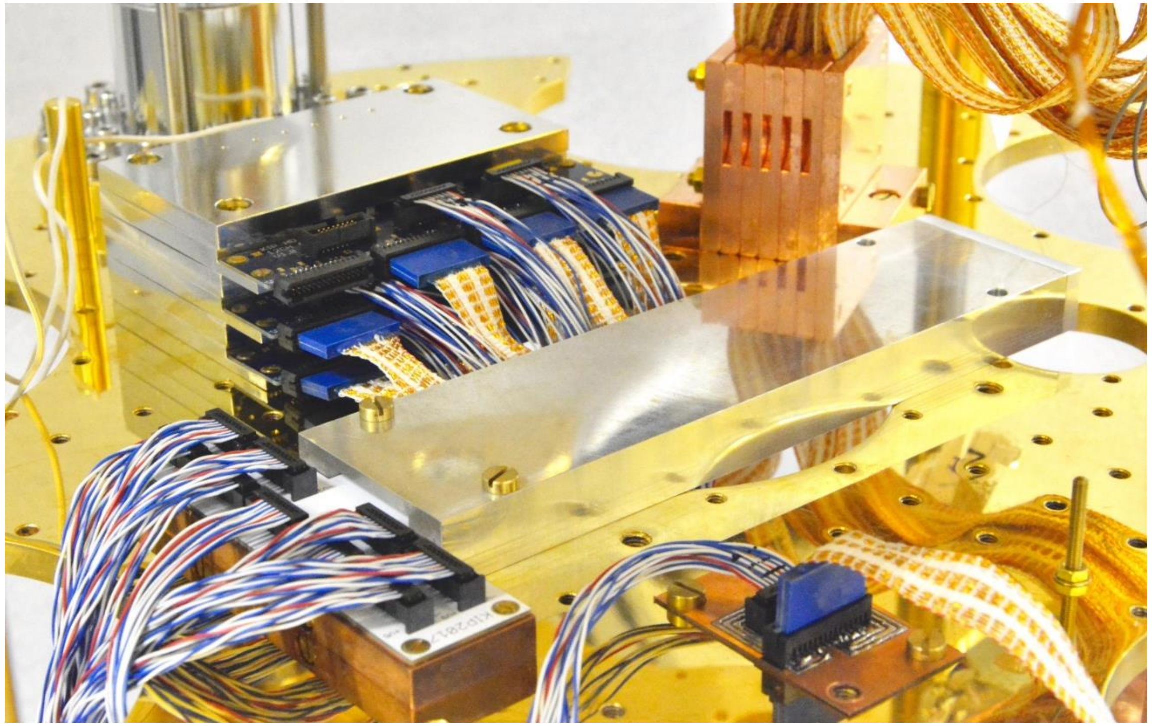
MMC readout

Detector module



Amplifier module

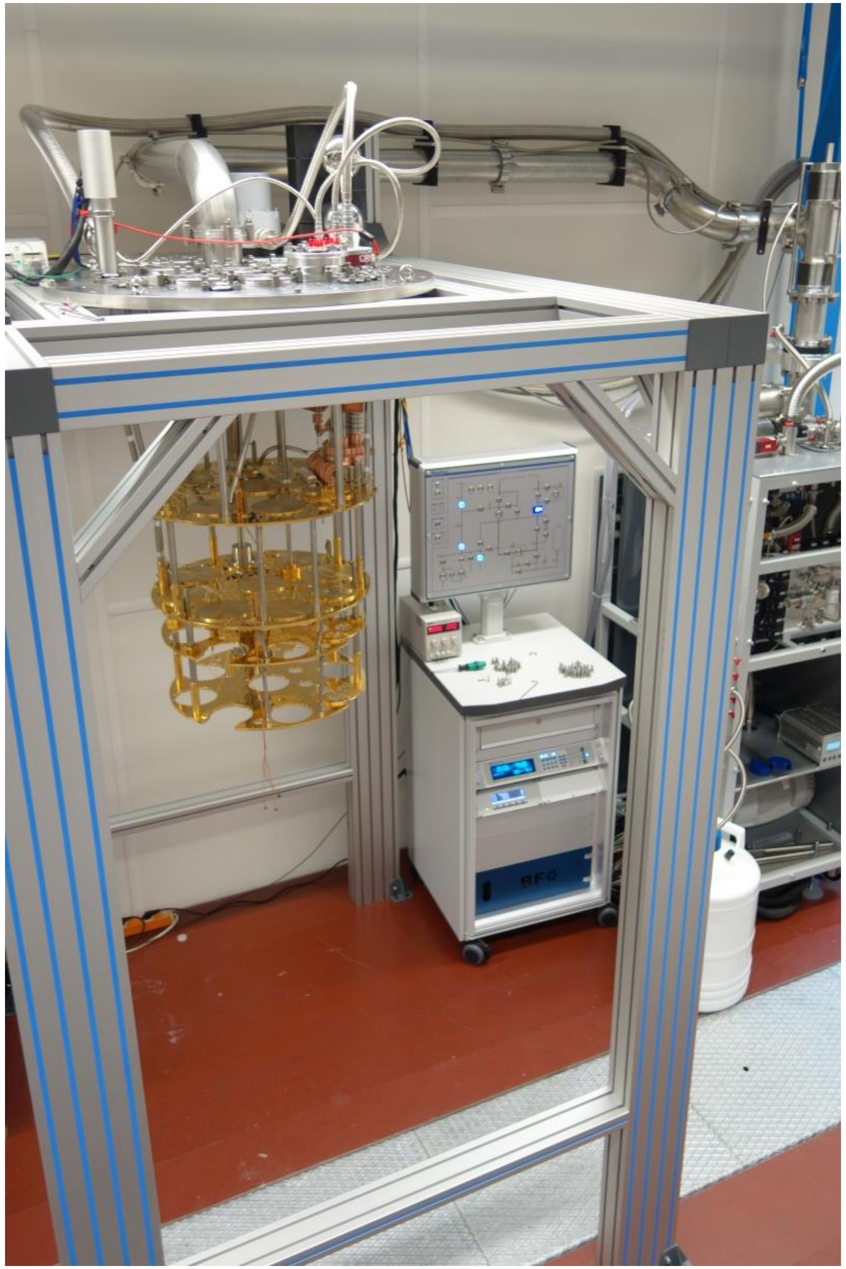


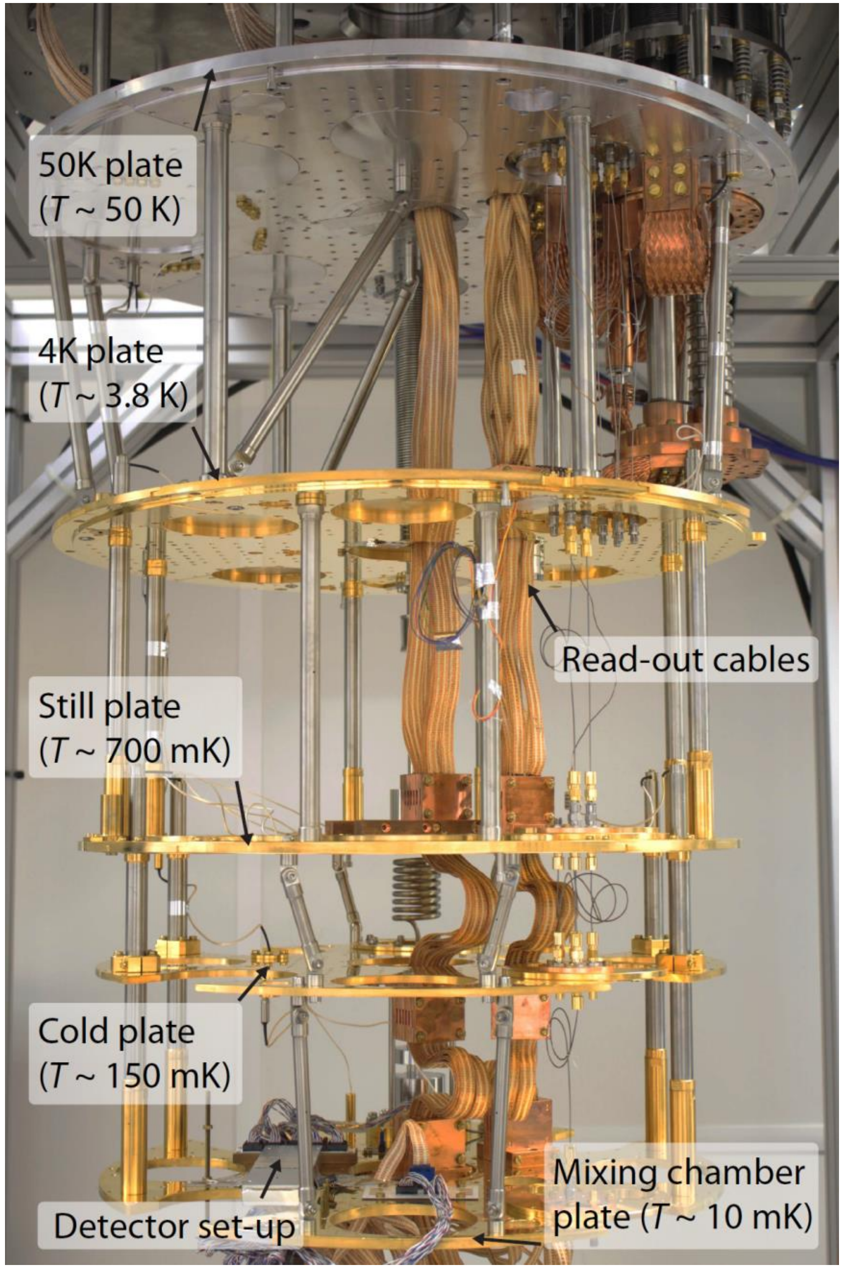


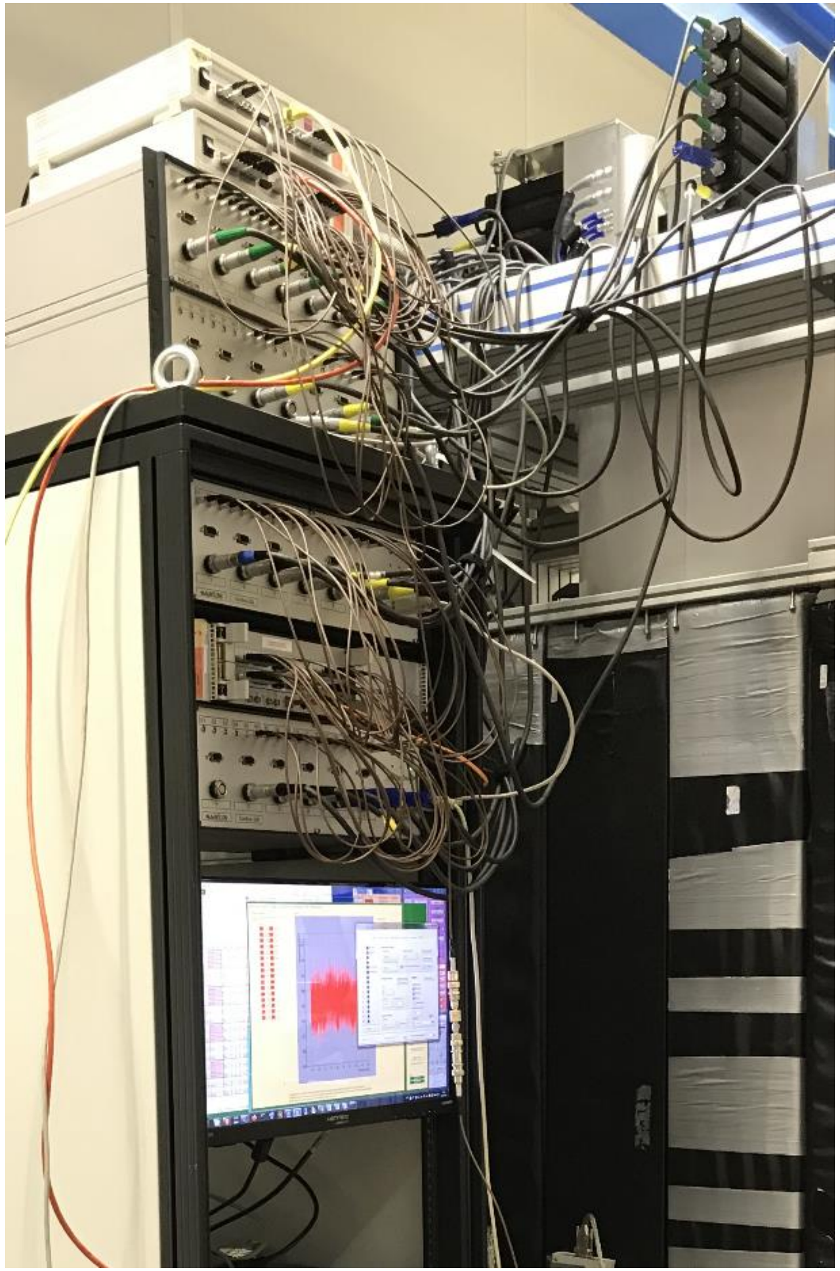
Detector and amplifier module mounted on the mixing chamber plate

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

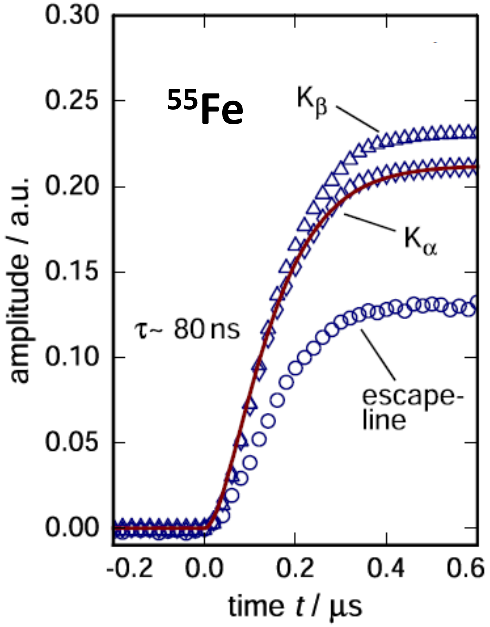
MMC readout

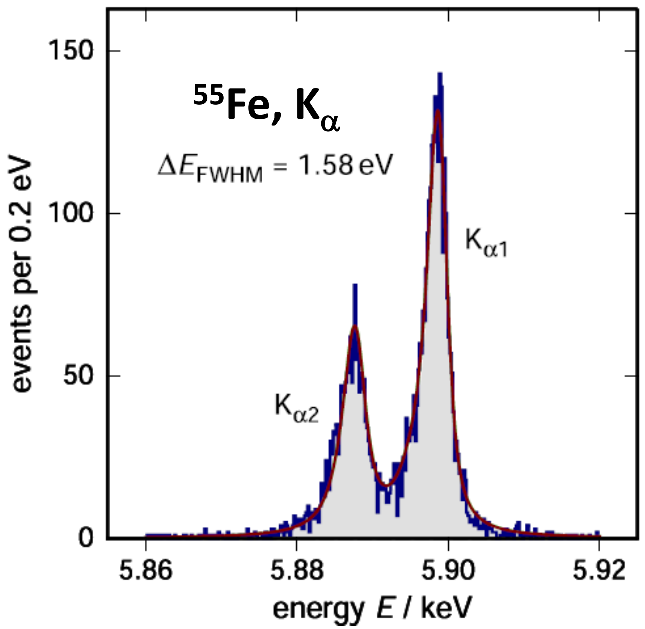


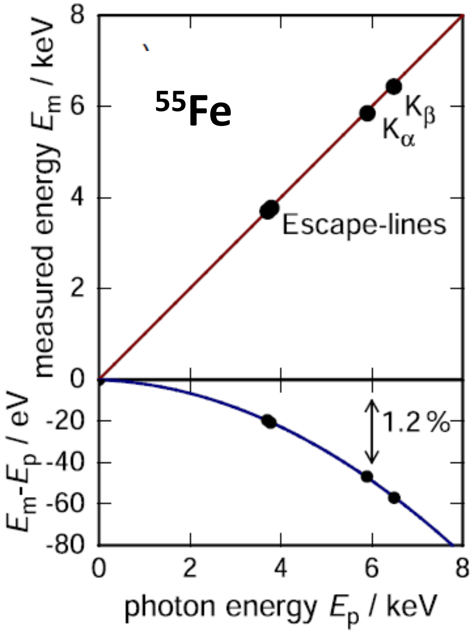

50K plate
(T ~ 50 K)
4K plate
(T ~ 3.8 K)
Read-out cables
Still plate
(T ~ 700 mK)
Cold plate
(T ~ 150 mK)
Mixing chamber
plate (T ~ 10 mK)
Detector set-up



Performance





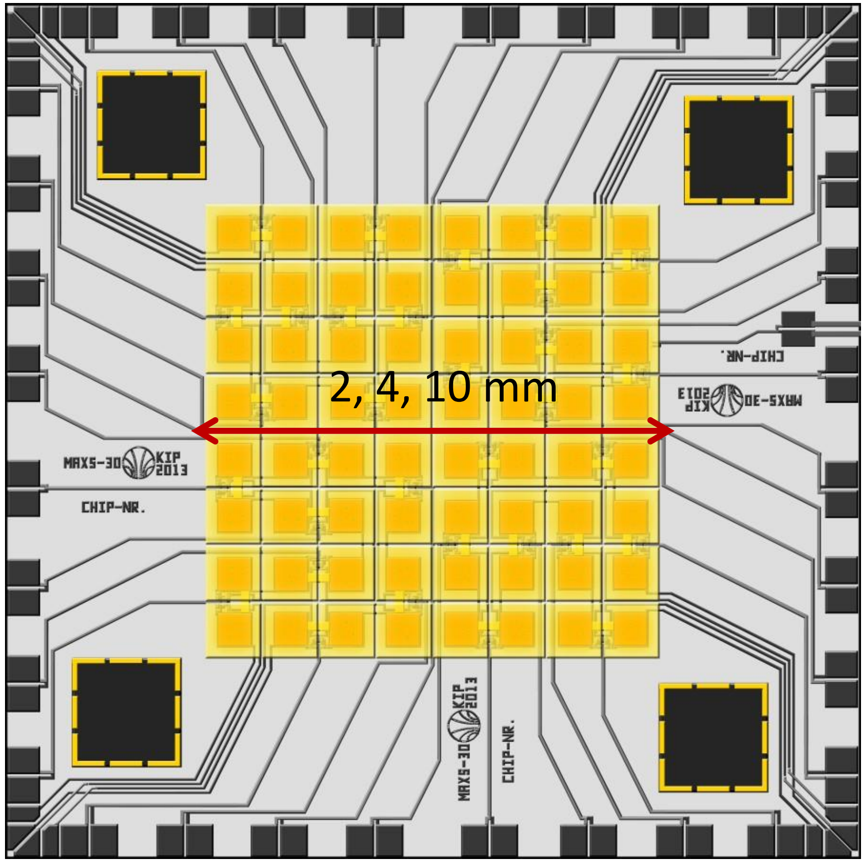


Fast risetime
→ Reduction un-resolved pile-up
→ coincidence study

Extremely good energy resolution
→ identification of small structures

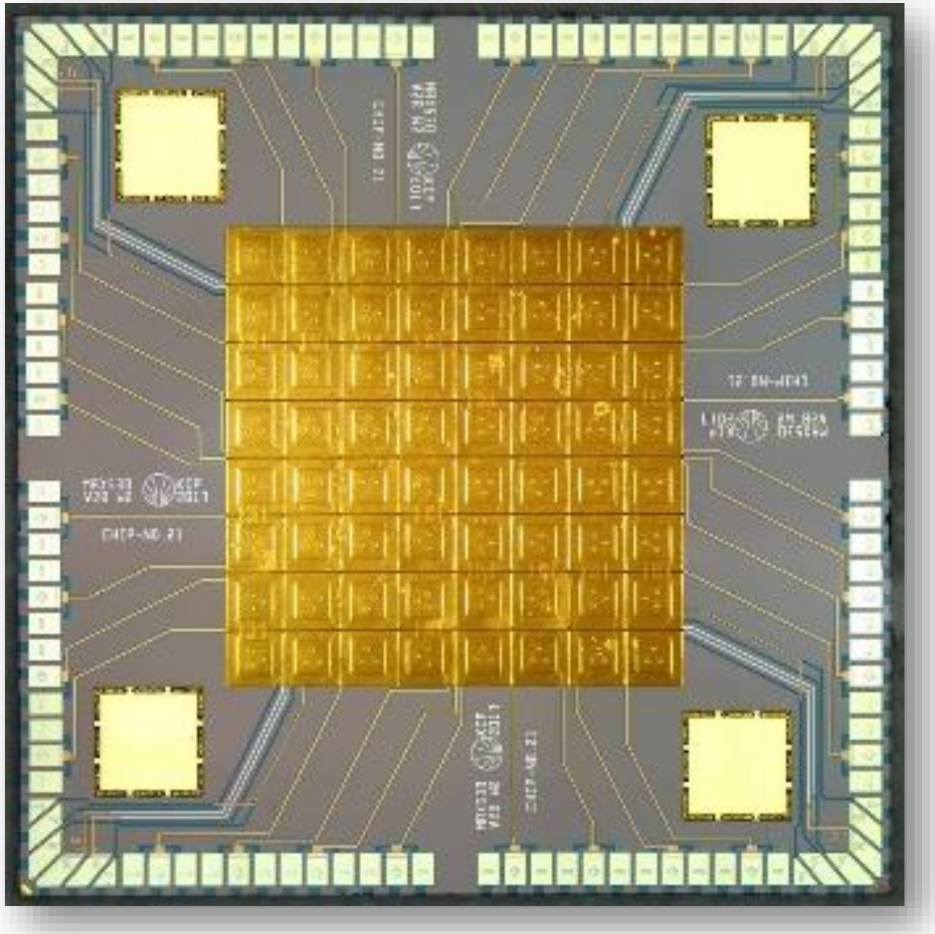
Excellent linearity
→ precise definition of the energy scale

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

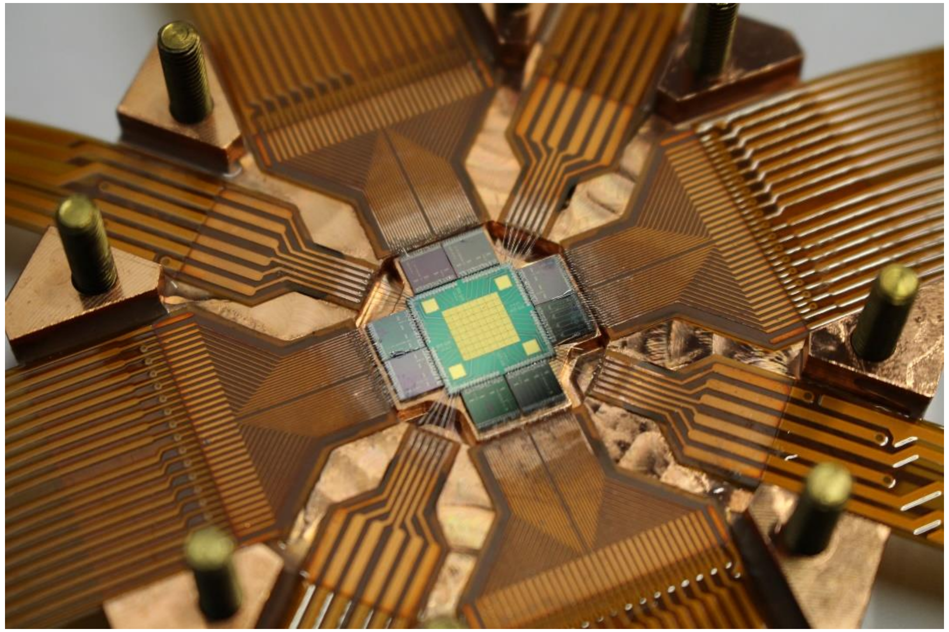


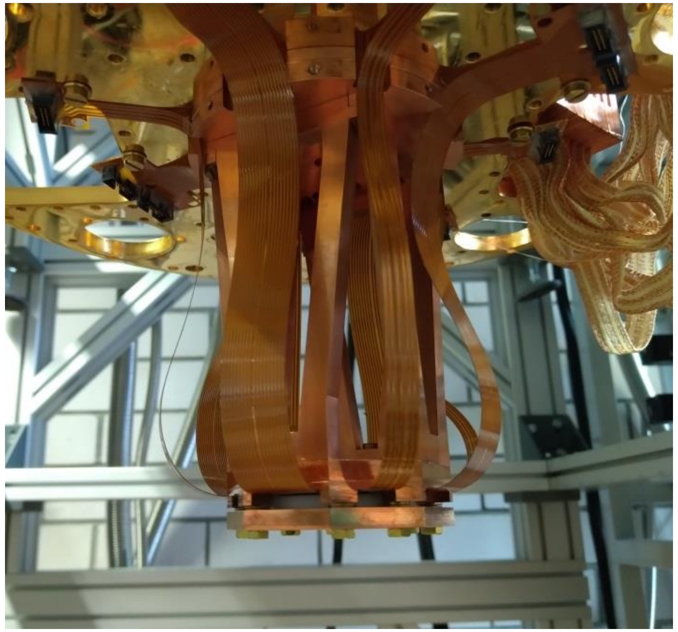
8 mm

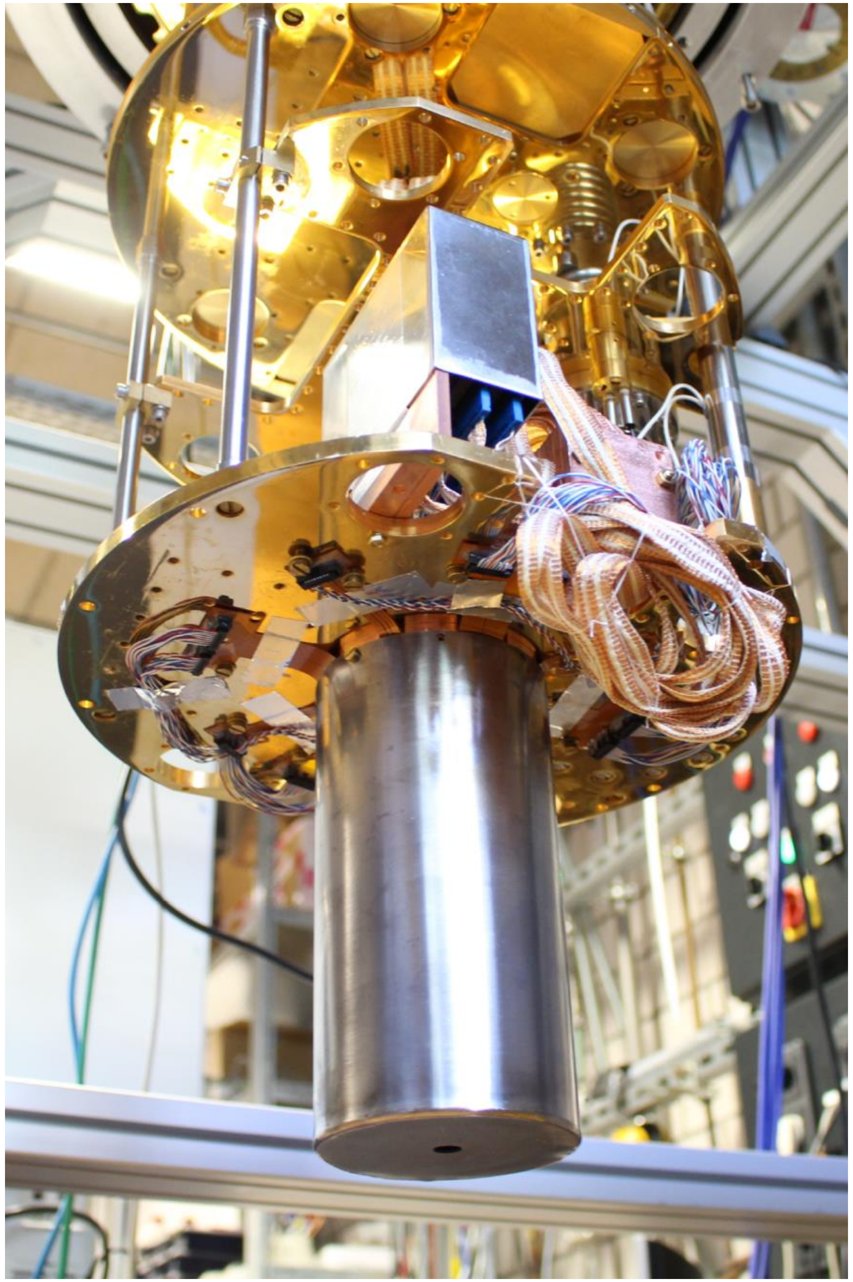
maXs-30

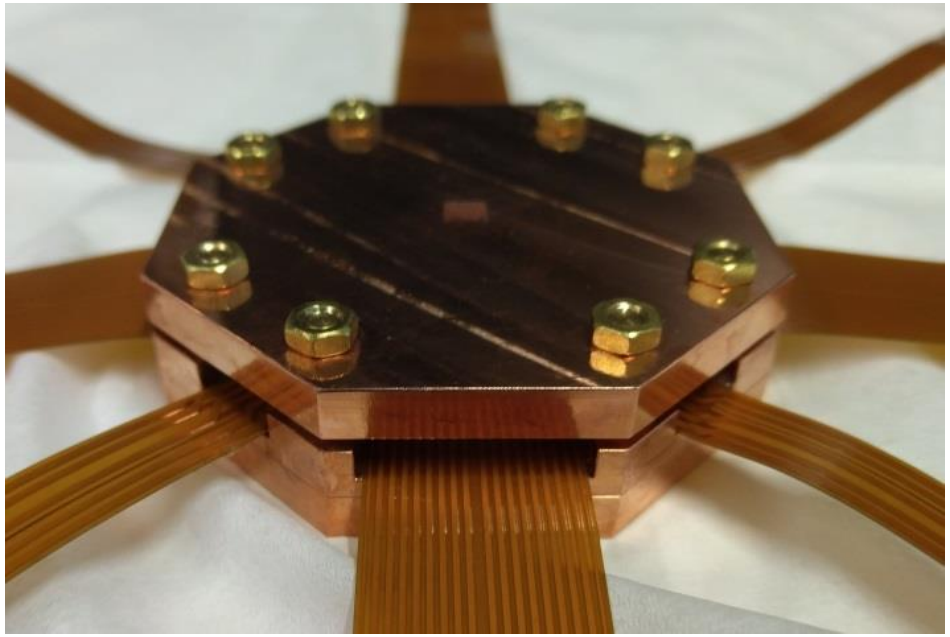
Absorber size: 500 × 500 × 30 µm^3

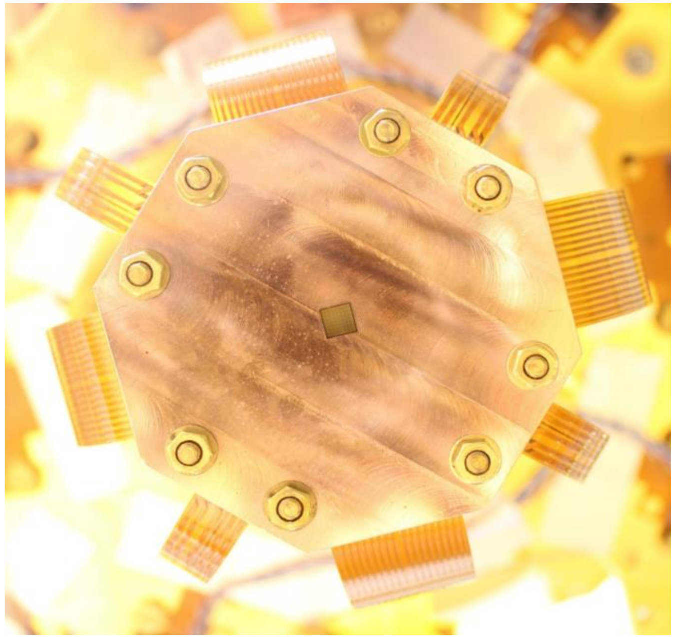
maXs-30 set-up for IAXO



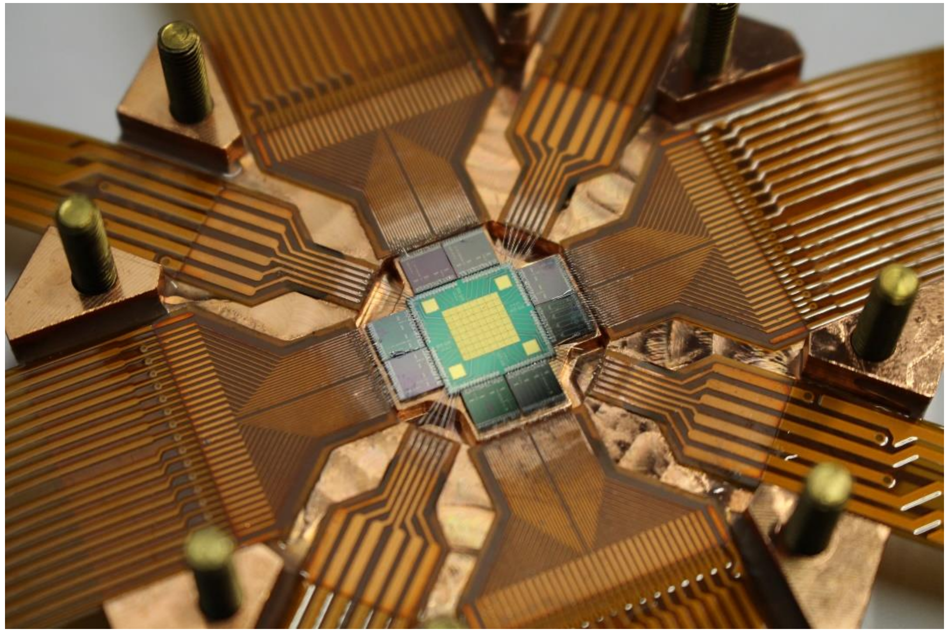


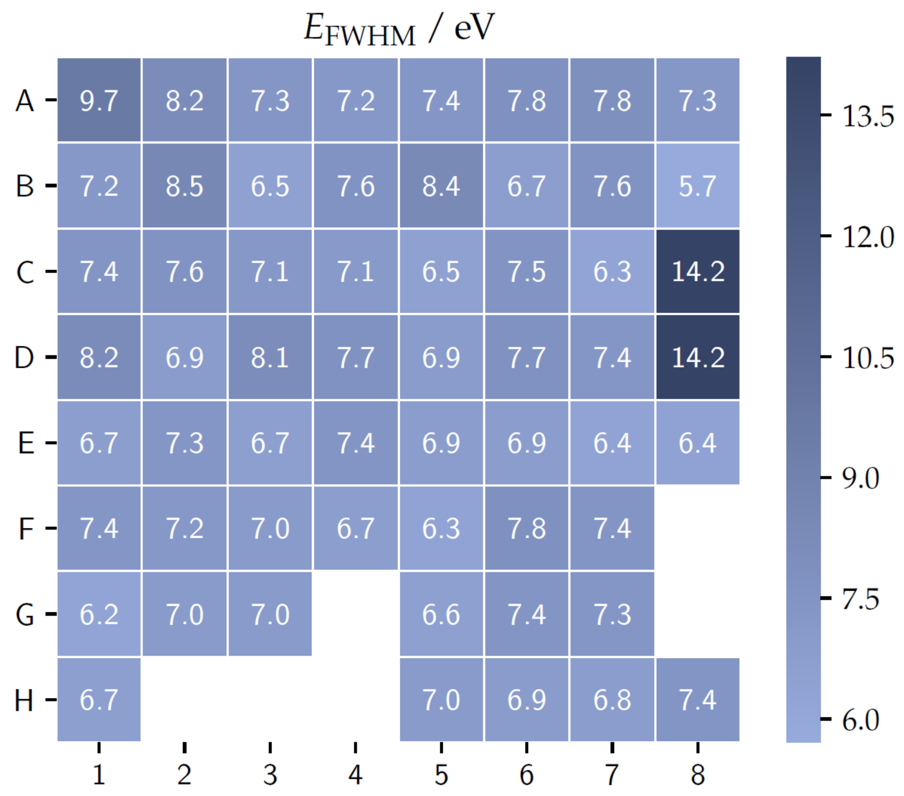




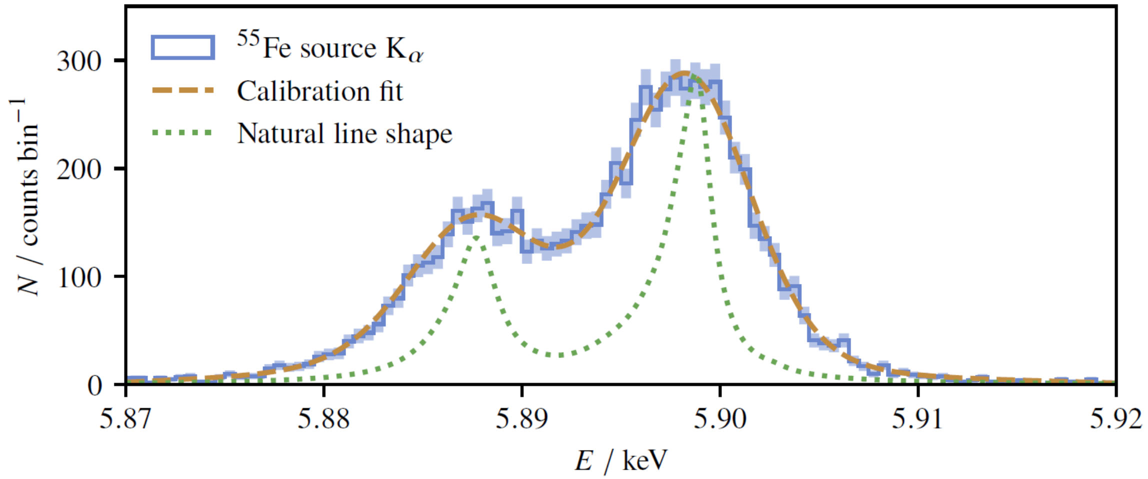


maXs-30 set-up for IAXO





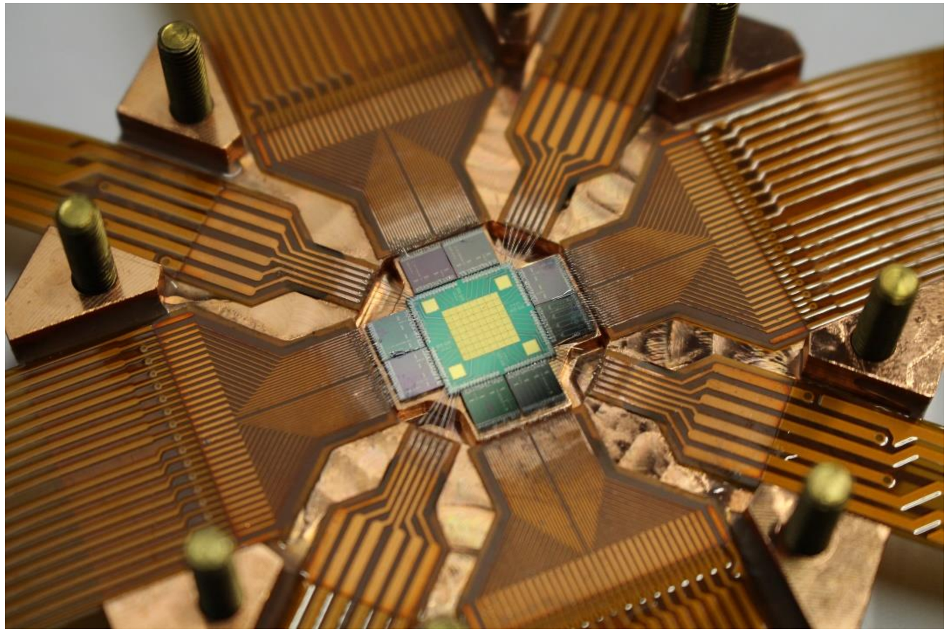
^{55}Fe calibration source
Stopping power @10 keV ~100%



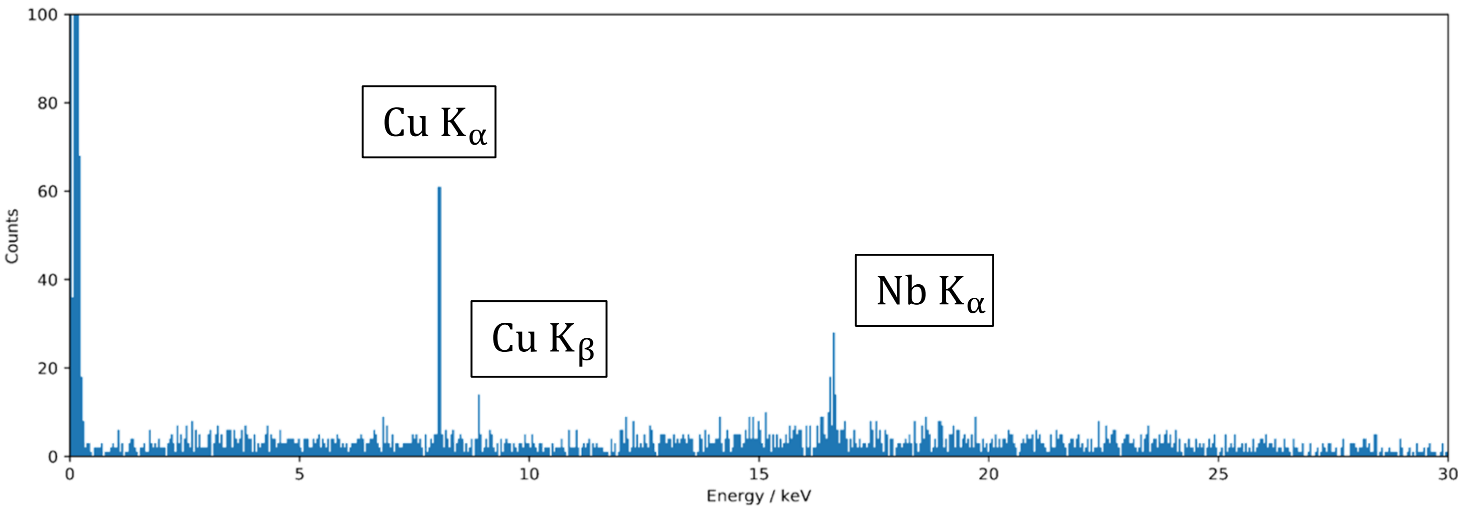
- Homogeneous performance over the array
- Stable operation over 1 month

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

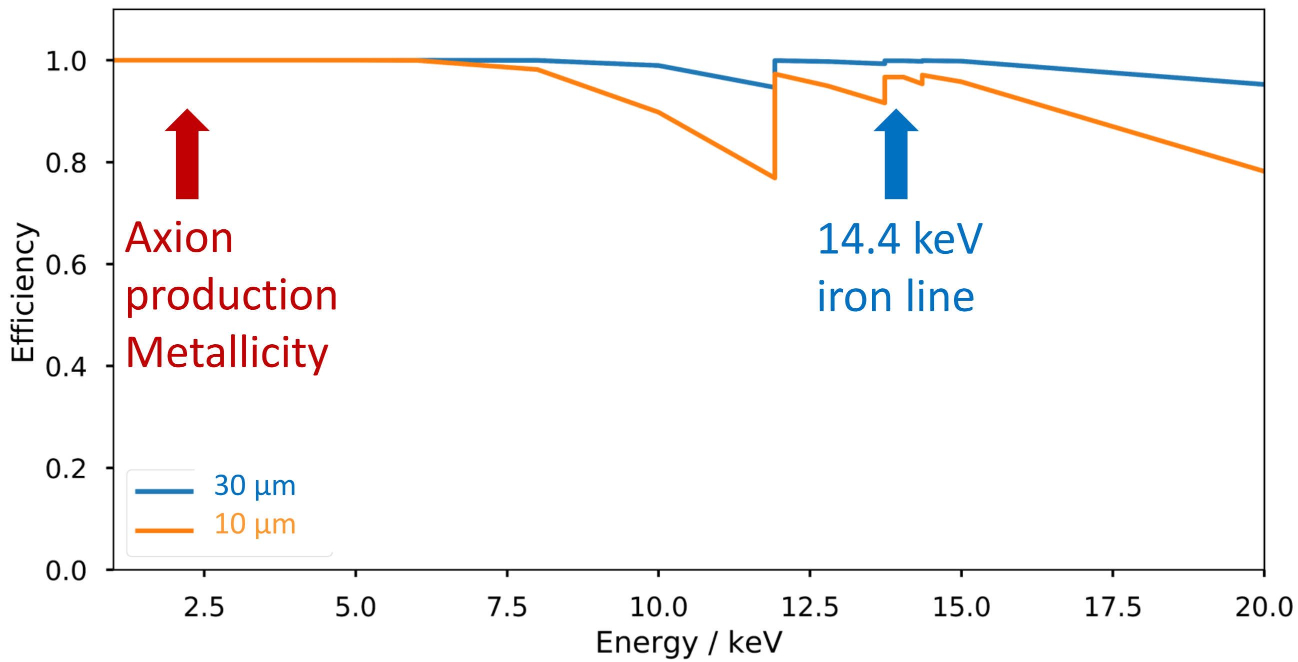
D. Unger et al., *JINST* **16** (2021) P06006,
arXiv:2010.15348 [physics.ins-det]

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

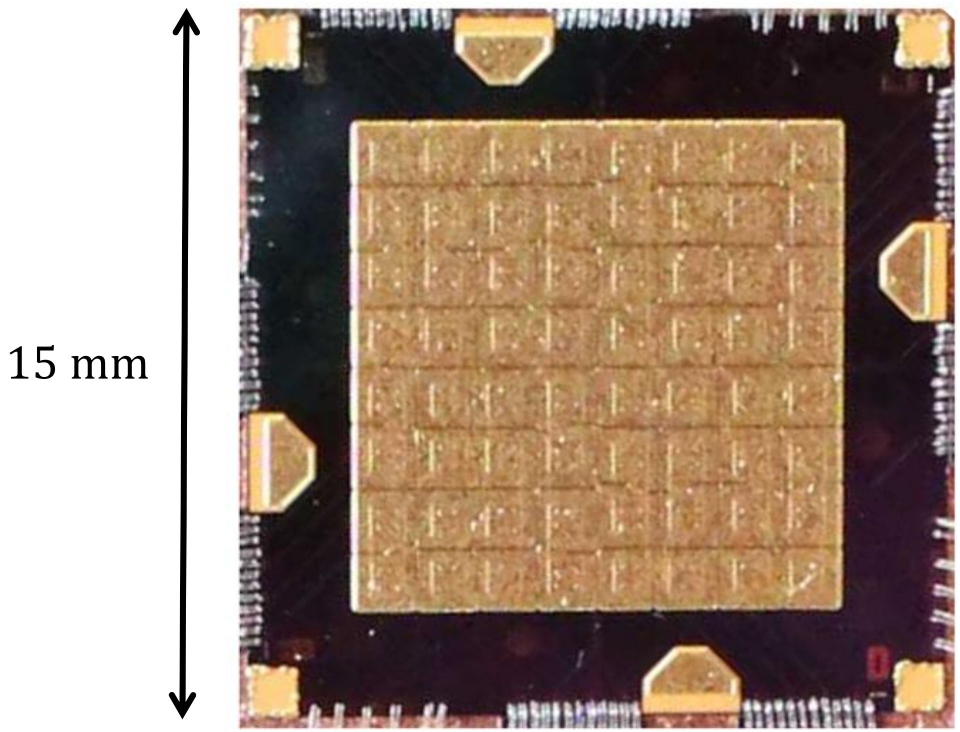
From maXs-30 to maXs-100



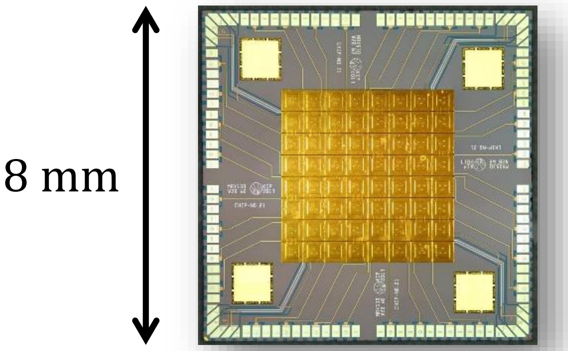
Au absorber volume can be adjusted for the particles to be detected

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

maXs-100



maXs-30



Same design, but scaled up!

MMCs in IAXO: Challenges

Detector challenges:

- ☑ High efficiency in energy range $0 \ldots 15\ \mathrm{keV}$
- ☑ 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:

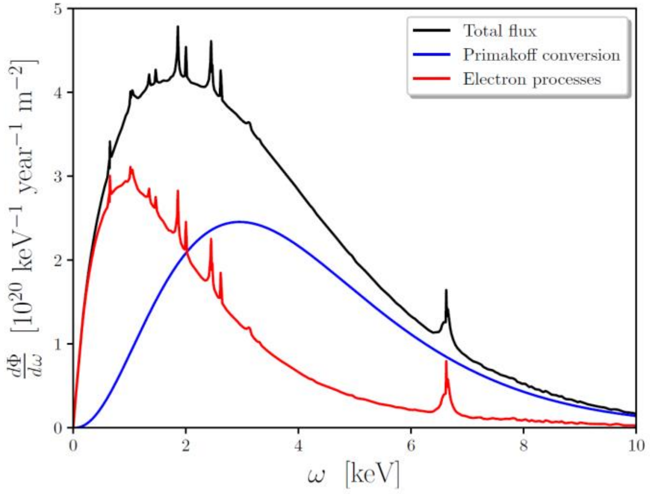
- ❑ Reliable operation @ $20\ \mathrm{mK}$
- ❑ Tiltable to 30°

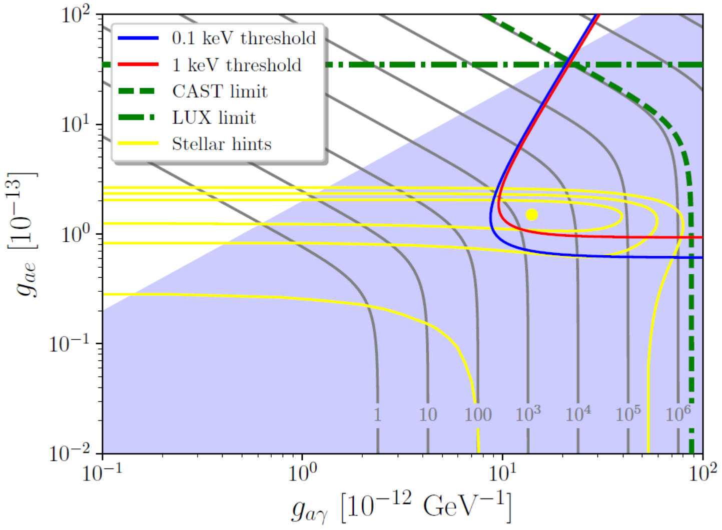
} existing technology

Post-discovery investigation

Distinguishing Axion Models with IAXO

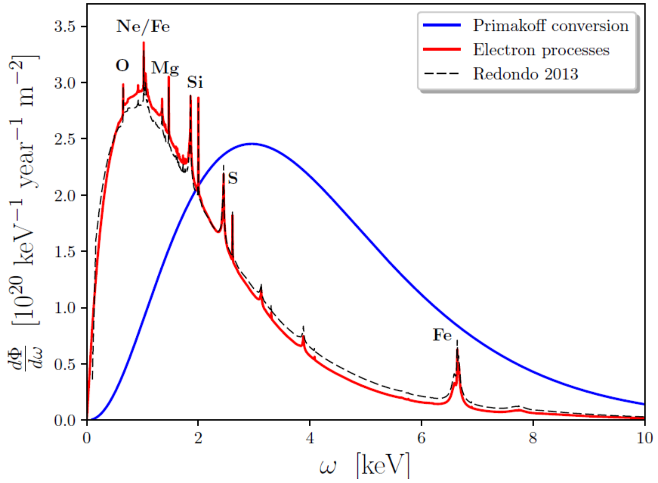
J. Jaeckel and L. J. Thormaehlen,
JCAP 03 (2019) 039

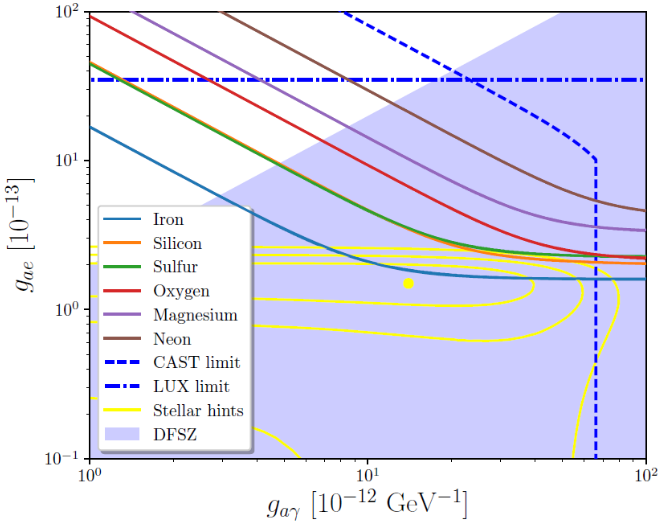




Solar metallicity

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

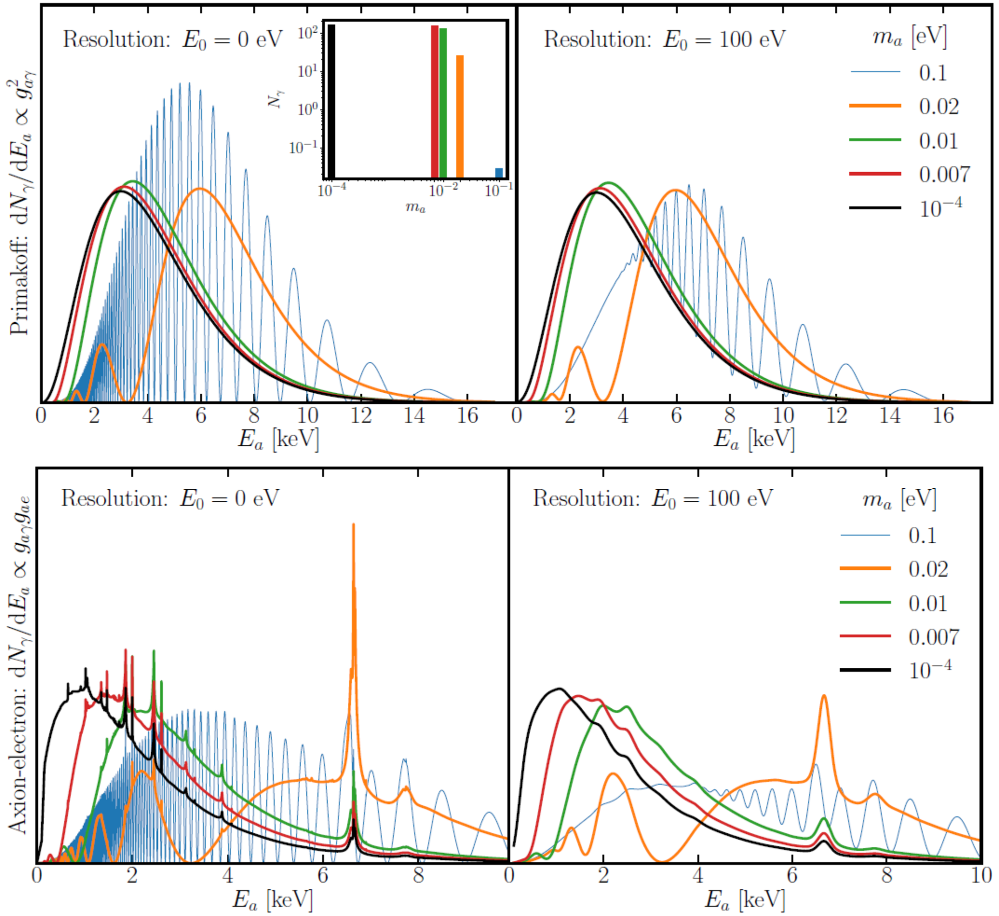




Post-discovery investigation

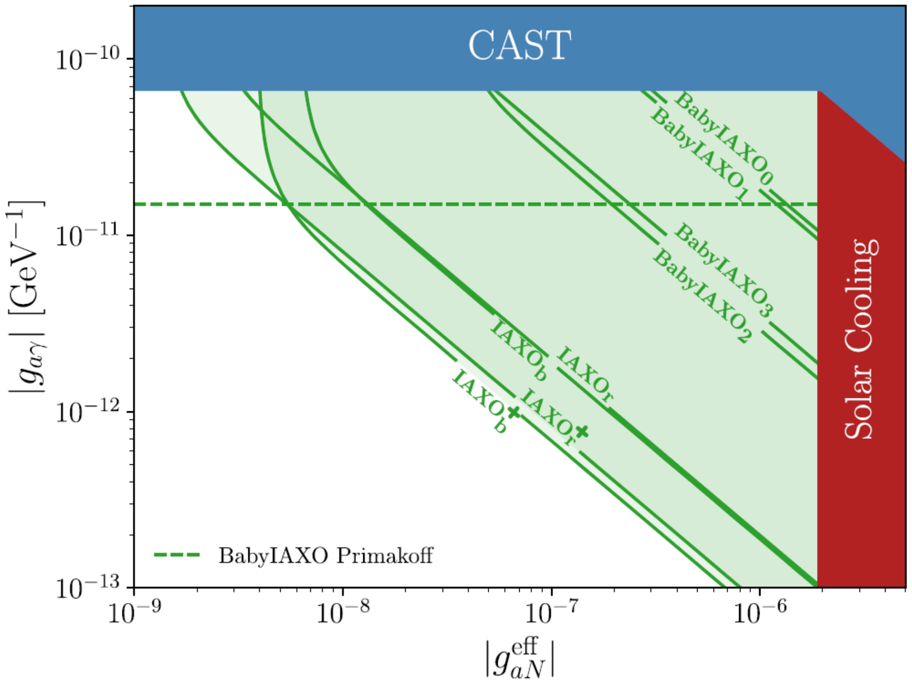
Weighing the Solar Axion

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



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

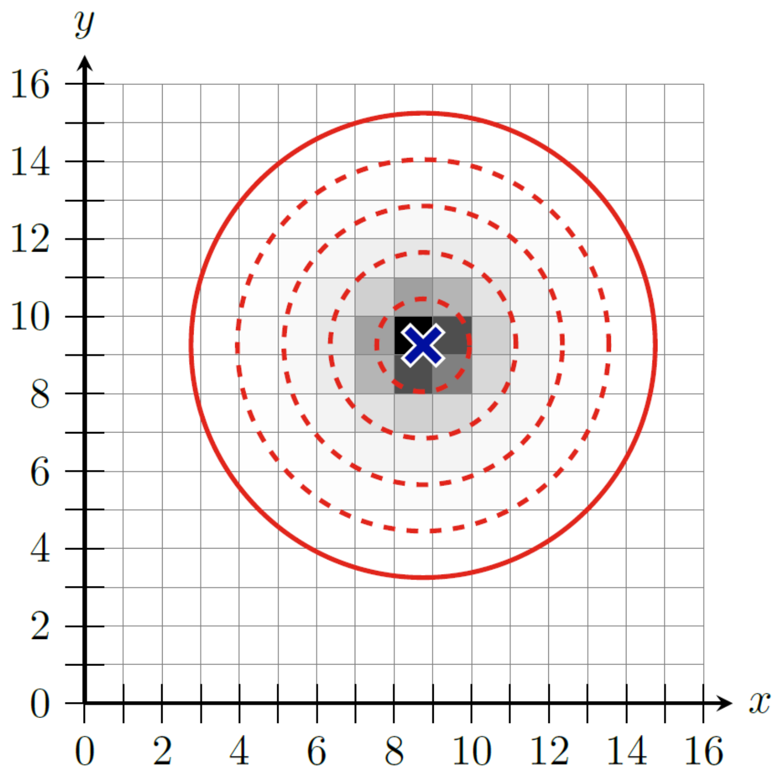
L. Di Luzio et al., EPJC 82 (2022) 120

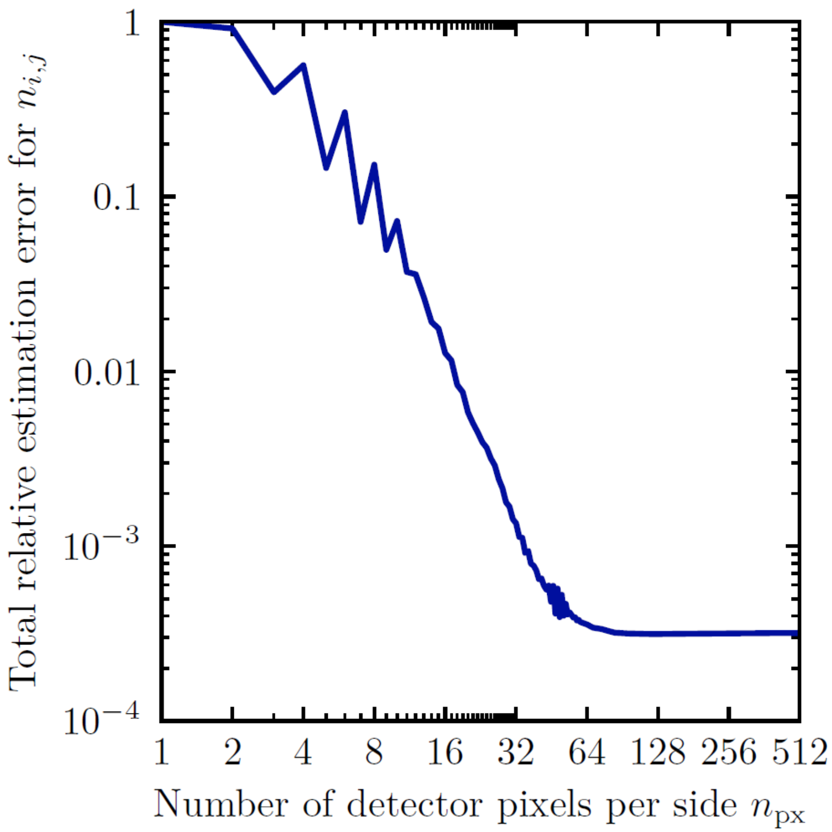


Post-discovery investigation

Axion Helioscopes as Solar Thermometers

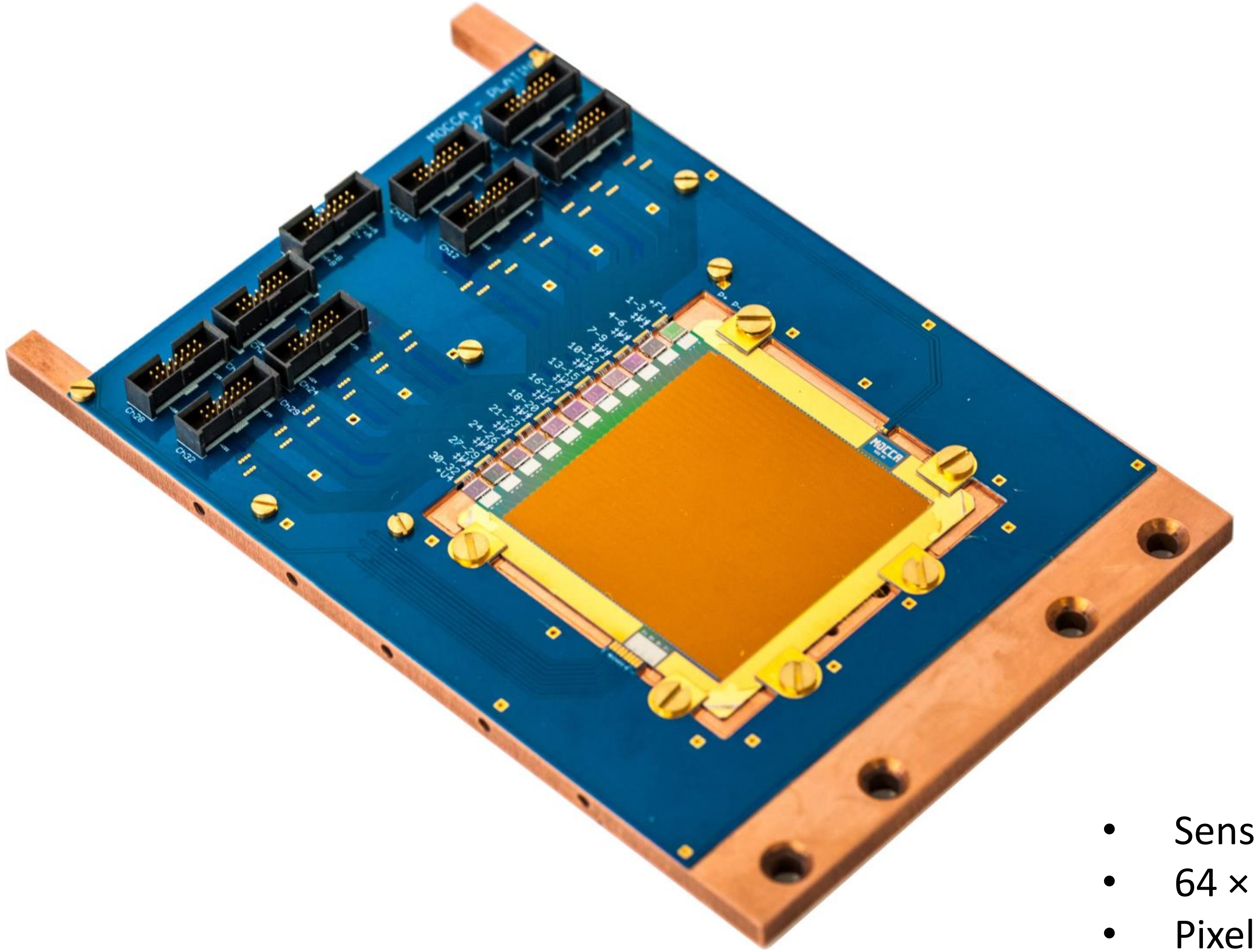
S. Hoof, J. Jaeckel and L. J. Thormaehlen, arXiv:2306.00077 [hep-ph]

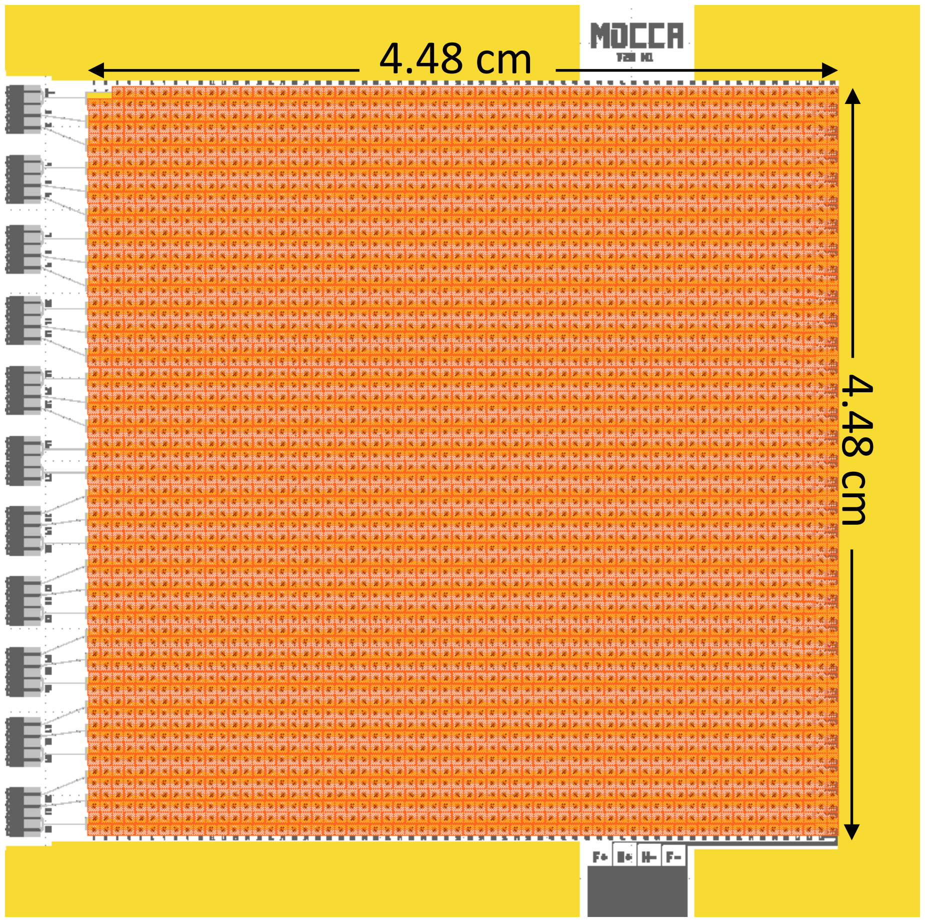




More details in
Sebastian Hoof's lecture

MOCCA - a 4k-Pixel Molecular Camera

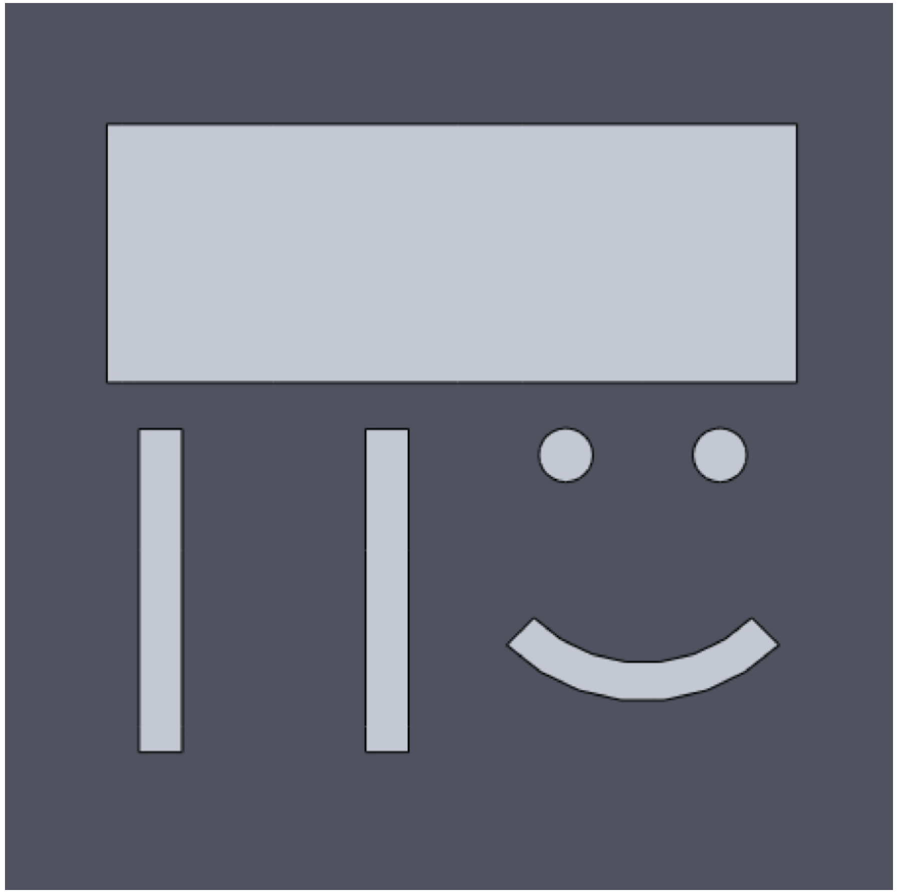




- Sensitive area: 4.48 cm × 4.48 cm
- 64 × 64 pixel
- Pixel size: 700 µm × 700 µm
- Readout by 32 two-stage SQUID channels

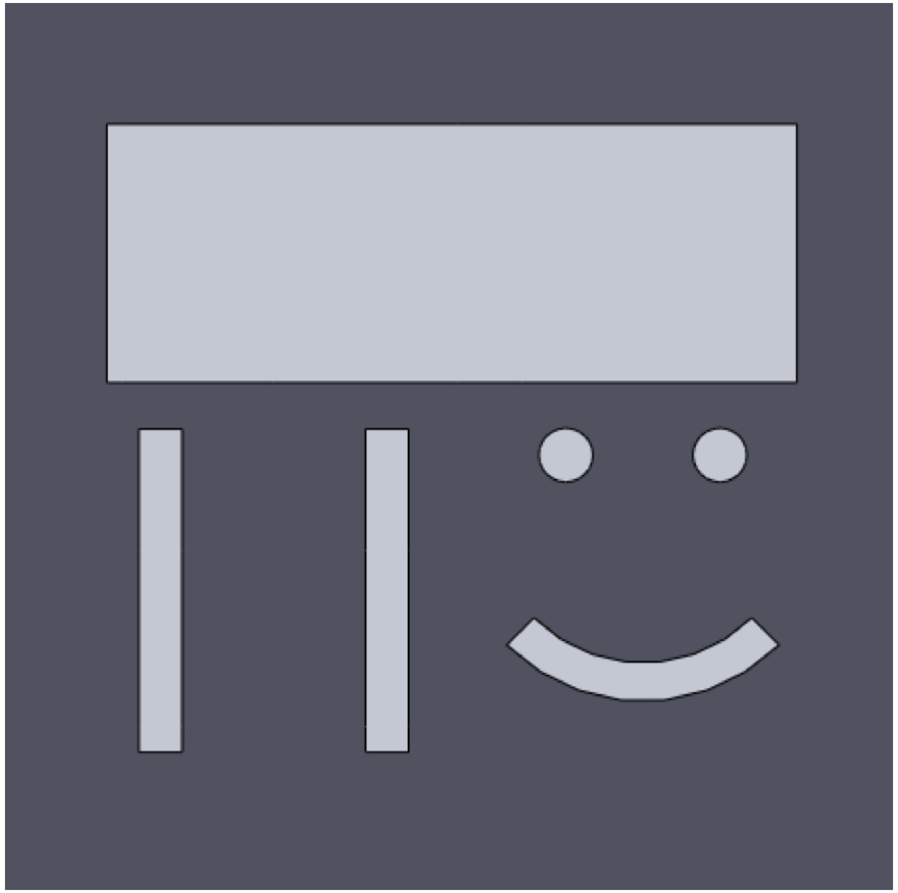
MOCCA - First characterization

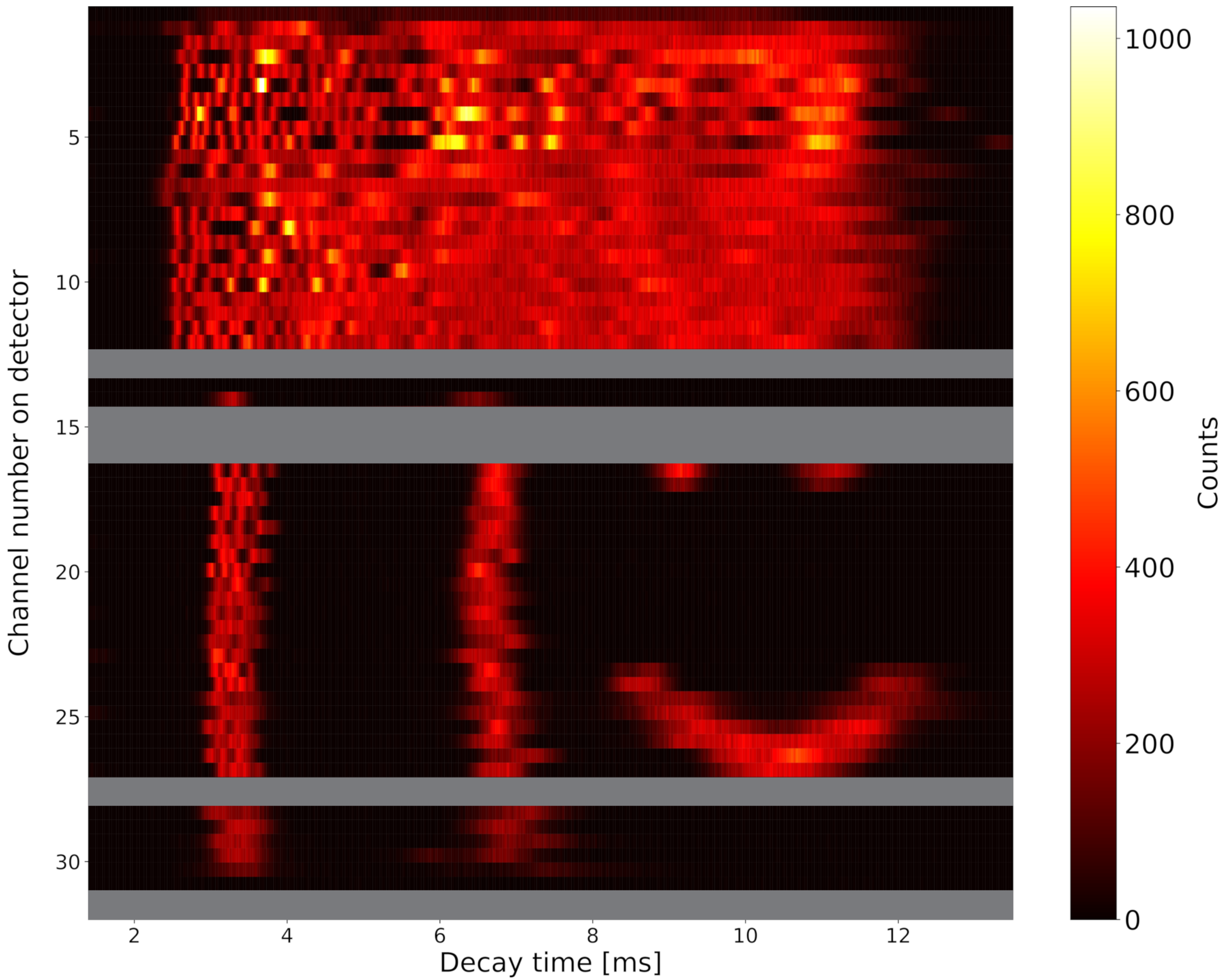
Mask



MOCCA - First characterization

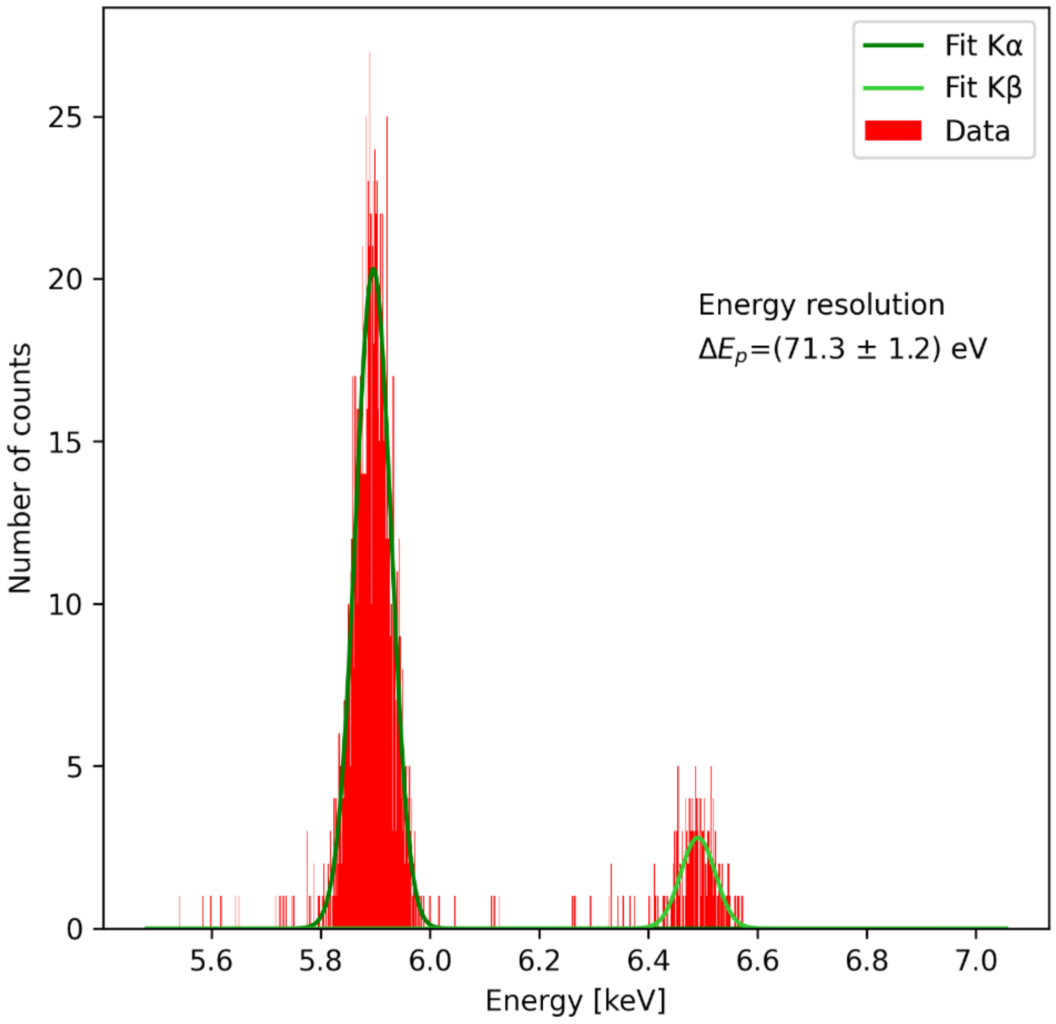
Mask

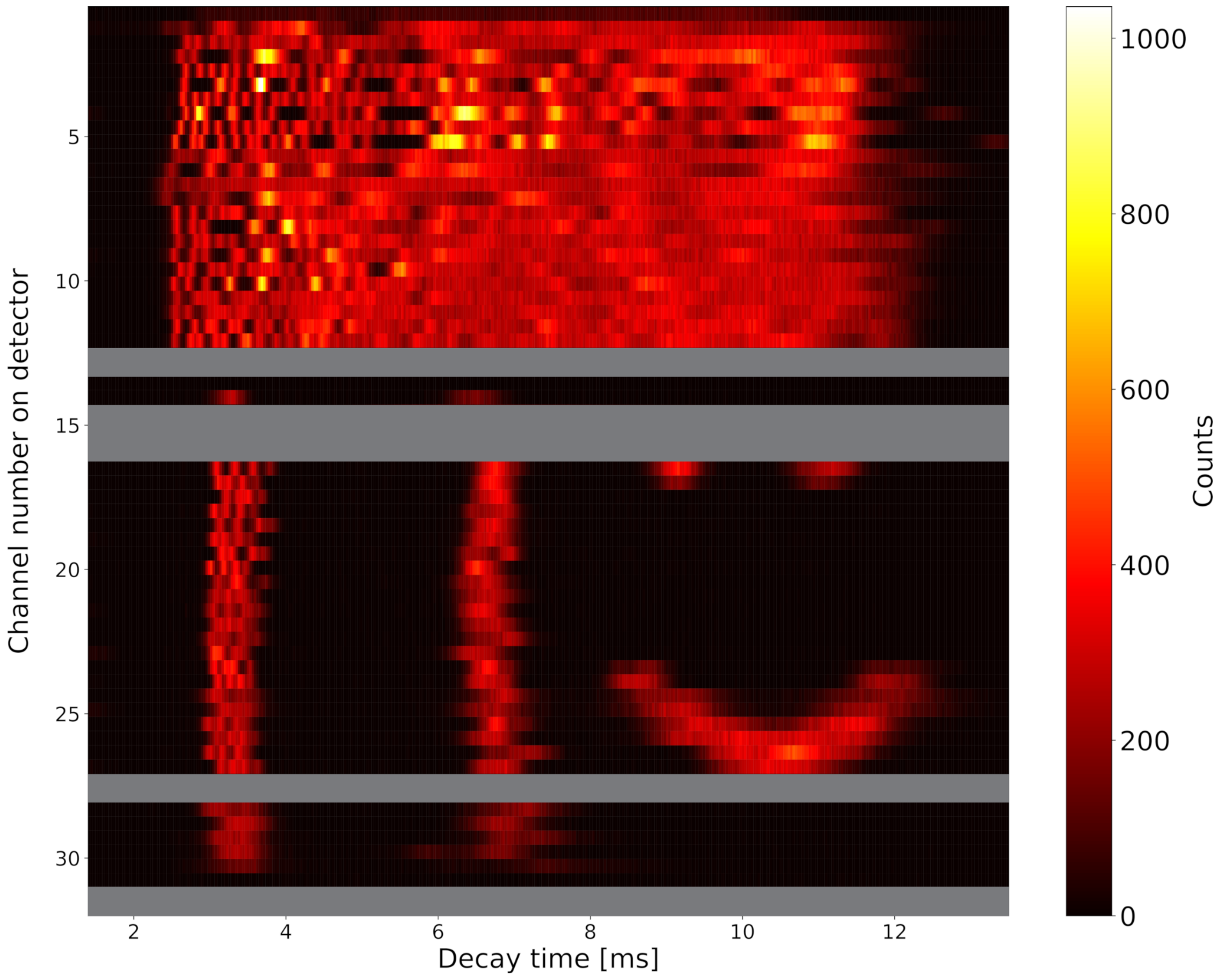




Kreuzberger, Master Thesis, Kirchhoff-Institute for Physics, Heidelberg University (2023)

MOCCA - First characterization

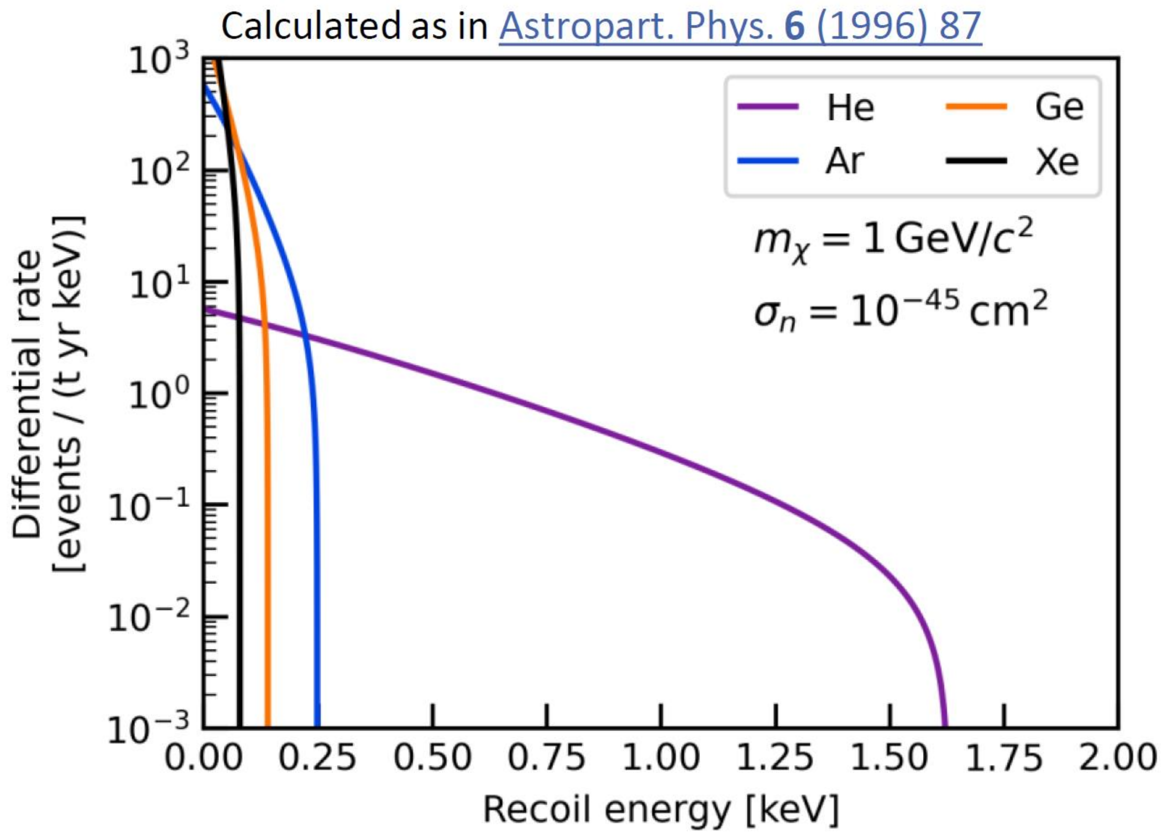




Kreuzberger, Master Thesis, Kirchhoff-Institute for Physics, Heidelberg University (2023)

Searching for light DM

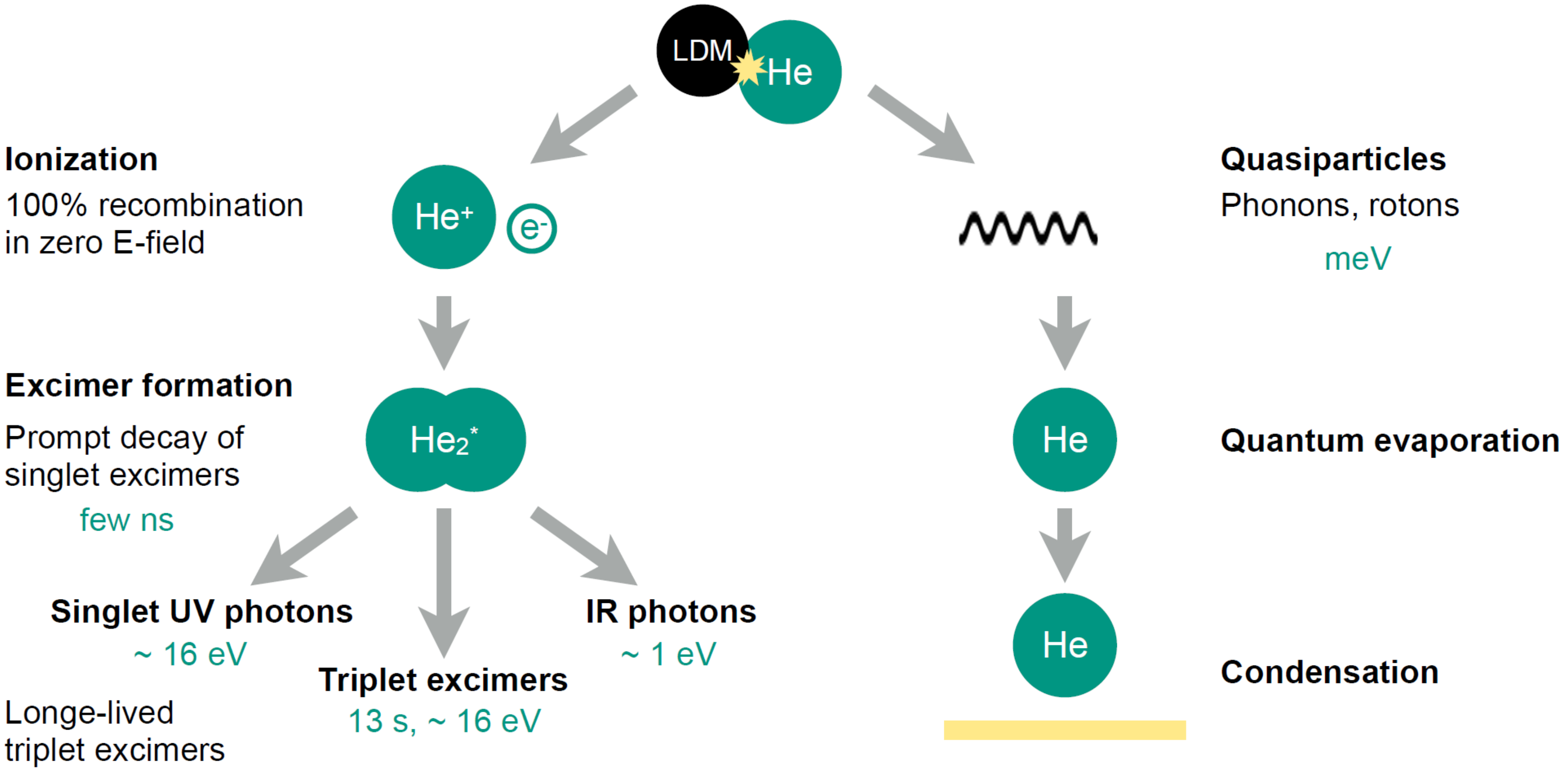
Direct detection – how to test lower DM masses?



Scattering on superfluid ^4He

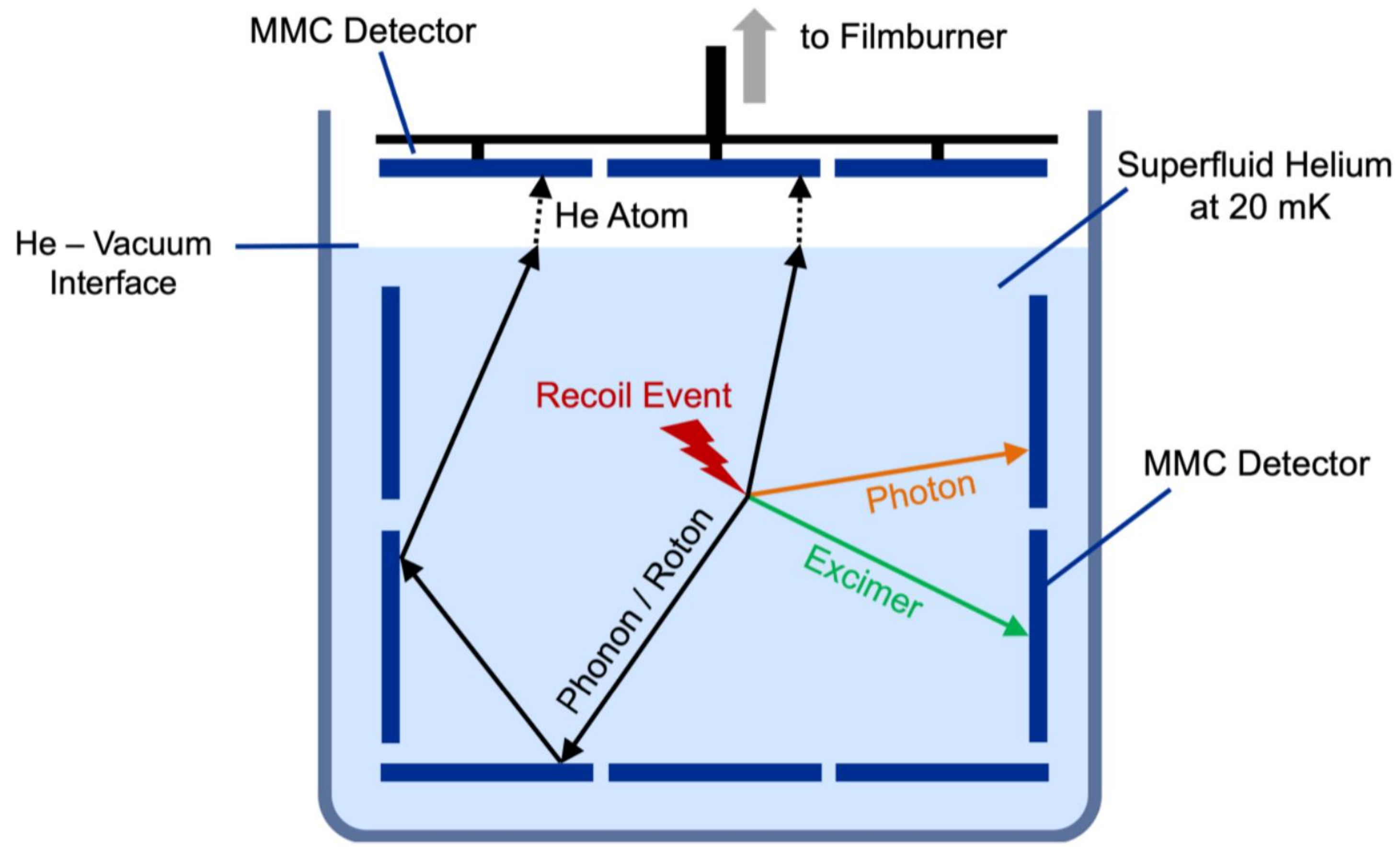
light baryonic target with multiple signal channel: light, charge, triplet excimers, phonons and rotons

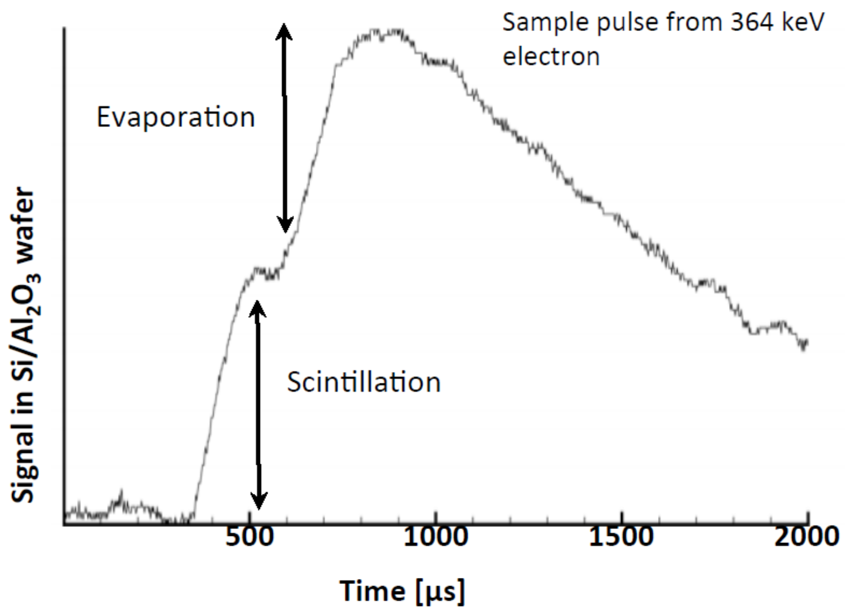
DM – superfluid ^{4}He interaction



Phys. Rev. D **87**, 115001 (2013)
Phys. Rev. Lett. **75**, 2510 (1995)
Phys. Rev. D **100**, 092007 (2019)

Superfluid ^{4}He: concept for experiment





"HERON as a dark matter detector?" in "Dark Matter, Quantum Measurement" ed Tran Thanh Van, Editions Frontieres, Gif-sur-Yvette (1996)

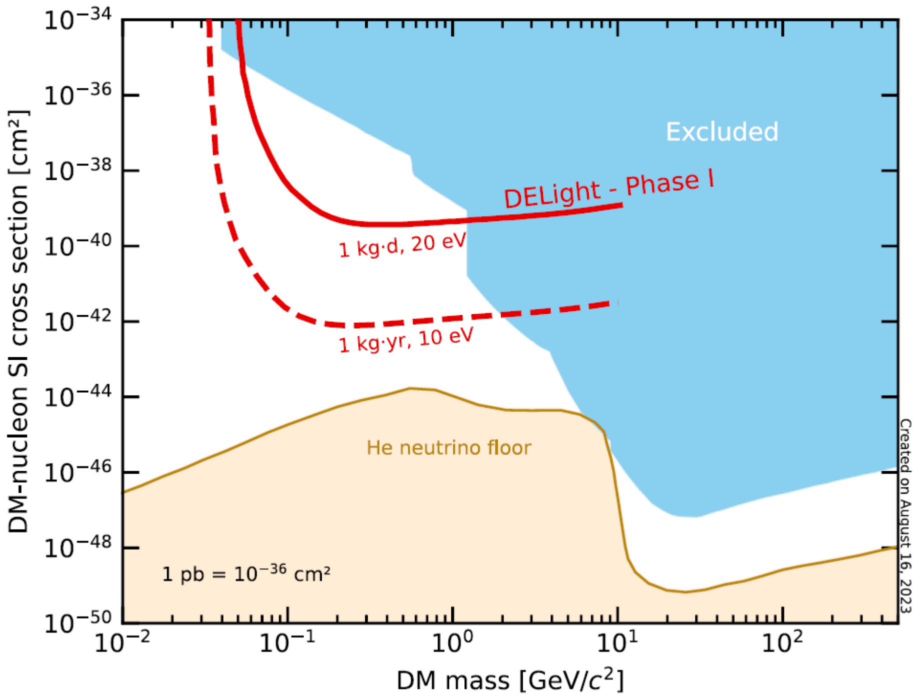
HeRALD S. A. Hertel et al., *Phys. Rev. D* 100 (2019) 092007

DElight B. von Krosigk et al., *SciPost Phys. Proc*. 12 (2023) 016

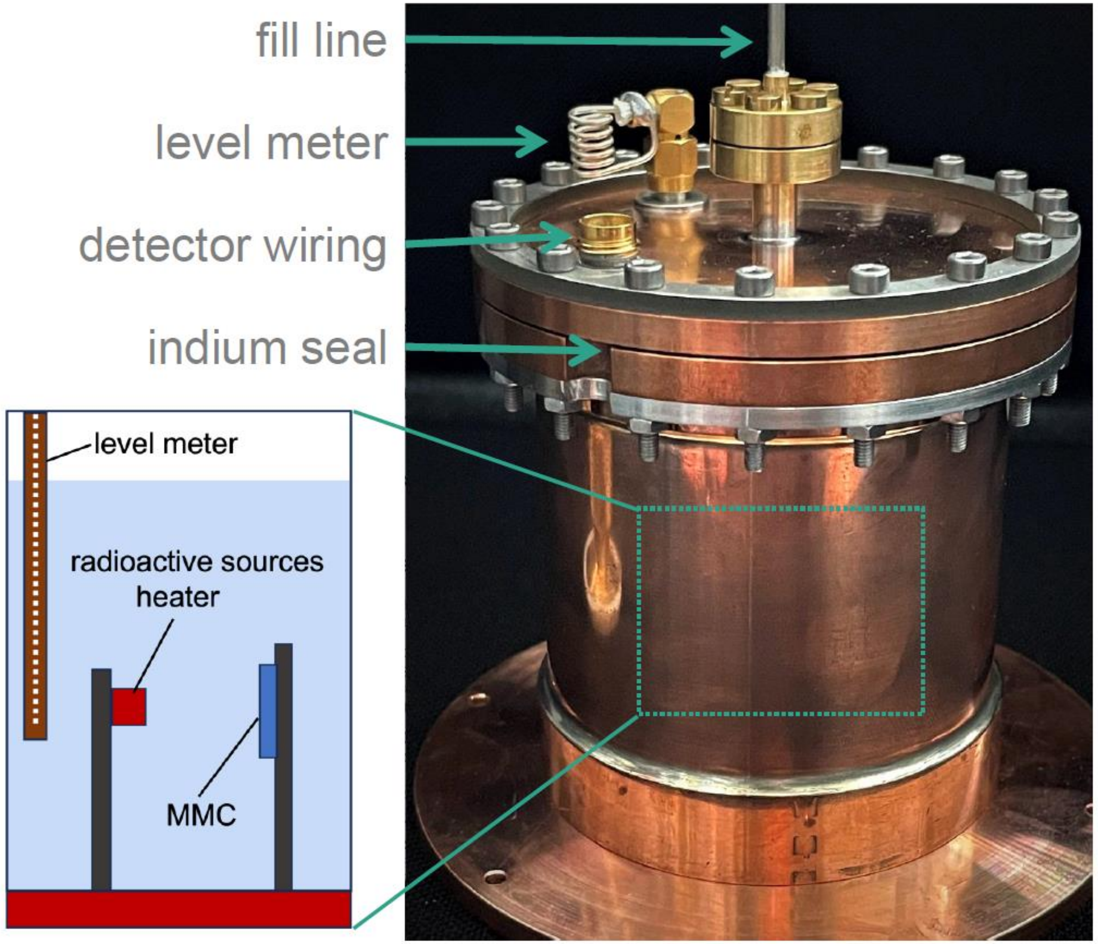
DElight : concept for experiment

Phase 1
- 10 l cell in shallow underground lab
- O(kg-d) exposure
- 20 eV threshold

Long time plan
- Up to 200 l cell underground
- O(kg-yr) exposure
- < 10 eV threshold



Proof of concept experiment



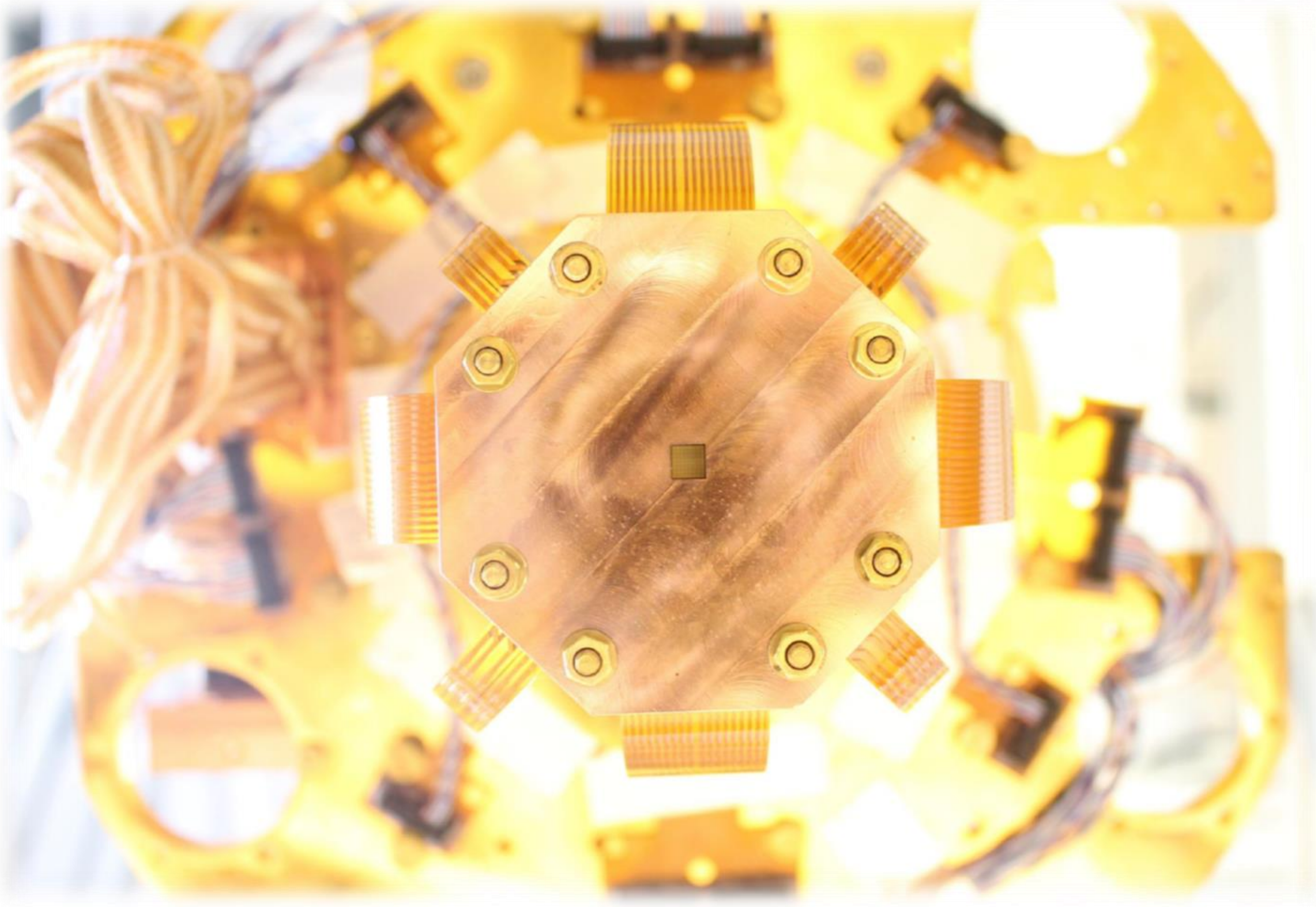
Conclusions

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 !

DElight for searching light DM with MMCs

Conclusions

Metallic magnetic calorimeters for IAXO

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

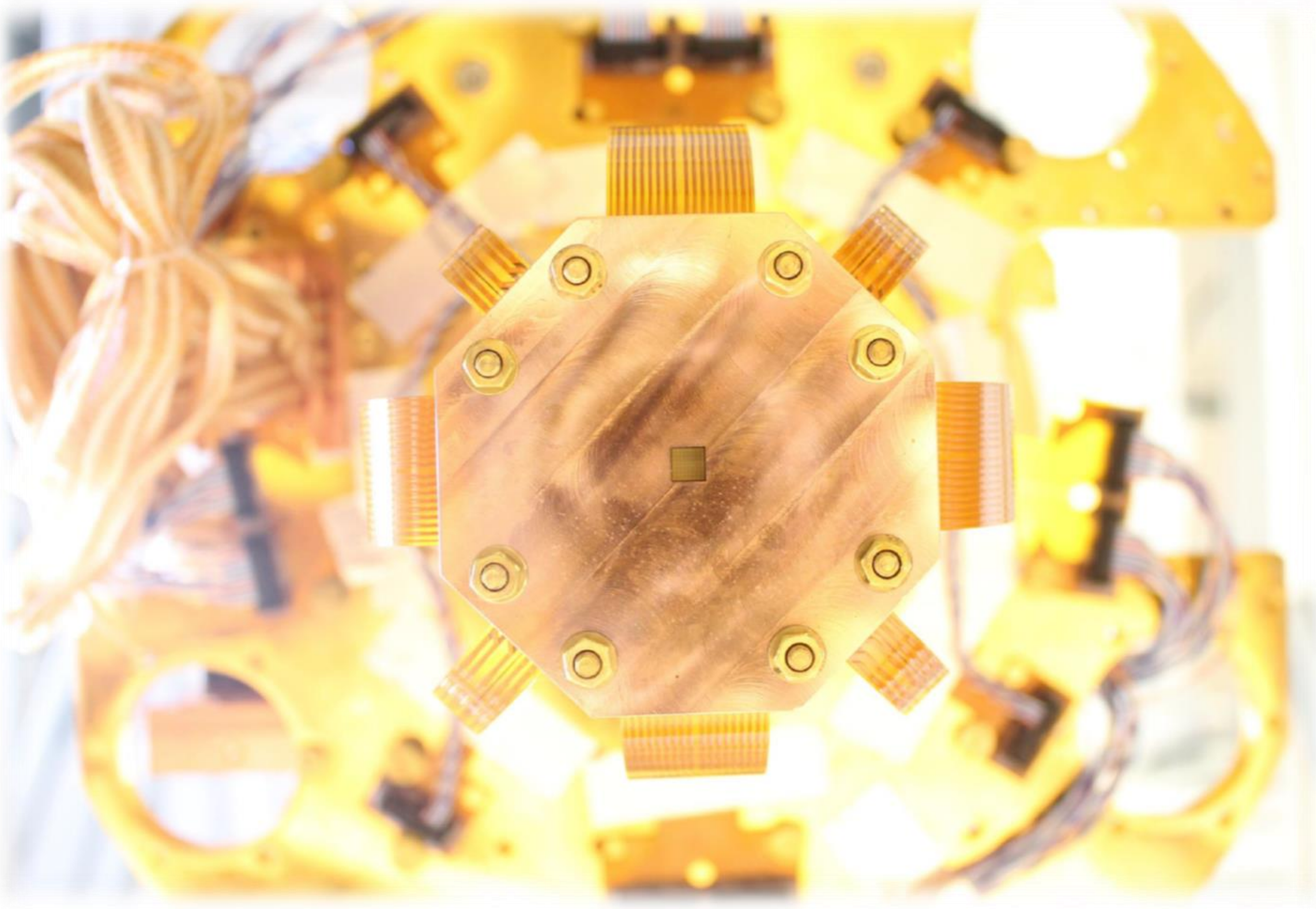
To demonstrate:

- suitable background
- stable operation while tracking the Sun

Achieved MMC performance motivates the efforts !

DElight for searching light DM with MMCs

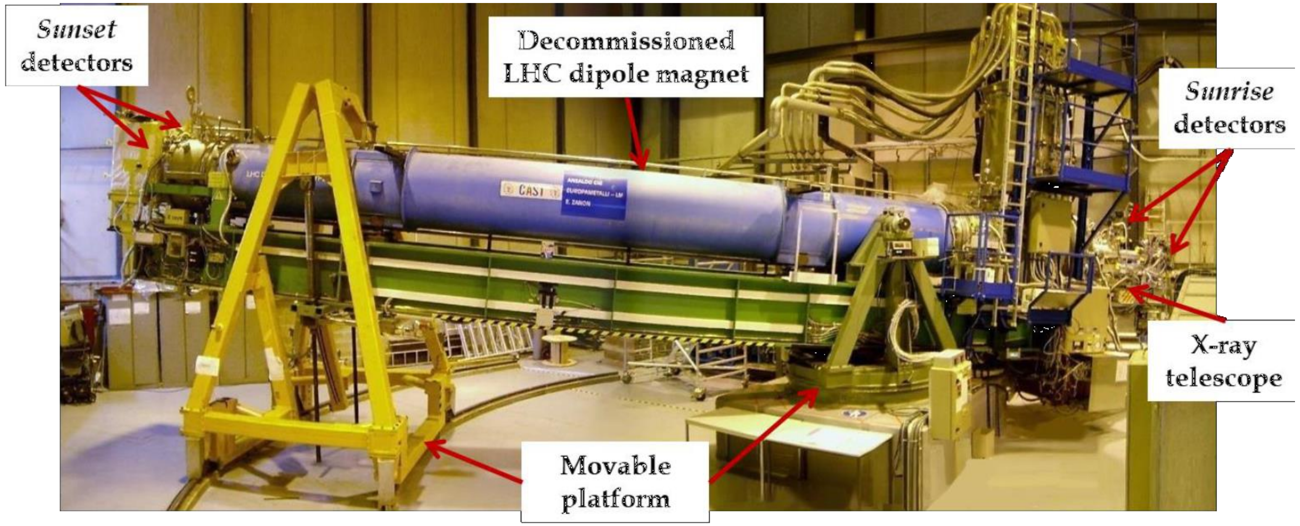
Thank you for the attention!

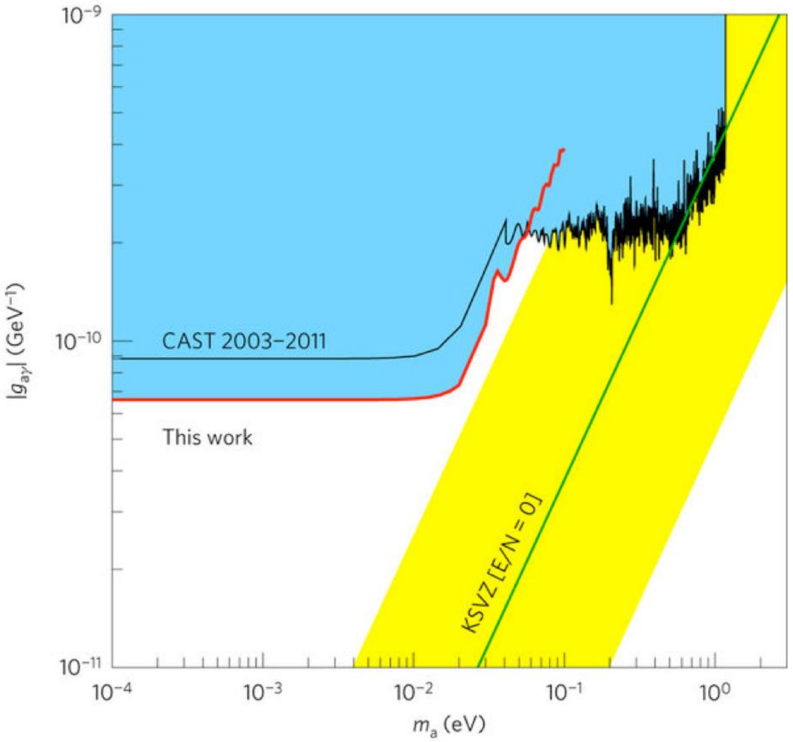


CAST

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% C.L.)





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

MMC fabrication

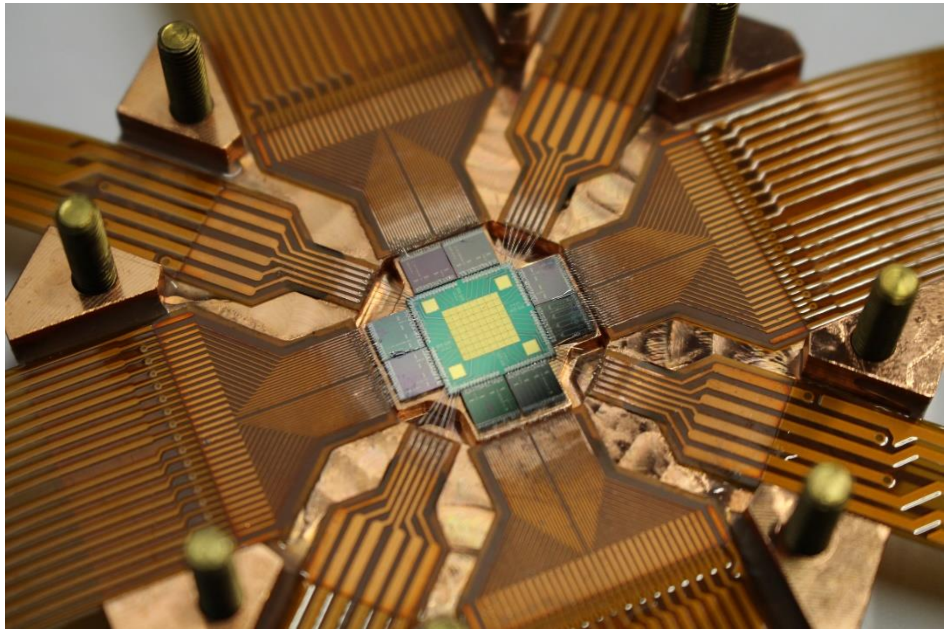
40 m^2 Cleanroom class 100
at Kirchhoff Institute for Physics

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

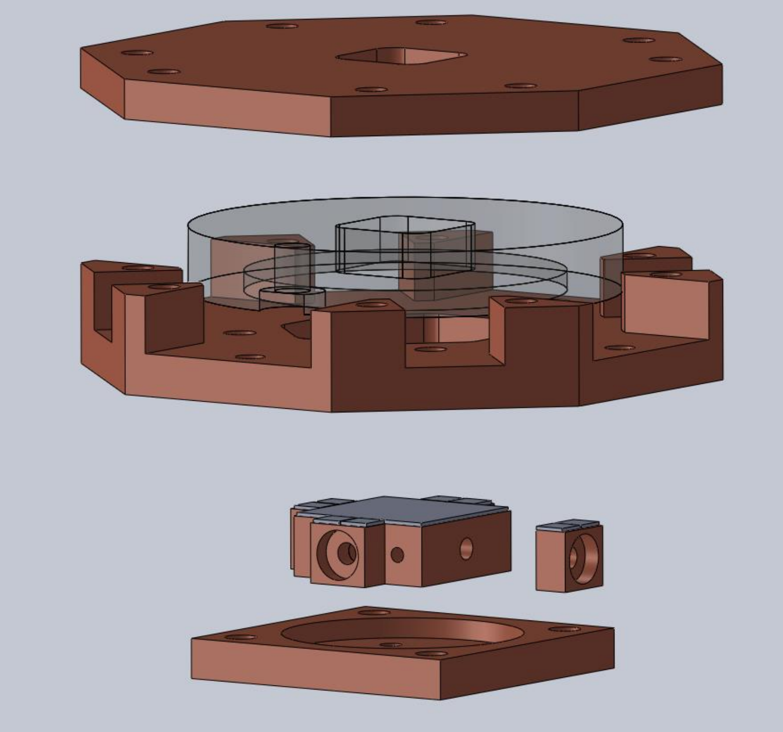
- Flexibility in design and fabrication
- Reliable processes for thin films
- Production of MMC array and superconducting electronics

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

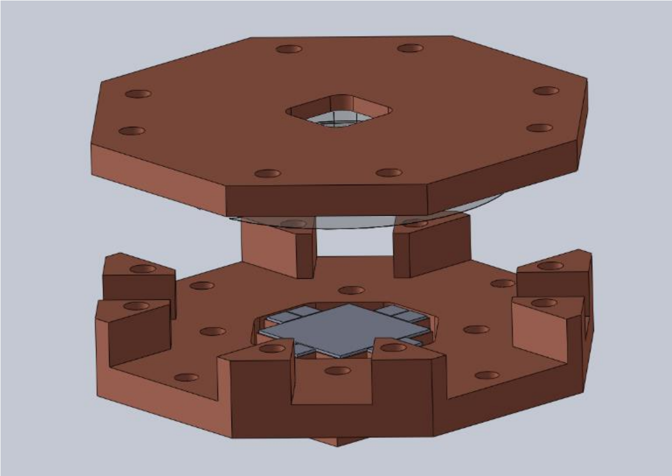


Detector setup V2



New features:

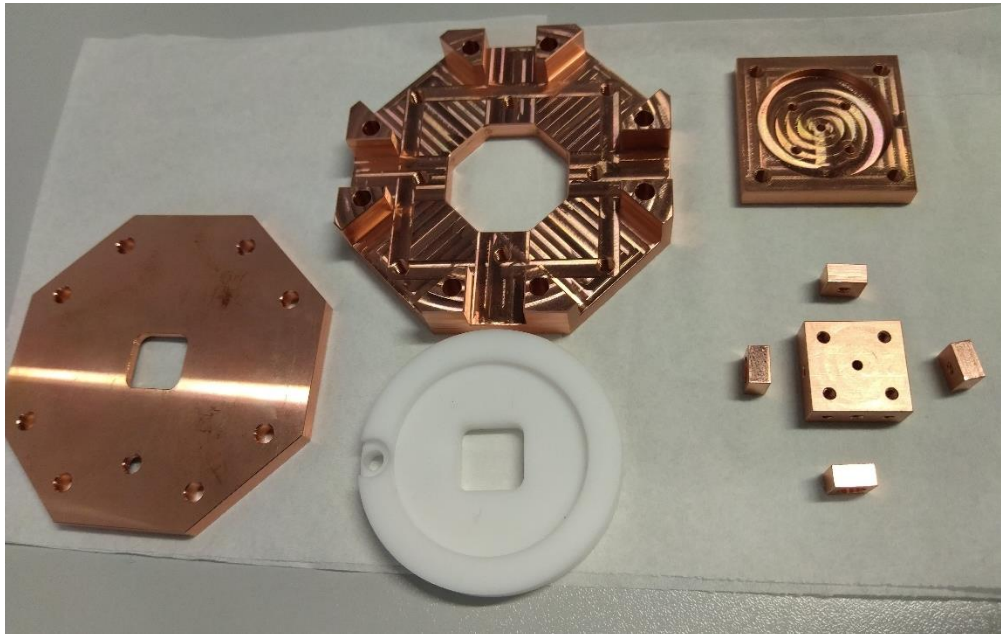
- Modularized detector and SQUID holder → easy repair
- Optimized for new detector *maXs*IAXO
- Additional inner teflon shield to reduce background



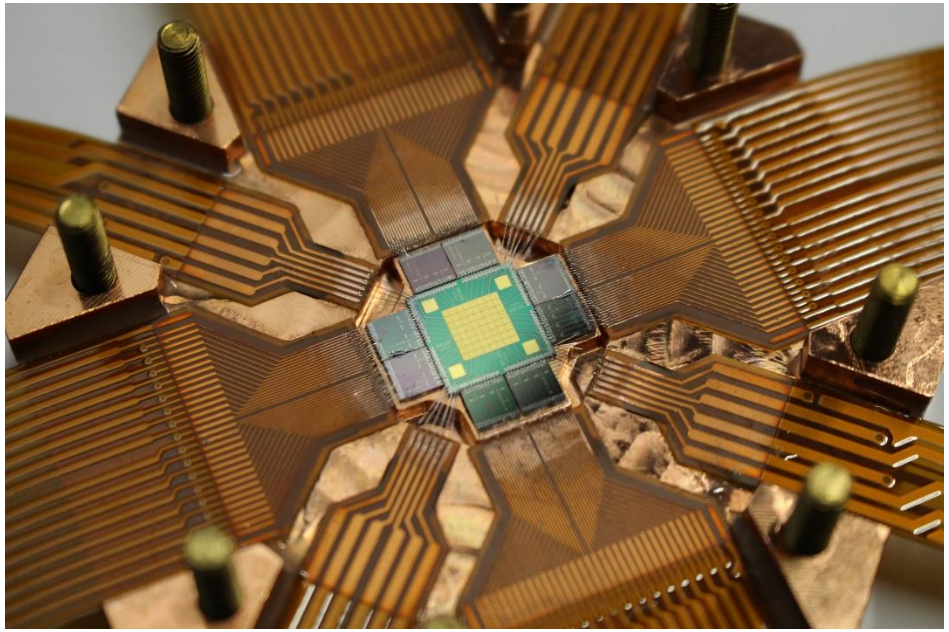
Detector setup V2

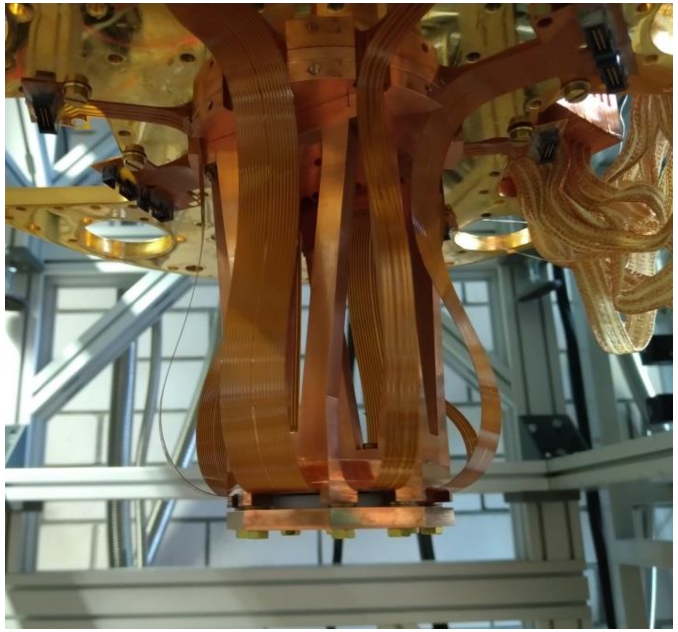
Current state:
- Copper parts are produced, ready to be assembled
- *maXs*IAXO is prepared to be produced in cleanroom

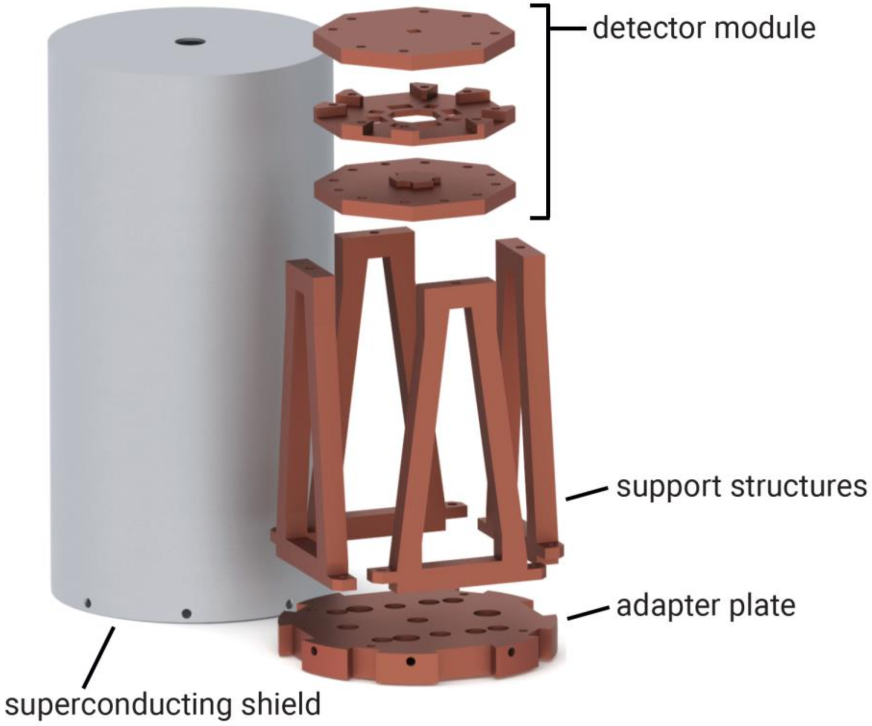
Next steps:
- *maXs*IAXO wafer production in cleanroom
- Assembling and characterization of *maXs*IAXO V2 setup
- Background measurements

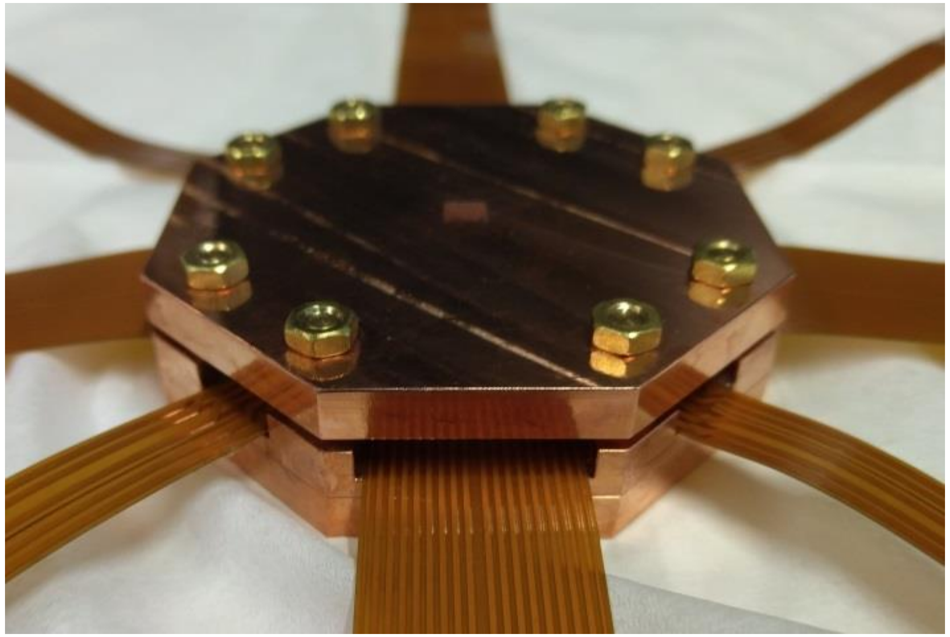


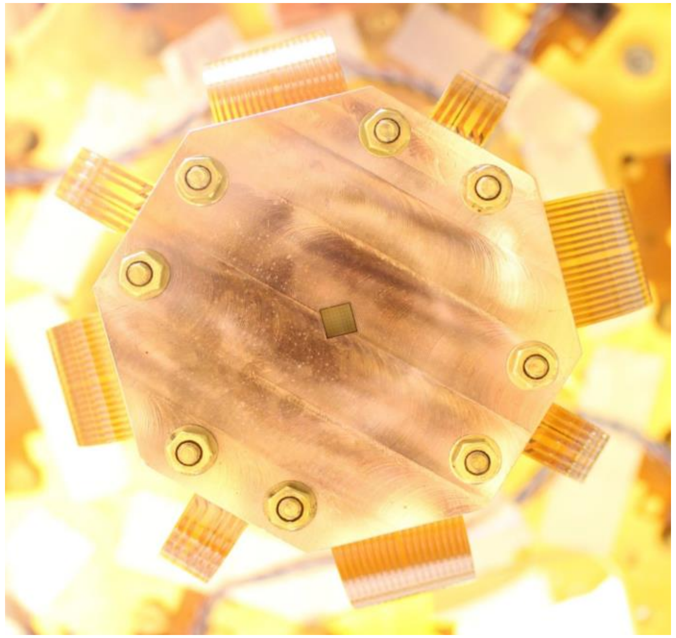
maXs-30 set-up for IAXO









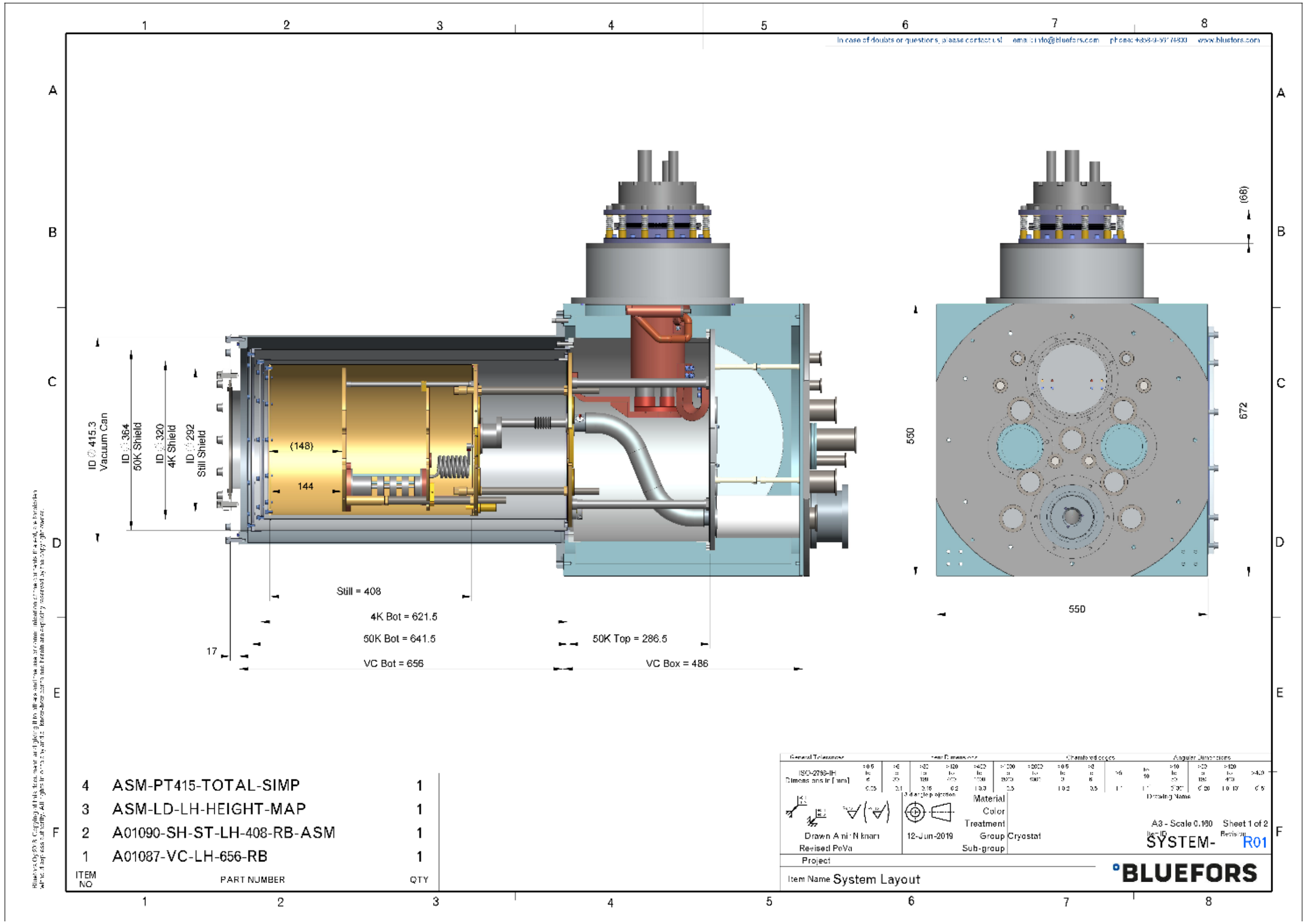


Design suitable for IAXO telescope

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



Superfluid ^{4}He: concept for experiment