Centro de Astropartículas y Física de Altas Energías
Universidad Zaragoza

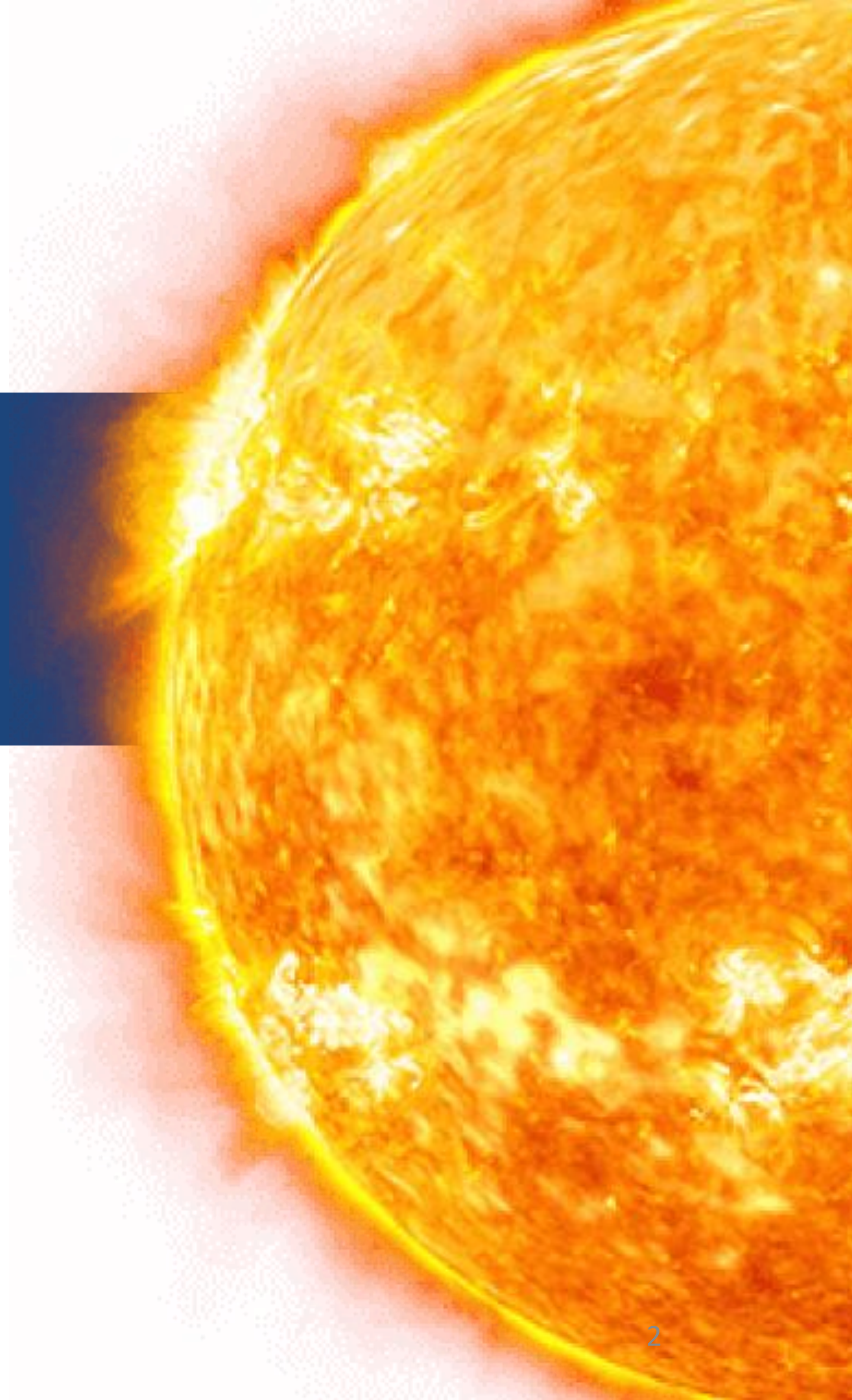
A new upper limit on the axion-photon coupling with an extended CAST run with a Xe-based Micromegas detector

Cristina Margalejo on behalf of the CAST Collaboration

15th International Workshop on the Identification of Dark Matter 2024

8th July 2024

L'Aquila - Italy



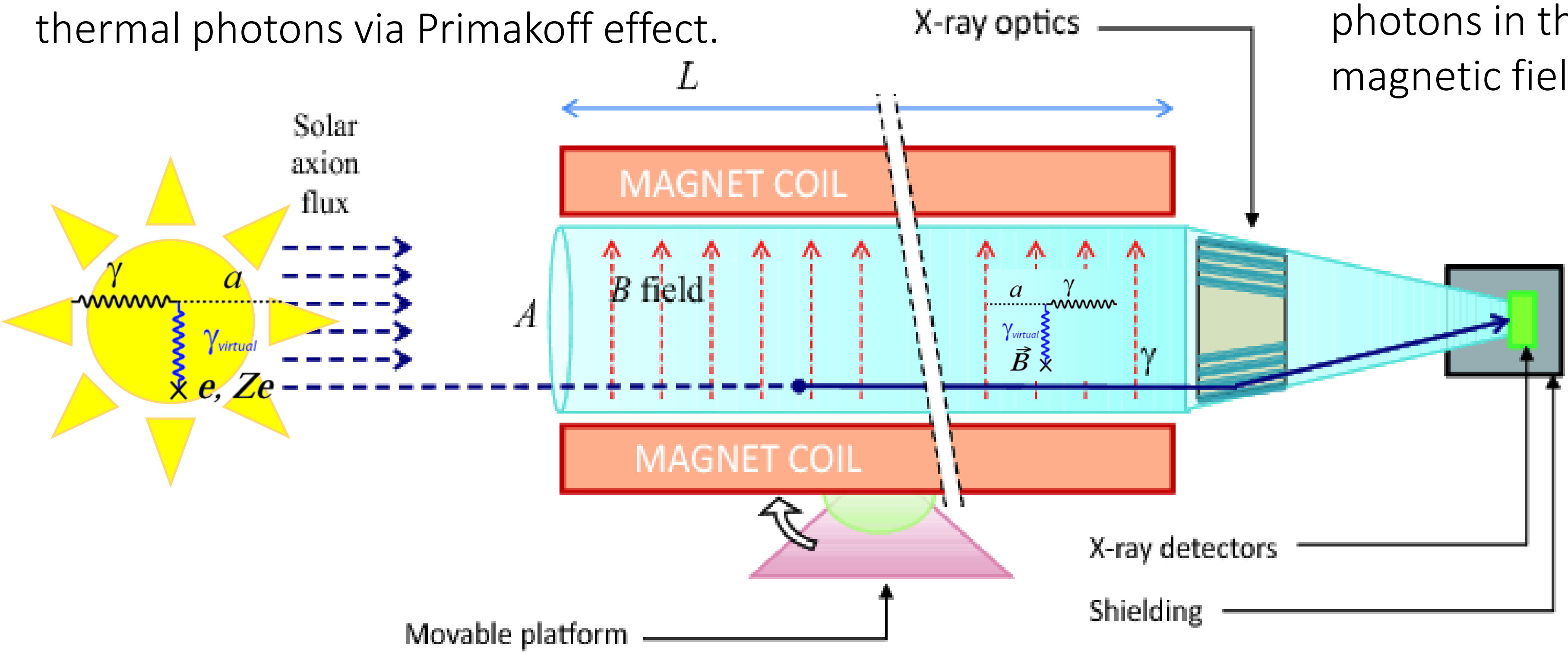
Introduction

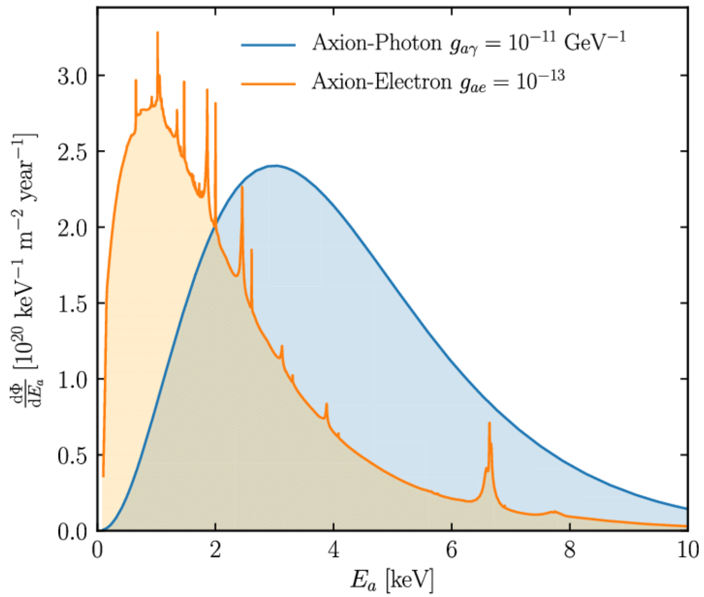
Axion heliosopes and state of the art

Solar axions and helioscopes

Production: stars produce axions from thermal photons via Primakoff effect.

Detection: conversion of axions into photons in the presence of a magnetic field.





Expected X-ray excess when the magnet points to the Sun.

See J. Vogel talks for more details!

State of the art: CAST

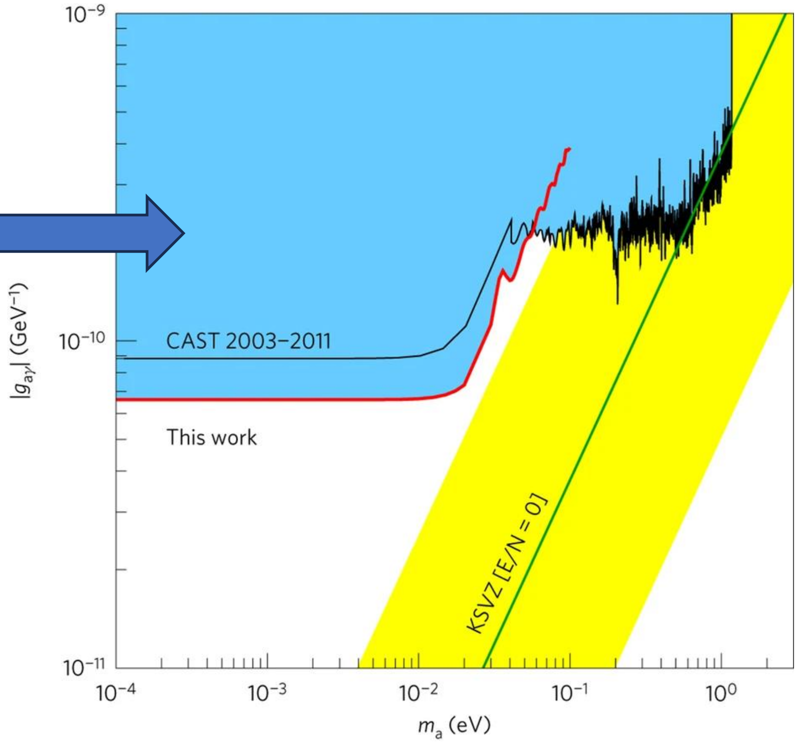
CERN Axion Solar Telescope

A powerful **axion helioscope** → more than 20 years of experience
Decommissioned prototype **LHC dipole magnet** → Length = 10 m; Magnetic field = 9 T
Solar tracking possible during sunrise and sunset (2 x 1.5 h per day)

2013-2015: IAXO pathfinder

Sunrise detector: x-ray focusing optics + Micromegas (IAXO Pathfinder)
Best experimental limit on axion-photon coupling over broad axion mass range

$g_{a\gamma} < 0.66 \times 10^{-10}$ [GeV^{-1}] (95% C.L.) for $m_a < 0.02$ eV



NPHYS4109

2017-2018: GridPix detector + X-ray focusing optics

2019-2021: new data taking campaign with IAXO pathfinder

State of the art: CAST

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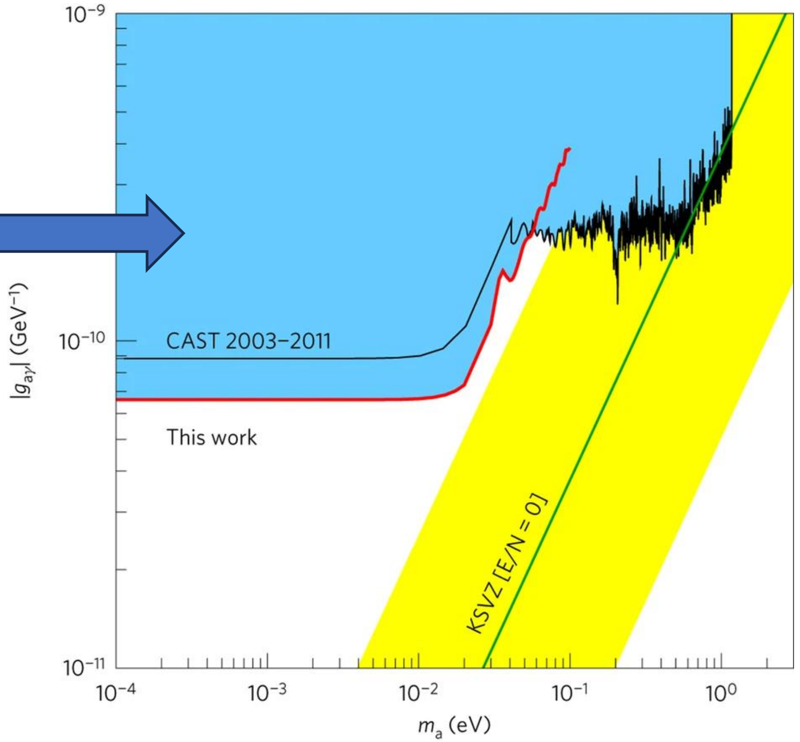

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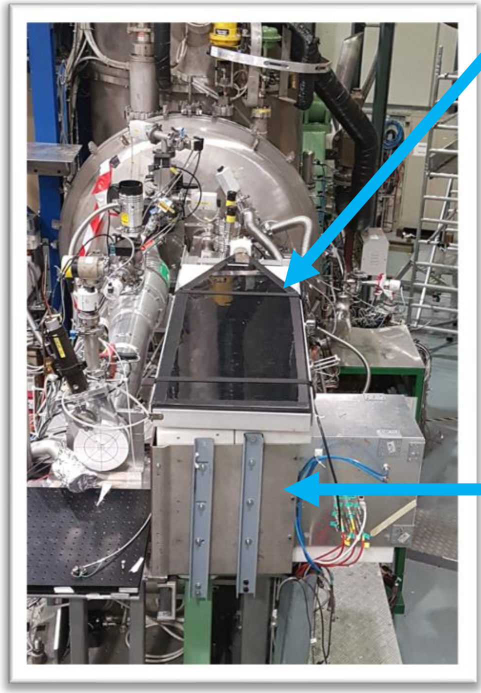
This presentation

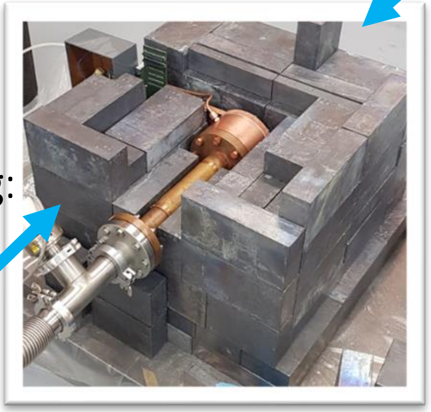
The IAXO pathfinder system at CAST

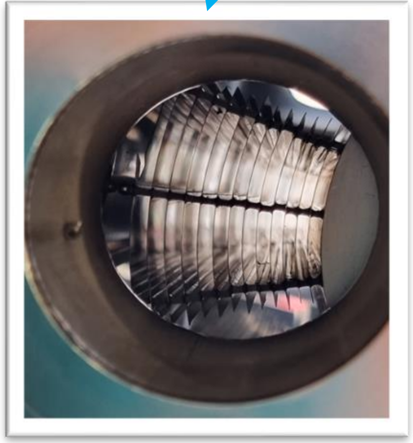
X-ray telescope



Active shielding: plastic scintillator as a cosmic muon veto.

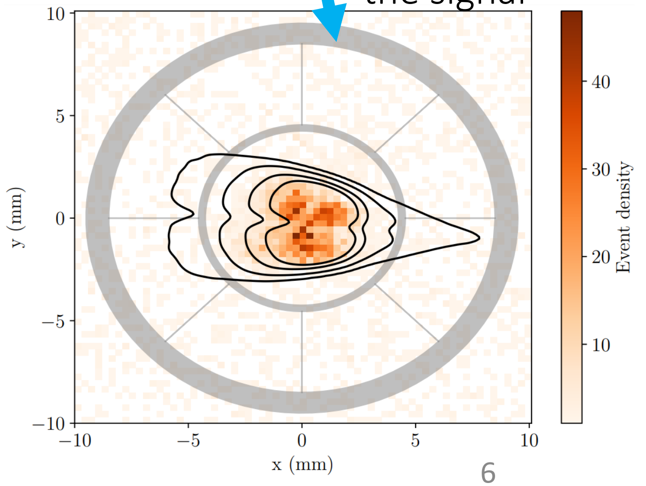
Passive shielding: 10 cm of lead around the detector.





X-ray optics

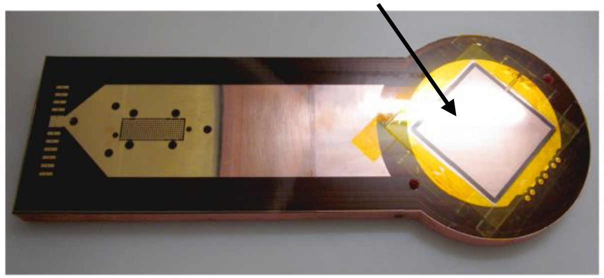
X-ray optics focus the signal



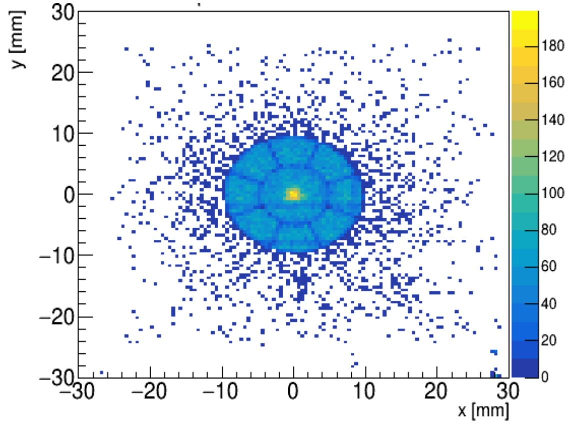
The IAXO pathfinder ultra-low background detector

Microbulk Micromegas detectors

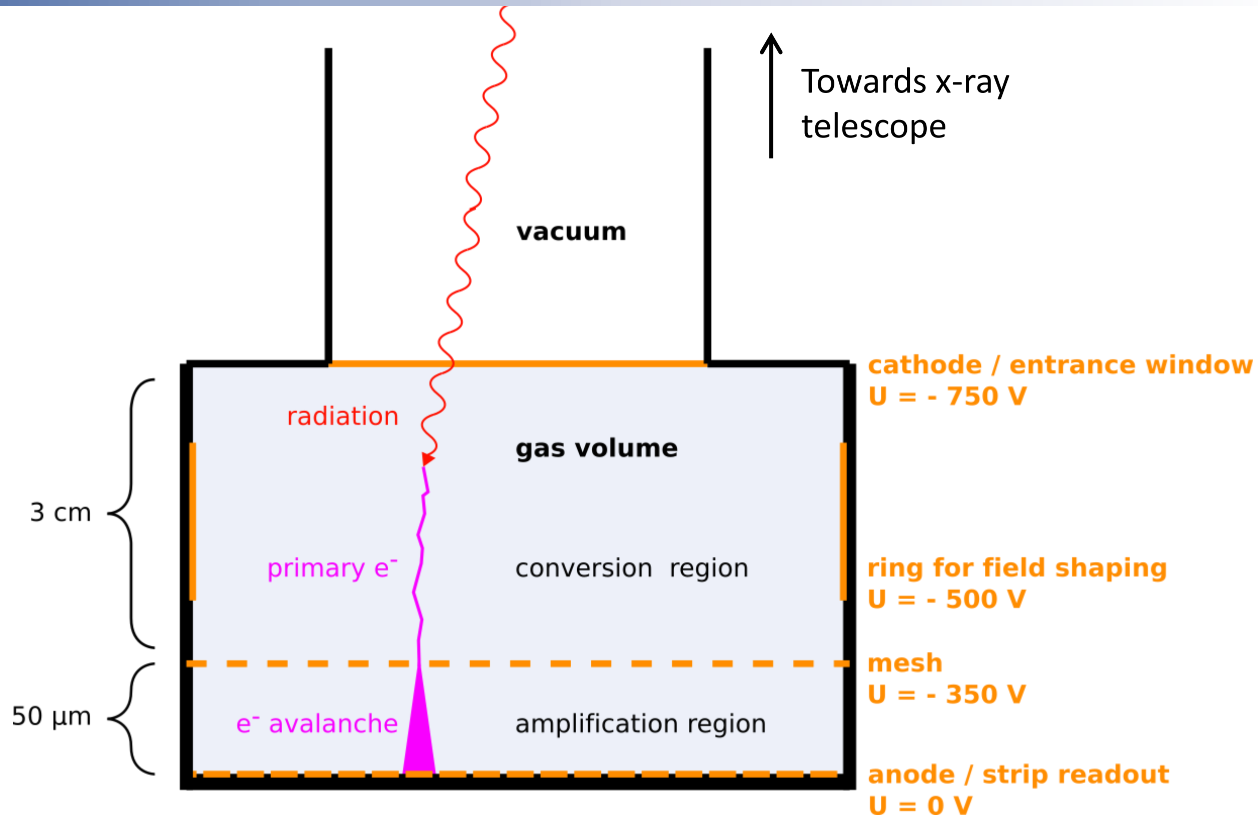
- Very homogeneous amplification gap, uniform gain.
- Intrinsically radiopure.
- Good energy and spatial resolution.
- Pixelized readout gives topological information.



^{55}Fe Calibration intensity map



X-ray window

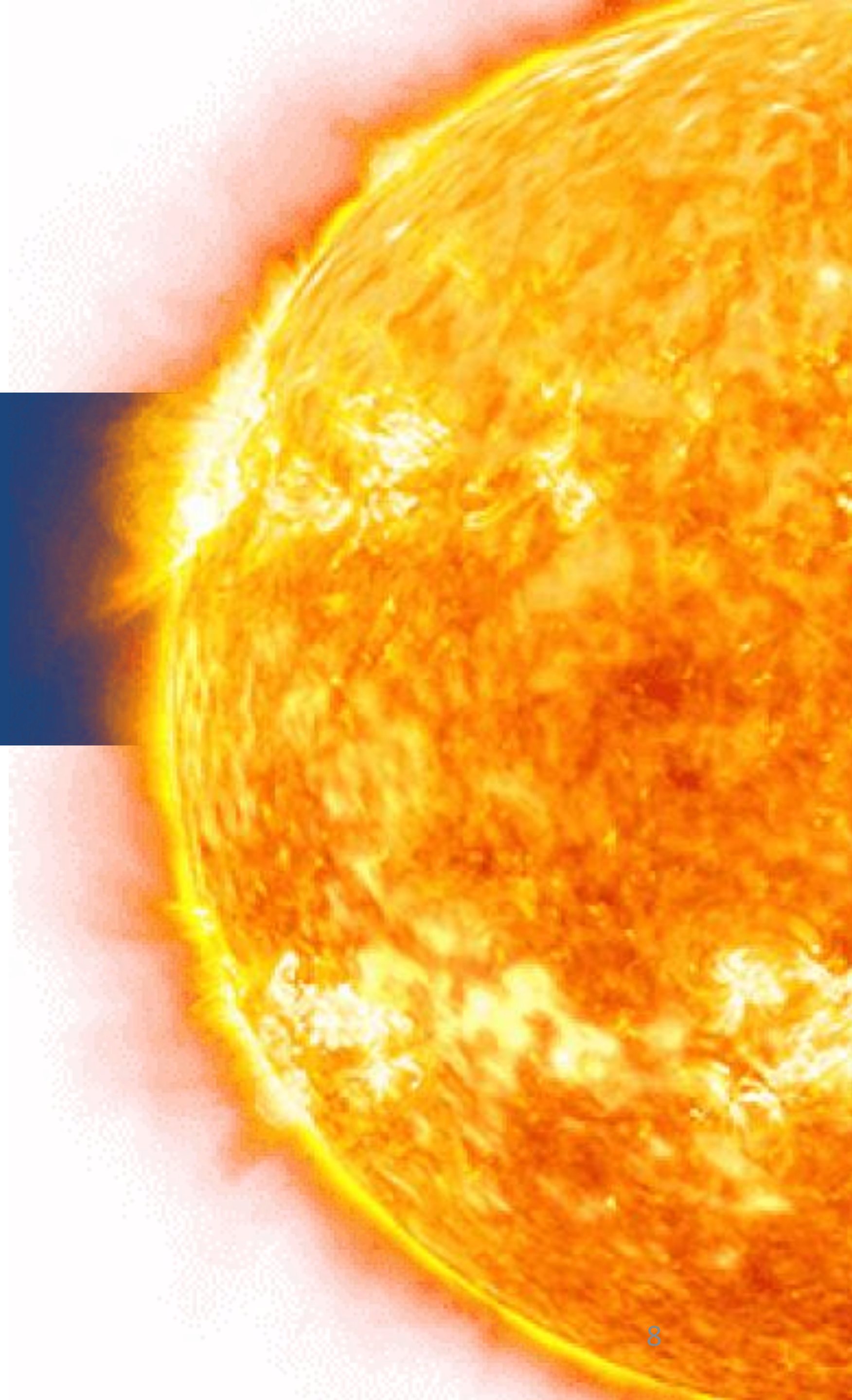


- Signal reaches the active volume through a mylar window.
- X-rays ionize the gas in the conversion region and the produced signal is read by the Micromegas.
- Data is analyzed with the REST-for-Physics framework (github.com/rest-for-physics).

Rare Event Searches Toolkit software

The new data taking campaign

1. Motivation
2. Use of Xe-based gas mixtures



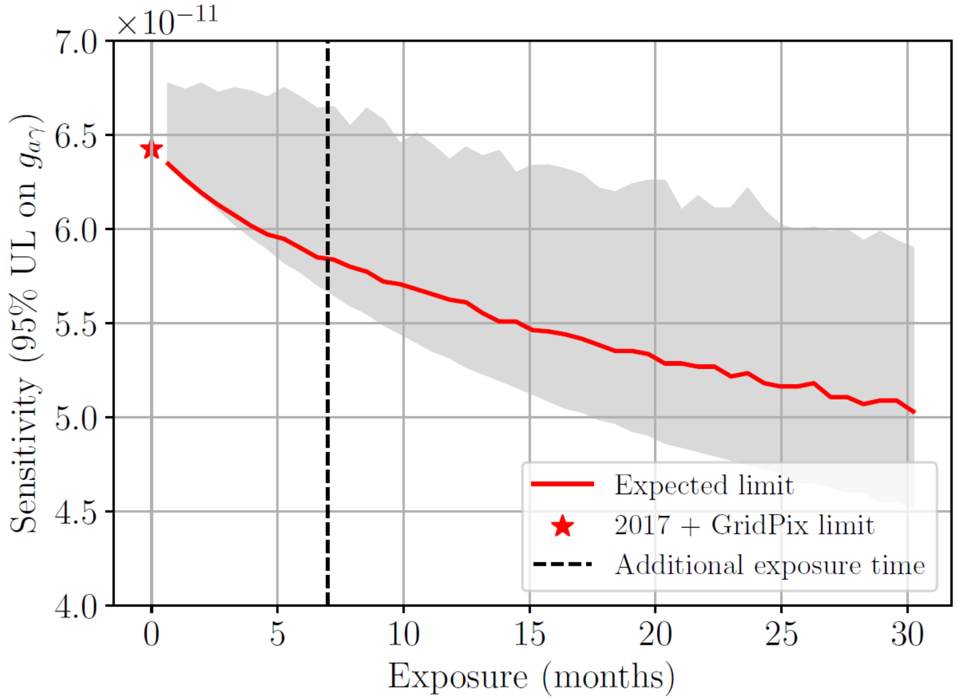
Motivation for the new data taking campaign

- **R&D for BabyIAXO and IAXO**
  - Closed-loop Xe-based gas system (Xe+Ne+2.3% iC4H10).
  - Insight into limitations of background and threshold.
  - Provide technical and operational experience.
  - Software development.
  - Identify challenges and reduce risks towards IAXO.

Rare Event Searches Toolkit **software**

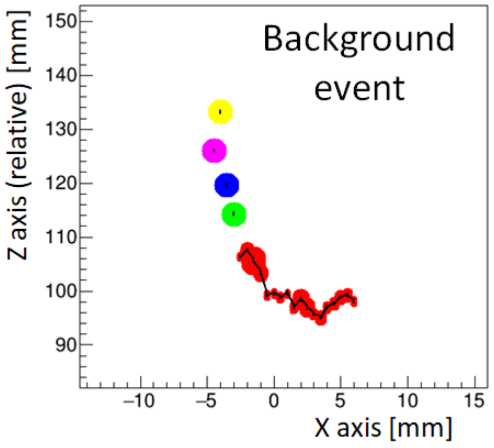
github.com/rest-for-physics

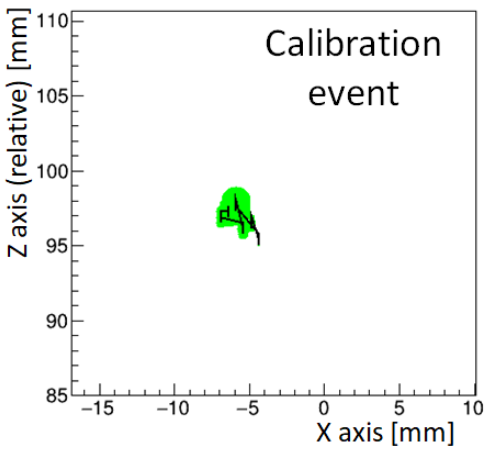
- **Increase the statistics and sensitivity in $g_{a\gamma}$**
  - ~160 hours with a GridPix detector.
  - ~320 hours with a Micromegas detector.

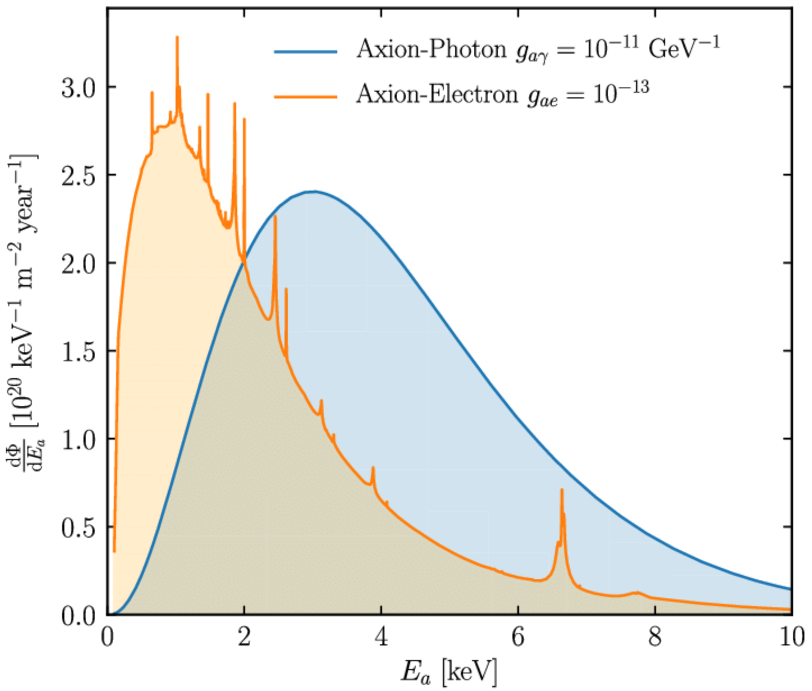


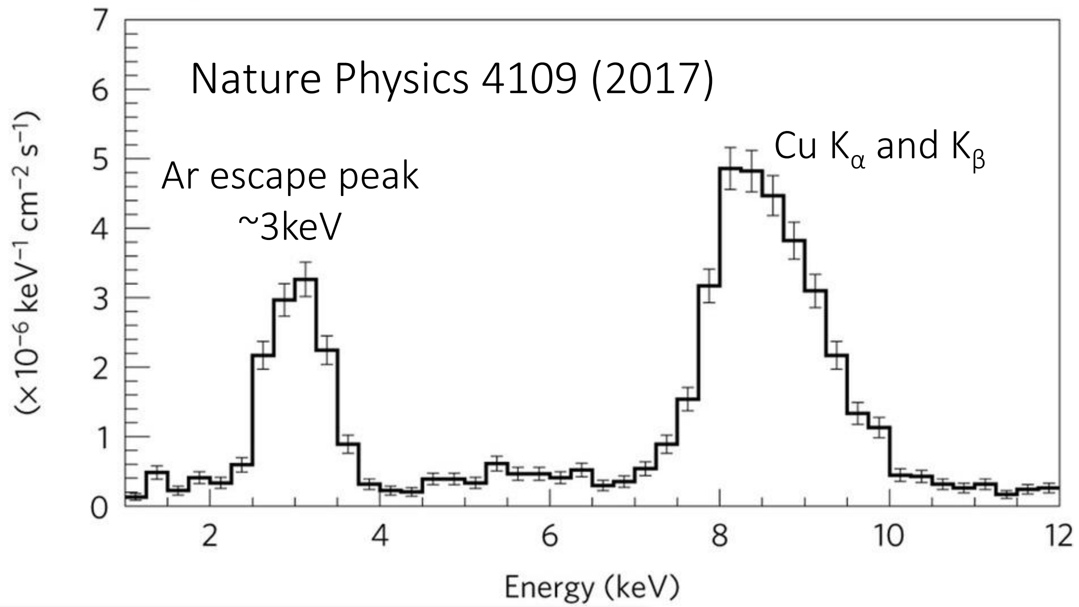
Towards Xe-based gas mixtures

- Background is reduced a few orders of magnitude based on the topological signature of X-rays: small, symmetric and point-like events.
- Typical background spectra with Ar-based mixtures has peak at ~3 keV.









Solar axion peak expected at ~3 keV.

For better results we need to reduce the background in this energy range.

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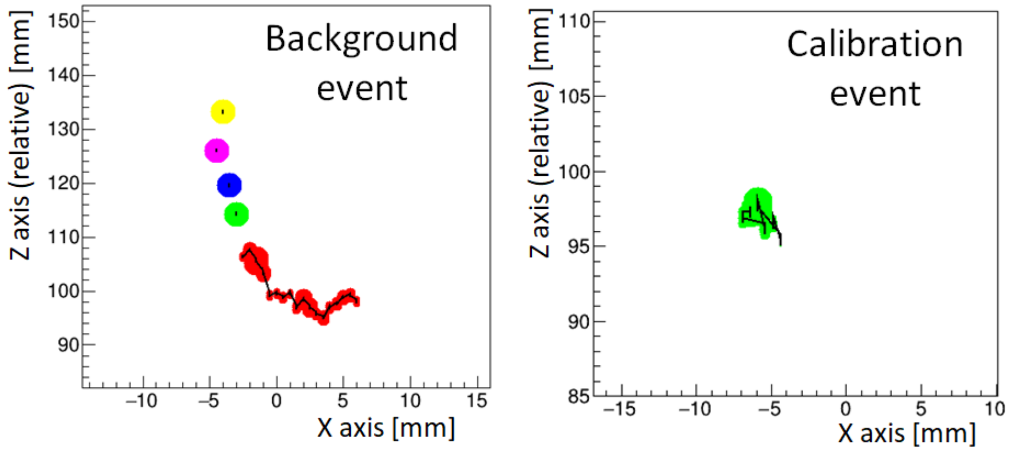

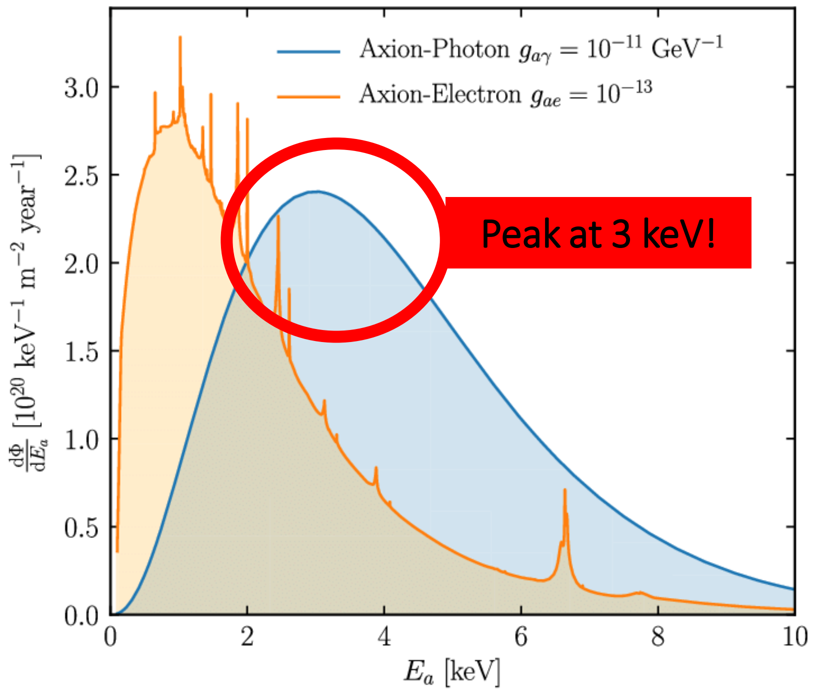

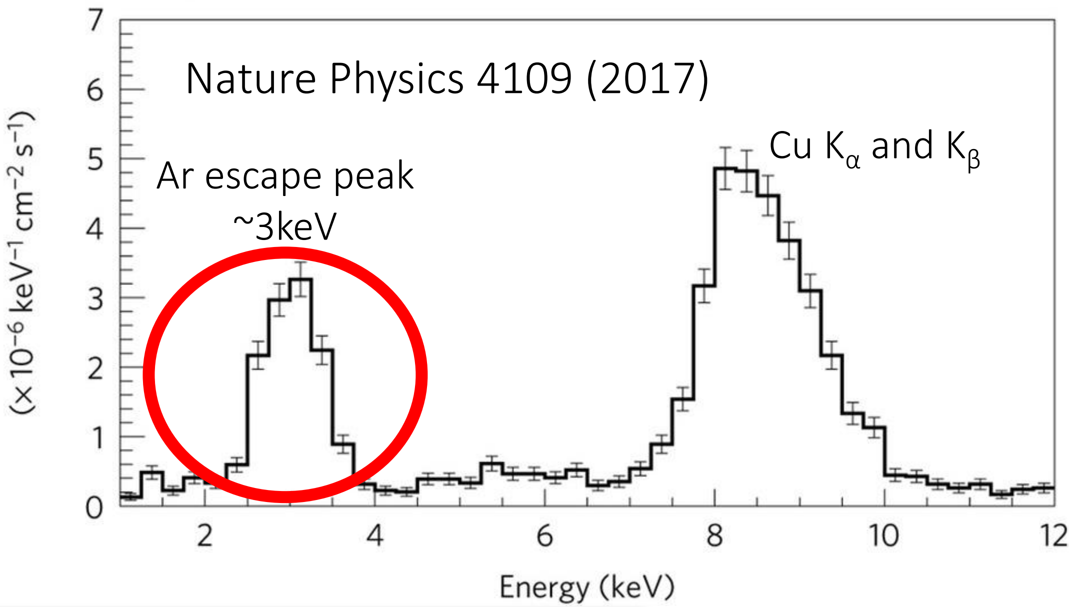

Solar axion peak expected at ~3 keV.

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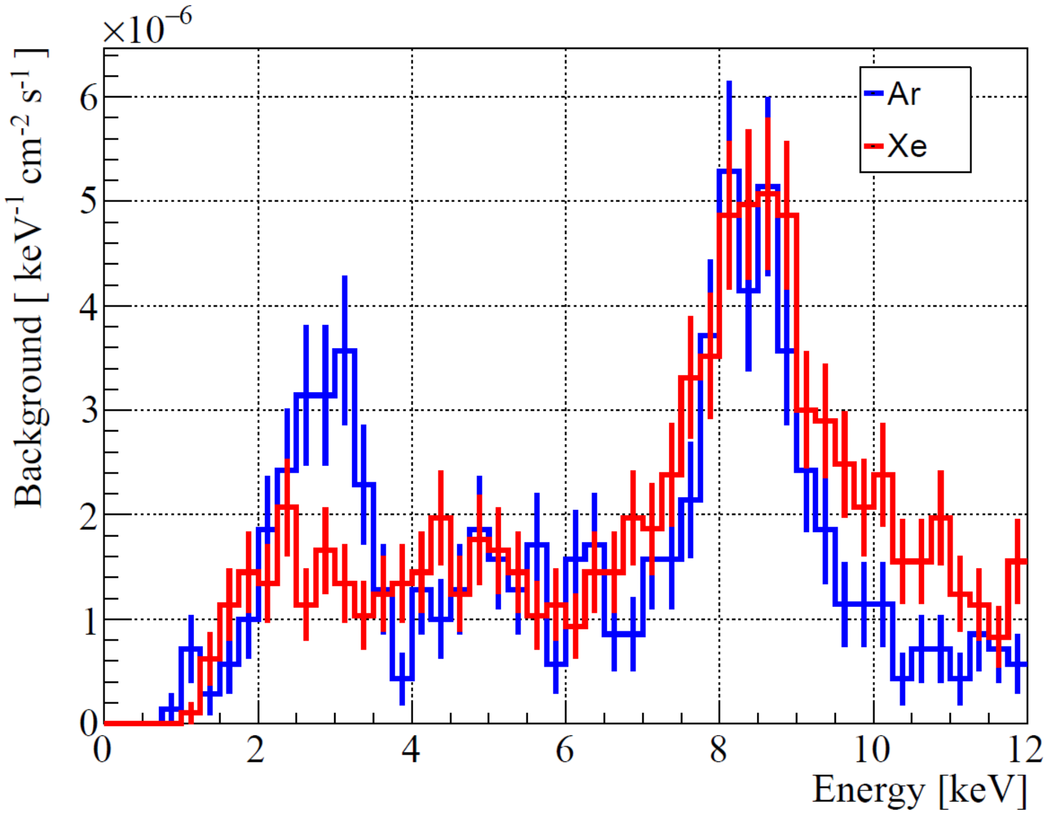
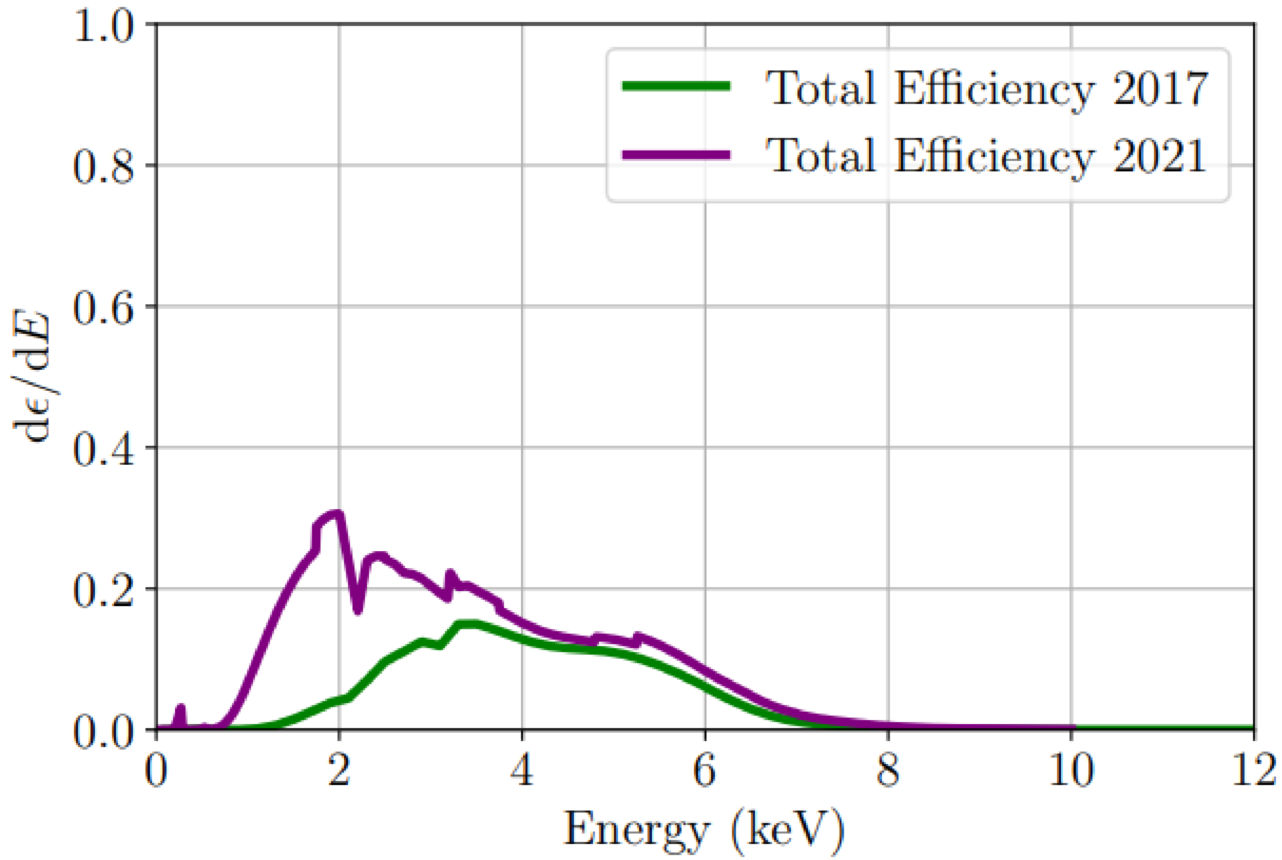
Towards Xe-based gas mixtures

Dataset	Background exposure (h)	Background level (2, 7) keV ($\times 10^{-6}$ c keV^{-1} cm^{-2} s^{-1})	Tracking exposure (h)	Gas	Years
1	2476	1.7 ± 0.1	130	Ar + 2.3% iso	2019-2020
2	335	2.3 ± 0.4	25.6	Ar + 2.3% iso	2020
3	3416	1.5 ± 0.1	159	48.85% Xe + 48.85% Ne + 2.3% iso	2020-2021
Total	6227		314.6		

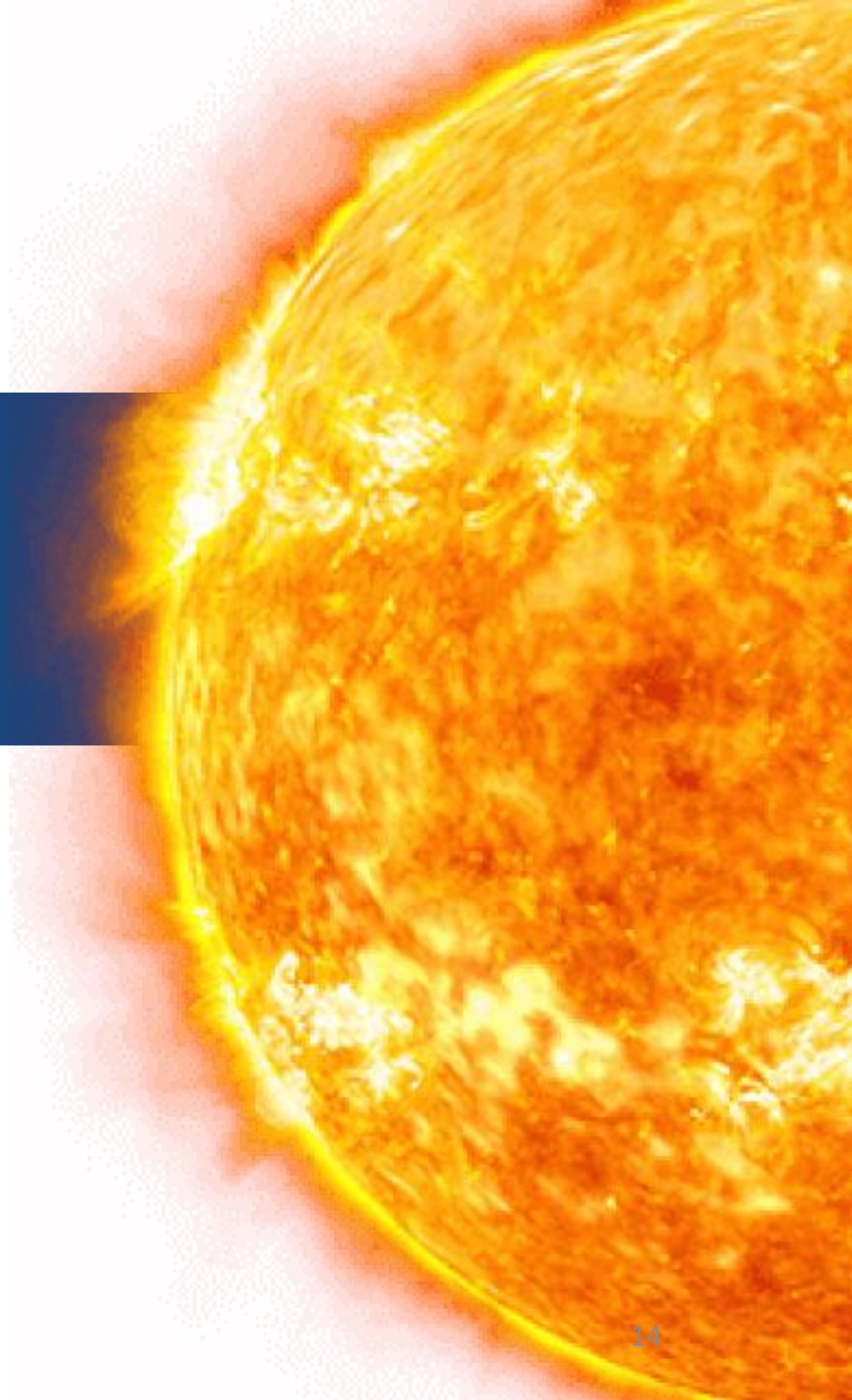


Improving the overall efficiency

- **Hardware efficiency:**
  - We don't use a differential window anymore. Especially noticeable at low energies.
  - Use of Xe-based gas mixtures.
- **Software efficiency:**
  - A sophisticated cut definition has increased the efficiency at low and high energies (away from the ^{55}Fe peaks).

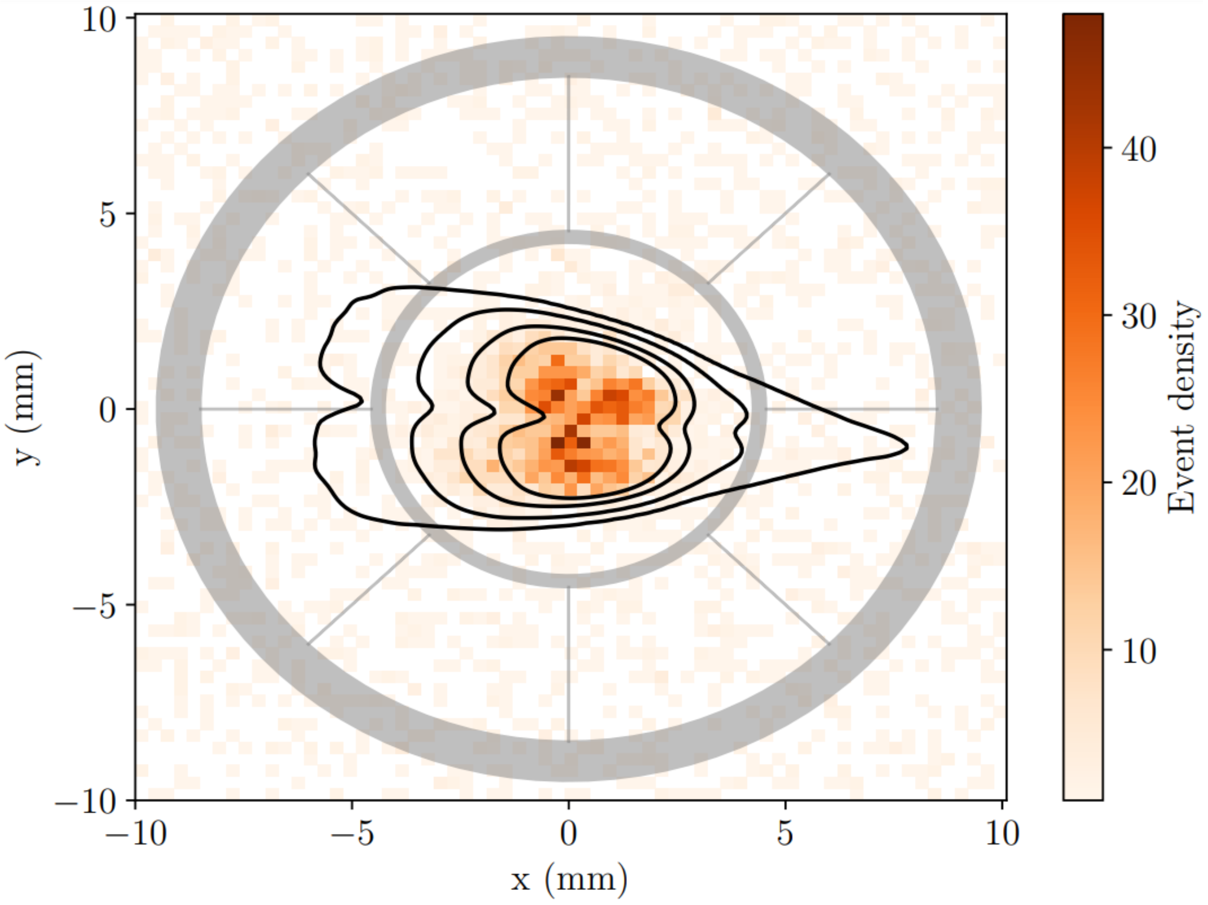


The new upper limit on $g_{a\gamma}$

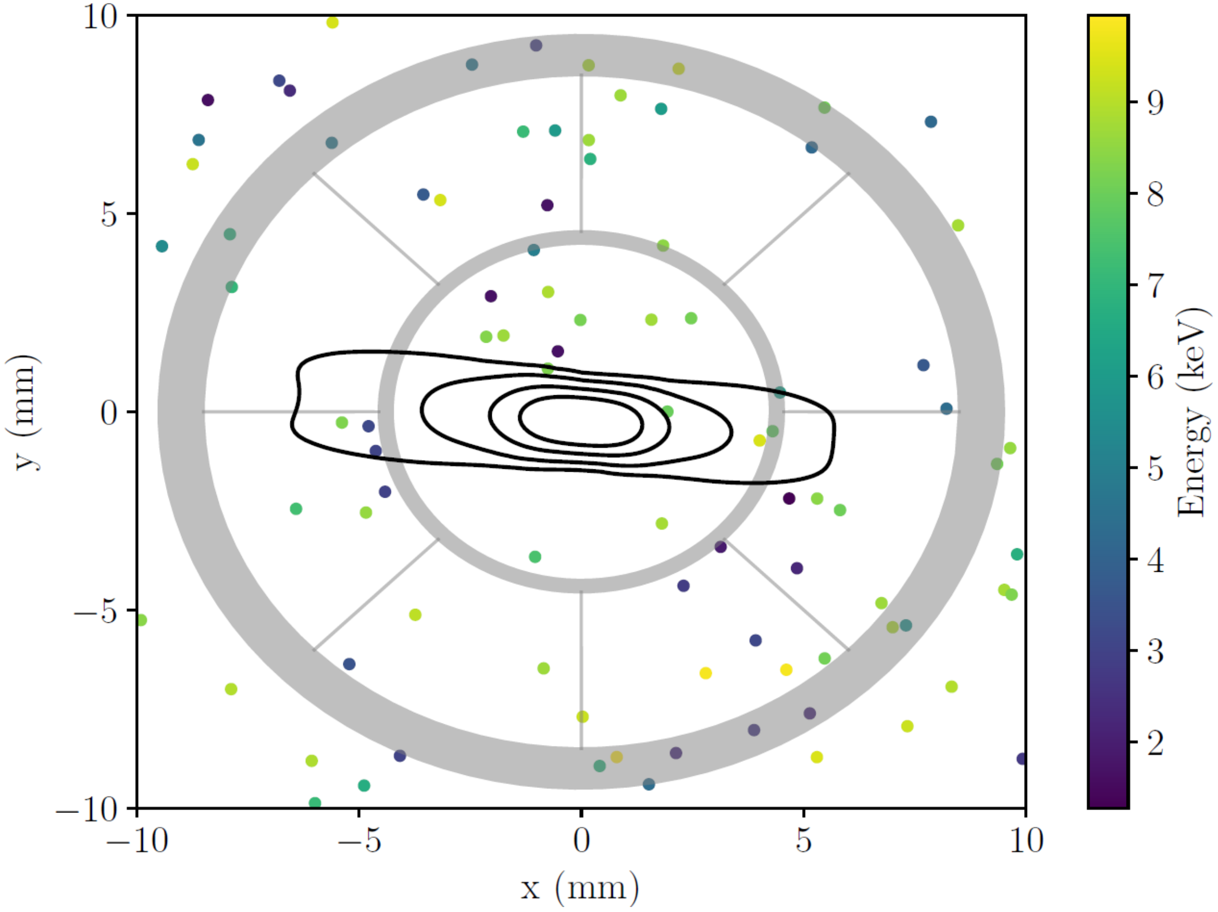


X-ray like events during tracking

Calibration data



“Axion” data



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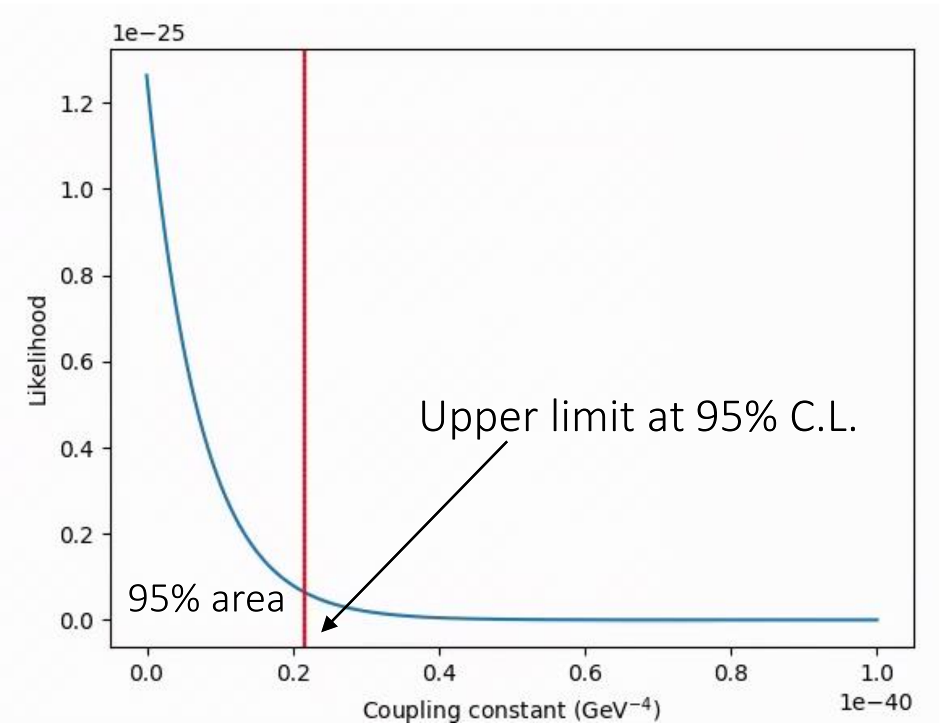
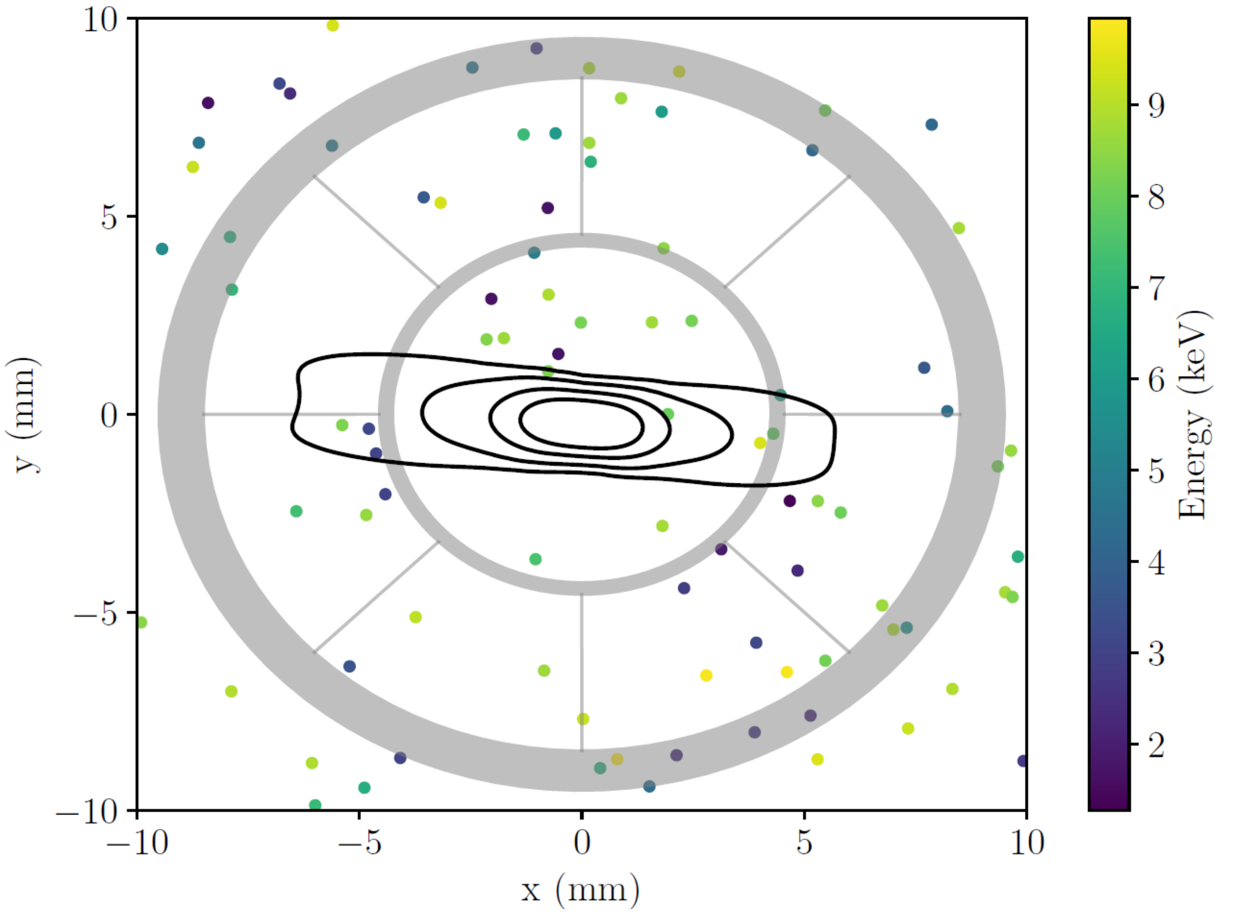


$$\ln \mathcal{L} = -R_T + \sum_{1}^{n} \ln R(E_i, \vec{x_i})$$

"Axion" data



Upper limit on $g_{a\gamma}$ using **only** the SRMM 2019-2021 data:

$g_{a\gamma}$ < 6.9×10^{-11} GeV^{-1} for m_a<0.02 eV (95% C.L.)

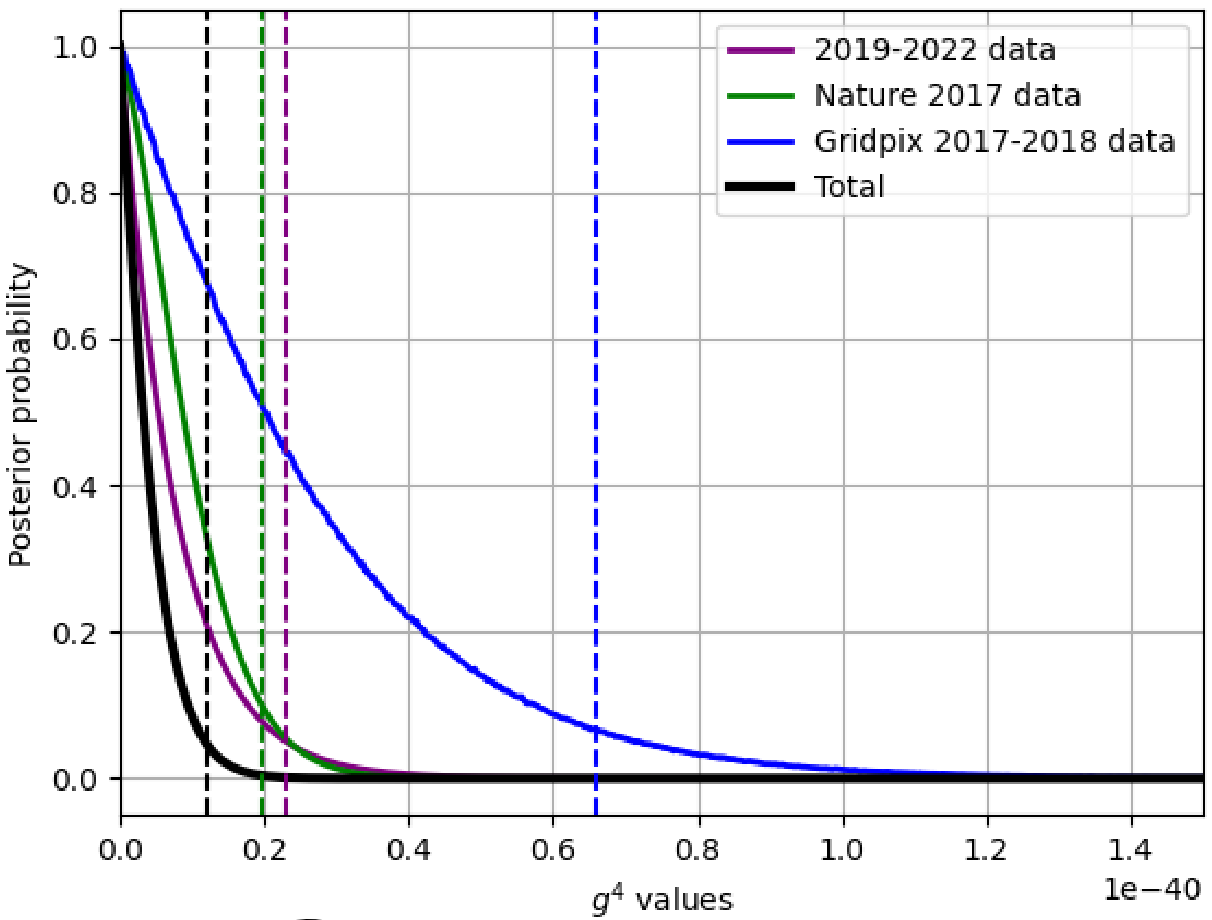
New upper limit on the axion-photon coupling

CAST benchmark for the axion-photon coupling

$g_{a\gamma}$ < 6.6×10^{-11} GeV^{-1} (NPHYS4109)

	Upper limit on $g_{a\gamma}$* (×10^{-11} GeV^{-1})
Limit new data	6.9
Limit new data + benchmark	5.9
Limit new data + benchmark + Gridpix	5.7

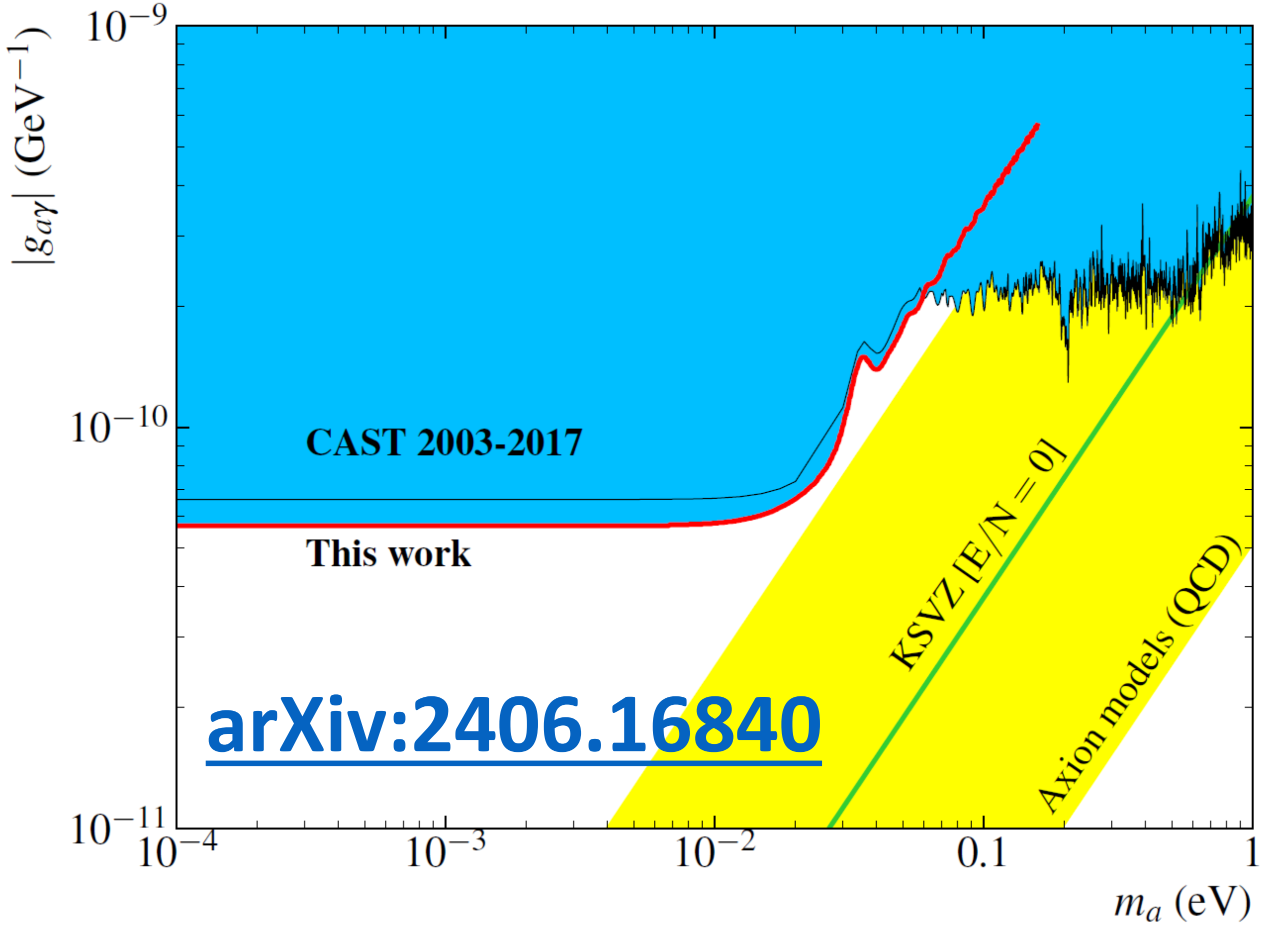
*at 95% C.L. for $m_a < 0.02$ eV



New CAST upper limit on $g_{a\gamma}$:

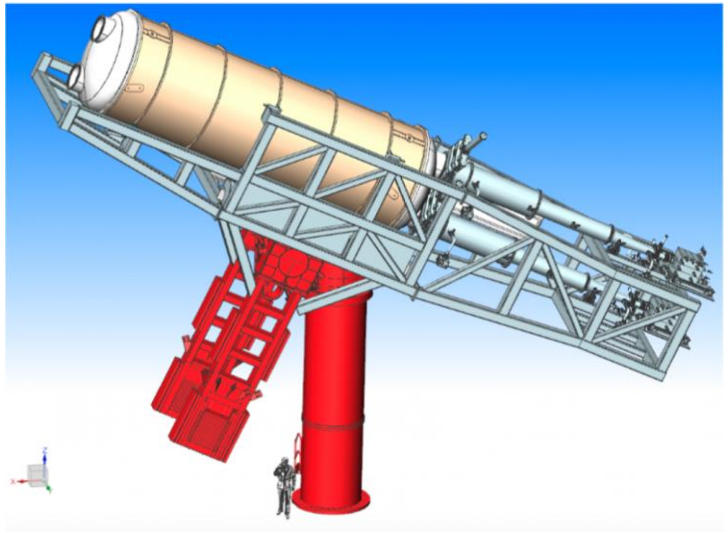
$g_{a\gamma}$ < 5.7×10^{-11} GeV^{-1} for m_a<0.02 eV (95% C.L.)

New upper limit on the axion-photon coupling



arXiv:2406.16840

Next step…



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Thank you for your attention

konstantin theodoros cenk aleksandr antonios antonis juanan justin kreso cristina biljana sebastian paco iñaki marios sergio javier elisa hector gloria mike sofia giovanni theopisti luis marin mehmet kostas asun christoph alfredo thomas christos javier arif

The CAST Collaboration

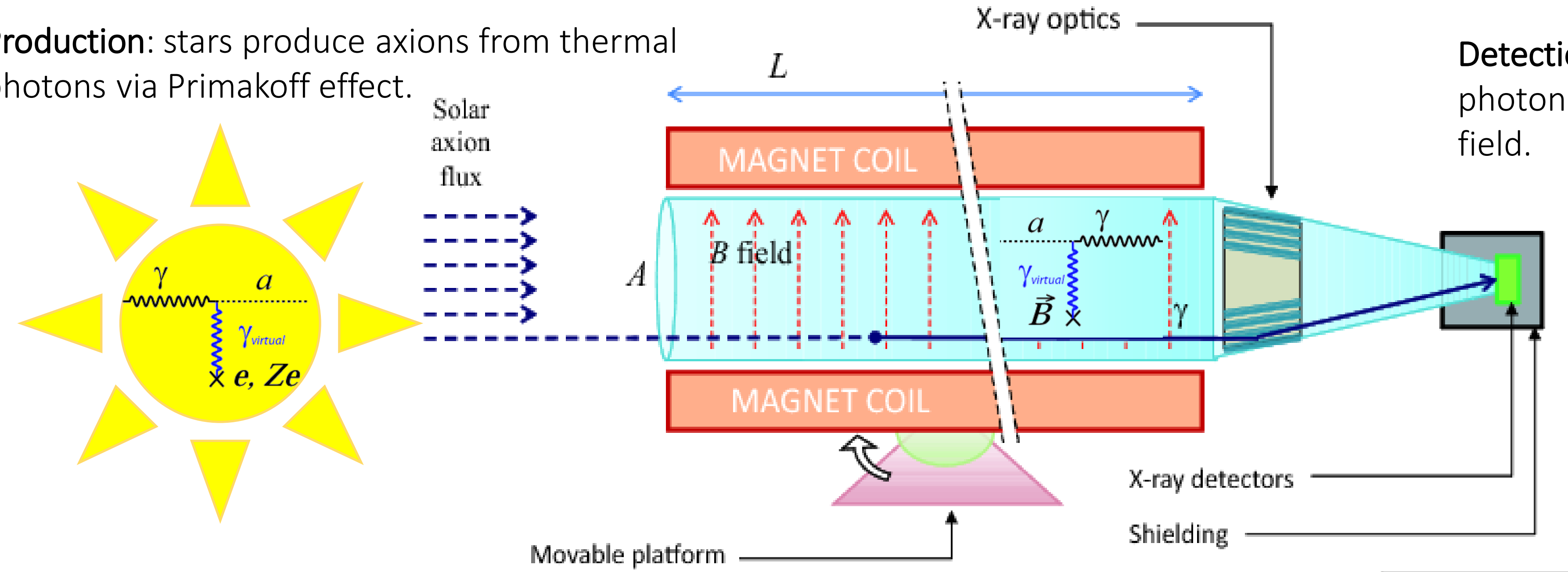
igor jose idan laura julia mario mike aydin jana pablo maria juan madalin david jessica kaan nenad yannis jaime jochen konrad martyn nuno valentina theodoros stephan fanny cristian esther george gonzalo eleni manousos steffen tillmann

Backup slides

Solar axions and helioscopes

Production: stars produce axions from thermal photons via Primakoff effect.

Detection: conversion of axions into photons in the presence of a magnetic field.



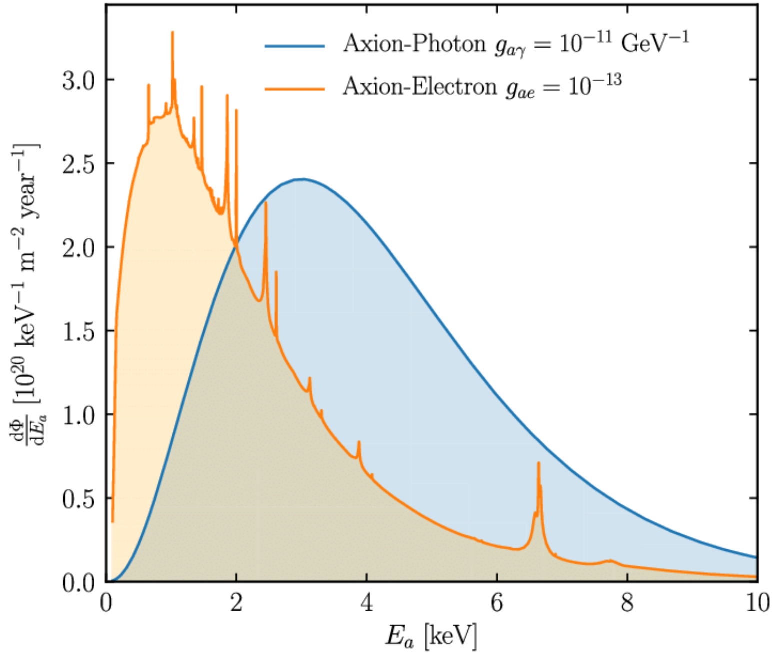
Expected X-ray excess when the magnet points to the Sun.

Layout description:

- A powerful and large dedicated magnet
- X-ray focusing optics optimized for axion spectrum
- Ultra-low background X-rays detectors

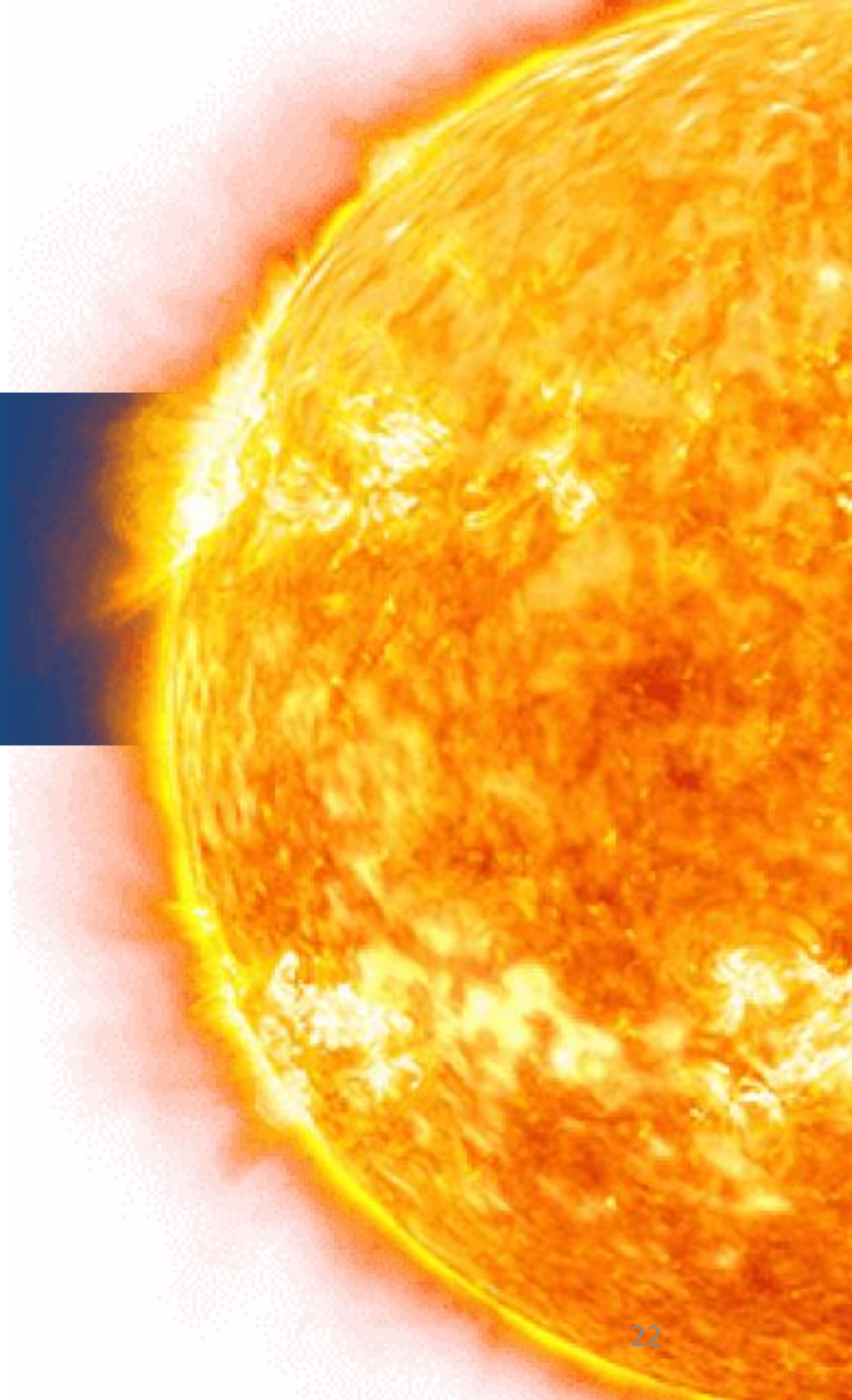
See J. Vogel and L. Gastaldo talks for more details!

$$FoM \sim \underbrace{B^2 L^2 A}_{\text{magnet}} \cdot \underbrace{\epsilon_d b^{-1/2}}_{\text{detector}} \cdot \underbrace{\epsilon_o \alpha^{-1/2}}_{\text{optics}} \cdot \underbrace{\epsilon_t^{1/2} t^{1/2}}_{\text{exposure}}$$

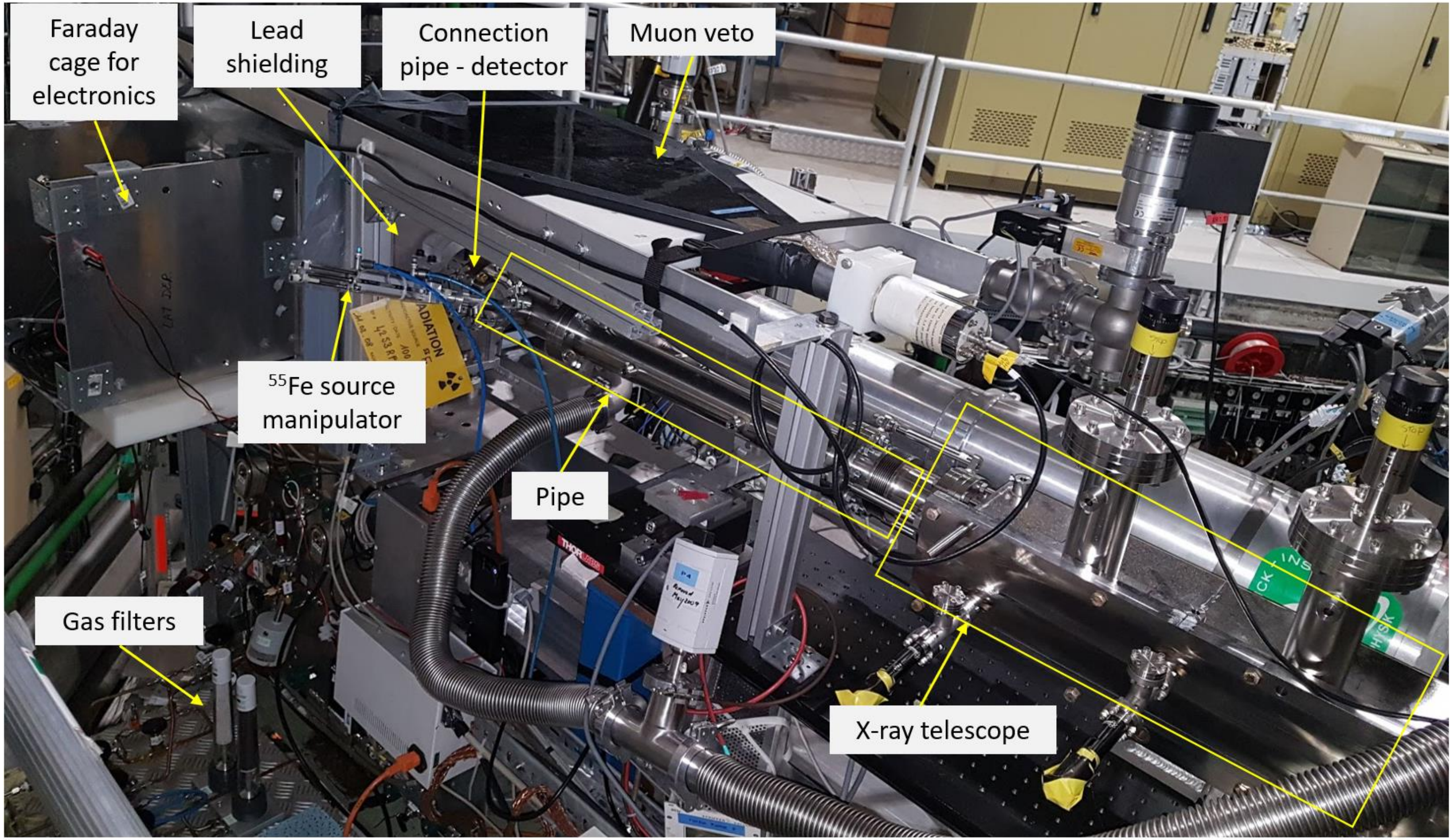


Hardware

The IAXO pathfinder system



The IAXO pathfinder system at CAST



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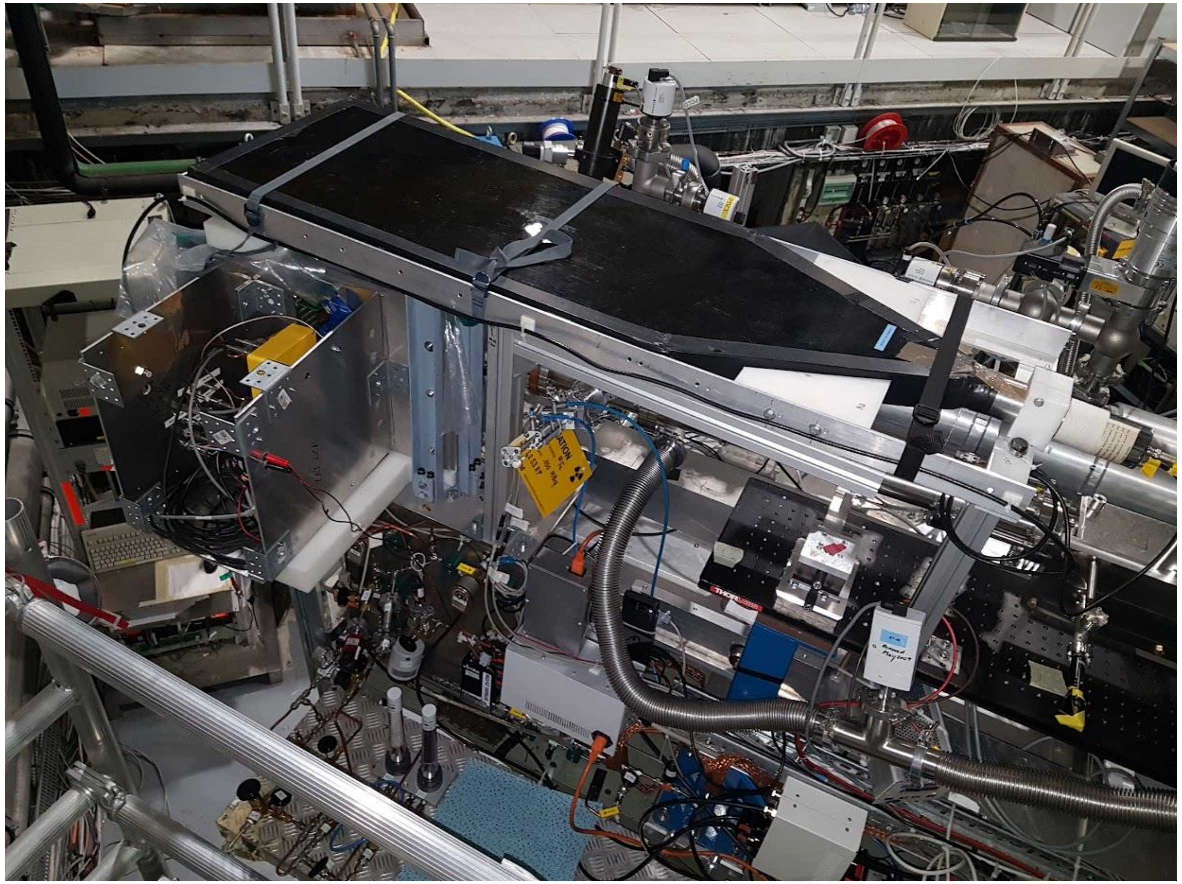
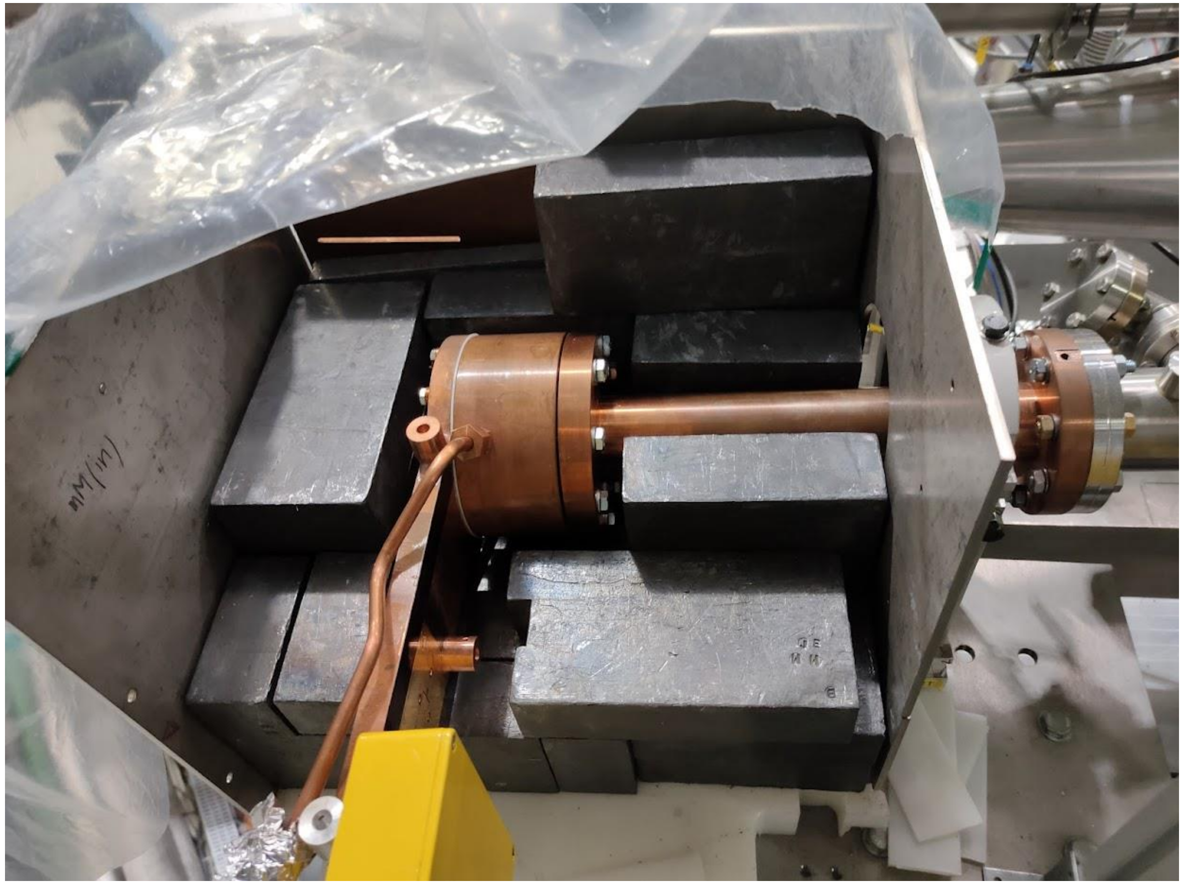
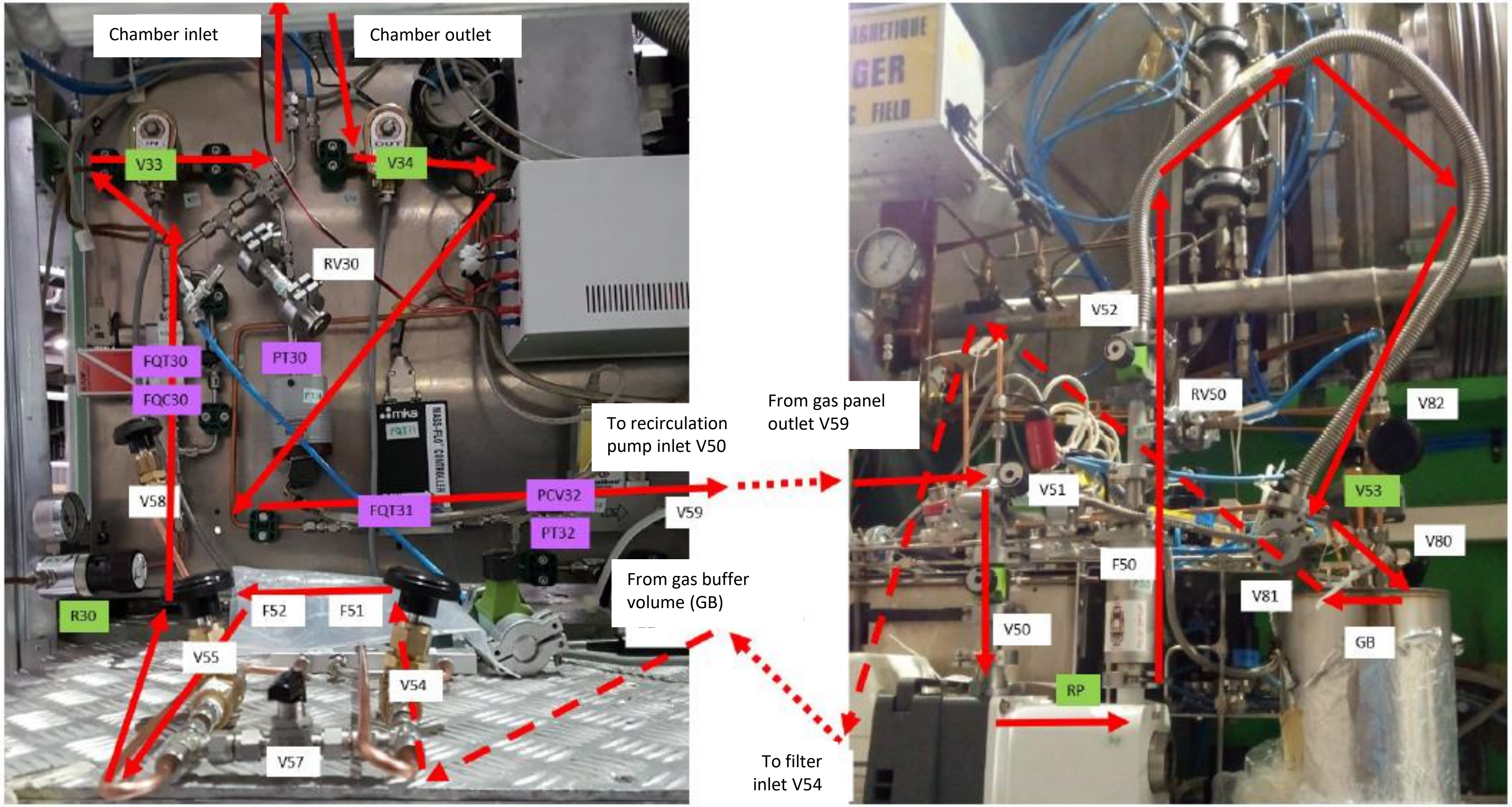




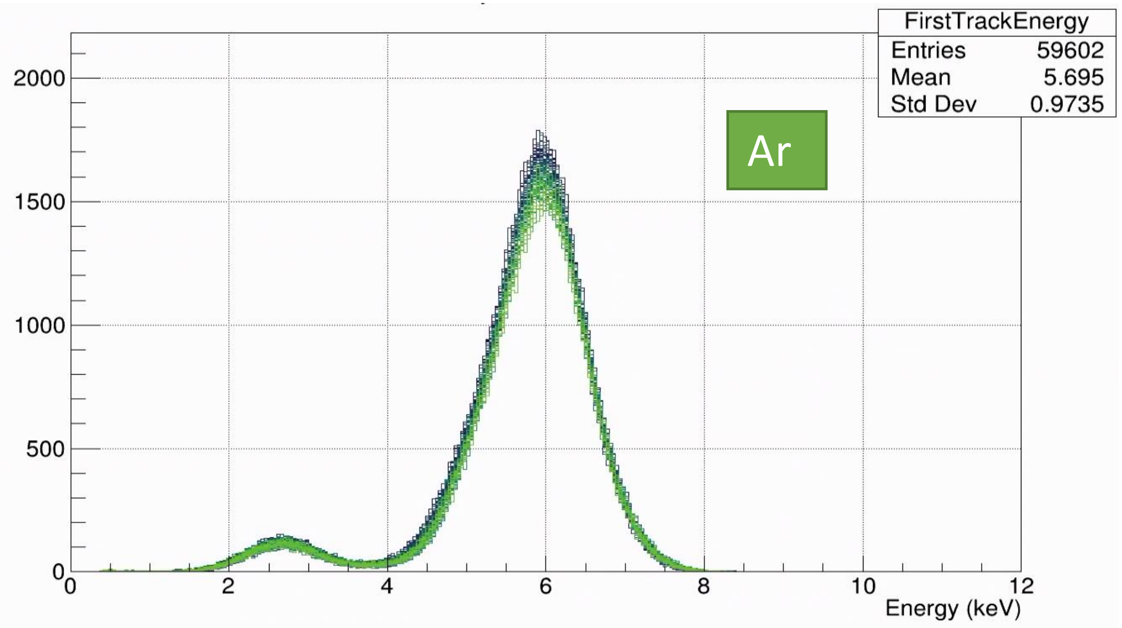
Gas system upgrade

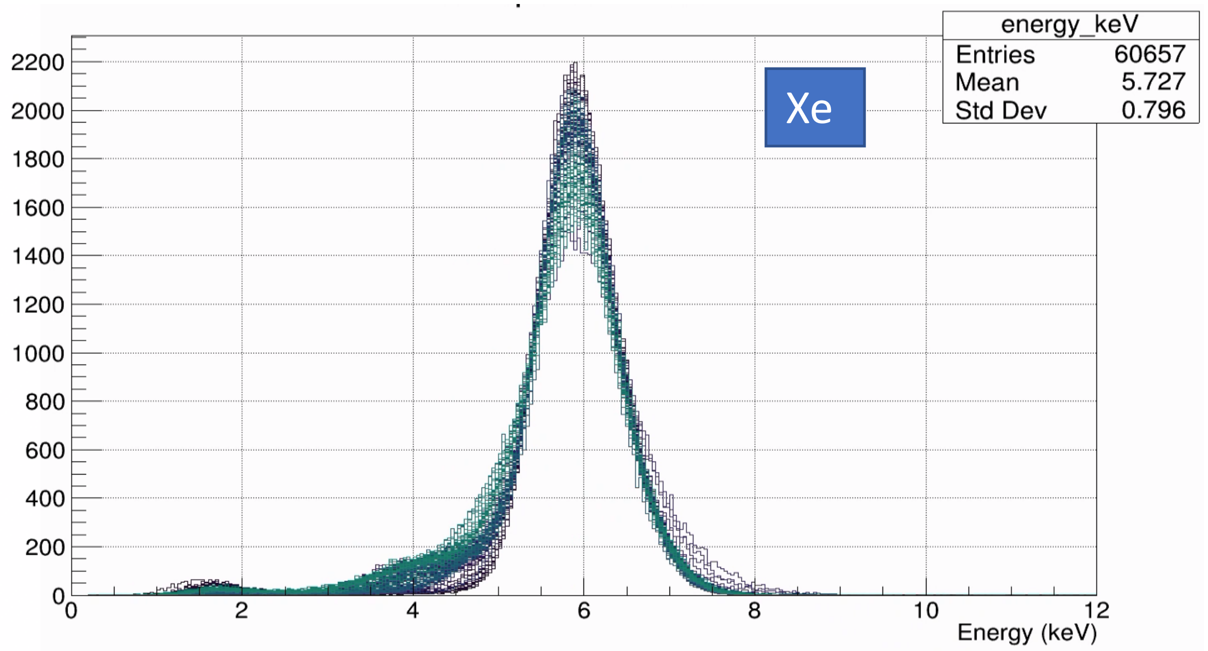
- Argon data taking was in open loop → clean and fresh gas always available.
- Xenon is too expensive → we need to recirculate the gas.
- Not free of challenges!

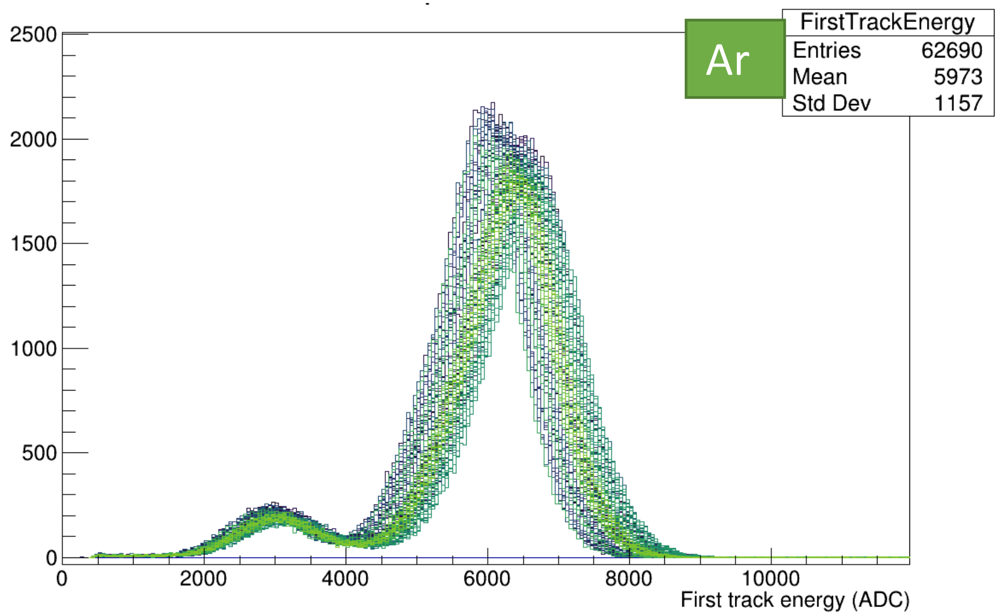


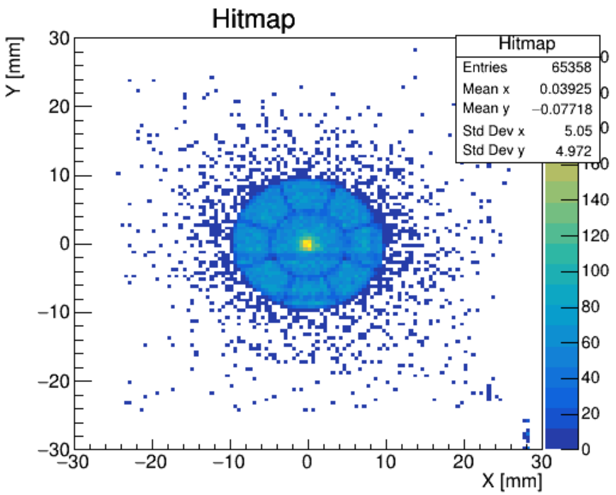
Filters were found to be Rn emitters!

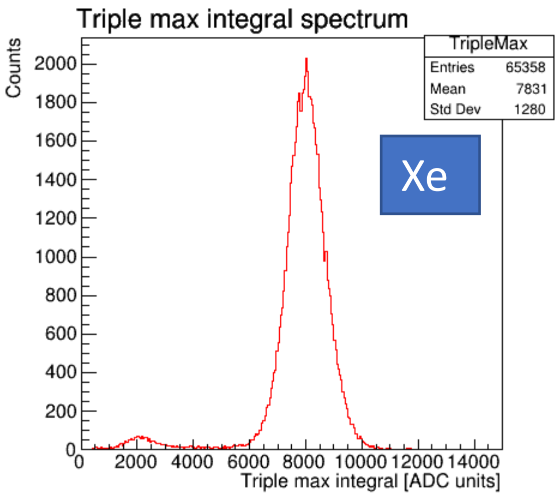
^{55}Fe calibrations and *live* data quality control



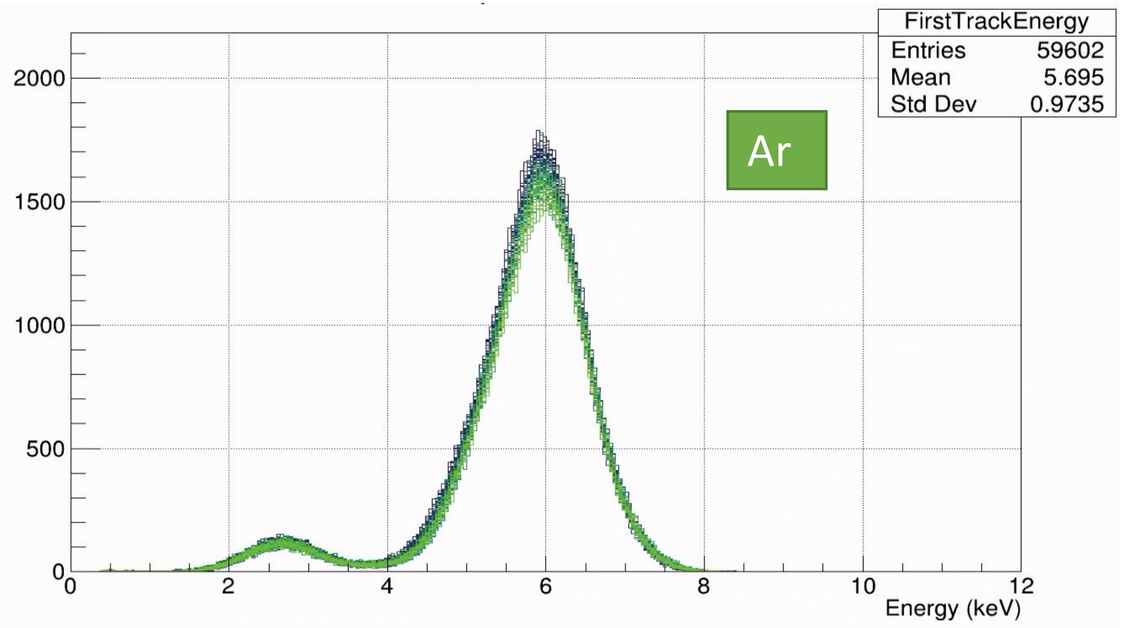


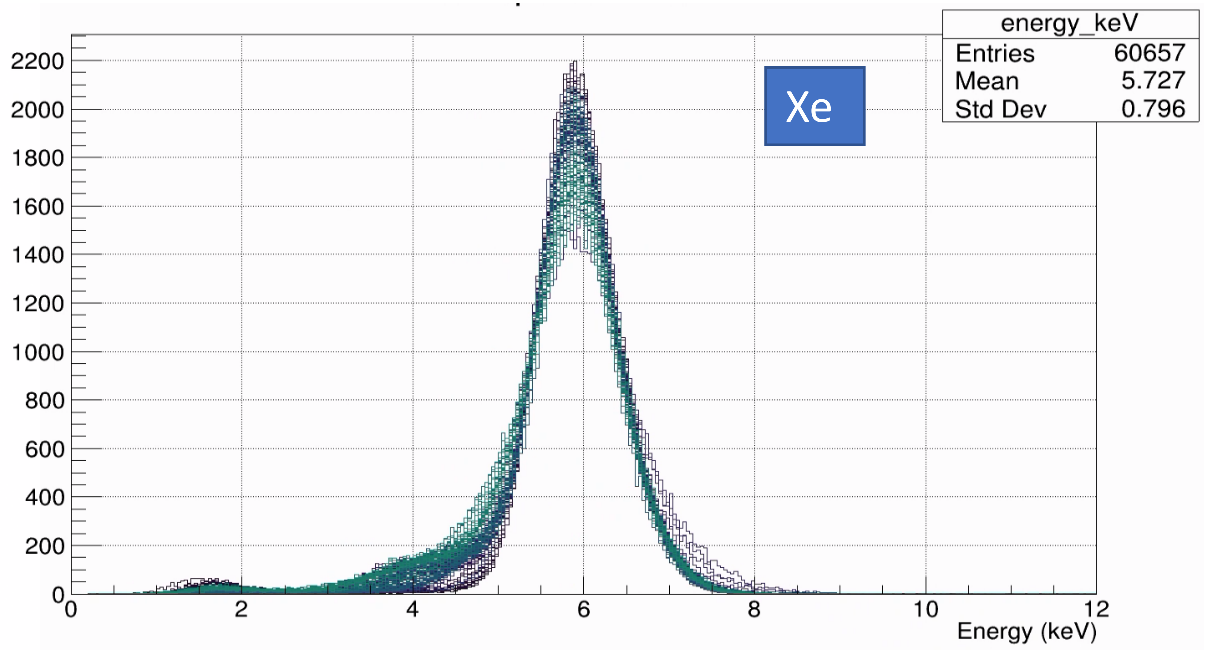


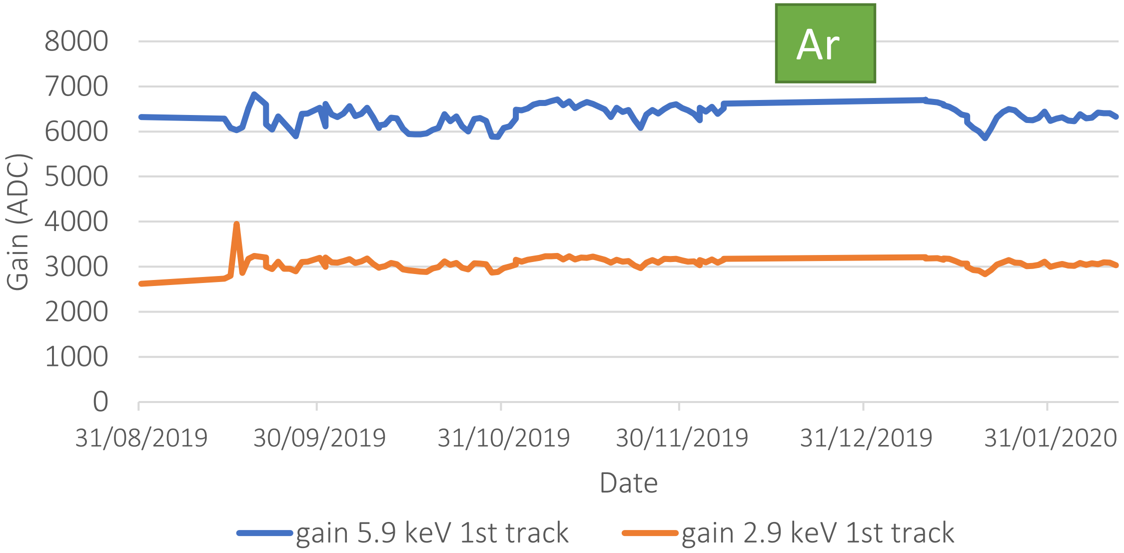


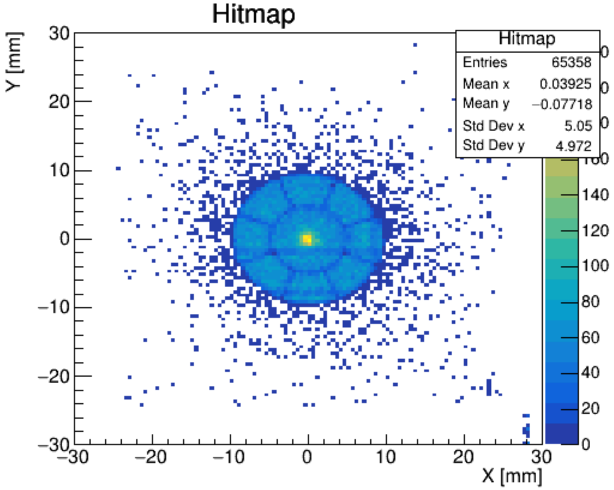


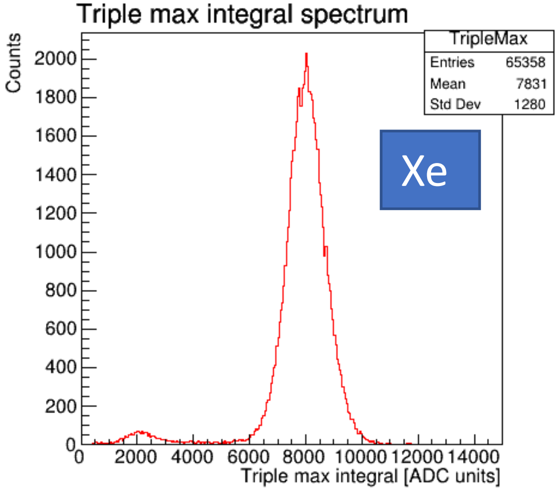
^{55}Fe calibrations and *live* data quality control



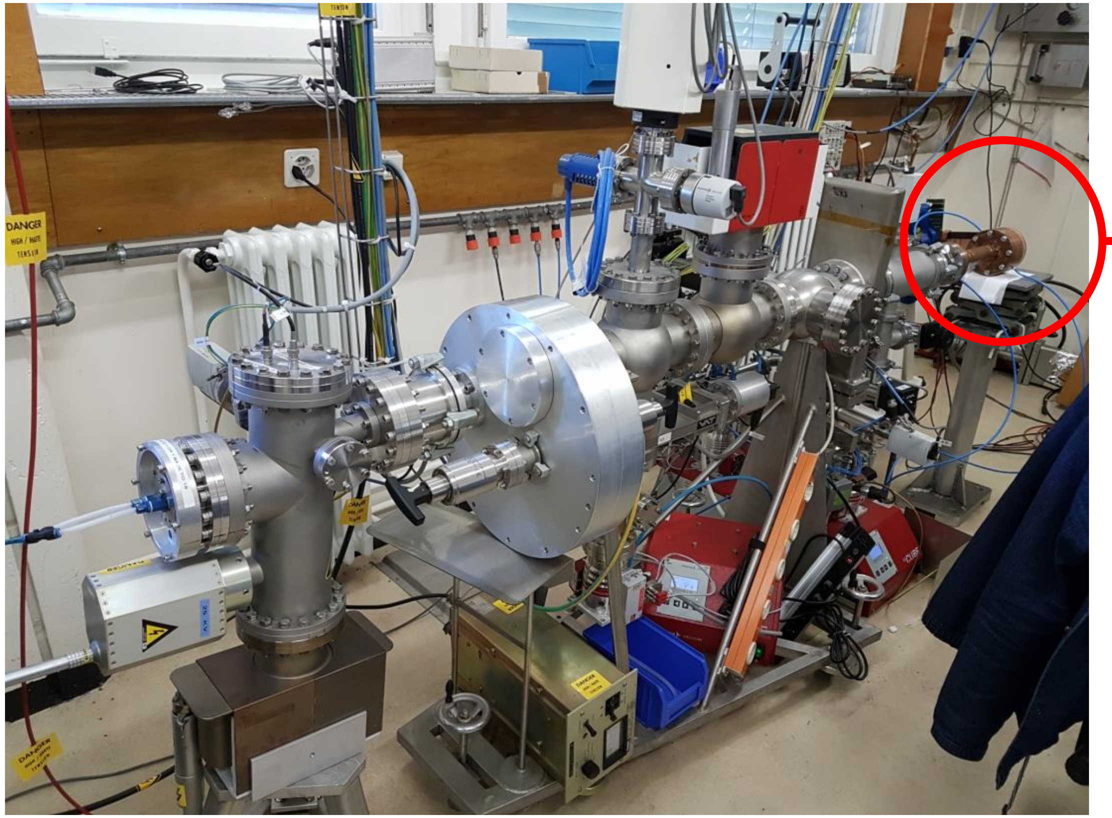


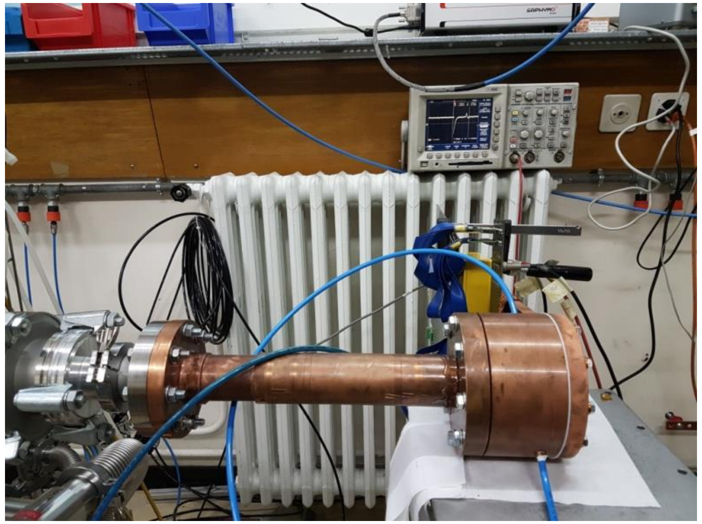




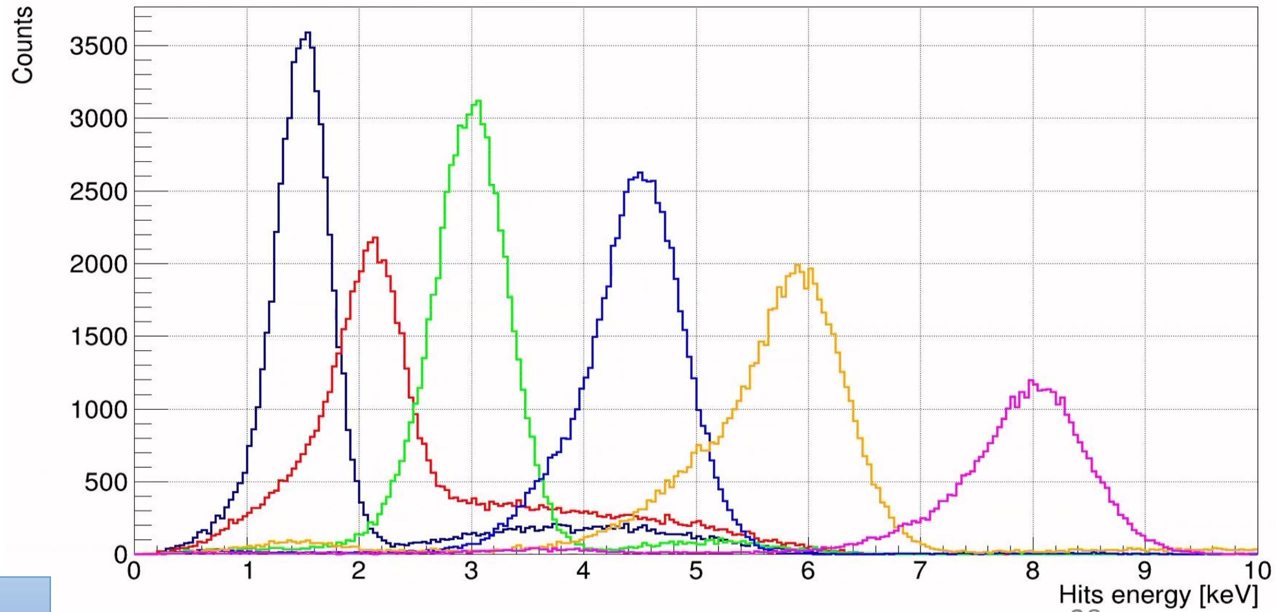


Calibrations in the X-ray lab at CERN





Target	Energy (keV)	Filter	Range (keV)
Al	1.5	Al	-
Au	2.1	PEEK	2.0-3.5
Ag	3.0	Ag	-
Ti	4.5	Ti	3.5-5.5
Mn	5.9	Cr	5.5-6.5
Co	6.9	Fe	6.5-7.5
Cu	8.0	–	7.5-10



We cover the energy RoI from solar axion flux : (0.1, 10)keV

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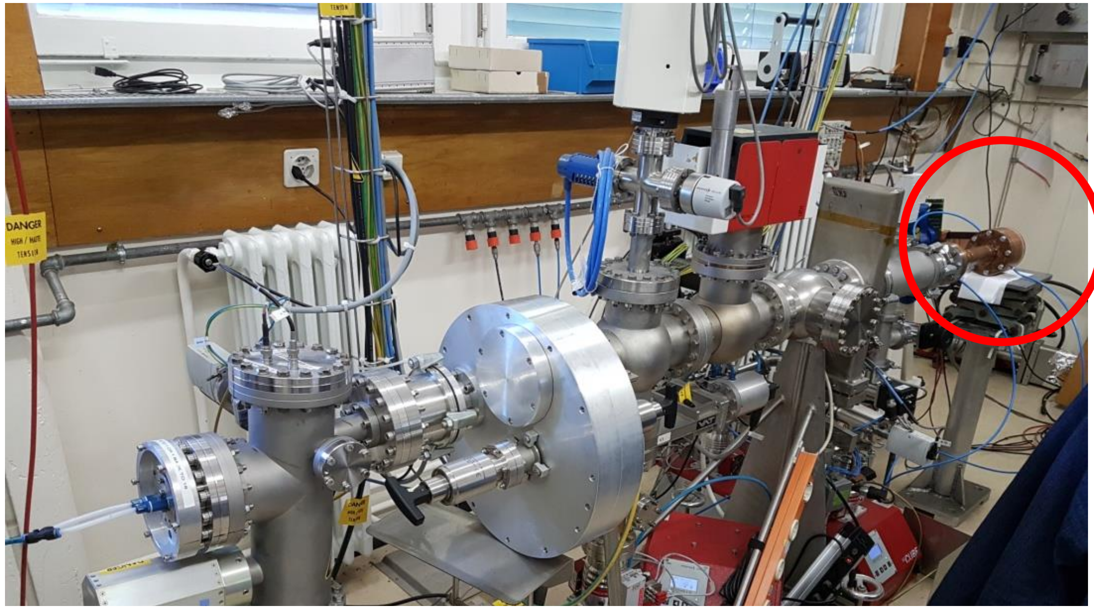
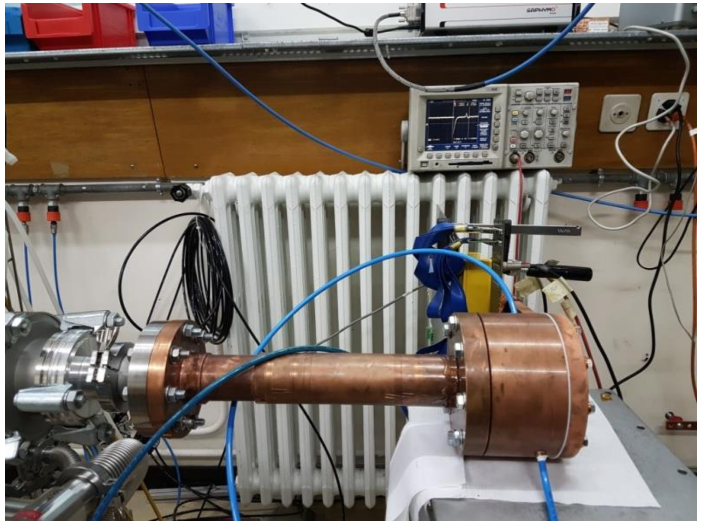
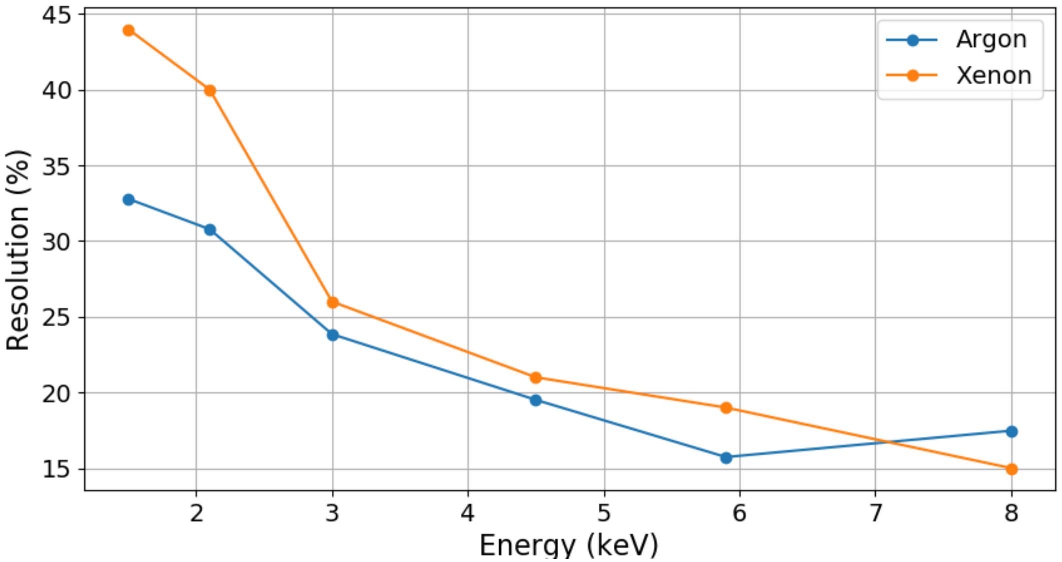
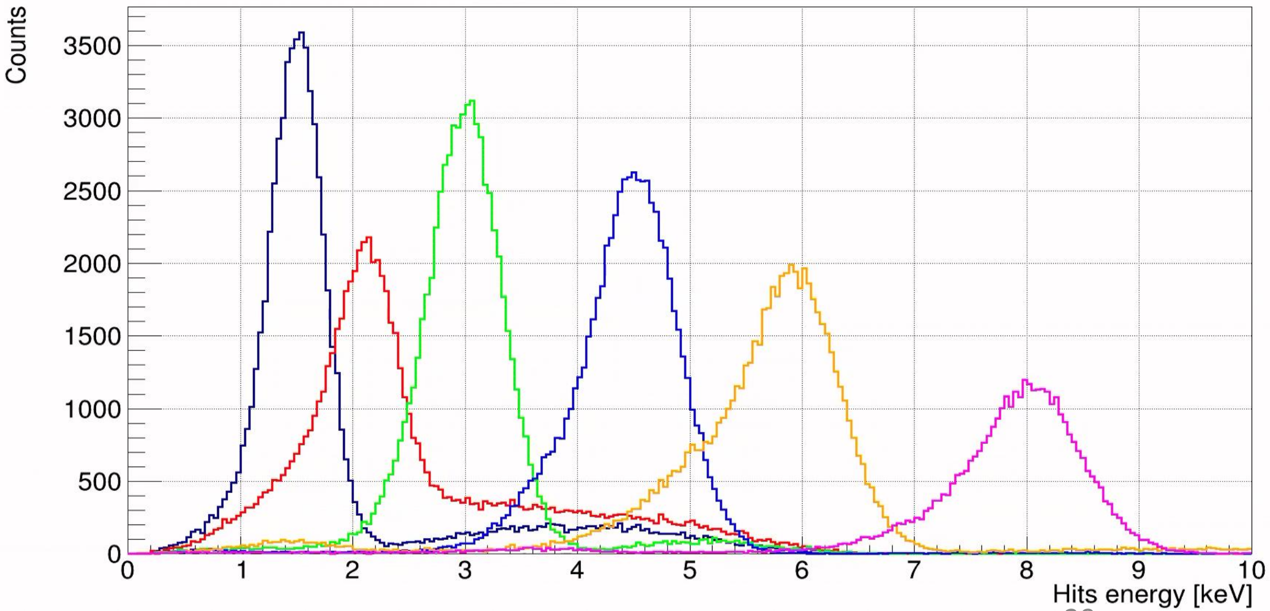


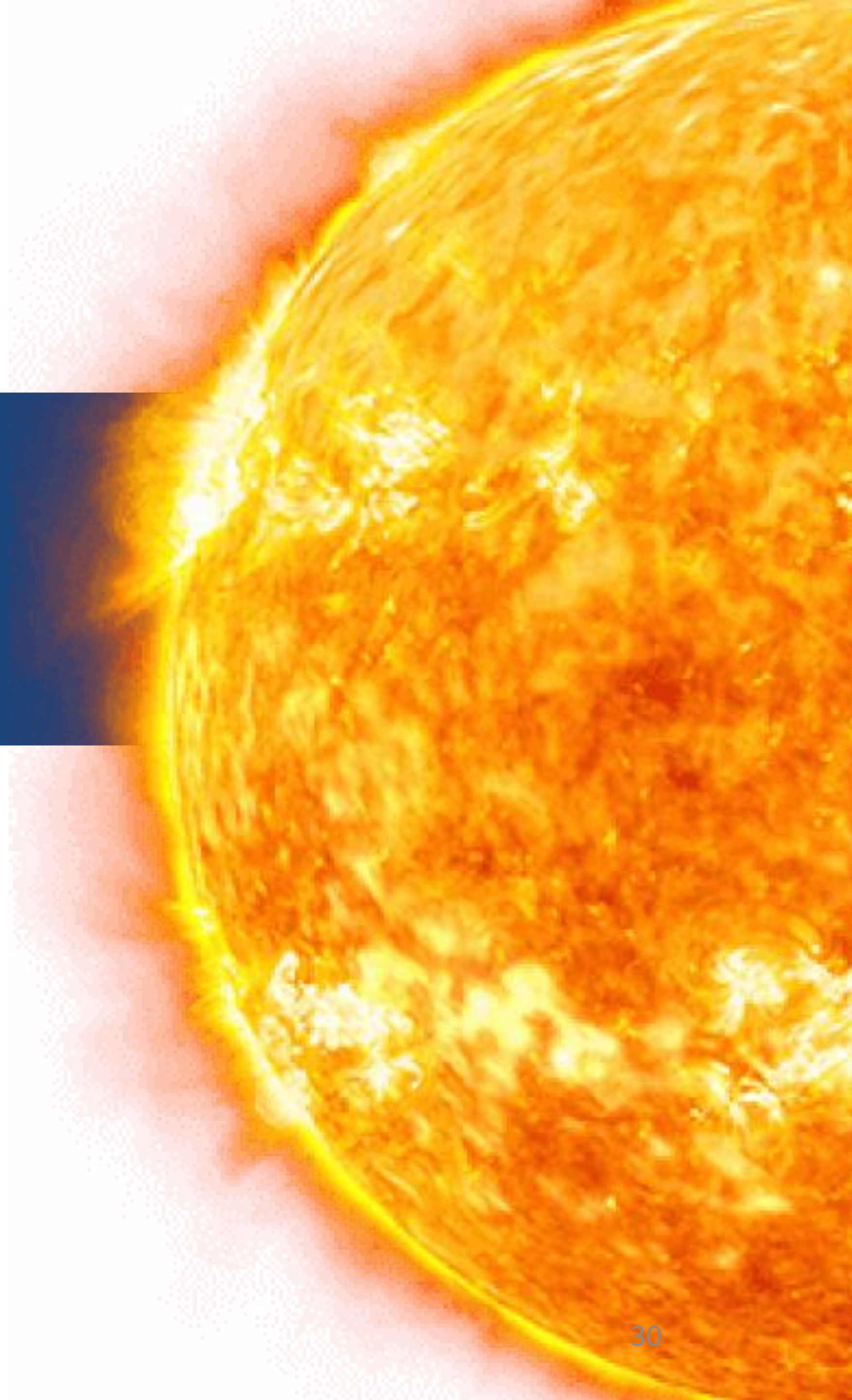






Software

The REST-for-physics framework



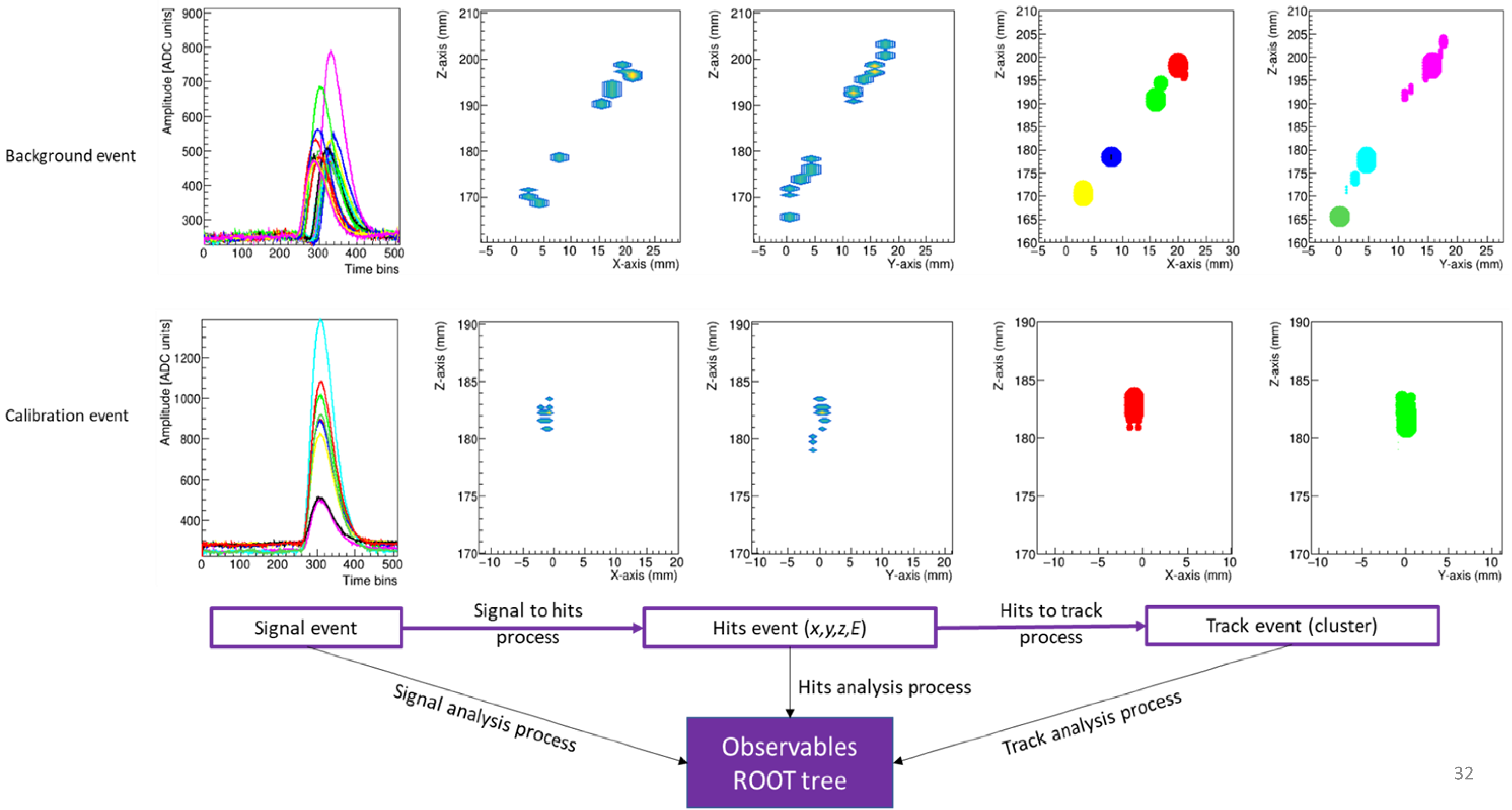
The REST-for-physics framework

github.com/rest-for-physics

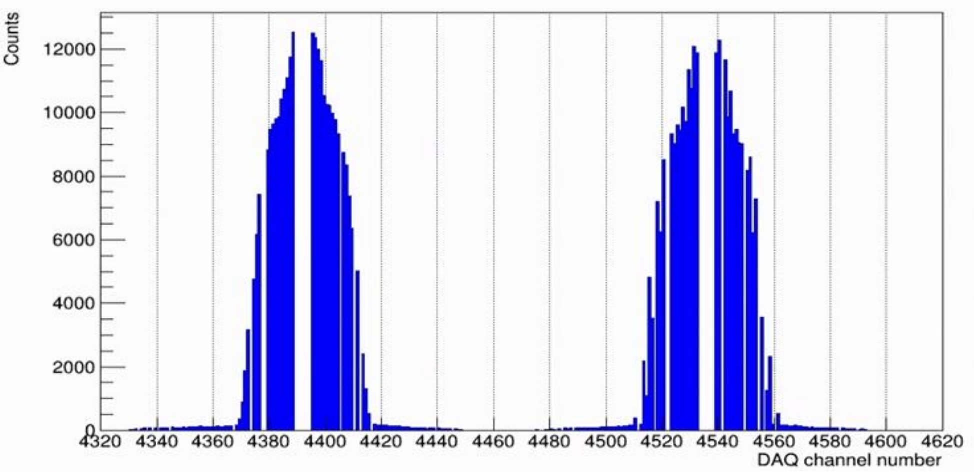
- The REST-for-Physics (Rare Event Searches Toolkit) Framework is a collaborative software effort that provides common tools for:
    - acquisition,
    - simulation,
    - data analysis
- It was originally designed to work with data of gaseous Time Projection Chambers (TPCs).
- It is mainly written in C++ and it is fully integrated with ROOT I/O interface.
- The REST framework establishes a common procedure and output data format to define input information, via configuration (.rml) files.
- It allows for official version control, so that all official data will be fully reproducible.

Centralizing site → https://rest-for-physics.github.io/

Event reconstruction with REST-for-physics

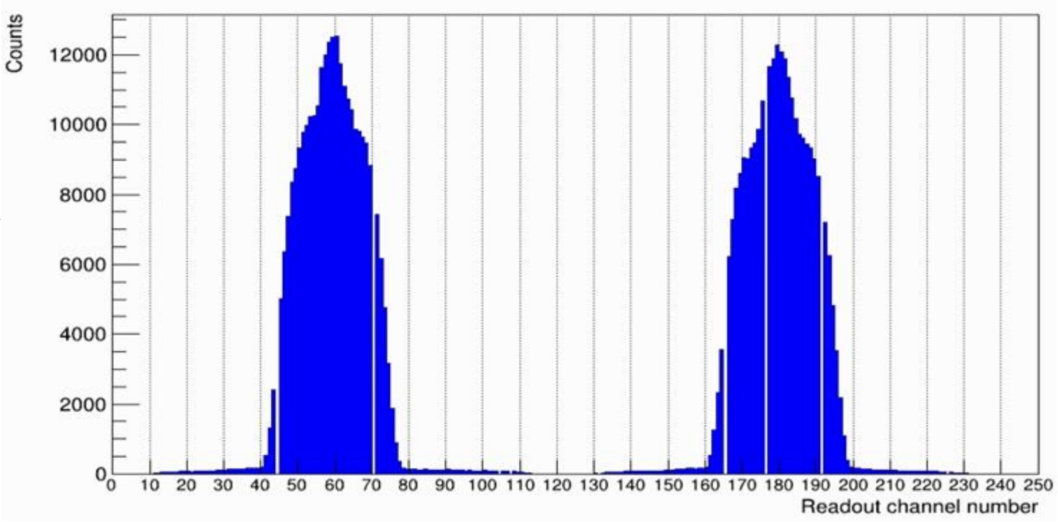


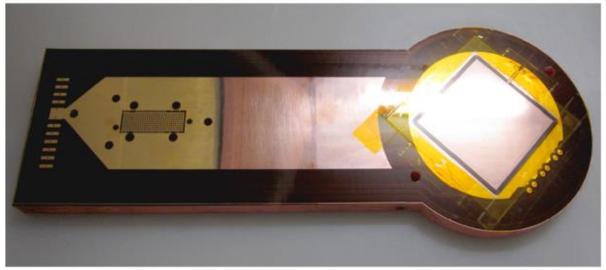
Example: microbulk detector for IAXO and event reconstruction from real detector data



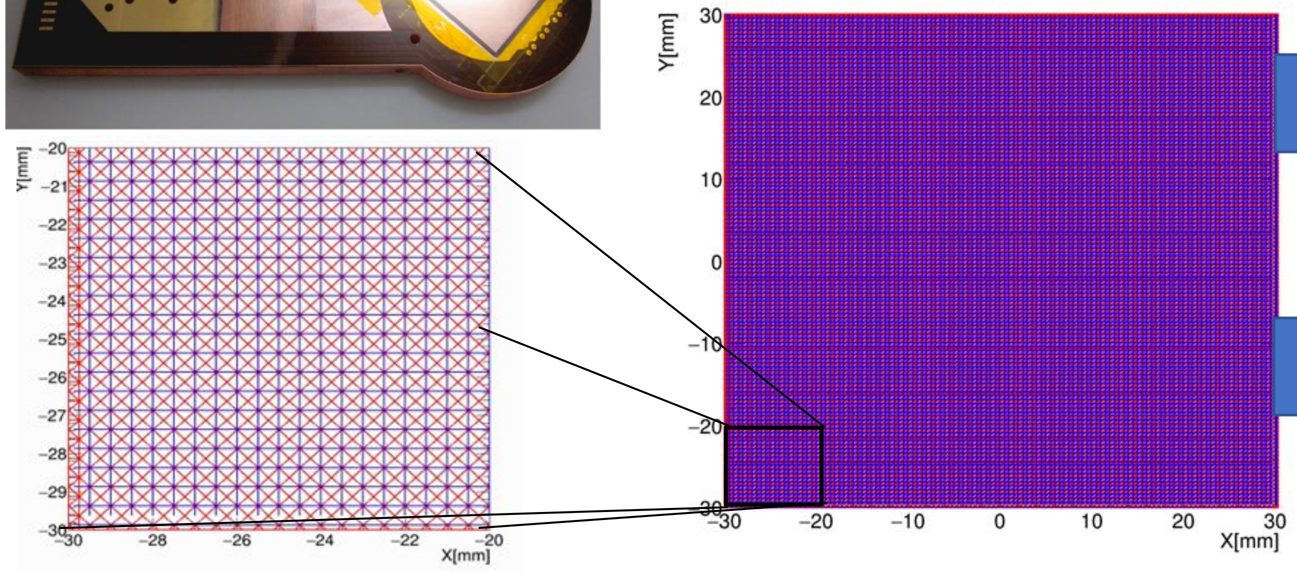
Decoding file

(DAQ to readout channel number correspondence)

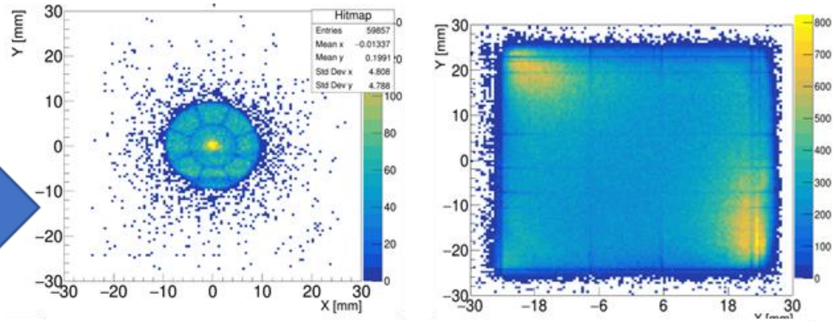




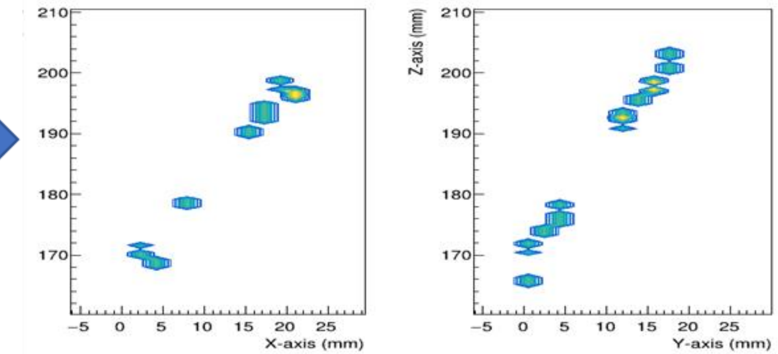
120x120 strips, pitch = 0.5 mm
Total area = 6x6 cm^2



Hitmaps



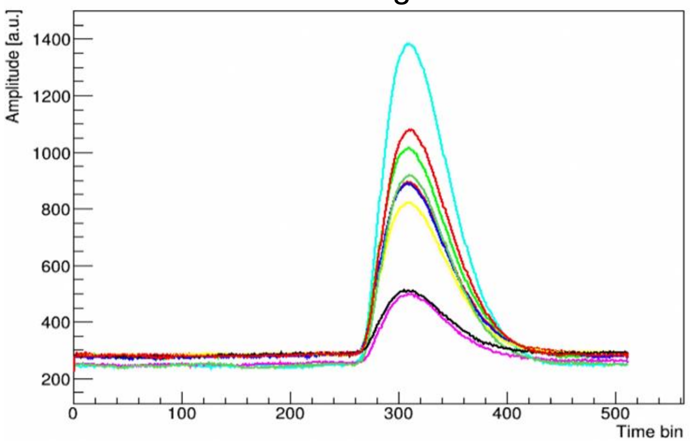
Hits events



Event reconstruction with REST-for-physics

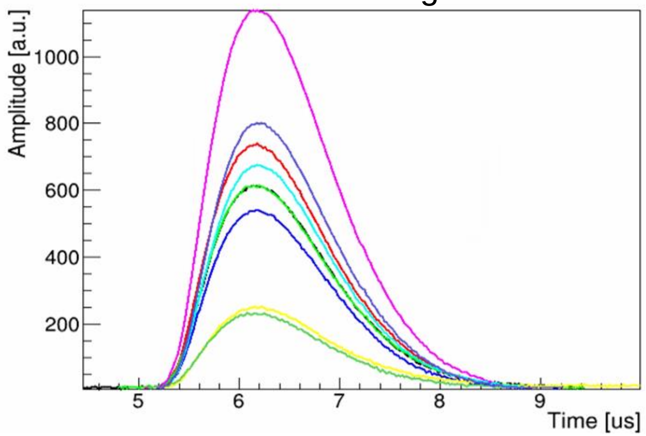
Experimental data

TRestRawSignalEvent



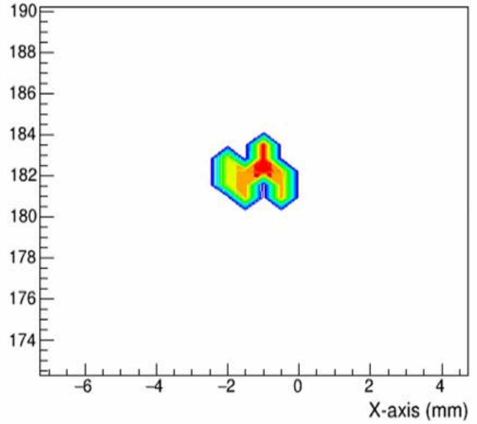
Raw signal as recorded by the electronics

TRestDetectorSignalEvent



Reconstructed signal in terms of time, energy and position

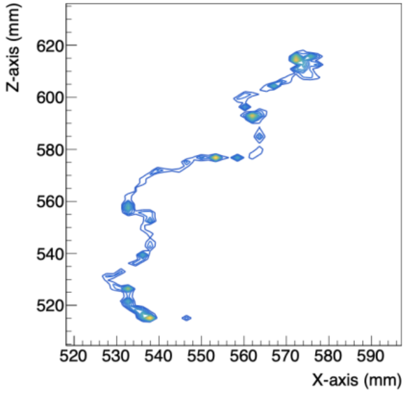
TRestDetectorHitsEvent



Reconstructed hits event

Simulation data

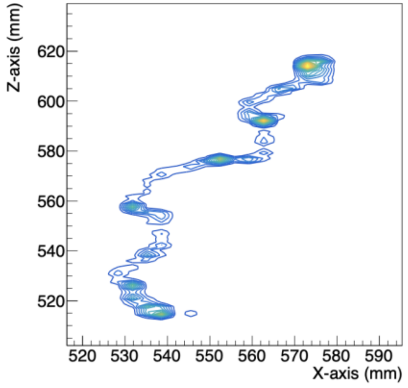
TRestGeant4Event



(a)

Simulated event

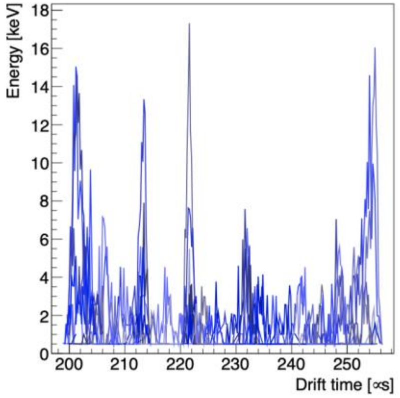
TRestDetectorHitsEvent



(b)

Appearance of the event after diffusion

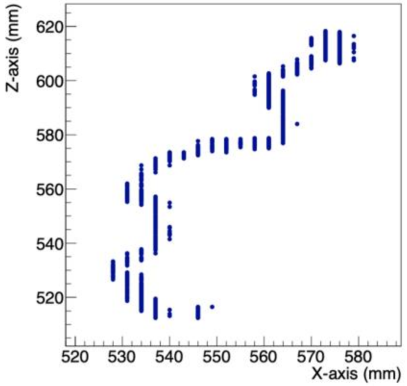
TRestDetectorSignalEvent



(c)

Reconstructed signal event

TRestDetectorHitslEvent

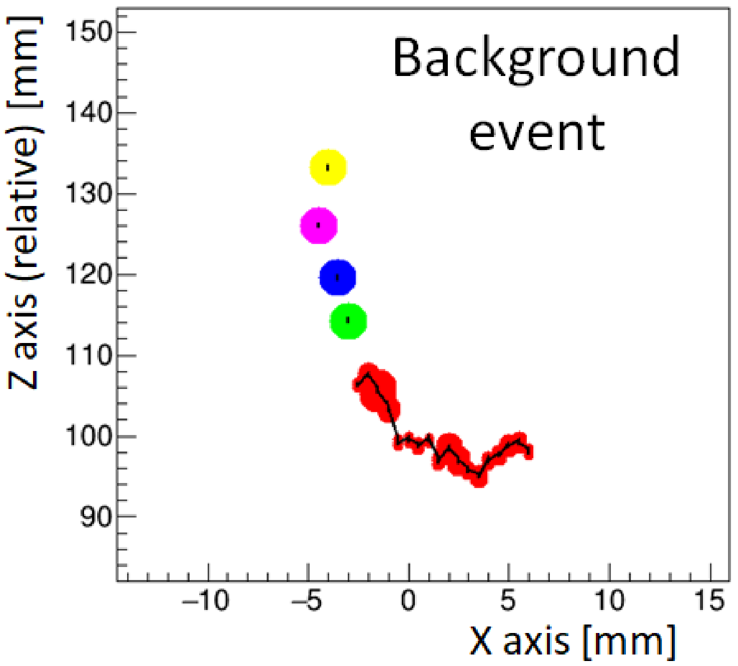


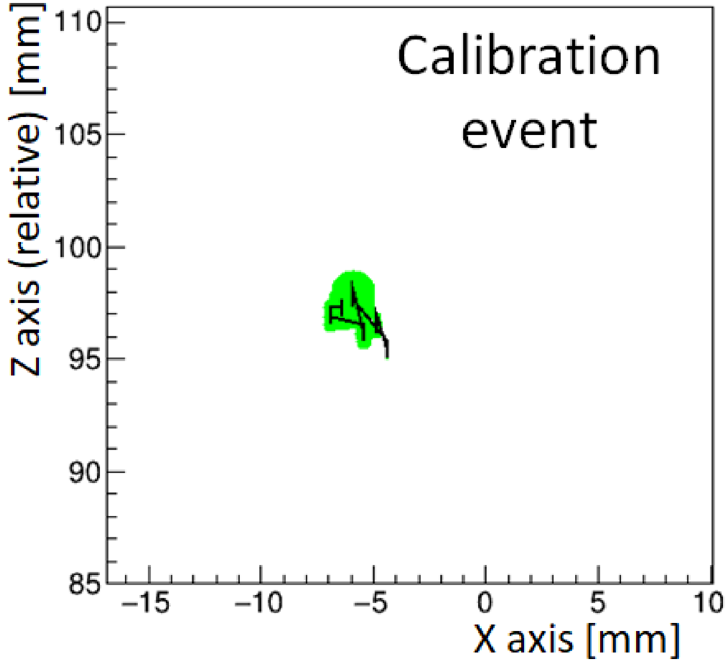
(d)

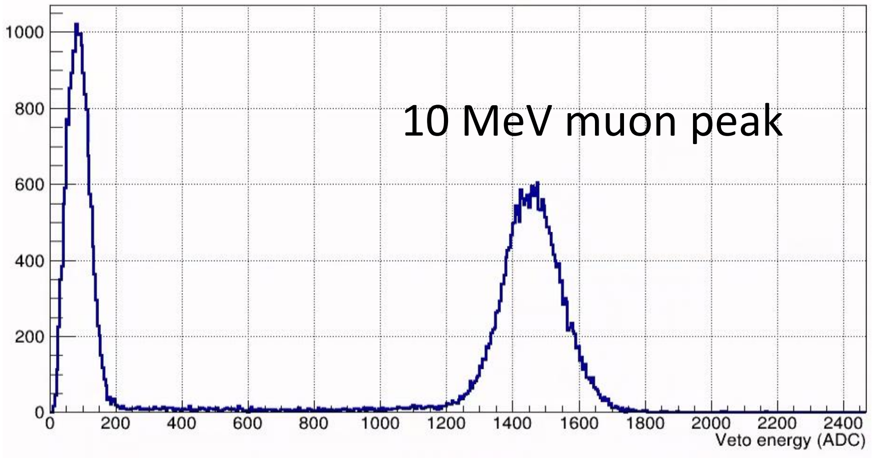
Reconstructed hits event. The effect of the readout is clearly seen.

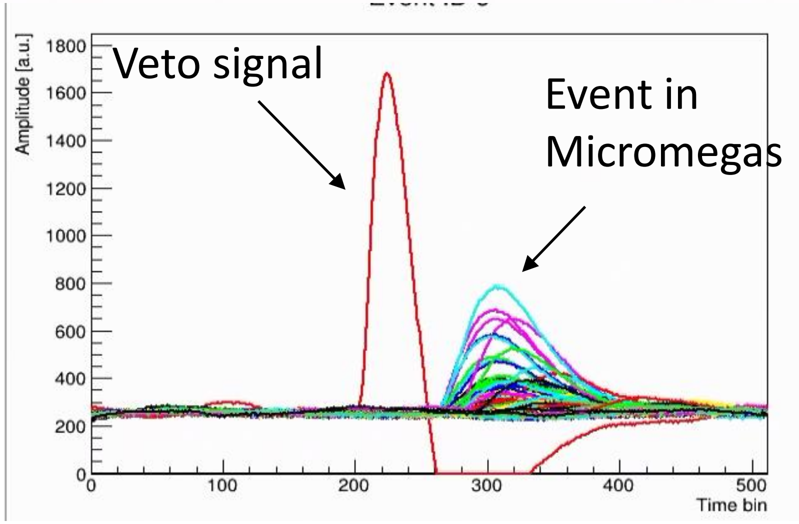
From *Topological background discrimination in the PandaX-III neutrinoless double beta decay experiment* https://arxiv.org/abs/1903.03979

Background discrimination





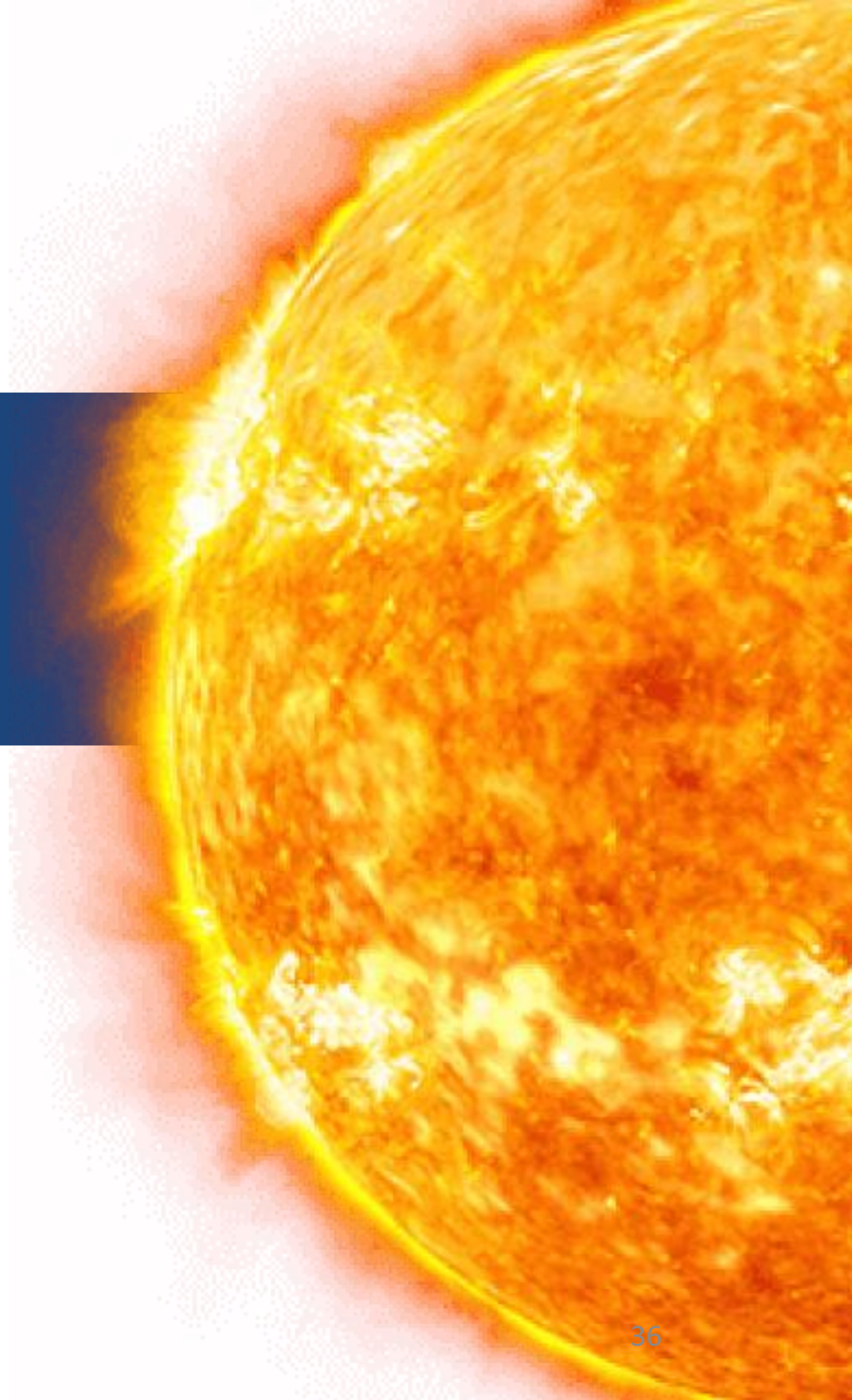




The computed observables are used to define selection algorithms.
Four main types of cuts are applied:

- Energy cuts: e.g. (1,10) keV.
- Fiducial cut: to select the size of the spot (e.g. 10 mm^2).
- Topological cuts: event size and shape in the XY plane and in the Z direction.
- Veto event coincidence cut.

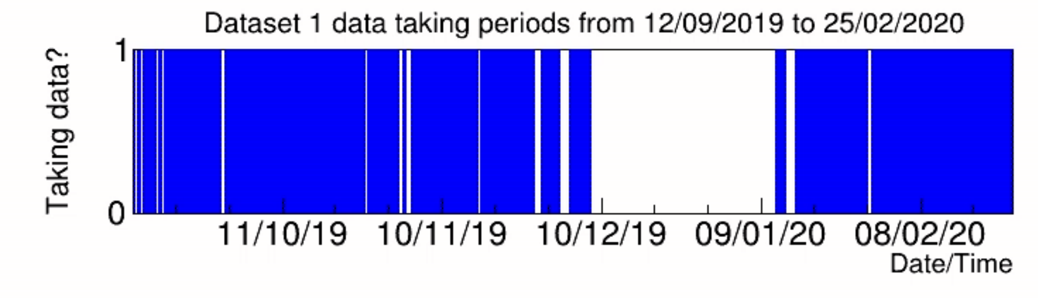
Data taking



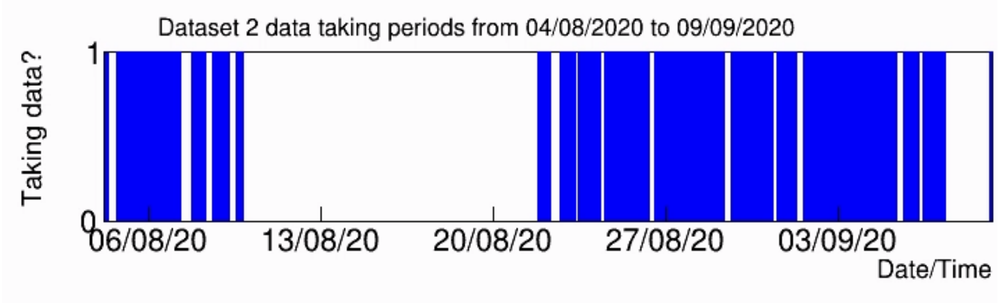
Summary of the data taking

Dataset	Background exposure (h)	Background level (2, 7) keV ($\times 10^{-6}$ c keV^{-1} cm^{-2} s^{-1})	Tracking exposure (h)	Gas	Years
1	2476	1.7 ± 0.1	130	Ar + 2.3% iso	2019-2020
2	335	2.3 ± 0.4	25.6	Ar + 2.3% iso	2020
3	3416	1.5 ± 0.1	159	48.85% Xe + 48.85% Ne + 2.3% iso	2020-2021
Total	6227		314.6		

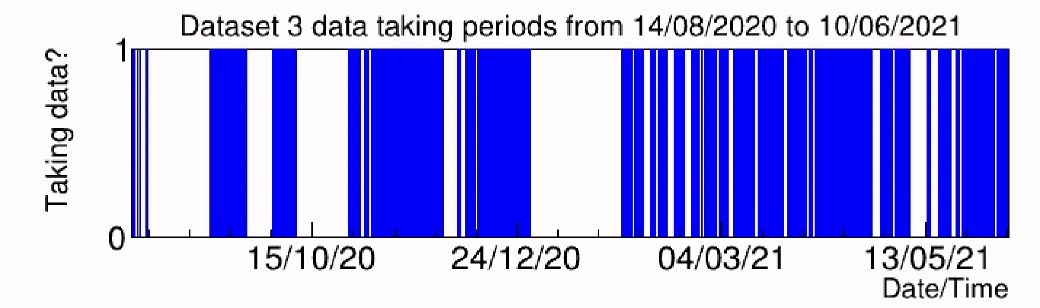
Ar dataset 1



Ar dataset 2

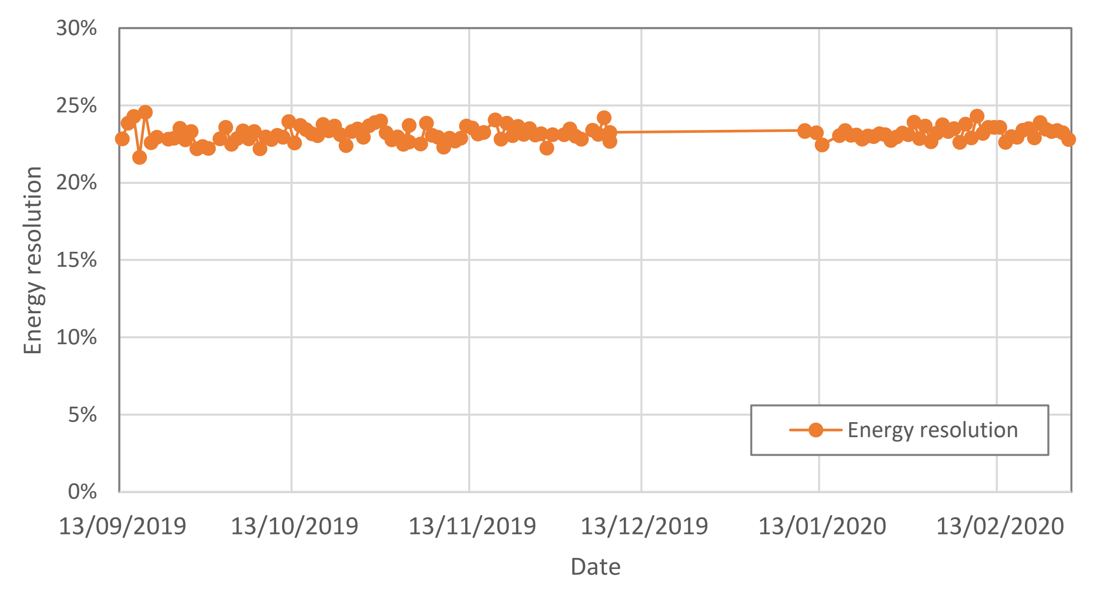


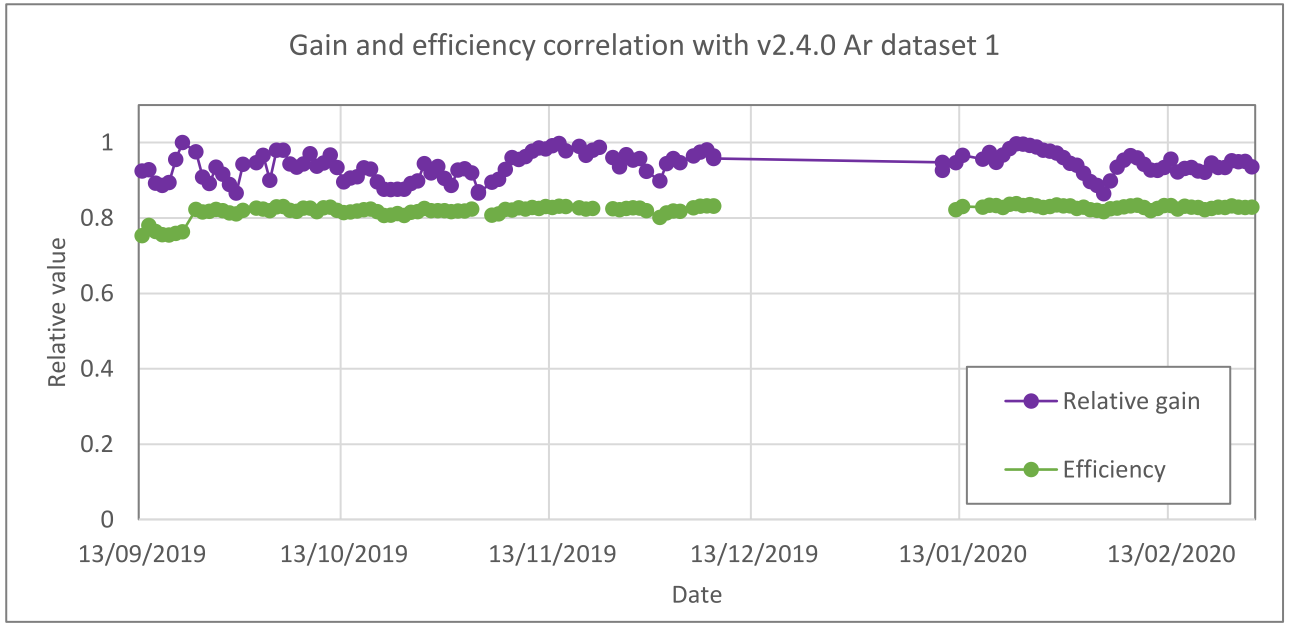
Xe dataset 3

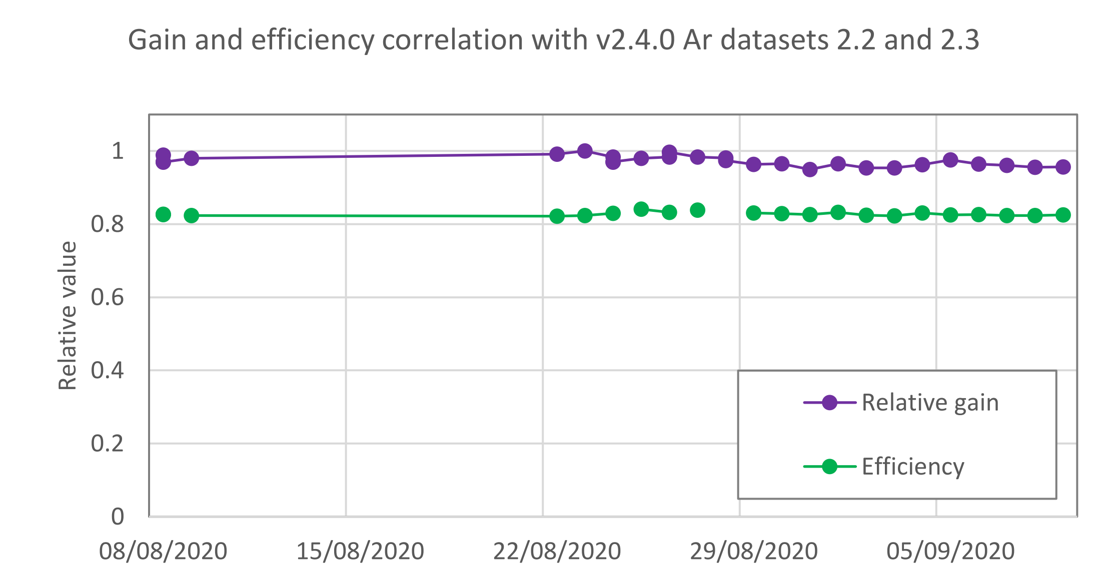


Datasets 1 and 2 (Ar)

- Energy threshold = 0.4 keV
- Energy resolution at 5.9 keV ~ 23 %
- Standard deviation of gain = 3.3%
- Efficiency ^{55}Fe peak ~ 80%



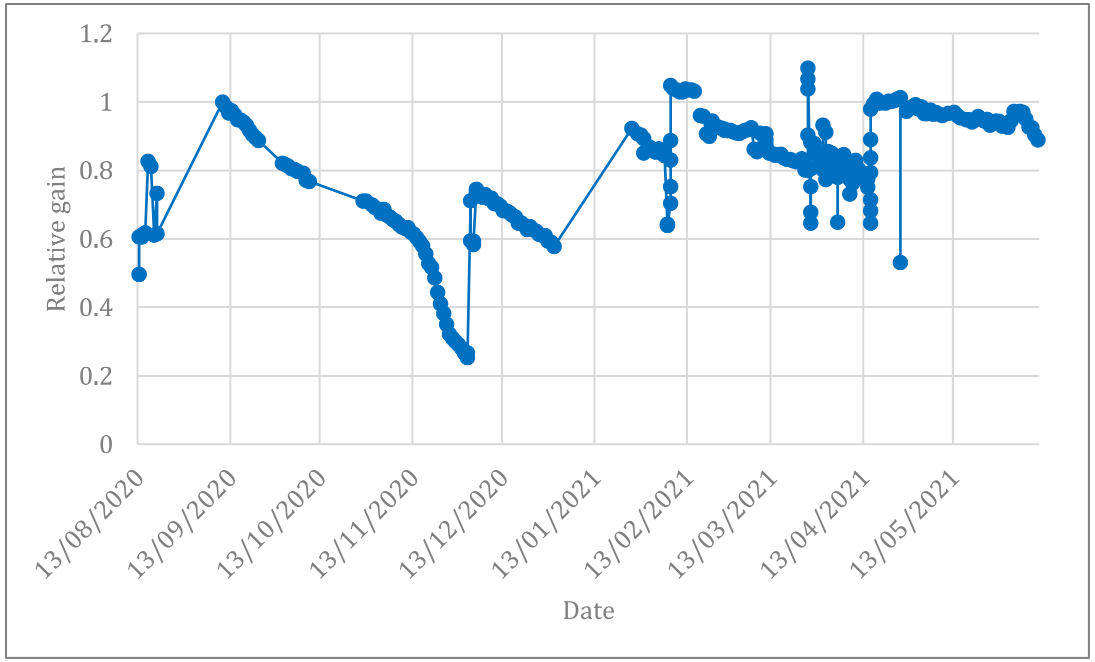


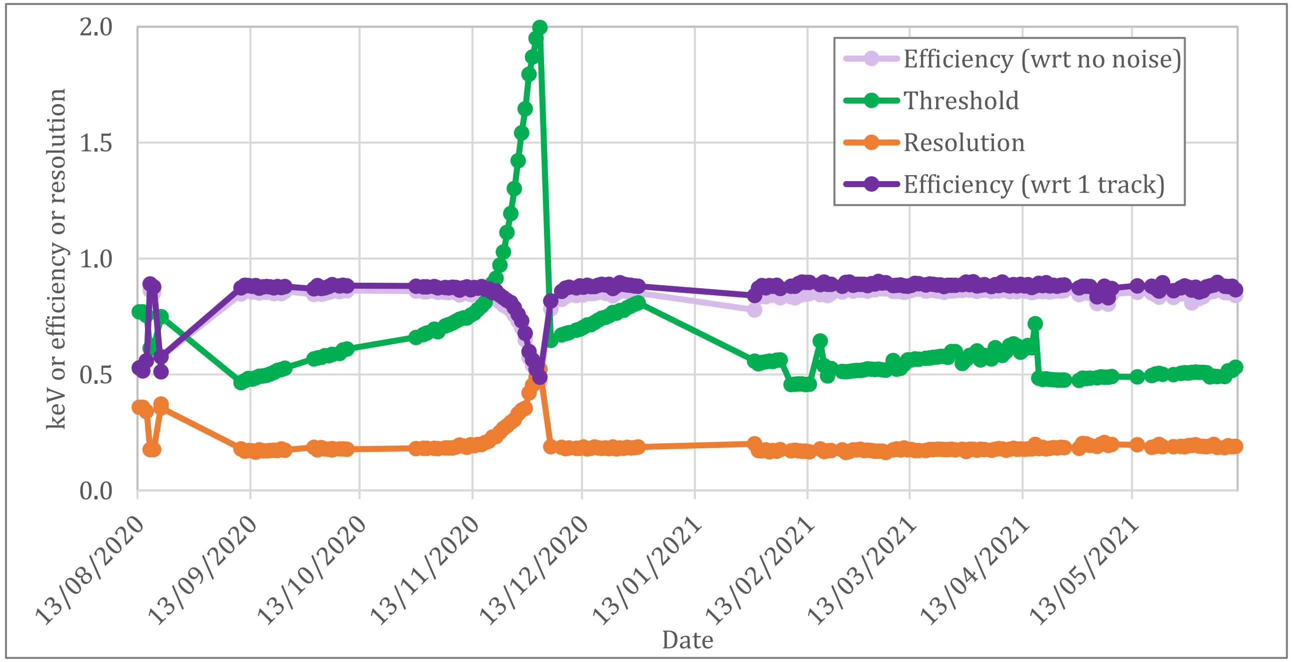


Dataset 3 (Xe)

- Standard deviation of gain = 2.5 – 9%.
- Energy threshold = 0.5 – 2 keV (~6 trackings with threshold > 1 keV).
- Energy resolution at 5.9 keV ~ 18 – 20%.
- Efficiency ^{55}Fe peak ~ 88 – 90%.
- 97% of 1 track events in ^{55}Fe calibrations according to simulations.

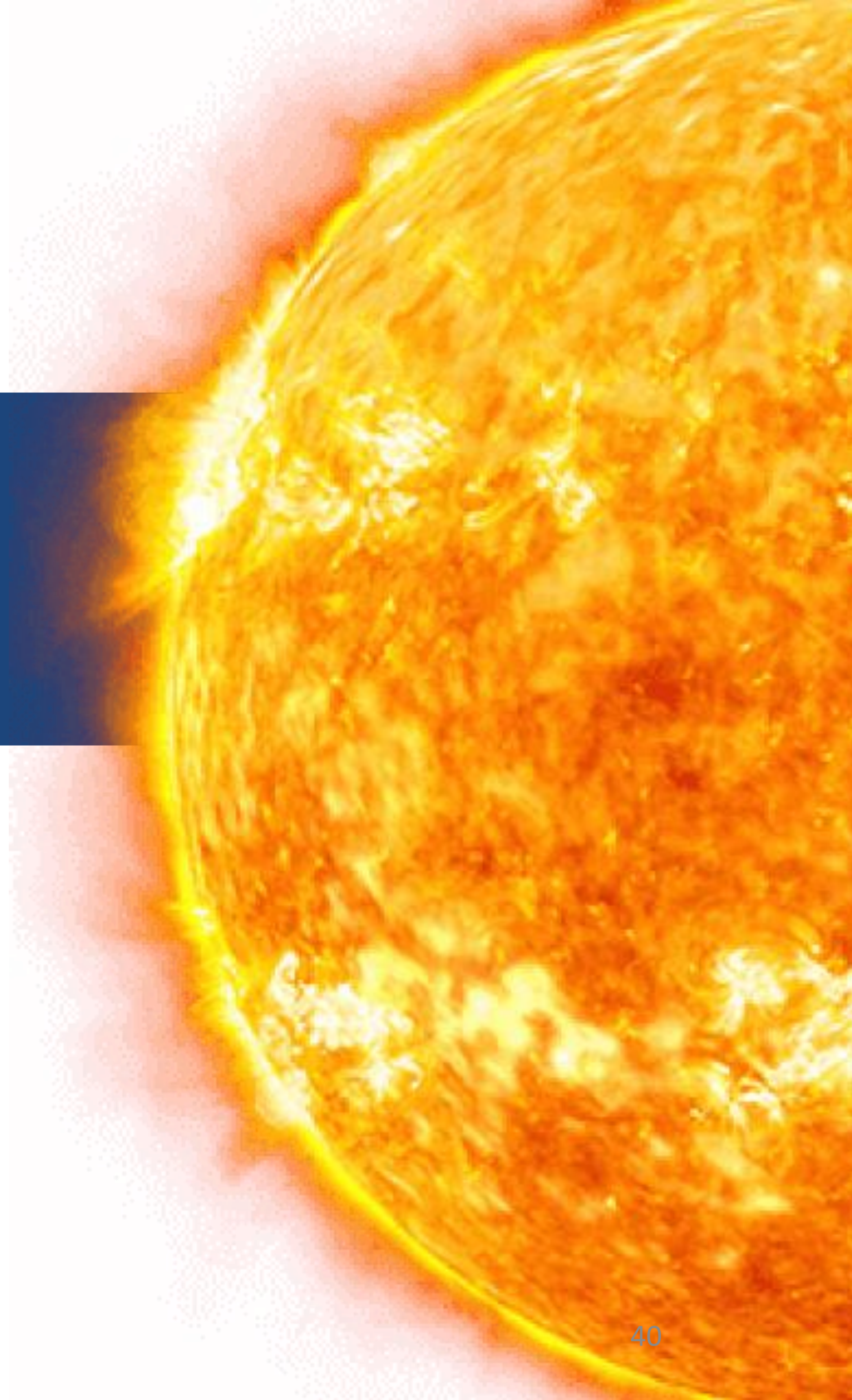
# trackings with threshold > 1 keV	6
# trackings with threshold > 1.5 keV	3
Total Xe trackings	109





Data analysis

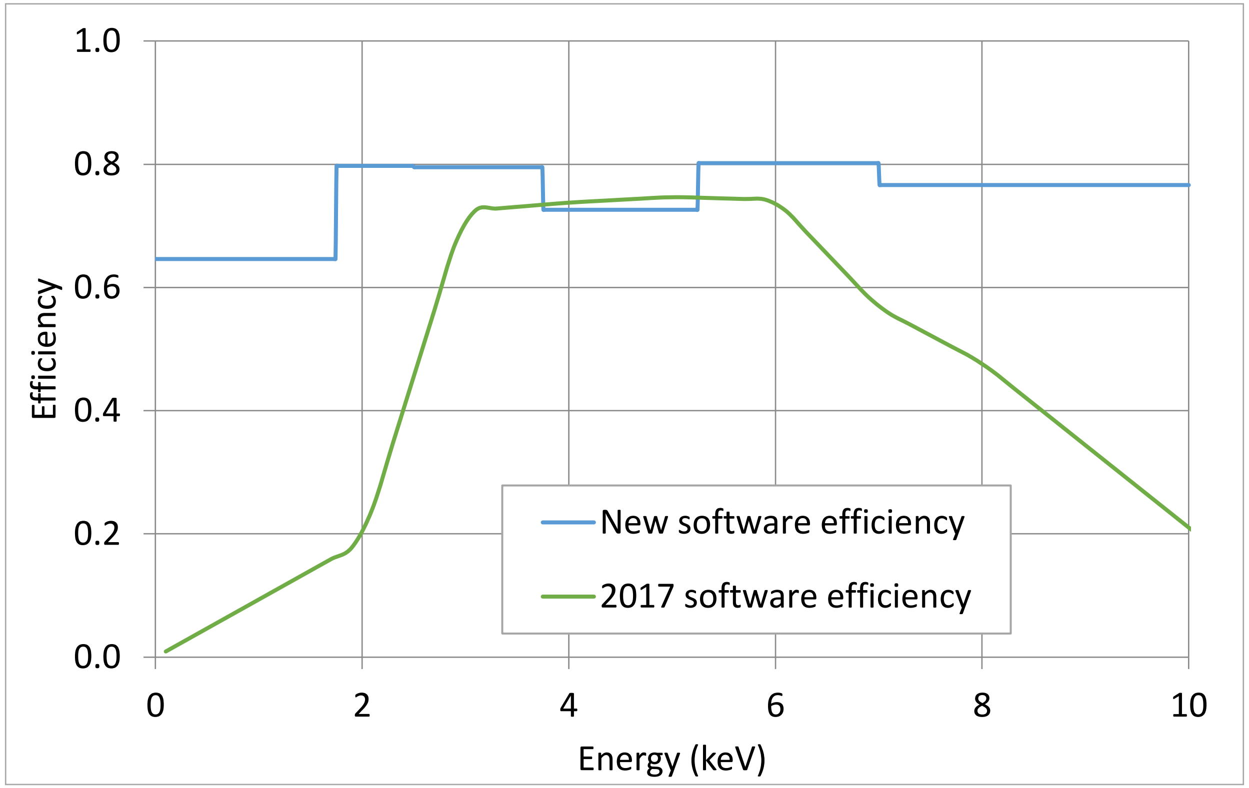
Background computation and expected limit



Different efficiency: 2017 vs current

The current analysis yields a higher efficiency.

- **Software efficiency:**
  - A more sophisticated cut definition has increased the efficiency at low and high energies (away from the ^{55}Fe peaks).
- **Hardware efficiency:**
  - We don't use a differential window anymore. Especially noticeable at low energies.
  - Use of Xe-based gas mixtures.
  - The detector response matrix has been taken into account.
- **Optics efficiency:**
  - Unchanged (LLNL).



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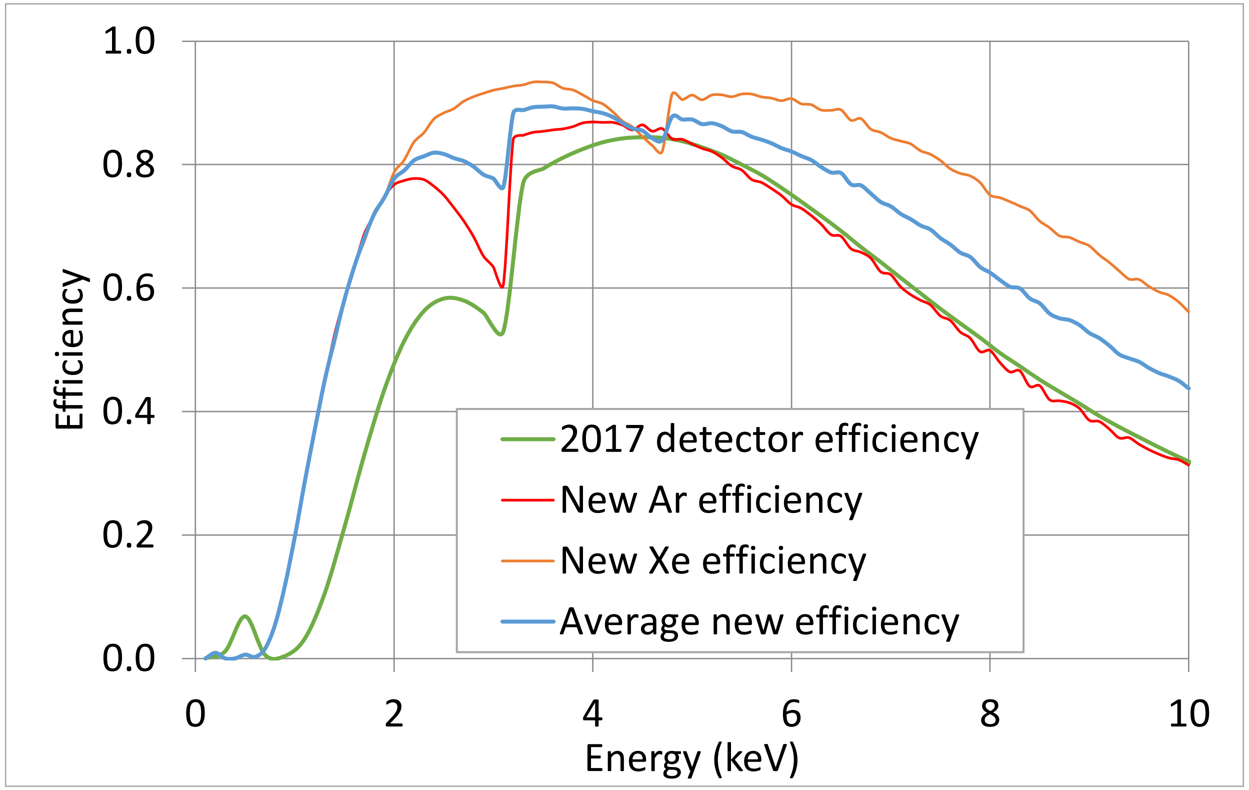

Improving the overall efficiency

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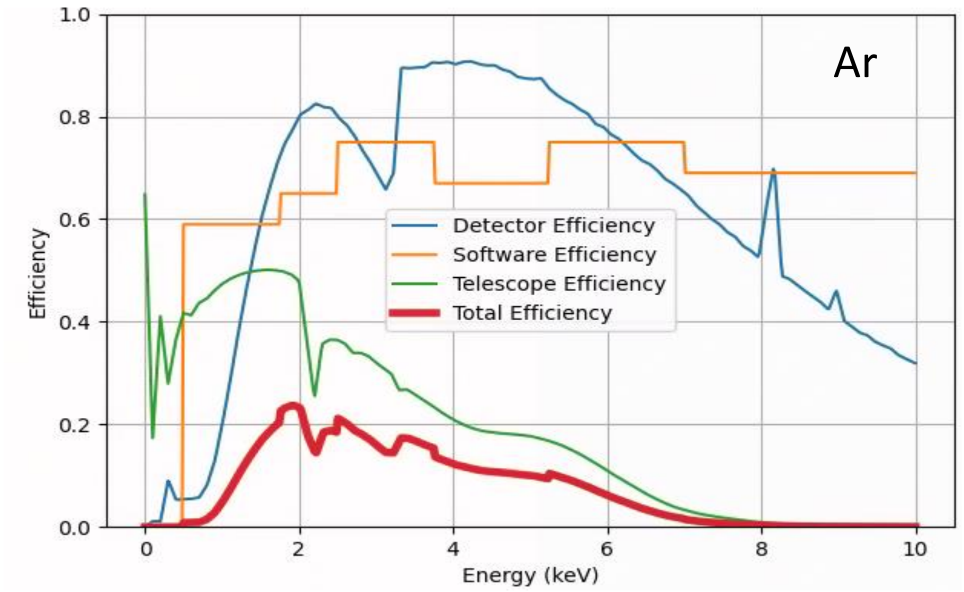
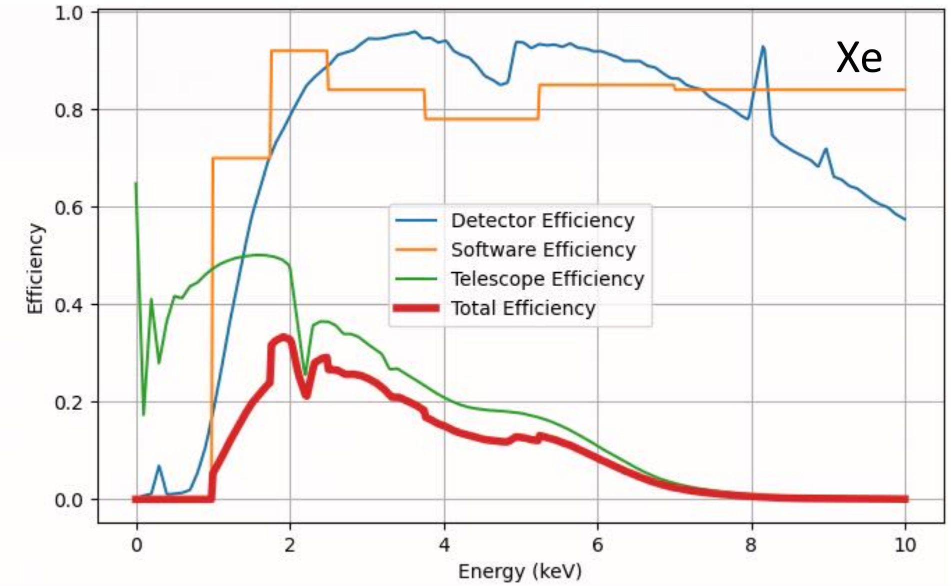
- **Optics efficiency:**
  - Unchanged.

$$FoM \sim \underbrace{B^2 L^2 A}_{\text{magnet}} \cdot \underbrace{\epsilon_d b^{-1/2}}_{\text{detector}} \cdot \underbrace{\epsilon_o \alpha^{-\frac{1}{2}}}_{\text{optics}} \cdot \underbrace{\epsilon_t^{-1/2} t^{-1/2}}_{\text{exposure}}$$





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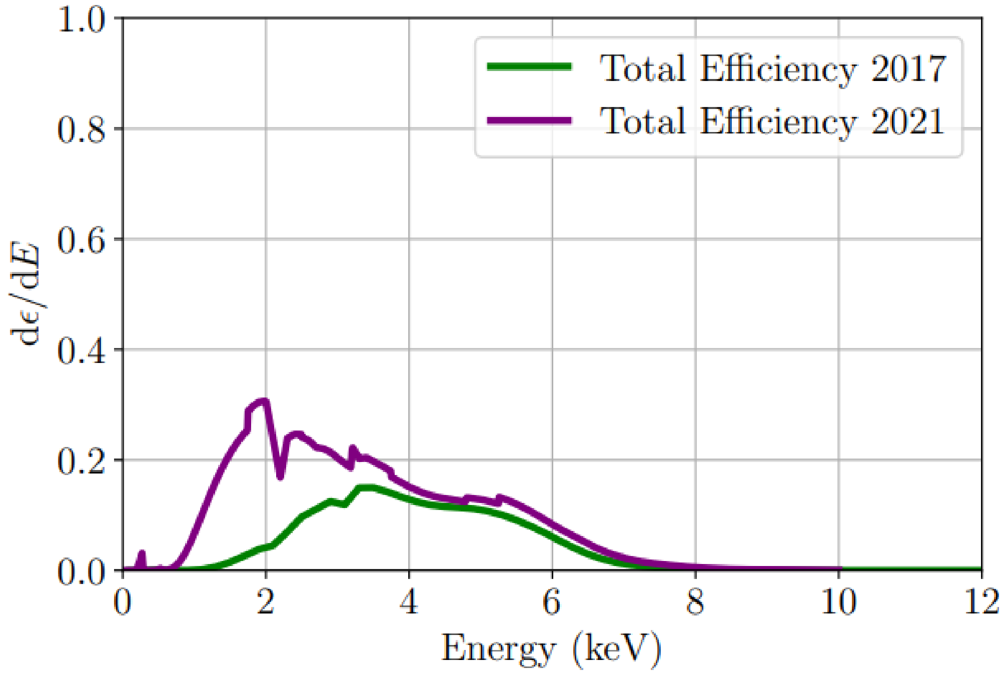
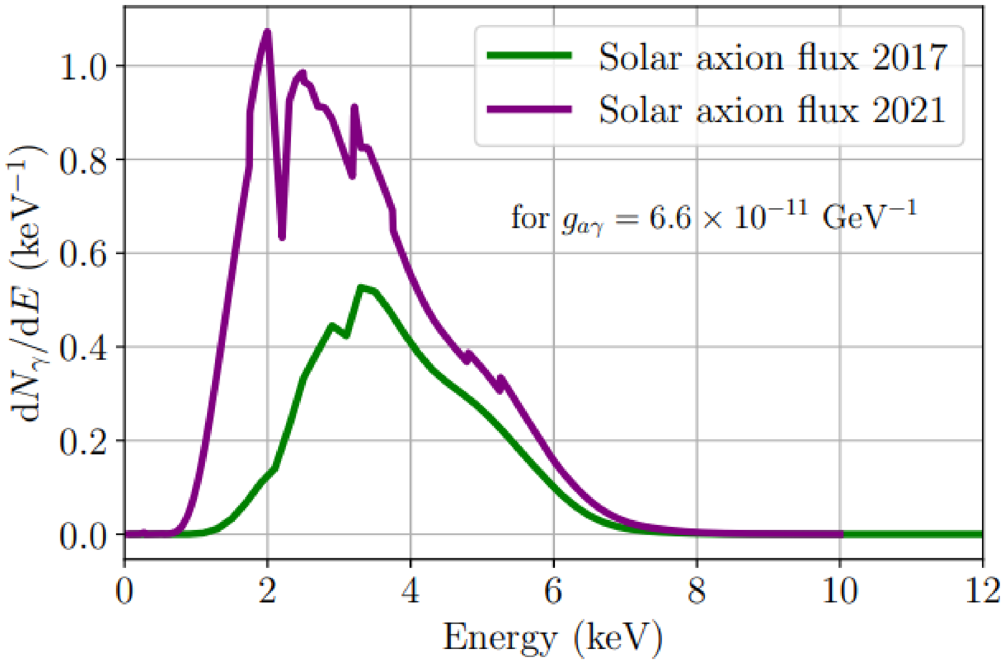
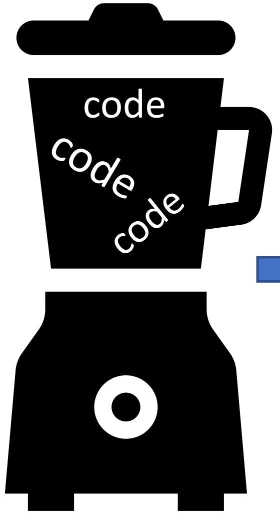




Opening the box: computing a limit

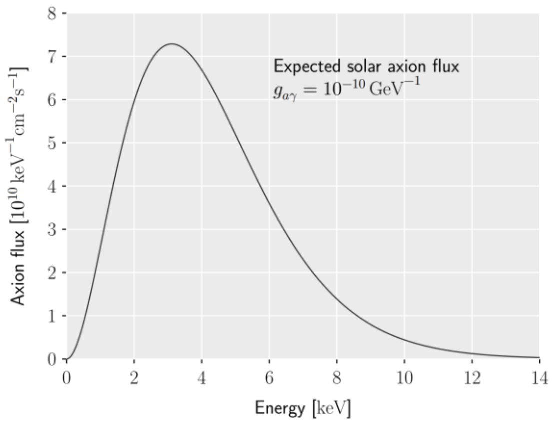
Inputs

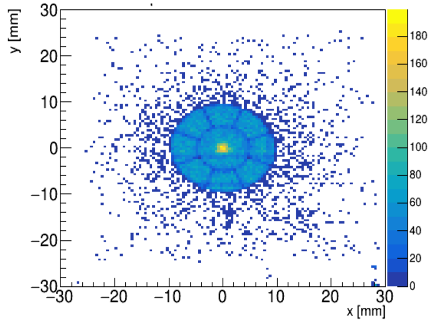
1. Background data (no tracking data)
2. Signal+background data (solar tracking data)
3. Primakoff spectrum corrected by our efficiency: telescope, window, gas, strongback.

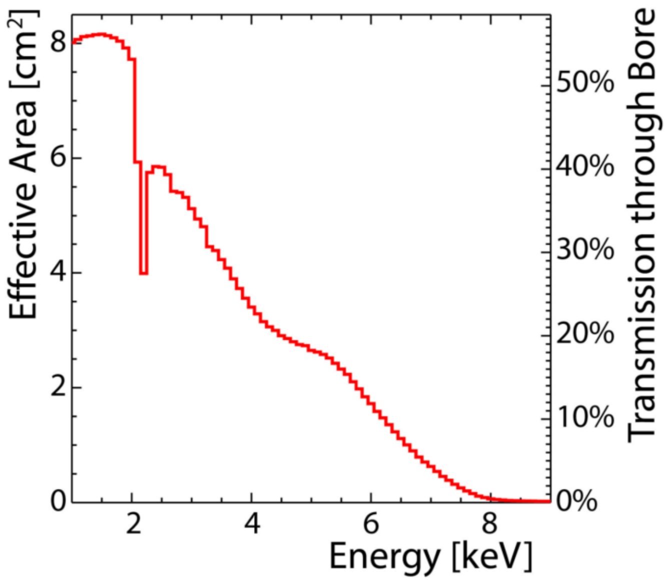


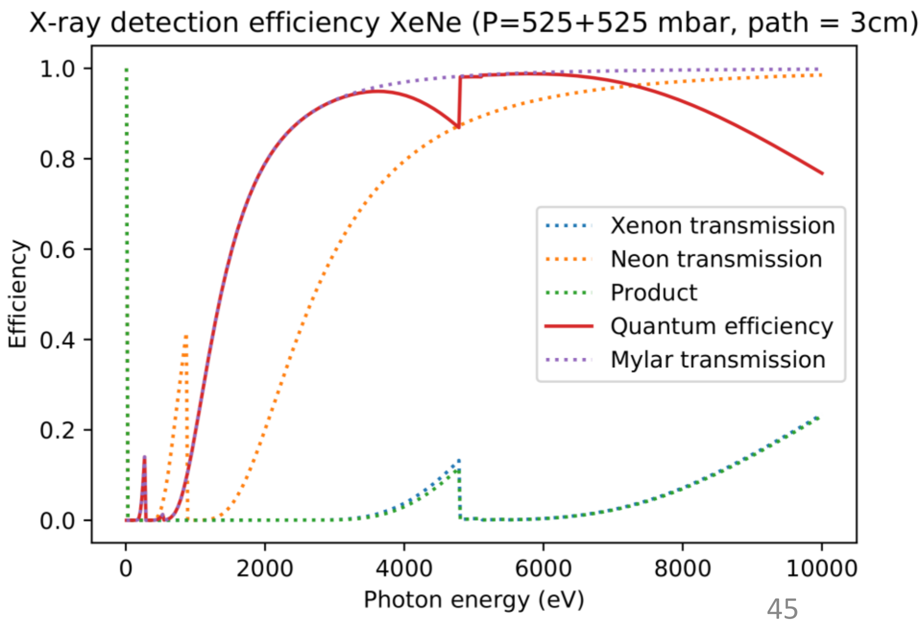
Output

Expected limit $g_{a\gamma}$

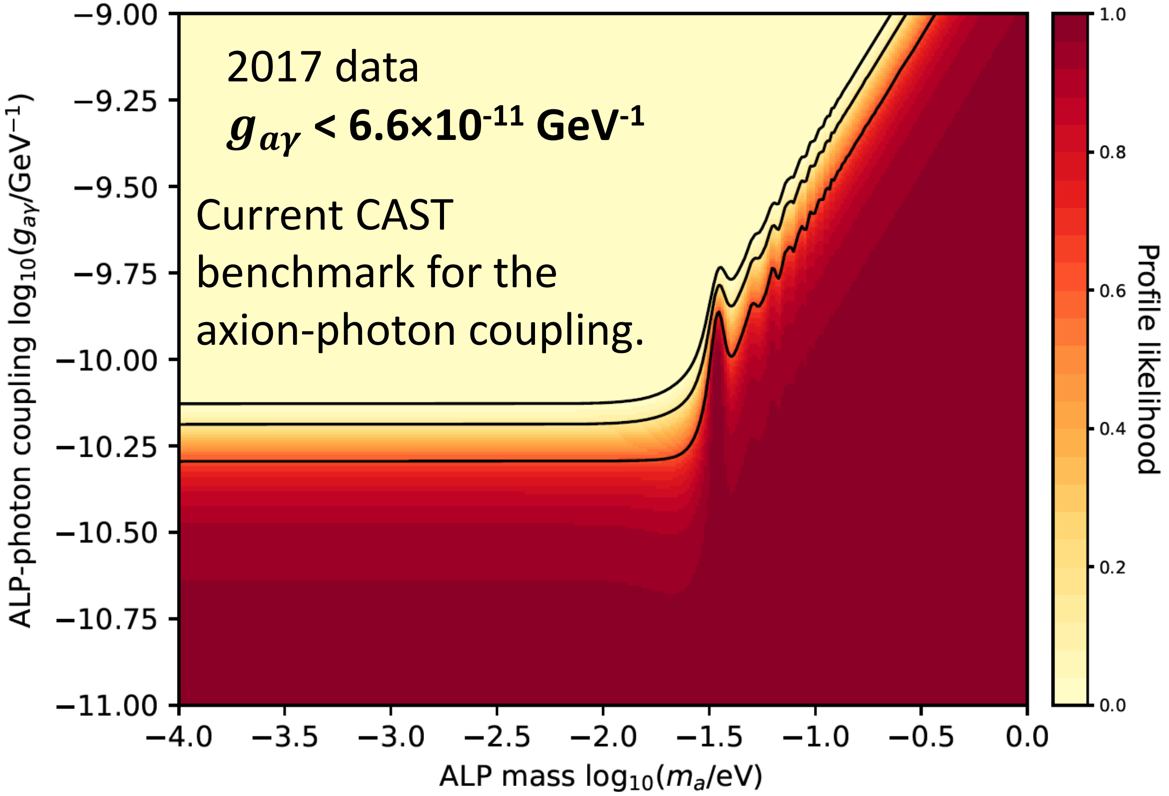


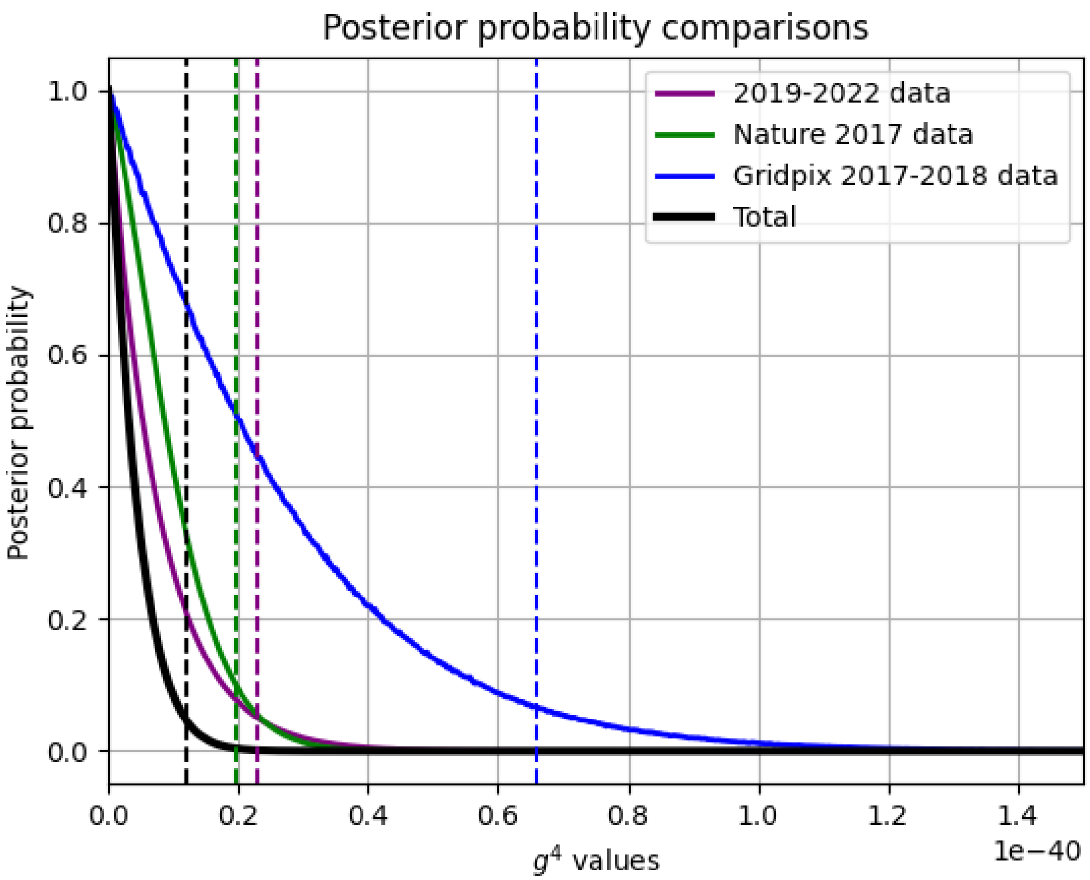






New upper limit on the axion-photon coupling





	Upper limit on $g_{a\gamma}$* (×10^{-11} GeV^{-1})
Limit new data	6.92
Limit new data + Nature	5.89
Limit new data + Nature + Gridpix	5.72

*at 95% C.L. for $m_a < 0.02$ eV

New CAST upper limit on $g_{a\gamma}$:

$g_{a\gamma}$ < 5.7×10^{-11} GeV^{-1} for m_a<0.02 eV (95% C.L.)