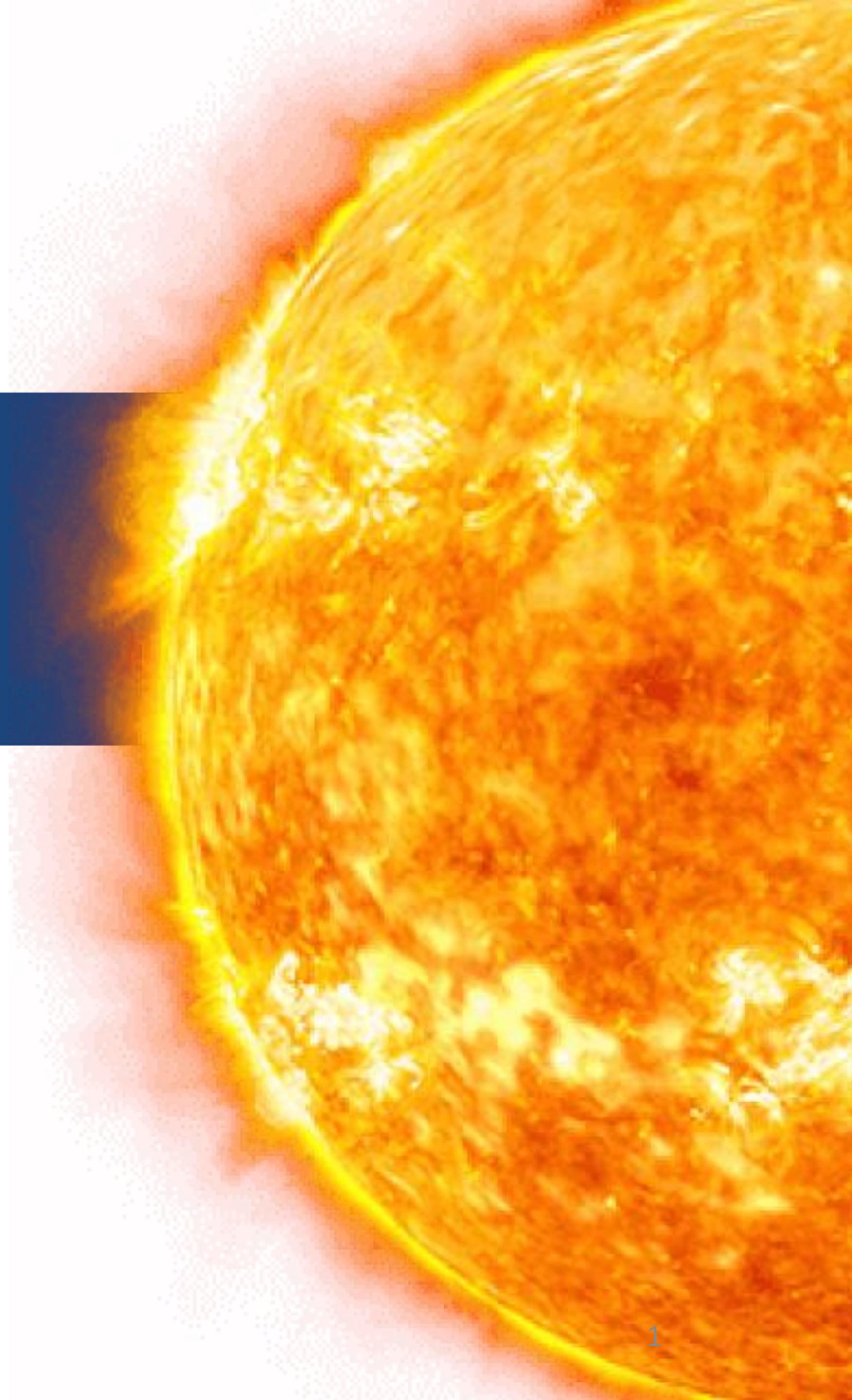
Data taking and analysis with the IAXO-pathfinder system

Cristina Margalejo on behalf of the IAXO MM detector group

GGI Axions across boundaries workshop

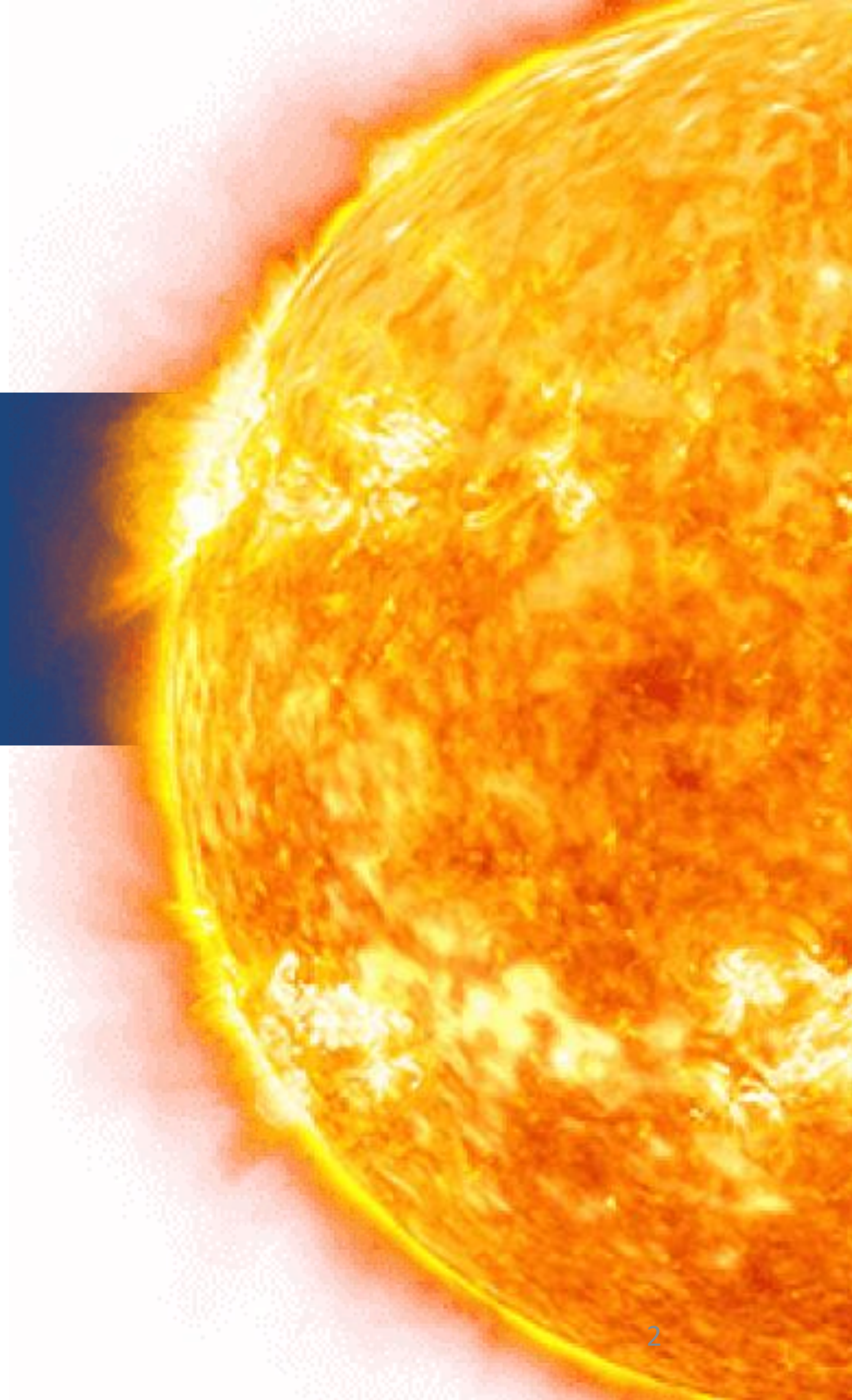
1st June 2023

Florence - Italy



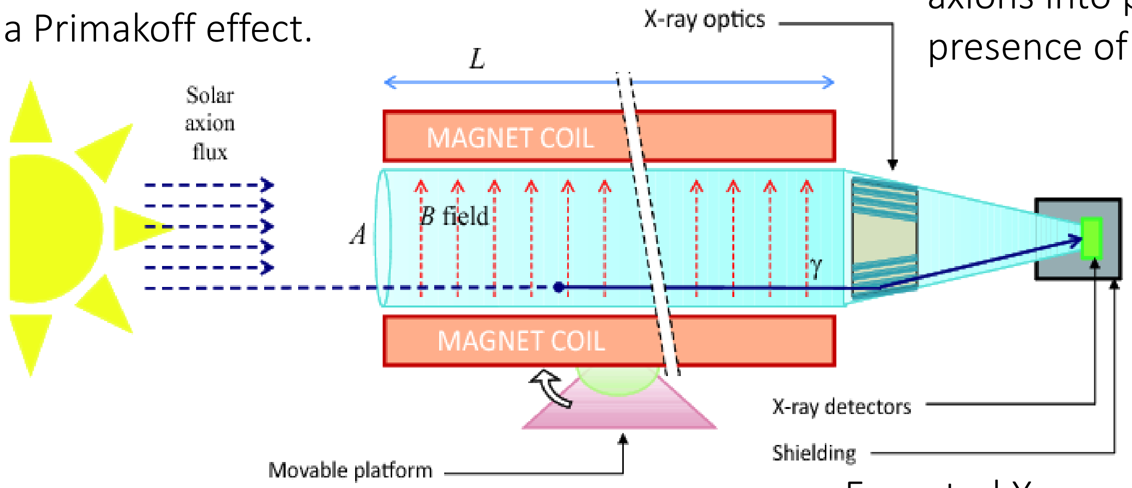
Introduction

Axion heliosopes and state of the art



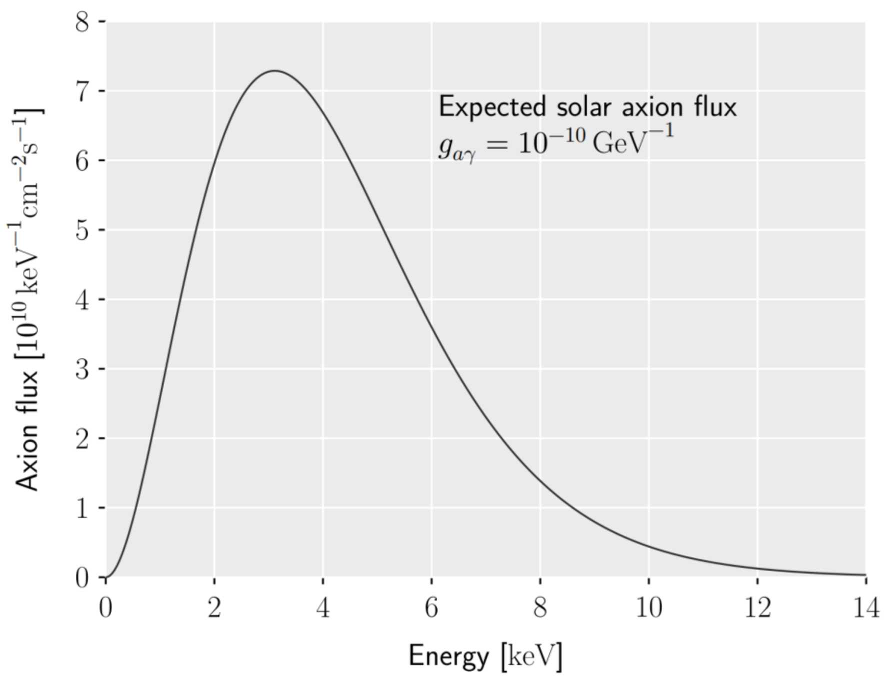
Solar axions and helioscopes

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.



Layout description:

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

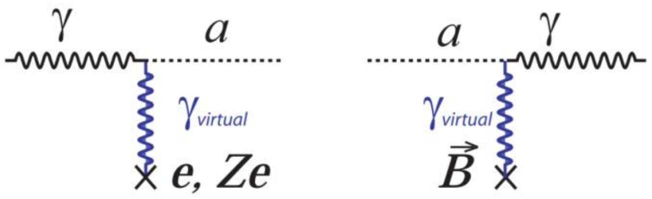


Figure of Merit (FoM): $g_{a\gamma}^4 \sim \underbrace{B^2 L^2 A}_{\text{magnet}} \quad \underbrace{\varepsilon_d b^{-1/2}}_{\text{detectors}} \quad \underbrace{\varepsilon_o a^{-1/2}}_{\text{optics}} \quad \underbrace{\varepsilon_t^{-1/2} t^{-1/2}}_{\text{time}}$

Diagram of the Primakoff effect (a-γ coupling)

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)

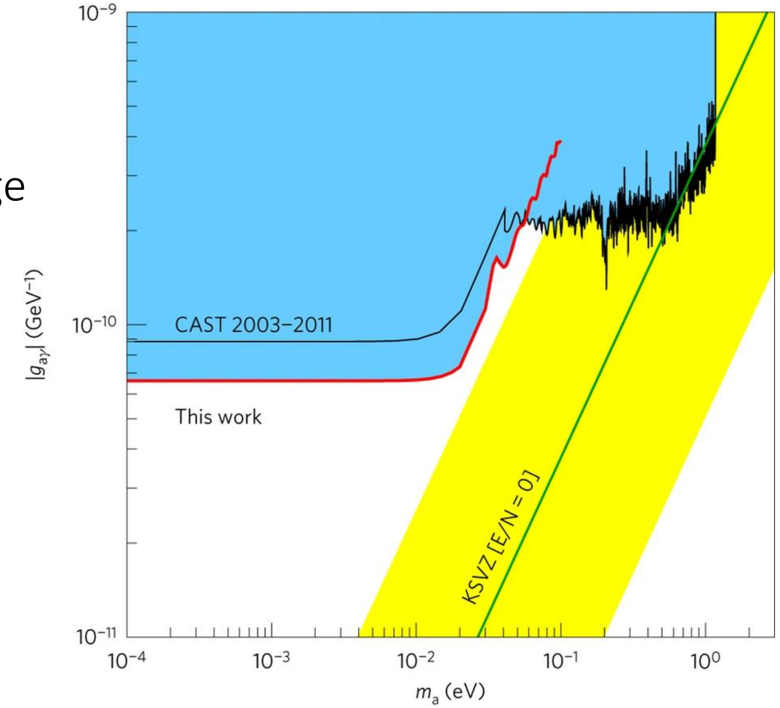
2013-2015: IAXO pathfinder

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.) [NPHYS4109]

<u>2019-2021: new data taking campaign with IAXO pathfinder</u>



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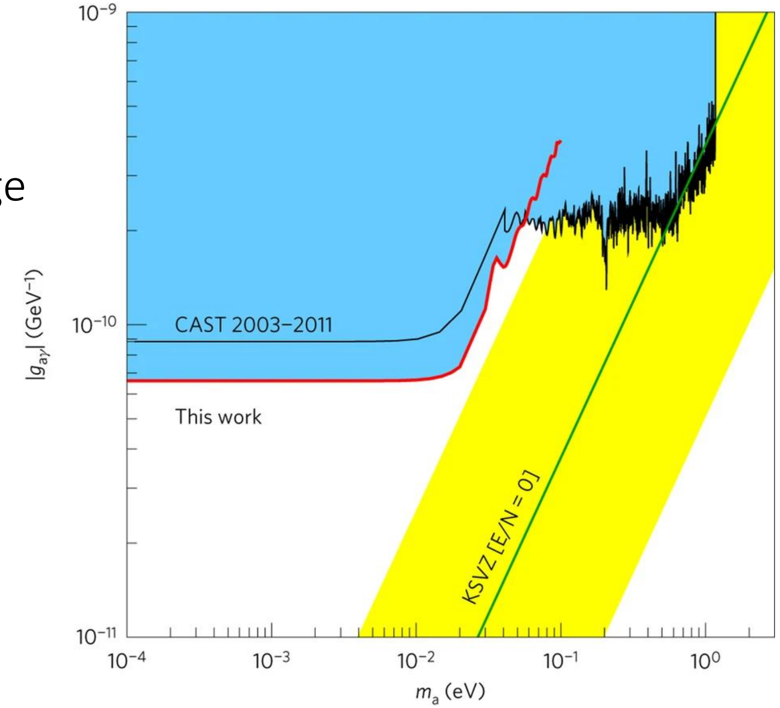
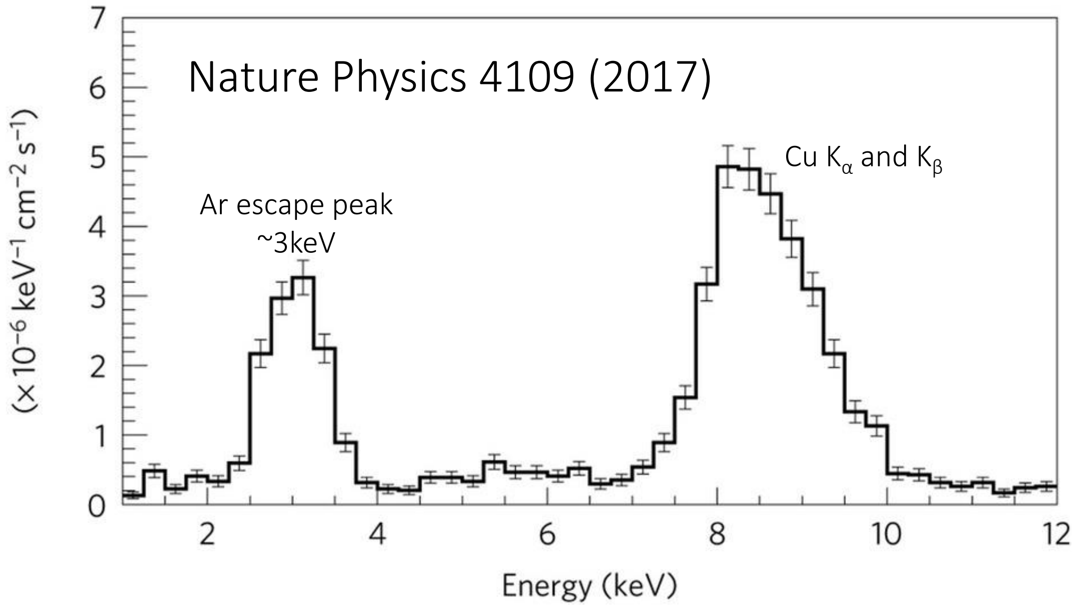


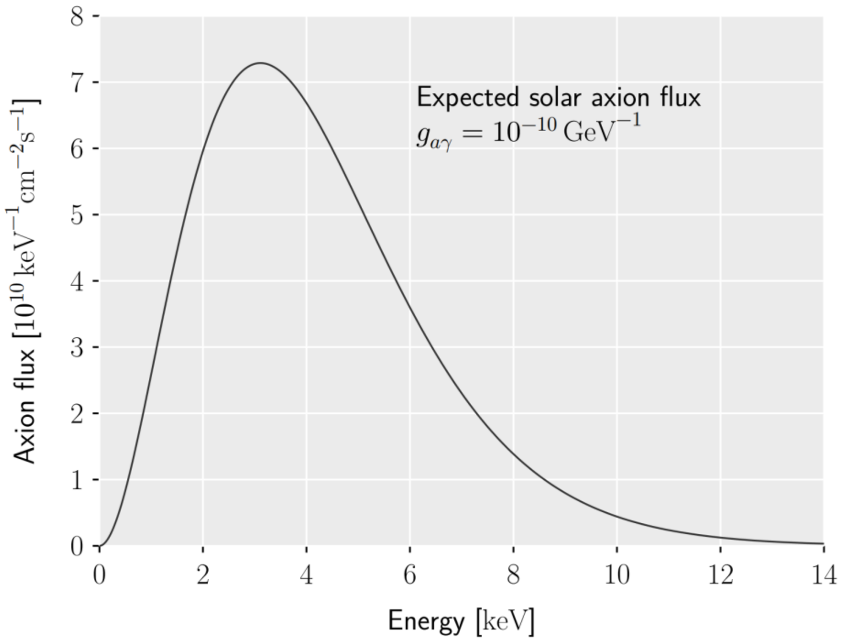
2019-2021: new data taking campaign with IAXO pathfinder

This presentation

Results with Ar-based gas mixtures

- Typical background spectra with Ar-based mixtures:
  - Background is reduced a few orders of magnitude based on the topological signature of X-rays: small, symmetric and point-like events.
  - Copper fluorescence lines at 8 and 8.9 keV. Intrinsic to the detector.
  - Argon escape 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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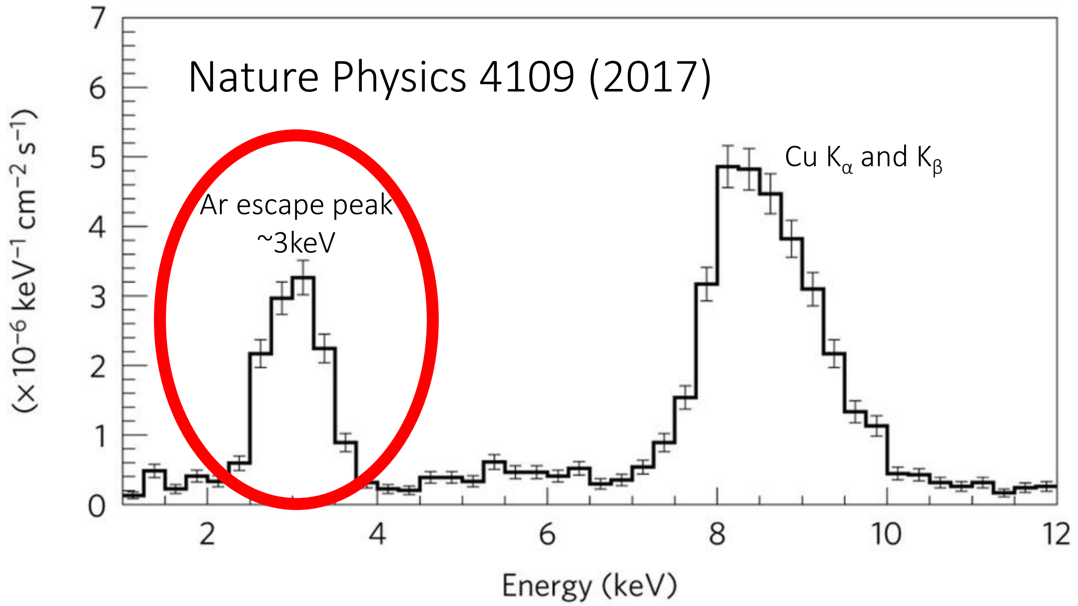
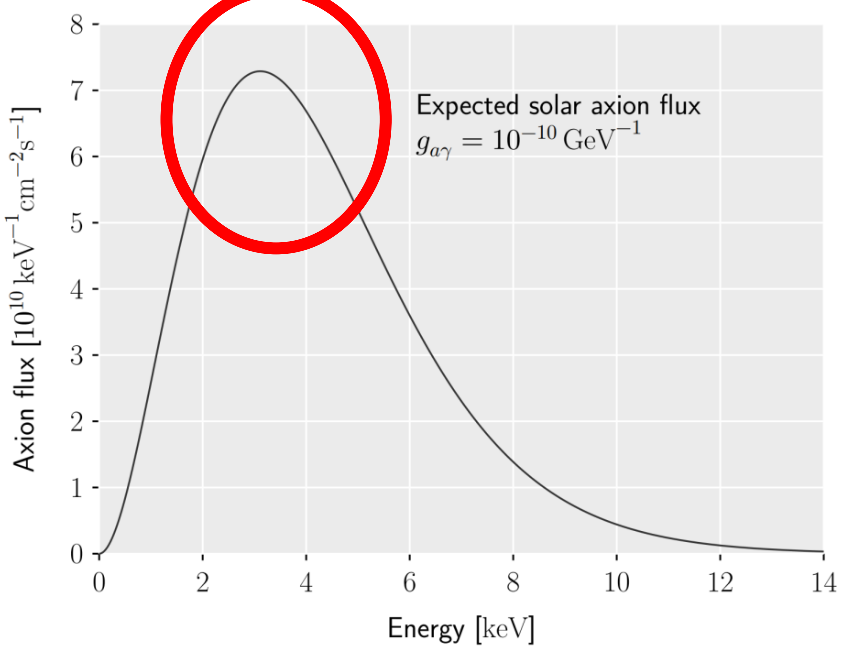


Peak at 3 keV!

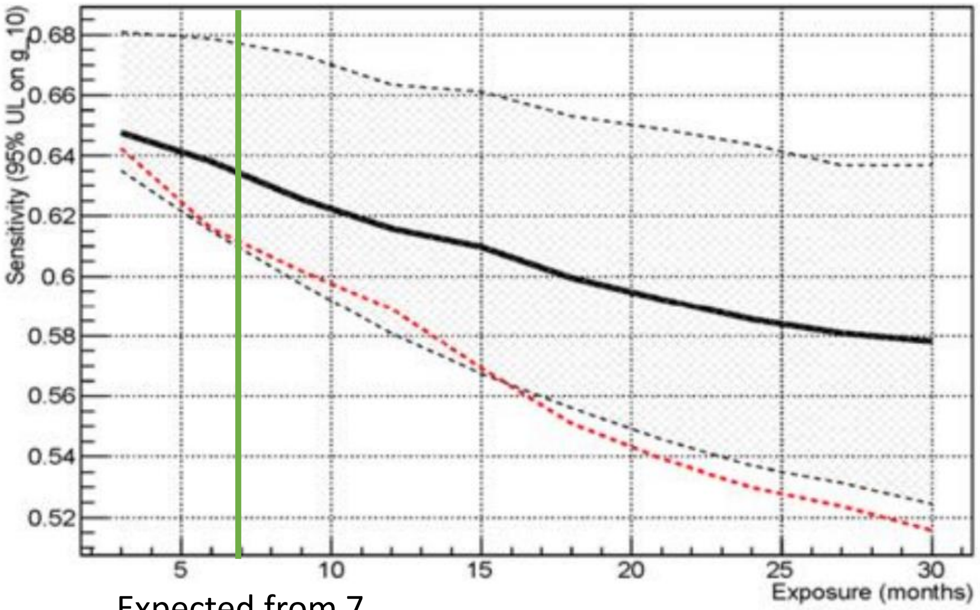


Solar axion peak expected at ~3 keV.
For better results we need to reduce the background in this energy range.

Motivation for the new data taking campaign

- Increase the statistics, which was limited to ~290 hours.
- Improve the sensitivity in $g_{a\gamma}$.

- **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.

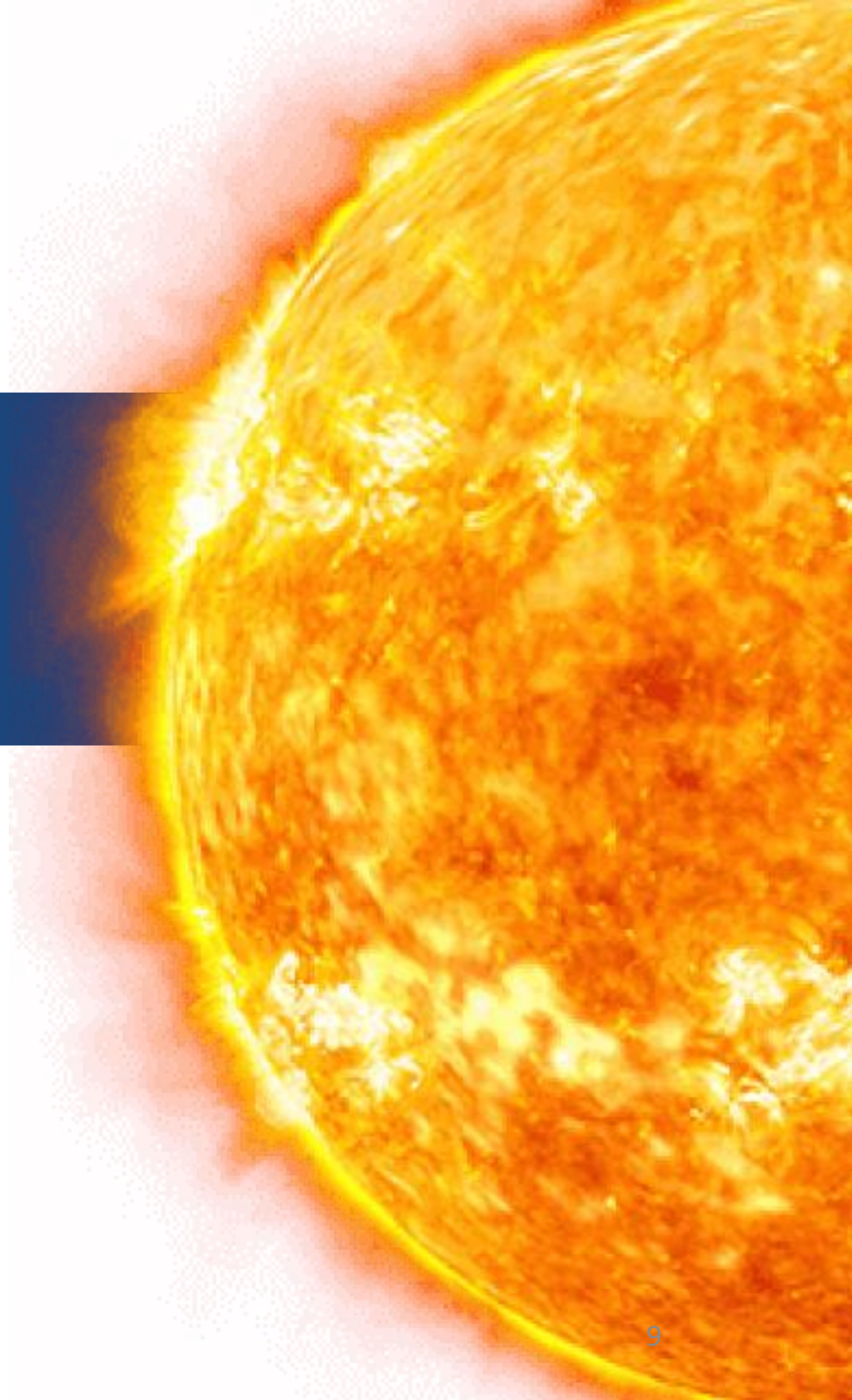


Expected from 7 months of tracking

Dataset	Period	Gas	Pressure [mbar]	Background time [h]	Solar tracking time [h]
1	2019 - Sep 2020	Ar + 2.3% isobutane	1400	~2900	~152
3	Late 2020 - 2021	48.85% Xe + 48.85% Ne + 2.3% isobutane	1050	~3600	~154

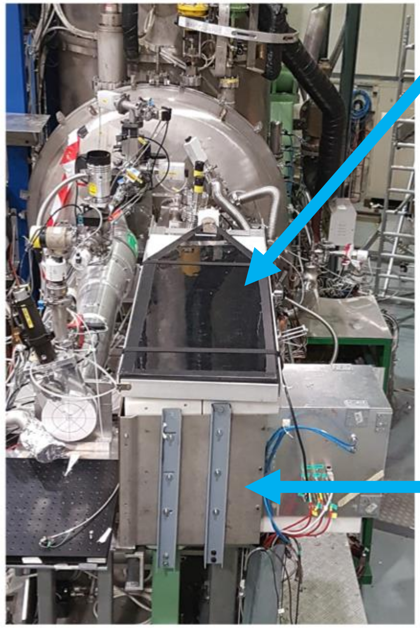
Hardware

The IAXO pathfinder system



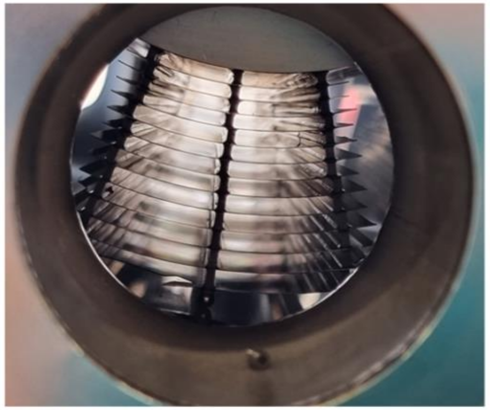
The IAXO pathfinder system at CAST

X-ray telescope



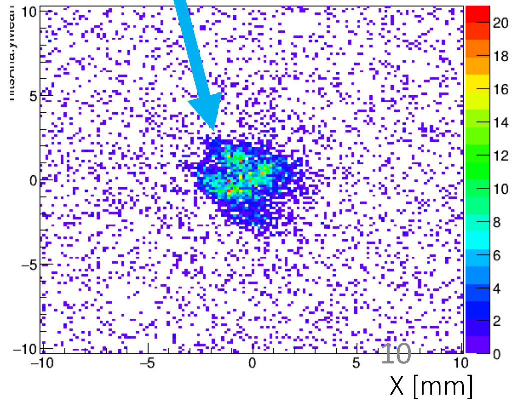
Active shielding:
plastic scintillator as a cosmic muon veto.

Passive shielding:
10 cm of lead around the detector.



X-ray optics

X-ray optics focus the signal



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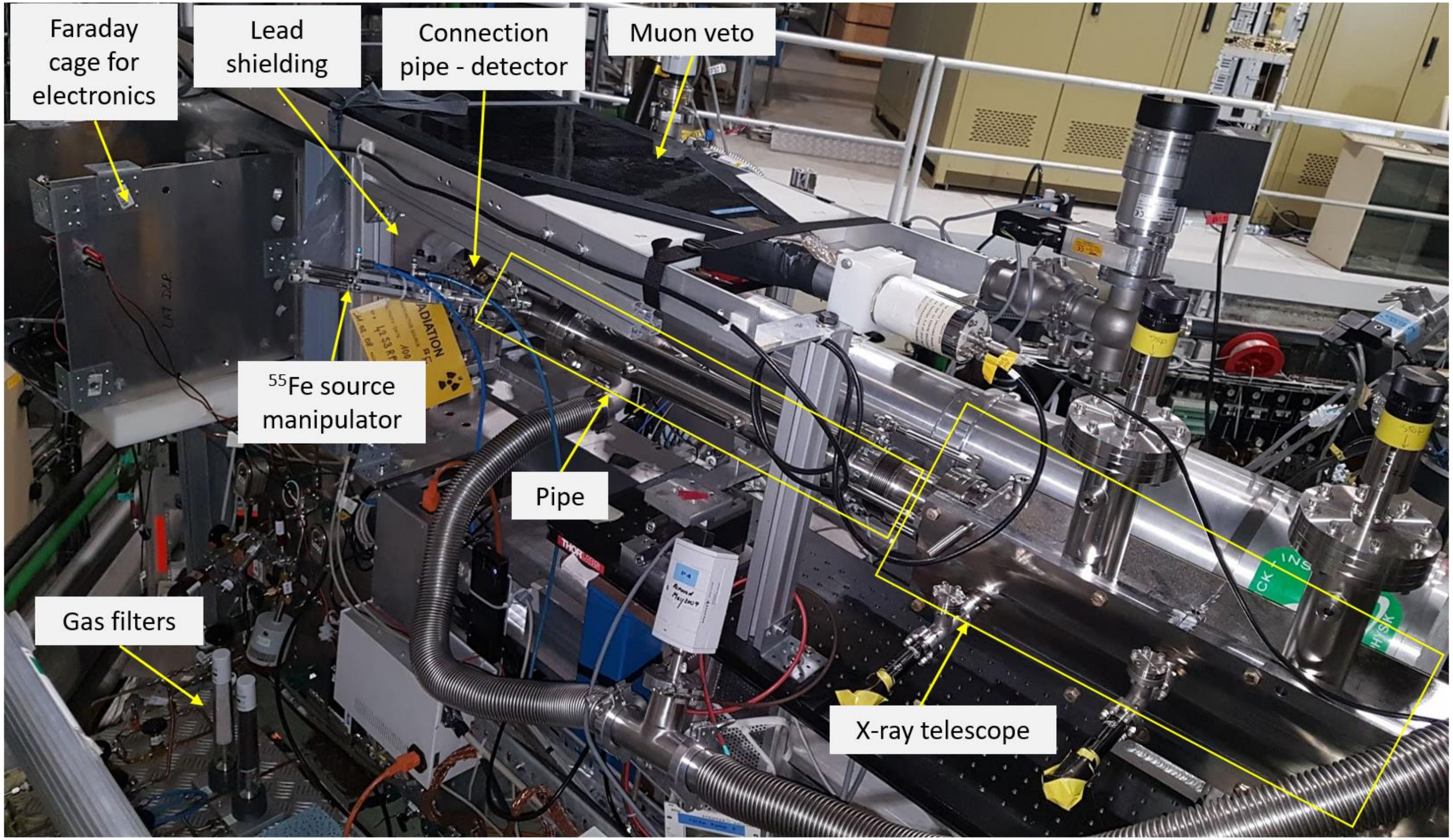

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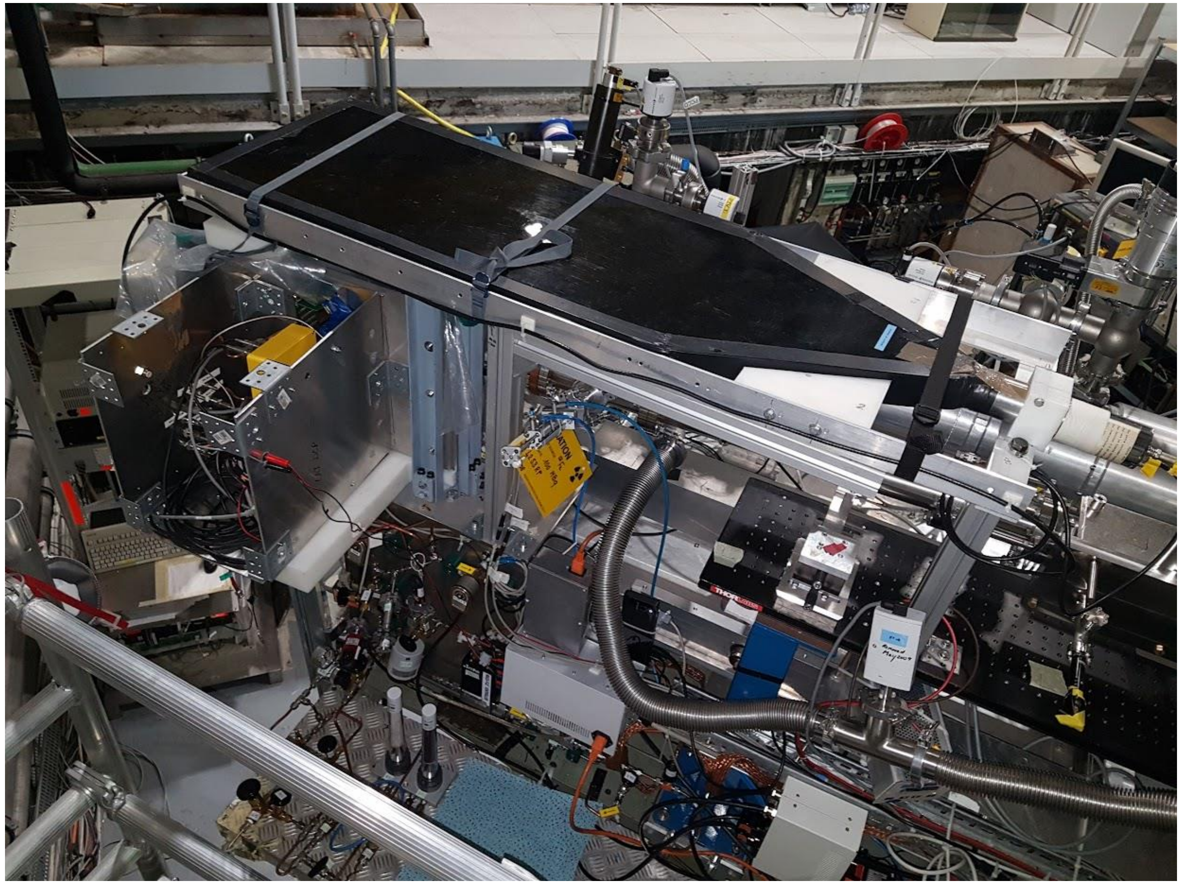
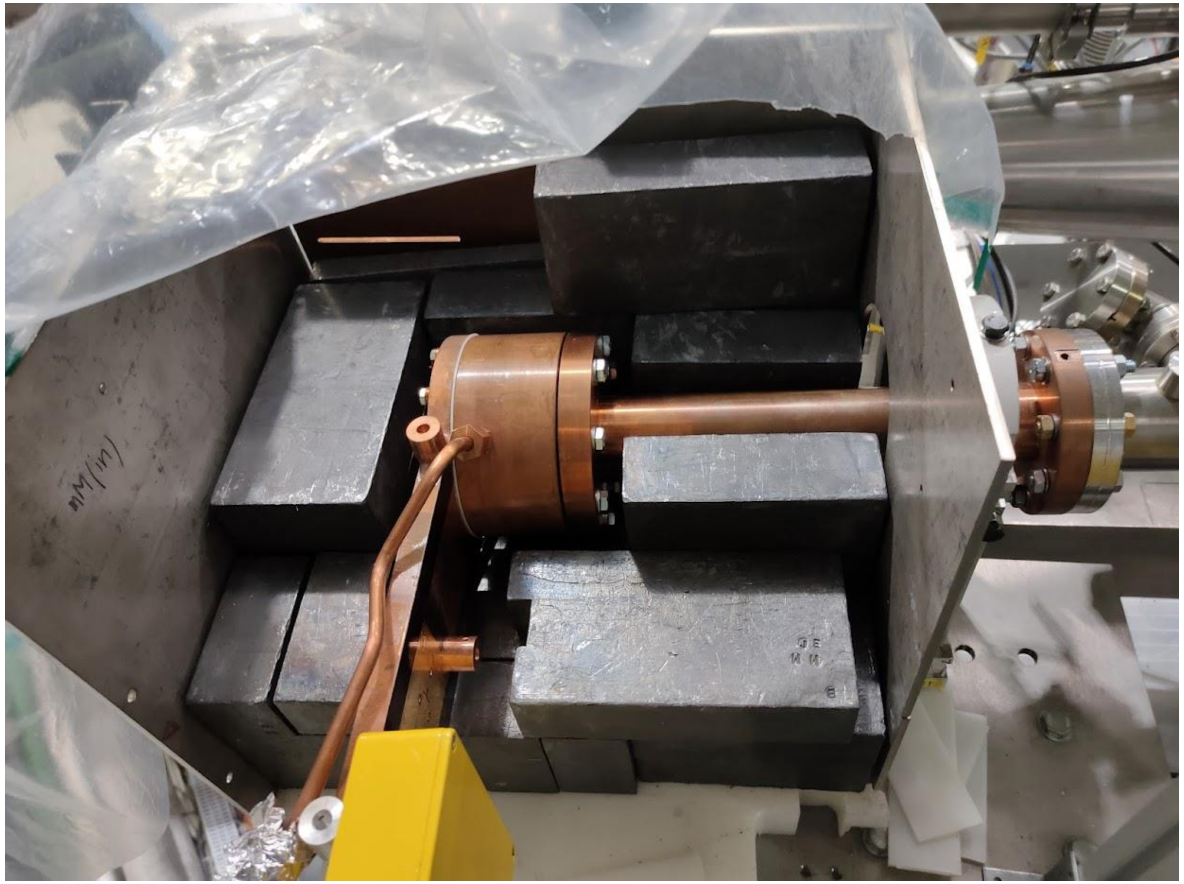
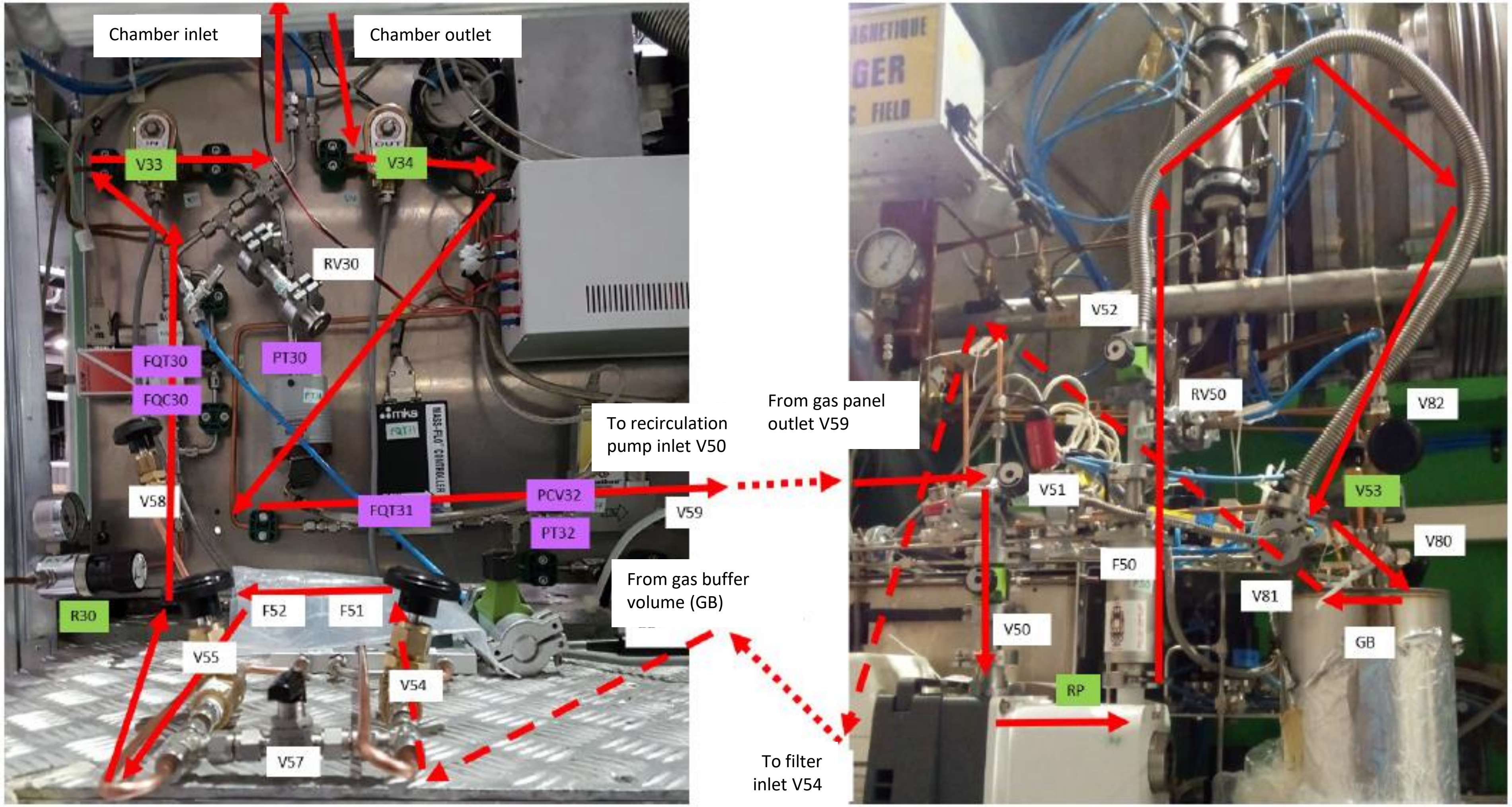




Gas system upgrade

- 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!



Moisture filter Oxygen filter

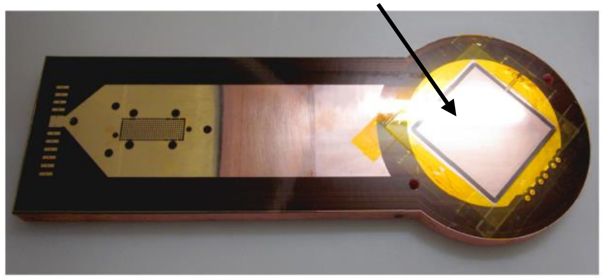
Filters were found to be Rn emitters!

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.

Micromegas readout

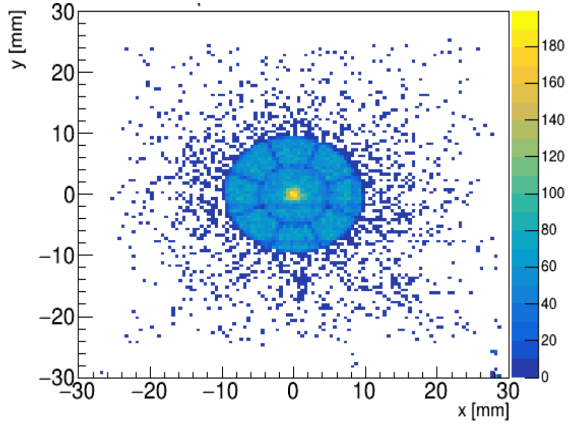


Interface copper tube

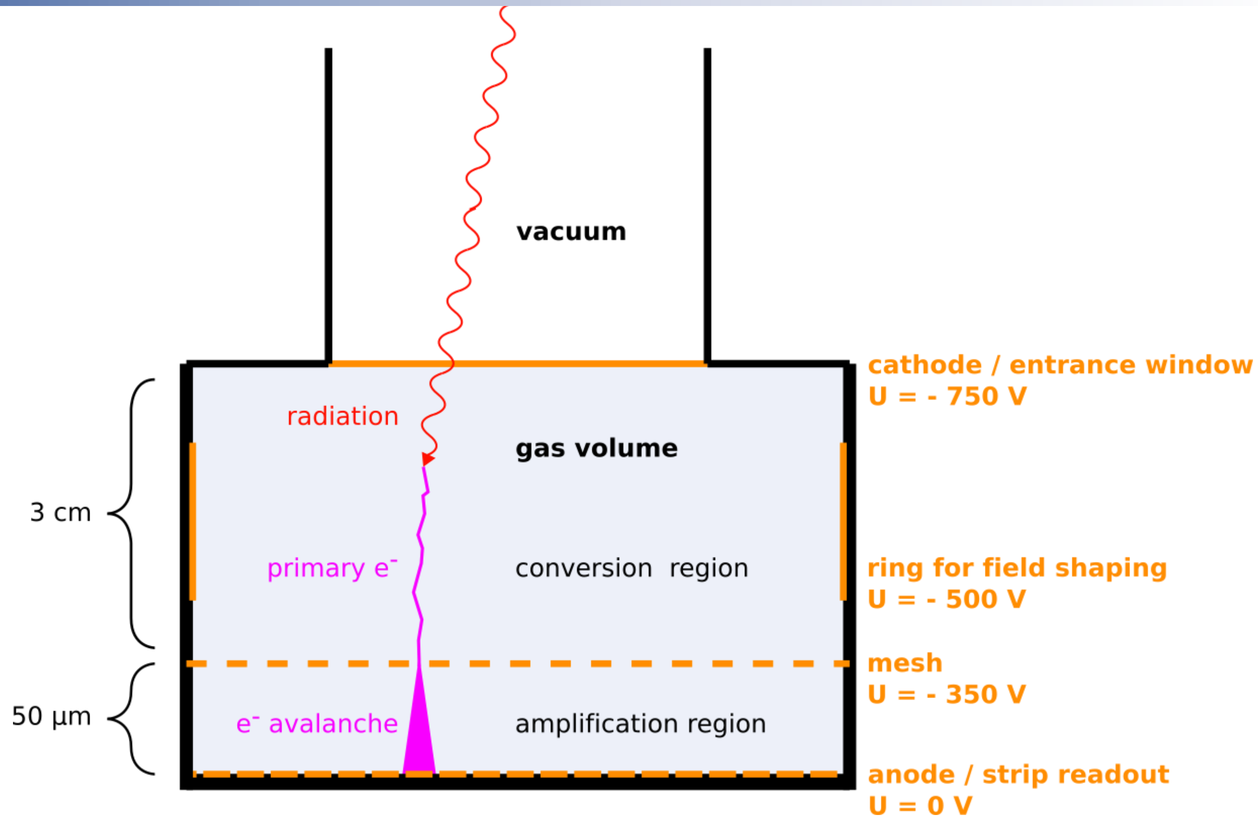
Detector chamber

Readout strips connector

^{55}Fe Calibration intensity map



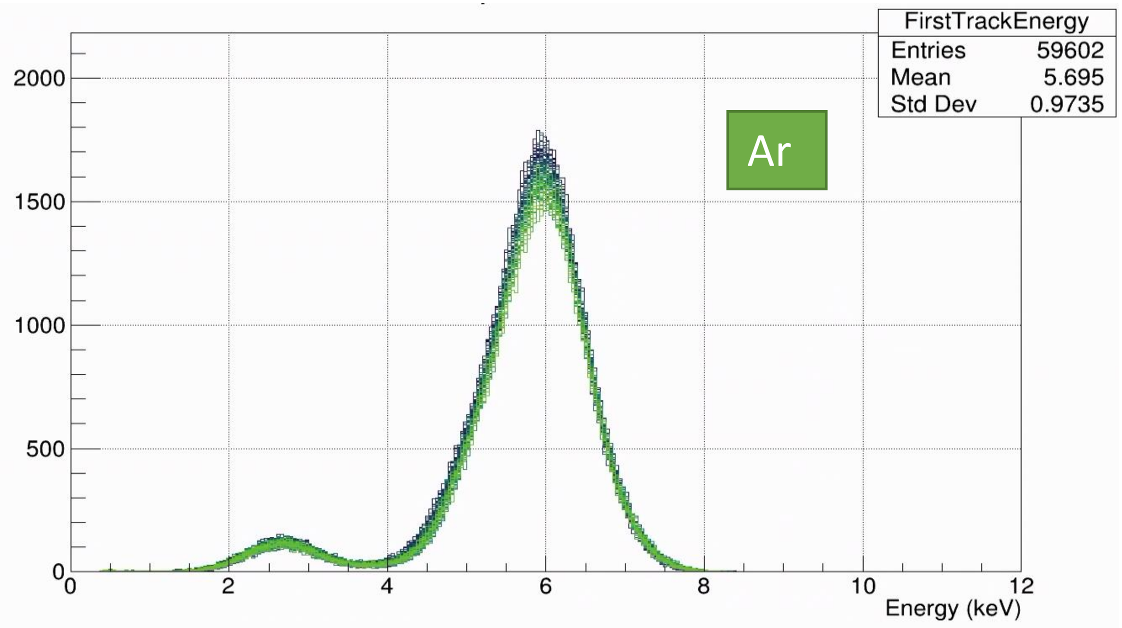
X-ray window

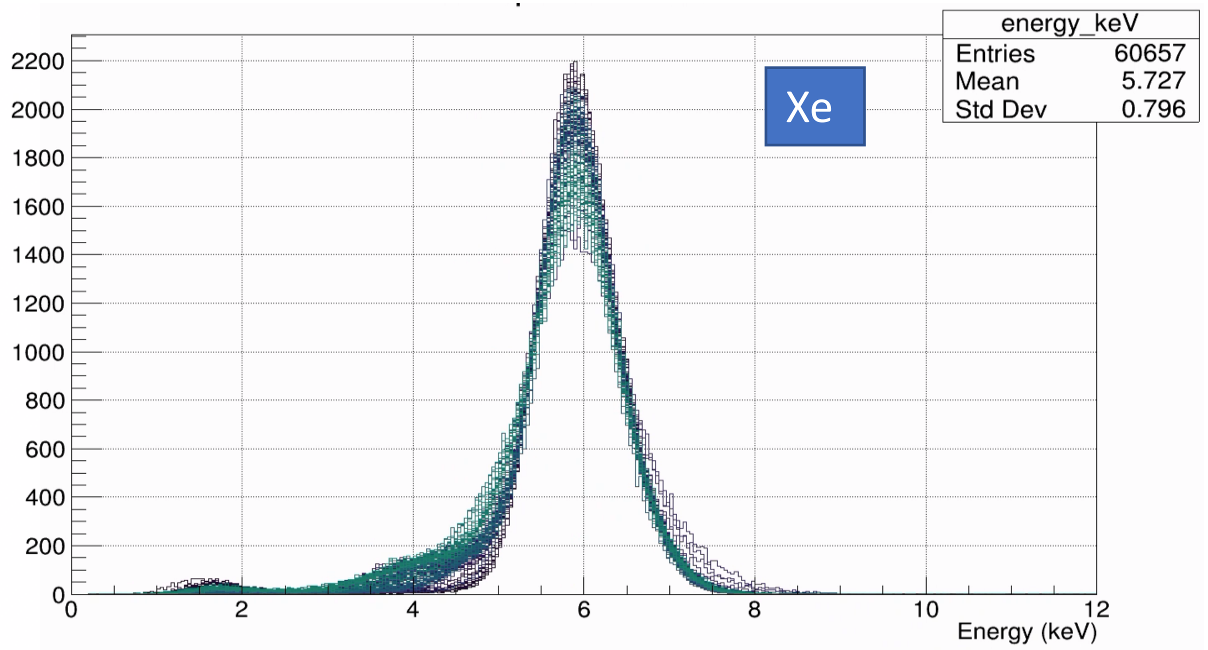


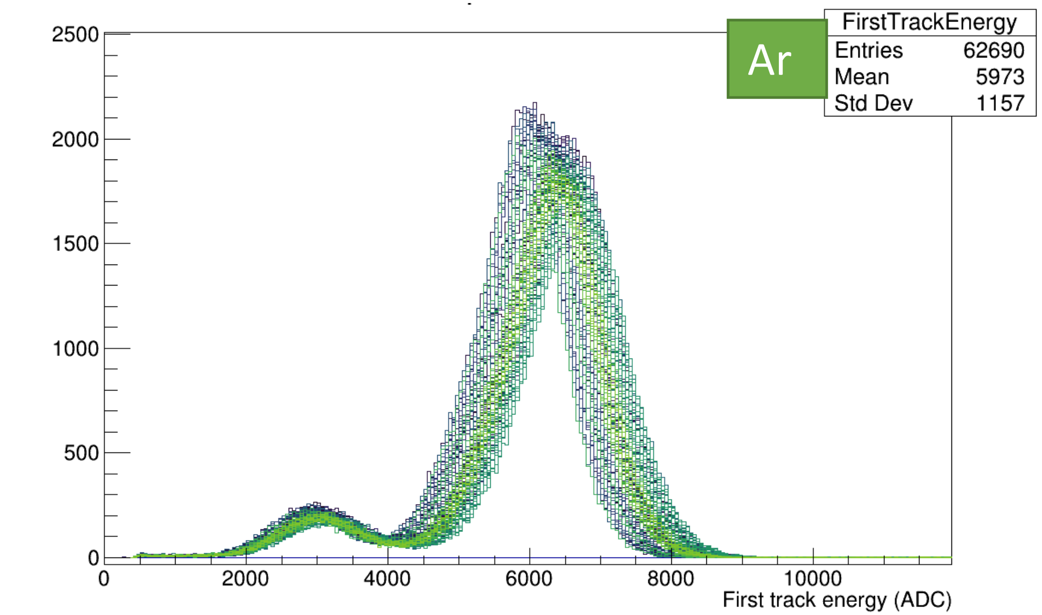
- Signal reaches the active volume through a mylar window.
- X-rays ionize the gas in the conversion region and the produced signal is read by the Micromegas.
- Data is analyzed with the REST-for-Physics framework (github.com/rest-for-physics).

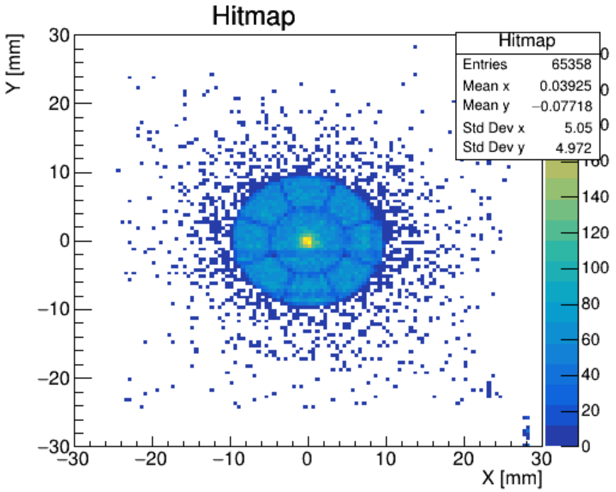
Rare Event Searches Toolkit software

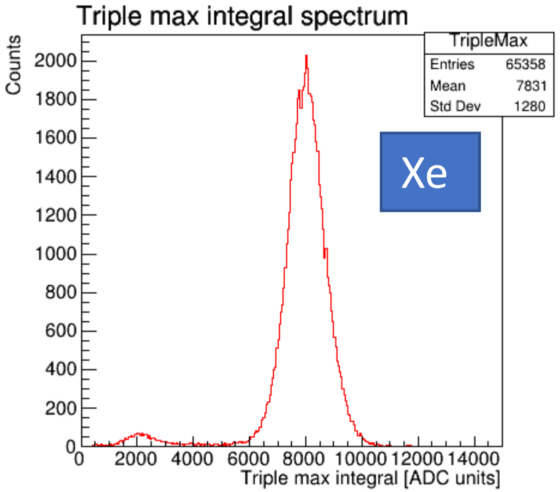
^{55}Fe calibrations and *live* data quality control











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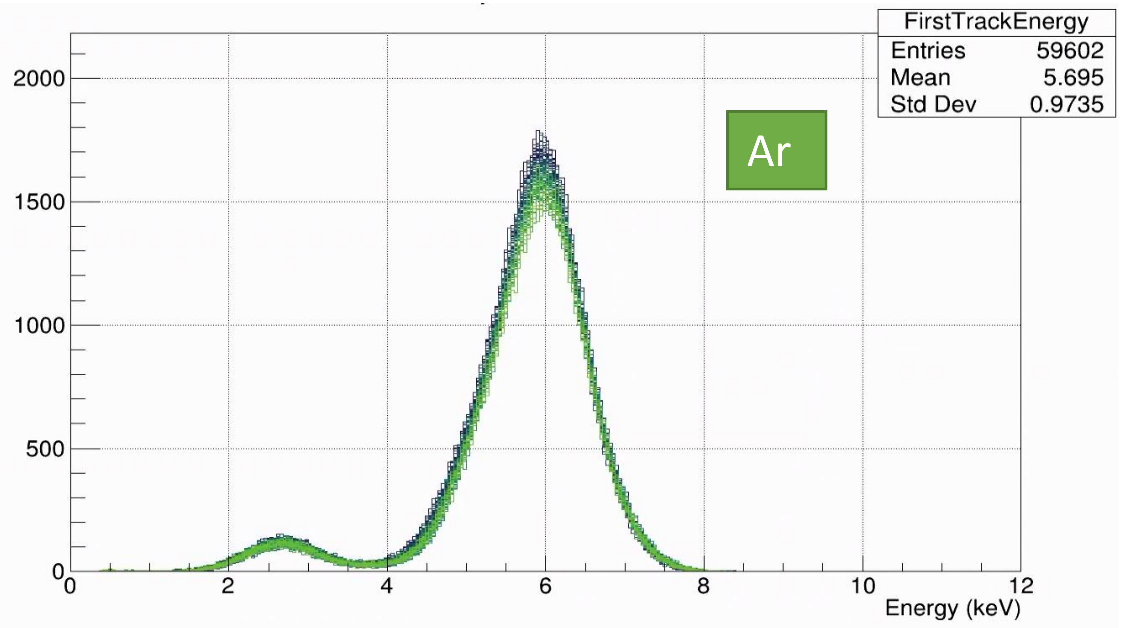
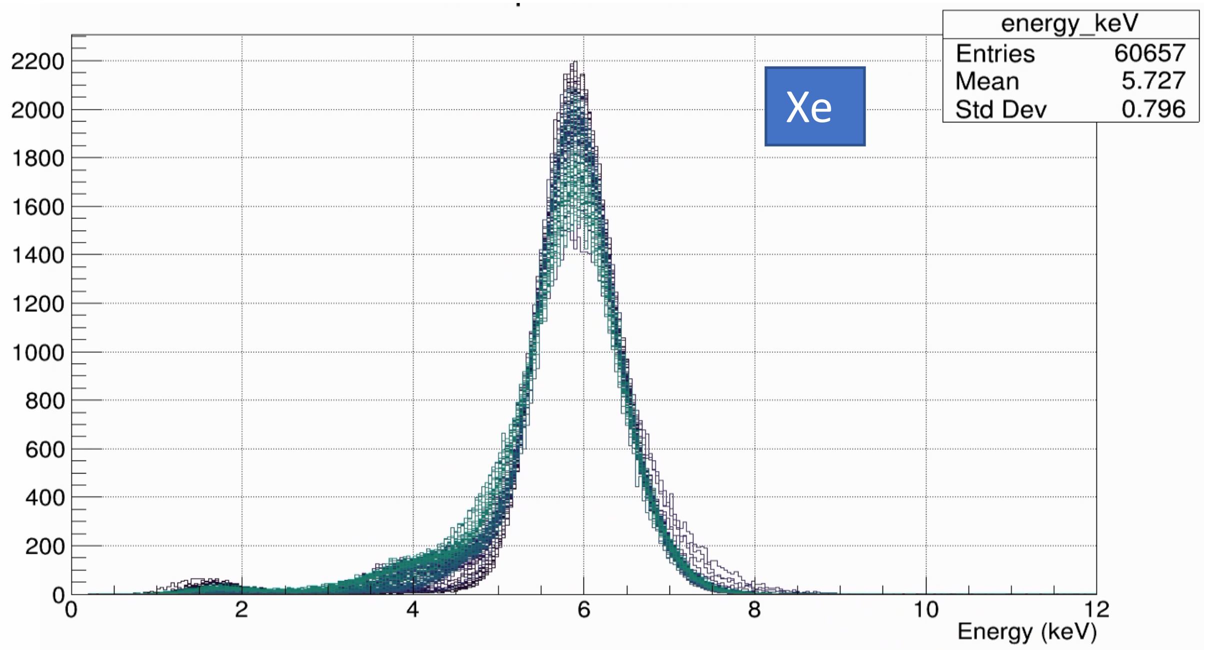
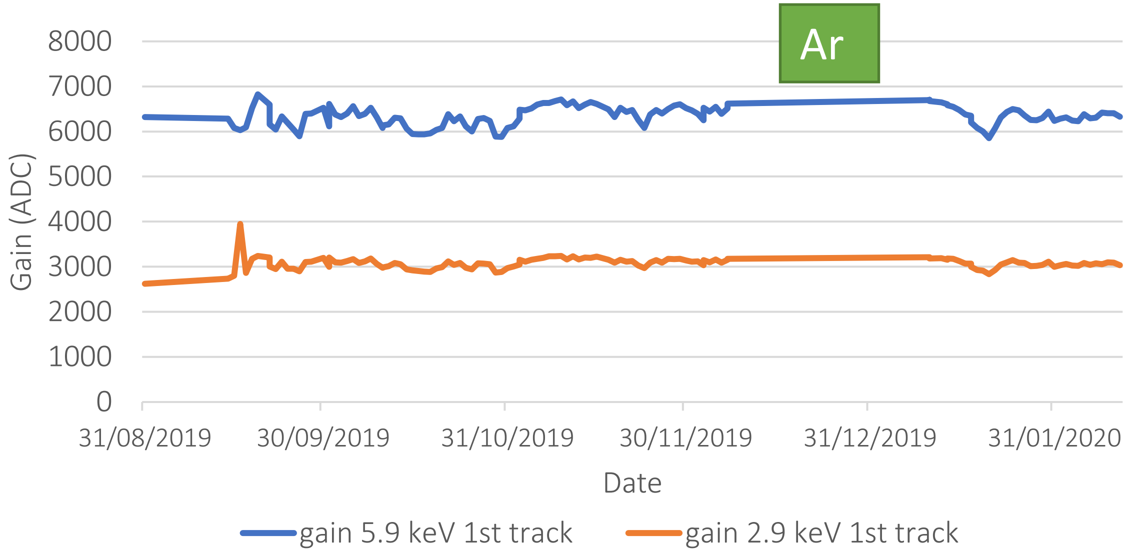
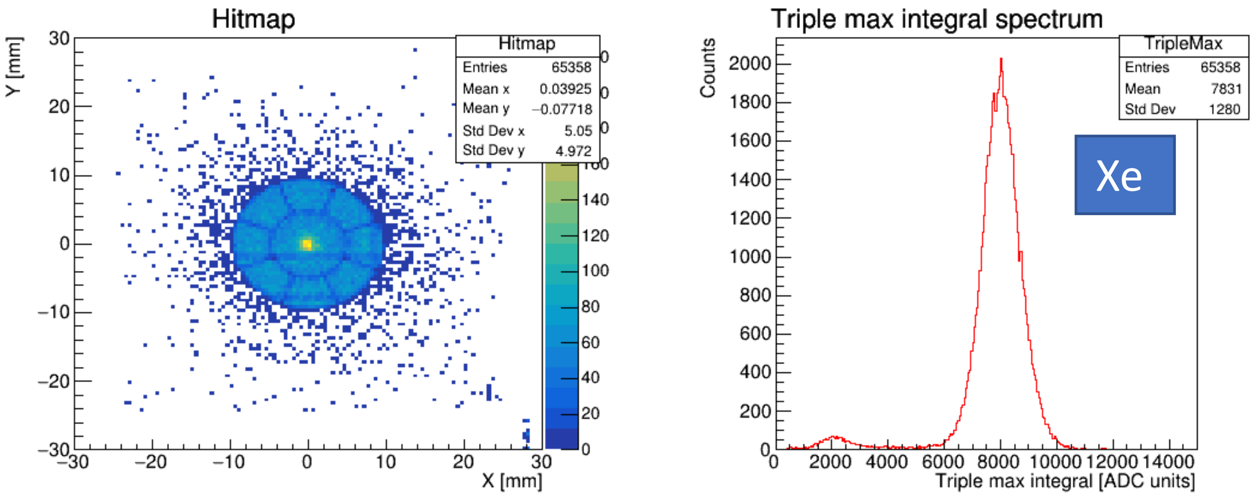
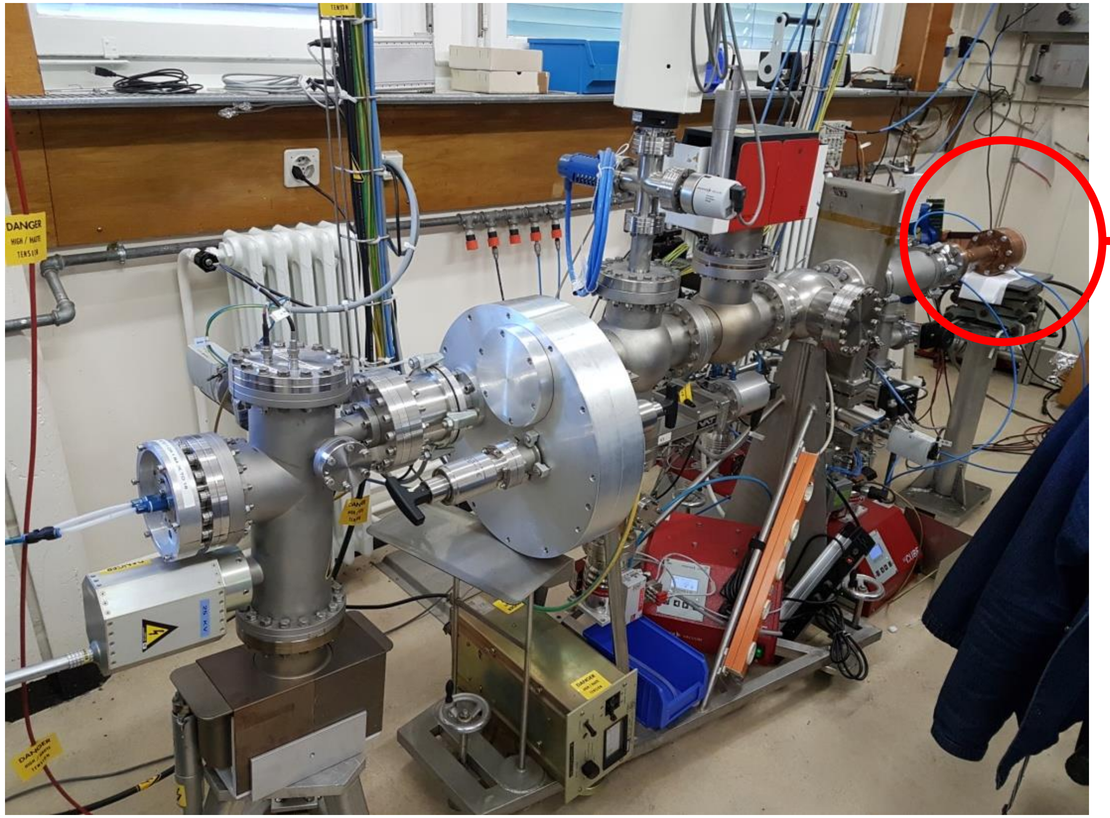


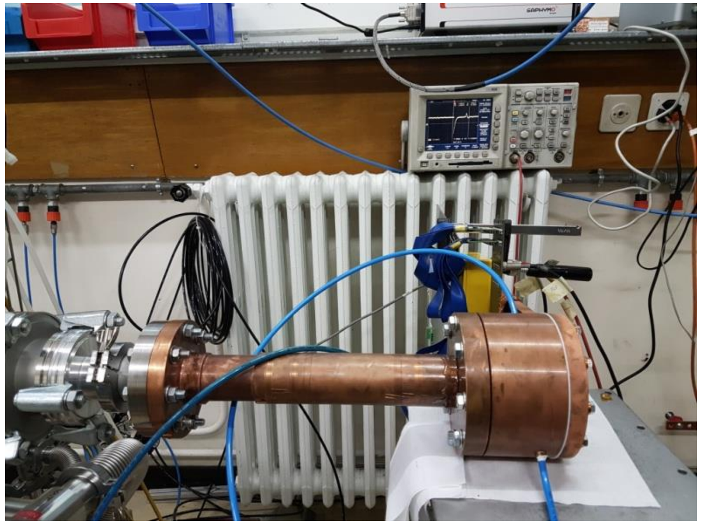




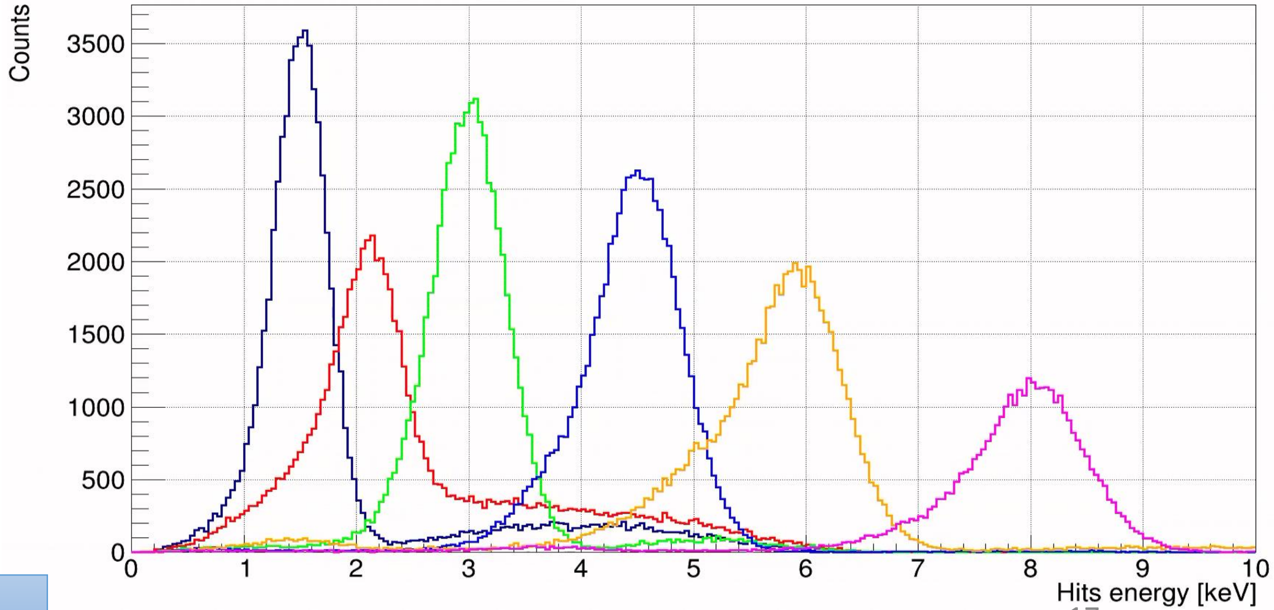


Calibrations in the X-ray lab at CERN





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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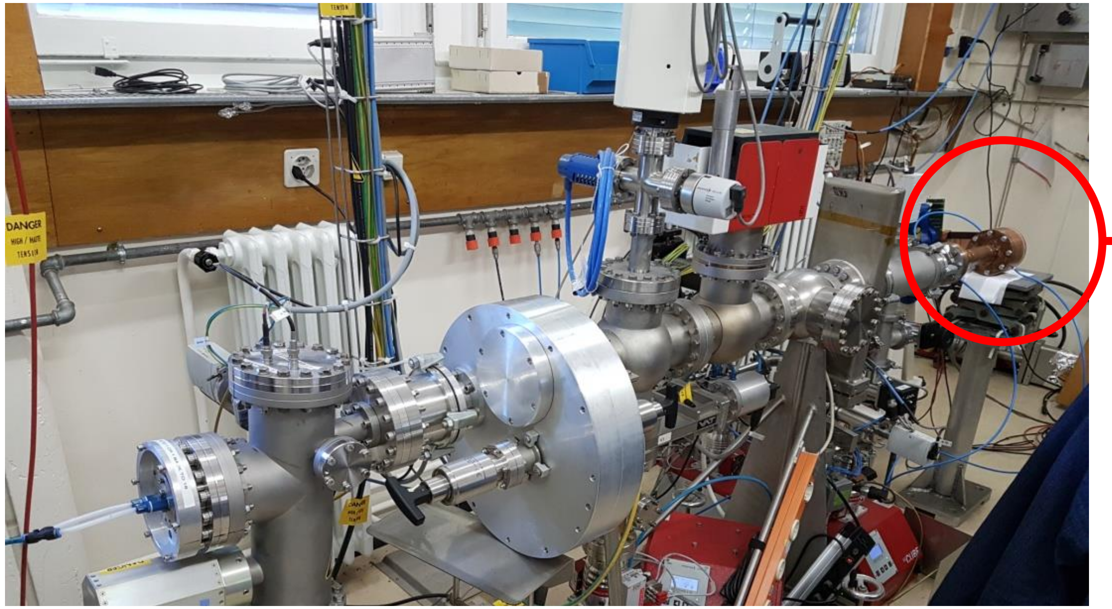
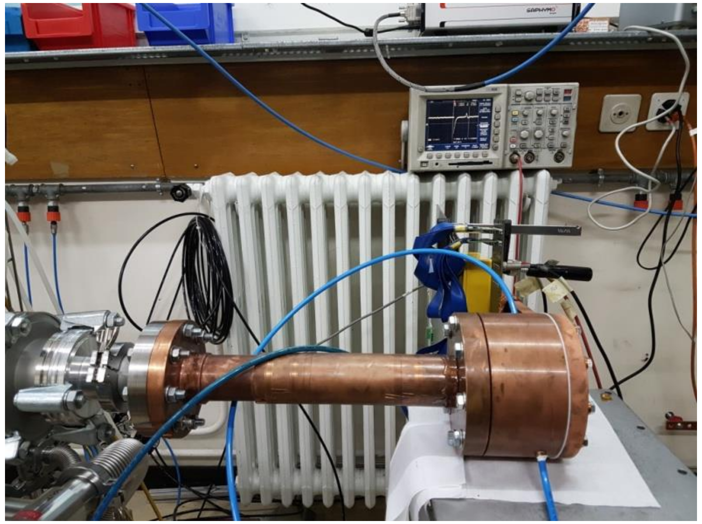
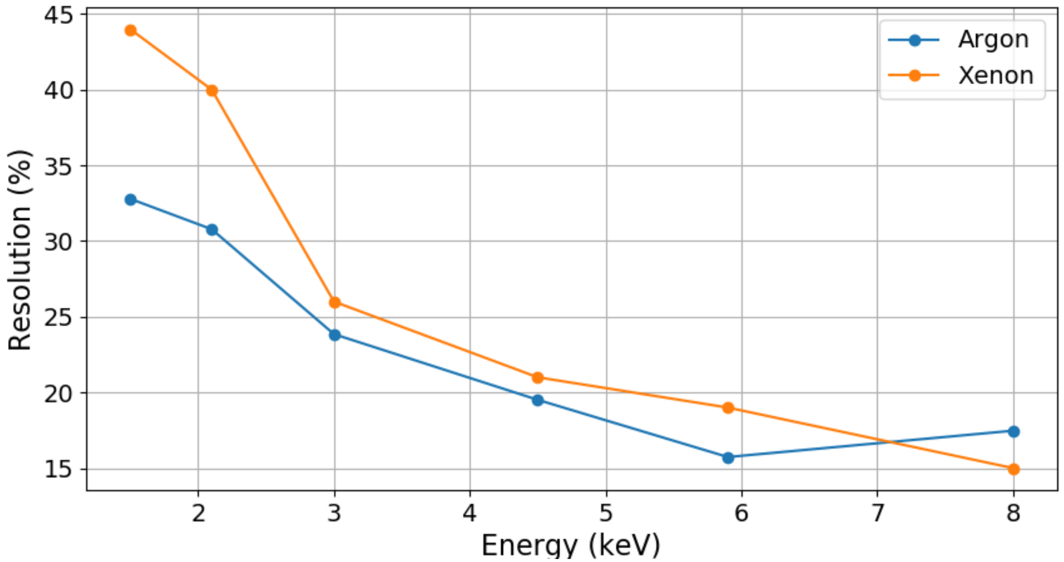
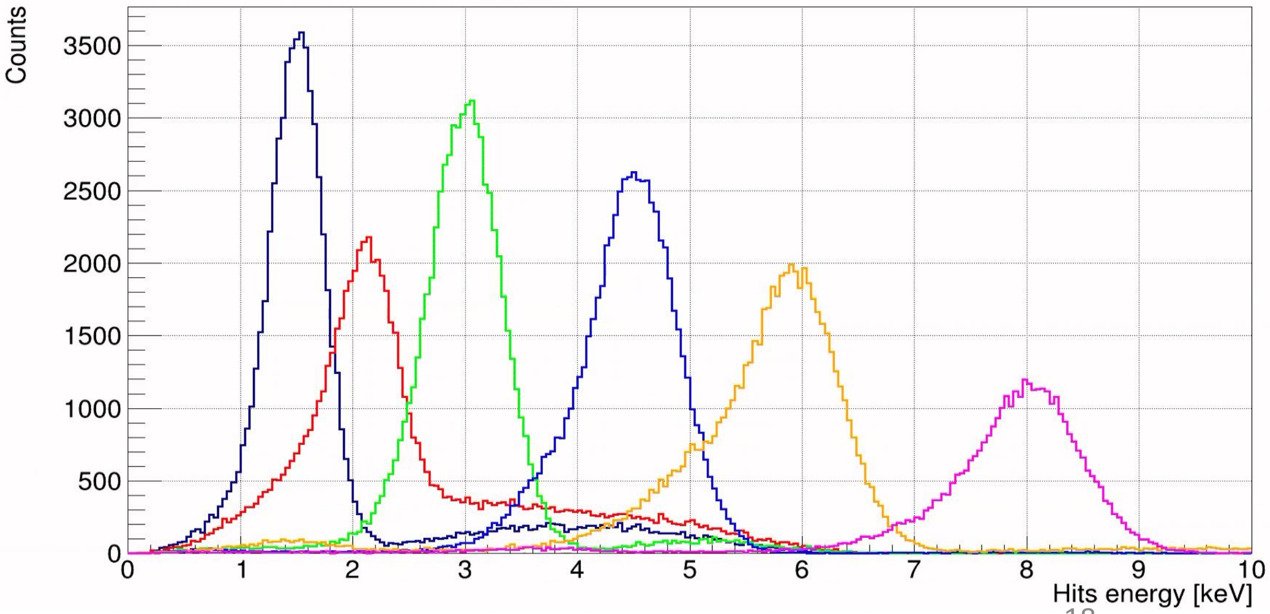


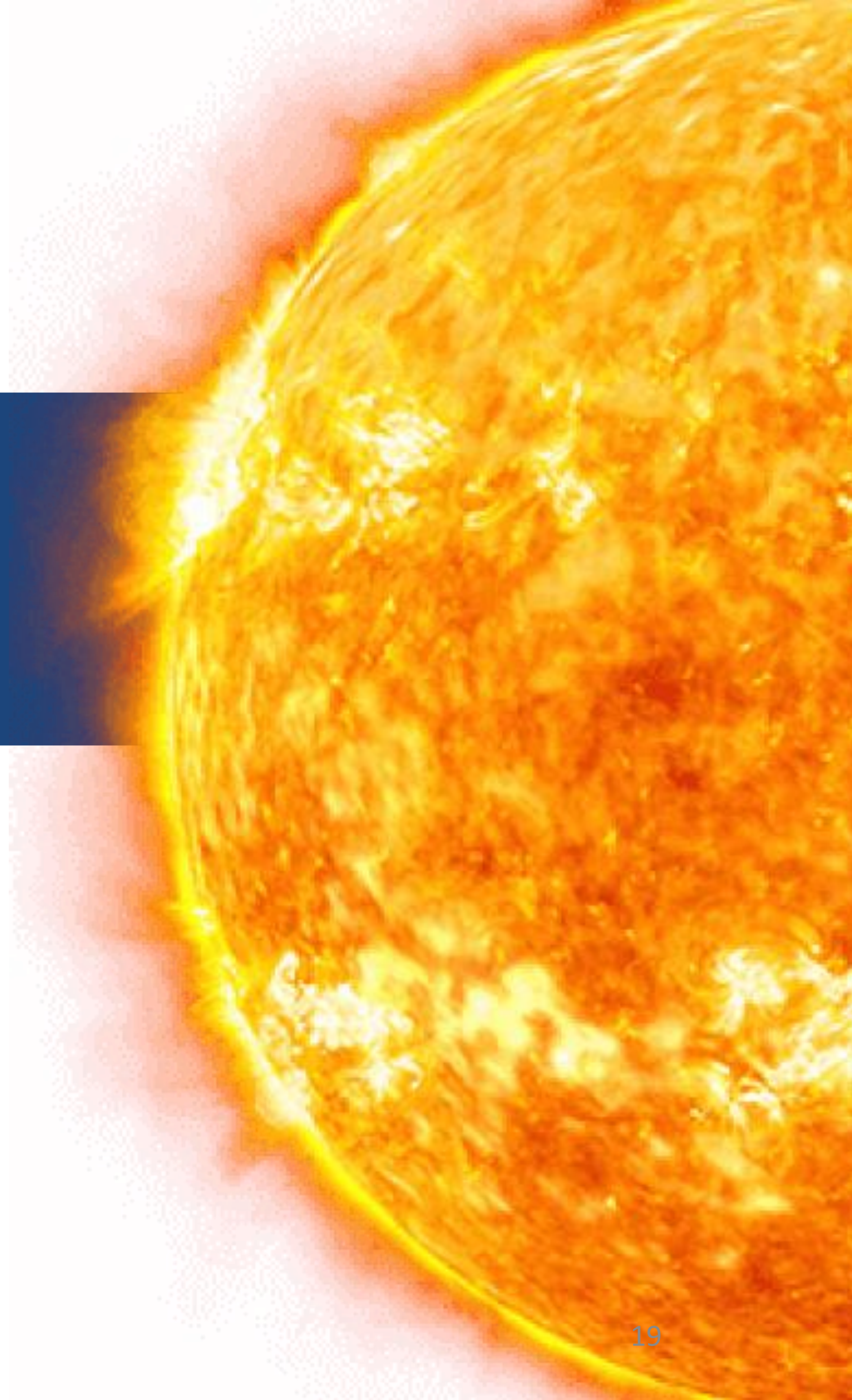






Software

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, <u>via configuration (.rml) files</u>.
- It allows for official version control, so that all official data will be fully reproducible.

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

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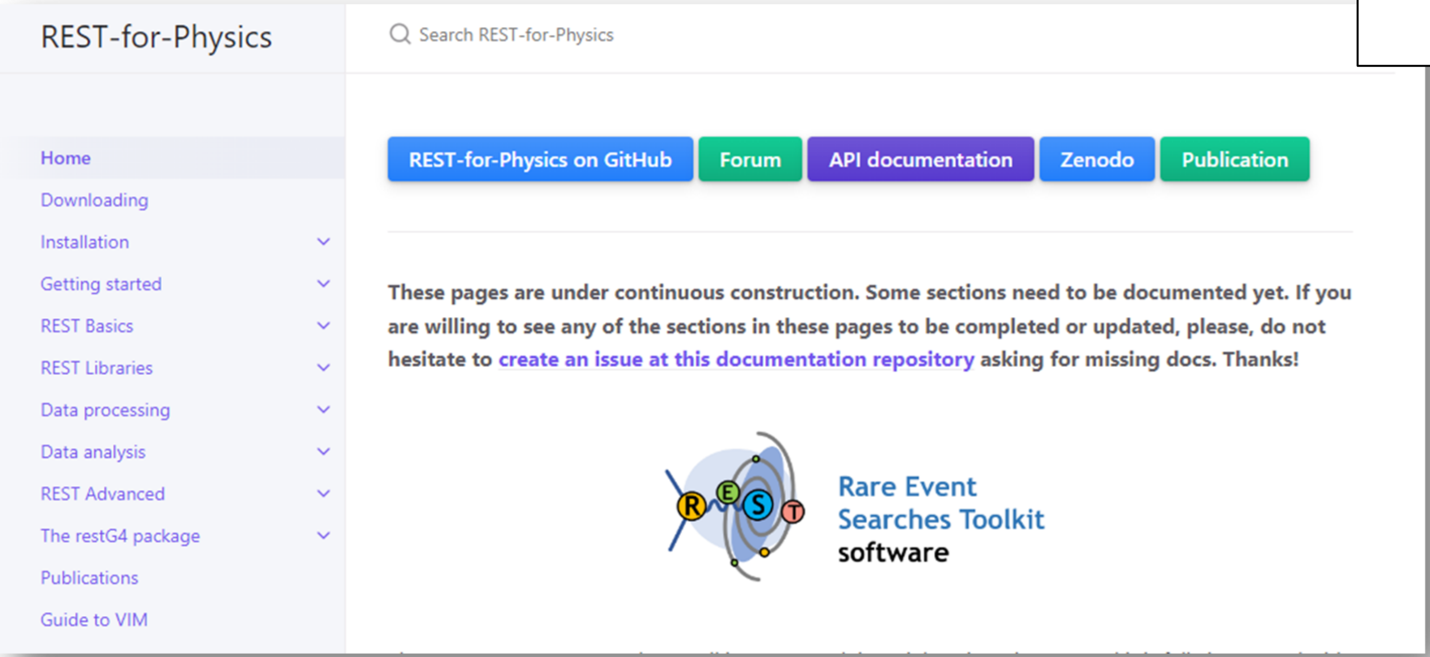

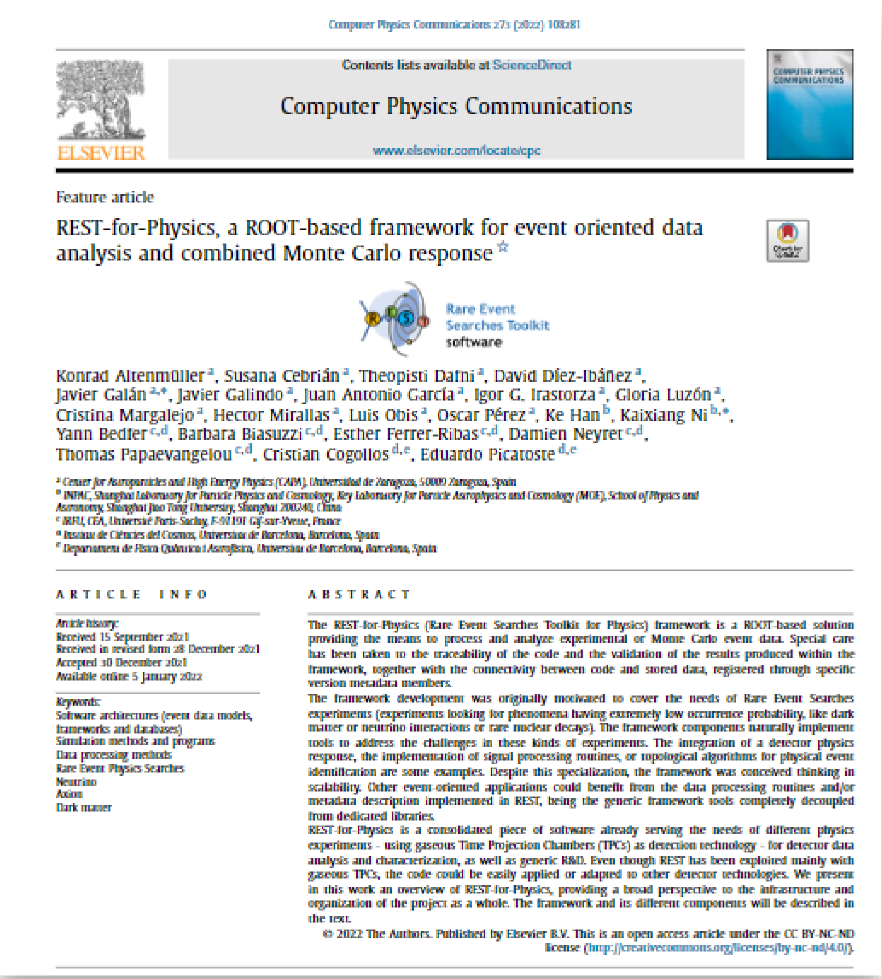

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Feature article

REST-for-Physics, a ROOT-based framework for event oriented data analysis and combined Monte Carlo response ☆

Rare Event Searches Toolkit software

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Neutrino
Axion
Dark matter

ABSTRACT

The REST-for-Physics (Rare Event Searches Toolkit for Physics) framework is a ROOT-based solution providing the means to process and analyze experimental or Monte Carlo event data. Special care has been taken to the traceability of the code and the validation of the results produced within the framework, together with the connectivity between code and stored data, registered through specific version metadata members.

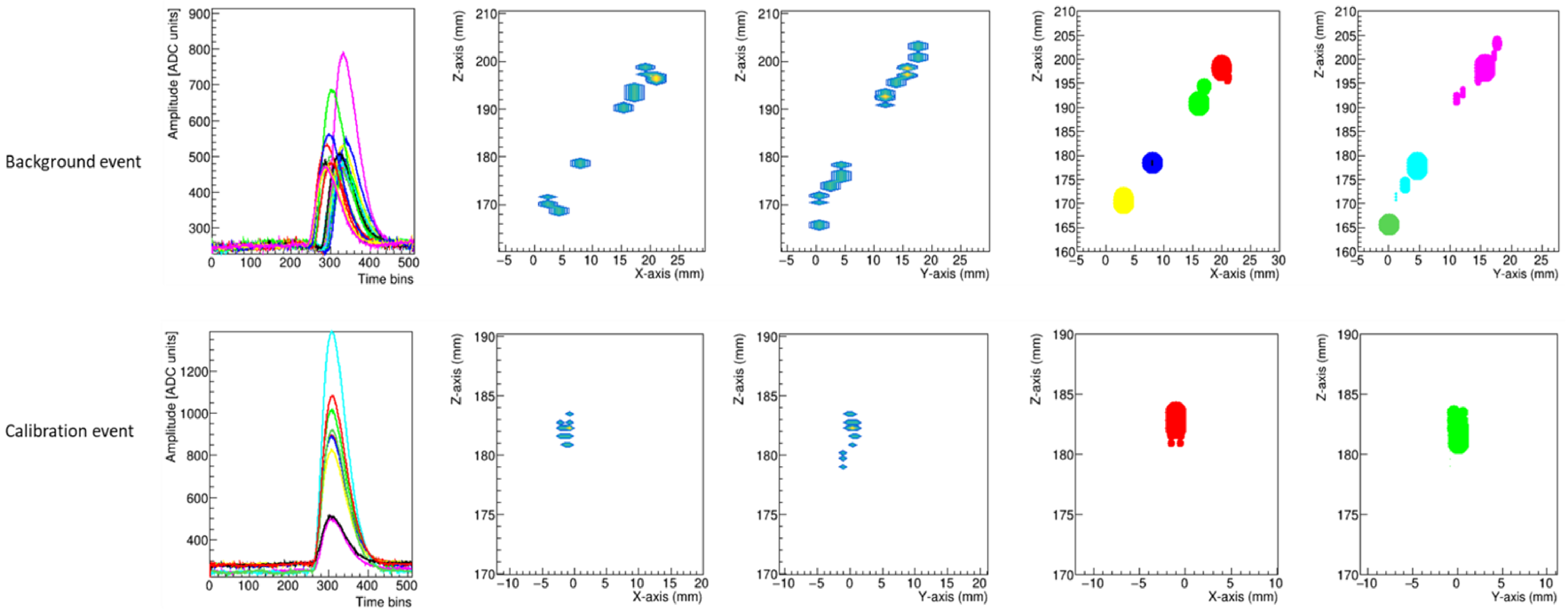
The framework development was originally motivated to cover the needs of Rare Event Searches experiments (experiments looking for phenomena having extremely low occurrence probability, like dark matter or neutrino interactions or rare nuclear decays). The framework components naturally implement tools to address the challenges in these kinds of experiments. The integration of a detector physics response, the implementation of signal processing routines, or topological algorithms for physical event identification are some examples. Despite this specialization, the framework was conceived thinking in scalability. Other event-oriented applications could benefit from the data processing routines and/or metadata description implemented in REST, being the generic framework tools completely decoupled from dedicated libraries.

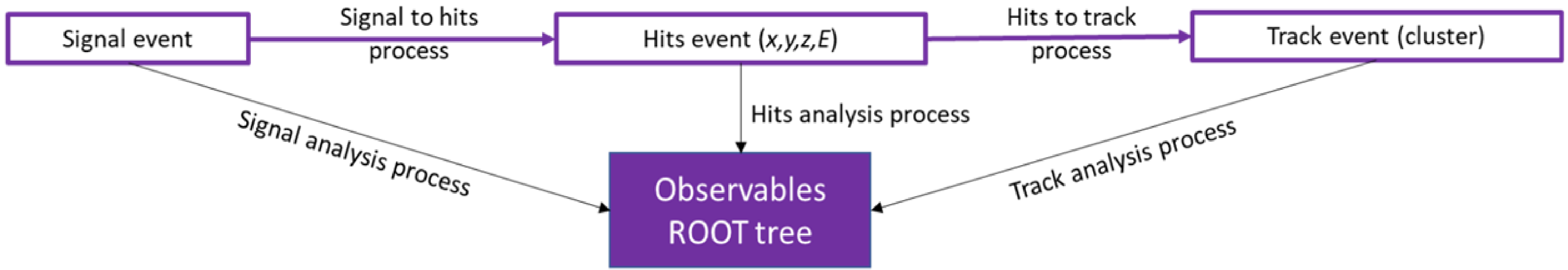
REST-for-Physics is a consolidated piece of software already serving the needs of different physics experiments - using gaseous Time Projection Chambers (TPCs) as detection technology - for detector data analysis and characterization, as well as generic R&D. Even though REST has been exploited mainly with gaseous TPCs, the code could be easily applied or adapted to other detector technologies. We present in this work an overview of REST-for-Physics, providing a broad perspective to the infrastructure and organization of the project as a whole. The framework and its different components will be described in the text.

REST-for-Physics publication:

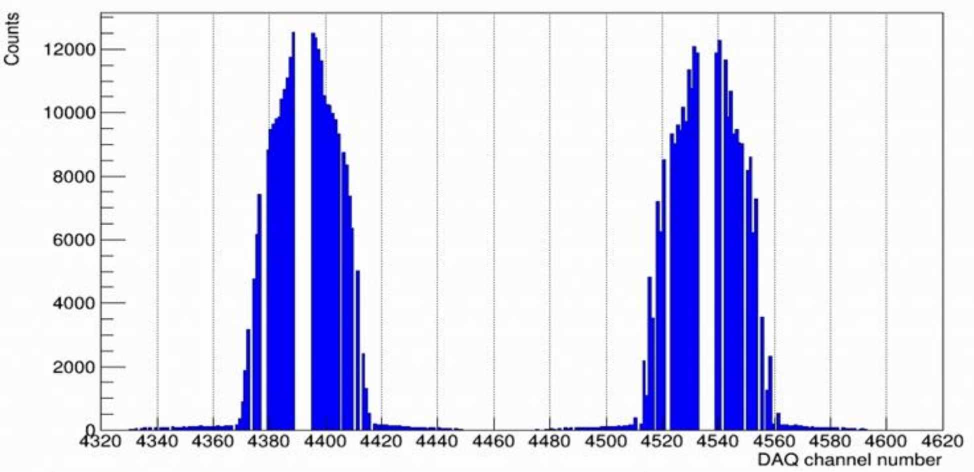
https://doi.org/10.1016/j.cpc.2021.108281

Event reconstruction with REST-for-physics



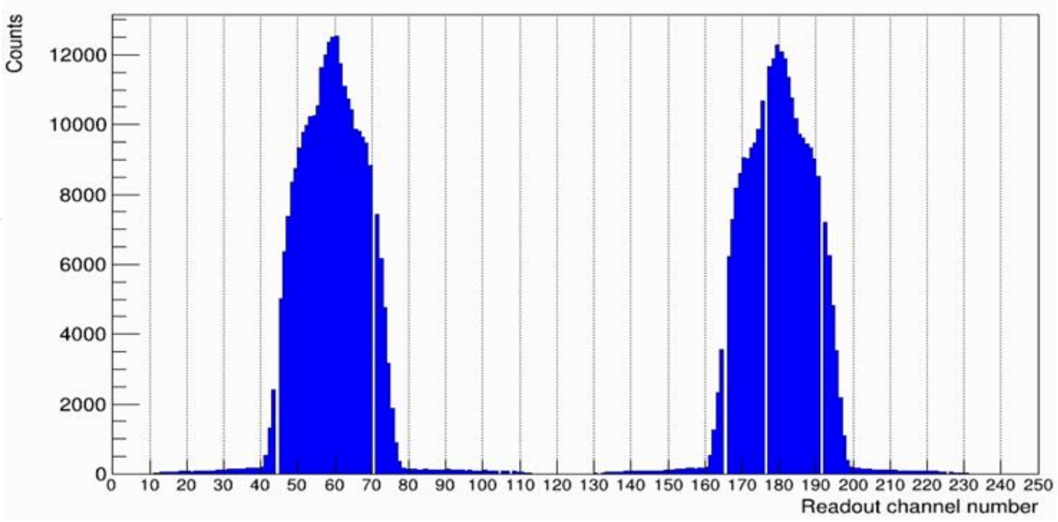


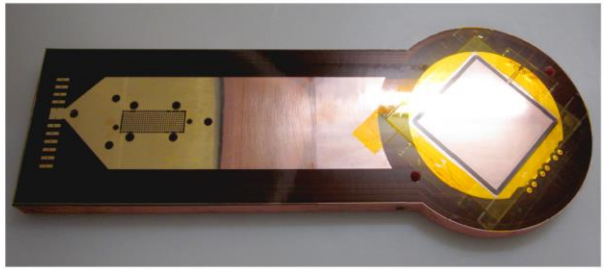
Example: microbulk detector for IAXO and event reconstruction from real detector data



Decoding file

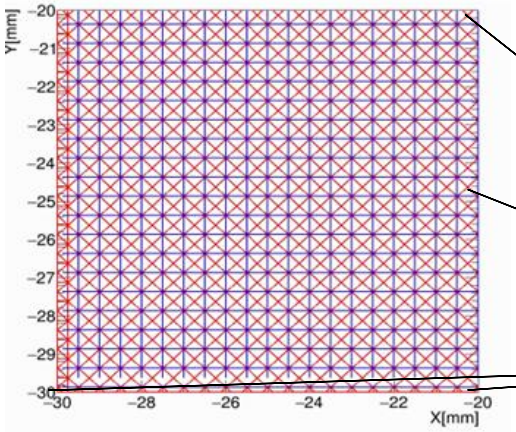
(DAQ to readout channel number correspondence)

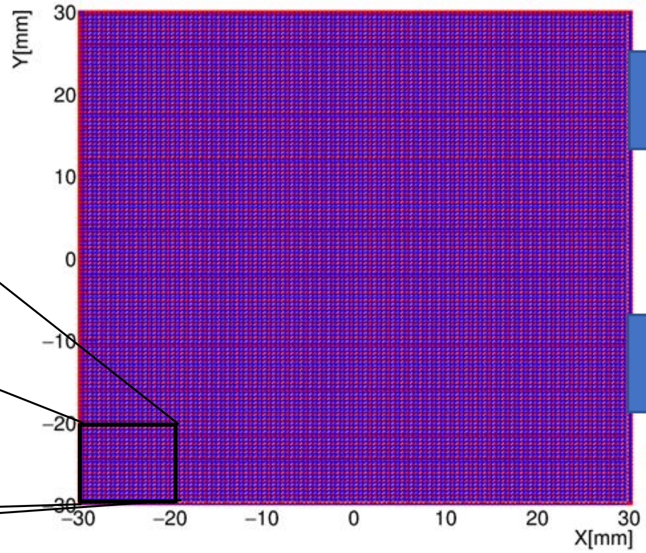




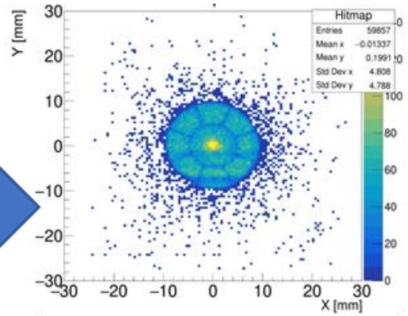
120x120 strips, pitch = 0.5 mm

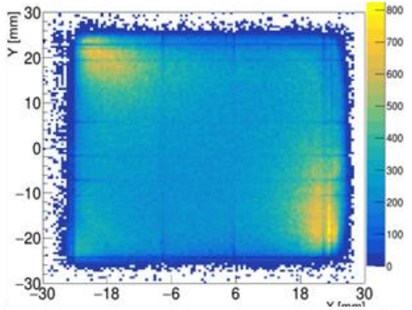
Total area = 6x6 cm^2



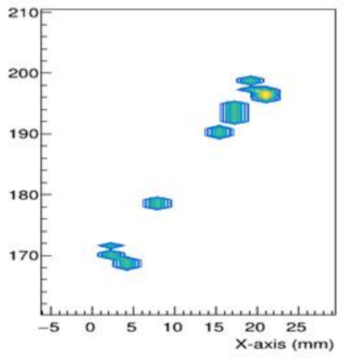


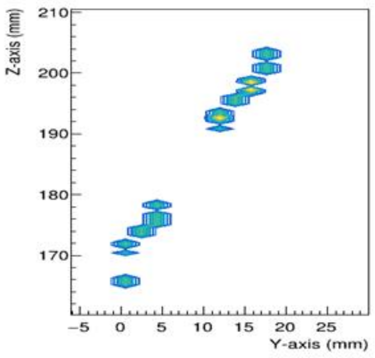
Hitmaps





Hits events

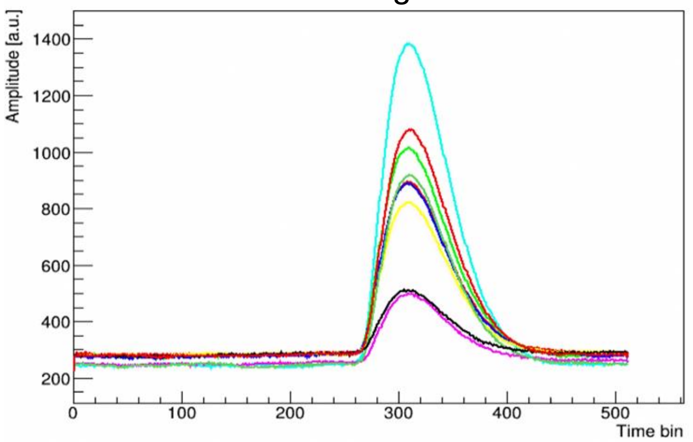




Event reconstruction with REST-for-physics

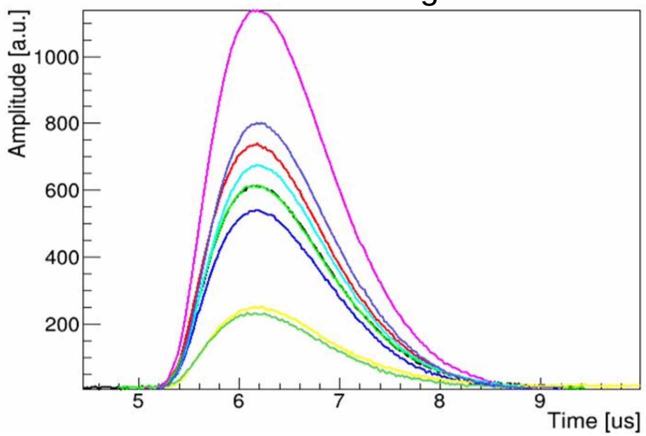
Experimental data

TRestRawSignalEvent



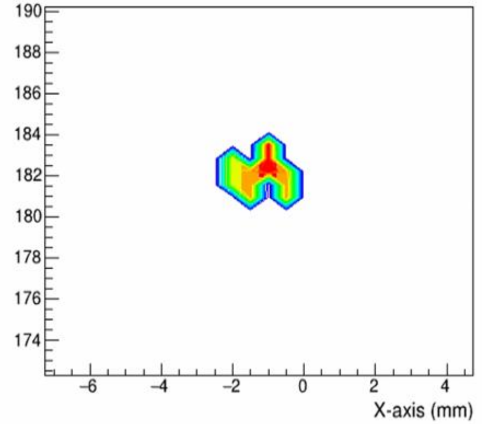
Raw signal as recorded by the electronics

TRestDetectorSignalEvent



Reconstructed signal in terms of time, energy and position

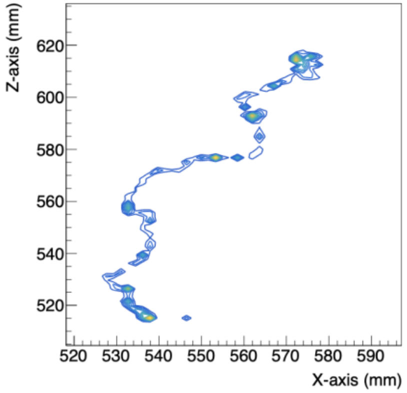
TRestDetectorHitsEvent



Reconstructed hits event

Simulation data

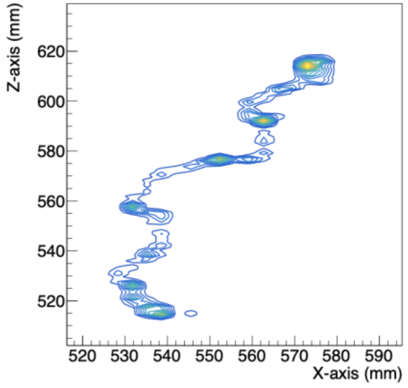
TRestGeant4Event



(a)

Simulated event

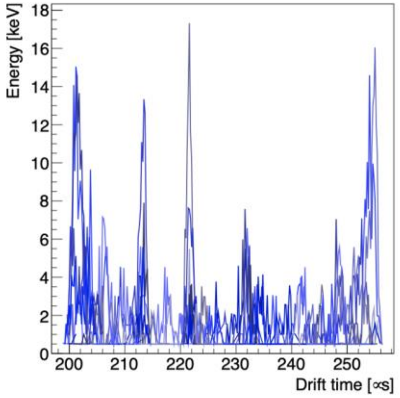
TRestDetectorHitsEvent



(b)

Appearance of the event after diffusion

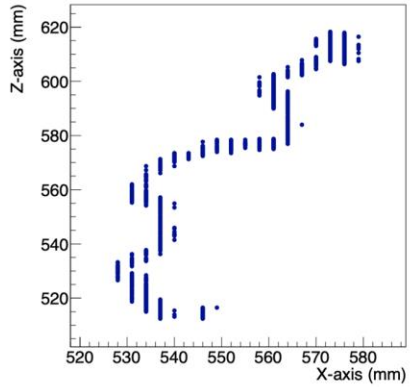
TRestDetectorSignalEvent



(c)

Reconstructed signal event

TRestDetectorHitslEvent

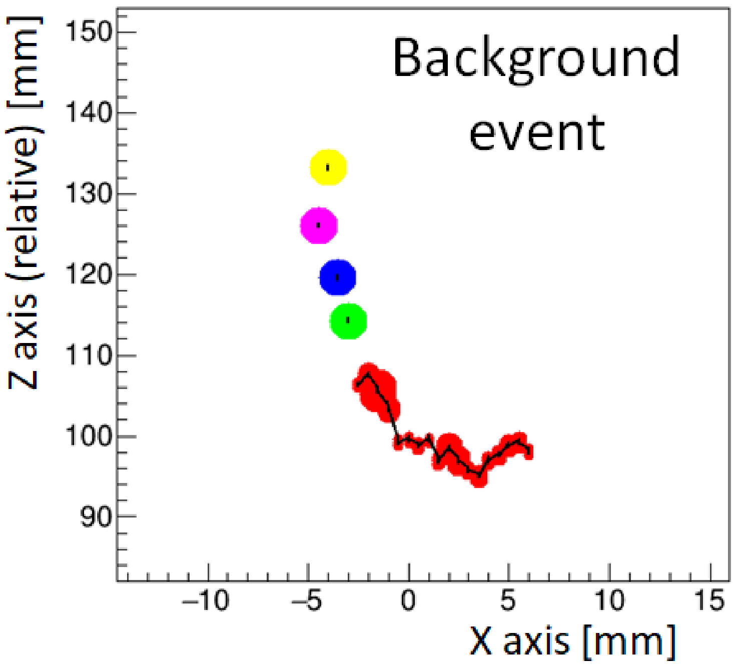


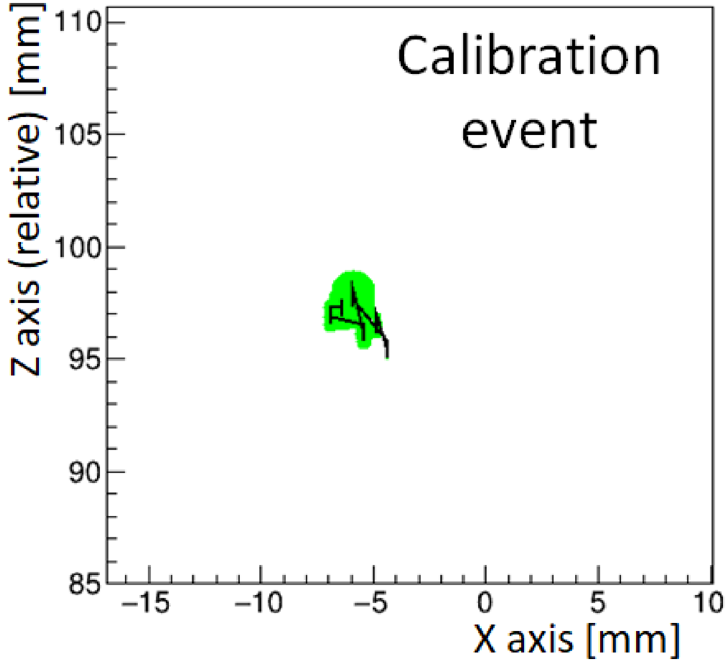
(d)

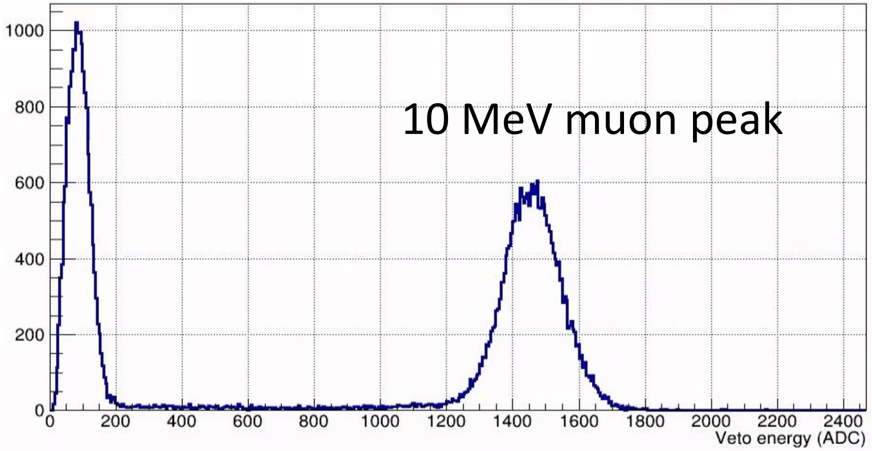
Reconstructed hits event. The effect of the readout is clearly seen.

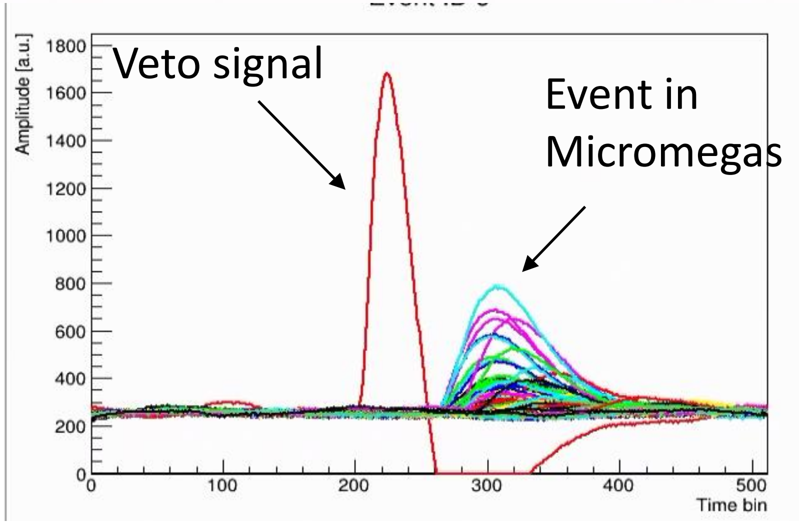
From *Topological background discrimination in the PandaX-III neutrinoless double beta decay experiment* https://arxiv.org/abs/1903.03979

Background discrimination







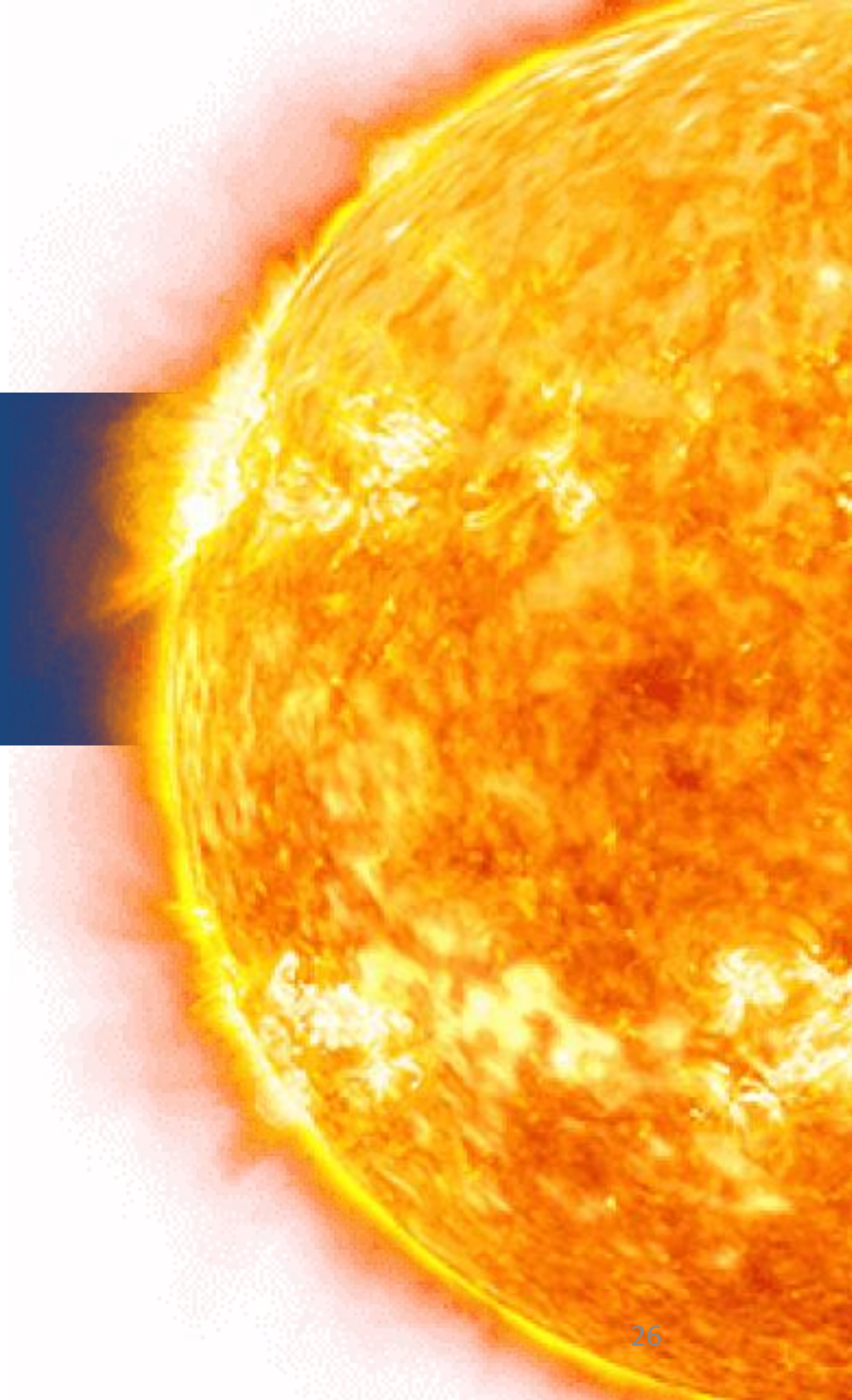


The computed observables are used to define selection algorithms.
Four main types of cuts are applied:

- 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 analysis

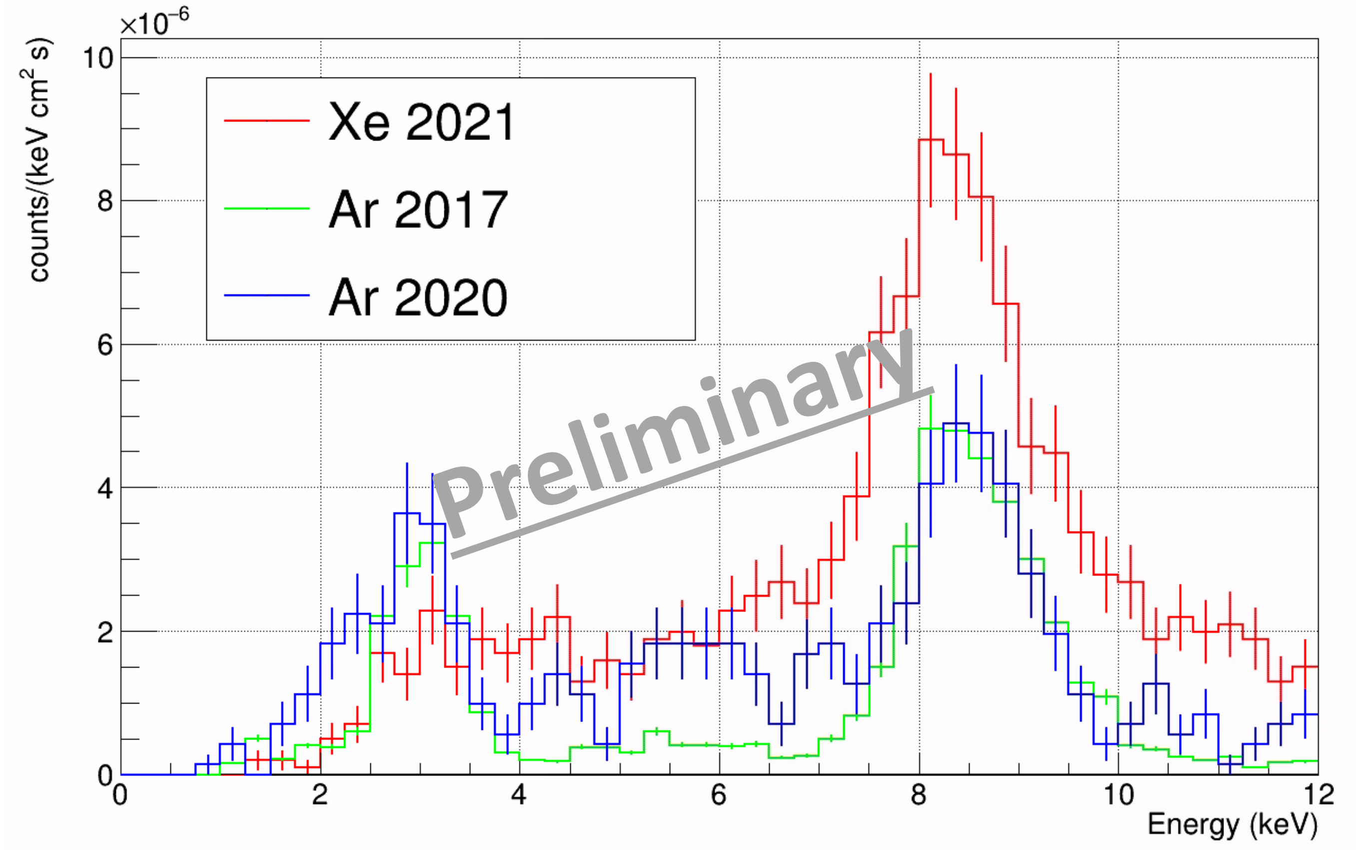
Background computation and expected limit

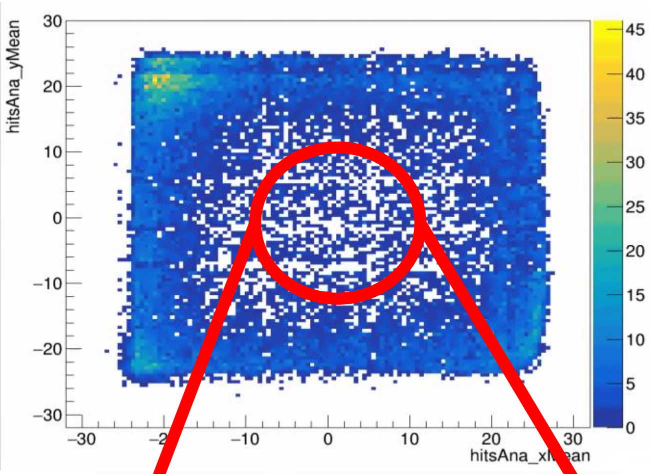


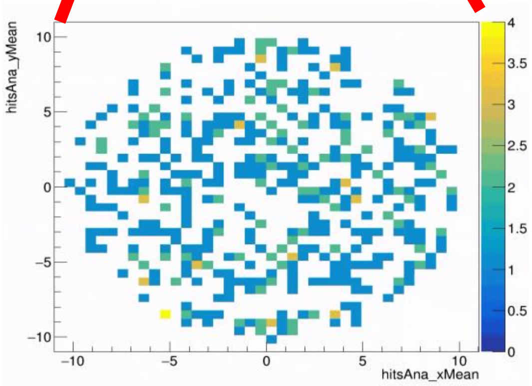
Preliminary results with Xe-based gas mixtures

Motivation:

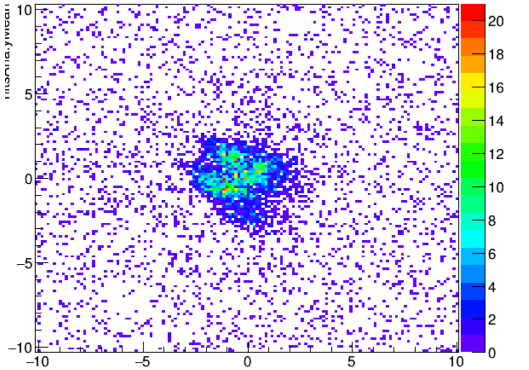
- Xe-based gas mixtures do not have characteristic X-rays in the energy region of interest.
- They allow for higher detection efficiency than Ar-based gas mixtures.





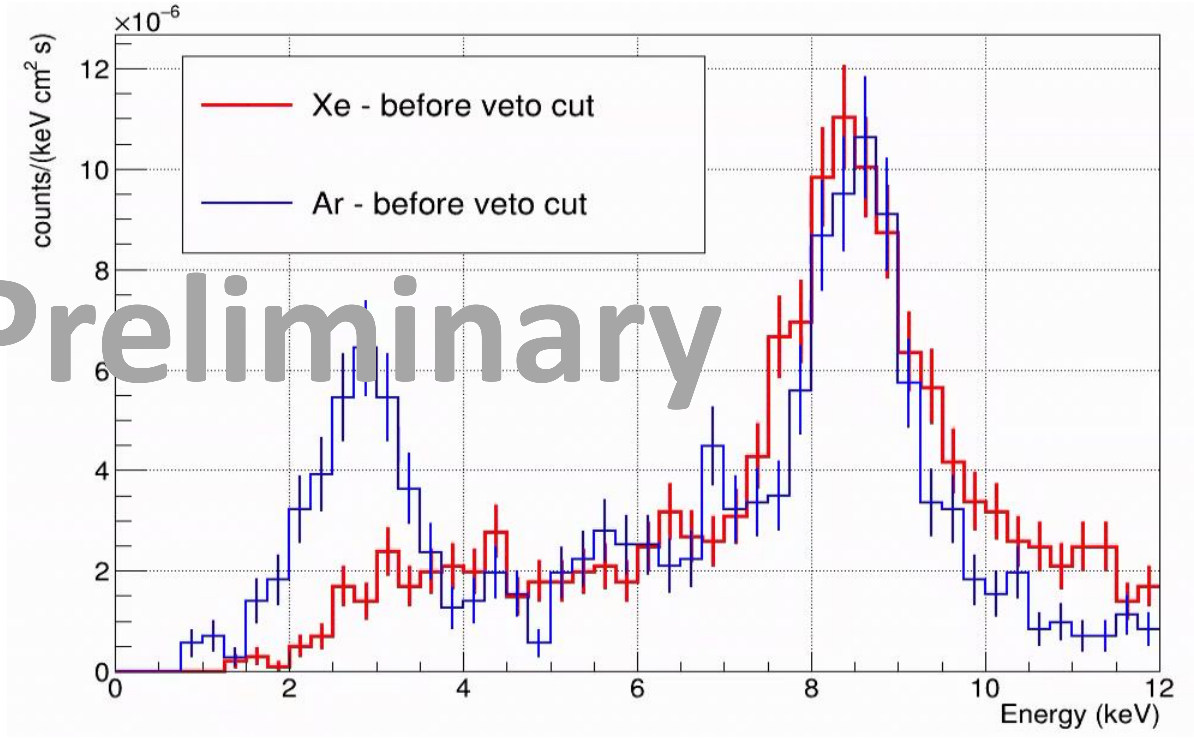


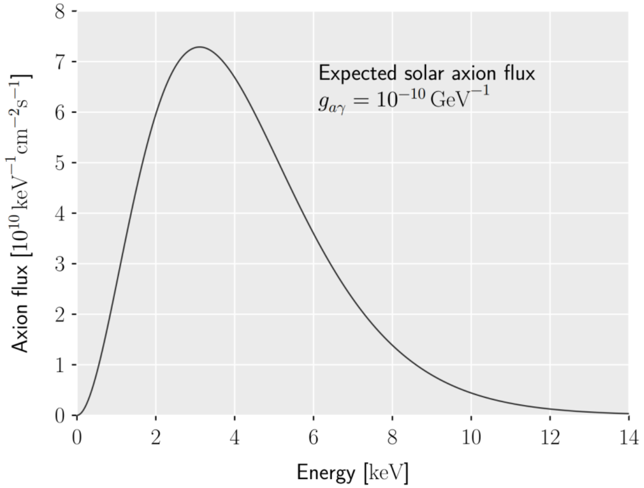
Focal spot even smaller

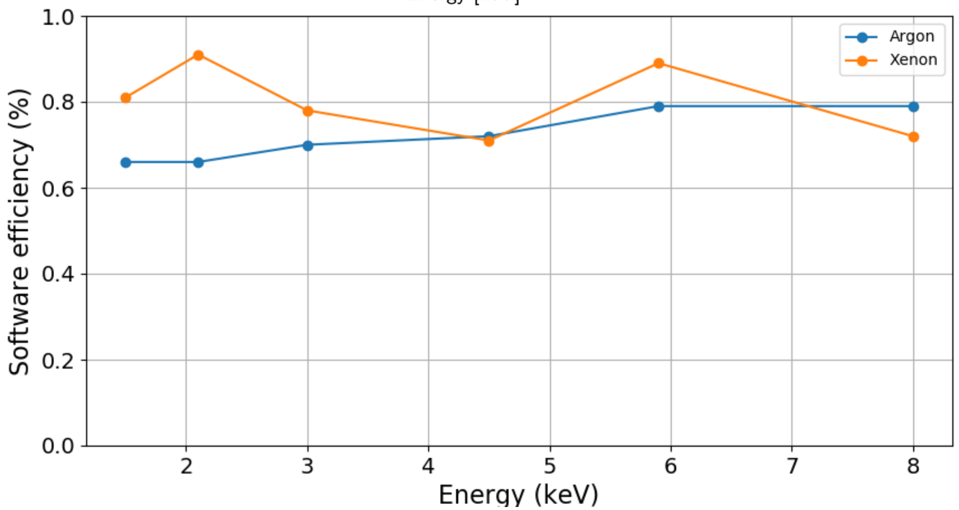


The background in the 3 keV range has no peak → important achievement since the peak of Primakoff produced axion is expected in that energy.

Preliminary results with Xe-based gas mixtures







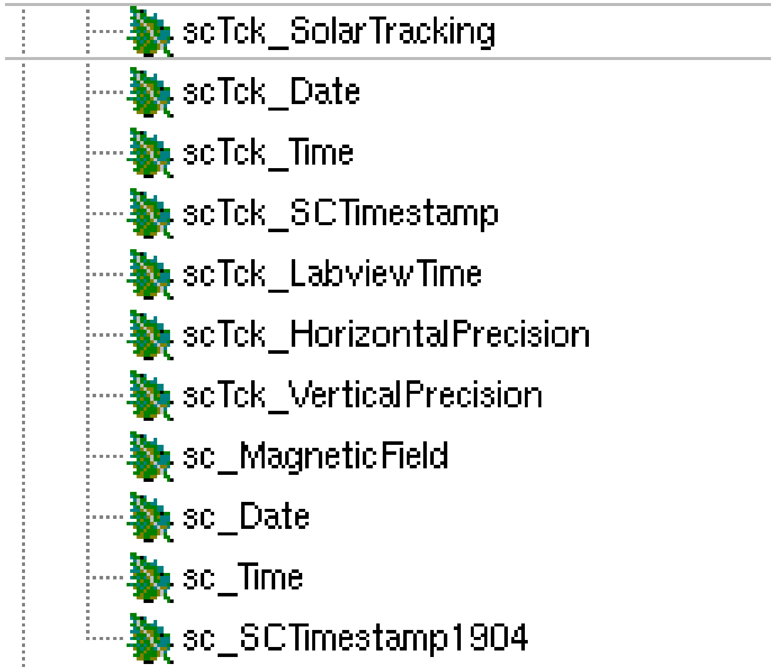
magnet optics

$$g_{a\gamma}^4 \sim B^2L^2A \quad \varepsilon_d b^{-1/2} \quad \varepsilon_o \alpha^{-1/2} \quad \varepsilon_t^{-1/2} t^{-1/2}$$

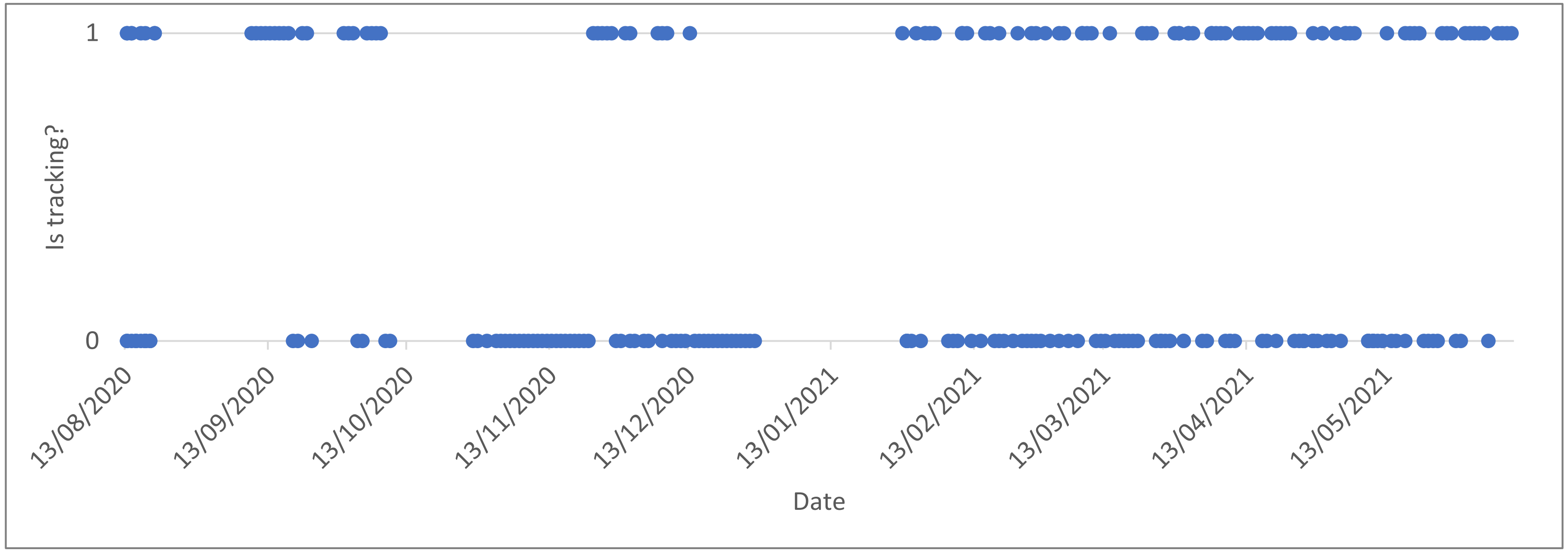
detectors time

Background in the (2,7) keV range	Ar	Xe
Before veto cut	$(2.99 \pm 0.14) \times 10^{-6}\mathrm{c\,keV^{-1}cm^{-2}s^{-1}}$	$(1.96 \pm 0.10) \times 10^{-6}\mathrm{c\,keV^{-1}cm^{-2}s^{-1}}$
After veto cut	$(1.73 \pm 0.11) \times 10^{-6}\mathrm{c\,keV^{-1}cm^{-2}s^{-1}}$	$(1.78 \pm 0.09) \times 10^{-6}\mathrm{c\,keV^{-1}cm^{-2}s^{-1}}$
Normalized FOM $\varepsilon/\sqrt{b}$	0.87	1

Opening the box: adding the slow control data



Total Xe trackings = 109



This will provide us with:

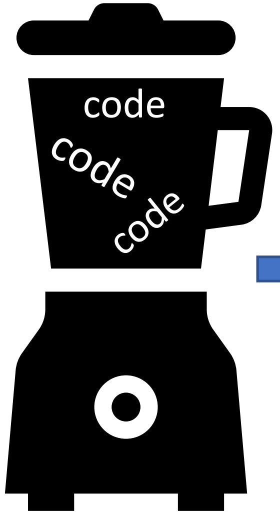
- background dataset (no tracking data)
- signal+background dataset (solar tracking data)

Still need the expected solar axion signal.

Opening the box: computing a limit

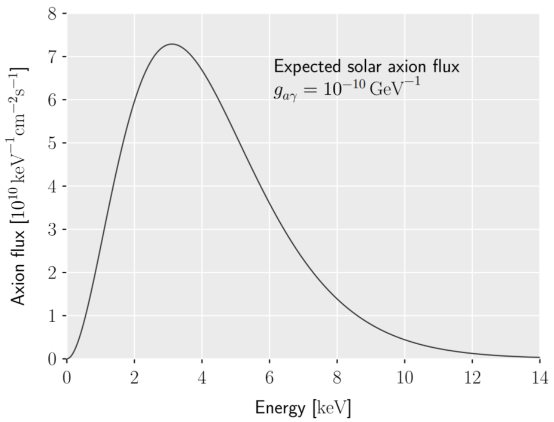
Inputs

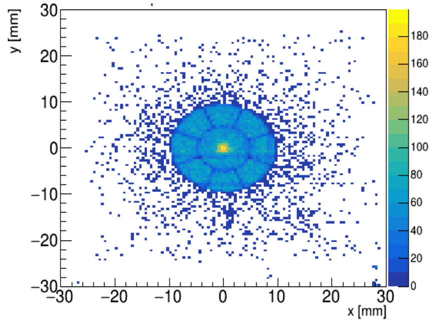
1. Background data (no tracking data)
2. Signal+background data (solar tracking data)
3. Primakoff spectrum corrected by our efficiency: telescope, window, gas, strongback.

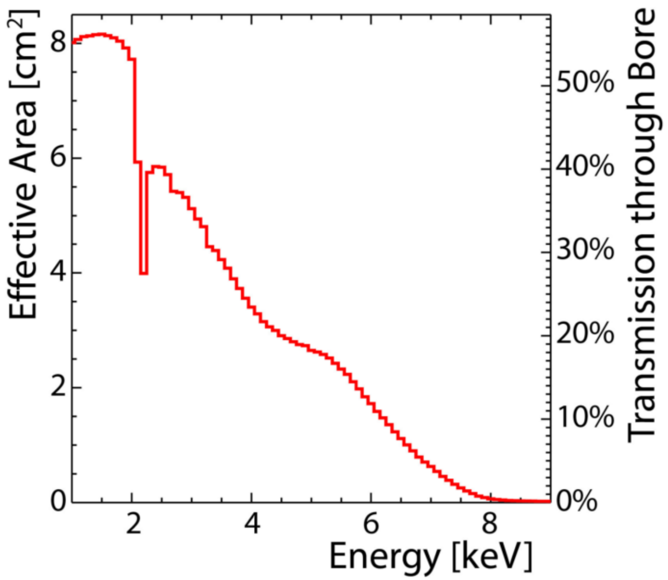


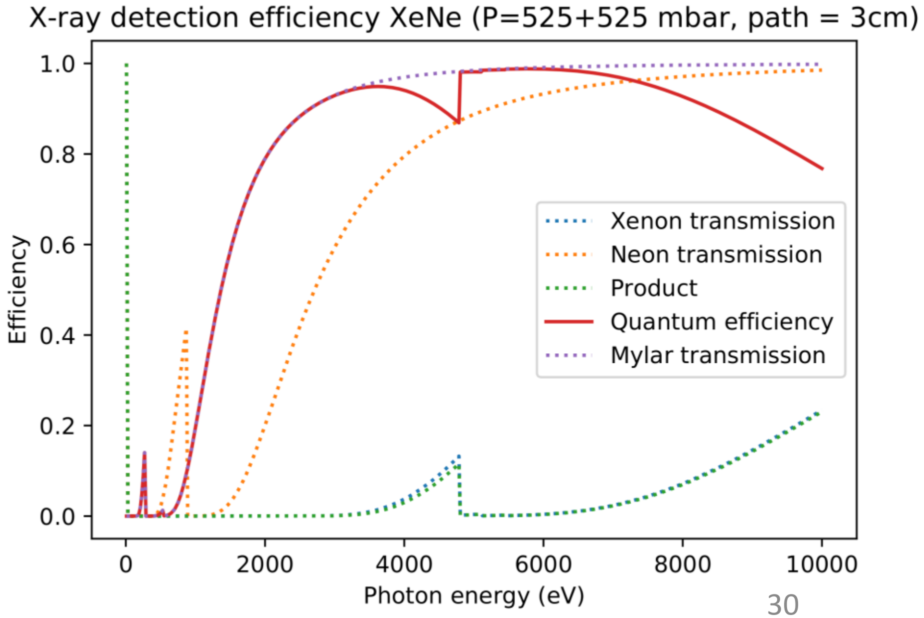
Output

Expected limit $g_{a\gamma}$









Conclusions and outlook

- New data taking campaign with the IAXO-pathfinder system at CAST.
- Statistics has been doubled with respect to former data.
- Technology and know how for the use of new gas mixtures has been developed.
- Xe-based gas mixtures have succesfully removed the ~3 keV contamination in the background spectrum.
- Possible improvements have been identified and are being tested in our other prototypes.
- Good experience towards BabyIAXO and IAXO.
- Background level compatible with former results.
- New axion-photon coupling limit will be computed soon.

The iaxo collaboration

Petersburg Nuclear Physics Institute

INR RAS

DESY

Columbia U.

IRFU CEA Saclay

Lawrence Livermore National Laboratory

Universidad de Zaragoza

Johannes Gutenberg University, Mainz

Barry University

Centro de Estudios de Física del Cosmos de Aragón

Heidelberg University

Universitat de Barcelona

Siegen University

Universität Bonn

CSIC Barcelona

MPP Munich

Ruđer Bošković Institute, Zagreb

CERN

INAF Milano

University of Cape Town