Search for solar axions with helioscopes: towards the IAXO project

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19th MultiDark Consolider Workshop

Direct Detection

Centro de Astropartículas y Física de Altas Energías
Universidad Zaragoza

Why axions?

Elegant solution to the strong CP problem of the SM.

Relevant parameter space at reach of current and near-future experiments

Very weakly interacting,
very light,
very long lived.

Experimental efforts growing fast but still small

Dark matter candidate, not *ad hoc* solution.

Astrophysical hints:

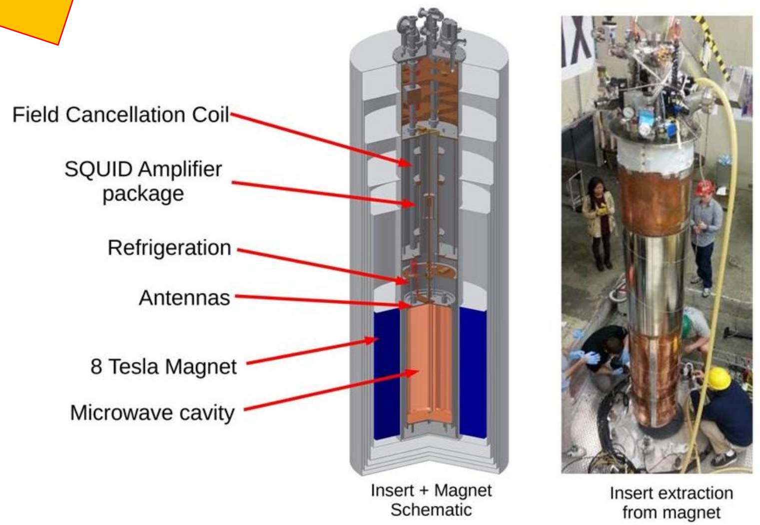
- Universe too transparent for HE gamma-rays
- Anomalous stellar cooling
- …

More generic axion-like particles (ALPs) predicted by many theories

Experimental axion searches

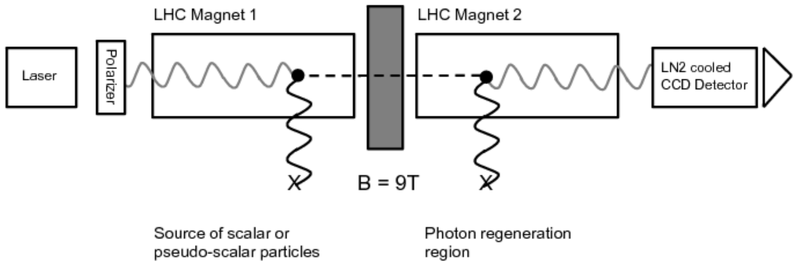
Large complementarity among categories

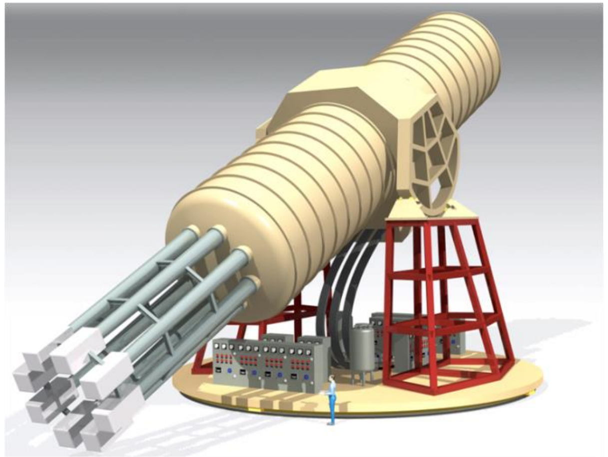
Source	Experiments	Model & Cosmology dependency	Technology
Relic axions	ADMX, HAYSTAC, CASPEr, CULTASK, CAST-CAPP, MADMAX, ORGAN, RADES, QUAX, …	High	New ideas emerging, Active R&D going on,…
Axions created in the lab	ALPS, OSQAR, CROWS, ARIADNE,…	Very low	
Solar axions	SUMICO, CAST, **(Baby)IAXO**	Low	Ready for large scale experiment



ADMX - serch for dark matter axions from the Galactic halo (adjusting resonant cavities for different masses)

OSQAR – light shinning through walls



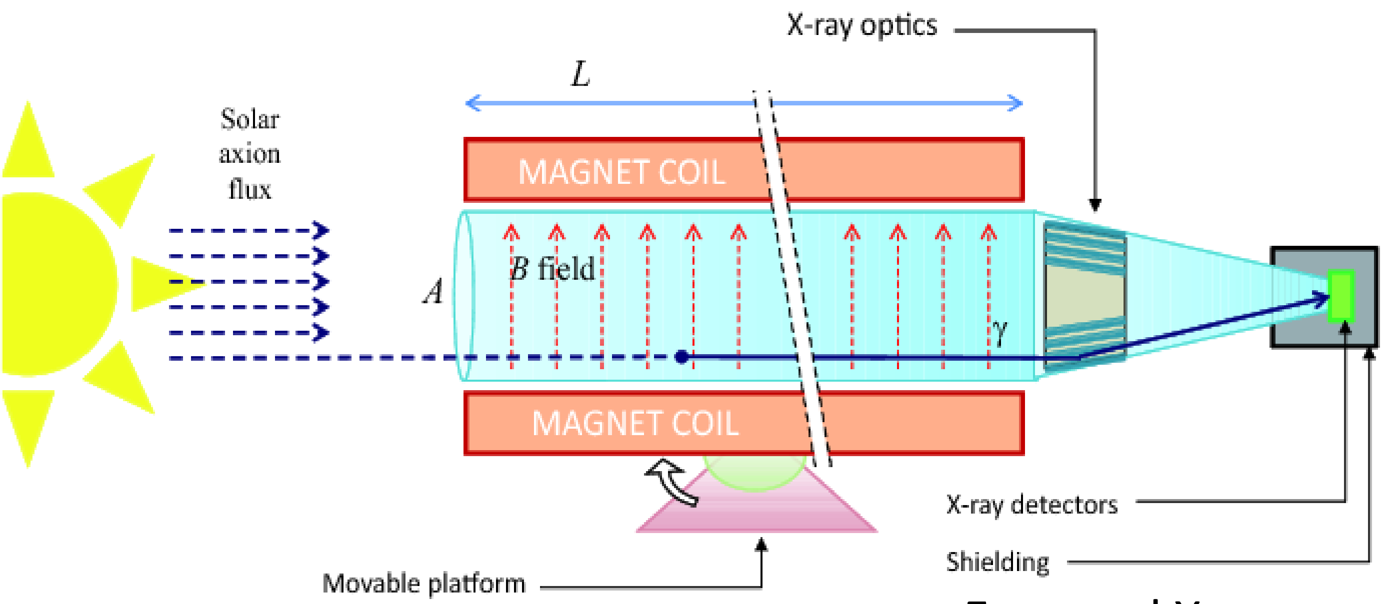


IAXO - search for solar axions

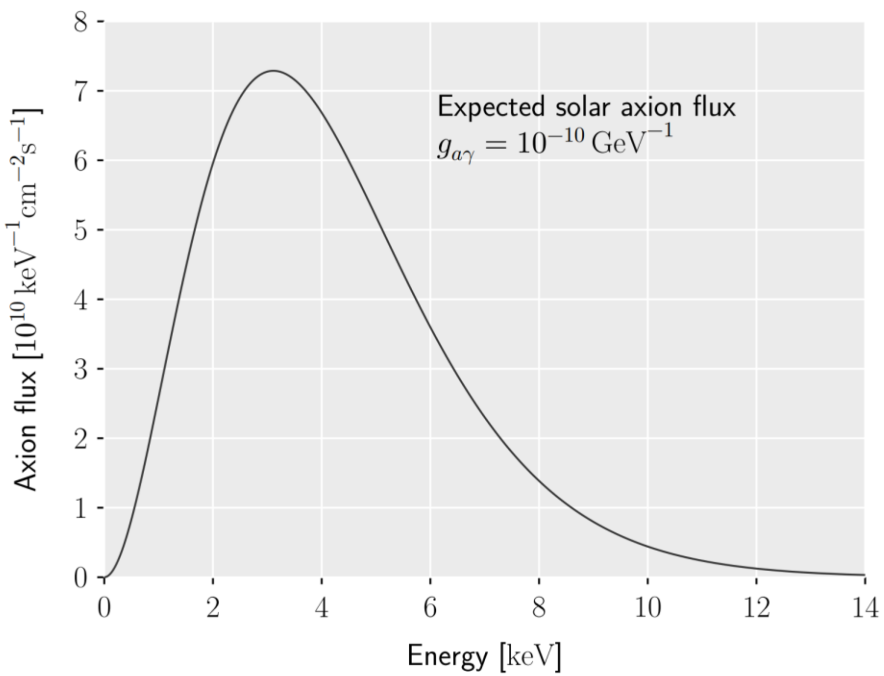
Solar axions and helioscopes

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.



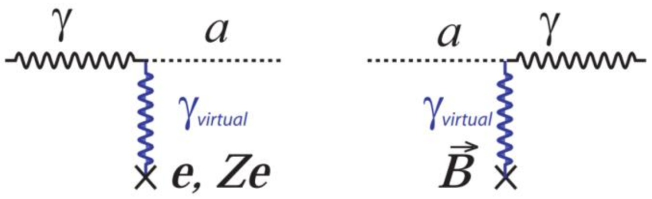


Diagram of the Primakoff effect

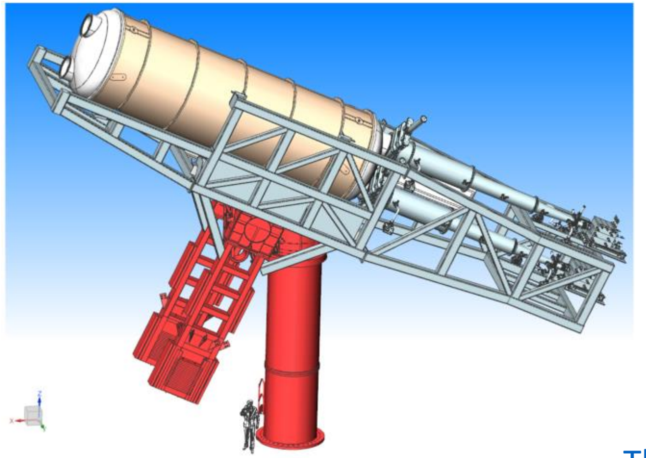
Very weak interaction ⇒ **ultra low background detectors** are required.

Solar axions and helioscopes

CAST (CERN Axion Solar Telescope)

- Most powerful axion helioscope to date.
- CAST sensitivity is the highest for a helioscope thanks to an unprecedented background level of ~ 10^{-6} counts/keV/cm^2/s achieved with the **microbulk technology**.

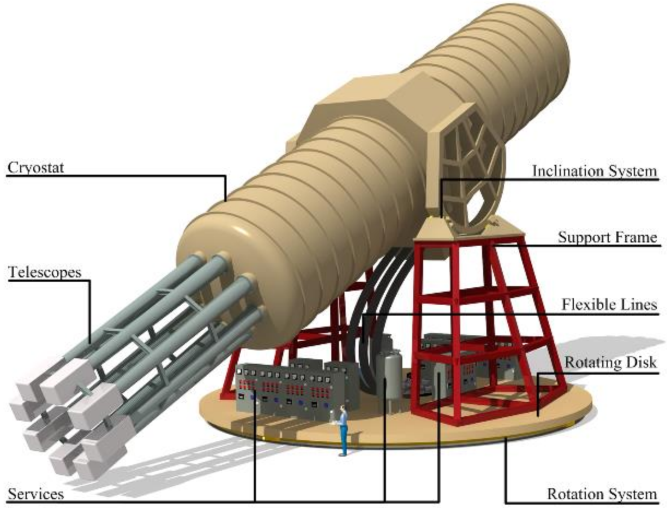
BabyIAXO



- Under construction.
- Technological prototype with only two magnet bores.
- Fully fledged helioscope that will deliver relevant physics results.

The IAXO collaboration, *JHEP.* **2021,** 137

IAXO (International Axion Observatory)



- 20-m long superconducting magnet, up to 5.4 T.
- 8 60-cm diameter magnet bores.
- X-ray optics with 0.2 cm² focal spot.
- 8 detectors.
- 12 h solar tracking per day.

E. Armengaud *et al* 2014 *JINST* **9** T05002

$$\underbrace{f_M = B^2\, L^2\, A}_{\text{Magnet}} \qquad \underbrace{f_{DO} = \frac{\epsilon_d\, \epsilon_o}{\sqrt{b\, a}}}_{\text{Detector \& optics}} \qquad \underbrace{f_T = \sqrt{\epsilon_t\, t}}_{\text{Exposure time}}$$

Solar axions and helioscopes

Parameter space:

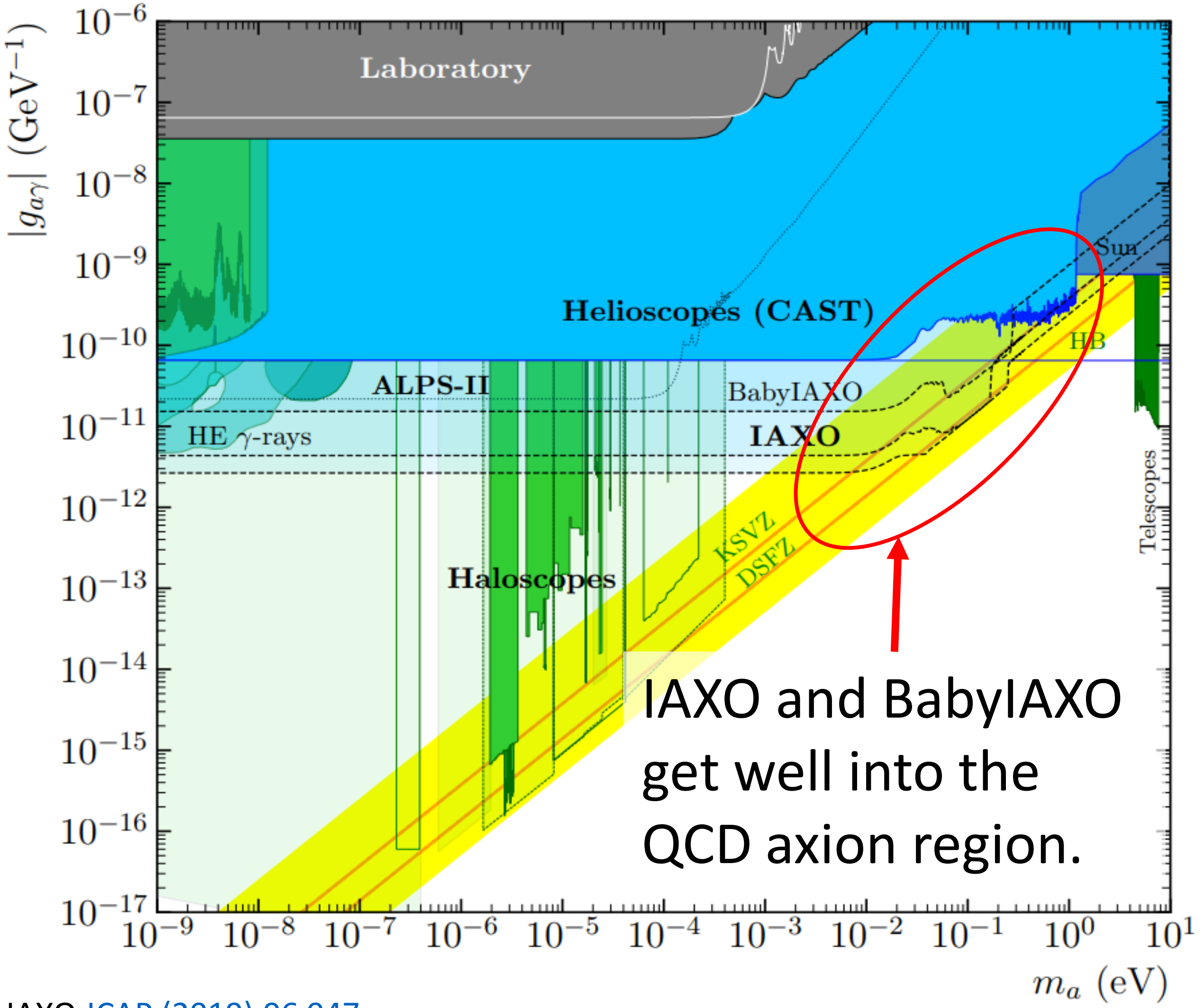
- Coupling constant to photons $g_{a\gamma}$
- Axion mass m_a

CAST has reached similar levels to the most restrictive astrophysical bounds.
Nature Physics 4109 (2017)

IAXO will probe:

- Large generic unexplored ALP space.
- QCD axion models in the meV to eV mass band.
- Astrophysically hinted regions.

All this, independent of the axion-as-DM hypothesis!

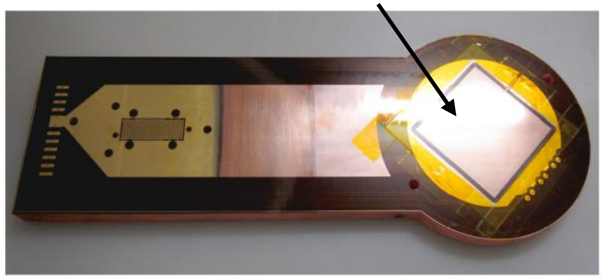


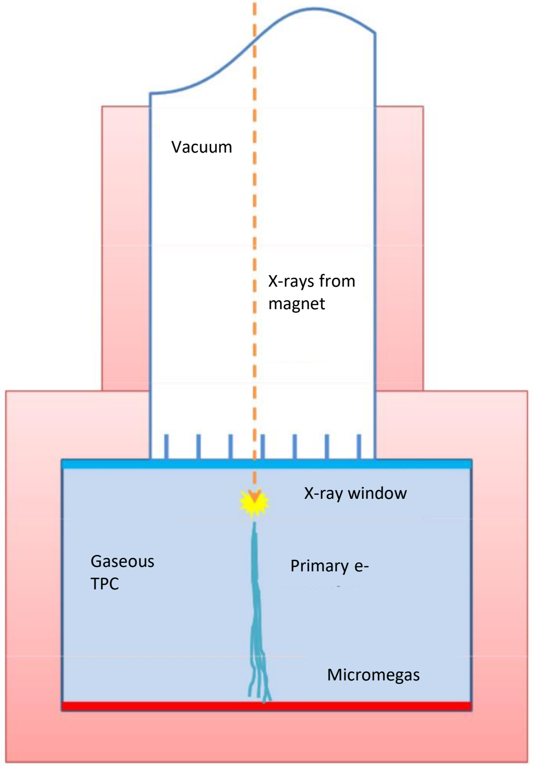
Review of Physics potential of IAXO JCAP (2019) 06 047

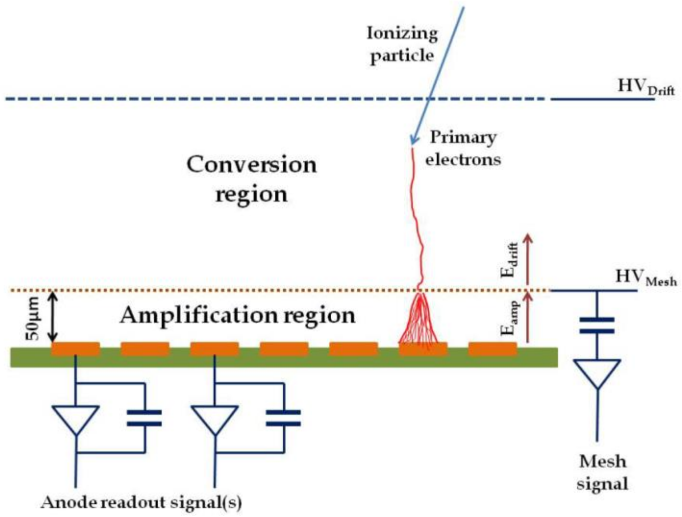
The IAXO pathfinder ultra-low background detector

Microbulk Micromegas detectors

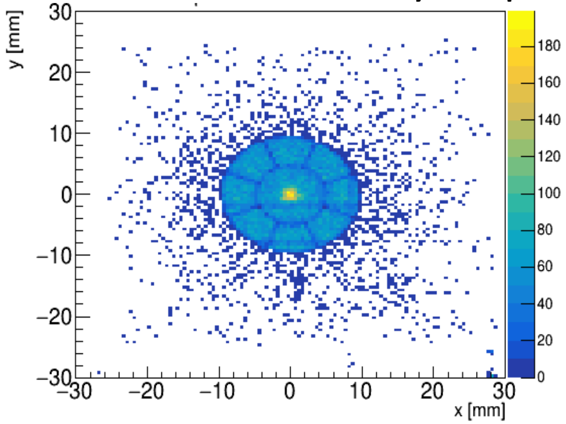
- Very homogeneous amplification gap, uniform gain.
- Intrinsically radiopure.
- Good energy and spatial resolution.
- Pixelized readout gives topological information.







Calibration intensity map

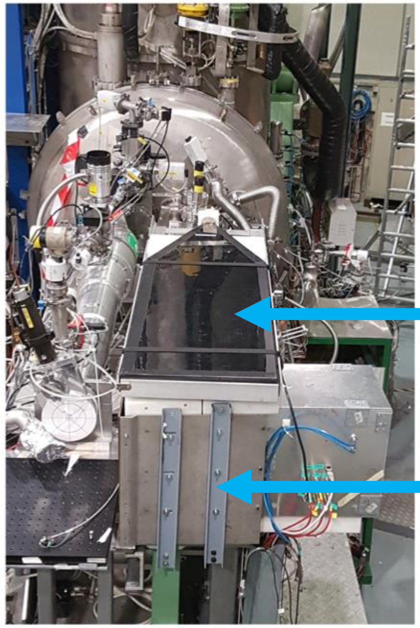


X-ray window

- Rare event searches require ultra-low background detectors.

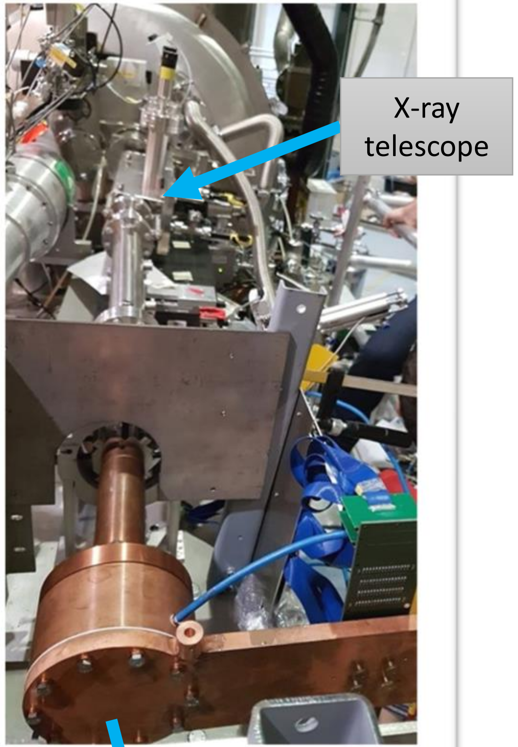
- Signal reaches the active volume through a mylar window.
- X-rays ionize the gas in the conversion region and the produced signal is read by the Micromegas.
- Data is analyzed with the REST-for-Physics framework (github.com/rest-for-physics).

The IAXO pathfinder system at CAST

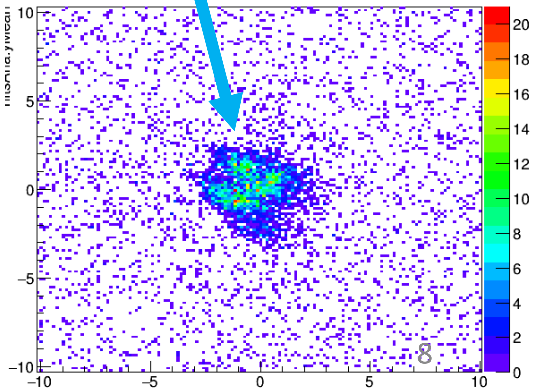


Active shielding:
plastic scintillator as a
cosmic muon veto.

Passive shielding:
10 cm of lead around the
detector.



X-ray optics focus the signal

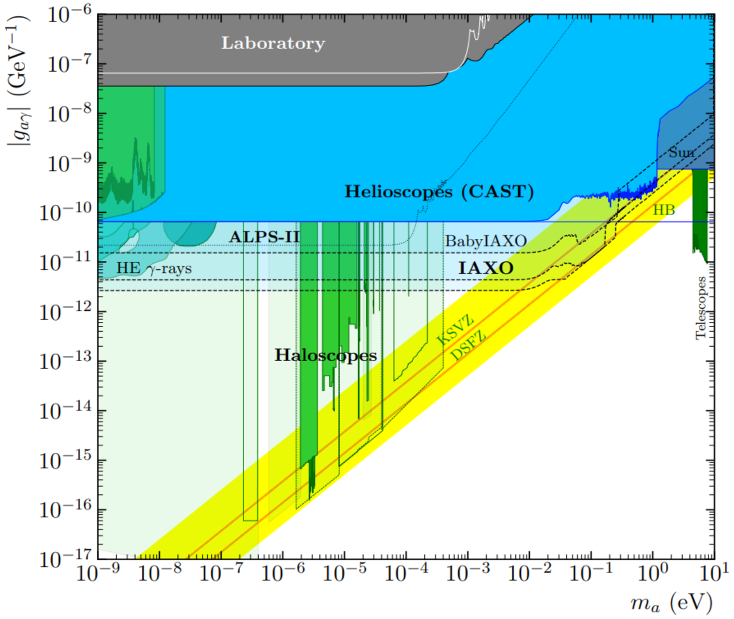


The IAXO pathfinder system at CAST

Scientific goals

- **Physics**
  - Improve sensitivity in $g_{a\gamma}$.
  - Clarify origin of 2σ-excess in the 2013-2015 results.

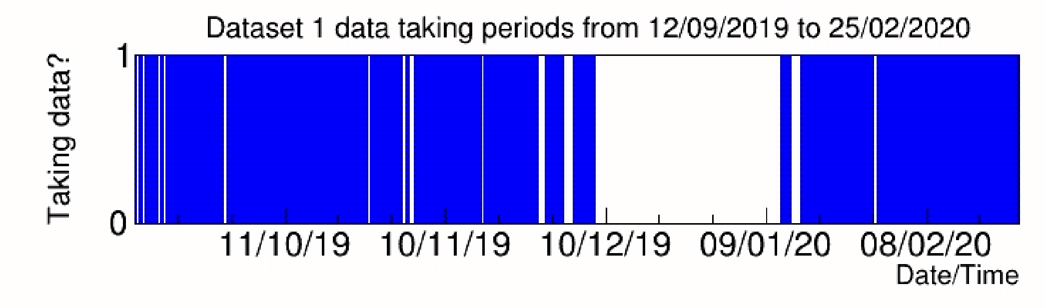
    [Nature Physics 4109 (2017)]



- **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.

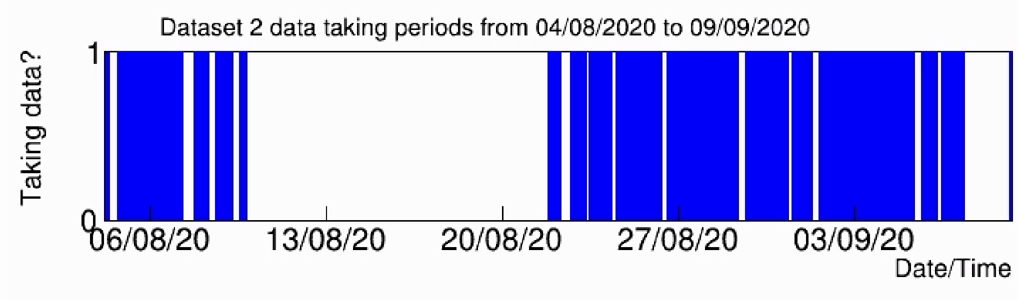
CAST data taking in a nutshell

- The 2019-2021 data taking campaign consists of **3 different datasets** and **2 calibration campaigns** in the X-ray lab at CERN with the IAXO-Pathfinder detector.
- Tracking time ~ 300 hours

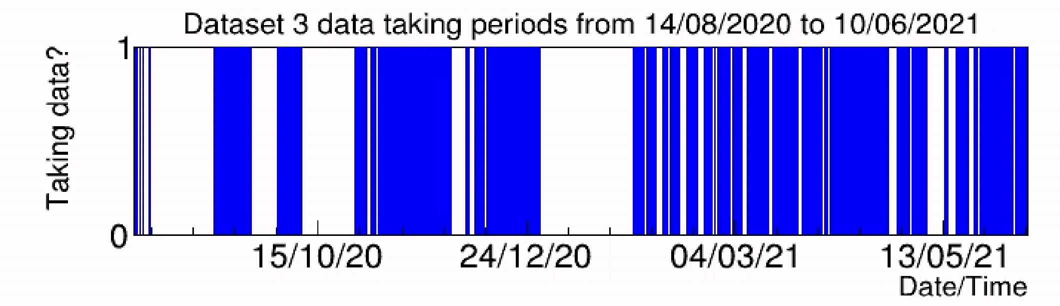


Gas mixture: Ar+2.3% isobutane.
12th September 2019 to 25th February 2020.
~2650 hours of background.

Total tracking time ~300 hours



Gas mixture: Ar+2.3% isobutane.
4th August 2020 to 9th September 2020.
~400 hours of background.

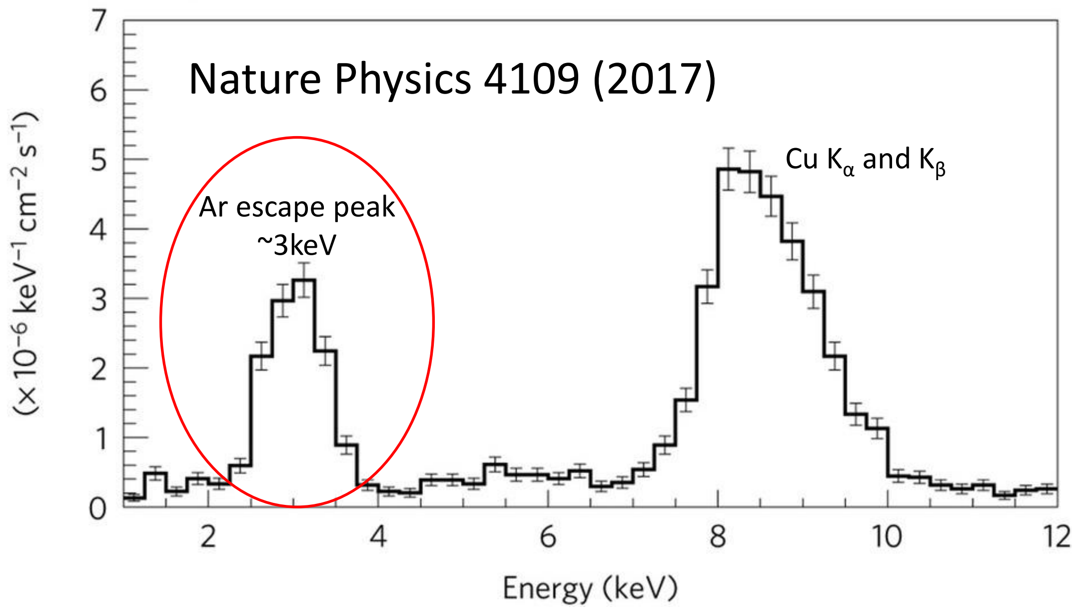


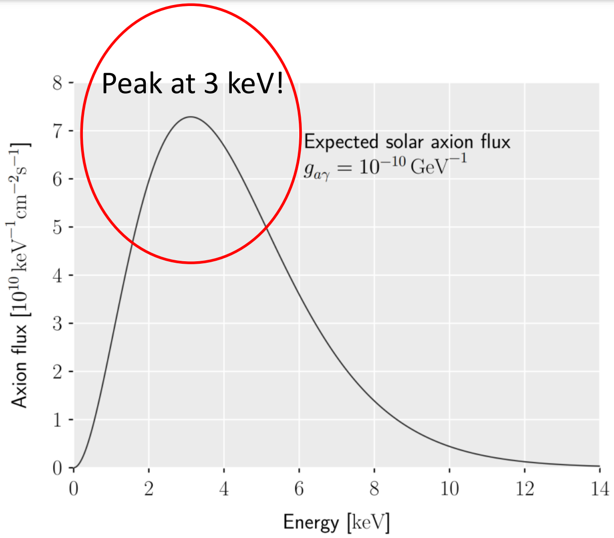
Gas mixture: 48.85% Xe + 48.85% Ne + 2.3% isobutane.
14th August 2020 to 10th June 2021
~3540 hours of background.

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.

Background ~1 count per day in the energy region of interest.





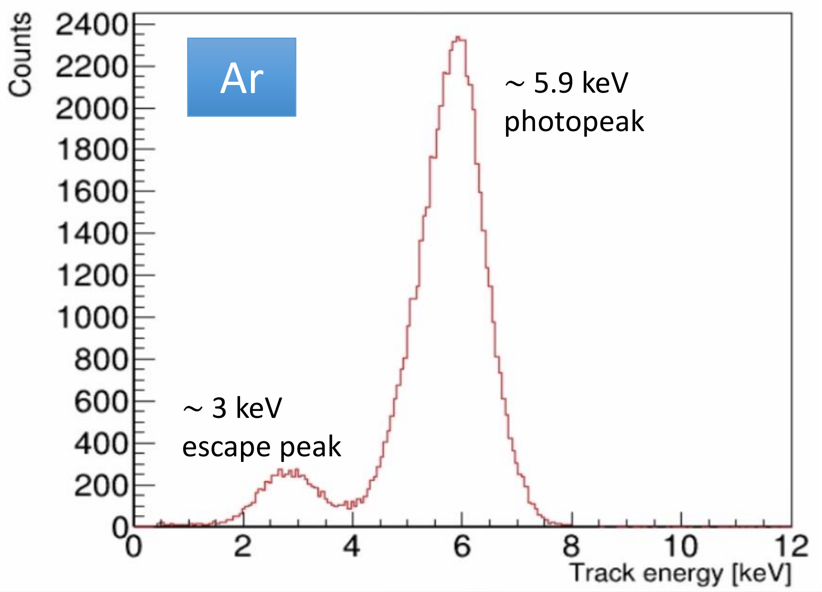
Solar axion peak expected at ~3 keV.

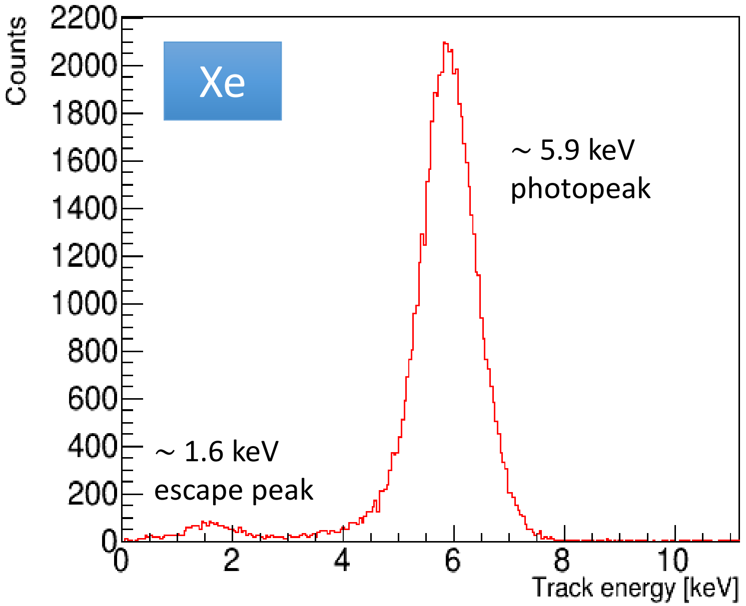
For better results we need to reduce the background in this energy range.

Towards 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.
- Challenges
  - Finding the appropriate gas mixture.
  - Building a new gas system.
  - Getting high enough gain and low energy threshold.
  - Dealing with possible gas different diffusion through the mylar window.

Sample calibrations with a ^{55}Fe source for the two gas mixtures.

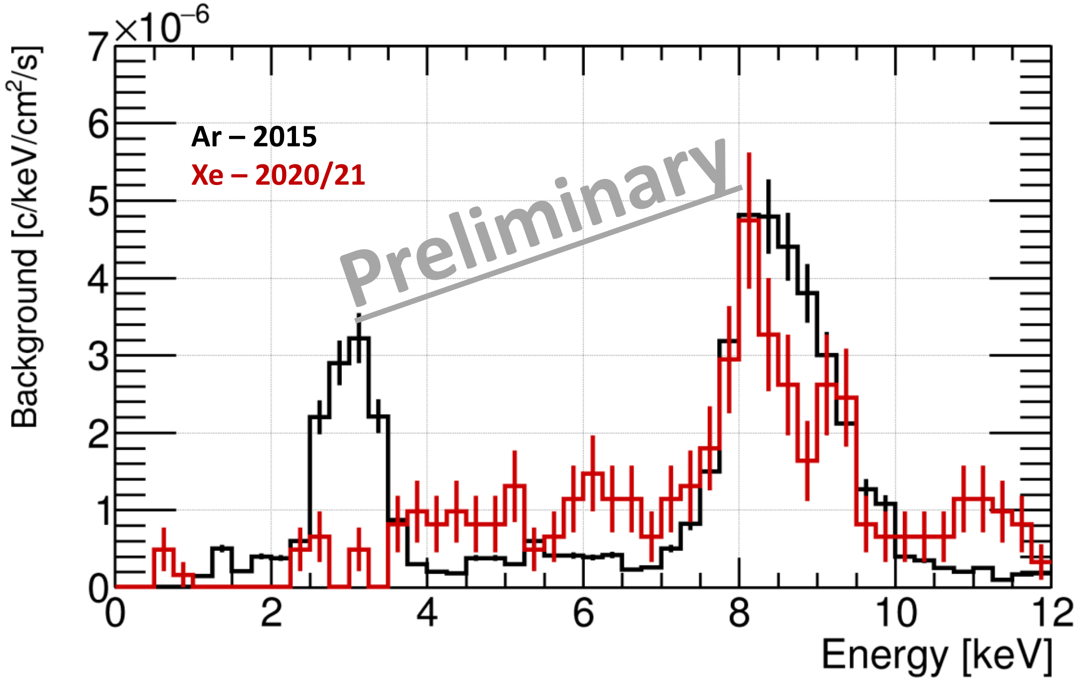




Preliminary results with Xe-based gas mixtures

Data taking campaign 2020-2022:
154 hours of solar tracking time + ~3500 h of background

Background spectrum of the Micromegas detector during 2015 (**black**) and 2020/2021 (**red**)



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

Summary

- **Helioscopes** can search for axions and ALPs from the sun in a wide mass range
- **BabyIAXO** is under construction as a prototype of the IAXO helioscope and will explore relevant parameter space down to $g_{a\gamma}$= 10-11 GeV^{-1}. Itis expected to see first light in 2024.
- Key technologies under development: magnet, X-ray optics. Low background detectors, Sun tracking system.
- Axion searches with helioscopes requires **ultra-low background detectors**
- **Microbulk Micromegas** detectors have been long used by our group for this purpose
- Chamber **typically filled with Ar**, which has an **escape peak at ~3 keV**, precisely where the peak of Primakoff produced axions is expected. A **new Xe-based gas mixture** has been implemented and tested.
- Data using Xe have been taken with the IAXO pathfinder system at CAST, providing ~150 hours of axion sensitive conditions with Xe. The **background level has been successfully reduced**, but not free of challenges.

The IAXO collaboration

Petersburg Nuclear Physics Institute

DESY

INR RAS

MIT

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

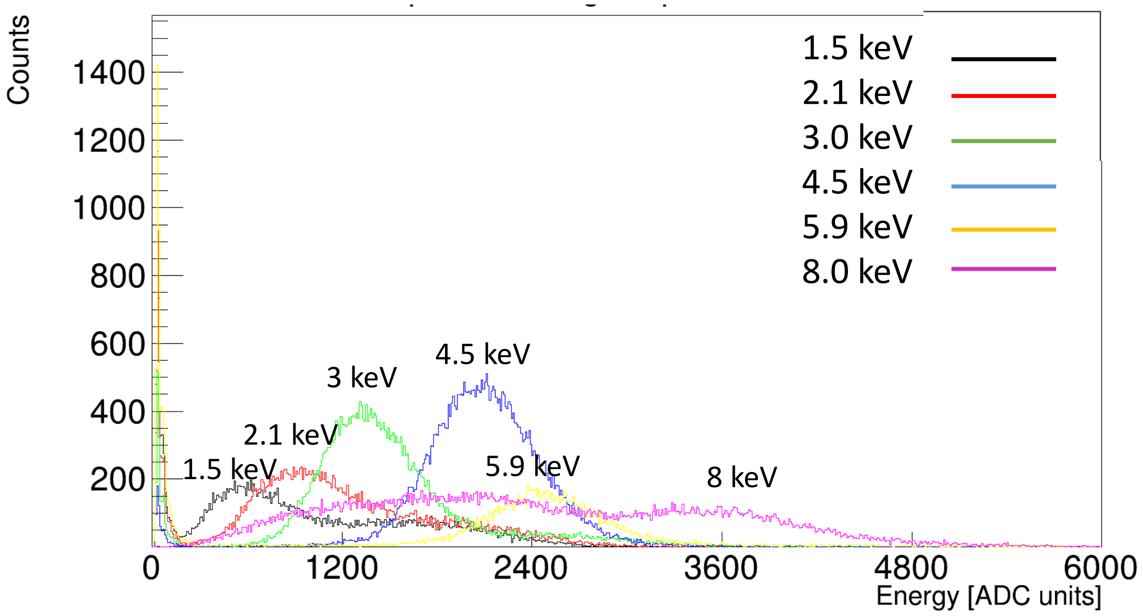
Backup slides

Saving information of all the channels

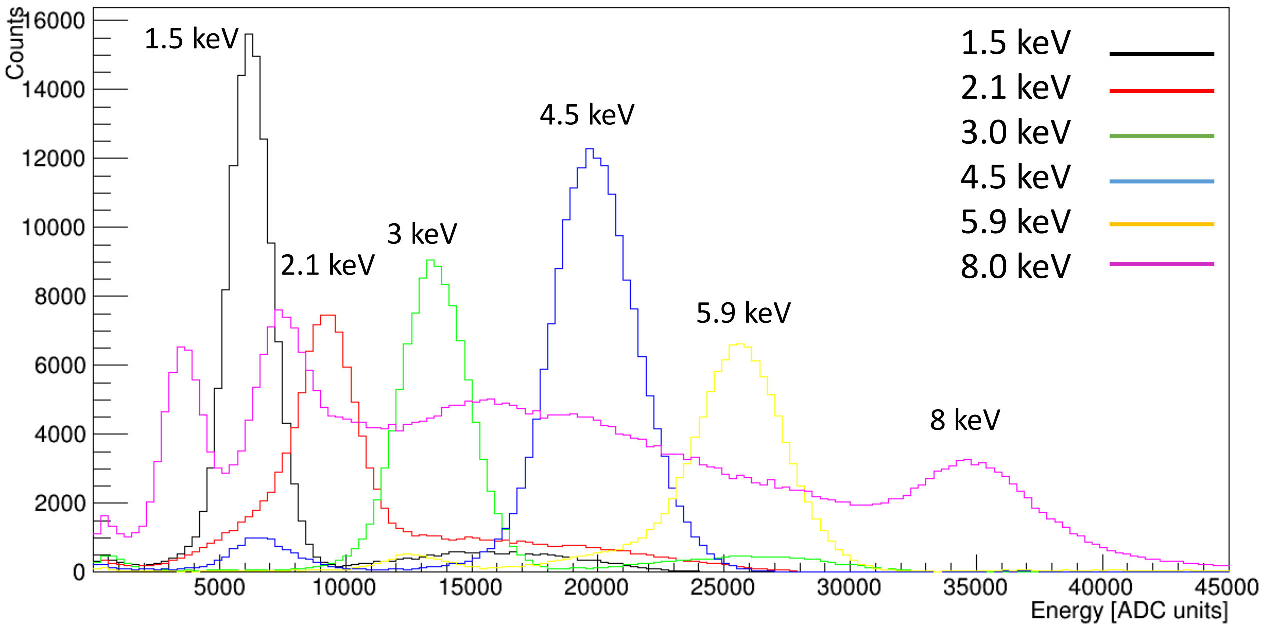
- New data taking strategy
- If there is a trigger, we save the signal of all the channels and not only those above the defined threshold
- Advantages
  - Increases the gain
  - Eliminates energy dependence of some observables
  - Improves event topological information and thus signal-like events are better identified.

IAXO-D0: calibrations with xenon

Energy spectrum in X-ray tube: **Xe+1.5%iso** at 0.5 bar



Energy spectrum in X-ray tube: **Ar+2.3%iso** at 1.4 bar



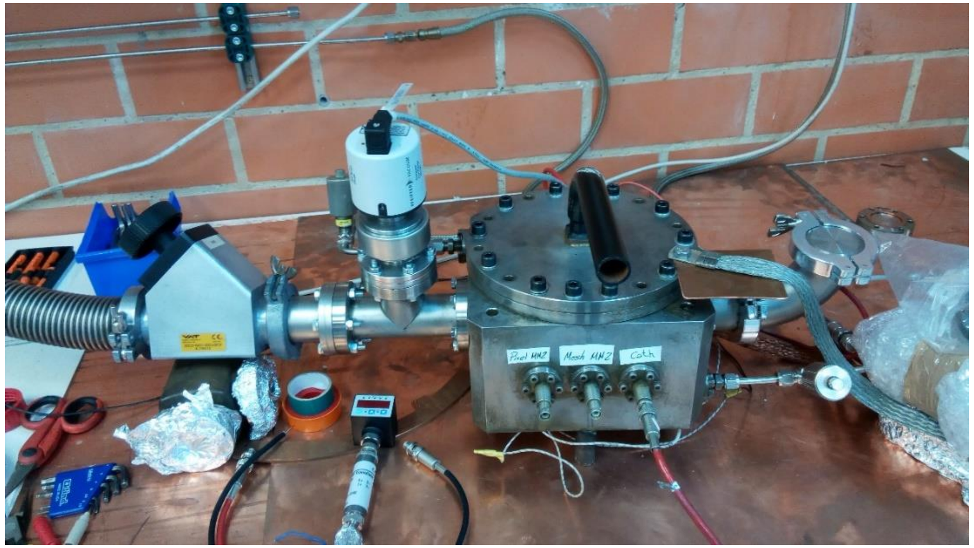
- Gain with Xe+1.5% isobutane is a **factor 10 lower** than with Ar+2.3% isobutane → need to test new mixtures
- Maximum isobutane to have a non-flammable mixture at CERN:

Xenon	Neon	Max. isobutane
100%	0%	2%
90%	10%	2.1%
67%	33%	2.3%
50%	50%	2.4%

IAXO-D0: tests with xenon-based gas mixtures

Aim: find the mixture that **maximizes the gain** and allows to rise the mesh voltage as much as posible.

- Tests performed at IAXO-lab in the University of Zaragoza with a small MM provided by Saclay
- Calibration source: ^{109}Cd
- Keep constant the amount of Xe in the chamber (500 mbar)

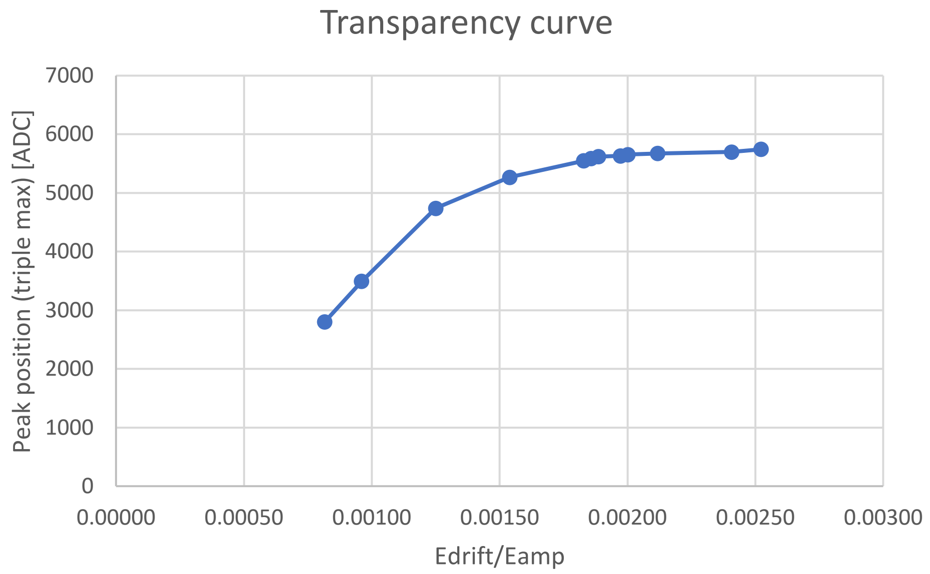


Setup for gas mixtures tests

Gas	V_{mesh}	22keV to ADC	Pressure
Xe + 1.5% iso	357 V	~320	507.6 mbar
67% Xe + 33% Ne + 2.3% iso	393 V	~ 560	763.4 mbar
50% Xe + 50% Ne + 2.4% iso	407 V	~ 550	1024 mbar

Gain is nearly doubled

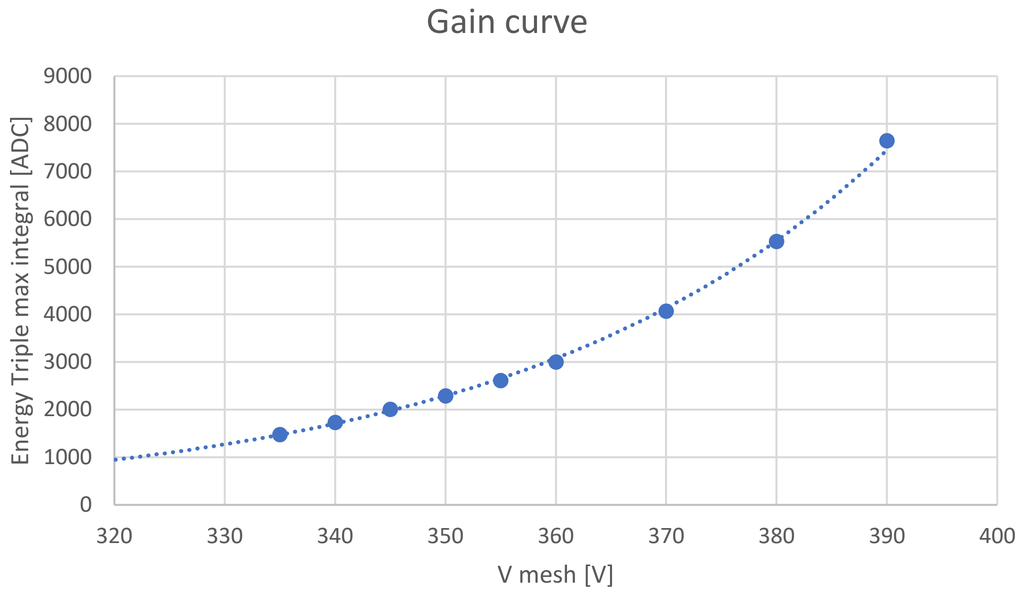
Gain and transparency curves



Transparency curve or electron transmission.
The selected operation point is $V_{cathode}$ = 710 V, as at higher voltages we have leak current.

Run number	Date	Vmesh (V)	Vrim (V)	Vring (V)	Vcath (V)	Edrift (V/cm/bar)	Edrif/Eamp	Peak (Triple Max)
R11197	21/02/21	384	384	400	450	21.0	0.00038	
R11196	21/02/21	384	384	450	500	36.8	0.00067	
R11198	21/02/21	384	384	480	525	44.8	0.00082	2800
R11186	21/02/21	384	384	500	550	52.7	0.00096	3494
R11194	21/02/21	384	384	500	600	68.6	0.00125	4737
R11187	21/02/21	384	384	500	650	84.4	0.00154	5267
R11188	21/02/21	384	384	500	700	100.3	0.00183	5547
R11202	21/02/21	384	384	500	705	101.9	0.00186	5586
R11203	21/02/21	384	384	500	710	103.5	0.00189	5619
R11199	21/02/21	384	384	500	725	108.3	0.00197	5630
R11201	21/02/21	384	384	500	730	109.8	0.00200	5652
R11189	21/02/21	384	384	500	750	116.2	0.00212	5671
R11191	21/02/21	384	384	700	800	132.1	0.00241	5698
R11200	21/02/21	384	384	500	820	138.4	0.00252	5744

Gain and transparency curves



Gain curve.
The selected operation point is V_{mesh} =(370, 390) V
The voltage we can use depends on the quality and conditions of the gas mixture

Run number	Date	Vmesh (V)	Vrim (V)	Vbottom (V)	Vtop (V)	Vcath (V)	Edrift (V/cm/bar)	Edrif/Eamp	Eamp (V/cm)	Peak
R11504	11/05/21	330	330	550	550	710	120.6	0.00256	66.0	
R11502	11/05/21	335	335	550	550	710	119.0	0.00249	67.0	1476
R11501	11/05/21	340	340	550	550	710	117.5	0.00242	68.0	1730
R11500	11/05/21	345	345	550	550	710	115.9	0.00235	69.0	2006
R11494	11/05/21	350	350	550	550	710	114.3	0.00229	70.0	2287
R11498	11/05/21	355	355	550	550	710	112.7	0.00222	71.0	2609
R11493	11/05/21	360	360	550	550	710	111.1	0.00216	72.0	2998
R11492	11/05/21	370	370	550	550	710	107.9	0.00204	74.0	4067
R11491	11/05/21	380	380	550	550	710	104.8	0.00193	76.0	5531
R11490	11/05/21	390	390	550	550	710	101.6	0.00182	78.0	7643

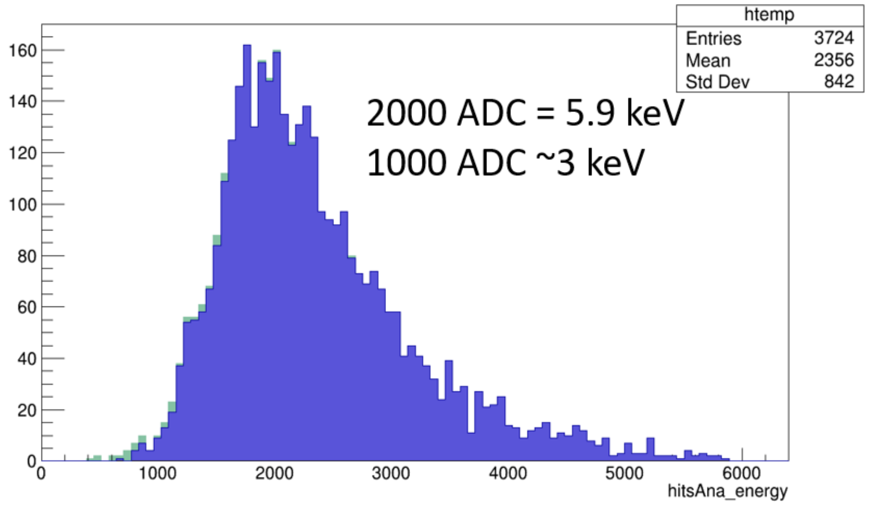
Detector performance: gain loss

- Energy resolution ~20% at 5.9 keV (slightly better than with Ar)
- Energy threshold affected by the quality of the gas. It will have to be defined using x-ray tube low energy calibrations (e.g. 1.5 keV peak).

Need to see the minimum threshold we accept → some data might have to be rejected

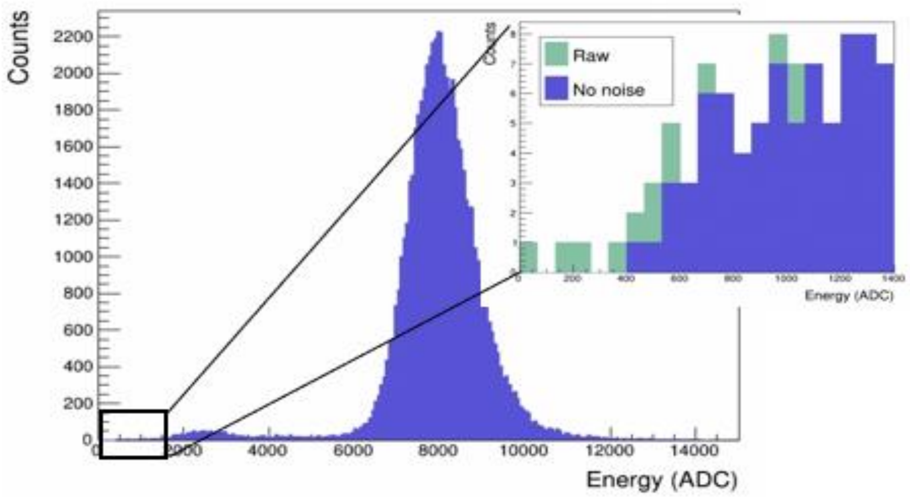
Lowest gain in the full dataset

R10989 1/12/2020



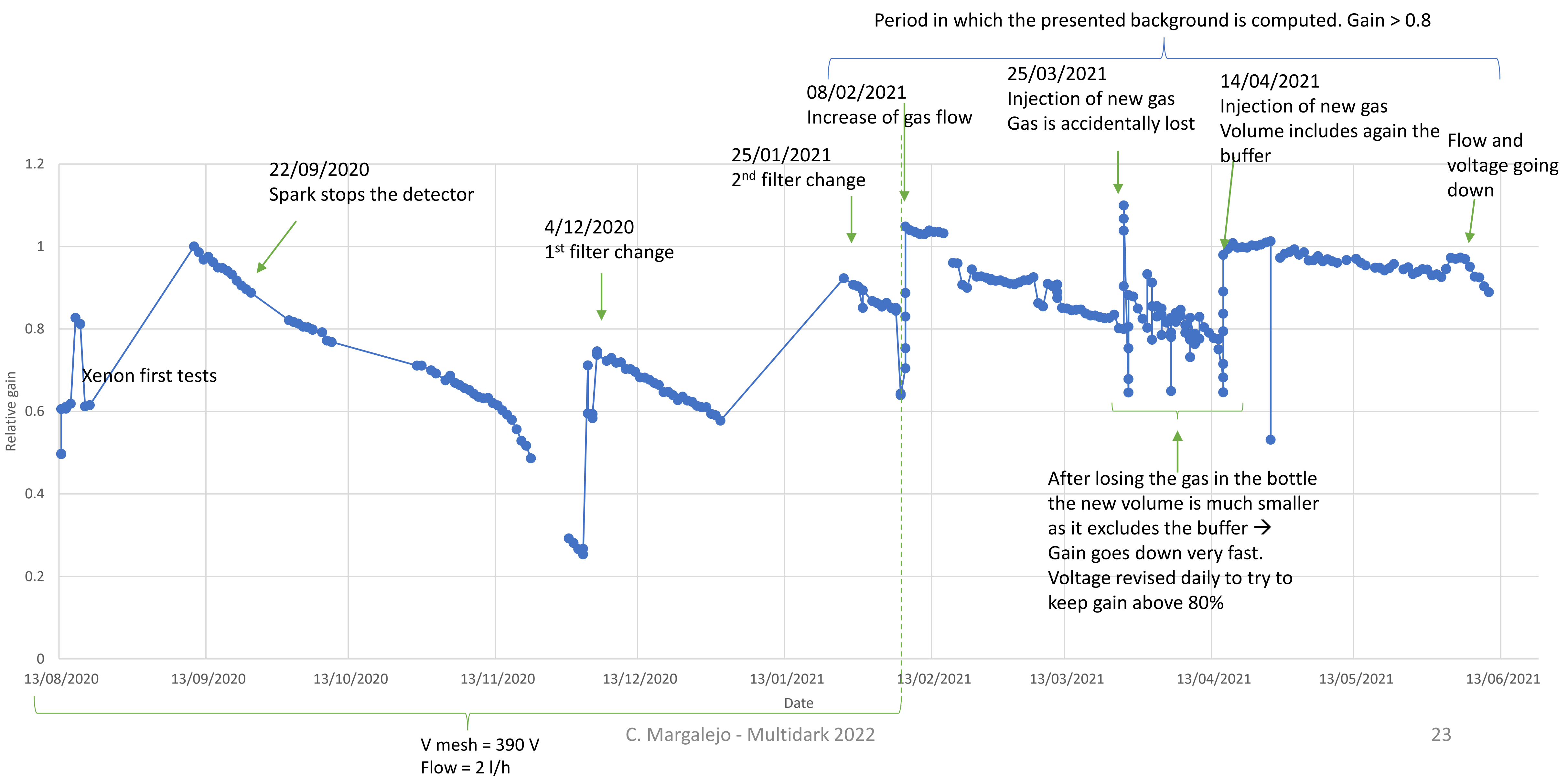
Reference run for gain, when the gas was totally new

R10852 10/09/2020

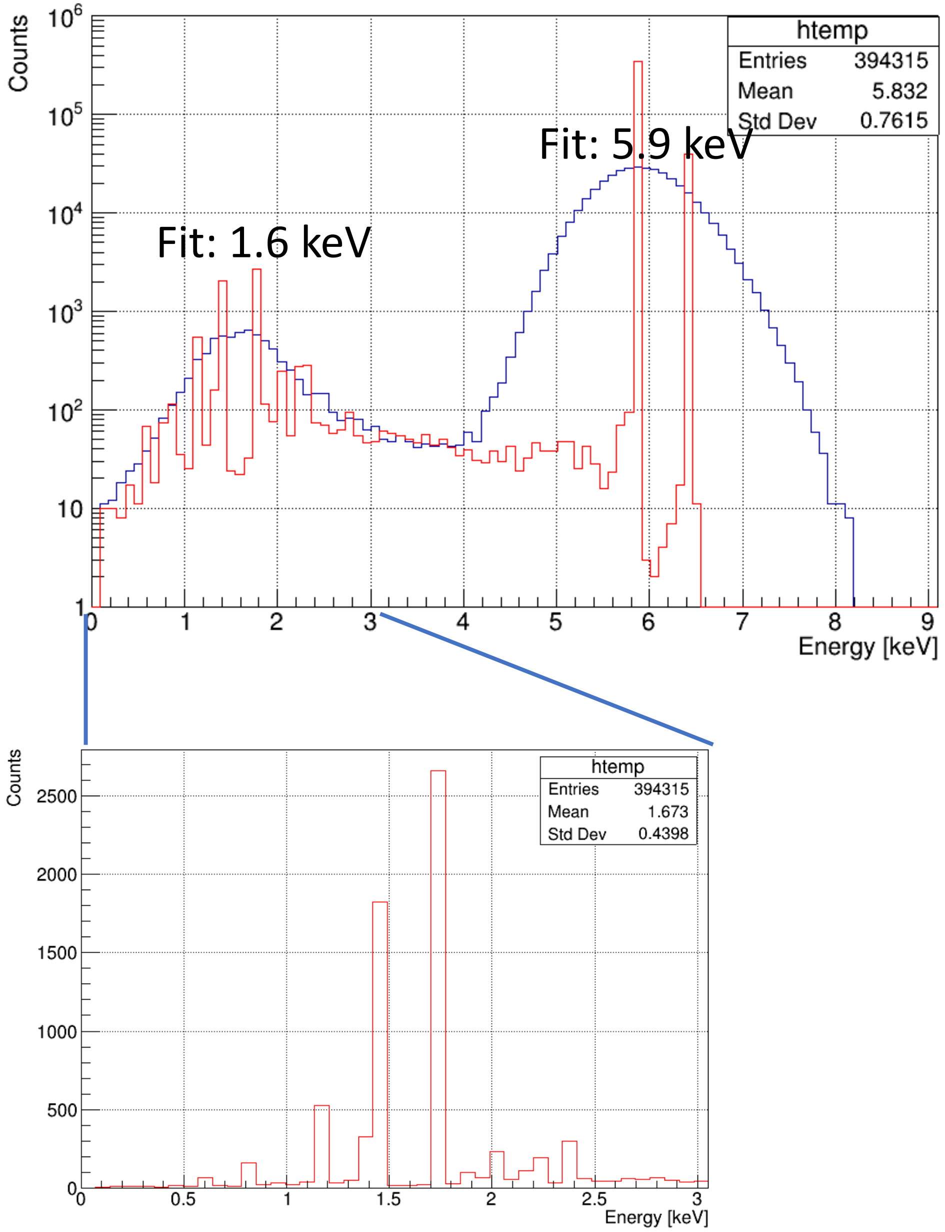


Towards Xe-based gas mixtures – detector performance

Gain evolution with time and possible differential permeation through the window



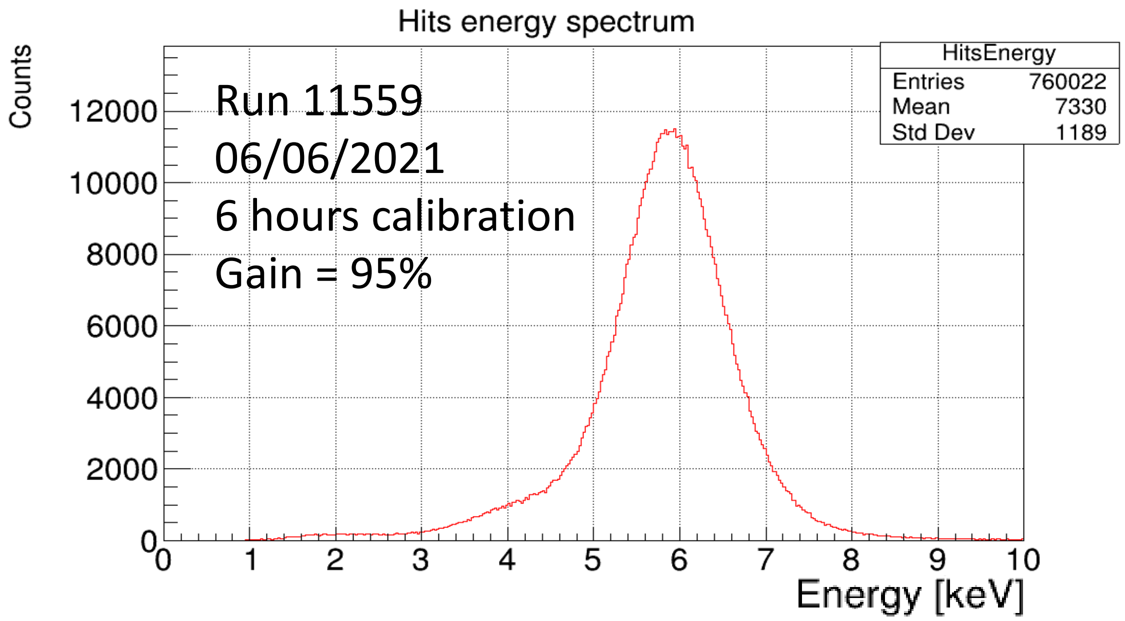
Understanding Xe calibrations: simulations

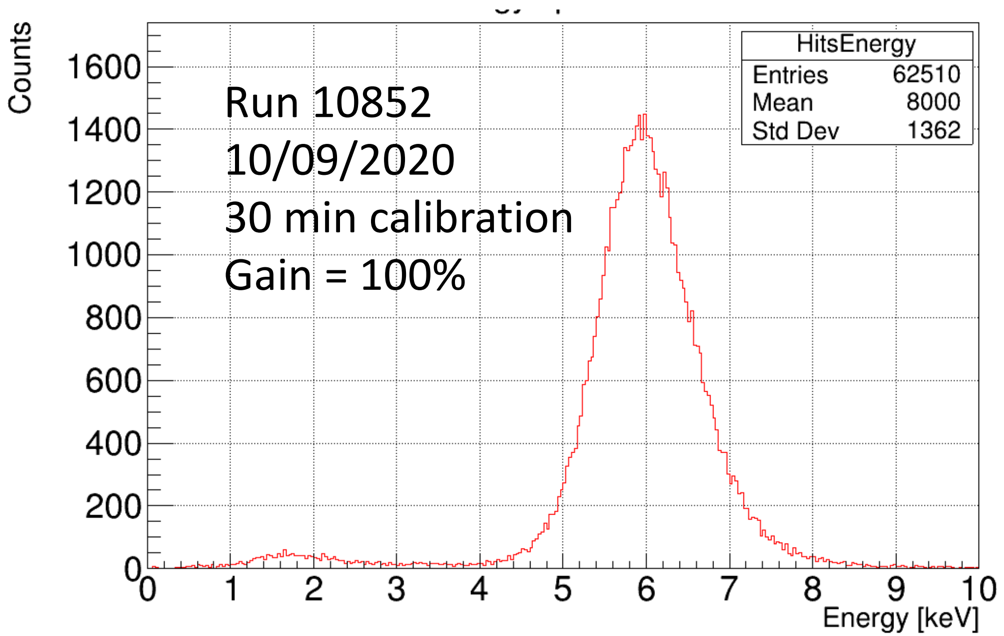


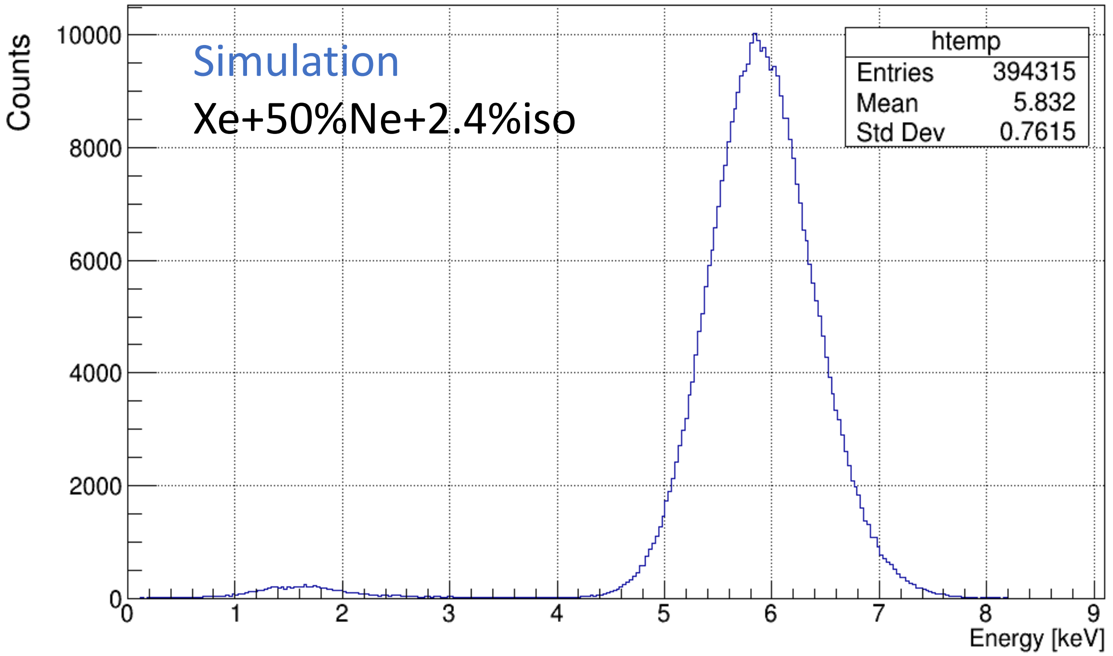
Xenon X-rays (link)		
Source keV	X-ray (keV)	Escape (keV)
5.9	3.633	2.267
	3.955	1.945
	4.093	1.807
	4.105	1.795
	4.414	1.486
	4.451	1.449
	4.512	1.388
	4.569	1.331
	4.714	1.186
	5.034	0.866
	5.307	0.593
	5.307	0.593

Neon X-rays (link)		
Source keV	X-ray (keV)	Escape (keV)
5.9	0.822	5.078
	1.848	4.052
	0.849	5.051

Understanding Xe calibrations: data vs simulations







Neon X-rays (link)		
Source keV	X-ray (keV)	Escape (keV)
5.9	0.822	5.078
	1.848	4.052
	0.849	5.051

Tables of isotopes

http://nucleardata.nuclear.lu.se/toi/

WWW Table of Radioactive Isotopes

X-rays and Auger electrons from Xe (Z=54)

Xe

20 X-rays found

Assignment	E (keV)	K-shell	L_1-shell	L_2-shell	L_3-shell
		Intensity per 100 vacancies in the			
Xe L_l	3,633	0.145 *19*	0.078 *14*	0.039 *9*	0.25 *3*
Xe L_η	3,955	0.065 *7*	0.040 *4*	0.213 *22*	
Xe $L_{\alpha2}$	4,093	0.40 *4*	0.22 *4*	0.107 *24*	0.70 *7*
Xe $L_{\alpha1}$	4,105	3.6 *4*	2.0 *3*	0.97 *22*	6.3 *6*
Xe $L_{\beta1}$	4,414	2.16 *22*	1.35 *14*	7.1 *7*	
Xe $L_{\beta4}$	4,451	0.069 *14*	1.4 *3*		
Xe $L_{\beta3}$	4,512	0.115 *23*	2.3 *5*		
Xe $L_{\beta6}$	4,569	0.029 *3*	0.015 *3*	0.0076 *17*	0.050 *5*
Xe $L_{\beta2}$	4,714	0.71 *7*	0.38 *7*	0.19 *4*	1.22 *13*
Xe $L_{\gamma1}$	5,034	0.30 *3*	0.189 *20*	0.99 *10*	
Xe $L_{\gamma3}$	5,307	0.027 *6*	0.54 *11*		
Xe $L_{\gamma2}$	5,307	0.018 *4*	0.37 *8*		
Xe $K_{\alpha3}$	29,112	0.00261 *8*			
Xe $K_{\alpha2}$	29,461	25.6 *6*			
Xe $K_{\alpha1}$	29,782	47.4 *11*			
Xe $K_{\beta3}$	33,562	4.35 *10*			
Xe $K_{\beta1}$	33,624	8.40 *19*			
Xe $K_{\beta5}$	33,881	0.085 *4*			
Xe $K_{\beta2}$	34,419	2.54 *6*			
Xe $K_{\beta4}$	34,496	0.492 *20*			

59 Auger electrons found

Assignment	E (keV)	K-shell	L_1-shell	L_2-shell	L_3-shell
		Intensity per 100 vacancies in the			
Xe L_3-X	4,491	47			92
Xe L_2-X	4,813	23		76	
Xe L_1-X	5,162	2.4	49		
Xe K-L_1L_1	23,659	0.86			

WWW Table of Radioactive Isotopes

X-rays and Auger electrons from Ne (Z=10)

Ne

3 X-rays found

Assignment	E (keV)	K-shell	L_1-shell	L_2-shell	L_3-shell
		Intensity per 100 vacancies in the			
Ne $K_{\alpha3}$	0,822	1.52E-09 *16*			
Ne $K_{\alpha2}$	0,848	0.50 *5*			
Ne $K_{\alpha1}$	0,849	1.01 *10*			

0 Auger electrons found

Assignment	E (keV)	K-shell	L_1-shell	L_2-shell	L_3-shell
		Intensity per 100 vacancies in the			

Main page | Radiation search | Nuclide search

^{55}Fe

3.1.1 X Radiations

		Energy keV	Relative probability
X_K			
	$K\alpha_2$	5,88765	51
	$K\alpha_1$	5,89875	100
	$K\beta_3$	6,49045	}
	$K\beta_5''$	6,5352	} 20,5
X_L			
	$L\ell$	0,556	
	$L\eta$	0,567	
	$L\beta$	0,649 – 0,721	

3.1.2 Auger Electrons

		Energy keV	Relative probability
Auger K			
	KLL	4,953 – 5,210	100
	KLX	5,671 – 5,895	27,2
	KXY	6,370 – 6,532	1,85
Auger L		0,47 – 0,67	

Ar

8 X-rays found

Assignment	E (keV)	K-shell	L_1-shell	L_2-shell	L_3-shell
		Intensity per 100 vacancies in the			
Ar $L_{\beta1}$	0,251	0.011 *3*	0.0068 *21*	0.022 *7*	
Ar $L_{\beta4}$	0,310	0.0024 *9*	0.0070 *24*		
Ar $L_{\beta3}$	0,310	0.0038 *14*	0.011 *4*		
Ar $K_{\alpha3}$	2,880	4.0E-07 *4*			
Ar $K_{\alpha2}$	2,955	3.7 *4*			
Ar $K_{\alpha1}$	2,957	7.4 *8*			
Ar $K_{\beta3}$	3,190	0.30 *3*			
Ar $K_{\beta1}$	3,190	0.59 *6*			

23 Auger electrons found

Assignment	E (keV)	K-shell	L_1-shell	L_2-shell	L_3-shell
		Intensity per 100 vacancies in the			
Ar L_3-X	0,249	48			100
Ar L_2-X	0,251	40		100	
Ar L_1-X	0,326	2.3	6.6		
Ar K-L_1L_1	2,553	6.1			
Ar K-L_1L_2	2,629	6.7			
Ar K-L_1L_3	2,631	13			
Ar K-L_2L_2	2,705	1.2			
Ar K-L_2L_3	2,707	30			
Ar K-L_3L_3	2,709	17			
Ar K-L_1M_1	2,851	1.4			
Ar K-L_1M_2	2,864	0.63			
Ar K-L_1M_3	2,864	1.2			
Ar K-L_2M_1	2,926	0.65			
Ar K-L_3M_1	2,928	1.3			
Ar K-L_2M_2	2,939	0.22			
Ar K-L_2M_3	2,940	2.5			
Ar K-L_3M_2	2,942	2.5			
Ar K-L_3M_3	2,942	2.9			
Ar K-M_1M_1	3,148	0.075			
Ar K-M_1M_2	3,161	0.063			
Ar K-M_1M_3	3,161	0.12			
Ar K-M_2M_3	3,174	0.22			
Ar K-M_3M_3	3,174	0.13			

Data taking at CAST

Dataset	Period	Gas	Quencher	Pressure [mbar]	Flow	Saved channels	Comments	Runs
1	2019-early 2020	Ar	2.3% isobutane	1400	Open loop	Hit	Found gain-cluster size relation	10155 to 10513
2	Jul-Aug 2020	Ar	2.3% isobutane	1400	Open loop	Hit /All	Problems with the electronics	10648 to 10694 10781 to 10844
3	Late 2020 - 2021	Xe+Ne	2.3% isobutane	1050	Recirculation	All	Gain loss with time. Many sparks	10710 to 10777 10850 to 11570

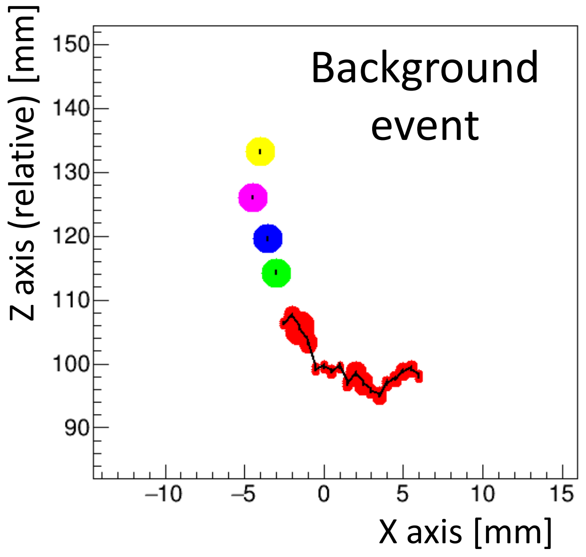
*Hit channels means channels above threshold

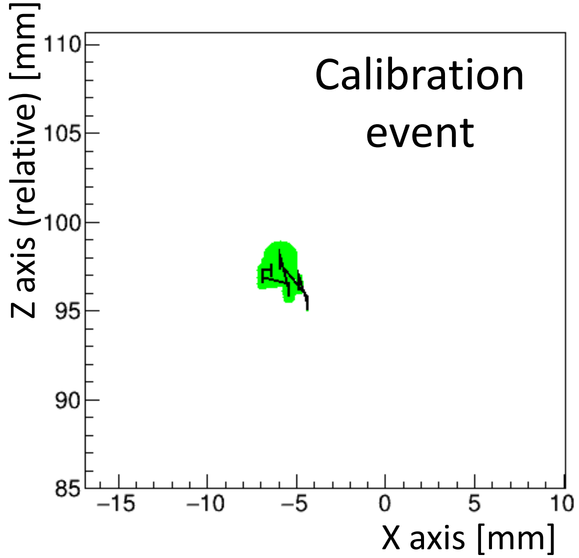
- Argon phase: 3030 hours of background, including 152 hours of tracking time
- Xenon phase: 3800 hours of background, including 154 hours of tracking time

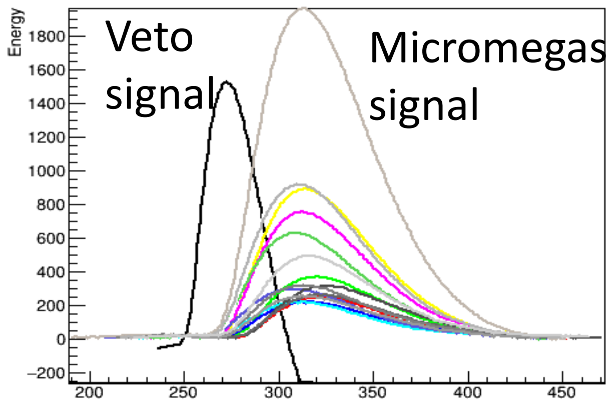
Datasets are not extremely different, but have to be analysed independently at the beginning, taking into account their own particularities.

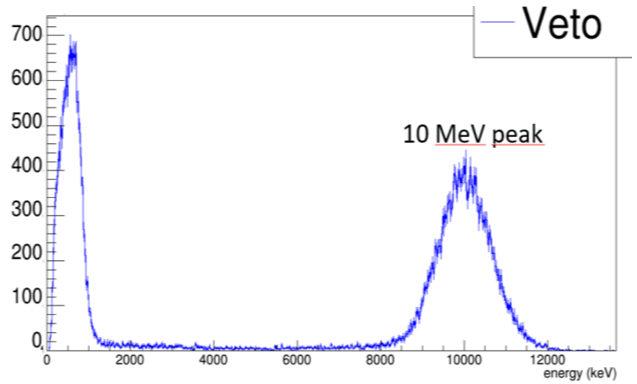
Event discrimination

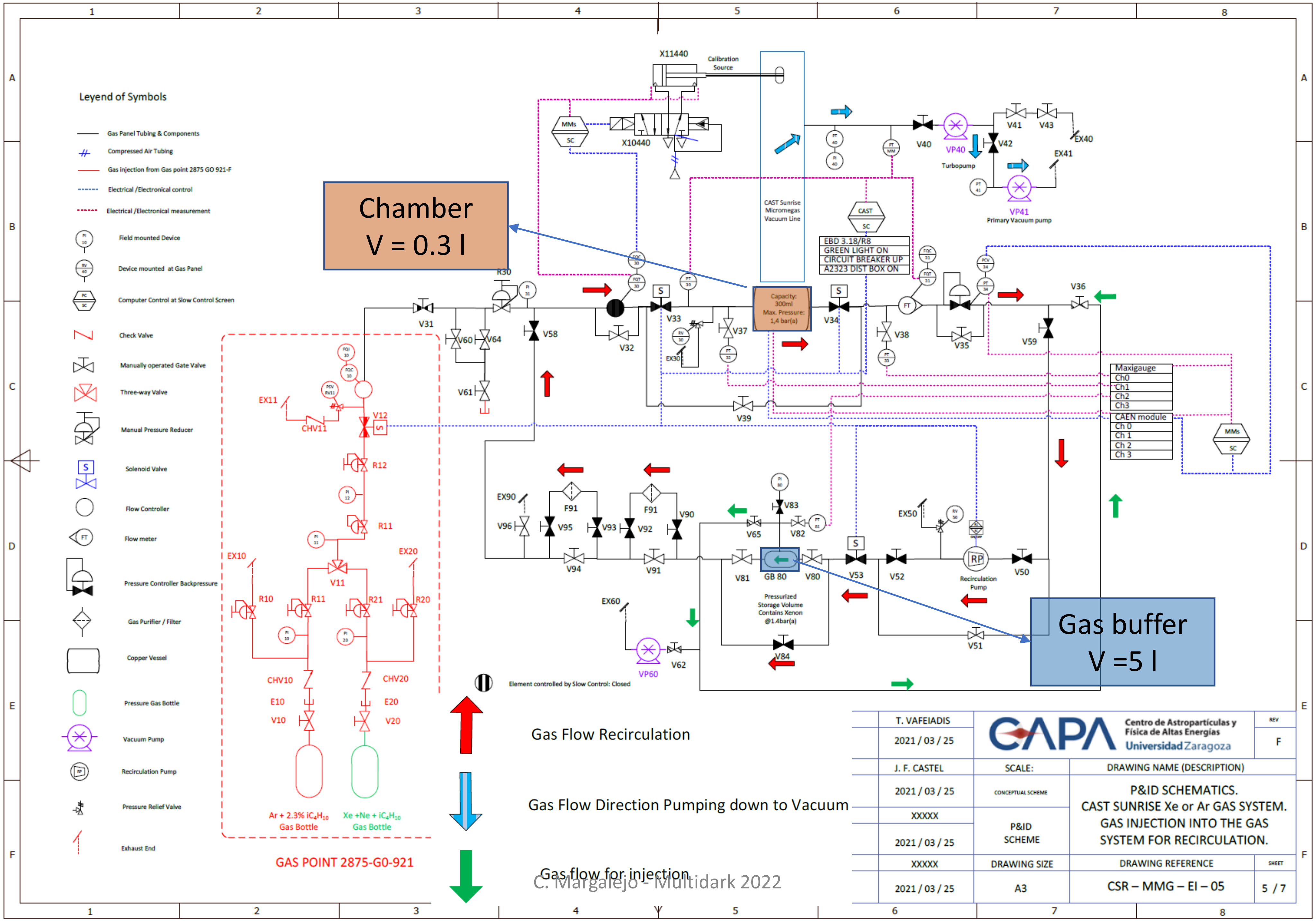
- X-rays are small, symmetric and point-like events.
- Observables are computed using the software REST-for-physics (github.com/rest-for-physics).
- Energy cuts: (1,10) keV.
- Fiducial cut: to select the size of the spot (~9 mm^2).
- Topological cuts: event size and shape in the XY plane and in the Z direction.







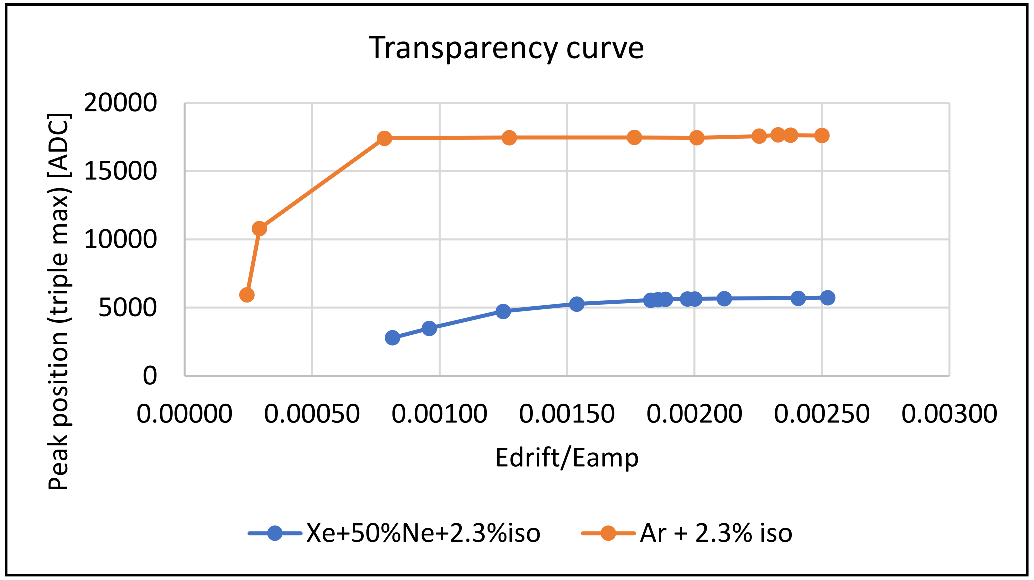


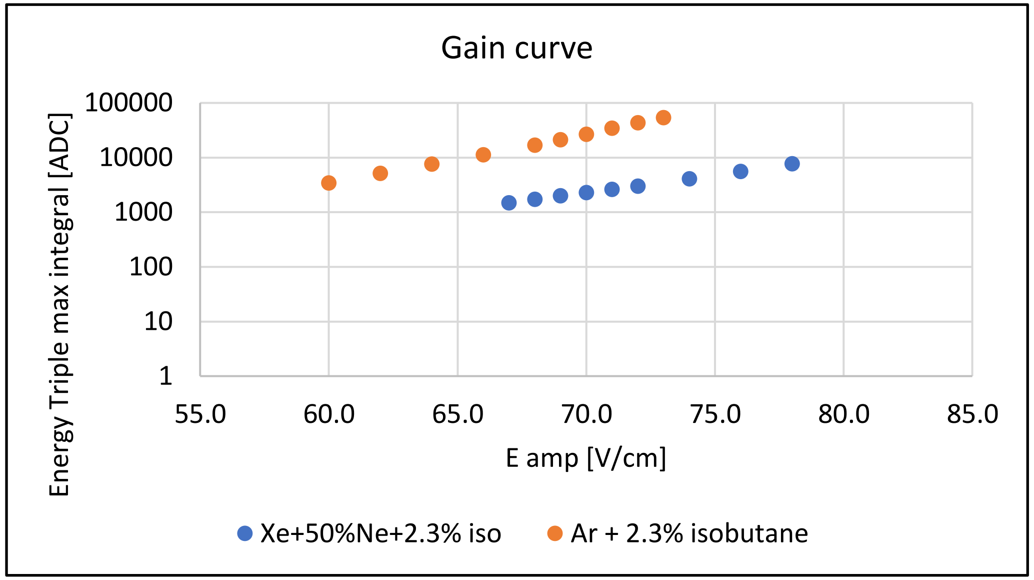


Chamber
V = 0.3 l
Gas buffer
V =5 l
Leyend of Symbols
Gas Panel Tubing & Components
Compressed Air Tubing
Gas injection from Gas point 2875 GO 921-F
Electrical /Electronical control
Electrical /Electronical measurement
Field mounted Device
Device mounted at Gas Panel
Computer Control at Slow Control Screen
Check Valve
Manually operated Gate Valve
Three-way Valve
Manual Pressure Reducer
Solenoid Valve
Flow Controller
Flow meter
Pressure Controller Backpressure
Gas Purifier / Filter
Copper Vessel
Pressure Gas Bottle
Vacuum Pump
Recirculation Pump
Pressure Relief Valve
Exhaust End
X11440
Calibration Source
X10440
CAST Sunrise Micromegas Vacuum Line
EBD 3.18/R8
GREEN LIGHT ON
CIRCUIT BREAKER UP
A2323 DIST BOX ON
Capacity: 300ml
Max. Pressure: 1,4 bar(a)
VP40
Turbopump
VP41
Primary Vacuum pump
Maxigauge
Ch0
Ch1
Ch2
Ch3
CAEN module
Ch 0
Ch 1
Ch 2
Ch 3
GB 80
Pressurized Storage Volume Contains Xenon @1.4bar(a)
Recirculation Pump
VP60
Element controlled by Slow Control: Closed
Ar + 2.3% iC4H10 Gas Bottle
Xe +Ne + iC4H10 Gas Bottle
GAS POINT 2875-G0-921
Gas Flow Recirculation
Gas Flow Direction Pumping down to Vacuum
Gas flow for injection
T. VAFEIADIS
2021 / 03 / 25
Centro de Astropartículas y Física de Altas Energías
Universidad Zaragoza
REV
F
J. F. CASTEL
2021 / 03 / 25
SCALE:
CONCEPTUAL SCHEME
DRAWING NAME (DESCRIPTION)
P&ID SCHEMATICS.
CAST SUNRISE Xe or Ar GAS SYSTEM.
GAS INJECTION INTO THE GAS SYSTEM FOR RECIRCULATION.
XXXXX
2021 / 03 / 25
P&ID SCHEME
XXXXX
2021 / 03 / 25
DRAWING SIZE
A3
DRAWING REFERENCE
CSR – MMG – EI – 05
SHEET
5 / 7

Towards Xe-based gas mixtures – detector performance

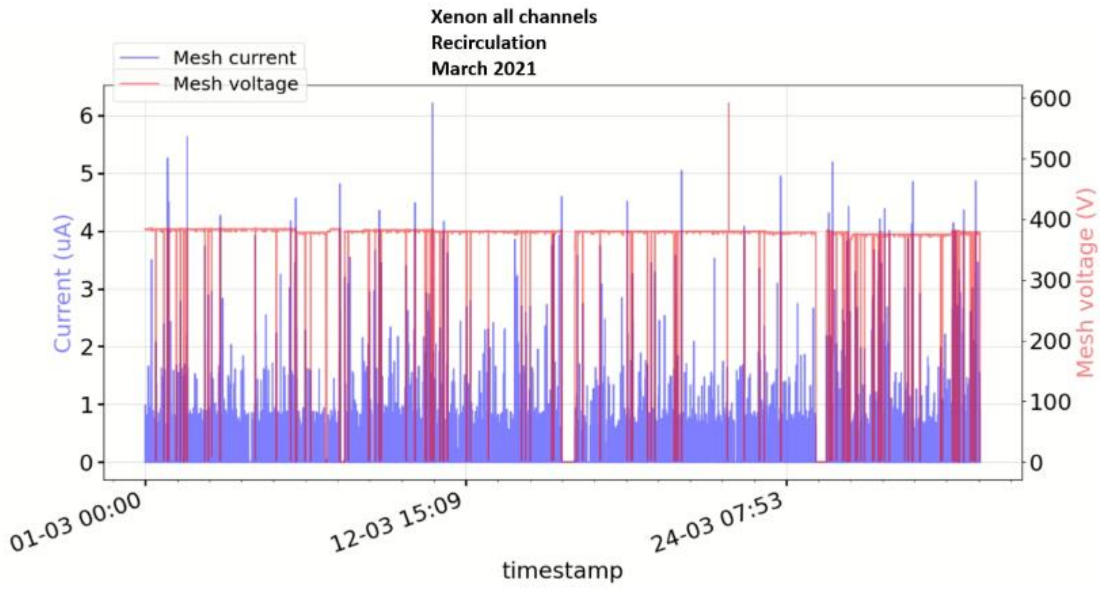
- Xe based gas mixtures have intrinsically lower gain.
  - Selected mixture is 48.85% Xe + 48.85% Ne + 2.3% isobutane.
- The energy threshold is higher than with Ar but still good.

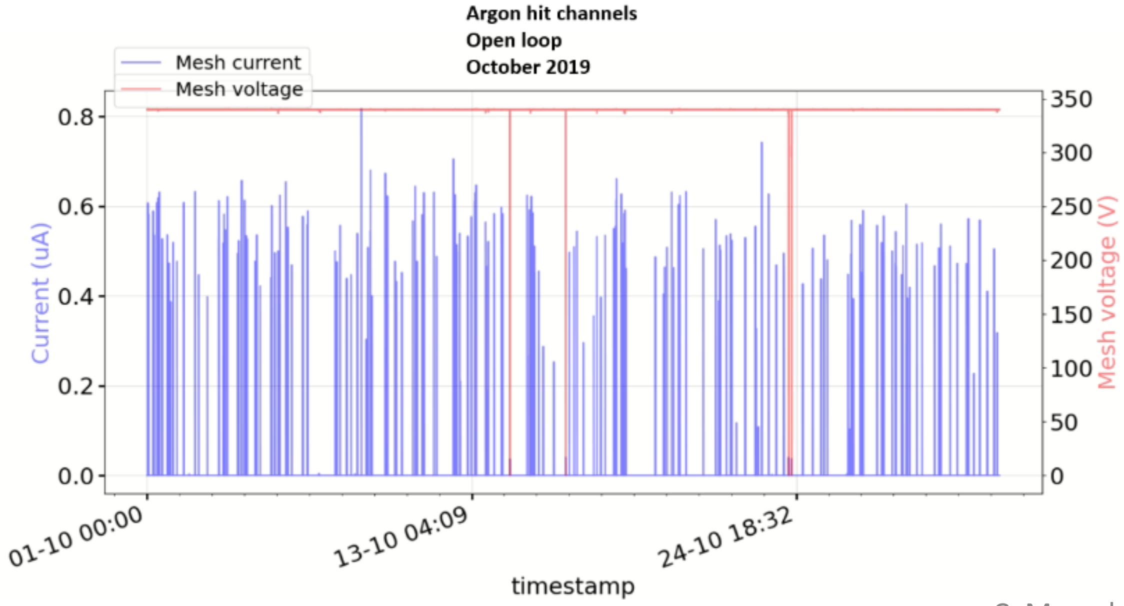


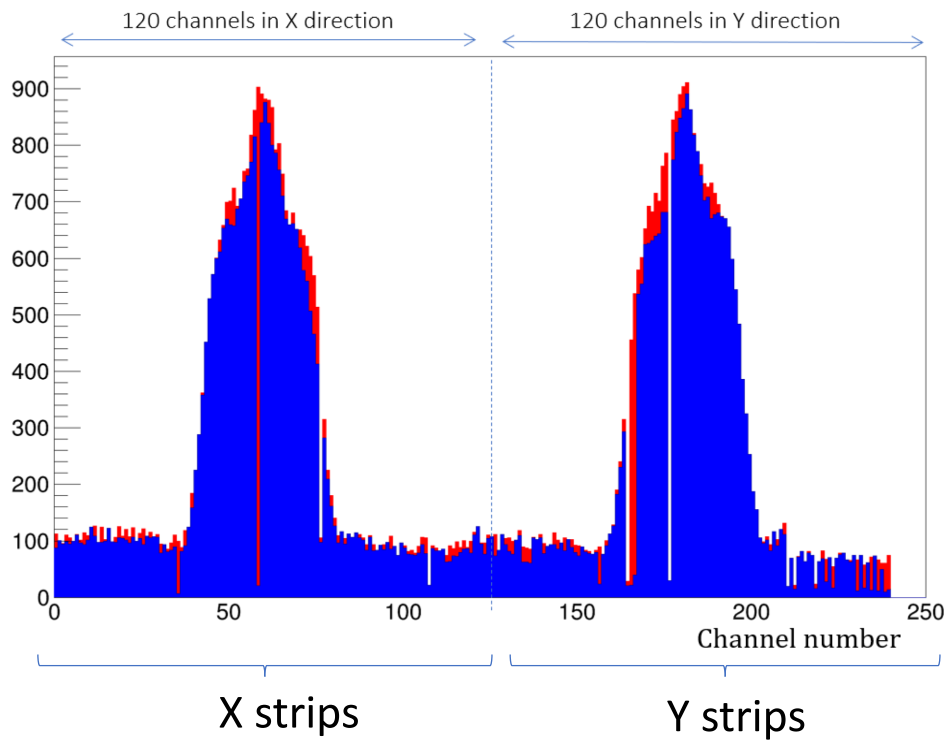


	Ar + 2.3% isobutane	48.85% Xe + 48.85% Ne + 2.3% isobutane
Mesh voltage	340 V	380 V
Cathode voltage	815 V	750 V
Energy threshold	~ 0.5 keV	~ 1 keV (depending on the gas conditions)
Normalised gain	1	0.5
Pressure	1.4 bar	1.05 bar

Towards Xe-based gas mixtures – detector performance





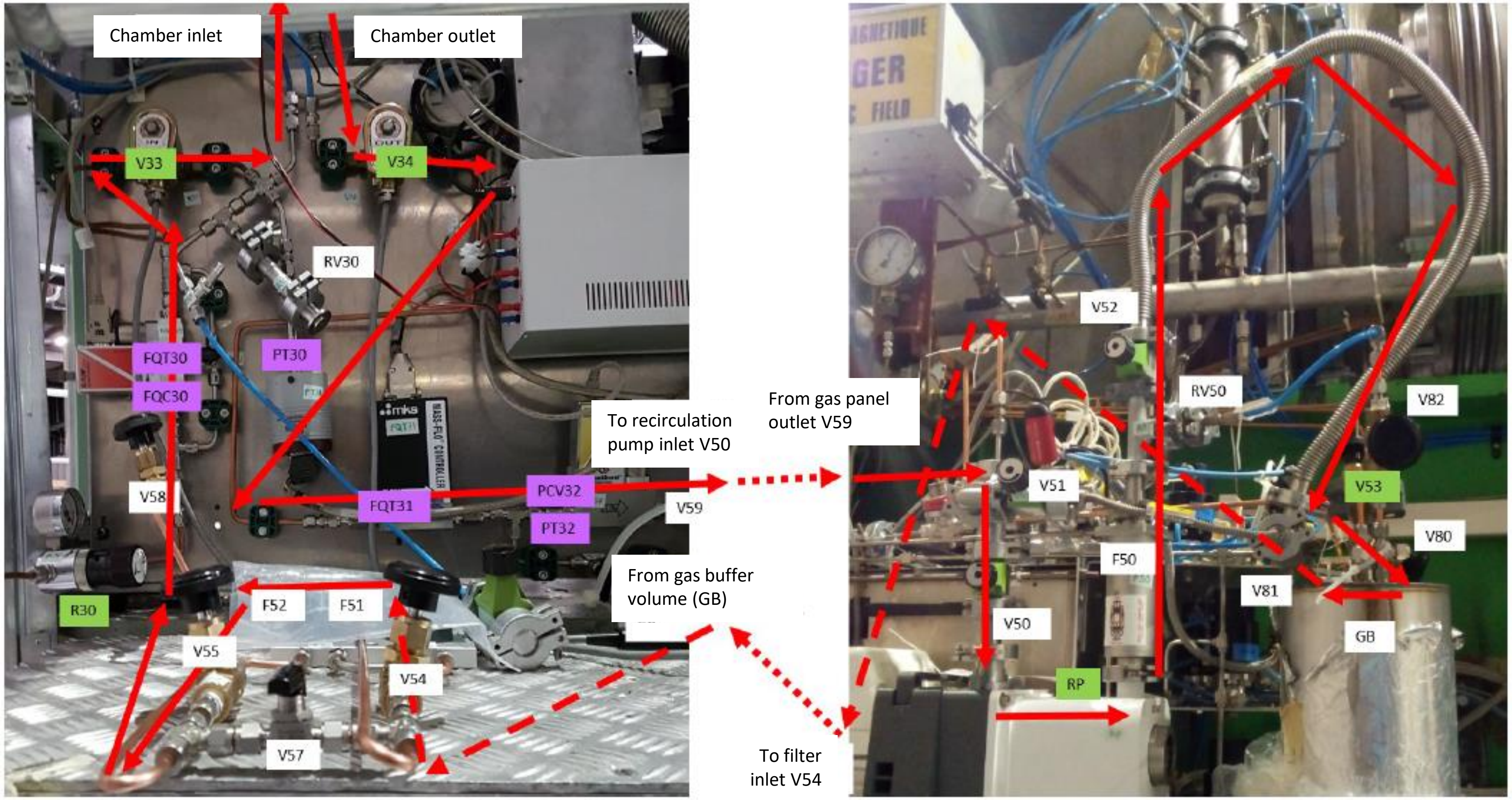


- New dead channel in the centre of the readout.
- The voltages required by the Xe-based gas mixture are pushing the detector to its limit.

Towards Xe-based gas mixtures – gas system upgrade

- Installation of new gas system with recirculation.
- Installation of gas filters and recirculation pump.

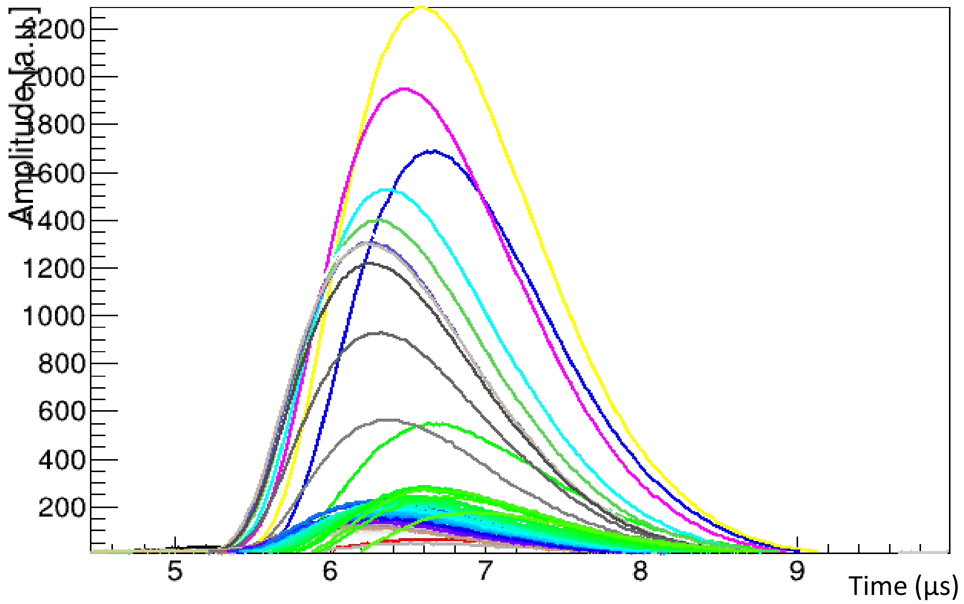
- Xe-based gas mixture, in particular 48.85% Xe + 48.85% Ne + 2.3% isobutane
- The detector runs on slight overpressure (1050 mbar) to avoid inwards gas leaks



Gas flow under normal recirculation conditions

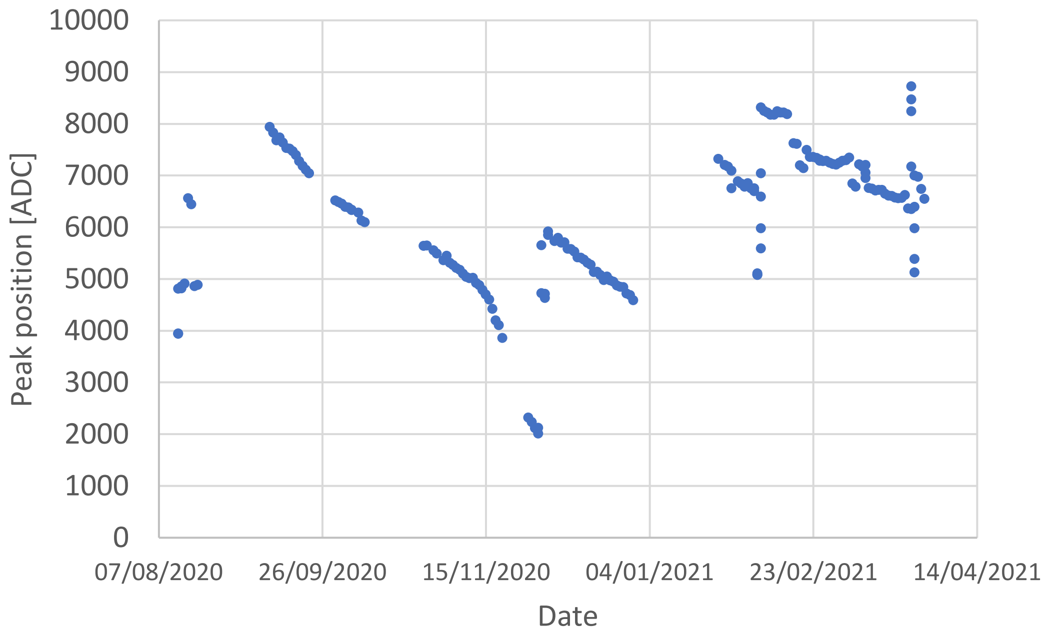
Towards Xe-based gas mixtures – gas system upgrade

- The system includes a moisture filter and an oxygen filter.
  - They are a source of Rn and thus alphas. We observe some high energy events (HEE) that trigger many strips
  - 86 hours of background with V_{mesh} = 250 or 270 V → low gain that allow seeing those HEE without saturation
  - Our chamber is small and in principle there are few HEE, so they should barely affect the background rate



Towards Xe-based gas mixtures – detector performance

- Gain decreases with time.
- This effect is seen for the first time under these new conditions.
- Hypothesis: different permeation through the window of the 3 gases in the mixture.
  - Isobutane is a big molecule and its relative concentration increases.
  - Typically more isobutane implies less gain for the same voltage.
  - Xe and especially Ne are very small and escape more easily through the window.



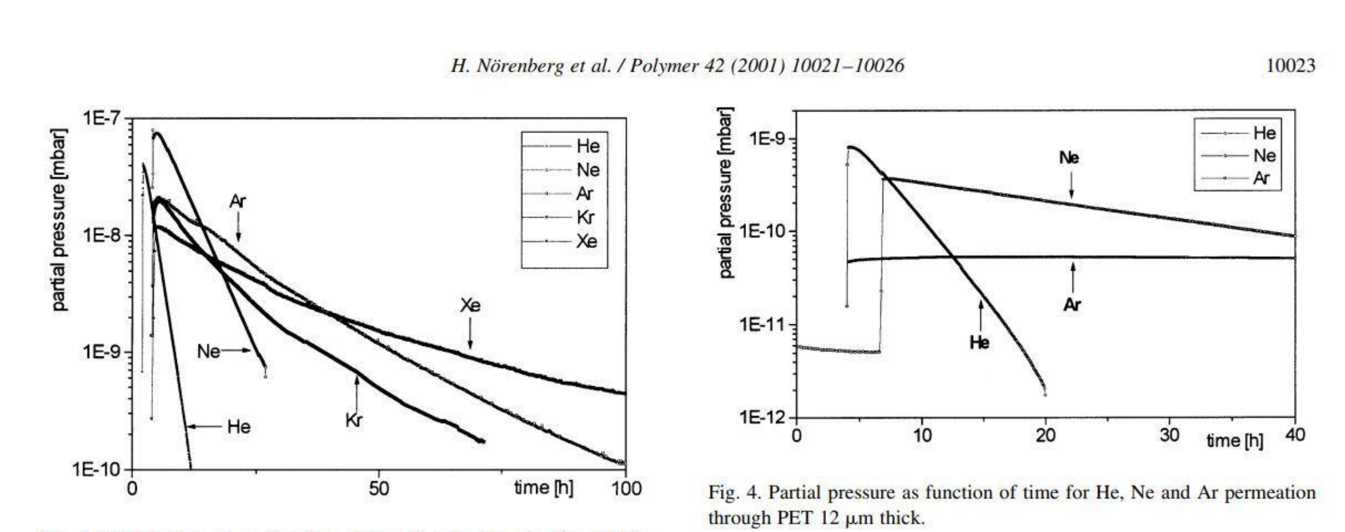
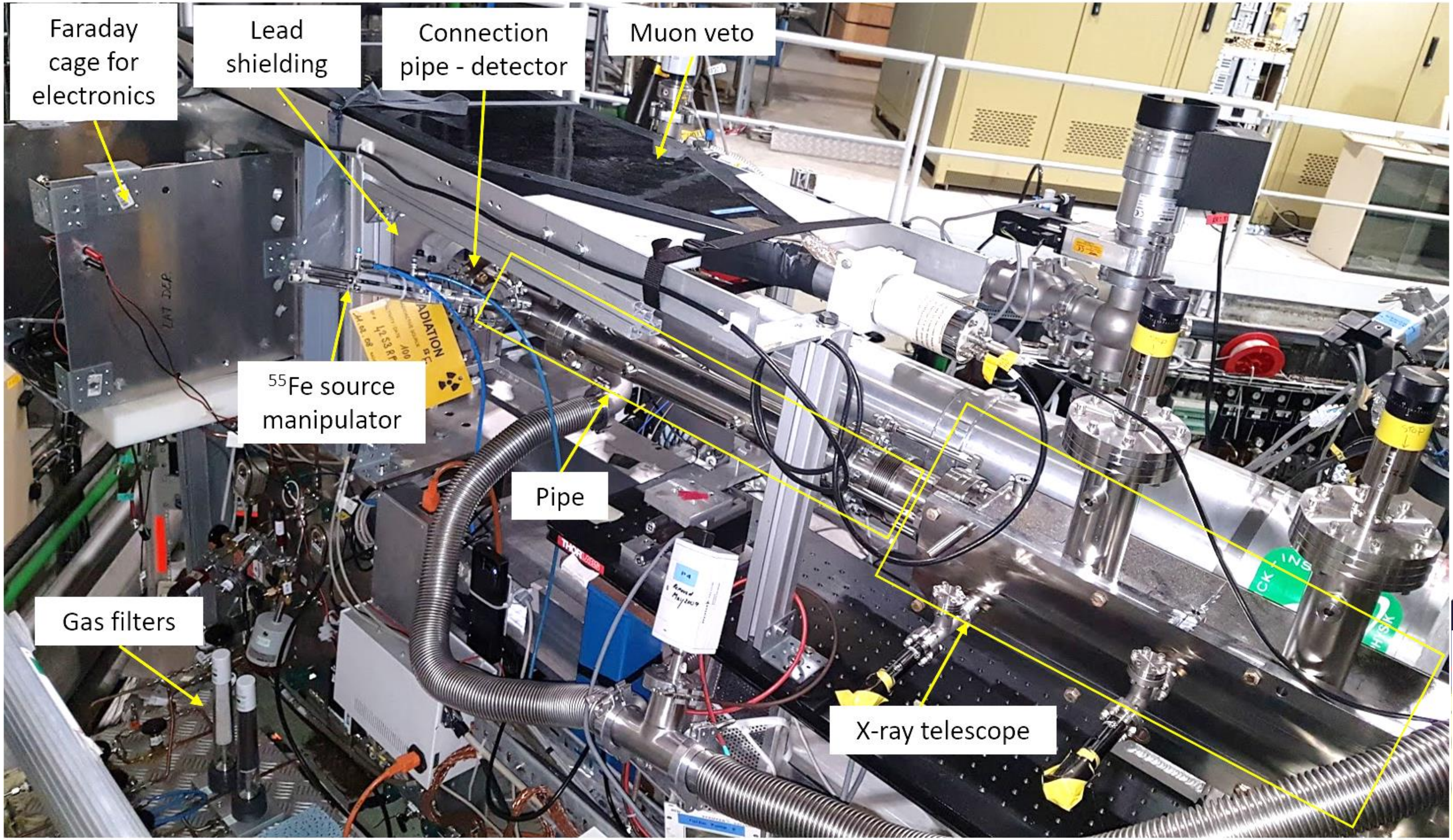
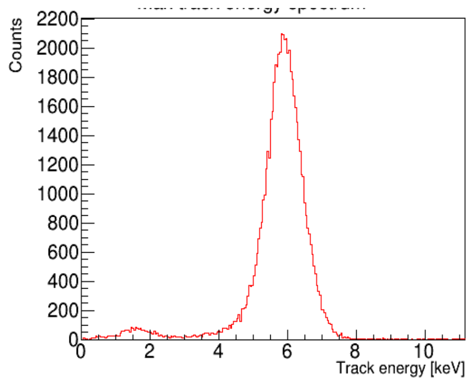


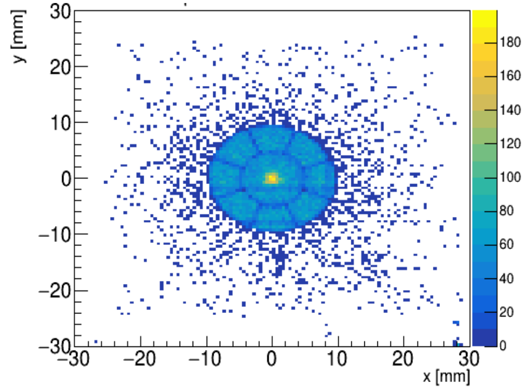
Fig. 3. Partial pressure as function of time for He, Ne, Ar, Kr and Xe permeation through OPP 20 μm thick.

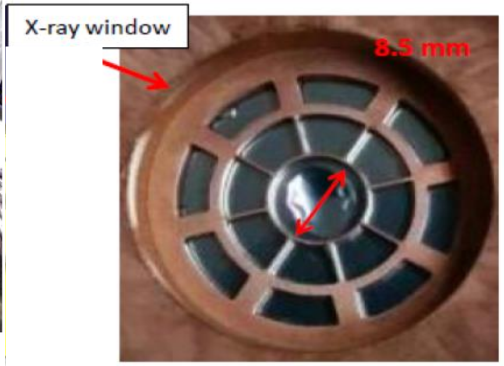
Fig. 4. Partial pressure as function of time for He, Ne and Ar permeation through PET 12 μm thick.

The IAXO pathfinder system at CAST





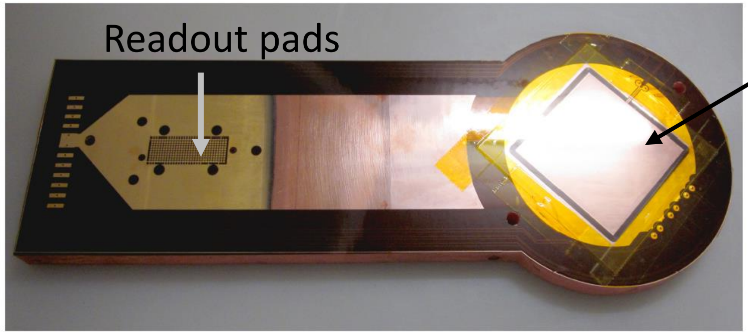




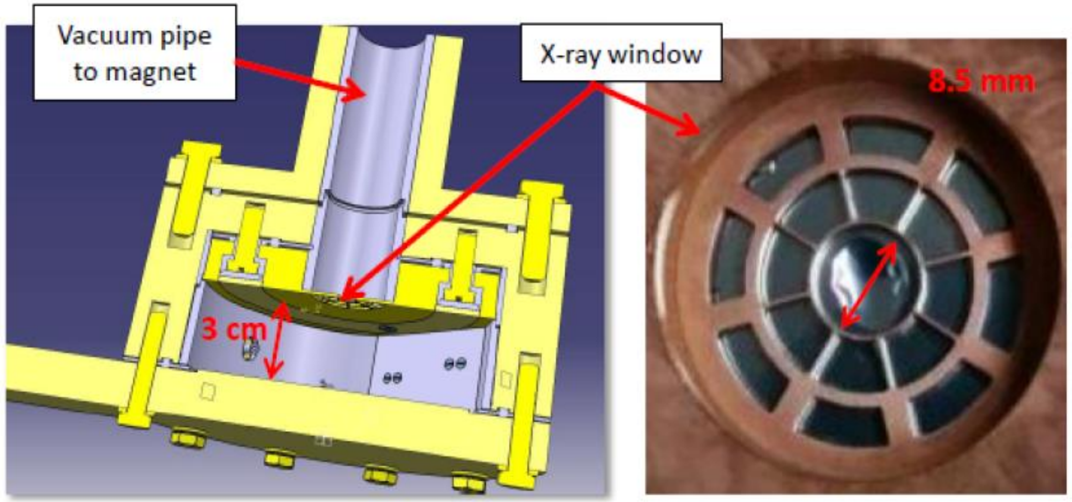
The IAXO pathfinder system at CAST

Microbulk Micromegas detectors

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



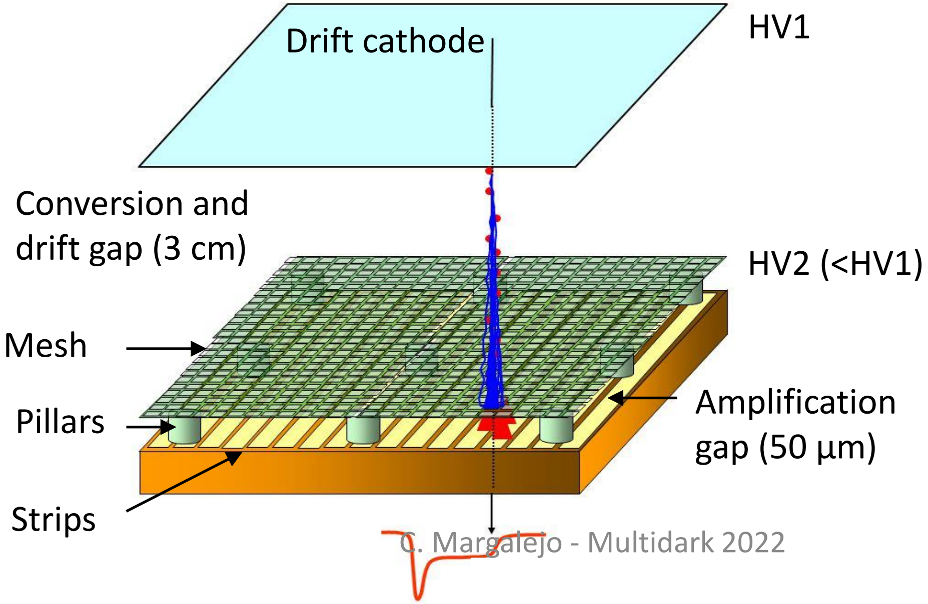
Micromegas readout
120 x 120 strips
Pitch = 0.5mm

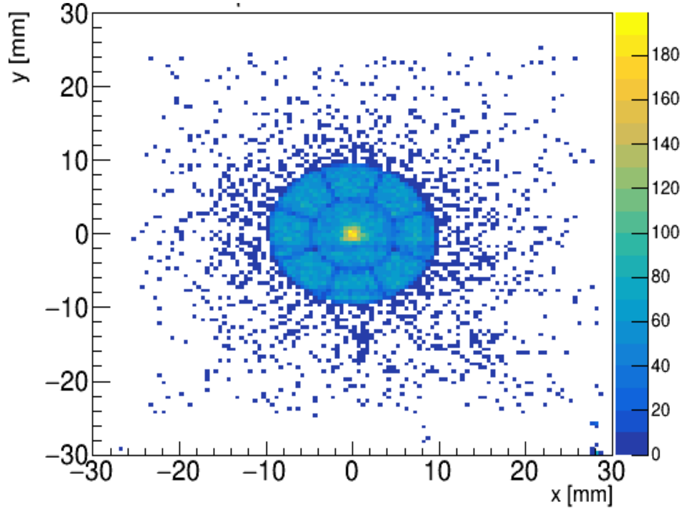


X-ray optics focus the signal, which reaches the active volume through a mylar window. X-rays ionize the gas in the conversion region and the produced signal is read by the Micromegas.

Rare Event Searches Toolkit software

Preprint in arXiv available [here]





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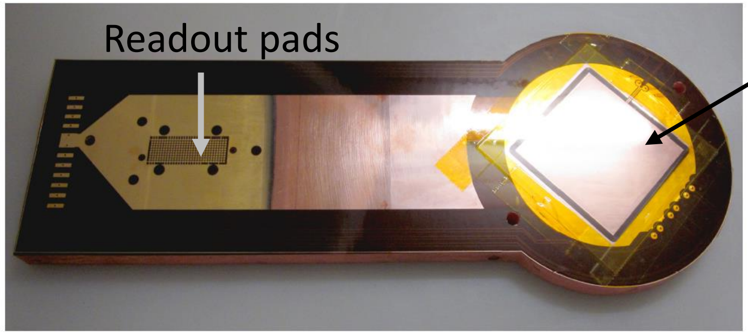
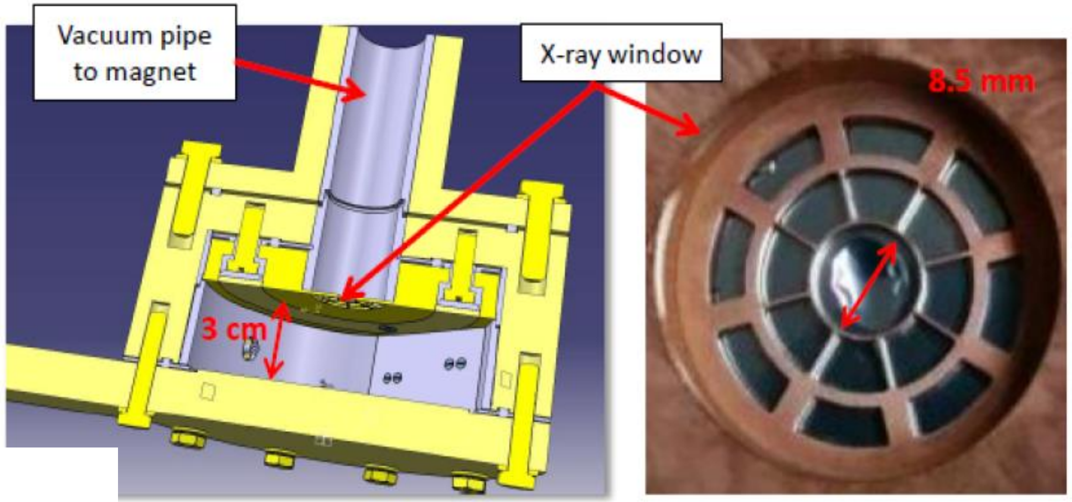


Micromegas
rea
120
Pitc



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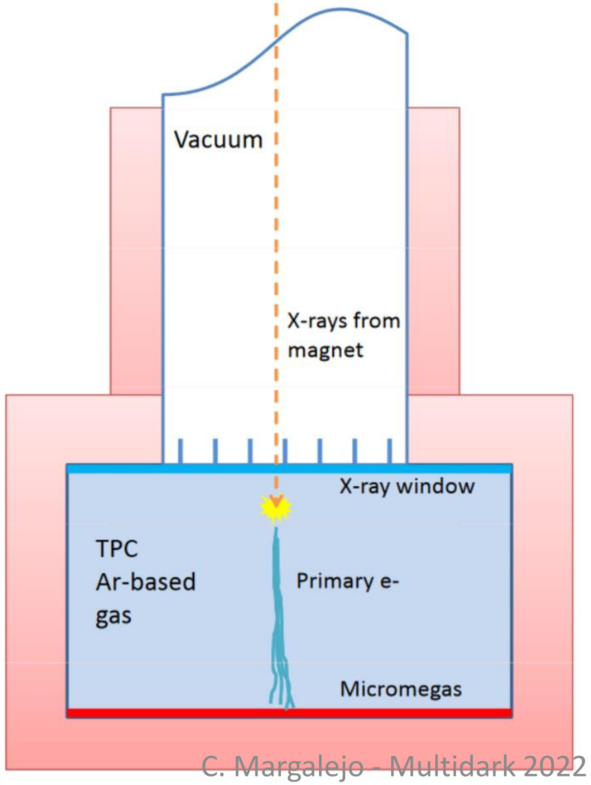
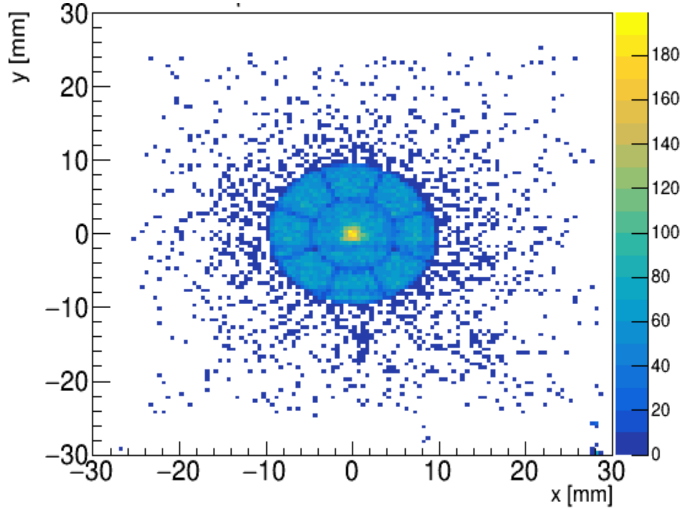




Rare Event Searches Toolkit software

Preprint in arXiv available [here]

The strong CP problem

- Electroweak interaction violates CP, just as the macroscopic world
- Strong interaction does not violet CP. Why?

$$\mathcal{L}_{\text{QCD}} = \underbrace{-\frac{1}{4}G_{\mu\nu a}G_a^{\mu\nu} + \sum_q i\bar{q}\gamma^\mu D_\mu q - \bar{q}mq}_{\text{Conserves CP}} + \underbrace{\frac{\alpha_s}{8\pi}\theta G_{\mu\nu a}\tilde{G}_a^{\mu\nu}}_{\text{Violation of CP} \propto \theta}$$

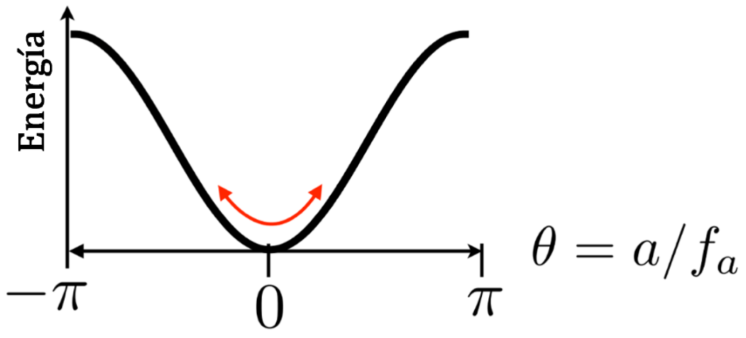
$\theta \in (-\pi, \pi) \longrightarrow$ It's value determines CP violation

- Observations: $|\theta| \leq 10^{-10}$,
- fine tunning problem (the strong CP problem).

Axions as solution to the strong CP problem

- Peccei & Quinn (1977) & Wilzec (1978):

There is a dynamic field *a* whose vacuum energy minimises at $\theta = 0$.



- New scale f_a
- Oscilllations about 0 give origin to a new particle: the axion.

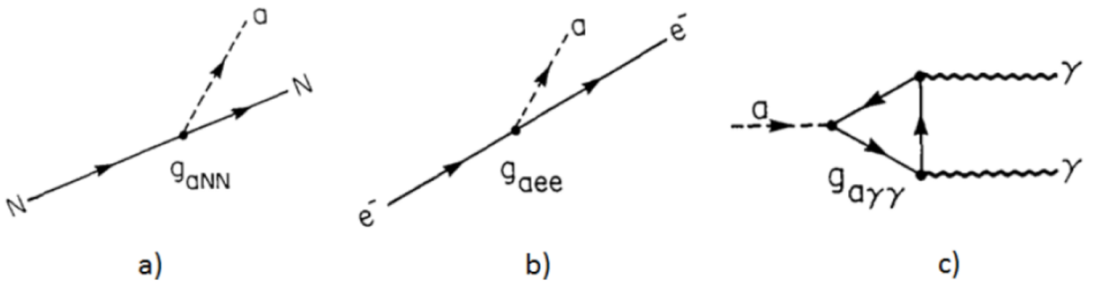
$$g_{a\gamma\gamma} \propto 1/f_a \propto m_a$$

Axions as solution to the strong CP problem

Characteristics of the Peccei-Quinn axion

$$f_a > 10^5 \text{ GeV} \qquad m_a = 6\,\text{MeV}\,\frac{10^9\,\text{GeV}}{f_a}$$

Couplings to ordinary matter



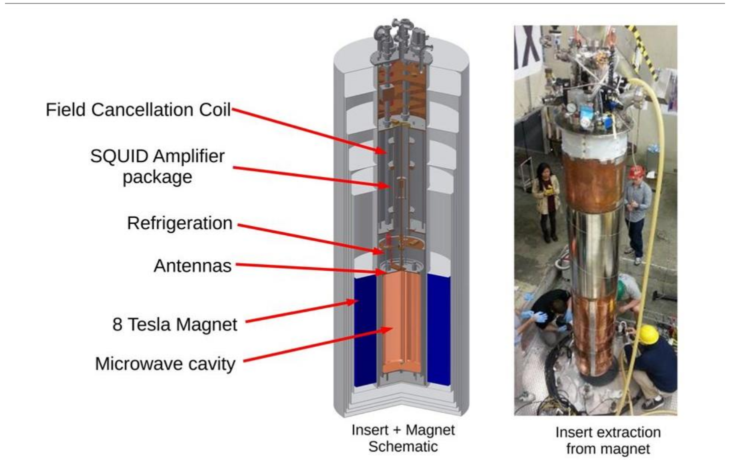
Axion-two photon coupling → Primakoff effect

$$g_{a\gamma\gamma} \propto 1/f_a \propto m_a$$

Axion searches

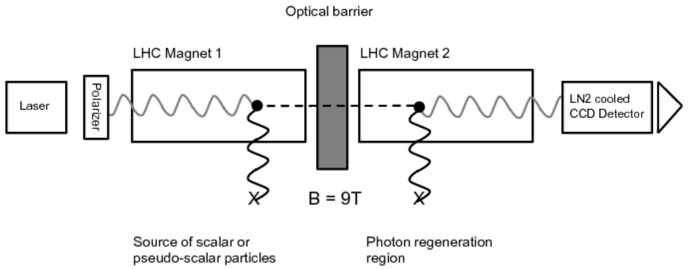
Large complementarity among categories

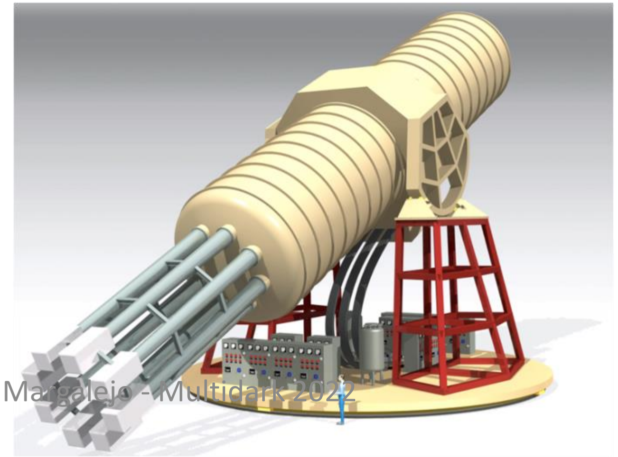
Source	Experiments	Model & Cosmology dependency	Technology
c ons	ADMX, HAYSTAC, CASPEr, CULTASK, CAST-CAPP, MADMAX, ORGAN, RADES, QUAX, …	High	New ideas emerging, Active R&D going on,…
xions created in the lab	ALPS, OSQAR, CROWS, ARIADNE,…	Very low	
Solar axions	SUMICO, CAST, **(Baby)IAXO**	Low	Ready for large scale experiment



ADMX - serch for dark matter axions from the Galactic halo (adjusting resonant cavities for different masses)

OSQAR – light shinning through walls





IAXO - search for solar axions