Searching for Solar Axions with BabyIAXO

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Outline

- Axion Physics
- Axion Detection
- Solar Axion Searches
- The IAXO Collaboration and BabyIAXO
- IAXO Micromegas Detector
- IAXO Background Model
- REST-for-Physics
- Cosmogenic background studies

About myself

- Physics PhD student at University of Zaragoza (Spain)
- Thesis on Solar Axion Searches with BabyIAXO (IAXO Collaboration)
- Core developer of the REST-for-Physics framework (IAXO Collaboration)
- Visiting Fermilab for 3 months on an IRIS-HEP Fellowship: working on uproot (integration of fsspec into uproot)
- My work is mostly software related

Rare Event Searches Toolkit software

Why Axions?

- Elegant solution to the Strong CP Problem of the SM
- Very weakly interacting, light, long-lived
- Dark Matter candidate (not *ad hoc* solution!)
- Experimental efforts growing fast (still smaller than WIMPs')
- Relevant parameter space at reach of current and future experiments
- Hinted by astrophysical data (HE-γ transparency, stellar cooling…)
- More generic ALPs (axion-like particles) predicted by many theories

- QCD: Strong interaction between quarks mediated by the gluon field

- The QCD Lagrangian allows an additional term:

$$\mathcal{L}_{\mathrm{QCD}} \supset \mathcal{L}_{\bar{\theta}} = -\frac{g^2}{32\pi^2}\bar{\theta}G^a_{\mu\nu}\tilde{G}^{a,\mu\nu}$$

Gluons

Constant

$\bar{\theta} \in [0,2\pi)$

- This term **breaks P symmetry**, so **CP should not be conserved in the strong interaction**

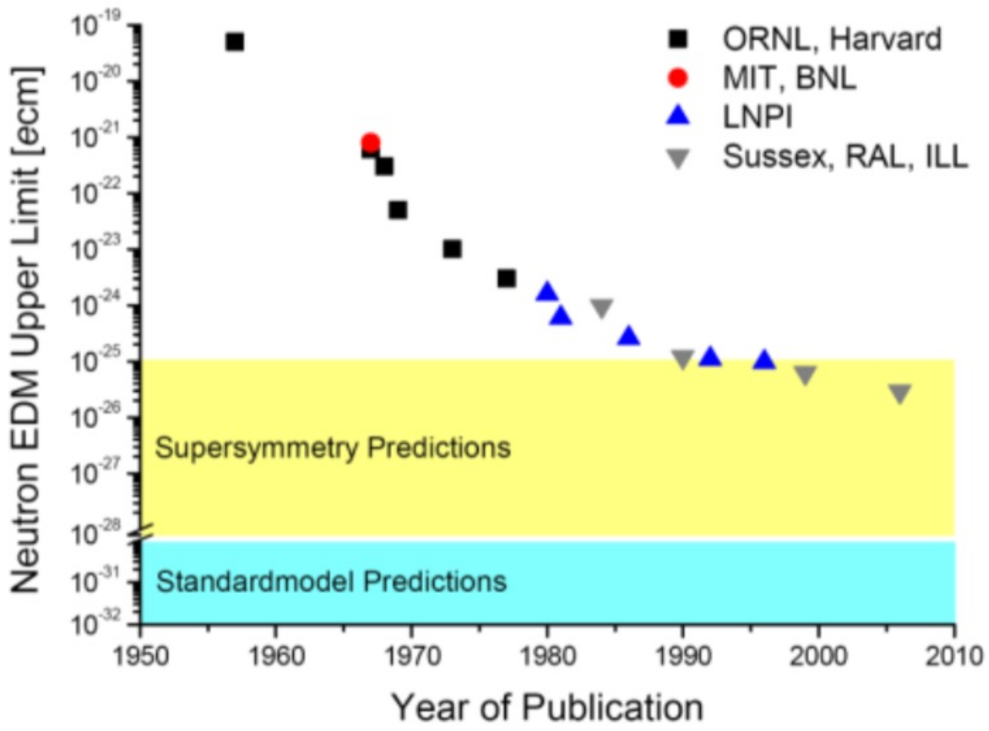
No P & No T & Always $CPT \rightarrow$ Yes C

Yes C & No $P \rightarrow$ No CP

- The $\bar{\theta}$ term has measurable implications: neutron electric dipole moment
- Best limit for $\bar{\theta}$ comes from nEDM measurements:

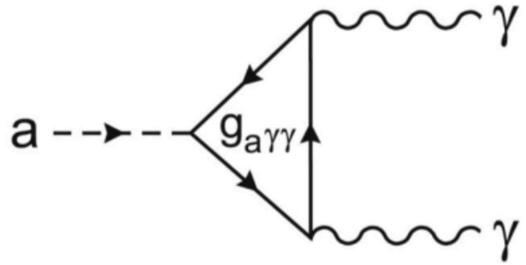
$$nEDM \ \leq \ 3.0 \times 10^{-26} \, e \, cm \Rightarrow \bar{\theta} \lesssim \ 10^{-10}$$

- CP violation in the strong interaction has not been observed.
- This fine-tuning is called the strong CP problem



Solutions to the Strong CP Problem:

- One massless quark? Problem solved!
- …
- Peccei-Quinn mechanism (1977) is the preferred solution: new global U(1) aprox. symmetry spontaneously broken resulting a pseudo-goldstone boson: **the axion**

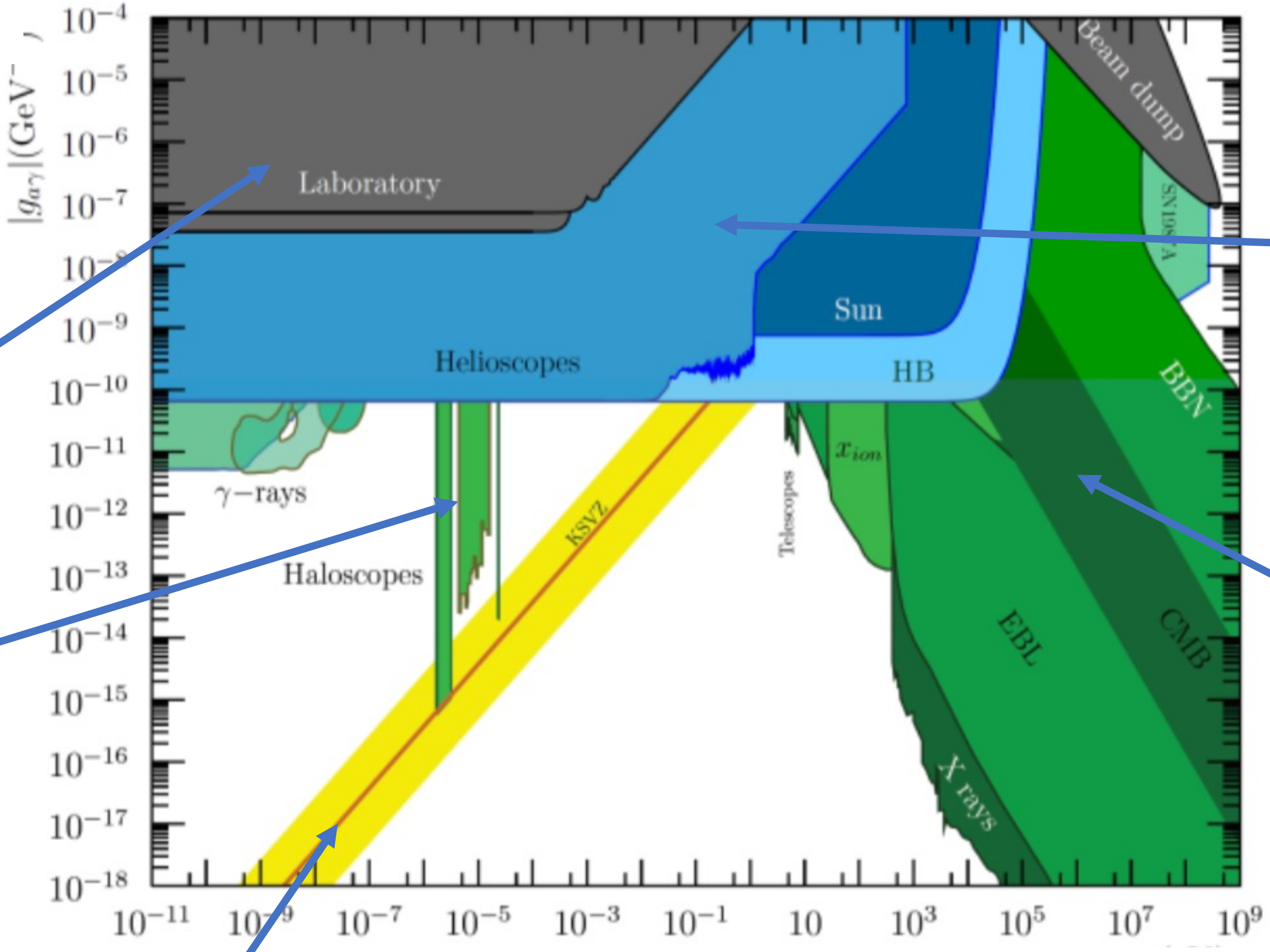


Axion properties:

- Very light: $\sim 10\mu eV - 1meV$
- (weak) interactions with the SM (model dependent: **photons**, fermions, …): most important for detection is the **coupling to photons** ($g_{a\gamma}$) via the **Primakoff effect**
- **Axions can be converted into photons (and vice-versa) under strong EM fields**
- Thermally produced axions would contribute to the **Hot DM** (just like neutrinos would)
- Axions produced by the **Vacuum Realignment Mechanism** can explain the **Cold DM**
- There are axion-like-particles with similar properties (QCD axion / axion | axion / ALP)

“The” Exclusion Plot

Coupling to photons



Mass (eV)

Light shinning through walls experiments (LSTW)

Haloscope experiments (DM)

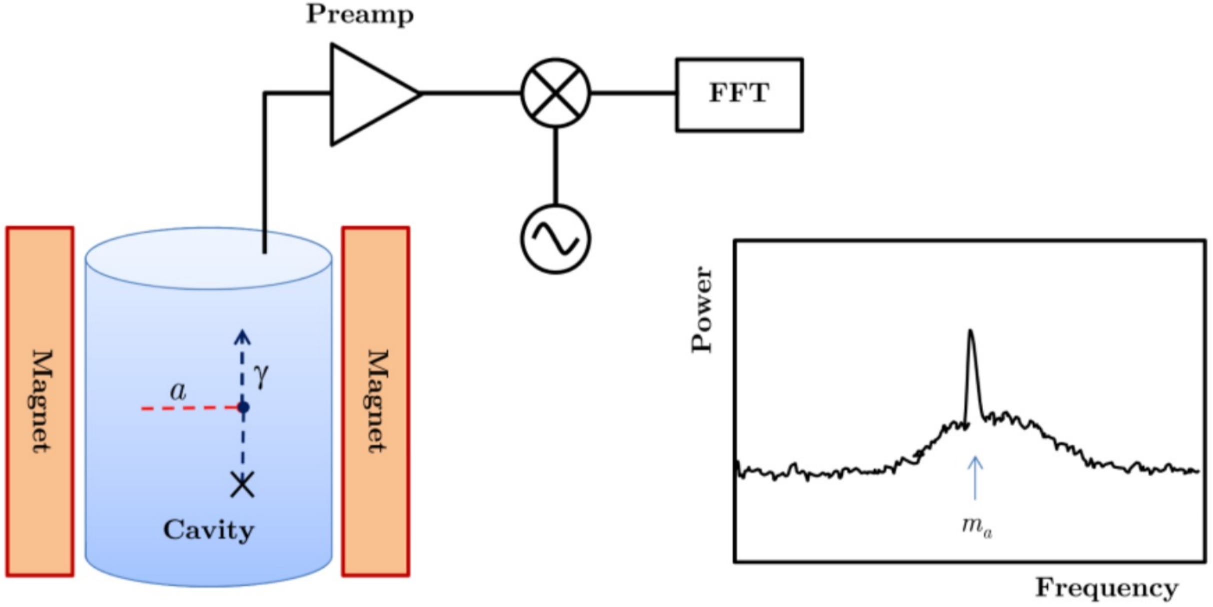
QCD axions lie on this band (most interesting region)

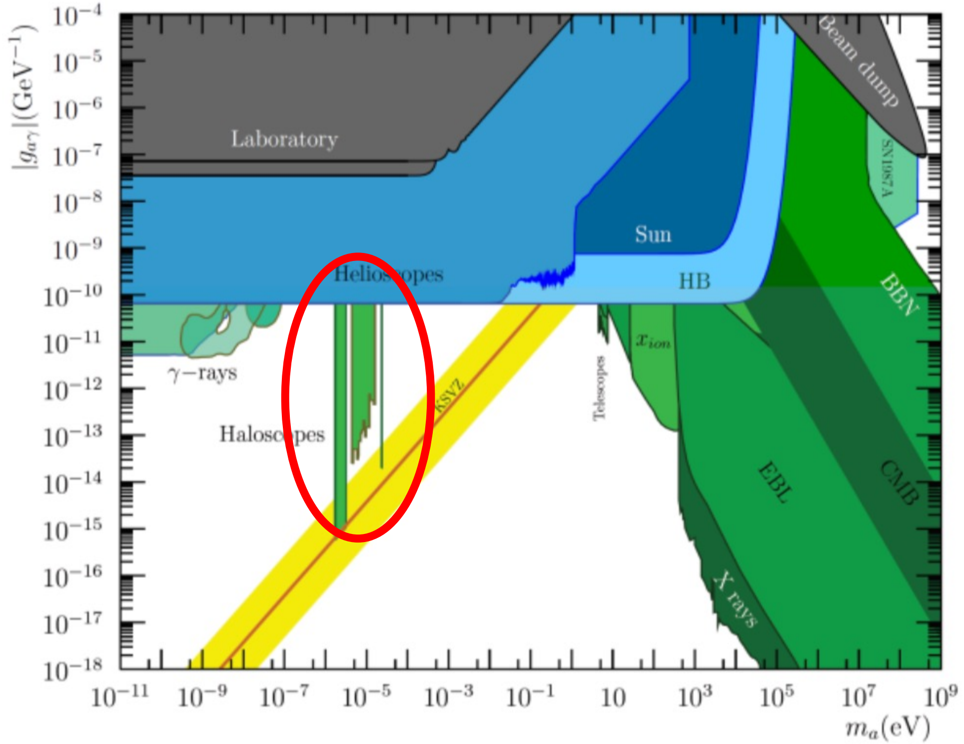
Helioscope experiments

Astrophysical / Cosmological limits

Haloscope experiments

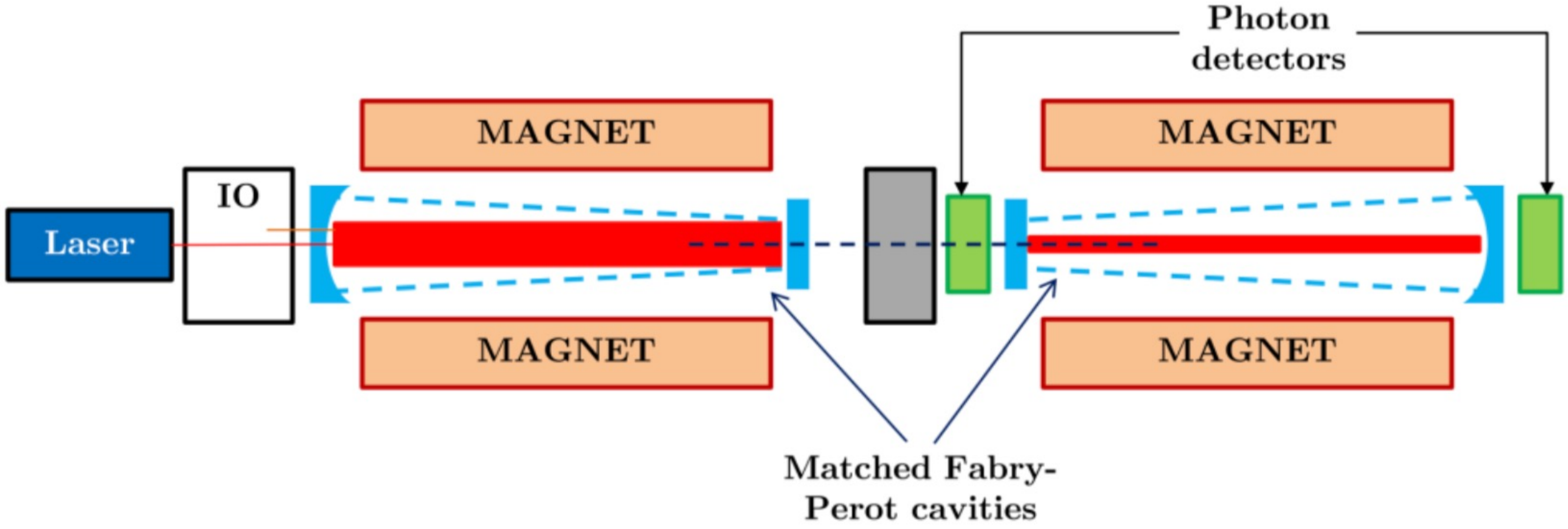
- Assume DM galactic halo is composed of axions
- Resonant cavity tuned to axion mass. Need strong magnetic field
- Reach lower coupling but on a narrow mass range

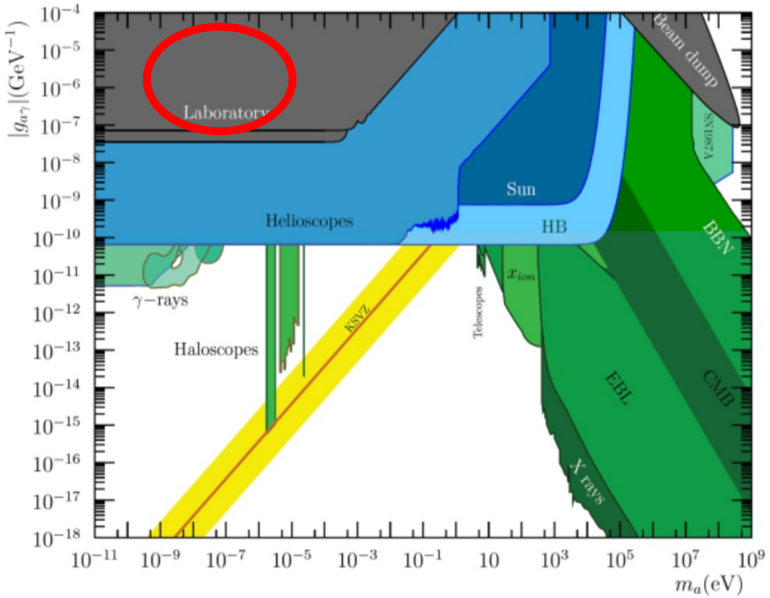




Light shinning through wall (LSTW) experiments:

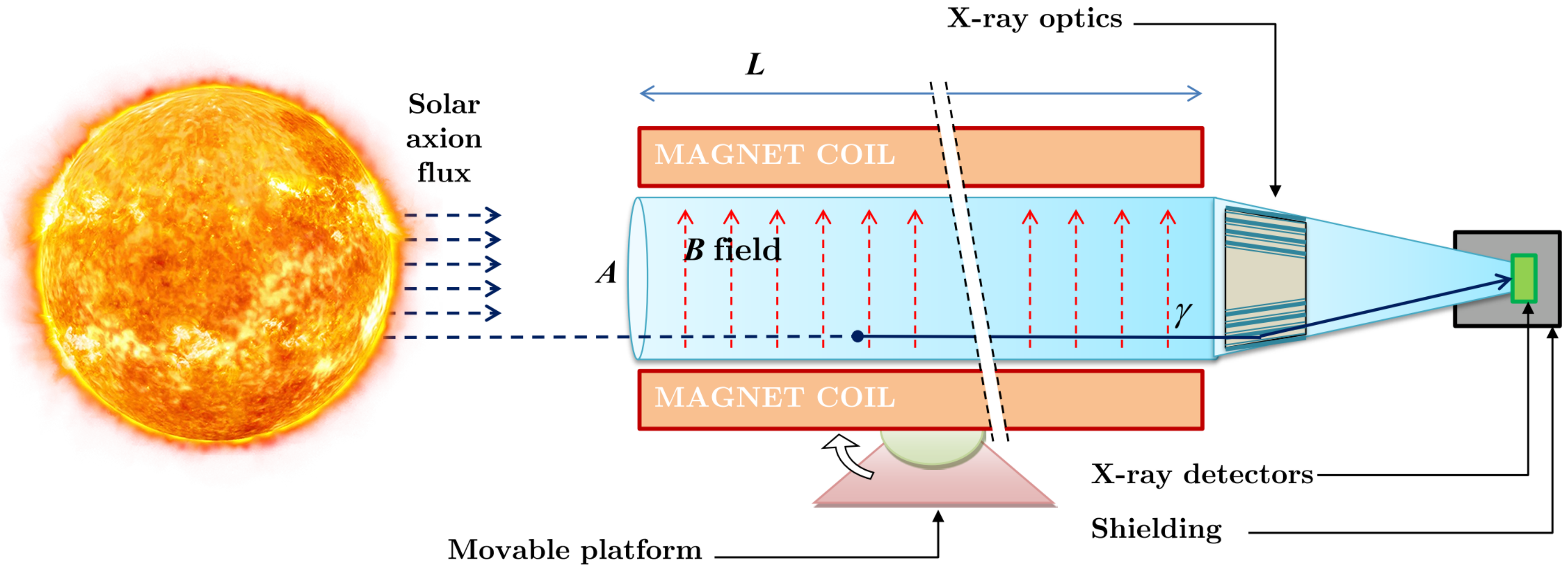
- Rely on the most fundamental properties of the axion: the most model independent
- No DM hypothesis
- Not very competitive

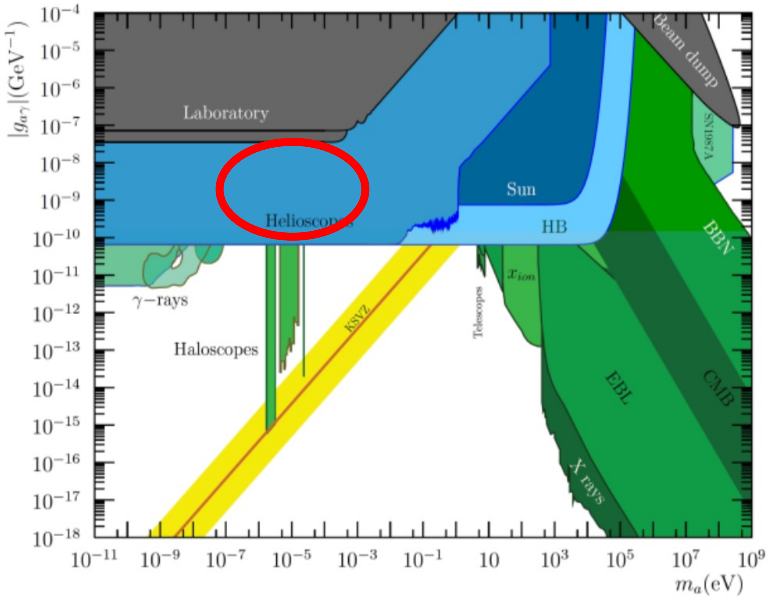




Helioscope experiments:

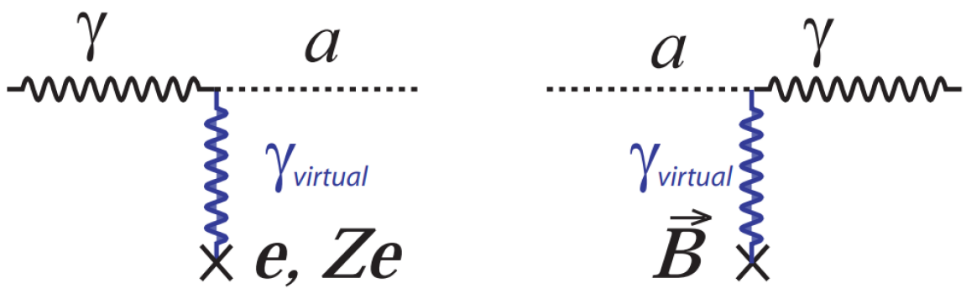
- Like LSTW but axions are produced in the Sun instead of in the lab
- Fairly model independent: no DM hypothesis but needs a solar model
- Same region of parameter space as LSTW but lower limits (horizontal line)

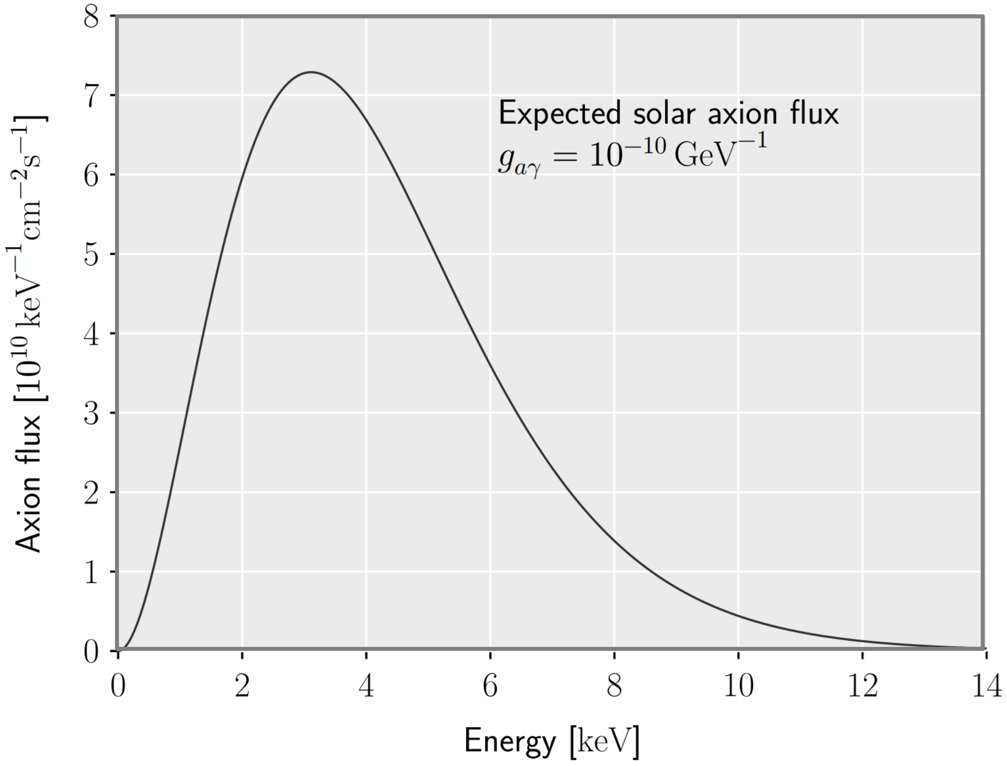




Solar axions:

- Primakoff effect: axion ↔ photon
- All stars produce axions (stellar EM field): The Sun is the brightest (surpernovas too!)
- Anomalous stellar cooling
- Solar model
- Spectrum in 1-10 keV range (RoI for helioscopes)





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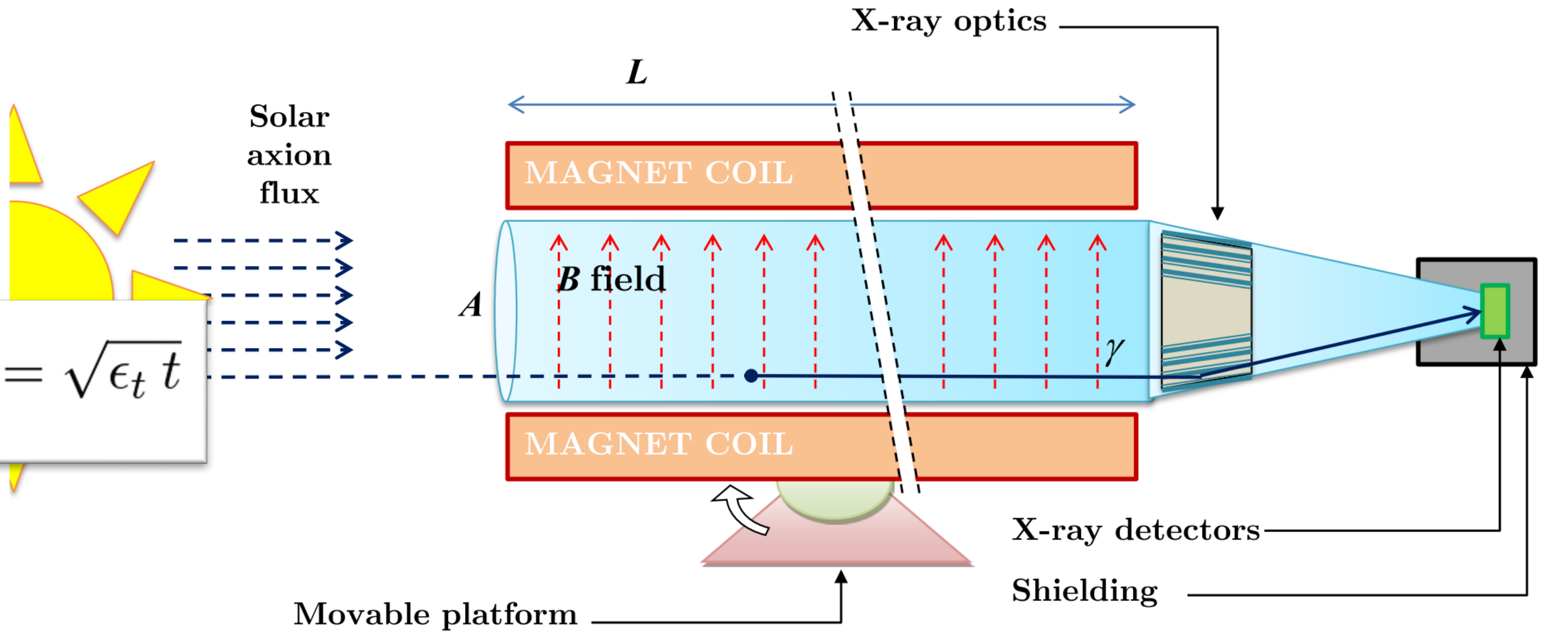
Key components:

- Movable platform: point at the sun
- Magnet: strong constant magnetic field (perpendicular to optical axis)
- X-ray optics: focus Primakoff photons into detector
- Low background X-ray detector
- FOM: $f \equiv f_M \, f_{DO} \, f_T$

$$f_M = B^2 \, L^2 \, A \qquad f_{DO} = \frac{\epsilon_d \, \epsilon_o}{\sqrt{b \, a}} \qquad f_T = \sqrt{\epsilon_t \, t}$$



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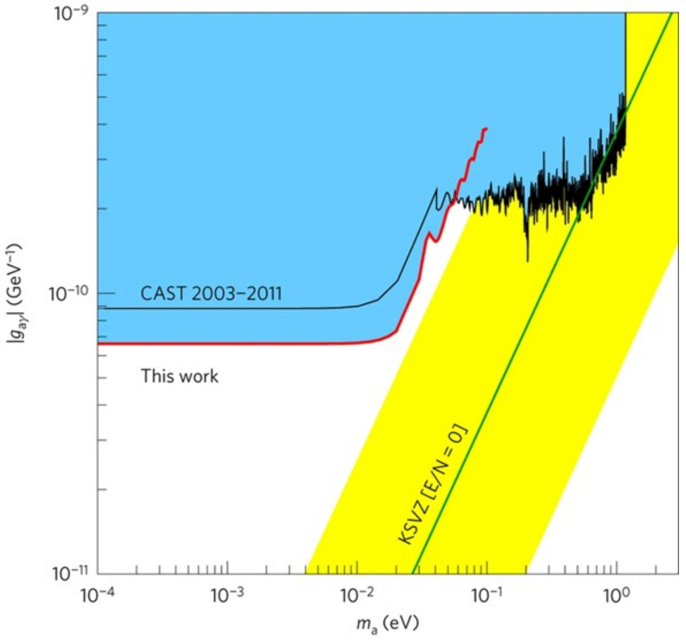
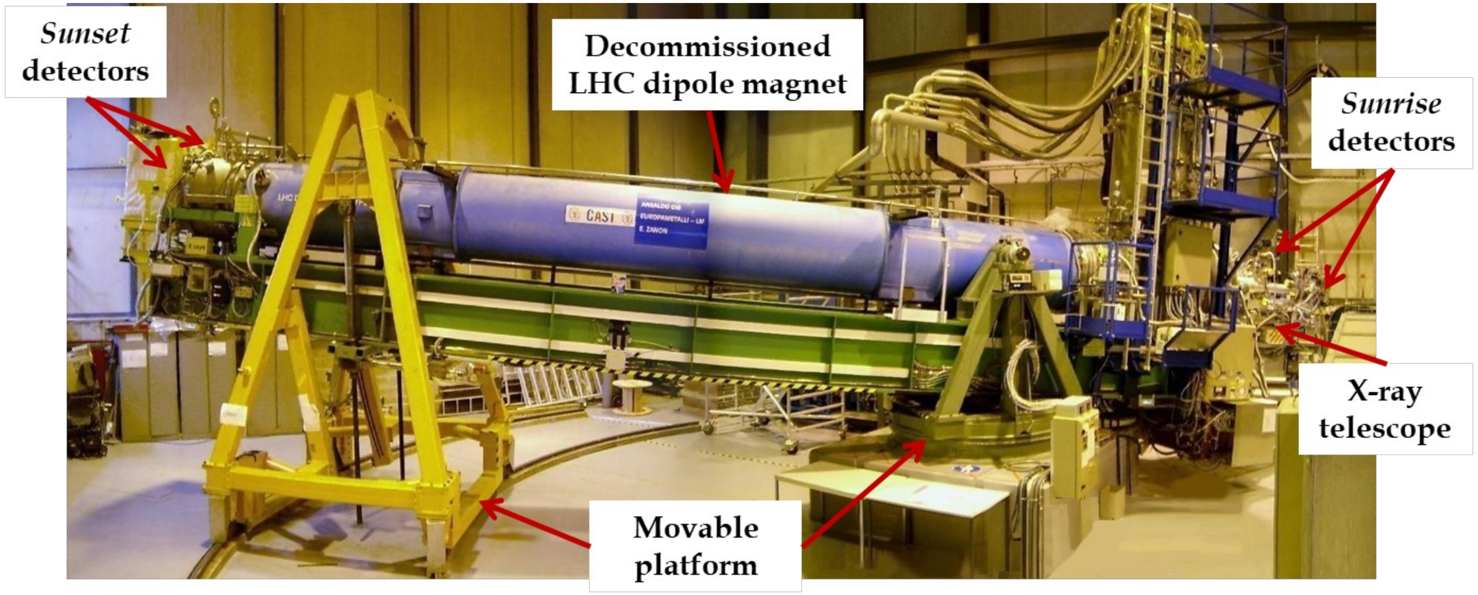
The CAST experiment:

- CERN Solar Axion Telescope: 2002-2022 (no longer active)
- LHC decommissioned dipole magnet: 8.8T L9.25m
- Current lowest helioscope limits are from CAST
- Multiple detector technologies

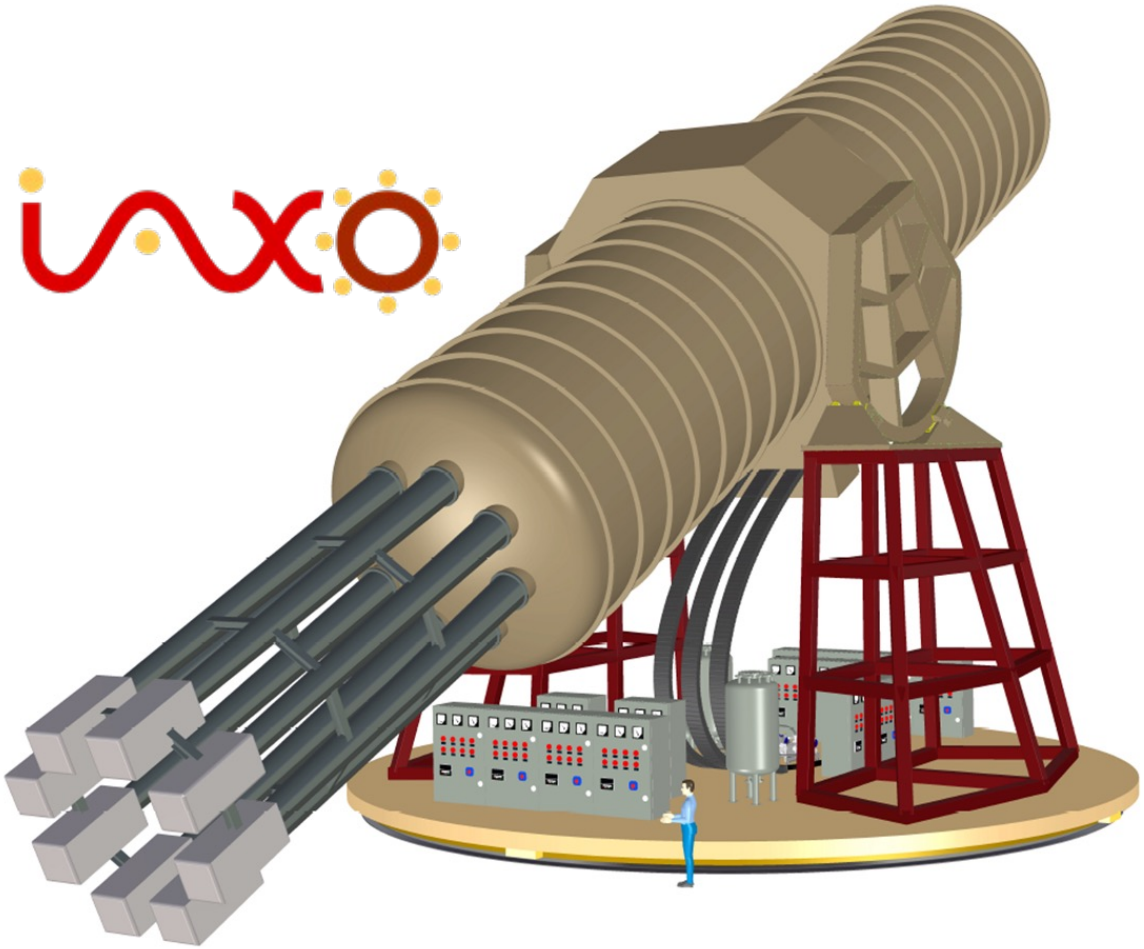


Coupling limit $m_a < 0.01$ eV
$|g_{a\gamma}| < 0.66 \times 10^{-10}$ [GeV^{-1}] (95% C.L.)
10.1038/nphys4109



The International Axion Observatory

Aims to improve CAST sensitivity by 1 order of magnitude



- Super toroidal magnet
  - 20 meters long
  - Magnetic field up to 5.4 T
  - 8 bores of Ø60 cm
- Dedicated X-ray optics
  - 0.2 cm^2 focal spot
- Tracking system
  - 50% of Sun-tracking time
- X-ray detector technologies
  - **Micromegas**
  - GridPix
  - Metallic Magnetic Calorimeters (MMC)
  - Transition Edge Sensors (TES)
  - Silicon Drift Detectors (SDD)

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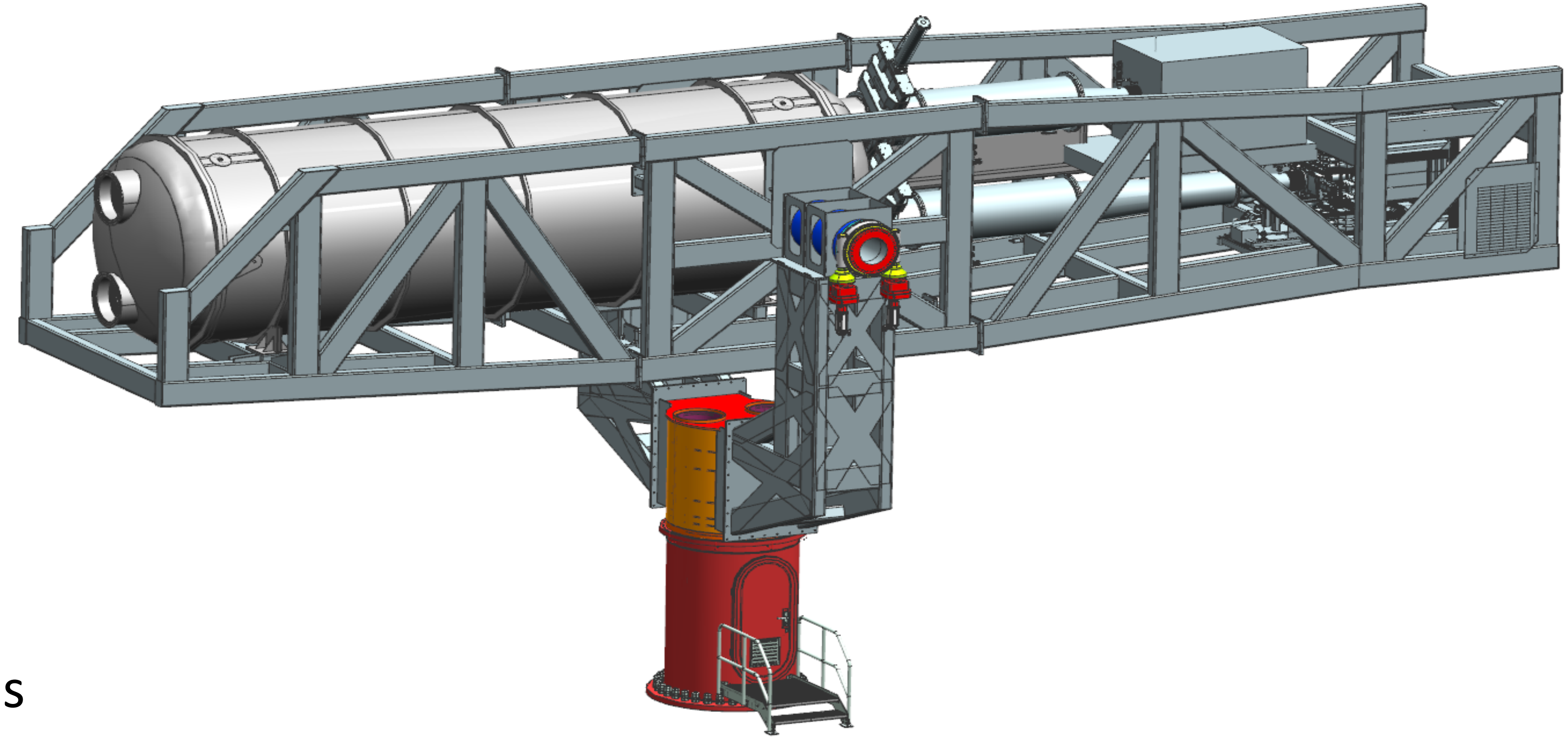
BabyIAXO: first steps towards IAXO

Currently under construction in DESY (Germany)

- Dipole magnet
  - 10 meters long
  - Magnetic field ~2 T
  - 2 bores of Ø70 cm
- Dedicated X-ray optics
  - 0.2 cm² focal spot
- X-ray detector technologies
  - Micromegas (baseline)



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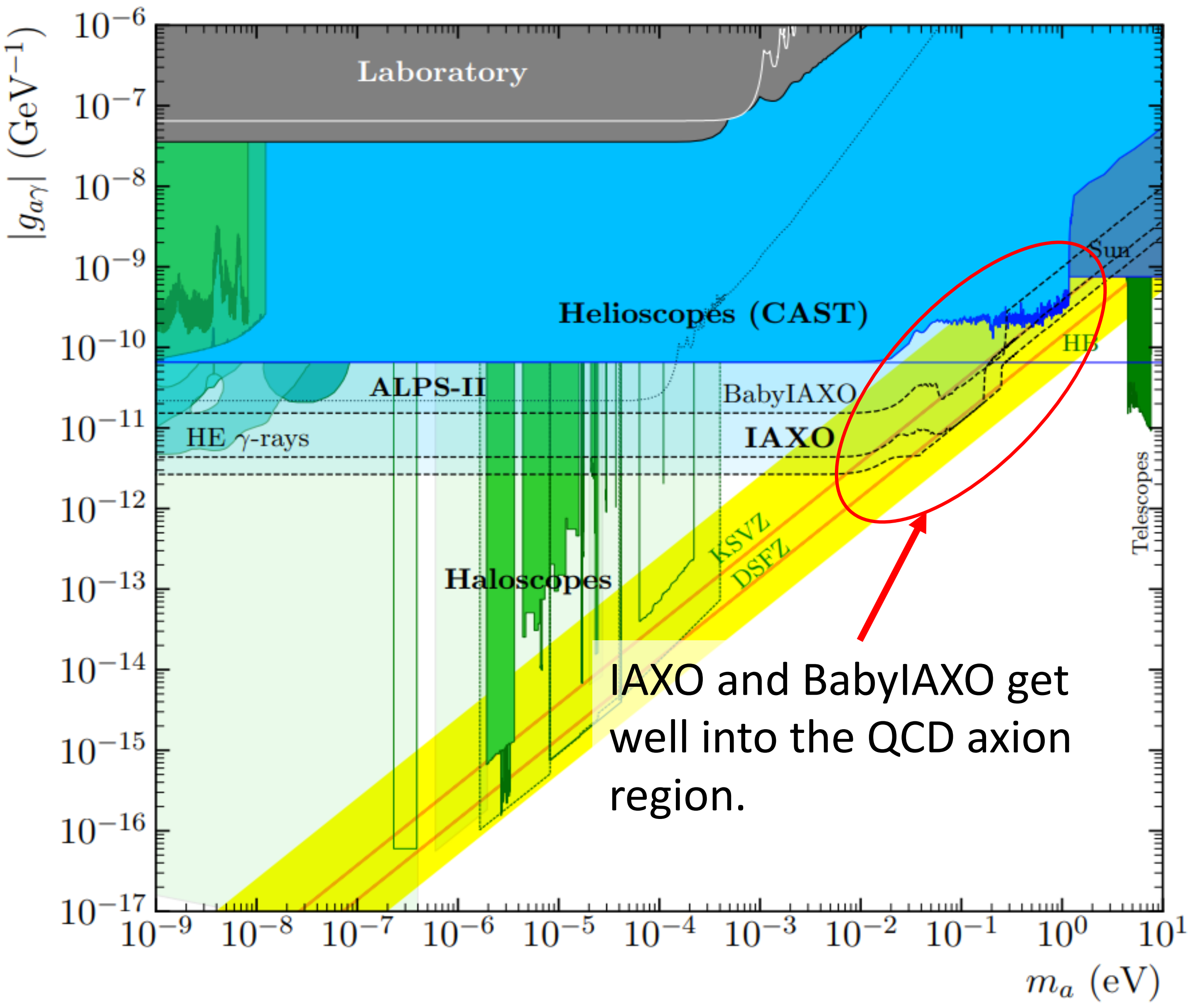
- **BabyIAXO**:
  - Probes part of the QCD band
  - Improves signal-to noise ratio (SNR) by a factor > 10^2 that of CAST
- **IAXO**:
  - Probes large generic unexplored ALP space, QCD axion models in the meV to eV mass band and astrophysically hinted regions.
  - Improves SNR by a factor > 10^4 and sensitivity in $g_{a\gamma}$ by > 1 order of magnitude



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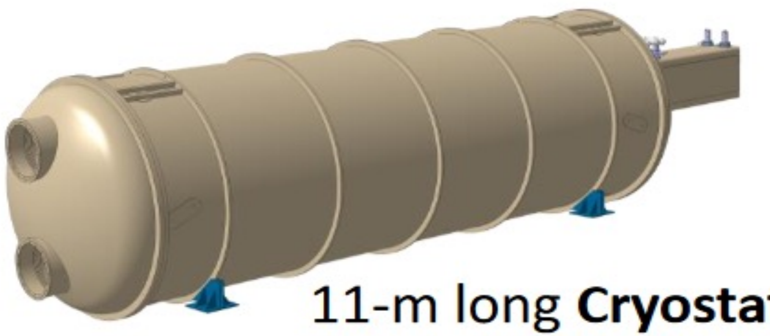
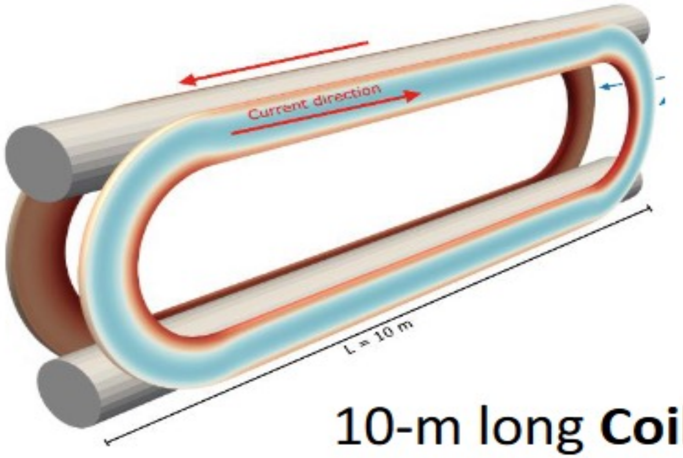
Superconducting magnet:

- 2 parallel flat coils: 10m long.
- Conductor: standard Rutherford cable with 30-40 strands of NbTi/Cu
- 2 bores: 70 cm diameter, vacuum & buffer gas
- Optimized layout: maximum magnetic field at bores
- Cold mass at 4.5 K
- Minimal risk: straightforward and robust design choices



11-m long **Cryostat**

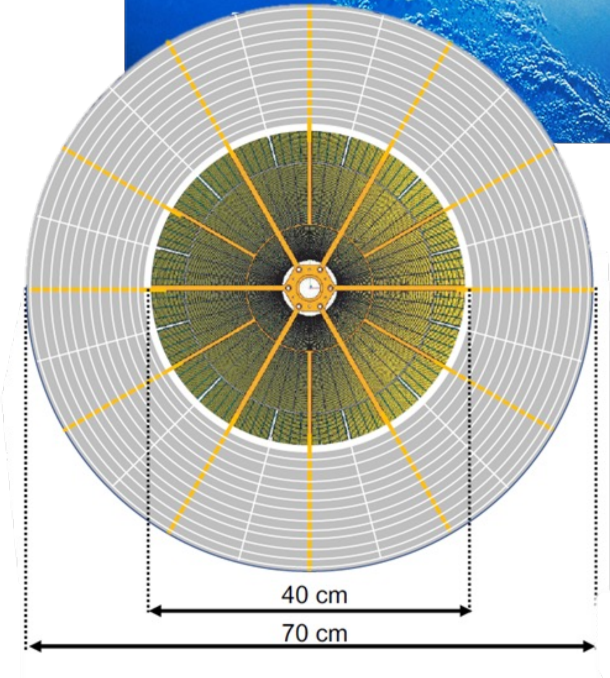


10-m long **Coils**

~35 km **Superconductor**

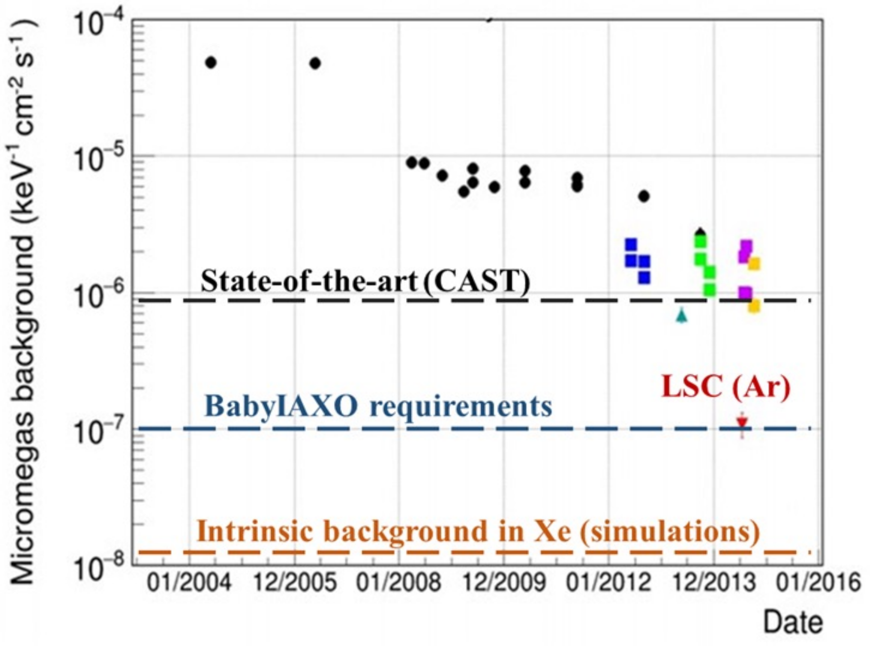
X-ray optics:

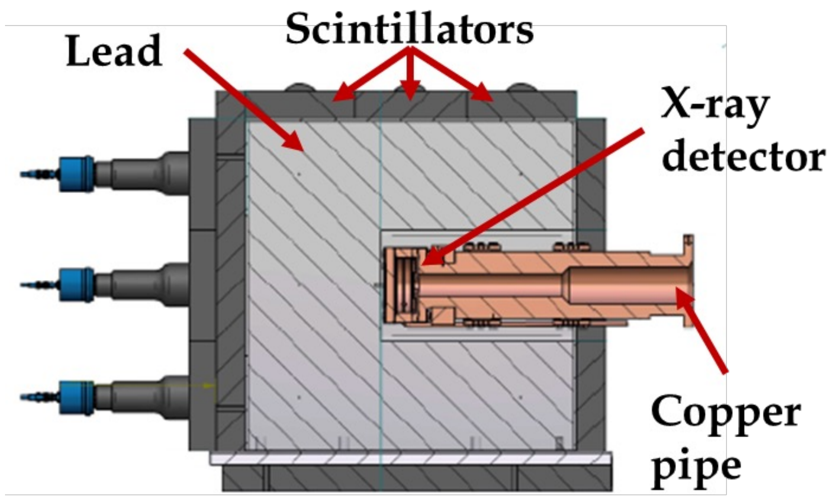
- Multilayer-coated segmented-glass Wolter-I optics
- Signal from the 0.7 m diameter bore focused to 0.2 cm2 area
- Mature technology based on NASA's NuSTAR telescopes
- Two different telescopes:
- Custom made telescope
  - 5 m focal length
  - Hybrid approach with different inner and outer optics to increase the diameter and cover the bore
- XMM flight spare
  - 7.5 m focal length
  - Already available and compatible with BabyIAXO



Ultra-low background X-ray detectors

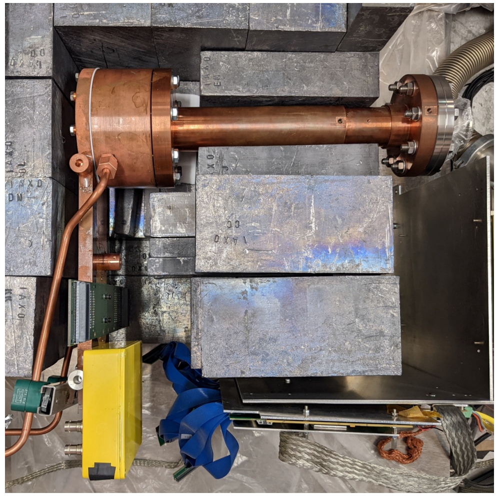
- Required to distinguish axion signal above the nominal background of the detector.
- Required background level 10^{-7} c keV^{-1} cm^{-2} s^{-1} in the RoI [0-7] keV
- Current baseline is Micromegas, but other technologies (GridPix, MMC, TES and SDD) are under study.
- Intrinsic radiopurity of the X-ray detector (measured at the LSC)
- Event discrimination (X-ray like events)
- Shielding strategies:
  - Radiopure copper
  - Lead shielding (20 cm)
  - Active muon veto (cosmic rays and secondaries)

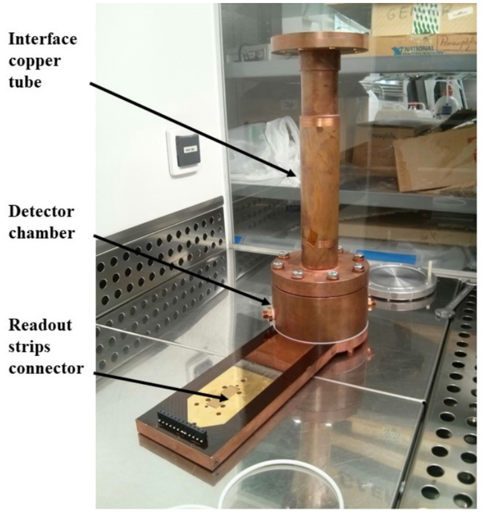


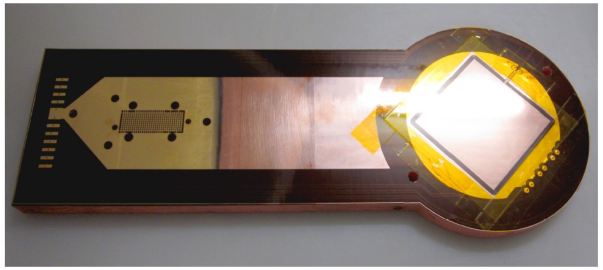


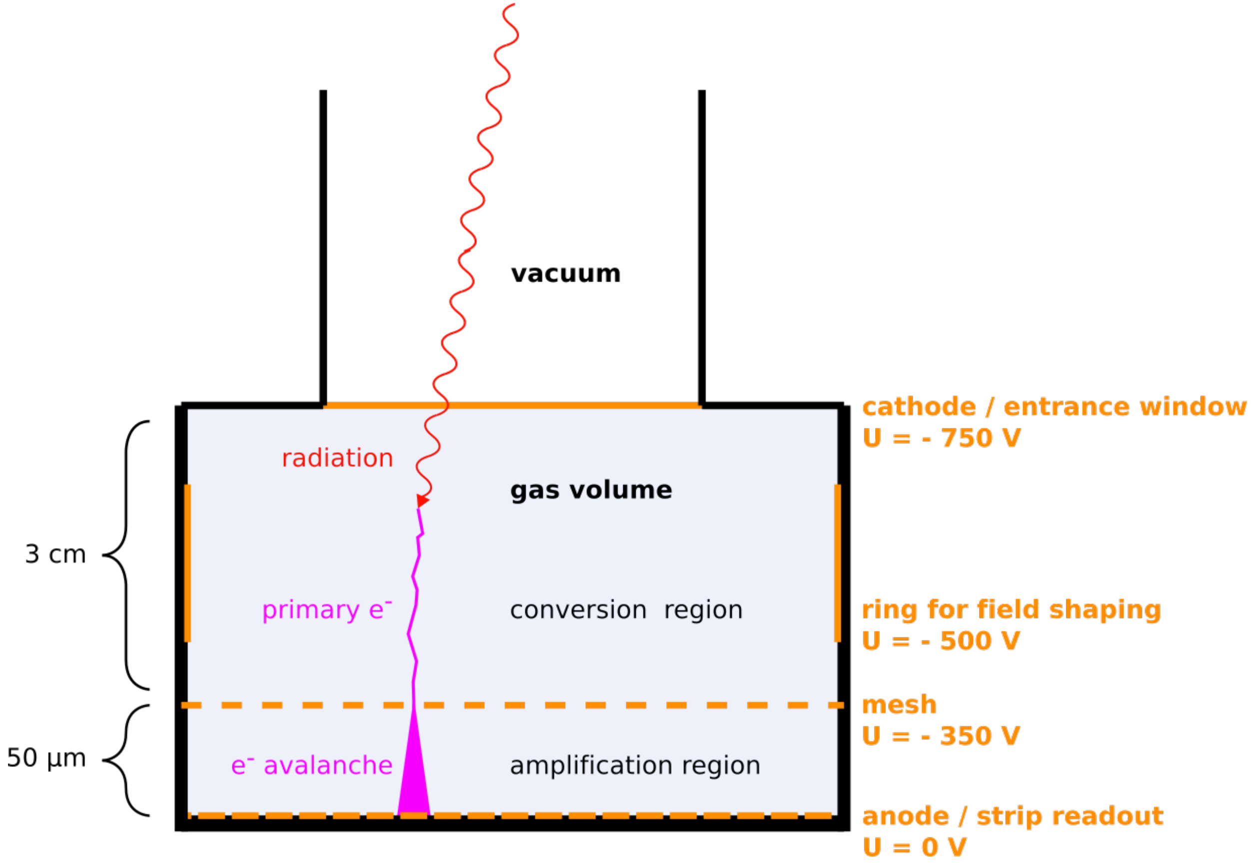
Micromegas detector

- Gaseous TPC
- Very homogeneous amplification gap, uniform gain
- Intrinsically radiopure.
- Good energy and spatial resolution
- Pixelized readout gives topological information
- Same technology as in CAST



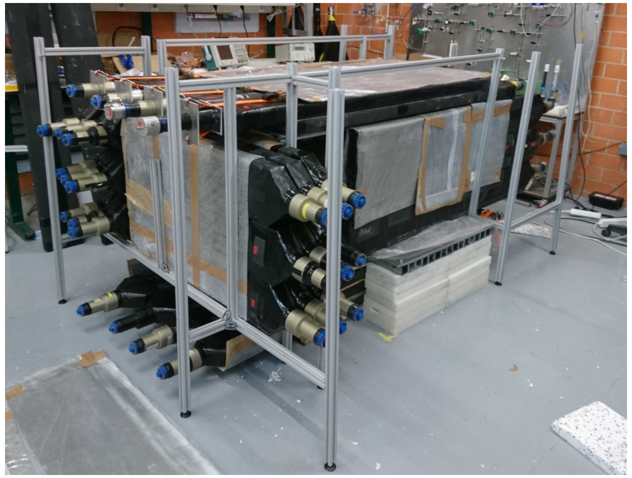






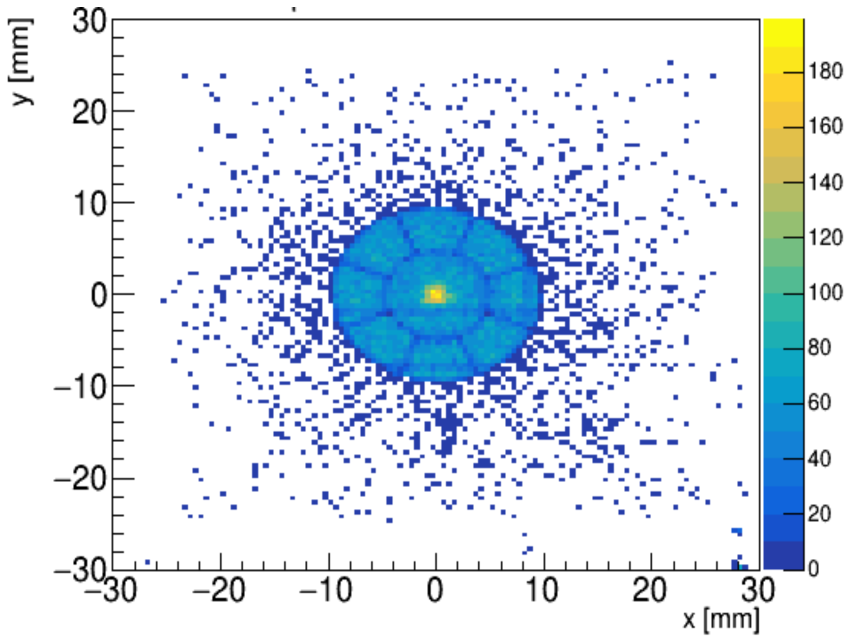
- Signal reaches the active volume through a mylar window
- X-rays ionize the gas in the conversion region and the produced signal is read by the Micromegas
- Data is analyzed with the REST-for-Physics framework (github.com/rest-for-physics)

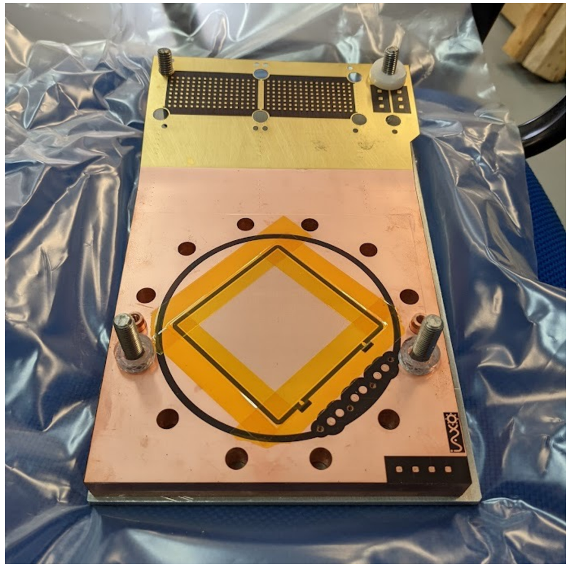
- Tests at Zaragoza (IAXO-D0) (above ground)
- Tests at LSC (IAXO-D1) (Canfranc Underground Laboratory)
- Characterize detector and background model: intrinsic vs cosmogenic background
- This is an ultra low-background experiment running above ground… very specific challenges!
- Cosmogenic background model is key



Micromegas detector

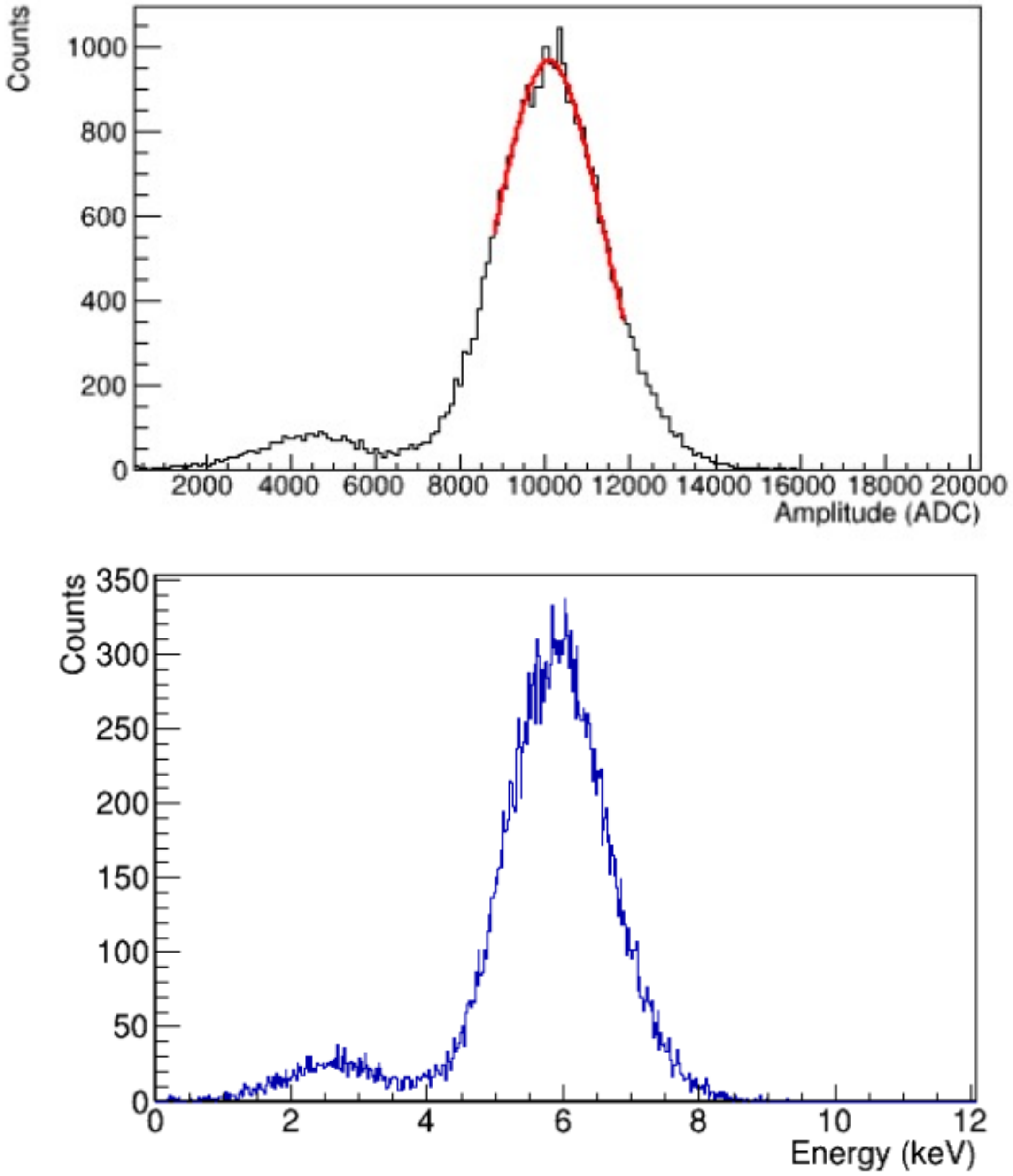
- Gaseous detector: Ar/C4H10 or Xe mixtures
- Microbulk micromegas: 6x6cm^2, 2x120 strips (500um pitch)
- **Radiopure**
- 20 cm of lead shielding (inner layer ancient roman lead)
- Mylar window as interface between gas and vacuum: very thin and transparent to x-rays
- Calibration with 55Fe source inside the pipe





Sample calibration run:

- 55Fe calibration source (5.9 keV peak)
- Ar + 1% isobutane (C4H10)
- Gas flow at 2 L/h (open loop)
- Pressure at 1.25 bar
- HV mesh 320V – HV drift 750V



Research group has extensive experience in radiopurity:

- Screening of detector components in LSC with germanium detectors: built a radiopurity database (epoxy glue, SMD resistors, capacitors, etc.)
- Work with micromegas detector manufacturers for radiopurity in manufacturing (materials, etching acids…)
- Simulation of known contaminants and their contribution to the background: 39Ar, 210Pb, 238U, 232Th, …

- A very detailed background model is critical
- Simulations using Geant4 and REST-for-Physics
- Contributions:
  - Contamination / radiogenic activation (vessel, shielding, electronics…): 238U, 232Th, 40K, 210Pb…
  - Environmental: gammas (from 238U, 232Th), neutrons…
  - Gas (39Ar)
  - Cosmic rays:
    - Muons
    - Gammas
    - Neutrons

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- A very detailed background model is critical
- Simulations using Geant4 and REST-for-Physics
- Contributions:
  - Contamination / radiogenic activation (vessel, shielding, electronics…): 238U, 232Th, 40K, 210Pb… → Radiopurity
  - Environmental: gammas (from 238U, 232Th), neutrons… → Shielding
  - Gas (39Ar) → Radiopure Ar / Use Xe (not limiting background)
  - Cosmic rays:
    - Muons → Muon vetos (scintillators) with 4pi coverage + cuts
    - Gammas → No clear solution, but background is low enough
    - Neutrons → Difficult / impossible to remove completely via cuts. Novel solution under development: **neutron tagging system**

- REST (Rare Event Searches Toolkit) is a **ROOT** based event-oriented data processing and analysis framework
- Created in University of Zaragoza from an effort to unify our experimental and analysis activities in a common environment. First "established" version from (~2014-2015)
- Used and contributed to by users from different institutions such as University of Zaragoza, University of Barcelona (Spain), University of Shanghai (China) or CEA Saclay (France)
- Made for physicists by physicists, in an academic environment
- Composed by different modular libraries and packages
- Can be used for simulation (Geant4) of background and signal, detector response, analysis…
- Unified event format for experimental and MC data, (mostly) same analysis chain
- REST provides ready to use examples. This is especially useful for (undergraduate) students

- REST official publication: https://doi.org/10.1016/j.cpc.2021.108281 (arxiv)
- Initially developed for rare event searches with TPC (time projection chamber), but not limited to this!
- Used in multiple experiments:
    - PandaX-III: $0\nu\beta\beta$ of 136Xe using high pressure gaseous TPC
    - TrexDM: Low mass WIMPs using high pressure gaseous TPC (Micromegas readout)
    - IAXO: Proposed solar axion detection platform
- Used extensively in research and teaching for undergraduate / graduate theses
- Software framework of the IAXO collaboration

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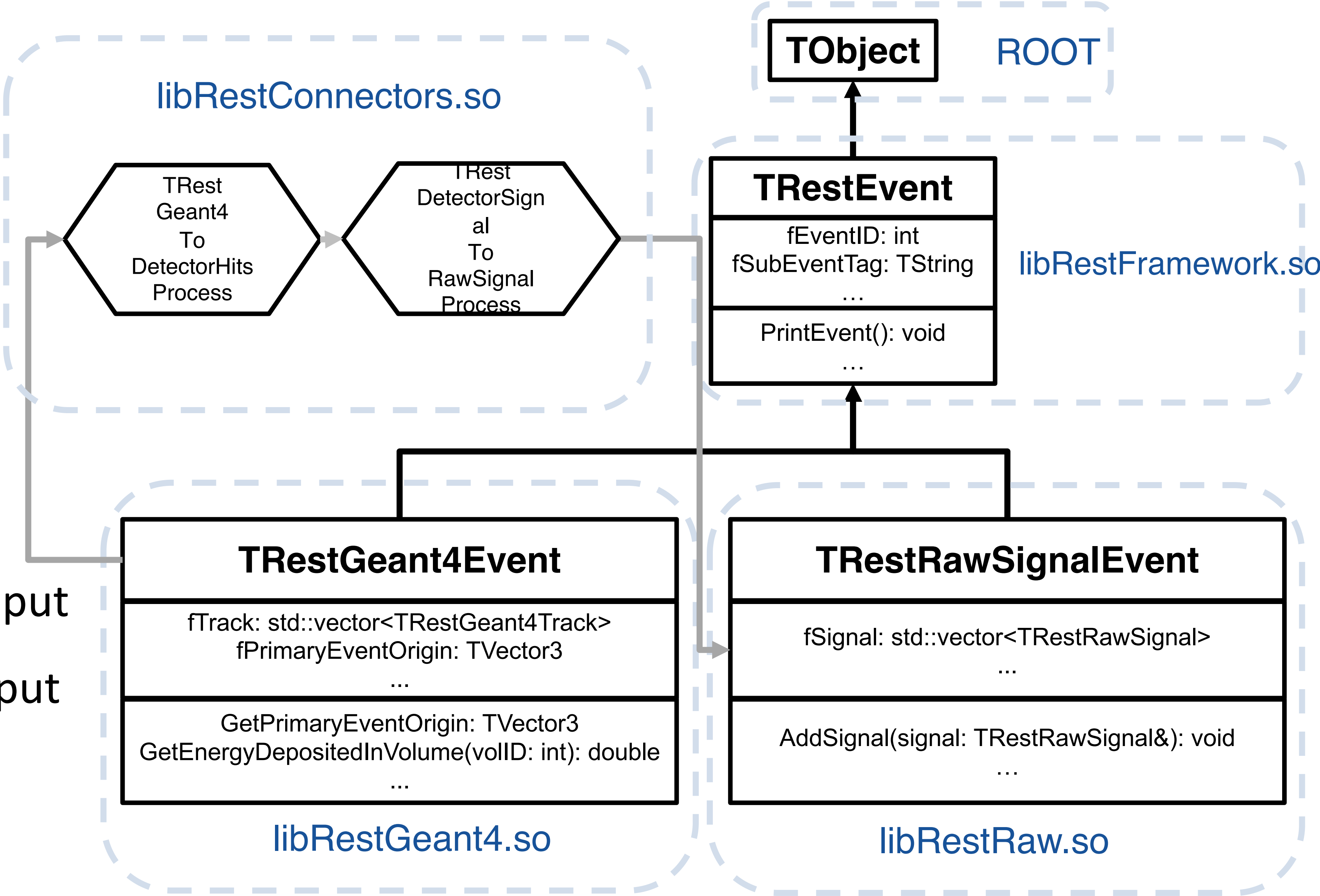
- **REST** is **event oriented**.
- Many kinds of events:
  - ***TRestGeant4Event***
  - ***TRestDetectorSignalEvent***
  - ***TRestRawSignalEvent***
  - **…**
- ***Event Processes*** take an input event and produce an output event



- ***TRestRun***: stores run information (1 run = 1 root file), handles I/O (via ROOT), provides convenient access to some objects
- ***TRestMetadata***: serialization/deserialization (XML), handles user configurations and persistence. Every user configurable object inherits from this class
- **TRestEvent**: run data is stored in a **TTree** with different types of **TRestEvent** as branches
- **TRestEventProcess**: base for all analysis processes: input event -> output event
- **TRestAnalysisTree**: TTree derived class, hosts event level observables produced by different processes, which can later be used in cuts…

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EventTree (TTree) for event storage

TRestRun object for run management

```
root [0] .ls
TFile**        filename
 TFile*
  OBJ: TTree     EventTree        TRestTrackEventTree : 0 at: 0x55cfeccd0f80
  OBJ: TRestAnalysisTree          AnalysisTree    REST Process Analysis Tree : 0 at: 0x55cfecf8f500
  KEY: TRestRun  IAXOD0-2021;2    IAXOD0 2021 data taking
  KEY: TRestProcessRunner         Signals;1       Signal to track analysis
  KEY: TRestDetectorSignalToHitsProcess signalToHits;1  A Signal To Hits reconstruction template.
  KEY: TRestDetectorHitsAnalysisProcess hitsAna;1       Hits analysis template
  KEY: TRestDetectorHitsGaussAnalysisProcess      hitsAnaGauss;1  defaultTitle
  KEY: TRestDetectorHitsToTrackProcess  hitsToTrack;1
  KEY: TRestTrackAnalysisProcess        tckAna;1        Track analysis template
  KEY: TTree     EventTree;1      TRestTrackEventTree
  KEY: TRestAnalysisTree          AnalysisTree;1  REST Process Analysis Tree
  KEY: TRestProcessRunner         RawSignals;1    Raw processing and analysis
  KEY: TRestRawMultiFEMINOSToSignalProcess        virtualDAQ;1    defaultTitle
  KEY: TRestRawVetoAnalysisProcess      veto;1  defaultTitle
  KEY: TRestRawSignalAnalysisProcess    sAna;1
  KEY: TRestRawZeroSuppresionProcess    zS;1
  KEY: TRestDetectorSignalChannelActivityProcess        chActivity;1    Channel activity process
  KEY: TRestDetectorReadout       iaxo_readout;2  IAXO D0 readout 0.5 mm-Pitch 120+120 channels
root [1]
```

AnalysisTree (TRestAnalysisTree) for analysis observables

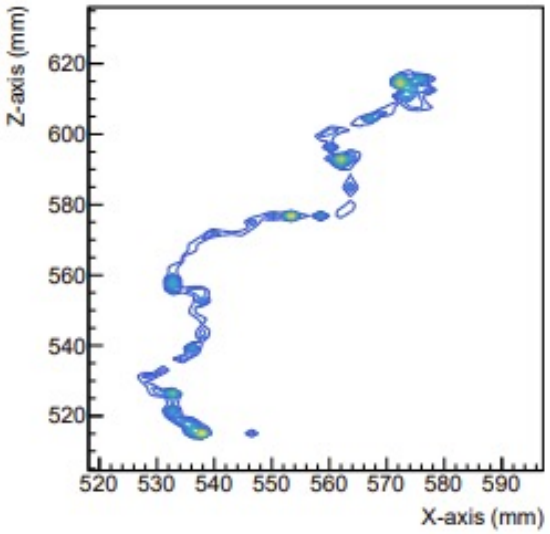
Analysis process metadata for traceability

Example processing

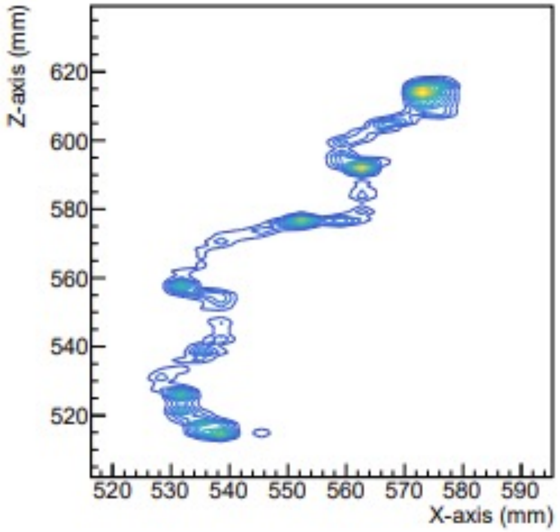
TRestGeant4Event → TRestGeant4To DetectorHitsProcess → **TRestDetectorHitsEvent**

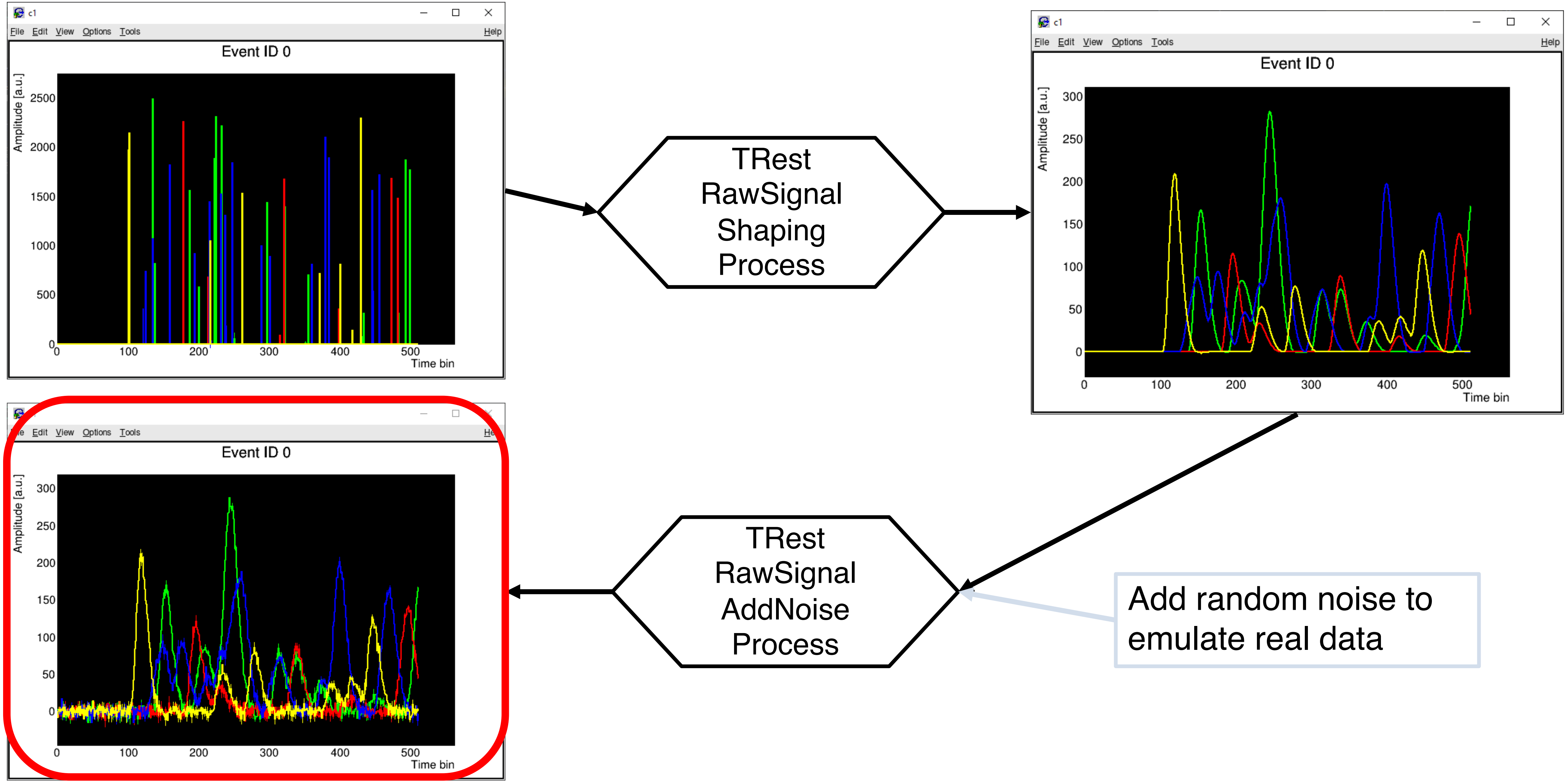
Store a set of {position, energy} hits, remove Geant4 track information, step processes names…
Ignore hits outside detector volume

TRestDetectorHitsEvent → TRestDetector ElectronDiffusionProcess → **TRestDetectorHitsEvent**



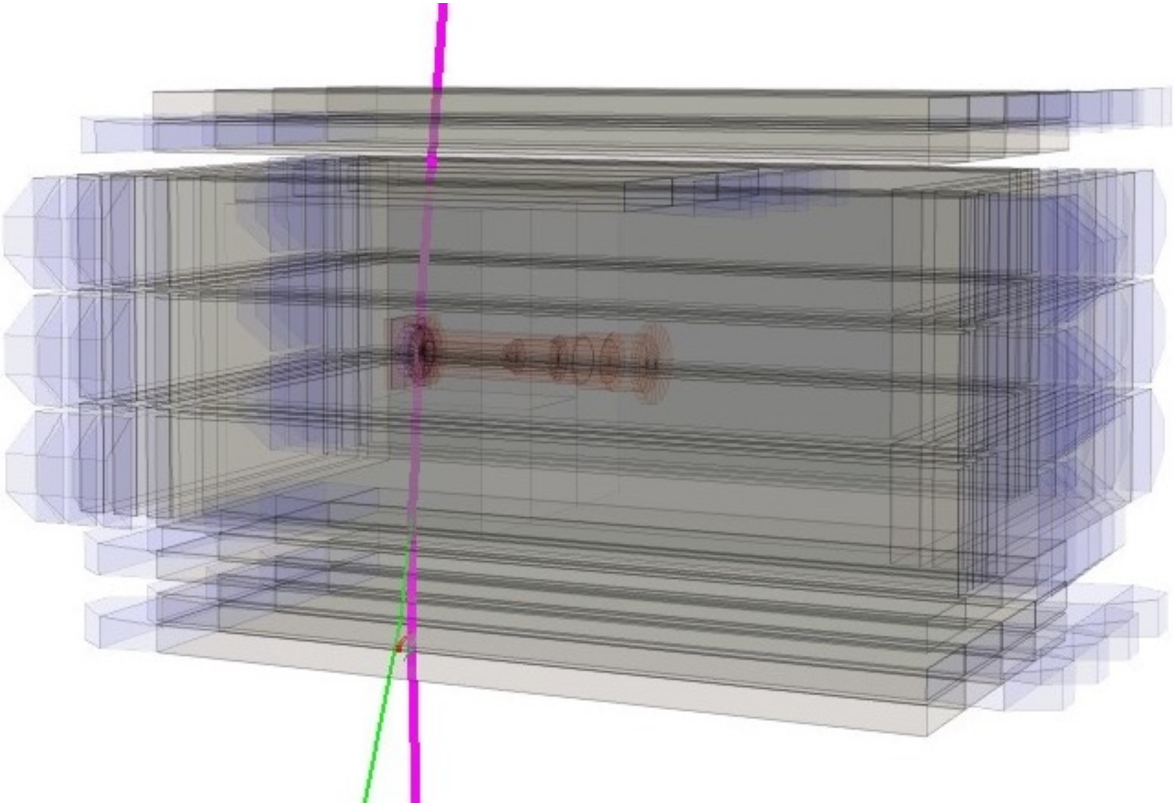
Geant4 simulation produces hits in gas (sensitive volume)
This process simulates the drift of electrons and diffusion, using detector properties such as drift electric field, gas properties and readout position




Event ID 0
Amplitude [a.u.]
Time bin
TRest RawSignal Shaping Process
Event ID 0
Amplitude [a.u.]
Time bin
TRest RawSignal AddNoise Process
Add random noise to emulate real data
Event ID 0
Amplitude [a.u.]
Time bin

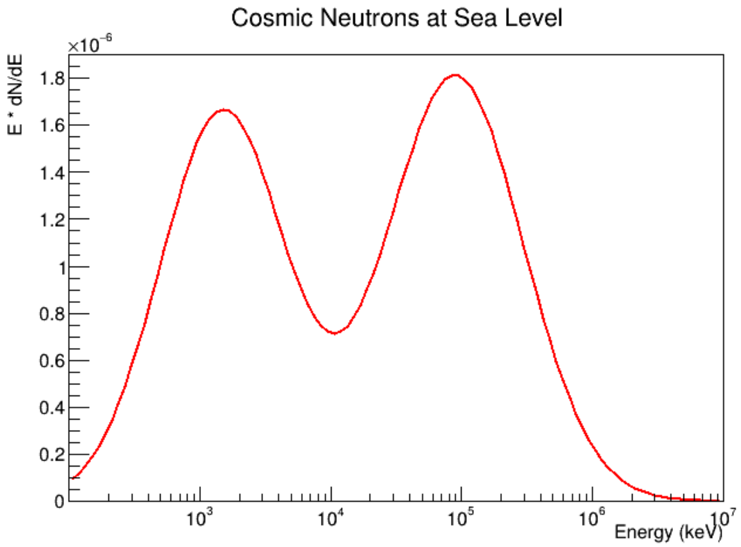
- Cosmogenic background: particles produced from cosmic rays: muons, neutrons, HE gamma…
- Low-background experiment above ground…
- Monte-Carlo simulations (Geant4 / restG4)
- Cosmogenic neutrons: assumed main source of background
- Background reduction:
  - Shielding: not very effective
  - Discrimination: sophisticated tagging system

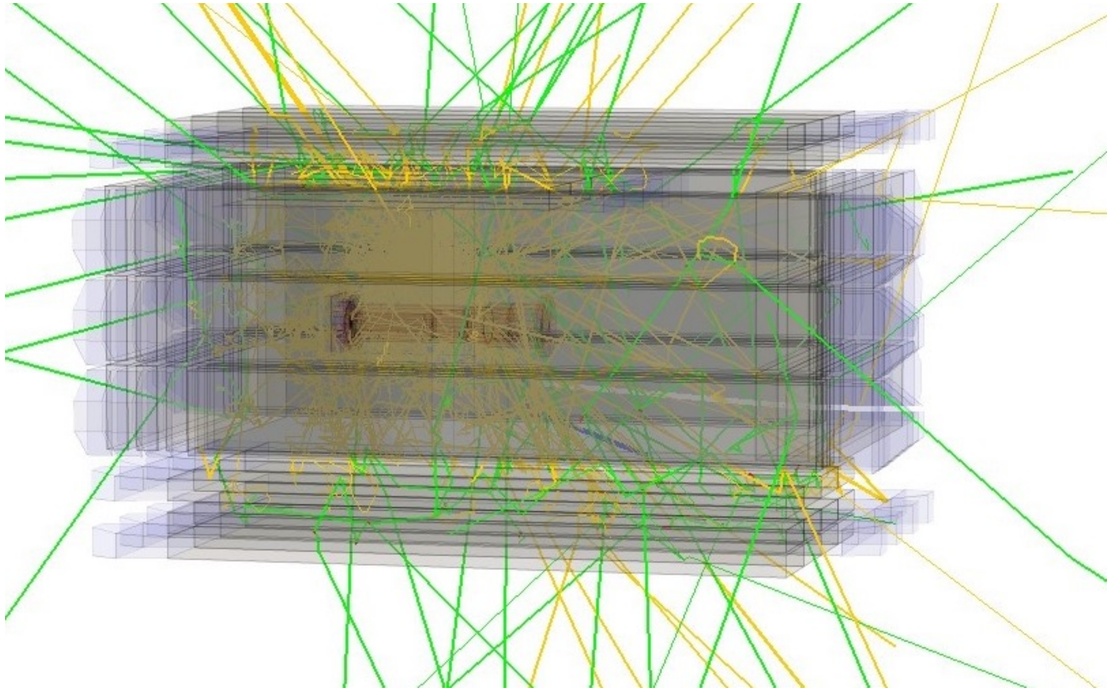
- Multi-layer veto system

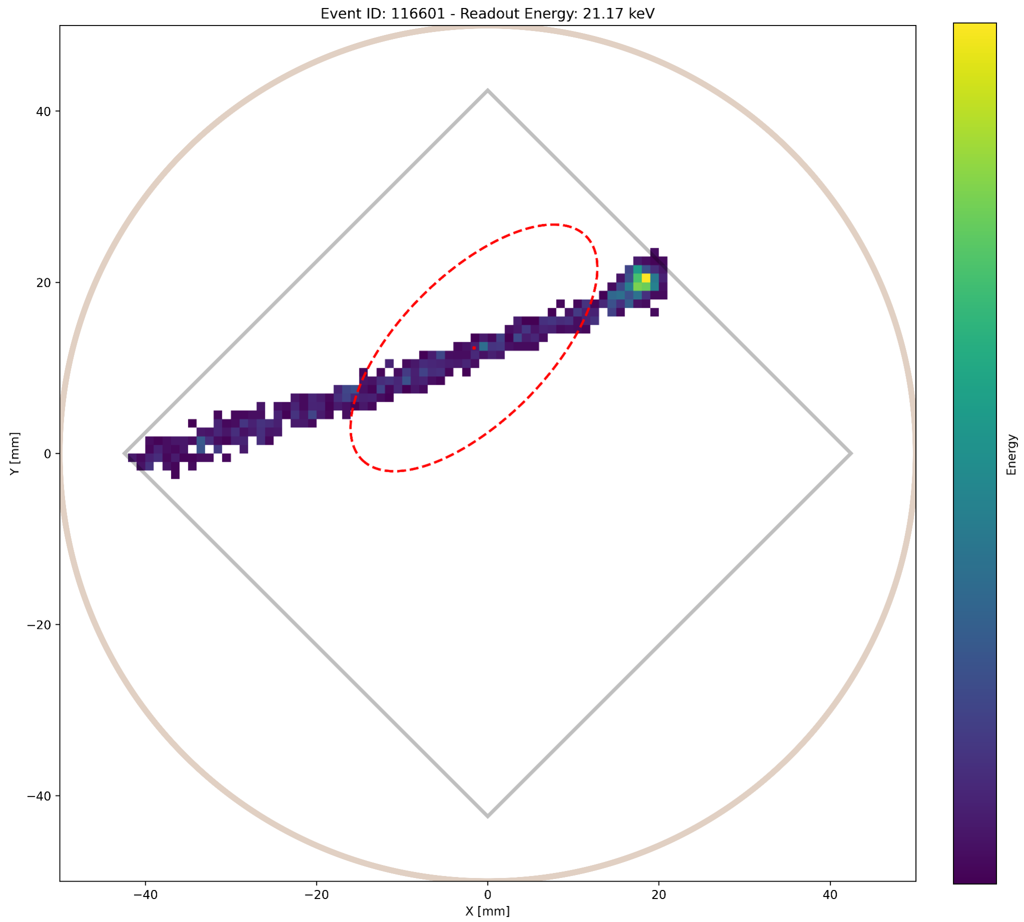


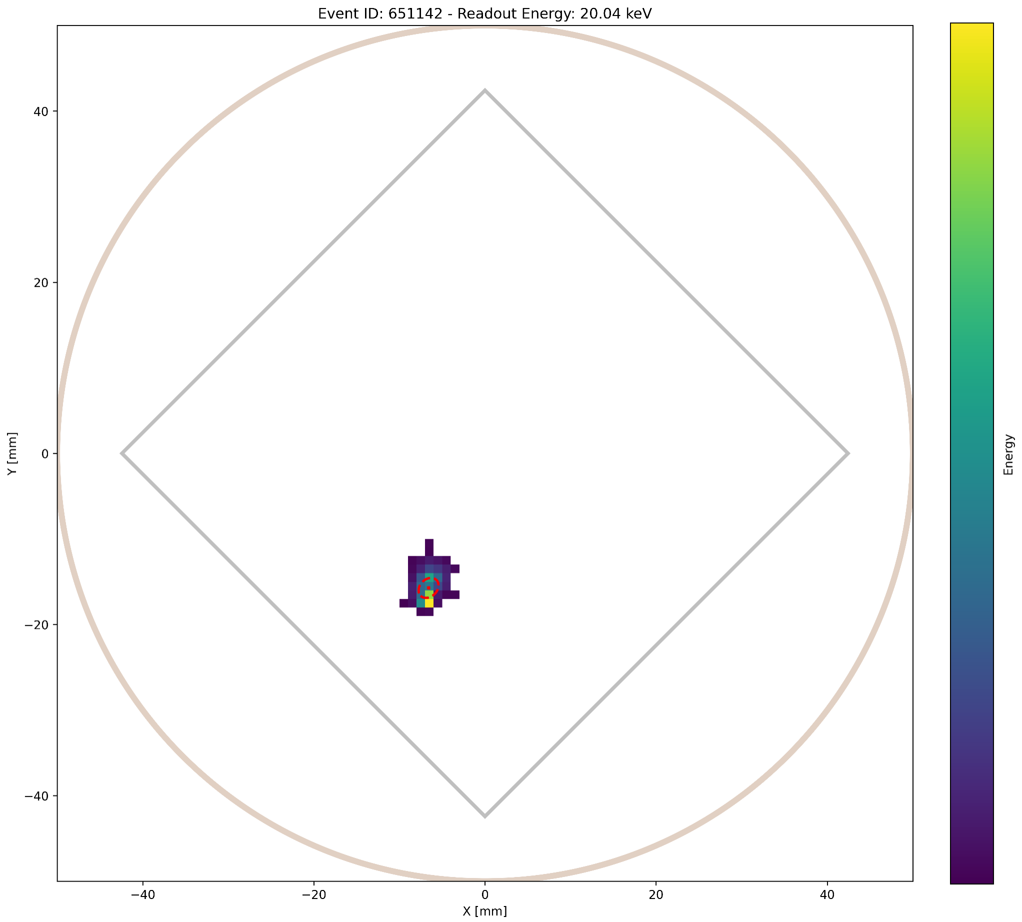
Cosmogenic neutrons:

- High energy: hard to shield from
- Extensive secondary production in the shielding
- Interaction in the detector is signal-like: point-like interaction in the energy RoI
- No clear spatial pattern unlike muons
- Plastic scintillator vetoes not as efficient

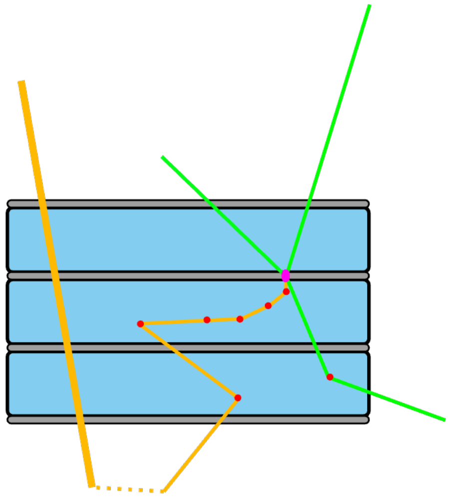




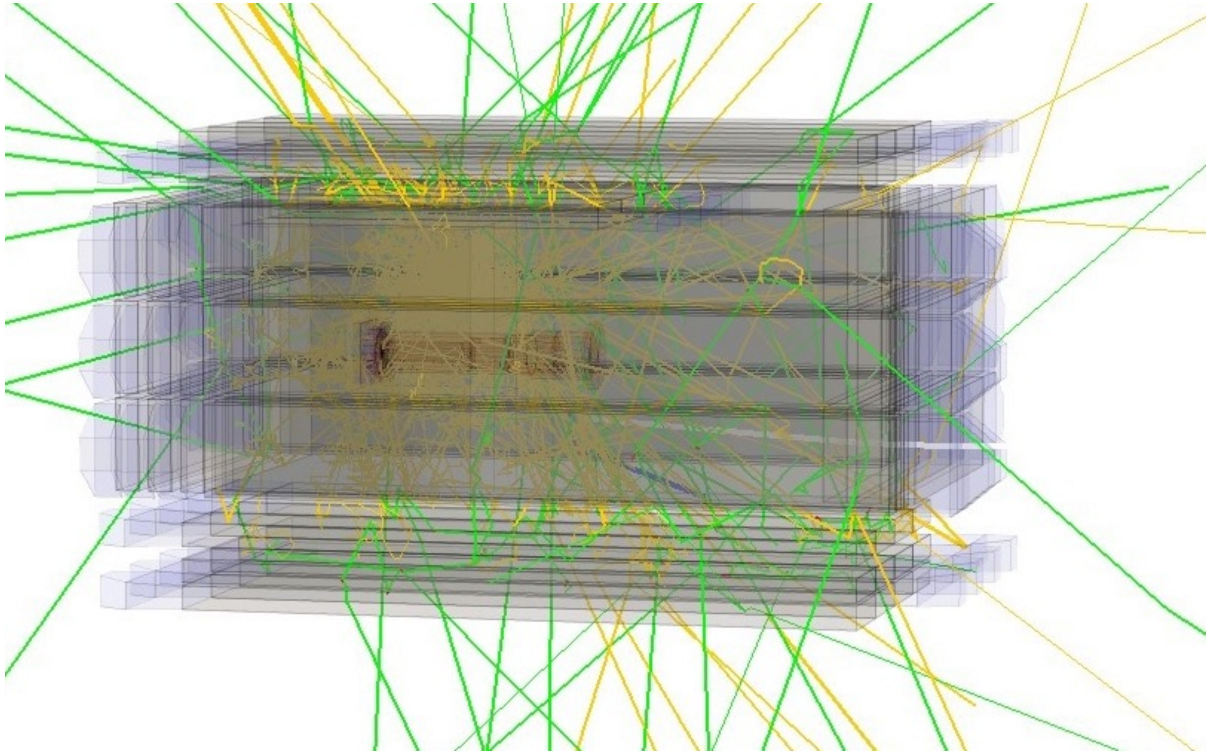

Event ID: 116601 - Readout Energy: 21.17 keV
Y [mm]
X [mm]
Energy

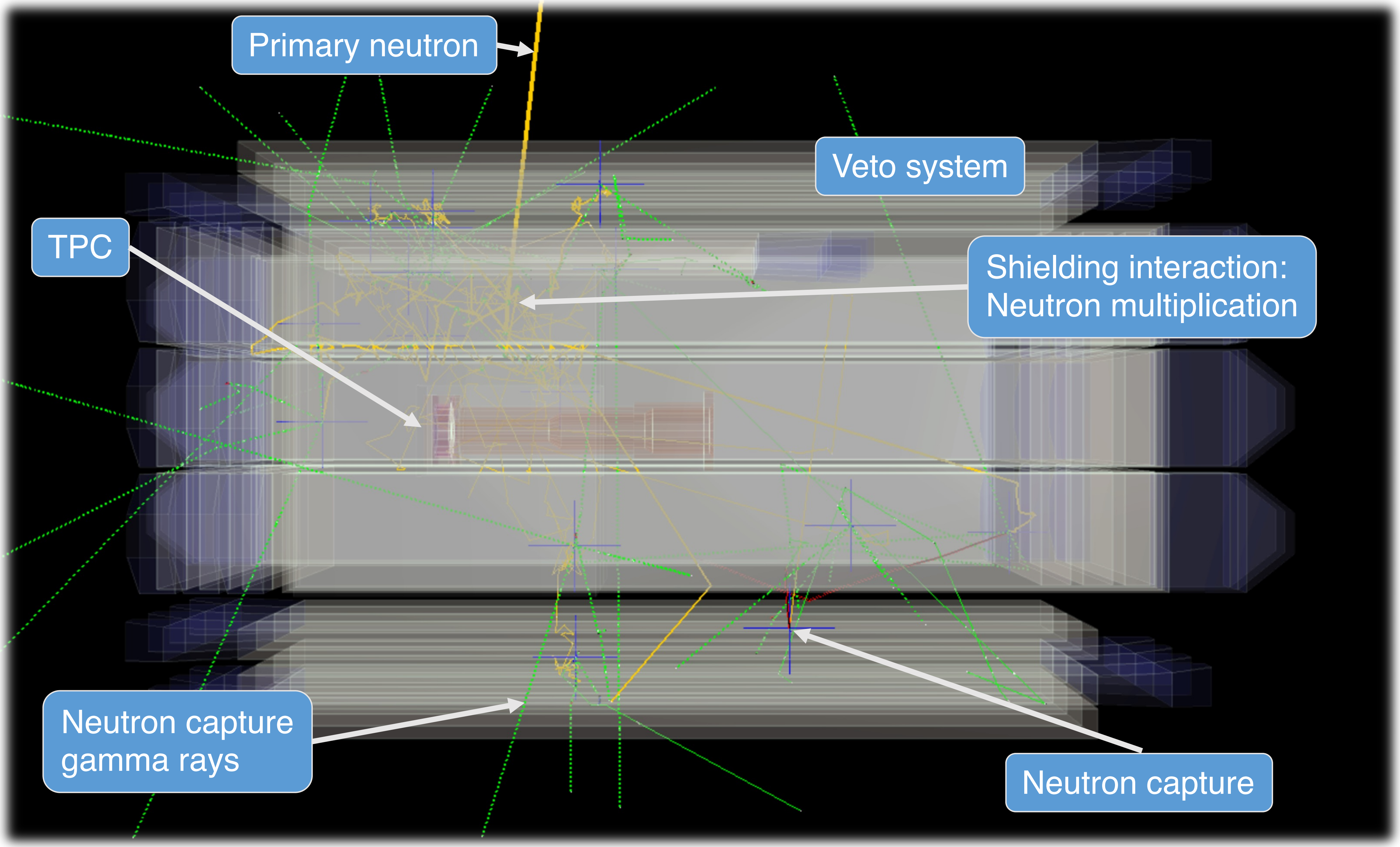

Event ID: 651142 - Readout Energy: 20.04 keV
Y [mm]
X [mm]
Energy

Neutron tagging strategy:



- Take advantage of secondary production
- Most secondaries produced in shielding
- Energy deposited in vetoes is quenched
- Layer veto system with Cd sheets to produce neutron captures
- Use vetoes to detector photons produced by captures

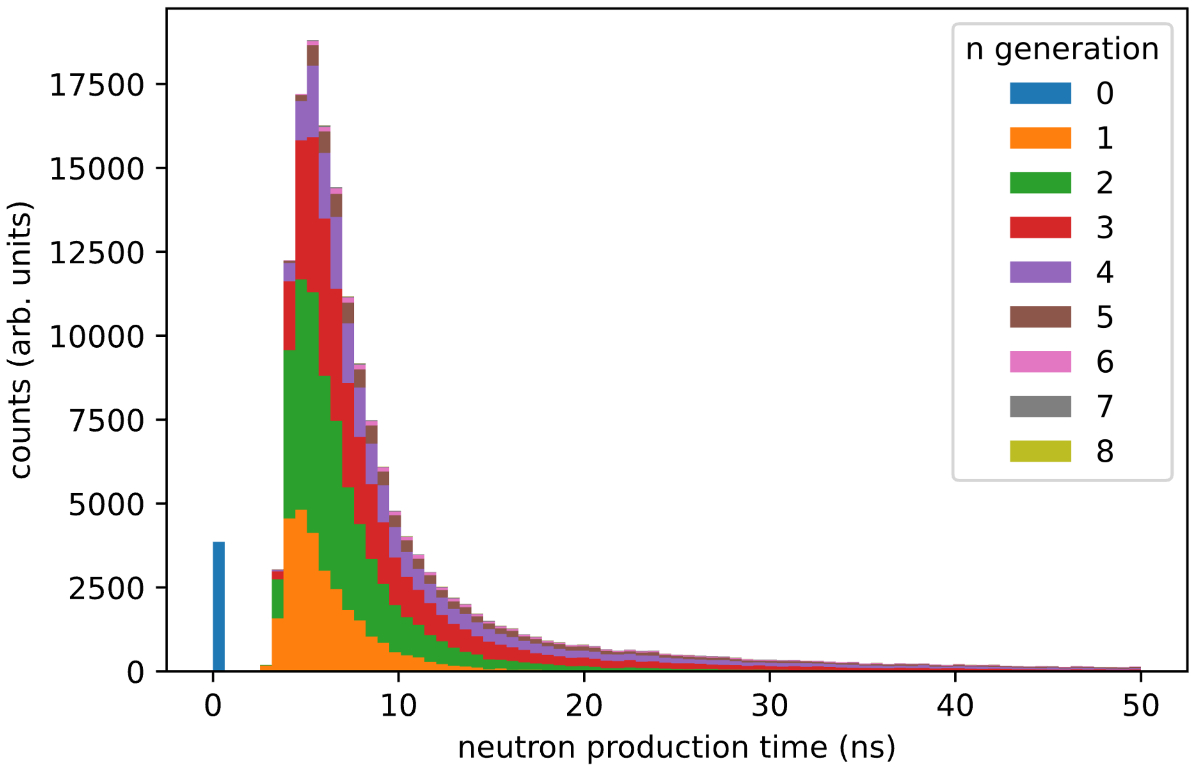


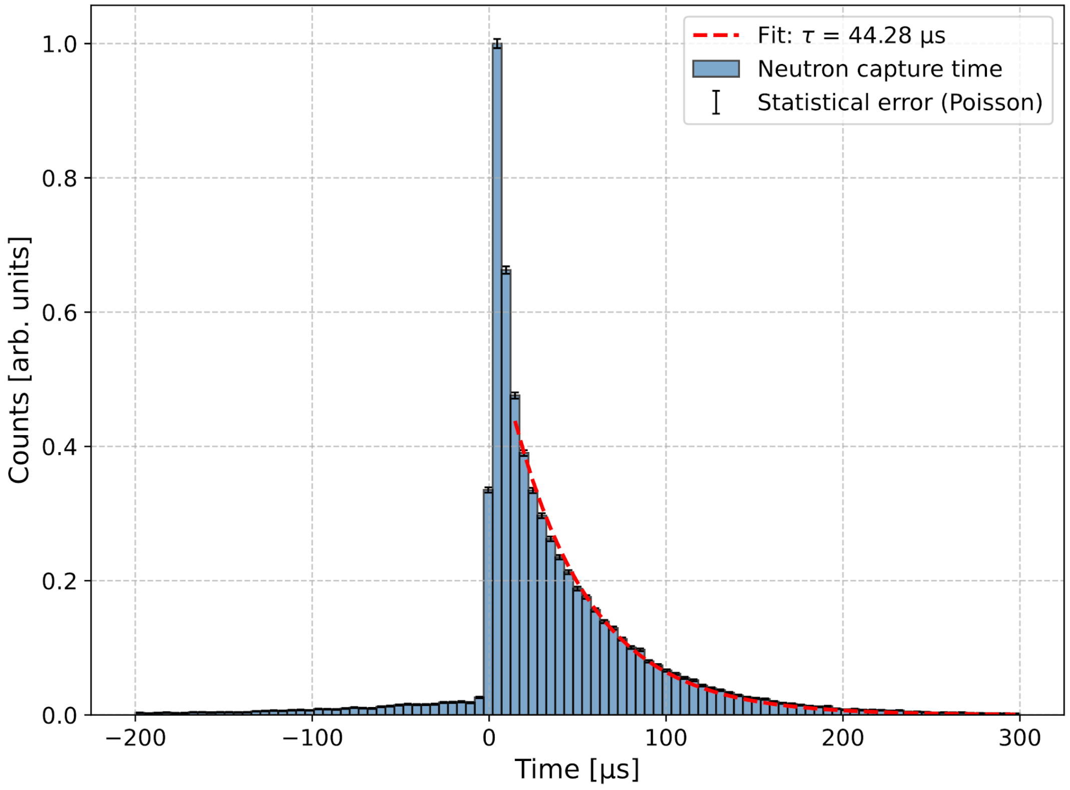

Primary neutron
Veto system
TPC
Shielding interaction: Neutron multiplication
Neutron capture gamma rays
Neutron capture

The detector time scale is given by the gas drift velocity (order of cm/us)

Secondary neutrons are produced virtually instantaneously

Neutron captures are delayed: need to tune acquisition window



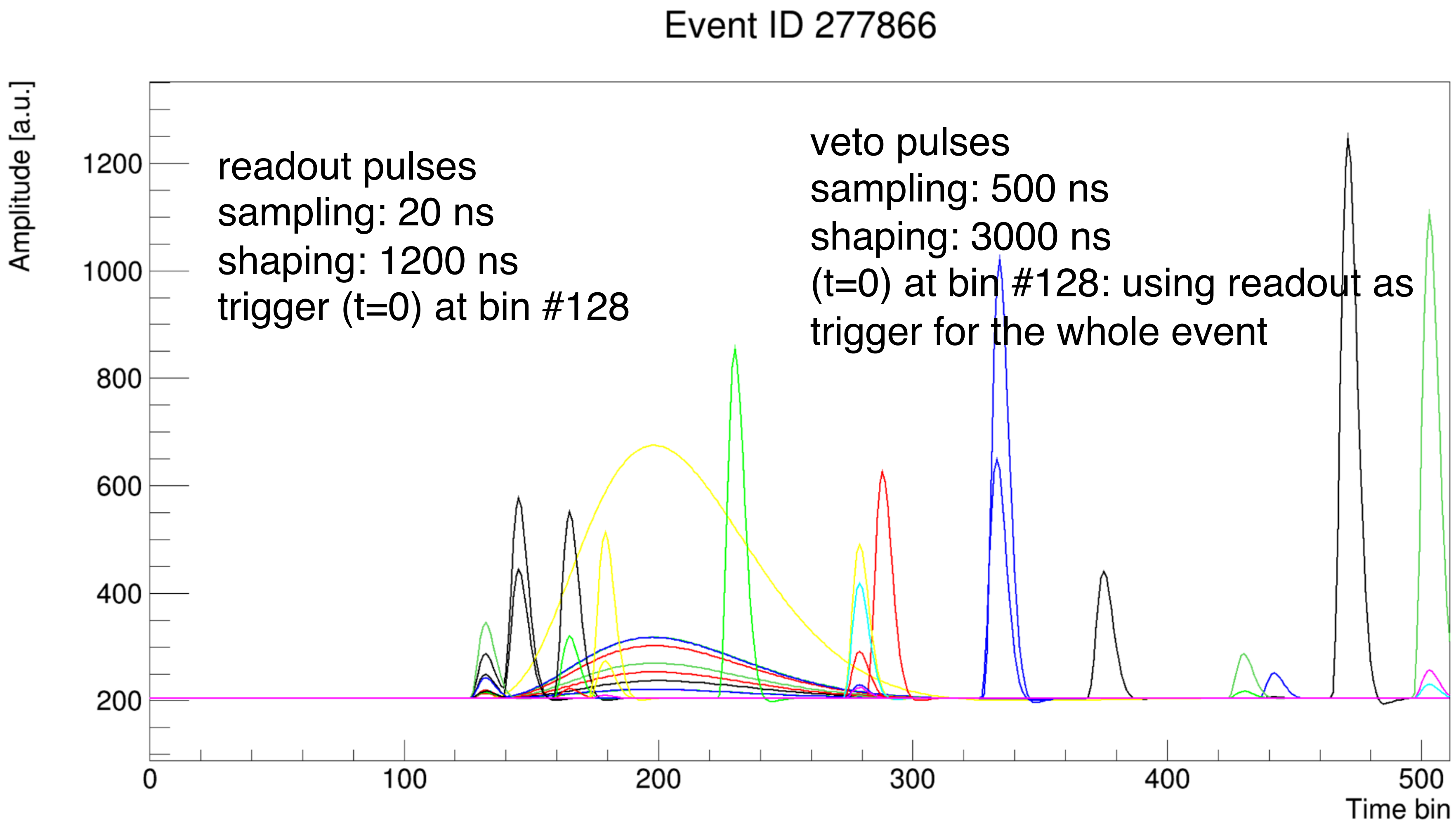


Veto signal simulation:

Pulses grouped in bunches (same neutron capture)

Delayed according to capture time distribution

Spatial pattern?



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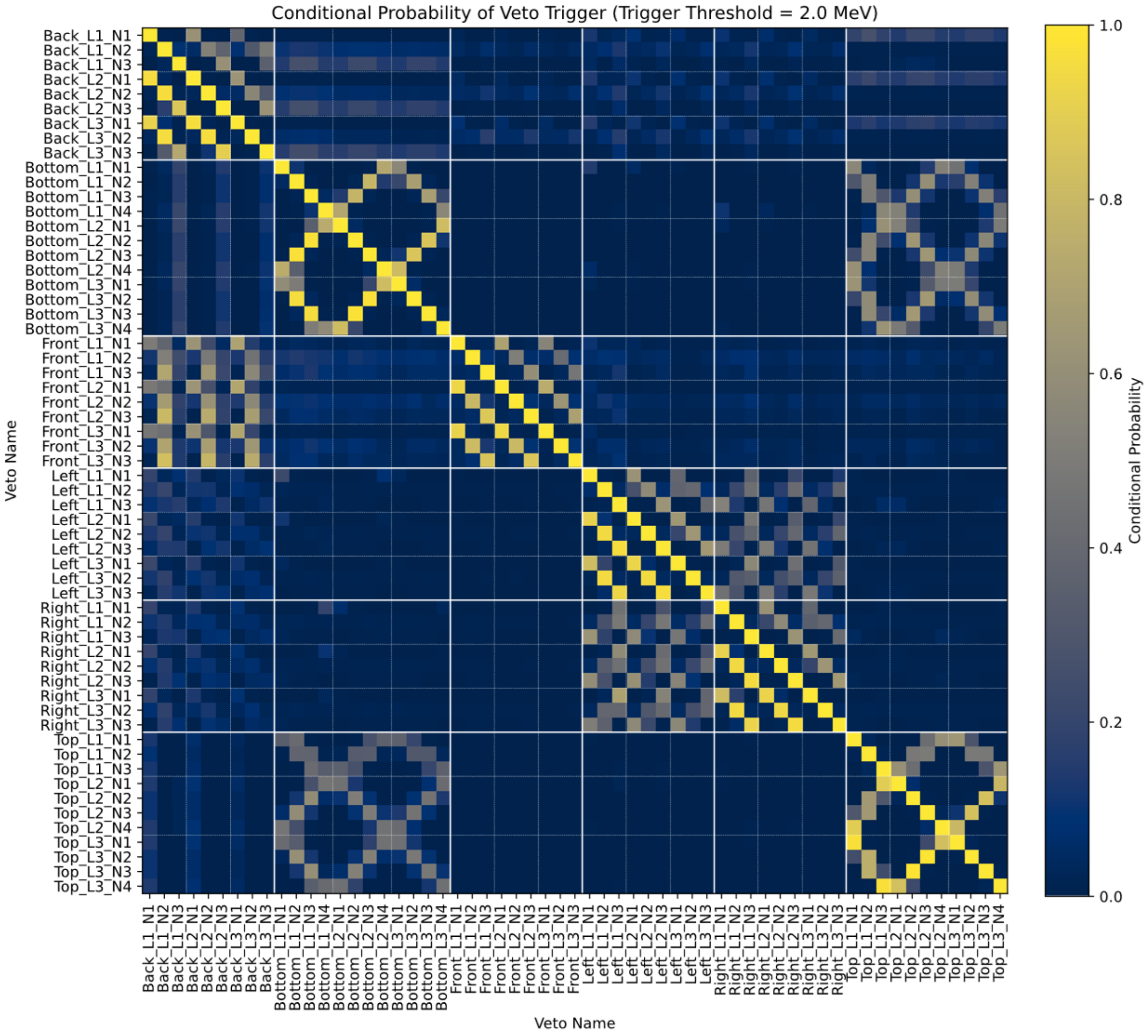
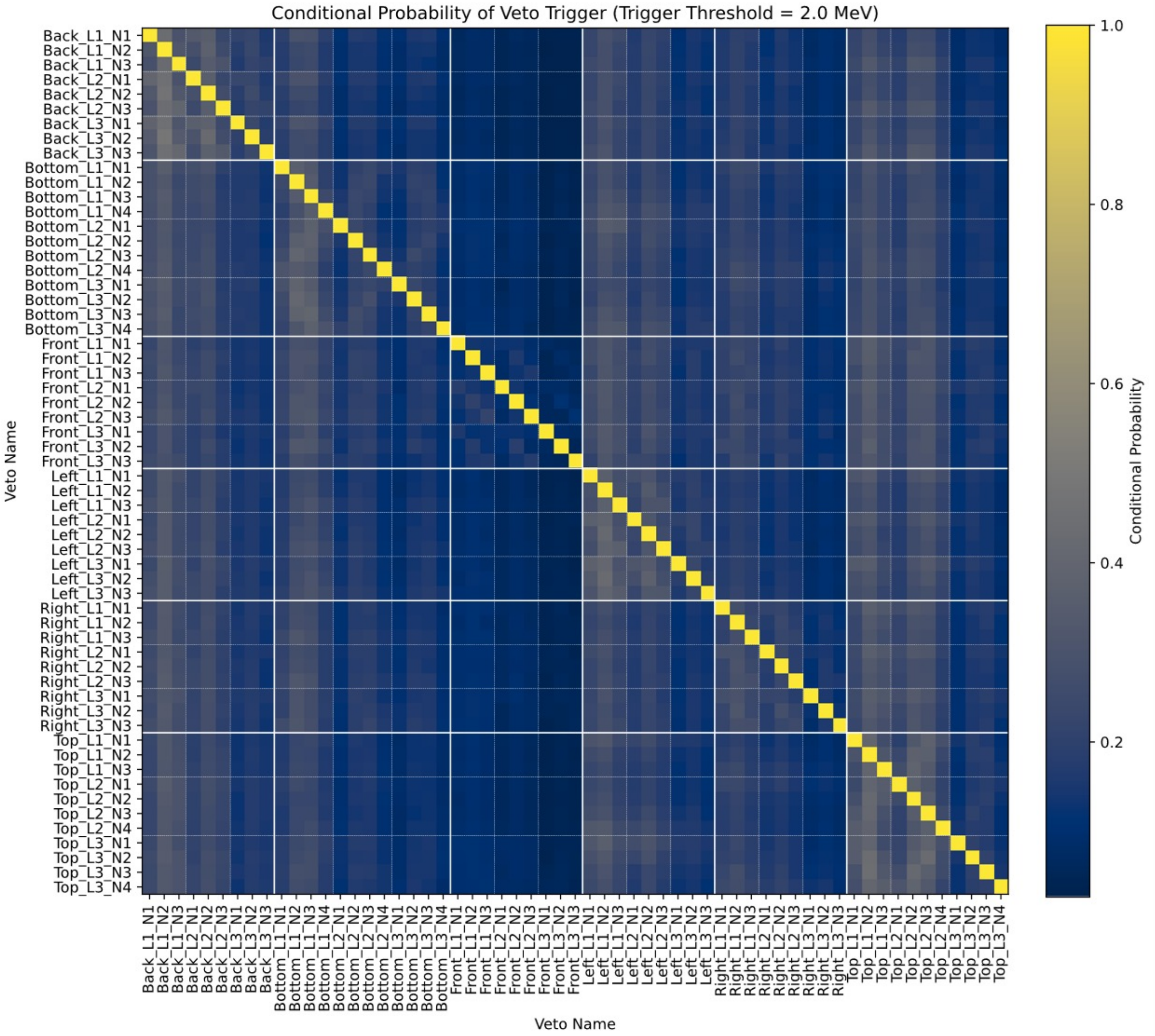
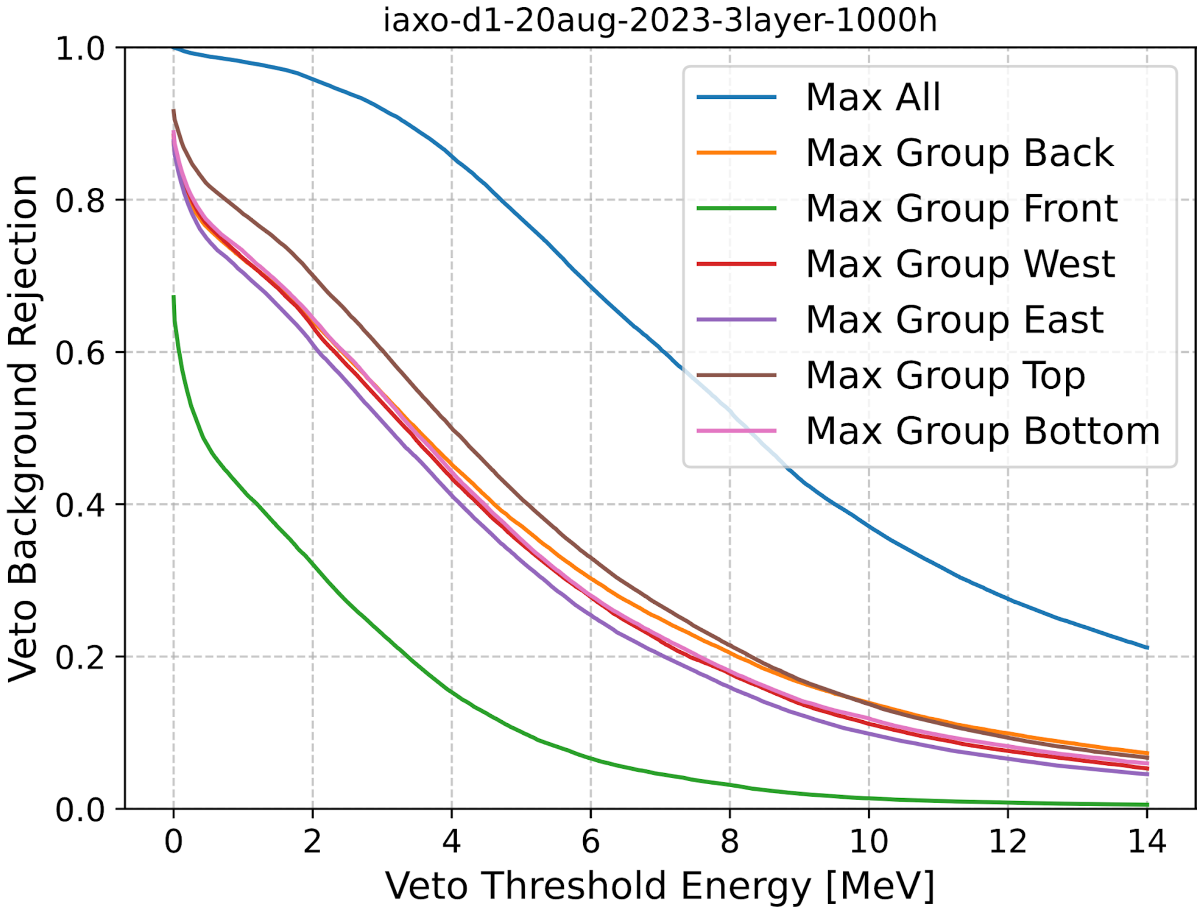
Muons: clear pattern



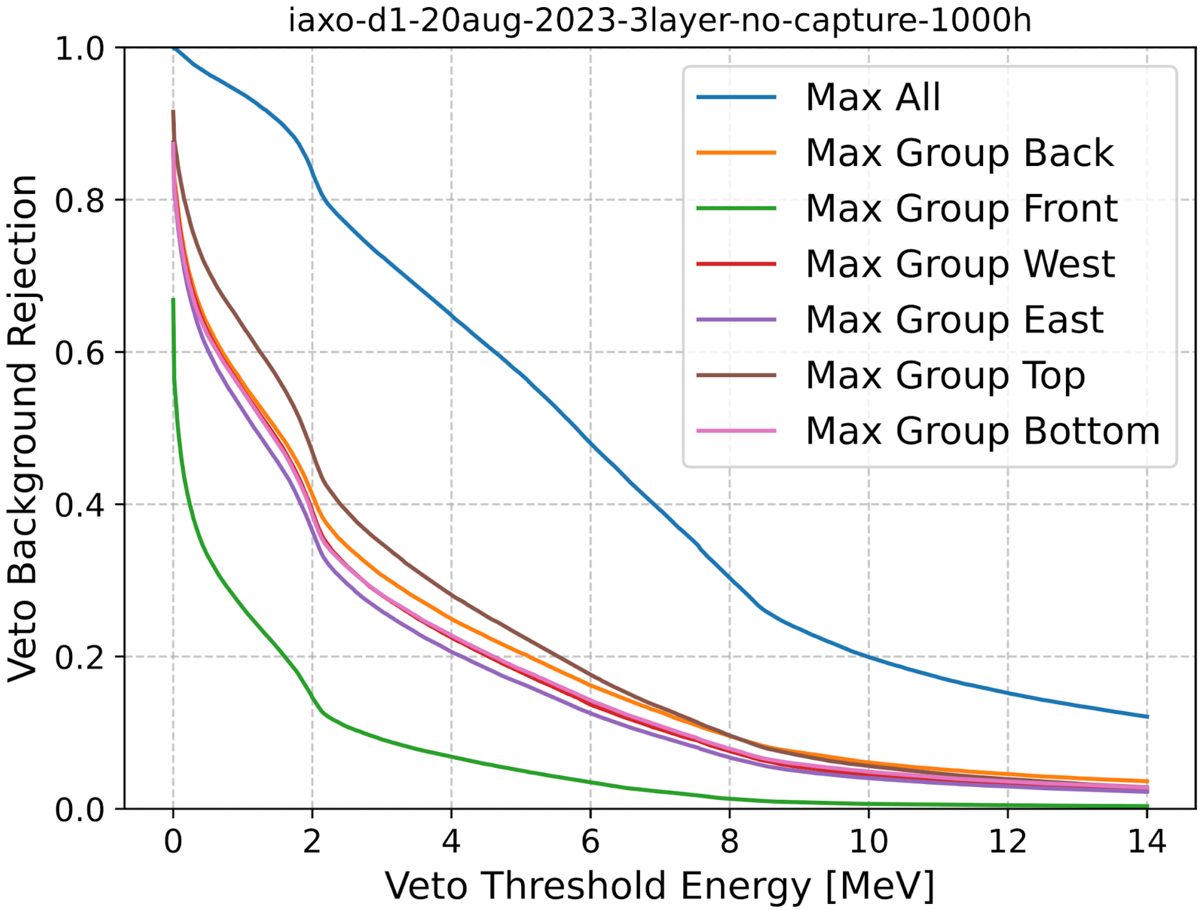
Neutrons: no significant pattern



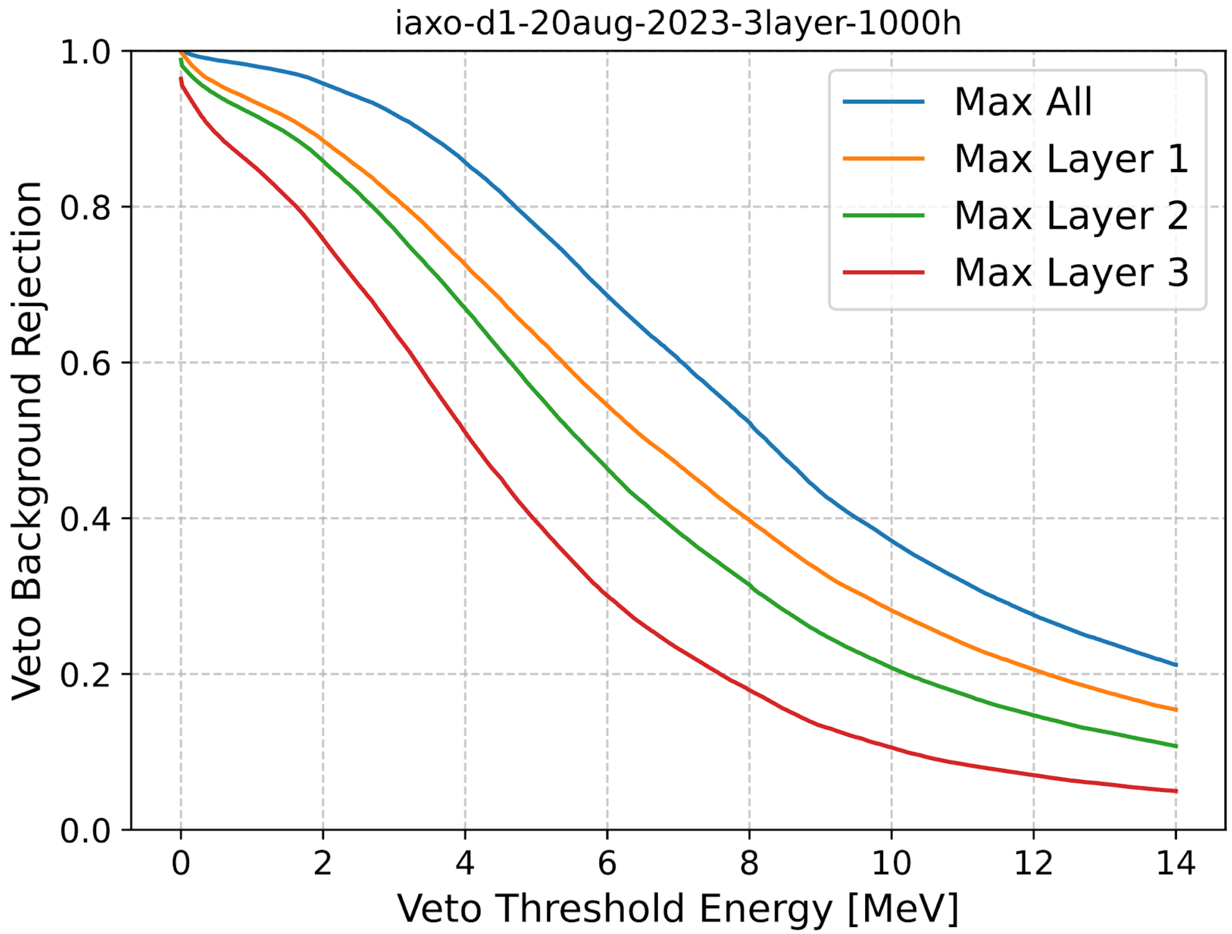
Capture layer



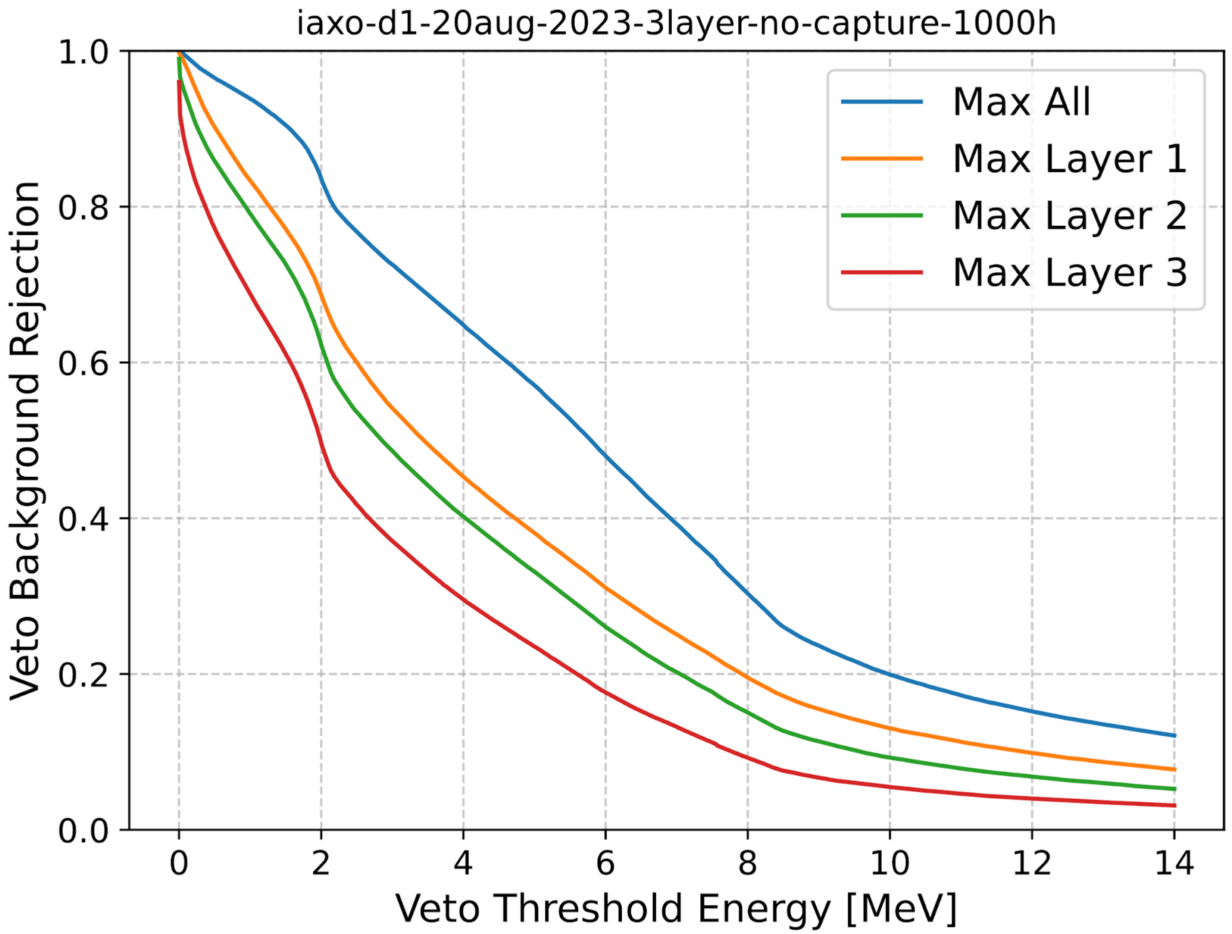
No capture layer



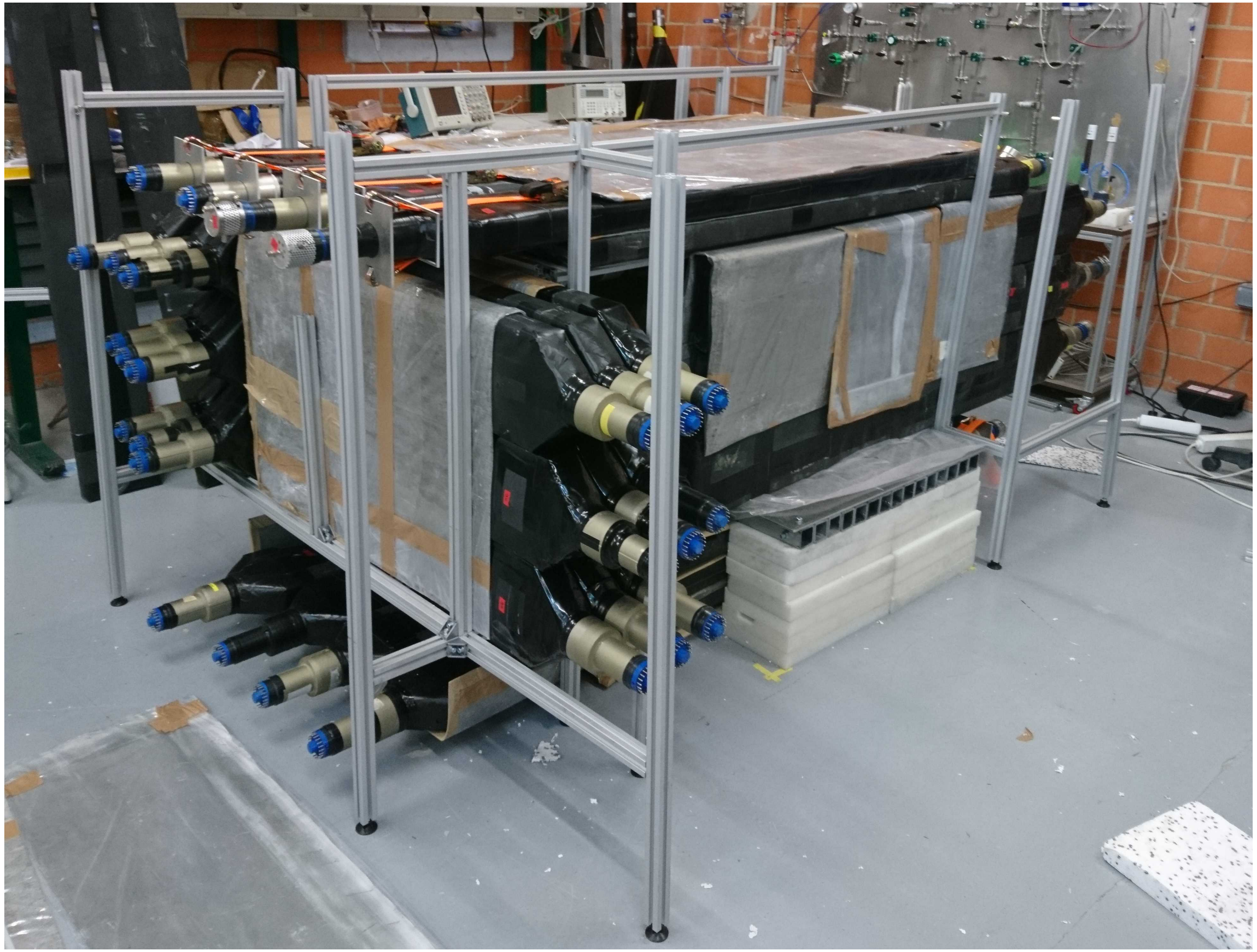
Capture layer



No capture layer



- Cosmogenic background levels are dependent on primary particle flux (needs to be measured), can be roughly estimated
- Ongoing studies to characterize this cosmogenic neutron flux
- Ongoing experimental work to tag cosmogenic neutrons



- Axions are interesting targets: CP problem, DM candidates (alternative to WIMPs)
- IAXO will probe an important region of the parameter space (QCD band)
- IAXO faces unique challenges in background reduction: ultra-low background above ground
- Micromegas detectors are a solid technology with proven track record on low background applications (CAST), but other detector technologies will also be used