Low Background MICROMEGAS in CAST

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On behalf of CAST/IAXO-Micromegas group.

7\textsuperscript{th} Symposium on Large TPCs for Low-Energy Rare Event Detection.

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Outline

• Axion helioscopes: CAST & IAXO.
• Micromegas in CAST.
• Background level and background model.
• Prospects for:
  - background reduction
  - lowering the energy threshold
• Conclusions.
Axion detection by an helioscope

**Production:** *Primakoff effect.* Thermal photons interacting with solar nuclei produce axions.

**Detection:** *inverse Primakoff* Axions in a magnetic field convert to photons.

**Axion Signal:** x-ray excess when the magnet points to the Sun. → need of low background x-ray detectors.

- Conversion probability depends on medium.
- In vacuum coherence is lost for $m_a > 0.02$ eV.
- In the presence of a buffer gas, the coherence can be restored for a narrow mass range.

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*Serpico & Raffelt, JCAP04 (2007) 010*

*Sikivie 1983, PRL 51 1415-1417*

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CAST: CERN Axion Solar Telescope

MAGNET:

- Length: 9.3 m.
- Field: 9 T.
- Apperture: 14.5 cm² (x2).
- Range of movement: 80° horizontally and ± 8° vertically.
- Solar tracking possible during sunrise and sunset (2 x 1.5 hours per day).

- CAST is operating at CERN since 2003, most sensitive helioscope so far.
- An important improve in sensitivity to axions and ALPs is only expected with a fully new helioscope as proposed by IAXO (4 orders of magnitude better in S/N wrt CAST, i.e. 1-2 orders in $g_{a\gamma}$). See Esther Ferrer-Ribas talk, «The IAXO helioscope».
CAST Physics program

1) CAST Phase I, Vacuum
   - $m_a < 0.02$ eV; $g_{aY} < 0.88 \cdot 10^{-10}$ GeV$^{-1}$.
   

2) CAST Phase II, $^4$He
   - $P < 13.4$ mbar (1.8K), 160 steps
   - $0.02 < m_a < 0.39$ eV; $g_{aY} < 2.2 \cdot 10^{-10}$ GeV$^{-1}$
   
   \textit{JCAP02 (2009) 008}

3) CAST Phase II, $^3$He
   - $P < 120$ mbar (1.8K), 160 steps
   - $0.39 < m_a < 1.17$ eV; $g_{aY} < 3.3 \cdot 10^{-10}$ GeV$^{-1}$
   
   \textit{PRL 107 (2011) 261302 & PRL 112 (2014) 091302}

Current activities

- Revisiting the vacuum phase (2013-2015) with more sensitive detectors.
- Looking for non-hadronic axions and other WISPs (chamaleons, paraphotons, etc.)
CAST X-ray Detectors

- **Sunset:** 2 Microbulk Micromegas detectors.
  - X-ray focusing device + CCD (2003-2013). CCD was replaced by InGrid detector in 2014 *(see Klaus Desch talk, «Ingrid detector in CAST»).*

- **Sunrise:**
  - Microbulk Micromegas detector (with x-ray optics since 2014).
  - X-ray optics produce an increase in S/N of around 150.

Detectors & optics figure of merit:

\[ f_{DO} = \frac{\varepsilon d \varepsilon_o}{\sqrt{ba}} \]

To increase sensitivity:

- increase efficiency of detector & optics \((\varepsilon)\).
- Reduce detector backgrounds \((b)\) and focusing area \((a)\).

Micromegas in CAST

CAST-MMFeatures

- Active area: 6x6 cm² (120x120 strips) microbulk produced at CERN workshop.
- Gas: Ar + 2% C₂H₄ at 1.4 bar.
- Conversion region: 3 cm (100 V/cm).
- Amplification gap: 50 µm (10⁴ V/cm).
- X-ray window: 4 µm aluminized mylar.
- AFTER-based readout electronics.

Mesh 5 µm of copper
Holes 30 µm diameter
Pitch 100 µm
Pads of 400 µm
Thickness 80 µm
Why Micromegas for axion helioscopes?

1) Highly granular readout allows strong background suppression based on signal topology and cluster analysis. 

- We look for x-rays, i.e. punctual energy depositions in a gas.
- High granular Micromegas have high power to discriminate x-rays from backgrounds, which usually present more extended, non-symmetric tracks.
- Daily $^{55}$Fe calibrations define reference data set for signal/background discrimination.

Comparison of a typical x-ray and background event:

![Comparison of a typical x-ray and background event](image)
Why Micromegas for axion helioscopes?

2) Shielding techniques (passive and active) from low background experiments are also applied.

Passive shielding: copper and lead around the detector to block gamma rays + N2 flush to avoid radon progeny around the detector.

Active shielding: scintillators as muon vetos registering the time difference between the Micromegas and scintillator triggers.

3) Intrinsically radiopure, very low radioactivity budget

Why Micromegas for axion helioscopes?

- Gain up to $10^4$, and highly uniform.
- Consolidated fabrication

![Uniformity of gain](image1)

- Good energy resolution
- (12% FWHM at 5.9 keV).
- Stable over long running periods.

![Absolute gain](image2)

Micromegas + X-ray Optics at CAST 2014

- X-ray optics specifically designed and built for CAST.
- XRT installed + commissioned in August 2014.
- Big milestone for CAST → ~150 improve in S/N.
- Pathfinder system for IAXO.
- X-ray source placed in the other side of magnet (13 m away), focused by the x-ray Optics to the Micromegas detector.

Micromegas + X-ray Optics

- Low background Micromegas.
- UNIZAR, CEA
- LLNL, DTU, UC
- 55Fe calibration.

Micromegas Intensity map:

Window + strongback

Micromegas intensity map of x-ray source through the optics.

Focusing spot

• Application of low background techniques: more than 2 orders of magnitude improvement in background over the years.

• **Underground level**: $10^{-7}$ keV$^2$cm$^{-2}$ s$^{-1}$, almost at required IAXO levels.

• XRT+MM in CAST-2014 for the first time below $10^{-6}$ keV$^2$cm$^{-2}$ s$^{-1}$ (< 6 counts per day !!).
Background level at CAST in 2014

XRT/MM Line: below $10^{-6} \text{ keV}^{-2} \text{cm}^{-2} \text{s}^{-1}$: $(8.7 \pm 0.6) \cdot 10^{-7}$ in 670 hours.

SUNSET Detectors CAST-2014

$$\begin{aligned}
& (1.00 \pm 0.06) \cdot 10^{-6} \\
& (0.99 \pm 0.06) \cdot 10^{-6}
\end{aligned}$$

in 1317 hours.

• CAST RoI: [2-7] keV.

• Background spectrum characteristic of an 8 keV x-ray (Cu, K$_\alpha$) + escape peak (5 keV) + 3 keV (Ar, K$_\alpha$).

• Further background reduction requires indentifying the origin of these events.
Background Model based on:

- In-situ measurements at CAST.
- Surface tests at Zaragoza.
- Canfranc Underground Laboratory (LSC): Upgrade CAST-MM replica.
- Geant4 Montecarlo simulations of CAST-MM.

<table>
<thead>
<tr>
<th>Contribution</th>
<th>Background Level (c/keV⁻¹/cm²/s⁻¹)</th>
<th>Technique</th>
<th>FINAL Background Level (c/keV⁻¹/cm²/s⁻¹)</th>
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</thead>
<tbody>
<tr>
<td>Gamma flux</td>
<td>~ 7 x 10⁻⁵</td>
<td>Lead/copper shield</td>
<td>Negligible</td>
</tr>
<tr>
<td>Radon</td>
<td>~ 8 x 10⁻⁷</td>
<td>N₂ flux</td>
<td>Negligible</td>
</tr>
<tr>
<td>Muons</td>
<td>~ 2 x 10⁻⁶</td>
<td>Active veto</td>
<td>~ 7 x 10⁻⁷</td>
</tr>
</tbody>
</table>

Underground (CAST-LSC) lower limit:

- Background: ~ 1 x 10⁻⁷ c/keV⁻¹/cm²/s⁻¹.

- R&D activity to reduce the dominant contributions to background (main IAXO-Micromegas TDR activity).
Prospects: background reduction.

SURFACE $\rightarrow$ achieve underground lower limits.

- Build a first prototype of a Micromegas detection line as would be in IAXO.
- Better (thicker) lead shielding with less openings.
- $4\pi$ muon veto.

UNDERGROUND $\rightarrow$ pushing lower limits

- **Gas change:** Argon $\rightarrow$ Xenon/Neon? **No** $^{39}\text{Ar radioactivity}$.
  - No fluorescences at 5 & 3 keV.
- **Detectors size:** larger detector $\rightarrow$ use it as active veto.
- **Neutron shielding:** polyethylene.
Prospects: Lowering the energy threshold

**Motivation:**
- With the XRT efficiency, big part of the axion flux is expected below 2 keV.
- In non-hadronic axion models, the solar axion flux peaks at sub-keV energies.
- Other searches also peak at lower energies: paraphotons, chamaleons, etc.

**R&D in this direction:**
- More transparent x-ray windows.
- New gas mixtures with higher gain (Neon?).
- Auto-trigger electronics (AGET)
- Resistive microbulk (higher gain?)
- Calibration and analysis at lower energies.

*J. Redondo, JCAP 12 (2013) 008
K. Barth et. al., JCAP 05 (2013) 010
CONCLUSIONS

In the last 12 years, the CAST Experiment has put the strictest limit on axion couplings for a wide range of axion masses.

**Micromegas**: mature technology for Rare Event Searches: axions, 0ν2β-decay (NEXT-MM), WIMPs (TREX-DM, see F.J. Iguaz talk).

The implementation of an Optics + MM system increases CAST sensitivity, and serves as demonstrator of a IAXO subsystem.

On the low background side:

- In CAST, 2 orders of magnitude of background reduction over the years
  - Currently in CAST: \(~ 10^{-6} \text{ keV}^2\text{cm}^{-2}\text{s}^{-1}\).
  - Underground: \(~ 10^{-7} \text{ keV}^2\text{cm}^{-2}\text{s}^{-1}\).
  - IAXO goals: \(< 10^{-7}-10^{-8} \text{ keV}^2\text{cm}^{-2}\text{s}^{-1}\).
- Clear strategy for background reduction both in surface and underground.

On the low threshold side:

- Sub-kev physics at CAST motivates R&D activities to lower the energy threshold: x-ray transparent windows, appropriate gas mixtures, better readout electronics, etc.
Thank you
Axions

- Axions are the most elegant solution to the Strong CP problem (why QCD does not seem to break the CP symmetry):
  - Pseudoscalar particles, neutral, practically stable.
- Candidates for both cold and hot dark matter.
- Axion-like particles (ALPs) are predicted by many extensions of the Standard Model
- Relevant axion/Axion-Like Particles parameter space at reach of current and near-future experiments
- New theory scenarios: string theory predicts axions/ALPs with detectable parameters
- Astrophysical hints for axion/ALPs?
  - transparency of the Universe to UHE gammas → very light ALPs
  - white dwarf cooling anomaly → few meV axions
What is the motivation of axions?

- Most compelling solution to the Strong CP problem of the SM.
- Axion-like particles (ALPs) predicted by many extensions of the Standard Model (like the string theory)
- Axions, like WIMPs, may solve the Dark Matter (DM) problem for free. (i.e. not an ad hoc solution to DM).
- Astrophysical hints for axion/ALPs?
  - Transparency of the Universe to UHE gammas.
  - White dwarfs anomalous cooling point to few meV axions
- Relevant axion/ALP parameter space at reach of current and near-future experiments
- Still too little experimental efforts devoted to axions when compared to WIMPs.
Axion as Dark Matter candidate

- Axions are produced in the early Universe by a number of processes:
  - Axion realignment
  - Decay of axion strings
  - Decay of axion walls
  \[ \text{Non relativistic COLD AXIONS} \]

- Axion mass giving the right CDM density? Depends on cosmological assumptions:
  - “classical window”: around $10^{-5}-10^{-3}$ eV
  - “anthropic window” ~ much lower masses possible
  - Other subdominant CDM / non standard scenarios

- Thermal production
  - Axion masses $m_a > \sim 0.9$ eV gives densities too much in excess to be compatible with latest CMB.
  \[ \text{Relativistic HOT AXIONS} \]

Hannestad et al, JCAP 08 (2010) 001
Axion detection by an helioscope

**Production:** Primakoff effect.
Thermal photons interacting with solar nuclei produce axions.

**Detection:** inverse Primakoff (Sikivie 1983)
Axions in a magnetic field convert to photons.
Expected x-ray excess when the magnet points to the Sun.

- Conversion probability depends on medium.
- In vacuum coherence is lost for $m_a > 0.02$ eV.
- In the presence of a buffer gas, the coherence can be restored for a narrow mass range.
The detection probability

Axion to photon conversion probability

\[ P_{a\rightarrow\gamma} = \left( \frac{B g_{a\gamma}}{2} \right)^2 \frac{1}{q^2 + \Gamma^2/4} \left[ 1 + e^{-\Gamma L} - 2e^{-\Gamma L/2} \cos(qL) \right] \]

\( L = \) magnet length, 
\( \Gamma = \) absorption coefficient

Coherence condition: \( qL < \pi, \quad \left| q \right| = \frac{m_a^2}{2E} \)

For CAST phase I (vacuum), coherence is lost for \( m_a > 0.02 \text{ eV} \)

With the presence of a buffer gas, the coherence can be restored for a narrow mass range

\[ qL < \pi \Rightarrow \sqrt{m_\gamma^2 - \frac{2\pi E_a}{L}} < m_a < \sqrt{m_\gamma^2 + \frac{2\pi E_a}{L}} \]
Probability of the axion-photon conversion:

\[ P_{a \rightarrow \gamma} = \left( \frac{g_{a\gamma}}{2} \right)^2 \frac{B^2}{q^2 + \Gamma^2/4} \left[ 1 + e^{-\Gamma L} - 2e^{-\Gamma L/2} \cos(qL) \right] \]

where

\[ q = \left| \frac{m_a^2 - m_c^2}{2E_a} \right| \]

Vacuum case:

\[ q = \frac{m_a^2}{2E_a} \quad \Gamma \approx 0 \]

\[ P_{a \rightarrow \gamma} = \left( \frac{g_{a\gamma} BL}{2} \right)^2 \left( \frac{\sin\left(\frac{qL}{2}\right)}{\frac{qL}{2}} \right)^2 \]

Coherence condition

\[ m_a < \sqrt{\frac{4\pi E_a}{L}} \]

Buffer gas case:

\[ m_\gamma = \omega_p = \sqrt{\frac{4\pi c n_e}{m_e}} \quad n_\theta = \frac{Z}{W} \rho \]

The coherence can be restored to higher axion masses
CAST Physics Program

1) CAST Phase I, Vacuum
   • \( m_a < 0.02 \) eV
   • \( g_{\text{ayy}} \lesssim 0.88 \times 10^{-10} \text{ GeV}^{-1} \)

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   • JCAP02 (2009) 008.

3) CAST Phase II, \(^3\)He
   • \( P < 120 \) mbar (1.8K), 160 steps
   • \( 0.39 \) eV \(< m_a < 1.17 \) eV
   • \( g_{\text{ayy}} \lesssim 3.3 \times 10^{-10} \text{ GeV}^{-1} \)
   • PRL 107 (2011) 261302 & PRL 112 (2014) 091302

Parallel searches:
   • 11.4 keV axions from M1 transitions: JCAP 0912 (2009) 002.
   • Constrains on axion-electron coupling: JCAP 1305 (2013) 010
CAST: latest results & current activities

Latest results:

• $^3$He phase results recently published: PRL 112 (2014) 091302 (only mM).
• Axion mass 0.64 – 1.17 eV excluded down to $\sim 3.3 \times 10^{-10}$ GeV$^{-1}$.
• Paper on the simulation of gas dynamics inside the magnet in preparation.

Current activities:

• Revisiting the vacuum phase with three high performance microbulk detectors.
• Search of exotic physics (chameleons, paraphotons, low energy axions).

Detector updates:

• An x-ray optics will increase the sensitivity of Sunrise detector.
• InGrid micromegas and Silicon Drift Detectors (SDD) are tested.
IAXO: International AXion Observatory

- New generation of axion helioscope.
- 4 orders of magnitude better in S/N wrt CAST, i.e. 1-2 orders in $g_{a\gamma}$.
- New features: toroidal magnet, dedicated optics, low background detectors.
- CAST & ADMX can explore a big part of the axion model region in next decade.
- Potential for new physics: white dwarfs, ALPs, low energy axions...
- Ideas under discussion to explore meV axions (resonant cavities, antenna dishes).
**IAXO: International AXion Observatory**

- New generation of axion helioscope.
- 4 orders of magnitude better in S/N wrt CAST, i.e. 1-2 orders in $g_{a\gamma}$.
- New features: toroidal magnet, dedicated optics, low background detectors.
- CAST can explore a big part of the axion model region in next decade.
- Positive recommendations from SPSC.

Several preparatory activities in parallel for the Technical Design Report (TDR):
- **IAXO-T0**: a demonstration coil.
- **IAXO-X0**: a prototype x-ray optics.
- **IAXO-DO**: a low background detector.
- **Pathfinder**: a small optics & detector at CAST. The same techniques as for IAXO.
Status of IAXO

- 90 signatures. 38 institutions. Enlarged community interested in IAXO physics.
- In International roadmaps of Europe (ASPERA/APPEC, ESPP) & US (Snowmass).
- Positive recommendations from SPSC.
- Preparation of a MoU to carry out TDR work. Search for new interested partners.
- Several preparatory activities in parallel for the Technical Design Report (TDR):
  - **IAXO-T0**: a demonstration coil.
  - **IAXO-X0**: a prototype x-ray optics.
  - **IAXO-DO**: a low background detector.
  - **Pathfinder**: a small optics & detector at CAST. The same techniques as for IAXO.
IAXO Magnet

- Large toroidal 8-coil magnet specifically built for axion physics.
- Many technical aspects studied and defined in the CDR.
- Magnetic length: 20 m.
- Bore diameter: 0.6 m.
- IAXO-T0 project to build a test coil.

IAXO magnet concept presented in:
IAXO Optics

- Technique of choice: optics made of thin glass substrates coated to enhance reflectivity in the energy regions for axions. Used in NuSTAR/HEFT project.
- Optimization study to maximize the efficiency in the focussing power:
  - Diameter: 600 mm. Focal length: 10 m.
  - First realistic drawings made.
  - New telescope for CAST in construction.
IAXO detector: Microbulk Micromegas

Why are they used in axion searches?
- High power to discriminate x-rays signals from other type of events.
- Intrinsic radiopure ([Astr. Part. 34 (2011) 354]).
- Shielding techniques from low background experiments can be also applied.

Status of Micromegas for IAXO
- Background levels below $10^{-6} \text{s}^{-1}\text{keV}^{-1}\text{cm}^{-2}$ obtained in CAST for the first time (2013).
- Levels at $10^{-7} \text{s}^{-1}\text{keV}^{-1}\text{cm}^{-2}$ at LSC.
- Roadmap to reach IAXO levels, based on
  - In-situ measurements at CAST.
  - Replica at Canfranc Laboratory (LSC).
  - Geant4 simulations of CAST-MM.

<table>
<thead>
<tr>
<th>Contribution</th>
<th>Background level in 2-7 keV (counts s$^{-1}$ keV$^{-1}$ cm$^{-2}$)</th>
<th>Technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gamma flux</td>
<td>$\sim 7 \times 10^{-5}$</td>
<td>Lead shielding</td>
</tr>
<tr>
<td>Muons</td>
<td>$2 \times 10^{-6}$ - $6 \times 10^{-7}$</td>
<td>Active veto</td>
</tr>
<tr>
<td>Al cathode</td>
<td>$(5.2 \pm 1.2) \times 10^{-7}$</td>
<td>Cu cathode</td>
</tr>
<tr>
<td>Radon</td>
<td>$\sim 8 \times 10^{-7}$</td>
<td>N$_2$ flux</td>
</tr>
<tr>
<td>CAST-LSC lower limit</td>
<td>$1.1 \times 10^{-7}$</td>
<td>Neutrons? Gas purity?</td>
</tr>
</tbody>
</table>
Micromegas for axion searches

It is an amplification structure used as readout in a Time Projection Chamber (Y. Giomataris, NIMA 376 (1996) 29).

• Excellent energy resolution (**12% FWHM at 5.9 keV**).
• High power to discriminate x-rays signals from other type of events.
• Consolidated manufacture (**microbulk technique**) & stable in time (S. Adriamonje et al., JINST 5 (2010) P02001).
Lowering the energy threshold of CAST

R&D on this direction for Micromegas:

• New thin windows for CAST detectors.
• Autotrigger electronics AGET. (S. Anvar et al, NSS/MIC/RTSD IEEE 2011)
• New analysis based on x-rays calibrations.

Cluster width in z

Energy resolution vs gain
Lowering the energy threshold of CAST

Physics motivation:
- In non-hadronic axion models, the Sun produces axions by BCA processes.
- The expected axion flux peaks at sub-keV energies.

Is it feasible for x-ray detectors?
- Evident for CCD & SDD.
- To be verified by MM & Ingrid.
Summary

In the last 12 years, the **CAST experiment**

- has put the strictest limit on axion coupling for a wide range of masses and has gained extensive experience on Helioscope Axion Searches.
- has just published the first results of 3He phase ([PRL 112 (2014) 091302]): $g_{\alpha\gamma\gamma} \lesssim 3.3 \times 10^{-10} \text{GeV}^{-1} \text{ (95\% CL)}$ for $0.64 \text{ eV} < m_a < 1.17 \text{ eV}$.
- is revisiting the vacuum phase to increase the sensitivity and explore other exotica like solar chameleons, paraphotons, improve the LE setup.

The future is the **International Axion Observatory (IAXO)** which

- will improve on CAST results more than one order of magnitude.
- will use a dedicated magnet, large area optics and low background detectors.
- can explore a big part of axion models in next decade together with ADMX.
- has published its LoI ([SPSC-2013-022]) & CDR ([2014 JINST 9 T05002]).
- develops several activities for the TDR: test coil, optics, detectors,...
The Committee recognizes the physics motivation of an International Axion Observatory as described in the Letter of Intent SPSC-I-242, and considers that the proposed setup makes appropriate use of state-of-the-art technologies i.e. magnets, x-ray optics and low-background detectors.

The Committee encourages the collaboration to take the next steps towards a Technical Design Report.

The Committee recommends that, in the process of preparing the TDR, the possibility to extend the physics reach with additional detectors compared to the baseline goal should be investigated. The collaboration should be further strengthened.

Considering the required funding, the SPSC recommends that the R&D for the TDR should be pursuit within an MOU involving all interested parties.
IAXO in astroparticle roadmaps

- **ASPERA/APPEC Roadmap** acknowledges axion physics, CAST, and recommends progress towards IAXO.

  "...A CAST follow-up is discussed as part of CERN’s physics landscape (new magnets, new cryogenic and X-ray devices). The Science Advisory Committee supports R&D on this follow up, as well as smaller ongoing activities on the search for axions and axion-like particles."

  C. Spiering, ESPP Krakow

- Important community input in the **European Strategy for Particle Physics**
- Presence in the Briefing Book of the ESPP, which reflects also APPEC roadmap recommendations.
- **ESPP recommends CERN to follow APPEC recommendations.**
- Important effort in relation with US roadmapping (Snowmass, and P5 process). **Snowmass reports speak very favorably of axion physics and IAXO.**
### Signal-to-noise ratio of IAXO

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>CAST-I</th>
<th>IAXO Nominal</th>
<th>IAXO Enhanced</th>
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<tbody>
<tr>
<td>$B$</td>
<td>T</td>
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<td>$b$</td>
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<td>$f^*$</td>
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</tbody>
</table>

Table 3: Values of the relevant experimental parameters representative of IAXO, both the *nominal* and *enhanced* ones, based on the considerations explained in section 4. They are compared to the ones representing the CAST vacuum phase result (CAST-I) [59]. Numbers shown for the figures of merit (equation 11) are relative to CAST-I, i.e. $f^* = f/f_{CAST}$, and are approximate.
IAXO timeline

- TDR + preparatory activities: 1.5 years.
- Construction: 3.5 years.
- Integration & commissioning: 2.5 years.
- Total: 6 years.
## IAXO costs

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost (MCHF)</th>
<th>Subtotals (MCHF)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Magnet</strong></td>
<td></td>
<td>31.3</td>
</tr>
<tr>
<td>Eight coils based assembled toroid</td>
<td>28</td>
<td></td>
</tr>
<tr>
<td>Magnet services</td>
<td>3.3</td>
<td></td>
</tr>
<tr>
<td><strong>Optics</strong></td>
<td></td>
<td>16.0</td>
</tr>
<tr>
<td>Prototype Optic: Design, Fabrication, Calibration, Analysis</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>IAXO telescopes (8 + 1 spare)</td>
<td>8.0</td>
<td></td>
</tr>
<tr>
<td>Calibration</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>Integration and alignment</td>
<td>5.0</td>
<td></td>
</tr>
<tr>
<td><strong>Detectors</strong></td>
<td></td>
<td>5.8</td>
</tr>
<tr>
<td>Shielding &amp; mechanics</td>
<td>2.1</td>
<td></td>
</tr>
<tr>
<td>Readouts, DAQ electronics &amp; computing</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>Calibration systems</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>Gas &amp; vacuum</td>
<td>1.4</td>
<td></td>
</tr>
<tr>
<td>Dome, base, services building and integration</td>
<td>3.7</td>
<td></td>
</tr>
<tr>
<td><strong>Sum</strong></td>
<td></td>
<td><strong>56.8</strong></td>
</tr>
</tbody>
</table>

Table 5: Estimated costs of the IAXO setup: magnet, optics and detectors. It does not include laboratory engineering, as well as maintenance & operation and physics exploitation of the experiment.
Micromegas for axion searches

It is an amplification structure used as readout in a Time Projection Chamber (Y. Giomataris, NIMA 376 (1996) 29).

- Excellent energy resolution (12% FWHM at 5.9 keV).
- High power to discriminate x-rays signals from other type of events.
- Consolidated manufacture ([microbulk technique]) & stable in time (S. Adriamonje et al., JINST 5 (2010) P02001).
C. Radiopurity issues: measurements

Microbulks are mostly Cu & Kapton
potentially very radiopure
Several samples measured with HPGe at LSC
  2 samples of raw material (double clad kapton foil)
  2 samples detached from old CAST detectors

S. Cebrian et al., Astropart. Phys 34 (2011) 354-359

<table>
<thead>
<tr>
<th>Results (in $\mu$Bq/cm$^2$)</th>
<th>$^{232}$Th</th>
<th>$^{235}$U</th>
<th>$^{238}$U</th>
<th>$^{40}$K</th>
<th>$^{60}$Co</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microbulk mM</td>
<td>&lt;9.3</td>
<td>&lt;13.9</td>
<td>26.3±13.9</td>
<td>57.3±24.8</td>
<td>&lt;3.1*</td>
</tr>
<tr>
<td>Kapton-Cu foil</td>
<td>&lt;4.6*</td>
<td>&lt;3.1*</td>
<td>&lt;10.8</td>
<td>&lt;7.7*</td>
<td>&lt;1.6*</td>
</tr>
<tr>
<td>Cu-Kapton-Cu foil</td>
<td>&lt;4.6*</td>
<td>&lt;3.1*</td>
<td>&lt;10.8</td>
<td>&lt;7.7*</td>
<td>&lt;1.6*</td>
</tr>
</tbody>
</table>

*Level obtained from the Minimum Detectable Activity of the detector

- Very low levels of radioactivity, compatible with the sensitivity of the measurement
- Contamination probably comes from the treatment of the materials used