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Next-Generation Search for Solar Axion Dark Matter with the International Axion Observatory

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Abstract

The International Axion Observatory (*IAXO*) was first proposed in 2011[1]-[5]. With this proposal our *LDRD* team, founding member of *IAXO* has been able to play a leading role in the *IAXO* experiment. We have participated in technical, scientific and organizational *IAXO* meetings to shape the future of the experiment. We accomplished the layout of the first-ever full-revolution telescope for solar axion searches[6]-[10] and expanded the science reach of *IAXO* from standard axion searches to new and potentially more exotic opportunities, such as other dark matter candidates, hidden sector particles or dark energy searches [11]-[20]. We also fulfilled the analysis of axion science data previously collected with the *LLNL IAXO* pathfinder x-ray telescope (*XRT*) [21] at the European Organization for Nuclear Research particle physics (*CERN*) located near Geneva, Switzerland, by means of the *CERN* Axion Solar Experiment (*CAST*). Moreover, LDRD PI Dr. Julia K. Vogel has officially been elected as Deputy Spokesperson of *IAXO*.

Background and Research Objectives

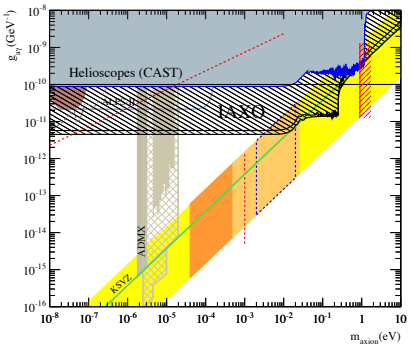

Figure 1. Expected sensitivity of *IAXO* as explained in [1]-[3], compared with current bounds from *CAST* and *ADMX*. Also future prospects of *ADMX* (dashed brown region) are shown. Note that the yellow band indicates the theoretical QCD-axion region and all parameter space below the dashed red line is viable axion/ALP DM parameter space. *IAXO* will therefore test large, theoretically well-motivated, yet uncharted axion territory.

The discovery of the Higgs boson—an elementary particle theorized to be the building block of the universe—at the Large Hadron Collider (*LHC*) at *CERN*, experimentally confirms the widely successful Standard Model of particle physics. However, the theory still falls short of explaining several fundamental features of our universe.

A major shortcoming is the Standard Model's silence on the nature of dark matter, which is a crucial component of the universe, yet its constituents are unknown. Axions are a leading dark matter candidate, but experiments have yet to confirm or refute the existence of these elusive particles. Lawrence Livermore National Laboratory has played an important role in two complementary efforts to search for this particle: (1) the Axion Dark Matter Experiment at the University of Washington studying halo axions with masses of micro- to milli- electron volts [22]-[24]; and (2) the CERN Axion Solar Telescope (CAST) striving to detect solar axions of up to 1 eV [25]-[31] (see Figure 1 for a plot of the axion parameter space of mass versus coupling constant).

We envisioned this LDR project with two main:

i) Designs the first-ever full-revolution telescope for solar axion searches to be used for the *IAXO* experiment and prototype these novel optics with *IAXO* partners.

ii) Expand the science reach of *IAXO* from standard axion searches to new and potentially more exotic opportunities, such as other dark matter candidates, hidden sector particles or dark energy searches

This project was also conceived to lead the scientific analysis of the Laboratory's *IAXO* pathfinder optic installed on the *CAST*, with the goal of either detecting axions or axion-like particles or placing new stringent limits on their existence. Lessons learned from the analysis of the pathfinder optic have been used to design and model the first full IAXO telescope.

Scientific Approach and Accomplishments

This project has enabled us to layout the first-ever full revolution telescope specifically designed for axion research and cutting-edge dark matter science, while establishing the Laboratory's leadership role in *IAXO*.

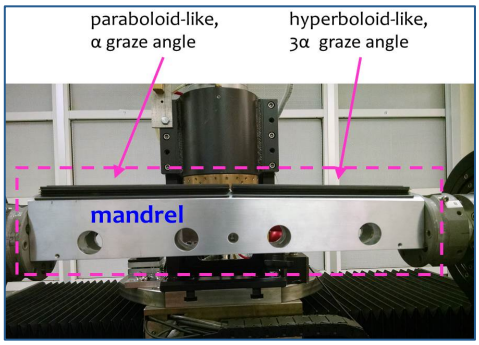

Figure 2. Photograph of the optic, located within the dashed box. At this point during construction, the optic had 4 nested layers integrated into the mandrel and support structure. The rest of the equipment is the precision lathe in which individual mirror segments are assembled into the telescope.

In FY17 we established the conceptual design of the first-ever, full-revolution optics purposely designed for axion research. More specifically, we (1) determined the best geometric layout for the telescope including lessons learned from the *IAXO* pathfinder optic, (2) studied various multilayer materials to optimize the performance of the *IAXO* optics in the x-ray energy range of interest, and (3) strengthened our leadership role in the observatory as the x-ray optics lead institution through strong contributions and representation at all relevant *IAXO* meetings. A major milestone achieved during FY17 was the completion and publication of the pathfinder data analysis with which CAST was able to establish the most restringing limit on axion-to-photon coupling for solar axions [32]. Our LDRD team received LLNL's PLS award for best publication. During FY18, we (1) refined the multilayer prescription of the mirrors based on the FY17 results of the analysis for prototype calibration; (2) studied potential hardware limitations for building a 50-to-70 centimeter diameter optic; and (3) replaced the initially planned proof-of-concept phase for *IAXO* with a Phase I stage ('*BabyIAXO*') [33] consisting of a fully operational magnet pathfinder together with two optic/detector lines with the advantage of enabling relevant axion science early on while demonstrating technology readiness. Throughout FY19 we (1) completed the design for the full-revolution optics and include requirements for an implementation of the optic in the *BabyIAXO*; (2) finalized the multilayer prescription of the mirrors based on the FY17 and FY18 results of the analysis for the prototype calibration; (3) continued to extend and

strengthen our leadership role in *IAXO* as the x-ray optics lead institution through our contributions and representation at all relevant *IAXO* meetings. Over the course of this LDRD we efficiently disseminated new results at relevant conferences and published refereed papers. Furthermore, the physics potential of the IAXO/BabyIAXO experiment has been extensively explained in [34] and we have been able to extend the actual search of CAST to more exotic particles [35] and [36].

IAXO is the key piece to the next generation of solar axion searches. The Laboratory's active role in both axion research and x-ray optics technology gives us a unique opportunity to leverage its deep expertise in astrophysical instrumentation and particle physics to position *LLNL* for participation in next-generation astrophysical and particle physics experiments.

Impact on Mission

Participation in space science is an important element in LLNL's cyber security, space, and intelligence strategic focus area. Next-generation capabilities for space security requires a trained workforce with demonstrated excellence in designing, fabricating, and performing science with advanced instrumentation. Our work with a Livermore-built x-ray telescope and the design of a next-generation optic for axion dark matter searches using space science technology has establish and strengthen the Laboratory's preeminence in particle astrophysics, dark matter research, x-ray optics, and instrumentation technology. The development of advanced x-ray optics supports DOE goals in science and energy and nuclear security with advances in diagnostics for laser-fusion facilities and for nuclear nonproliferation.

Conclusion

IAXO is to be built at the Deutsches Elektronen-Synchrotron (*DESY*). Our LDRD team helped securing initial funding from the European Research Council and the experiment is already part of the budgeting tables at *DESY*. LLNL Research Scientist and PI of this LDRD project, Dr. Julia K. Vogel has officially been elected as Deputy Spokesperson of *IAXO*. Her leadership role and vision of *IAXO* has position her and LLNL in a privilege situation within the *IAXO*.

We foresee that the natural path forward after the completion of this LDRD cycle requires the continuation of LLNL's activities within the *IAXO* collaboration. Phase I stage of *IAXO* is well define and *BabyIAXO* is expected to be operational by FY23 at DESY, Hamburg, Germany. At present, the members of our LDRD team lead the x-ray optics effort of the IAXO collaboration. We are extremely well position to coordinate and manage the construction and characterization of the first full-revolution x-ray optics for axion searches in *BabyIAXO*. We thrive to secure the required funds for the completion of that key item of the experiment.

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Publications and Presentations

Journals:

- LLNL-JRNL-788468	First Results on the Search for Chameleons with the KWISP Detector at CAST
- LLNL-JRNL-772500	Physics Potential of the International Axion Observatory (IAXO)
- LLNL-JRNL-755191	Improved Search for Solar Chameleons with a GridPix Detector at CAST
- LLNL-JRNL-727500	CAST solar axion search achieves forefront sensitivity
- LLNL-PROC-764331	Next Generation Search for Axion and ALP DarkMatter with the International Axion Observatory
- LLNL-PROC-709579	IAXO, next generation of helioscopes

Presentations:

- LLNL-PRES-793012	X-ray optics overview for BabyIAXO
- LLNL-PRES-789255	Update on BabyIAXO to search for solar axions
- LLNL-POST-782737	Focusing on Axions and ALPs with the New Optics for the

	International Axion Observatory (IAXO) and BabyIAXO
- LLNL-PROP-782017	Experiment Proposal to DESY PRC BabyIAXO: the first stage of the International Axion Observatory (IAXO)
- LLNL-PRES-771227	BabyIAXO movement requirements for optics
- LLNL-PRES-769938	(B)IAXO optics status overview
- LLNL-MI-760671	Letter of Intent to DESY PRCB
- LLNL-PRES-760509	Next Generation Search for Axion and ALP Dark Matter with the International Axion Observatory
- LLNL-PRES-758435	IAXO Optics Development in the US
- LLNL-PRES-752985	A Fresh look at Solar Axions & ALPS using the Nuclear Spectroscopy Telescope Array (NuSTAR)