Detecting Solar Axions with SABRE

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The Strong CP Problem

A key unanswered question in Quantum Chromodynamics (QCD) is the “Strong CP Problem,” which asks why observed strong-force interactions preserve Charge-Parity symmetry when that condition is not needed under current QCD models.

The Dark Matter Problem

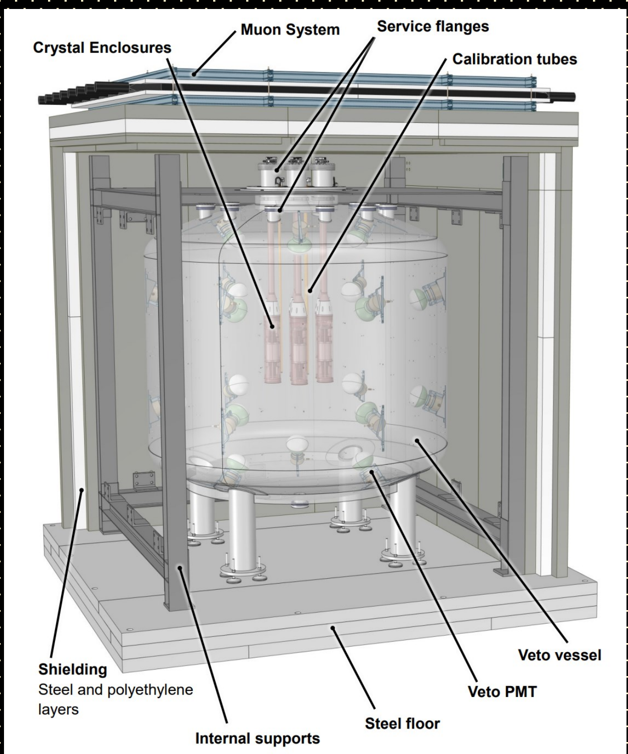
Within several scales in our universe—from galactic rotation curves to the cosmic microwave background—there appears to be invisible mass influencing gravity. This mass is called ‘Dark Matter’, and several theories exist to explain its existence.

The Axion: a Potential Solution

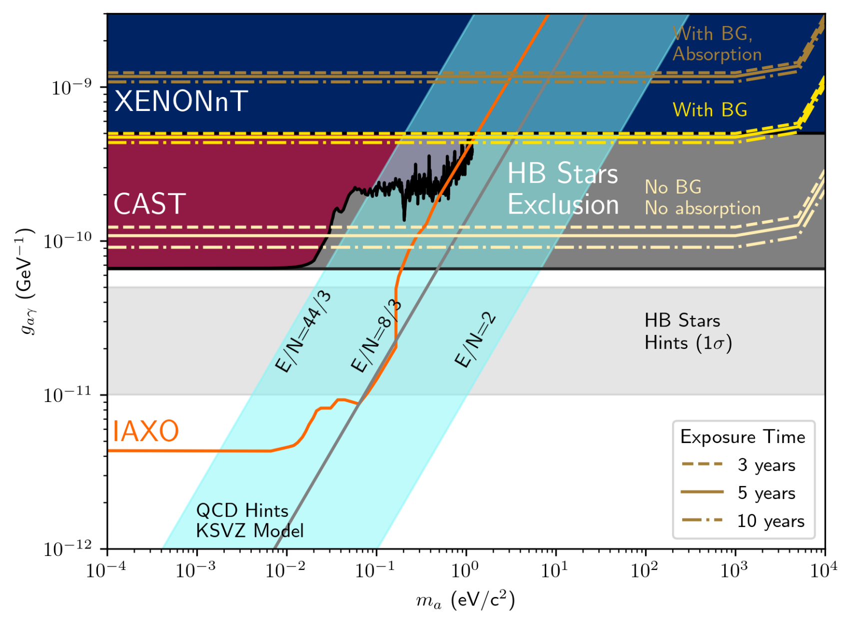
Axions are a hypothetical boson which solve both the strong CP and dark matter problems. Axions solve the strong CP problem by spontaneous symmetry breaking over a new symmetry called the Peccei-Quinn mechanism—which forces CP symmetry to exist—while axions solve the dark matter problem as low-mass weakly interacting bosons to account for dark matter mass. Axions interact with both photons and charged particles, meaning they can be produced in stars from several emission processes—affecting stars’ cooling rates.

The SABRE-South Experiment

SABRE-South (Sodium iodide with Active Background REjection) is an upcoming dark-matter detection experiment scheduled for data collection in 2025 at the Stawell Underground Physics Laboratory (SUPL) in Victoria. SABRE-South aims to verify or refute previous work by the DAMA/LIBRA collaboration in Italy which had claimed to detect annual modulation in their signal—a sign of a Milky Way dark matter halo—using NaI detectors. SABRE-South improves on DAMA/LIBRA by using the same NaI crystal detection method with stronger background rejection and a southern hemisphere location to counter seasonal effects.



The SABRE-South detection chamber, located at SUPL in the Stawell Gold Mine



SABRE projected exclusion (2σ unless otherwise) and other studies:

Direct detection: CAST[3] (magnetic helioscope), XENONnT[2] (liquid xenon)
Future direct detection: IAXO[4] (helioscope)
HB Stars[5]: from axion cooling rates to contradict or correlate with observed HB star count
QCD Hints[5]: from KSVZ QCD model relating $g_{a\gamma}$ to m_a with a factor E/N. E/N=8/3 is equivalent to the DFSZ model

Detection: The Primakoff Process

Due to their coupling with photons and electrons, Axions can interact with electrons to produce a photon—called the ‘Primakoff Process’. This occurs within an NaI crystal at an enhanced rate due to its lattice structure. This rate depends on the Sun’s position to the crystal rather than the Earth’s speed against the galaxy’s, creating a signal distinct from annual modulation.

The detection rate follows an equation dependent on the axion mass and the axion-photon coupling constant $g_{a\gamma}$, so unsuccessful detection of axions limits these values. The rate also depends on absorption, from axions converted to photons being reabsorbed in the crystal before detection.

$$\frac{dN}{dt} = \pi g_{a\gamma}^2 (\hbar c)^3 \frac{V}{v_{cell}^2} \sum_{\boldsymbol{G}} I(\boldsymbol{k}, \boldsymbol{G}) \left[\frac{d\Phi}{dE} \frac{|F(\boldsymbol{G}) S(\boldsymbol{G})|^2}{|\boldsymbol{G}|^2} \sin^2(\theta)\, \mathcal{W}\big(E_1, E_2, E_a(\boldsymbol{k}, \boldsymbol{G})\big) \right]$$

$g_{a\gamma}$: Axion-Photon Coupling
V: Volume of crystal
v_{cell}: Volume of a unit cell in the lattice
$\boldsymbol{G}$: Reciprocal lattice vector
$\boldsymbol{k}$: Unit vector pointing to the sun
$I(\boldsymbol{k}, \boldsymbol{G})$: Unitless absorption factor
$\frac{d\Phi}{dE}$: Solar Axion flux, proportional to $g_{a\gamma}^2$
$F(\boldsymbol{G})$: Atomic form factor
$S(\boldsymbol{G})$: Atomic scattering factor
θ: Angle between $\boldsymbol{G}$ and $\boldsymbol{k}$
$\mathcal{W}$: Filter function for energy bounds E_1, E_2
$E_a(\boldsymbol{k}, \boldsymbol{G})$: Diffracted Axion energy

Axion Detection Rate Formula[1]

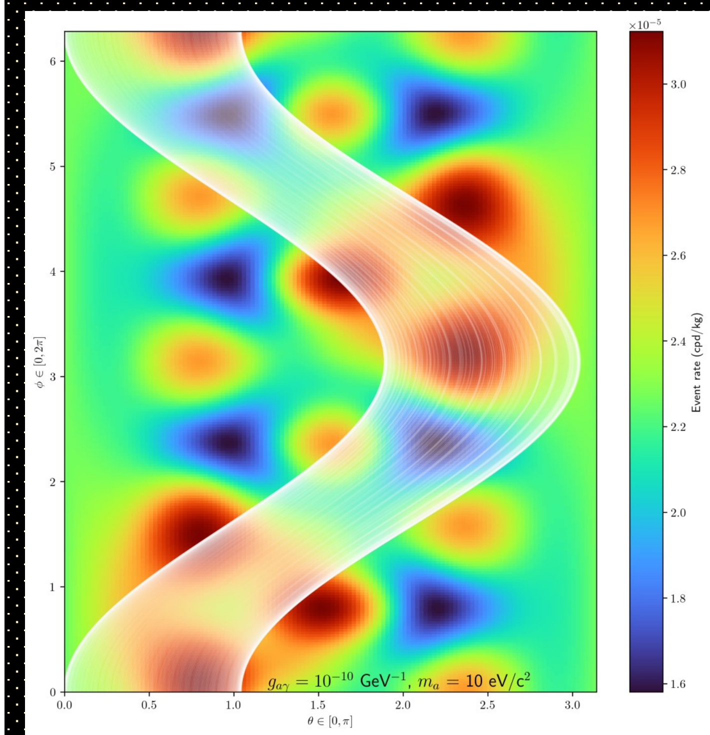
Results

Assuming zero background and no absorption, this work finds exclusion limits (see above) agreeing with recent work by Dent et.al[1]. With an energy independent background of 0.600 cpd/kg/keV (after 180 days of cooldown) and an energy range of 3.3-9.5 keV, background shifts the exclusion region to just below what has been covered by XENONnT[2]—which used liquid xenon scintillation instead of NaI crystals.

The effects of absorption on SABRE crystals have not been experimentally tested, so this work uses recent theoretical results[2] assuming its effects are independent to the effects of background. Including absorption in this way shifts the exclusion region of SABRE to what has already been tested by XENONnT.

While the current results show that SABRE is not competitive to current and upcoming experiments in the search for solar axions—given that its purpose is to find annual modulation—SABRE uses a different detection method from them—which can test different models of axions—and has stronger background rejection than previous NaI experiments. A more robust analysis of background and experimental analysis on absorption in SABRE crystals will improve the accuracy of the current results.

[2]: “Bragg-Primakoff Axion Photoconversion in Crystal Detectors” Dent et.al (2023)



Axion detection rate as a function of solar position in spherical polar co-ordinates. Each white line represents the position of the Sun over one day at SUPL, and each day in a year is plotted separately.

[1]: “Bragg-Primakoff Axion Photoconversion in Crystal Detectors” Dent et.al (2023)
[2]: “Search for New Physics in Electronic Recoil Data from XENONnT” XENON Collaboration (2022)
[3]: “New CAST Limit on the Axion-Photon Interaction” CAST Collaboration (2017)
[4]: “Physics Potential of the International Axion Observatory” IAXO Collaboration (2019)
[5]: “The landscape of QCD axion models” Di Luzio et.al (2020)