Constraining axion couplings with the JUNO detector

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Why axions?
Fig. 1. Many extensions of the Standard Model predict additional massive bosons, beyond the $W$, $Z$, and Higgs bosons of the Standard Model. They

[Chadha-Day, Ellis, Marsh, Sci.Adv. 8 (2022)]
Why axions?

Hunts for axions are growing with the technologically advanced experiments.

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Why axions?

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Massive bosons (integer spin)
- Ultralight bosons
- Moduli and dilatons
- Scalars (spin 0, CP even)
- Vectors (spin 1)

Theory
- Strong CP problem

Cosmology
- Cold DM candidate

Axions
- ALPs

Astrophysics
- Anomalous stellar cooling
- UHE γ transparency

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[Chadha-Day, Ellis, Marsh, Sci.Adv. 8 (2022)]

Credits: I. G. Irastorza

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Strong CP problem

- The QCD Lagrangian:

\[ \mathcal{L}_{\text{QCD}} = \sum_q \bar{q} \left( i \slashed{\partial} - m_q e^{i \theta q} \gamma^5 \right) q - \frac{1}{4} G_{\mu\nu}^a G^{a\mu\nu} + \theta \frac{g_s^2}{32\pi^2} G_{\mu\nu}^a \tilde{G}^{a\mu\nu} \]

- \( \theta \)-term is a total derivative and does not affect the classical EoM. But, it has important effects on the quantum theory.

- It is the difference \( \bar{\theta} = \theta - \theta_q \) has physical meaning

- Non-zero \( \bar{\theta} \)-term has observational consequences to the neutron electric dipole moment \( d_n \)

\[ d_n = (2.4 \pm 1.0) \bar{\theta} \times 10^{-3} \text{ e fm} \]

- At present \( d_n \) is constrained to \( |d_n| < 1.8 \times 10^{-13} \text{ e fm} \) (at 90% C.L.)

Strong CP problem: “Experimentally \( \bar{\theta} \lesssim 10^{-10} \), why is CP-violation so much suppressed in strong interactions?”
The axion

- To solve the problem, Peccei Quinn introduced a global $U(1)_{PQ}$ symmetry to the QCD

- This $U(1)_{PQ}$ symmetry would be spontaneously broken at a high energy scale $f_a$

- Such an spontaneously broken symmetry implied a new pNG boson, “Axion”

- Under the symmetry axion field transform additively as $a \to a + \alpha f_a$

- The axion Lagrangian: $\mathcal{L}_{\text{eff}} = \left( \bar{\theta} + \frac{a}{f_a} \right) \frac{\alpha_s}{8\pi} G_{\mu\nu}^a \tilde{G}_{\mu\nu}^a - \frac{1}{2} \partial^\mu a \partial_\mu a + \mathcal{L}(\partial_\mu a, \psi)$

[Pecei, Quinn (1977), Weinberg (1978), Wilczek (1978)]
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[Peeccei, Quinn (1977), Weinberg (1978), Wilczek (1978)]
Axion Landscape

- Axion mass $\sim 1/f_a$;

$$m_a \sim m_\pi \frac{f_\pi}{f_a} \sim 6 \text{ meV} \frac{10^9 \text{ GeV}}{f_a}$$
Axion Landscape

- Axion mass \( \sim 1/f_a \);

\[
m_a \approx m_\pi \frac{f_\pi}{f_a} \approx 6 \text{ meV} \frac{10^9 \text{ GeV}}{f_a}
\]

The effective low energy axion-Lagrangian

\[
\mathcal{L} = \frac{1}{2} \left( \partial_\mu a \right)^2 - m_a^2 a^2 - \frac{1}{4} g_{a\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} - i g_{ae} a \bar{e} \gamma_5 e - i a \bar{N} \gamma_5 \left( g_{0aN} + \tau_3 g_{3aN} \right) N
\]

Accessible couplings for experimental detection

- All axion couplings \( \sim 1/f_a \);
Experimental efforts
Current constraint on axion-photon couplings

Credit: C. O’Hare, https://cajohare.github.io/AxionLimits/
Experimental efforts

Current constraint on axion-photon couplings

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Experimental efforts
Projected constraint on axion-photon couplings

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JUNO: Jiangmen Underground Neutrino Observatory

- It is a medium-baseline (53km) reactor neutrino experiment located in China, under construction
- JUNO features a 20 kton multi-purpose underground liquid scintillator detector
- Aims to determine neutrino mass ordering and precision measurement of PMNS parameters
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- It offers exciting opportunities for addressing many important topics in neutrino and astro-particle physics.
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Supernova neutrinos
Atmospheric neutrinos
Solar neutrinos, etc...

Dark matter
NSI's
Sterile ν’s
Lorentz violation

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Solar axion

- Sun provides an ideal platform to study solar axions by producing very intense flux.
- We consider solar axion produced in the $p + d \rightarrow ^3\text{He} + a \ (5.49 \text{ MeV})$ reaction
- Axion flux $\propto \nu \nu$ neutrino flux and is known with a high accuracy
  
  $\Phi_{a0} = 3.23 \times 10^{10} (g_{3aN})^2 (p_a/p_\gamma)^3$ where $p_\gamma$ and $p_a$ are the photon and axion momenta

Solar axions flux on the Earth’s surface:

- We consider
  
  $a + e \rightarrow e + \gamma$ (Compton conversion of axions to photon)
  $a \rightarrow e^+e^-$ (Axion decays to electron-positron pair)
  $a + Z \rightarrow \gamma + Z$ (Inverse Primakoff conversion)
  $a \rightarrow \gamma\gamma$ (Axion decays to two photons)
Numerical Procedure: $\chi^2$ is defined as

$$\chi^2 = 2 \times \sum_{i=1}^{240} \left( N_{pre}^i - N_{obs}^i + N_{obs}^i \times \log \frac{N_{obs}^i}{N_{pre}^i} \right) + \left( \frac{\varepsilon_s}{\sigma_s} \right)^2 + \left( \frac{\varepsilon_b}{\sigma_b} \right)^2,$$

$$N_{pre}^i = (1 + \varepsilon_s) \times T_i + (1 + \varepsilon_b) \times B_i + \frac{S}{\sqrt{2\pi}\sigma} \times e^{-\frac{(E_{6.5} - E_i)^2}{2\sigma^2}},$$
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- **Total signal**
- **Total Background**
- **Axion peak Intensity**
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**Nuisance parameters**

**Signal and background Uncertainties, 5% & 15%**
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Nuisance parameters
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Nuisance parameters

Signal and background uncertainties, 5% & 15%

$S_{\text{lim}} = 97$ at 90% C. L.
• Expected number of events in presence of solar axion:

\[ S_{\text{events}} = \Phi_a \sigma_{a-e,p,c} N_{e,p,c} T \varepsilon \leq S^{\text{lim}} \]

Axion flux
Interaction Cross-section
# of electrons, protons, carbon nuclei
Measurement time
Efficiency
Upper limits on # of events

Borexino Collaboration, Bellini, et. al. PRD 85 (2012) 092003
Cont...

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- Interaction Cross-section
- # of electrons, protons, carbon nuclei
- Measurement time
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- Upper limits on # of events

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Axion detection

- Compton conversion of axions to photons: $a + e \rightarrow e + \gamma$

  Cross-section is given by \( \sigma_{CC} \approx g_{ae}^2 \times 4.3 \times 10^{-25} \)

  for \( m_a < 1 \text{ MeV} \)

- We obtain at 90% c.l.

  \[ |g_{3aN} \times g_{ae}| \leq 6.33 \times 10^{-14} \text{ for JUNO} \]

  \[ |g_{3aN} \times g_{ae}| \leq 5.5 \times 10^{-13} \text{ for Borexino} \]

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Cont...

- Axion decays to electron-positron pair

Expected number of events for \( a \rightarrow e^+e^- \)

\[
S_{e^+e^-} = N_{e^+e^-} T
\]

where \( N_{e^+e^-} = \Phi_a \frac{V m_a}{\beta E_a \tau_{e^+e^-}} \)

\[ \propto (g_{3aN}, g_{ae}) \]
Cont...

• Axion decays to electron-positron pair

Expected number of events for $a \rightarrow e^+e^-$

$$S_{e^+e^-} = N_{e^+e^-}T$$

where

$$N_{e^+e^-} = \Phi_a \frac{V m_a}{\beta E_a \tau_{e^+e^-}}$$

$$\propto (g_{3aN}, g_{ae})$$
Axion electron and axion nucleon couplings

- For varying axion mass: \( S_{\text{events}} = \Phi \sigma_{a-e,p,c} N_{e,p,c} T \bar{\varepsilon} \leq S^{\text{lim}} \)
Axion electron and axion nucleon couplings

- For varying axion mass: $S_{\text{events}} = \Phi_a \sigma_{a-e,p,C} N_{e,p,C} T \varepsilon \leq S_{\text{lim}}$

- JUNO can provide the most stringent bound around sub-MeV axion mass
Axion photon and axion nucleon couplings

- Inverse Primakoff conversion $a + Z \rightarrow \gamma + Z$

$$S_{PC} = \Phi_a \sigma_{PC} N_C T \varepsilon_{PC}$$

for $m_a < 1\text{ MeV}$

$\propto g_{a\gamma}$

$\propto g_{3aN}$

- We obtain at 90% c.l.

$$|g_{3aN} \times g_{a\gamma}| \leq 2.0 \times 10^{-12}\text{ GeV}^{-1} \text{ for JUNO}$$

$$|g_{3aN} \times g_{ae}| \leq 4.6 \times 10^{-11}\text{ GeV}^{-1} \text{ for Borexino}$$

$m_a = 10\text{ keV}$
Axion photon and axion nucleon couplings

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\[ \propto g_{3aN} \]

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\[ m_a = 10 \text{ keV} \]

Excluded by JUNO

Compton Ge

Borexino

SN 1987A cooling
Axion photon and axion nucleon couplings

- Axion decays to two photons

\[ a \rightarrow \gamma \gamma \]

Expected number of events for \( a \rightarrow \gamma \gamma \)

\[ S_{\gamma \gamma} = N_{\gamma} T \]

where \( N_{\gamma} = \Phi_a \frac{V m_a}{\beta E_a \tau_\gamma} \)

\[ \propto (g_{3aN}, g_{a\gamma}) \]

\[ m_a = 1.2 \text{ MeV} \]
Axion photon and axion nucleon couplings

- Axion decays to two photons

Expected number of events for $a \rightarrow \gamma\gamma$

$$S_{\gamma\gamma} = N_\gamma T$$

where

$$N_\gamma = \Phi_a \frac{V m_a}{\beta E_\gamma \tau_\gamma} \propto (g_{3aN}, g_{a\gamma})$$

$$m_a = 1.2 \text{ MeV}$$

Excluded by JUNO

Axion photon and axion nucleon couplings

- Axion decays to two photons

Expected number of events for $a \rightarrow \gamma\gamma$

$$S_{\gamma\gamma} = N_\gamma T$$

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Excluded by JUNO

Axion photon and axion nucleon couplings

- Axion decays to two photons

Expected number of events for $a \rightarrow \gamma\gamma$

$$S_{\gamma\gamma} = N_\gamma T$$

where

$$N_\gamma = \Phi_a \frac{V m_a}{\beta E_\gamma \tau_\gamma} \propto (g_{3aN}, g_{a\gamma})$$

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Excluded by JUNO

Axion photon and axion nucleon couplings

- Axion decays to two photons

Expected number of events for $a \rightarrow \gamma\gamma$

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Excluded by JUNO

Axion photon and axion nucleon couplings

- Axion decays to two photons

Expected number of events for $a \rightarrow \gamma\gamma$

$$S_{\gamma\gamma} = N_\gamma T$$

where

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$$m_a = 1.2 \text{ MeV}$$

Excluded by JUNO
Axion photon and axion nucleon couplings

- For varying axion mass: \( S_{\text{events}} = \Phi_a \sigma_{a-e,p} C N_{e,p} T \varepsilon \leq S_{\text{lim}} \)
Final remarks:

- Aimed to search for 5.5 MeV solar axions for the JUNO detector

- The processes that are examined:

  \[ a + e \rightarrow e + \gamma \]
  \[ a \rightarrow e^+e^- \]
  \[ a + Z \rightarrow \gamma + Z \] and
  \[ a \rightarrow \gamma\gamma \]

- Bounds obtained for JUNO:

  \[ |g_{3aN} \times g_{ae}| \leq 6.33 \times 10^{-14} \]

  \[ |g_{3aN} \times g_{a\gamma}| \leq 2.0 \times 10^{-12} GeV^{-1} \]

- JUNO can provide the most stringent bound around sub-MeV axion mass for the axion electron times axion nucleon plane.
thank you