Uncertainties of the Solar Axion Flux and Their Impact on Identifying QCD Axion Models

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Why revisit the solar axion flux?

- **Current & future experimental prospects**
  - (Baby)IAXO can explore the QCD axion band \(^{1904.09155}\), talk by Elisa Ruiz Chóliz (Thu)
  - XENON1T excess \(^{2006.09721}\), talk by Adam Brown (today)
  - ...

- **Recent activity for solar production processes**
  - Axion production in atomic transitions \(^{1908.10878}\)
  - Plasmon conversion in large-scale solar \(B\)-fields \(^{2005.00078, 2006.12431, 2010.06601}\)

- **Measurements beyond detection**
  - Determining the axion mass & couplings \(^{1811.09278, 1811.09290}\)
  - Solar composition, metallicity, \(B\)-fields \(^{1908.10878, 2006.12431}\)
What did we do?

1. Revisited the solar axion flux calculation, *included electron degeneracy effects* for the Primakoff flux

2. Surveyed available solar models & opacity codes, wrote light-weight, *publicly available library* compatible with standard solar model formats

3. Quantified statistical & systematic uncertainties, investigated their relevance for axion detection, parameter estimates, & solar probes
Axion interactions in the Sun

\[ \mathcal{L}_{\text{ALP}} = \frac{1}{2} (\partial_{\mu} a)^2 - \frac{1}{2} m_a^2 a^2 - \frac{g_{\gamma\gamma}}{4} a F \tilde{F} + \frac{g_{\text{ee}}}{2m_e} (\partial_{\mu} a) \bar{e} \gamma^\mu \gamma^5 e + \mathcal{L}_{a,\text{nucl}} + \mathcal{L}_{\text{CP}} \]

\( m_a \ll T_\odot \sim \text{keV} \)

Works by Raffelt(+) Redondo, ... (see our paper for detailed list of refs)
Systematic uncertainties: different solar models

Clearly visible difference because some models do not track important heavier elements e.g. Fe...
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Systematic uncertainties

- Not all solar models provide complete information for the abundance of various "metals" use not recommended!

- Solar models: systematics due to \textit{solar metallicity problem}: \textit{avg. uncertainty} \( \sim 5\% \), but can be up to 11\% (Primakoff flux) or 19\% (peaks in the ABC flux)

- Opacity codes disagree on average less than 2\%, but can be up to 440\% (sic!) at ABC flux peaks
What about statistical uncertainties?

- Propagate full statistical uncertainties from 10,000 Monte Carlo samples of representative low-$Z$ (AGSS09) & high-$Z$ (GS98) models

astro-ph/0511337 + A. Serenelli updates
What about statistical uncertainties?

- Propagate full statistical uncertainties from 10,000 Monte Carlo samples of representative low-$Z$ (AGSS09) & high-$Z$ (GS98) models

- However: no statistical error estimates for monochromatic opacities $\kappa(T,...)$ available

- Use heuristic ansatz that captures known properties of the uncertainties

$$\frac{\kappa}{\hat{\kappa}} = 1 + a \frac{\log_{10}(T_0/T)}{\log_{10}(T_0/T_{CZ})}, \text{ with } a \sim \mathcal{N}(0, 0.02), \ b \sim \mathcal{N}(0, 0.07)$$
Statistical uncertainties from Monte Carlo

Primakoff fluxes

ABC fluxes

Flux relative to AGSS09 mean

Energy $\omega$ [keV]

AGSS09

GS98

Mean $\langle d\Phi^P_a / d\omega \rangle$

$\langle d\Phi^P_a / d\omega \rangle \pm 1\sigma$

Difference in mean values = metallicity problem in low-Z (AGSS09) vs high-Z (GS98) models

$1\sigma$ error bands = spectral statistical uncertainty; similar for AGSS09 and GS98, smaller than syst. uncertainty

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- Solar models: *stat. uncertainties ~ 2% on average* and up to 5% for the ABC flux in both low-Z & high-Z models
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⇒ Stat. uncertainties small compared to systematics from solar models, opacity codes, & theory uncertainties/neglected effects

⇒ Focus improving theoretical calculations & solar $B$-field models (for plasmons) to reach percent-level accuracy
Consider 15 preferred KSVZ models with $N_Q = 1^{1610.07593, 1705.05370}$:

Primakoff flux dominant, signal $\propto g_{a\gamma\gamma}^4$

IAXO could not just find KSVZ axions but also provide a hint for the solar metallicity problem.
Looking ahead: KSVZ axion models with $N_Q \geq 1$

- Extend $N_Q = 1$ preferred models to $N_Q > 1$
- Esp. Landau Pole (LP) criterion is very powerful

*Histogram of all non-equivalent KSVZ models with additive representations from dim·5 operators (lifetime constraints) that respect LP.
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- Extend $N_Q = 1$ preferred models to $N_Q > 1$
- Esp. Landau Pole (LP) criterion is very powerful
- **Upper limit on** $N_Q$ i.e. finite number of KSVZ axion models; exact value depends on operators & constraints
- We find* $N_Q \leq 28$, less than 60,000 non-equivalent models, & 443 distinct $E/N$

*Histogram of all non-equivalent KSVZ models with additive representations from dim $\leq 5$ operators (lifetime constraints) that respect LP $< m_{\text{Pl}}$.
Looking ahead: KSVZ axion models with $N_Q \geq 1$

- Can interpret model catalogue as a statistical distribution

  **Theory-inspired prior** on the axion-photon coupling
  
  $|g_{a\gamma\gamma}| \propto |E/N - 1.92(4)|$ from $E/N$ catalogue
Looking ahead: KSVZ axion models with $N_Q \geq 1$

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- **Theory-inspired prior** on the axion-photon coupling $|g_{a\gamma\gamma}| \propto |E/N - 1.92(4)|$ from $E/N$ catalogue
- Here: every representation = equally probable + LP criterion

![Graph showing axion mass vs. axion-photon coupling](image)

Credit to Ciaran O'Hare for digitised limits
- Primakoff (P) flux predicted at percent level, ABC flux has larger uncertainties
- We included electron degeneracy for P but still more work: solar $B$-fields, subleading effects, plasma simulation incl. axion emission (opacity), QCD calculations & measurements, ...
- IAXO can distinguish (preferred) QCD axion models when $m_a$ is detected; hint towards high-$Z$ or low-$Z$ solar models in ideal case
- Code (library+Python wrapper) on Github
- Catalogue for KSVZ models with $N_Q > 1$; stay tuned!