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

Sebastian Hoof, J. Jaeckel, & L. J. Thormaehlen, `arXiv:2101.08789`

V. Plakkot & **SH**, *in preparation*

16th Patras Workshop on Axions, WIMPs and WISPs

Online, 16 June 2021

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?

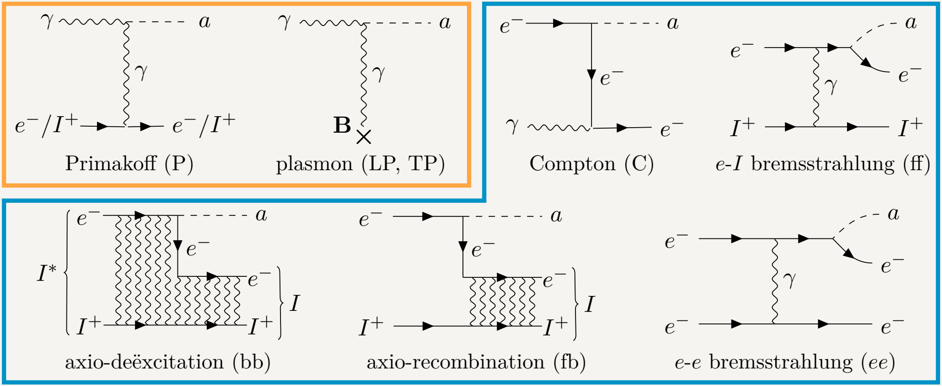
1. Revisited the solar axion flux calculation, *included electron degeneracy effects* for the Primakoff flux

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

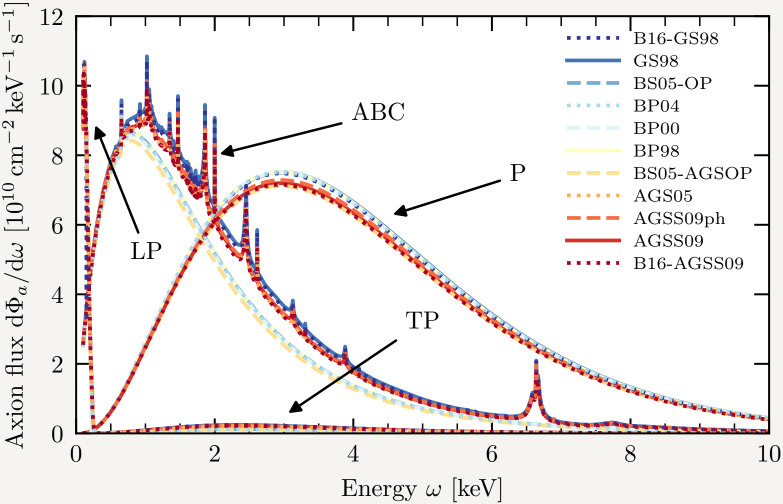
Axion interactions in the Sun

$$\mathscr{L}_{\text{ALP}} = \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2}\underbrace{m_a^2}_{m_a \ll T_\odot \sim \text{keV}} a^2 - \frac{g_{a\gamma\gamma}}{4} a F\tilde{F} + \frac{g_{aee}}{2m_e}(\partial_\mu a)\,\bar{e}\gamma^\mu\gamma^5 e \underbrace{+\mathscr{L}_{a,\text{nucl}} + \mathscr{L}_{\not{CP}}}_{\text{not included}}$$

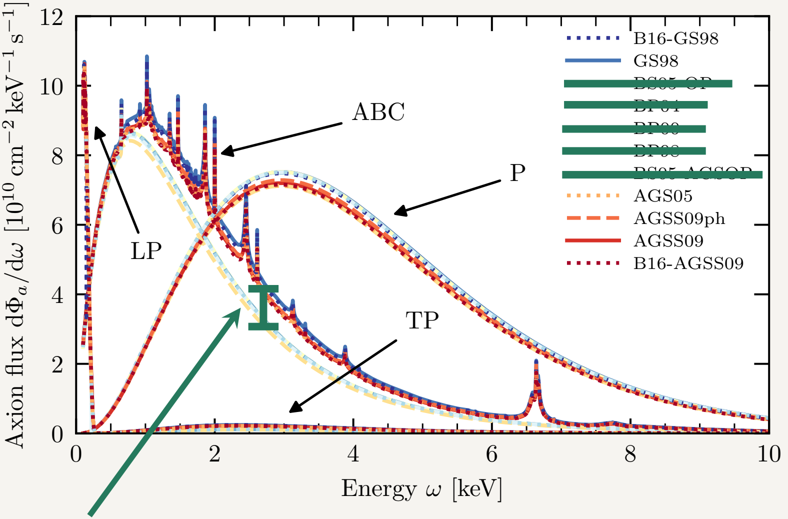


Works by Raffelt(+), Redondo, ... (see our paper for detailed list of refs)

Systematic uncertainties: different solar models



Systematic uncertainties: different solar models



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

Systematic uncertainties

- Not all solar models provide complete information for the abundance of various "metals" ➻ use not recommended!
- Solar models: systematics due to *solar metallicity problem: 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]

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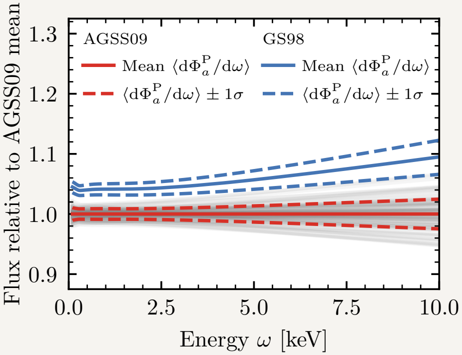
- Propagate full statistical uncertainties from 10,000 Monte Carlo samples of representative low-Z (AGSS09) & high-Z (GS98) models[astro-ph/0511337 + A. Serenelli updates]
- However: no statistical error estimates for monochromatic opacities $\kappa(T, \ldots)$ available
- Use heuristic ansatz that captures known properties of the uncertainties[1611.09867]

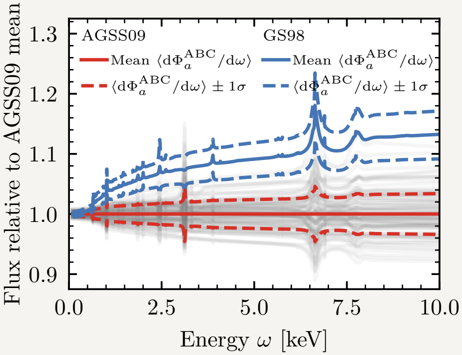
$$\frac{\kappa}{\hat{\kappa}} = 1 + a + b\,\frac{\log_{10}(T_0/T)}{\log_{10}(T_0/T_{\mathrm{CZ}})}, \text{ with } a \sim \mathcal{N}(0, 0.02),\; b \sim \mathcal{N}(0, 0.07)$$

Statistical uncertainties from Monte Carlo

Primakoff fluxes



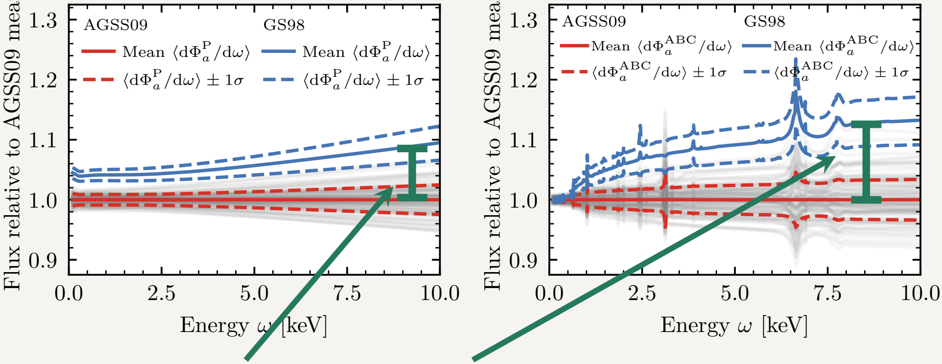
ABC fluxes



Statistical uncertainties from Monte Carlo

Primakoff fluxes

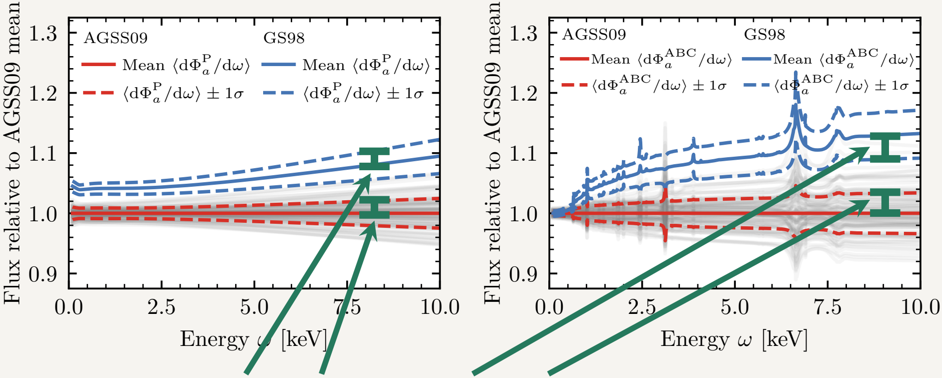
ABC fluxes



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

Statistical uncertainties from Monte Carlo

Primakoff fluxes   ABC fluxes



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

Statistical uncertainties from Monte Carlo

- Solar models: *stat. uncertainties ~ 2% on average* and up to 5% for the ABC flux in both low-Z & high-Z models
- Averaged opacity uncertainty at the sub-percent level; up to 17% for specific energies

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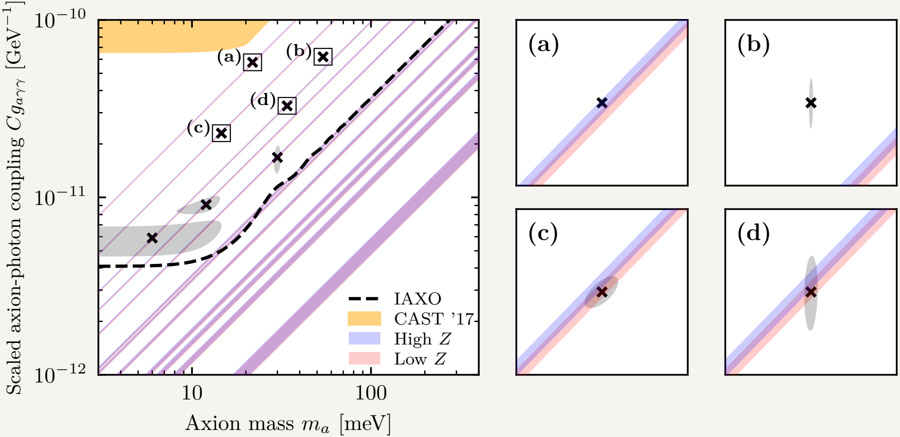
➽ Stat. uncertainties small compared to systematics from solar models, opacity codes, & theory uncertainties/ neglected effects

➽ Focus improving theoretical calculations & solar B-field models (for plasmons) to reach percent-level accuracy

Identifying KSVZ axions with IAXO: hypothetical signals

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

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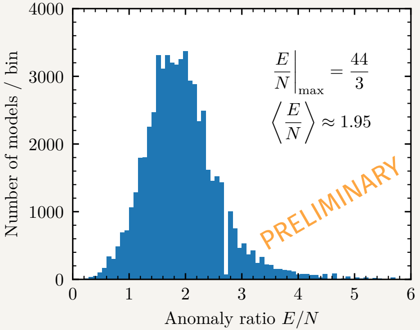
- Esp. Landau Pole (LP) criterion is very powerful
- *Upper limit on N_Q* i.e. finite number of KSVZ axion models; exact value depends on operators & constraints
- We find* $N_Q \leq 28$, less than 60,000 non-equivalent models, & 443 distinct E/N



*Histogram of all non-equivalent KSVZ models with additive representations from dim ≤ 5 operators (lifetime constraints) that respect LP $< m_{\mathrm{Pl}}$.

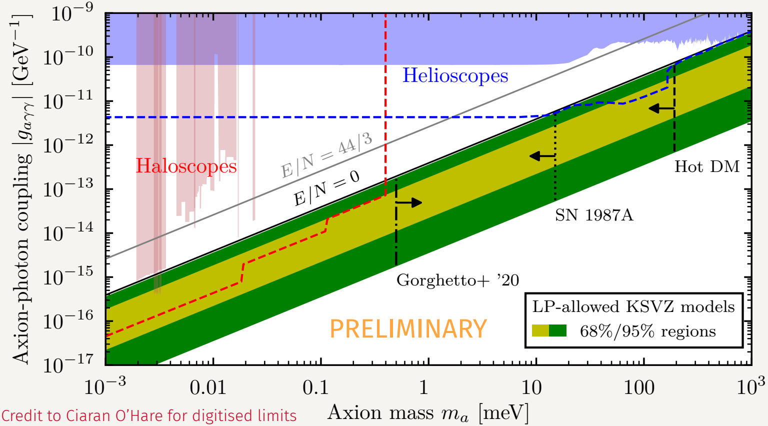
Looking ahead: KSVZ axion models with $N_Q \geq 1$

- 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 $N_Q \geq 1$

- 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
- Here: every representation = equally probable + LP criterion



Credit to Ciaran O'Hare for digitised limits

Summary

- 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!