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Searching for Axionlike Particles

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Abstract

Axionlike particles (ALPs) are promising candidates for dark matter (e.g. Bertone & Tait 2018). A tiny interaction between photons and ALPs gives rise to achromatic birefringence and the birefringence angle oscillates with a time-period determined by their mass. The differential polarization angle measured between the images of gravitationally lensed quasars contains a clean ALP-induced birefringence signal which is free of observational and astrophysical systematics. This allows us to probe ALPs at sensitivity comparable to, or better than, lab-experiments.
We demonstrate the new technique with the help of existing observations and propose multi-epoch spectropolarimetric observations of 5 gravitational lens systems using the JVLA and the VLBA.

ALPs cause Birefringence

The interaction of ALPs with photons causes left- and right-circularly polarized light to travel at different velocities in the ALP field – the **birefringence phenomena** (Harari & Sikivie 1992). Consequently, the plane of polarization of linearly polarized light is rotated with respect to the plane at emission by the birefringence angle $\Delta\theta_a$. It depends on the coupling, $g_{a\gamma}$, and strength of the ALP field. The ALP field oscillates in time with period given by the mass, $T_a = 2\pi/m_a$. Therefore, $\Delta\theta_a$ also oscillates, allowing us to measure m_a. For $m_a = \mathcal{O}(10^{-22}\text{eV})$, T_a is expected to be of the order of several months. A major advantage of searching for ALPs via birefringence is that it is a direct search and the detection signal is independent of astrophysical assumptions.

New Technique

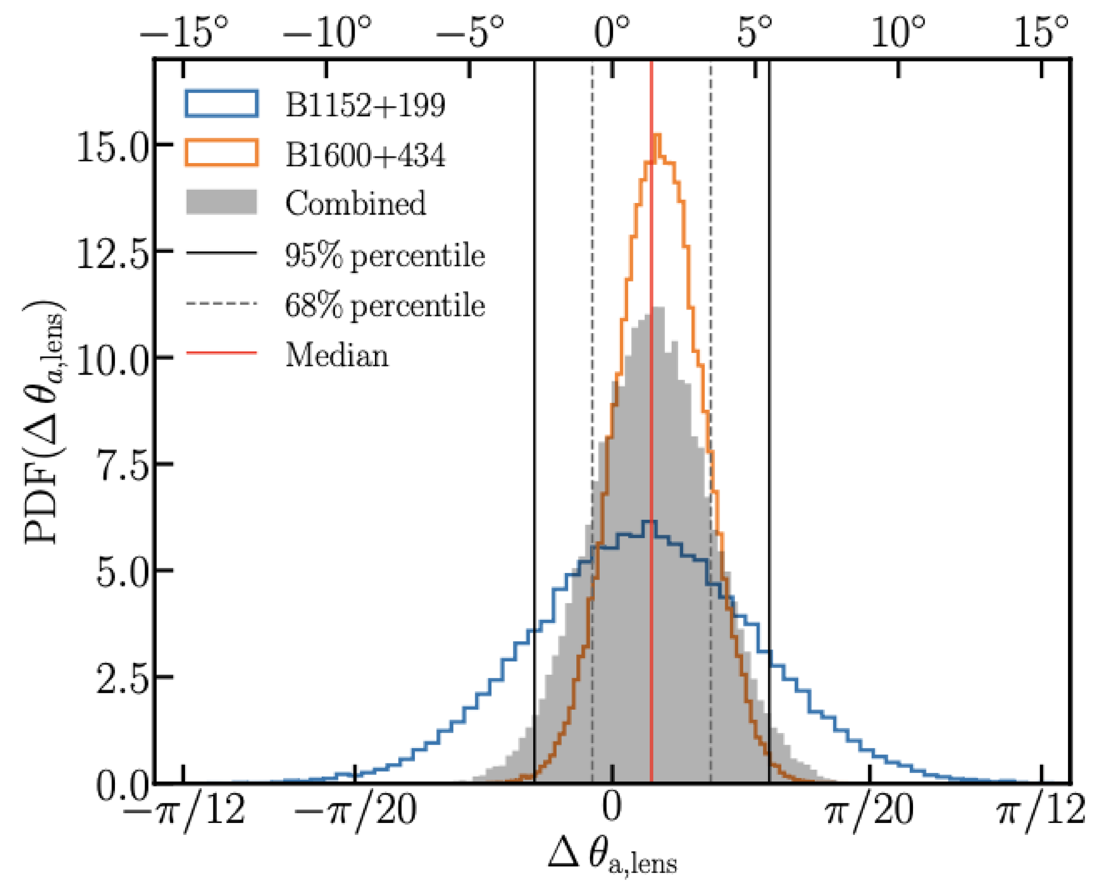
The observed polarization angle (θ_{obs}) contains contributions from the birefringence angle of ALP-photon interaction ($\Delta\theta_a$), the astrophysical source (θ_{src}), and instrumental calibration offsets ($\delta\theta_{\text{cal}}$). That means, the angle measured on the Earth is given by, $\theta_{\text{obs}} = \theta_{\text{src}} + \Delta\theta_a + \delta\theta_{\text{cal}}$.
Strong gravitational lensing allows simultaneous observation of time-separated emission from a source, due to gravitational time delay, as lensed images. This helps mitigate the unknown θ_{src} and $\delta\theta_{\text{cal}}$. At radio frequencies and ultralight ALPs the limit of geometric optics applies (Schwarz et al. 2021).
In our novel technique (Basu et al. 2021), the birefringence is measured by comparing the polarization angles of multiple images of a gravitationally lensed, linearly polarized quasar. The differential birefringence angle ($\Delta\theta_{a,\,\text{lens}}$) is given as,

$$\Delta\theta_{a,\,\text{lens}} = K \sin\left[\frac{m_a \Delta t}{2}\right] \sin\left[m_a t_{\text{em}} + \delta_{\text{em}} - \frac{\pi}{2}\right],$$

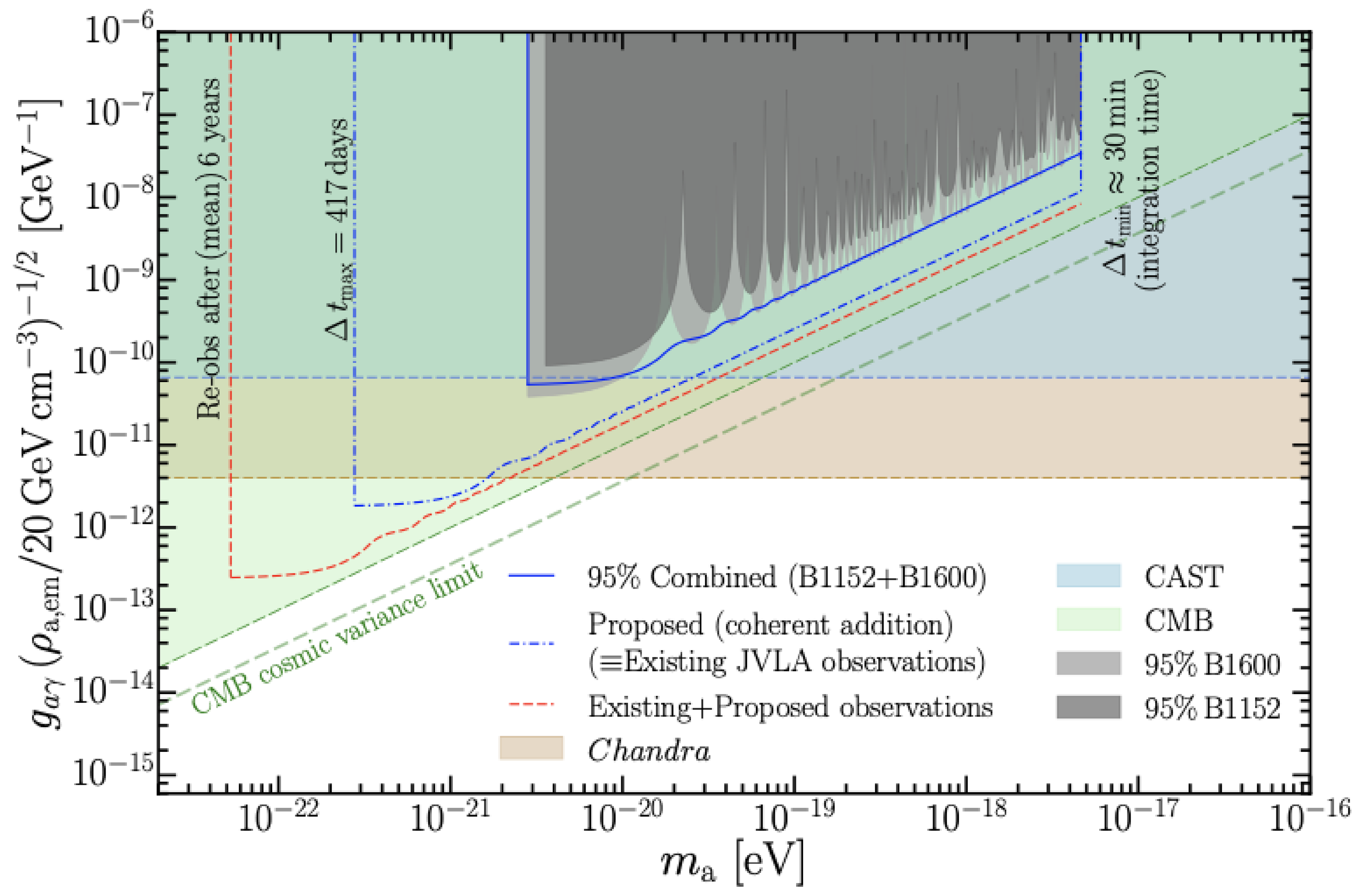
where

$$K = 10^\circ \left[\frac{\rho_{a,\,\text{em}}}{20\ \text{GeV cm}^{-3}}\right]^{1/2} \left[\frac{g_{a\gamma}}{10^{-12}\ \text{GeV}^{-1}}\right] \left[\frac{m_a}{10^{-22}\ \text{eV}}\right]^{-1}.$$

Current and Projected Constraints

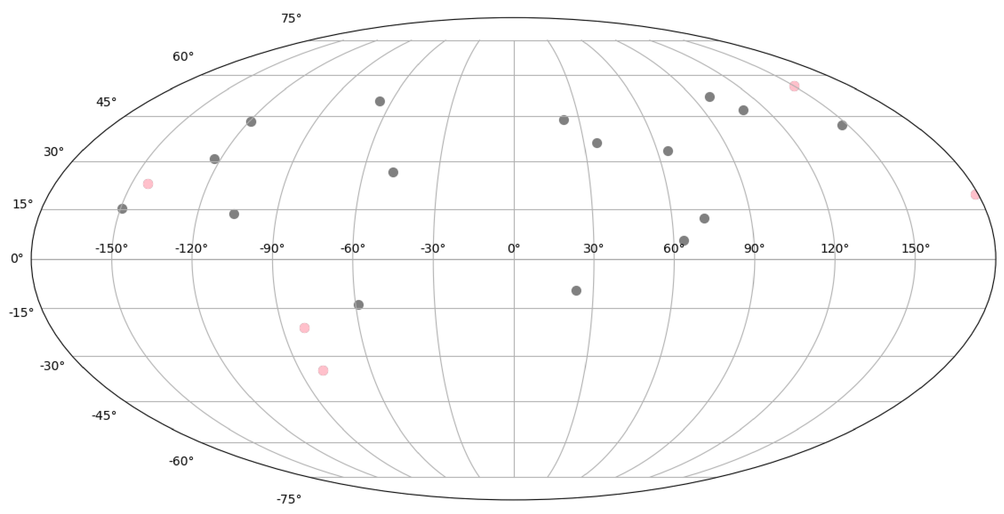


Distribution of $\Delta\theta_{a,\,\text{lens}}$ where the blue and the orange histograms are for the lensed quasars B1152+199 (Basu et al. 2021) and B1600+434 (JVLA observations, 12B-180). The shaded histogram is for $\Delta\theta_{a,\,\text{lens}}$ combined from the two systems.



Exclusion region for $g_{a\gamma}$ and m_a at 95% confidence for B1152+199 (dark grey) and for B1600+434 (light grey). The solid blue line is the new exclusion obtained from the combined $\Delta\theta_{a,\,\text{lens}}$. The dash-dotted blue and dashed red lines show parameter space we expect to probe using the proposed (coherent addition) and existing observations.

Suitable Gravitational Lenses



We present a list of 21 strong gravitationally lensed quasars with linear polarization which are most likely to be good candidates for this ALP search technique (Deshmukh 2021). We choose only those systems with a polarization flux density greater than NVSS rms noise, i.e., 0.35 mJy. The highlighted five lens systems are selected for the first search run.

Lens System	Separation (in arcsec)	N_{img}	z_d	z_s
B1152+199	1.59	2	0.439	1.019
B1600+434	1.4	2	0.41	1.59
B0128+437	0.55	4		3.124
PMNJ0134-0931	0.73	5	0.77	2.216
B0218+357	0.34	2	0.68	0.96
MG0414+0534	2.4	4	0.96	2.64
B0445+123	1.35	2	0.557	
B0631+519	1.16	2	0.62	
B0712+472	1.46	4	0.41	1.34
Q0957+561	6.26	2	0.36	1.41
B1359+154	1.71	6		3.235
B1422+231	1.68	4	0.34	3.62
MG1549+3047	1.7	0	0.11	1.17
MG1654+1346	2.1	0	0.25	1.74
PKS1830-211	0.99	2	0.89	2.51
PMNJ1838-3427	0.99	2		2.78
B1933+503	1	10	0.76	2.63
PMNJ2004-1349	1.18	2		
B2045+265	2.74	4	0.87	1.28
PSJ0417+3325	1.68	2		1.41
PSJ0949+4208	2.6	2	0.508	1.27

Conclusion

This new ALP detection method probes ultralight ALPs with high sensitivity, and is independent of astrophysical assumptions and systematics. It covers a broad region in m_a and $g_{a\gamma}$ and provides a realistic chance to detect ultralight ALPs. An advantage of this method is that, $\Delta\theta_{a,\,\text{lens}}$ obtained from different lens systems can be combined to improve the signal statistically.
We received approval from NRAO (National Radio Astronomy Observatory) for ~ 100 hours of observation time with high priority on the JVLA and the VLBA, in order to carry out a pilot survey of five lens systems for five epochs spanning the entire three-month duration of the JVLA's A-configuration. The observations are scheduled for the first half 2022. Eventually, the SKA will allow us to reach sensitivities beyond the CMB cosmic variance limit.

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