Constraints on axion-like ultralight dark matter from observations of the HL Tauri protoplanetary disk

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Daniil Davydov, **Alexander Libanov**

INR
Institute for Nuclear Research
of the Russian Academy of Sciences

Physics Department
Lomonosov Moscow State University

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Motivation

- Dark matter consists of ultra-light axion-like particles;
- When polarized radiation passes through ALPs interaction with background ALPs will affect the polarization of photons;
- On the other hand, the condensate of axionic dark matter experiences periodic oscillations - for ULDM with periods of the order of years;
- The result is periodic changes in the polarization plane of the source;
- The polarization phase is determined by the phase of the axion field at the Earth and at the source.

In this work we considered HL Tauri protoplanetary disk that was observed over several years to evaluate the effect.

D. Harari and P. Sikivie, Phys. Lett. B (1993)

Model

ALP-photon interaction Lagrangian:

$$\mathscr{L} = -\frac{1}{4}F_{\mu\nu}^2 + \frac{1}{2}(\partial_\mu a \partial^\mu a - m^2 a^2) + \frac{g_{a\gamma}}{4} a F_{\mu\nu}\widetilde{F}^{\mu\nu}, \tag{1}$$

The rotation angle of the polarization plane is given by:

$$\Delta\phi = \frac{1}{2}\int_{t_1}^{t_2} \Delta\omega \, dt = \frac{1}{2} g_{a\gamma} \int_{t_1}^{t_2} \partial_0 a \, dt, \tag{2}$$

The ALP dark-matter field oscillates as

$$a(t) = a_0 \cos(mt + \delta), \tag{3}$$

The final expression for the change of the polarization angle with time is given by

$$\Delta\phi \approx 1.4 \times 10^{-2} \sin(mt + \text{const})\, g_{12} m_{22}^{-1}. \tag{4}$$

M. M. Ivanov et al, JCAP (2019)

Data and Analysis: Polarization Map

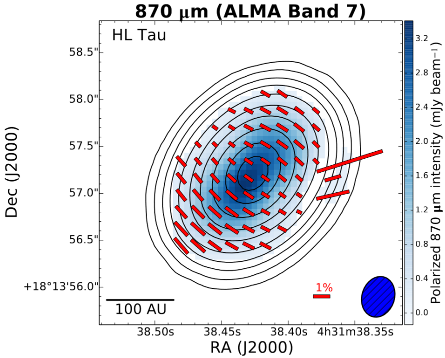

Figure: The polarization map presented in I. W. Stephens et al, Astrophys. J. (2017) was obtained from observations performed on December 4, 2016.

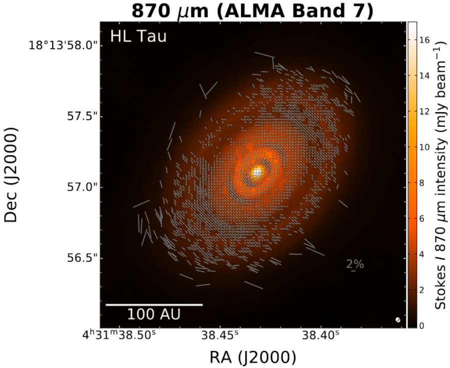

Figure: The public data accompanying I. W. Stephens et al, Nature (2023) is based on a series of observations between June and October, 2021.

Data and Analysis: Fitting

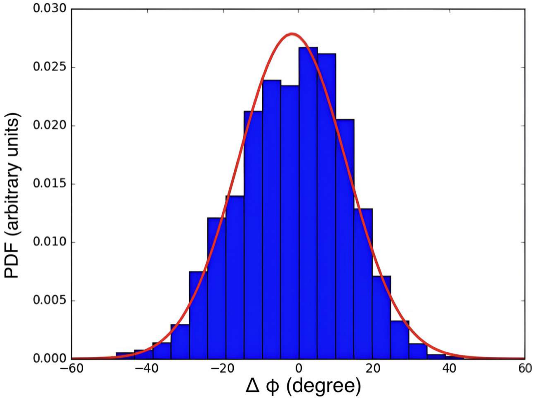

Figure: Distribution of the polarization angle differences between 2016 and 2021 observations (blue histogram) and the best-fit Gaussian distribution (red line).

Data and Analysis: Fitting

We fit distribution with a Gaussian, keeping both the central value and the width free. The best-fit values of the expectation, $\langle \Delta\phi \rangle \approx -1.58^\circ$, and the standard deviation, $\sigma_{\Delta\phi} \approx 14.33^\circ$, allow one to constrain

$$\Delta\phi < \langle \Delta\phi \rangle \pm 1.96 \frac{\sigma_{\Delta\phi}}{\sqrt{N}} \approx 0.0276 \pm 0.0586 \text{ rad}, 95\% \text{ C.L.}, \qquad (5)$$

Results

We obtain the constraint

$$\sin(mt + \text{const})\, g_{12} m_{22}^{-1} \lesssim 2. \quad (6)$$

Since we have only two measurements, and one of them is a result of observations during five months, it is hard to use the shape of the sine function here. In addition, the initial phase of the oscillation is unknown. Therefore, following T. Fujita et al, Phys. Rev. Lett. (2019) , we simply replace the sine by $1/\sqrt{2}$ to obtain the final approximate constraint on the ALP-photon coupling constant as a function of the ALP mass,

$$g_{a\gamma} \lesssim 2.788 \times 10^{-12}\ \text{GeV}^{-1} \left(\frac{m}{10^{-22}\ \text{eV}} \right) \quad (7)$$

at the 95% C.L.

Results

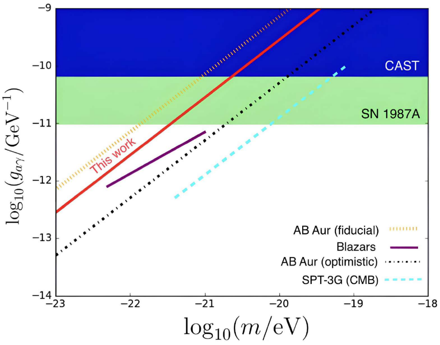

Figure: Comparison of restrictions for constant of interaction between axions and photons $g_{a\gamma}$ and as a function of axion mass. The red line is for restriction from this work. Purple line is for restrictions from M. M. Ivanov et al, JCAP (2019). The dashed black and yellow lines is for restriction from T. Fujita et al, Phys. Rev. Lett. (2019). The blue line is for restriction from SPT-3G collaboration, Phys. Rev. D (2022).

THANK YOU FOR YOUR ATTENTION!

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