Axion-like Dark Matter Search with Space-based Gravitational Wave Detectors

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ALDM birefringence

Lagrangian of the ALDM-photon system:

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}\partial^\mu a \partial_\mu a - \frac{1}{2}m_a^2 a^2 - \frac{1}{4}g_{a\gamma\gamma} a F_{\mu\nu}\tilde{F}^{\mu\nu}, \tag{1}$$

Weyl gauge $A_0 = A^0 = 0$:

$$\omega^2 \boldsymbol{A} + \boldsymbol{k} \times (\boldsymbol{k} \times \boldsymbol{A}) = i g_{a\gamma\gamma}(\omega \boldsymbol{\nabla} a + \partial_t \boldsymbol{k}) \times \boldsymbol{A}. \tag{2}$$

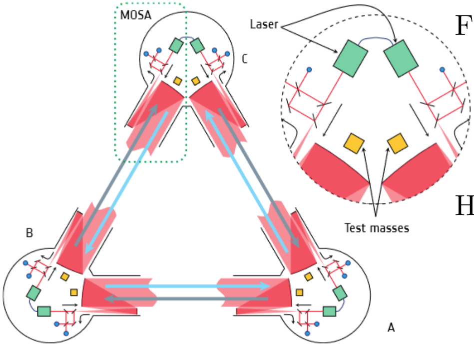
Dispersion relations:

$$\omega_\pm \simeq k \pm g_{a\gamma\gamma}\left(\frac{\partial a}{\partial t} + \nabla a \cdot \hat{\boldsymbol{k}}\right) = k \pm g_{a\gamma\gamma} n^\mu \nabla_\mu a. \tag{3}$$

EVPA change for a linearly polarized light:

$$\Delta\phi_a = \frac{1}{2}\int_{t_{\rm emit}}^{t_{\rm obs}} (\omega_+ - \omega_-)\, dt = \frac{1}{2} g_{a\gamma\gamma}\left[a(x^\mu_{\rm obs}) - a(x^\mu_{\rm emit})\right]. \tag{4}$$

Space-based gravitational wave detectors



Credit: Colpi et al., 2024

Local transmitted beam: $E_{TX} = \sqrt{2I_0}\, e^{i\omega_T t}$
Received beam: $E_{RX} = p\sqrt{2I_0}\, e^{i(\omega_R t+\phi)}$
Fields at the photodiodes

$$S_A = |E_{TX} + e^{i\pi/2} E_{RX}|^2, \quad (5)$$

$$S_B = |e^{i\pi/2} E_{TX} + E_{RX}|^2. \quad (6)$$

Heterodyne signal:

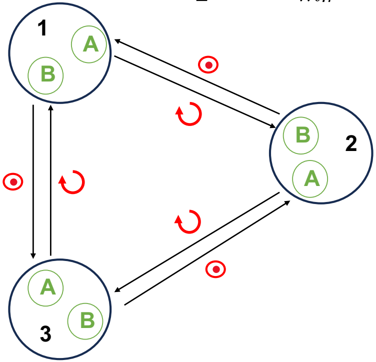
$$\arg\left[\int_0^{2\pi n/\Omega} (S_B - S_A)\, e^{-i\Omega t}\, dt\right] \approx \phi + \pi/2 \quad (7)$$

Heterodyne frequency $\Omega = \omega_R - \omega_T$;

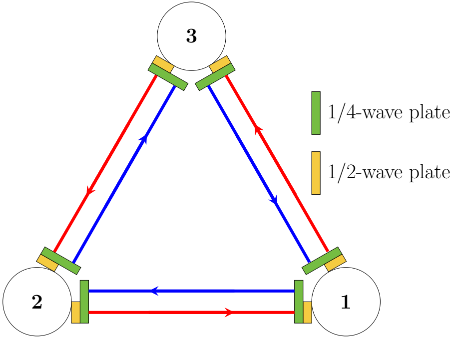
Recent proposals

ALDM field collective velocity $v \sim 10^{-3}$, coherence length $\lambda_a \gg L$:

$$\Delta\phi_a = \frac{1}{2} g_{a\gamma\gamma} \frac{\sqrt{2\rho_{\mathrm{DM}}}}{m_a} \left\{\cos(m_a t + \Phi) - \cos\left[m_a(t-L) + \Phi\right]\right\}. \tag{8}$$



Credit: Gué, Hees, and Wolf, 2024

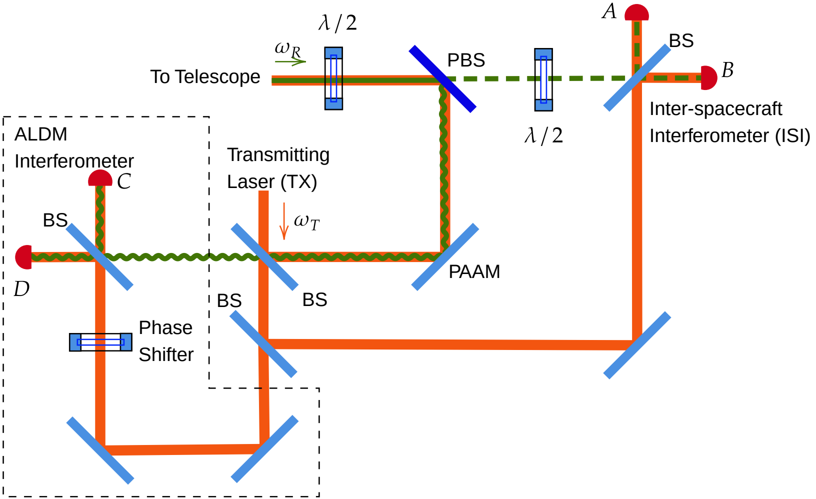


Credit: Yao, Jiang, and Tang, 2024

Motivation

- Although the current design of SGWDs utilize linearly polarized laser links, the past designs of SGWDs favored circularly polarized light for the inter-satellite path, and both options were under consideration.
- Circular polarization in phase sensitive ranging yields a susceptibility to roll rotations of the S/C.
- Optical components, such as quarter-wave plates, are main sources of backreflection, and it is easier to design and to predict the behavior of the antireflection coatings of the optics working only with linear polarization.

Our proposal



Phase signals of ALDM

$$\boldsymbol{E}_{\mathrm{RX}} = \cos\Delta\phi_a E_{\mathrm{TX}}\hat{\boldsymbol{s}} + \sin\Delta\phi_a E_{\mathrm{TX}}\hat{\boldsymbol{p}}. \tag{9}$$

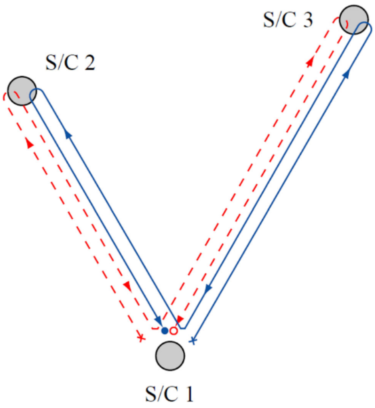
$$\phi_{\mathrm{ALDM}} \equiv \arg\left[\int_0^{2\pi n/\Omega} [(S_D - S_C) + (S_B - S_A)] e^{-i\Omega t} dt\right] \tag{10}$$

$$\phi_{\mathrm{ISI}} \equiv \arg\left[\int_0^{2\pi n/\Omega} (S_B - S_A) e^{-i\Omega t} dt\right] \tag{11}$$

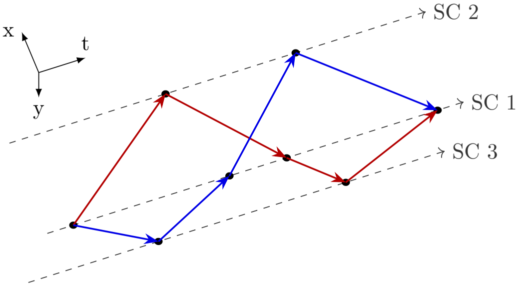
Phase shift between two interferometers: $\Delta\phi = \Delta\phi_{\mathrm{Tx}} + \Delta\phi_{\mathrm{Rx}} + \Delta\phi_{\mathrm{PS}}$;
Impose $I_{\mathrm{ALDM}} = I_{\mathrm{ISI}}$ and fix $\Delta\phi = \pi/2$:

$$\Delta\phi_a \simeq \phi_{\mathrm{ALDM}} - \phi_{\mathrm{ISI}} \tag{12}$$

Time-delay interferometry

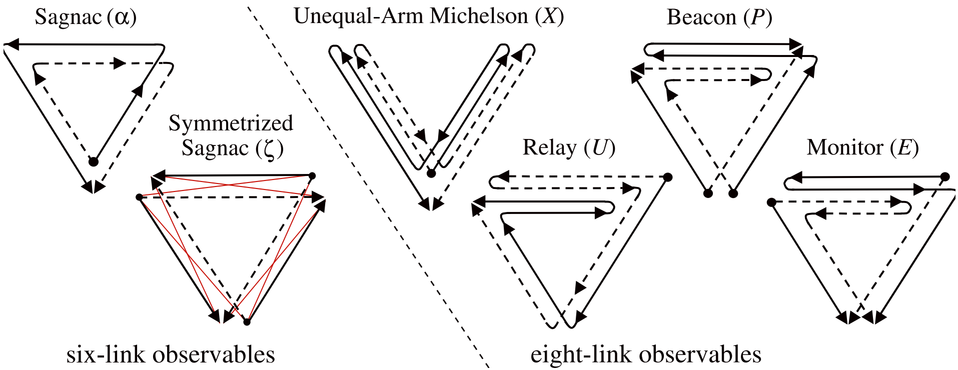


Credit: Tinto and Dhurandhar, 2021



Credit: Hartwig et al., 2022

Different TDI combinations



Credit: Vallisneri, 2005

Doppler signals

Single-arm signal

$$\eta_{rs} \equiv \frac{1}{\omega_r}\frac{d\left(\phi_{\mathrm{ALDM}}-\phi_{\mathrm{ISI}}\right)}{dt} \approx \frac{1}{\omega_r}\frac{d\Delta\phi_a}{dt} \tag{13}$$

$$\bar{\eta}_{rs} \equiv \frac{1}{\omega_r}\frac{d\left(\phi_{\mathrm{ISI}}-\phi_{\mathrm{ALDM}}\right)}{dt} \approx -\frac{1}{\omega_r}\frac{d\Delta\phi_a}{dt}, \tag{14}$$

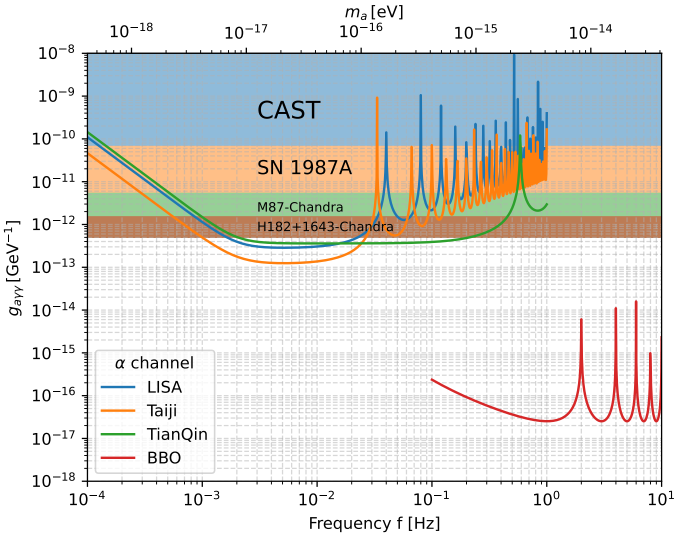
Sagnac variable α:

$$\begin{aligned}\alpha(t) &= \left[\bar{\eta}_{12} + D_{12}\bar{\eta}_{23} + D_{12}D_{23}\bar{\eta}_{31}\right] - \left[\eta_{13} + D_{13}\eta_{32} + D_{13}D_{32}\eta_{21}\right] \\ &= 2\,\frac{g_{a\gamma\gamma}}{\omega_r}\sqrt{2\rho_{\mathrm{DM}}}\,\sin\frac{3m_aL}{2}\,\cos\left(m_at + \Phi - \frac{3m_aL}{2}\right),\end{aligned} \tag{15}$$

One-sided PSD:

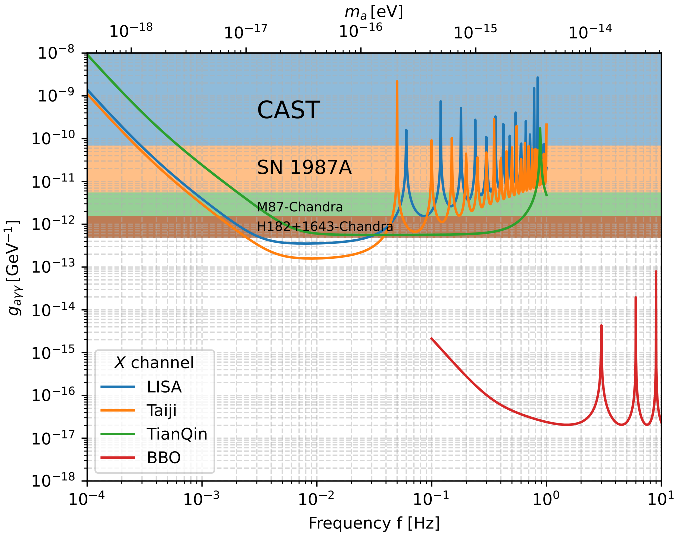
$$S_\alpha(f) = \frac{4\sin^2(3\pi fL)\,g_{a\gamma\gamma}^2\rho_{\mathrm{DM}}}{\pi^2\omega_r^2\,T_{\mathrm{obs}}}\,\frac{\sin^2[\pi(f-f_a)\,T_{\mathrm{obs}}]}{(f-f_a)^2}, \tag{16}$$

Results



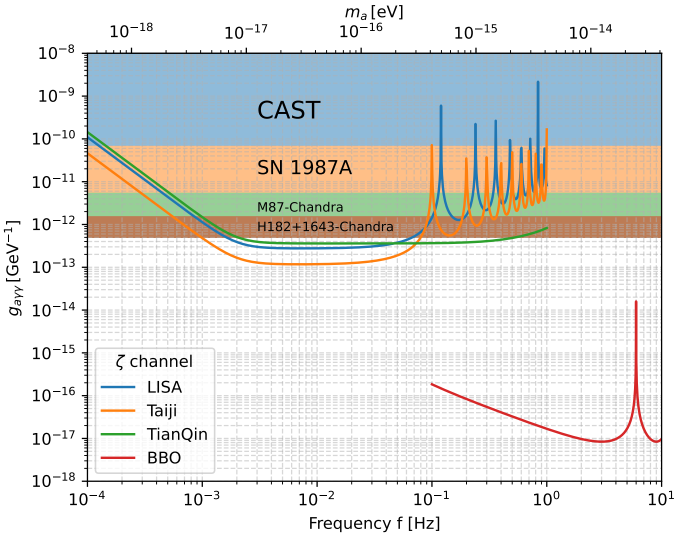
α channel

Results



X channel

Results



ζ channel

Summary

- Propose a novel modification to the space-based gravitational wave detectors to probe axion-like dark matter by introducing an auxiliary interferometer for the p-polarized component of the received light.
- Do not change the polarization state of the beam exchanged between the spacecraft.
- Applicability in different TDI combinations.

Thanks!

References I

Colpi, Monica et al. (Feb. 2024). "LISA Definition Study Report". arXiv: 2402.07571 [astro-ph.CO].

Gué, Jordan, Aurélien Hees, and Peter Wolf (Oct. 2024). "Probing the axion-photon coupling with space-based gravitational waves detectors". arXiv: 2410.17763 [hep-ph].

Hartwig, Olaf et al. (2022). "Time-delay interferometry without clock synchronization". *Phys. Rev. D* 105.12, p. 122008. DOI: 10.1103/PhysRevD.105.122008. arXiv: 2202.01124 [gr-qc].

Tinto, Massimo and Sanjeev V. Dhurandhar (2021). "Time-delay interferometry". *Living Rev. Rel.* 24.1, p. 1. DOI: 10.1007/s41114-020-00029-6.

Vallisneri, Michele (2005). "Geometric time delay interferometry". *Phys. Rev. D* 72. [Erratum: Phys.Rev.D 76, 109903 (2007)], p. 042003. DOI: 10.1103/PhysRevD.76.109903. arXiv: gr-qc/0504145.

References II

Yao, Yue-Hui, Tingyuan Jiang, and Yong Tang (Oct. 2024). "Prospects for Axion Dark Matter Searches at LISA-like Interferometers". arXiv: 2410.22072 [hep-ph].