Reply to the comment on “Quantum sensor networks as exotic field telescopes for multi-messenger astronomy”

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The comment by Stadnik [arXiv:2111.14351v1] claims that “back-action”, i.e. interaction of exotic low-mass fields (ELF) with ordinary matter, “prevents the multi-messenger astronomy on human timescales.” We strongly disagree with this blanket claim. This is not a general conclusion, as Stadnik’s statement entirely relies on a specific sign of the ELF-matter interaction. As we demonstrate, there are coupling constant ranges when, in fact, the screening effects are irrelevant. In addition, the delay between the arrival of the ELF and gravitational wave bursts is reduced by the ELF-ordinary matter interaction, improving the discovery reach of our proposed novel, exotic physics, modality in multi-messenger astronomy.

The comment by Stadnik [1] claims that “back-action”, i.e. interaction of exotic low-mass fields (ELF) with ordinary matter, “prevents the multi-messenger astronomy on human timescales.” We strongly disagree with this blanket claim. This is not a general conclusion, as this statement entirely relies on a specific sign of the ELF-matter interaction. One of us (A.D.) pointed out this counter-argument to Stadnik in private communications. While we are delighted to see that the counter-argument stems from his parameterization of the square of real $\Lambda_X$. The improper relation should have been $\Gamma_X^{(2)} = +1/\Lambda^2_X$, where the square of real $\Lambda_X$ obscures the sign of $\Gamma_X^{(2)}$. The proper relation should have been $\Gamma_X^{(2)} = \pm 1/\Lambda^2_X$. The choice of sign here is the key to our counter-argument. Stadnik erroneously claims that the choice of sign in his Eq. (1) is identical to our paper (we used the parameterization (1) with $\Gamma_X^{(2)}$, see Eqs.(58,59) of Ref. [2]).

As explicitly stated in the paper [2], we ignored effects of Galactic dust on the propagation and attenuation of the ELF waves. Stadnik focuses on such “back-action” effects. When $\mathcal{L}_{\text{clock}}^{(2)}$ is combined with free-field ELF Lagrangian, one obtains equation of motion $\partial \mu \partial_\mu \phi + \left( m^2 - 2 \sum_X \Gamma_X^{(2)} \mathcal{L}_{\text{SM}}^X \right) \phi = 0$. Assuming constant background $\mathcal{L}_{\text{SM}}^X$ of ordinary matter Lagrangian densities $\mathcal{L}_{\text{SM}}^X$, solutions are the conventional plane (or spherical) waves with dispersion relation $k^2 = \omega^2 - m^2 + 2 \sum_X \Gamma_X^{(2)} \mathcal{L}_{\text{SM}}^X$. Introducing index of refraction (with $\beta = -2 \sum_X \Gamma_X^{(2)} \mathcal{L}_{\text{SM}}^X$),

$$n(\omega) = \frac{k}{\omega} = \sqrt{1 - \frac{m^2 + \beta}{\omega^2}},$$

maps this problem into well-understood wave-propagation in electrodynamics [3]. The combination $m^2 + \beta$ is $m_{\text{eff}}^2$ in the Stadnik’s comment. $\beta > 0$ corresponds to $\Gamma_X^{(2)} > 0$ and $\beta < 0$ — to $\Gamma_X^{(2)} < 0$. The square of the effective mass can be misleading as $m_{\text{eff}}^2$ can be negative.

Now we quickly recover Stadnik’s results, but we keep track of the interaction sign, so that it is clear where his blanket claims fail.

By screening effect, Stadnik means that when $m^2 + \beta > \omega^2$ in Eq. (2), the index of refraction becomes purely imaginary and the ELF wave is attenuated by the sensor environment. This is identical to the screening phenomena in plasma physics [3]. In the ultra-relativistic limit of our paper ($m \ll \omega$), this translates into $\beta > 0$. However, in the opposite regime of $\beta < 0$ (corresponding to $\Gamma_X^{(2)} < 0$), the argument of the square root in the index of refraction is positive. Then the attenuation never occurs and there is no screening by the sensor physical package and by the atmosphere. In this case, there is no reduction in sensitivity.

Another point raised by Stadnik is the increase in the lag time between the gravitational wave (GW) and
 ELF bursts due to propagation through interstellar gas. Once again this only holds for his particular choice of sign of $\Gamma^{(2)}_X$. Indeed, group velocity is given by \[ v_g = \sqrt{1 - \frac{m^2 + \beta}{\omega^2}}. \] (3)

Positive $\beta$ (Stadnik case) translate into smaller group velocities and longer GW-ELF lag time. However, $\beta < 0$ leads to increasing $v_g$ and shorter GW-ELF lag time, thus opening up a larger ELF discovery reach.

Formally, if $m^2 + \beta < 0$, $v_g > 1$ and it seems that the ELF burst would propagate faster than the speed of light (tachyonic solutions). This is, of course, not the case, as the underlying approximation in introducing the concept of group velocity breaks down, see relevant discussion in electrodynamics textbook [3].

Another important point is that, as noted by Stadnik, there are no back-action effects at leading order for ELF signals searched for by magnetometer networks (such as the Global Network of Optical Magnetometers for Exotic physics searches, GNOME [4]) because of their derivative, spin-dependent nature. Back-action effects due to magnetic shielding have been considered in Ref. [5] and are already accounted for in all GNOME analysis. Similarly there no back-action effects for clock couplings that are linear in ELFs.

To summarize, we appreciate Stadnik’s analysis of “back-action” effects. However, his blanket claims of reduced sensitivity and that the back-action “prevents the multi-messenger astronomy on human timescales” are not general. As we demonstrated, there is a large parameter space that is not excluded by his analysis.

Competing interests The authors declare no competing interests.

Author contributions A.D. wrote the reply. D.F.J.K. and C.D. provided comments on the draft.

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