

Reply to: Highlighting the back-action contribution of matter to quantum sensor network performance in multi-messenger astronomy

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REPLYING TO Y. Stadnik *Nature Astronomy* <https://doi.org/10.1038/s41550-024-02245-4> (2024) Check for updates

Recently, along with a team of collaborators, we proposed that quantum sensor networks could be used for a multi-messenger astronomy in a new exotic physics modality¹; that is, a search for signals from high-energy astrophysical events that produce intense bursts of exotic low-mass fields (ELFs) associated with beyond-the-standard-model physics. The Matters Arising by Stadnik² claims that ‘back-action’ effects (that is, the interaction of ELFs with ordinary matter) “prevent multi-messenger astronomy on human timescales”. We disagree with this claim: this is not a general conclusion, as this statement relies entirely on a specific sign of the ELF–matter interaction. While we do not fundamentally disagree with Stadnik’s point that back-action effects can be important in some cases, it is crucial for this nascent research direction to emphasize that back-action effects do not universally preclude the possibility of ELF observation with quantum sensor networks. Below we present our counter-argument, which in fact demonstrates that there remains a large parameter space for detecting ELFs.

A generic quadratic ELF–matter interaction portal (equations (58) and (59) of our paper¹) reads:

$$\mathcal{L}_{\text{clock}}^{(2)} = - \sum_X \Gamma_X^{(2)} \phi^2 \mathcal{L}_{\text{SM}}^X, \quad (1)$$

where ϕ is the exotic field and $\mathcal{L}_{\text{SM}}^X$ are various pieces of the standard model Lagrangian, specifically $\mathcal{L}_{\text{SM}}^V = -F_{\mu\nu}^2/4$ and $\mathcal{L}_{\text{SM}}^f = \sum_\psi m_\psi \bar{\psi}\psi$ with $F_{\mu\nu}$ being Faraday tensor and the sum extending over standard model fermion fields ψ with masses m_ψ . Here and below we use natural units, $\hbar = c = 1$, where $\hbar$ is the reduced Planck constant and c is the velocity of light in a vacuum. The symbols $\Gamma_X^{(2)}$ in equation (1) are coupling constants and importantly their sign can be both positive and negative. Stadnik’s comment focuses on $\Gamma_X^{(2)} > 0$. Part of the confusion stems from his parameterization $\Gamma_X^{(2)} = +1/\Lambda_X^2$ where the square of real-valued

energy scale Λ_X obscures the sign of $\Gamma_X^{(2)}$. The proper relation should have been $\Gamma_X^{(2)} = \pm 1/\Lambda_X^2$. The choice of sign here is the key to our counter-argument.

As explicitly stated in our paper¹, 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 $\partial^\mu \partial_\mu \phi + (m^2 - 2 \sum_X \Gamma_X^{(2)} \mathcal{L}_{\text{SM}}^X) \phi = 0$. Assuming constant background $\mathcal{L}_{\text{SM}}^X$ of ordinary matter Lagrangian densities $\mathcal{L}_{\text{SM}}^X$, solutions to this equation are the conventional plane (or spherical) waves with dispersion relation $k^2 = \omega^2 - m^2 + 2 \sum_X \Gamma_X^{(2)} \mathcal{L}_{\text{SM}}^X$. Here k is the wave vector and ω is the corresponding angular frequency. Introducing an index of refraction (with $\beta \equiv -2 \sum_X \Gamma_X^{(2)} \mathcal{L}_{\text{SM}}^X$)

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

maps this problem into well-understood wave propagation in electrodynamics³. The combination $m^2 + \beta$ is m_{eff}^2 in Stadnik’s Matters Arising². Here $\beta > 0$ corresponds to $\Gamma_X^{(2)} > 0$ and $\beta < 0$ corresponds to $\Gamma_X^{(2)} < 0$. The square of the effective mass can be misleading as m_{eff}^2 can be negative.

Now we quickly recover Stadnik’s results², but we keep track of the interaction sign so it is clear where his conclusions do not apply.

By screening effect, Stadnik² means that when $m^2 + \beta > \omega^2$ in equation (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 physics³. In the ultra-relativistic limit of our study¹ ($m \ll \omega$), this translated 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. The attenuation then never

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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 Stadnik² is the increase in the lag time between the gravitational wave and ELF bursts due to propagation through interstellar gas. Once again this only holds for his particular choice of sign for $I_X^{(2)}$. Indeed, group velocity is given by $1/(n + \omega dn/d\omega)$ (ref. 3):

$$v_g = \sqrt{1 - \frac{m^2 + \beta}{\omega^2}}. \quad (3)$$

Positive β (Stadnik's case) translates into smaller v_g and longer gravitational wave–ELF lag times. However, $\beta < 0$ leads to increasing v_g and shorter gravitational wave–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 velocity of light (tachyonic solutions). This is, of course, not the case, as the underlying approximation breaks down when the concept of group velocity is introduced—see, for example, the relevant discussion in electrodynamics textbooks such as ref. 3.

Another important point is that, as noted by Stadnik², 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, GNOME⁴) 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 analyses. Similarly, there are no back-action effects for clock couplings that are linear in ELFs, which was also considered in ref. 1.

To summarize, we appreciate Stadnik's analysis² of back-action effects. However, his claims that sensitivity is reduced and that back-action effects prevent multi-messenger astronomy on practical timescales are not general. As we demonstrated, there is a large parameter space that is not excluded by his analysis.

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Competing interests

The authors declare no competing interests.

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