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Dark Matter Detection in the Stratosphere

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Abstract: We investigate the prospects for the direct detection of dark matter (DM) particles, incident on the upper atmosphere. A recent work relating the burst-like temperature excursions in the stratosphere at heights of ≈38–47 km with low speed incident invisible streaming matter is the motivation behind this proposal. As an example, dark photons could match the reasoning presented in that work provided they constitute part of the local DM density. Dark photons emerge as a U(1) symmetry within extensions of the standard model. Dark photons mix with real photons with the same total energy without the need for an external field, as would be required, for instance, for axions. Furthermore, the ionospheric plasma column above the stratosphere can resonantly enhance the dark photon-to-photon conversion. Noticeably, the stratosphere is easily accessible with balloon flights. Balloon missions with up to a few tons of payload can be readily assembled to operate for months at such atmospheric heights. This proposal is not limited to streaming dark photons, as other DM constituents could be involved in the observed seasonal heating of the upper stratosphere. Therefore, we advocate a combination of different types of measurements within a multi-purpose parallel detector system, in order to increase the direct detection potential for invisible streaming constituents that affect, annually and around January, the upper stratosphere.

Keywords: streaming dark matter; direct detection; stratospheric anomaly

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1. Introduction

Since the first astrophysical observation of the "Dunkle Materie" by Zwicky in 1933, we know that dark matter (DM) makes up to 27% of the matter–energy budget in the Universe. Its elemental composition, however, remains one of the greatest mysteries in all of physics. We recall that DM plays a major role in the structure formation of the Universe. There is no lack of DM candidates, and therefore a large number of experimental searches are being undertaken to answer this physics question of fundamental importance.

With the direct DM searches being in the forefront, accelerator experiments (e.g., LHC experiments, see reference [1]) and other efforts have also targeted this question aiming to produce or detect some DM particles. Notably, the ultimate identification of DM species can be effected only with those species who fill the Universe and are also expected in our neighborhood. In a recent investigation of the stratospheric temperature excursions occurring annually around December–January (see reference [2]), it was suggested that their planetary dependence points at streams of invisible matter from the dark universe being the cause [2]. In this work, we go a step further, and suggest how to detect them in situ, i.e., in the stratosphere, where the hours- or days-long heating occurs. As it was explained in [2–8], the widely mentioned axions or WIMPs do not come in question, at least not those which various experimental groups have been searching for in recent decades, given that their interaction cross-section with normal matter is far too small to account for the observed heating. Therefore, inspired by the reasoning about the origin of the stratospheric temperature anomalies, the stratosphere may be the place wherein occasionally enhanced, converted DM constituents are present. We outline here a direct experimental search for DM candidates in the stratosphere, i.e., some 40 km above the Earth's surface. This novel idea of direct detection brings the experiment from underground or ground to the upper atmosphere.

In this proposal, we focus primarily on dark photons, which are also DM candidates. Dark photons arise naturally when an extra U(1) symmetry is considered in the extensions to the standard model [9].

The reasoning behind this choice is the following: dark photons can convert kinetically into ordinary photons, in contrast to the case of axions or axion-like particles, wherein a magnetic or electric field is needed to assist their photon conversion [4]. In particular, the conversion is enhanced due to resonance/coherence effects if the charge density has a plasma frequency which matches the rest mass of the dark photon [10,11]. In reference [10], details of on-shell and off-shell processes are described, where the on-shell process shown in Figure 1 dominates in resonance conditions.

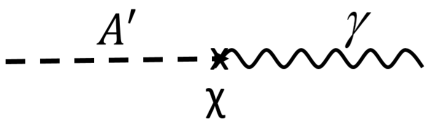

Figure 1. Feynman diagram illustrating the dominant on-shell process for dark photon-to-photon wherein χ is the kinetic mixing parameter.

Following previous astrophysical observations combined with the axion or axion-like exclusions by the CAST experiment [12,13], the dark photon rest mass may be up to the neV range. The corresponding plasma density is of the order of 10^{12} electrons/m^3. Interestingly, such electron densities exist in the ionosphere above the stratosphere (altitude above 100 km) [3]. Then, the dark photon scenario could fit as a cause for the heating. Assuming low speed streams of dark photons incident on the solar system, they experience, in addition to solar and planetary gravitational focusing, intrinsic self-focusing toward the Earth's opposite surface as well, before entering the ionosphere with the appropriate plasma density from 100 s to 1000 s km above the Earth's surface, where they can convert to real photons. For typical ionospheric density and plasma frequency, the photons from resonant conversion due to kinetic mixing may be RF photons in the MHz range. However, non-resonant conversions at other bands could be happening, albeit with much smaller probability compared to resonant ones.

Another region of interest is the UV range around 6–8 eV (150–200 nm) due to the absorption in the upper stratosphere, which strongly prevents these photons from reaching ground level.

Thus, once an instrument, with its field-of-view pointing away from the Earth, observes temporally enhanced radio signals or UV photons in the stratosphere, this will be the new direct DM signature, e.g., for converted dark photons or in other ways indirectly. If a detected signature correlates with the local stratospheric temperature variation, as well as exhibits planetary dependence, this strongly points to an invisible matter origin of the signal, at the same time excluding background sources. This will be a novel signature in direct DM search, with the potential for a major discovery.

Once such measurements in the stratosphere have been performed, they could also be correlated with missions in space, including the International Space Station.

Furthermore, a multi-purpose detector system may have the potential to unravel more species from the dark sector, which may well show enhanced fluxes in the upper atmosphere.

It is worth stressing that the widely assumed annual modulation of the DM wind is here overruled by planetary impact [14], which has not been so far considered in direct DM searches.

2. The Concept

We suggest to directly search for streaming DM incident on the Earth's atmosphere. Our motivation also stems from the fact that a possible signature of DM at the surface of the Earth may be shielded by the atmosphere, for instance from the resonant absorption of molecules [15] or due to large cross-sections [6], in which case ground and underground DM search experiments may be almost blind. We propose as the detector location the stratosphere, due to the planetary dependence of the temperature excursions already observed there [2,6], as well as to the natural occurring plasma in the ionosphere above, which could produce coherent conversion effects from dark photons to real photons in the neV energy range. A cartoon illustration of the concept is shown in Figure 2.

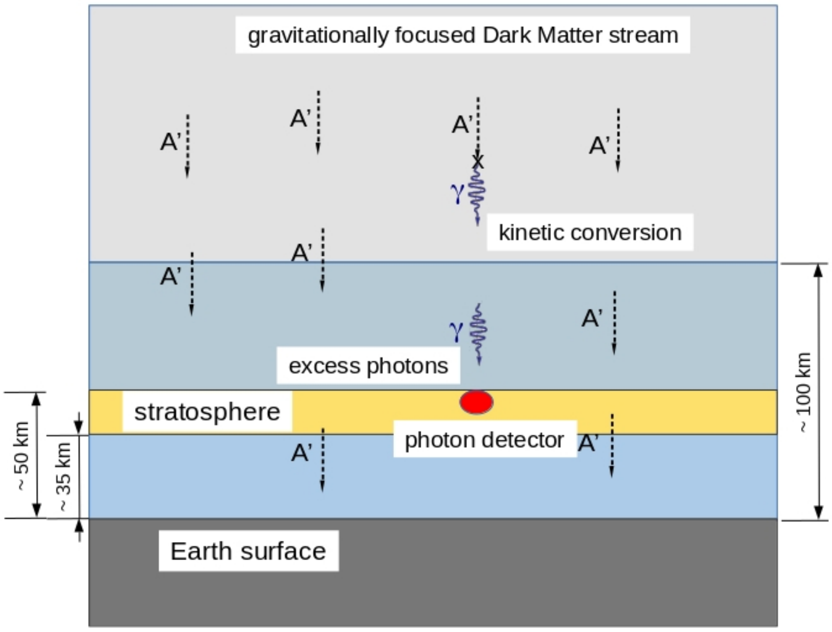

Figure 2. Cartoon illustration of the direct search concept, not to scale. For example, a gravitationally focused stream of incident dark photons can partially convert into real photons in a region of ≈100 km above the surface of the Earth, where the plasma density has the resonant value. Converted photons at around 6–8 eV are eventually absorbed in the upper stratosphere, ≈40 km above the surface, causing the observed local temperature excursions around January [2]. A photon detector placed in the upper stratosphere, represented by a red ellipse in the figure, could directly measure excess photons coming from converted dark photons (A') or secondary photons from DM particles interaction or decay.

In addition, the known solar photon irradiation of the atmosphere exhibits various characteristic absorption layers. The stratosphere around 40–45 km above the surface absorbs UV photons in the energy range of ∼6–8 eV due to the overall oxygen absorption bands [7]. Therefore, we suggest here that new DM searches should also be extended in this energy range.

Following the present scenario, we assume that incoming slow DM constituents first experience gravitational effects by the Solar System bodies, including the Sun, and are then transformed into photons directly or indirectly in the energy ranges mentioned above. Only photons emerging from slow DM constituents would exhibit a planetary relationship. Interestingly, light or relativistic cosmic radiation cannot exhibit a planetary dependence, since even the strongest possible gravitational focusing effect by the Sun has a focal length of ∼550 Astronomical Units (A.U.) for photons or any relativistic radiation.

A favored candidate may be the dark photon since it kinetically mixes with real photons without the need for electric or magnetic fields, and, in addition, this conversion could be resonantly enhanced if the plasma density matches the rest mass of the dark photon $(A^{'})$, $\hbar\omega_p = m_{A'}$ [16]. The interaction of a dark photon with a plasma medium is described, for example, in [16–18]. The ionospheric plasma density changes steadily, reaching a wide maximum in electron density at an altitude of about 300 km. The typical electron density of the ionosphere is $n_e = 10^6$ electrons/cm^3 resulting, for $\hbar = c = 1$, in a plasma frequency of [19,20]:

$$\omega_p = \sqrt{\frac{4\pi n_e \alpha}{m_e}} = 10^{-11}\,\mathrm{eV} \cdot \sqrt{n_e/\mathrm{cm}^{-3}} \approx 10\,\mathrm{neV} \tag{1}$$

Therefore, if the dark photon mass is in the neV mass range, corresponding to about 30 MHz, then the resonant interaction of a dark photon with the ionospheric plasma enhances the production of real photons. However, when the dark photon mass is in the eV range, the conversion in the ionosphere is off resonance and therefore negligibly small [17,19,20].

The radiation flux and power of real photons due to dark photon-to-photon conversion depend on kinetic mixing, gravitational focusing, resonance effects, ionization profile, and local dark matter density (see [16,20]).

For a ∼neV dark photon, the coherence effects are determined by level crossings depending on the profile of the ionization column as a function of altitude z. The variation of electron density in ionosphere is described by a Chapman profile [21]

$$n_e(z) = n_{max} \exp\left\{\frac{1}{2}\left[1 - \frac{z - h_{max}}{H} - \exp\left(-\frac{z - h_{max'}}{H}\right)\right]\right\} \tag{2}$$

where $n_{max} = 10^6$ electrons/cm^3, $H = 100$ km, $h_{max} = 300$ km are some typical values. Comparing the probabilities for a dark photon-to-photon conversion under resonant conditions and in vacuum as outlined in references [10,19,20,22], we define a resonant factor SF which describes the amplification due to resonance in the plasma versus vacuum conversions.The resonant factor is approximately given by

$$SF \approx m_{A'}[\mathrm{eV}] \left| \frac{d\,log(\omega_p^2(z))}{dz} \right|_{z_c}^{-1} [\mathrm{km}] \approx 10^4, \tag{3}$$

where z_c corresponds to the level-crossing location ($\hbar\omega_p = m_{A'}$). The photons that are generated can undergo scattering or absorption within the ionosphere, as discussed in Ref. [23]. As a result, the effective scale factor is reduced by approximately a factor of 10 due to absorption and scattering. Consequently, the effective scale factor can be estimated to be approximately $SF \approx 1000$. A better estimate of this factor can be obtained, for instance, by conducting a GEANT4 simulation (see: https://geant4.web.cern.ch, URL accessed on 23 May 2023), and will be included in a forthcoming publication. In references [24,25], gravitational focusing primarily from the Earth could produce transient density enhancements of a couple of orders of magnitude, assuming the DM is in the form of fine-grained streams. In the current work, we assume a density enhancement of ∼100 over a nominal density of $0.3\,\mathrm{GeV/cm}^3$ due to the gravitational focusing of the Earth.

3. Numerical Calculations

In this section, we will present some numerical calculations, choosing dark photon-to-photon conversion as an example.
The power from kinetically converted dark photons can be calculated as described in reference [26]:

$$P_{det} = SF \cdot \chi^2 \cdot \rho_{CDM} \cdot A_{eff}, \tag{4}$$

where SF is the resonant factor, χ the kinetic mixing, ρ_{CDM} is local DM density, and A_{eff} is the effective area of the collector [26]. Expressing Equation (4) in terms of kinetic mixing and modifying it for scale factors, one finds [26]

$$\chi_{sens} \simeq 4.5 \times 10^{-14} \left[\left(\frac{P_{det}}{SF \cdot 10^{-23}\,\mathrm{W}} \right) \left(\frac{0.3\,\mathrm{GeV/cm^3}}{\rho_{CDM}} \right) \left(\frac{1\,\mathrm{m}^2}{A_{eff}} \right) \right]^{1/2} \tag{5}$$

3.1. neV Range

The detectable power at these frequencies (≈30 MHz) is limited by system temperature and bandwidth. In this range, the system temperature is dominated by sky noise and receiver noise [27]. The low-velocity dispersion of DM and the capabilities of the current receivers as discussed in reference [28] allow for the use of small bandwidths of as little as 10 Hz. For a nominal system temperature of 5000 K, and a bandwidth of 10 Hz, the background noise power is $P_{noise} \approx 7 \times 10^{-19}$ W [27,29]. A signal power of $P_{det} \approx 7 \times 10^{-19}$ W, corresponding to a signal-to-noise ratio of 1, may be sufficient to extract the modulated DM signal. For a comprehensive review on noise at these frequencies, see reference [30]. For a dark matter density 100 times the nominal, and an effective collection area of about 1 m^2, the kinetic mixing sensitivity is $\chi_{sens} \sim 3 \cdot 10^{-14}$ (confidence level of ∼68%). The parameter space that can be probed using this band is shown at the top of Figure 3. Detailed descriptions of the different constraints in this figure are given in reference [10]. As can be seen from Figure 3, a measurement carried out in the stratosphere could yield an excellent sensitivity in this energy range.

3.2. eV Range

We now consider the 6–8 eV energy range. For a dark photon with eV energy, the ionospheric plasma is very diluted and the conversions to photons are non-resonant, similarly to those in vacuum. The sensitivity of a measurement in this interval depends on the capabilities of the detectors to measure an excess in the presence of daytime and/or nighttime background.

3.2.1. Daytime Measurements

The Sun is the dominant contributor of photon flux for daytime measurements. Solar irradiance varies approximately linearly over the wavelength range of 150–200 nm, from about $0.1\,\mathrm{mW \cdot m^{-2} \cdot nm^{-1}}$ to $10\,\mathrm{mW \cdot m^{-2} \cdot nm^{-1}}$ (1 mW $\sim 10^{16}$ photons/s) at the top of the atmosphere, which then, at an altitude of ≈45 km, is attenuated by $1/e$ [7]. This constitutes a very large background for such a measurement and we do not discuss it further.

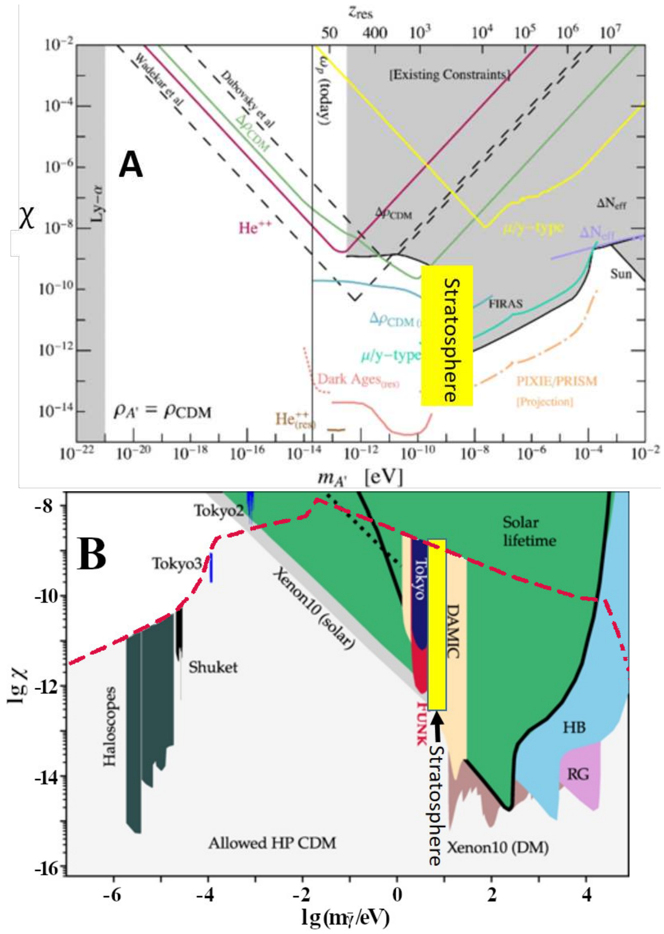

Figure 3. The yellow region marked as stratosphere is the parameter space that this work could probe. The kinetic mixing parameter χ is on the y-axis and the mass on the x-axis. For (Graph **B**), the x and y scale is logarithmic. (Graph **A**) at the top was adapted with permission from S. McDermott [10] and (Graph **B**) at the bottom was adapted with permission from D. Veberic [31].

3.2.2. Night-Time Measurements

Night-time missions have made measurements in the low Earth orbit (≈600 km) in this energy range and they report a baseline spectral flux of $\approx 10^4$ photons $\cdot$ cm^{-2} $\cdot$ s^{-1} $\cdot$ nm^{-1}, which comes primarily from diffuse galactic and extragalactic light, and airglow of the atmosphere [8]. Reducing the flux by a factor of one optical depth to scale at altitudes of 45 km, and considering different absorption bands in this wavelength region, the estimated cosmic background level is $N_b \sim 500$ photons $\cdot$ cm^{-2} $\cdot$ s^{-1} for the 150–200 nm wavelength range. Equation (4) could be used for this band with $SF = 1$ (no resonance enhancement) and a density enhancement of 100 over the nominal. The photon background flux could be reduced by experimental setups with a large collector area but a small photo-detector area as in reference [31]. An antenna area of 1 m^2 with a photo-detector area of 1 cm^2 is assumed for this calculation. In order to determine the lowest count for a particular signal-to-noise ratio, we use the definition of signal-to-noise ratio for counting applications from [32]

$$SNR \approx \frac{N_s\sqrt{t}}{\sqrt{2(N_b + N_d)}}, \tag{6}$$

where N_s is signal count per second, t is the total live time of the experiment in seconds, N_b is the background light, and N_d is the dark count of the detector. For balloon measurements operating over two months with a 50% duty cycle (night-time only), and a photo-detector with a dark count rate of about 50 counts/s, in order to obtain a signal-to-noise ratio of 5, one needs a minimum signal count of 0.1 counts/s. Assuming, then, a signal of order

$N_s \sim 0.1\,\text{photons} \cdot \text{cm}^{-2} \cdot \text{s}^{-1}$ for the excess to be extracted from the background (A better estimate of this number from a Geant4 simulation will be included in a future publication.) and an average photon energy of 7 eV, the power detection limit is $P_{det} \sim (0.1 \cdot 7 \cdot 1.6) \times 10^{-19} \sim 10^{-19} W$, resulting in a kinetic mixing sensitivity of $\chi_{sens} \sim 5 \cdot 10^{-13}$ (confidence level of ∼99%). The parameter space that can be probed with this band is shown at the bottom in Figure 3. A detailed description of the different constraints in this figure is given in reference [31]. A measurement in the stratosphere following this proposal could probe the kinetic mixing, closing the gap between the FUNK and DAMIC experiments.

The overall signature may be a modulated 6–8 eV photon flux or an RF power in the MHz range coming from dark photon conversions, concurrent with some planetary correlation or simultaneous temperature excursions in the stratosphere. Thus, at the beginning, the primary detector choices would be UV photon detectors and low noise radio receivers. Other detectors, with wider field of view and direction discrimination, could be added on to probe other energy bands along with ancillary parasitic detectors, as payload limits allow.

Small payloads could be sent out first in weather balloon flights lasting hours to measure the day and night background and establish the best detector combinations for these measurements. These could then be followed by larger and longer duration balloon missions with multi-purpose detectors.

4. Possible Detectors

Balloon flights carrying a payload of several hundred kilograms in the stratosphere can last for months, fitting the time period of stratospheric temperature excursions (see for instance Ref. [33] for a road-map of a balloon program at NASA). This is a window of opportunity to attempt the direct detection of DM as outlined above. The ideal device fitting the proposed search would be a highly efficient, wide sensitive area, with a low noise photon detector covering a 4π field-of-view (FOV), divided at least into two separate halves. The detector sections pointing away from Earth would search for variations in the incoming photon flux in the energy range of interest. The opposite-side sectors would act as background monitors. In a possible payload configuration, RF receivers such as those developed for radio astronomy could be used to provide sensitivity in the MHz range, and eventually at other frequencies to widen the window of opportunity. For instance, receivers with a dipole-like antenna developed for The Long Wavelength Array [34] would suffice.

For the detection of 6–8 eV photons, an option would be to use Silicon PhotoMultipliers (SiPMs) [35]. Commercially available SiPMs can be arranged in arrays to cover active areas of several cm^2, and identical arrays could be combined with light guides to effectively cover large opposite portions of the sky. This would allow for a pairwise comparison between detectors looking skywards and earthwards. A preliminary test payload could also be equipped with UV-sensitive photo-diodes for complementary monitoring. Balloon payloads could also be integrated with unconventional state-of-the-art detectors such as ultra-high sensitivity opto-mechanical force sensors [36]. The force sensors could be operated either in "dark mode", where photons are blocked from reaching the sensitive elements, or in "standard mode", where photons being reflected or absorbed by the detector surface are sensed due to their radiation pressure. In "dark mode", the force sensors could look for interactions of dark sector particles with their active surface [37].

The presence of a time-dependent signal exhibiting the characteristic planetary relationship would be the peculiar signature of streaming DM. In addition, a relationship with the concurrent transient heating of the stratosphere would strongly support the DM origin of the signal. The signature would be further strengthened by finding the directional dependence provided by the detector segments. Combining such features will allow one to disentangle a signal from the background.

Indeed, the directional and transient converted dark photons with a mass ∼eV could be detected by telescopes, such as the CTA Cherenkov telescope [38]. This proposal, when combined with Earth-bound photon telescopes, has the potential to reveal the origins of both cosmic photons and cosmic dark photons, as the nature of cosmic photon radiation is not yet fully understood.

5. Conclusions

We have presented here a novel proposal to search for dark sector constituents converted into standard model particles, which then cause observable effects at stratospheric altitudes. The main motivation for this work stems from recent observations of the planetary dependence of the annual transient temperature excursions of the upper stratosphere.

Although we mainly focus on the example of dark photons kinetically converting into real photons, where the mixing can also be resonantly enhanced by the intervening ionospheric plasma, the search may be extended to other candidates from the dark sector by using a suitable multi-purpose detector. With our scheme, significant levels of sensitivity can be reached for the conversion of dark photons into photons, as low as 10^{-14} in the neV range and 10^{-13} in the eV range. We wish to stress here that the real photons could originate from some decay or interaction product of DM particles with ordinary matter. The proposed search could also be complemented with other concurrent observations in orbit.

The important feature is that a signature of dark sector candidates must display a planetary dependence. Conventional cosmic rays are mostly relativistic, and therefore the Solar System cannot exert a significant gravitational impact on their trajectories, neither, *a fortiori*, on those of photons. The new search strategy proposed in this work is fully complementary to underground experiments. For certain dark sector candidates, surface detectors cannot perform this type of search as they may be shielded by the Earth's atmosphere.

We remark, finally, that although a detailed explanation of the origin of the seasonal heating of the stratosphere lays outside the scope of the present paper, our proposal for an experimental search is not limited to dark photons. A multi-purpose detector performing a combination of measurements will enhance the discovery potential for DM constituents seasonally affecting the upper stratosphere.

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Data Availability Statement: No new data were created for this work. Further details about computations are available by contacting the authors.

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Conflicts of Interest: The authors declare no conflict of interest.

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