

## GRB 221009A: A light dark matter burst or an extremely bright Inverse Compton component?

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Gamma-Ray Bursts (GRBs) are considered potential Very High-Energy (VHE) photon emitters because the large amount of energy released and the strong magnetic fields involved in their jets. However, VHE photons are not expected from bursts beyond a redshift of  $z \gtrsim 0.1$  because of the attenuation of photons with the Extragalactic Background Light (EBL). The recent observation of photons with energies of 18 and 251 TeV from GRB 221009A ( $z=0.151$ ) last October 9th, 2022, could be challenging what we know about the TeV-emission mechanisms and the EBL. Recent works exploring candidates of dark matter, cosmic rays, and other alternatives appeared. In this work, we explore possible scenarios regarding Axion-Like Particles (ALPs) and dark photon mechanisms and discuss the implications in GRB energetics. We find that the ALPs and dark photon scenarios can explain the 18 TeV photon but not the 251 TeV photon.

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GRBs are intense bursts of energy that emit radiation in the keV to MeV range. They consist of a prompt emission and a longer-lasting afterglow phase observed across various energy bands. GRBs are classified based on their hardness ratio and duration, with longer bursts associated with the core-collapse of massive stars. The *fireball* model explains the prompt emission as the dissipation of kinetic energy in internal shocks, and the afterglow phase arises from shocks generated by the blast wave colliding with the surrounding medium. High-Energy (HE) and Very-High-Energy emissions ( $> 10$  GeV and  $> 100$  GeV, respectively) are attributed to inverse Compton scattering of lower-energy photons by electrons in different regions of the jet. The delayed appearance of VHE emission is due to the shock's approach to the deceleration radius and the decrease in  $\gamma\gamma$ -opacity. Notably, the H.E.S.S. and MAGIC observatories have detected GRBs emitting above 100-300 GeV energies, which were attributed to inverse Compton processes [1, 2].

On October 9th, 2022, a highly luminous GRB (GRB 221009A) was detected by the Fermi-GBM instrument [3], followed by observations from SWIFT [4] and other missions. The fluence estimations varied among missions due to instrument saturation at high energies, but all reported values on the order of  $10^{-2}$  erg  $\text{cm}^{-2}$ . The counterpart of GRB 221009A was observed in various bands, starting with X-rays [5] and later in the IR, radio, and optical bands [6–11]. Spectroscopic observations estimated a redshift of  $z = 0.151$  [12, 13]. Further observations of the afterglow were conducted by multiple missions, including the *James Webb Space Telescope* [14] and the *Hubble Space Telescope* [15]. Notably, the *Large High-Altitude Air-Shower Observatory* (LHAASO) detected the GRB with energies above 500 GeV and a significance above  $100\sigma$ , marking the first-ever detection of a GRB with energies above 10 TeV [16]. A report also mentioned a photon-like air shower corresponding to a 251 TeV photon [17], although some PeV sources with consistent locations were identified.

The observations of GRB 221009A raise questions about the possibility of inverse Compton scattering to explain the HE photons detected. The significant attenuation of the flux of photons at energies of 18 TeV and 251 TeV by the EBL suggests the consideration of alternative explanations involving Dark Matter (DM) particles. The detection of VHE photons by LHAASO could be explained by proton synchrotron emission from accelerated Ultra-High-Energy Cosmic Rays (UHECRs) [18]. Some studies explore Lorentz Invariance violation effects on  $\gamma - \gamma$  absorption [19–21]. The nature of DM remains unknown, but candidates such as Weakly Interacting Massive Particles (WIMPs), Axion-Like Particles, and dark photons are being considered in addition to supersymmetric particles.

Although VHE emission from GRBs is commonly explained by inverse Compton scattering, the combination of VHE emissions and a moderate redshift in GRB 221009A suggests the involvement of more complex scenarios, potentially related to the production of DM particles [22–24]. The details of how these particles are released, created, or accelerated within GRBs are not explored here but are important for future investigations in this area.

In the analysis that this proceeding refers [25], we investigated the HE emission observed in GRB 221009A, considering two main scenarios. We examined the microphysical parameters necessary for the Synchrotron Self-Compton (SSC) emission to occur, ensuring that electron energies remain below the Klein-Nishina limit. We assumed a surrounding medium density ( $\eta$ ) greater than  $1 \text{ cm}^{-3}$ , as typical for long bursts. We explored an alternative explanation involving the release of DM during the burst. We calculated the minimum survival probability for photons originating from

DM oscillations to reach Earth and investigate the parameter space for ALPs and dark photons as potential DM candidates produced in the burst. Finally, we summarized our findings and provide concluding remarks.

## 1. Discussion and Conclusions

We explore three scenarios that produce TeV photons. Based on our analysis within the *fireball* scenario, specifically the SSC emission in the external forward-shock model, we find that extremely small and improbable values of microphysical parameters are needed to avoid the Klein-Nishina regime. Even without considering EBL attenuation, the resulting flux is insufficient to explain the detection of an 18 TeV photon. Previous studies by [26] also modeled the afterglow observations of GRB 221009A, taking into account the Klein-Nishina effect. They found bright emission in the energy range of 0.1 to 10 TeV, peaking at 300 GeV. However, further calculations are required to determine if the observations from LHAASO can be reproduced, considering the significant EBL attenuation at 18 TeV. The forthcoming LHAASO light curve and spectra for GRB 221009A may provide definitive insights into whether the SSC mechanism is appropriate. However, due to the Klein-Nishina break energy being below 1 TeV, it is unlikely and impossible to explain the 251 TeV photon solely through SSC emission. Therefore, it remains uncertain if a population of TeV photons is actually emitted by SSC alone in this burst, leading us to explore alternative scenarios involving DM.

Then, we consider two DM scenarios, ALPs and dark photons. Previous studies by various authors (e.g., [27], [28], and [29]) have considered scenarios where a population of photons is transformed into DM and then reconverted into photons within the Milky Way. However, we adopt a different approach in this paper. Instead of assuming a starting population of photons, we consider a beam of light DM particles initially released by the GRB.

We identify DM candidates that fall outside of the excluded regions and have the potential to explain the observation of TeV photons in GRB 221009A. In the case of ALPs, candidates with lower masses and higher coupling coefficients have the capability to explain both the 18 and 251 TeV photons simultaneously, although they are located near the excluded region. On the other hand, dark photons naturally offer an explanation for both photons, especially if the survival probability is independent of the magnetic field. In such a scenario, the TeV photons would acquire spectral characteristics from the dark photons. However, further investigations are necessary to determine the extent to which the survival probability depends on the magnetic field.

We have examined the potential contribution of ALPs in different energy ranges. This includes analyzing the parameter space to explain past observations of GRBs at hundreds of GeV, as well as the recent observation of GRB 221009A by LHAASO. The presence of light-dark photons with energies in the hundreds of GeV range could naturally account for these observations, whereas ALPs exhibit a significant decrease in the allowed parameter space at lower masses and coupling constants. The discovered survival probability values suggest that ALPs could still play a role in explaining emissions at hundreds of GeV. However, a more comprehensive investigation is needed, taking into account various dark matter spectra, including spectral lines. By comparing the results with spectra observed beyond 10 TeV, we can better discern the mechanism required to generate such HE emissions from extremely distant sources.

We have determined the survival probabilities for our two DM scenarios, taking into account the observable parameters of the burst. To account for unknown quantities, we have utilized conservative values typically associated with long bursts. Our calculations encompassed the jet, host galaxy, and Milky Way environments. It was discovered that approximately 30% of photons are lost due to ALP conversion before reaching the Milky Way. This outcome can be attributed to the small size of the jet and the weak magnetic field within the host galaxy. Considering the intergalactic magnetic field yields negligible corrections. If dark photons remain as potential candidates, a thorough analysis is required to assess the dependence of the survival probability on the magnetic field. Nonetheless, we have demonstrated that dark photons could also serve as viable candidates, even though ALPs have been the subject of more extensive research. Our conservative assumptions regarding the energy absorbed by DM from the burst align with the fraction of energy attributed to the kinetic energy of electrons responsible for emissions at lower frequencies. Consequently, the inclusion of DM would not impact other aspects of the burst's evolution. If DM exists in GRBs, the information contained within the light curve will be essential for untangling potential theories elucidating the production and release mechanisms of DM in GRBs, as well as deciphering the nature of the DM particle involved.

Please refer to the publication by [25] for a comprehensive analysis of the topic.

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