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The Propagation of Light through Dark Matter

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PURPOSE

The electromagnetic interactions of dark matter engender the cosmos with non-trivial optical properties. If we attribute any frequency-dependent arrival time of photons from distant astrophysical observables to dispersive matter interactions, then we can constrain the properties of that matter. For a first application, we use the arrival time of high-energy photons from gamma-ray bursts to constrain the electric millicharge and mass of dark atoms.

BACKGROUND

Dark matter accounts for 24% of the density of the universe, as seen in Figure 1 [1]. Its existence is known only from the observation of its gravitational interactions; beyond this we know only that it is non-relativistic (or cold), non-baryonic, relatively stable, and any non-gravitational interactions are extremely weak. A host of dark matter candidates have been proposed, including weakly interacting massive particles (WIMPs), superWIMPs, sterile neutrinos, and axions [2]. The dark atom is an example of a composite candidate, and is the subject of this research [3].

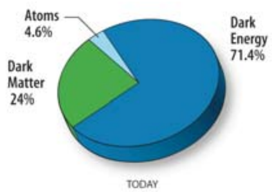

Figure 1. Energy density of the universe, present-day. [4]

Dark matter will generically have electromagnetic interactions, though suppressed [5]. This implies that a dark matter medium will have non-trivial optical properties. In particular, the medium will be dispersive; that is, light traveling through the medium experiences a frequency-dependent index of refraction. The index of refraction controls the speed at which a wave propagates through a medium. Typically, higher frequency waves travel more slowly than lower frequency waves.

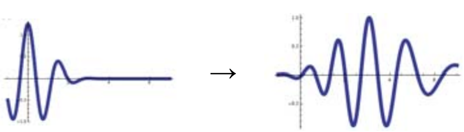

Figure 2. Example of propagation of light in a dispersive medium. Dispersion causes the wave packet to broaden and travel more slowly than a wave packet in a vacuum.

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MODEL CONSTRAINTS

The dispersion of light traveling through dark matter leads to a time lag between simultaneously emitted pulses of light with different frequencies. Gamma ray bursts are extremely bright, high-energy explosions that can be seen from very far away, and thus are perfect for our purposes. Supposing the arrival time of light on Earth from a gamma ray burst has a measurable time lag between high and low frequencies, we can measure the dispersion of the cosmos. If this dispersion is due to dark matter, it is possible to constrain a particular model of dark particles; in this case, the characteristics of our dark atom are constrained. We consider a model of a dark atom roughly analogous to normal hydrogen, with a "dark electron" orbiting a nucleus. By operating in a dark electromagnetic sector, the dark atom's constituents have both a "dark" charge and a real, normal electric millicharge. Kinetic mixing mediates the two sectors, as seen in Figure 5.

We use a semiclassical treatment of hydrogen interacting with light to calculate dark matter's index of refraction; for photon frequencies below the threshold energy ω_0, the index takes the form

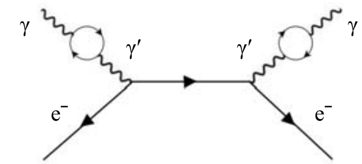

Figure 5. A normal photon kinetically mixes with a dark photon, which then interacts with a dark electron.

$n(\omega) = 1+A+B\omega^2$, where ω is the angular frequency of light [6]. In terms of a dark atom's mass and binding energy, the index of refraction can be approximated as

$$n(\omega) = 1 + A + A\left(\frac{\omega}{\omega_0}\right)^2, \quad A = \frac{\pi c^5 \alpha^5 m_e}{\omega_0^4 \hbar}\frac{N}{V}\left(\frac{2}{3}\right)^8$$

The formula to find the travel time of light is the distance traveled divided by the wave's speed. Taking into account the effects of dispersion and cosmological expansion, distance becomes dependent on the universe's rate of expansion, while the speed depends on the redshifted frequency due to dispersion.

EXPANSION OF THE UNIVERSE

The accelerated expansion of the universe affects the index of refraction formula in two ways. First, as the volume of space is increasing while the amount of dark matter in existence remains constant, the density of dark matter is continually decreasing. As density is a factor in the formula for index of refraction, dark matter's index of refraction is continually decreasing as well.

Second, the expansion of the universe causes cosmological redshift, in which light waves are "stretched" as the space they are occupying expands. The frequency of the light therefore decreases, or is shifted towards the red, low-frequency side of the electromagnetic spectrum.

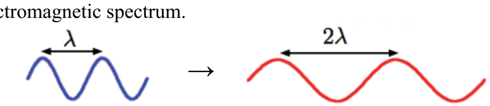

Figure 3. The expansion of the universe causes redshifting, in which the frequency of a light wave decreases as its wavelength increases.

The present rate of expansion is given by the Hubble constant, 69 km/s/Mpc. Assuming a Λ-CDM model with 28% matter and 72% dark energy in the form of a cosmological constant, we can determine the expansion rate in the past at redshift z.

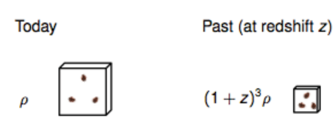

Figure 4. Objects in the universe today are farther apart than they were in the past, due to the expansion of space.

RESULTS

The Fermi Gamma-ray Space Telescope has taken data on light arriving on Earth from gamma ray burst GRB 080916C. This data shows that between photon energies of about 8 keV and 10 GeV, there was approximately a 5 second time lag [7]. Using these numbers, we find that our constraints lead to a lower bound of $m/\varepsilon^2\alpha$ = 55761.6 GeV. Mass over epsilon squared times alpha represents the ratio of the dark atom's mass to the dark electron's millicharge squared multiplied by the regular fine structure constant.

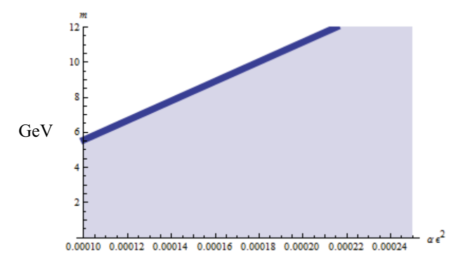

Figure 6. Lower bound on $m/\varepsilon^2\alpha$ of a dark atom — the shaded region is excluded by our calculations.

For a dark atom of 8.6 GeV, the fractional electric charge is constrained to about 0.14e.

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