Constraining Dark Matter Through a Cosmic Index of Refraction

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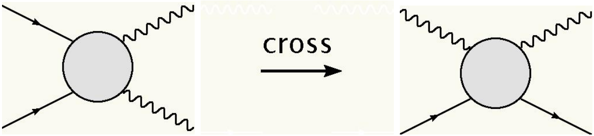
Motivation

Indirect DM searches look for the products of DM annihilation: ν, e^+, $\overline{p}$, γ. E.g., IceCube, Fermi, PAMELA, ATIC.

In many models, DM annihilation into photons is permitted (if only at the loop level). Such models will also result in light-DM scattering engendering the cosmos with a refractive index.



The real part of the refractive index will result in a time lag between simultaneously emitted pulses of light. The imaginary part of the index results in attenuation of a signal.

> An advantage to this new method of DM detection is that effects are not sensitive to local fluctuations of DM density; instead, they rely upon the average density, measured by WMAP, over a *very* long baseline.

Index of refraction

- In the DM rest frame, the relationship between the refractive index and the forward Compton amplitude is locally

$$n(\omega) = 1 + \frac{\rho}{4 m_{dm}^2 \omega^2} \mathcal{M}_{\rm fwd} \quad \text{in the limit} \quad |n-1| \ll 1.$$

Here, ω is the measured photon frequency, and $\rho \approx 1.2 \times 10^{-6}$ GeV/cm^3 the present day DM density. [E. Komatsu *et al.* [WMAP Collab.], ApJ Suppl. **180**(2009).]

Note: For low mass ($m_{dm} < 5$ GeV) DM candidates, the number density of DM particles can exceed that of normal matter.

- Assuming Lorentz invariance, we may decompose the amplitude as follows

$$\mathcal{M}_{\rm fwd} = f_1(\omega) \boldsymbol{\epsilon}'^{\,*} \cdot \boldsymbol{\epsilon} + i\, f_2(\omega) \mathcal{S} \cdot \boldsymbol{\epsilon}'^{\,*} \times \boldsymbol{\epsilon}\,,$$

where $\mathcal{S}$ is the spin operator associated with the dark-matter particle and $\boldsymbol{\epsilon}$ ($\boldsymbol{\epsilon}'$) is the photon polarization in its initial (final) state. Only f_1 will affect the phase speed of the light in the medium.

Forward Compton amplitude

- From causality, analyticity, and unitarity, dispersion relations show that $f_1(\omega)$ is a real and even function of ω for photon energies below the inelastic threshold. Additionally, the coefficients of the $\mathcal{O}(\omega^{2k})$ terms are positive, $k \geq 1$.

  [Gell-Mann, Goldberger, and Thirring, PR **95** (1954); Goldberger, PR **97** (1955) .]

- As the photon energy approaches zero, the leading order behavior of the forward amplitude is known *exactly* for particles of arbitrary spin regardless of their structure.

  [Low, PR **96** (1954); Gell-Mann and Goldberger, PR **96** (1954); Lapidus and Kuang-Chao, Sov. Phys. JETP **12** (1961); Brodsky and Primack, Ann. Phys. **52** (1969).]

- The fully coherent amplitude has the form

$$\mathcal{M}_{\text{fwd}} = A_0 + A_2\omega^2 + A_4\omega^4 + \mathcal{O}(\omega^6).$$

  The low energy theorem sets $A_0 = -2\varepsilon^2 e^2$, and the remaining coefficients A_{2k} are positive.

Refractive index

- The refractive index governing the phase speed is

$$n(\omega) = 1 + \frac{\rho}{4m_{dm}^2}\left[\frac{A_0}{\omega^2} + A_2 + A_4\omega^2 + \mathcal{O}(\omega^4)\right].$$

- The group speed governs the propagation time $v_g = \mathrm{d}\omega/\mathrm{d}k = (n + \omega(\mathrm{d}n/\mathrm{d}\omega))^{-1}$. The propagation time for a pulse to travel a distance L is

$$t(\omega) = L\left(1 + \frac{\rho}{4m_{dm}^2}\left(\frac{-A_0}{\omega^2} + A_2 + 3A_4\omega^2 + \mathcal{O}(\omega^4)\right)\right).$$

Time lag due to dispersion

At cosmological scales, the dispersive time lag for simultaneously emitted photons of energy ω_1 and ω_2 at redshift z is

$$\Delta t(\omega_1, \omega_2, z) \approx \frac{\rho}{4m_{dm}^2}\left[-A_0\left(\frac{1}{\omega_1^2} - \frac{1}{\omega_2^2}\right)K_0(z) + 3A_4(\omega_1^2 - \omega_2^2)K_4(z)\right].$$

where $K_0(z) = \int_0^z (1+z')H(z')^{-1}\mathrm{d}z'$ and $K_4(z) = \int_0^z (1+z')^5 H(z')^{-1}\mathrm{d}z'$. We solve for the Hubble constant at redshift z using the Friedman equation with

$$H(z) = H_0\sqrt{(1+z)^3\Omega_M + \Omega_\Lambda}$$

and the present day value for the Hubble constant $H_0 = 70.5 \pm 1.3$ km/s/Mpc.
[E. Komatsu *et al.* [WMAP Collab.], ApJ Suppl. **180**(2009).]

The DM density accrues a scale factor of $(1+z)^3$, and the observed frequency requires a blueshift factor of $1+z$ when looking into the past.

Searches for Lorentz violation

- Searches for the violation of Lorentz invariance also look for frequency-dependent time lags. [E.g., Amelino-Camelia *et al.*, Nature **393** (1998); Ellis *et al.*, ApJ **535** (2000); Ellis *et al.* Astropart. Phys. **25** (2006), **29** (2008); Fermi LAT and GBM Collaborations, Science **323** (2009) .]

- Deviations from the normal dispersion relation for a photon can take the form [Jacob and Piran, JCAP **0801** (2008).]

$$E^2 = p^2 \left(1 + \xi_1 \frac{p}{M} + \xi_2 \frac{p^2}{M^2} + \cdots \right)$$

- The factors of momenta p^k accrue factors $(1+z)^k$ at cosmological scales. (Note: There is no density factor in this time lag formula.) [Jacob and Piran, JCAP **0801** (2008).]

- LV signals could be confused with (dark) matter interactions though the energy dependence of the LV terms can be different and the z dependence of the two time lags will be different.

Assessing the coefficients

What observations would allow one to determine the A_k from the time lag?

$$\Delta t(\omega_1, \omega_2, z) \approx \frac{\rho}{4m_{dm}^2}\left[-A_0\left(\frac{1}{\omega_1^2} - \frac{1}{\omega_2^2}\right)K_0(z) + 3A_4(\omega_1^2 - \omega_2^2)K_4(z)\right].$$

- A_4 is fixed by the higher order terms in the DM polarizability.
  This energy dependence of this term goes as ω^2 and is best assessed through observations of optical and gamma ray photons.

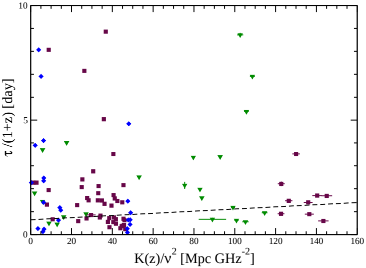
- A_0 is fixed by the DM electric charge.
  The energy dependence of this term goes as ω^{-2} so that low frequency observations provide the best limits. The radio afterglow of GRBs fix the size of this coefficient.

Millicharged limits

We plot the observed time lag of the radio afterglow of GRBs, and fit with the following equation allowing a frequency dependent time lag (and require $\tilde{A}_0 \geq 0$)

$$\frac{\tau}{1+z} = \tilde{A}_0 \frac{K(z)}{\nu^2} + \delta((1+z)\nu).$$

The observational limit on millicharged DM at 95% CL is $|\varepsilon|/m_{dm} < 1 \times 10^{-5}$ eV^{-1}.

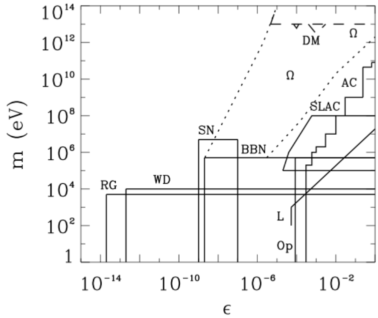


The points correspond to frequencies (in GRB rest frame) of 4-12 GHz (▼, green), 12-30 GHz (■, maroon), 30-75 GHz (♦, blue).

Our limit on charged DM is comparable with limits on the existence of millicharges from terrestrial experiments: $|\varepsilon| < 3 - 4 \times 10^{-7}$ for $m \lesssim 0.05$ eV. [Ahlers *et al.*, PRD **77** (2008).]

Some other limits on millicharges

- Stellar evolution provides stringent indirect limits on the existence of millicharges. [Davidson, Hannestad, and Raffelt, JHEP **05** (2000).]



- The most stringent limits on $U(1)$ charged dark matter come from elastic scattering constraints in conjunction with the formation of small scale structure in the universe. [Ackerman *et al.* arXiv:0810.5126; Feng *et al.* arXiv:0905.3039.]
- These constraints are indirect and can be evaded. Our limits should improve with further radio observations of GRBs (e.g., GASE, LOFAR).

Summary

- We have developed a new method to detect DM through its modification of the propagation of light. In principle, time lags accrued by light passing through a DM medium should be distinguishable from Lorentz violation effects.
- Improved constraints on the frequency dependence of the speed of light from distant GRBs lead to stronger limits on DM models.
- From the time lags of radio afterglows associated with GRBs, we find a limit on the charge-to-mass ratio of DM at 95% CL of $|\varepsilon|/m_{dm} < 1 \times 10^{-5}$ eV^{-1}. This can further improve with observations.