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Mirror dark matter explanation of the DAMA, CoGeNT and CRESST-II data

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Dark matter might reside in a hidden sector which contains an unbroken $U(1)'$ gauge interaction kinetically mixed with standard $U(1)_Y$. Mirror dark matter provides a well motivated example of such a theory. We show that the DAMA, CoGeNT and CRESST-II experiments can be simultaneously explained within this hidden sector framework. An experiment in the Southern Hemisphere is needed to test this explanation via a diurnal modulation signal.

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There is strong evidence for non-baryonic dark matter from a variety of astrophysical and cosmological observations. Efforts to directly detect dark matter have achieved some very exciting positive results. The DAMA/NaI[1] and DAMA/LIBRA[2] experiments have observed an annual modulation in their 'single hit' event rate consistent with dark matter expectations[3]. Low energy excesses in the CoGeNT[4, 5] and CRESST-II[6] experiments have also been reported.

A specific theory is needed to explain these experiments. One promising idea is that dark matter resides in a hidden sector which contains an unbroken $U(1)'$ gauge interaction kinetically mixed with standard $U(1)_Y$. That such a theory could provide an explanation of the direct detection experiments has been discussed in the context of mirror dark matter[7]. [References and astrophysical/cosmological discussions can be found in the reviews[8]]. Our purpose here is to review and update the most recent work[9] on the experimental status of mirror dark matter.

Mirror dark matter features a hidden sector exactly isomorphic to the ordinary sector. That is, fundamental interactions are described by the Lagrangian[10]:

$$\mathcal{L} = \mathcal{L}_{SM}(e,\mu,u,d,A_\mu,...) + \mathcal{L}_{SM}(e',\mu',u',d',A'_\mu,...) + \mathcal{L}_{mix} \ . \tag{1}$$

If left and right chiral fields are interchanged in the mirror sector, then the theory exhibits an exact parity symmetry: $x \to -x$. The bit $\mathcal{L}_{mix}$ contains possible terms coupling the two sectors together, and includes kinetic mixing of the $U(1)_Y$ and $U(1)'_Y$ gauge bosons - a renormalizable interaction[11]. This $U(1)$ kinetic mixing induces photon-mirror photon kinetic mixing:

$$\mathcal{L}_{mix} = \frac{\varepsilon}{2} F^{\mu\nu} F'_{\mu\nu} \tag{2}$$

where $F_{\mu\nu}$ [$F'_{\mu\nu}$] is the field strength tensor for the photon [mirror photon]. This interaction enables charged mirror sector particles of charge e to couple to ordinary photons with electric charge εe [12]. A mirror nucleus, A', with atomic number Z' and velocity v can thereby elastically scatter off an ordinary nucleus, A, with atomic number Z. This imparts an observable recoil energy, E_R with

$$\frac{d\sigma}{dE_R} = \frac{2\pi\varepsilon^2 Z^2 Z'^2 \alpha^2 F_A^2 F_{A'}^2}{m_A E_R^2 v^2} \tag{3}$$

where F_A [$F_{A'}$] is the form factor of the nucleus [mirror nucleus] and natural units are used.

In this theory, galactic dark matter halos are composed of mirror particles. These particles form a pressure supported, multi-component plasma containing e', H', He', O', Fe',...[13]. The temperature of this plasma can be estimated from the condition of hydrostatic equilibrium:

$$T = \frac{1}{2}\bar{m} v_{rot}^2 \tag{4}$$

where v_{rot} is the galactic rotational velocity and $\bar{m} = \sum n_{A'} m_{A'} / \sum n_{A'}$ is the mean mass of the particles in the halo. Mirror BBN calculations[14] suggests that $\bar{m} \approx 1.1$ GeV. The halo distribution of a mirror nuclei, A', is:

$$f_{A'}(\mathbf{v},\mathbf{v}_E) = exp(-E/T) = exp(-\frac{1}{2} m_{A'} \mathbf{u}^2/T) = exp(-\mathbf{u}^2/v_0^2) \tag{5}$$

where $\mathbf{u} = \mathbf{v} + \mathbf{v}_E$ [$\mathbf{v}$ is the velocity of the halo particles relative to the Earth and $\mathbf{v}_E$ is the velocity of the Earth relative to the galactic center]. Clearly

$$v_0[A'] = \sqrt{\frac{2T}{m_{A'}}} = v_{rot}\sqrt{\frac{\bar{m}}{m_{A'}}} \ . \tag{6}$$

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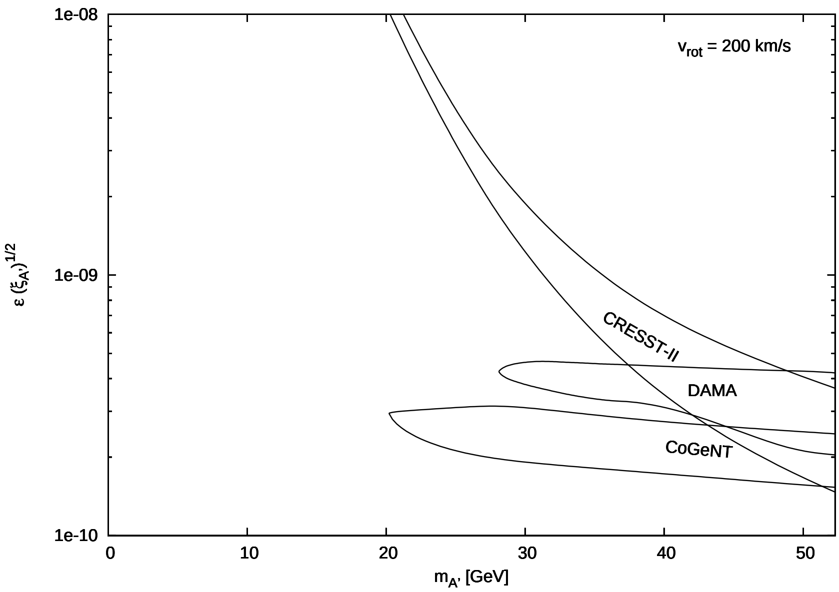

Figure 1: DAMA, CoGeNT and CRESST-II favored regions of parameter space in the mirror dark matter model for $v_{rot} = 200$ km/s.

The differential rate for A' scattering on a target nuclei, A, is

$$\frac{dR}{dE_R} = N_T n_{A'} \int_{|\mathbf{v}|>v_{min}}^{\infty} \frac{d\sigma}{dE_R} \frac{f_{A'}(\mathbf{v},\mathbf{v}_E)}{k} |\mathbf{v}| d^3\mathbf{v} \tag{7}$$

where the integration limit is, in natural units, $v_{min} = \sqrt{(m_A + m_{A'})^2 E_R / 2 m_A m_{A'}^2}$. In Eq.(7), $k = v_0^3\, \pi^{3/2}$, N_T is the number of target nuclei and $n_{A'} = \rho_{dm} \xi_{A'}/m_{A'}$ is the number density of the halo A' particles. [$\rho_{dm} = 0.3\ \mathrm{GeV/cm^3}$ and $\xi_{A'}$ is the halo mass fraction of species A']. The integral, Eq.(7), can be evaluated in terms of error functions and numerically solved.

Detector resolution effects can be incorporated by convolving the rate with a Gaussian. The relevant rates for the DAMA, CoGeNT and CRESST-II experiments can then be computed and compared with the data. Note that the expected predominant H', He' halo components are too light to give significant signal contributions due to exponential kinematic suppression. Only heavier 'metal' components can give a signal above the detector energy thresholds. We assume for simplicity that the rate in each experiment is dominated by the scattering from a single such metal component, A'. Of course this is an approximation, however it can be a reasonable one given the narrow energy range probed in the experiments [the signal regions are mainly: 2-4 keVee (DAMA), 0.5-1 keVee (CoGeNT), 12-14 keV (CRESST-II)]. With this assumption we find that $v_{rot} = 200$ km/s is an example where all three experiments have overlapping favored regions of parameter space. In this case a χ^2 analysis of each experiment leads to the favored regions of parameter space shown in figure 1. Details of the analysis are similar to ref.[9] except that the most recent CoGeNT data with surface event correction are used[5]. This figure indicates a substantial region of parameter space where all three experiments could be explained within this theoretical framework. An example point, near the combined best fit of the DAMA, CoGeNT and CRESST-II data, is:

$$A' = \mathrm{Fe}'\ (m_{Fe'} \simeq 56 m_p),\ v_{rot} = 200\ \mathrm{km/s},\ \varepsilon\sqrt{\xi_{Fe'}} = 2.5 \times 10^{-10}\ . \tag{8}$$

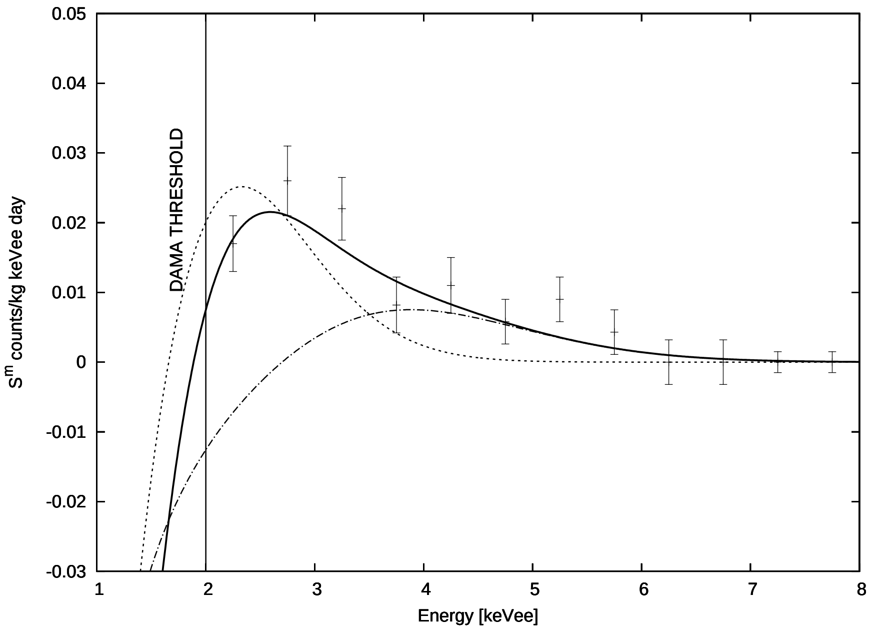

Figure 2: DAMA annual modulation spectrum for mirror dark matter with parameter choice, Eq.(8) (solid line). The separate contributions from dark matter scattering off Sodium (dashed-dotted line) and Iodine (dotted line) are shown.

The results for this example point are shown in figures 2,3,4. These figures confirm that this type of dark matter candidate can explain all three experiments simultaneously. Note that the change in sign of the DAMA annual modulation suggested in figure 2 need not happen if there is a lighter and more abundant $A' \sim O'$ component, since the positive contribution to the annual modulation from O' can outweigh the negative contribution from Fe'[9].

This mirror dark matter explanation is consistent (although not without some tension) with the null results of the other experiments, including XENON100 and CDMS, when systematic uncertainties in energy scale are included[9]. Future data from DAMA, CoGeNT, CRESST-II and other experiments will be able to further test and constrain the mirror dark matter framework. As discussed recently[15], a particularly striking diurnal modulation signal, shown in figure 5, is predicted for a detector located in the Southern Hemisphere. Just ~ 30 days of operation of the CoGeNT or DAMA detector in say, Sierra Grande, Argentina or Bendigo, Australia would be sufficient to detect the diurnal signal at 5σ C.L.

To conclude, we have examined the DAMA, CoGeNT and CRESST-II results in the context of the mirror dark matter framework. In this scheme dark matter consists of a spectrum of mirror particles: e', H', He', O', Fe', ... of known masses. We have shown that this theory can simultaneously explain the data from each experiment by $A' \sim Fe'$ interactions if $\varepsilon\sqrt{\xi_{Fe'}} \approx 2 \times 10^{-10}$ and $v_{rot} \sim 200$ km/s. Other regions of parameter space, and also, more generic hidden sector dark matter are also possible. An experiment in the Southern Hemisphere is needed to test this explanation via a diurnal modulation signal.

Acknowledgments

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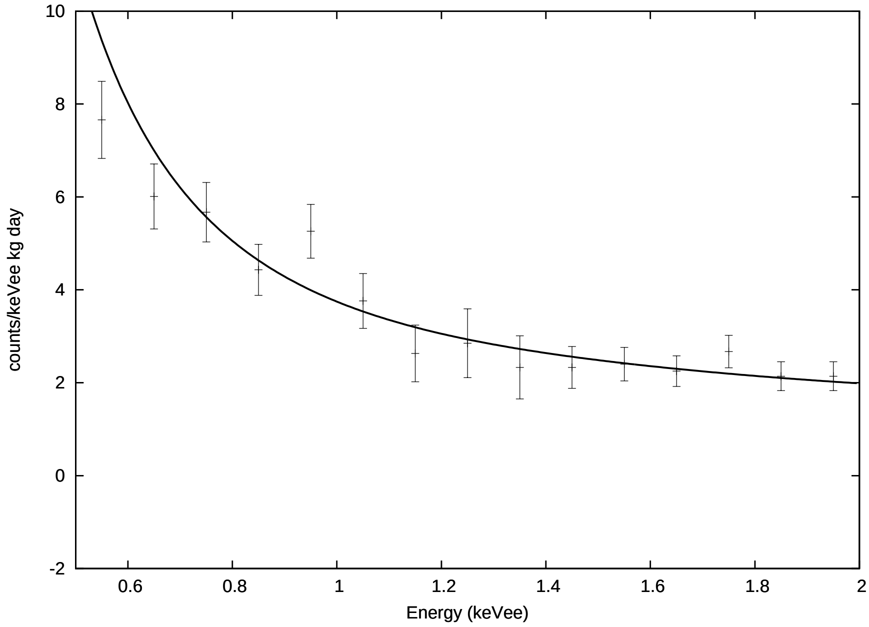

Figure 3: CoGeNT spectrum for mirror dark matter with the same parameters as figure 2.

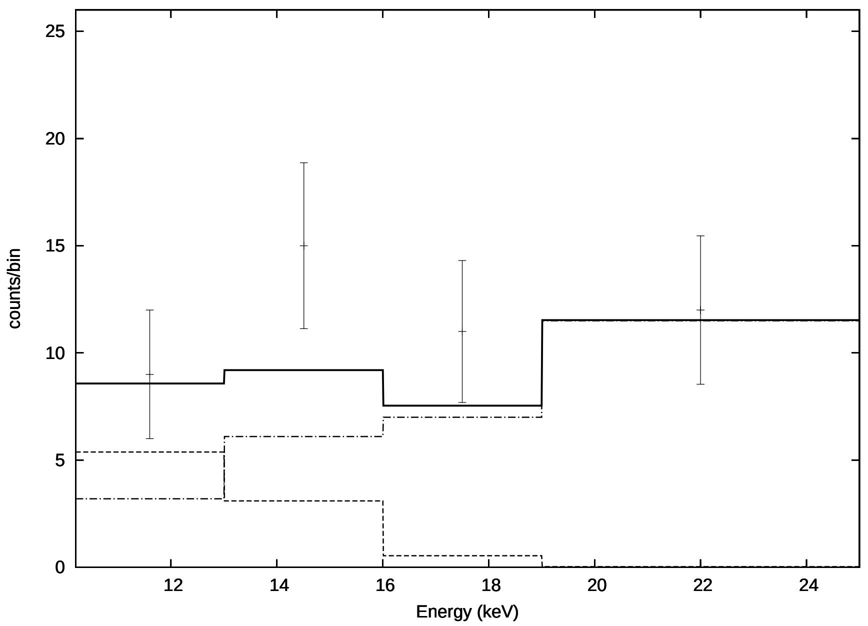

Figure 4: CRESST-II spectrum for mirror dark matter with the same parameters as figure 2 (solid line). The signal component (dotted line) and background component (dashed-dotted line) are also shown.

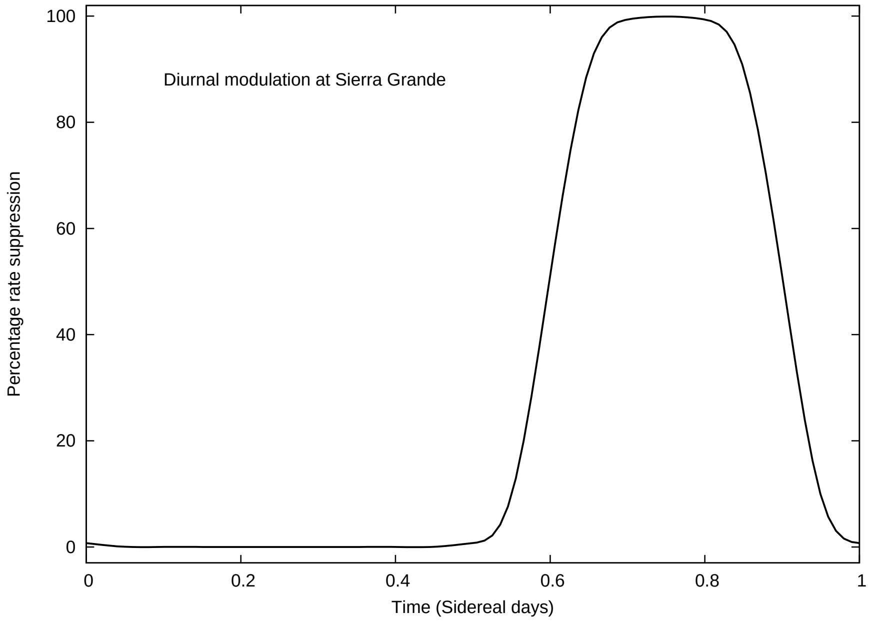

Figure 5: Percentage rate suppression due to the shielding of dark matter in the Earth's core versus time, for a detector located at Sierra Grande, Argentina.

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