Observing the dark sector with supernovae

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Abstract. It has been long known that the excessive cooling of supernovae places strong limits on models of light dark sectors. However, even at couplings where the flux of new particles produced in a supernova is too low to violate the cooling bound, the flux remains large and can be observed through a variety of signatures, both direct and indirect. We analyze two different models with radically different behavior. The first model is that of a dark photon on the MeV scale. This model can be probed via the observation of electromagnetic signals produced in dark photon decay. The second model is that of a dark U(1) sector with heavy mediator and MeV-scale dark fermions. In this case, the flux emerging from supernovae is much hotter than the galactic dark matter, allowing it to be detected in existing direct detection experiments designed to hunt for GeV-scale dark matter. In both cases, we find that these signatures allow new bounds to be placed well outside existing cooling limits. Furthermore, these new signals may allow for a future discovery of the dark matter.

1. Introduction
Dark matter (DM) may be formed by degrees of freedom with masses significantly below the weak scale if the new particles are coupled only feebly to the Standard Model (SM) by some mediator. Such scenarios are often known as “dark sectors” and naturally appear in many extensions of the SM. If the dark sector lives on the MeV scale, supernovae, which reach temperatures in excess of 30 MeV for $\sim 10$ seconds, will produce vast fluxes of these new particles. This has been recognized for decades, though prior to this work, the major constraints placed on dark sectors through supernovae were derived from excess cooling of the supernovae [1].

However, even well outside these cooling limits, supernovae can still produce vast quantities of particles on the MeV scale. We focus on two particular realizations of a dark sector and demonstrate novel ways to probe each. In both cases, we are able to extend existing bounds on these models by orders of magnitude. The work described here is simply a concise summary of the results presented in Refs. [2; 3]. A conference proceeding is far too brief to describe the analyses in detail, so we refer interested readers to the full publications for a detailed explanation of the results.

2. Results
Below, we discuss each of the two models and the direct and indirect signals that supernova fluxes of these particles can produce.
2.1. **Model 1: Light dark photon**

Model 1 contains a MeV-scale dark photon, which is a $U(1)'$ gauge boson kinetically mixed with the SM photon with coupling $\epsilon$. We focus on the scenario in which the dark photon decays purely into electron-positron pairs, which is the natural expectation if the dark photon is lighter than the other particles in the dark sector and is above the electron-positron mass threshold.

Dark photons produced within the core of a supernova can escape the progenitor star before decaying into electrons and positrons. Even in the regime where too few dark photons escape to yield a cooling bound, observable signatures are still produced by their decays. We extend limits to couplings weaker than those required for a cooling bound by considering three specific observational signatures, described in the following three subsections.

### 2.1.1. Signature 1: Positron escape

In the region on parameter space of interest, dark photons will escape the supernova and decay to $e^+e^-$ pairs. The escaping positrons have a long lifetime ($10^5$ to $10^6$ years) in the interstellar medium and can slow down and contribute to the observable 511 keV line. The results from the SPI gamma ray spectrometer on the INTEGRAL satellite have greatly improved the measurements of the galactic 511 keV gamma ray flux [4], which can be used to estimate galactic positron production rate. If some set of astrophysical sources were to produce positrons in excess of the derived rate, the resulting positrons would produce an excess of 511 keV photons in the galaxy in disagreement with INTEGRAL’s result. This allows us to place a bound on the production of dark photons in supernovae. (See Fig. 1, “Positrons.”)

### 2.1.2. Signature 2: Prompt gamma-ray emission

In roughly a hundredth of dark photon decays, a hard gamma-ray will be emitted along with the $e^+e^-$ as final state radiation. This prompt flux of gamma rays would have been observed following SN1987a. The non-observation of a gamma-ray flux above background following the arrival of SN1987a’s neutrinos on Earth by the Gamma Ray Spectrometer (GRS) aboard the Solar Maximum Mission results in a strong bound on the flux of dark photons that could have been decaying outside of SN1987a [5]. (See Fig. 1, “Gamma rays (SN1987a).”)

### 2.1.3. Signature 3: Diffuse extragalactic flux

At high coupling, both the decay length of the dark photon becomes short and the overall production increases. This causes for the formation of an electron-positron plasma outside the progenitor star as the decay products of dark photons interact with each other. This plasma rapidly expands and cools, releasing most of its energy as $\sim 100$ keV photons. The dynamics of this plasma resembles that of the fireball model [6] which is used to describe gamma-ray bursts.

The collective effect of extragalactic supernovae producing these fireballs would be to contribute to the diffuse extragalactic background of gamma rays. The extragalactic flux has been measured by the Solar Maximum Mission (SMM) [7] and the High Energy Astronomy Observatory (HEAO-1) [8], which allows us to place a limit on the injection of gamma rays by “fireballs” produced via dark photon decay outside of SNe. The resulting bound is shown in Fig. 1 (“Gamma rays (diffuse flux”).

2.2. **Model 2: Dark fermions**

Model 2 contains MeV-scale Dirac fermions which interact with the SM via the four-fermion operator

$$\frac{\varepsilon g_d}{\Lambda^2} \bar{\chi} \gamma_\mu \chi J^\mu_{em}$$

(1)

where $\chi$ is the DM field and $J^\mu_{em}$ is the electromagnetic current of the SM. Such an interaction can be generated if, for example, DM is charged under a dark gauge boson with mass $m_{A'} = \Lambda$ and DM-DM coupling $g_d$ that kinetically mixes with the SM with mixing parameter $\epsilon$. 


In the regions of parameter space we are interested in for this analysis, the dark sector fermions have a sufficiently strong coupling to the Standard Model that they become diffusively trapped near the protoneutron star that forms from the SN core. The diffusive trapping is primarily due to scatterings off of free protons generated by the dissociation of nuclei in the SN shock. The dark fermions also scatter off of electrons and positrons, allowing thermal exchange with the SM bath. Additionally, dark fermions may annihilate into electron-positron pairs. The decoupling of these three interactions at different radii sets the outgoing spectrum of the DM.

The dark fermions that do eventually escape are produced with a distribution of semi-relativistic velocities. This results in a time-spreading effect during their propagation to Earth. The difference in arrival time of the high-momentum and low-momentum ends of the spectrum is of order the dark fermion travel time between Earth and the SN, hence the dark fermions produced by a single SN arrive on Earth over a timescale of $10^5$ years for an average galactic SN. Given the typical rates and distances of galactic supernovae, in addition to the inherent signal spread, the dark fermion fluxes from various SN overlap in time, producing a diffuse galactic SN flux of dark fermions with $v \sim c$.

This diffuse flux of DM is detectable in existing and next-generation liquid xenon (LXe) WIMP detectors. Though these detectors are designed to search for dark matter on the GeV scale, the semi-relativistic velocity of the dark fermions compensates for their low mass and allows them to transfer detectable energy to xenon nuclei in the detector. This may be surprising, but it is easily understood simply from the fact that a 10 GeV WIMP with $v \sim 10^{-3}c$ has roughly the same momentum as a 10 MeV dark fermion with $v \sim c$. See Figure 2 for the resulting sensitivities of existing and future liquid xenon WIMP detectors to this hot population of SN-produced DM.

3. Conclusions
We have shown that even well outside cooling constraints, supernovae are a powerful tool to probe models of dark matter on the MeV scale. Our novel signatures, both direct and indirect, allow us to bound these models over several orders of magnitude beyond existing limits. For a full discussion of these bounds, please refer to our papers (Refs. 2, 3).
Figure 2. Sensitivity regions for WIMP detectors observing the diffuse galactic flux of dark fermions produced in supernovae, reproduced from Ref. [3]. For a full discussion of each bound, see that reference.

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