

Long-lived particles and the Quiet Sun

R. Andrew Gustafson,^{1,*} Ryan Plestid,^{2,†} Ian M. Shoemaker,^{1,‡} and Albert Zhou³

¹*Center for Neutrino Physics, Department of Physics, Virginia Tech, Blacksburg, VA 24061, USA*

²*Walter Burke Institute for Theoretical Physics, California Institute of Technology, Pasadena, CA 91125, USA*

³*Institut für Astroteilchenphysik, Karlsruher Institut für Technologie (KIT), D-76021 Karlsruhe, Germany*

The nuclear reaction network within the interior of the Sun is an efficient MeV physics factory, and can produce long-lived particles generic to dark sector models. In this work we consider the sensitivity of satellite instruments, primarily the RHESSI Spectrometer, that observe the Quiet Sun in the MeV regime where backgrounds are low. We find that Quiet Sun observations offer a powerful and complementary probe in regions of parameter space where the long-lived particle decay length is longer than the radius of the Sun, and shorter than the distance between the Sun and Earth. We comment on connections to recent model-building work on heavy neutral leptons coupled to neutrinos and high-quality axions from mirror symmetries.

I. INTRODUCTION

It has long been recognized that the solar interior can serve as an efficient factory for keV-scale physics beyond the Standard Model (BSM), e.g. solar axions and dark photons [1–8]. In addition to thermal production mechanisms, nuclear reactions within the Sun may also source BSM particles up to masses and energies of roughly 15 MeV [4, 9–14]. If a flux of long-lived particles (LLPs) in this energy regime emanates from the solar interior, they may transit toward the Earth and their decay products can leave detectable signatures. It is important to emphasize that LLPs are generic consequences of a dark sector with relatively light particles and feeble couplings to the SM [15–18]. As decay lengths become long, LLPs become increasingly difficult to detect and strategies to attack this “lifetime frontier” are valuable tools in the search for BSM physics. This idea has been previously investigated, largely considering FERMI-LAT, in the high energy, i.e. $\gtrsim 100$ MeV, regime for annihilating dark matter [19–22].

In this work we point out that existing data from the RHESSI satellite spectrometer [23], which observed the Quiet Sun,¹ can place interesting limits on dark sectors with LLPs in the range of $\mathcal{O}(100 \text{ keV}) - \mathcal{O}(1 \text{ MeV})$. This is an old idea, first proposed by Stodolsky and Raffelt in 1982 in the context of a 200 keV axion [9], however, it has remained unexplored despite new data in the intervening decades [24]. We illustrate the potential sensitivity of Quiet Sun data with a number of BSM examples, emphasizing different production mechanisms which may operate in this mass window. A conservative analysis of existing data from RHESSI is capable of offering complementary constraints on production mechanisms involving neutrino upscattering, and can probe previously untouched regions of parameter space for axion like particles

(ALPs) with masses close to ~ 1 MeV. Upcoming missions, such as the COSI satellite [25, 26], may be able to substantially improve on the capabilities of RHESSI by *i*) taking advantage of a larger instrument surface area, *ii*) making use of dead time to carefully study backgrounds, and *iii*) taking advantage of distinctive spectral features.

We focus on LLPs that decay primarily to photons,² and have decay lengths, ℓ_{LLP} , that satisfy

$$R_{\odot} \ll \ell_{\text{LLP}} \ll d_{\odot} , \quad (1)$$

where R_{\odot} is the radius of the Sun and d_{\odot} is the distance from the Sun to the Earth. This allows an $O(1)$ fraction of the LLPs to decay en-route to the satellite instrument. In this limit, the flux of LLPs will never reach any terrestrial experiment since they will decay in flight and their daughter photons will be absorbed in the upper atmosphere. In this sense, Quiet Sun observations are complimentary to terrestrial searches for LLPs from the Sun such as those that have been performed by CAST [10] and Borexino [11].

We perform a straightforward (and conservative) rate-only analysis the details of which can be found at the end of Section II. In the body of the paper we organize our discussion along the lines of specific BSM scenarios. We discuss neutrino upscattering in Section II and solar axion production in Section III. We also spend time focusing on model-independent LLP constraints in Section IV. In Section V we discuss the physics potential for dark sector searches using future missions such as COSI. We close by summarizing our results in Section VI.

* gustafr@vt.edu

† rplestid@caltech.edu

‡ shoemaker@vt.edu

¹ Time periods without intense surface activity such as solar flares.

² We could also consider decays to e^+e^- pairs but an analysis is complicated by the magnetic fields that surround the Earth.

II. NEUTRINO UPSCATTERING - TRANSITION DIPOLE

We begin by considering a production mechanism involving the upscattering of solar neutrinos transiting through the Sun, e.g. $\nu A \rightarrow \text{LLPA}$ with a A a nucleus such as hydrogen or helium (see e.g. [13, 14, 27] for results on neutrino upscattering in the Earth). This mechanism leverages the large solar neutrino flux which is copious in the few-hundred keV region, and extends up to ~ 15 MeV. Solar neutrinos have a small probability of being absorbed in the SM because of the small charged current scattering cross section at $E_\nu \sim \text{MeV}$ energies. It is, however, possible to have BSM cross sections that exceed the weak interaction at low energies if neutrinos couple via a transition magnetic dipole moment [28, 29]. This can lead to sizable conversion probabilities into an unstable right-handed neutrino, N (also called a heavy neutral lepton or HNL), for neutrinos transiting from the center to the surface of the Sun. As it is unstable, N may decay in flight supplying a broad flux of photons in RHESSI. Similar phenomena may occur in the aftermath of SN 1987A [30, 31] leading to tight limits below the supernova floor derived in [28].

This ‘‘dipole portal’’ can dominate low energy phenomenology since it is a dimension-five operator and competes with the dimension-six four-Fermi contact interaction at low energies. The effective Lagrangian is given by

$$\mathcal{L}_{\text{int}} \supset \sum_{\alpha} d_{\alpha} F^{\mu\nu} \bar{N} \sigma_{\mu\nu} P_L \nu_{\alpha}. \quad (2)$$

Here, d_{α} represents the coupling between N and each of the 3 SM neutrinos. In this work, we consider the cases where N couples to a single flavor. This effective interaction has been studied recently in the context of accelerator, solar, atmospheric, and collider neutrinos as

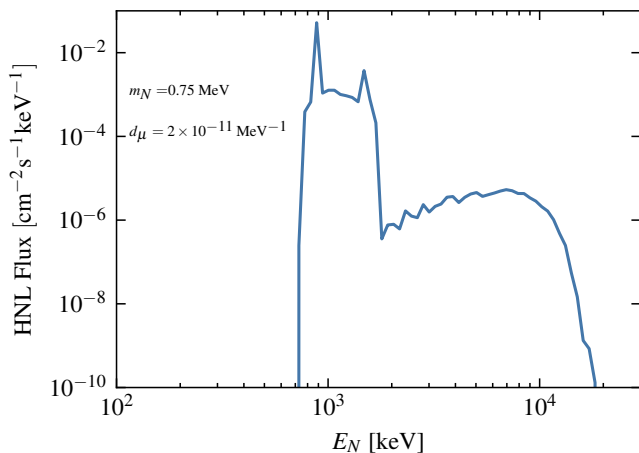


FIG. 1. The flux of solar HNLs at Earth (ignoring decays) as calculated through the dipole model Monte Carlo simulation, where $m_N = 0.75$ MeV and $d_{\mu} = 2 \times 10^{-11}$ MeV $^{-1}$.

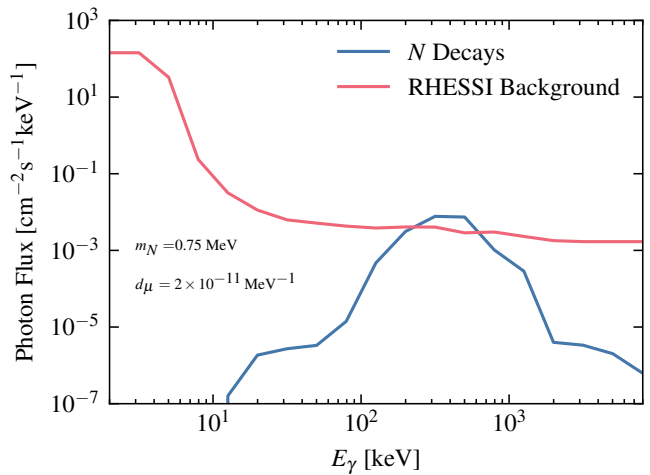


FIG. 2. The flux of photons at RHESSI from N decays calculated using a Monte Carlo integration with a 90° opening angle, compared with the RHESSI background in the front segment. Since the flux from decays exceeds the background, we consider $m_N = 0.75$ MeV, $d_{\mu} = 2 \times 10^{-11}$ MeV $^{-1}$ to be excluded.

well as in the context of early universe cosmology and constraints from SN 1987A [28, 29, 32–56].

Unlike the monoenergetic LLP cases discussed later in this paper, the spectrum of E_ν (and hence E_N) spans several orders of magnitude. For that reason, we implement a Monte Carlo integration to sample neutrino energy, production location, and upscattering location. We also account for flavor transformation during the neutrino propagation (both due to adiabatic conversion and oscillations).

We consider the Sun to be solely comprised of ^1H and ^4He with densities given by the Standard Solar Model [57–59]. All scattering is calculated to be off free nucleons, ignoring the coherent enhancement due to helium. This only leads to an $\sim 10\%$ change in the bounds, which we will see is a much smaller effect than uncertainty in the detector opening angle/background. The cross section for scattering on a free proton is given by $d\sigma_{\text{dip}} = d\sigma_1 + d\sigma_2$ with,

$$\begin{aligned} \frac{d\sigma_1}{dE_r} = & \alpha(2d)^2 F_1^2 \left(\frac{1}{E_r} - \frac{1}{E_\nu} \right. \\ & \left. + \frac{m_N^2(E_r - 2E_\nu - m_p)}{4E_\nu^2 E_r m_p} + \frac{m_N^4(E_r - m_p)}{8E_\nu^2 E_r^2 m_p^2} \right), \end{aligned} \quad (3)$$

and

$$\begin{aligned} \frac{d\sigma_2}{dE_r} = & \alpha d^2 \mu_n^2 F_2^2 \left[\frac{2m_p}{E_\nu^2} \left((2E_\nu - E_r)^2 - 2E_r m_p \right) \right. \\ & \left. + m_N^2 \frac{E_r - 4E_\nu}{E_\nu^2} + \frac{m_N^4}{E_\nu E_r} \right]. \end{aligned} \quad (4)$$

Here, F_1 and F_2 are electromagnetic form factors, μ_n is the magnetic moment of the nucleon in question, E_r is the

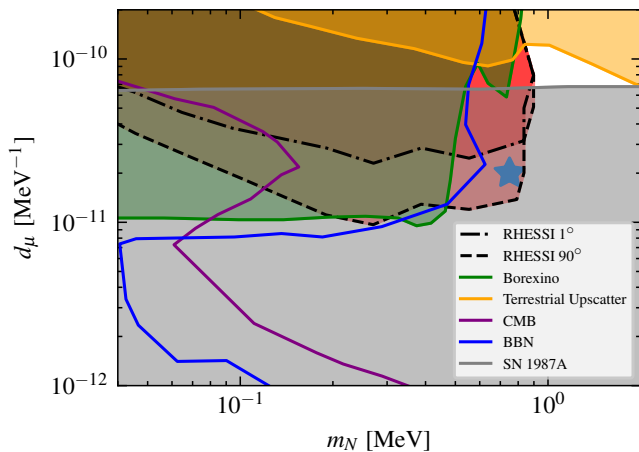


FIG. 3. Excluded parameter space for a muon neutrino transition dipole moment. Along with our bounds, we show 90% CL exclusions from Borexino $e - \nu$ scattering [29, 63], terrestrial solar neutrino upscattering [14], Supernova 1987A [28], big-bang nucleosynthesis and the cosmic microwave background [29]. For RHESSI excluded parameter space, we include exclusions from taking a 1° opening angle and a 90° opening angle. The star represents the parameter point show in Fig. 1 and Fig. 2.

recoil energy, and m_p is the proton mass [60, 61]. Since the neutrino energy is much less than the proton mass, the HNL energy E_N is nearly identical to the neutrino energy E_ν . Thus, the flux of HNLs has similar features to the solar neutrino flux (see Fig. 1).

The HNL has decay channels $N \rightarrow \nu_\alpha \gamma$. We consider the ν to be massless, and the decays to be isotropic in the rest frame of the HNL.³ The decay length is calculated as

$$\lambda = \frac{4\pi}{d_\alpha^2 m_N^3} \gamma \beta. \quad (5)$$

The Monte Carlo simulation samples locations for N decays along with the energy and direction of the decay photon. This is used to calculate the resulting photon flux with respect to energy and angle observed by RHESSI. We consider opening angles of 1° and 90° , where we reject all photons arriving at larger angles. The background flux observed by RHESSI is calculated by using the reported number of counts and effective area of the front segment (ignoring narrow peaks) [23]. We reject a parameter point if the flux from N decays exceeds the observed flux at any energy (see Fig. 2).

Our resulting exclusion curves from the RHESSI data are shown in Fig. 3 for a muon neutrino dipole coupling.

³ In complete generality the HNL may have some angular correlation with its polarization, but this depends on the details of the model e.g. Dirac vs. Majorana neutrinos [62] and we neglect this in what follows.

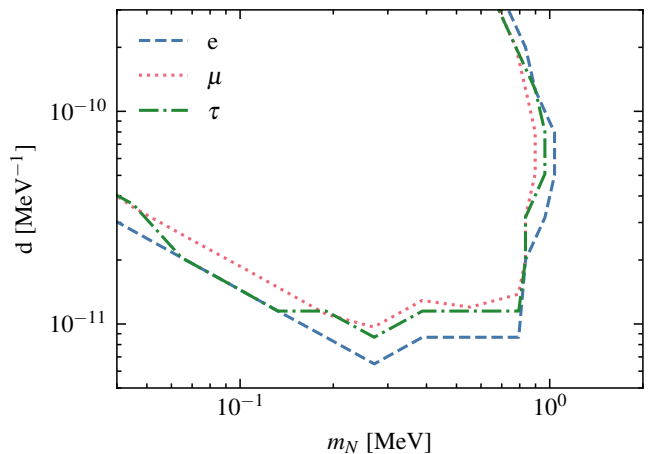


FIG. 4. Excluded parameter space of a transition dipole moment for each of the three active neutrinos. We see that the constraints all take a similar form, only varying by $\mathcal{O}(1)$ factors.

We find that RHESSI data can offer a complimentary (and direct) probe of regions of parameter space that are already probed by SN-1987A. Constraints are strongest in the low mass region (sub-MeV), and this may also be probed using coherent elastic neutrino nucleus scattering. We see that the exclusions for the three neutrino flavors all have similar values in Fig. 4.

III. HEAVY SOLAR AXIONS

Another production mechanism is solar axions with energies in excess of $E_a \gtrsim 500$ keV. These energies are too high to allow for thermal production (except for in exponentially suppressed tails), and so the background photon fluxes are much smaller than for typically considered keV solar axion searches. The study of MeV-scale solar axions has a long history, and they have been searched for in terrestrial experiments such as Borexino and CAST [10, 11]. As we discuss below, satellite measurements of the Quiet Sun provide a complimentary probe that excels for decay lengths that are short relative to the Earth-Sun distance.

It is worth highlighting recent work on model building for axions with an extended matter content [64–67]. These models are motivated by the axion quality problem and seek to protect the axion against Planck suppressed corrections. The simplest mechanism to achieve this is to simply break the canonical relation $f_a m_a \approx f_\pi m_\pi$ and to allow for m_a to be “heavy” relative to predictions of conventional (i.e. DSVZ [68, 69] or KSVZ [70, 71]) axion models. It is interesting to note that these independent model building considerations often push the mass and couplings of the axion into regions of parameter space that are well suited for solar axion detection; we will comment on this in great detail below. For instance,

following the benchmark scenarios presented in [67] one finds that masses in the ~ 10 MeV regime with axion decay constants $f_a \sim 10^{-5}$ GeV $^{-1}$ fall squarely within the “natural” window of parameter space whilst simultaneously predicting a sizeable coupling to nucleons and a decay length that is a few times longer than the radius of the Sun. For slightly lighter axions, solar production and detection is a useful complimentary probe.

The primary production mechanism for heavy solar axions is the $p d \rightarrow {}^3\text{He} \gamma$ reaction which takes place in the solar pp chain. Other mechanisms are energetically allowed, such as $M1$ transitions in the CNO chain [72], and e^+e^- annihilation from ${}^8\text{B}$ neutrinos in the solar interior, however, we find that the production rates are sufficiently small so as to be uninteresting.

The flux of axions (prior to decay) can be related to the flux of pp neutrinos, and depends on the isovector coupling of axions to nucleons g_{3aN} [73]. The axions must first escape the Sun and then decay before reaching Earth. The escape probability depends both on axion absorption and decay processes. Putting all of this together and setting $\text{BR}_{a\gamma\gamma} = 1$, we arrive at the flux of axions arriving at a detector orbiting the Earth,

$$\frac{\Phi_\gamma}{\Phi_\nu^{(pp)}} = 0.54 |g_{3aN}|^2 \left[\frac{p_a}{p_\gamma} \right]^3 \left[e^{-R_\odot/\ell_{\text{abs}}} - e^{-d_\odot/\ell_{\text{dec}}} \right], \quad (6)$$

where $\ell_{\text{abs}}^{-1} = \ell_{\text{MFP}}^{-1} + \ell_{\text{dec}}^{-1}$ with ℓ_{MFP}^{-1} the averaged mean free path in the Sun and ℓ_{dec} the axion decay length. The coupling g_{3aN} is the isovector coupling strength of the axion to nucleons, and p_a/p_γ is the ratio of three-momenta between an axion and photon emitted with $E = 5.49$ MeV. The pp neutrino flux is given by $\Phi_\nu^{(pp)} = 6 \times 10^{10}$ cm $^{-2}$ s $^{-1}$. We account for axion-absorption, Primakoff scattering, and axion electron scattering in our calculation of ℓ_{MFP}^{-1} .

Our results are shown in Fig. 5. We note that our exclusions depend on the axion nucleon coupling, captured by g_{3aN} , and the decay constant $g_{a\gamma\gamma}$. If $g_{a\gamma\gamma}$ vanishes at some scale $\mu = \mu_0$, but $g_{aee} \neq 0$ then an effective $g_{a\gamma\gamma} \sim (\alpha/4\pi)g_{aee}/m_e$ will be generated via a 1-loop triangle diagram, and in this way one can re-cast our limits⁴ in terms of those on g_{aee} . We do not include exclusions from SN1987 typically plotted in the $m_a - g_{a\gamma\gamma}$ plane because the values of g_{3aN} that are required to produce a sufficient axion flux in the Sun lead to axion trapping within a core-collapse supernova [74].⁵ This is an important distinction between the hadronically coupled axion models we considered here vs. an axion like particle which couples exclusively to photons (see e.g. [75]). The

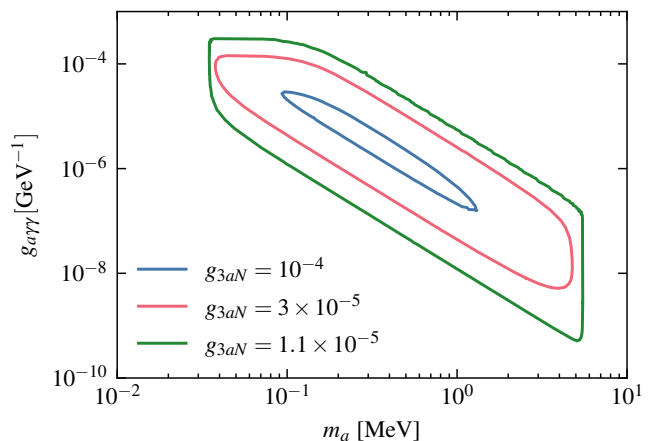


FIG. 5. Contours of g_{3aN} for which the solar axion flux of photons would overwhelm the the RHESSI background measurements for the front segments. Sensitivity is exhausted for $g_{3aN} \sim 1 \times 10^{-5}$ however further reach can be obtained with better data and/or a more sophisticated analysis.

solar axion constraints we discuss here are therefore complimentary to supernova cooling ones. If the axion nucleon coupling, g_{aN} , is large enough to evade SN-1987 bounds via self trapping then it is also large enough to be probed with RHESSI data. Low energy supernovae observations have been used to place constraints on axions which decay in-flight and deposit energy to the ejecta [76]. These constraints also disappear in the strong coupling regime, and are complimentary to ours. Constraints from NA62 [77], E787 [78], and E949 [79] are subject to $O(m_K^4/m_\rho^4)$ hadronic uncertainties in the prediction of $K \rightarrow a\pi$ [67, 80]. Finally, our constraints on $g_{a\gamma\gamma}$ lie above the ceiling of searches performed with the Borexino collaboration [11] because we are sensitive to decay lengths much shorter than d_\odot . This is demonstrative of the way in which constraints from solar axion may compliment existing search techniques using accelerator based experiments, underground detectors, and astrophysical constraints.

Constraints from big bang nucleosynthesis (BBN) will generically apply both because the axions we consider have lifetimes in the vicinity of a few seconds, and because the same reaction, $p d \rightarrow {}^3\text{He} \gamma$, is a key driver of BBN. In the absence of any additional dark sector decay modes, measurements of N_{eff} will generically exclude axions with masses below 5 MeV or so. These constraints can be alleviated if the dark sector contains additional degrees of freedom see e.g. [67]. Searches for gamma rays from the Quiet Sun offer a complimentary direct probe of axion (or other light particle) production that is independent of early universe cosmology.

We consider a 90° opening angle for our signal, meaning all decays between the Sun’s surface and Earth’s orbit contribute. The monoenergetic nature of the axion means the photon flux is constant in energy (see Section IV for more details on monoenergetic pro-

⁴ This requires accounting for the branching ratio to photons, as well as adjusting the decay length.

⁵ This occurs because axion-nucleon scattering leads to mean free paths much shorter than the typical size of a supernova, trapping the axions.

duction). We demand that this flux exceed $1.8 \times 10^{-3} \text{s}^{-1} \text{cm}^{-2} \text{keV}^{-1}$ for photon energies above 1 MeV, so that this flux is above the observed RHESSI background flux in the front segments.

IV. MODEL-INDEPENDENT SEARCHES

Let us now consider a model-independent production of LLPs (here called ϕ) which decay via $\phi \rightarrow \gamma\gamma$. In this simplified model, we consider all production to occur at the solar center, and ϕ only interacts with SM physics through its decay. We also assume there is no preferential direction for decay in the rest frame of ϕ , so the flux of photons is a uniform distribution between $E_{\gamma,\min}$ and $E_{\gamma,\max}$ where $E_{\gamma,\max/\min} = 1/2 \times (E_\phi \pm \sqrt{E_\phi^2 - m_\phi^2})$. Inverting this equation, we find $E_\phi \geq E_\gamma + m_\phi^2/(4E_\gamma)$ (we will call this lowest energy $E_{\phi,\min}$). Therefore, if we know the rate of production R_ϕ and decay length λ as a function of E_ϕ , then we can determine the BSM flux of photons at Earth.

$$\frac{d\Phi_\gamma}{dE_\gamma} = \frac{2}{4\pi d_\odot^2} \times \int_{E_{\phi,\min}}^{\infty} dE_\phi \frac{e^{-R_\odot/\lambda(E_\phi)} - e^{-d_\odot/\lambda(E_\phi)}}{\sqrt{E_\phi^2 - m_\phi^2}} \frac{dR_\phi}{dE_\phi} \quad (7)$$

One particularly well motivated morphology is where ϕ has a mono-energetic production spectrum. This would occur if ϕ is produced via a 2-body decay $\chi \rightarrow \phi X$ or via annihilation $\chi\chi \rightarrow \phi X$ for $v_\chi \ll 1$. Performing the integral in Eq. (7) with a delta-function distribution leads to a flux of photons that is constant in energy between $E_{\gamma,\min}$ and $E_{\gamma,\max}$.

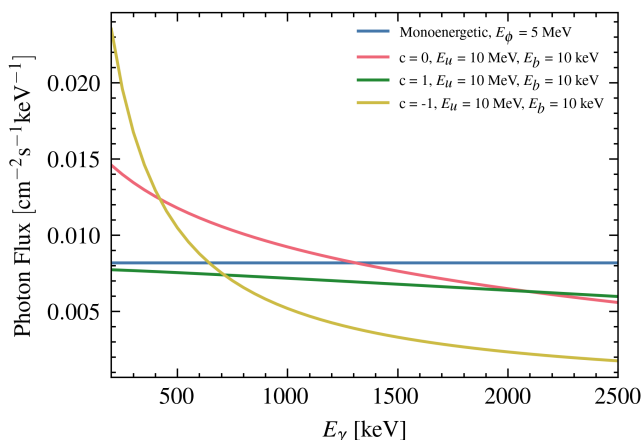


FIG. 6. Comparison of photon fluxes for different ϕ production scenarios. The fluxes are normalized so that the total production rate is $N_\phi = 10^{28} \text{s}^{-1}$, and the decay length is $\lambda = 10R_\odot$ at $E_\phi = 1 \text{MeV}$. We consider m_ϕ to be negligibly small.

Remaining more agnostic to the source of ϕ production, we may consider a power-law distribution with respect to energy for $E_b \leq E_\phi \leq E_u$

$$\left. \frac{dR_\phi}{dE_\phi} \right|_{\text{power}} = R_c \times E_\phi^c \Theta(E_u - E_\phi) \Theta(E_\phi - E_b). \quad (8)$$

For $m_\phi \ll E_\gamma, E_\phi$ the photon flux is calculable in closed form,

$$\left. \frac{d\Phi_\gamma}{dE_\gamma} \right|_{\text{power}} = \frac{2R_c}{4\pi d_\odot^2} \times \left[\left(\frac{R_\odot \tilde{E}}{\tilde{\lambda}} \right)^c \left(\Gamma(-c, \frac{R_\odot \tilde{E}}{\tilde{\lambda} E_u}) - \Gamma(-c, \frac{R_\odot \tilde{E}}{\tilde{\lambda} E_l}) \right) - \left(\frac{d_\odot \tilde{E}}{\tilde{\lambda}} \right)^c \left(\Gamma(-c, \frac{d_\odot \tilde{E}}{\tilde{\lambda} E_u}) - \Gamma(-c, \frac{d_\odot \tilde{E}}{\tilde{\lambda} E_l}) \right) \right], \quad (9)$$

with $\Gamma(a, x)$ the incomplete gamma function, $E_l = \max\{E_b, E_{\phi,\min}\}$, and $\tilde{\lambda}$ is the decay length at characteristic energy \tilde{E} . We normalize to the total rate of ϕ produced, N_ϕ . For the mono-energetic case, we have $N_\phi = R_\phi$, while for the power-law production, we have

$$R_c = \begin{cases} \frac{N_\phi(c+1)}{E_u^{c+1} - E_b^{c+1}} & \text{for } c \neq -1, \\ \frac{N_\phi}{\log(E_u/E_b)} & \text{for } c = -1. \end{cases} \quad (10)$$

Constraints on the number of ϕ produced per second in the Sun are shown in Fig. 7. Constraints are set as described at the end of Sections II and III.

V. FUTURE PROSPECTS

In the above discussion, we have found that repurposing existing RHESSI data is able to provide interesting constraints on light dark sectors with MeV scale LLPs. Our analysis should be viewed as a proof of principle and certainly underestimates the sensitivity of experiments like RHESSI to new physics models. The major limitations in our analysis are a lack of reliable peak-subtracted spectra and the ability to suppress backgrounds (see [81] for recent work in the keV regime for a more sophisticated statistical analysis). For example, much of the background for RHESSI comes not from solar activity but rather from cosmic ray interactions with the Earth's atmosphere i.e. the radiation comes from the rear rather than forward field of view. Much of this background can presumably be suppressed (or perhaps eliminated) with a future instrument, especially if a dedicated search is performed. In what follows we sketch potential improvements using a near-term MeV telescope. For concreteness we will anchor our discussion around the COSI satellite.⁶

⁶ We thank Albert Shih for pointing out the COSI mission to us.

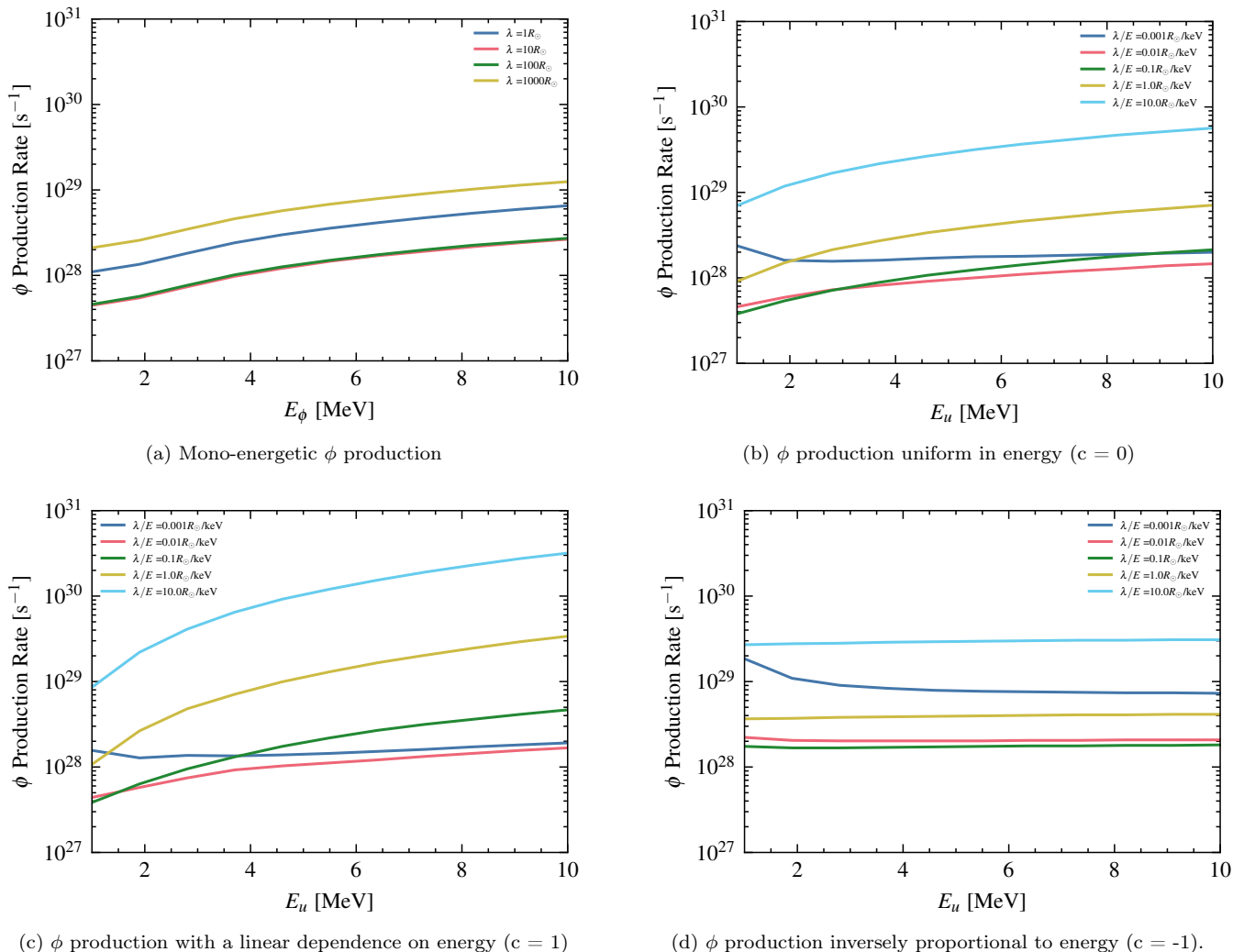


FIG. 7. Exclusion of ϕ production for some of the special cases considered. Production rates above the lines are excluded. In all cases, the mass is considered negligible, and there is no production below 10 keV ($E_b = 10$ keV).

RHESSI operated with minimal shielding to minimize weight. This made the instrument an effectively “all sky” observation with a high level of cosmic ray background activity. In contrast COSI will operate with active shielding, and its further use of Compton kinematic discrimination offers further background reduction [82]. Moreover, ongoing work to better understand gamma ray emission from the Quiet Sun will further improve on irreducible backgrounds [83, 84].

Other strategies that could be pursued with a future instrument are to go beyond the rate-only analysis presented above. For example, COSI will have 25% sky coverage and excellent angular resolution. One could image the MeV photon flux differential in both energy and angular position. Depending on the lifetime of LLPs a “halo” of photons could be searched for outside the solar corona. The shape of the photon distribution will be model dependent, but can be computed using the Monte Carlo simulations outline above. Similarly, taking advantage of

COSI’s large field of view, other local planetary systems could be used to search for LLPs. This was suggested recently in the context of Jupiter where the capture of light dark matter is better motivated [22, 85].

Finally, let us comment on a second channel of interest: $\text{LLP} \rightarrow e^+e^-$. This may occur for a dark vector which dominantly decays via $V \rightarrow e^+e^-$, and has recently been considered (in the context of large volume underground detectors) for the same $p d \rightarrow {}^3\text{He} \gamma$ reaction considered here [86]. A search for electrons and/or positron would require accurate modeling for propagation through magnetic fields in the vicinity of the Earth.

VI. CONCLUSIONS AND OUTLOOK

We have discussed simple particle physics models that predict an MeV flux of photons produced by the Sun. The generic requirement is the existence of some LLP which can efficiently transport energy from the interior (fueled by nuclear reactions) to beyond the Sun's surface. Provided the LLP has a sizeable branching ratio to final states including at least one photon e.g. $\gamma\gamma$, $\nu\gamma$, and/or $e^+e^-\gamma$ final states, one can search for energetic gamma rays emanating from the Quiet Sun.

We find that constraints from existing data from RHESSI, with a very conservative analysis strategy, can probe small pockets of untouched parameter space for both MeV scale axions and a neutrino dipole portal. In both cases, the RHESSI analysis provides complimentary coverage to existing search strategies (including cosmological probes such as BBN).

Our major motivation is a simple proof of principle that MeV-scale LLPs with decay lengths larger than the radius of the Sun can be efficiently searched for using solar telescopes. The analysis presented here is conservative and fairly crude; we define exclusions by the condition that the BSM signal prediction exceeds the *total signal* observed in any energy window by RHESSI. Constraints and/or discovery potential could be substantially improved with a better understanding of instrument backgrounds and more sophisticated analysis techniques. For example, one could make use of angular profiles of incident photons to search for new physics, as an LLP flux will produce a photon flux outside the stellar corona with a predictable angular shape/morphology. We encourage future missions with MeV scale instrumentation below the cut-off of Fermi-Lat, such as COSI [25, 26], to consider searches for BSM particles, with the Sun being a well-motivated engine for MeV-scale LLPs.

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Appendix A: Inefficient production mechanisms

In this section we discuss production mechanisms which we have found to be too inefficient to allow for detection prospects with our RHESSI analysis.

1. Mass-Mixing portal for HNLs

Another BSM model involving HNLs has N couple directly to active neutrinos through added elements in the PMNS matrix[13, 48, 87–108]. Active neutrinos contain a small admixture of the HNLs along with the three known mass states,

$$\nu_\alpha = U_{\alpha N} N + \sum_{i=1}^3 U_{\alpha i} \nu_i, \quad (\text{A1})$$

where $U_{\alpha N}$ represents the coupling of HNLs to active neutrinos. Since the Sun only has nuclear reactions that produce electron neutrinos, our constraint is on U_{eN} . The N flux from upscattering is subdominant by orders of magnitude to that from direct production. Therefore, the flux is given by rescaling the neutrino flux

$$\Phi_N = |U_{eN}|^2 \Phi_\nu \sqrt{1 - m_N^2/E_N^2}. \quad (\text{A2})$$

For the masses considered here, there are only three decay channels; *i*) $N \rightarrow 3\nu$, *ii*) $N \rightarrow \nu\gamma$, and *iii*) $N \rightarrow \nu e^+ e^-$. As with other production mechanisms, we only consider signals from photons. The geometry of this decay (into a massless neutrino and photon) is identical to the case of the dipole portal. The decay rate for each of the processes follows the general form

$$\Gamma_{N \rightarrow SM} \propto G_F^2 |U_{eN}|^2 m_N^5, \quad (\text{A3})$$

which has the steep power-law dependence on mass typical of weak decays. We find that since decay lengths are always long enough to fall outside the range given in Eq. (1) that sensitivity from RHESSI is subdominant to searches at Borexino (which benefits from a large detector volume) and from direct laboratory searches (see Fig. 8).

2. Captured dark matter in the Sun

If heavy dark matter, χ , has interactions beyond gravity, it may scatter within large celestial bodies and become gravitationally captured. The Sun, being by far the most massive object in the solar system, is a strong candidate in searching for the signals from captured χ [21, 109–125].

For the case of symmetric dark matter with a long-lived particle mediator, there is the interaction $\chi\bar{\chi} \rightarrow$ LLPs. The energies of these final observable particles are $\mathcal{O}(m_\chi)$. However, as discussed in [112], for thermal

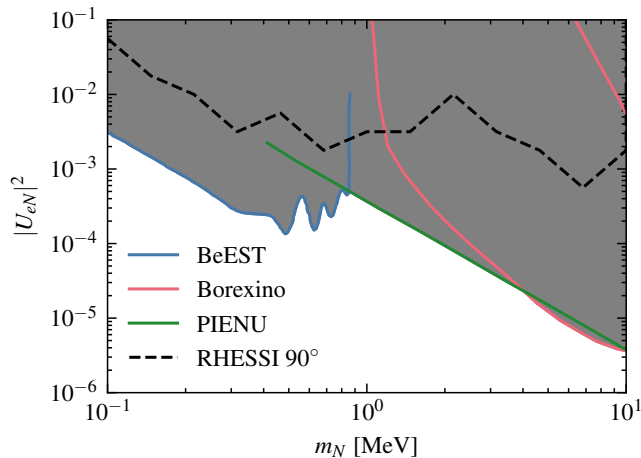


FIG. 8. Excluded parameter space for HNLs in the mass mixing model. The dashed line shows the RHESSI exclusion, while shaded regions come from BeEST [87], PIENU [88], and Borexino [89].

relic annihilation cross sections, short range interactions with SM, and m_χ below a few GeV, most of the χ evaporates from the Sun before annihilating. We note that for dark matter with long range interaction, evaporation may be suppressed [85] and RHESSI data could provide

interesting limits on lighter dark matter in these scenarios. Also, Jupiter has low evaporation for $m_\chi > 30$ MeV for long-range interactions ($m_\chi > 200$ MeV – 1 GeV for short-range interactions) [22, 85].

We also considered the case of asymmetric dark matter with self-interactions via a scalar ϕ with a Yukawa like interaction $\mathcal{L} \subset \bar{\chi}\chi\phi$. As there is no annihilation, in the absence of evaporation, the χ population grows indefinitely. Virialized dark matter passing through the Sun can scatter on the trapped overdensity and produce LLPs via the bremsstrahlung-like reaction $\chi\chi \rightarrow \chi\chi\phi$. In order to produce MeV gamma rays, we require heavy dark matter, $m_\chi \gtrsim 1$ TeV, such that there is sufficient available kinetic energy $m_\chi v_\chi^2 \gtrsim 1$ MeV.⁷ In order to produce a sufficiently large flux of LLPs, we require a sizeable $\chi\chi \rightarrow \chi\chi$ cross section. This can only be achieved with a light mediator for TeV scale (or heavier) dark matter. The cross section relies on a small momentum transfers. Non-relativistic kinematics, however, demand a parametrically larger momentum transfer in the bremsstrahlung like reaction than for elastic scattering. For example, demanding $E_\phi \sim \mathcal{O}(\text{MeV})$ bremsstrahlung, requires a momentum transfer on the order of $\Delta p^2 \sim m_\chi E_\phi \sim (1 \text{ GeV})^2$. Due to this kinematic suppression, we find that RHESSI is incapable of setting competitive limits even with the most generous/optimistic model building choices to maximize the bremsstrahlung like cross section.

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⁷ Dark matter nucleon scattering cannot induce MeV bremsstrahlung (i.e. via $\chi N \rightarrow \chi N\phi$), because the available kinetic energy is set by $m_N v_\chi^2 \sim 1 \text{ keV} \times (v_\chi/10^{-3})^2$. This is most easily seen in the rest frame of the heavy dark matter.

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