Snowmass2021 - Letter of Interest

Observing the High-Energy Sun

Thematic Areas: (check all that apply □/■)

■ (CF1) Dark Matter: Particle Like
■ (CF7) Cosmic Probes of Fundamental Physics
■ (NF4) Neutrinos from Natural Sources

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Abstract:

Searches for high-energy neutrinos and gamma-rays from the Sun are of interest to current and next-generation experiments. The current generation of neutrino telescopes have carried out searches for neutrinos created by self-annihilating dark matter in the Sun. While such searches have only yielded null results, they have set the most stringent constraints on the spin-dependent DM-nucleon cross sections for DM with mass above $\sim$100 GeV. Additionally, the first search for solar atmospheric neutrinos was recently completed. While a signal was not observed, it is well-predicted and lies within the sensitivities of next-generation detectors. Observing this flux would allow neutrino telescopes to extend their analyses into new baselines, matter densities, and decay pipe lengths. The so called 'solar disk' created by cosmic rays interacting with solar matter has been observed by gamma-ray observatories up to energies of $\sim$100 GeV; however, observing or constraining this flux above these energies may shed light on the mechanisms producing the solar magnetic field. Furthermore, there is strong evidence for a dip in the gamma-ray spectrum between $\sim$30 GeV and 50 GeV, which is not by any current model. Understanding the origin of this dip necessitates further observation during all periods of solar activity.[1]

[1] A related LoI specifically focusing on the sensitivity of current and next-generation TeV gamma-ray detectors has been prepared by Albert *et al.*[1]

Introduction.— The Sun has been observed and studied by humans since prehistoric times. As our closest star, it has been extensively studied over many photon wavelengths through the decades. The Sun has also been observed in neutrinos initially by SuperKamiokande[2] and later on by SNO and Borexino.[3–5] Low-energy solar neutrinos, produced in nuclear processes,[6;7] have been fundamental in the development of neutrino physics[8;9] since the observations at the Homestake Mine.[10] We believe that, similarly, high-energy particles from the Sun offer an exciting avenue for discovery for current and next-generation neutrino, cosmic-ray, and gamma-ray detectors.[11] In this letter, we point out that the importance of studying the Sun, as a natural high-energy source, by providing some examples of what we could learn.

Dark Matter Searches.— If dark matter (DM) is comprised of weakly-interacting massive particles (WIMPs), it should accumulate at the center of the Sun. DM can then annihilate or decay to Standard Model (SM) particles, which will undergo further decays to stable SM particles; see Fig. 2 for a cartoon.

Neutrinos are the only such particles that escape the dense solar center, and the observation of these neutrinos would be a smoking-gun signature of WIMP DM.[13] Since the rate of WIMP capture and annihilation or decay are expected to be in equilibrium in the Sun, detection of neutrinos from the previously described process are sensitive to the capture rate. When interactions are rare, the capture rate is directly proportional to the WIMP-nucleon cross section, and thus such indirect searches can probe the same parameter as direct searches, namely the WIMP-nucleon cross section. In fact, for WIMPs with mass $\gtrsim 10^2$ GeV annihilating to τ leptons or W bosons, the most stringent constraints on the spin-dependent WIMP-nucleon cross section come from indirect searches with neutrinos[14;15]. While indirect solar neutrino searches are less sensitive compared to the spin-independent WIMP-nucleon cross section with noble gas direct detection experiments, they offer a complementary as each search is subject to different systematic uncertainties. Current searches for WIMP-generated neutrinos are limited mostly by statistics, and thus larger next-generation neutrinos telescopes such as Baikal-GVD, Hyper Kamiokande, IceCube Gen2, and KM3Net will greatly enhance the power of these searches.

High-energy gamma rays are not expected to reach detectors in the standard WIMP annihilation scenario. However, in secluded dark matter models,[16] where DM annihilates to an unstable long-lived mediator which in turn decays to SM particles, gamma-rays can escape the Sun. In such a model, gamma-rays can be produced from these decays and can reach detectors in the Earth. This would lead to correlated gamma-ray and neutrino signatures.[17;18] Such a search was recently performed by the HAWC gamma-ray observatory,[19] yielding constraints on this scenario.

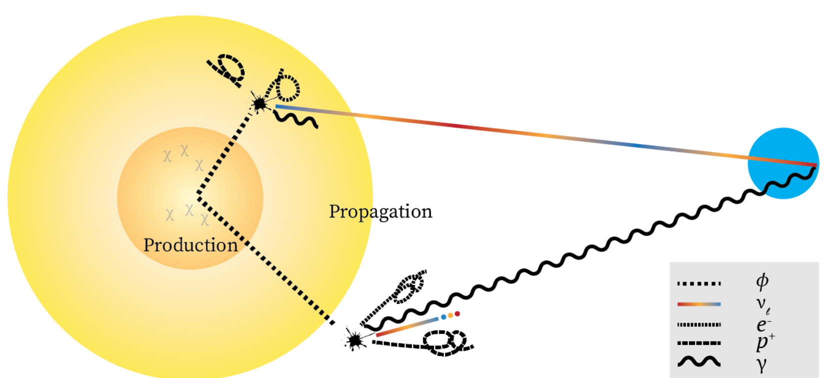

Figure 1: ***Illustration of a DM scenario producing signatures in gamma-rays, neutrinos, and cosmic-rays.*** Figure reproduced from[12] showing the secluded dark matter scenario, where dark matter annihilates to a long-lived mediator, which in turns decays in or outside of the Sun to gamma-rays, neutrinos, and cosmic-rays.

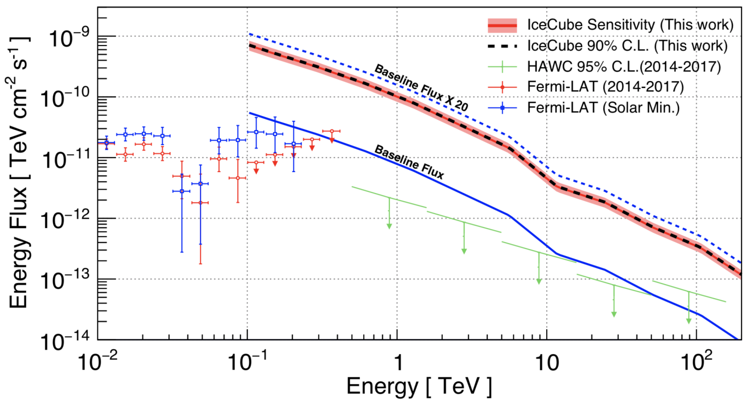

Figure 2: ***Summary of current status of solar atmospherics.*** Reproduced from[20], showing the current measurements and limits on high-energy neutrinos and gamma-rays from the Sun as well as the predicted neutrino flux.

Solar Atmospheric Neutrinos.— High-energy cosmic rays can interact with the solar atmosphere giving rise to a well-predicted, but yet unmeasured flux of 'solar atmospheric' neutrinos.[21–26] This flux creates is an irreducible background for the previously mentioned WIMP searches, but also serves as an interesting neutrino source in that neutrinos as they are expected to maintain coherence from their source to the Earth. Since the average distance to the Sun is about 10^4 larger than the radius of the Earth, one would see the first oscillation maximum at around 10 TeV, yielding a unique ratio of baseline to energy which allows new oscillation measurements. Although this flux is known to be larger than the Earth atmospheric flux above a TeV it remains unobserved,[27] due to the limited angular resolution of current neutrino detectors.[26] In addition to solar atmospheric neutrinos, high-energy neutrinos are also produced in solar flares, where protons can be accelerated to energies of tens of GeV. The transient nature of this phenomena allows one to reduce the background, and it has been predicted that it is potentially observable in megaton-mass scale neutrino detectors.[28] The IceCube Neutrino Observatory recently performed a coincidence search for neutrino candidate events and solar flares, but this analysis yielded only constraints.[29;30]

Solar Atmospheric Gamma-Rays.— The so-called solar disk is a source of gamma-rays from the hadronic interactions in the Sun; in fact gamma-rays above 100 MeV have been observed using *Fermi*-LAT data.[31] As in the case of neutrinos a TeV gamma-ray flux is expected from the sun,[32] and evidence of a high-energy component has been put forward in the data.[33;34] The current observation is greater than naively expected and it is believed that this enhancement is due to the solar magnetic field which can reverse the course of some cosmic rays from ingoing to outgoing.[35] Thus, measuring this flux provides a probe of solar magnetic fields. However, this flux remains unmeasured above 200 GeV.[36] Extending measurements into the higher-energy regime is essential because this is the region where reflection by the magnetic field turns off. Therefore, measurements or even limits will offer insight into solar magnetic fields. Additionally, the lower-energy spectrum exhibits a theoretically unpredicted dip in the energy range from ∼30-50 GeV.[37] Understanding the origin of this dip, as well as the magnitude of the high-energy spectrum may offer a unique insight into the solar magnetic field and gamma-ray emission mechanism or may shed light on yet unknown phenomena.

Outlook.— The next generation neutrino experiments and gamma-ray detectors have the opportunity both to observe signatures of dark matter and to observe a new high-energy neutrino source. We believe that these observations will open up a new frontier in particle and astroparticle physics, as was the case for the pioneering measurements of solar neutrinos.

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