Snowmass2021 - Letter of Interest

*Signatures of Dark Matter from Solar Gamma Rays**

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

■ (CF1) Dark Matter: Particle Like
□ (CF2) Dark Matter: Wavelike
□ (CF3) Dark Matter: Cosmic Probes
□ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
□ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
□ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
■ (CF7) Cosmic Probes of Fundamental Physics
□ (Other) *[Please specify frontier/topical group]*

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Abstract: The Sun is an excellent laboratory for astroparticle physics but remains poorly understood at GeV–TeV energies. Despite the immense relevance for both cosmic-ray propagation and dark matter searches, only in recent years has the Sun become a target for precision gamma-ray astronomy with the *Fermi*-LAT instrument. Among the most surprising results from these observations is a hard excess of GeV gamma-ray flux that strongly anti-correlates with solar activity, especially at the highest energies accessible to *Fermi*-LAT. Most of the observed properties of the gamma-ray emission cannot be explained by existing models of cosmic-ray interactions with the solar atmosphere. GeV–TeV gamma-ray observations of the Sun spanning an entire solar cycle would provide key insights into the origin of these gamma rays, and consequently improve our understanding of the Sun's environment as well as the foregrounds for new physics searches, such as dark matter. These can be complemented with new observations with neutrinos and cosmic rays. Together these observations make the Sun a new testing ground for particle physics in dynamic environments, especially towards the search for particle dark matter.

*This Letter contains excerpts and material from White Papers submitted for the Astro2020 Decadal Survey [1;2]

Long-exposure observations of the Sun extending into the GeV range only became a reality in the last decade. The quiescent Sun was first detect at GeV energies by EGRET[3] and later studied with more precision with the *Fermi*-LAT[4]. Analysis of nine years of data collected by the *Fermi*-LAT from the Sun revealed a very bright steady emission of gamma rays at energies above 100 GeV that contradicted all theoretical expectations[5;6]. This anomalous emission has become a new puzzle, the resolution of which would be a major step in our understanding of the Sun in an energy range that was not previously accessible.

The search for particle dark matter is one of many motivations for precision studies of the Sun at GeV–TeV energies. Dark matter can be gravitationally captured in the Sun and settle in thermal equilibrium in the core following scatterings with solar nuclei. The dark matter in the core can annihilate to produce Standard Model (SM) particles, which may be detectable upon escaping the Sun and serve as a probe of dark matter-proton scattering rate[7–19]. Neutrinos are the only SM particle that can escape when produced in the interior of the Sun, and so are the most sought after signature of dark matter annihilation in the Sun. In the well-motivated case that the dark matter first annihilates to long-lived mediators, neutrinos can be produced further away from the solar core, and so are less attenuated. Furthermore, other SM particles can escape the Sun to produce detectable gamma rays[20–28]. The main foreground for these searches is the flux of neutrinos/gamma rays from hadronic cascades in the Sun's atmosphere, which is an important complication that limits our sensitivity to dark matter signatures.

Gamma rays and neutrinos from dark matter have a distinct spectral and angular profile compared to the astrophysical foreground emission. Cosmic rays impinging on the back side of the Sun produce a steady flux of high-energy neutrinos. The flux of these solar atmospheric neutrinos has been estimated and is potentially detectable with neutrino observatories on Earth[29–32]. Neutrinos from solar dark matter annihilation would be correlated in direction with the center of the Sun, whereas the foreground neutrino emission would have a more extended profile with a dip towards the center[31]. Once the neutrino detectors are sufficiently sensitive to the flux of solar atmospheric neutrinos, their sensitivity to dark matter searches will approach a soft sensitivity floor. The current neutrino telescopes cannot distinguish between the solar atmospheric flux and dark matter due to their limited energy and angular resolution.

On the other hand, the gamma-ray searches in then TeV energy regime have yet to establish a sensitivity floor. Gamma rays from dark matter could be distinguished from cosmic-ray-induced emission based on their spectrum and the time variation of the flux. Precision measurements of the above-mentioned astrophysical foregrounds and their accurate modeling are the major challenges that need to be addressed for future searches[33].

Figure 1 illustrates the current status of observations and also shows the gaps in sensitivity and energy coverage that future studies need to fill to aid our understanding of the solar-disk spectrum. The *Fermi*-LAT has been able to measure photons up to 200 GeV, beyond which, satellite experiments have limited sensitivity. At higher energies, the strongest limits are available from the High-Altitude Water Cherenkov (HAWC) Observatory[34] at energies from 1–100 TeV for a search performed outside the solar minimum[33;35], and from ARGO-YBJ above 300 GeV[36]. If the spectrum observed by *Fermi*-LAT during the last solar minimum continues into the next (appx. 2018–2020), then the prospects for a first TeV detection are promising given HAWC and the upcoming LHAASO sensitivity. However, at lower energies (300–800 GeV), neither HAWC nor ARGO-YBJ have sufficient sensitivity to exclude a simple $E^{-2.7}$ extrapolation of the spectrum measured by the *Fermi*-LAT during any part of the solar cycle. Long-exposure measurements in the energy range not covered by the *Fermi*-LAT or current ground-based observatories is a key observational challenge for future.

The next decade will see radical improvements in particle astrophysics with a number of planned upgrades and new experiments on the horizon. Dark matter-proton scattering limits from gamma-ray observations can outperform limits from direct-detection experiments by several orders of magnitude[33], and will be

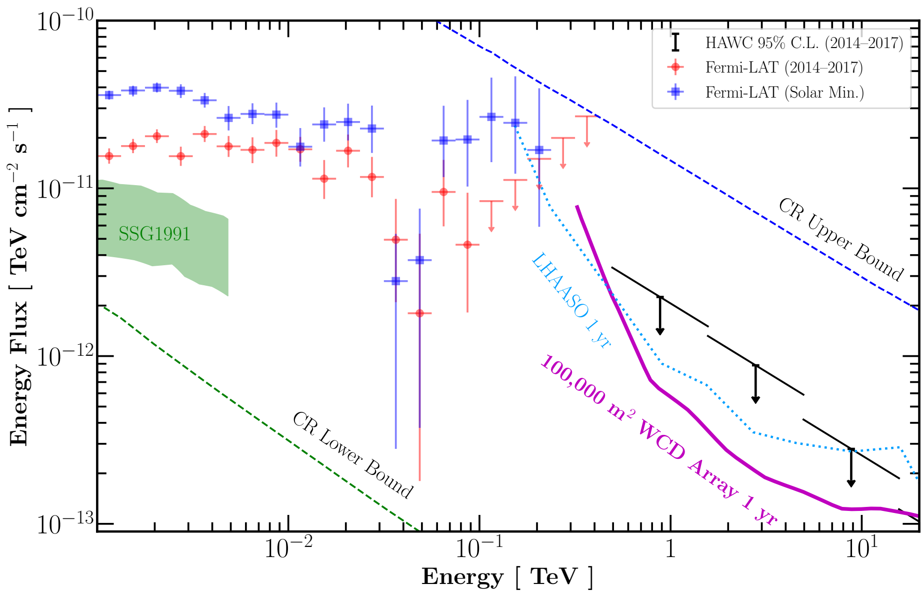

Figure 1: The observational status and future prospects of the solar gamma-ray spectrum (from Ref. 1; reproduced with permission). The red and blue data points show the *Fermi*-LAT measurements away from and during the solar minimum respectively. The nominal prediction from Ref. 37 is represented by the green band. TeV limits from HAWC and the one-year LHAASO sensitivity show the possibility of constraining certain extrapolations of the GeV flux[35]. (The ARGO-YBJ limits[36] are just under the cosmic-ray (CR) upper bound line.) The solid magenta line represents the potential gain in coverage from a next generation water Cherenkov detector (WCD) array in the Southern Hemisphere— the Southern Wide-field Gamma-ray Observatory (SWGO)[38].

the world-leading probe of dark matter with precision measurements in the next decade. While HAWC will continue to monitor the Sun for at least the next half of the solar cycle, LHAASO[39], beginning operations in 2020, will also be able to provide useful data with better sensitivity than HAWC. The Sun, being a bright, moving source, can only be efficiently probed using an all-sky survey instrument that is capable of day-time operations. Observation of the Sun is therefore beyond the reach of any Imaging Air Cherenkov Telescope (IACT) regardless of its sensitivity. While CTA[40] would be an excellent means of high-sensitivity pointed observations, it will not be able to probe the Sun due to intrinsic operational limitations. Only air-shower arrays monitoring the whole sky can provide uninterrupted, high-statistics data from the Sun. We anticipate increasing importance of synoptic surveys to perform measurements of challenging extended sources that cannot be probed by both satellites, due to limited sensitivity, and IACTs, due to their limited field-of-view. A new gamma-ray survey observatory in the Southern Hemisphere, the Southern Wide-field Gamma-ray Observatory (SWGO)[2;38]—with $10\times$ better sensitivity than HAWC, but similarly able to observe $\sim 2/3$ of the sky every day with a near-100% duty cycle—would be a drastic improvement over the limitations of current arrays. We anticipate that the pursuit of gamma rays from the Sun would fit neatly in the goals of such an instrument.

For more information about the Sun as a priority science case, please see *The Sun at GeV–TeV Energies: A New Laboratory for Astroparticle Physics*, an LOI submitted by Andrea Albert to CF07, and *Observing the High-Energy Sun*, an LOI submitted by Jeffrey Lazar to CF01, CF07, and NF04.

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