Snowmass2021 - Letter of Interest

The Sun at GeV–TeV Energies: A New Laboratory for Astroparticle Physics[*]

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 cosmic-ray propagation, only in recent years has the Sun become a target for precision gamma-ray astronomy with the *Fermi*-LAT instrument. Part of the observed properties of the gamma-ray emission cannot be explained by existing models of cosmic-ray interactions with the solar atmosphere. 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. To observe TeV gamma rays from the Sun you need a wide-field-of-view observatory with a large duty cycle (i.e., with the ability to observe during the day). In this Letter, we propose that the capabilities of the Southern Wide-field Gamma-ray Observatory (SWGO) would make the Sun a new testing ground for particle physics in dynamic environments.

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

The Sun is the most extensively studied star in a multitude of wavelengths. However, its complicated magnetic environment and its influence on cosmic rays at high energies remains a subject of open theoretical and observational investigations. It has long been of interest to the particle-astrophysics community for its role in modulating the cosmic-ray flux in the Solar System, and as a potential window to physics beyond the Standard Model. Cosmic rays entering the heliosphere are subject to propagation effects dominated by the solar wind and solar magnetic field. The cosmic-ray flux varies with solar activity throughout the 11-year cycle. In recent years, the time and energy dependence of the effect of solar magnetic fields has also been studied with the cosmic-ray shadow of the Sun[3–5].

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[6] and later studied with more precision with the *Fermi*-LAT[7]. 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[8;9]. 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 accessible before.

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 at energies 1–100 TeV for a search performed outside the solar minimum[5;10], and from ARGO-YBJ above 300 GeV[11]. If the spectrum observed by the *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's, and the upcoming LHAASO's[12], 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.

Current questions about the Sun that TeV observations can help answer include:

- How far into the GeV–TeV range does the emission extend without a rigidity cutoff? What does that tell us about the spatial extent of the magnetic fields that confine the cosmic rays near the Sun?
- Will the bright emission seen during the last solar minimum (2008–2010) repeat in the next cycle? Is the amplitude of the modulation constant from one cycle to the next?
- Is there a contribution to the emission from a new mechanism[13], and how do we use the spectral and spatial information to distinguish between multiple mechanisms of gamma-ray production?

Even though HAWC is a ground-based observatory, it can observe gamma rays both during the night and day (observations during daytime being necessary for Solar observations), allowing it to study the Sun at TeV energies. We propose a next generation gamma-ray observatory that will similarly be able to observe during the day and have the best sensitivity at high energies (> 10 TeV). The Southern Wide-field Gamma-ray Observatory (SWGO)[14;15] is planned to be located in the Southern Hemisphere and have a sensitivity $\sim 10\times$ better than HAWC[16]. Both detect relativistic particles in extensive air showers caused by cosmic-ray and gamma-ray interactions in the atmosphere. These arrays have a wide field-of-view and observe $\sim 2/3$ of the sky every day with a near-100% duty cycle. This wide field-of-view and the ability to observe during the day make these arrays unique, TeV gamma-ray observatories capable of observing the Sun.

The Sun, being a bright, moving source, can only be efficiently probed using an all-sky survey instrument—like SWGO—that is capable of day-time operations. Observation of the Sun is therefore beyond the reach

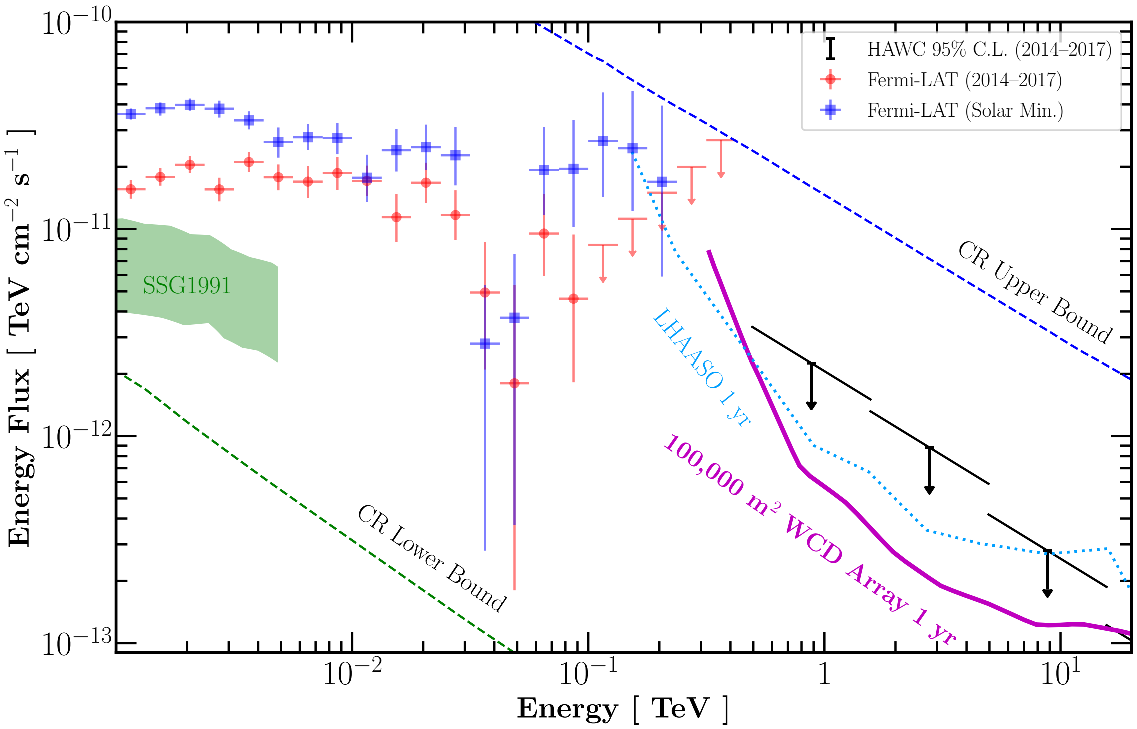

Figure 1: The observational status and future prospects of the Solar disk gamma-ray spectrum (from Ref. 1; reproduced with permission). The red and blue data points show the *Fermi*-LAT measurements away from and during the solar minimum respectively. The nominal prediction from Ref. 17 is displayed as the green band. TeV limits from HAWC and the one-year LHAASO sensitivity show the possibility of constraining certain extrapolations of the GeV flux[5] (the ARGO-YBJ limits[11] are just under the CR upper bound line). The solid magenta line represents the potential gain in coverage from an instrument like SWGO[18].

of any Imaging Air Cherenkov Telescope (IACT), regardless of its sensitivity. While CTA[19] 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.

We note there is an additional LOI on neutrino studies with the Sun (*Observing the High-Energy Sun*; submitted by Jeffrey Lazar to CF01, CF07, and NF04). These combined with gamma-ray observations allows for multimessenger studies of the Sun[20]. For more information about the Sun as a priority science case, please see *Signatures of Dark Matter from Solar Gamma Rays*, an LOI submitted by Kristi Engel to CF01 and CF07.

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