StellarICS: Inverse Compton Emission from the Quiet Sun and Stars from keV to TeV

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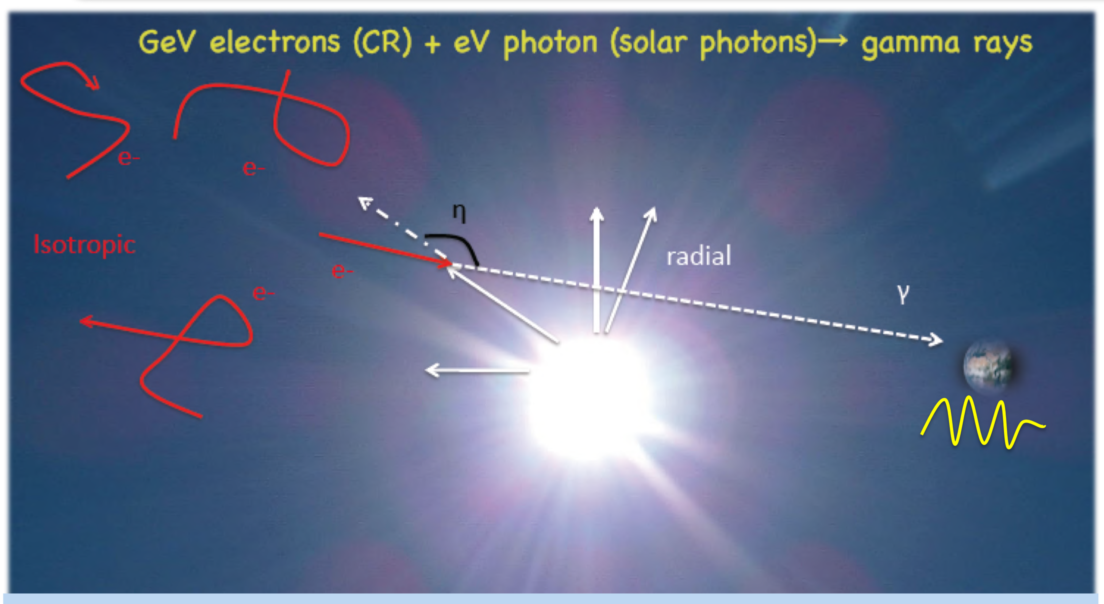
Gamma rays from the quiet Sun are produced by Cosmic Rays (CRs) interacting with its surface (disk component) and with its photon field (spatially extended inverse-Compton component, IC). IC is maximum close to the Sun and it extends over the whole sky. Monitoring the IC component with Fermi-LAT allows us to obtain information on CR electrons close to the Sun and in the heliosphere for different solar activity and polarity. The detection of IC emission from stars allows us to learn about CR electrons in their photosphere of stars. Fermi-LAT data analyses are usually model-driven. Hence advances in model calculations and constraints from precise CR measurements are timely and needed.

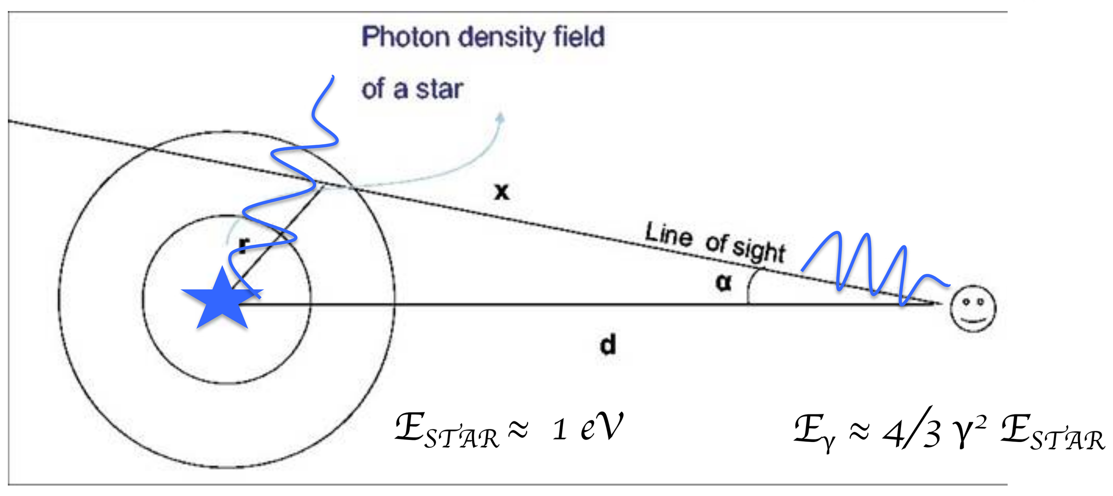
We present our StellarICS code to compute the gamma-ray IC emission from the Sun and also from single stars. The code is publicly available and it is extensively used by the scientific community to analyze Fermi-LAT data. It has been used by the Fermi-LAT collaboration to produce the solar models released with the FSSC Fermi Tools. Our modeling provides the basis for analyzing and interpreting high-energy data of the Sun and of stars. After presenting examples of updated solar IC models in the Fermi-LAT energy range that account for the various CR measurements, we extend the models to keV, MeV, and TeV energies for predictions for future possible telescopes such as AMEGO, e-ASTROGAM, HAWC, LHAASO, SWGO, and present X-ray telescopes. We also present predictions for some of the closest and most luminous stars. **Work published in JCAP04(2021)004 (arXiv:2012.13126)**.

The ASI-INAF agreement n.2017-14-H.0 and the NASA Grant No. 80NSSC20K1558 are acknowledged.

FIRST MODELING OF EXTENDED GAMMA-RAY INVERSE COMPTON (IC) EMISSION FROM THE SUN



Orlando & Strong, 2006 (arXiv:astro-ph/0607563; 2007 Ap&SS, 309, 59) [13]
Moskalenko et at, 2006 (ApJ, 652, L65) [12]



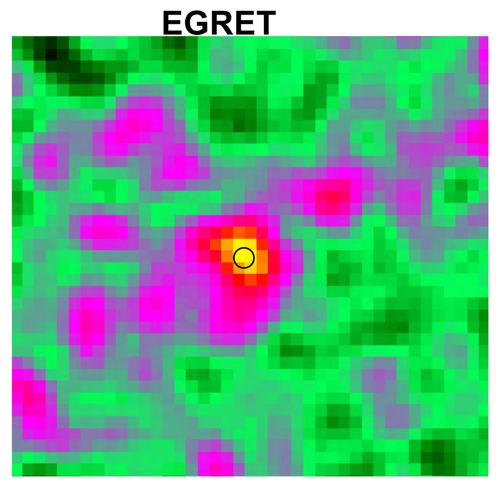
Gamma-ray intensity: $\mathcal{I}(\mathcal{E}_\gamma, \alpha) \approx \mathcal{L}_{SUN} / \alpha$

Gamma-ray flux: $\mathcal{F}(\mathcal{E}_\gamma) \approx \alpha$

FIRST DETECTION OF THE STEADY SUN IN GAMMAS (Orlando & Strong 2008 [14])

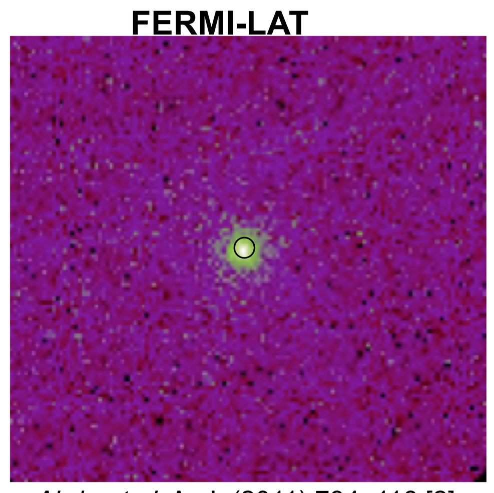
After the discovery of the quiet sun in EGRET data (left), now Fermi-LAT (right) is so sensitive that even the electron propagation in the inner heliosphere can be studied. **Observations as predicted !**

EGRET



Orlando & Strong, (2008) A&A, 480, 847 [14]

FERMI-LAT



Abdo et al. ApJ. (2011) 734, 116 [2]

THE STELLARICS PACKAGE

- Computes IC from the solar heliosphere.
  Can be used for any star.
- C++ PROGRAM freely available in gitlab.
- Package contains C++ routines, build instructions and description.
- MODULAR - Independent classes: anisotropic Klein-Nishina formulation, Stellar Radiation field, electron and positron spectra separately, Solar Modulation.
- Parallel compilation in OpenMP → high resolution computations in reasonable time

FLEXIBLE & USER FRIENDLY

- Description, instruction, examples of input parameters, example of outputs.

- User-defined parameters for steps, electron spectra, modulation, etc.

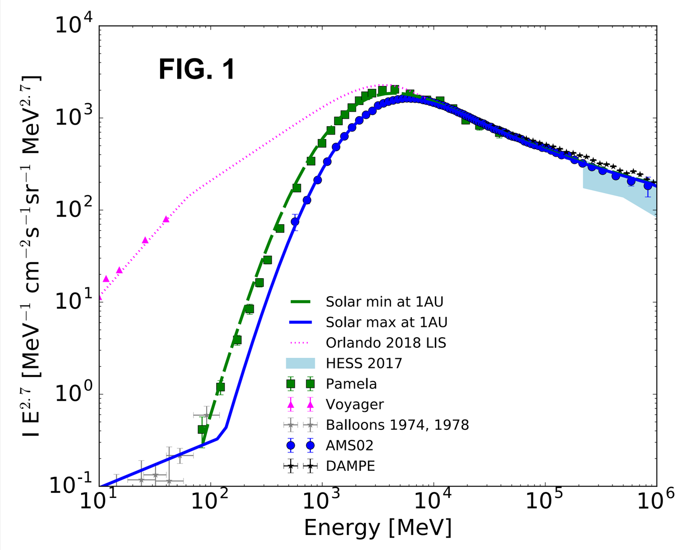
- Many models of e^+e^- and modulation, and more can be easily implemented.

- It is under continuous development, accounting for updated observations in gamma rays and CRs

OUTPUTS

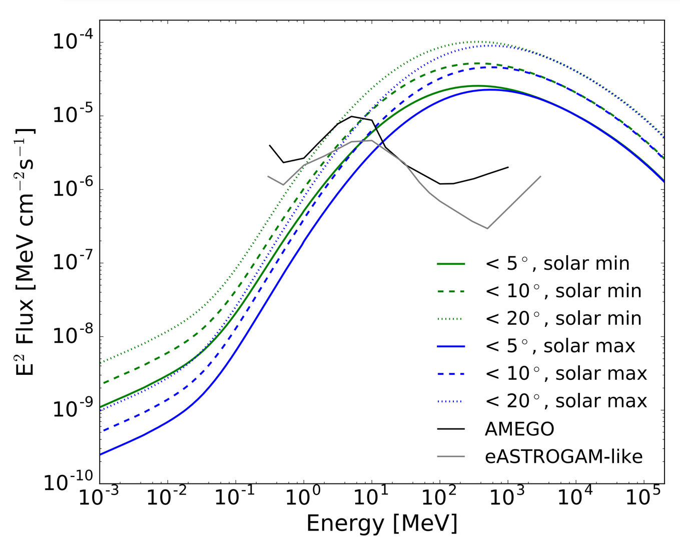
FITS files with various extensions (flux vs. angle, spectra, profiles...)
idl commands and some plots that can be customized

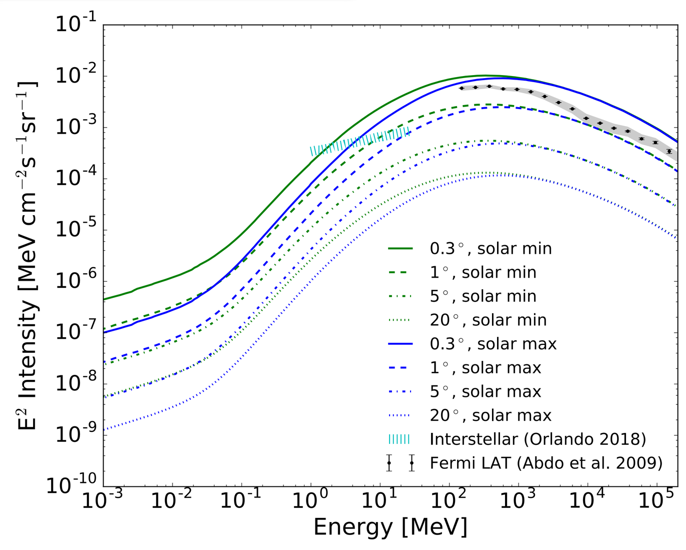
ELECTRON SPECTRA



All-electron spectra for two sample models compared with data. Green dashed line: model mainly based on the Pamela [4] all-electron spectrum for 2008 (green squares), representative of the solar minimum; blue solid line: model mainly based on the AMS-02 [5] all-electron spectrum for the period of 2013 (blue points), representative of the solar maximum; magenta dotted line: local interstellar spectrum from [15] constrained by radio-microwave and gamma rays observations of the interstellar diffuse emission and direct CR measurements.

SOLAR CALCULATIONS keV - GeV

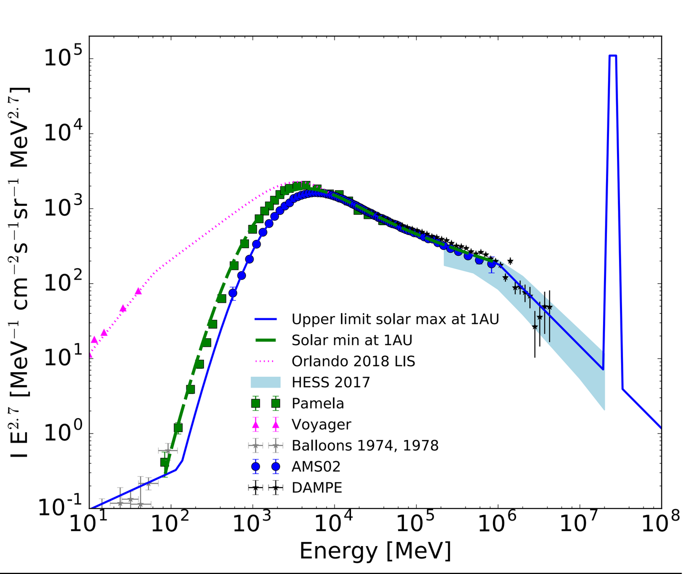


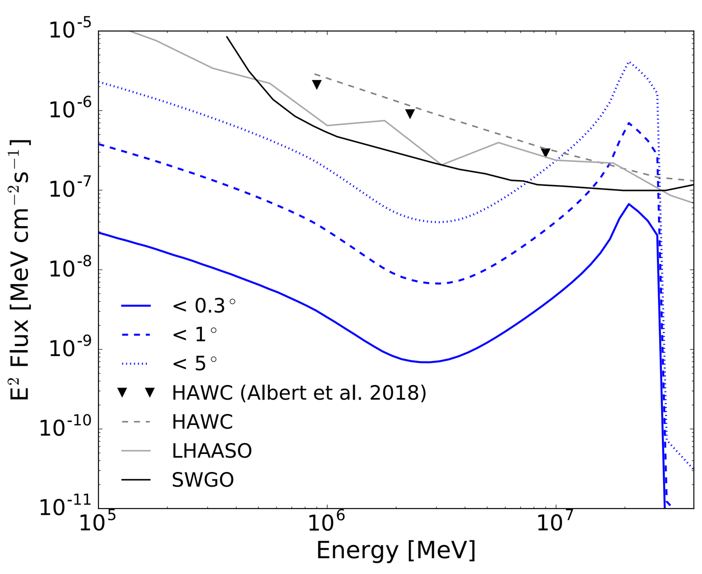


Left: Calculated IC spectral flux integrated over areas with various angular amplitudes based on the green and blue all-electron spectra shown in Figure 1. Solid lines are the spectral fluxes integrated in 5° around the Sun, while dashed lines in 10° around the Sun, and dotted lines in 20° around the Sun. AMEGO sensitivity (grey solid line, preliminary point source sensitivity for 5-year mission, private communication) and e-ASTROGAM- like instrument point source sensitivity [9] (grey dashed line, for 1-year effective exposure) are also shown.

Right: Calculated IC spectral intensity for various angular distances from the Sun based on the green and blue all-electron spectra shown in Figure 1. Solid lines are the spectral intensity at 0.3° from the Sun, while dashed lines at 1° from the Sun, dotted-dashed lines at 5° from the Sun, and dotted lines at 20° from the Sun. In both plots the blue lines represent the solar maximum condition (all- electron model that fits AMS-02 data), while the green lines represents the solar minimum condition (all-electron model that fits Pamela data). Black points and grey region are data and systematic errors of the total emission at intermediate latitudes observed by Fermi-LAT [1], which includes the extended interstellar emission, the extragalactic component, and sources. The cyan region shows the interstellar emission at intermediate latitudes as predicted in [15].

SOLAR CALCULATIONS AT TeV

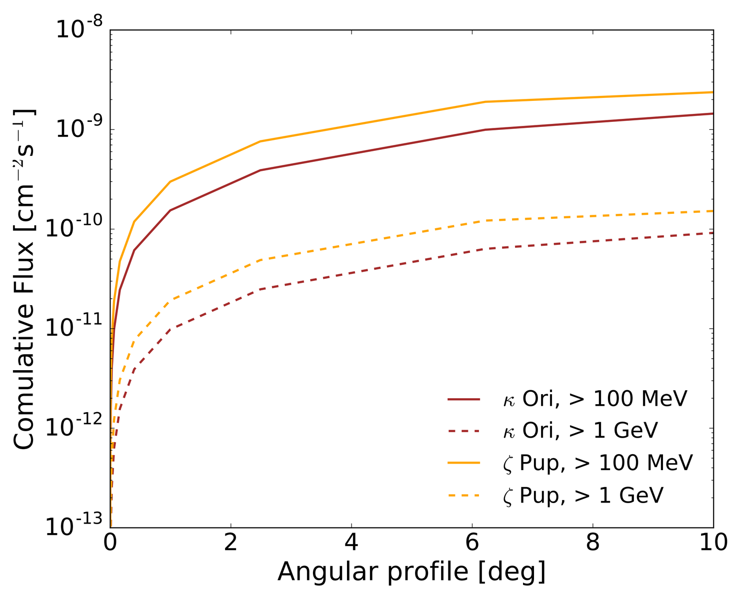




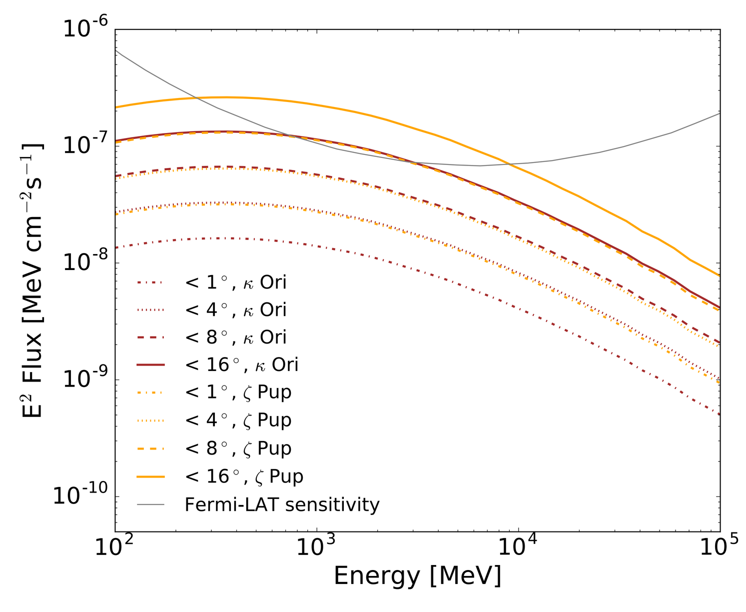
Left: Modeled all-electron spectra compared with data. For energies below 1 TeV, details are provided in Figure 1. Up to 20 TeV the modeled spectrum (blue line) reproduces the HESS data [11] and other CR electron data, while at higher energies the upper limit to the spectrum (spike in the figure) is given by the CR proton spectrum and by ground-based observations of nearby sources. This spectrum represents an extreme case that provides the upper limit to the calculated IC emission.

Right: Extension of the solar IC model calculations at TeV energies based on the all-electron model as in Figure 6 (blue line). This gives the expected upper limit to the IC emission. Left: calculated spectral flux integrated over areas with various angular amplitudes: 0.3° (solid line), 1° (dashed line) and 5° (dotted line) around the Sun. Black triangles show HAWC upper limits of the disk emission [7]. HAWC 3-year sensitivity [7] (dashed grey line), LHAASO sensitivity [8] (solid grey line, 1-year sensitivity private communications), and SWGO sensitivity [6] (solid black line, the SWGO straw man model) for point sources are also shown.

CALCULATIONS FOR SINGLE STARS



Top: Cumulative flux from κ Ori (brown lines) and ζ Pup (orange lines) as a function of integration angle for integrated energies above 100 MeV (solid lines) and 1 GeV (dashed lines).
The IGRB [3] has a total intensity of (7.2±0.6) ×10−6 cm−2s−1sr−1.
See also Poster De Menezes, R., Orlando, E., De Mauro this conference on luminous stars [10]



Bottom: Calculated IC spectral flux of κ Ori (brown lines) and ζ Pup (orange lines) in the energy range of Fermi-LAT integrated over areas with various angular amplitudes for the AMS02 spectrum with Φ0 = 600 MV. Solid lines are the spectral fluxes integrated in 8° around the Sun, dashed lines in 4° around the Sun, and dotted lines in 1° around the Sun. The grey line is the Fermi-LAT point source sensitivity for 10 years

CONCLUSIONS

Models for the solar IC emission are important for assisting analyses and for interpreting recent and forthcoming observations of the Sun from keV to TeV energies for various solar conditions. The StellarICS code for calculating the IC emission from the Sun and stars provides computations accounting for various electron and positron spectral models, the isotropic or anisotropic Klein-Nishina formulation, various treatments for the solar (stellar) modulation, given technical parameters, such as the energy grid and angular steps, and given physical ones, such as distances, radius, temperatures of the Sun (stars), that can be freely chosen by the user. The code is publicly available and can be easily extended by the user to include additional and more sophisticated models.

We have presented examples of updated solar IC models for the Fermi-LAT energy band based on the various CR electron measurements. In particular, we have shown expectations for two baseline models, one for solar minimum conditions mainly based on Pamela CR measurements, and one for solar maximum conditions mainly based on AMS-02 CR measurements. LAT observes the Sun with high statistical significance. Current observations include data for the entire Cycle 24 for different solar conditions and polarity.

We have also extended our calculations down to keV energies. We have estimated the solar extended IC emission to be very important for future MeV missions (e.g. AMEGO, e-Astrogam-like, and possibly GECCO), as it is for Fermi-LAT. Indeed, for the IC below 100 MeV the solar modulation effect is at its maximum, thus allowing to easily distinguish among different models. On the contrary, we have shown that below 100 keV the substantially higher contribution from the extragalactic x-ray background would make the solar large-scale emission hardly detectable even by present sensitive x-ray survey telescopes, such as eRosita, being the expected IC solar emission many orders of magnitude below the extragalactic background.

Additionally, we have extended our calculations of the solar IC emission to TeV energies. We have accounted for an extreme CR all-electron spectrum to provide an upper limit to the expected IC emission. We found that current upper limits from the Sun with HAWC are consistent with these IC calculations. By comparing this extreme model with the expected sensitivity of HAWC, LHAASO, and SWGO in the next years, we found that the solar IC emission could be barely detectable by these telescopes. This would require the flux of the all-electrons ~20 TeV to be comparable to the flux of protons, which would be totally unexpected.

Finally, we have given calculations from a sample of closest luminous stars. Single stars and associations produce gamma rays by the same IC mechanism. This IC emission is expected to be detected by Fermi-LAT from the closest most luminous stars and for OB associations. We expect the smooth large-scale interstellar IC emission to be clumpy in these directions.

Comparison of gamma-ray observations in the direction of stars with stellar models produced with the StellarICS code will also help to probe the all-electron spectrum in the proximity of the stars and thus at different positions in the Galaxy.

REFERENCES

[1] Abdo, A. A., Ackermann, M., Ajello, M., et al. 2009, Physical Review Letters, 103, 251101
[2] Abdo, A. A., Ackermann, M., Ajello, M., et al. 2011, ApJ, 734, 116
[3] Ackermann, M., et al. 2015, ApJ, 799, 86. doi:10.1088/0004-637X/799/1/86
[4] Adriani, O., Barbarino, G. C., Bazilevskaya, G. A., et al. 2009, Nature, 458, 607
[5] Aguilar, M., Aisa, D., Alvino, A., et al. 2014, Physical Review Letters, 113, 121102
[6] Albert, A., Alfaro, R., Ashkar, H., et al. 2019, arXiv:1902.08429
[7] Albert, A., Alfaro, R., Alvarez, C., et al. 2018, PhRvD, 98, 123011. oi:10.1103/PhysRevD.98.123011
[8] Bai, X., Bi, B. Y., Bi, X. J., et al. 2019, arXiv:1905.02773
[9] de Angelis, A., Tatischeff, V., Grenier, I. A., et al. 2018, Journal of High Energy Astrophysics, 19, 1. doi:10.1016/j.jheap.2018.07.001
[10] De Menezes, R., Orlando, E., et al. in preparation
[11] H.E.S.S. Collaboration, Kerszberg, D., et al. 2017, Talk at the 35th International Cosmic Ray Conference (ICRC), Busan, Korea
[12] Moskalenko, I. V., Porter, T. A., & Digel, S. W. 2006, ApJL, 652, L65
[13] Orlando, E., & Strong, A. W. 2006, arXiv:astro-ph/0607563, 2007 Ap&SS, 309, 359
[14] Orlando, E., & Strong, A. W. 2008, A&A, 480, 847
[15] Orlando, E. 2018, MNRAS, 475, 2724. doi:10.1093/mnras/stx3280