A study of super-luminous stars with the *Fermi*-LAT

Raniere de Menezes[1]*, Elena Orlando[2,3] and Mattia Di Mauro[4]

on behalf of the *Fermi*-LAT Collaboration

[1]Institut für Th. Physik und Astrophysik, University of Würzburg, Germany

[2]INFN Sezione di Trieste and Università degli Studi di Trieste, Italy

[3]Kavli Institute for Particle Astrophysics and Cosmology and Hansen Exp. Physics Lab., Stanford University, USA

[4]INFN Torino, Physics Department, Italy

*raniere.m.menezes@gmail.com

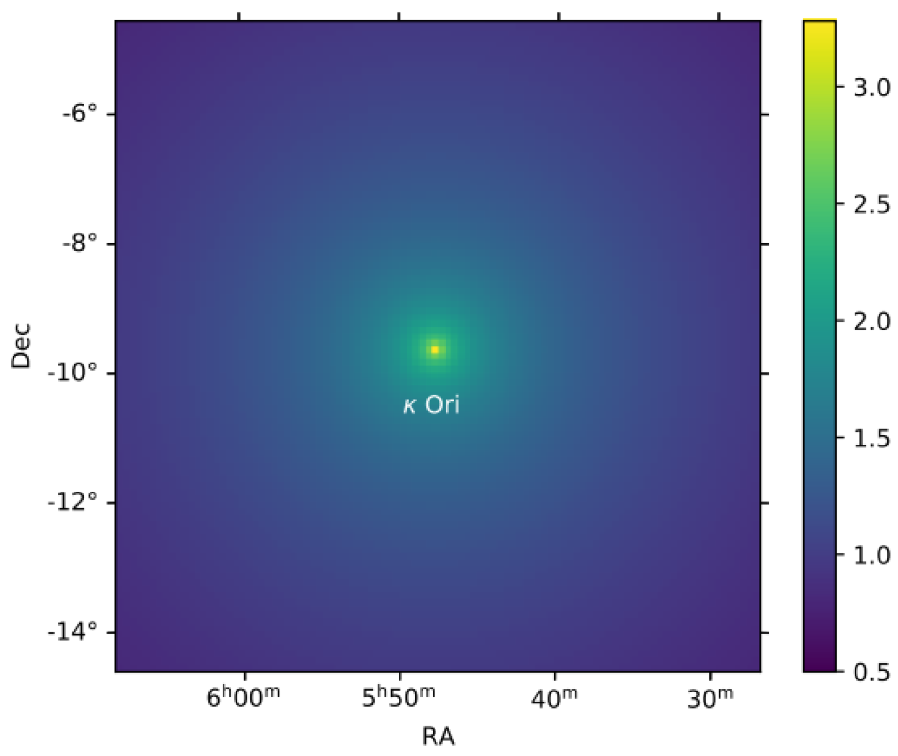
Stars are relatively shy non-thermal sources of γ-rays with quiescent emission expected to come in two distinct components, both determined by the cosmic ray spectrum in the neighborhood of the star: a stellar disk component, where γ-rays are produced by hadronic cascades in the stellar atmospheres, and an extended halo component, where thermal photons from the stars are scattered up to the γ-ray domain by cosmic ray electrons. These components have never been observed in other stars but the Sun. In this work we investigate the γ-ray emission from 9 nearby super-luminous stars, for which the extended halo component is predicted to be detectable with the *Fermi* Large Area Telescope after a decade of observations. Our results show no significant γ-ray emission, but allow us to restrict the stellar γ-ray fluxes to be on average < 3.3 x 10^{-11} ph cm^{-2} s^{-1}, and the density of cosmic ray electrons in the surroundings of our targets to be less than twice the value measured in the Solar System.

1. The context

There is not a single isolated star listed in the *Fermi* Large Area Telescope (LAT) fourth source catalog (4FGL; Abdollahi et al. 2020). However, the predicted inverse Compton (IC) γ-ray emission from extended halos (Moskalenko et al. 2006) of nearby super-luminous stars could in principle be high enough to be detected in γ-rays. Orlando & Strong (2007) showed that if we consider a distribution of cosmic ray electrons similar to that observed in the Solar System, the γ-ray emission from the halo component of a few nearby stars could exceed ~10^{-9} ph cm^{-2} s^{-1}, which is well within *Fermi*-LAT sensitivity threshold. In this work we present the first systematic study of a population of super-luminous stars in γ-rays, where we test if the IC γ-ray emission model for stellar halos is supported by *Fermi*-LAT observations.

3. The methods

In our analysis we consider 12 years of *Fermi*-LAT observations in the energy range between 0.5 - 100 GeV. We assume a power-law spectrum for all targets in our sample and test their γ-ray emission with i) a point-like model, and ii) an extended stellar halo model based on the predicted IC emission described in Orlando & Strong (2007). The extended model for κ Orionis is show in the figure below, where the color map is in log scale and normalized such that its integrated flux is equal to 1.



The individual emission from these stars is relatively faint. Therefore, in order to observe their collective emission, we perform a stacking analysis assuming that this population can be characterized by an average photon index.

5. Discussion and conclusions

Our results show no detection of significant γ-ray emission from individual stars. Future observations with the upcoming All-sky Medium Energy Gamma-ray Observatory, which will be more sensitive than *Fermi*-LAT at energies < 500 MeV, will likely be suited for this kind of analysis.

In this work we tested if *Fermi*-LAT could detect the IC emission from extended stellar photon halos, and our main conclusions are summarized as follows:

- The IC γ-ray emission from stellar halos (other than the Sun) is too weak to be detected by *Fermi*-LAT with current data. We got no detection after stacking 12 years of γ-ray observations for 9 nearby super-luminous stars.

- We found that the stars in our sample must emit on average < 3.3 x 10^{-11} ph cm^{-2} s^{-1} at an energy range between 0.5 - 100 GeV, otherwise we should detect them as a population at the 3σ confidence level. This result constrain the density of cosmic ray electrons in the surroundings of our targets to be less than twice the value we measure in the Solar System.

These results are going to be published soon in de Menezes et al. (in prep).

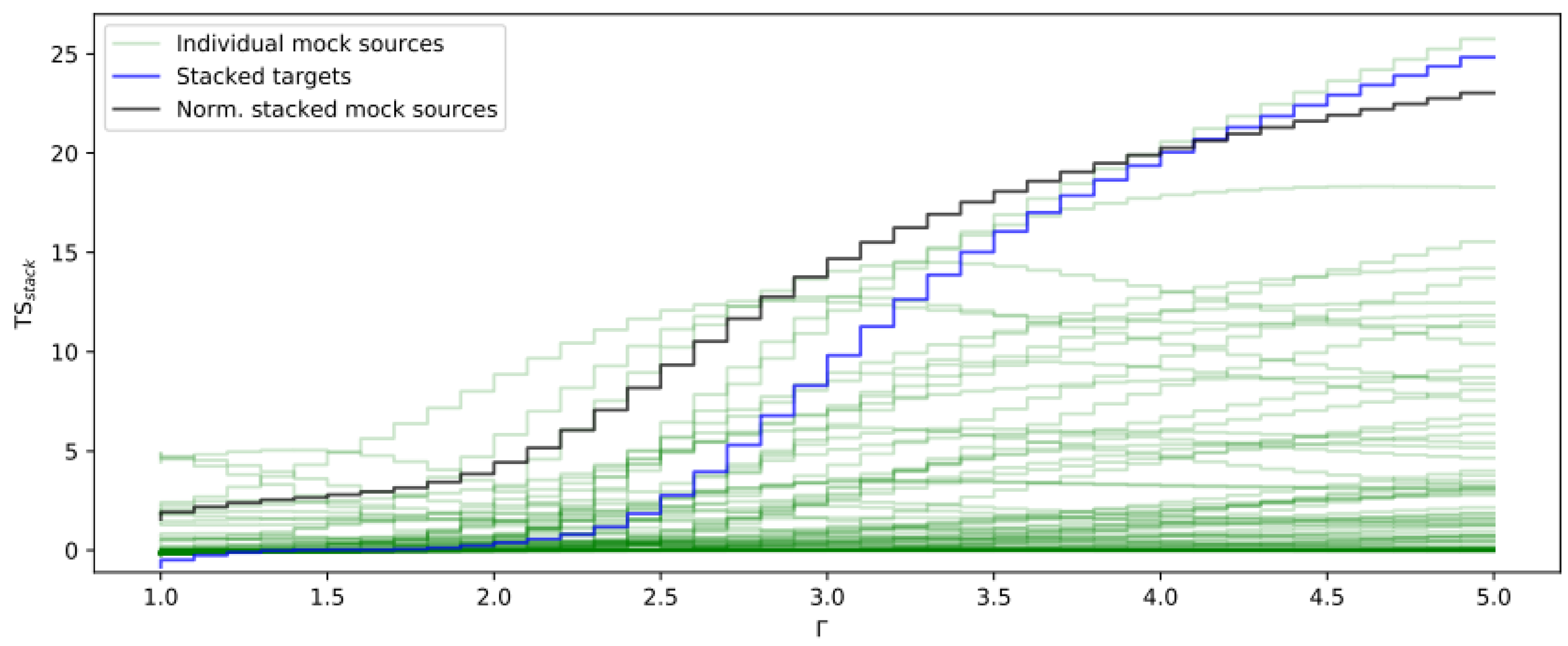
2. The sample

Our sample consists of 9 super-luminous nearby stars with the highest expected IC fluxes, as calculated and listed in Orlando & Strong (2007). These stars have been chosen from an original list containing the 70 most luminous stars in the Hipparcos and Tycho Catalogues lying up to a distance of 600 pc from the Sun. They are κ Orionis, ζ Puppis, ζ Orionis, Betelgeuse, δ Orionis, Rigel, ζ Persei, λ Orionis, and ε Canis Majoris.

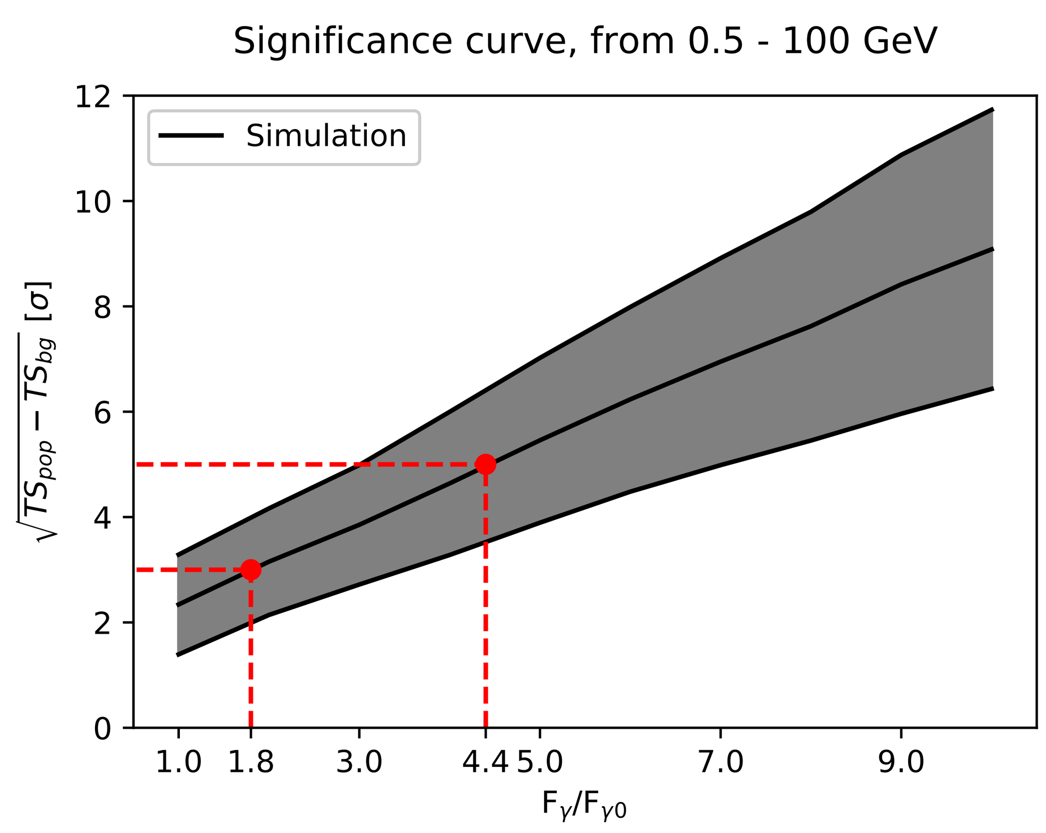
Their IC halo emissions have been computed assuming a cosmic ray electron spectrum similar to that observed at Earth and locally in the Galaxy (Orlando 2018). Although in stars like the Sun two components significantly contribute to the total quiescent γ-ray output, i.e., the stellar disk and the IC halo, in super-luminous stars the IC component is expected to be dominant.

4. Results

The results from the stacking analysis are shown in the plot below as a distribution of the test statistic (TS) in terms of photon index Γ. The blue line represents the stacked TS for the 9 targets, while the black line represents the normalized stacked background, built with the stacking of more than 100 mock sources (green lines). Our results are consistent with random background fluctuations.



In order to constrain the total γ-ray flux from our sample, we simulate 12 γ-ray stellar halos in the neighborhoods of each one of our targets and collect their average flux. We start by simulating halos with exactly the same IC luminosity predicted for our targets and then gradually increase their luminosity up to 10 times its original value.



In the figure above, we show the significance of a sample of simulated super-luminous stars in terms of the total predicted γ-ray flux of our original sample, $F_{\gamma 0}$. The simulation indicates that a population of 9 stars with IC emission similar to that of our original sample should be at least 1.8 times brighter in order to be detected by *Fermi*-LAT at the 3σ confidence level. Furthermore, the simulation assures us that these stars have, on average, γ-ray fluxes smaller than 3.3 x 10^{-11} ph cm^{-2} s^{-1}, otherwise they should be detected as a population at the 3σ confidence level.

References

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Fermi Gamma-ray Space Telescope