



RANIERE DE MENEZES, ELENA ORLANDO, MATTIA DI MAURO, AND ANDREW STRONG

# A study of super-luminous stars with the Fermi-LAT: a probe to cosmic rays throughout the Galaxy



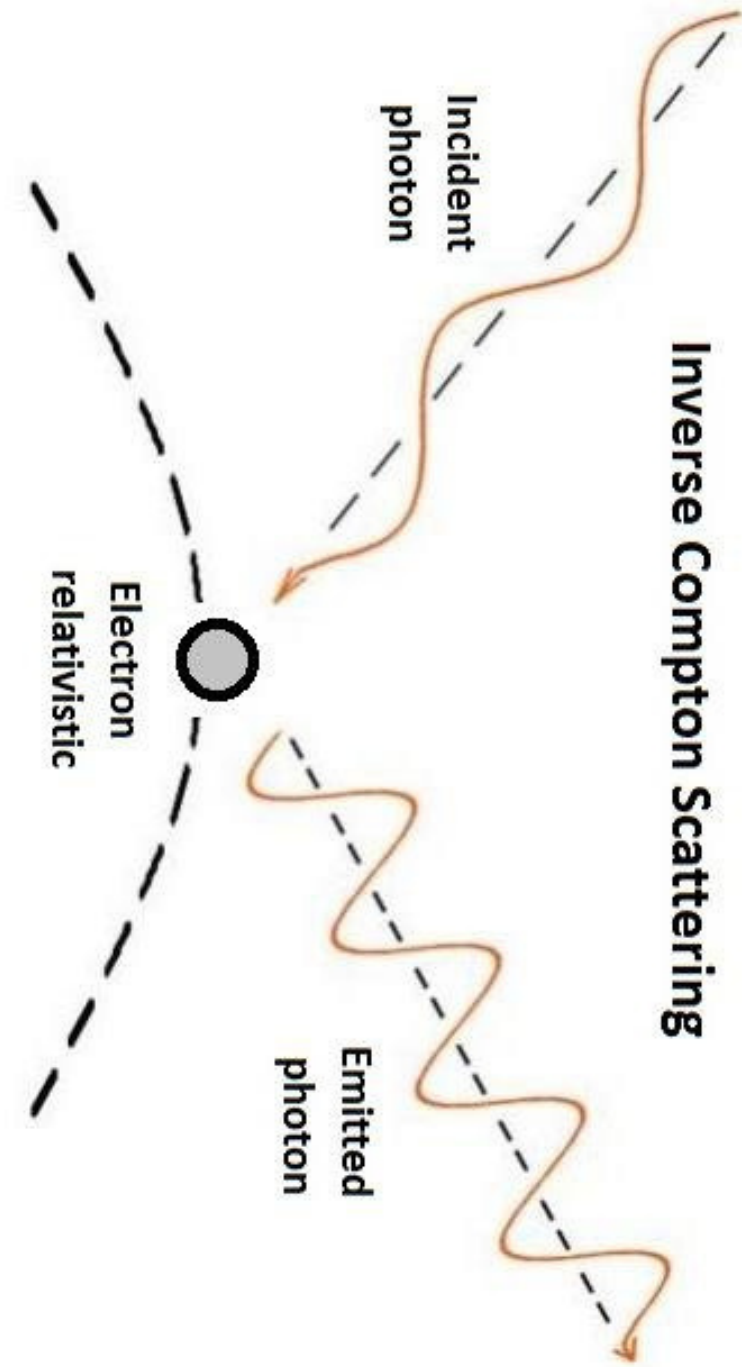
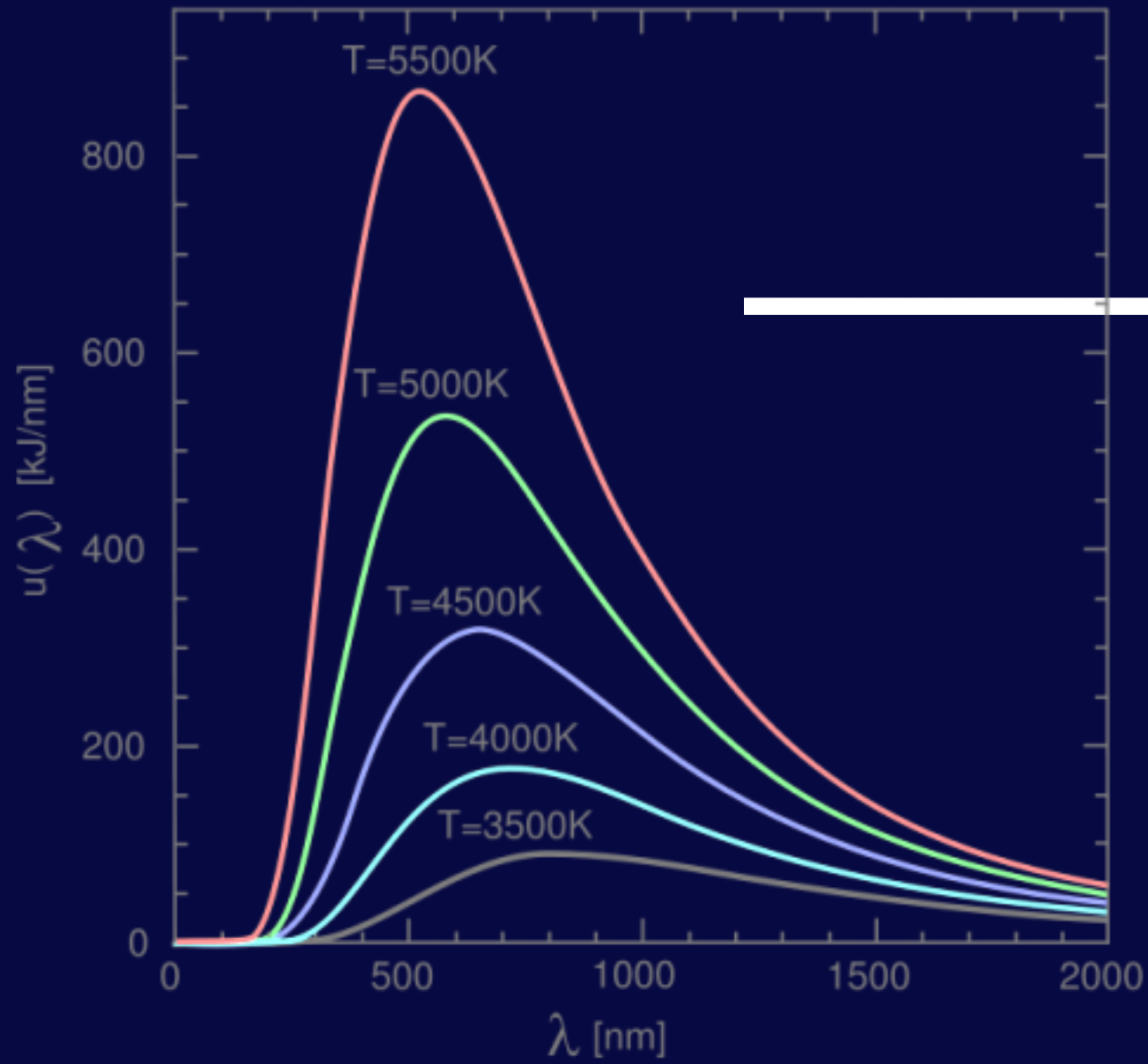
**UNIVERSITÀ  
DI TORINO**



Istituto Nazionale di Fisica Nucleare  
SEZIONE DI TORINO

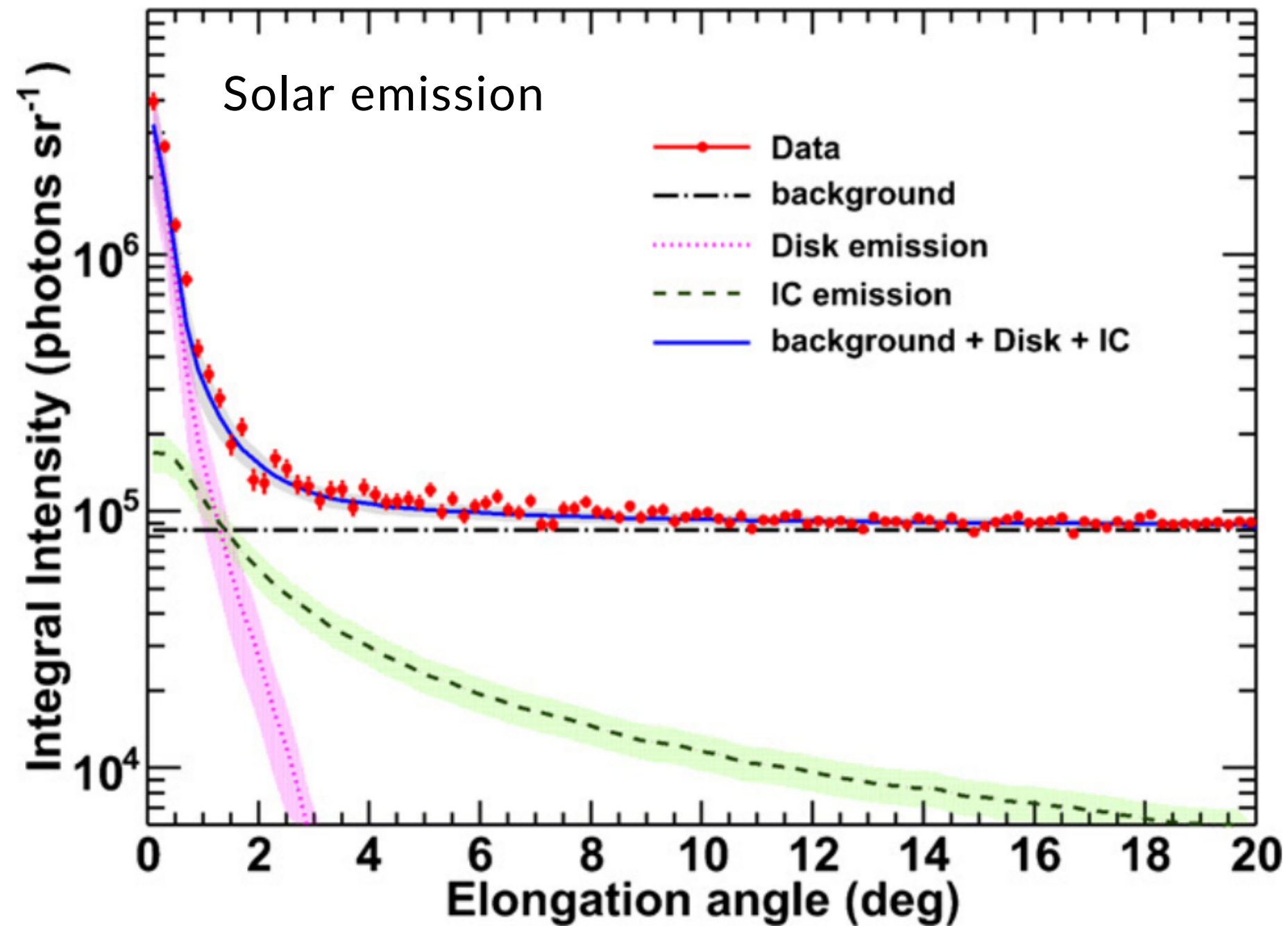


# Stars emit thermal radiation: where do gamma-rays come from?



III

## The gamma-ray emission from stars has two main components



- Emission from the stellar disk due to CR cascades in the star's atmosphere.
- Extended emission from IC scattering of CR electrons on stellar thermal photons.

FIGURE: ABDO ET AL. (2011).

≡

We can use the gamma-ray emission from stars to constrain the density of cosmic-ray electrons throughout the Galaxy

Gamma-ray intensity:

$$I(E_\gamma) = \frac{1}{4\pi} \int \epsilon(E_\gamma) dx$$

$$\epsilon(E_\gamma) = \int dE_e \int \sigma(\gamma, E_{\text{ph}}, E_\gamma) n_{\text{ph}}(E_{\text{ph}}) c N(E_e) dE_{\text{ph}}$$

↓  
 Emissivity

↓  
 CR e<sup>-</sup> spectrum

↓  
 Photon density

↓  
 K-N cross sec.

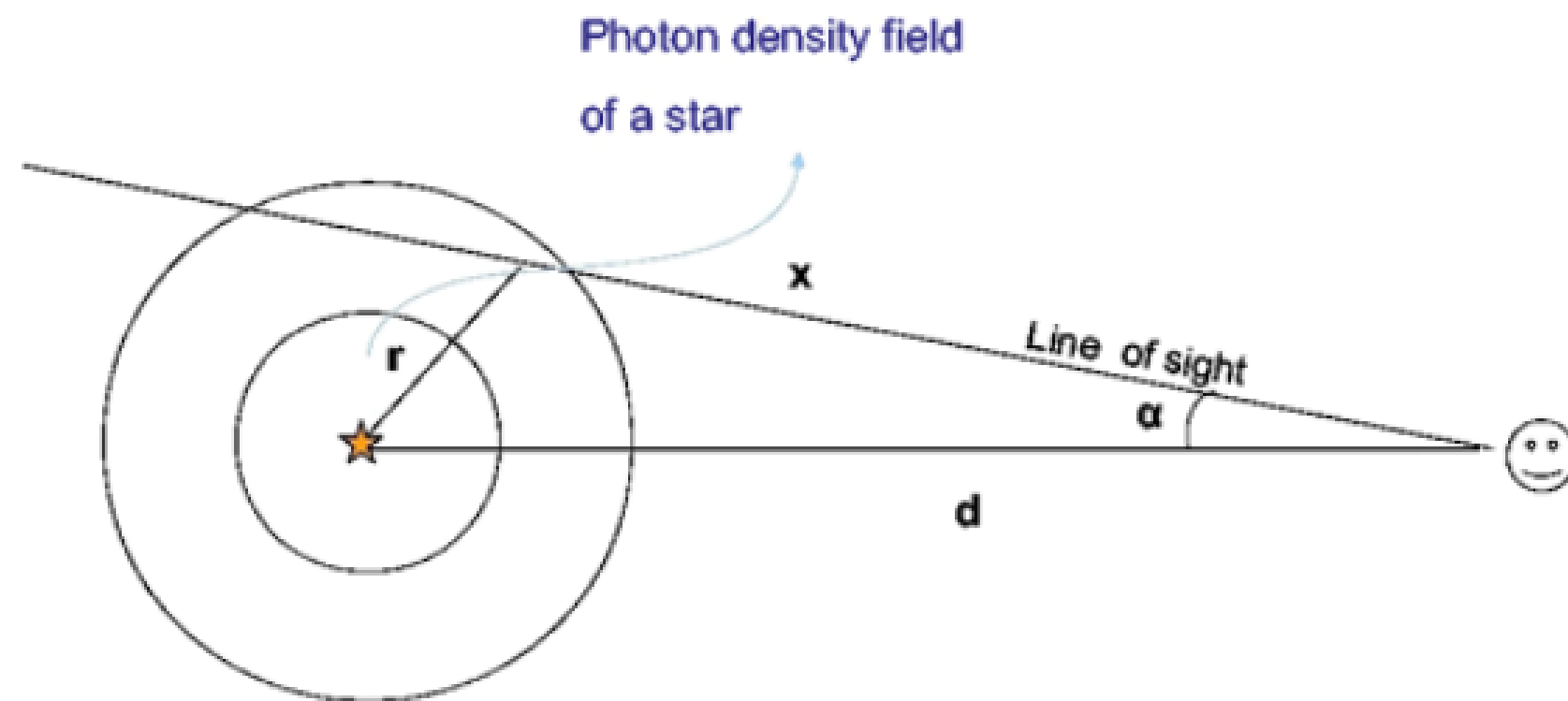


FIGURE: ORLANDO & STRONG (2007).

≡ Nearby superluminous stars are expected to be observed as extended gamma-ray sources

$$L_{IC} \propto r L_{STAR}$$

$$flux_{IC} \propto L_{STAR} \propto 1/d$$

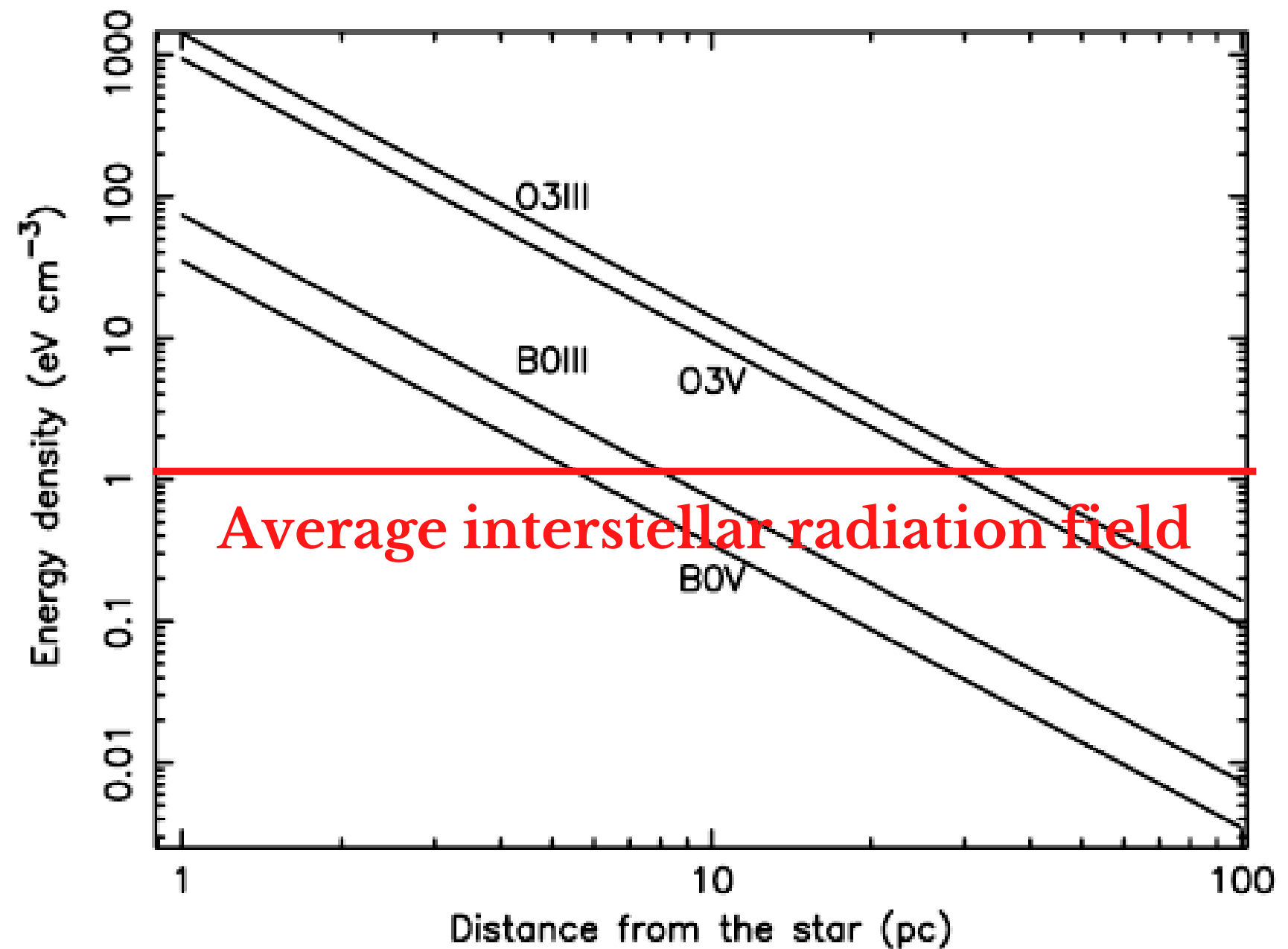


FIGURE (MODIFIED): ORLANDO & STRONG (2007).

≡

We selected a sample of 9 nearby superluminous stars expected to be on the edge of Fermi-LAT sensitivity

$\kappa Ori$

$\zeta Pup$

$\zeta Ori$

*Betelgeuse*

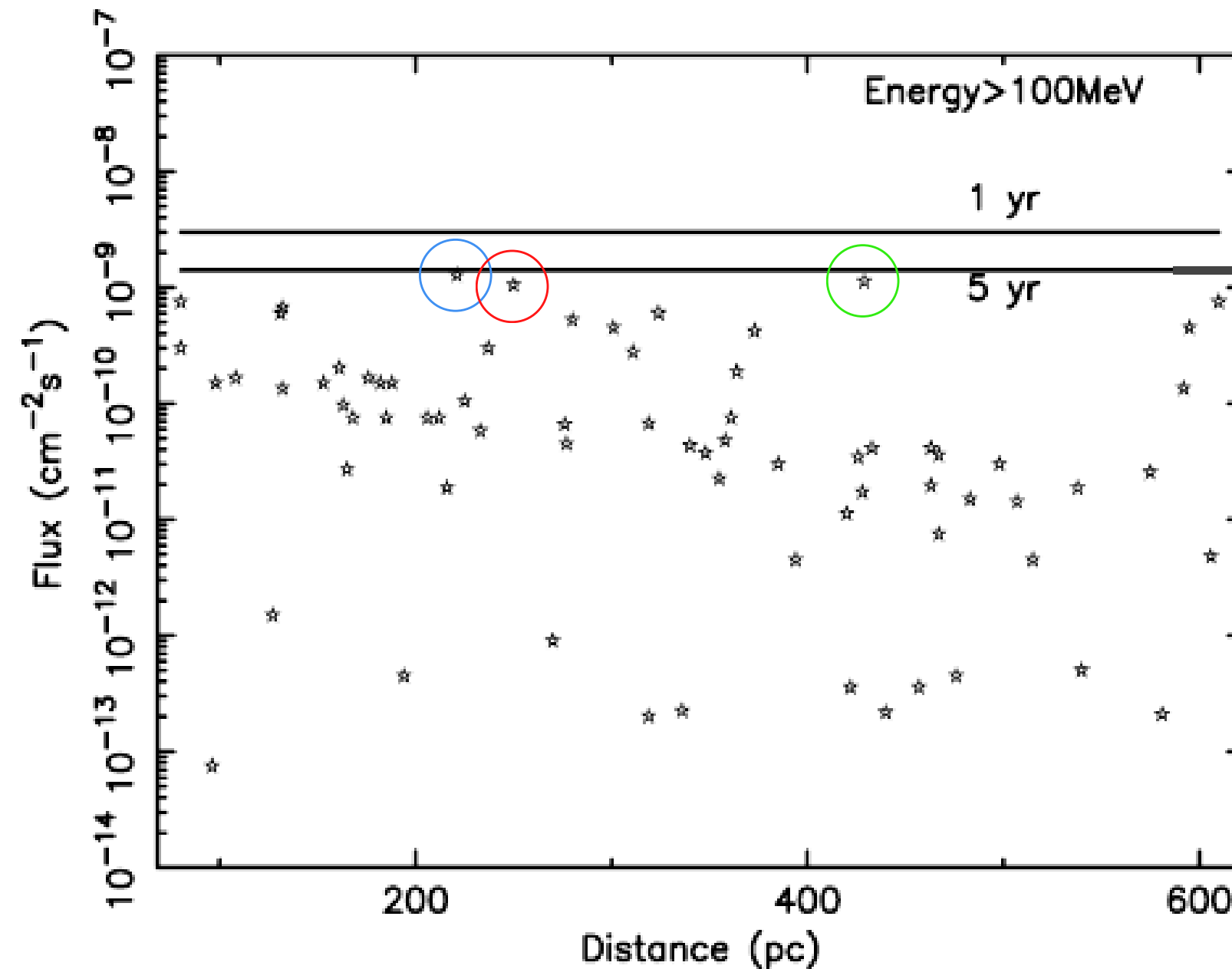
$\delta Ori$

*Rigel*

$\zeta Per$

$\lambda Ori$

$\epsilon CMa$

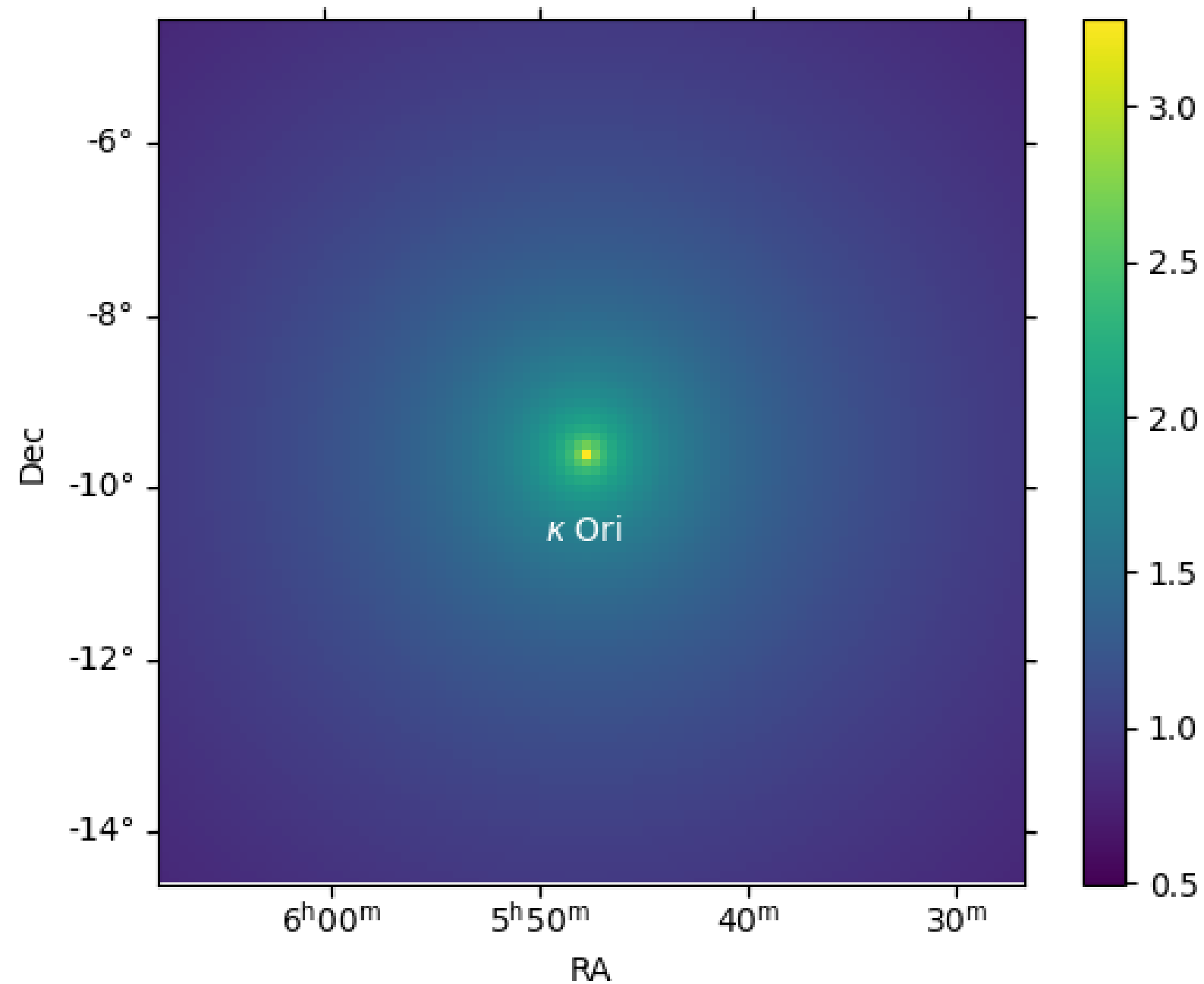


LAT 5 years  
sensitivity

FIGURE: ORLANDO & STRONG (2007).

### III

## Each star was modeled as an extended gamma-ray halo



Spectral models computed with StellarICS (Orlando & Strong, 2021)

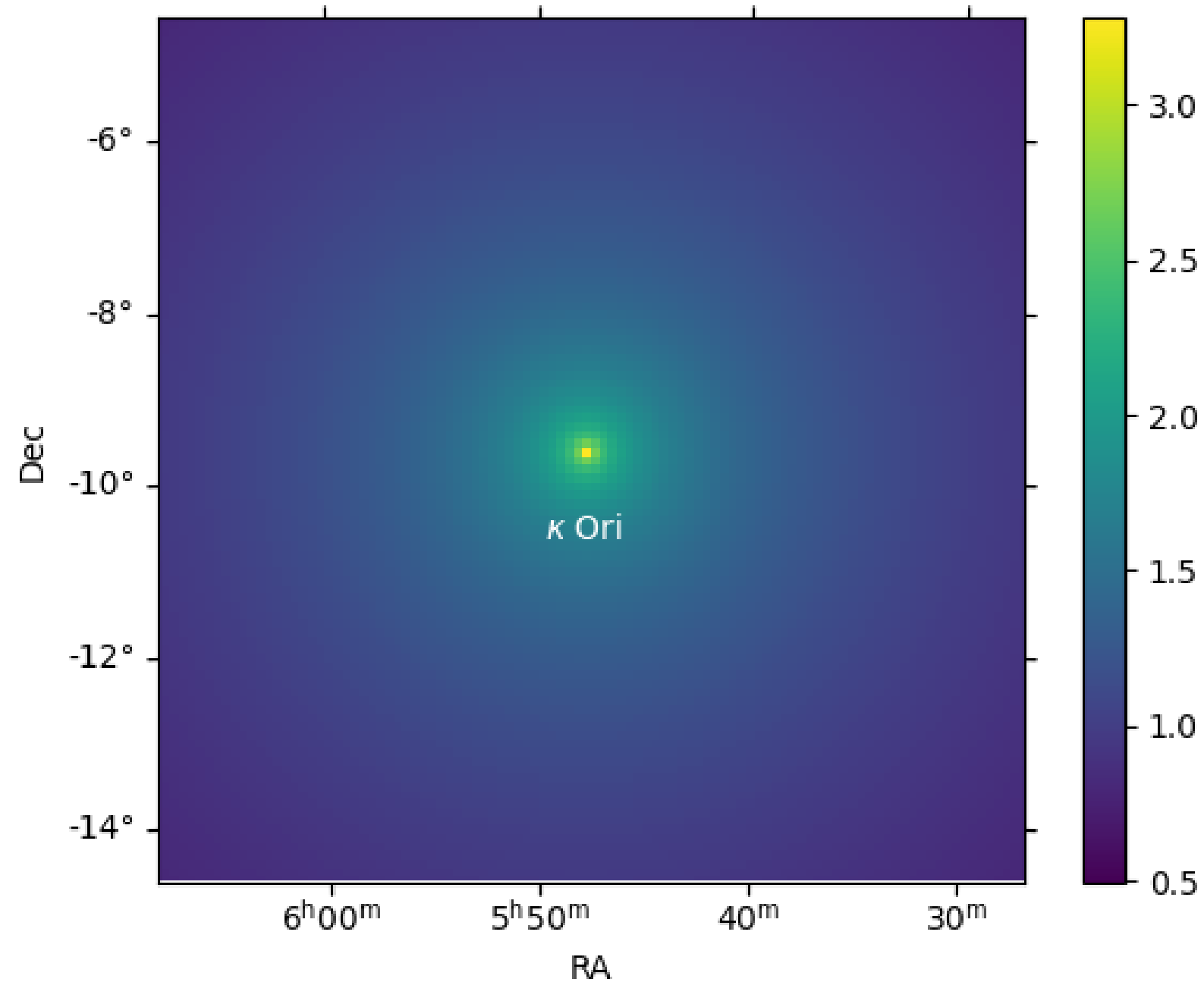
→ Gamma-rays from each star give us information about the density of CR electrons around them

→ CR electrons cannot penetrate closer than  $0.025^\circ$

FIGURE: DE MENEZES ET AL. (2021).

### III

## Each star was modeled as an extended gamma-ray halo



→ By knowing the optical and gamma-ray luminosities of stars, we can map the density of CR electrons around the Galaxy

→ Superluminous and non-variable stars are better suited for this

FIGURE: DE MENEZES ET AL. (2021).



III

We found no significant gamma-ray emission coming from the stars

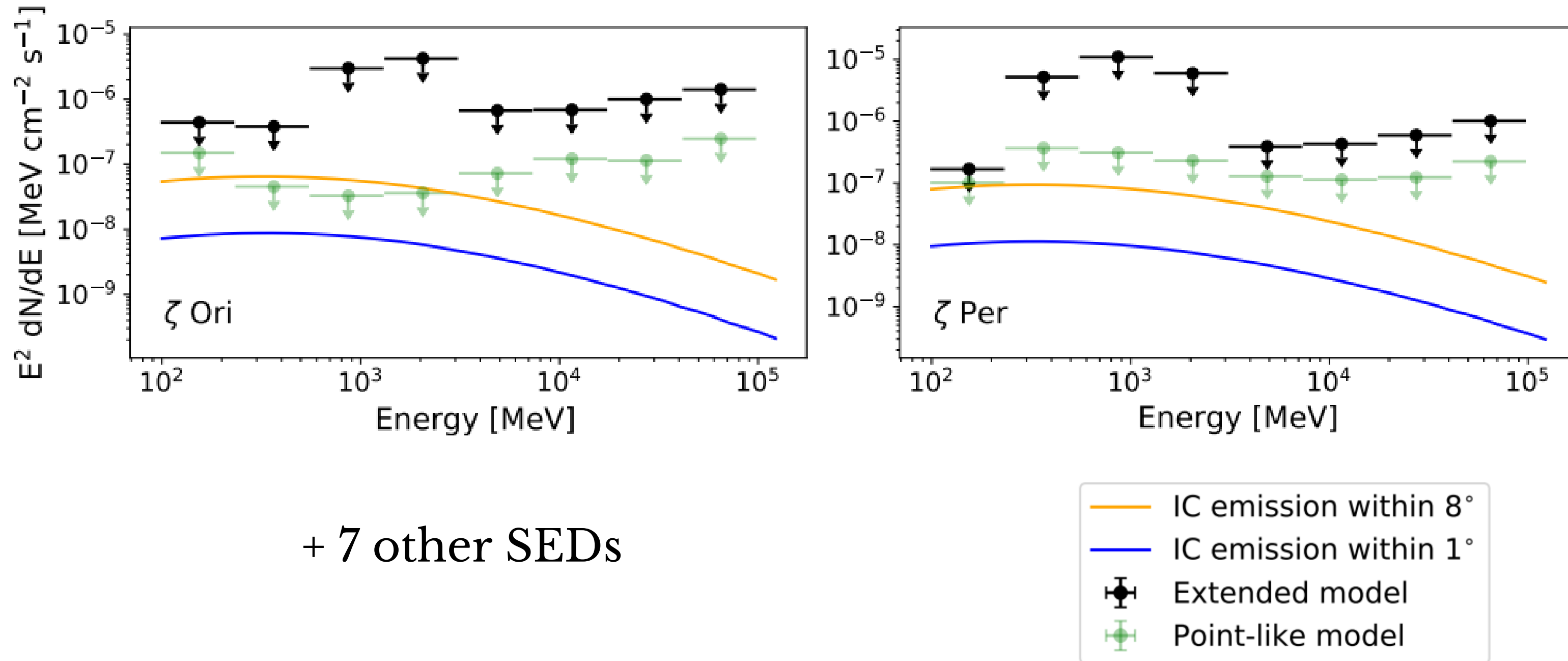
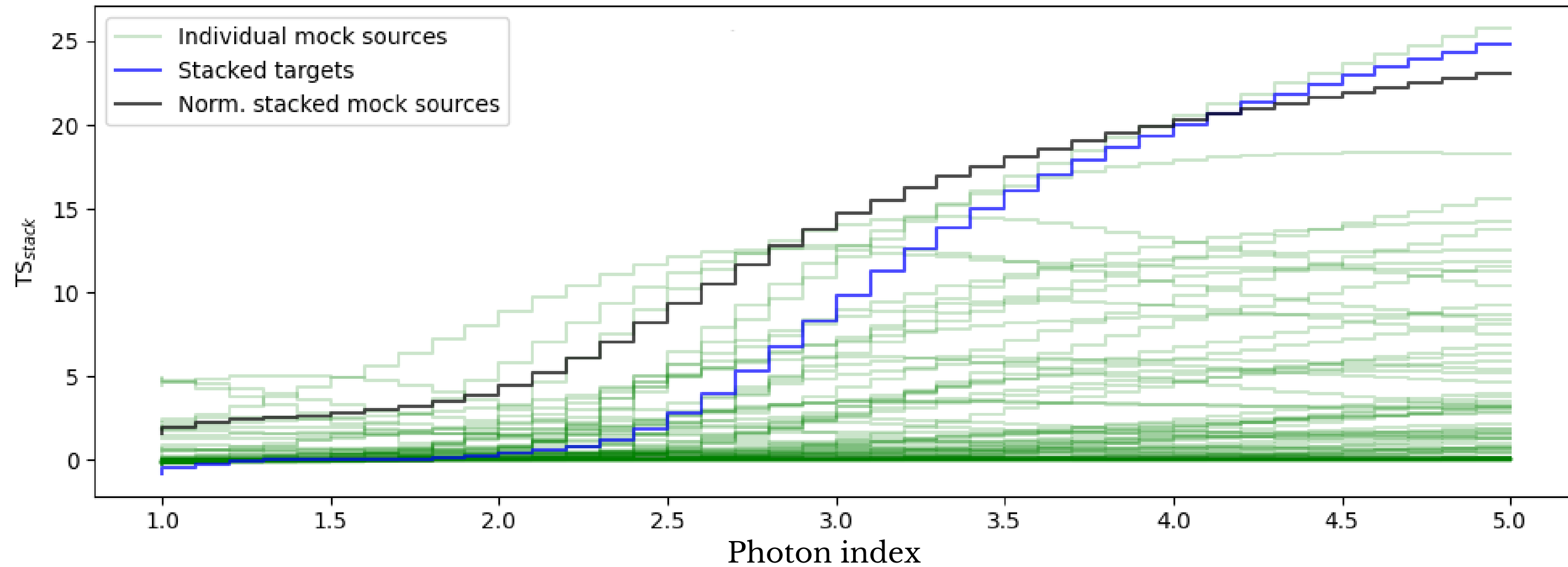


FIGURE (MODIFIED): DE MENEZES ET AL. (2021).



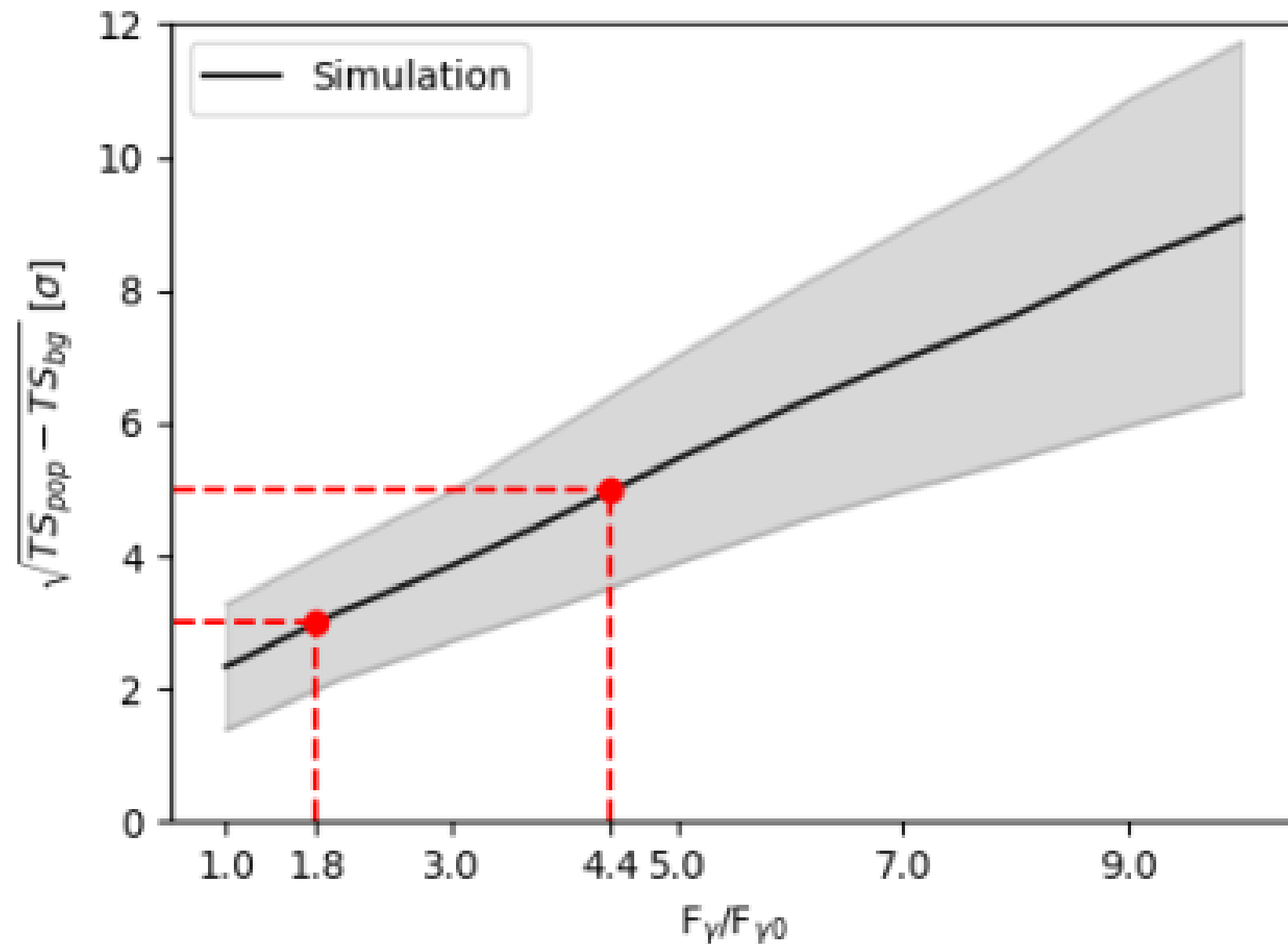
We stacked the Fermi-LAT data from all 9 stars



The population of stars as a whole is not emitting gamma-rays at a significant level

≡

We constrain the average density of CR electrons surrounding these stars



The average flux for each star has to be

$$< 3.3 \times 10^{-11} \text{ ph cm}^{-2} \text{ s}^{-1}$$

Otherwise we should detect them as a population at the  $3\sigma$  level

The density of CR electrons has to be less than  $\sim 2$  ( $\sim 4$ ) times that observed in the Solar System at the  $3\sigma$  ( $5\sigma$ ) level

FIGURE: DE MENEZES ET AL. (2021).

# Before concluding

## Links to install easyFermi:

<https://pypi.org/project/easyFermi/>

<https://github.com/ranieremenezes/easyFermi>

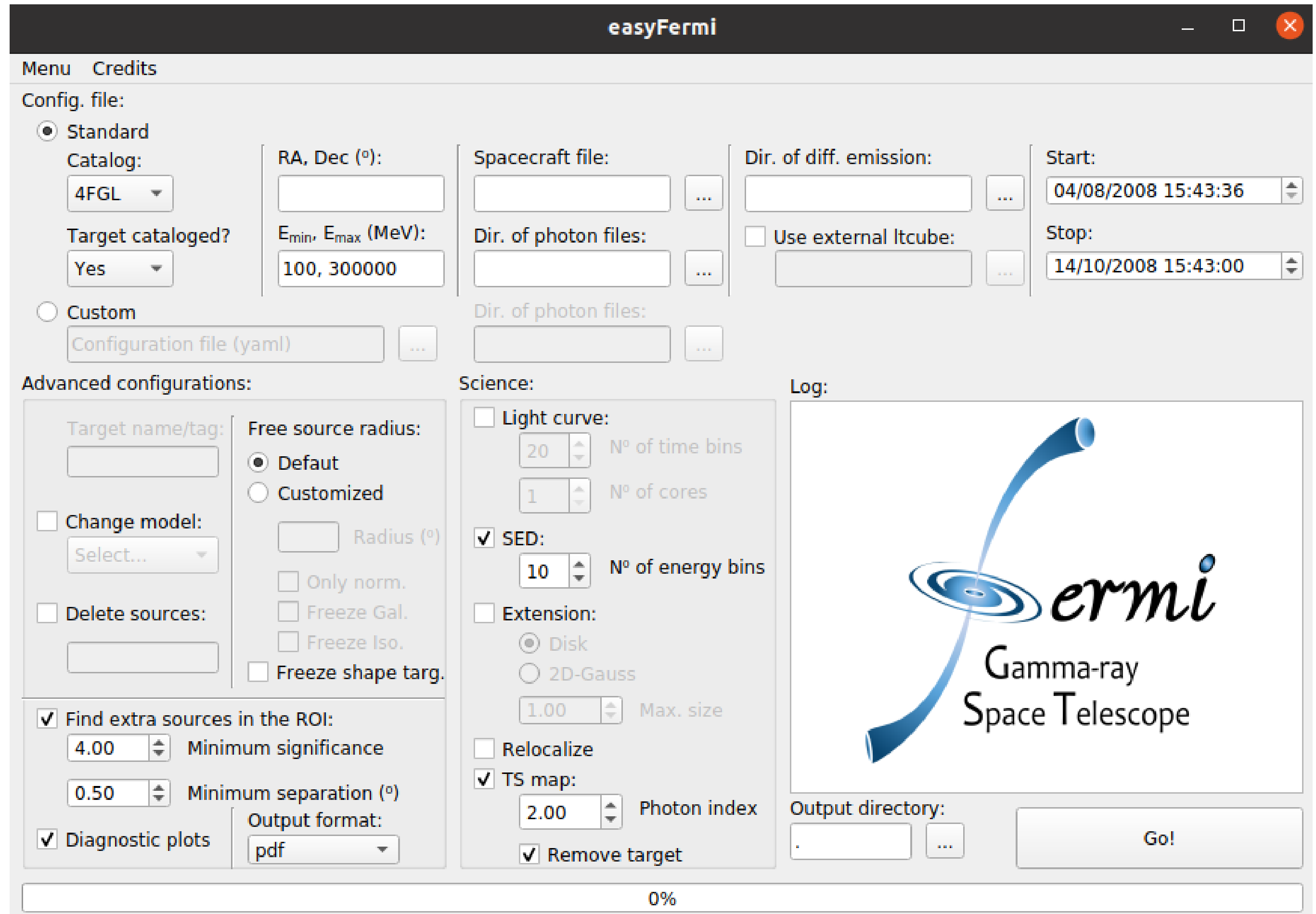
## Tutorials:

[https://www.youtube.com/channel/UCeLCfEoWasUKky6CPNN\\_opQ](https://www.youtube.com/channel/UCeLCfEoWasUKky6CPNN_opQ)

**Binned likelihood  
Fermipy on background**

## Paper:

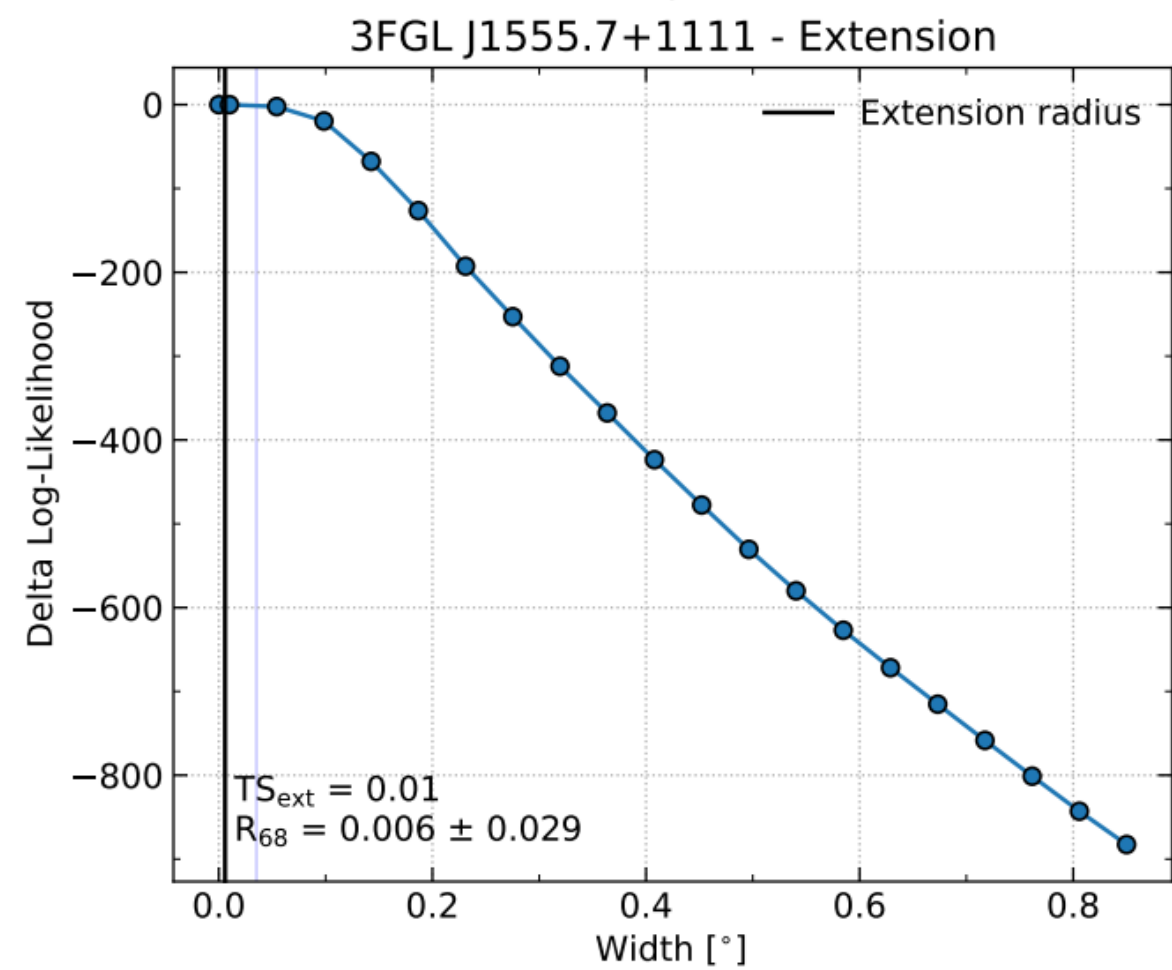
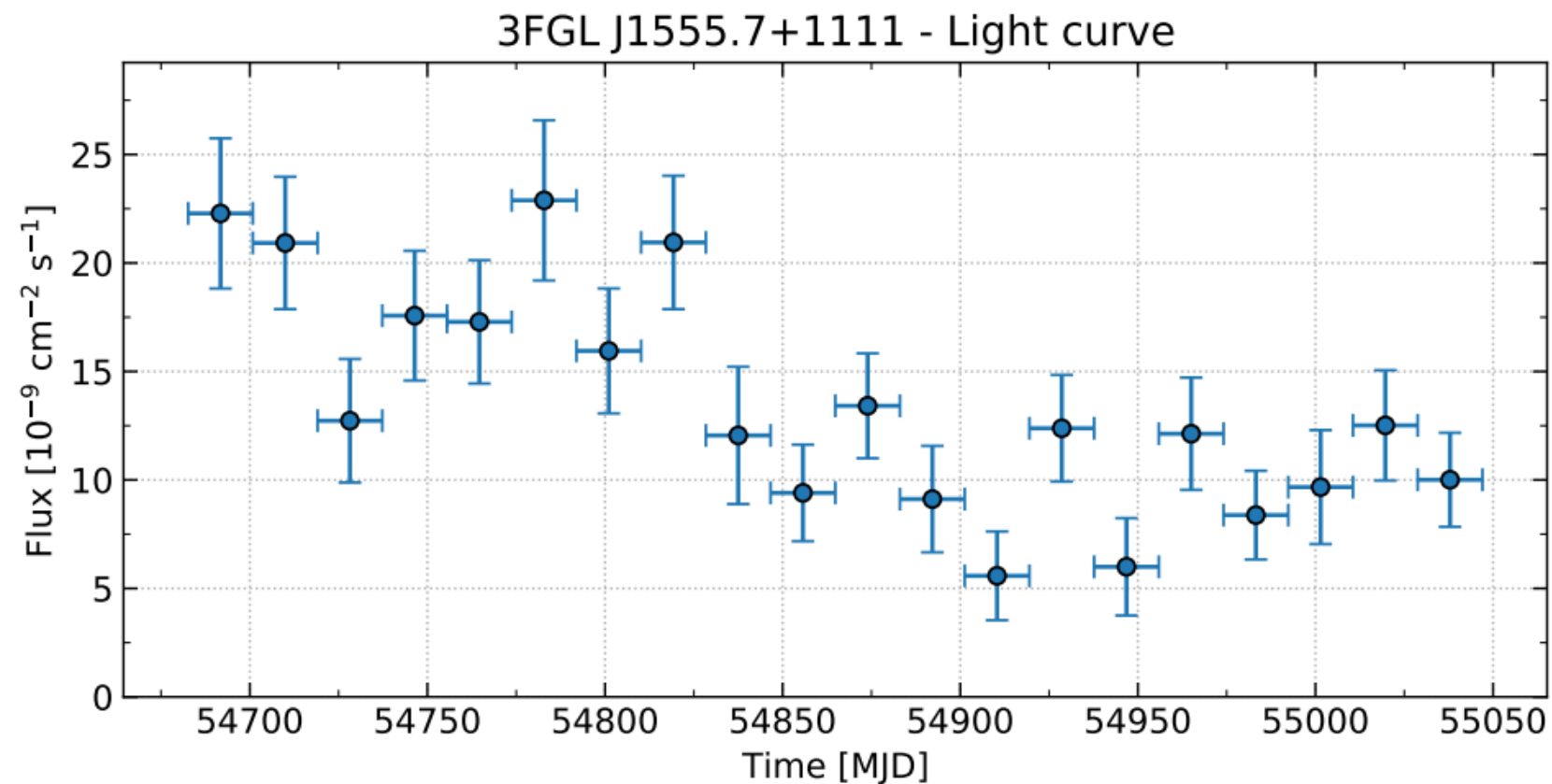
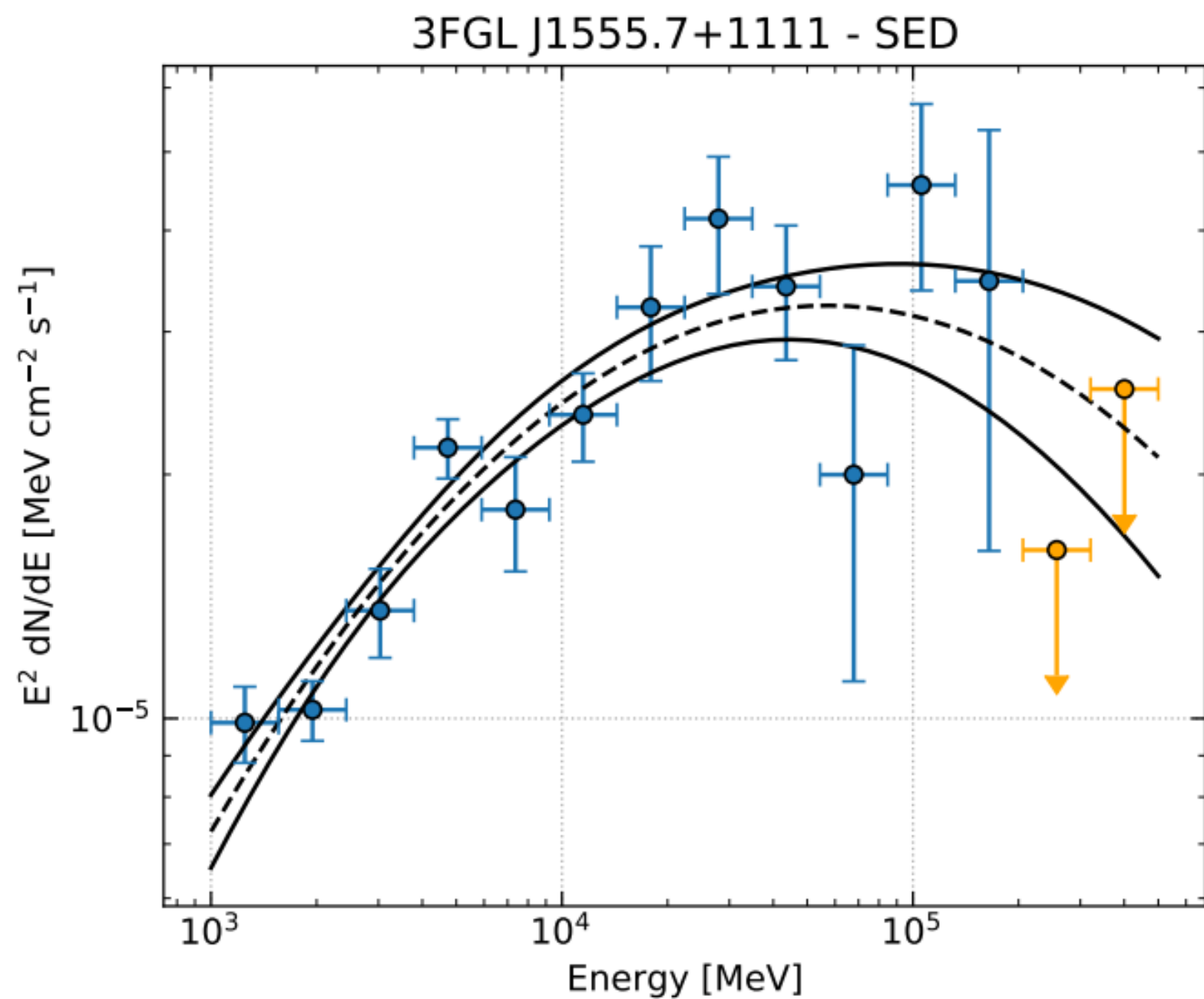
[de Menezes, R \(2022\).](#)



The screenshot shows the 'easyFermi' application window. The interface is divided into several sections:

- Config. file:** Includes radio buttons for 'Standard' (selected) and 'Custom'. Under 'Standard', there are dropdowns for 'Catalog:' (4FGL) and 'Target cataloged?' (Yes). Input fields for 'RA, Dec (°)', 'E<sub>min</sub>, E<sub>max</sub> (MeV)' (100, 300000), 'Spacecraft file:', 'Dir. of photon files:', 'Dir. of diff. emission:', and 'Start:' (04/08/2008 15:43:36) and 'Stop:' (14/10/2008 15:43:00) are present. A checkbox for 'Use external Itcube:' is also visible.
- Advanced configurations:** Includes a 'Target name/tag:' field, a 'Change model:' dropdown (Select...), and a 'Delete sources:' field. Under 'Free source radius:', there are radio buttons for 'Default' (selected) and 'Customized', and a 'Radius (°)' field. Checkboxes for 'Only norm.', 'Freeze Gal.', 'Freeze Iso.', and 'Freeze shape targ.' are also present.
- Science:** Includes a 'Light curve:' section with 'N° of time bins' (20) and 'N° of cores' (1). The 'SED:' section is checked, with 'N° of energy bins' (10). The 'Extension:' section has 'Disk' selected. 'Relocalize' is unchecked, and 'TS map:' is checked with 'Photon index' (2.00). 'Remove target' is also checked.
- Log:** A large text area containing the Fermi logo and the text 'ermi Gamma-ray Space Telescope'.
- Output directory:** A field with a file browser icon and a 'Go!' button.
- Progress bar:** Located at the bottom, showing 0% completion.

# ≡ Main results





## Summary

- Stars can be used as CR e- detectors throughout the Galaxy.
- Fermi-LAT has insufficient sensitivity to detect the gamma-ray emission from nearby superluminous stars.
- The stacked analysis allowed us to constrain the gamma-ray emission from the population to be  $< 3.3\text{E-}11 \text{ ph cm}^{-2} \text{ s}^{-1}$  (500 MeV to 100 GeV).
- We constrain the density of CR electrons to be less than 2 that observed in the Solar System at the  $3\sigma$  level.
- **easyFermi** is powerful. Give it a try!

Monthly Notices  
of the  
ROYAL ASTRONOMICAL SOCIETY

MNRAS **507**, 680–686 (2021)  
Advance Access publication 2021 July 26

<https://doi.org/10.1093/mnras/stab2150>



## A study of superluminous stars with the *Fermi*-Large Area Telescope

Raniere de Menezes,<sup>1★</sup> Elena Orlando,<sup>2,3</sup> Mattia Di Mauro<sup>4</sup> and Andrew Strong<sup>5</sup>

<sup>1</sup>*Departamento de Astronomia, Universidade de São Paulo, Rua do Matão, 1226, São Paulo SP 05508-090, Brazil*

<sup>2</sup>*INFN Sezione di Trieste, Università degli Studi di Trieste, Via Valerio 2, I-34127 Trieste, Italy*

<sup>3</sup>*Kavli Institute for Particle Astrophysics and Cosmology and Hansen Experimental Physics Laboratory, Stanford University, 94305-4085 California, CA, USA*

<sup>4</sup>*INFN Torino, Physics Department, Via Pietro Giuria 1, I-10125 Torino, Italy*

<sup>5</sup>*Max-Planck-Institut für extraterrestrische Physik, Germany*