SLAC-WP-126

Modeling High-Energy Gamma-Rays from the Fermi Bubbles

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Office of Science, Science Undergraduate Laboratory Internship (SULI) Program

This work was supported in part by the U.S. Department of Energy, Office of Science, Office of Workforce Development for Teachers and Scientists (WDTS) under the Science Undergraduate Laboratory Internship (SULI) program, under Contract No. DE-AC02-76SF00515.

U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

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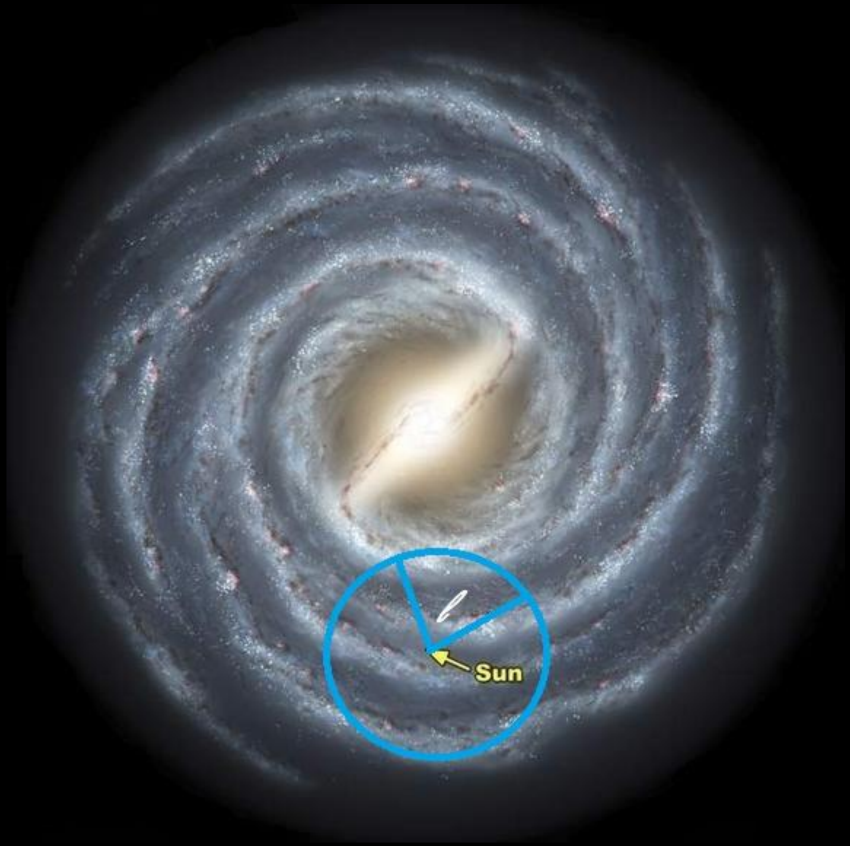
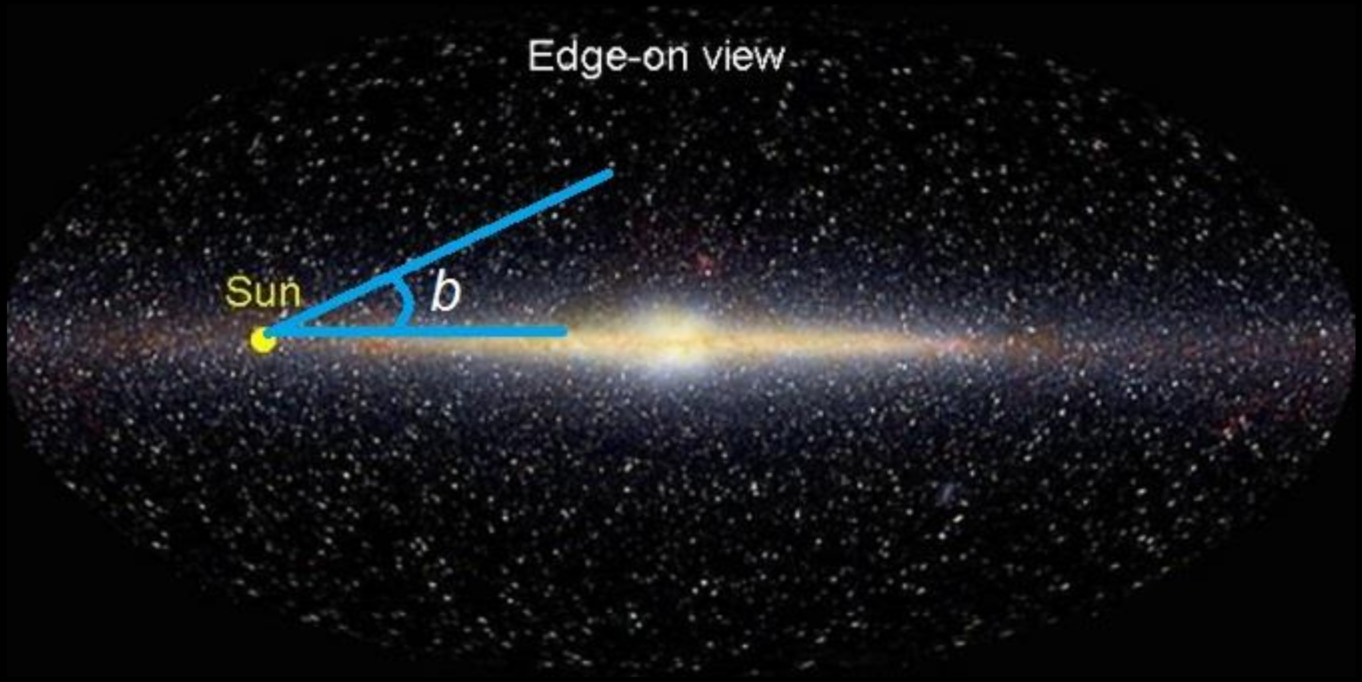
Abstract

In 2010, the Fermi Bubbles were discovered at the galactic center of the Milky Way. These giant gamma-ray structures, extending 50 degrees in galactic latitude and 20-30 degrees in galactic longitude, were not predicted. We wish to develop a model for the gamma-ray emission of the Fermi Bubbles. To do so, we assume that second order Fermi acceleration is responsible for the high-energy emission of the bubbles. Second order Fermi acceleration requires charged particles and irregular magnetic fields—both of which are present in the disk of the Milky Way galaxy. I use the assumption of second order Fermi acceleration in the transport equation, which describes the diffusion of particles. By solving the steady-state case of the transport equation, I compute the proton spectrum due to Fermi second order acceleration and compare this analytical solution to a numerical solution provided by Dr. P. Mertsch. Analytical solutions to the transport equation are taken from Becker, Le, & Dermer and are used to further test the numerical solution. I find that the numerical solution converges to the analytical solution in all cases. Thus, we know the numerical solution accurately calculates the proton spectrum. The gamma-ray spectrum follows the proton spectrum, and will be computed in the future.

The Milky Way Galaxy

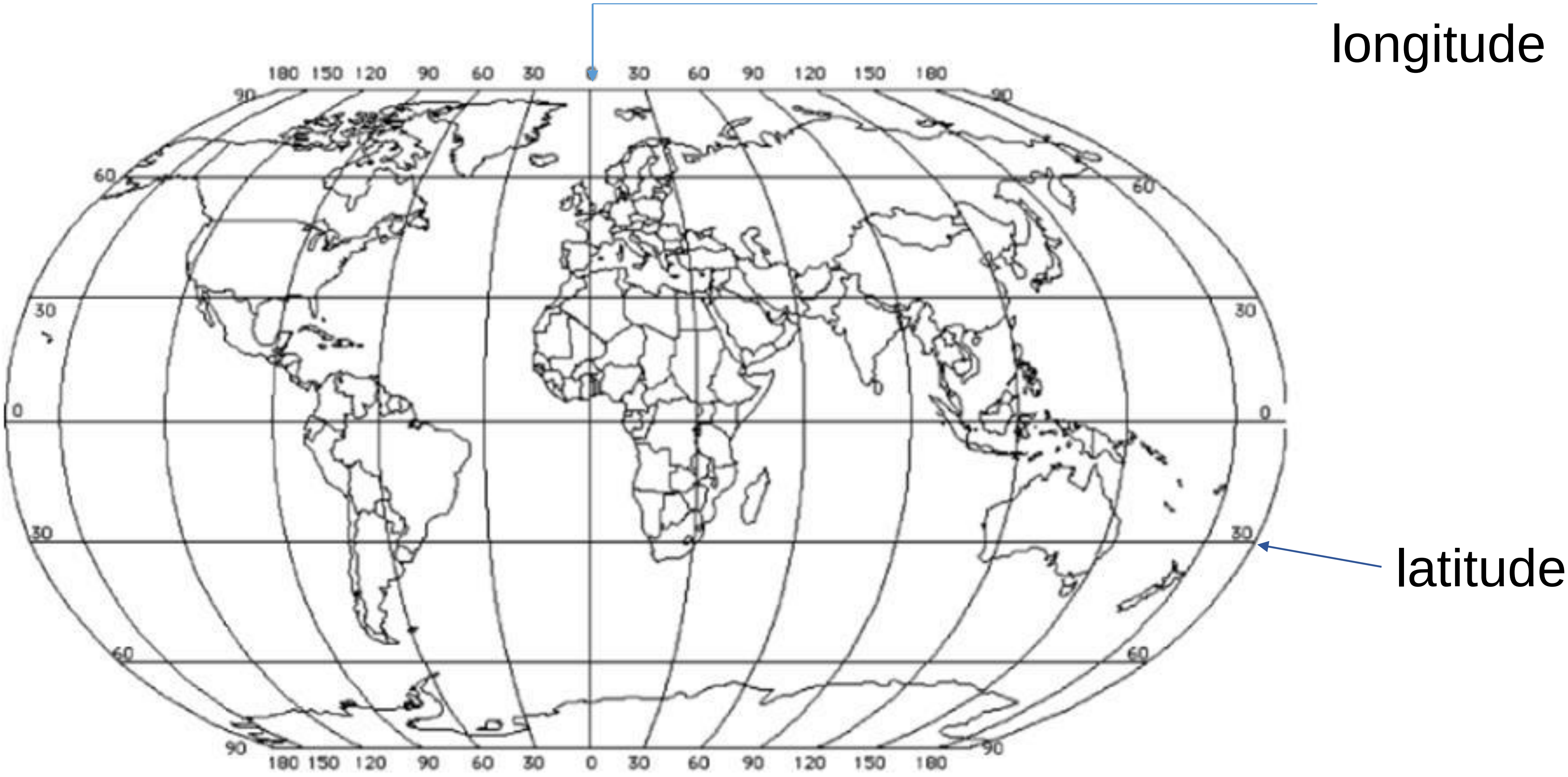
Face-on view:
the galactic plane



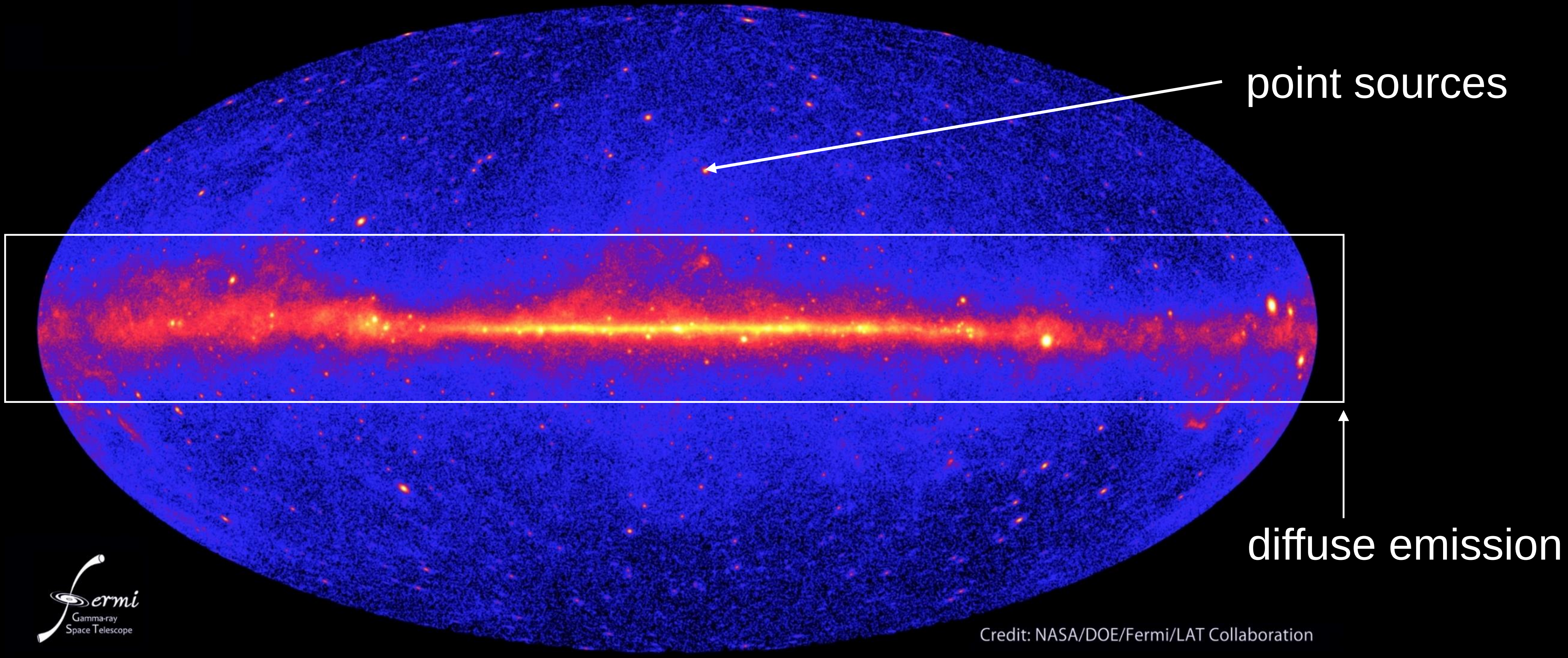


longitude

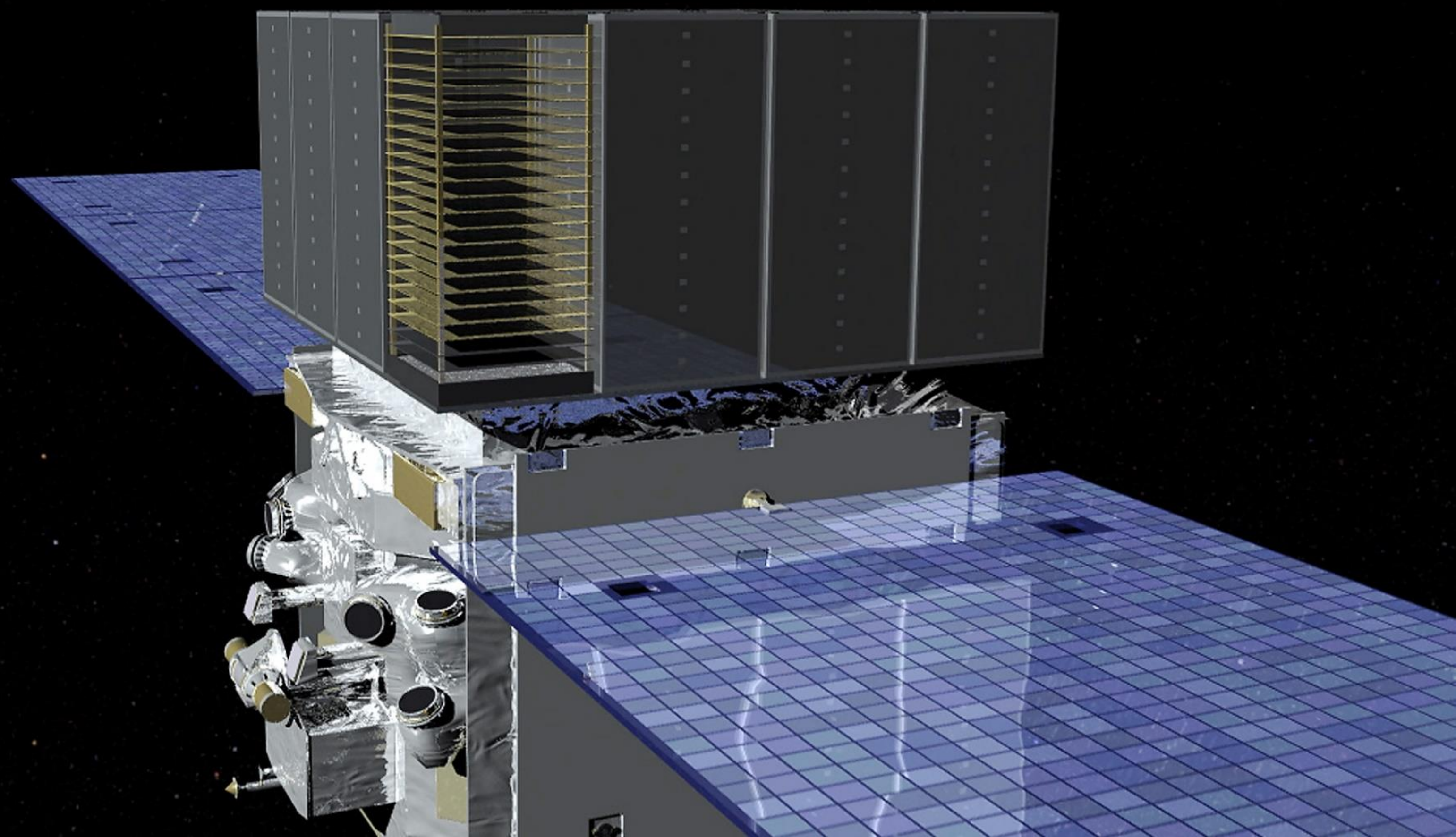
latitude


longitude
latitude
180 150 120 90 60 30 0 30 60 90 120 150 180
90
60
30
0
30
60
90

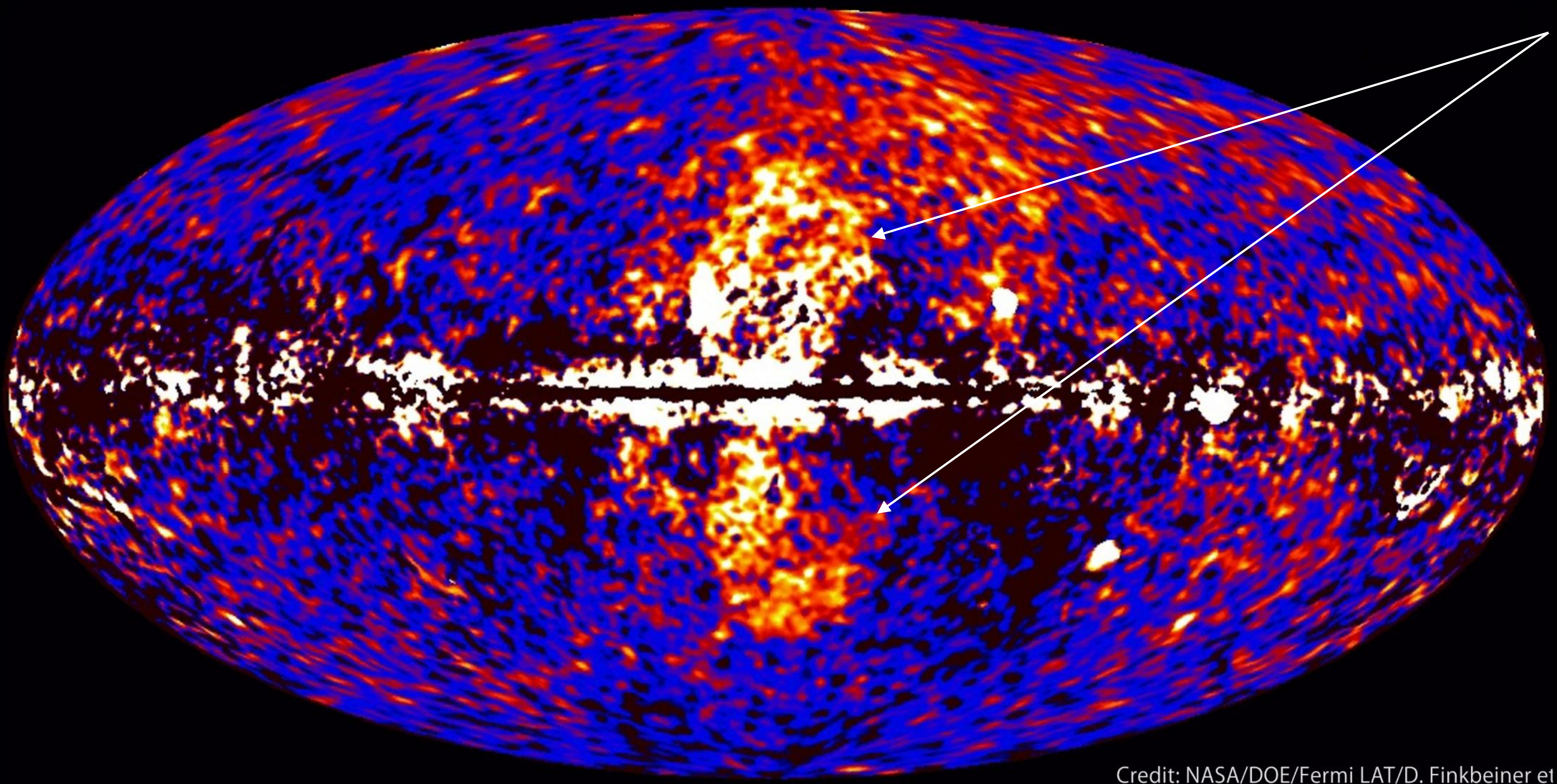
Five years ago, this was our view of the Milky Way:



The Fermi Large Area Telescope (LAT)



Now, we know the Milky Way looks like:



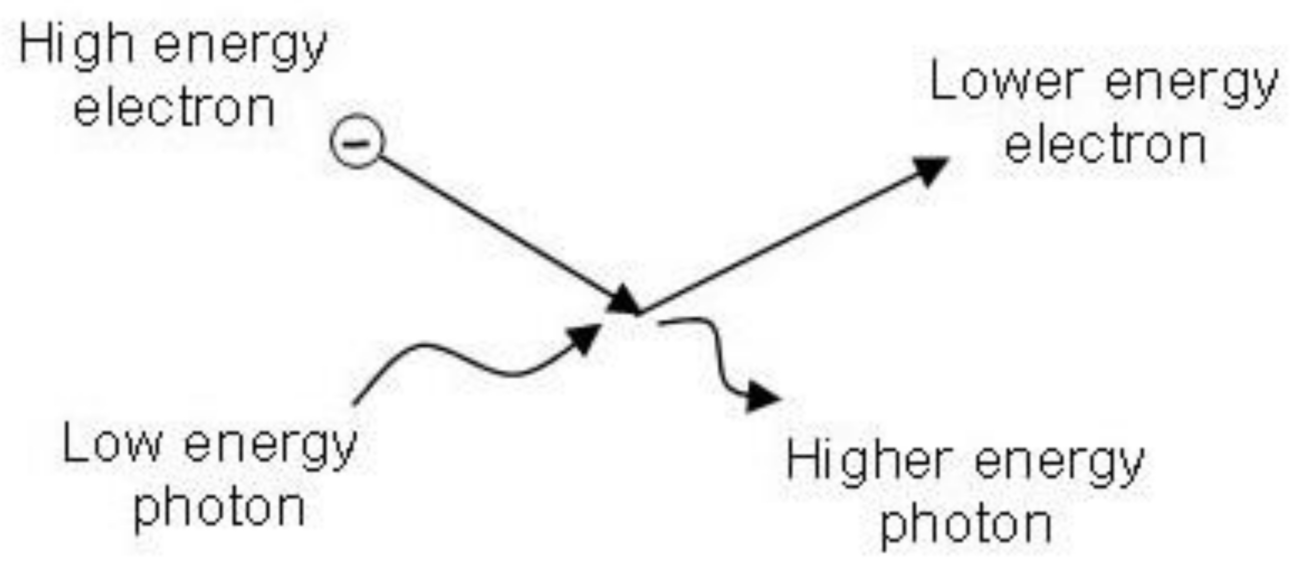
Credit: NASA/DOE/Fermi LAT/D. Finkbeiner et al.

The Production of ɣ-rays

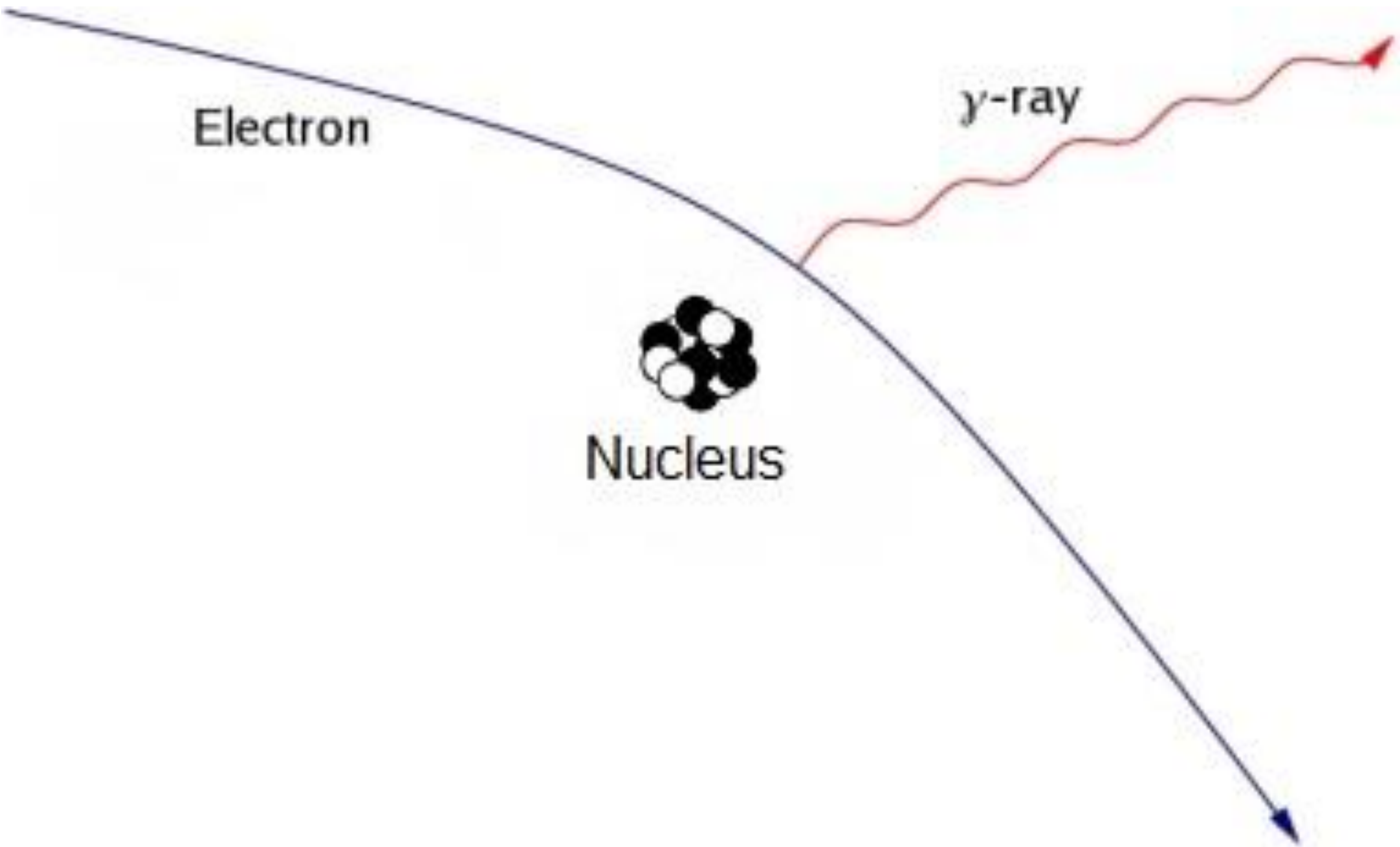
- Dominant processes for gamma-ray (ɣ-ray) production in the Galactic ridge:
  - Inverse Compton scattering
  - Bremsstrahlung
  - Neutral pion decay
- Thermal particles at a temperature of 10^6K have energies of a couple eV. Gamma rays are in the GeV to TeV range. So, we need an acceleration mechanism.

Inverse Compton Scattering

- The electrons lose energy
- The photons gain energy—possibly up to the gamma-ray regime



Bremsstrahlung



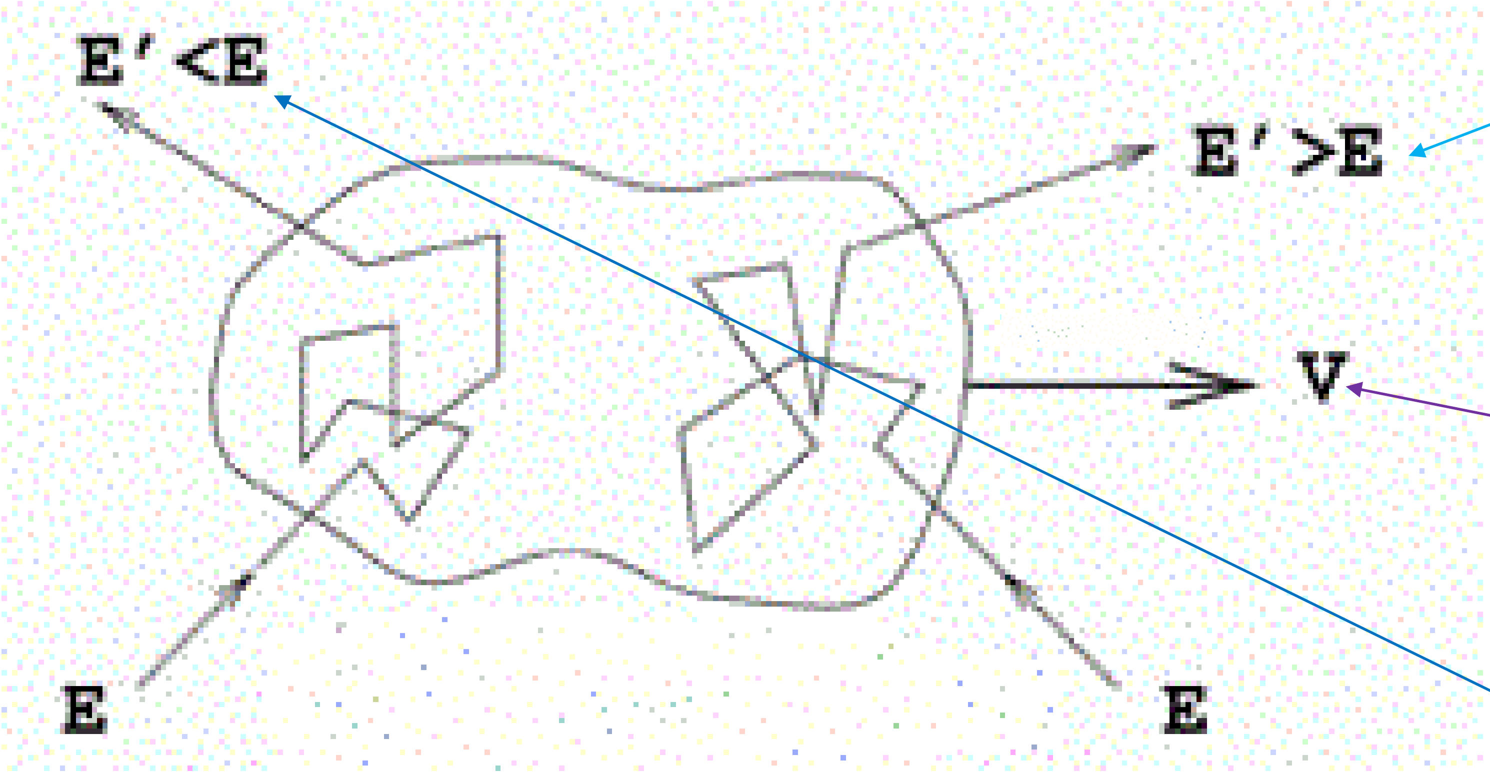
Neutral Pion Decay

- Cosmic rays (CR) are of non-solar origin.
- p_{CR} : cosmic ray proton
- N_{gas} : gas nucleus
- π^0 : neutral pion

$$p_{CR} + N_{gas} \rightarrow \pi^0 + X$$

$$\pi^0 \rightarrow \gamma + \gamma$$

The Model: Second Order Fermi Acceleration



head-on collision; particle gains energy

Cloud velocity classifies the collision

Following collision; particle loses energy

The Heat Equation:

$$\frac{\partial \phi(x,t)}{\partial t} = \alpha \frac{\partial^2 \phi(x,t)}{\partial x^2}$$

independent of x and t

Finite-Difference Approximation to the Heat Equation:

$$\frac{\phi_i^{m+1} - \phi_i^m}{\Delta t} = \alpha \frac{\phi_{i-1}^m - 2\phi_{i+1}^m}{\Delta x^2} + \mathcal{O}(\Delta t) + \mathcal{O}(\Delta x^2)$$

- This obtains numerical solutions.

[Recktenwald]

The Transport Equation Compared to the Heat Equation

$$\frac{\partial \phi(x,t)}{\partial t} = \alpha \frac{\partial^2 \phi(x,t)}{\partial x^2}$$

$$\frac{\partial f(p,t)}{\partial t} = \frac{1}{p^2} \frac{\partial}{\partial p} \left(p^2 D_{pp}(p) \frac{\partial f(p,t)}{\partial p} \right) - \frac{f(p,t)}{\tau_{esc}} + \frac{\delta(p - p_0)}{4\pi p^2}$$

The Transport Equation for Second Order Fermi Acceleration

$$\frac{\partial f(p,t)}{\partial t} = \frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2 D_{pp}(p)\frac{\partial f(p,t)}{\partial p}\right) - \frac{f(p,t)}{\tau_{esc}} + \frac{\delta(p-p_0)}{4\pi p^2}$$

The Transport Equation for Second Order Fermi Acceleration

Assumptions:

$$\frac{\partial f(p,t)}{\partial t} = 0$$

$$\tau_{esc} = \tau_{esc,0}\, p^{q-2}$$

q=2

$$D_{pp}(p) = D_0 p^q = \frac{p^q}{\tau_{acc,0}}$$

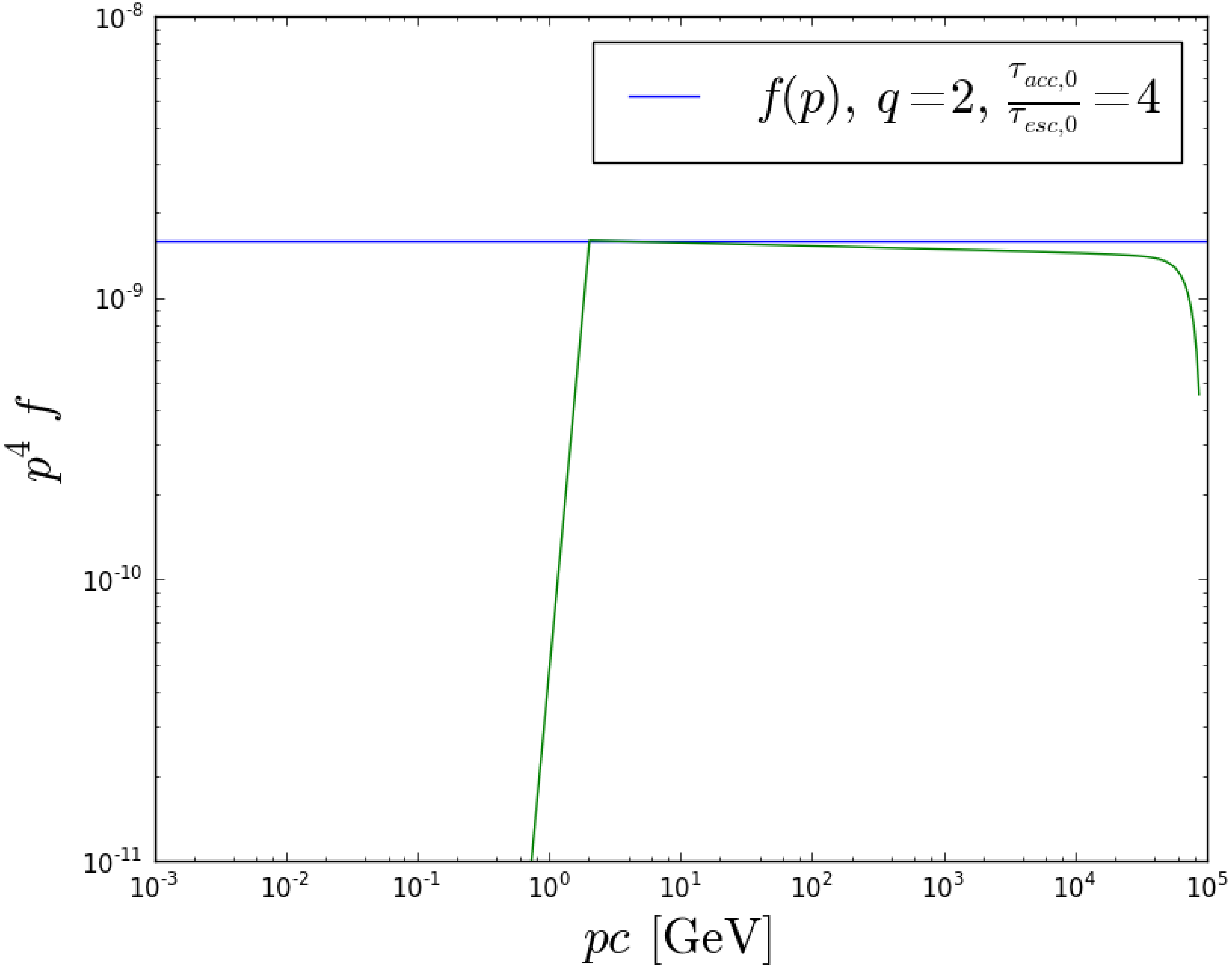
Solve for the steady-state solution with a momentum-independent escape time.

The analytic solution:

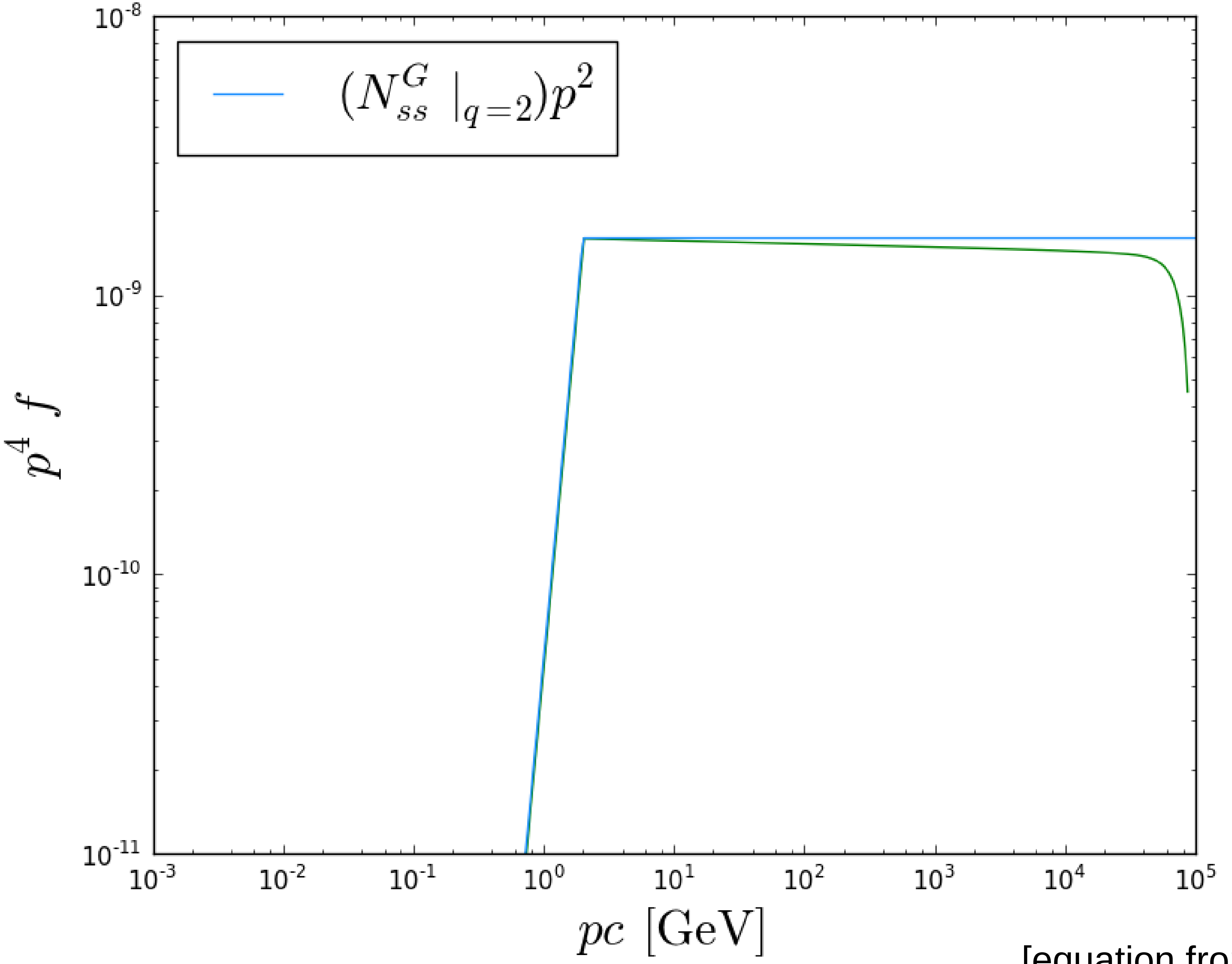
$$f(p) \propto p^{-\frac{3}{2}-\sqrt{\frac{9}{4}+\frac{\tau_{acc,0}}{\tau_{esc,0}}}}$$

Dependent on the ratio of particle acceleration time and escape time.

Proton Spectrum

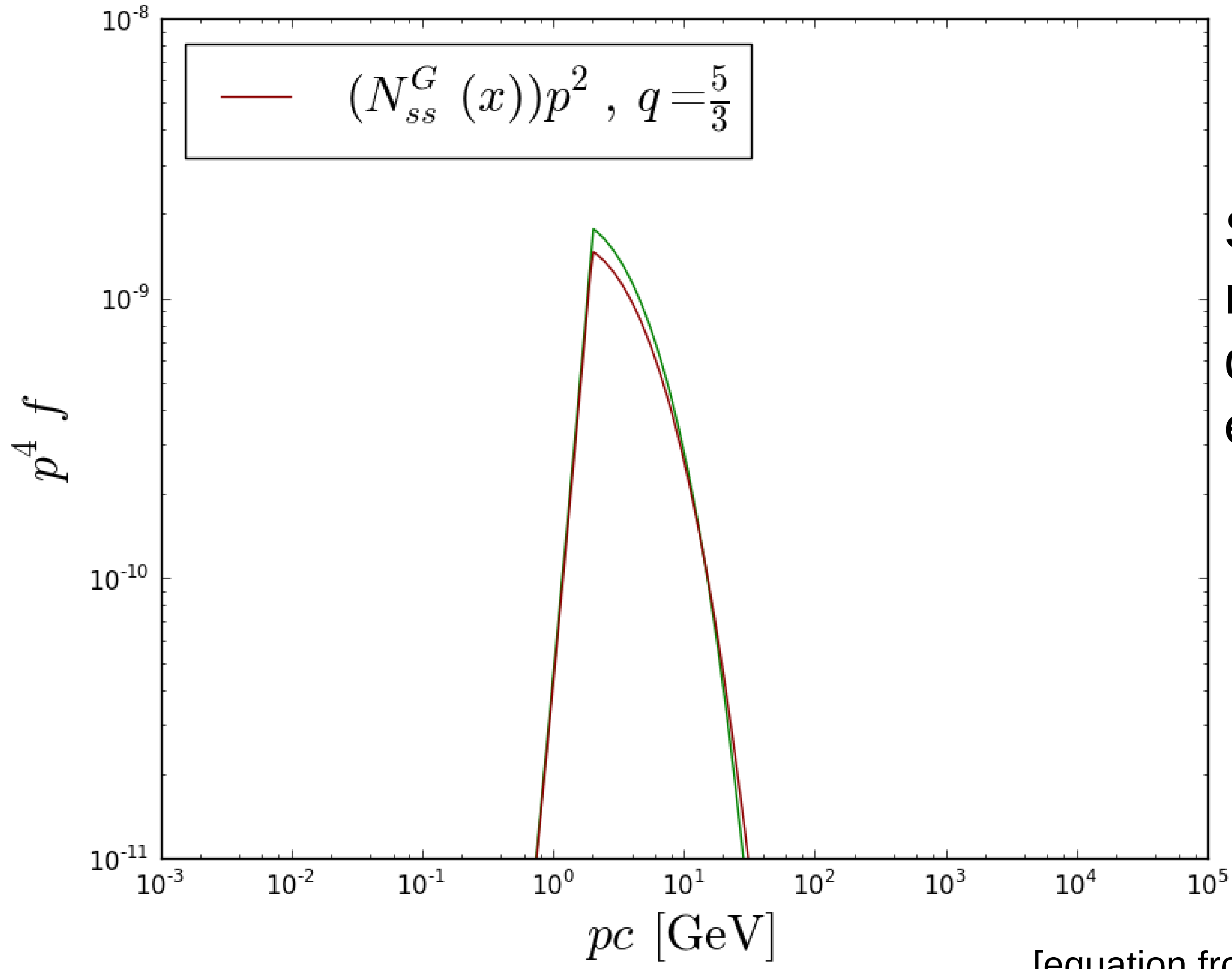


Proton Spectrum



[equation from Becker, Le, & Dermer]

Proton Spectrum



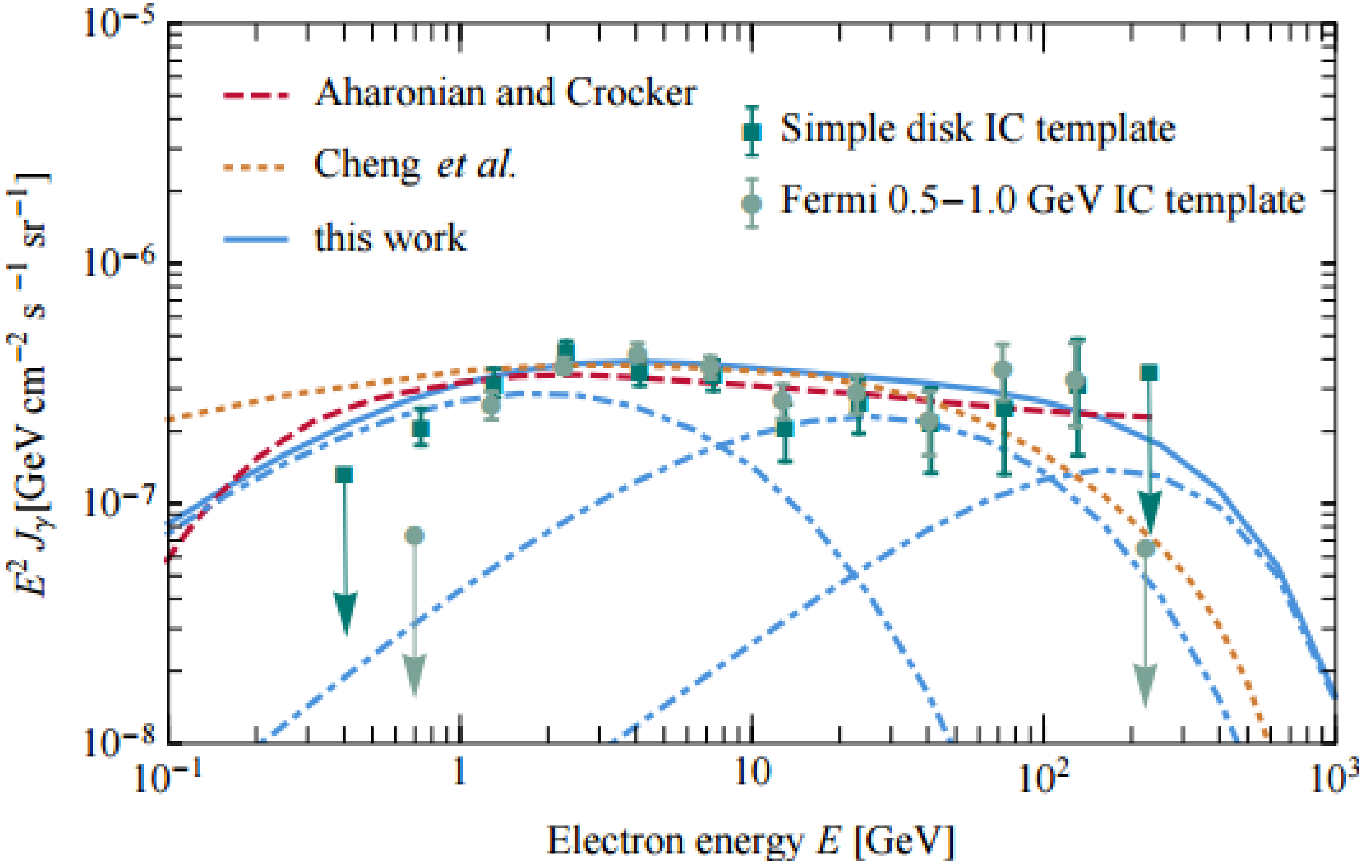
Solution for a momentum-dependent escape time (q≠2)

[equation from Becker, Le, & Dermer]

Future Work

- Model the gamma-ray spectrum due to proton-proton interaction.

Example of an electron energy spectrum for the Fermi Bubbles:



[plot from Mertsch & Sarkar]

Acknowledgements

- Dr. Philipp Mertsch
- SULI Program, Enrique Cuellar, and the DOE
- SULI interns and colleagues

References:

-Becker, Le, & Dermer, 2006, Time-Dependent Stochastic Particle Acceleration in Astrophysical Plasmas: Exact Solutions Including Momentum-Dependent Escape

-Recktenwald, 2011, Finite-Difference Approximations to the Heat Equation

-Kamae et al., 2006, Parametrization of $\gamma, e^{\pm}$, and Neutrino Spectra Produced by $p - p$ Interaction in Astronomical Environments

-corresponding code at https://github.com/niklask/cparamlib