The Positron Puzzle - Solving the Mystery of the 511 keV Line in our Galaxy

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A brief intro

Part of my work at Mount Stromlo Observatory, Australia

Figure: Mount Stromlo Observatory

The galactic center

The central region of the Milky Way is an eminent source of high-energy particles - gamma rays, nuclei, electrons, positrons, neutrinos etc. It is visible with the naked eye as a bright band with dark clouds, an over-density of stars and Messier objects (diffuse bright patches).

Figure: The Milky Way band as seen in visible light

The galactic center (contd.)

Not only visible light, but every messenger gives a strong signal at the galactic band and center.

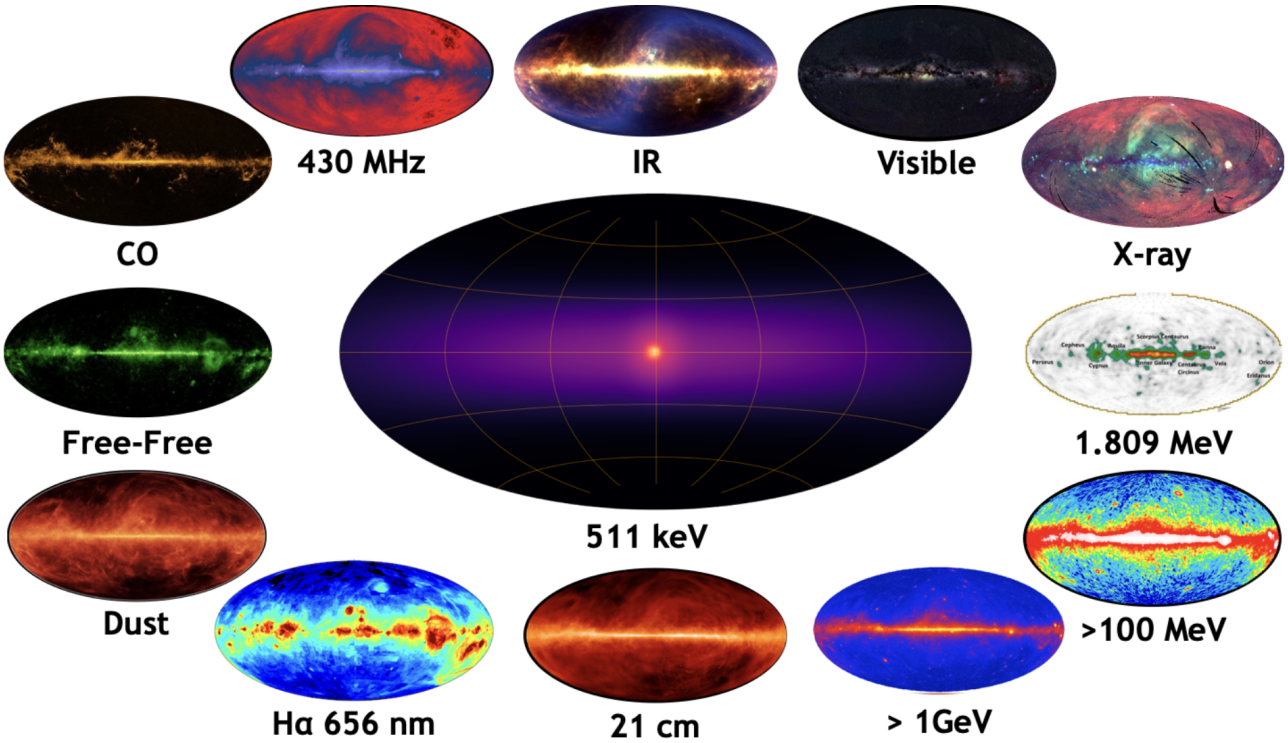

Figure: The galactic band in different photon wavelengths. Credits: [2]

The galactic center (contd.)

You may be aware that now we have seen the galactic center using neutrinos!

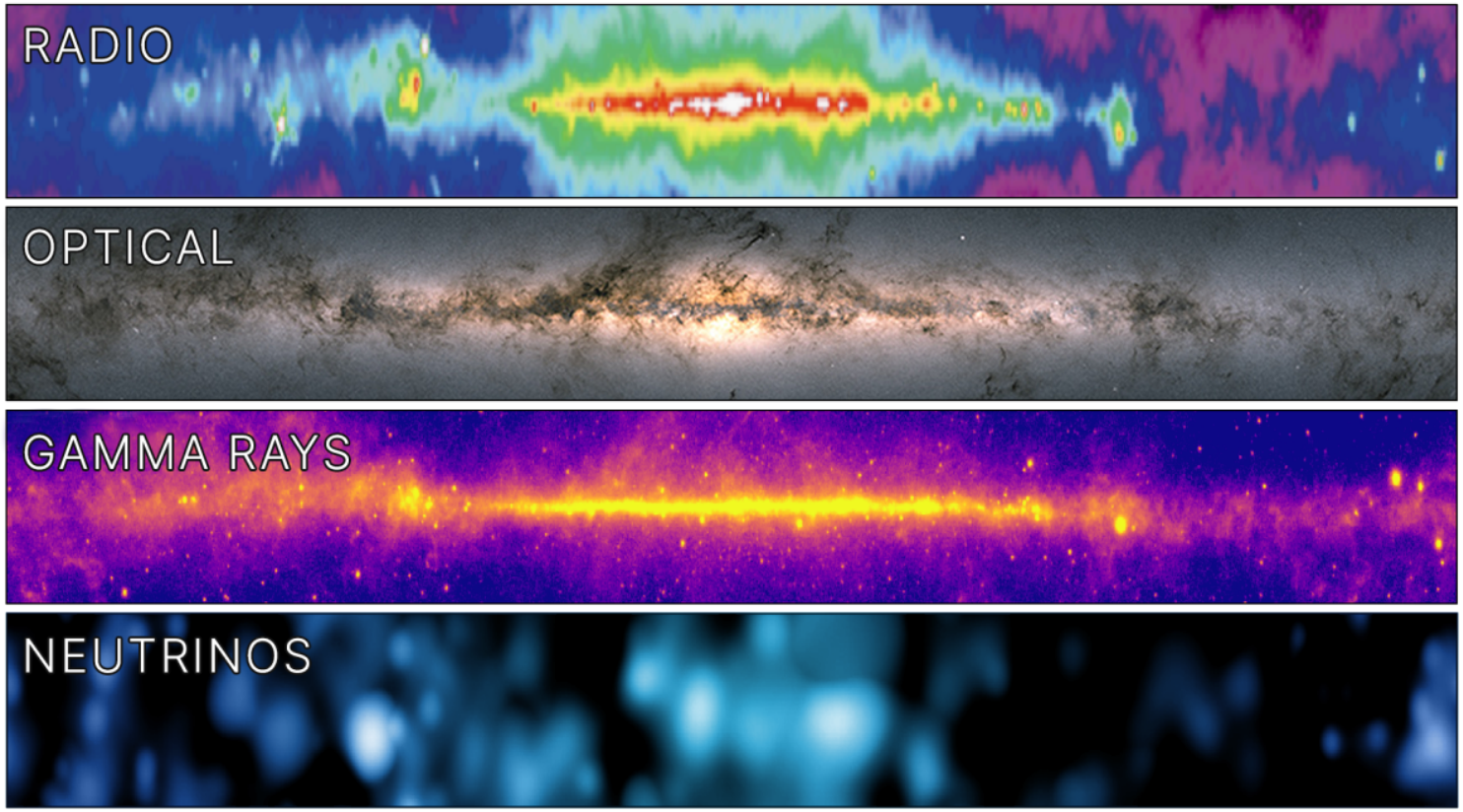

Figure: The galactic band in electromagnetic waves and neutrinos. Credits: Icecube Collaboration

Gamma-ray picture of our Galaxy

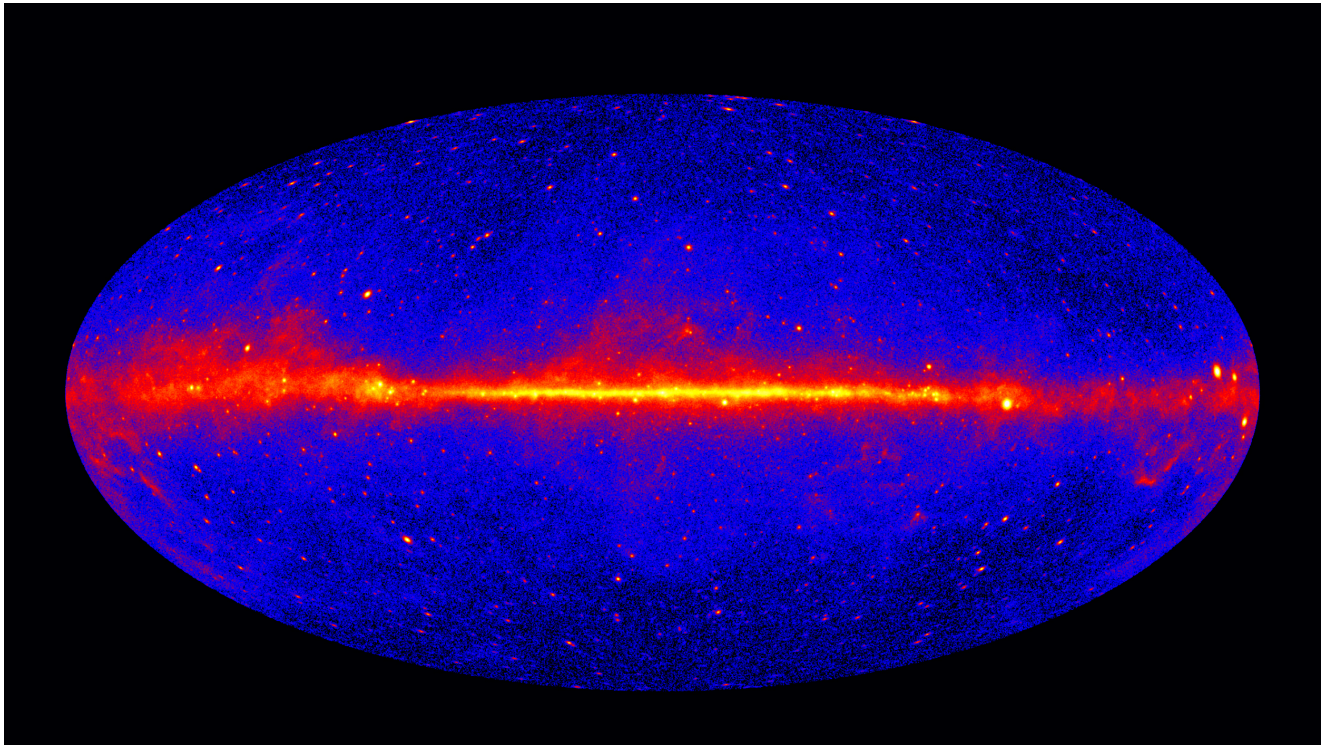

Figure: High-energy (>1 GeV) gamma-ray map of the Milky Way. Data from *Fermi-LAT*.

Gamma-ray picture of our Galaxy

- We saw that the galactic disk features in the high-energy gamma-ray band, just like most other wavelengths.
- Now we adopt an alternative approach where group photons according to their exact energies and ignore their directions.
- Then we see a 'line' at 511 keV along with a continuum around it. This means there is significant emission of that particular energy.

Gamma-ray spectrum of our Galaxy

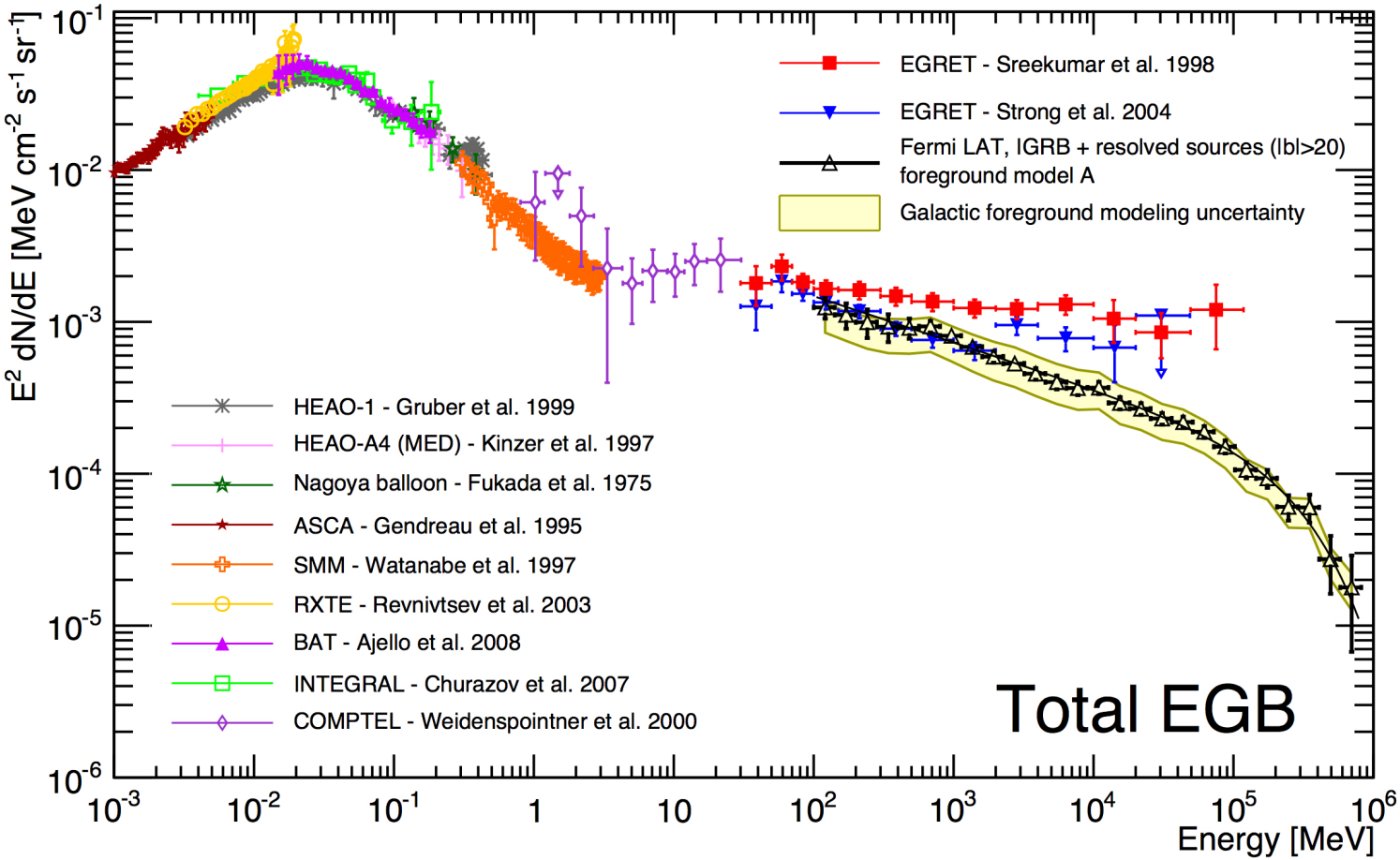

Figure: Gamma-ray spectrum of the Milky Way as obtained from different missions. *Credits:* [1]

511 keV line

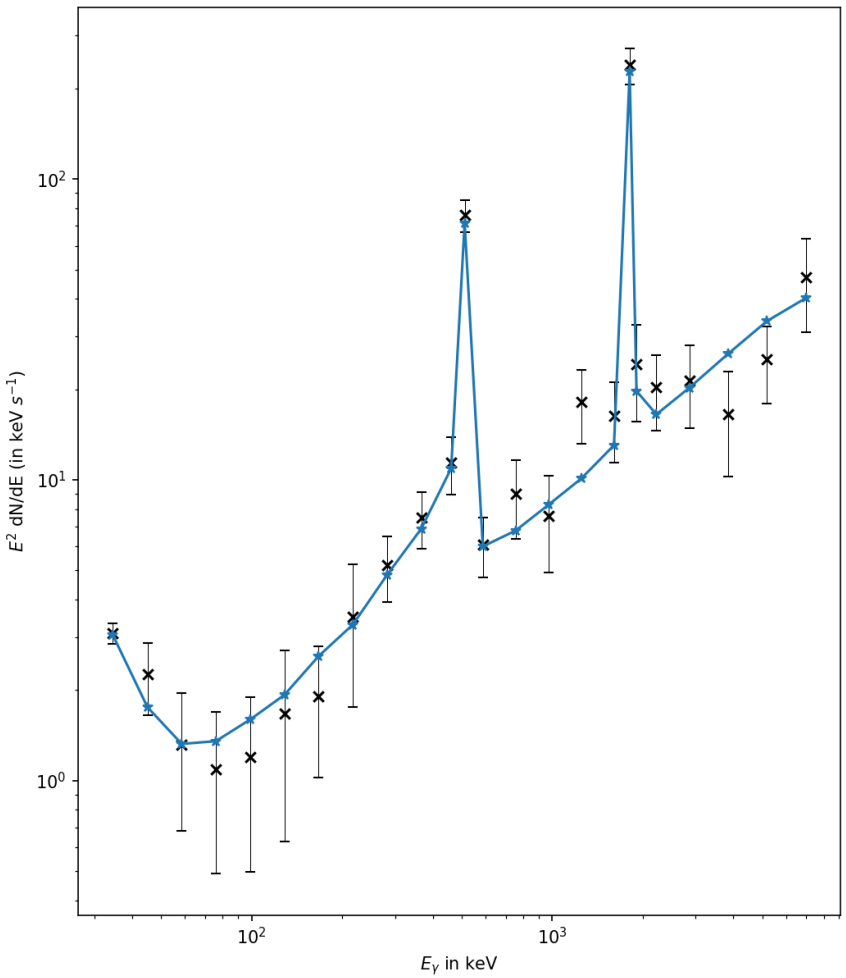

Figure: The 511 keV line from SPI data

Map of the 511 keV line

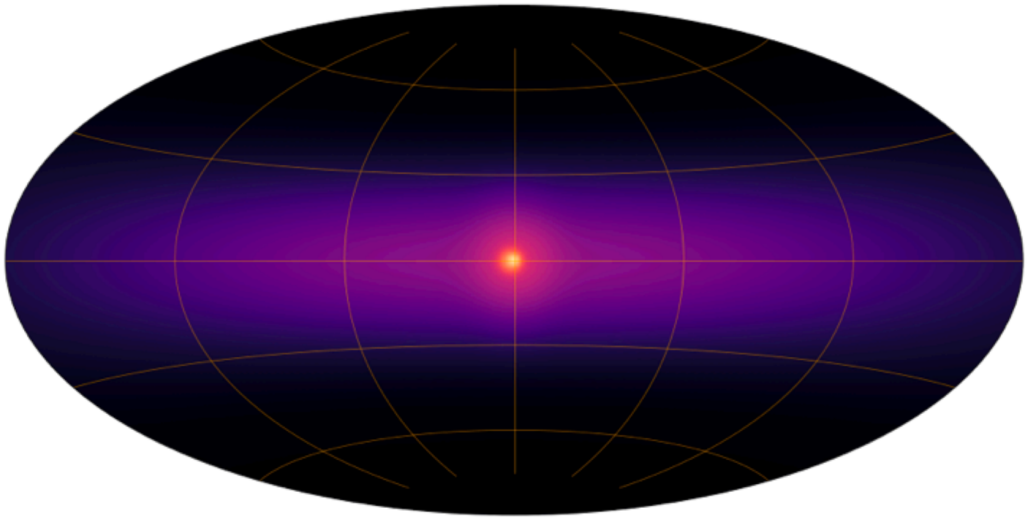

Figure: Best-fit model of the galactic diffuse gamma-ray emission at 511 keV. Credits: [2]

Positrons in Cosmic rays

- Positrons form a minute fraction of the cosmic rays observed at the Earth's surface.
- Most of these positrons are produced in the atmosphere itself, due to the interaction of primary cosmic rays with atoms and molecules in the atmosphere resulting in secondary cosmic ray showers.
- A small fraction of positrons are estimated to be coming from outer space - astrophysical positrons.

Positrons in the Galaxy

- Wrong to assume that astrophysical positrons give a full picture of the actual positron population in the Galaxy - shielding by the solar magnetic field.
- We only get the most energetic positrons from outside - those not affected by the magnetic field.
- But we know of processes that generate positrons in the Galaxy.

Sources of positrons

- Acceleration and collision of particles (for example through pion decay): Black hole accretion disks, pulsars
- Decay of nuclei (such as ^{26}Al, ^{56}Ni) through β^+-decay: Supernovae, cosmic ray nuclei
- $\gamma - \gamma$ pair production: Compact objects
- Evaporation of black holes: PBHs
- Annihilation of dark matter (WIMP)

The Puzzle

The 511 keV line has been known to astronomers for 50 years. But it still poses challenge to explanations on two grounds:

- **Morphology:** Why does the emission not occur in the disk, like at other wavelengths? In fact, the disk has ongoing star formation and supernova activity, so it is expected to produce more positrons than other regions.
- **Magnitude:** The luminosity of the 511 keV line suggests that nearly 5×10^{43} positrons must be produced in the entire Galaxy per second. But the known physical processes cannot produce this flux of positrons.

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Origin of the 511 keV line

- It is clear that the 511 keV line is generated due to the annihilation of positrons in cosmic rays with electrons in the interstellar medium (ISM).
- But that does not explain:
  - Where are these positrons produced? (to give this diffuse pattern)
  - How are they produced? ($\approx 10^{43}\ s^{-1}$ in our Galaxy)

The problem in hand

We tried to find out how these positrons were injected into the Galaxy. A part of the answer is known: Positrons are injected through inverse beta decay of radioactive species produced in stars and supernovae. We want to find if there are other, interesting sources. We are focused on two main questions:

- What is the distribution of the injected positrons among various energies?
- How much of the 511 keV line can be explained with inverse beta decay, and do we need to incorporate other high-energy sources?

Methods

- Simulated the propagation of positrons and electrons in the Galaxy (as cosmic rays).
- Obtained the γ-ray emission in the entire Galaxy from the simulation, as specific luminosity $\left(\frac{\mathrm{d}L}{\mathrm{d}E_\gamma}\right)$ vs energy (E_γ).
- Combine the various components of the luminosity from simulations to obtain the expected spectrum, according to our models of positrons and electron injection.
- Compare the expected spectrum to the observed spectrum from the INTEGRAL satellite and obtained meaningful constraints on the relevant properties of the injection spectrum such as the energy of injection.

What exactly do we inject?

Our injection into the galaxy consists of:

- Positrons from the β^+-decay of ^{26}Al and other short-lived radioactive species (such as ^{44}Ti), following a theoretically motivated spectrum.
- Relativistic positron-electron pairs at a specific (kinetic) energy T_i. This follows a mono-energetic spectrum. This component can be modified to suit dark-matter models or other injection models.

Fitting model with observations

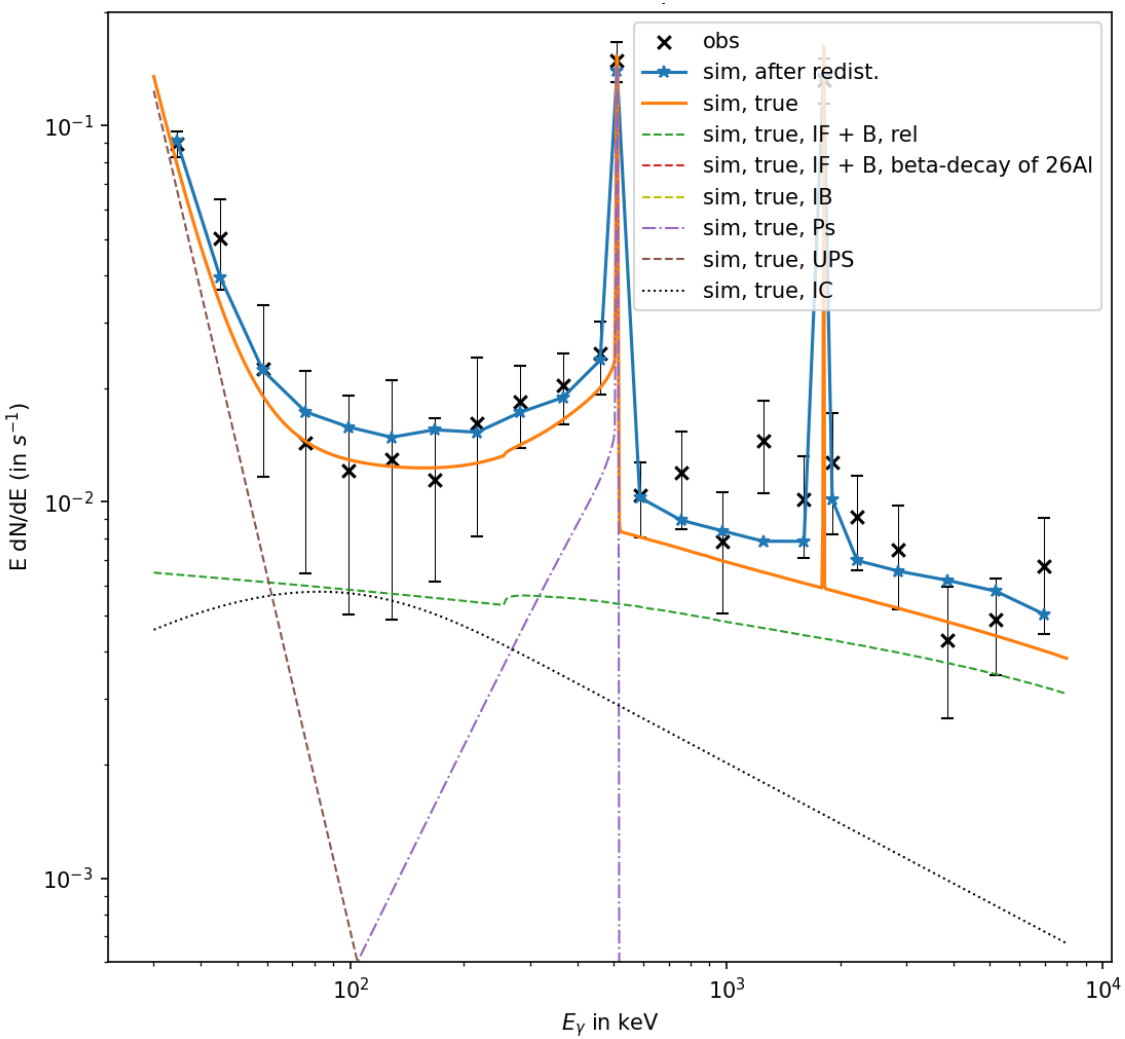


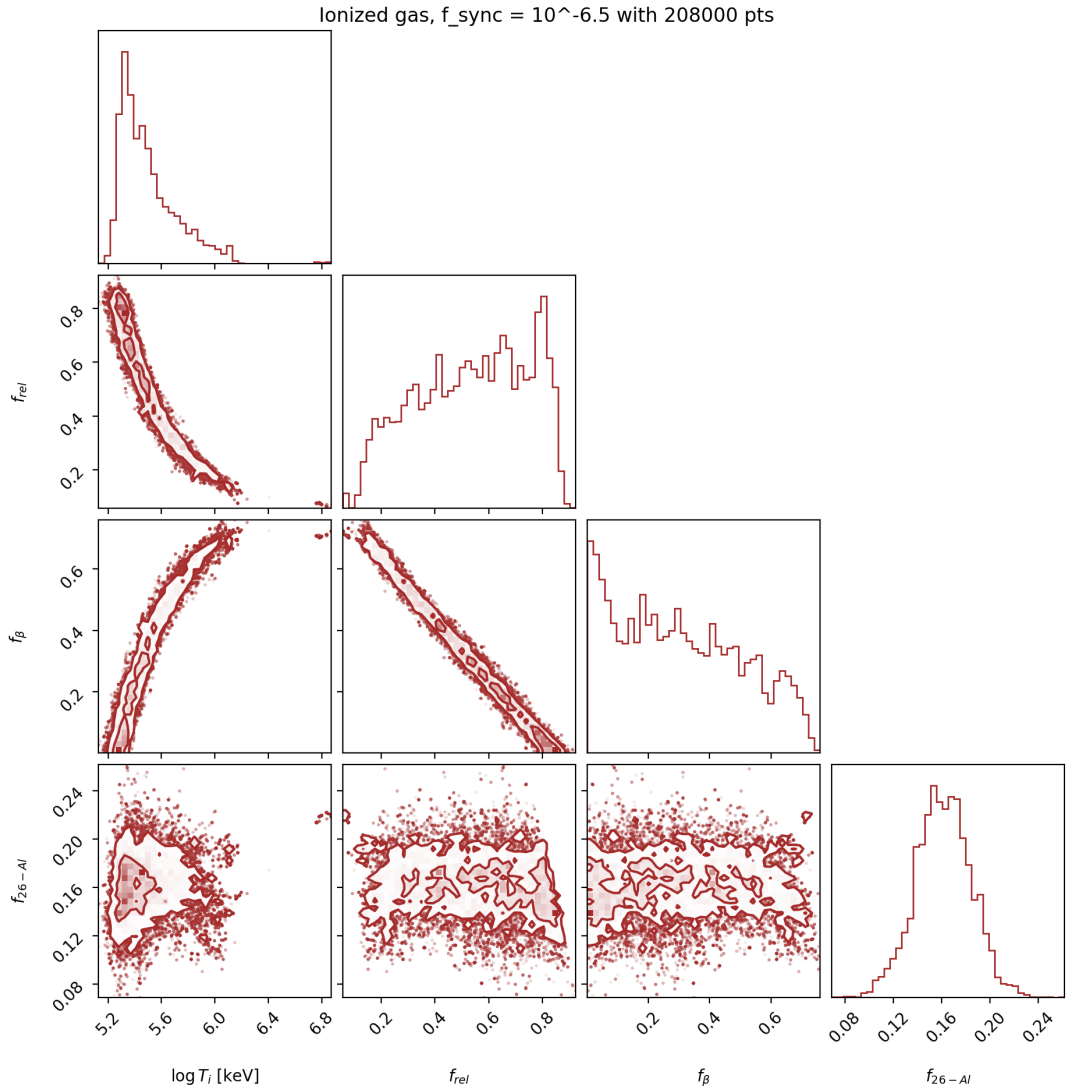
Figure: A best-fit model vs observed data

Gamma-ray components in our Model

In the previous slide, the theoretical luminosity is a sum of multiple components:

- Annihilation of positrons (by ISM electrons) at rest - mostly as *ortho* (75%) or *para* (25%) Positronium.
- Annihilation of positrons in-flight.
- *Bremsstrahlung* - braking radiation due to deceleration of $e^{\pm}$ in the field of other charged particles.
- Inverse Compton scattering of galactic background radiation by extremely energetic electrons.
- Unresolved point sources.
- Internal *Bremsstrahlung* when e^+e^- pairs are produced.
- A line at 1.809 MeV from the decay of ^{26}Al.

Glimpse of Results



Glimpse of Results

Main conclusions from our simulations:

- The relativistic injection energy T_i is constrained between $\sim$180 MeV and $\sim$1 GeV with 95% confidence.
- It is likely that a large fraction ($\gtrsim 50\%$) of the 511 keV line is produced from positrons that were injected at relativistic energies.

Useful Resources

- CRIPTIC - Simulation package for cosmic ray simulations used by me.
- `zenodo.org` - The data that I used for my simulations is available here. I used `spec_0030-8000keV_total.fits.gz`

References

[1] M. Ackermann, M. Ajello, A. Albert, et al. The Spectrum of Isotropic Diffuse Gamma-Ray Emission between 100 MeV and 820 GeV. *ApJ*, 799(1):86, 2015. doi: 10.1088/0004-637X/799/1/86.

[2] Thomas Siegert. The Positron Puzzle. *APSS*, 368(4):27, April 2023. doi: 10.1007/s10509-023-04184-4.