A Model for Cosmic Ray Interactions in M82

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Starburst Galaxy M82

- Current (~10 Myr) starburst activity is centered in the inner 300 pc.
- Highly dense star forming region ($n \sim 210\ cm^{-3}$)
- Supernova rate of

$$\nu_{SN} = 0.07\ yr^{-1}$$

- Large-scale, hot superwind powered by supernovae.
- Strong magnetic field

$$B \sim 120\ \mu G$$

Figure : M82 – HST Image.

Objectives

- To build a simple model of cosmic ray interactions.
- To reproduce the gamma-ray flux and radio emission of M82.
- To build a model readily scalable to other systems (NGC 253, Arp 220).
- To apply the model to better understand the Radio-FIR correlation and explore connections to galaxy evolution.

Primary Cosmic Rays

- Assume a power-law source function,

  $Q(E) = A\,E^{-p}$, which is related to the supernova rate:

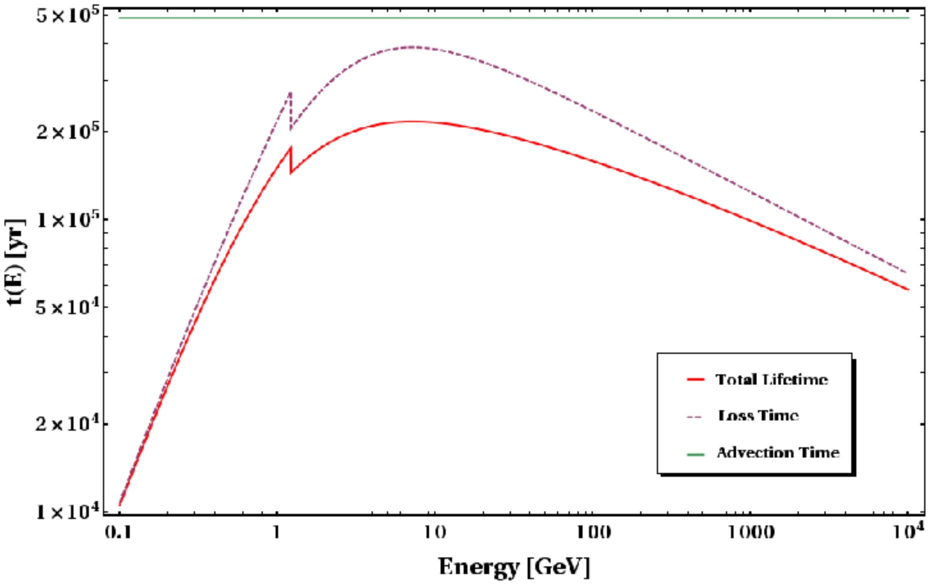
$$\int_{E_{min}}^{E_{max}} Q(E)\,E\,dE = \frac{\nu_{SN}\eta E_{51}}{V}$$

- Proton spectrum is the product of the source function and the particle lifetime.

$$N(E) = Q(E)\,\tau(E) = \frac{(p-2)}{E_{min}^{-p+2}} \cdot \frac{\nu_{SN}\eta E_{51}}{V} \cdot E^{-p} \cdot \tau(E)$$

Cosmic Ray Lifetimes

- Total lifetime includes energy losses and advection.
- Energy losses include:
  - Ionization (p,e)
  - Coulomb Effect (p)
  - Pion Decay (p)
  - Bremsstrahlung (e)
  - Inverse Compton (e)
  - Synchrotron (e)



Figures : Cosmic Ray Proton Lifetimes with Energy Loss and Advection Timescales (Yoast-Hull+ 2012).

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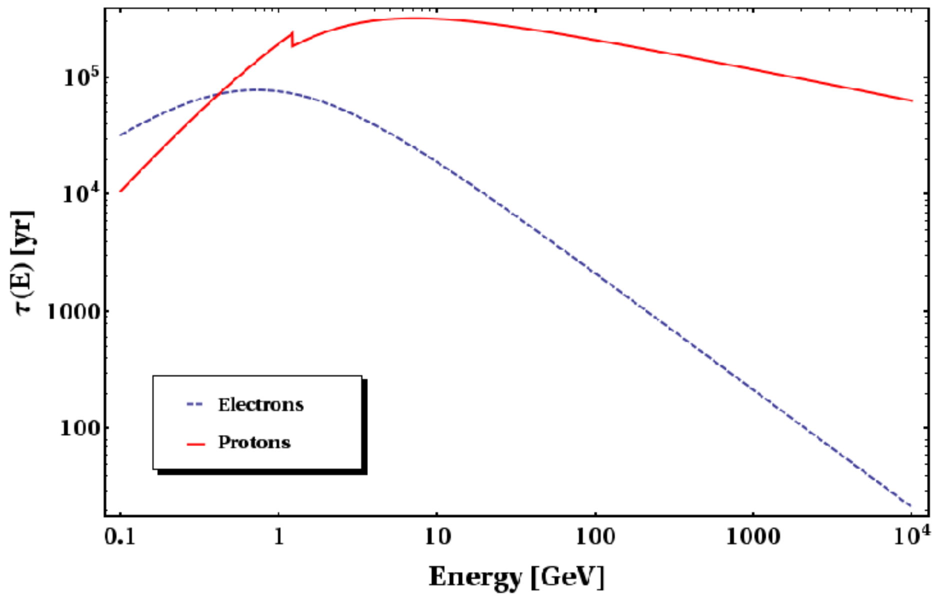

Figures : Cosmic Ray Proton and Electron Lifetimes (Yoast-Hull+ 2012).

Secondary Cosmic Rays

- Pions produced in proton-proton collision quickly decay into a number of different particles:
  - Gamma Rays (γ)
  - Electrons (e^-)
  - Positrons (e^+)
  - Neutrinos (ν_μ, ν_e, $\bar{\nu}_\mu$)

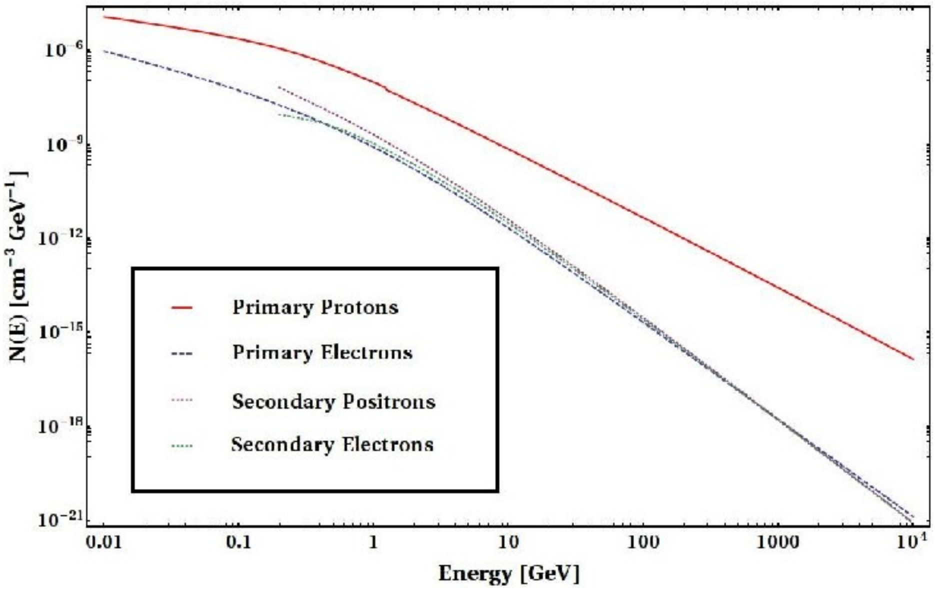

Figure : Primary and Secondary Cosmic Ray Spectra (Yoast-Hull+ 2012).

Radio Spectrum

- Primary and secondary electrons and positrons all contribute to the radio spectrum.
- Intensity and shape of the radio spectrum depend on:
  - Magnetic Field Strength
  - Advection Speed
  - Gas Density and Temperature
- Chi-squared tests are used to find the best-fit parameters.

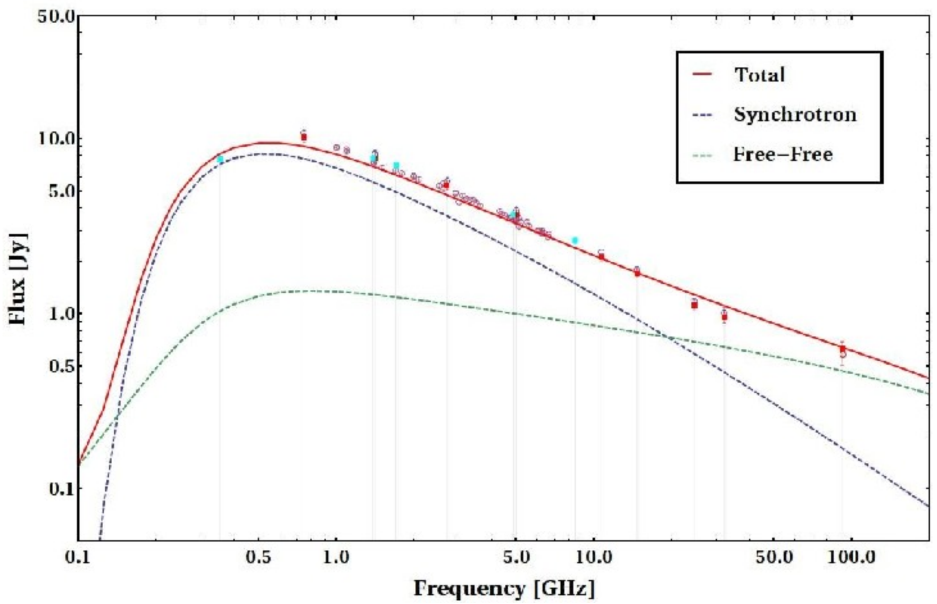

Figure : Radio Spectrum (Yoast-Hull+ 2012) – Data from Adebahr+ (2012), Klein+ (1988), Williams+ (2010).

Gamma Rays

- We calculate source function for neutral pions from the proton spectrum:

$$q_\pi(E_\pi) = c n_H \, N_p(E_\pi) \, \sigma_{p\text{-}p}(E_\pi)$$

- Gamma-ray source function:

$$q_\gamma(E_\gamma) = \int_{E_{min}}^{\infty} \frac{q_{\pi 0}(E_\pi)}{(E_\pi{}^2 - m_\pi{}^2 c^4)^{1/2}} \, dE_\pi$$

where $E_{min} = E_\gamma + (m_\pi c^2)^2/(4E_\gamma)$

Gamma Ray Flux

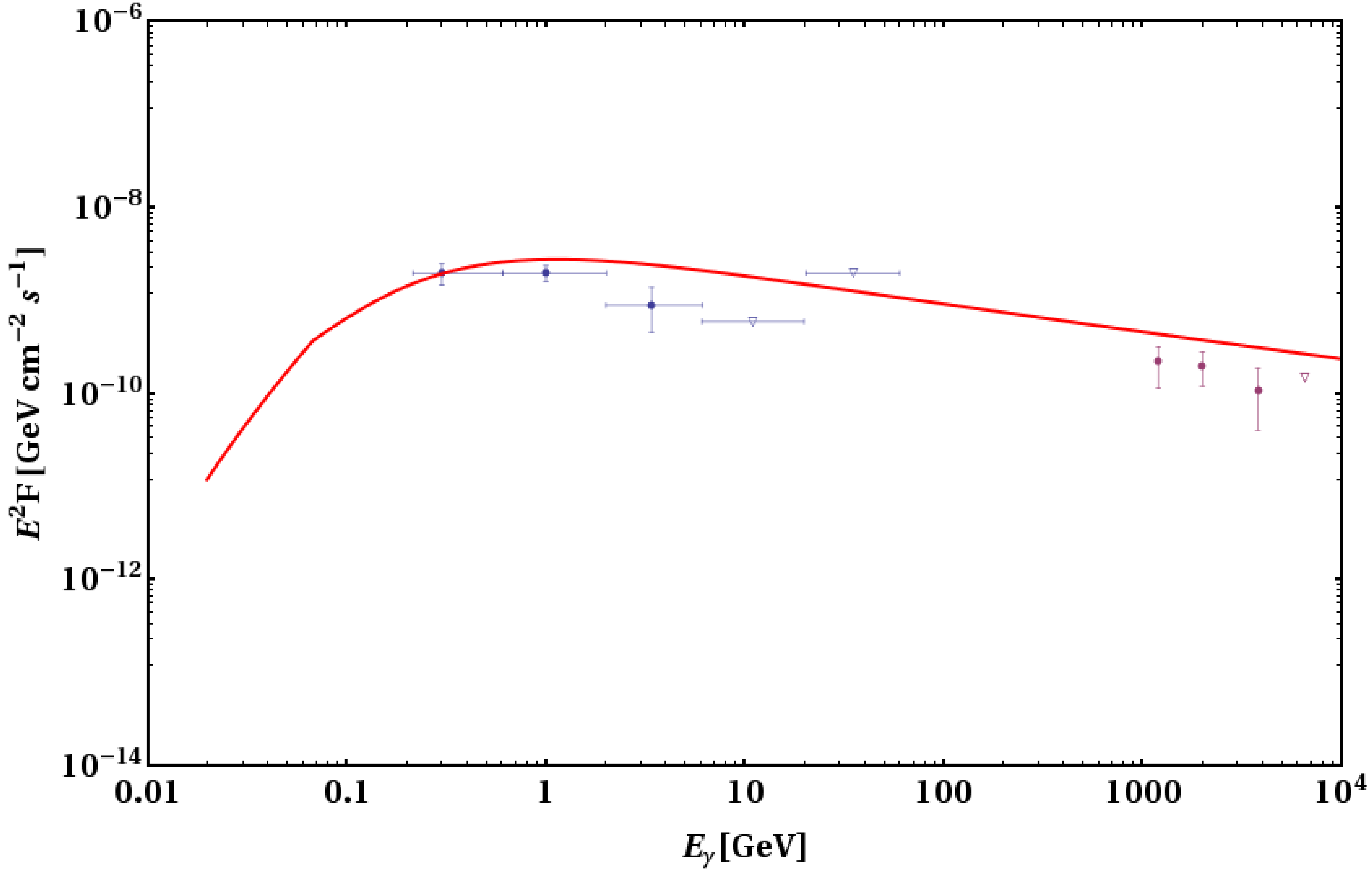

Figure : Gamma Ray Flux (Yoast-Hull+ 2012) – Data from Abdo+ (2010), Acciari+ (2009).

Gamma Ray Flux

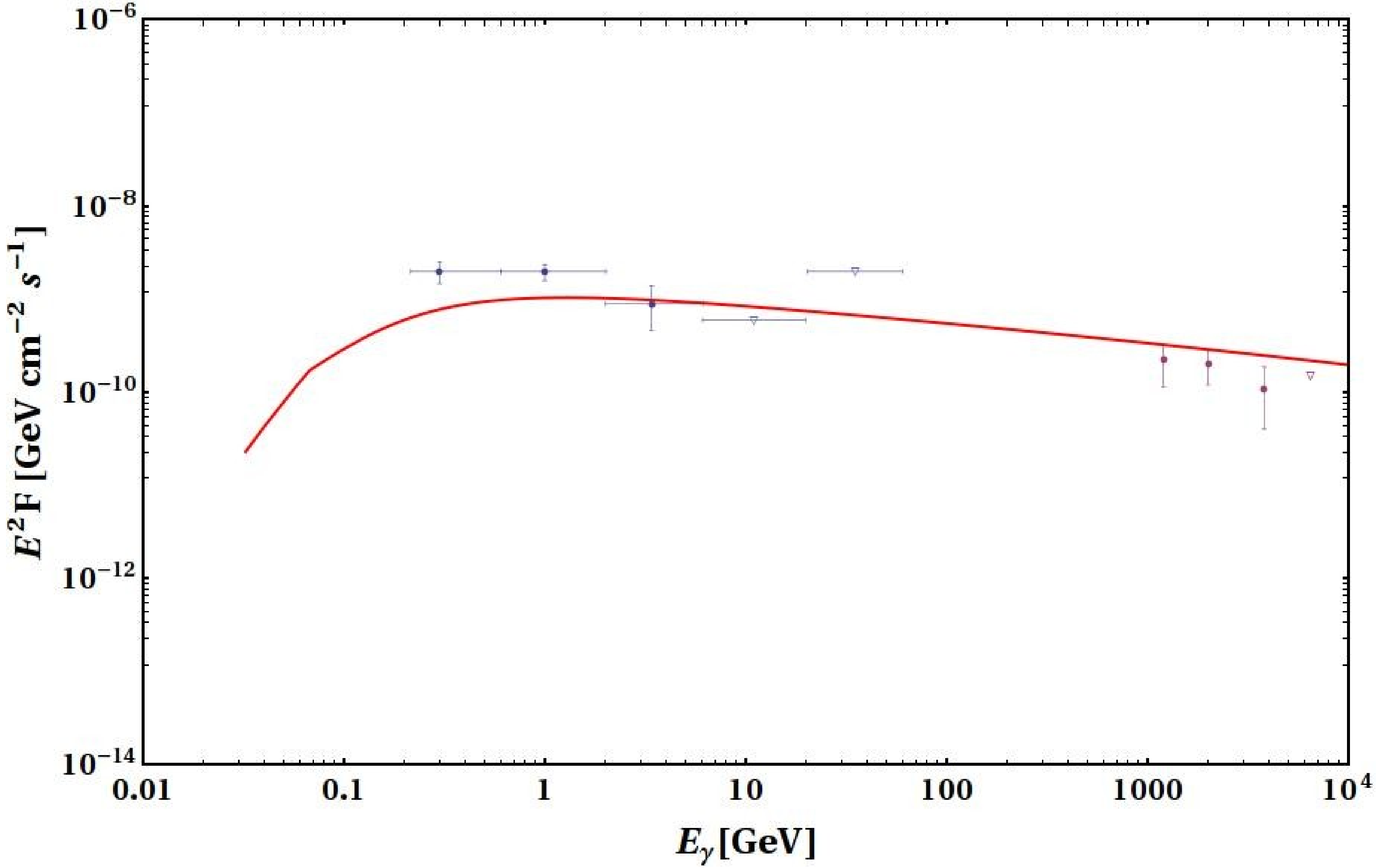

Figure : Gamma Ray Flux (Yoast-Hull+ 2012) – Data from Abdo+ (2010), Acciari+ (2009).

Conclusions

- Model for gamma-rays agrees with observations within a factor of a few.
- A limit on the advection speed is the gamma-ray flux. If the wind speed is too high, the model will no longer fit the Fermi data.
- In the future, we will apply the model to NGC 253 and Arp 220.