# The *Fermi* Bubble Mystery: What Powers Our Galaxy's Twin Lobes?

## Relative acceleration of electrons and protons by turbulent magnetosonic waves

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## Abstract

Su et. al. (2010) revealed two large-scale Galactic structures, the *Fermi* bubbles, in 1.6 yr *Fermi-LAT* data. Mertsch & Sarkar (2011) attributed the radiation to electrons, accelerated stochastically by magnetosonic turbulence in a weakly magnetized plasma. I revisit this scenario in the presence of protons and examine the implications of my result for the feasibility of future leptonic models.

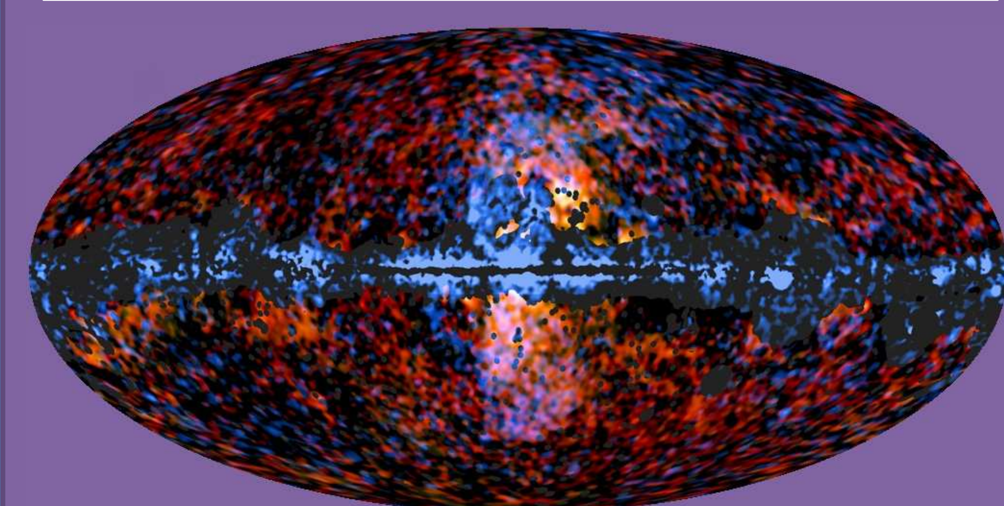

## The *Fermi* Bubbles

### Features

1. Bilobular shape aligned with galactic axis
2. 100° (20 kpc) end-to-end, 40° (6 kpc) wide (huge)
3. Twin jets tilted 15°
4. Hard ($E^{-2}$) γ-ray spectrum (0.1–100 GeV)
5. Flat intensity profile
6. Hard edges
7. Colocated microwave haze
8. Inside X-ray shell
9. Probably ~10 Myr old

### All-sky maps

Data from *Fermi-LAT* in the γ-ray range, in blue, superimposed on microwave data (red) from the Planck satellite. Note that the north and south bubble edges are significantly farther from Earth than the GC, so the bubbles are even taller than they appear.



## Electrons *and* Protons?

The leptonic compressional SA model agrees with nearly all of the morphology observed and produces a spectrum that matches observation, but it does not account for protons. If CR protons are introduced, does the model maintain reasonable results?

### Goals of the project

1. Reproduce leptonic spectrum
2. Calculate proton spectrum using the same parameters
3. Compare energies required; evaluate feasibility

### Parameters

1. Electrons and protons injected at 100 MeV in equal proportions
2. Turbulence is generated at 2 kpc and dissipates at ~0.01 kpc; Kolmogorov spectrum in between; turbulence is isotropic and is convected from the edge towards the center
3. Energy-independent spatial diffusion: mean free path = turbulence dissipation scale
4. Turbulent magnetosonic waves accelerate CRs stochastically by compression. This gives a momentum diffusion coefficient (also energy-independent):

$$D_{pp} = p^2 \frac{8\pi D_{xx}}{9} \int_{k_m}^{k_d} dk \frac{W(k)k^4}{v_F^2 + D_{xx}^2 k^2}$$

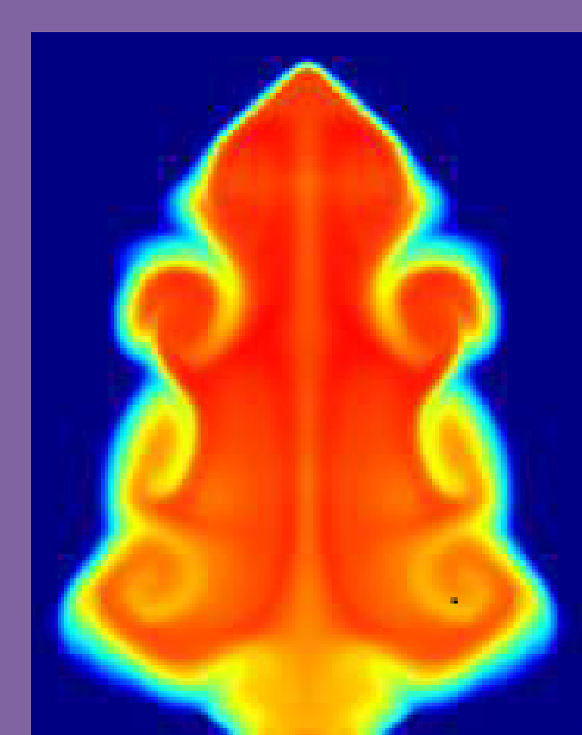
5. $n \sim 0.003$ cm$^{-3}$; $B \sim 4$ μG; $T \sim 2\times10^7$
6. Shock velocity $2.6\times10^8$ m/s; speed of sound at shock = Alfvén velocity
7. Protons cool by pion production, Coulomb, IC and synchrotron

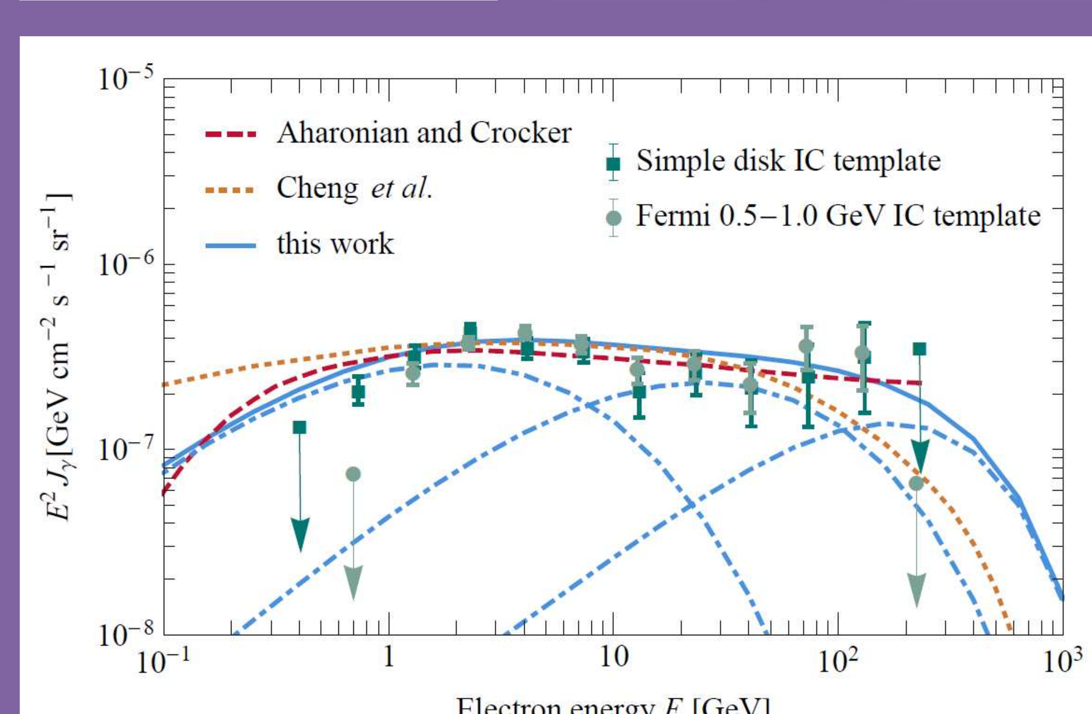
## Competing Explanations

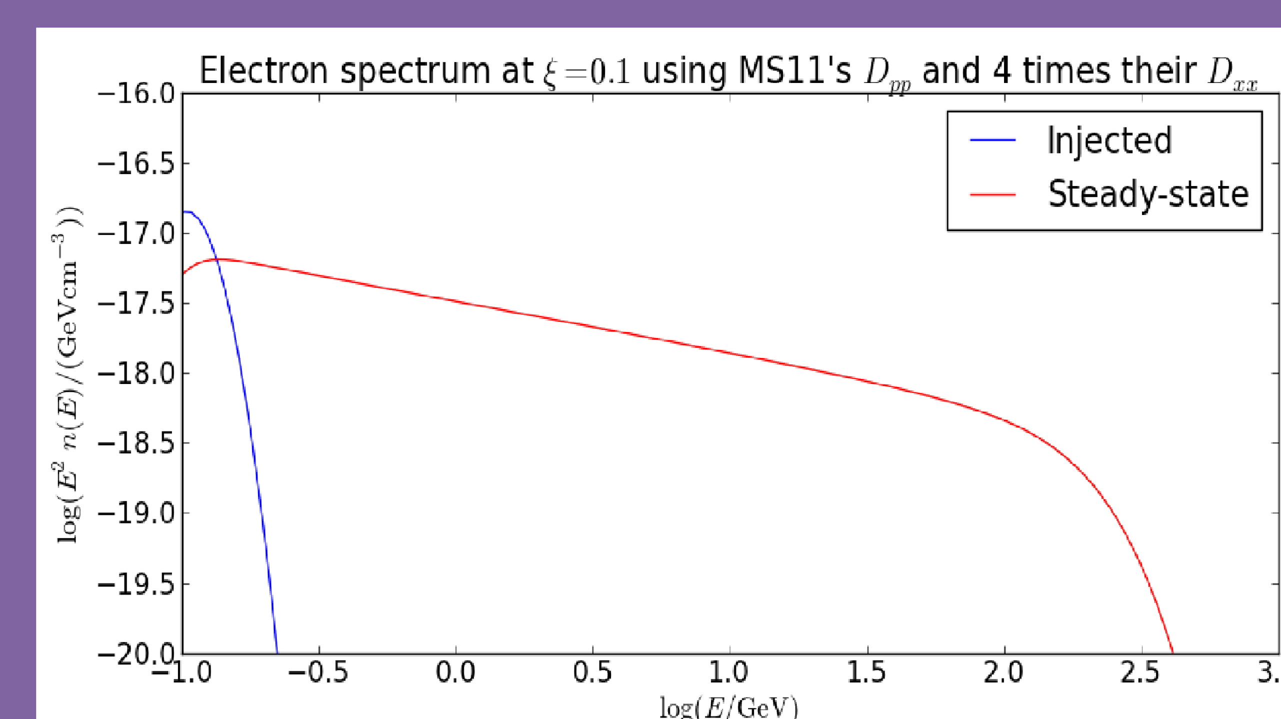
| Mertsch & Sarkar 2011 | Crocker & Aharonian 2011 |
|---|---|
| **Particles responsible** | |
| Electron CRs | Proton CRs |
| **Injection/acceleration mechanism** | |
| AGN jet; SA by compressional turbulence | Outflow from Sgr A* (from AGN or SF) |
| **Mechanism for γ-ray, microwave production** | |
| IC off of CMB & ISRF, synchrotron | $\pi^0$ decay → γ-rays, $\pi^\pm \to e^\pm \to$ synchrotron |
| Ignores feature 3 | Ignores features 5, 6 |

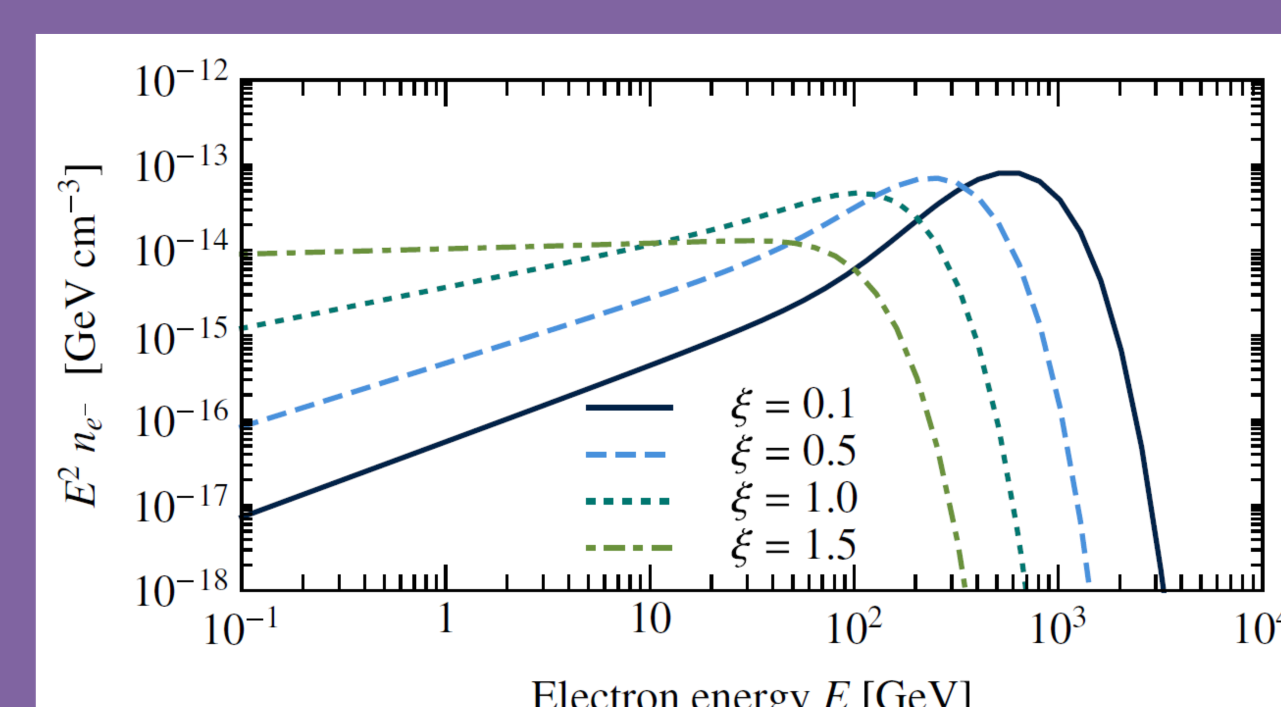
## MS11 model

*Right:* This MHD simulation predicts that an AGN jet will create a cocoon with a turbulent surface. *Below:* In blue, the MS11 γ-ray spectrum. The three dashed curves correspond to scattering of CMB, FIR, and optical/UV.






## Calculated spectra

### Initial difficulties

- Electron spectrum successfully reproduced using the parameters above (not shown)
- The corresponding proton distribution (not shown) was problematic
  - Extended to very high energies, such that parameters 3 and 4 were questionable
  - Required a total energy $10^{10}$ times that of the electrons
- Conclusion: Protons cannot be ignored.

### Adjusting $D_{xx}$

- Allowed spatial diffusion to increase until total energies were comparable
- High-energy proton excess resolved
- Recalculated electron spectrum (shown at left, compared to the MS11 original) was too soft to explain γ-rays
- Conclusion: Sufficient electron acceleration leads to excessive proton acceleration.

## Results

### Conclusion

For the above turbulence spectrum (2) and a variable, energy-independent $D_{xx}$, the relatively efficient acceleration of protons prevents the evolution of an electron spectrum hard enough to explain the bubble radiation.

### Next Steps

- Investigate radiation by secondary electrons
- Look into the energy and particle dependency of $D_{xx}$
- Update turbulence spectrum and dynamics to agree with recent MHD simulations
- Examine the spectrum of Alfvén waves and their resonance with CRs