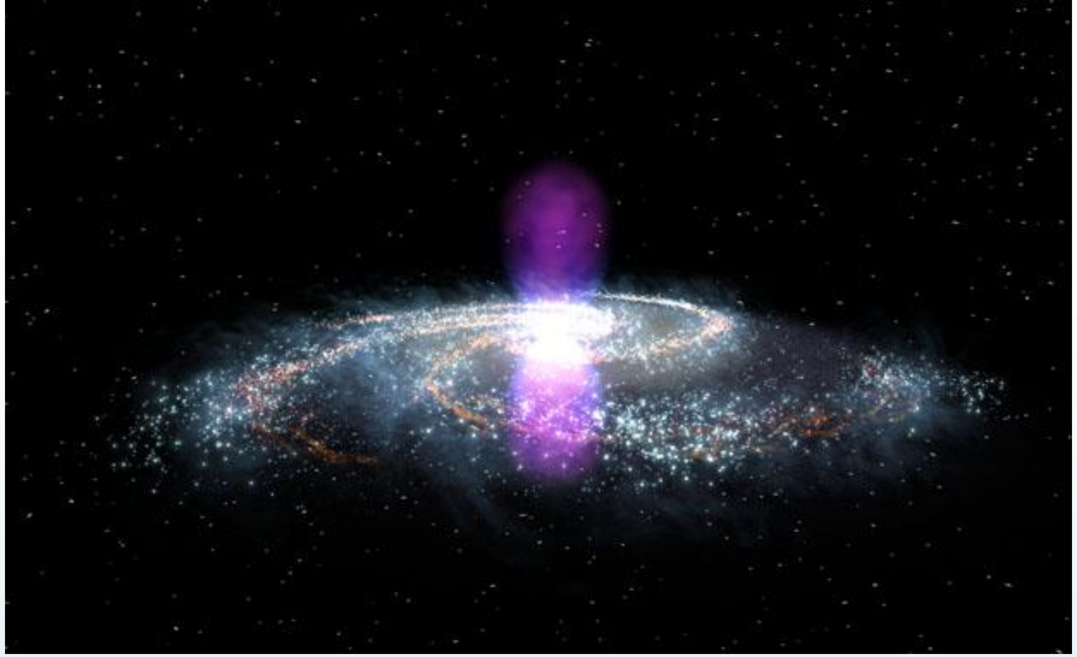

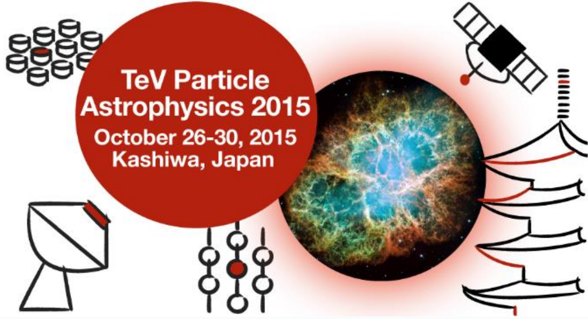

Natural Model for the Fermi Bubbles and Galactic Haze

Ilya Gurwich[1,2] and **Uri Keshet**[3]

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Outline

- The Fermi Bubbles and Galactic Haze
- Spectral Models – Short Overview
- Self Consistent Leptonic Model
- Results and Discussion

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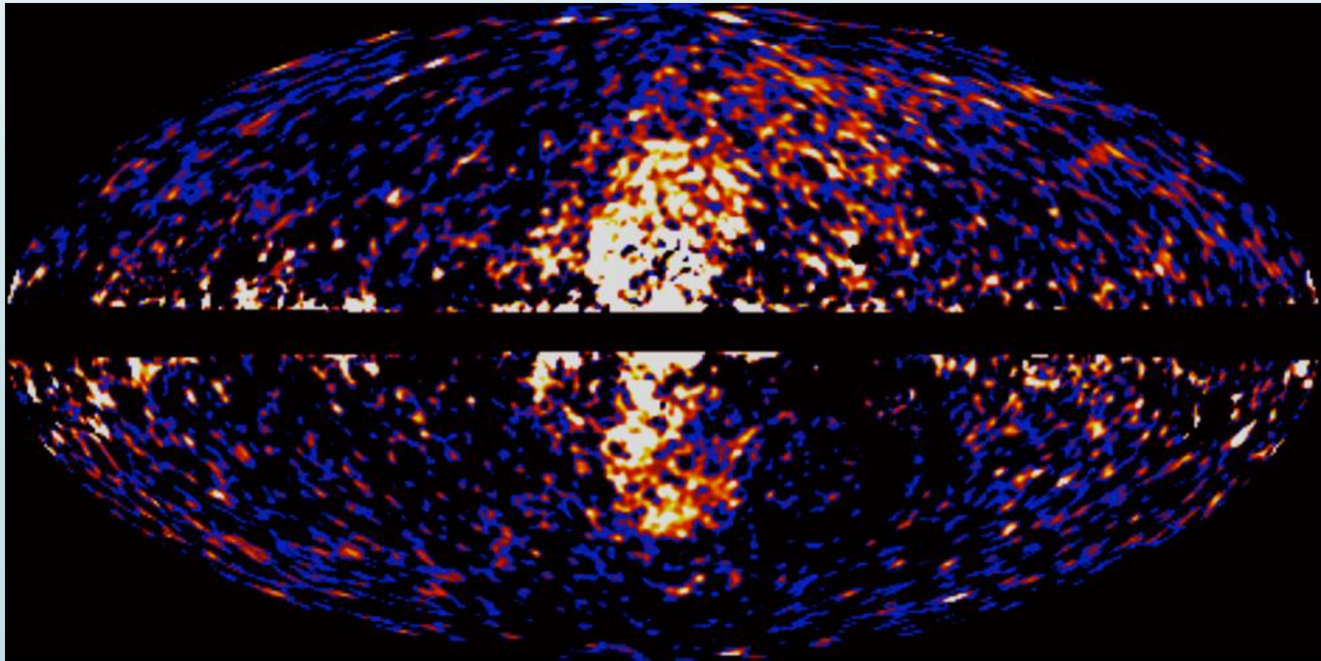
The Fermi Bubbles

- Using Fermi data - two giant gamma-ray emitting structures have been discovered (Dobler et al. 2010; Su et al. 2010).
- These "bubbles" extend nearly 10kpc north and south of the galactic center and appear to have a roughly uniform emission.



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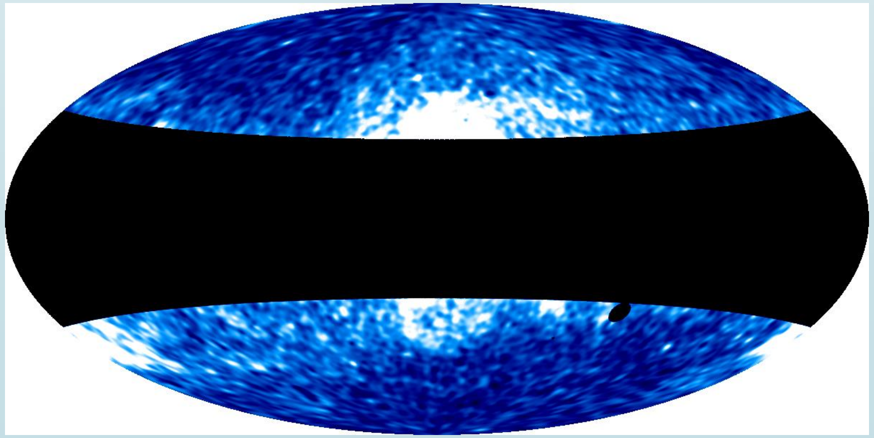
- These “bubbles” extend nearly 10kpc north and south of the galactic center and appear to have a roughly uniform emission.

- **Initial analysis used template reduction method to identify the bubbles. However, the bubble edges are visible even without template reduction.**



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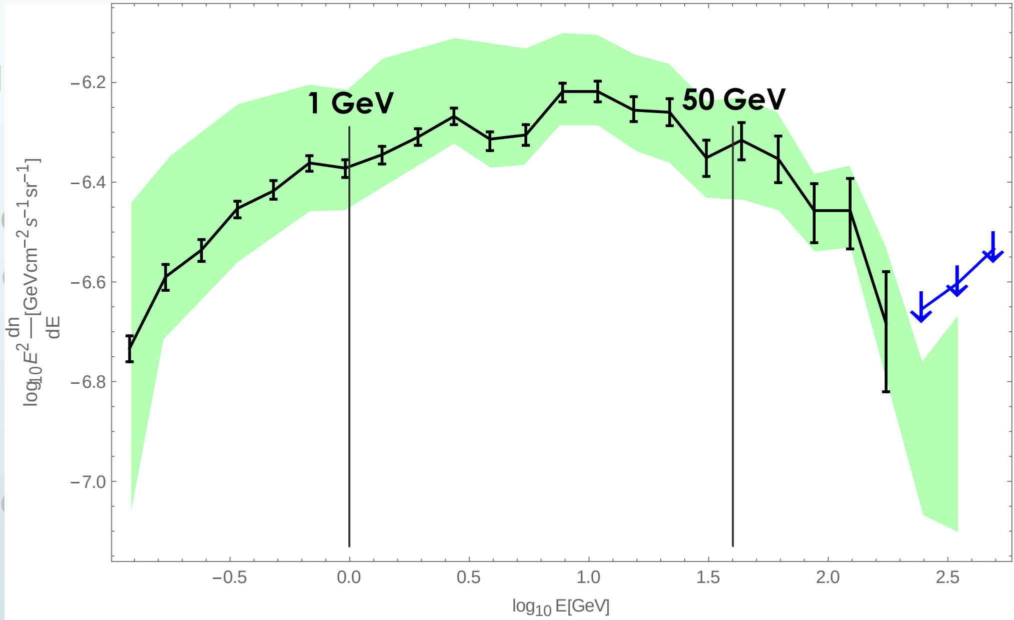
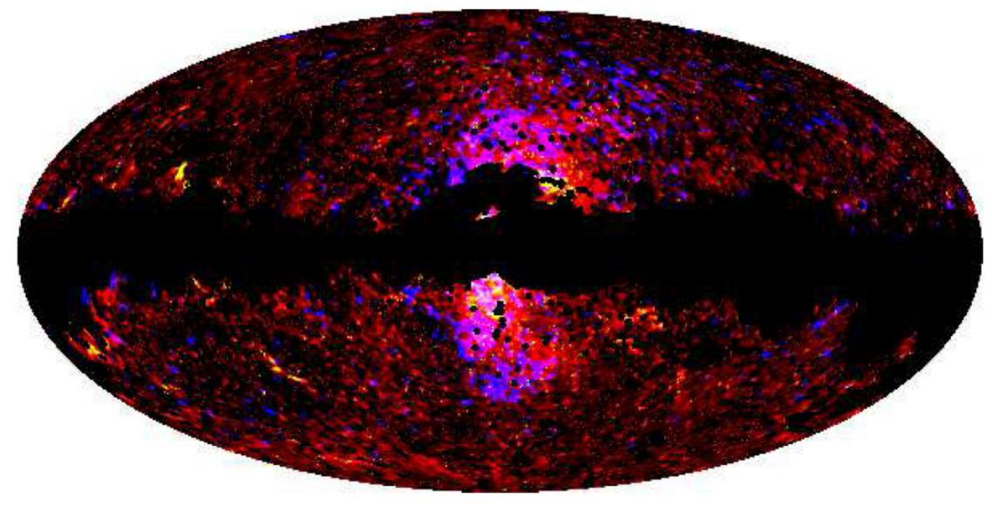


- **The emission is characterized by a power spectrum of $\frac{dN_\gamma}{dE} \sim E^{-3/2}$ below 1 GeV $\frac{dN_\gamma}{dE} \sim E^{-2}$ between ~3 and ~50 GeV and a spectral break above these energies.**

The Galactic Haze

- Discovered before the Fermi Bubbles – Using WMAP data (Finkbeiner 2004).
- An excess of synchrotron radiation was found around the galactic center.
- Only observed in a narrow frequency rage (23-44(61?) GHz). In this range, exhibits a flat $\frac{dN_\nu}{dE} \sim E^{-3/2}$ spectrum
- Appears to morphologically coincide in part with the Fermi Bubbles (Dobler 2012)



Blue – Fermi
Red (Yellow) – Planck 30 (44)

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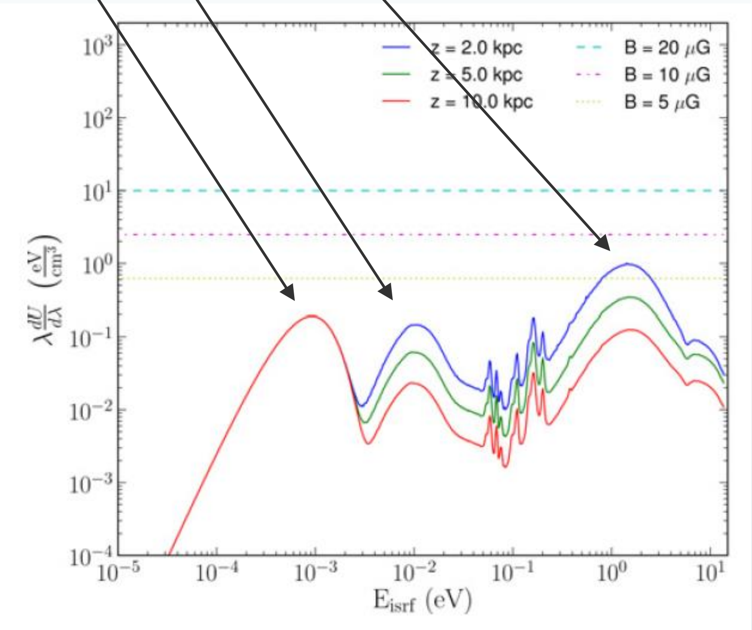
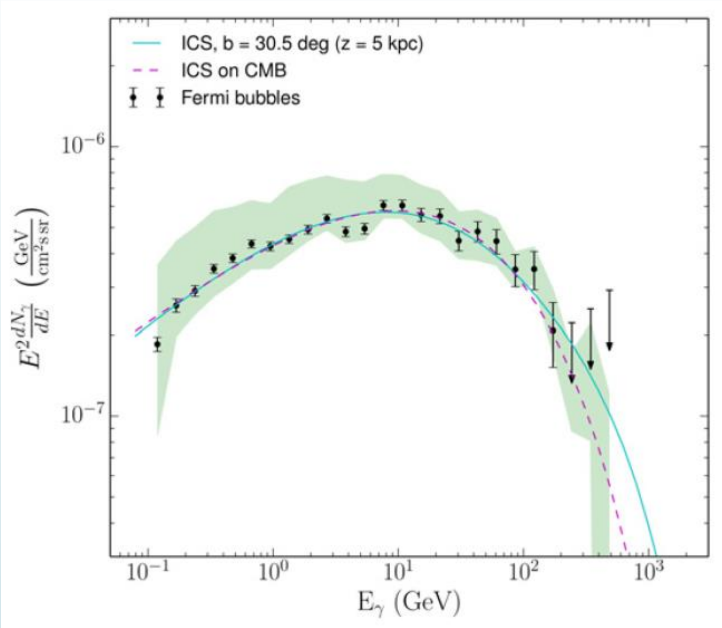
Leptonic Model

See for example: Su et al. 2010 & Ackermann et al. 2014

- Inverse Compton of the radiation field above the Galactic plane (CMB, IR and SL) via CRes gives an excellent fit to the observed spectrum





Ackermann et al. 2014

Overall ISRF of 1.5 eV/cm^3

Magnetic field of 5-20 μG

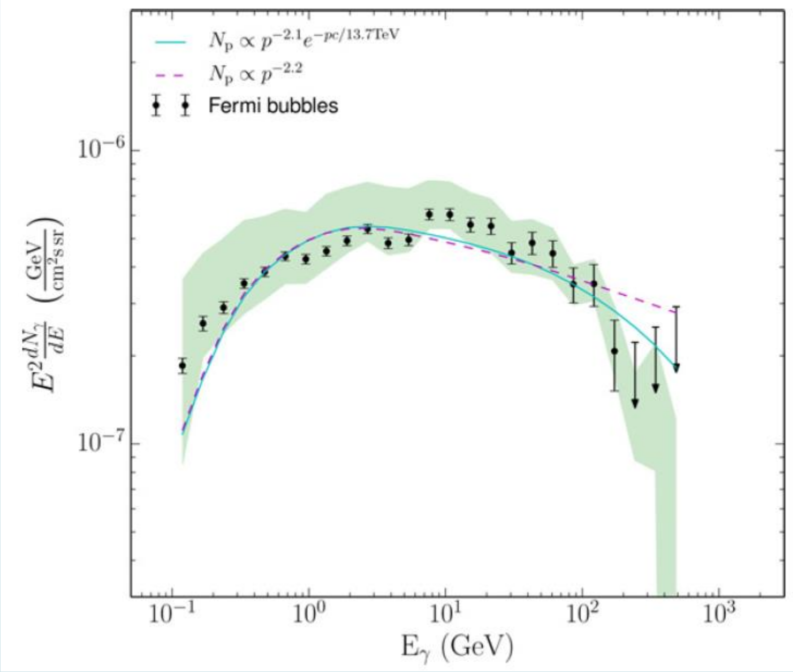
However, only if an unnaturally high cutoff (~1.3 Tev) is invoked

Electrons with such energies would be **cooled via IC and synchrotron over ~10^5 years**. If the bubbles were this young, they would be relativistic – Require an incredibly energetic source and be extremely bright in x-rays and soft gamma rays

Hadronic Model

See for example: Crocker & Aharonian 2011

- Assuming π decay as the only source – gives a good fit to the flat $\frac{dN_\gamma}{dE} \sim E^{-2}$ region, however fails to reproduce both the low-energy and high-energy parts of the spectrum



Ackermann et al. 2014

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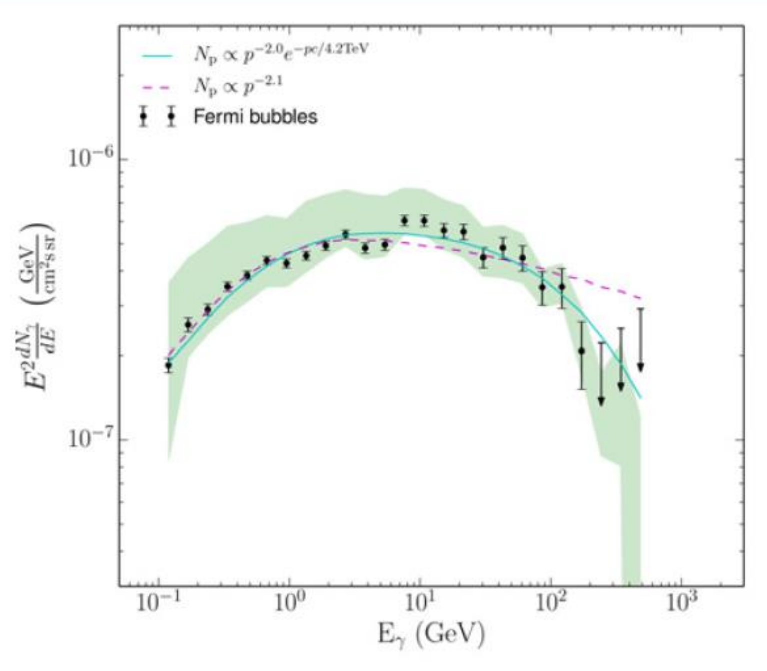

To fit the spectrum below 1 GeV, one must include the secondary electron IC component to soften the hadronic spectrum

Ackermann et al. 2014

Even then, the synchrotron does not match the haze.

Hadronic Model

- First proposed by Crocker & Aharonian 2011
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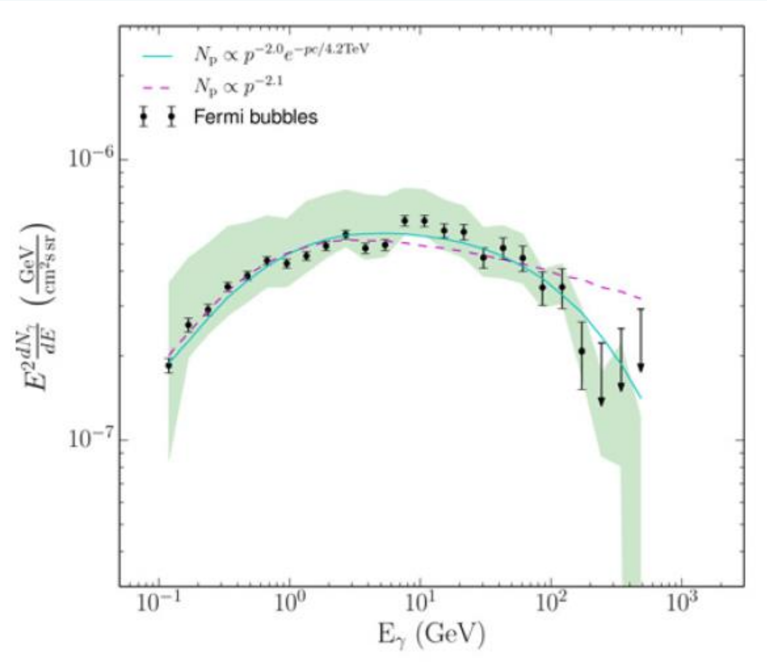

To fit the spectral break above 50 GeV, an arbitrary cutoff must be invoked (~4 TeV)

Ackermann et al. 2014

The natural scale for an acceleration cutoff is

$$E_{max} \approx \beta^2 ZeBct \approx \frac{ZeBR^2}{ct}$$

$$\approx 5 \times 10^{17} Z \left(\frac{B}{5\mu G}\right)\left(\frac{t}{3Myr}\right)^{-1}\left(\frac{R}{10kpc}\right)^2 eV$$

For 4 TeV to be a natural scale – the acceleration time would be too short for so much energy to be in CRs.

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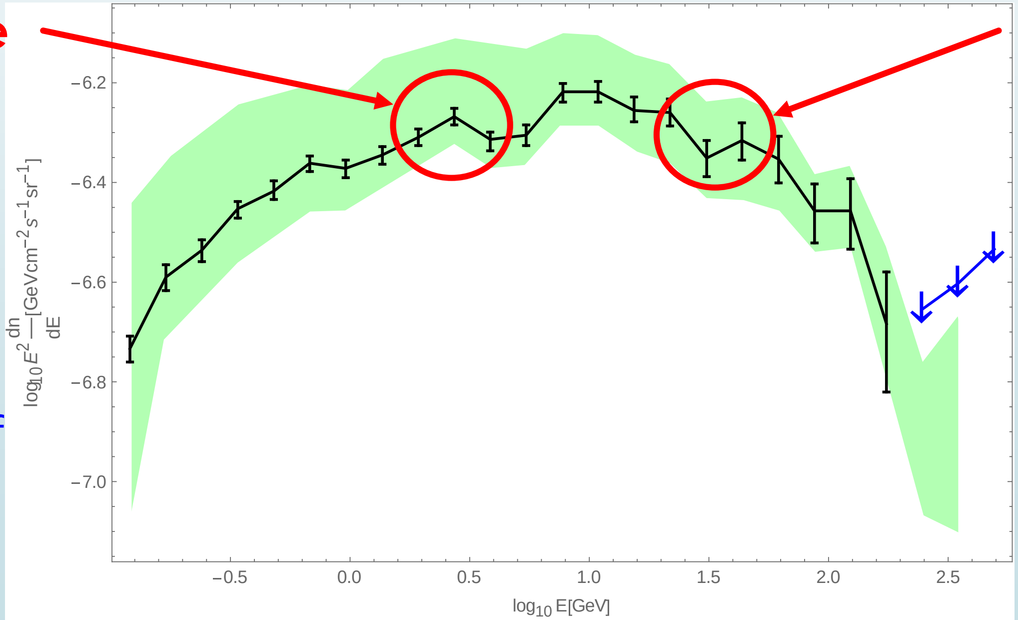
Self Consistent Leptonic Model

- We identify the FB edges as a shock continuously injecting CRs.
- For a 1-10 Myr old shock, we expect the CRe population to have a cooling break ($E_C = \frac{3m_e^2c^3}{4\sigma_T(U_B+U_R)t}$) of *O(10GeV)* and thus visible in the gamma-ray spectrum

Identified as SL, IC scattered off the cooling break

This is the only interpretation that does not require an unnatural cutoff



Must be identified as KN cutoff of IC SL

Same as previous leptonic model

Self Consistent Leptonic Model

- Requiring the cooling break in the FB spectrum to be at the appropriate energy:
  - $$\left(\frac{B}{5\mu G}\right)^2\left(\frac{t}{3Myr}\right)\left(1+\frac{U_R}{U_B}\right)\approx 7\sqrt{\frac{\epsilon_{SL}/1eV}{E_{cb}/3GeV}}$$
- Requiring the haze spectrum to be unaffected by the cooling break:
  - $$\left(\frac{B}{5\mu G}\right)^3\left(\frac{t}{3Myr}\right)^2\left(1+\frac{U_R}{U_B}\right)^2<45\left(\frac{\nu_{H,max}}{44GHz}\right)^{-2}$$
- And finally, requiring the appropriate intensity ratio between the FB and haze:
  - $$\left(\frac{B}{5\mu G}\right)^3\approx 0.4\left(\frac{U_R}{2.5eV/cm^3}\right)^2$$
- **The Last equation dictates a dominant radiation field.**
  - $$\frac{U_R}{U_B}\approx 7.5\left(\frac{U_R}{2.5eV/cm^3}\right)^{-1/3}$$

Self Consistent Leptonic Model

- Therefore, assuming $1 \ll \frac{U_R}{U_B}$:

(cooling break in the FB spectrum) ➨ $t \approx 5\sqrt{\frac{\epsilon_{SL}/1eV}{E_{cb}/3GeV}}\left(\frac{U_R}{2.5eV/cm^3}\right)^{-1} Myr$

(uncooled haze) ➨ $t < 4.3\left(\frac{\nu_{H,max}}{44GHz}\right)^{-2}\left(\frac{U_R}{2.5eV/cm^3}\right)^{-2/3} Myr$

- **This gives us a constraint on the radiation energy density:**

➨ $U_R > 4\left(\frac{\nu_{H,max}}{44GHz}\right)^{6}\left(\frac{\epsilon_{SL}/1eV}{E_{cb}/3GeV}\right)^{3/2}\frac{eV}{cm^3}$

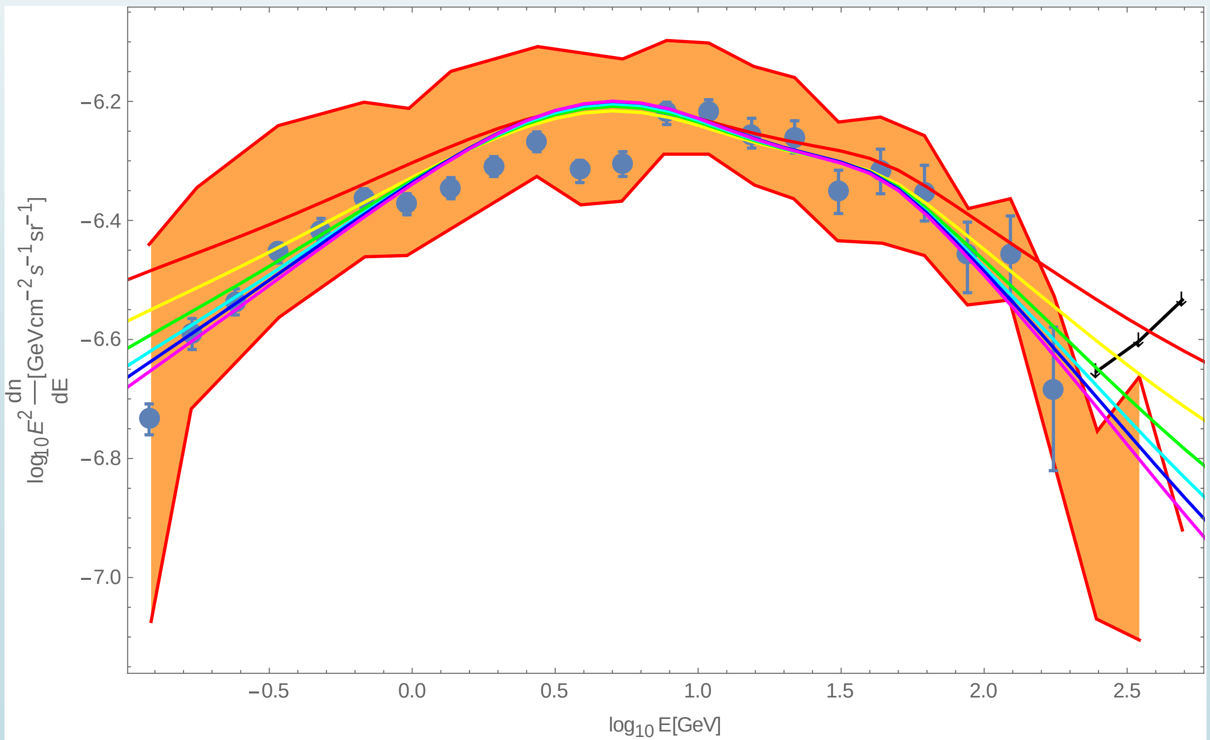
- And therefore an upper limit on the age of the bubbles:

➨ $t < 3\left(\frac{\nu_{H,max}}{44GHz}\right)^{-6}\left(\frac{\epsilon_{SL}/1eV}{E_{cb}/3GeV}\right)^{-1} Myr$

- As well as a lower bound of ≈5μG on the magnetic field.
- **Due to KN corrections, the actual constraint on U_R is lower (2.5-3 eV/cm^3). However, the high radiation energy density remains a key feature of the model.**

Starlight Component

- The starlight component must be dominant in the radiation field.
- Otherwise, the cooled electrons IC scattering CMB and IR would soften the spectrum below 1GeV and harden it above the KN break.
- For nominal values of IR radiation, this means $U_R > 3$ eV/cm^3.



$\frac{U_{SL}}{U_R} \approx 0.83$

$\frac{U_{SL}}{U_R} \approx 0.88$

$\frac{U_{SL}}{U_R} \approx 0.92$

$\frac{U_{SL}}{U_R} \approx 0.94$

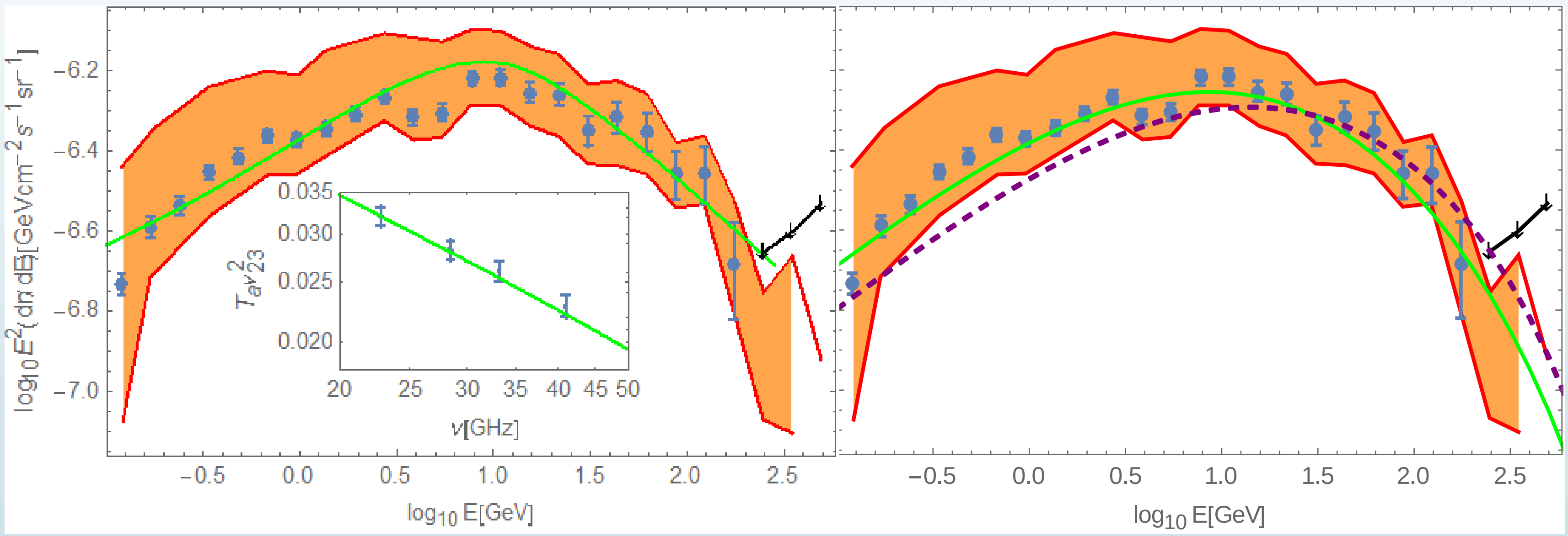
$\frac{U_{SL}}{U_R} \approx 0.95$

$\frac{U_{SL}}{U_R} \approx 0.96$

Results

- The presented model gives a good fit to the data (both FB and haze)

Example (B ≈ 2.5 μG, t ≈ 3 Myr) **Fermi Fit**



Self Consistent Leptonic Model

- The bubble however is not homogeneous: in the high latitude areas (large |b|), the shock velocity is greater and the cooling rate is lower due to the evanescent SL and IR components.
- We therefore expect the Cre spectrum to be a sum over several spectra with slightly different cooling breaks:

$$\frac{dN_e}{dE} \propto \begin{cases} E^{-2} & for \quad E < minimal\ cooling\ energy \\ E^{-p} & for \quad minimal < E < maximal \\ E^{-3} & for \quad E > maximal\ cooling\ energy \end{cases}$$

- With 2<p<3 (and not necessarily constant).
- This feature may be the source of the kink at ~10 GeV in the FB spectrum.

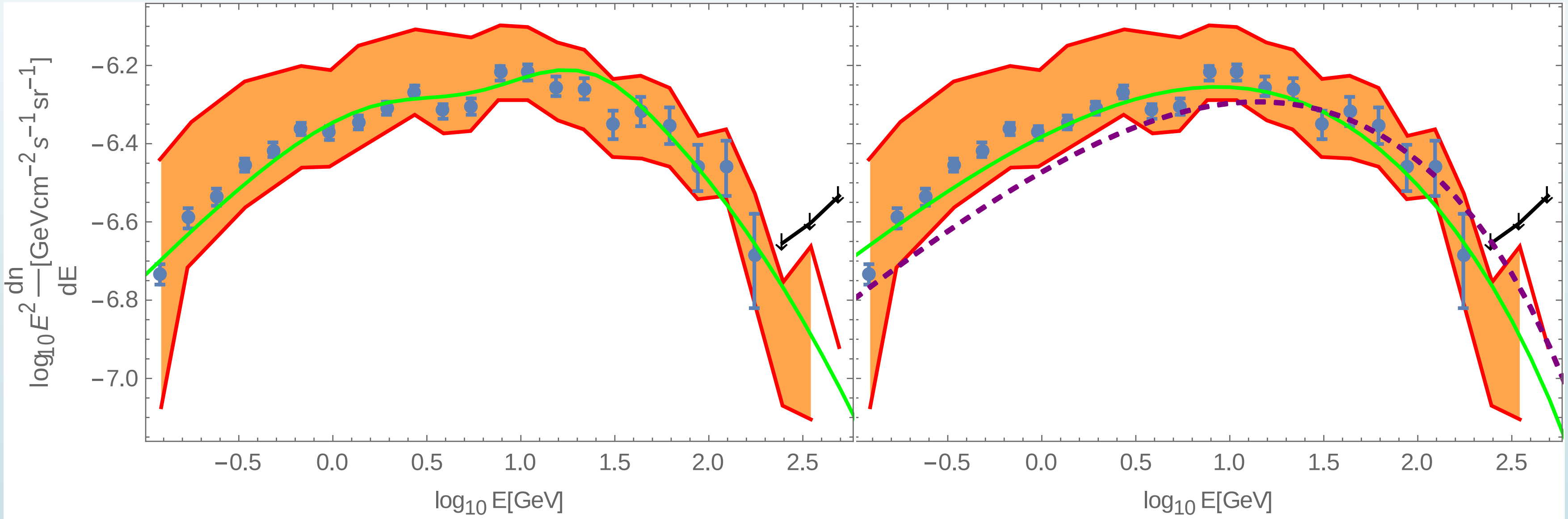
Self Consistent Leptonic Model

Warning: Preliminary results!!!

Example:

Min E_c=15Gev, Max E_c=70GeV

Fermi Fit



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Summary of Results

- **We presented a fully consistent model for the Fermi bubbles and Galactic haze, based on shock accelerated CRe. We claim this to be the only natural (free of ad-hoc spectral features) model for these objects.**

- The model gives significant constraints on the age and average magnetic field of these objects:
  - The magnetic field is estimated to be **2.5-4 μG** (in agreement with previous estimated)
  - The age of the bubbles is **2-3 Myr** (For younger bubbles we would expect a more significant x-ray signature).

- The relatively young age of the bubble seems to favor an AGN origin for the bubbles.

- **We also require starlight intensity of at least twice the value previously estimated (overall ISRF energy density of ~3 eV/cm^3).**

Discussion

- The FB prove to be a unique object for the study of CR acceleration, transport and emission mechanisms – being the most resolved (in γ-rays) CR source.

- **Interestingly, as we have shown, the FB may also provide a remarkable diagnostic tool for the Milky Way – Providing, perhaps the best source to date to measure the ISRF above the Galactic plane.**

- Pinpointing the age of the FB may give us insight to the recent activity in the Galactic center.

- **The FB are also a possible source for UHECR, capable of accelerating protons to energies of** $\approx 2\times 10^{17}\left(\frac{U_R}{2.5eV/cm^3}\right)^{5/3}\left(\frac{\epsilon_{SL}/1eV}{E_{cb}/3GeV}\right)^{-1/2}\left(\frac{R}{10kpc}\right)^{2} eV$ **and Iron nuclei to** $\approx 5\times 10^{18}\left(\frac{U_R}{2.5eV/cm^3}\right)^{5/3}\left(\frac{\epsilon_{SL}/1eV}{E_{cb}/3GeV}\right)^{-1/2}\left(\frac{R}{10kpc}\right)^{2} eV$.