Spectrum of Pairs injected by Geminga into the Interstellar Medium

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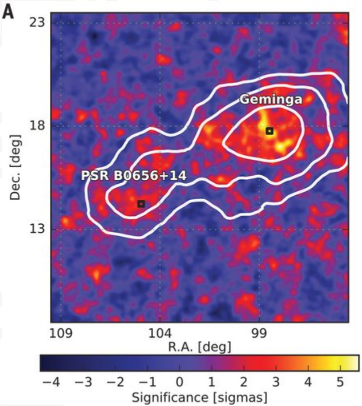
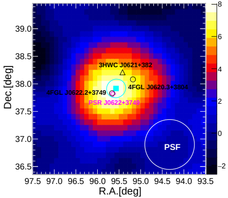
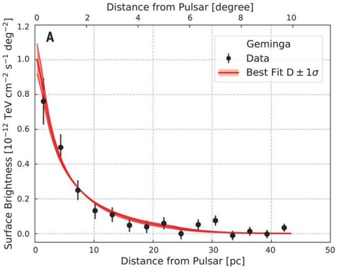
Content

Observations

Observations and Motivation







- Hints for strongly reduced diffusion coefficients observed in extended region around at least three PWNe [Abeysekara et al. 2017; Aharonian et al. 2021]

Open Questions

- Many open Questions:
  - What is the origin of the suppressed diffusion? [Evoli et al. 2018; Mukhopadhyay,Linden 2021; Fang et al. 2019]
  - How large is the suppressed diffusion region? [Di Mauro et al. 2019]
  - How strong is the suppression?
  - How common are these objects? [Giacinti et al. 2020; Sudoh et al. 2019, Martin et al. 2022]

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  - How strong is the suppression?
  - How common are these objects? [Giacinti et al. 2020; Sudoh et al. 2019, Martin et al. 2022]
- Viability of theories of their origin depends on size and amount of suppression
- Results of population studies of PWNe explaining the e^+ fraction might be influenced by the presence of halos
  - Without halos rather steep $e^{\pm}$ spectra with mean spectral indices $\gamma \sim 2.8$ are inferred [Evoli et al. 2021] while multiwavelength studies suggest ~ 2.5 $\Rightarrow$ effect of a common halo?

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Model

Model

- Goal: Infer a minimum halo size, minimally needed suppression and the spectral index range of pairs for the Geminga halo based on HAWC observations
- Use Greens function approach to solve transport equation of pairs analytically:

$$\frac{\partial n(E,r,t)}{\partial t} = \frac{1}{r^2}\partial_r(r^2 D(E,r)\partial_r n(E,r,t)) \\ + \partial_E\left(b(E)n(E,r,t)\right) + Q(E,r,t)$$

- With two different diffusion coefficients, inside and outside of halo
- Boundary conditions: $n_{in}(r_0) = n_{out}(r_0)$ and $D_{in}\partial_r n_{in}|_{r=r_0} = D_{out}\partial_r n_{out}|_{r=r_0}$

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- In the literature so far an incorrect two-zone model was used
  $\Rightarrow$ Difference becomes important for small halo size / large loss lengths or positron flux calculations [Osipov et al. 2020]
- Calculate LOS integral of γ-ray emission as well as total γ-ray flux and compare to data

Injection

- Spectra of $e^{\pm}$ released by bow shock PWNe are well fit by broken power laws [Bykov et al. 2017; Bucciantini et al. 2010]

$$Q(E,t) = Q_0(t) e^{-\frac{E}{E_c(t)}} \begin{cases} \left(\frac{E}{E_b}\right)^{-\gamma_L}, E < E_b \\ \left(\frac{E}{E_b}\right)^{-\gamma_H}, E_b < E \end{cases}$$

- Typically: $\gamma_L \sim 1 - 1.9$ and $\gamma_H \sim 2.5$, $E_b \sim 300 - 1000\,\mathrm{GeV}$ and potential drop $E_c \approx 300\,\mathrm{TeV}$ for Geminga today
- Normalization related to spin-down luminosity

$$\epsilon L(t) = \epsilon L_0 \frac{(1 + t_{age}/\tau_0)^{\frac{n+1}{n-1}}}{(1 + t/\tau_0)^{\frac{n+1}{n-1}}} := \int \mathrm{d}E\, Q(E,t)$$

- Here we fix $E_b = 1\,\mathrm{TeV}$ for Geminga and $\gamma_L = 1.5$ because they are degenerate with the injection efficiency and vary only γ_H
- Conversion efficiency of viable solutions is required to be $< 100\,\%$

Protons

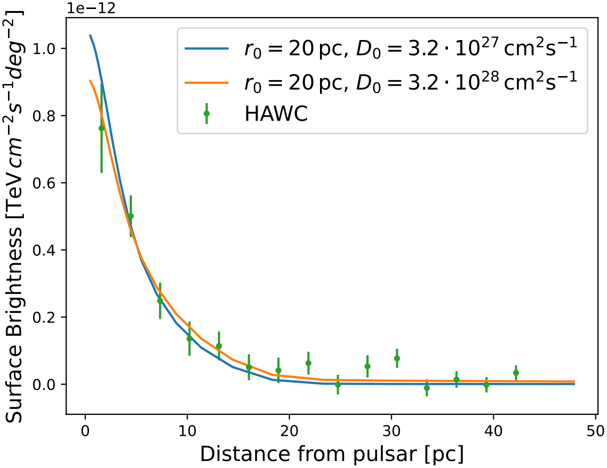
- Some models suggest that protons are stripped off the pulsar surface
$\Rightarrow$ monoenergetic injection of protons at the pulsar [Venkatesan et al. 1997; Blasi et al. 2000]:

$$Q_p(E_p, t) = \eta_p \dot{N}_{GJ}(t) \delta(E_p - E_c(t))\,,$$

- This leads to typically very hard spectra $\propto E^{-(n-1)/2}$ which gives E^{-1} for $n = 3$
- For the first time we consider that these protons can produce TeV γ-rays that might influence the inferred spectral index of electrons from observations
- Expected γ-rays dependent on gas density, here assumed as $1\,\mathrm{cm}^{-3}$

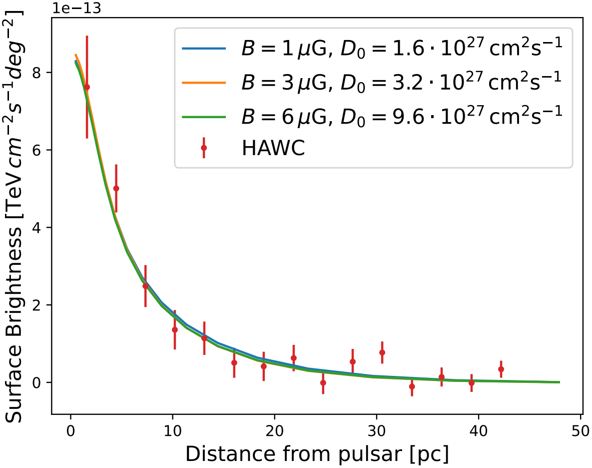
Results

Halo Size



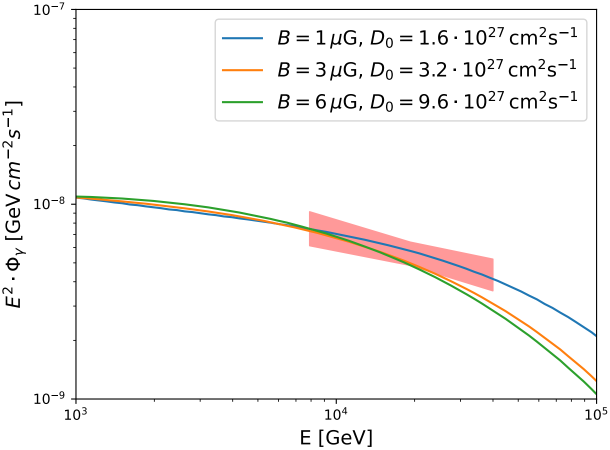
- Small halo size allows much larger diffusion coefficient

Different Magnetic Fields



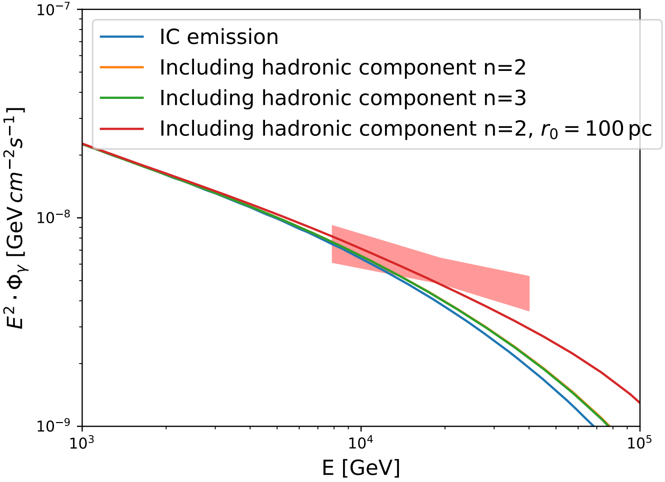
- Spatial profile depends only on loss length for large enough halos
  $\Rightarrow$ degenerate B and D_0

Total Flux



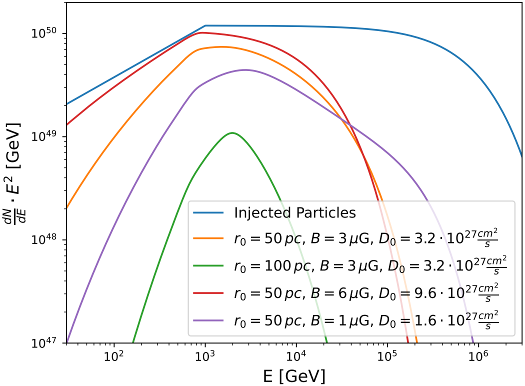
- Total flux gives way to disentangle equivalent spatial morphologies
- Explains why spectra harder than 2 were inferred in the past

Protons



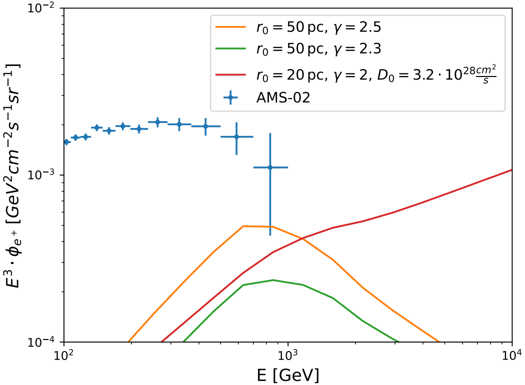
- Proton component might be important for large halos or small diffusion coefficients

Escape Flux



- Escape flux defined as: $\int_0^{t_{age}} \mathrm{d}t D \partial_r f|_{z=r_0}$
- Strongly influenced by halo size and magnetic field
- We obtain an effective cutoff after propagation that can be relevant for the positron fraction

Positron Flux



- Steeper spectra $\rightarrow$ higher contribution to local flux
- Data at higher energies will allow constrain on minimum halo size around Geminga
- New corrected model important

Conclusions

Conclusions

- Geminga Halo has to be at least 20 pc large
- Diffusion coefficient is uncertain by a factor of ~ 10 but still requires suppression of ~ 100
- Taking into account the total flux, small magnetic field with intermediately steep spectra $\gamma_e \sim 2 - 2.3$ are able to explain observations
- Contribution of protons most likely negligible, except for very large halos and/or small diffusion coefficients (small B)
- Future measurements of positron flux can rule out extremely small halo sizes
- Presence of halo steepens released spectra, possible explanation for inferred steep slope of population study

Appendix

Two Zone Model

- $$H(r,E,t) = \int_0^\infty \mathrm{d}\psi \frac{\xi e^{-\psi}}{\pi^2\lambda_0^2(A^2(\psi)+B^2(\psi))} \begin{cases} \frac{\sin(2\sqrt{\psi}\frac{r}{\lambda_0})}{r} & , 0 < r < r_0 \\ A(\psi)\frac{\sin(2\sqrt{\psi}\frac{r\xi}{\lambda_0})}{r} + B(\psi)\frac{\cos(2\sqrt{\psi}\frac{r\xi}{\lambda_0})}{r} & , r \geq r_0, \end{cases}$$

  with

  $$\begin{aligned} A(\psi) = \xi \cos(2\sqrt{\psi}\frac{r_0}{\lambda_0})\cos(2\xi\sqrt{\psi}\frac{r_0}{\lambda_0}) \\ + \sin(2\sqrt{\psi}\frac{r_0}{\lambda_0})\sin(2\xi\sqrt{\psi}\frac{r_0}{\lambda_0}) \\ + \frac{\lambda_0}{2\sqrt{\psi}r_0}(\frac{1-\xi^2}{\xi}\sin(2\sqrt{\psi}\frac{r_0}{\lambda_0})\cos(2\xi\sqrt{\psi}\frac{r_0}{\lambda_0}) \end{aligned}$$

  and

  $$B(\psi) = \frac{\sin(2\sqrt{\psi}\frac{r_0}{\lambda_0}) - A(\psi)\sin(2\xi\sqrt{\psi}\frac{r_0}{\lambda_0})}{\cos(2\xi\sqrt{\psi}\frac{r_0}{\lambda_0})},$$

Positron Flux