Detection of a gamma-ray halo around Geminga with the Fermi-LAT and implications for the positron flux

based on: M. Di Mauro (NASA), SM, F. Donato (University of Turin), arXiv:1903.05647

Silvia Manconi

June 5, 2019

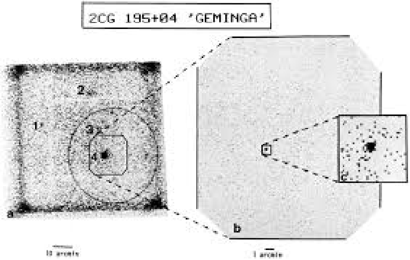
Photon 2019, LNF

Introduction

How we use photons in the GeV-TeV range detected from Galactic sources to constrain the origin of e^+ in cosmic-rays

GEMINGA, **Gemin**i **ga**mma-ray source (B0633+17)

- Pulsar: fast rotating neutron star
- Distance: 250 parsec
  (∼ 800 light years)
- Age: 340 kyr
- Particular signs: first radio-quiet pulsar; proper motion of 211 km/s



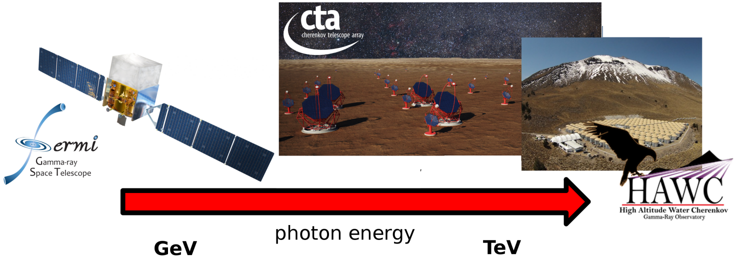
[Bignami+96]

MONOGEM (B056+14)

- Distance: 288 parsec
- Age: 110 kyr

Experiments and energy ranges

Gamma rays:



Charged cosmic rays:

Talk overview

Introduction

1. The cosmic-ray positron puzzle
2. Sources and propagation of cosmic-ray positrons in the Galaxy

Gamma-ray constraints on PWN contribution to cosmic-ray e^+

3. HAWC measurement of gamma-ray halos at TeV
4. First Fermi-LAT measurement of Geminga gamma-ray halo

Summary and Perspectives

Talk overview

Introduction

1. The cosmic-ray positron puzzle
2. Sources and propagation of cosmic-ray positrons in the Galaxy

Gamma-ray constraints on PWN contribution to cosmic-ray e^+

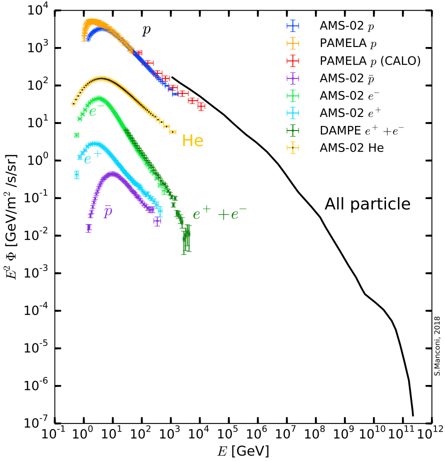
3. HAWC measurement of gamma-ray halos at TeV
4. First Fermi-LAT measurement of Geminga gamma-ray halo

Summary and Perspectives

Introduction

The flux of cosmic rays at the Earth

Cosmic-ray flux: dominated by *matter*: **e^+,$\bar{p}$ less than %**

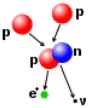


Up to 10^{15} eV: Galactic origin

Production of antimatter in cosmic-rays:

- "Standard / secondary": Spallation of hadronic cosmic-rays in the interstellar medium

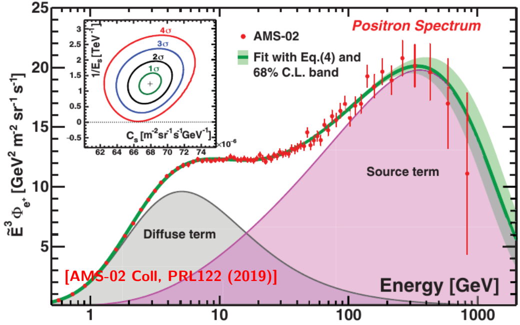
$$\mathrm{p_{CR}} + \mathrm{H_{ISM}} \rightarrow X + \pi^{\pm} \rightarrow \ldots$$



Deviation from standard expectation: **new source/phenomena**

The rise (and fall?) of the cosmic-ray positron flux

- 2008: PAMELA measures a rise in the positron fraction $e^+/(e^+ + e^-)$, lately confirmed by Fermi-LAT, AMS-02.
- The e^+ flux above about 10 GeV exceeds the predicted secondary component
- AMS-02 recently reported a sharp fall above about 300 GeV.



A new, primary source of e^+ in addition to secondaries is needed to explain data.

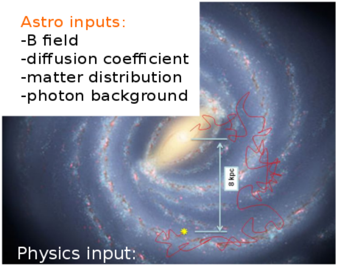
Modeling cosmic ray electrons and positrons

Cosmic ray sources

-acceleration mechanism
-source distribution
-source spectrum

Propagation

Astro inputs:
-B field
-diffusion coefficient
-matter distribution
-photon background



Physics input:
-cross sections
-EM interactions

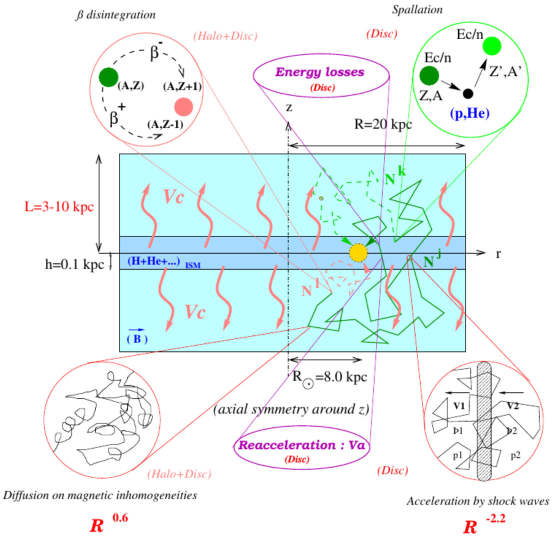
Earth

-propagated spectrum

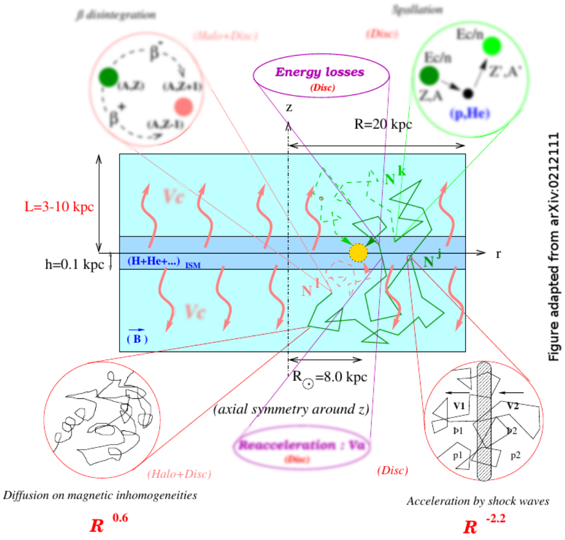
$$Q(E, \mathbf{x}, t) = \hat{D}\psi$$

$$\mathrm{sourceterm} = (\mathrm{Propagation})(\mathrm{FluxatEarth})$$

The Galaxy: view from a cosmic ray physicist



The Galaxy: view from a cosmic ray physicist



Dominant effects for $E_{e^\pm} > 10$ GeV:

-**Energy losses**: Synchrotron; Inverse Compton on Interstellar Radiation Fields

-**Diffusion (space)**: [Fermi'49, Chandrasekhar'43, Jones'90]
random scattering in B_{gal} irregularities $\Leftrightarrow$ spatial diffusion

-**Solar modulation**: [Strauss+2014]
sub-dominant for $E_{e^\pm} > 10 - 20$ GeV

Propagation of cosmic-ray $e^{\pm}$ in the Galaxy

Diffusion-loss equation for $e^{\pm}$

$$\frac{\partial \psi}{\partial t} - \nabla \cdot \{K(E)\nabla\psi\} + \frac{\partial}{\partial E}\left\{\frac{dE}{dt}\psi\right\} = Q(E, \mathbf{x}, t)$$

Propagation of cosmic-ray $e^{\pm}$ in the Galaxy

Diffusion-loss equation for $e^{\pm}$

$$\frac{\partial \psi}{\partial t} - \nabla \cdot \{K(E)\nabla\psi\} + \frac{\partial}{\partial E}\left\{\frac{dE}{dt}\psi\right\} = Q(E, \mathbf{x}, t)$$

Spatial diffusion

Random scattering in B_{gal} irregularities $\Leftrightarrow$ spatial diffusion $K(\mathbf{x}, \mathcal{R})$ in general $K_{//}, K_{\perp}$, but:
B inhomogeneities difficult to model
$\Rightarrow$ **isotropic** (see later...)

$$K(E) = K_0 E^{\delta}$$

-K_0, δ constrained by Sec/Primary cosmic-ray ratio, e.g. Boron/Carbon

Energy losses

$$\frac{dE}{dt} = b_{\mathrm{loss}}(E)$$

-Synchrotron on B_{gal}
-Inverse Compton on Interstellar Radiation Fields: CMB, Stellar,IR, UV

Propagation of cosmic-ray $e^{\pm}$ in the Galaxy

Diffusion-loss equation for $e^{\pm}$

$$\frac{\partial \psi}{\partial t} - \nabla \cdot \{K(E)\nabla\psi\} + \frac{\partial}{\partial E}\left\{\frac{dE}{dt}\psi\right\} = Q(E, \mathbf{x}, t)$$

Spatial diffusion

Random scattering in B_{gal} irregularities $\Leftrightarrow$ spatial diffusion $K(\mathbf{x}, \mathcal{R})$ in general $K_{//}, K_{\perp}$, but:
B inhomogeneities difficult to model
$\Rightarrow$ **isotropic** (see later...)

$$K(E) = K_0 E^{\delta}$$

-K_0, δ constrained by Sec/Primary cosmic-ray ratio, e.g. Boron/Carbon

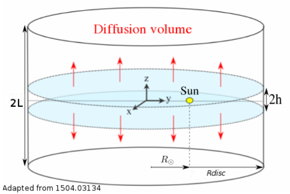
Energy losses

$$\frac{dE}{dt} = b_{\rm loss}(E)$$

-Synchrotron on $B_{\rm gal}$
-Inverse Compton on Interstellar Radiation Fields: CMB, Stellar,IR, UV

Solutions: Semi analytical approach

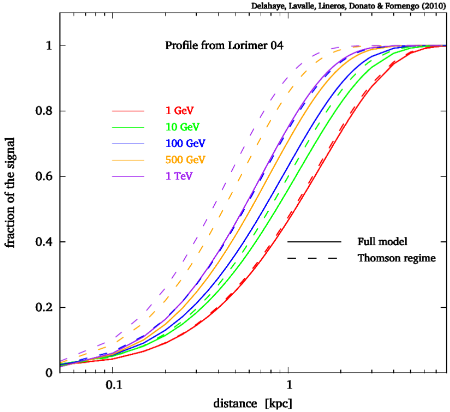
or **Numerical codes** GALPROP, DRAGON, USINE



Adapted from 1504.03134

GeV-TeV $e^{\pm}$ probe the few kpc near the Earth

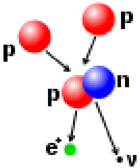
For GeV-TeV $e^{\pm}$ the **energy loss timescale is smaller than the diffusion one.**



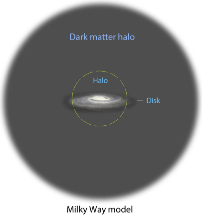
- 80% of flux at Earth at 1 TeV is produced at less than 1kpc
- $E_{e^{\pm}} \gtrsim 10$ GeV: typical propagation scale $\lambda < 5$ kpc
- Importance of modeling the **local sources** of cosmic rays

Cosmic-ray $e^{\pm}$ sources in the Galaxy

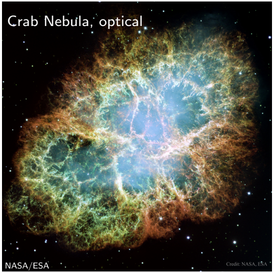
Spallation of hadronic cosmic rays in the interstellar medium ($e^{\pm}$)



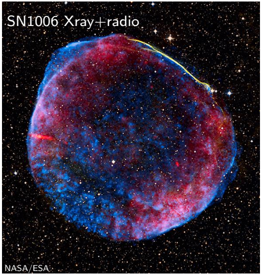
Dark matter annihilation/decay ($e^{\pm}$)



Pulsar Wind Nebulae(PWNe)($e^{\pm}$)



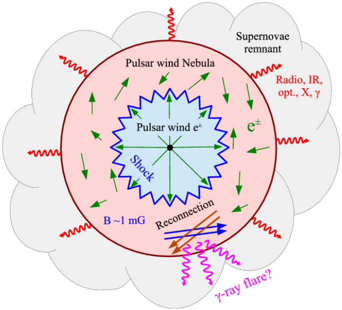
Supernova Remnants (SNRs) (e^{-})



Pulsar Wind Nebulae as cosmic-ray $e^{\pm}$ sources

Engine of Pulsar Wind Nebula (PWN): pulsar, fast rotating magnetized neutron star from collapse of $> 8\ M_{\odot}$ star

- High magnetic fields $\sim 10^9 - 10^{12}$ G: wind of particles extracted from the surface, $e^{\pm}$ **pairs produced** in EM cascades
- **Pulsar Spin-down energy (W_0) transfered to** $e^{\pm}$ **pairs** accelerated up to very high-energies, $Q(E) \propto E^{-\gamma}$
- After few kyrs: $e^{\pm}$ **pairs possibly released** in interstellar medium
- Relativistic $e^{\pm}$ pairs in PWNe shines from radio to gamma rays

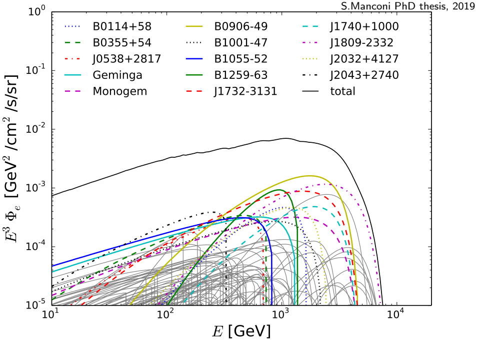


Important parameters for $e^{\pm}$:
Spectral index of $e^{\pm}$ distribution (γ), conversion efficiency of W_0 in $e^{\pm}$ pairs (η)

Cosmic ray $e^{\pm}$ flux from pulsars in source catalogs

Assume that each pulsar has powered a PWN in the past, and produced $e^{\pm}$

1. Pulsars are numerous in our Galaxy: 1000+ sources in the catalogs
2. Few nearby candidates: e.g. Geminga and Monogem at $d < 500$ pc



Uncertainties: acceleration, release in the interstellar medium, spectrum of $e^{\pm}$...

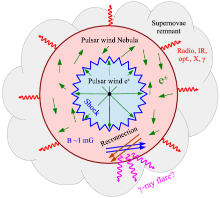
Multimessenger constraints!

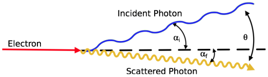
Multi-wavelenght emission in PWNe

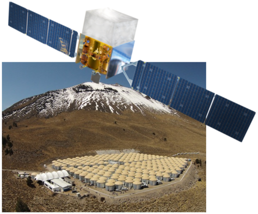
$e^{\pm}$ of GeV-TeV energies suffer significant **energy losses** by Inverse Compton scattering and synchrotron emission.

- $e^{\pm}$ pairs accelerated and emitted by PWNe loose energy, and give origin to a cascade of photons in a broad range of frequency

By modeling the intensity and distribution of photon emission in $e^{\pm}$ sources we learn about the properties of the $e^{\pm}$ they accelerate.







GeV-TeV photon emission from Inverse Compton scattering in HAWC and Fermi-LAT data.

Gamma-ray constraints on PWN contribution to cosmic-ray e^+

Geminga: one of the most studied nearby pulsars

AN IDENTIFICATION FOR "GEMINGA" (2CG 195+04) 1E 0630+178: A UNIQUE OBJECT IN THE ERROR BOX OF THE HIGH-ENERGY GAMMA-RAY SOURCE[1]

G. F. BIGNAMI AND P. A. CARAVEO
Istituto di Fisica Cosmica del C. N. R., Milano

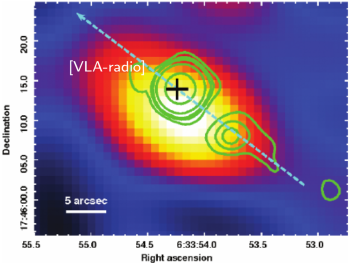
AND

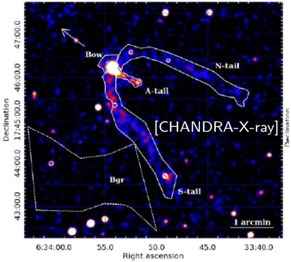
R. C. LAMB
Iowa State University

[2] The reader may be puzzled about the origin of the name "Geminga": this source is in the constellation of *Gemin*i and it is a *ga*mma-ray source. Pronounced with both G's as in "get," the word means "does not exist" or "it's not there" in Milanese dialect.

Geminga: one of the most studied nearby pulsars

- Pulsar (point-like): first radio-quiet discovered [Bignami+Apj83]
- Pulsar Wind Nebula in X-rays and Radio **(arcsec-arcmin angular scale)**:



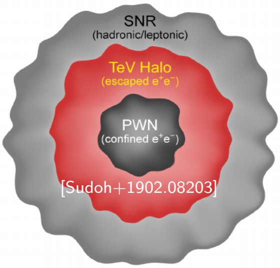


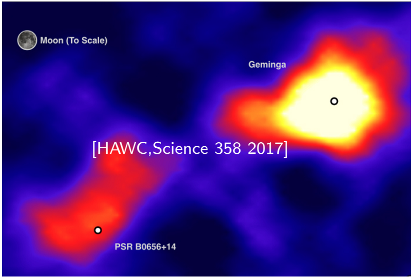
- Bow-shock PWNe: proper motion $v_T \sim 211$ (d/250pc) km s^{-1} consequences for X-ray ang GeV gamma-ray morphology (see later)

Extended Gamma-ray halo of Geminga and Monogem

The HAWC recently detected a **few-degrees extended γ-ray emission** at $E > 5$ TeV around Geminga and Monogem pulsars [HAWC Collaboration, Science 358 2017].

- First evidence of $e^{\pm}$ diffusing away from the pulsar and up-scatter CMB photons, **inverse Compton emission**



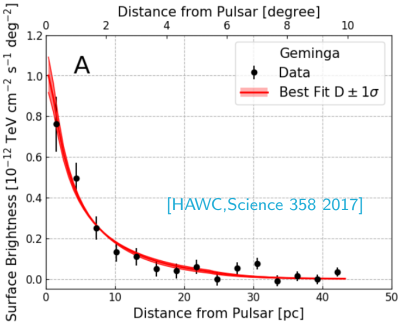


Interpreted as $e^{\pm}$ accelerated, and then released in the interstellar medium, from the PWNe.

Strong support to PWNe as e^{+} sources.

What we learn from HAWC discovery?

1. **Efficiency of conversion of pulsar spin-down energy in high-energy $e^{\pm}$** is $\eta = 40(4)\%$ for Geminga (Monogem) for $\gamma_{e^{\pm}} = 2.3$
2. **Diffusion in the vicinity of Geminga and Monogem is inhibited**
   - HAWC finds $K(1\ \mathrm{GeV}) \sim 7 \times 10^{25}\mathrm{cm}^2/\mathrm{s}$
     $\sim$ 500 times smaller than the average value in the Galaxy

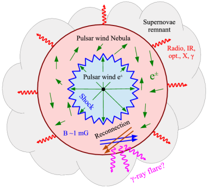


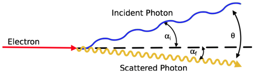
←Gamma-ray emission intensity profile (surface brightness): how $e^{\pm}$ diffuse away from the pulsar

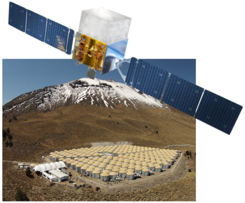
Beyond HAWC: the role of Fermi-LAT (I)

- HAWC measures gamma-rays of 5-40 TeV $\Rightarrow$ produced by Inverse Compton of $e^{\pm}$ of at least tens of TeV
- AMS-02 e^{+} excess is between $\sim$10-500 GeV
- $\Rightarrow$ using HAWC to predict e^{+} at AMS-02 energies *is an extrapolation*

In Di Mauro, SM, Donato, arXiv:1903.05647 we search for the first time for a counterpart of Geminga and Monogem halos seen by HAWC in Fermi-LAT data



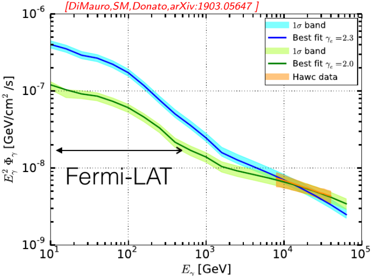




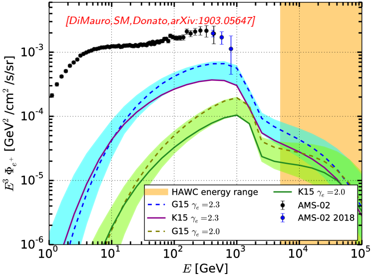
Beyond HAWC: the role of Fermi-LAT (II)

We use the HAWC results to calibrate:

Spectral energy distribution of Inverse Compton emission



e^+ flux at Earth



HAWC data alone cannot constrain the contribution to the e^+ flux

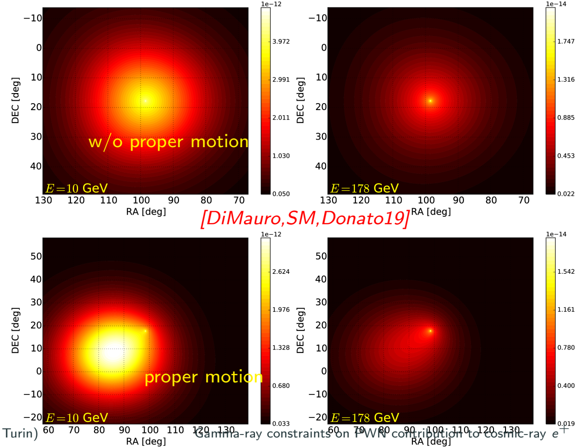
Role of Fermi-LAT data:

1. **test the extrapolation of HAWC results** to lower gamma-ray energies
2. **discriminate between different spectral index** γ_e of the e^+ distribution

Setup for Fermi-LAT data analysis

- 115 months of Fermi-LAT data in the energy range [8,1000] GeV
- Region of Interest of 70deg x 70deg: extension is predicted to increase at GeV

We account for the energy dependence of the spatial morphology of Inverse Compton emission by creating templates for $K(1\ \mathrm{GeV})$ in the range $10^{25} - 10^{29}\mathrm{cm}^2/\mathrm{s}$:



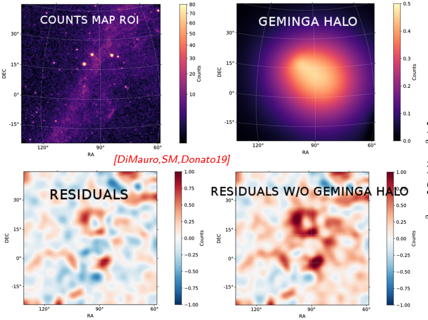
[DiMauro,SM,Donato19]

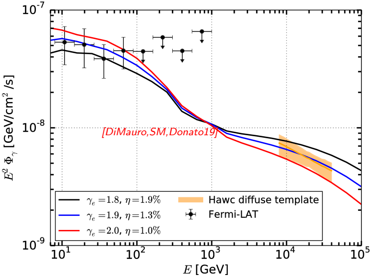
Geminga halo in Fermi-LAT data... it's there!

We detect Geminga extended emission in Fermi-LAT data:

- **7.8-11.8σ significance** depending on background emission model
- Diffusion $K(1GeV) = 1.6 - 3.5 \times 10^{26}$ cm^2/s, compatible within 2σ with HAWC
- Size of ~ 60 **pc at 100 GeV**, $\gamma_{PWN} = 1.8 - 2$

Inverse Compton emission from $e^{\pm}$ accelerated and escaped from PWN.

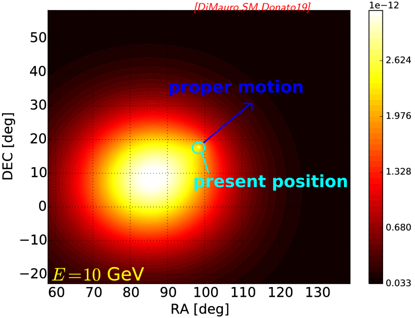




Monogem halo is not significantly detected: upper limits.

Proper motion of Geminga pulsar

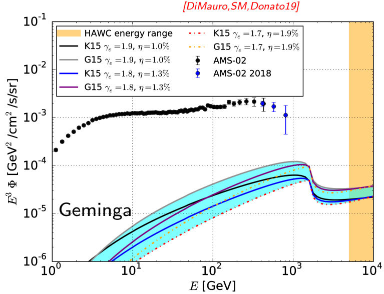
- Geminga pulsar has a proper motion, with transverse velocity of $v_t \sim 211$km/s [Faherty+AS07]: ~ 70 pc across its age
- Transverse velocity affects significantly morphology of Geminga halo gamma-ray emission at $E < 100$ GeV

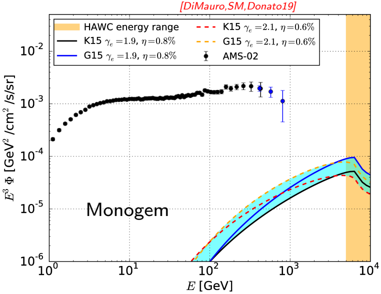


Model fit with proper motion preferred at least at 4σ: our analysis is unique in gamma-ray astronomy, we detected a source moving across the sky

Consequences for the cosmic e^+ flux at Earth (I)

We compute Geminga and Monogem e^+ flux using results of Fermi-LAT (η, γ_e) within **two-zone diffusion model**: inhibited diffusion $r_b < 60$ pc, $\sim$ angular size of Geminga at 100 GeV





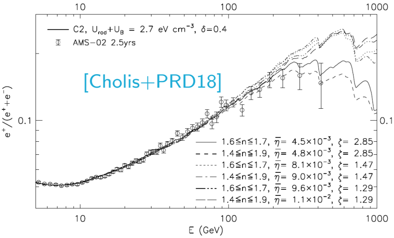
- Geminga contributes 1% (10%) to e^+ at 100 GeV (800 GeV); Monogem at most 3%

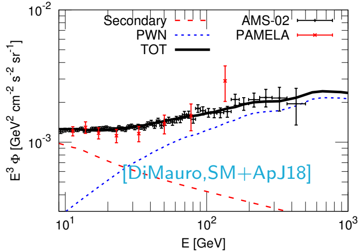
Geminga and Monogem alone, as constrained by Fermi-LAT, cannot be major contributors to e^+ excess

Consequences for the cosmic e^+ flux at Earth (II)

Geminga and Monogem are not the only PWNe in our Galaxy.

- The authors of [Cholis+PRD18] found that an efficiency of 1-3% for the conversion of pulsar spin down in $e^\pm$ pairs considering a smooth Galactic distribution of PWN (including nearby source stochasticity) can explain the e^+ excess
- Previous studies considering PWNe in the ATNF catalog [DiMauro+JCAP14,Manconi+JCAP17,DiMauro,SM+ApJ18] also find similar values





The cumulative e^+ emission from Galactic PWNe remains a viable interpretation for the e^+ excess

Summary and Perspectives

Summary

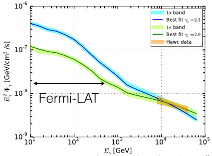
- Interpretation of cosmic-ray e^+ flux at Earth requires a primary source of e^+ at $E \gtrsim 10$ GeV
- Pulsars and their nebulae (PWNe) are the most promising candidates to explain the observed e^+
- HAWC detected an extended gamma-ray halo from Geminga and Monogem, two close PWNe: evidence for gamma-rays from Inverse Compton scattering from accelerated $e^\pm$

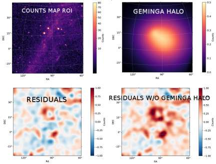
Summary

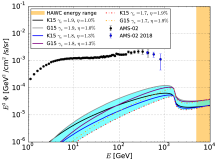
- Interpretation of cosmic-ray e^+ flux at Earth requires a primary source of e^+ at $E \gtrsim 10$ GeV
- Pulsars and their nebulae (PWNe) are the most promising candidates to explain the observed e^+
- HAWC detected an extended gamma-ray halo from Geminga and Monogem, two close PWNe: evidence for gamma-rays from Inverse Compton scattering from accelerated $e^\pm$

Results:

- A counterpart of the Geminga halo is detected in Fermi-LAT data
- Diffusion is inhibited around pulsars; diffusion coefficient around Geminga is $K(1GeV) = 1.6 - 3.5 \times 10^{26}$ cm^2/s
- Fermi-LAT and HAWC data are used to constrain the contribution of these PWNe to the e^+ flux
- Geminga and Monogem, as constrained from Fermi-LAT, contribute at most 10% to the flux of e^+ at 800 GeV

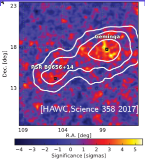


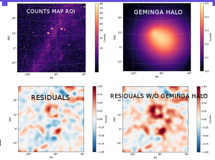




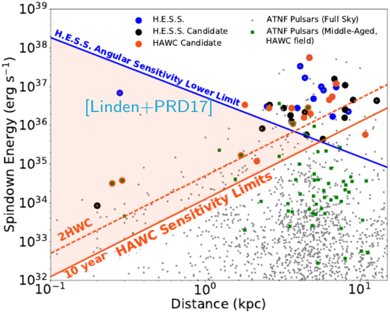
Multi-wavelength/messenger for cosmic ray $e^{\pm}$ sources

Application of multi-wavelength and multi-messenger approach to constrain the origin of e^{+} flux and cosmic ray emission models from PWNe.





PWNe gamma-ray halos are a **new and promising** source class: New halos discovered by HAWC, more (O(30) [Linden+PRD17]) expected in the next years!



HAWC detection of TeV emission near PSR B0540+23

ATel #10941; *Colas Riviere (University of Maryland), Henrike Fleischhack (Michigan Technological University), Andres Sandoval (Universidad Nacional Autonoma de Mexico) on behalf of the HAWC collaboration*
on 9 Nov 2017; 23:11 UT
Credential Certification: Colas Riviere (riviere@umd.edu)

Subjects: Gamma Ray, TeV, VHE, Pulsar

Tweet

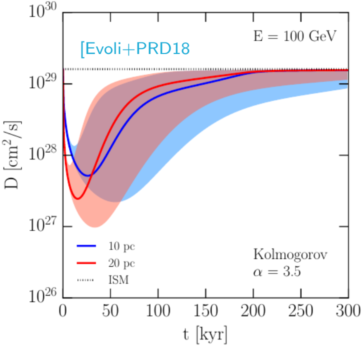
The High Altitude Water Cherenkov (HAWC) collaboration reports the discovery of a new TeV gamma-ray source HAWC J0543+233. It was discovered in a search for extended sources of radius 0.5° in a dataset of 911 days (ranging from November 2014 to August 2017) with a test statistic value of 36 (6σ pre-trials), following the method presented in Abeysekara et al. 2017, ApJ, 843, 40. The measured J2000.0 equatorial position is RA=85.78°, Dec=23.40° with a statistical uncertainty of 0.2°. HAWC J0543+233 was close to passing the selection criteria of the 2HWC catalog (Abeysekara et al. 2017, ApJ, 843, 40, see HAWC J0543+233 in 2HWC map), which it now fulfills with the additional data.
HAWC J0543+233 is positionally coincident with the pulsar PSR B0540+23 (Edot = 4.1e+34 erg s-1, dist = 1.56 kpc, age = 253 kyr). It is the third low Edot, middle-aged pulsar announced to be detected with a TeV halo, along with Geminga and B0656+14. It was predicted to be one of the next such detection by HAWC by Linden et al., 2017, arXiv:1703.09704.
Using a simple source model consisting of a disk of radius 0.5°, the measured spectral index is -2.3 ± 0.2 and the differential flux at 7 TeV is (7.9 ± 2.3) × 10^-15 TeV-1 cm-2 s-1. The errors are statistical only. Further morphological and spectral analysis as well as studies of the systematic uncertainty are ongoing.

Bright future in gamma-rays (CTA, AMEEGO), cosmic rays (full dataset of DAMPE, CALET)

Multi-wavelength/messenger for cosmic ray $e^{\pm}$ sources

PWNe gamma-ray halos many interesting roads ahead:

- Search for counterpart in other wavelengths: radio, X-rays
- Constrain and refine production and emission models of cosmic $e^{\pm}$ from PWNe
- Study propagation of cosmic rays around sources
- Other evidence of inhomogenous diffusion in the Galaxy (H,He breaks)



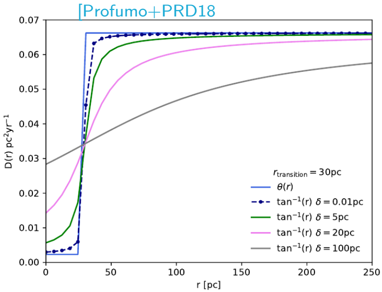


figure: Diffusion coefficient around PWNe as a function of source age and distance

Thank you!

BACKUP

The quest for the interpretation of the e^+ flux

Different sources have been invoked in the literature.
A (not at all exhaustive) view of the main proposals:

Dark matter annihilation /decay: interpretations and constraints:

[Baltz+PRD98],[Hooper+JCAP09], [Ibarra+JCAP09], [Bertone+JCAP09], [Cirelli+NPB09],[Kopp,PRD13] [Cirelli+PRD14],[Lin+,PRD15],[Cheng+,JCAP17]....

Production in Supernova Remnants:

[Blasi+PRL09], [Ahlers+PRD09], [Mertsch+PRD14], [Cholis+PRD14] , ...

Production and acceleration in Pulsars and their nebulae:

[Chi+ApJL96], [Boulars+ApJ89], [Malyshev+,PRD09] [Pato+JCAP10],[Profumo,CEJP11] [Serpico2012], [Linden+ApJ13], [Cholis+PRD13], [Boudad+A&A15],[DiMauro+JCAP14,JCAP16], ...

Modification of secondary production mechanism:

[Mertsch+,PRL09], [Cholis+PRD14], [Tomassetti+ApJ15], ...

Reviews: [Serpico 2012,2018], [Bykov+,SSR17] (PWN)

What we learn from HAWC discovery (I)

(I) **Estimate efficiency of conversion of pulsar spin-down energy in high-energy $e^{\pm}$**

Assuming that all the observed gamma-ray luminosity of Geminga and Monogem ([8,40] TeV $\sim 10^{32}$ ergs per second) is produced by relativistic $e^{\pm}$ emitted by the PWNe, they infer $e^{\pm}$ properties.

Total energy emitted in $e^{\pm}$ from the PWNe, continous injection:

$$E_{e^{\pm}} = \int dt\, dE\, E\, Q(E,t) = \eta W_0$$

We know pulsar spin-down W_0, $\Rightarrow$ we infer efficiency η!

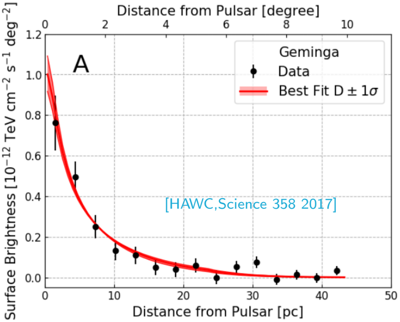
HAWC finds $\eta = 40(4)\%$ for Geminga (Monogem) and using $\gamma_{PWN} = 2.3$

[HAWC Collaboration, Science 358 2017]

What we learn from HAWC discovery (II)

(II) Diffusion in the vicinity of Geminga and Monogem is inhibited.

Gamma-ray emission intensity profile (= surface brightness): how $e^{\pm}$ diffuse away from the pulsar



HAWC finds $K(1\ \mathrm{GeV}) \sim 7 10^{25}\mathrm{cm}^2/\mathrm{s}$ ($K(E) = K_0(E/1\ \mathrm{GeV})^{-0.33}$)): $\sim$ 500 times smaller than the average value in the Galaxy (inferred e.g. from cosmic-ray B/C)

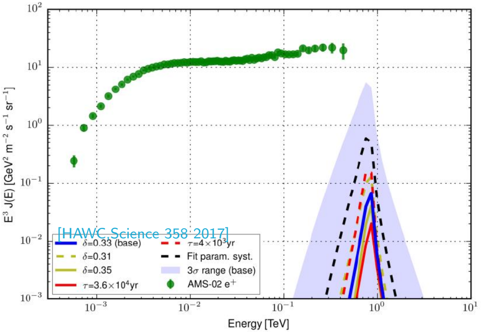
For average Galactic value of $K(E)$: angular extent of gamma-ray halo would be 10 times larger: 20deg, undetectable by HAWC [Hooper+PRD17]

Evidence for inhomogeneos diffusion in the Galaxy, see [Evoli+PRD18] for theoretical models

What we learn from HAWC discovery (III)

(III) *"We demonstrate that the lepton emitted by Geminga and Monogem are therefore unlikely to be the origin of the excess of positrons, which may have a more exotic origin"* [HAWC,Science17]

Assuming the same diffusion coefficient found around the sources to diffuse e^+ to the Earth:

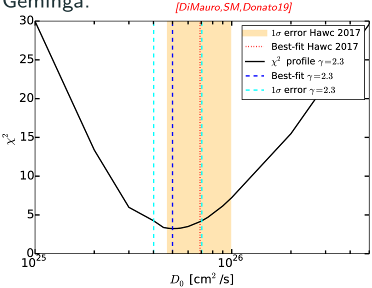


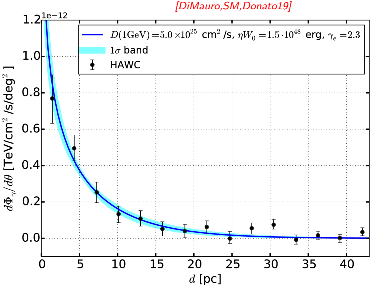
However, the extension of gamma-ray emission is $\sim 1\%$ of the propagation volume.
Using the mean value of $K(1\ \mathrm{GeV})$ in the Galaxy, [Hooper+PRD17, Profumo+PRD18] extimate the contribution of Geminga to more than $\sim 10\%$ of AMS-02 e^+ data.

Analysis of HAWC data: fit to surface brightness

- We fit HAWC surface brightness for Geminga and Monogem

Geminga:

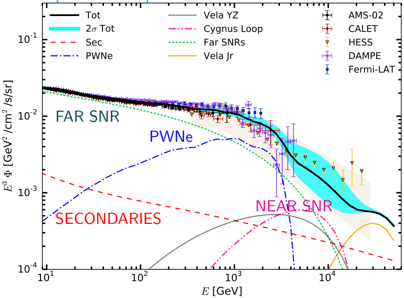




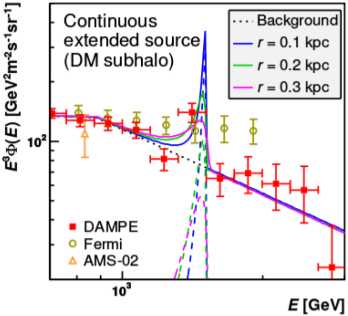
- We find $K(1\text{ GeV}) = 5.0^{+2.0}_{-1.0} \times 10^{25}\text{cm}^2/\text{s}$ and $\eta W0 = 1.5 \times 10^{48}$ erg for Geminga and $K(1\text{ GeV}) = 2.5^{+3.3}_{-2.1} \times 10^{26}\text{cm}^2/\text{s}$ and $\eta W0 = 4.2 \times 10^{46}$ erg for Monogem using spectral index for $e^\pm$ of $\gamma_{PWN} = 2.3$
- Results are compatible with [HAWC Collaboration, Science 358 2017]
- Similar results using spectral index for $e^\pm$ $\gamma_{PWN} = 2$ (see backup)

Interpretation of cosmic-ray electron and positron data

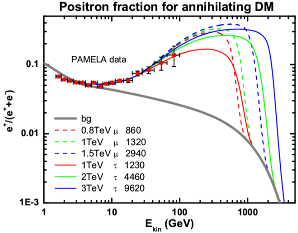
[Manconi+18]



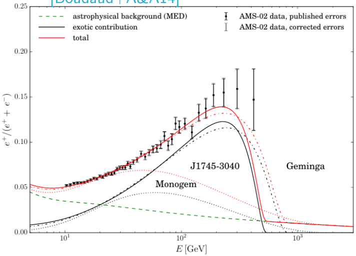
[Huang+17]



[Liu+09]



[Boudaud+A&A14]

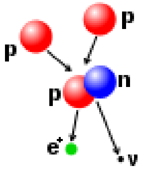


Spallation of hadronic cosmic-rays in the interstellar medium

Interstellar medium: gas (mainly H and He, 10:1), 0.5-1% of dust

- Cosmic-ray nuclei (p, He) spallation on the H, He
- Dominant mechanism for $e^{\pm}$ production above few GeV:

$$\mathrm{p_{CR}} + \mathrm{H_{ISM}} \rightarrow X + \pi^{\pm} \rightarrow \ldots$$



Source term: [Delahaye+A&A 2009]

$$Q_{\rm sec}(\mathbf{x}, E_e) = 4\pi \, n_{\rm ISM}(\mathbf{x}) \int dE_{\rm CR} \Phi_{\rm CR}(\mathbf{x}, E_{\rm CR}) \frac{d\sigma}{dE_e}(E_{\rm CR}, E_e)$$

interstellar gas density
$n_{\rm ISM} \sim 1$ cm^{-3}

primary flux
$\Phi_{\rm CR}$ (p, He) from AMS-02 data

inclusive cross section parametrization, ex. [Kamae+2006]

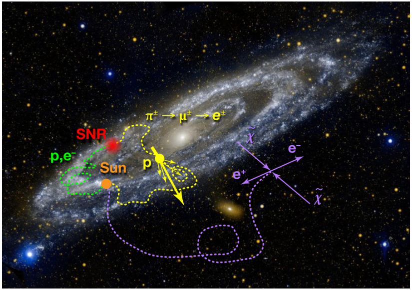
$\Rightarrow$ Uncertainties coming from cross section parametrization, [Delahaye+A&A08,Reinert+JCAP18]

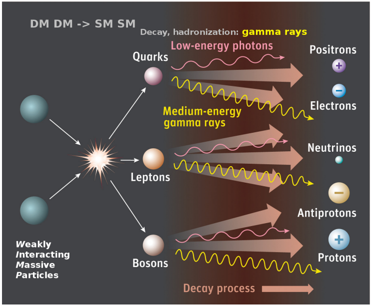
Galactic dark matter

Overwhelming evidence that dark matter is required to explain distribution and amount of structures, from Galactic to cosmological scales.
It accounts for the $\sim 85\%$ of matter content of the universe.

Indirect detection of dark matter signals: spectral distortions, anomalous components in cosmic-rays:

$$\chi + \chi \rightarrow q\bar{q}, \tau^+\tau^-, ... \rightarrow \gamma, e^+, \nu, \bar{p}...$$





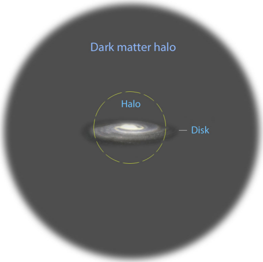
Weakly Interacting Massive Particles with $m_{\mathrm{DM}} \sim$ GeV-TeV as benchmark, but also MeV [Boudaud+PRL17]

Galactic dark matter

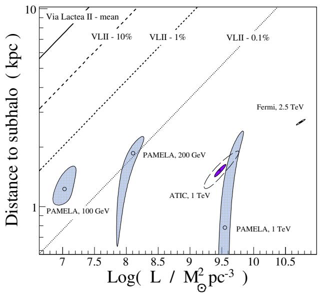
Galactic dark matter halo:

$$Q_{\mathrm{DMhalo}}(\mathbf{x}, E) = \frac{1}{2} < \sigma v > \left(\frac{\rho_{\mathrm{DM}}(\mathbf{x})}{m_{DM}}\right)^2 \frac{dN_{e^\pm}}{dE}$$

Subhalos: predicted by N-body simulations.
Nearby and dense substructures may led to signatures...



Milky Way model

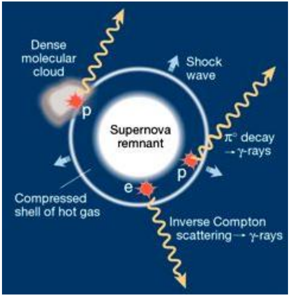


However...

- Subhalos explaining all e^+ data are disfavored according to cosmological simulation [Brun+2009]
- Tipycal $< \sigma v >$, m_{DM} required to explain all $e^\pm$ data tested by other indirect searches, e.g. gamma-rays
- Exotic mechanism required, ex. [Cai+JHEP2018], [Demir+PRD10], [Cholis+PRD09]
- **Background from other astrophysical sources**

Supernova Remnants

Supernova remnants are considered as main sources of cosmic-rays (p, e^-) in the Galaxy.



- **Fermi diffusive shock acceleration**
  see particle-in-cell simulations [Crumley+ApJ 2017]
- *Evidence*: γ from π_0,"pion bump" [FermiLAT+2010], radio from e^-
- *Injection spectrum*:

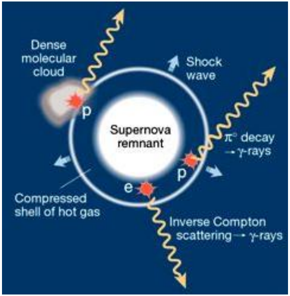
$$Q(E) = Q_{0,\mathrm{SNR}} \left(\frac{E}{E_0}\right)^{-\gamma_{\mathrm{SNR}}} \exp\left(-\frac{E}{E_c}\right)$$

Supernova Remnants

Supernova remnants are considered as main sources of cosmic-rays (p, e^-) in the Galaxy.

- **Fermi diffusive shock acceleration**
  see particle-in-cell simulations [Crumley+ApJ 2017]
- *Evidence*: γ from π_0,"pion bump" [FermiLAT+2010], radio from e^-
- *Injection spectrum*:

$$Q(E) = Q_{0,\mathrm{SNR}} \left(\frac{E}{E_0}\right)^{-\gamma_{\mathrm{SNR}}} \exp\left(-\frac{E}{E_c}\right)$$



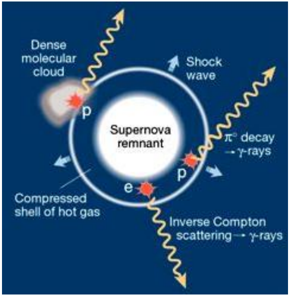
- **Constraints to $Q_{0,\mathrm{SNR}}$, γ_{SNR}:**
  synchrotron radiation (single SNRs, see [Manconi+2018])

Supernova Remnants

Supernova remnants are considered as main sources of cosmic-rays (p, e^-) in the Galaxy.

- **Fermi diffusive shock acceleration**
  see particle-in-cell simulations [Crumley+ApJ 2017]
- *Evidence*: γ from π_0,"pion bump" [FermiLAT+2010], radio from e^-
- *Injection spectrum*:

$$Q(E) = Q_{0,\mathrm{SNR}} \left(\frac{E}{E_0}\right)^{-\gamma_{\mathrm{SNR}}} \exp\left(-\frac{E}{E_c}\right)$$

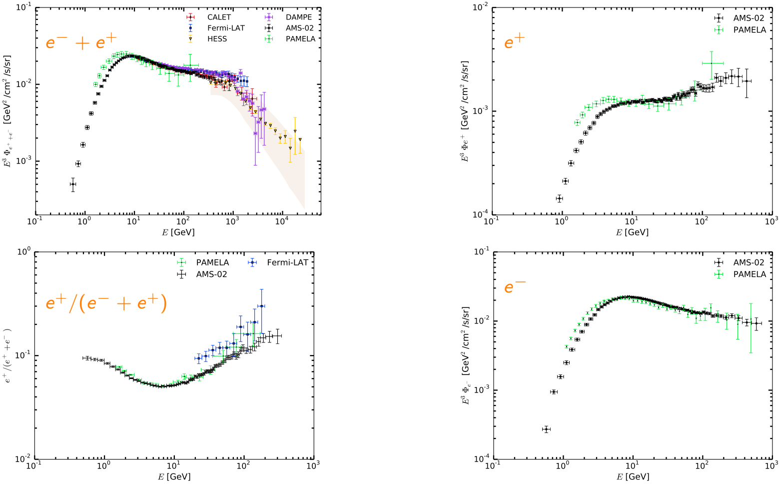


- **Constraints to $Q_{0,\mathrm{SNR}}$, γ_{SNR}:**
  synchrotron radiation (single SNRs, see [Manconi+2018])

- Antimatter production ($\bar{p}$, e^+): particles accelerated at SN shock produce secondary particles through (mainly) hadronic interactions [Blasi PRL09]
  This effect should produce also a rise of secondary over primary ratios, ex. B/C [Cholis+PRD14]

Cosmic-ray electron and positron data: present status

Unprecented energy coverage, high statistical accuracy

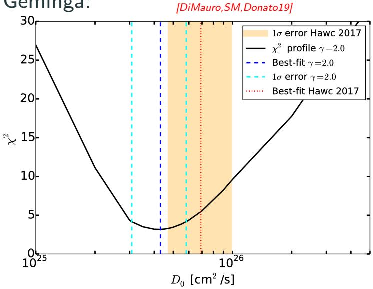


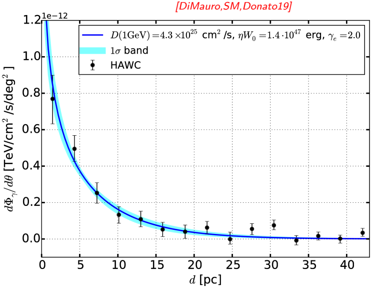
Spectral characteristics are the result of different mechanisms and source classes

Analysis of HAWC data: fit to surface brightness

- We fit HAWC surface brightness for Geminga and Monogem

Geminga:





- Results are compatible with [HAWC Collaboration, Science 358 2017]
- Similar results using spectral index for $e^{\pm}$ $\gamma_{PWN} = 2.3$