UNIVERSITÀ
DEGLI STUDI
DI TORINO

Istituto Nazionale di Fisica Nucleare

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

based on:

M. Di Mauro, SM, F. Donato , arXiv:1903.05647

Silvia Manconi

July 31, 2019

ICRC 2019, Madison WI

Outline

1. The cosmic-ray e^+ excess and the HAWC measurement of extended halos around pulsars

2. First detection of GeV counterpart of Geminga halo with *Fermi*-LAT
   M. Di Mauro, SM, F. Donato , arXiv:1903.05647

3. Perspectives

GeV-TeV gamma-rays detected from Galactic sources to constrain the origin of e^+ in cosmic-rays.

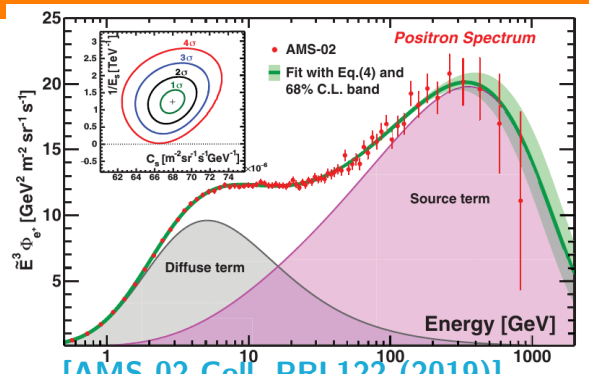
Introduction: cosmic-ray e^+ at Earth

1. e^+ **excess** PAMELA, AMS-02 data:
   flux above 10 GeV exceeds secondary component
   CRD2h Weng, H9 Bertucci

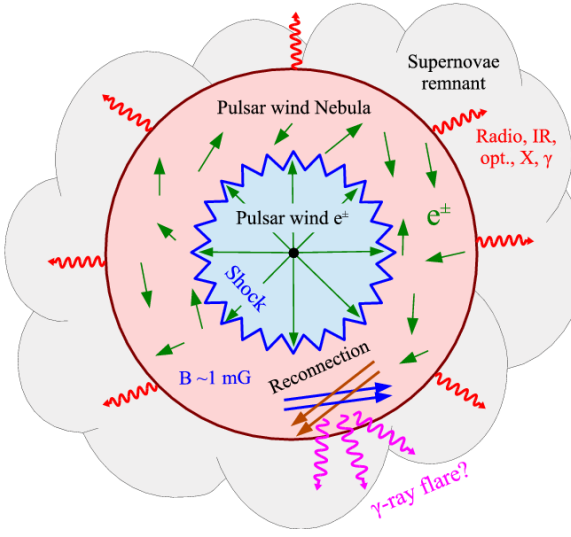
2. e^+ **probe local Galaxy**: severe energy losses
   for $E_{e^\pm} \gtrsim 10$ GeV: typical propagation scale $\lambda < 5$ kpc

3. **Pulsars and their nebulae (PWNe)**:
   main candidates to explain e^+ excess
   CRD2g Donato, RE3 Linden, CRD1c Fornieri, CRI9c Lopez-Coto

4. **Nearby PWNe**: Geminga, Monogem, $d < 500$ pc
   Uncertainties: $e^\pm$ acceleration, release, energy spectrum... **Multimessenger constraints!**
   GAI7c Fang, GAI11e Smith, GAI2c Giacinti



[AMS-02 Coll, PRL122 (2019)]

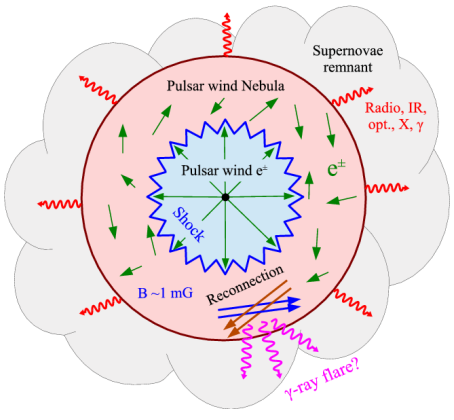


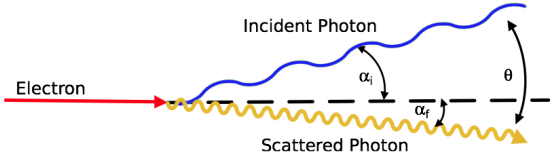
Multi-wavelenght emission in PWNe

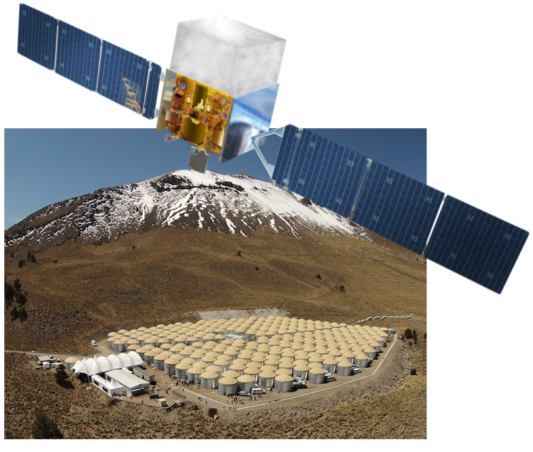
$\Rightarrow$ $e^{\pm}$ pairs accelerated by PWNe loose energy by Inverse Compton scattering, synchrotron emission:

cascade of photons in a broad range of frequency

Modeling intensity, distribution of photon emission in PWNe: properties of accelerated $e^{\pm}$





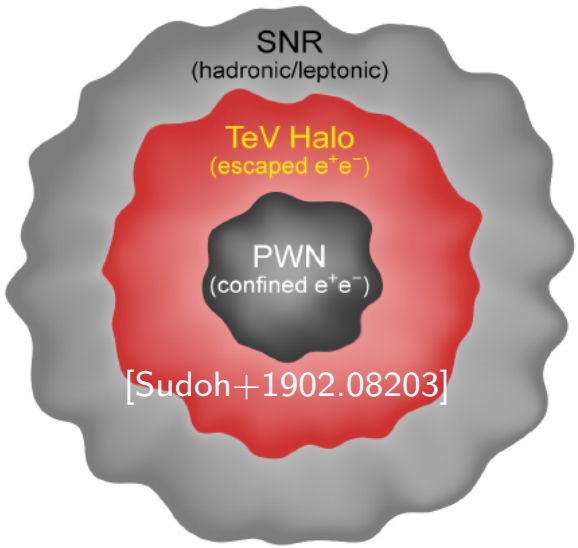


- Traditionally applied to pulsar, PWNe emission: *arcmin-arcsec scale*
- **GeV-TeV Inverse Compton emission in HAWC, Fermi-LAT data:** *few-degree scale*

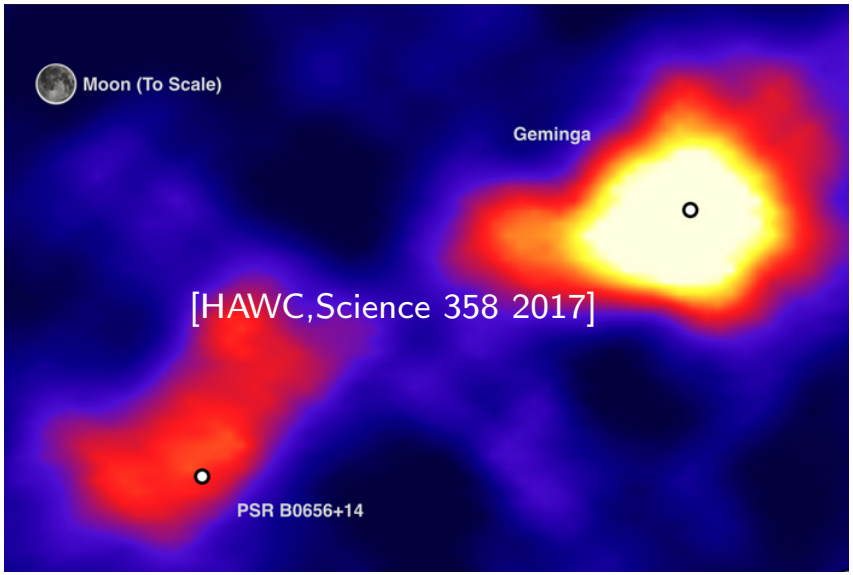
Extended γ-ray halo of Geminga and Monogem

HAWC detects **few-degrees extended γ-ray emission** at $E > 5$ TeV around **Geminga** and **Monogem** pulsars [HAWC Collaboration, Science 358 2017]
MILAGRO observed similar extended Geminga emission at 1-100 TeV. [Abdo+ApJL09]

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



$\sim$ 20 pc extension around Geminga



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

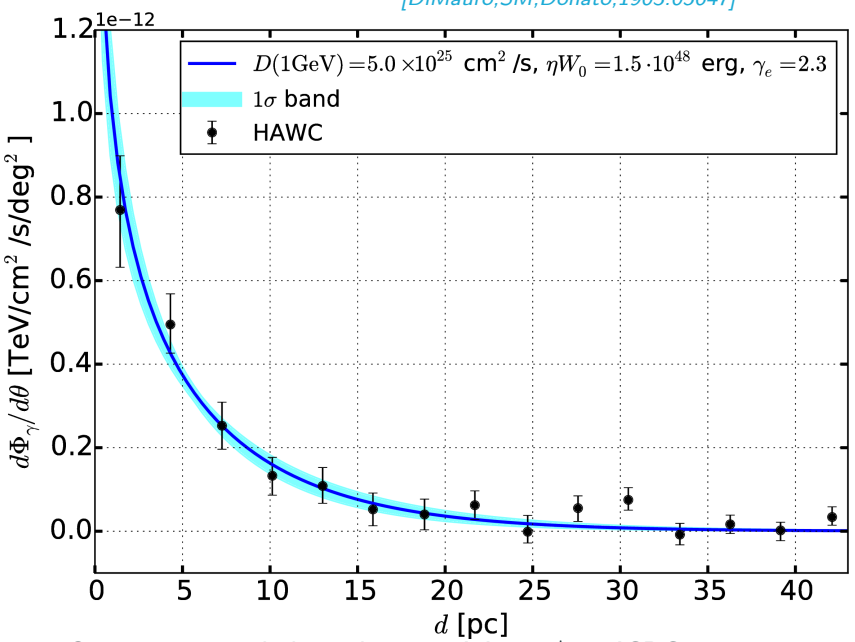
Strong support to PWNe as e^{+} sources.

What we learn from HAWC data?

1. **Continous injection** of $e^{\pm}$, $Q(E,t) \propto L(t) E^{-\gamma_e} \exp(-E/E_c)$
   $L(t) = W_0(1+t/\tau)^{-2}$ evolution of pulsar luminosity
2. **Pulsar spin-down energy converted in high-energy $e^{\pm}$** $\eta W0 = 1.5 \times 10^{48}$ erg for Geminga, $\eta W0 = 4.2 \times 10^{46}$ erg for Monogem
3. **Diffusion in the vicinity of Geminga and Monogem is inhibited**
   - $D(1\ \mathrm{GeV}) = 5.0^{+2.0}_{-1.0} \times 10^{25} \mathrm{cm}^2/\mathrm{s}$
     $\sim$ 500 times smaller than the average value in the Galaxy from B/C

$\rightarrow$ **γ-ray emission intensity profile: how $e^{\pm}$ diffuse away from the pulsar**

[DiMauro,SM,Donato,1903.05647]



Following HAWC observation of Geminga and Monogem

[Hooper+1702.08436], [Fang+1803.02640], [Sudoh+1902.08203], [Johannesson+1903.05509], [Tang+1808.02445], ...

- Phenomenological description of inibithed diffusion: two- zone diffusion model [Tang+1808.02445]

$$D(r) = \left\{ \begin{array}{l} D_0 (E/1\,\mathrm{GeV})^{\delta} \text{ for } 0 < r < r_b, \\ D_2 (E/1\,\mathrm{GeV})^{\delta} \text{ for } r \geq r_b, \end{array} \right\}$$

Consequences for the e^+ excess:

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

GeV gamma-rays probe Geminga e^+ production relevant for e^+ excess at Earth

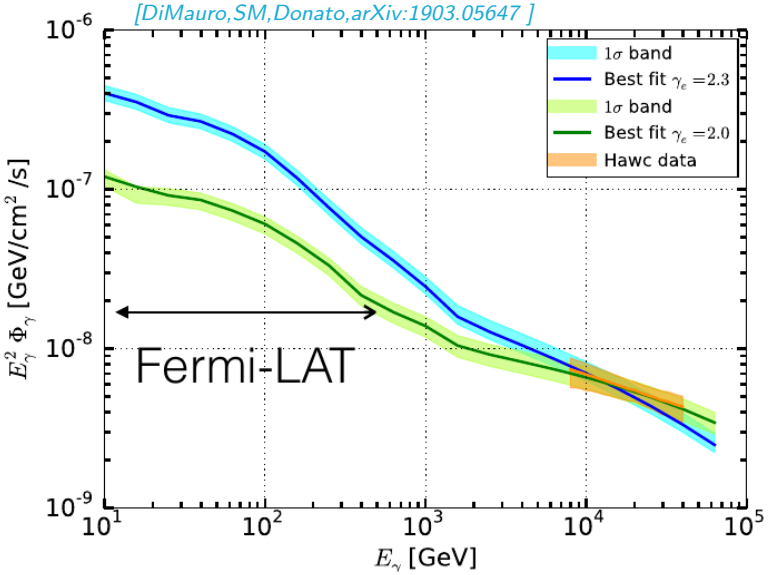
Fermi-LAT data!

Beyond HAWC: the role of Fermi-LAT

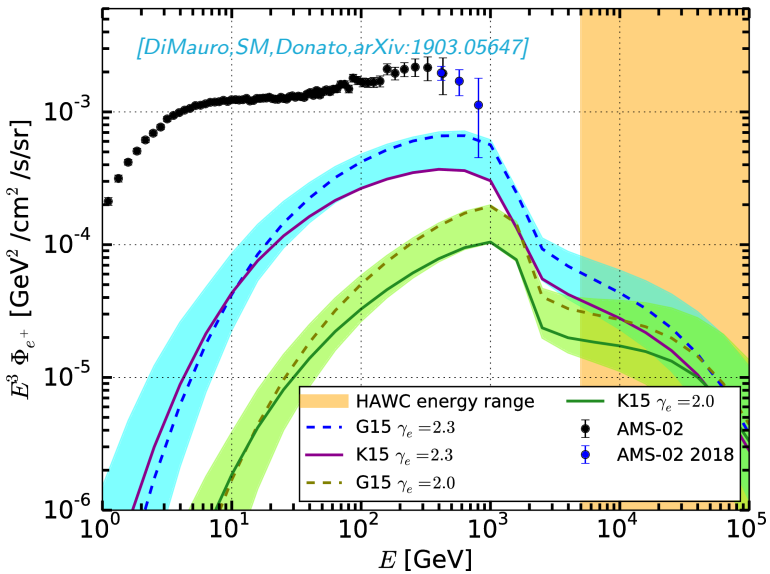
If we use *only* the HAWC results to calibrate:

Spectral energy distribution of Inverse Compton emission

[DiMauro,SM,Donato,arXiv:1903.05647]



e^+ flux at Earth



Geminga contribution to e^+ flux is not constrained.

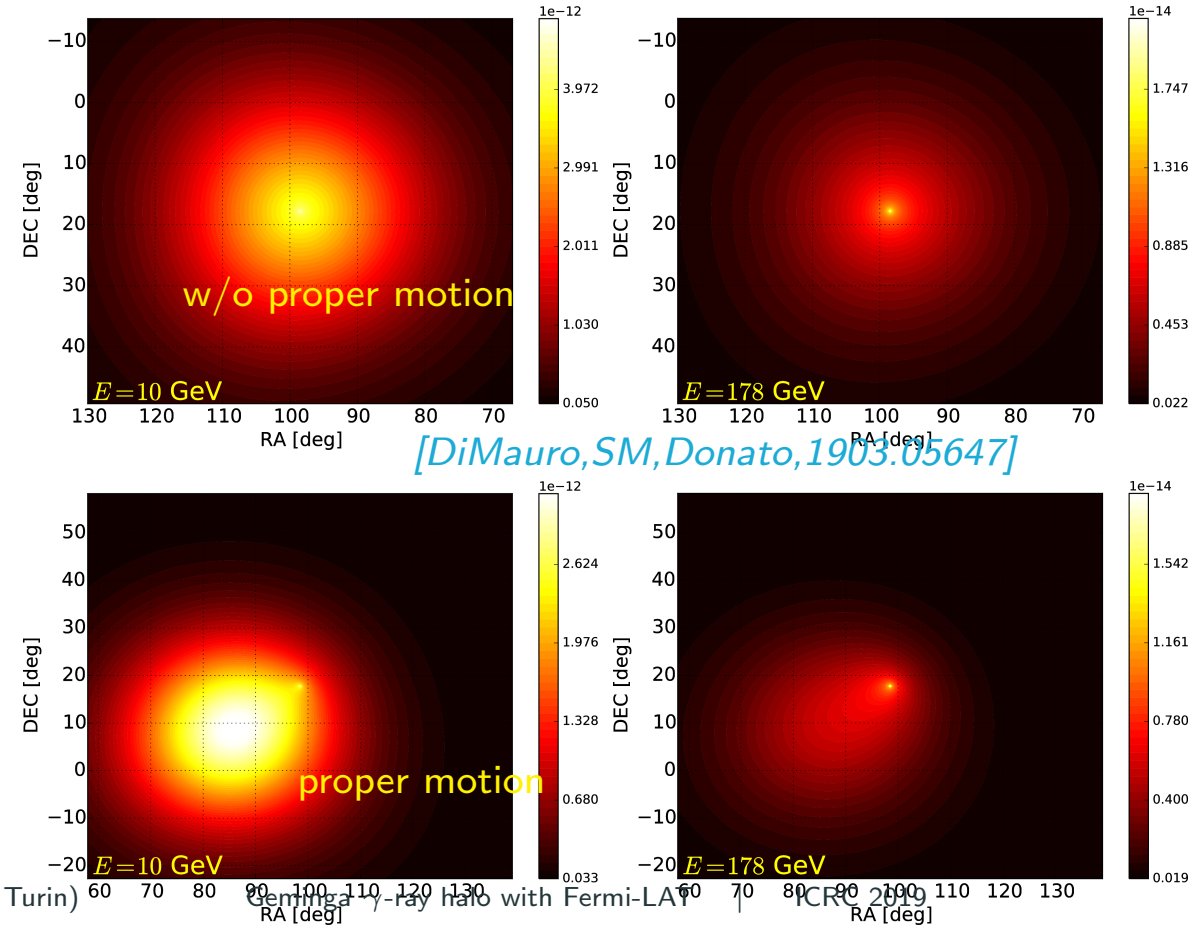
Fermi-LAT data:

1. **test the extrapolation of HAWC results** to lower γ -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**

Energy dependence of the spatial morphology of Inverse Compton emission:
we create templates for $D(1\ \mathrm{GeV})$ in the range $10^{25} - 10^{29}\mathrm{cm}^2/\mathrm{s}$:

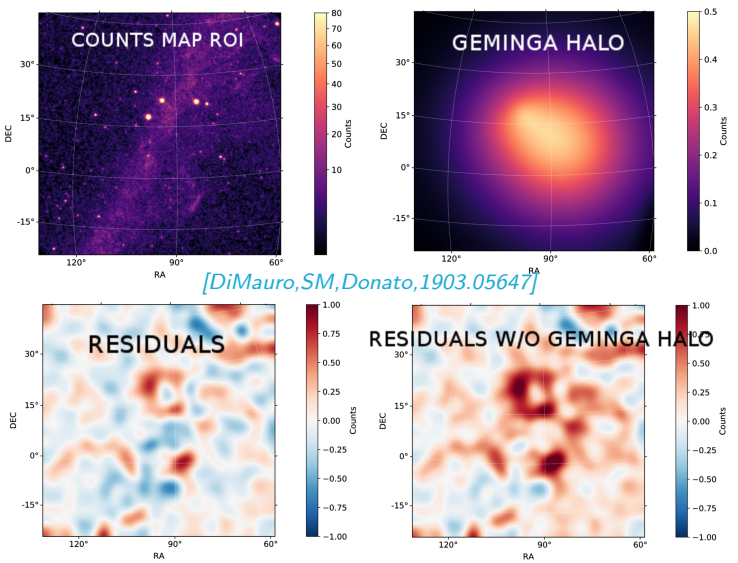


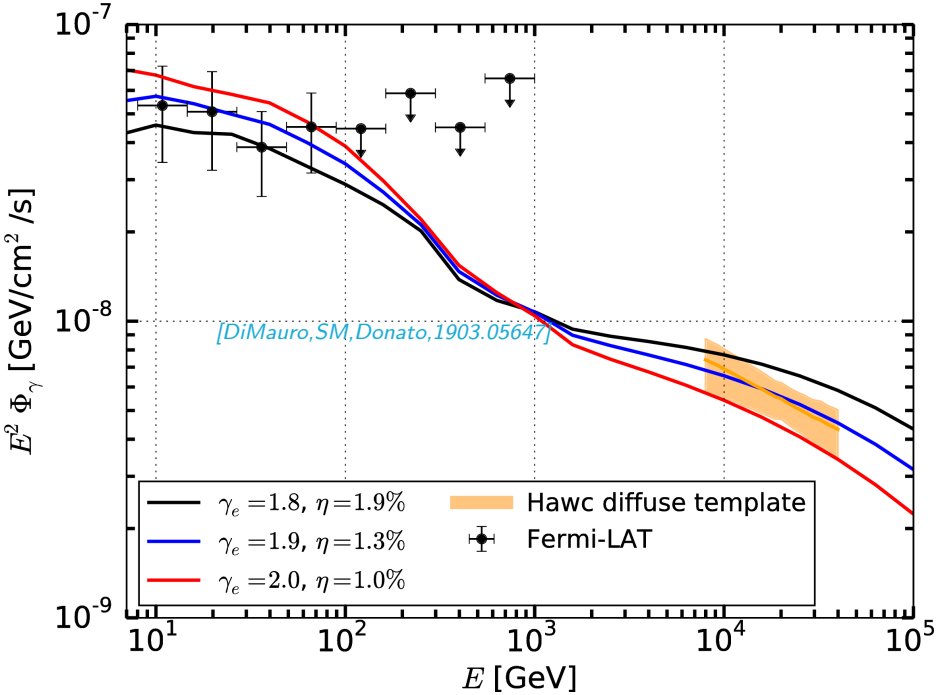
[DiMauro,SM,Donato,1903.05647]

Detection of Geminga extended halo in Fermi-LAT data

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

Inverse Compton emission from $e^{\pm}$ accelerated, and escaped, from Geminga

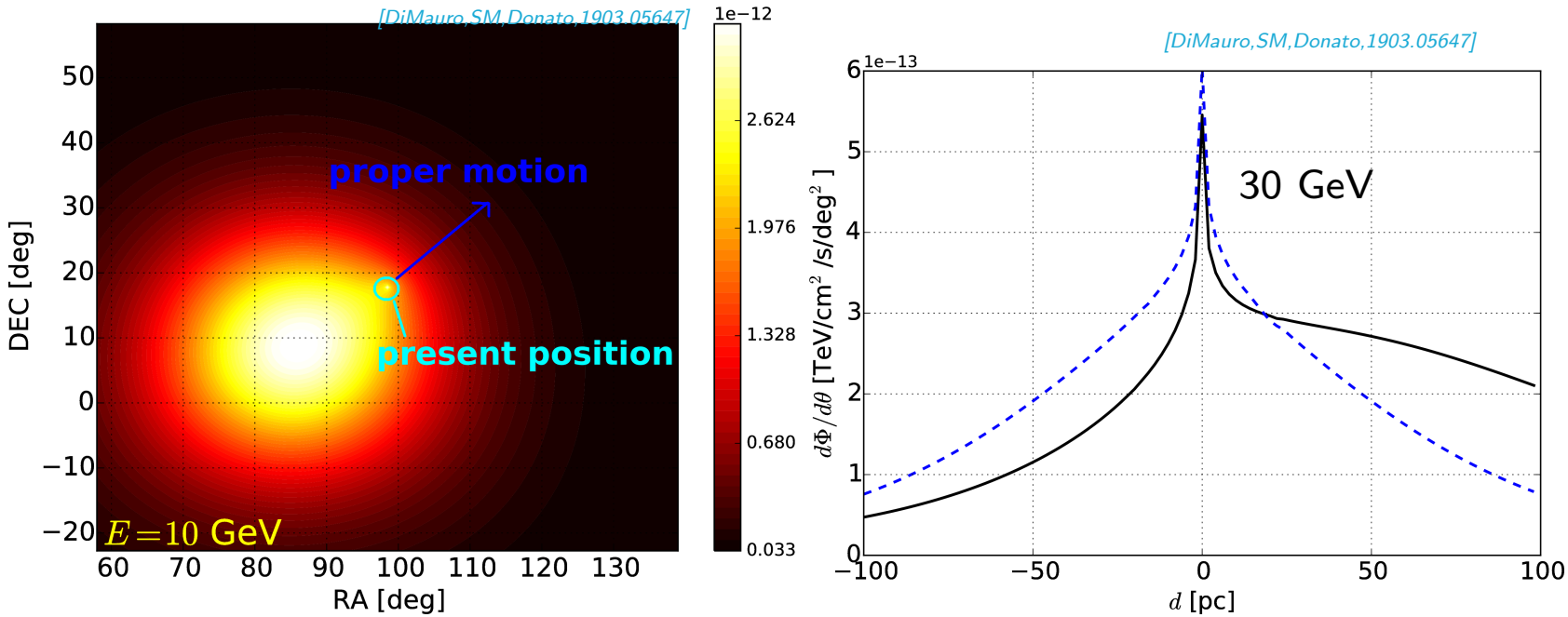




Monogem halo not significantly detected: upper limits.

Detection of Geminga pulsar proper motion with γ -rays

- Geminga pulsar has a proper motion, with transverse velocity of $v_t \sim 211$km/s [Faherty+AS07]: ~ 70 pc across its age (342 kyr)
- Transverse velocity affects significantly morphology of Geminga halo γ -ray emission at $E < 100$ GeV



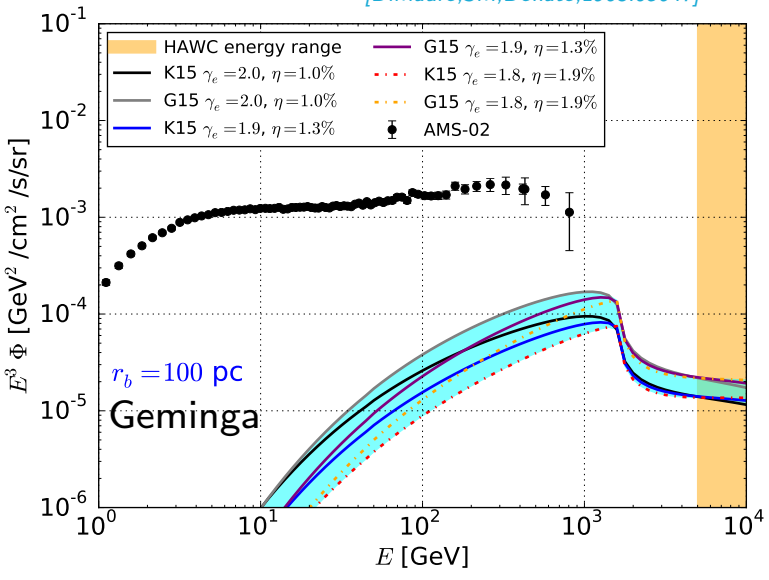
Model fit with proper motion preferred at least at 4σ:

analysis is unique in γ -ray astronomy, we detected a source moving across the sky

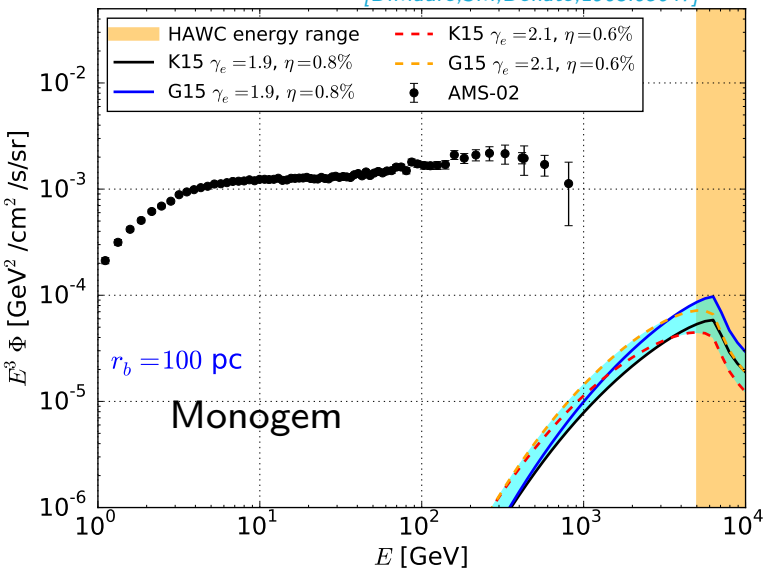
Consequences for the cosmic e^+ flux at Earth (I)

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

[DiMauro,SM,Donato,1903.05647]



[DiMauro,SM,Donato,1903.05647]



- 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)

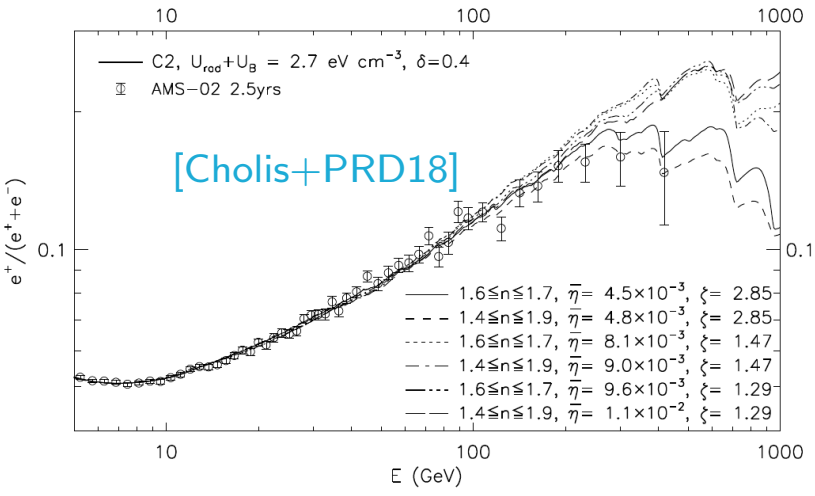
Geminga and Monogem are not the only PWNe in our Galaxy.

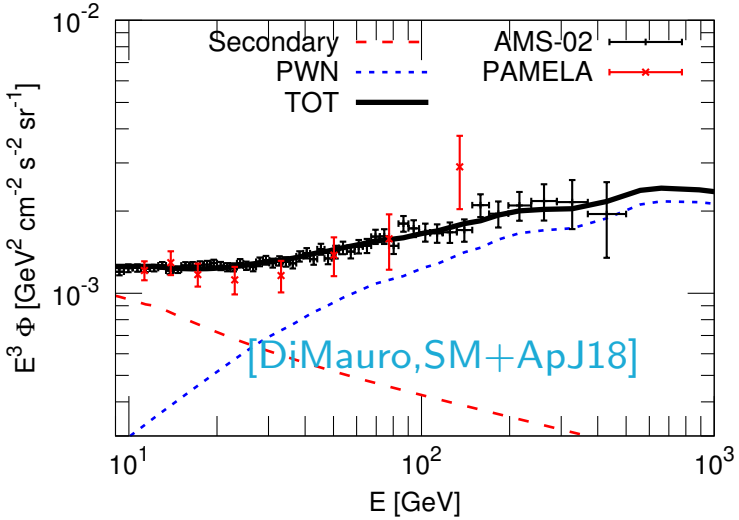
- An efficiency of 1-3% for the conversion of pulsar spin down in $e^{\pm}$ pairs for a smooth Galactic distribution of PWN can explain the e^+ excess

  [Cholis+PRD18], [DiMauro+19, in preparation]

- 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 - Geminga γ-ray halo with Fermi-LAT

- Pulsars and their nebulae are the most promising candidates to explain the e^+ flux at Earth
- Extended γ -ray halo from Geminga and Monogem in HAWC: evidence for $e^{\pm}$ diffusing away from PWNe

A counterpart of the Geminga halo is detected in Fermi-LAT data

- Diffusion is inhibited around pulsars; around Geminga is $D(1GeV) = 1.6 - 3.5 \times 10^{26}$ cm^2/s
- Geminga and Monogem, as constrained from Fermi-LAT, contribute at most 10% to the flux of e^+ at 800 GeV