Fermi-LAT results on Geminga extended emission

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1st Workshop of gamma-ray halos around pulsars, Online

Outline

* **Introduction**
* **Geminga gamma -ray halo at GeV energies**
* **Detection of Geminga halo with Fermi-LAT data**
* **Consequences of Fermi-LAT results for AMS-02 e^+ excess**
* **Summary**

Based on:

[REF1] M. Di Mauro, SM, F. Donato, Phys.Rev.D 100 (2019) 12

https://journals.aps.org/prd/abstract/10.1103/PhysRevD.100.123015

See also:

[REF2] M. Di Mauro, SM, F. Donato, Phys.Rev.D 101 (2020) 10
https://journals.aps.org/prd/abstract/10.1103/PhysRevD.101.103035

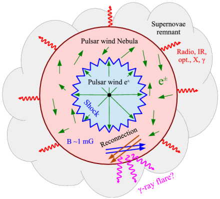
[REF3] SM, M. Di Mauro, F. Donato,Phys.Rev.D 102 (2020) 2
https://journals.aps.org/prd/abstract/10.1103/PhysRevD.102.023015

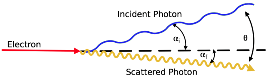
Multi-wavelenght emission around pulsars

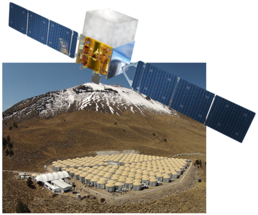
⇒ $e^{\pm}$ pairs accelerated by PWNe loose energy by Inverse Compton scattering, synchrotron emission:

cascade of photons in a broad range of frequency

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







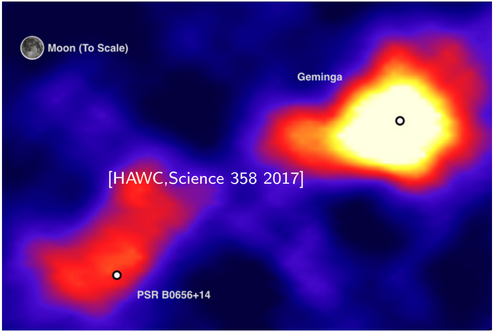
- Traditionally applied to pulsar, PWNe emission: *arcmin-arcsec scale*
- **GeV-TeV Inverse Compton emission in HAWC, Fermi-LAT data:** *few-degree scale*

Extended TeV gamma-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 at $d = 250$ pc



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

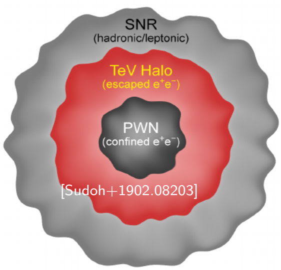
Strong support to PWNe as e^{+} sources.

Cosmic-ray $e^{\pm}$ and photons from PWN: modeling

See Workshop session tomorrow!

Our templates: GeV-TeV photons produced by inverse Compton scattering of $e^{\pm}$ around PWN on interstellar radiation field

- **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, bow-shock PWNe: $e^{\pm}$ **pairs possibly released** in interstellar medium
- **Continous injection**: $Q(E,t) \propto L(t)E^{-\gamma_e}\exp(-E/E_c)$ $L(t) = W_0(1+t/\tau)^{-2}$ evolution of pulsar luminosity, $\tau \sim 10$ kyr
- **Propagation: energy losses + diffusion , in a inibithed diffusion zone**: $D_0 \sim 500$ smaller wrt average ISM value



Normalization of $Q(E,t)$ connected to the spin-down energy W_0 with η (conversion efficiency):

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

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

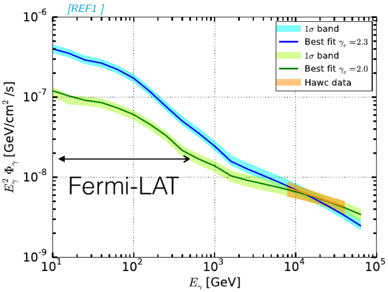
Geminga gamma -ray halo at Fermi-LAT energies

Beyond HAWC: Fermi-LAT and the e^+ excess

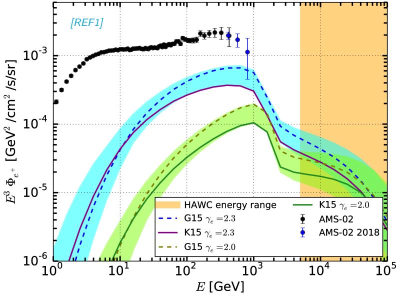
$\Rightarrow$ Using 5-40 TeV γ-rays to predict e^+ at 10-500 GeV **is a strong extrapolation**.

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

Spectral energy distribution of Inverse Compton emission



e^+ flux at Earth



Geminga contribution to e^+ flux is not constrained.

Fermi-LAT data at GeV:

1. probe Geminga e^+ production relevant for e^+ excess
2. **discriminate between different spectral index** γ_e of the accelerated e^+

Inverse Compton emission in pulsar gamma-ray halos

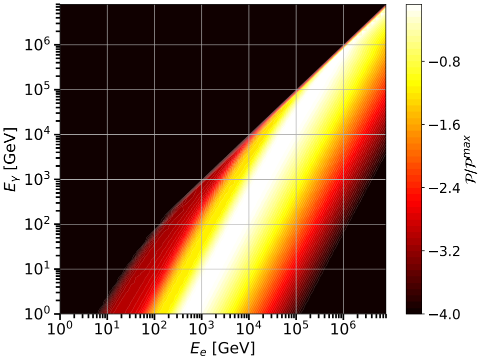
AMS-02 e^+ excess is at few hundreds of GeV: we need Inverse Compton γ-rays at $10 - 1000$ GeV to constrain $e^\pm$ at $350 - 1500$ GeV.

Inverse Compton gamma-ray flux produced at energy E_γ within $\Delta\Omega$:

$$\Phi_\gamma(E_\gamma, \Delta\Omega) = \int_{m_e c^2}^{\infty} dE_e \int_{\Delta\Omega} d\Omega \int_0^{\infty} ds\, \mathcal{N}_e(E_e, s, T)\mathcal{P}(E_e, E_\gamma)\,,$$

where $\mathcal{P}(E_e, E_\gamma)$: inverse Compton power by $e^\pm$ with E_e ; $\mathcal{N}_e(E_e, s, T)$ $e^\pm$ number density
Interstellar radiation field as in [Vernetto+PRD16]

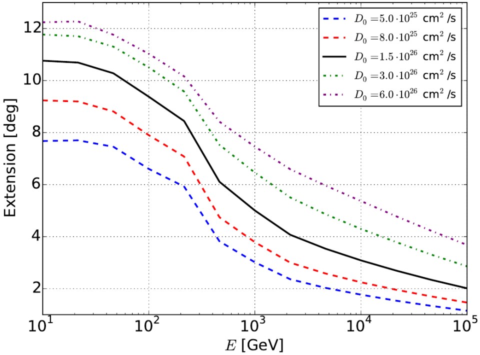
[DiMauro,SM+, in preparation]



Inverse-Compton halo extension depends on energy + diffusion

Expected **angular extension of Geminga** as a function on energy:

[REF1]



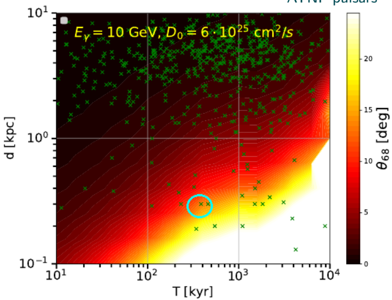
- At VHE Geminga halo is smaller, < 5 deg; **at GeV could be even** > 8 **deg**
- For $D_0 \sim 10^{28}$ cm^2/s the "halo" around Geminga would be spread out widely in the interstellar medium

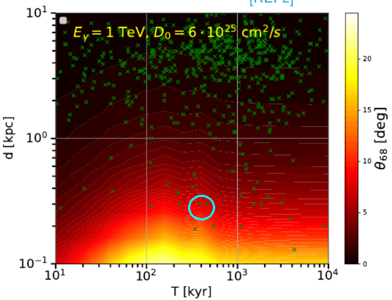
*extension = angle containing 68% of the ICS flux

Angular size: key parameter for detectability from GeV to TeV

Fermi-LAT: challenging detection for > 10 degrees
VHE experiments: few degrees instantaneous field of view

$$\Phi_\gamma^{68\%}(E_\gamma) = 2\pi \int_0^{\theta_{68}} \frac{d\Phi_\gamma}{d\theta}(E_\gamma) \sin\theta d\theta$$



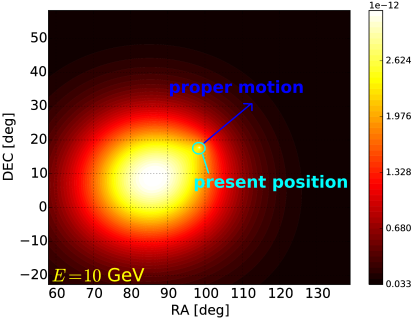


- 10 GeV: a source of 100 kyr should be far at least 0.9 kpc to be detected with extension smaller than 2 deg
- 1 TeV: D_0 is similar to Geminga value: most ATNF pulsars would be good targets for inverse Compton gamma-ray halo

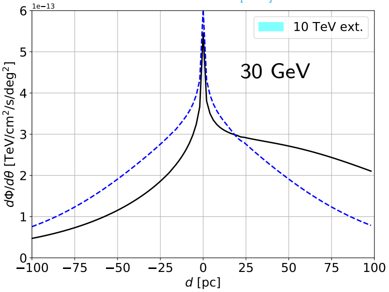
Geminga pulsar proper motion: consequences for GeV halo

As first pointed out by [Tang&Piran MNRAS19], transverse velocity affects significantly morphology of Geminga halo γ -ray emission at $E < 100$ GeV. See also [Johannesson+ApJ19]

[REF1]



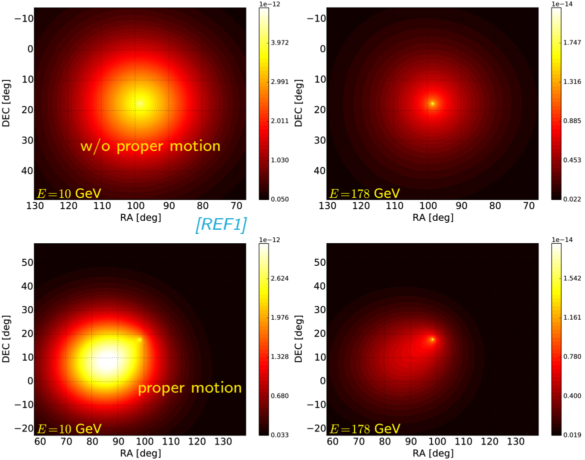
[REF1]



- Geminga pulsar proper motion: transverse velocity of $v_t \sim 211$km/s [Faherty+AS07]: ~ 70 pc across its age (342 kyr)
- Expected distortion of about 10 deg in opposite direction wrt proper motion at tens of GeV

Setup for Fermi-LAT data analysis

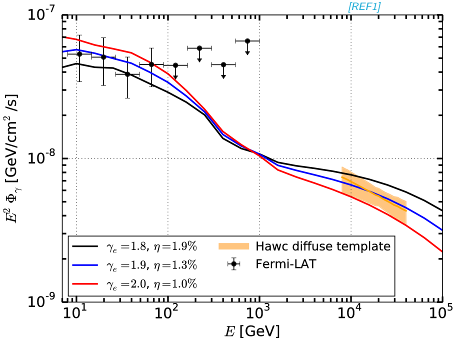
- 115 months of Fermi-LAT data in the **energy range [8,1000] GeV**
- Region of Interest of 70deg x 70deg: **extension is predicted to increase at GeV**
- **Energy dependence of the spatial morphology** of Inverse Compton emission: implemented in physical motivated templates for $D(1\ \mathrm{GeV})$ in the range $10^{25} - 10^{29}\mathrm{cm}^2/\mathrm{s}$

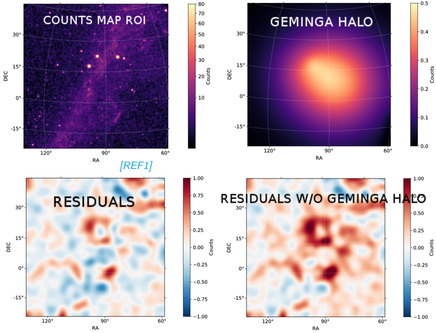


Detection of Geminga extended halo in Fermi-LAT data

- **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**, $\gamma_e = 1.8 - 2$, $\eta \sim 1\%$
- Model fit with **proper motion preferred at least at** 4σ

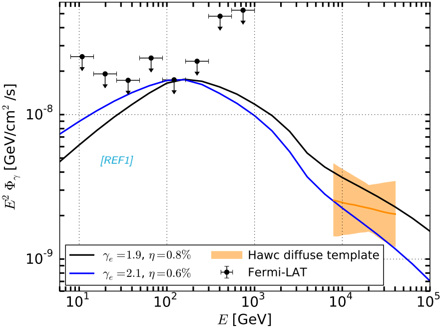
Inverse Compton emission from $e^{\pm}$ accelerated, and escaped, from Geminga

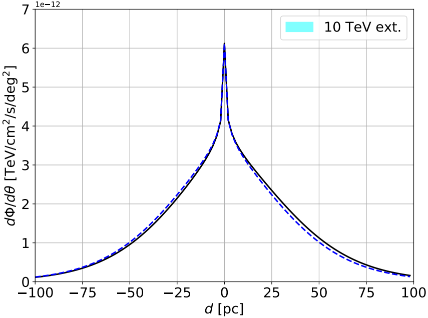




Monogem halo not significantly detected: upper limits

- **Lower limits on** $D_0 > 1 - 10 \cdot 10^{26}$**cm^2/s**,compatible with HAWC
- Upper limits on spectral energy distribution in all GeV range
- Proper motion **not affecting gamma-ray morphology**



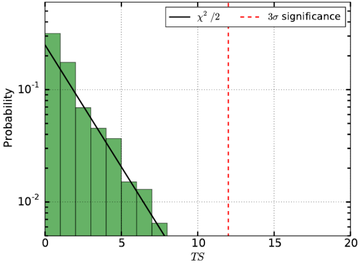


Systematics checks on Geminga halo detection

Several systematics checks performed. Detection is stable against all checks performed so far.

- **10 different background** diffuse emission models, as used in Fermi-LAT SNR catalog [Acero+ApJ16]
- **Null hypothesis** test: 1000 simulations w/o signal, TS distribution compatible with χ^2
- Weak anti-correlation with isotropic and background diffuse emission (always less than -0.3)
- **Point Spread Function**: residuals when analysing bright sources? Analysis toward brightest Fermi-LAT sources, same Geminga template: $TS < 2$.
- **Proper motion**: we rotated the template by 90, 180, 270 deg. Model with physical direction always preferred at $TS > 30$
- Slightly lower significance with CLEAN and ULTRACLEANVETO event classes

Comparison with non-detection reported by [Xi+ApJ19]: different energy range, smaller ROI (40x40deg), no proper motion; same conclusions for AMS-02 e^+ excess



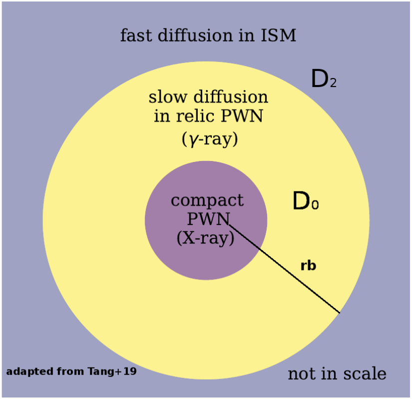
IEM	$TS^{\rm Geminga}$	$D_0^{\rm Geminga}$ [10^{26} cm^2/s]	$TS^{\rm motion}$	$TS^{\rm Monogem}$	$D_0^{\rm Monogem}$ [10^{26} cm^2/s]
Off.	65	$2.1^{+1.0}_{-0.7}$	28	25	> 2
Alt. 1	104	$2.6^{+1.4}_{-0.8}$	30	3	> 1
Alt. 2	92	$2.6^{+1.2}_{-0.8}$	22	14	> 3
Alt. 3	87	$3.3^{+1.6}_{-1.1}$	24	16	> 4
Alt. 4	102	$3.5^{+1.8}_{-1.1}$	20	26	> 3
Alt. 5	111	$2.4^{+1.0}_{-0.6}$	51	12	> 2
Alt. 6	143	$2.6^{+1.2}_{-0.8}$	43	10	> 3
Alt. 7	128	$2.8^{+1.3}_{-0.9}$	41	12	> 10
Alt. 8	134	$3.1^{+1.3}_{-0.9}$	39	25	> 8
GC	71	$1.6^{+0.6}_{-0.4}$	35	8	> 1

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

Cosmic-ray e^+ flux using results of Fermi-LAT: **two-zone diffusion model**:

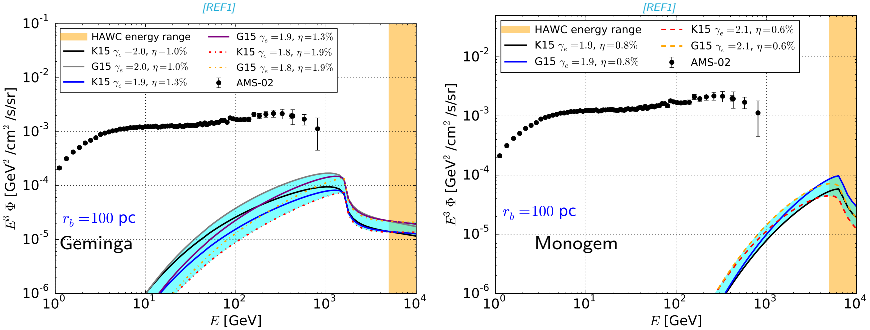
[Tang&Piran MNRAS19]

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



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

Inhibited diffusion $r_b < 100$ pc, $\sim$ angular size of Geminga at 100 GeV

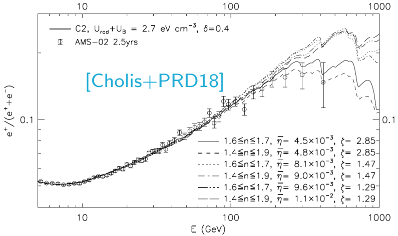


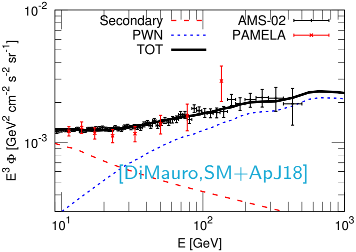
- Geminga contributes 1% (10%) to e^+ at 100 GeV (800 GeV); Monogem at most 3%

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

Geminga and Monogem: 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], [Manconi+2019]
- Previous studies considering PWNe in the ATNF catalog [DiMauro+JCAP14,Manconi+JCAP17,DiMauro,SM+ApJ18] also find similar values



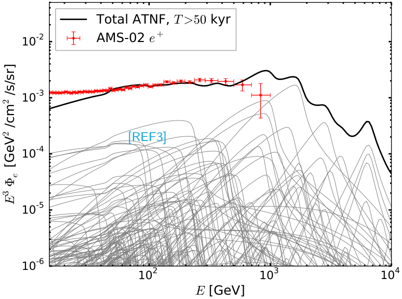


What is the effect of the low-diffusion bubbles around pulsars on these conclusions?

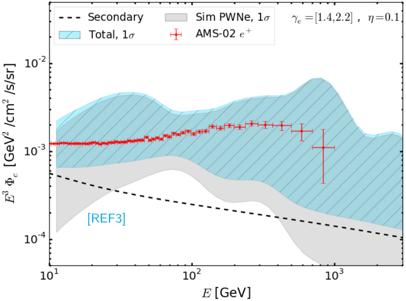
Galactic PWNe emission in two-zone diffusion model

Propagation proprierties around Galactic PWNe set from representative values of D_0, *rb* found analyzing HESS sources in [REF2]
$r_b \sim 90$ pc, $\gamma_e = [1.4, 2.2]$, $\eta = [2\%, 30\%]$

ATNF pulsars



Simulated Galactic pulsars in spiral arms



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

Summary and Perspectives

- GeV observation of gamma-ray halos fundamental to constrain $e^{\pm}$ population in PWNe relevant for the AMS-02 e^{+} excess

Counterpart of Geminga halo detected in Fermi-LAT at > 8 GeV

- inibithed diffusion $D(1GeV) = 1.6 - 3.5 \times 10^{26}$ cm^2/s, compatible with HAWC results
- Geminga and Monogem (as constrained from Fermi-LAT) contribute at most 10% to the flux of e^{+} at 800 GeV in a two-zone diffusion model

- Pulsars and their nebulae remain the most promising candidates to explain the e^{+} flux at Earth:
  more insights into cosmic-ray production/emission mechanism
- Gamma-ray halos emerging as general characteristics of pulsars: **new and promising** source class for HAWC, CTA, AMEEGO, ...