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, arXiv:1908.03216

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Oct 10, 2019

CRA2019, GSSI

Introduction

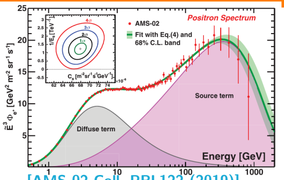
Introduction: cosmic-ray e^+ at Earth

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

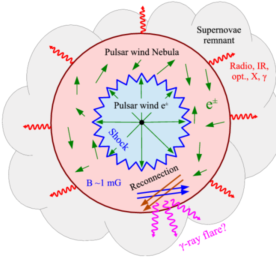
2. e^+ **probe local Galaxy**: severe energy losses
   for $E_{e^\pm} \gtrsim 10$ GeV: typical propagation scale $\lambda < 5$ kpc

3. **Pulsars and their nebulae (PWNe)**:
   main candidates to explain e^+ excess

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



[AMS-02 Coll, PRL122 (2019)]

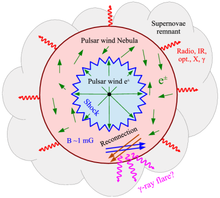


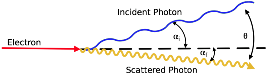
Multi-wavelenght emission in PWNe

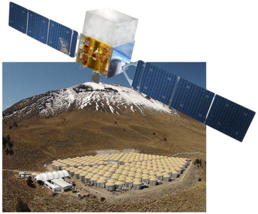
⇒ $e^{\pm}$ pairs accelerated by PWNe loose energy by Inverse Compton scattering, synchrotron emission:

cascade of photons in a broad range of frequency

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





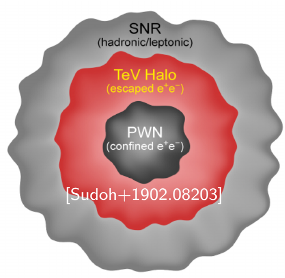


- Traditionally applied to pulsar, PWNe emission: *arcmin-arcsec scale*
- **GeV-TeV Inverse Compton emission in HAWC, Fermi-LAT data:** *few-degree scale*

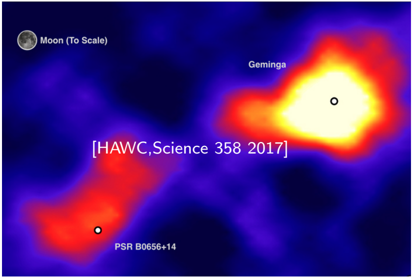
Extended γ-ray halo of Geminga and Monogem

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 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.

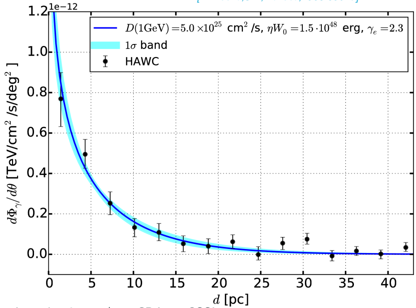
What we learn from HAWC data for Geminga/Monogem?

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, $\tau \sim 10$ kyr
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 (~ 20 pc) of Geminga and Monogem is inhibited**
   - $D(1\ \mathrm{GeV}) = 5.0^{+2.0}_{-1.0} \times 10^{25} \mathrm{cm}^2/\mathrm{s}$

     ~ 500 times smaller than the average value in the Galaxy from B/C

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

[DiMauro,SM,Donato,1903.05647]



Following HAWC observations of Geminga/Monogem

Outline:

1. Follow-up of Geminga and Monogem HAWC halo with **Fermi-LAT GeV** data
2. Are TeV halos* a **general property** of pulsars?
3. Consequences for the **interpretation of the AMS-02** e^+ flux

Results in: M. Di Mauro, SM, F. Donato
arXiv:1903.05647, arXiv:1908.03216, arXiv:19XX.XXXX

Many other interesting references (2017-2019):
Linden+PRD96, Hooper+PRD98, PRD96, Lopez-Coto+MNRAS479, PRL121, Fang+ApJ863, MNRAS488, Profumo+PRD97, Sudoh+PRD100, Xi+ApJ878, Tang+MNRAS48, , Evoli+PRD98, Johannesson+ApJ879, Giacinti+arXiv:1907.12121

detection prospects in VHE experiments; consequences for propagation models, cosmic-ray fluxes interpretation; magnetic field properties around sources, ...

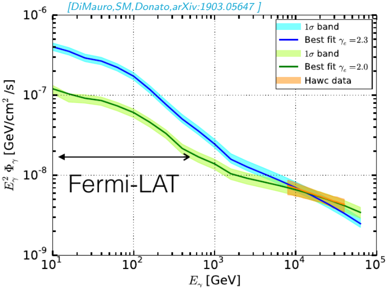
* *probably not final name: not only TeV...*

Geminga γ -ray halo with Fermi-LAT

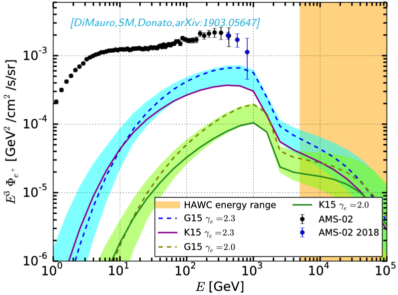
⇒ Using 5-40 TeV γ-rays to predict e^+ at 10-500 GeV **is a strong extrapolation**.

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

Spectral energy distribution of Inverse Compton emission



e^+ flux at Earth



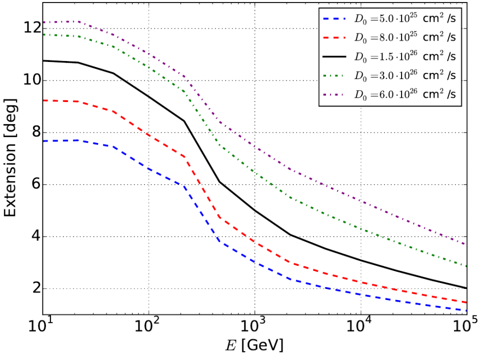
Geminga contribution to e$^+$ flux is not constrained.

GeV Fermi-LAT data:

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

Inverse-Compton halo extension depends on energy + diffusion

[DiMauro,SM,Donato,1903.05647]



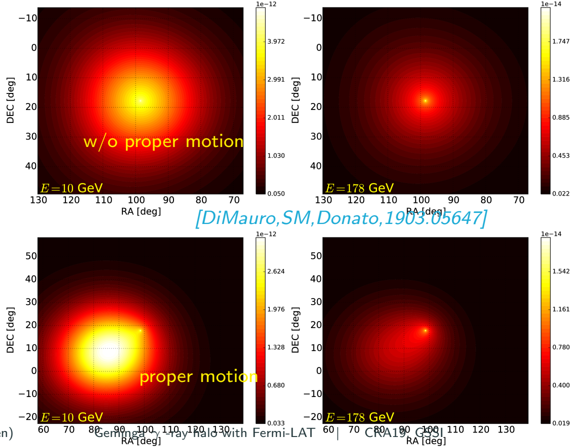
- At VHE Geminga halo is smaller, < 5 deg; at GeV could be even > 8 deg
- For $D_0 \sim 10^{28}$ cm^2/s the "halo" around Geminga would be spread out widely in the interstellar medium

*extension = angle containing 68% of the ICS flux

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 $10^{25} - 10^{29}\mathrm{cm}^2/\mathrm{s}$:

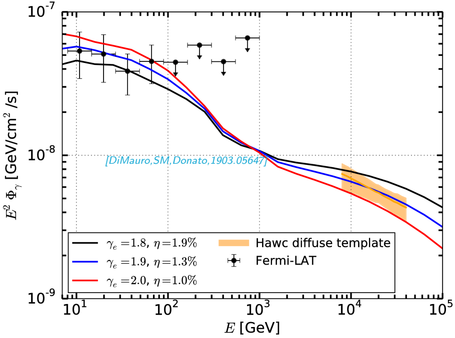


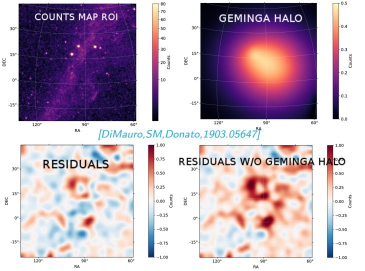
[DiMauro,SM,Donato,1903.05647]

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 $\sim$ 60 **pc at 100 GeV**, $\gamma_e = 1.8 - 2$

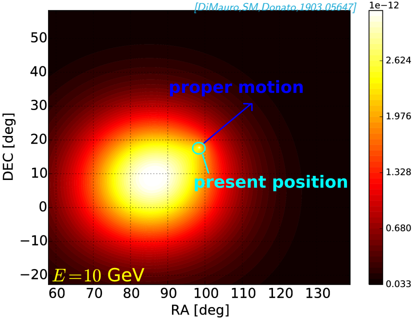
Inverse Compton emission from $e^{\pm}$ accelerated, and escaped, from Geminga

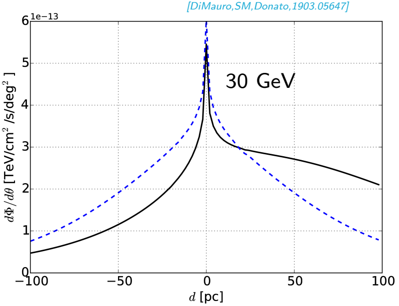




Monogem halo not significantly detected: upper limits.

- 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 [Tang&Piran18]



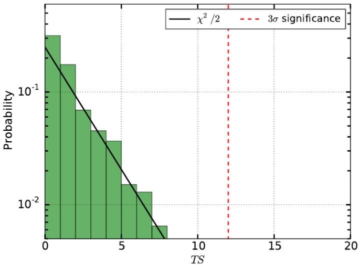


Model fit with proper motion preferred at least at 4σ.

Systematics checks

- **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 right direction always preferred at $TS > 30$
- Slightly lower significance with CLEAN (55) and ULTRACLEANVETO (48) event class

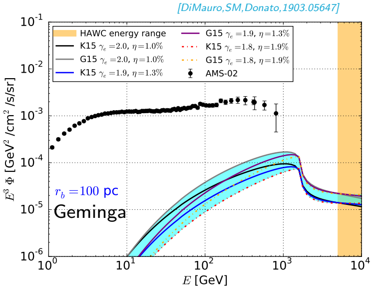
IEM	$TS^{\rm Geminga}$	$D_0^{\rm Geminga}$ $[10^{26}\ {\rm cm^2/s}]$	$TS^{\rm motion}$	$TS^{\rm Monogem}$	$D_0^{\rm Monogem}$ $[10^{26}\ {\rm cm^2/s}]$
Off.	65	$2.1^{+1.0}_{-0.7}$	28	25	> 2
Alt. 1	104	$2.6^{+1.4}_{-0.8}$	30	3	> 1
Alt. 2	92	$2.6^{+1.2}_{-0.8}$	22	14	> 3
Alt. 3	87	$3.3^{+1.6}_{-1.1}$	24	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

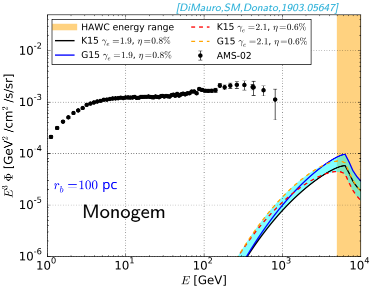


Consequences for the cosmic e^+ flux at Earth (I)

e^+ flux using results of Fermi-LAT: **two-zone diffusion model** [Tang+1808.02445]:
inhibited diffusion $r_b < 100$ pc, $\sim$ angular size of Geminga at 100 GeV

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





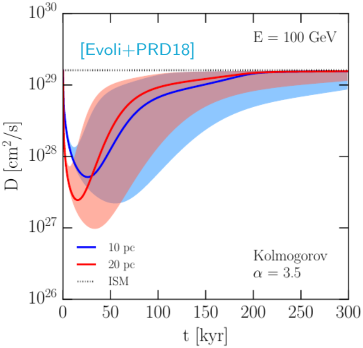
- Geminga contributes 1% (10%) to e^+ at 100 GeV (800 GeV); Monogem at most 3%

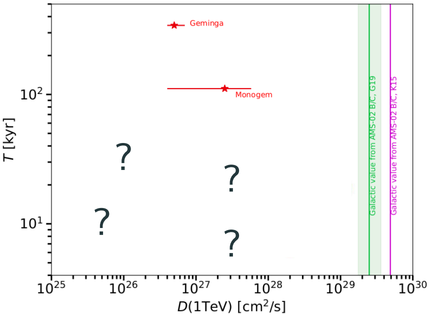
Geminga and Monogem alone, **as constrained by Fermi-LAT**, cannot be major contributors to e^+ excess

Perspectives and open questions

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

- **General feature around each Galactic pulsar?**
- Constrain and refine production and emission models of cosmic $e^{\pm}$ from PWNe
- Study propagation of cosmic rays around sources
- Connect to other evidence of inhomogenous diffusion (H,He breaks)





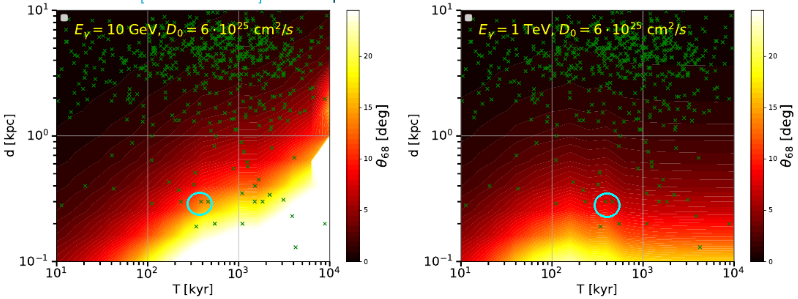
Are TeV halos a general property of pulsars?

Angular size: key parameter for detectability

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

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

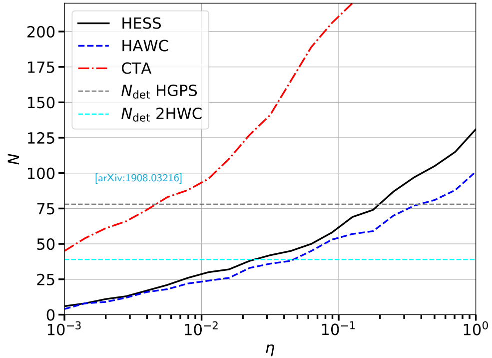
[arXiv:1908.03216] ATNF pulsars



- 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

Prediction for number of TeV halos in HESS, HAWC, CTA

Number of sources above HESS, HAWC, CTA sensitivity as a function of the efficiency of conversion of pulsar spin down into $e^{\pm}$:



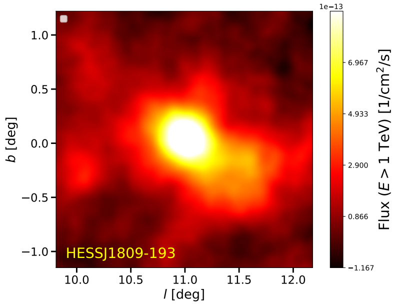
- HAWC/HESS might have already detected 25-35 TeV halos (see also [Linden+PRD17])
- **Tens of halos** could be detected even if $\eta \sim 1\%$

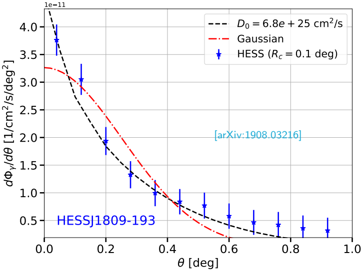
Difference with previous works: we do not rescale the results of HAWC for Geminga, we compute for each ATNF source the inverse Compton flux with catalog properties.

Analysis tecnique and source sample

- **Rank** the ATNF pulsars according to gamma-ray flux at 10 TeV: majority already detected by HAWC,HESS
- Flux maps from HESS HGPS catalog: surface brightness above 1 TeV
- Gamma-ray emission interpreted as **purely leptonic**
- Fit to surface brightness to derive D_0 for each source

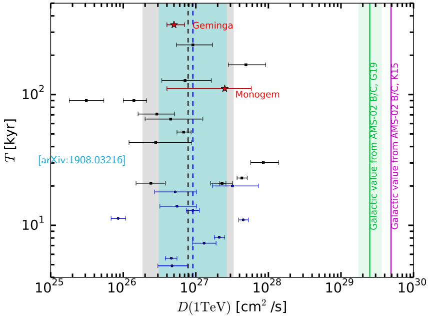
Example: HESSJ1809-193 associated to J1809-1917, $d = 3.27$ kpc, 52 kyr

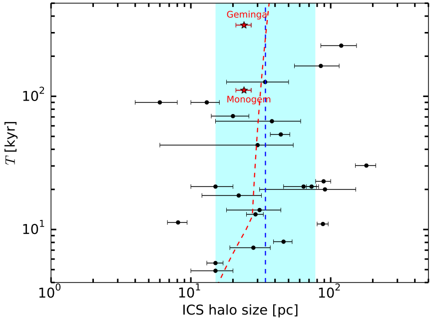




A low-diffusion zone around pulsars

Results for our sample of HESS sources:





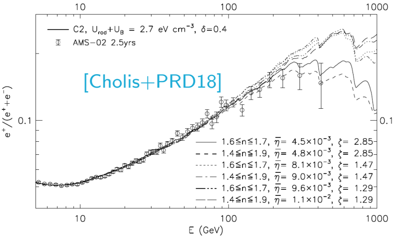
- The diffusion coefficient around PWNe is **systematically lower by 2 orders of magnitude** with respect to mean Galactic value found from B/C data fits
- **No clear trend** with respect to age
- Inverse Compton TeV halos have typical size of about 35 pc above 1 TeV

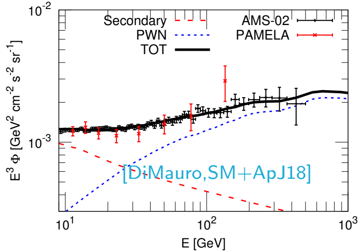
Consequences for the e^+ flux

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

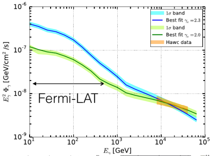
Summary

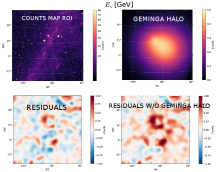
- Extended γ -ray halo from Geminga and Monogem in HAWC: evidence for $e^{\pm}$ diffusing away from PWNe

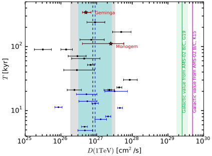
A counterpart of the Geminga halo is detected in Fermi-LAT data

- inibithed diffusion $D(1 GeV) = 1.6 - 3.5 \times 10^{26}$ 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

- TeV halos emerging as general characteristics of Galactic pulsars
- Pulsars and their nebulae remain the most promising candidates to explain the e^+ flux at Earth: starting to probe production and emission mechanism







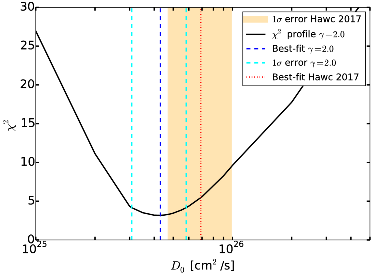
Thank you!

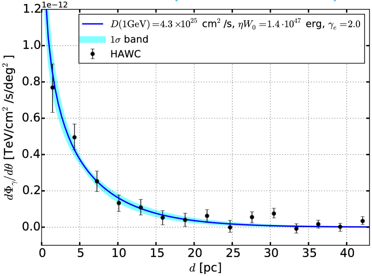
BACKUP

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 $e^{\pm}$ $\gamma_e = 2.3$