Multi-wavelength observations of Pulsar TeV halos & LHAASO prospects

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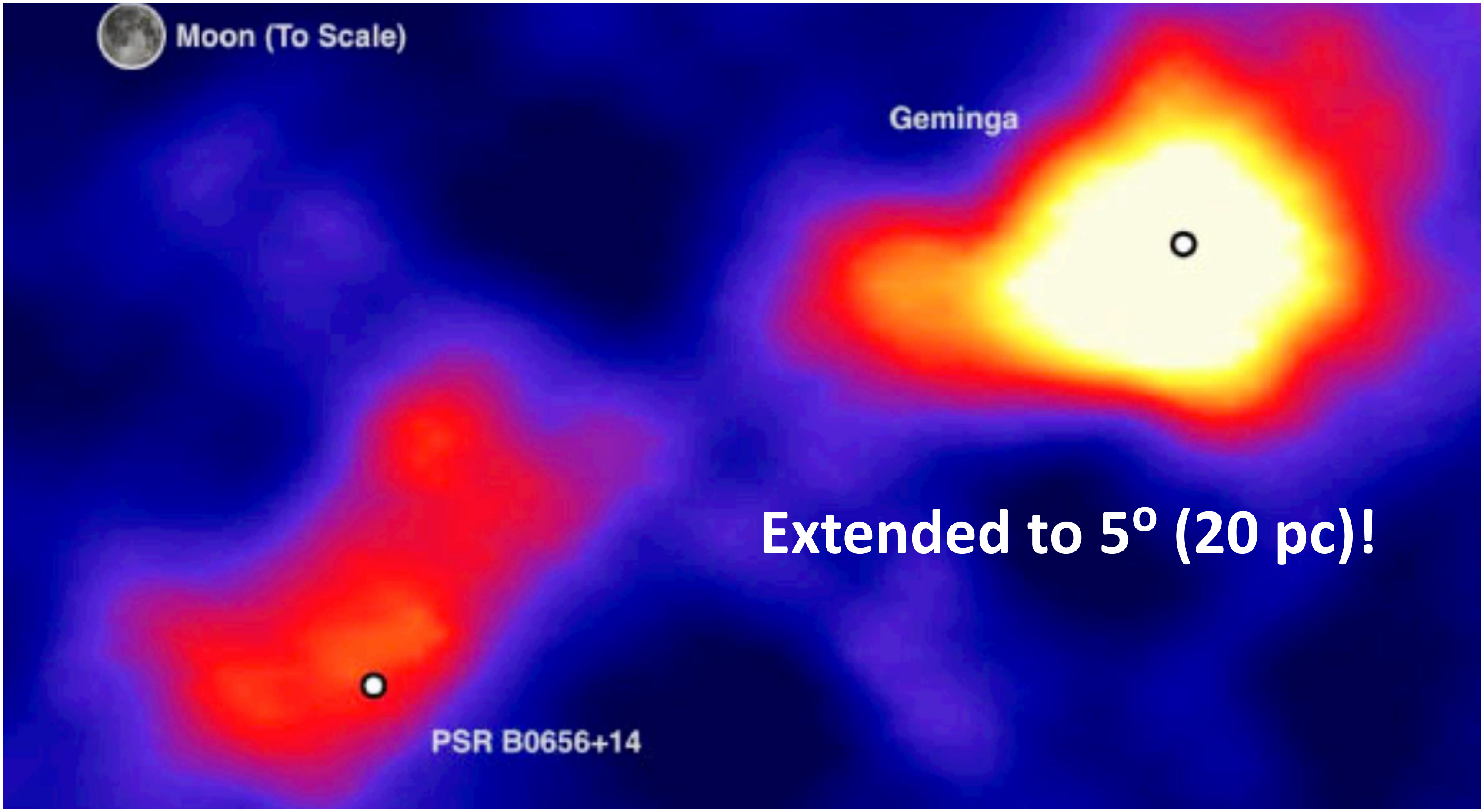
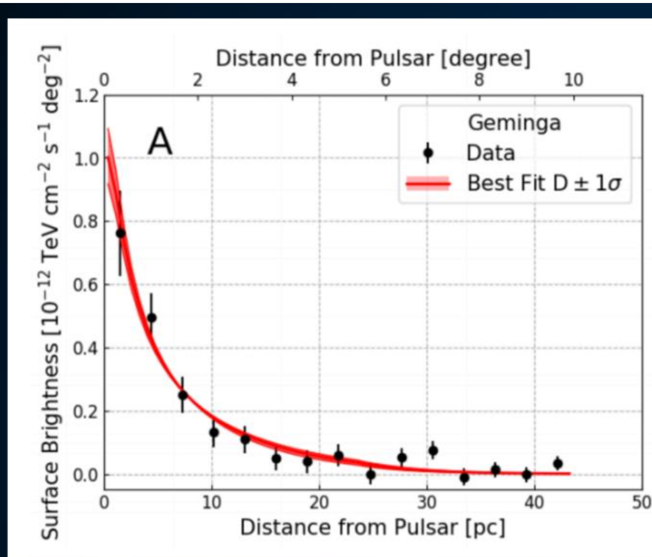
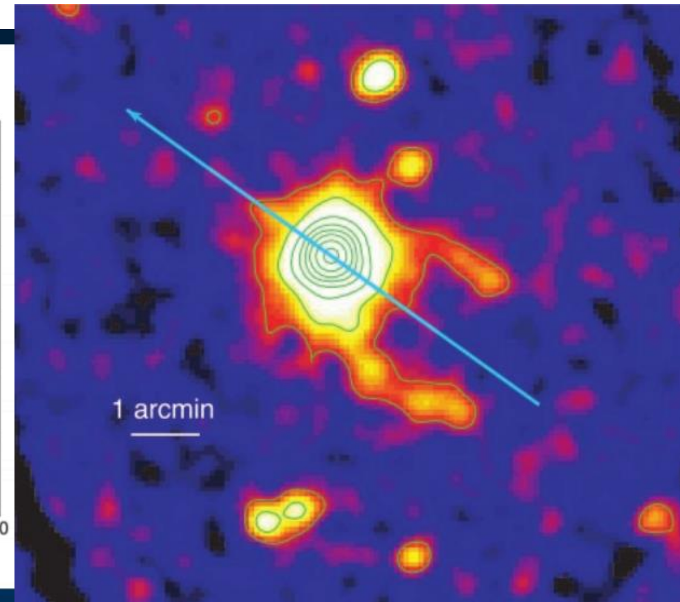
Pulsar TeV halos-very extended PWNe



HAWC Collaboration (Science; 1711.06223)

Much larger sizes

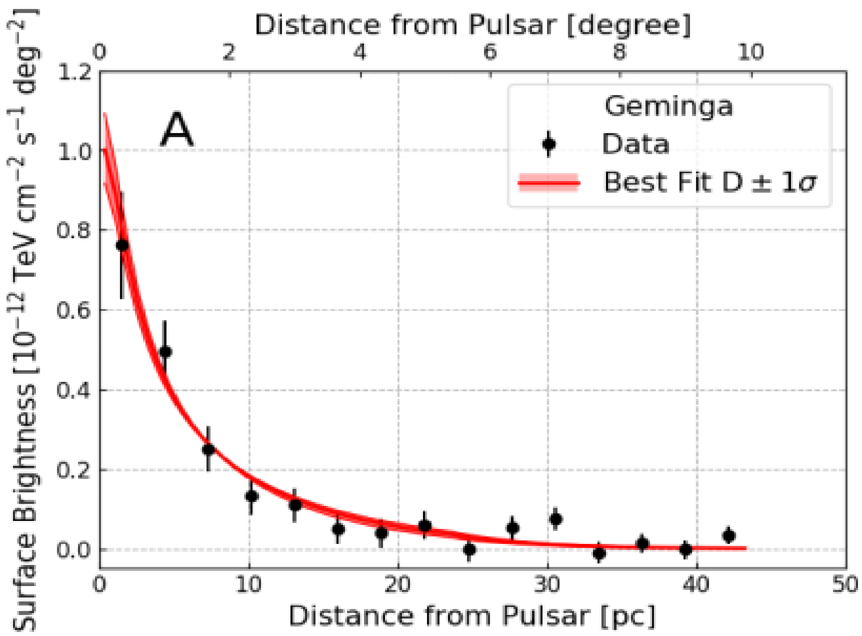




- **Why TeV Halos?**
  - **These sources are <u>much larger</u> than X-Ray PWN**

$$R_{\rm PWN} \simeq 1.5 \left(\frac{\dot{E}}{10^{35}\ \rm erg/s}\right)^{1/2} \times \left(\frac{n_{\rm gas}}{1\ \rm cm^{-3}}\right)^{-1/2} \left(\frac{v}{100\ \rm km/s}\right)^{-3/2} \rm pc$$

Inefficient diffusion

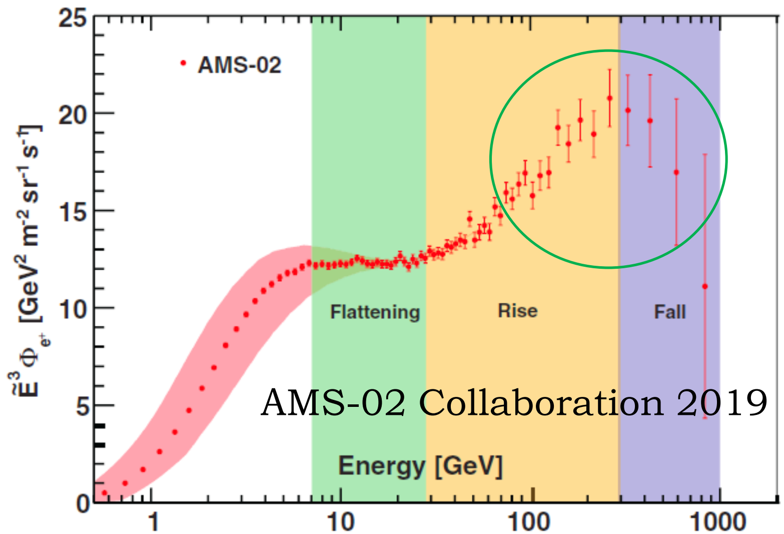


D_{100} (Diffusion coefficient of 100TeV electrons from joint fit of two PWNe)	[x10^{27} cm^2/sec]	4.5 ± 1.2

HAWC Collaboration 2017, Science, 2017, 358, 911

Diffusion: two orders of magnitude slower than the typical ISM !

Implications for the positron excess

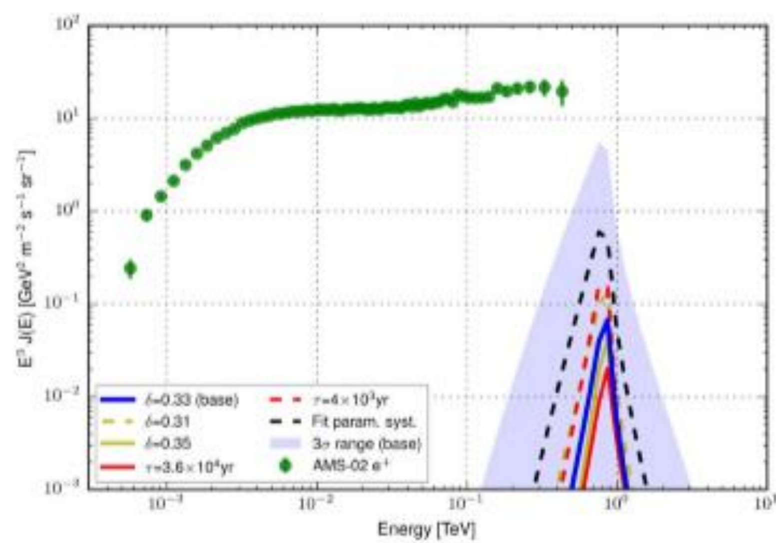


Positron excess

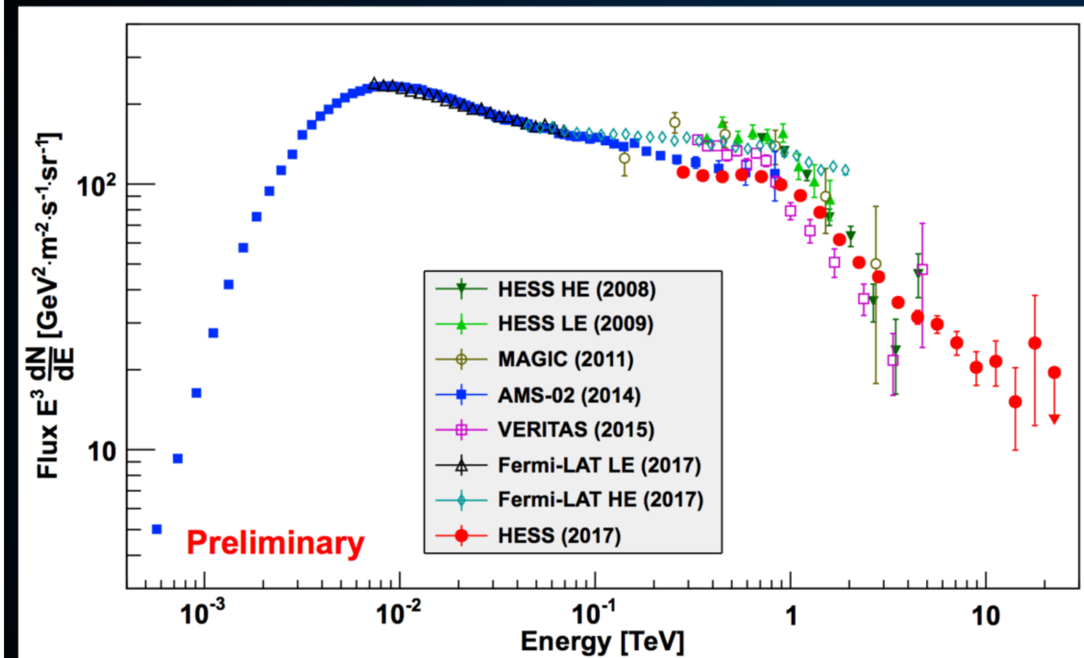
1. Dark Matter
2. Nearby pulsars
   (Geminga, 250pc)

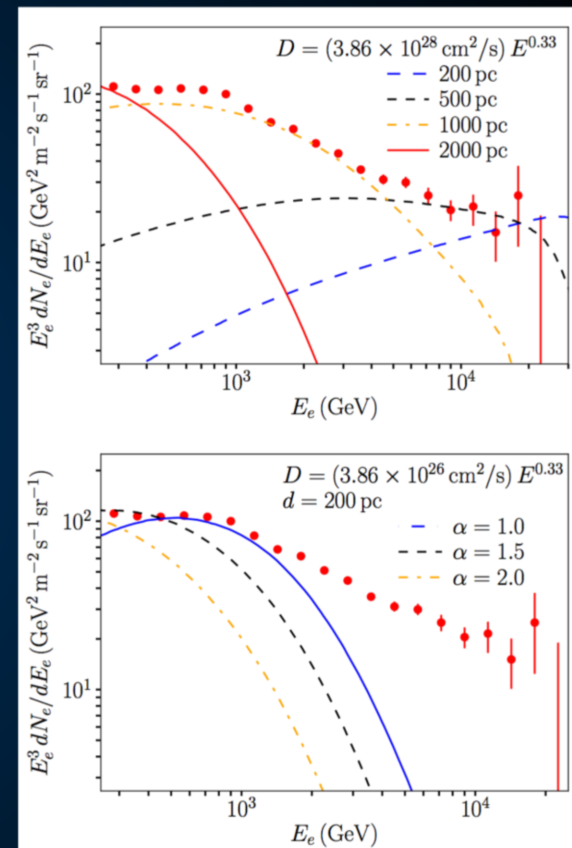
Seems good news for dark matter model !

- Injected positrons are well confined in the surrounding of Geminga
- has not reached Earth for an age of 340kyr



Can the diffusion be so low near Earth?





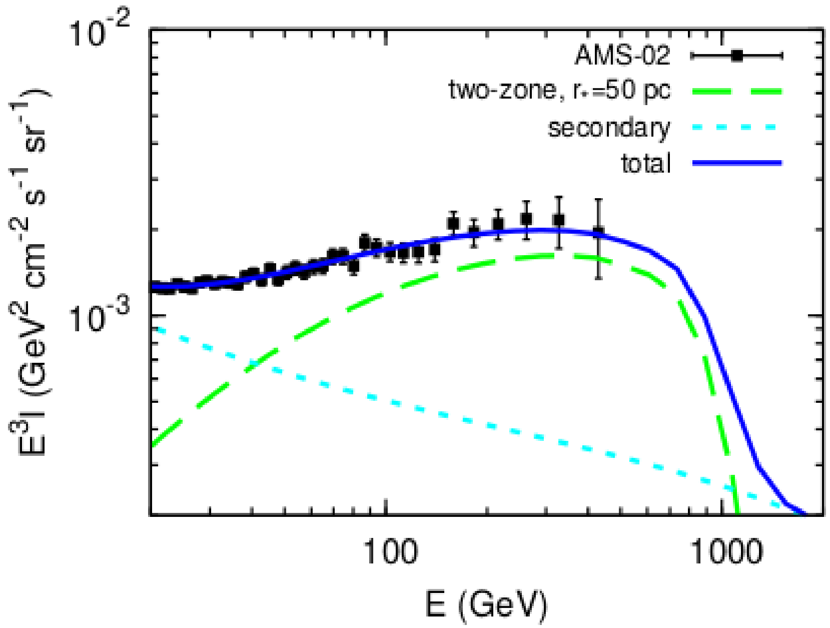
- HESS Observations of 20 TeV electrons resolve this.
- If diffusion near Earth is low, then there is no source for these particles.

Hooper et al. 2018

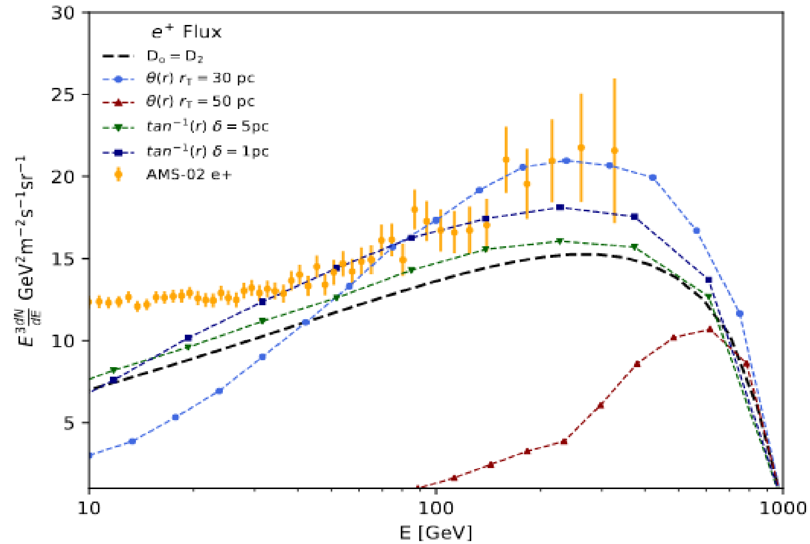
Two-zone diffusion: save the pulsar model

Introduce an outer normal diffusion zone

$$D(E_e, r) = \begin{cases} D_1, & r < r_0 \\ D_2, & r \geq r_0. \end{cases}$$

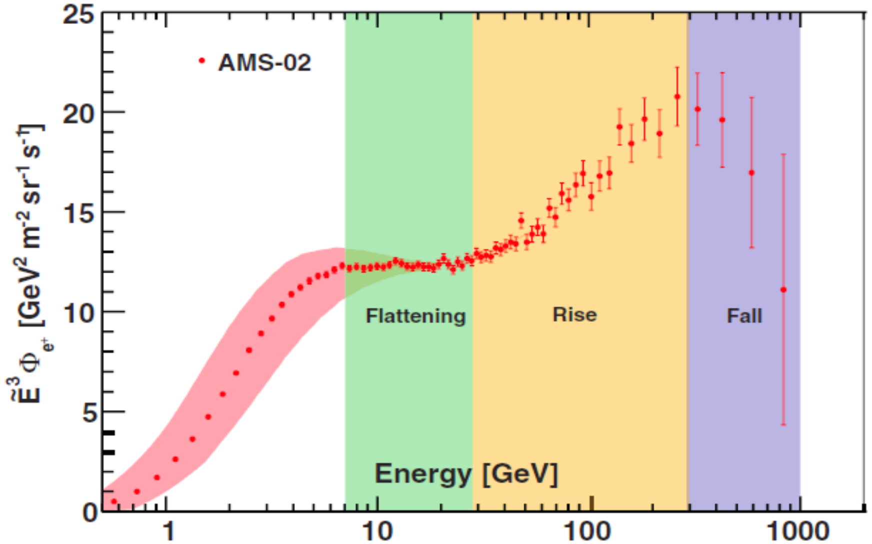


Fang et al. 2018



Profumo et al. 2018

Importance of GeV gamma-ray observations



300GeV electron/positron up-scatter IR photon field
ε=10GeV $(E_e/300GeV)^2(T/300K)$

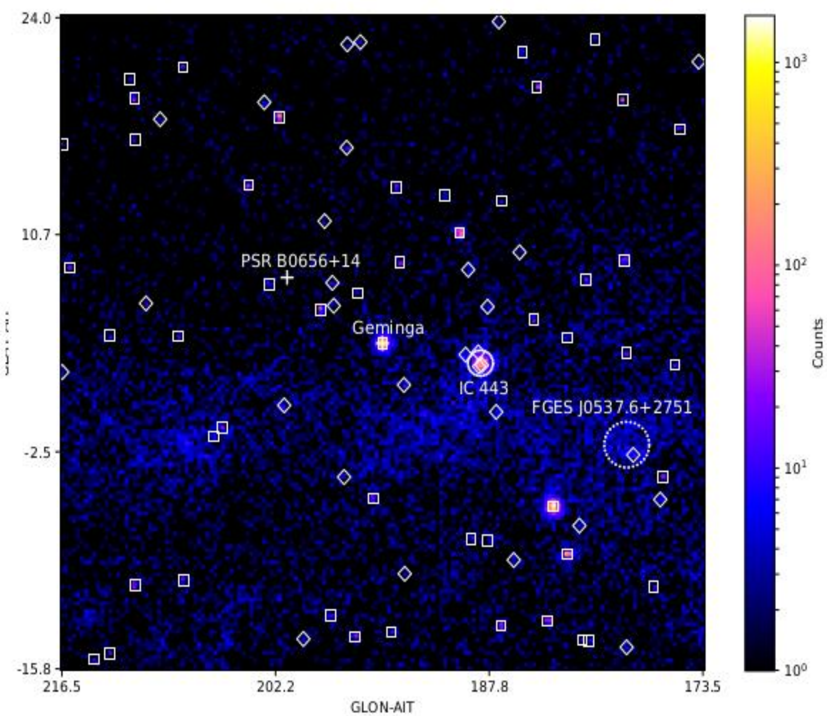
GeV gamma-ray emission can put more direct constraints!

so we should look at Fermi/LAT data !

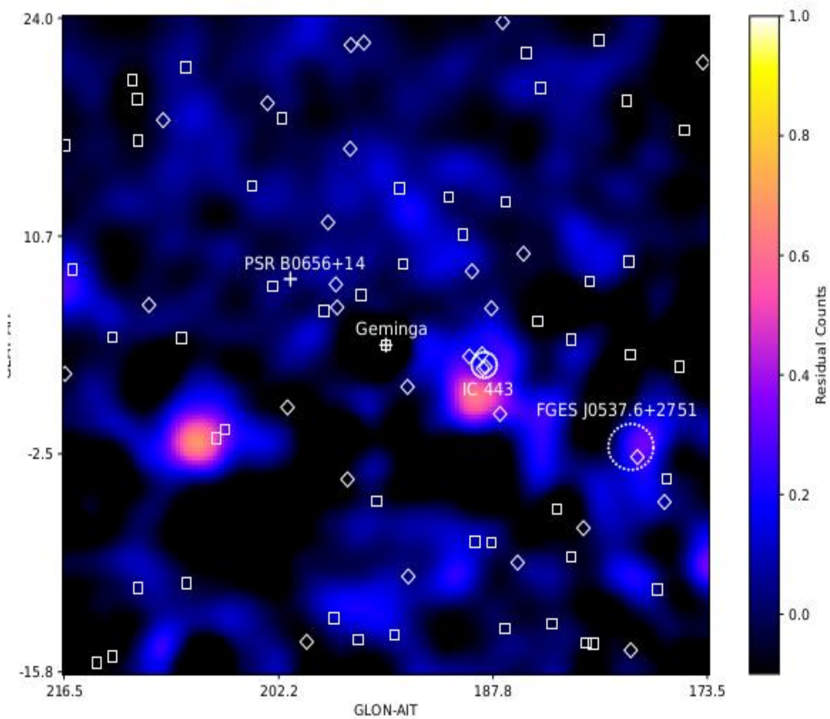
Analyzing the Fermi-LAT data of the TeV halos

(Xi et al., 2018)

$D(100GeV) \sim 2x10^{26} cm^2/s$, $(Dt_{gem})^{1/2} \sim 30pc \sim 7^\circ$



Count map



Residual map

40° x40° ROI, 10-500GeV

No LAT detections

We produce spatial templates (on the premise of fitting HAWC’ s observation

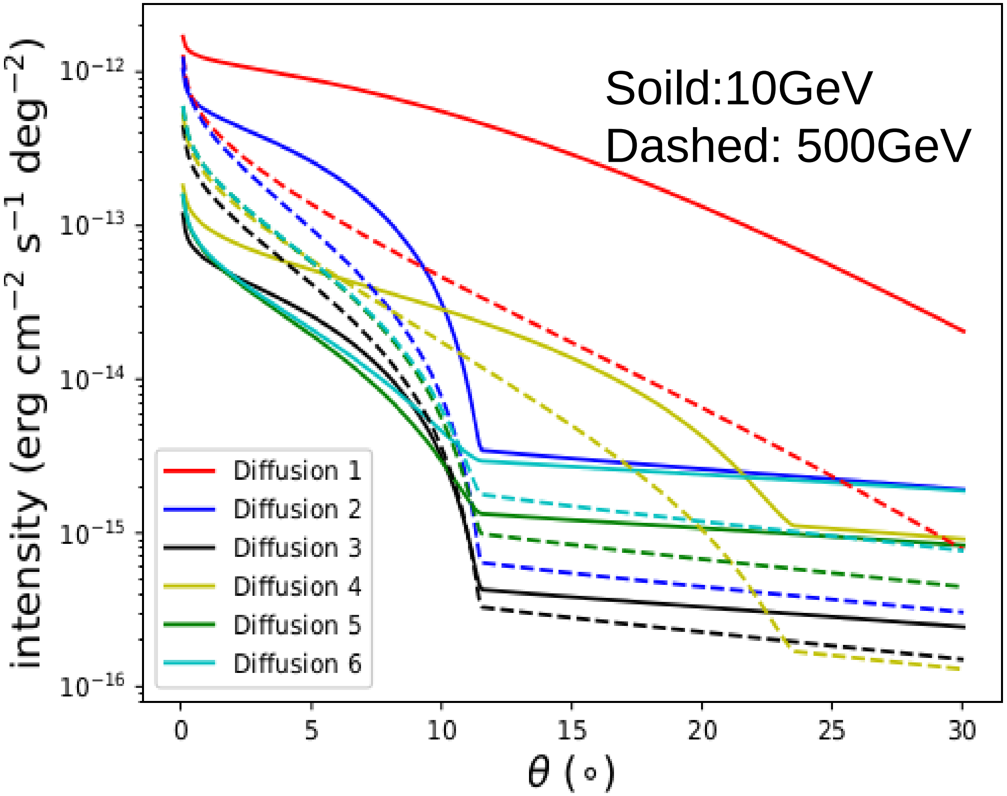
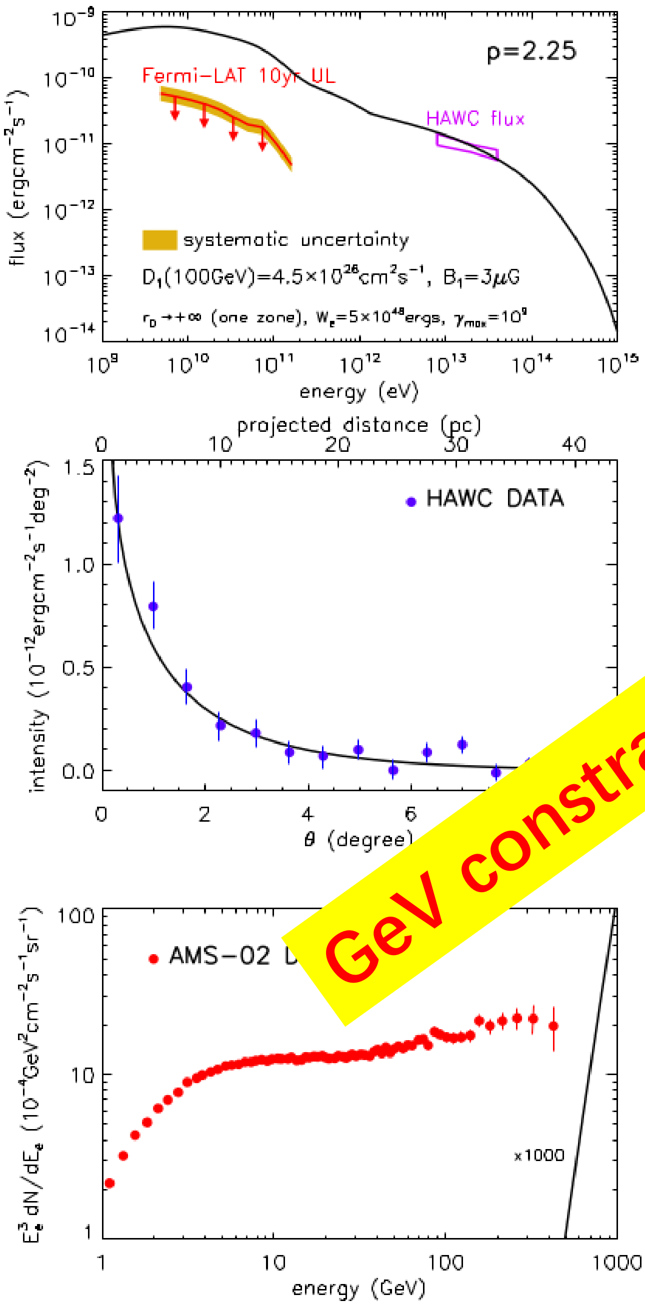


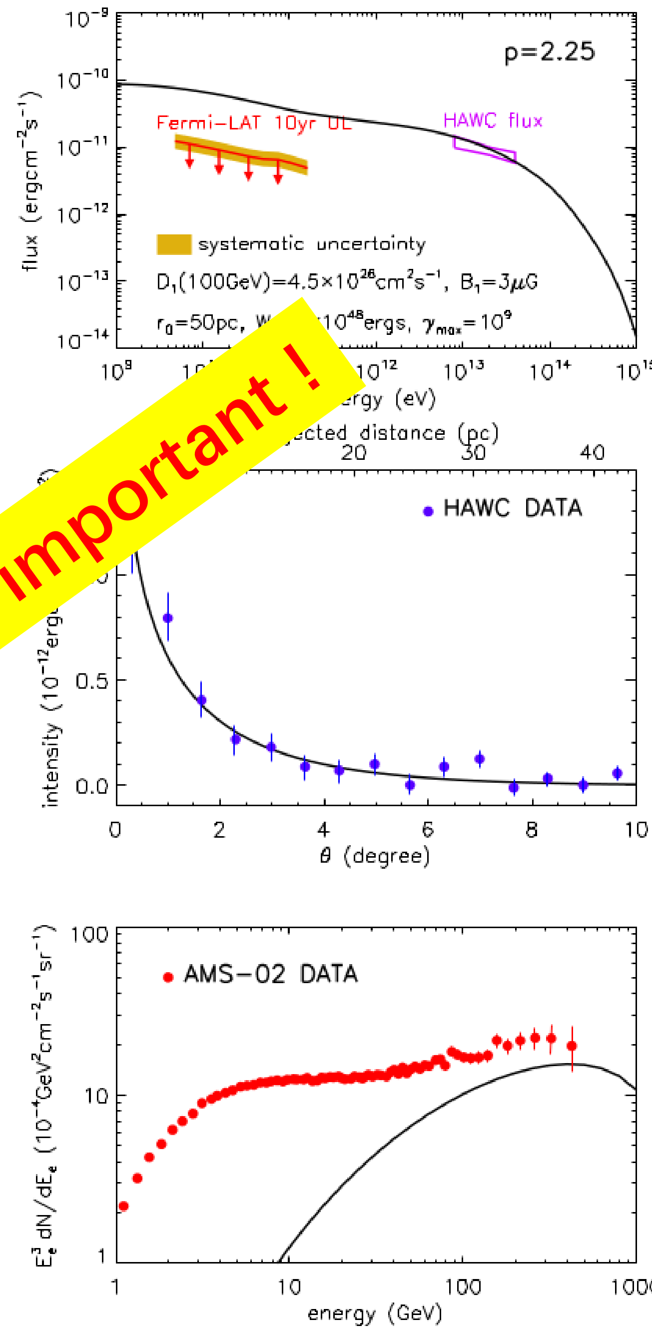
Table 1: Statistic test and 95% upper limit fluxes for each extended Template

Model name (Geminga)	UL (10-500 GeV) $\times 10^{-10}$ph cm^{-2} s^{-1}	TS	Model name (PSR B0656+14)	UL (10-500 GeV) $\times 10^{-10}$ph cm^{-2} s^{-1}	TS
2° Disk	0.44	0.1	2° Disk	0.61	0.3
Diffusion 1	29.1	16.1	Diffusion 6	2.8	0.5
Diffusion 2	6.3	4.1	Diffusion 7	4.9	0.5
Diffusion 3	4.5	2.1			
Diffusion 4	14.3	6.6			
Diffusion 5	3.9	1.0			

HAWC's best-fit parameters:

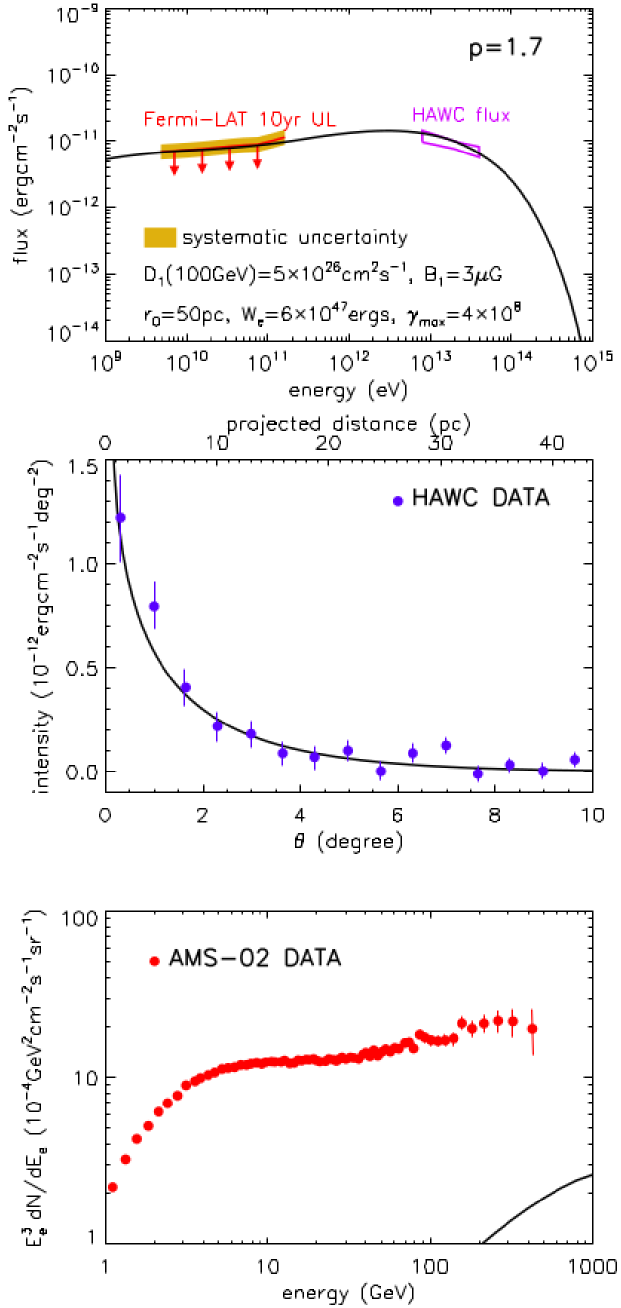


Two-zone diffusion model:



GeV constraints are important !

A harder injection spectrum: p=1.7



- A hard spectrum leads to a lower positron flux at GeV energies
- Insufficient to explain the positron excess at Earth

II. X-ray observation of the TeV halo

(Liu et al. 2019, ApJ)

Motivation:

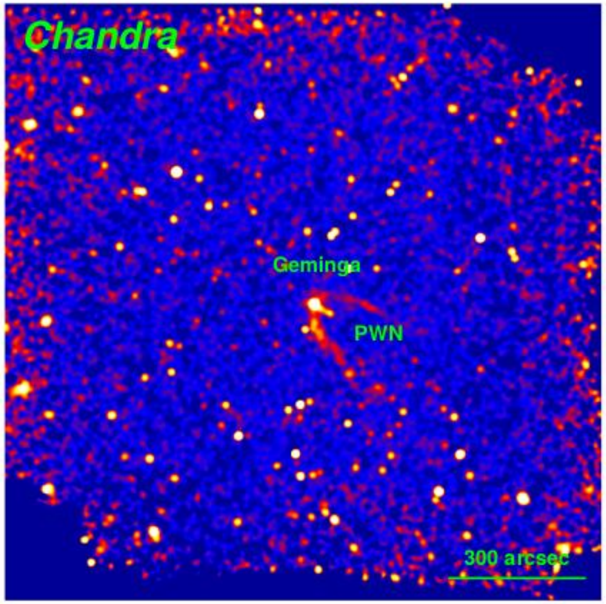
$$\epsilon_{\mathrm{IC}} \sim 20(E_e/100\mathrm{TeV})^2\,\mathrm{TeV}.$$

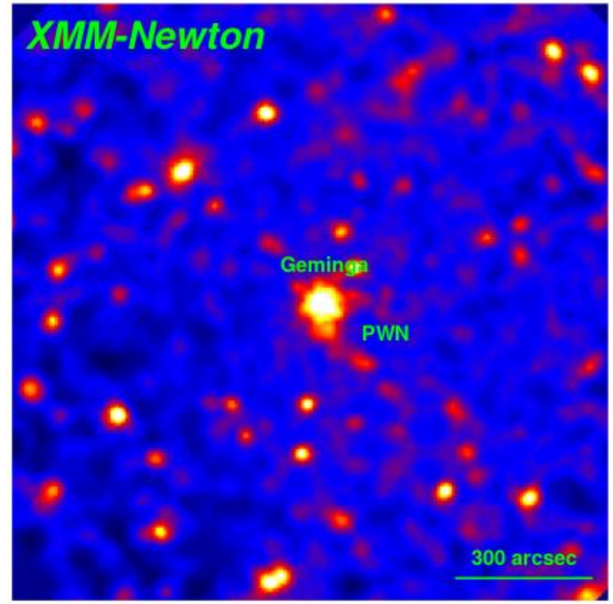
$$\epsilon_{\mathrm{syn}} \sim 0.6(E_e/100\mathrm{TeV})^2(B/3\mu\mathrm{G})\,\mathrm{keV}$$

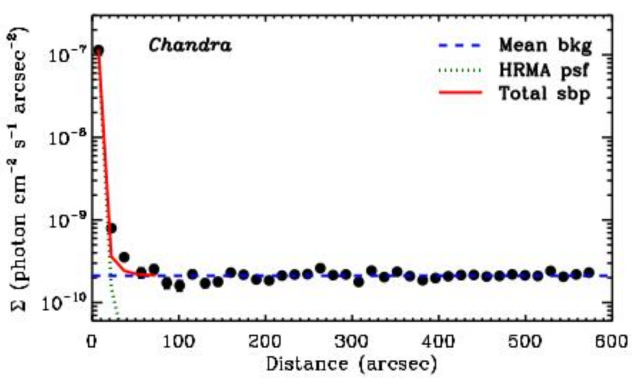
$$\Rightarrow F_{\mathrm{keV}}/F_{10\mathrm{TeV}} \simeq B^2/8\pi U_{\mathrm{CMB}}$$

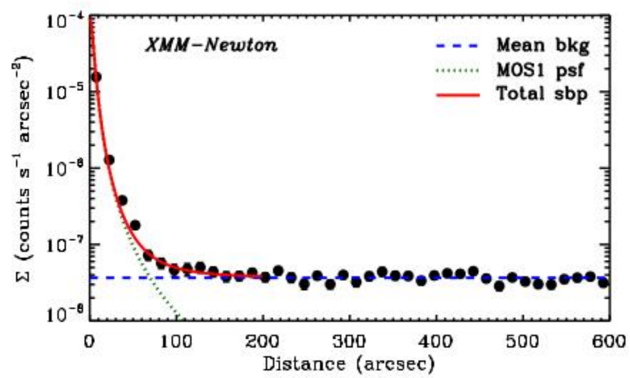
We expect to see the X-ray halo around Geminga

Analysis results –No X-ray counterparts







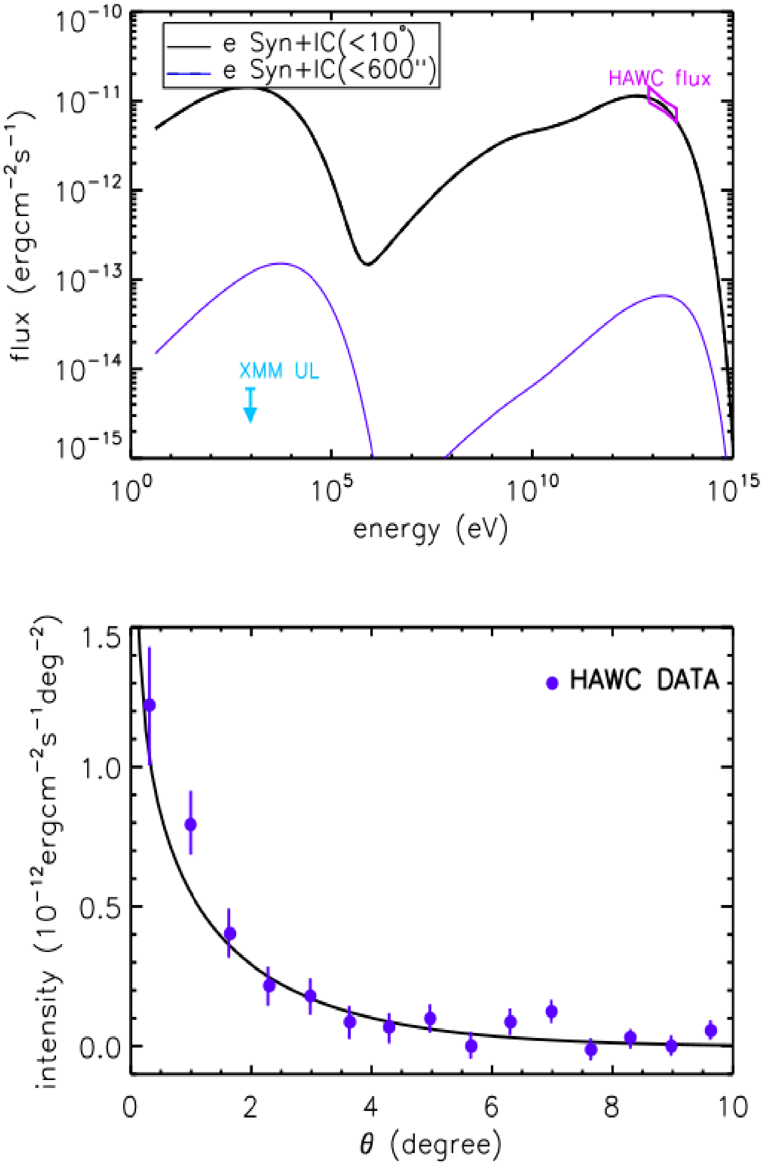


$f_{0.7-2.0\ \mathrm{keV}} = 6.1 \times 10^{-15}\ \mathrm{erg\ cm^{-2} s^{-1}}$

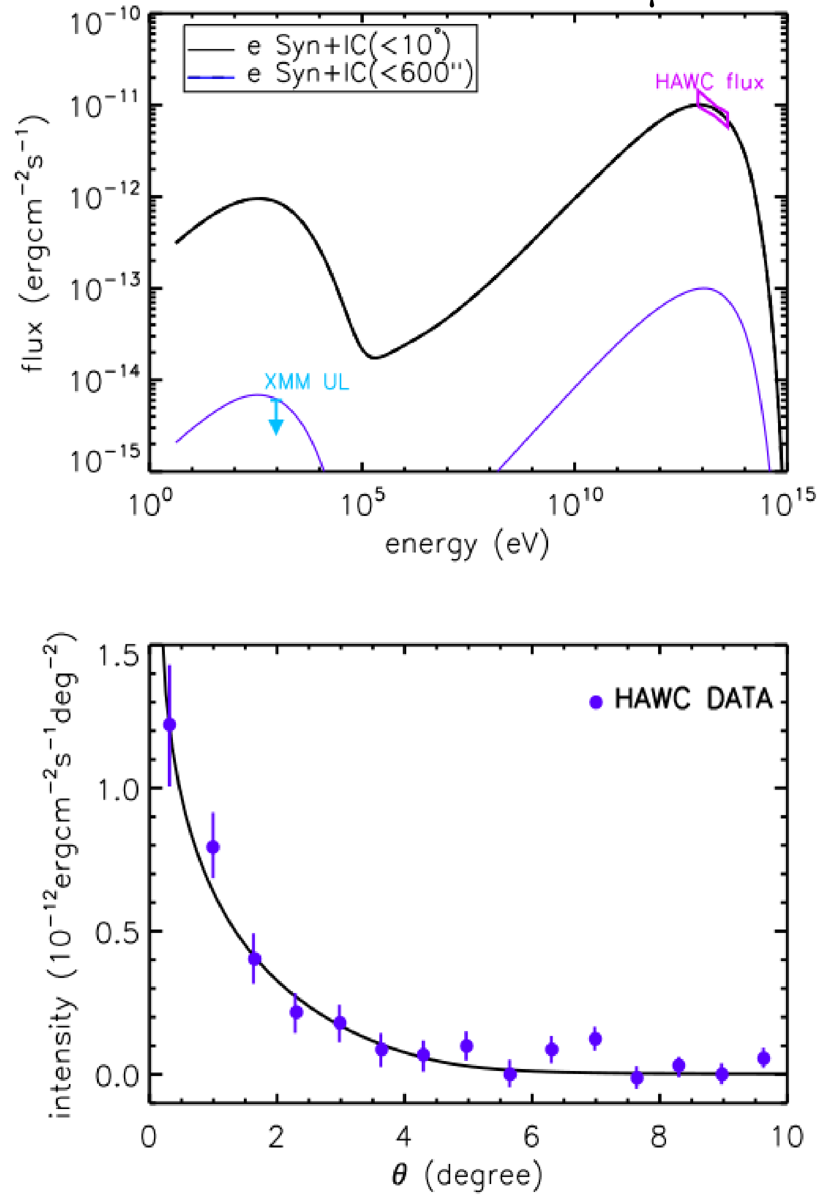
$f_{\mathrm{xmm},0.7-1.3\ \mathrm{keV}} = 5.0 \times 10^{-15}\ \mathrm{erg\ cm^{-2} s^{-1}}$

Constraints on the magnetic filed

B=3μG



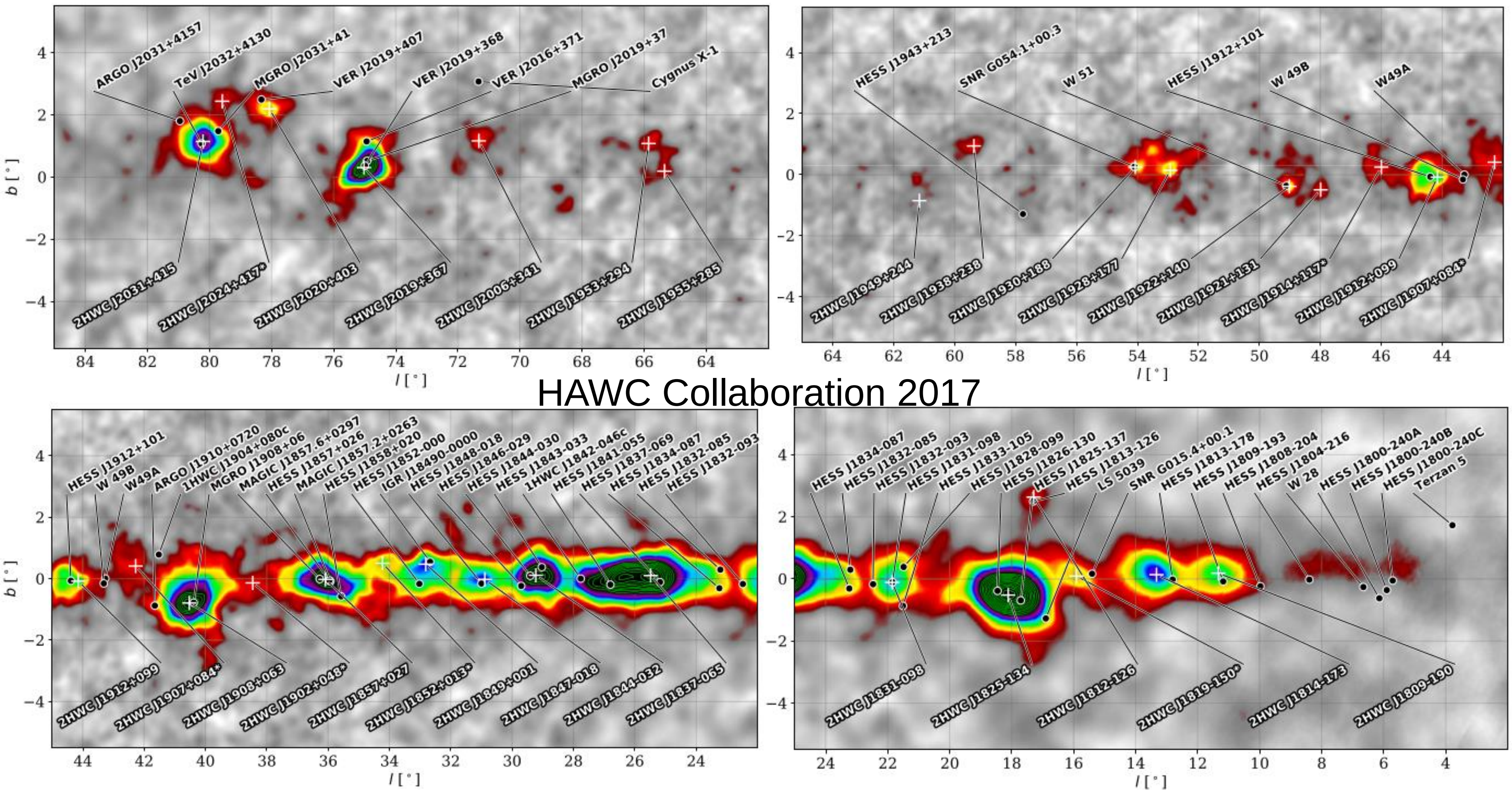
B=0.8μG



Summary so far

- ➢ HAWC has detected diffuse TeV halos extending at least 30pc, but no significant diffuse GeV and X-ray halos around Geminga have been detected
- - a hard electron spectrum is needed ($p<1.7$)
- - difficult to explain positron flux
- ➢ In the framework of isotropic diffusion, a highly turbulent region with very weak magnetic field is required.
  - - unique objects
- ➢ Need more pulsar TeV halos

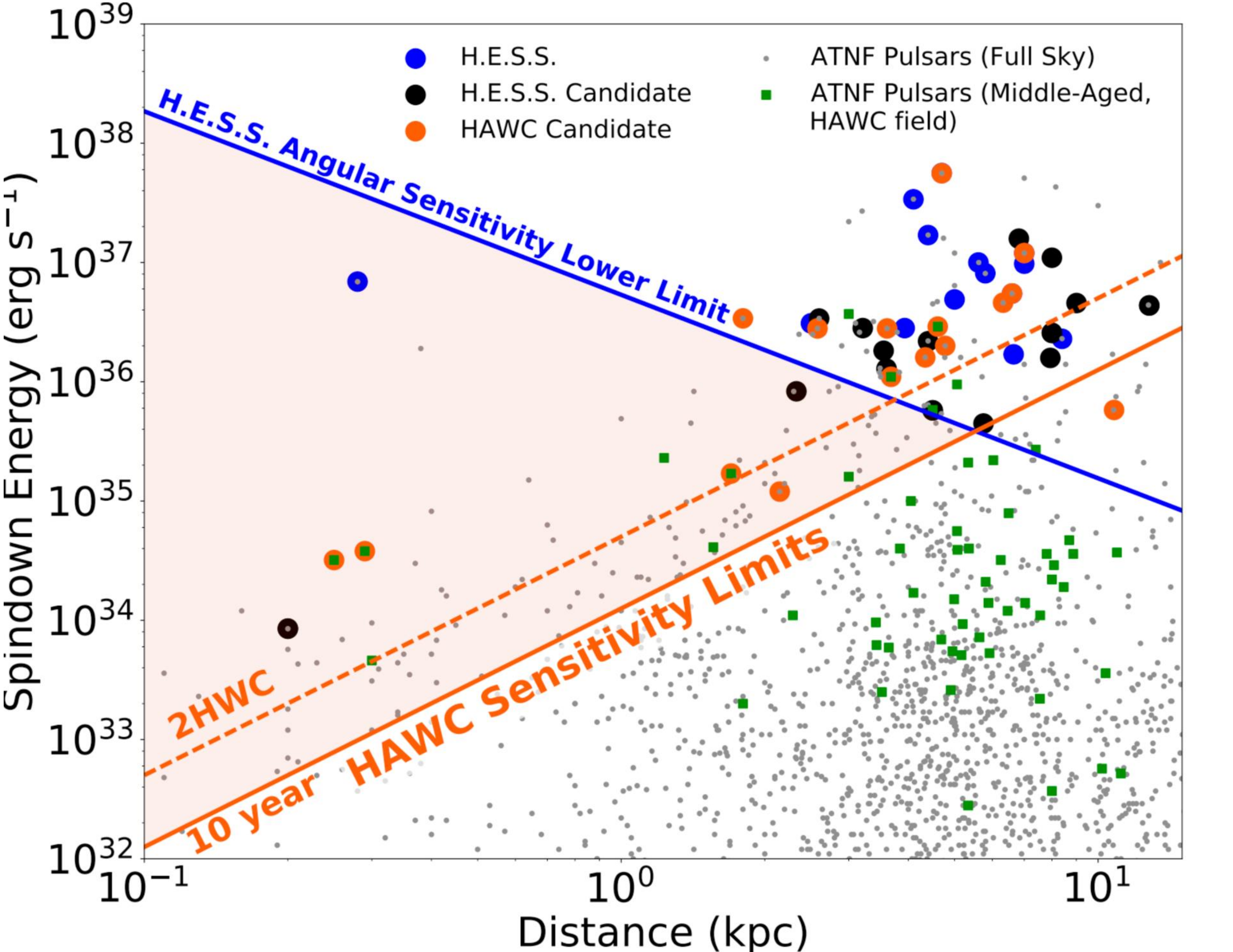
- better to have wider energy coverage (>100 TeV)



HAWC Collaboration 2017

HAWC Catalog about 1/3 sources are PWN or PWN candidates

- ➢ an almost guaranteed outcome of LHAASO
- ➢ LHAASO may go to >100 TeV



H.E.S.S.
H.E.S.S. Candidate
HAWC Candidate
ATNF Pulsars (Full Sky)
ATNF Pulsars (Middle-Aged, HAWC field)
H.E.S.S. Angular Sensitivity Lower Limit
2HWC
10 year HAWC Sensitivity Limits
Spindown Energy (erg s⁻¹)
Distance (kpc)
10^{39}
10^{38}
10^{37}
10^{36}
10^{35}
10^{34}
10^{33}
10^{32}
10^{-1}
10^{0}
10^{1}

Summary

- High Expectation on LHAASO’s contribution in this field, which will be important to understand CR propagation in Galaxy and the properties of PWN

- LHAASO can go to >100 TeV, probing the acceleration and transport of the highest electrons by pulsars

Backup Slides

Di Mauro et al. 2019