Pulsar emission of positrons and electrons, and its connections with gamma rays

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Virtual seminar on Multi-messenger astronomy
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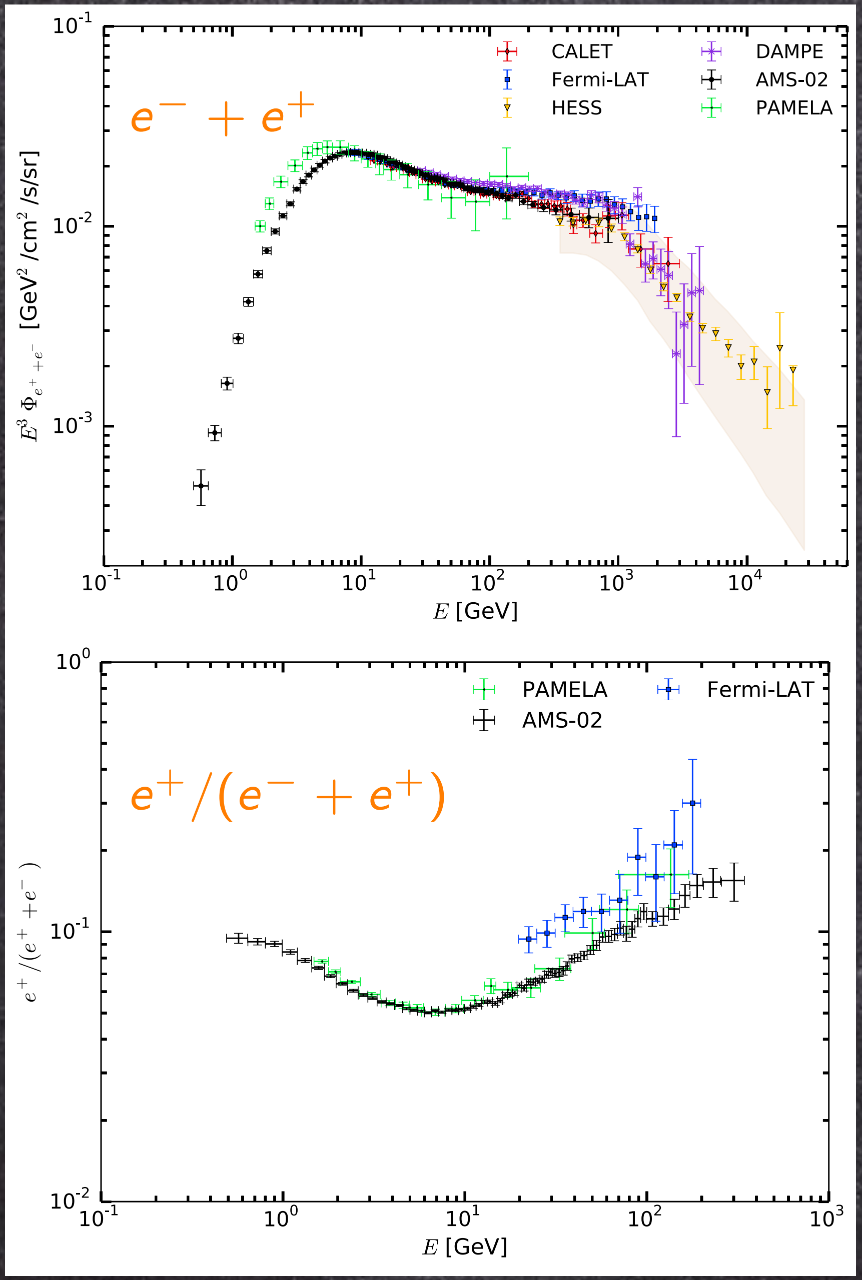
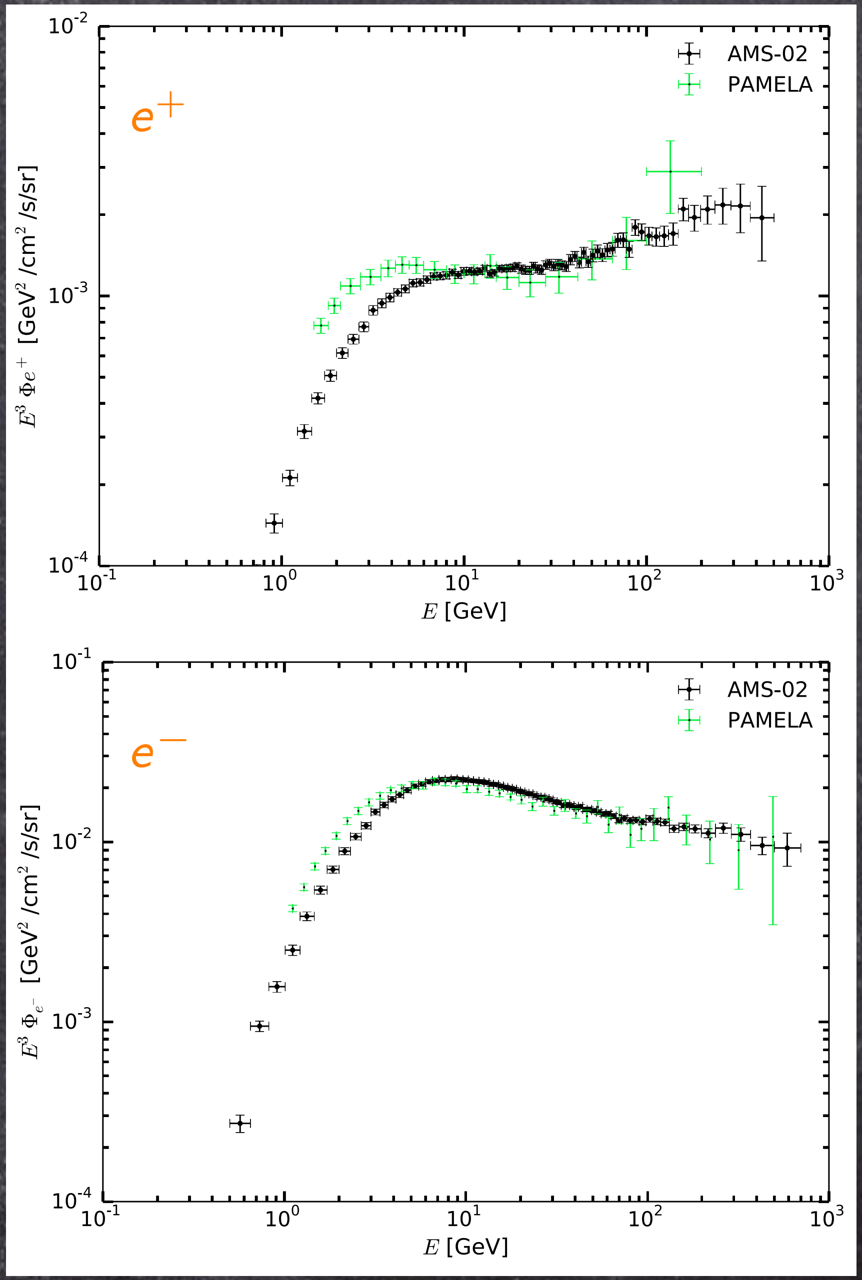
SFB 1258 | Neutrinos Dark Matter Messengers

works done in collaboration with Mattia Di Mauro and Silvia Manconi

The journey started with the attempt - shared by many - to interpret the e+ data





Unprecedented statistics and energy coverage

Sources of $e^{\pm}$ in the Milky Way

- Inelastic hadronic collisions (asymm.)
- Pulsar wind nebulae (PWN) (symm.)
- Supernova remnants (SNR) (only e+)
- (Particle Dark Matter annihilation)

From the source to a detector

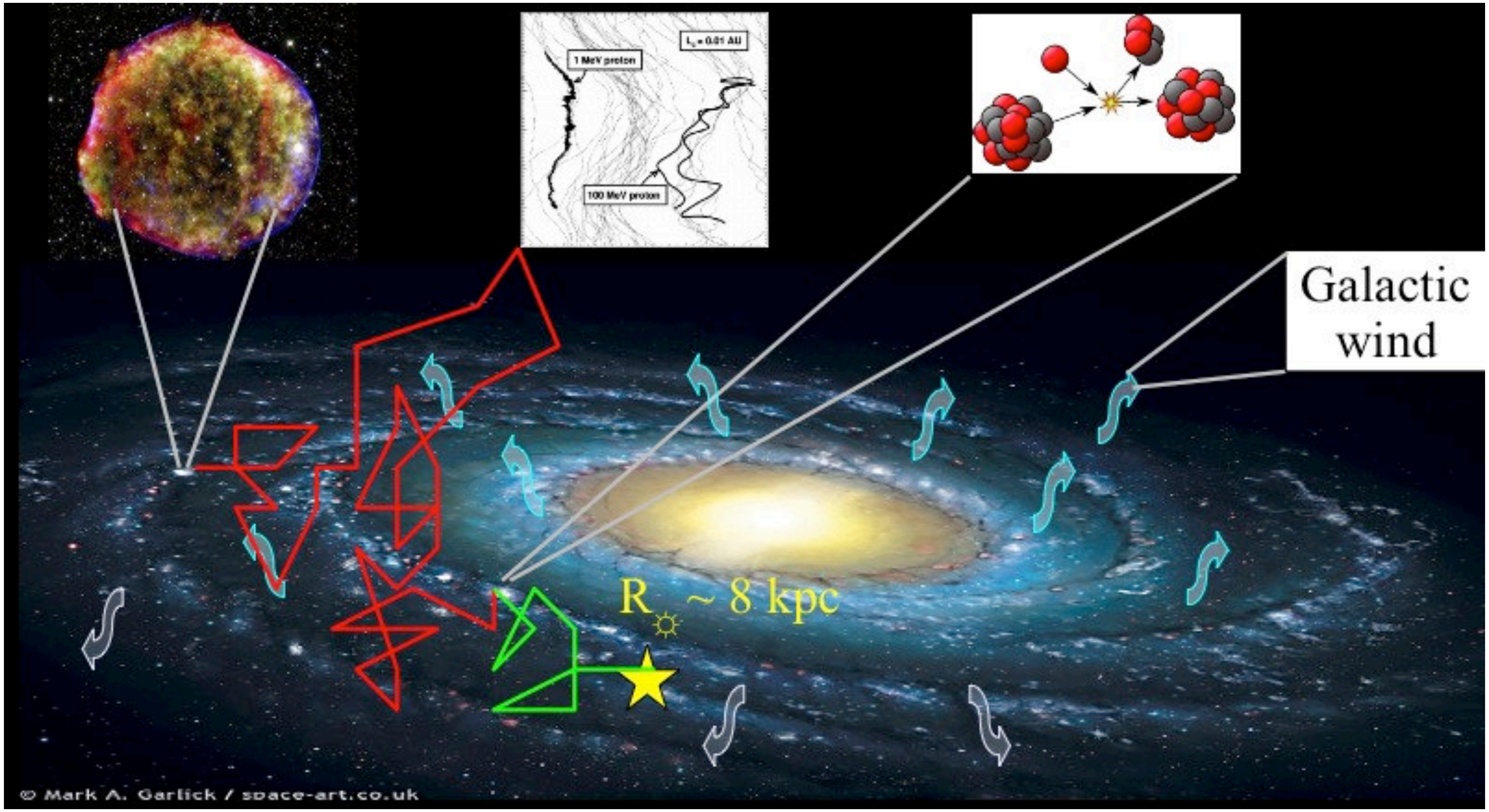
Sources: production mechanism
acceleration to high energies
injection into the interstellar space

Propagation: diffusion on the magnetic inhomogeneities of the Galaxy
energy losses and gains (B, E, cross sections)
convection

Energy losses: from the production site to the detector

Propagation in the Galaxy

Sources Diffusion Fragmentation



from D. Maurin

The galactic disc is embedded in a diffusive halo (L~4-10 kpc) where particle diffuse and can loose energy

Propagation equation

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

diffusion en. losses source spectrum

Diffusion: D(x,R) a priori
usually assumed isotropic in the Galaxy: $D(R)=D_0 R^{\delta}$
D_0 and δ fixed by secondary/primary nuclei (kappl+15; Genolini+15 (K15))

Energy losses: Synchrotron on the galactic B~3.6 μG
full relativistic of Compton effect (w/ Klein-Nishijna)
on photon fields (stellar, CMB, UV, IR)

Solution of the eq.: semi-analytic (Maurin+ 2001, Donato+ 2004, ...), USINE codes
or fully numerical: GALPROP, DRAGON codes

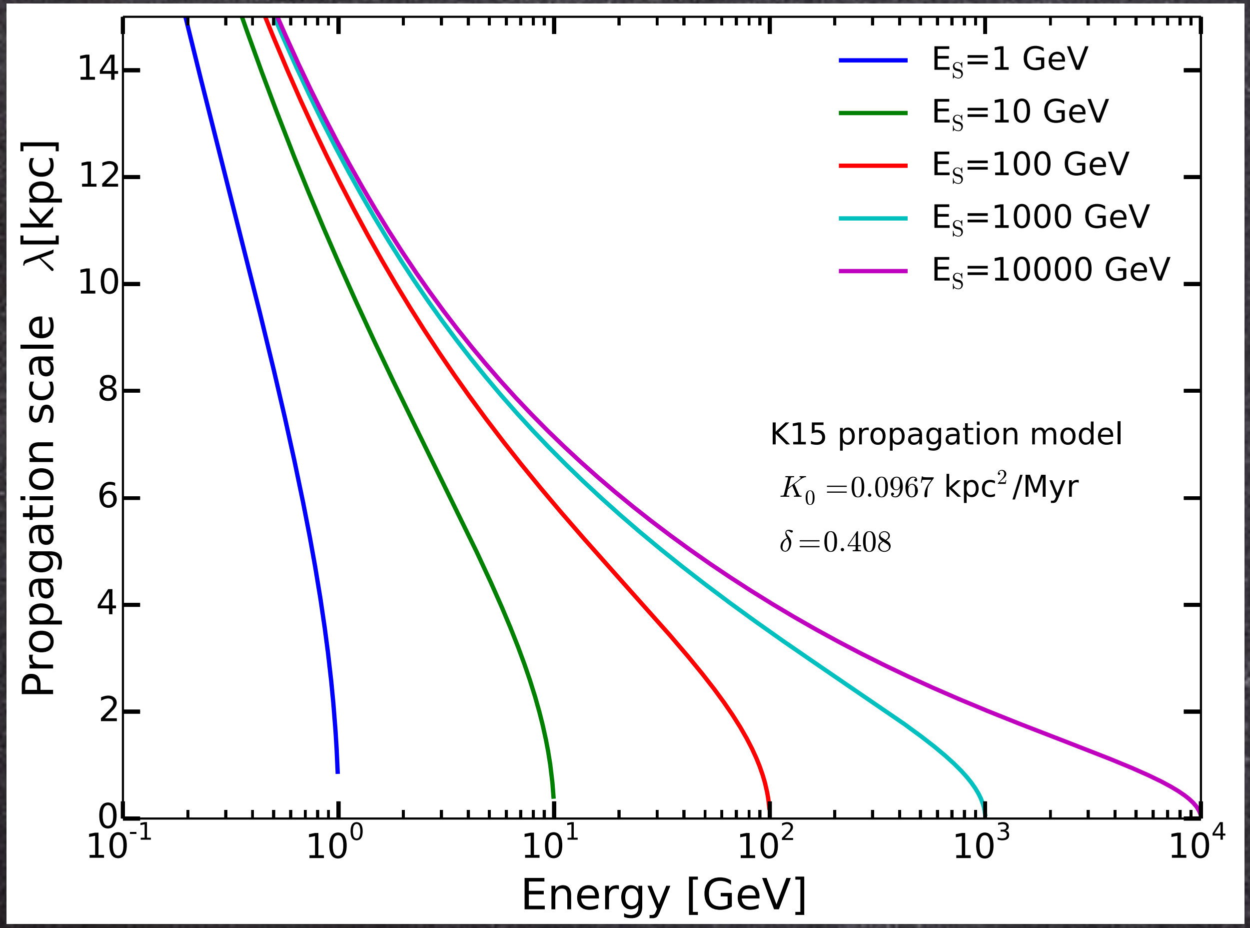
Geometry of the Galaxy: cylinder with height L

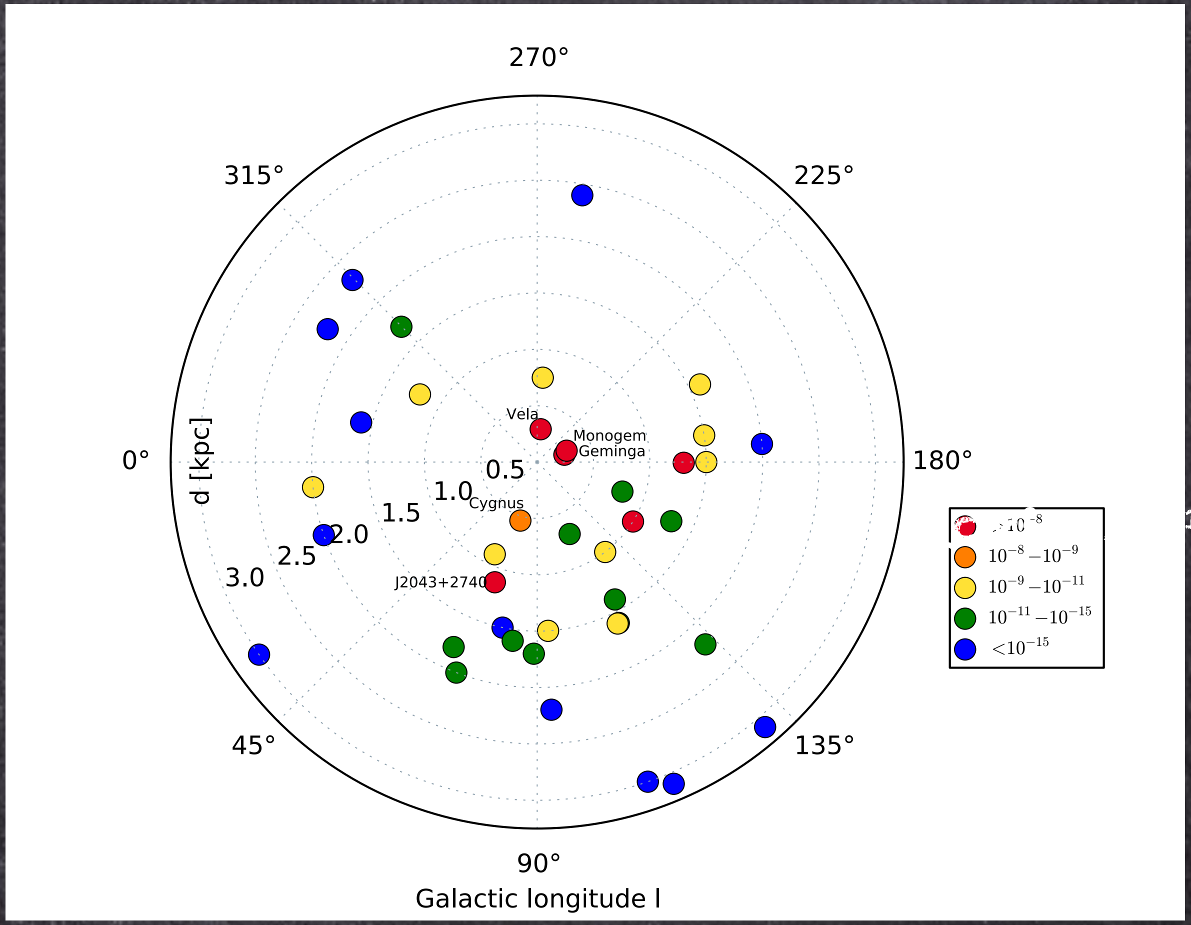
Detected e± are local

$$\lambda^2(E, E_S) = 4 \int_E^{E_S} dE' \, \frac{D(E')}{b_{\rm loss}(E')}$$

Typical propagation length in the Galaxy

Manconi, Di Mauro, FD JCAP 2017





e−, e+ have strong radiative cooling and arrive at Earth if produced within few kpc around it

Most powerful sources within 3 kpc from the Sun.
SNRs (e−) and PWN (e+e−)

A word worth on $e^{\pm}$ energy losses

Inverse Compton $e^{\pm}(E_0) + \gamma(E) \rightarrow e^{\pm}(E_1) + \gamma(E')$

$E_0 > E_1$ a loss

$E < E'$ a gain, and a **MESSANGER**

X-rays, γ-rays

Synchrotron emission radiated from the interaction with a B

$e^{\pm}$ losses energy

a photon is created, a **MESSENGER**

radio, X-ray

Secondary e+e-

Delahaye+ A&A2009, 2010

Produced by inelastic collisions of CRs (p and He mosly) on the interstellar GAS (H and He)

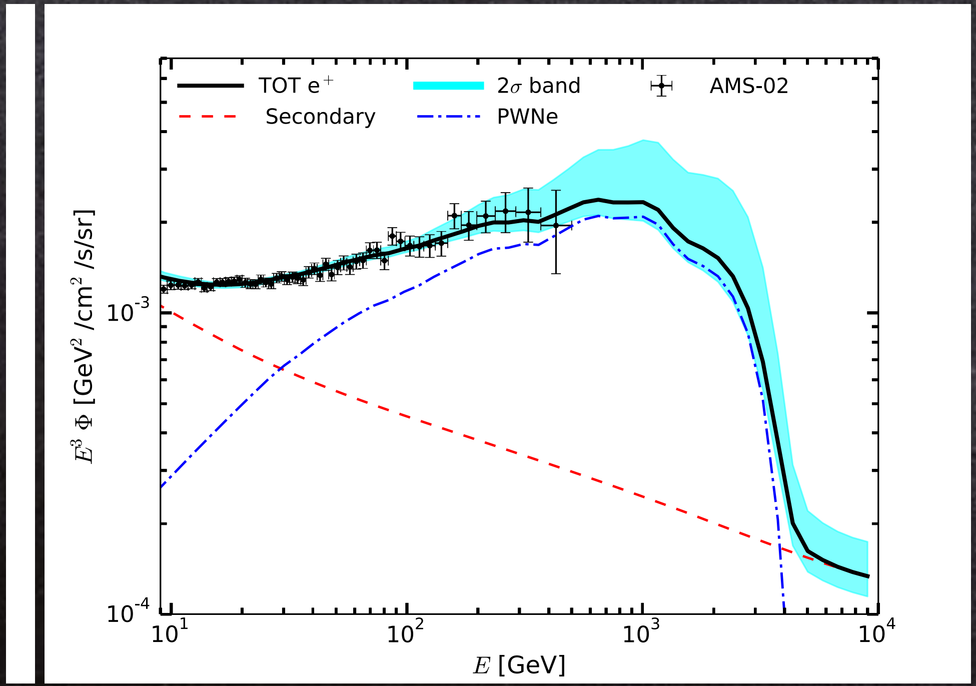
$$\left.\begin{array}{l} p+H \rightarrow \pi^\pm + X \\ p+H \rightarrow K^\pm + X \end{array}\right\} \rightarrow e^\pm$$

$d\sigma(p+H \rightarrow \pi^\pm + X)$ has to be measured -> UNCERTAINTY ~ 2

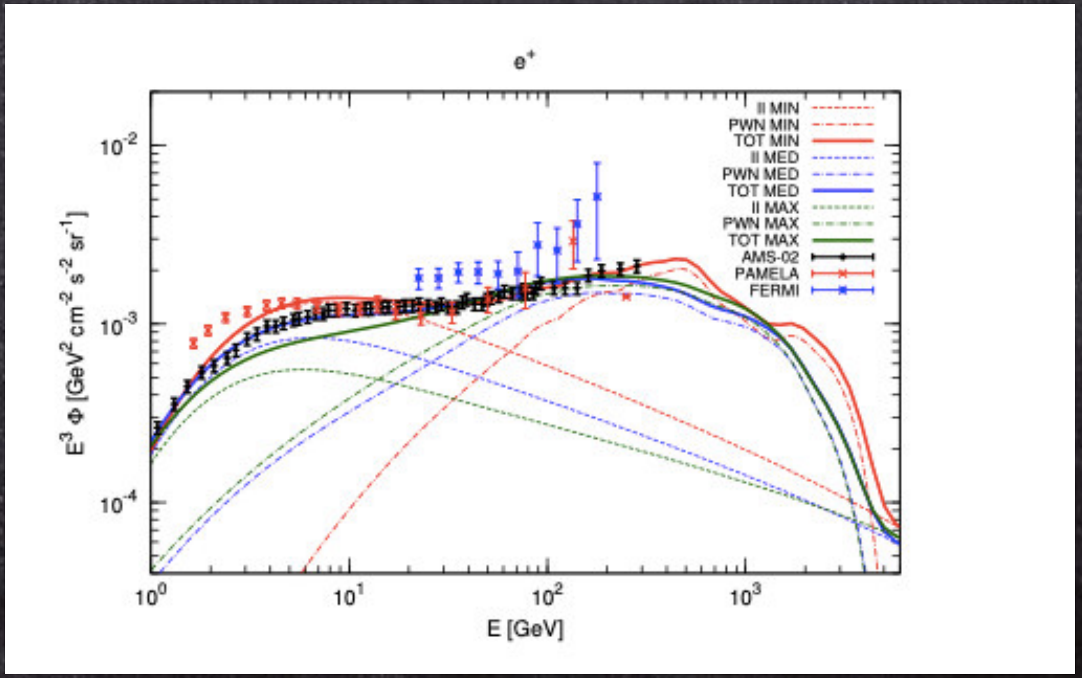
$P(\pi^\pm \rightarrow e^\pm)$ is computed by QED

Need for high energy data cross sections from collider experiments

Di Mauro + JCAP 2019

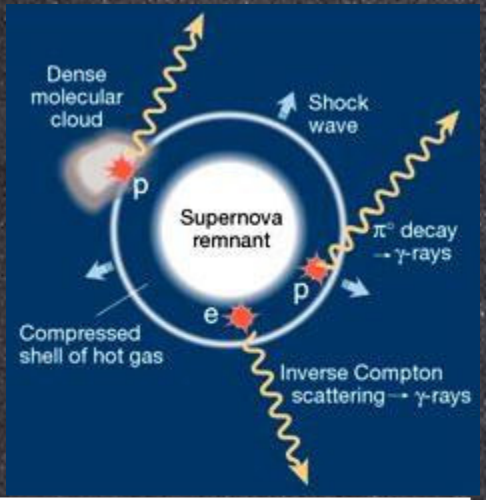


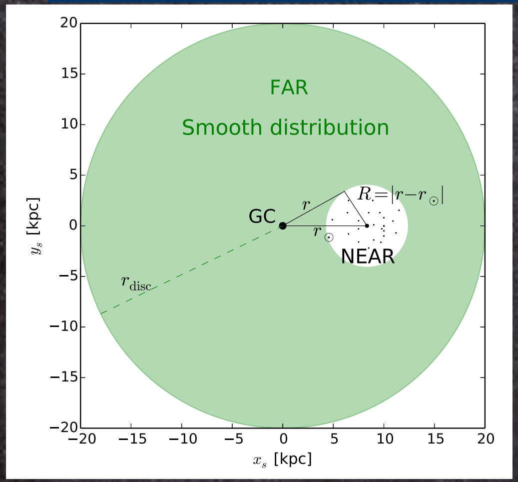
Di Mauro + JCAP 2014



Electrons from supernova remnants

Ellison+ ApJ 2007; Blasi 2013; Di Mauro+ JCAP 2014; ApJ 2017





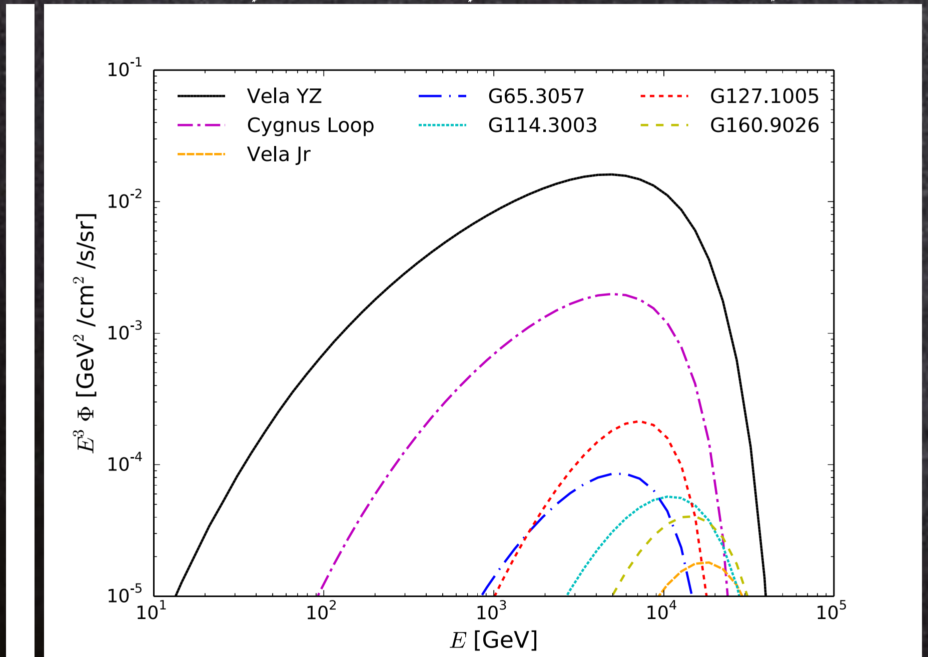
SNR are considered the main sources of galactic CRs - nuclei from p to Fe, and e-

- Hadronic acceleration: evidence of π° bump (Fermi-LAT+ 2010)
- Leptonic acceleration: evidence of synchrotron emission in radio and X-rays

Injection spectrum:

$$Q(E) = Q_0 \left(\frac{E}{E_0}\right)^{-\gamma} \exp\left(-\frac{E}{E_c}\right)$$

Manconi, Di Mauro, FD JCAP2017; JCAP 2019



e- flux from near SNR (Vela XY and Cygnus Loop at d<0.5 kpc)

Few SNR can contribute to TeV flux

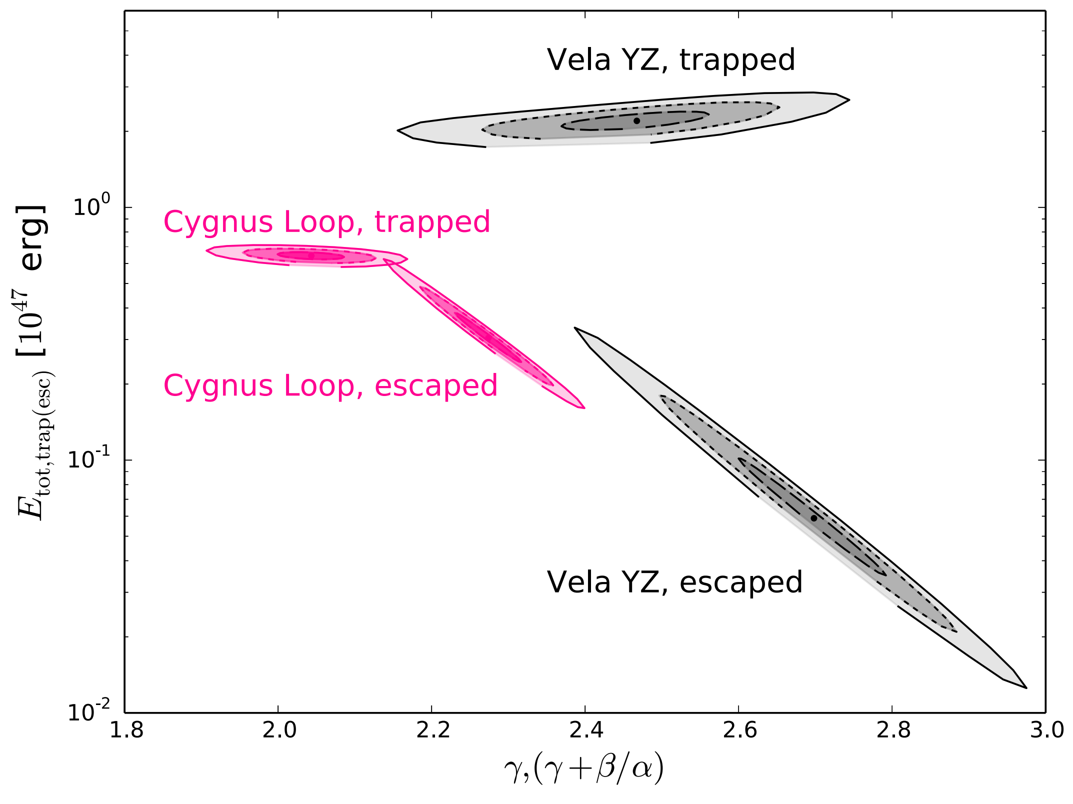
Additional e- from a smooth SNR distribution

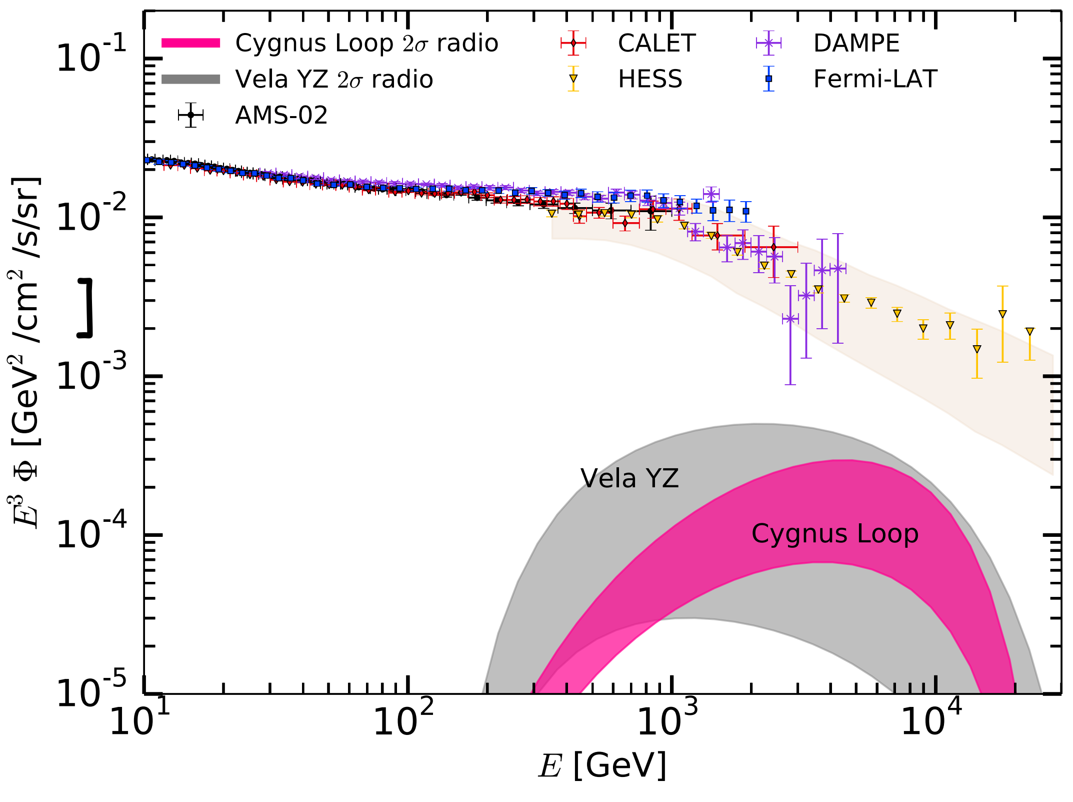
SNR acceleration & radio emission

Manconi, Di Mauro, FD JCAP 2019

Hyp: Radio flux due to synchrotron emission from accelerated e- in the SNR

$$Q_{0,\mathrm{SNR}} = 1.2 \cdot 10^{47} \mathrm{GeV}^{-1} (0.79)^{\gamma} \frac{B_r^{\nu}(\nu)}{\mathrm{Jy}} \left[\frac{d}{\mathrm{kpc}}\right]^2 \left[\frac{\nu}{\mathrm{GHz}}\right]^{\frac{\gamma-1}{2}} \left[\frac{B}{100\mu\mathrm{G}}\right]^{-\frac{\gamma+1}{2}}$$



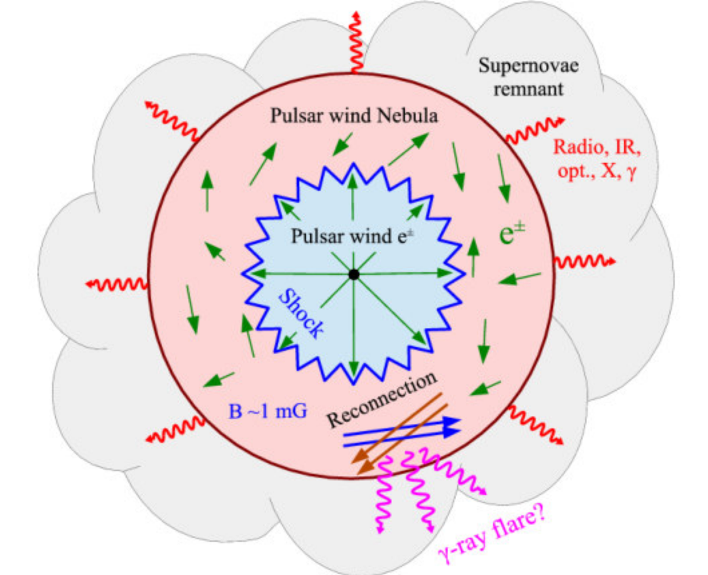


We fit all the available radio data fixing B_{Vela} =36 μG and C_{ygnus} = 60 μG.
Vela has energetic trapped e-, and only E>88 GeV have escaped (17 GeV for Cygnus).
The flux of e- as constrained by radio data contribute few % to the (e+e-) data

Pulsars (PWN) as CR e^+e^- sources

Shen ApJL 1970; Amato arvin:1312.5945; Di Mauro+ JCAP 2014

Pulsar wind nebulae (PWNe) as engines of $e^\pm$



- High magnetic fields (10^9-10^{12} G) extract wind of e^- from the pulsar surface, $e^\pm$ pairs produced in EM cascades
- Pulsar spin-down energy (W_0) is transferred to $e^\pm$ pairs, accelerated to very high energy with $Q(E) \sim E^{-\gamma}$.
- After several kyrs $e^\pm$ can be released in the ISM
- These $e^\pm$ pairs radiate by IC and synch., and shine at many frequencies

$$E_{\rm tot} = \eta W_0 = \int_0^T dt \int_{E_1}^{\infty} dE E Q(E,t)$$

The total energy E_{tot} emitted in $e^\pm$ by a PWN is a fraction η (efficiency conversion) of the spin-down energy W_0. Relevant parameters: γ and η

Anisotropy in a diffusion model

Manconi, Di Mauro, FD JCAP 2017

Anisotropy should be computed by development on spherical harmonics.
For one or few sources,
we can expect only the dipole term to have some relevance (if any).
In diffusive propagation regime (Ginzburg & Syrovatskii 1964):

$$\Delta = \frac{3K}{c}\left|\frac{\nabla\psi}{\psi}\right|$$

For example, for a source at d_s:

$$\Delta(E)_{e^+ + e^-} = \frac{3K(E)}{c}\,\frac{2d_s}{\lambda^2(E,E_s)}\,\frac{\psi^s_{e^+ + e^-}(E)}{\psi^{\rm tot}_{e^+ + e^-}(E)}$$

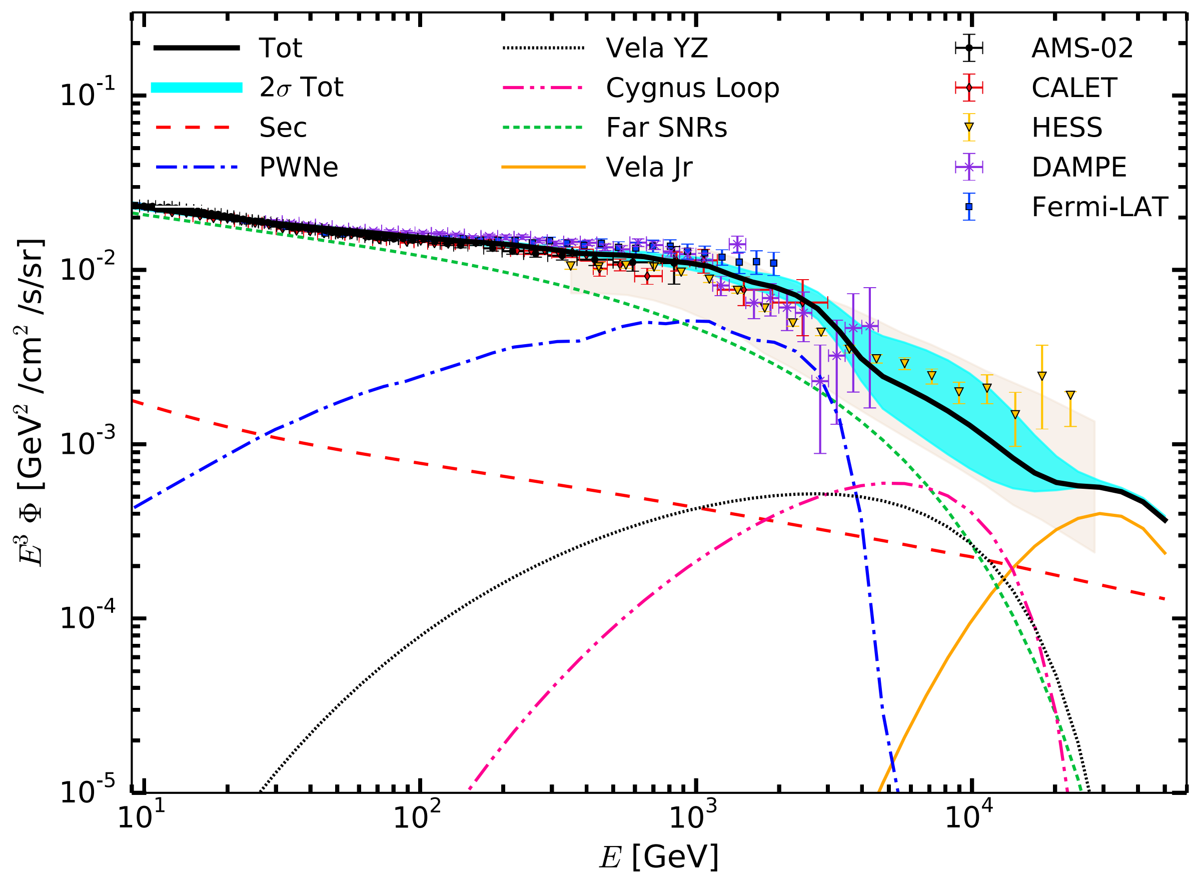
More generally, for a collection of sources (Shen & Mao, ApJL 1971):

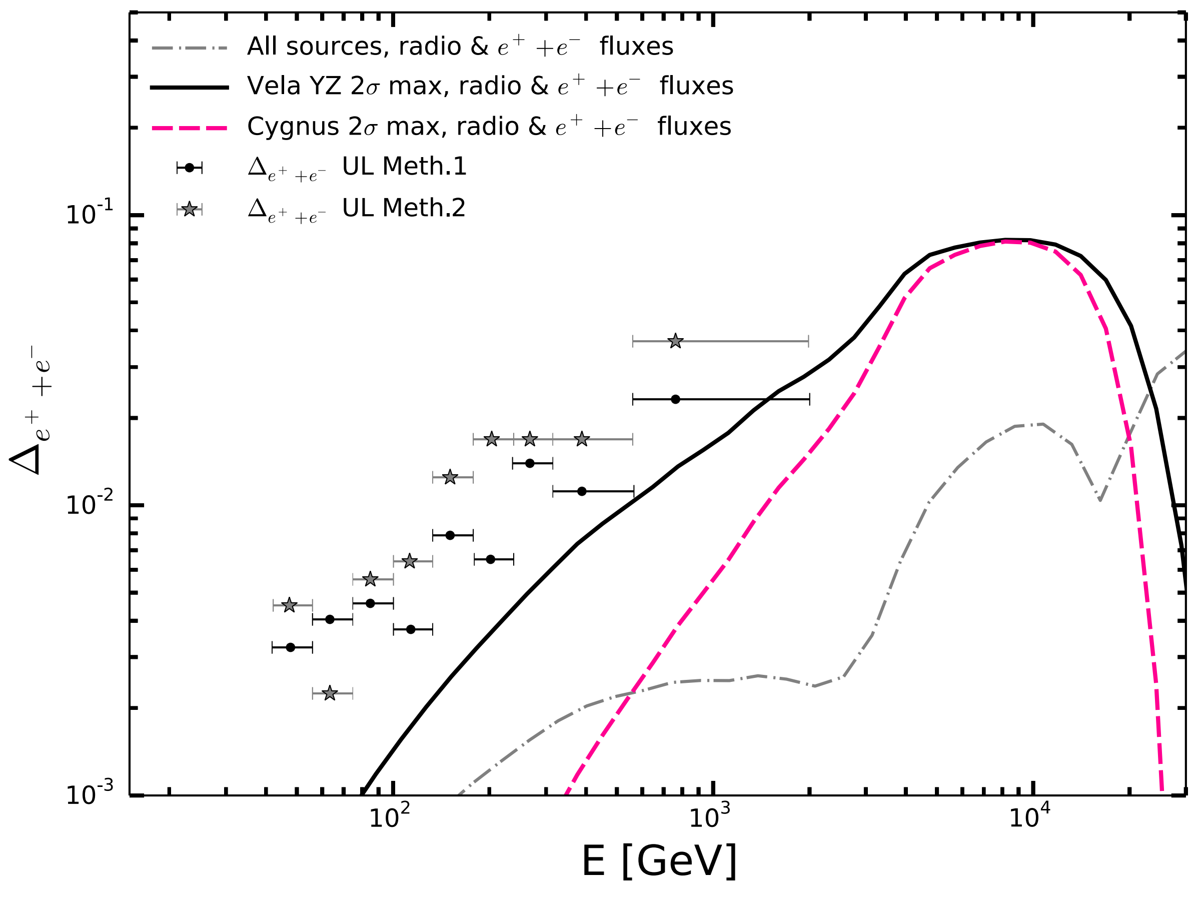
$$\Delta(n_{\max},E) = \frac{1}{\psi^{\rm tot}(E)}\cdot\sum_i \frac{\mathbf{r}_i\cdot\mathbf{n}_{\max}}{||\mathbf{r}_i||}\cdot\psi_i(E)\,\Delta_i(E)$$

A multi-wavelength & multi-messenger analysis

We fit the parameters selected by radio and e+e- flux data and check against dipole anisotropy data

Manconi, Di Mauro, FD JCAP 2019

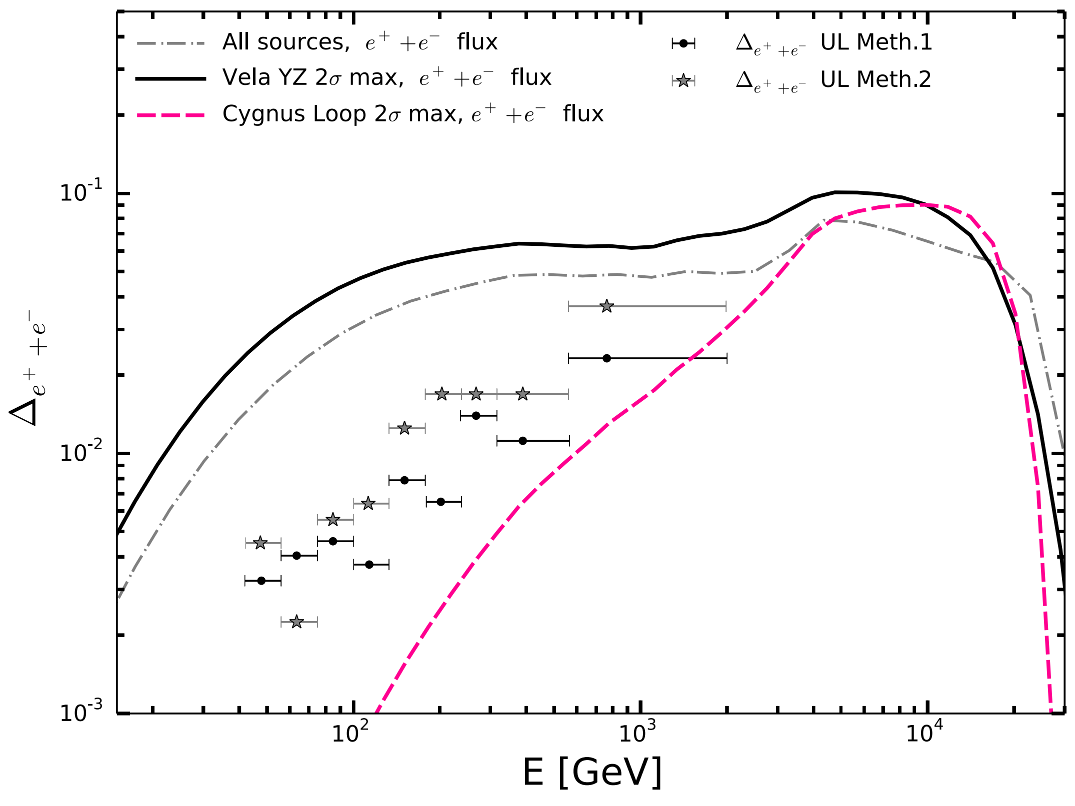




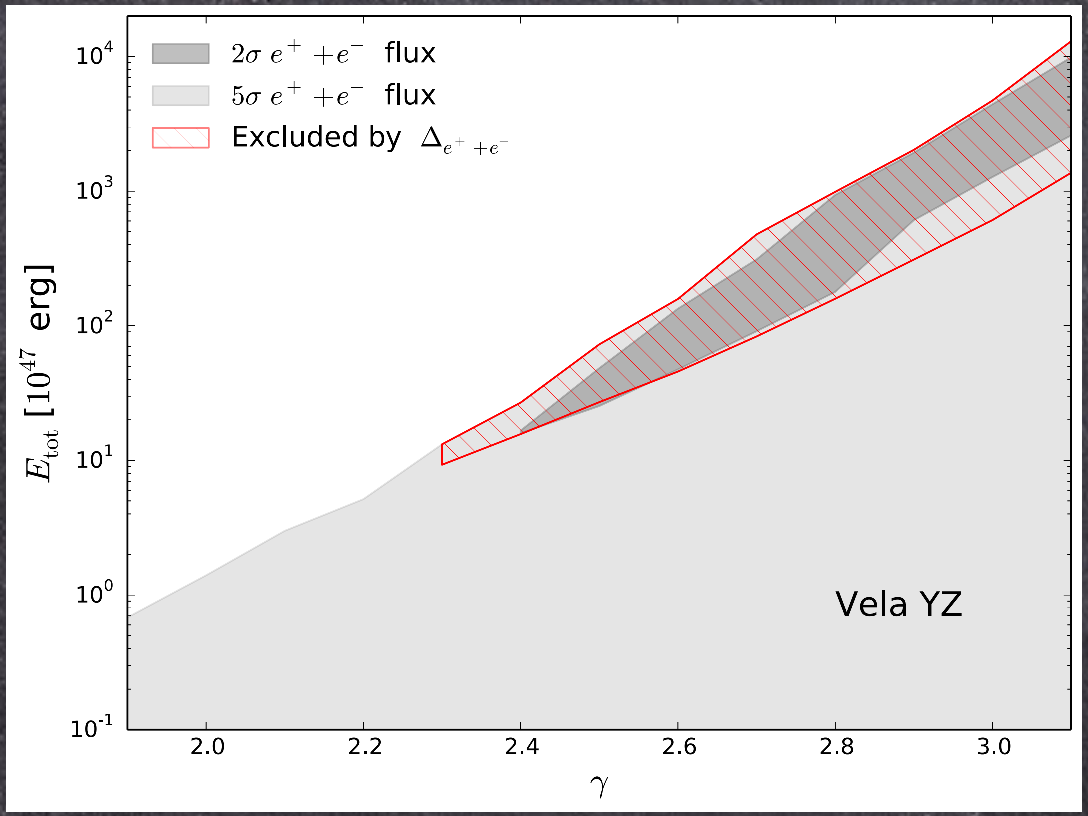
We find models compatible with three independent observables: radio flux from SNR; e+e- flux; e+e- dipole anisotropy

Bounds from dipole anisotropy

Fermi-LAT data from e+e- dipole anisotropy are upper bounds vs E (Abdollahi+ PRL 2017)



Manconi, Di Mauro, FD JCAP 2019



Maximal anisotropy from e+e- flux selected configurations

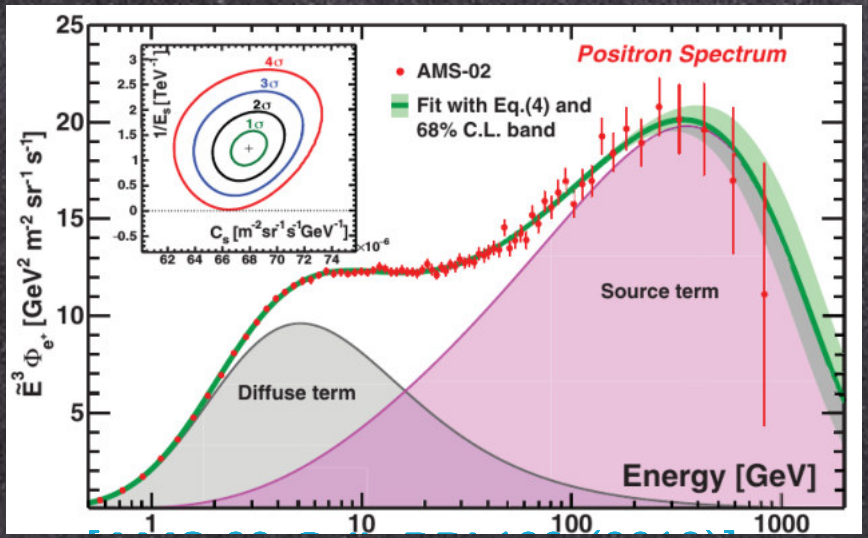
Anisotropy excludes configurations selected by e+e- flux

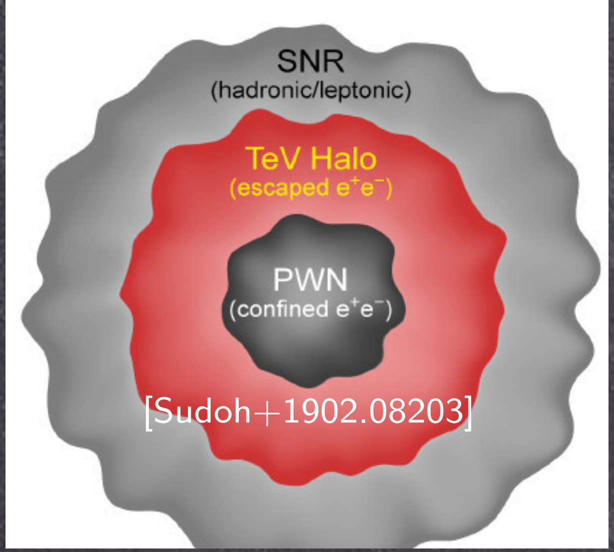
Dipole anisotropy in CR leptons is a valuable observable to study the properties of local sources - SNRs

Positron flux and γ-ray haloes

- The positron flux shows (Pamela, AMS data) the need of primary source at high energies. Pulsars could do the job.

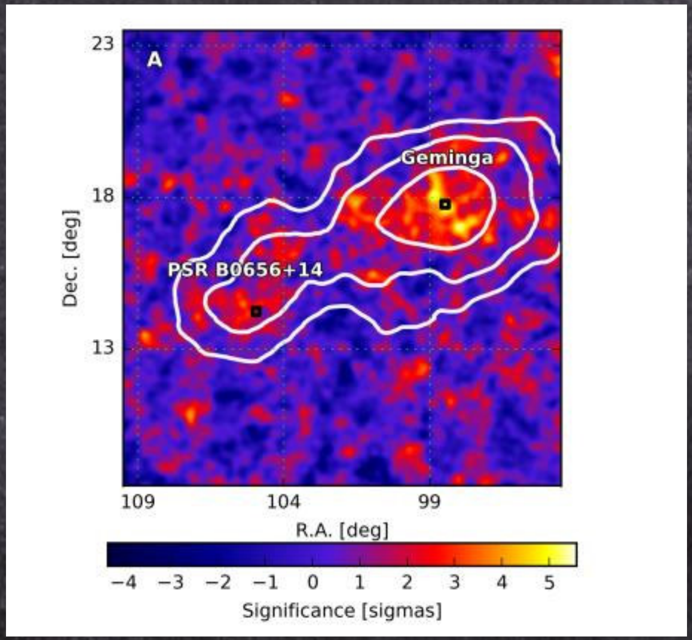
AMS Coll. PRL 2019s





[Sudoh+1902.08203]

- HAWC has detected a TeV gamma-ray halo around Geminga and Monogem pulsars. Interpreted as e+e- accelerated by the pulsar, then released in the ISM, A low diffusion region around the pulsars is favored by data



HAWC Collaboration, Science 358, 2017
Milagro, Abdo et al., ApJL 2009

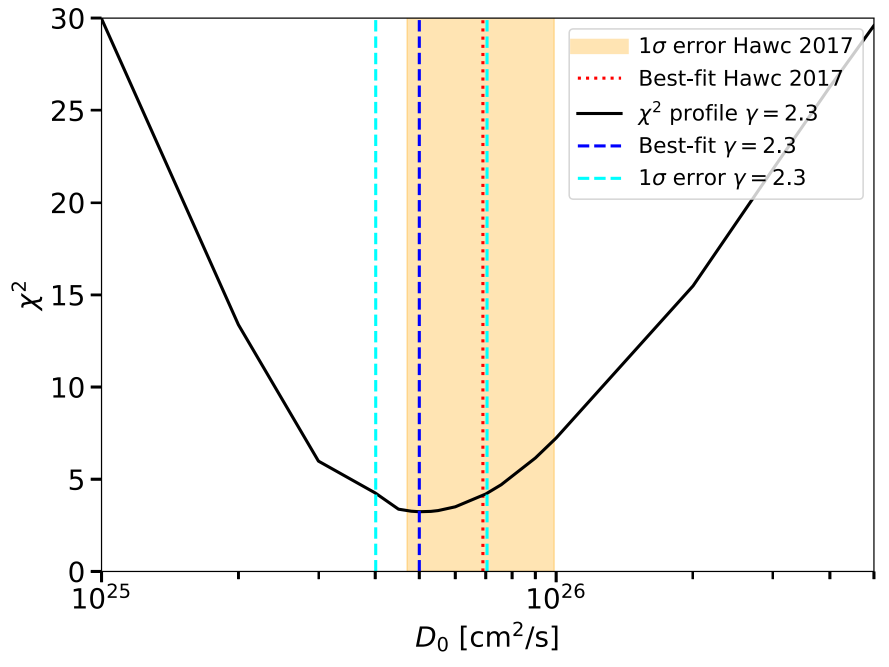
What we learn from HAWC data

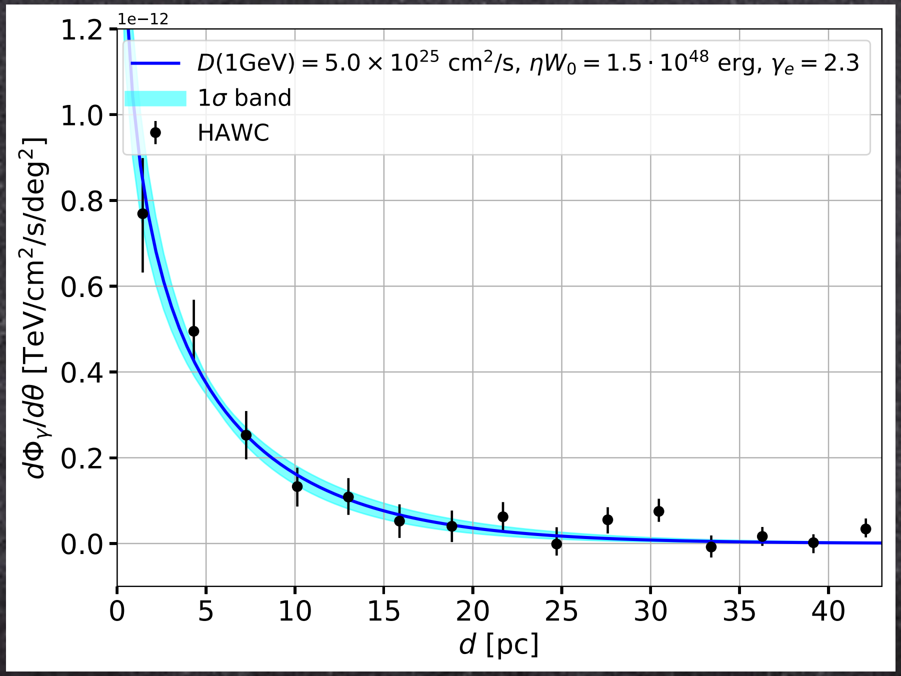
Di Mauro, Manconi, FD PRD 2020 Hooper+1702.08436, Fang+1803.02640
Sudoh+1902.08203, Johannesson+1903.05509, Tang+1808.02445

- The $e^\pm$ injection is continuous (not burst-like)

$$Q(E,t) = L(t)\left(\frac{E}{E_0}\right)^{-\gamma} \exp\left(-\frac{E}{E_c}\right) \qquad L(t) = \frac{L_0}{\left(1+\frac{t}{\tau_0}\right)^2}$$

- The spin-down luminosity converted into HAWC high energy e+e- is ηW_0= 1.5 10^{48} (4.2 $1s^{46}$) erg for Geminga (Monogem)
- The diffusion is inhibited around the pulsar by ~ 500 times wrt the average in the ISM: D0(1 GeV) + 5 10^{25} cm²/s



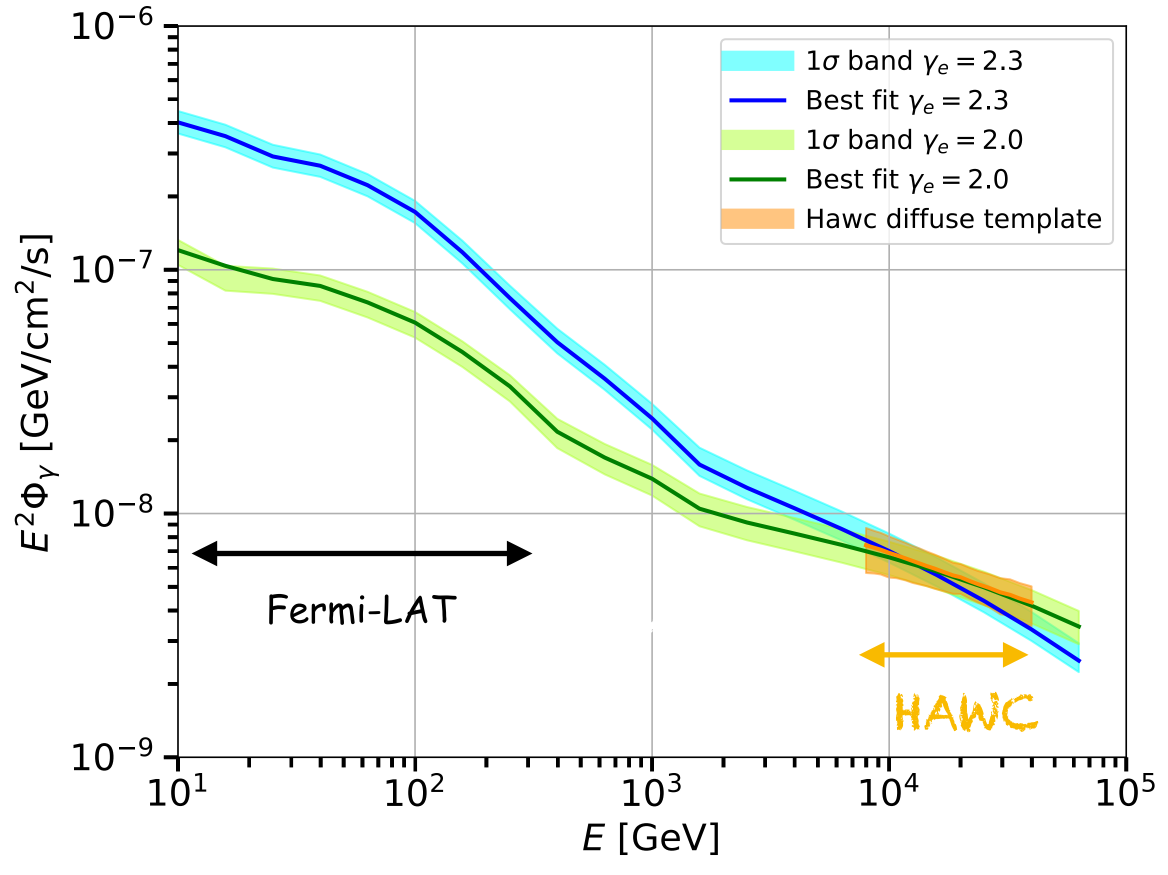


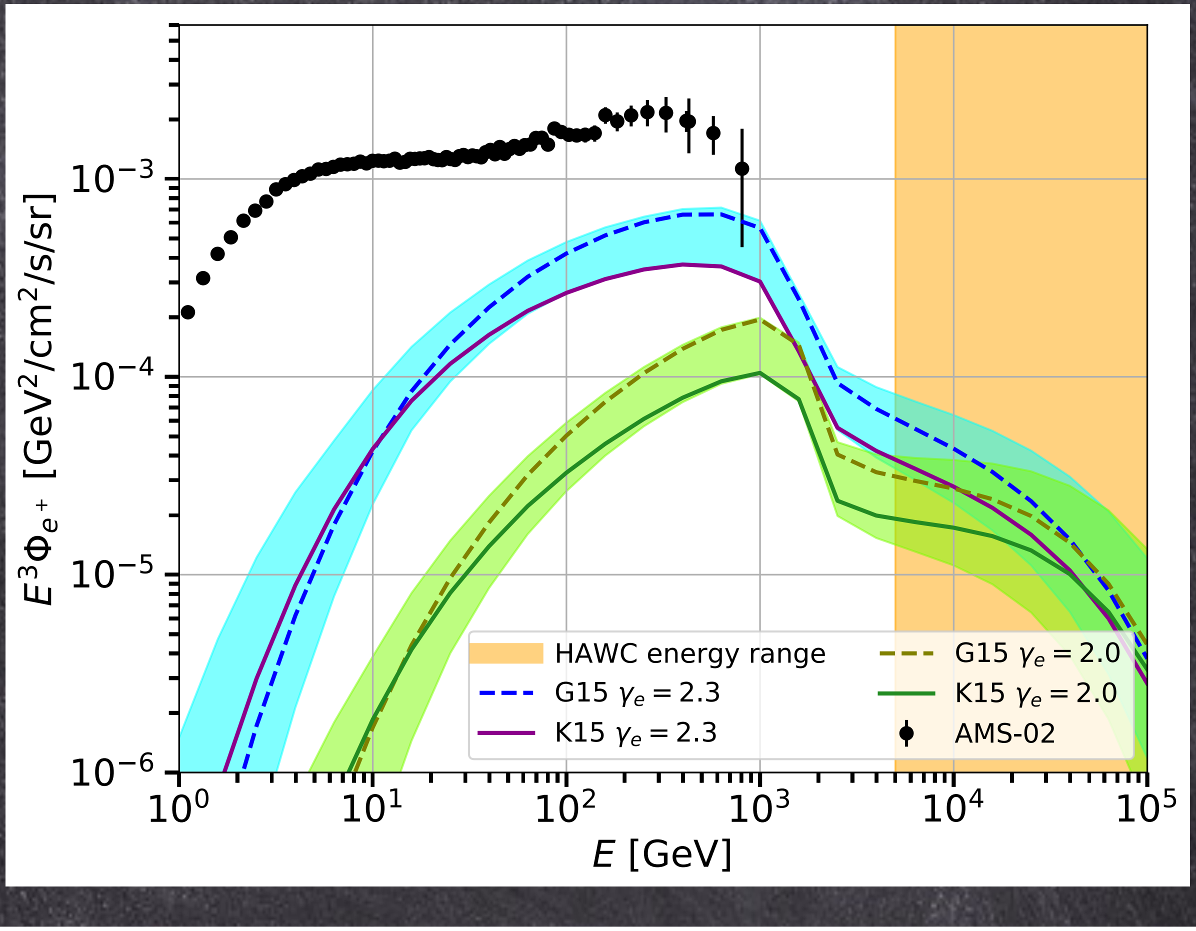
Fit to Geminga surface brightness

Di Mauro, Manconi, FD PRD 2020

Which e± produce HAWC photons?

Di Mauro, Manconi, FD PRD 2020





The fit to HAWC surface brightness comes with uncertainties / degeneracies

The extrapolation down to Fermi-LAT energies gives remarkable differences

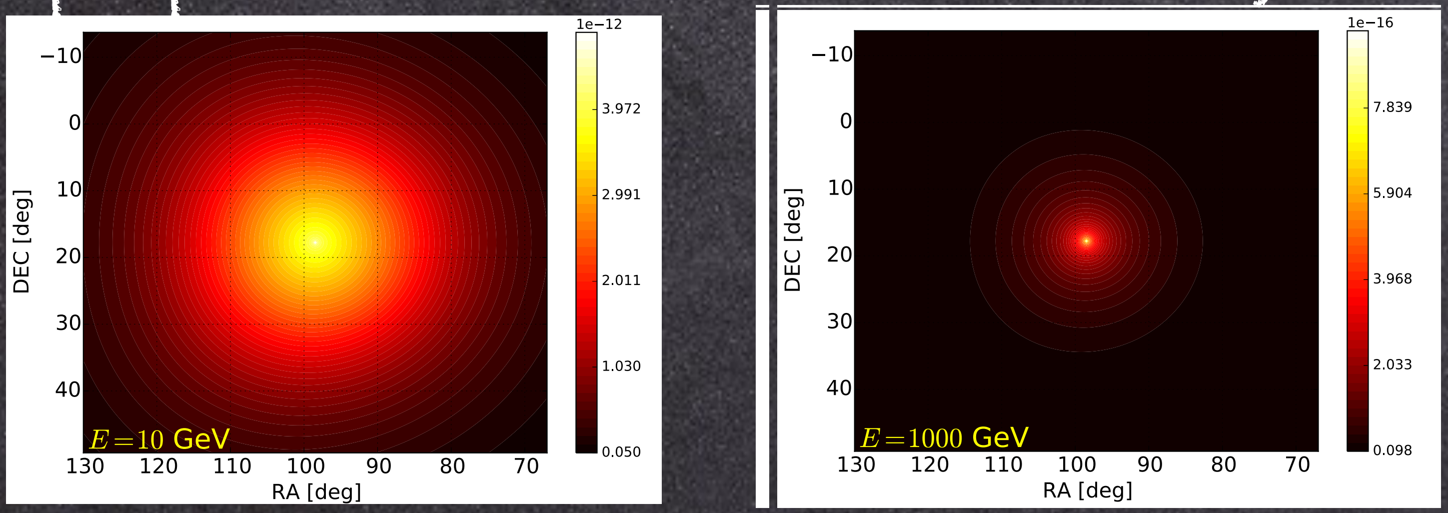
The HAWC data do not constrain the e+ measured by experiments (AMS02)

The e± injection power spectrum is one key parameter

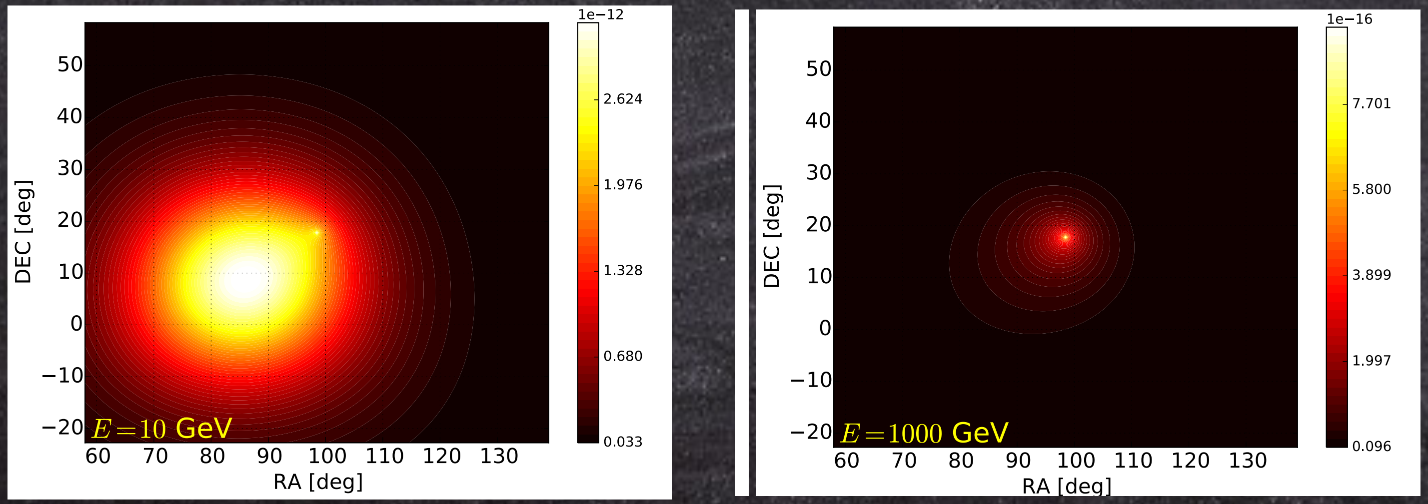
Searching for γ-rays around Geminga in the Fermi-LAT data

Di Mauro, Manconi, FD PRD 2020

- We implement a **Inverse Compton Scattering** template with background Interstellar radiation field (ISRF, needs a model)
- Pulsar proper motion: $v_T=211$ km/s (Faherty+AS2007) (70 pc travelled)



Without proper motion



With proper motion

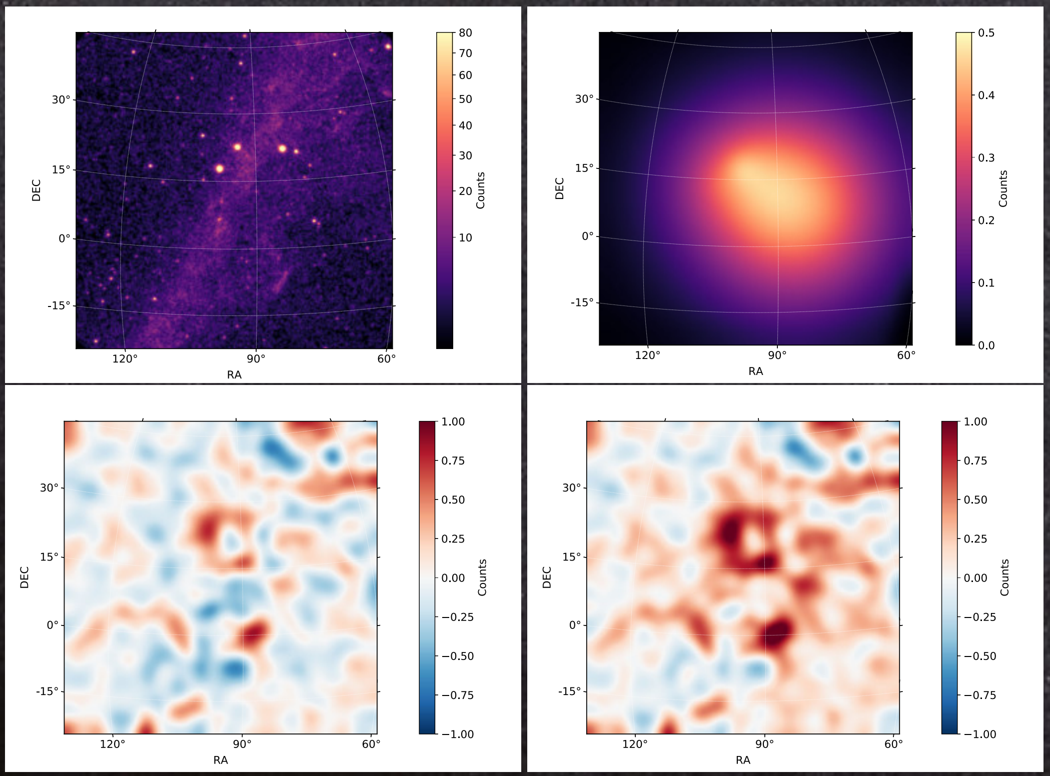
Detection of a γ-ray halo in Fermi-LAT data around Geminga

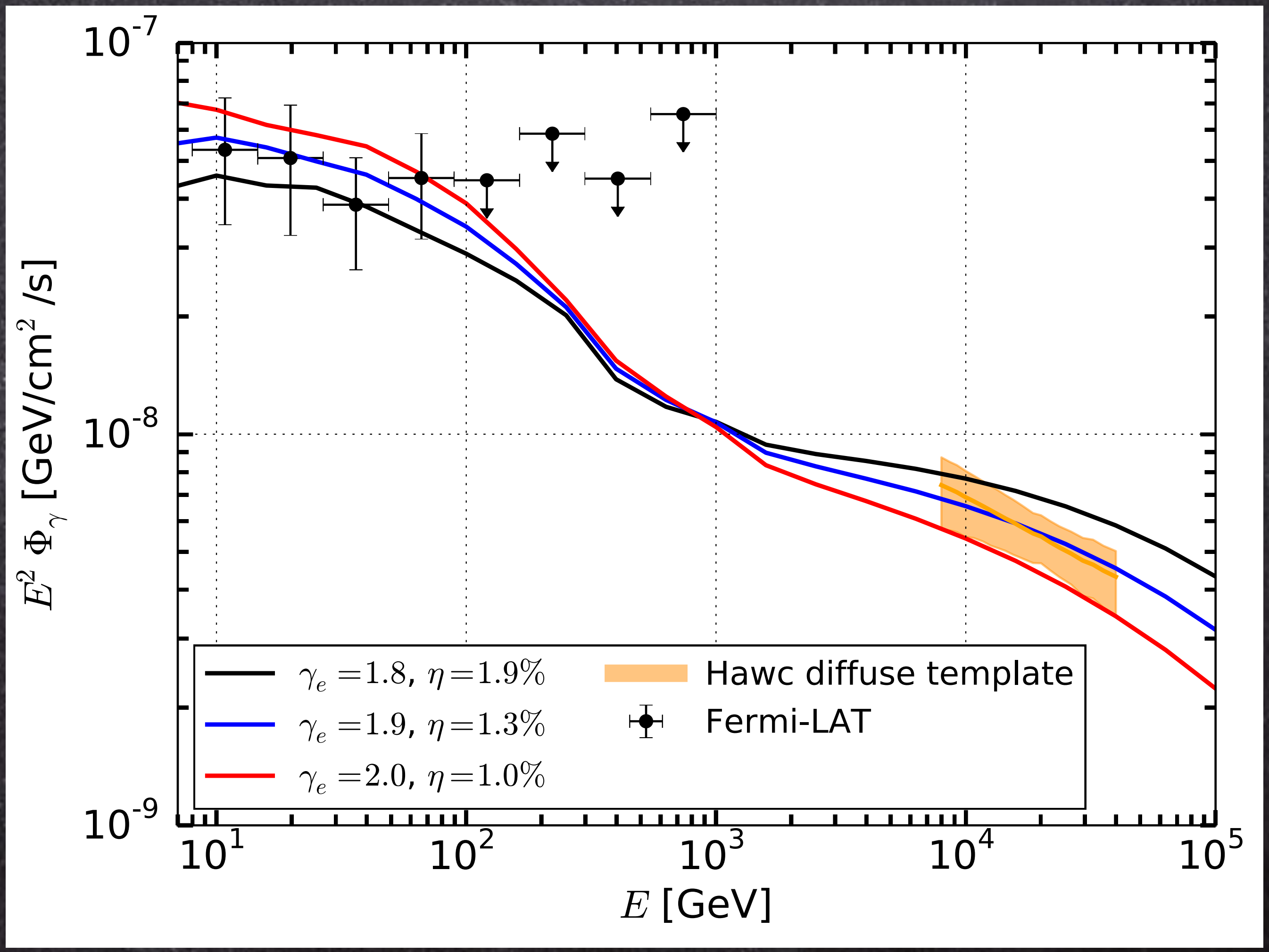
We detect a γ-ray halo around Geminga at 7.8-11.8σ

(depending on background models)

- Fit improves with proper motion included.
- Diffusion D(1GeV) = 1.6-3.5 10^{26} cm2/s (compatible w/ HAWK)
- Extension ~ 60 pc at 100 GeV
- γ_e = 1.8-2

Di Mauro, Manconi, FD PRD 2020





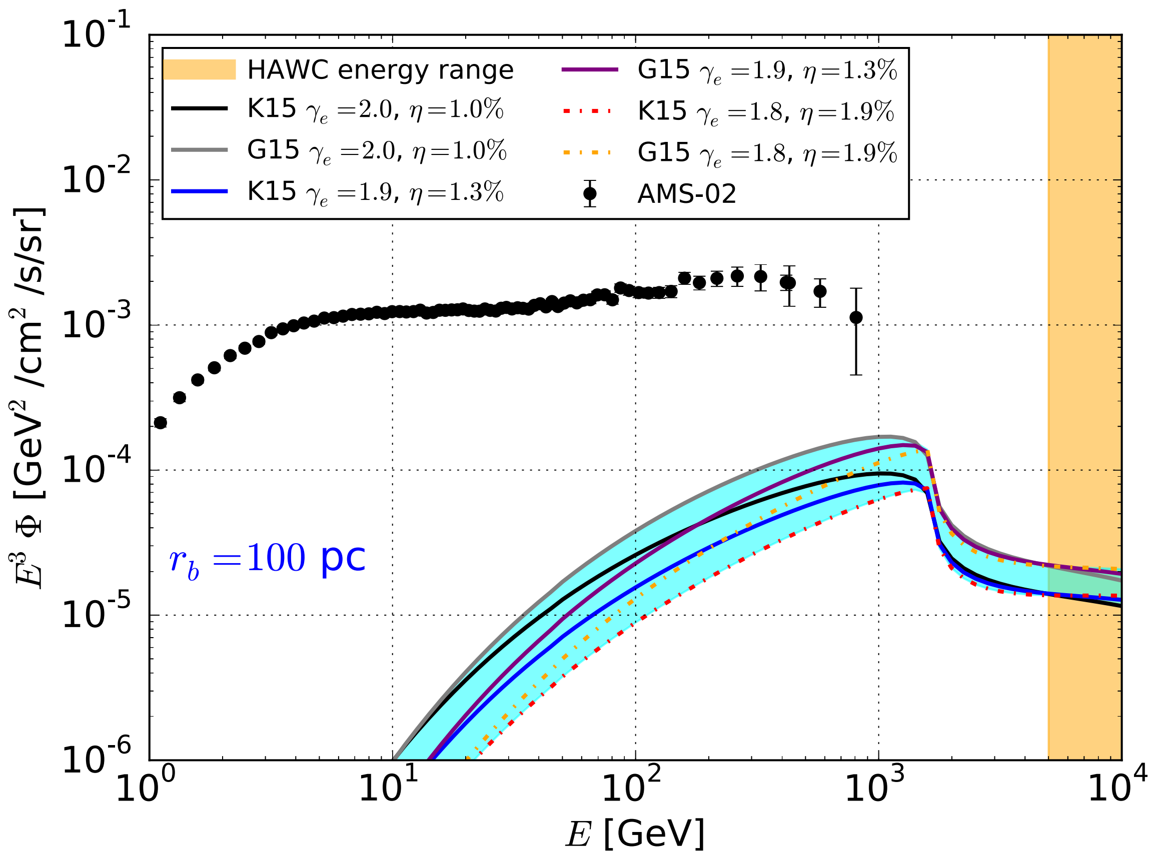
γ-ray haloes influence e+ at the Earth

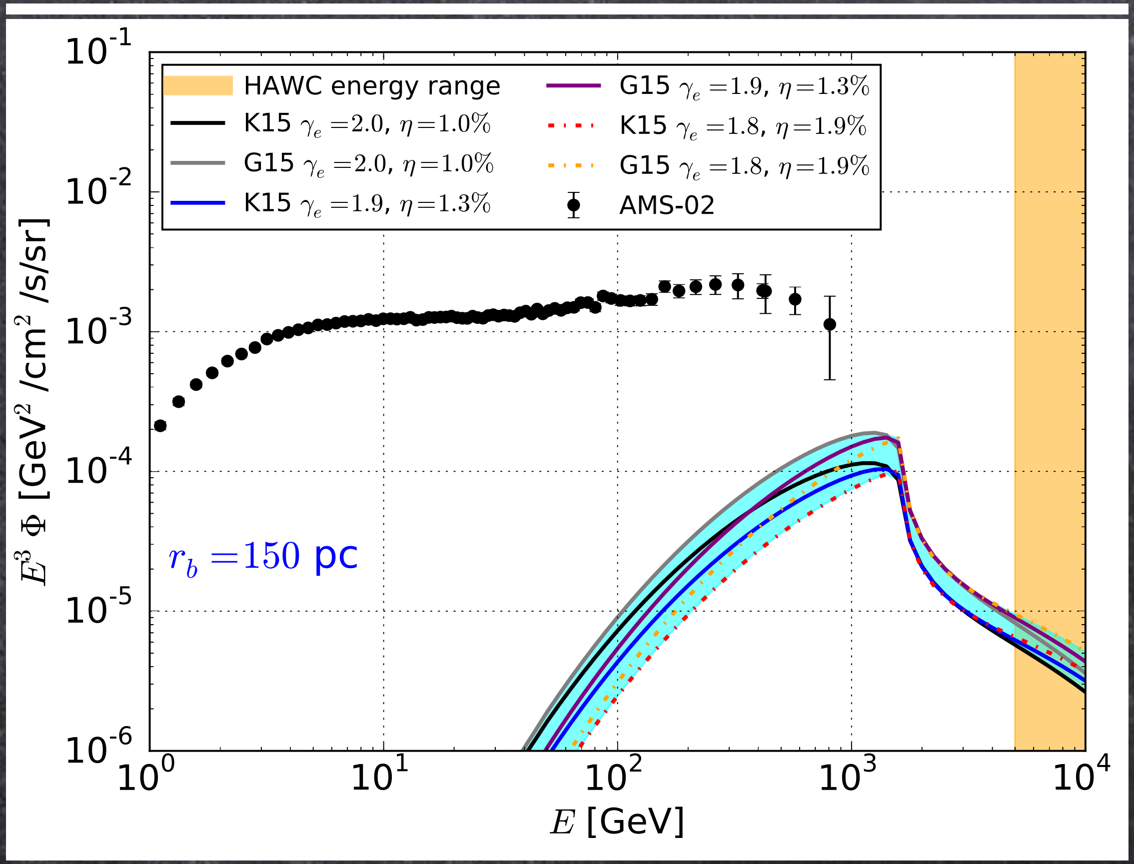
2-zones diffusion model:

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

r_b is the boundary between low and high diffusion zones

Di Mauro, Manconi, FD PRD 2020

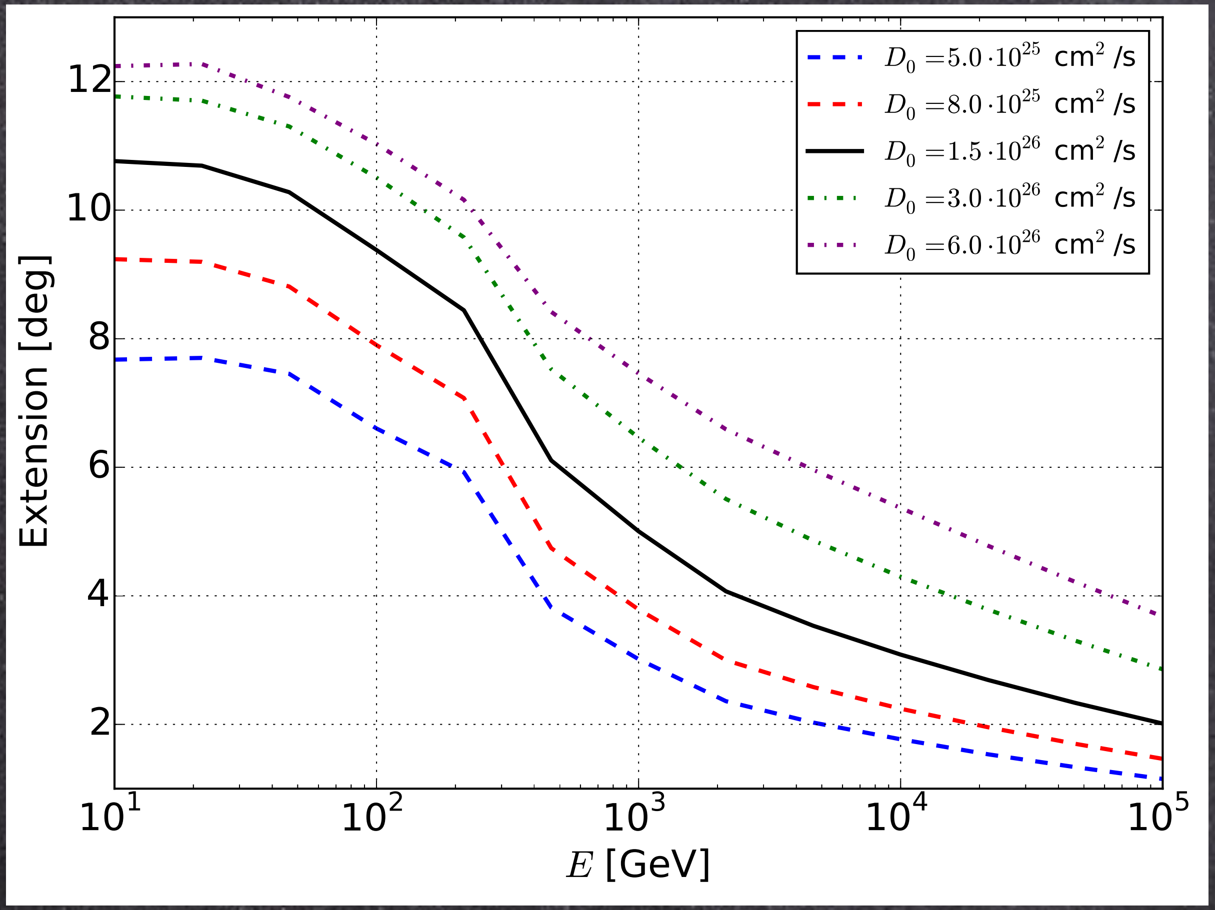




Geminga contributes few % to the e+ flux at the Earth.
The ICS halo is about 80 pc at Fermi-LAT energies

Halo extension depends on energy and diffusion physics

Smaller haloes expected at higher energies



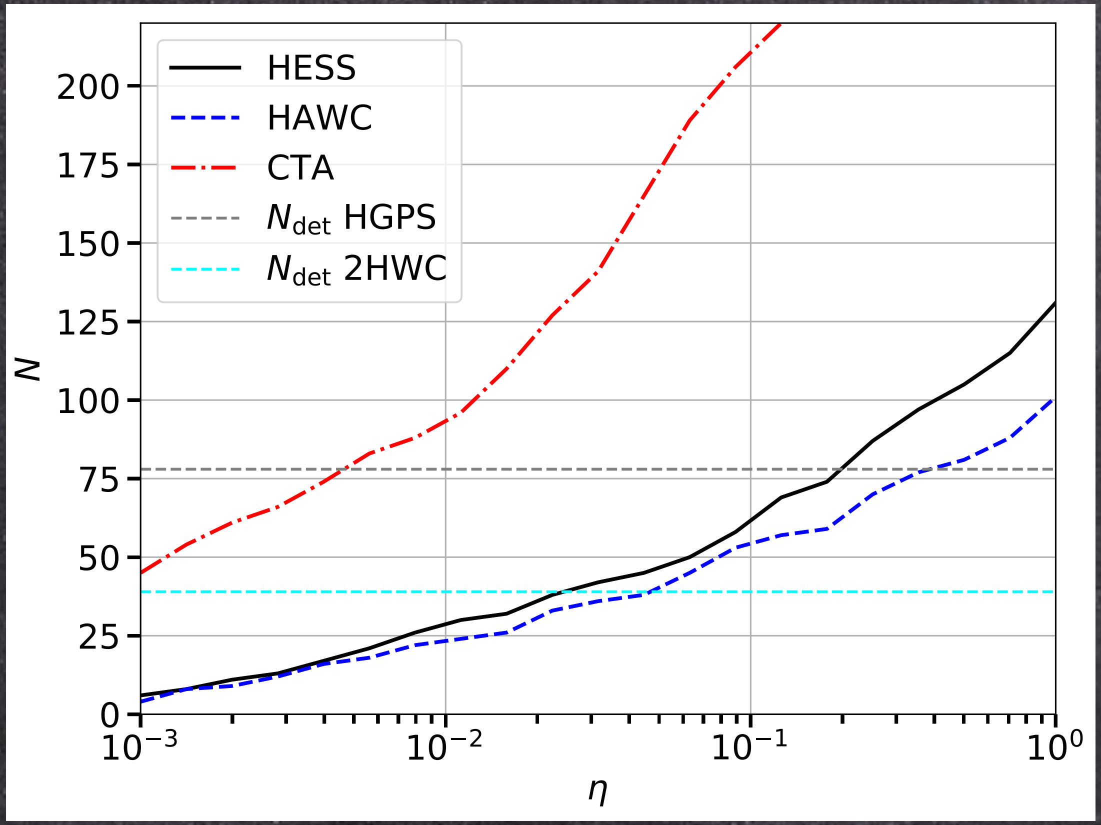
Higher diffusion coefficients get the halo spread out.
ISM D(E) values (~ 10^{28} cm2/s) would get low energy γ-rays around Geminga spread widely in the ISM (no longer a halo….)

γ-ray haloes: a general property of pulsars?

M. Di MAuro, S. Manconi, FD arxiv:1908.03216

We select sources from ATNF catalog with highest ICS halo above 1 TeV

Compute the number of sources above HESS, HAWC and CTA sensitivity as a function of η, efficiency conversion into e±.



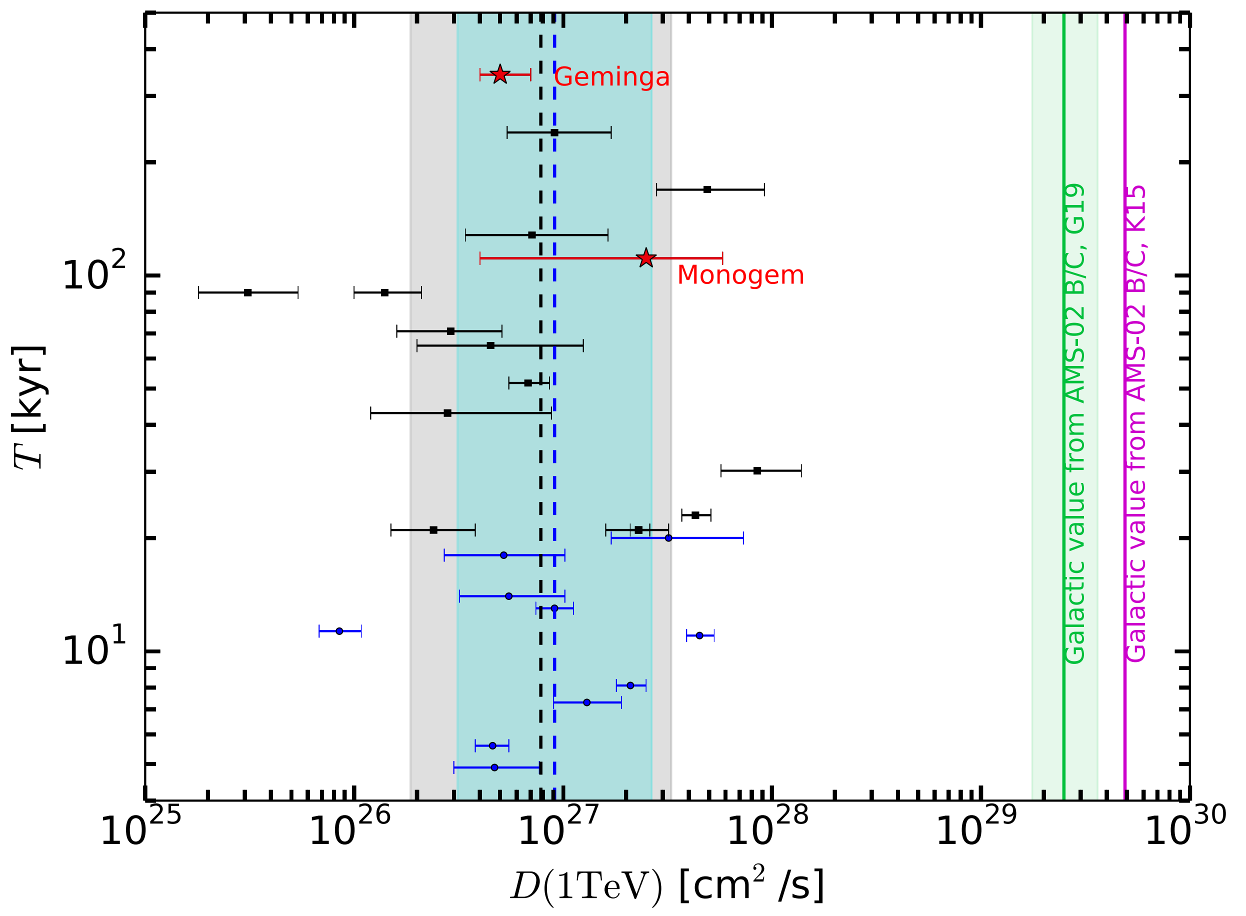
Tens of haloes could/will be detected even with 1% efficiency conversion into e±

A low diffusion zone around PWNe

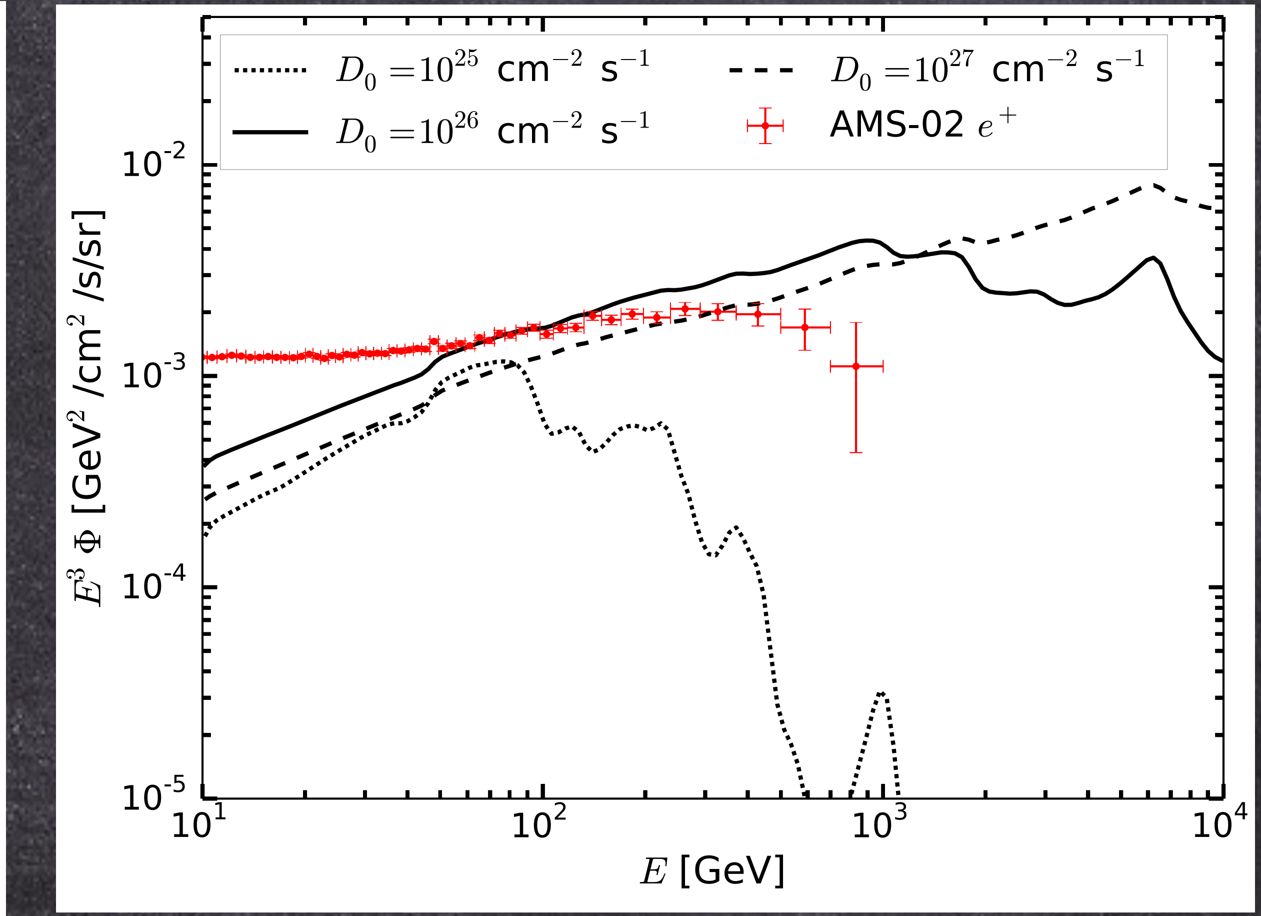
We select sources detected mainly by HESS (they provide flux maps)

Interpret the data in terms of ICS halo and fit D(1TeV) and size

Di Mauro, Manconi, FD 1908.03216 to app. PRD



Manconi, Di Mauro, FD 2001.09985, subm. PRD



The diffusion coefficient around PWNe is systematically lower by 2 orders of magnitude w.r.t. the ISM diffusion coefficient found from CR data (B/C).

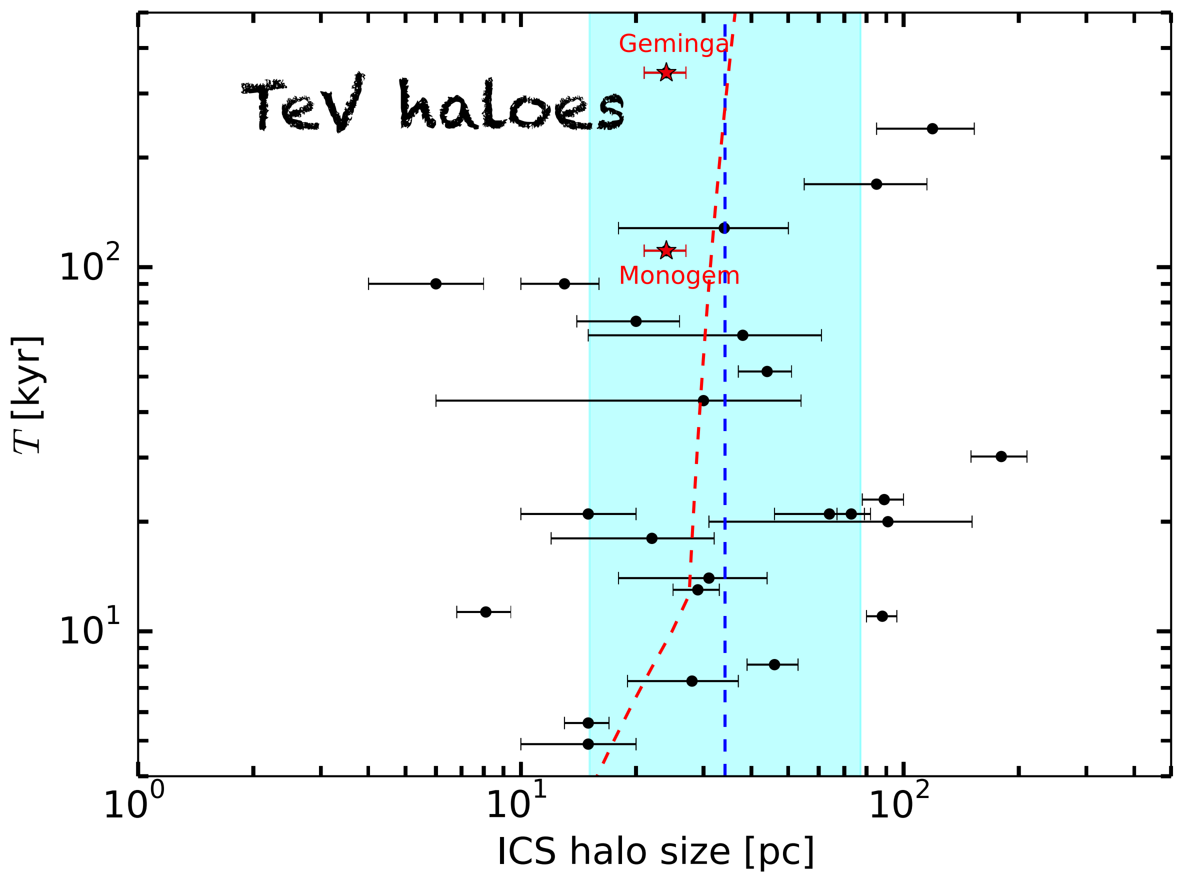
γ-ray haloes have tens pc size

We fit also the ICS halo size

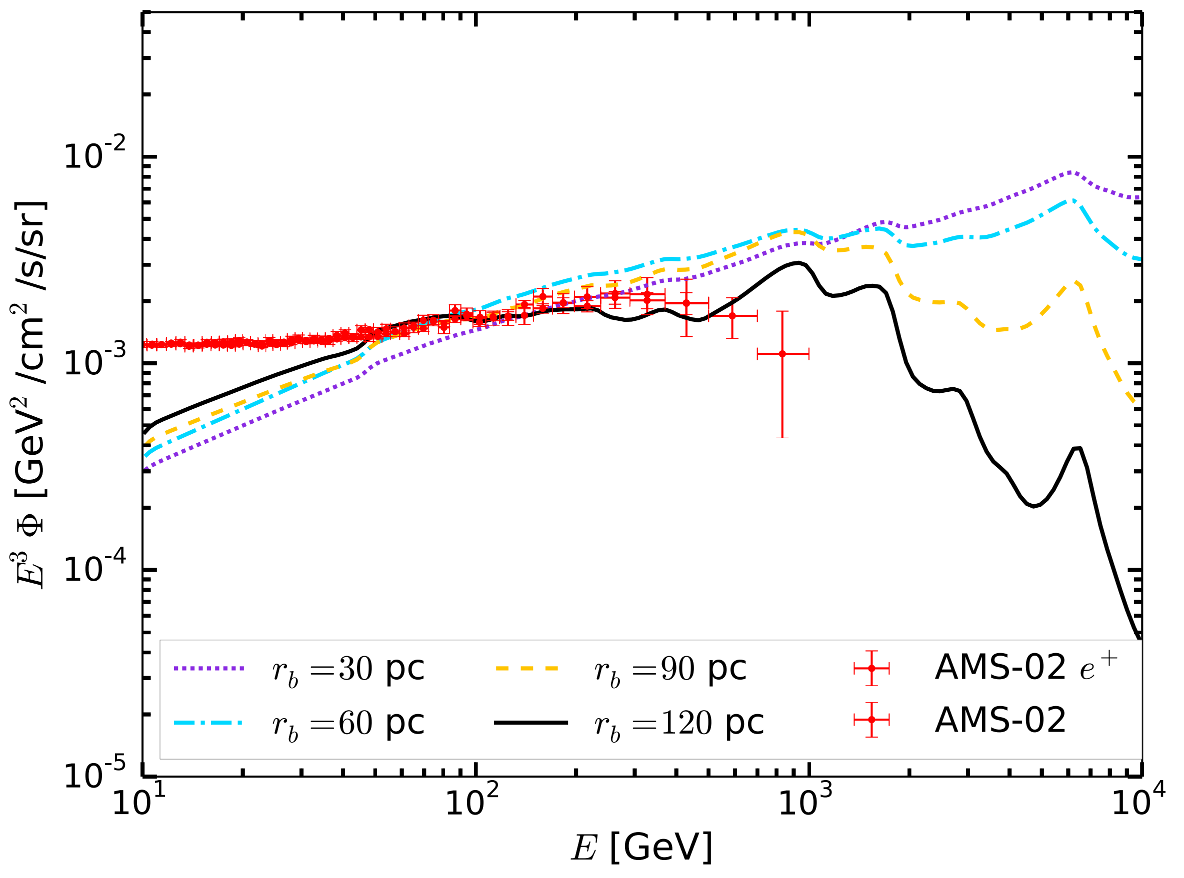
The trend with the age is compatible with models of PWN evolution

The low diffusion zone around PWN should be larger than the halo size

Di Mauro, Manconi, FD 1908.03216 to app. PRD



Manconi, Di Mauro, FD 2001.09985, subm. PRD



The halo size can shape the high energy e+ flux

ATNF pulsar catalog

Manconi, Di Mauro, FD 2001.09985, subm. PRD

Distance d, age T ($50\,\mathrm{kyr} < T < 10^5\,\mathrm{kyr}$), spin-down energy dE/dt

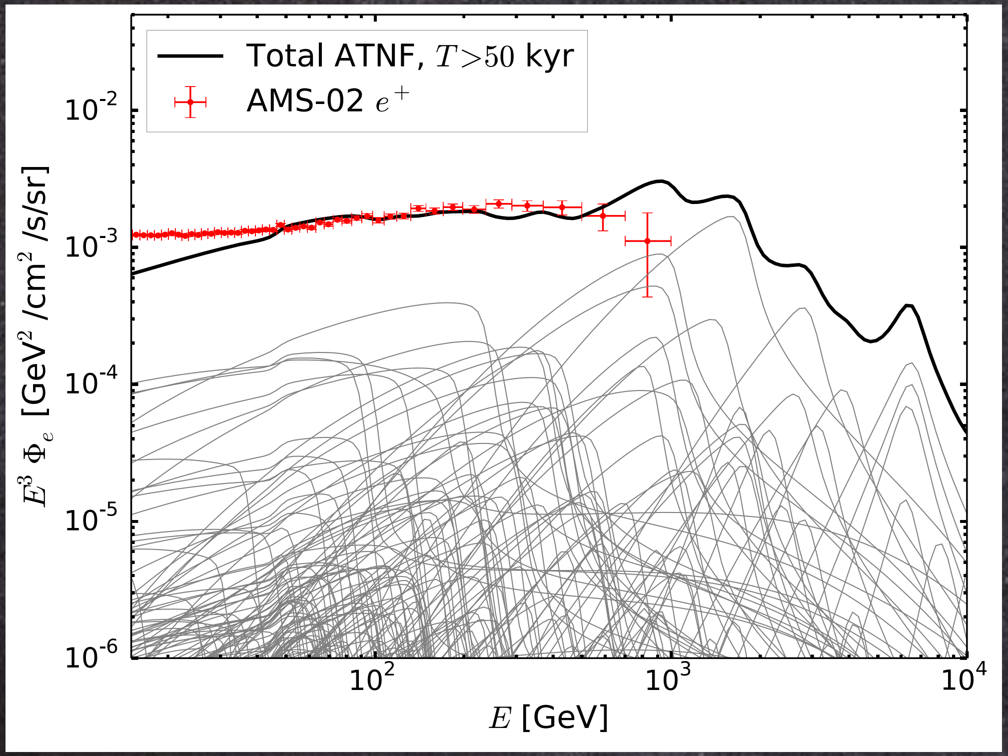
Continuous injection:

$$Q(E,t) = L(t) \left(\frac{E}{E_0}\right)^{-\gamma_e} \exp\left(-\frac{E}{E_c}\right) \qquad L(t) = \frac{L_0}{\left(1+\frac{t}{\tau_0}\right)^{\frac{k+1}{k-1}}}.$$

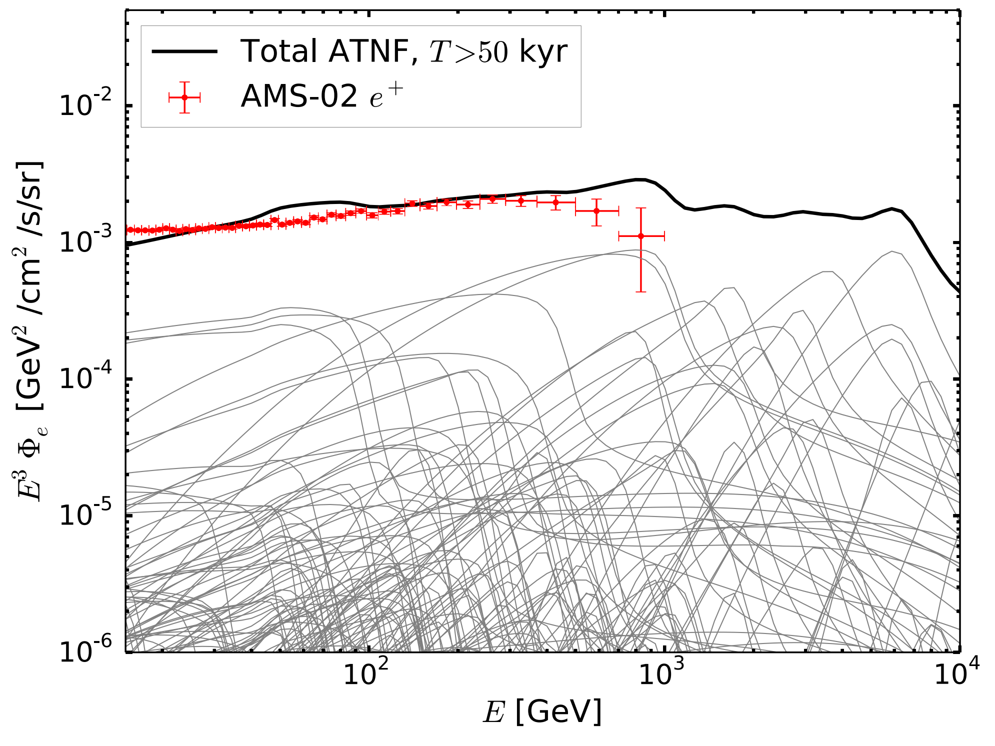
From catalog data:

$$W_0 = \tau_0 \dot{E} \left(1 + \frac{T}{\tau_0}\right)^{\frac{k+1}{k-1}} \qquad E_{\rm tot} = \eta W_0 = \int_0^T dt \int_{E_1}^{\infty} dE\, E Q(E,t),$$

r_b=120 pc, D_0=7.8 10^{25} cm2/s, η=0.12, γ_e=1.9



r_b=90 pc, D_0=7.8 10^{25} cm2/s, η=[0.02,0.30], γ_e=[1.4,2.0]



Few sources above 10% data - Cumulative flux ~ AMS-02 data

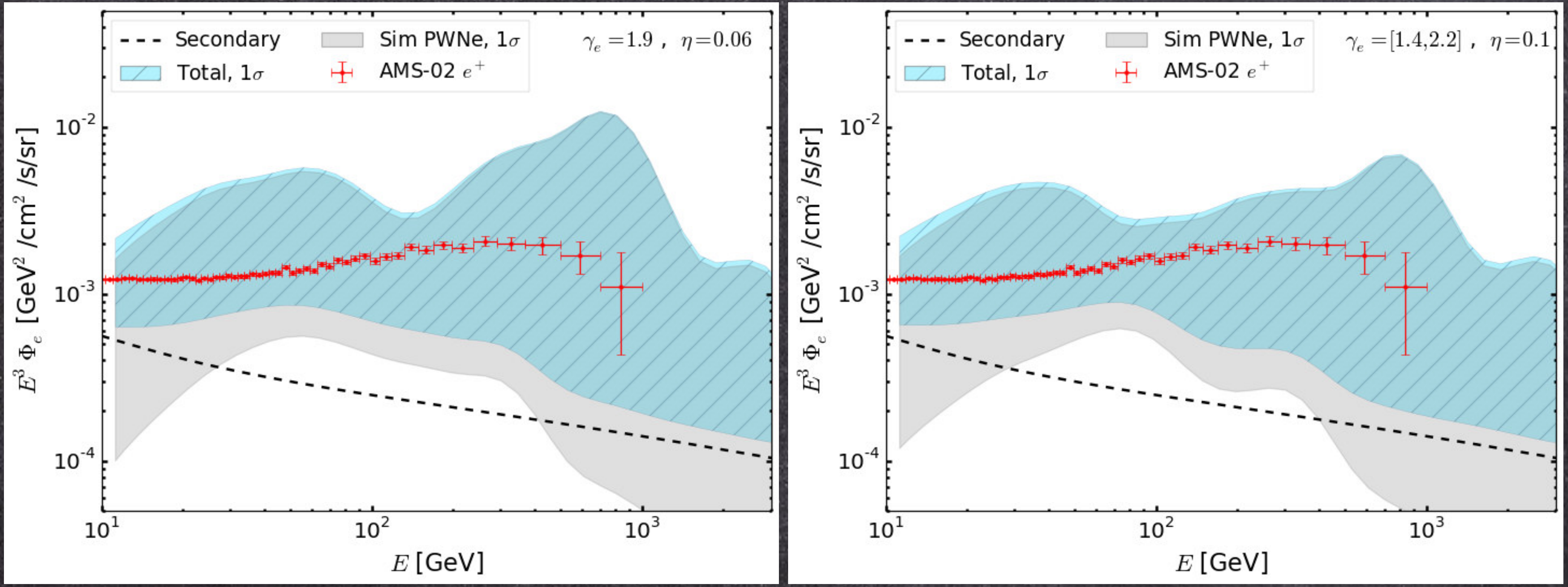
The h.e. trend dictated by low diffusion (D_0) within r_b

Simulations of galactic pulsar population

Manconi, Di Mauro, FD 2001.09985, subm. PRD

The ATNF catalog may be incomplete

We simulate a galactic Pulsar population with physics inputs:



The uncertainty band is ~ 10

The flux is NEVER negligible up to TeV

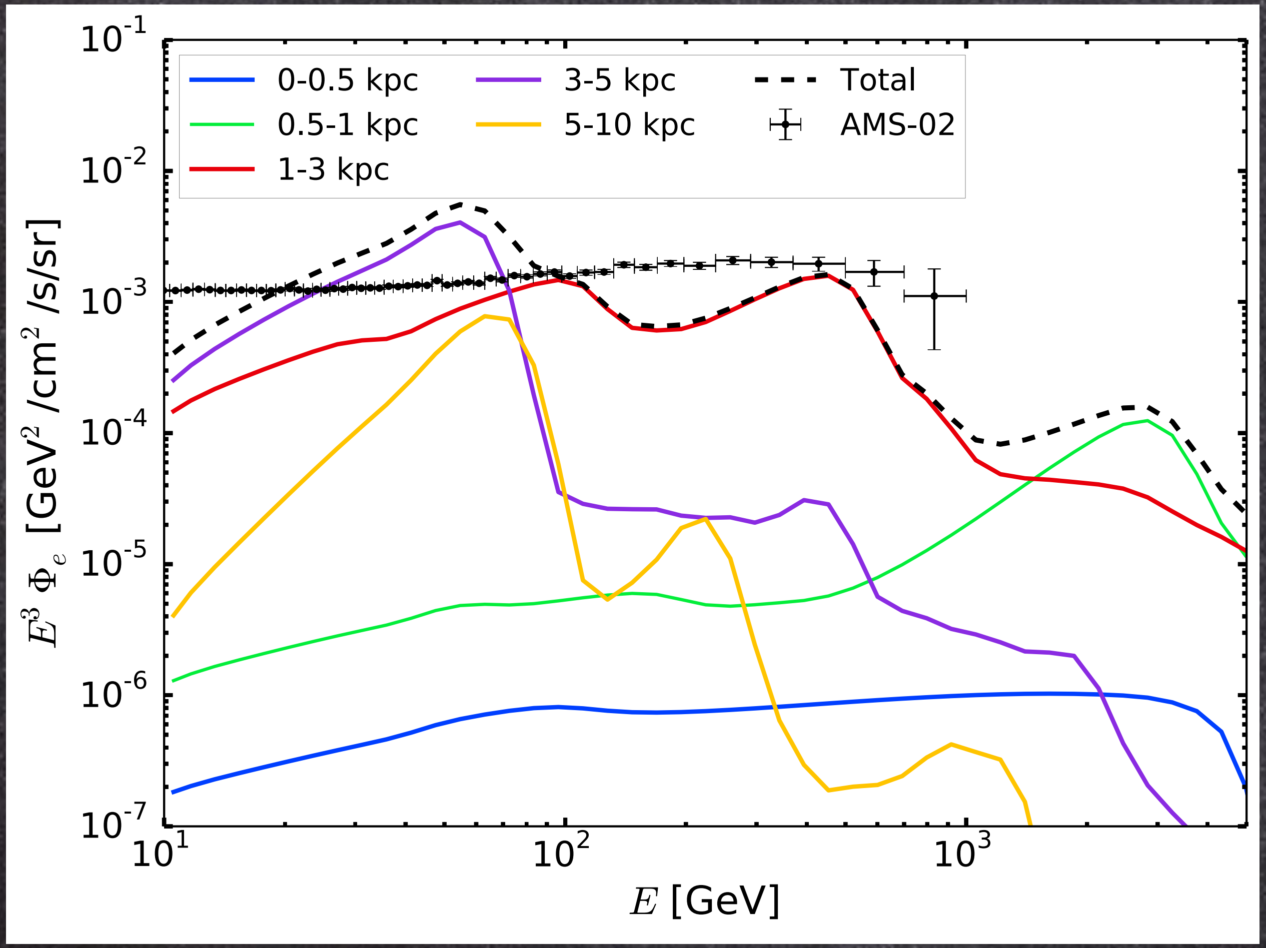
Predictions fall around AMS-02 data

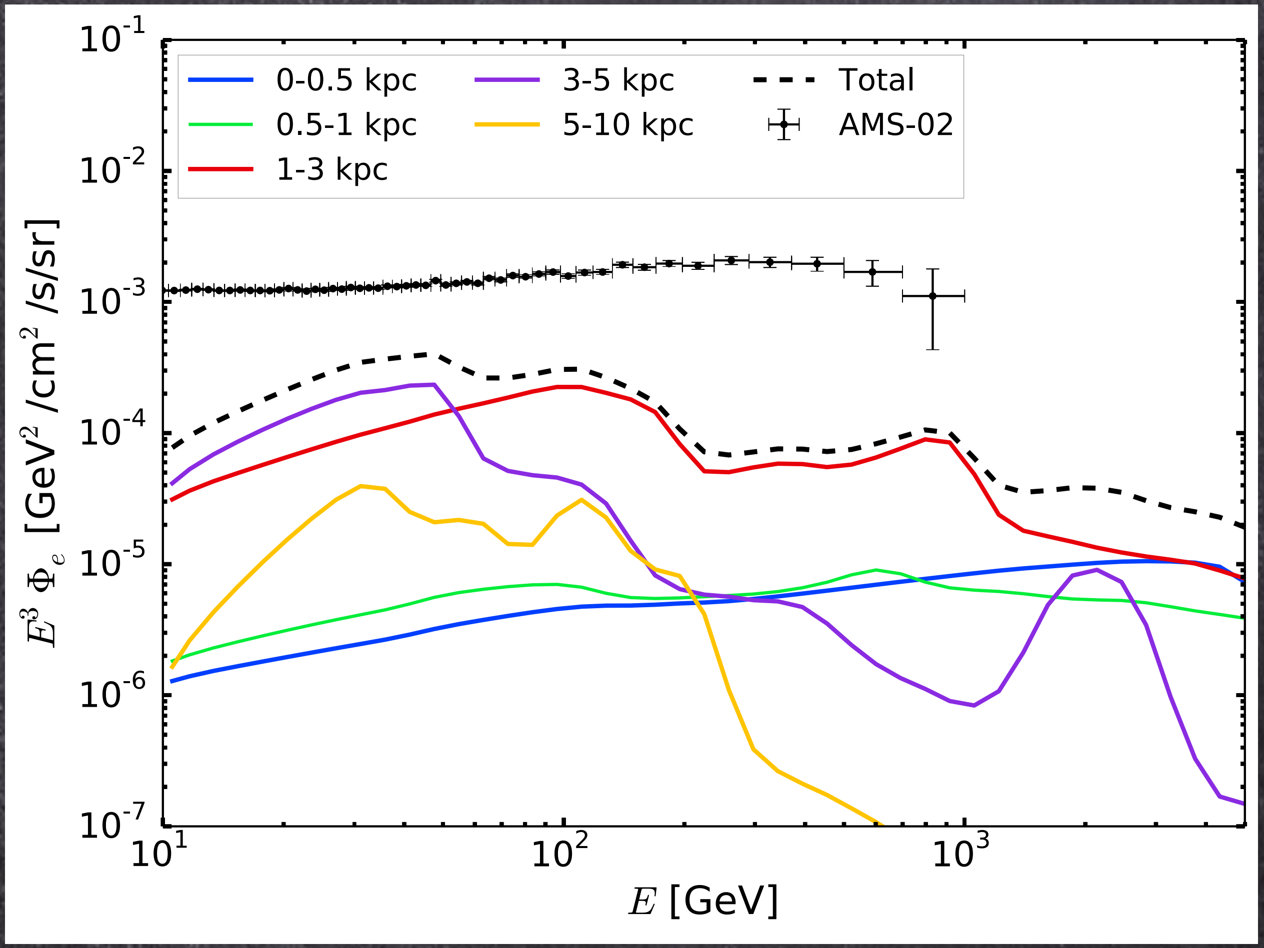
Conclusions

- Leptons at Earth have a composite origin: e- from far smooth and near catalog SNR, e+e- from PWN, e+e- as secondaries in the ISM
- e+ (with p-) are a major antimatter CR component in the Galaxy
- The violent radiative cooling provides invaluable and different messengers
- We discovered an ICS γ-ray halo around Geminga pulsar (U.L. for Monogem) in the Fermi-LAT data at 8-100 GeV
- CRs at high energies, dipole anisotropy, radiation from radio to γ rays are giving us an innovative view of the Galaxy and an explanation of the CR e+ data on the whole energy range

Contribution of pulsars to e+ flux as a function of distance from Earth

Manconi, Di Mauro, FD 2001.09985, subm. PRD





Burst-like or continuous injection

Di Mauro, Manconi, FD PRD 2020