ORIGIN OF POSITRONS AND ELECTRONS COSMIC RAYS AND DARK MATTER CONSTRAINTS.

UNIVERSITÉ DE GRENOBLE

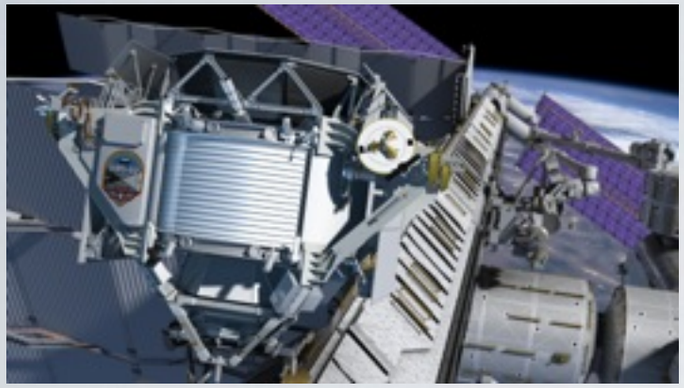
MATTIA DI MAURO

BASED ON

Interpretation of AMS-02 electrons and positrons data.
M.D.M., F. Donato, N. Fornengo R. Lineros and A. Vittino.
JCAP 1404 (2014) 006

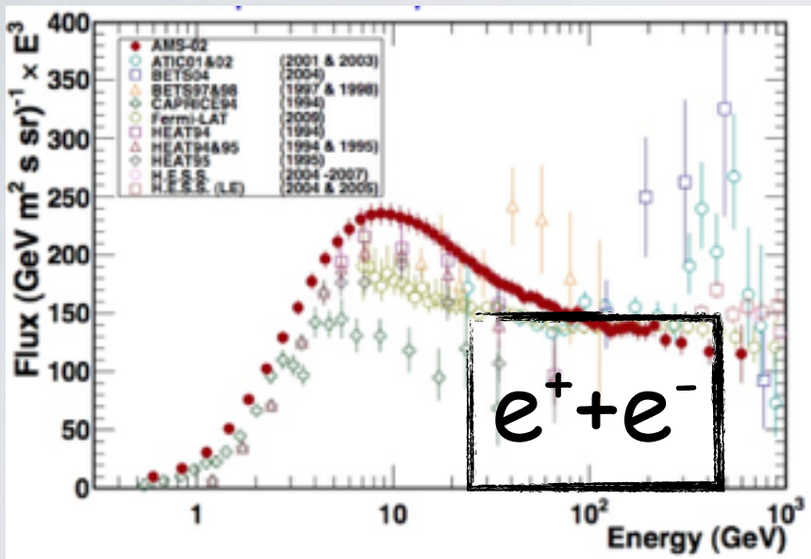
Astroparticle Physics: a joint TeVPA/IDM conference
23-28 June 2014 Amsterdam

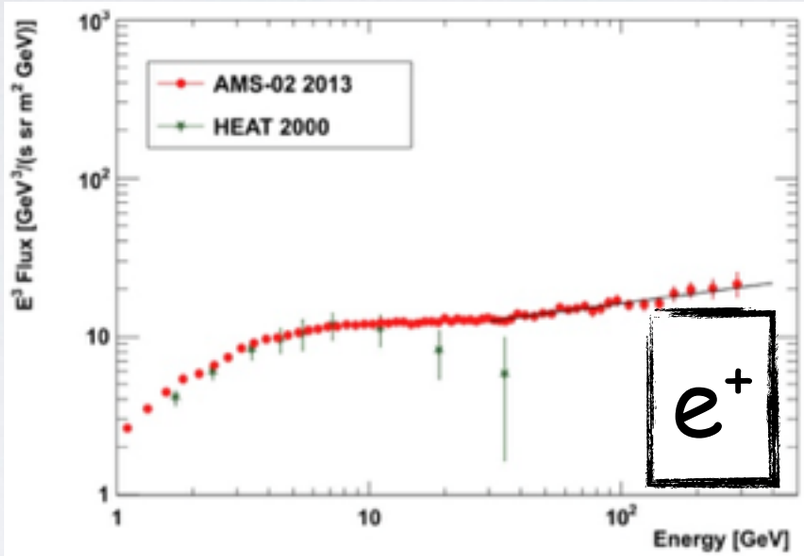
Crab Nebula supernova remnant optical (HST, NASA/ESA)

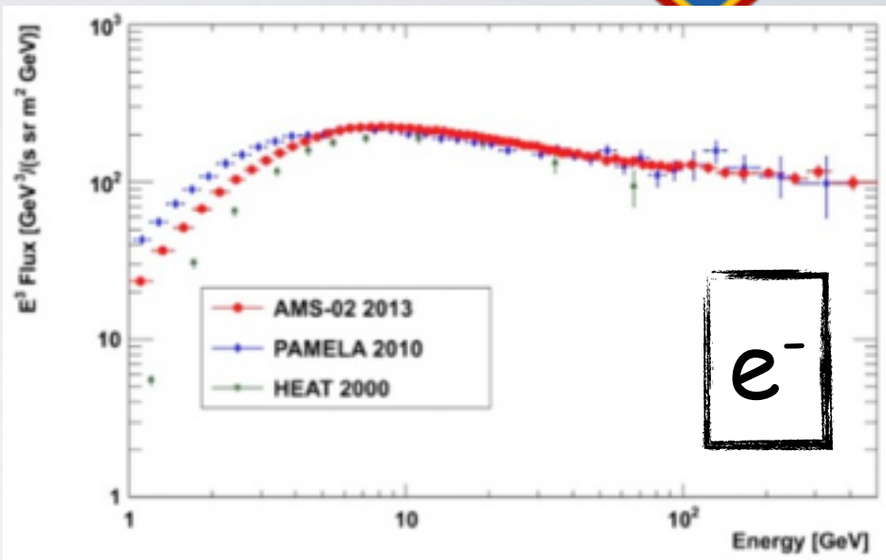


AMS-02

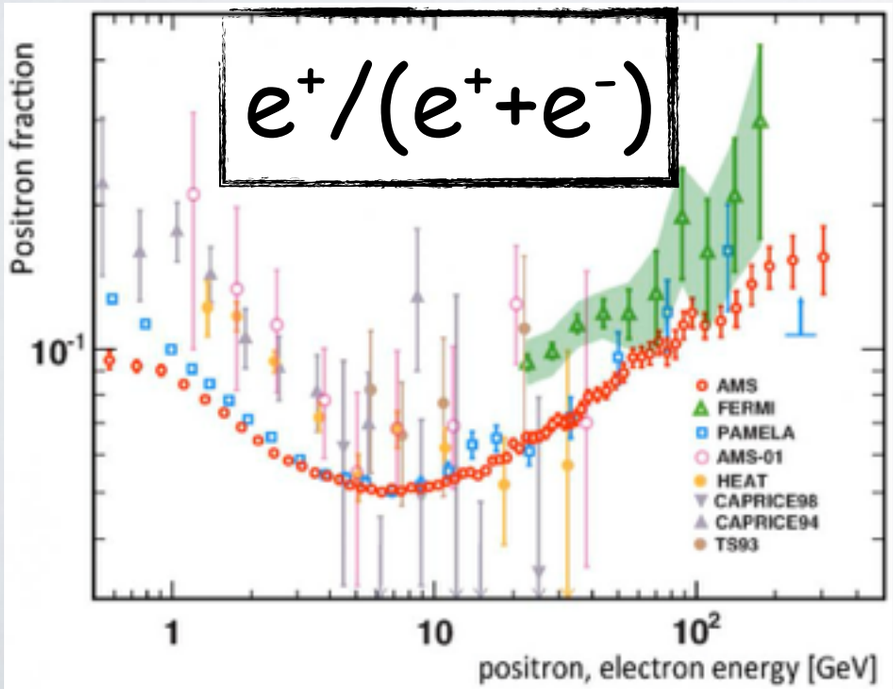
The **Alpha Magnetic Spectrometer** (AMS-02) is a state-of-the-art particle physics detector designed to operate as an external module on the International Space Station.



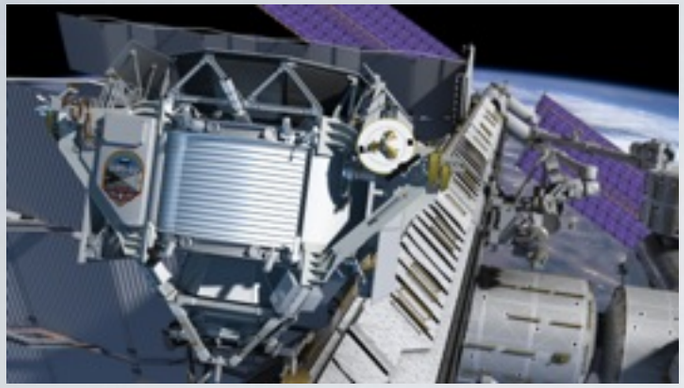




http://www.ams02.org/2013/07/new-results-from-ams-presented-at-icrc-2013/



Aguilar et al. PRL 110 (2013)



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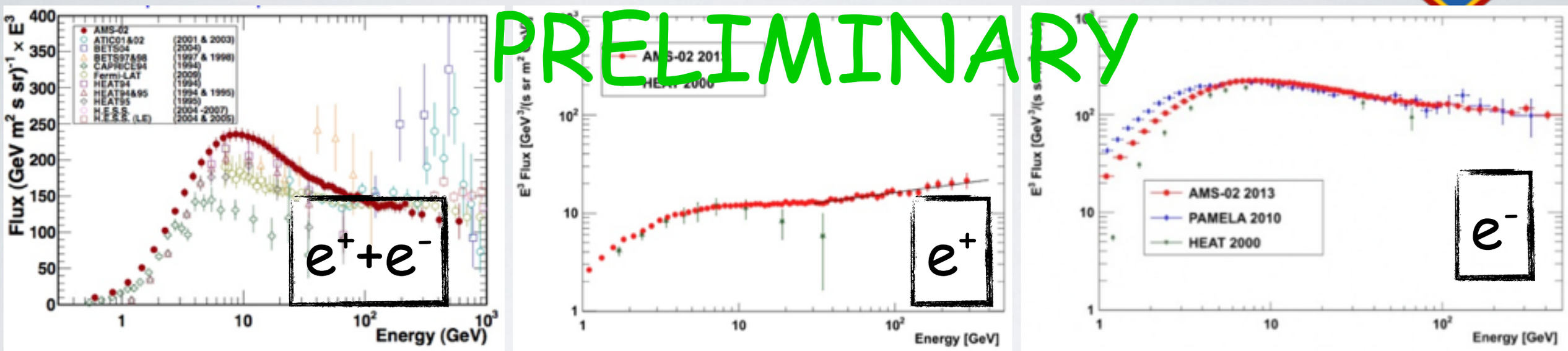

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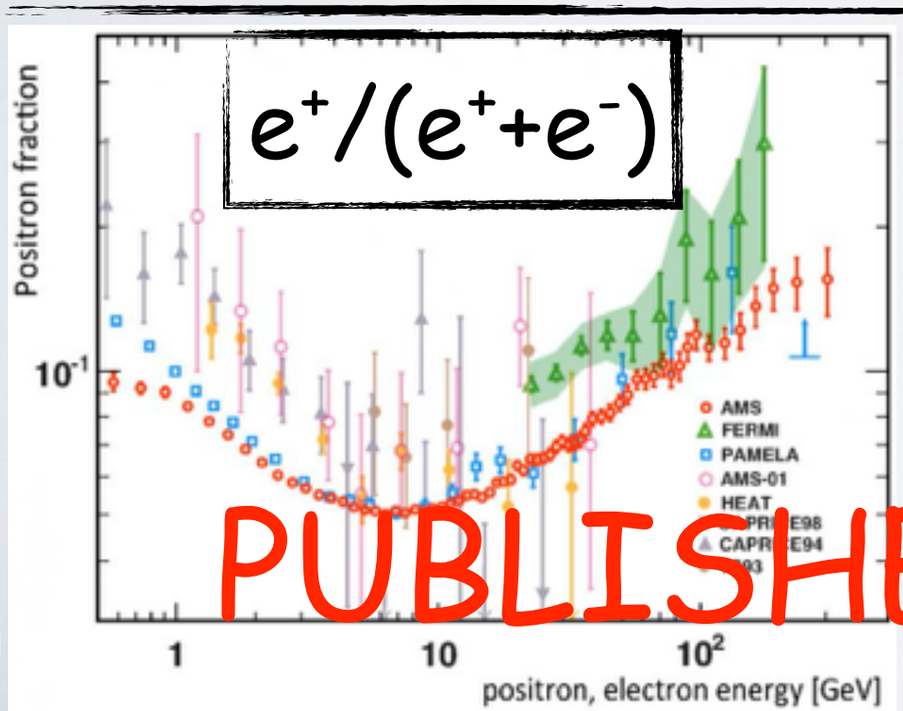


Aguilar et al. PRL 110 (2013)

Most of these results are based on statistical and systematic errors of a few %.

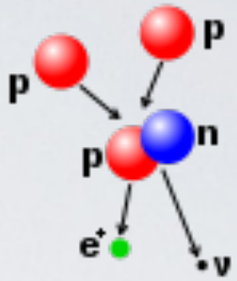
SOURCE OF POSITRONS AND ELECTRONS

- **Secondary production**: electrons and positrons originate from the spallation reactions of hadronic CR species with the interstellar material.

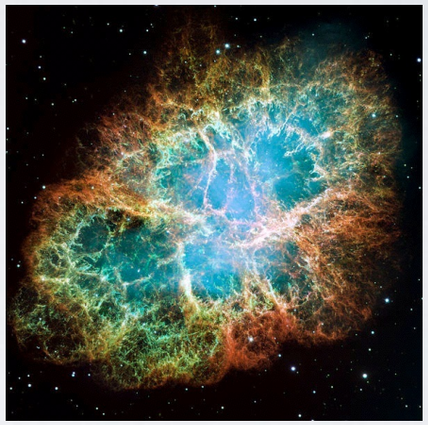
- **Supernova remnants** are believed to be the major accelerators of charged particles up to very high energies, via a first-type Fermi mechanism.

- **Pulsars**, rapidly spinning neutron stars with a strong surface magnetic field, are considered to be among the most powerful sources of electrons and positrons in the Galaxy.

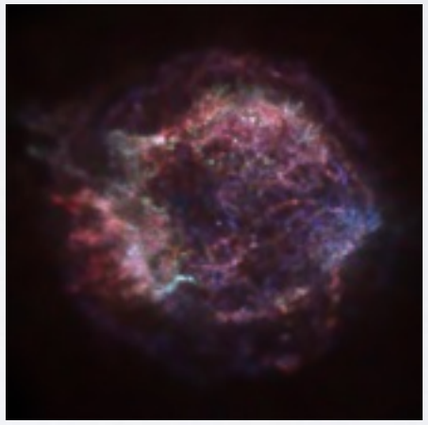
- **Dark Matter** can also be an exotic source of positrons and electrons.



Proton interaction with helium



Crab Nebula pulsar wind nebula optical (HST, NASA/ESA)



Cassiopea A supernova remnant optical (HST, NASA/ESA)

ELECTRONS AND POSITRONS PROPAGATION

- Electrons and positrons produced in the sources propagate throughout the Galaxy, where they diffuse on the magnetic field inhomogeneities.
- Most importantly, they lose their energy by electromagnetic interactions with the interstellar radiation field (ISRF) through inverse Compton (IC) scattering, and by synchrotron emission on the galactic magnetic field

$$\partial_t \mathcal{N} - \nabla \cdot \{K(E)\nabla\mathcal{N}\} + \partial_E \left\{ \frac{dE}{dt}\mathcal{N} \right\} = \mathcal{Q}(E, x, t)$$

Convection and reacceleration could be neglected above a few GeV.

Electron density

Energy-dependent diffusion coefficient

$$K(E) \equiv \beta K_0 \left(\frac{\mathcal{R}}{1\,\mathrm{GV}}\right)^{\delta} \simeq K_0 \epsilon^{\delta}$$

Energy-loss term

Fully relativistic inverse Compton regime

Source term.

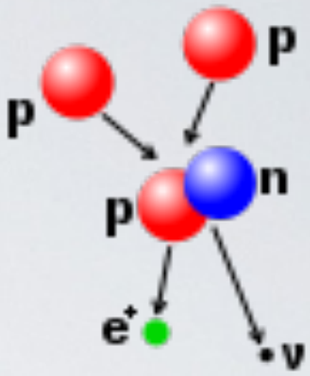
-SNRs
-PWNs
-Secondary production
-Dark matter

- We adopted a semi-analytical propagation modeling including a full relativistic calculation of the energy losses and the time-dependent solution which has to be used when dealing with local sources.
- Assuming that spatial diffusion and energy losses are isotropic and homogeneous and a the steady-state solution.

Delahaye et al. (2009)A&A 501, 821 Delahaye 2010 A&A 524, A51

SECONDARY PRODUCTION

- Secondary electrons and positrons originate from the spallation reactions of hadronic CR species (mostly protons and a particles) with the interstellar material (mostly made of hydrogen and helium).
- Since secondary positrons and electrons originate from positively charged ions, the charge conservation implies a greater production of positrons with respect to electrons.



The steady state source term for secondaries has the form:

$$q_{e^\pm}(\mathbf{x}, E_e) = 4\pi\, n_{\rm ISM}(\mathbf{x}) \int dE_{\rm CR} \Phi_{\rm CR}(\mathbf{x}, E_{\rm CR}) \frac{d\sigma}{dE_e}(E_{\rm CR}, E_e)$$

- where n_{ISM} is the interstellar gas density,
- the primary incoming CR fluxes are denoted by ΦCR (from AMS02 data)
- and $d\sigma/dE_e$ refers to the inclusive nucleon nucleon cross section.
- we have computed the source term by fixing here the proton and helium primary fluxes to the new measurements of AMS-02.

FIT TO AMS02 PROTON AND HELIUM

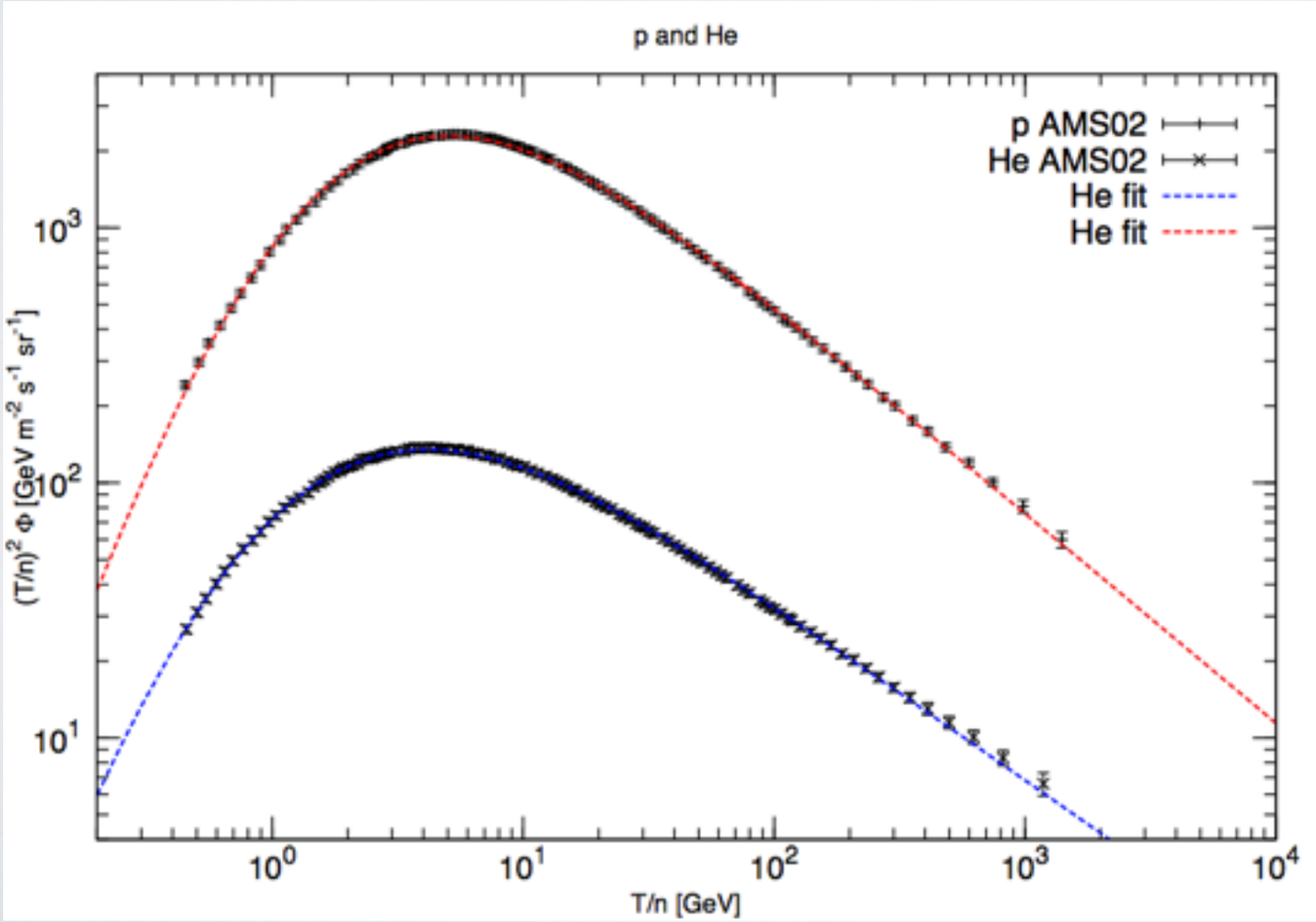
- A power-law in kinetic energy and rigidity plus solar modulation does not provide an adeguate fit.

$$\Phi(T/n) = K\, R(T/n)^b \qquad \Phi(T/n) = K\, (T/n)^b$$

- We have fitted the spectra of proton and helium considering as interstellar flux the following function:

$$\Phi(T/n) = K\, \beta(T/n)^a\, R(T/n)^b$$

- where $\beta = v/c$ and R is the rigidity.
- The interstellar flux with a solar modulation parametrized using a Fisk potential φ fit.



$b_{proton} = -2.823 \pm 0.005$

$b_{helium} = -2.690 \pm 0.004$

$\varphi = 0.615 \pm 0.029$ MV

http://www.ams02.org/2013/07/new-results-from-ams-presented-at-icrc-2013/

ELECTRONS FROM SNR

- SNR in our Galaxy are believed to be the major accelerators of charged particles up to very high energies (at least 10^2 TeV), via a first-type Fermi mechanism.
- The mechanism of acceleration of CRs through non-relativistic expanding shock-waves, activated by the star explosion, predicts power-law spectra with a cutoff at high energies:

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

E_c = 2 TeV and E_0 = 1 GeV.

- The value of Q_0 can in principle be estimated from radio data on single sources, assuming that the radio flux B_r at a specific frequency v is entirely due to synchrotron emission of the ambient electrons in the SNR magnetic field B:

$$Q_0 = 1.2 \cdot 10^{47} (0.79)^{\gamma} \left[\frac{d}{\mathrm{kpc}}\right]^2 \left[\frac{\nu}{\mathrm{GHz}}\right]^{(\gamma-1)/2} \left[\frac{B}{100\mu\mathrm{G}}\right]^{-(\gamma-1)/2} \left[\frac{B_r^{\nu}}{\mathrm{Jy}}\right]$$

d is the distance of the source from the observer.

B SNR magnetic field

B_v^r radio flux at frequency v

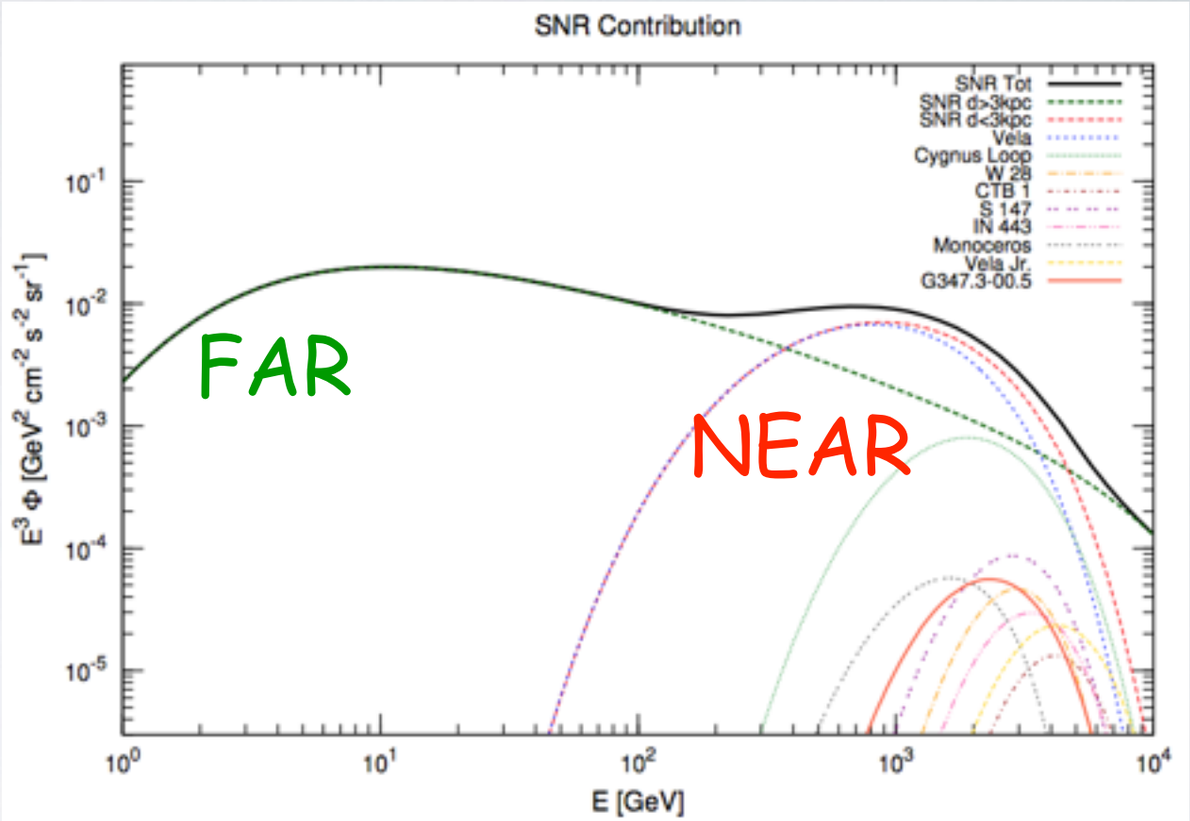
Delahaye 2010 A&A 524, A51

ELECTRON FLUX FROM SNR

Green Catalog: the most complete SNR catalog with 265 SNRs (88 objects with distance measurement).

The average values for the relevant parameters for those 88 SNRs are:

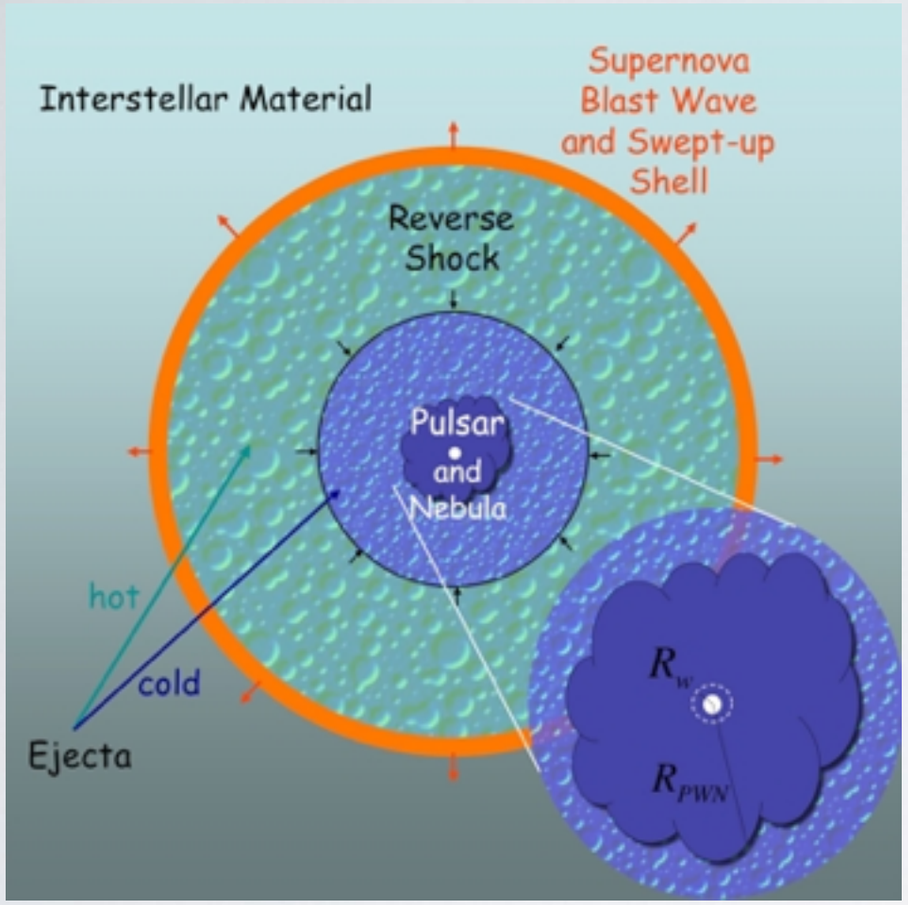
- $\langle \alpha \rangle = 0.50 \pm 0.15$,
- $\langle \gamma \rangle = 2 \cdot \langle \gamma_r \rangle + 1 = 2.0 \pm 0.3$
- and fixing $B = 30\ \mu G$, $\langle Q_0 \rangle = 9.0 \cdot 10^{49}\ GeV^{-1}$
- total emitted energy $\langle E^* \cdot f \cdot \Gamma^* \rangle = 8.9 \times 10^{50}$ GeV $= 1.4 \times 10^{48}$ erg.



- We divide the SNR population into a near component, for sources ($d \leq 3$ kpc) and a far component.
- In the catalog we find 41 near SNRs, out of which only 35 have measured parameters.
- The far-SNR population is instead treated as an average source population, with typical parameters (Q_0 and γ) fixed a priori according to our analysis, and following the radial profile of Lorimer 2004.

D. A. Green Bulletin of the Astronomical Society of India 37 (Mar., 2009) 45–61
D. R. Lorimer 2004 vol. 218 of IAU Symposium, p. 105, 2004

PWN EMISSION MECHANISM



Rotating magnetic field of the pulsar tear particles apart from the neutron star surface which in turns produces particle/antiparticle pairs through an electromagnetic cascade.

The impact of the relativistic wind produced by the pulsar on the much slower ejecta of the SNR usually creates a termination shock that propagates backwards, towards the pulsar.

The termination shock is the place where the incoming pairs are accelerated to very high energies. After acceleration, these particles enter the PWN and then are trapped by the PWN magnetic field.

In the region bound by the wind termination shock on one side and the ejecta on the other side, a bubble of relativistically hot magnetized plasma is created: this is the so-called pulsar wind nebula (PWN).

What is usually assumed is that the accelerated particles are completely released into the interstellar medium (ISM) in a time not greater than 50 kyr. Since this injection is assumed to be quite fast and the subsequent energy emission of the pulsar negligible, a mature pulsar can be treated as a burst-like source of $e^{\pm}$.

We have taken into account all the PWNs into the ATNF catalog with an age larger than 50 kyr

Manchester et al. 2005, AJ, 129, 1993

PWN CONTRIBUTION

- Spectrum of electrons and positrons trapped inside the PWN inferred by observing their broadband emission which is due to synchrotron radiation (at low energies) and to inverse Compton (IC) scattering off background photons (at higher energies).
- We consider a source spectrum of the same form as the SNR (E_C =2 TeV). The normalization of the spectrum, Q_0 can be fixed through the total spin-down energy W_0 emitted by the pulsar:.
- η is the efficiency of the conversion of the total spin down energy into electrons and positrons.

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

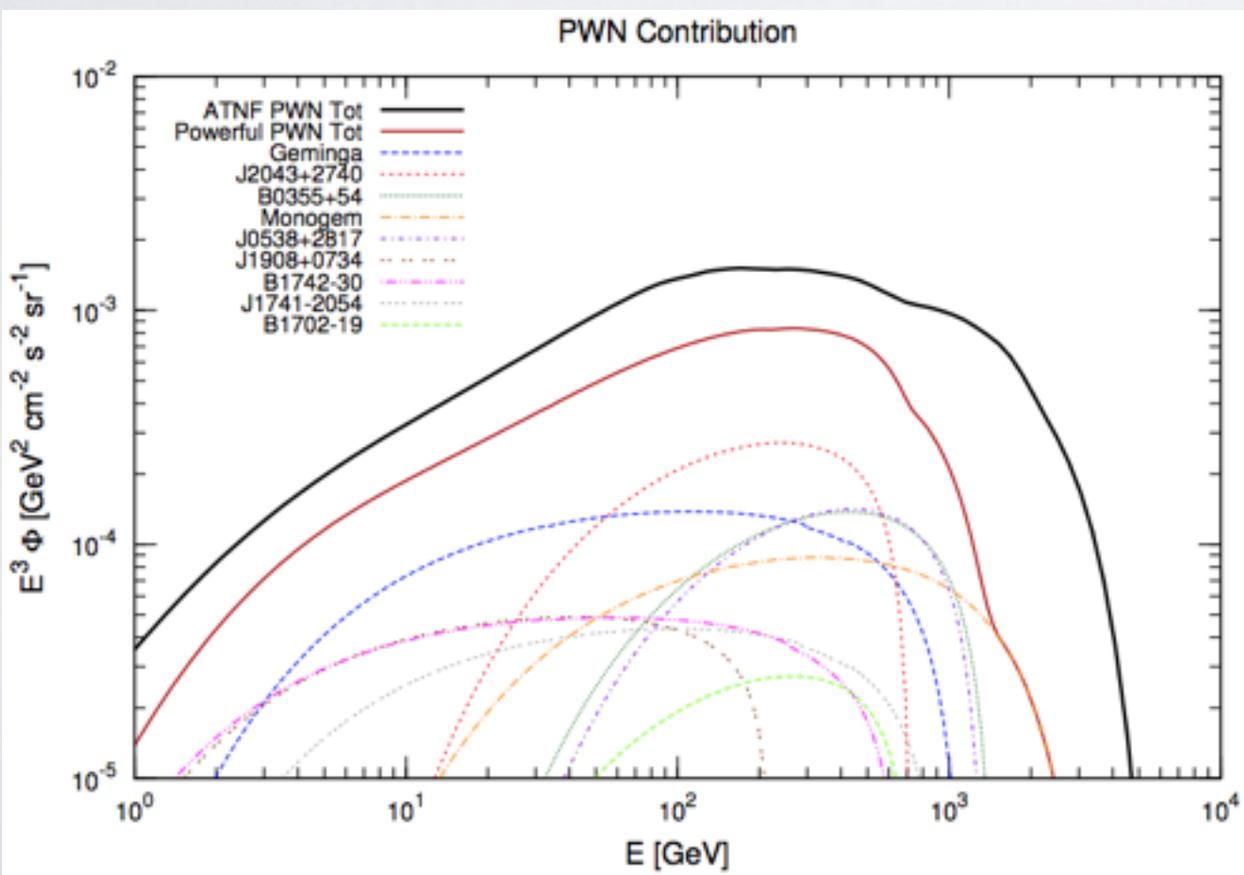
$$\int_{E_{\min}}^{\infty} dE\, E\, Q(E) = \eta\, W_0$$

$$W_0 = t_* \dot{E} \left(1 + \frac{t_*}{\tau_0}\right) \approx \tau_0 \dot{E} \left(1 + \frac{t_*}{\tau_0}\right)^2$$

Present age of the pulsar

the spin-down luminosity

typical pulsar decay time



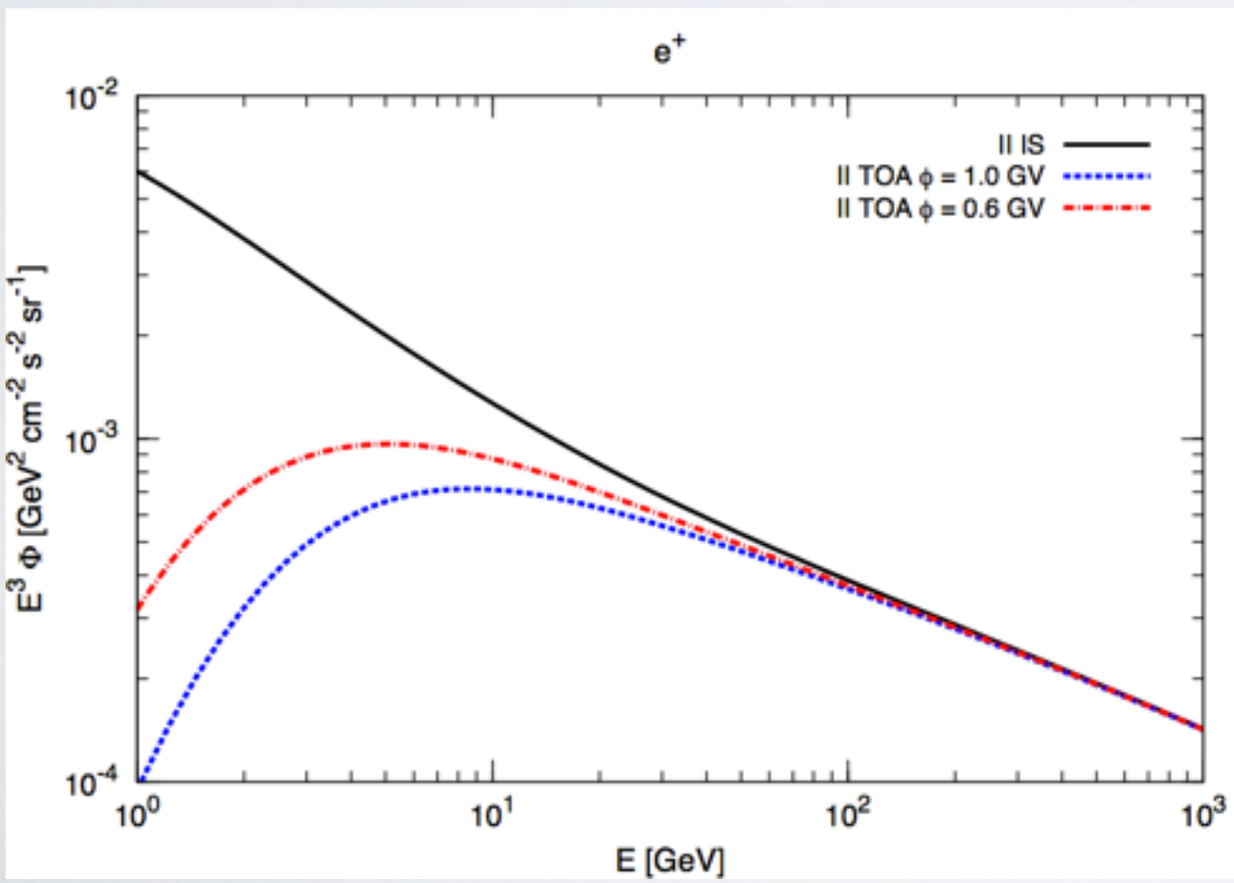
γ_{PWN} and η are the same for all the PWN.

- **Galactic propagation with the med model; solar modulation parameter φ = 830 MV.**
- **γ = 1.90, η = 0.032 for all PWNs.**
- **Q0 found from the values of the ATNF catalog.**

SOLAR MODULATION

- In order to calculate the flux of a charged cosmic ray species at Earth, one has to take into account the effect of the solar wind. We adopt the effective theory of a spherically symmetric and charge-independent force field.
- In this simplified model, the net effect of the solar wind is an electric potential generated by the Sun leading to an energy loss of each charged particle.
- Then the flux Φ_{TOA} at the top of the Earth's atmosphere TOA is related to the interstellar flux IS Φ_{IS} through:

$$\Phi_{\rm TOA}\left(T_{\rm TOA}\right) = \frac{p_{\rm TOA}^2}{p_{\rm IS}^2}\Phi_{\rm IS}\left(T_{\rm IS}\right) = \left(\frac{2m\,{\rm A}\,T_{\rm TOA} + ({\rm A}\,T_{\rm TOA})^2}{2m\,{\rm A}\,T_{\rm IS} + ({\rm A}\,T_{\rm IS})^2}\right)\Phi_{\rm IS}\left(T_{\rm IS}\right)$$



$T_{IS} = T_{TOA} + (|Z|/A)\,\varphi$

T kinetc energy per nucleon, m proton mass, A atomic number.

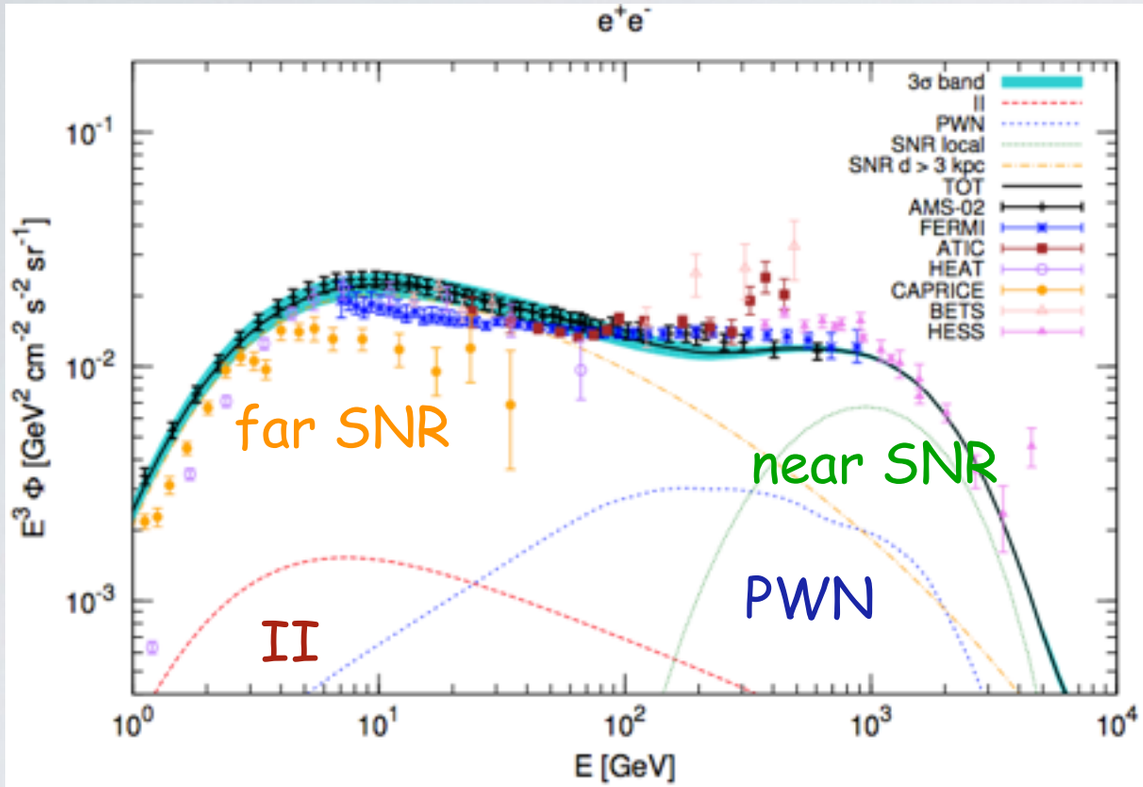
FIT TO AMS-02 DATA ON ELECTRONS AND POSITRONS

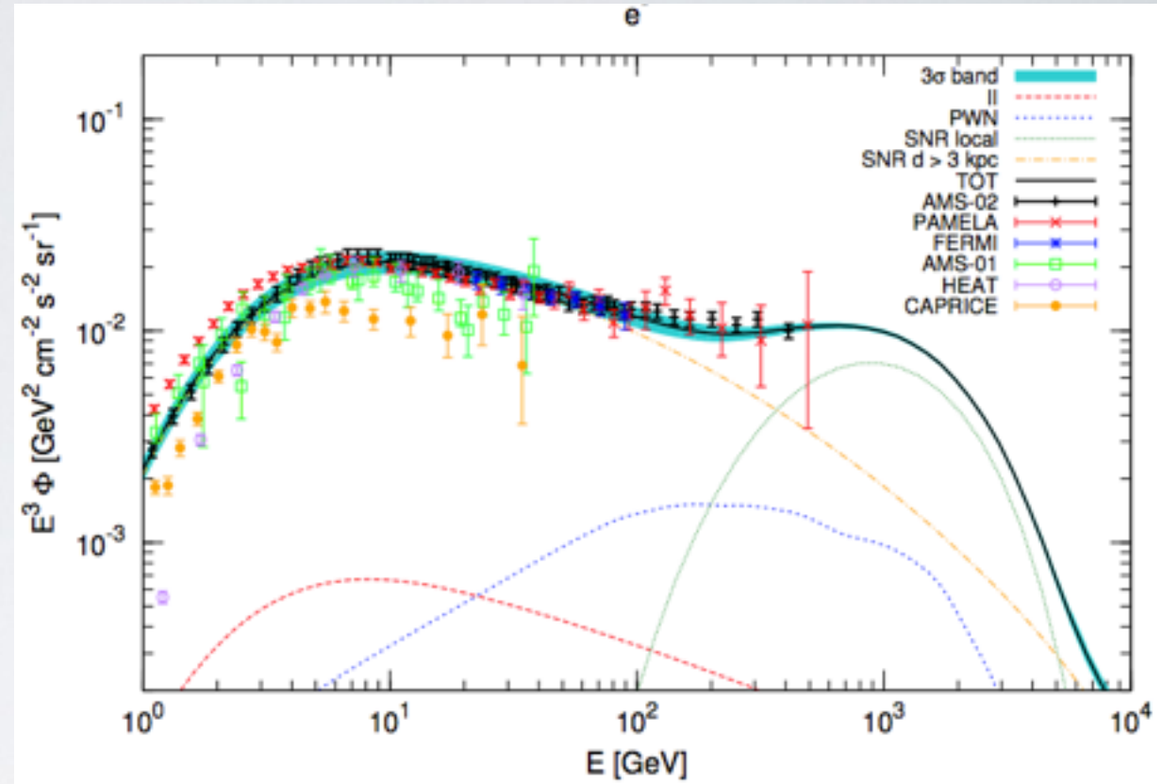
- For the **SNRs** electrons emitted by the far (> 3 kpc) population we leave the spectral index γ and the overall normalization Q_0 as free parameters.
- The ATNF catalog **PWN** are included by making the simplifying hypothesis that they all shine with a common spectral index γ_{PWN} and efficiency η.
- The **secondary** positrons and electrons are computed from the observed primary p and He and we allow the normalization to be adjusted by an overall renormalization factor that we call here q.
- Finally alle the above cited spectra are the interstellar so they must be modified according to the **solar modulation** parametrized with a Fisk potential φ.

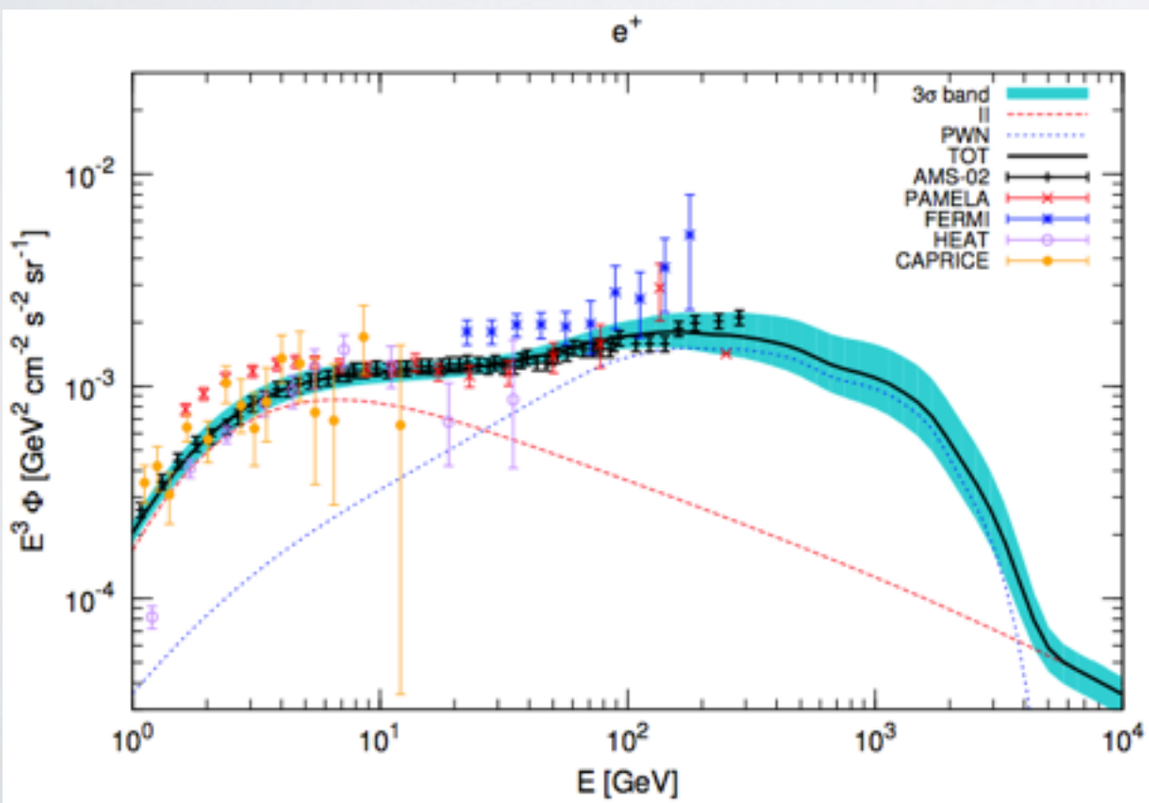
- We make a fit on the electrons, positrons, electrons+positrons and positron fraction spectra measured by AMS-02.
- In summary, the free parameters of the model are: γ, Q_0 , γ_{PWN} , η , q and φ. We jointly fit all the four datasets together and we derive a 3σ uncertainty band.

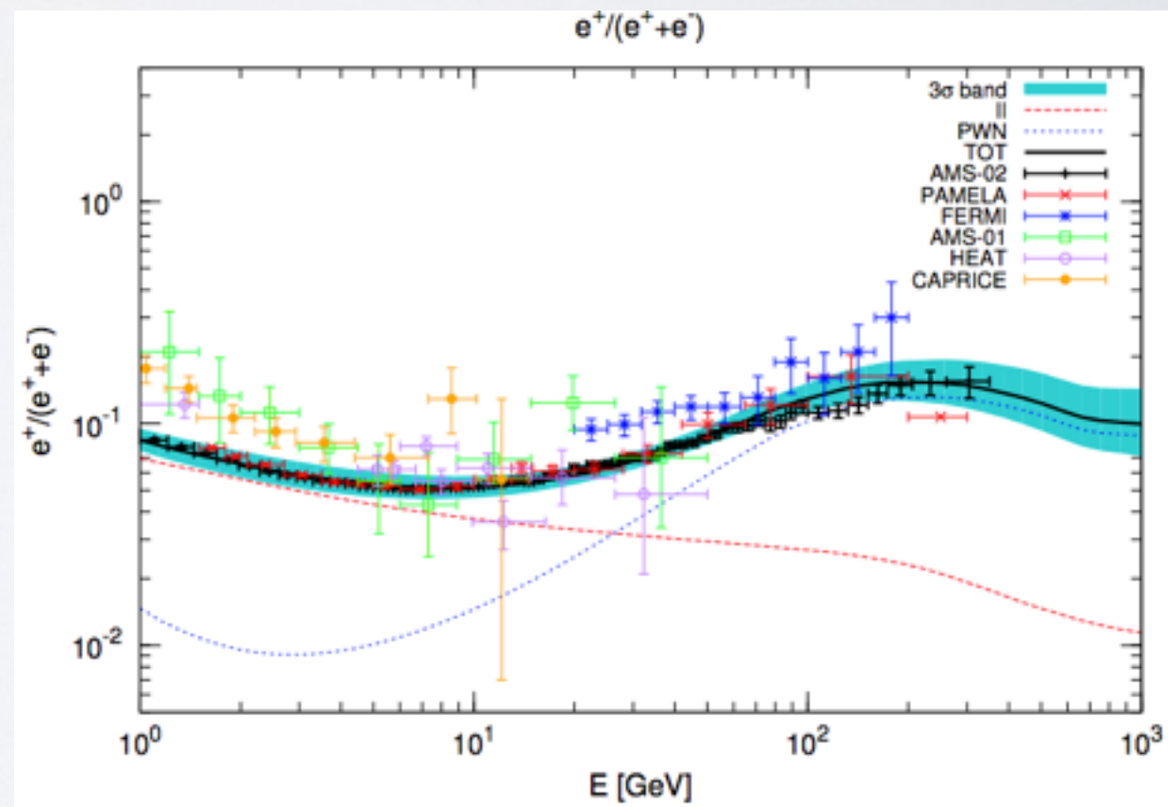
2 YEARS

FIT TO AMS-02





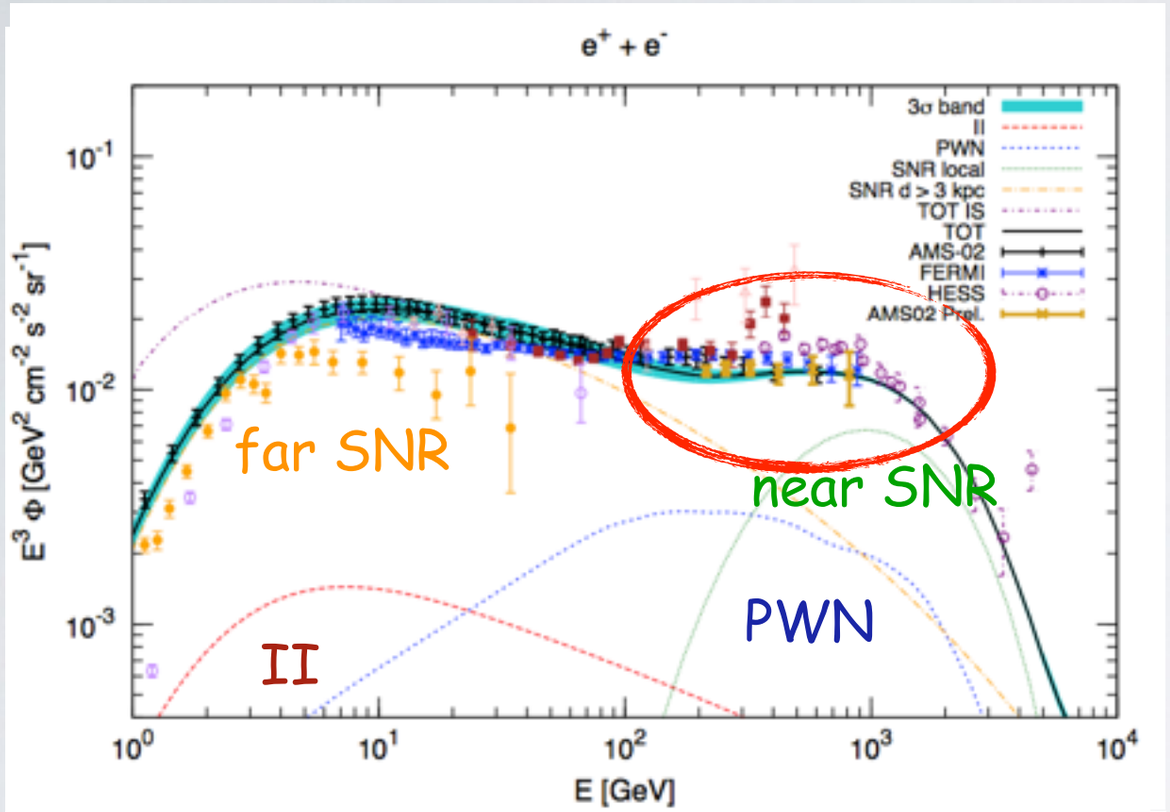


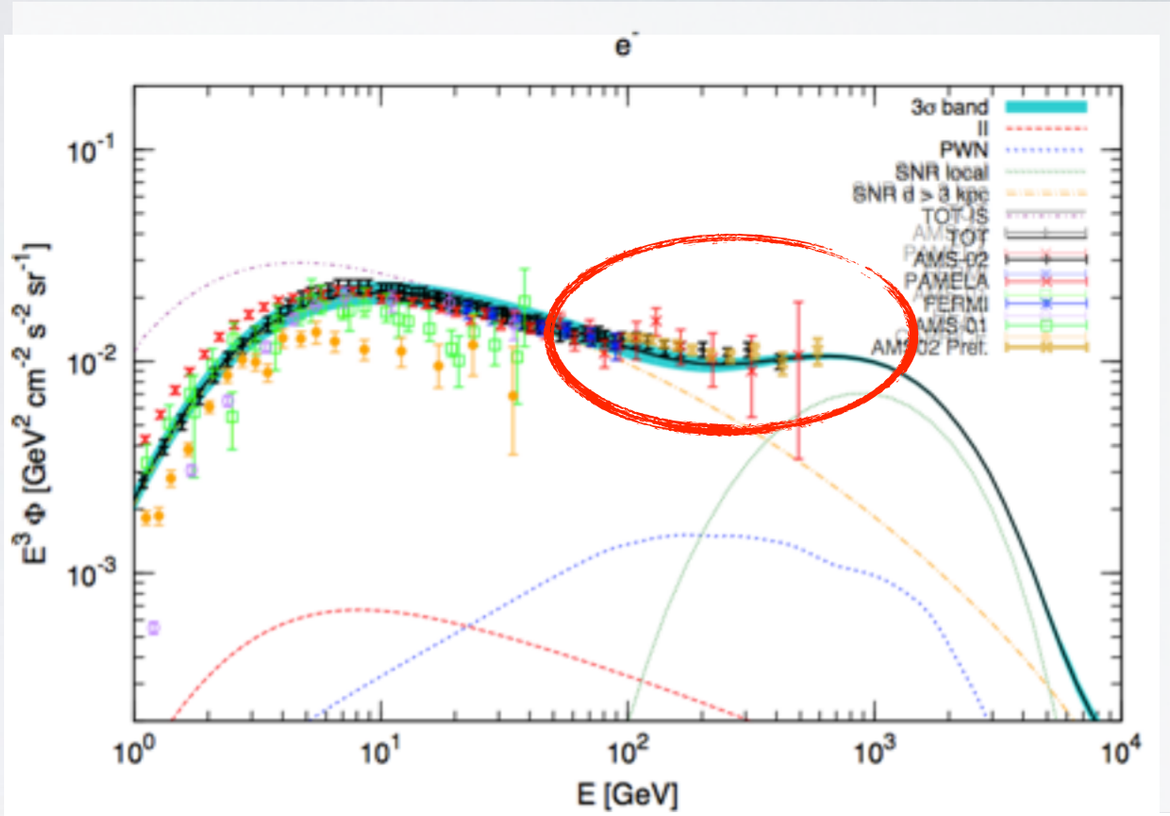


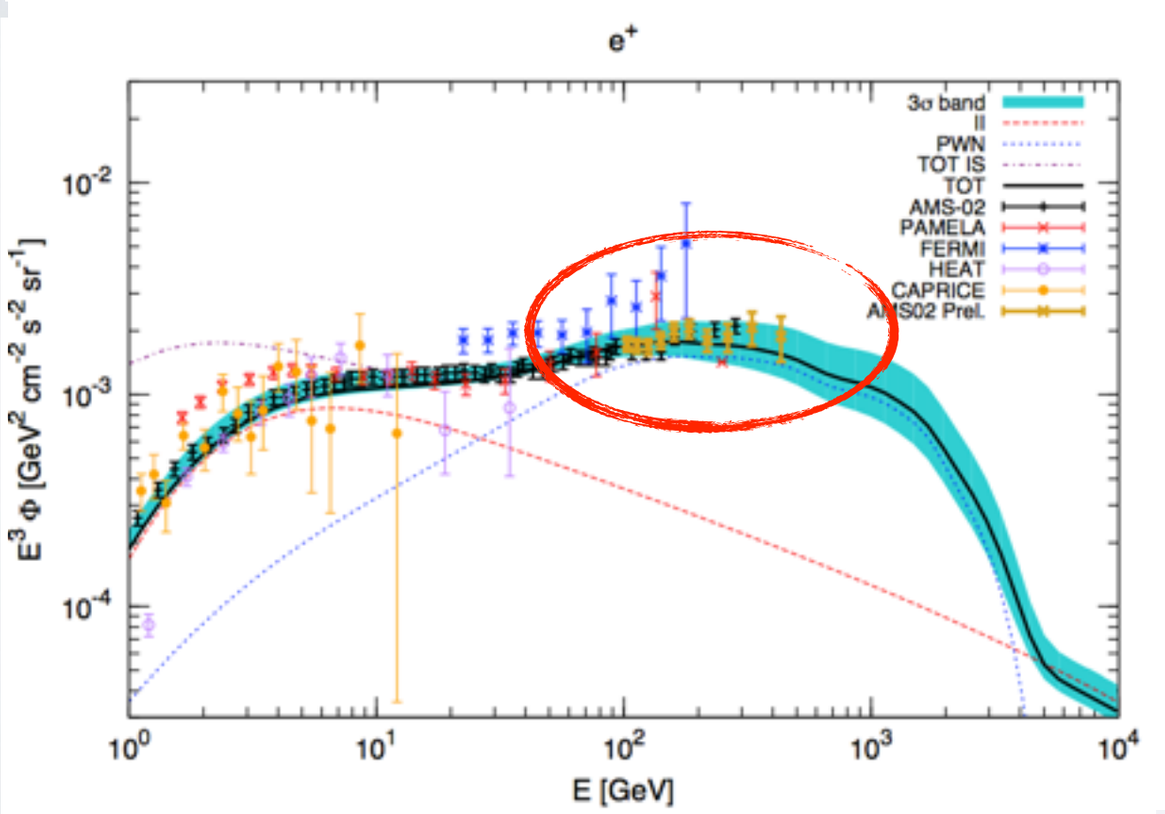
2.5 YEARS

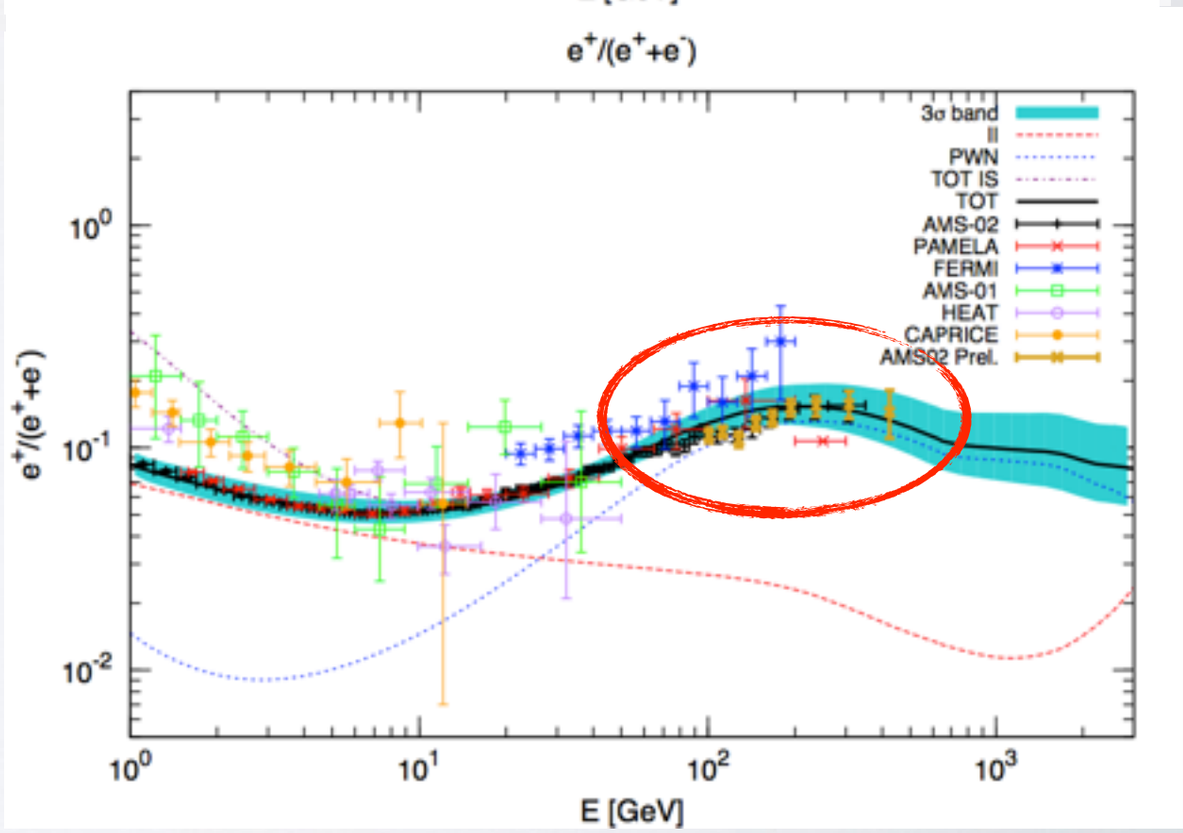
FIT TO AMS-02

http://ams.nasa.gov/Documents/AMS_Publications/NASA%20JUNE-2014C.pdf









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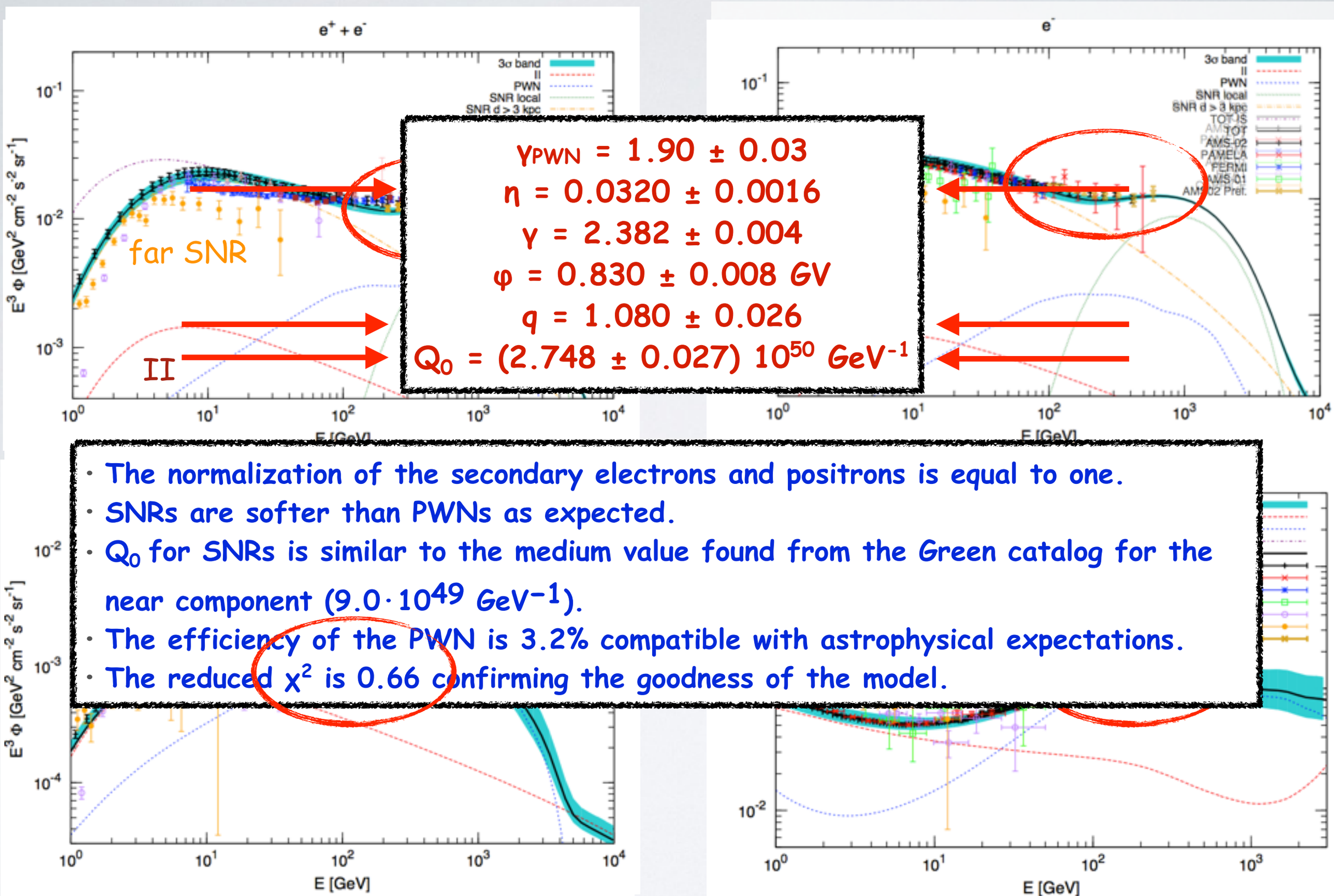


$\gamma_{PWN} = 1.90 \pm 0.03$

$\eta = 0.0320 \pm 0.0016$

$\gamma = 2.382 \pm 0.004$

$\varphi = 0.830 \pm 0.008$ GV

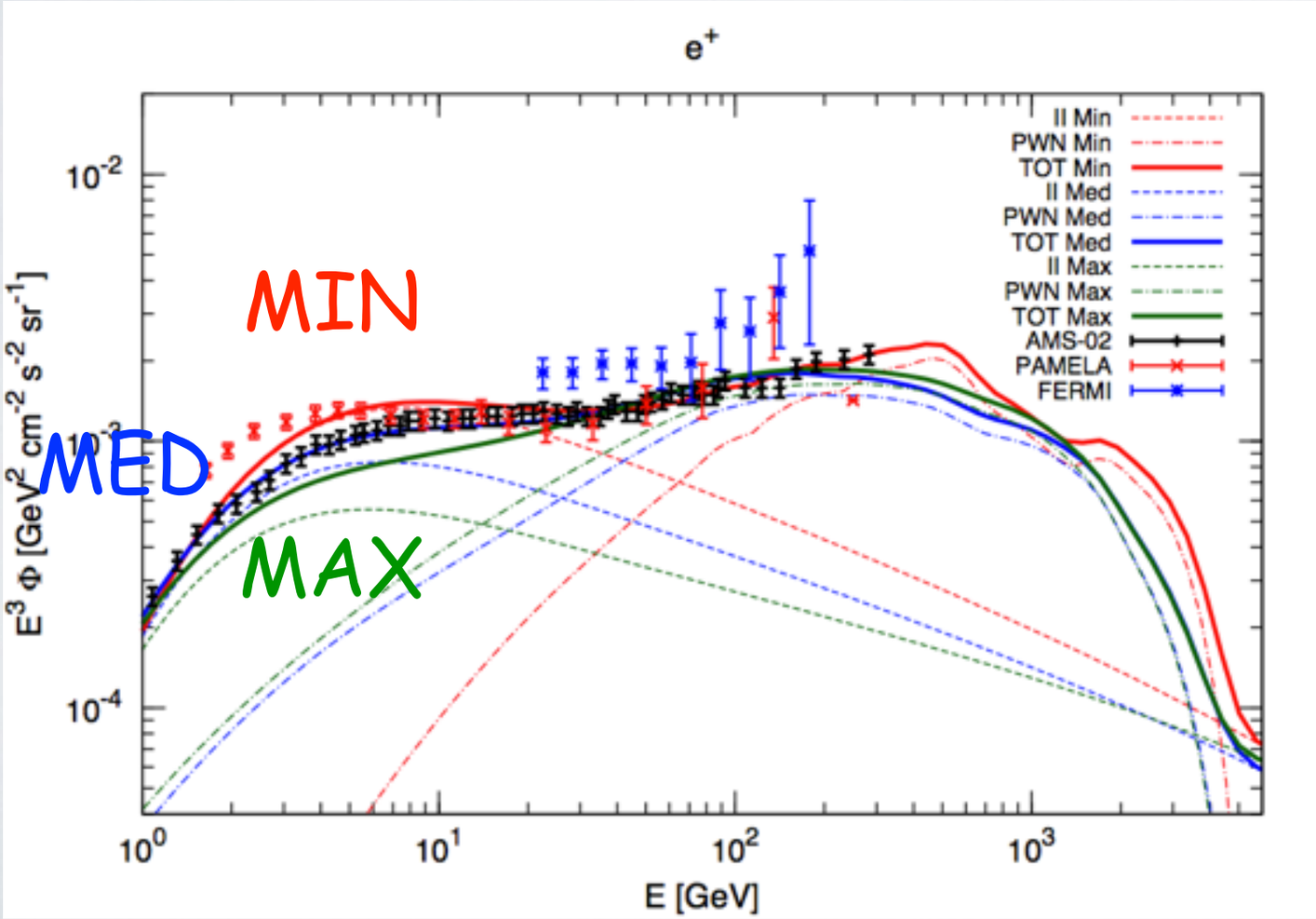
$q = 1.080 \pm 0.026$

$Q_0 = (2.748 \pm 0.027)\ 10^{50}$ GeV^{-1}

- The normalization of the secondary electrons and positrons is equal to one.
- SNRs are softer than PWNs as expected.
- Q_0 for SNRs is similar to the medium value found from the Green catalog for the near component ($9.0 \cdot 10^{49}$ GeV^{-1}).
- The efficiency of the PWN is 3.2% compatible with astrophysical expectations.
- The reduced χ^2 is 0.66 confirming the goodness of the model.

CONSTRAINTS ON THE PROPAGATION PARAMETERS

- The spectra of positrons can be used to constraints the propagation parameters
- We have taken into account the min/med/max propagations models for the positrons from secondary production and emitted by PWN and we have fitted them with positrons data.
- We have considered as free parameters only the Fisk potential (in the range 0.6-1.0 GV) for the low energy solar modulation and the index and efficiency of PWNs.
- We have fixed to 1 the normalization q of secondary positrons.



- Only the med model can account the positron spectra with a φ = 0.77 GV.
- The best fit values of the Fisk potential are for the max and min models the lowest (0.6 GV) and highest (1 GV) permitted in the calculation.
- The min (max) model is at low energy higher (lower) respect data.
- In order to be consistent with data secondary positrons should be renormalized with a factor of 0.85 (1.79).

Maurin et al. ApJ 555 (2001) 585-596

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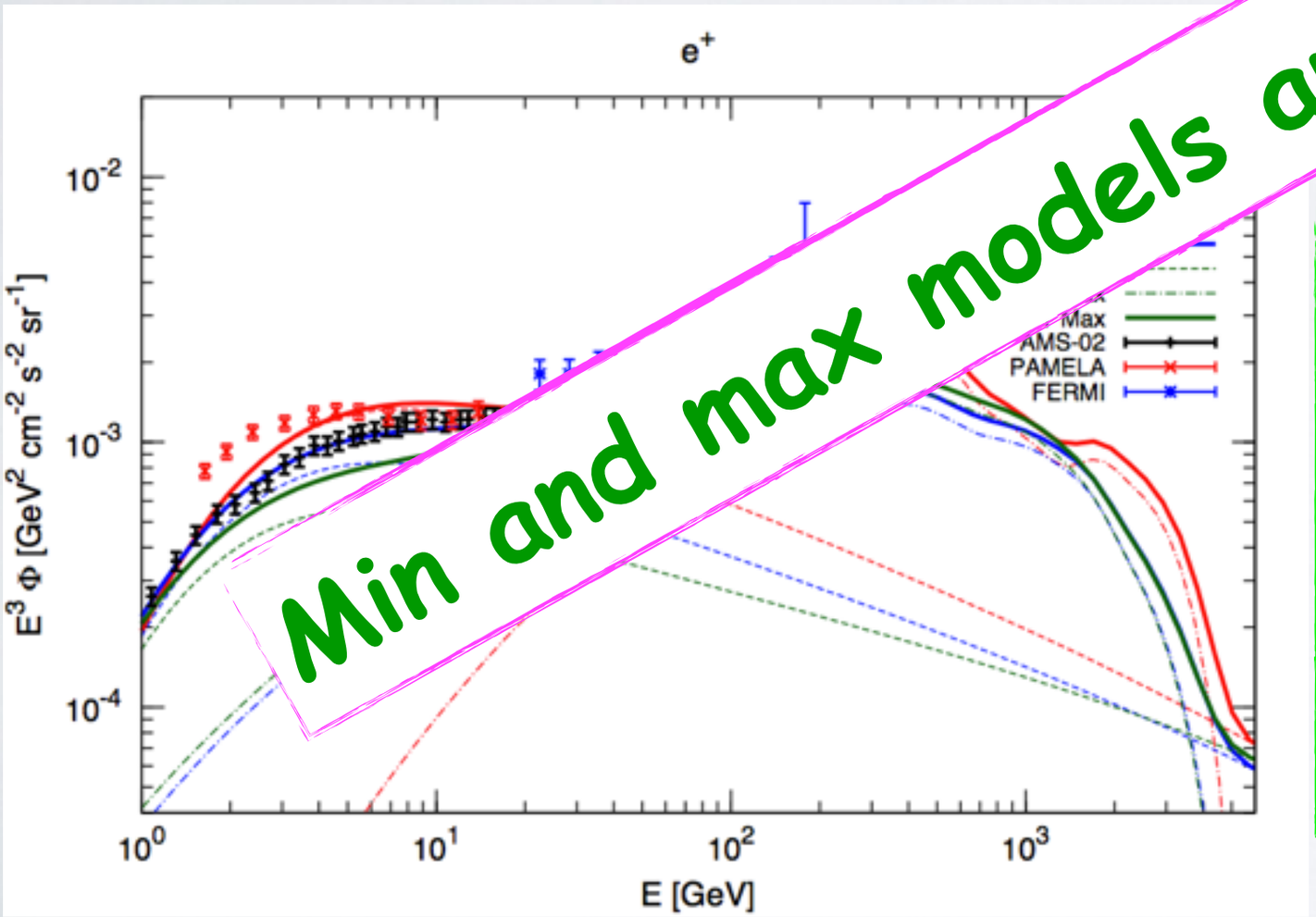
Min and max models are disfavored!!!!



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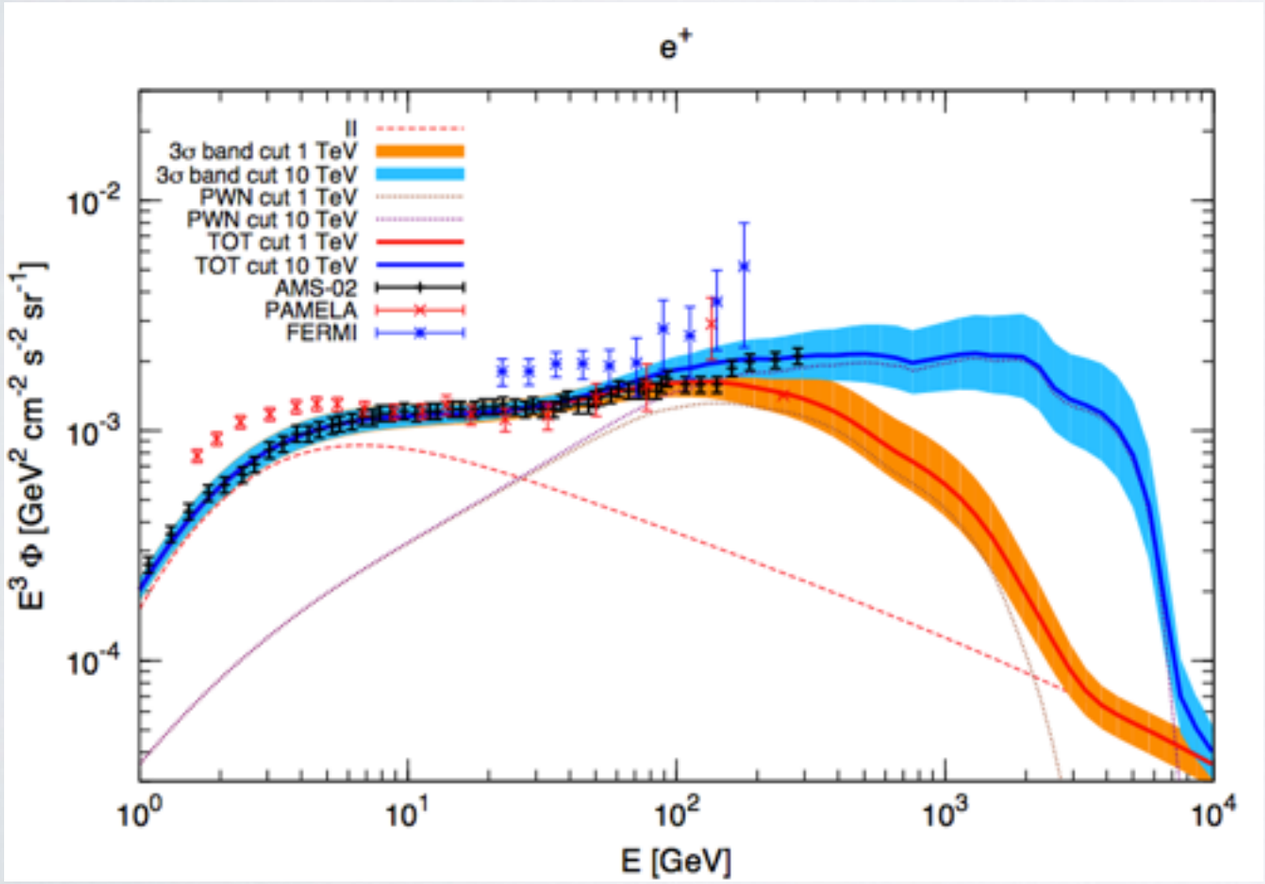
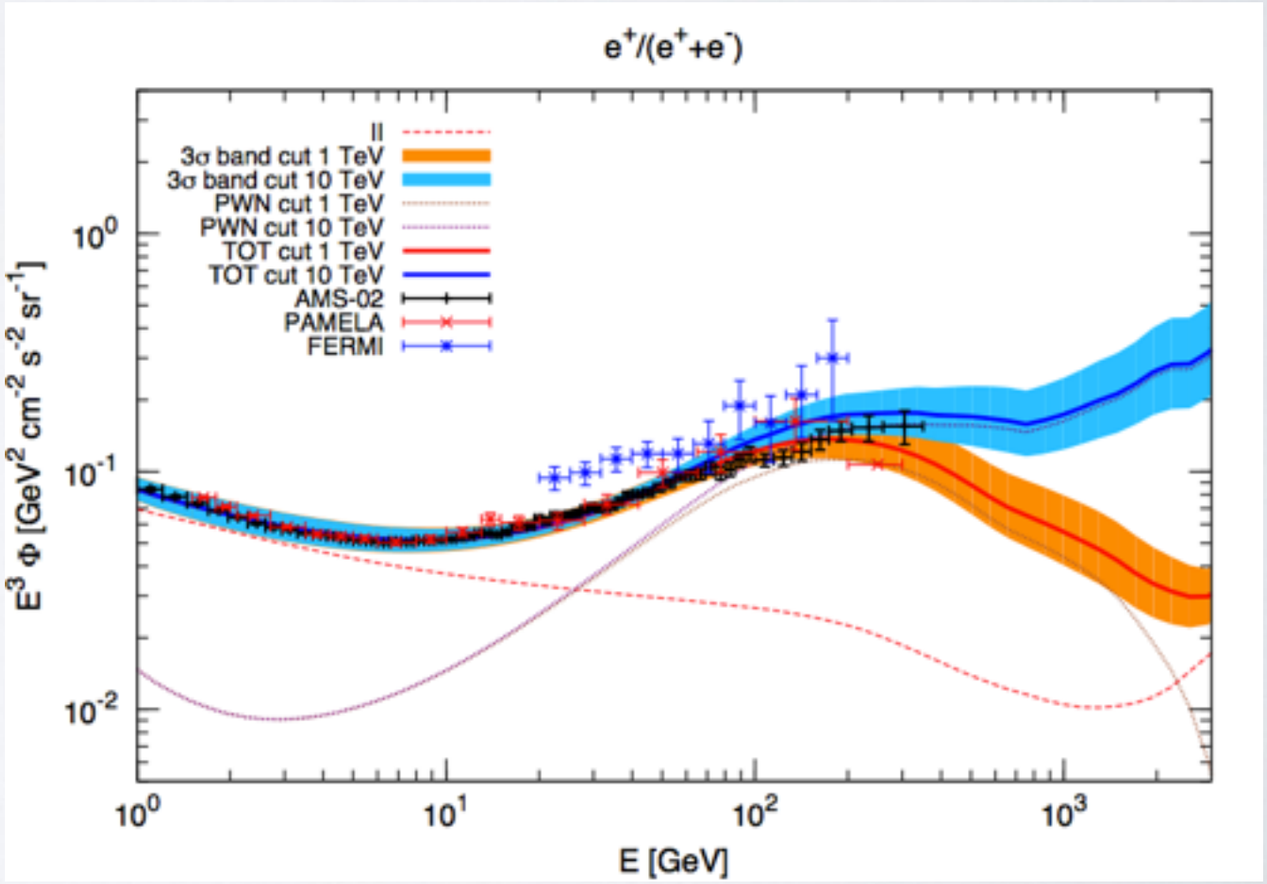
HIGH ENERGY TREND

- We have analyzed the possible trend of the spectra for very high positrons energy modifying the cut off energy of PWNs.
- The PWNs energy cut off is not directly measured by is expected to be in the range 1-10 TeV.
- Even with very high energy cut off values (10 TeV), the increasing of positrons and positrons fraction spectra for E > 300 GeV is disfavoured.
- A future increasing of the measured spectra could be a signal of an unexpected source of positrons.





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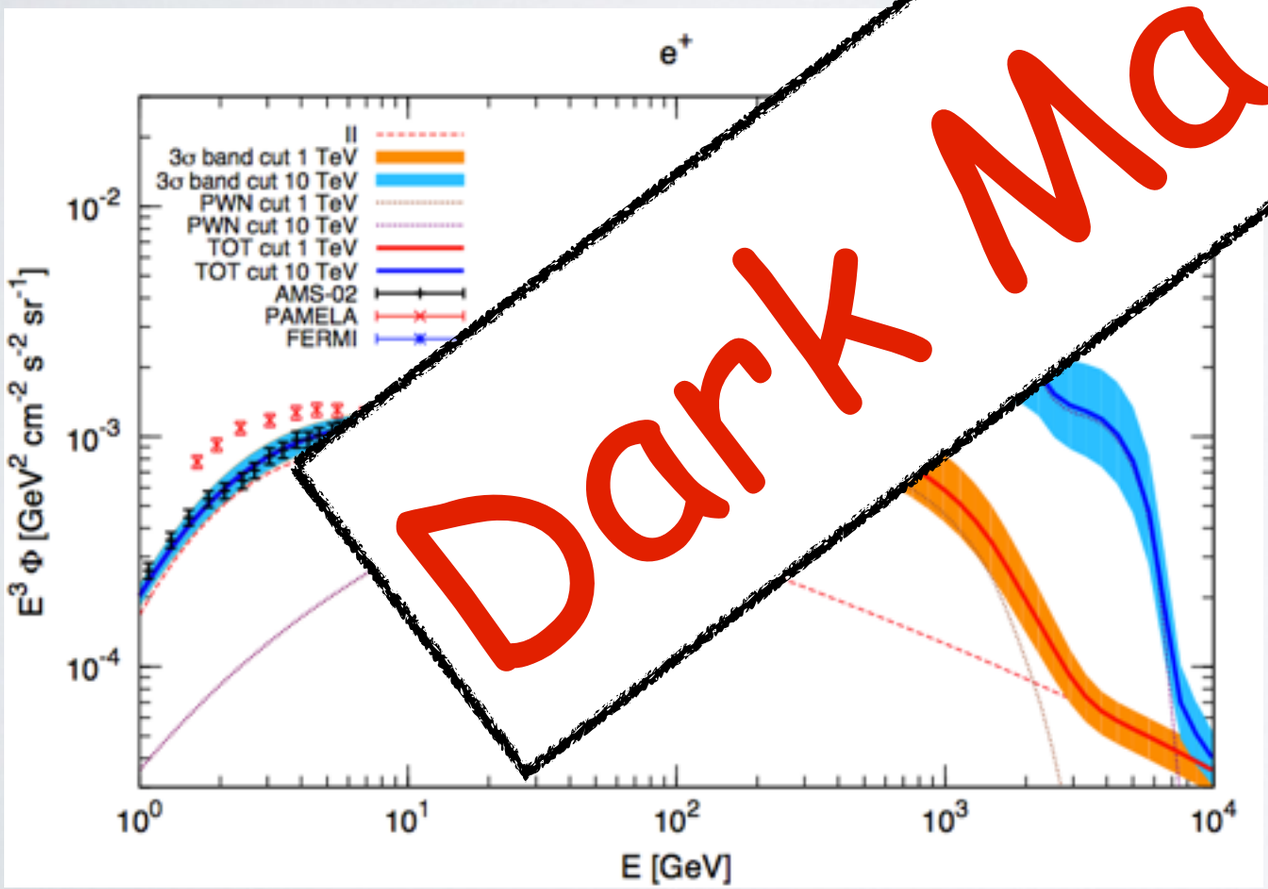
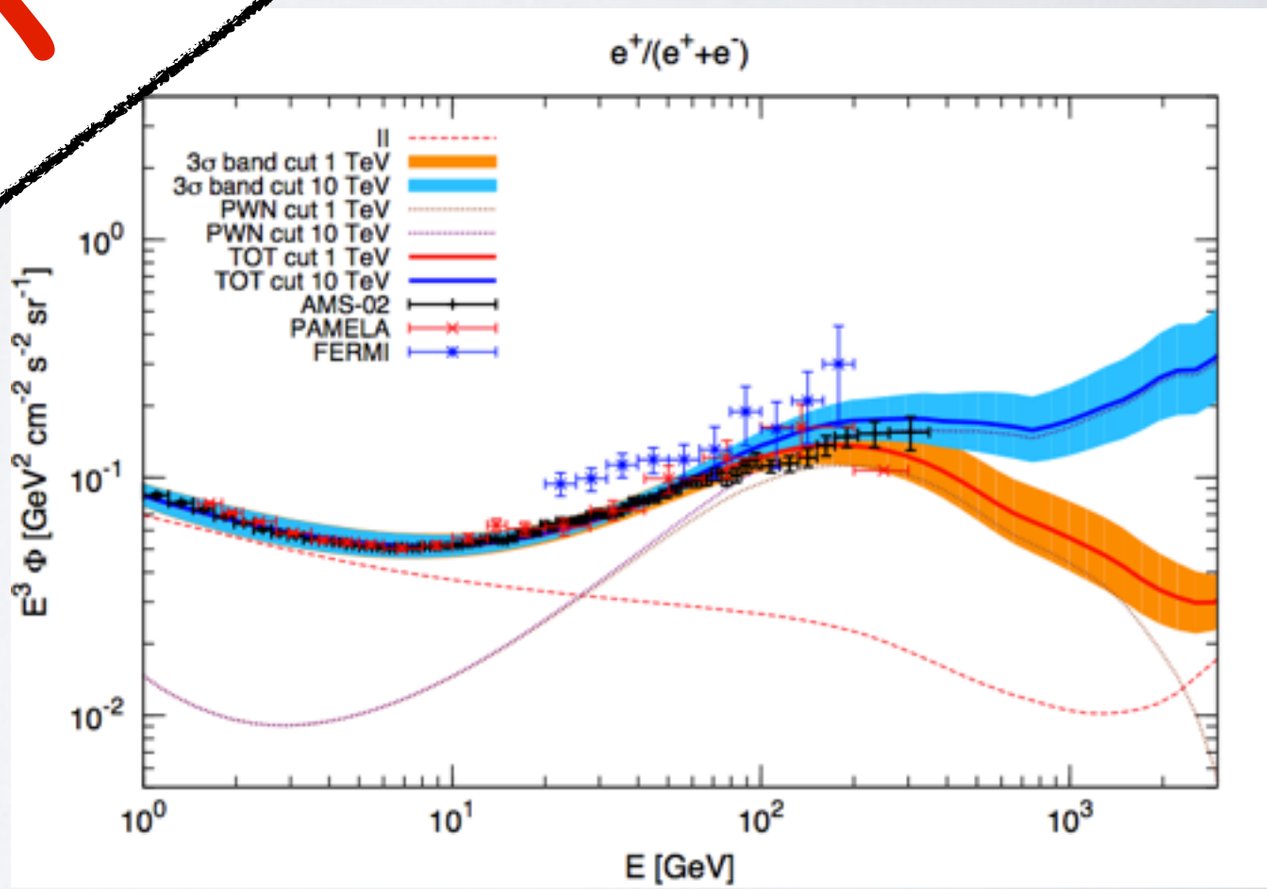
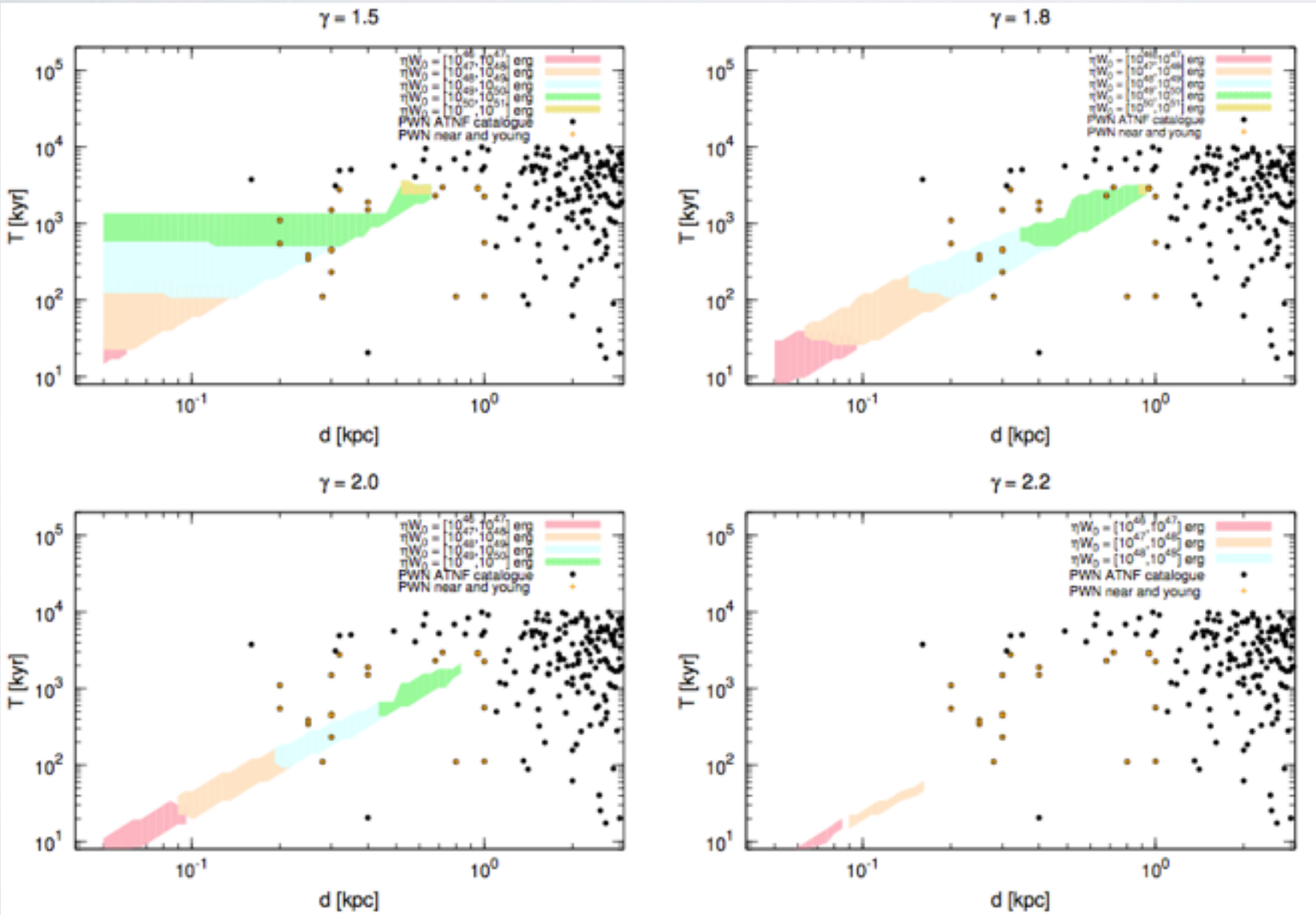
Dark Matter????





SINGLE SOURCE ANALYSIS

- The rising of the positron fraction measured by AMS-02 and Pamela could be due to PWNs.
- Supposing the contribution is due to the emission of only or at least mainly one source, what should be the age, distance, index and emitted energy of this source?
- We have varied the parameters of a fake source and we have found the space of parameters the PWN should have to fit all the four spectra of electrons and positrons up to 3σ.



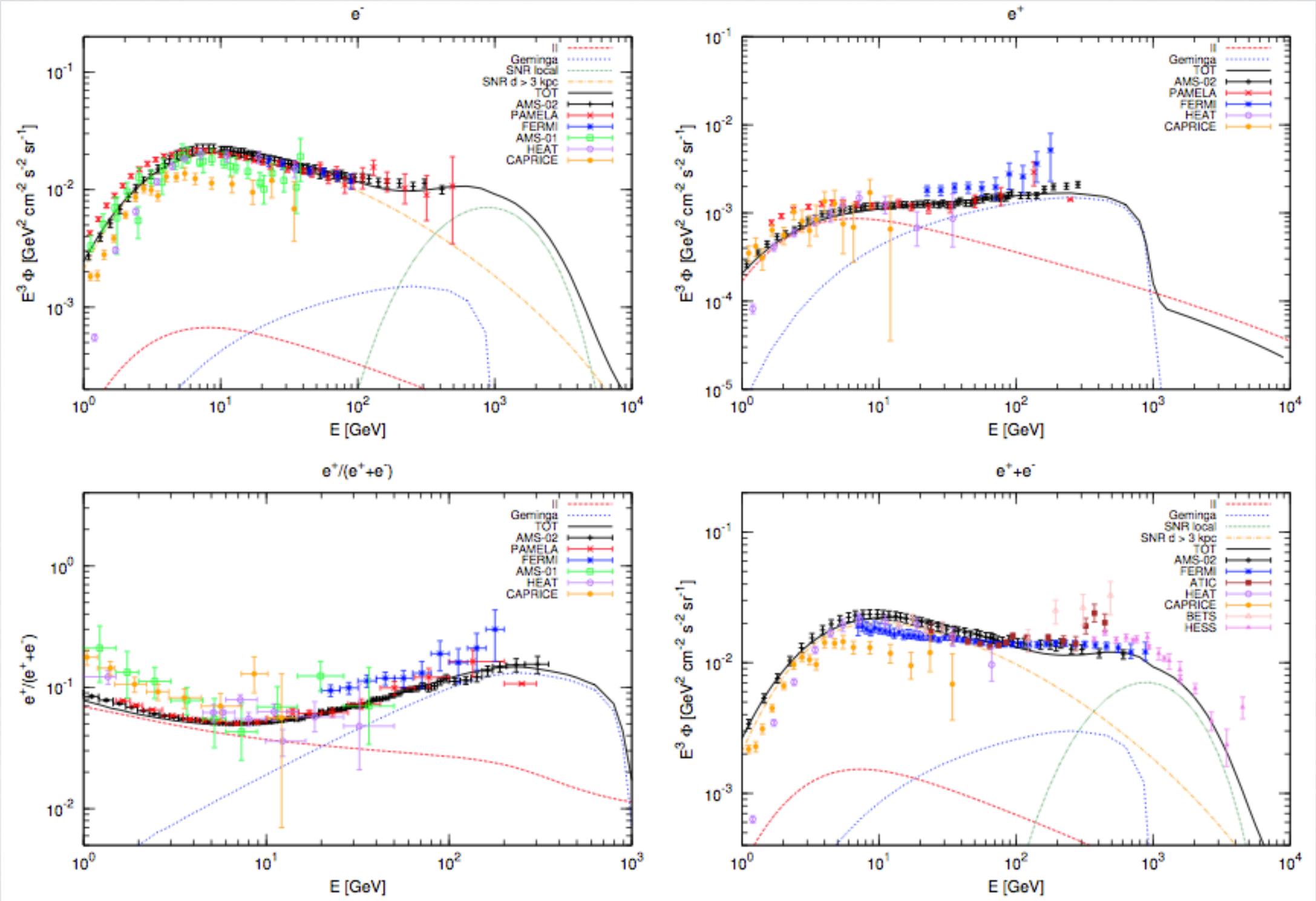
- Each color represent a decade in ηW_0.
- Each panel is valid for a fixed value of the spectral index γ_{PWN}.
- The point are the PWNs of the ATNF catalog.
- The gold point are the near and young PWNs of the ATNF catalog.

SINGLE SOURCE ANALYSIS RESULTS

- Nine sources have an age and a distance compatible with the 3σ region of compatability with AMS-02.
- However only three of them fit AMS-02 data with an emitted energy $W_{0,fit}$ which is compatible with the catalog $W_{0,fit}$ value so that the efficiency is minor than 1.
- The emitted power derived from the ATNF catalog could not be the exact value of the source so we have considered all the source with η<3.
- Only five sources among the 2302 of the ATNF catalog have η<3 and are compatible up to 3σ with AMS-02 data !!!!

code	γ	$\eta W_{0,fit}$	T_{fit}	d_{fit}	$\chi^2/d.o.f.$	d_{cat}	T_{cat}	$W_{0,cat}$	η_{fit}
Geminga	1.74	0.341	344.61	0.244647	0.68	0.25	342	1.25	0.27
J1741-2054	1.68	0.413	377.976	0.254214	0.62	0.25	386	0.47	0.88
B1742-30	1.52	0.770	539.114	0.19127	0.54	0.2	546	0.83	0.92
B0940-55	1.70	0.588	474.328	0.293016	0.66	0.3	461	0.21	2.8
J1918+1541	1.65	6.48	2355.15	0.641331	0.92	0.68	2310	3.4	1.90

GEMINGA


e⁻
II
Geminga
SNR local
SNR d > 3 kpc
TOT
AMS-02
PAMELA
FERMI
AMS-01
HEAT
CAPRICE
E³ Φ [GeV² cm⁻² s⁻² sr⁻¹]
E [GeV]
e⁺
II
Geminga
TOT
AMS-02
PAMELA
FERMI
HEAT
CAPRICE
E³ Φ [GeV² cm⁻² s⁻² sr⁻¹]
E [GeV]
e⁺/(e⁺+e⁻)
II
Geminga
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PAMELA
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E [GeV]
e⁺+e⁻
II
Geminga
SNR local
SNR d > 3 kpc
TOT
AMS-02
FERMI
ATIC
HEAT
CAPRICE
BETS
HESS
E³ Φ [GeV² cm⁻² s⁻² sr⁻¹]
E [GeV]

DARK MATTER CONSTRAINTS

- The normalization and the shape of PWNs are not constrained by observations.
- PWN emission could hide a DM contribution to the positron and positron fraction spectrum.
- We have derived constraints on the DM annihilation cross section considering the WIMP hypothesis.

$$q(r,p) = \frac{\langle \sigma v \rangle}{2m_\chi^2} \frac{dN}{dp} \times \rho^2(r)$$

- dN/dp: electron and positron spectra from DM annihilation.
- ρ: DM density.
- <σv>: annihilation DM cross section.
- m_χ: DM mass

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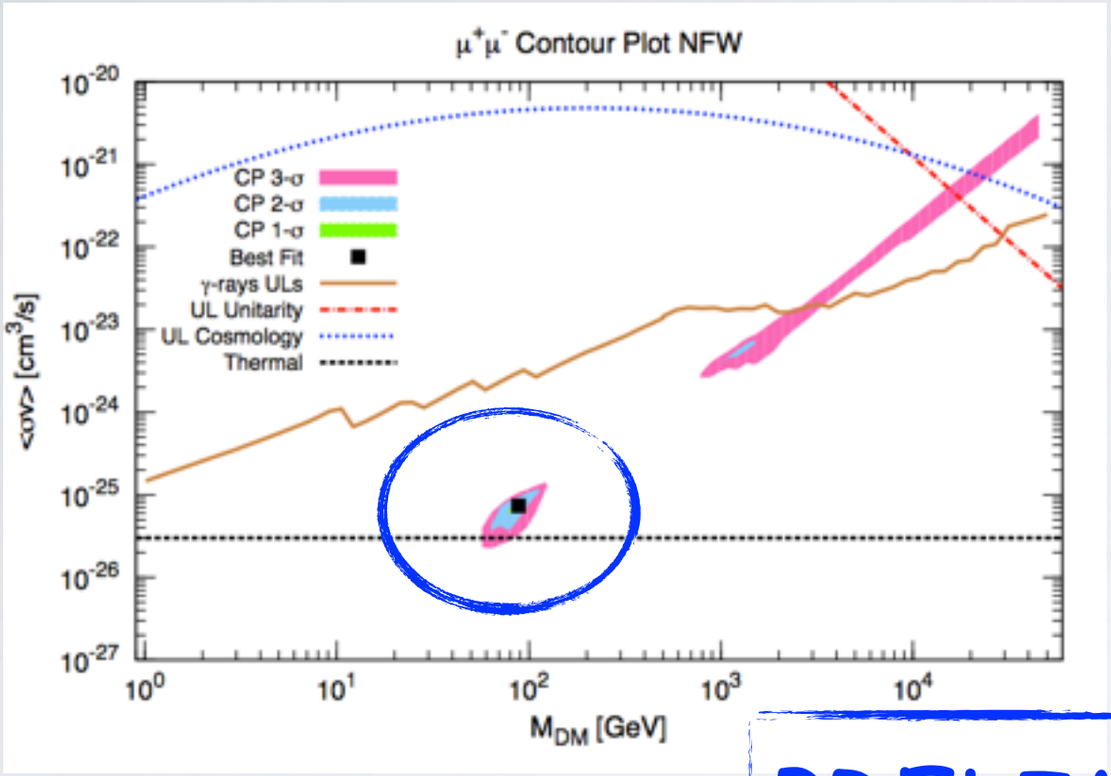
Method

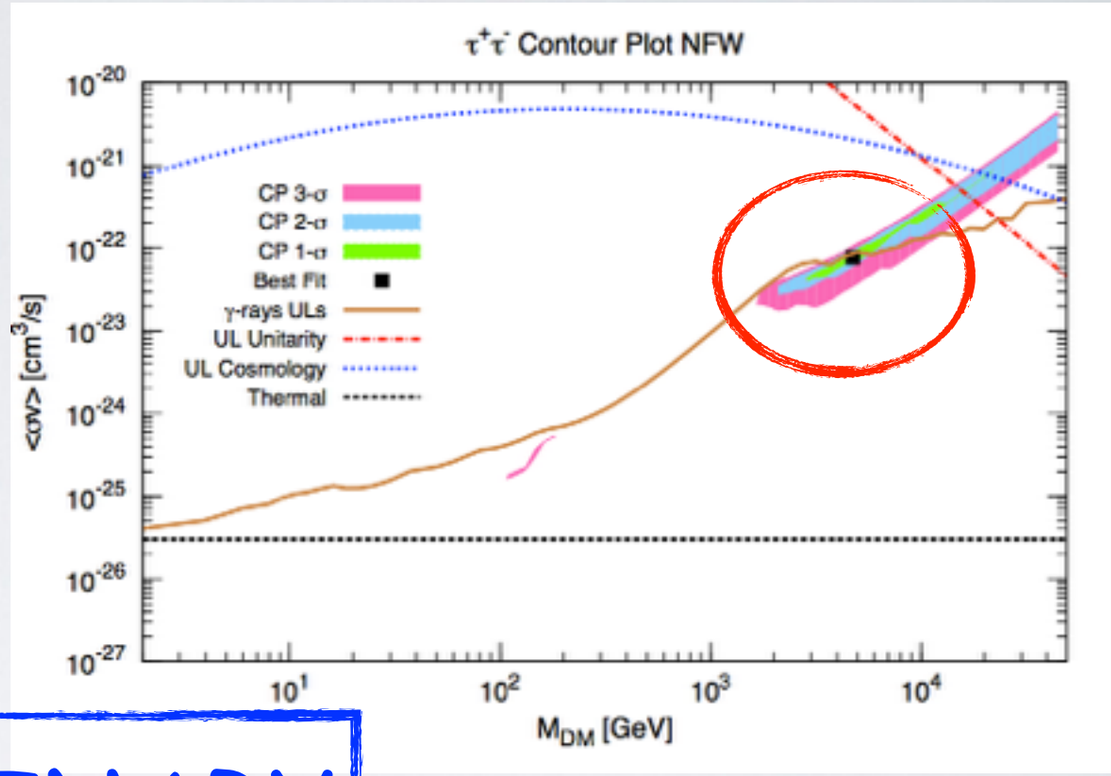
1. We derive the positrons and electrons spectra varying the DM parameters of the mass and the annihilation cross section, the PWN efficiency and slope and the secondary normalization and Fisk potential.

2. We find the best fit configuration and its chi square χ_{min}.

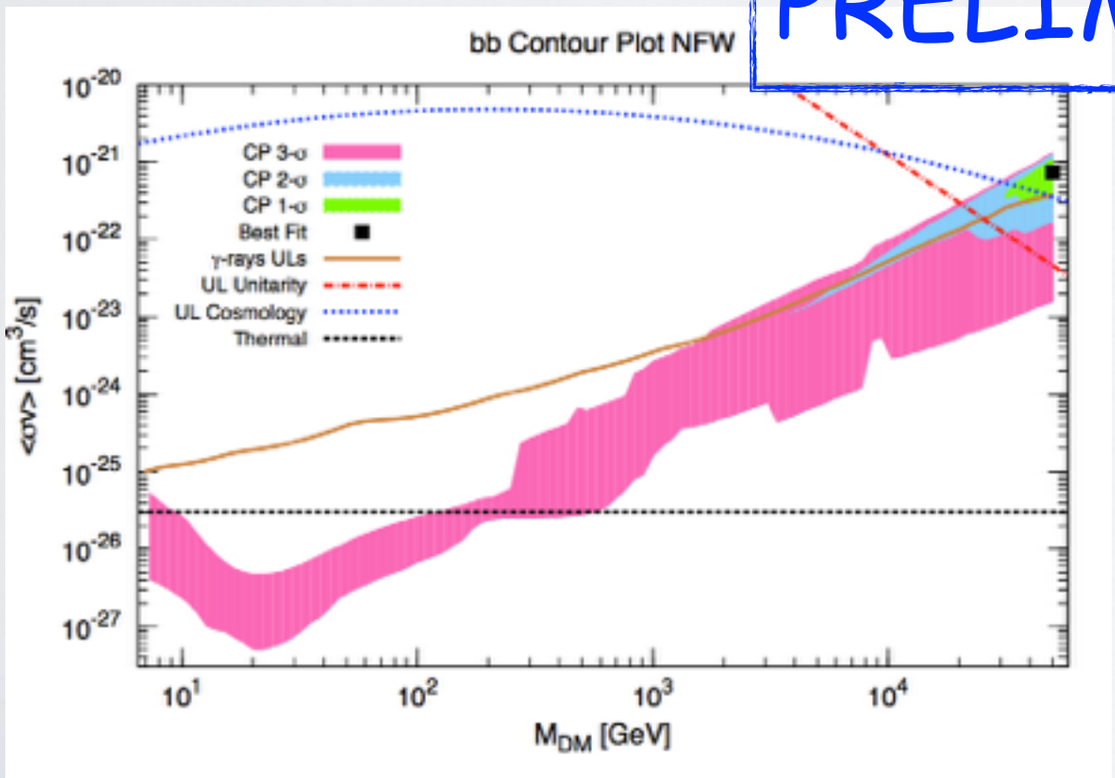
3. Finally we derive the 1/2/3σ contour plots.

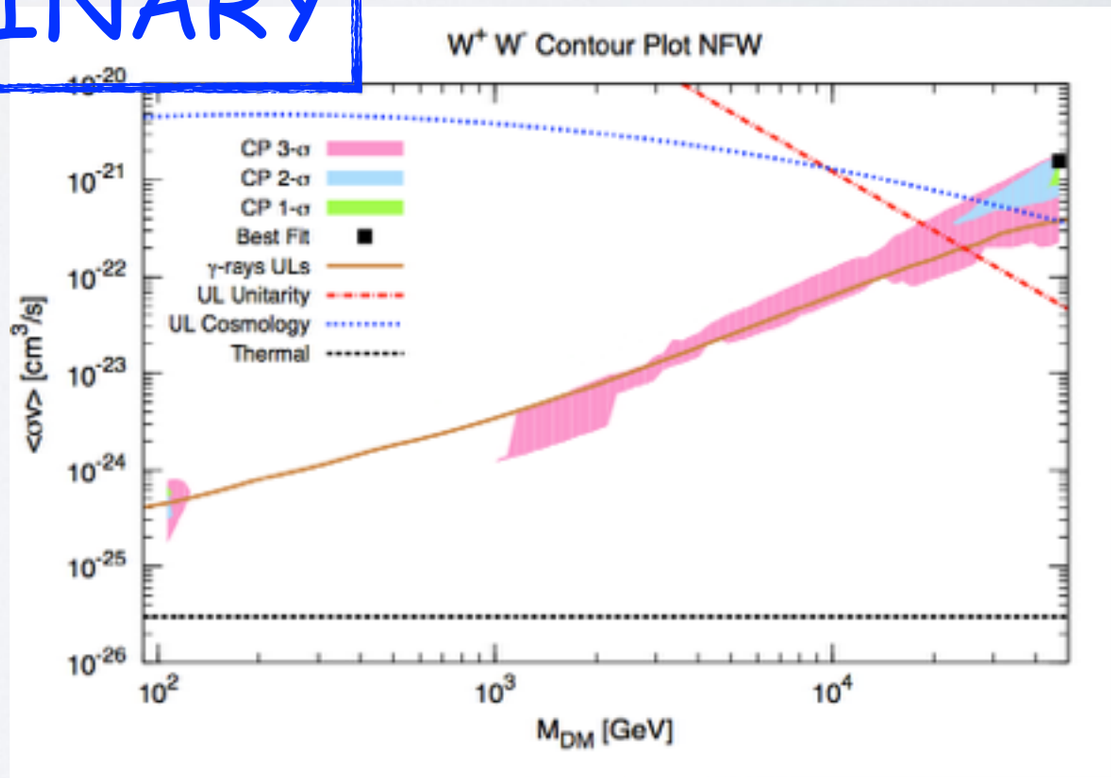
DM+ASTROPHYSICS





PRELIMINARY

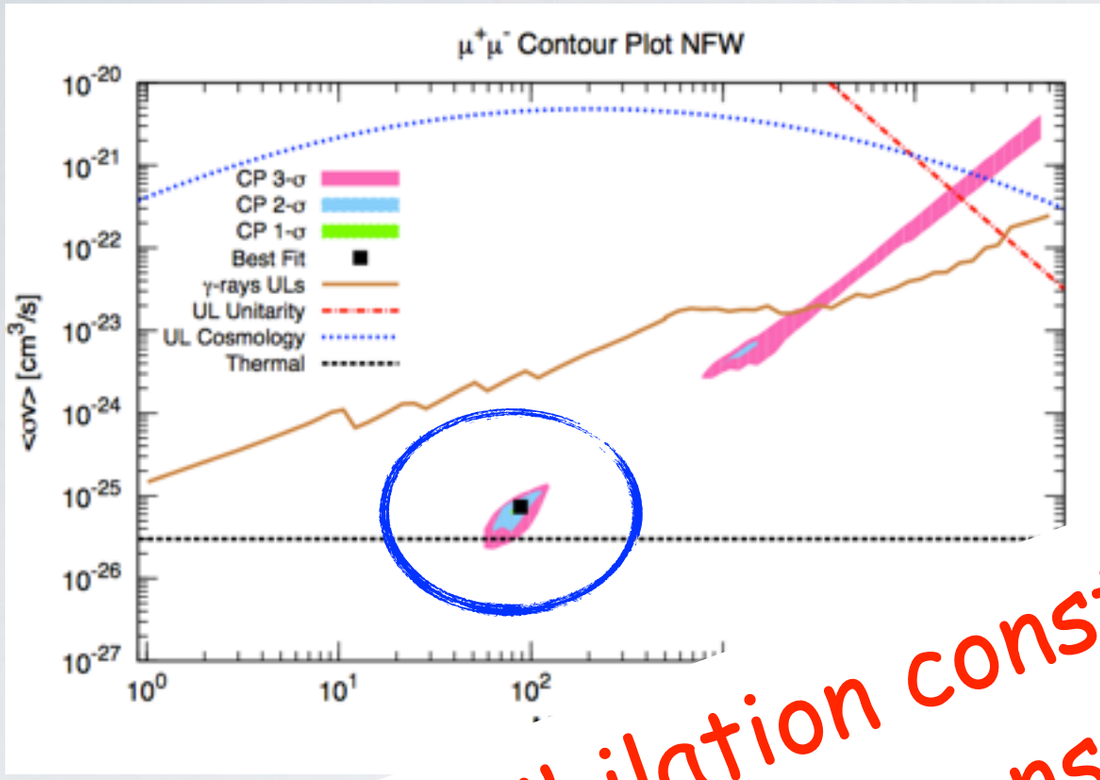


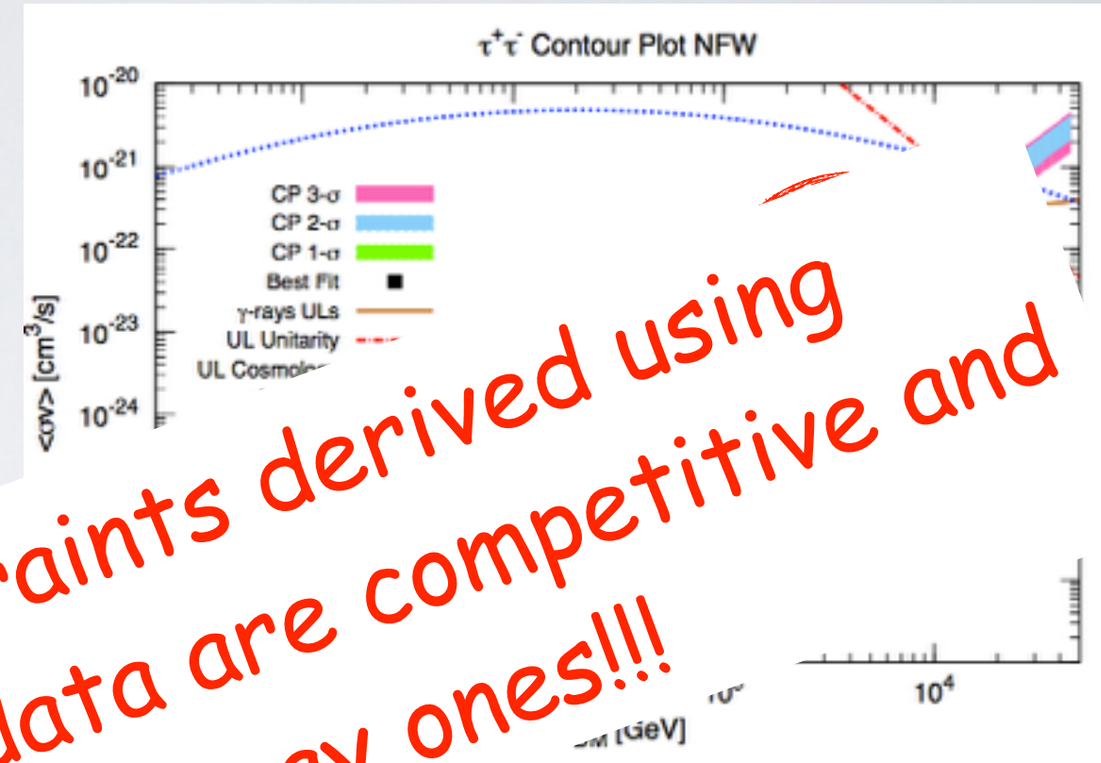


Unitarity and Cosmological ULs are taken from Yuksel et al. Phys.Rev. D76 (2007) 123506

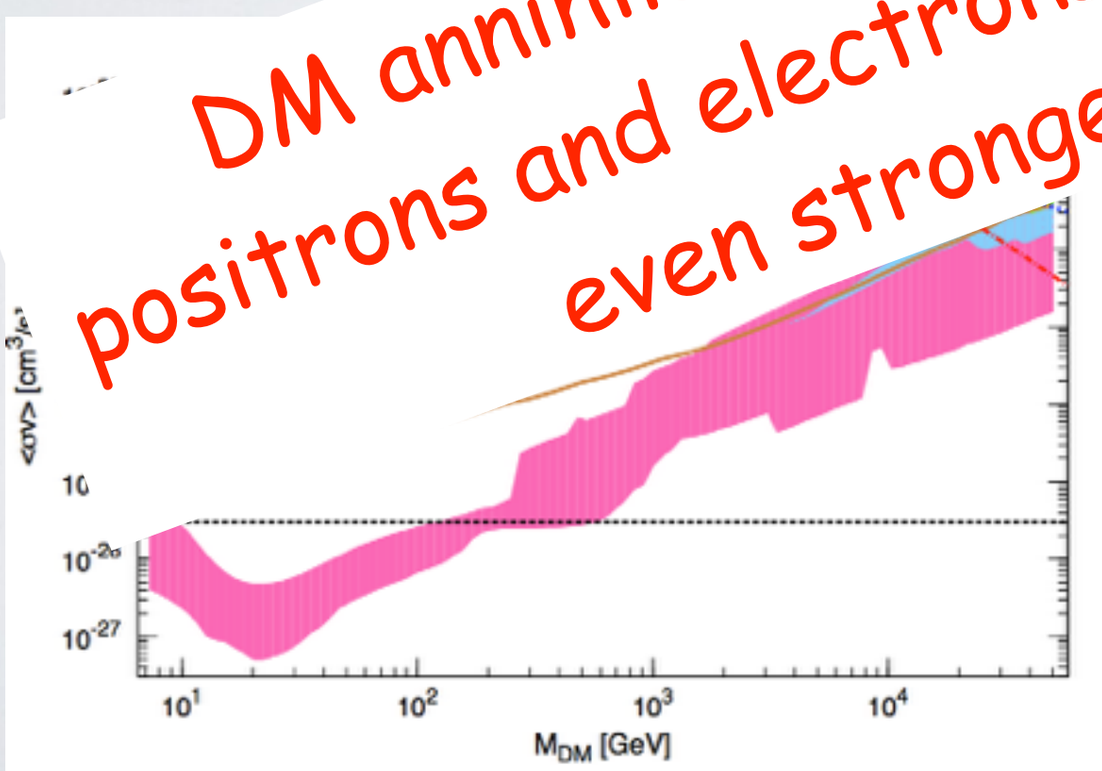
γ-ray ULs taken from Calore et al. Phys.Rev. D89 (2014) 023012

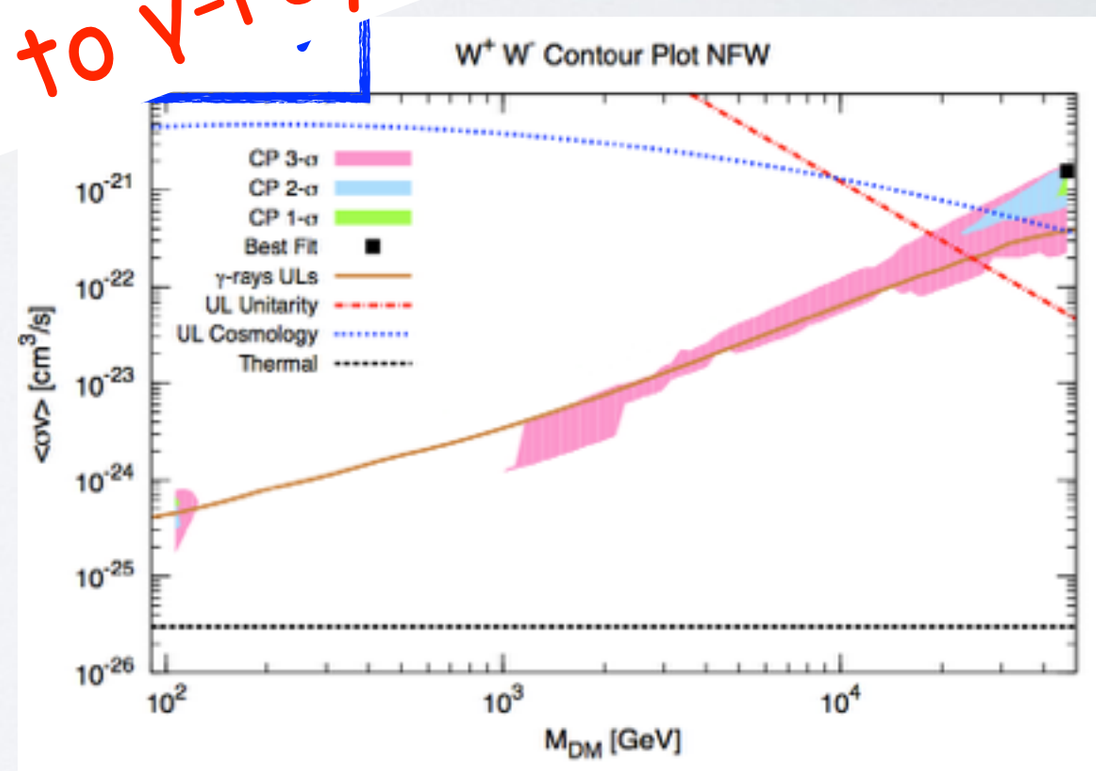
DM+ASTROPHYSICS





DM annihilation constraints derived using positrons and electrons data are competitive and even stronger to γ-ray ones!!!





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ONLY DM

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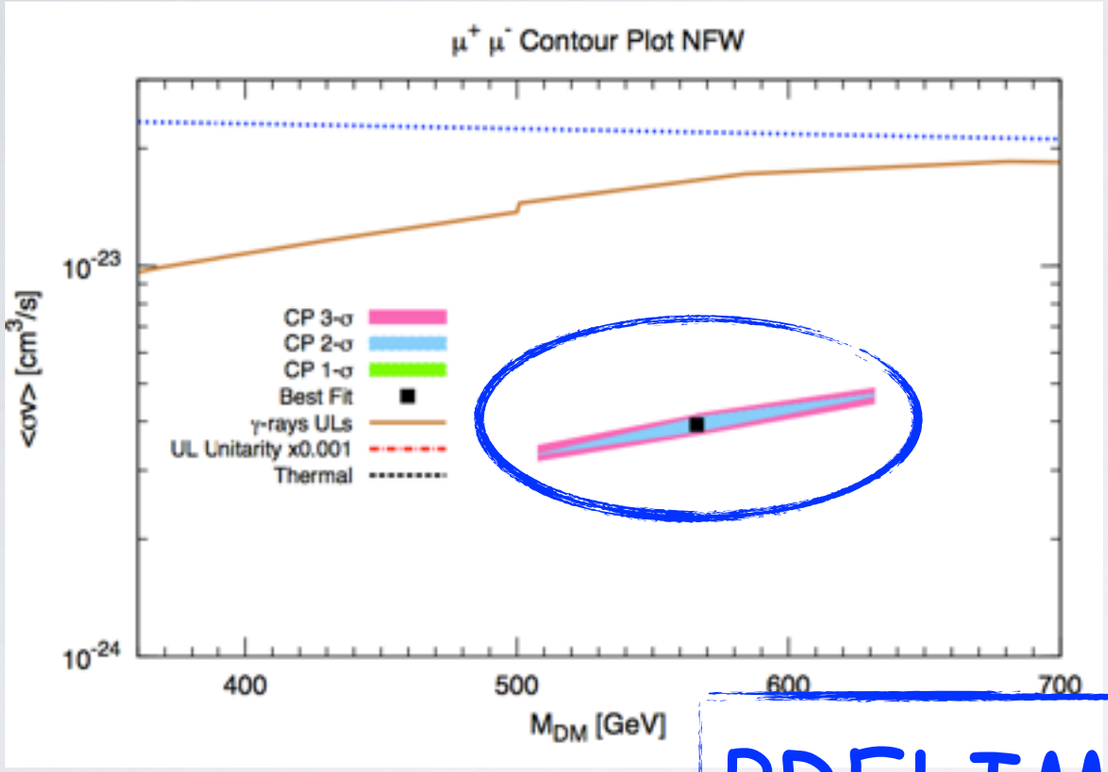
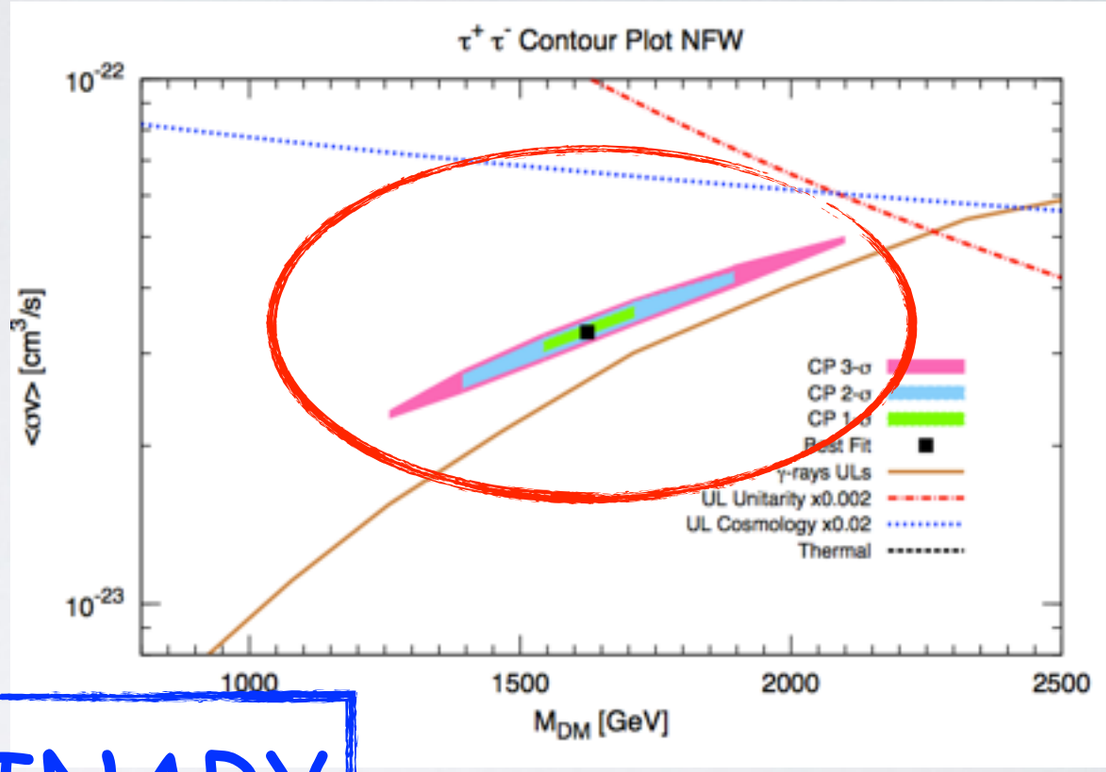
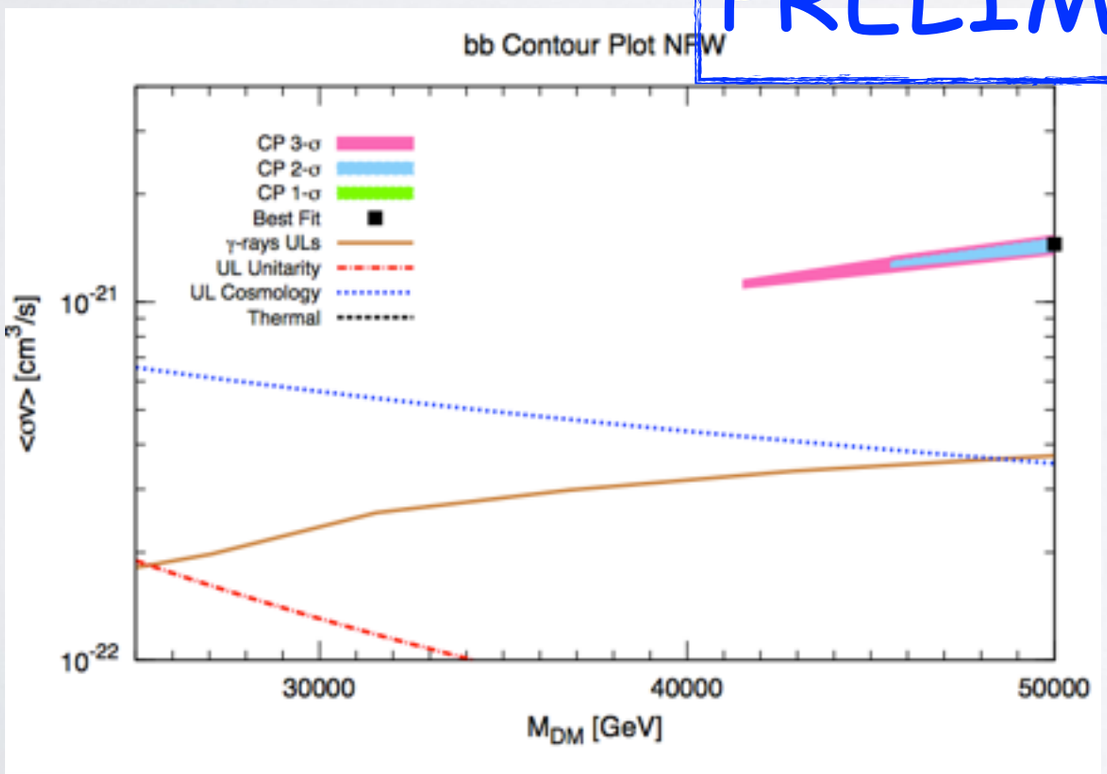
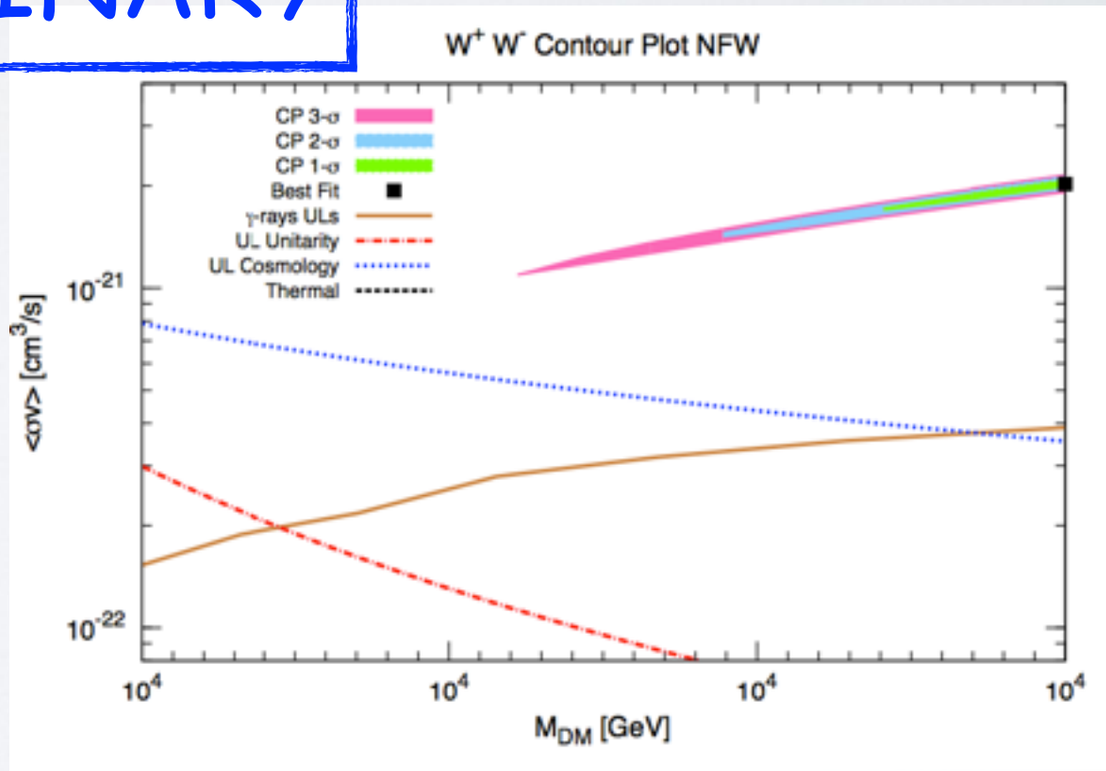




PRELIMINARY





CONCLUSIONS

- We have derived the emission of electrons and positrons from galactic PWNs, SNRs and secondary production.
- Distant and near SNRs could entirely explain AMS02 data of electrons spectrum.
- PWNs and secondary production could entirely explain the positron spectrum.
- Our model for SNRs, PWN and secondary production of electrons and positrons fully explains in the entire energy range the positrons, electrons, electrons+positrons and positron fraction AMS02 data.
- We have deduced that in the min/med/max contest for the propagation model the min and max models are disfavored.
- If only one PWN source contribute to the positron flux we have found that Geminga, J1741.2054 and B1742.30 have the correct parameter to fit AMS02 data.
- WIMP annihilating particles which produce electrons and positrons are severely constrained as DM particles.

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THANK YOU!!

Nicolao Fornengo

Dipartimento di Fisica,
Università di Torino,
INFN Torino

1) Interpretation of AMS-02 electrons and positrons data. M.D.M., F. Donato, N. Fornengo R. Lineros and A. Vittino. JCAP 1404 (2014) 006

2) Dark Matter constraints from electrons and positrons AMS-02 data. M.D.M., F. Donato, N. Fornengo R. Lineros and A. Vittino. In preparation.

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BACKGROUND

SOURCE ELECTRONS AND POSITRONS PROPAGATION

Assuming that spatial diffusion and energy losses are isotropic and homogeneous, the steady-state Green function in an infinite 3D space is:

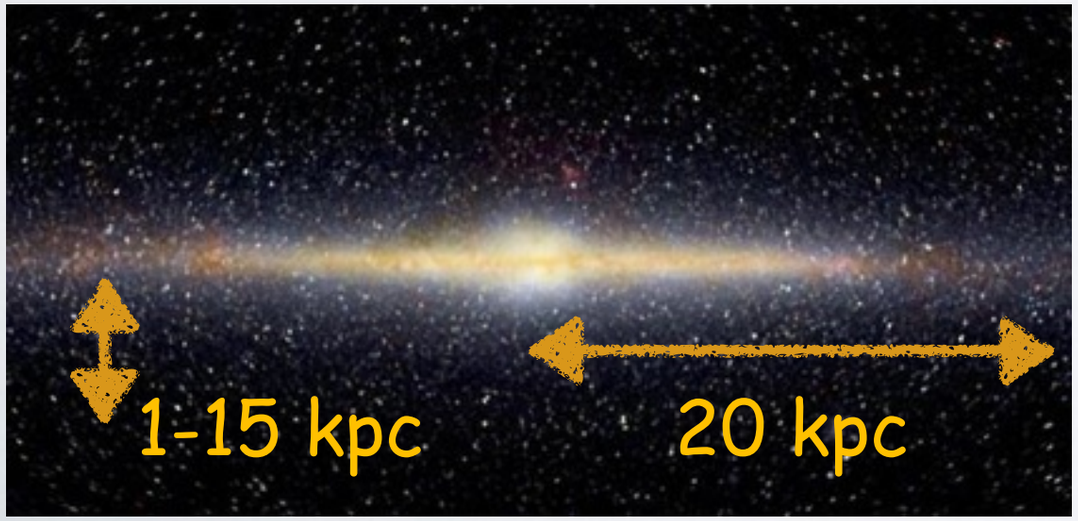
$$\widetilde{\mathcal{D}}_{\bar{t}}\,\mathcal{G} = \delta^3(\boldsymbol{x}-\boldsymbol{x}_s)\delta(E-E_s)$$

$$\mathcal{G}(\boldsymbol{x}, E \leftarrow \boldsymbol{x}_s, E_s) = \frac{1}{b(E)\,(\pi\,\lambda^2)^{\frac{3}{2}}}\exp\left\{\frac{(\boldsymbol{x}_s-\boldsymbol{x})^2}{\lambda^2}\right\}$$

$$b(E) \equiv -\frac{\mathrm{d}E}{\mathrm{d}t};\quad \lambda^2 \equiv 4\int_E^{E_s}\mathrm{d}E'\,\frac{K(E')}{b(E')}.$$

Interstellar (IS) flux at the Earth:

$$\phi_\odot(E) = \frac{\beta\,c}{4\,\pi} \times \iiint \mathrm{d}t_s\mathrm{d}E_s\mathrm{d}^3\boldsymbol{x}_s\,\mathcal{G}(E, \boldsymbol{x}_\odot \leftarrow t_s, E_s, \boldsymbol{x}_s)\,Q(t_s, E_s, \boldsymbol{x}_s).$$



Propagation parameters constrained by the MIN MED and MAX model:

Model	δ	K_0 (kpc^2/Myr)	L (kpc)	V_c (km/s)	V_A (km/s)
MIN	0.85	0.0016	1	13.5	22.4
MED	0.70	0.0112	4	12	52.9
MAX	0.46	0.0765	15	5	117.6

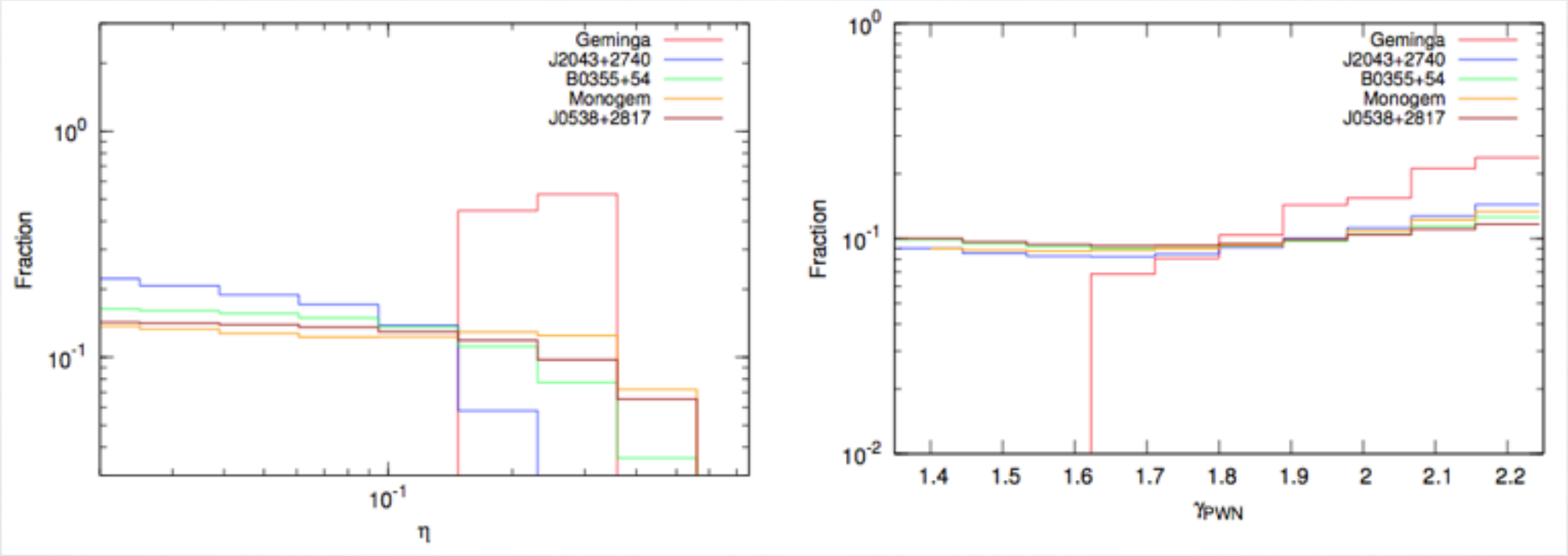
Donato Phys. Rev. D 69, 063501

Delahaye 2010 A&A 524, A51

MOST POWERFUL SOURCE ANALYSIS

- The rising of the positron fraction measured by AMS-02 and Pamela could be due to PWNs.
- Here we consider the five most powerful sources.
- We have varied the efficiency η and the index γ_{PWN} independently for each PWNs and we have found all the configurations which are compatible up to 3σ with the four spectra of electrons and positrons.

ATNF NAME	Ass. name	d[kpc]	T[kyr]	$W_0[10^{49}$ erg]
J0633+1746	Geminga	0.25	343	1.26
J2043+2740		1.13	1204	26.0
B0355+54		1	567	4.73
B0656+14	Monogem	0.28	112	0.178
J0538+2817		1.3	622	6.18



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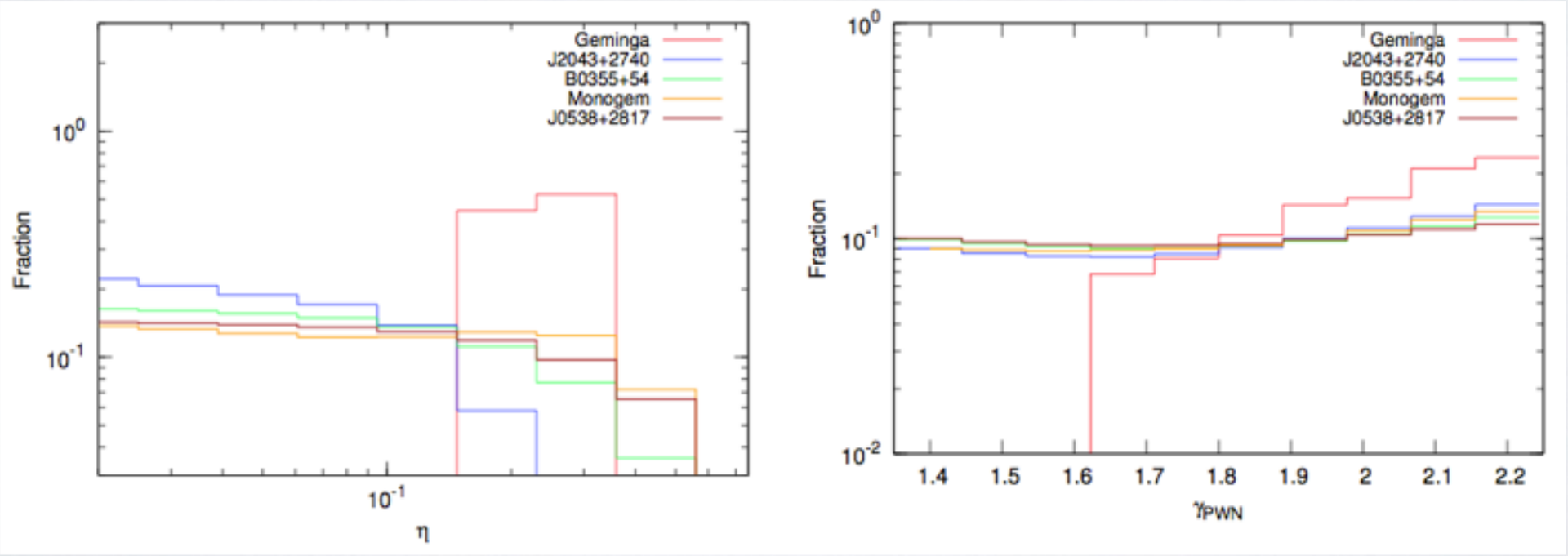
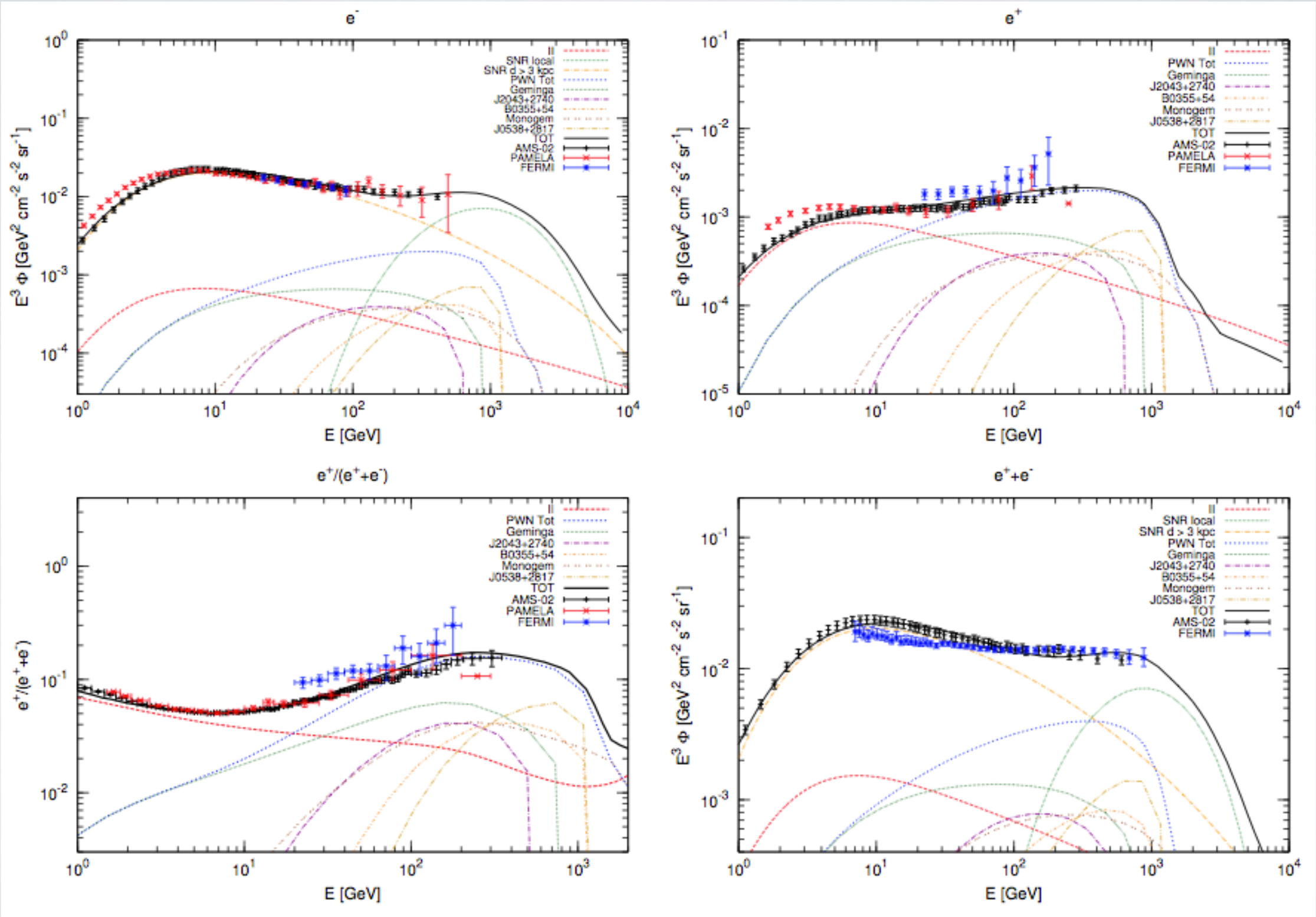
- **The efficiency distribution of Geminga in very narrow η=[0.12,0.4].**
- **The efficiency distribution of the other sources is broad.**

B0355+54	Monogem	1	567	4.73
B0656+14		0.28	112	0.178
J0538+2817		1.3	622	6.18

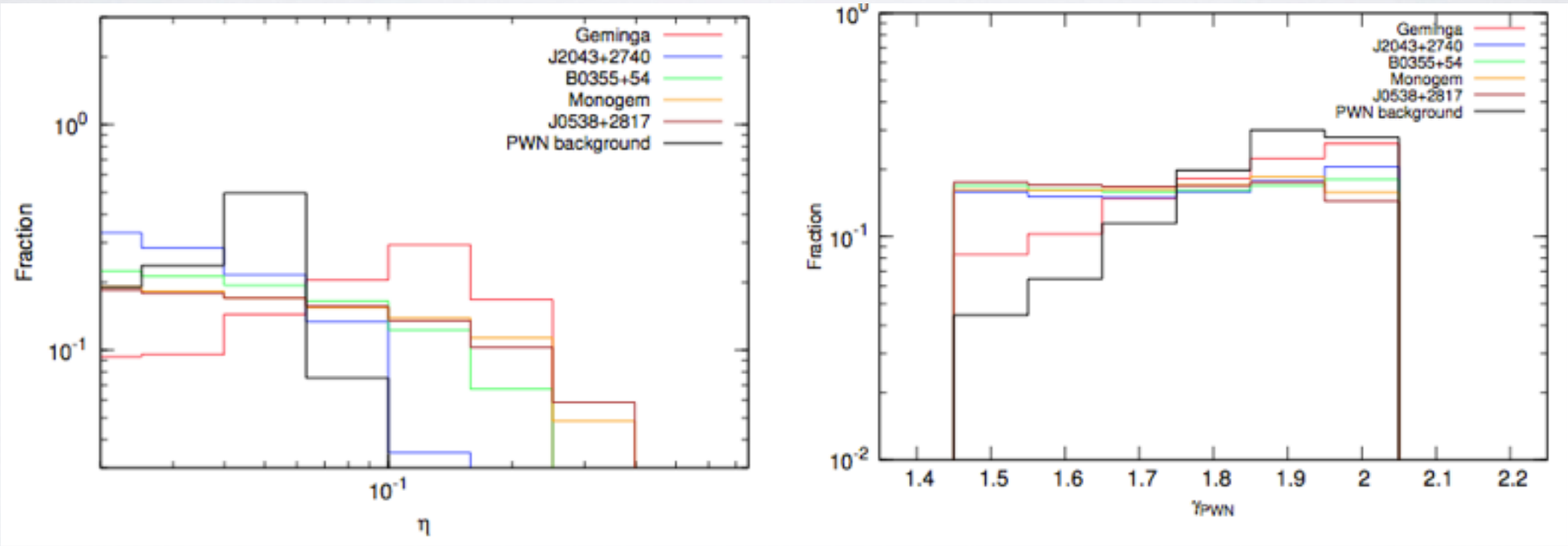


MOST POWERFUL SOURCE ANALYSIS ONE EXAMPLE



MOST POWERFUL SOURCE ANALYSIS + ATNF PWNS

- The rising of the positron fraction measured by AMS-02 and Pamela could be due to PWNs.
- Here we consider the five most powerful sources and all the other ATNF sources.
- We have varied the efficiency η and the index γ_{PWN} independently for each PWNs and we have found all the configurations which are compatible up to 3σ with the four spectra of electrons and positrons.



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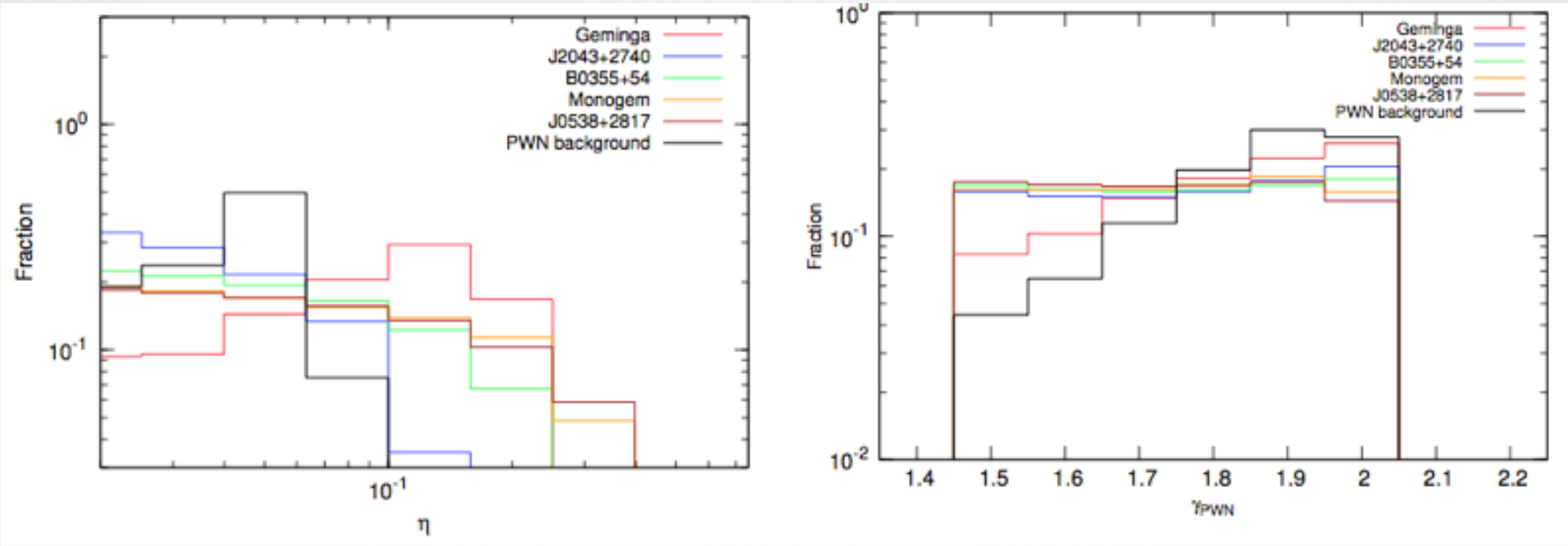
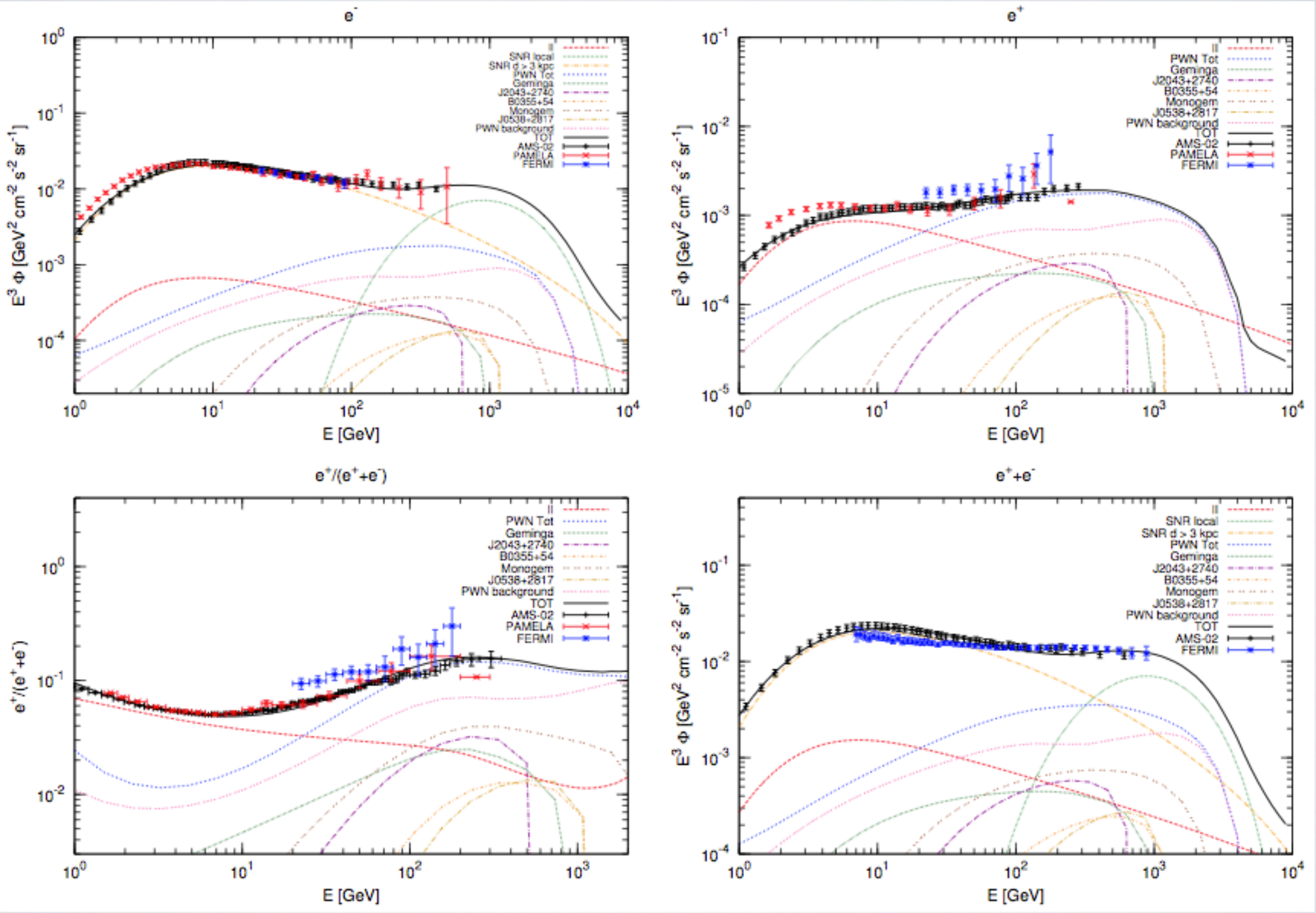
- We have varied the efficiency η and the index γ_{PWN} independently for each PWNs and we have found all the configurations which are compatible up to 3σ with the four spectra of electrons and

- **The efficiency distribution of Geminga is broader respect to the previous case.**
- **The efficiency distribution of the all the other sources of the ATNF catalog peaked at η = 0.04 near the best fit value**



MOST POWERFUL SOURCE AND ATNF PWNS ANALYSIS ONE EXAMPLE



2.5 YEARS

FIT WITH PRELIMINARY AMS-02 DATA