SCIPP
Santa Cruz Institute for Particle Physics

UC Santa Cruz

TASC

Stefano Profumo

UC Santa Cruz
Santa Cruz Institute for Particle Physics
T.A.S.C. [Theoretical Astrophysics, Santa Cruz]

Astrophysical Interpretation of the PAMELA and ATIC results

New Paradigms for Dark Matter
UC Davis, December 5-6, 2008

1. Brief Data Overview

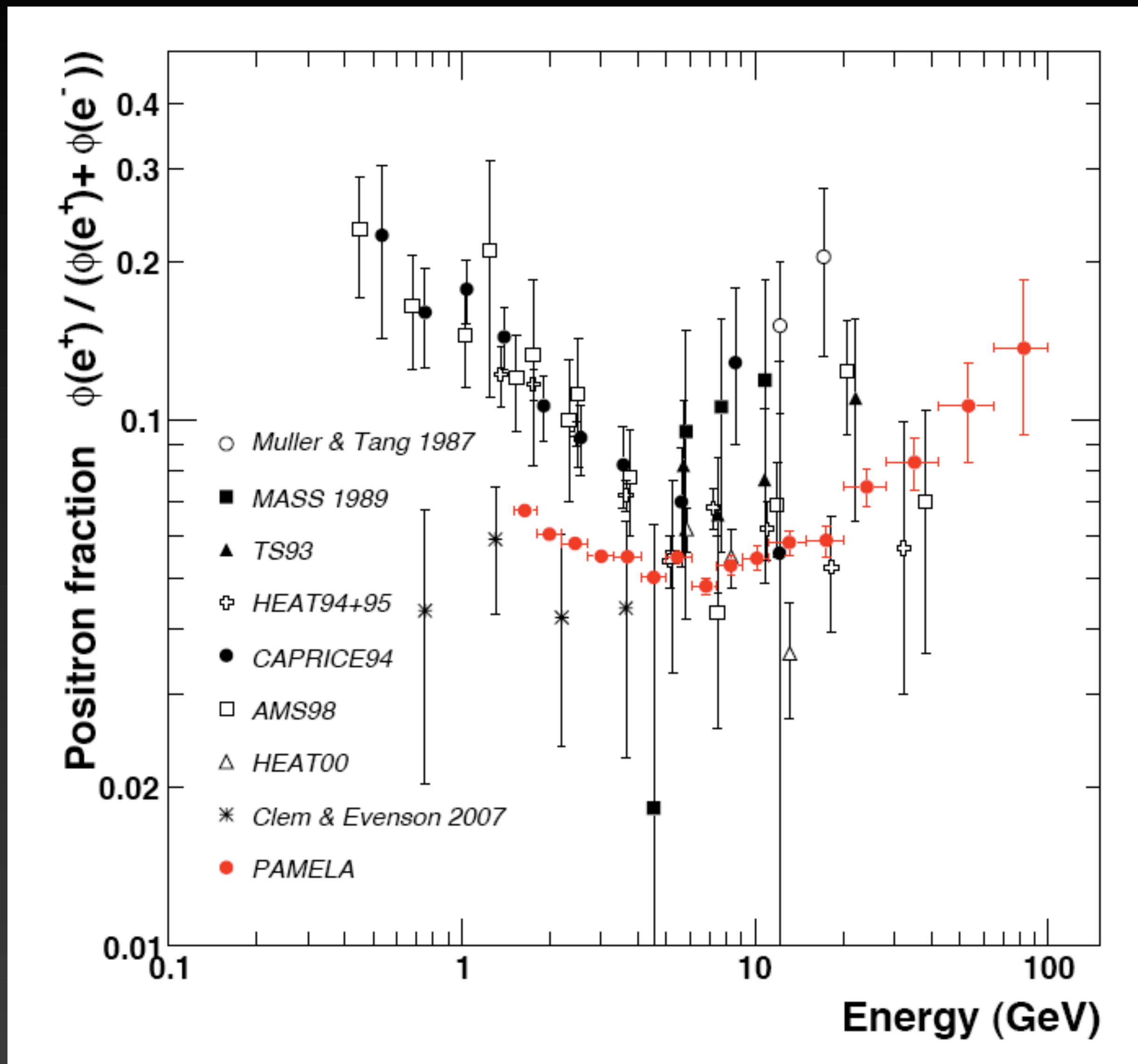
2. The Standard Story:
   secondary Cosmic-Ray e^+e^-, primary e^-

3. Astrophysical sources of primary e^+e^-

4. Putting all together

PaMeLa

a Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics



arXiv: 0810.4995

PaMeLa

a Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics

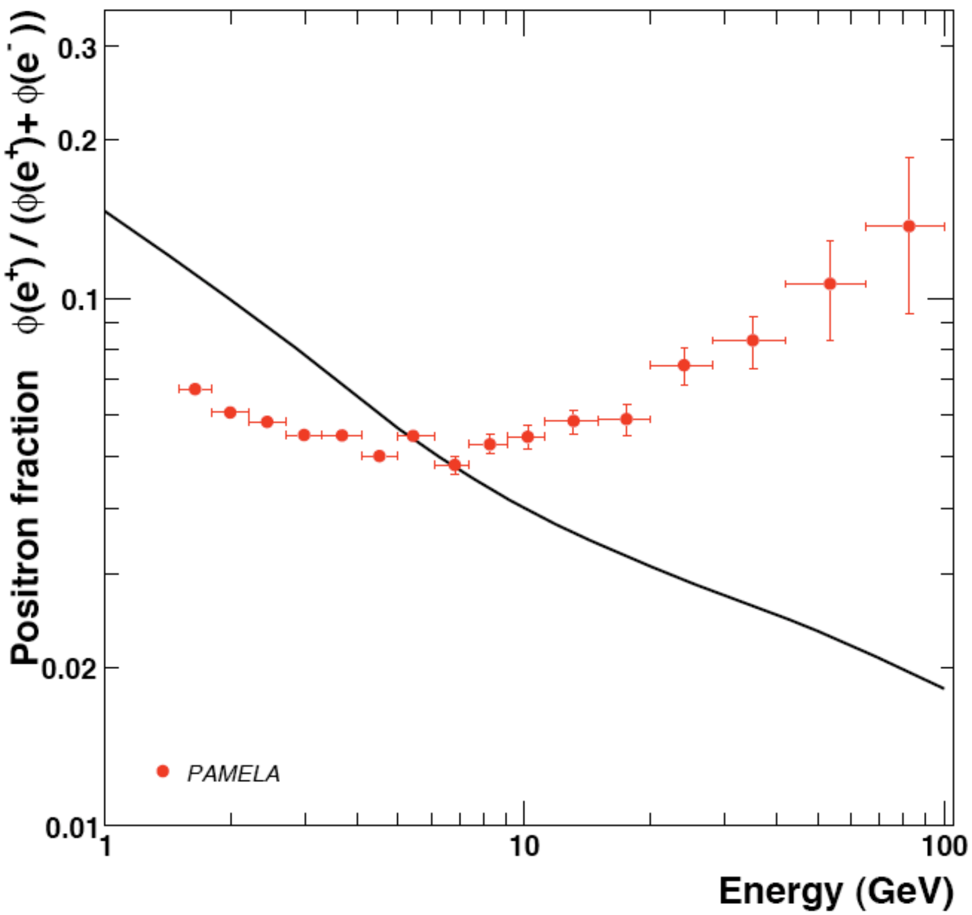
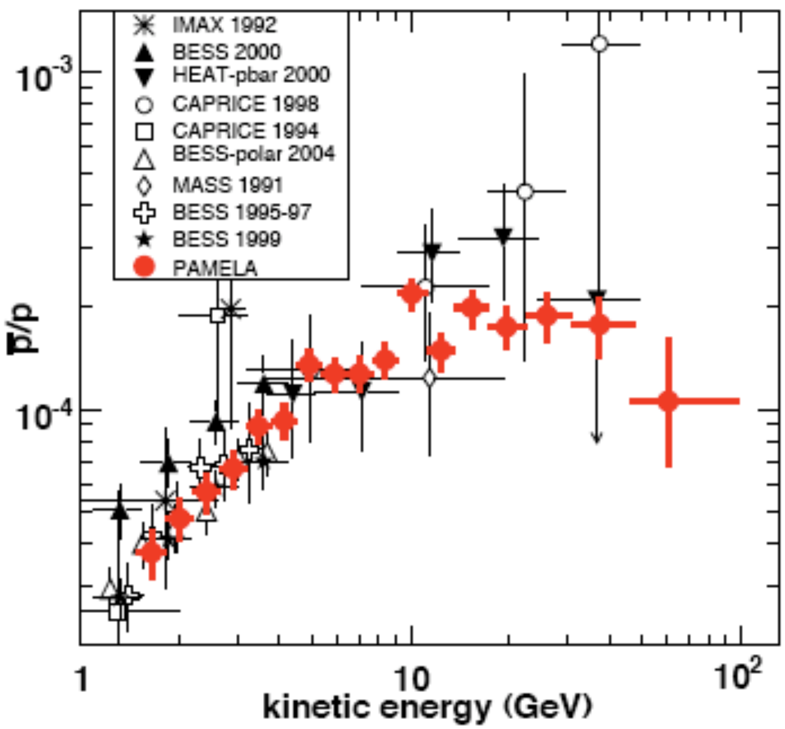


FIG. 4: **PAMELA positron fraction with theoretical models.** The PAMELA positron fraction compared with theoretical model. The solid line shows a calculation by Moskalenko & Strong[39] for pure secondary production of positrons during the propagation of cosmic-rays in the galaxy. One standard deviation error bars are shown. If not visible, they lie inside the data points.

arXiv: 0810.4995

PaMeLa a Payload for Antimatter Matter Exploration and Light–nuclei Astrophysics



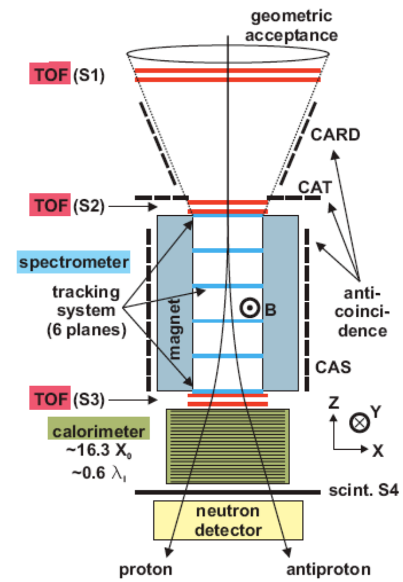
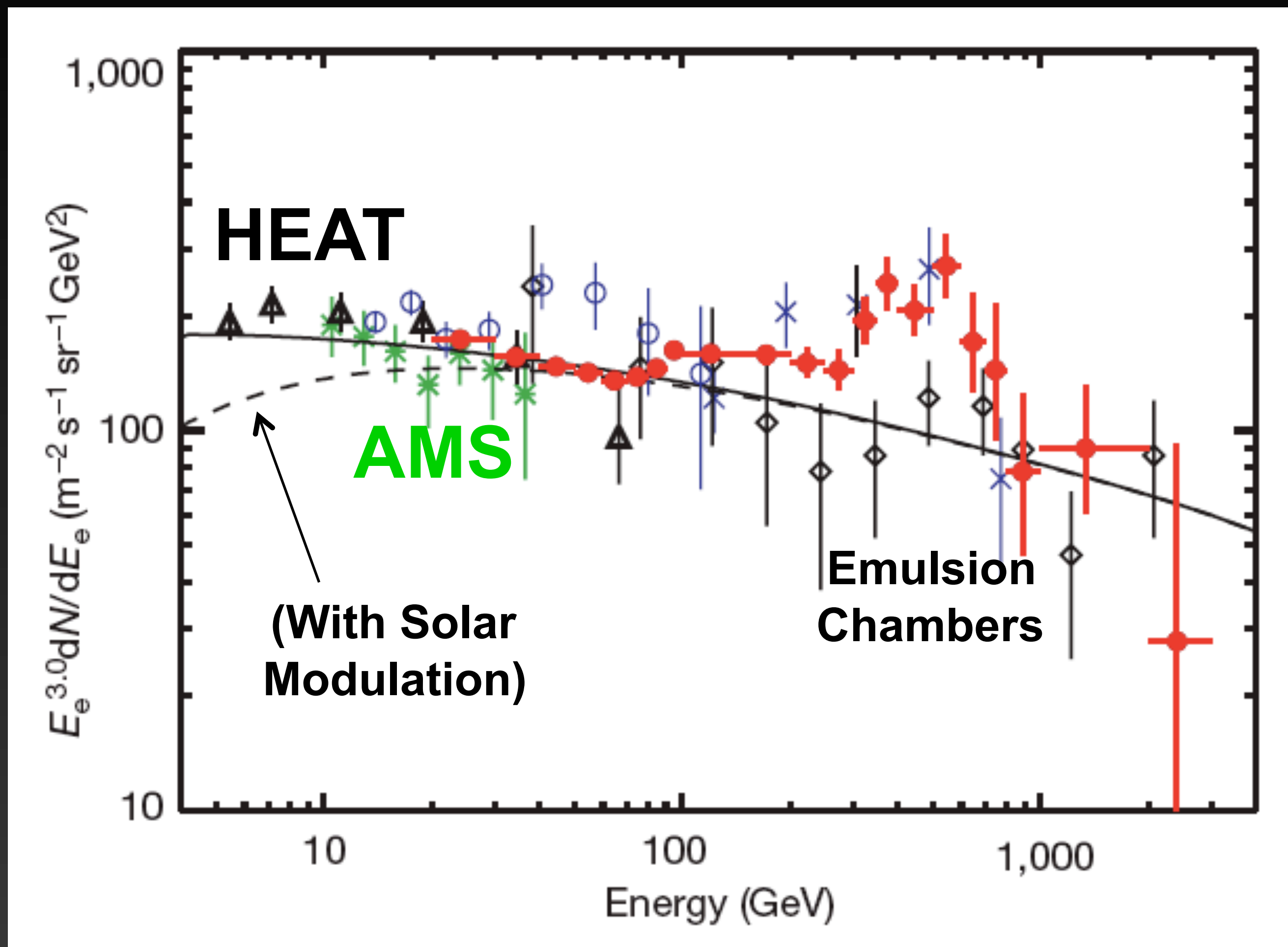


FIG. 1: Schematic overview of the PAMELA apparatus that is approximately 1.3 m high, has a mass of 470 kg and an average power consumption of 355 W. The magnetic field lines inside the spectrometer cavity are oriented along the y direction. The average value of the magnetic field is 0.43 T.

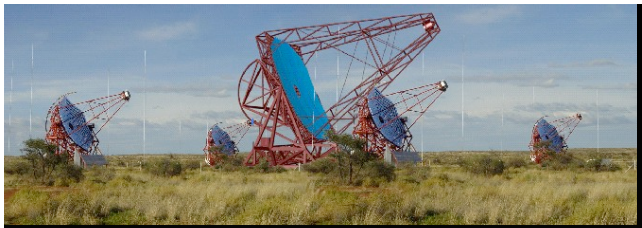
- Amazing improvement over old data
- Small payload, tricky positron/antiproton discrimination
- Any interpretation of positron data must be consistent with this!

$$r_g/\mathrm{m} = 3.3 \times \frac{p_\perp/(\mathrm{GeV/c})}{|Z|(B/\mathrm{T})}$$

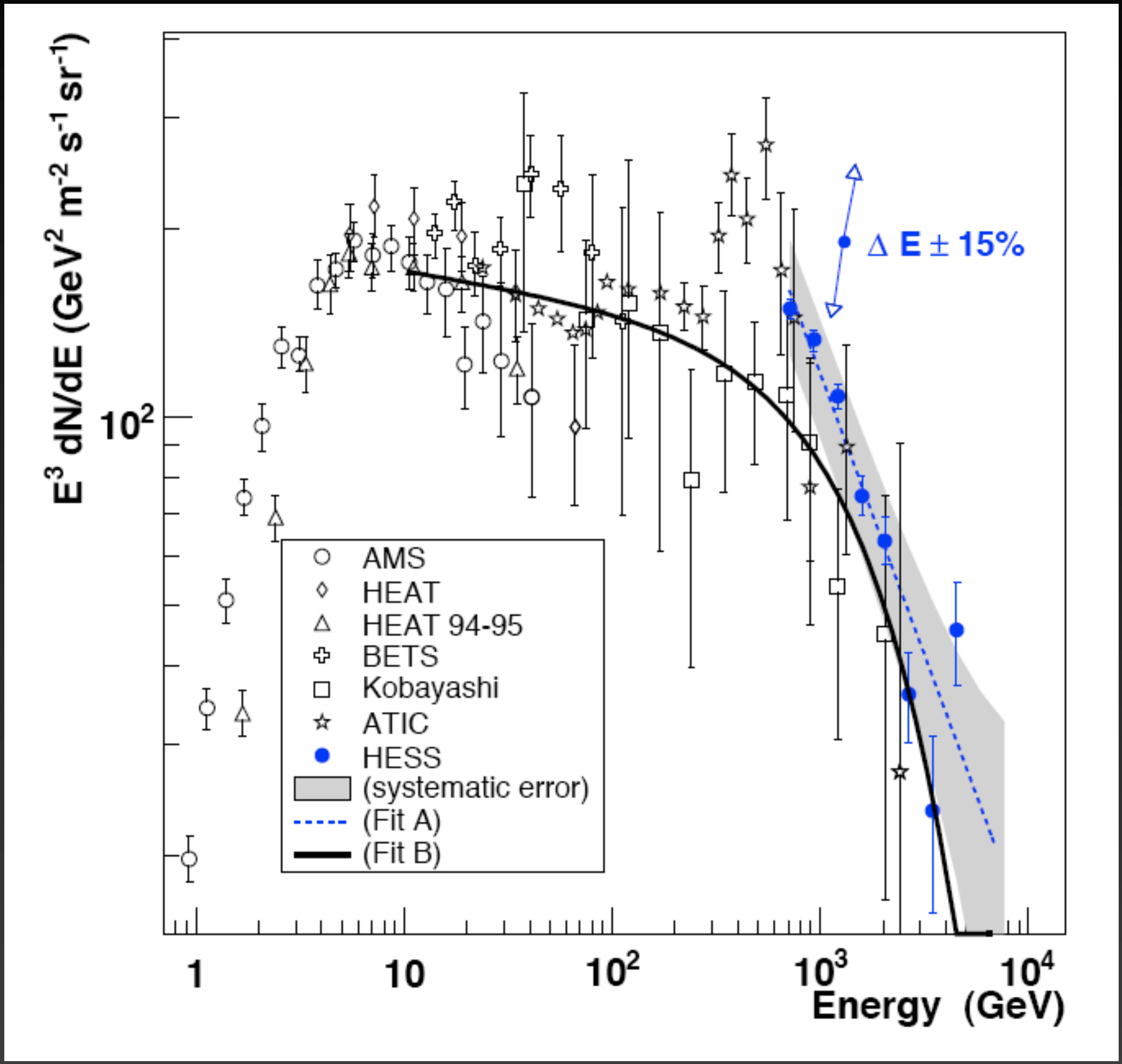
arXiv: 0810.4994



Nature, Nov 2008



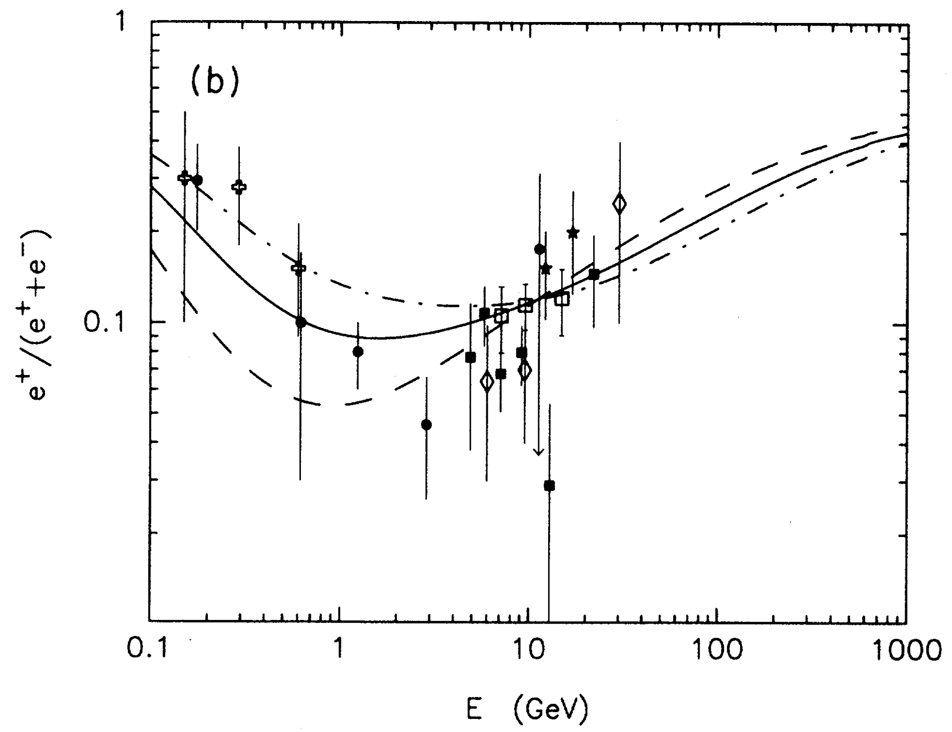
- EGRB plus CR electrons
- power-law, 3.9
- all data: power law (3.05) plus exp cutoff at 2.1 TeV

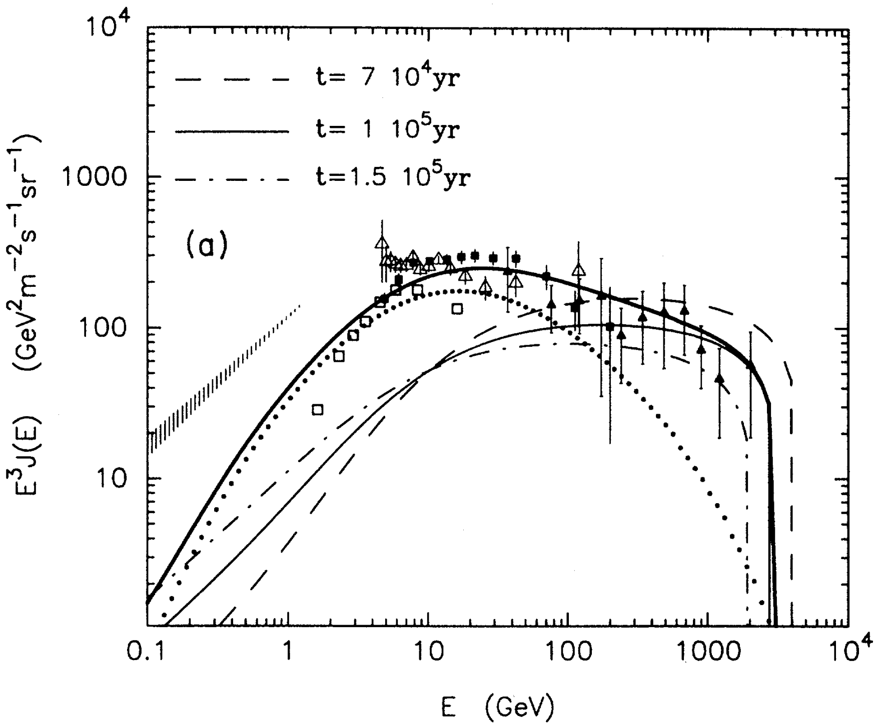


arXiv:0811.3894

"There Is Nothing New Under The Sun" ?

(*Qoheleth, 1:9*)





From Atoyan, Aharonian and Volk, PRD 52 (1995) 6:

"The measured content of positrons in the total electron flux [data from 1990] is regarded as a possible "enigma" awaiting an explanation […] it is obvious that some source of positrons is needed."

Not only do we have better data, we also have Fermi!

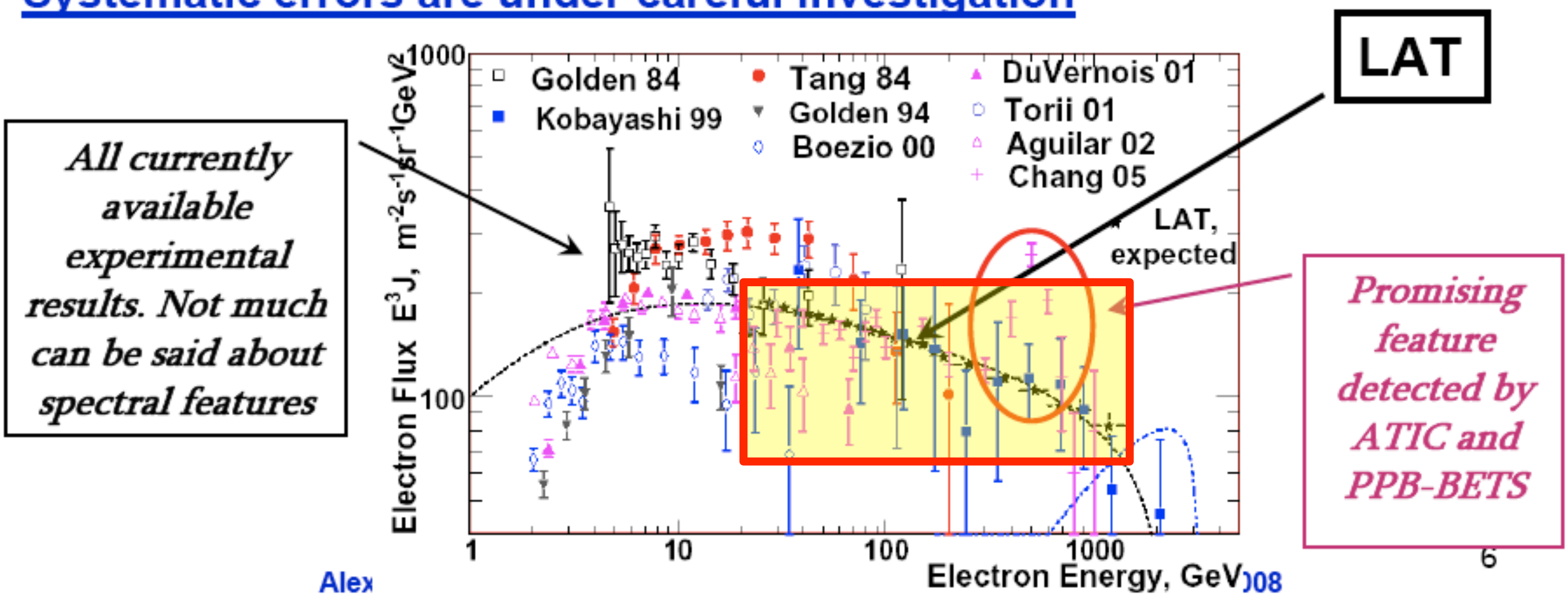
- We have shown that LAT can efficiently detect cosmic ray electrons from 20 GeV to ~1 TeV with ~3% residual contamination of hadrons (with respect to the number of detected electrons)
- The effective geometric factor after applying our electron selections is ~1 m^2sr and energy resolution (σ) is 5-20% depending on the energy (compare with ~0.06 m^2sr for Pamela "calorimeter only" mode)

Fermi Gamma-ray Space Telescope

[slide from Alex Moiseev]

- LAT will be able to **precisely reconstruct the electron spectrum** in 20 GeV – 1 TeV energy range. We are working on extending this range in both directions

- **LAT should detect > 10^7 electrons above 20 GeV (> 2,500 above 500 GeV) per year of operation.** ***Excellent statistics, never achieved before.*** **Systematic errors are under careful investigation**



[slide from Alex Moiseev]

Secondary e^+e^- from primary CR protons colliding with nuclei in the interstellar medium

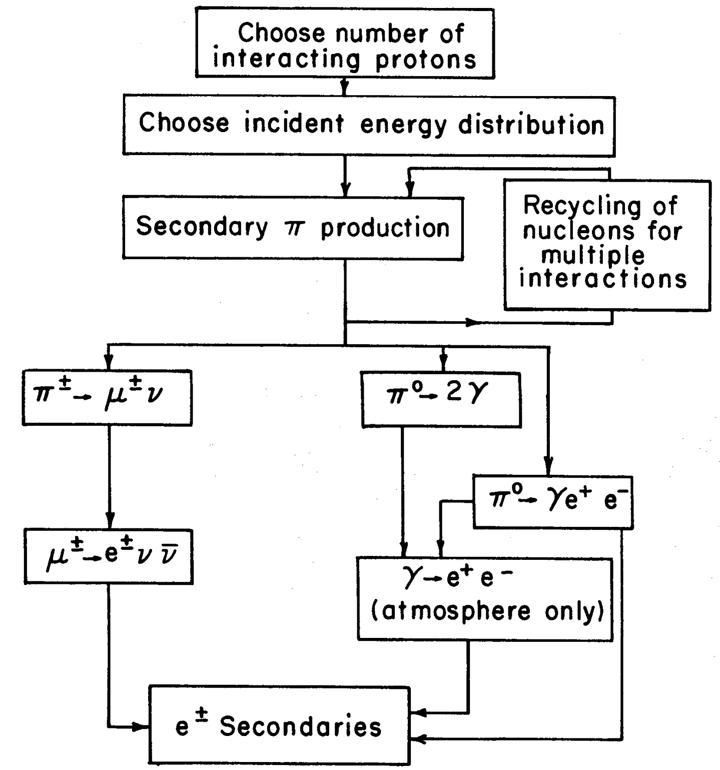
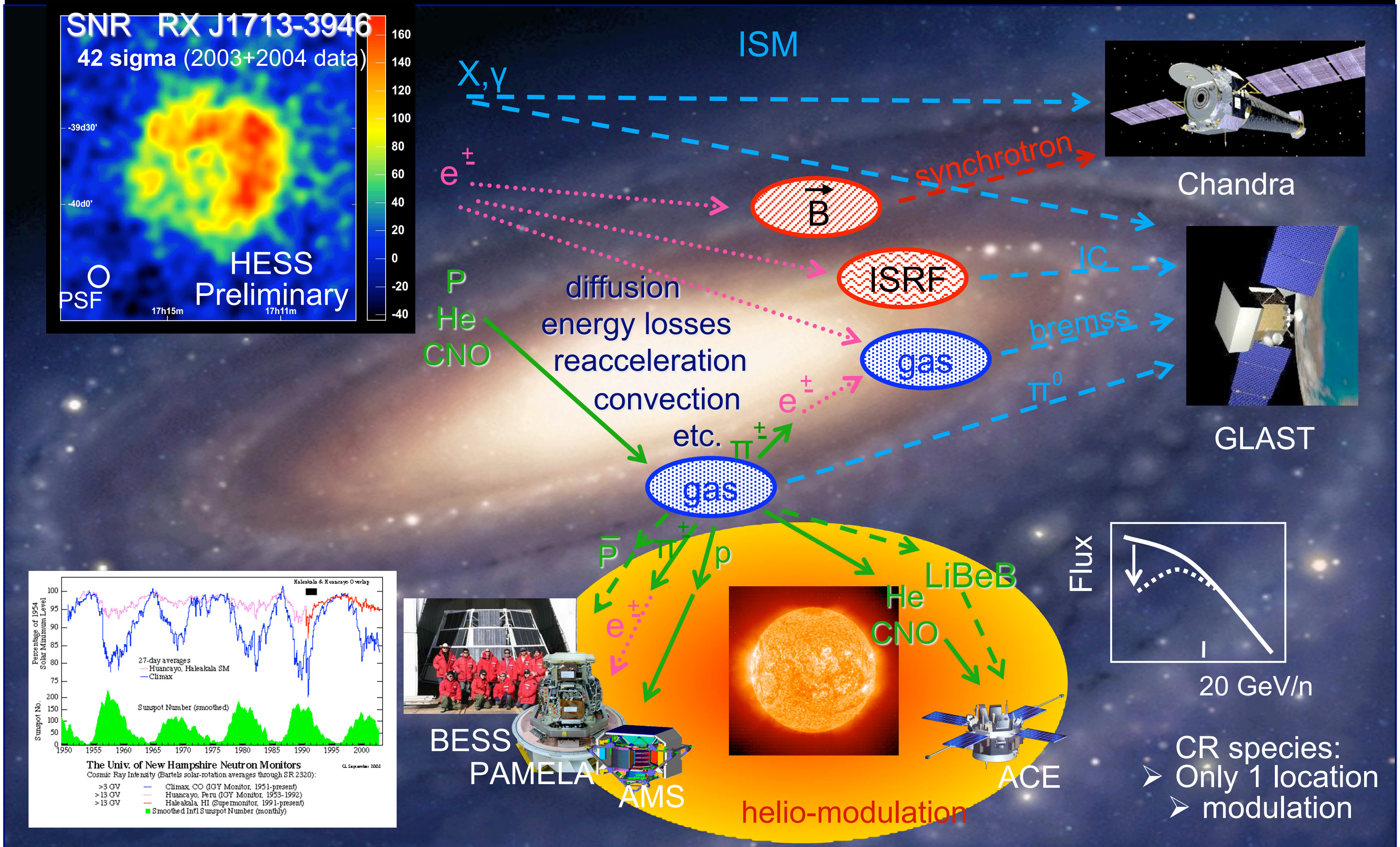


FIG. 7.—Flow diagram for the Monte Carlo program

Diffusion is self-consistently treated (e.g. studying the secondary-to-primary ratio B/C, the H and He abundance diffuse gamma-ray and X-ray data)

An old industry: from early codes (Orth and Buffington, 1976) to complex numerical suites (e.g. Galprop)

Primary electrons: injection specral index of 2.1 below 10 GeV, 2.4 above 10 GeV, consistently with direct measures, gamma-ray data and synchrotron radiation studies



[slide from Igor Moskalenko]

Main feature of high-energy e^+e^-: they loose energy very efficiently

Energy losses ~ E^2, via synchrotron and inverse Compton

$$\frac{t_{\rm Liftime}}{yr} \approx 5\times 10^5 \left(\frac{1\ \rm TeV}{E}\right)\left[\left(\frac{B}{5\ \mu \rm G}\right)^2 + 1.6\times\left(\frac{w}{1\ \rm eV/cm^3}\right)\right]^{-1}$$

In conjunction with the conventional CR diffusion coefficient, this short radiative cooling time limits the sources of high energy electron/positron both in space and time

Astrophysical sources must be young (~10^5 yr) and nearby (<kpc)

Approximate solution to the electron/positron distribution function(*)

(only IC and Synch losses)

$$f(r,t,\gamma) = \frac{N_0\gamma^{-\alpha}}{\pi^{3/2}r^3}(1 - p_2 t\gamma)^{\alpha-2}\left(\frac{r}{r_{\rm dif}}\right)^3 e^{-(r/r_{\rm dif})^2}$$

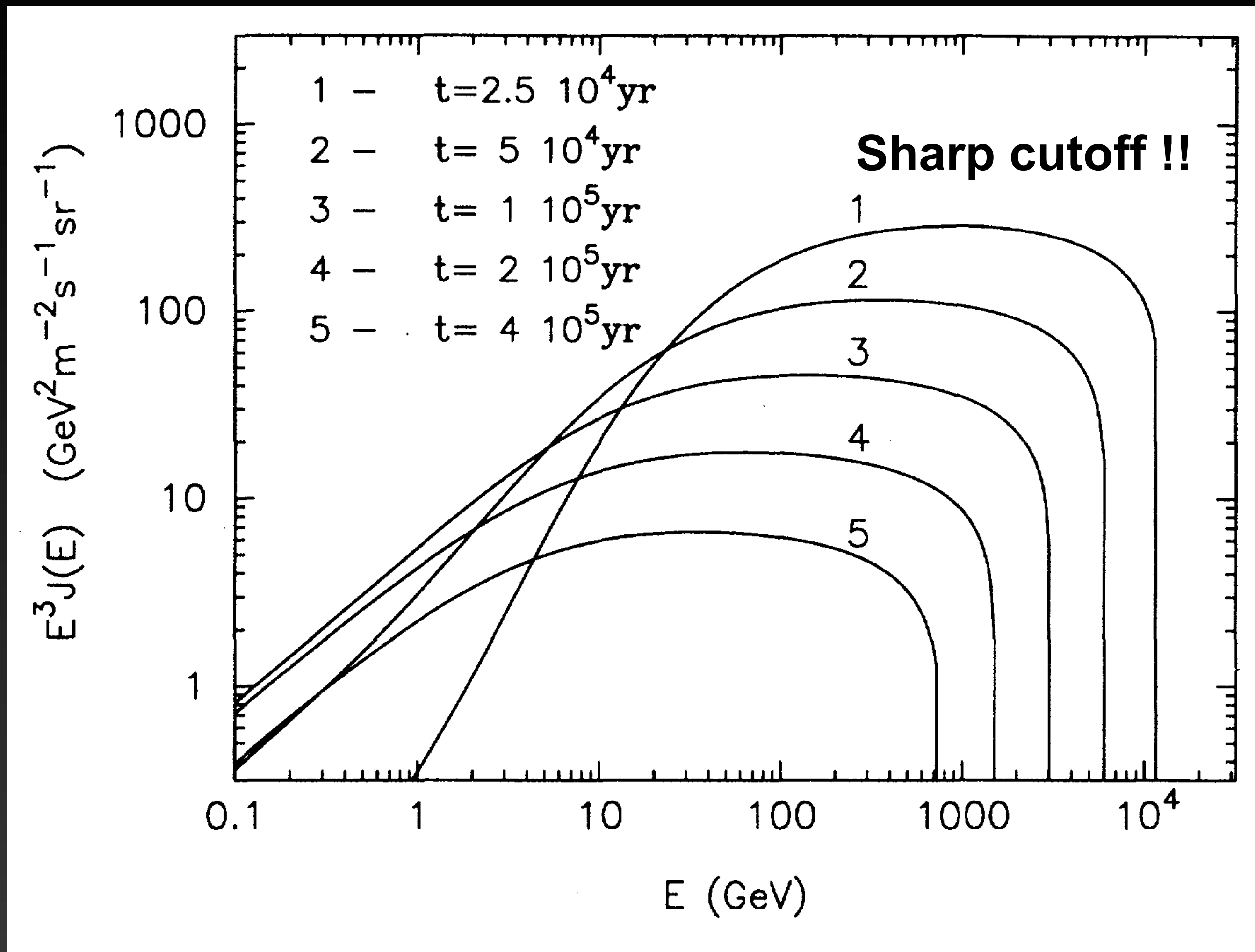
$$\gamma < \gamma_{\rm cut} \equiv \gamma_{\rm cut}(t) = (p_2 t)^{-1}$$

$$p_2 = 5.2\times 10^{-20}\frac{w_0}{1\ {\rm eV/cm^3}}\ {\rm s}^{-1}$$

$$r_{\rm dif}(\gamma,t) \simeq 2\sqrt{D(\gamma)t\frac{1-(1-\gamma/\gamma_{\rm cut})^{1-\delta}}{(1-\delta)\gamma/\gamma_{\rm cut}}}.$$

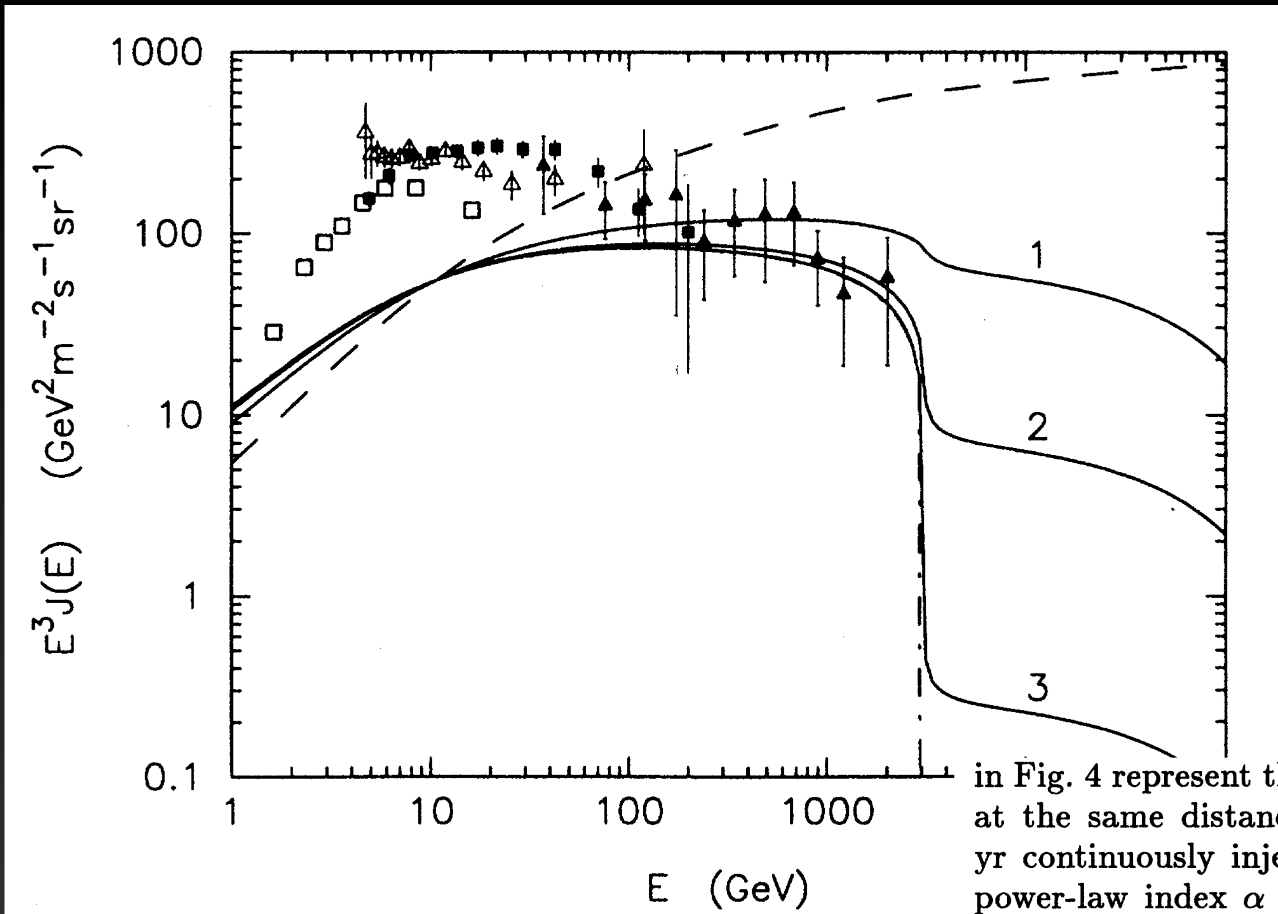
(*) Atoyan, Aharonian, Volk, 1995

Example of a burst-like injection at different times, r=100 pc, injection power-law:2.2



(*) Atoyan, Aharonian, Volk, 1995

The effects of a non-burst-like injection



in Fig. 4 represent the fluxes of electrons from the source at the same distance $r = 100$ pc and of age $t = 10^5$ yr continuously injecting relativistic electrons with the power-law index $\alpha = 2.2$ into ISM, but with the total luminosity varying in time during $0 \leq \tau \leq t$ as

$$L_e(\tau) = \frac{L_0}{(1 + \tau/\tau_*)^k} \qquad (24)$$

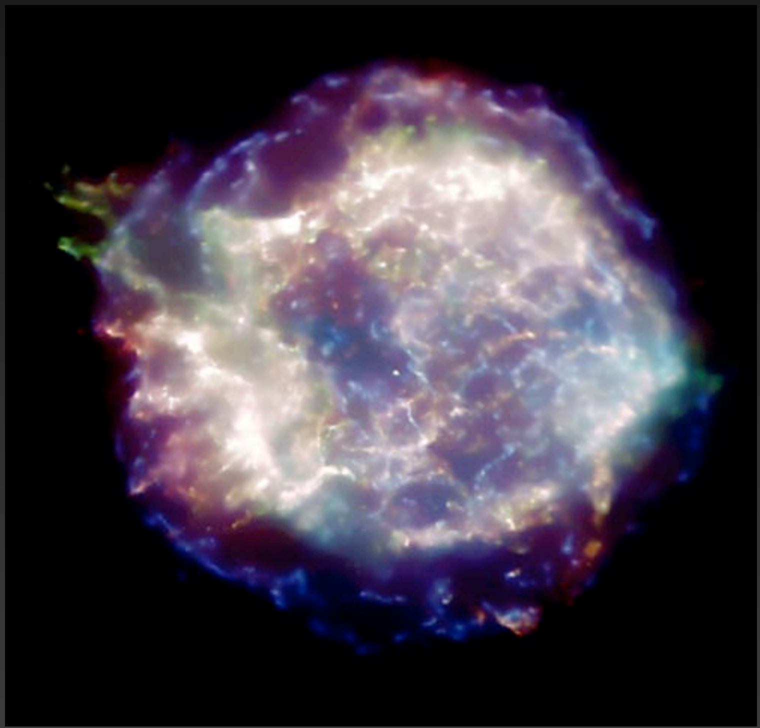
for three different values of the characteristic "decay" time τ_*: $\tau_*/t = 0.1$ (curve 1), $\tau_*/t = 0.01$ (curve 2), $\tau_*/t = 0.001$ (curve 3). This kind of time-dependent in-

(*) Atoyan, Aharonian, Volk, 1995

(existing) nearby sources of CRE's: SNR/Pulsars

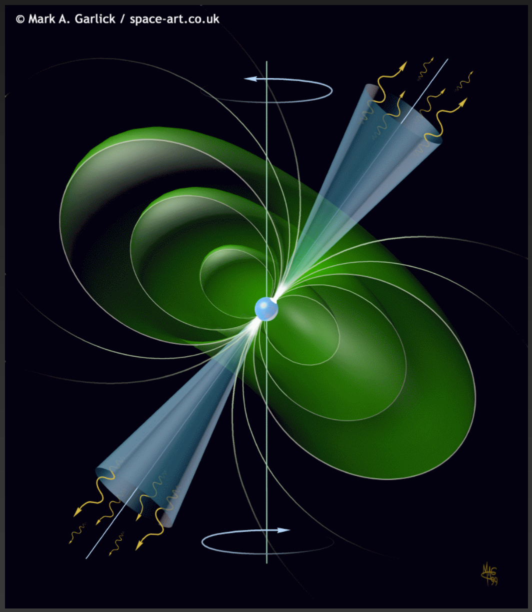
- **SNR shock acceleration**

(MHD turbolence, with maximal energy limited by SNR age, free escape or synchro losses, at 10-100 TeV)



- **Pulsar Direct (e+e-) direct pair acceleration**

(rotationally induced electric field in the magnetoshpere sufficient to drive pair cascades, which then escape the magnetosphere from the polar cap regions)



Which objects are out there? A partial list:

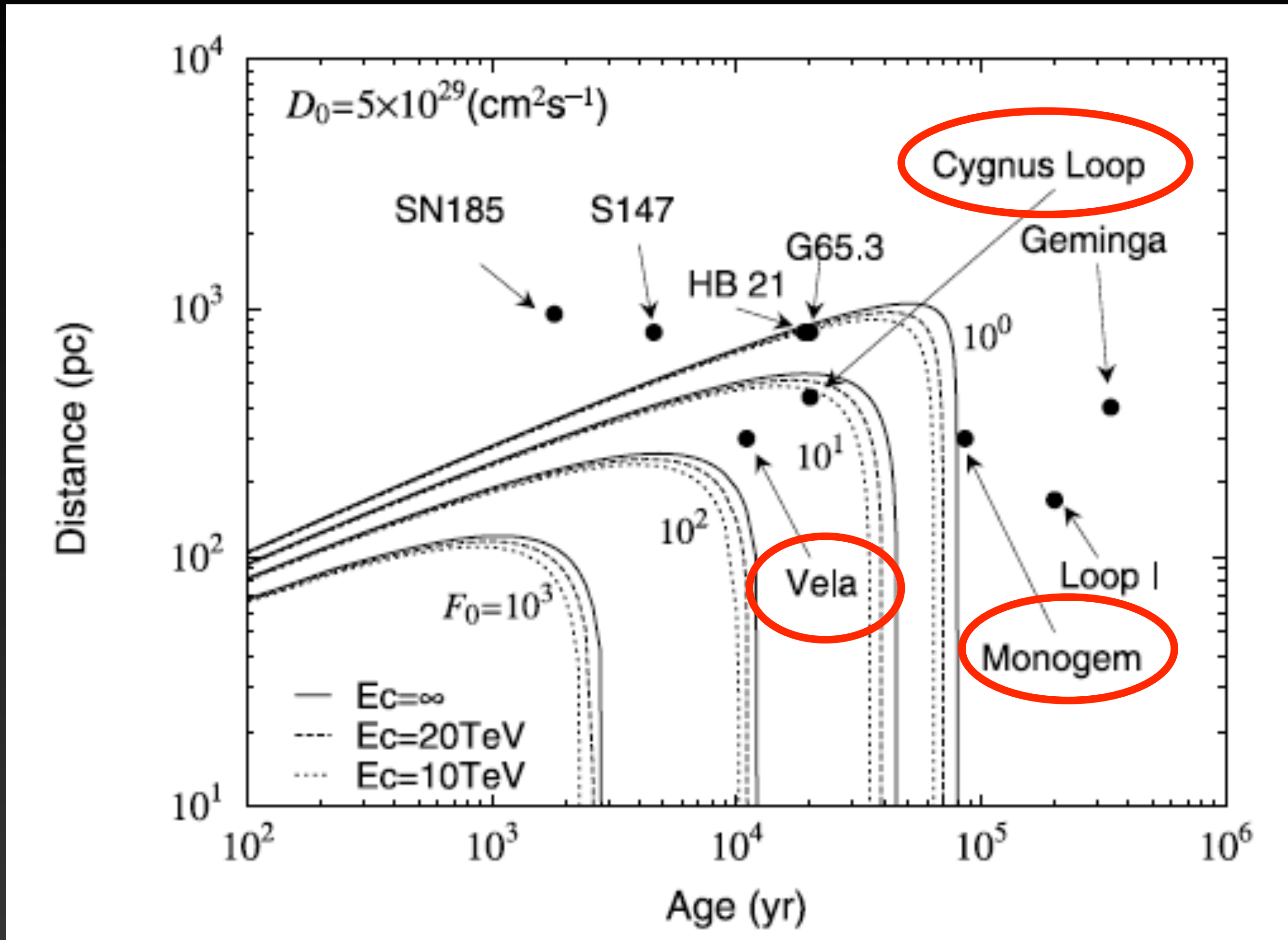
TABLE 1

List of Nearby SNRs

SNR	Distance (kpc)	Age (yr)	E_{max} [a] (TeV)	Reference
SN 185	0.95	1.8×10^3	1.7×10^2	1
S147	0.80	4.6×10^3	63	2
HB 21	0.80	1.9×10^4	14	3, 4
G65.3+5.7	0.80	2.0×10^4	13	5
Cygnus Loop	0.44	2.0×10^4	13	6, 7
Vela	0.30	1.1×10^4	25	8
Monogem	0.30	8.6×10^4	2.8	9
Loop1	0.17	2.0×10^5	1.2	10
Geminga	0.4	3.4×10^5	0.67	11

Kobayashi et al, ApJ 2004

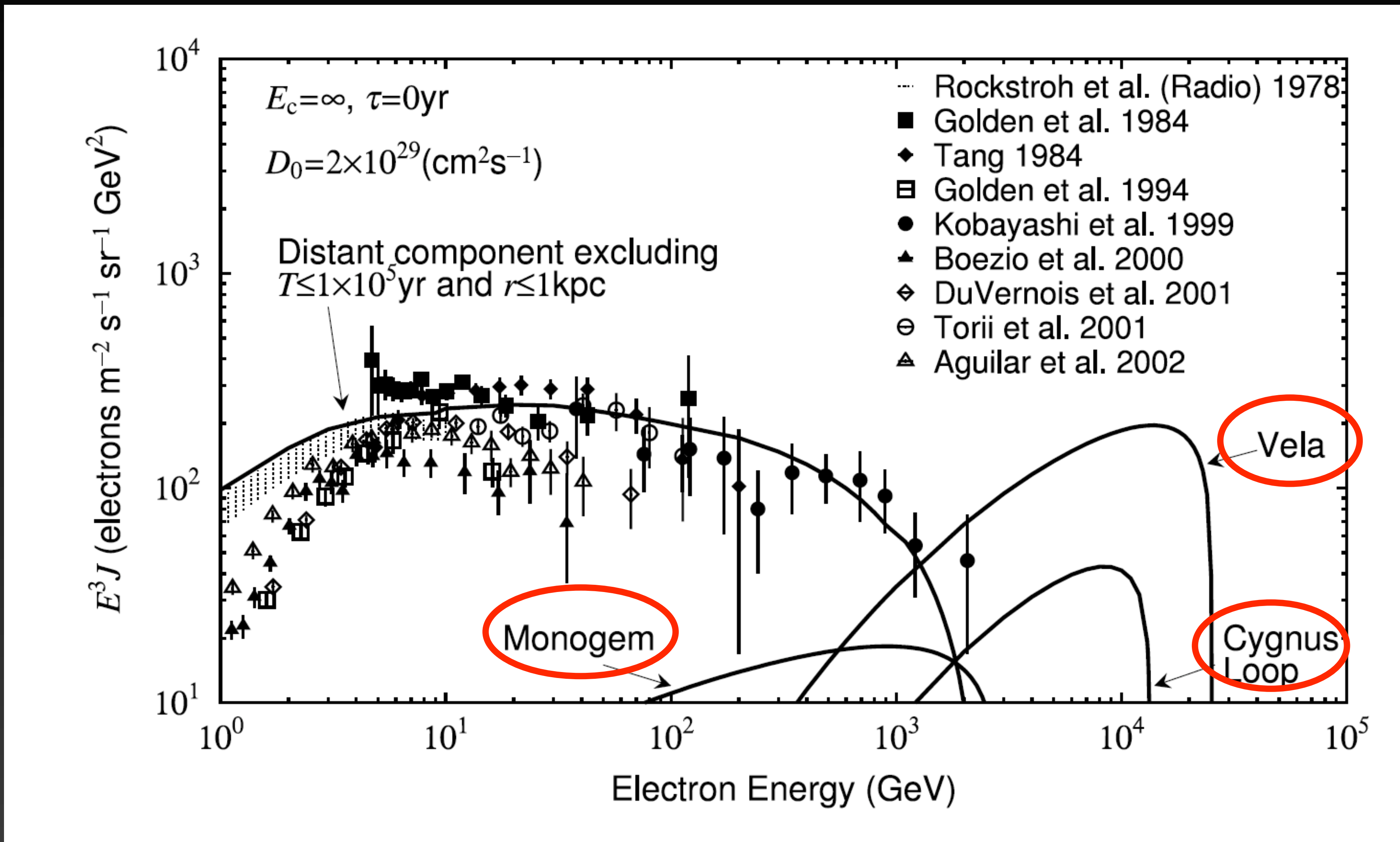
Which objects are out there?



Contours of constant e^+e^- flux at 3 TeV, with differenct cut-offs

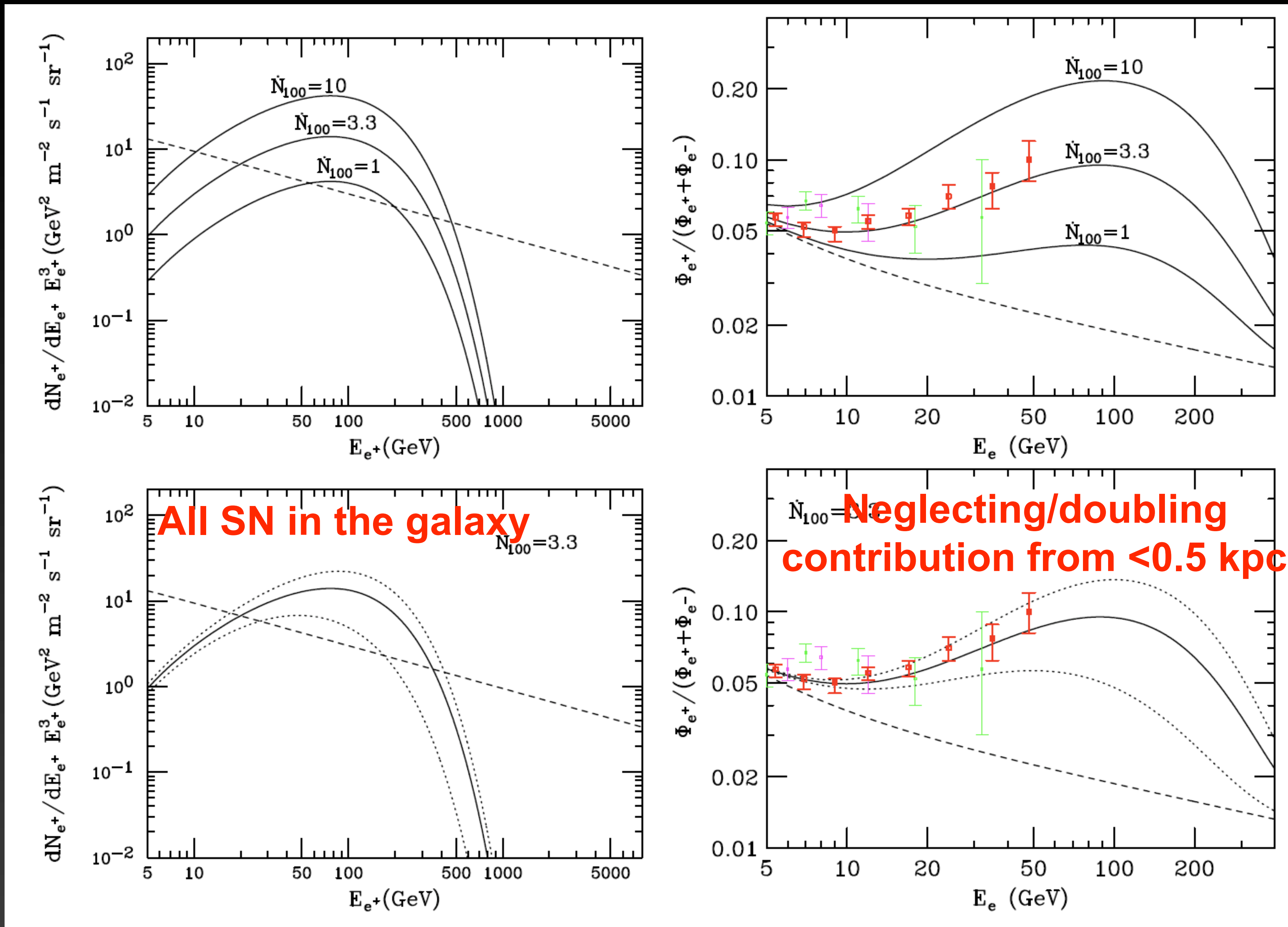
Kobayashi et al, ApJ 2004

Example of predicted e+e- spectra
(probably not consistent with the HESS data!)

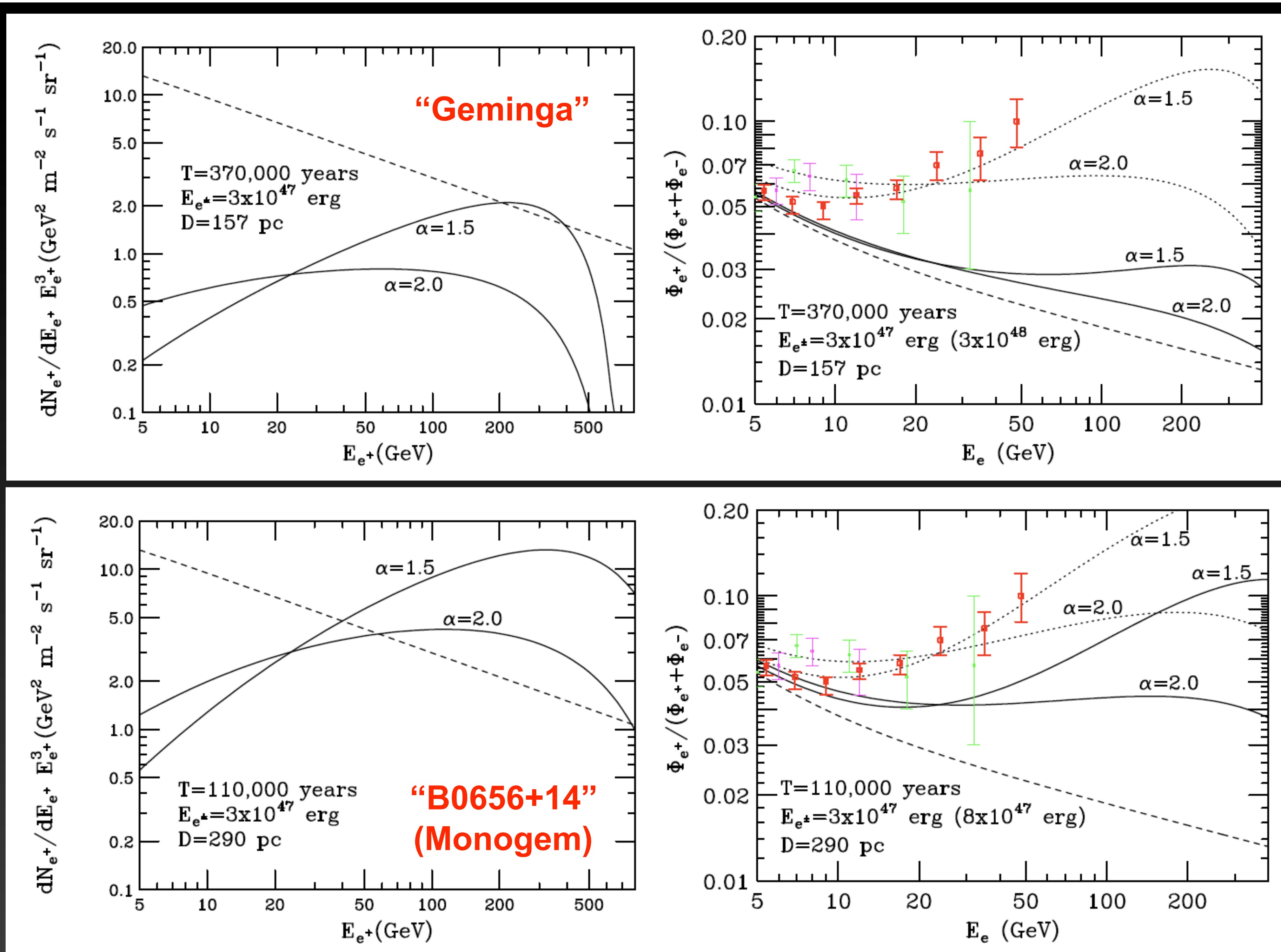


Kobayashi et al, ApJ 2004

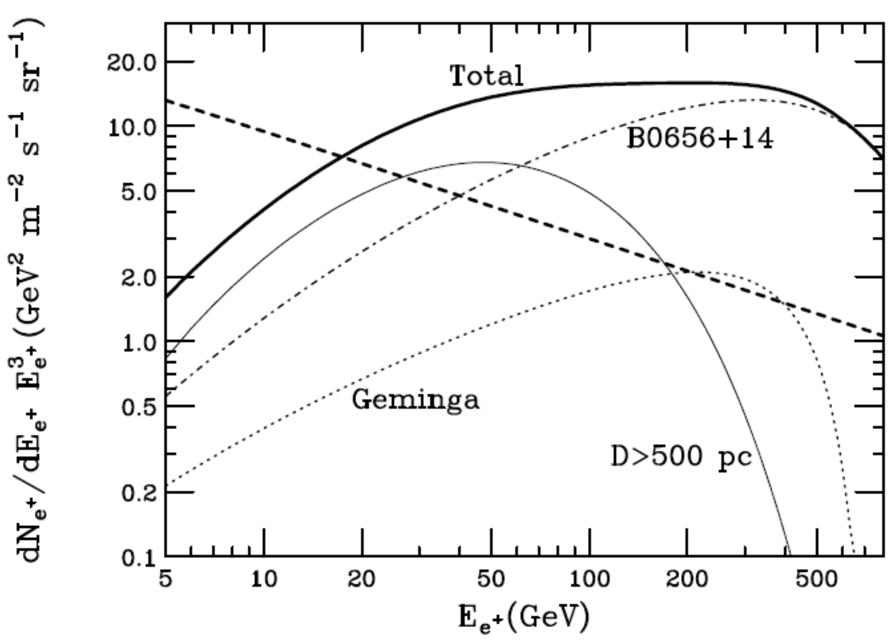
Same type of analysis applied to Pamela data

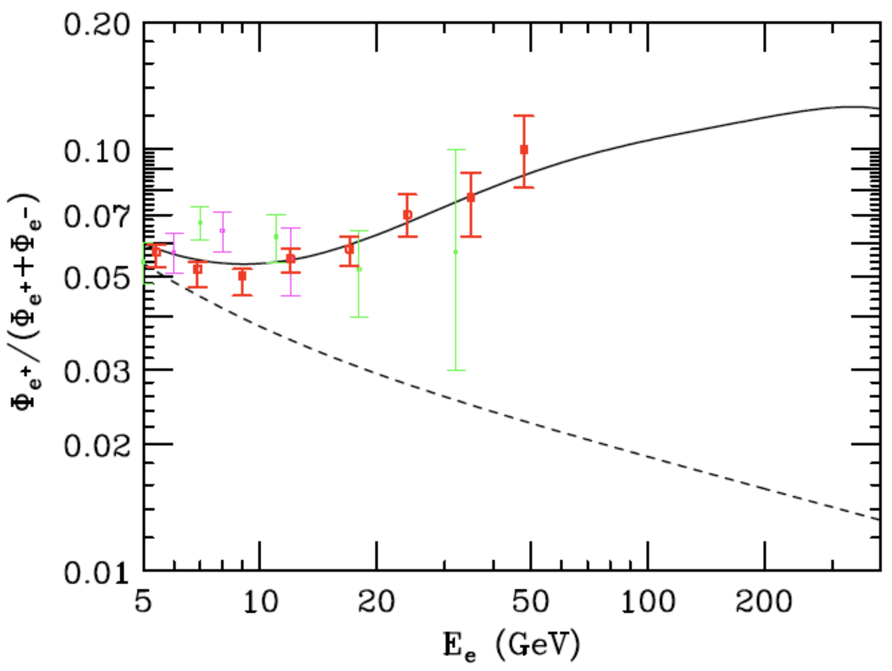


Hooper, Blasi, Serpico, 0810.1527



Hooper, Blasi, Serpico, 0810.1527





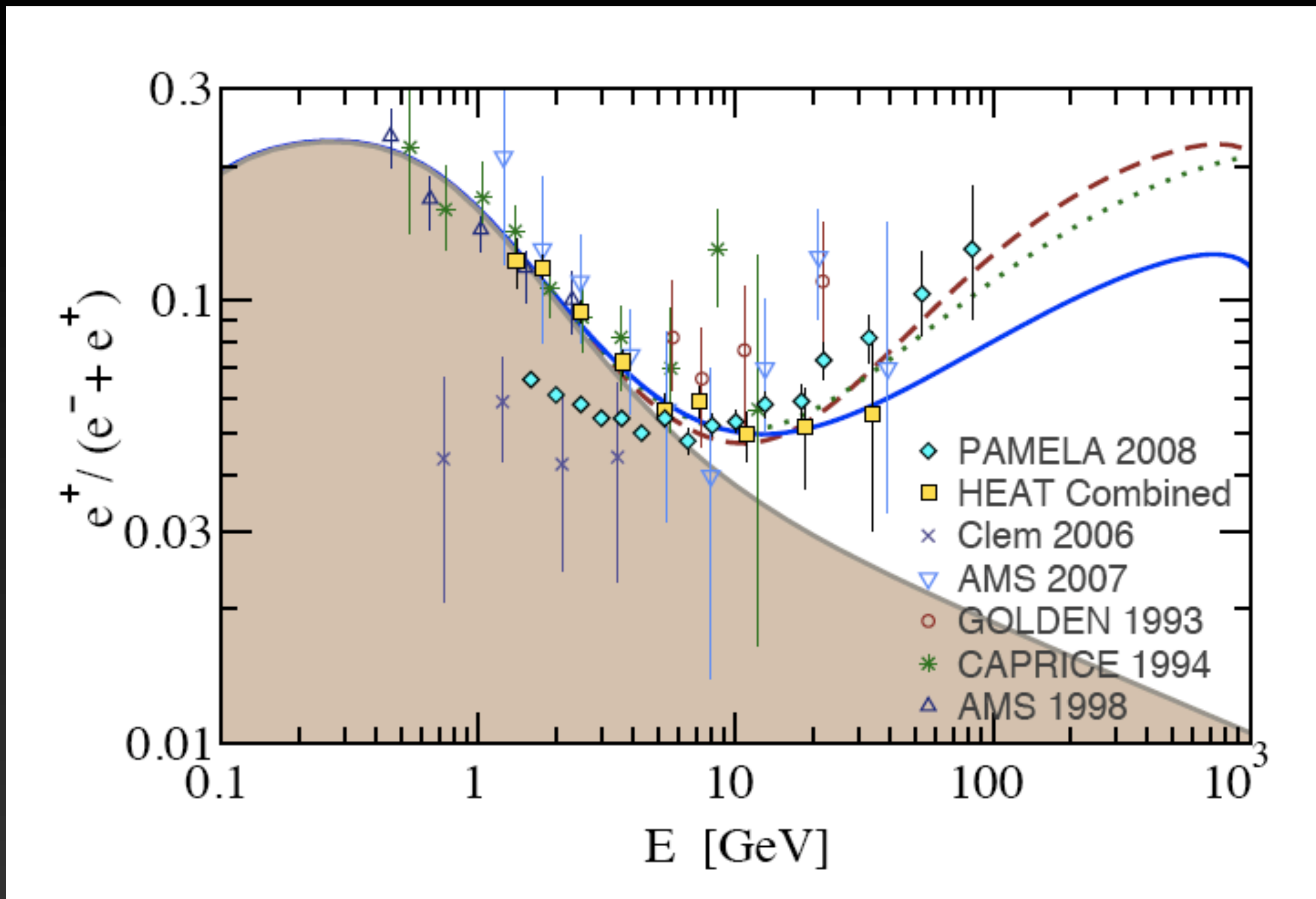
• Pulsars throughout the MW and a few nearby mature pulsars (such as Geminga and B0656+14) could each plausibly generate the observed flux of positrons

• To normalize the overall flux, on the order of a **few percent** of the pulsars’ spin down power is required to be transferred into the production of electron-positron pairs.

• Possible handle over a DM scenario: **anisotropy**

Hooper, Blasi, Serpico, 0810.1527

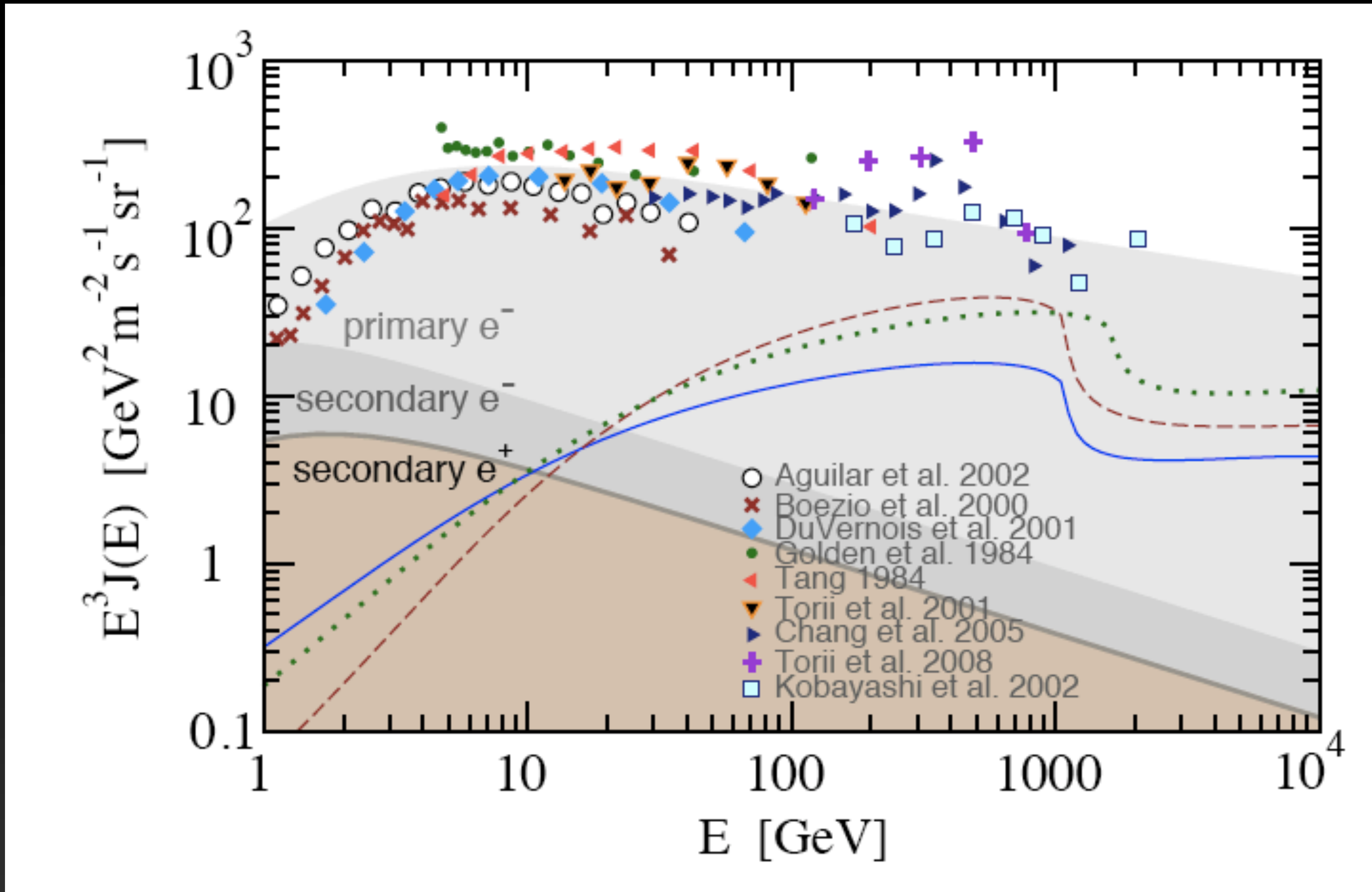
Similar conclusions for Geminga



Three lines employ different spectra, energy output and age

Consistent with IC emission detected by MILAGRO

Yuksel, Kistler, Stanev, 0810.2784



Non-burst-like injection model employed here

data probably compatible with ATIC, HESS

Yuksel, Kistler, Stanev, 0810.2784

Can we invoke Occam's razor to "dissect"

PAMELA and ATIC data?

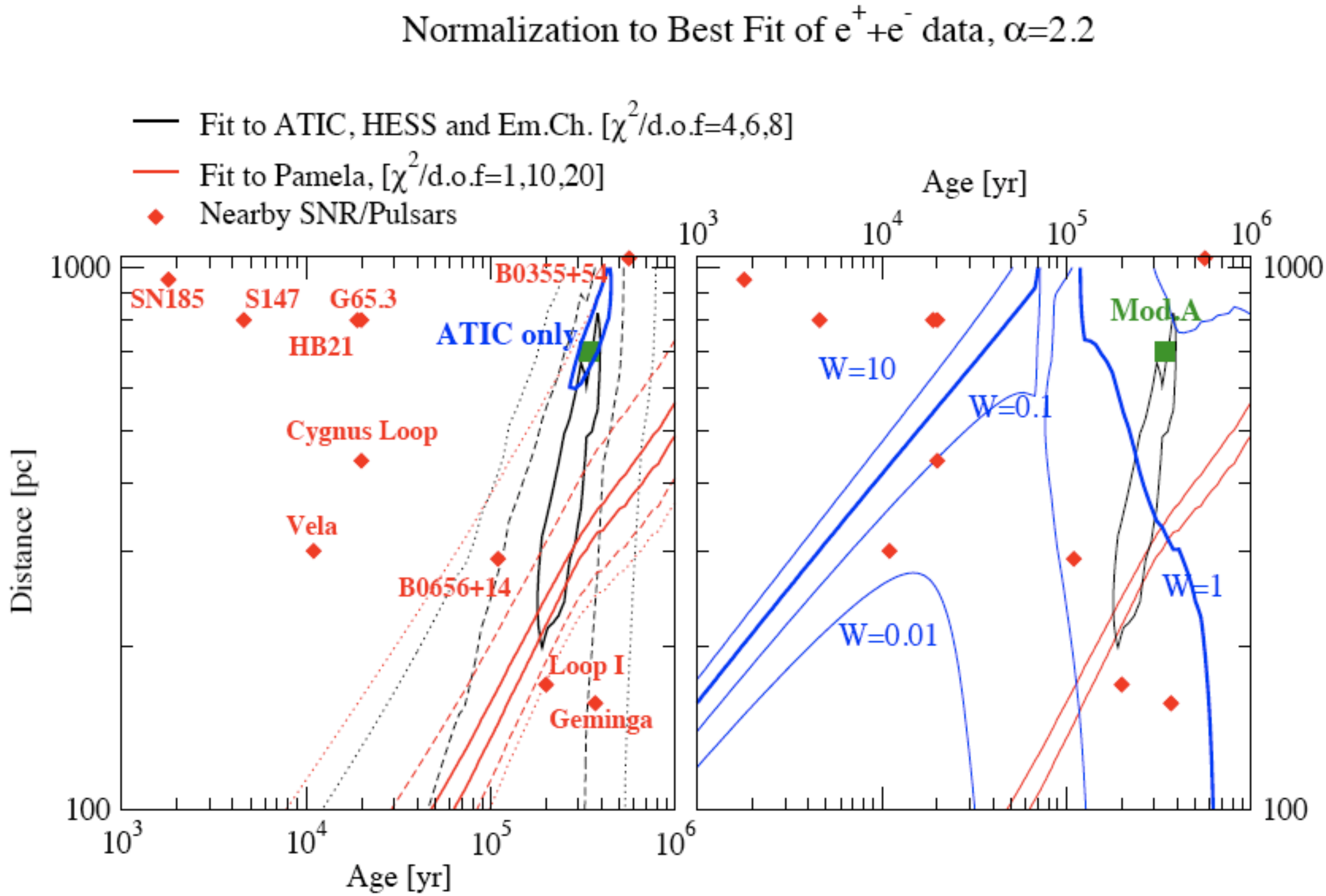
Any SNR/pulsar is characterized by:

- Emitted **power** W/10^{48} ergs above 1 GeV
- **Distance**
- **Age** [assuming burst-like injection]
- Electron/Positron **spectral index** α

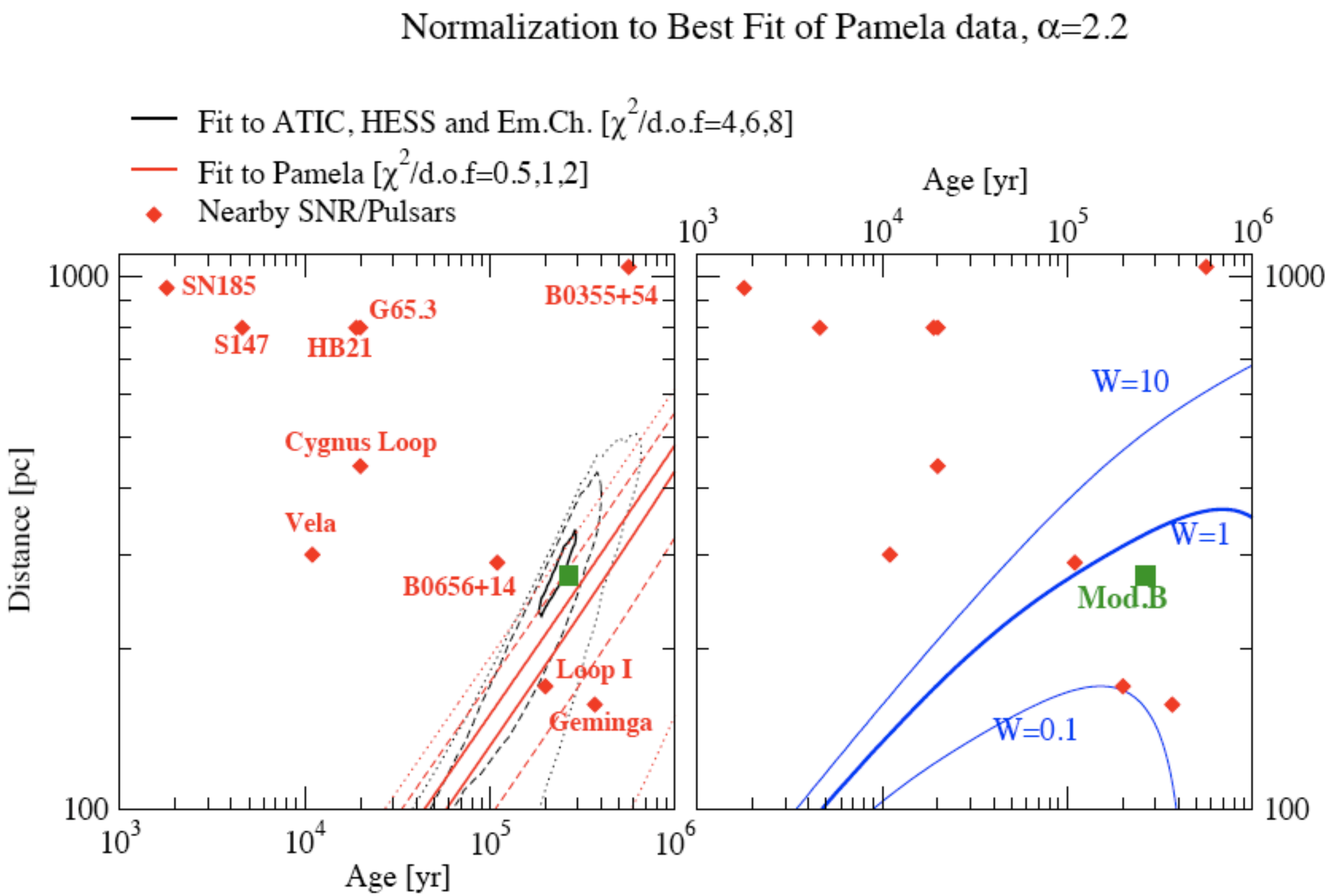
Normalize W to get the best fit to either the e+e- or the Pamela data, use δ=0.55 and D=1.8×10^{27} cm^2/s (fav.by Pamela CR data)

See if we can fit data with **existing** pulsars

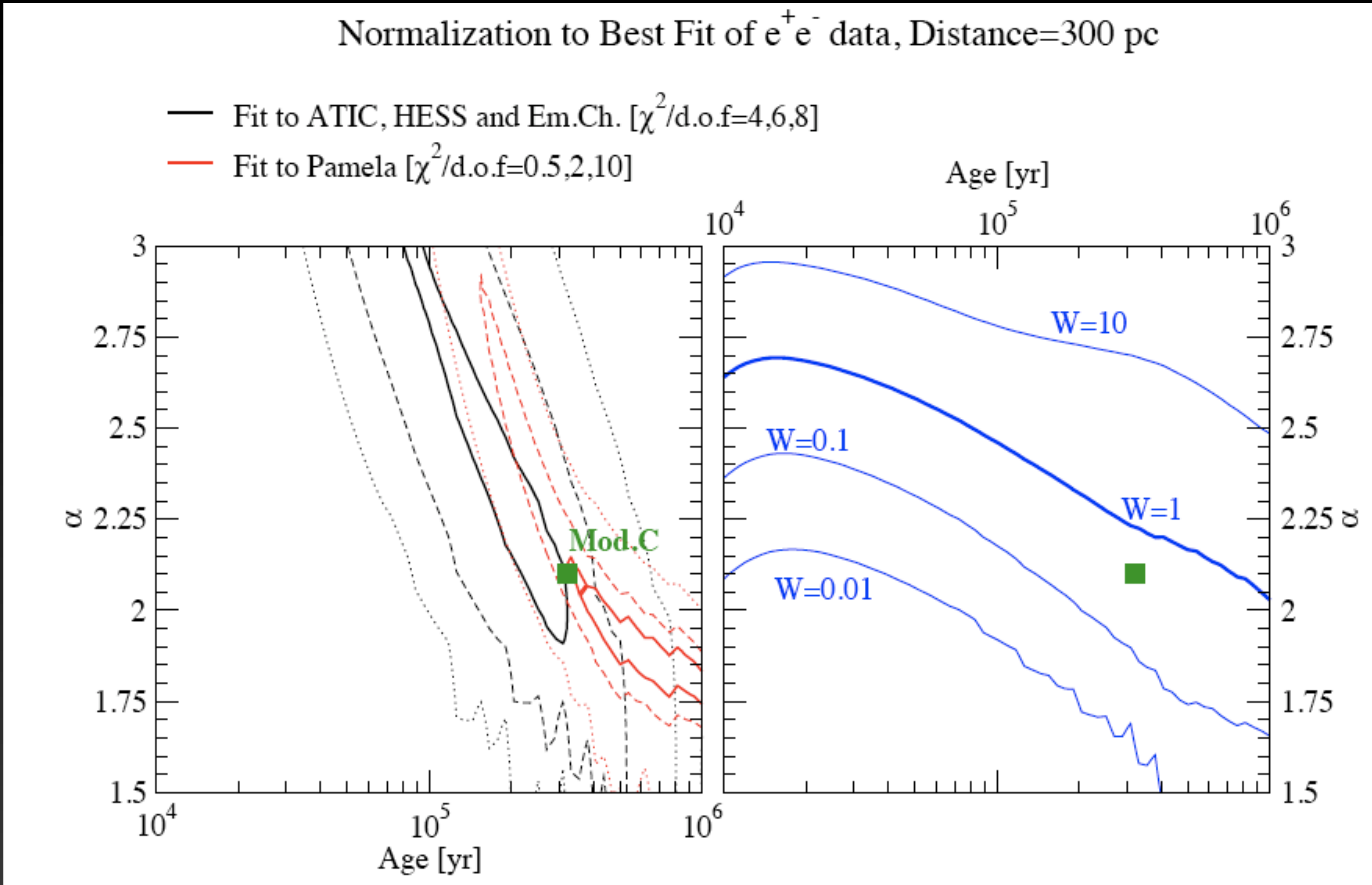
Profumo, in prepraration



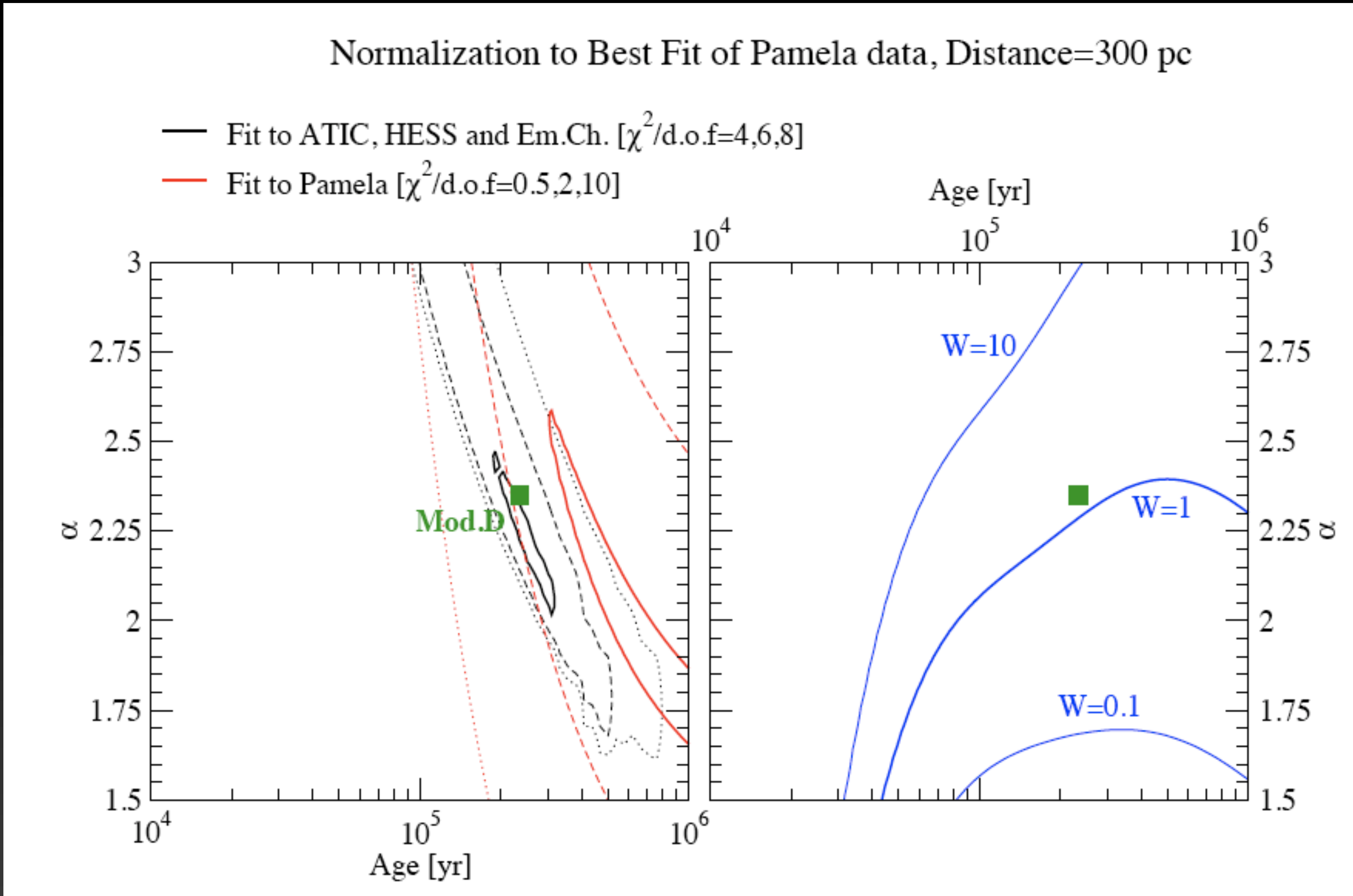
Profumo, in prepraration



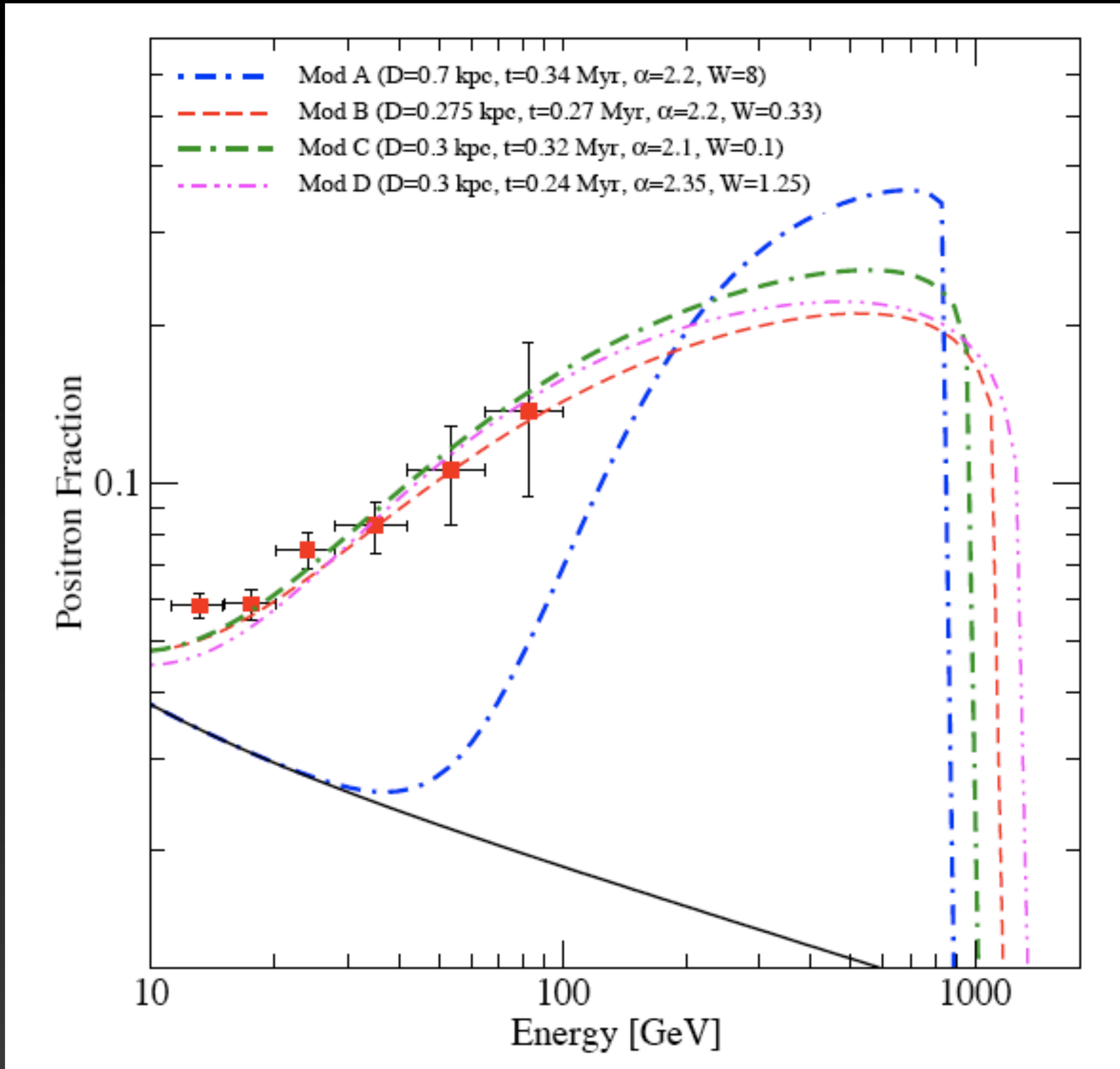
Profumo, in prepraration



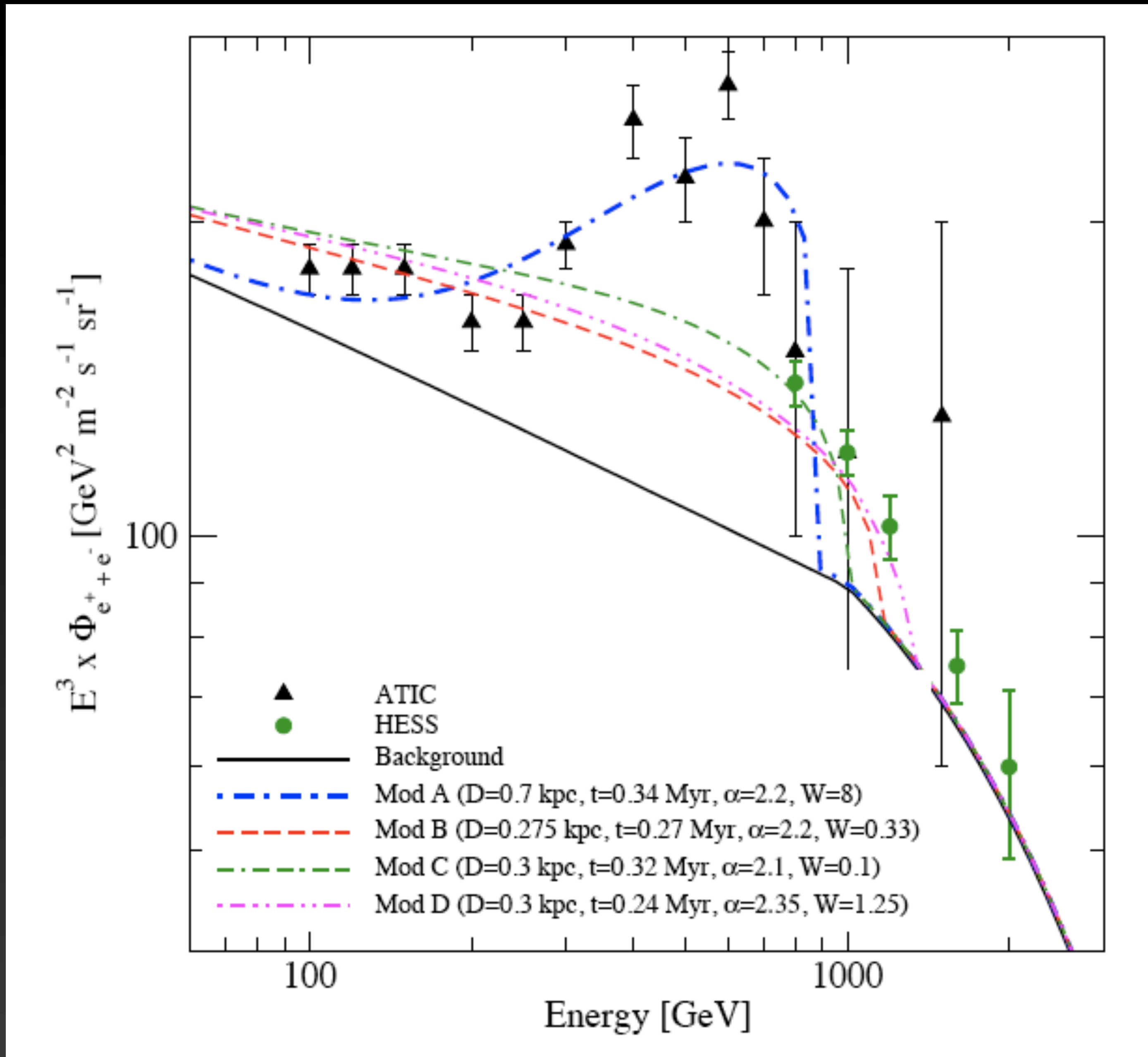
Profumo, in prepraration



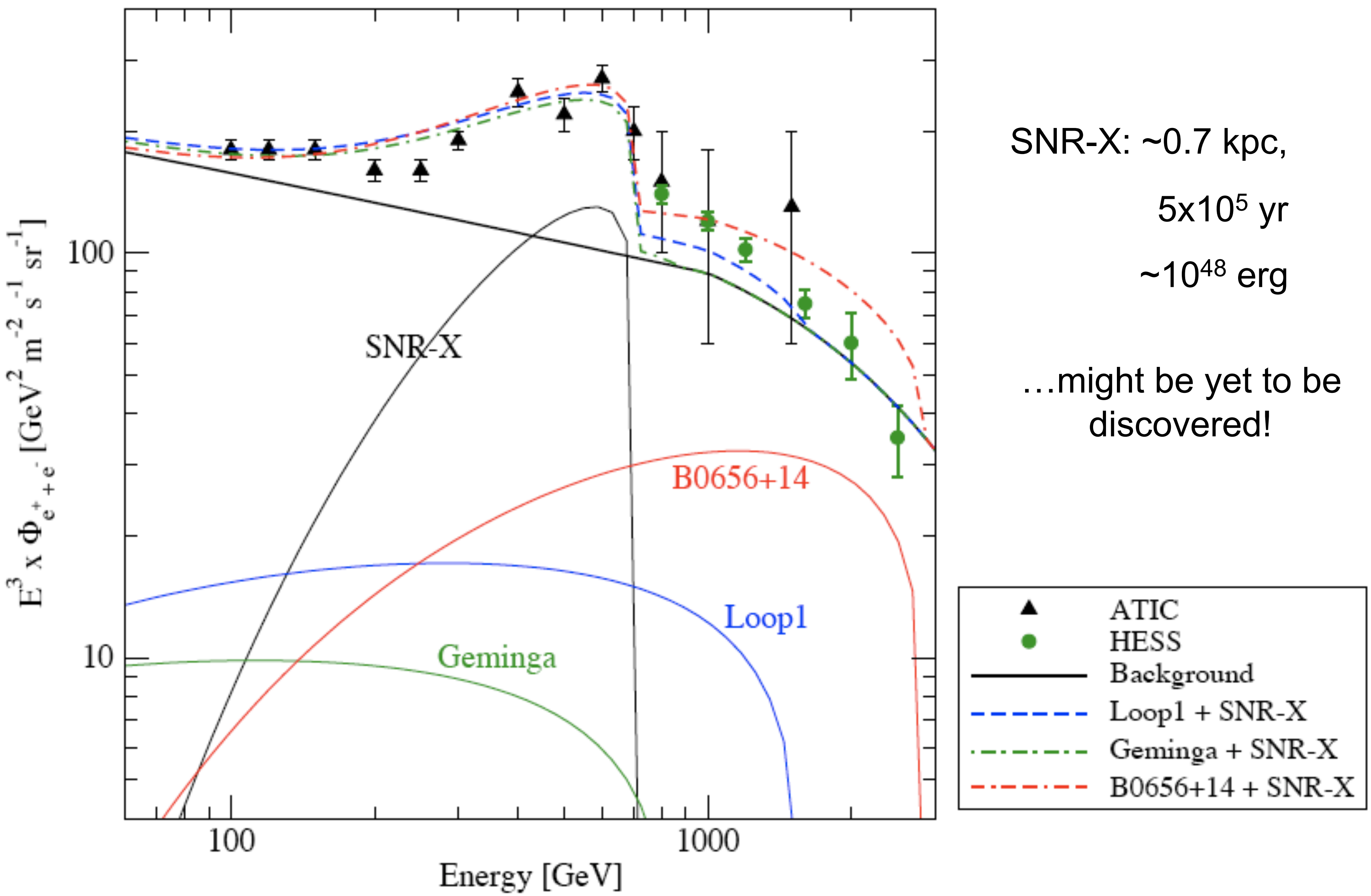
Profumo, in prepraration



Profumo, in prepraration



Profumo, in prepraration



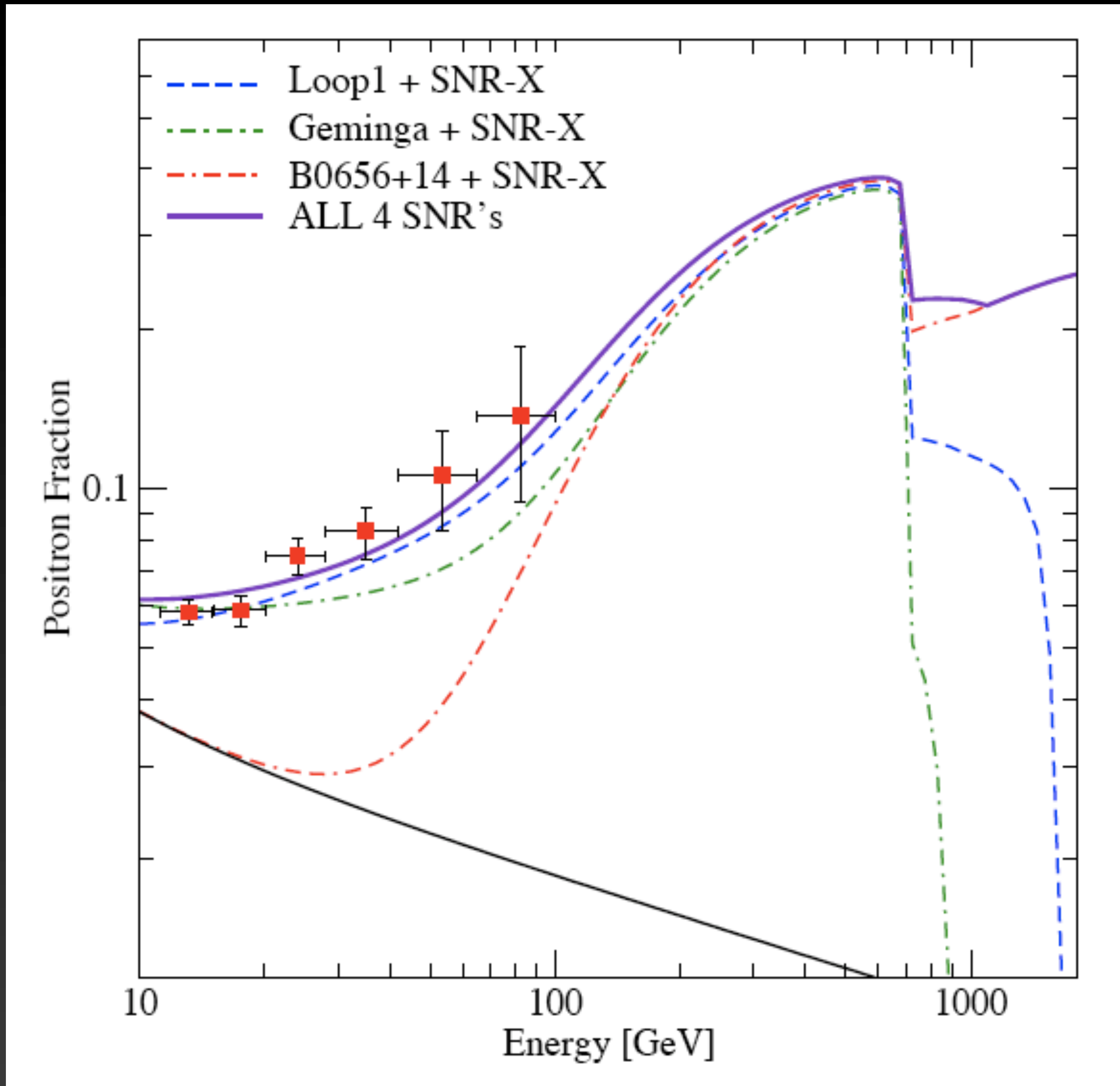
SNR-X: ~0.7 kpc,

5×10^5 yr

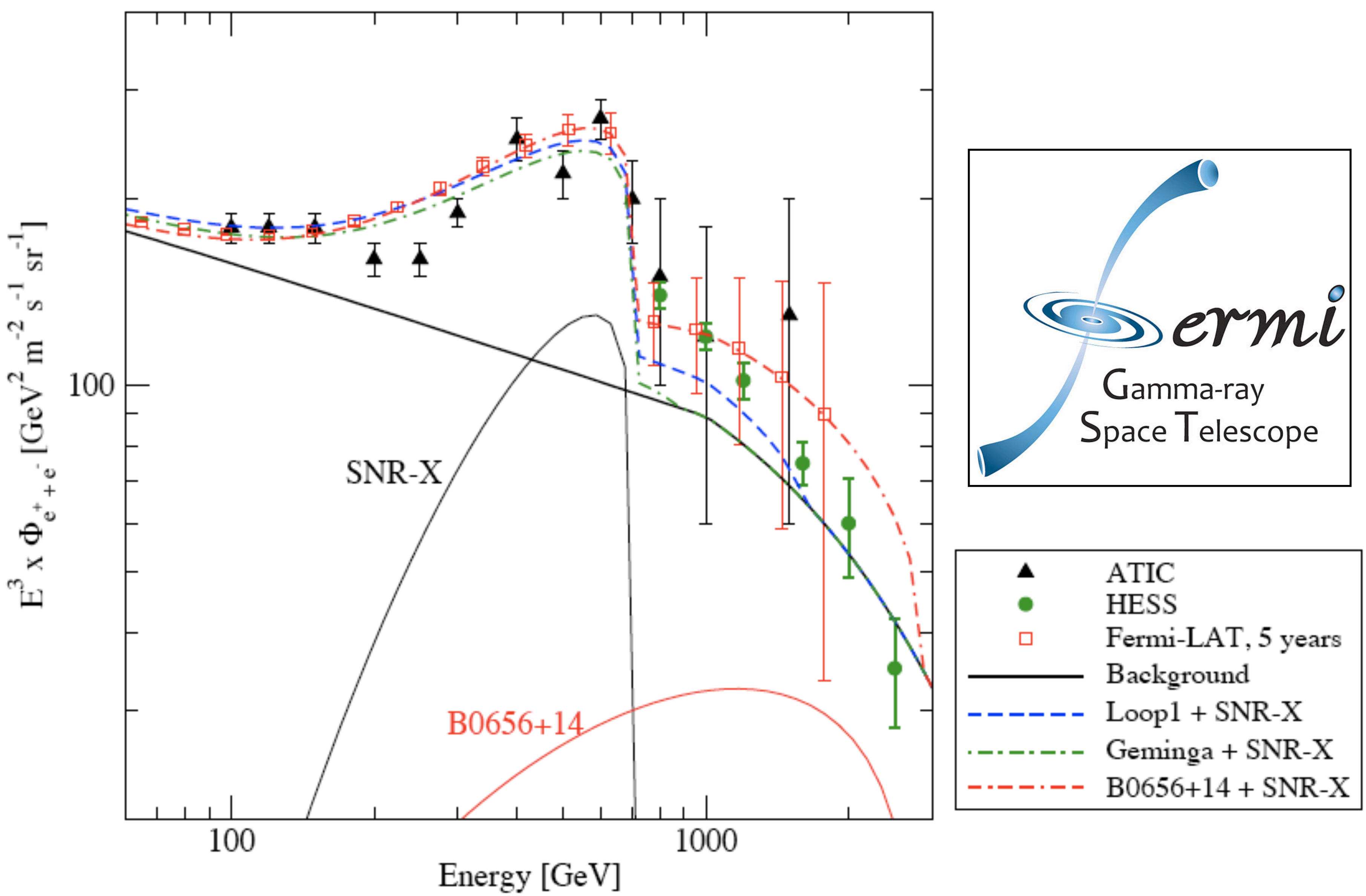
~10^{48} erg

…might be yet to be discovered!

Profumo, in prepraration

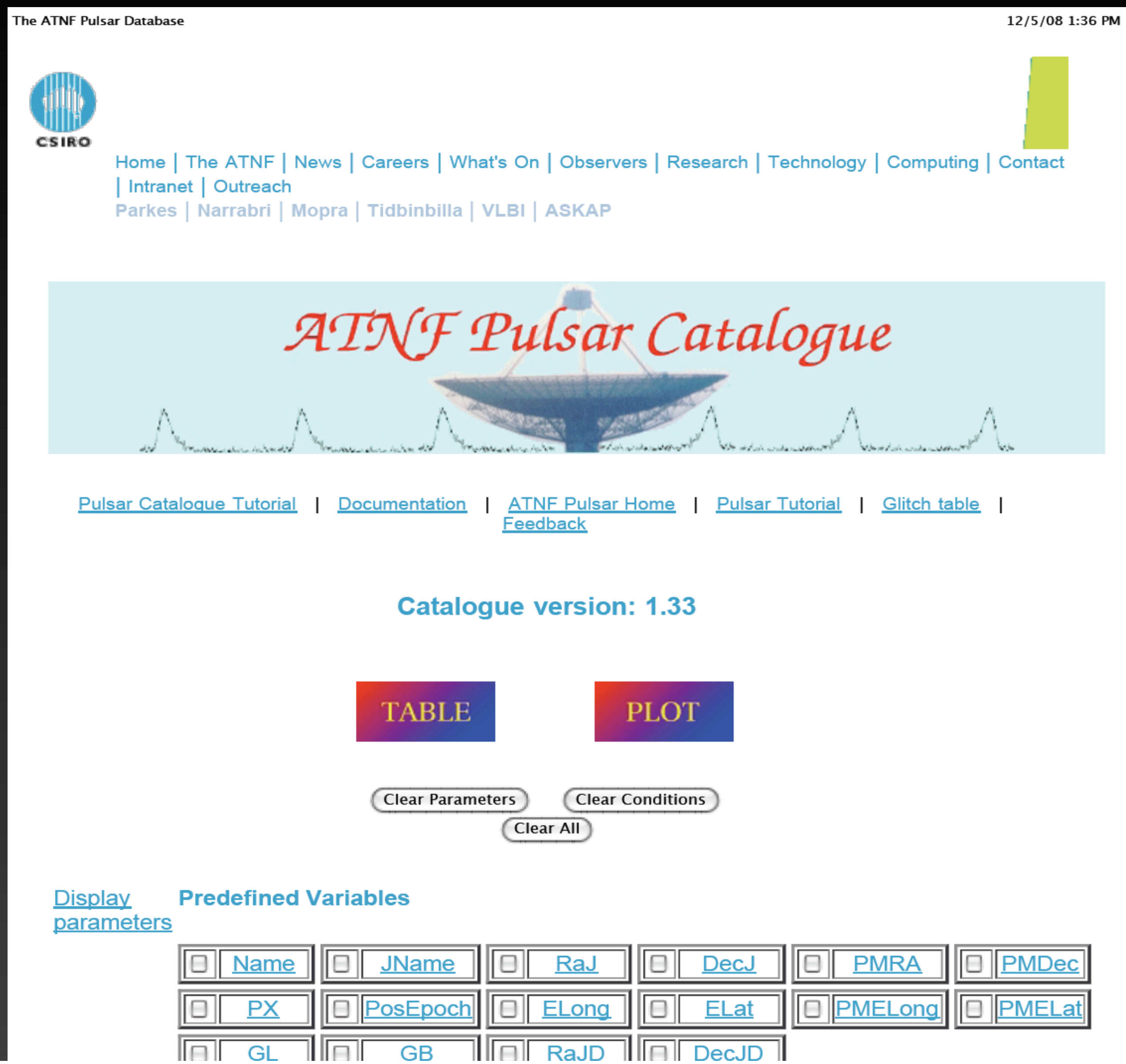


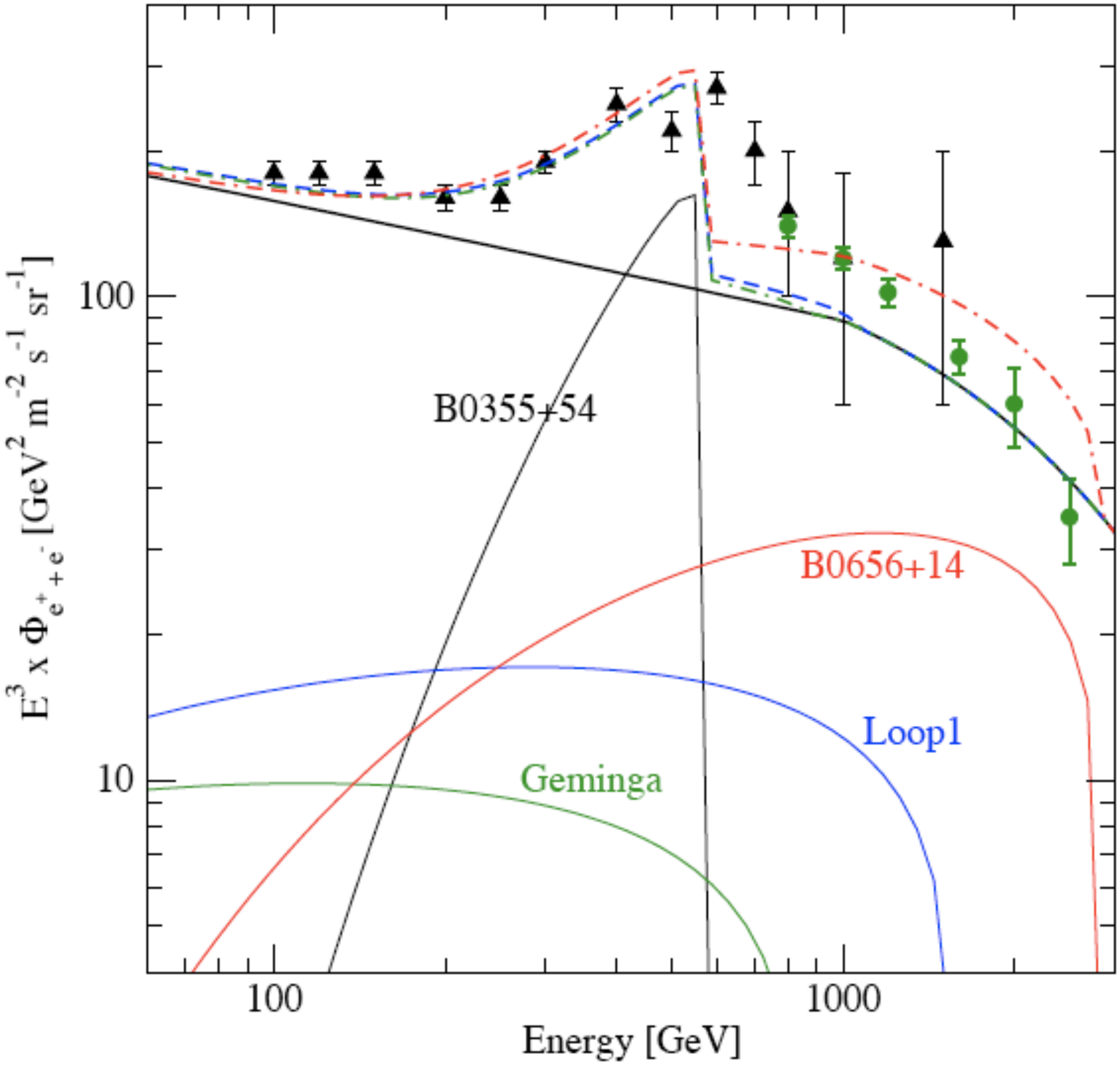
Profumo, in prepraration



Profumo, in prepraration

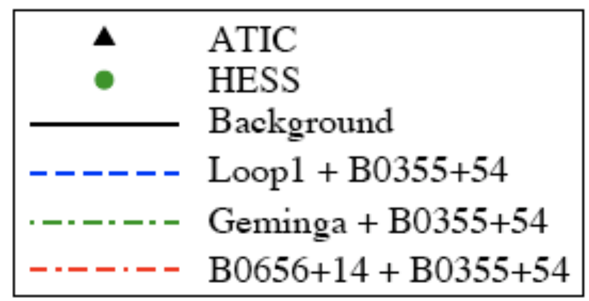
Are there SNR-X candidates in actual Pulsar catalogue?





A candidate for SNR-X:

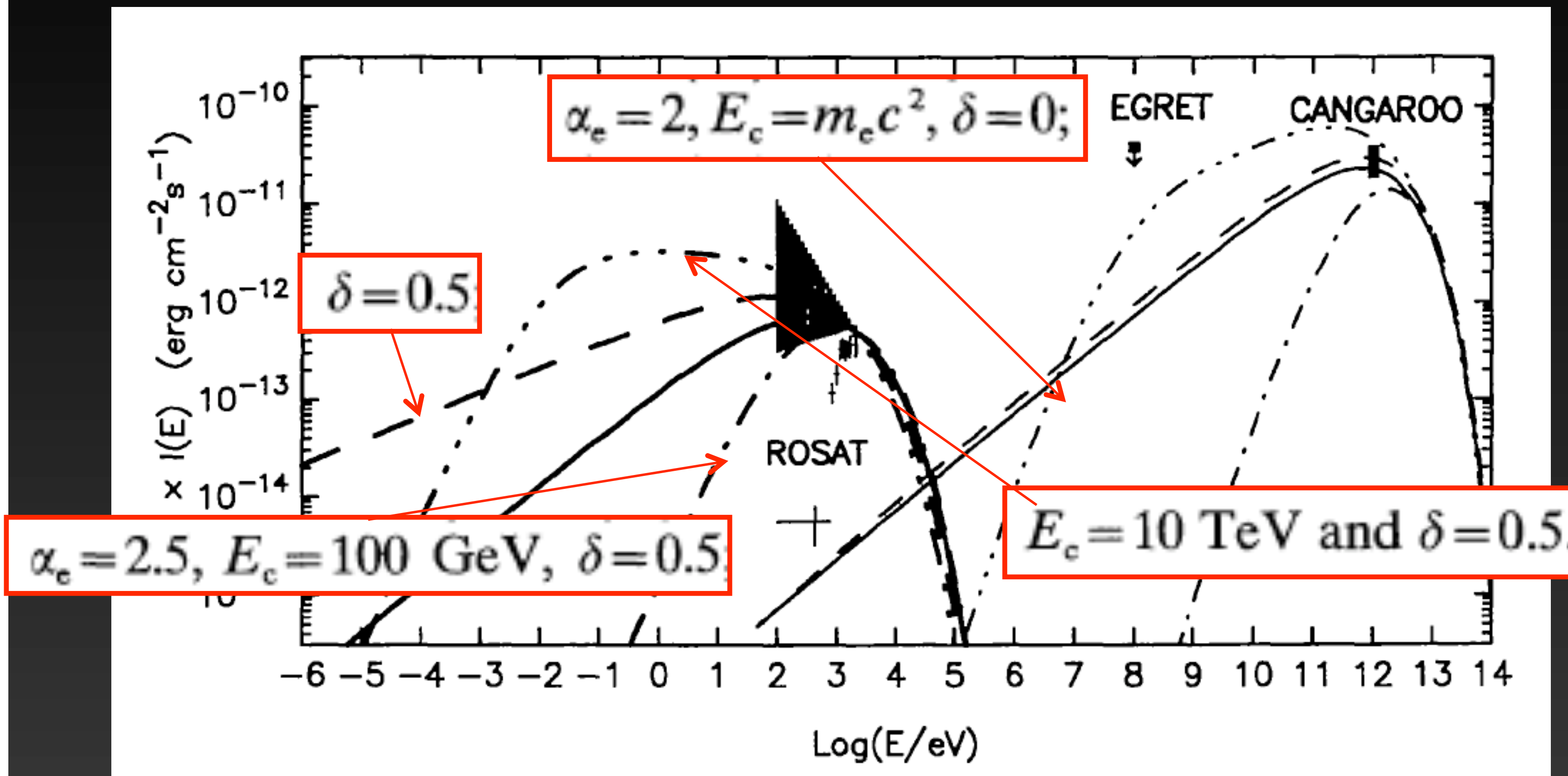
B0355+54



Profumo, in prepraration

$$\tau(E_e) = 10(E/20\ \text{TeV})^{-\delta}\ \text{yr.}$$

$$B_x = 2 \times 10^{-5}\ \text{G and } B_y = 3 \times 10^{-6}\ \text{G}$$



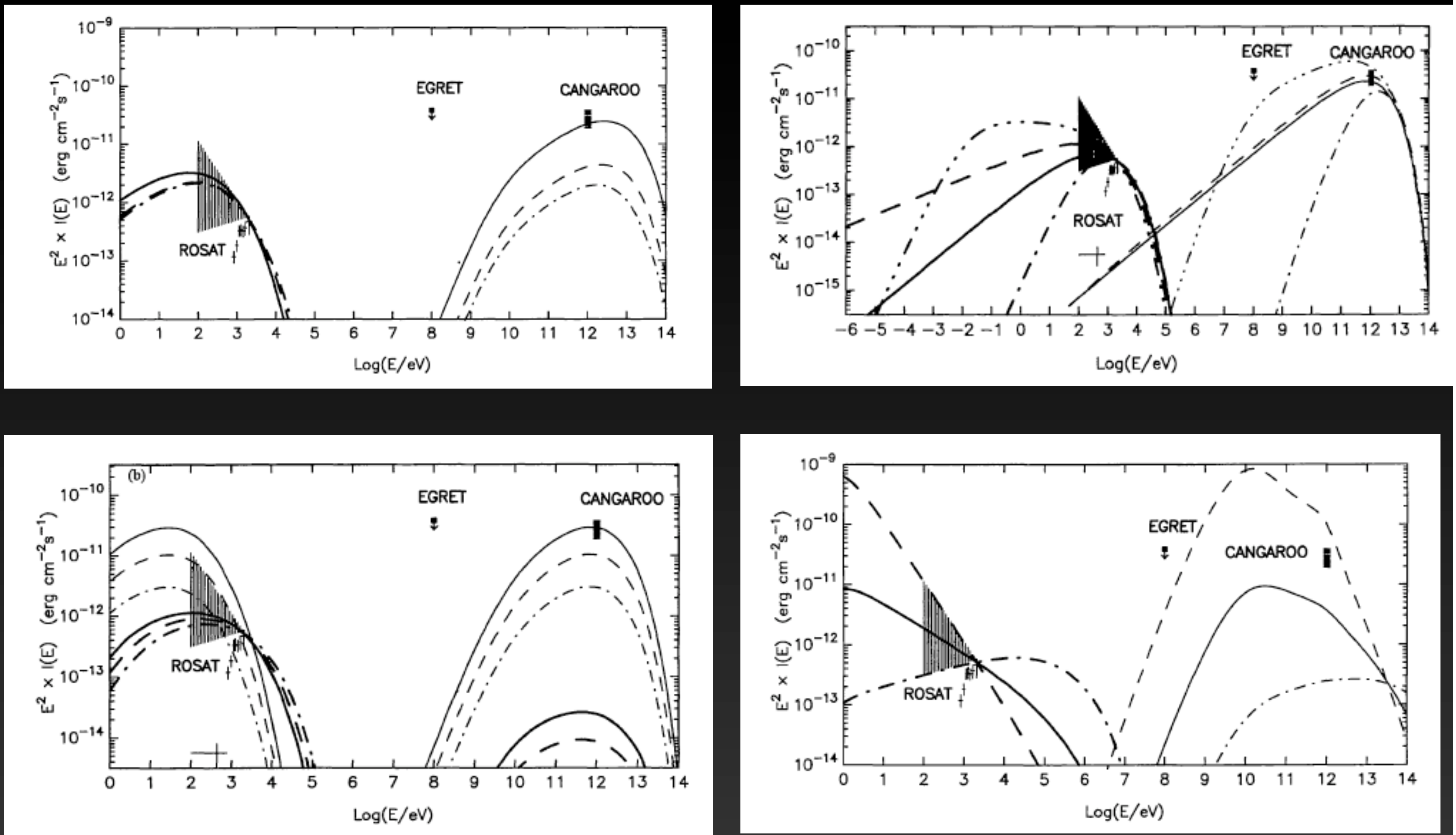
Examples of multi-wavelength predictions for leptonic SNR

Aharonian et al, 1997

- SN are widely believed to be the primary source of galactic CR
- SN are known to exist, and to produce e^+e^-
- Perfect fits to PAMELA, ATIC and HESS data with SNR/Pulsars
- Existing things are enough: a case for Occam's razor?

Entia non sunt multiplicanda praseter necessitatem

- Fermi-LAT is discovering new pulsars almost every day
- The e^+e^- produced in SNR have several observable signatures (gamma rays, X-ray, Radio…)
- e^+e^- data from Fermi-LAT will also tell us where the positrons come from



Examples of multi-wavelength predictions for leptonic SNR

Aharonian et al, 1997