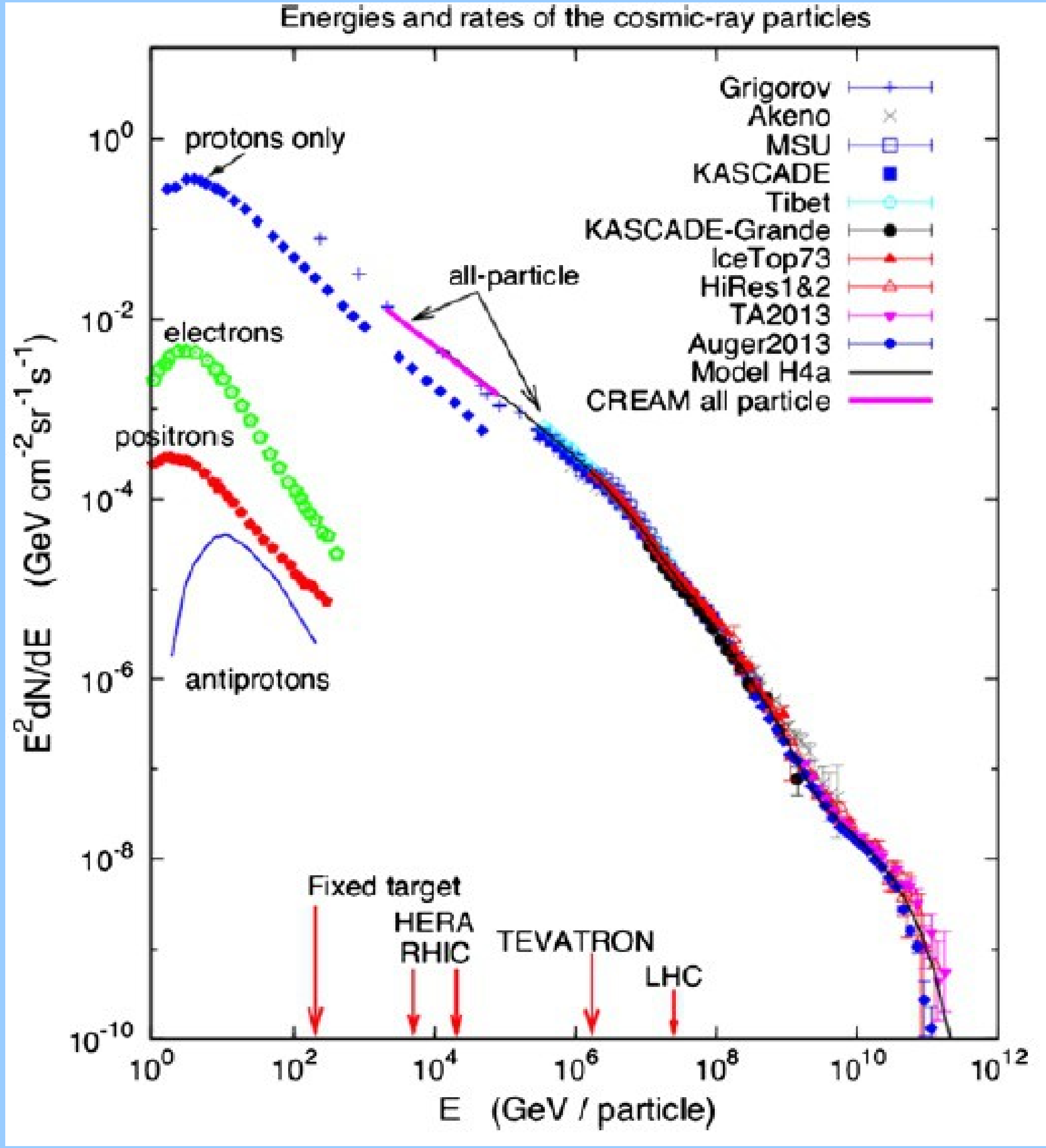
Modeling of the production of the observed primary positrons by the nearest bow shock pulsar PSR J0437-4715

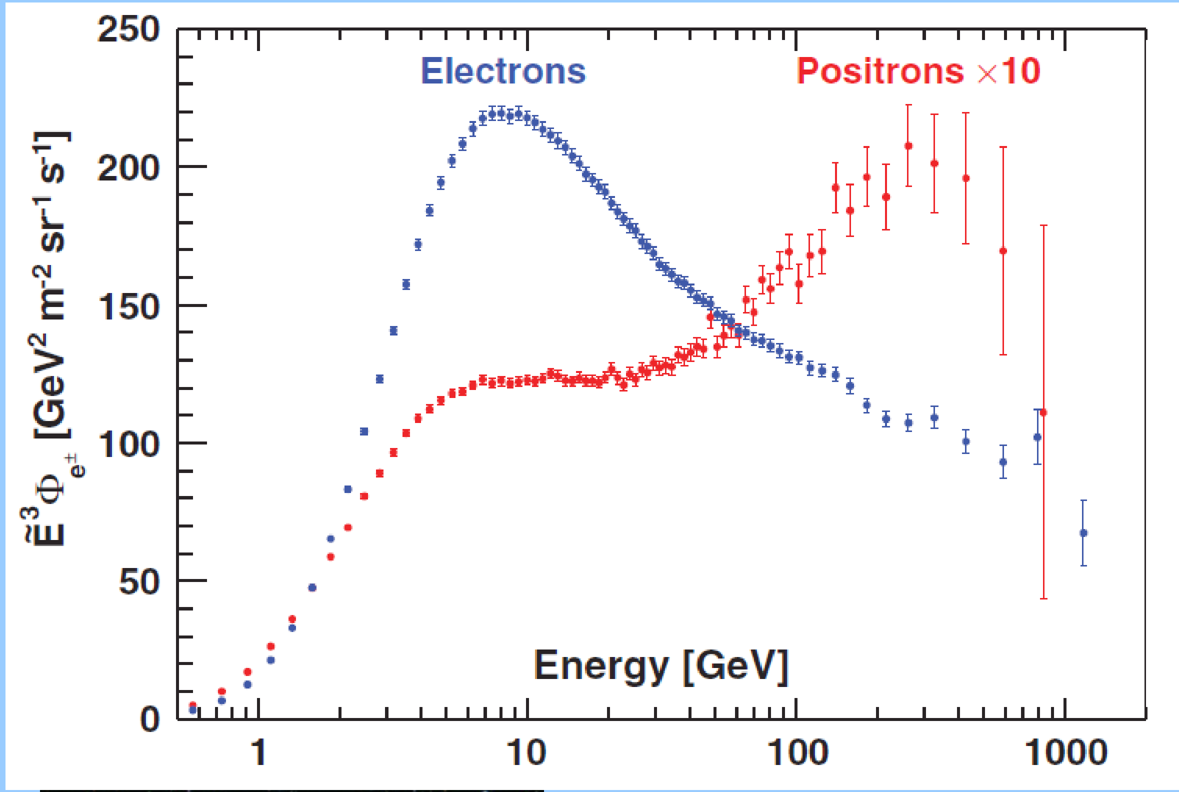
Petrov A. E., Bykov A. M.

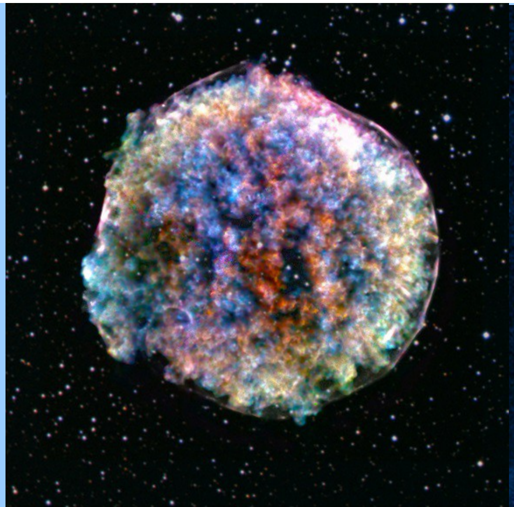
26th June, 2025

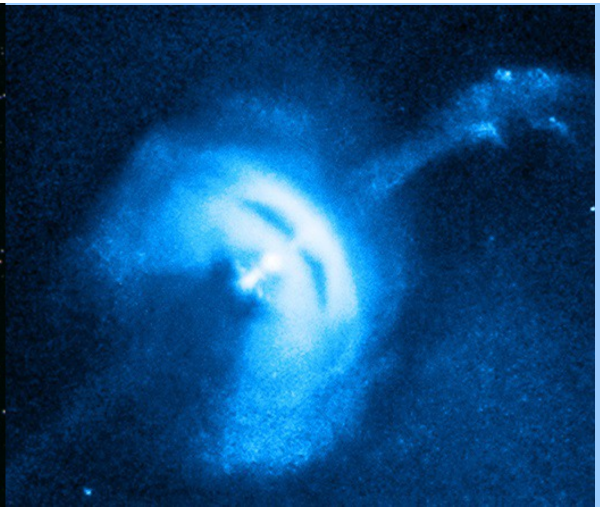
Support: Foundation for the Advancement of Theoretical Physics and Mathematics «BASIS» (grant No. 24-1-3-28-1)

Cosmic rays



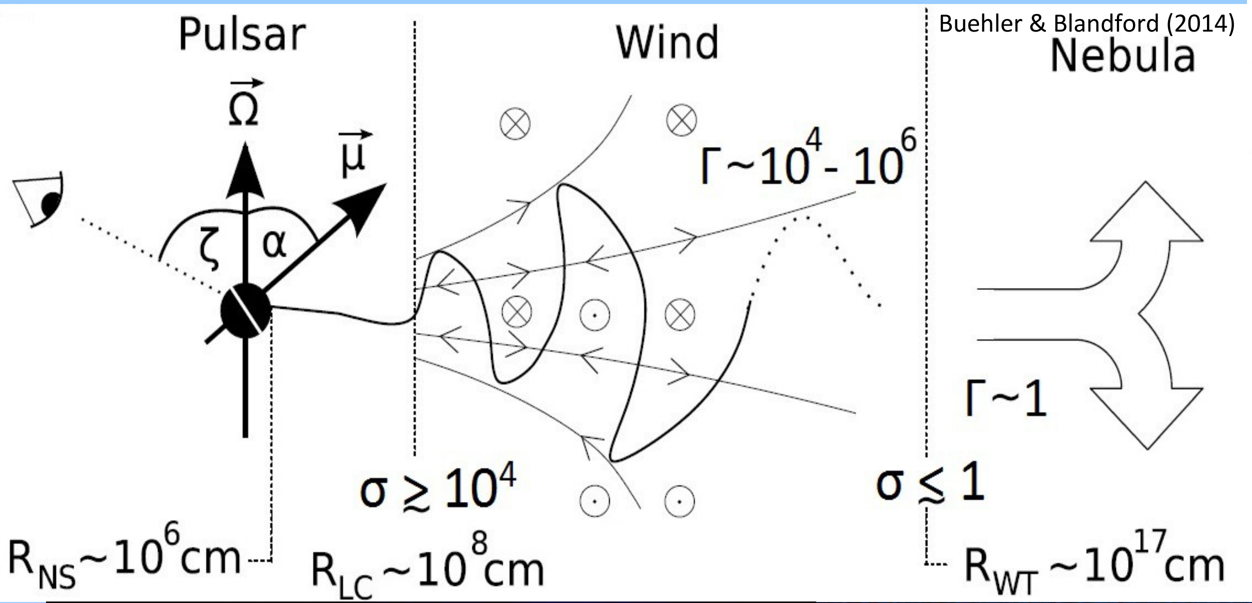




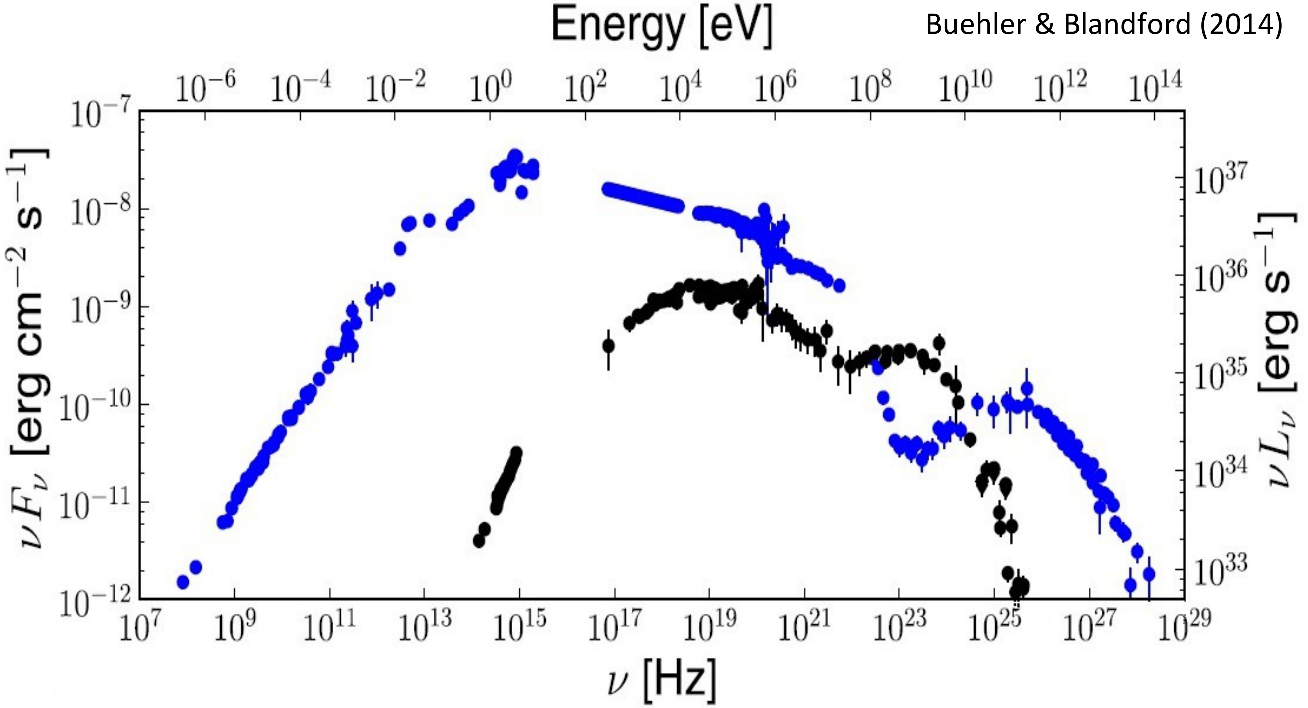


Credit: Blasi (2013), Aguilar et al. (2021); Tycho: X-ray: NASA/CXC/RIKEN & GSFC/T. Sato et al, Optical: DSS; Vela: NASA/CXC/Univ of Toronto/M.Durant et al

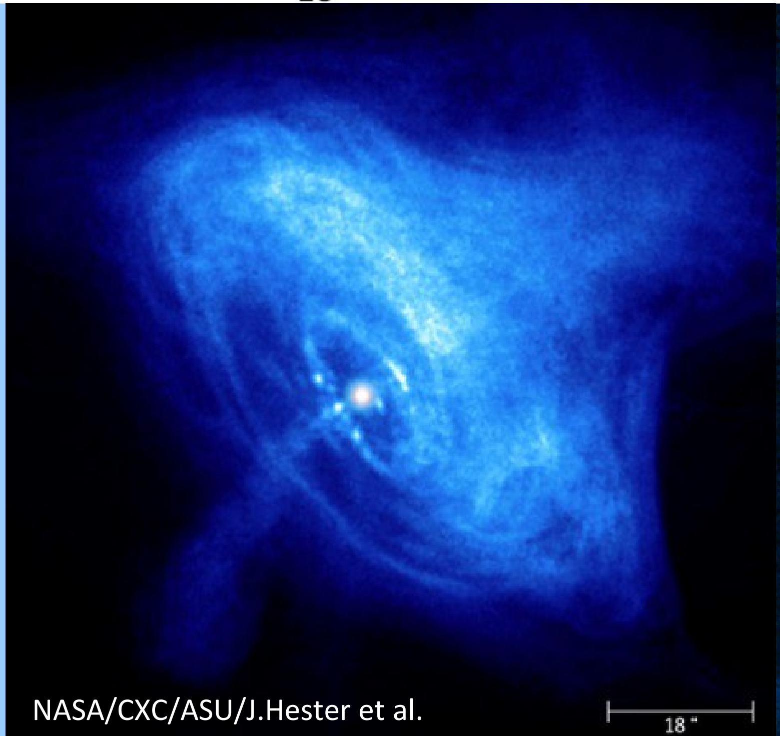
Pulsar wind nebulae



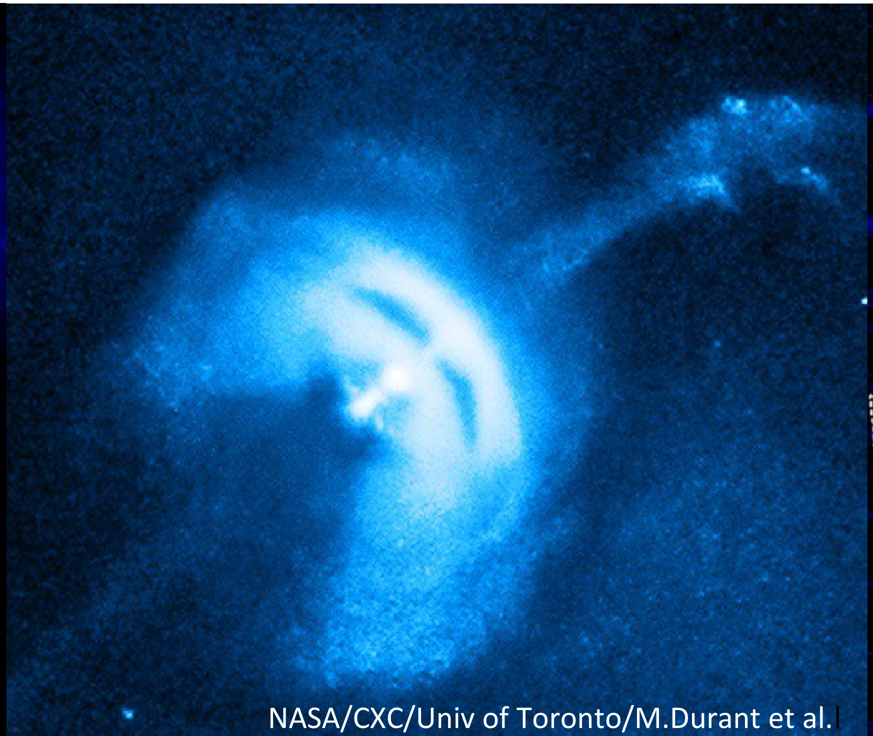
Buehler & Blandford (2014)

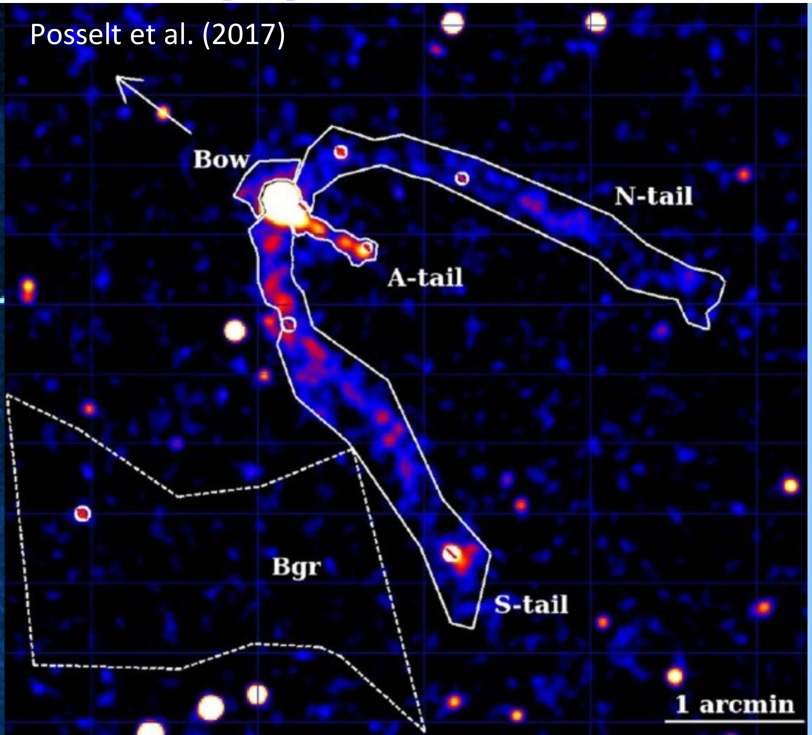


Buehler & Blandford (2014)



NASA/CXC/ASU/J.Hester et al.


NASA/CXC/Univ of Toronto/M.Durant et al.

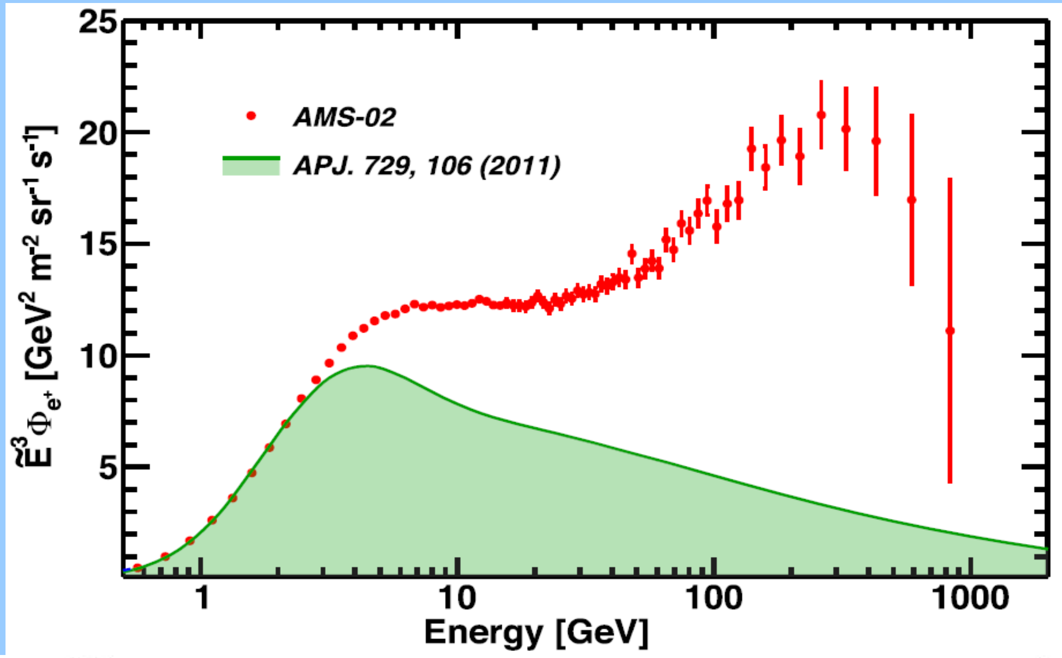


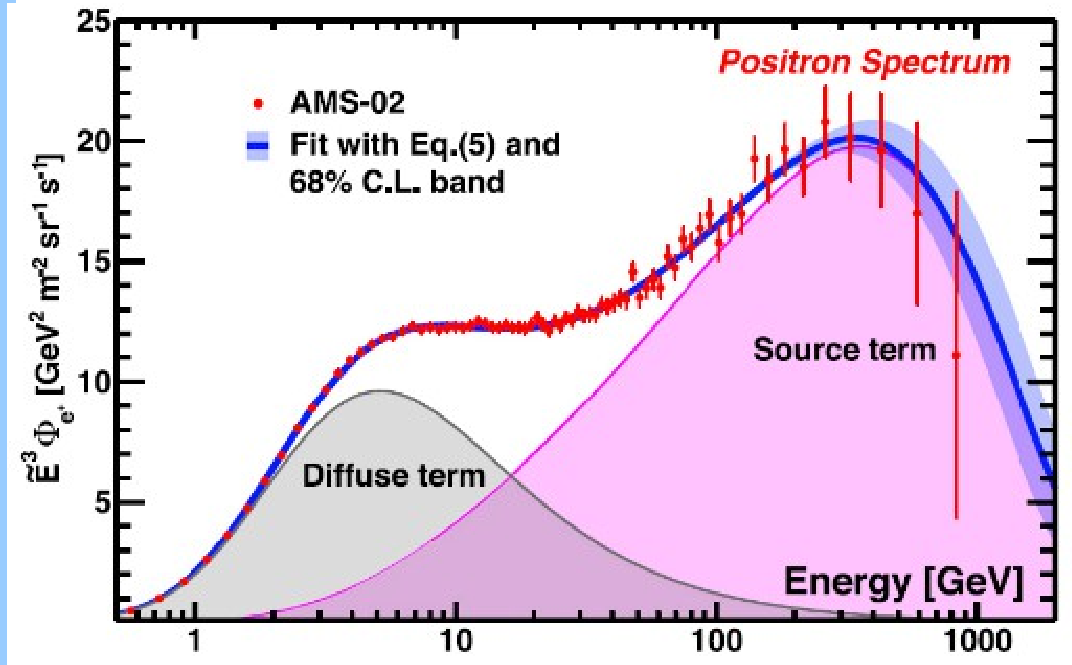
Posselt et al. (2017)

Cosmic ray positrons: excess

- Where the CR positrons are produced?
  - Primary: sources of particles and antiparticles (e.g., pulsars and their winds)
  - Secondary: energetic primary CR nuclei interact with the interstellar medium

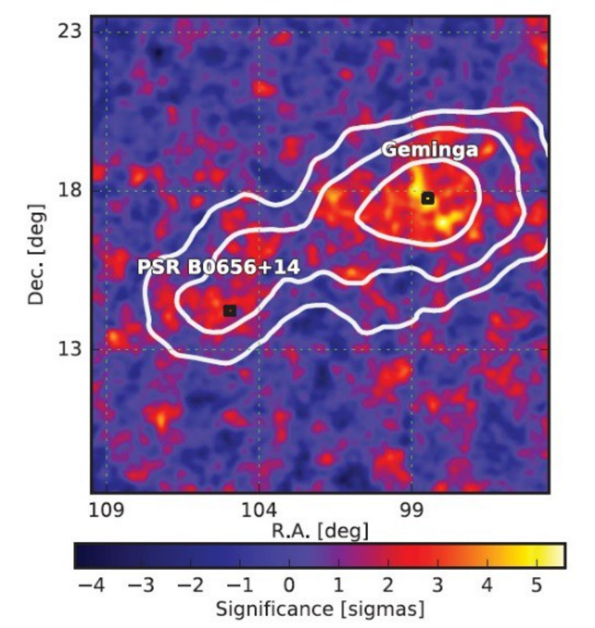
AMS-02, PAMELA: 10 GeV – 1 TeV – more positrons, than the secondary scenario predicts (e.g., the GALPROP model)





Credit: Aguilar et al. (2021)

The magnetic field and particle diffusion in the Galaxy. HAWC results



- Diffusion in the turbulent Galactic magnetic field: «global» diffusion coefficient

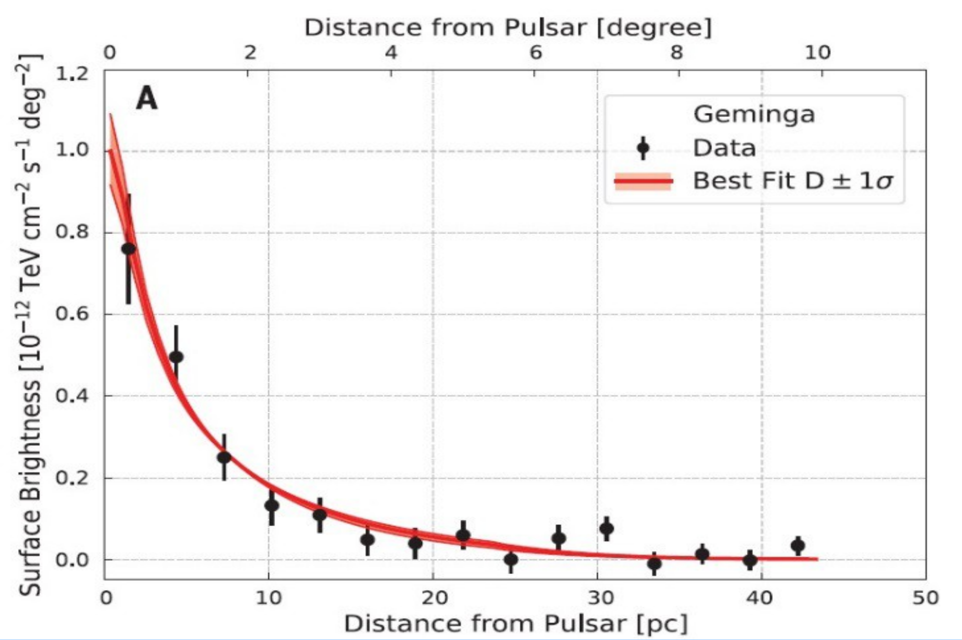
$$D_{global}(R) = 3 \times 10^{28} \left(\frac{R}{1\,\mathrm{GV}}\right)^{1/3}\ \mathrm{cm}^2\mathrm{s}^{-1}, \qquad R = pc/Ze$$

- Correlation length ~ 100 pc. Strong fluctuations of such scale make diffusion isotropic on Galatic scales
- At lower scales – anisotropy. Strong et al. (2007), diffusion along the magnetic field:

$$D_{||}(R) = 2 \times 10^{27} \left(\frac{R}{1\,\mathrm{GV}}\right)^{1/3}\ \mathrm{cm}^2\mathrm{s}^{-1}$$

- Small scales (1-10 pc): physics of local sources. Particle acceleration – turbulent field amplification
- Abeysekara et al. (2017): local diffusion coefficient near the Geminga pulsar is inferred from the simulations of the TeV galo brightness distribution

$$D_{HAWC}(R) = 10^{26} \left(\frac{R}{1\,\mathrm{GV}}\right)^{1/3}\ \mathrm{cm}^2\mathrm{s}^{-1}$$



Credit: Abeysekara et al. (2017)

Geminga pulsar and HAWC results

Geminga:

$d \sim 250$ pc
$\dot{E} \sim 3.3 \times 10^{34}$ erg s^{-1}
age $\tau \sim 340$ kyr

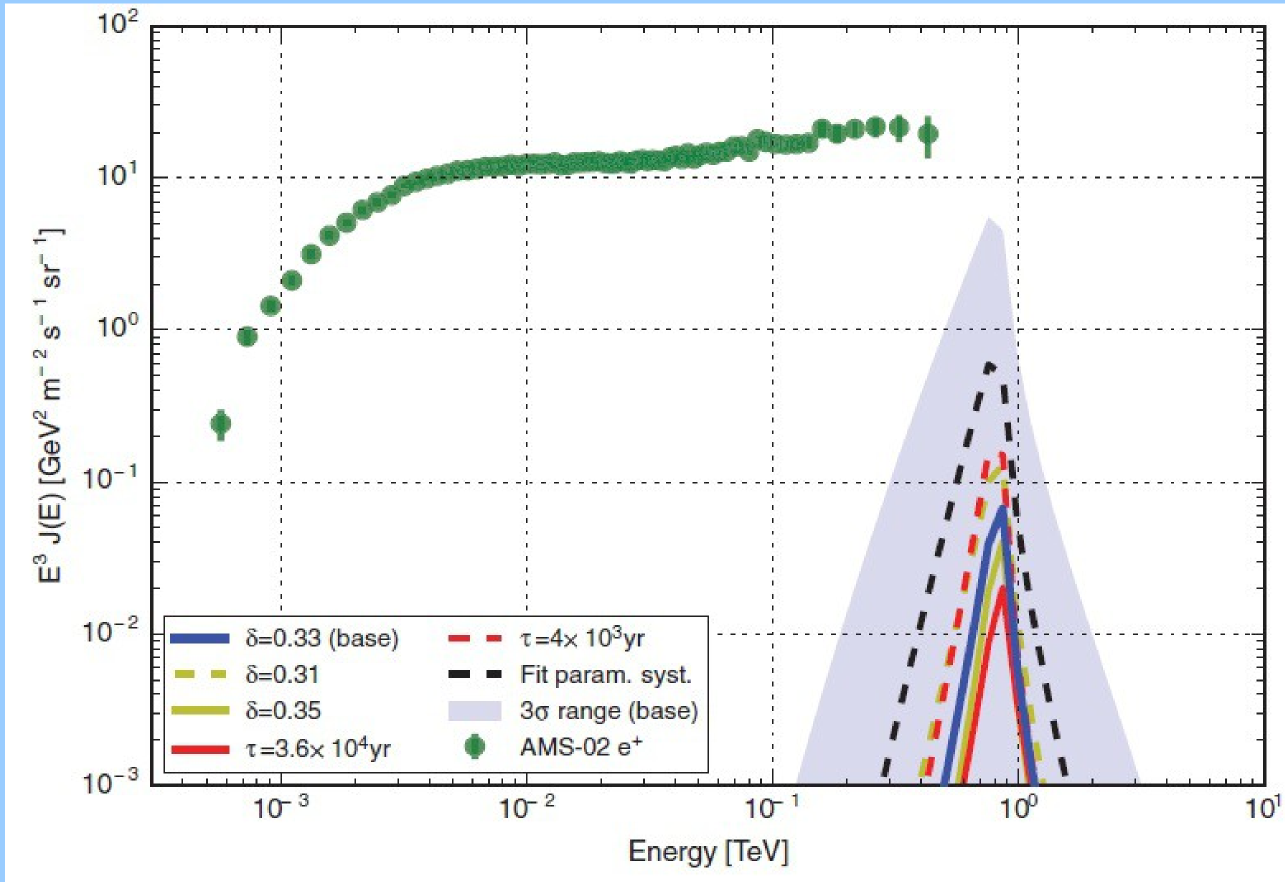
Diffusion time:

$$t = 4.5 \times 10^6 \times \left(10^{26}/D(1\,\mathrm{GV})\right) \times (E, \text{ТэВ})\ \text{yr}$$

Positrons of energy 1 TeV and below don't have time to reach the Earth! Higher energy positrons lose their energy due to radiative losses

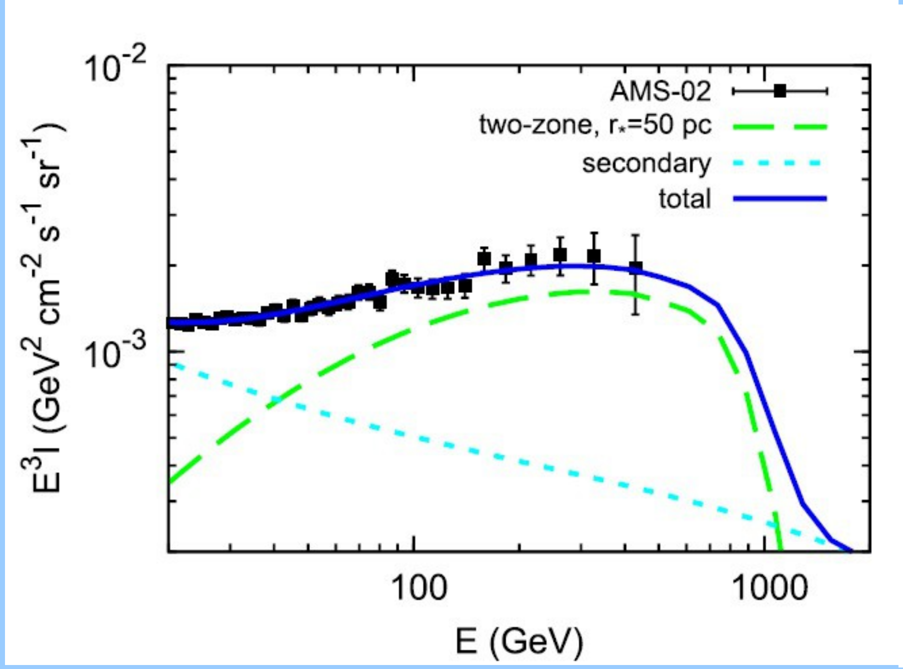
Following the «scales hierarchy»: two-zone model

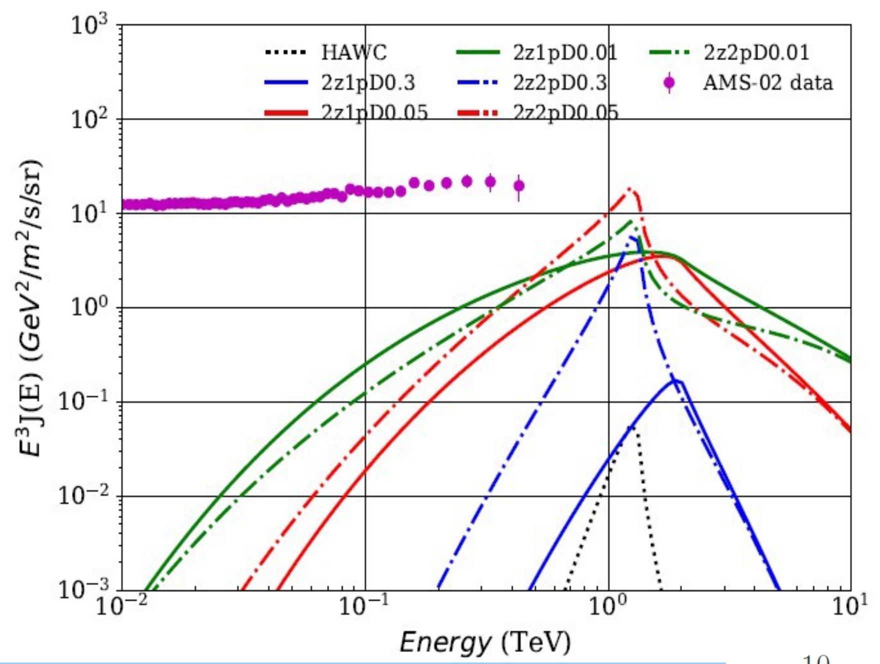
$$D(r,R) = \begin{cases} 10^{26}\left(\frac{R}{1\,\mathrm{GV}}\right)^{1/3} \mathrm{cm}^2\mathrm{s}^{-1}, & r < r_* \sim 50\ \mathrm{pc} \\ 2 \times 10^{27-28}\left(\frac{R}{1\,\mathrm{GV}}\right)^{1/3} \mathrm{cm}^2\mathrm{s}^{-1}, & r > r_* \end{cases}$$



Credit: Abeysekara et al. (2017)

Models of Geminga PSR as the positrons source





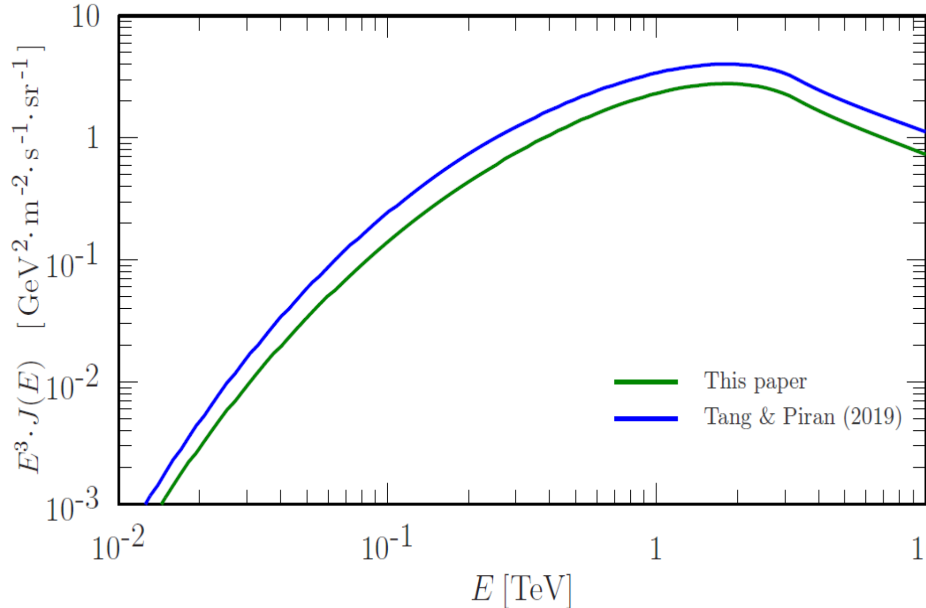
Fang et al. (2018): numerical two-zone model

Tang & Piran (2019), Osipov et al. (2020): analytical two-zone models

$$D(r,R) = \begin{cases} D_{HAWC}(R) = 10^{26}\left(\dfrac{R}{1\,\mathrm{GV}}\right)^{1/3} \mathrm{cm}^2\mathrm{s}^{-1} & r < r_* \\ D_{out}(E) = 2\times 10^{28}\cdot Const\cdot\left(\dfrac{R}{1\,\mathrm{GV}}\right)^{\delta} \mathrm{cm}^2\mathrm{s}^{-1} & r > r_* \end{cases}$$

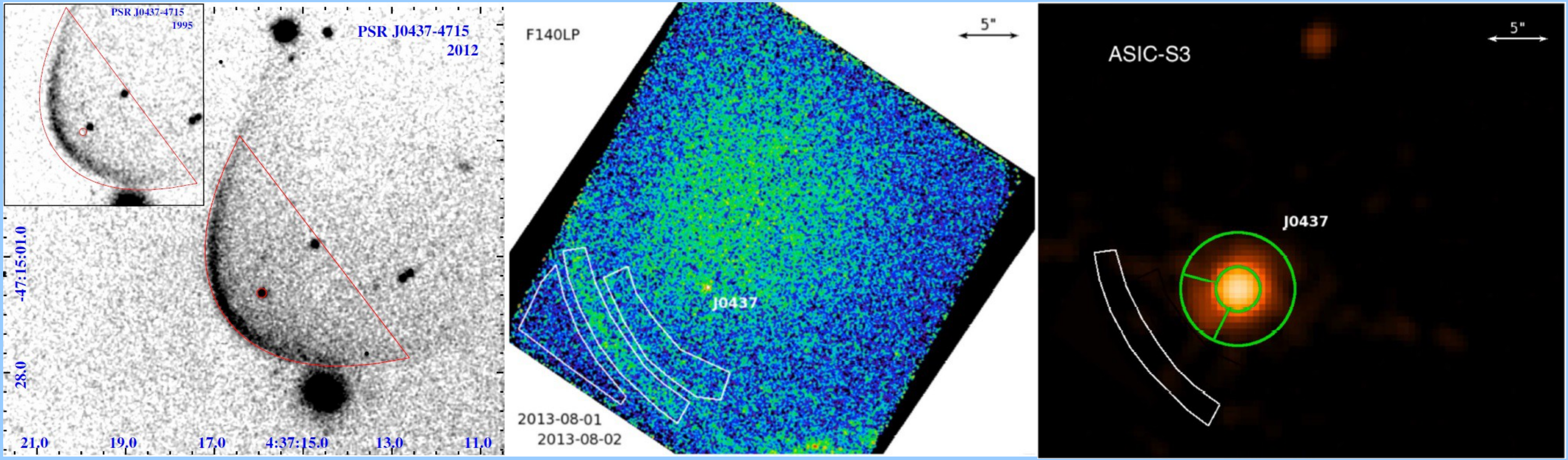
Fang et al. (2018): $Const = 1, \quad \delta = 0.5, \quad r_* = 50\ \mathrm{pc}, \quad 75\%\dot{E}$

Tang, Piran (2019): $Const = 0.1, \quad \delta = \frac{1}{3}, \quad r_* = 60\ \mathrm{pc}, \quad < 40\%\dot{E}$



Credit: Fang et al. (2018), Tang & Piran (2019)

Pulsar wind nebula of PSR J0437-4715



Spin-down power: $\dot{E} = 3 \times 10^{33} (I/10^{45}\ \mathrm{g \cdot cm^2})\ \mathrm{erg\ s^{-1}}$

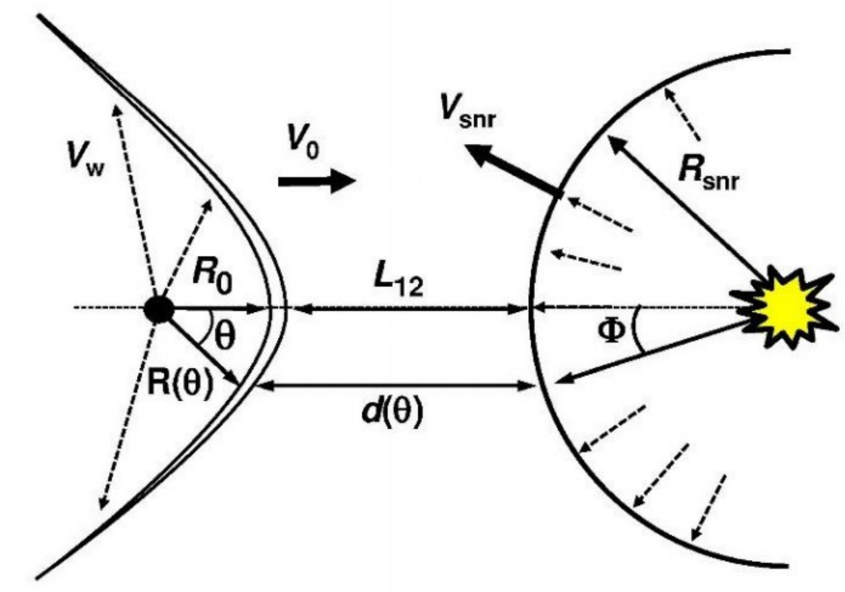
Distance: $d = 156.3 \pm 1.3$ pc (Deller et al. 2008)

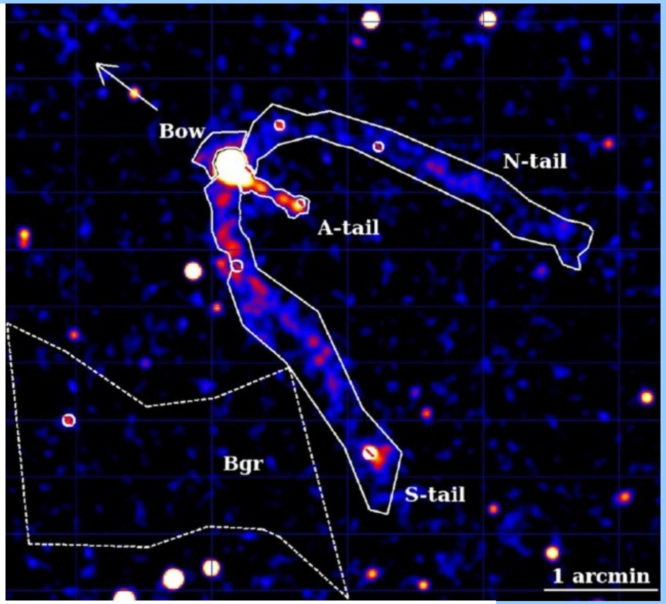
Proper velocity: $v_{\perp} = 104.1 \pm 0.2$ km/s (Reardon et al. 2016)

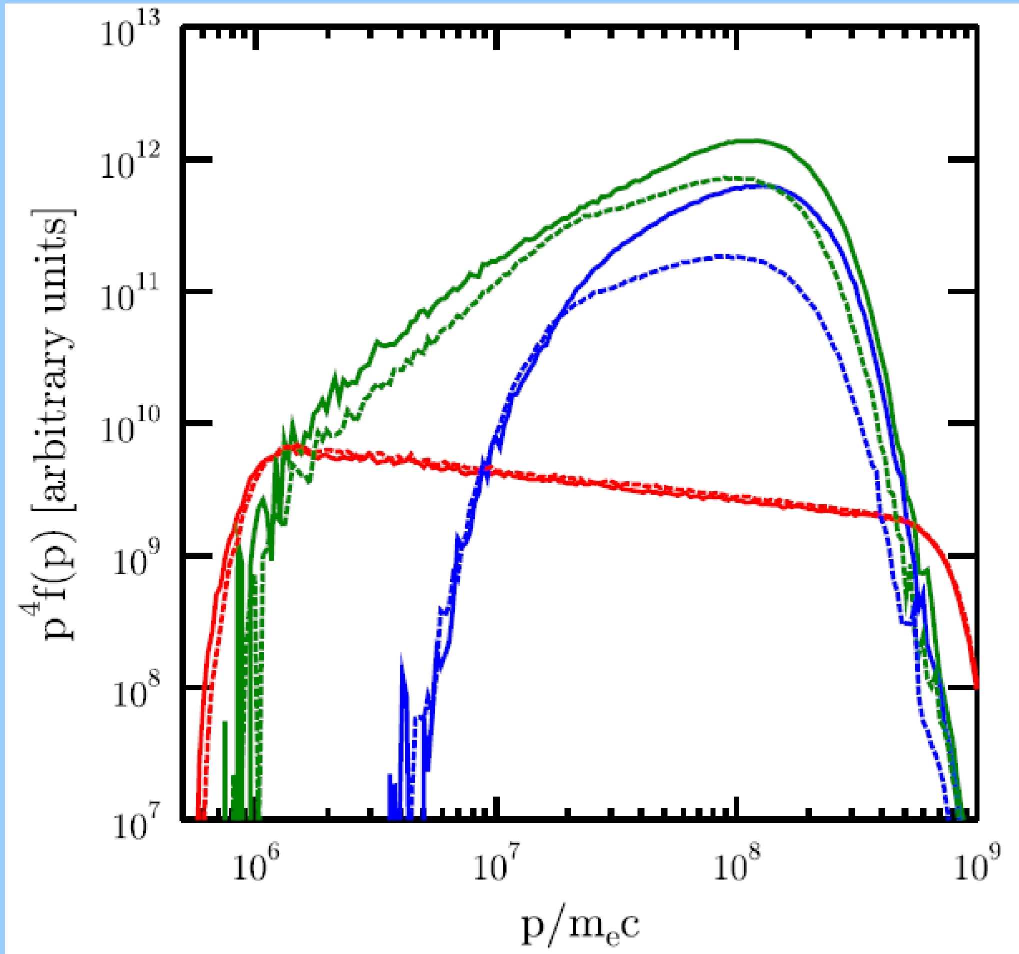
Age: $\tau \sim \tau_{WD} \sim 6$ billion years

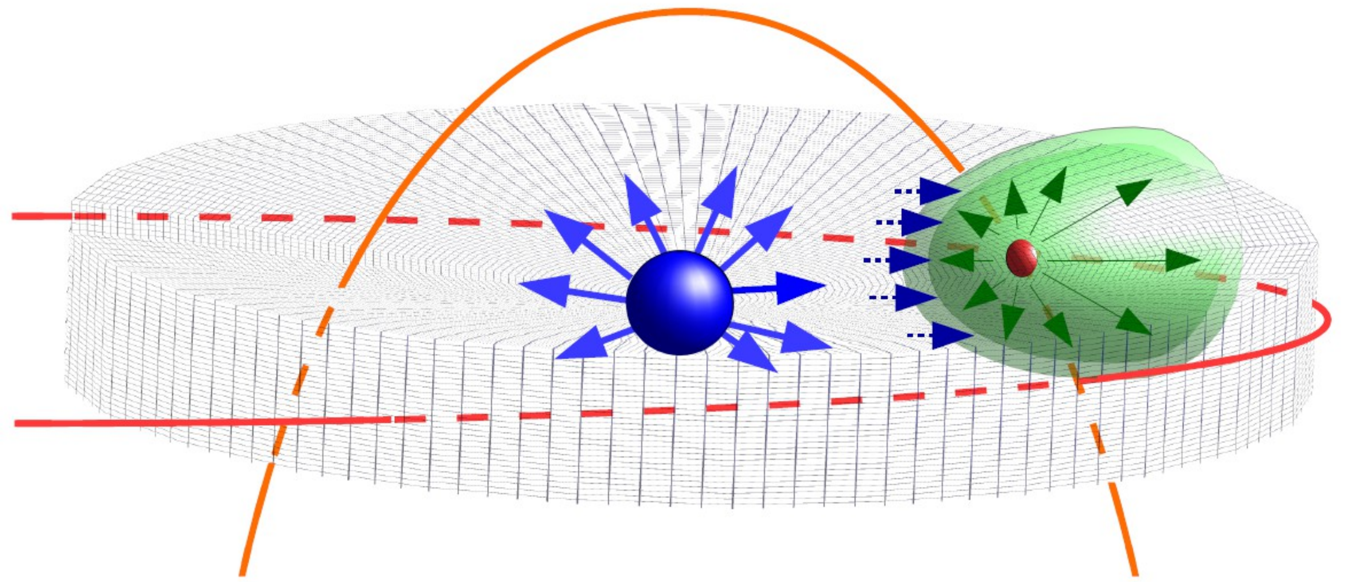
Credit: Brownsberger & Romani (2014), Rangelov et al. (2016)

Fermi I in the colliding flows









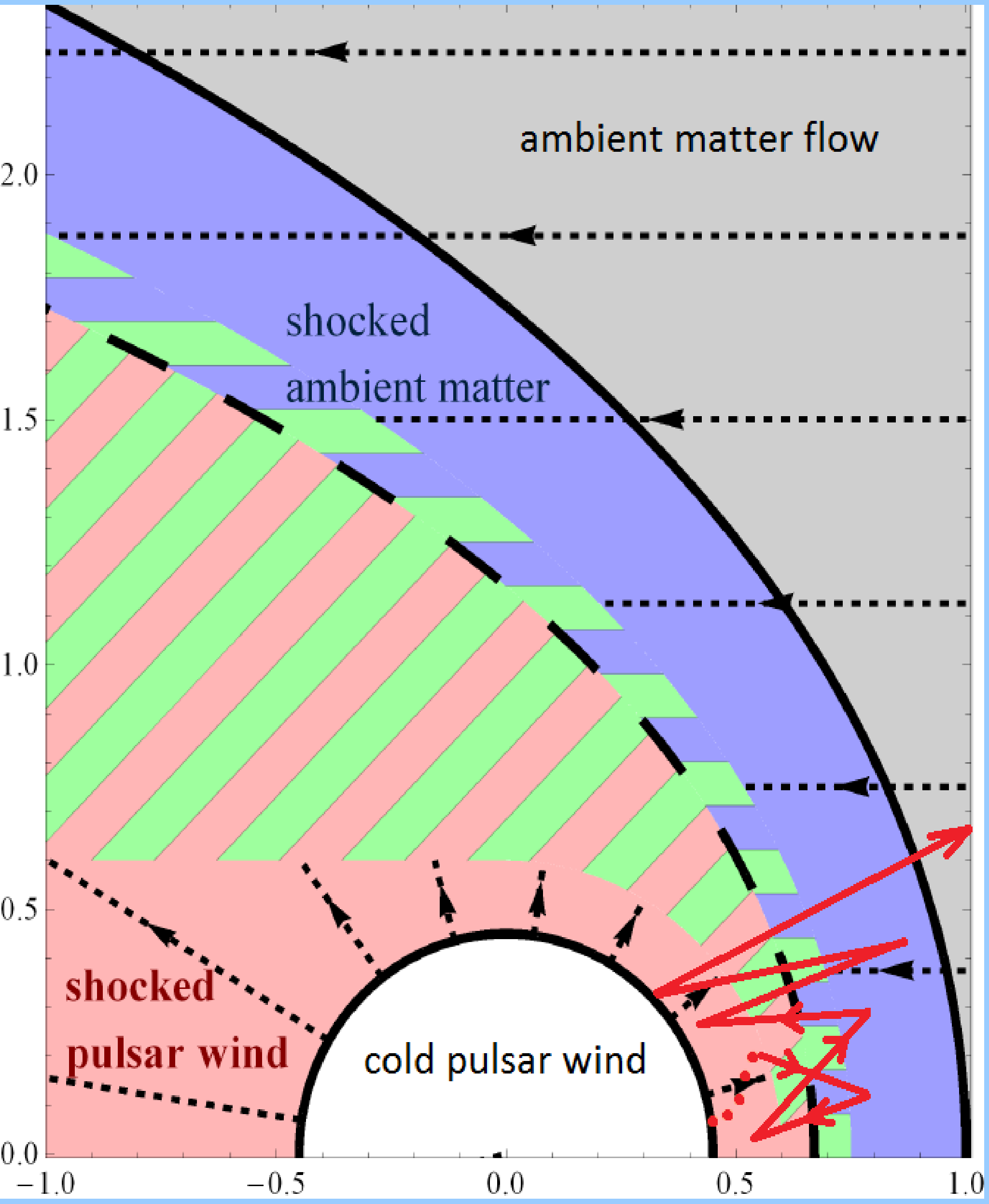
$f(E) \propto E^{-1}$, not E^{-2} and softer

Particle index s=1 gives photon index Γ=(s+1)/2 =1

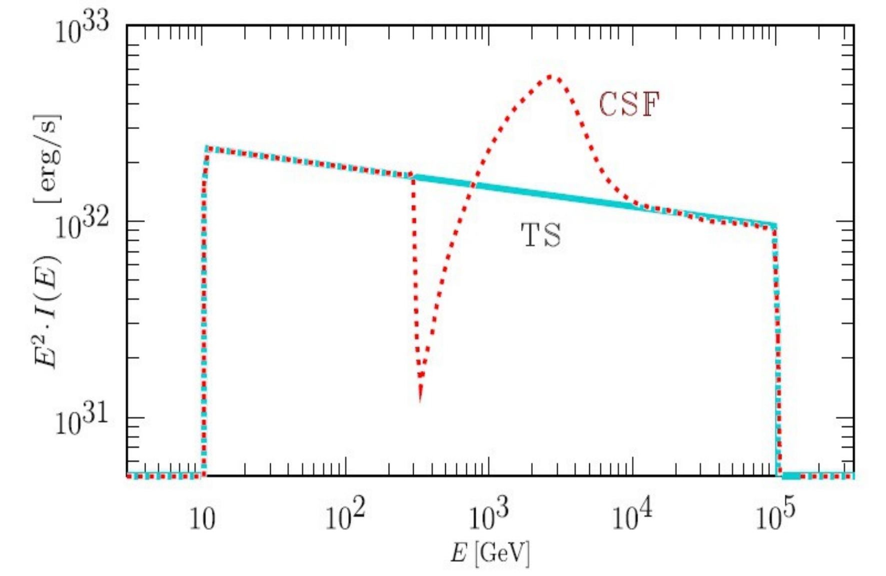
s=1 predicted analytically (Bykov 2005), obtained in simulations

Credit: Bykov et al. (2015), Posselt et al. (2017)

Particle transport in the colliding flows: modeling

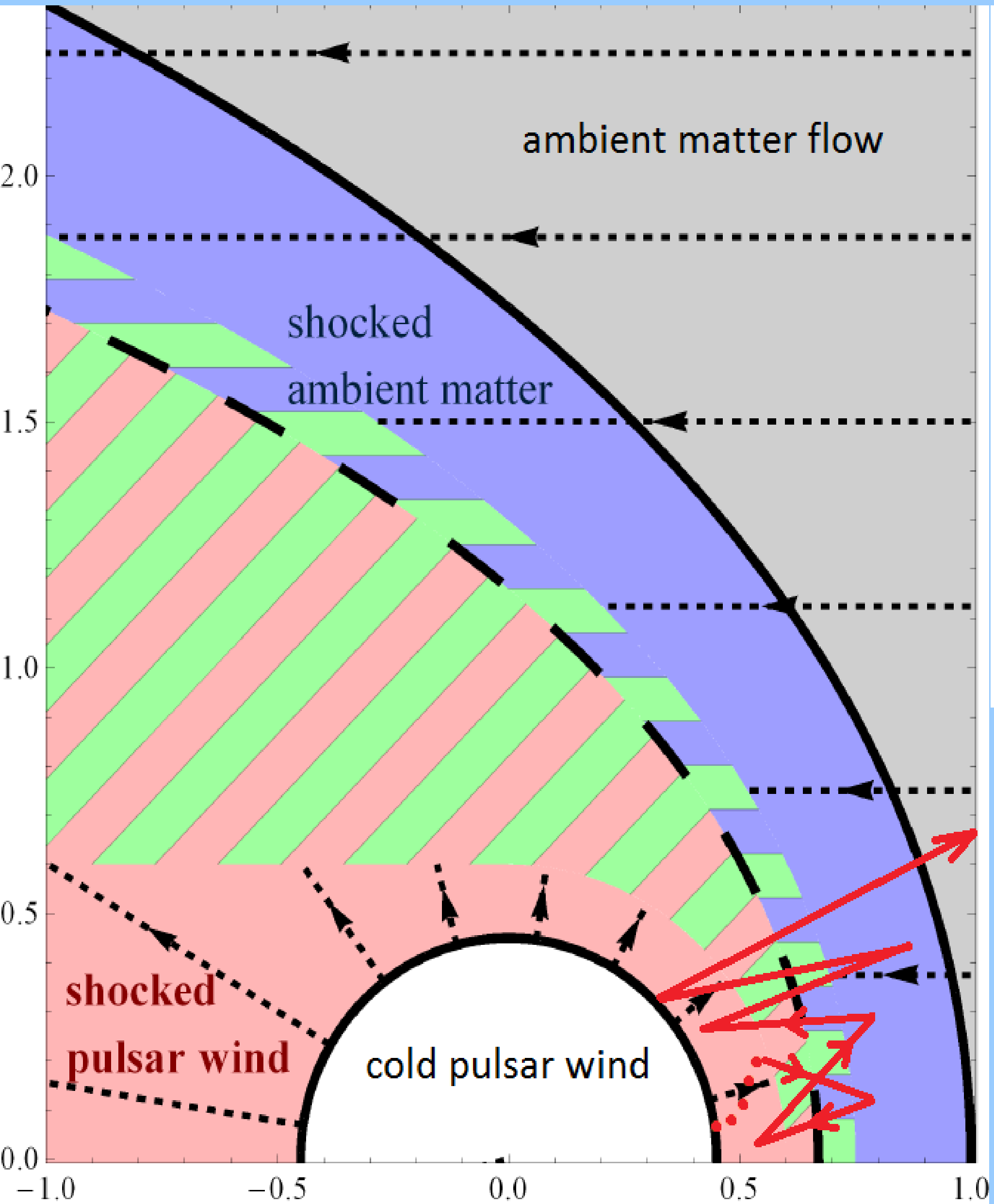


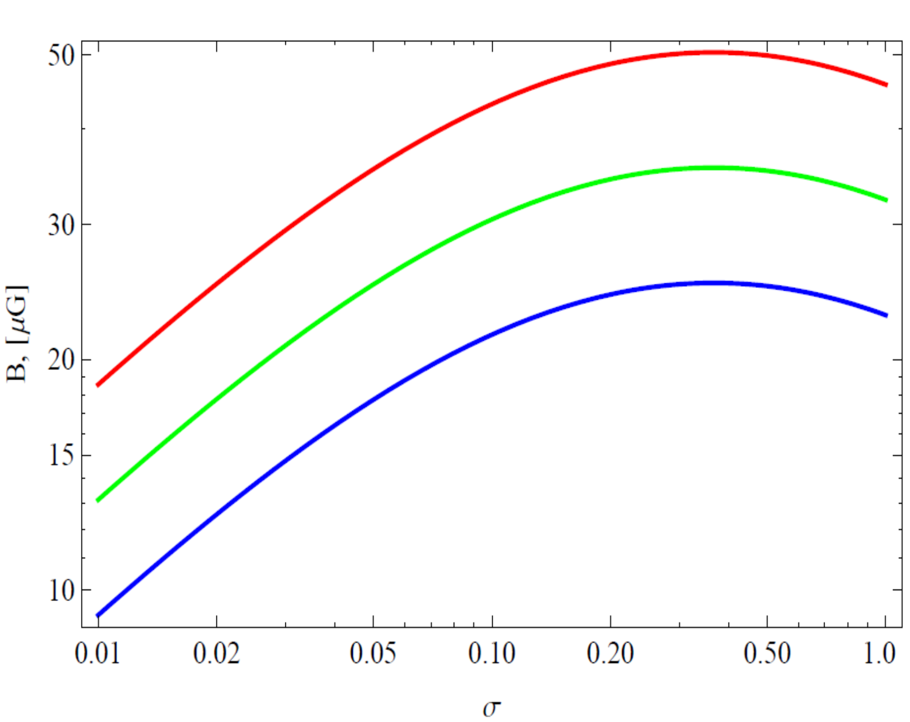
- Model takes into account the BSPWN structure
  - 3D model
  - regions with defined magnetic fields, velocities, diffusion parameters with realistic shapes
  - accurate account for particles escape from the simulation area
- Particles injected at the pulsar wind termination shock $f(E) \propto E^{-2.1-2.3}$
- Transport = diffusion and advection in the model structure of flows. Scatterings – isotropic in the background plasma frame. Propagation until particle crosses the simulation box boundary (free escape)
- «Detection» of model particle distribution over three momentum's components
  - Significant anisotropy of the distribution function, account for the Doppler effect, resolution of fine structures
  – require long runs to smooth the spectra



Details: Bykov et al. (2017), SSRv, Vol. 207, pp 235-290

Simulation details





$$\lambda = \begin{cases} \eta\, r_g(E), & < E_1 \\ \eta\, r_g(E)\cdot E/E_1, & E < E_1 \end{cases}$$

$r_g(E)$ -- gyroradius of a particle with energy E

E_1 -- model's free parameter

Magnetic field just beyond the termination shock:
Kennel & Coroniti 1984a

$$B_{bow} = \sqrt{\zeta\cdot 8\pi\rho u^2} = 20\,\mu\mathrm{G}\left(\frac{\zeta}{0.1}\right)^{1/2}\left(\frac{n_{ism}}{0.2\ \mathrm{cm}^{-3}}\right)^{1/2}\left(\frac{u_{psr}}{180\ \mathrm{km\ s}^{-1}}\right)$$

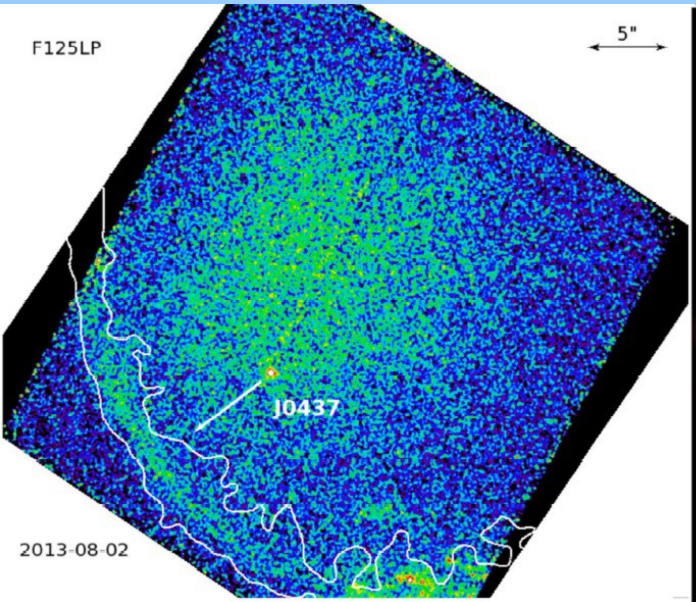
Normalization of the model fluxes of accelerated particles – via simulation of the PWN's non-thermal emission spectra

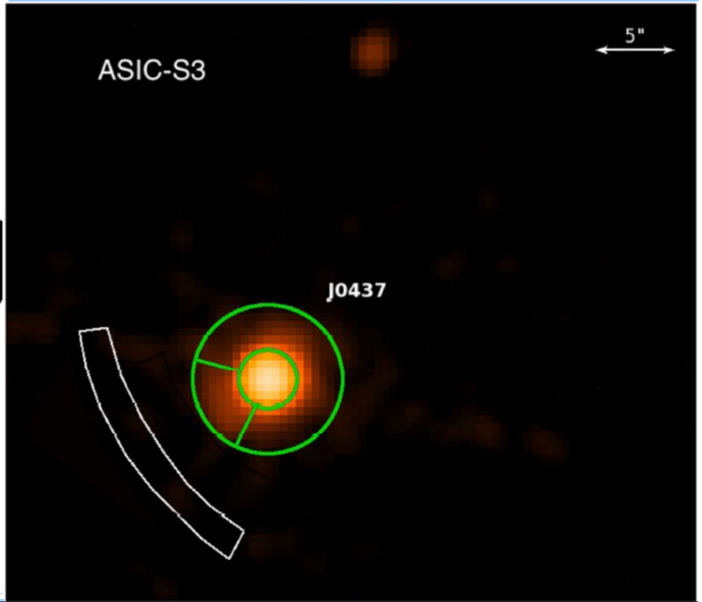
$$J_{cgs} = \frac{F_{obs}^{cgs}}{F_{code}} J_{code}$$

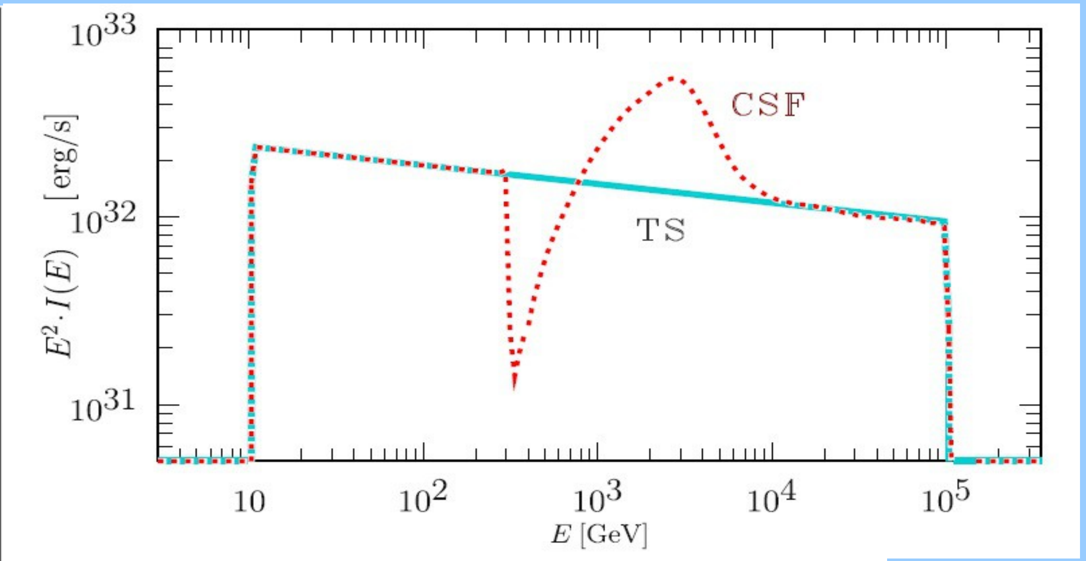
We DO NOT PRESCRIBE MANUALLY the spin-down fraction that is required to produce our fluxes. We calculate it from the PWN's emission modeling!

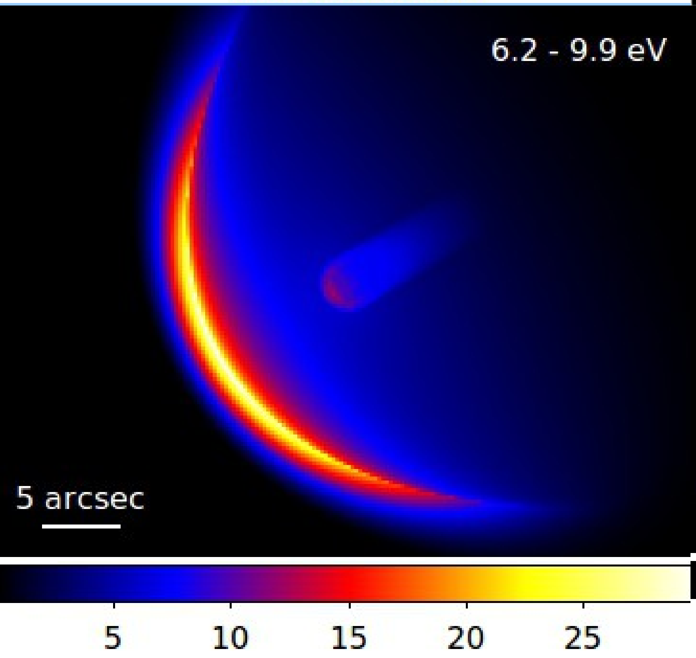
More details: (1) Bykov et al. (2017), SSRv, Vol. 207, pp 235-290; (2) Bykov et al. (2019), ApJL, 876, L8

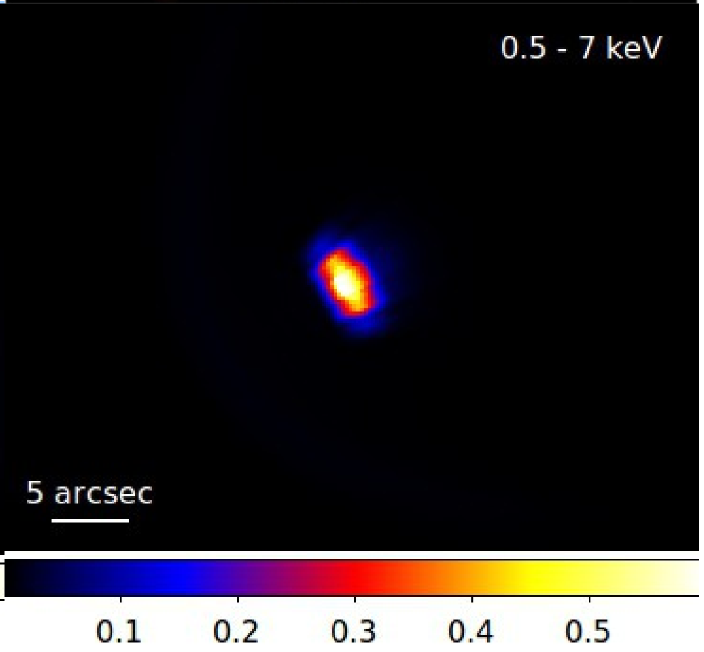
Modeling results: particle acceleration and emission

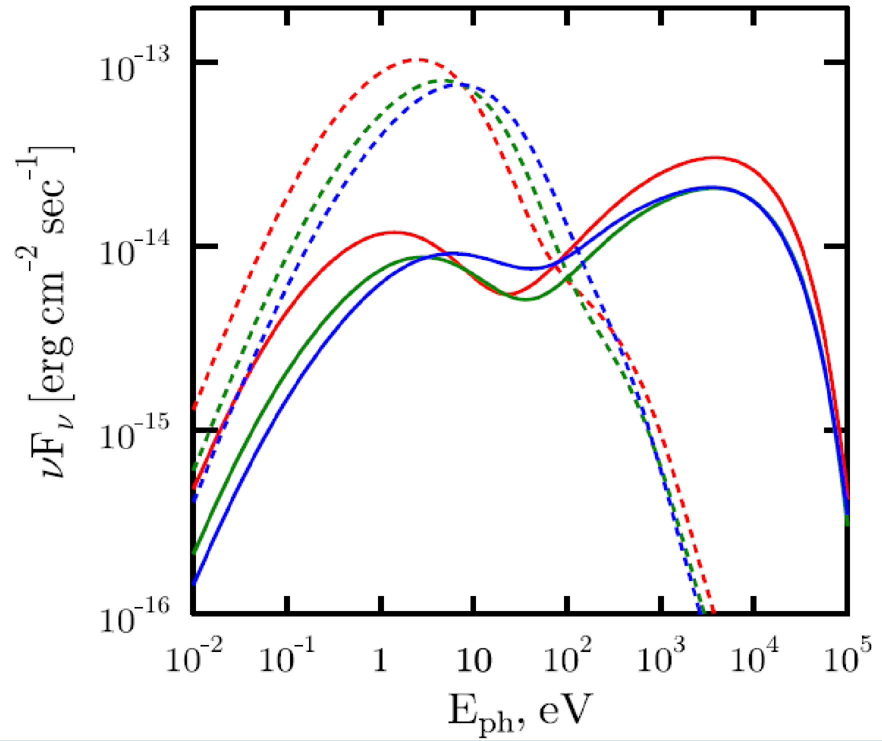








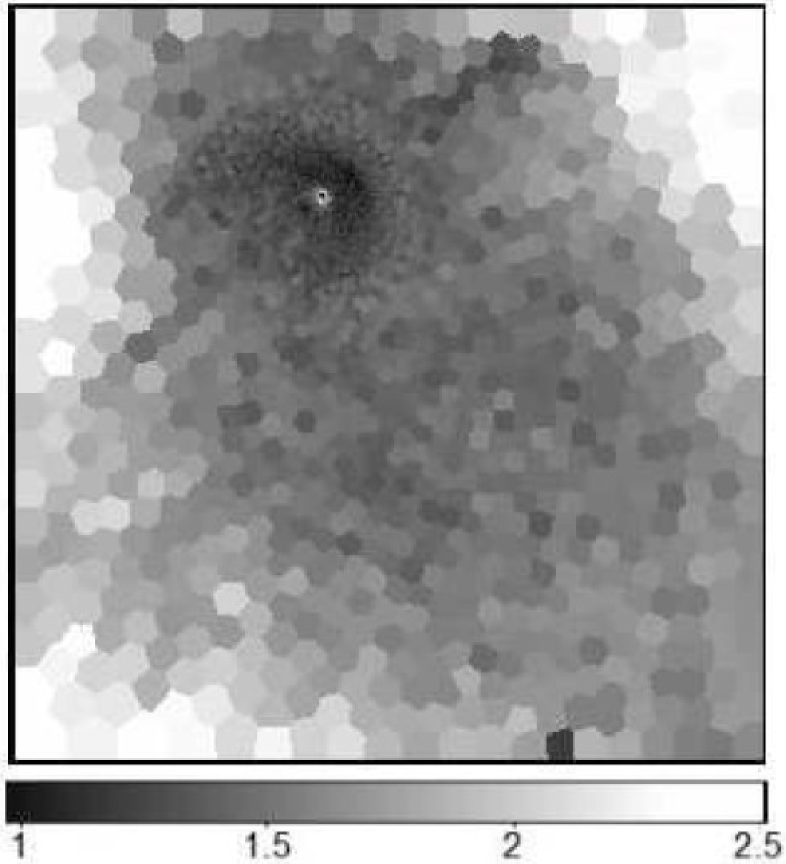


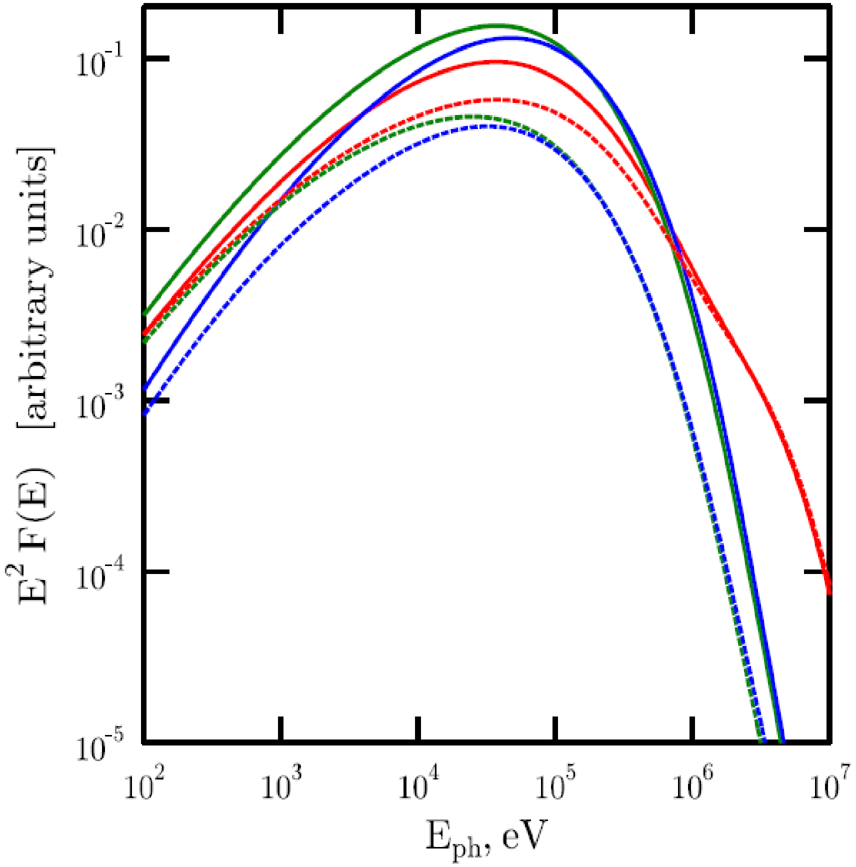


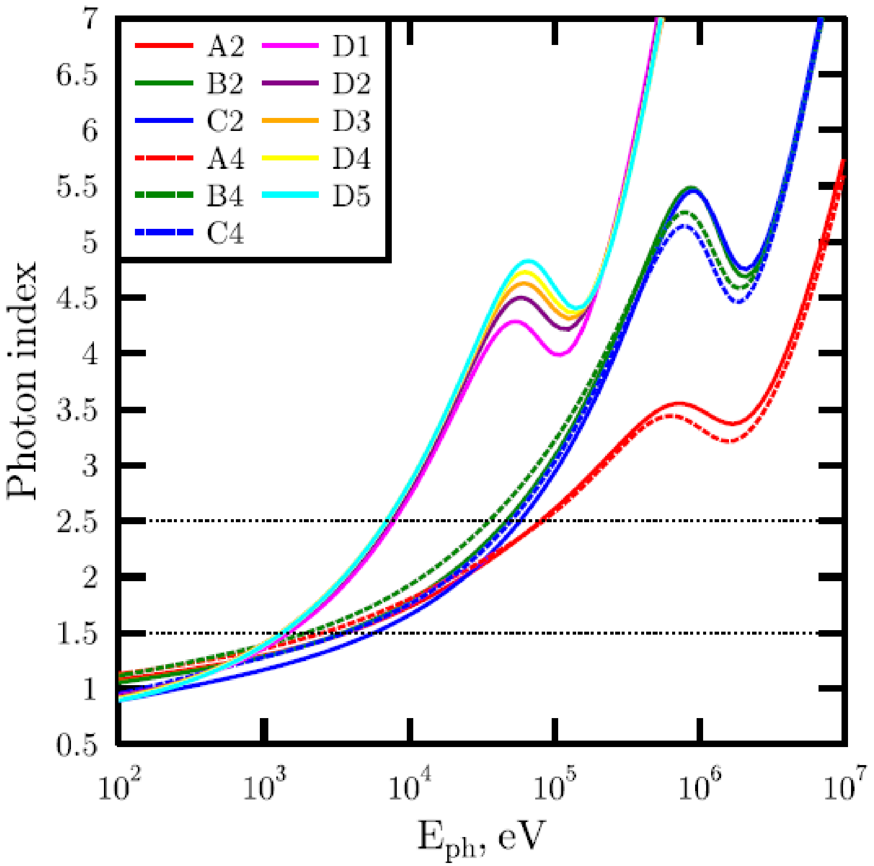
Ratio of modeled luminosities: $L_{FUV}/L_X \sim 1-2$

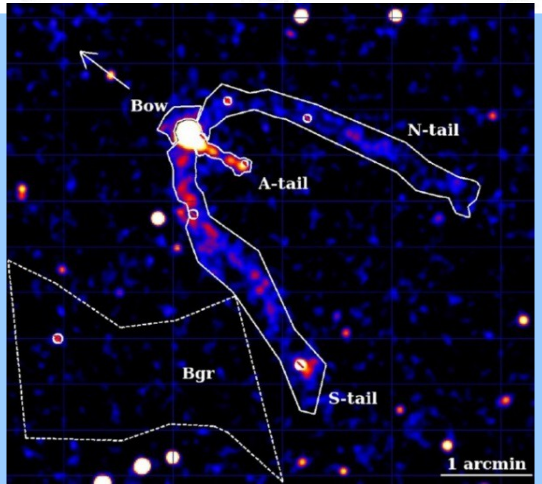
Observations (top row): Rangelov et al. (2016)

Acceleration in colliding flows and hard spectra









- The model explains the hard photon indices Γ<1.5 observed in the Vela pulsar nebula. The spectral energy distributions of the PWN's emission peak at several tens of keV, in agreement with Mattana et al. (2011)
- The model allows to explain the spatial distribution of photon indices observed in the Geminga pulsar nebula: hard indices ≈1 near the bow shock, softer indices ≈1.6 in the middle tail behind the pulsar

Details: Bykov et al. (2017), SSRv, Vol. 207, pp 235-290;

Obervations: Kargaltsev & Pavlov (2008), Posselt et al. (2017)

Diffusion in the local interstellar medium

- Diffusion coefficients(Casse et al., 2001)

$$D_{\|}(R) = 2 \times 10^{27} \left(\frac{R}{1\,\mathrm{GV}}\right)^{1/3} \mathrm{cm^2 s^{-1}}$$
$$D_{\perp}(R) \approx 0.03 D_{\|}(R)$$

- Galactic coordinates of PSR J0437-4715

$$(l, b) = 253°, -43°$$

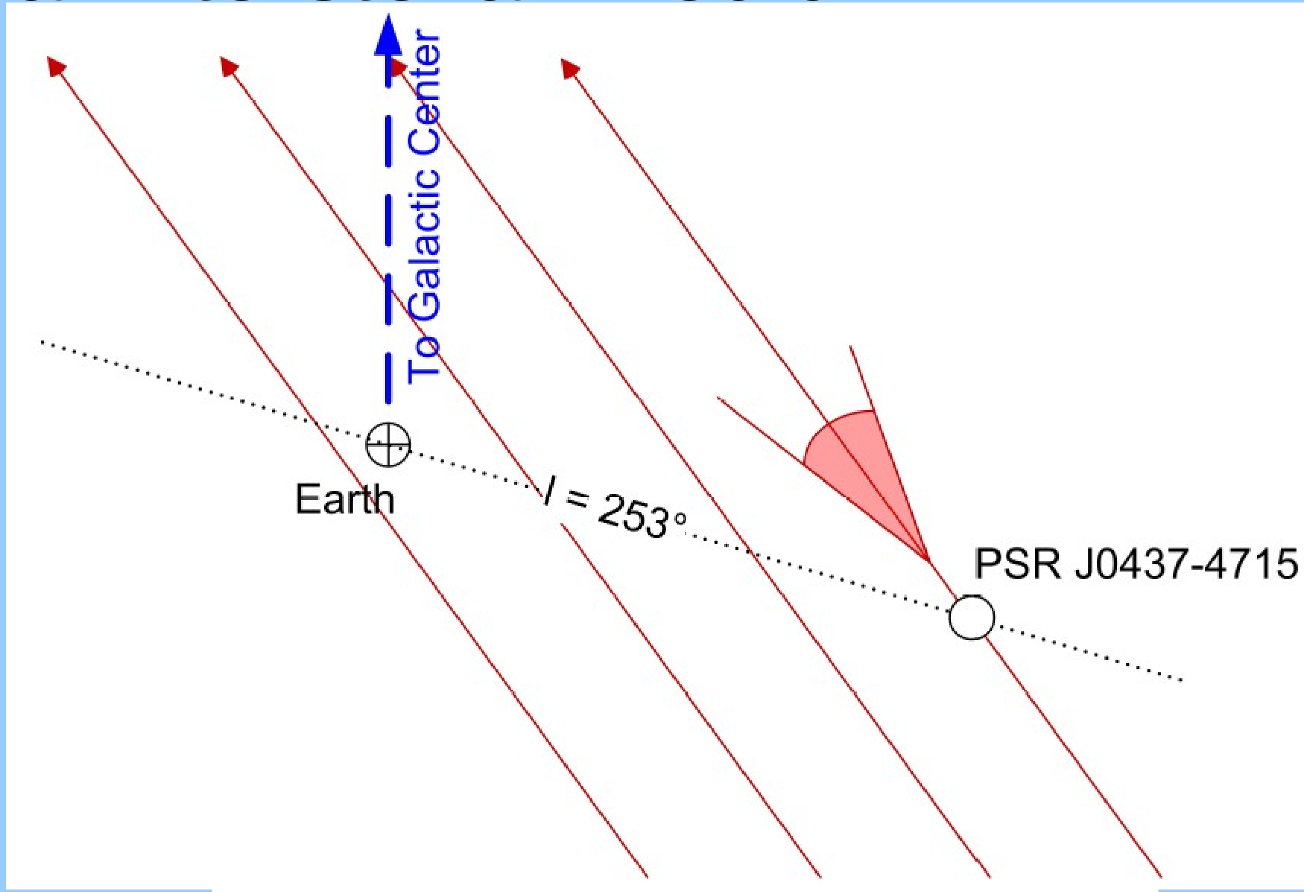
- Local ISM magnetic field direction (Frisch et al. 2015):

$$(l, b) = 36.2°, 49.0° (\pm 16.0°)$$

- Radiative losses: synchrotron

$$(B \sim 3 - 5\ \mu\mathrm{G})$$

and inverse Compton emission



photon field	T(K)	U(eV/cm^3)
CMB	2.7	0.26
IR	20	0.3
Optical	5000	0.3

Table: Tang & Piran (2019)

Diffusion in the local interstellar medium: modeling

Stationary convection-diffusion equation with a point source:

$$\frac{\partial F}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(rD_\perp \frac{\partial F}{\partial r}\right) + \frac{\partial}{\partial z}\left(D_\| \frac{\partial F}{\partial z}\right) + \frac{\partial}{\partial p}(\dot{p}F) + Q = 0$$

$$Q = J(p)\delta(\boldsymbol{r})$$

Equal momentum dependency:

$$D_\| = D_{\|,0}\, g(p); \quad D_\perp = Const(p)\cdot D_\|$$

$$\zeta = z/\sqrt{D_{\|,0}T_0}, \quad \rho = r/\sqrt{D_{\perp,0}T_0}, \quad \tau = t/T_0$$

$$\gamma = p/mc\,, \qquad f(\gamma) = \frac{F(p)p^2}{c}, \qquad \tilde{b}(\gamma) = -T_0 b(p), \qquad \tilde{g}(\gamma) = g(p)$$

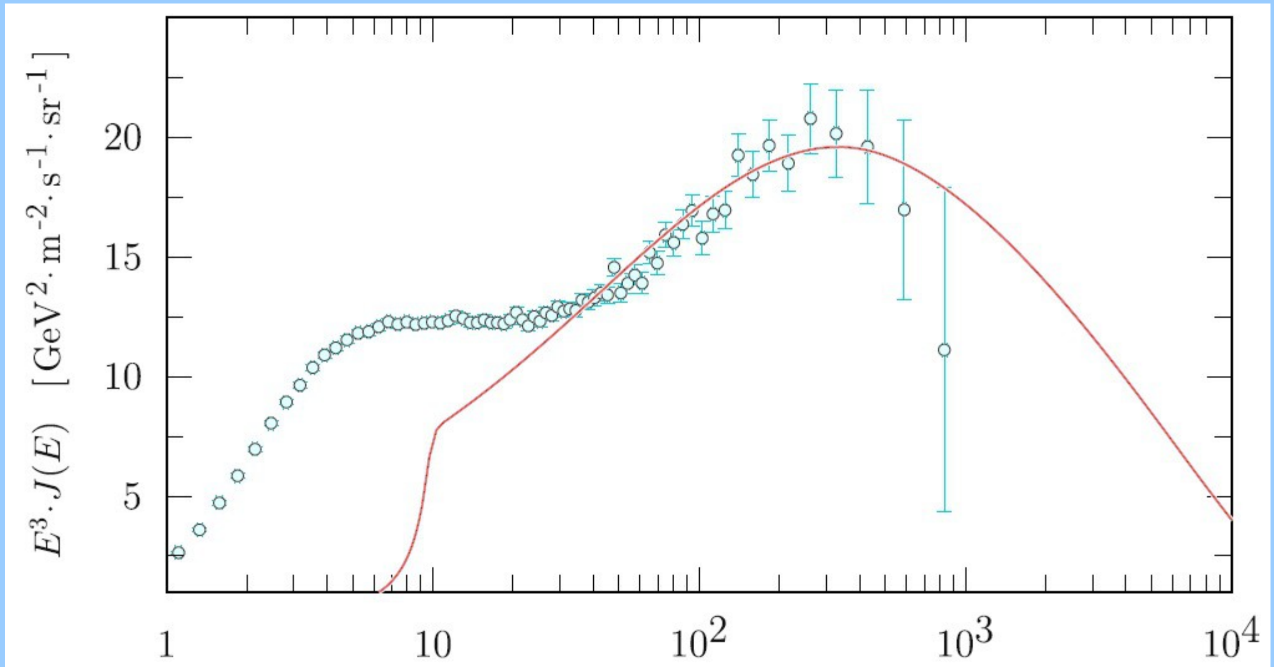
Solution (following Ginzburg & Syrovatskii 1963):

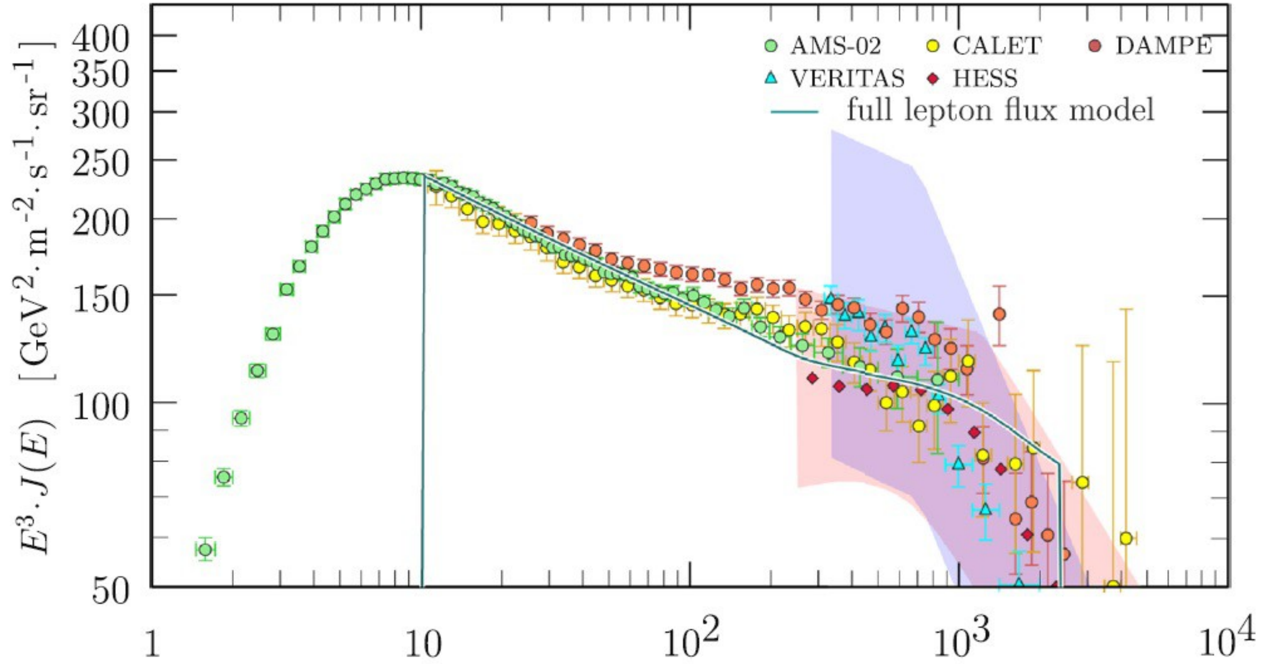
$$f = \frac{1}{cD_{\perp,0}\sqrt{D_{\|,0}T_0}} \int_0^\infty d\gamma_0 \cdot p_0^2 J(p_0) \cdot \frac{\Theta[\chi(\gamma,\gamma_0)]}{\left(4\pi\lambda(\gamma,\gamma_0)\right)^{3/2}\tilde{b}(\gamma)} \cdot exp\left[-\frac{\rho^2+\zeta^2}{4\lambda(\gamma,\gamma_0)}\right]$$

$$\chi(\gamma,\gamma_0) = \int_{\gamma_0}^{\gamma} \frac{d\gamma'}{\tilde{b}(\gamma')}; \quad \lambda(\gamma,\gamma_0) = \int_{\gamma_0}^{\gamma} \frac{\tilde{g}(\gamma')d\gamma'}{\tilde{b}(\gamma')};$$

Θ – Heaviside function

Modeling results





- The simulated positron flux in the vicinity of the Solar System (excluding modulation by the solar wind, which is insignificant at energies above several tens of GeV) in comparison with the AMS-02 data
- Model of the total lepton flux: contribution from PSR J0437-4715 + model "background" spectrum from other sources. Power-law models of the AMS-02 collaboration (Aguilar et al. 2014) with indices 2.94 and 3.25 are taken as the background
- To produce required flux from PSR J0437-4715 only 15-30% of pulsar's spin-down power is needed

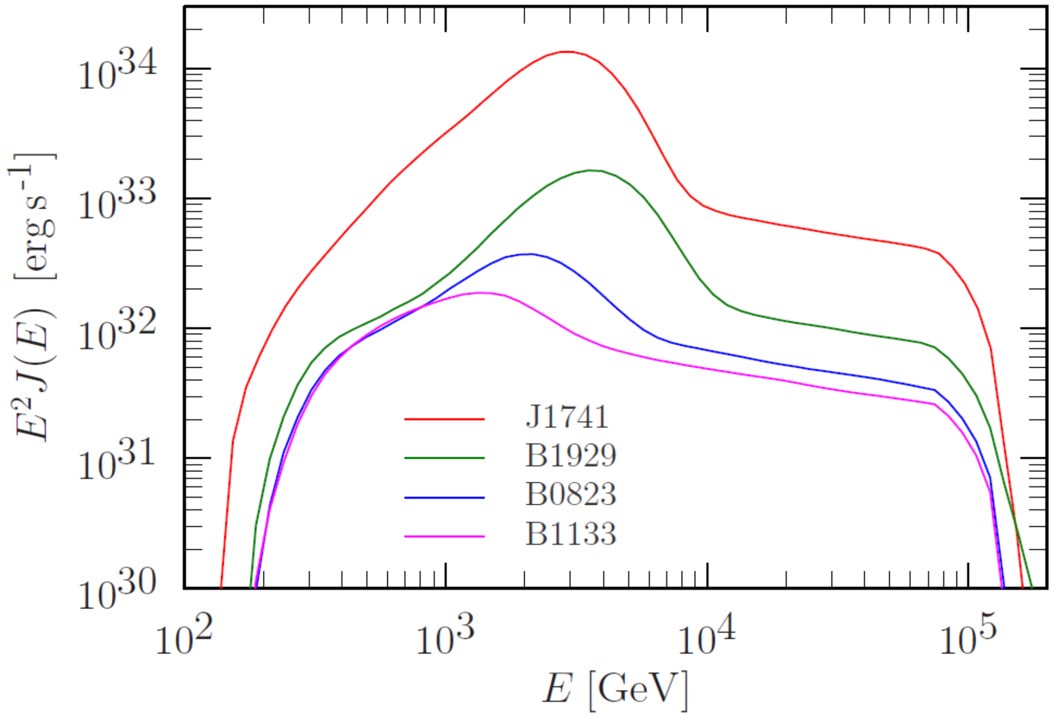
Details: Bykov et al. (2019), ApJL, 876, L8

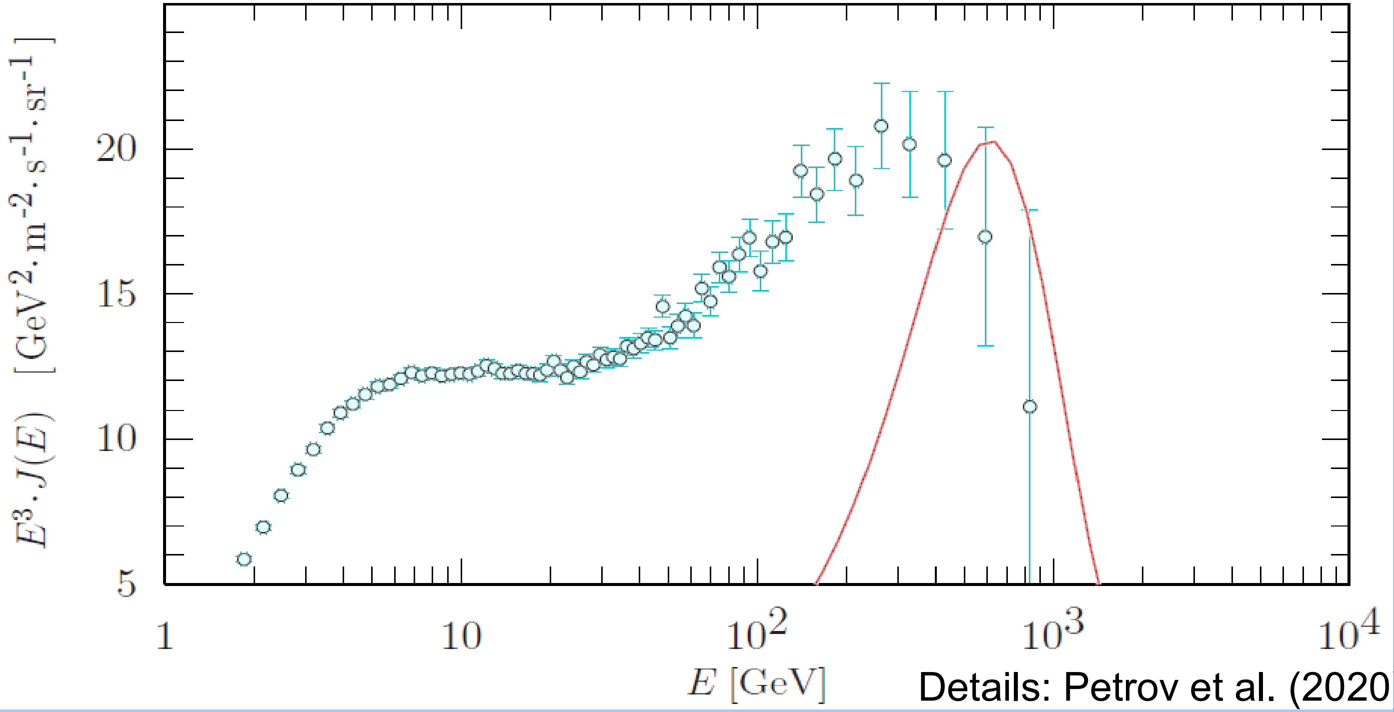
Possible contributions from other nearby pulsars

Vela PWN:
d ~ 300 pc (close!)
$\dot{E}$ ~ 7x10^{36} erg /s (excellent!)
τ ~ 11 kyr (too young... the observed PWN is even younger)

PSR J1741-2054:
d ~ 380 pc
$\dot{E}$ ~ 9.5x10^{33} erg /s
τ ~ 390 kyr

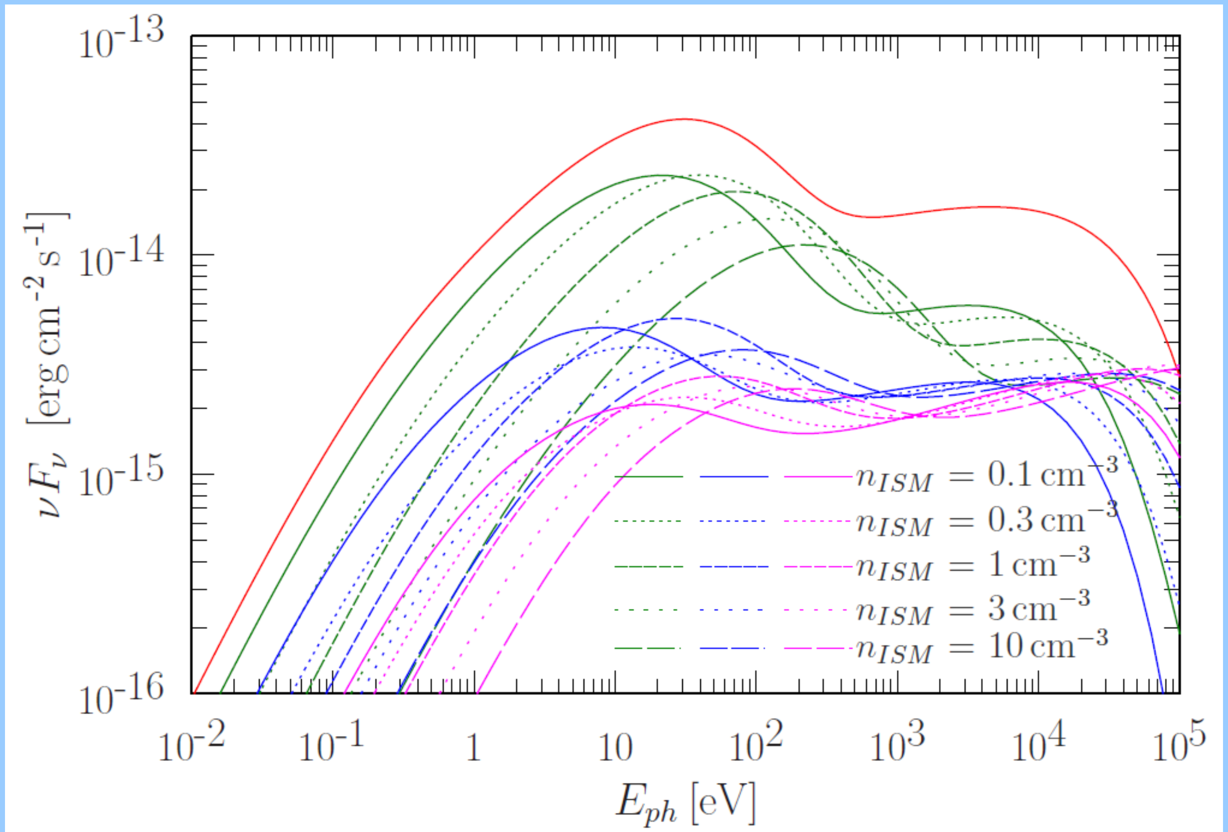
	PSR J1741-2054	PSR B1929+10	PSR B0823+26	PSR B1133+16
$\dot{E}$, erg s^{-1}	9.5×10^{33}	3.9×10^{33}	4.6×10^{32}	8.8×10^{31}
u_{psr}, km s^{-1}	196 ± 18	177^{+4}_{-5}	194 ± 41	631 ± 30
d, pc	380	361^{+10}_{-8}	340	360 ± 19
N_H, cm^{-2}	1.2×10^{21}	1.7×10^{21}	6×10^{20}	1.5×10^{20}

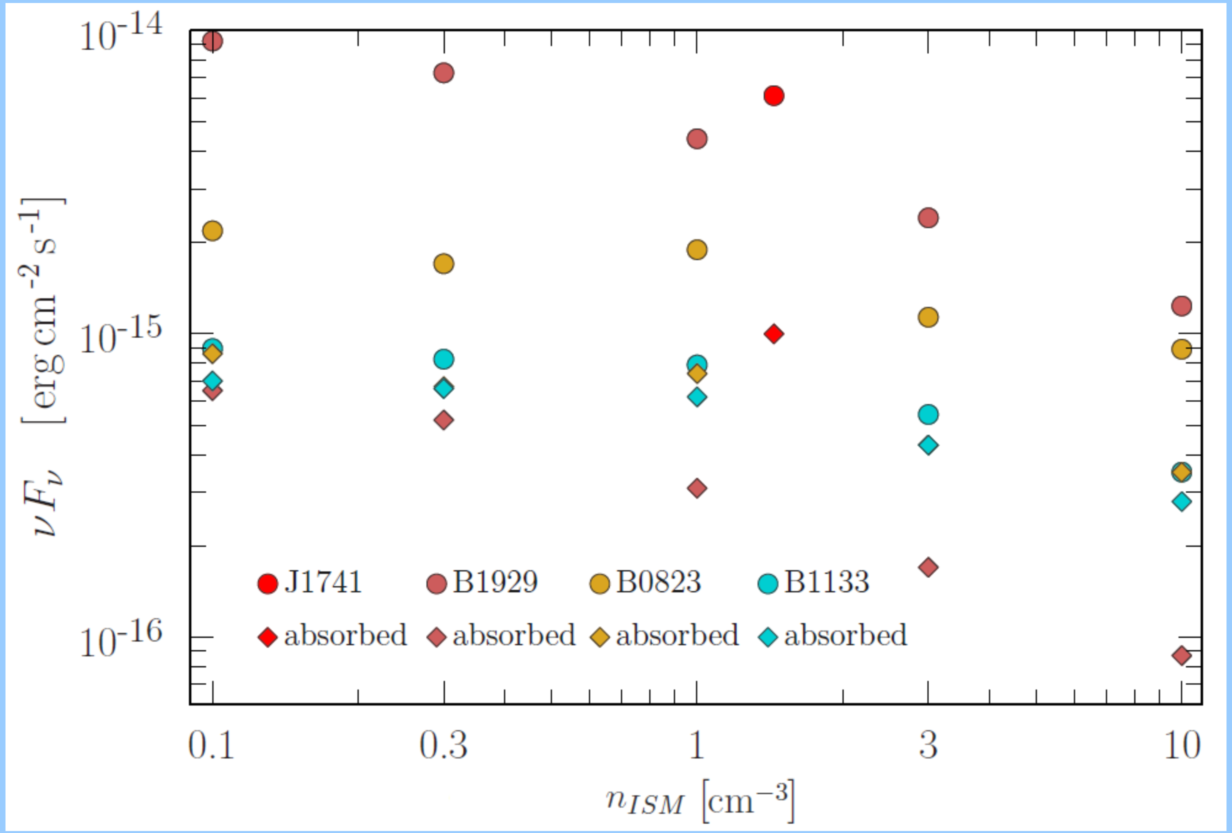




Details: Petrov et al. (2020)

Modeling of synchrotron emission of nearby pulsars





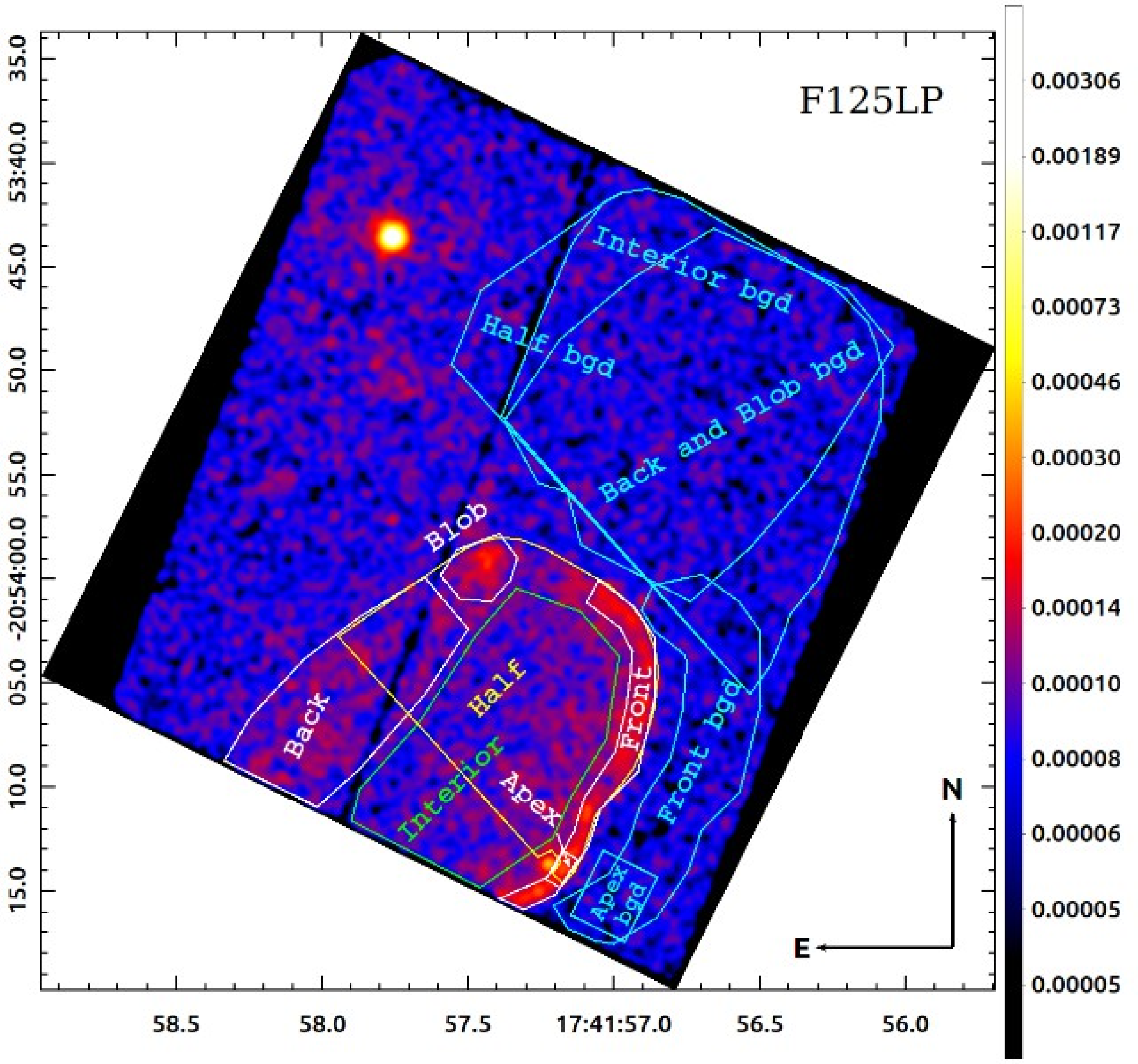
	PSR J1741-2054	PSR B1929+10	PSR B0823+26	PSR B1133+16
$\dot{E}$, erg s^{-1}	9.5×10^{33}	3.9×10^{33}	4.6×10^{32}	8.8×10^{31}
u_{psr}, km s^{-1}	196 ± 18	177^{+4}_{-5}	194 ± 41	631 ± 30
d, pc	380	361^{+10}_{-8}	340	360 ± 19
N_H, cm^{-2}	1.2×10^{21}	1.7×10^{21}	6×10^{20}	1.5×10^{20}

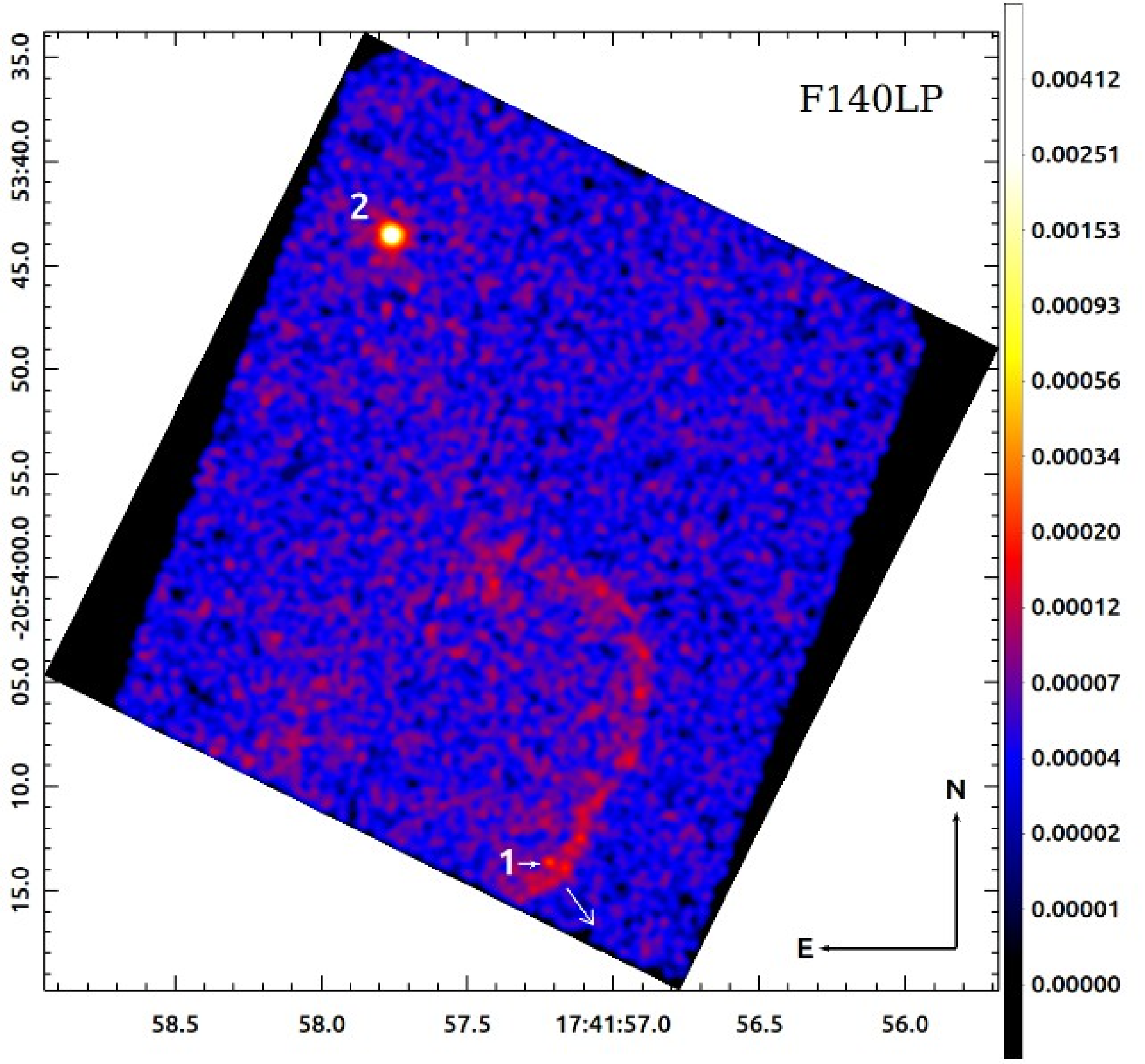
FUV: 125-200 nm, 6-10 eV

We predicted that the bow shock PWN of PSR J1741-2054 can be observed in FUV

Details: Petrov et al. (2020)

FUV bow shock in PSR J1741-2054: detected!





Credit: Abramkin et al., 2025, A&A, Vol. 696, id.A121

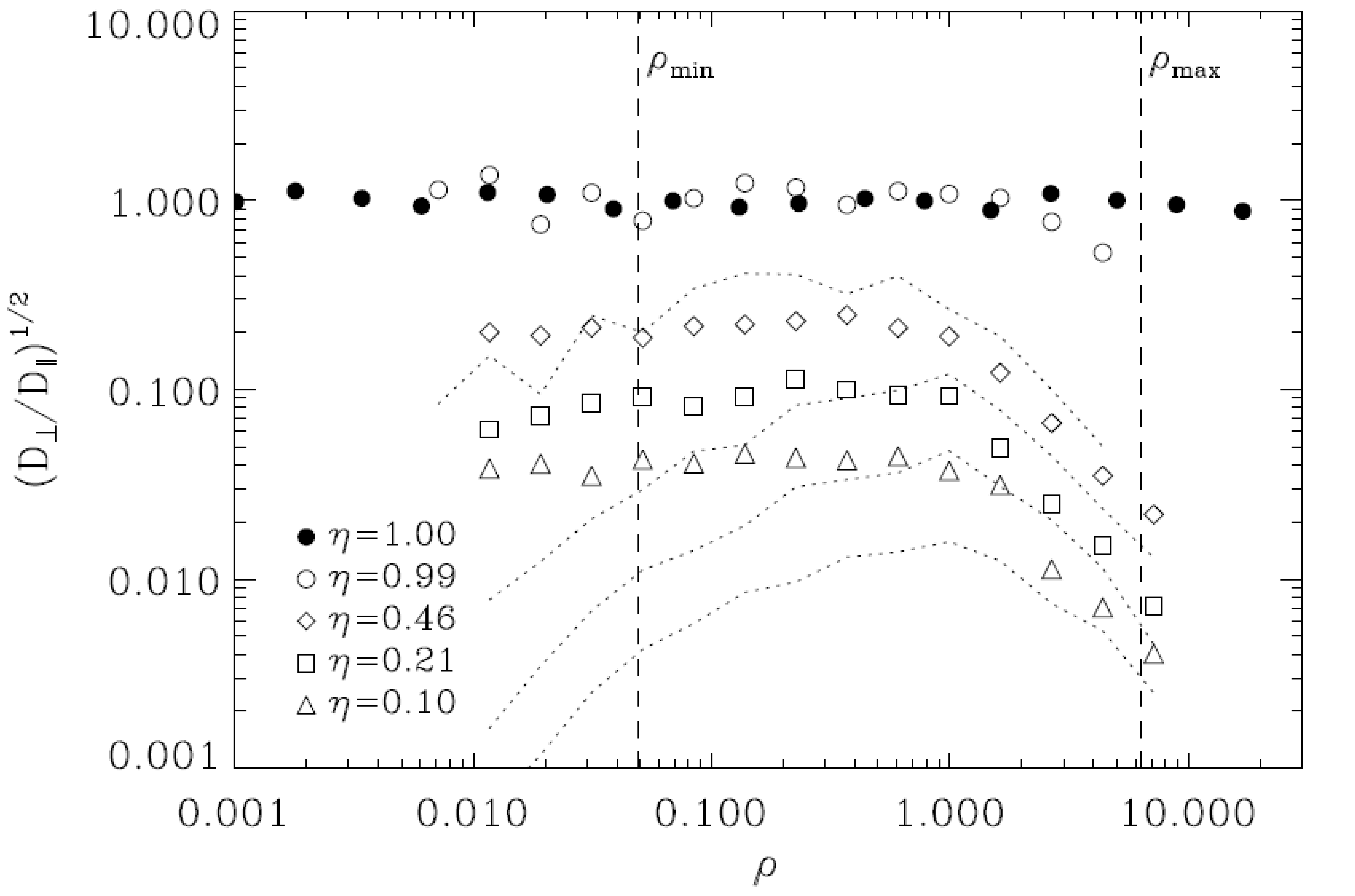
Conclusions

- According to our modeling, PSR J0437-4715 can produce the CR positron flux detected by AMS-02 from tens GeV to 1 TeV. The corresponding model lepton (positron+electron) flux does not contradict data of AMS-02, CALET, DAMPE, VERITAS, HESS
- To produce the total lepton flux from PSR J0437-4715 only 15-30% of pulsar's spin-down power is needed
- The most likely source of the positron excess observed by PAMELA and AMS-02 is the nearest millisecond pulsar to the Earth, PSR J0437-4715. Other nearby pulsars also may contribute in the measured positron flux at hundreds GeV

Thanks for your attention!

A.E. Petrov acknowledges support from the Foundation for the Advancement of Theoretical Physics and Mathematics «BASIS» (grant No. 24-1-3-28-1)

Casse et al. (2001)



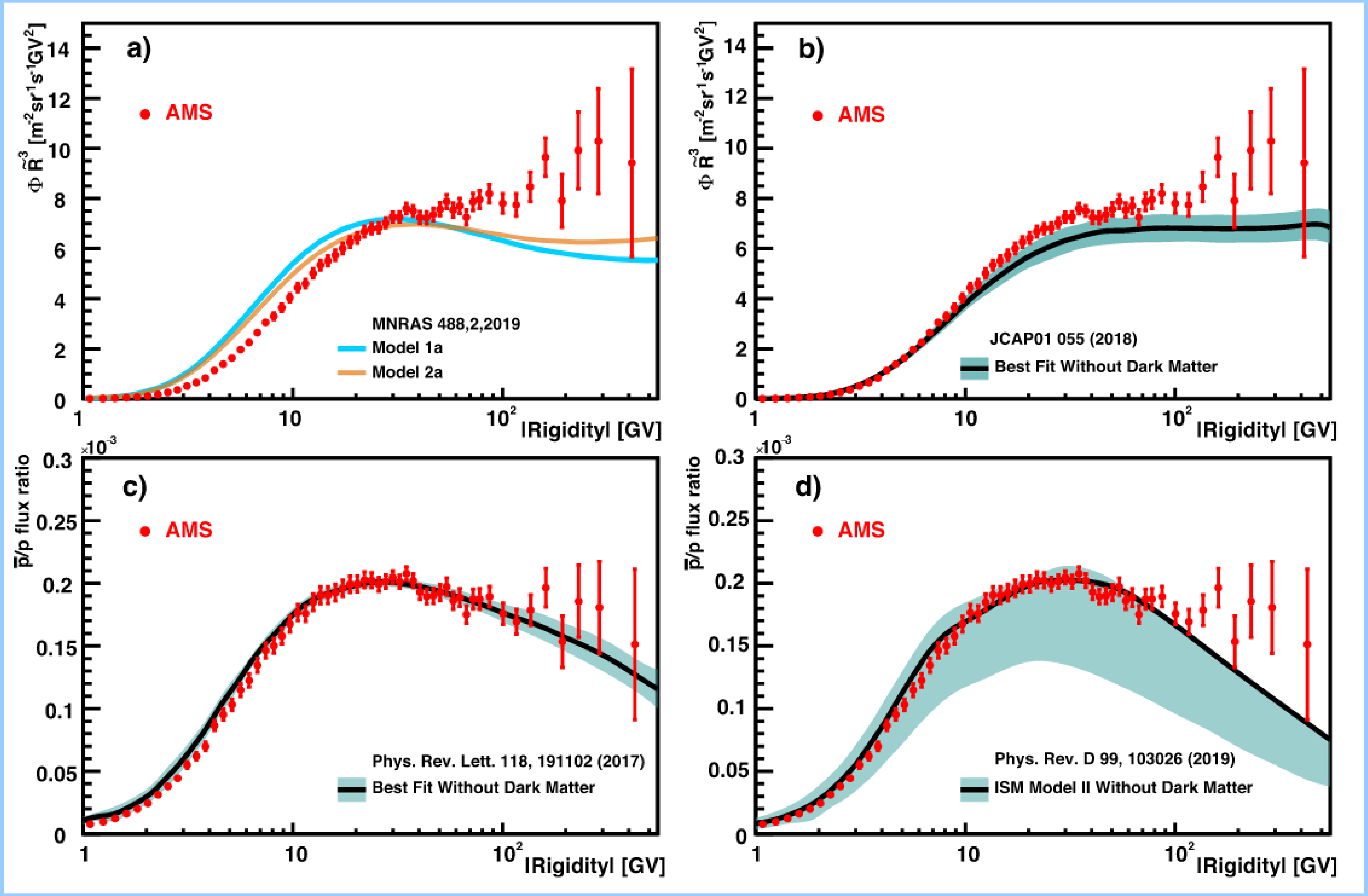
Turbulence:

$$\frac{2\pi}{L_{max}} < k < \frac{2\pi}{L_{min}}$$

$$\rho = 2\pi R_g / L_{max}$$

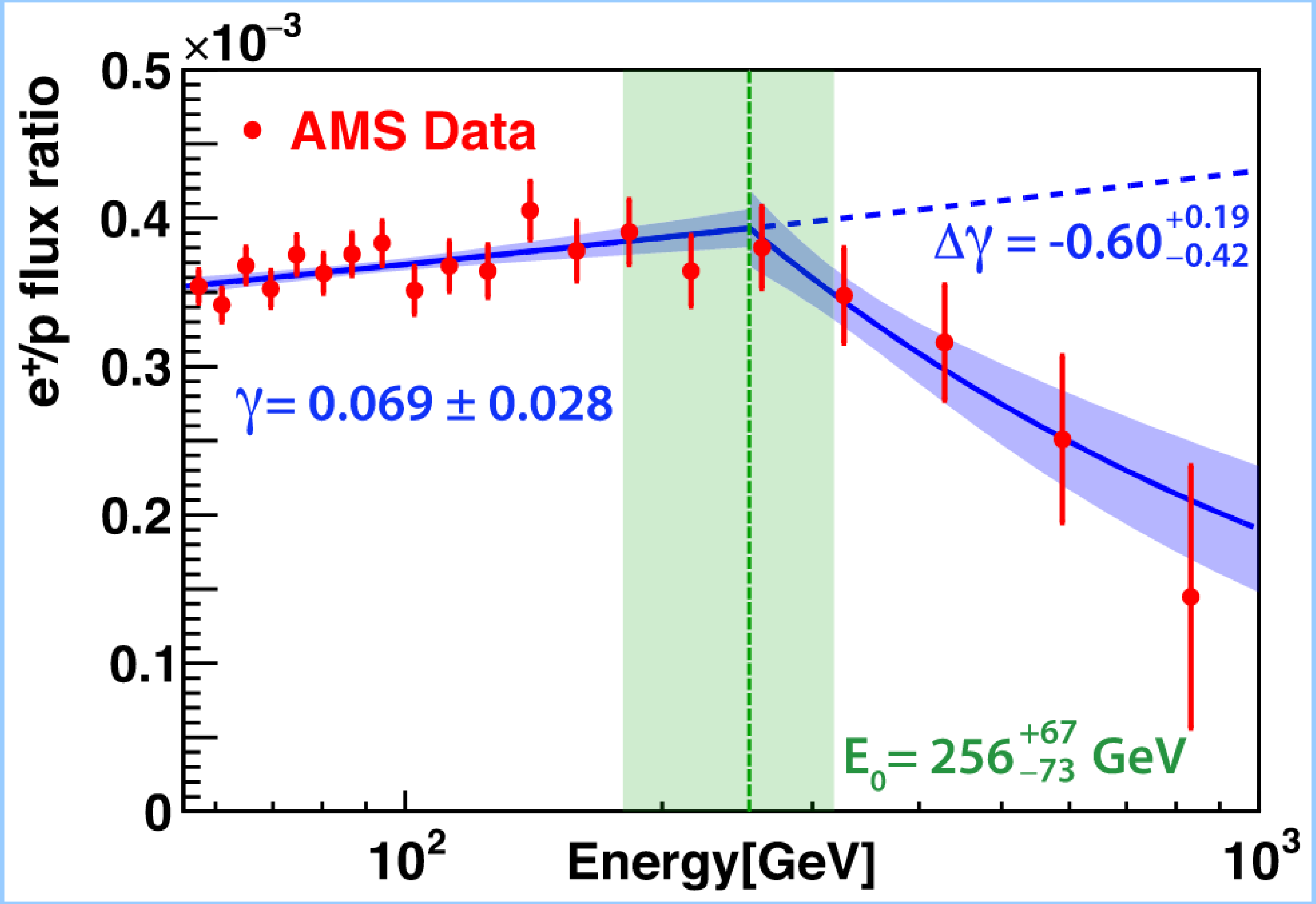
$$\eta = \langle B^2 \rangle / (B_0^2 + \langle B^2 \rangle)$$

Antiprotons vs protons. Ratios of fluxes



Credit: Aguilar et al. (2021)

Positrons vs protons. Ratios of fluxes



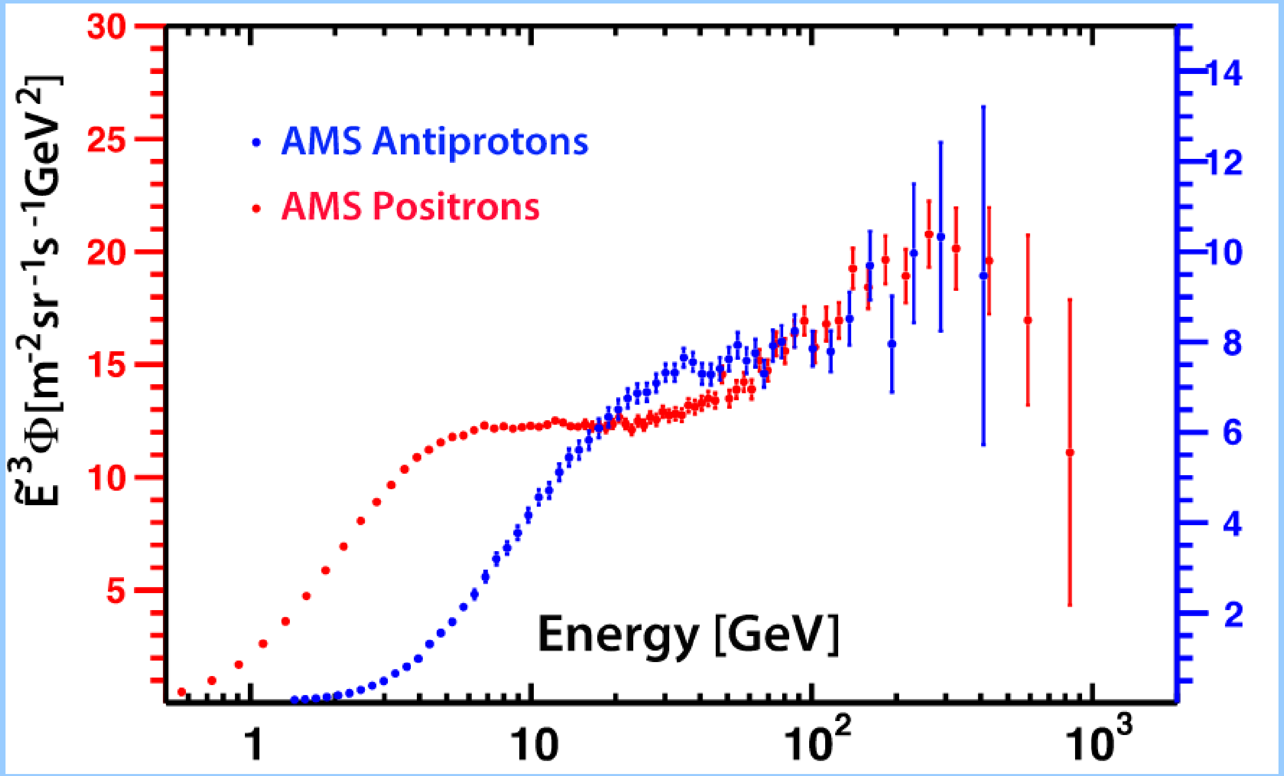
A lot of sources of primary protons vs one local source of primary positrons?

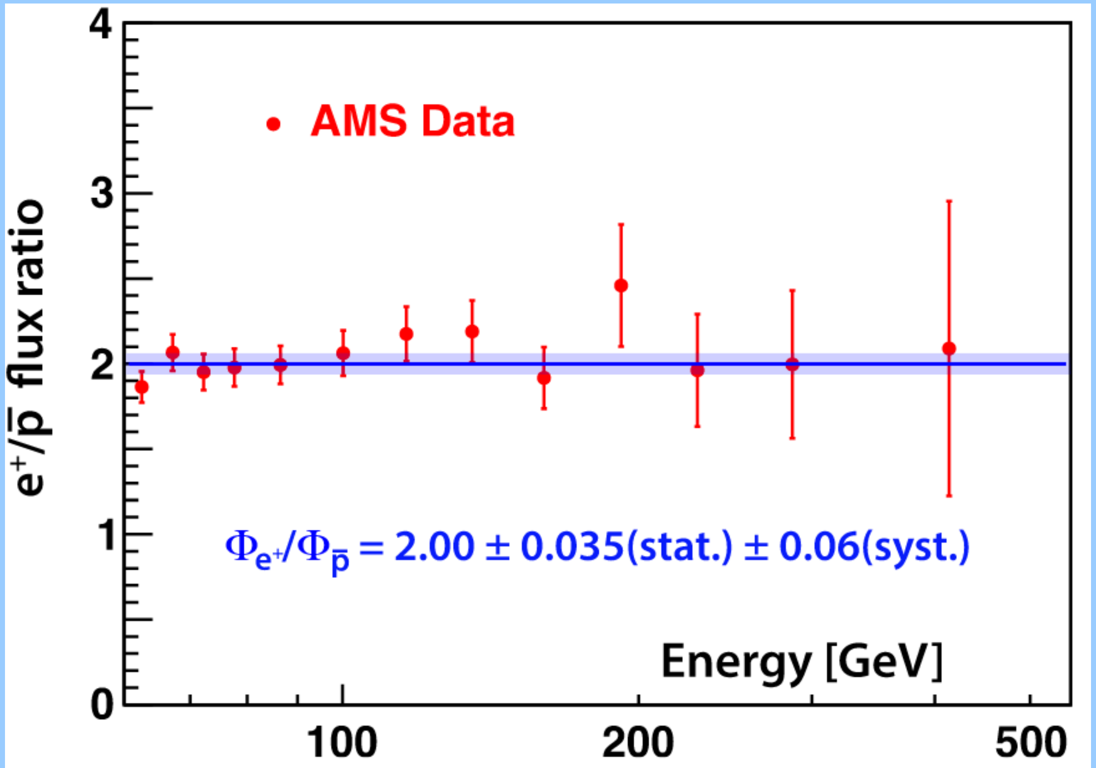
Protons do not suffer from radiative energy losses. Leptons lose energy – different spectra AT HIGH ENERGIES

In principle, protons may be accelerated by the same source!

Credit: Aguilar et al. (2021)

Positrons vs antiprotons. Ratios of fluxes. Bow shock pulsar?





Positrons and antiprotons have almost constant ratio of fluxes at hundred GeV! Antiprotons may be accelerated by the same source – pulsar with bow shock.

Positrons – injected from pulsar, secondary antiprotons – from the interstellar medium. But they have the same accelerator – and finally similar spectra at the Earth!

Credit: Aguilar et al. (2021)