Cosmic-ray self-generated turbulence in galactic sites

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Evoli, Linden and Morlino, PRD 2018, arXiv:1807.09263

Evoli, Amato, Blasi and Aloisio, arXiv:2010.11955

The spatial diffusion coefficient

Jokipii, ApJ 1966

- The transport of CRs in our Galaxy is still better understood in terms of the so-called QLT
- Here we assume that a charged particle propagates in a turbulent B-field which is a small fluctuation with respect to the regular component

$$\langle \delta B^2 \rangle (k) \ll B_0^2 \text{ for } k \gg k_0$$

- As a consequence the particle is subjected to pitch-angle scattering:

$$D_{\mu\mu} = \frac{\pi}{4} \Omega \, k_{\rm res} W(k_{\rm res})$$

where

$$\Omega = \frac{qB_0}{mc\gamma} = \frac{v}{r_L} \quad \text{and} \quad k_{\rm res} = \frac{\Omega}{v\mu}$$

- The particle interacts resonantly with the waves, when the condition $k_{\rm res}^{-1} \sim r_L$ is met
- The isotropisation time $\tau_{\rm s}$ is the time in which particles lose memory of the initial pitch angle

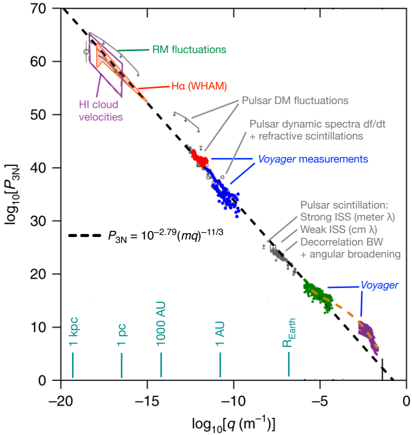
$$\tau_{\rm s} \simeq \frac{1}{D_{\mu\mu}} \simeq \frac{1}{\Omega k_{\rm res} W(k_{\rm res})}$$

- Finally the spatial diffusion coefficient can be derived as

$$D_{||}(E) \simeq v\lambda \simeq v^2 \tau_{\rm s} \simeq \frac{v^2}{\Omega} \frac{1}{k_{\rm res} W(k_{\rm res})}$$

Origin of the waves: the interstellar turbulence

Armstrong+, ApJ 1995, Chepurnov & Lazarian, ApJ 2010, Lee & Lee, Nature Astr. 2019



Electron-density fluctuations in the ISM
or "The (second) Great Power-Law in the Sky"
(according to Jokipii)

- Turbulence is stirred by Supernovae at a typical scale $L \sim 10 - 100$ pc
- Fluctuations of velocity and magnetic field are Alfvénic $\to v_A$
- They have a Kolmogorov $\alpha \simeq 5/3$ spectrum (density is a passive tracer so it shares the same spectrum: $\delta n_e \sim \delta B^2$):

$$kW(k) \simeq \frac{\langle \delta B \rangle_k^2}{B_0^2} \sim \eta_B (\alpha - 1) \left(\frac{k}{k_0} \right)^{1-\alpha}$$

- where $k_0 = L^{-1}$ and the level of turbulence is

$$\eta_B = \int_{k_0}^{\infty} dk\, W(k) \sim 0.1$$

Charged particle in a turbulent field

Jokipii, ApJ 1966

- The parallel diffusion coefficient becomes:

$$D_{\parallel}(E) = \frac{r_L v}{3} \frac{1}{k_{\rm res} W(k_{\rm res})} = D_{\rm B}(E) \frac{1}{k_{\rm res} W(k_{\rm res})}$$

where $k_{\rm res} = r_L^{-1}$ and $D_{\rm B}(E)$ is the Bohm diffusion coefficient, namely the minimum diffusion coefficient possible as it corresponds to $r_L \simeq \lambda$

- The ISM diffusion coefficient depends on the turbulence injection scale $L \sim 10$ pc and the level turbulence $\eta_B \sim 0.1$

$$D_{\parallel}(E) \simeq 10^{29}\,{\rm cm}^2\,{\rm s}^{-1} \left(\frac{\eta_B}{0.1}\right)^{-1} \left(\frac{E}{\rm TeV}\right)^{2-\alpha} \left(\frac{B}{\mu{\rm G}}\right)^{-\alpha+2} \left(\frac{L}{10\,{\rm pc}}\right)^{\alpha-1}$$

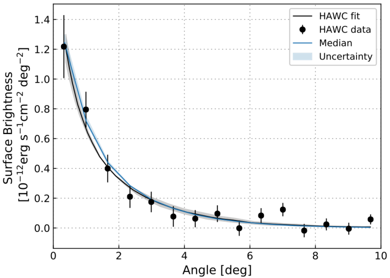
since $r_L \simeq 10^{-3}\,E_{\rm TeV} B_{\mu{\rm G}}^{-1}$ pc

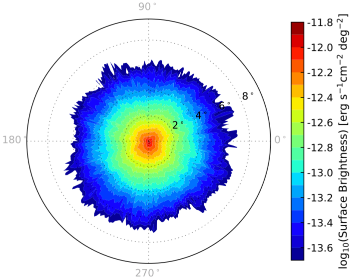
- For $\alpha = 5/3$ we obtain the Kolmogorov diffusion coefficient:

$$D_{\parallel}(E) \simeq 10^{29}\,{\rm cm}^2\,{\rm s}^{-1} \left(\frac{E}{\rm TeV}\right)^{\frac{1}{3}} \longrightarrow \lambda(E) \sim 3D/v \simeq 3\,{\rm pc} \left(\frac{E}{\rm TeV}\right)^{\frac{1}{3}}$$

- As a reference $k_{\rm TeV} W(k_{\rm TeV}) \sim 10^{-4} \rightarrow$ little things affect big things

Reducing diffusivity





- $L \downarrow \quad D_{\parallel} \downarrow$ (Lopez-Coto, Giacinti, MNRAS 479, 2018)
- $k_{\rm res} W(k_{\rm res}) \uparrow \quad D_{\parallel} \downarrow$
- Pressure gradients by not-resonant instability (Schroer et al., arXiv:2011.02238)

Self-generated waves

Kulsrud's book

- As we assume that CRs are isotropized by the waves (in the rest frame of the waves), there must be momentum transfer between CRs and waves.
- The momentum before scattering (v_D = CR streaming velocity):

$$P_{\rm CR}^b = n_{\rm CR} m \gamma_{\rm CR} v_D$$

  and after scattering (v_A is the wave speed):

$$P_{\rm CR}^a = n_{\rm CR} m \gamma_{\rm CR} v_A < P_{\rm CR}^b$$

- The momentum lost has gone to the waves

$$\frac{dP_{\rm CR}}{dt} \sim \frac{P_{\rm CR}^b - P_{\rm CR}^a}{\tau_s} = \frac{n_{\rm CR} m \gamma_{\rm CR}}{\tau_s}(v_D - v_A) \longrightarrow \frac{dE_W}{dt} \sim 2\Gamma_{\rm CR}\frac{(\delta B)^2}{8\pi}$$

  where

$$\Gamma_{\rm CR} \propto \frac{n_{\rm CR}(r_g > k^{-1})}{n_i}\left(\frac{v_D}{v_A} - 1\right)$$

- If CR stream faster than the waves, the net effect of diffusion is to make waves grow and make CR diffusive motion slow down: this process is known as self-generation of waves (notice also that self-generated waves have $k \sim r_L$)

Wave damping

Wentzel (1974), Zirakashvili (2014)

- In the warm partially ionized ISM (e.g. disk) the damping is due to ion-neutral collisions

$$\Gamma_{\rm ion} = \frac{1}{2} v_{\rm th} \sigma_{\rm ex} n_n \to \tau_{\rm d,ion} \sim 10\,{\rm yr}$$

where $n_n \sim 1\,{\rm cm}^{-3}$ is the number density of neutrals, $v_{\rm th} \sim 10$ km/s is the thermal velocity of plasma and $\sigma_{\rm ex} = 10^{-14}\,{\rm cm}^2$ is the charge exchange cross-section.

- In fully ionized ISM damping (e.g. halo) due to wave-wave interactions (non-linear Landau damping)

$$\Gamma_{\rm nl}(E) = c_k v_A k \sqrt{kW(k)} \sim \frac{v_A}{r_L} \frac{\delta B(k)}{B_0} \to \tau_{\rm d,nl} \sim {\rm kyr} \left(\frac{E}{\rm TeV} \right) \left(\frac{\delta B(k)}{B_0} \right)^{-1}$$

- The diffusion coefficient of self-generated turbulence can be simply estimated by equating damping and growth:

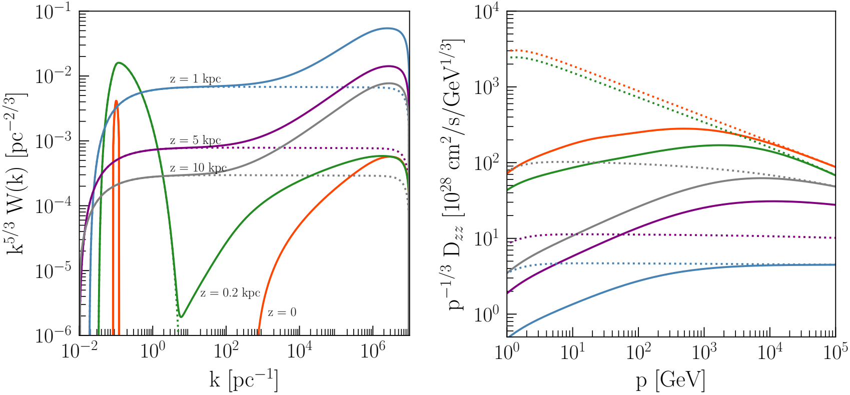
$$\Gamma_{\rm CR} = \Gamma_{\rm nl} \to \frac{P_{\rm CR}(>1\,{\rm GeV})}{P_B} \frac{v_A}{H} \frac{1}{kW(k)} = c_k k v_A \left[kW(k) \right]^{1/2}$$

assuming equipartition $P_{\rm CR} = P_B$:

$$kW(k)_{\rm sg} \simeq \left[\left(\frac{r_L}{r_{L,0}} \right)^{-0.7} \frac{r_L}{H} \frac{1}{c_k} \right]^{\frac{2}{3}} \to D_{\rm sg} \simeq 10^{28} \left(\frac{E}{\rm GeV} \right)^{-0.7} {\rm cm}^2 {\rm s}^{-1}$$

Non-linear cosmic ray transport in the Galaxy

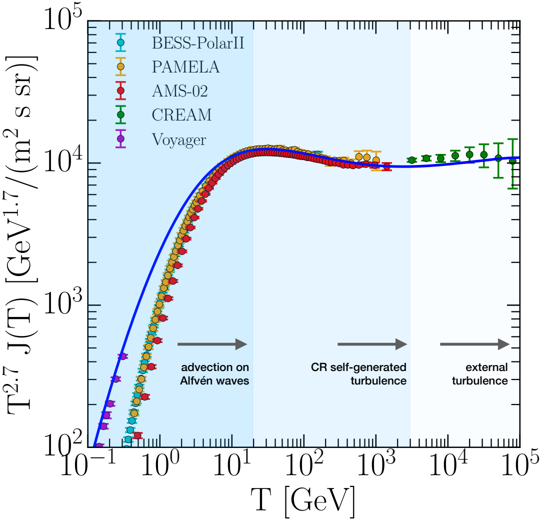
Blasi, Amato & Serpico, 2012, PRL; Evoli, Blasi, Morlino & Aloisio, 2018, PRL



- ▷ Turbulence spectrum without (dotted) and with (solid) CR self-generated waves at different distance from the galactic plane.
- ▷ Large-scale injected waves (Kolmogorov spectrum) dominates above the break.
- ▷ Self-generated turbulence predominant between $\sim 1 - 100$ GeV.

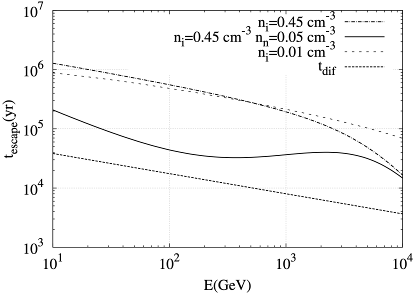
Non-linear cosmic ray transport in the Galaxy

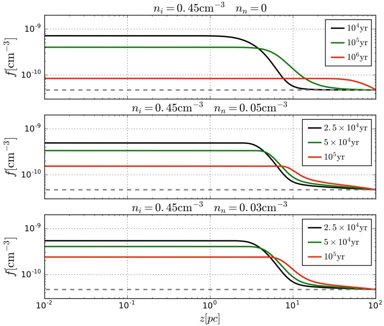
Evoli, Blasi, Morlino & Aloisio, 2018, PRL



Self-generation close to sources

D'Angelo+, Malkov+, Nava+

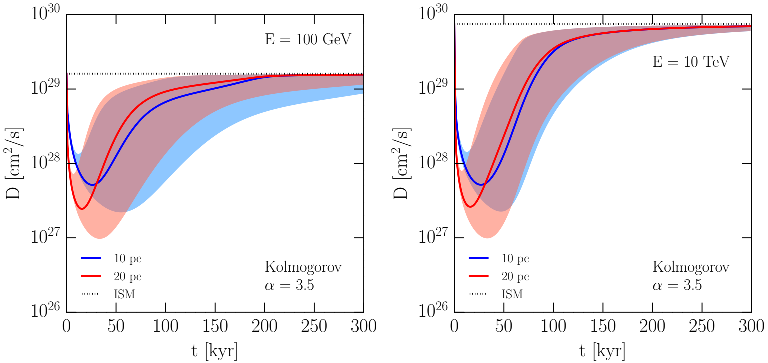




- CR transport near sources is strongly non-linear (large CR density and density gradients) [D'Angelo+, MNRAS 2016,2018]
- Particles are self-trapped around the source to an extent that depends upon the level of ionization of the surrounding ISM [Nava+, MNRAS 2016,2019]
- Ineffective above ∼ TeV

Self-generated cosmic-ray confinement in Pulsar halos

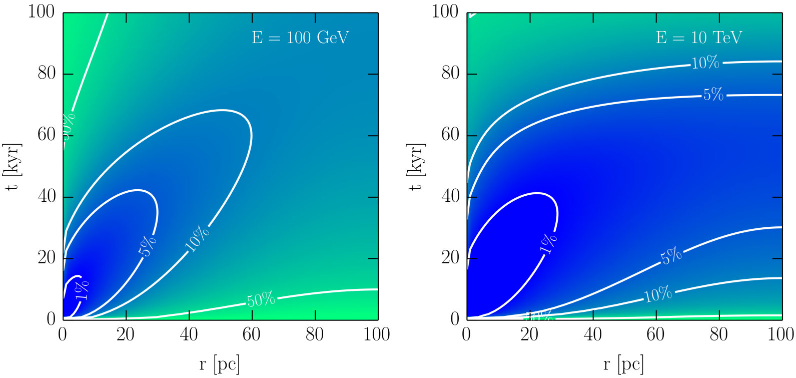
Evoli, Linden and Morlino, PRD 98 (2020)



- ▷ Main result: **Pairs may grow waves!**
- ▷ We assume that the time-dependent pair injection follows the spin-down power $L_e(t) = L_0(1 + t/\tau_0)^2$ where $\tau_0 \sim 10$ kyr and $L_0 \sim 10^{37}$ erg/s to match the actual luminosity $L_{\rm now} \sim 10^{34}$ erg/s
- ▷ cooling time of 10 TeV electrons is ~ 10 kyrs $\rightarrow$ today only few %'s of the total energy available to sustain turbulence

Self-generated cosmic-ray confinement in Pulsar halo

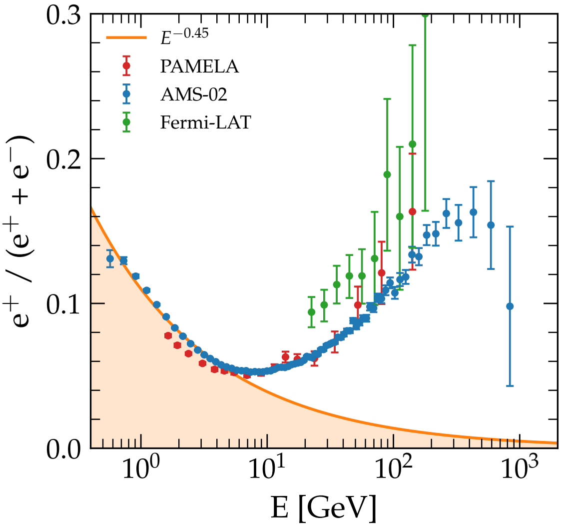
Evoli, Linden and Morlino, PRD 98 (2020)



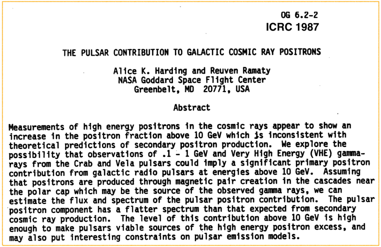
- Predicts energy-dependent features in cosmic-ray diffusion
- As the increasing size of TeV halos as a function of the pulsar age but only for young objects
- Kraichnan turbulence induces a significantly slower relaxation time → low D for a longer time

The positron fraction

PAMELA coll., Nature 458 (2009); FERMI-LAT coll., PRD 95 (2017); AMS-02 coll., PRL 110 (2013)



Pulsars as positron galactic factories



OG 6.2-2
ICRC 1987

THE PULSAR CONTRIBUTION TO GALACTIC COSMIC RAY POSITRONS

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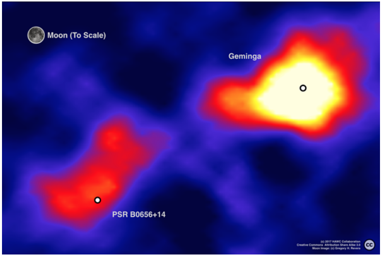
Abstract

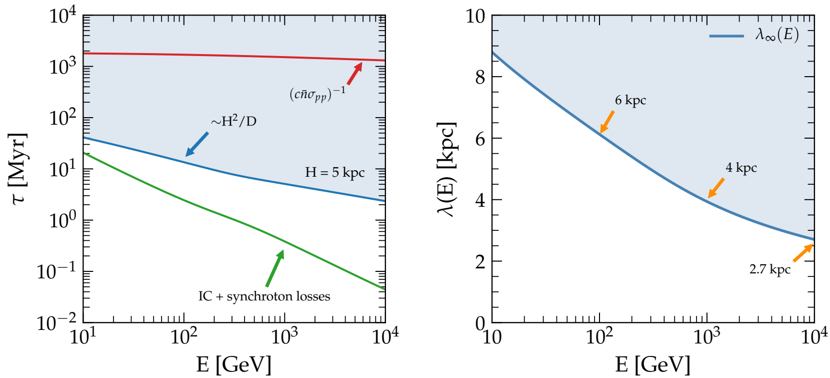
Measurements of high energy positrons in the cosmic rays appear to show an increase in the positron fraction above 10 GeV which is inconsistent with theoretical predictions of secondary positron production. We explore the possibility that observations of .1 - 1 GeV and Very High Energy (VHE) gamma-rays from the Crab and Vela pulsars could imply a significant primary positron contribution from galactic radio pulsars at energies above 10 GeV. Assuming that positrons are produced through magnetic pair creation in the cascades near the polar cap which may be the source of the observed gamma rays, we can estimate the flux and spectrum of the pulsar positron contribution. The pulsar positron component has a flatter spectrum than that expected from secondary cosmic ray production. The level of this contribution above 10 GeV is high enough to make pulsars viable sources of the high energy positron excess, and may also put interesting constraints on pulsar emission models.



- PWNe **pre-dicted** as galactic positron factories even before PAMELA [Harding & Ramaty, ICRC 1987; Boulares, ApJ 342 (1989); Atoyan, Aharonian & Völk, PRD 52 (1995)]
- Particle acceleration at the highest speed shocks in nature ($10^4 < \Gamma < 10^7$) $\rightarrow$ only sources showing direct evidence for PeV particles [Bykov+, Space Sci. Rev. 2017]
- HAWC has detected bright and spatially extended TeV gamma-ray sources surrounding the Geminga and Monogem pulsars [HAWC coll., Science 358 (2017)]
- TeV halos detected also in FERMI [Linden+, PRD 2019; Di Mauro+, PRD 2019]

Nuclei and electron timescales

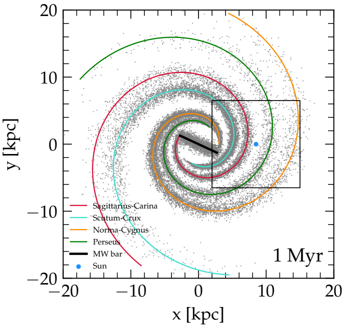
Delahaye+, A&A 201; Evoli, Amato, Blasi & Aloisio, PRL (2020)

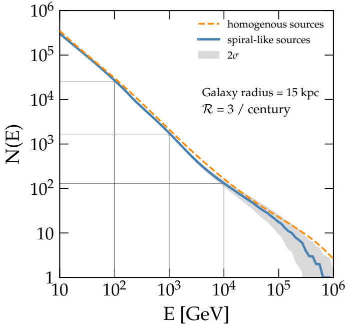


- Leptons lose their energy through e.m. interactions mainly with the interstellar radiation fields (ISRFs) and the magnetic fields
- The Milky Way is a very inefficient calorimeter for nuclei and a perfect calorimeter for leptons
- Translate losses into propagation scale: $\lambda \sim \sqrt{4D(E)\tau_{\rm loss}} \rightarrow$ horizon

Modelling the sources of leptons in the Galaxy

Evoli et al., arXiv:2010.11955



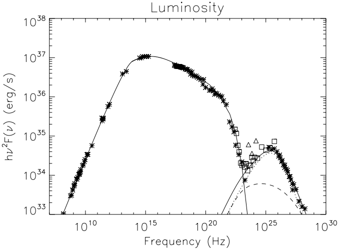


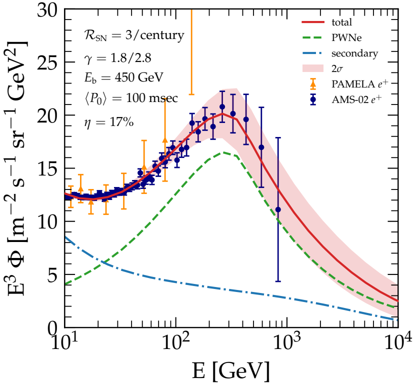
- Spiral arm structure of our Galaxy is of the utmost importance for the prediction of the lepton flux
- Most SN explosions are located in star-forming regions which in turn cluster inside the spiral arms of the Galaxy and in the Galactic bar → we assume a SNR of $\mathcal{R} = 1/30$ years
- The sources that can contribute to the flux at Earth at a given energy E are

$$N(E) \sim \mathcal{R} \tau_{\rm loss}(E) \frac{\lambda_e^2(E)}{R_g^2}$$

The CR positron flux with a primary component by PWNe

Hooper+, JCAP 2009; Grasso+, APh 2009; Delahaye+, A&A 2010; Blasi & Amato 2011; Manconi+, PRD 2020

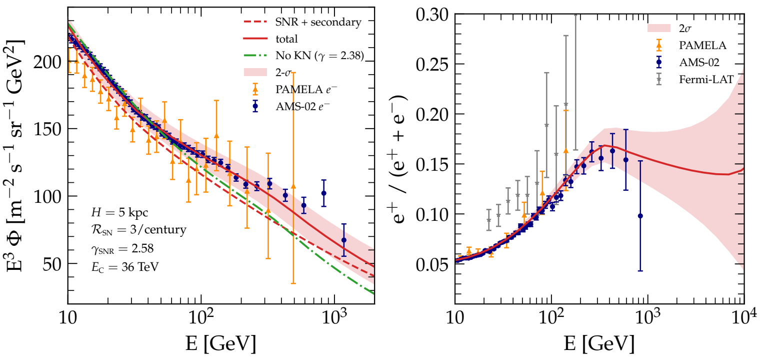




- The $e^{\pm}$ pairs created in the pulsar magnetosphere become part of the relativistic wind into which pulsars convert most of their rotational energy
- γ/X-ray emissions by these objects are described by a flat spectrum (with $1 < \alpha_L < 2$) at low energies, which then steepens to $\sim E^{-2.5}$ beyond $\sim$ few hundred GeV [Bucciantini+, MNRAS 2011]
- Efficiency of conversion: $\sim 20\%$ of the energy released after the Bow-Shock phase

The electron spectrum

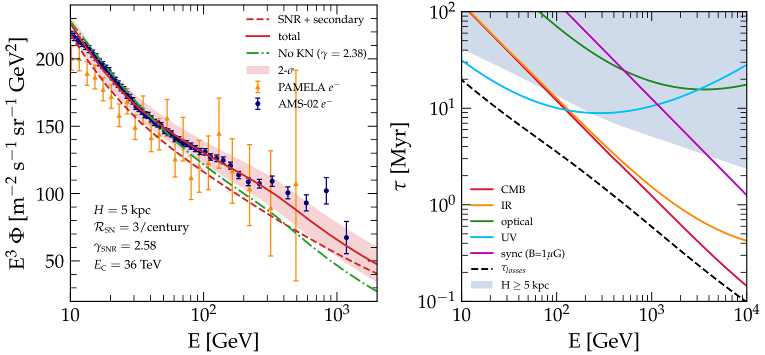
Evoli et al., arXiv:2010.11955



- Electrons injected with a spectrum steeper than protons by ~ 0.3 and a cutoff a ~ 30TeV
- The only aspect that is different between e$^-$ and p is the loss rate $\rightarrow$ negligible inside the sources unless B is very strongly amplified [Diesing & Caprioli, PRL 2020]
- The rising positron fraction is naturally reproduced by the pulsar contribution to the positron flux. At energies of a few hundred GeV, the fraction starts declining slightly.

The signature of energy losses on the cosmic ray electron spectrum

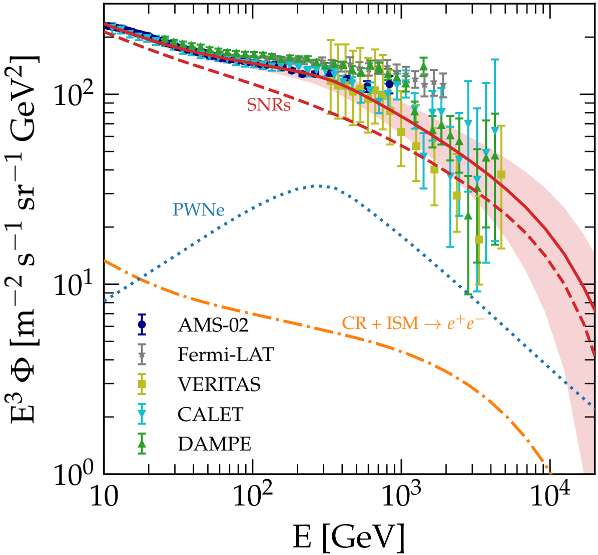
Evoli, Blasi, Amato & Aloisio, PRL (2020); Evoli et al., arXiv:2010.11955



- The existence of a fine structure at ~ 42 GeV was first noted by the AMS02 collaboration (and erroneously attributed to more than one CR electron population)
- Thomson regime only valid for $\gamma_e E_{ph} \lesssim m_e c^2$
- For the UV background, the typical temperature is $T \sim 10^4$K [Moskalenko, Porter and Strong, ApJ 640 (2006), Popescu et al., MNRAS 470 (2017)] hence the KN effects become important at $E \sim 50$ GeV.
- We proved that the feature in the e^- spectrum is the result of KN effects in the ICS on the UV bkg

The total lepton spectrum

Evoli et al., arXiv:2010.11955



Conclusions

- Impressive progress on the experimental side in the GeV-TeV range over the past ~ 20 years, both in direct (AMS-02, CALET, DAMPE, PAMELA) and indirect (HAWC, HESS, MAGIC, VERITAS) observations. [Gabici, Evoli et al., IJMPD (2019)]
- Diffusion of CRs is intrinsically non linear in nature due to momentum conservation.
- Non-linearities might play an essential role for propagation (as they do for CR acceleration) $\rightarrow$ possible explanation for some unexpected features in CR local spectra.
- Non-linear transport more efficient near CR sources $\rightarrow$ leading to several implications (additional grammage, cavities, coccons...). Ongoing investigations.
- Still a number of puzzles implore for an explanation: Electrons and protons injected with different slopes, the source spectra of H, He and heavier nuclei have to be different (and steeper than 2!)...
- Does the environment surrounding sources play a relevant role?

Thank you!

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