On the Cosmic-Ray lifetime in the Galaxy

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Multimessenger high energy astrophysics in the era of LHAASO
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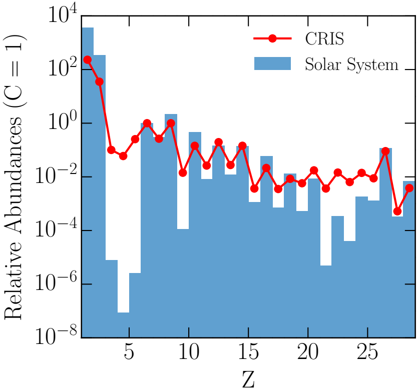
Based on:
Evoli, Blasi, Amato and Aloisio, PRL 2020, arXiv:2007.01302

Evoli, Morlino, Blasi and Aloisio, PRD 2020, arXiv:1910.04113

The Grammage pillar



- ▷ Thermal particles in the average interstellar medium are somehow accelerated to relativistic energies becoming CRs $\rightarrow$ primary
- ▷ It must exist also a second population which is produced during the propagation by primary spallation $\rightarrow$ secondary

The Grammage pillar

- The grammage χ $[m/l^2]$ is the amount of material that the particle go trough along propagation (a kind of "column density"):

$$\chi = \int dl \rho(l) \qquad l = \text{trajectory}$$

- The average grammage can be inferred by the observed secondary-over-primary ratio:

$$\frac{\mathrm{B}}{\mathrm{C}} \sim \chi \frac{\sigma_{C \to B}}{\langle m \rangle_{\mathrm{ISM}}} \sim 0.3 \to \chi_{\mathrm{obs}} \sim 5 \text{ g/cm}^2$$

- At each crossing of the disk ($h \sim 200$ pc) the accumulated grammage amounts roughly to:

$$\chi_d \sim m_p n_{\mathrm{gas}} h \sim 10^{-3} \text{ g/cm}^2 \ll \chi_{\mathrm{obs}}$$

  for comparison, in a molecular cloud as Ophiuchus: $\chi_c \sim 0.1$ g / cm^2

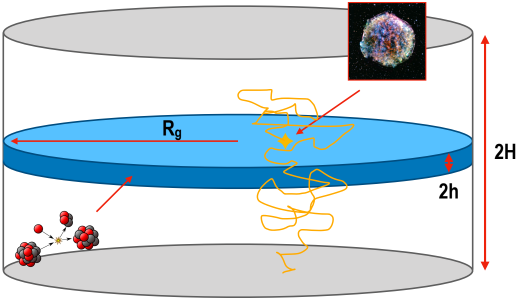
- Therefore the particles must cross the disk many times in order to accumulate the grammage necessary to reproduce composition $\longrightarrow$ random walk
- The minimum time spent in the gas region is:

$$t_{\mathrm{prop}} \sim \frac{\chi_{\mathrm{B/C}}}{\chi_{\mathrm{d}}} \frac{h}{v} \sim 5 \times 10^6 \text{ years} \gg \frac{R_{\mathrm{G}}}{c}$$

- The grammage sets only a lower limit to the mean age of CRs and to the extent of the diffusive region: Where is χ accumulated?

The Galactic halo model

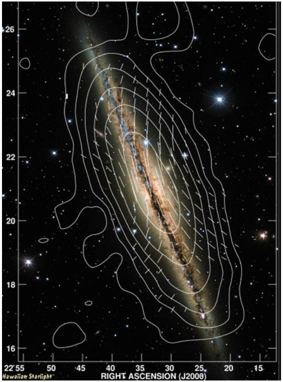
Morrison, Olbert and Rossi, Phys. Rev (1954), Ginzburg and Syrovatskii (1964)



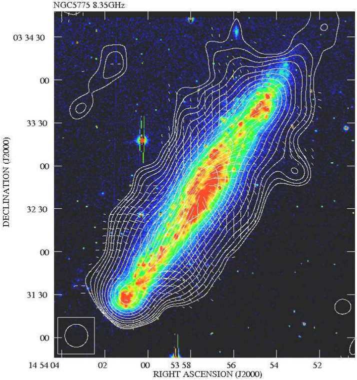
- In the standard model for the origin of Galactic CRs, these are accelerated in the disc by blast waves of SN explosions with a spectrum $Q_s \propto E^{-\alpha}$ where $\alpha \gtrsim 2$
- and propagate diffusively throughout the Galactic halo ($\sim 1D$) with a diffusion coefficient $D \propto E^{\delta}$ where $\delta \sim 1/3 - 1/2$
- Secondary production, e.g. LiBeB, takes place predominantly in the disc where all the gas is confined

The radio halo as observed in external galaxies

R. Beck, arXiv:0810.2923



NGC 891



NGC 5775

Total radio intensity and B-vectors of edge-on galaxies. Combined from observations at 3.6 cm wavelength with the VLA and Effelsberg telescopes. [Credit: MPIfR Bonn]

The propagated spectrum after injection and transport

- At the steady-state (and after a number of simplifications) the spectrum Φ of a given CR nuclear species is

$$\Phi_i(E) = \text{Injection rate} \times \text{Escape timescale}$$

- where the escape rate is $\propto l^2$ as typical in any “random walk” problem:

$$\text{Escape timescale} \rightarrow t_{\text{esc}} = \frac{H^2}{D(E)}$$

- In fact, H is the diffusive halo size (free escape boundary)
- The injection rate is different if we are dealing with a primary or a secondary species.

The secondary-over-primary ratio as grammage indicator

- Let me describe a simplified case with only one secondary species and one parent nucleus: C→B. [1]
- For Carbon:

$$Q_{\mathrm{C}} = \frac{N_{\mathrm{SN}}(E)\mathcal{R}_{\mathrm{SN}}}{\pi R_d^2 H} \Rightarrow \Phi_{\mathrm{C}}(E) = \frac{N_{\mathrm{SN}}(E)\mathcal{R}_{\mathrm{SN}}}{\pi R_d^2 H} \frac{H^2}{D(E)}$$

- While for Boron:

$$Q_{\mathrm{B}} = v\bar{n}\,\sigma_{\mathrm{C}\to\mathrm{B}}\,\Phi_{\mathrm{C}}(E) \Rightarrow \Phi_{\mathrm{B}}(E) = v\bar{n}\,\sigma_{\mathrm{C}\to\mathrm{B}}\Phi_{\mathrm{C}}(E)\frac{H^2}{D(E)}$$

- The ratio between the two becomes:

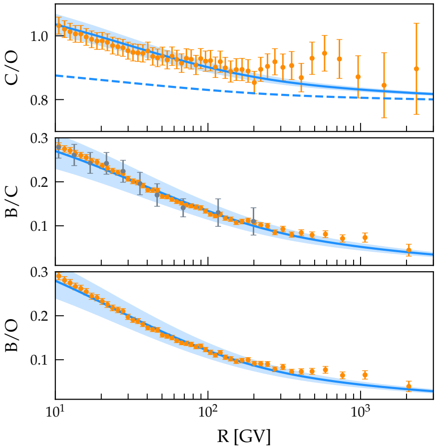
$$\frac{\mathrm{B}}{\mathrm{C}} \propto \bar{n}\frac{H^2}{D(E)} \propto E^{-\delta}$$

Notice however that $\bar{n} = n_d \frac{h}{H}$ so that B/C is sensitive only to the H/D ratio!

[1] In real applications the situation is more complex because the whole chain of spallation reactions and decays of heavier nuclei must be accounted for.

The energy dependent secondary-over-primary ratios

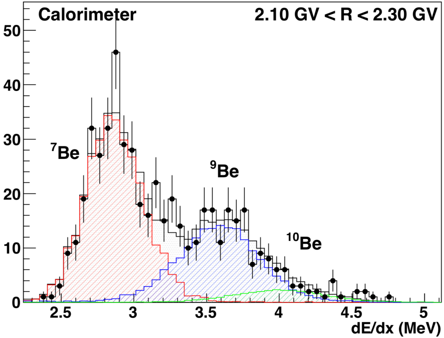
PAMELA Collaboration, ApJ 791 (2014), AMS-02 Collaboration, PRL 117 (2016)



- CRs propagate diffusively with an energy-dependent coefficient $\delta \sim 0.54$ and $D_0 \sim 10^{28}$ cm^2/s, mainly due to their interaction with the pre-existing or self-generated turbulent magnetic fields.
- Consistent fit of secondary over primary ratios [Evoli et al., PRD 99 (2019); Weinrich et al., A&A 639 (2020)]

Can we hope to measure the escape timescale?

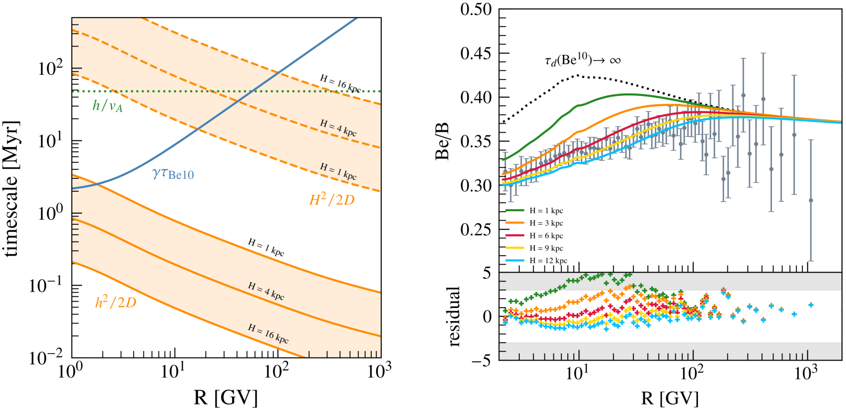
PAMELA Collaboration, ApJ, Vol. 862, 141 (2018)



- ^{10}Be is a β^- unstable isotope with an half-life of ~ 1.5 Myr
- Similar production rate $\sigma_{\rm Be9} \sim \sigma_{\rm Be10}$
- The observed isotopic ratio hints to an escape timescale of $O(100)$ Myr at ~ 1 GeV

The Beryllium-over-Boron ratio and the escape time

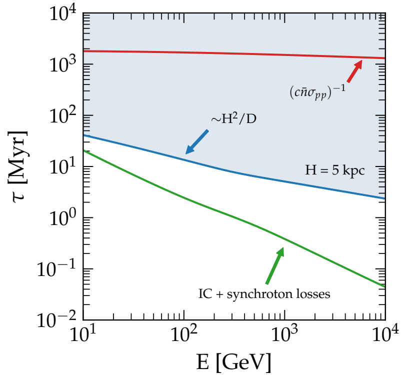
Evoli et al., PRD 101 (2020)

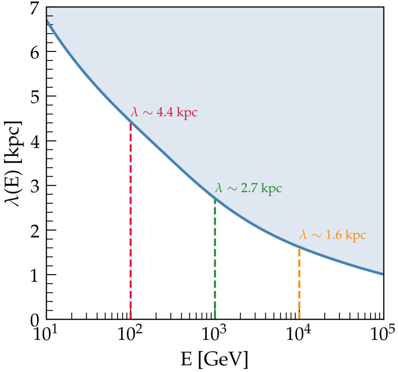


- ▷ Only the total Be is measured by AMS-02, but with extreme precision [AMS-02 Coll., PRL 120 (2018)]
- ▷ Preference for large halos $H \gtrsim 5$ kpc [see also Weinrich et al., A&A (2020)]
- ▷ Notice that H and $\tau_{\rm esc}$ are mutual corresponding, since $\tau_{\rm esc} \simeq \frac{H^2}{D} = \left(\frac{H}{D}\right)_{B/C} H$

Nuclei and electron timescales

Evoli, Blasi, Amato & Aloisio, PRL (2020)

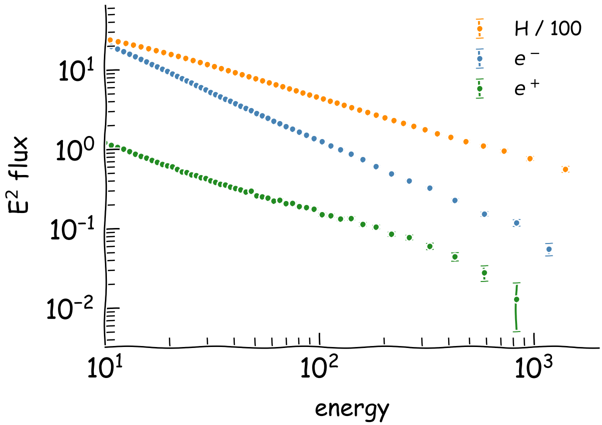




- Leptons lose their energy through e.m. interactions mainly with the interstellar radiation fields (ISRFs) and the magnetic fields
- The Milky Way is a very inefficient calorimeter for nuclei and a perfect calorimeter for leptons
- Translate losses into propagation scale: $\lambda \sim \sqrt{4D(E)\tau_{\rm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

The CR leptonic counterpart

AMS-02 coll., PRL 122 (2019)



- ▷ AMS-02 local measurements of e^+ and e^- compared with protons
- ▷ It is not compatible with all leptons being secondary: $pp_{\rm ISM} \to e^\pm$, then we need a primary component for electrons.

Secondary positrons and the positron fraction

P. Serpico, Astroparticle Physics 39 (2012)

- The injection rate of secondary positrons (and electrons) is $\propto$ to the proton spectrum:

$$Q_{e^+}(E) \sim c\bar{n}_{\rm gas}\sigma_{pp}\Phi_{\rm p}(E) \propto E^{-\alpha_p-\delta}$$

- while primary electrons have the same source term as primary nuclei:

$$Q_{e^-} = \frac{N_{\rm SN}(E)\mathcal{R}_{\rm SN}}{\pi R_d^2 H} \propto E^{-\alpha_e}$$

- The escape time is now set by the energy losses

$$\tau \propto \frac{\tau_{\rm loss}}{\sqrt{D(E)\tau_{\rm loss}}} \propto E^{-1/2-3\delta/2}$$

- However, their ratio after propagation is independent on τ:

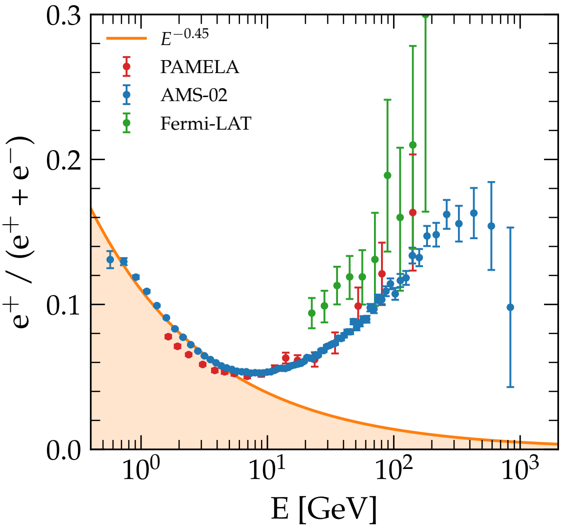
$$\frac{e^+}{e^-} \sim \frac{Q_{e^+}\cancel{\tau}}{Q_{e^-}\cancel{\tau}} \sim E^{-(\alpha_p-\alpha_e)-\delta}$$

- if e^+ are secondaries (and $\alpha_p = \alpha_e$) $\rightarrow$ the positron fraction must be a monotonically decreasing function of energy

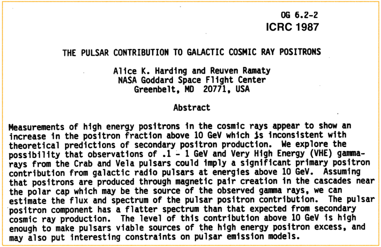
$$\longrightarrow \frac{e^+}{e^-} \propto E^{-\delta}$$

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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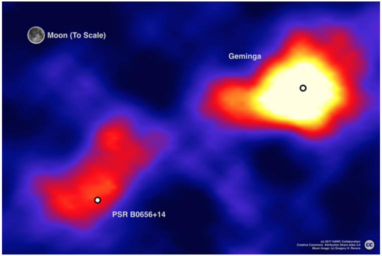
Abstract

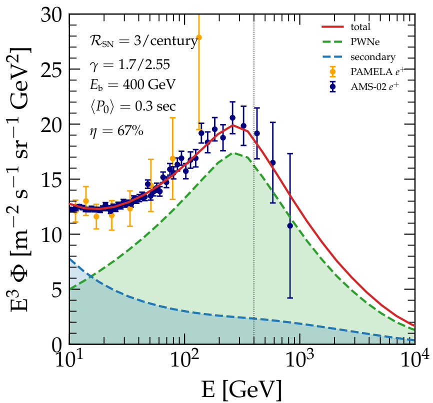
Measurements of high energy positrons in the cosmic rays appear to show an increase in the positron fraction above 10 GeV which is inconsistent with theoretical predictions of secondary positron production. We explore the possibility that observations of .1 - 1 GeV and Very High Energy (VHE) gamma-rays 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)]
- HAWC has detected bright and spatially extended TeV gamma-ray sources surrounding the Geminga and Monogem pulsars [HAWC coll., Science 358 (2017)]

The CR positron flux with a primary component by PWNe

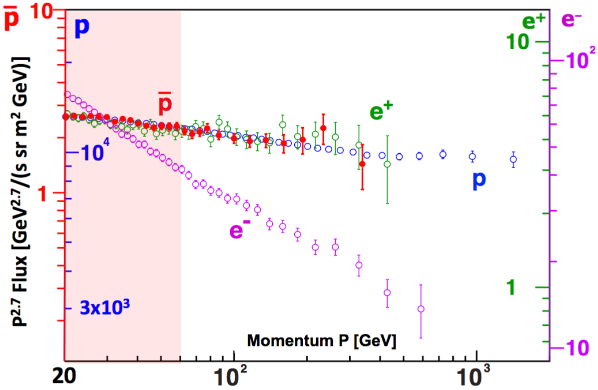
Hooper, Blasi & Serpico, JCAP 25 (2009); Grasso et al., APP 32 (2009); Delahaye et al., A&A 524 (2010); Blasi & Amato (2011)



- ▷ 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

Are positrons truly primary?

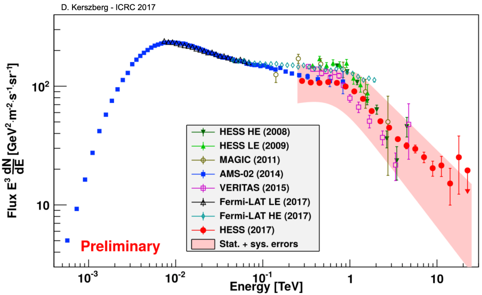
Blum et al., PRL 111 (2013); Cowsik & Madziwa-Nussinov ApJ 827 (2016); Lipari, PRD 95 (2019)

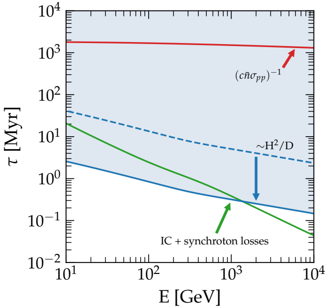


- Positrons and anti-protons share the same spectrum (likewise electrons)!
- The $e^+/\bar{p}$ ratio is very close (2.04 ± 0.04) to the one expected by pure secondary production
- Can it be just a (actually two!) coincidence?

Are positrons truly primary?

Lipari, PRD, 2019

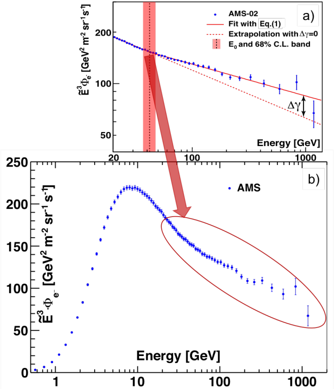




- In order to have just secondary positrons however we need to get rid of the energy losses.
- The lepton $e^- + e^+$ spectrum exhibits a sharp and large ($\Delta\gamma \sim 1$) break at $E \simeq 1$ TeV which could be associated with the onset of energy losses.
- Given the systematics, the feature might indicate either a break in the powerlaw spectrum or a kind of cutoff, see also CALET and DAMPE for direct measurements [CALET coll., PRL 119 (2017); DAMPE coll., Nature 552 (2017)].

A new structure in the cosmic-ray electron spectrum

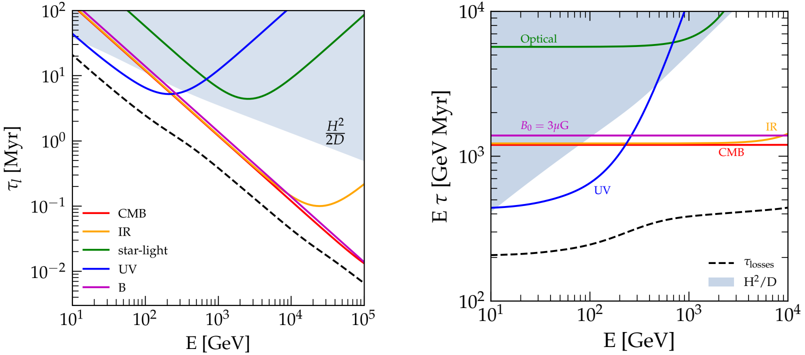
AMS-02 collaboration, PRL 122, 2019



- The question we wanted to adress was if it is possible to identify signatures associated to energy losses in the electron or positron spectra (below 1 TeV).
- 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)

A closer look at the energy losses

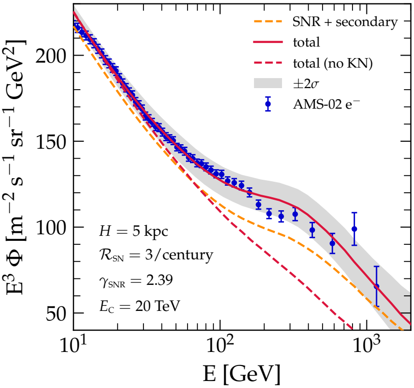
Evoli, Blasi, Amato & Aloisio, PRL (2020)



- $b(E) = (4/3)\sigma(E)c\gamma_e^2 \rightarrow \tau = E/b(E)$
- Thomson regime only valid for $\gamma_e E_{ph} \lesssim m_e c^2$ [Klein and Nishina, Zeitschrift für Physik 52, (1929)]
- 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.

The signature of energy losses on the cosmic ray electron spectrum

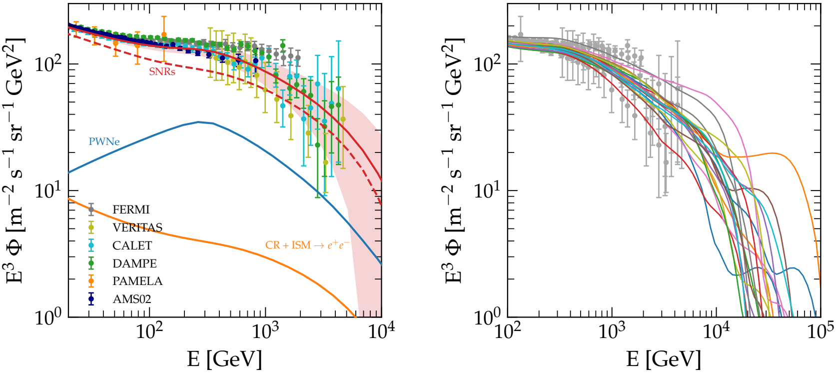
Evoli, Blasi, Amato & Aloisio, PRL (2020)



- We proved that the feature in the e^- spectrum is the result of KN effects in the ICS on the UV bkg.
- Although at different energies, a feature associated with KN has been anticipated in several works [Aharonian & Ambartsumyan, Astrofizika (1986); van der Walt & Steenkamp, MNRAS 251 (1991); Schlickeiser & Ruppel, New JoP 12 (2010); Stawarz, Petrosian & Blandford, ApJ 710 (2010)]
- We exclude that the feature may reflect the spectral hardening in the diffusion coefficient.
- Fluctuations due to source stochasticity (gray band) are not significant where the feature is observed.

The lepton spectrum

Evoli et al., in preparation



Conclusions - I

- The CR grammage and lifetime provide valuable piece of information to build up a model of CR propagation in the Galaxy.
- We presented two independent evidences that $\gtrsim$ GeV CRs propagate in a relatively large halo $H \gtrsim 2$ kpc corresponding to an escape time of $\mathcal{O}(50)$ Myr at ~ 10 GeV.
- In particular, the change of slope at ~ 40 GeV detected for the first time by AMS-02 in the electron spectrum could the unambiguous signature of the energy losses experienced by leptons while propagating in the Milky Way large halo.
- In this scenario, the positron excess is easily accounted for in terms of primary positrons (and electrons) liberated in the ISM by pulsars that abandoned their parent supernova remnant.

Conclusions - II

- 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)]
- The enormous amount of data of unprecedented quality allowed us to study Galactic CRs in much greater detail, but also revealed a number of "anomalies"
- Most of these anomalies could be fully addressed by good quality measurements in the TeV-PeV range in the next ~ 20 years. Looking forward at LHAASO, HERD, CTA...!

谢谢!

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