Life and death of a cosmic particle in the Galaxy

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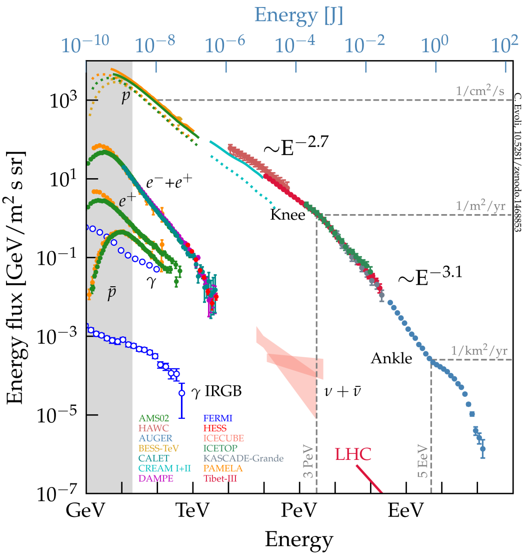
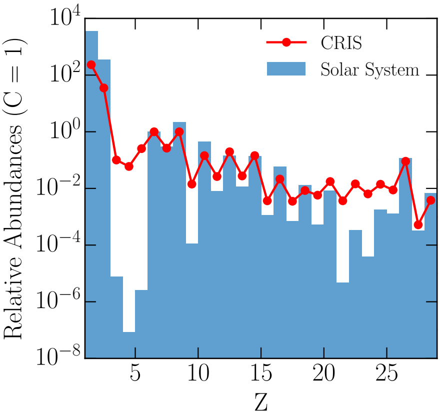
Based on: Evoli et al., PRL, arXiv:2007.01302

The cosmic ray spectrum

Gabici, Evoli+, arXiv:1903.11584



The Grammage pillar



- ▷ Thermal particles in the average interstellar medium are somehow accelerated to relativistic energies becoming CRs $\rightarrow$ primary
- ▷ But it exists also a second population which must be produced by primaries during the propagation $\rightarrow$ secondary

The Grammage pillar

- The grammage, $\chi\ [m/l^2]$, is the amount of material that the particle go trough along propagation (a sort 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:

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

- Let me assume that the grammage is accumulated in the disk (it is more than an academic exercise!). At each crossing of the disk ($h \sim 200$ pc) it accumulates:

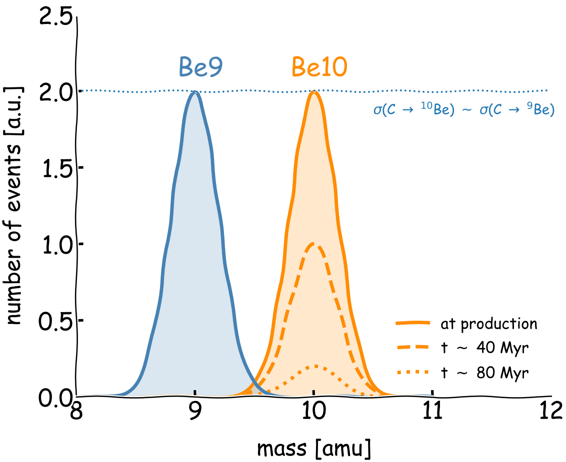
$$\chi_d \sim m_p n_{\mathrm{gas}} h \sim 10^{-3}\ \mathrm{g/cm}^2 \ll \chi_{\mathrm{obs}}$$

- Therefore the particles must cross the disk many times in order to accumulate the grammage we need to reproduce composition $\to$ random walk

- The minimum time spent in the gas region is:

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

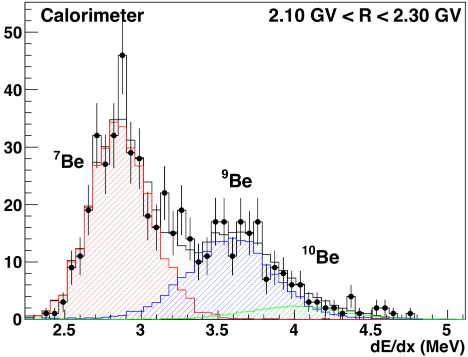
Can we hope to measure the escape timescale?



- ^{10}Be is a β^- unstable isotope with an half-life of ~ 1.5 Myr
- The observed isotopic ratio suggests an escape timescale of $O(100)$ Myr at ~ 1 GeV

Can we hope to measure the escape timescale?

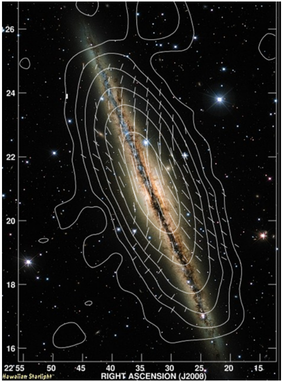
PAMELA Collaboration, ApJ, Vol. 862, 141 (2018)



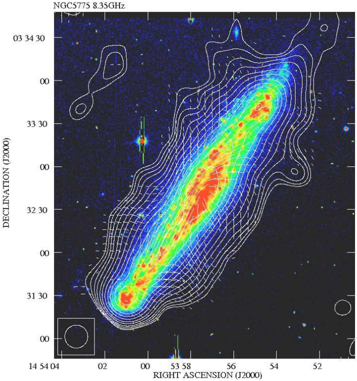
- ^{10}Be is a β^- unstable isotope with an half-life of ~ 1.5 Myr
- The observed isotopic ratio suggests an escape timescale of $O(100)$ Myr at ~ 1 GeV
- As a consequence, the presence of a low-density halo since $t_{\rm prop} \propto H$

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]

Cosmic ray escape time and galactic sources: The SNR paradigm

D. Ter Haar, Reviews of Modern Physics (1950), Ginzburg and Syrovatskii (1964)

- The escape time is crucial to identify potential CR source.
- The luminosity required to sustain the galactic CR population:

$$L_{\mathrm{CR}} = \frac{\epsilon_{\mathrm{CR}} V_{\mathrm{MW}}}{\tau_{\mathrm{esc}}} \sim 10^{41} \text{ erg/s}$$

  where

  - $\epsilon_{\mathrm{CR}} \sim 1$ eV/cm^3 is the local CR energy density
  - $V_{\mathrm{MW}} = \pi R_d^2 2H \sim 2 \times 10^{68}$ cm^{-3} is the Milky Way Volume
  - $\tau_{\mathrm{esc}} \sim 100$ Myr is the “escape” time

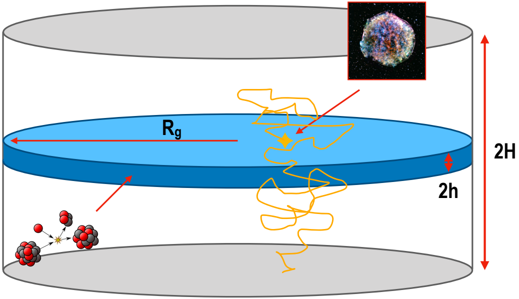
- SNe energy rate in our Galaxy:

$$L_{\mathrm{SN}} = E_{\mathrm{SN}} R_{\mathrm{SN}} \sim 10^{42} \text{ erg/s}$$

- Galactic SNe are able to sustain the CR population if $\sim 10\%$ of the explosion kinetic energy is converted in the acceleration of CR particles.

The Galactic halo model is now the reference model for CR transport

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 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:

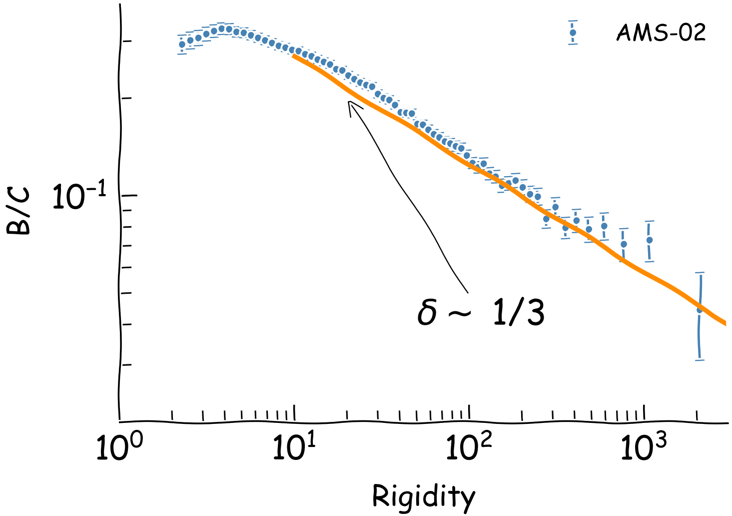
$$\frac{\mathrm{B}}{\mathrm{C}} \propto \bar{n}\frac{H^2}{D(E)} \propto E^{-\delta}$$

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 tracked.

The energy dependent secondary-over-primary ratio

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



The energy dependent secondary-over-primary ratio

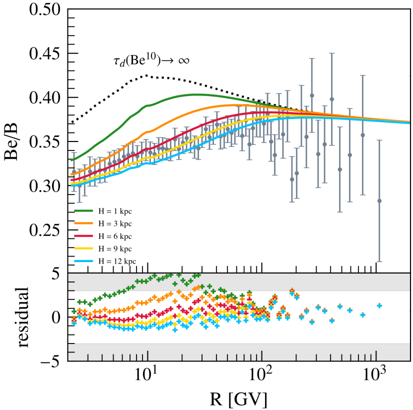
- CRs propagate diffusively with an energy-dependent coefficient mainly due to their interaction with the pre-existing or self-generated turbulent magnetic fields.
- The higher the CR energy, the smaller is the escape time $\rightarrow$ less time to produce secondary particle by spallation.
- The measurement of such ratios provides information on the grammage traversed by CRs, and indirectly on the diffusion coefficient, which represents the connection between the micro-physics of particle scattering and the macro-physics of CR transport

$$\chi(E) \xleftarrow{\text{macroscopic}} D(E) \xleftarrow{\text{microscopic}} W(k)$$

- However the secondary-to-primary ratios leaves the confinement time $H^2/D(E)$ weakly constrained (since it depends mostly on H/D)!

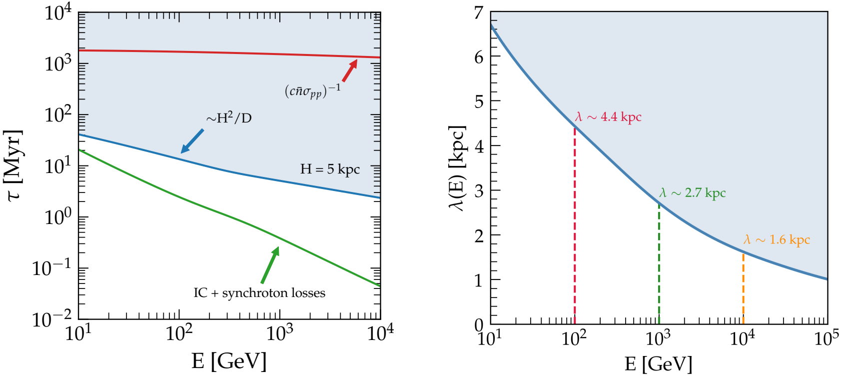
The Beryllium-over-Boron ratio and the escape time

Evoli et al., PRD 101 (2020)



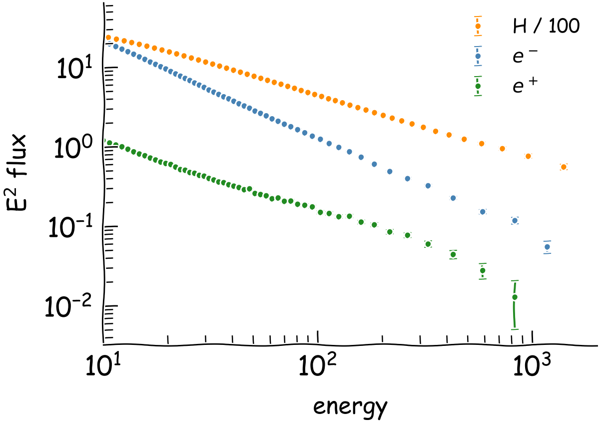
- ▷ Only the total Be is measured by AMS-02, but with extreme precision [AMS-02 Coll., PRL 120 (2018)]
- ▷ Preference for large halos $H \gtrsim 5$ kpc [Weinrich et al., A&A (2020)]
- ▷ Notice that H and $\tau_{\rm esc}$ are mutual corresponding, since $\tau_{\rm esc} \simeq \frac{H^2}{D} = \left(\frac{H}{D}\right)_{\rm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

Nuclei and electron timescales



- 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: $\lambda \sim \sqrt{4D(E)\tau_{\rm loss}} \to$ horizon

CR electrons must be primary. What about positrons?



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

Secondary positrons and the positron fraction

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

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

- The escape time is now set by the energy losses:

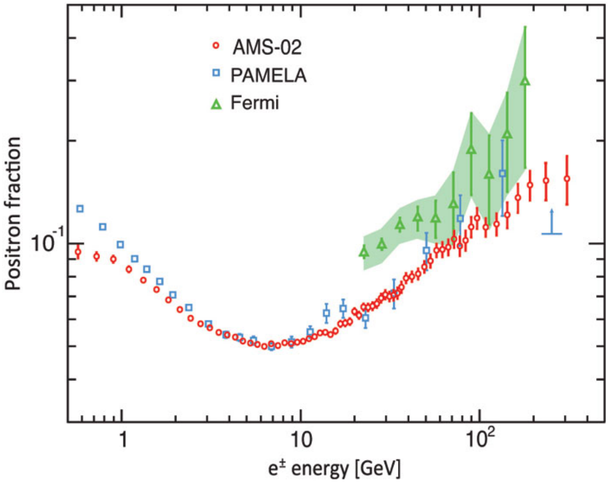
$$\tau \sim \frac{h\tau_{\rm loss}}{\sqrt{D(E)\tau_{\rm loss}}}$$

- The equilibrium spectrum of secondary positrons (and electrons) at Earth:

$$\Phi_{e^+} \sim \frac{Q_{e^+}(E)\tau_{\rm loss}(E)}{\sqrt{D(E)\tau_{\rm loss}(E)}} \propto E^{-\alpha-1/2-3\delta/2} \longrightarrow \frac{e^+}{e^-} \propto E^{-\delta}$$

- if secondary $\rightarrow$ the positron fraction must be a monotonically decreasing function of energy

Secondary positrons and the positron fraction



Pulsars as positron galactic factories

OG 6.2-2
ICRC 1987

THE PULSAR CONTRIBUTION TO GALACTIC COSMIC RAY POSITRONS

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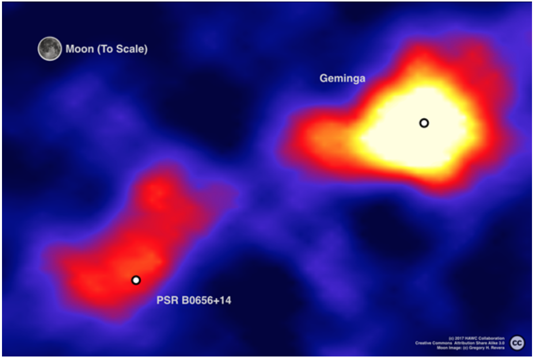
Abstract

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 and Ramaty, ICRC 1987]
- HAWC has detected bright and spatially extended TeV gamma-ray sources surrounding the Geminga and Monogem pulsars [Abeysekara et al, Science 358, 2017]

Pulsars as positron galactic factories



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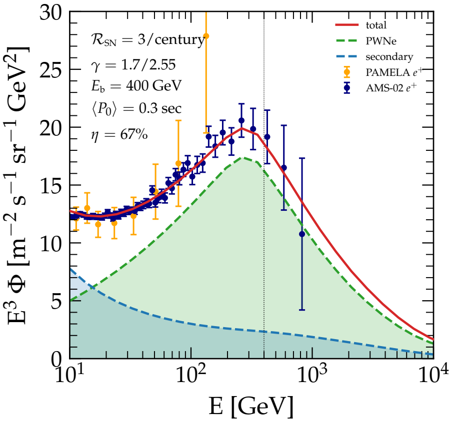
- HAWC has detected bright and spatially extended TeV gamma-ray sources surrounding the Geminga and Monogem pulsars [Abeysekara et al, Science 358, 2017]

The CR positron flux

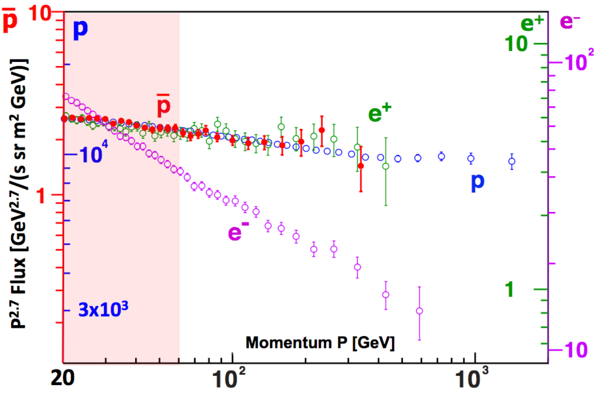
Delahaye et al., A&A (2010), Blasi and Amato, JCAP (2012), Manconi et al., JCAP (2019), Fornieri et al., JCAP (2020)



- ▷ The $e^{\pm}$ pairs created in the pulsar magnetosphere become part of the relativistic wind into which pulsars convert most of their rotational energy
- ▷ The $e^{\pm}$ pairs are seen to be described by a flat spectrum ($\propto E^{-\alpha_L}$ with $1 < \alpha_L < 2$) at low energies, which then steepens to $\sim E^{-2.5}$ beyond a few hundred GeV

Are positrons truly primary?

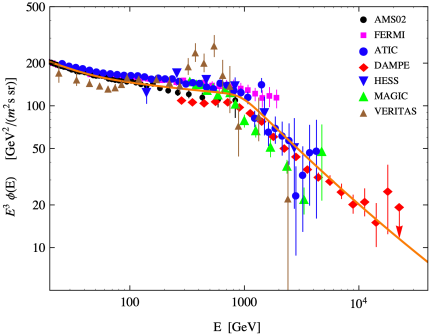
Lipari, PRD, 2019

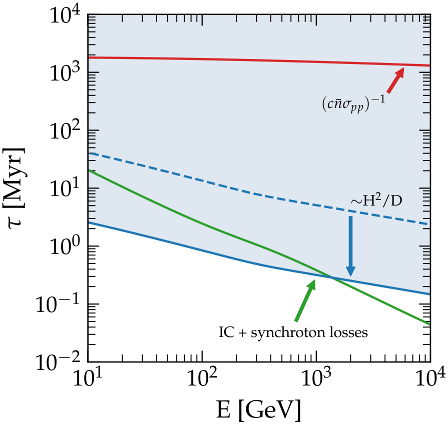


- Positrons and anti-protons share the same spectrum (likewise protons)!
- The $e^+/\bar{p}$ ratio is very close to the one expected by pure secondary production
- Can it be just a (actually two!) coincidence?

Are positrons truly primary?

Lipari, PRD, 2019

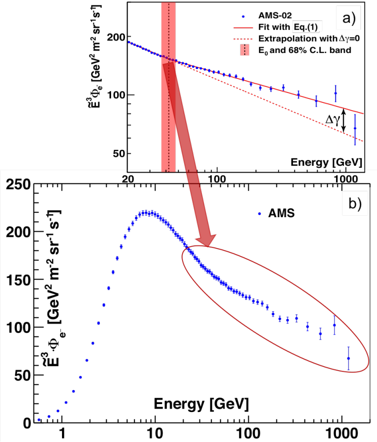




- In order to have pure secondary positrons however we need to get rid of the energy losses!
- The spectrum of the sum $(e^- + e^+)$ exhibit a sharp and large break at $E \simeq 1$ TeV.
- These new ideas have been thriving a number of unorthodox approaches!

A new structure in the cosmic-ray electron spectrum

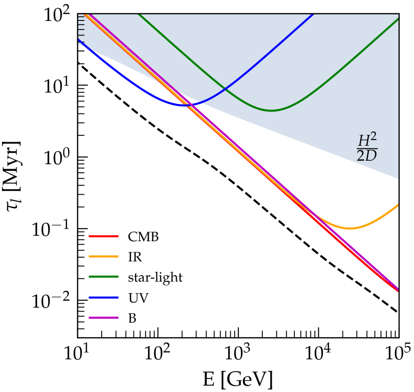
AMS-02 collaboration, PRL 122, 2019



- ▷ 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 population)

A closer look to the energy losses

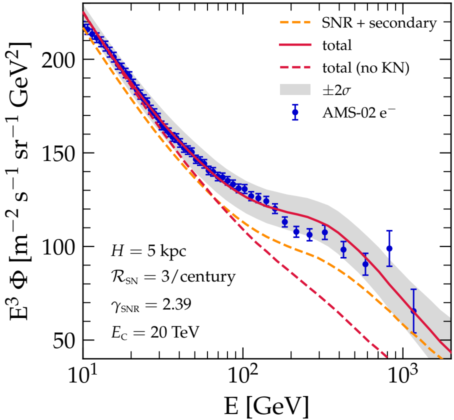
Evoli et al., PRL, 2020



- $b(E) = (4/3)\sigma(E)c\gamma_e^2 \to \tau = E/b(E)$
- 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 et al., PRL, 2020



- ▷ The feature in the electron spectrum is the result of the KN effects in the ICS on the UV bkg.
- ▷ We exclude that the feature may reflect the spectral hardening in the diffusion coefficient.
- ▷ Fluctuations due to source stochasticity are not significant at the energies where the feature is observed.

Conclusions

- Relativistic leptons provide valuable piece of information about the processes that regulate CR transport
- The unprecedented measurements achieved by AMS-02 revealed new features in the lepton spectra
- In particular, the change of slope at ~ 40 GeV could be the concluding proof that galactic CRs propagate diffusively in the Milky Way halo
- The positron excess is easily accounted for in terms of positrons (and electrons) liberated in the ISM by pulsars that abandoned their parent supernova remnant.

Thank you!

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