

Making sense of recent results on electrons and positrons from cosmic ray experiments

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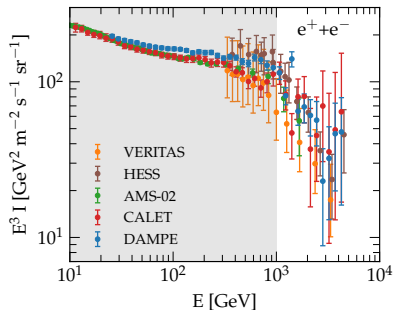
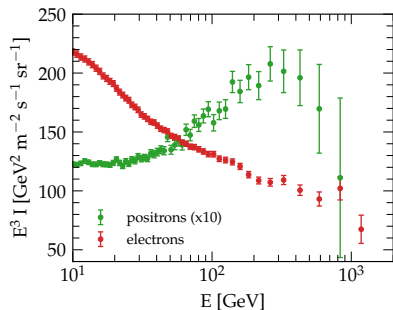
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Cosmic Rays in the Multi-Messenger Era @ Paris

December 5, 2022



Galactic factories of cosmic electrons and positrons

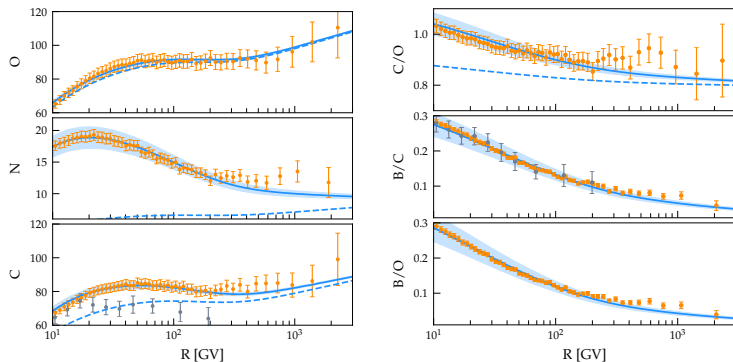


Rationale

- ▶ In recent years there has been a dramatic improvement in the measurement of the spectrum of e^\pm
- ▶ Significant progresses also in understanding galactic cosmic-ray transport
- ▶ We revised the prevailing approach in which leptons are the product of three classes of sources: **secondary, SNR (e^-) and PWN (pairs)**
- ▶ Are the observed fluxes well fitted by what we know about the Galactic properties of these populations and their energetic budgets?

CR phenomenology: secondary-over-primary ratios

Evoli et al., PRD 99 (2019); Weinrich et al., A&A 639 (2020)

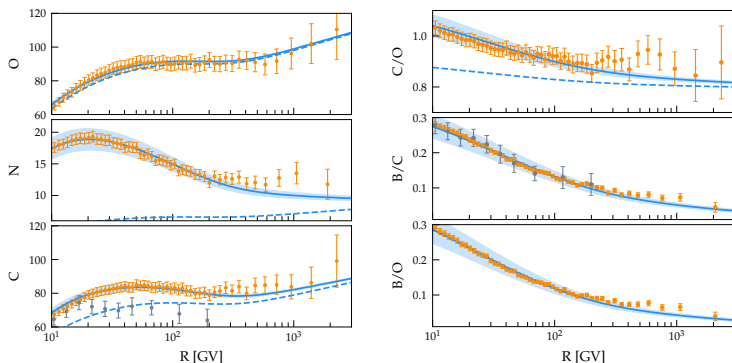


- ▷ Driven by theoretical arguments, we model $D(R)$ as a smoothly-broken power-law [Evoli et al., PRL 2018]:

$$D(R) = 2v_A H + \frac{\beta D_0 (R/\text{GV})^\delta}{[1 + (R/R_b)^{\Delta\delta/s}]^s}$$

CR phenomenology: secondary-over-primary ratios

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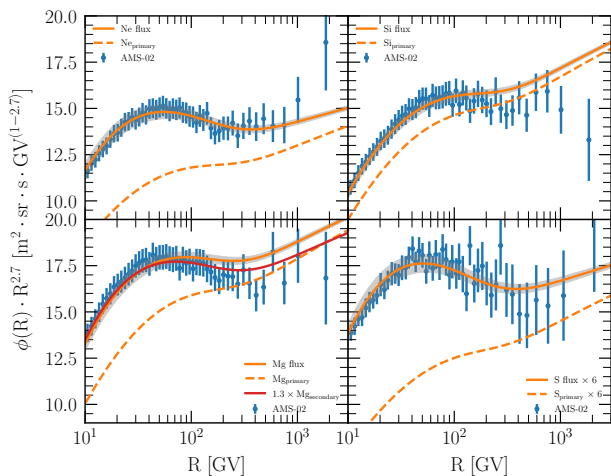
- ▷ by fitting primary and secondary/primary measurements we infer the properties of galactic transport:

$$\delta \sim 0.54, D_0/H \sim 0.5 \times 10^{28} \text{ cm/s}^2/\text{kpc}, \Delta\delta \sim 0.2, v_A \sim 5 \text{ km/s}$$

- ▷ All nuclei injected with $\gamma \sim 4.3$ (It remains true even for intermediate mass elements Ne, Si, Mg, and S) [Schroer, CE, and Blasi, PRD 2021]
- ▷ Shaded areas show **uncertainty from fragmentation cross sections** [Genolini et al., PRC 2018]

The nuclear realm

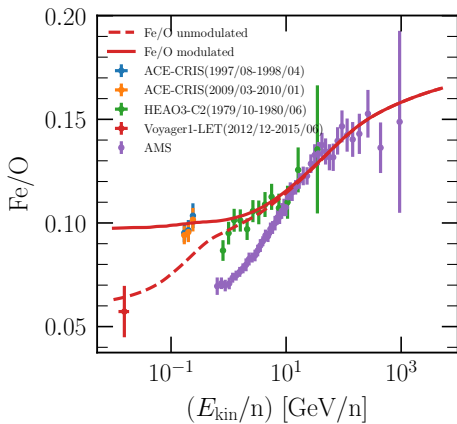
Schroer, CE, and Blasi, PRD 2021



Well explained in terms of a **primary** and a **secondary** component...

The nuclear realm

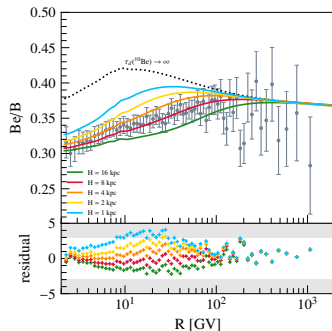
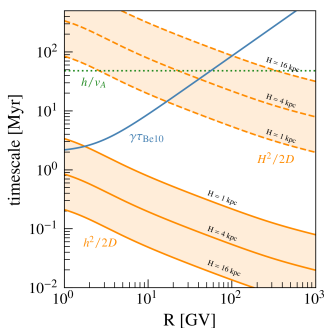
Schroer, CE, and Blasi, PRD 2021



...with one noticeable exception.

The Beryllium-over-Boron ratio and the escape time

Evoli et al., PRD 101 (2020)

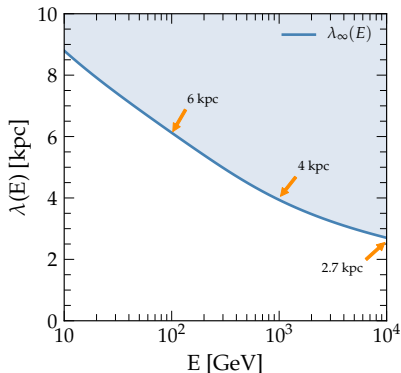
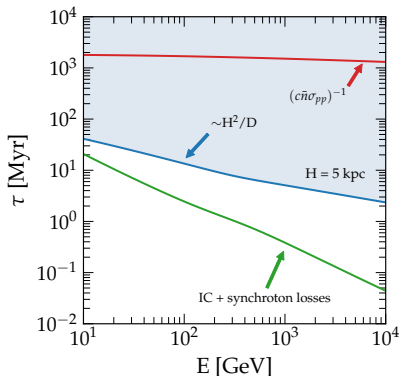


- Traditionally the ratio $^9\text{Be}/^{10}\text{Be}$ has been used as **CR clock** → however no measurements of this ratio at $E \gtrsim 1 \text{ GeV}/n$
- Make sure that ^{10}Be decays outside the disc (hostile to CR transport) → at \gtrsim few GeV this is certainly the case
- Preference for **large halos** $H \gtrsim 5 \text{ kpc}$ [Weinrich et al., A&A (2020), Maurin et al., arXiv:2203.07265]
- Notice that H and τ_{esc} are mutual corresponding

$$\tau_{esc}(10 \text{ GV}) \sim \frac{H^2}{2D} \sim 50 \text{ Myr} \left(\frac{H}{5 \text{ kpc}} \right) \left(\frac{1.5 \times 10^{28} \text{ cm}^2/\text{s}/\text{kpc}}{D_0/H} \right)$$

Nuclei and electron timescales

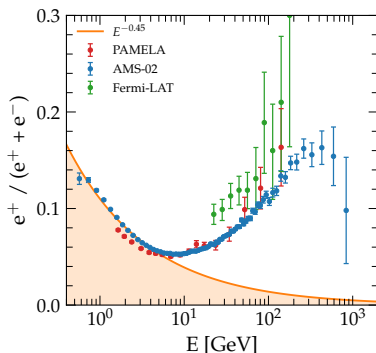
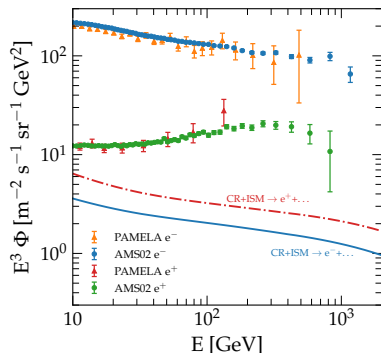
Evoli, Amato, Blasi & Aloisio, PRD 103, 8 (2021)



- ▶ Leptons lose their energy mainly by IC with the interstellar radiation fields (ISRFs) or synchrotron emission
- ▶ Milky Way is a very inefficient calorimeter for nuclei and **an almost perfect calorimeter for leptons**
- ▶ Translate losses into propagation scale: $\lambda \sim \sqrt{4D(E)\tau_{\text{loss}}}$ → **horizon**

Secondary electrons and positrons

PAMELA coll., Nature 458 (2009); FERMI-LAT coll., PRD 95 (2017); AMS-02 coll., PRL 110 (2013); Orusa+, PRD 2022



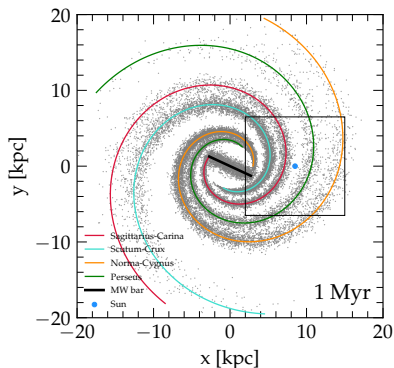
- ▷ AMS-02 local measurements of e^+ and e^- compared with secondary predictions $pp|_{\text{ISM}} \rightarrow e^\pm$
- ▷ It is not compatible with all leptons being secondary \rightarrow we need a **primary component** for electrons
- ▷ If e^+ are secondaries (and $\alpha_p = \alpha_e$) the **positron fraction** must be a decreasing function of E :

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

Requires a new hard source of positrons!

The Green function formalism

Lee, ApJ, 1979; Ptuskin+, APPh 2006; Delahaye+, A&A 2010; Mertsch, JCAP 2011; Blasi & Amato 2011; Mertsch, JCAP 2018



$$n(t_{\odot}, E, \vec{r}_{\odot}) = \iiint dt_s dE_s d^3\vec{r}_s \delta(\Delta t - \Delta\tau) \overset{\text{transport}}{\mathcal{G}_{\vec{r}}(E, \vec{r}_{\odot} \leftarrow E_s, \vec{r}_s)} \overset{\text{sources}}{\mathcal{Q}(t_s, E_s, \vec{r}_s)}$$

At high-energy release the assumption of smooth and continuous injection \rightarrow studying fluctuations

Primary lepton sources

Hooper+, JCAP 2009; Grasso+, APH 2009; Delahaye+, A&A 2010; Blasi & Amato 2011; Manconi+, PRD 2020; Evoli, Amato, Blasi & Aloisio, PRD 2021

SNR primary electrons

- ▶ Electrons released by **SNRs** with efficiency $\epsilon \sim 0.1\%$ in burst-like events
- ▶ Following DSA, the injection spectrum is a power law with an **intrinsic cutoff at $\sim 40\text{TeV}$** (cooling dominated)

$$Q_{\text{SNR}}(E) = Q_0 \left(\frac{E}{E_0} \right)^{-\gamma} e^{-\frac{E}{E_c}}$$

PWN primary pairs

- ▶ e^\pm **pairs** are created in the pulsar magnetosphere become part of the relativistic wind into which pulsars convert most of their rotational energy \rightarrow the only sources showing **direct evidence for PeV particles** [Bykov+, Space Sci. Rev. 2017]
- ▶ Continuous injection after the **bow-shock phase**
- ▶ 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]:

$$Q_{\text{PWN}}(E, t) = Q_0(t) e^{-E/E_c(t)} \times \begin{cases} (E/E_b)^{-\gamma_L} & E < E_b \\ (E/E_b)^{-\gamma_H} & E \geq E_b \end{cases}$$

- ▶ Cutoff is associated to the potential drop [Kotera, JCAP2015]

$$E_c(t) \sim 3 \text{ PeV} \left(\frac{P_0}{0.1 \text{ s}} \right)^{-2} \frac{1}{1 + t/\tau_0}$$

The break in the pulsar spectrum

Principe et al., A&A 640, A76 (2020), H.E.S.S. Collaboration, A&A 621, A116 (2019)

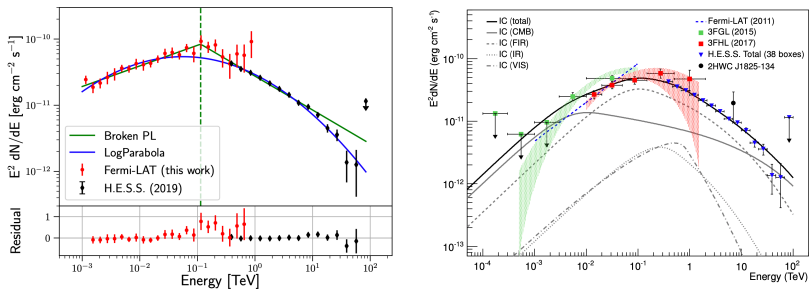
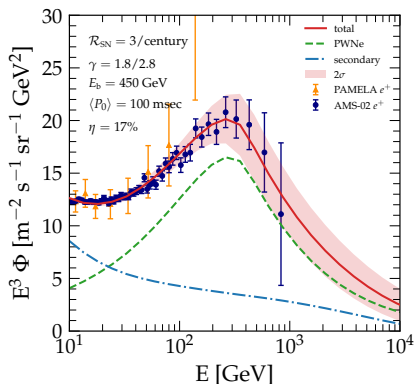


Figure: Combined spectra of PWN HESS J1825-137 (left) and HESS J1825-137 (right) with the spectral measurements obtained Fermi-LAT data (from \sim GeV to \sim TeV) and the H.E.S.S. data for the $\gtrsim 100$ GeV energy range

Pulsars as positron galactic factories

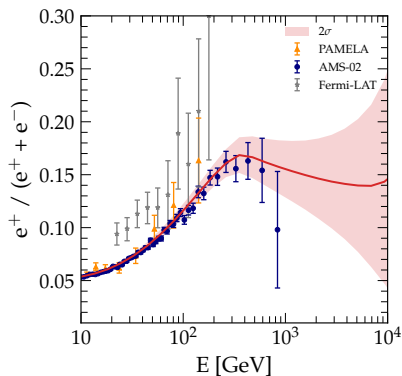
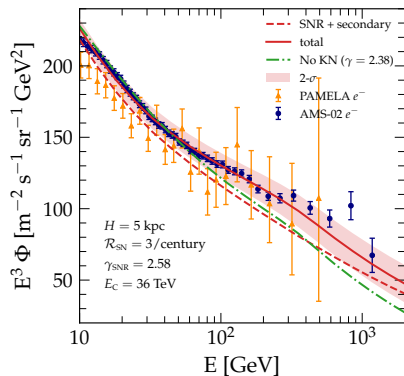
Evoli, Amato, Blasi & Aloisio, PRD 2021



- ▶ AMS-02 data requires an efficiency of conversion: $\sim 20\%$ of the energy released **after the Bow-Shock phase** ($t_{\text{BS}} \simeq 56 \text{ ky}$) although degenerate with $\langle P_0 \rangle$.
- ▶ The required slopes $\gamma \sim 1.8/2.8$ are **very steep** with respect to values we usually infer from γ -rays [Torres+, JHEA 2014]
- ▶ Shaded areas: 2-sigma fluctuations due to **cosmic variance** (CDF)
- ▶ HAWC has detected **bright and spatially extended** TeV gamma-ray sources surrounding the Geminga and Monogem pulsars [HAWC coll., Science 358, 2017] showing similar efficiencies

The electron spectrum from SNRs

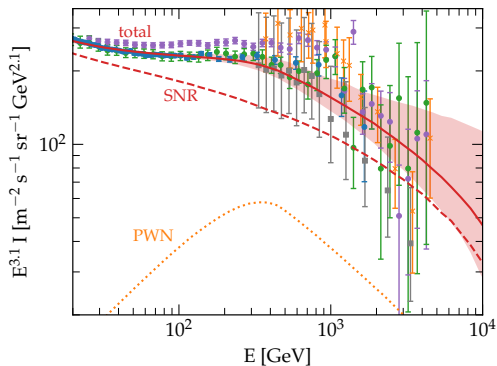
Evoli, Amato, Blasi & Aloisio, PRD 2021



- ▶ Existence of a **fine structure** at ~ 42 GeV \rightarrow result of KN effects in the ICS on the UV bkg [Evoli+, PRL 2020]
see also alternative interpretation in [Di Mauro et al, PRD, 104, 2021]
- ▶ Electrons require a spectrum **steeper than protons** by ~ 0.3 \rightarrow puzzling!
- ▶ 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; Cristofari+, A&A 2021]
- ▶ Expected **flatness** of the high-energy positron fraction!

The total lepton flux

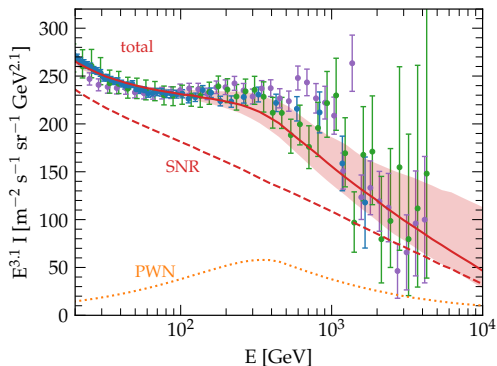
Evoli, Amato, Blasi & Aloisio, PRD 2021



- ▷ spectrum of $e^+ + e^-$ from SNRs and from pulsars (CR interactions in the ISM are below)
- ▷ data from AMS-02, CALET, DAMPE, H.E.S.S., FERMI, PAMELA, and VERITAS
- ▷ what is the origin of the observed **cutoff**?

The total lepton flux

Evoli, Amato, Blasi & Aloisio, PRD 2021



- ▶ We show only **direct** measurements: AMS-02, CALET, and DAMPE → consistent feature at ~ 600 GeV
- ▶ Notice now the y-axis is in **linear** scale
- ▶ The data points of DAMPE have also been rescaled in energy by 3% to explore their compatibility with the results of other direct measurements.

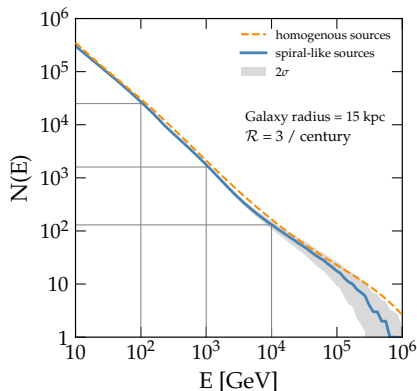
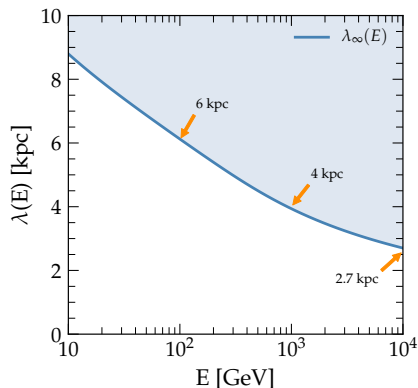
Cosmic Ray Positrons From Pulsars?

Take home message

- ▶ What's new here? Still the most promising explanation with **few puzzles to be addressed**
- ▶ Considerable research activity has been directed toward understanding exactly how pulsars generate their observed emission → converge to a unified picture?
- ▶ Alternative astrophysical explanations still viable, e.g., acceleration of secondary positrons within cosmic-ray sources [\[Mertsch+, PRD 2021\]](#)

Counting the sources of leptons in the Galaxy

Evoli, Blasi, Amato & Aloisio, PRD 2021

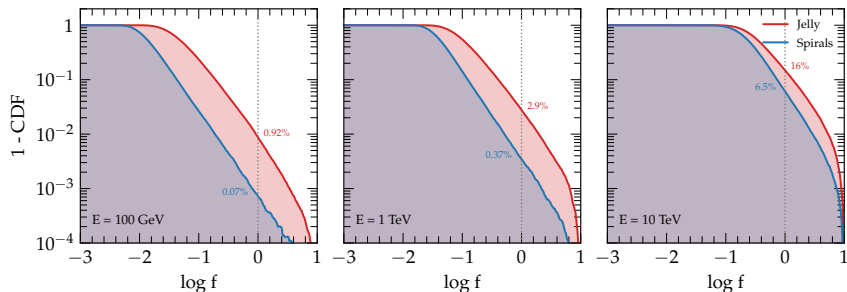


- ▶ Most SN explosions are located in star-forming regions which cluster inside the spiral arms and in the Galactic bar with a Galactic rate of $\mathcal{R} = 1/30$ years
- ▶ The sources that can contribute to the flux at Earth at a given energy E are

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

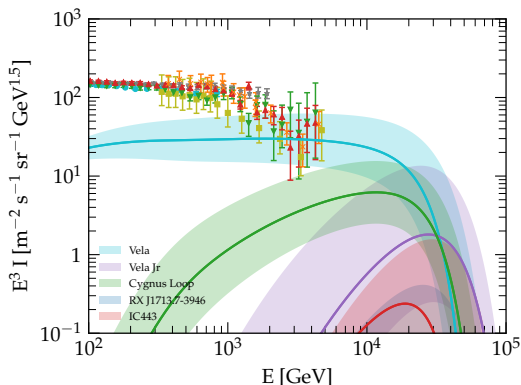
The odds of a prominent nearby source

Evoli+, PRD 2021



- ▶ Regularly invoked to explain features in the CR spectrum.
- ▶ $f = 1$ shows when 1 source contributes to local flux **at least** as much as all others added together.
- ▶ Assuming Spiral pattern and standard properties for transport \rightarrow
at $\sim 1 \text{ TeV}$ chances of $f > 1$ are $\sim 0.01\%$ for nuclei and $\sim 0.4\%$ for leptons [Genolini+, A&A 2017]









A dominant source is behind the corner



- ▷ Prediction for the electron flux at the Earth from individual (known) nearby sources assuming the same efficiency and parameters as for **the rest of the Galactic population**
- ▷ A dominating source, presumably Vela, might be the main contributor above ~ 10 TeV \rightarrow **to be tested soon by DAMPE and CALET**

Thank you!

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Electrons and positrons in AMS-02

