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

Carmelo Evoli

in collaboration with R. Aloisio, E. Amato, P. Blasi, G. Morlino

Gran Sasso Science Institute, L'Aquila (Italy)

INFN/Laboratori Nazionali del Gran Sasso (LNGS), Assergi (Italy)

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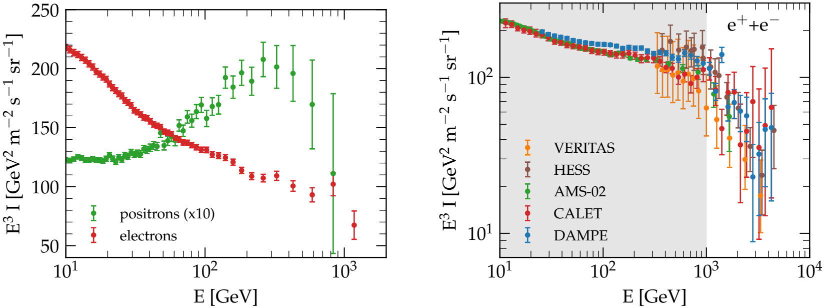
Galactic factories of cosmic electrons and positrons

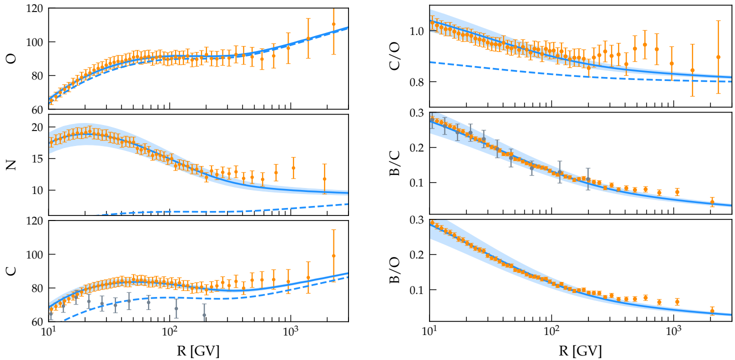


Rationale

- 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]:

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

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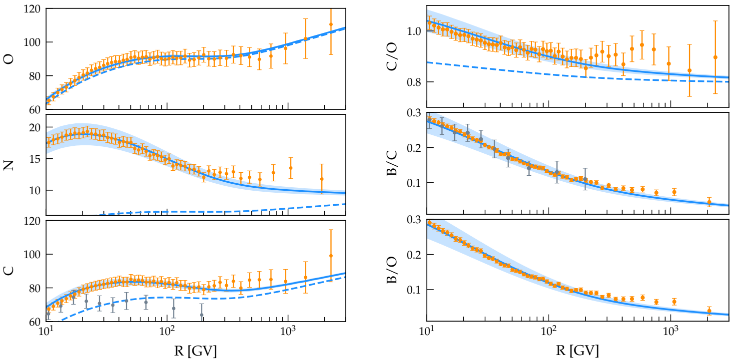


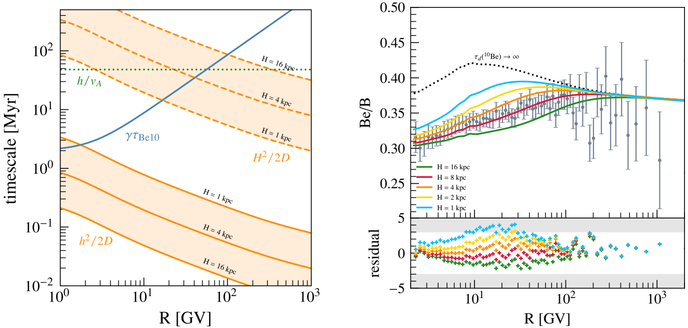
- by fitting primary and secondary/primary measurements we infer the properties of galactic transport:

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

- 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 Beryllium-over-Boron ratio and the escape time

Evoli et al., PRD 101 (2020)

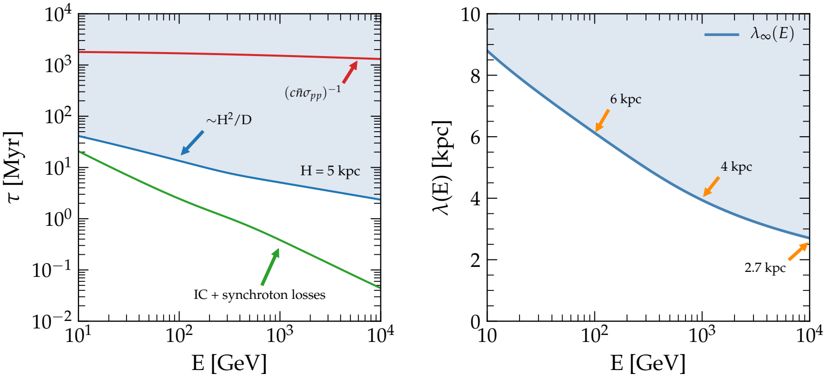


- ▷ Traditionally the ratio ^{9}Be/^{10}Be has been used as CR clock $\to$ however no measurements of this ratio at $E \gtrsim 1$ GeV/n
- ▷ Make sure that ^{10}Be decays outside the disc (hostile to CR transport) $\to$ at $\gtrsim$ few GeV this is certainly the case
- ▷ Preference for large halos $H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

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

Nuclei and electron timescales

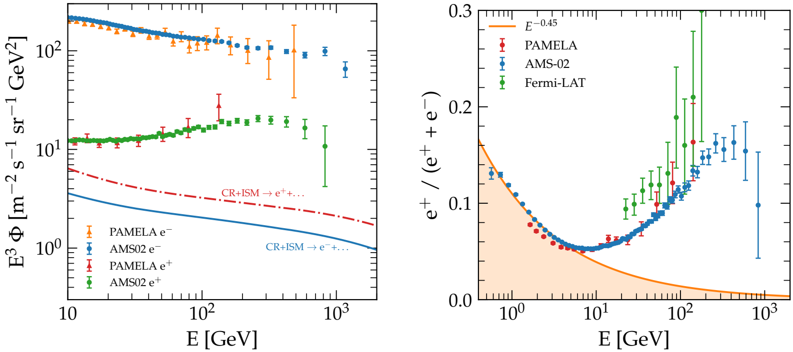
Evoli, Amato, Blasi & Aloisio, PRD 103, 8 (2021)



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



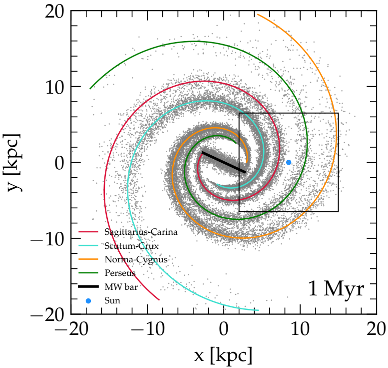
- AMS-02 local measurements of e^+ and e^- compared with secondary predictions $pp_{\rm ISM} \to e^\pm$
- It is not compatible with all leptons being secondary $\to$ we need a primary component for electrons
- If e^+ are secondaries (and $\alpha_p = \alpha_e$) the positron fraction must be a decreasing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

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

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



transport sources

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

At high-energy release the assumption of smooth and continuous injection ⟶ studying fluctuactions

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 ~ 40TeV (cooling dominated)

$$Q_{\rm SNR}(E) = Q_0 \left(\frac{E}{E_0} \right)^{-\gamma} {\rm e}^{-\frac{E}{E_{\rm c}}}$$

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 $\longrightarrow$ 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]:

$$Q_{\rm PWN}(E,t) = Q_0(t) {\rm e}^{-E/E_{\rm c}(t)} \times \begin{cases} (E/E_{\rm b})^{-\gamma_{\rm L}} & E < E_{\rm b} \\ (E/E_{\rm b})^{-\gamma_{\rm H}} & E \geq E_{\rm b} \end{cases}$$

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

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

The break in the pulsar spectrum

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

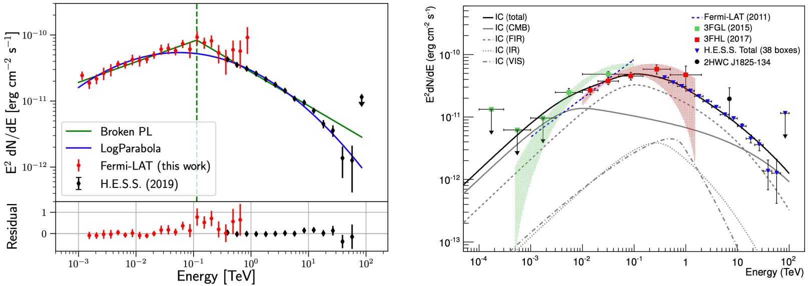
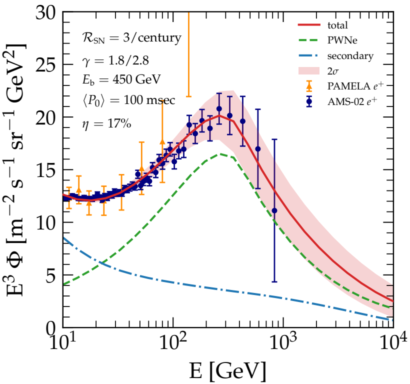


Figure: Combined spectra of PWN HESS J1825-137 (left) and HESS J1825−137 (right) with the spectral measurements obtained Fermi-LAT data (from $\sim$ GeV to $\sim$ TeV) and the H.E.S.S. data for the $\gtrsim 100$ GeV energy range

Pulsars as positron galactic factories

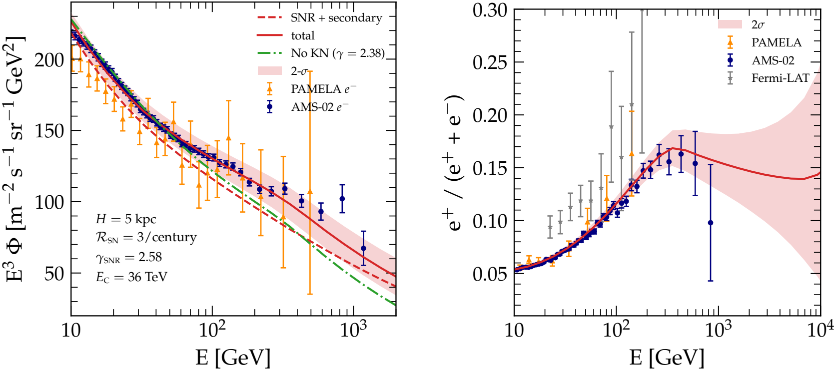
Evoli, Amato, Blasi & Aloisio, PRD 2021



- AMS-02 data requires an efficiency of conversion: $\sim 20\%$ of the energy released after the Bow-Shock phase ($t_{BS} \simeq 56$ 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

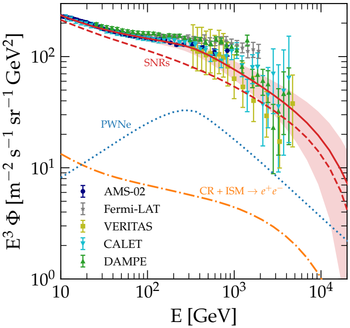
Evoli, Amato, Blasi & Aloisio, PRD 2021

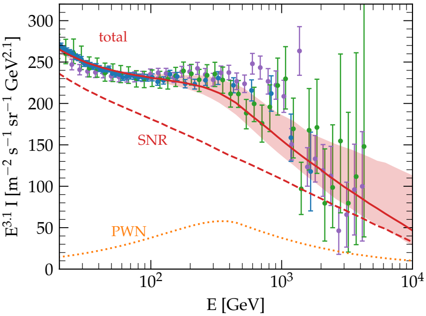


- ▷ Existence of a fine structure at ~ 42 GeV $\to$ result of KN effects in the ICS on the UV bkg [Evoli+, PRL 2020]
- ▷ Electrons require a spectrum steeper than protons by $\sim 0.3 \to$ puzzling!
- ▷ The only aspect that is different between e^- and p is the loss rate $\to$ negligible inside the sources 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





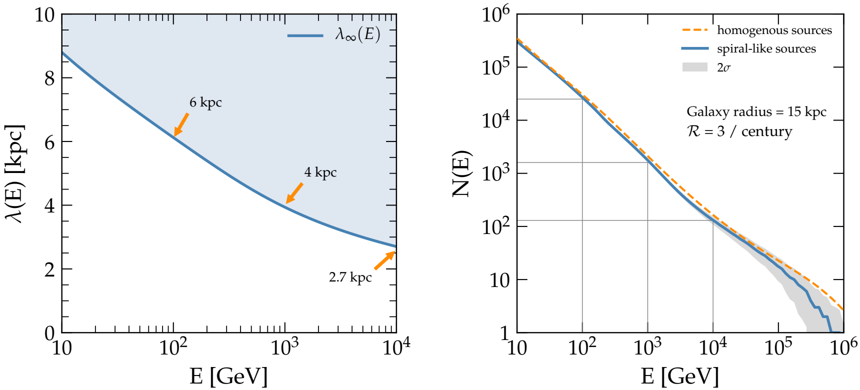
Cosmic Ray Positrons From Pulsars?

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 (see B. Olmi's talk) $\longrightarrow$ 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

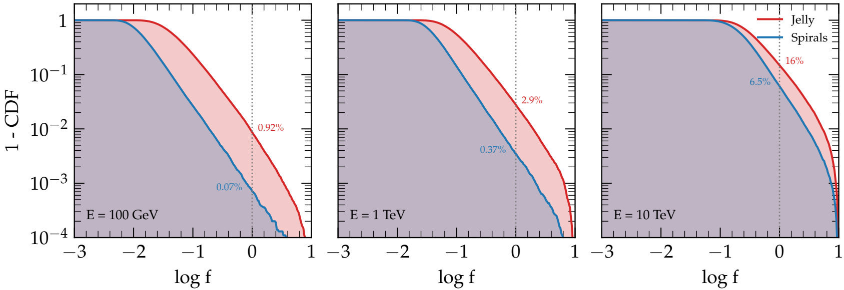


- Most SN explosions are located in star-forming regions which cluster inside the spiral arms and in the Galactic bar with a Galactic rate of $\mathcal{R} = 1/30$ years
- The sources that can contribute to the flux at Earth at a given energy E are

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

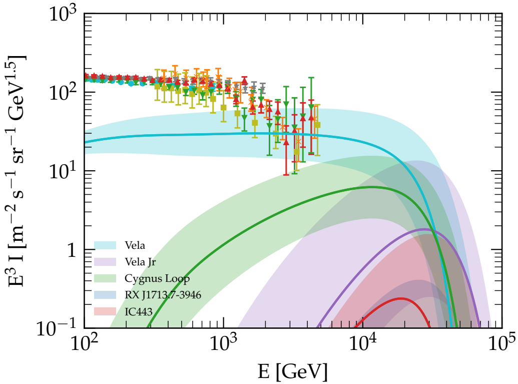
The odds of a prominent nearby source

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 ~ 1 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!

Carmelo Evoli

- GRAN SASSO SCIENCE INSTITUTE
- Via Michele Iacobucci, 2, L'Aquila (Italy)
- mailto: carmelo.evoli@gssi.it
- @carmeloevoli
- carmeloevoli
- e.carmelo
- 0000-0002-6023-5253
- slides available at: https://zenodo.org/communities/carmeloevoli_talks