Galactic factories of cosmic electrons and positrons

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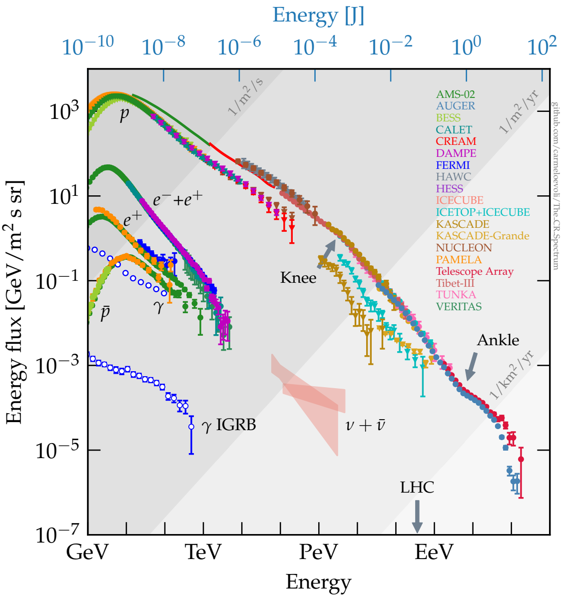
The cosmic-ray spectrum in 2021



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?

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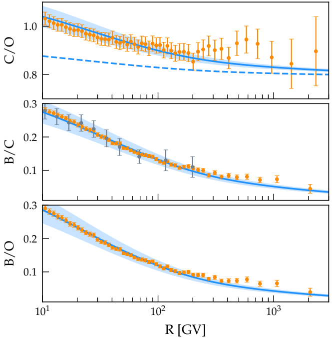
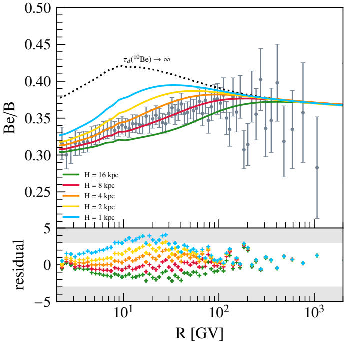
Conclusions

- Yes, but...

Key results of the Galactic halo model

Evoli, Blasi, and Aloisio, PRD, 2019; Evoli et al., PRD, 2020; Schroer, Evoli, and Blasi, PRD, 2021





▷ We assume a phenomenological motivated $D(R)$ (rigidity $R \equiv p/Z$) as a smoothly-broken power-law:

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

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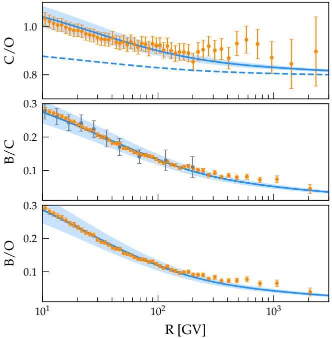

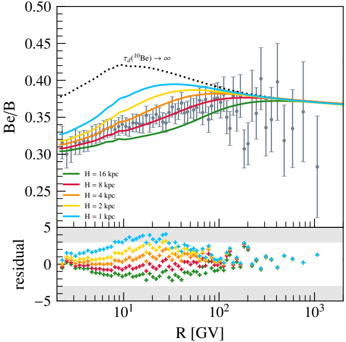

- By fitting primary and secondary/primary measurements we obtain:
  $\delta \sim 0.54/0.34$, $R_b \sim 400$ GV, $D_0/H \sim 0.45 \times 10^{28}$ cm/s^2/kpc, $v_A \sim 5$ km/s
- All nuclei with $Z > 2$ are injected with $\gamma \sim 4.3$ (Oxygen here is the only pure primary species)
- Escape time weakly constrained since $\tau_{\rm esc} \simeq \frac{H^2}{D} = \left(\frac{H}{D}\right)_{\rm B/C} H$
- Shaded areas: uncertainty from cross sections

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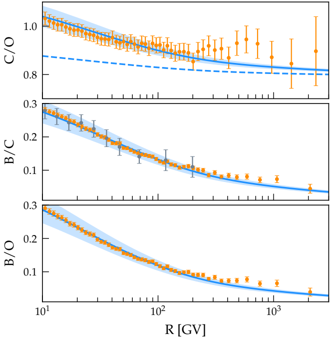
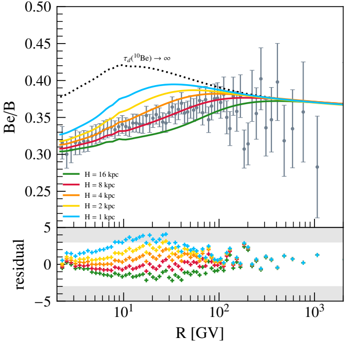


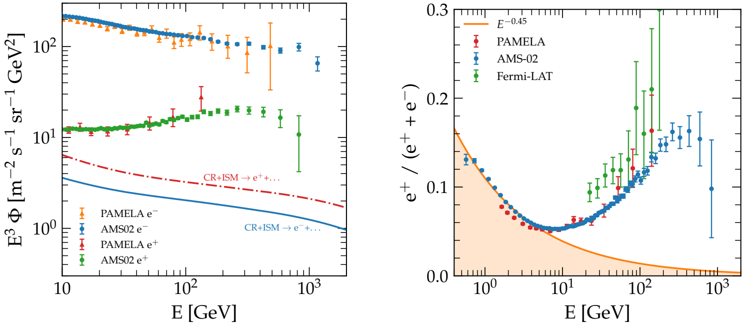


- ▷ Traditionally ^{9}Be/^{10}Be has been used as CR clock $\to$ no measurements at $E \gtrsim 1$ GeV/n [Lipari, arXiv:1407.5223]
- ▷ Since ^{10}Be decays to ^{10}B the ratio Be/B is affected twice (excellent recent AMS-02 data!)
- ▷ Preference for large halos $H \gtrsim 5$ kpc [see also Weinrich et al., A&A (2020)]

$$\tau_{\rm esc}(10\,\text{GV}) \sim \frac{H^2}{2D} \sim 20\,\text{Myr} \left(\frac{H}{\text{kpc}}\right) \left(\frac{0.45 \times 10^{28}\,\text{cm}^2/\text{s}/\text{kpc}}{D_0/H}\right)$$

Secondary leptons in the Galactic Halo model

Evoli et al., PRD, 2021

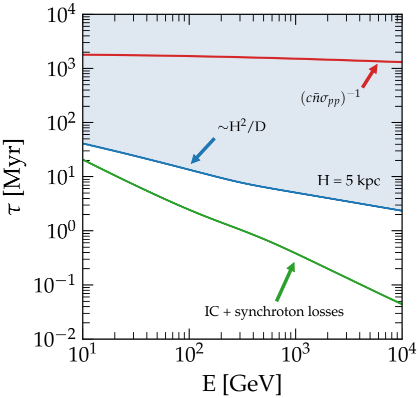


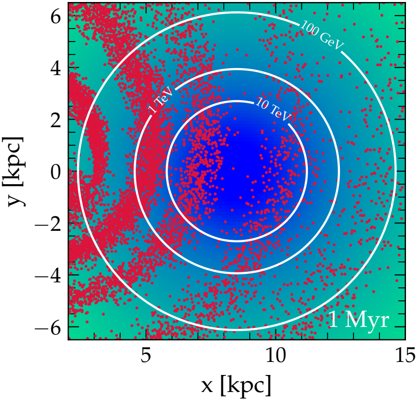
- AMS-02 local measurements of e^+ and e^- compared with secondary predictions CR+ISM$\to e^\pm$
- It is not compatible with all leptons being secondary $\to$ we need a primary component for electrons
- If e^+ are secondaries (and $\alpha_p = \alpha_e$) the positron fraction must be a monotonically decreasing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

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

Nuclei and electron timescales

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

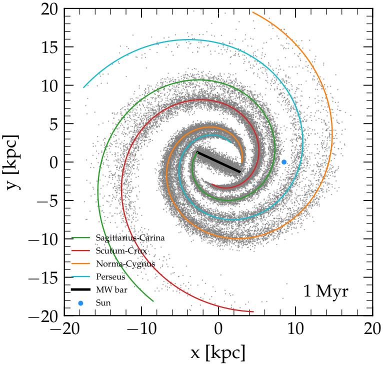




- Leptons lose their energy mainly by IC with the interstellar radiation fields (ISRFs) or synchrotron emission
- Milky Way is a very inefficient calorimeter for nuclei and a perfect calorimeter for leptons
- Translate losses into propagation scale: $\lambda \sim \sqrt{4D(E)\tau_{\rm loss}} \longrightarrow$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

The Green function formalism

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

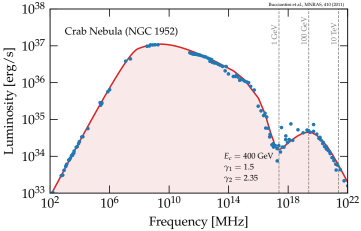


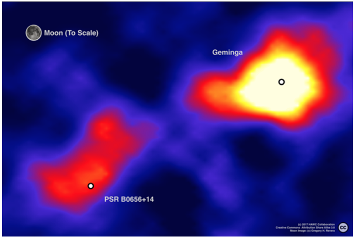
$$n(t_\odot, E, \vec{r}_\odot) = \iiint dt_s\, dE_s\, d^3\vec{r}_s\, \delta(\Delta t - \Delta\tau) \mathcal{G}_{\vec{r}}(E, \vec{r}_\odot \leftarrow E_s, \vec{r}_s) \mathcal{Q}(t_s, E_s, \vec{r}_s).$$

Pulsars as positron galactic factories

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

- $e^{\pm}$ pairs 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]
- 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]
- HAWC has detected bright and spatially extended TeV gamma-ray sources surrounding the Geminga and Monogem pulsars [HAWC coll., Science 358 (2017)] (detected also in FERMI [Linden+, PRD 2019; Di Mauro+, PRD 2019]) associated with the release of pairs in the ISM





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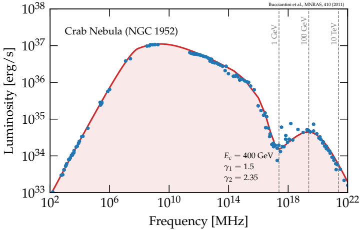
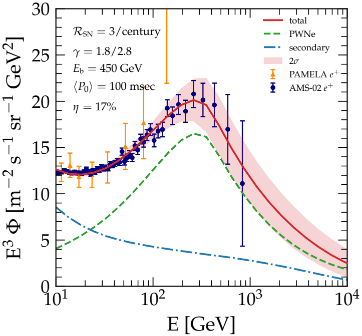
$$Q_0(t) e^{-E/E_c(t)} \times \begin{cases} (E/E_b)^{-\gamma_L} & E < E_b \\ (E/E_b)^{-\gamma_H} & E \geq E_b \end{cases}$$

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

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

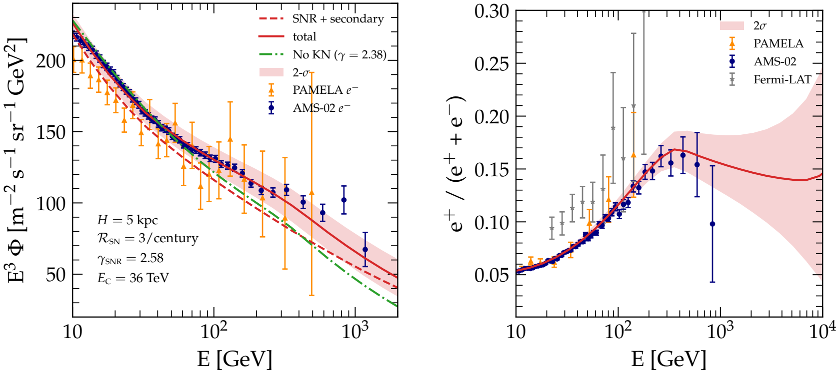
- AMS-02 data requires an efficiency of conversion: $\sim 20\%$ of the energy released after the Bow-Shock phase ($t_{BS} \simeq 56$ ky)
- Shaded areas: 2-sigma fluctuations due to cosmic variance





The electron spectrum from SNRs

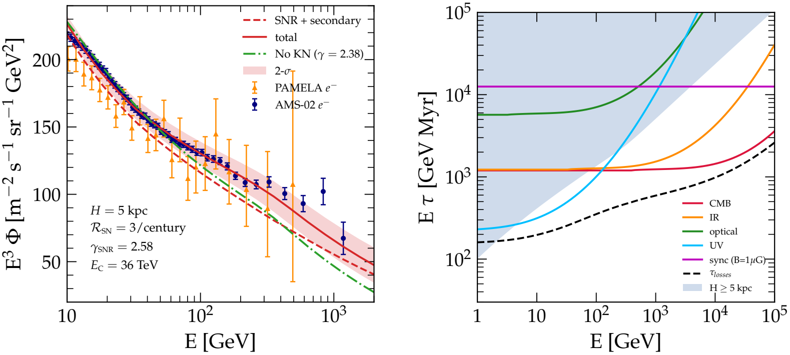
Evoli, Amato, Blasi & Aloisio, PRD 2021



- ▷ Electrons injected by SNRs with a power law with an intrinsic cutoff at ~ 40TeV (cooling dominated)
- ▷ Electrons require a spectrum steeper than protons by $\sim 0.3 \rightarrow$ 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]
- ▷ Watch at the positron fraction!

The signature of energy losses on the cosmic ray electron spectrum

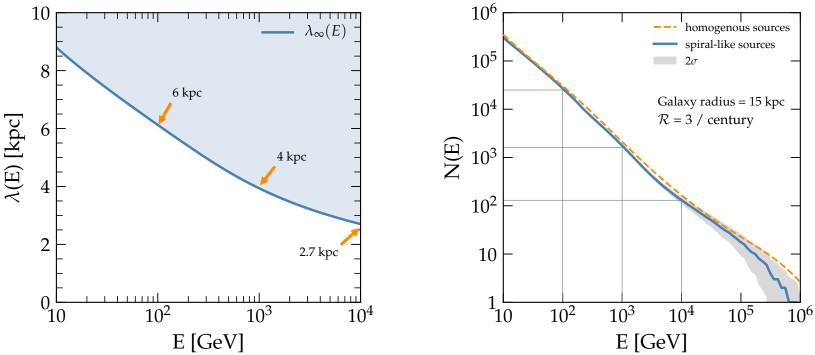
Evoli, Blasi, Amato & Aloisio, PRL 2020



- ▷ 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)
- ▷ The feature in the e^- spectrum is the result of KN effects in the ICS on the UV bkg $\longrightarrow$ electrons do lose energy in the ISM at odds with unorthodox transport models [Blum et al., PRL 2013; Kachelriess+, PRL 2015; Cowsik & Madziwa-Nussinov ApJ 2016; Lipari, PRD 2019]
- ▷ See also Di Mauro, Donato, and Manconi, PRD, 2021, for a different interpretation.

Counting the sources of leptons in the Galaxy

Evoli, Blasi, Amato & Aloisio, PRD 2021

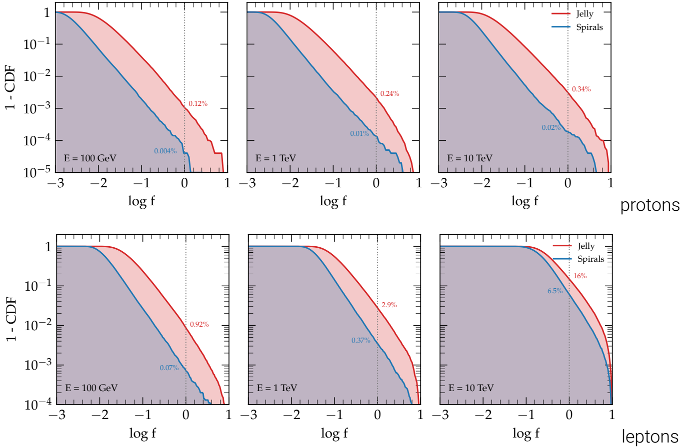


- ▷ Most SN explosions are located in star-forming regions which cluster inside the spiral arms and in the Galactic bar $\to$ SNR of $\mathcal{R} = 1/30$ years
- ▷ The sources that can contribute to the flux at Earth at a given energy E are

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

The odds of a prominent nearby source

work in progress...



- Regularly adduced to explain features in the CR spectrum.
- $f = 1$ shows the case in which 1 source contributes to the local flux as much as all others added together.
- Assuming Spiral pattern and standard properties for transport $\rightarrow$ at ~ 1 TeV chances are $\sim 0.01\%$ for nuclei and $\sim 0.4\%$ for leptons

Thank you!

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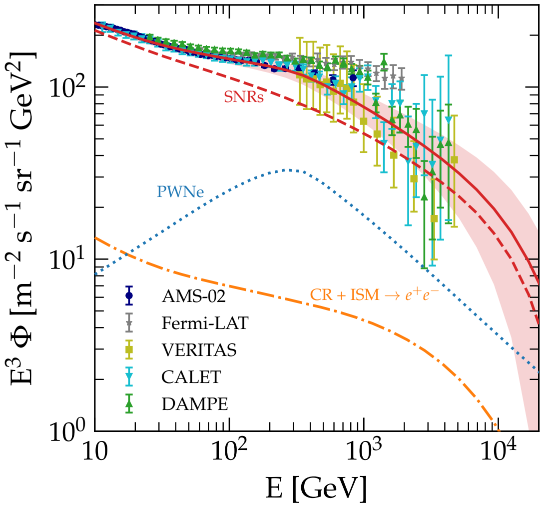
Backup slides



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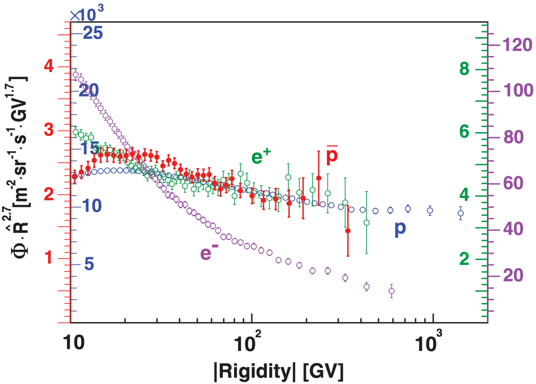

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