The Playbook of Galactic Cosmic Ray Electrons and Positrons

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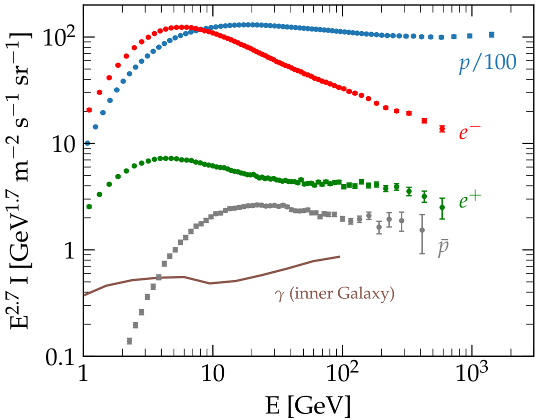
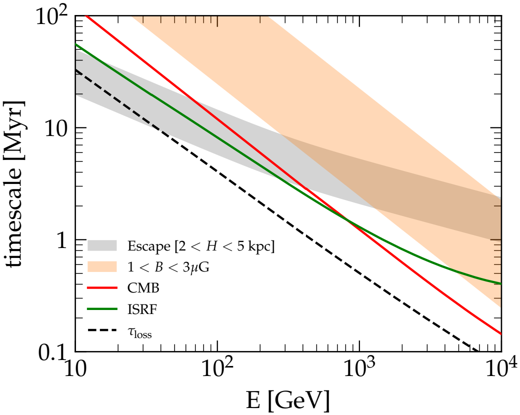
Electrons and Positrons in Cosmic Rays

AMS-02 Coll., Phys. Rep 2021; Fermi Coll., ApJ 2012



- Although the fraction of electrons in the total cosmic ray flux is small ($\times 100$), their unique properties make them crucial for understanding the origin of cosmic rays.
- A substantial amount of high-precision experimental data on primary electrons and positrons has been gathered from current-generation experiments: PAMELA, AMS-02, CALET, DAMPE, VERITAS, HESS, ...
- Several observed features in the data were unexpected, leading to an exciting and intriguing situation in the field.
- The study of cosmic ray electrons and positrons is also important due to their potential connection with dark matter annihilation or decay, as well as other exotic sources such as black hole evaporation, and so on.

The CR Standard Model: Primary Electrons



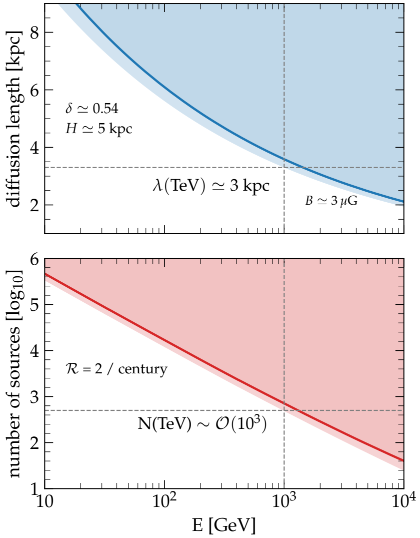
- Since we detect significantly more electrons than positrons, it necessitates positing a primary source of electrons.
- The most natural assumption is that the sources of primary electrons and protons are the same, with their spectra following a rigidity-dependent pattern:

$$q_p \propto E^{-\gamma_p},\ q_e \propto E^{-\gamma_e} \rightarrow \gamma_p \simeq \gamma_e$$

- Following injection, electrons diffuse through the turbulent magnetic field of our Galaxy $D \sim E^\delta$ with $\delta \sim 0.5$
- Unlike nuclei, they lose energy primarily through:
  - Synchrotron emission in the halo magnetic field $\langle B \rangle \simeq 1\ \mu$G
  - IC scattering on interstellar radiation fields (CMB, IR, UV, ...)
- Under standard assumptions, energy losses dominate over diffusion across the entire energy range:

$$\tau_{\rm loss}(E) \lesssim \frac{H^2}{2D(E)}, \quad E \gtrsim 10\ \text{GeV}$$

The CR Standard Model: The Lepton Horizon



- The Milky Way acts as a highly efficient calorimeter for leptons.
- Energy losses can be translated into a propagation scale:

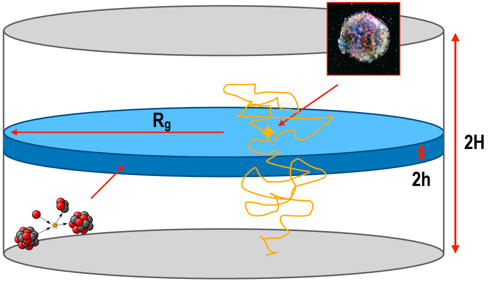
$$\lambda_e^2(E) = 4\int_E^\infty dE' \frac{D(E')}{|b(E')|} \simeq (3\ \text{kpc})^2 \left(\frac{E}{\text{TeV}}\right)^{\delta-1}$$

- What is the maximum number of sources contributing to the local flux?
- Assuming ~ 2 events/century over a Galactic disk of radius $R_\text{G} \sim 15$ kpc:

$$N(E) \sim \mathcal{R}_\text{S}\tau_\text{loss}(E)\,\text{min}\left[\frac{\lambda_e^2(E)}{R_\text{G}^2}, 1\right] \propto E^{\delta-2}$$

- Exploring the $\gtrsim 10$ TeV energy window will be crucial to have $\mathcal{O}(1)$ local source contribution to the local flux.
- Within the reach of upcoming measurements from HESS, DAMPE, and CALET.

The CR Standard Model: Primary Electrons



- The transport equation governing electron propagation in the Galaxy is given by:

$$\underbrace{-D(E)\nabla^2 n_e(E,\vec{r})}_{\text{diffusion}} + \underbrace{\frac{\partial}{\partial E}\left[b(E) n_e(E,\vec{r})\right]}_{\text{losses}} = \underbrace{Q_e(E,\vec{r})}_{\text{sources}}$$

- Assuming $\tau_{\rm loss} \gg \tau_{\rm esc}$, I can model the Galaxy as an infinitely thin and homogeneous disk:

$$Q_e(E,\vec{r}) \to q_e(E)\delta(z)$$

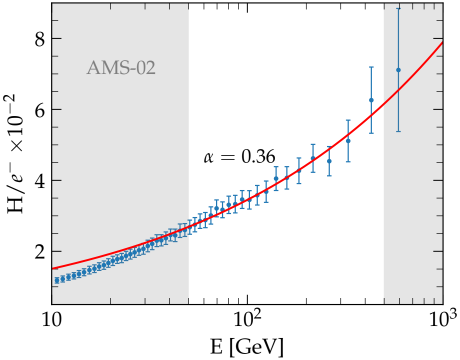
along with an infinitely thick Galactic halo:

$$H \to \infty$$

- The solution to the transport equation at the disk then becomes:

$$n_e(E, z=0) = \frac{1}{\sqrt{2\pi}}\frac{1}{b(E)}\int_E^\infty \frac{q_e(E')}{\lambda_e(E,E')} dE'$$

Confronting Measurements: The Injection Slope Problem



- In Thomson regime energy losses scale as $b \propto E^2$, and the equilibrium spectrum of electrons is steepened by $\frac{1+\delta}{2} \sim 0.75$:

$$n_e \sim \frac{1}{b(E)} \frac{q_e(E)}{\lambda(E)} \propto E^{-\gamma_e - \frac{1+\delta}{2}}$$

- In contrast, for protons (where energy losses are negligible), the steepening is only due to diffusion:

$$n_p \sim \frac{q_p(E)}{D(E)} \propto E^{-\gamma_p - \delta} \quad \rightarrow \quad \frac{p}{e^-} \propto E^{\gamma_e - \gamma_p + \frac{1-\delta}{2}}$$

- Since the measured proton-to-electron ratio is harder than $(1-\delta)/2$, we are led to conclude that:

$$\gamma_e \gtrsim \gamma_p$$

unlike the initial assumption.

- More precise calculations in a homogeneous source scenario suggest that the injection spectrum of electrons must be steeper than that of protons by approximately 0.3—this result is puzzling!

Understanding CR Electron Acceleration

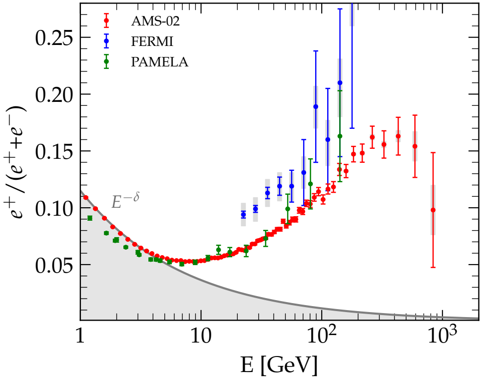
Blasi, A&AR 2013; Funk, ARNPS 2015

%	ISRF	Propagation	Spiral Arms	ICS	q	γ_{SNR}	$W_{\rm SNR}$	$\gamma_{1,2}$	$\eta_{\rm PWN}$	$\tilde{\chi}^2$	σ_{PWN}
							$[10^{49}$ erg]				
1	Vernetto2016	Genolini2015	No	numerical	1.32	2.57	1.35	1.88/2.31	0.009	0.92	5.8
2	Vernetto2016	Genolini2015	Yes	numerical	1.54	2.43	1.53	1.61/2.20	0.017	1.64	8.2
3	Vernetto2016	BPLDiffusion	No	numerical	1.32	2.50	1.15	1.80/2.58	0.010	0.82	4.0
4	Delahaye2010	Genolini2015	No	numerical	1.31	2.59	1.44	1.90/2.27	0.009	0.95	6.1
5	Delahaye2010	BPLDiffusion	Yes	approx	1.78	2.43	2.13	1.56/2.80	0.018	0.71	0.2
6	Evoli10/2020	BPLDiffusion	Yes	numerical	1.50	2.56	3.34	1.82/2.21	0.022	0.84	3.9

- A non-uniform source distribution can result in a harder injection spectrum, as suggested by Gaggero+, PRL 2013. The Sun's location in an underdense region leads to stronger electron losses over greater distances between the Galactic arms and the observer.
- Recent calculations, incorporating SNR locations within the spiral structure and pulsar wind nebulae contributions in Di Mauro+, PRD 2021, suggest a slightly steeper spectrum $\Delta\gamma \simeq 0.14$ due to the spiral structure (see also Evoli+, PRD 2021).
- Energy losses during acceleration, particularly synchrotron losses from magnetic field amplification (MFA) via cosmic ray streaming instability, may also steepen the spectrum Diesing & Caprioli, PRL 2019.
- However, Cristofari+, A&A 2021 and Brose+, A&A 2020 found that amplified fields alone are insufficient to explain the observed steepening below 1 TeV.
- Additional steepening could occur during later SNR stages, when most low-energy cosmic rays form, or in low-diffusivity regions surrounding sources, more in Morlino & Celli, MNRAS 2021.

Cosmic Ray Standard Model: Secondary Positrons

Orusa+, PRD 2022



- Secondary positrons are generated through hadronic interactions $pp \to \pi^\pm + \ldots$. Typically, the energy of the secondary positron is a fraction $\xi \sim \mathcal{O}(10\%)$ of the parent proton's energy E_p:

$$E_{e^+} \simeq \xi E_p \quad \leftarrow \text{Inelasticity}$$

- The production rate of positrons e^+ in the ISM can be expressed as:

$$q_{e^+}(E) = c\sigma_{\rm pp}\xi^{-1}\mu_d\delta(z)n_p(E/\xi) \propto E^{-\gamma_p-\delta}$$

- Consequently, the equilibrium spectrum of positrons is given by:

$$n_{e^+}(E) \propto E^{-(\gamma_p+\delta)-\frac{1+\delta}{2}}$$

- Therefore, the positron-to-electron ratio behaves as:

$$\frac{e^+}{e^-}(E) \sim E^{\gamma_e-\gamma_p-\delta} \sim E^{-\delta}$$

A new – harder – source of positrons is needed!

The Pulsar Wind Nebulae Paradigm

- The observed population of cosmic positrons contains an energy density in particles at $E \gtrsim 100$ GeV of approximately:

$$E^2 I_+ \approx 0.2\,\text{GeV m}^{-2}\text{s}^{-1}\text{sr}^{-1} \quad \rightarrow \quad \epsilon_+ \sim \frac{4\pi}{c} E^2 I_+ \sim 8 \times 10^{-6}\,\text{eV cm}^{-3}$$

- A viable Galactic source population should be capable of providing a luminosity on the order of:

$$\mathcal{L}_+ \sim \frac{\epsilon_+ V_\text{G}}{\tau_\text{loss}} \sim 3 \times 10^{37}\,\text{erg s}^{-1}$$

where $\tau_\text{loss} \sim 4$ Myr and $V_\text{G} \sim \pi R_\text{G}^2 \times 2\lambda_e \sim \pi(13\,\text{kpc})^3$.

- The maximum energy released by a typical pulsar with $P_0 = 0.1$ s is the time integrated spin-down luminosity:

$$E_\text{pwn} \simeq \int_0^\infty dt\, \mathcal{L}_\text{bs}(t) = \frac{\pi}{4} I \Omega_0^2 \sim 5 \times 10^{47}\,\text{erg}$$

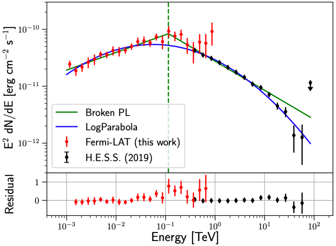
over a timescale on the order of the spin-down age $\tau \sim \mathcal{O}(10)$ kyr $\ll \tau_\text{loss}$.

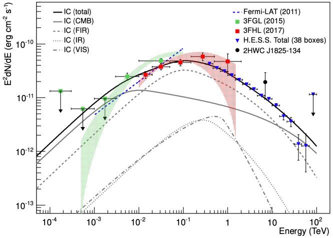
- The luminosity of the Galactic PWN population in positrons, assuming a rate of $\mathcal{R}_\text{pwn} \sim 2/$century, and an efficiency $\eta \lesssim 1$, would be:

$$\mathcal{L}_\text{pwn} \sim \frac{1}{2} \eta E_\text{pwn} \mathcal{R}_\text{pwn} \sim 3 \times 10^{38} \eta\,\text{erg s}^{-1}$$

A Break in the PWN Spectrum

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





- Combined spectra of PWN HESS J1825-137 and HESS J1825-137 with spectral measurements obtained from Fermi-LAT data (from $\sim$ GeV to $\sim$ TeV) and from HESS/HAWC data in the $\gtrsim 100$ GeV energy range.
- The γ/X-ray emissions in nearly all these objects are characterized by a flat spectrum (with $1 \lesssim \alpha_L \lesssim 2$) at low energies, which then steepens to approximately $E^{-2.5}$ beyond a few hundred GeV [Bucciantini+, MNRAS 2011]:

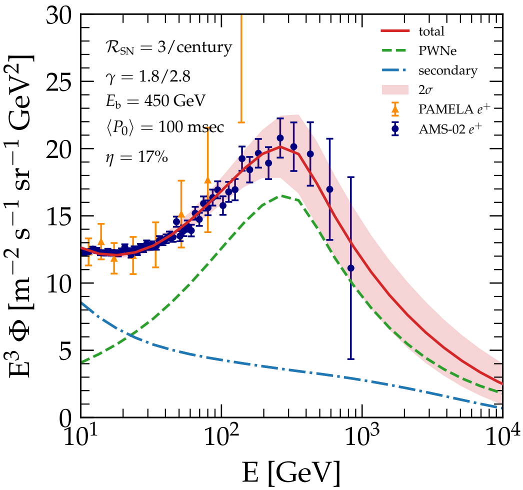
$$Q_{\rm PWN}(E,t) = Q_0(t) {\rm e}^{-E/E_{\rm c}(t)} \times \begin{cases} (E/E_{\rm b})^{-\gamma_{\rm L}} & E < E_{\rm b} \\ (E/E_{\rm b})^{-\gamma_{\rm H}} & E \geq E_{\rm b} \end{cases}$$

- These are the only sources exhibiting direct evidence for PeV particles [LHAASO Coll., ApJS 2024] $\longrightarrow$ the $\sim$ PeV cutoff is associated with the potential drop [Kotera, JCAP 2015]:

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

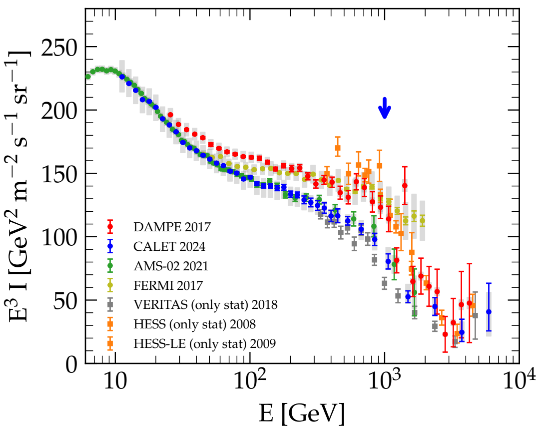
Pulsars as Galactic Positron Factories

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



- To reproduce AMS-02 data is required an efficiency of approximately 20% of the energy released after the Bow-Shock phase ($t_{\rm BS} \simeq 56$ kyr), although this is degenerate with $\langle P_0 \rangle$ [Orusa+, JCAP 2021]
- The required spectral slopes $\gamma \sim 1.8/2.8$ are remarkably steep compared to typical values inferred from γ-ray observations [Torres+, JHEA 2014] $\longrightarrow$ what is the spectrum released in the ISM?
- Shaded areas indicate 2-sigma fluctuations due to cosmic variance (CDF).
- In terms of energetics and spectral features, the pulsar interpretation prevails undoubtedly as the most compelling explanation.

Confronting Measurements: The TeV break

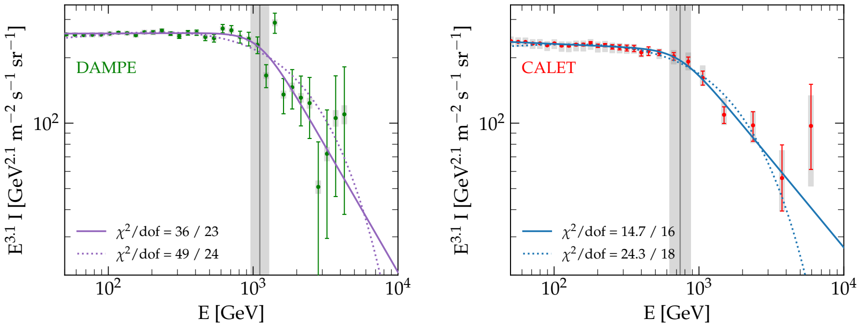


- HESS measurements up to $\sim$4 TeV revealed a break in the CR $e^+ + e^-$ spectrum around 1 TeV, later confirmed by VERITAS. This remains one of the most prominent features in the cosmic ray spectrum, with $\Delta\gamma \gtrsim 1$.
- Direct measurements by Fermi-LAT and AMS-02 reached the onset of the break, allowing for discrimination between electrons and positrons:

$$\frac{e^+}{e^-} \lesssim 15\%$$

- Further extensions to 4.6 TeV and 7.5 TeV by DAMPE and CALET provided the first direct confirmation of the break.
- A cutoff was expected when $\lambda \sim \langle d \rangle$, but it should occur at much higher energies.

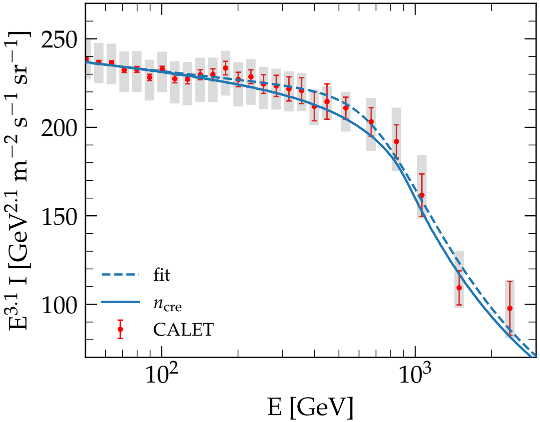
Characterizing the TeV Puzzling Anomaly



Exponential cut-off is excluded with more than 5σ significance compared to a spectral break.

	$\gamma_{\rm le}$	$\log E_b$	$\Delta\gamma$	s	γ	$\log E_c$
CALET	3.13 +/- 0.02	2.87 +/- 0.07	0.8 +/- 0.2	4.6 +/- 2.4	3.04 +/- 0.02	3.29 +/- 0.05
DAMPE	3.097 +/- 0.009	3.05 +/- 0.06	1.16 +/- 0.33	5	3.01 +/- 0.02	3.41 +/- 0.05

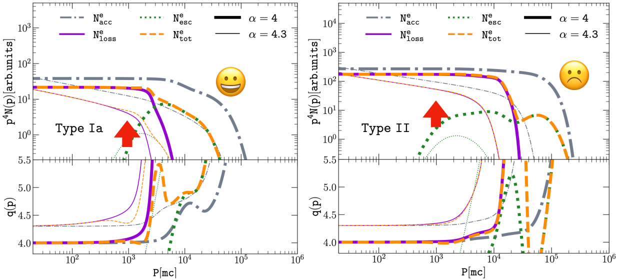
TeV Puzzling Anomaly: Challenges with a Sharp Break



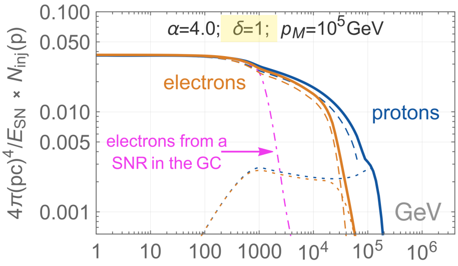
- The most plausible explanation lies in the injection process rather than propagation.
- However, the break at injection would need to be even sharper!
- Even an infinitely sharp feature $s \to \infty$ at injection is broadened by energy losses, creating a (weak) tension with observations.
- Is it statistically compatible with a stochastic distribution of Galactic sources? [Mertsch, JCAP 2018]

Understanding CR Electron Acceleration

Blasi, A&AR 2013; Funk, ARNPS 2015



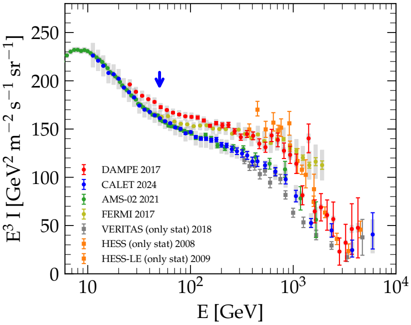
Cristofari, Blasi & Caprioli, A&A 2021

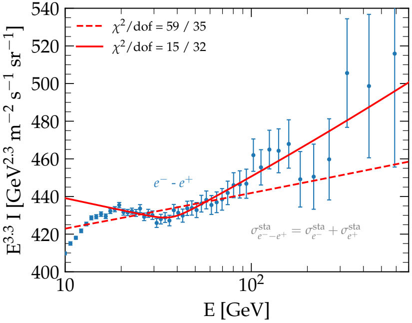


Morlino & Celli, MNRAS 2021

- The injection spectrum represents the time-integrated release of accelerated particles at the SNR.
- A spectral break is expected at the maximum energy achieved at the end of the ST phase.
- Under specific conditions, a break can occur at around 1 TeV.
- What about Galactic variance? It makes it challenging to produce a sharp break.

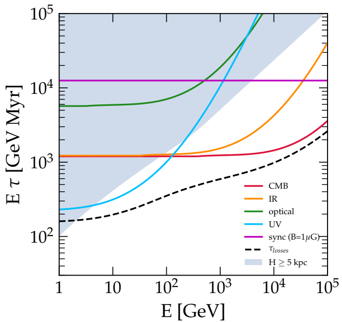
A Primary Excess in Electrons?

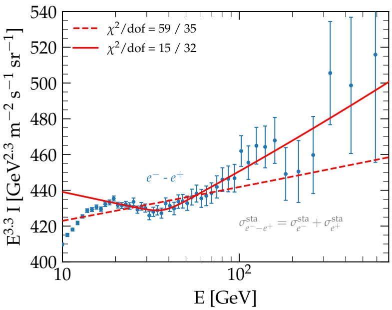




- The excess in the electron spectrum is interpreted as evidence of a new primary electron source.
- Focusing on $e^- - e^+$ data, dominated by propagated primary CR electrons, helps minimize uncertainties related to the (symmetric) positron primary source.
- This analysis is possible thanks to the AMS-02 release of electron/positron absolute spectra in the same energy bin with correlated systematics.
- The significance of the excess is at least 3σ C.L.

A Primary Excess in Electrons?





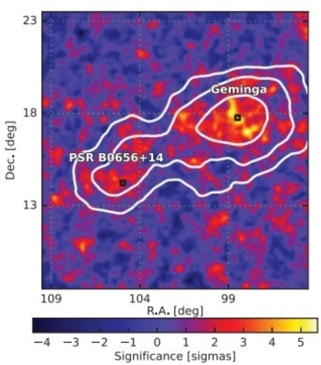
- Existence of a fine structure at ~ 42 GeV $\rightarrow$ result of KN effects in the ICS on the UV bkg [Evoli+, PRL 2020]

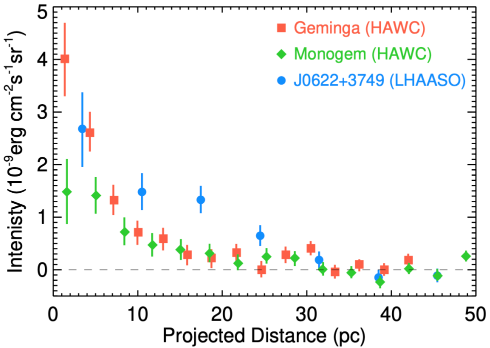
$$E_{\mathrm{KN}} \sim \frac{m_e^2}{kT} \simeq 40\,\mathrm{GeV} \left(\frac{T_i}{3 \times 10^4\,\mathrm{K}} \right)^{-1}$$

- Electrons do lose energy in the ISM at odds with unorthodox transport models [Blum+, PRL 2013; Cowsik & Madziwa-Nussinov, ApJ 2016; Lipari, PRD 2019]
- See also alternative interpretation in [Di Mauro+, PRD 2021]

The Era of TeV Halos

Ruo-Yu Liu, IJMPA 2022; Amato & Recchia, Nuovo Cimento 2024





- 2017: HAWC reported the discovery of extended gamma-ray emissions, up to about 50 TeV, around two nearby middle-aged pulsars: the Geminga pulsar and PSR B0656+14 [Abeysekara+, Science 2017].
- 2021: A third TeV halo was detected around PSR J0622+3749 by LHAASO [Aharonian+, PRL 2021].
- These TeV halos are significantly more extended than the associated PWNe, which have sizes of approximately 0.1 pc, revealing a new and unexpected source class in high-energy astrophysics.

The Era of TeV Halos

- The observed gamma-ray photons are up-scattered CMB photons with an average energy of $\langle \epsilon \rangle \sim 10^{-3}$ eV. The corresponding electron energy is:

$$\gamma_e \simeq \left(\frac{E_\gamma}{\langle \epsilon \rangle} \right)^{1/2} \rightarrow E_{e^\pm} \sim 100 \left(\frac{\langle E_\gamma \rangle}{10 \text{ TeV}} \right)^{1/2} \text{TeV}$$

$\longrightarrow$ VHE electron-positron pairs efficiently escape the PWN.

- For ∼100 TeV electrons, the energy loss timescale is $\tau_{\text{loss}} \sim 10$ kyr:

$$D(E_{e^\pm} \sim 100 \text{ TeV}) \sim \frac{d^2}{\tau_{\text{loss}}} \sim 3 \times 10^{27} \left(\frac{d}{10 \text{ pc}} \right)^2 \text{cm}^2\text{s}^{-1} \ll D_{\text{ISM}}$$

$\longrightarrow$ TeV halos provide an indirect opportunity to probe turbulence in localized regions around sources.

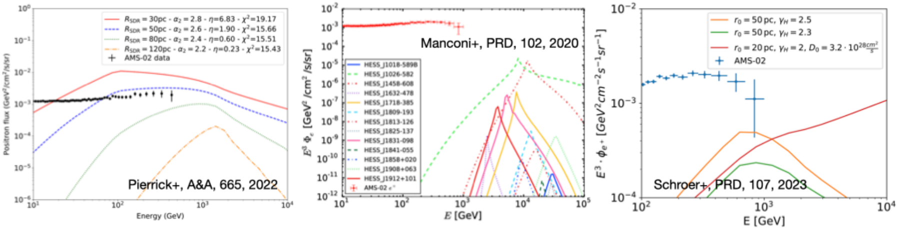
- The efficiency of converting spin-down power into electron-positron pairs must be:

$$\epsilon^\pm \simeq \frac{\mathcal{L}_{\text{HAWC}}(> E_\gamma)}{\dot{E}_s(> E_{e^\pm})} \sim 30\%$$

$\longrightarrow$ Consistent with the observed positron fraction!

Open Questions about TeV Halos

Amato & Recchia, Nuovo Cimento 2024



- **What is the origin of the confinement?**
  - Self-confinement by streaming electron-positron pairs [Evoli et al. 2018; Mukhopadhyay et al. 2021]
  - Pre-existing fluid turbulence [Lopez Coto & Giacinti et al. 2018; Fang et al. 2019]
  - Pre-existing kinetic turbulence [Mukhopadhyay et al. 2021; Schroer et al., 2022]
- **Are TeV halos ubiquitous?**
  - Interpretation of extended gamma-ray sources [Linden et al. 2017; Di Mauro et al. 2020]
  - Contribution to diffuse gamma-ray emission as an unresolved population [Linden & Buckman 2018; Hooper & Linden 2022; Martin et al. 2022b]
  - Impact on large-scale transport of Galactic cosmic rays (GCRs) due to inhomogeneous diffusion [Jacobs et al. 2023; Johannesson et al. 2019]
  - Influence on the interpretation of local positron and electron fluxes [Fang et al. 2018, 2019; Manconi et al. 2020; Martin et al. 2022a; Schroer et al. 2023]

These questions are crucial before assessing the role of TeV halos on the positron and electron flux.

Conclusions

- Understanding the origin of the electron and positron fluxes is crucial for advancing High Energy Astrophysics.

- Recent measurements represent a significant leap forward in both accuracy and energy coverage PAMELA, AMS-02, HESS, VERITAS, DAMPE, CALET

- Prompt phenomenological consequences:

- $e^- / e^+ \rightarrow$ Evidence of a primary component for positrons, indicating a second Galactic population of cosmic rays. Most likely Pulsars.
- $e^- + e^+ \rightarrow$ The break at ~ 1 TeV remains the most prominent feature in the VHE electron spectrum, posing challenges to current acceleration models.
- $e^- - e^+ \rightarrow$ The Galactic halo model continues to be the most plausible description of the transport of Galactic cosmic rays.

- The coming years promise to deliver more intriguing results, particularly in the multi-TeV energy region.

Thank you!

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