Recent Results in Galactic Cosmic Ray Physics and Their Interpretation

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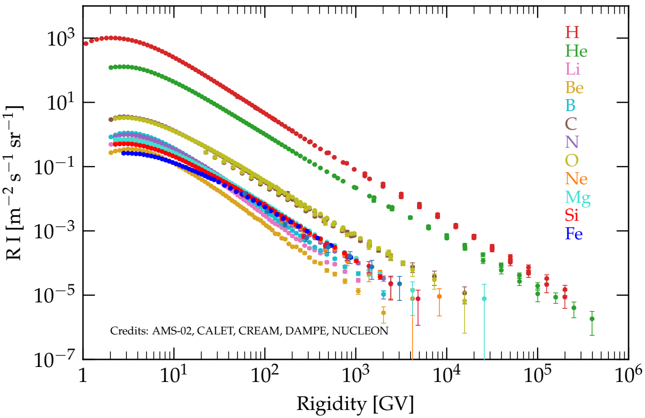
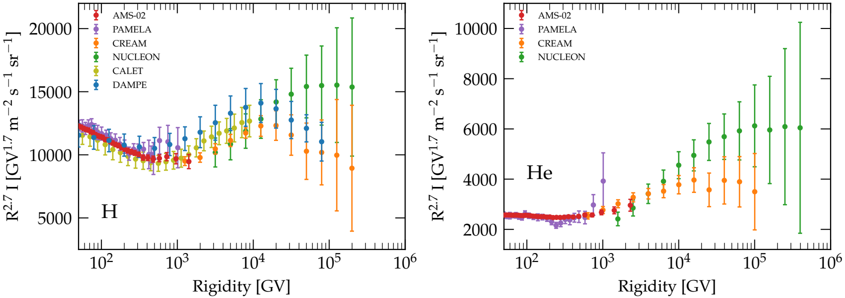
Galactic Cosmic Rays: unprecedented measurements



The spectrum of each isotope includes contributions from many different parents (both in terms of fragmentation and decays) giving to each observed isotope a potentially very complex history

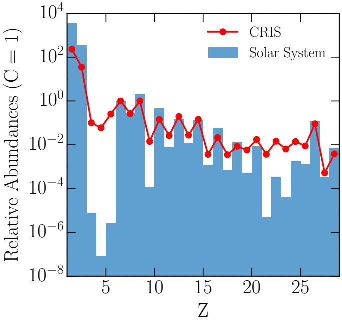
Galactic Cosmic Rays: a decade of surprises!

PAMELA Coll., Science 2011; AMS-02 Coll., PRL 2015; CREAM Coll., ApJ 2017; NUCLEON Coll., JETP 2018; DAMPE Coll., Science 2019



- Spectra of protons and helium are not a single power law below the knee $\rightarrow$ some physics kicking in?
- The hardening at $R = p/Z \sim 300 - 400$ GV is well established since first observation by PAMELA
- AMS-02 confirmed the same break for almost all nuclei
- The softening at $R = p/Z \sim 10$ TV is observed by different experiments, first strong evidence in DAMPE
- The He spectrum (at Earth!) is slightly harder than that of protons

The cosmic-ray composition at $E \sim$ GeV



- ▷ The average galactic grammage χ_{gal} can be directly inferred from this plot:

$$\frac{\text{B}}{\text{C}} \sim \chi_{\text{gal}} \frac{\sigma_{C \to B}}{\langle m \rangle_{\text{ISM}}} \sim 0.3 \to \chi_{\text{gal}} \sim 5 \text{ g cm}^{-2}$$

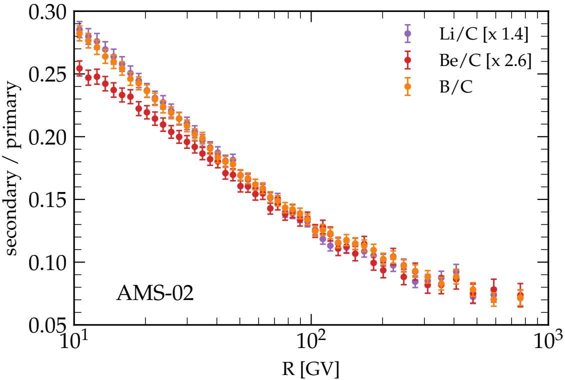
- ▷ To be compared with the grammage X_d accumulated at each crossing of the gas disk $h \sim 100$ pc:

$$X_d \sim m_p n_{\text{gas}} h \sim 10^{-3} \text{ g cm}^{-2} \ll X_{\text{gal}}$$

- ▷ Robust evidence of diffusive transport!

Measurements of the B-Li-Be in CRs up to $\sim$ TeV

AMS-02 Coll., PRL 120, 021101 (2018)

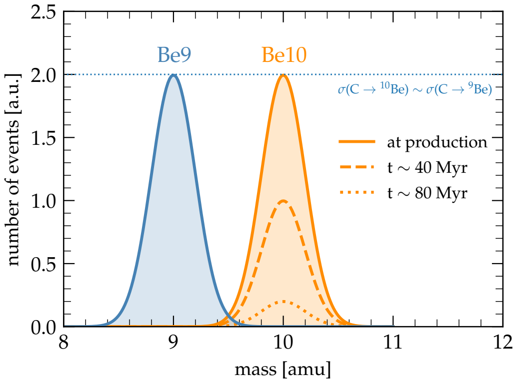


Key points

Evidence of rigidity dependent grammage $\rightarrow$ high-energy particles spend less time in our Galaxy than low-energy ones

Cosmic-ray lifetime

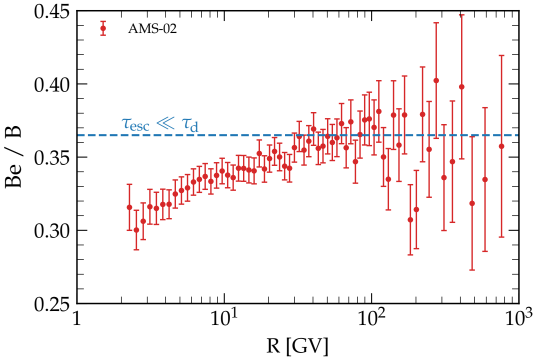
Garcia-Munoz et al., ApJ (1977); PAMELA Collaboration, ApJ, Vol. 862, 141 (2018)



- ^{10}Be is a β^- unstable isotope decaying in ^{10}B with an half-life of ~ 1.5 Myr
- Similar production rates than other (stable) isotopes $\sigma_{\text{Be9}} \sim \sigma_{\text{Be10}}$
- 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

Cosmic-ray lifetime

AMS-02 Coll., PRL 120, 021101 (2018); Evoli et al., PRD 101, 023013 (2020); Weinrich+, A&A 639, A74 (2020)

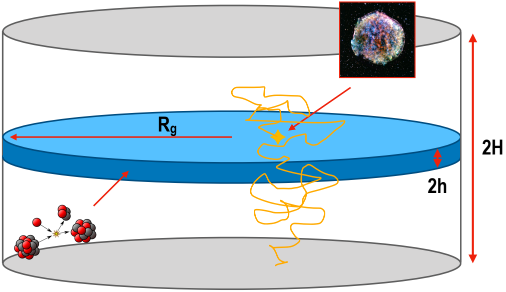


- Since ^{10}Be decays to ^{10}B the ratio Be/B is affected twice (excellent recent AMS-02 data!)
- The observed ratio hints to a CR lifetime ($\equiv$ from production to escape) of

$$t_{\rm esc} \sim \mathcal{O}(100)\,\text{Myr} \gg \frac{R_{\rm G}}{c}$$

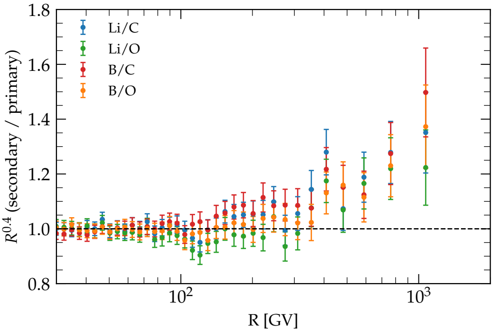
The Galactic halo model

Morrison, Olbert and Rossi, Phys. Rev (1954); Ginzburg and Syrovatskii (1964)



- Galactic CRs are accelerated in the disc h by SNRs and hence are injected with a spectrum $Q_s \propto p^{-\alpha}$ where $\alpha \gtrsim 4$
- after injection, CRs propagate diffusively throughout the Galactic halo ($\sim 1D$) with a diffusion coefficient $D \propto p^{\delta}$ where $\delta \sim 1/3 - 1/2$
- Secondary production, e.g. LiBeB, takes place predominantly in the disc h where all the gas is confined.
- H is the diffusive halo size (free escape boundary) and R_d is the radius of the Galactic disc.
- Simplifying assumptions: symmetry, homogeneity, isotropy, stationarity, linearity, ...

Galactic halo model predictions



- ▷ Stable secondary over primary ratio:

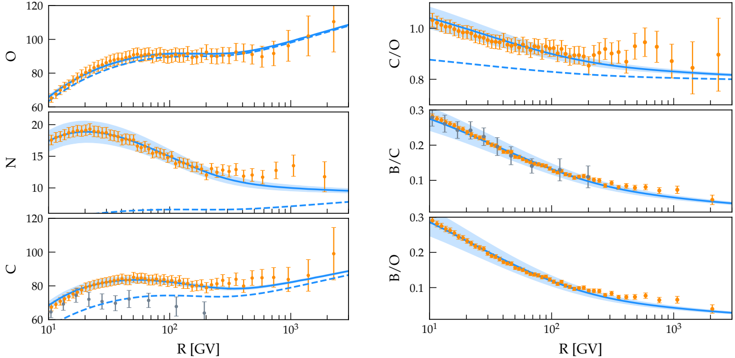
$$\frac{I_s(T)}{I_p(T)} \propto \chi(T) \propto \frac{H}{D(T)}$$

- ▷ Unstable secondary over stable secondary ratio:

$$\frac{I_s^*(T)}{I_s(T)} \propto \frac{\sqrt{D(T)}}{H^2} \quad \leftarrow \text{break the degeneracy!}$$

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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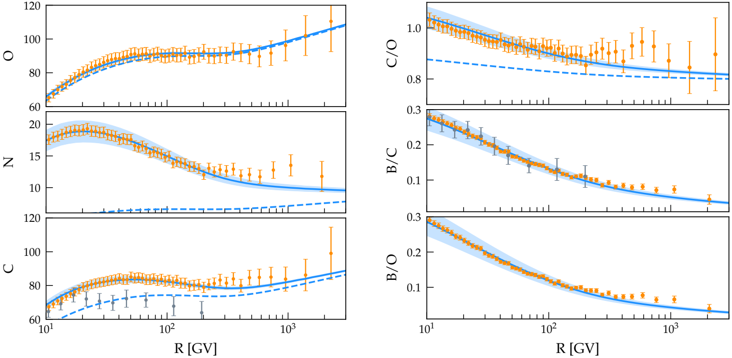


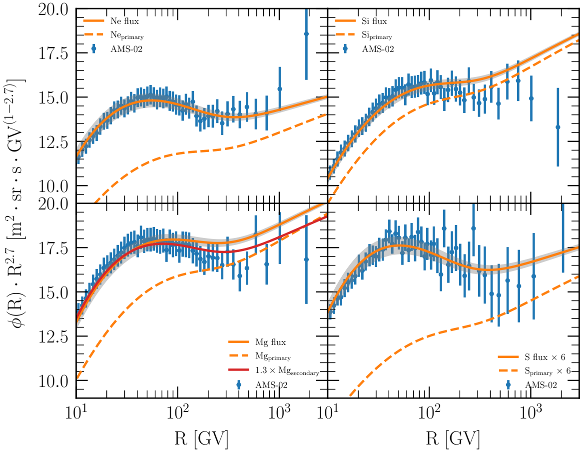
- by fitting primary and secondary/primary measurements we infer the properties of galactic transport:

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

- All nuclei injected with $\gamma \sim 4.3$
- All species are a mixture of a primary and a secondary component!
- Shaded areas show uncertainty from fragmentation cross sections [Genolini et al., PRC 2018]

Intermediate mass nuclei: Ne, Mg, Si, S

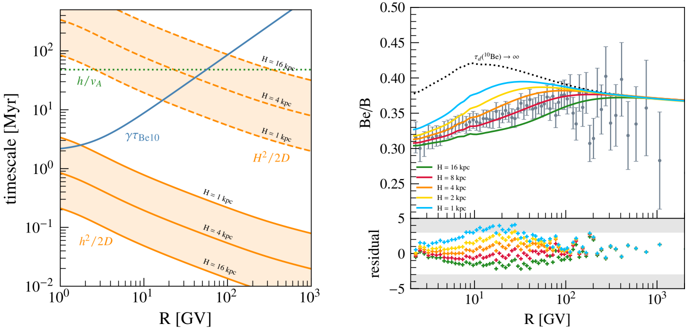
Schroer, CE, and Blasi, PRD 2021



- ▷ Well compatible as a combination of a primary (dashed line) and a secondary contribution and an universal injection slope $\gamma \simeq 4.3$

The Beryllium-over-Boron ratio and the escape time

Evoli et al., PRD 101 (2020)

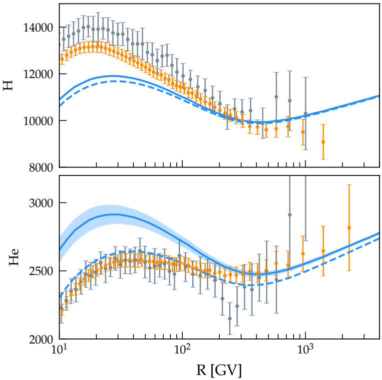


- Traditionally the ratio ^{9}Be/^{10}Be has been used as CR clock $\rightarrow$ however no measurements of this ratio at $E \gtrsim 1$ GeV/n
- Make sure that ^{10}Be decays outside the disc (hostile to CR transport) $\rightarrow$ at $\gtrsim$ few GeV this is certainly the case
- Preference for large 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

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

The injection of light nuclei: proton and helium

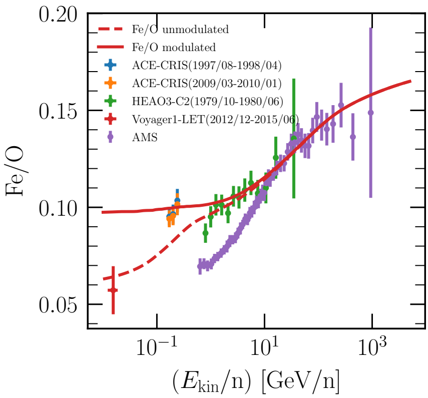
Evoli et al., PRD 99 (2019)



- H is softer than nuclei, while He is harder: $\Delta\gamma \sim \pm 0.05$
- At odds with what one would expect in the case of pure rigidity dependent acceleration [Serpico, ICRC 2015]
- Problematic even for models of the difference between H and He injection based on the different A/Z at shocks [Hanusch+, Apj 2019]
- For He the problem arises from secondary production of ^{3}He that populates the low-energy spectrum

The strange case of the Iron spectrum

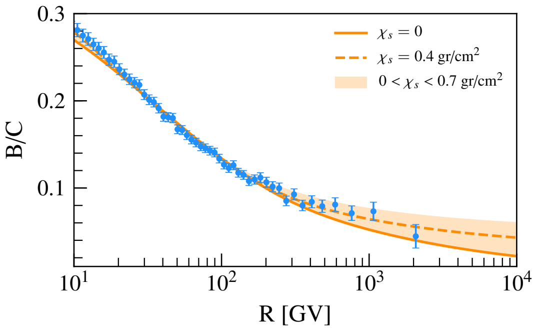
Schroer, CE, and Blasi, PRD 2021



We found that AMS-02 data on Fe/O flux are hard to reconcile not only with the results of existing calculations of CR transport on Galactic scales, but also with the results of previous experimental endeavours.

Additional effects not included in this picture

Evoli et al., PRD 99 (2019)



- Second-order Fermi acceleration in the ISM [Ptuskin et al., 2006, ApJ 642; Drury & Strong, 2017, A&A 597]
- Shock re-acceleration of secondary nuclei [Blasi, 2017, MNRAS 471; Bresci et al., 2019, MNRAS 488]
- Grammage at the sources [D'Angelo et al., 2016, PRD 94; Nava et al., 2016, MNRAS 461; Jacobs et al., 2022, JCAP 05]
- Secondary production at the sources [Blasi, 2009, PRL 103; Mertsch & Sarkar, 2014, PRD 90]
- ...

Hints on a flattering of the B/C have been whispered by DAMPE, NUCLEON...

From phenomenology to a more fundamental theory

Phenomenology accomplishments

- Very remarkable that such a simple approach provides explanation of data at few % level! [Schroer+, PRD 2021]
- Nuclei $Z \geq 6$ share the same source spectrum but different from H and He: critical issue for the SN paradigm? [see also Weinrich et al., A&A 2020]
- The (sharp!) break at $\sim$300 GV is due to transport [Genolini+, PRL 119, 24 (2017)]
- Transport at 10-100 GeV is diffusive with $\langle D \rangle \propto E^{-0.5}$ (and Kolmogorov-ish at higher energies)
- CRs fill a magnetized halo above and below the disk of size $H \gtrsim 5$ kpc

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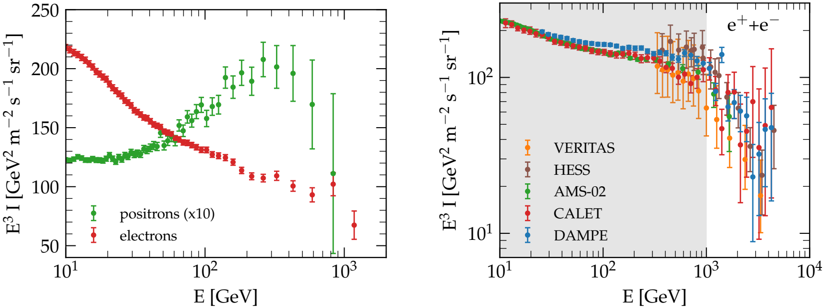
Theoretical issues

- Clear separation between acceleration and transport?
- Physicality of halo boundaries at H? [Dogiel+, ApJ 2020]
- Role of anisotropic diffusion? $\longrightarrow$ maybe relevant for γ's [Cerri+, JCAP 2017]
- What is the origin of the scattering centres? External turbulent cascade or self-generated? What is the role of ion-neutral damping? [Zirakashvili, NPB 2014; Evoli+, PRL 2018]
- Is it the grammage accumulated close to the sources relevant at high-energy? [Bykov+, SSRv 2020]

Galactic factories of cosmic electrons and positrons

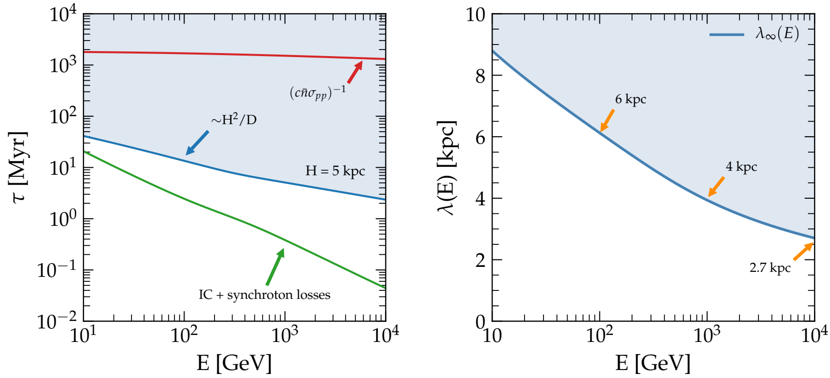


Rationale

- 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?

Nuclei and electron timescales

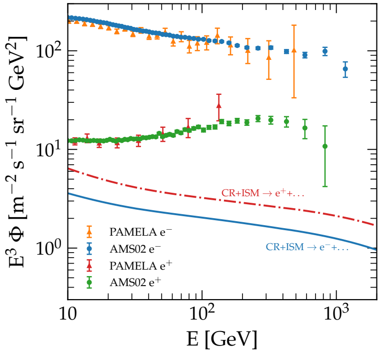
Evoli, Amato, Blasi & Aloisio, PRD 103, 8 (2021)

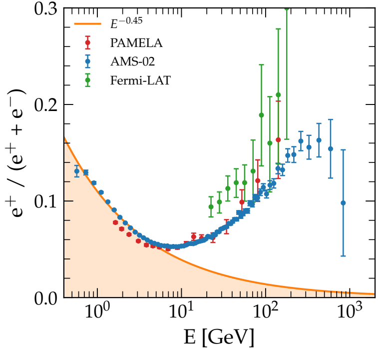


- ▷ Leptons lose their energy mainly by IC with the interstellar radiation fields (ISRFs) or synchrotron emission
- ▷ Milky Way is a very inefficient calorimeter for nuclei and an almost perfect calorimeter for leptons
- ▷ Translate losses into propagation scale: $\lambda \sim \sqrt{4D(E)\tau_{\rm loss}}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





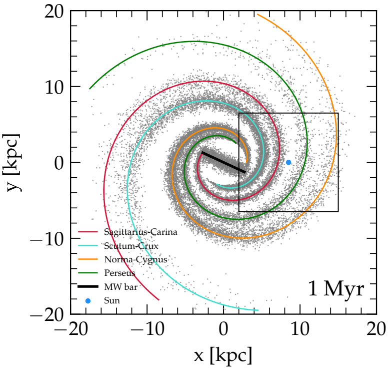
- AMS-02 local measurements of e^+ and e^- compared with secondary predictions $pp_{\rm ISM} \to e^\pm$
- It is not compatible with all leptons being secondary $\to$ we need a primary component for electrons
- If e^+ are secondaries (and $\alpha_p = \alpha_e$) the positron fraction must be a decreasing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

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

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]:

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

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

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

The break in the pulsar spectrum

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

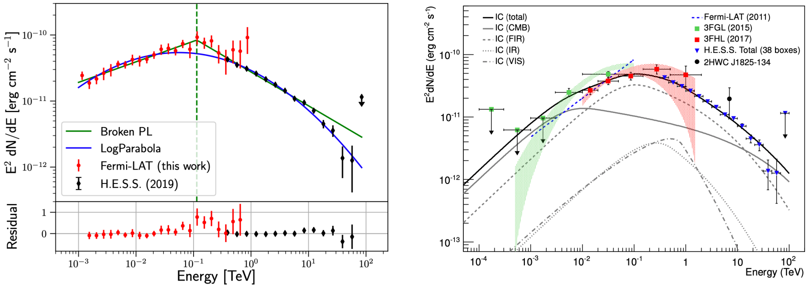
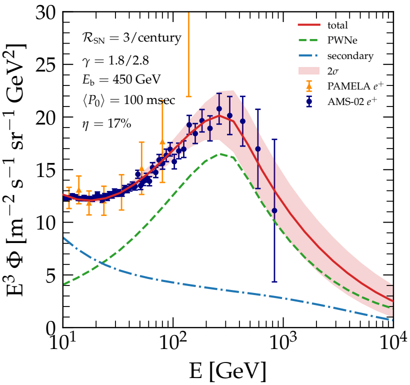


Figure: Combined spectra of PWN HESS J1825-137 (left) and HESS J1825−137 (right) with the spectral measurements obtained Fermi-LAT data (from $\sim$ GeV to $\sim$ TeV) and the H.E.S.S. data for the $\gtrsim 100$ GeV energy range

Pulsars as positron galactic factories

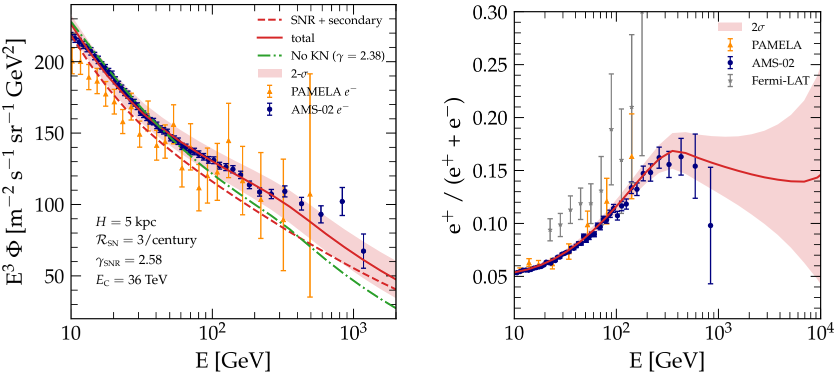
Evoli, Amato, Blasi & Aloisio, PRD 2021



- 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

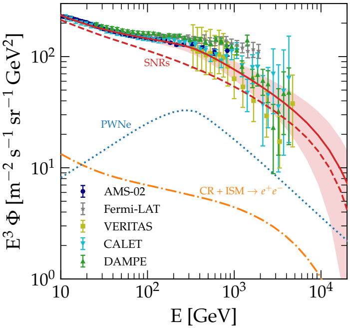
Evoli, Amato, Blasi & Aloisio, PRD 2021

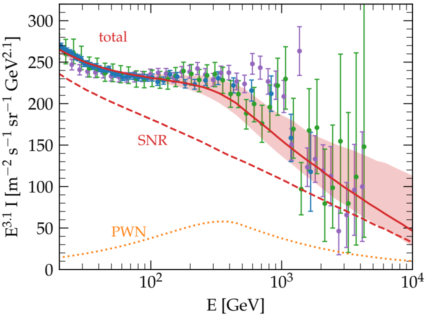


- ▷ Existence of a fine structure at ~ 42 GeV $\rightarrow$ result of KN effects in the ICS on the UV bkg [Evoli+, PRL 2020]
- ▷ Electrons require a spectrum steeper than protons by $\sim 0.3 \rightarrow$ puzzling!
- ▷ The only aspect that is different between e$^-$ and p is the loss rate $\rightarrow$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





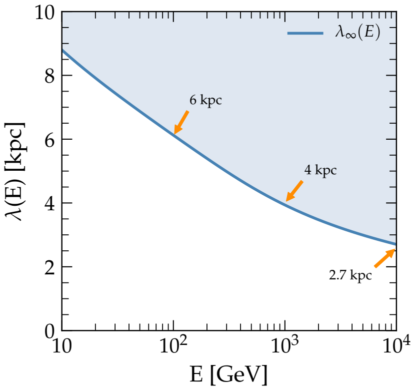
Cosmic Ray Positrons From Pulsars?

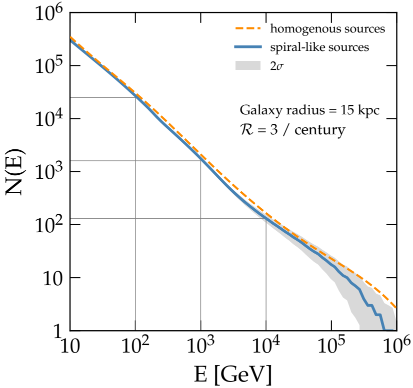
Take home message

- 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 $\longrightarrow$ converge to a unified picture?
- Alternative astrophysical explanations still viable, e.g., acceleration of secondary positrons within cosmic-ray sources [Mertsch+, PRD 2021]
- Dark matter interpretation strongly constrained by γ-rays, $\bar{p}$, CMB, ...

Counting the sources of leptons in the Galaxy

Evoli, Blasi, Amato & Aloisio, PRD 2021



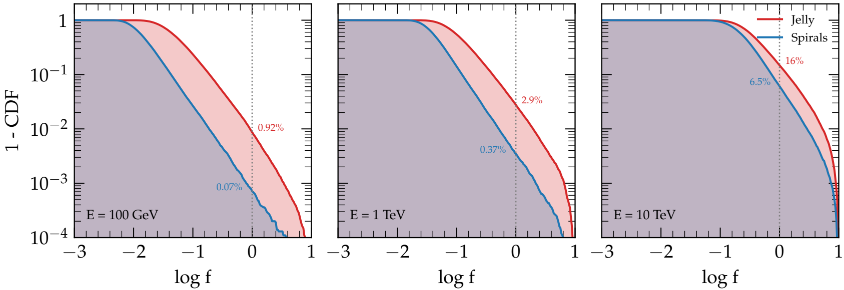


- Most SN explosions are located in star-forming regions which cluster inside the spiral arms and in the Galactic bar with a Galactic rate of $\mathcal{R} = 1/30$ years
- The sources that can contribute to the flux at Earth at a given energy E are

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

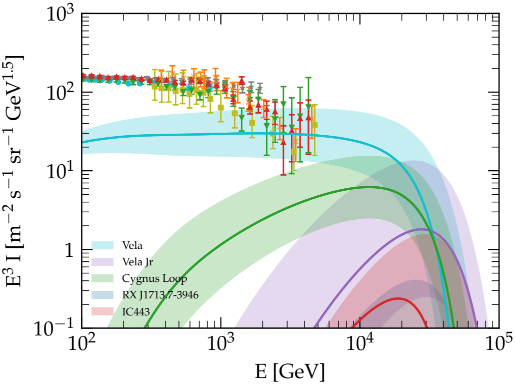
The odds of a prominent nearby source

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]

The identification of a dominant source might be just 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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