Phenomenology and theory of Galactic cosmic-ray propagation

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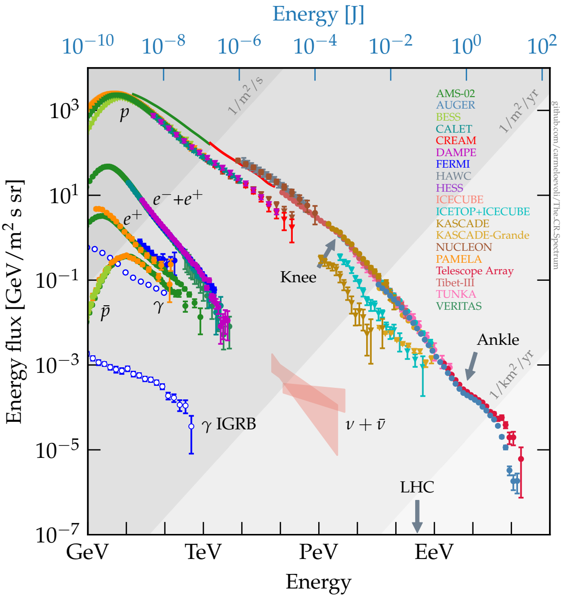
The cosmic-ray spectrum in 2021

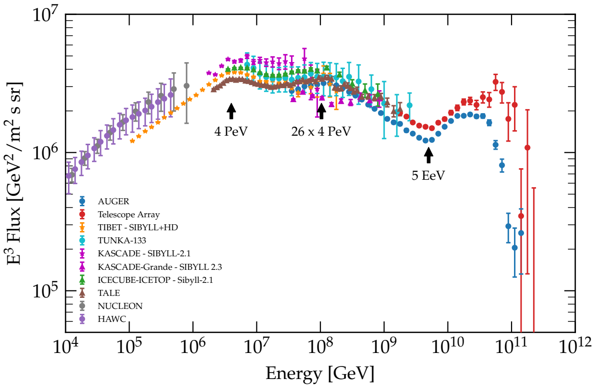


The cosmic-ray spectrum in 2021

- CRs are a non-thermal population of relativistic particles that pervade the solar system, galaxies, clusters and intergalactic space
- Almost a perfect power law over more than 11 energy decades!
- At low energy $dN/dE \propto E^{-2.7} \rightarrow dI/dE \propto E^{-0.7}$
  $\rightarrow$ most of the energy is in $\sim$ GeV CR protons
- energy density near Earth $\sim 2 \times 10^{-12}$ erg cm^{-3} $\sim$ eV cm^{-3}
  $\rightarrow$ equipartition, CR driven winds, ...
- Evidence of departures from a perfect power law: most spectacular are the knee and the ankle
- Spectrum cut-off at $\gtrsim 10^{20}$ eV $\rightarrow$ GZK or cosmic-ray sources out of steam?
- Particles observed at energy higher than any terrestrial laboratory $\sqrt{s_{\rm LHC}} \sim 2 \times 10^{17}$ eV
- Composition at 10 GeV: ~ 99.2% are nuclei, ~ 0.7% are electrons, ~ 0.1% are anti-matter particles (positrons and antiprotons)

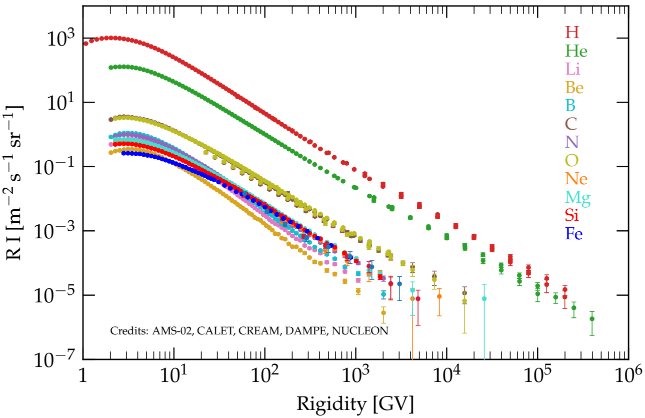
The end of the Galactic spectrum

Aloisio+, JCAP 2014; Globus+, PRD 2015; Thoudam+, A&A 2016; Evoli & Boncioli, in prep.



- ▷ If (first) knee is made by H+He $\longrightarrow$ Galactic CRs end with heavy elements at ~ 100 PeV (second knee)
- ▷ Maximum energy of Galactic accelerators OR the effect of transport (e.g., from pitch angle to small deflection)?
- ▷ The Larmor radius of these particles in the Galactic B-field $r_L = \frac{p}{ZeB} \sim 100\,\text{pc} \left(\frac{E}{\text{PeV}}\right)\left(\frac{\mu\text{G}}{ZB}\right)$

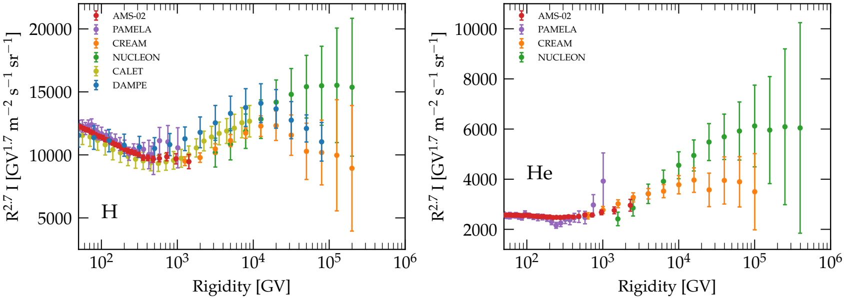
Galactic Cosmic Rays: unprecedented measurements



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!

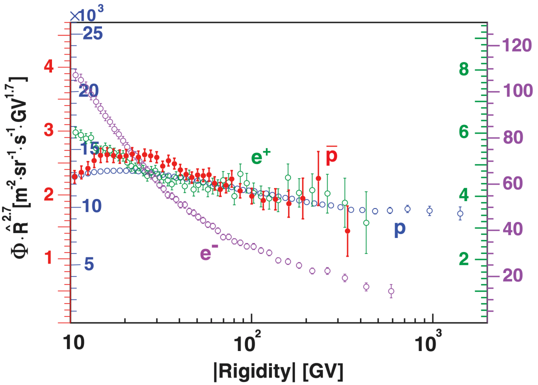
PAMELA Coll., Science 2011; AMS-02 Coll., PRL 2015; CREAM Coll., ApJ 2017; NUCLEON Coll., JETP 2018; DAMPE Coll., Science 2019



- ▷ Spectra of protons and helium are not a single power law below the knee → 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 curious case of CR anti-matter

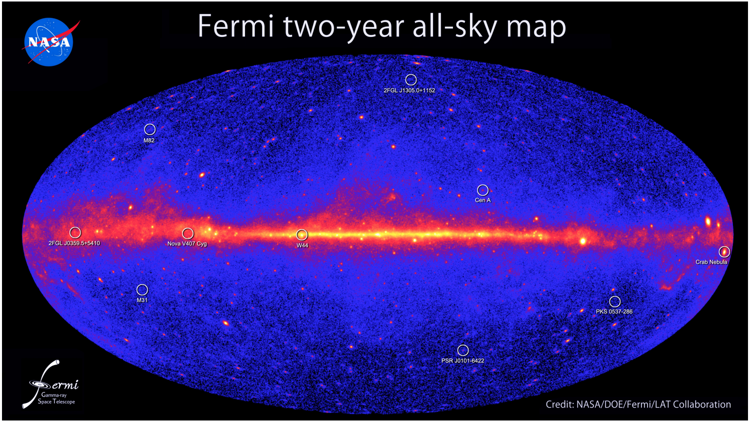
Plot from: AMS-02 Coll., PRL 117, 091103 (2016)



- ▷ Anti-protons $pp \to \bar{p}ppp$ ✔ [Boudaud+, PRR 2020; Heisig+, PRR 2020]
- ▷ Positrons $pp \to \pi^{\pm} \to e^+e^-$ ✘ [Bykov+, SSRs 2017; Amato & Blasi, Space Adv. Res. 2018; Manconi+, PRD 2020]

The γ-ray sky > 100 MeV

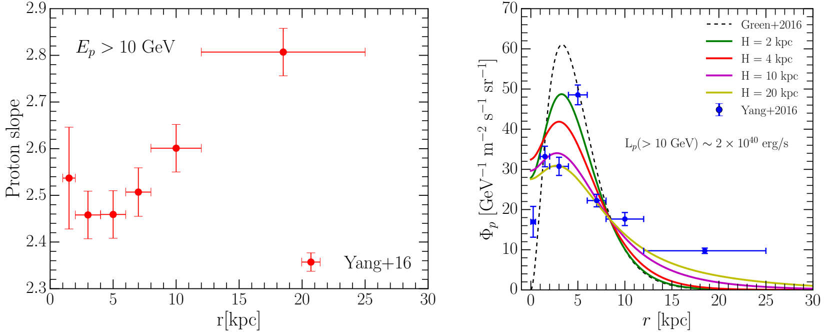
FERMI-Lat Coll., ApJ 2012



- Dominated by the diffuse emissions from interactions of CRs with the interstellar gas and radiation fields
- Cutting along the Galactic Plane $|b| < 5^{\circ}$ the main mechanism is $p_{\rm CR} + p_{\rm target} \longrightarrow \pi^0 \to \gamma\gamma$
- Abundant information to study Galactic CRs globally in the MW

Diffuse emissions: CR nuclei in the Galaxy

Yang, Aharonian & Evoli, PRD 2016; Tibaldo+, arXiv:2103.16423



- The correlation between diffuse galactic γ-rays and gas tracers can be studied to fit the γ-ray emissivity ($\propto$ CR density) in the Galaxy [Strong+, A&A 1988, Gaggero+, PRD 2015; Acero+, ApJS 2016]
- The measured gas emissivity spectra confirm that the CR proton density decreases beyond 5 kpc from the Galactic Center
- The measurements also suggest a softening of the proton spectrum with Galactocentric distance

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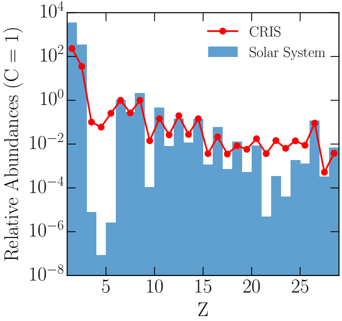
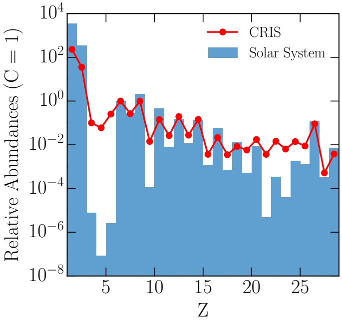
The cosmic-ray composition at $E \sim$ GeV



- ▷ Thermal particles in the average interstellar medium are somehow accelerated to relativistic energies becoming CRs $\longrightarrow$ primary CRs
- ▷ It must exist also a second population which is produced during propagation by primary spallation $\longrightarrow$ secondary CRs

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



- The average galactic grammage $\chi_{\rm gal}$ can be directly inferred from this plot:

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

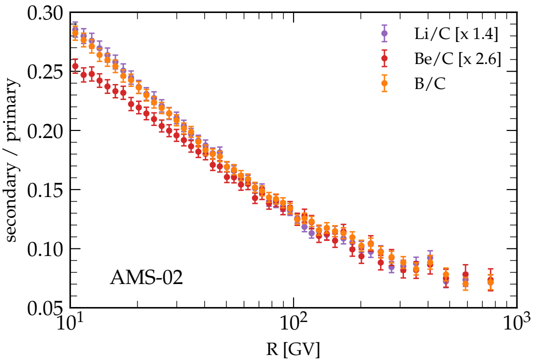
- To be compared with the grammage X_d accumulated at each crossing of the gas disk $h \sim 100$ pc:

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

- Robust evidence of diffusive transport!

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

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

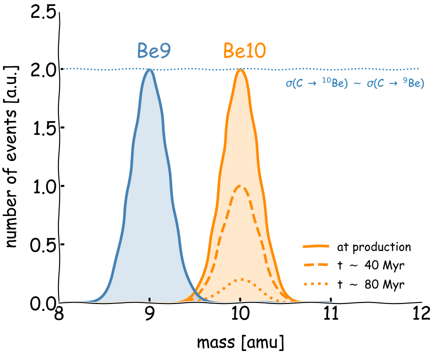


Key points

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

Cosmic-ray lifetime

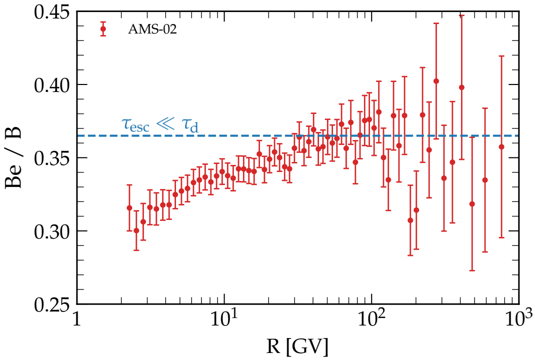
Garcia-Munoz et al., ApJ (1977); PAMELA Collaboration, ApJ, Vol. 862, 141 (2018)



- ^{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 $\sigma_{\rm Be9} \sim \sigma_{\rm Be10}$
- 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

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

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

Cosmic ray escape time and sources

D. Ter Haar, Reviews of Modern Physics, 1950; Ginzburg & Syrovatskii, 1963

- The CR escape time is crucial to identify source candidates.
- The galactic CR luminosity is:

$$L_{\rm CR} = \frac{\epsilon_{\rm CR} V_{\rm MW}}{\tau_{\rm esc}} \sim 10^{41} \text{ erg/s}$$

where

- $\epsilon_{\rm CR} \sim 1$ eV/cm^3 is the local CR energy density
- $V_{\rm MW} = \pi R_d^2 2H \sim 2 \times 10^{68}$ cm^{-3} is the Milky Way Volume
- $\tau_{\rm esc} \sim 100$ Myr is the “escape” time

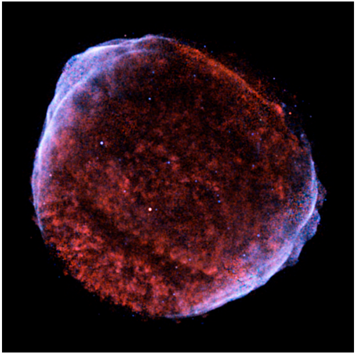
- This is also the luminosity required (on a timescale of $\sim \tau_{\rm esc}$) to sustain the CR population.
- The SNe energy rate in our Galaxy:

$$L_{\rm SN} = E_{\rm SN} R_{\rm SN} \sim 10^{42} \text{ erg/s} \sim 10 \times L_{\rm CR}$$

- Galactic SNe provide the right energetics if $\sim 10\%$ efficiency in CR acceleration is achieved.

Galactic cosmic-ray factories

A.R. Bell, Astroparticle Physics, 43, 56 (2013)

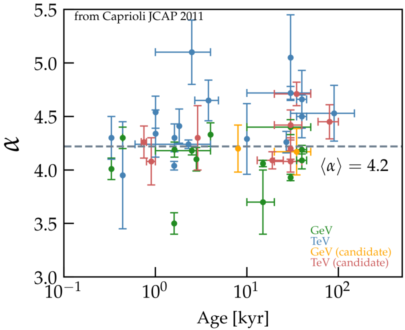


Chandra's image of SN 1006. In blue the emission by high-energy electrons.

- Strong evidence of relativistic electrons in SNRs
- Virtually all young remnants show X-ray synchrotron tiny filaments [Vink, A&AR 2012] ⟶ amplified magnetic fields
- Indirect evidence of efficient CR nuclei acceleration!

Acceleration process in SNR

Krymskii 77, Bell 78, Blandford & Ostriker 1978



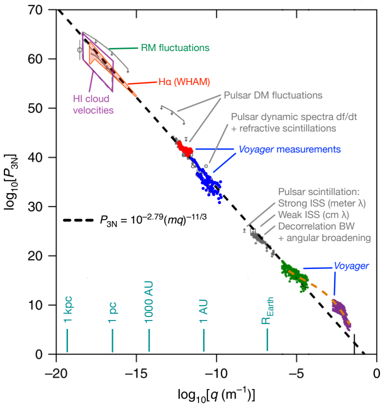
- Diffusive shock acceleration (DSA) predicts an injection spectrum, independent of the microphysics, that for strong shocks gives:

$$Q(p) \equiv \frac{dn}{dt\, d^3p} \propto p^{-4} \quad \xrightarrow[pc\sim E]{} \quad Q(E) \equiv \frac{dn}{dt\, dE} \propto E^{-2}$$

- maybe softer because of non-linear effects [Blandford & Eichler, PhR 1987; Berezhko & Ellison, ApJ 1999; Caprioli et al., MNRAS 2009]
- Standard predictions: pure rigidity dependent acceleration (universality) with a unique power-law in momentum (scale-free) in the GeV-TeV energy range

The interstellar turbulent environment

Armstrong+, ApJ 1995; Chepurnov & Lazarian, ApJ 2010; Lee & Lee, Nature Astr. 2019



Electron density fluctuations in ISM: an indirect probe of the interstellar magnetic power spectrum $\delta n_e \sim \delta B^2$

- ISM is a compressible magnetized plasma with $\langle B \rangle \sim \mathcal{O}(3\mu\mathrm{G}) \to \beta_p \lesssim 1$
- Turbulence is ubiquitous in the ISM with $\delta B / B_0 \lesssim 1$ at the outer (driving) scale $L \to$ weak turbulence
- Several mechanisms (SNe, stellar feedback, extragalactic gas accretion, large-scale shear, ...) contribute to turbulence injection at large-scales ($L \sim 10 - 100$ pc) [Scalo & Elmegreen, ARA&A 2004]
- The outer scale of turbulence can be constrained from fluctuactions in the Galactic synchrotron foreground, e.g. LOFAR $\to L \sim 20$ pc [Iacobelli+, A&A 2013]

How MHD turbulence cascades from injection to dissipation scales ($\lesssim 10^7$ cm) in the different phases of ISM is still an **open** problem of modern astrophysics

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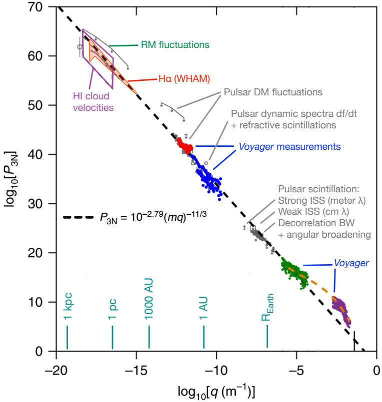

Electron density fluctuations in ISM: an indirect probe of the interstellar magnetic power spectrum $\delta n_e \sim \delta B^2$

- Weak MHD turbulence can be roughly decomposed into 3 MHD waves: slow MS, fast MS, Alfvén $\longrightarrow$ we assume that CRs scatter predominantly on Alfvénic fluctuations
- Alfvén waves propagates along $\vec{B}_0$ ($\vec{k} \perp \vec{B}_0$) at a speed:

$$v_A = \frac{B_0}{\sqrt{4\pi n_i m_i}} \sim 10\ \mathrm{km/s} \ll c$$

- Waves energy density follows a Kolmogorov $\alpha \sim 5/3$ spectrum

$$W(k)dk \equiv \frac{\langle \delta B \rangle^2(k)}{B_0^2} \sim \eta_B \left(\frac{k}{k_0} \right)^{-\alpha} \frac{dk}{k_0}$$

- where $k_0 \equiv L^{-1}$ and the level of turbulence is

$$\eta_B = \int_{k_0}^{\infty} dk\, W(k) \sim \mathcal{O}(0.1)$$

Charged particles transport in a turbulent field

Jokipii, ApJ 1966; Kulsrud & Pearce 1969; Wentzel 1969

- For $\alpha > 1$ and very small scales $k \gg k_0$ the turbulent B-field produces small fluctuations:

$$\langle \delta B^2 \rangle (k) \ll B_0^2$$

- Diffusion along the mean field can be computed exactly using QLT $\rightarrow$ particle scatters (nearly) inelastically with waves $k_{\rm res}^{-1} \sim \mu r_L(p)$ at a rate $\nu \sim \Omega \frac{\delta B^2}{B_0^2}$
- The diffusion coefficient becomes:

$$D_{\rm QLT}(p) = \frac{v r_L(p)}{3} \frac{1}{k_{\rm res} W(k_{\rm res})} \simeq \frac{3 \times 10^{27}\ {\rm cm^2 s^{-1}}}{\eta_B} \left(\frac{p}{\rm GeV/c} \right)^{2-\alpha} \longrightarrow p^{1/3}$$

- A ~ 10 GeV proton is resonant with scales $k_{\rm res}^{-1} \sim$ A.U. (10^{-6} pc), thereby:

$$k_{\rm res} W(k_{\rm res}) \sim 10^{-6} \rightarrow \lambda \sim 3D/v \sim \text{parsec}$$

- Because of the resonant condition particles can be retained in the Galaxy up to an energy of $r_L(p_{\rm max}) \sim L^{-1} \rightarrow E_{\rm max} \sim$ PeV [Candia+, JHEP 2002; Giacinti+, PRD 2015]

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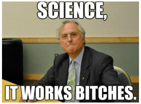
More sophisticated approaches (e.g., based on scattering of CRs on fast MS waves) still predicts a power law behaviour for $D(R)$, although the relation with α is less trivial [Yan & Lazarian, 2002, 2004; Fornieri+, MNRAS 2020]

Another example of “Little things affect Big things”

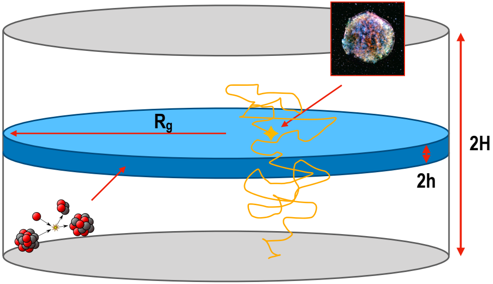
Transport ($\sim 10^{22}$ cm) $\longrightarrow$ mean free path ($\sim 10^{18}$ cm) $\longrightarrow$ waves wavelenght ($\sim 10^{13}$ cm)

If diffusion: $t \simeq \frac{d^2}{D} \sim \mathcal{O}(100\,\text{Myr}) \left(\frac{d}{3\,\text{kpc}}\right)^2$



The Galactic halo model

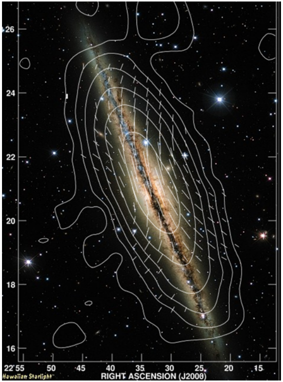
Morrison, Olbert and Rossi, Phys. Rev (1954); Ginzburg and Syrovatskii (1964)



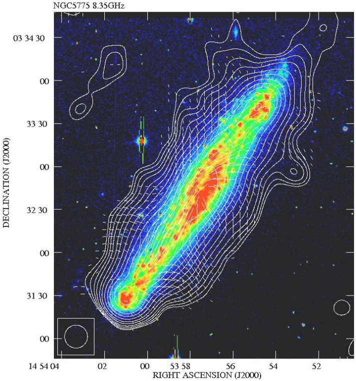
- In the standard model for the origin of Galactic CRs, these are accelerated in the disc h by blast waves of SN explosions and hence to have a spectrum $Q_s \propto p^{-\alpha}$ where $\alpha \gtrsim 4$
- after injection, CRs propagate diffusively throughout the Galactic halo ($\sim 1D$) with a diffusion 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.

The radio halo in external galaxies

Credit: MPIfR Bonn



Total radio emission and B-vectors of edge-on galaxy NGC891 observed at 3.6 cm wavelength with the Effelsberg telescope



Total radio intensity and B-vectors of edge-on galaxy NGC 5775 combined from observations at 3.6 cm wavelength with the VLA and Effelsberg telescopes

The Galactic halo model

Morrison, Olbert and Rossi, Phys. Rev (1954); Ginzburg and Syrovatskii (1964); Berezinskii et al. (1980)

The transport of a CR species $\alpha = \mathrm{H}, \ldots, \mathrm{Fe}$ is well described by an advection-diffusion equation with losses:

$$\cancelto{0}{\frac{\partial f_i}{\partial t}} - \frac{\partial}{\partial z}\left(D\frac{\partial f_\alpha}{\partial z}\right) + u\frac{\partial f_\alpha}{\partial z} - \frac{du}{dz}\frac{p}{3}\frac{\partial f_\alpha}{\partial p} = q_{\mathrm{SN}}\delta(z) - \frac{1}{p^2}\frac{\partial}{\partial p}\left[p^2\dot{p}f_\alpha\right] - \frac{f_\alpha}{\tau_\alpha^{\mathrm{in}}} + \sum_{\alpha'>\alpha} b_{\alpha'\alpha}\frac{f_{\alpha'}}{\tau_{\alpha'}^{\mathrm{in}}}$$

- Stationarity is ensured by proper boundary conditions $f_\alpha(z = \pm H) = 0$

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- Source term proportional to Galactic SN rate $\mathcal{R}$: $q_{\mathrm{SN}} \propto E_{\mathrm{SN}}\mathcal{R}/\pi R_g^2$
- Energy losses: ionization, Coulomb losses, Inverse Compton, Synchrotron, ...

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Morrison, Olbert and Rossi, Phys. Rev (1954); Ginzburg and Syrovatskii (1964); Berezinskii et al. (1980)

The transport of a CR species $\alpha = \text{H}, \dots, \text{Fe}$ is well described by an advection-diffusion equation with losses:

$$\cancelto{0}{\frac{\partial f_i}{\partial t}} - \frac{\partial}{\partial z}\left(D \frac{\partial f_\alpha}{\partial z}\right) + u \frac{\partial f_\alpha}{\partial z} - \frac{du}{dz}\frac{p}{3}\frac{\partial f_\alpha}{\partial p} = q_{\text{SN}}\delta(z) - \frac{1}{p^2}\frac{\partial}{\partial p}\left[p^2 \dot{p} f_\alpha\right] - \frac{f_\alpha}{\tau_\alpha^{\text{in}}} + \sum_{\alpha' > \alpha} b_{\alpha'\alpha} \frac{f_{\alpha'}}{\tau_{\alpha'}^{\text{in}}}$$

- Stationarity is ensured by proper boundary conditions $f_\alpha(z = \pm H) = 0$
- Spatial diffusion: $\vec{\nabla} \cdot \vec{J}$
- Advection by Galactic winds/outflows: $u = u_w + v_A \sim v_A$
- Source term proportional to Galactic SN rate $\mathcal{R}$: $q_{\text{SN}} \propto E_{\text{SN}} \mathcal{R} / \pi R_g^2$
- Energy losses: ionization, Coulomb losses, Inverse Compton, Synchrotron, ...
- Production/destruction of nuclei due to inelastic scattering (or decay) $\to b_{\alpha'\alpha}\sigma_\alpha^{\text{in}}$

The Galactic halo model: a toy-model approach

- Focus on a simplified case with only one secondary species and one parent nucleus: C⟶B. [1]
- For Carbon (primary):

$$Q_{\rm C} = \frac{N_{\rm SN}(E)\mathcal{R}_{\rm SN}}{\pi R_d^2 H} \Rightarrow f_{\rm C}(E) = \underbrace{\frac{N_{\rm SN}(E)\mathcal{R}_{\rm SN}}{\pi R_d^2 H}}_{\text{injection}} \underbrace{\frac{H^2}{D(E)}}_{\text{escape}} \propto p^{-\alpha-\delta}$$

- While for Boron (secondary):

$$Q_{\rm B} = v\bar{n}\,\sigma_{\rm C\to B}\,f_{\rm C}(E) \Rightarrow f_{\rm B}(E) = \underbrace{v\bar{n}\,\sigma_{\rm C\to B} f_{\rm C}(E)}_{\text{injection}} \underbrace{\frac{H^2}{D(E)}}_{\text{escape}} \propto p^{-\alpha-2\delta}$$

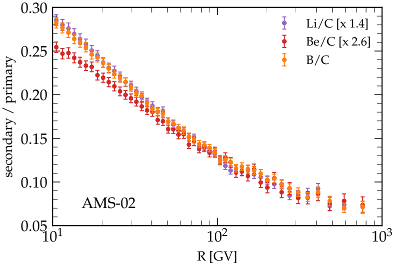
- The ratio between the two becomes:

$$\frac{\rm B}{\rm C} = v\bar{n}\,\sigma_{\rm C\to B}\frac{H^2}{D(E)} \propto \frac{H}{D_0} p^{-\delta}$$

Notice however that $\bar{n} = n_d \frac{h}{H}$ so that B/C is sensitive only to the H/D ratio

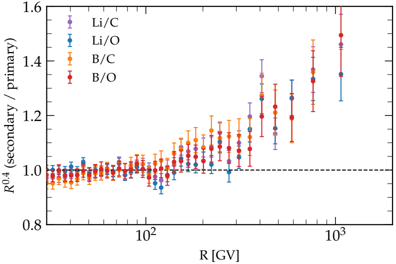
[1] In real applications the whole chain of spallation reactions and decays of heavier nuclei must be accounted for.

The Galactic halo model: a toy-model approach



- Secondary/Primary provide key information on transport (in QLT from $\delta \longrightarrow$ turbulence)
- The spectra of nuclei behave as $p^{-(\alpha+\delta)} \longrightarrow$ also information on the injection α
- Advection (e.g., galactic outflows) would cause this ratio being flat $\longrightarrow$ relevant at $R \lesssim 10$ GV
- Same for the nuclear energy losses ($\sigma_{\rm inel}$'s are almost energy independent) $\longrightarrow$ nuclei do not appreciably lose energy in the Galaxy

The Galactic halo model: a toy-model approach



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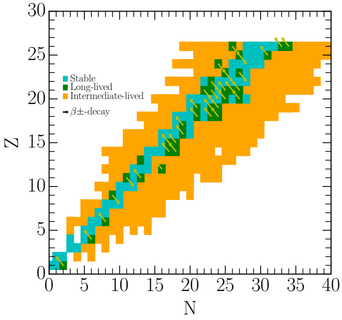
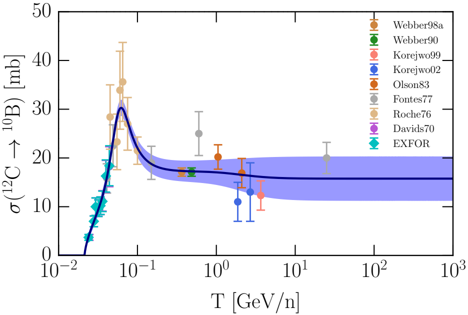
Secondary/Primary ratio shows the same break as primaries $\rightarrow$ it must follow from a change in the diffusion properties of the ISM and not in the injection of particles

The nuclear reaction network

Evoli et al., JCAP (2018); Evoli et al., PRD (2019)

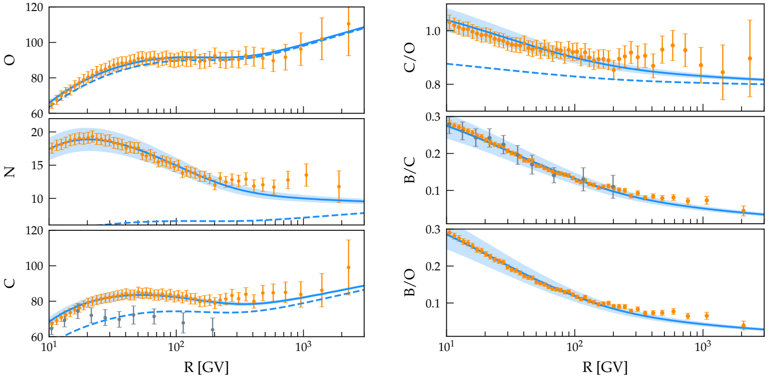




- ▷ In real-life simulations we have to solve a system of ∼80 coupled partial differential equations
- ▷ Poorly known cross-sections for spallation reactions are the main limiting factors to extract valuable information from data [Tomassetti, PRD 2012; Genolini, Maurin & Moskalenko, PRC 2018]

CR phenomenology: secondary-over-primary ratios

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



- We assume a phenomenological motivated $D(R)$ 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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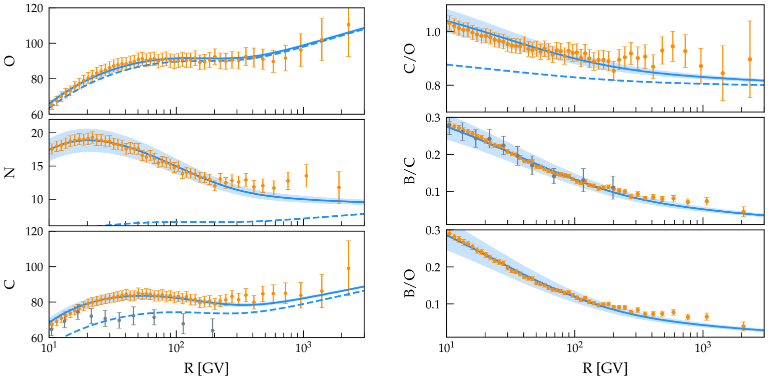
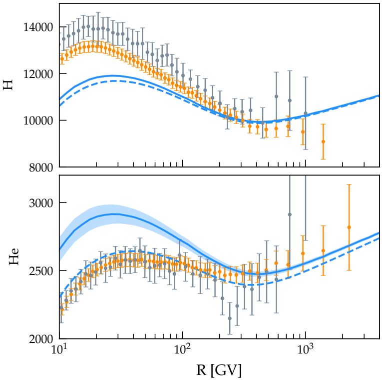


- by fitting primary and secondary/primary measurements we found: $\delta \sim 0.54$, $D_0/H \sim 0.5 \times 10^{28}$ cm/s^2/kpc, $\Delta\delta \sim 0.2$, $v_A \sim 5$ km/s
- All nuclei injected with $\gamma \sim 4.3$ (Oxygen - with H - is the only pure primary species)
- Shaded areas: uncertainty from cross sections

The injection of light nuclei: proton and helium

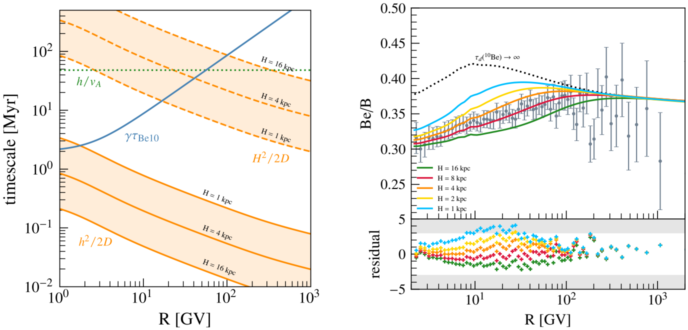
Evoli et al., PRD 99 (2019)



- 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 Beryllium-over-Boron ratio and the escape time

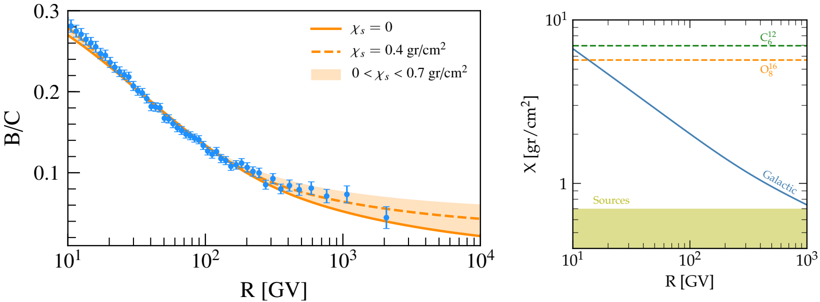
Evoli et al., PRD 101 (2020)



- We want to make sure that ^{10}Be decays outside the disc (maybe hostile to CR transport) $\to$ at $\gtrsim$ few GeV this is certainly the case
- Preference for large halos $H \gtrsim 5$ kpc [see also Weinrich et al., A&A (2020)]
- Notice that H and $\tau_{\rm esc}$ are mutual corresponding

$$\tau_{\rm esc}(10\,\text{GV}) \sim \frac{H^2}{2D} \sim 20\,\text{Myr}\left(\frac{H}{\text{kpc}}\right)\left(\frac{0.25\times 10^{28}\,\text{cm}^2/\text{s/kpc}}{D_0/H}\right)$$

Effect of grammage at sources



- ▷ Several evidences of low-diffusion regions around sources [Hanabata+, ApJ 2014; Aharonian+, Nature Ast. 2019; Abeysekara+, Science 2017]
- ▷ At high energies the secondary/primary ratio must be affected by the grammage accumulated in the environment surrounding sources [Malkov+, ApJ 2013; D'Angelo+, PRD 2016; Nava+, MNRAS 2016]
- ▷ This effect leads to a flattening of the S/P at high energies ($\gtrsim$ TeV/n)
- ▷ The source grammage however is severely constrained by the data $\chi_S \lesssim 0.7$ gr cm^{-2}

From phenomenology to more fundamental theory

Phenomenology accomplishments

- Very remarkable that such a simple approach provides explanation of data at few % level! [Schroer+, arXiv:2102.12576]
- Nuclei $Z \geq 6$ share the same source spectrum but different from H and He [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 $\langle D \rangle \propto E^{-0.5}$
- 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]
- Is it the grammage accumulated close to the sources relevant at high-energy? [Bykov+, SSRv 2020]

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Non-linear cosmic ray transport

Skilling, ApJ 1971; Kulsrud & Cesarsky, ApJL 1971; Wentzel, ARAA 1974

- Spatial diffusion tends to reduce the CR momentum forcing them to move at the wave speed v_A [Kulsrud's book (2004)]:

$$\frac{dP_{\rm CR}}{dt} = -\frac{n_{\rm CR} m (v_D - v_A)}{\tau} \longrightarrow \text{Waves}$$

- If CR stream faster than the waves ($v_D > v_A$) the net effect of diffusion is to make waves grow: this process is known as self-generation of waves (notice that self-generated waves are such $k \sim r_L$)
- Waves are amplified by CRs through streaming instability:

$$\Gamma_{\rm CR} = \frac{16\pi^2}{3} \frac{v_A}{kW(k) B_0^2} \left[v(p) p^4 \frac{\partial f}{\partial z} \right] \propto \frac{P_{\rm CR}(>p)}{P_{\rm B}} \frac{v_A}{H} \frac{1}{kW(k)}$$

- and are damped by wave-wave interactions that lead the development of a turbulent cascade (NLLD):

$$\Gamma_{\rm NLLD} = (2c_k)^{-3/2} k v_A (kW)^{1/2}$$

What is the typical scale/energy up to which self-generated turbulence is dominant?

Non-linear cosmic ray transport

Blasi, Amato & Serpico, PRL, 2012

- Transition occurs at scale where external turbulence equals in energy density the self-generated turbulence:

$$W_{\text{ext}}(k_{\text{tr}}) = W_{\text{CR}}(k_{\text{tr}})$$

where W_{CR} corresponds to $\Gamma_{\text{CR}} = \Gamma_{\text{NLLD}}$

- After normalization of W_{ext} is set to reproduce the CR flux much above the break:

$$E_{\text{tr}} = 228\,\text{GeV} \left(\frac{R_{d,10}^2 H_3^{-1/3}}{\epsilon_{0.1} E_{51} \mathcal{R}_{30}} \right)^{3/2(\gamma_p - 4)} B_{0,\mu}^{(2\gamma_p - 5)/2(\gamma_p - 4)}$$

- Applying QLT it follows:

$$D_{\text{sg}}(1\,\text{GV}) \sim \frac{c r_L}{3} \frac{1}{k W_{\text{CR}}(k)} \sim 10^{28} \text{cm}^2 \text{s}^{-1}$$

The turbulence evolution equation

Eilek, ApJ 1979

$$\frac{\partial W}{\partial t} = \frac{\partial}{\partial k}\left[D_{kk}\frac{\partial W}{\partial k}\right] + \frac{\partial}{\partial z}\left(v_A W\right) + \Gamma_{\rm CR} W + Q(k)$$

- Diffusion in k-space damping: $D_{kk} = c_k |v_A| k^{7/2} W^{1/2}$

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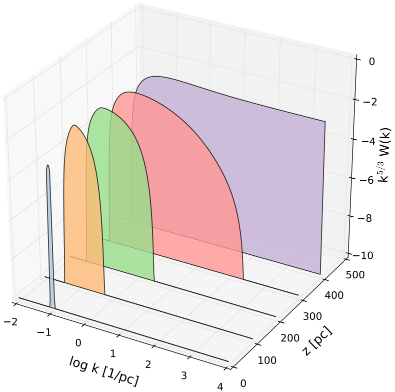
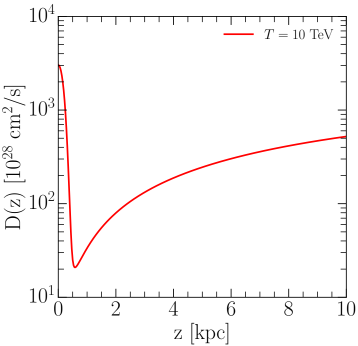
Non-linear evolution: turbulence and CR transport equations are now strongly coupled!

The wave advection originates the turbulent halo

Evoli, Blasi, Morlino & Aloisio, PRL 2018

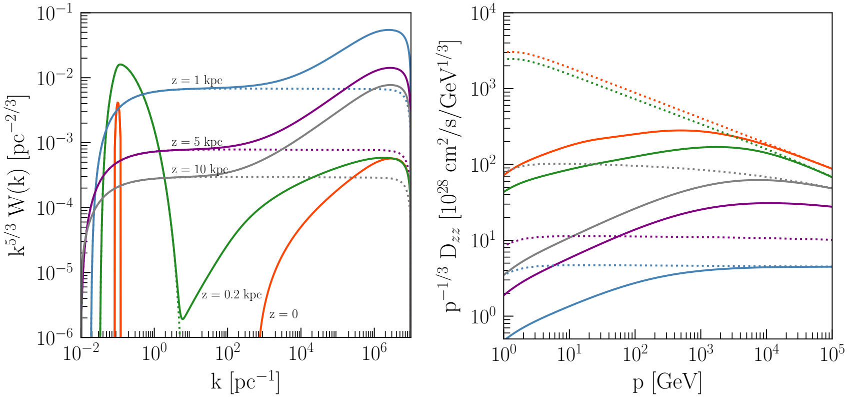




$$\tau_{\text{cascade}} = \tau_{\text{adv}} \to \frac{k_0^2}{D_{kk}} = \frac{z_{\text{peak}}}{v_A} \to z_{\text{peak}} \sim \mathcal{O}(\text{kpc})$$

Non-linear cosmic ray transport: diffusion coefficient

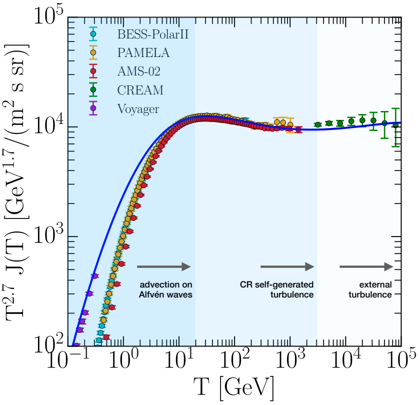
Evoli, Blasi, Morlino & Aloisio, PRL 2018



- ▷ Turbulence spectrum (left) and diffusion coefficient (right) without (dotted) and with (solid) CR self-generated waves at different distances from Galactic plane
- ▷ $D(p, z)$ is now an output of the model

Non-linear cosmic ray transport: a global picture

Evoli, Blasi, Morlino & Aloisio, PRL 2018



Main remarks:

- Pre-existing waves (Kolmogorov) dominates above the break.
- Self-generated turbulence between 1-100 GeV.
- Voyager data are reproduced with no additional breaks (single injection slope), but due to advection with self-generated waves (+ ionization losses).
- H is not predetermined here.
- None of these effects were included in the numerical simulations of CR transport before.

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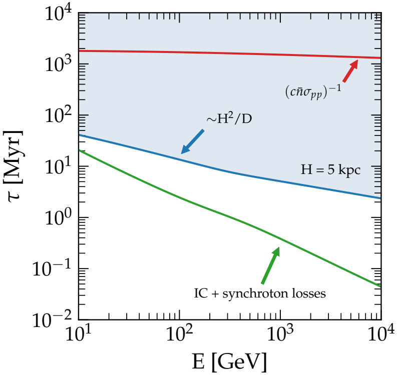
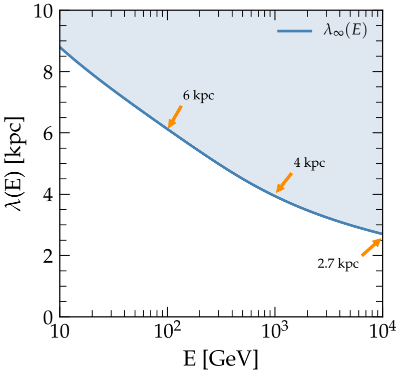
Nuclei and electron timescales

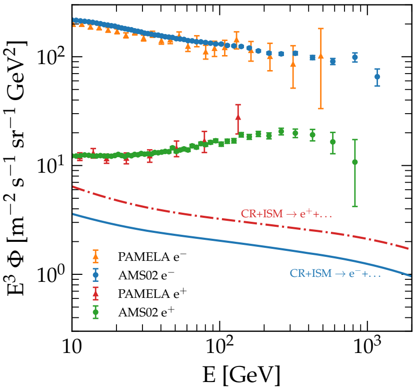
Evoli, Amato, Blasi & Aloisio, PRD 103, 8 (2021)





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

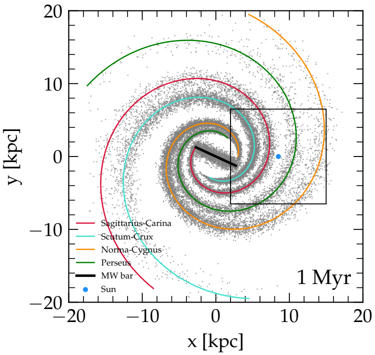
Electrons and positrons

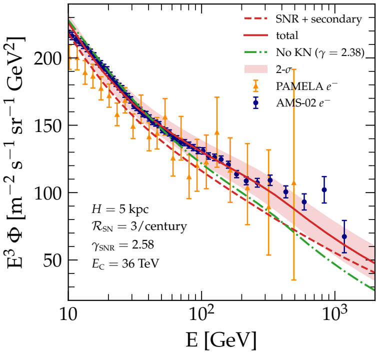


- AMS-02 local measurements of e^+ and e^- compared with secondary predictions $pp_{\rm ISM} \to e^\pm$
- It is not compatible with all leptons being secondary → we need a primary component for electrons

The electron spectrum from SNRs

Evoli, Amato, Blasi & Aloisio, PRD 2021

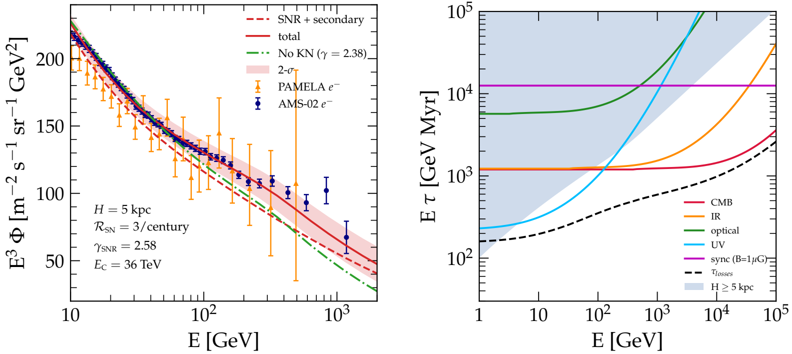




- Electrons injected by SNRs as nuclei with a intrinsic cutoff at ~ 30TeV
- Electrons require a spectrum steeper than protons by $\sim 0.3 \to$ puzzling!
- The only aspect that is different between e$^-$ and p is the loss rate $\to$ negligible inside the sources unless B is very strongly amplified [Diesing & Caprioli, PRL 2020; Cristofari+, A&A 2021]

The signature of energy losses on the cosmic ray electron spectrum

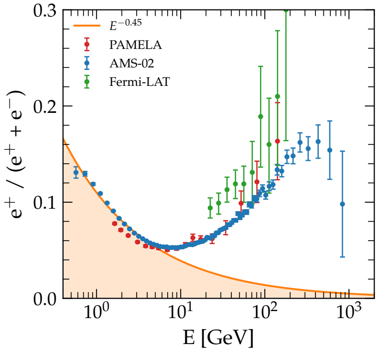
Evoli, Blasi, Amato & Aloisio, PRL 2020



- ▷ 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]

Secondary positrons and the positron fraction

P. Serpico, Astroparticle Physics 39 (2012)



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

- The injection rate of secondary positrons (and electrons) is $\propto$ to the proton spectrum:

$$Q_{e^+}(E) \sim c \bar{n}_{\rm gas} \sigma_{pp} f_{\rm p}(E) \propto E^{-\alpha_p - \delta}$$

- while primary electrons have the same source term as primary nuclei:

$$Q_{e^-} = \frac{N_{\rm SN}(E) \mathcal{R}_{\rm SN}}{\pi R_d^2 H} \propto E^{-\alpha_e}$$

- The escape time is now set by the energy losses

$$\tau \propto \frac{\tau_{\rm loss}}{\sqrt{D(E)\tau_{\rm loss}}} \propto E^{-1/2 - 3\delta/2}$$

- However, their ratio after propagation is independent on τ:

$$\frac{e^+}{e^-} \sim \frac{Q_{e^+} \not{\tau}}{Q_{e^-} \not{\tau}} \sim E^{-(\alpha_p - \alpha_e) - \delta}$$

- if e^+ are secondaries (and $\alpha_p = \alpha_e$)
$\rightarrow$ positron fraction must be a monotonically decreasing function of E:

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

Pulsars as positron galactic factories

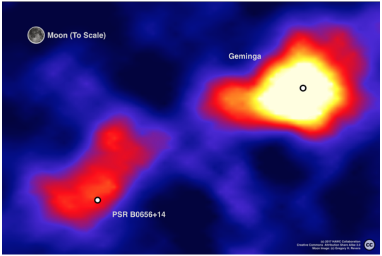
OG 6.2-2
ICRC 1987

THE PULSAR CONTRIBUTION TO GALACTIC COSMIC RAY POSITRONS

Alice K. Harding and Reuven Ramaty
NASA Goddard Space Flight Center
Greenbelt, MD 20771, USA

Abstract

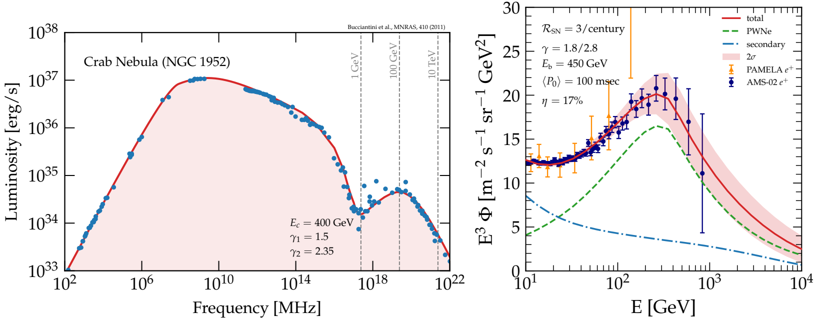
Measurements of high energy positrons in the cosmic rays appear to show an increase in the positron fraction above 10 GeV which is inconsistent with theoretical predictions of secondary positron production. We explore the possibility that observations of .1 - 1 GeV and Very High Energy (VHE) gamma-rays from the Crab and Vela pulsars could imply a significant primary positron contribution from galactic radio pulsars at energies above 10 GeV. Assuming that positrons are produced through magnetic pair creation in the cascades near the polar cap which may be the source of the observed gamma rays, we can estimate the flux and spectrum of the pulsar positron contribution. The pulsar positron component has a flatter spectrum than that expected from secondary cosmic ray production. The level of this contribution above 10 GeV is high enough to make pulsars viable sources of the high energy positron excess, and may also put interesting constraints on pulsar emission models.



- PWNe pre-dicted as galactic positron factories even before PAMELA [Harding & Ramaty, ICRC 1987; Boulares, ApJ 342 (1989); Atoyan, Aharonian & Völk, PRD 52 (1995)]
- Particle acceleration at the highest speed shocks in nature $(10^4 < \Gamma < 10^7) \rightarrow$ only sources showing direct evidence for PeV particles [Bykov+, Space Sci. Rev. 2017]
- HAWC has detected bright and spatially extended TeV gamma-ray sources surrounding the Geminga and Monogem pulsars [HAWC coll., Science 358 (2017)]
- TeV halos detected also in FERMI [Linden+, PRD 2019; Di Mauro+, PRD 2019]

CR positron flux with a primary component by PWNe

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
- 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]
- Efficiency of conversion: ~ 20% of the energy released after the BS phase

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Conclusions

- Impressive progress on the experimental side in the GeV-TeV range over the past ~ 20 years, both in direct (AMS-02, CALET, DAMPE, PAMELA) and indirect (HAWC, HESS, MAGIC, VERITAS) observations. Exciting news from gamma-ray and neutrino observations as well! [Gabici, Evoli et al., IJMPD (2019)]
- These unprecedented data allowed us to study Galactic CRs in much greater detail, but also revealed a number of "anomalies" triggering several unorthodox proposals on the origin and transport of galactic CRs
- We have tried to explain them within a more standard description of CR origin and propagation, finding that some of the new features can be accounted for taking into account:
  1. $\gtrsim$ GeV CRs propagate in a relatively large halo $H \gtrsim 5$ kpc corresponding to an escape time of $\mathcal{O}(50)$ Myr at ~ 10 GeV.
  2. Pulsars provide a non-negligible source of leptonic antimatter in the Galaxy and their contribution is likely to be at the origin of the observed positron excess
  3. Low energy particles are numerous enough to modify the scattering properties of the ISM, and this effect naturally translates into a spectral break in the hundreds of GeV energy range.

Conclusions

- Still a number of puzzles urge an explanation:
  1. The maximum energy achieved by CR nuclear factories has to be $\gtrsim$ PeV
  2. The source spectra of H, He and heavier nuclei have to be different (and steeper than 2!)
  3. Electrons and protons injected with different slopes
  4. Does the environment surrounding sources play a relevant role?
- Most of these anomalies could be fully addressed by good quality measurements in the TeV-PeV range in the next ~ 20 years. Looking forward at LHAASO, HERD, CTA...!

Thank you!

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