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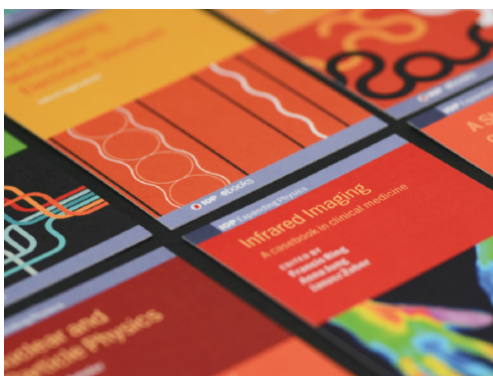
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Vela as the source of Galactic cosmic rays above 100 TeV

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Abstract. We model the contribution of the nearest young supernova remnant Vela to the local cosmic ray flux taking into account both the influence of the Local Superbubble and the effect of anisotropic diffusion. The magnetic field in the bubble wall prevents low-energy particles to penetrate into the bubble, leading to an energy-dependent suppression of CRs from Vela inside the bubble. The resulting CR flux at Earth in the energy region around the cosmic ray knee can naturally explain the observed fluxes of individual groups of nuclei and their total flux. Adding the CR flux from a 2–3 Myr old local CR source suggested earlier, the CR spectra in the whole energy range between 200 GeV and the transition to extragalactic CRs are described well by the combined fluxes from these two local Galactic sources.

Keywords: cosmic ray theory, galactic magnetic fields

ArXiv ePrint: [1812.03522](https://arxiv.org/abs/1812.03522)

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1 Introduction

The measured energy spectrum of cosmic rays (CRs) extends smoothly over more than 11 decades as a nearly featureless power law, $I(E) \propto E^{-\beta}$. One of its most prominent features is the knee, a break in the all-particle energy spectrum at the energy $E_k \simeq 4$ PeV, which was discovered by Kulikov and Khristiansen in the data of the MSU experiment already in 1958 [1]. The second knee corresponds to a change in the spectral slope of the all-particle energy spectrum at $\simeq 5 \times 10^{17}$ eV where the slope hardens by $\Delta\beta \simeq 0.2$. There is a general consensus that the knee in the total CR spectrum at $E_k \simeq 4$ PeV coincides with a suppression of the primary proton and/or helium flux, and that the composition becomes increasingly heavier in the energy range between the knee and 10^{17} eV [2–5].

Explanations for the origin of the knee fall in two main categories, connecting it either with a change in the propagation or the injection of CRs. In the first case, the knee energy may either corresponds to the rigidity at which the CR Larmor radius R_L is of the order of the coherence length l_c of the turbulent magnetic field in the Galactic disk [6, 7]. Alternatively, the knee corresponds to a transition between the dominance of pitch angle scattering to Hall diffusion or drift along the regular field [8–10]. In both cases, the energy dependence of the confinement time changes which in turn induces a steepening of the CR spectrum [6–11]. In the second class of models, the knee is connected to properties in the injection spectrum of the Galactic CR sources. For instance, the knee might correspond to the maximal rigidity to which CRs can be accelerated by the population of Galactic CR sources dominating the CR flux below PeV [12–14]. Alternatively, the knee may be caused by a break in the source CR energy spectrum at this rigidity [15, 16]. A variant of this model is the suggestion that the spectrum below the knee is dominated by a single, nearby source and that the knee correspond to the maximal energy of this specific source [17, 18]. All these models lead to a sequence of knees at ZE_k , a behaviour first suggested by Peters [19].

In the isotropic diffusion approximation one defines a scalar diffusion coefficient which depends on energy as $D(E) = D_0(E/E_0)^\delta$. Measurements of the Boron and Carbon fluxes especially by the AMS-02 experiment are consistent with Kolmogorov turbulence, i.e. $\delta = 1/3$, at rigidities above ~ 100 GV [20]. The normalisation D_0 is only weakly constrained using measurements of stable nuclei, but can be restricted considering the ratio of radioactive isotopes as, e.g., $^{10}\text{Be}/^9\text{Be}$: fitting successfully these ratios requires values of the normalisation

constant D_0 in the range $D_0 = (3 - 8) \times 10^{28} \text{cm}^2/\text{s}$ at $E_0 = 10 \text{GeV}$ [21–23]. For typical magnetic field strengths of order μG and maximal length scales of fluctuations in the turbulent field of order 10pc , numerically calculated diffusion coefficients are two orders of magnitude below this value for D_0 . Since D scales for Kolmogorov turbulence as $D \propto B^{-1/3}$, the magnetic field strengths B would have to be scaled down by a factor 10^{-6} to obtain agreement between the two approaches. This discrepancy can be resolved, if the diffusion is sufficiently anisotropic and the magnetic field contains a non-zero component perpendicular to the Galactic disk [24]. As a result, the number of sources contributing to the locally observed flux is reduced by two orders of magnitude. Thus only few sources contribute to the local CR flux at energies above 200GeV .

In the energy range between 200GeV and 100TeV a 2–3 Myr old local supernova (SN), can dominate the local CR flux, as shown in refs. [25–27]. A local SN event of the same age was deduced from ^{60}Fe found in sediments in the ocean crust of the Earth [28–30] and on the Moon [31]. Such a local SN is able to resolve the anomalies which were found recently by CR experiments. This includes the energy dependence of the proton to helium ratio, the breaks in the energy spectrum of primary nuclei at the rigidity 200GV , the positron excess, and the ratio $R \simeq 2$ of positron to antiproton fluxes, see refs. [25–27] for details.

The phase of the CR dipole amplitude is constant between $\simeq 20 \text{TeV}$ and 100PeV , except for abrupt flip by 180° at $\simeq 200 \text{TeV}$. Similarly, the dipole amplitude is approximately constant above and below 200TeV . This behaviour of the dipole anisotropy suggests that two CR sources located in the two opposite hemispheres relative to the local magnetic field line dominate the CR flux below and above this energy [32]. We suggest in this work that Vela, a 11 kyr old supernova remnant (SNR) at the distance 270pc , is the source dominating the local CR flux above 200TeV . We study the expected CR flux from Vela, which is connected with the Solar system by a magnetic field line in models of the global Galactic magnetic field as, e.g., the Jansson-Farrar model [33]. If this source would be indeed directly connected to the Solar system by a magnetic field line, its flux would however overshoot the locally measured one by 3 orders of magnitude in case of anisotropic diffusion. Such an excess is avoided, if one takes into account that the Earth is located inside the Local Superbubble. We use a simplified model for the structure of the magnetic field inside the Local Superbubble similar to the one of refs. [34, 35], and follow individual CR trajectories solving the Lorentz equation. Despite of using a simplified model for the Local Superbubble we obtain a good description of the fluxes of individual groups of CR nuclei in the knee region and above. Adding additionally the CR flux from the 2–3 Myr old source, the CR spectra in the whole energy range between 200GeV and the transition to extragalactic CRs are described well combining the fluxes from only these two local sources.

2 Theoretical framework

2.1 Local Bubble and the geometry of the local magnetic field

The Sun resides in a low-density region of the interstellar medium (ISM) called the Local Bubble (LB). The LB extends roughly 200pc in the Galactic plane, and 600pc perpendicular to it, with an inclination of about 20° [36]. Observations and simulations [37, 38] show that the bubble walls are fragmented and twisted. Moreover, outflows away from the Galactic plane may open up the bubble [37]. In view of this complicated geometry, we idealise the LB in our numerical simulation as follows [35]: we assume for the magnetic field profile $\mathbf{B}(\mathbf{x})$ parallel to the Galactic plane (x, y) a cylindrical symmetry, i.e. we imply that the changes

as function of the Galactic height z are small compared on the considered length scales. Then $\mathbf{B}(\mathbf{x})$ is only a function of $r = \sqrt{x^2 + y^2}$. We use as a base radius R of the bubble $R = 100$ pc and set the wall thickness to $w = 3$ pc. We assume inside the bubble and the wall a clockwise oriented magnetic field for $y > 0$ and an anticlockwise one for $y < 0$. The strength of the regular magnetic field depends only on the radius and is set to $B_{\text{in}} = 0.1\mu\text{G}$ inside the bubble, $B_{\text{sh}} = 12\mu\text{G}$ in the wall, and $B_{\text{out}} = 1\mu\text{G}$ outside the bubble. The Sun is assumed to be at the centre of the LB, while Vela is situated at the distance 270 pc from the Sun at $y = 0$.

We interpolate the transition between different magnetic field regimes by logistic functions $T(r)$, with a transition width parameter $w_0 = 1 \times 10^{-4}$ pc. For the inside region $r \leq R$, we set

$$T_1 = \left[1 + \exp\left(-\frac{r - R + w/2}{w_0}\right) \right]^{-1}. \quad (2.1)$$

For $y > 0$, the regular magnetic field $B_{\text{reg}} = (B_x^2 + B_y^2)^{1/2}$ is given by

$$B_x = + [B_{\text{in}}(1 - T_1) + B_{\text{sh}}T_1] \sin(\vartheta), \quad (2.2)$$

$$B_y = - [B_{\text{in}}(1 - T_1) + B_{\text{sh}}T_1] \cos(\vartheta), \quad (2.3)$$

while for $y < 0$ it is

$$B_x = - [B_{\text{in}}(1 - T_1) + B_{\text{sh}}T_1] \sin(\vartheta), \quad (2.4)$$

$$B_y = + [B_{\text{in}}(1 - T_1) + B_{\text{sh}}T_1] \cos(\vartheta). \quad (2.5)$$

For the outside region $r \geq R$, we set

$$T_2 = \left[1 + \exp\left(-\frac{r - R - w/2}{w_0}\right) \right]^{-1} \quad (2.6)$$

and

$$B_x = B_{\text{sh}}(1 - T_2) + B_{\text{out}}T_2, \quad (2.7)$$

$$B_y = B_{\text{sh}}(1 - T_2). \quad (2.8)$$

The turbulent magnetic field is taken to be randomly directed with a strength equal to $B_{\text{reg}}/2$. The field modes were distributed between $L_{\text{min}} = 1$ AU and $L_{\text{max}} = 25$ pc according to an isotropic Kolmogorov power spectrum. In the actual simulations, only field modes above $L'_{\text{min}} = 0.01$ pc were included.

2.2 Injection spectrum

We use as CR injection spectrum for Vela a broken power law in rigidity $\mathcal{R} = E/(Ze)$ with an exponential cut off at $\mathcal{R}_{\text{max}} = 8 \times 10^{15}$ V, and a break at $\mathcal{R}_{\text{br}} = 2 \times 10^{15}$ V,

$$\frac{dN}{dE} \propto \begin{cases} E^{-2.2}, & \text{if } E < ZE_{\text{br}} \\ E^{-3.1} \exp(-E/(ZE_{\text{max}})), & \text{if } E \geq ZE_{\text{br}}. \end{cases} \quad (2.9)$$

The normalisation of the spectra for different groups of CR nuclei will be fixed such that the propagated fluxes at Earth agree with observations.

The injection spectrum steepens at $\mathcal{R}_{\text{br}} = 2$ PV by $\Delta\beta = 0.9$. Such a steepening is motivated e.g. by the analysis of ref. [15]: including strong field amplification as suggested by Bell and Lucek [39, 40] into a toy acceleration model, these authors found a break in the energy spectrum of accelerated protons, coinciding for typical values SNR parameters with the knee region. The strength $\Delta\beta$ of the steepening depends among others on the injection history, and in a typical test particle ansatz $\Delta\beta = 0.9$ was found.

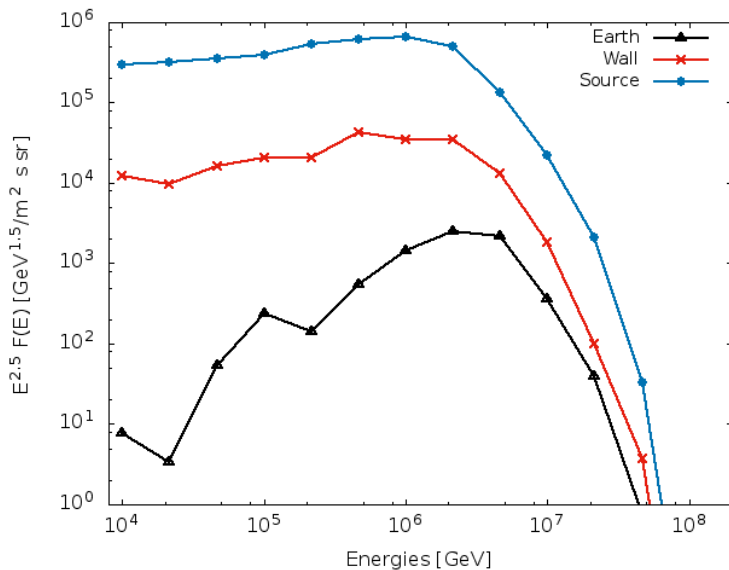


Figure 1. Flux of protons as function of energy computed inside the bubble centred on the Sun’s position, on the bubble wall and around the source.

2.3 Calculation of the flux

In order to compute the flux, we injected 10^4 protons per energy at the position of Vela and propagated them for 12.000 yr. We calculated the CR density $n(E)$ in three regions of interest averaging the CR densities between 8 to 12 kyr: around the source, on the bubble wall, and inside the bubble. The CR flux $F(E) = c/(4\pi)n(E)$ was then computed from the CR densities in the considered volumes. For energies below 100 TeV we deduced the flux from earlier times and higher energies using the scaling relation $(E_{\text{low}}/E_{\text{high}})^{1/3} \approx t_{\text{early}}/t_{\text{now}}$.

We defined the flux around the source considering the y - z plan centred on the source with a thickness of $\Delta x = 5$ pc and $\Delta y = 100$ pc, and $\Delta z = 100$ pc from -50 pc to $+50$ pc on each side. For the flux inside the bubble wall, we considered a ring of 1 pc thickness at the shell, and computed the flux from $z = -50$ pc to $z = 50$ pc. Finally, we computed the flux at the position of the Earth from the CR density inside a cube of 100 pc side length centred at the Sun.

3 Cosmic ray flux from Vela

In figure 1, we show the normalised proton flux in the bubble wall, inside the bubble and around the source. We can see that for high energies ($E_p > 10^{17}$ eV) the bubble is transparent, since the Larmor radius ($R_L \sim 100$ pc) of such protons is large compared to the thickness of the bubble wall. For energies below 1 PeV, particles start to be trapped in the wall and the flux inside the bubble is increasingly suppressed.

In figure 2a, we show the proton flux received at Earth from Vela together with the proton flux from a 2–3 Myr old SN in the model of refs. [25, 27]. The combined flux of these two sources covers the energy range from 200 GeV up to the extragalactic transition region, fitting well the experimental data. Additionally, we show the extragalactic proton flux which

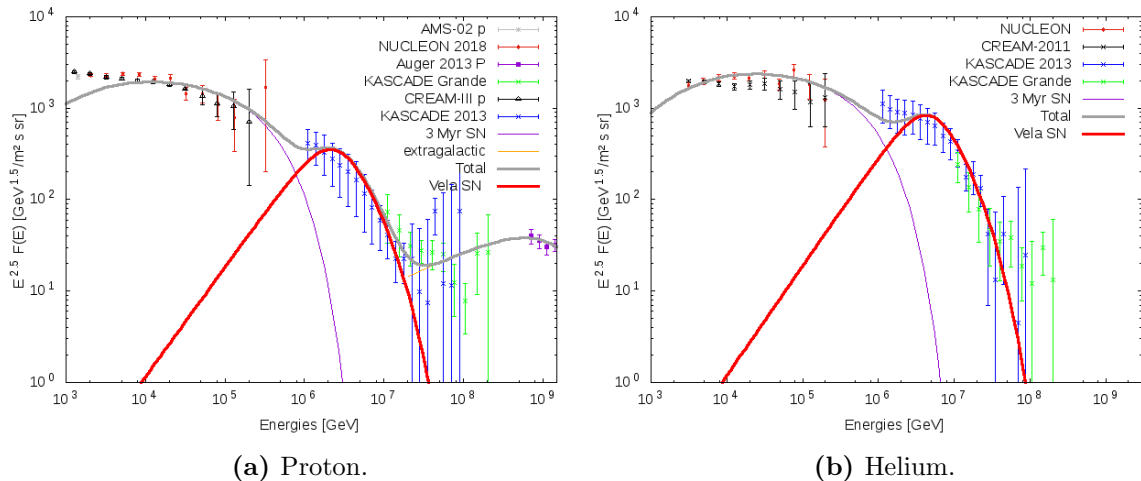


Figure 2. Proton (left) and Helium (right) flux as function of energy from experiments NUCLEON [41], CREAM [42], KASCADE and KASCADE-Grande [5] and AUGER [43]. Vela flux shown with red line, flux from 2–3 Myr SN with violet line, extragalactic proton flux with orange line and total flux with black line.

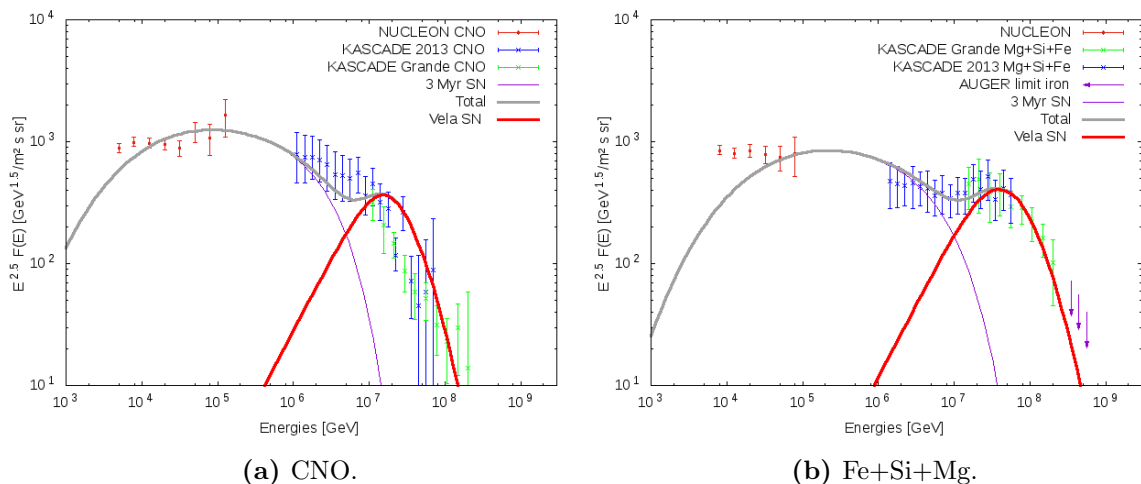
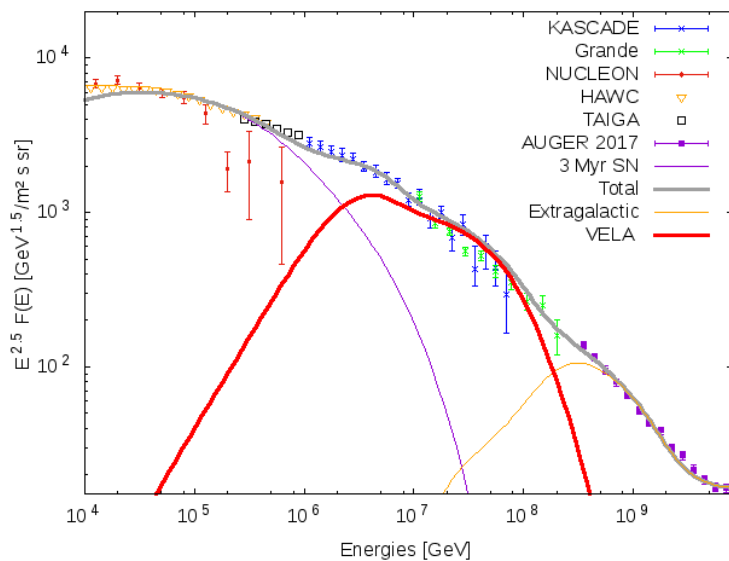


Figure 3. Flux for the CNO nuclei (left) and the Mg-Si-Fe group (right) from Vela and the 2–3 Myr SN as a function of energy; in the violet the Auger limit on the iron flux. Both with same experimental data as in figure 2.

we obtained from a fit to the AUGER data as

$$E^{2.5} F(E) = 5.10^{10} \left(\frac{E}{10^{16} \text{eV}} \right)^{0.3} \exp \left(\frac{-E}{1.5 \times 10^{18} \text{eV}} \right) \frac{\text{GeV}^{1.5}}{\text{m}^2 \text{s sr}}.$$

We also compute the flux for other nuclei: the flux of helium is shown in figure 2b, of the CNO group in figure 3a and of the SiMgFe group in figure 3b, respectively. From figure 4, we see that the all-particles flux fits well the experimental data up to 10^{17} eV. In the energy range above 10^{17} eV, the extragalactic contribution becomes important which we model following ref. [44]. We also remark that the iron flux shown in figure 3b is consistent with the latest Auger composition data which limit the iron flux to 20% of the all-particles flux [48].



(a) All particles.

Figure 4. The all-particles flux from Vela and from the 2–3 Myr SN and the extragalactic contribution from ref. [44] together with experimental data from NUCLEON [41], HAWC [45], TAIGA [46], CREAM [42], KASCADE and KASCADE Grande [5], and AUGER [47].

We computed the total energy output of Vela from the normalisation of the simulated data to the experimental ones: the relative energy fraction in protons found is 0.15, the one of helium 0.25, of carbon 0.02 and of iron 0.02, respectively. For the other nuclei, we calculated the flux ratios of the different nuclei using data from the NUCLEON experiment, taking for each nuclei three points with same energy and with the smallest error-bars. Averaging then the ratios, we obtain $F_N/F_C = 0.25$, $F_O/F_C = 1.6$, $F_{Ne}/F_C = 0.3$, $F_{Mg}/F_{Fe} = 0.6$, and $F_{Si}/F_{Fe} = 0.6$. We obtain then as total energy output in CRs 4.5×10^{49} erg. The total kinetic energy of the Vela supernova calculated in ref. [49] is 1.4×10^{50} erg. We note also that the CR acceleration efficiency of Vela should be high, as it is expected in the scenario of strong magnetic field amplification of refs. [39, 40]. Since the dependence of E_{CR} on the exact numerical values of the parameters (like e.g. the width and the magnetic field strength of the bubble wall) in our model is rather large, we conclude that the two values are in good agreement.

The Vela complex contains two recent SNe, Vela X and Vela Jr. The age and distance to Vela Jr are very uncertain [52]. If the age of Vela Jr is as small as 700 yr, cosmic rays do not have enough time to diffuse through the wall of the Local Bubble and to reach the Earth. For the larger age ~ 10 kyr suggested in ref. [52], the contribution from Vela Jr is expected to be of the same order and with similar characteristics as the one of Vela X. Studies of anisotropies are similar for both sources, since they are located in the same part of sky. However, they are also affected by the uncertain age of Vela Jr, see e.g. the recent ref. [53]. In order to avoid additional parameters and uncertainties in our model, we restrict ourselves in this work therefore to the more certain contribution from Vela X.

4 Conclusions

In the standard diffusion picture it is assumed that Galactic CRs form a smooth, stationary “sea” around the Galactic disk. Evidence for this assumption comes from γ -ray observations, which indicate a rather small variation of the parent CR populations below ≈ 100 GeV throughout the Galaxy outside of several kpc from the Galactic center [50]. Going to higher energies, CRs escape faster and thus the number of CR sources contributing to the local flux diminishes. In order to match the required diffusion coefficient with micro-gauss magnetic fields observed in the local Galaxy the CR propagation should be strongly anisotropic [24]. Then the number of CR sources decreases by a factor 100 relative to the case of isotropic diffusion. As a result, the CR flux should be dominated by few local CR sources except for the lowest energies.

In this work, we have examined the suggestion put forward in refs. [17, 18] that the spectrum below the knee is dominated by CRs accelerated in the Vela SNR and that the knee corresponds to the maximal energy of this source, or a complex of sources taking into account the contribution of Vela Jr SN as suggested in refs. [52, 53]. As an important improvement compared to these earlier studies, we have taken into account that the Sun is located inside the Local Superbubble and that CRs propagate anisotropically. Without the influence of the Local Superbubble, the CR flux from Vela at the position of the Sun would overshoot the observed one by 3 order of magnitude, because the Sun and Vela are connected by field lines of the regular magnetic field. Using a CR injection spectrum with a break $\Delta\beta \simeq 0.9$ at $E_{\text{br}} = 2$ PeV as motivated by studies of ref. [15], we have obtained a good description of the flux of individual groups of CR nuclei both in the knee region and above. Adding additionally the CR flux from the 2–3 Myr old source suggested in refs. [25–27], the CR spectra in the whole energy range between 200 GV and the transition to extragalactic CRs are described well combining the fluxes from only these two Galactic sources.

Finally, we stress that, while including the effect of the Local Superbubble is an important improvement, the uncertainties connected to the strength and shape of the magnetic field in the bubble are large. In a future study, we plan therefore to study in depth the dependence of the spectrum and amplitude of the CR flux from Vela received on Earth on the parameters and the geometry of the Local Superbubble. Another important question to be addressed is how strong the dipole anisotropy from Vela will be decreased, since the CR flux is effectively emitted not by a point source but the bubble wall. Last but not least, we note that the suggestion from ref. [35] that the Galactic soft neutrino component [51] in the ICeCube data is produced by CRs interacting in the wall of a superbubble fits well in the scenario presented here.

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