Galactic factories of cosmic electrons and positrons

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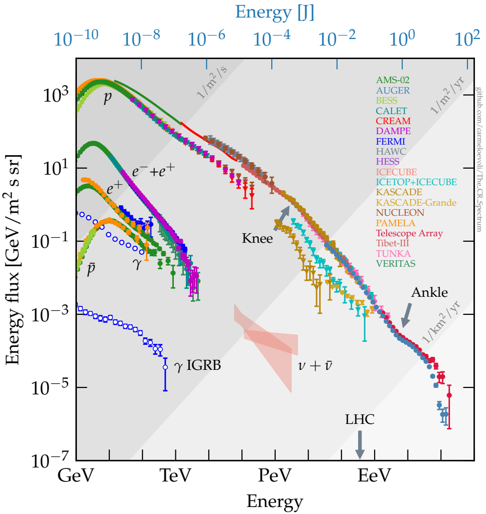
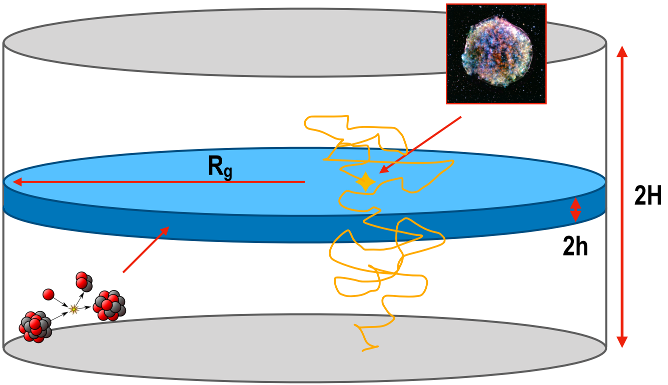
The cosmic-ray spectrum in 2021



Looking forward to adding GAPS measurements to this plot! ☺

Our spherical “cow”



From phenomenology to more fundamental theory

Phenomenology accomplishments

- Very remarkable that simple approaches provides explanation of data at few % level! [Schroer+, PRD 103, 2021; Korsmeier & Cuoco, PRD 103, 2021]
- Nuclei $Z \geq 6$ share the same source spectrum but different from H and He [Evoli+, PRD 2018; Weinrich et al., A&A 2020]
- The (sharp!) break at ∼300 GV is due to transport [Genolini+, PRL 119, 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 [Evoli+, PRD 2019; Weinrich et al., A&A 2020]

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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]

Galactic factories of cosmic electrons and positrons

Rationale

- In recent years there has been a dramatic improvement in the measurement of the spectrum of $e^{\pm}$
- Significant progresses also in understanding galactic cosmic-ray transport
- We revised the prevailing approach in which leptons are the product of three classes of sources: secondary, SNR (e^{-}) and PWN (pairs)
- Are the observed fluxes well fitted by what we know about the Galactic properties of these populations and their energetic budgets?

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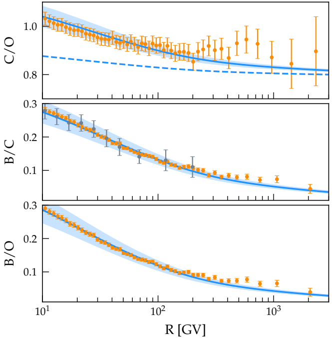
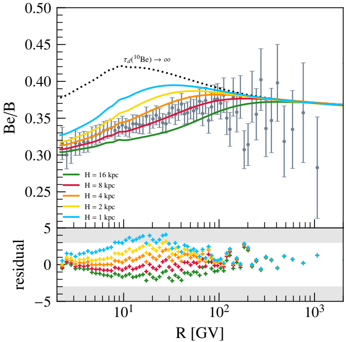
A word of caution

- An example of “crying wolf” for Dark Matter (blame on theorists though!)

Key results of the Galactic halo model

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





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

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

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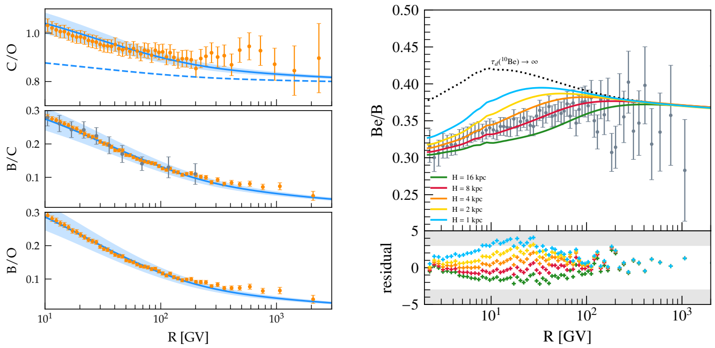

- By fitting primary and secondary/primary measurements we obtain: $\delta \sim 0.54/0.34$, $R_b \sim 400$ GV, $D_0/H \sim 0.45 \times 10^{28}$ cm/s^2/kpc, $v_A \sim 5$ km/s
- All nuclei with $Z > 2$ are injected with $\gamma \sim 4.3$ (Oxygen here is the only pure primary species)
- Escape time weakly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

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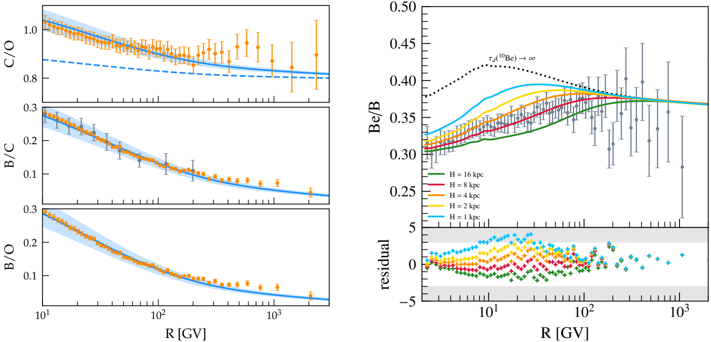
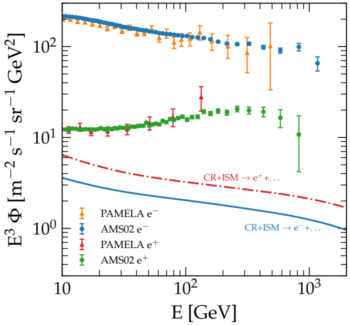


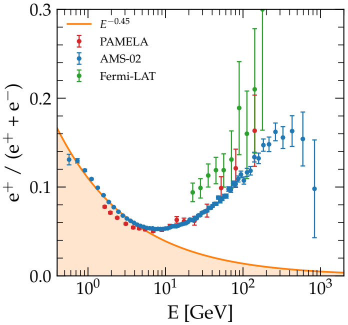
- ▷ Traditionally ^{9}Be/^{10}Be has been used as CR clock $\to$ no measurements at $E \gtrsim 1$ GeV/n [Lipari, arXiv:1407.5223]
- ▷ Since ^{10}Be decays to ^{10}B the ratio Be/B is affected twice (excellent recent AMS-02 data!)
- ▷ Preference for large halos $H \gtrsim 5$ kpc [see also Weinrich et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

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

Secondary leptons in the Galactic Halo model

Evoli et al., PRD, 2021



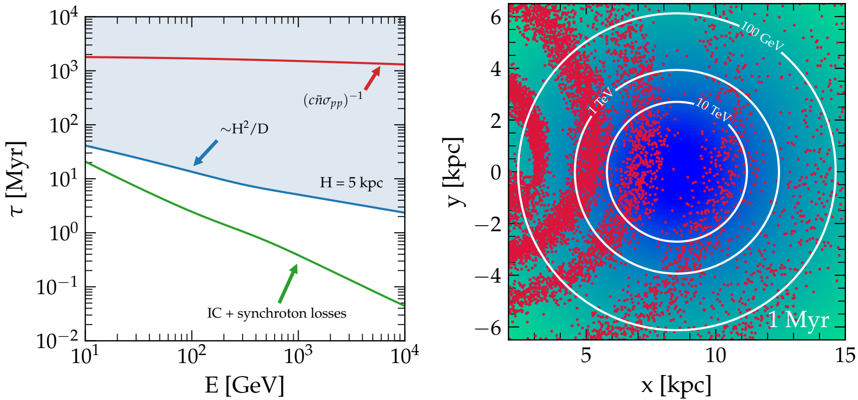


- AMS-02 local measurements of e^+ and e^- compared with secondary predictions CR+ISM$\rightarrow e^\pm$
- It is not compatible with all leptons being secondary $\rightarrow$ we need a primary component for electrons
- If e^+ are secondaries (and $\alpha_p = \alpha_e$) the positron fraction must be a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

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

Nuclei and electron timescales

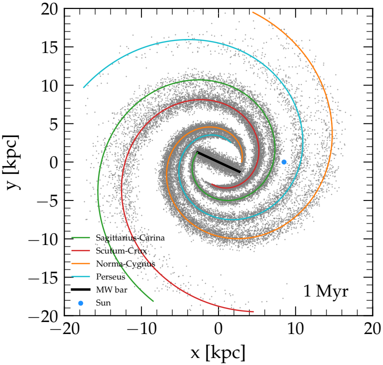
Evoli, Amato, Blasi & Aloisio, PRD 103, 8 (2021)



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

The Green function formalism

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

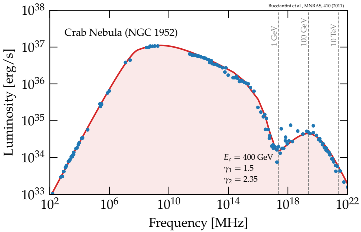


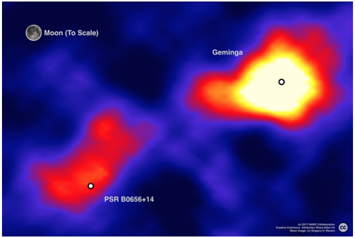
$$n(t_\odot, E, \vec{r}_\odot) = \iiint dt_s\, dE_s\, d^3\vec{r}_s\, \delta(\Delta t - \Delta\tau) \mathcal{G}_{\vec{r}}(E, \vec{r}_\odot \leftarrow E_s, \vec{r}_s) \mathcal{Q}(t_s, E_s, \vec{r}_s).$$

Pulsars as positron galactic factories

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

- ▷ $e^{\pm}$ pairs created in the pulsar magnetosphere become part of the relativistic wind into which pulsars convert most of their rotational energy $\rightarrow$ the only sources showing direct evidence for PeV particles [Bykov+, Space Sci. Rev. 2017]
- ▷ γ/X-ray emissions by these objects are described by a flat spectrum (with $1 < \alpha_L < 2$) at low energies, which then steepens to $\sim E^{-2.5}$ beyond $\sim$ few hundred GeV [Bucciantini+, MNRAS 2011]
- ▷ HAWC has detected bright and spatially extended TeV gamma-ray sources surrounding the Geminga and Monogem pulsars [HAWC coll., Science 358 (2017)] (detected also in FERMI [Linden+, PRD 2019; Di Mauro+, PRD 2019]) associated with the release of pairs in the ISM





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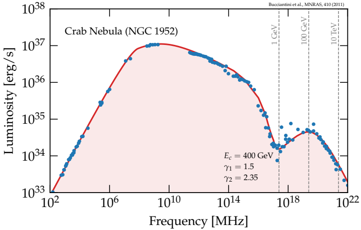
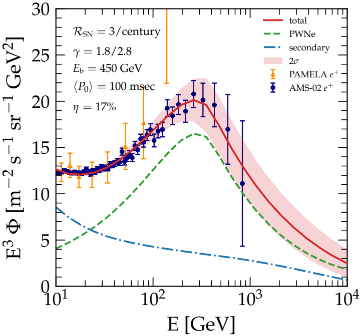
$$Q_0(t)\mathrm{e}^{-E/E_{\mathrm{c}}(t)} \times \begin{cases} (E/E_{\mathrm{b}})^{-\gamma_{\mathrm{L}}} & E < E_{\mathrm{b}} \\ (E/E_{\mathrm{b}})^{-\gamma_{\mathrm{H}}} & E \geq E_{\mathrm{b}} \end{cases}$$



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

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

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



Pulsars as positron galactic factories

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

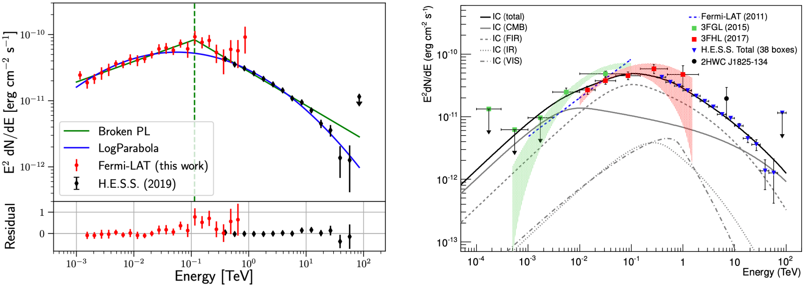
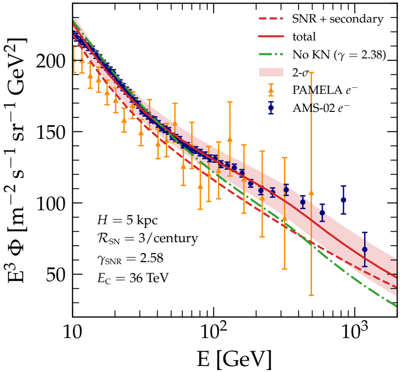
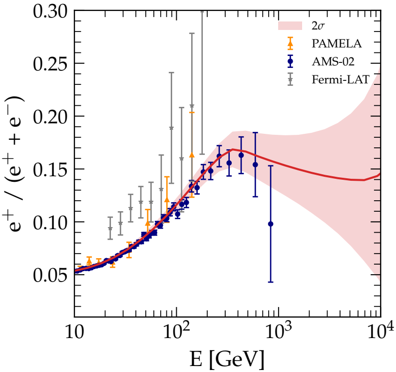


Figure: Combined spectra of PWN HESS J1825-137 (left) and HESS J1825−137 (right) with the spectral measurements obtained Fermi-LAT data (from $\sim$ GeV to $\sim$ TeV) and the H.E.S.S. data for the $\gtrsim 100$ GeV energy range

The electron spectrum from SNRs

Evoli, Amato, Blasi & Aloisio, PRD 2021

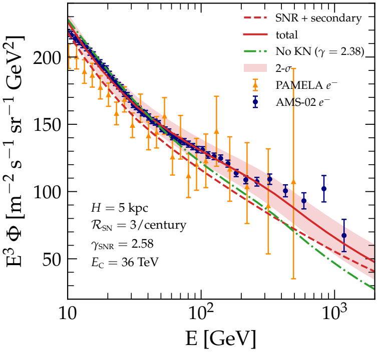


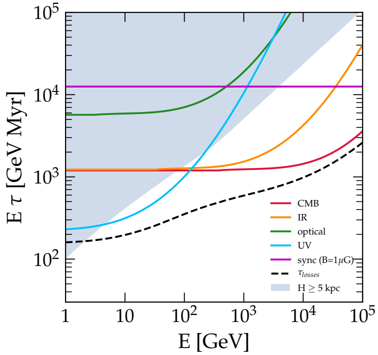


- ▷ Electrons injected by SNRs with a power law with an intrinsic cutoff at ~ 40TeV (cooling dominated)
- ▷ Electrons require a spectrum steeper than protons by $\sim 0.3 \to$ puzzling!
- ▷ The only aspect that is different between e$^-$ and p is the loss rate $\to$ negligible inside the sources unless B is very strongly amplified [Diesing & Caprioli, PRL 2020; Cristofari+, A&A 2021]
- ▷ Watch at the positron fraction!

The signature of energy losses on the cosmic ray electron spectrum

Evoli, Blasi, Amato & Aloisio, PRL 2020

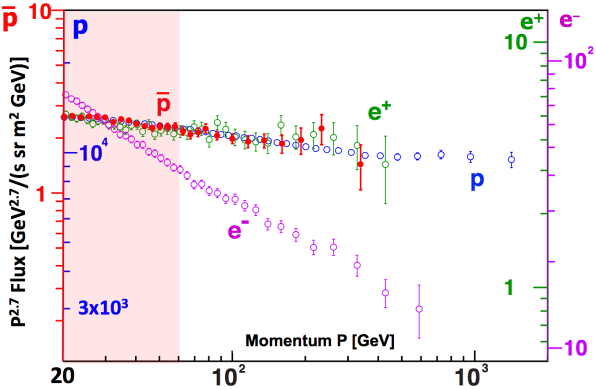




- ▷ Existence of a fine structure at ~ 42 GeV was first noted by the AMS02 collaboration (and erroneously attributed to more than one CR electron population)
- ▷ The feature in the e^- spectrum is the result of KN effects in the ICS on the UV bkg $\longrightarrow$ electrons do lose energy in the ISM at odds with unorthodox transport models [Blum et al., PRL 2013; Kachelriess+, PRL 2015; Cowsik & Madziwa-Nussinov ApJ 2016; Lipari, PRD 2019]
- ▷ See also Di Mauro, Donato, and Manconi, PRD, 2021, for a different interpretation.

Are positrons truly primary?

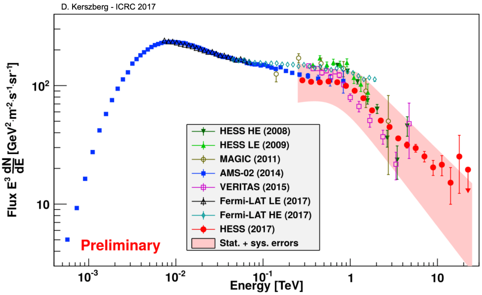
Blum et al., PRL 111 (2013); Cowsik & Madziwa-Nussinov ApJ 827 (2016); Lipari, PRD 95 (2019)

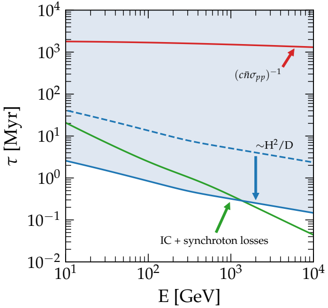


- Positrons and anti-protons share the same spectrum (likewise electrons)!
- The $e^+/\bar{p}$ ratio is very close (2.04 ± 0.04) to the one expected by pure secondary production
- Can it be just a (actually two!) coincidence?

Are positrons truly primary?

Lipari, PRD, 2019

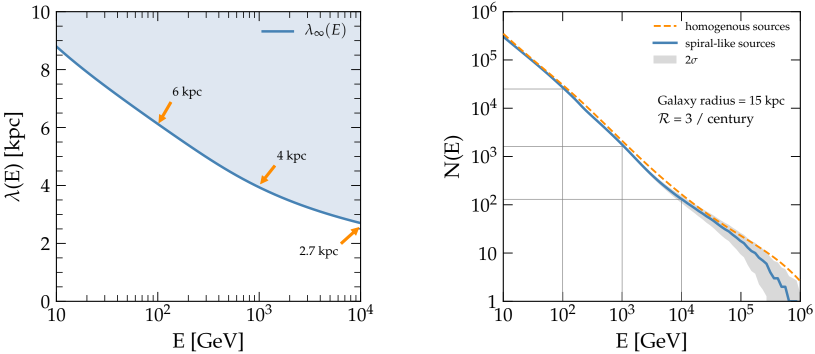




- In order to have just secondary positrons however we need to get rid of the energy losses.
- The lepton $e^- + e^+$ spectrum exhibits a sharp and large ($\Delta\gamma \sim 1$) break at $E \simeq 1$ TeV which could be associated with the onset of energy losses.
- Given the systematics, the feature might indicate either a break in the powerlaw spectrum or a kind of cutoff, see also CALET and DAMPE for direct measurements [CALET coll., PRL 119 (2017); DAMPE coll., Nature 552 (2017)].

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 $\longrightarrow$ SNR of $\mathcal{R} = 1/30$ years
- ▷ The sources that can contribute to the flux at Earth at a given energy E are

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

The trouble with fluctuations

Evoli et al., arXiv:2111.01171

- The spectrum we observe is due to the contribution of many sources, in the **true** Galaxy:

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

  where the particle transport mechanisms and boundary conditions are incorporated into $\mathcal{G}$.

- As we don't know $\{t_s, \vec{r}_s\} \rightarrow$ we must rely on **ensemble average** quantities $\langle n_{\rm nuc}\rangle$
- Assuming **burst injection** and **uniform energy losses** this integral is analytical and in the limit of $H \ll R_g$ gives:
  - for nuclei:

$$\langle n_{\rm nuc}\rangle = \frac{N(E)\mathcal{R}_{\rm SN}}{2\pi R_d^2 H}\frac{H^2}{D(E)} \propto N(E)\tau_{\rm esc}(E) \propto E^{-\alpha-\delta}$$

  - while for electrons (in the limit of energy-losses dominated):

$$\langle n_e\rangle = \frac{N(E)\mathcal{R}_{\rm SN}}{2\pi R_d^2}\frac{\tau_{\rm loss}(E)}{\sqrt{D(E)\tau_{\rm loss}(E)}} \propto E^{-\alpha-\frac{\delta}{2}-\frac{1}{2}}$$

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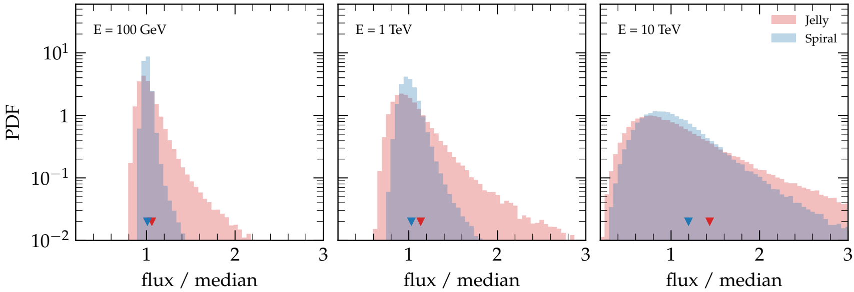
⚠ The variance is however $\sigma(n_i) \rightarrow \infty$! What is the significance of any excess?

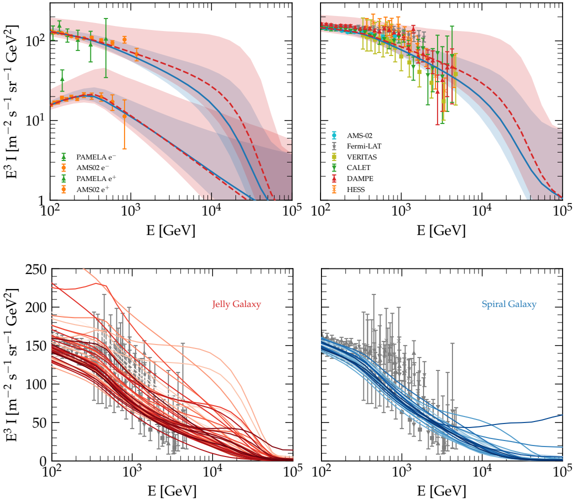
The trouble with fluctuations

Evoli et al., arXiv:2111.01171



- Divergence is due to the fact that the density $n \to \infty$ as $r_s \to 0$
- Cannot be cured with spirals!
- Heavy-tailed PDF $\to$ mean $\neq$ median (problematic for codes based on the mean field approach!)
- More relevant for high-energy electrons as the horizon reduces the number of contributing sources

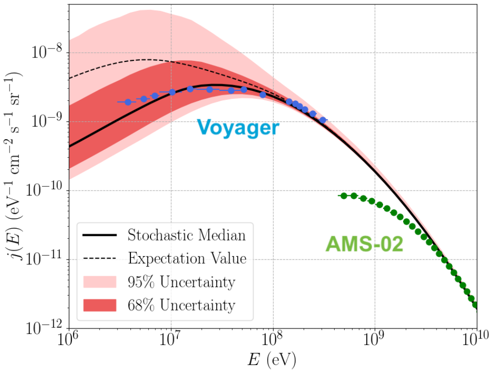
Revisiting fluctuations



Revisiting fluctuations as CDF of the flux distribution $\rightarrow$ same problem for χ^2!

Fluctuations in the low-energy spectrum

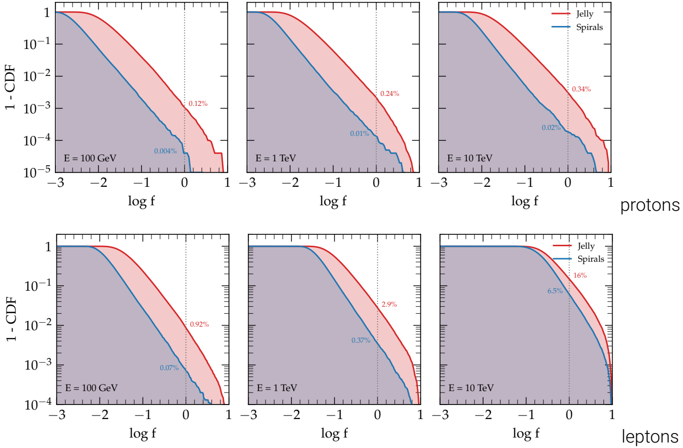
Phan et al., PRL, 2021



- At low energies nuclei losses are severe!
- These effects neglected in standard approaches $\longrightarrow$ a potential issue for new physics searches in the very-low energy range, certainly smaller for secondaries.

The odds of a prominent nearby source

Evoli et al., arXiv:2111.01171



- ▷ 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 $\to$
  at ~ 1 TeV chances of $f > 1$ are $\sim 0.01\%$ for nuclei and $\sim 0.4\%$ for leptons

Thank you!

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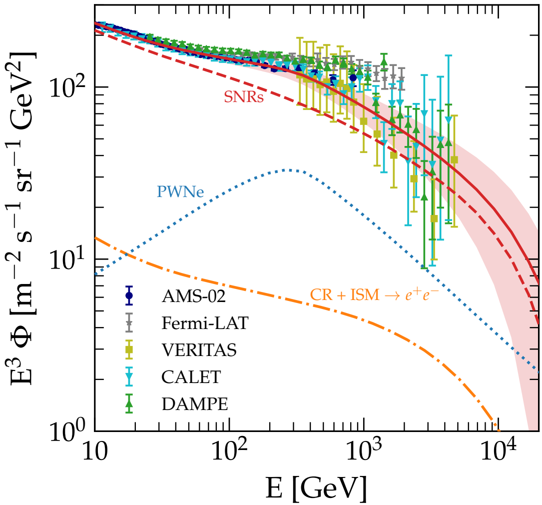
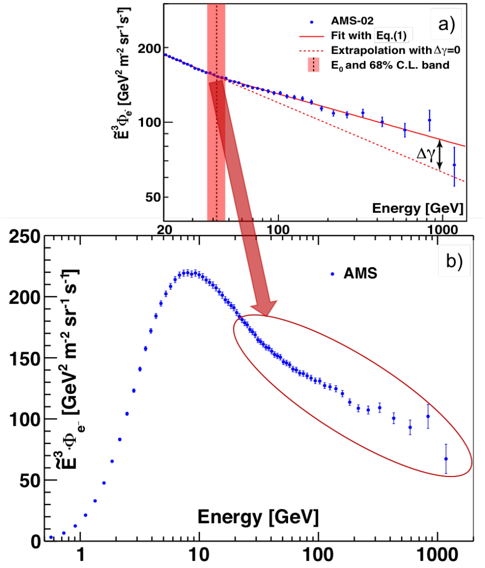
- 0000-0002-6023-5253

- slides available at: https://zenodo.org/communities/carmeloevoli_talks

Backup slides: total lepton spectrum



Backup slides: AMS-02 electron spectrum



Backup slides: anisotropy