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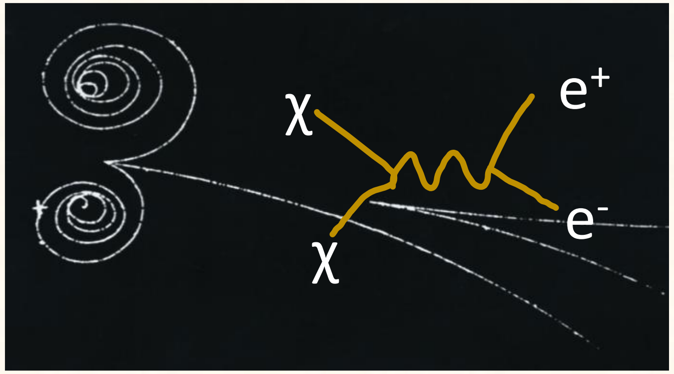
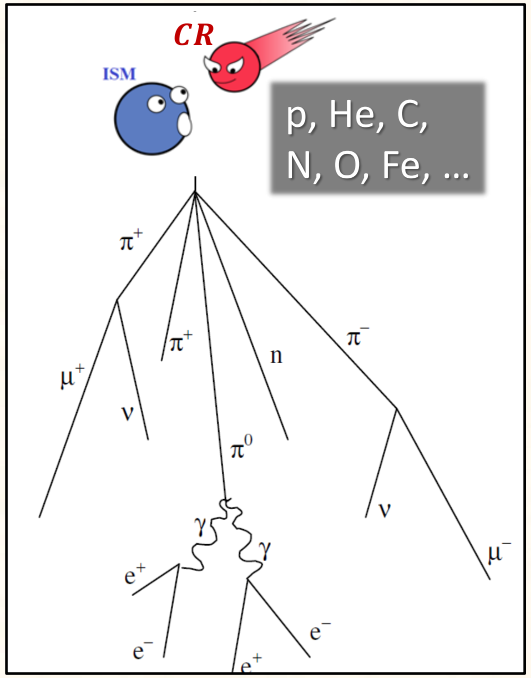
Scrutinizing current uncertainties on cosmic-ray positron predictions

(ArXiv:2305.02958)





Current situation and the importance of CR positrons

High precision data for the fluxes of CR nuclei allow us to accurately model the production of CR antiparticles and uncertainties related.

The positron spectrum allows us to strongly constrain the existence of BSM physics and provides crucial information about the astrophysical environment.

Known sources of positron production are CR interactions with interstellar gas and PWNe. Other exotic and non exotic sources may also contribute.

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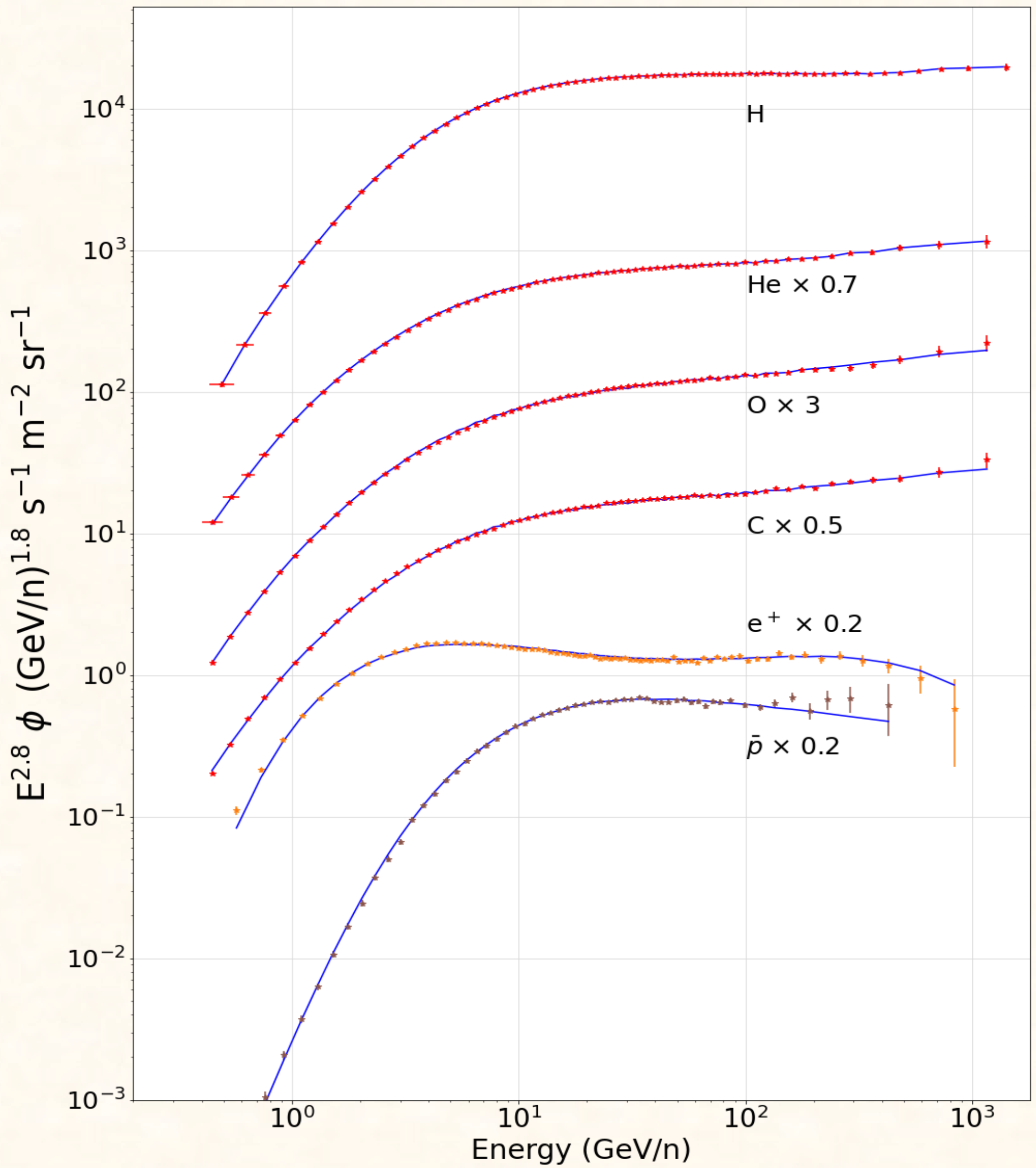

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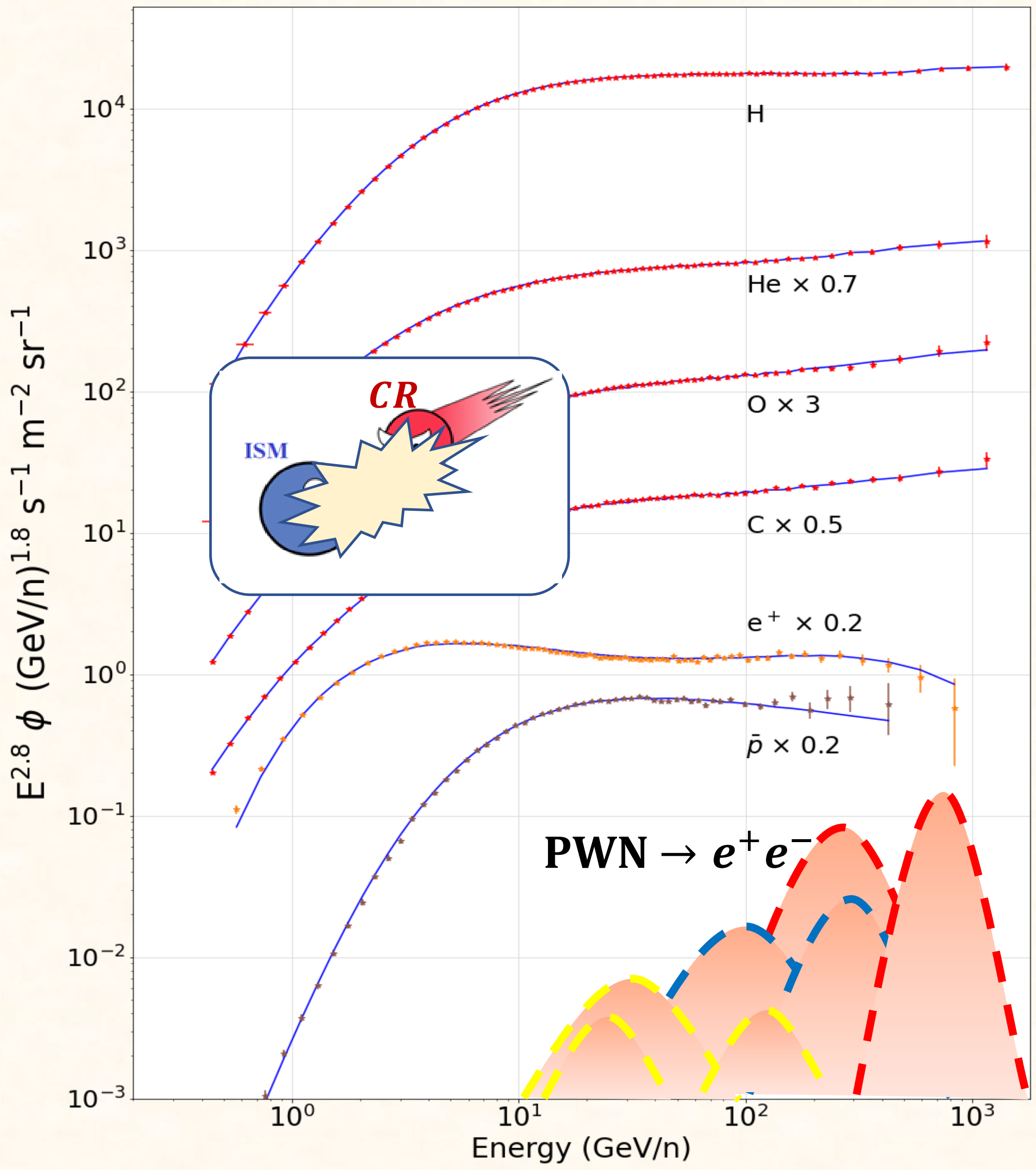

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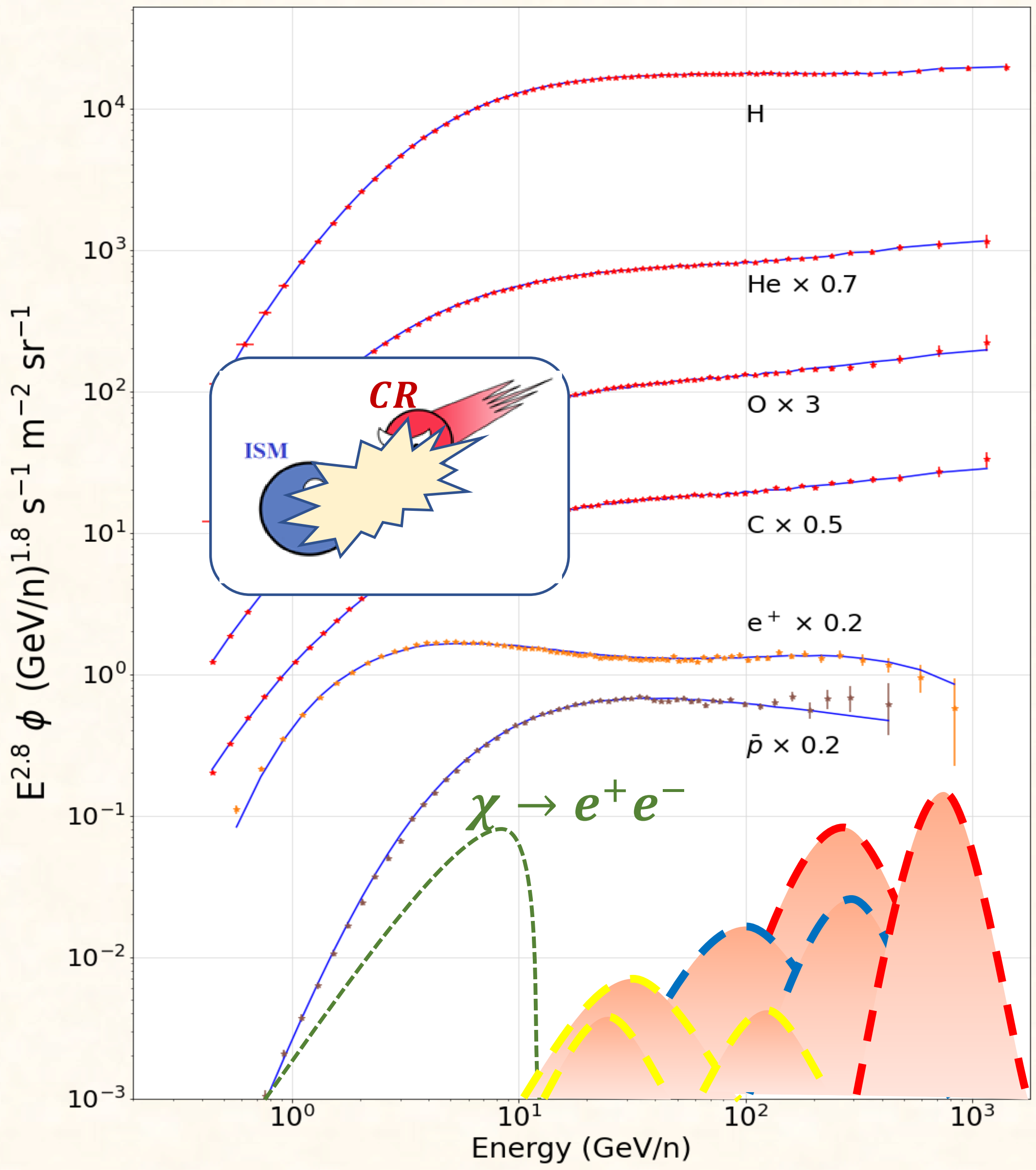


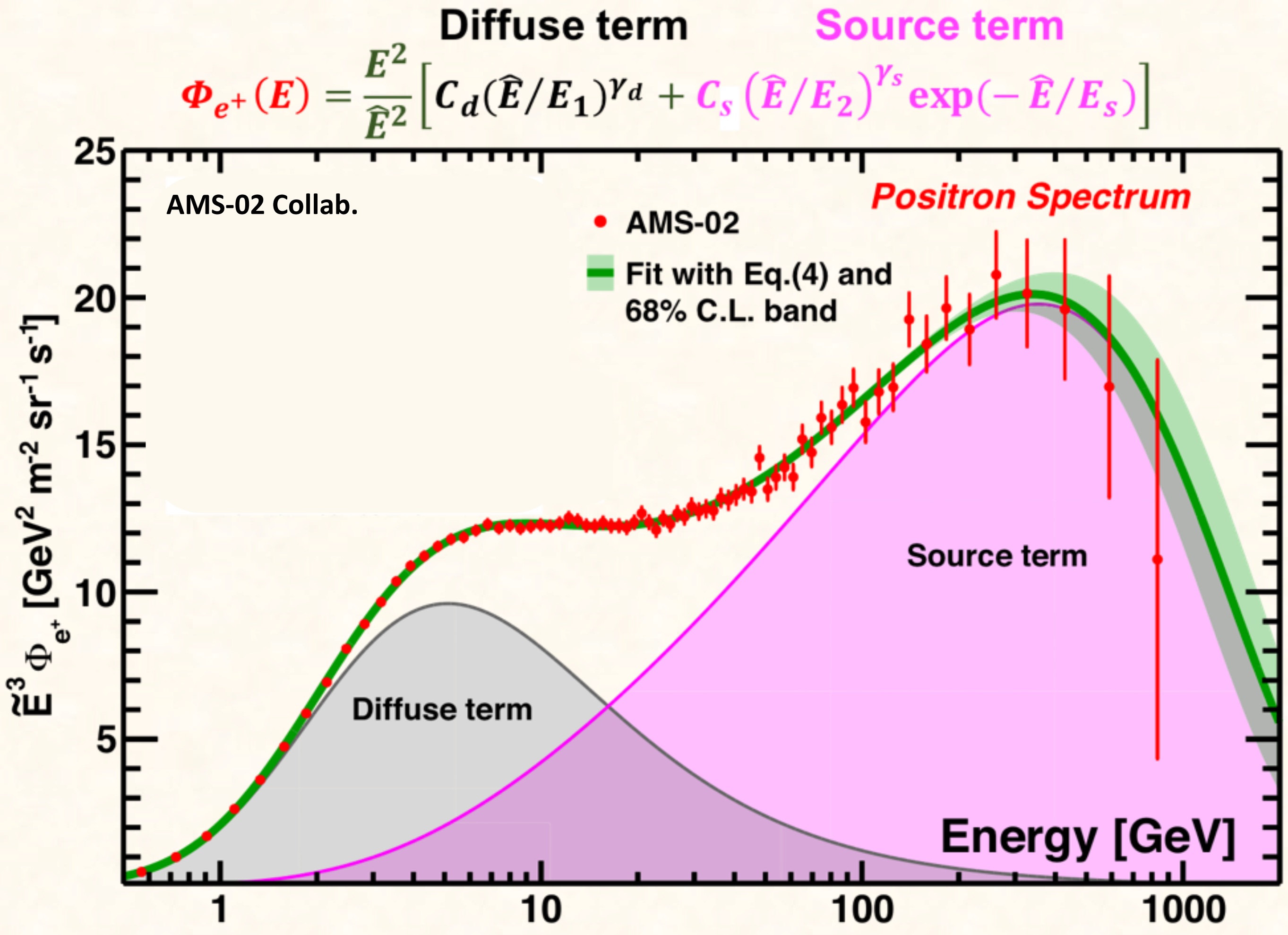
Positron production and identification of exotic signals

The stochastic nature of the PWN emission makes it difficult to find signatures of exotic physics at high E:

1. Sharp features can be easily masked by PWN contribution
2. High masses contributing to the e+ spectrum at those energies

Easier to spot these signals at low E

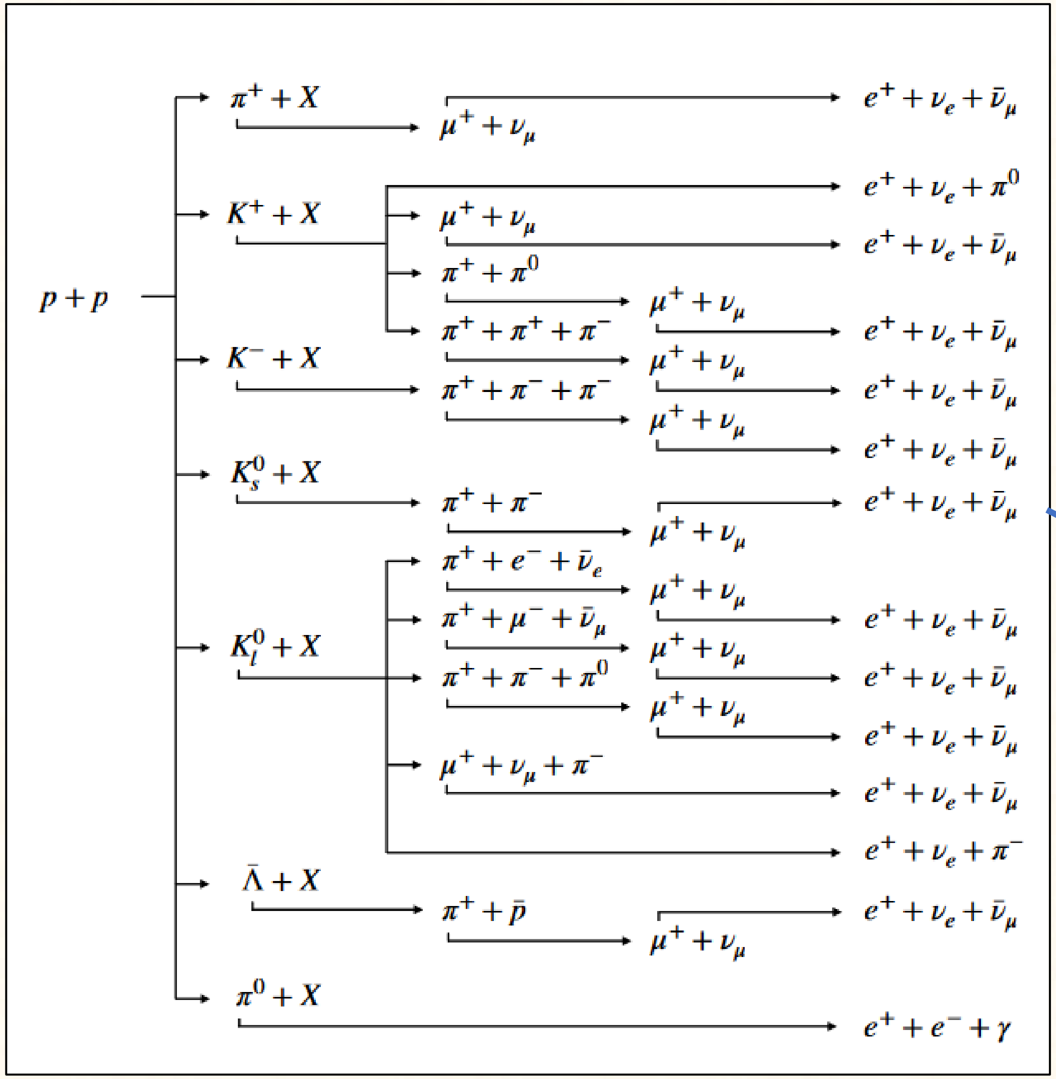
- Diffusion process
- Magnetised halo
- Nearby Galactic environment
- Solar modulation
- Cross sections

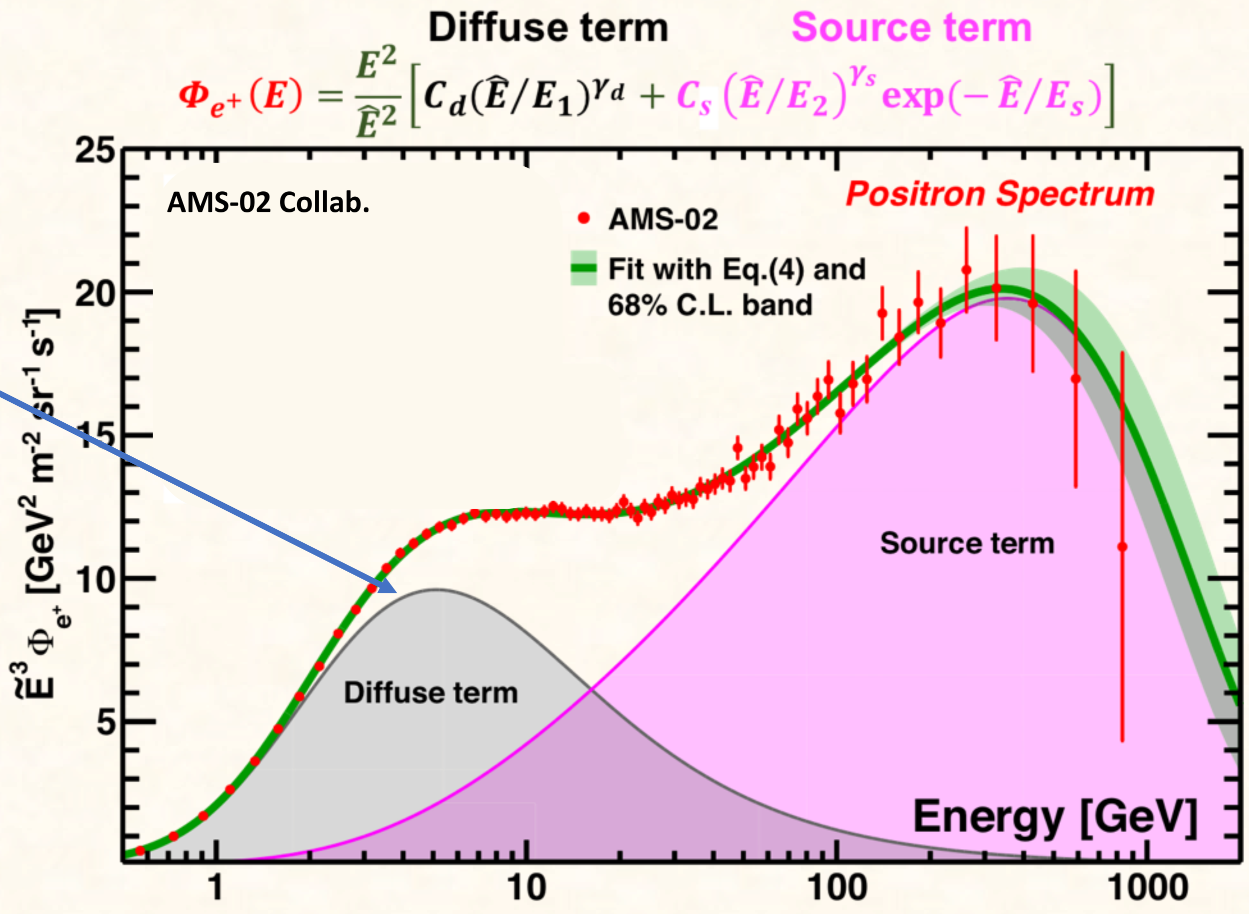


The cross section problem

Positrons mainly produced from p+p interactions, but also He and heavier CRs are also involved and produce positrons!

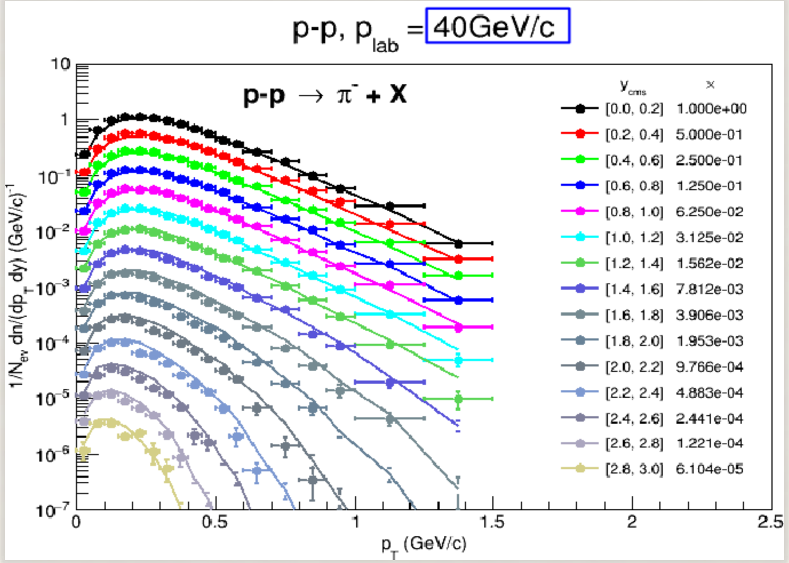
Orusa et al PRD 105 (2022) 12

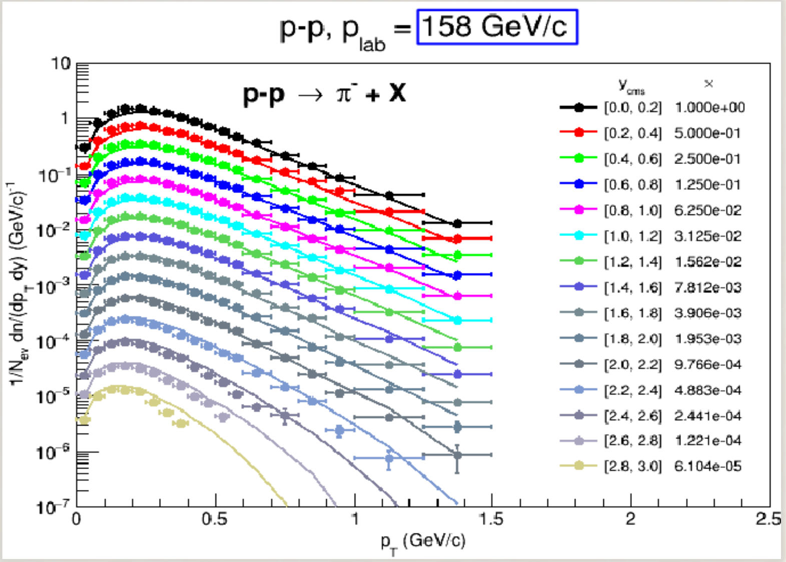


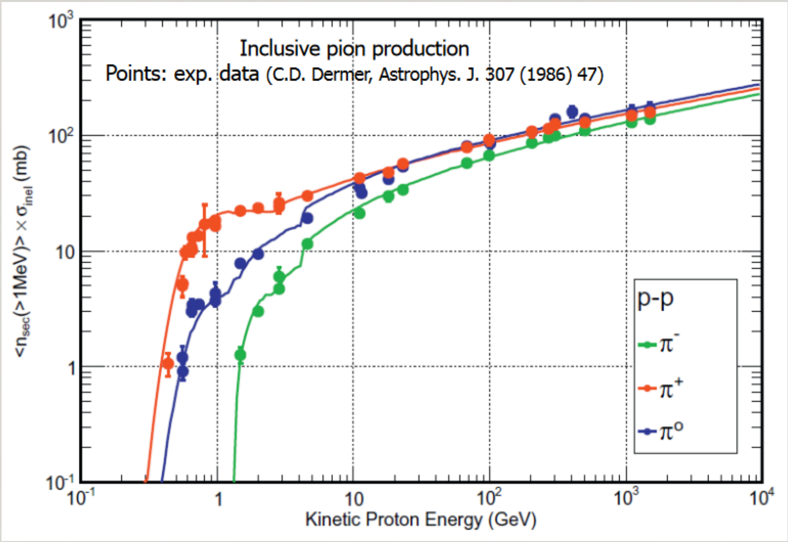


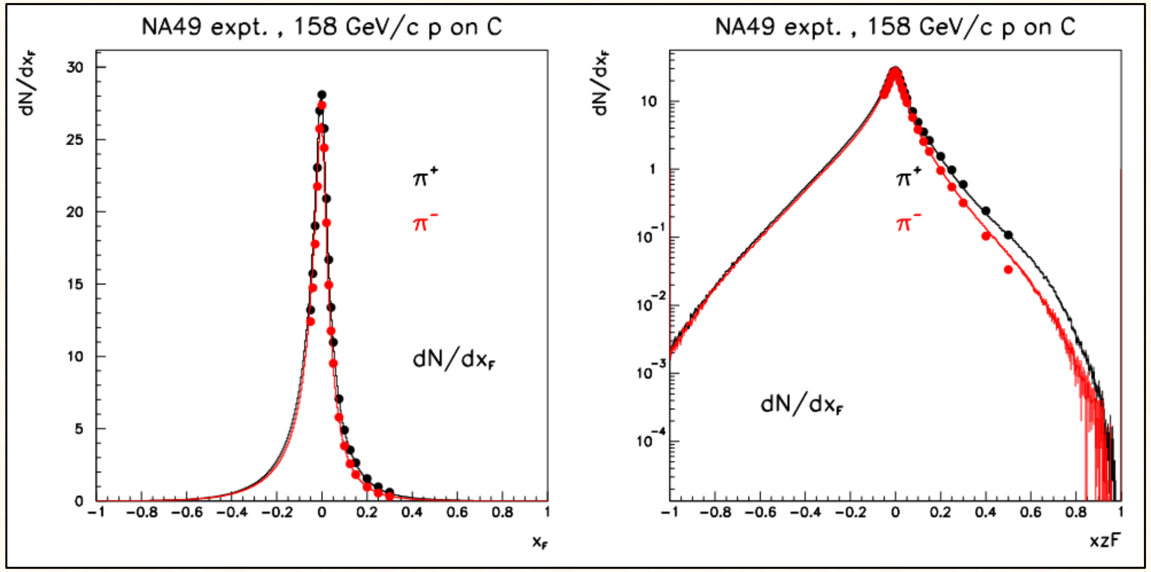
Fluka cross sections

http://www.fluka.org/fluka.php









A few Refs:

G. Battistoni et al, Annals of Nuclear Energy, Vol. 82 (2015)

T. Böhlen Nuclear data sheets, Vol. 120 (2014)

F. Cerutti, "FLUKA: theoretical grounds and wished new data", Talk at XSCR (2017)

Fluka cross sections

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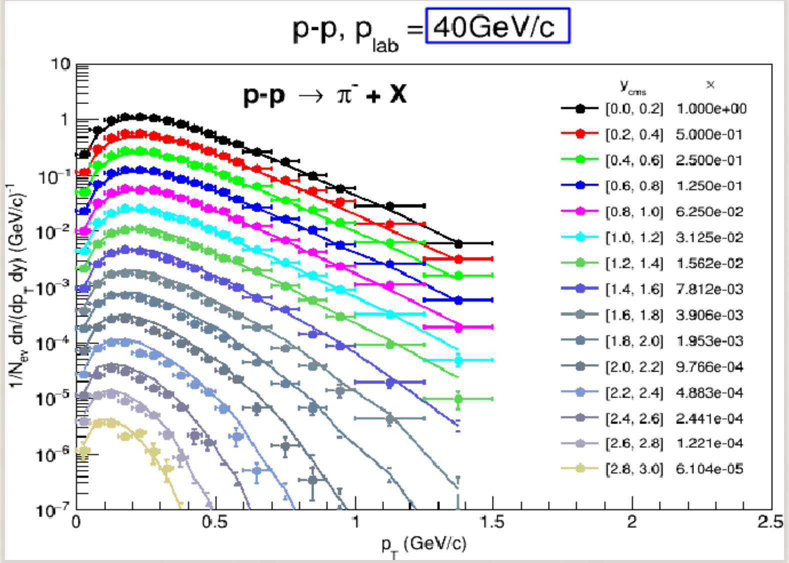
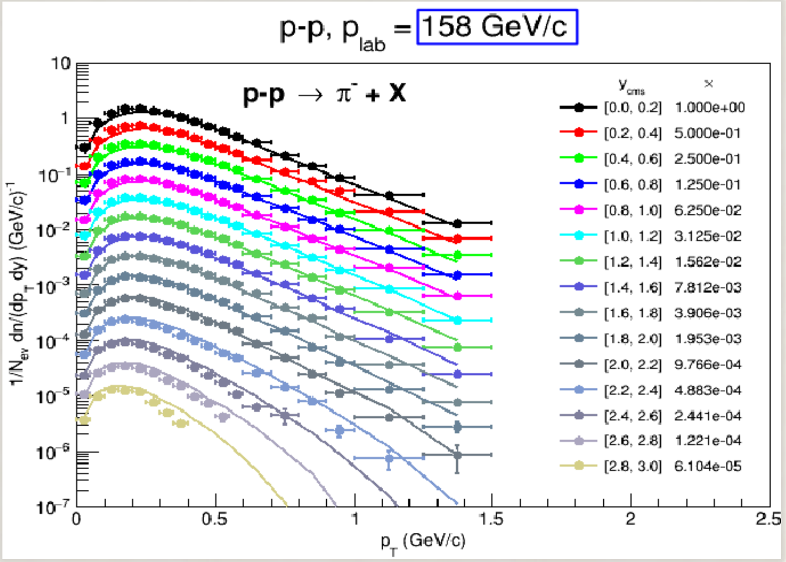
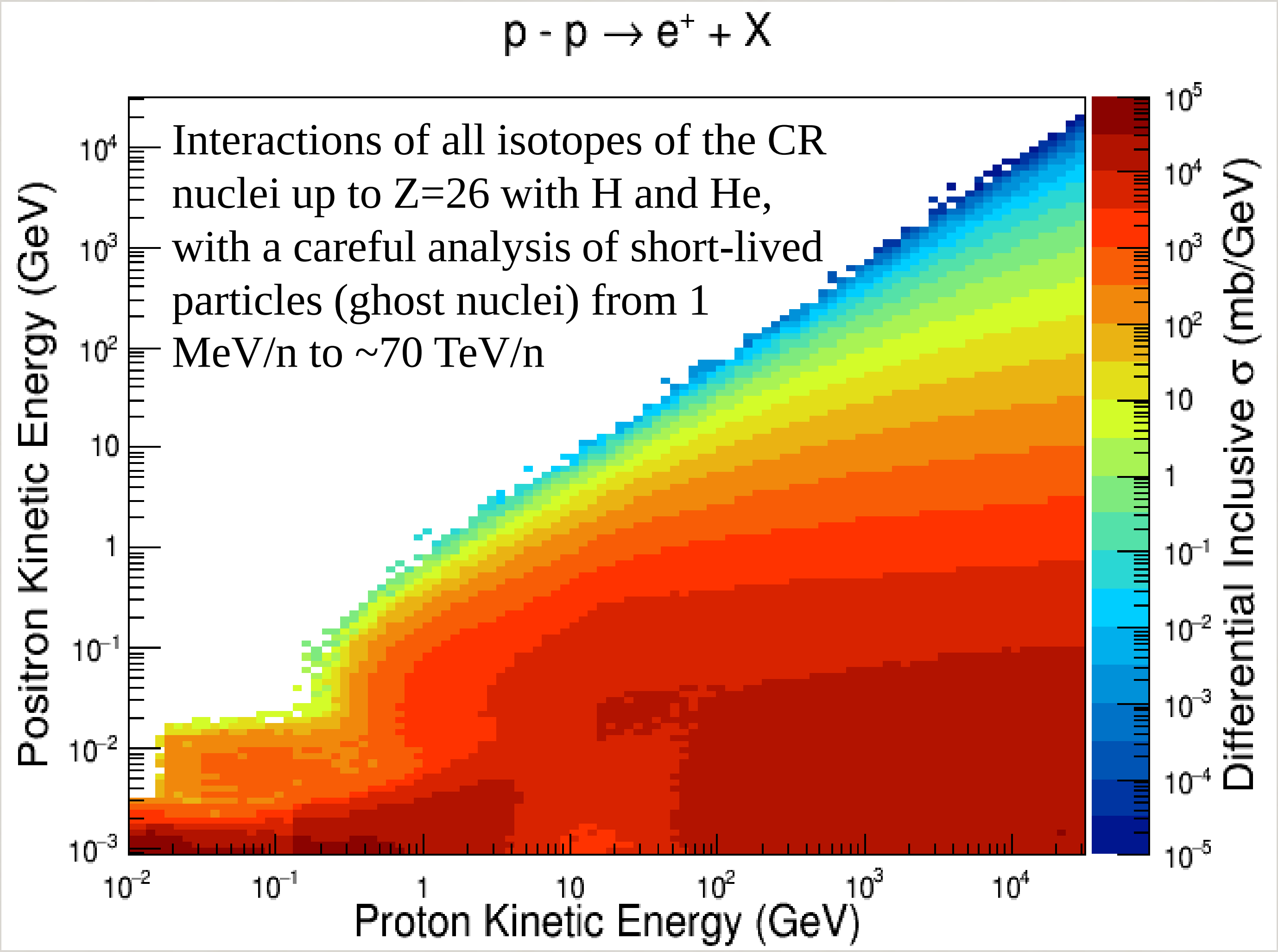




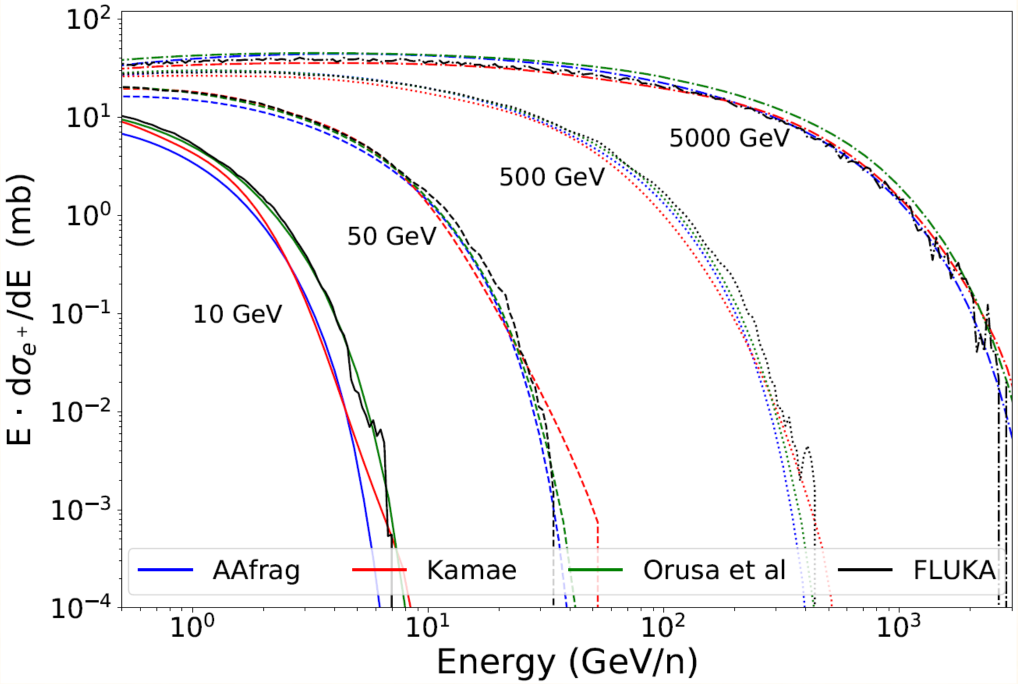


Fluka cross sections: e^+ uncertainties

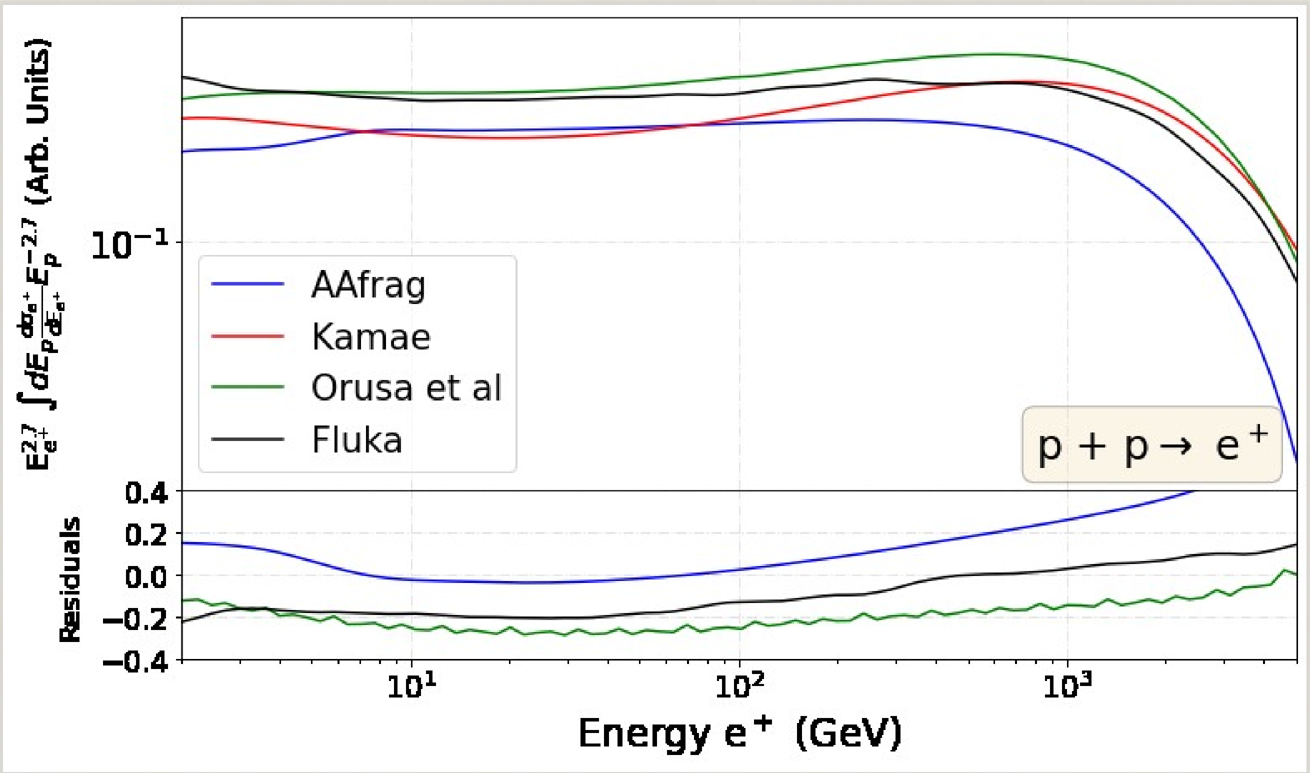
Different cross sections differ by up to 25%-30% below 30 GeV in the p+p channel. The different XS show very similar trends in this energy range.

Other main cross sections data-sets available:

- Kamae 2006 APJ 647:692–708 (2006)
- AAfrag 2021 PRD 104, 123027 (2021)
- Orusa 2022 PRD 105 (2022) 12, 123021



Residuals w.r.t. Kamae (Kamae - σ /Kamae)

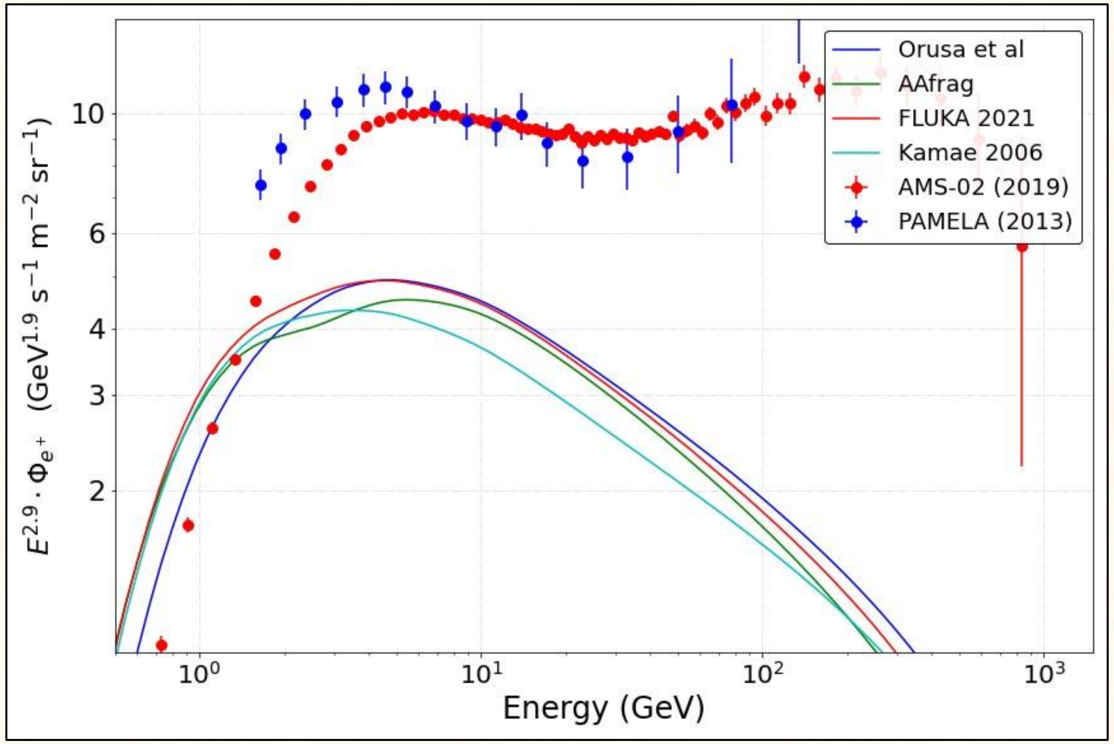


Cross sections e^+ uncertainties

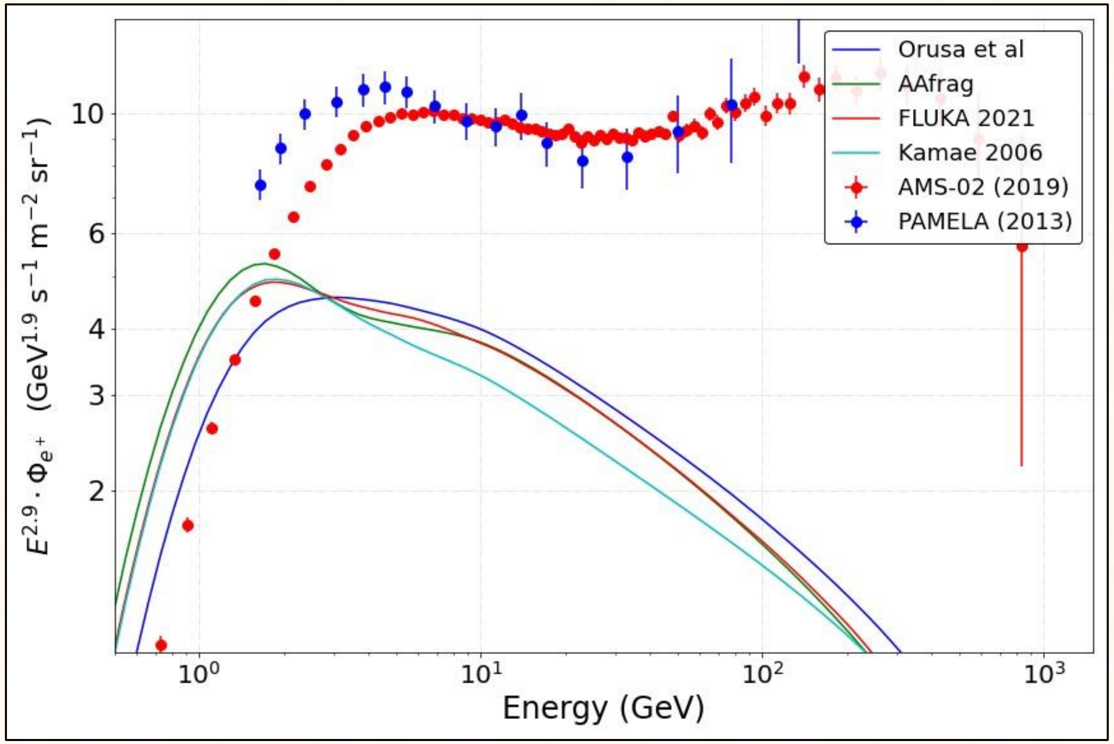
$$D(R) = D_0 \beta^\eta \frac{(R/R_0)^\delta}{\left[1 + (R/R_b)^{\Delta\delta/s}\right]^s}$$

Conventional set-up: Cylindrical symmetry of gas density (dependence on **r** and **z**), source distribution, magnetic field and ISRFs. Prop. adjusted from secondary CRs (ArXiv:2202.03559)

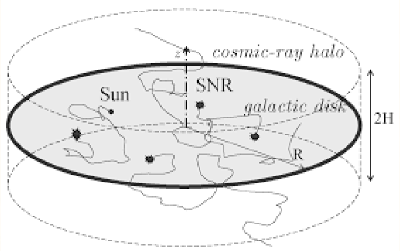
Parameters from fit to B/C ratio



Parameters from fit to combination of B, Be and Li

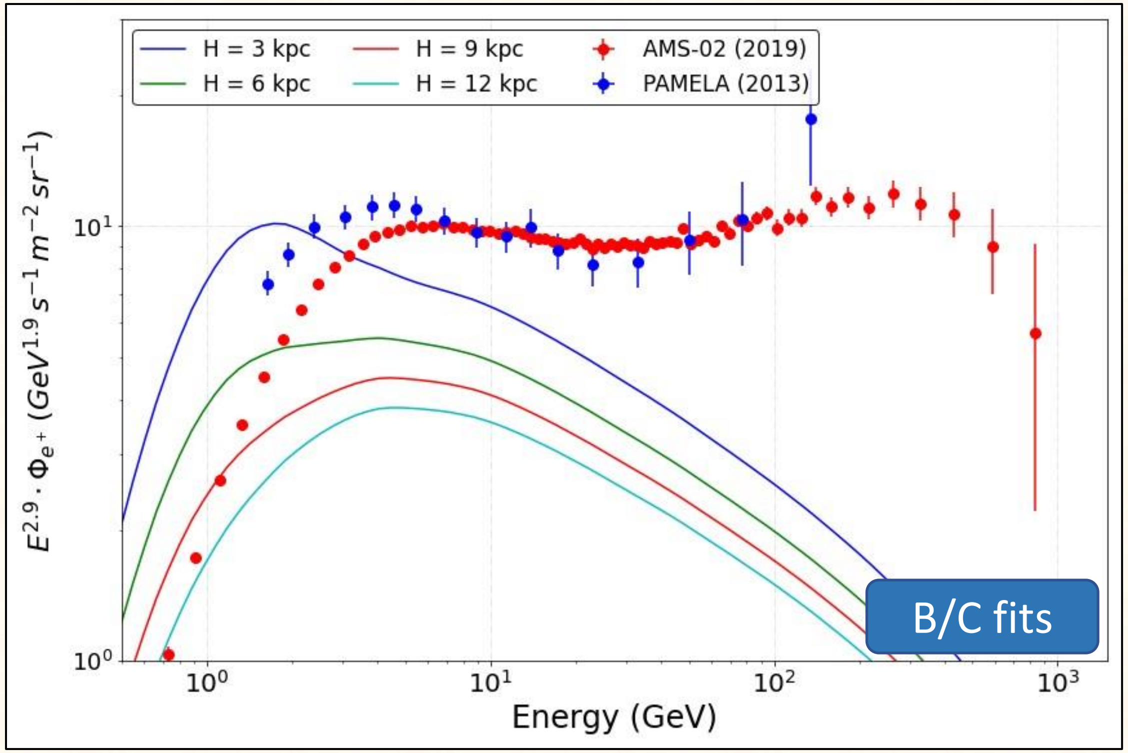


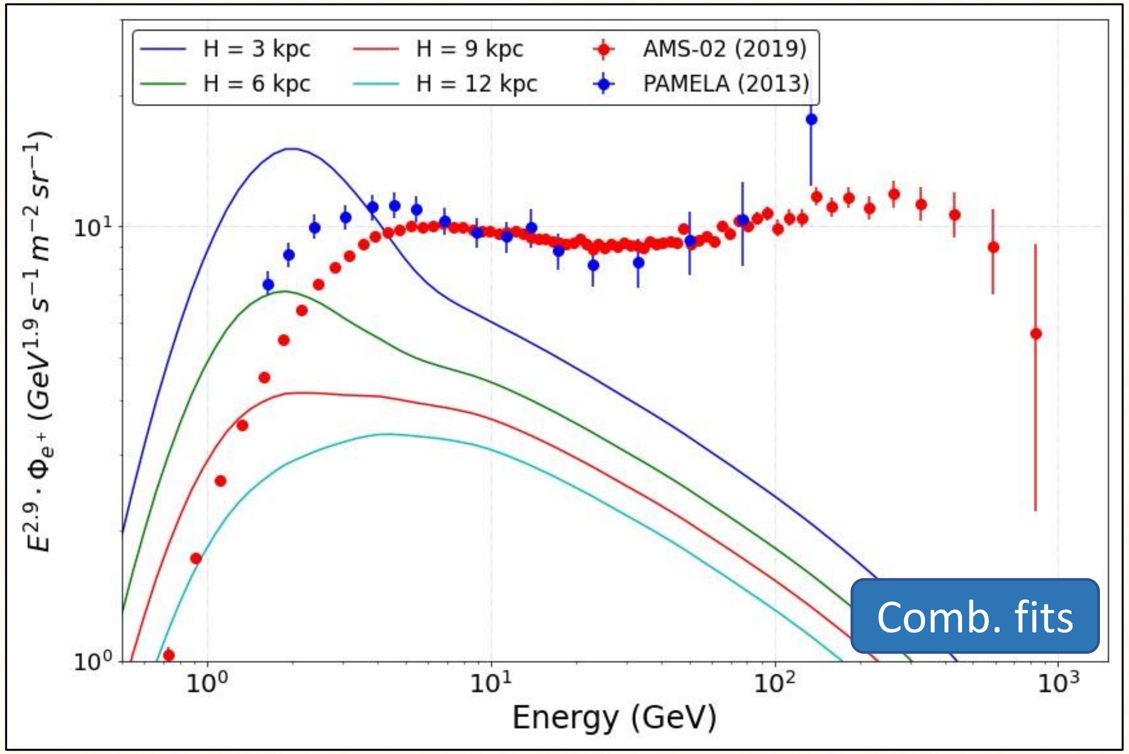
Propagation uncertainties: the halo height



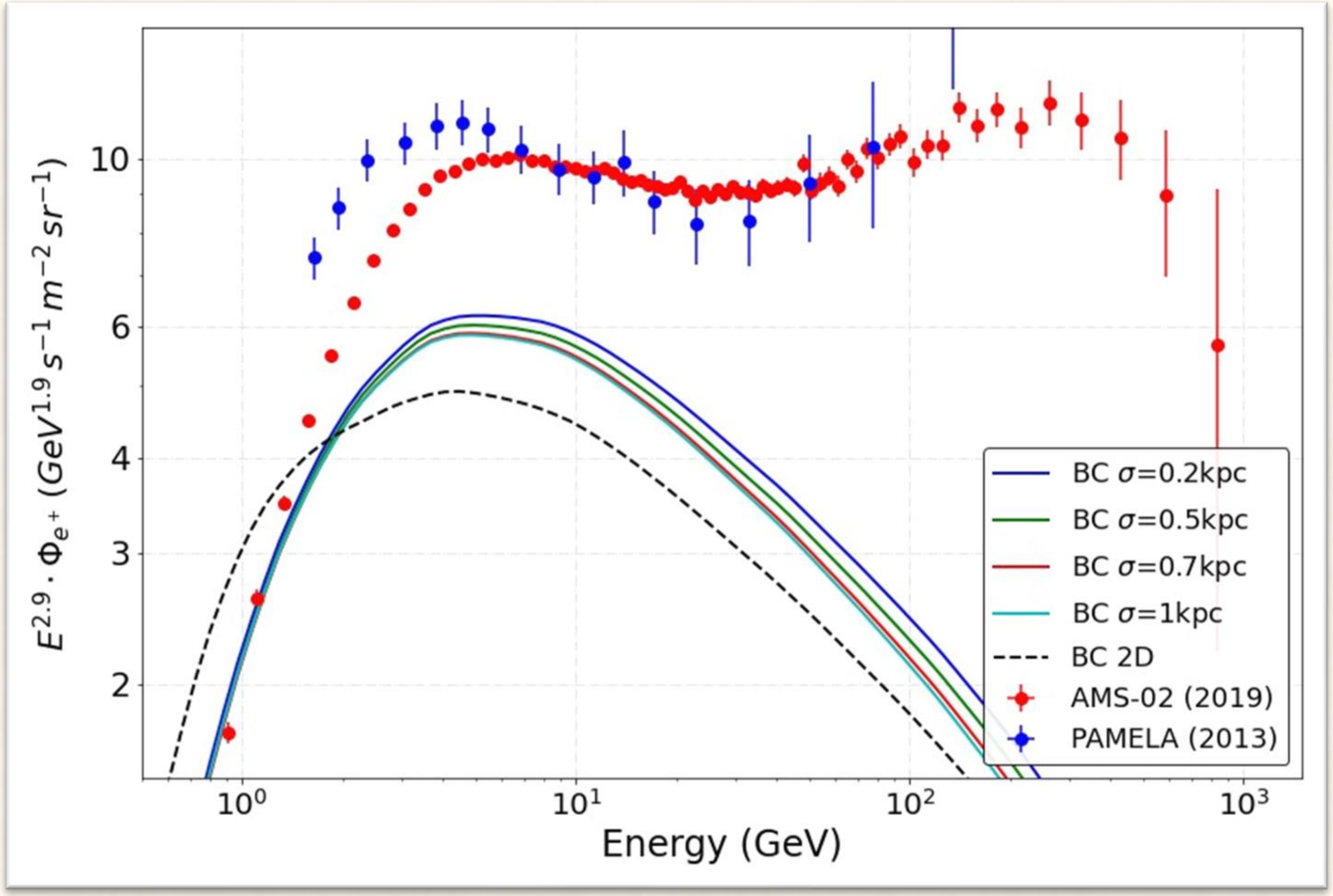
Because of electrons propagation horizon, a smaller halo size implies a larger density of positrons that can be detected at Earth. Halo height is almost totally unconstrained due to XS uncertainties!

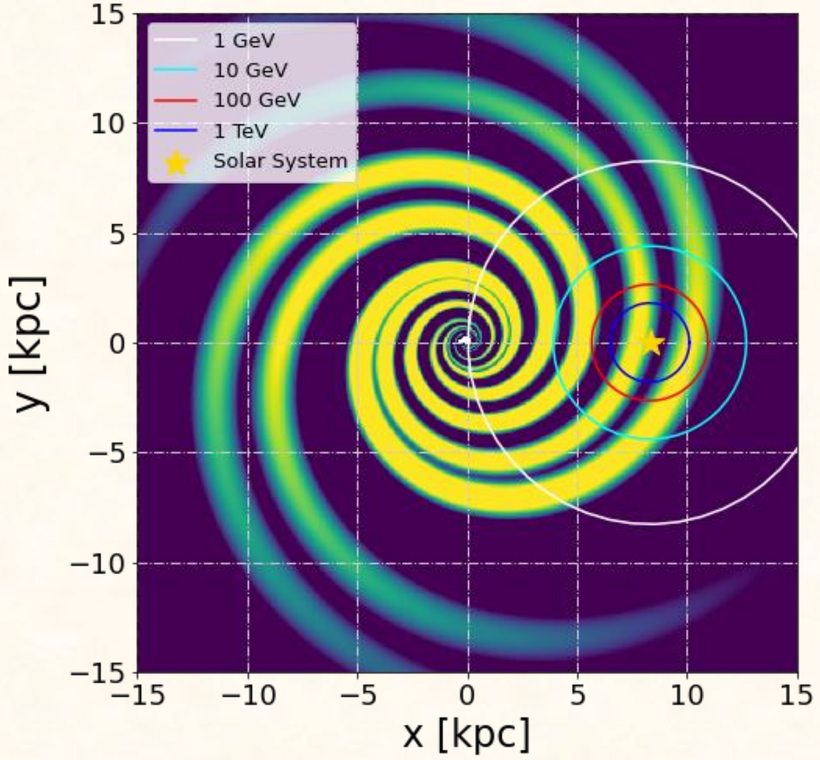
Effect of reacceleration very clear as we decrease the diffusion volume (since Reacc. $\propto V_a{}^2/D$)





Effect of gas density distribution





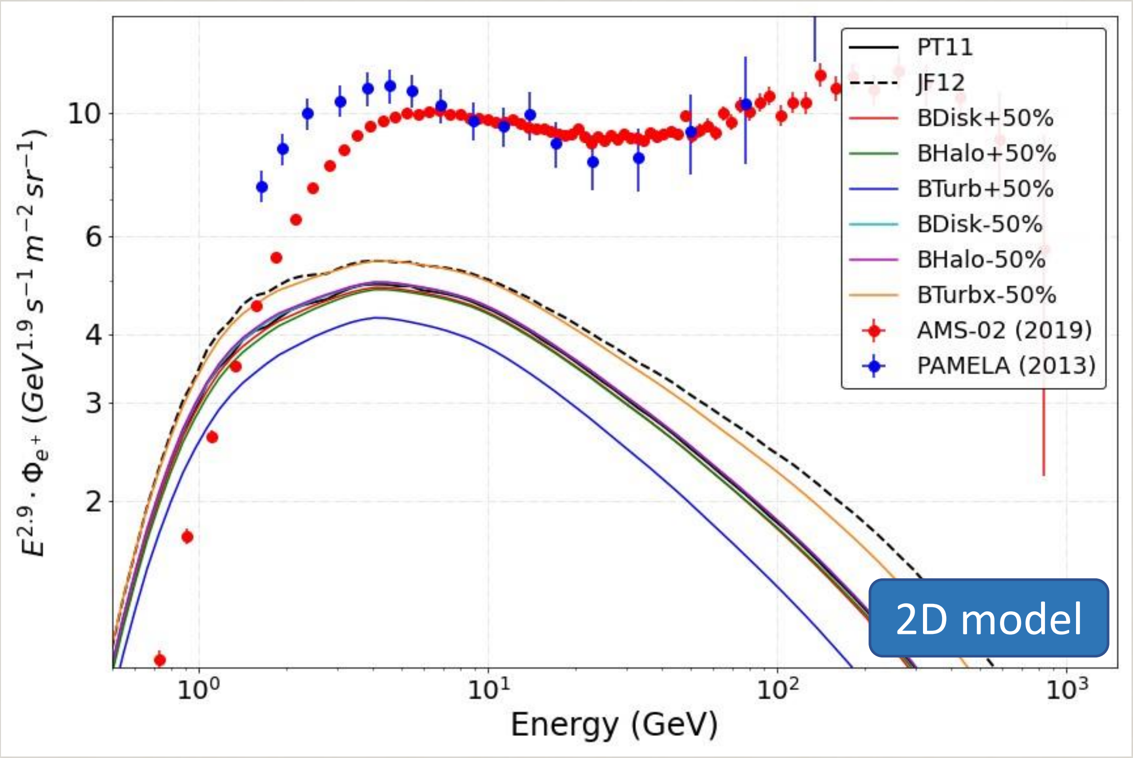
It constitutes up to a 30% increase of the e^+ flux at 10 GeV!

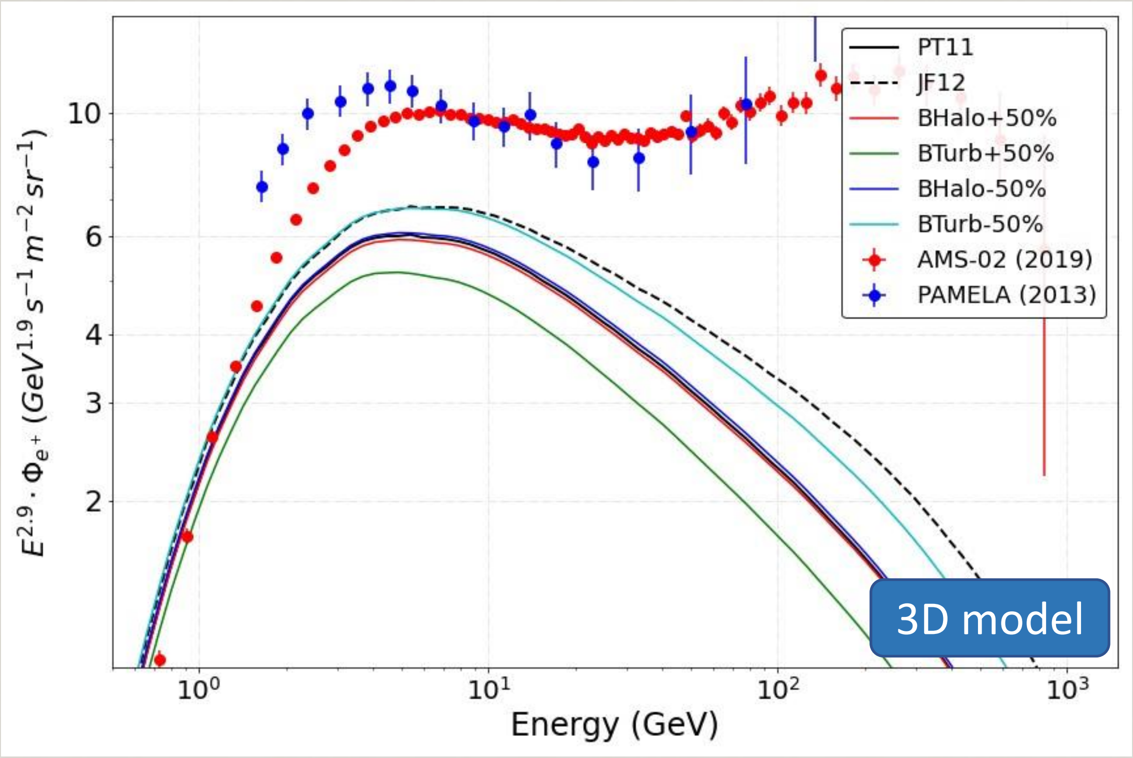
Bremsstrahlung, Coulomb or ionization energy losses also change significantly → Important for sub-GeV positrons!

Effect of magnetic field distribution (synch. losses)

Turbulent magnetic field that CR experience is crucial here: The local one is ~$6 \pm 2\ \mu G$

Uncerts. on IC losses are less important since energy density of ISRFs at Earth is better known





Conclusions

- The ***FLUKA* cross sections for the production of CR positrons** are able to extend the range of energies **from the MeV to hundreds of TeV**, including more than 60 resonances and ghost nuclei. They are compatible with current state-of-the-art datasets and allow us to understand better the associated uncertainties

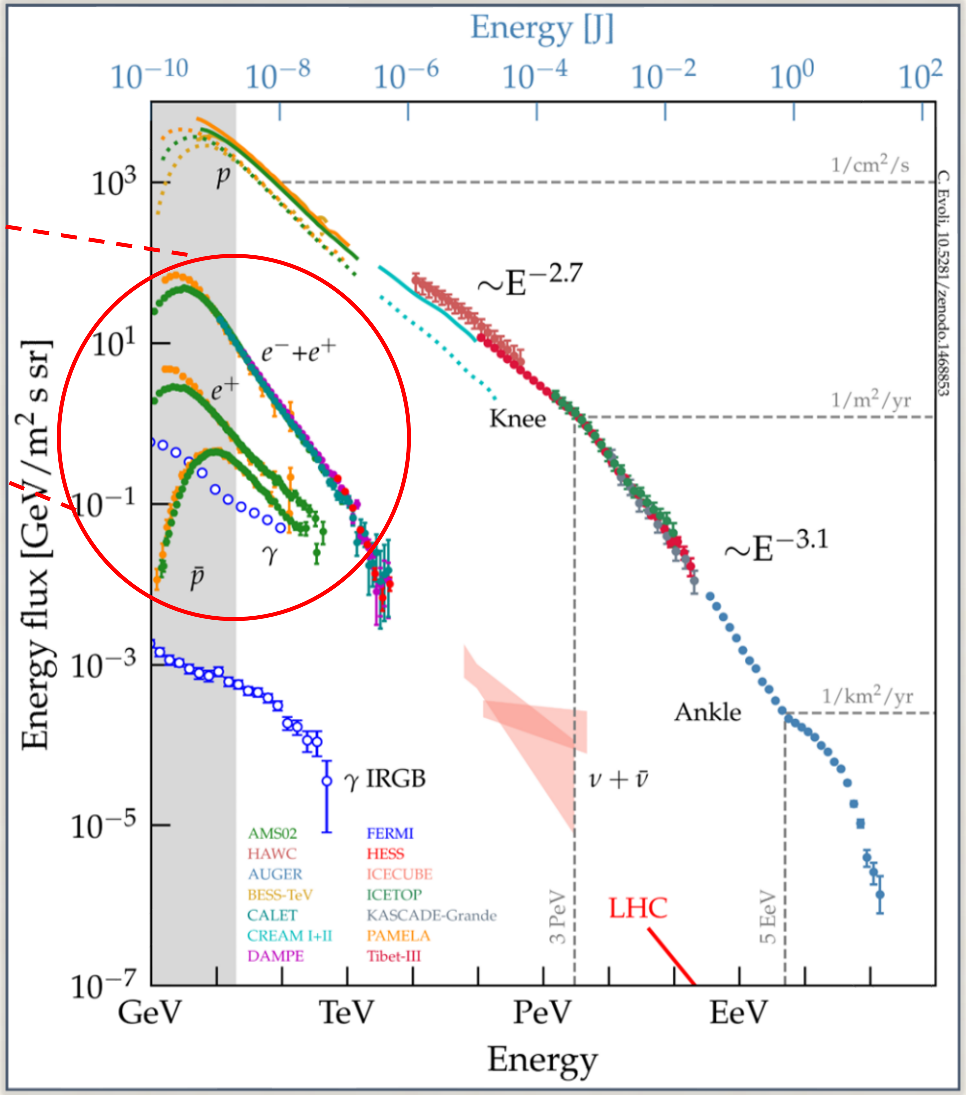
- **Uncertainties** related to propagation parameters, halo height, gas density distribution, solar modulation and energy losses can sum to **more than a factor 3**, while uncertainties in PWN injection can be more than one order of magnitude

- That uncertainty allows us to reproduce the positron spectrum below a few GeV without any extra source, but implies a real problem to identify any signal from dark matter or other exotic production mechanisms

BACK UP

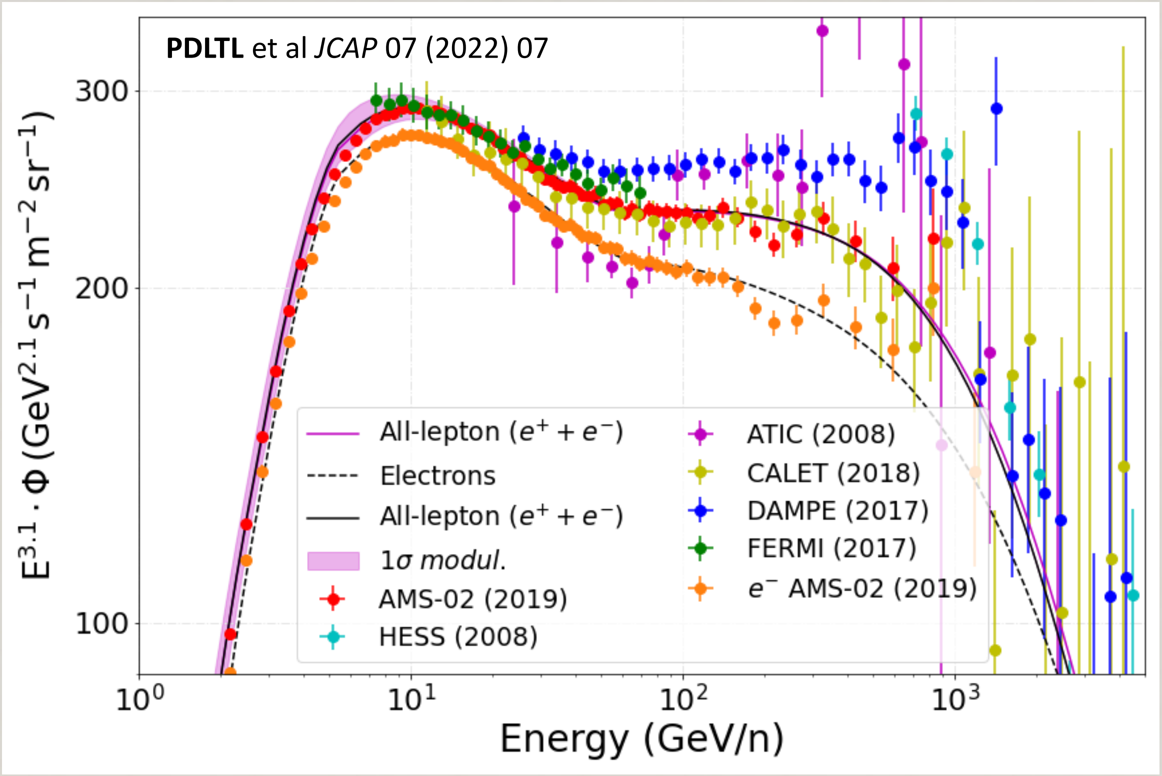
The current generation of detectors provides accurate measurements on the spectra of Galactic cosmic rays l**eaving many open questions**

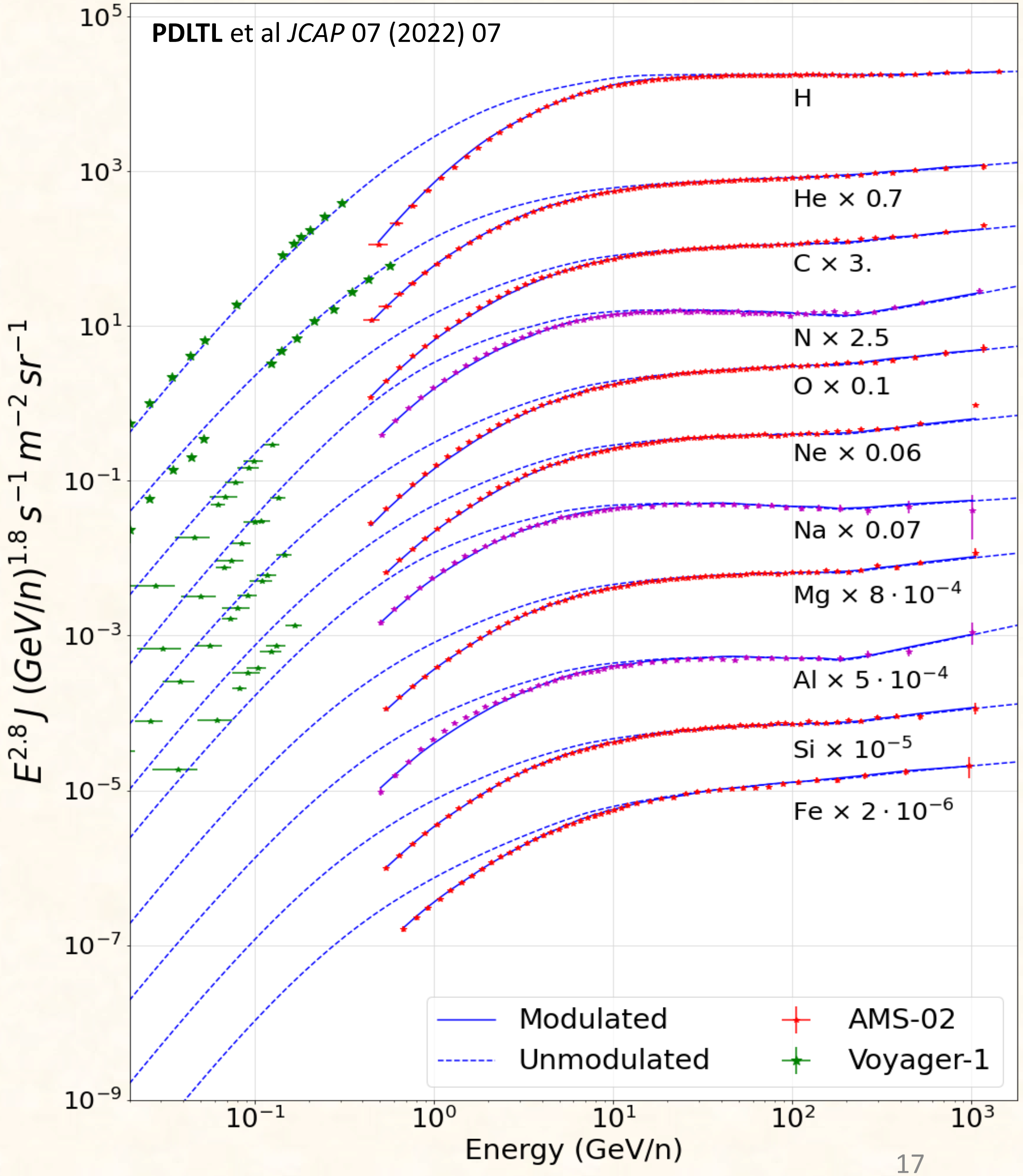
We focus in the GeV-TeV part, where diffusion dominates and WIMPs can leave imprints in CR antiparticles



Injection of CRs by sources

In Galactic CR studies, the injection spectrum is parametrized as a (broken) power-law and the distribution of sources follow SNR distrib.





Potential of antiparticles to reveal the existence of BSM physics

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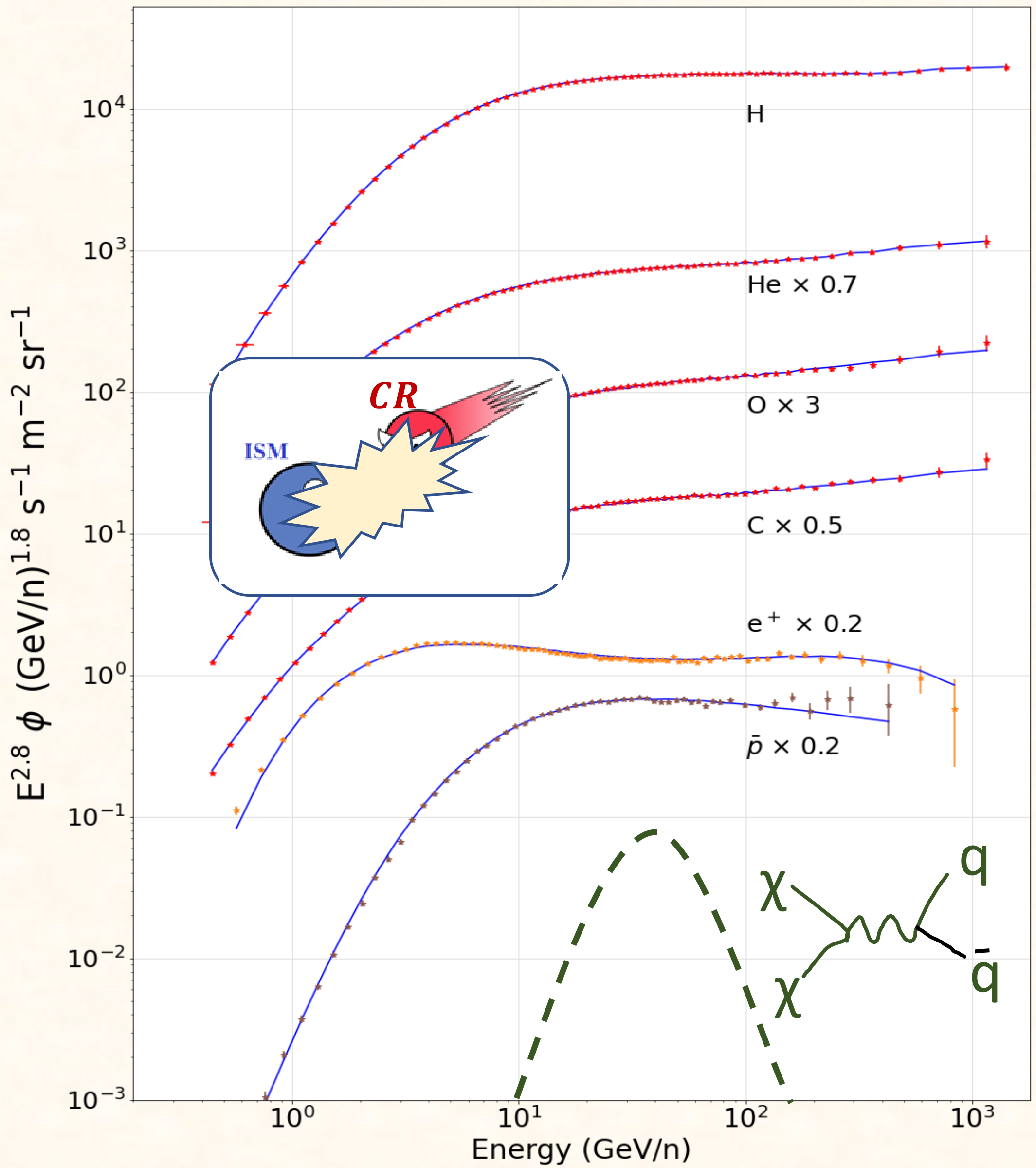


Production of positrons and DM identification

The stochastic nature of the PWN emission makes it difficult to find signatures of DM at high energies:

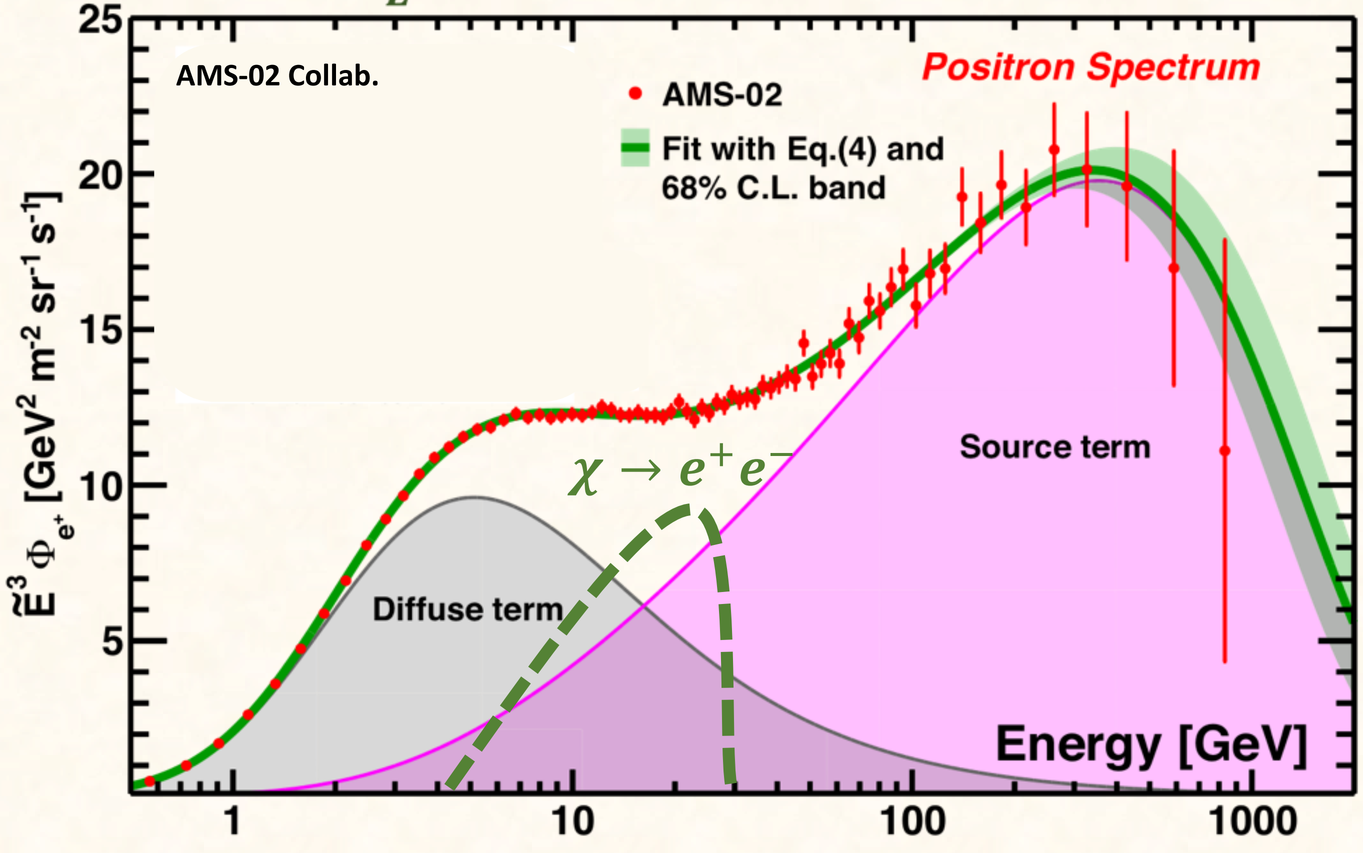
1. Sharp features can be easily masked by PWN contribution
2. High masses contributing to the e+ spectrum at those energies

Easier to spot DM signals at low E

- Diffusion process
- Magnetised halo
- Nearby Galactic environment
- Solar modulation
- Cross sections

Diffuse term Source term

$$\Phi_{e^+}(E) = \frac{E^2}{\hat{E}^2}\left[C_d(\hat{E}/E_1)^{\gamma_d} + C_s\,(\hat{E}/E_2)^{\gamma_s}\exp(-\hat{E}/E_s)\right]$$



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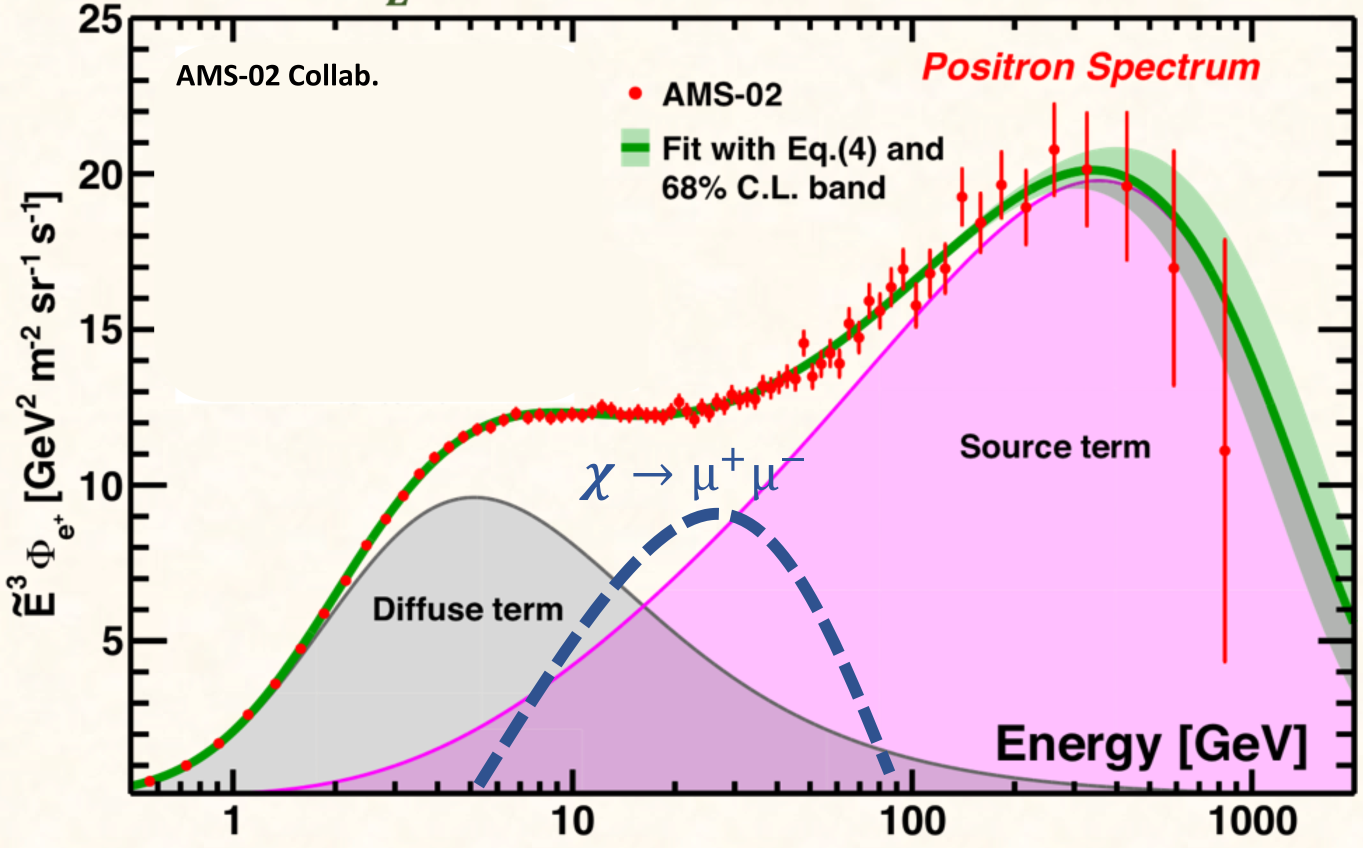

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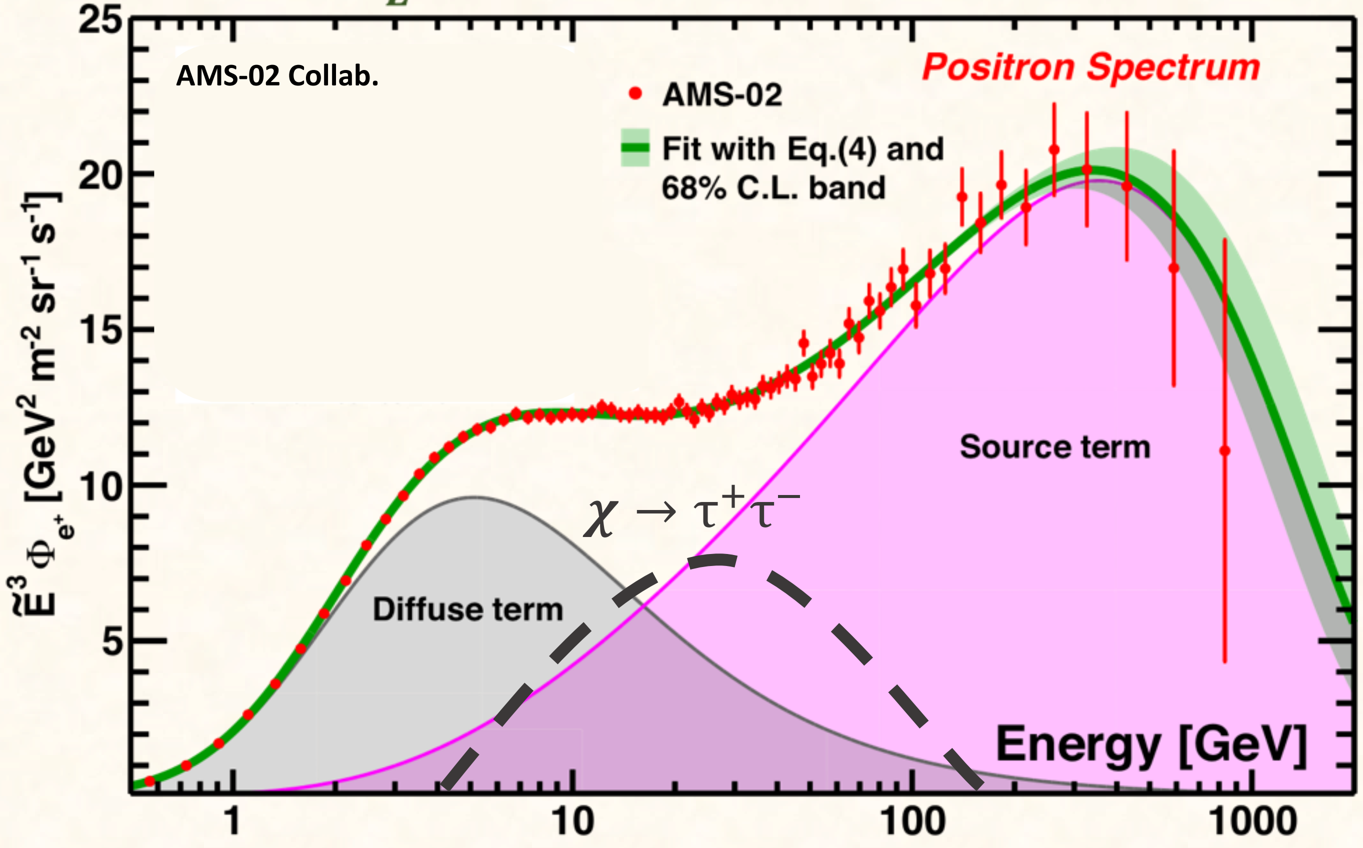
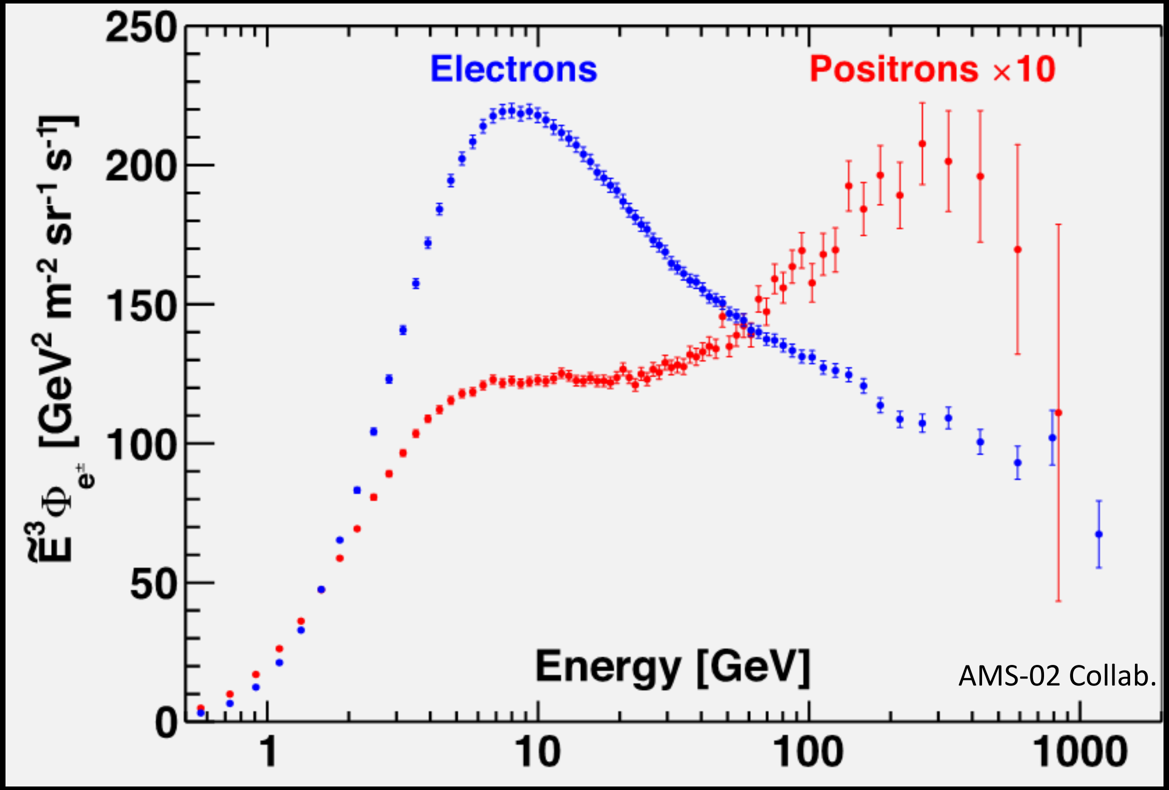
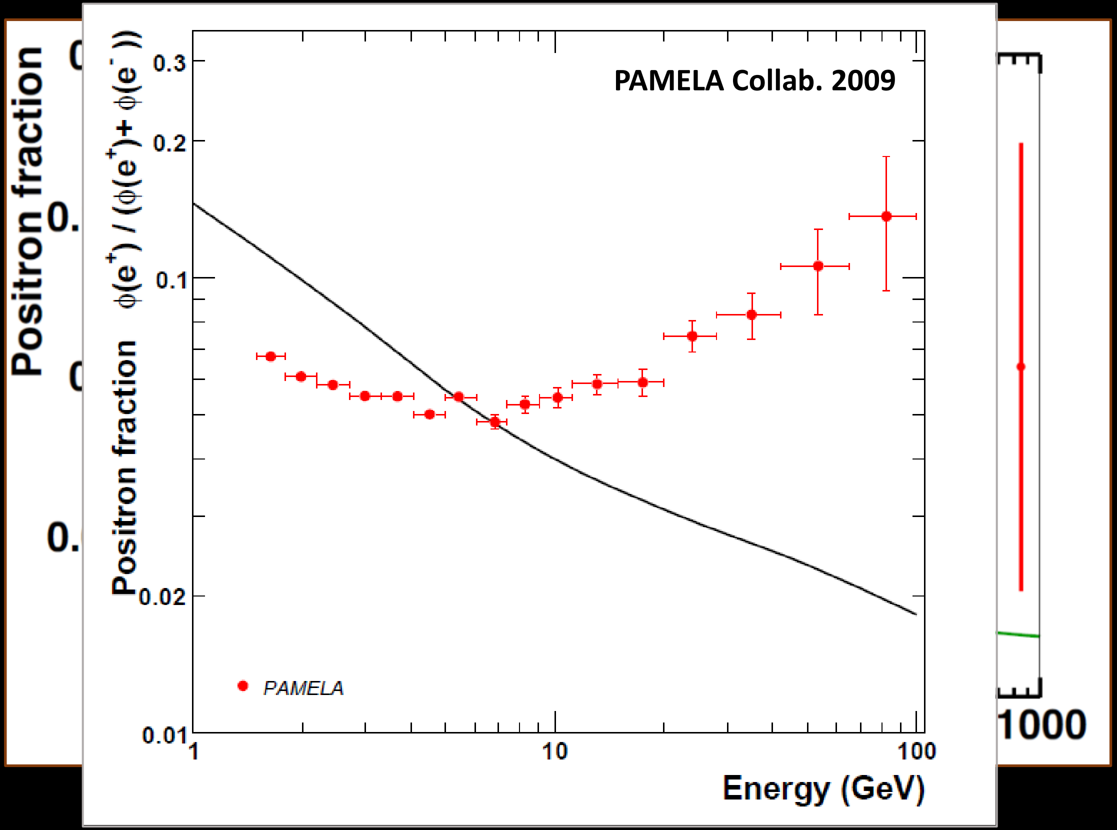


The positron spectrum





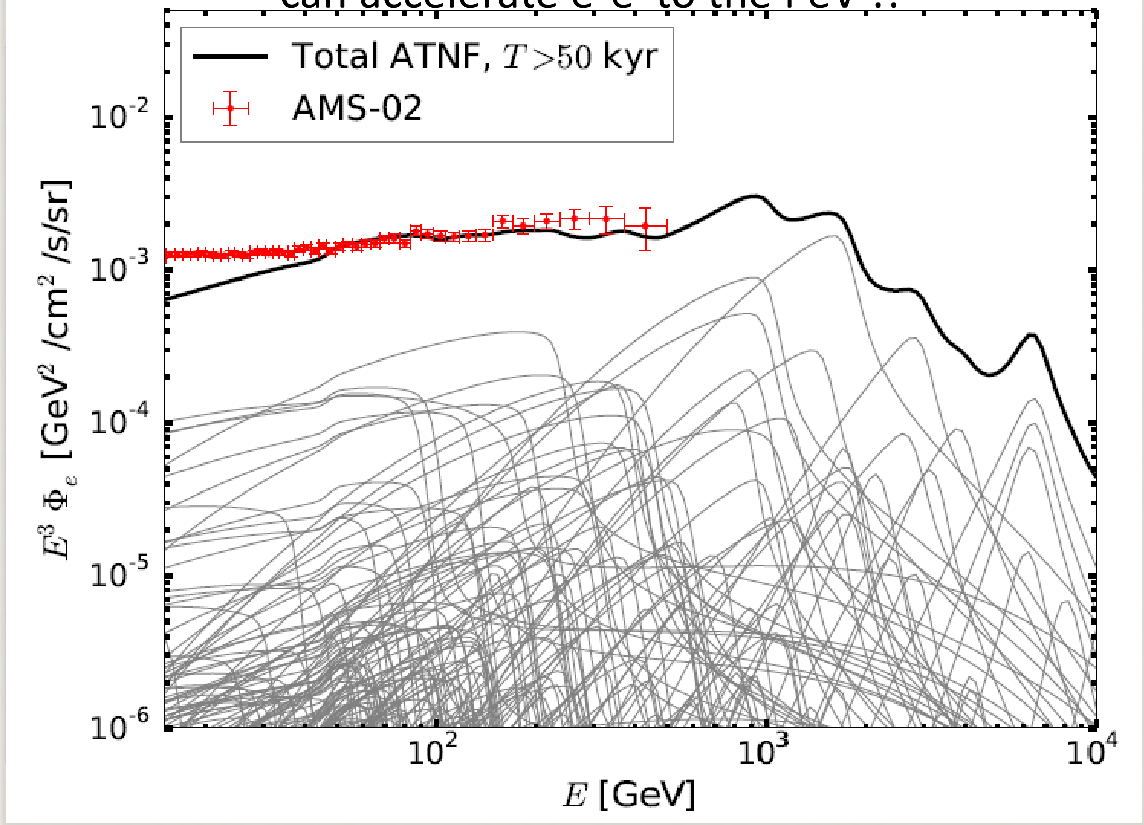
Unexpected and clear rise in the detected flux of positrons requires a new source of positrons. What is this source of e^+?

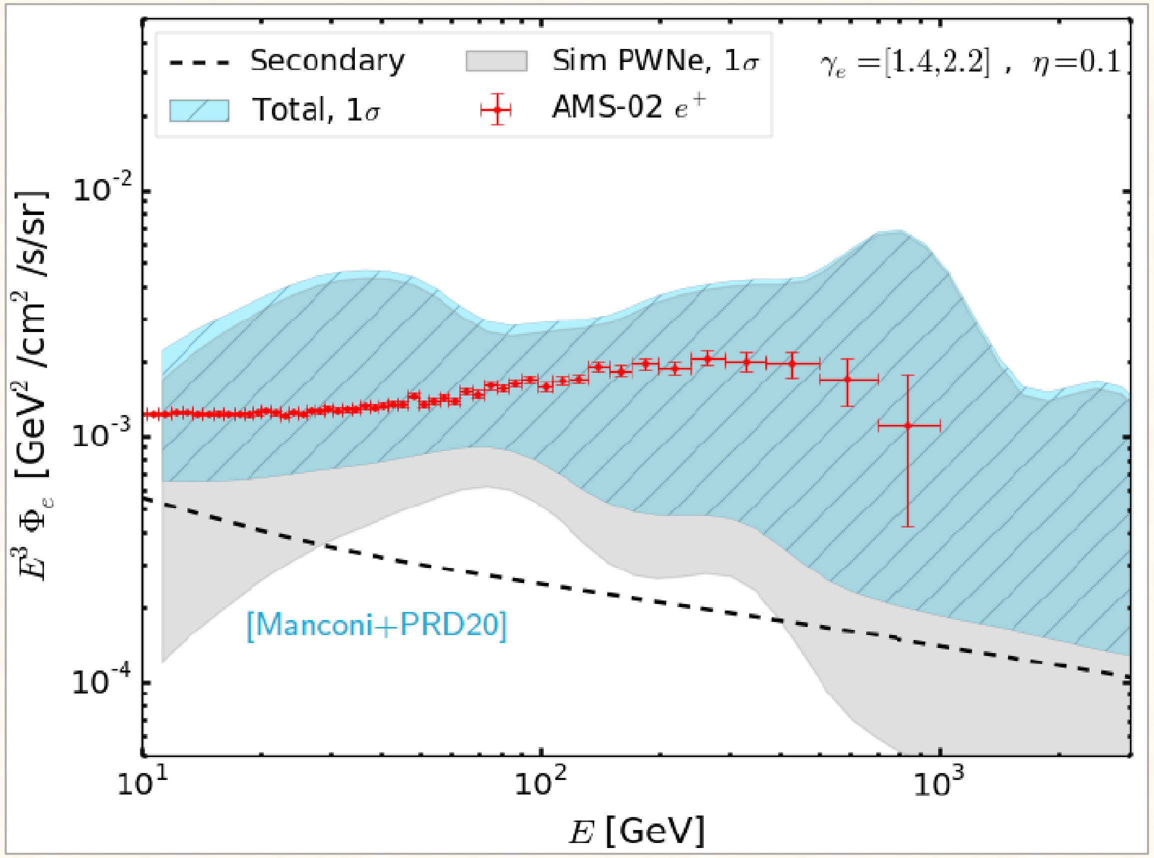
The positron excess

An astrophysical source of cosmic-ray positrons (and electrons) was not considered: **Pulsar Wind Nebulae (PWN)**

Manconi et al PRD 102, 023015 (2020)

Gamma-ray observations reveal that pulsars can accelerate e^+e^- to the PeV !!

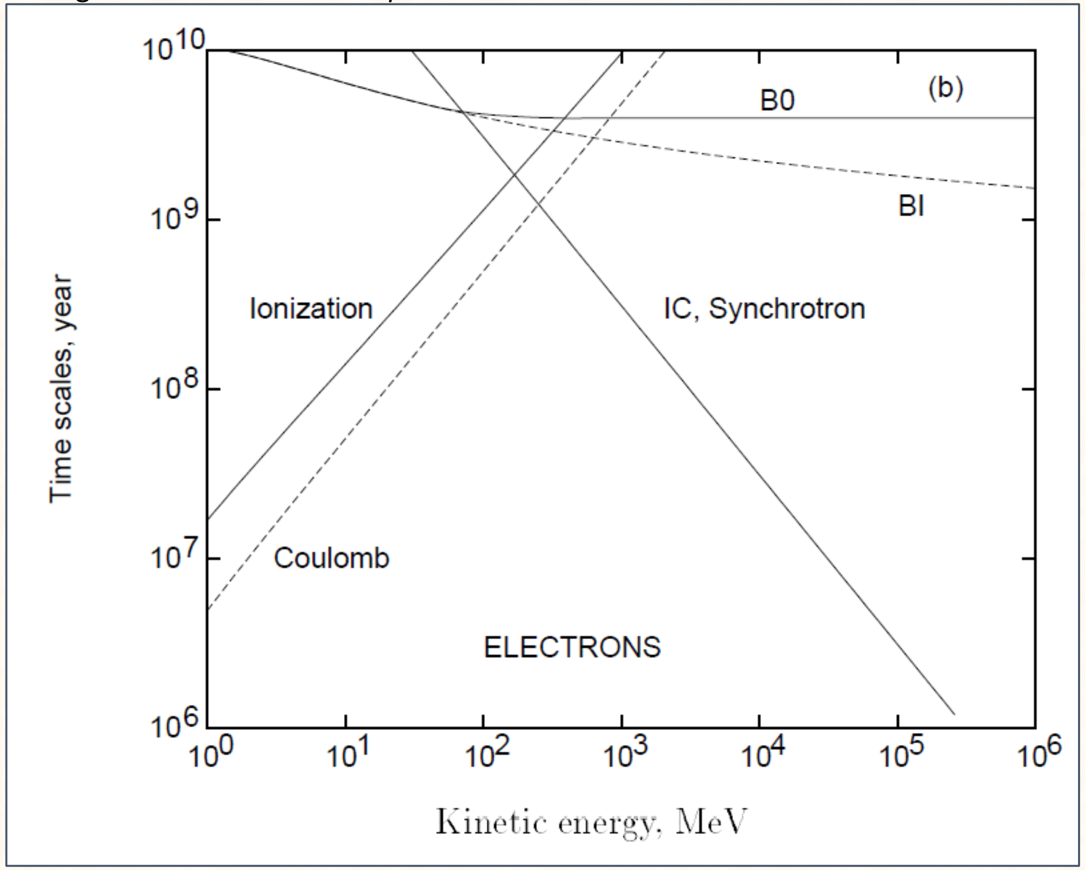




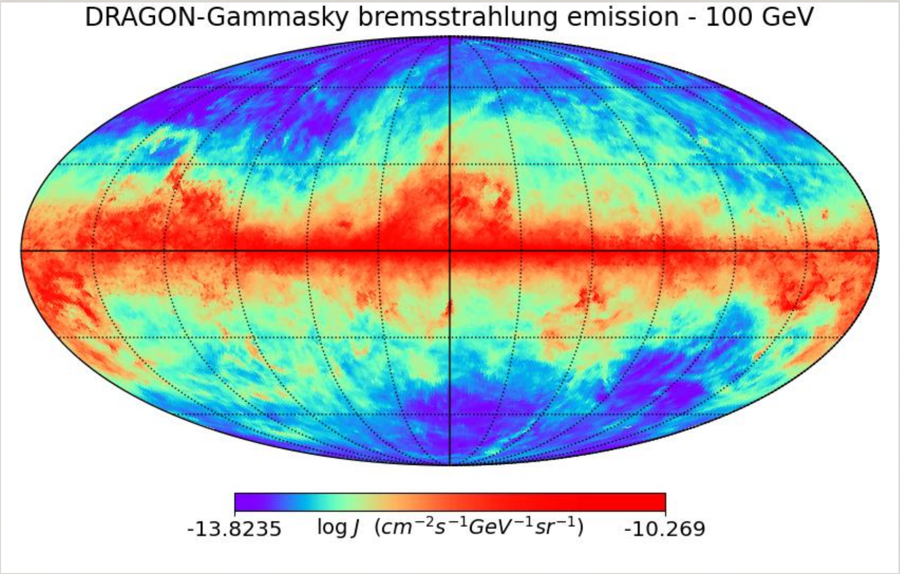
Lepton energy losses

$$\frac{\partial p}{\partial t} = \left(\frac{\partial p}{\partial t}\right)_{Coul,\ Ioniz} + \left(\frac{\partial p}{\partial t}\right)_{\mathrm{IC,\ Bremss,\ Sync}}$$

Strong & Moiskalenko 1998 *ApJ* **509** 212



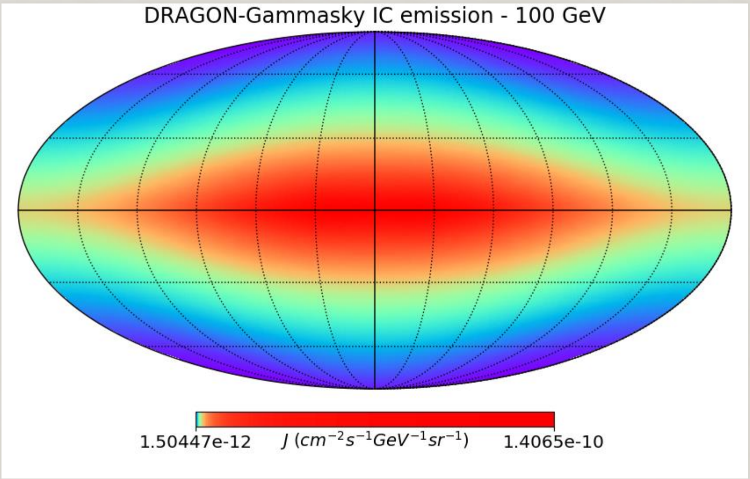
$$e + N \rightarrow e' + \gamma' + \mathrm{N}$$



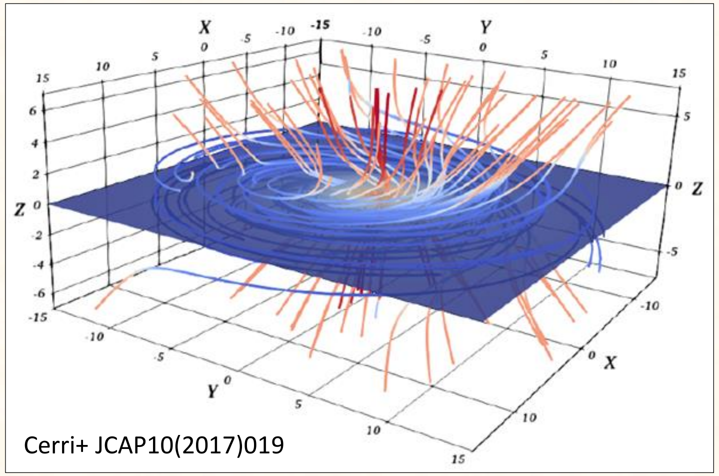
Ionization, Coulomb and bremsstrahlung energy losses depend on the gas distribution and are subdominant above the GeV

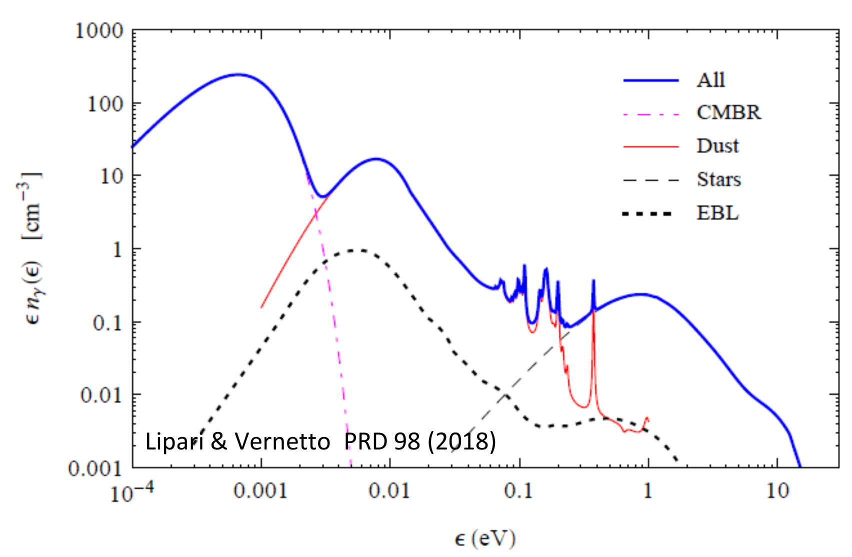
e^+e^- energy losses

IC and Synchrotron losses impede high energy electrons and positrons travel long distances!



$e + \gamma \rightarrow e' + \gamma'$





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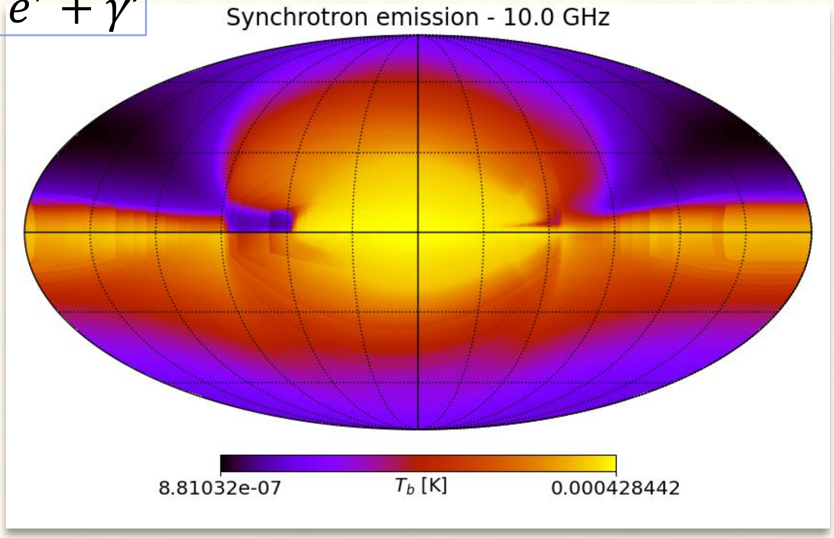
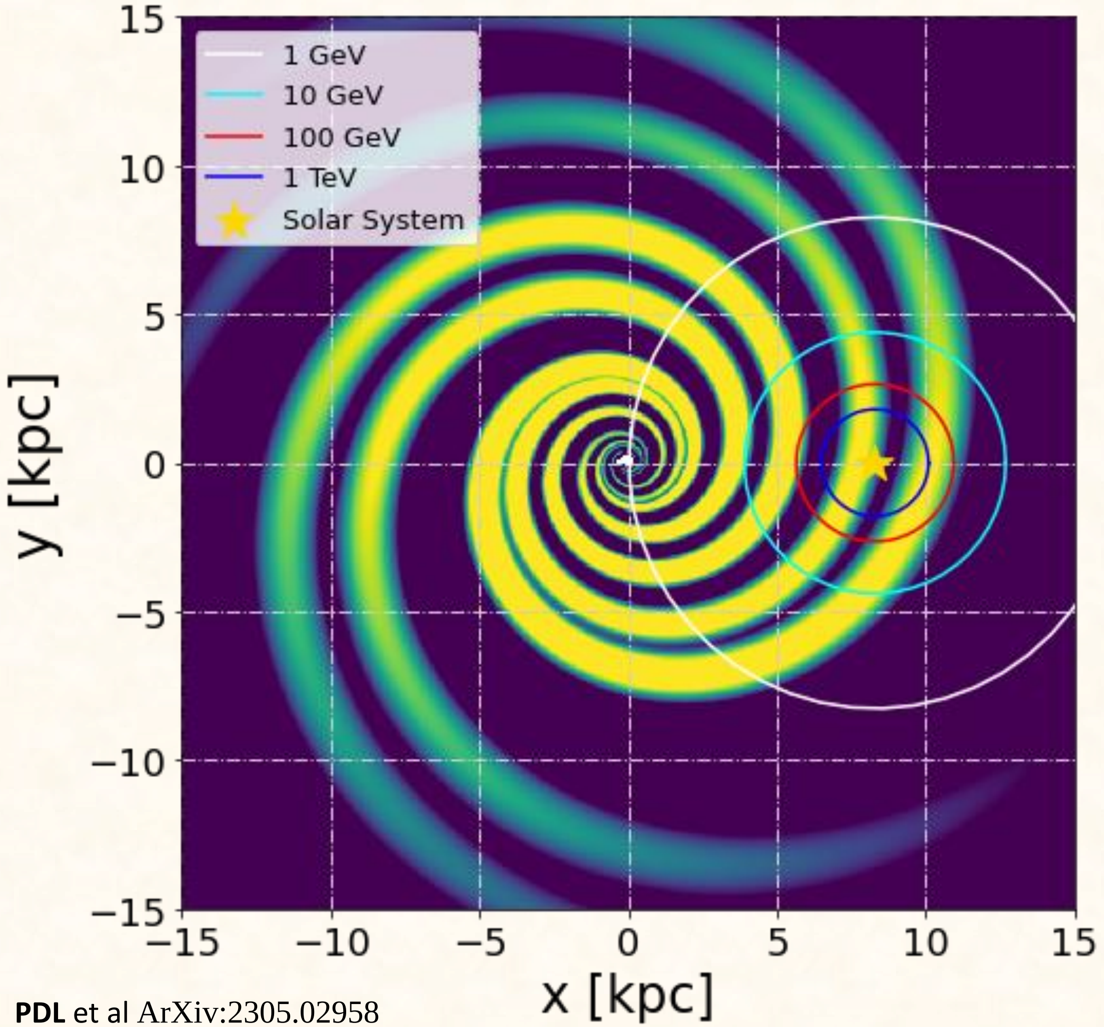
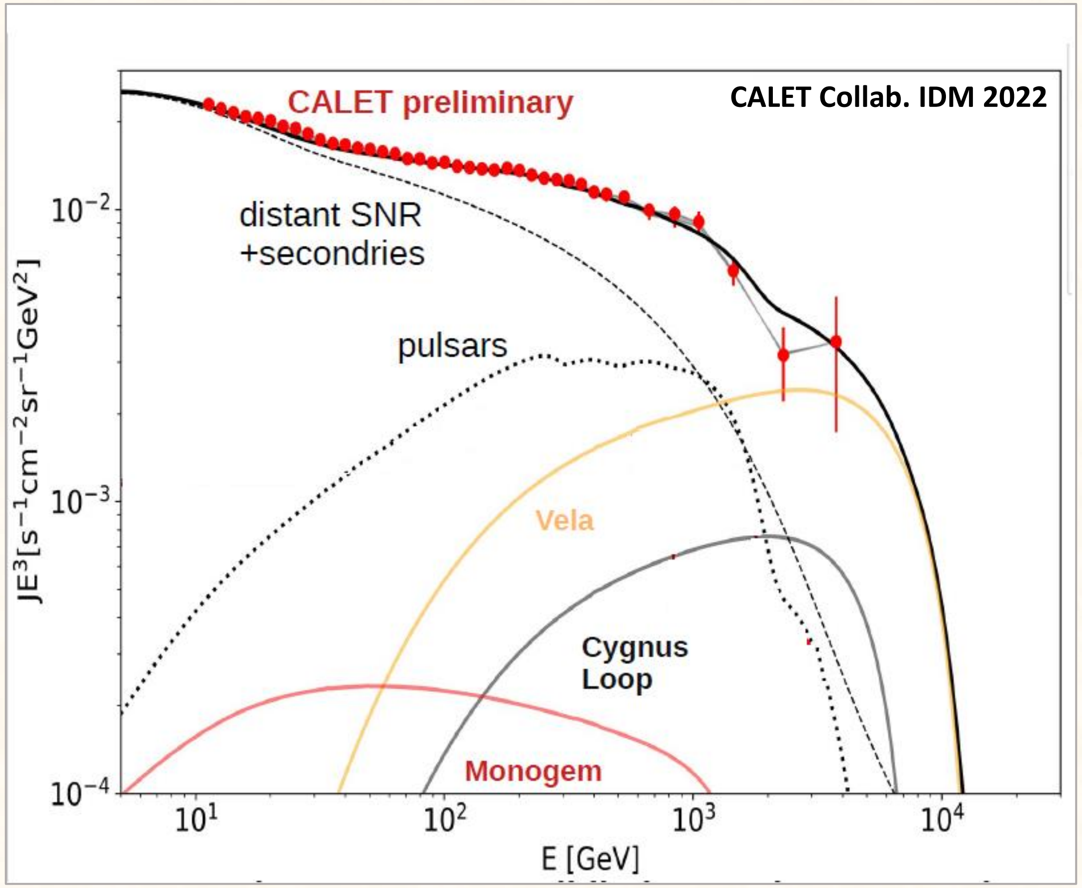


e^+e^- propagation horizon

GeV-TeV e^- are dominated by the emission from local sources!



PDL et al ArXiv:2305.02958



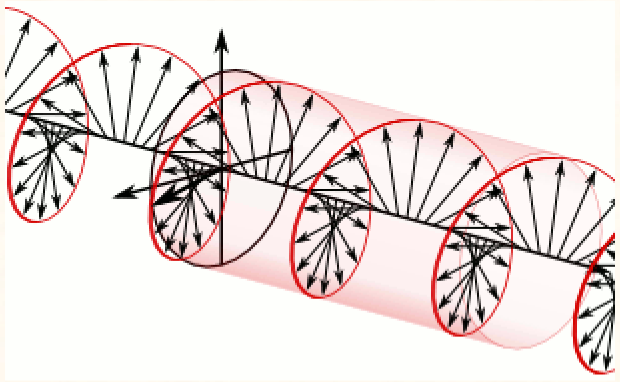
The **Milky Way** *is a magnetised plasma medium following the Magnetohydrodynamic equations*

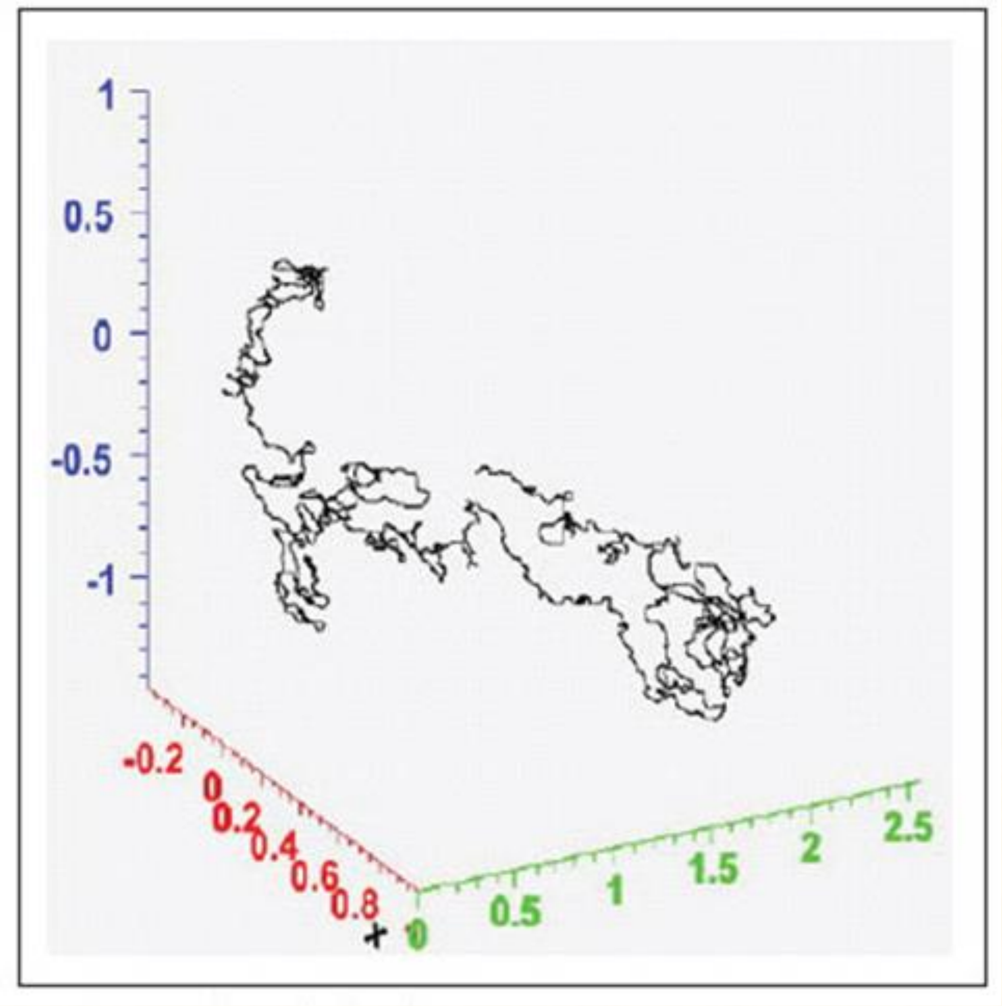
$$\mathbf{B} = \mathbf{B}_0 + \delta\mathbf{B} \rightarrow \langle\mathbf{B}\rangle = \mathbf{B}_0$$

$$\mathbf{E} = 0 + \delta\mathbf{E} \rightarrow \langle\mathbf{E}\rangle = 0$$

Longitudinal modes are compressional waves which are severely damped by the gas

Shear Alfven waves are circularly polarized whose resonant interaction governs the CR scattering





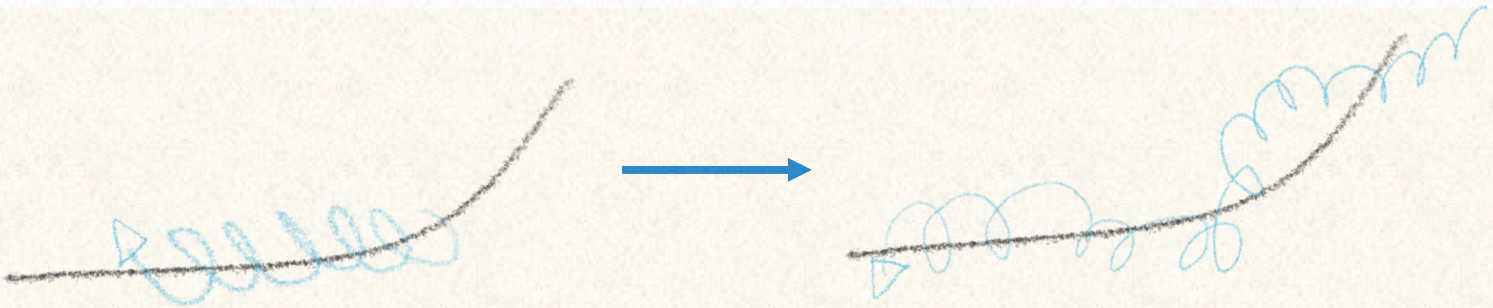
The propagation of CRs – Diffusion equation

❖ The basic idea is that primary particles are accelerated in astrophysical sources (namely SNRs) and propagate throughout the Galaxy during millions of years, due to scattering with plasma waves. Occasionally, they interact with gas and produce secondary nuclei through spallation.

$$\vec{\nabla}\cdot\left(-D\,\nabla N_i - \vec{v}_\omega N_i\right) + \frac{\partial}{\partial p}\left[p^2 D_{pp}\frac{\partial}{\partial p}\left(\frac{N_i}{p^2}\right)\right] = Q_i + \frac{\partial}{\partial p}\left[\dot{p}N_i - \frac{p}{3}\left(\vec{\nabla}\cdot\vec{v}_\omega N_i\right)\right] - \frac{N_i}{\tau_i^f} + \sum \Gamma^s_{j\to i}(N_j) - \frac{N_i}{\tau_i^r} + \sum \frac{N_j}{\tau^r_{j\to i}}$$

$$D_{pp} \propto \frac{p^2\, V A^2}{D}$$

$$D = D_0 \beta^\eta \left(\frac{R}{R_0}\right)^\delta F(\vec{r}, z)$$



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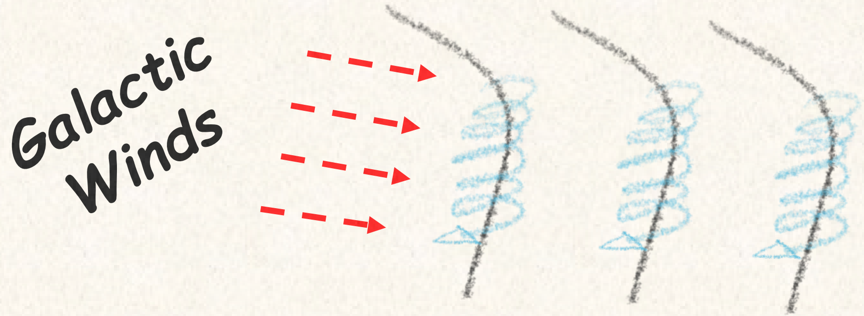
$$-\frac{N_i}{\tau_i^f} + \sum \Gamma^s_{j\to i}(N_j) - \frac{N_i}{\tau_i^r} + \sum \frac{N_j}{\tau^r_{j\to i}}$$

$$D_{pp} \propto \frac{p^2\, VA^2}{D}$$

$$D = D_0\beta^\eta\left(\frac{R}{R_0}\right)^\delta F(\vec{r},z)$$



The propagation of CRs – Diffusion equation

- The basic idea is that primary particles are accelerated in astrophysical sources (namely SNRs) and propagate throughout the Galaxy during millions of years, due to scattering with plasma waves. Occasionally, they interact with gas and produce secondary nuclei through spallation.

$$\frac{\partial N}{\partial R} q(x,y,z)$$

$$\vec{\nabla}\cdot\left(-D\,\nabla N_i + \vec{v}_\omega N_i\right) + \frac{\partial}{\partial p}\left[p^2 D_{pp}\frac{\partial}{\partial p}\left(\frac{N_i}{p^2}\right)\right] = Q_i + \frac{\partial}{\partial p}\left[\dot{p}N_i - \frac{p}{3}\left(\vec{\nabla}\cdot\vec{v}_\omega N_i\right)\right]$$

$$-\frac{N_i}{\tau_i^f} + \sum \Gamma^s_{j\to i}(N_j) - \frac{N_i}{\tau_i^r} + \sum \frac{N_j}{\tau^r_{j\to i}}$$

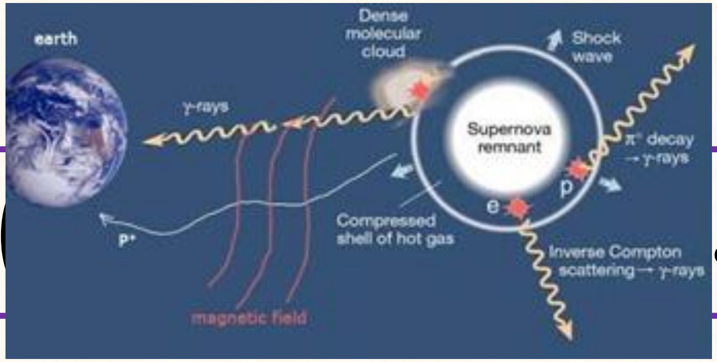
$$D_{pp} \propto \frac{p^2\,VA^2}{D}$$

$$\frac{1}{\tau_i^f(T)} = c n_H \beta(T)\left[\sigma_{iP}(T) + f_{He}\,\sigma_{iHe}(T)\right]$$

$$\frac{1}{\tau_i^r(T)} = \frac{1}{\gamma(T)\tau_i^0}$$

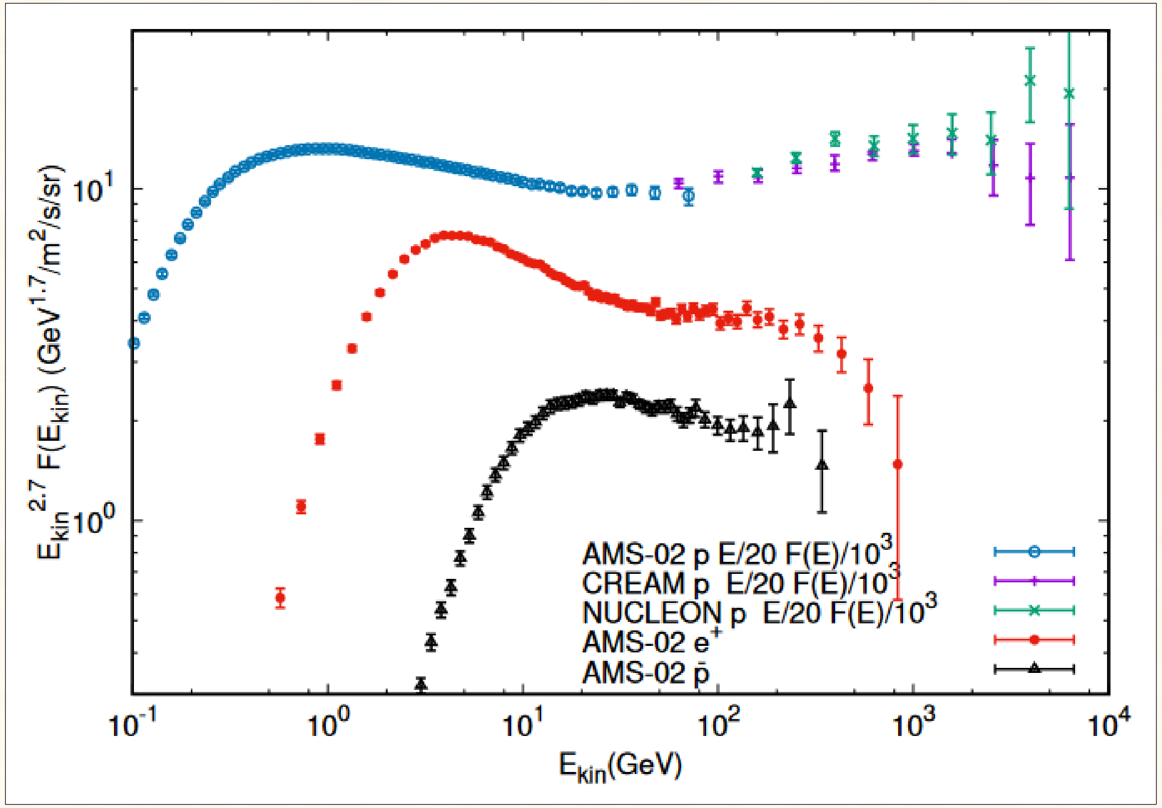
$$D = D_0\beta^\eta\left(\frac{R}{R_0}\right)^\delta F(\vec{r},z)$$

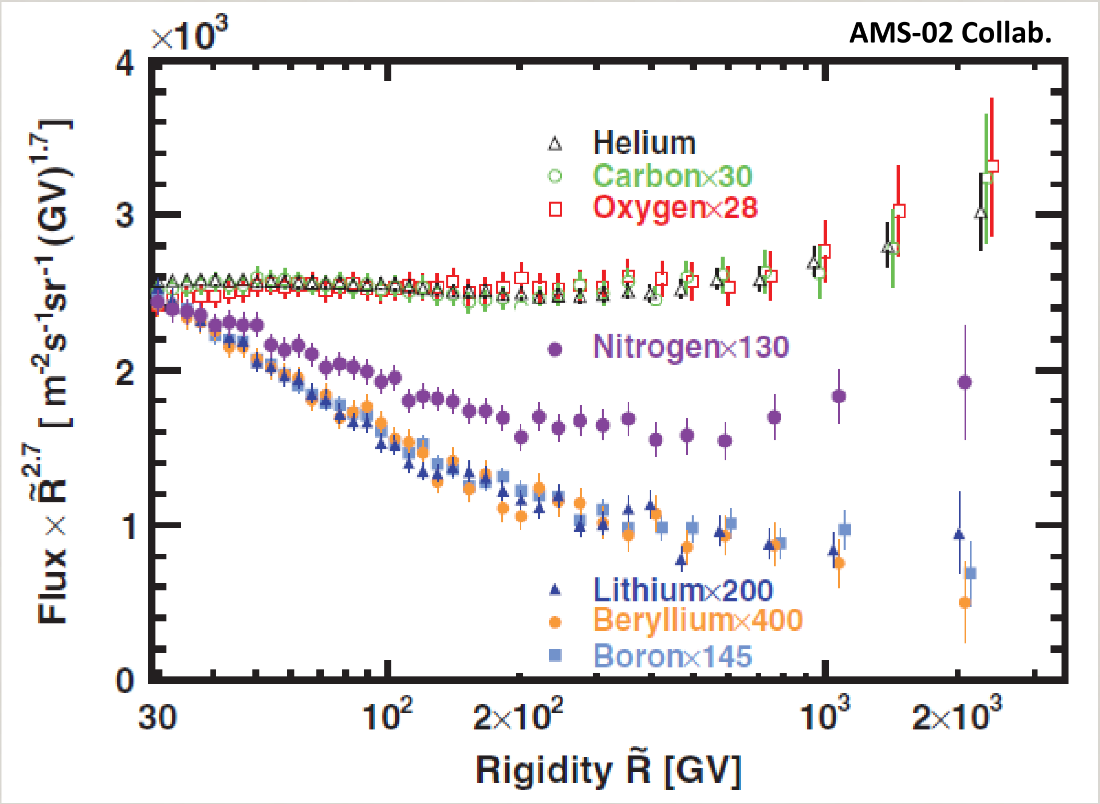
$$\frac{\partial p}{\partial t} = (\ldots c$$



$$\Gamma^s_{j\to i} = \beta_j c n_t \sigma_{j\to i} N_j$$

The positron spectrum





The current measurements give us most of the ingredients to build estimations on the spectra of antiparticles at Earth http://www.fluka.org/fluka.php

The FLUKA toolkit and the evaluation of cross sections for CR interactions

- **FLUKA** is a general purpose tool that can be used to study electromagnetic and hadronic interactions of particles and their transport in arbitrarily complex geometries.
- Nuclear interactions are optimized in the range from the MeV up to tens of TeV and are treated in a Monte Carlo fashion.
- A code such as FLUKA allows us to precisely study the cross sections of any CR interacting with **any gas nucleus** and the formation of **long and short-living particles produced**, in the whole energy range for which we have experimental CR data.
- FLUKA has been used in other CR studies as in Mazziotta, **P.D.L**. et al PRD 101(8):083011 (2020), as well as for other astrophysical applications as atmospheric neutrino studies (Astropart. Phys., 23:526–534, 2005) or gamma-ray flares from the Sun (Solar Phys., 294(8):103, 2019).

The FLUKA toolkit and the evaluation of cross sections for CR interactions

http://www.fluka.org/fluka.php

Nucleus-nucleus hadronic interactions are treated as following in FLUKA:

- **Resonances** produced in hadron-nucleon inelastic collisions dominate from the MeV up to 3-5 GeV
- Above 3-5 GeV hadronizations through Dual Parton Model (**DPMJET-3**) takes over
- Extension to hadron-nucleus collisions is achieved through the **PEANUT** model (GINC) + relaxation
- Nucleus-Nucleus use **Boltzmann thermal equation** at E<0.1GeV/u, **rQMD** model up to 5 GeV/u and **DPMJET** above

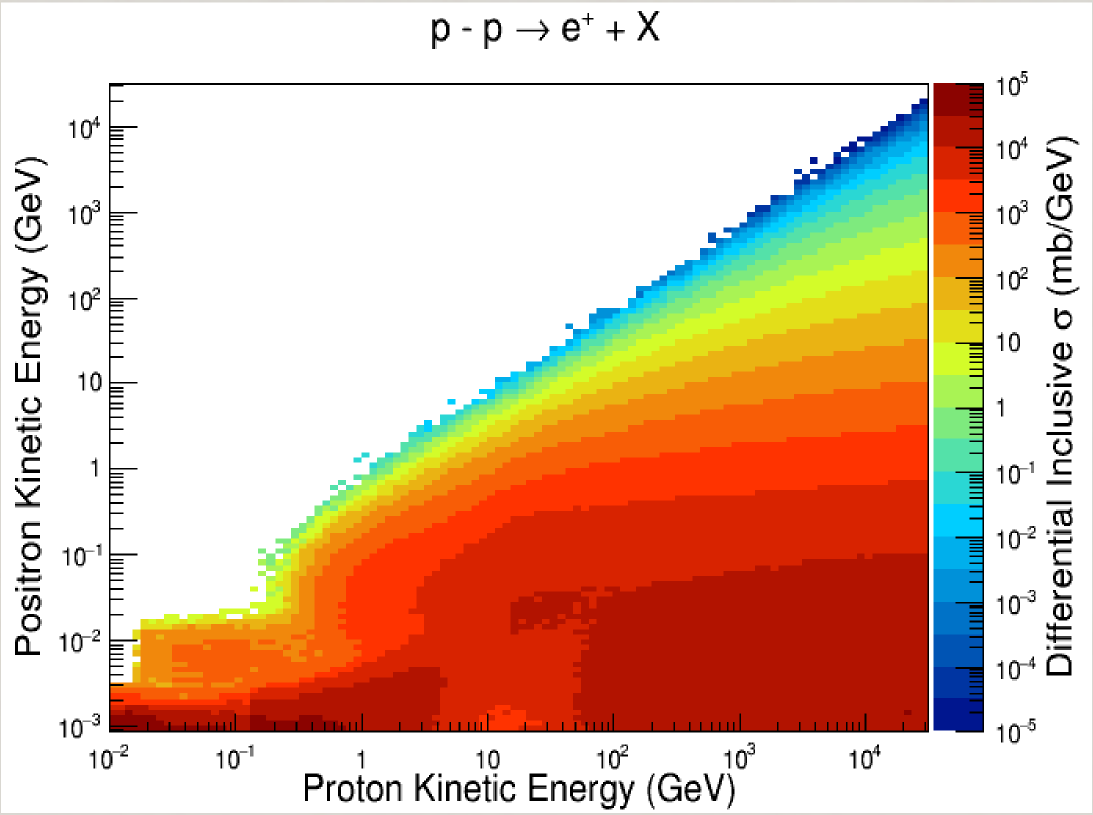
We have computed inelastic and inclusive cross sections of interactions of all isotopes of the CR nuclei up to Z=26 (Iron) with protons and helium, including a careful analysis of those short-living particles produced (ghost nuclei) from 1 MeV/n to 35 TeV/n.

The result is a set a cross sections of secondary CRs that can be used in CR propagation codes. We have also computed cross sections for gamma-ray production and those for secondary leptons, neutrinos and antiproton production will be soon investigated.

Fluka cross sections

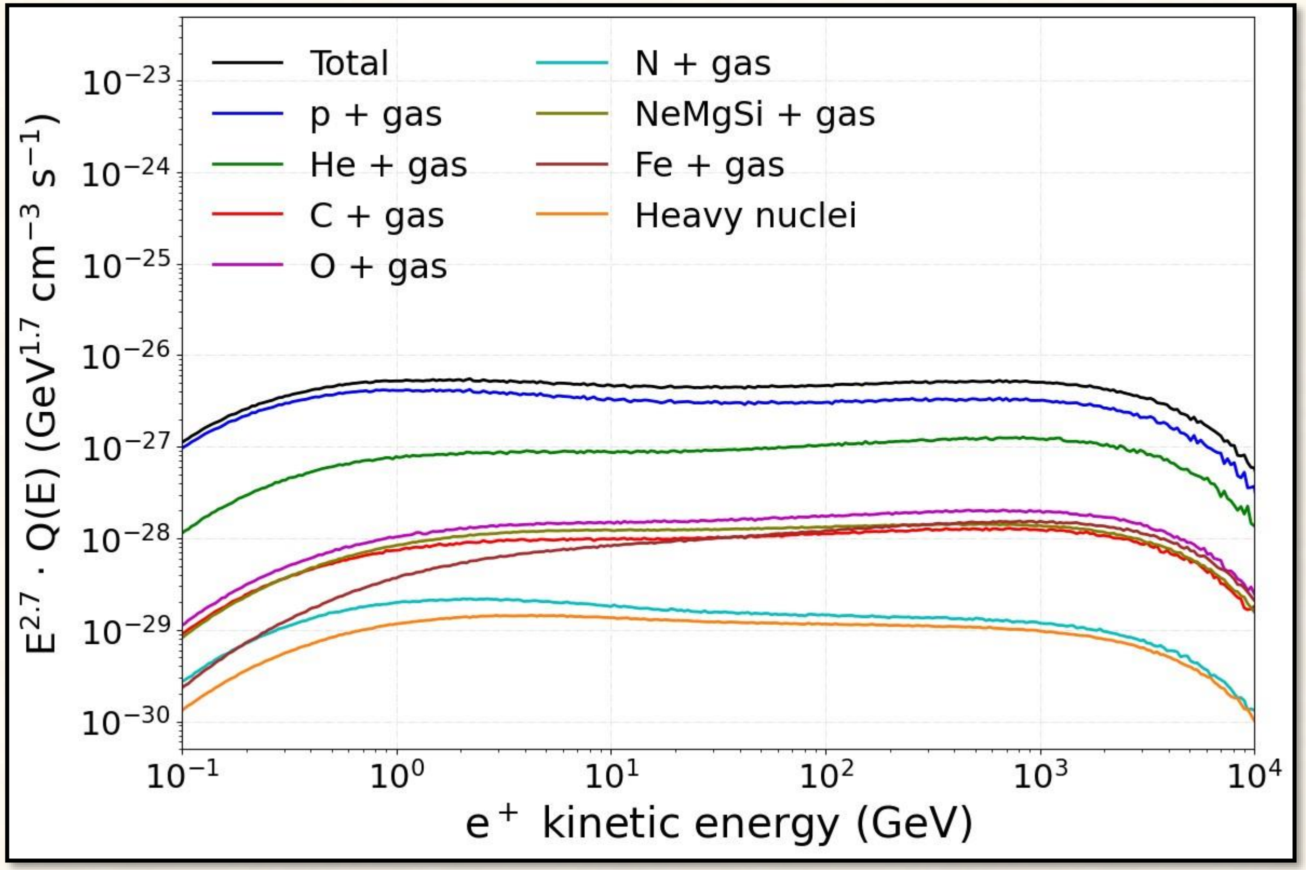
http://www.fluka.org/fluka.php

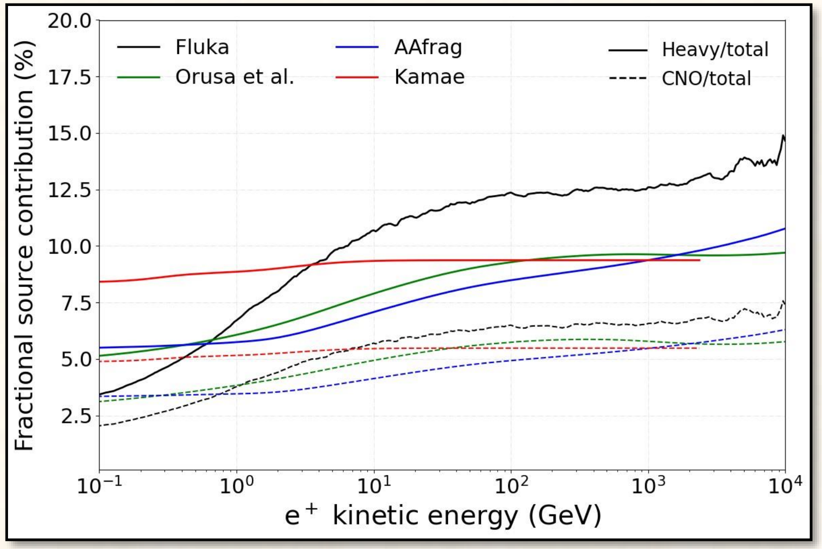
- FLUKA allows us to study CR interactions with **any gas nucleus** and the formation of **long and short-living particles produced**, in the whole energy range for which we have experimental CR data.
- We have computed inelastic and inclusive cross sections of interactions of all isotopes of the CR nuclei up to Z=26 (Iron) with p and He, including a careful analysis of those short-living particles produced (ghost nuclei) from 1 MeV/n to ~50 TeV/n.
- The result **is a set a cross sections of secondary CRs, gamma-ray, secondary leptons, neutrinos and antiprotons that can be used in CR propagation codes**.



Fluka cross sections: e^+ uncertainties

$$Q^e(E_k) = \sum_{i=p,He}^{Gas} \sum_{k}^{Prim} 4\pi n_i \int_{E^{kmin}}^{70TeV} \left(\frac{d\sigma}{dE_e}\right)_{ik} \Phi_k(E_k)\, dE_k$$



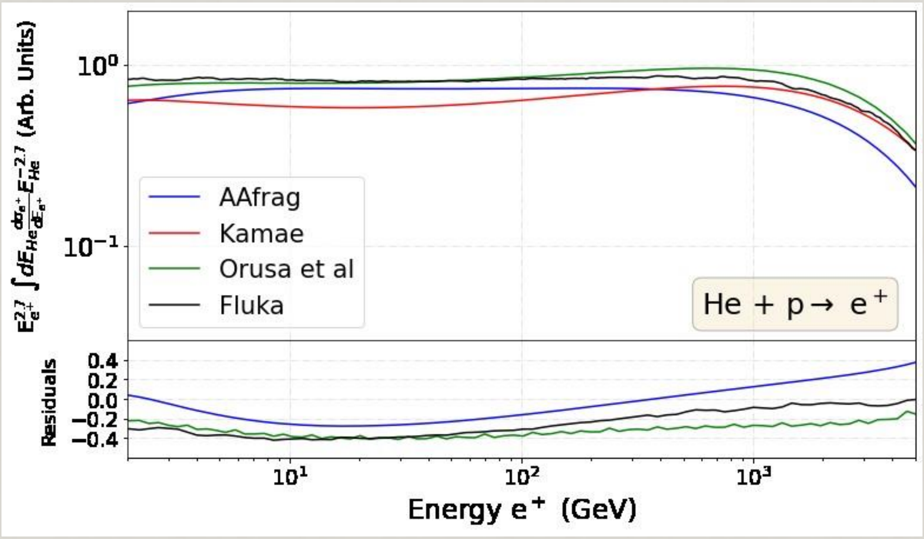


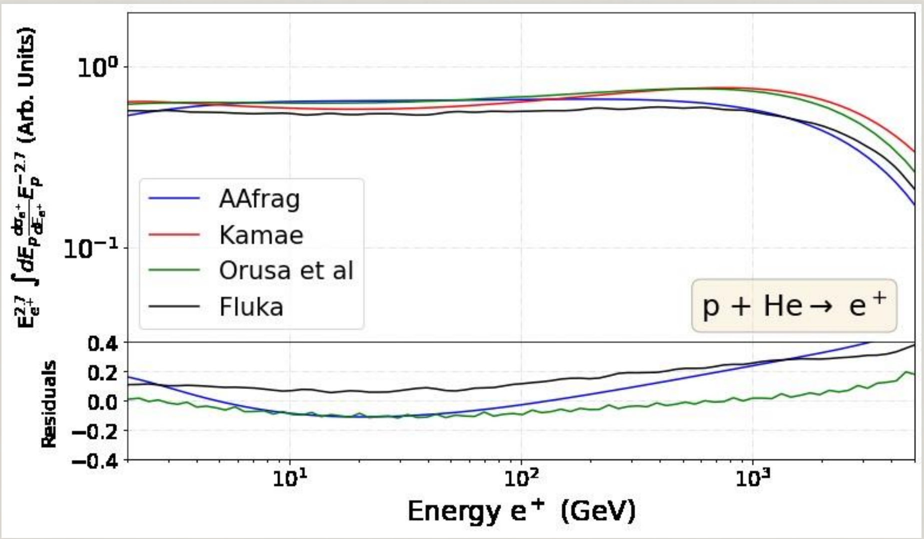
The contribution of elements with high mass number is as important as that from C or O above ~10 GeV

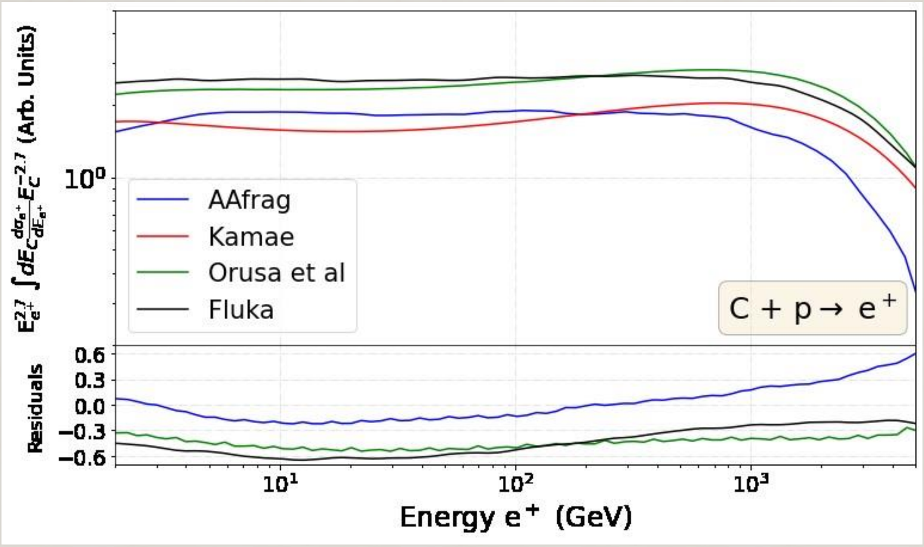
Contribution of heavy nuclei (from He to ^{56}Fe) constitutes between 8 and 10% of the total e^+flux at 10 GeV

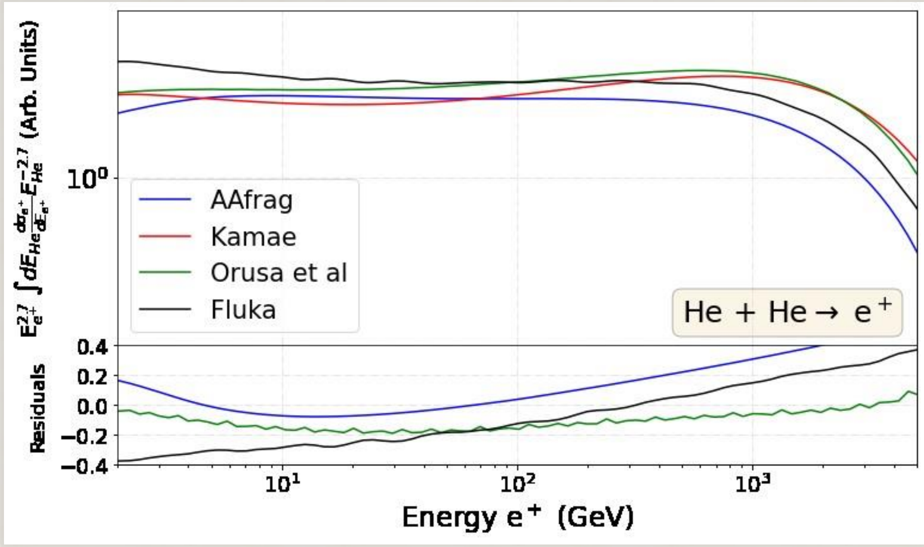
Also the production of ghost nuclei and 60 resonances other than pions and kaons are considered here

Fluka cross sections: e^+ uncertainties





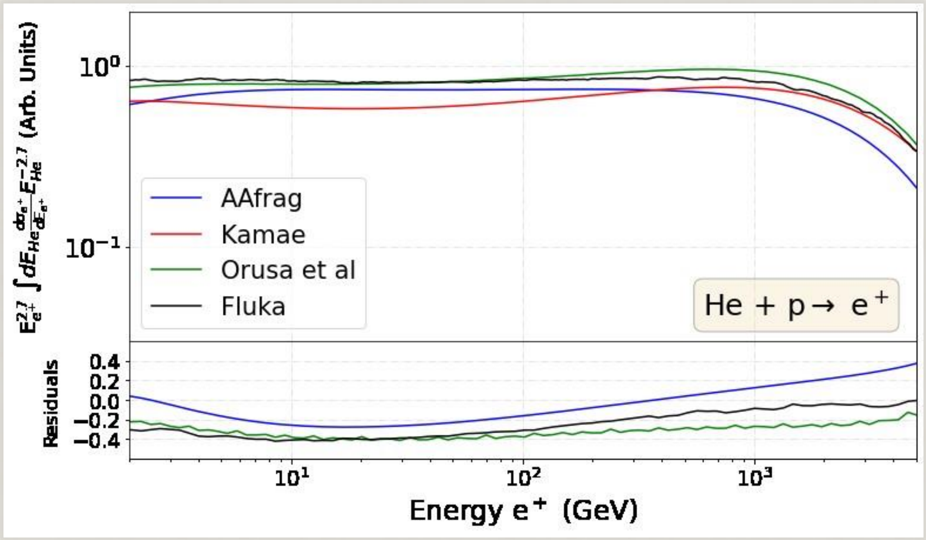


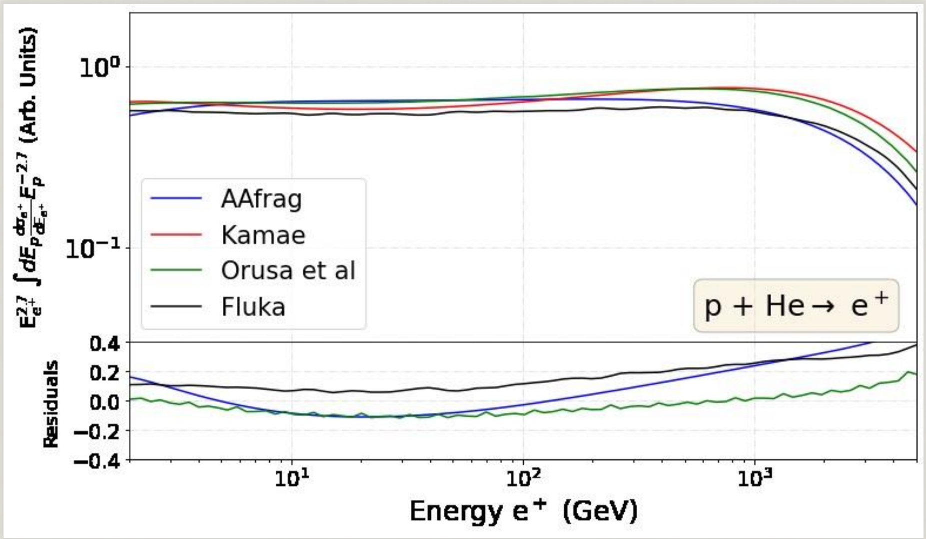


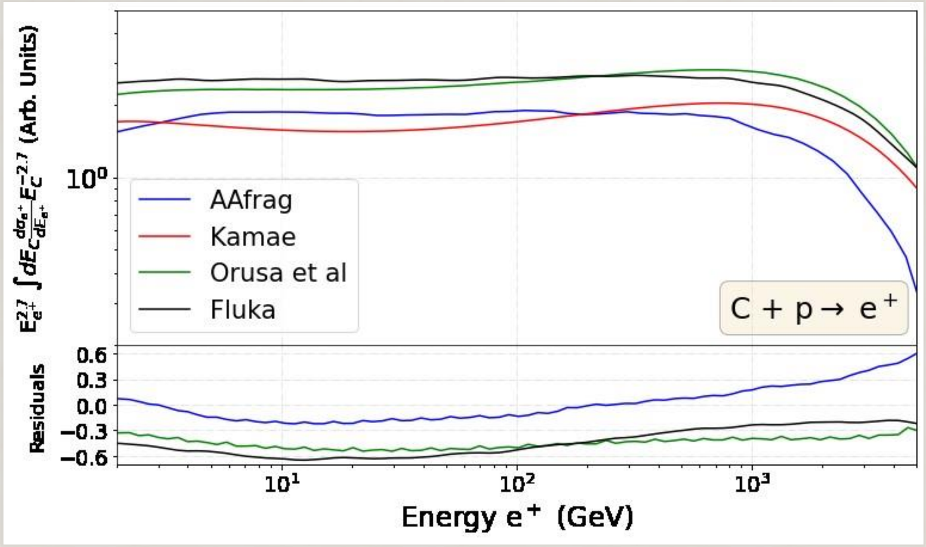
Fluka cross sections: e^+ uncertainties

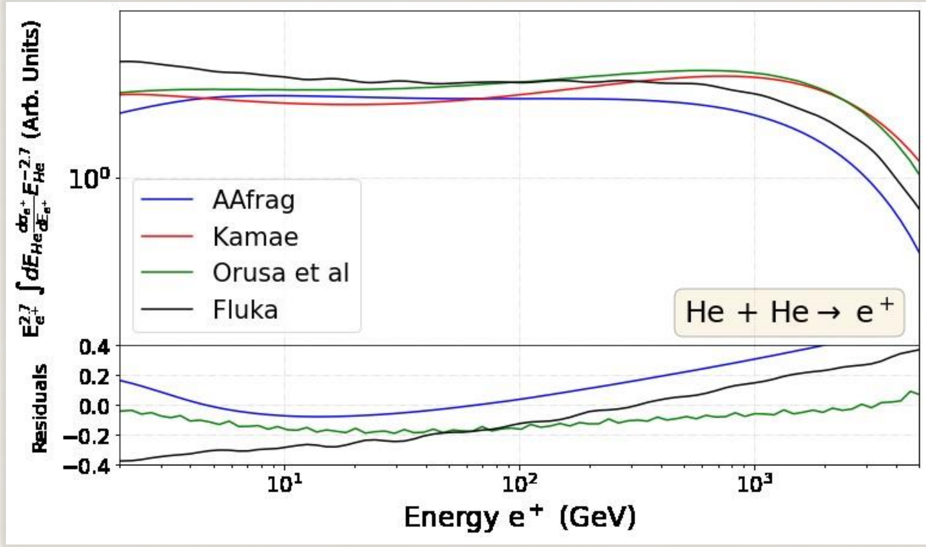
Scaling –> $\frac{\sigma_{A+p}}{\sigma_{p+p}} \sim A^s$

s found to be 0.9-1.1









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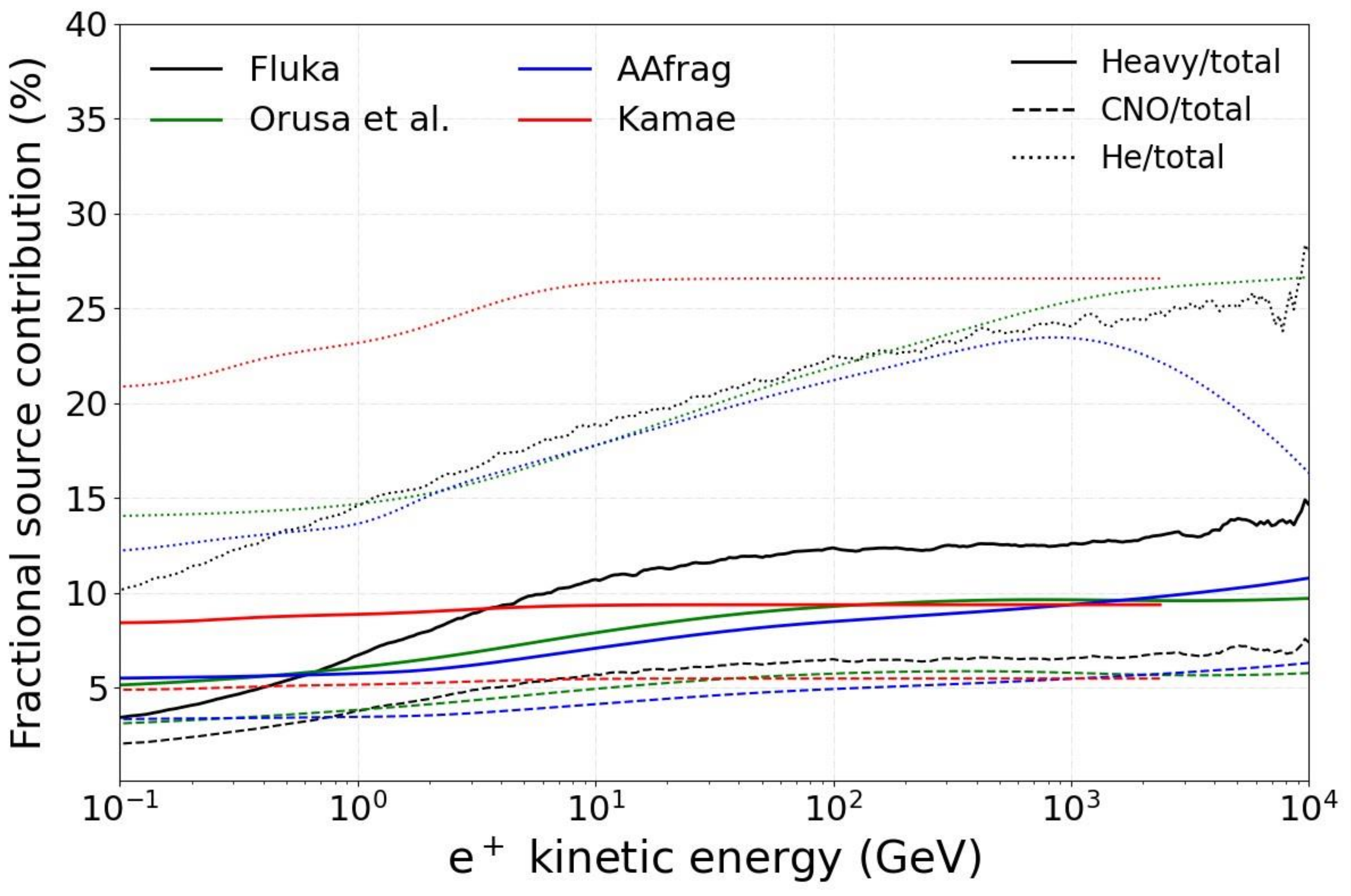
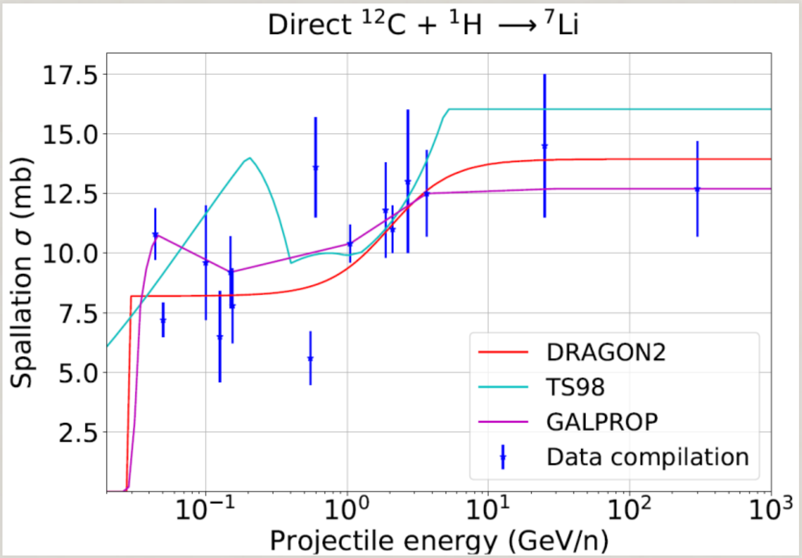
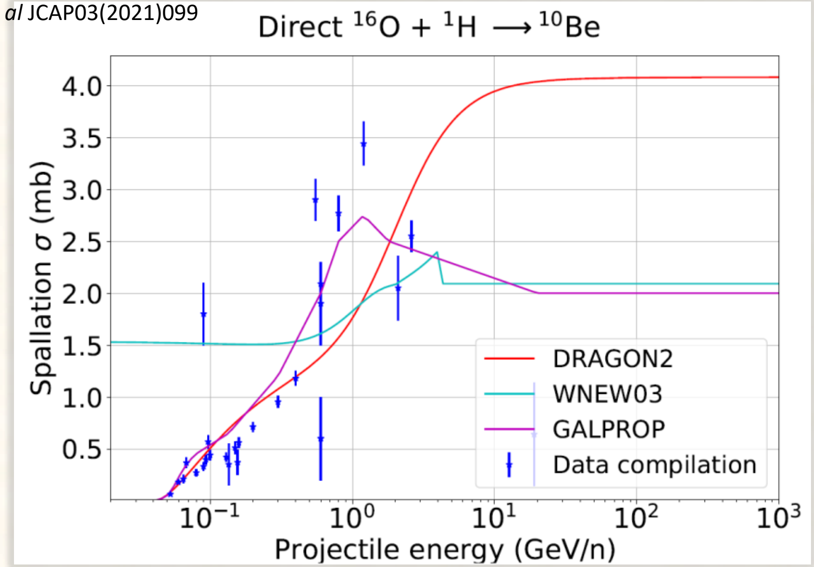


The contribution of elements with high mass number is as important as that from C or O above ~10 GeV

Contribution of heavy nuclei (from protons to ^{56}Fe) constitutes between 8 and 10% of the total e^+flux at 10 GeV → Overestimation due to the lack of data on sub-Fe elements

The cross section problem

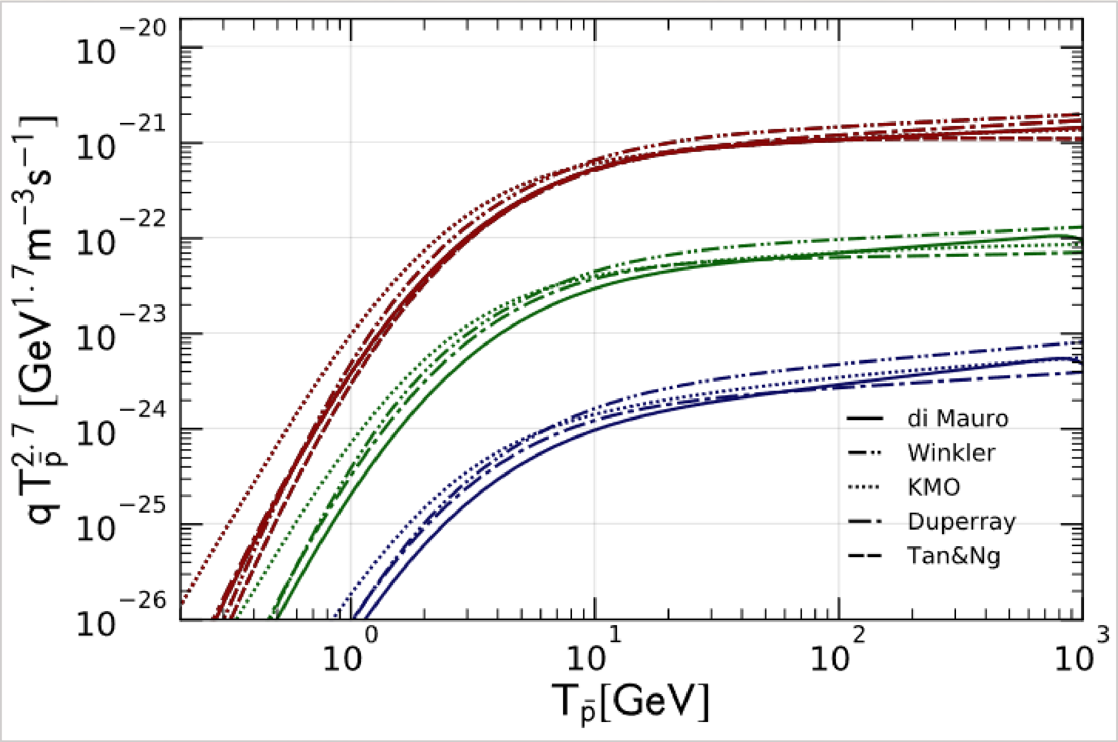




PDLTL *et al* JCAP03(2021)099

Cross sections of secondary CRs is the main limitation for the determination of the transport parameters and significantly affects our searches for dark matter with antiparticles!

Korsmeier et al, 2018



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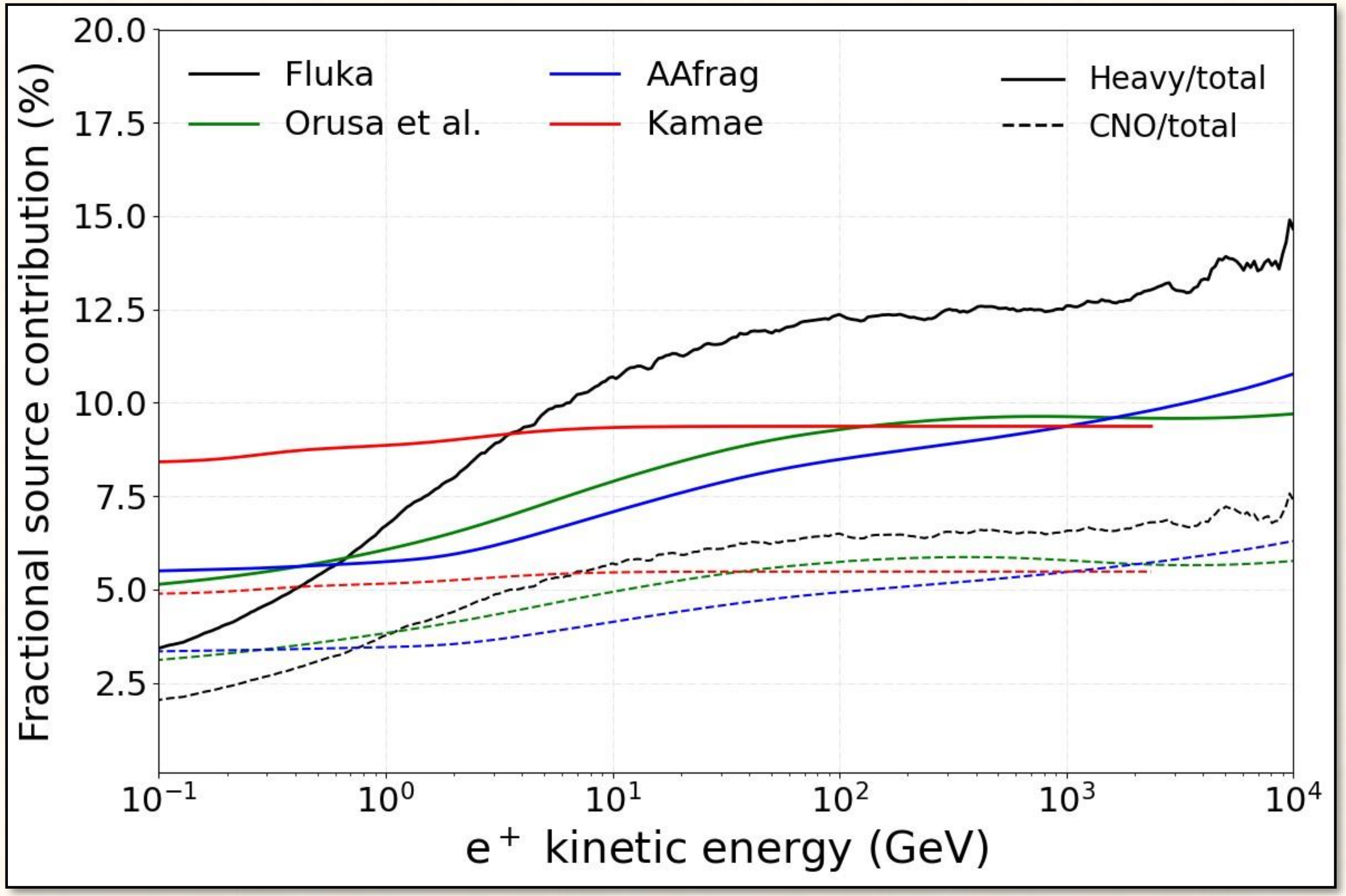

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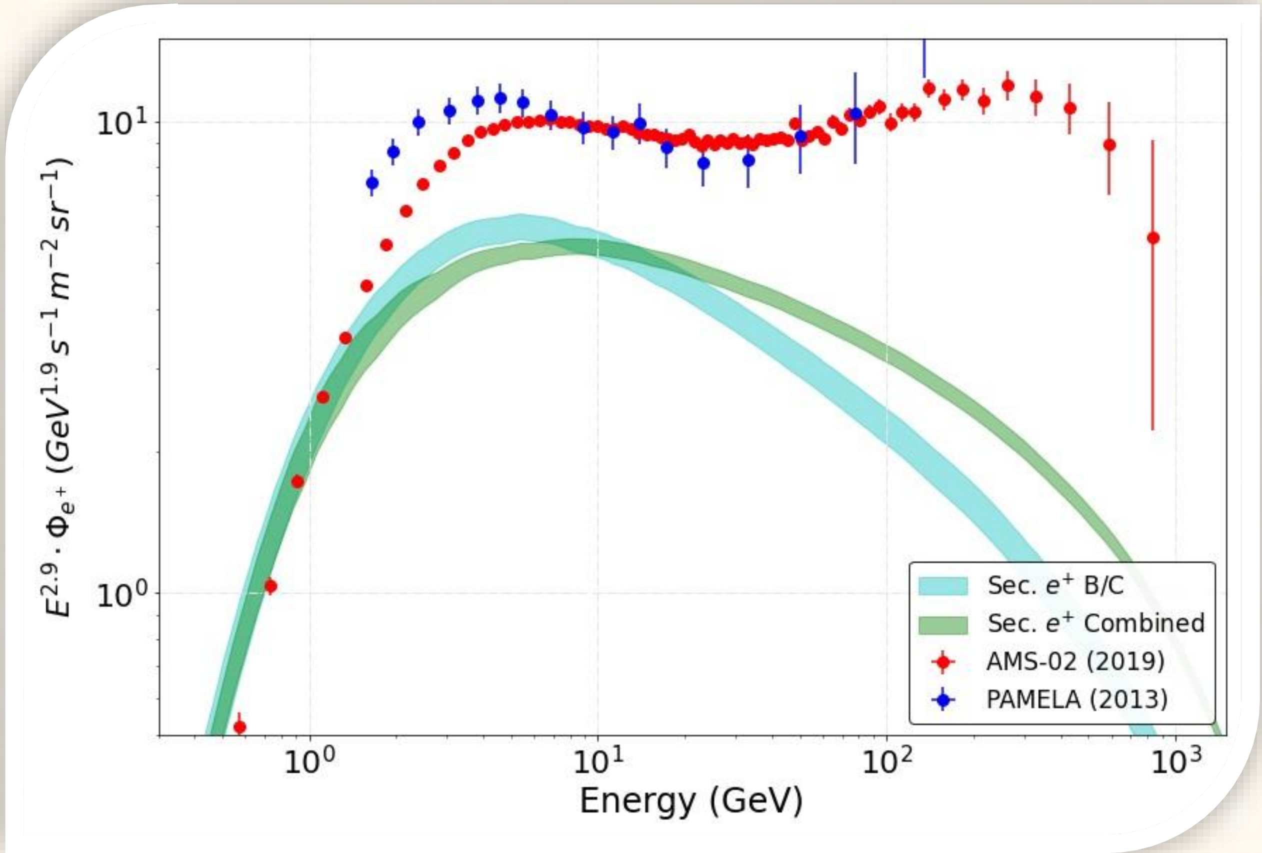
Diffusion e^+ uncertainties

$$D(R) = D_0 \beta^{\eta} \frac{(R/R_0)^{\delta}}{\left[1 + (R/R_b)^{\Delta\delta/s}\right]^{s}}$$

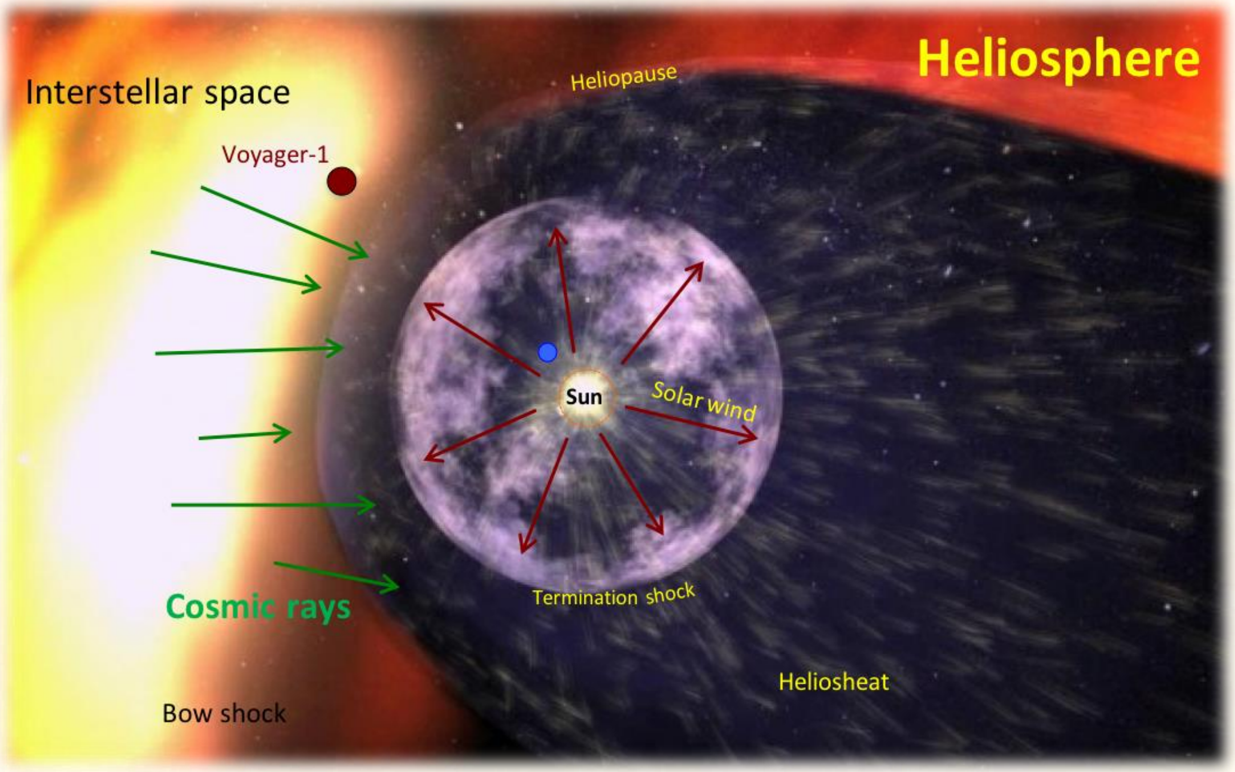
The determination of the propagation parameters make our estimations of the positron flux quite uncertain yet. Spallation cross sections contribute to the systematics too.



Injection spectra of primary nuclei adjusted independently and diffusion coefficient adjusted from secondary CRs (using Fluka spallation cross sections - ArXiv:2202.03559)

Other systematic uncertainties are dominant in our predictions. Even above cross sections uncertainties

Effect of the Heliosphere – Solar modulation



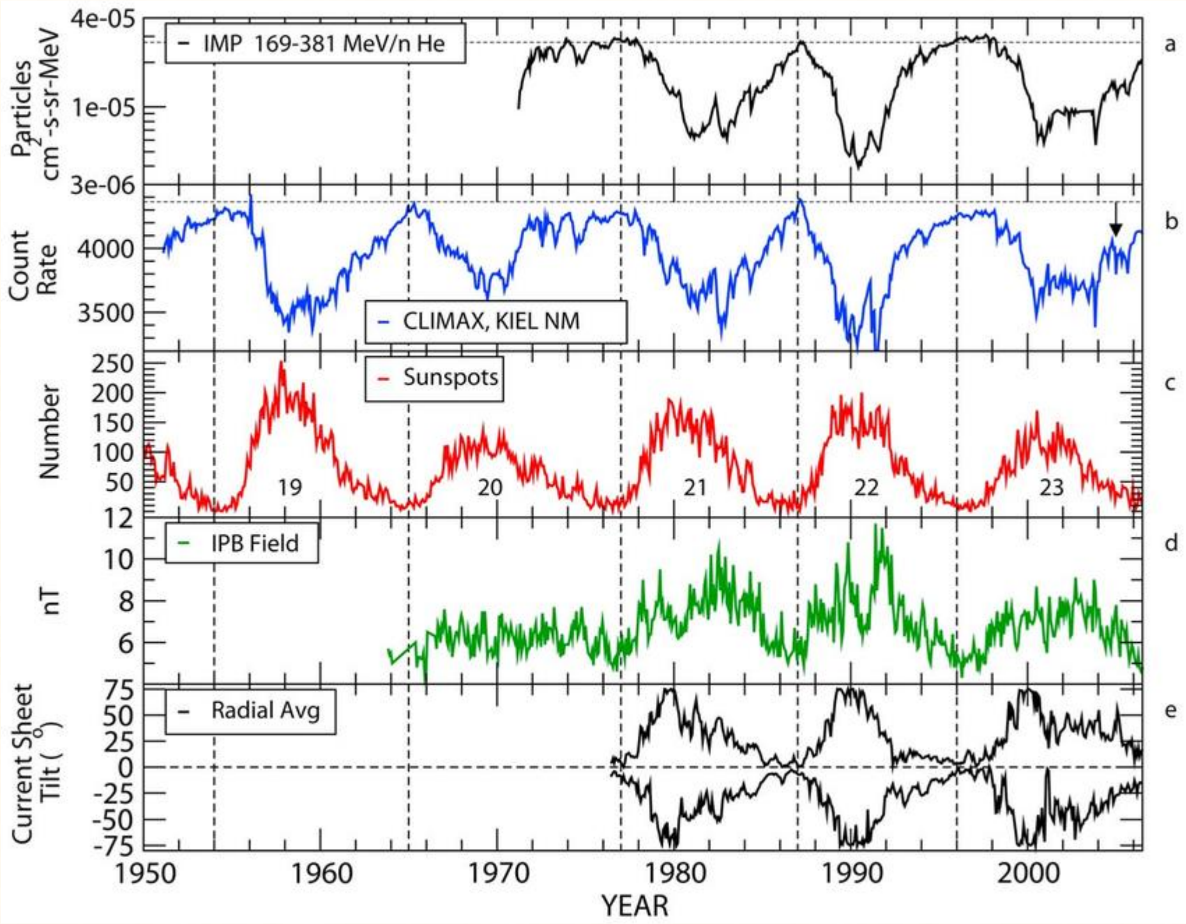
CRs experience a "firewall" when they enter the heliosphere from interstellar space

It significantly affects the propagation of low-energy CRs (below $E \sim 10$ GeV/n)

High uncertainty related with its treatment:

- ❖ Neutron monitor experiments + Voyager-1 data with Force-Field approx.
- ❖ Detailed heliosphere simulations or refined semi-analytical approximations

Effect of the Heliosphere – Solar modulation



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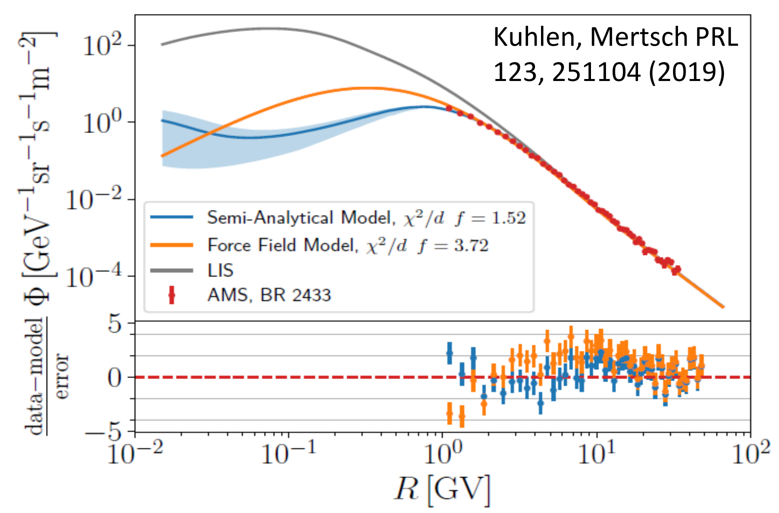
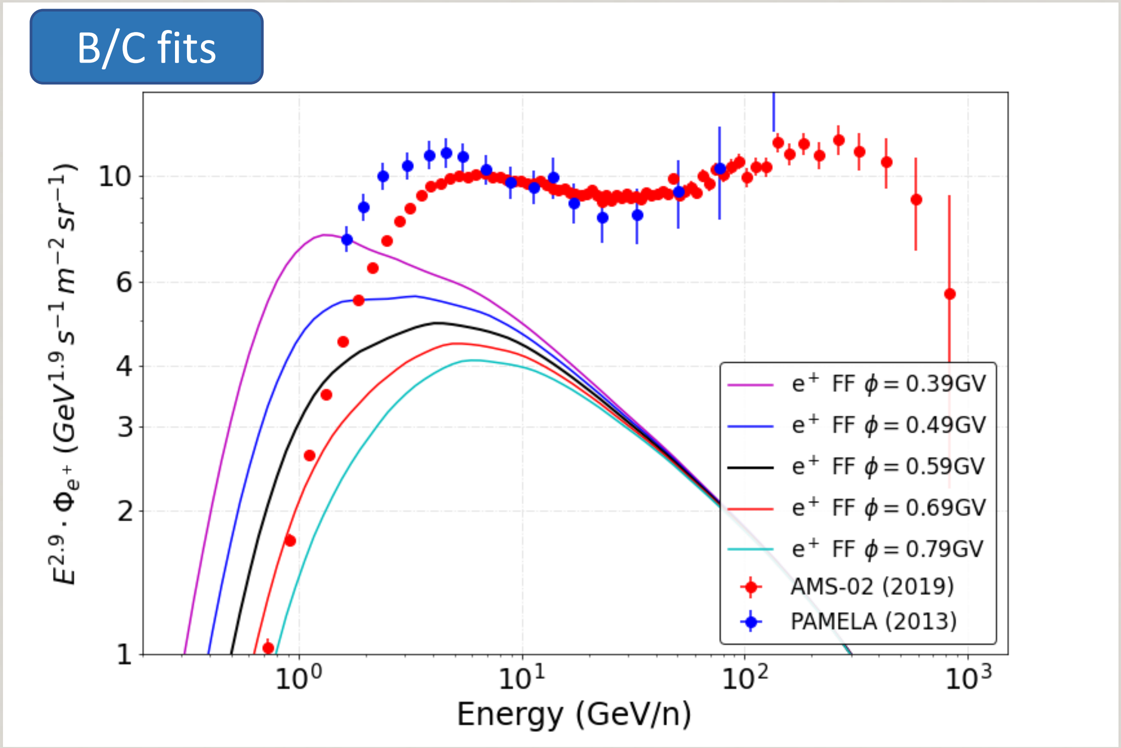
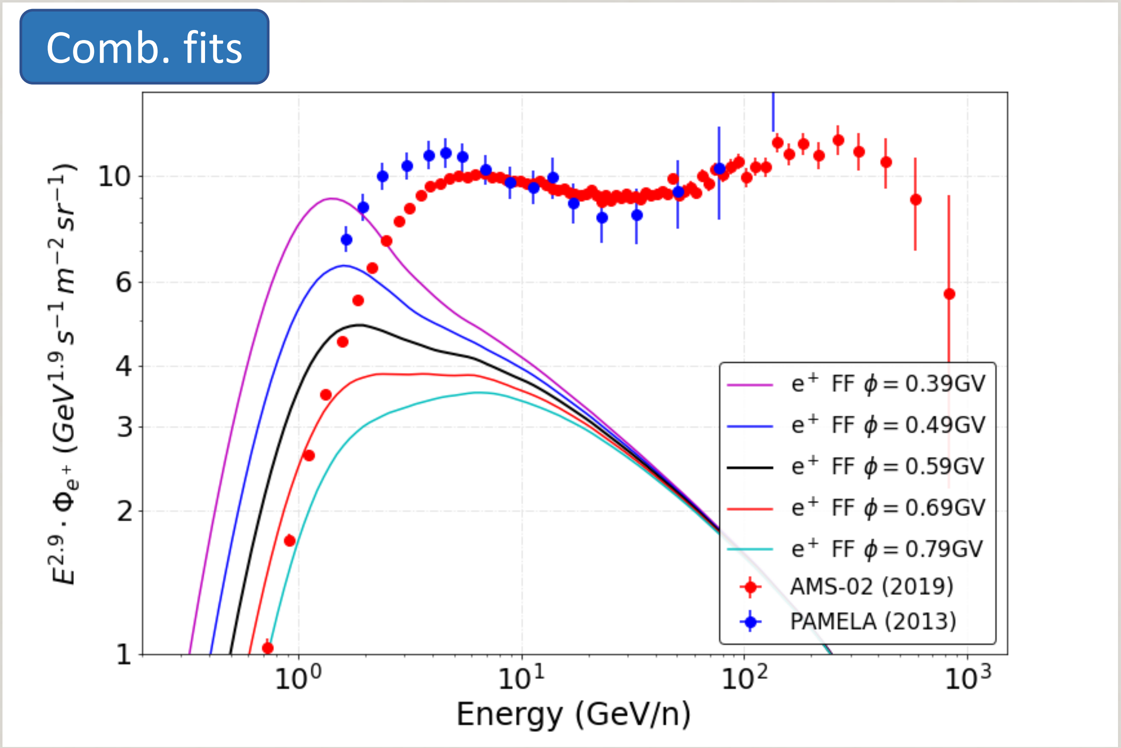


Modulation uncertainties

Force-Field approximation allows us to see the effect of solar modulation on positrons. However, it is a very crude approximation!

The higher the flux suppression (i.e. larger Fisk potential) the less clear the effect of reacceleration gets

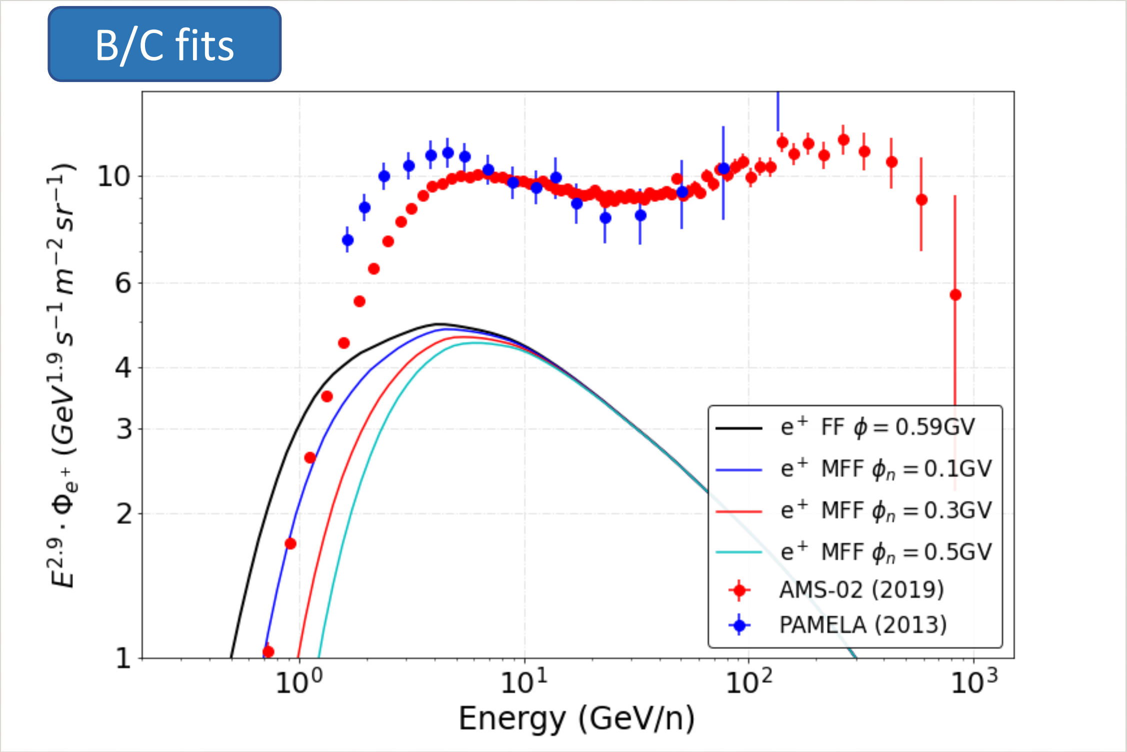


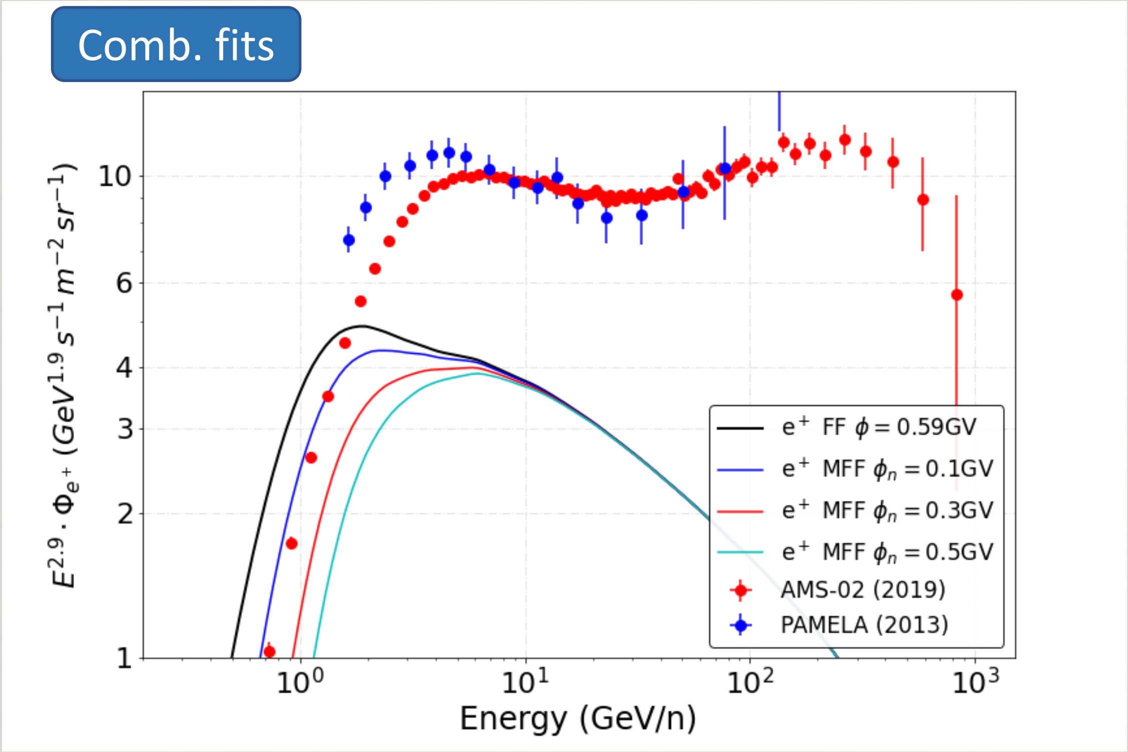


Modulation uncertainties

Modified Force-Field approximation (it accounts for charge-sign effects) - arXiv:2007.00669.
It "shifts" the low energy part of the e^+ spectrum but it still does **not** allow us to **reproduce e^+ ratio**

Work in progress using numerical simulations of the modulation effect…





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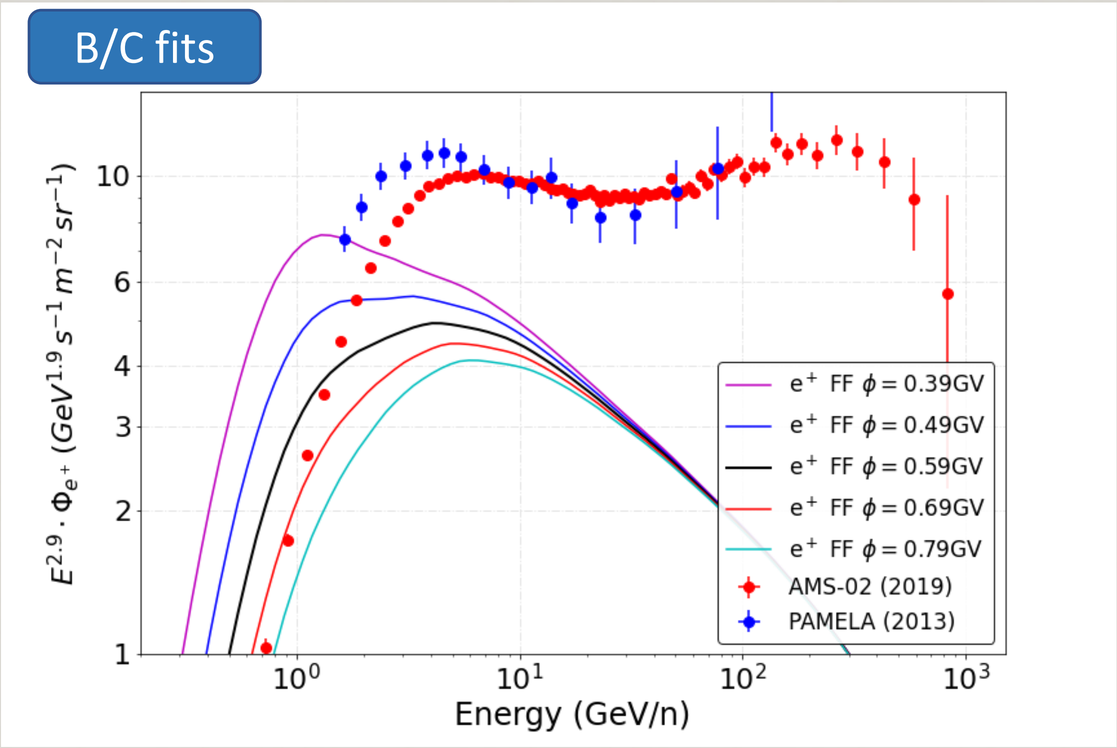
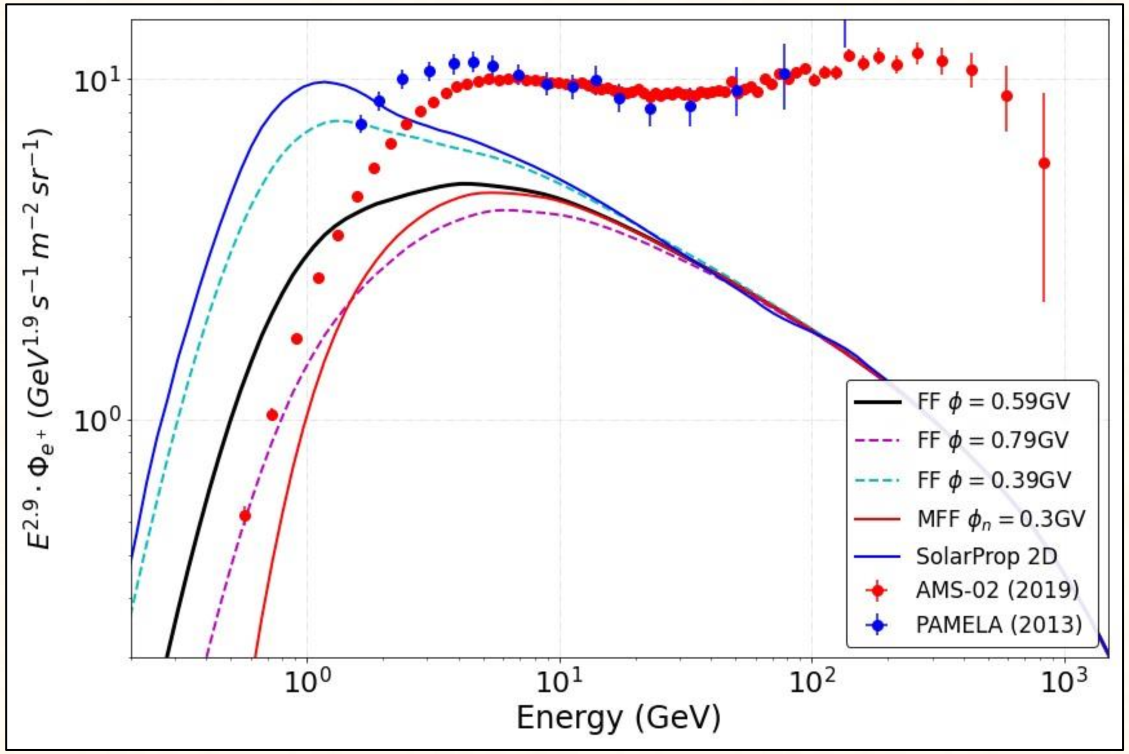
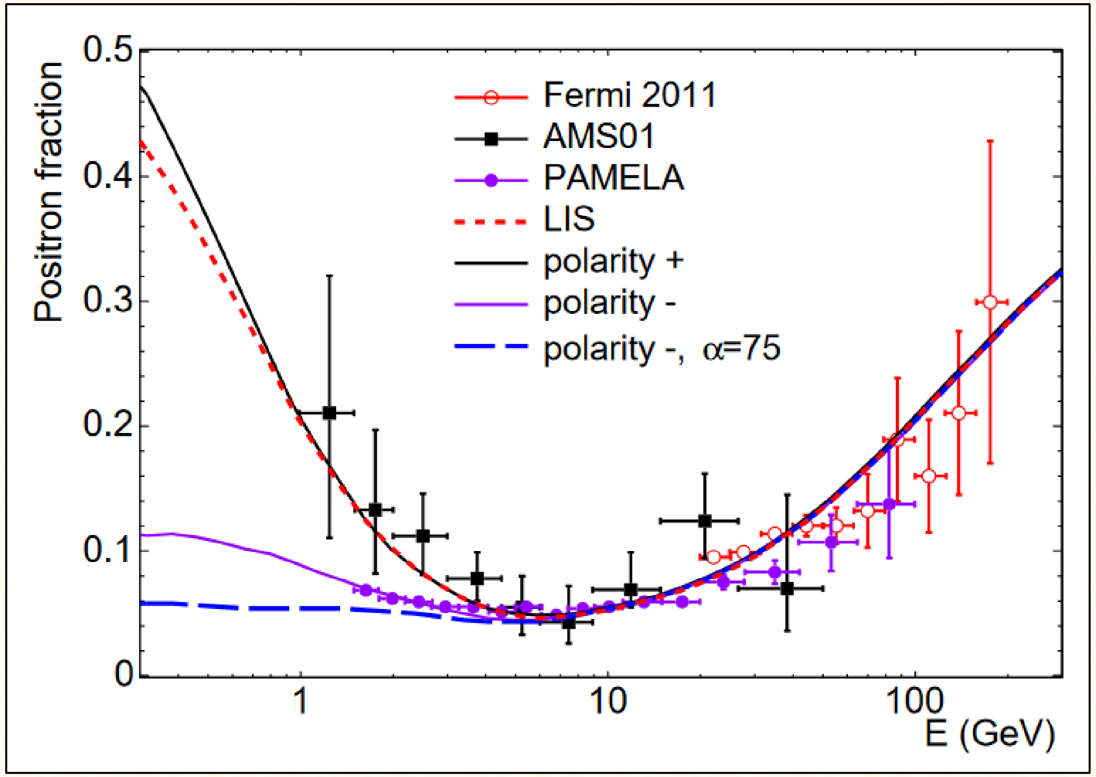


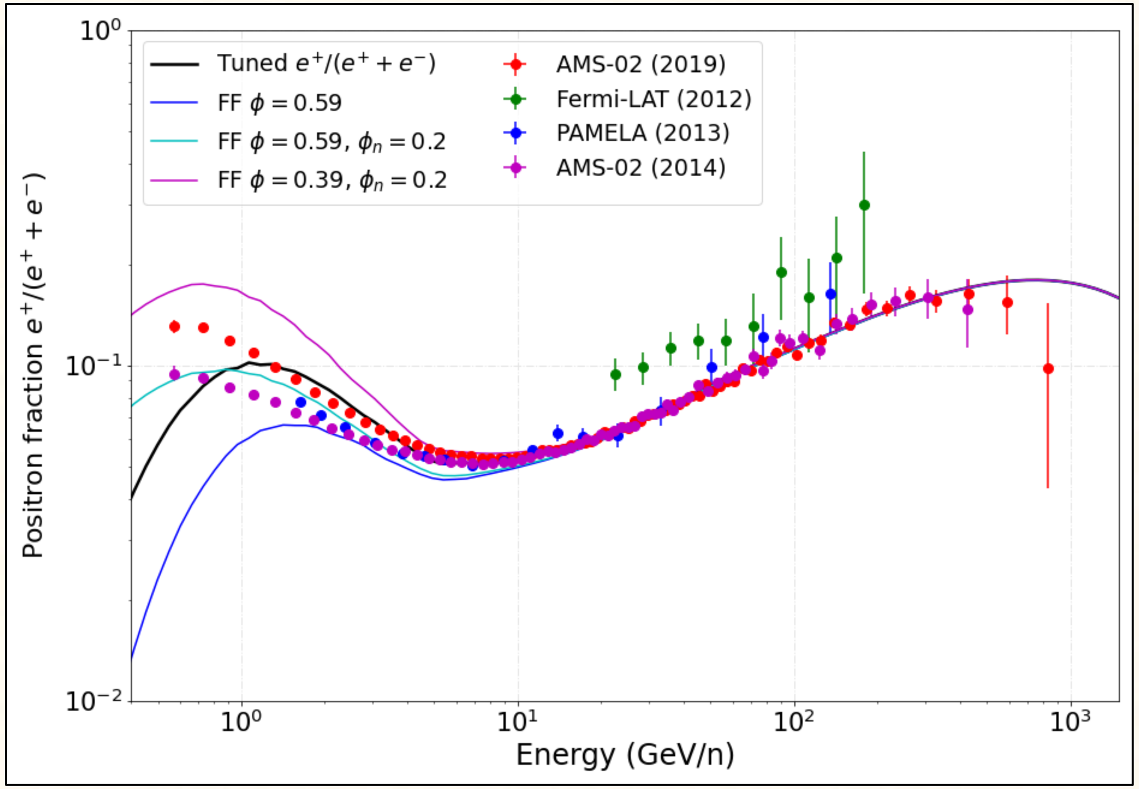


Modulation and positron ratio

Work in progress using numerical simulations of the modulation effect…

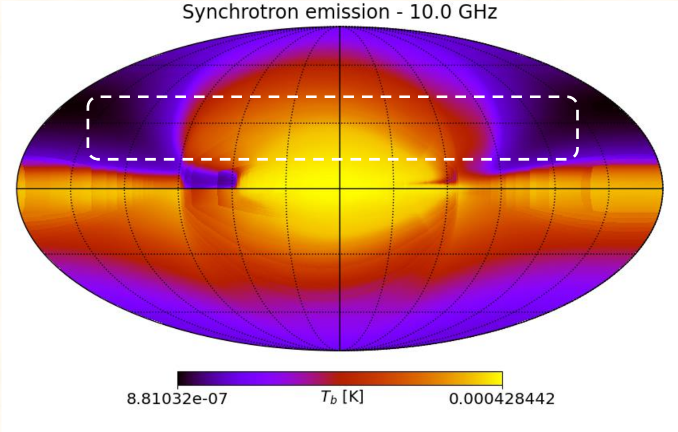
Maccione et al PRL 110, 081101

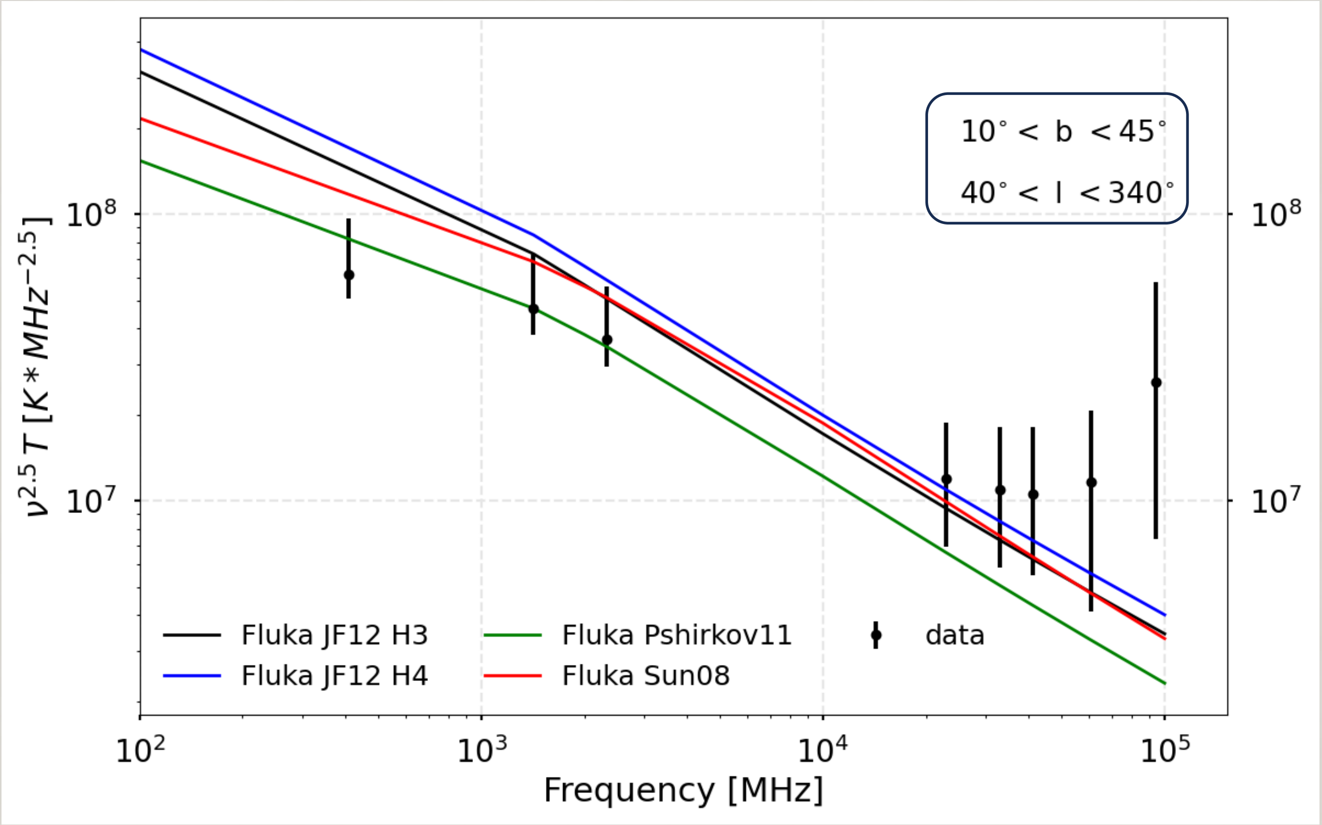




Synchrotron emission

Adjusting the synchrotron emission allows us to constrain the turbulent component. However electron flux can be different in different zones of the Galaxy (sources and diffusion dependence with z)





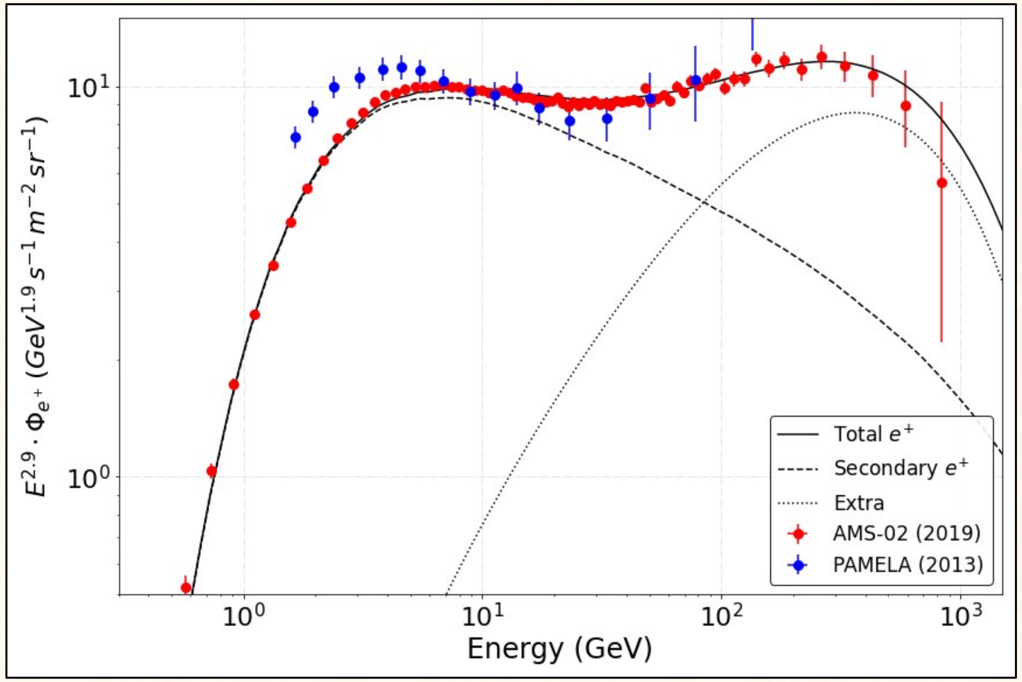
Data from a wide set of radio surveys and WMAP data as catalogued by Oliveira-Costa+ (2008) - arXiv:0802.1525.

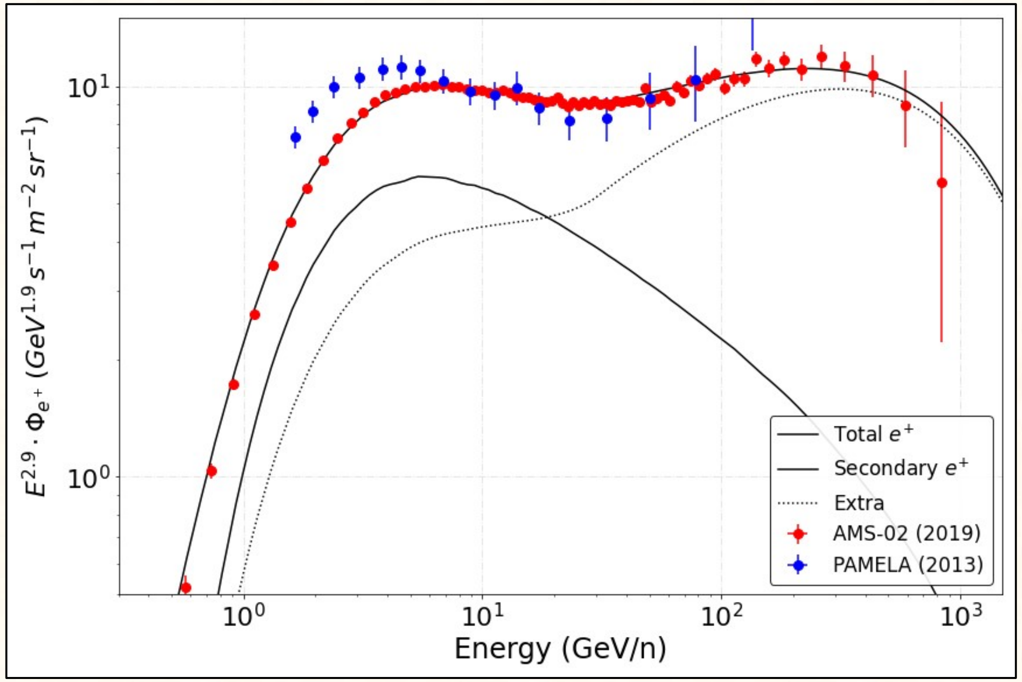
Microwave data above 20 GHz expected to be contaminated by non-synchrotron emission! (see arXiv:1210.4546)

Implications of these uncertainties

For some plausible values of the halo height, modulation parameters, cross sections, … we can reproduce the positron spectrum with no significant extra contribution below ~10 GeV

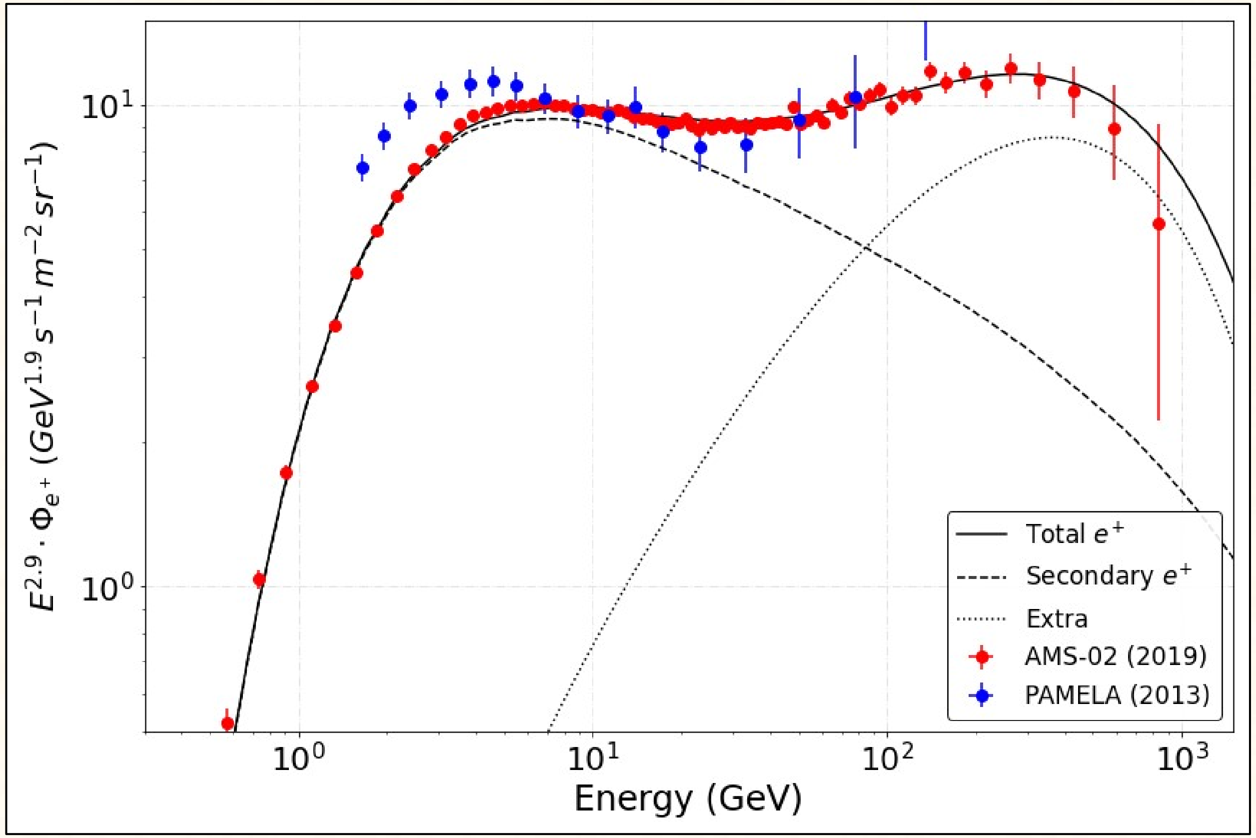
With best-fit values, contribution from sources at 5 GeV is >30%. A bit larger to previous estimations, but not ruled out at all. Room for more exotic sources of positrons?

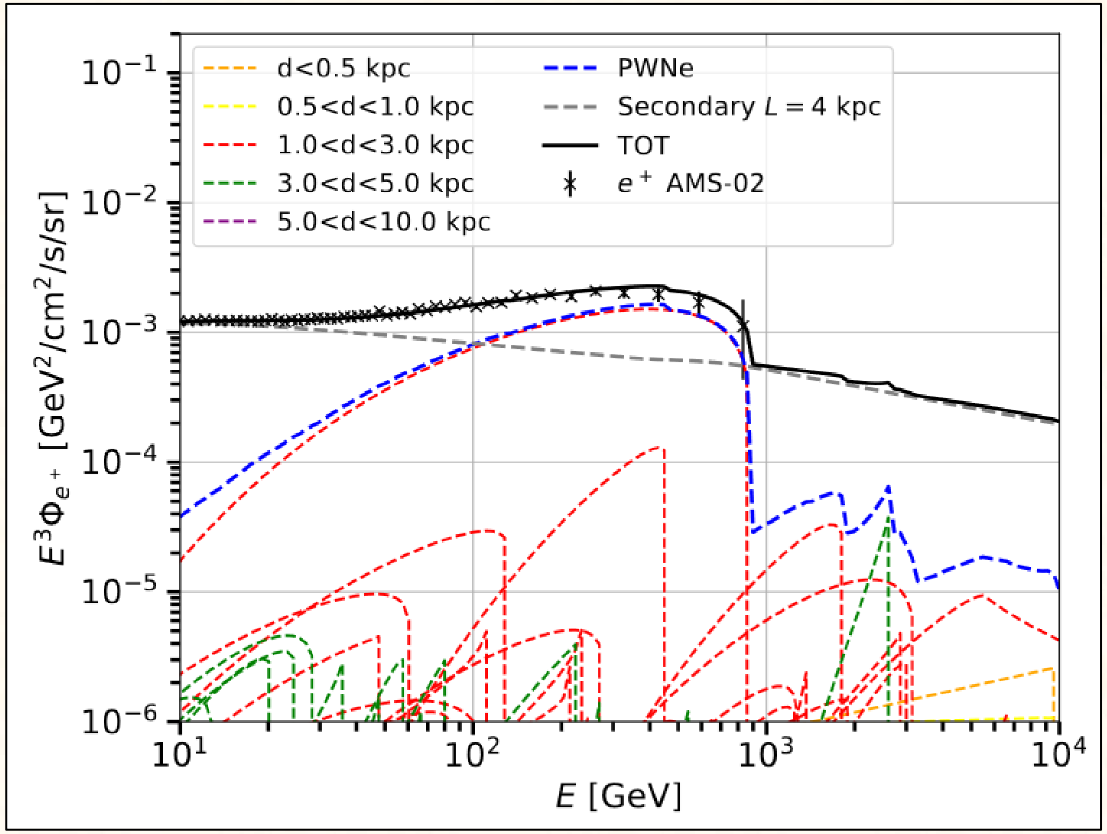




Impact on the determination of the PWN emission

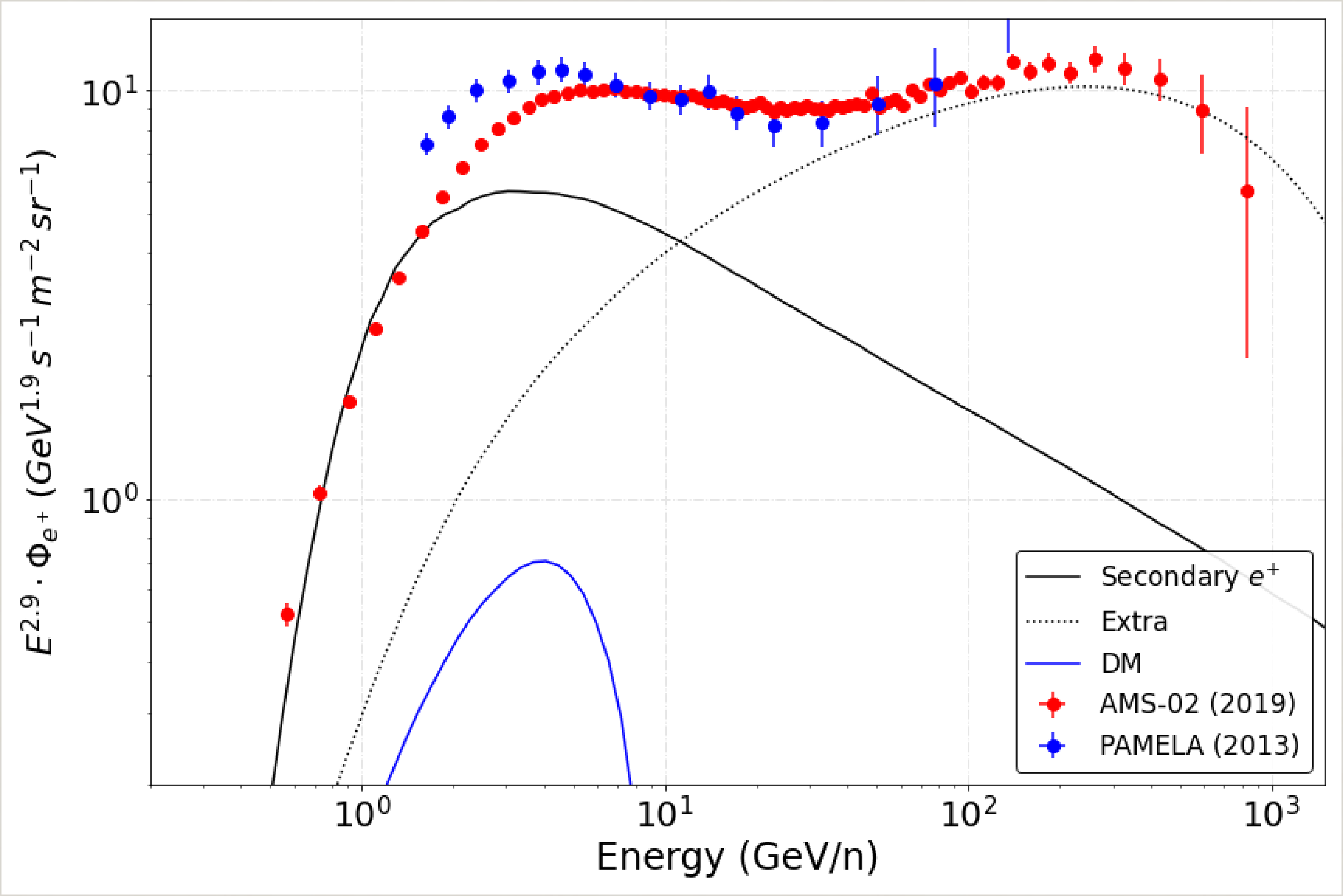
Orusa et al JCAP12(2021)014



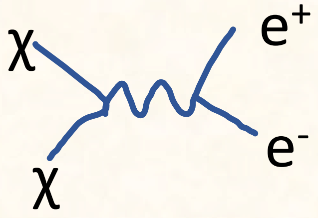


DM searches

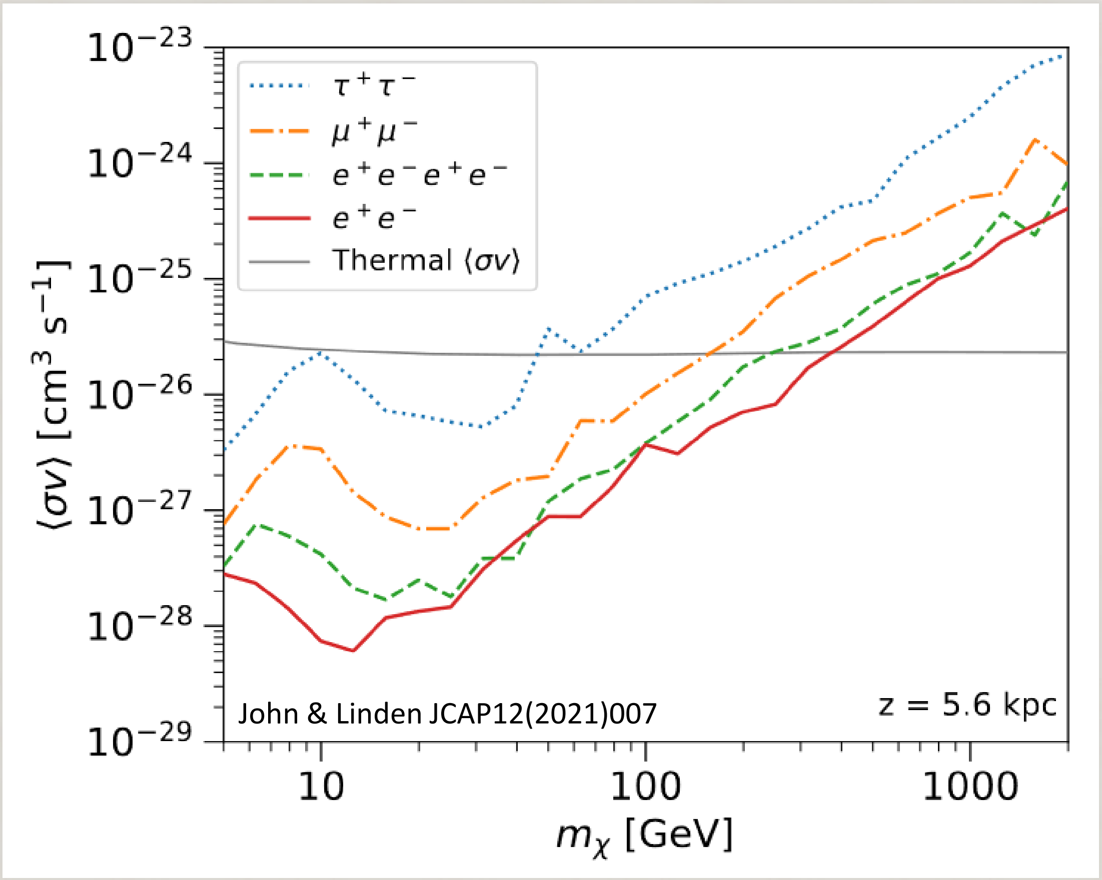
$\mu\mu$ channel
M_χ = 15 GeV
σv = 3e-26 cm^{-3}/s

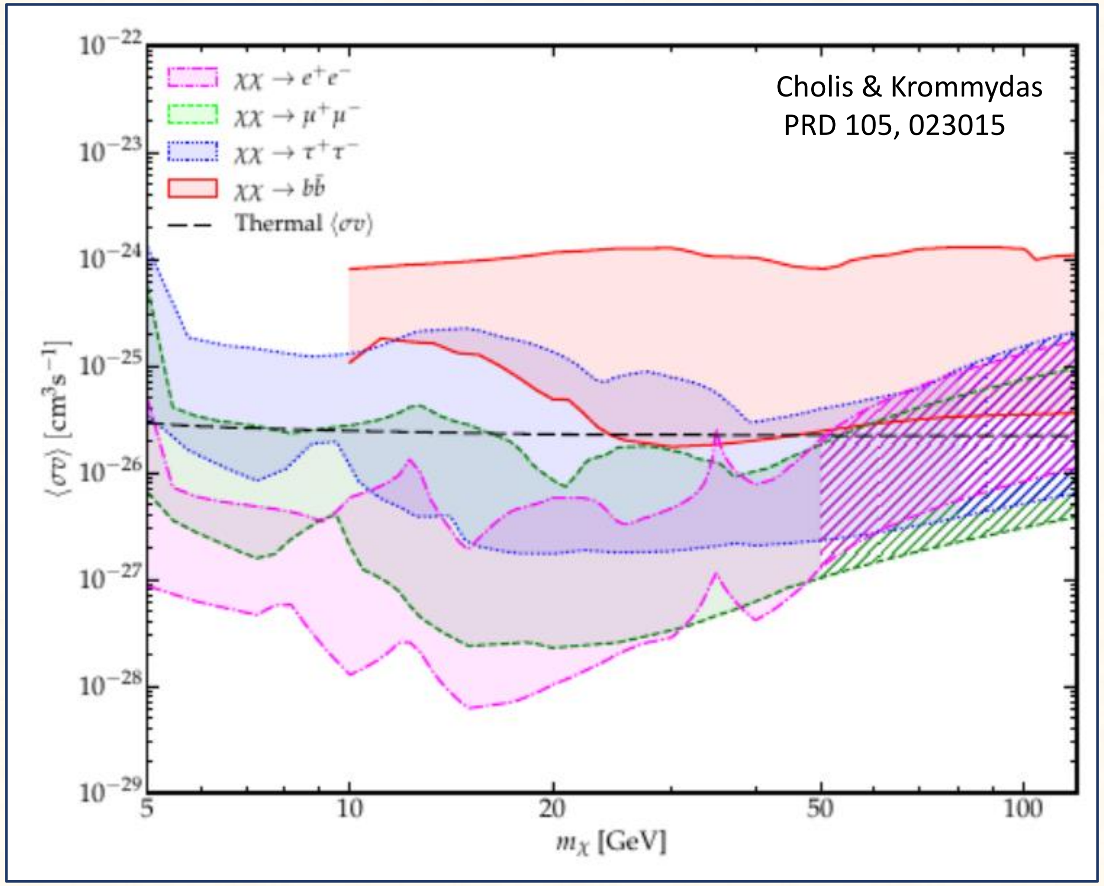


Impact on WIMP searches



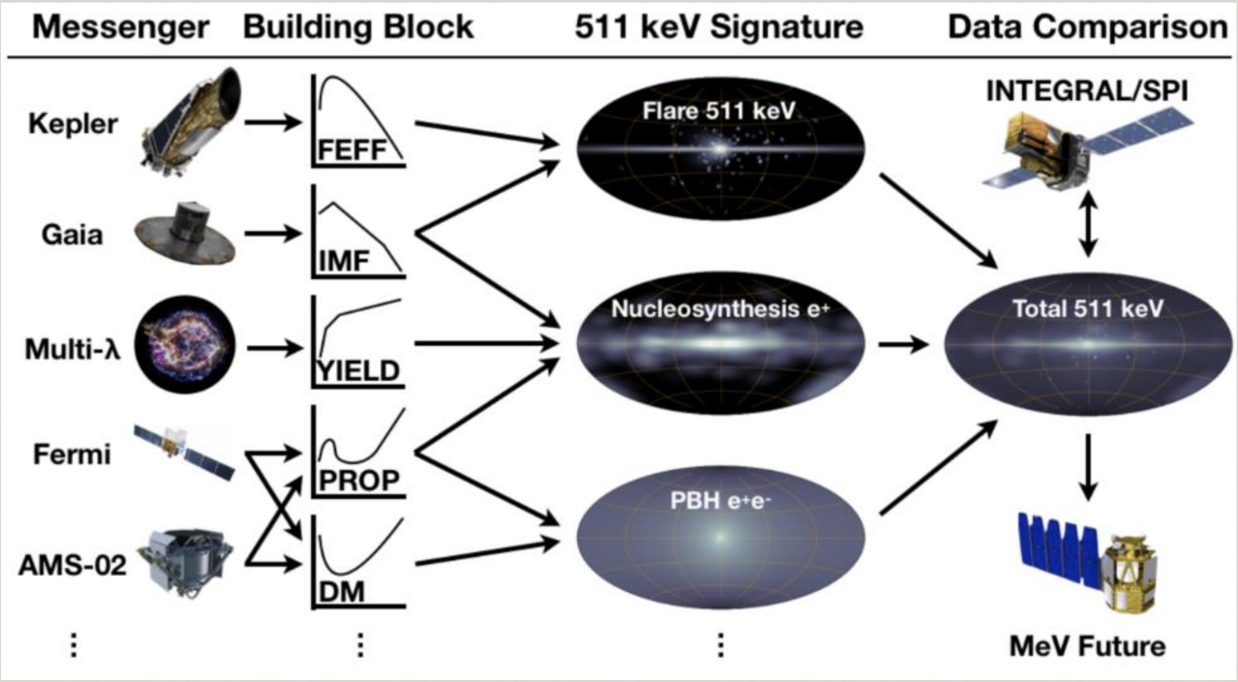
Can we identify the properties of a DM particle from our positron searches?



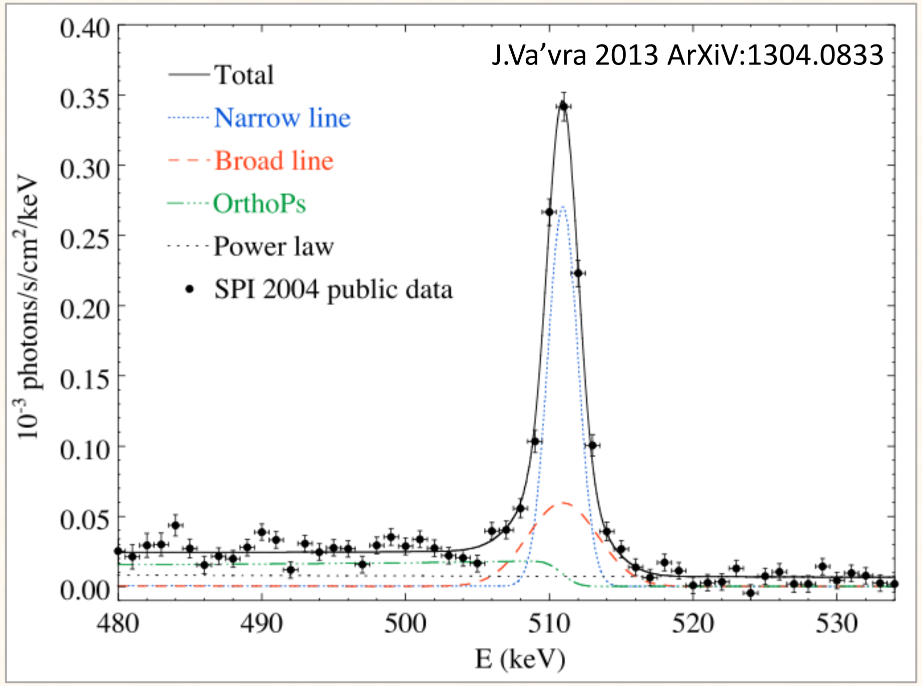


Beyond GeV positrons

A better characterization on the production and propagation of positrons (and electrons) can be fundamental to solve some puzzles in this field.



T. Siegert 2023 arXiv:2303.15582

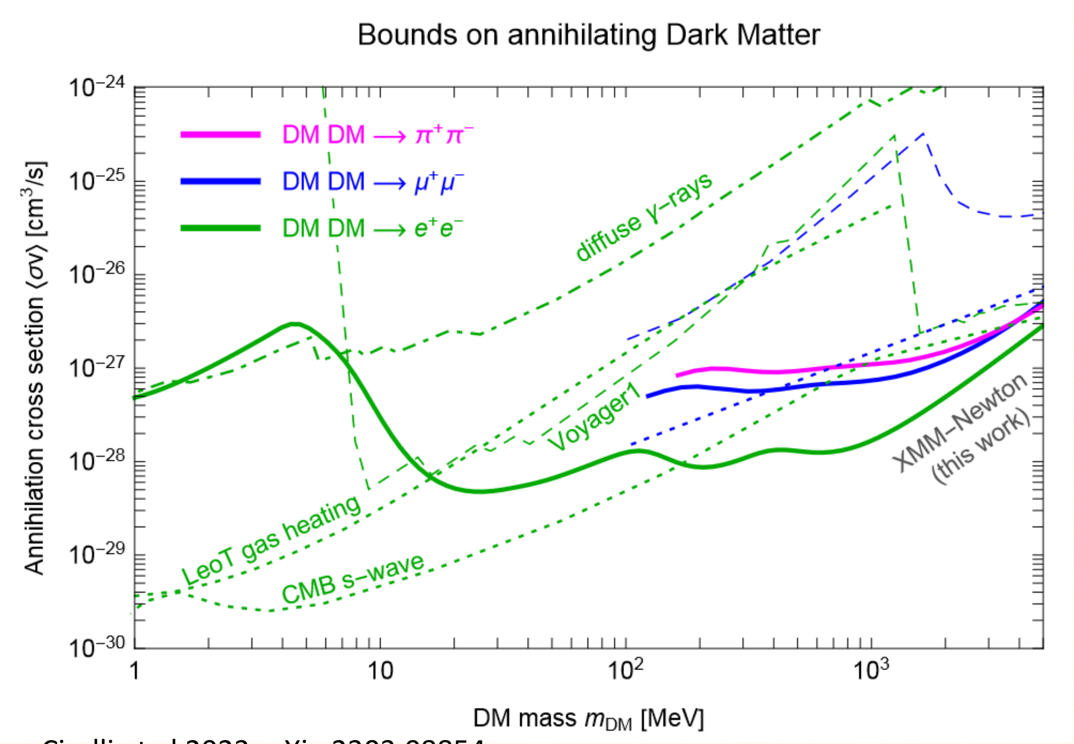


The distribution of the emission line at 511 keV constitutes a mystery that does not have a clear explanation yet. Better modelling on the production of positrons from different sources is crucial!

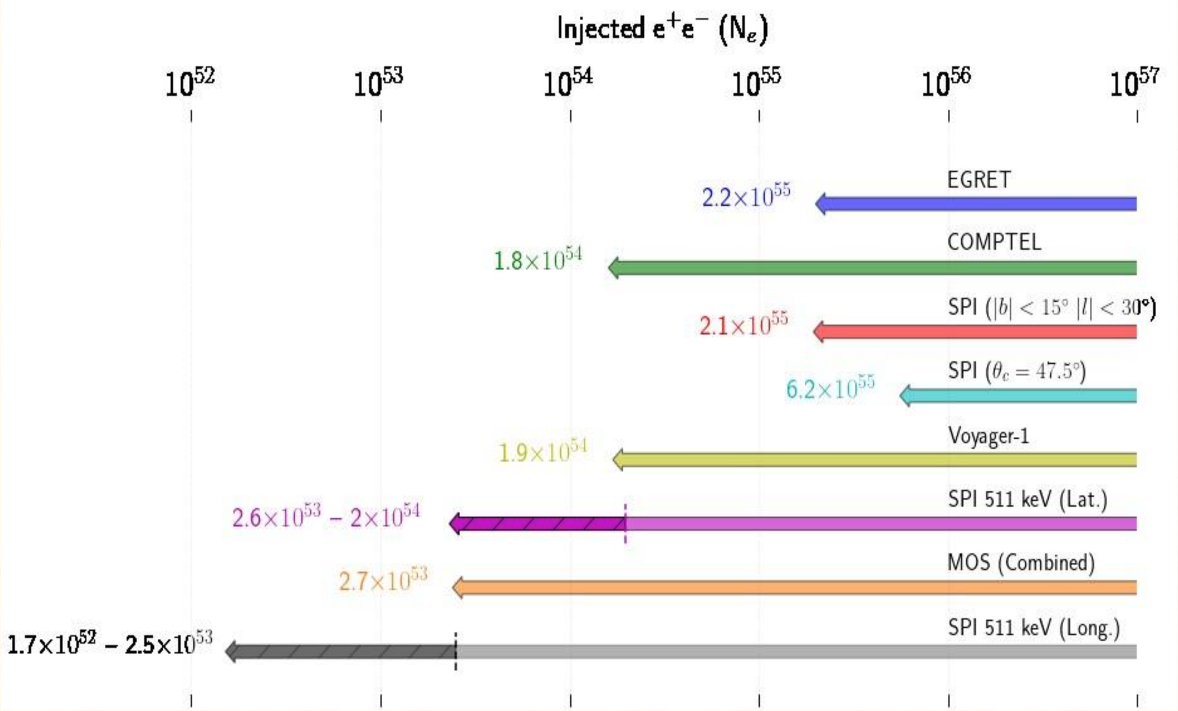
Beyond GeV positrons

A better knowledge on the **spatial distribution and production of positrons and electrons in the sub-GeV range** can **improve** also our **constraints** on the **existence and production of exotic particles in the Galaxy**.

The combination of gamma-ray with cosmic-ray data is crucial here!



Cirelli et al 2023 arXiv:2303.08854



P.D.L et al 2023 arXiv:2307.13731