Galactic Cosmic Rays Anomalies

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Anomalies in Cosmic Rays (CRs)

Effetcs in the data not straightforwardly explained by state-of-the-art theories

Charged particles (and gamma rays) of galactic origin

Here I discuss charged particles at GeV - TeV

Primary and secondary CRs in the Galaxy

Primaries: produced in the sources (SNR and Pulsars)
H, He, CNO, Fe; e−, e+; possibly e^+, p^-, d^- from Dark Matter annihilation

Secondaries: produced by spallation of primary CRs (p, He,C, O, Fe) on the interstellar medium (ISM): Li, Be, B, sub-Fe, [...], (radioactive) isotopes ; e^+, p^-, d^-

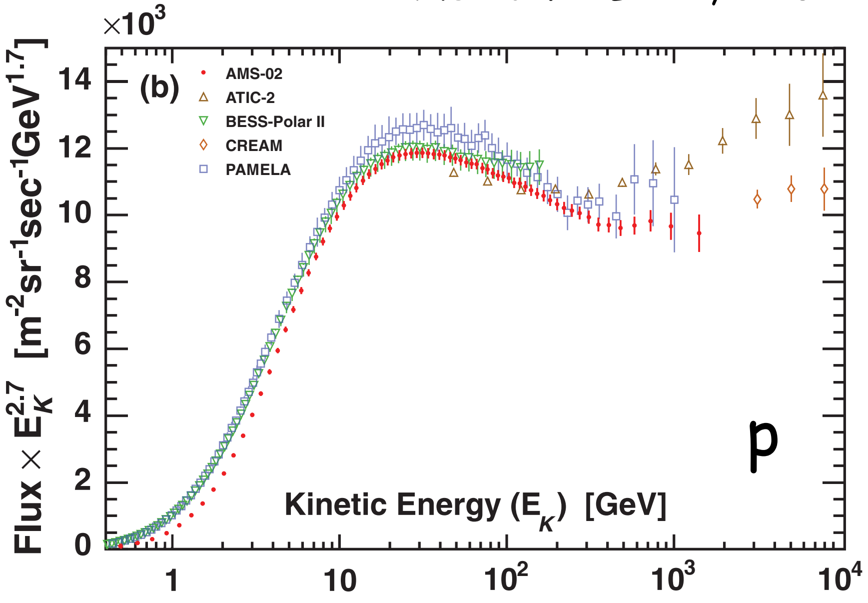
At first order, we understand fluxes at Earth as shaped by few, simple, isotropic effects:

- acceleration in shocked stellar environments (SNR, PWN)
- particle interactions between CRs and ISM
- diffusion of the galactic magnetic fields
- particle energy losses

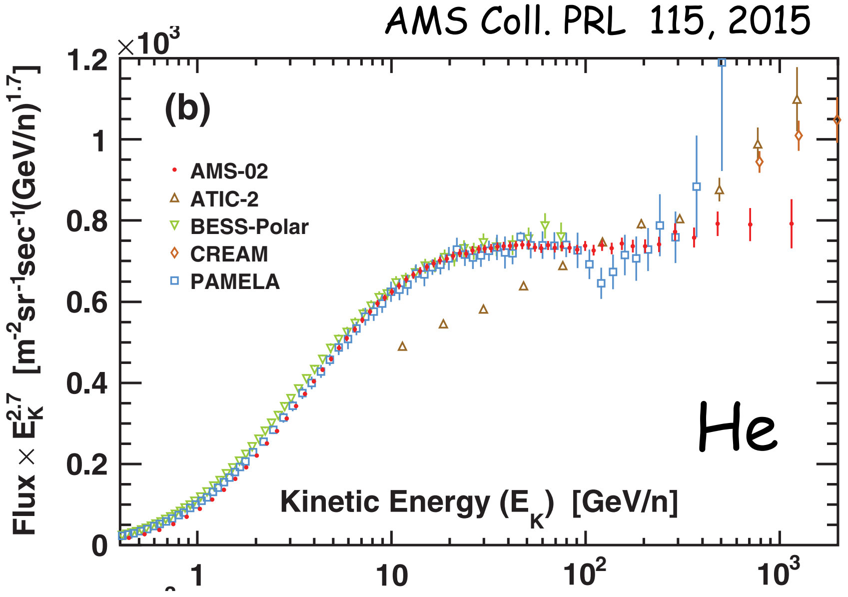
A spectral break in the primary fluxes: p & He

See G. Ambrosi's talk

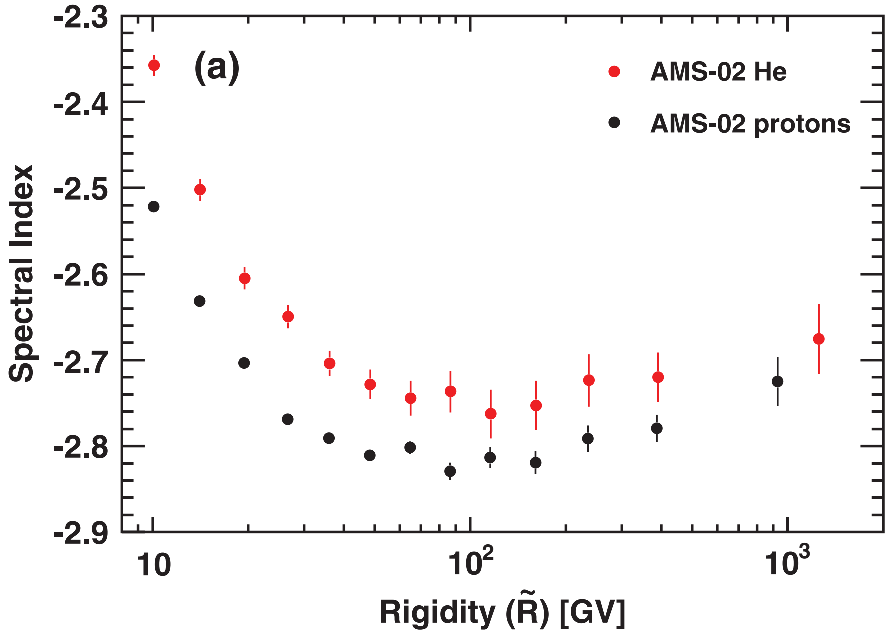
AMS Coll. PRL 114, 2015



AMS Coll. PRL 115, 2015



- The flux is not a single power law in energy
- A spectral break is measured for H, He and for heavier nuclei (C, O)



$$\gamma_{p/\mathrm{He}} = -0.077$$

A different high energy spectral index is measured for H and He

Discrepant hardening in p and nuclei

- Presence of a near source (Genolini et al. 2017)

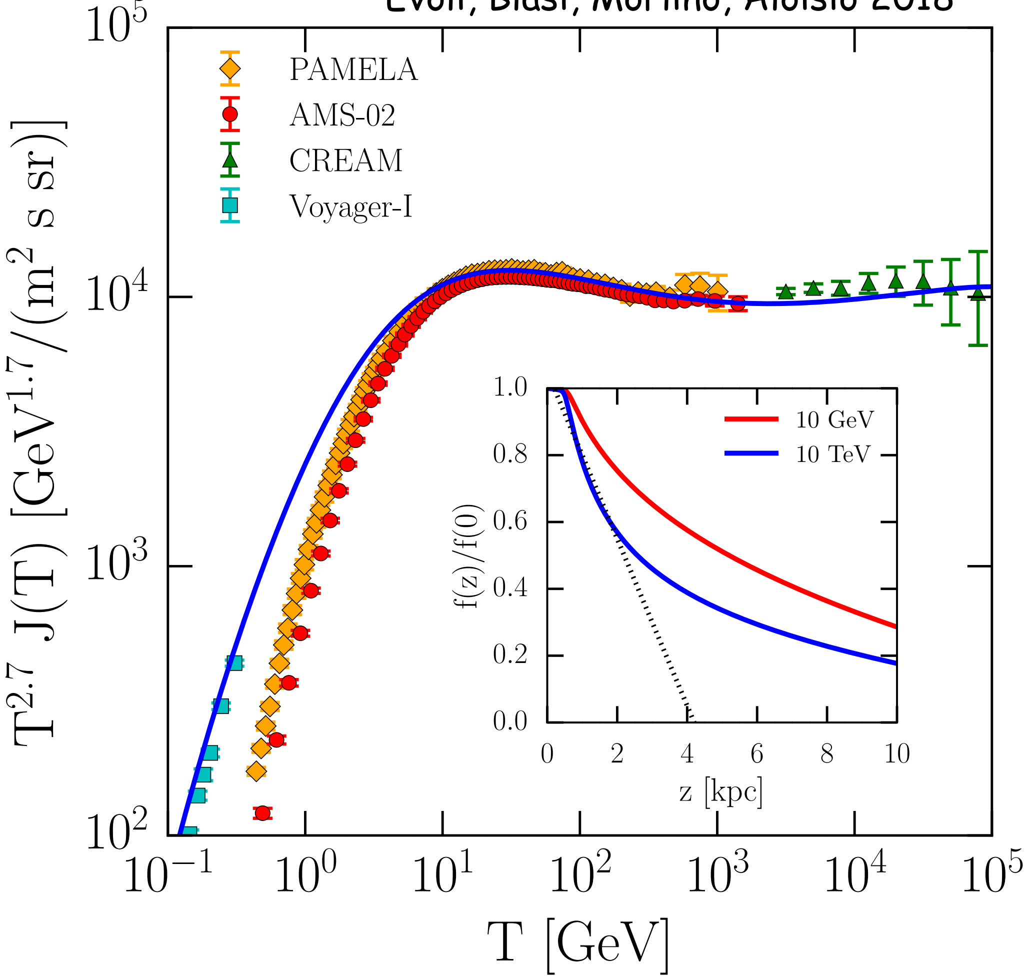
- Two SNR populations - old and younger (Tomassetti & FD 2015; Mertsch &Sarkar 2009)

- Non-isotropic diffusion, i.e. 2-zones diffusion model - D(E,z) (Tomassetti 2012, +)

- New phenomenon in galactic transport - self-generated waves and disc advection

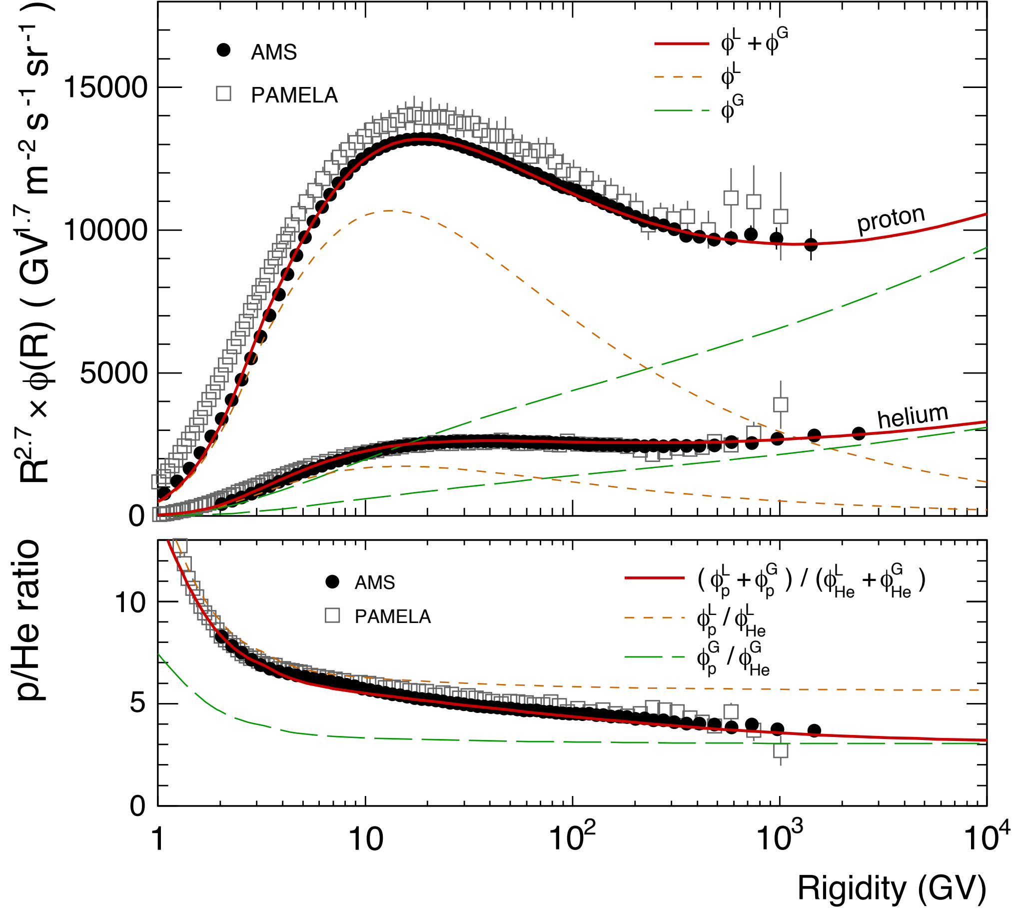
  (Blasi+2012, Aloisio, Blasi, Serpico 2015; Evoli+ 2018)

Evoli, Blasi, Morlino, Aloisio 2018

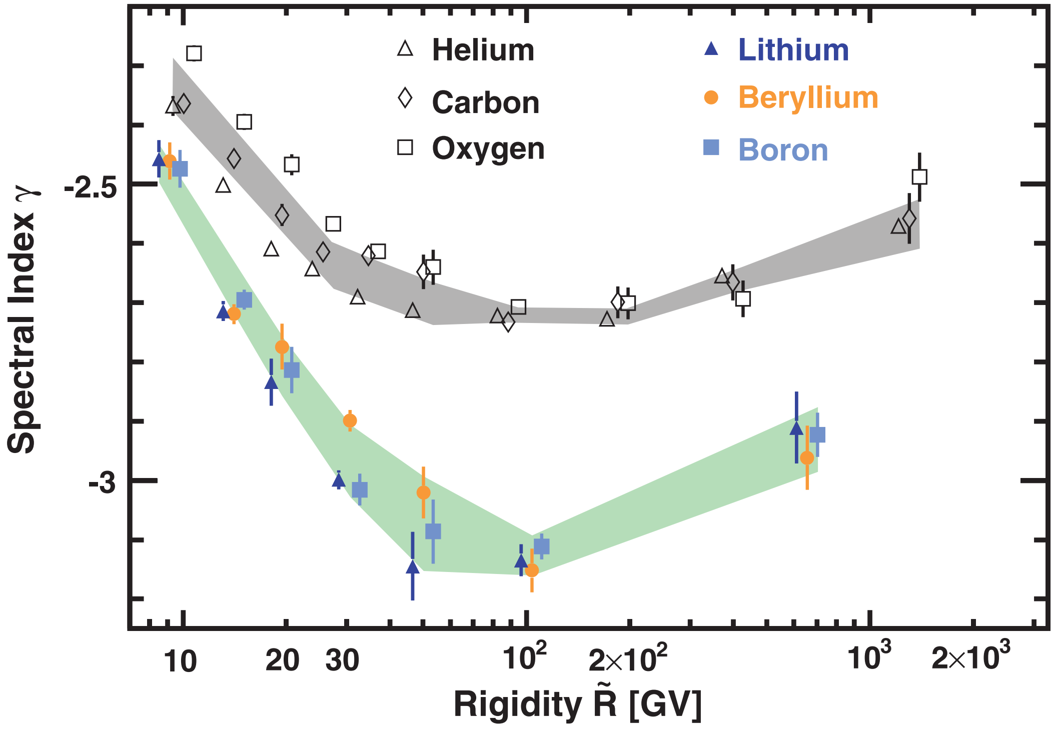


2 SNR pop. & D(E,z)

Tomassetti 2015

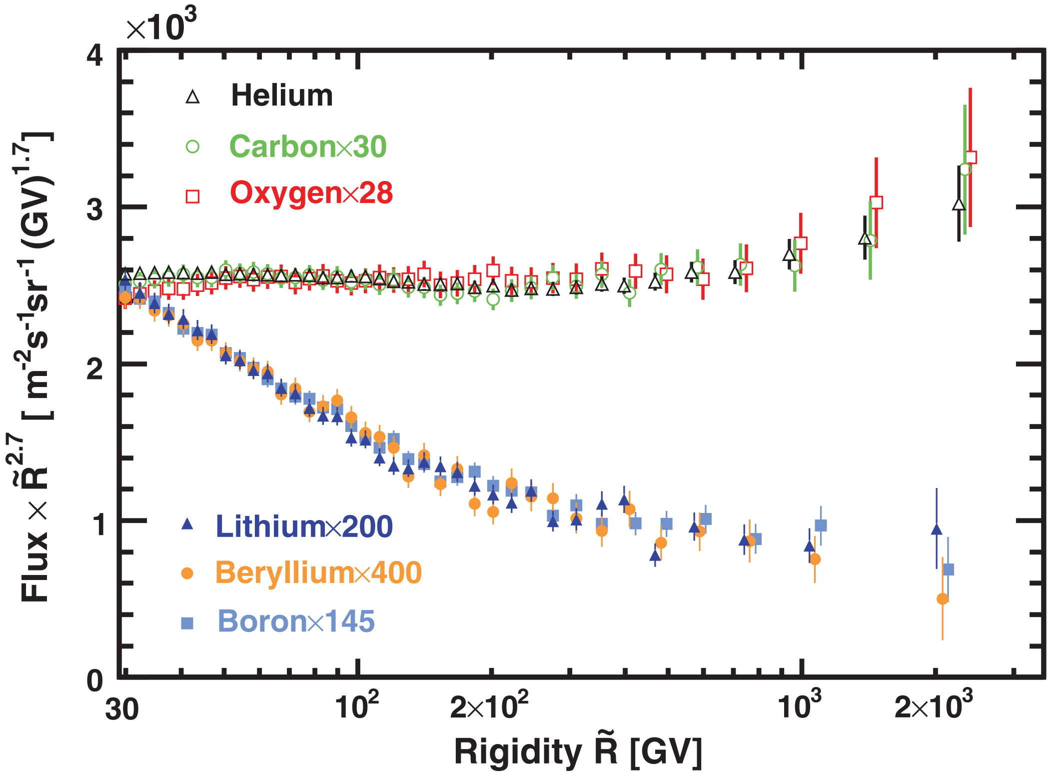


A spectral break in the secondary fluxes



The rigidity dependence of Li, Be and B
are nearly identical,
but different from the primary
He, C and O (and also p).

Li, Be, B fluxes measured by Pamela and AMS
show an identical hardening
w.r.t. energy above 200 GV.



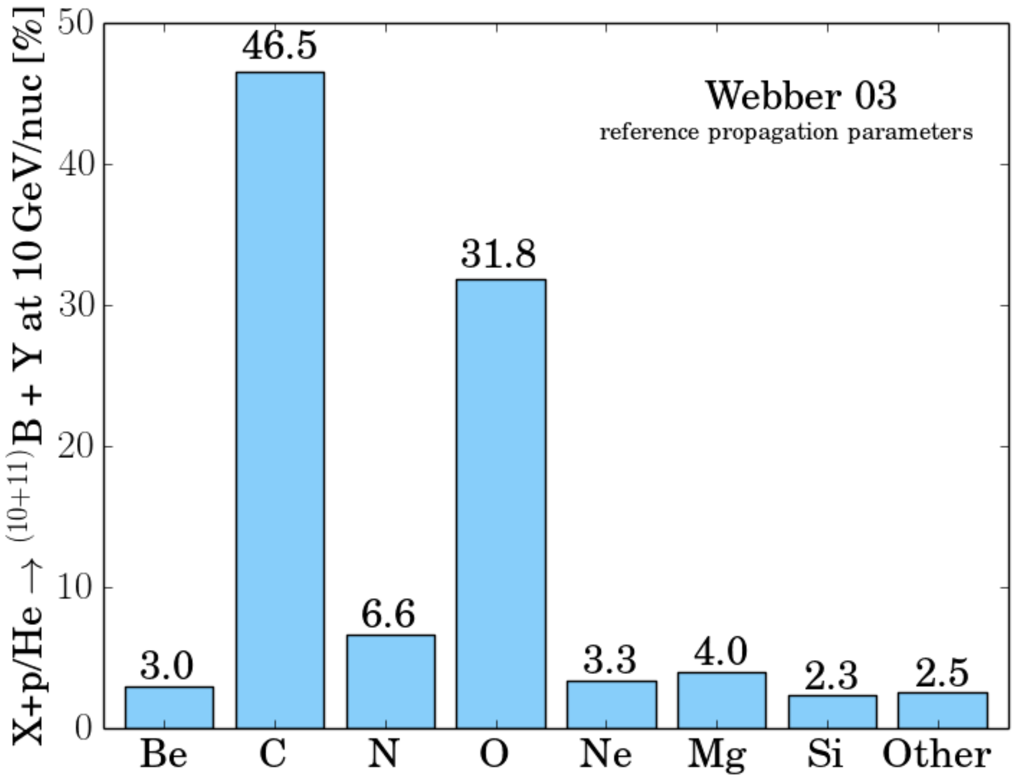
The spectral index of secondaries
hardens 0.13 +- 0.03 more than
for primaries

Boron-to-Carbon: a standard candle for fixing GALACTIC PROPAGATION

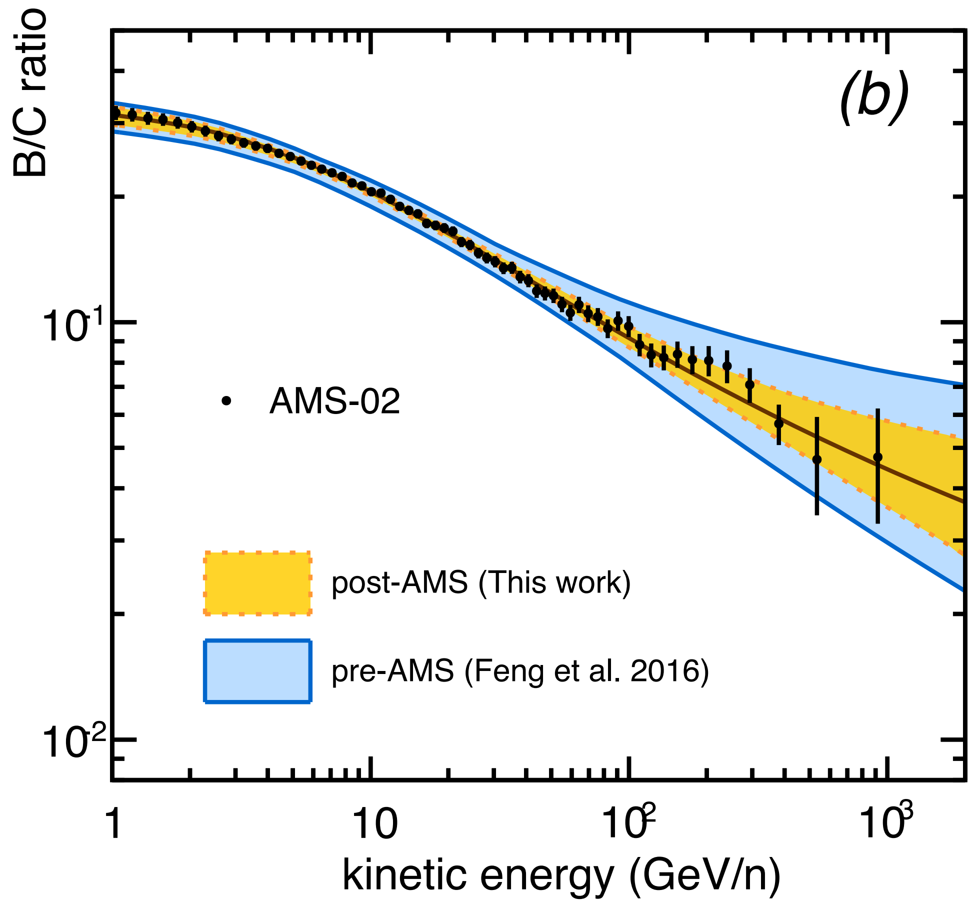
Li, Be, B are produced by fragmentation of heavier nuclei (mostly C, N, O) on H and He: production cross sections

B/C is very sensitive to **propagation effects**, kind of standard candle

Genolini, Putze, Serpico, Salati 2015

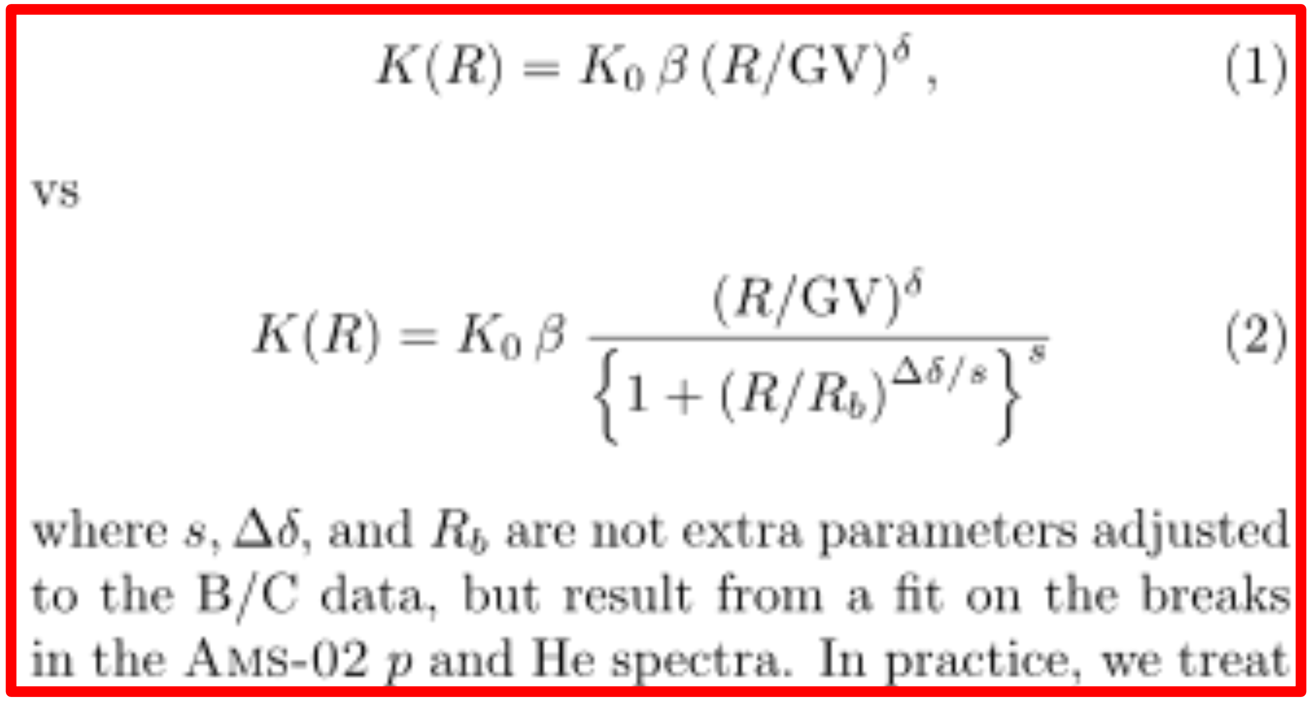


Tomassetti, Feng, Oliva PRD 2017



B/C (AMS, PRL 117, 2016) does not show features at high energies

A break in the diffusion coefficient?



$$K(R) = K_0\,\beta\,(R/\mathrm{GV})^{\delta}\,, \qquad (1)$$

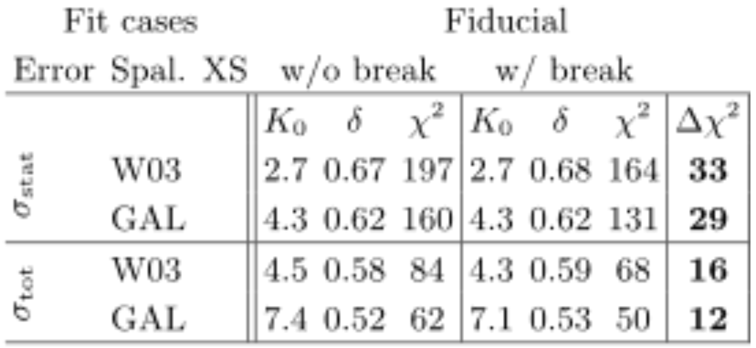
vs

$$K(R) = K_0\,\beta\,\frac{(R/\mathrm{GV})^{\delta}}{\left\{1+(R/R_b)^{\Delta\delta/s}\right\}^{s}} \qquad (2)$$

where s, $\Delta\delta$, and R_b are not extra parameters adjusted to the B/C data, but result from a fit on the breaks in the AMS-02 p and He spectra. In practice, we treat

R_b=312 GV, $\Delta\delta$=0.142, s=0.040

(Diffusive halo size fixed L= 10 kpc)



Fit cases		Fiducial						
Error	Spal. XS	w/o break			w/ break			
		K_0	δ	χ^2	K_0	δ	χ^2	$\Delta\chi^2$
$\sigma_{\rm stat}$	W03	2.7	0.67	197	2.7	0.68	164	**33**
	GAL	4.3	0.62	160	4.3	0.62	131	**29**
$\sigma_{\rm tot}$	W03	4.5	0.58	84	4.3	0.59	68	**16**
	GAL	7.4	0.52	62	7.1	0.53	50	**12**

Genolini et al. PRL 2017

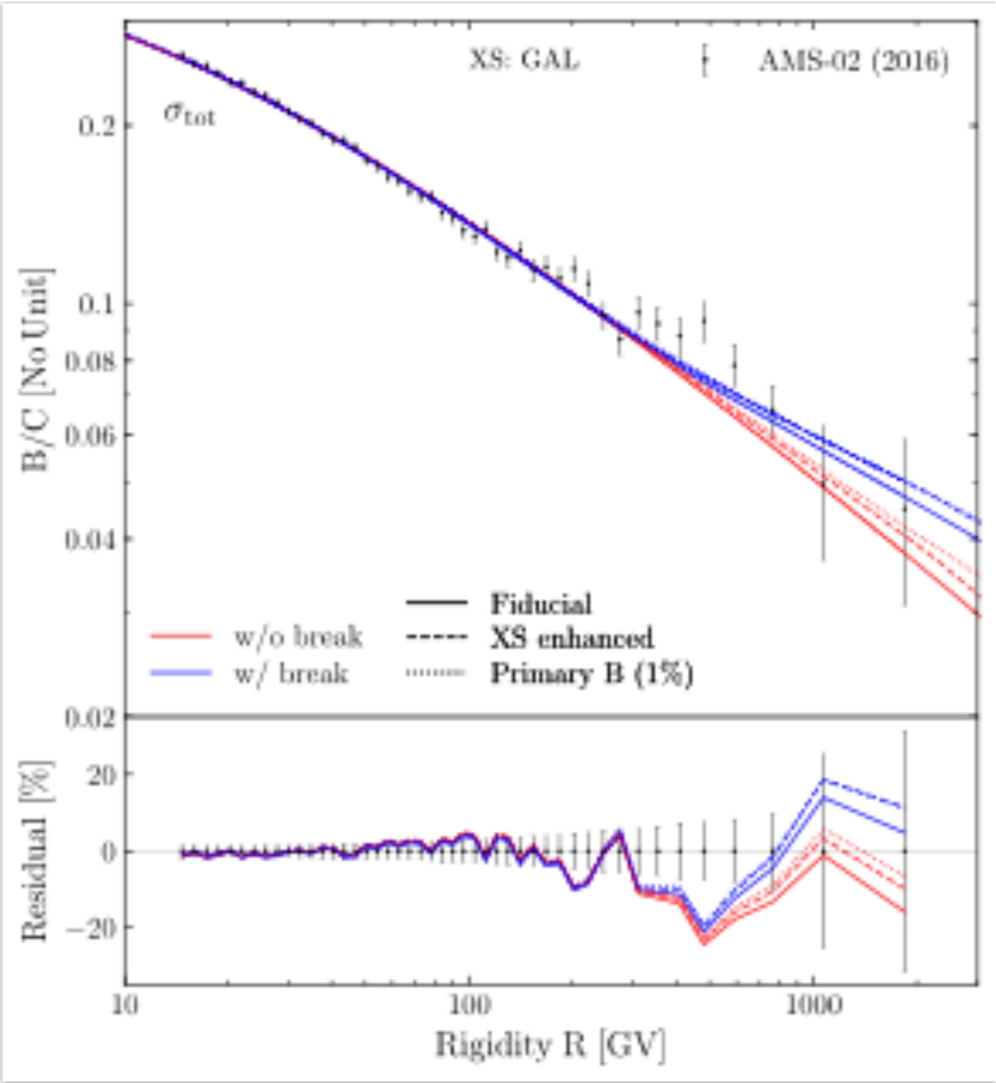


FIG. 2: Best fits and residuals with (blue) and without (red) the break using GALPROP cross sections and $\sigma_{\rm tot}$, for the different models considered in the text.

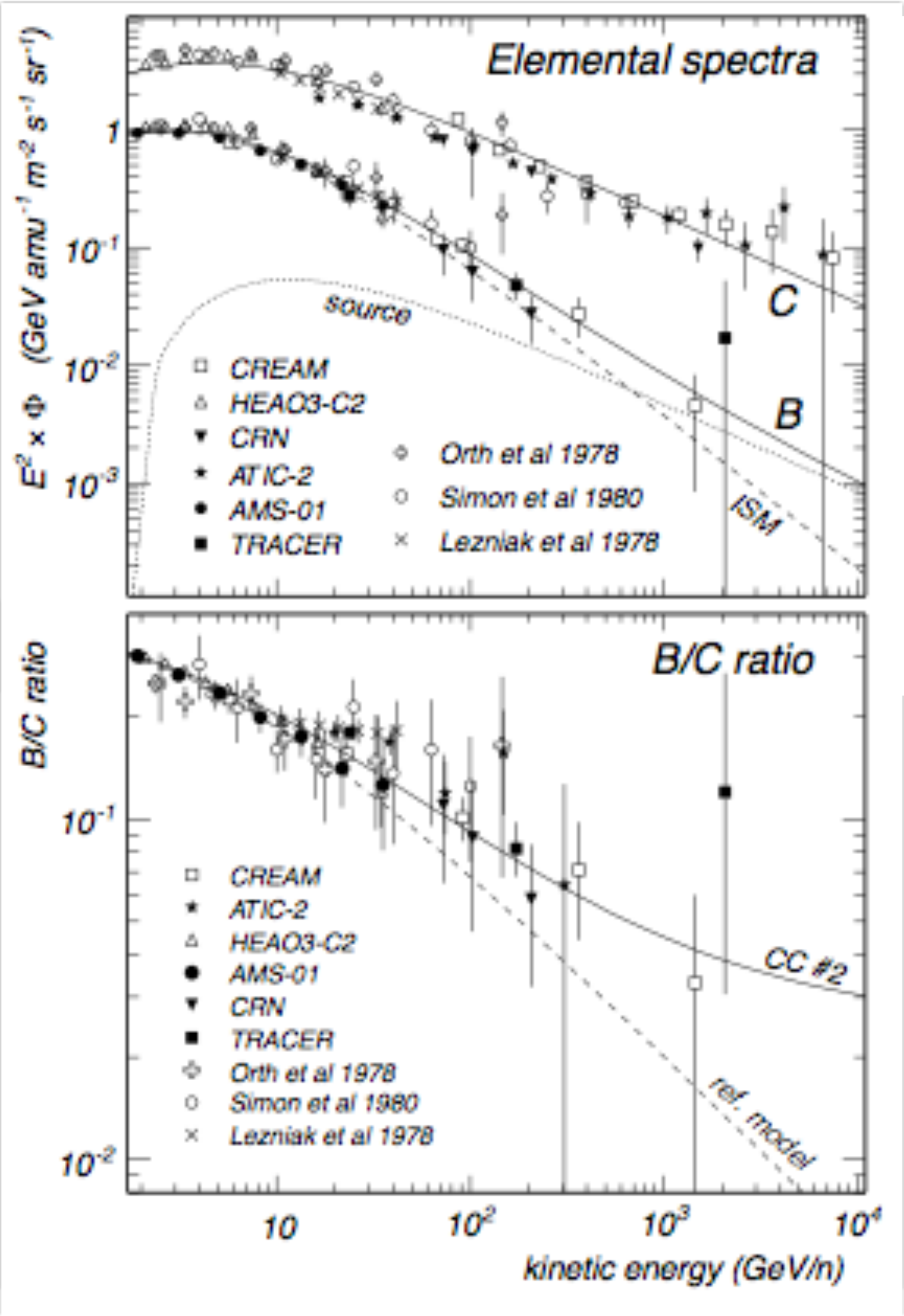
Strong indication from B/C of the **diffusive** origin of the p and He break

Re-acceleration of background CRs

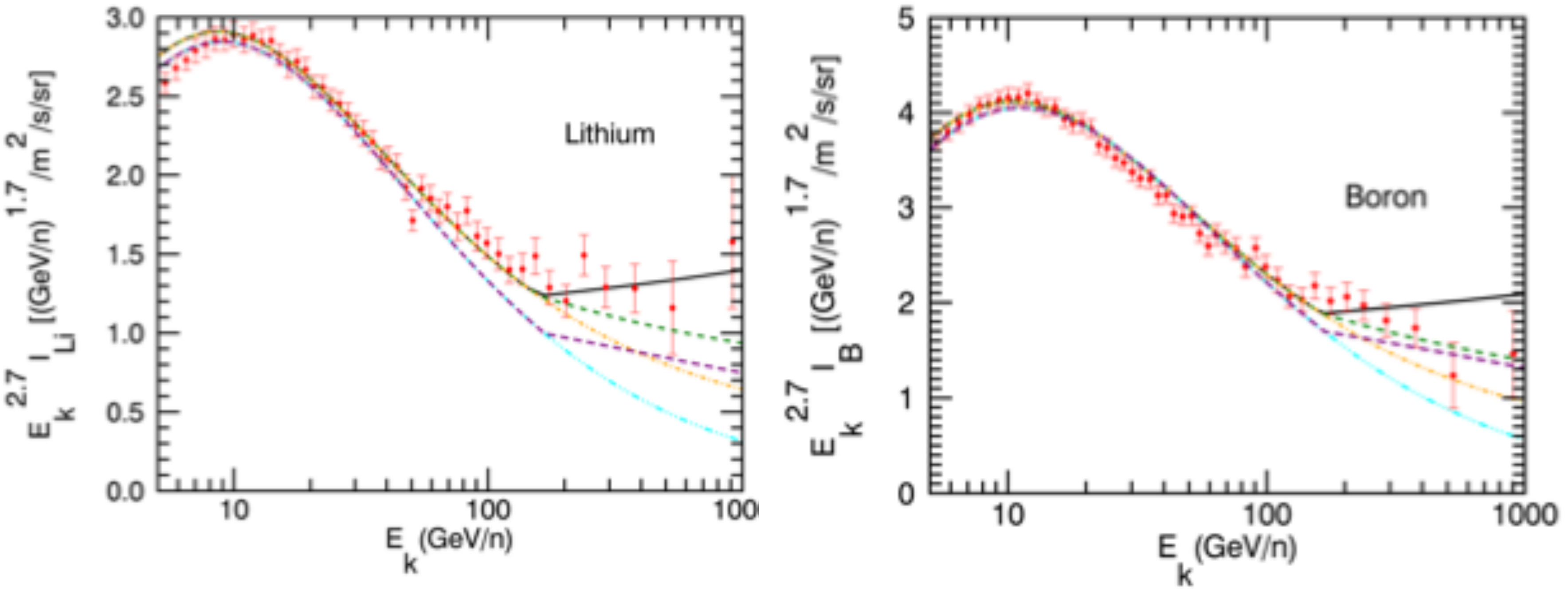
Wandel et al. ApJ 1987

Nuclei accelerated in SNRs, diffusing on galactic MFs and propagating in the Galaxy, can encounter a strong shock SNR accelerating them further

Tomassetti&FD, A&A 2012

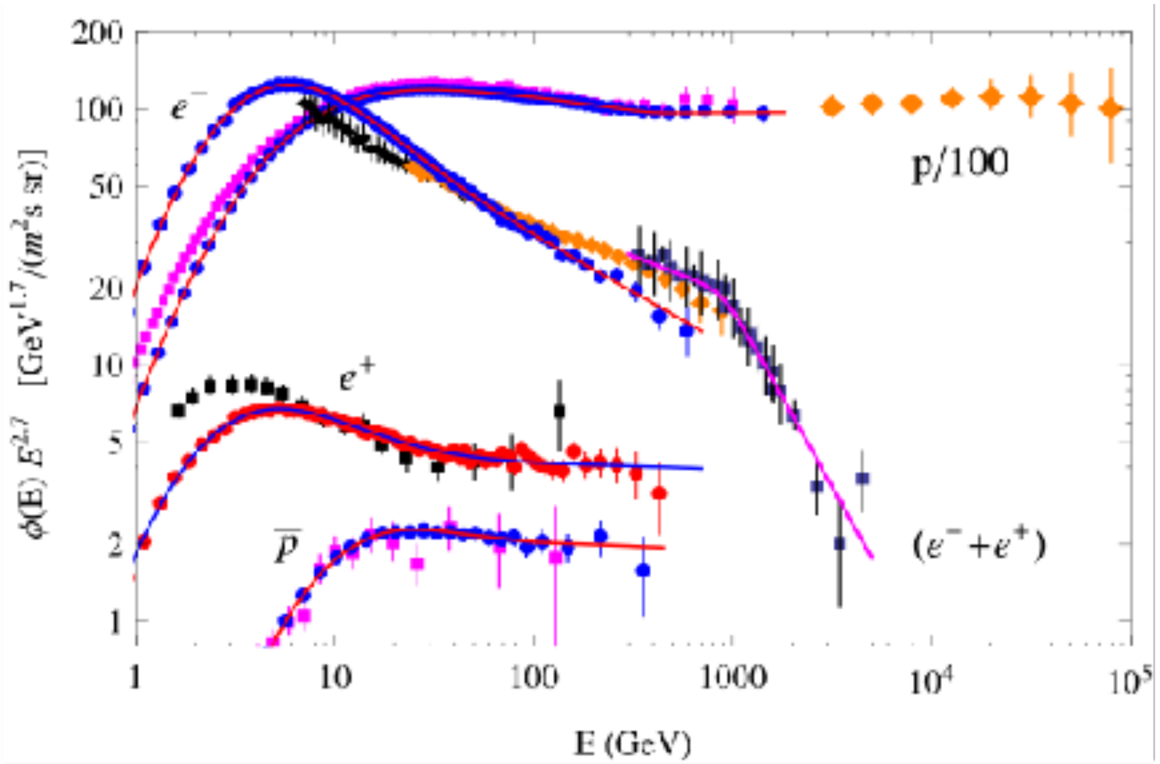


Blasi 2017

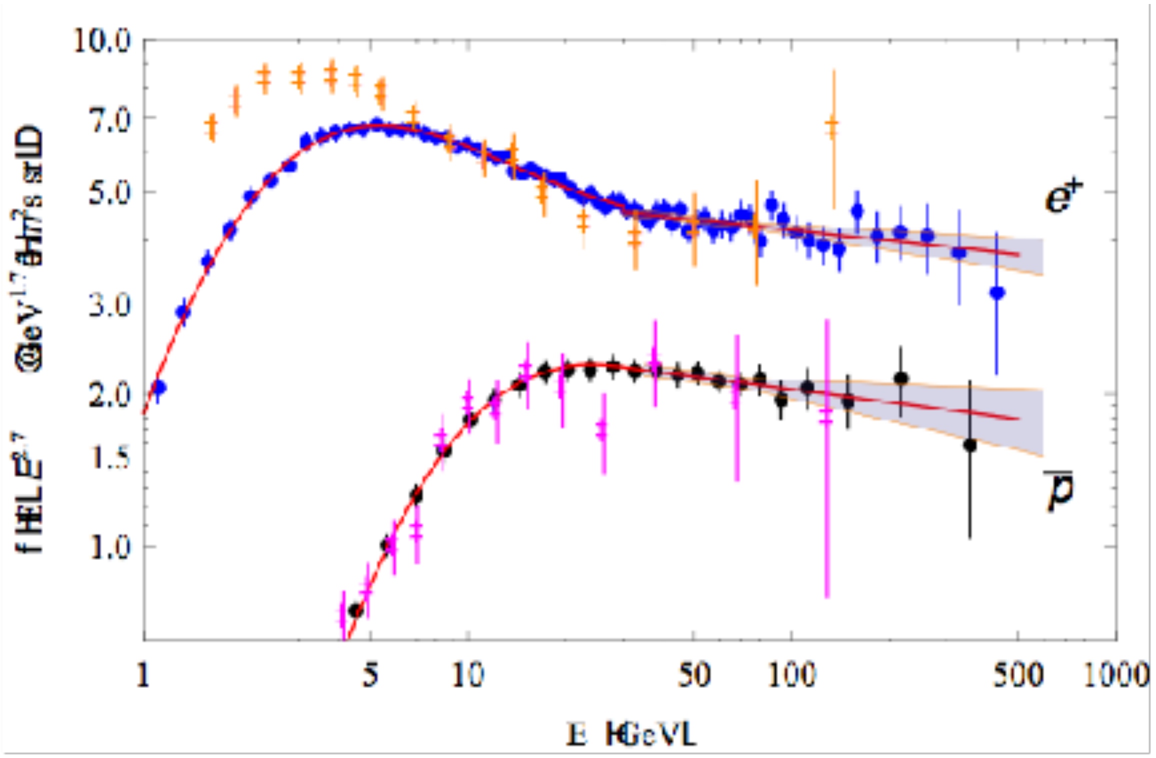


The observation by AMS of a hardening in many species could be at least partially explained by a re-acceleration inside the sources of CRs

More on CR spectral behavior from data



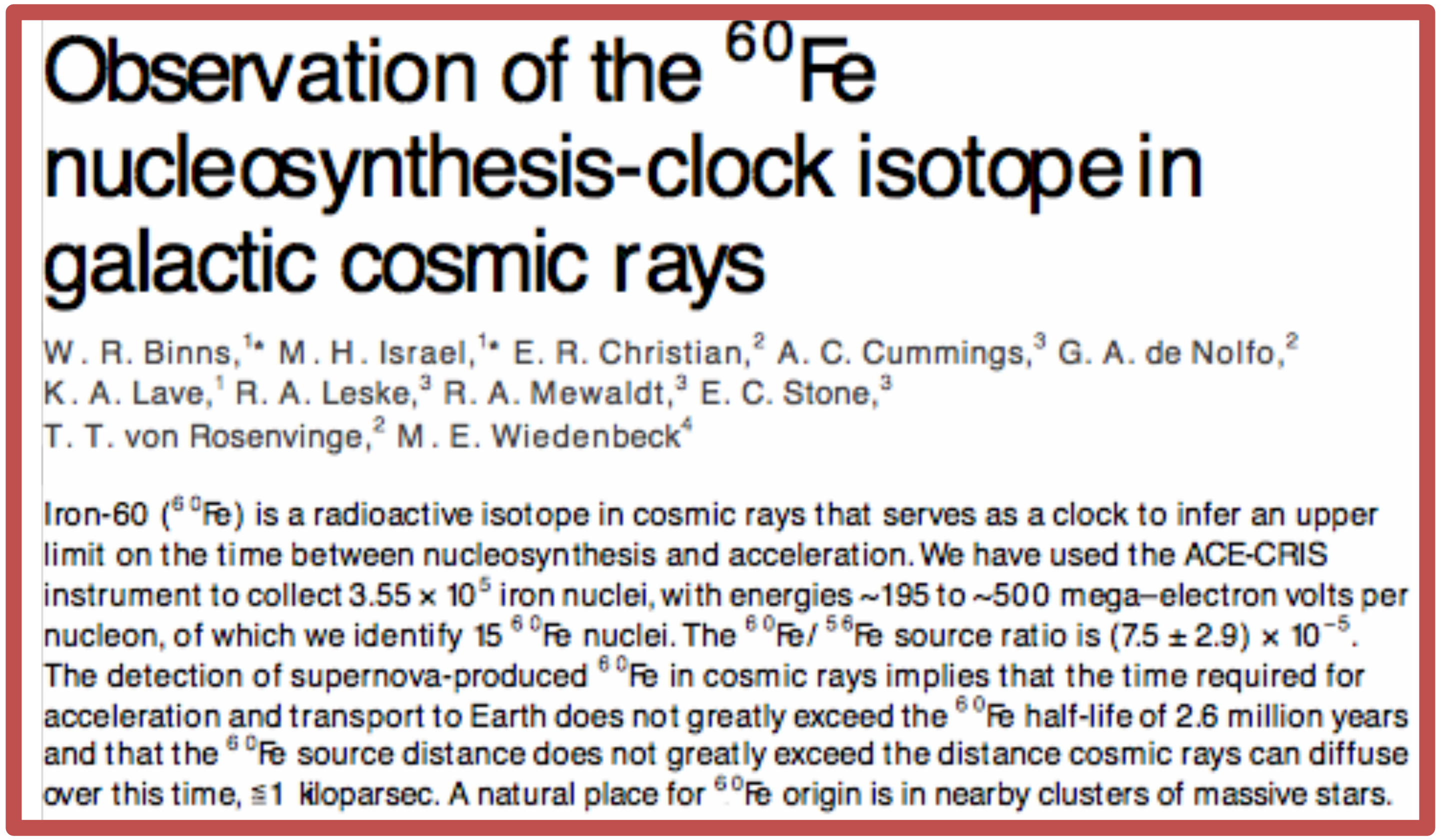
Lipari PRD 2017



Spectra of CRs are similarly hard, especially p- and e+ (but 2018 data).

It could be a coincidence,

Or hint at same secondary origin and short distances, equivalent to small energy losses for e-e+.



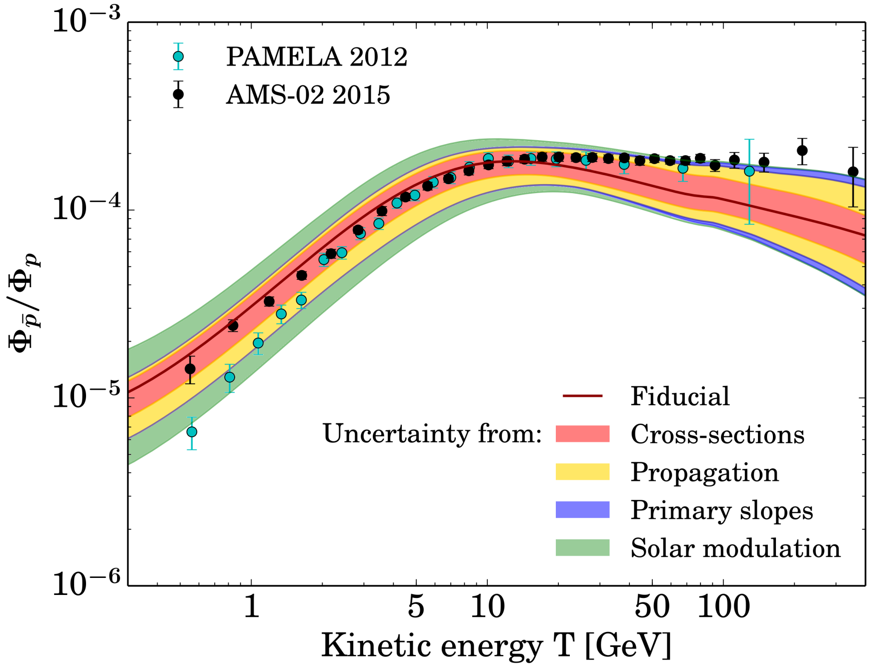
Observation of the ^{60}Fe nucleosynthesis-clock isotope in galactic cosmic rays

W. R. Binns,[1*] M. H. Israel,[1*] E. R. Christian,[2] A. C. Cummings,[3] G. A. de Nolfo,[2]
K. A. Lave,[1] R. A. Leske,[3] R. A. Mewaldt,[3] E. C. Stone,[3]
T. T. von Rosenvinge,[2] M. E. Wiedenbeck[4]

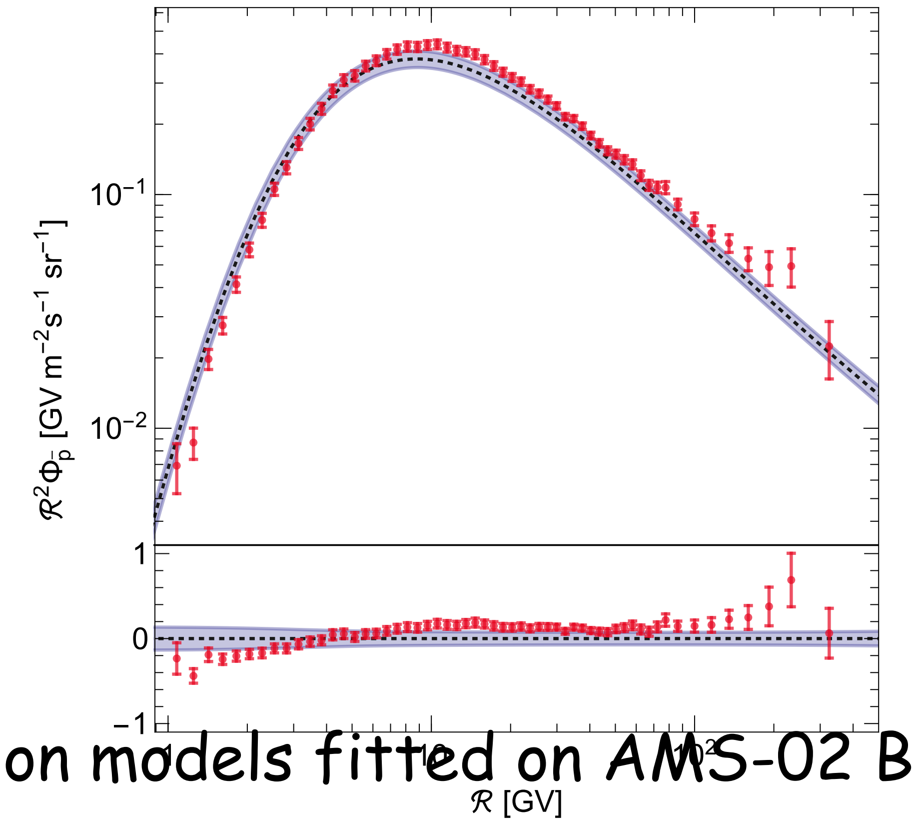
Iron-60 (^{60}Fe) is a radioactive isotope in cosmic rays that serves as a clock to infer an upper limit on the time between nucleosynthesis and acceleration. We have used the ACE-CRIS instrument to collect 3.55×10^5 iron nuclei, with energies ~195 to ~500 mega–electron volts per nucleon, of which we identify 15 ^{60}Fe nuclei. The ^{60}Fe/^{56}Fe source ratio is $(7.5 \pm 2.9) \times 10^{-5}$. The detection of supernova-produced ^{60}Fe in cosmic rays implies that the time required for acceleration and transport to Earth does not greatly exceed the ^{60}Fe half-life of 2.6 million years and that the ^{60}Fe source distance does not greatly exceed the distance cosmic rays can diffuse over this time, ≲1 kiloparsec. A natural place for ^{60}Fe origin is in nearby clusters of massive stars.

Antiproton flux at high energy: do secondaries fit all?

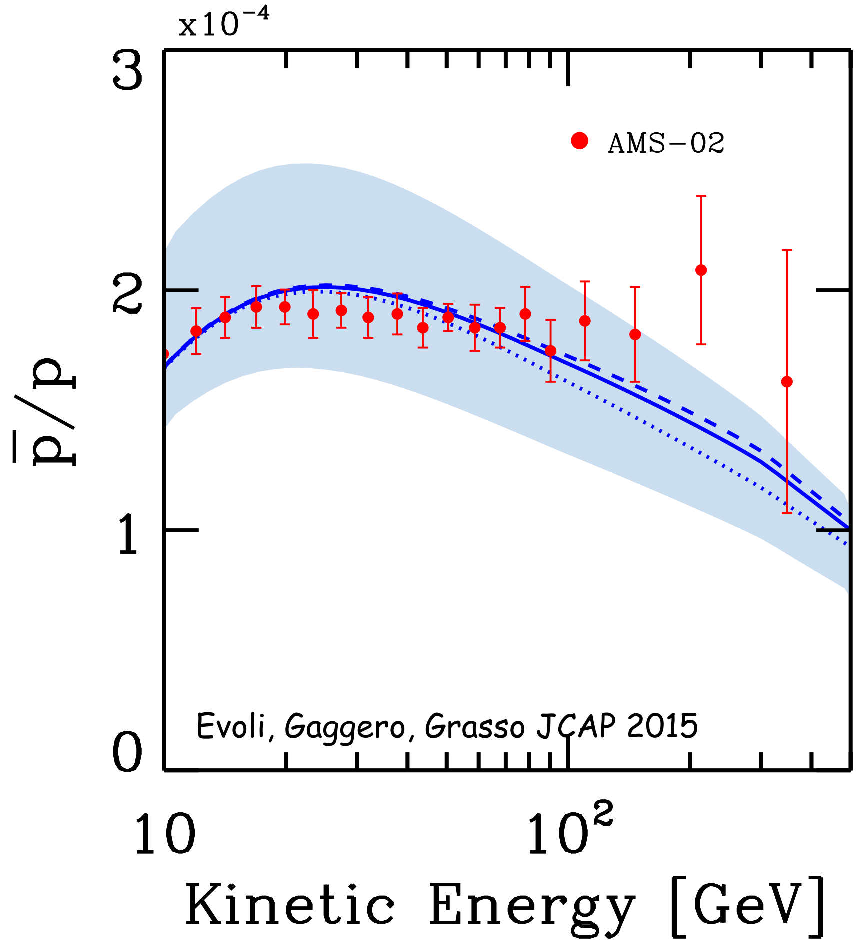
Giesen + JCAP 2015



Reinert & Winkler JCAP 2018



Propagation models fitted on AMS-02 B/C data.



Evoli, Gaggero, Grasso JCAP 2015

Secondary antiprotons from

(p, He)$_{CR}$ + (H, He)$_{ISM}$

can explain data naturally, mainly because

of the small diffusion coefficient slope indicated by B/C.

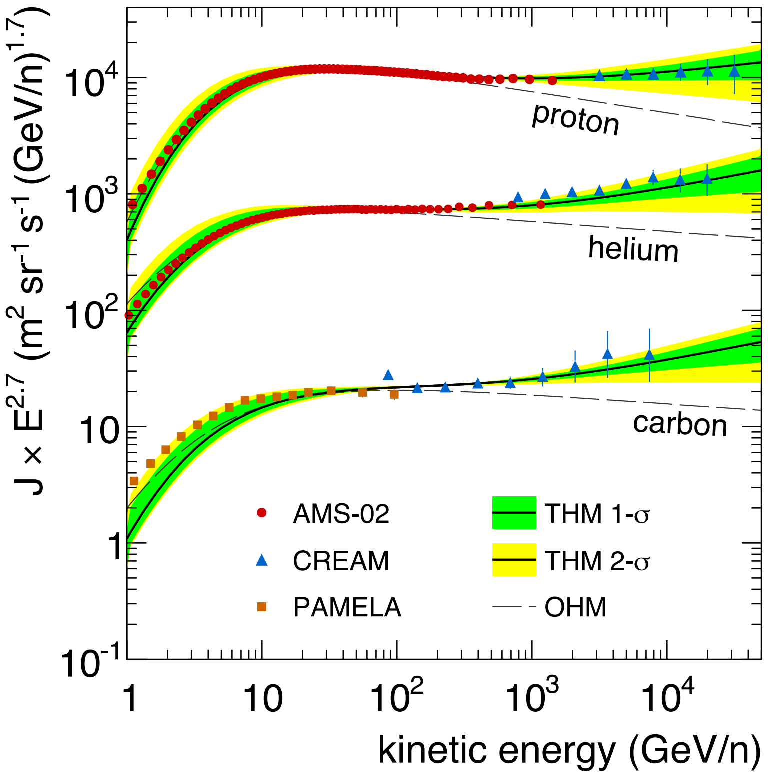
Greatest uncertainty set by nuclear cross sections.

Two halo transport for secondary antiprotons

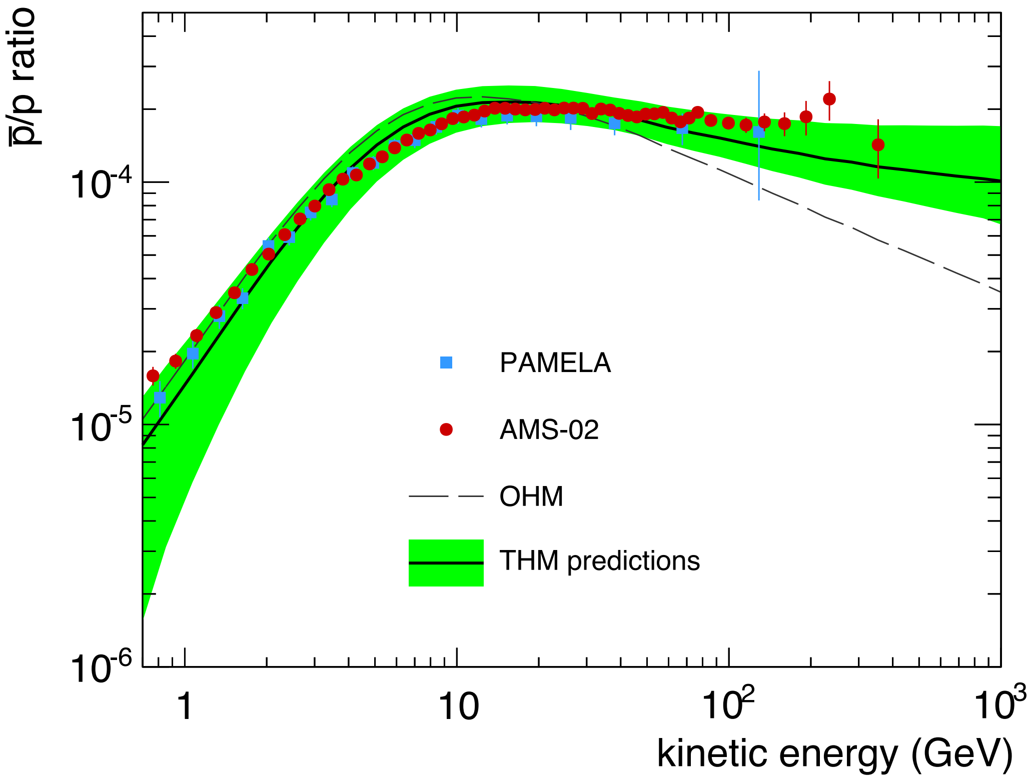
Tomassetti ApJ 2012, PRD 2015

Cosmic rays are allowed to experience a different type of diffusion when they propagate closer to the Galactic plane

$$D(\mathcal{R},z) = \begin{cases} D_0\beta^\eta\left(\frac{\mathcal{R}}{\mathcal{R}_0}\right)^{\delta} & (|z|<\xi L) \\ \chi D_0\beta^\eta\left(\frac{\mathcal{R}}{\mathcal{R}_0}\right)^{\delta+\Delta} & (|z|>\xi L) \end{cases}$$



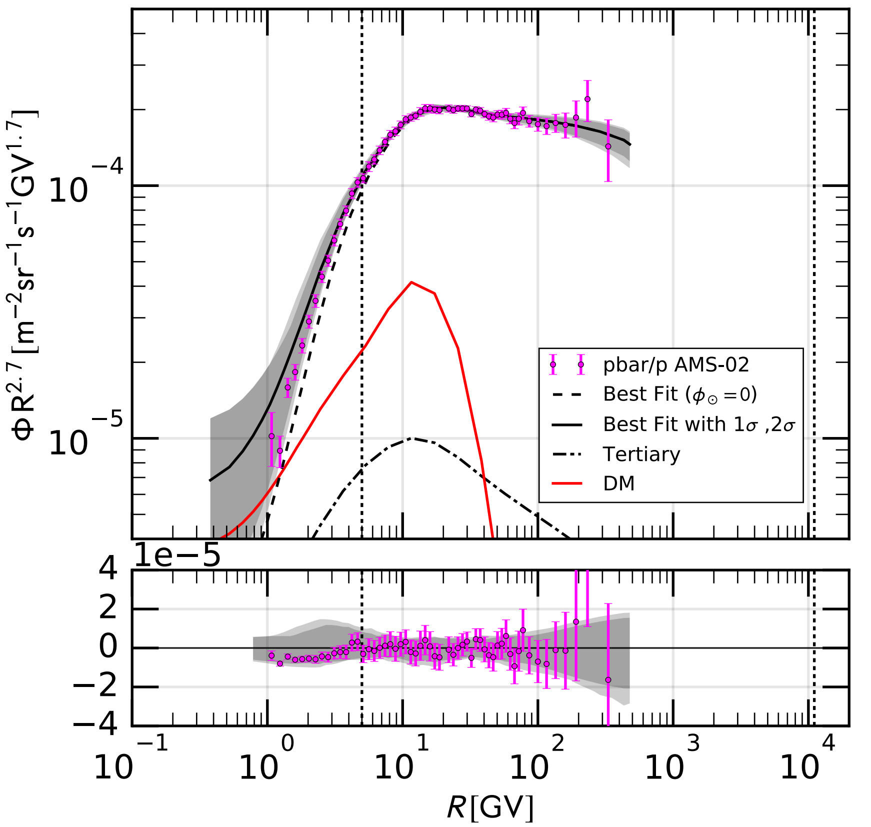
Feng, Tomassetti, Oliva PRD2016



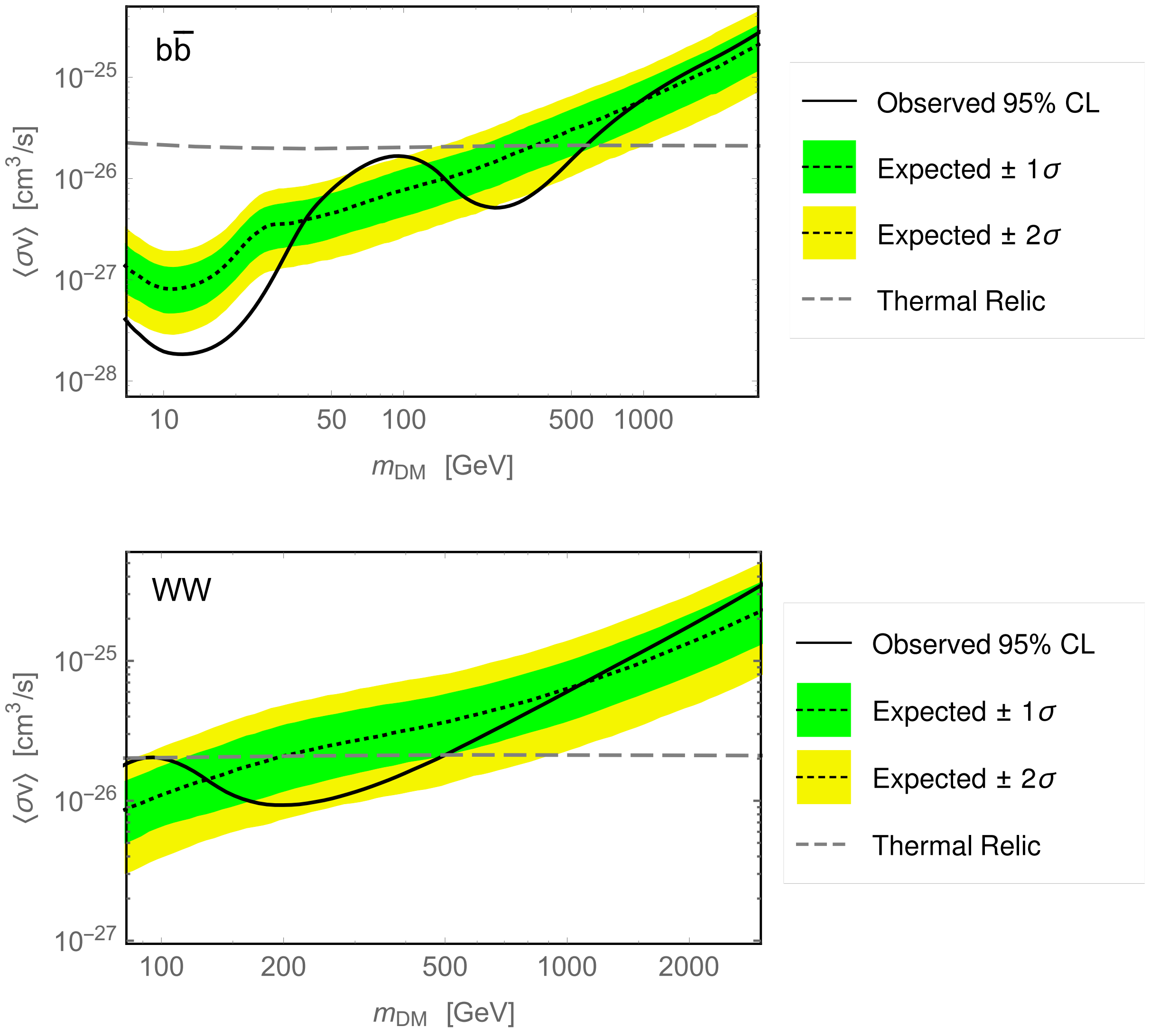
Antiprotons and other species are consistent with the 2 halo diffusive model

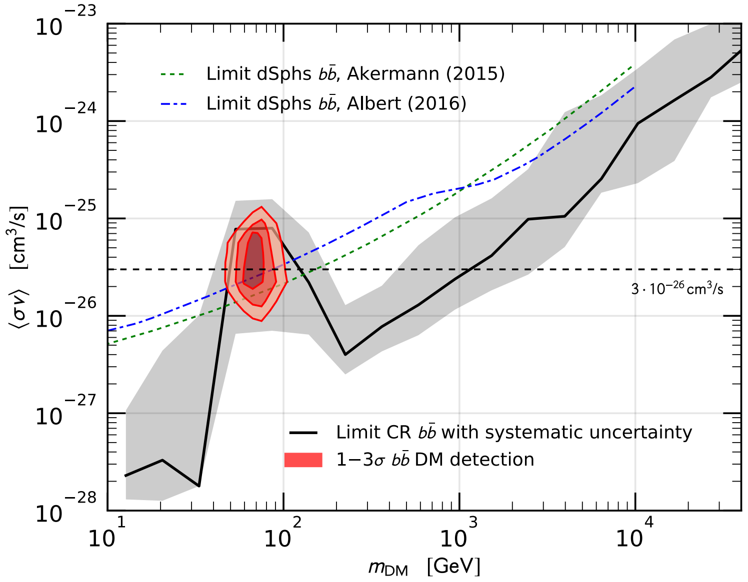
Possible contribution from dark matter

Cuoco, Korsmeier, Kraemer PRL 2017



Reinert & Winkler JCAP2018





Antiproton data are so precise that permit
to set strong upper bounds on
the dark matter annihilation cross section,
or to improve the fit w.r.t. to the secondaries
alone adding a tine DM contribution

Antiproton production cross sections

FD, Korsmeier, Di Mauro PRD 2017

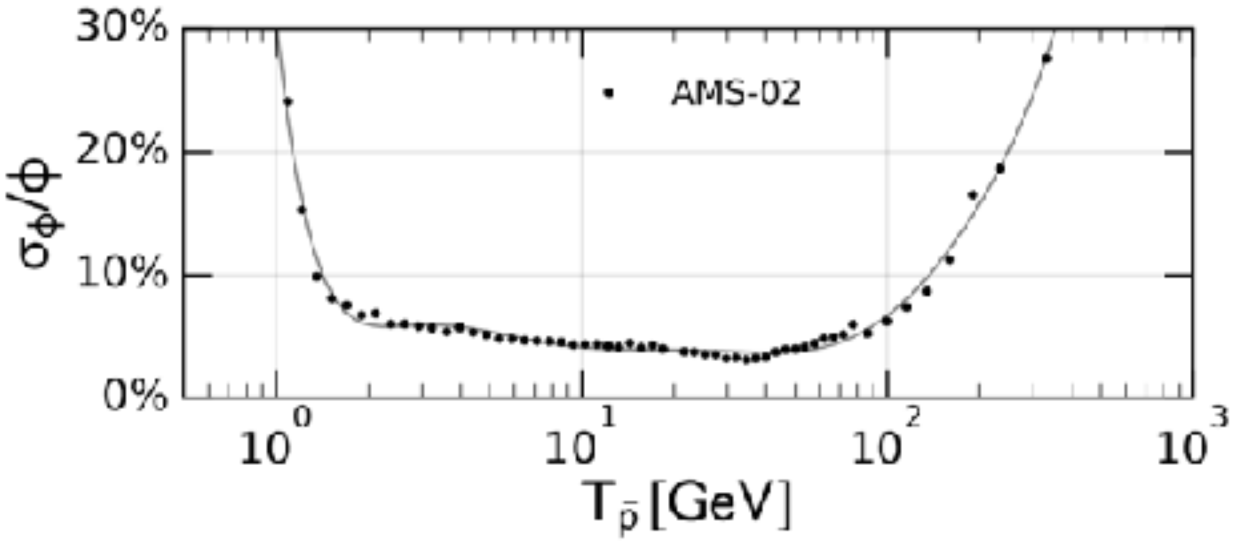
$$q_{ij}(T_{\bar{p}}) = \int_{T_{\rm th}}^{\infty} dT_i \; 4\pi \, n_{{\rm ISM},j} \, \phi_i(T_i) \, \frac{d\sigma_{ij}}{dT_{\bar{p}}}(T_i, T_{\bar{p}})$$

Source term

i, j = proton, helium

both in CRs and ISM

4 main reactions



Cosmic antiproton data are very precise:

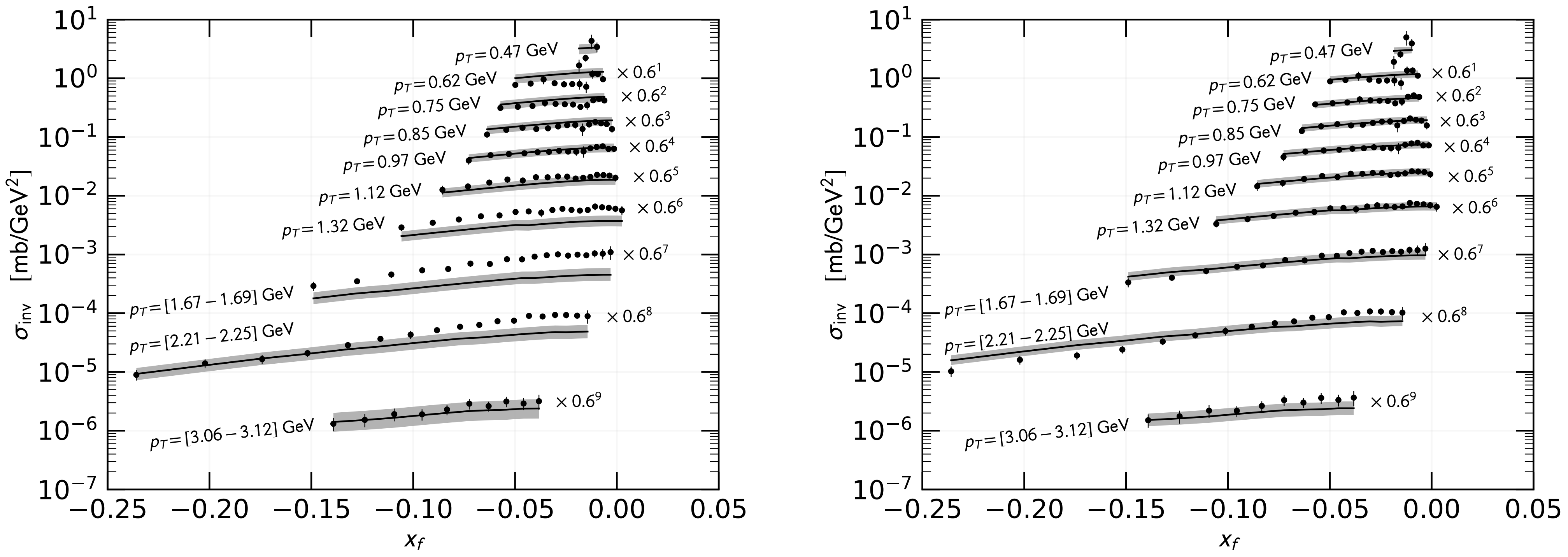
production cross sections should be known with high accuracy

in order not to introduce high **theoretical** uncertainties

New high energy data analysis

Korsmeier, FD, Di Mauro, PRD 2018
LHCb Coll. 1808.06127

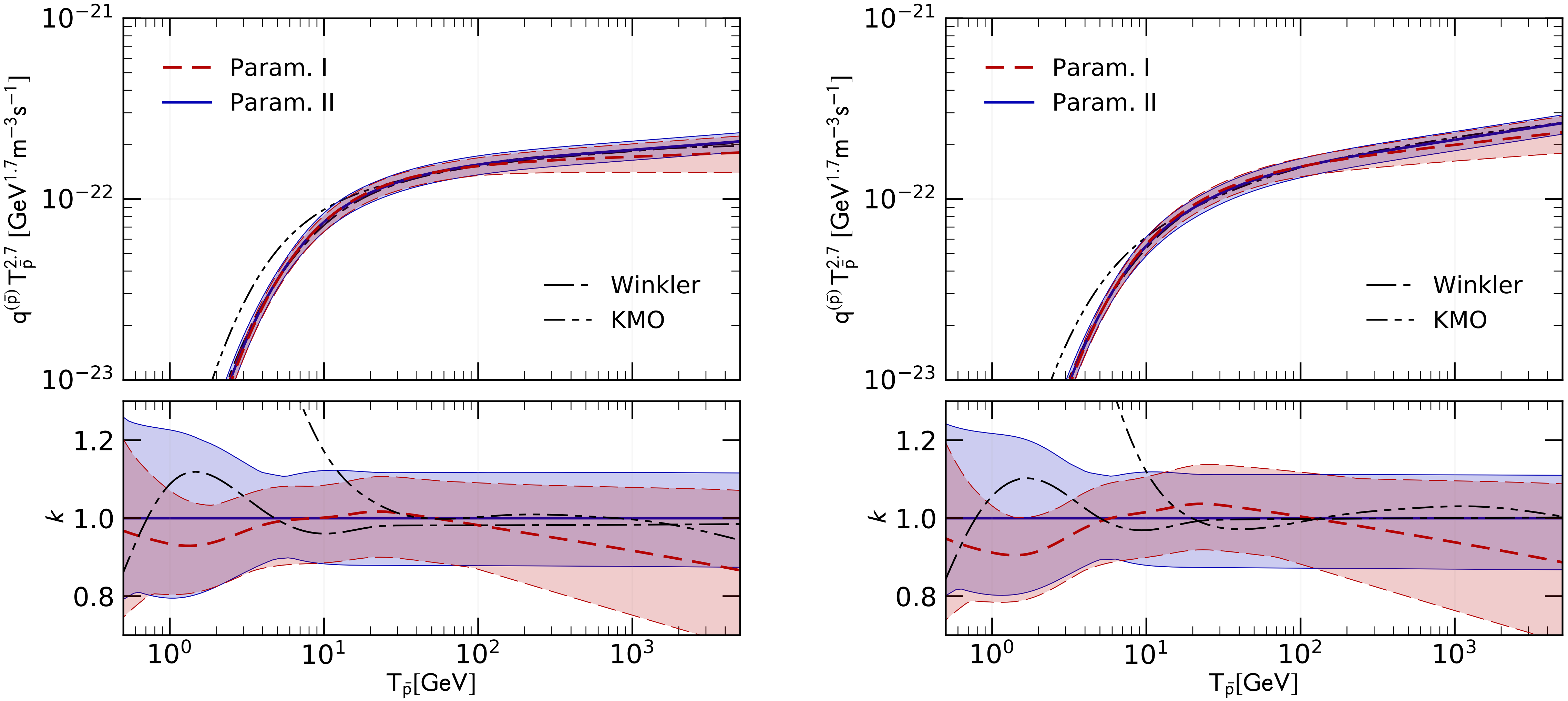
1. Fit to NA61 pp —> pbar + X data
2. Calibration of pA XS on NA49 pC —> pbar + X data
3. Inclusion of LHCb pHe —> pbar + X data



LHCb data (1808.06127, PRL subm.) agree better with one of the two pp parameterizations. They select the high energy behavior of the Lorentz invariant cross section

The antiproton source spectrum

Korsmeier, FD, Di Mauro PRD 2018



Param II is preferred by the fits.

The effect of LHCb data is to select a h.e. trend of the pbar source term.

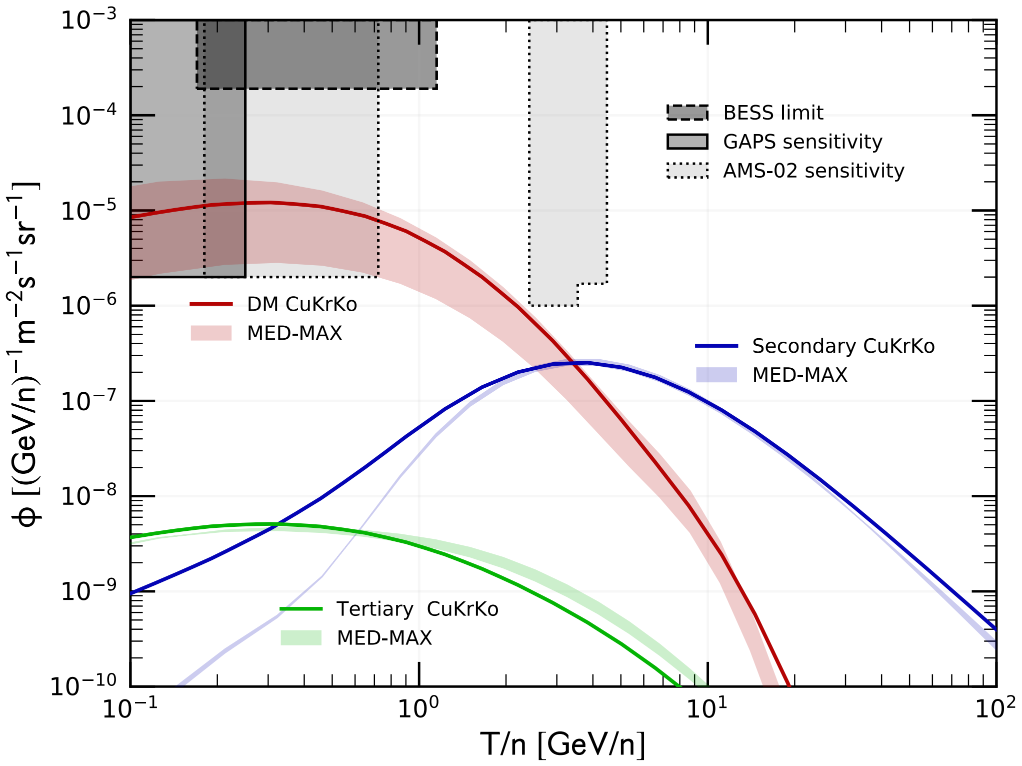
A harder trend at high energies is preferred.

Uncertainties still range about 20%, and increase at low energies.

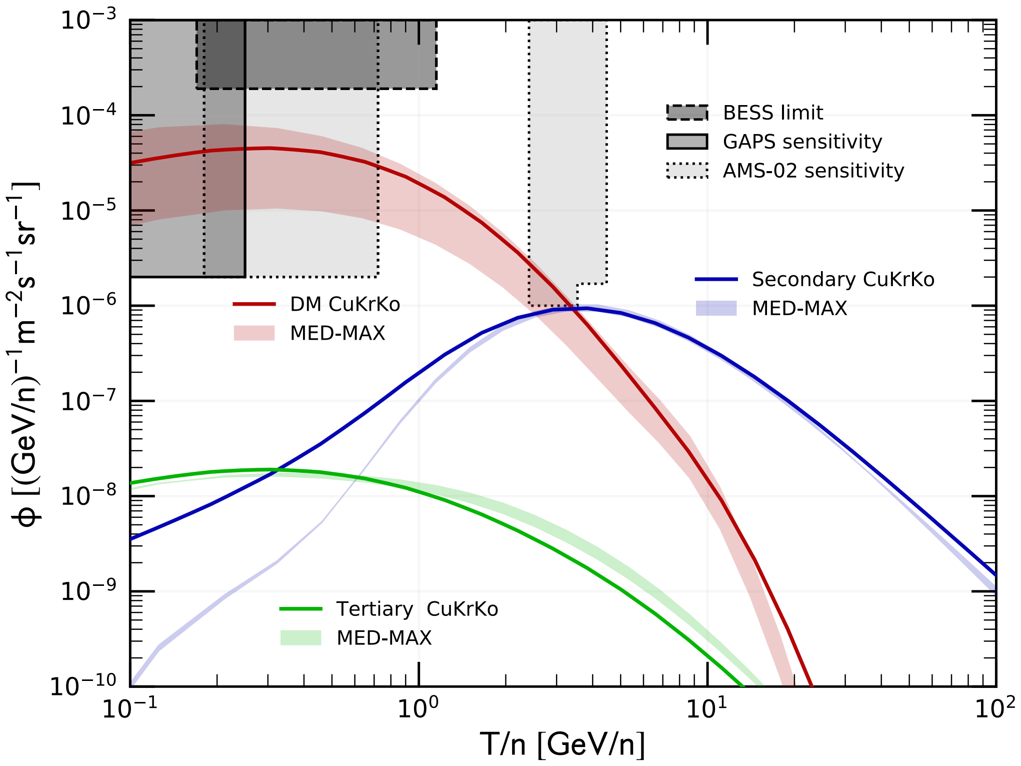
Possible **antideuteron** verification of Dark Matter hint in antiprotons

FD, Fornengo, Korsmeier, PRD 2018

P_{coal} = 124 (62) MeV

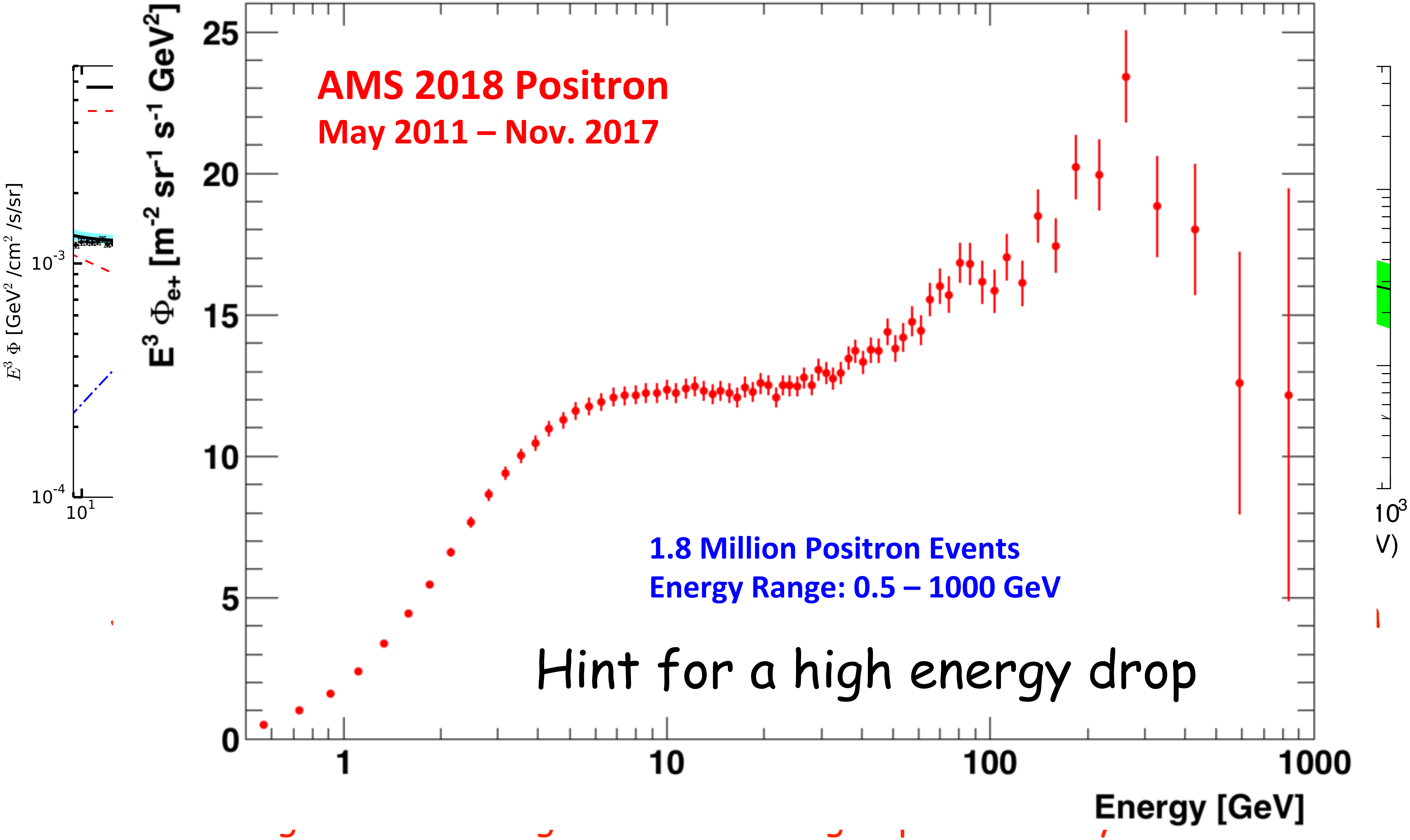


P_{coal} = 248 (124) MeV



DM antiprotons possibly hidden in AMS data are potentially testable by AMS and GAPS

The cosmic positrons



Hint for a high energy drop

A multi-wavelength, multi-messenger analysis

S. Manconi, M. Di Mauro, FD 1803:01009 PRD subm.

We build a model for the production and propagation of e- and e+ in the Galaxy and test it against 3 observables:

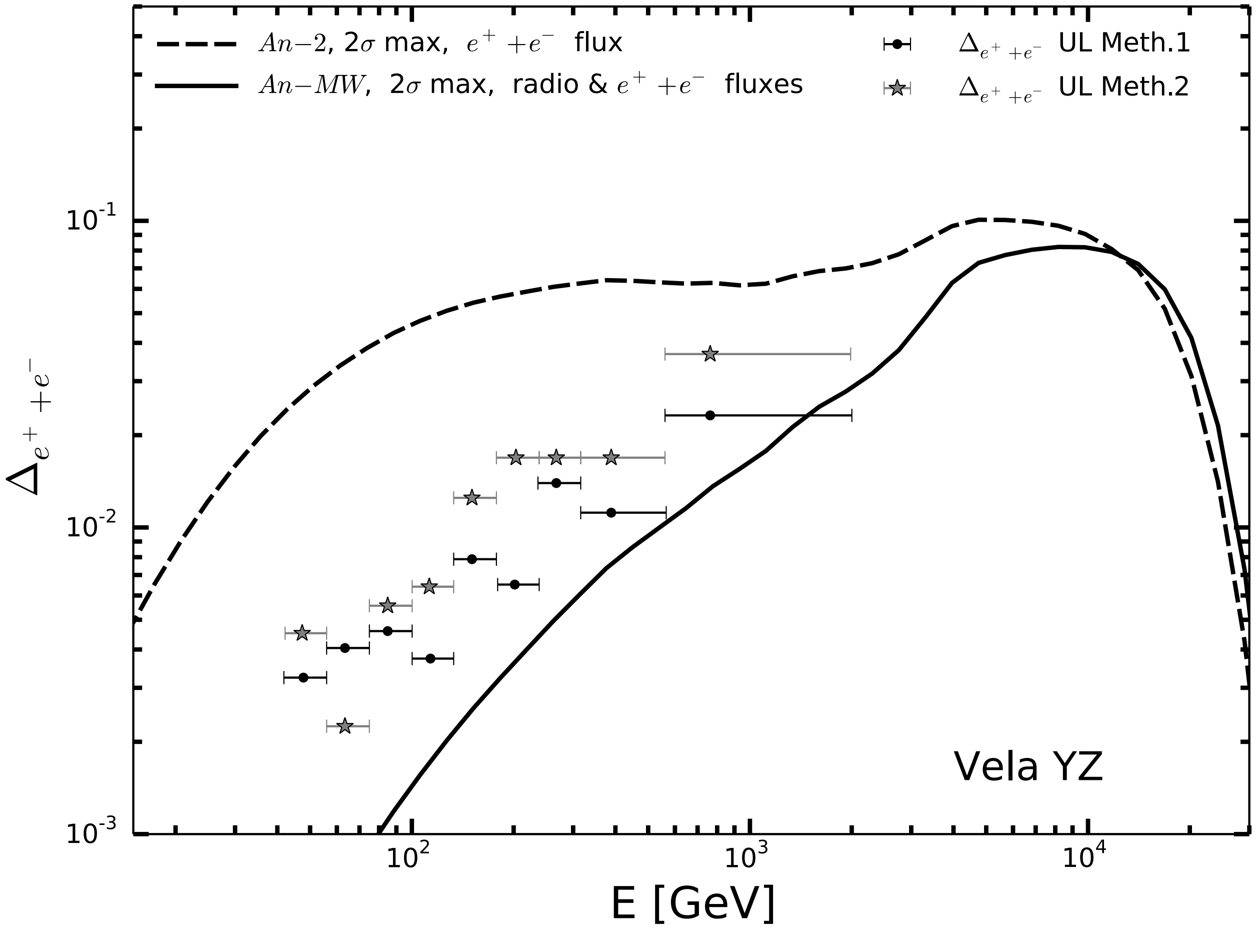
1. **Radio brightness data** from Vela YZ and Cygnus Loop at all frequencies.
   The radio emission is all synchrotron from e- accelerated by the source

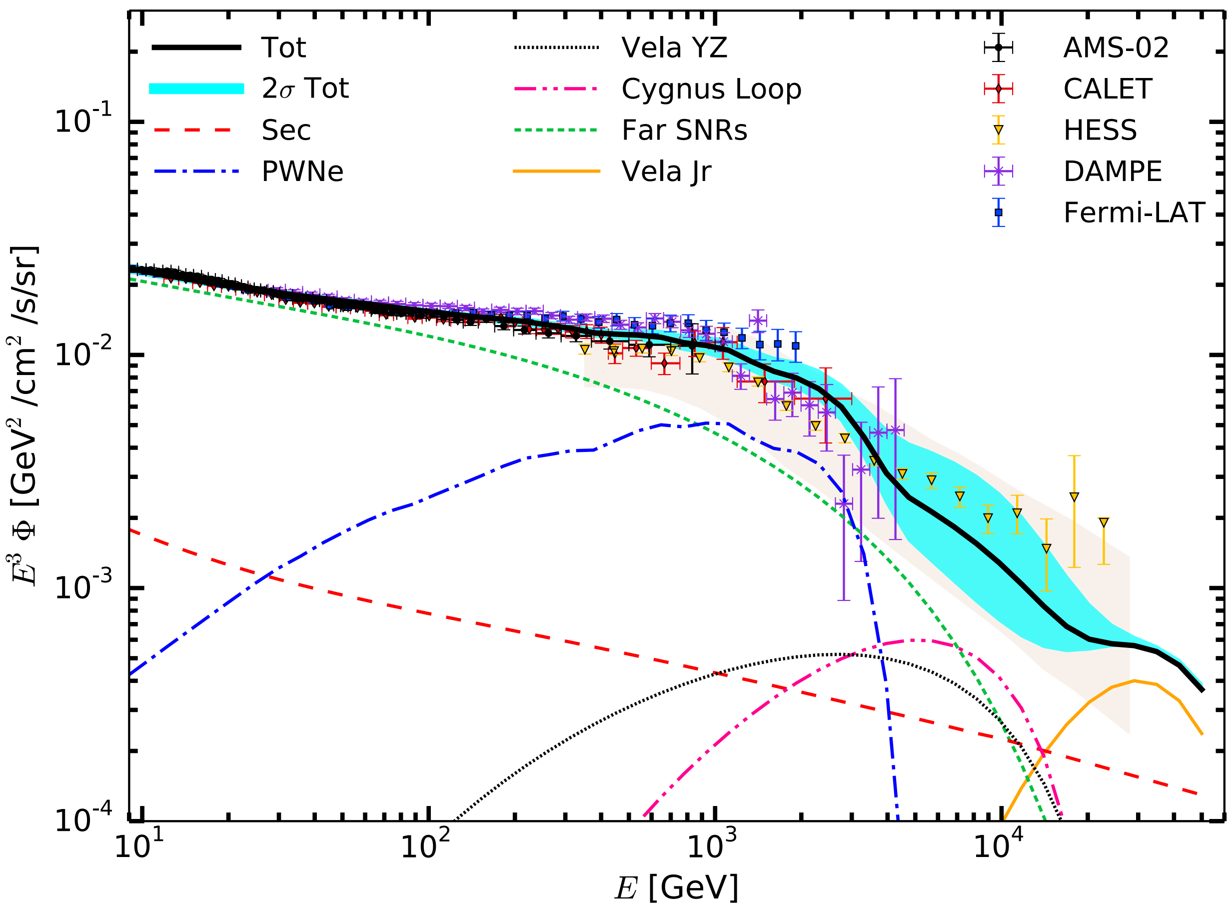
2. **e+e- flux** from 5 experiments, e+ flux from AMS
   Far and near SNRs, near SNRs and PWNe, secondaries for e+e-.
   The e+ flux constrains the PWN emission.
   e+e- data taken with their uncertainty on the energy scale.

3. e+e- **dipole anisotropy** upper bounds from Fermi-LAT
   Test on the power of this observable on the closest SNRs.

A multi-messenger analysis

S. Manconi, M. Di Mauro, FD 1803:01009

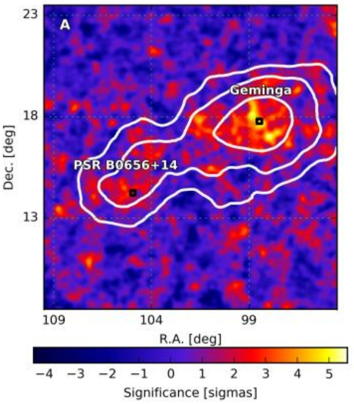




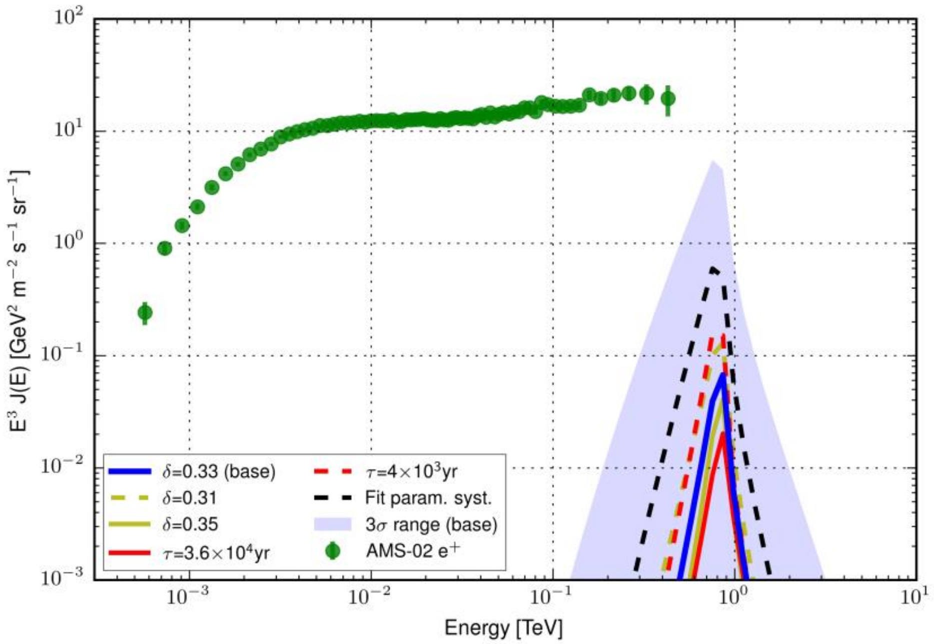
We can fit the whole data with a consistent model [provided that the proper systematic errors on the **energy scale** of each experiment are included].
Anisotropies from charged particles start to be constraining

Different physical contributions shape **non trivial slope changes**

Positrons from nearby sources



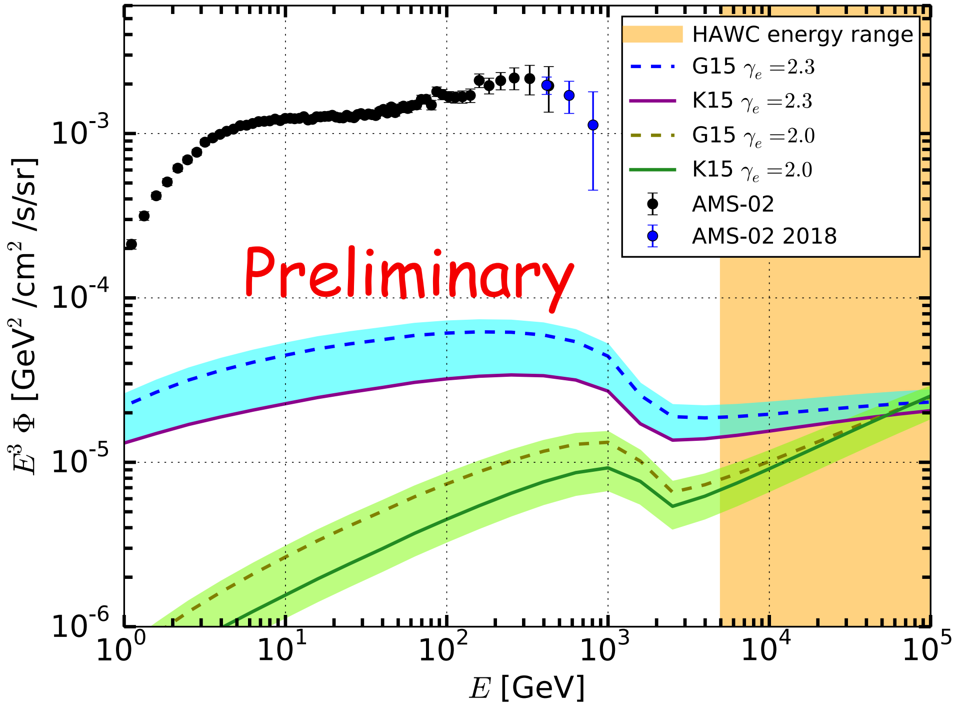
HAWC Coll. Science 2017



- HAWC detected an extended emission from Geminga and Monogem PWNe for E>5 TeV.
- Interpreted as Inverse Compton (IC) emission from e^+ and e^- accelerated from the PWN.
- In the vicinity of the PWN, the diffusion coefficient D must be about 500 times smaller than the average in the Galaxy.
- "We demonstrate that the leptons emitted by these objects are therefore unlikely to be the origin of the excess positrons, which may have a more exotic origin."

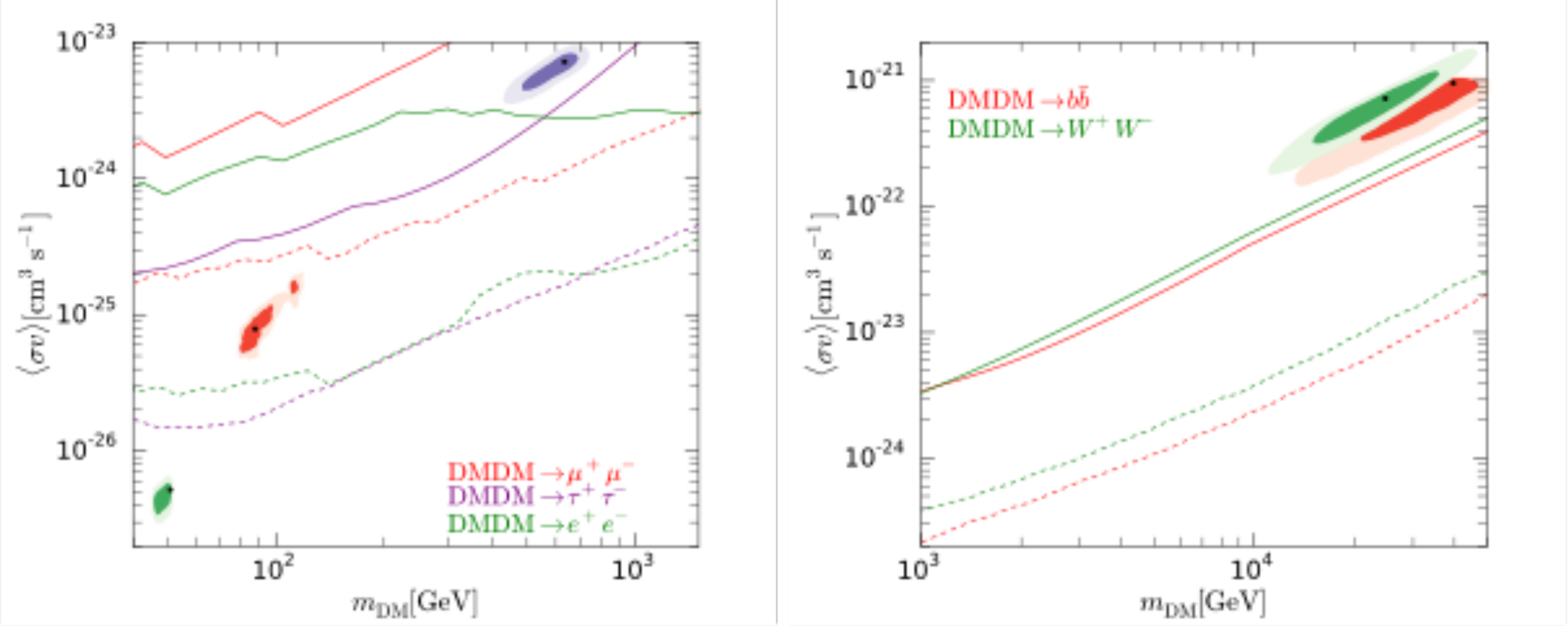
<u>**Di Mauro, Manconi, FD to appear**</u>

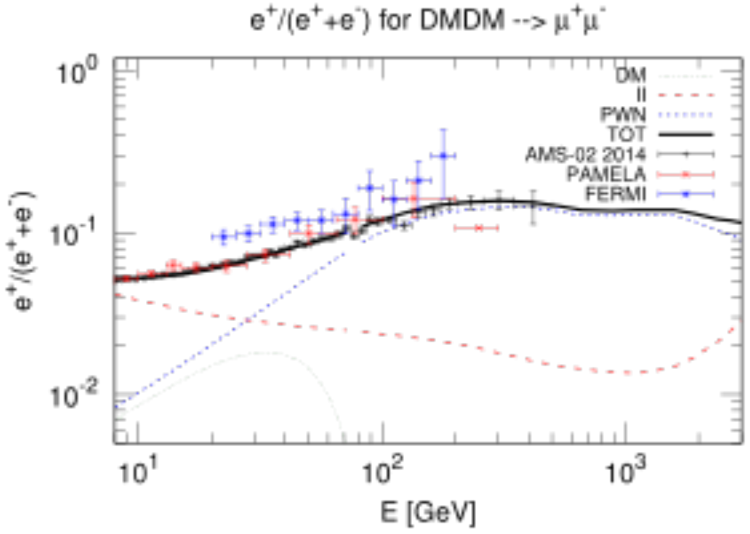
- Using HAWC data only it is **difficult to have a precise predictions for the contribution of PWNe to the AMS-02 e^+ flux.**
- **We are discovering Geminga in the Fermi-LAT gamma rays**
- **Monogem and Geminga PWNe contribute at the per mille level to the positron flux**

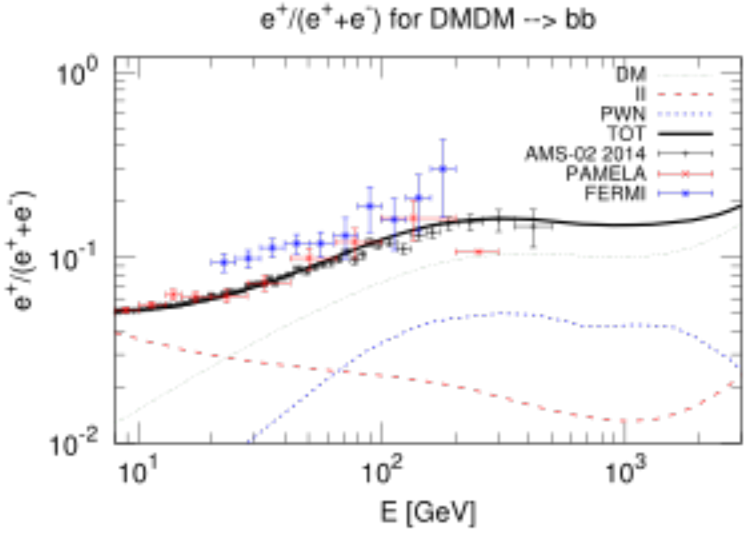


AMS lepton data: the dark matter case

Di Mauro, FD, Fornengo, Vittino 1507.07001




$e^+/(e^++e^-)$ for DMDM --> $\mu^+\mu^-$


$e^+/(e^++e^-)$ for DMDM --> bb

Very good fit are obtained adding DM annihilation (or decay)
Hadronic and tau final states are disfavored by searched in gamma-rays

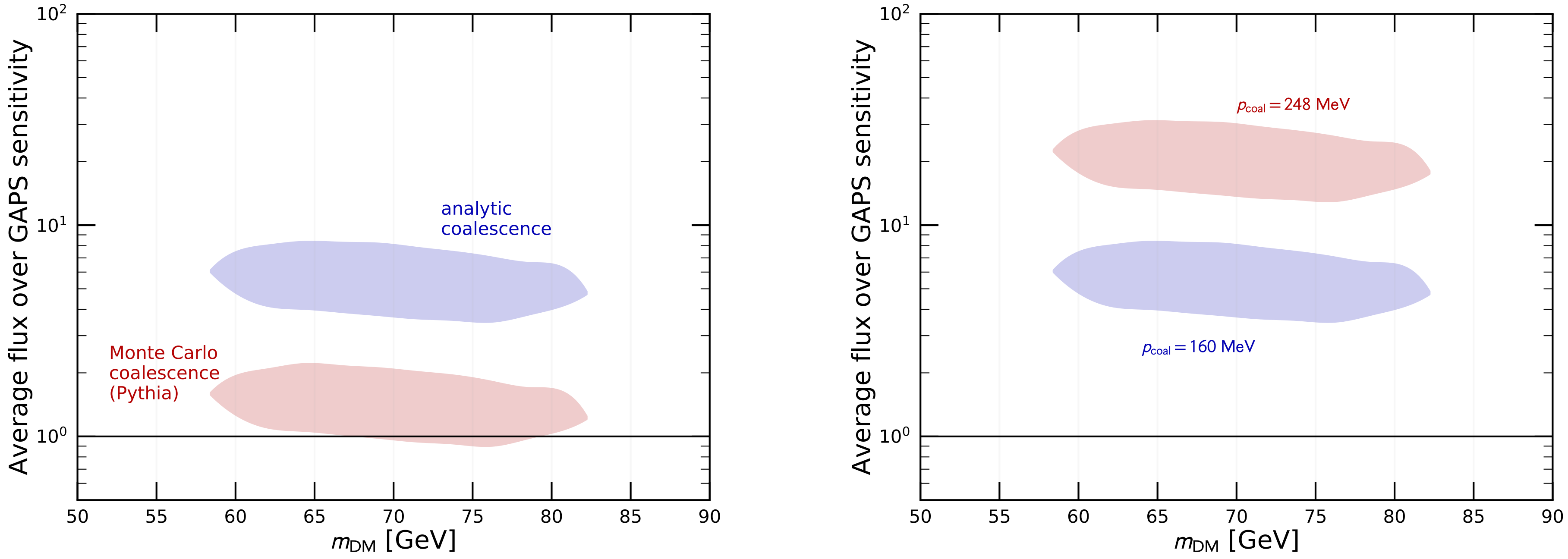
Conclusions

- Breaks in nuclei spectra - Secondari nuclei slightly different break than primaries - Protons different from other primaries - Positron excess - Hard antiproton spectrum - 60Fe radioactive abundance - [Gamma rays at the galactic center]
- Non trivial spectral behaviors or abundances have come to light thanks to high precision space-borne experiments.
- State-of-the-art galactic source and propagation models require continuous modifications - more complex treatments, new effects
- More data are needed: 10Be, higher isotopes, high energy antimatter, …
- Multi-wave & multi-messenger approach

Uncertainties on the detection predictions

FD, Fornengo, Korsmeier, 1711.08465 subm. PRD

Coalescence Model:
a factor > 10
(does not affect pbar flux)



(a) Coalescence model

(b) Coalescence momentum

Propagation models:
a factor > 10
(affects pbar flux)