Interpretation of direct measurements of cosmic rays

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TAUP - Vienna 01/09/2023

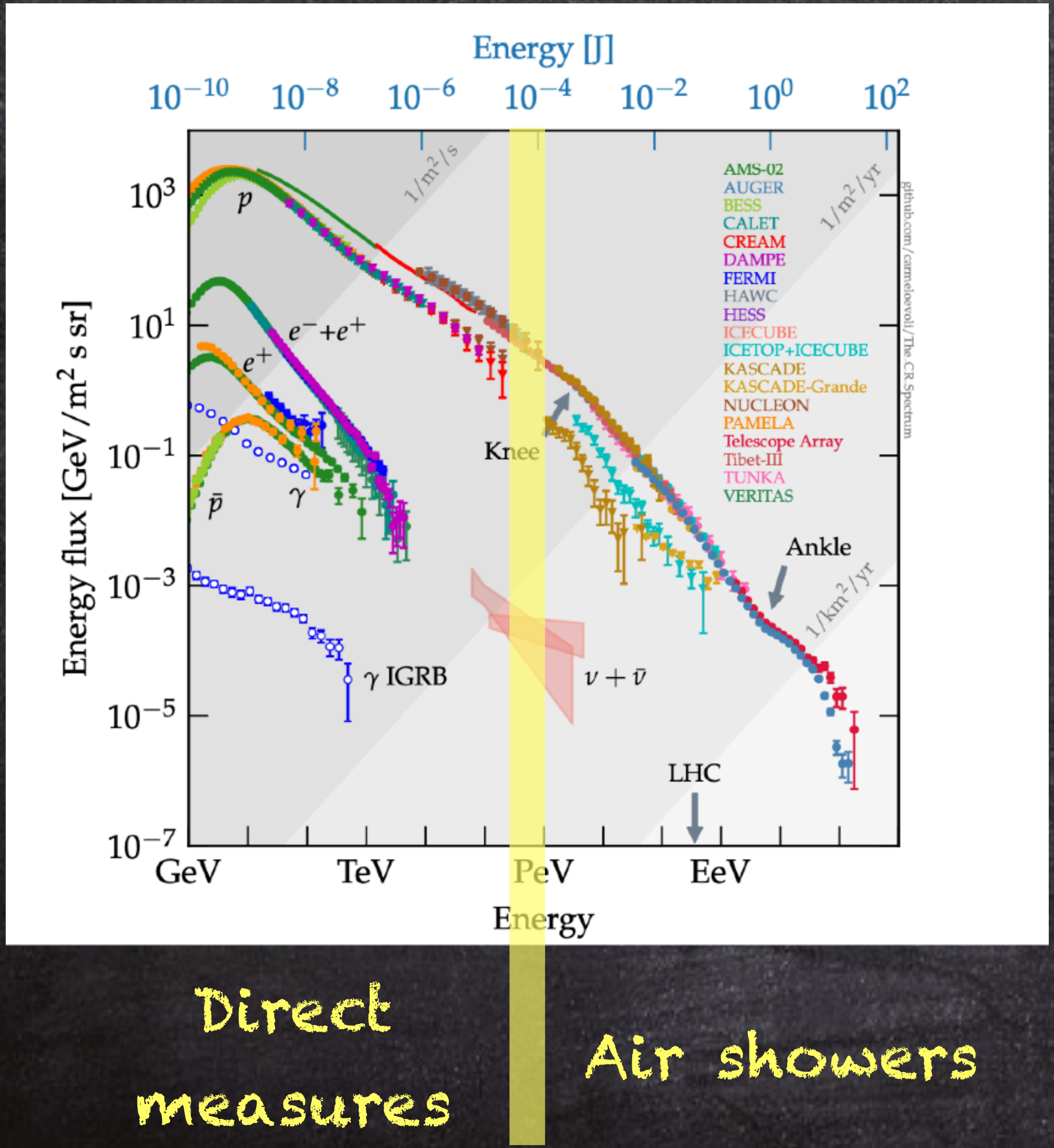
The measured Cosmic Ray (CR) spectrum

CR database: D. Maurin+ 2306:08901

C. Evoli at https://agenda.infn.it/event/21891/

See also N. Tomassetti 2301.10255

Gabici, Evoli, Gaggero, Lipari, Mertsch, Orlando, Strong, Vittino 1903.11584



Direct measures

Air showers

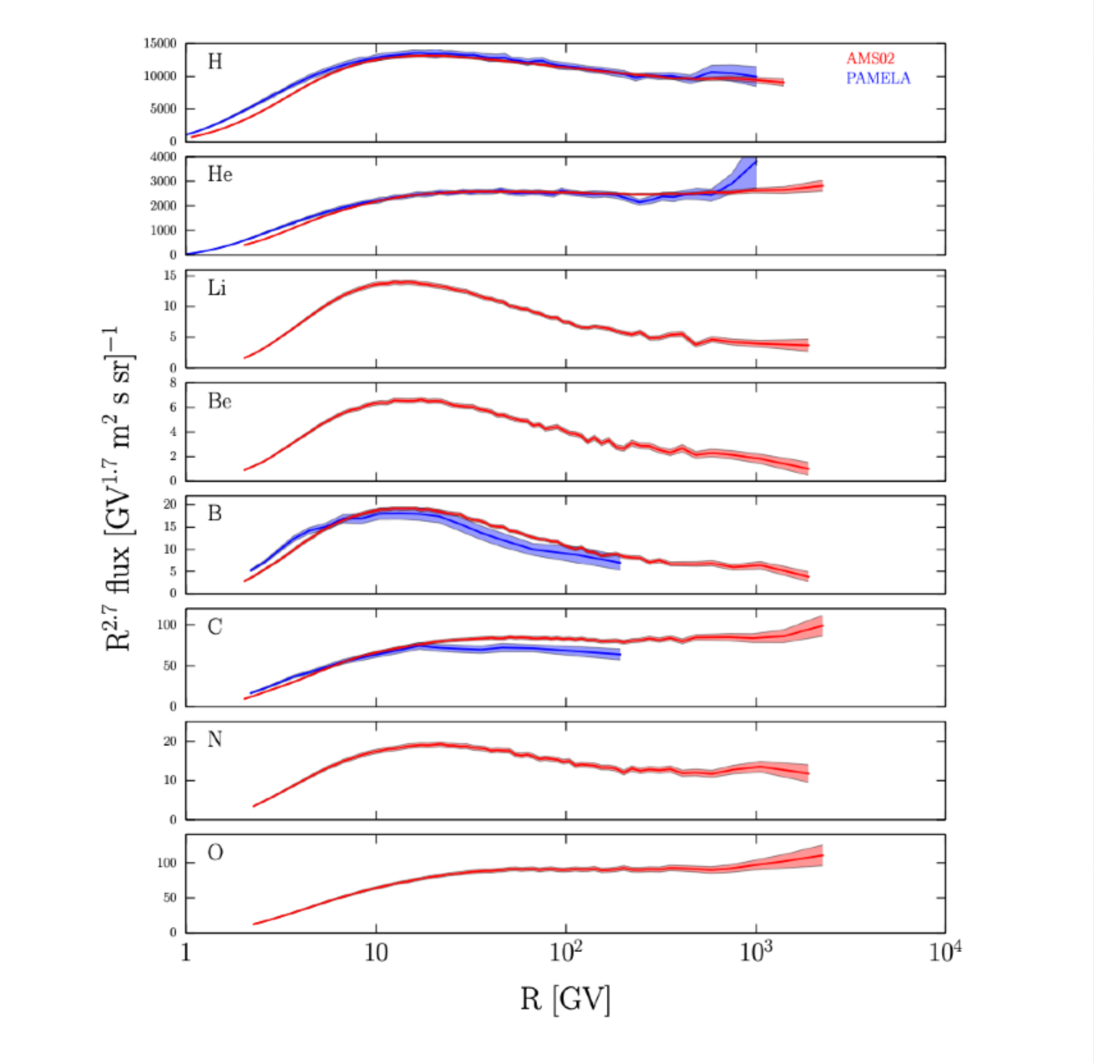
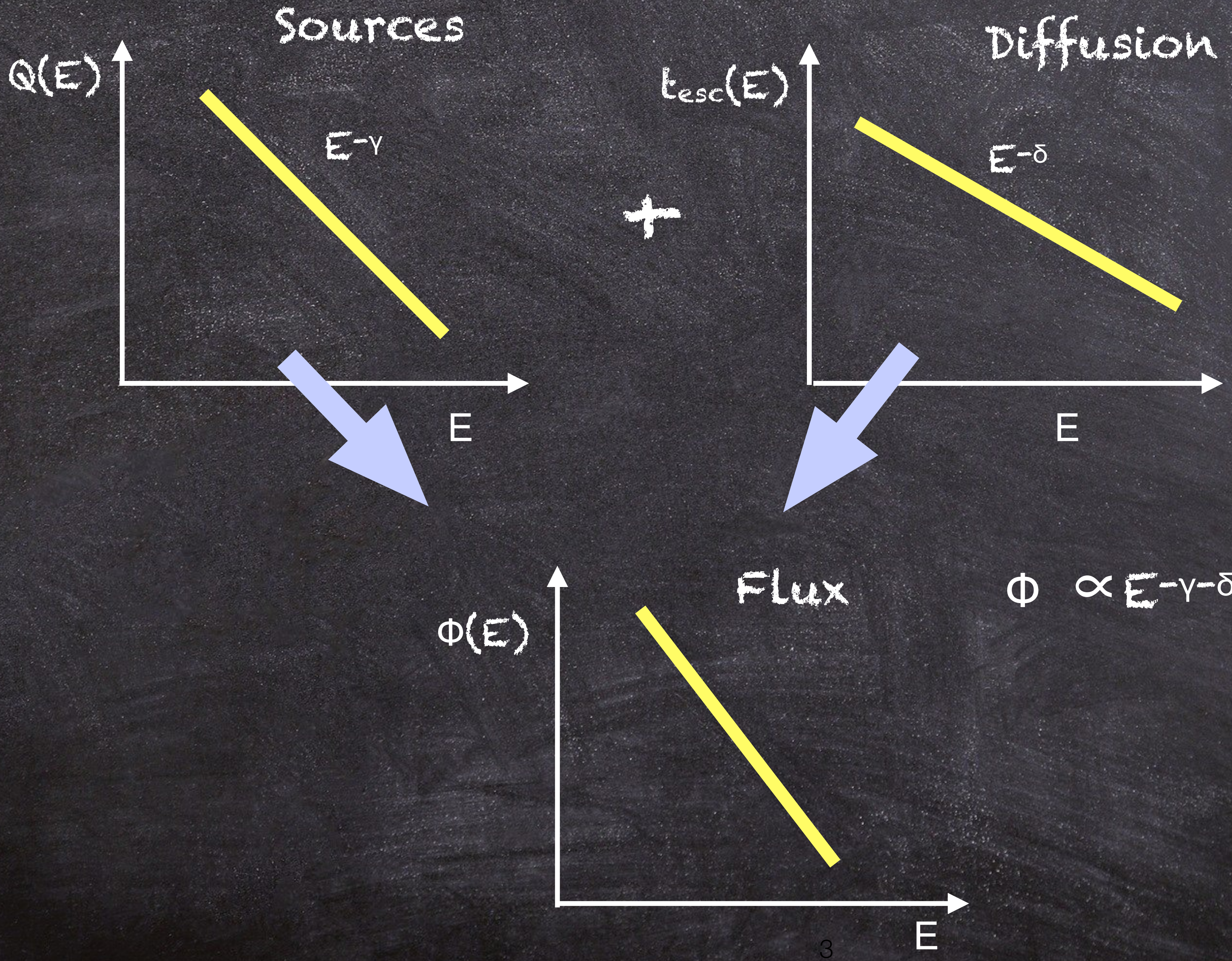


Fig. 1. The individual CR flux for nuclear species up to Oxygen as measured by PAMELA and AMS02. Shadow regions correspond to 1 sigma total errors (systematic and statistical added in quadrature).

CRs at zero-th order, or
In the old times there were power laws



$$\Phi \propto E^{-\gamma-\delta}\, t_{loss}(E)$$

1. The bulk of the energy of CRs comes from SNR explosions in the galactic disk

The power of ~ GeV CRs can be computed (Strong+ApJL 2010) from γ rays as P_{CR}~ 10^{41} erg/s. It is equivalent to the power of observed SNRs in the Galaxy

2. CRs are accelerated through diffusive shock acceleration in SNRs

SNRs provide the right energy needed for CRs (Baade&Zwicky 1934)
Classical test is through γ-rays observations of SNRs (O'Drury+ A&A1994)
Still some ambiguities on hadron acceleration by SNRs which, could be explained by leptonic emission (i.e. SNR RX J1713.7-3946)

See Bell MNRAS 1978, MNRAS2004, Bell+MNRAS2013; Caprioli+ MNRAS2009; Blasi+ApJ2012 ; Recchia&Gabici MNRAS2018

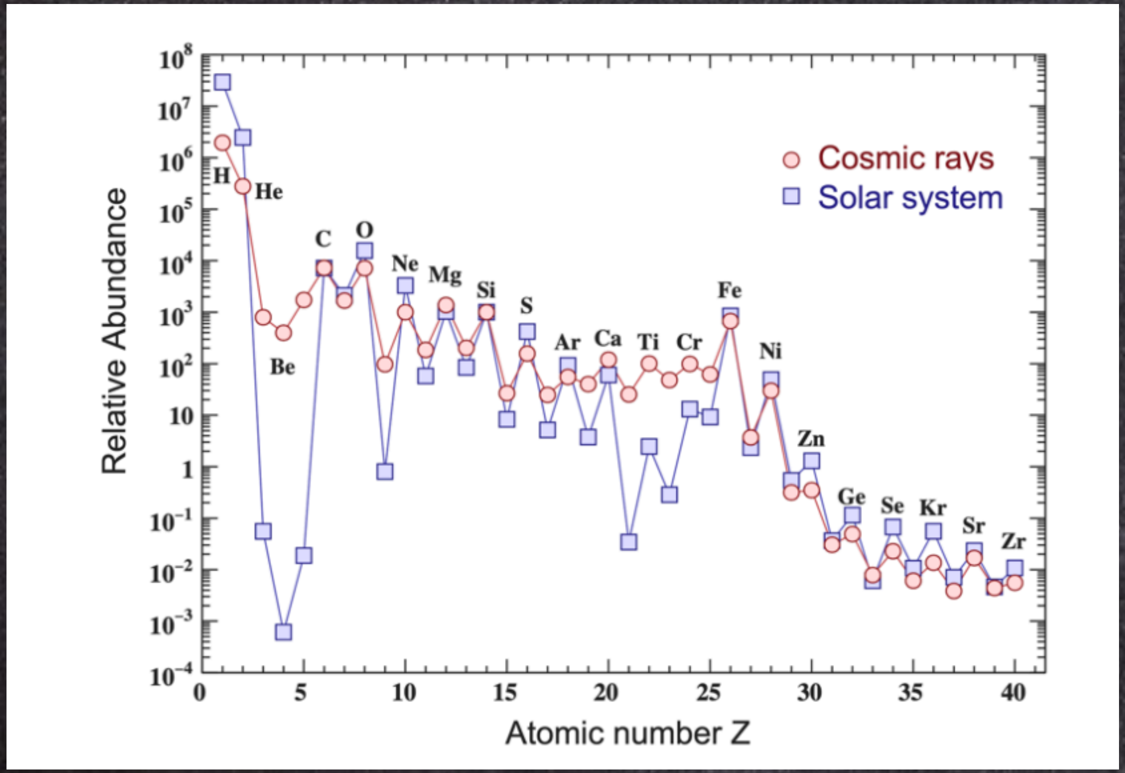
Probe: detection of the maximum energy at 67.5 MeV in the π^0 decay;γ rays from molecular clouds illuminated by nearby, freshly accelerated protons

3. Composition: primary, secondaries, both

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

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^-

N. Tomassetti 2301.10255



Solar System abundances, similar to interstellar ones, are deprived of nuclei such as Li, Be, B, sub-Fe, believed to be of secondary origin

All species are, at some extent, both primary and secondary

4. CRs are diffusively confined in an extended magnetic halo

CRs must be confined a region much thicker than the Galactic disk. Radioactive isotopes such as ^{10}Be indicate the existence of a magnetic diffusive halo several kpc thick (L or H)

$$D(R) \sim D_0 \times f(R) \sim D_0 \times R^{\delta}$$

$$D_0 \sim 3 \times 10^{28} \left(\frac{H}{5\ \mathrm{kpc}}\right) \left(\frac{\Lambda}{10\ \mathrm{g/cm^2}}\right)^{-1} \mathrm{cm^2/s}\ .$$

Radio haloes observed in external galaxies.
A very extended halo, > 100 kpc, has been observed across M31 (karwin+ ApJ2019).
DM annihilation has been explored (Karwin+2020).
Non-standard propagation of CRs can explain it (Recchia+ ApJ2021)

Propagation equation

$$\frac{\partial \psi_i(\boldsymbol{x},p,t)}{\partial t} = q_i(\boldsymbol{x},p) + \boldsymbol{\nabla}\cdot(D_{xx}\boldsymbol{\nabla}\psi_i - \boldsymbol{V}\psi_i) + \frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{1}{p^2}\psi_i - \frac{\partial}{\partial p}\left(\frac{\mathrm{d}p}{\mathrm{d}t}\psi_i - \frac{p}{3}(\boldsymbol{\nabla}\cdot\boldsymbol{V})\psi_i\right) - \frac{1}{\tau_{f,i}}\psi_i - \frac{1}{\tau_{r,i}}\psi_i.$$

Diffusion: D(x,R) a priori
usually assumed isotropic in the Galaxy: $D(R)=D_0R^\delta$ (R=pc/Ze)
D_0 and δ preferably fixed by B/C (kappl+15; Genolini+15 (K15))

Sources: injection from stellar relics (SNRs, PWN)
Spallation from nuclei scattering off the interstellar medium (ISM)

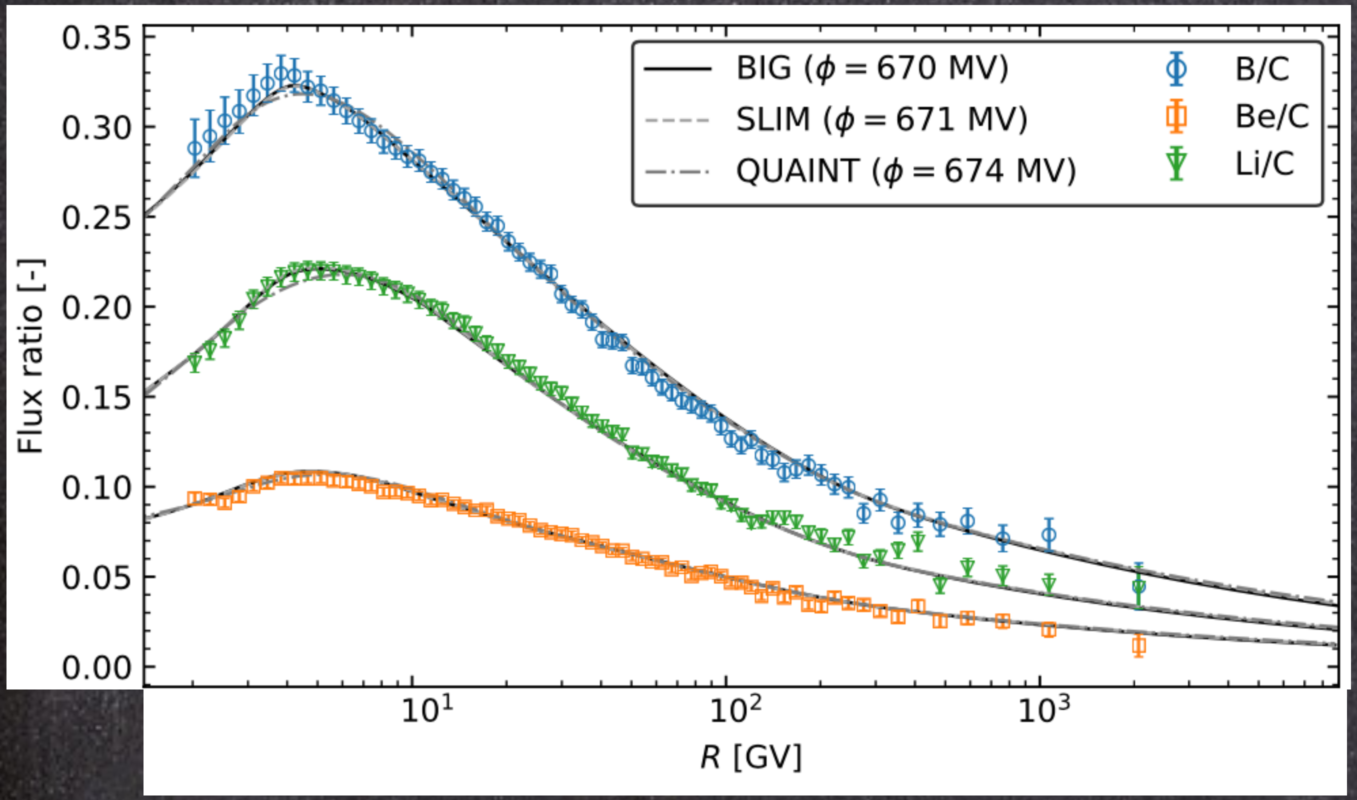
Energy losses: Nuclei: ionisation, Coulomb (spallations)
Leptons: Synchrotron on the galactic B~3 μG
Inverse Compton on photon fields (stellar, CMB, UV, IR)

Geometry of the Galaxy: cylinder with half-height L ~ kpc

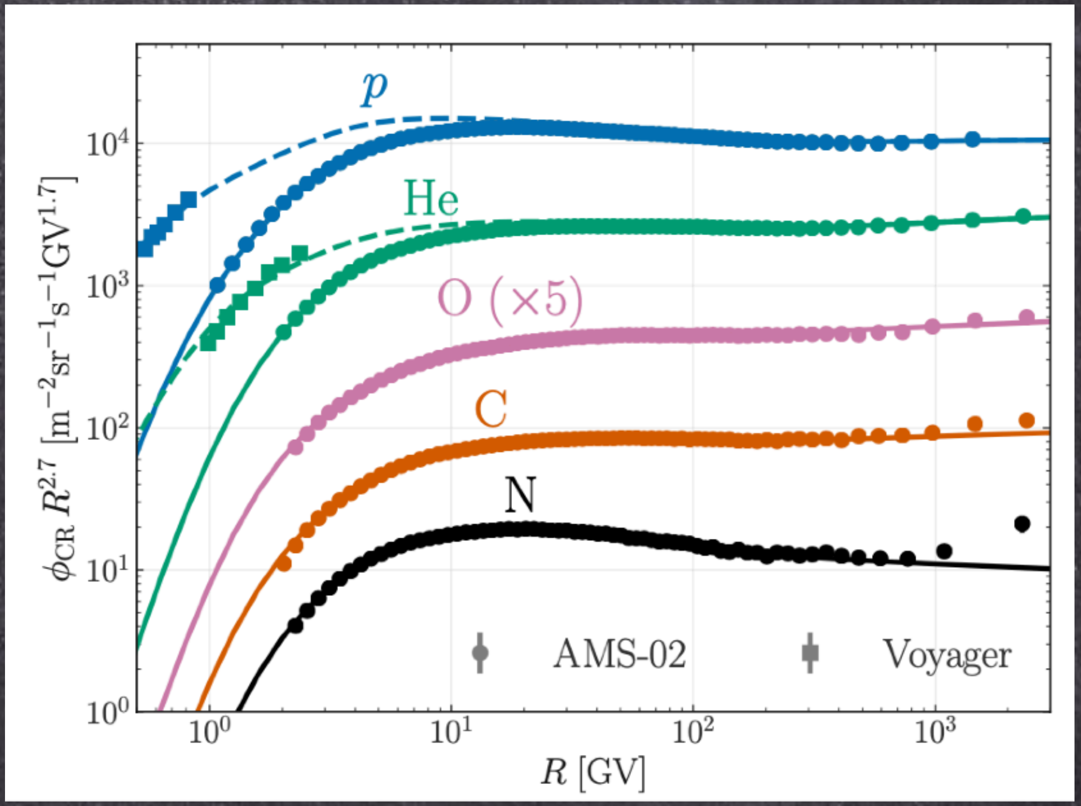
Solution of the eq.: semi-analytic (Maurin+ 2001, Donato+ 2004, Maurin 2018 ...), USINE codes
or fully numerical: GALPROP (Strong&Moskalenko 1998), DRAGON (Evoli+ 2008; 2016), PICARD (Kisskmann, 2014, Kissmann+ 2015)

Propagation models vs data

Weinrich+ A&A 2020



Di Mauro, FD+ 2023



See also Evoli+ PRD 2020; Schroer+ PRD 2021; Cuoco&Korsmeier PRD 2021, 2022

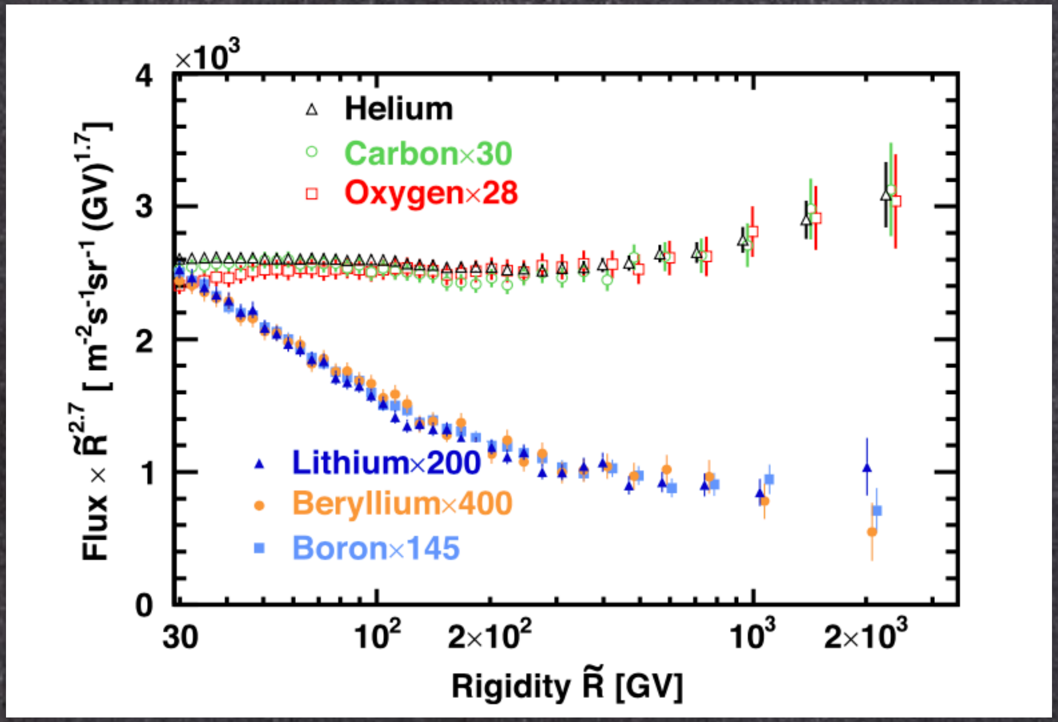
Data on nuclear species are well described by propagation models with diffusion coefficient power index $\delta = 0.50 \pm 0.03$.

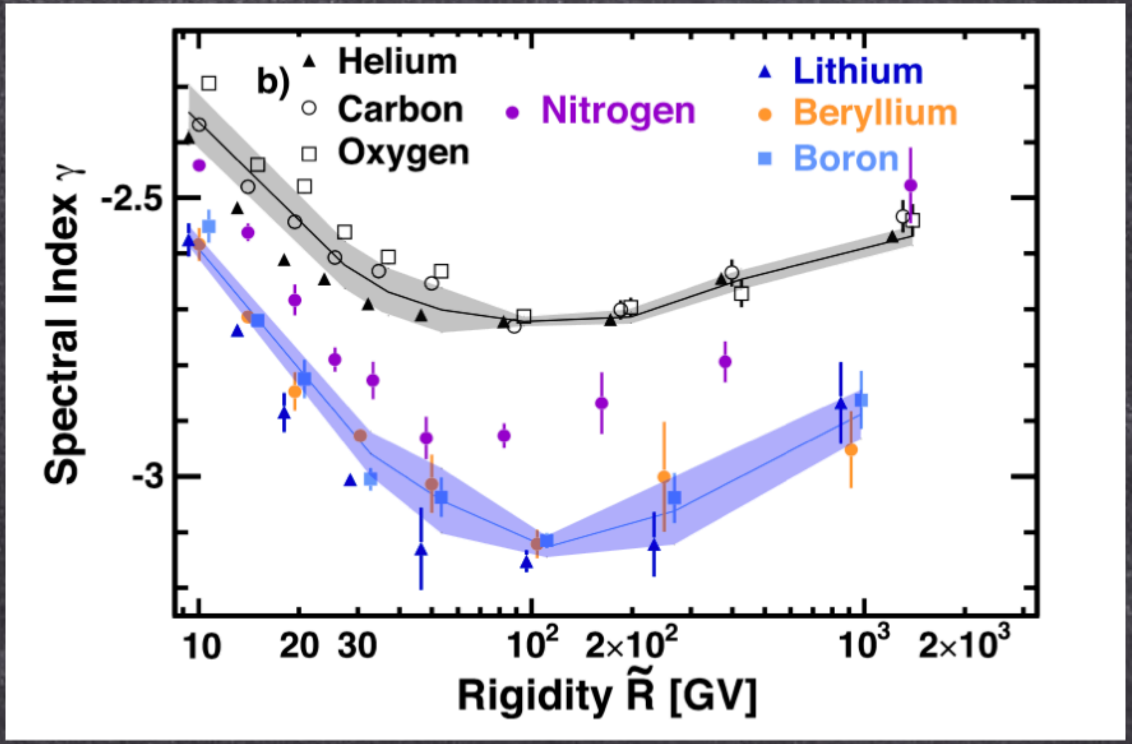
Convection or reacceleration models both work.

Interpretation hampered by cross sections

Hardening of nuclear spectra

PAMELA Coll. Science 2011; AMS Coll Phys Rept 2021; PRL2017; PRL2018





A general hardening is observed at ~ 300 GV

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

The spectral index of secondaries hardens ~0.13 more than for primaries

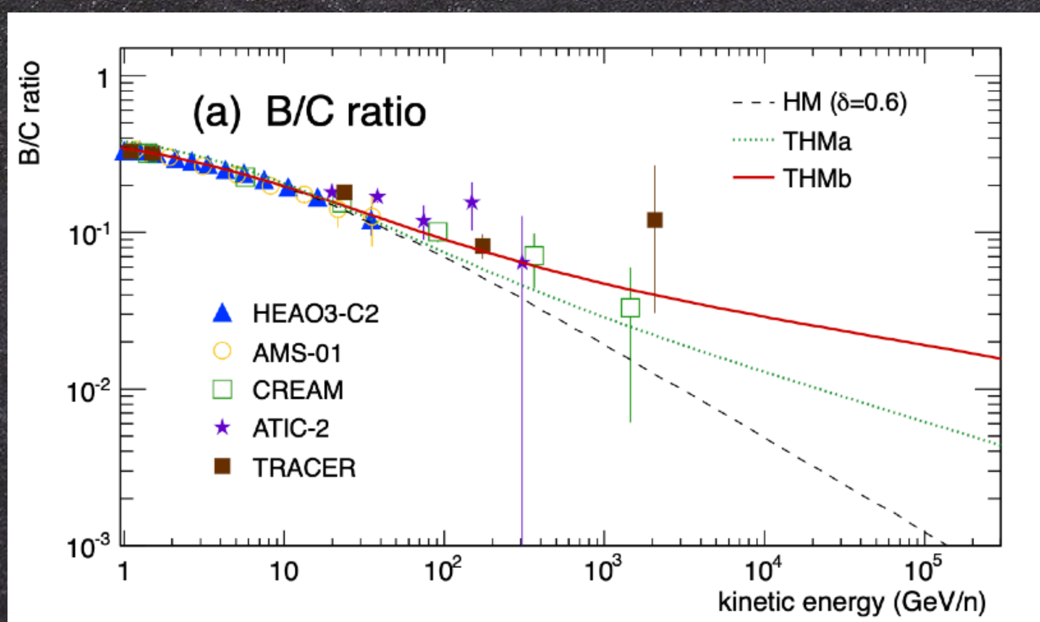
Hardening of nuclear spectra: diffusion

Most credited explanation is a DIFFUSION effect at ~ 300 GV, naturally with a twice power law for secondaries.

(Genolini+ PRL 2017;; Evoli+ PRD2019)

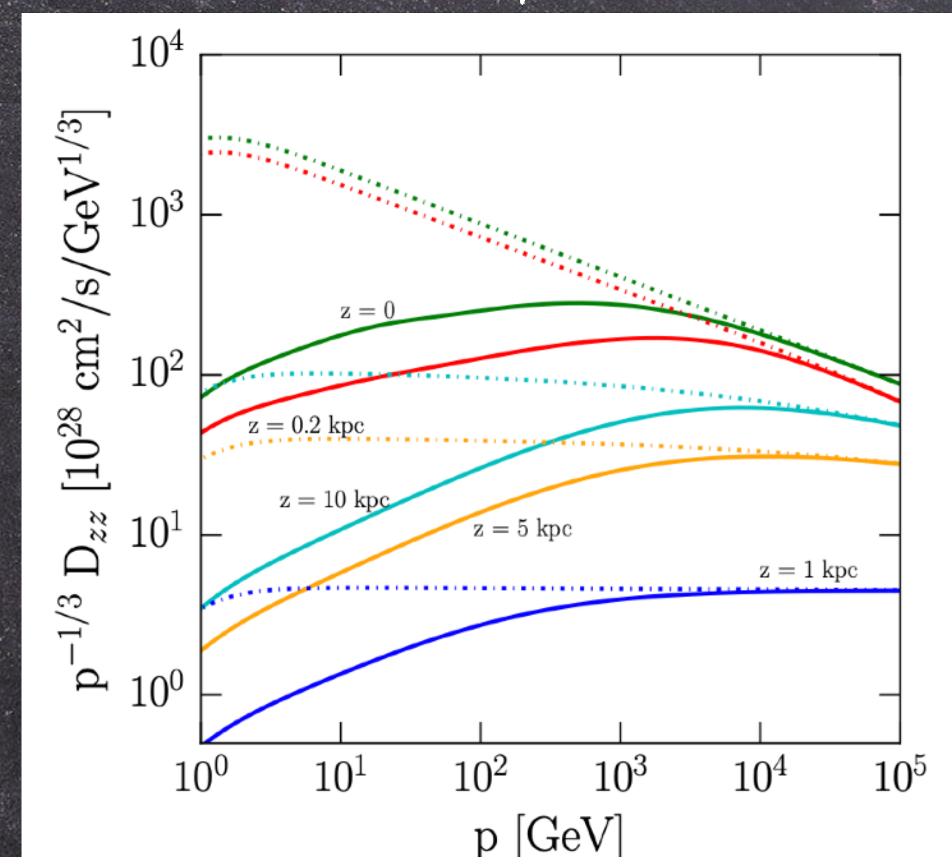
Tomassetti ApJL 2012

$$K(z,\rho) = \begin{cases} k_0 \beta \rho^{\delta} & \textit{for } |z| < \xi L \ (\textit{inner halo}) \\ k_0 \beta \rho^{\delta+\Delta} & \textit{for } |z| > \xi L \ (\textit{outer halo}) \end{cases}$$



The diffusion coefficient close to the disk is different than in outer diffusive halo

Evoli+ PRL 2018 - Blasi, Serpico, Amato PRL 2012



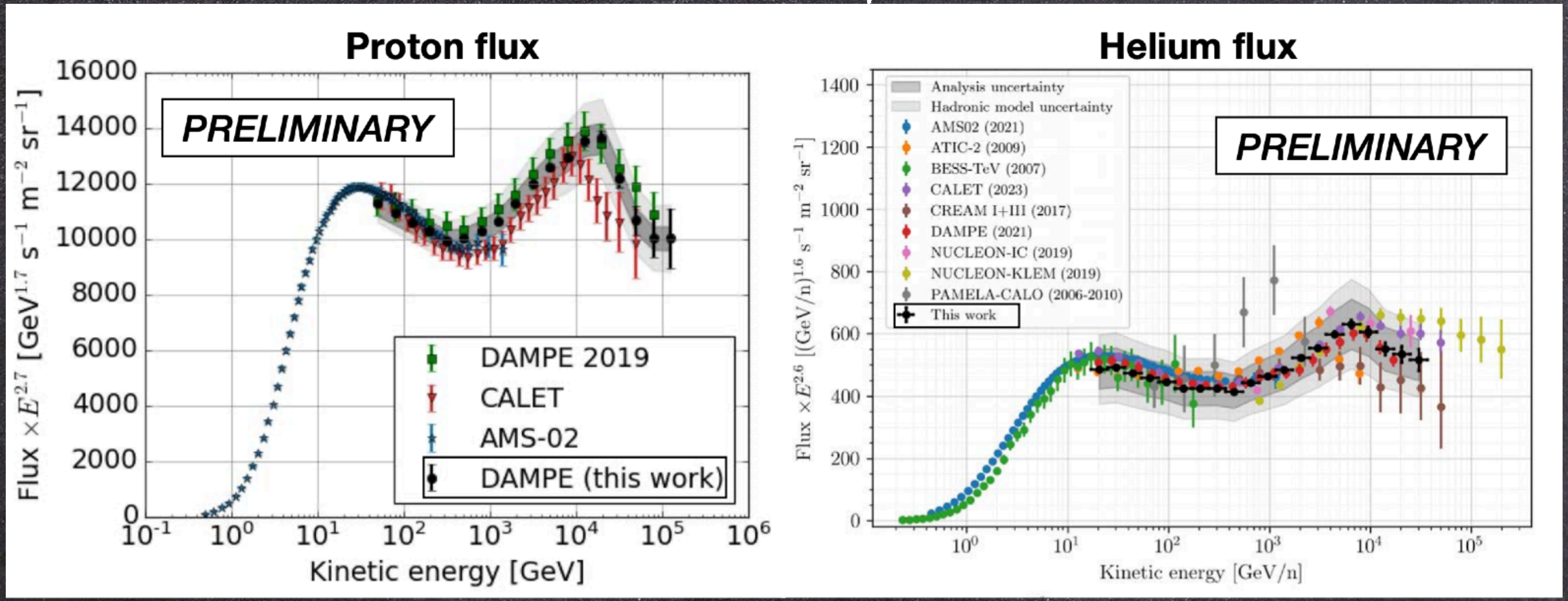
CRs diffuse on external turbulence (mainly above the break) and on the waves generated by CRs themselves

Interpretations still hampered by spallation cross sections

P and He spectra: shifts, breaks and bumps

1. p spectrum is distinctly softer ($\Delta\gamma$ ~ 0.1) than He at all energies (shift): Not understood yet
2. R dependence of He, C, O are very similar, all (also p) break at 300 GV: ~ understood
3. The p and He spectra > TeV show a bump: suggestions

Dampe Coll - see Ivan De Mitri's talk



See also CALET Coll, PRL 2022 and @ ICRC2023

Bump: probably an effect in acceleration or escape from the sources

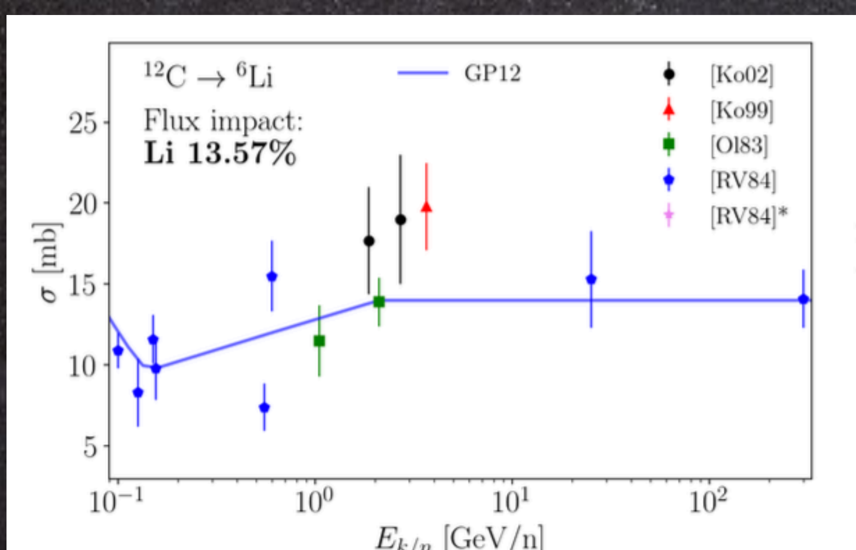
Evoli+ PRD2019; Di Mauro, FD+ 2023

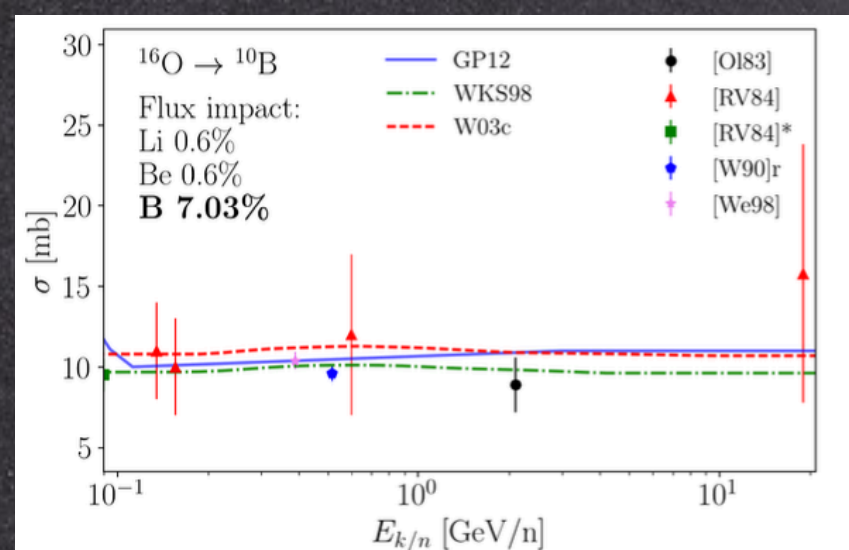
Cross sections for Galactic CRs

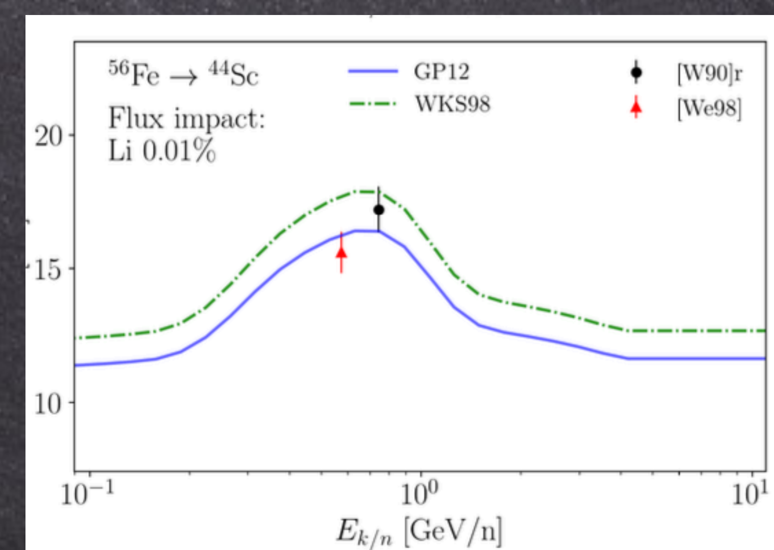
Production cross sections (source of CRs), and to a lesser extent inelastic cross sections (loss of CRs)

Data driven parameterizations (Silberberg&Tsao), semi-empirical formulae (Webber+), parametric formulae/direct fit to the data (Galprop), MonteCarlo codes (Fluka, Geant, …)

Genolini, Moskalenko, Maurin, Unger PRC 2018







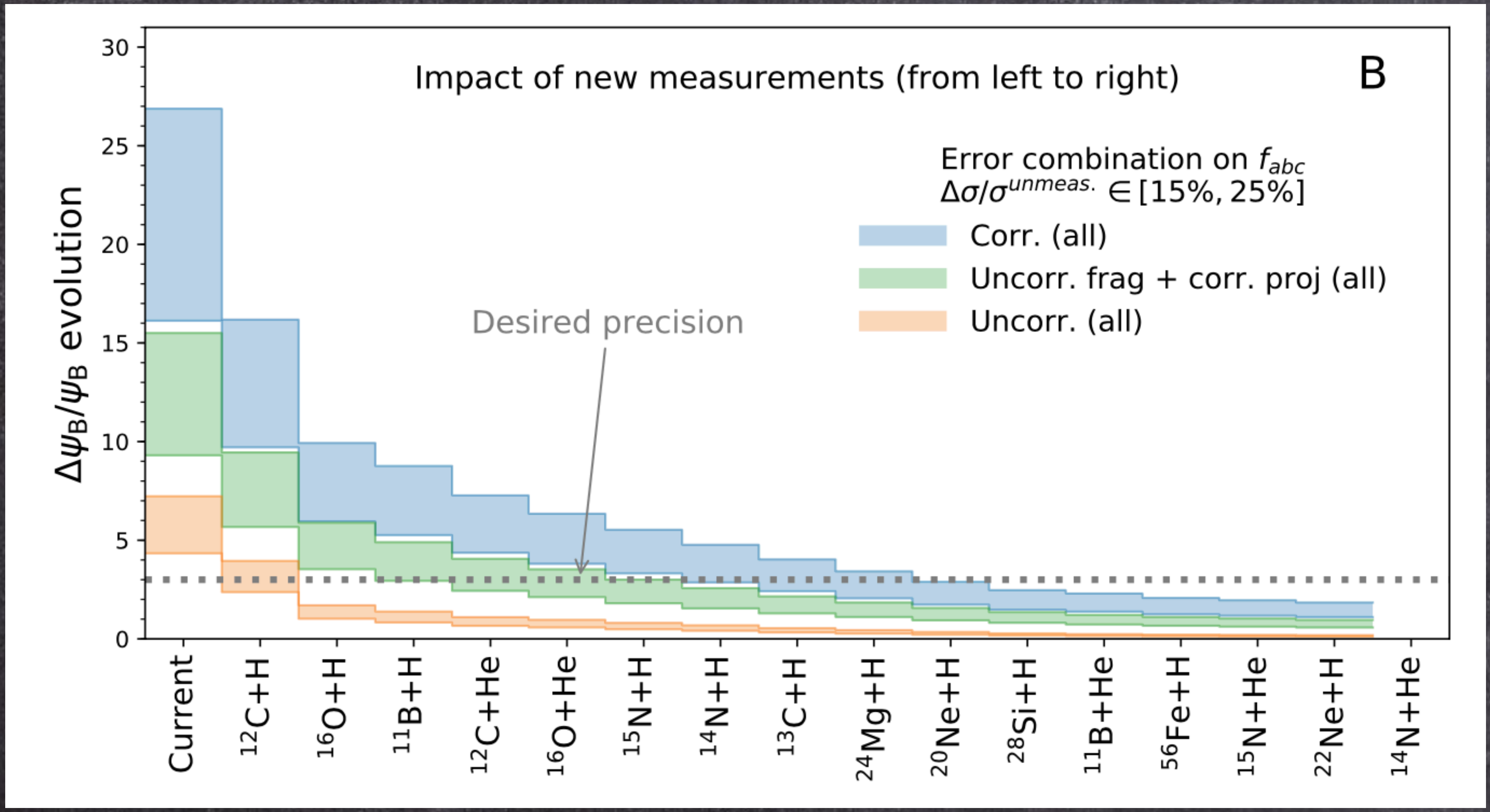
Now probably the most limiting aspect now for a clear interpretation of precise CR data coming from space

See also N. Tomassetti PRD 2017

Cross sections: the most relevant ones

First: Improve Boron production cross sections

Genolini, Moskalenko, Maurin, Unger PRC 2018; 2307.06798

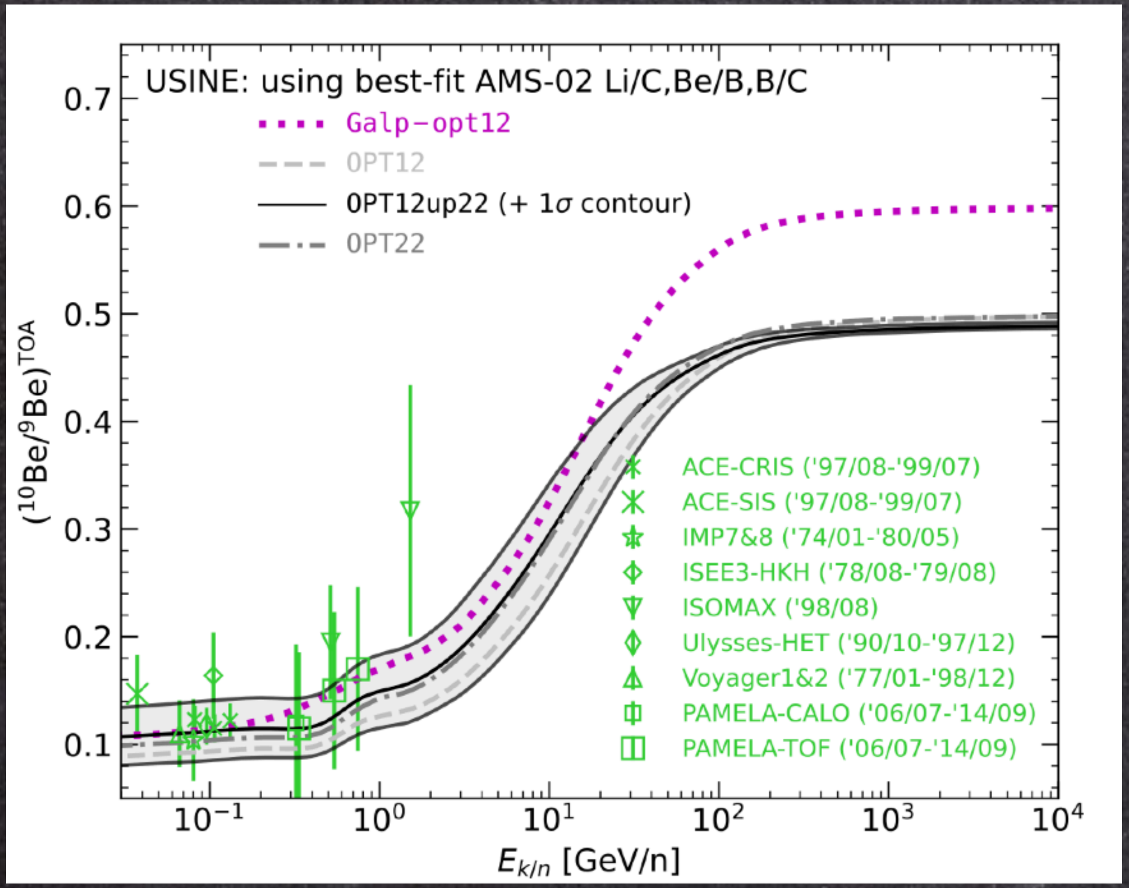


Dedicated campaigns at COLLIDERS are needed.
Some already started or planned
(LHCf, LHCb, NA61, Amber/Compass, ...)

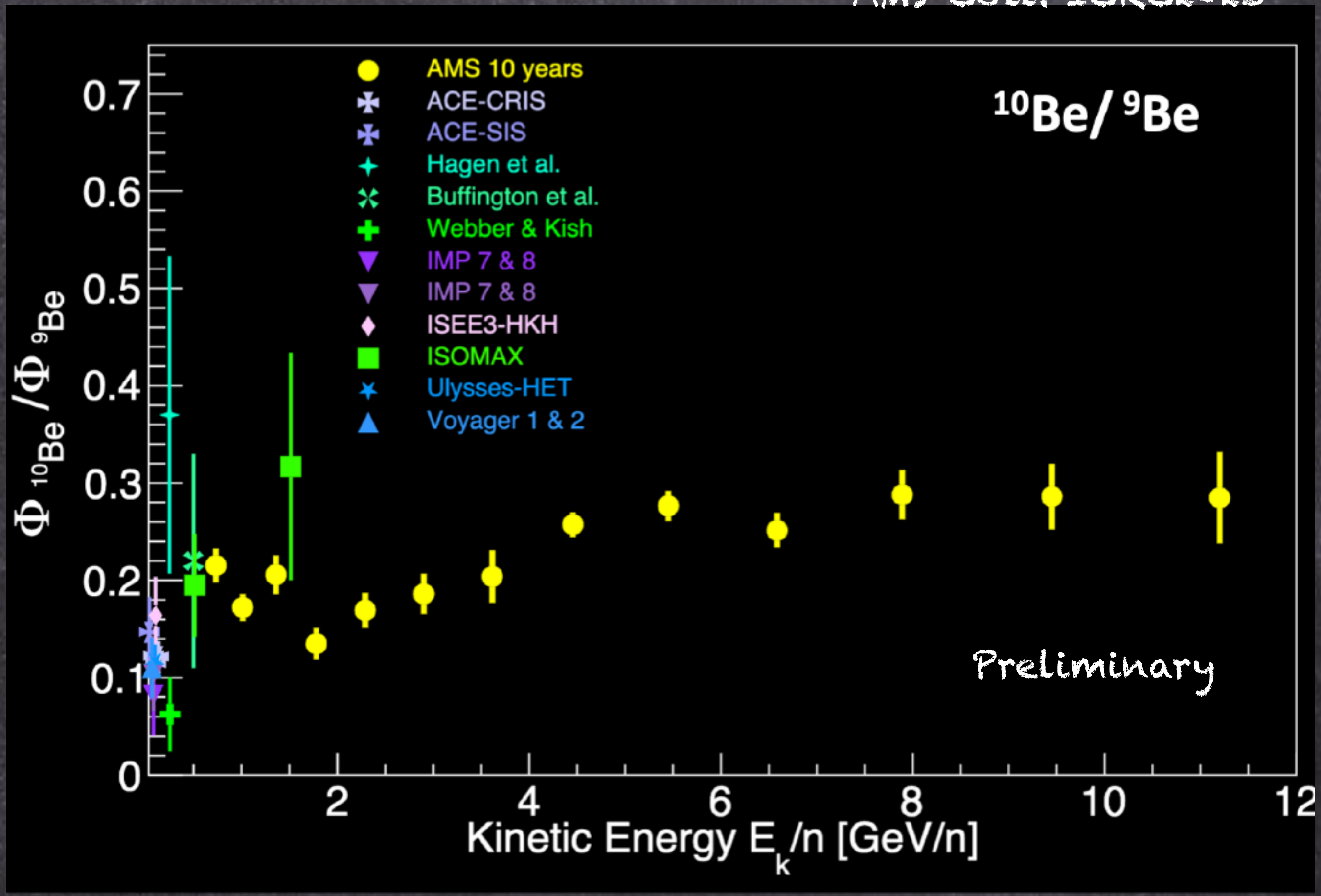
Radioactive light isotopes

Radioactive isotopes (^{10}Be, ^{26}Al) can track the diffusive halo size
Important to test origin and propagation of CRs

Maurin et al, A&A 2002



AMS Coll. ICRC2023



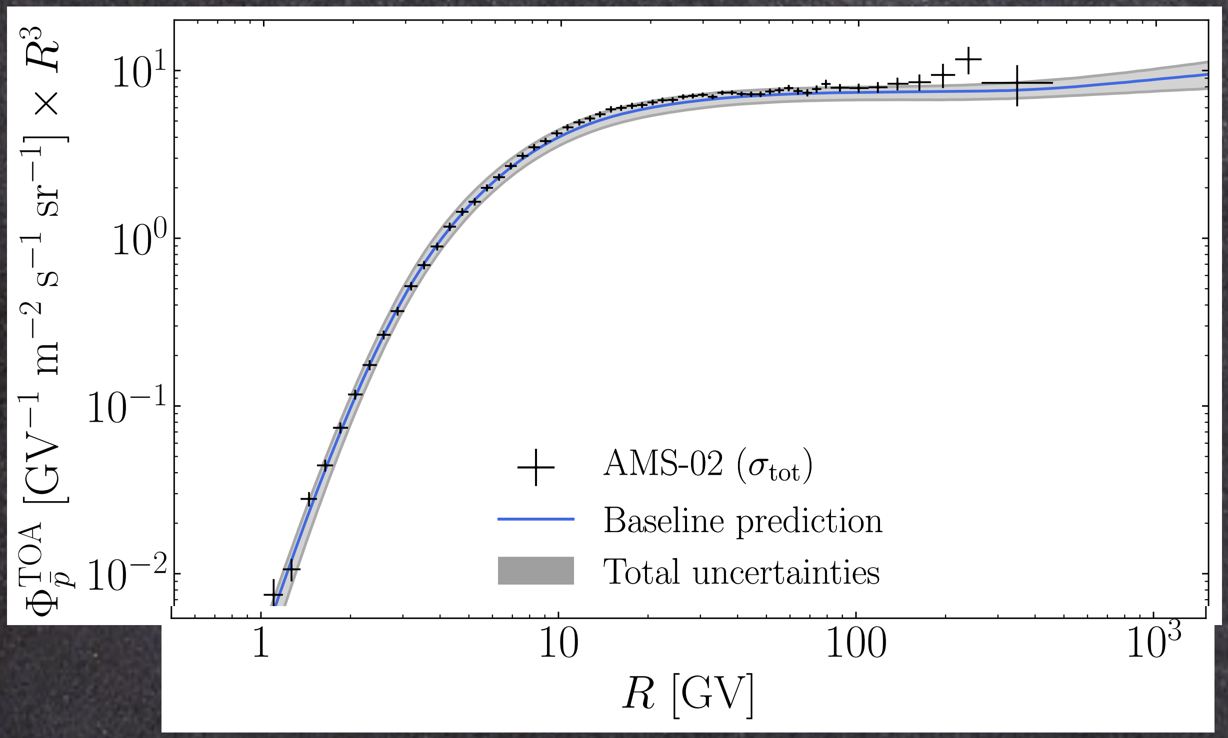
Weinrich et al. A&A 2020
Jacobs, Mertsch, Pahn 2305.10337

Need of precise data on light radioactive isotopes (^{10}Be mainly) up to 100 GeV/n (and cross sections)

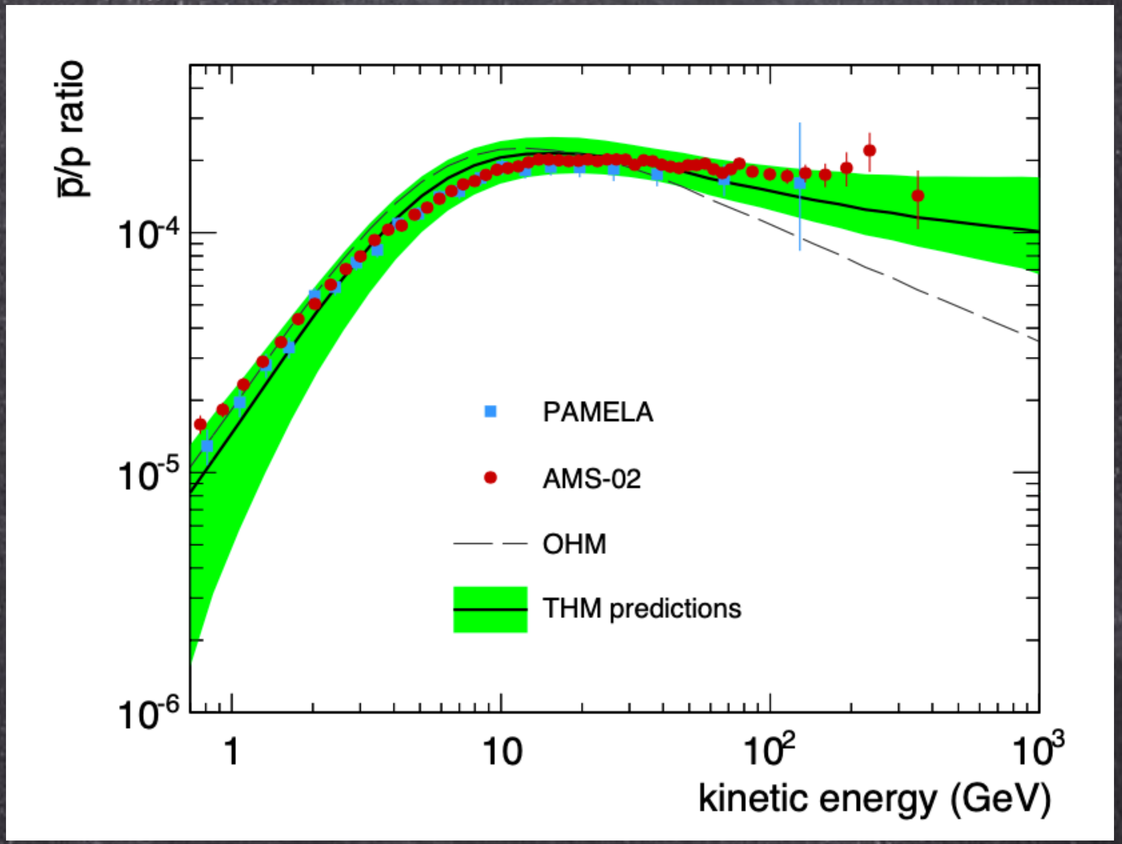
Antiprotons in CRs

AMS-02 antiprotons are consistent with a secondary astrophysical origin

M. Boudaud+ PRD 2020



Feng, Tomassetti, Oliva PRD2016

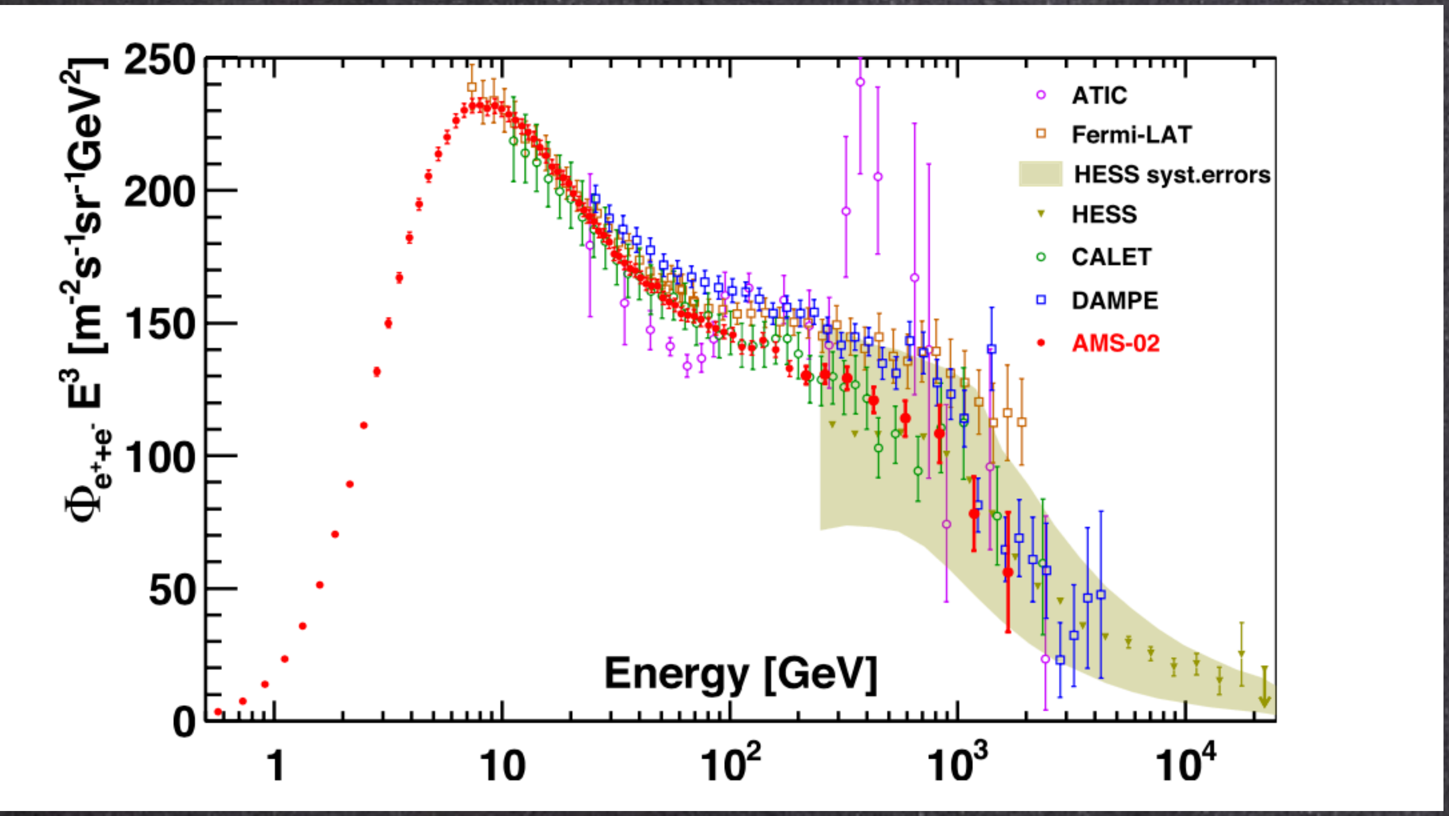


- Secondary pbar flux is predicted consistent with AMS-02 data
- Transport and cross section uncertainties are comparable
- A tiny dark matter contribution cannot be excluded
- Precise predictions are mandatory

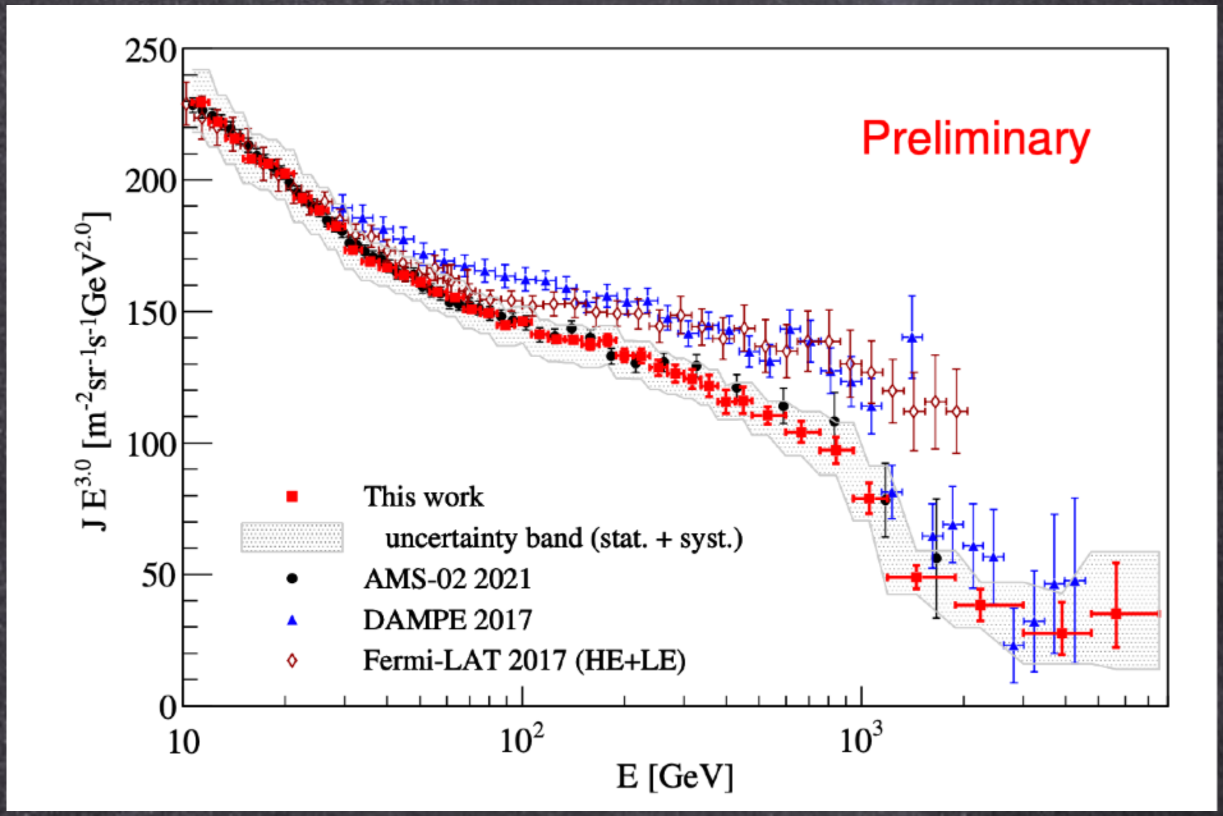
See also Korsmeier, FD, Di Mauro PRD 2018, Reinert&Winkler JCAP2018

The observed electron spectrum

AMS Coll Phys.Rept. 2021



CALET Coll. @ ICRC2023



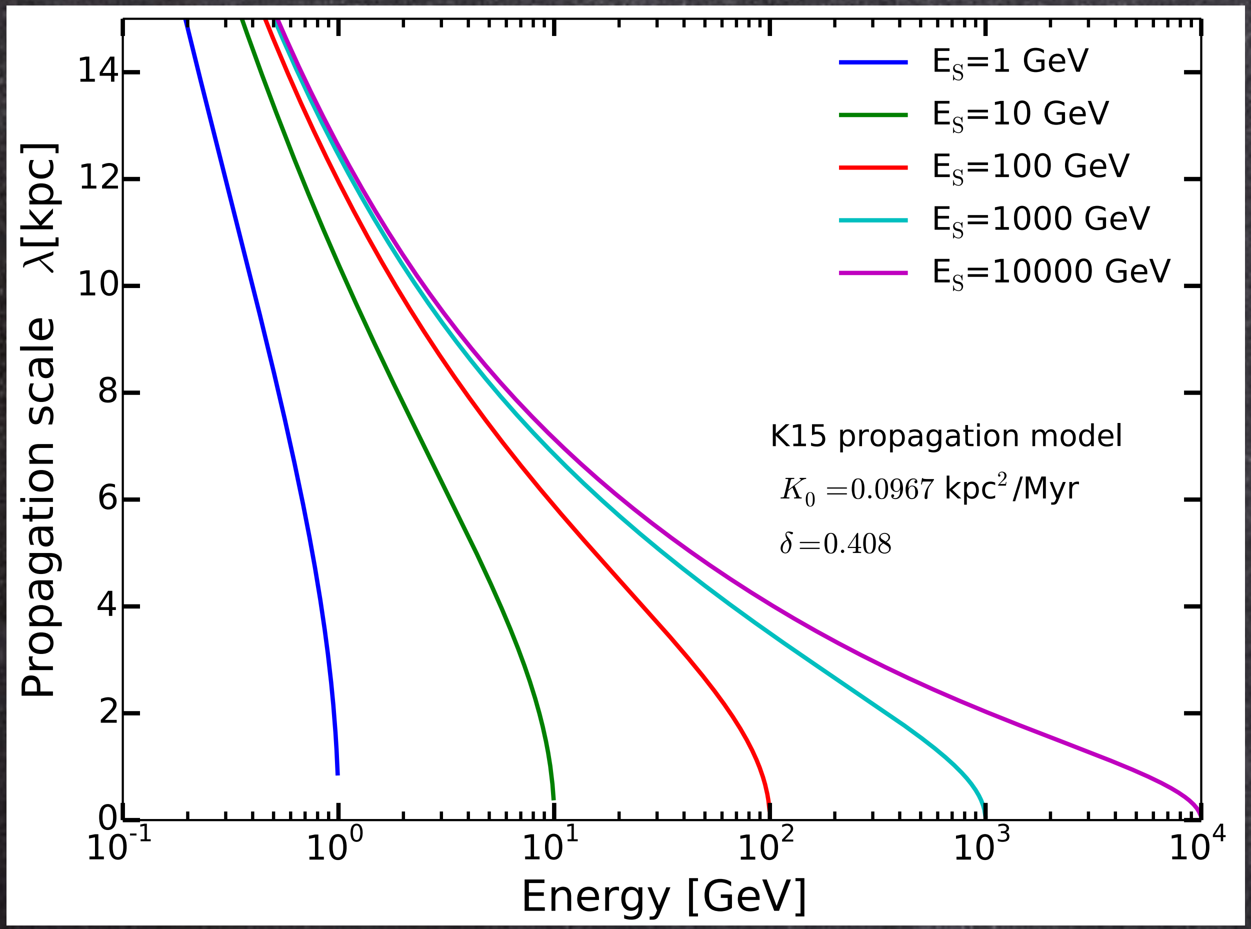
Data on total electron not fully compatible among them
A prominent break is observed at ~ TeV, (see Dampe talk by De Mitri)
still too uncertain to fix models. Pulsars can do the job

Detected e+ and e- are local

$$\lambda^2(E, E_S) = 4 \int_E^{E_S} dE' \, \frac{D(E')}{b_{\rm loss}(E')}$$

Typical propagation length in the Galaxy

Manconi, Di Mauro, FD JCAP 2017



Sources of e+ & e- in the Galaxy

- Inelastic hadronic collisions (asymm.)
- Pulsar wind nebulae (PWN) (symm.)
- Supernova remnants (SNR) (only e-)
- Particle Dark Matter annihilation (e+,e-)?

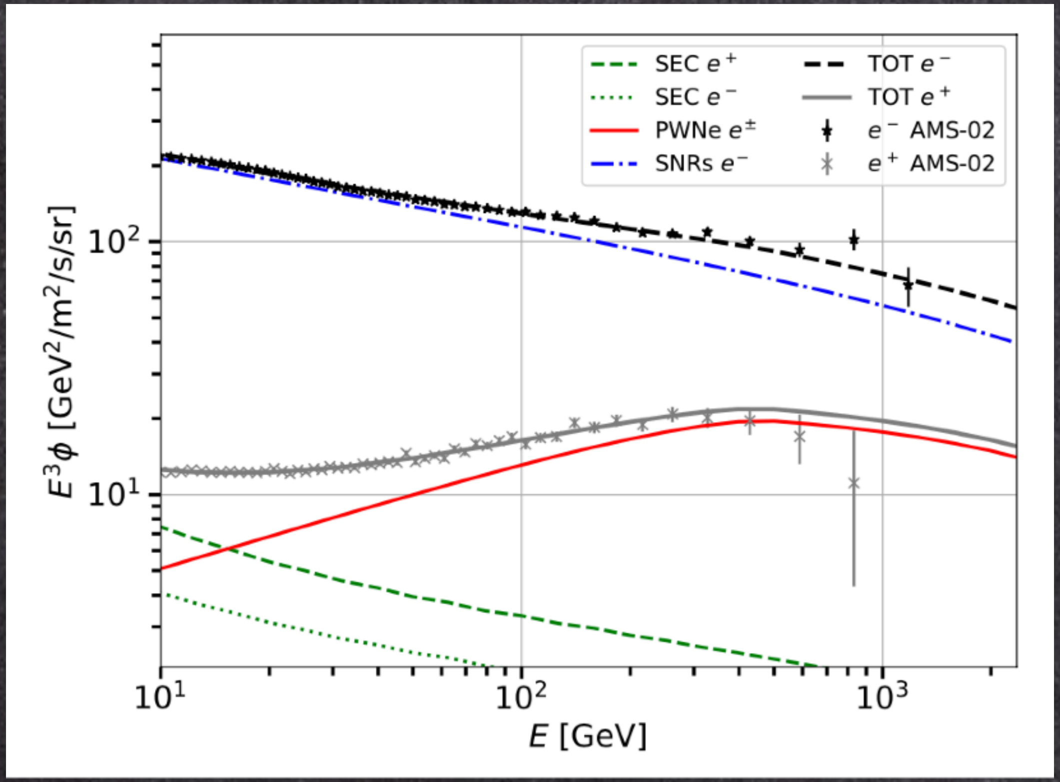
e-, e+ suffer strong radiative cooling and arrive at Earth if produced within few kpc around it.

Local sources very likely leave their imprints in the spectra

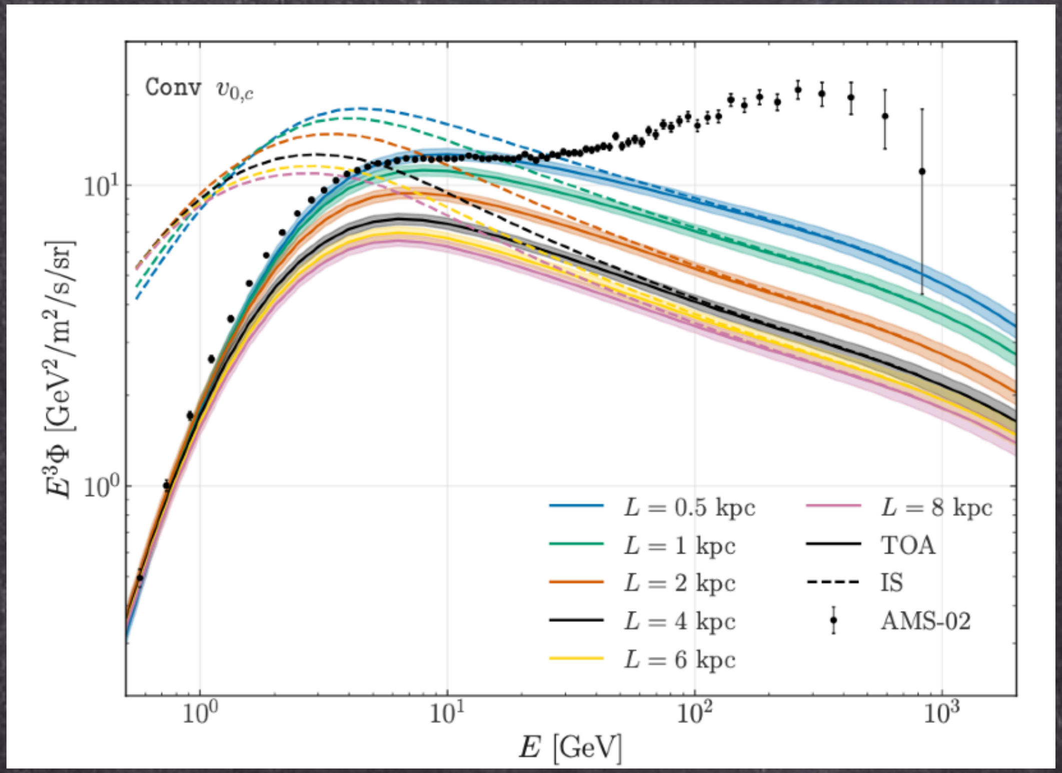
e+ & e- spectra, a natural explanation

e+ and e- AMS-02 spectra fitted with a multi-component model: secondary production, e- from SNR, e+ from PWN

Di Mauro, FD, Manconi PRD 2021



Di MAuro, FD, Korsmeier, Manconi, Orusa 2304.01261



The break at 42 GeV in e- is explained by interplay between SNR and PWN
Secondary e+ depend strongly on L. Deficit from ~ 1 GeV

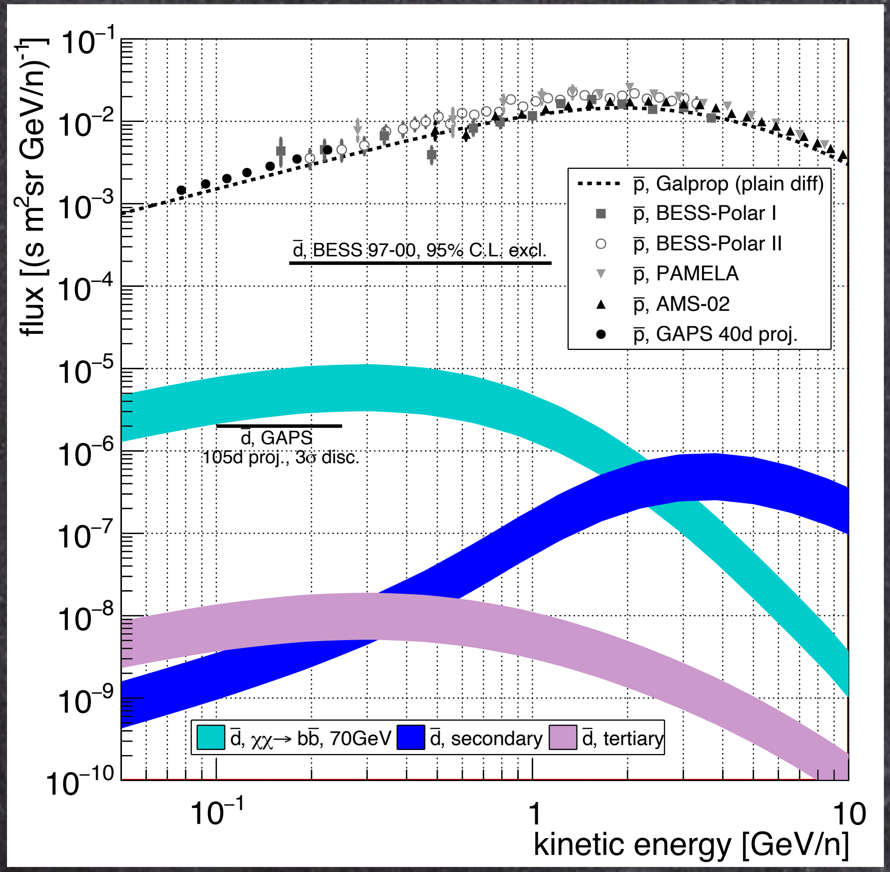
See also Fang+ 2007. 15601, Evoli+PRD 2021, Cuoco+ PRD2020

Antideuterons in cosmic rays

FD, Fornengo, Salati PRD2000

See also Baer&Profumo JCAP2008, FD, Fornengo, Maurin PRD2008, Ibarr&Wild JCAP2012, PRD2013, Fornengo, Maccione, Fitting JCAP2013, Serksnyte et al,PRD 2022, Gomez-Coral PRD2018, Kachelriess+ JCAP2020, CPC2023

P. Von Doetinchem et al. Phys. Rep. 2021
FD, Fornengo, Korsmeier, PRD 2018



AMS-02 antiproton data

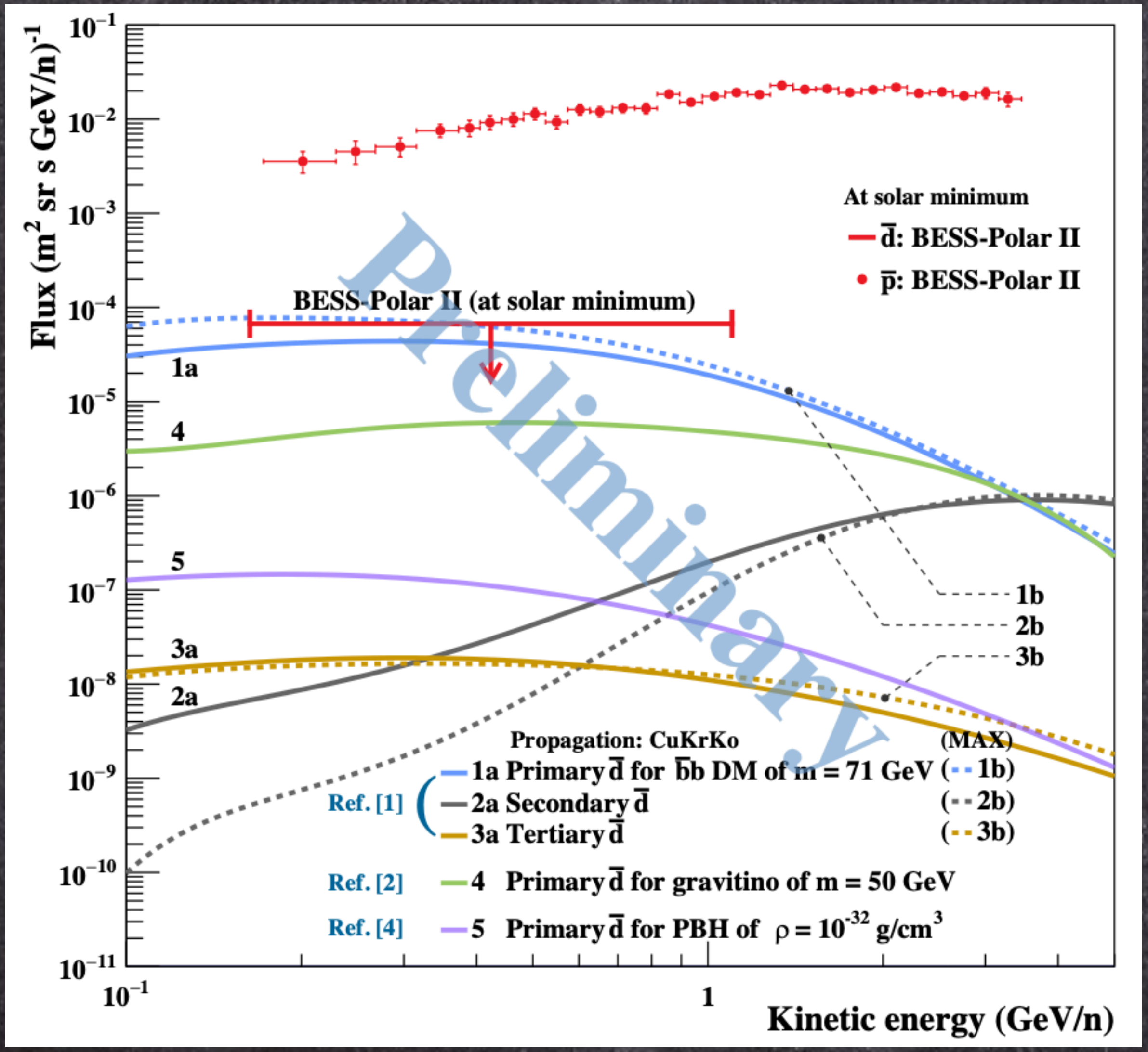
Antideuteron predictions for DM model indicated by pbar AMS-02 data

Bands are for coalescence uncertainty

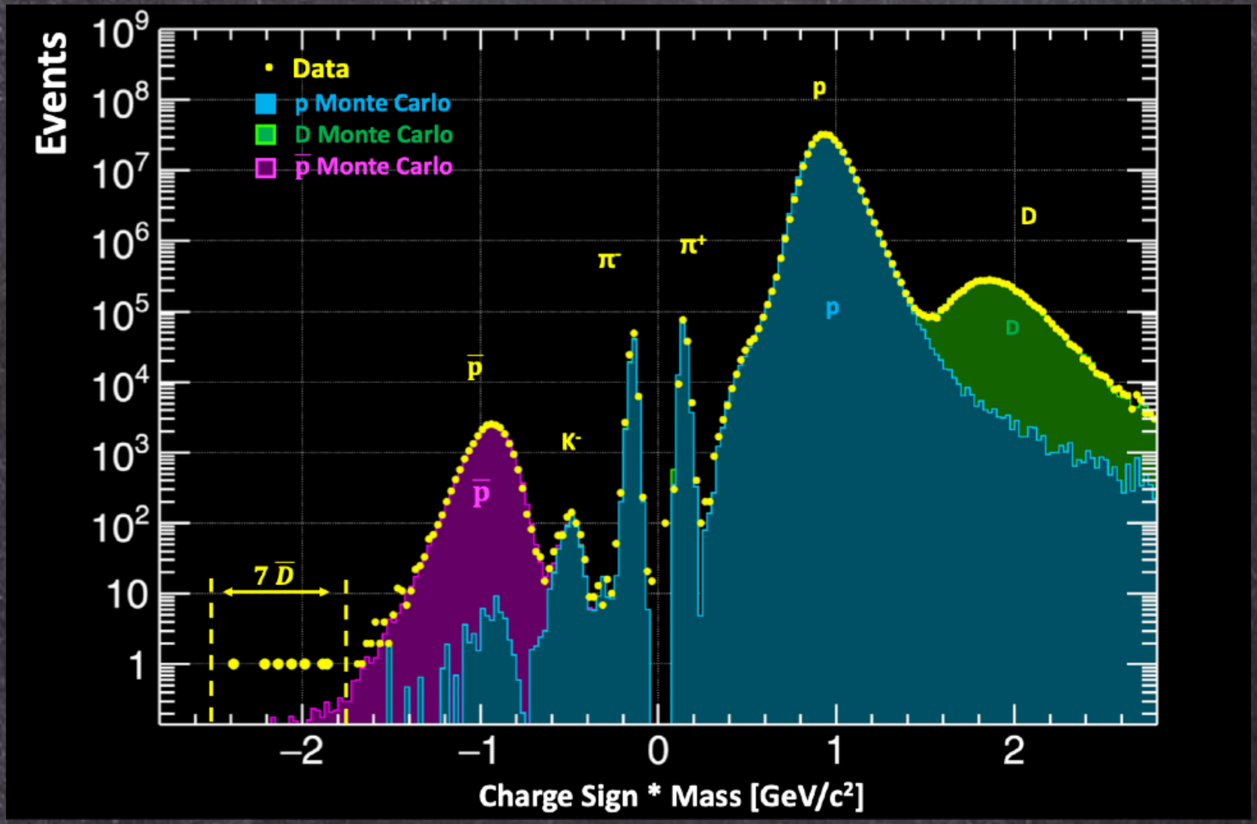
Antideuterons will be a unique window to probe nuclear fusion in secondary events, and to search for Dark Matter annihilation Or decay below ~ 1GeV/n

Perspectives with antideuterons

Bess Polar-II @ ICRC2023



AMS preliminary @ICRC 2023

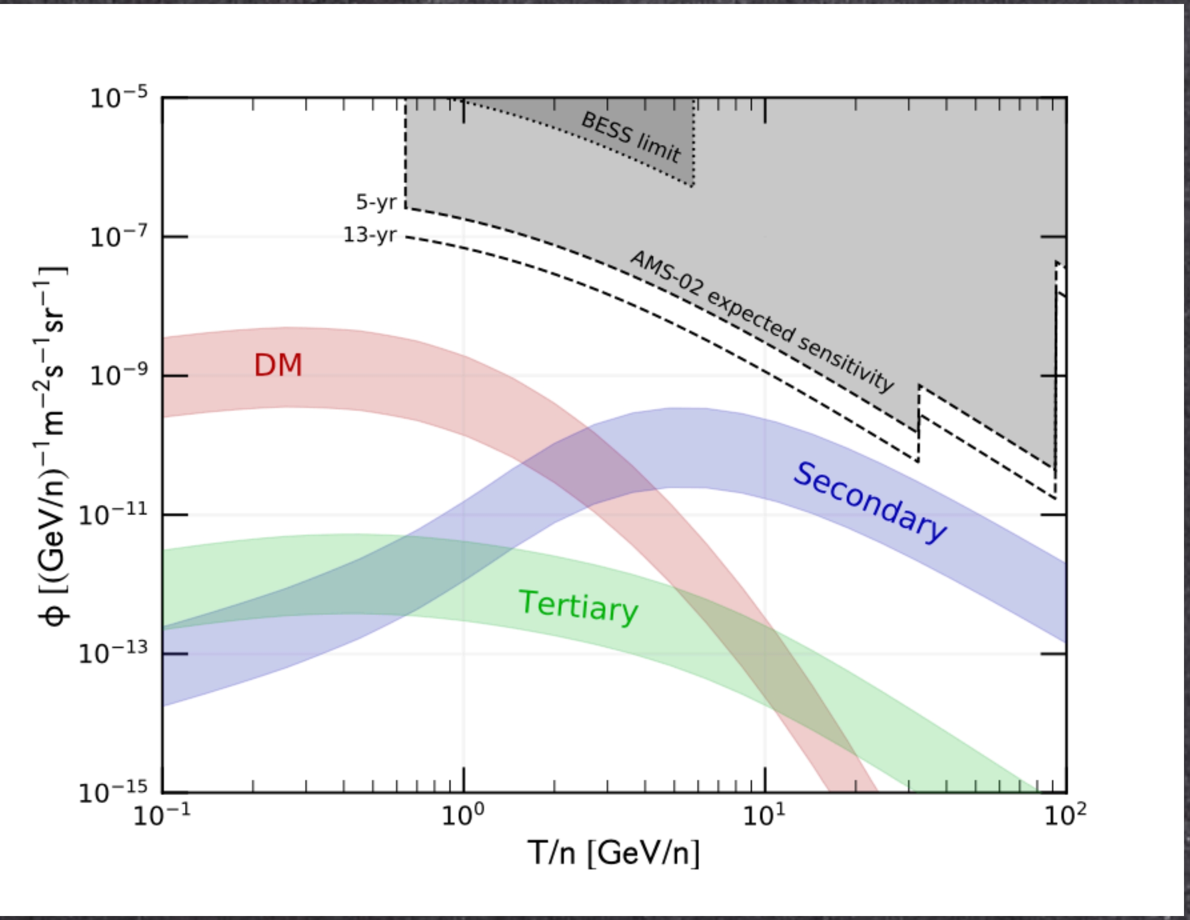


GAPS - dedicated to antineutron searches - will fly from Antarctica Dec 2024

Perspectives with antihelium

Cirelli+JHEP2014; Carlson+ PRD2014

FD, Fornengo, Korsmeier, PRD 2018



- Good signal-to-bkgd ratios
- Predictions for most DM models much lower than experimental reach
- Nuclear physics brings relevant effects through $(p_{coal})^6$

Challenging for present day experiments

Looking at antimatter is fundamental for exotic physics

Concluding remarks

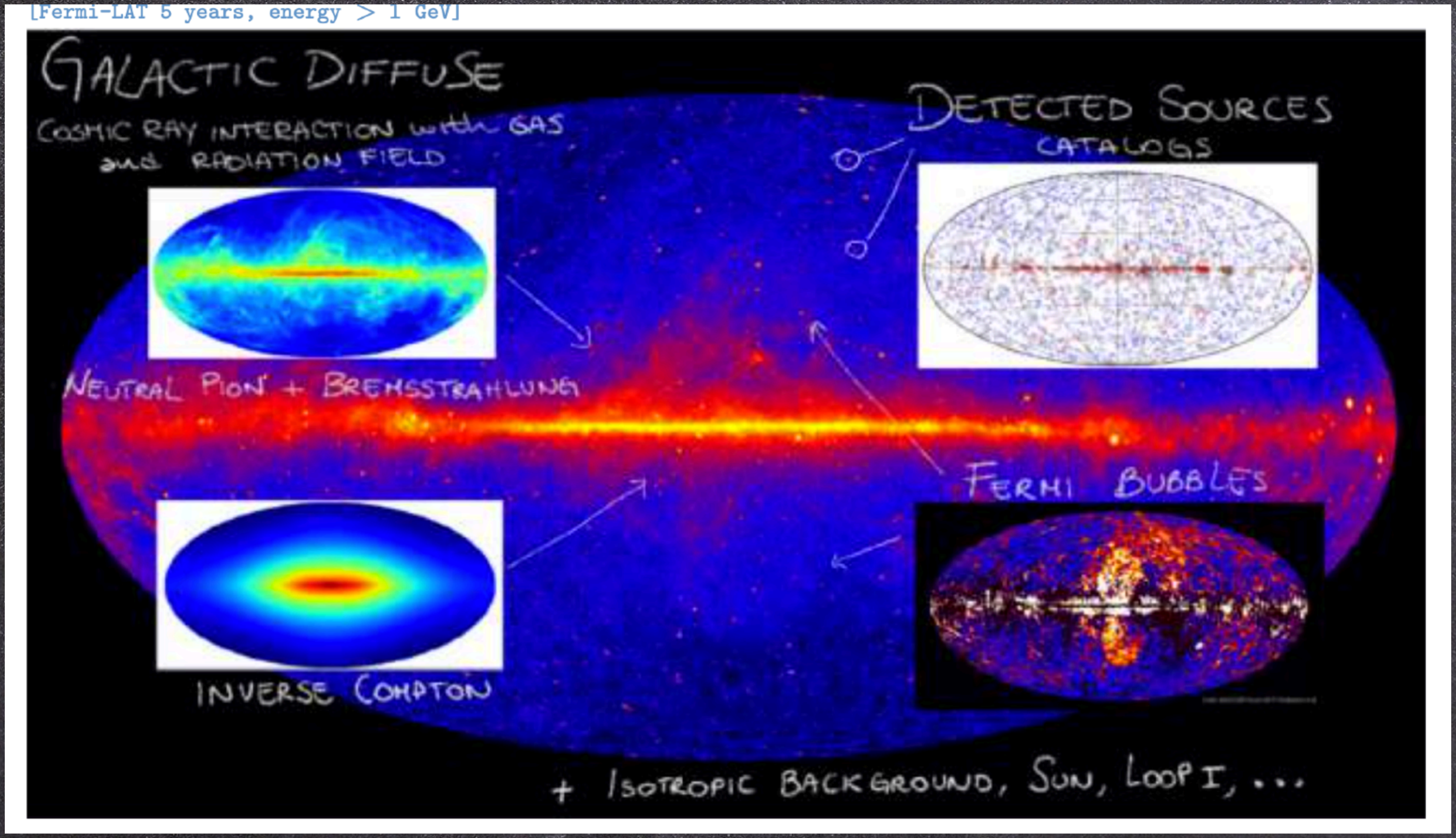
Current theoretical modeling answers to a number of fundamental questions at "zero-th order".
General features (i.e. power laws) are theoretically motivated

New data continuously force us to further theoretical efforts.

We cannot fully understand data from charged CRs and γ rays without multi-wavelength and multi-messenger approach, as well as the harvest at colliders' dedicated campaigns

The γ-ray counterpart of the sky

Courtesy of Silvia Manconi, TMEX 2023



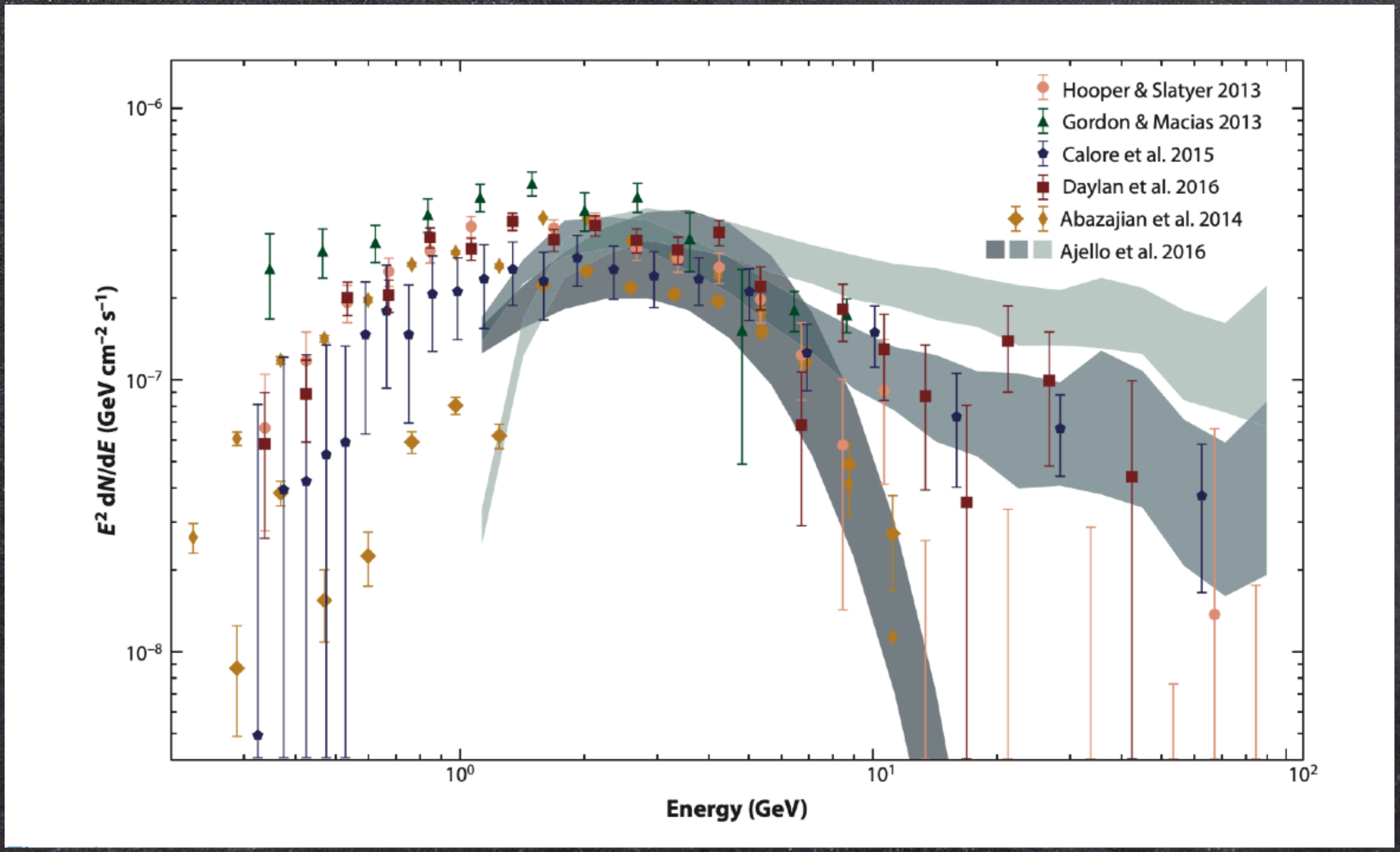
A prediction of the emission from all diffuse, point and extended sources, at all latitudes, is possible.

However, predictions often lack estimation uncertainties from many and diverse channels. We expect them to be relevant

The GeV excess at the Galactic center

Goodenough+'09,Vitale+'09,Abazajan+PRD'12,Hooper+PDU'13,Daylan+PDU'16, Calore+JCAP'15, Cholis+JCAP'15, Calore+PRD'15, Ajello+2015, Linden+PRD'16, Ackermann+ApJ'17,...500+papers

Found with template fitting (Calore+JCAP2015), adaptive template fitting (Storms+ 2017), weighted likelihood (Di Mauro PRD2021, Abdollahi AJS2020) photon counts statistics (1pPDF: Calore, FD,+ PRL2021; NPTF Lee+2016), machine learning (List+PRL20,Mishra-JCAPSharma+PRD21,Caron+22), wavelet transforms (Bartels+PRL16)



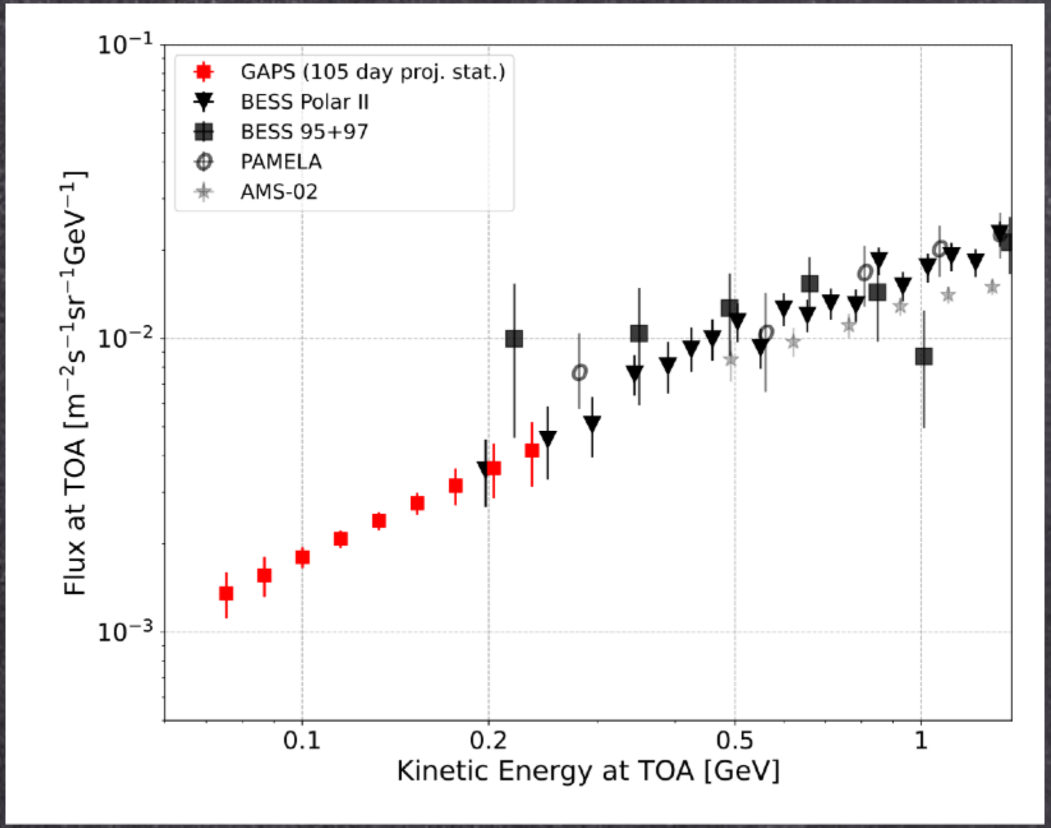
MurgiaAR 2020

No matter the method, the GC excess is statistically significant

GAPS detector to fly in Antarctic by 2023

Dedicated to antideuterons searches

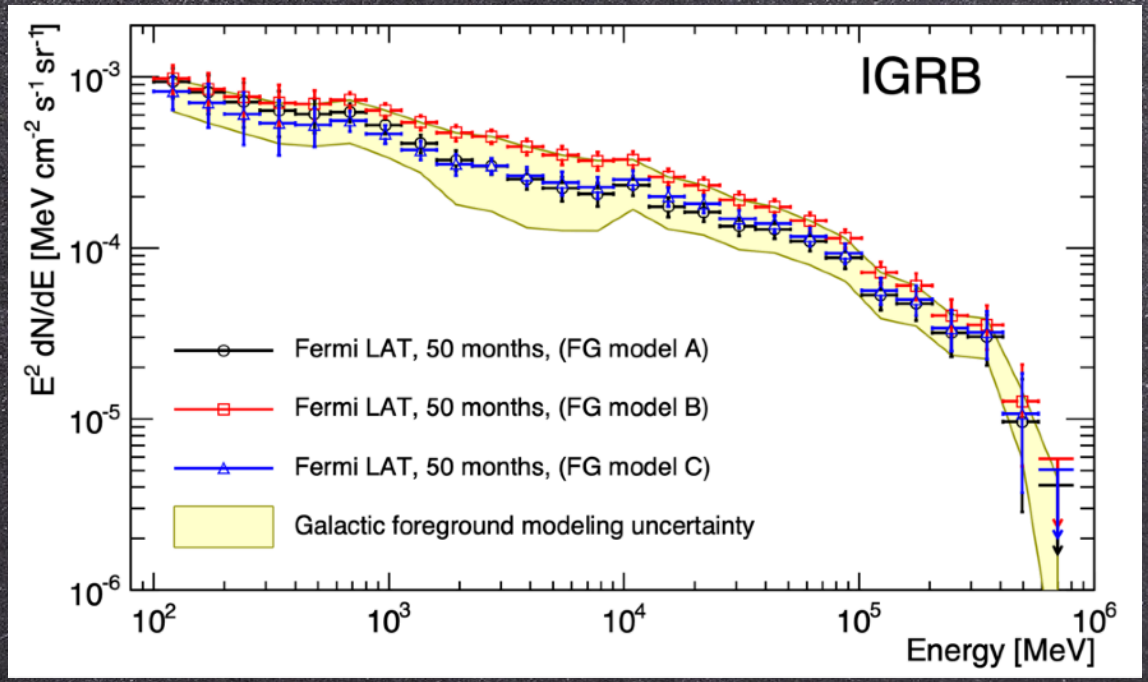
F. Rogers et al. Astrop. Phys. 2023



Secure results on very low energy antiprotons

Extragalctic γ-ray background

Fermi-LAT Coll ApJ 2015

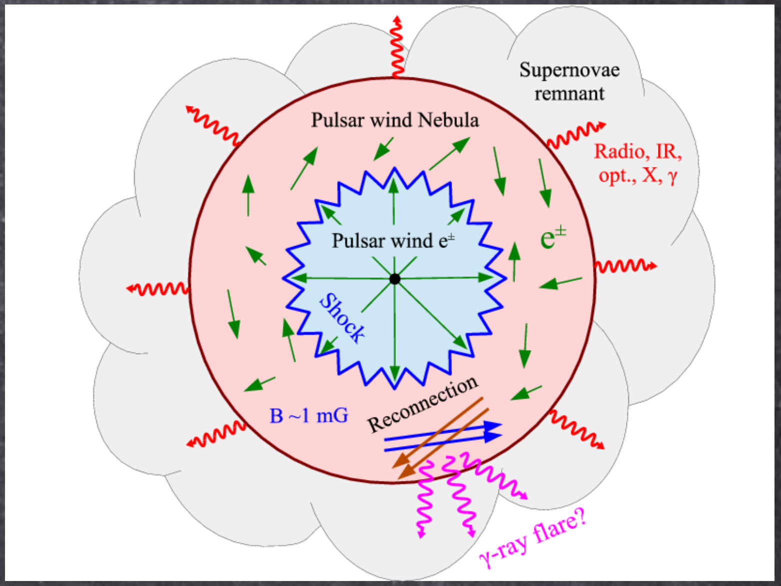


How to improve it?

Gas Maps, precise knowledge of CR density in the Galaxy, Density of various components, exact spectrum of electrons in al the valume, gradient of CRs.

Pulsars (PWN) as CR e+e- sources

High magnetic fields (10^9-10^{12} G) extract wind of e-
from the pulsar surface, e± pairs produced in EM cascades



Pulsar spin-down energy (W_0) is transferred to e± pairs,
accelerated to very high energy with $Q \sim E^{-\gamma}$.

After several kyrs e± can be released in the ISM

These e± pairs radiate by Inverse Compton scattering
and synchrotoron,
and shine at many frequencies

$$E_{\rm tot} = \eta W_0 = \int_0^T dt \int_{E_1}^{\infty} dE E Q(E,t)$$

The total energy E_{tot} emitted in e± by a PWN is a fraction η (efficiency conversion) of the spin-down energy W_0. Relevant parameters: γ and η

Supernova remnants (SNRs) as sources of e-

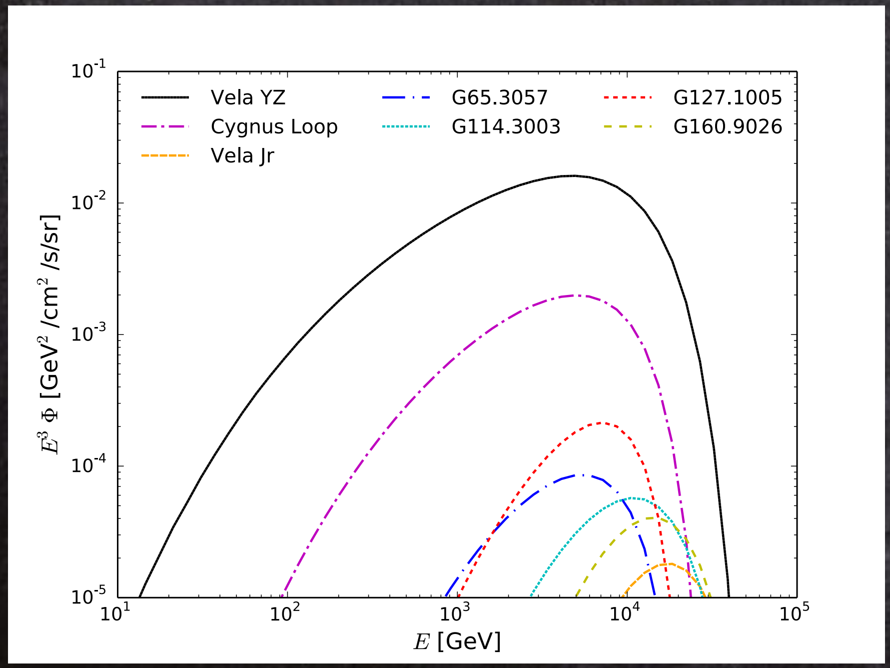
Ellison+ ApJ 2007; Blasi 2013; Di Mauro+ JCAP 2014; Di Mauro+ ApJ 2017; Evoli+ PRD 2021

SNR are considered the main sources of galactic CRs - nuclei from p to Fe, and e-

Hadronic acceleration: evidence of π^0 bump (Fermi-LAT+ 2010)
Leptonic acceleration: evidence of synchrotron emission in radio and X-rays

Injection spectrum:

Manconi, Di Mauro, FD JCAP2017; JCAP 2019



$$Q(E) = Q_0 \left(\frac{E}{E_0}\right)^{-\gamma} \exp\left(-\frac{E}{E_c}\right)$$

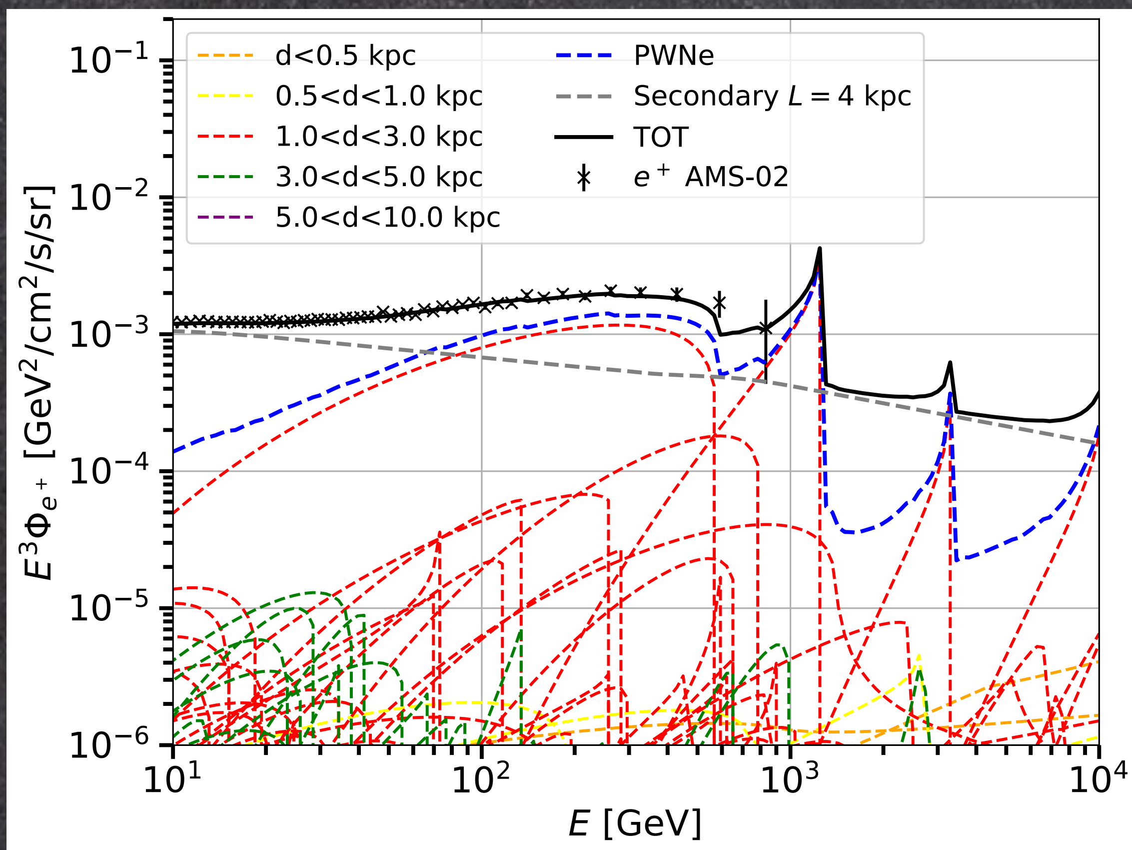
e- flux from near SNR (Vela XY and Cygnus Loop at d<0.5 kpc)

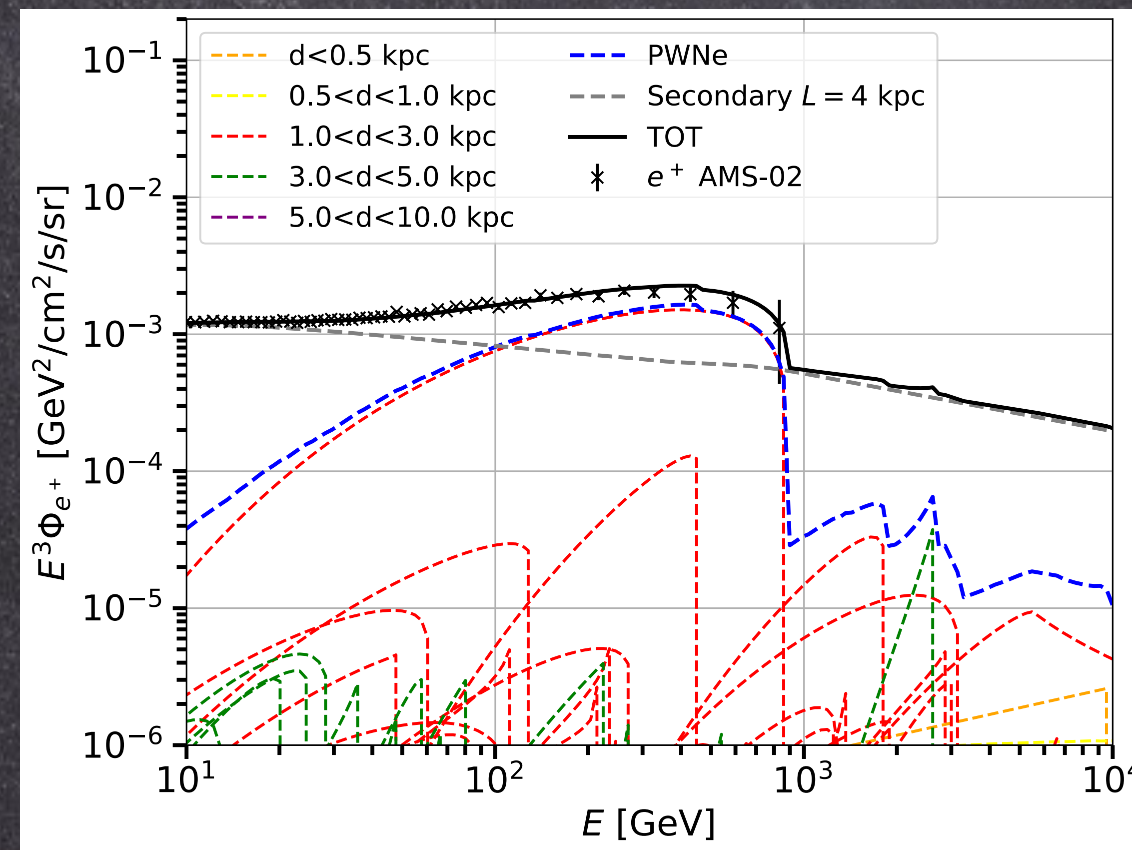
Few SNR can contribute to TeV flux

Additional e- from a smooth SNR distribution

Fit of Galactic pulsar populations to AMS-02 e+ data

Orusa, Di Mauro, FD, Manconi JCAP 2021





The contribution of pulsars to e+ is dominant above 100 GeV and may have different features.
E>1 TeV: unconstrained by data.
Secondaries forbid evidence of sharp cut-off.

No need for Dark Matter, indeed

Possible origin of anti-helium: anti-clouds, anti-stars

V. Poulin et al. PRD 2019

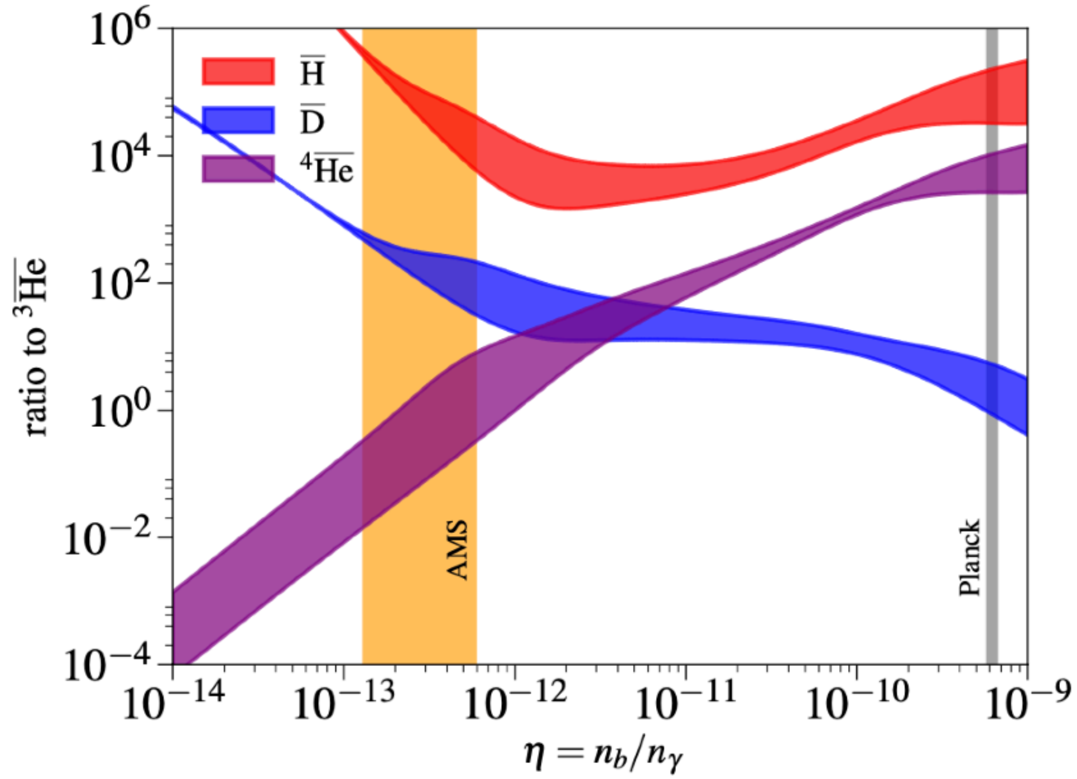


FIG. 4. Abundance of $\overline{\text{H}}$, $\overline{\text{D}}$ and $\overline{^4\text{He}}$ with respect to that of $\overline{^3\text{He}}$ as a function of the (anti-)baryon-to-photon ratio $\bar{\eta}$. The *Planck* value is represented by the grey band. The value required by the *AMS-02* experiment is shown by the orange band.

Anti-clouds: require anisotropic BBN for the right ^{3}He/^{4}He

AMS-02 measures are local, Planck's ones averaged over the Universe

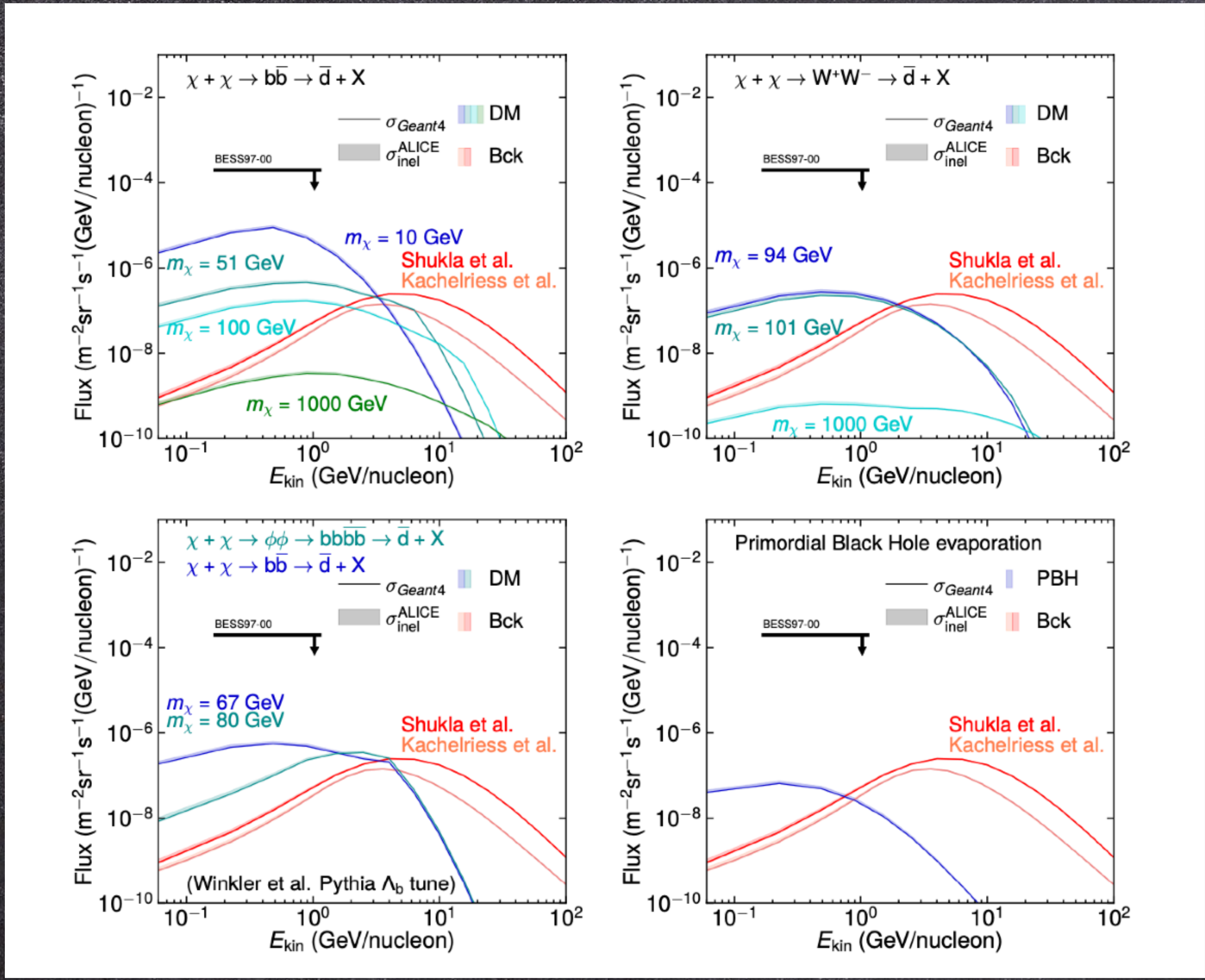
Exotic mechanism for segregation of anti-clouds is needed

Traces in p-bar and D-bar

One anti-star could make the job. How did they survive?

Antideuterons persepctives

Serksnyte et al,PRD 2022



Low energy window keeps being a discovery field

Uncertainties on P_c is ± 70%

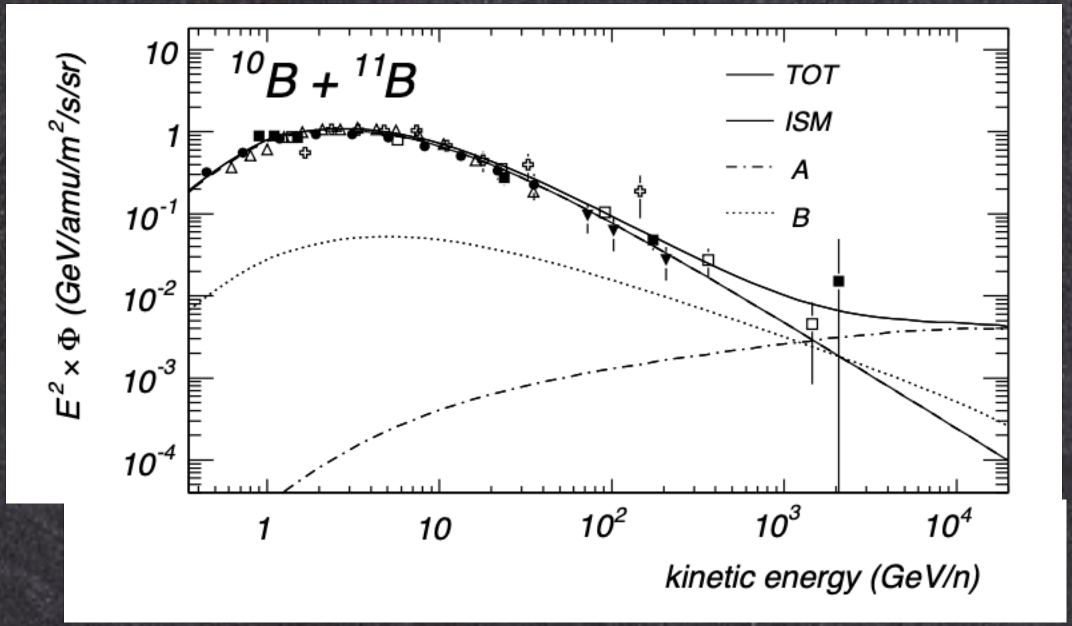
See also Korsmeier, FD, Fornengo PRD 2018

Hardening of nuclear spectra

If it were acceleration, the hardening would be the same for primaries and secondaries

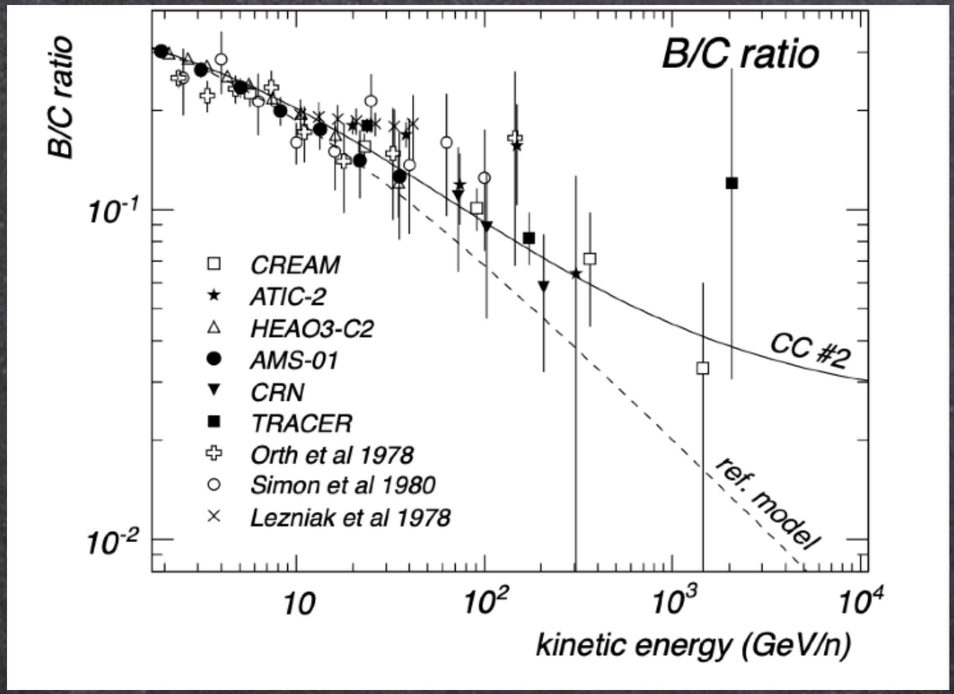
Recchia & Gabici MNRAS 2014; Ptuskin &Zirakashvili ApJ 2013; Zatsepin & Sokolskaya A&A 2006; Yuan+ PRD 2011

Tomassetti&FD A&A2021



An hardening is expected from fragmentation in the SNRs

Tomassetti&Oliva ApJL 2017



An hardening is expected from reacceleration in the SNRs

Also Tomassetti & FD ApJL 2015

Interpretations of current data is not clear, and still hampered by spallation cross sections

Antideuterons from relic WIMPS

FD, Fornengo, Salati PRD 62 (2000)043003

In order for fusion to take place, the two antinucleons must have low kinetic energy

Kinematics of spallation reactions prevents the formation of very low antiprotons (antineutrons).
At variance, dark matter annihilates almost at rest

$$\frac{dN_{\bar{D}}}{dE_{\bar{D}}} = \left(\frac{4\,P_{\rm coal}{}^3}{3\,k_{\bar{D}}}\right) \left(\frac{m_{\bar{D}}}{m_{\bar{p}}\, m_{\bar{n}}}\right) \sum_{\rm F,h} B_{\chi \rm h}^{(\rm F)} \left\{ \frac{dN_{\bar{p}}^{\rm h}}{dE_{\bar{p}}} \left(E_{\bar{p}} = \frac{E_{\bar{D}}}{2}\right) \right\}^2$$

Background and DM have different kinematics and source spectra