Challenges in theoretical astroparticle physics

Fiorenza Donato
Torino University & INFN

CORTONA - XXXVII Convegno Nazionale di Fisica Teorica

Overview of the talk

Particles as messengers from the Universe

Charged cosmic rays

Photons - γ rays

GALACTIC COSMIC RAYS

are charged particles (nuclei, isotopes, leptons, antiparticles)
diffusing in the galactic magnetic field
Observed at Earth with E~ 10 MeV/n - 10^3 TeV/n

1. SOURCES

PRIMARIES: directly produced in their sources
Supernova remnants (SNR), pulsars, dark matter annihilation, ...

SECONDARIES: produced by spallation reactions of primaries on the interstellar medium (ISM), made of H and He

2. ACCELERATION

SNR are considered the powerhouses for CRs.
They can accelerate particles at least up to 10^2 TeV

3. PROPAGATION

CRs are diffused in the Galaxy galactic magnetic field (µG)

\+ loose/gain energy with different mechanisms (leptons)

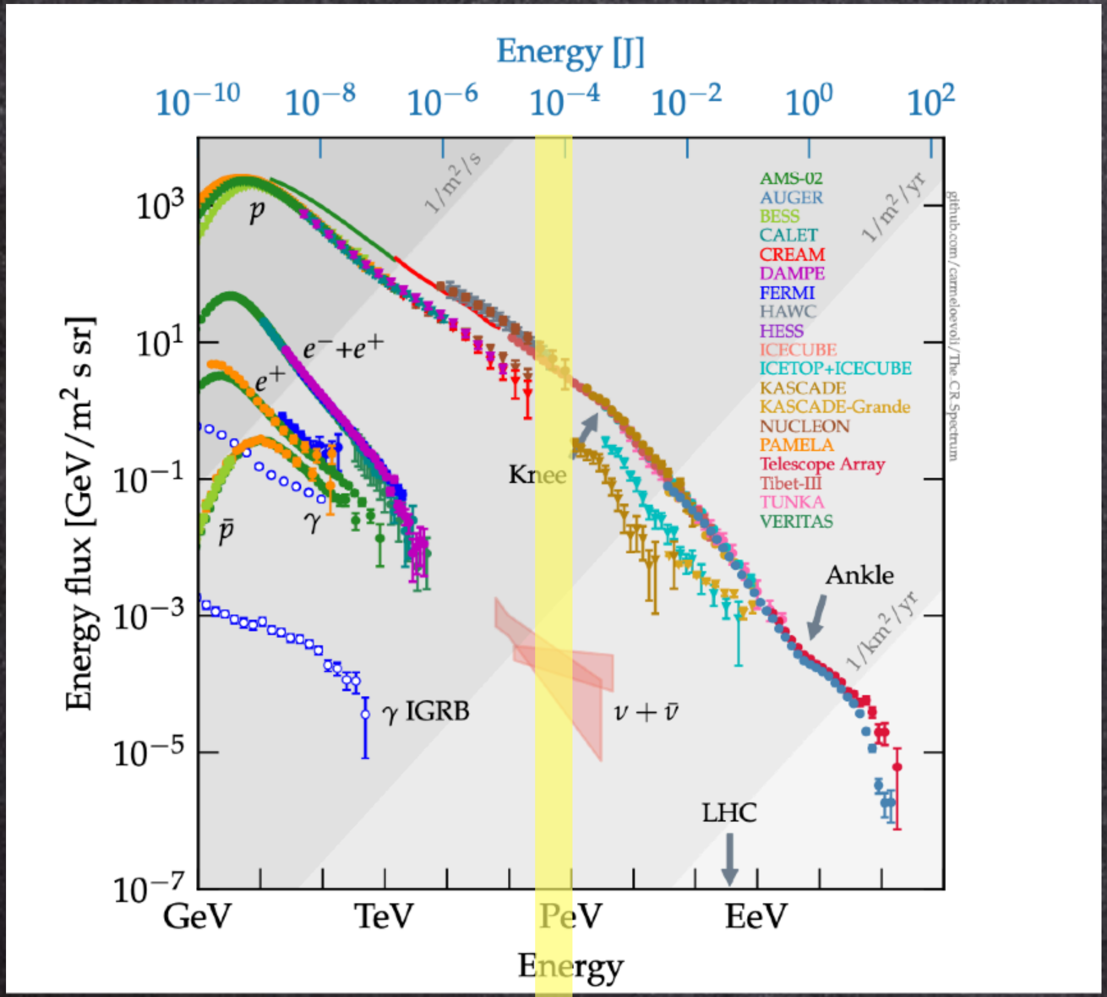
The measured Cosmic Ray (CR) spectrum

CR database: D. Maurin+ 2306:08901

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

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

See also N. Tomassetti 2301.10255



Direct measures

Air showers

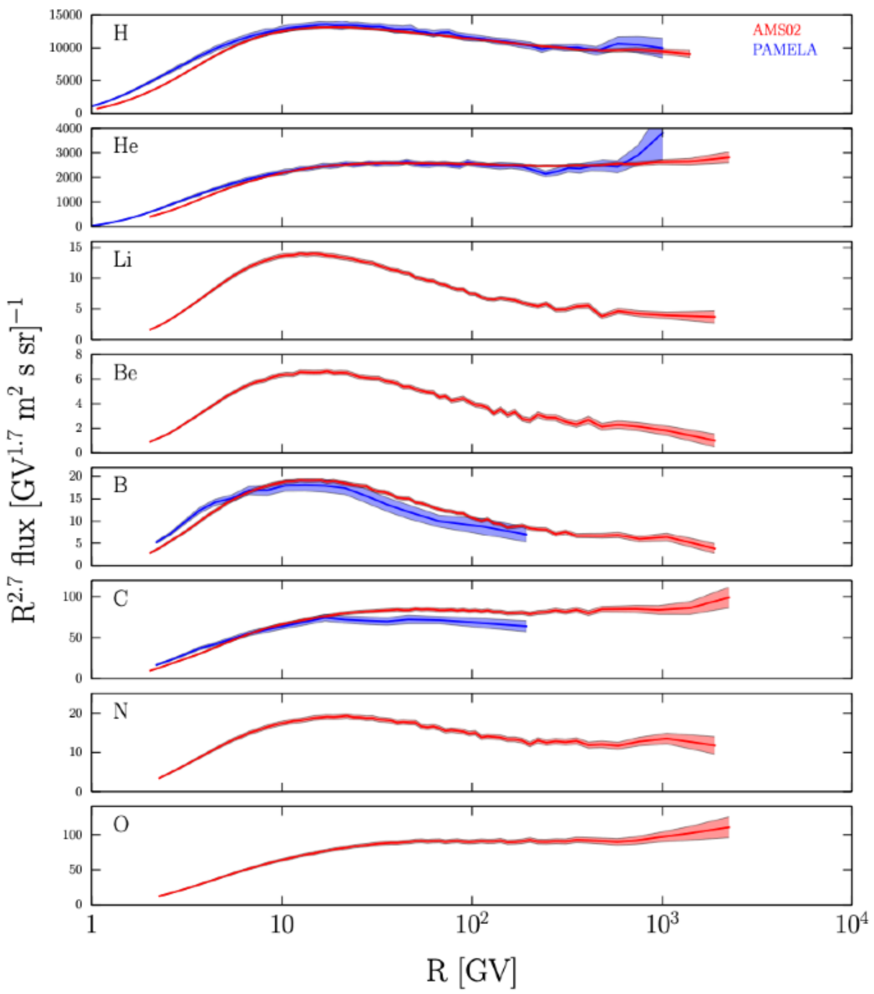
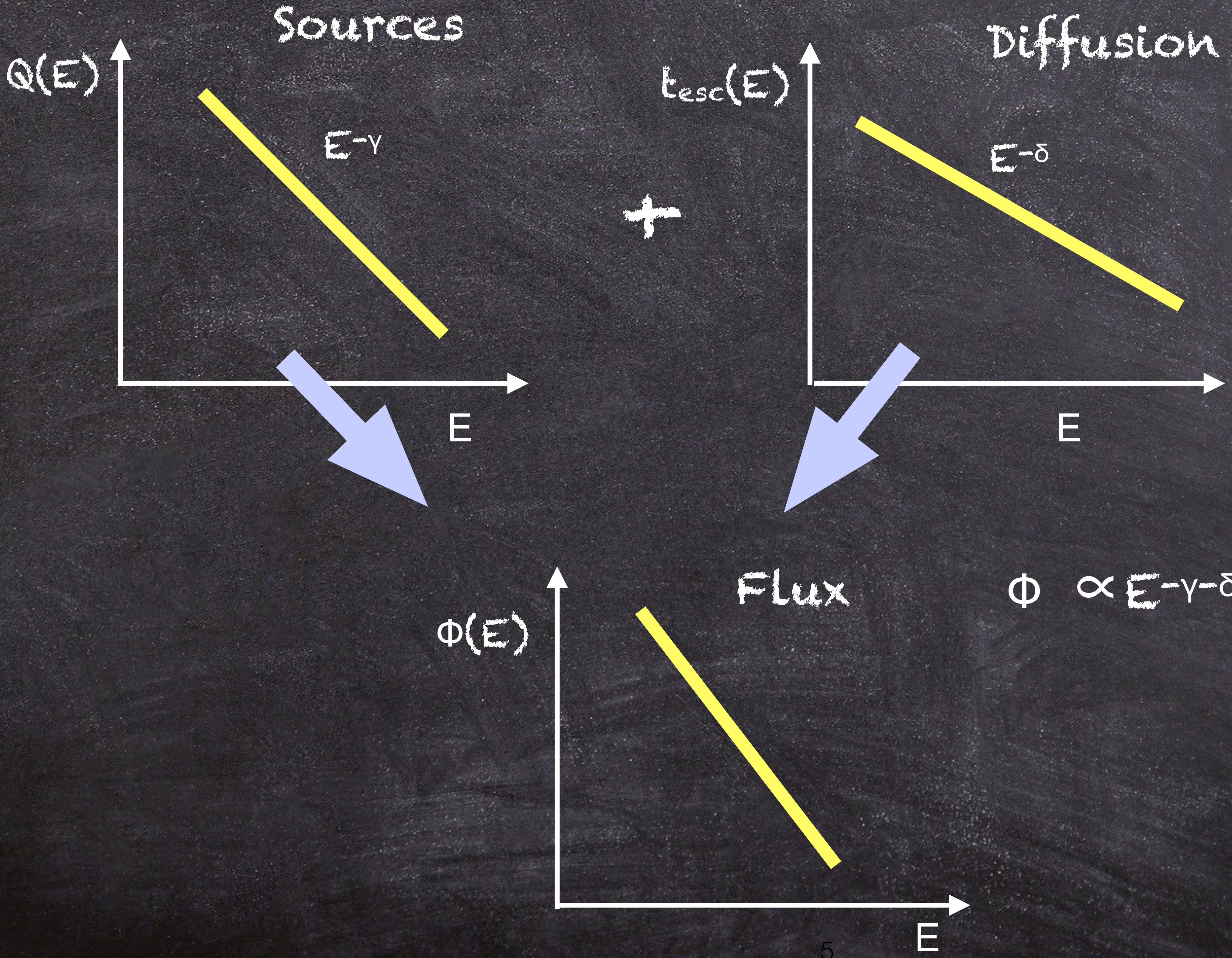


Fig. 1. The individual CR flux for nuclear species up to Oxygen as measured by PAMELA and AMS02. Shadow regions correspond to 1 sigma total errors (systematic and statistical added in quadrature).

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 $P_{CR} \sim 10^{41}$ 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

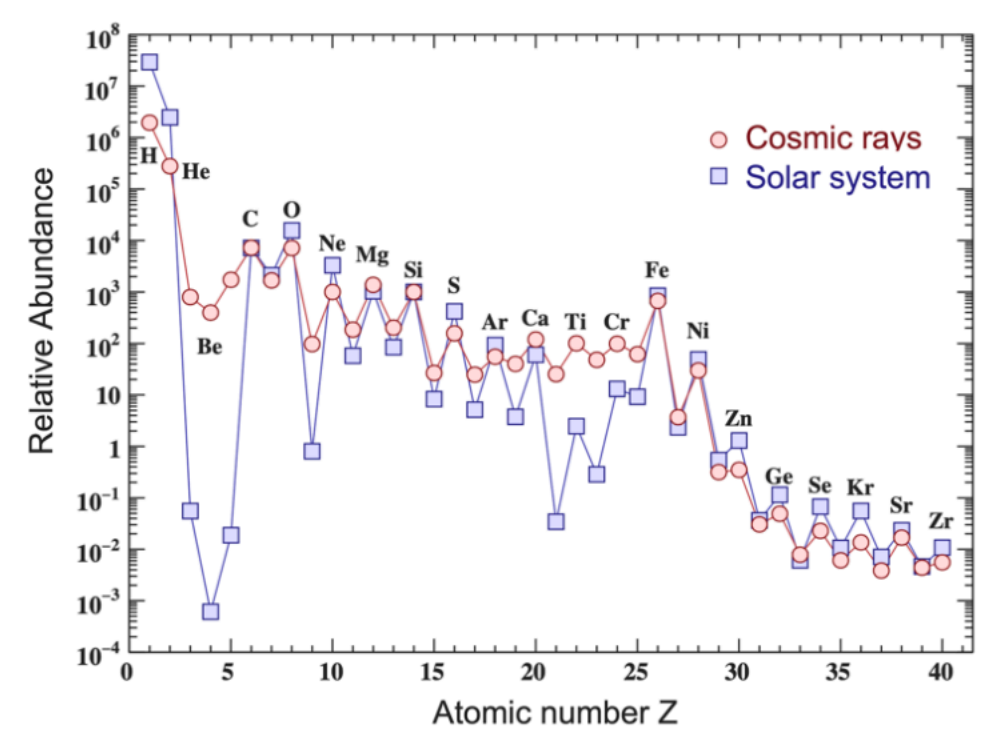
Probe: detection of the maximum energy at 67.5 MeV in the π^0 decay;γ rays from molecular clouds illuminated by nearby, freshly accelerated protons

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

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

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)

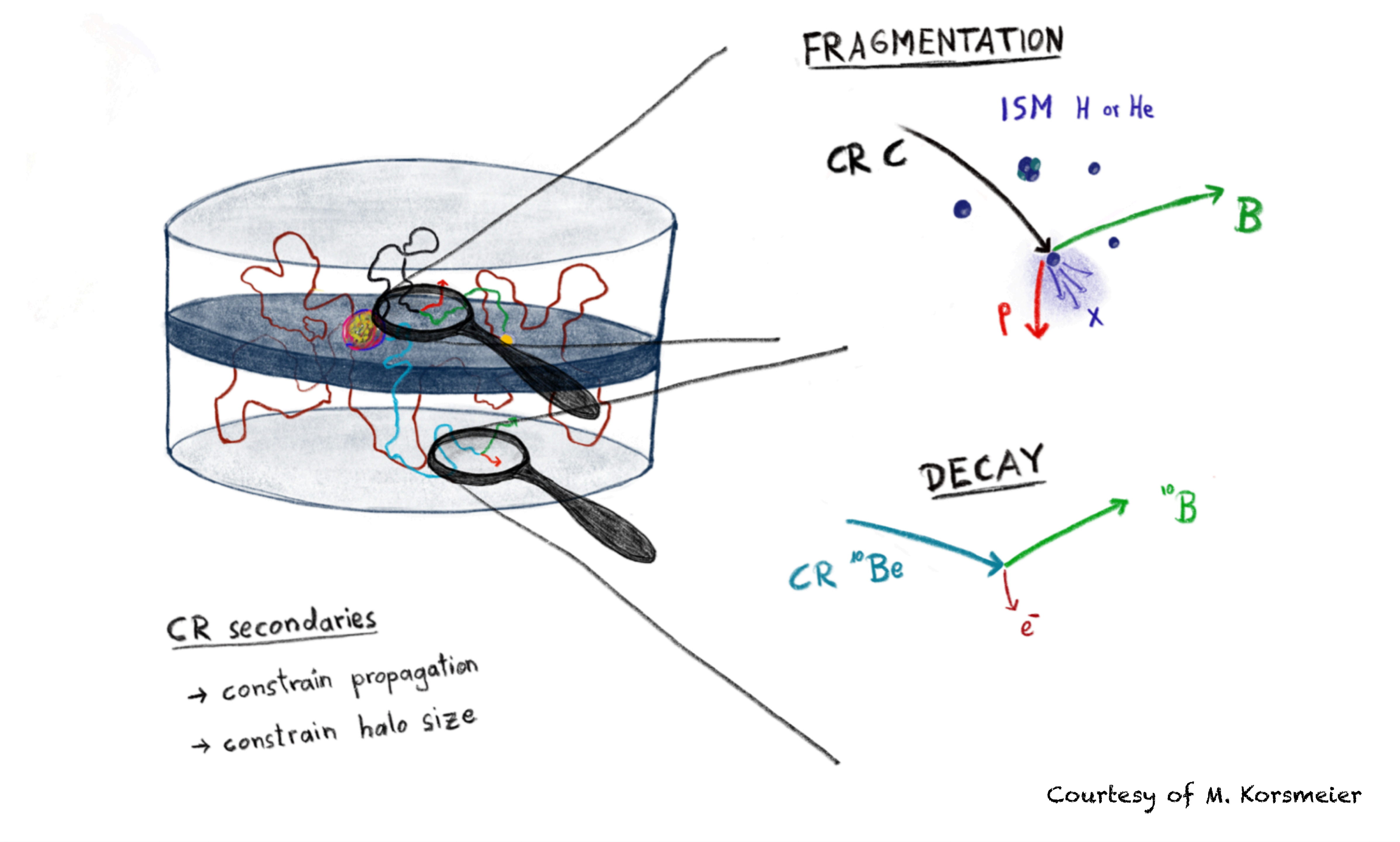
Leptons: Synchrotron on the galactic B~3 μG

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)

The Galaxy seen by a wandering particle



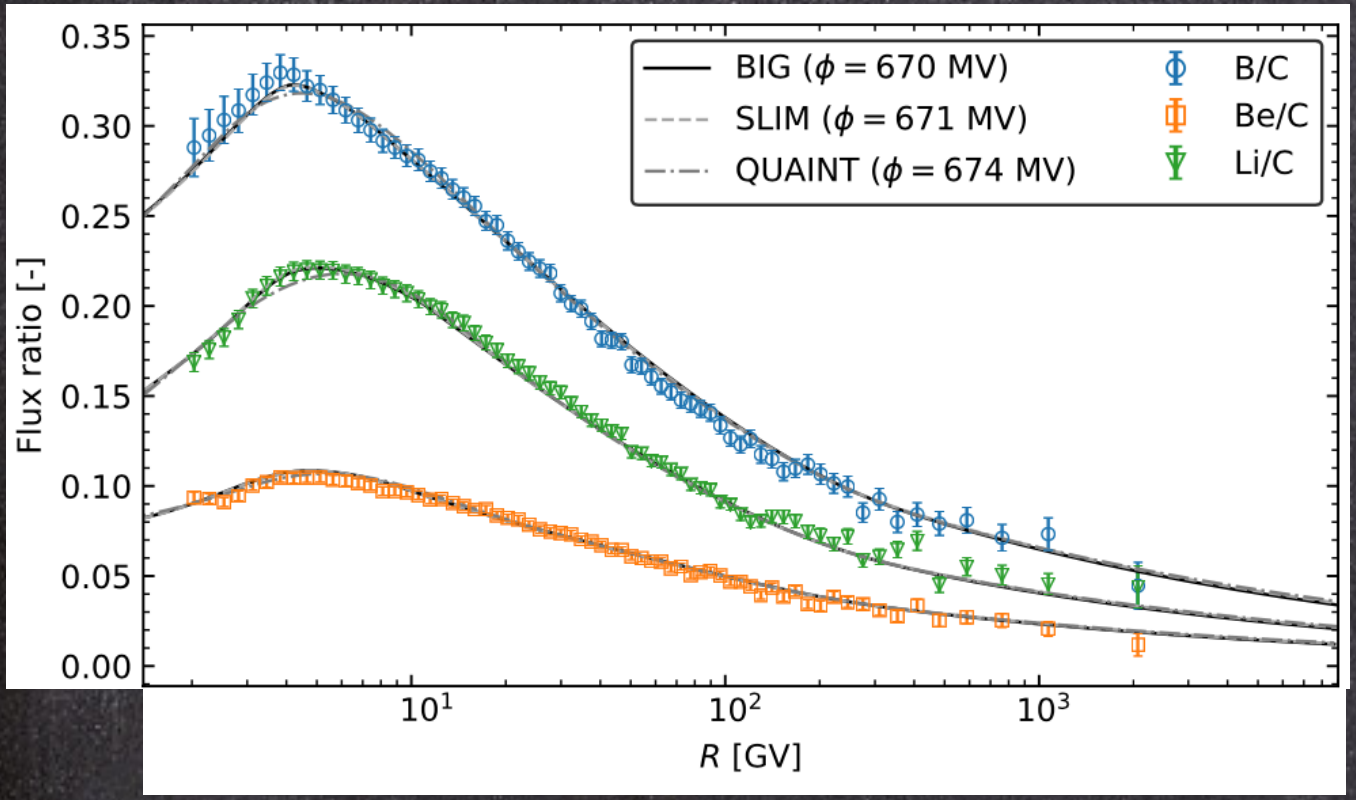
CR secondaries

- → constrain propagation
- → constrain halo size

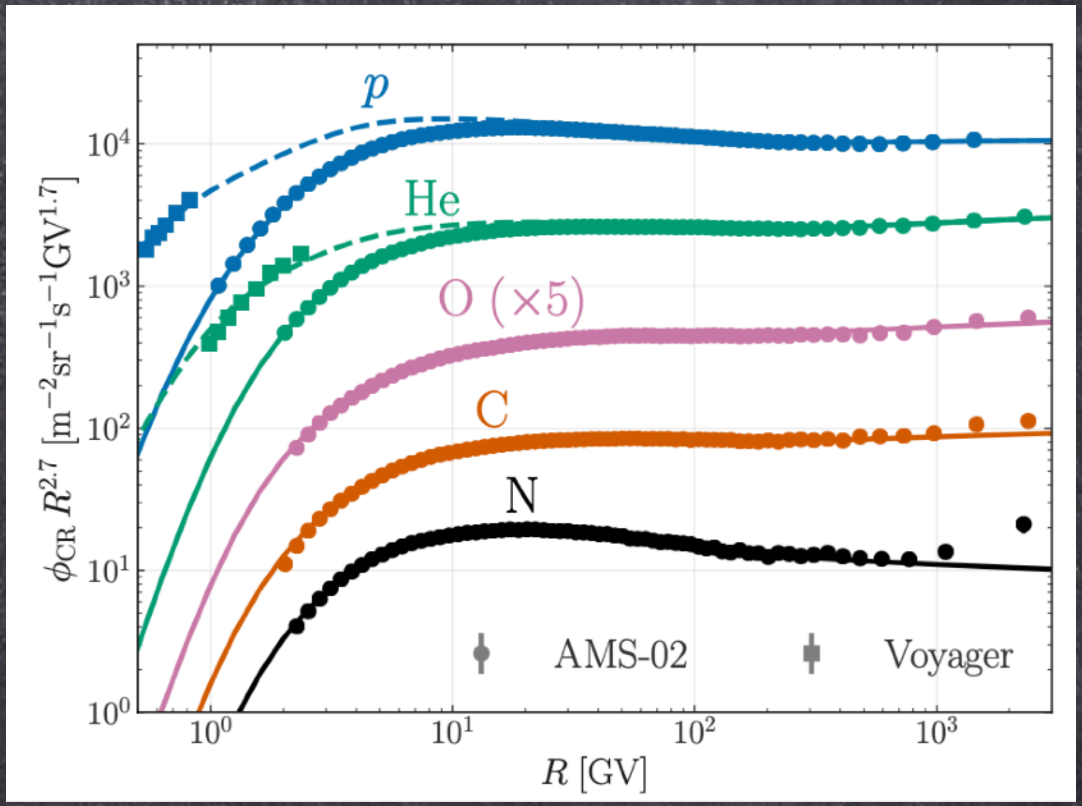
Courtesy of M. Korsmeier

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

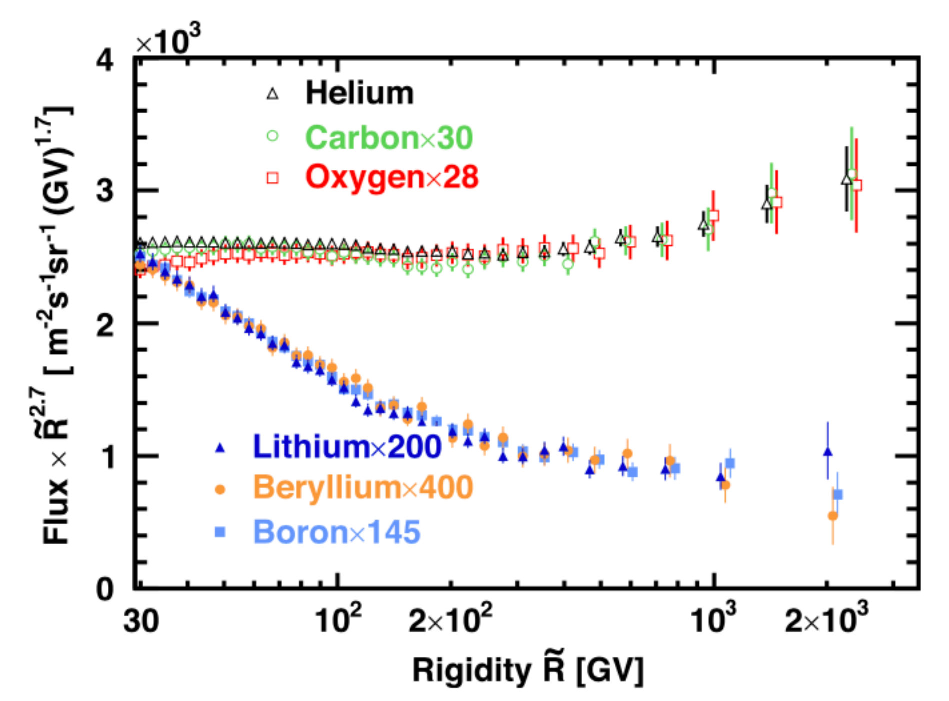
Data on nuclear species are well described by propagation models with diffusion coefficient power index $\delta = 0.50 \pm 0.03$.

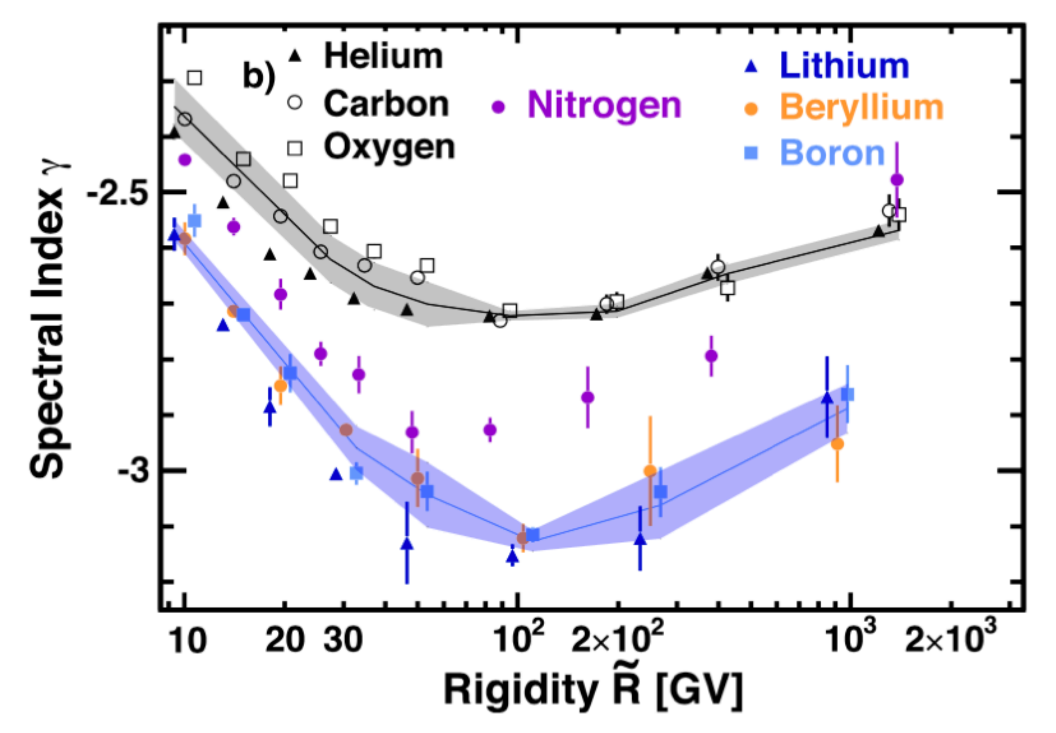
Convection or reacceleration models both work.

Interpretation hampered by spallation 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

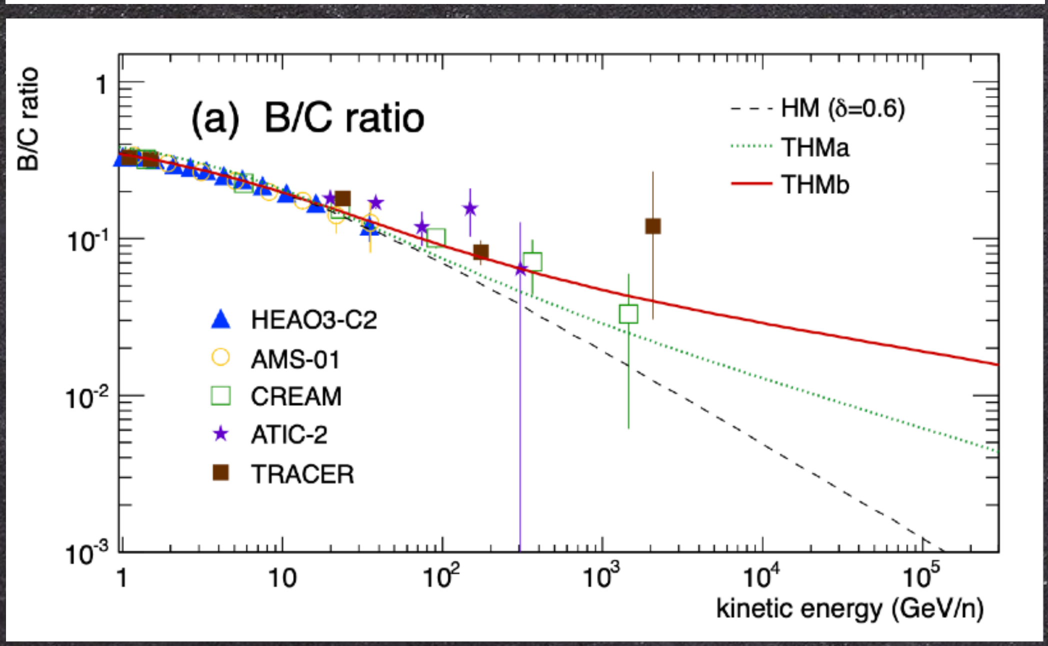
Hardening of nuclear spectra: diffusion

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

(Genolini+ PRL 2017;; Evoli+ PRD2019)

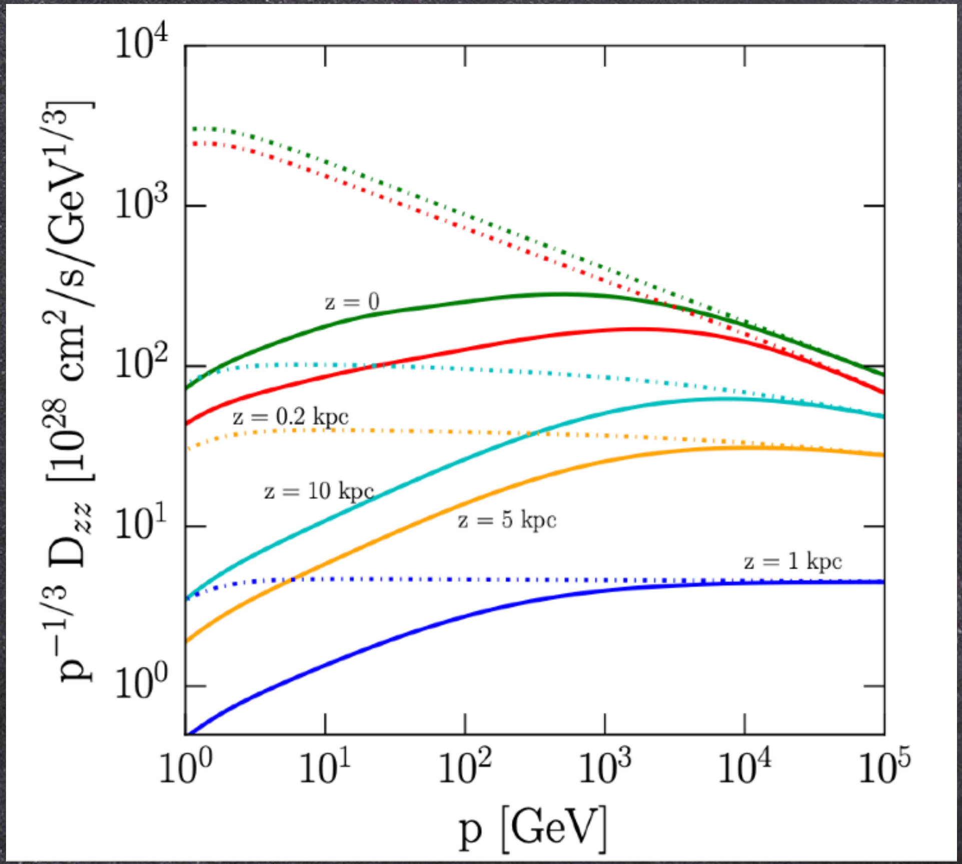
Tomassetti ApJL 2012

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



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

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



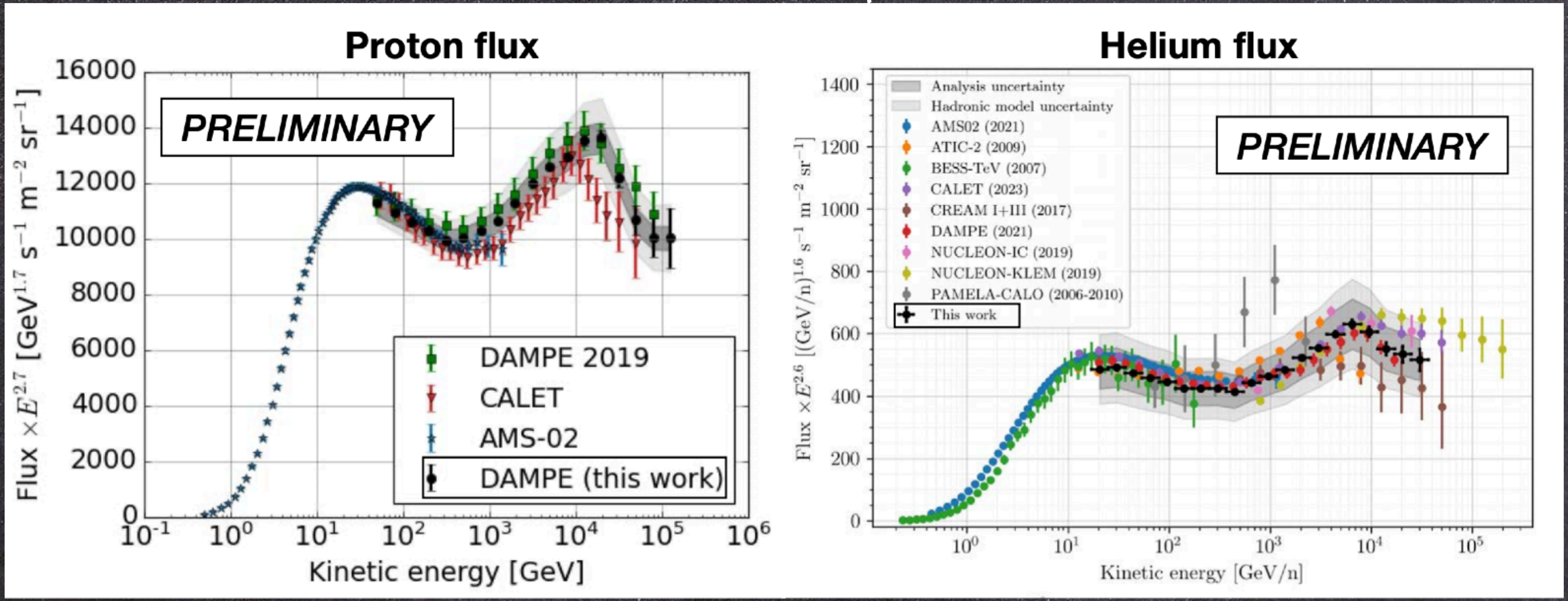
CRs diffuse on external turbulence (mainly above the break) and on the waves generated by CRs themselves

Interpretations still hampered by spallation cross sections

P and He spectra: shifts, breaks and bumps

1. p spectrum is distinctly softer ($\Delta\gamma \sim 0.1$) 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

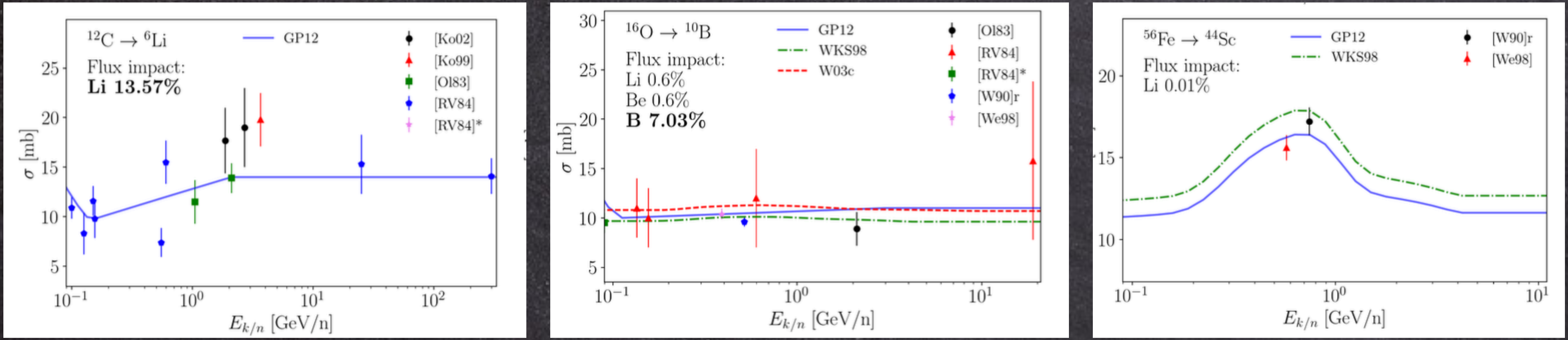
Evoli+ PRD2019; Di Mauro, FD+ 2023

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



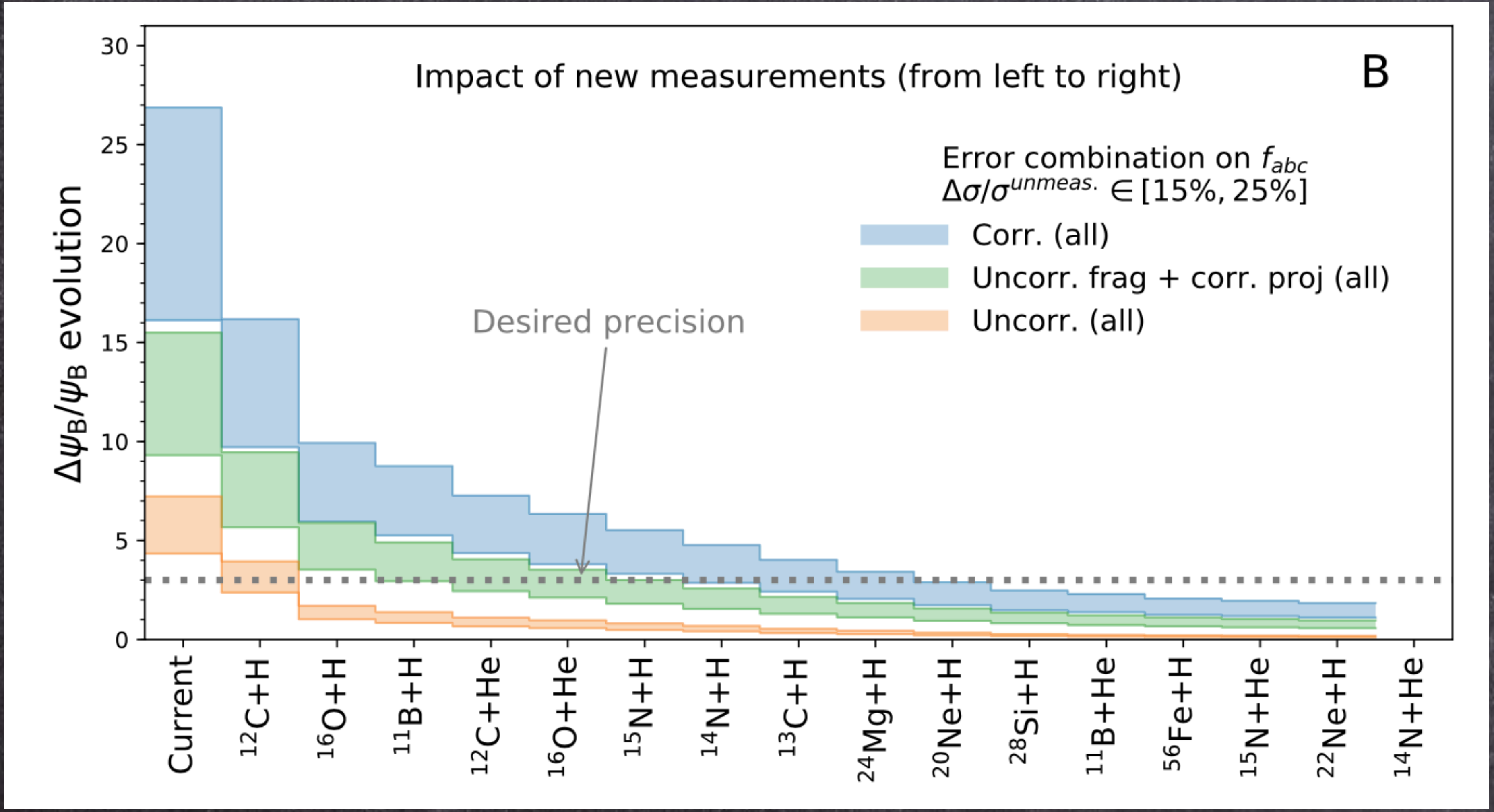
Now probably the most limiting aspect now for a clear interpretation of precise CR data coming from space

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

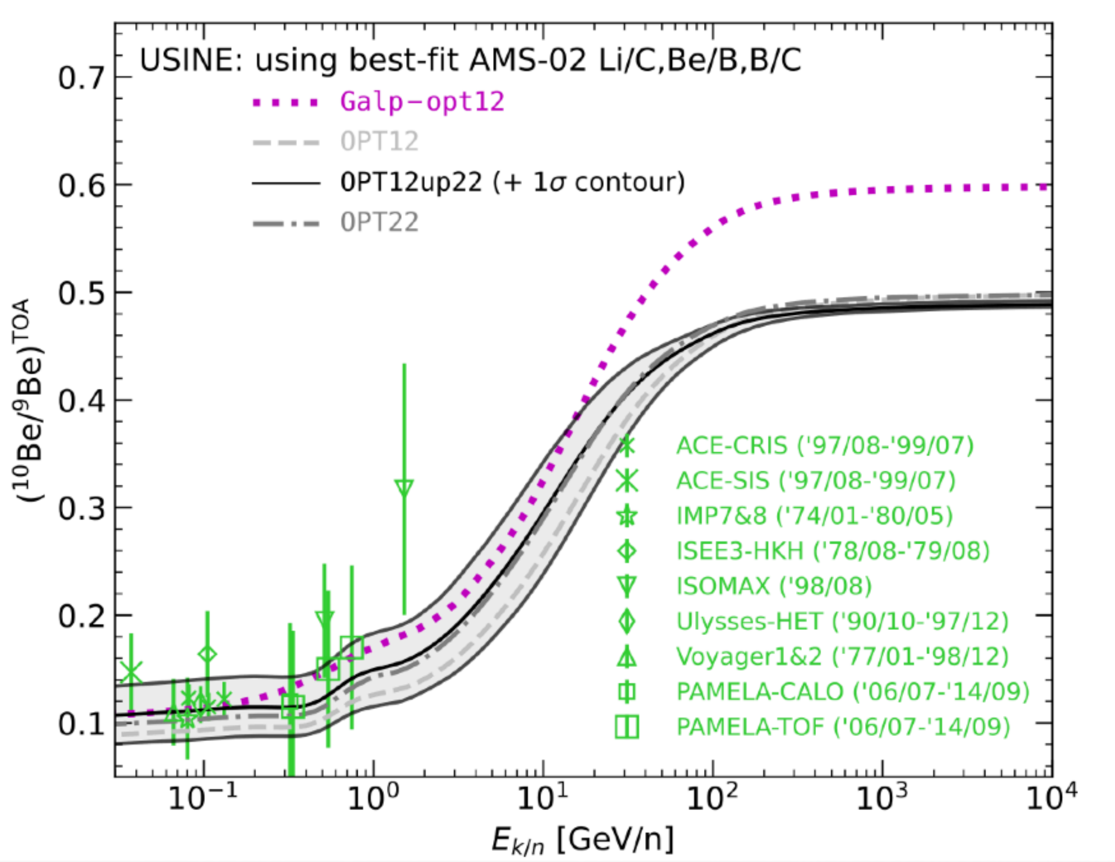


Dedicated campaigns at COLLIDERS are needed.
Some already started or planned
(LHCf, LHCb, NA61, Amber/Compass, ...)

Radioactive light isotopes

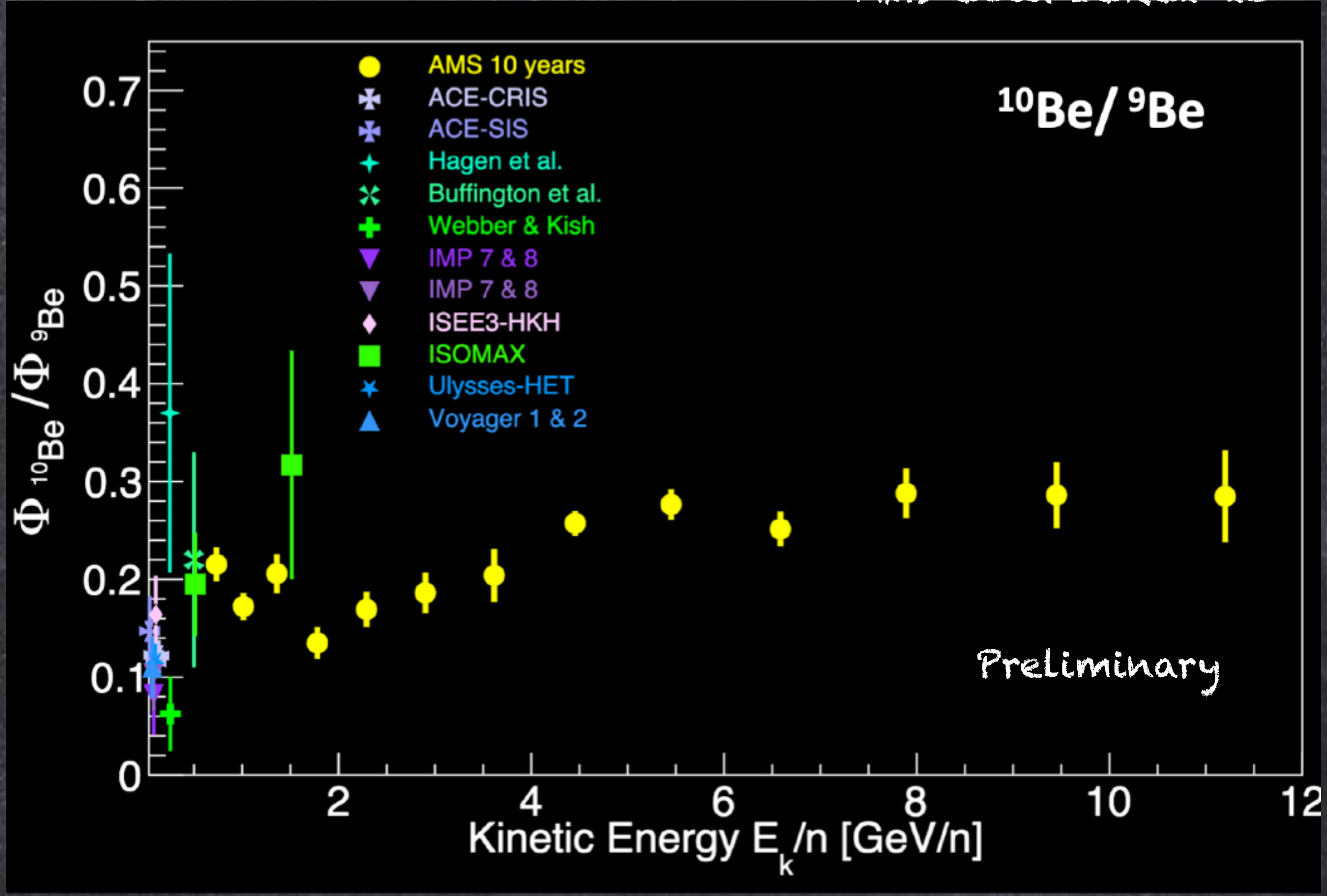
Radioactive isotopes (^{10}Be, ^{26}Al) can track the diffusive halo size
Important to test origin and propagation of CRs

Maurin et al, A&A 2002



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

AMS Coll. ICRC2023



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

Dark Matter in Cosmic Rays?

Indirect Dark Matter detection

Annihilation inside celestial bodies (Sun, Earth):

ν at neutrino telescopes as up-going muons

Annihilation in the galactic halo:

γ-rays (diffuse, monochromatic line), multiwavelength

antimatter, searched as rare components in cosmic rays (CRs)

ν and γ keep directionality

Charged particles diffuse in the galactic halo

ASTROPHYSICS OF COSMIC RAYS!

Antimatter or γ-rays sources from DARK MATTER

Annihilation

$$Q_{\rm ann}(\vec{x}, E) = \epsilon \left(\frac{\rho(\vec{x})}{m_{DM}} \right)^2 \sum_f \langle \sigma v \rangle_f \frac{dN^f_{e^\pm}}{dE}$$

Decay

$$Q_{\rm dec}(\vec{x}, E) = \left(\frac{\rho(\vec{x})}{m_{DM}} \right) \sum_f \Gamma_f \frac{dN^f_{e^\pm}}{dE}$$

- ρ DM density in the halo of the MW
- m_{DM} DM mass
- $\langle \sigma v \rangle$ thermally averaged annihilation cross section in SM channel f
- Γ DM decay time
- e+, e- energy spectrum generated in a single annihilation or decay event

Annihilations take place in the whole diffusive halo

Antimatter in Cosmic rays!

> 10^6 antiprotons

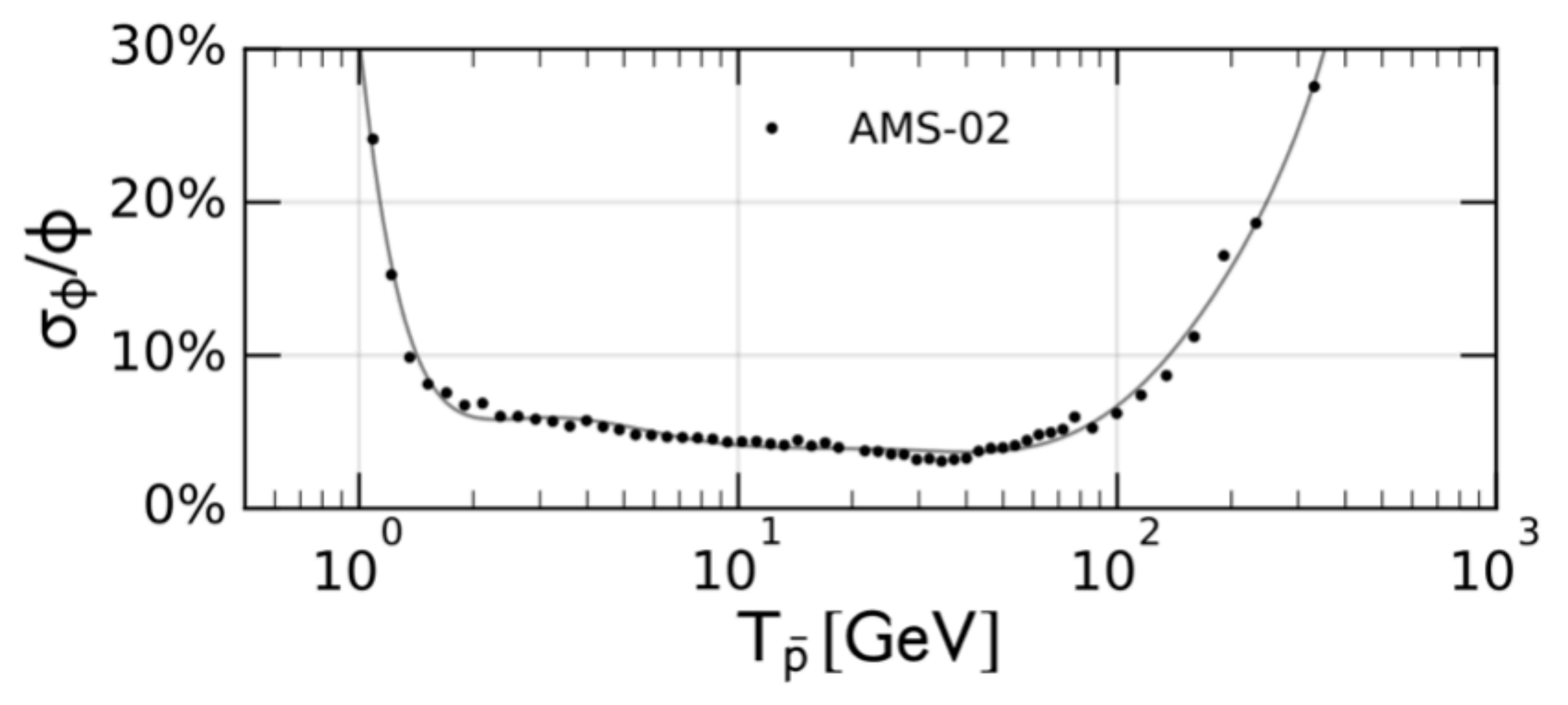
> 3 10^6 positrons

Collected by AMS02/ISS

Antiproton production by inelastic scatterings

$$q_{ij}(T_{\bar{p}}) = \int_{T_{\rm th}}^{\infty} dT_i \; 4\pi \, n_{{\rm ISM},j} \, \phi_i(T_i) \, \frac{d\sigma_{ij}}{dT_{\bar{p}}}(T_i, T_{\bar{p}}). \qquad \frac{d\sigma_{ij}}{dT_{\bar{p}}}(T, T_{\bar{p}}) = p_{\bar{p}} \int d\Omega \; \sigma_{\rm inv}^{(ij)}(T_i, T_{\bar{p}}, \theta).$$

Data from space are very precise

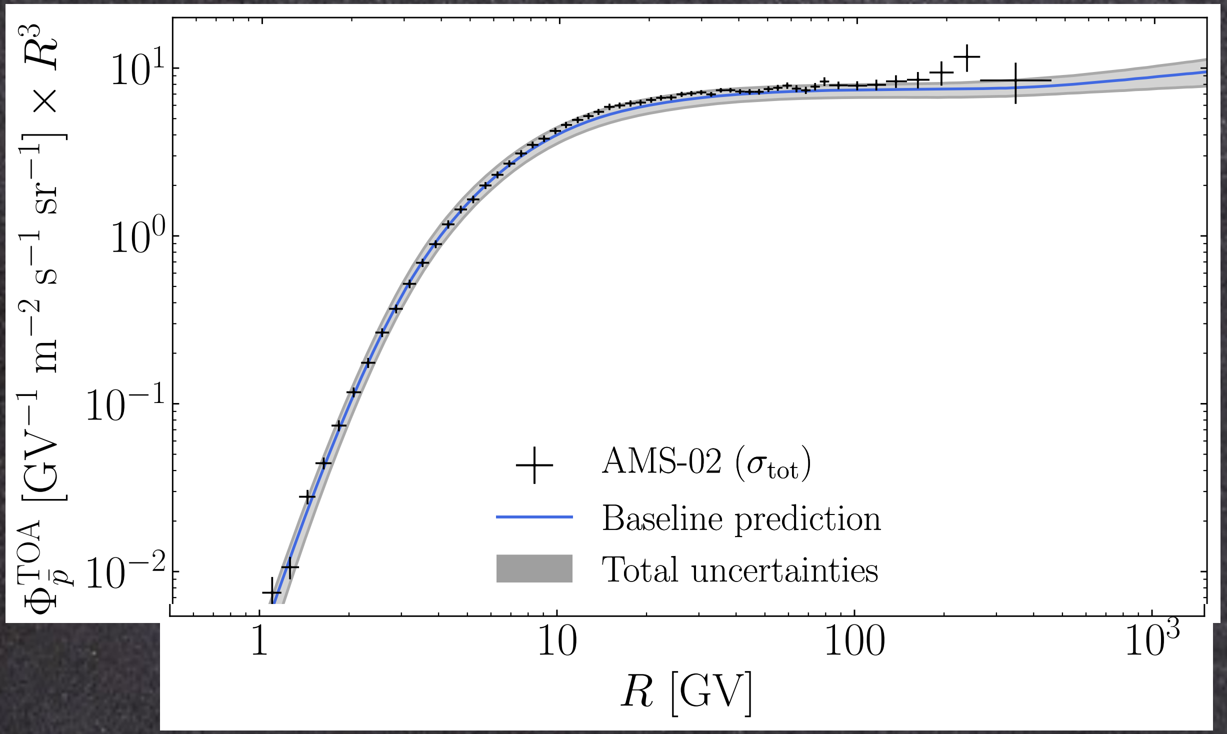


We need cross sections at <3% —> Colliders

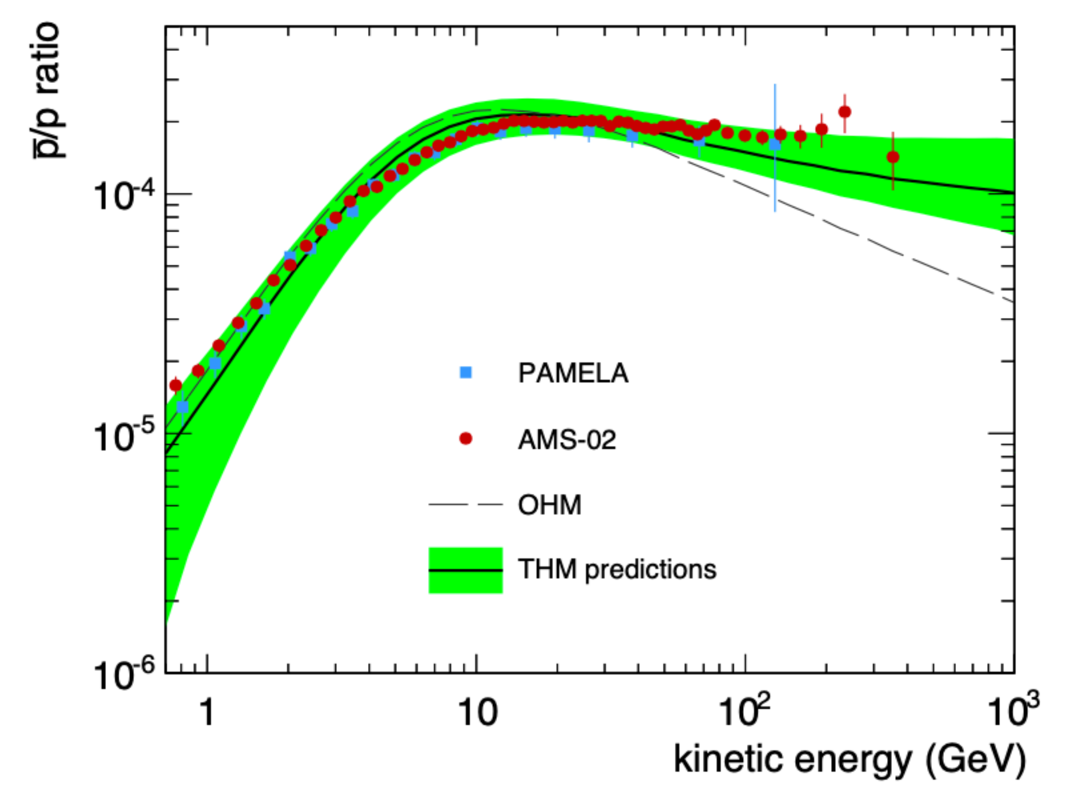
Antiprotons in CRs

AMS-02 antiprotons are consistent with a secondary astrophysical origin

M. Boudaud+ PRD 2020



Feng, Tomassetti, Oliva PRD2016



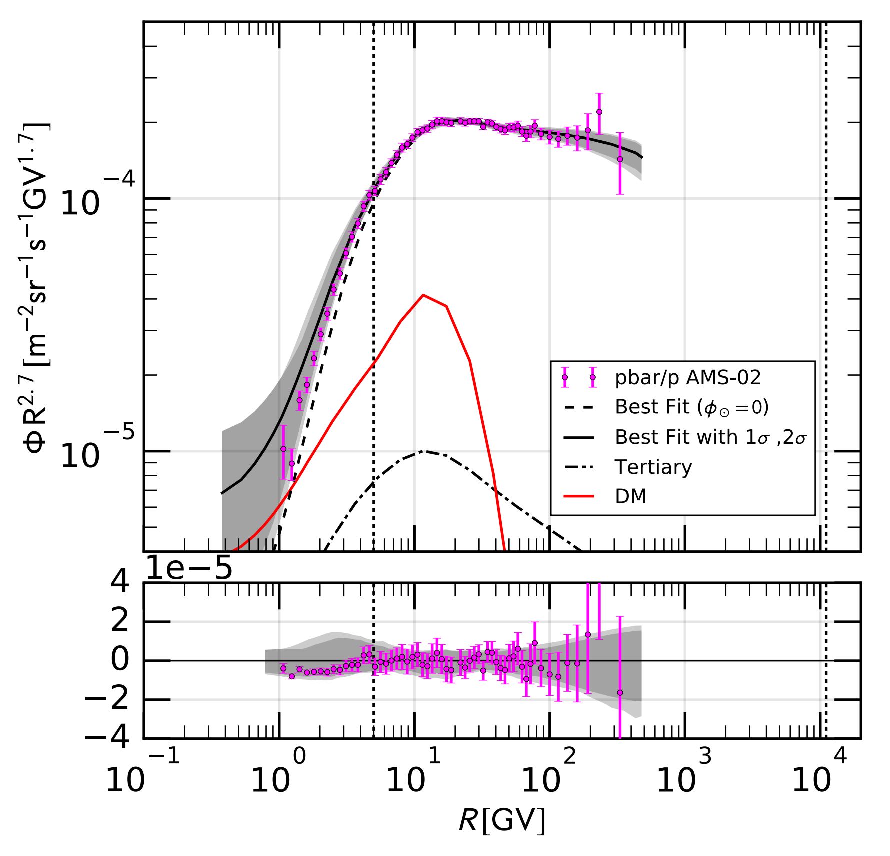
- Secondary pbar flux is predicted consistent with AMS-02 data
- Transport and cross section uncertainties are comparable
- A tiny dark matter contribution cannot be excluded
- Precise predictions are mandatory

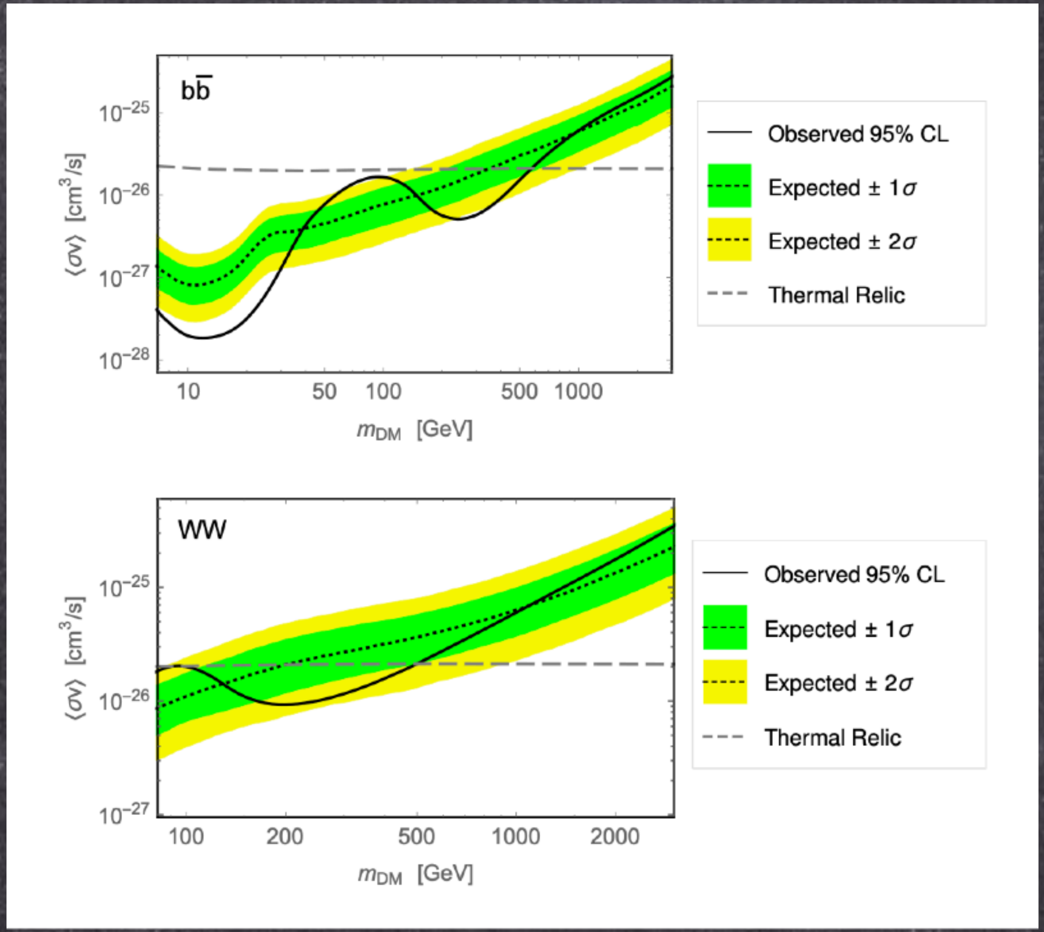
See also Korsmeier, FD, Di Mauro PRD 2018, Reinert&Winkler JCAP2018

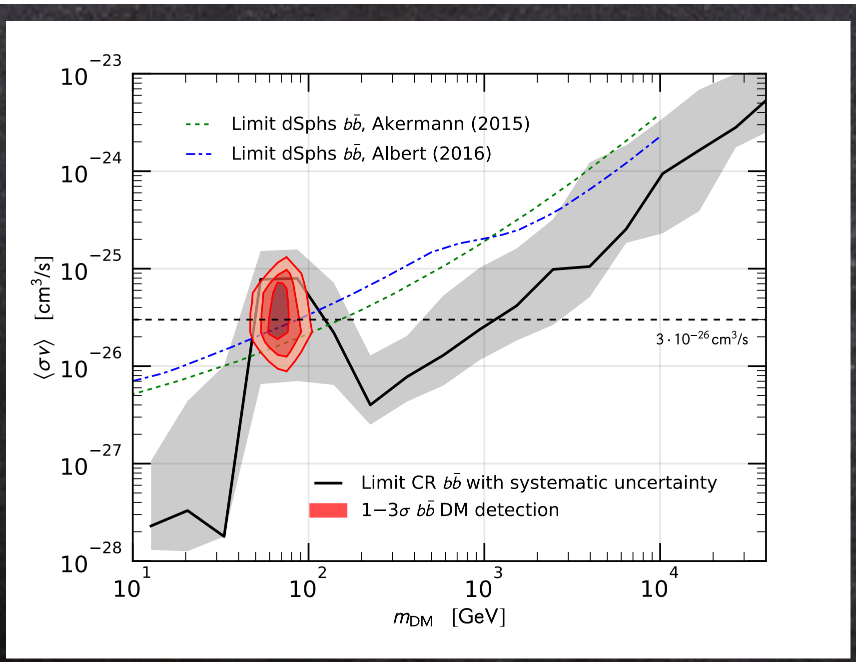
Possible contribution from dark matter

Cuoco, Korsmeier, Kraemer PRL 2017

Reinert & Winkler JCAP2018





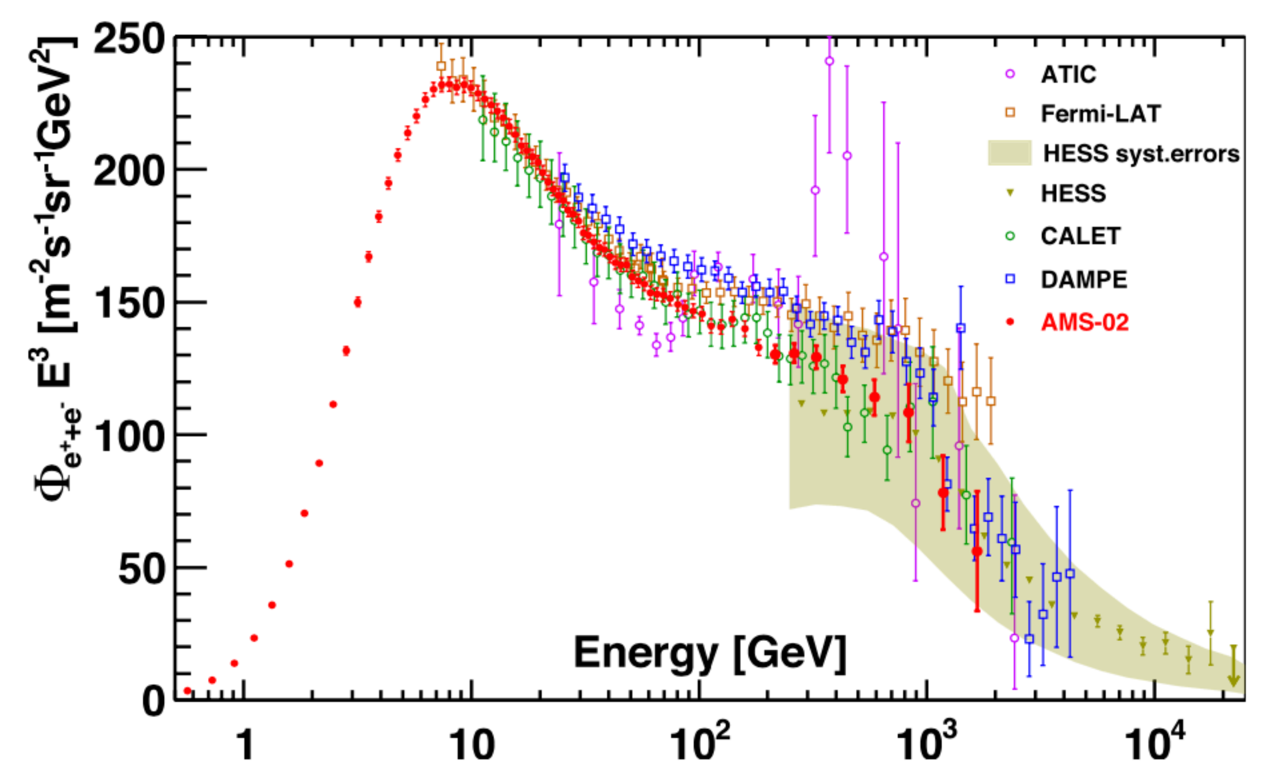


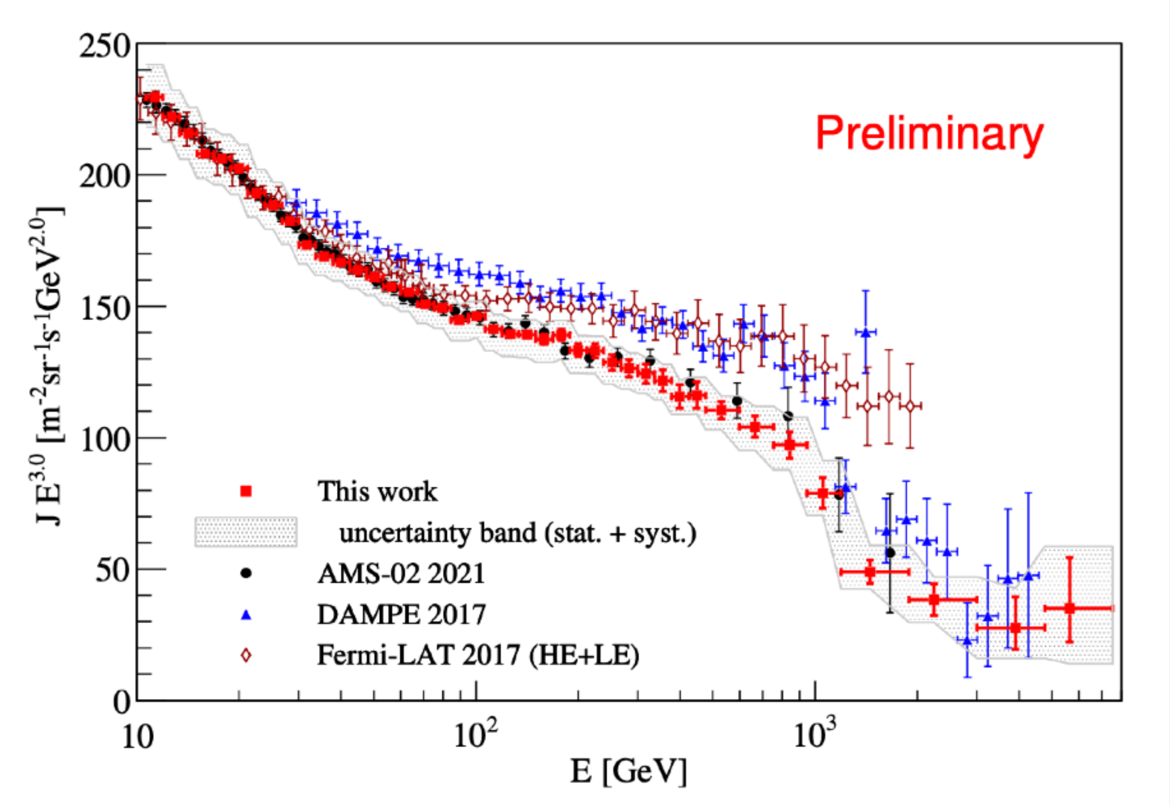
Antiproton data are so precise that permit
to set strong upper bounds on
the dark matter annihilation cross section,
or to improve the fit w.r.t. to the secondaries
alone adding a tine DM contribution

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

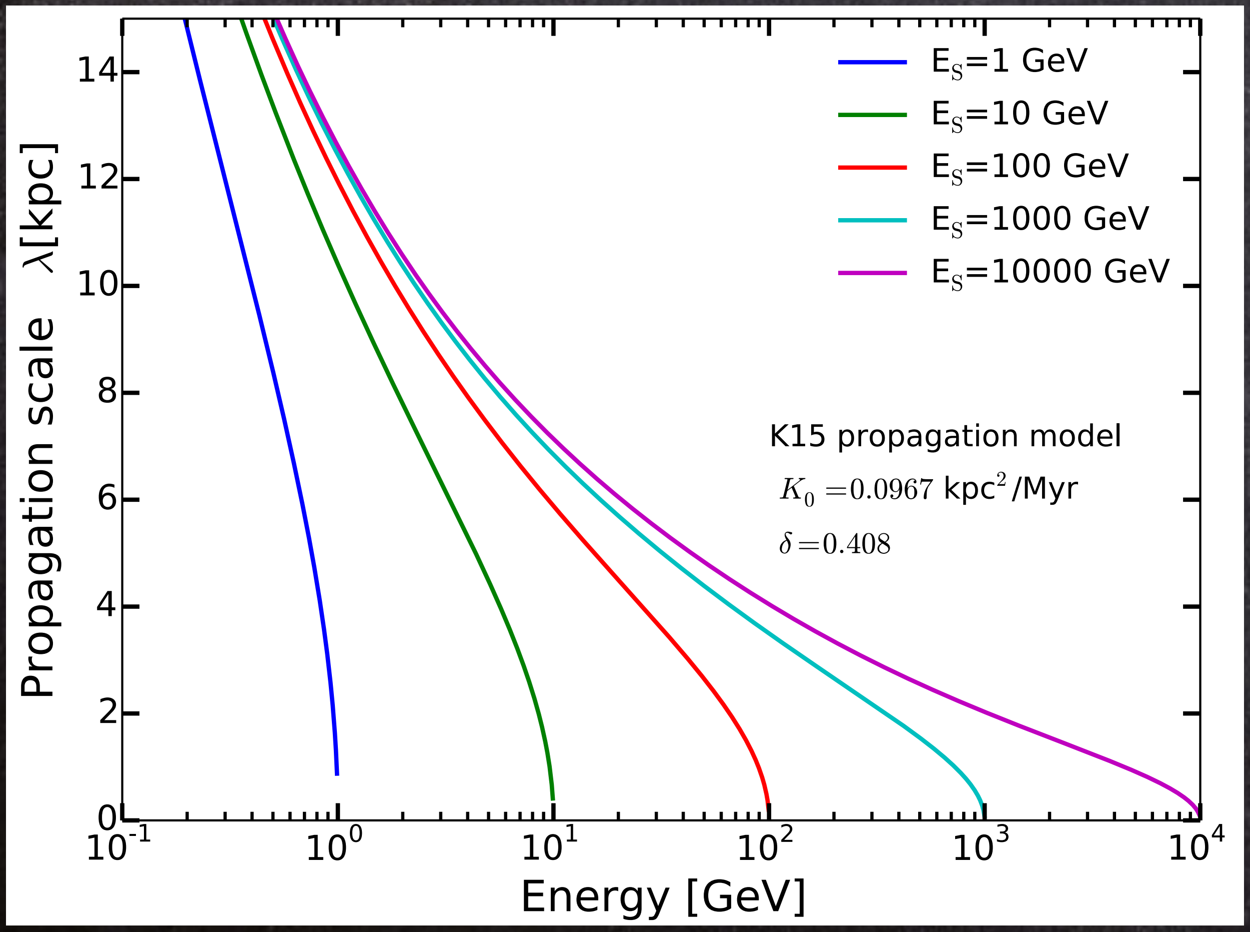
$$\lambda^2(E, E_S) = 4 \int_E^{E_S} dE' \frac{D(E')}{b_{\rm loss}(E')}$$

Typical propagation length in the Galaxy

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

Inverse Compton scattering and synchrotron emission

Local sources very likely leave their imprints in the spectra

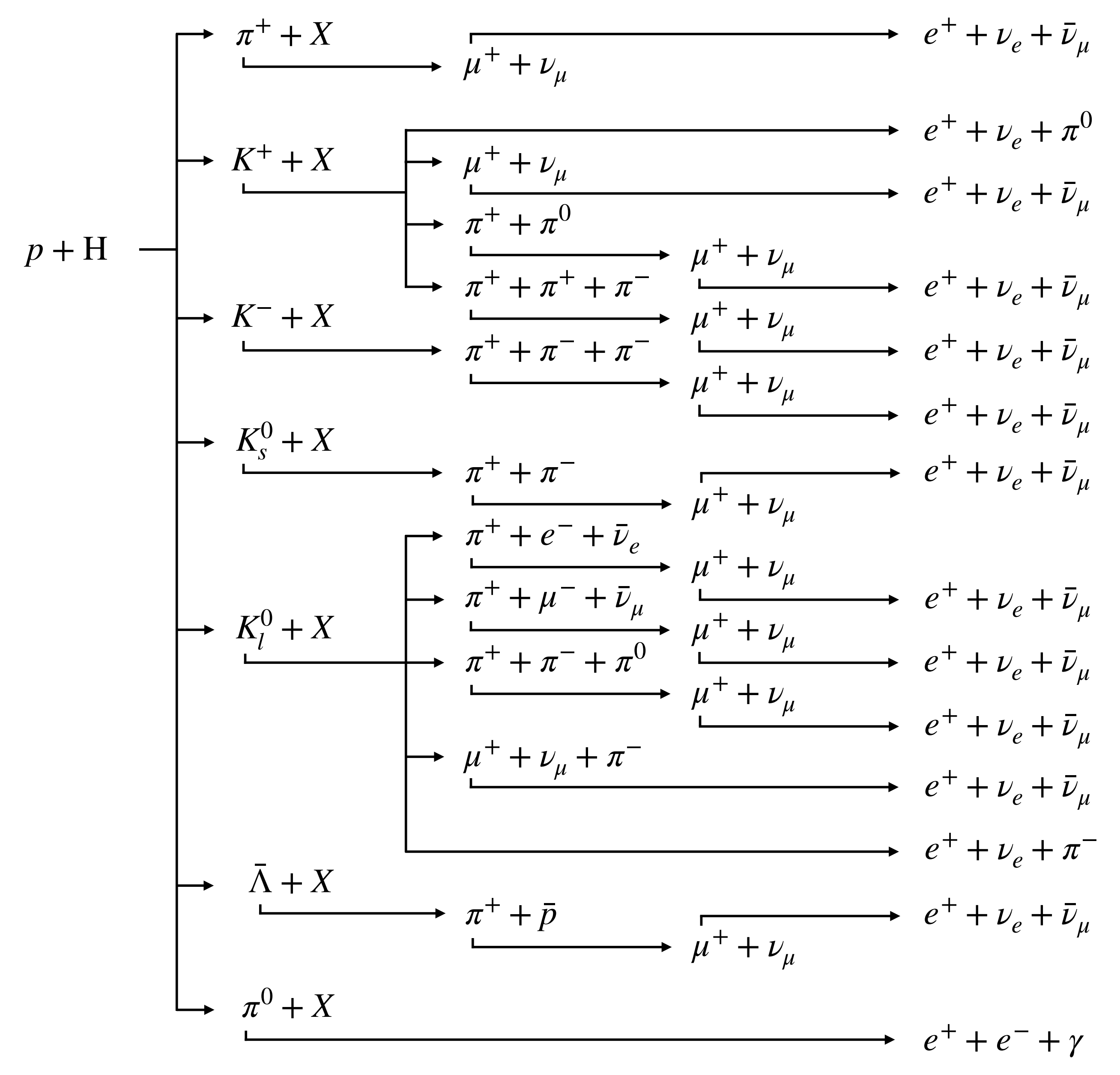


Sources of e+ & e- in the Galaxy

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

e+ secondary production channels

$$q_{ij}(T_{e^+}) = 4\pi\, n_{\mathrm{ISM},j} \int dT_i\, \phi_i(T_i) \boxed{\frac{d\sigma_{ij}}{dT_{e^+}}(T_i, T_{e^+})}$$



$p + \mathrm{H}$

$\pi^+ + X$
$e^+ + \nu_e + \bar{\nu}_\mu$
$\mu^+ + \nu_\mu$

$K^+ + X$
$e^+ + \nu_e + \pi^0$
$\mu^+ + \nu_\mu$
$e^+ + \nu_e + \bar{\nu}_\mu$
$\pi^+ + \pi^0$
$\mu^+ + \nu_\mu$
$\pi^+ + \pi^+ + \pi^-$
$e^+ + \nu_e + \bar{\nu}_\mu$

$K^- + X$
$\mu^+ + \nu_\mu$
$\pi^+ + \pi^- + \pi^-$
$e^+ + \nu_e + \bar{\nu}_\mu$
$\mu^+ + \nu_\mu$
$e^+ + \nu_e + \bar{\nu}_\mu$

$K_s^0 + X$
$\pi^+ + \pi^-$
$e^+ + \nu_e + \bar{\nu}_\mu$
$\mu^+ + \nu_\mu$

$\pi^+ + e^- + \bar{\nu}_e$
$\mu^+ + \nu_\mu$
$\pi^+ + \mu^- + \bar{\nu}_\mu$
$e^+ + \nu_e + \bar{\nu}_\mu$
$K_l^0 + X$
$\mu^+ + \nu_\mu$
$\pi^+ + \pi^- + \pi^0$
$e^+ + \nu_e + \bar{\nu}_\mu$
$\mu^+ + \nu_\mu$
$e^+ + \nu_e + \bar{\nu}_\mu$
$\mu^+ + \nu_\mu + \pi^-$
$e^+ + \nu_e + \bar{\nu}_\mu$
$e^+ + \nu_e + \pi^-$

$\bar{\Lambda} + X$
$\pi^+ + \bar{p}$
$e^+ + \nu_e + \bar{\nu}_\mu$
$\mu^+ + \nu_\mu$

$\pi^0 + X$
$e^+ + e^- + \gamma$

Similarly for collisions with nuclei.

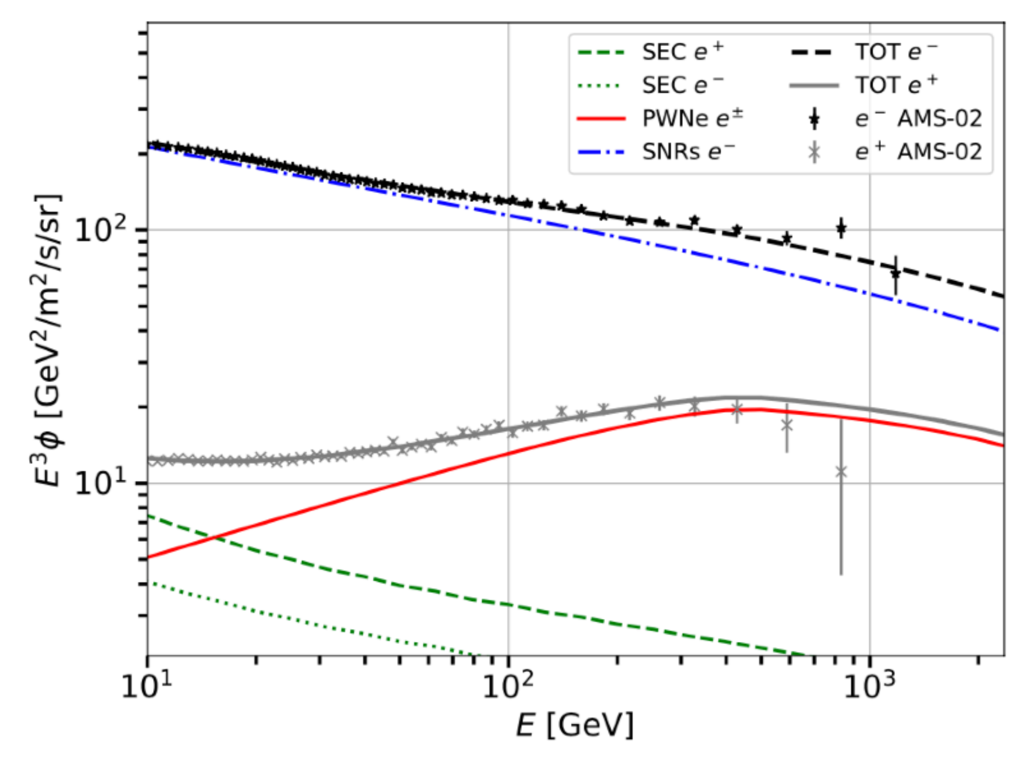
Similarly for Secondary e-
(under charge conjugation)

L. Orusa, M. Di Mauro, FD, M. Korsmeier PRD 2022

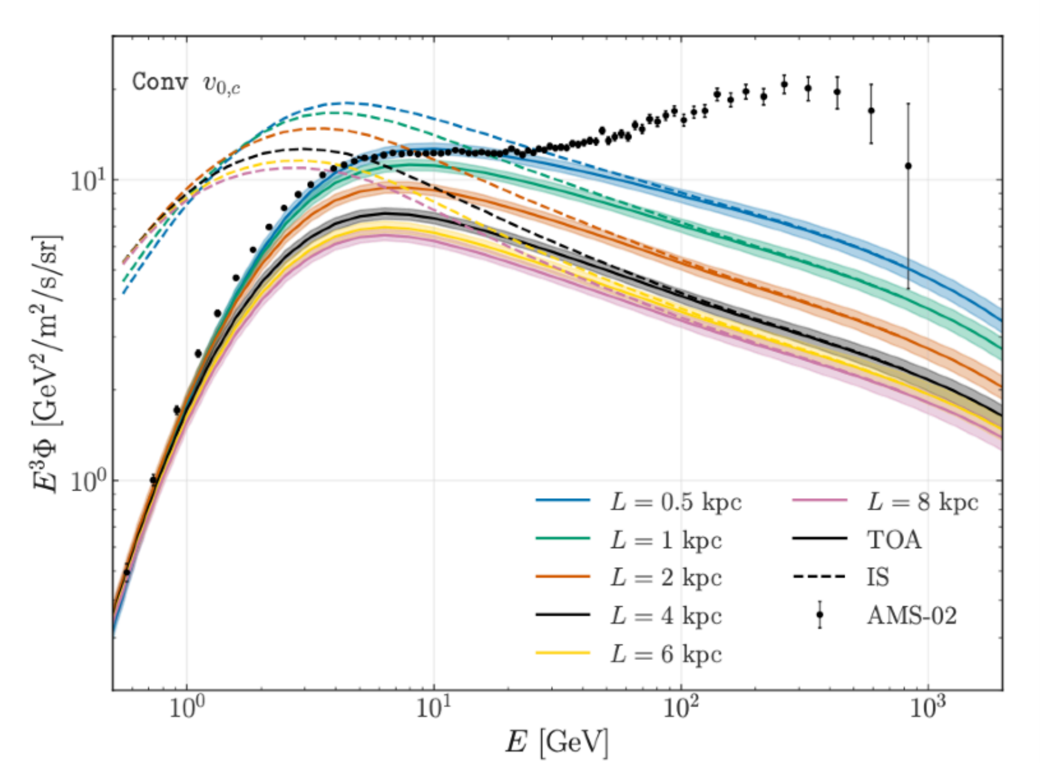
e+ & e- spectra, a natural explanation

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

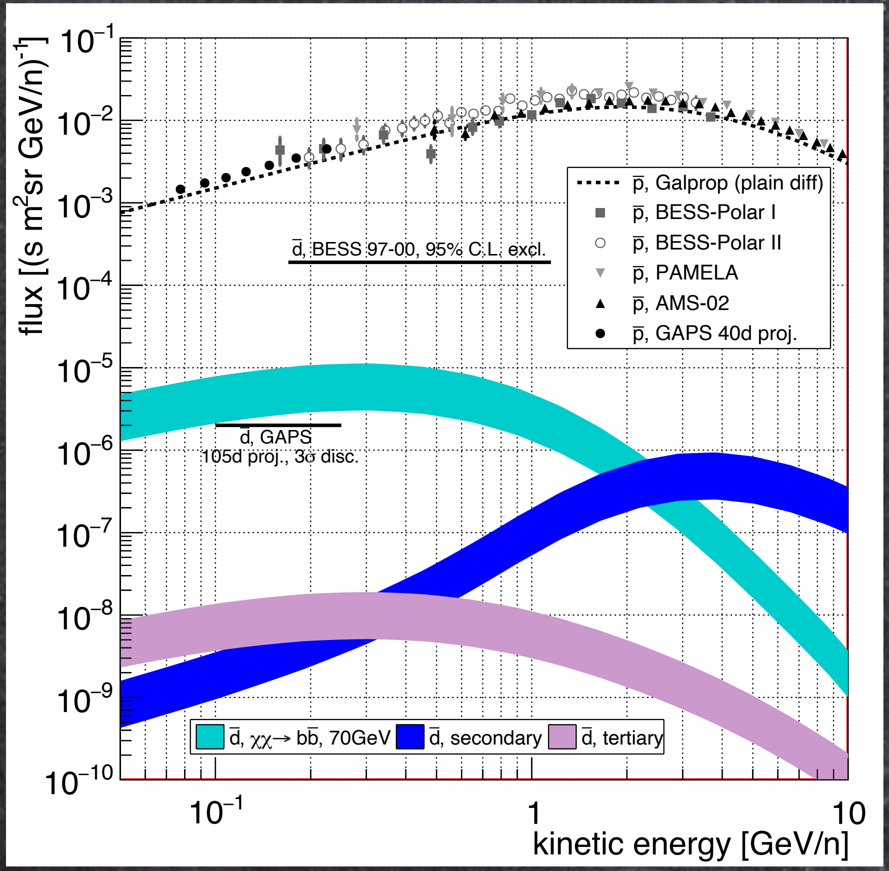
See also Fang+ 2007.15601, Evoli+PRD 2021, Cuoco+ PRD2020

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

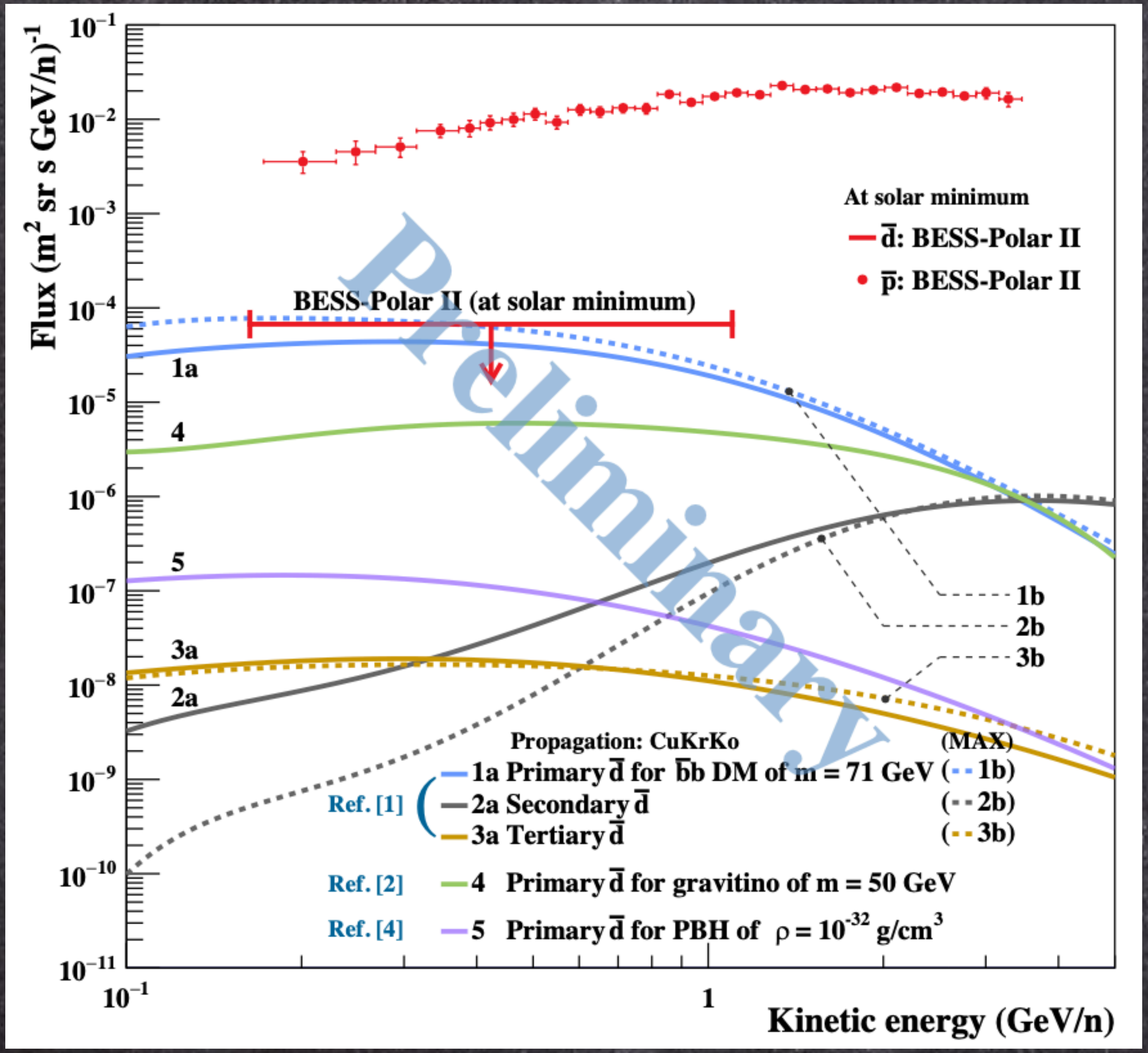
Antideuteron predictions for DM model indicated by pbar AMS-02 data

Bands are for coalescence uncertainty

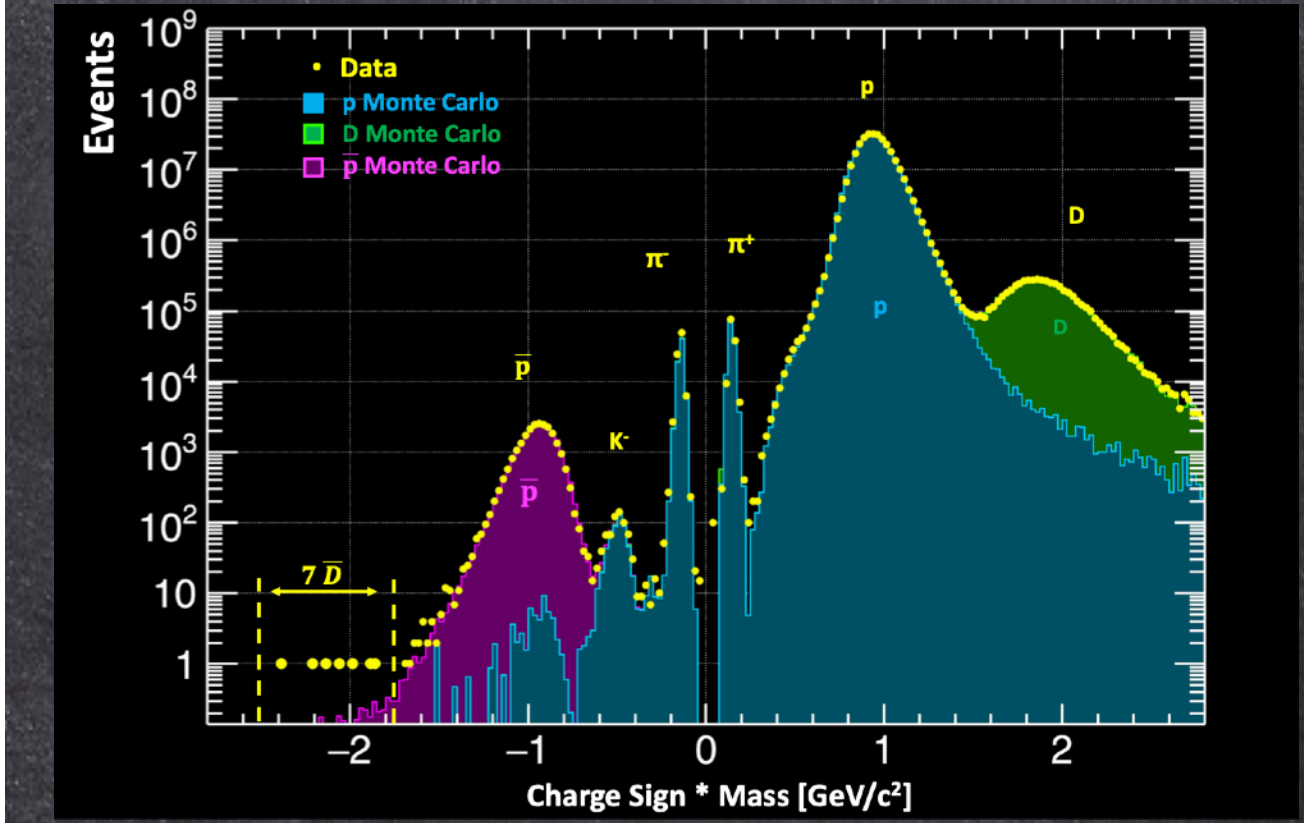
Antideuterons will be a unique window to probe nuclear fusion in secondary events, and to search for Dark Matter annihilation Or decay below ~ 1GeV/n

Perspectives with antideuterons

Bess Polar-II @ ICRC2023



AMS preliminary @ICRC 2023

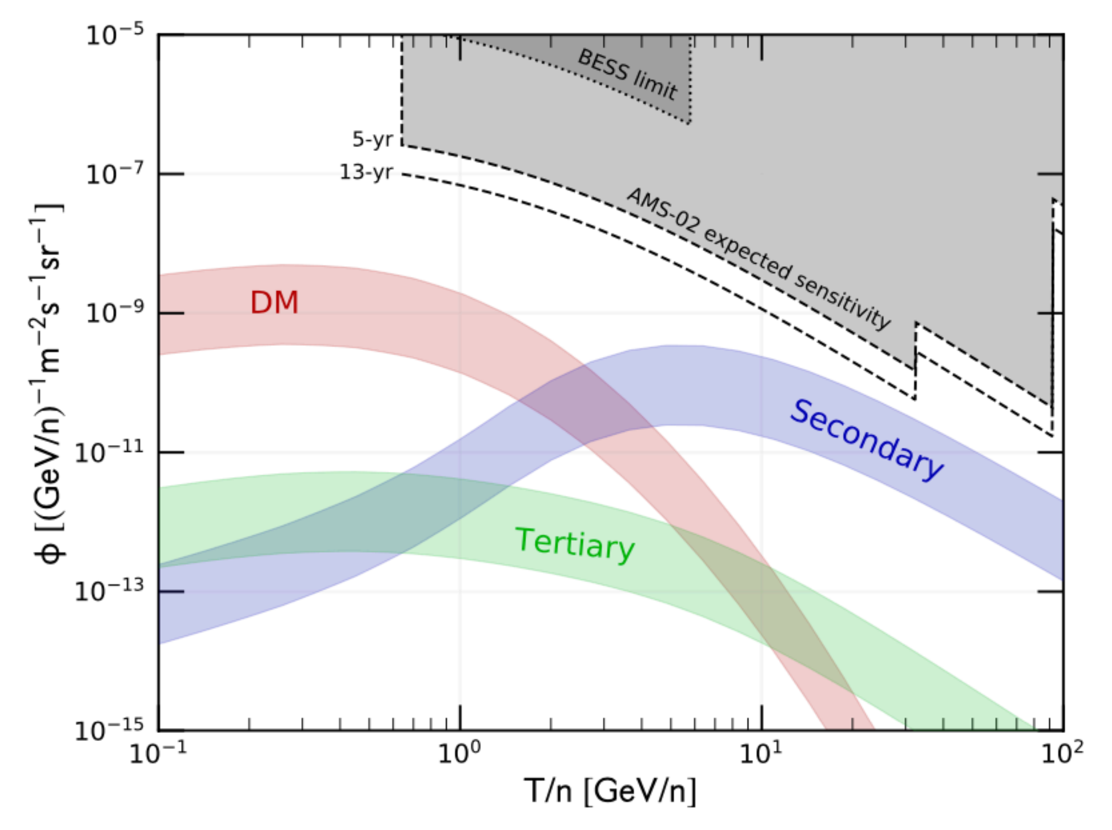


GAPS - dedicated to antineutron searches -
will fly from Antarctica Dec 2024

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

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

V. Poulin et al. PRD 2019

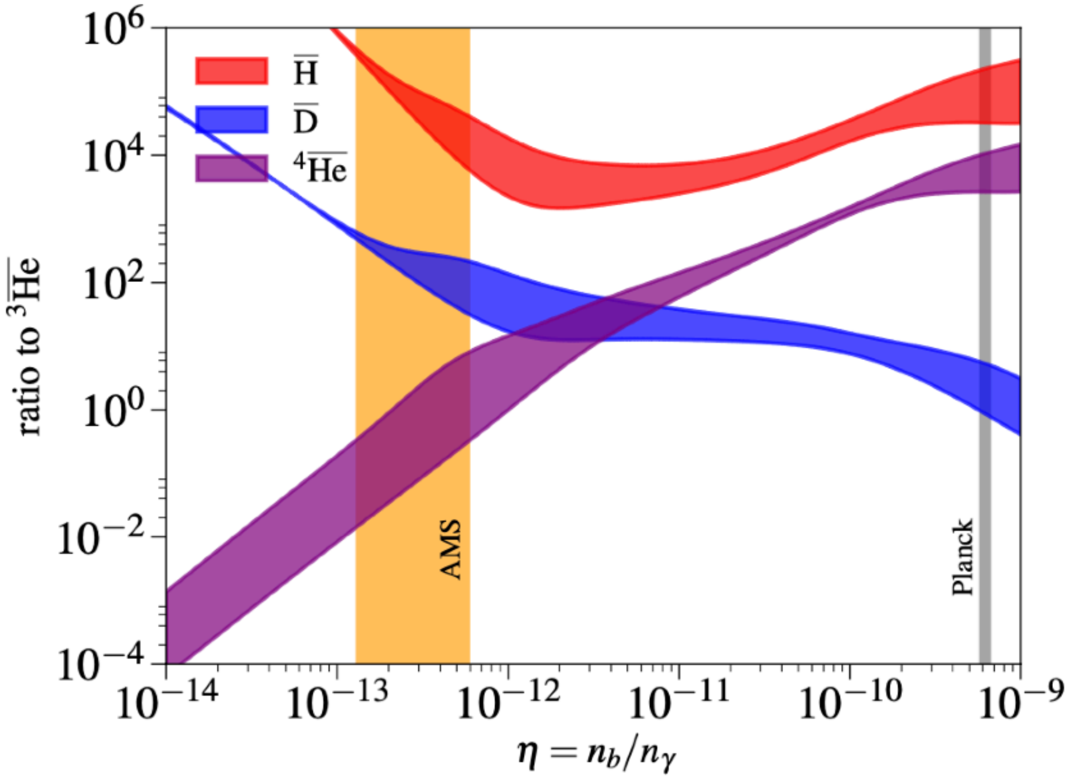


FIG. 4. Abundance of $\overline{\mathrm{H}}$, $\overline{\mathrm{D}}$ and $\overline{^4\mathrm{He}}$ with respect to that of $\overline{^3\mathrm{He}}$ as a function of the (anti-)baryon-to-photon ratio $\bar{\eta}$. The *Planck* value is represented by the grey band. The value required by the *AMS-02*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

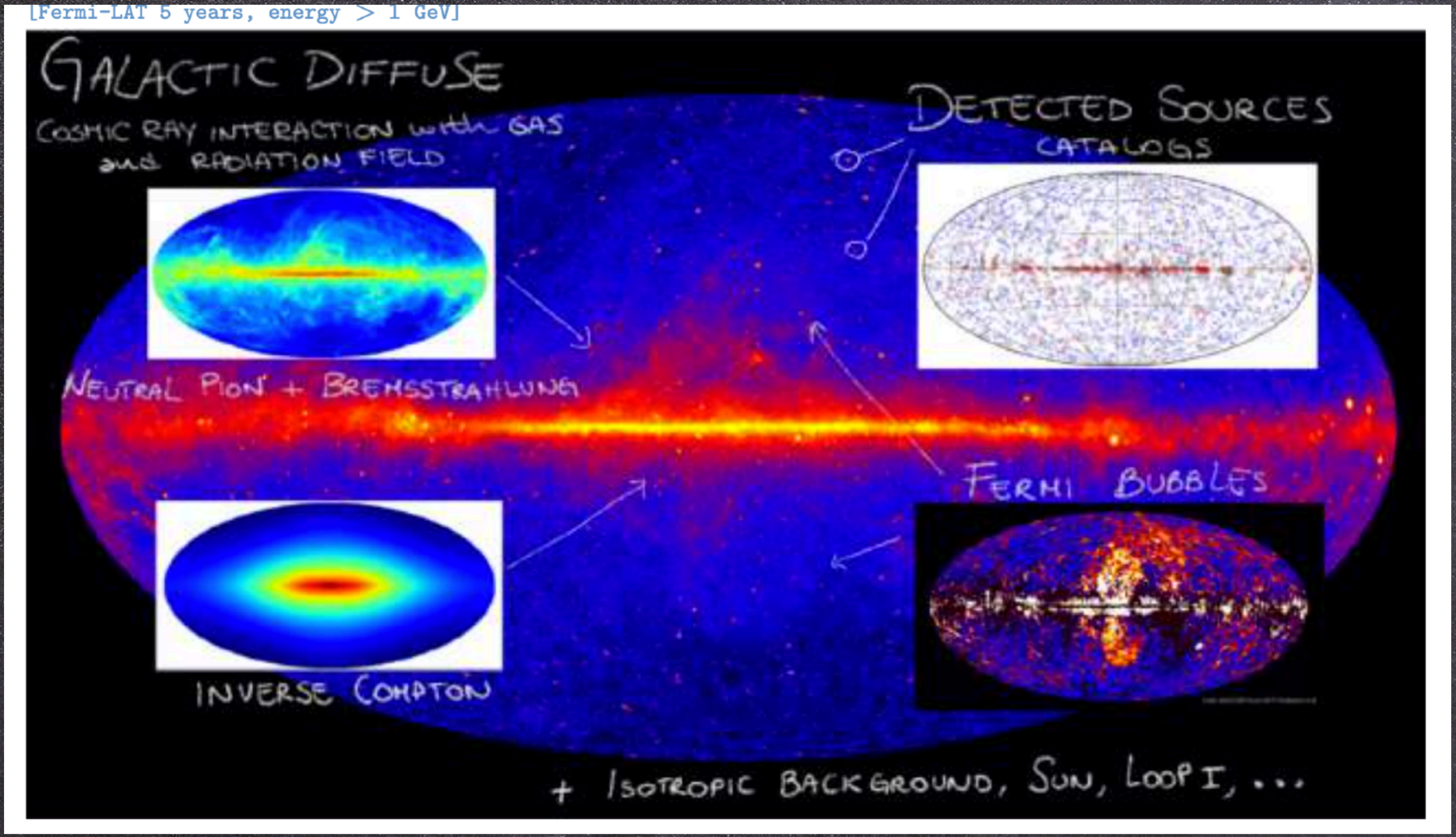
Anti-clouds: require anisotropic BBN for the right ^{3}He/^{4}He
AMS-02 measures are local, Planck's ones averaged over the Universe

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?

The γ-ray counterpart of the sky

Courtesy of Silvia Manconi, TMEX 2023



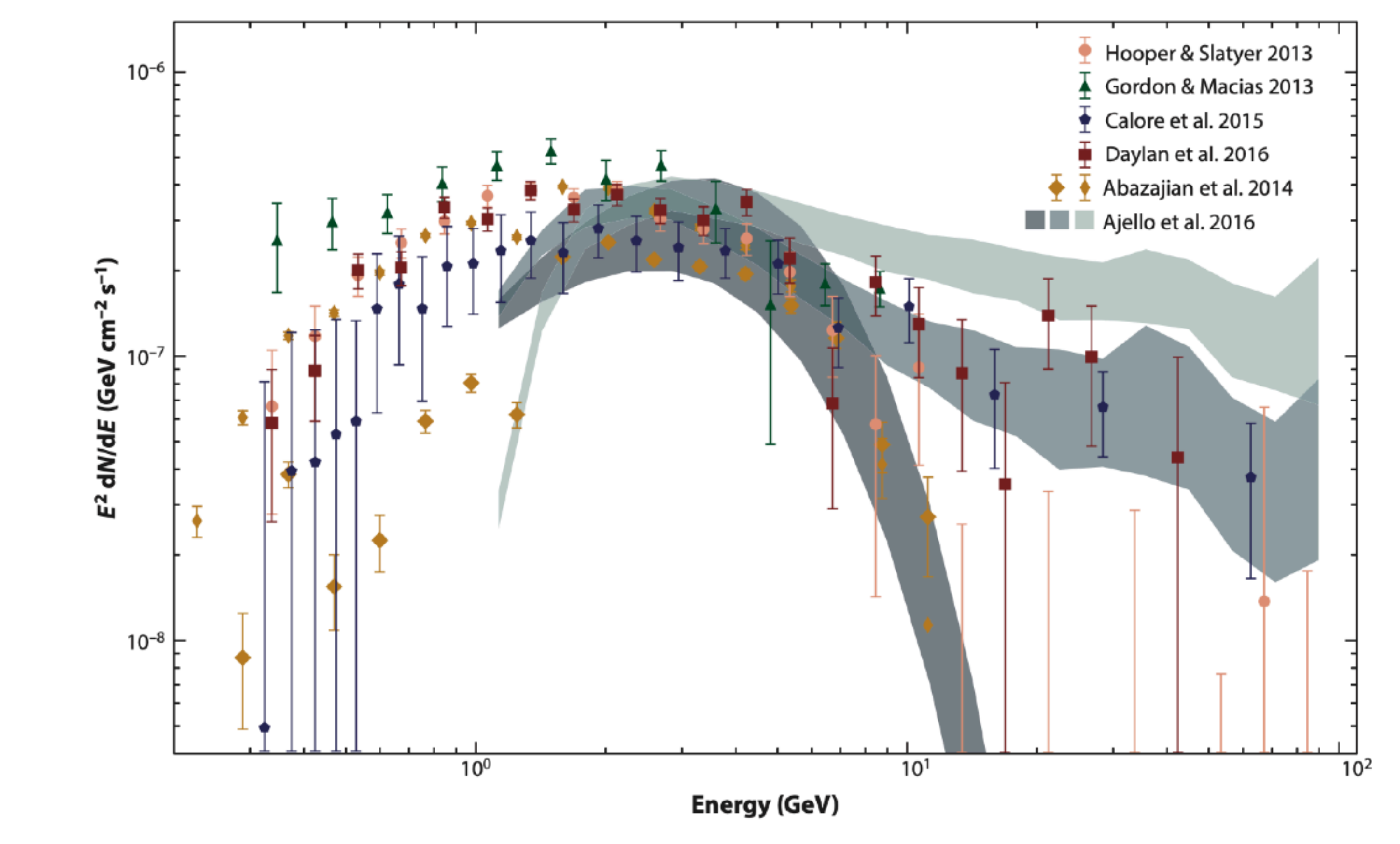
A prediction of the emission from all diffuse, point and extended sources, at all latitudes, is possible.

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)



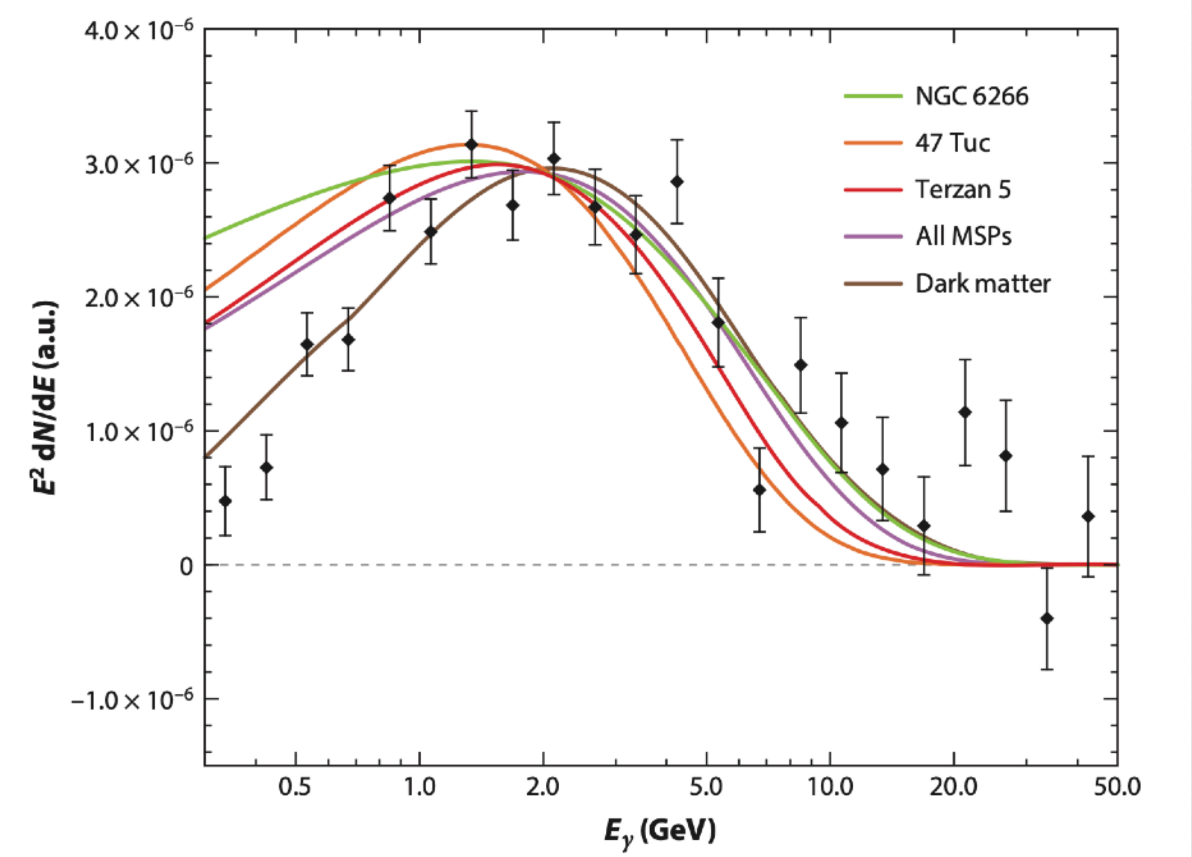
MurgiaAR 2020

No matter the method, the GC excess is statistically significant

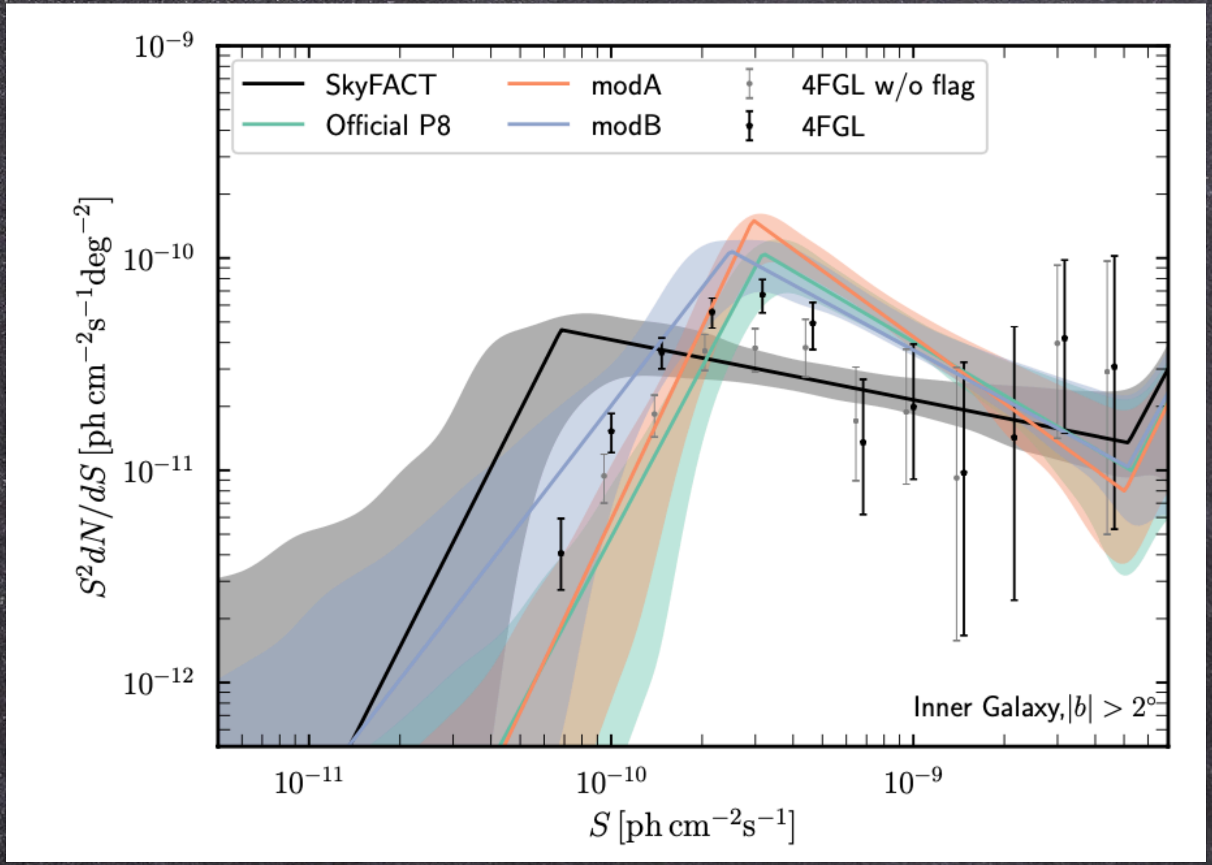
The GeV excess at the Galactic center

Possible explanations:
dark matter annihilation and/or point sources (MSPs)

Murgia AR 2020



Calore, FD, Manconi PRL 2021



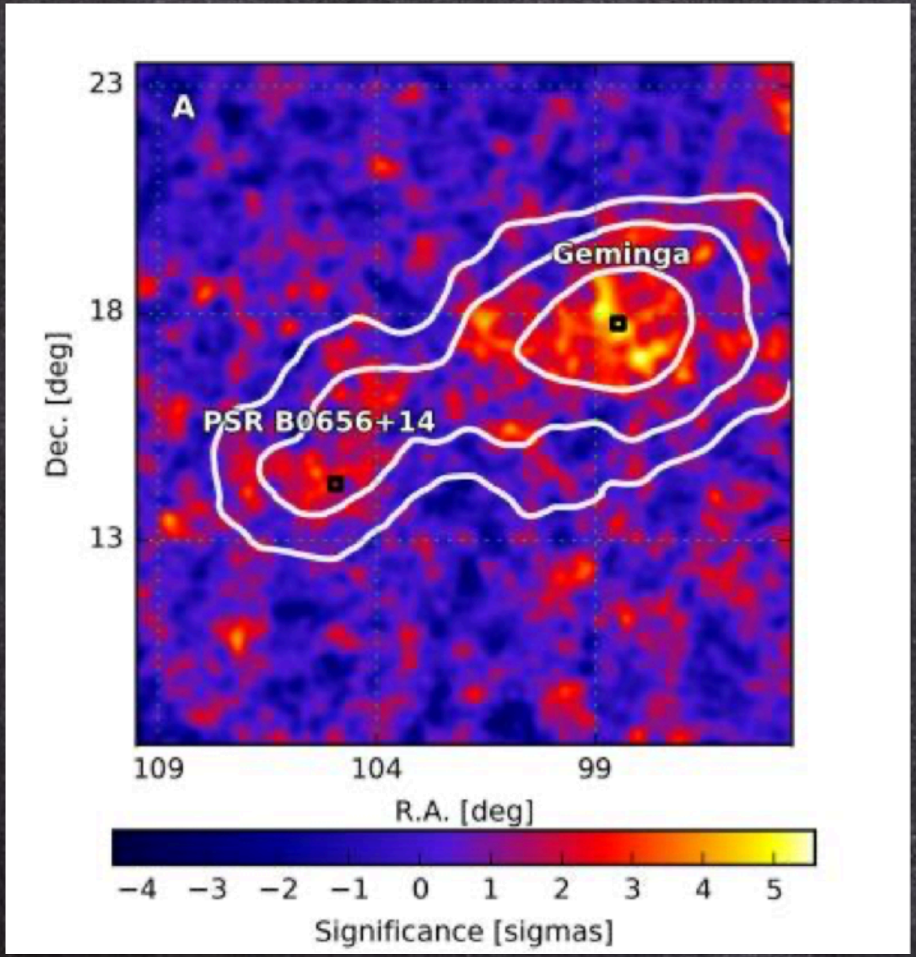
We need a multi-wavelength campaign of sources at the GC

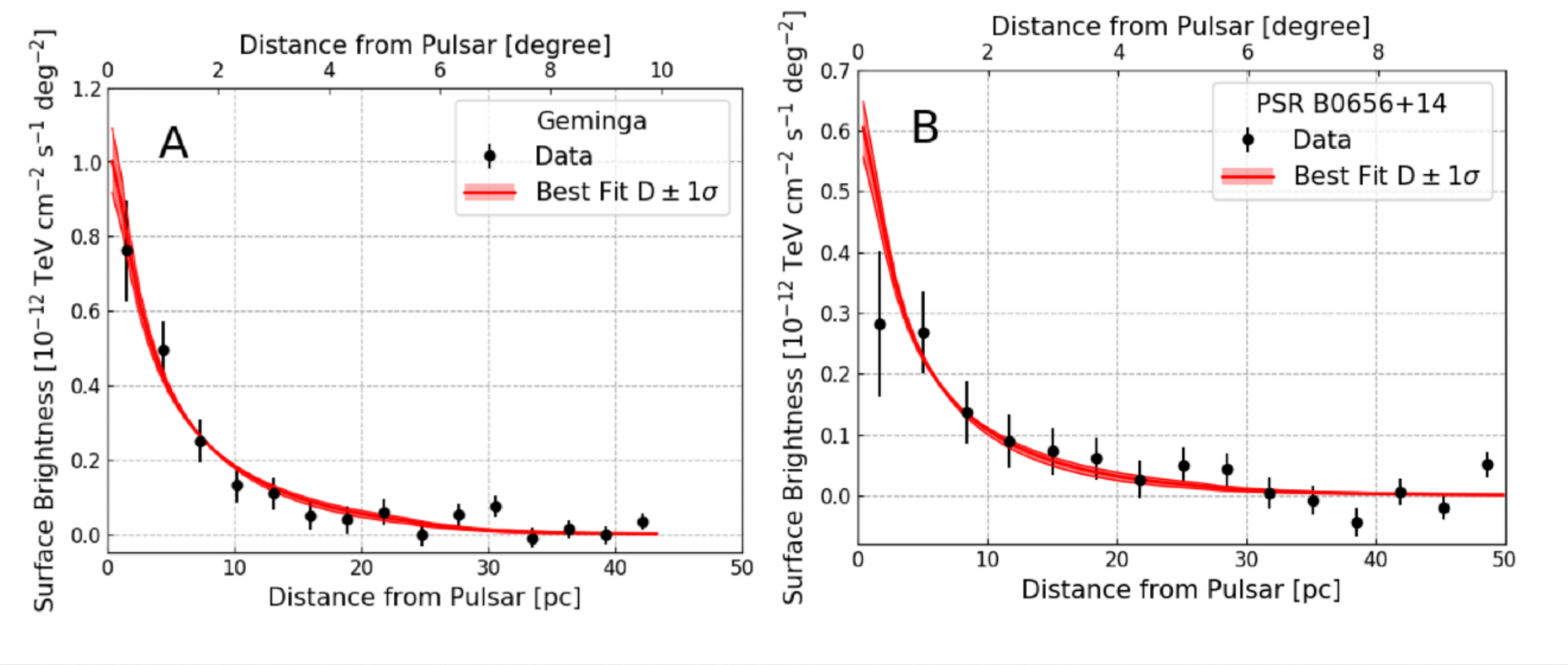
Galactic diffuse emission MISMODELING is a major issue

Detections of γ-ray haloes around pulsars

Extended haloes have been detected by HAWC around Geminga and Monogem, and by Lhaaso around PRS J0622+3749

HAWC Collaboration, Sience 2017





Detections of γ-ray haloes around pulsars

Lhaaso Coll. PRL 2021

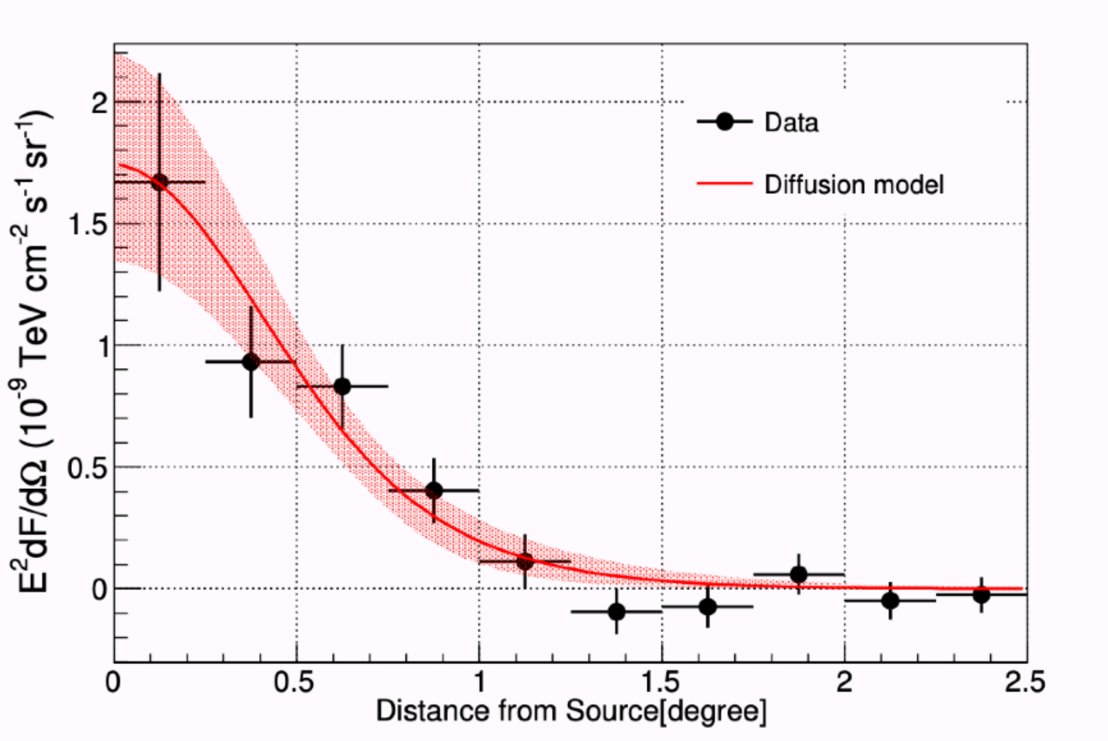
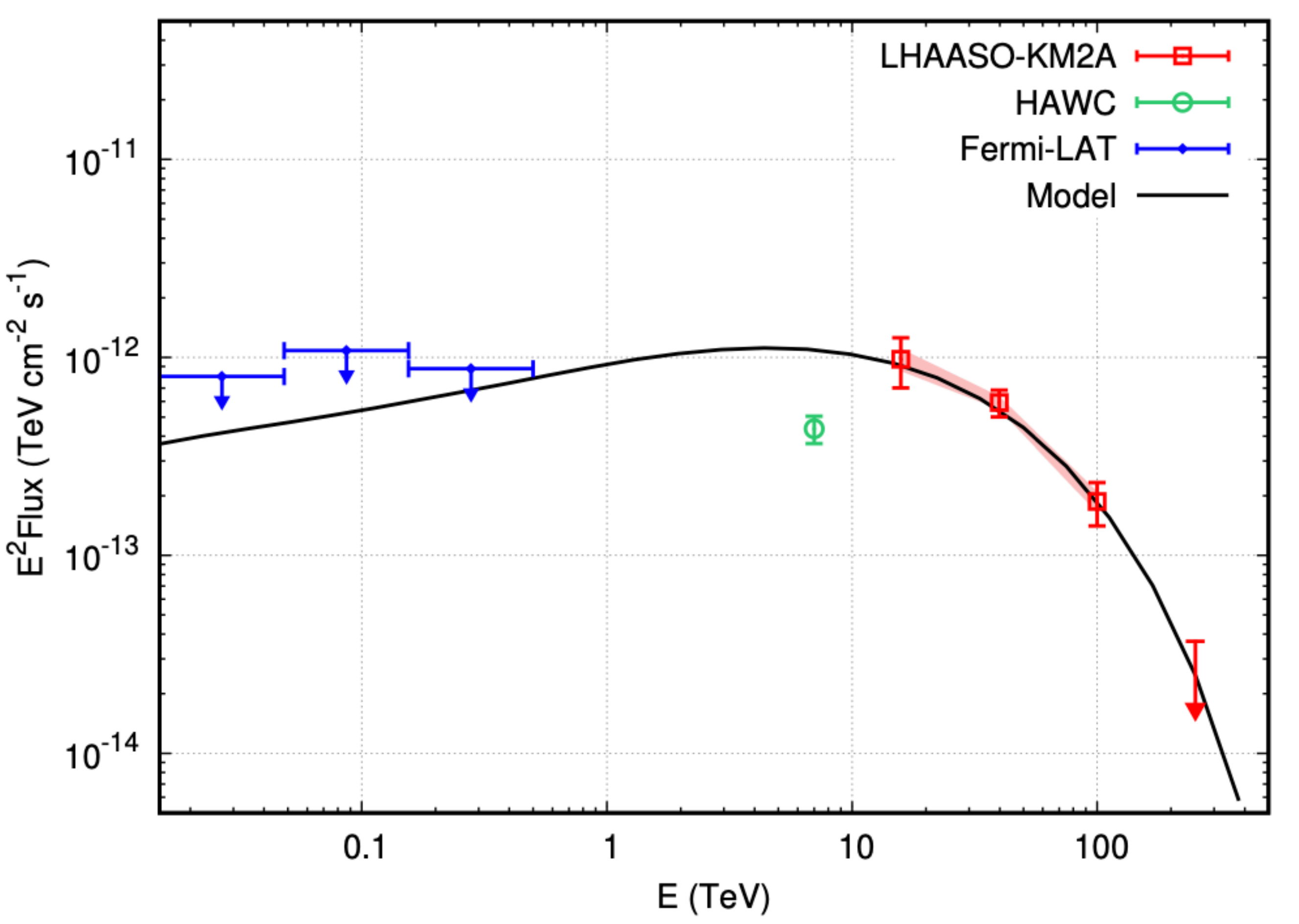


FIG. 2. One-dimensional distribution of the > 25 TeV γ-ray emission of LHAASO J0621+3755. The solid line and shaded band show the best fit and $\Delta\chi^2 = 2.3$ range of the diffusion model fit, which is the convolution of Eq. (1) with the PSF.



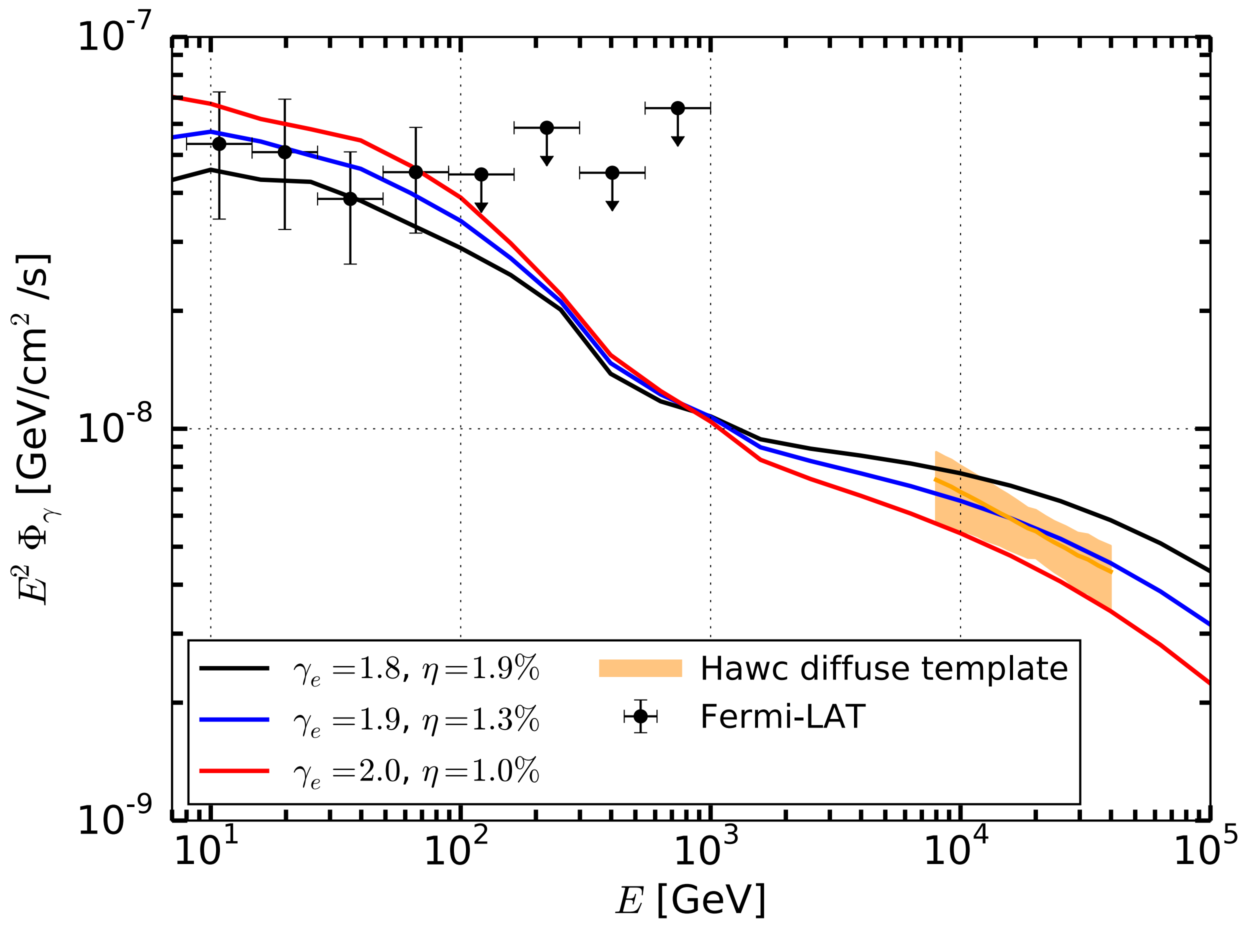
Extremely high energy γ -rays are observed around the pulsar as an extended halo. A spectrum is measured.

This new class of observations needs revisiting our understanding of acceleration of leptons to very high energies and emission of photons

Detection of a γ-ray halo in Fermi-LAT data around Geminga

M. Di Mauro, S. Manconi, FD PRD 2019

- A γ-ray halo around Geminga detected at 7.8-11.8σ depending on diffuse background models.
- Fit improves with proper motion included.
- Diffusion D(1GeV) = 1.6-3.5 10^{26} cm2/s (comp. HAWK)
- Extension ~60 pc @ 100 GeV



Inverse Compton emission can explain all the data

BUT

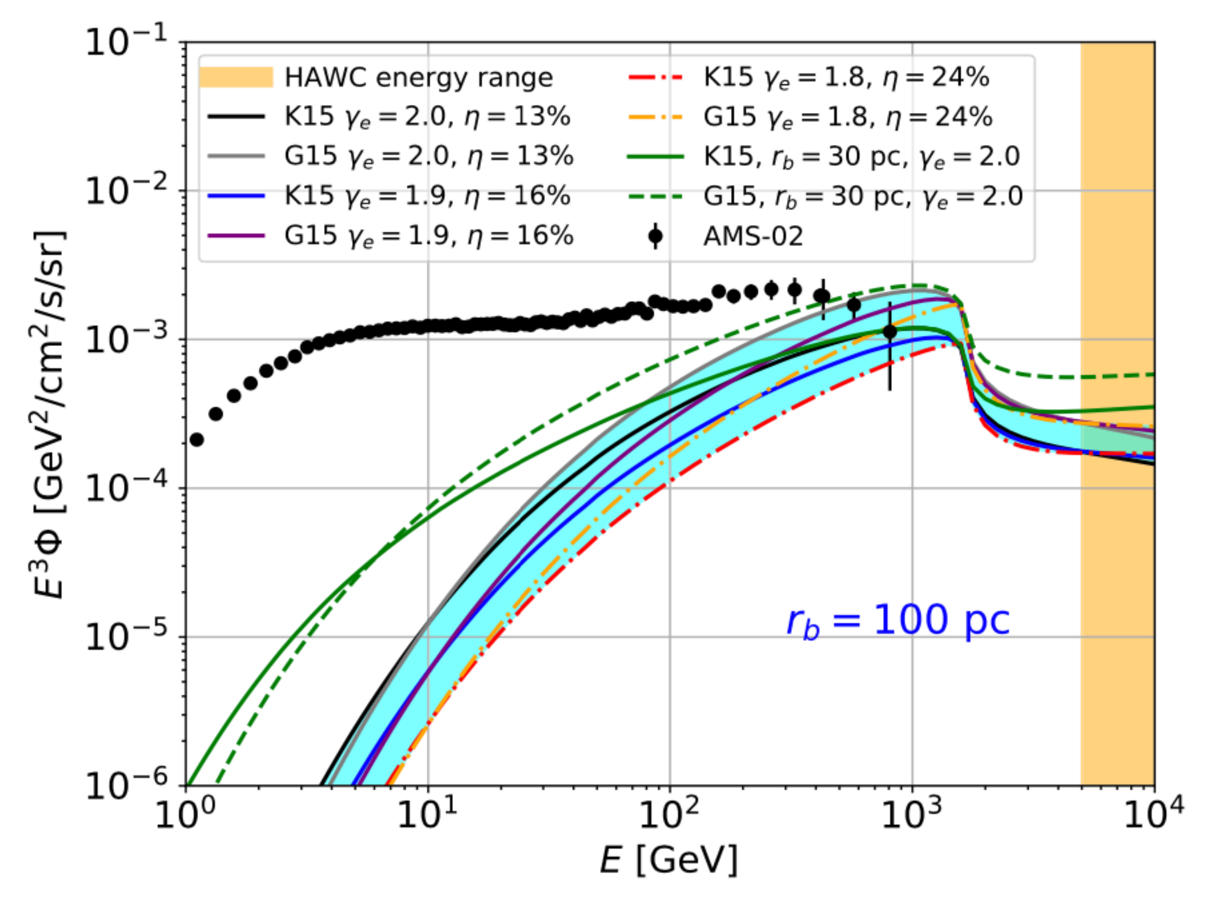
with a suppressed diffusion coefficient around the source

A ballistic diffusion next to source is a natural explanation

Recchia, FD+ PRD 2022

Consequence of ICS Geminga halo on positron flux at Earth

M. Di Mauro, S. Manconi, FD PRD 2019



One single source as Geminga contributes significantly to high energy positrons as measured by AMS

Uncertainty in the diffusion around the source(s)

See also Schroer, Evoli, Blasi PRD 2023

Concluding remarks

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

Ps. I overlooked anisotrpy, neutrinos, solar modulation &time-dependent CRS …