# Challenges in cosmic ray physics: Galactic sources, antimatter, dark matter

Fiorenza Donato
Torino University & INFN

Seminar at Genova University
24 Novembre 2022

# 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)

# CRs in the Galaxy

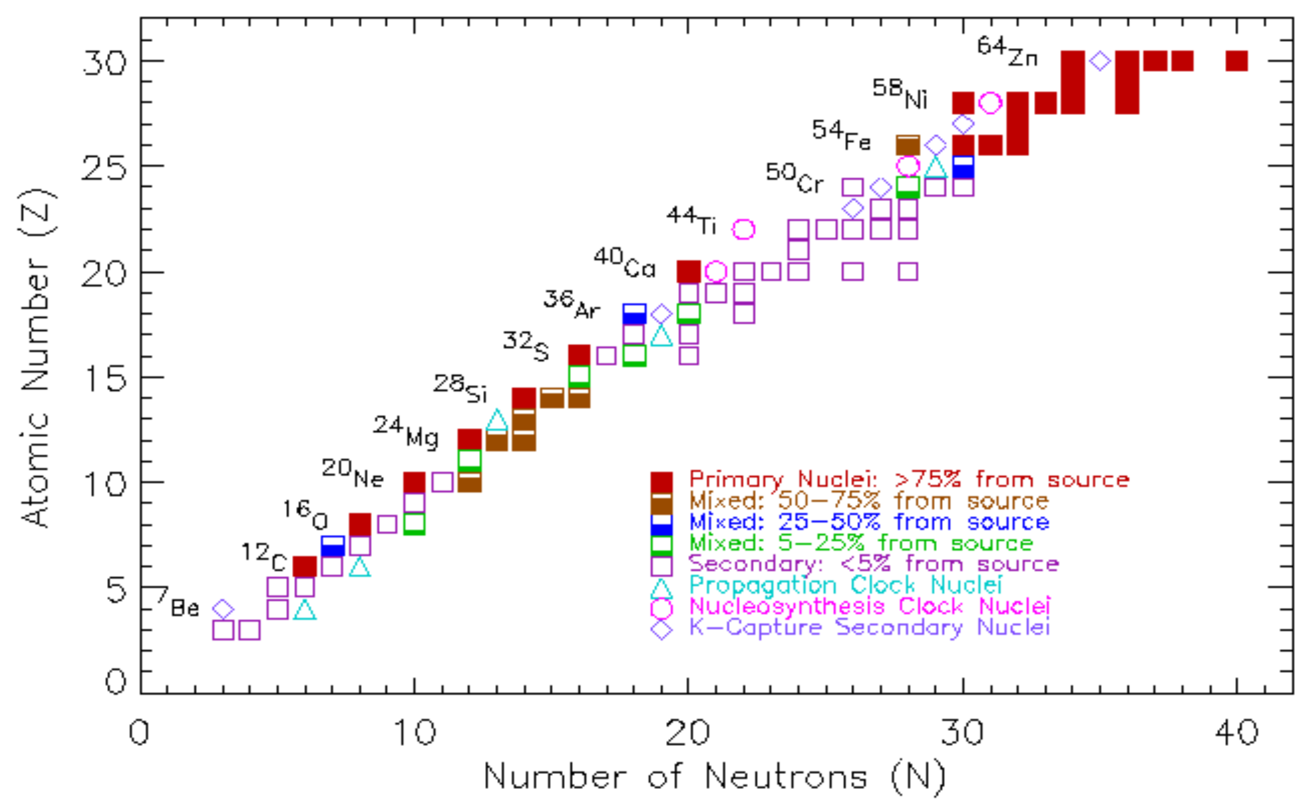
**Primaries**: produced in the sources (SNR and Pulsars)

H, He, CNO, Fe; e-, e+; possibly $e^+$, $p^-$, $d^-$ from Dark Matter annihilation

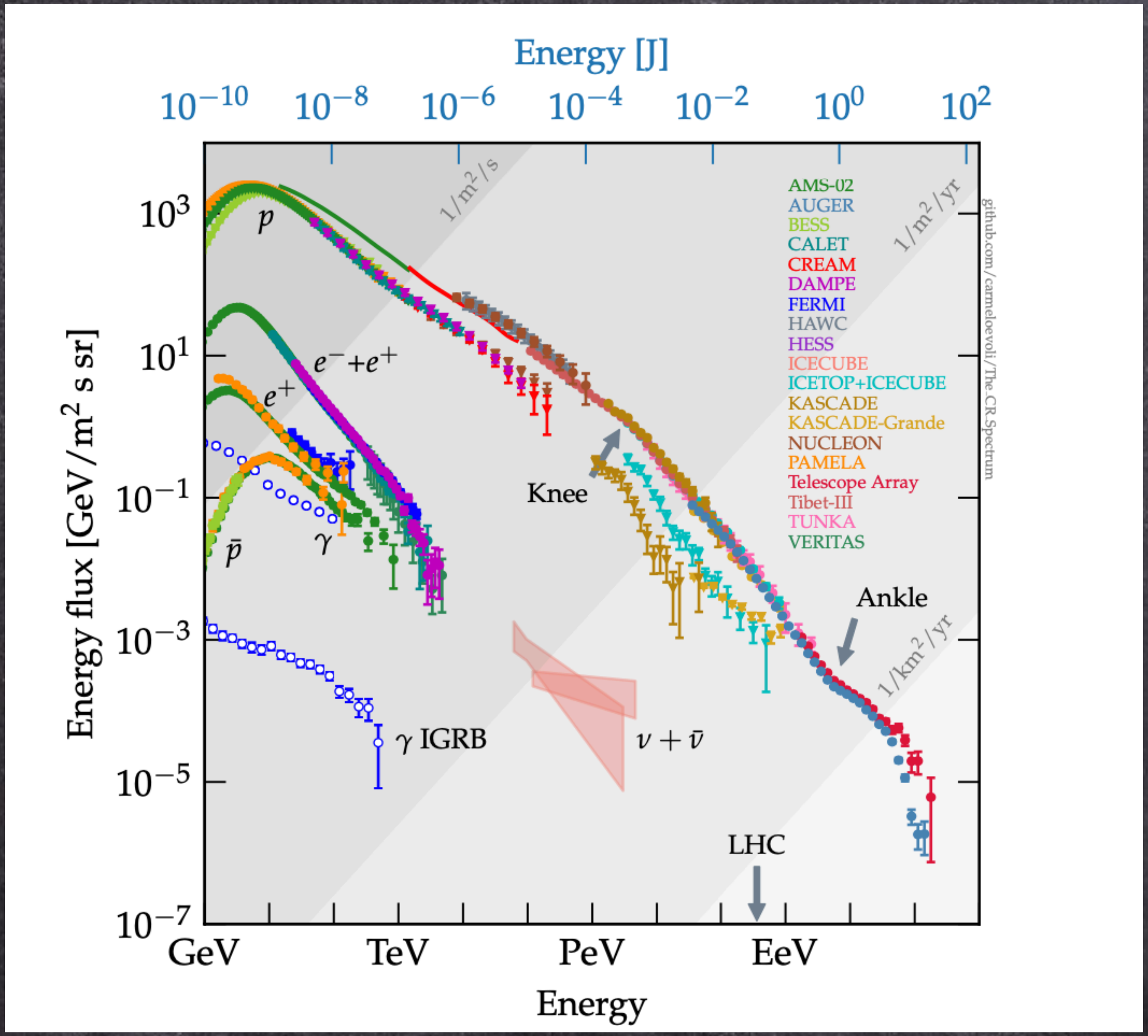
**Secondaries**: produced by spallation of primary CRs (p, He,C, O, Fe) on the interstellar medium (ISM): Li, Be, B, sub-Fe, [...], (radioactive) isotopes ; $e^+$, $p^-$, $d^-$

**Primaries** = present in sources:
Nuclei: H, He, CNO, Fe; e-, (e+) in SNR (& pulsars)
$e^+$, $p^+$, $d^+$ from Dark Matter annihilation

**Secondaries** = NOT present in sources, thus produced by
**spallation** of primary CRs (p, He, C, O, Fe) on ISM
Nuclei: LiBeB, sub-Fe, … ;
$e^+$, $p^+$, $d^+$; … from inelastic scatterings

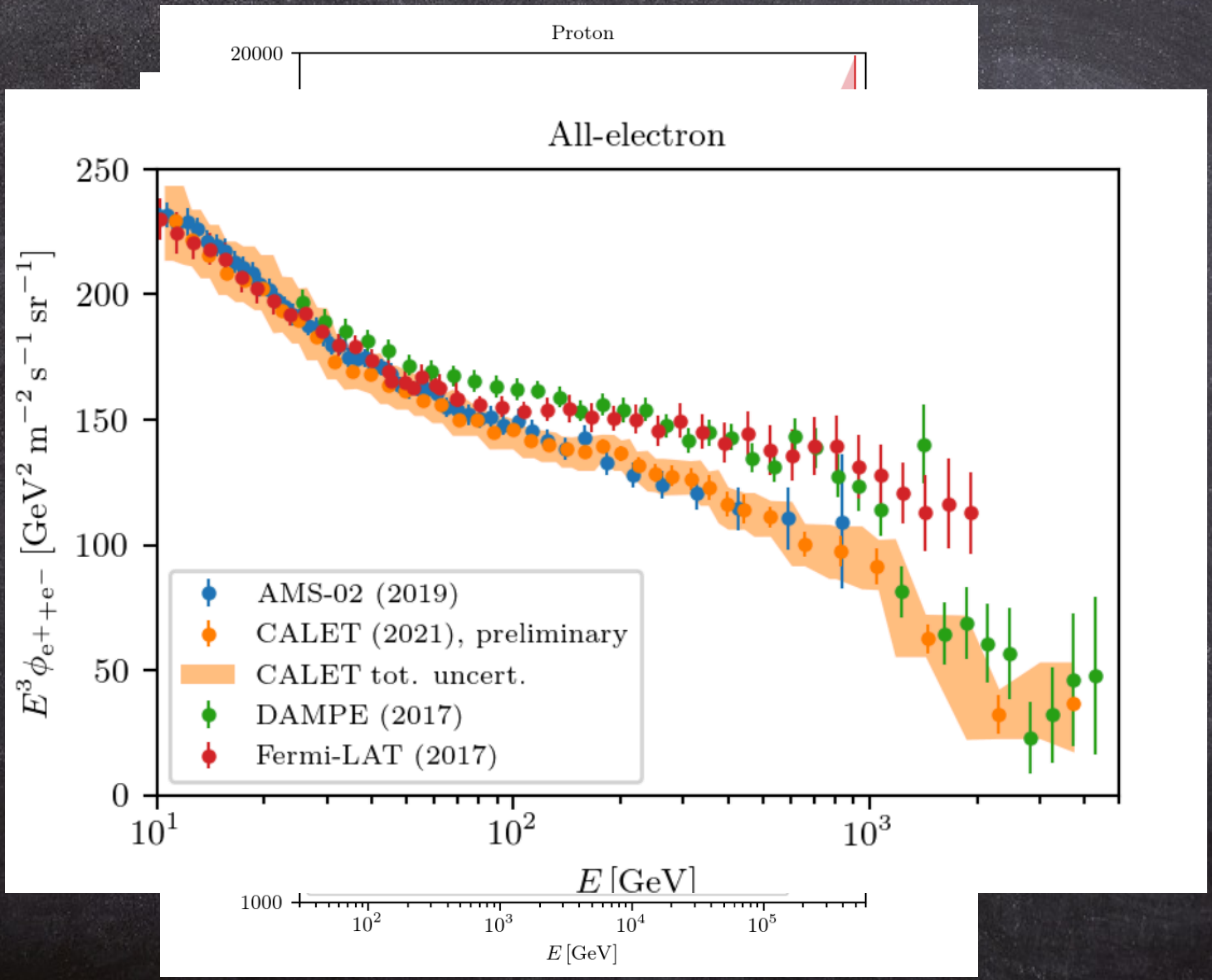


# The measured Cosmic Ray spectrum




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

# Precision data from space: nuclei, electrons



# 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 $\delta$ usually fixed by B/C (kappl+15; Genolini+15 (K15))

Energy losses: Synchrotron on the galactic B~3.6 μG

full relativistic of Compton effect (w/ Klein-Nishijna)

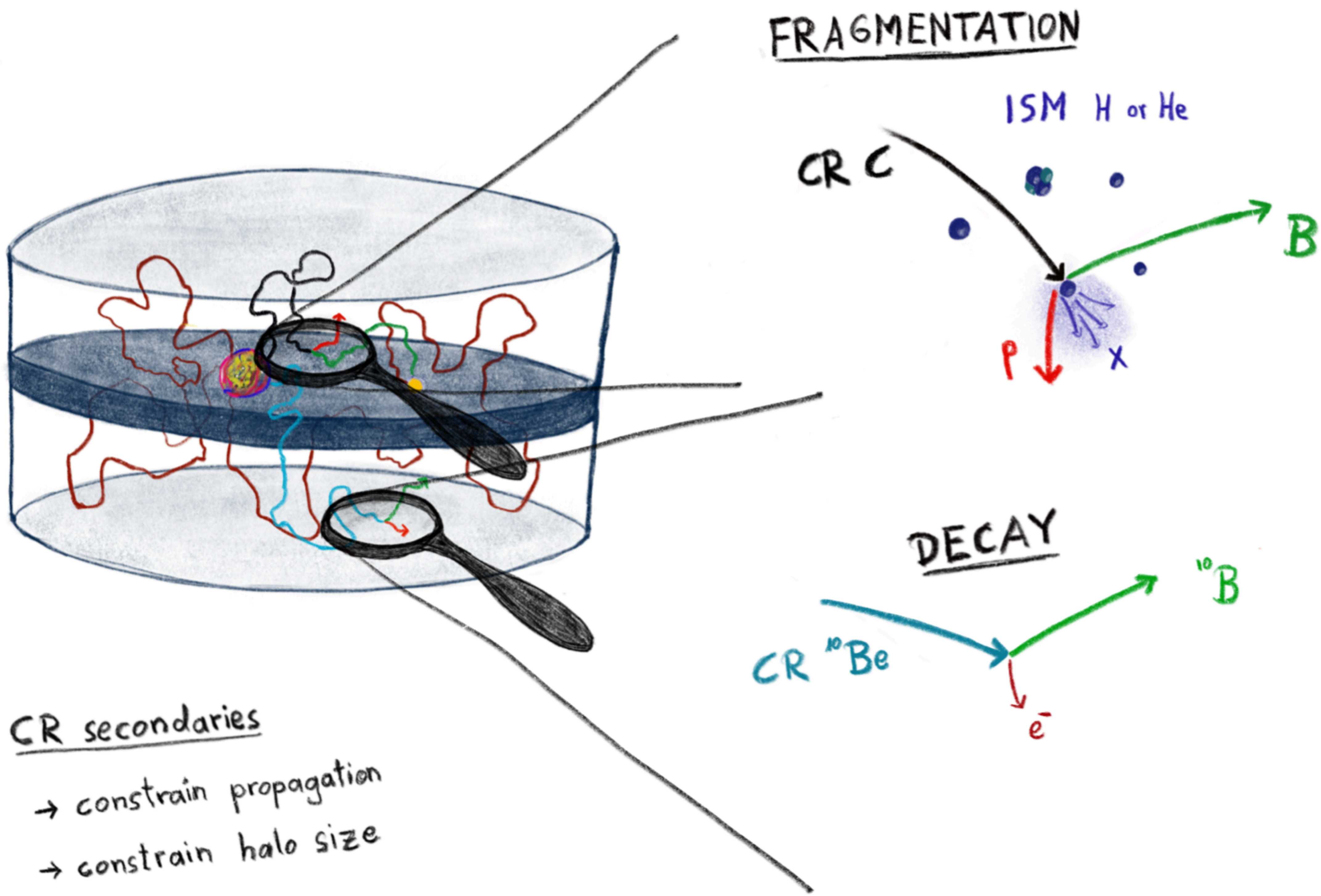
on photon fields (stellar, CMB, UV, IR)

Solution of the eq.: semi-analytic (Maurin+ 2001, Donato+ 2004, ...), USINE codes

or fully numerical: GALPROP, DRAGON codes

Geometry of the Galaxy: cylinder with height L ~ kpc

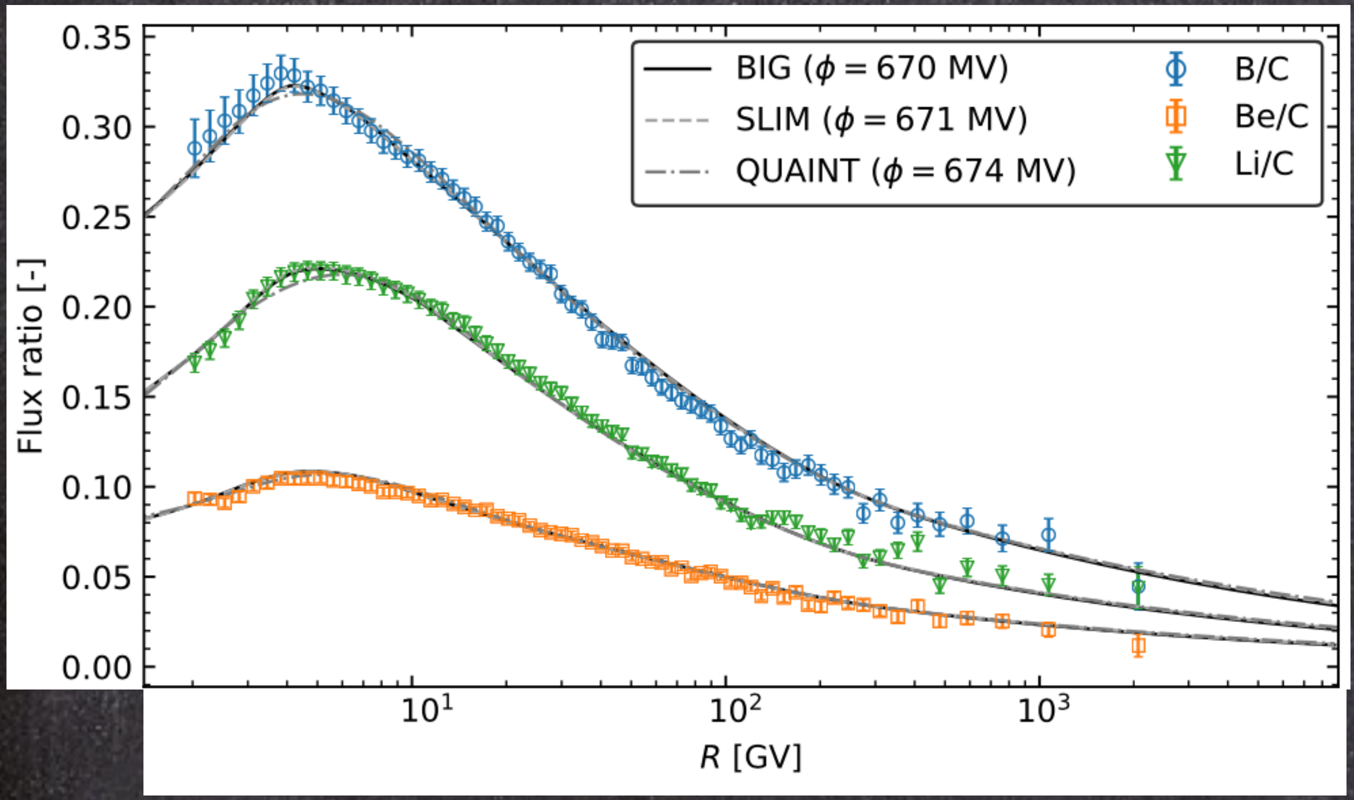
# Interactions and decays in the Galaxy

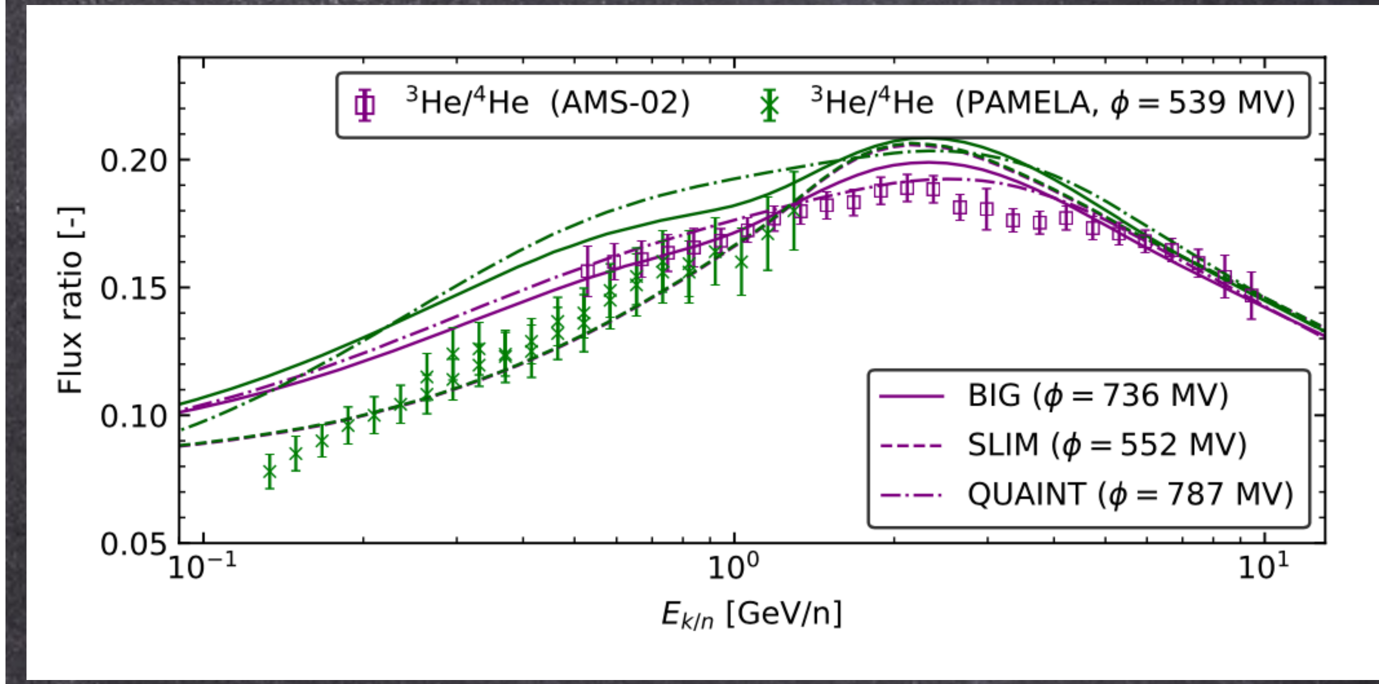



Courtesy of M. Korsmeier

# Propagation models vs data

Weinrich+ A&A 2020



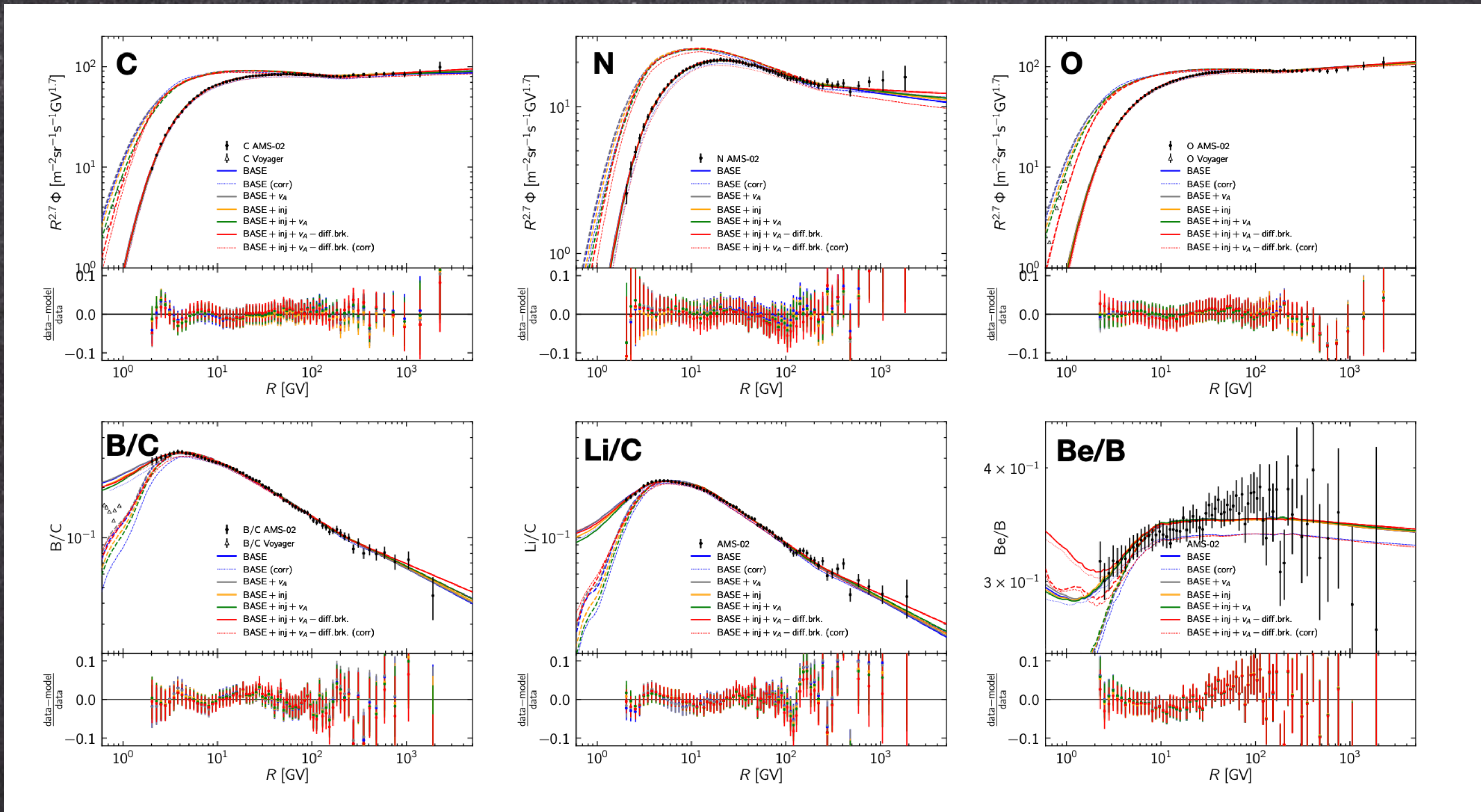

Data on secondary/primary species are well described by propagation model with diffusione coefficient power index $\delta = 0.50 \pm 0.03$.

Convection + reacceleration, or pure diffusion both work.

See also Evoli+ PRD 2020; Schroer+ PRD 2021

# Propagation models vs data

Korsmeier & Cuoco, PRD 2021



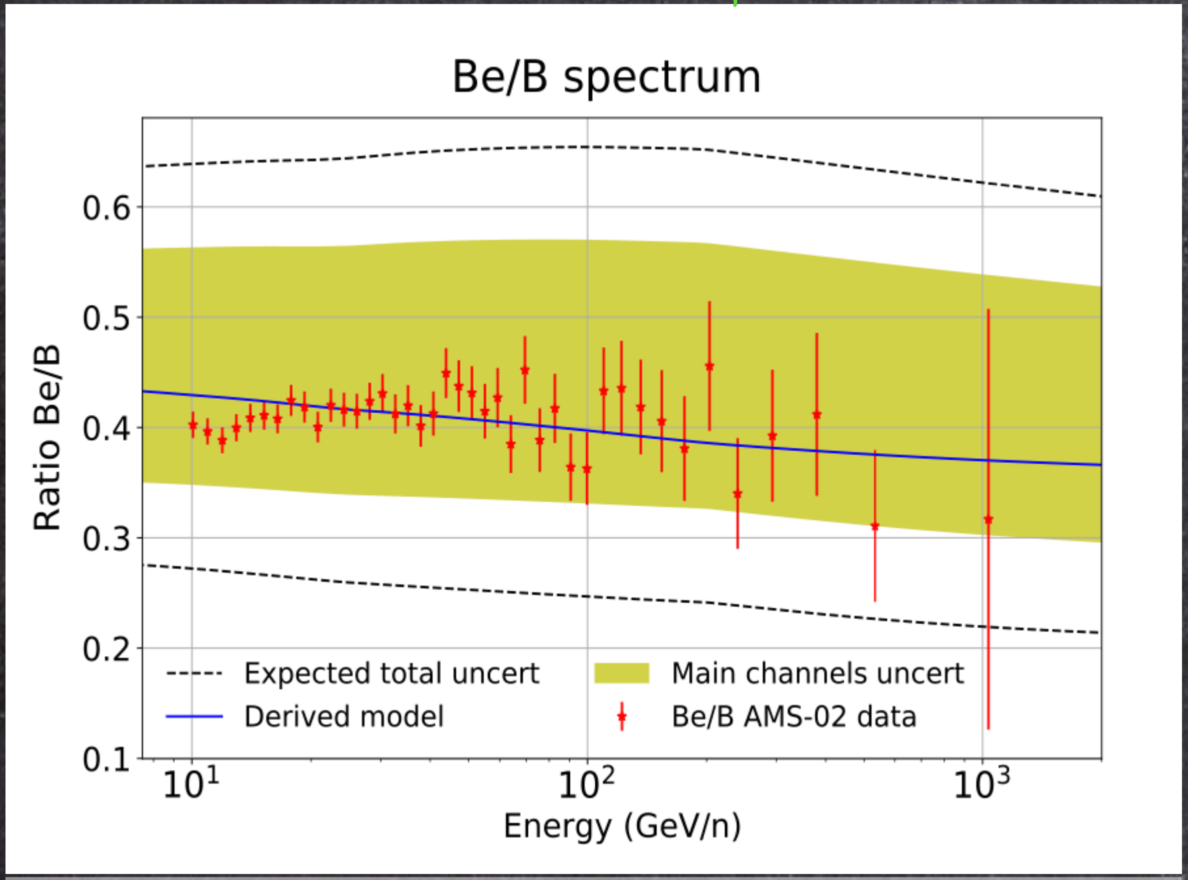

Several propagation models are tested, including fragmentation cross section uncertainties.

They currently prevent a better understanding of CR propagation

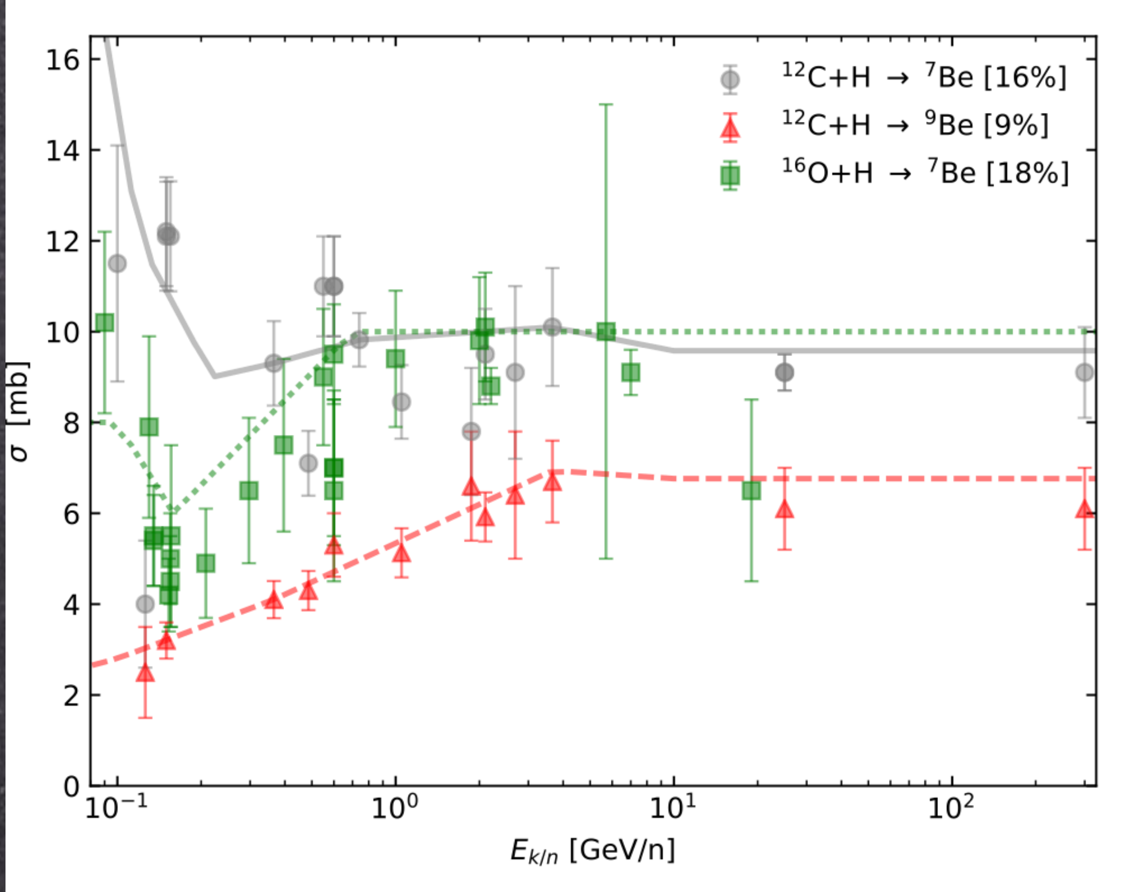
# Fragmentation cross sections

They matter in both directions: as a loss term for progenitors, as a source term for daughters

De La Torre Luque+ JCAP 2021




Weinrich+ A&A 2021




Probably the most limiting aspect now

Dedicated campaigns are needed (LHCb, NA61, Amber/Compass, ...)

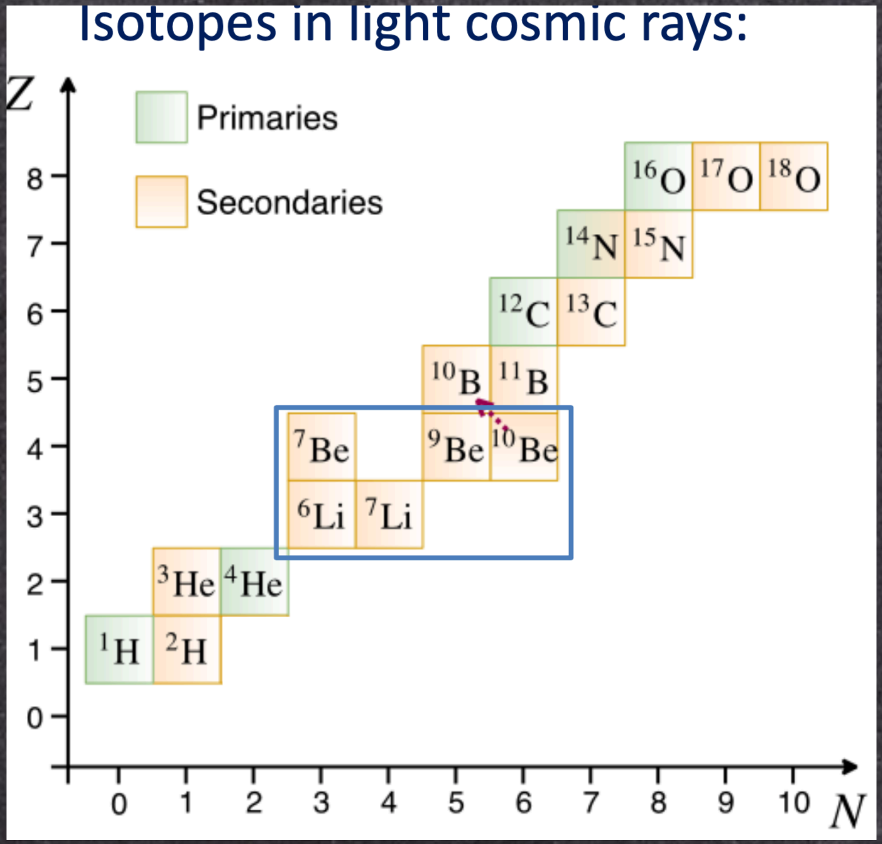
# Light isotopes in cosmic rays

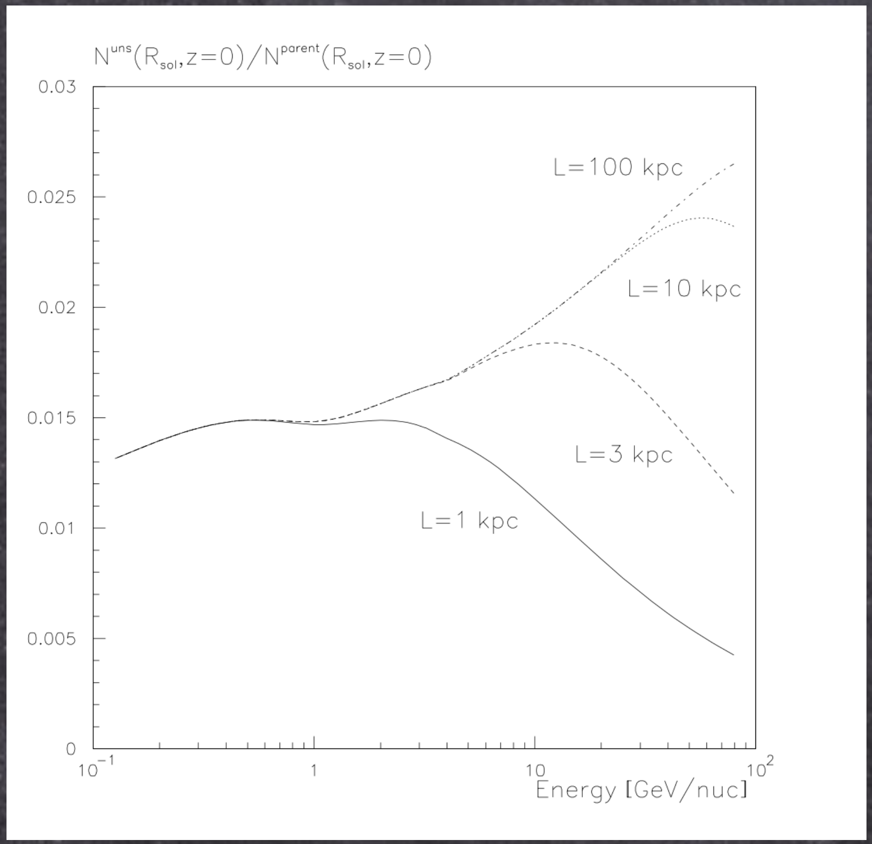
Important to test origin and propagation of CRs

Radioactive isotopes can track the diffusive halo size

Derome PoS ICRC 2021

FD, Maurin, Taillet A&A 2001




Radioactive isotopes have different propagation history

Unstable $^{26}$Al to stable $^{28}$Si parent ratio

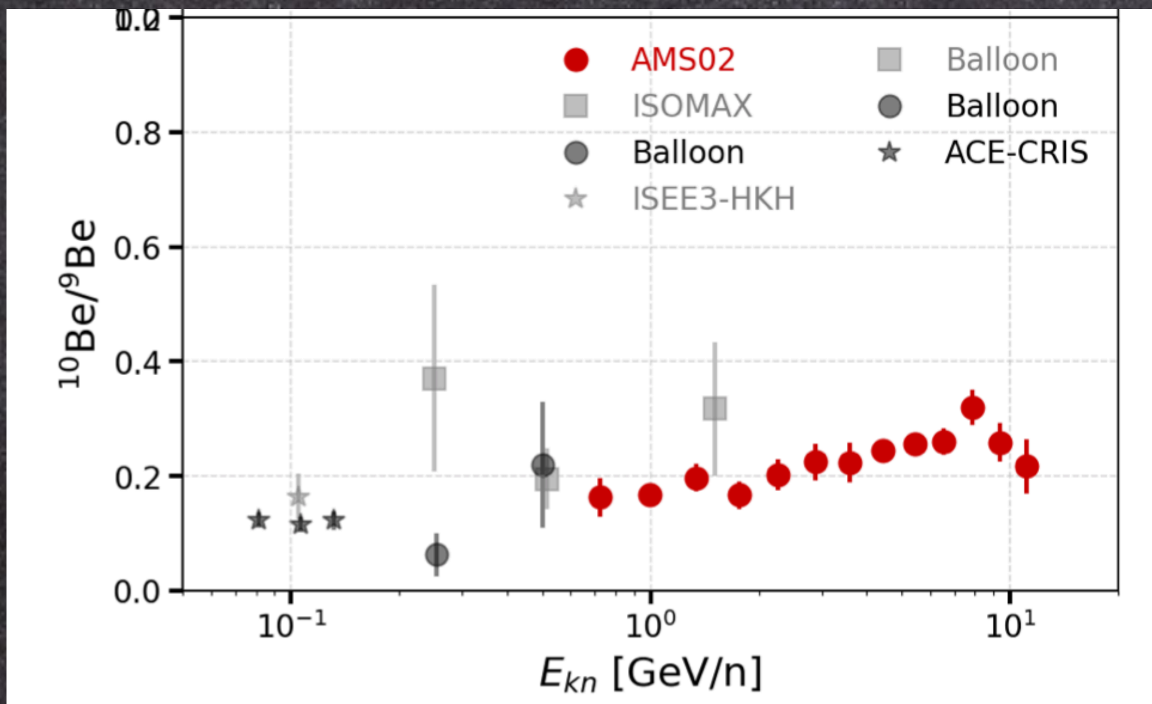
$$l_{rad} = \sqrt{D(E)\gamma\tau_0} < L$$

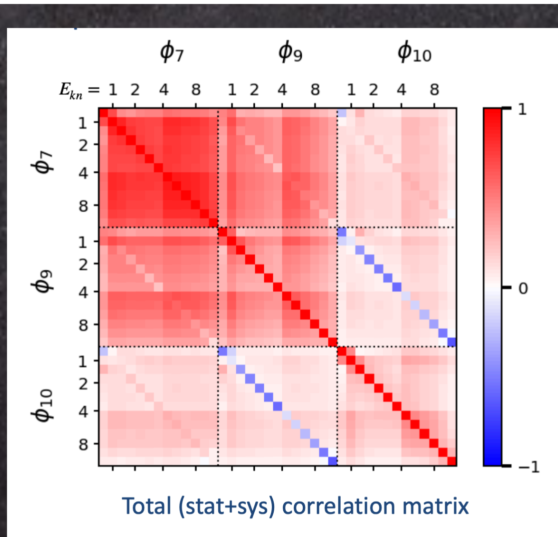
: insensitive to halo size

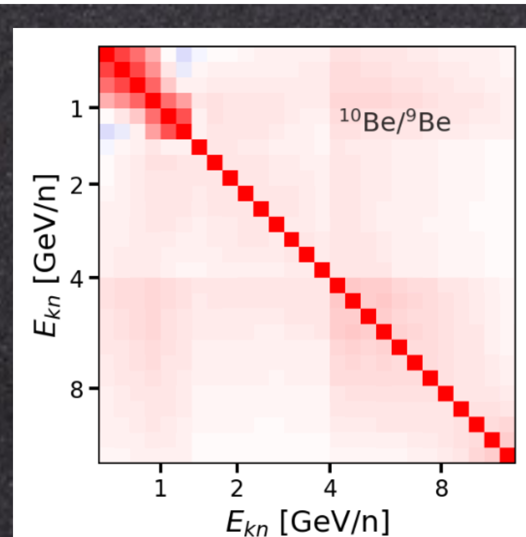
# Recent results with light nuclei isotopes

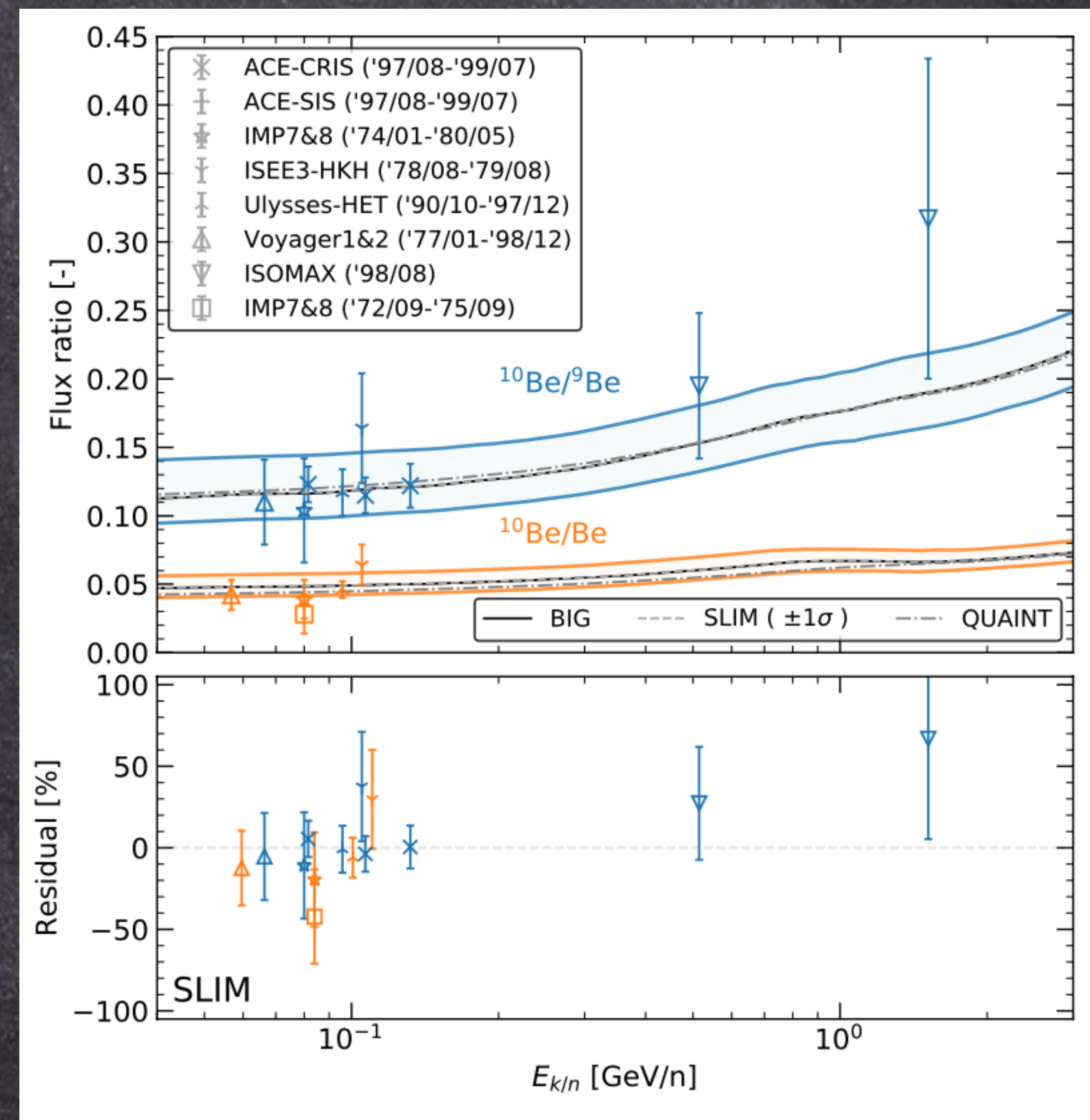
L.Derome AMS-02, ICRC 2021 PoS

Weinrich et al. A&A 2020




Several isotopes measured up to 10 GeV/n, with correlation matrices

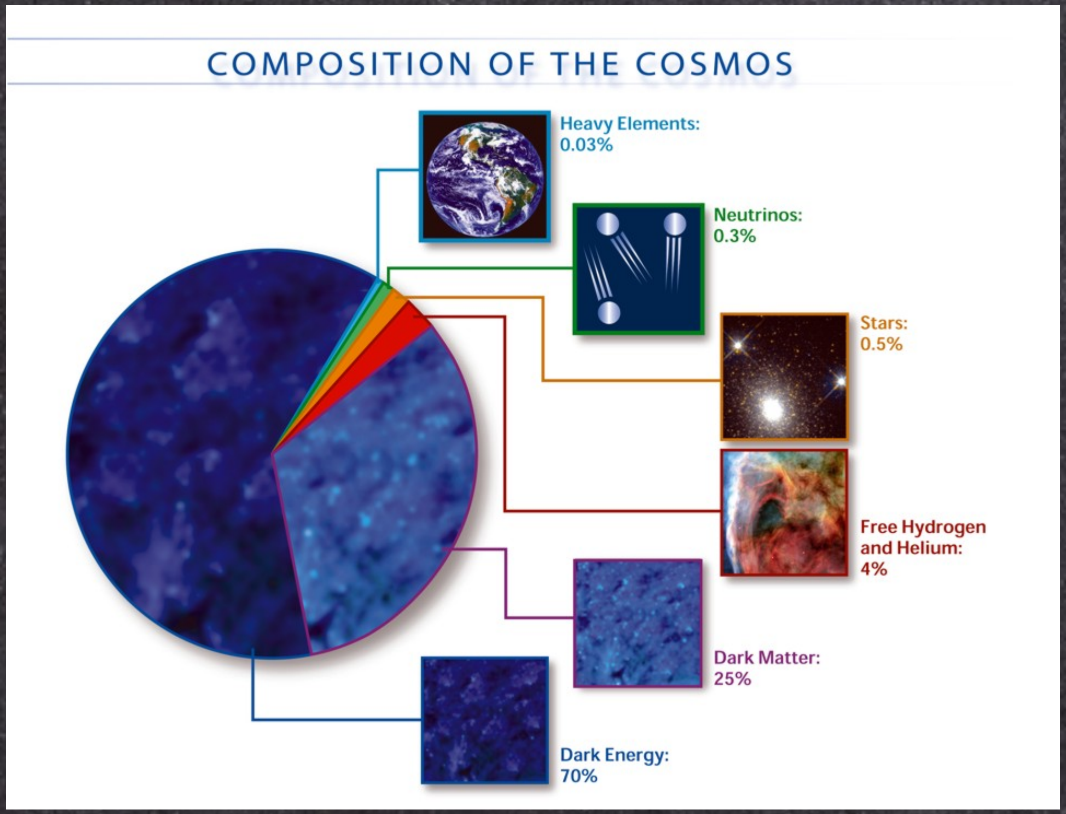
Indications to rather high diffusive halo (>=5 kpc)

Dark Matter

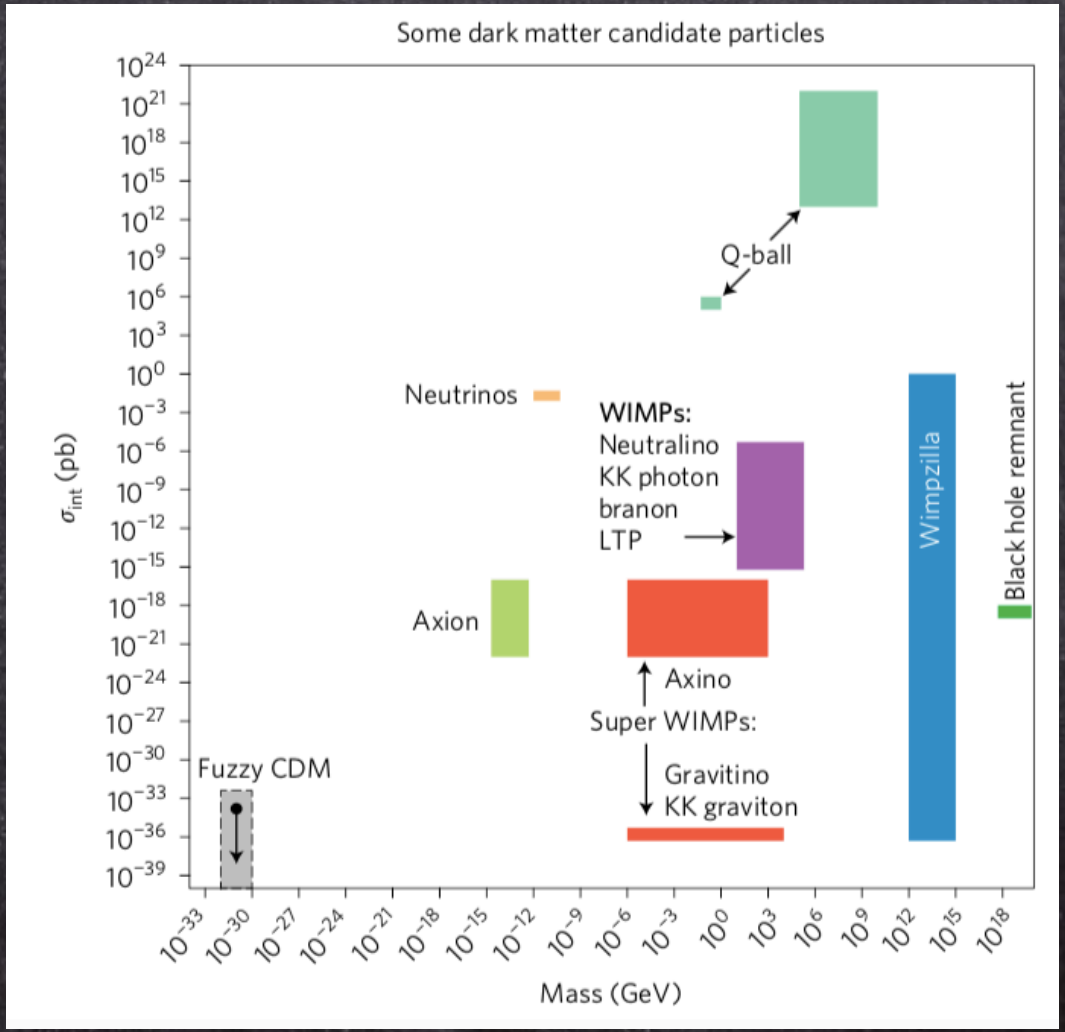
in the Cosmic Rays?

# Dark matter in the Universe

DM is there, gravitationally




One possible solution is a massive, stable, particle




Conrad&Reimer, Nature Phys. 2017

WIMP = Weakly Interacting Massive Particle

# SIGNALS from RELIC WIMPs

Direct searches: (deeply underground experiments) :

elastic scattering of a WIMP off detector nuclei

Measure of the recoil energy

Annual modulation and directionality of the measured rate

Indirect searches: in Cosmic Rays (mostly space based experiments)

signals due to annihilation of accumulated

$\chi\chi$ in the of Sun/Earth (neutrinos)

signals due to $\chi\chi$ annihilation in the galactic halo

(antimatter, gamma-rays)

**New particles are searched at colliders but we cannot say anything about being the solution to the DM in the Universe!**

# Indirect Dark Matter detection

Annihilation inside celestial bodies (Sun, Earth):

$\nu$ at neutrino telescopes as up-going muons

Annihilation in the galactic halo:

$\gamma$-rays (diffuse, monochromatic line), multiwavelength

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

$\nu$ and $\gamma$ 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

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

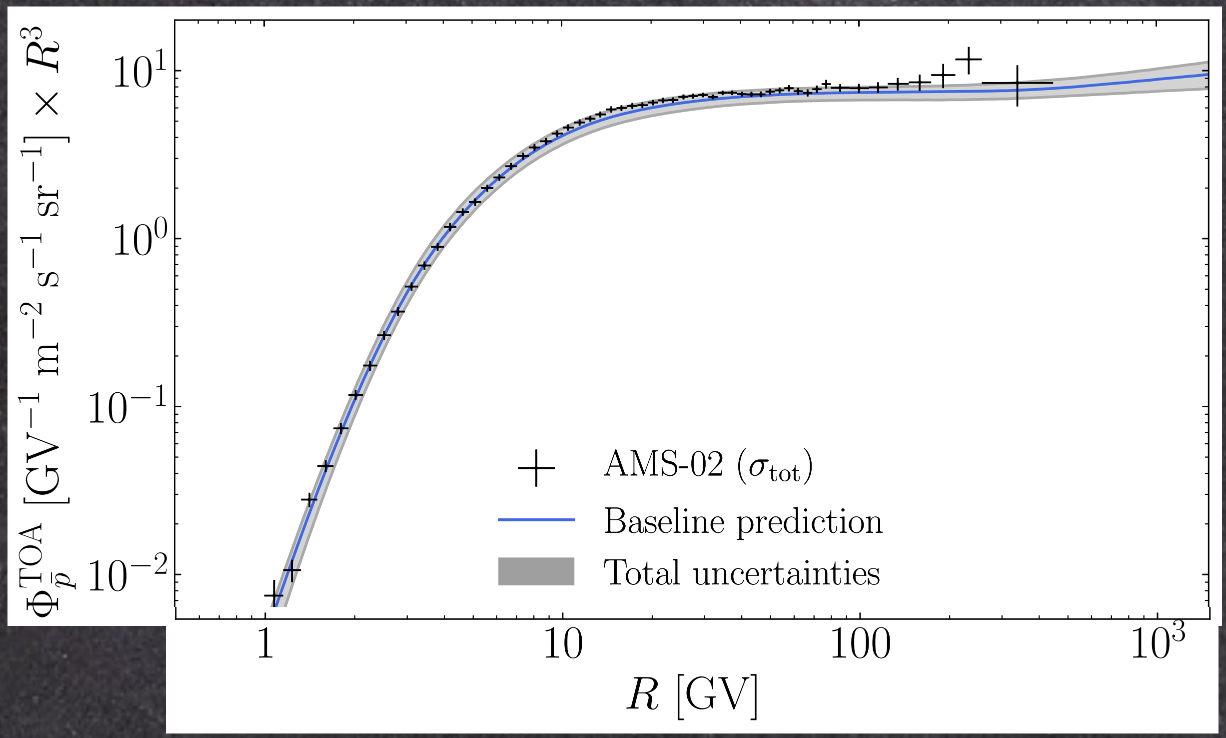
- ρ DM density in the halo of the MW
- $m_{DM}$ DM mass
- <σv> thermally averaged annihilation cross section in SM channel f
- Γ DM decay time
- e+, e- energy spectrum generated in a single annihilation or decay event

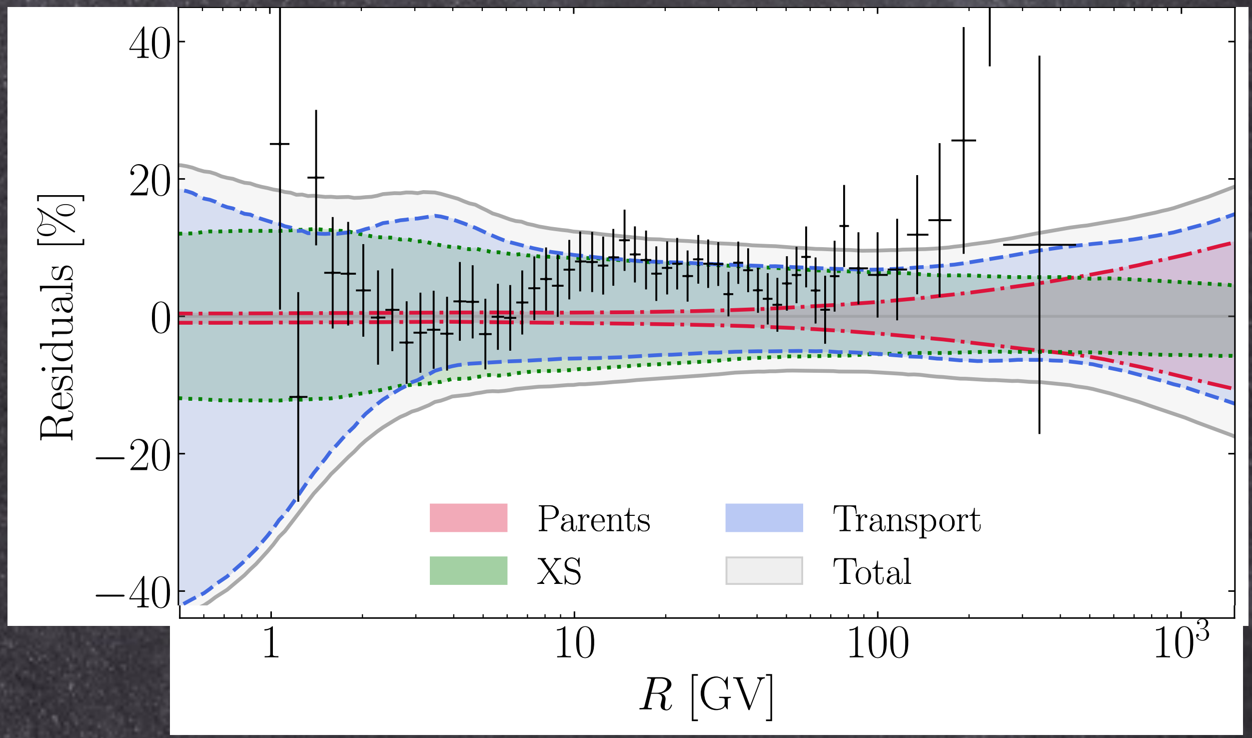
Annihilations take place in the whole diffusive halo

# The case for antiprotons

# AMS-02 antiprotons are consistent with a secondary astrophysical origin

M. Boudaud, Y. Genolini, L. Derome, J.Lavalle, D.Maurin, P. Salati, P.D. Serpico PRD 2020

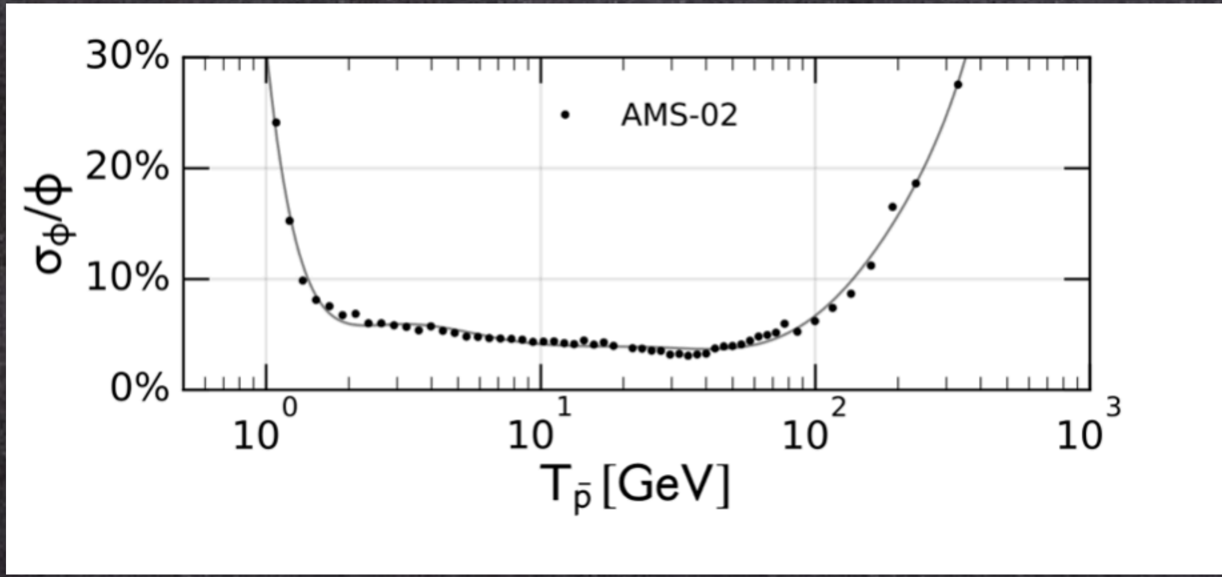



- Secondary pbar flux is predicted consistent with AMS-02 data
- Transport and cross section uncertainties are comparable
- A dark matter contribution would come as a tiny effect
- Precise predictions are mandatory

# 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

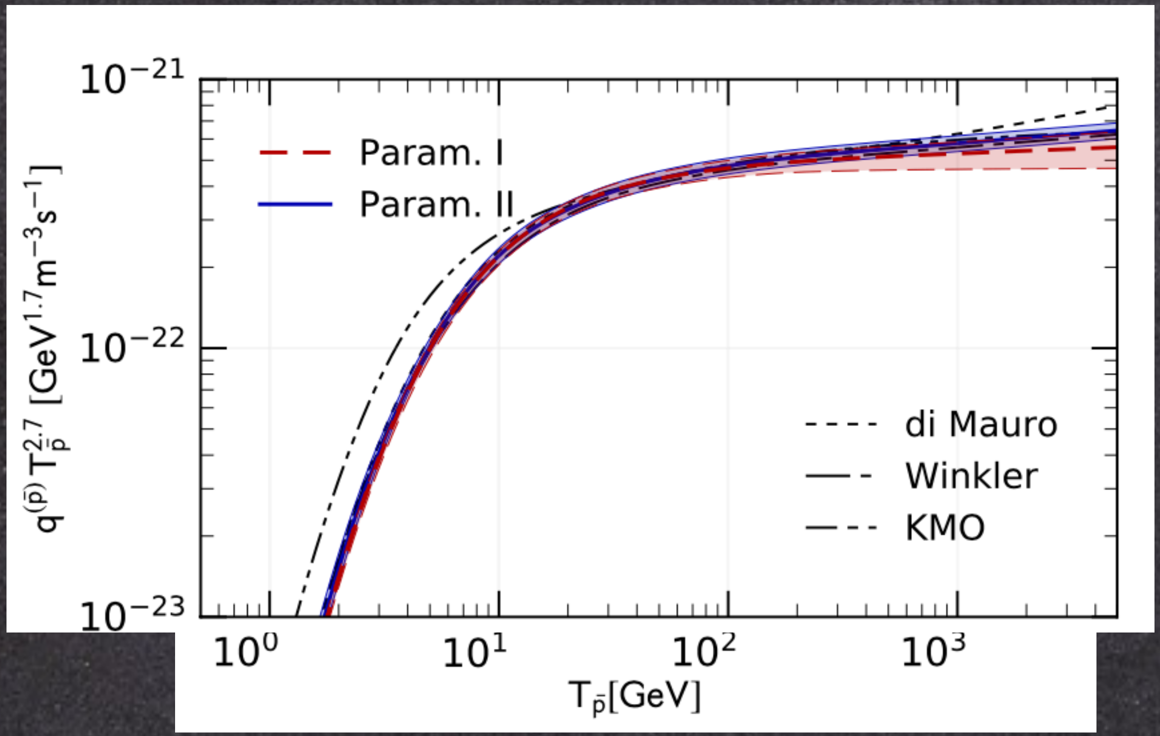
| pp —> pbar+X | pHe —> pbar + X |
|---|---|
| **NA61** (Aduszkiewicz Eur. Phys. J. C77 (2017)) | **LHCb** (Graziani et al. Moriond 2017) |
| $\sqrt{s}$=7.7, 8.8, 12.3 and 17.3 GeV | $\sqrt{s} = 110$ GeV |
| $T_p$ = 31, 40, 80, 158 GeV | $T_p$ = 6.5 TeV |

Most recent cross section data

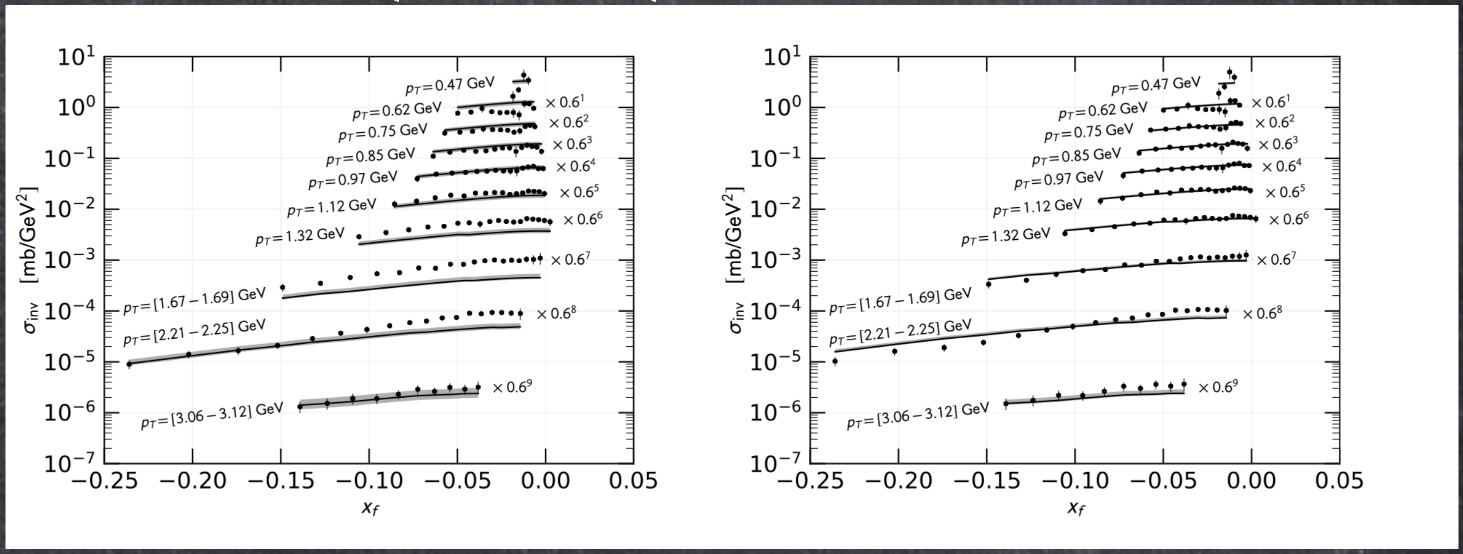
# The antiproton source spectrum

Korsmeier, FD, Di Mauro, PRD 2018

pp -> p- X source term



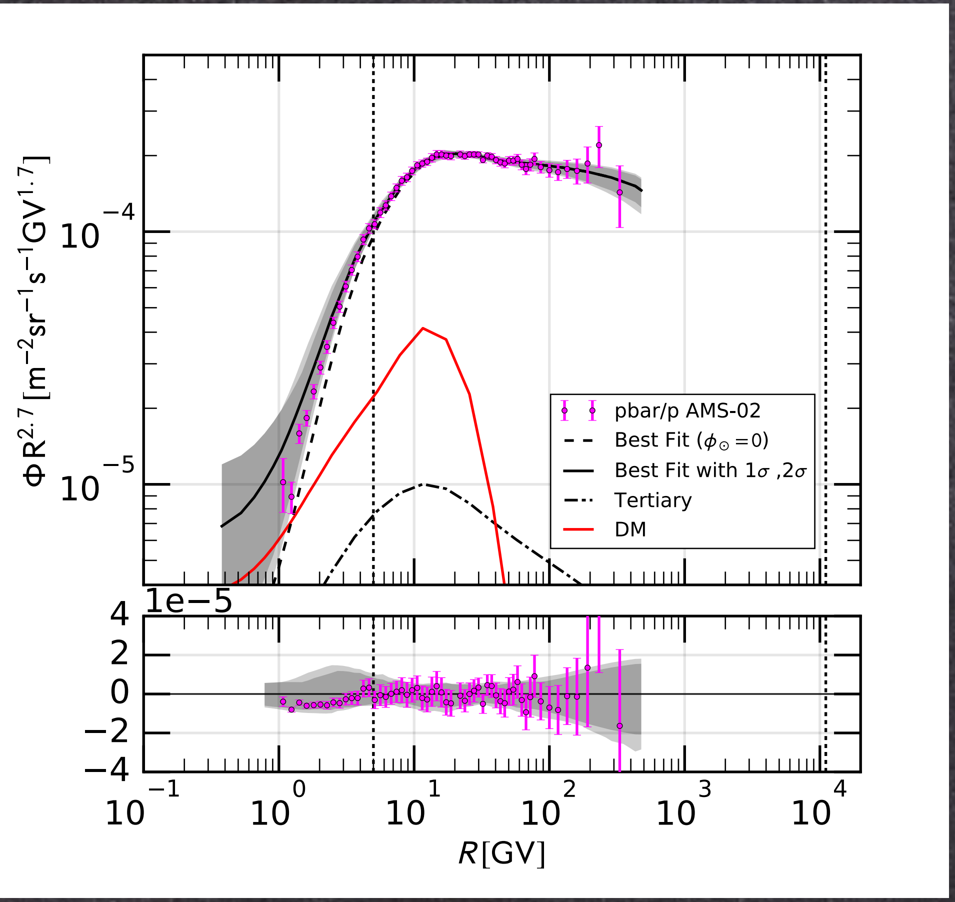

LHCb pHe -> p- X data & our fit

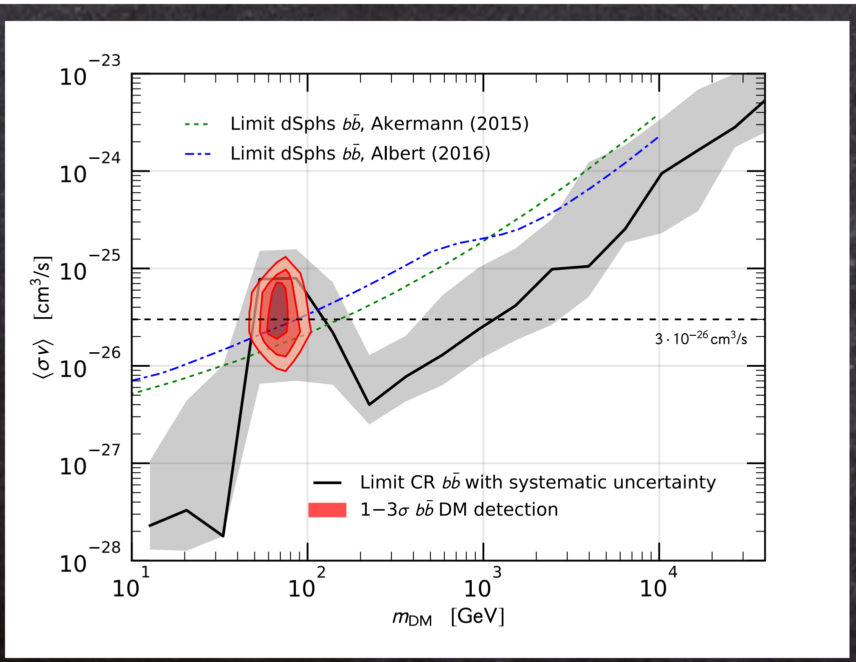



The effect of LHCb data is to select a high energy trend of the pbar source
A harder trend is preferred.

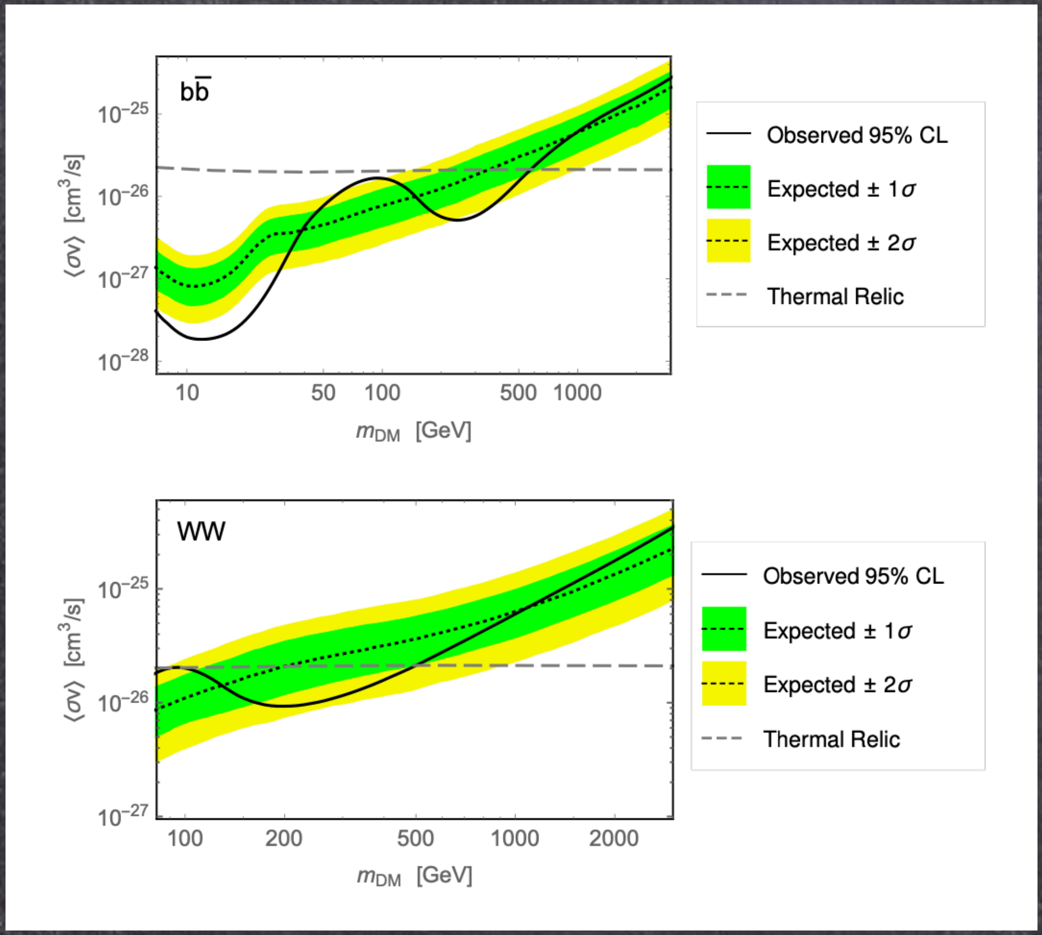
# Possible contribution from dark matter

Cuoco, Korsmeier, Kraemer PRL 2017




Reinert & Winkler JCAP2018



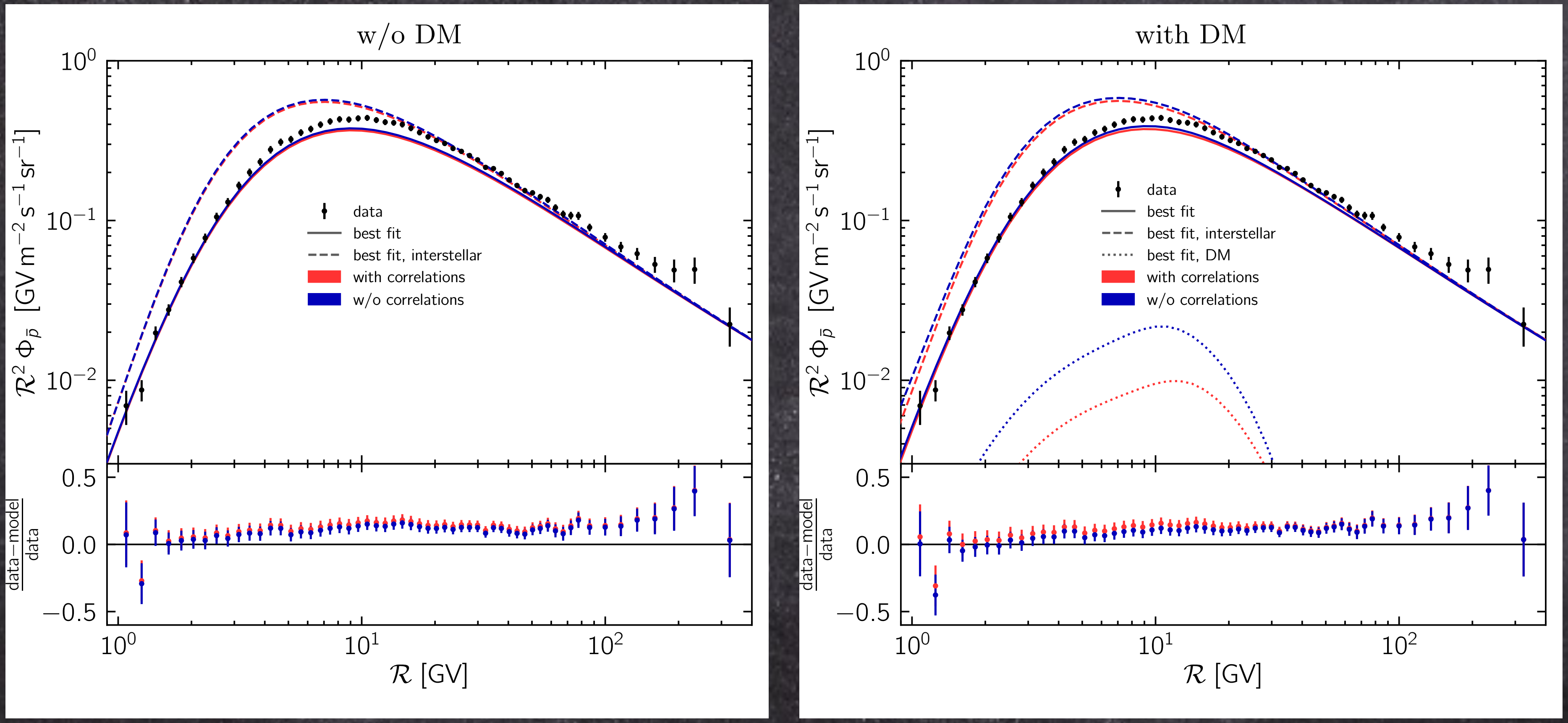

Antiproton data are so precise that permit to set strong upper bounds on the dark matter annihilation cross section, or to improve the fit w.r.t. to the secondaries alone adding a tine DM contribution

# A matter of correlations

Heisig, Korsmeier, Winkler PRD2020 2020

Derivation of covariance matrix for systematic errors (dominated by p(bar)C absorption cross section)

B/C, p-bar fit

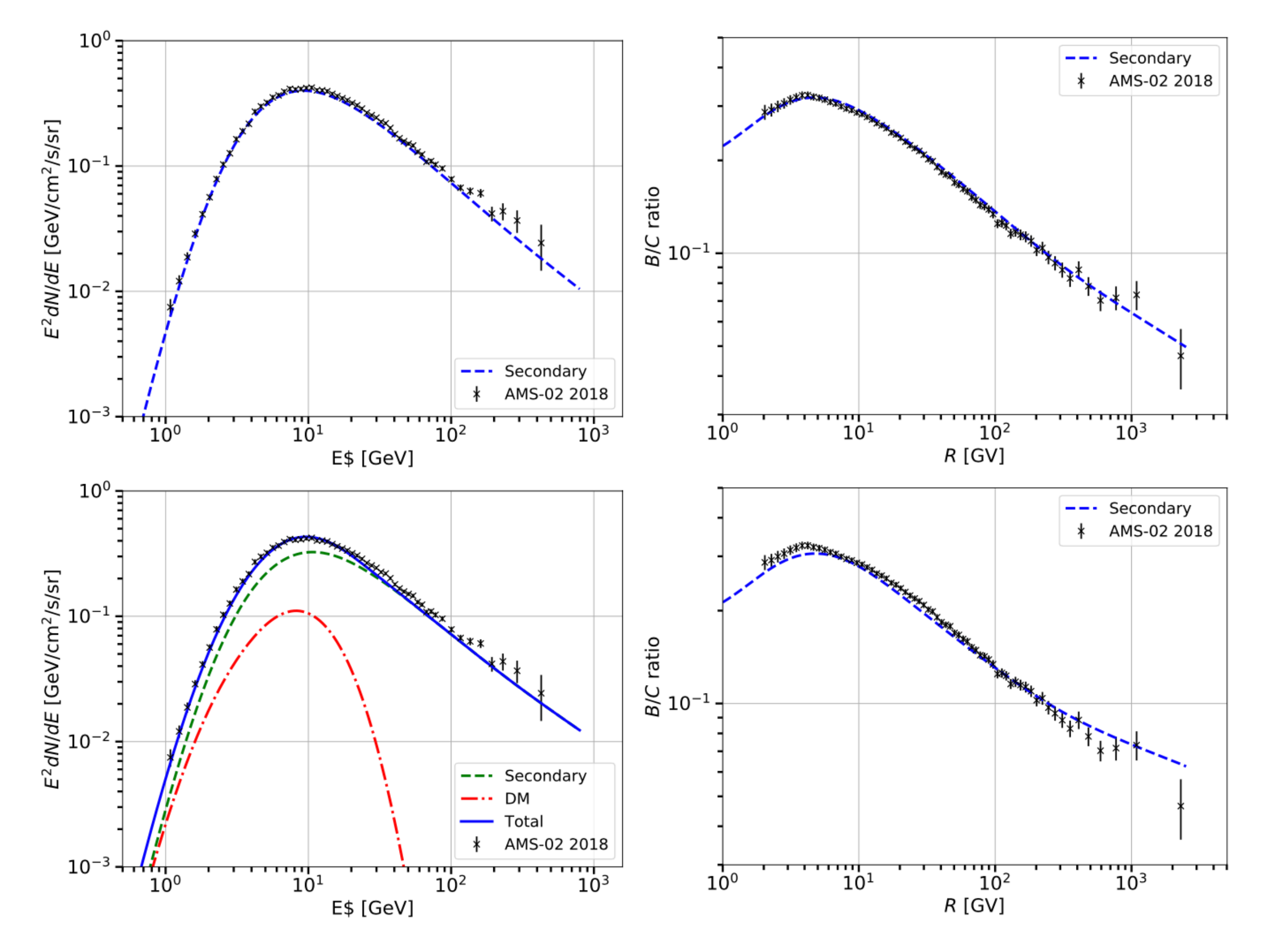



The significance for DM drops below 1sigma

# AMS-02 antiprotons wrt Fermi-LAT Galactic center excess - I

Di Mauro & Winkler PRD 2021

Candidate possibly explaining the Galactic center excess in Fermi-LAT data



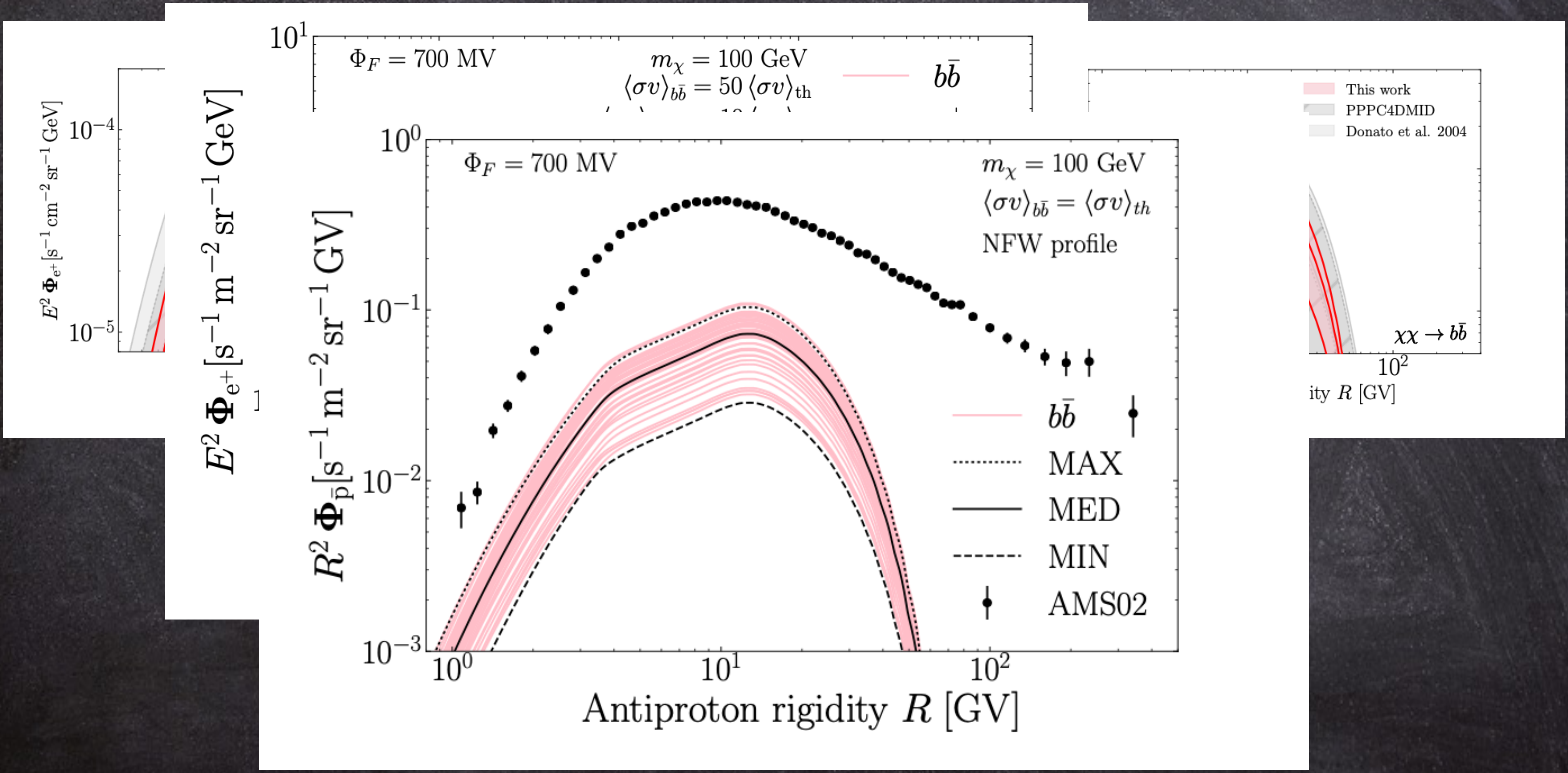

The pbar data are compatible with DM/GCE

Tension is with magnetic halo size L: here L< 1.7 kpc, $5^{+3}_{-2}$ kpc from Be/B and L> 2 kpc from e+ at low energy

# Effect of galactic propagation

Genolini+ 2103.04108

New AMS-02 sec/prim data allow reduction of propagation uncertainties

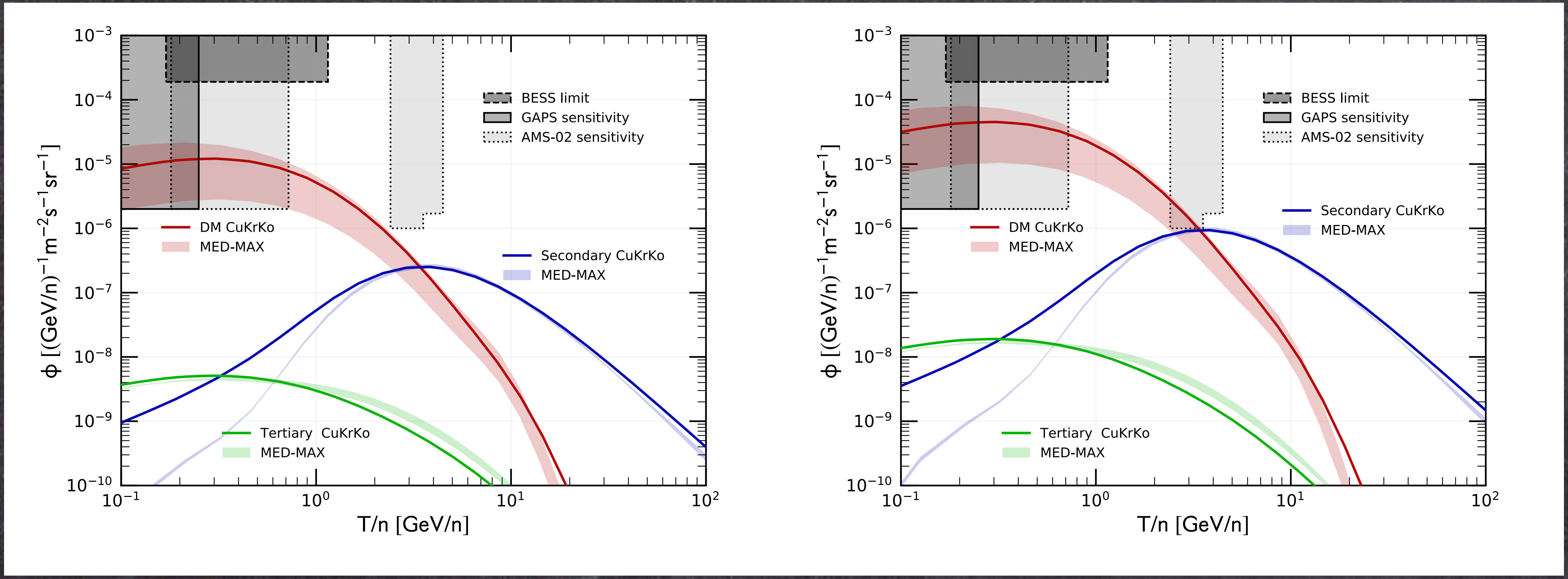


# Possible antideuteron verification of Dark Matter hint in antiprotons

FD, Fornengo, Korsmeier, PRD 2018

$P_{coal}$ = 124 (62) MeV

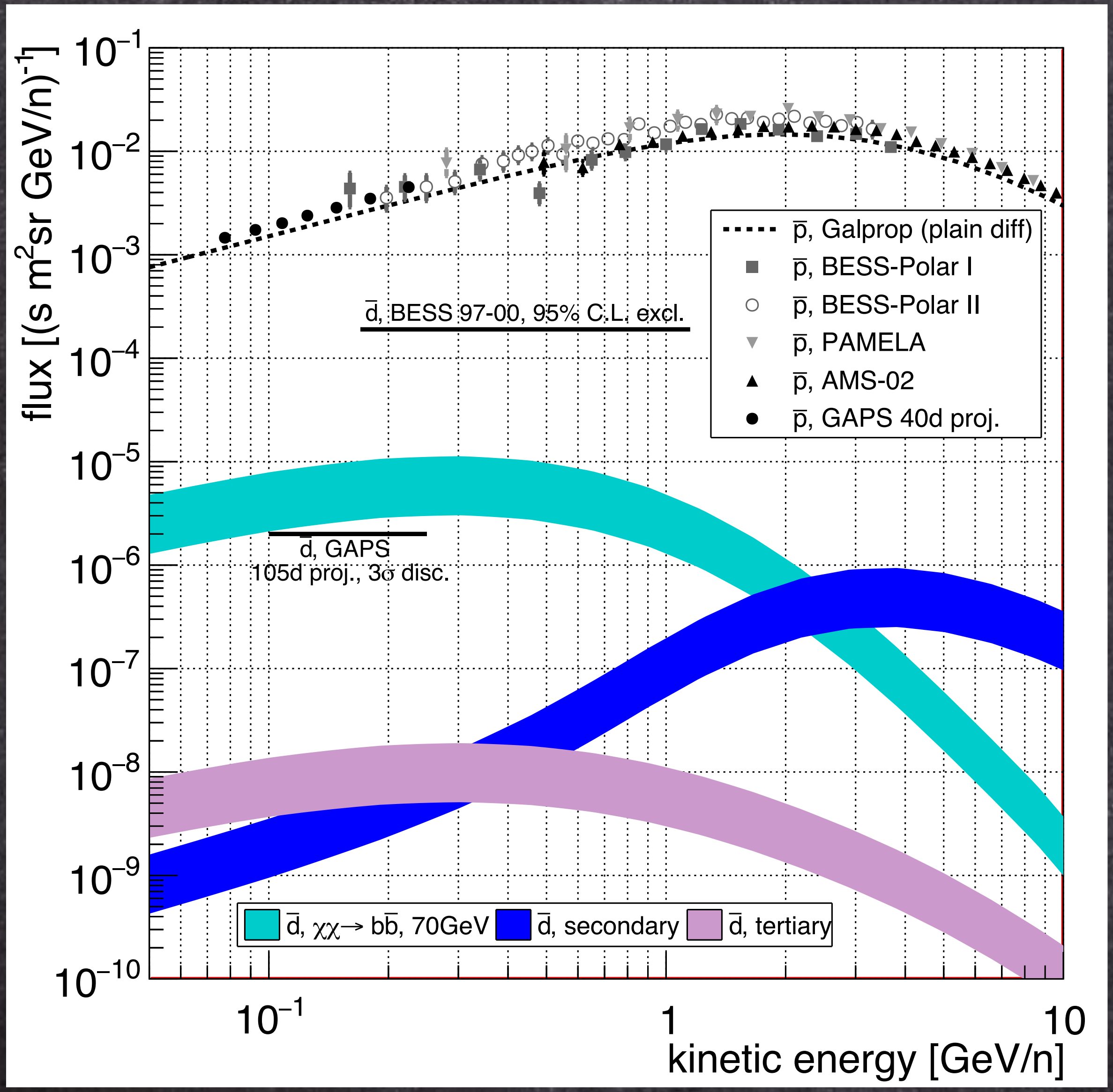
$P_{coal}$ = 248 (124) MeV




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

# Antideuterons persepcthves

P. Von Doetinchem et al. Phys. Rep. 2021




AMS-02 antiproton data

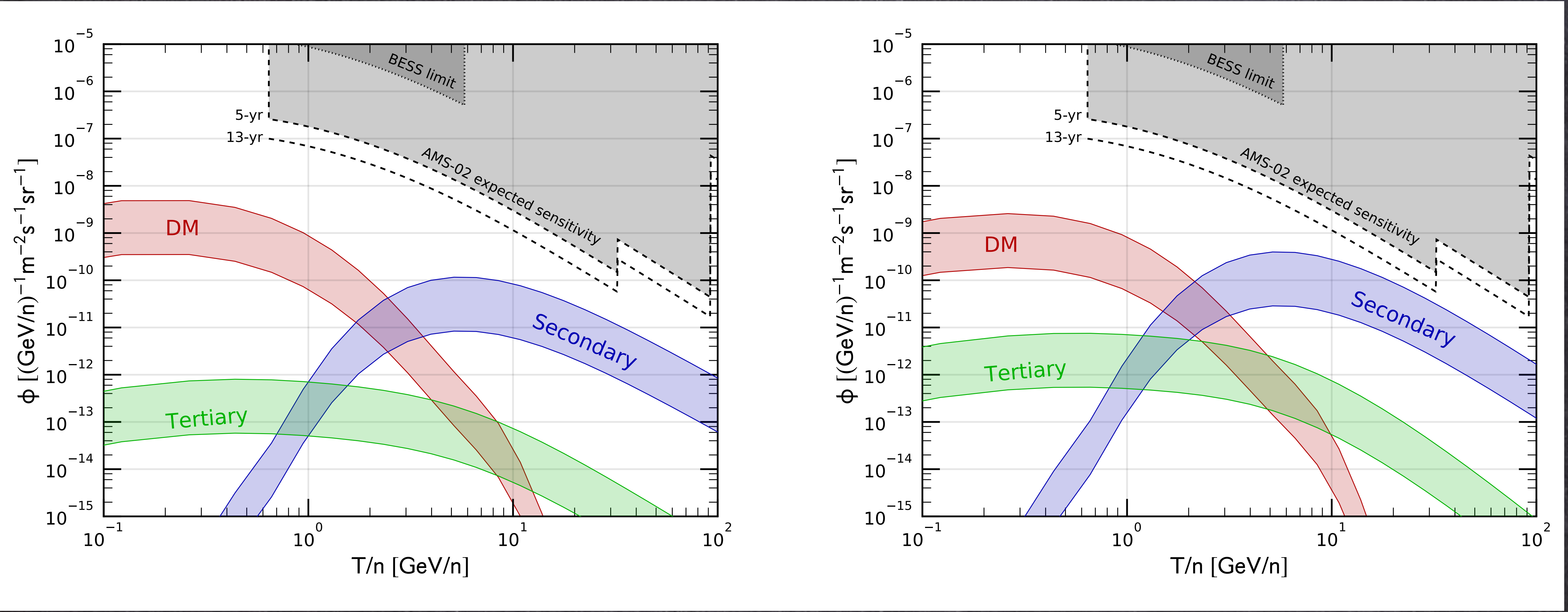
Antideuteron predictions for DM model indicated by pbar AMS-02 data

Bands are for coalescence uncertainty

GAPS experiment is under construction

# Perspectives with antihelium

FD, Fornengo, Korsmeier, PRD 2018




The Dark Matter signal is ways higher than secondaries

Below ~ 2 GeV/n: discovery window

Challenging for present day experiments

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

V. Poulin et al. PRD 2019

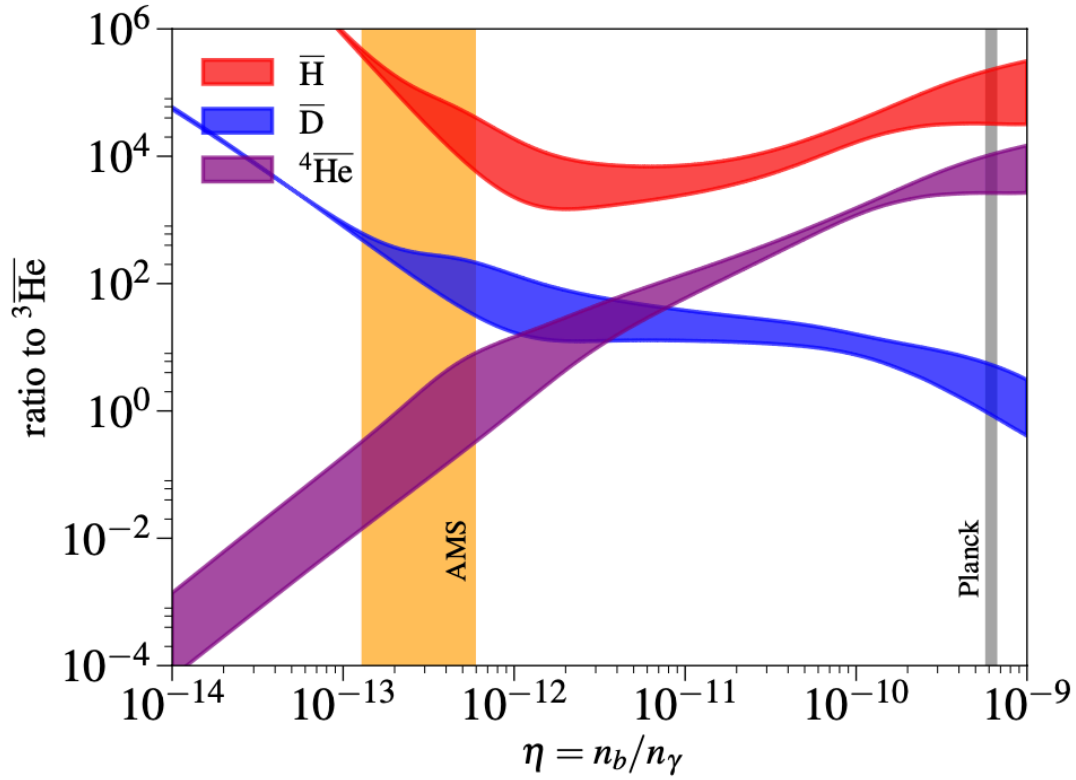



FIG. 4. Abundance of $\overline{\mathrm{H}}$, $\overline{\mathrm{D}}$ and $^{4}\overline{\mathrm{He}}$ with respect to that of $^{3}\overline{\mathrm{He}}$ as a function of the (anti-)baryon-to-photon ratio $\bar{\eta}$. The *Planck* value is represented by the grey band. The value required by the *AMS-02*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

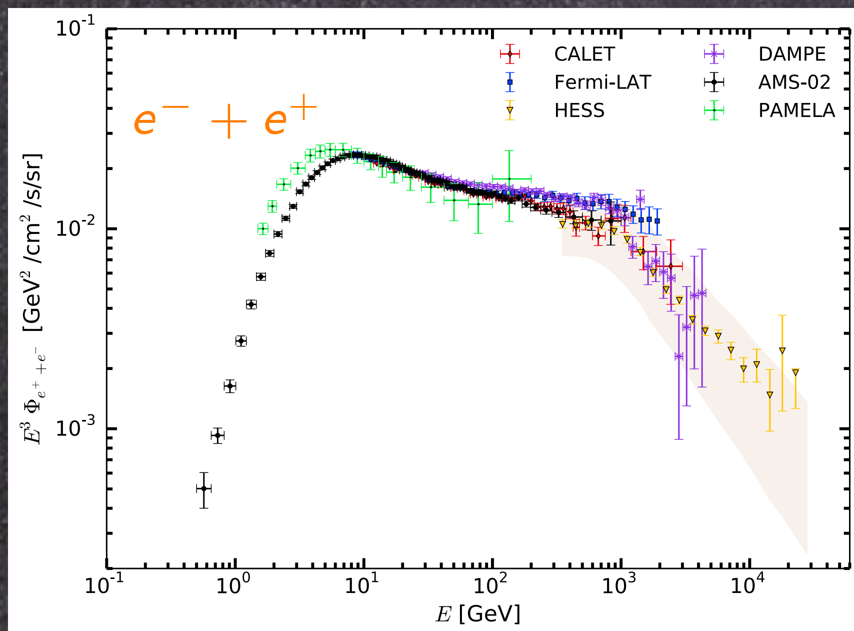
Traces in p-bar and D-bar

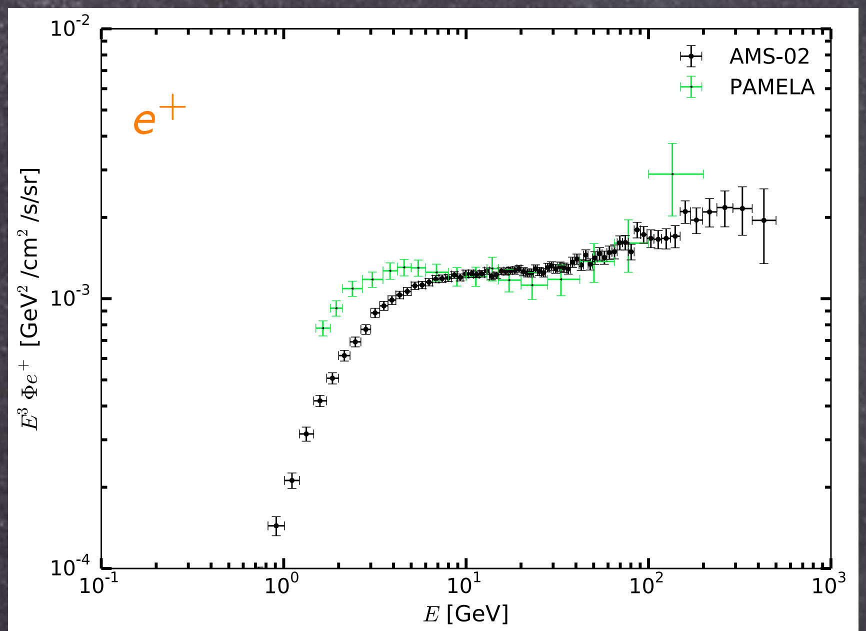
One anti-star could make the job. How did they survive?

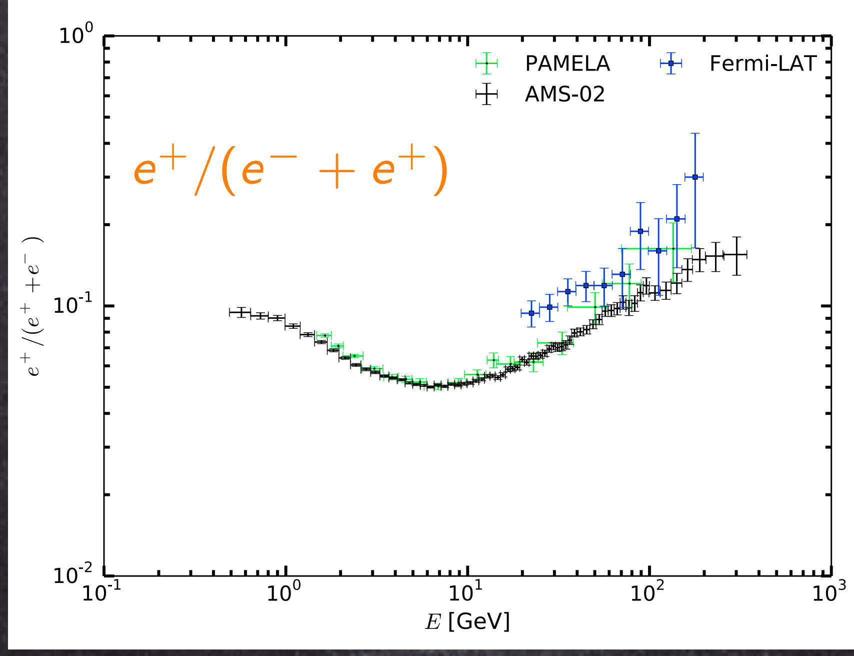
# Sources of $e^{\pm}$ in the Milky Way

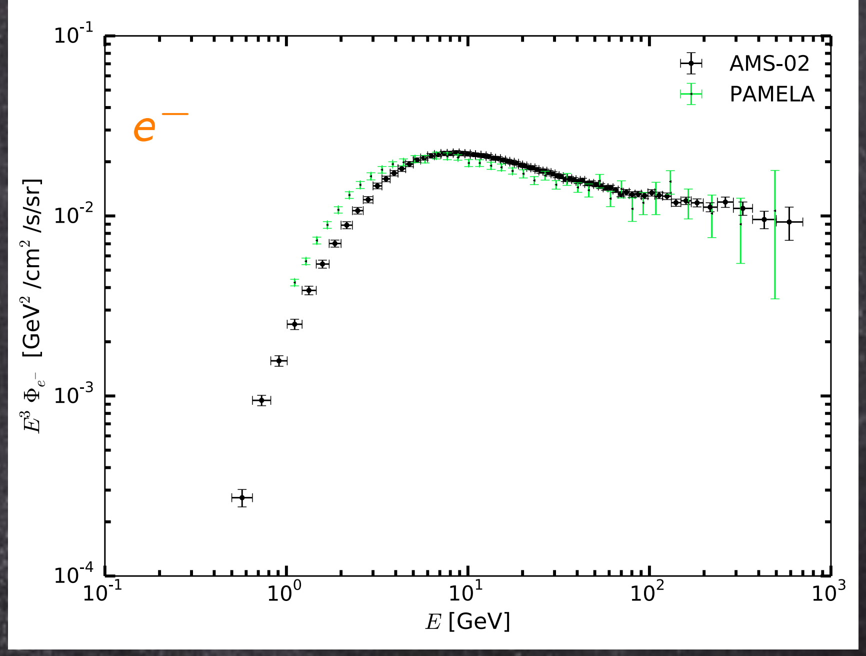
- Inelastic hadronic collisions (asymm.)
- Pulsar wind nebulae (PWN) (symm.)
- Supernova remnants (SNR) (only e-)
- Particle Dark Matter annihilation (e+,e-)?

# The journey started with the attempt – shared by many – to interpret the e+ data



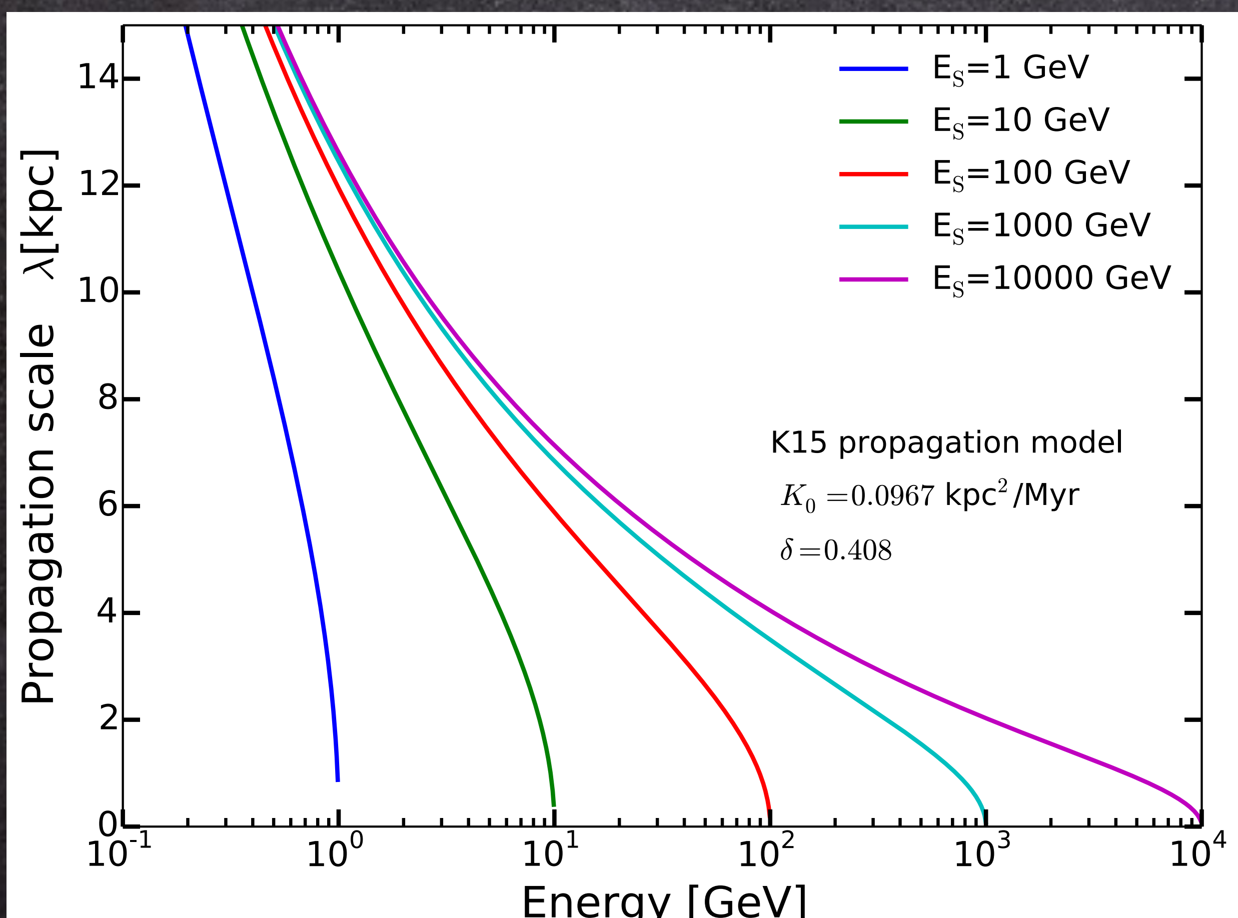

Unprecedented statistics and energy coverage

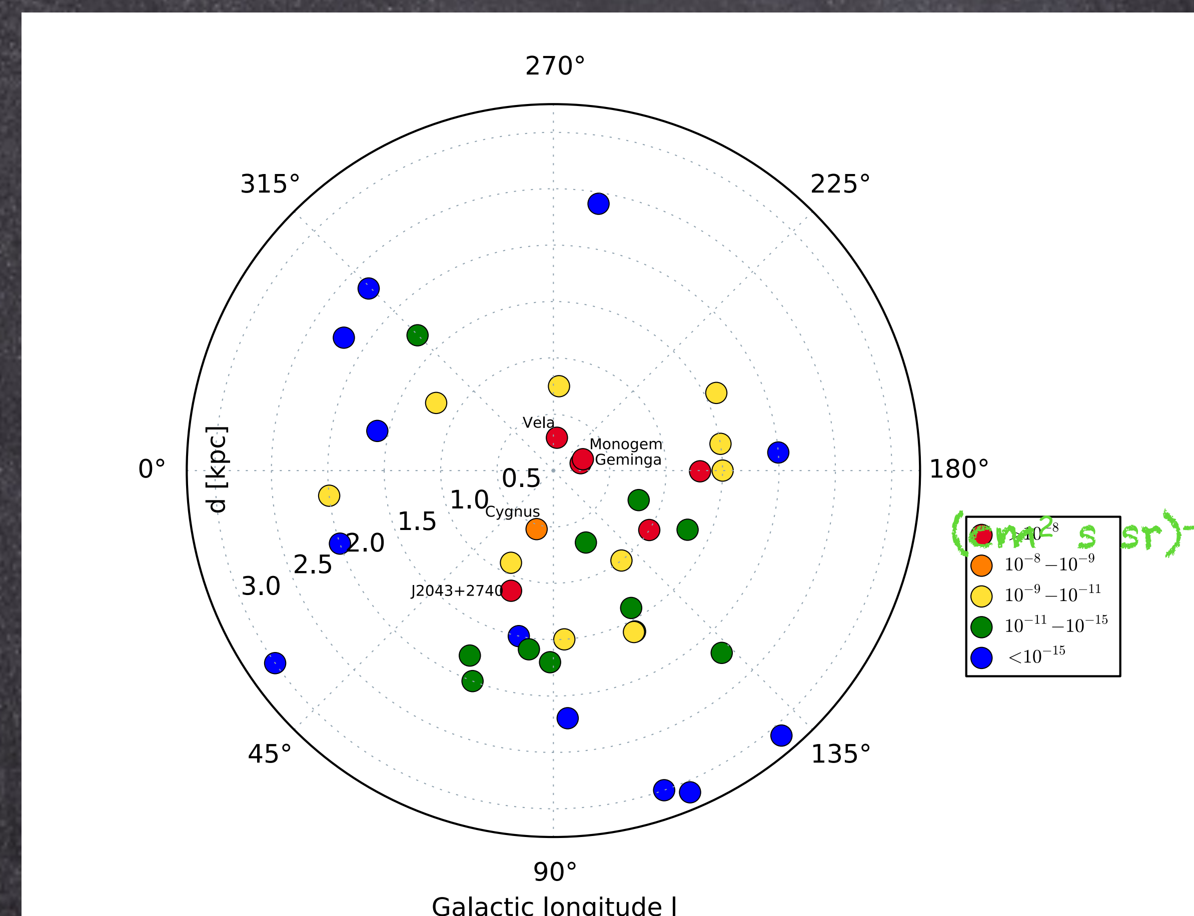
# Detected e+ and e- are local

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

Typical propagation length in the Galaxy

Manconi, Di Mauro, FD JCAP 2017




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

Most powerful sources within 3 kpc from the Sun.
SNRs (e-) and PWN (e+e-)

# The secondary, hadronic e± source term

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

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

i, j: nuclei. Specifically pp, pHe, Hep, HeHe

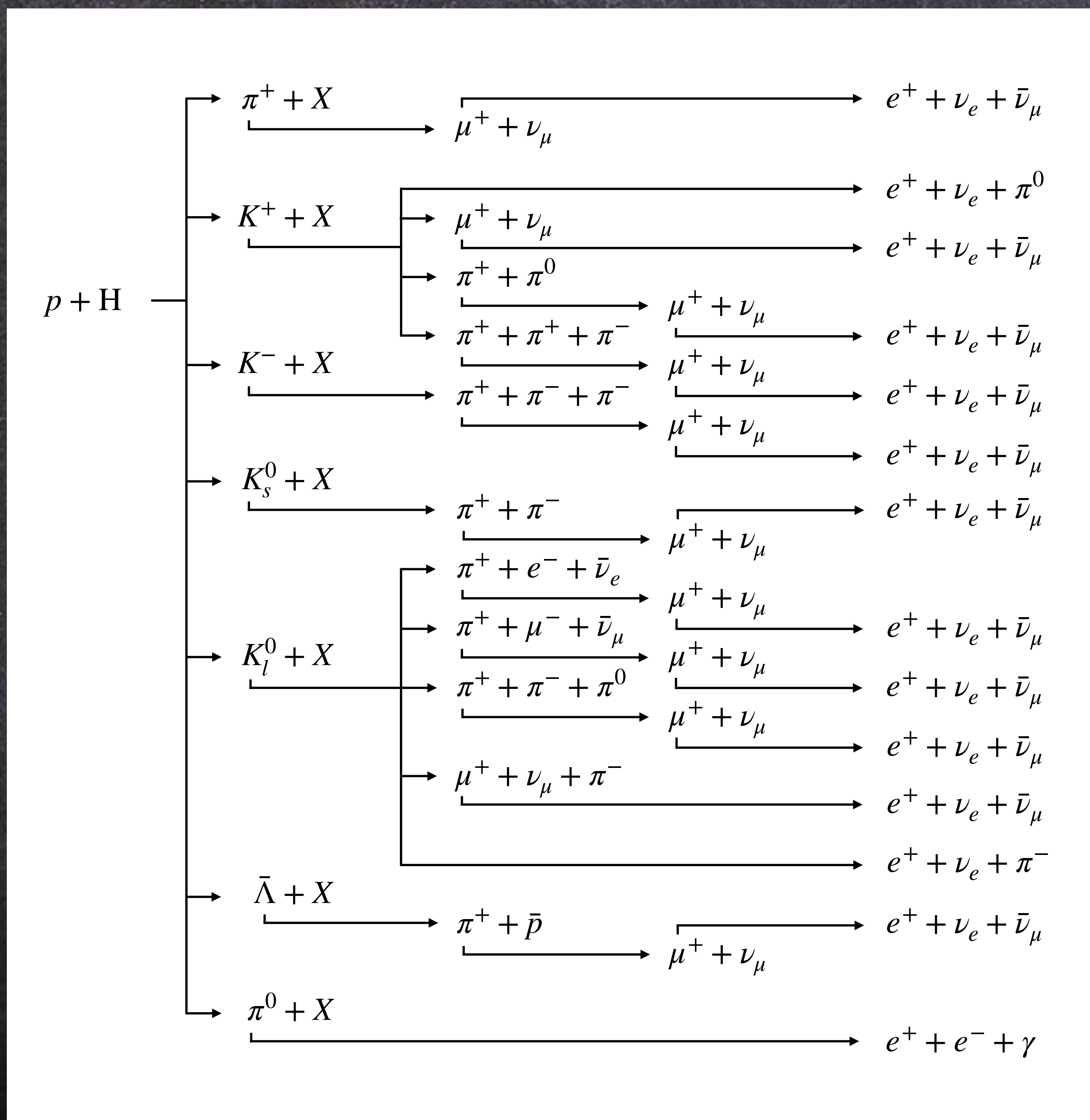
$n_{ISM}$: density of the interstellar medium

$\Phi_i(T_i)$: flux of incoming CR nucleus ($\sim T_i^{-2.7}$)

$d\sigma_{ij}/dT_e(T_i,T_e)$; e± production cross section in a ij collision, for a given CR (beam) energy

# e+ production channels

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



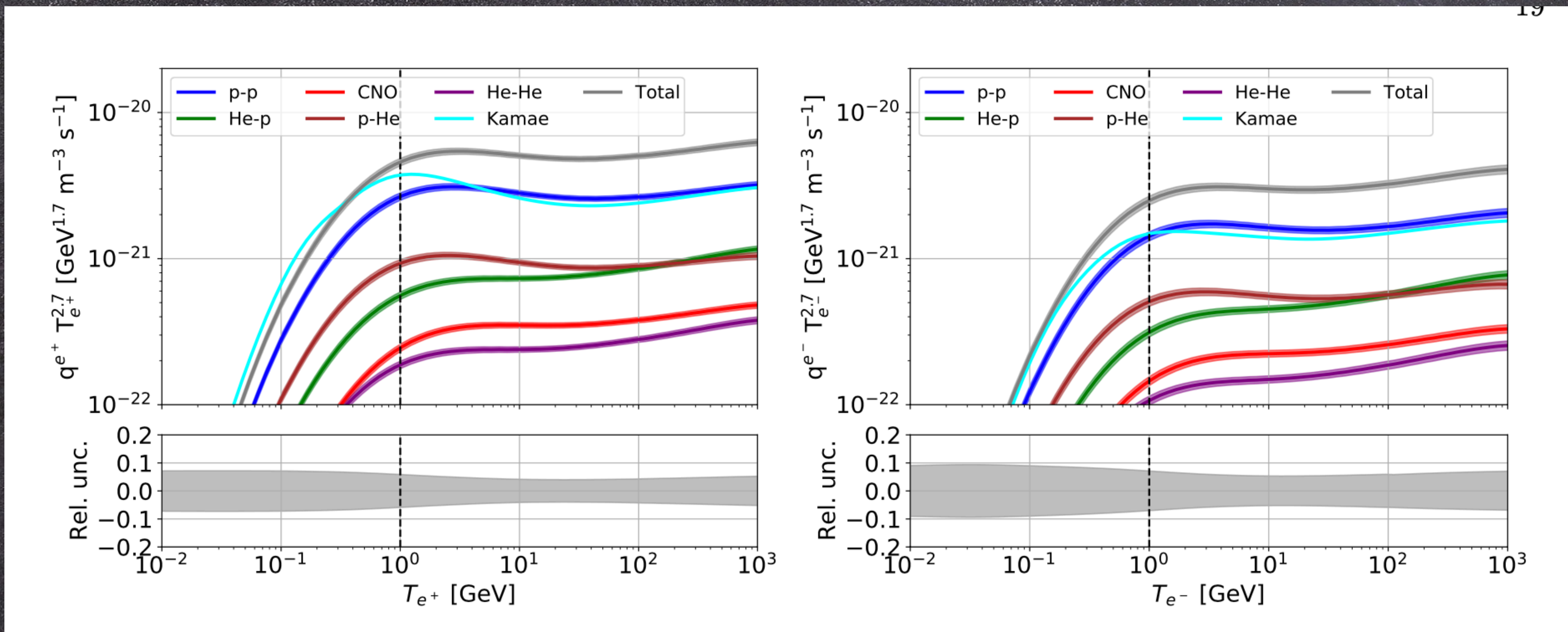

We include all these contributions.

Similarly for collisions with nuclei.

We repeat ALL the analysis for e- under charge conjugation

# Result on the e+ and e- source terms

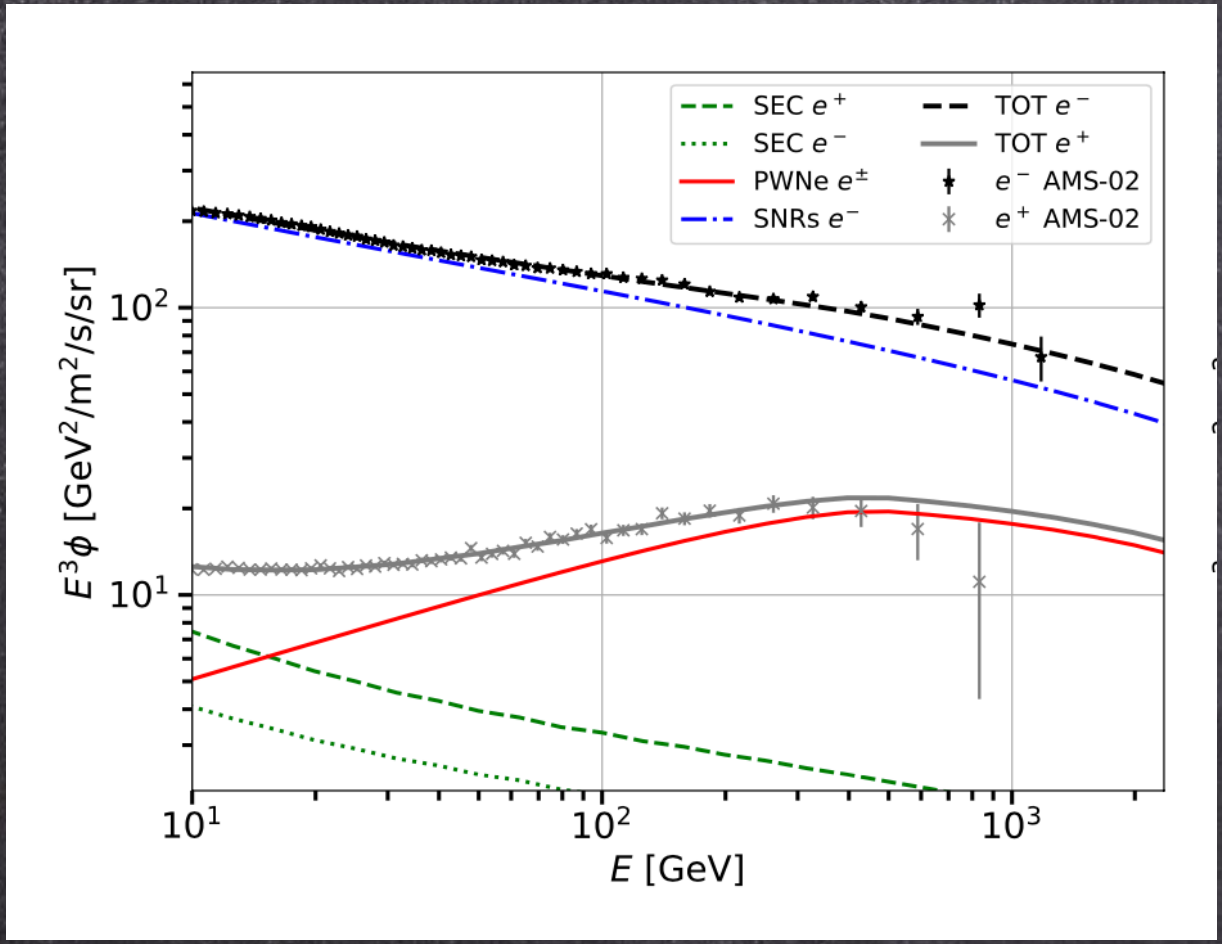
L. Orusa, M. Di Mauro, FD, M. Korsmeier PRD 2022




Secondary e± are now extremely well defined
Different room (from state of the art) is now left to e± from pulsars (or dark matter ...)

# The role of e± secondaries

M. Di Mauro, FD, S. Manconi PRD 2021



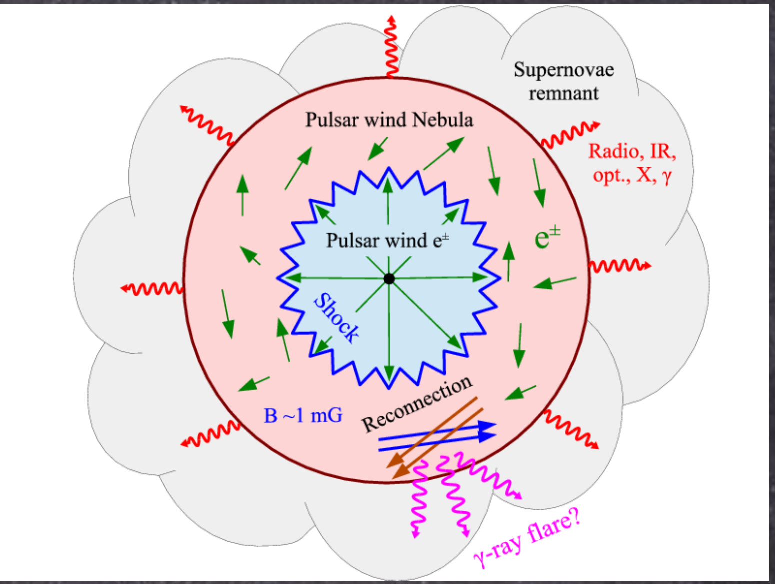

e+ secondaries contribute significantly to shape the spectrum at Earth.

The flux in the GeV region is likely dominated by secondaries

A PRIMARY component is surely there at high energies

# 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

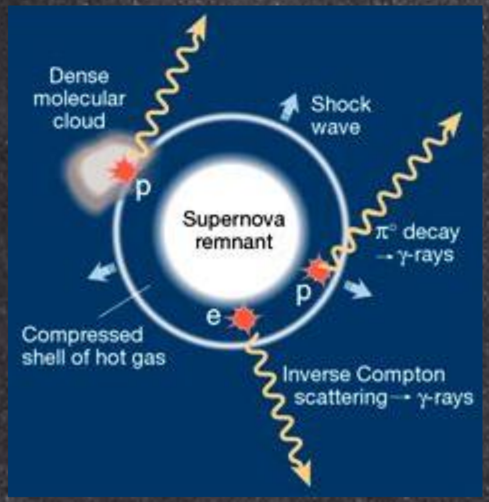
These e± pairs radiate by Inverse Compton scattering
and synchrotoron,
and shine at many frequencies

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

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

# Electrons from supernova remnants

Ellison+ ApJ 2007; Blasi 2013; Di Mauro+ JCAP 2014




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

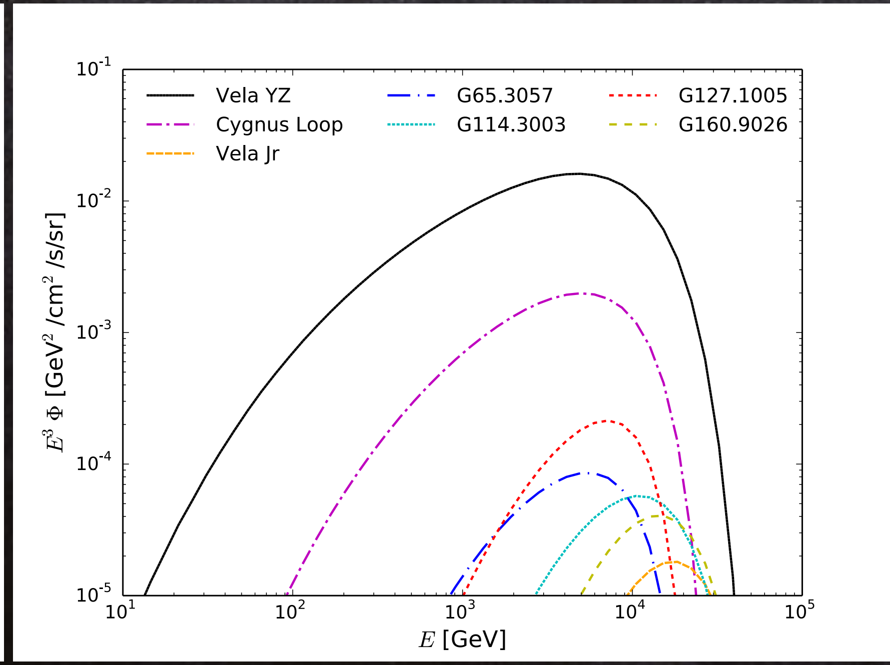
Hadronic acceleration: evidence of $\pi^0$ bump
(Fermi-LAT+ 2010)

Leptonic acceleration: evidence of synchrotron emission in radio and X-rays

Manconi, Di Mauro, FD JCAP2017; JCAP 2019

Injection spectrum:

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



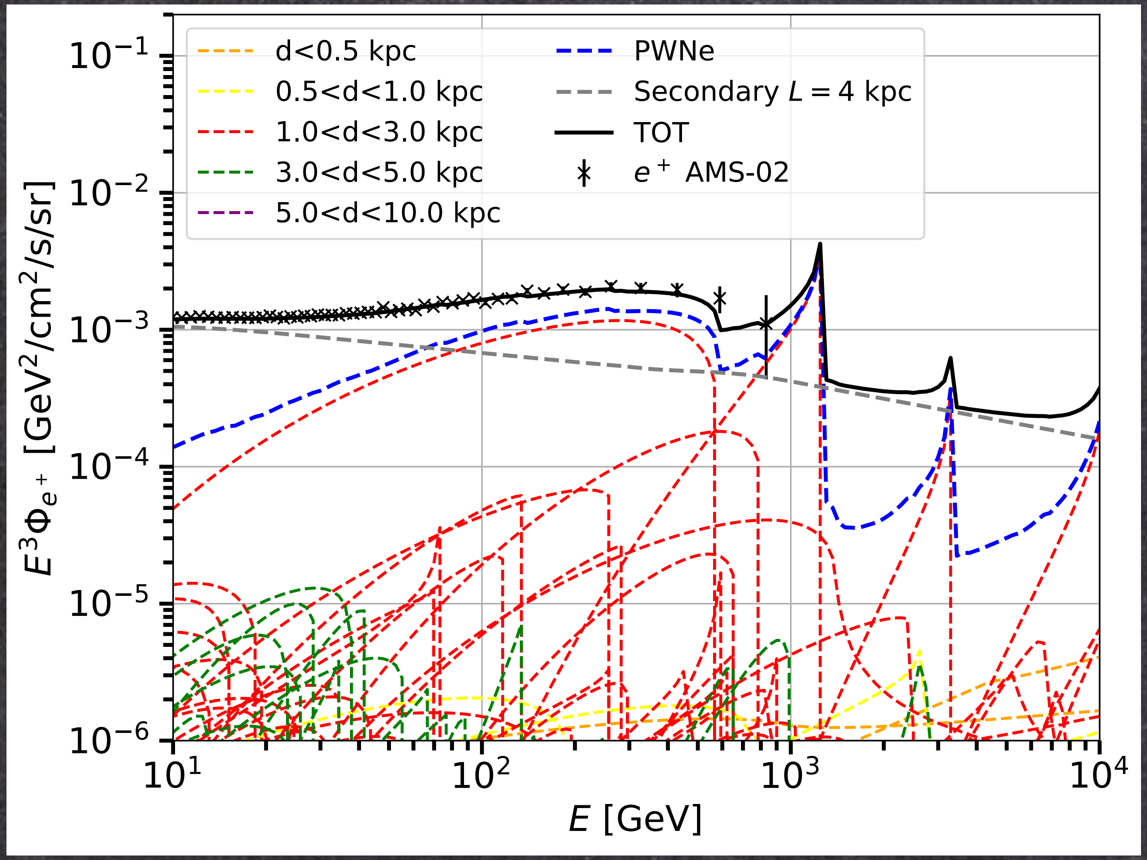

e- flux from near SNR (Vela XY and Cygnus Loop at d<0.5 kpc)

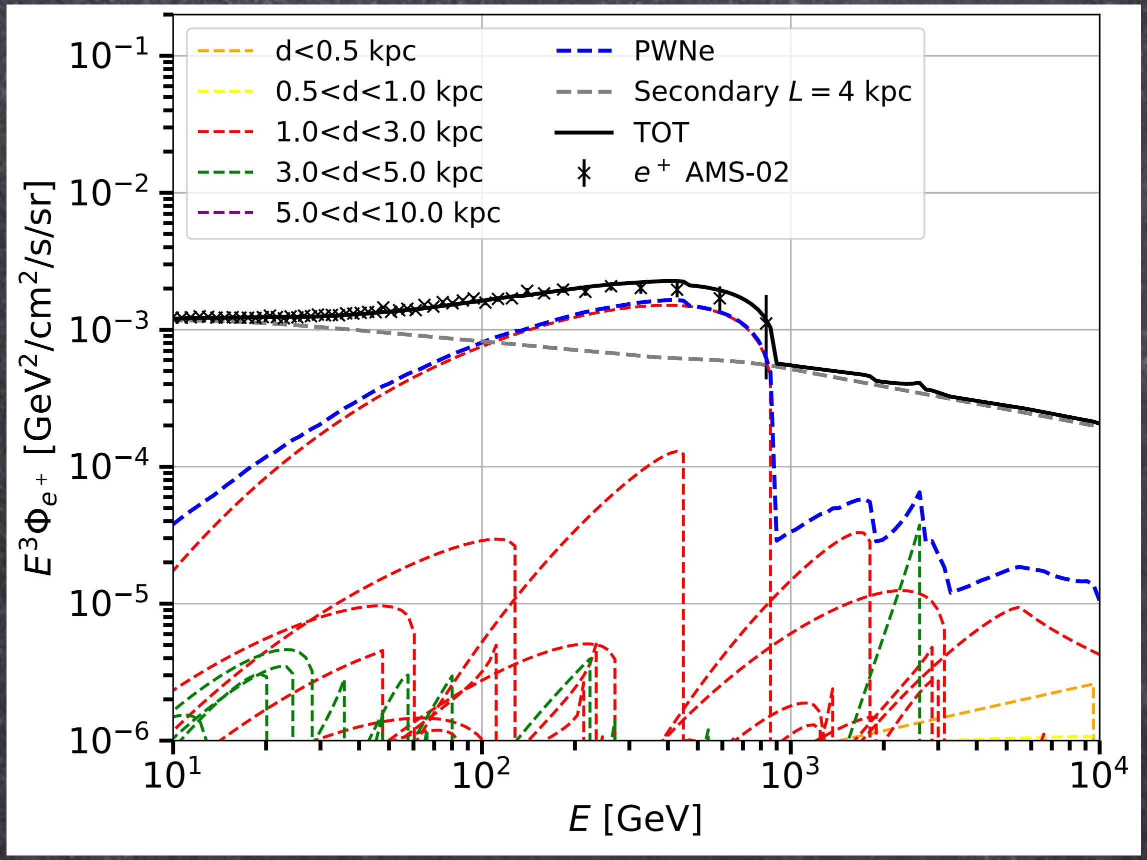
Few SNR can contribute to TeV flux

Additional e- from a smooth SNR distribution

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

Orusa, Di Mauro, FD, Manconi JCAP 2021



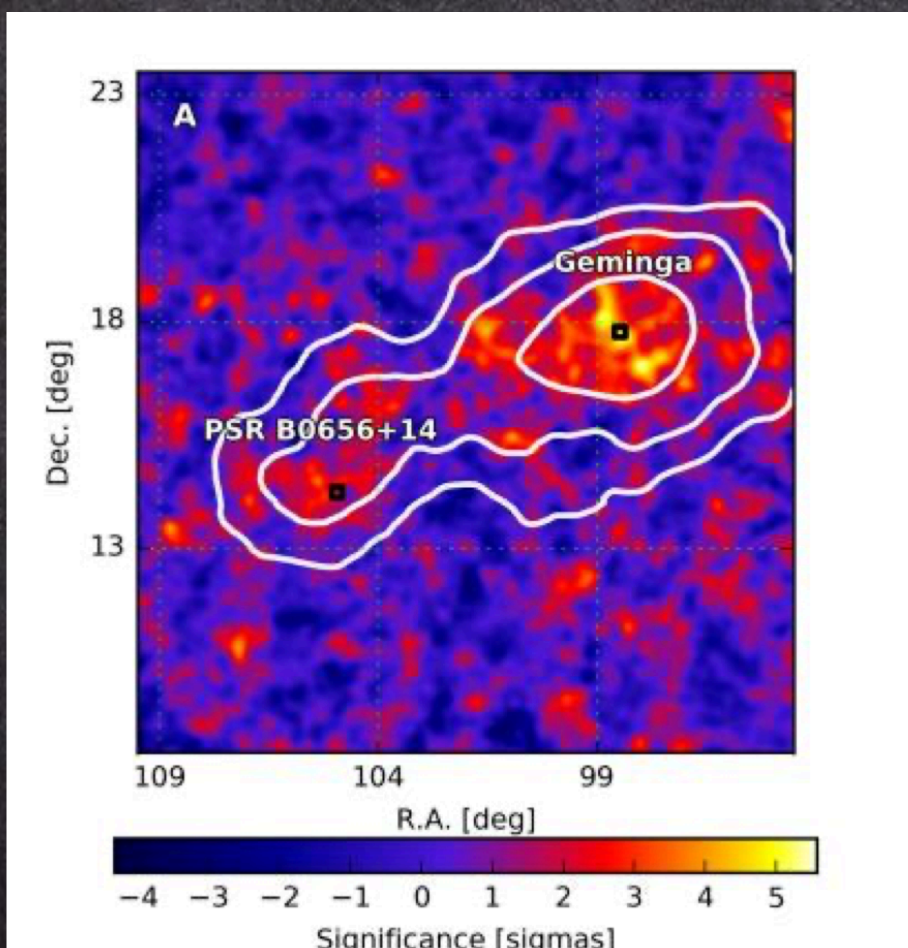




The contribution of pulsars to e+ is dominant above 100 GeV
and may have different features.
E>1 TeV: unconstrained by data.
Secondaries forbid evidence of sharp cut-off.

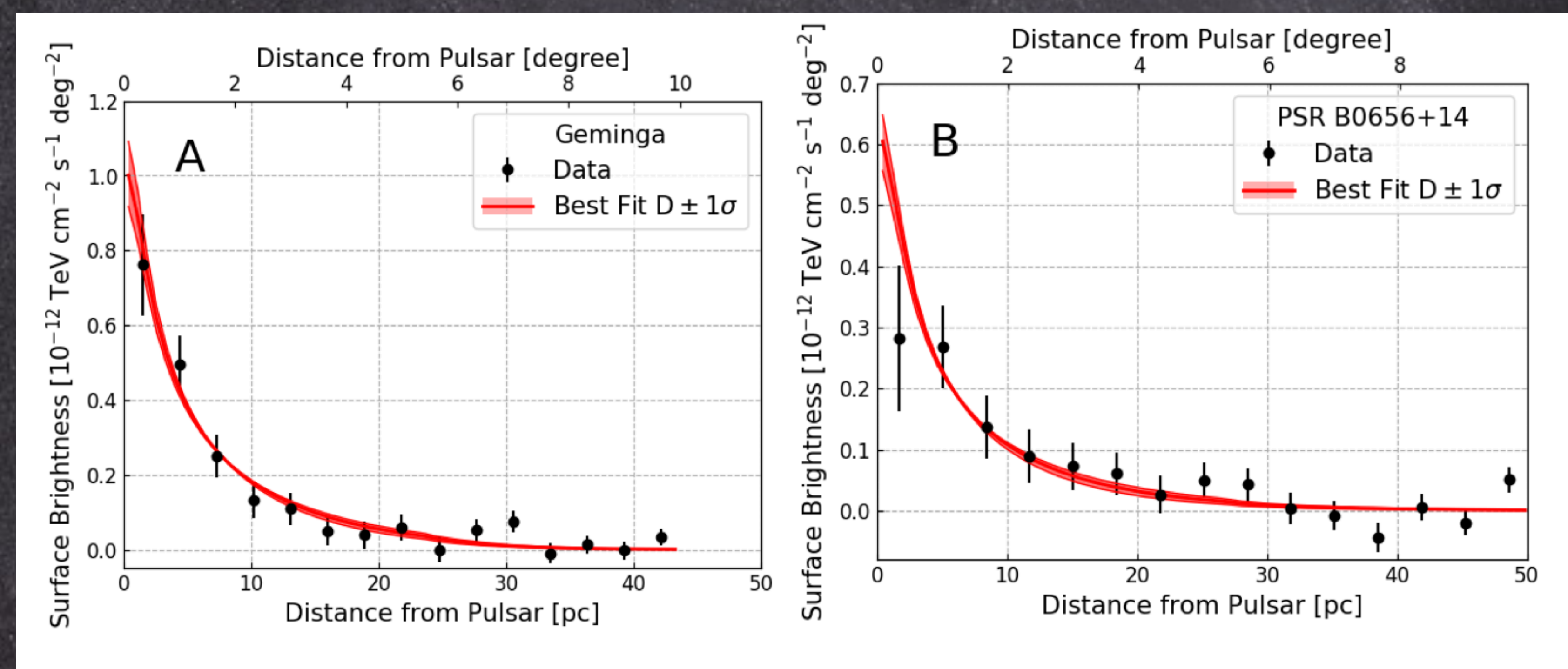
**No need for Dark Matter, indeed**

# Detections of $\gamma$-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

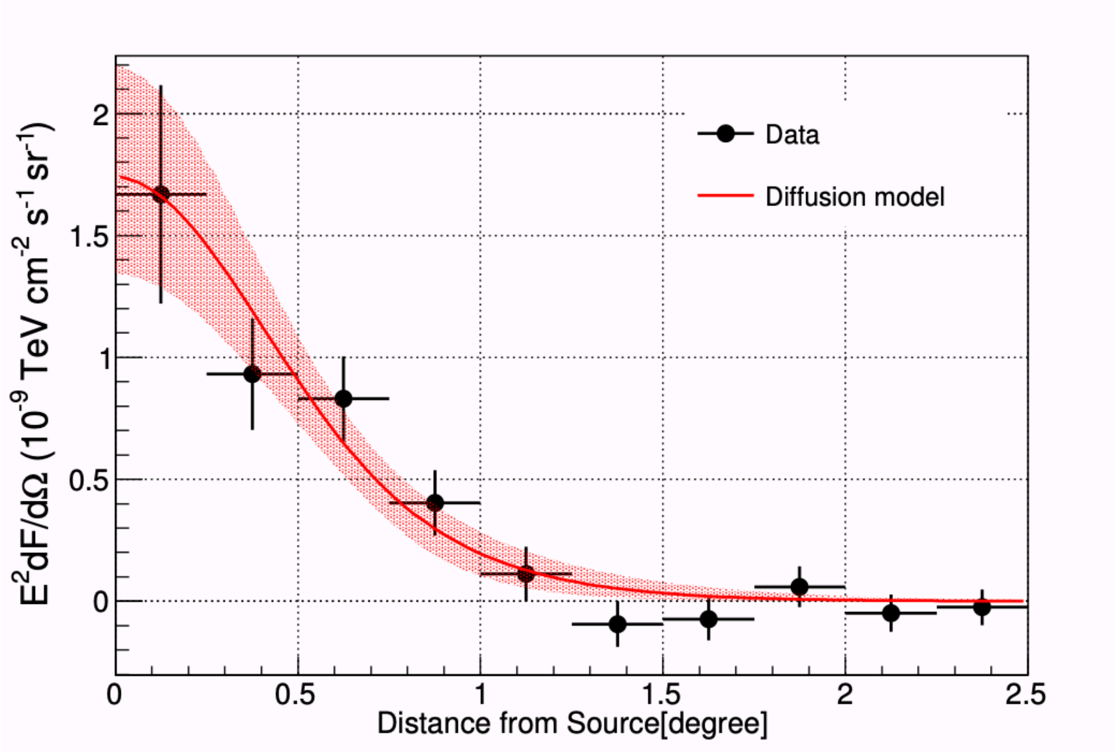
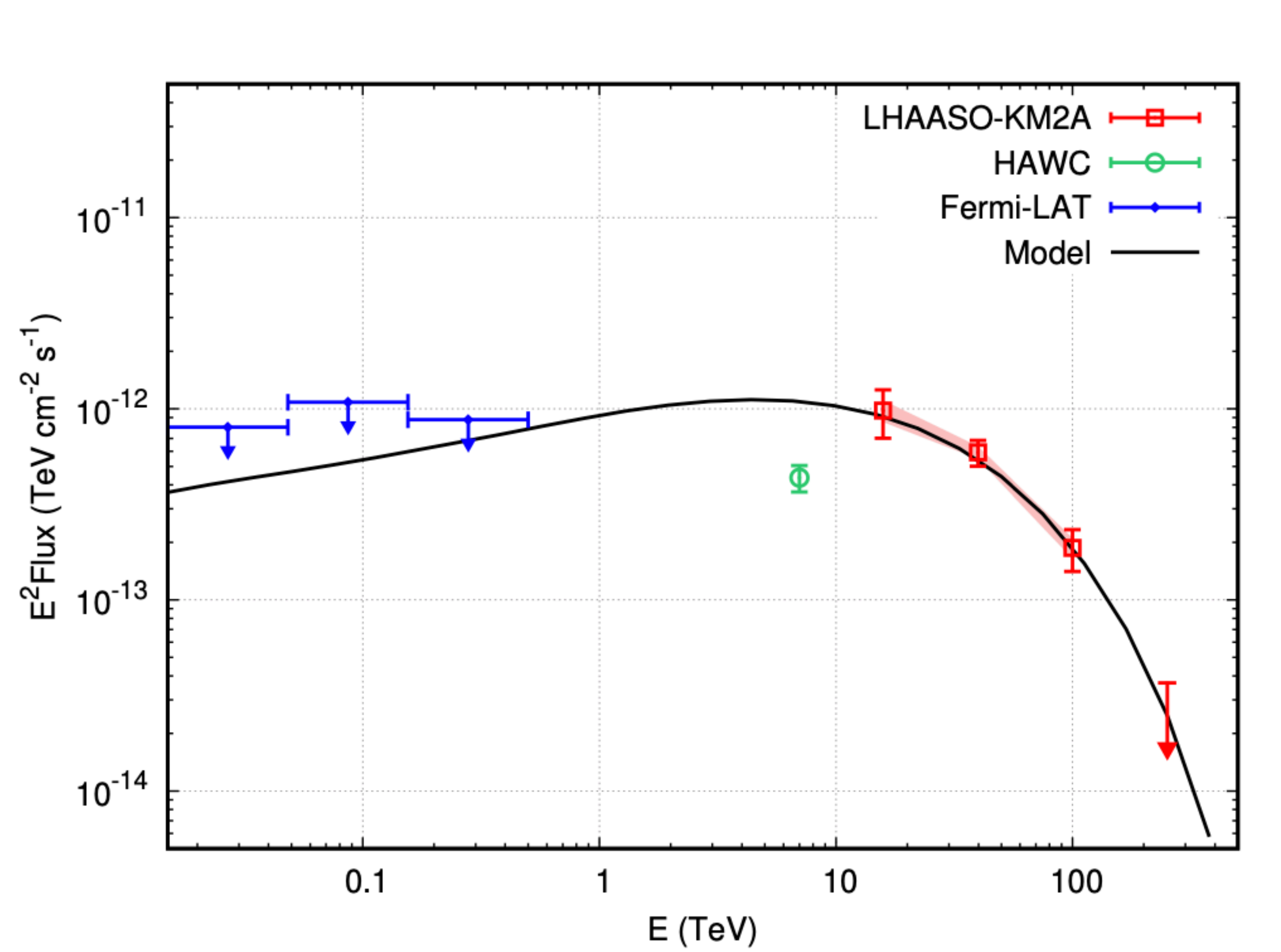



FIG. 2. One-dimensional distribution of the > 25 TeV $\gamma$-ray emission of LHAASO J0621+3755. The solid line and shaded band show the best fit and $\Delta\chi^2 = 2.3$ range of the diffusion model fit, which is the convolution of Eq. (1) with the PSF.

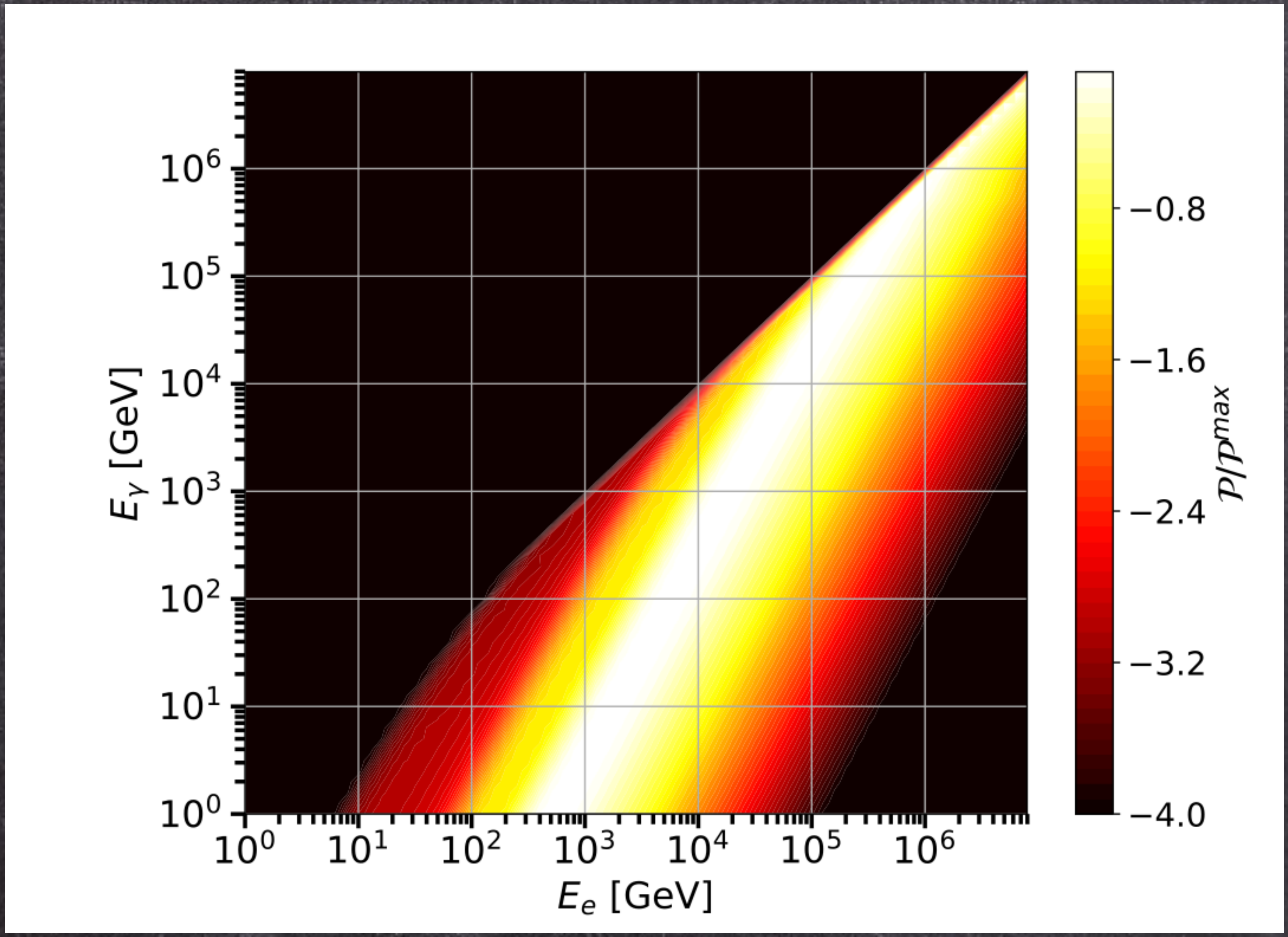



Extremely high energy γ-rays are observed around the pulsar as an extended halo. A spectrum is measured.

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

# Inverse Compton scattering power

M. Di Mauro, S. Manconi, M. Negro, FD, PRD 2021



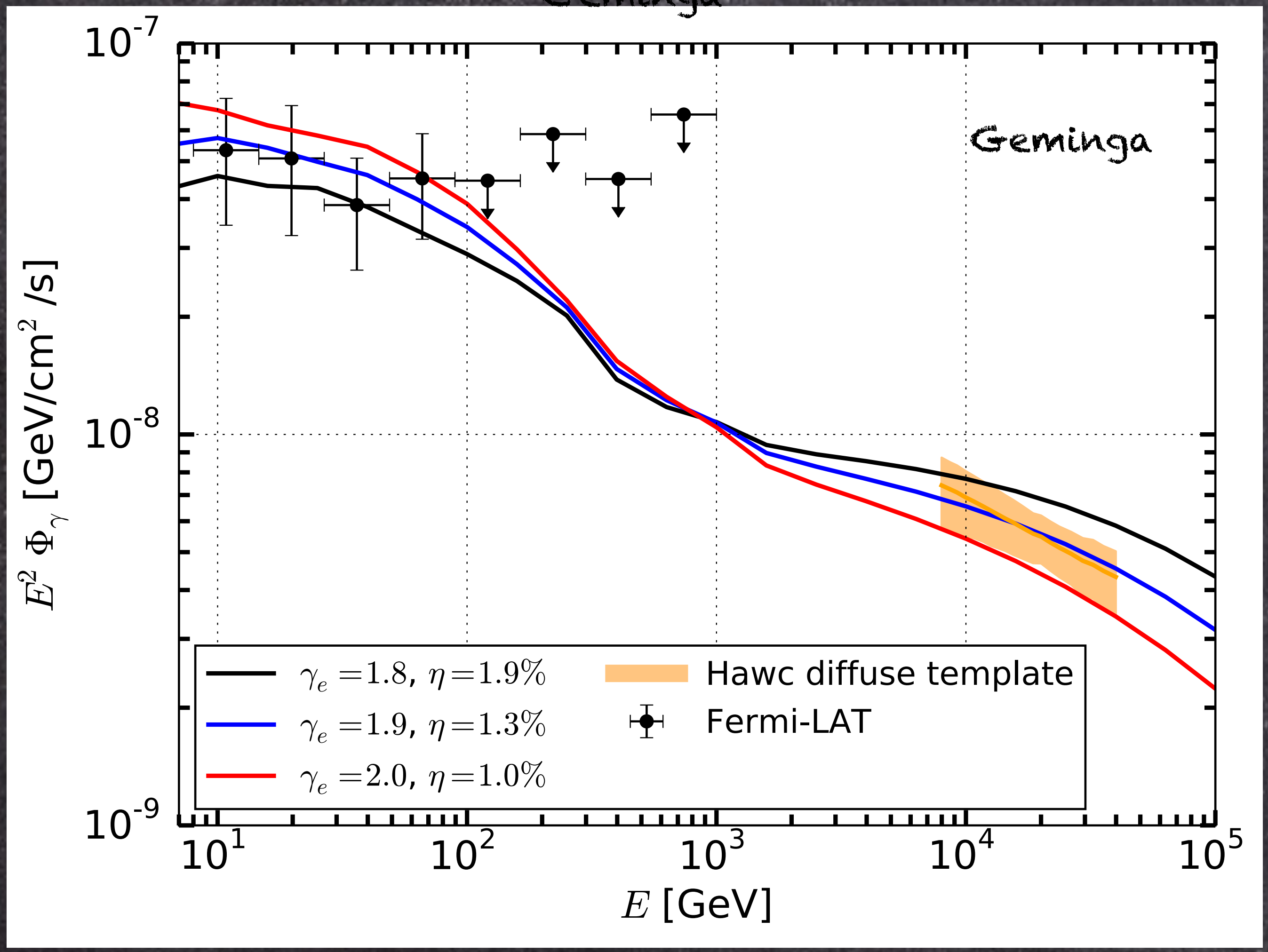

The γ-rays are 5-60 times less energetic than parent leptons
HAWC γ-rays probe electrons with 100-1000 TeV

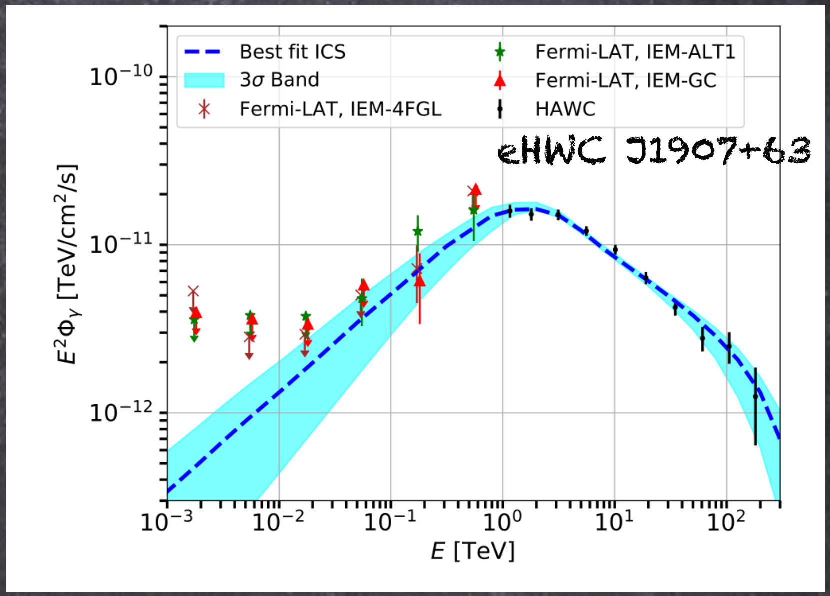
# Discovers of γ-ray halos in Fermi-LAT data

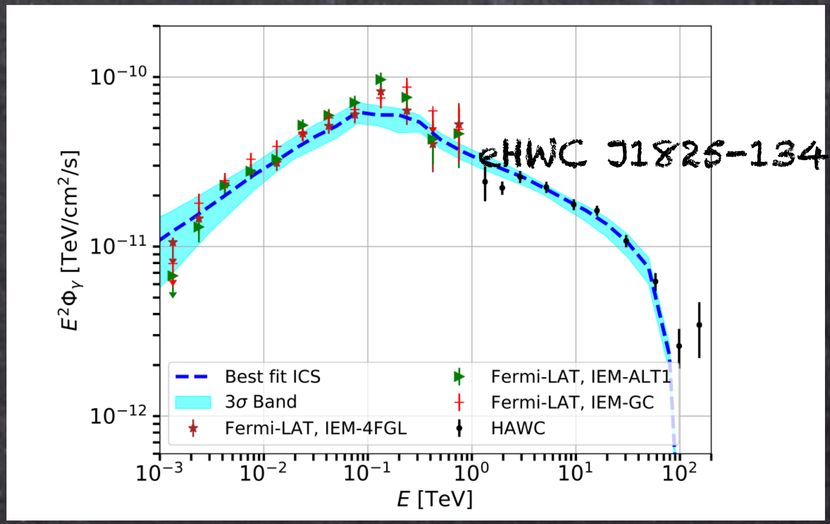
M. Di Mauro, S. Manconi, FD, PRD 2019

M. Di Mauro, S. Manconi, M. Negro, FD, PRD 2021

Geminga




Interpreted as γ-rays from Inverse Compton scattering
e± are produced in and around pulsars

# Final remarks

Precise data from space have triggered an impressive amount of research in several different fields regarding the production and the propagation of Galactic cosmic rays

Data cannot be interpreted without the nuclear component

Possible contributions from dark matter annihilation can be hidden in the data - spectral discrimination if often difficult - propagation spreads different source spectra

Strong expectations for anti-deuterons

The $\gamma$-ray observation of haloes around pulsars is the new frontier for the understanding of leptonic sources in the Galaxy