Dark sector physics:

candidates and searches

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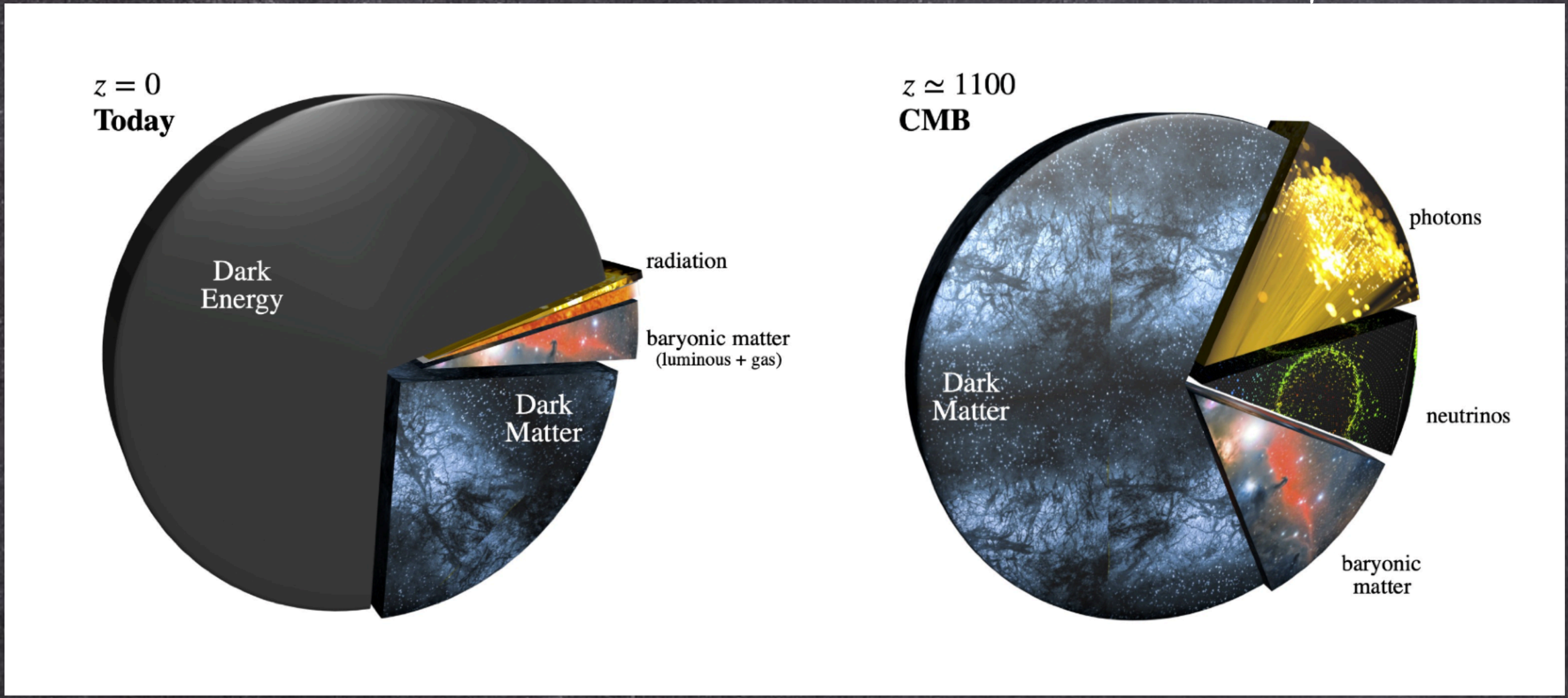
Dark matter in the Universe

DM is there, gravitationally

Cirelli, Strumia, Zupan 2406.01705



Content of the Universe today (left)
and at the time of photon decoupling (right)

Properties of DM particles

- Must be cold (hot DM fraction very small)
- Electric charge null (or very small)
- Cross section smaller than a typical weak cross section
- The cross section between 2 DM particles smaller than typical QCD (collisisonless)
- Stable on lifetime of the Universe
- If femrion, m>~ keV. If bosonic, also much lighter

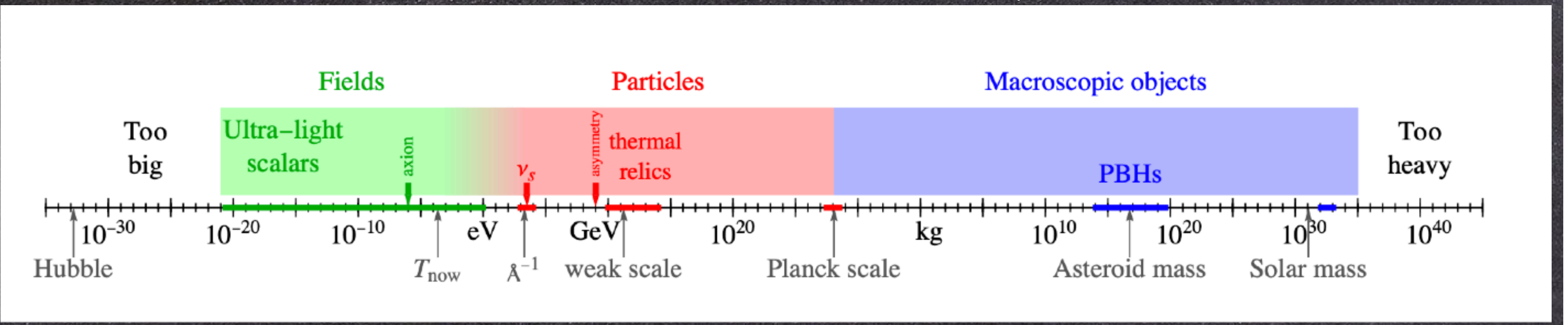
A plethora of candidates, and BSM theories

WIMP (weakly interacting massive particle), milli-charged, warm DM,
Ultra-light fuzzy (m~ 10-21 eV), WISP (weakly interacting slim particle) DM, …..

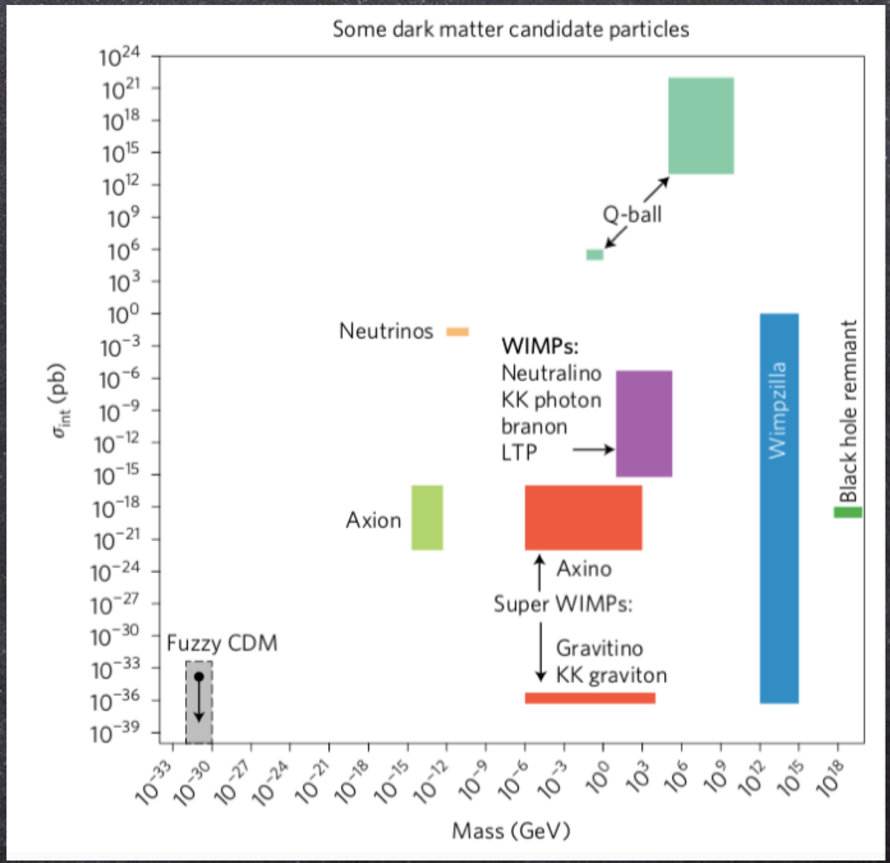
Particle DM candidates

All known properties of DM are derived from gravitational interaction, which is very weak. Properties of a DM particle requires stronger-than-gravitational interactions

Cirelli, Strumia, Zupan 2406.01705



Conrad&Reimer, Nature Phys. 2017



Possible range for Dark Matter particles, and some notable candidates.
A mass spectrum spanning almost 80 orders of magnitude

SIGNALS from RELIC WIMP DM particles

Direct searches (deeply underground experiments)

elastic scattering of a WIMP off detector nuclei

Measure of the recoil energy

Annual modulation and directionality of the rate

Indirect searches in Cosmic Rays (mostly space based experiments)

signals due to annihilation of accumulated $\chi\chi$ in the of Sun/Earth (neutrinos)

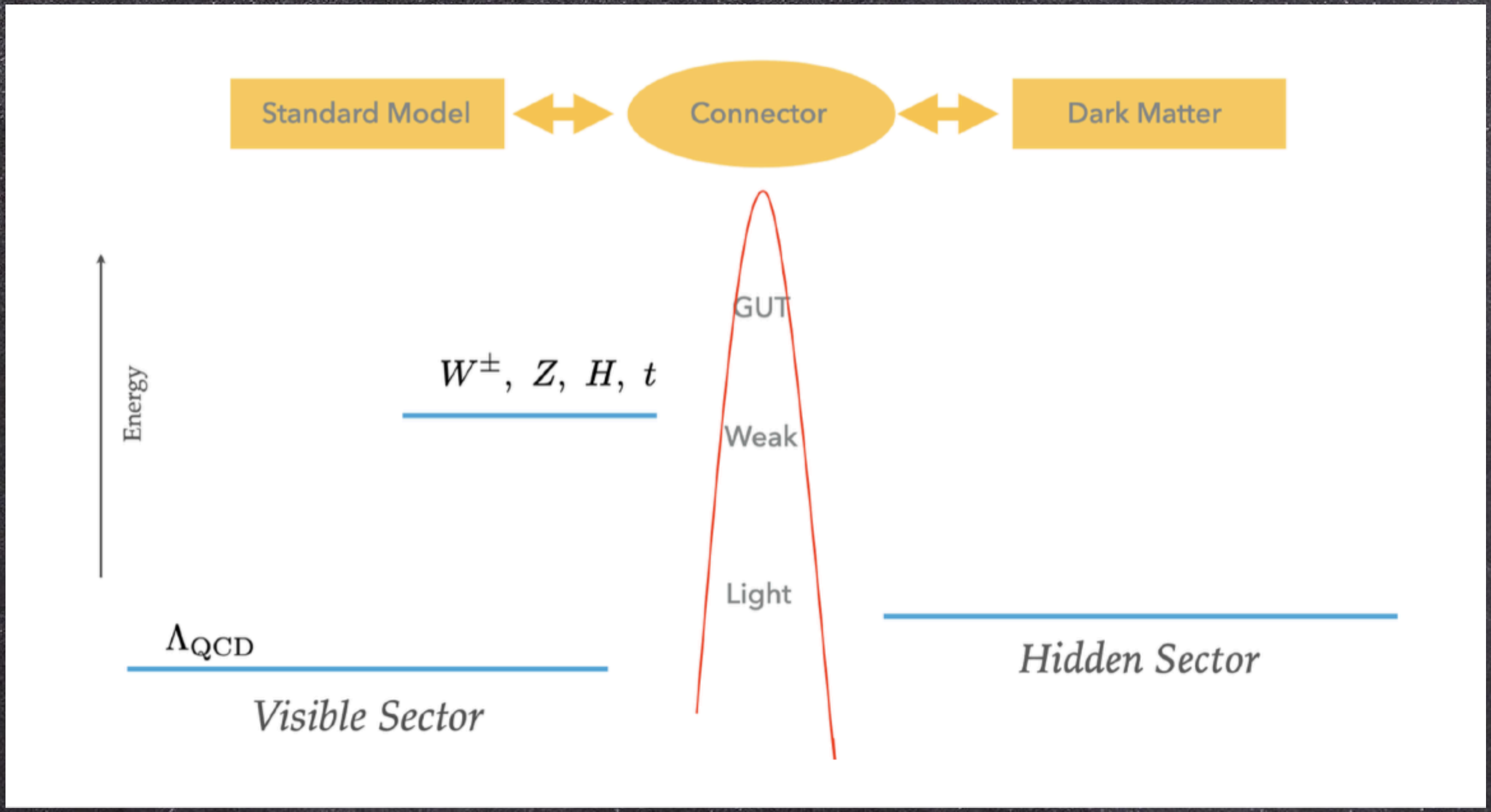
signals due to $\chi\chi$ annihilation in the galactic halo (antimatter, gamma-rays)

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

Light DM (below ~ 10 GeV)

Relic abundance still generated by thermal freeze-out
Requires new interaction beyond weak interaction

See Zurek 2401.03025



Boehm+ 2004,
Pospelov+ 2008,
Feng+2008

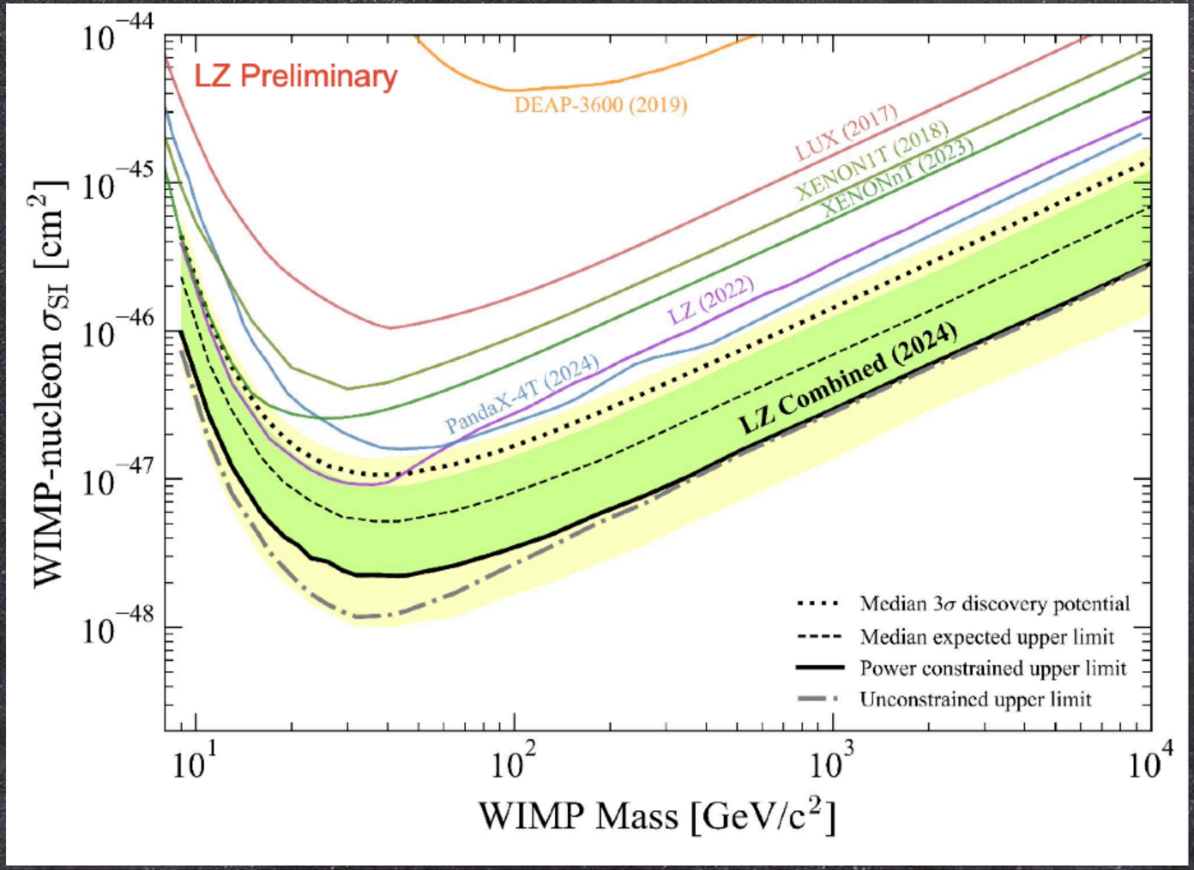
Hidden sectors (QCD-like, QED-like remnant of Susy,...)
Hidden portals (vector, scalar (via Huggs) portals...)

Direct detection of DM

Relies on the hypothesis that the DM particle interacts weakly with nuclei

Experiments conducted deep underground, shielding cosmic rays.
Free neutrons can mimic a DM event

S. Haselschwardt for LZ Coll. at TeVPA2024



WIMP DM has an interaction, if any, comparable to the neutrino one

The neutrino floor in direct detection

DM direct detection experiments are now reaching a sensitivity of $\sigma \sim 10^{-40}$ cm², very weak interaction at the level of Coherent elastic neutrino-nucleus scattering (CEνNS)

Solar ^{8}B neutrinos (8-15 MeV) are predicted to contribute significantly to CEνNS in underground DM detectors, albeit at keV energies

First scatterings measured by XENONnT (Aprile+, 2408.02877)

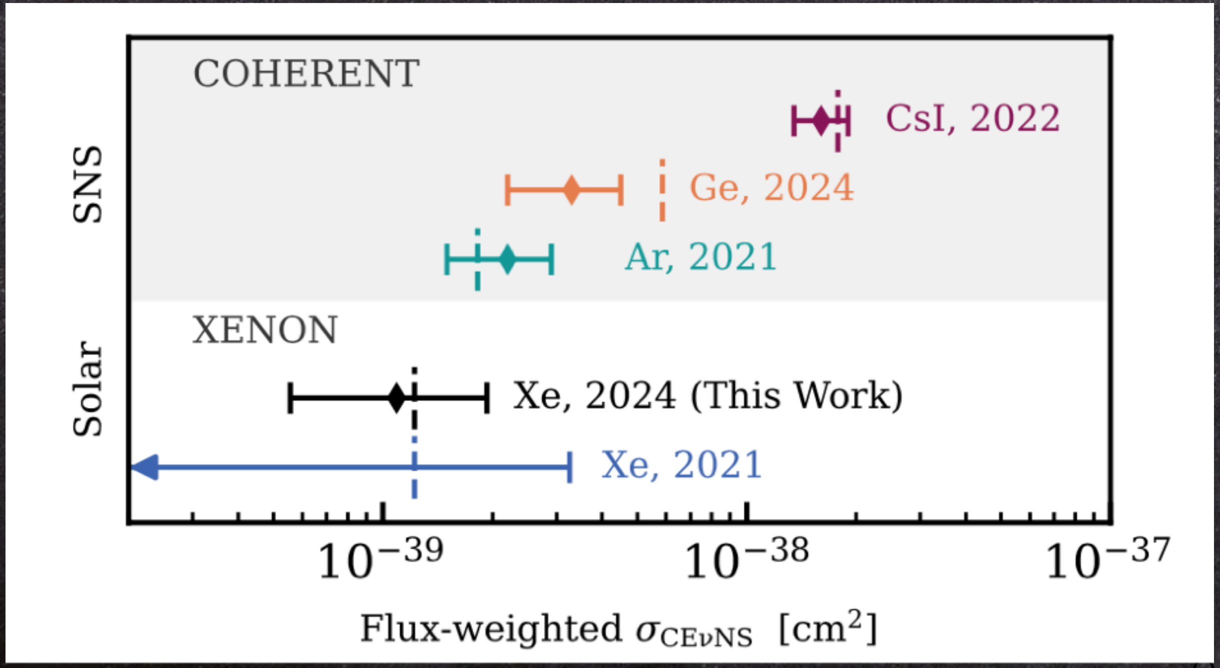
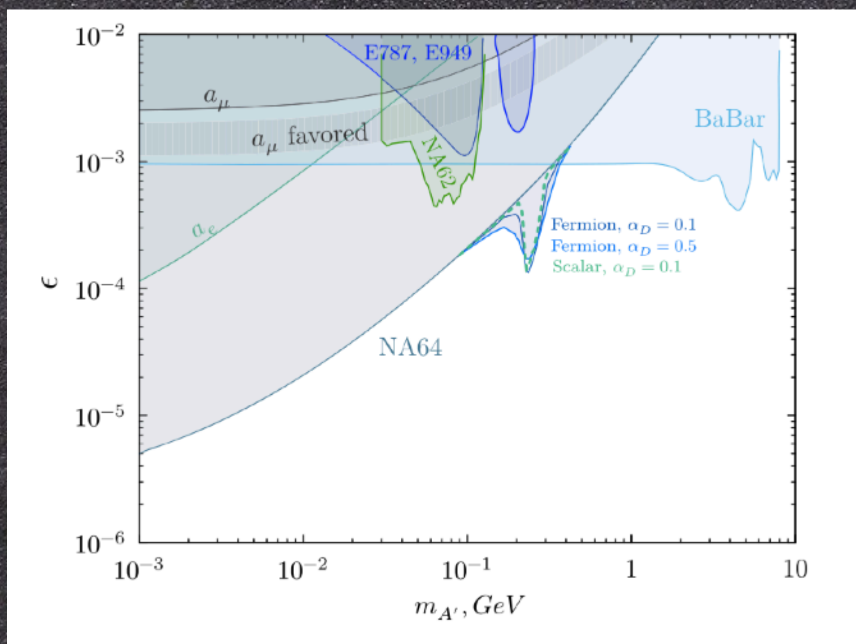


FIG. 4. Measurements of the flux-weighted CEνNS cross-section $\sigma_{\mathrm{CE}\nu\mathrm{NS}}$. The measurement using Xe nuclei solar ^{8}B neutrinos from this work is shown in black. The 90% CL upper limit from XENON1T [6] is shown in blue. The measurements with neutrinos from the SNS by the COHERENT collaboration using CsI [42] (red), Ar [4] (green) and Ge [43] (orange) nuclei are also shown. For comparison, the SM predictions are shown by vertical dashed lines, assuming the nuclear form factors from [44].

Light DM searches

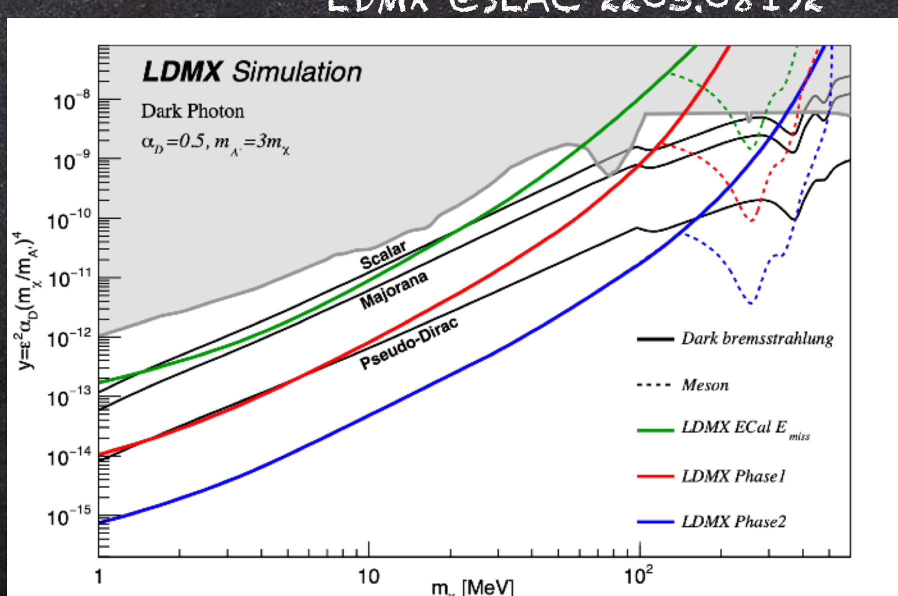
See talks by S. Stengel (MESA), M. Bondi (BDX)

NA64 PRL131, 2023



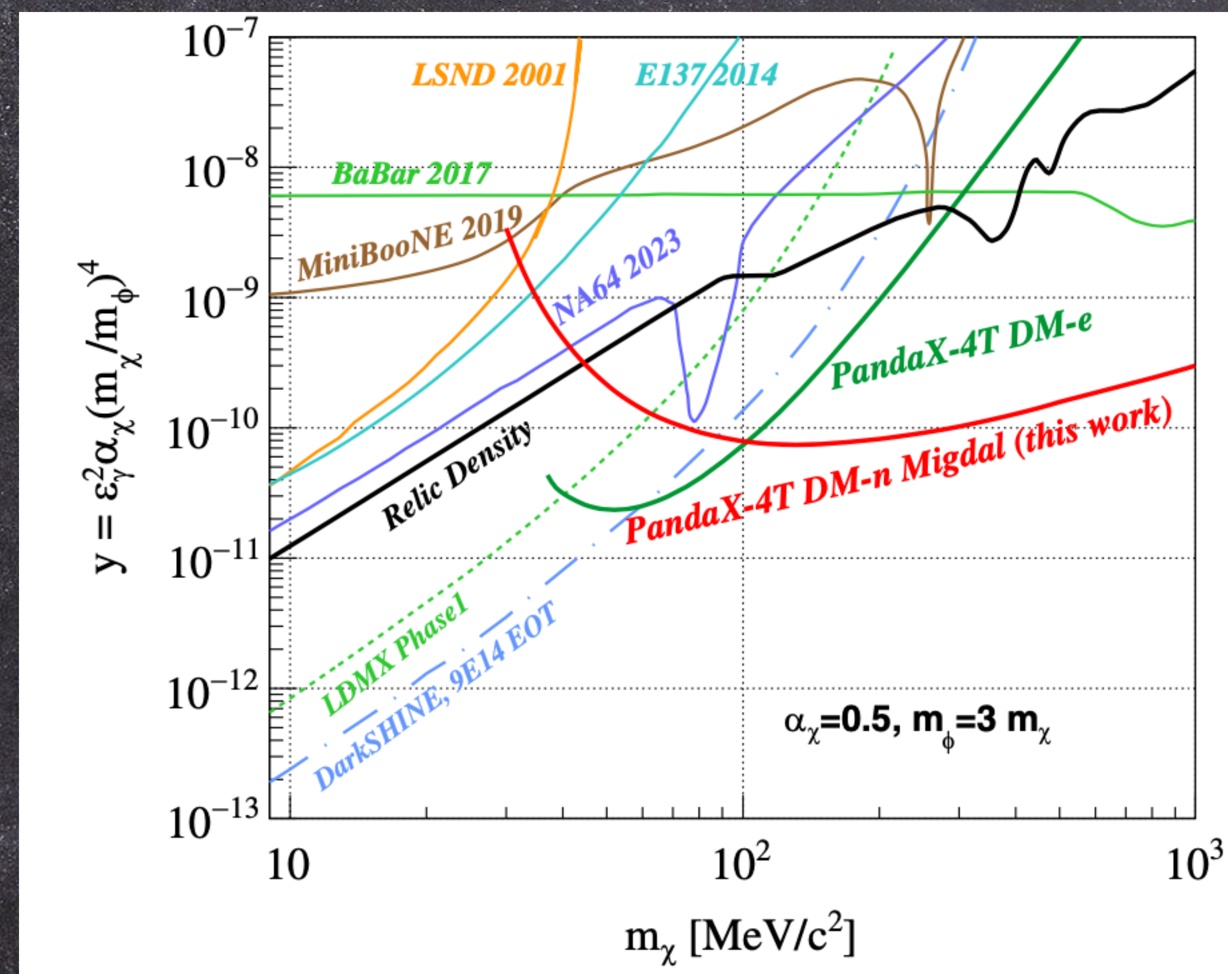
NA64 bounds on dark photon A'

LDMX @SLAC 2203.08192



Projected sensitivity

PandaX-4T Coll. PRL 131(2023)

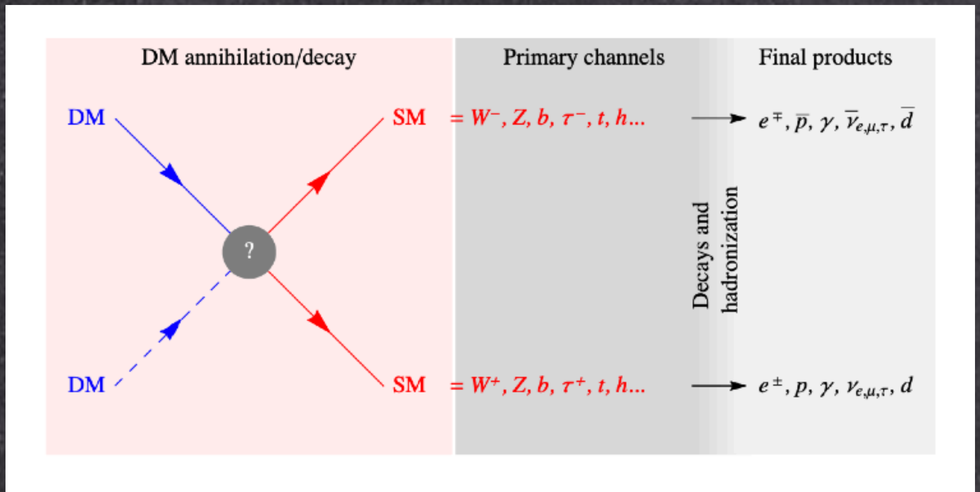


Bounds on dark mediator, using Migdal effect

Indirect Dark Matter detection

Annihilation or decay:

γ-rays (diffuse, monochromatic line), X-rays and radio, neutrinos, antimatter, searched as RARE COMPONENTS in cosmic rays (CRs): antiprotons, positrons, antideuterons, antihelium



ν and γ keep directionality

Charged particles diffuse in the galactic halo

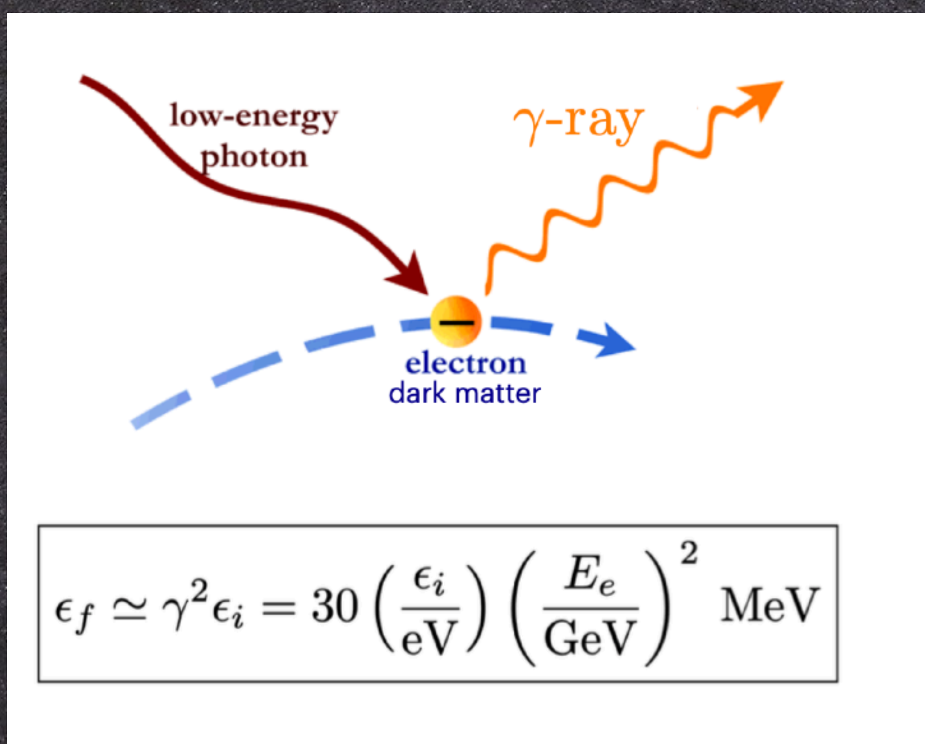
ASTROPHYSICS OF COSMIC RAYS

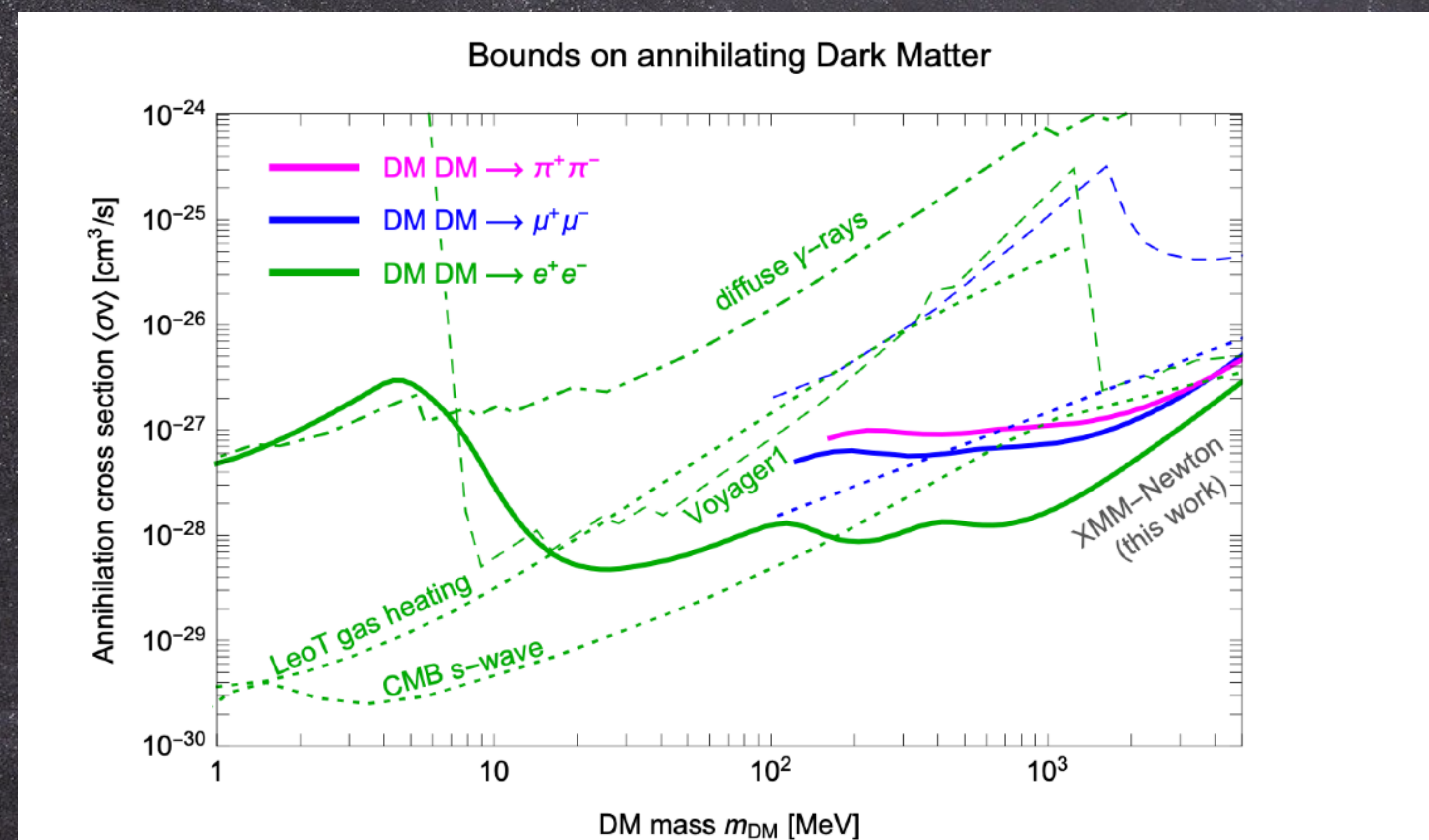
Indirect detections bounds on light DM

X-rays produced via inverse Comptons scattering (ICS)
of e± off the interstellar light

Cirelli, Fornengo+JCAP 2023

ICS



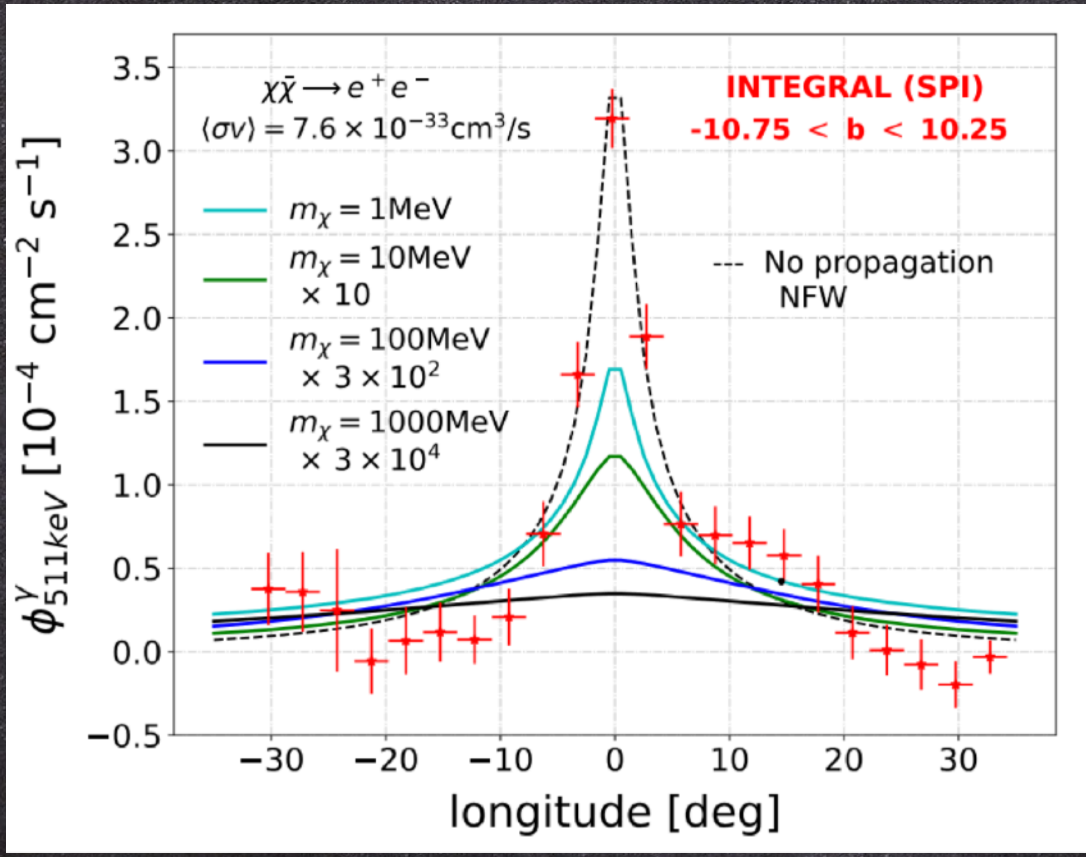


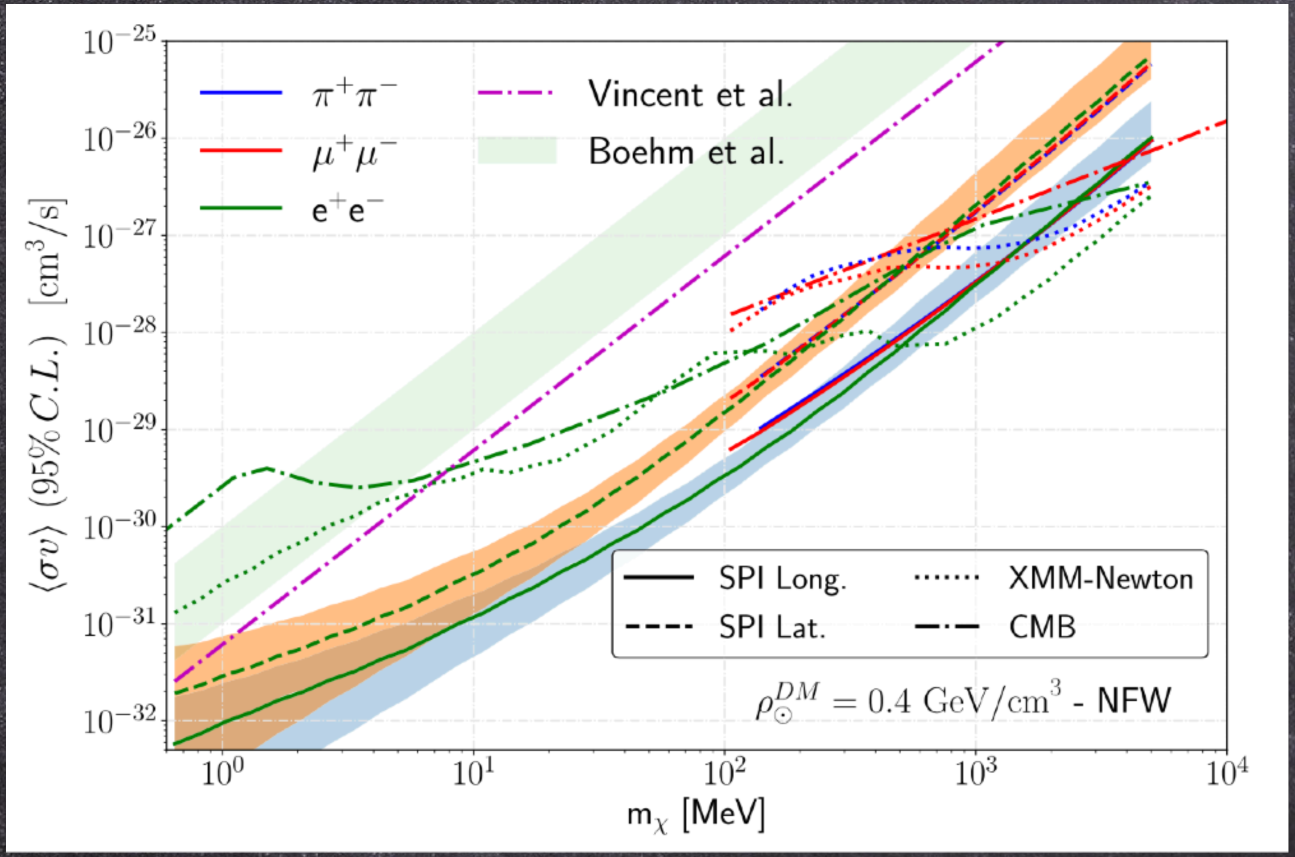
Strong bounds from XMM-Newton X-ray data interpreted as
ICS photons from e- coming from DM annihilation

Bounds from 511 keV line

The 511 keV γ-ray line from the Galactic bulge indicates e+e- annihilation into γγ via positronium in the interstellar medium.
Data from INTEGRAL-SPI.
These X-rays could also come from DM annihilation

P. De La Torre +, ApJL 2024





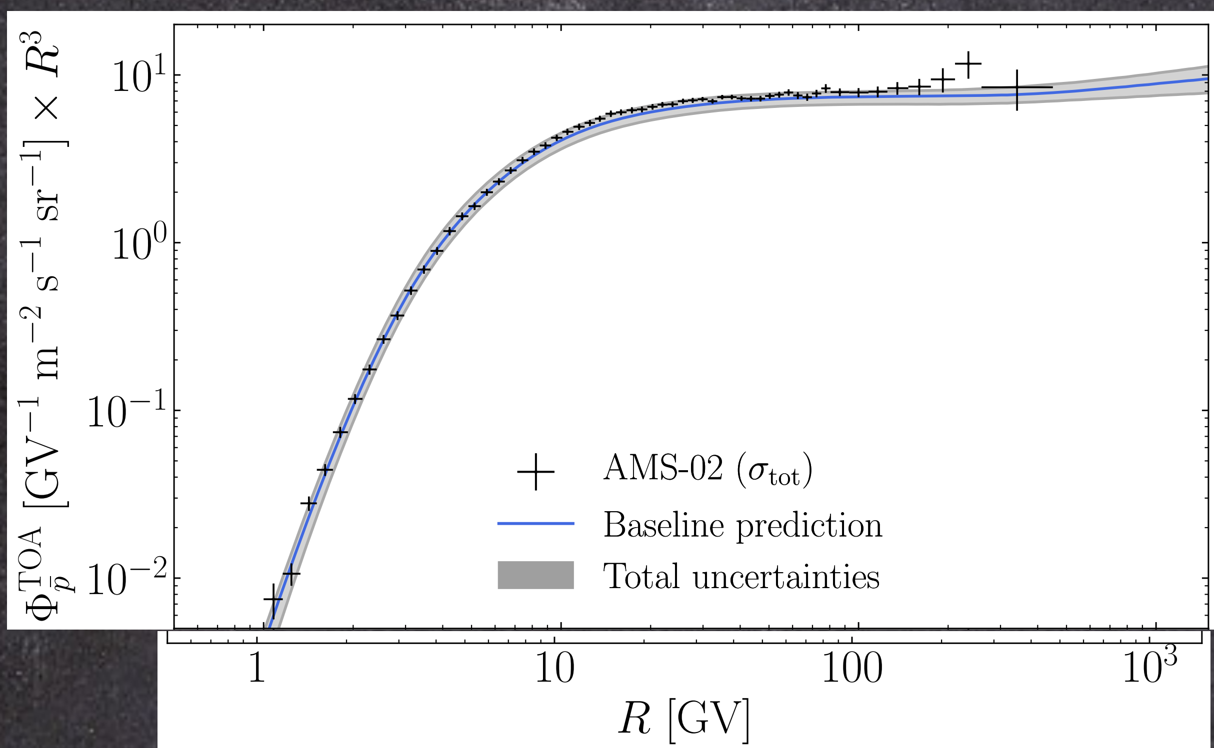
(See also Cirelli+ PRD 2021)

Strong bounds on DM explanation are set, mainly by INTEGRAL longitude profile

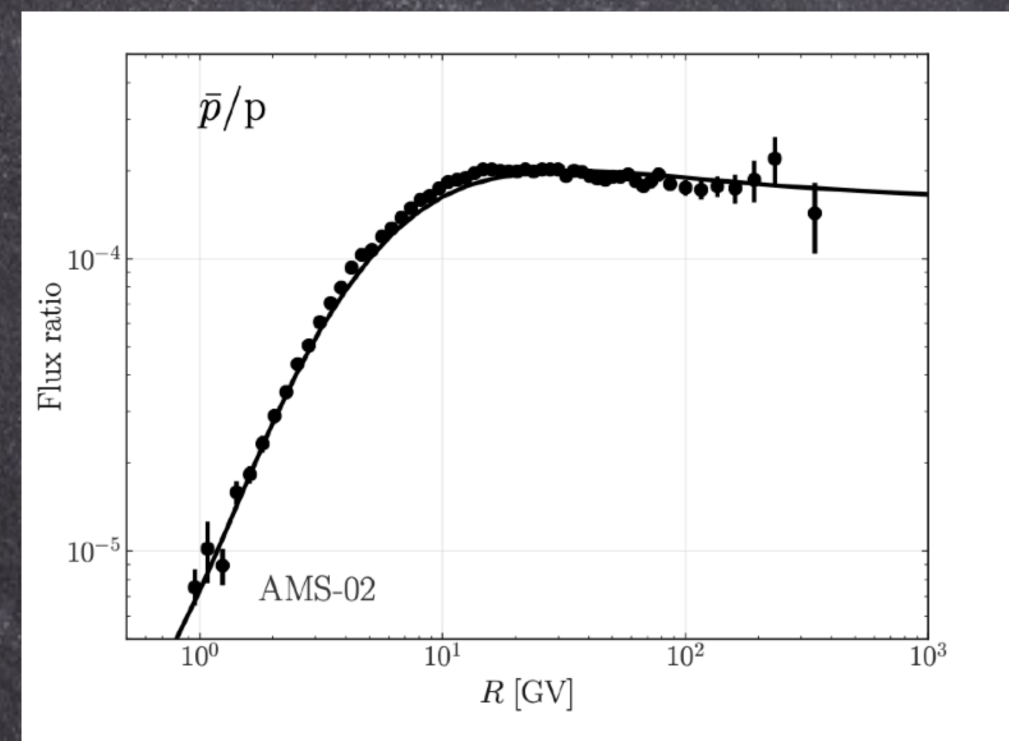
Antiprotons in CRs

Secondary CRs: via spallations of CRs on the interstellar medium

M. Boudaud+ PRD 2020



Di Mauro, Korsmeier, Cuoco PRD 2024



- 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

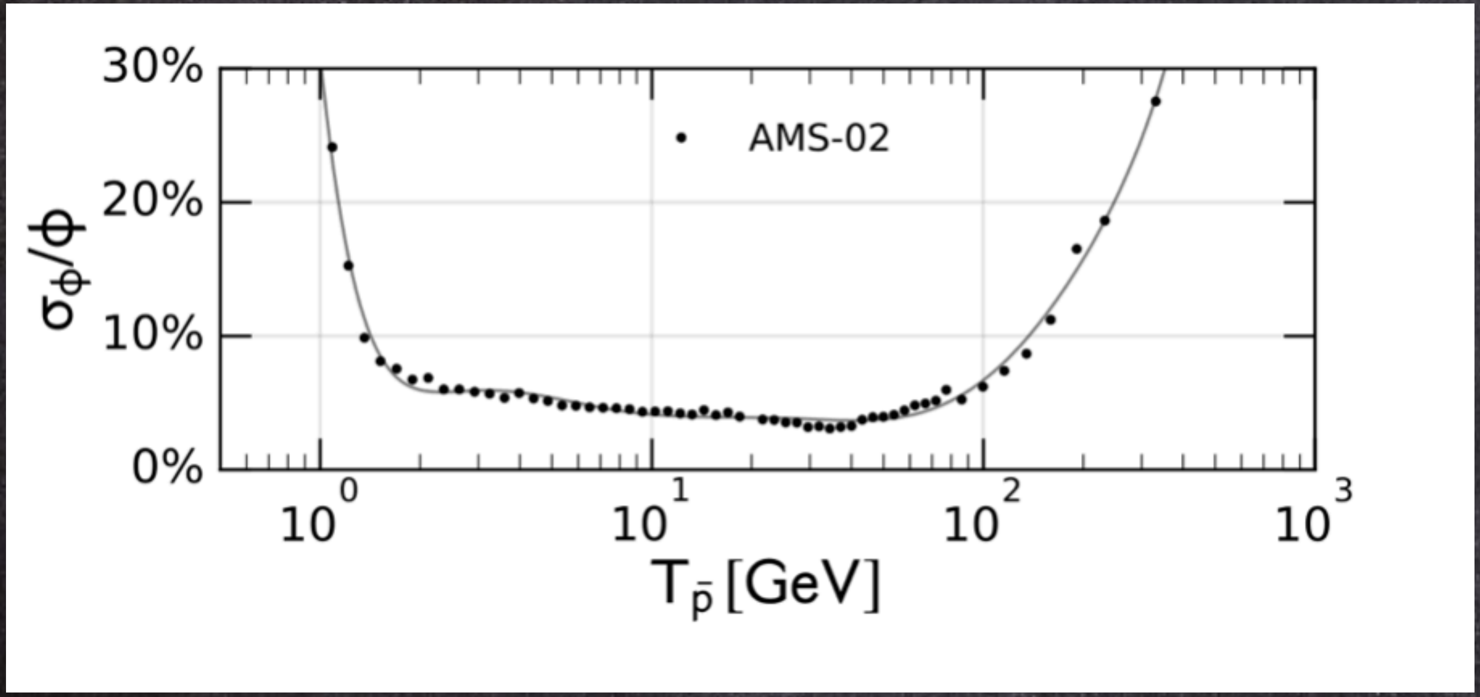
See also Feng, Tomassetti, Oliva 2016; Korsmeier, FD, Di Mauro PRD 2018, Reinert&Winkler JCAP2018; De La Torre Luque+ JCAP2024

Antiproton production by inelastic scatterings

Korsmeier, FD, Di Mauro PRD 2018

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

Data from space are very precis(AMS02)



We need cross sections at <3%

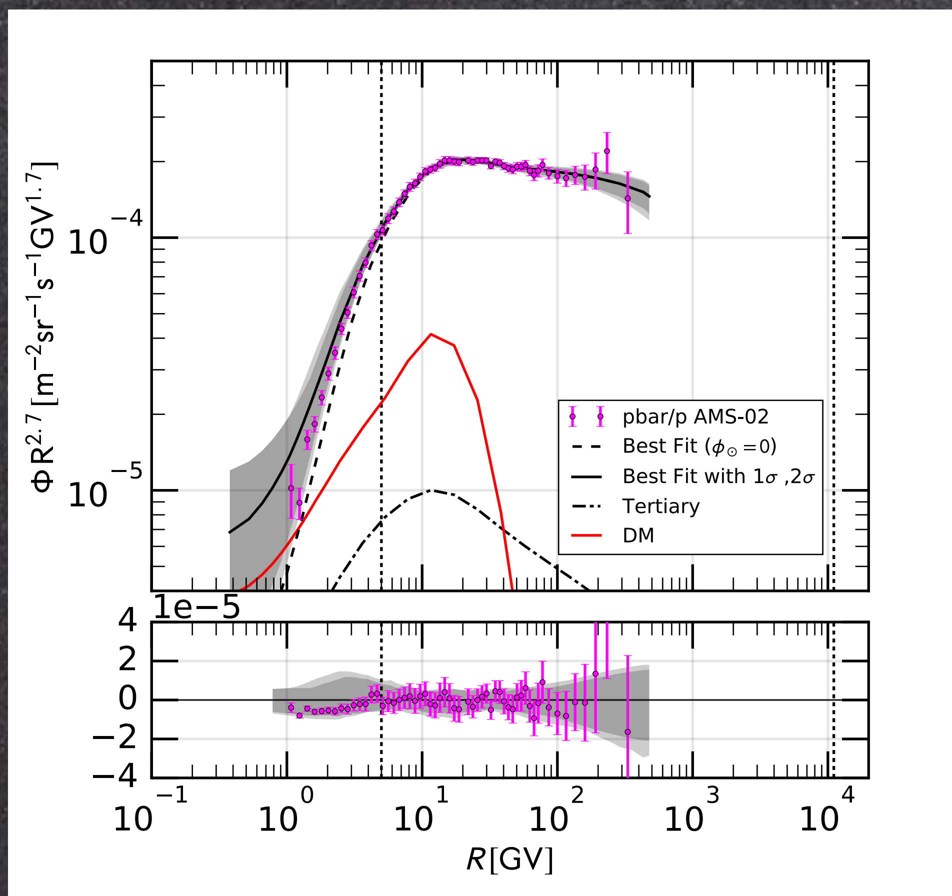
LHCb Coll. PRL2018,
Korsmeier, FD, Di Mauro, PRD 2018

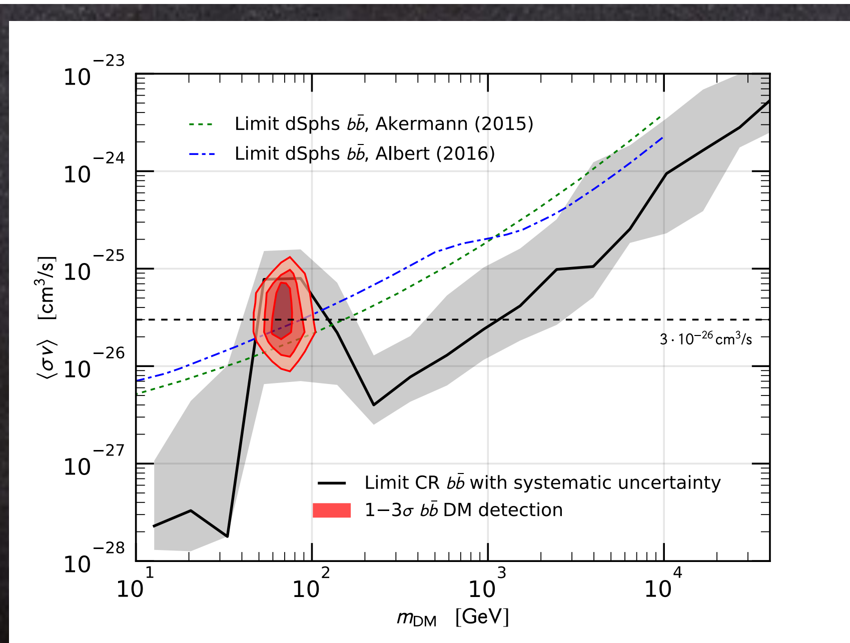
See talk by Davide Giordano

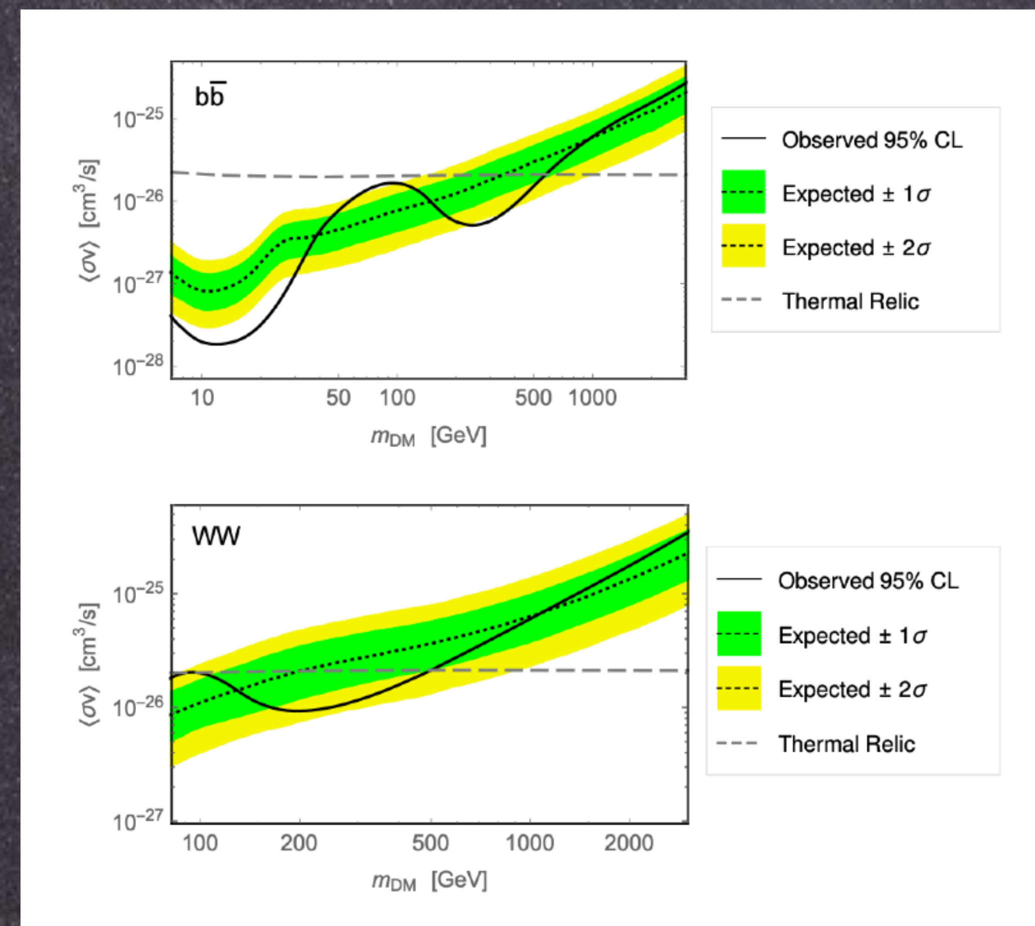
Possible contribution from dark matter

Cuoco, Korsmeier, Kraemer PRL 2017

Reinert & Winkler JCAP2018







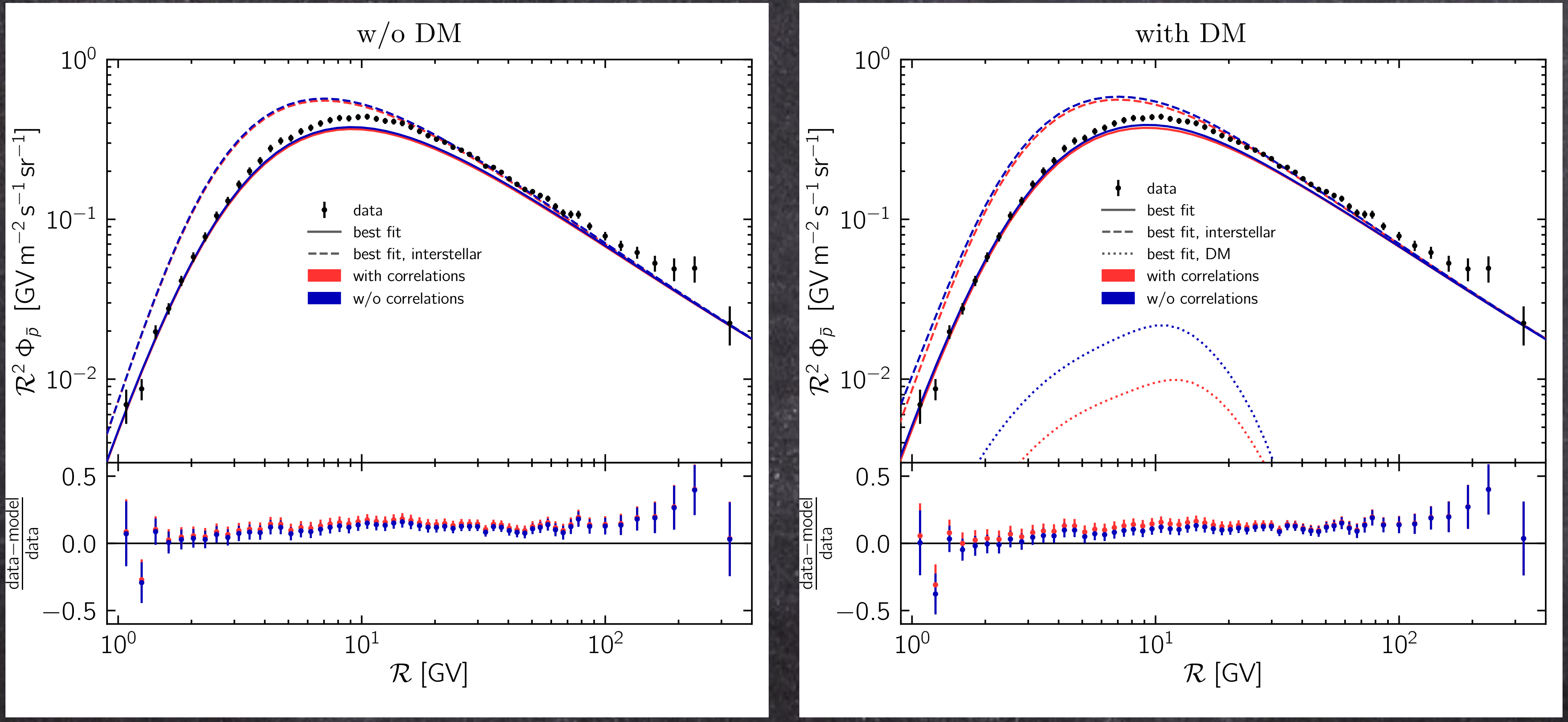
Antiproton data are so precise that permit
to set strong upper bounds on
the dark matter annihilation cross section,
or to improve the fit w.r.t. to the secondaries
alone adding a tine DM contribution

A matter of correlations

Heisig, Korsmeier, Winkler PRD2020

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

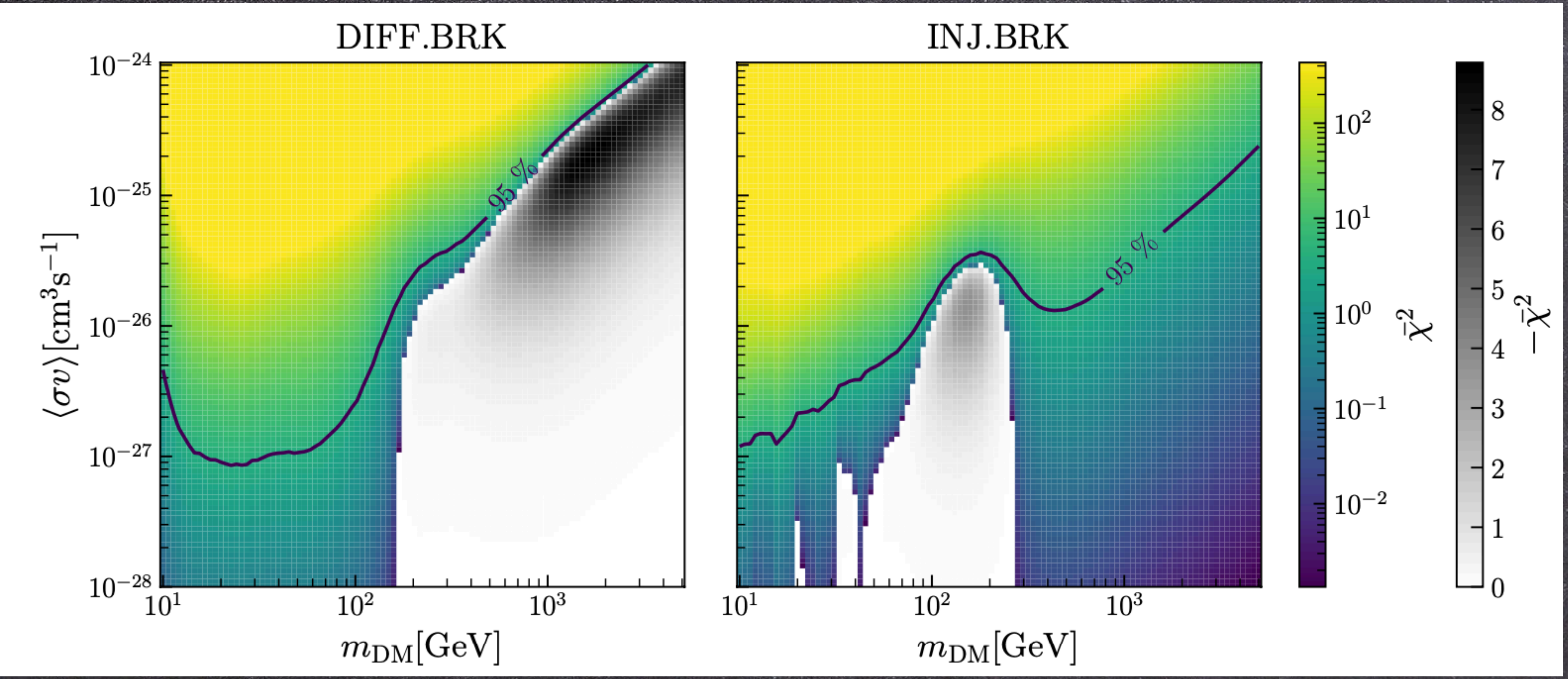
B/C, p-bar fit



The significance for DM drops below 1sigma

Limits on DM in antiproton data

Balan, Khalhoefer, Korsmeier, Manconi, Nippel JCAP 2023



New public tool to predict primary (DM) and secondary fluxes by neural networks, marginalizaiton over propagation parameters, with global fits interfaces to theoretical models (from Lagrangian level).

Test on several particle physics models

No DM evidence in AMS-02 data, but strong potential

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

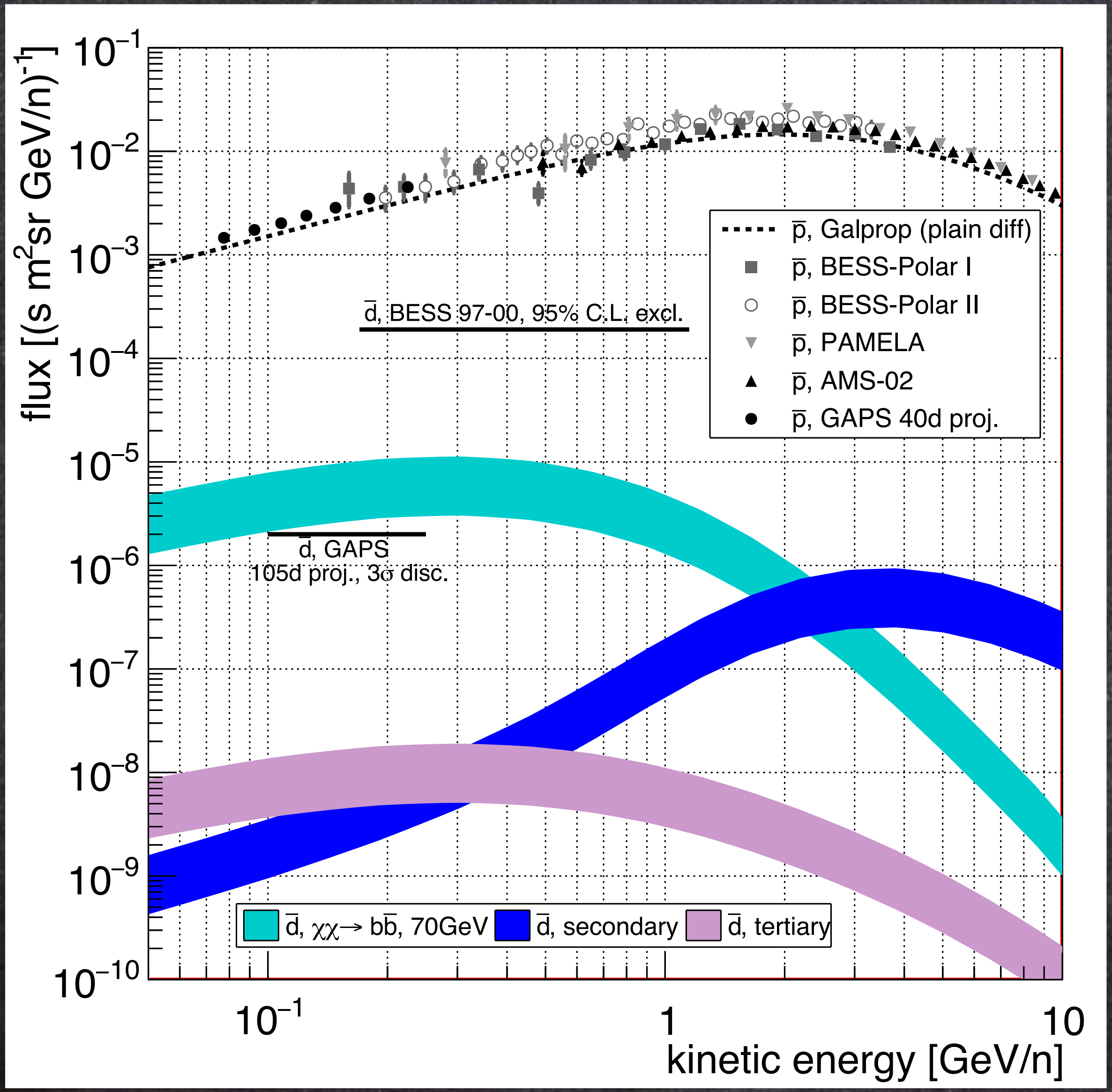
$$\frac{dN_{\bar{D}}}{dE_{\bar{D}}} = \left(\frac{4\,P_{\rm coal}^{3}}{3\,k_{\bar{D}}}\right) \left(\frac{m_{\bar{D}}}{m_{\bar{p}}\,m_{\bar{n}}}\right) \sum_{\rm F,h} B_{\chi \rm h}^{(\rm F)} \left\{ \frac{dN_{\bar{p}}^{\rm h}}{dE_{\bar{p}}} \left(E_{\bar{p}} = \frac{E_{\bar{D}}}{2} \right) \right\}^{2}$$

Background and DM have different kinematics and source spectra

Antideuterons persepctives

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

GAPS experiment is traveling now to Antarctica



AMS-02 antiproton data

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

Bands are for coalescence uncertainty

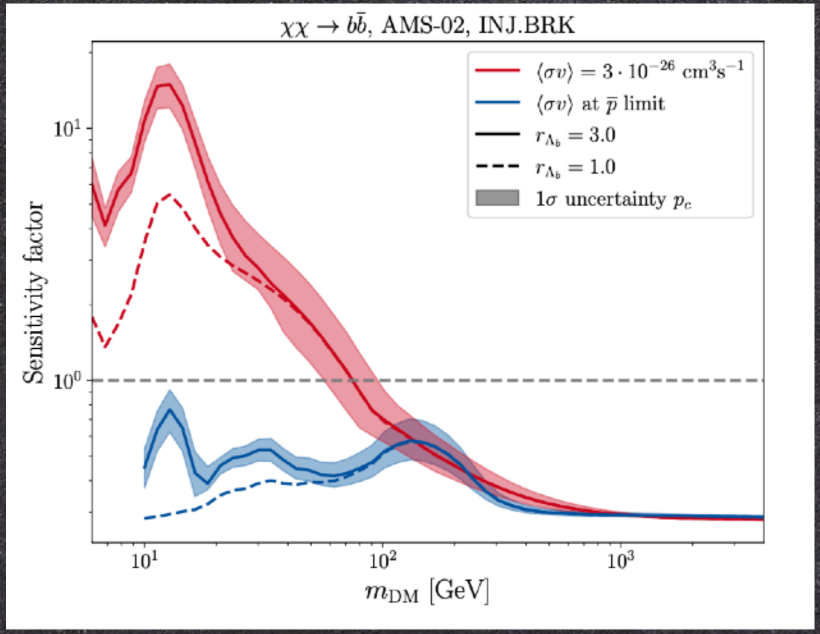
Donato+ PRD 2008; Ibarra&Wild PRD, JCAP 2013; Fornengo+ JCAP 2013; Tomassetti&Oliva ApJL2017; Aramaki+ Phys. Rep. 2021

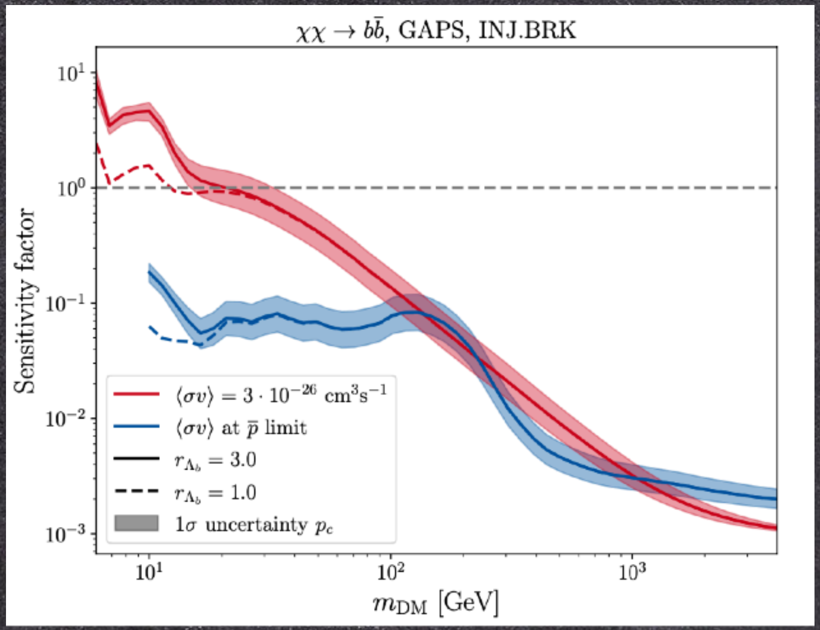
Antideuteron projected sensitivity

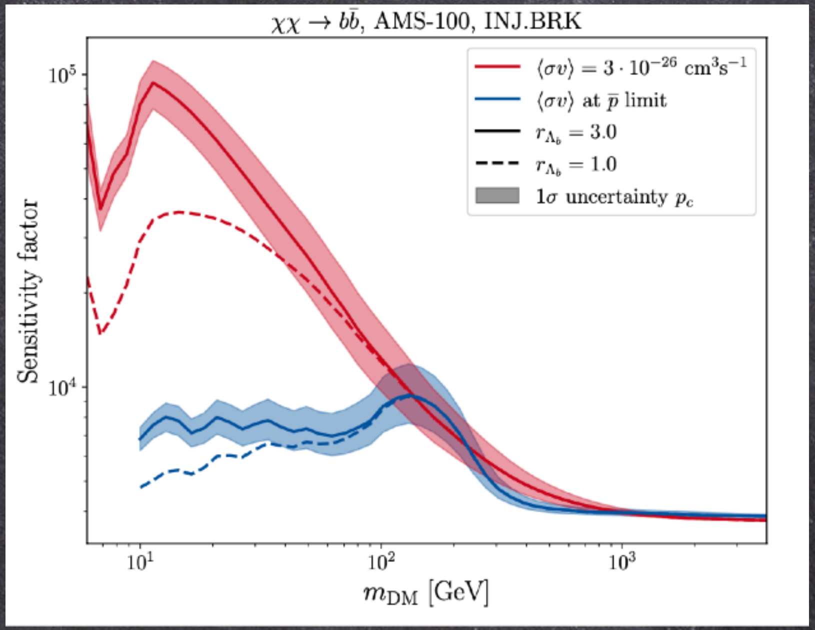
Heisig+ 2406.18642

$$\text{Sensitivity factor} := \frac{\langle \Phi \rangle_{\bar{d},E_{\text{exp}}}}{\Phi_{\text{sens},E_{\text{exp}}}}$$

>1 —> experiment is sensitive to the DM signal





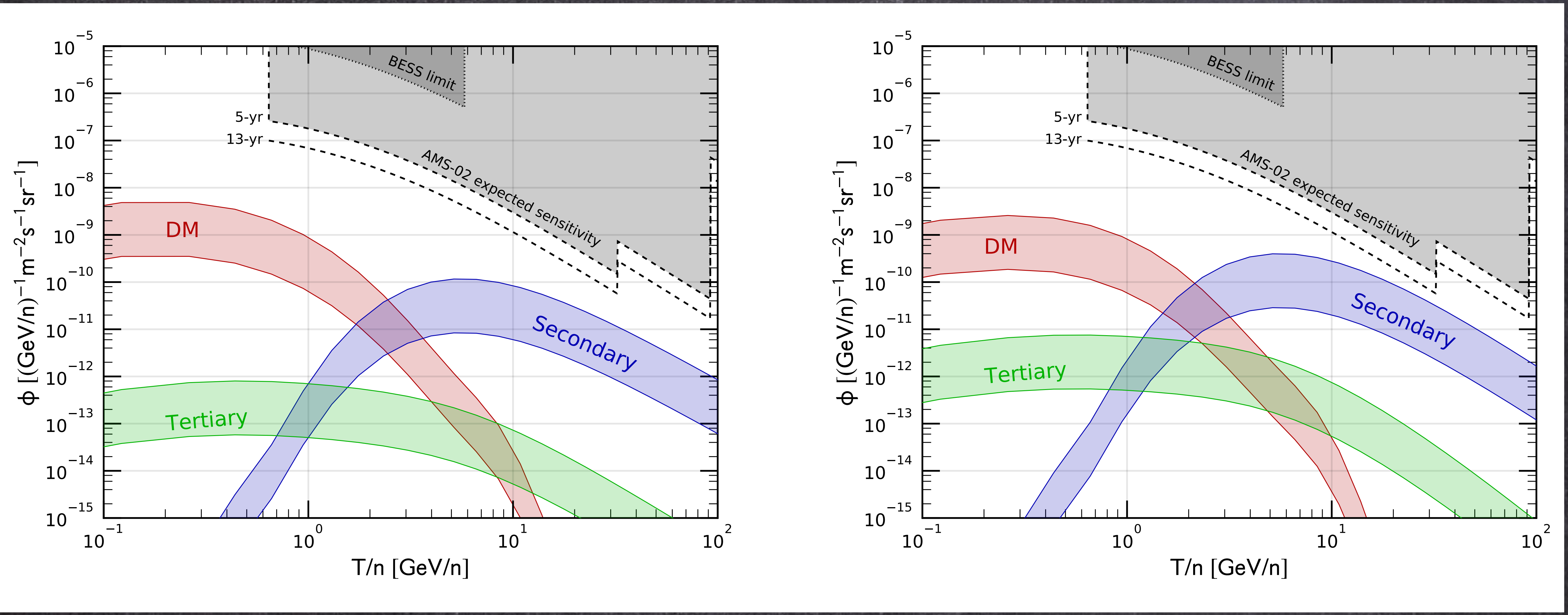


Predictions compatible with antiproton data are close to 1 for present generation experiments

GAPS Experment is traveling to Antarctica right now

Perspectives with antihelium

FD, Fornengo, Korsmeier, PRD 2018



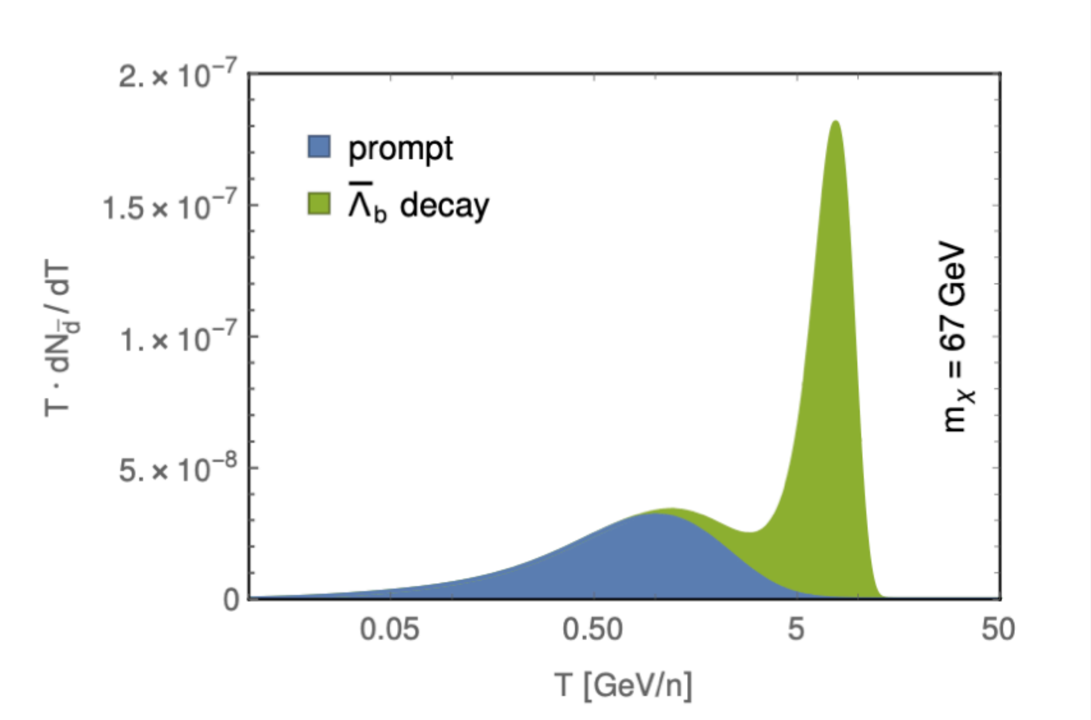
The Dark Matter signal is ways higher than secondaries
Below ~ 2 GeV/n: discovery window

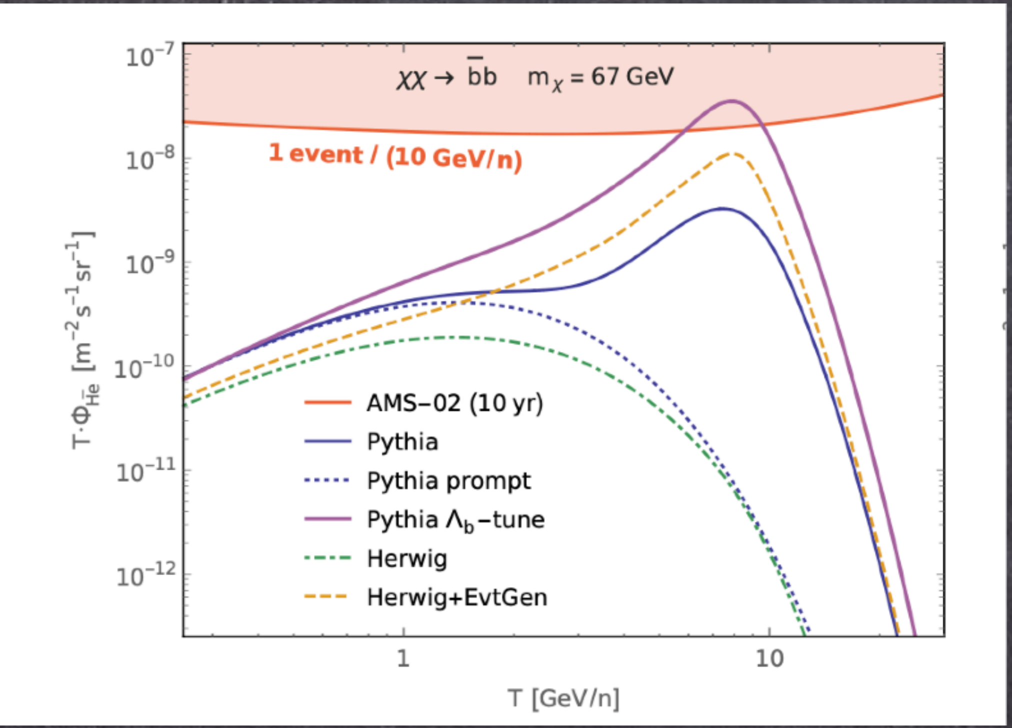
Few preliminary events in AMS-02 experiments

Enhancement of ³He-bar production

Winkler & Linden PRL 2021

Consider the production of ³He-bar through bar-Λb (anti udb) decays.



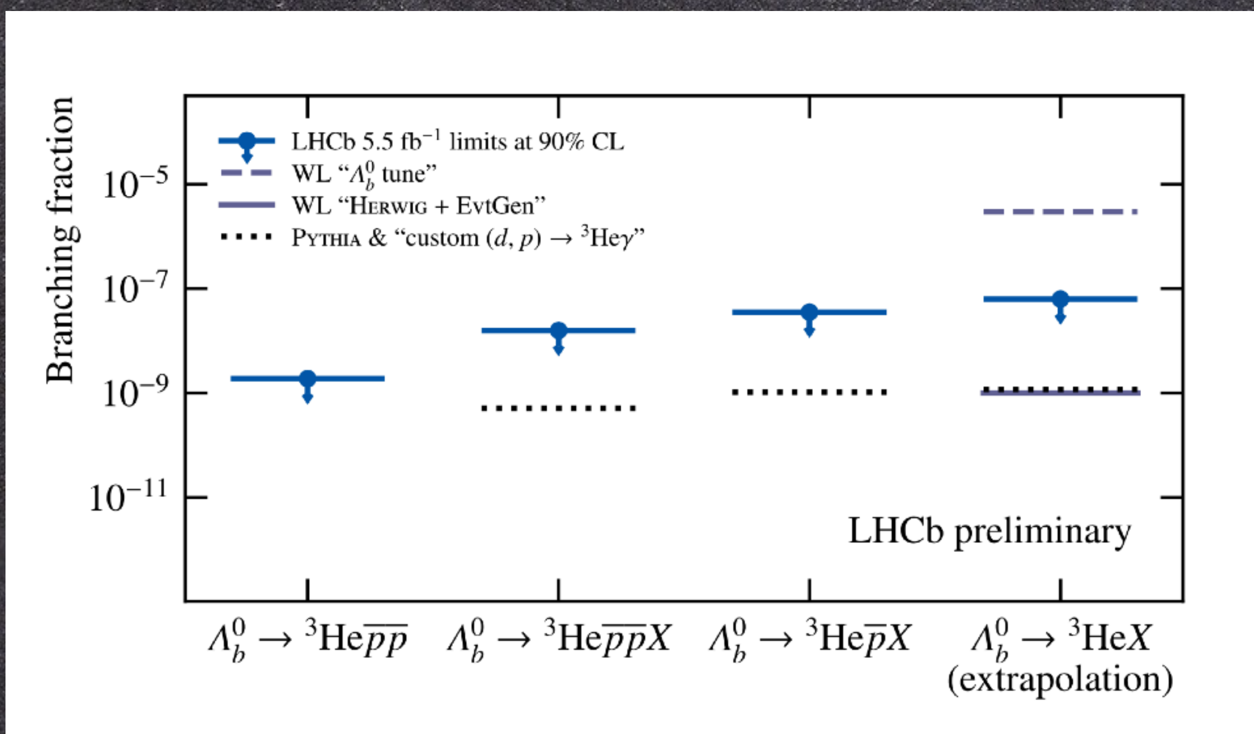


Production of anti-helium is strikingly enhanced at few GeV.
Strong dependence on MC - Pythia, Herwig - tuning

Kachelrieß, Ostapchenko & Tjemsland 2105.00799 a strong criticism is raised.
The Pythia tune by WL21 affects all processes involving baryon and meson production

Results from LHCb measurements

LHCb Coll. at ICHEP2024, LHCb-CONF-2024-005



$$\mathcal{B}(\overline{\Lambda}_b^0 \to {}^3\overline{\mathrm{He}}pp) < 1.9 \times 10^{-9} \text{ at } 90\% \text{ CL},$$
$$\mathcal{B}(\overline{\Lambda}_b^0 \to {}^3\overline{\mathrm{He}}ppX) < 1.6 \times 10^{-8} \text{ at } 90\% \text{ CL},$$
$$\mathcal{B}(\overline{\Lambda}_b^0 \to {}^3\overline{\mathrm{He}}pX) < 3.6 \times 10^{-8} \text{ at } 90\% \text{ CL}.$$

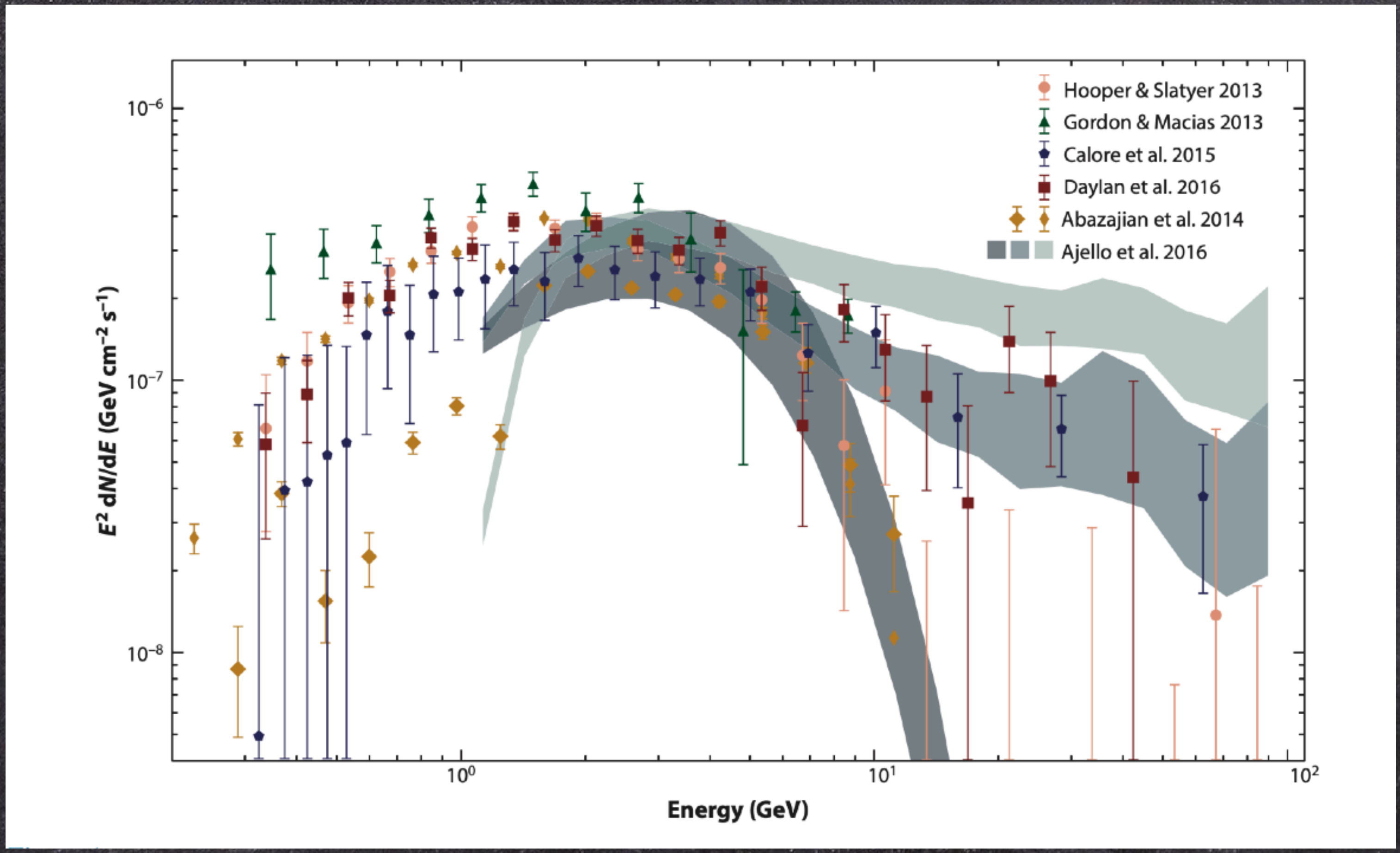
LHCb sets strong upper bounds on Λ Branching ratios

Enhancement, if any, is small

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)



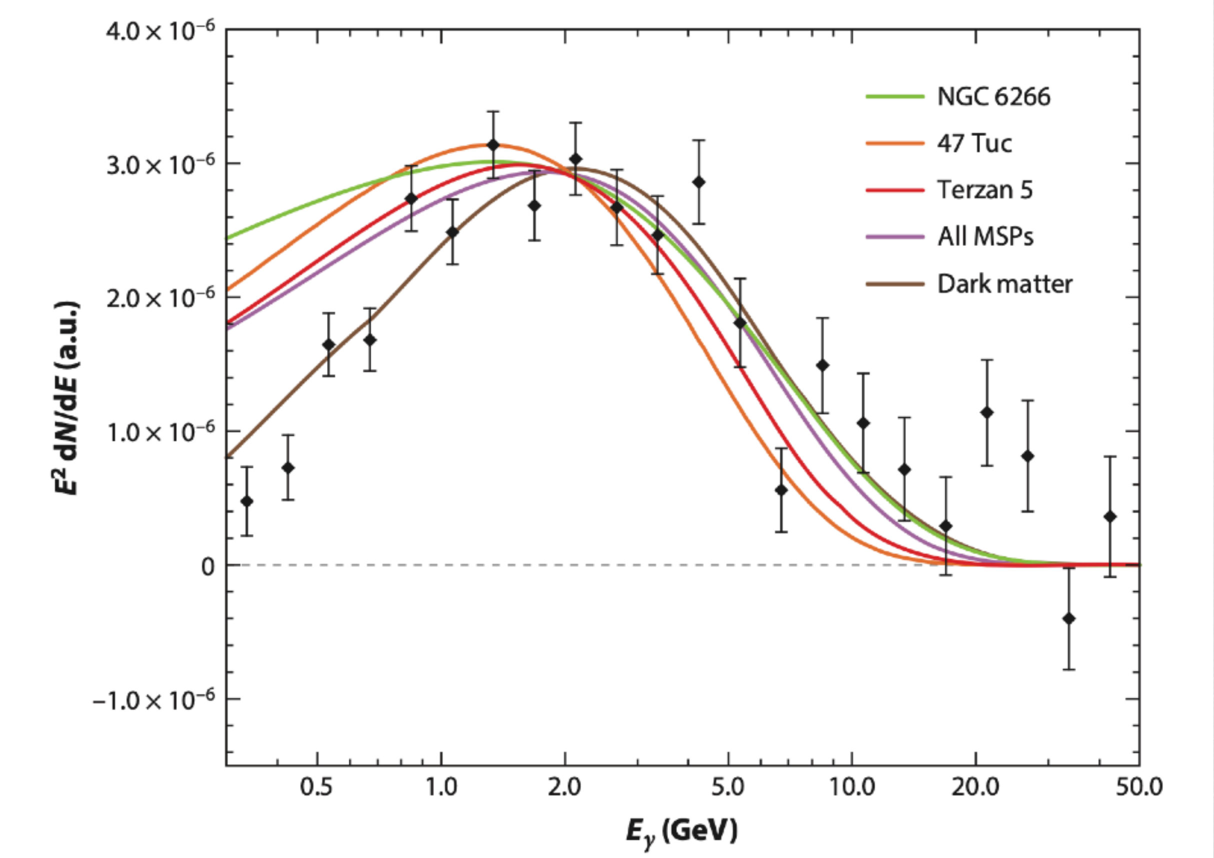
MurgiaAR 2020

No matter the method, the GC excess is statistically significant

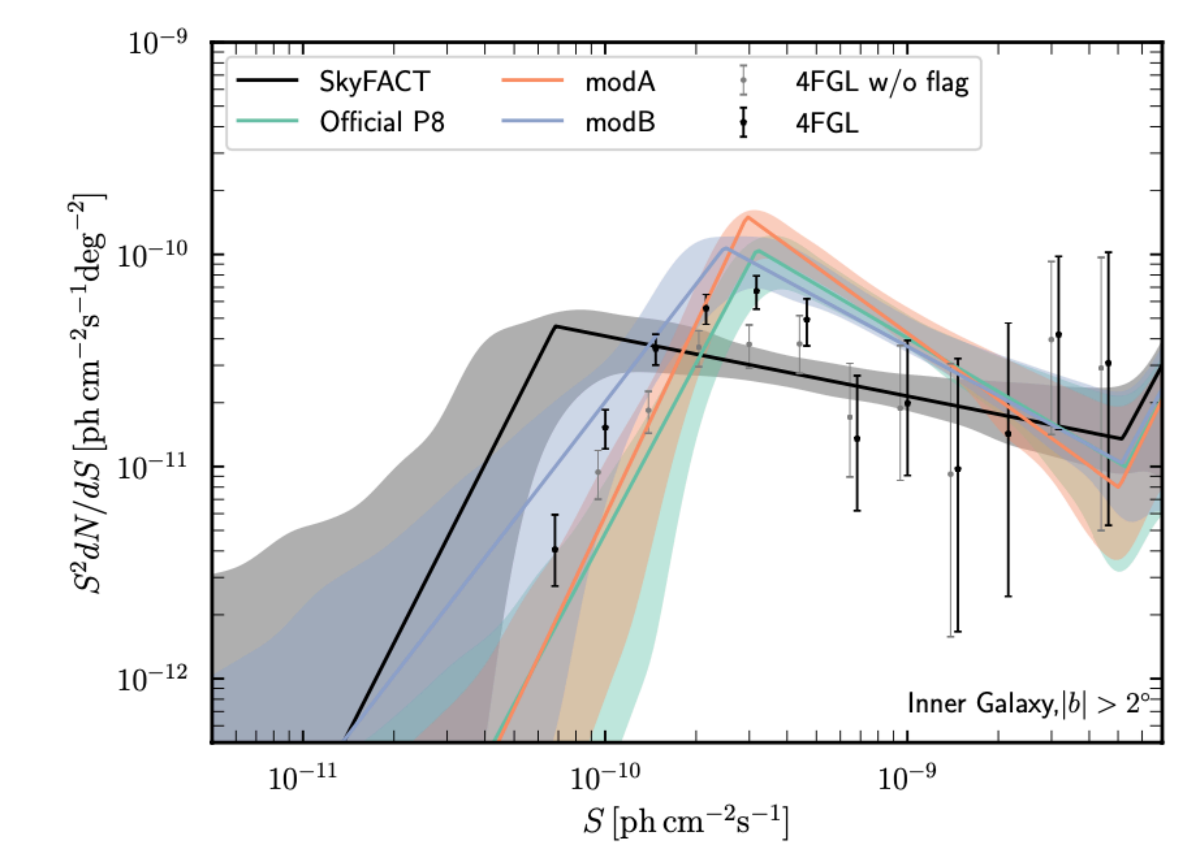
The GeV excess at the Galactic center (GCE)

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

Murgia AR 2020



Calore, FD, Manconi PRL 2021; PRD 2024



Point sources (MSP) explain the morphology of the GCE

Galactic diffuse emission MISMODELING is a major issue

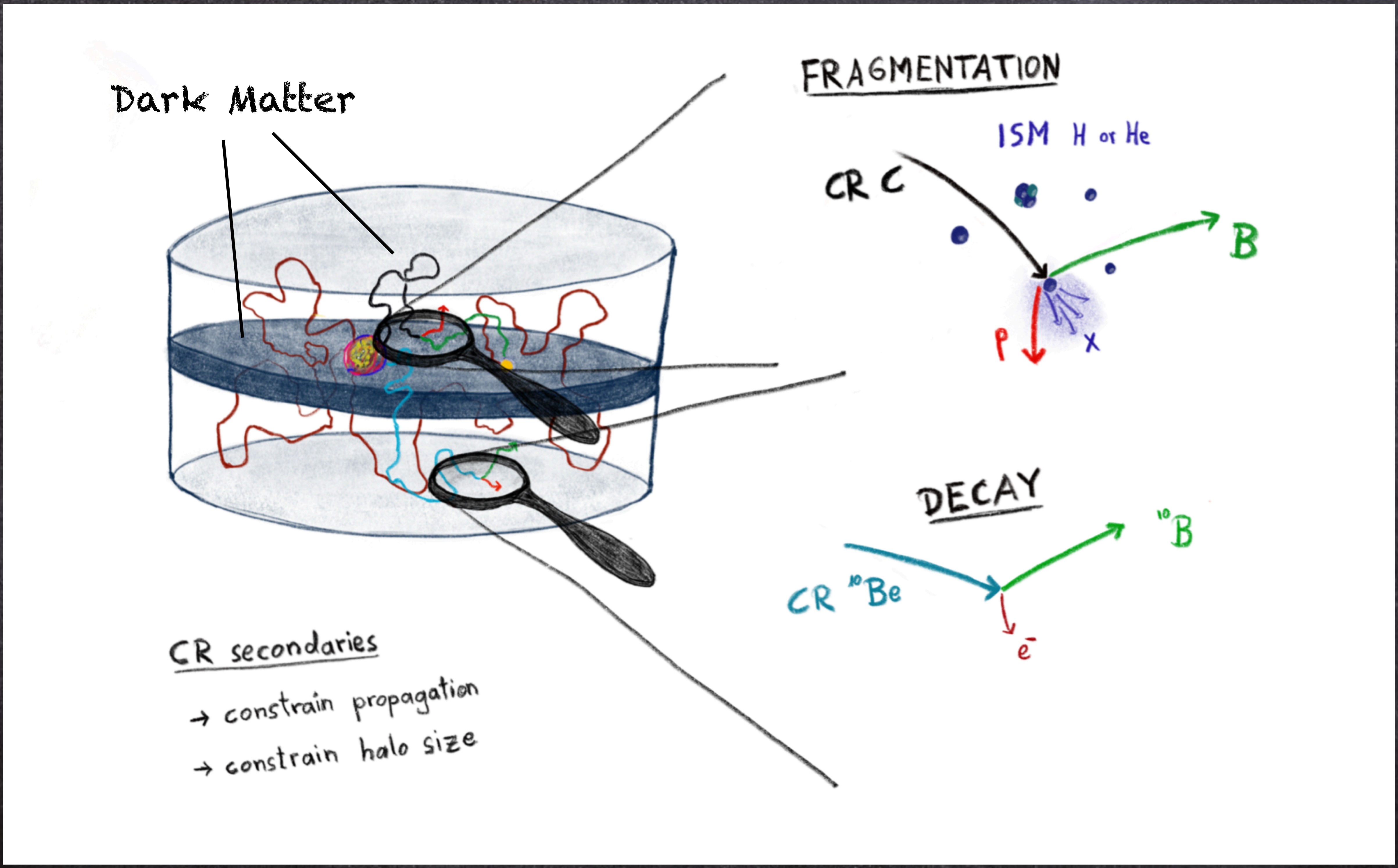
Conclusions

The search for DM is wide and diverse

So far no significant evidence - all putative excesses have been interpreted as due to (then) known sources

Efforts must be pursued at accelerators, in space, on the ground, deep underground. Difficult to figure out a signal in one channel only

CRs in the Galaxy



Courtesy of M. Korsmeier

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

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

V. Poulin et al. PRD 2019

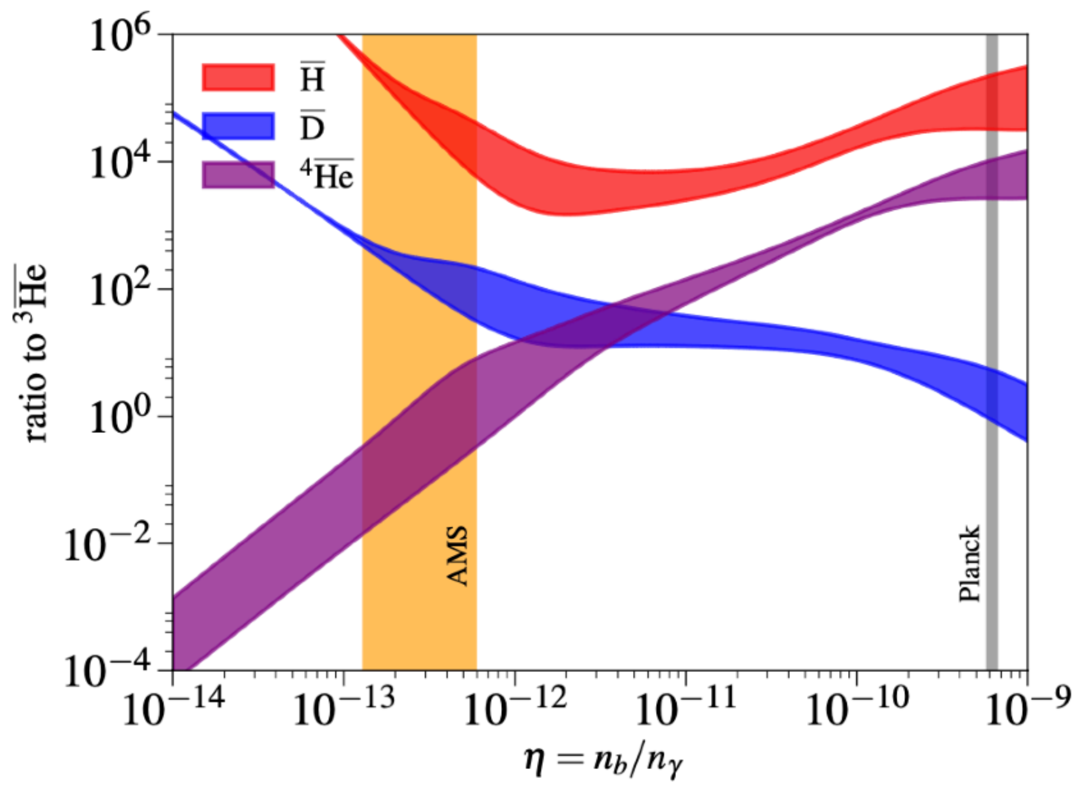


FIG. 4. Abundance of $\overline{\text{H}}$, $\overline{\text{D}}$ and $\overline{^4\text{He}}$ with respect to that of $\overline{^3\text{He}}$ as a function of the (anti-)baryon-to-photon ratio $\bar{\eta}$. The *Planck* value is represented by the grey band. The value required by the *AMS-02* experiment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

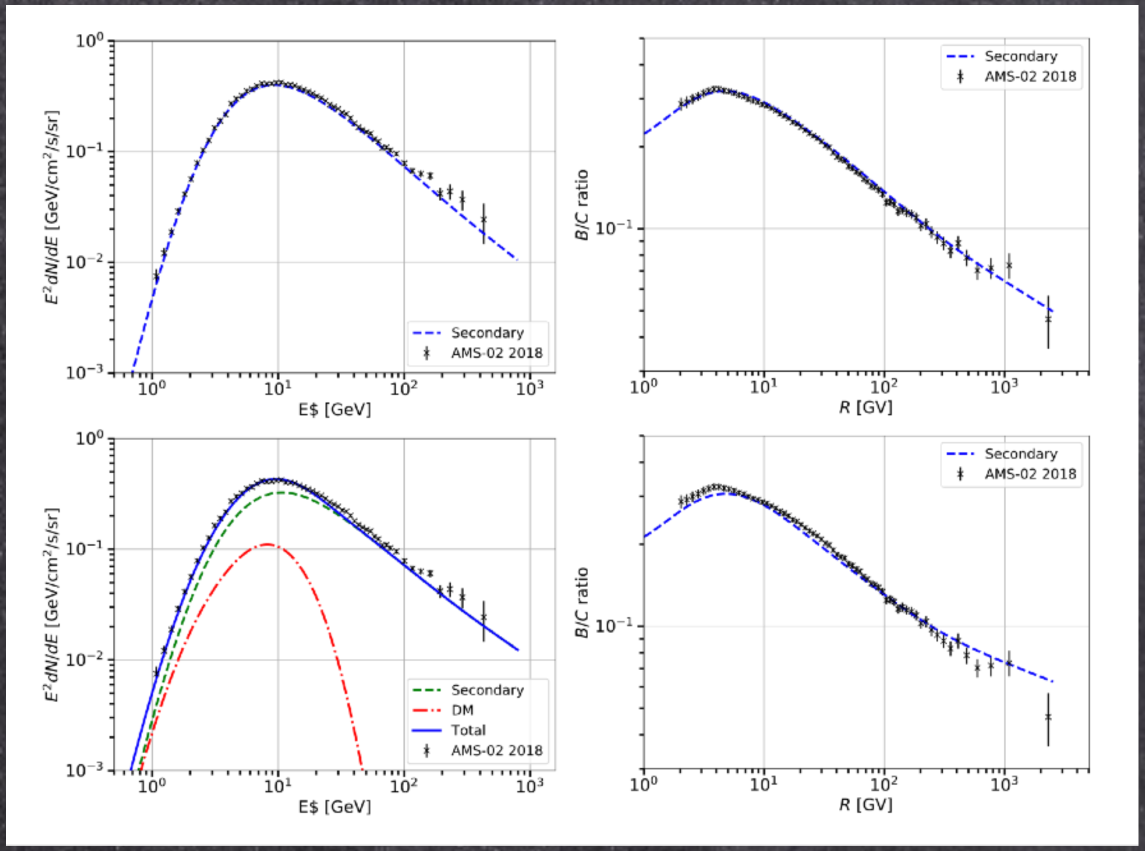
One anti-star could make the job.

How did they survive?

AMS-02 antiprotons wrt Fermi-LAT GCE

Di Mauro & Winkler PRD 2021

DM candidate possibly explaining the GCE 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 ^{10}Be/^{9}Be L> 2 kpc from e+ at low energy

Propagation equation

$$\frac{\partial \psi}{\partial t} - \nabla \cdot \{D(E)\nabla\psi\} + \frac{\partial}{\partial E}\left\{\frac{dE}{dt}\psi\right\} = Q(E, \mathbf{x}, t)$$

diffusion en. losses source spectrum

Diffusion: D(x,R) a priori
usually assumed isotropic in the Galaxy: $D \sim D_0 R^\delta$
D_0 and δ usually fixed by B/C

Energy losses: Nuclei: ionisation, Coulomb
Leptons: Synchrotron on the galactic B~3.6 μG
Inverse Compton on photon fields (stellar, CMB, UV, IR)

Sources: Supernova Remnants, $Q(E) \propto E^{-\gamma}$
Nuclear fragmentation, $Q_j(E) \propto n_{ISM}\,\sigma_{ij}\,\psi_i$
** Dark Matter annihilation or decay

Axion and Axion-like particles (ALPs)

Axions answer to Standard Model problem of the smallness of CP violation in QCD. Interactions with photons

$$\mathscr{L}_{\rm axion} = \frac{(\partial_\mu a)^2}{2} - \frac{a}{f_a}\left[\frac{\alpha_s}{8\pi}G^a_{\mu\nu}\tilde{G}^a_{\mu\nu} + c_2\frac{\alpha_2}{8\pi}W^a_{\mu\nu}\tilde{W}^a_{\mu\nu} + c_1\frac{\alpha_Y}{8\pi}B_{\mu\nu}\tilde{B}_{\mu\nu}\right] + \\ + \frac{\partial_\mu a}{f_a}\left[c_H(H^\dagger i D_\mu H) + \sum_i c_i(\bar{\psi}_i\gamma_\mu\psi_i) + \text{h.c.}\right].$$

$$\mathcal{L} = \frac{1}{4}g_{a\gamma\gamma}\, a\, F_{\mu\nu}\tilde{F}_{\mu\nu} = -g_{a\gamma\gamma}\, a\, \vec{E}\cdot\vec{B}$$