Ricerche indirette di materia oscura

Commissione Scientifica Nazionale Seconda – INFN
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Venezia – Palazzo Loredan
9 aprile 2025

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Premessa

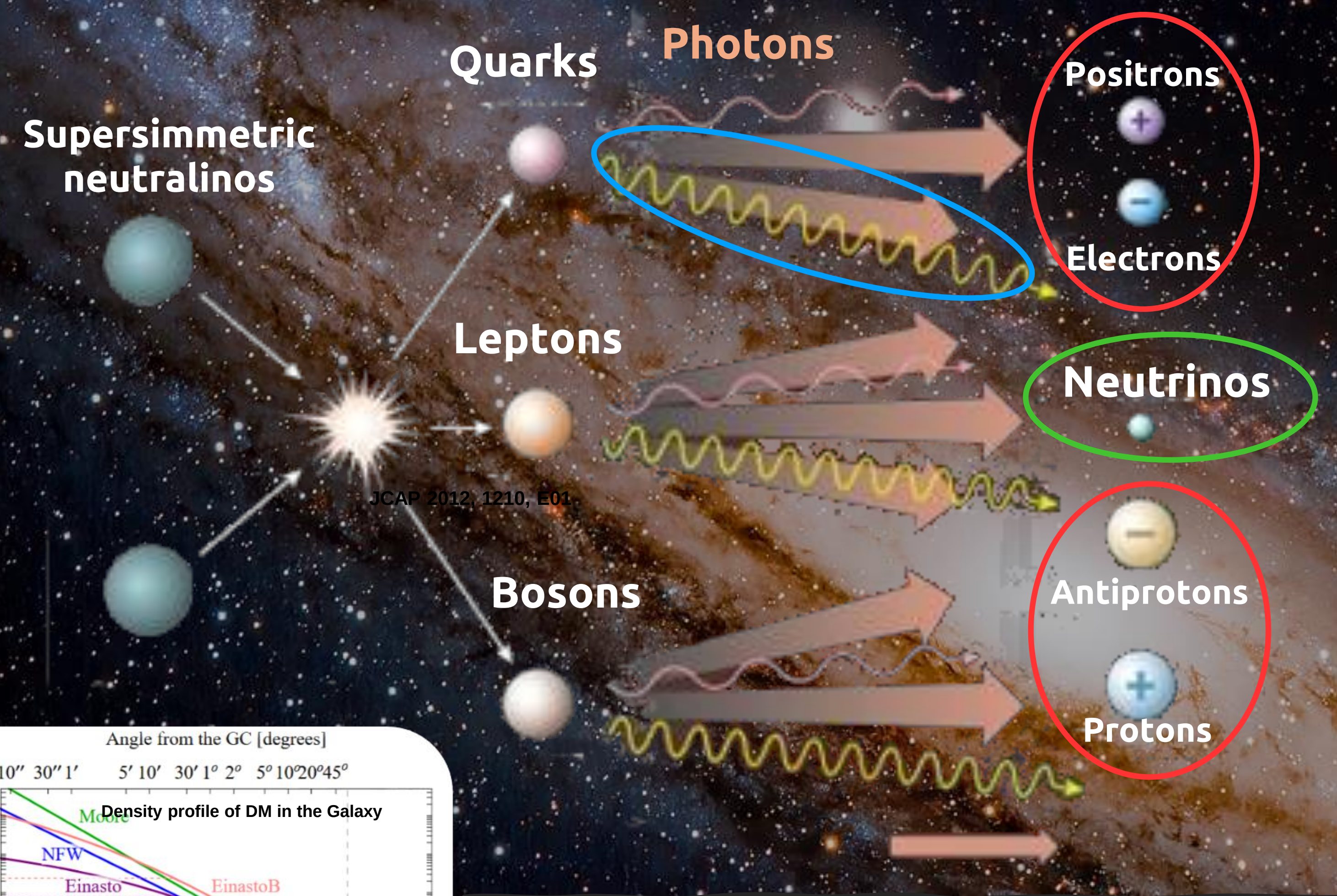
- ❑ Ho gia' tenuto questa presentazione nella riunione di aprile della CSN2 del 2022.

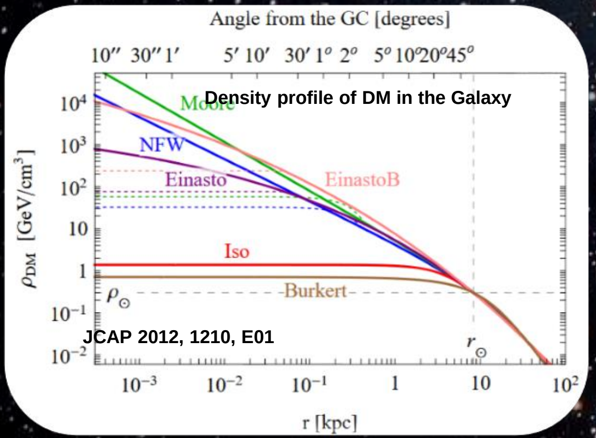
- ❑ Da allora ci sono pochi (forse nessun) nuovo risultato sperimentale particolarmente rilevante in questo ambito.

- ❑ Inoltre il paradigma delle WIMP, su cui si basano tutte queste ricerche, viene messo sempre di piu` in discussion dalla comunita`.

- ❑ Presentero` i risultati che ritengo piu` importante e rilevanti, ma sicuramente non sono riuscito a raccogliere tutti i risultati nel campo di ricerca!

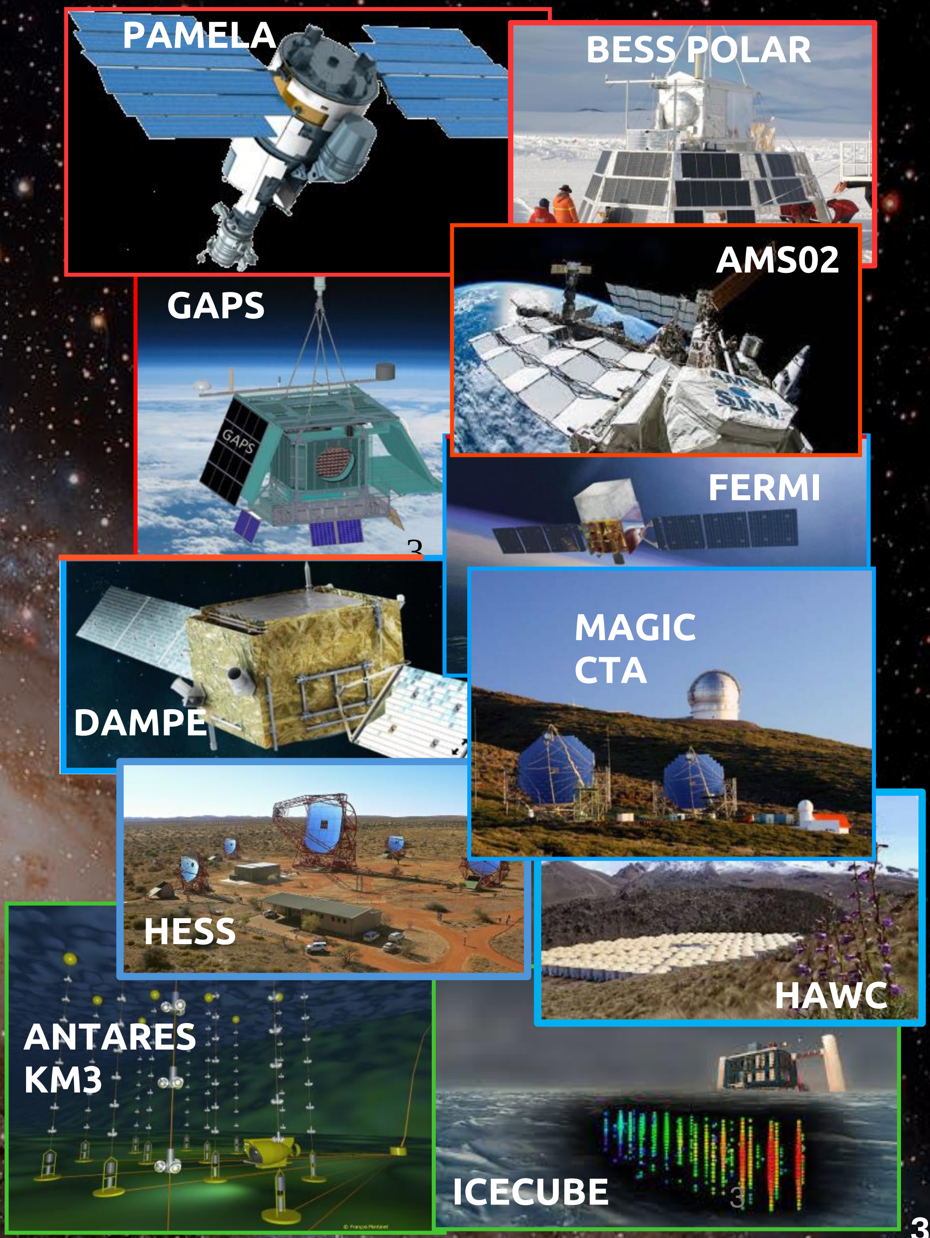
Indirect Dark Matter search





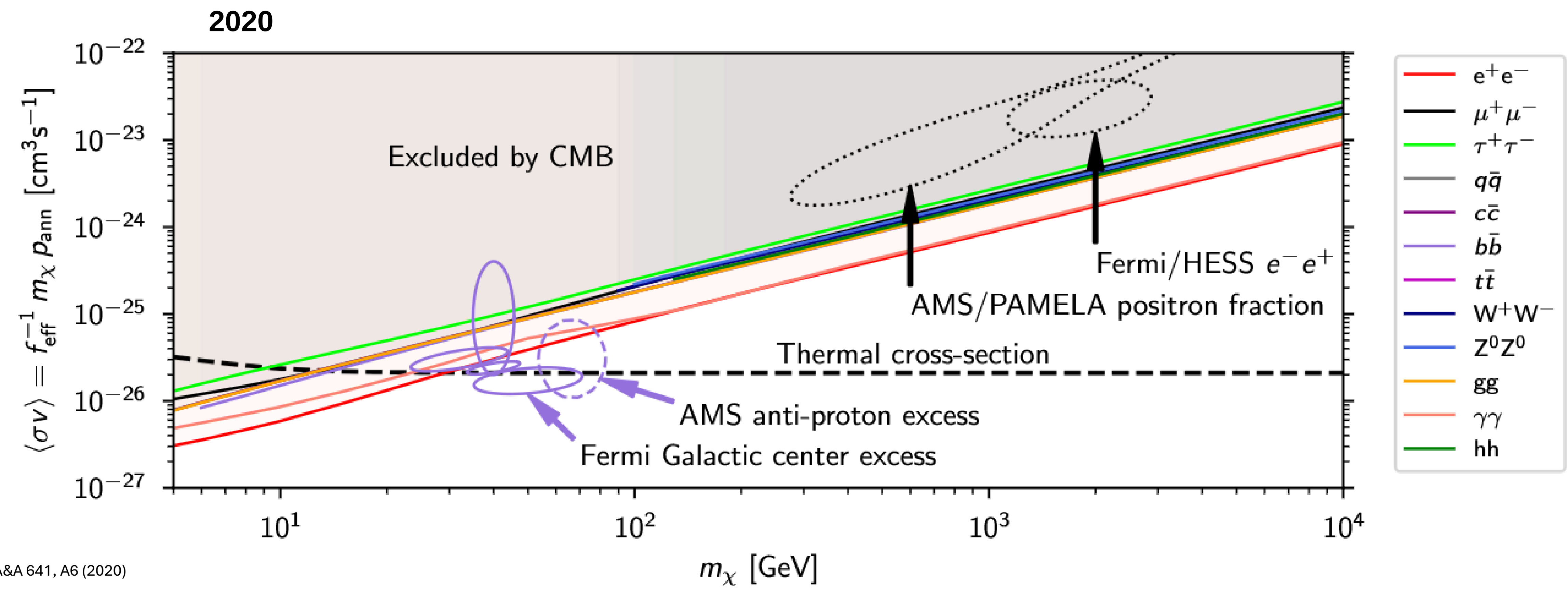
$$Q(E,r) \propto \frac{1}{2}\frac{\rho(r)}{m_{DM}^2}\frac{1}{\tau_{DM}}\frac{dN}{dE}$$ DM decay

$$Q(E,r) \propto \frac{1}{2}\frac{\rho^2(r)}{m_{DM}^2}\langle\sigma v\rangle\frac{dN}{dE}$$ DM annihilation



Constrains from CMB

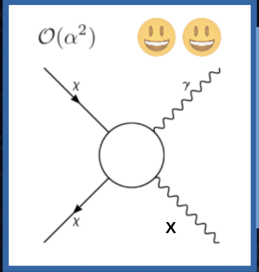
Anisotropies are sensitive to energy injection in the intergalactic medium that could be a consequence, for example, of dark-matter (DM). The current CMB sensitivity to the annihilation cross section of weakly-interactive massive particles (WIMPs) is competitive with and complementary to that of indirect DM search experiments.



A&A 641, A6 (2020)

Gamma Ray Lines

Gamma-ray lines

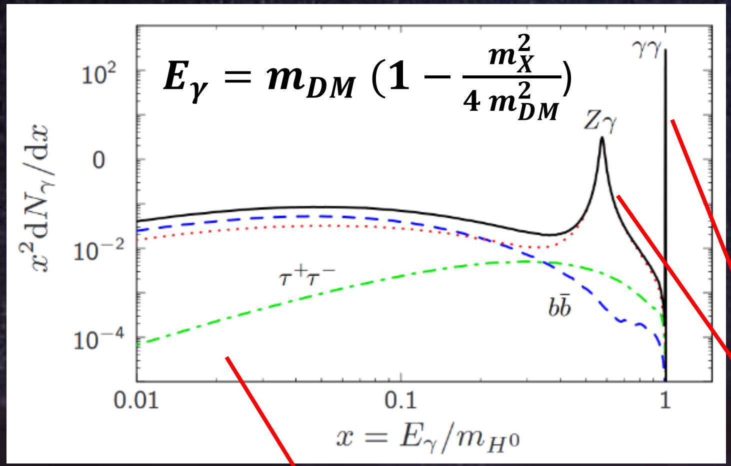


× Processo soppresso (secondo ordine)

✓✓ Linea spettrale

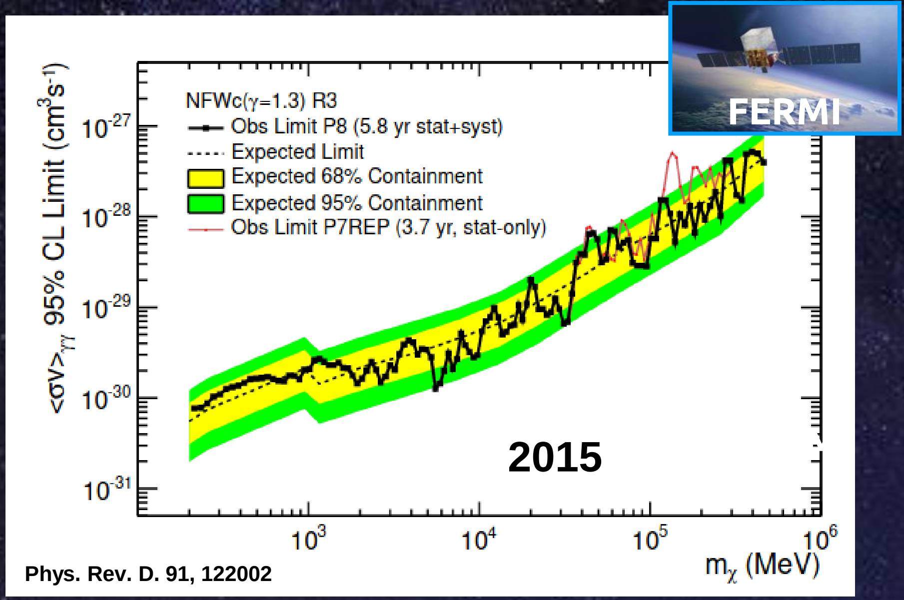
✓✓ Misura diretta di m_χ

$$\langle\sigma v\rangle_{\gamma\gamma} \sim (10^{-4} - 10^{-2})\,\langle\sigma v\rangle_{tot}$$

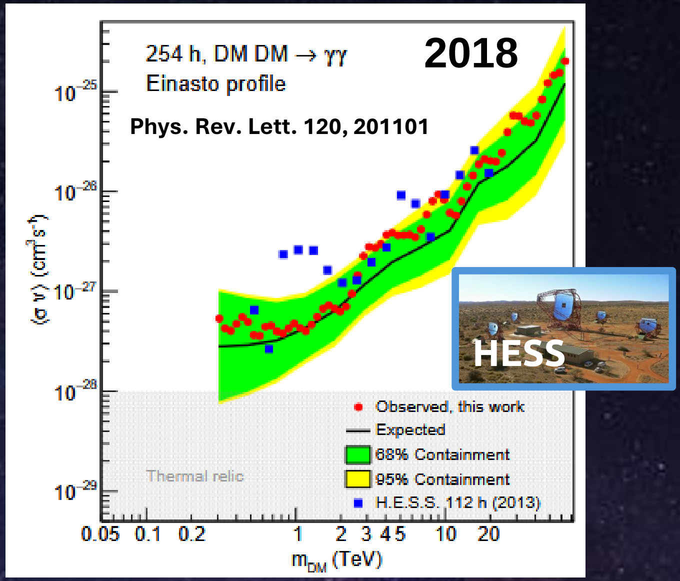


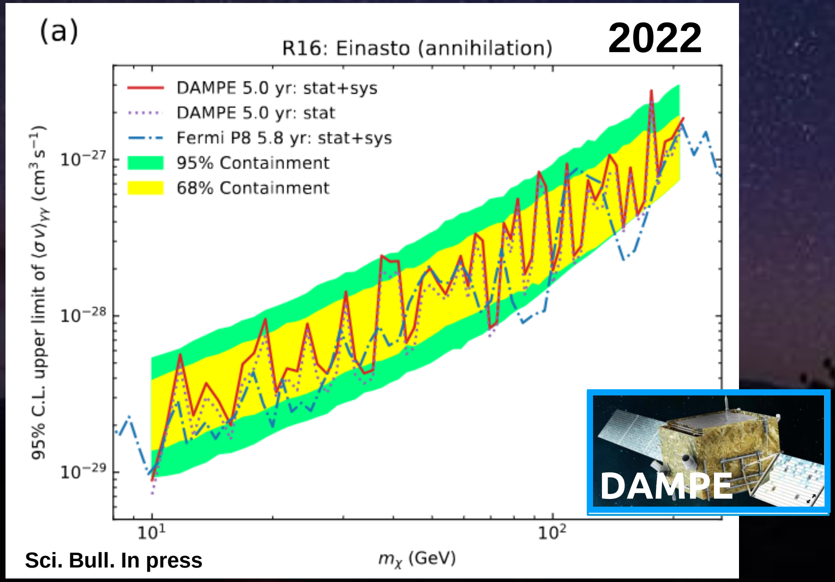
Lines

Continuum

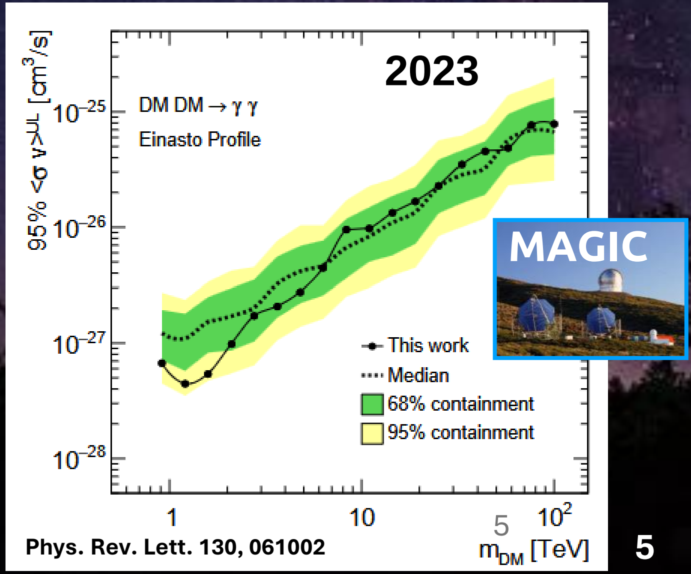


Phys. Rev. D. 91, 122002





Sci. Bull. In press

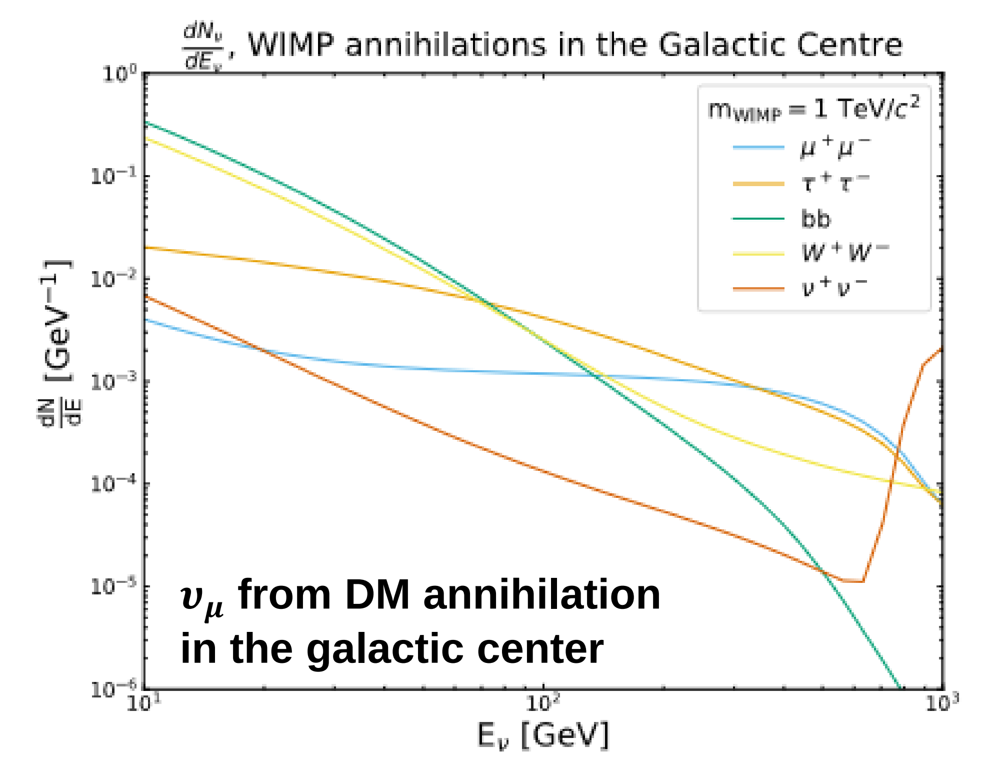


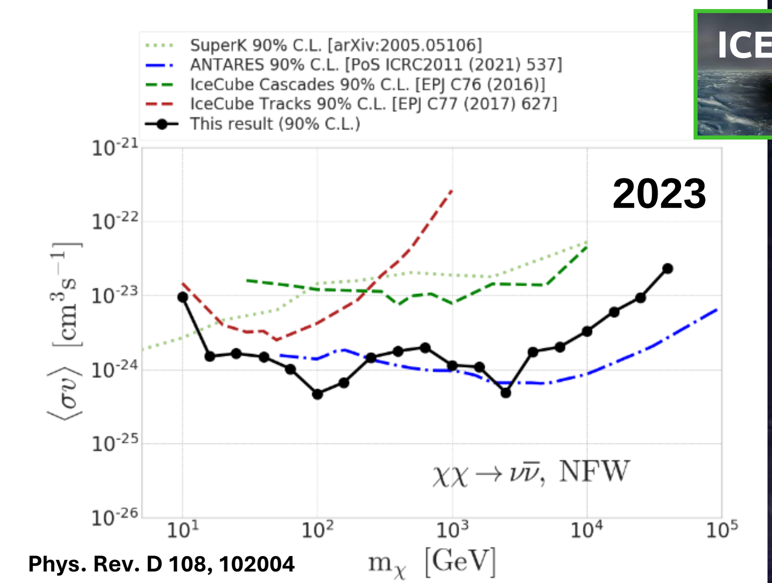
Phys. Rev. Lett. 130, 061002

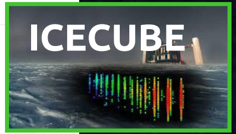
Observed region: galactic center

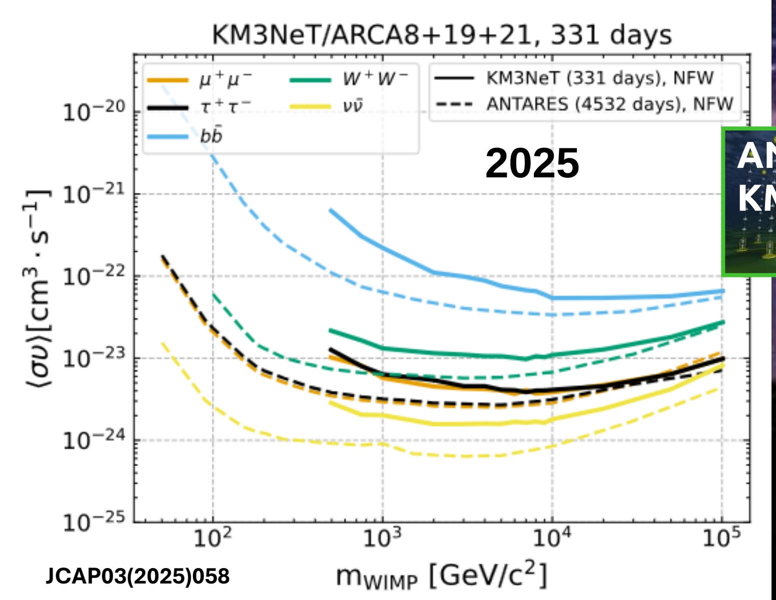
Neutrino Lines

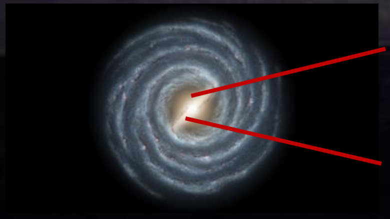
Neutrino line production can proceed at tree level







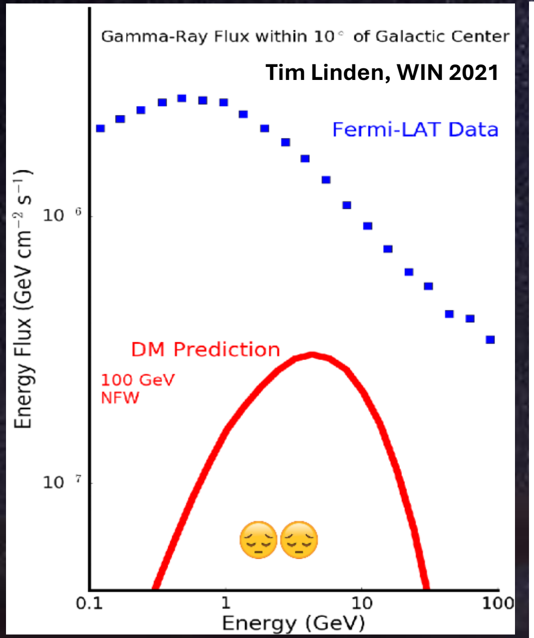


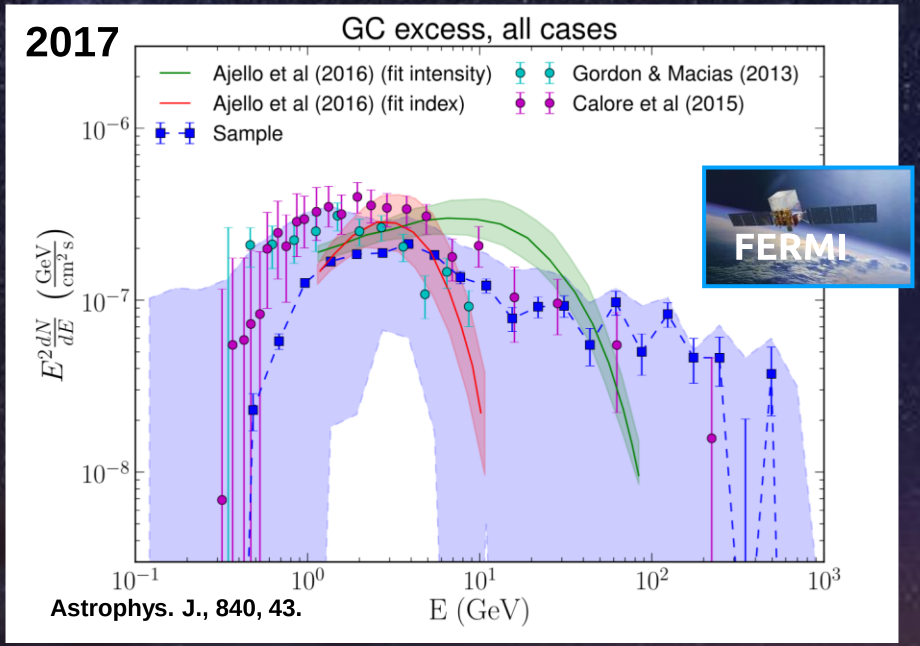


Observed region: galactic center

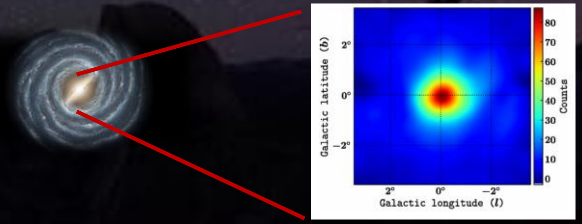
Continuum gamma ray emission

An excess of gamma ray from the Galactic Center has been claimed during the years by independent groups





The channel is dominated by the background

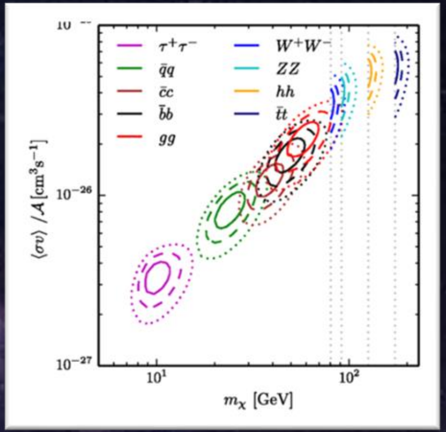


Debated interpretation:

Excess is spherical

Compatible with annihilating dark matter of mass~ 30-70 GeV thermal relic.

Phys. Rev. D 103, 063029 (2021),
Phys. Rev. D 105, 103023 (2022),
SciPost Phys. Proc. 12, 006 (2023)

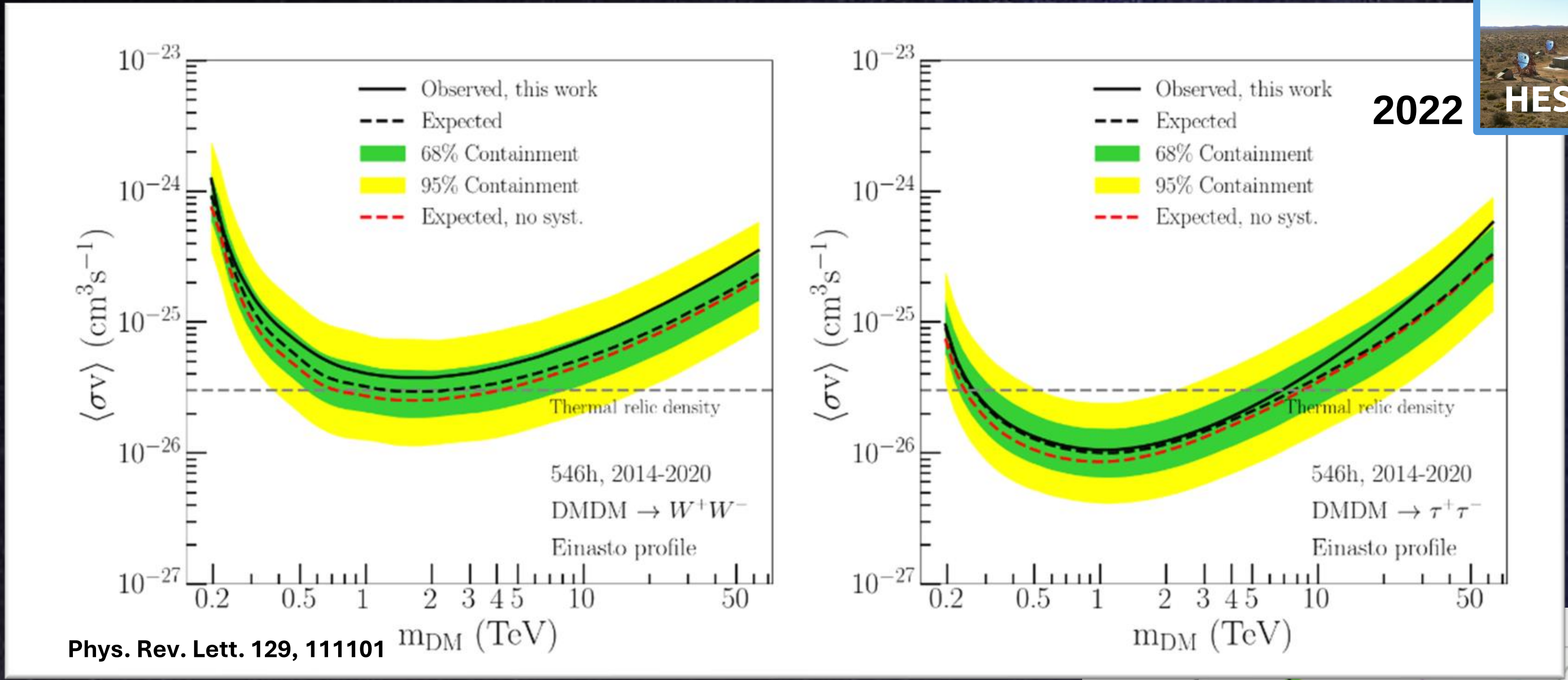


Excess is clumpy

But also with a population of faint gamma-ray point sources (**millisecond pulsars**).

Nat. Astron. 2, 819 (2018),
J. Cosmol. Astropart. Phys. 042 (2019)
Astrophys. J. 929, 136 (2022)

Continuum gamma ray emission



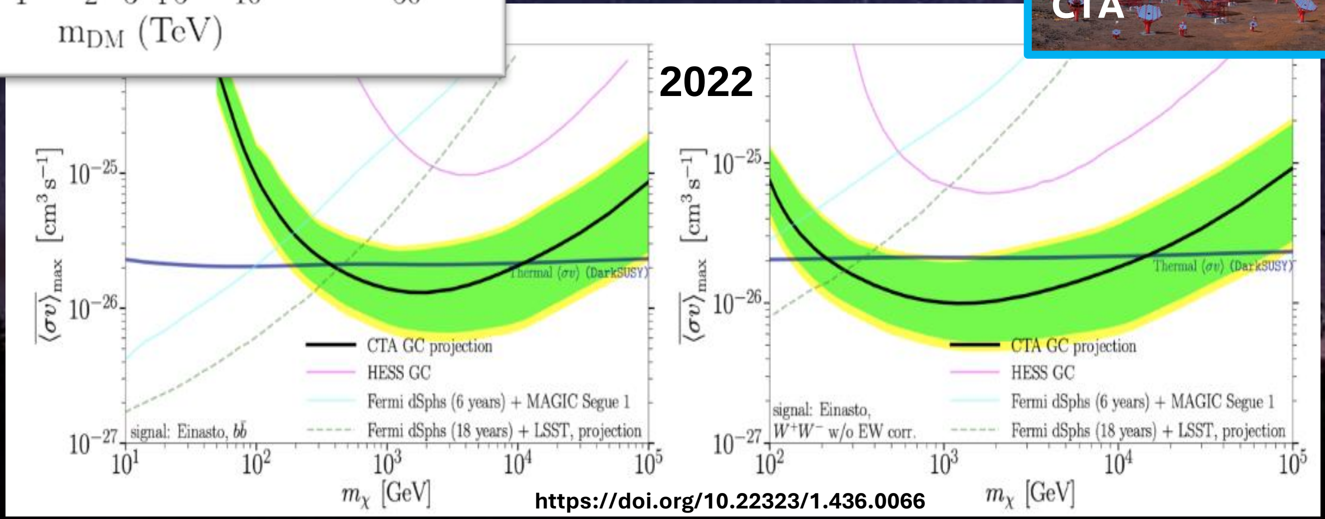
Phys. Rev. Lett. 129, 111101

2022

Best limits from Galactic Center observation provided by HESS.

Future

2022

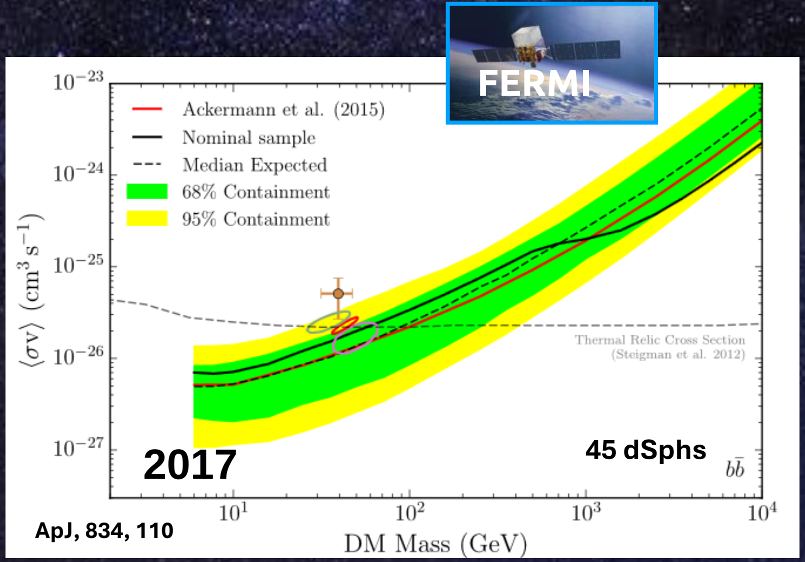


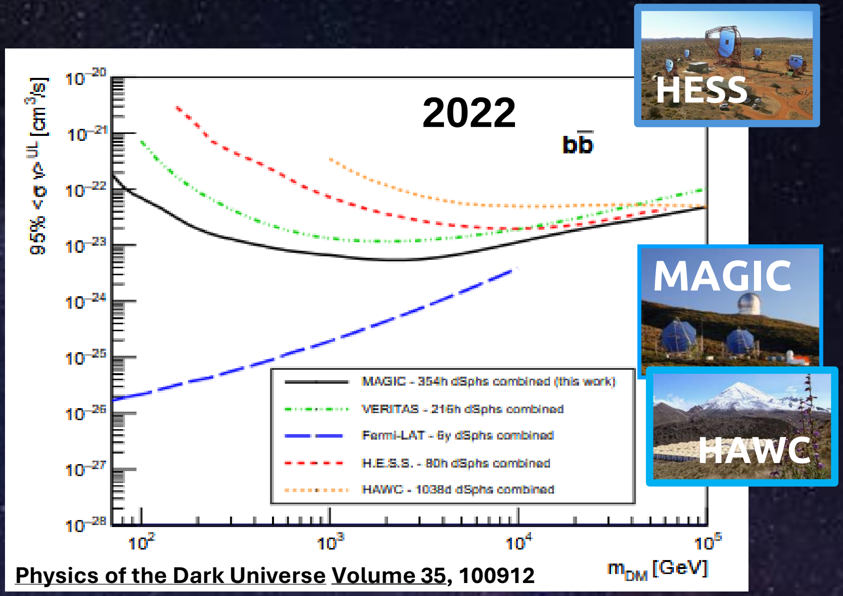
https://doi.org/10.22323/1.436.0066

Observed region: galactic center

Dwarf Galaxies

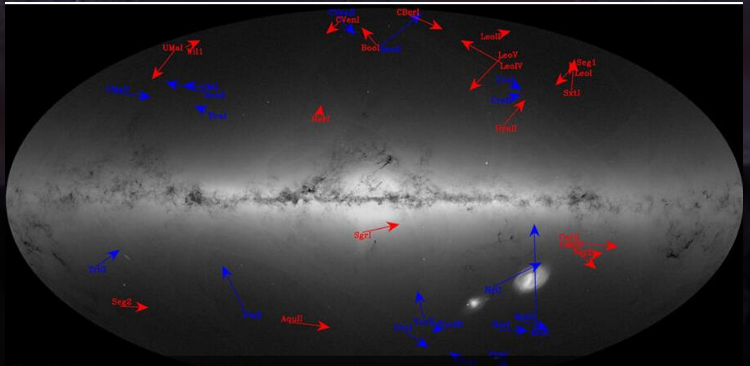
The dwarf spheroidal galaxies (dSphs) represent one of the most promising targets for DM indirect searches due to their high DM content and their negligible astrophysical background .



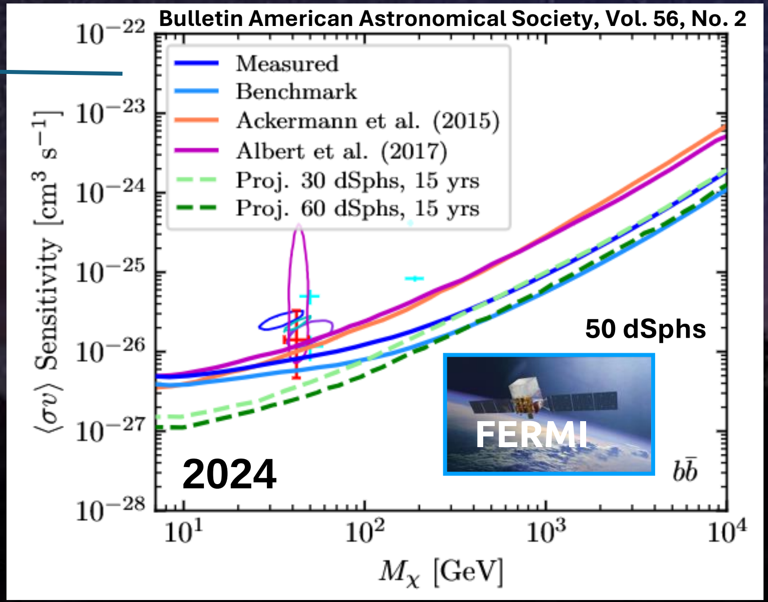


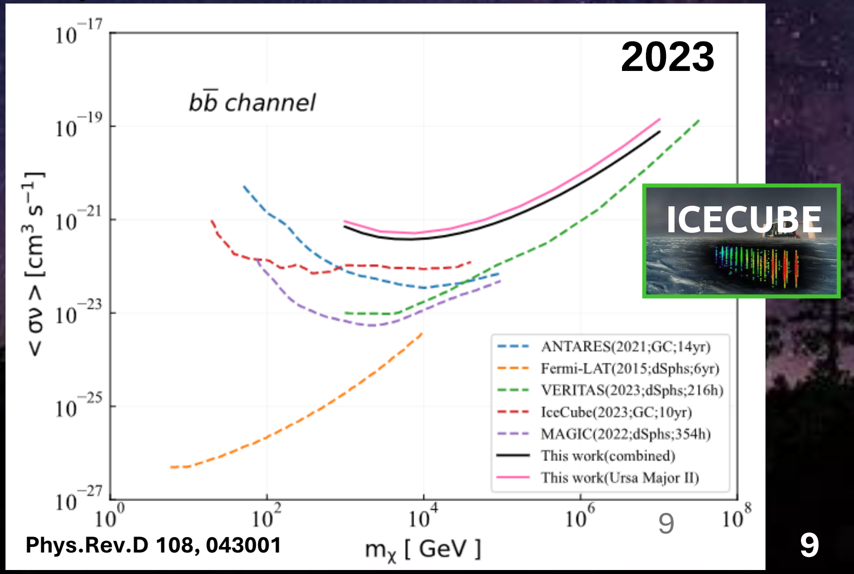
Physics of the Dark Universe, 35, 100912

Found escess in Reticulum II (~ 2 σ) masses of 290 < Mχ/GeV < 588 for the b ̄b channel 27 < Mχ/GeV < 70 τ +τ − annihilation



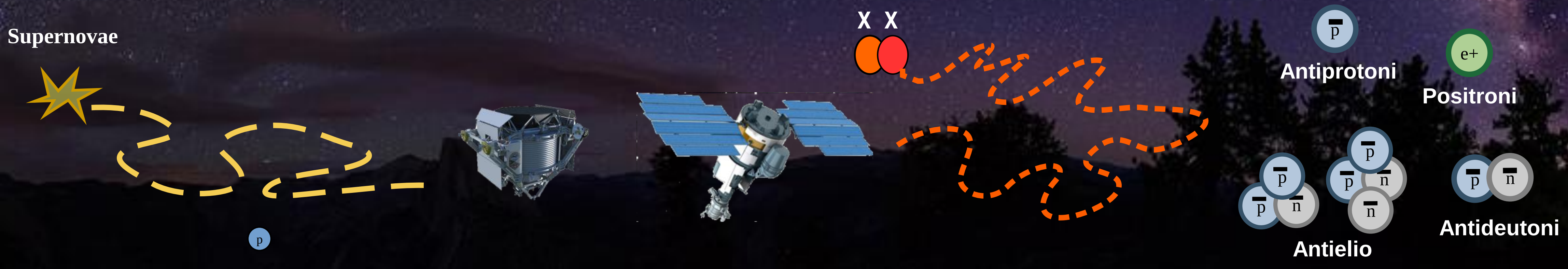
Map of satellite galaxies around the Milky Way





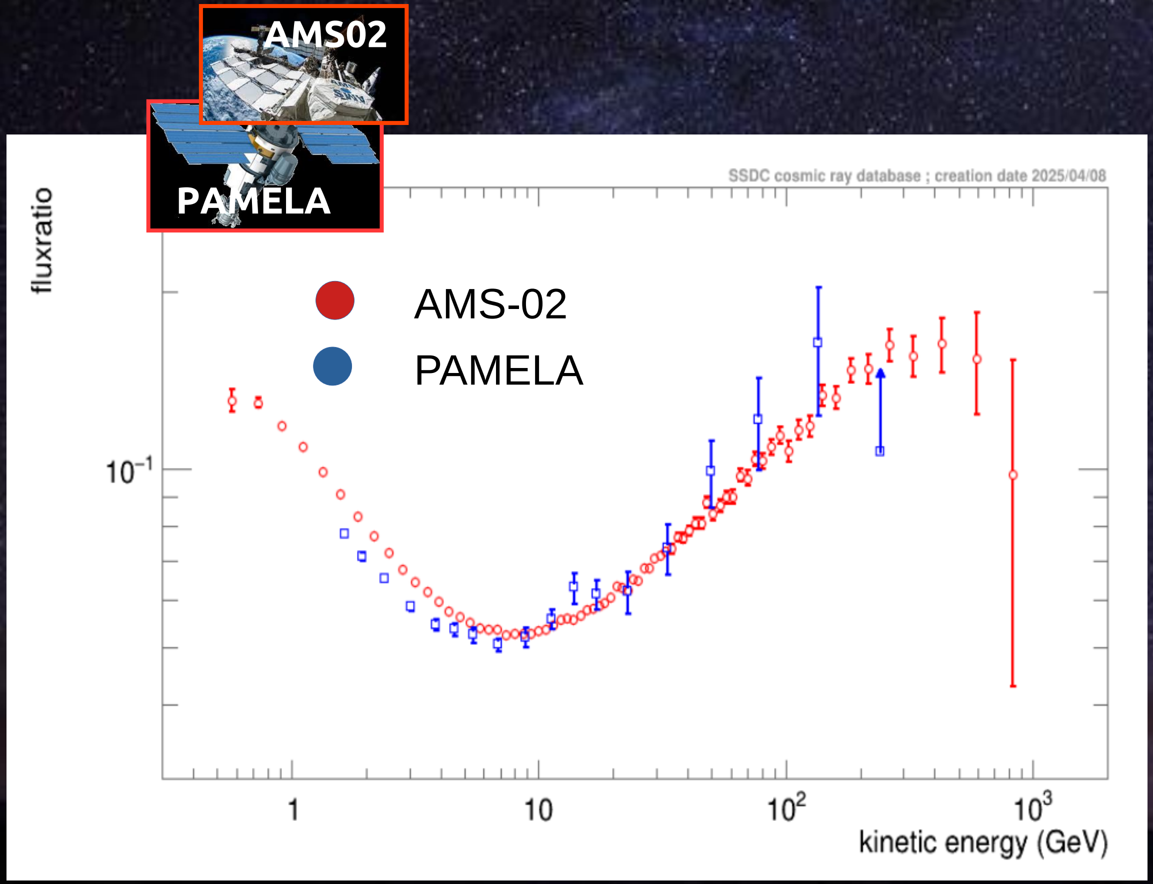
Charged messengers

- ❑ Deflected: they diffuse on the Galactic magnetic field
- ❑ Propagation in the Galaxy and in the Heliosphere is complicated to be modelled precisely
- ❑ Easy to detect, high statistics
- ❑ Good energy resolution
- ❑ Huge astrophysical background for matter
- ❑ Possibly low astrophysical background for antimatter

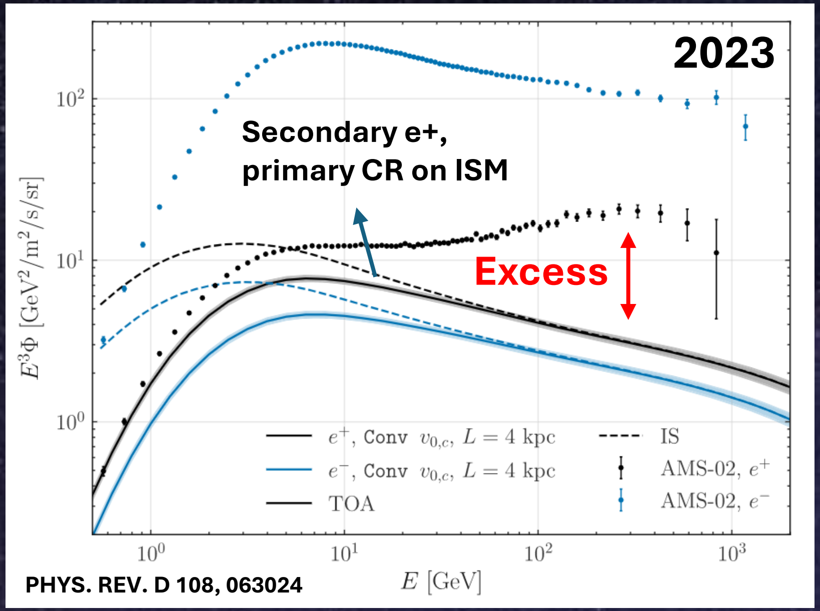


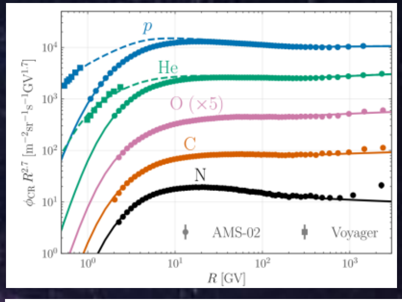
Positron excess

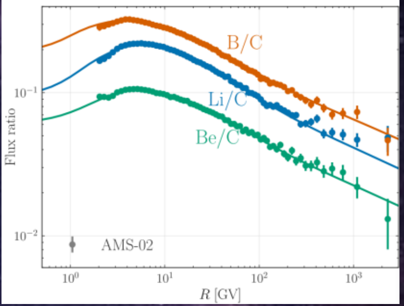
Unambiguous excess respect to secondary positron measured by multiple detectors.

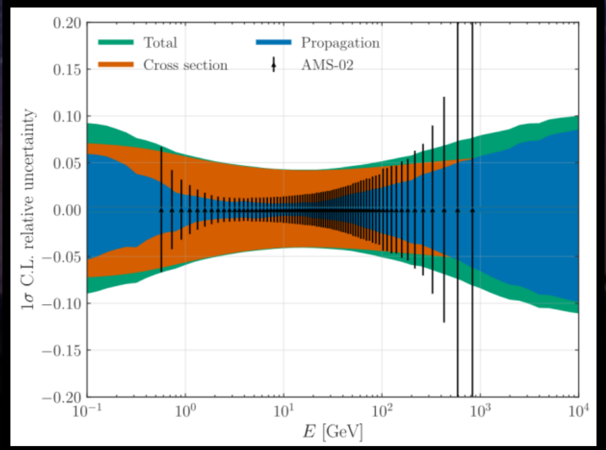


Updated propagation model to fit latest AMS02 results.
Updated production cross section parameters from collider



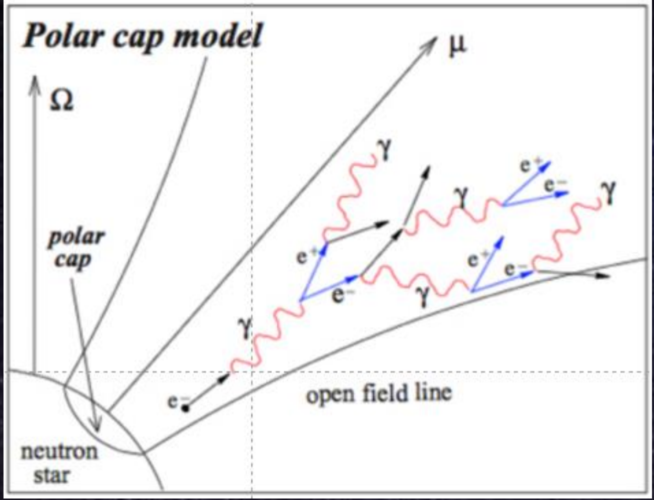






Noticeably, the experimental uncertainties (syst+stats) are already lower than the total model systematics for almost the entire the energy range.

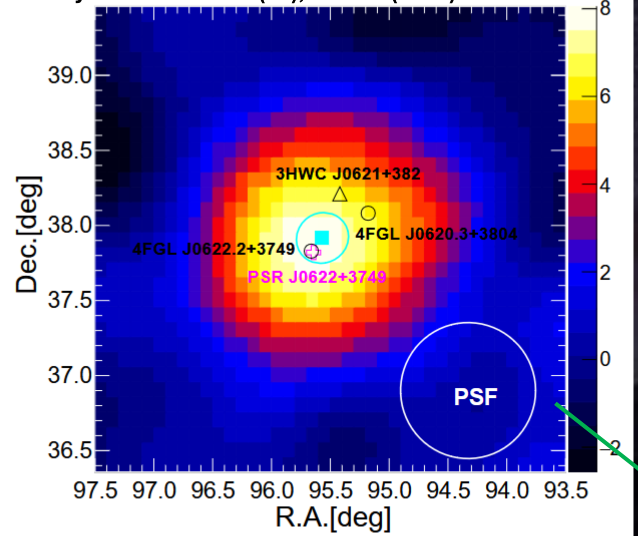
Pulsars as positron sources



Largely accepted as the most likely explanation for the positron excess

High energy e- accelerated in the strong pulsar magnetic field can radiate photons which in turn produce e+ e- pairs.

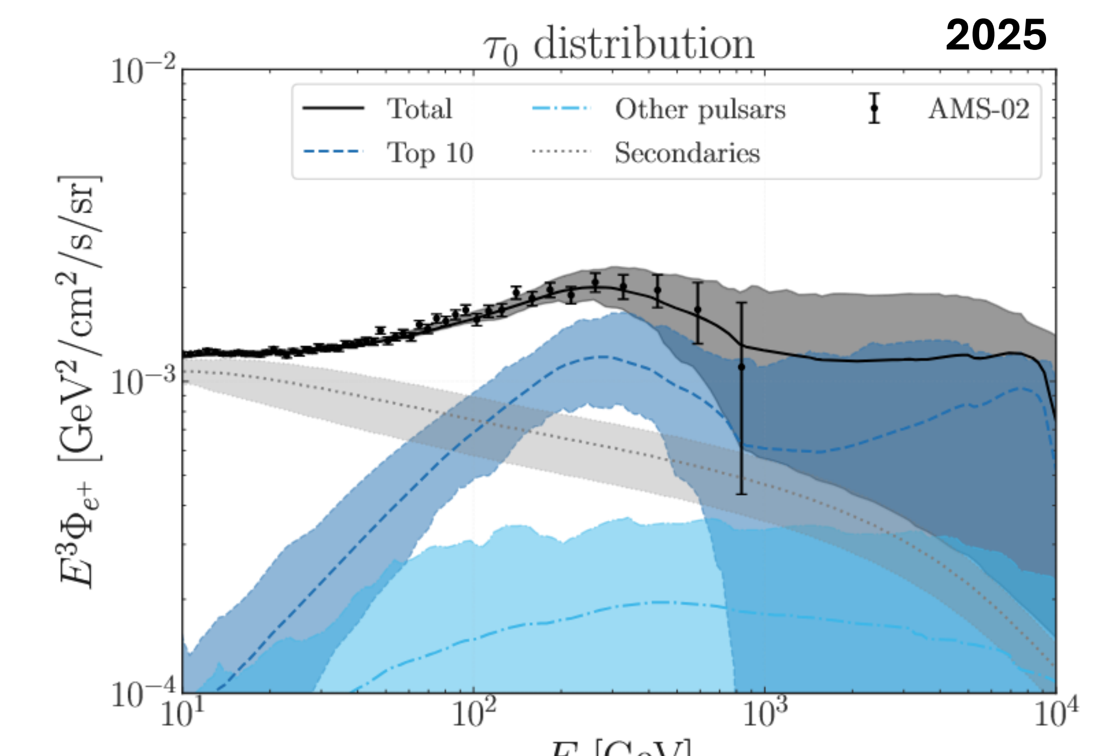
Phys. Rev. Lett. 126(24), 241103 (2021)



γ-ray halos at TeV energies observed by HAWC, LHAASO, MAGIC, HESS, Milagro favored pulsar as primary source of e+ e- (gamma from IC with the ambient interstellar photon). Riv. Nuovo Cim. 47 (2024) 399

LHAASO TeV emission from PSR J0622+3749

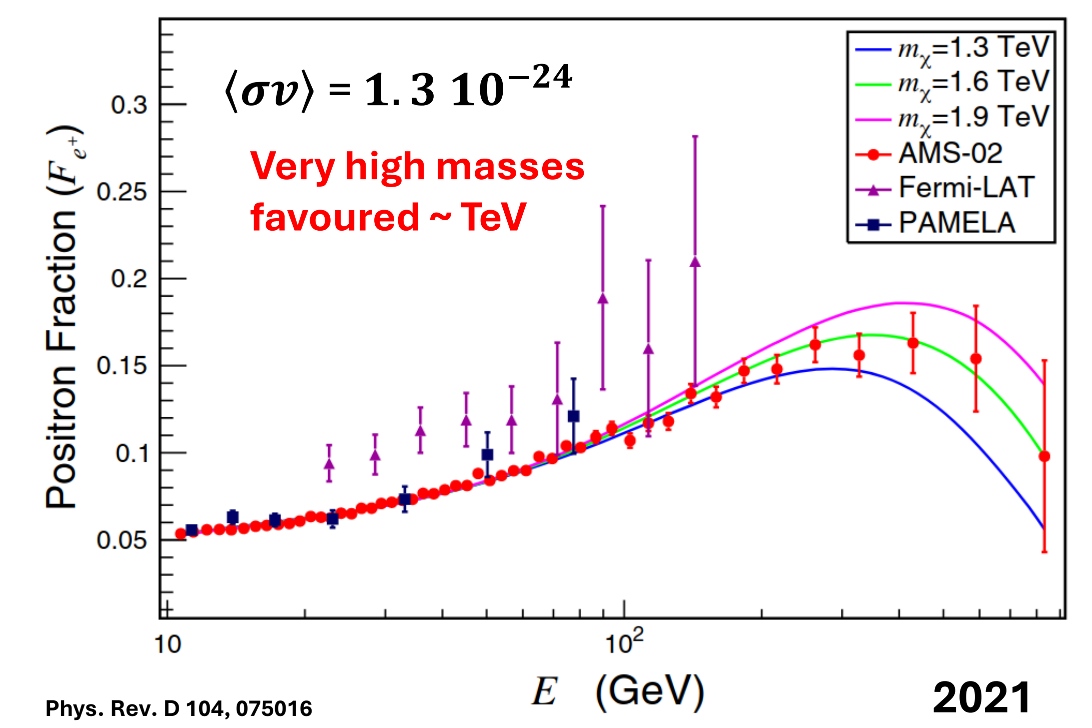
The know population of galactic pulsars can reproduce the positron flux measured at Earth.



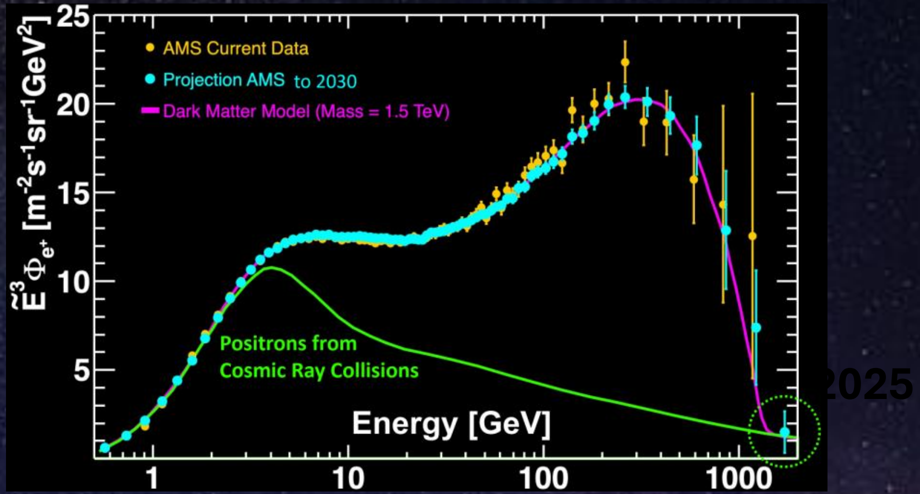
Luca Orusa *et al* JCAP02(2025)029

Dark Matter as positron sources

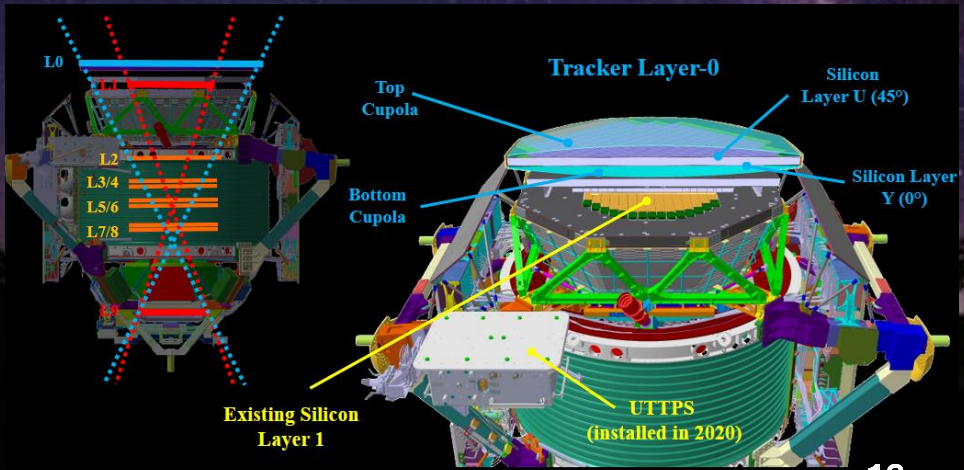
Very ad-hoc models, leptophilic, Sommerfeld enhancement, needs to be introduced in order to reconcile other channels like the antiproton.



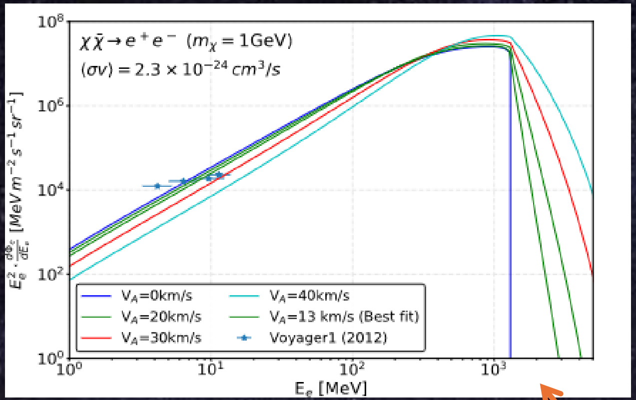
Future

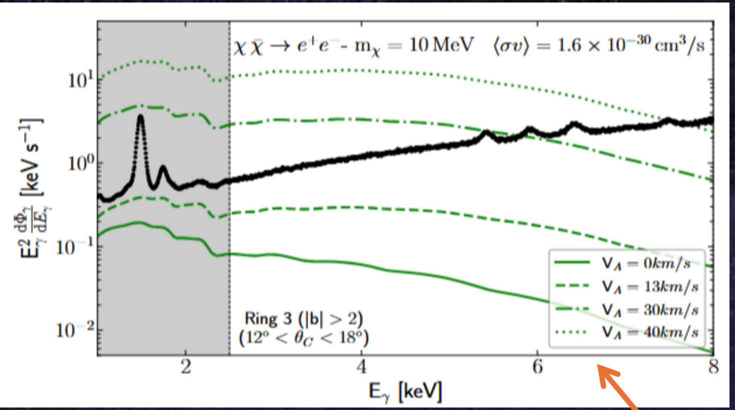


Could be useful to measure more precisely if there is a clear cutoff and if the flux after the cutoff is consistent with only a secondary component. 300% increase in acceptance in AMS02 with a new Tracker Layer. Early 2026.

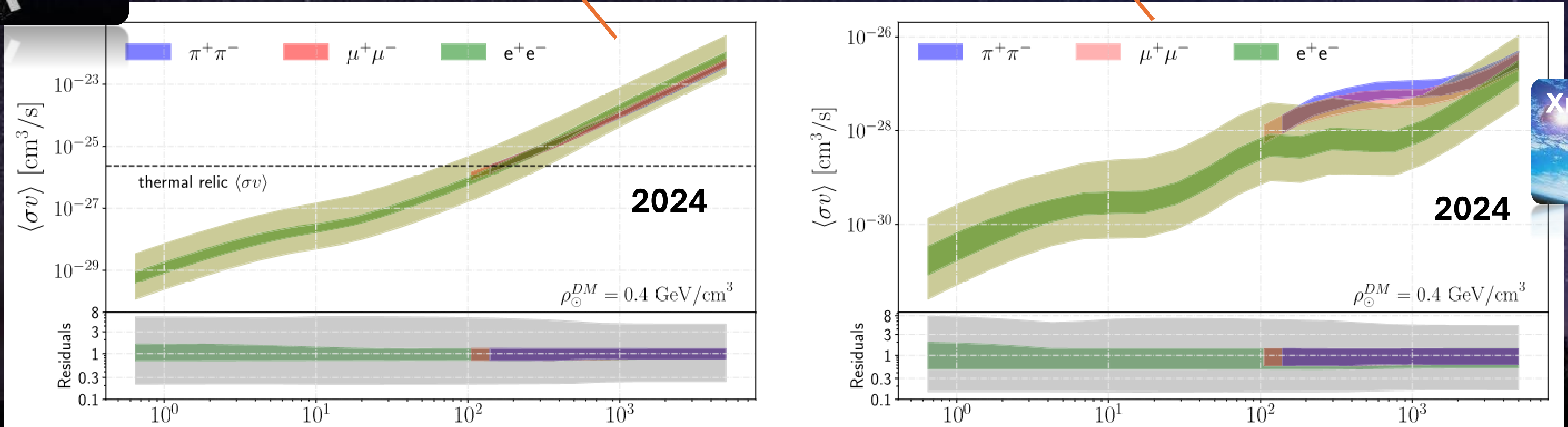


Very low mass DM searches





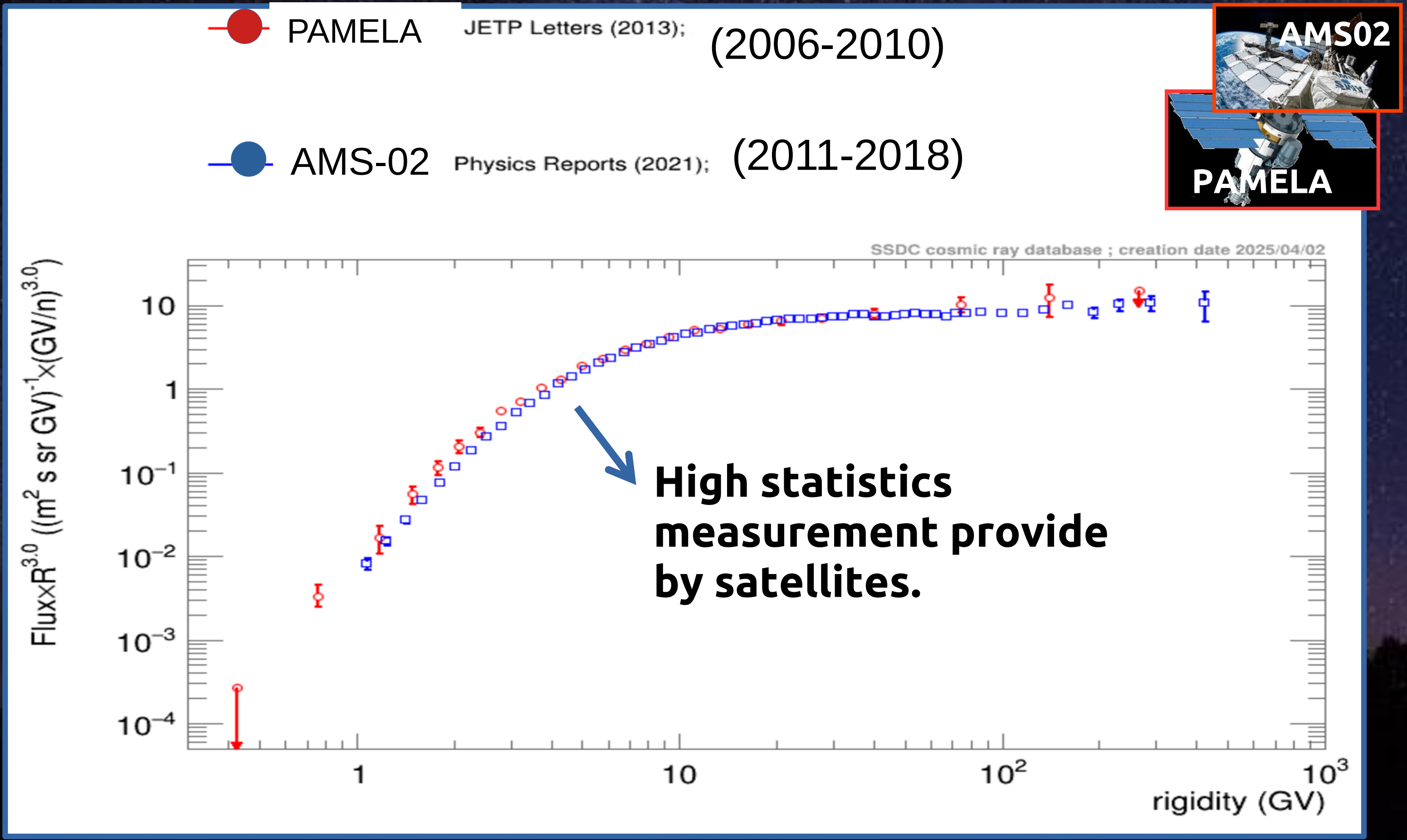
Bremsstrahlung radiation and upscatter the low-energy Galactic photon fields via the inverse Compton process, generating a broad emission from X-ray to γ-ray energies observable in experiments such as XMM-Newton

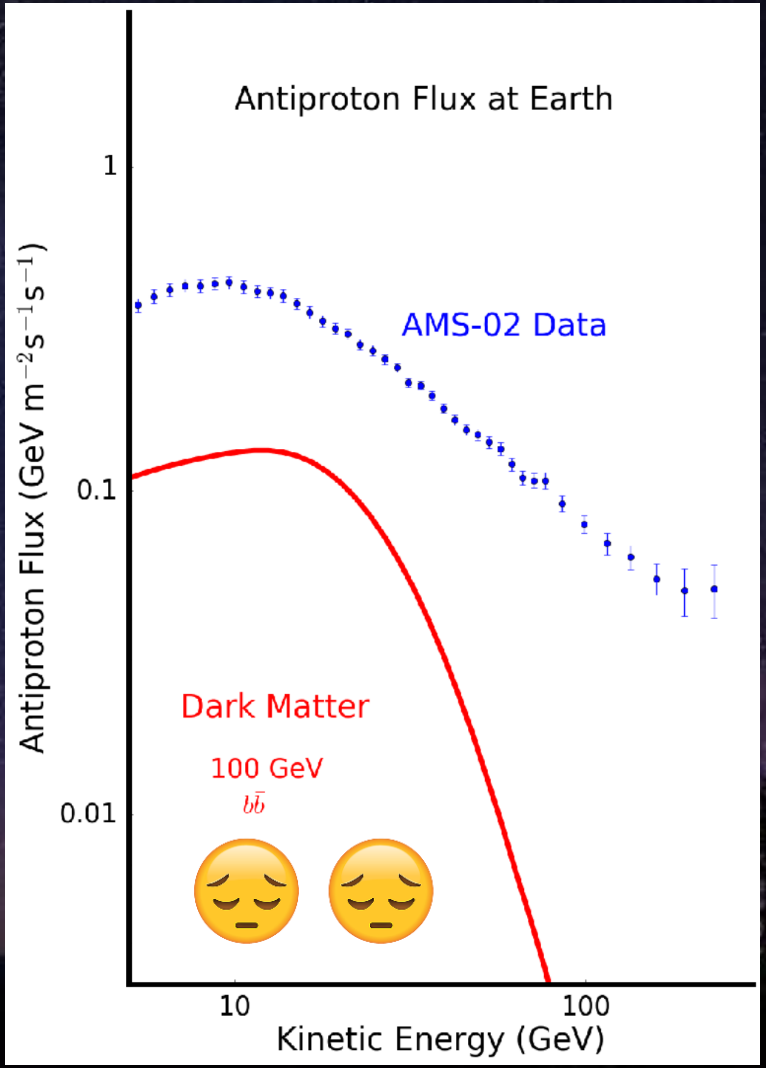


The Astrophysical Journal, 968:46 (16pp), June 10

Antiproton as DM messenger

The DM signal it's only a fraction of the total signal, dominater by the secondary antiprotons produced by primary CR with the ISM

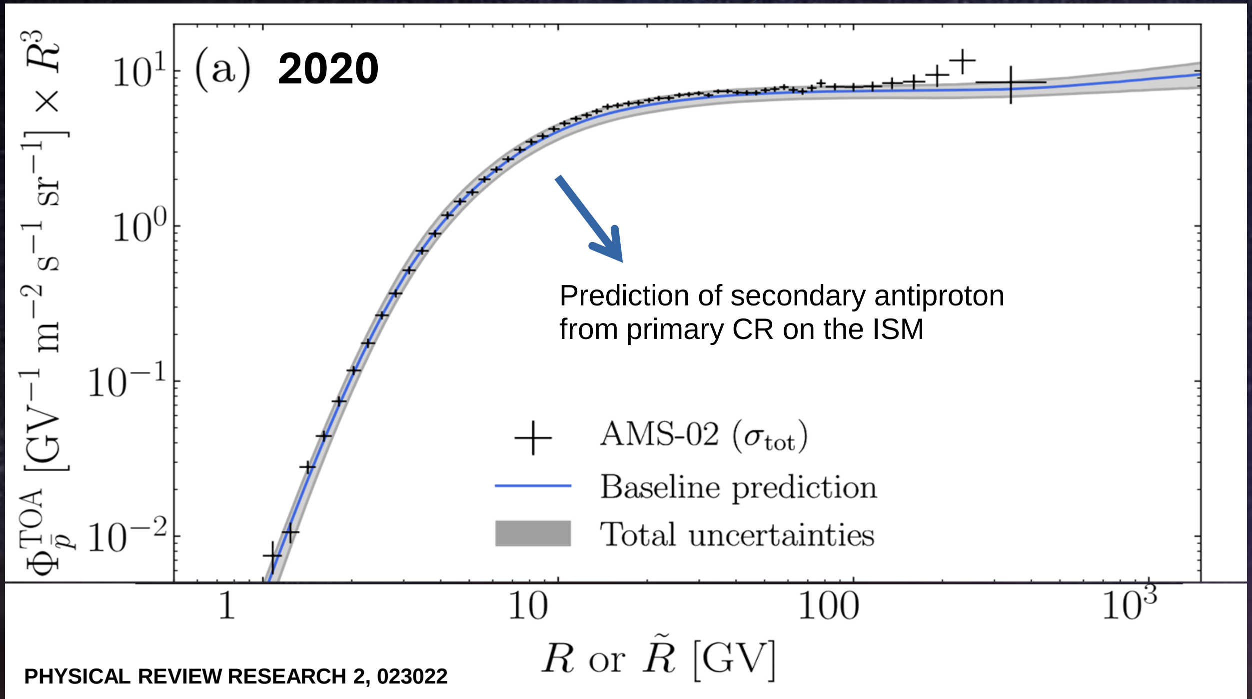


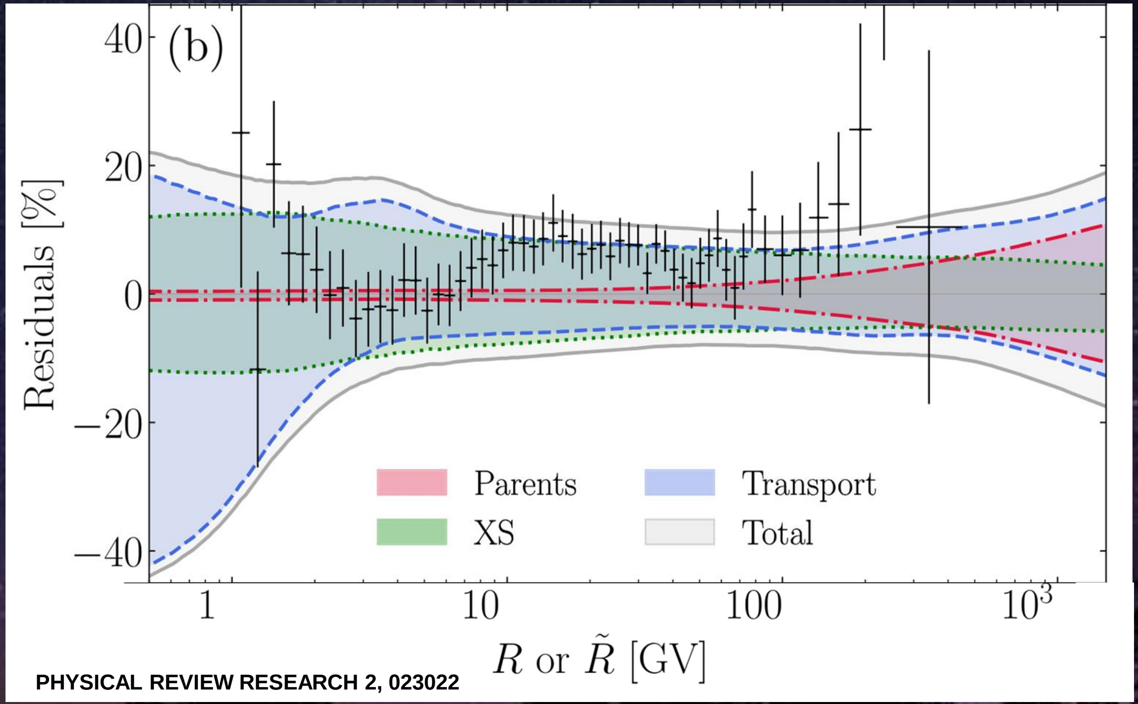


Antiproton as DM messenger

Overall, the secondary pbar flux is predicted consistent with AMS-02 data

As for e+, the statistical+systematics uncertainties of experimental data are lower than the model.

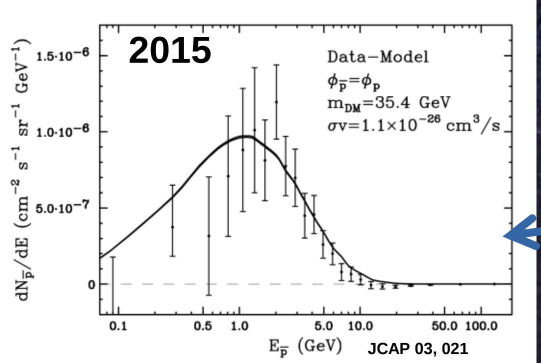


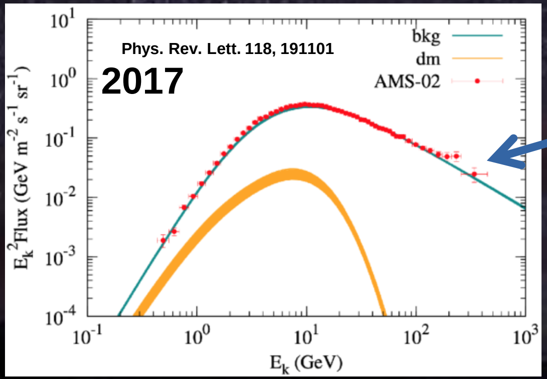


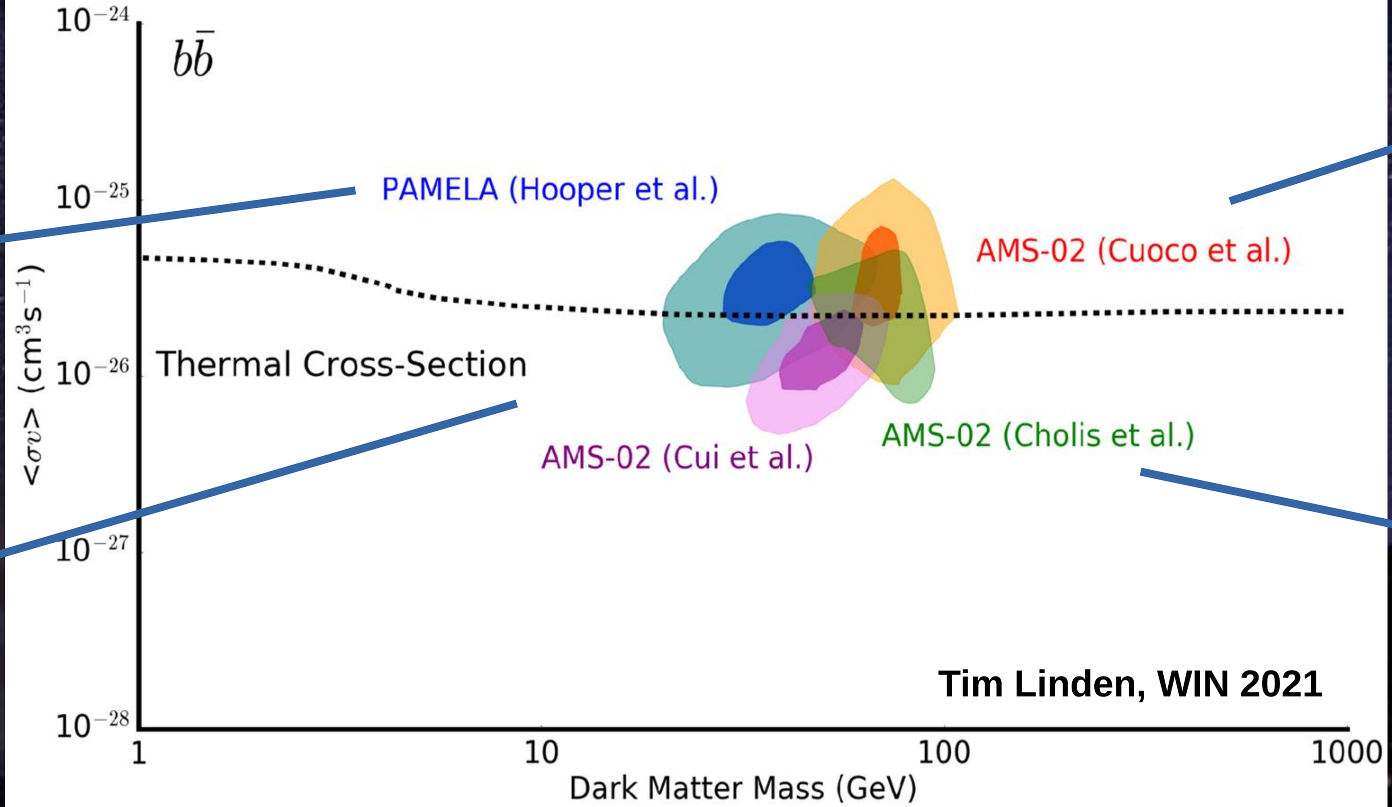
A tiny dark matter contribution cannot be excluded

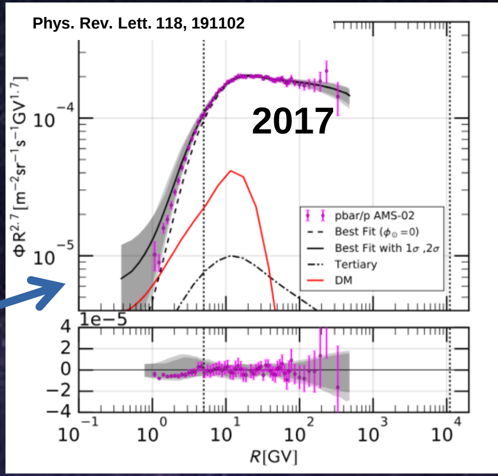
The low energy antiproton excess

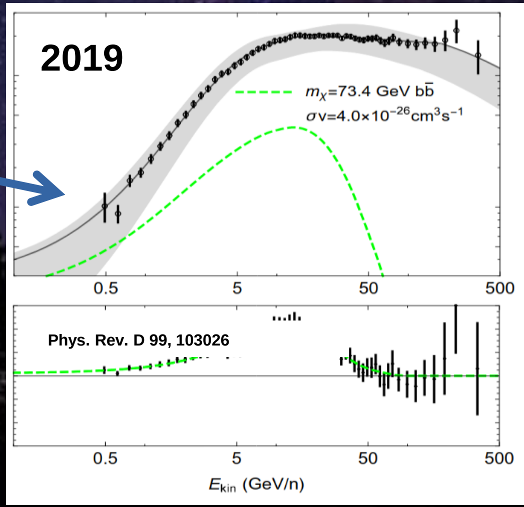
Multiple independent groups found excess in low energy AMS02 (PAMELA) data. Mass 30-100 GeV





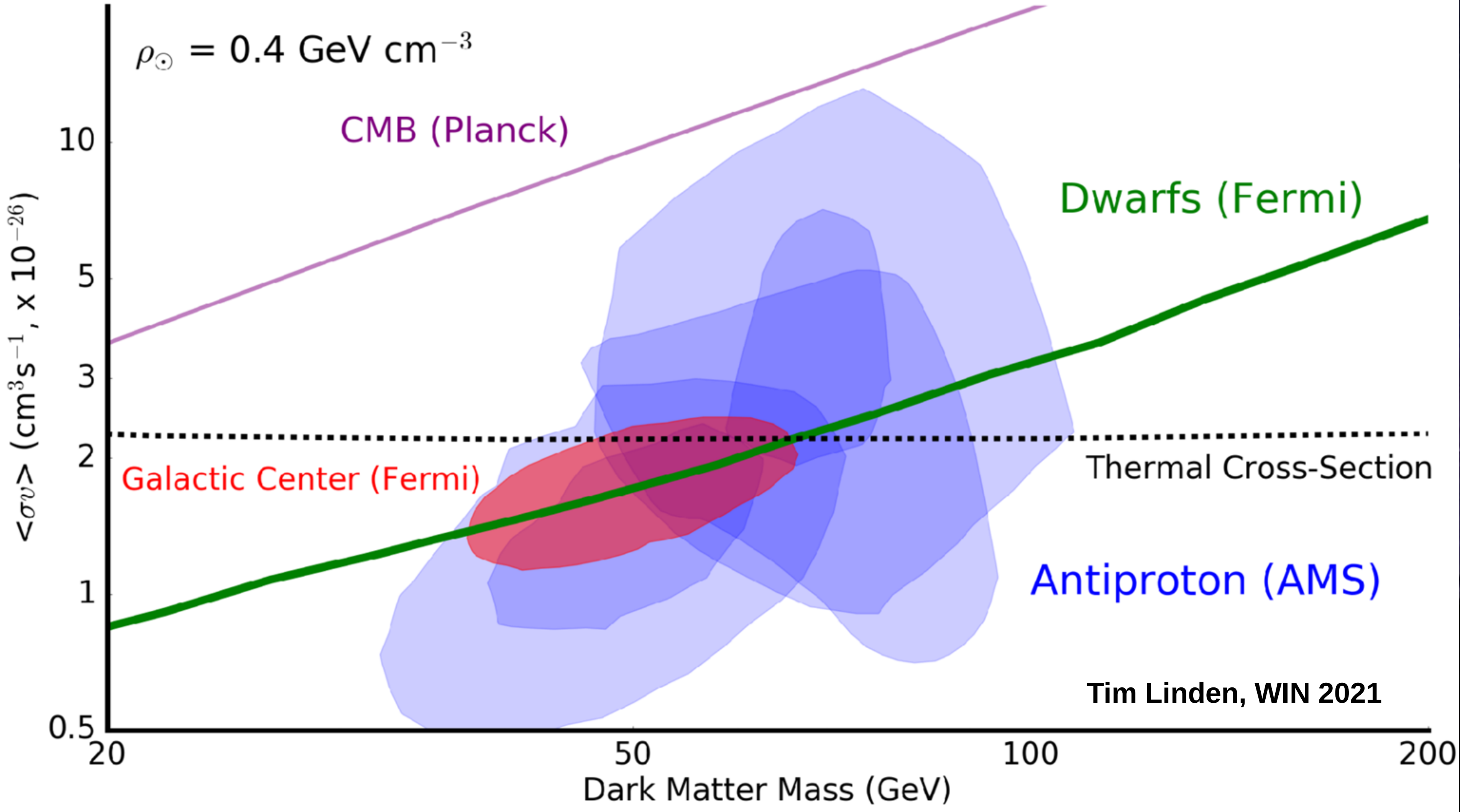




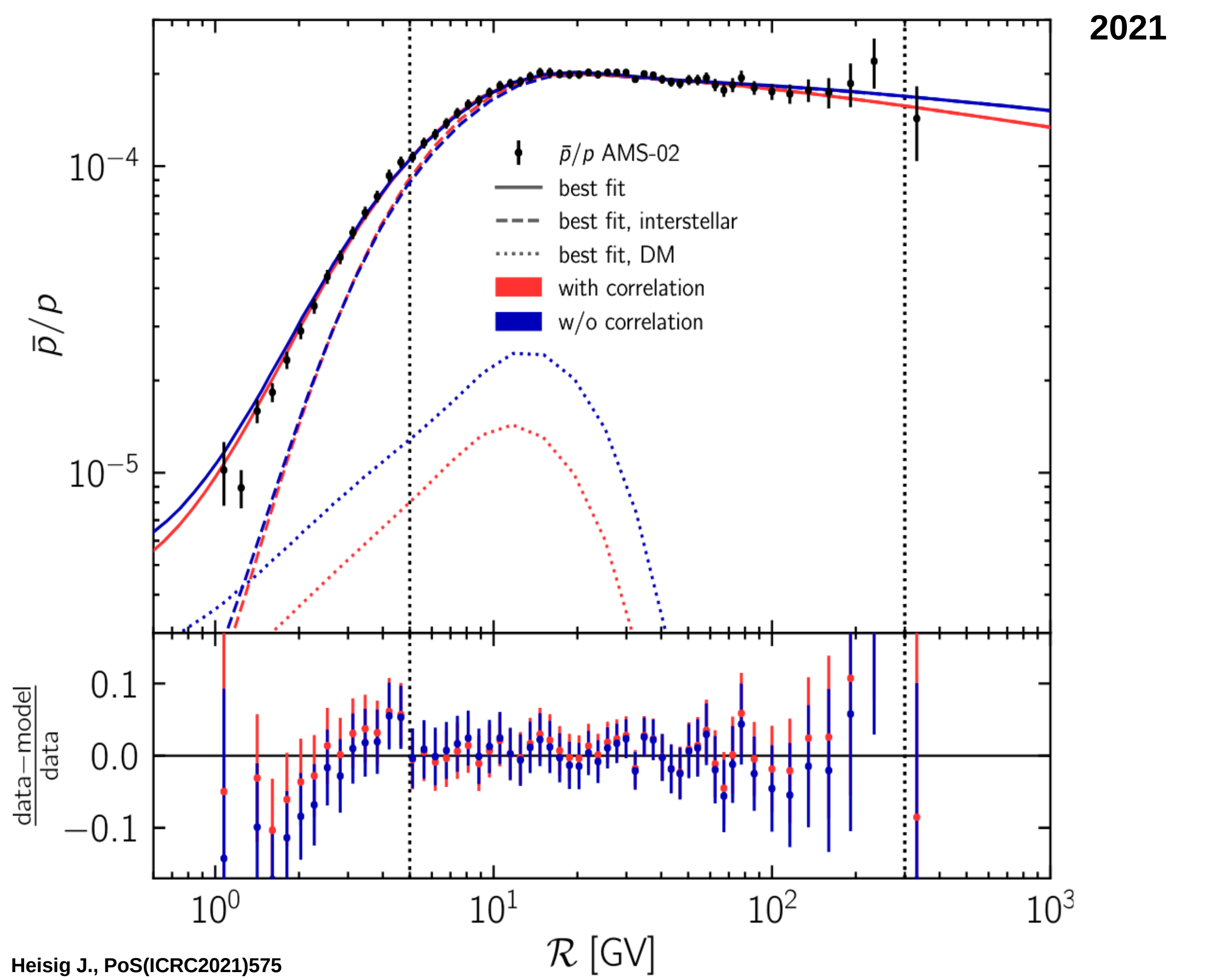


The low energy antiproton excess

The antiproton excess is compatible with excess from Galactic Center



The low energy antiproton excess?



Heisig J., PoS(ICRC2021)575

"Here, we have considered another source of uncertainties, namely correlations in the AMS-02 systematic errors... The most relevant of these stem from cross sections for cosmic-ray absorption in the detector…

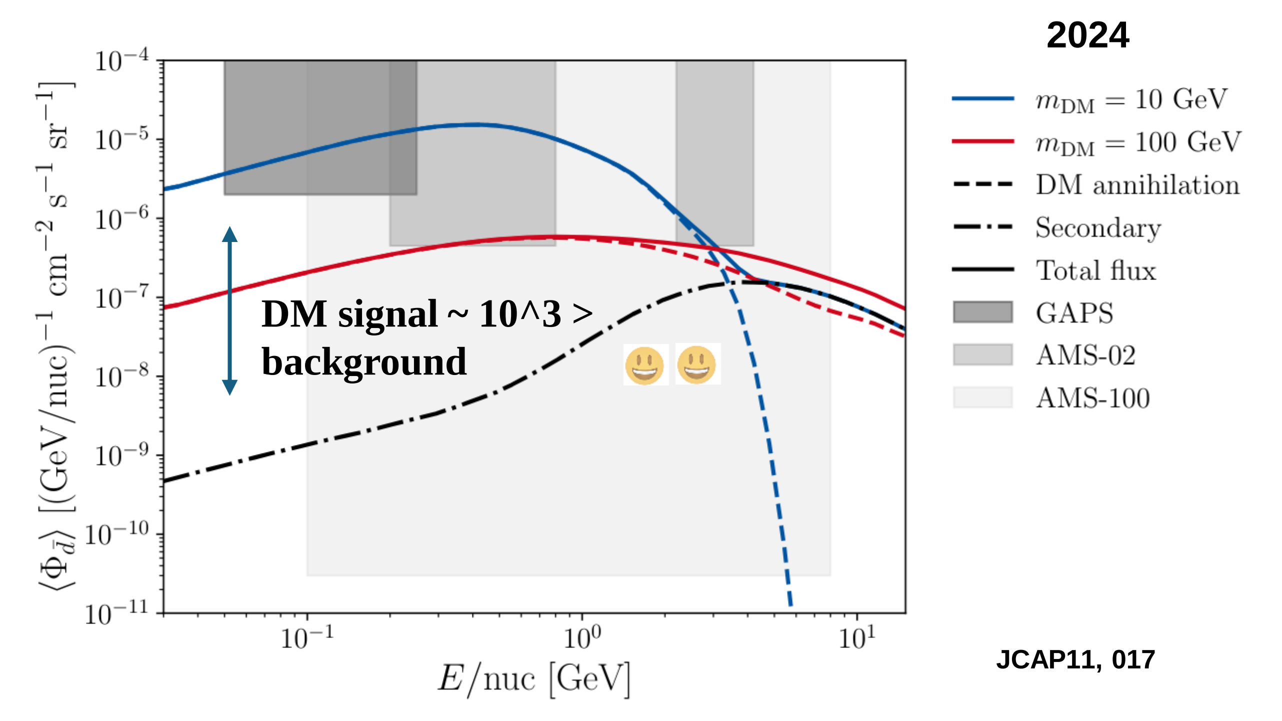
Their inclusion reveals that the excess is not robust."

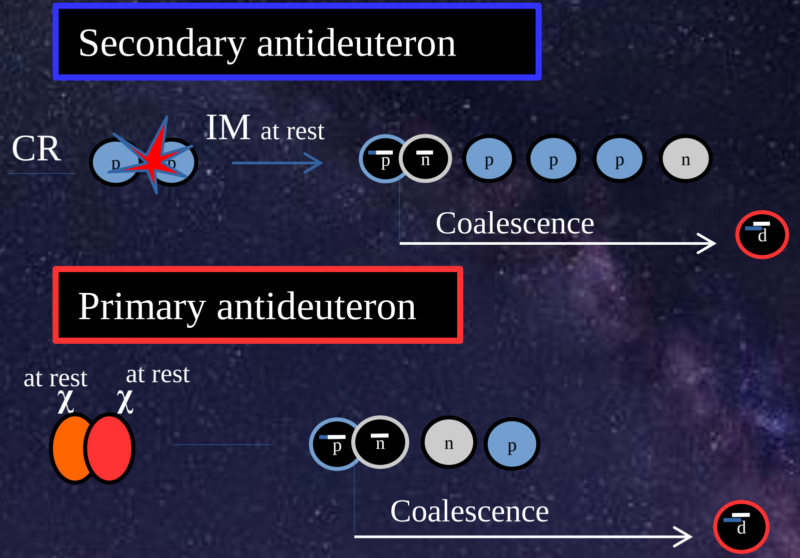
How one treats these correlations can lead to very different conclusions; some groups find that the excess persists at >4**σ** significance, while others find that the significance of this feature can disappear almost entirely

Dan Hooper, IDM 2024, L'Aquila

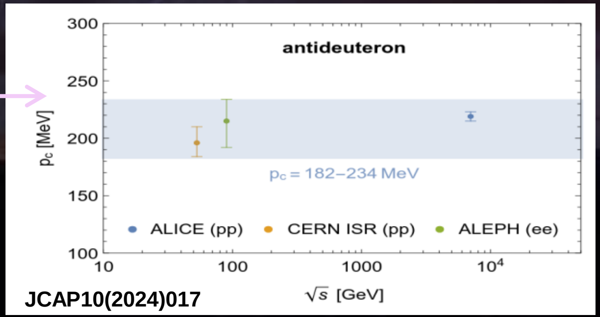
Antideuteron as DM messenger

Potentially a background free channel for a specific energy range due to very low secondary signal.

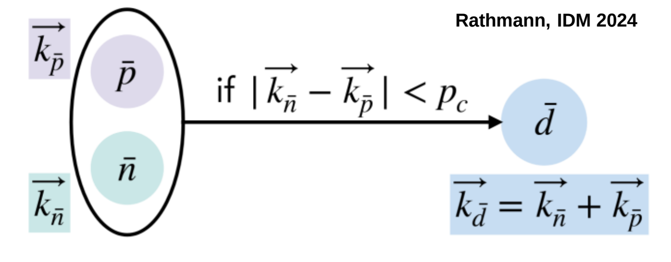




10-15 % uncertainties

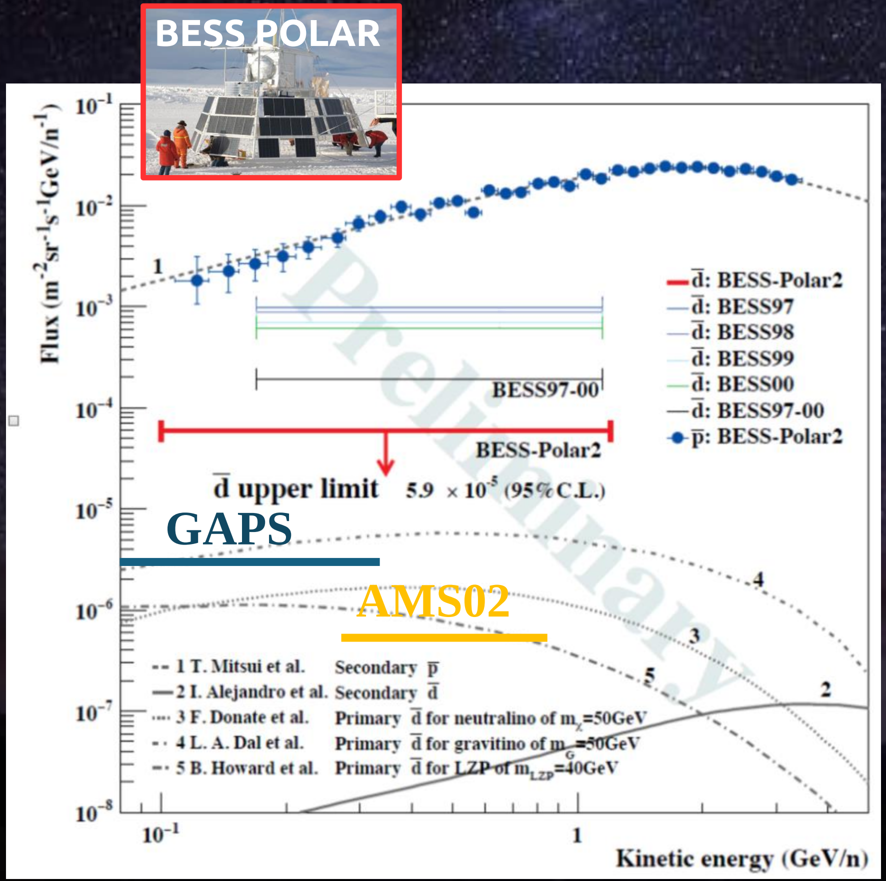


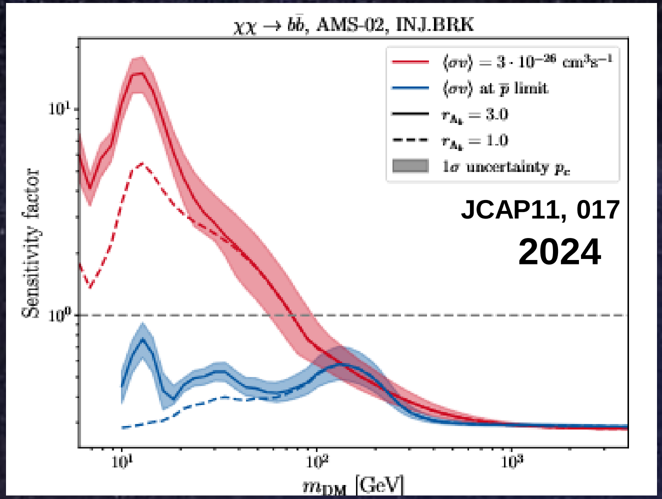
Coalescence momentum p_c is a key parameter in order to predict fluxes. Obtained from experiment at colliders.

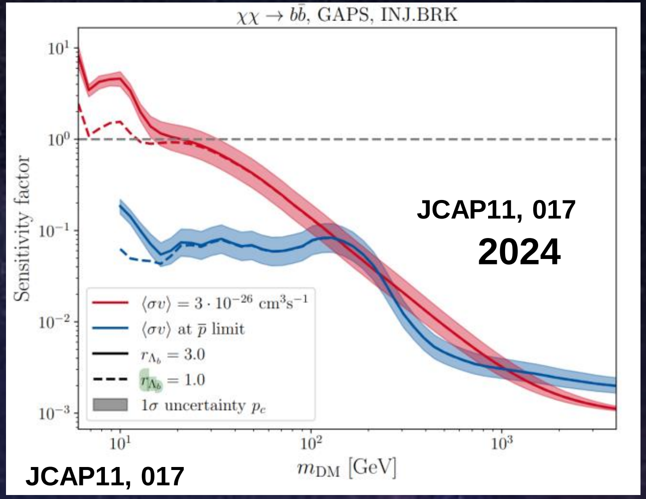


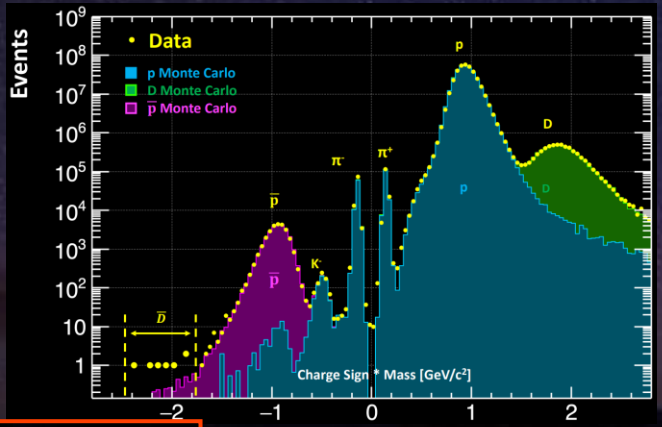
Antideuteron as DM messenger

BESS Polar 2 set the best limits on the antideuteron flux in cosmic rays









Current Status with 11 Years of AMS Data: Antideuterons in 5.7<|R|<9.3 GV Events

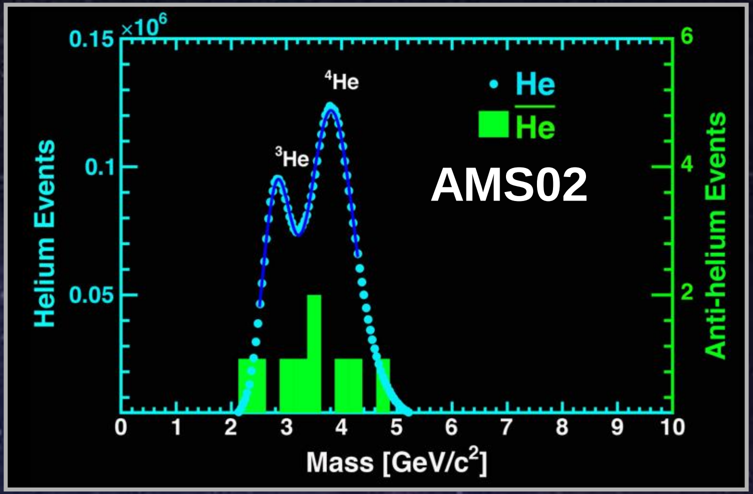
GAPS launch was delayed to the end of 2025.

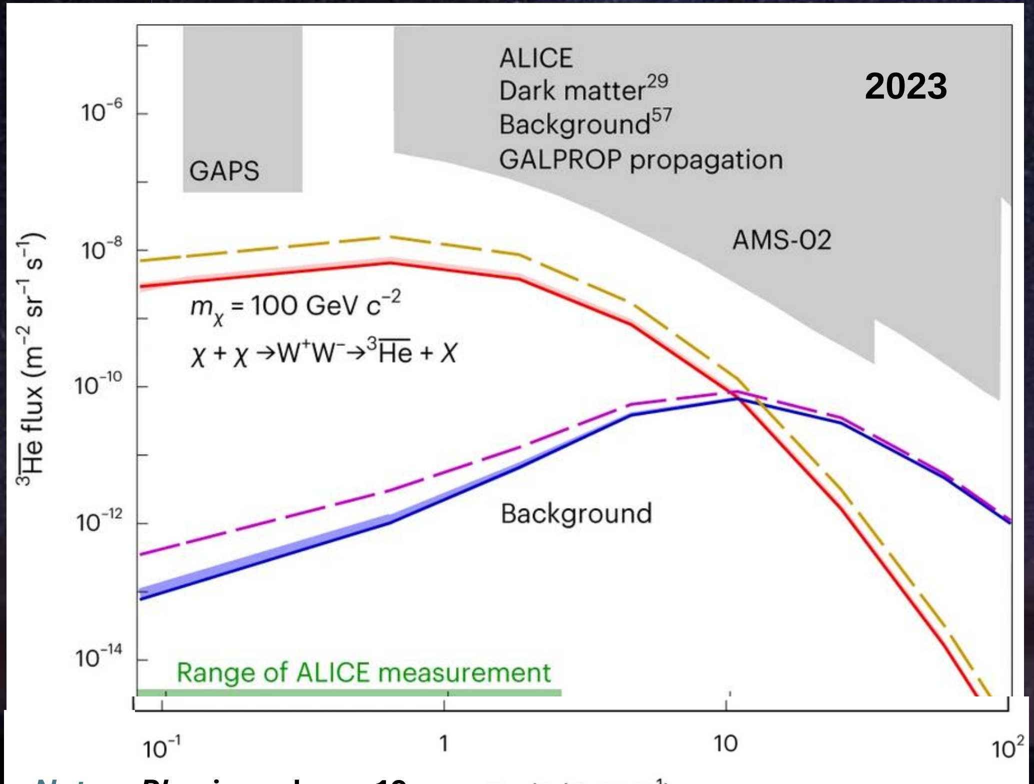
Future

Antihelium as DM messenger

Secondary $\overline{^3He}$ negligible below few GeV.

AMS02 $\overline{He}$ "candidate" ~ 1/year.
Energies > 10 GeV
Mixture of $\overline{^3He}$ and $\overline{^4He}$





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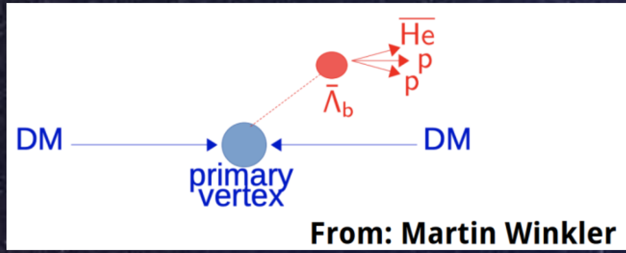
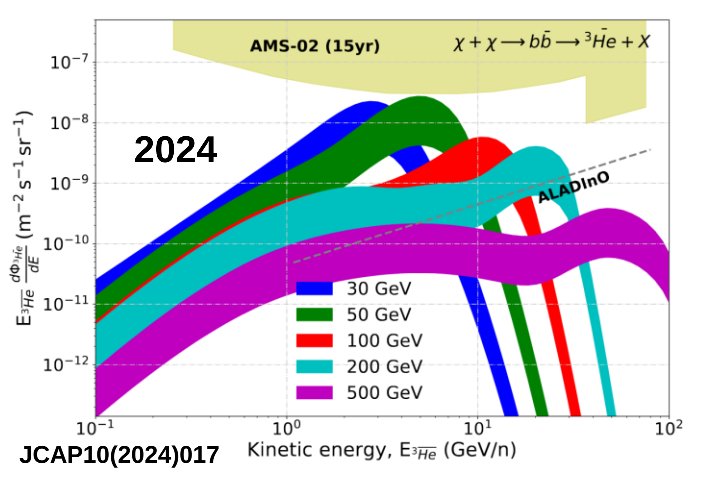


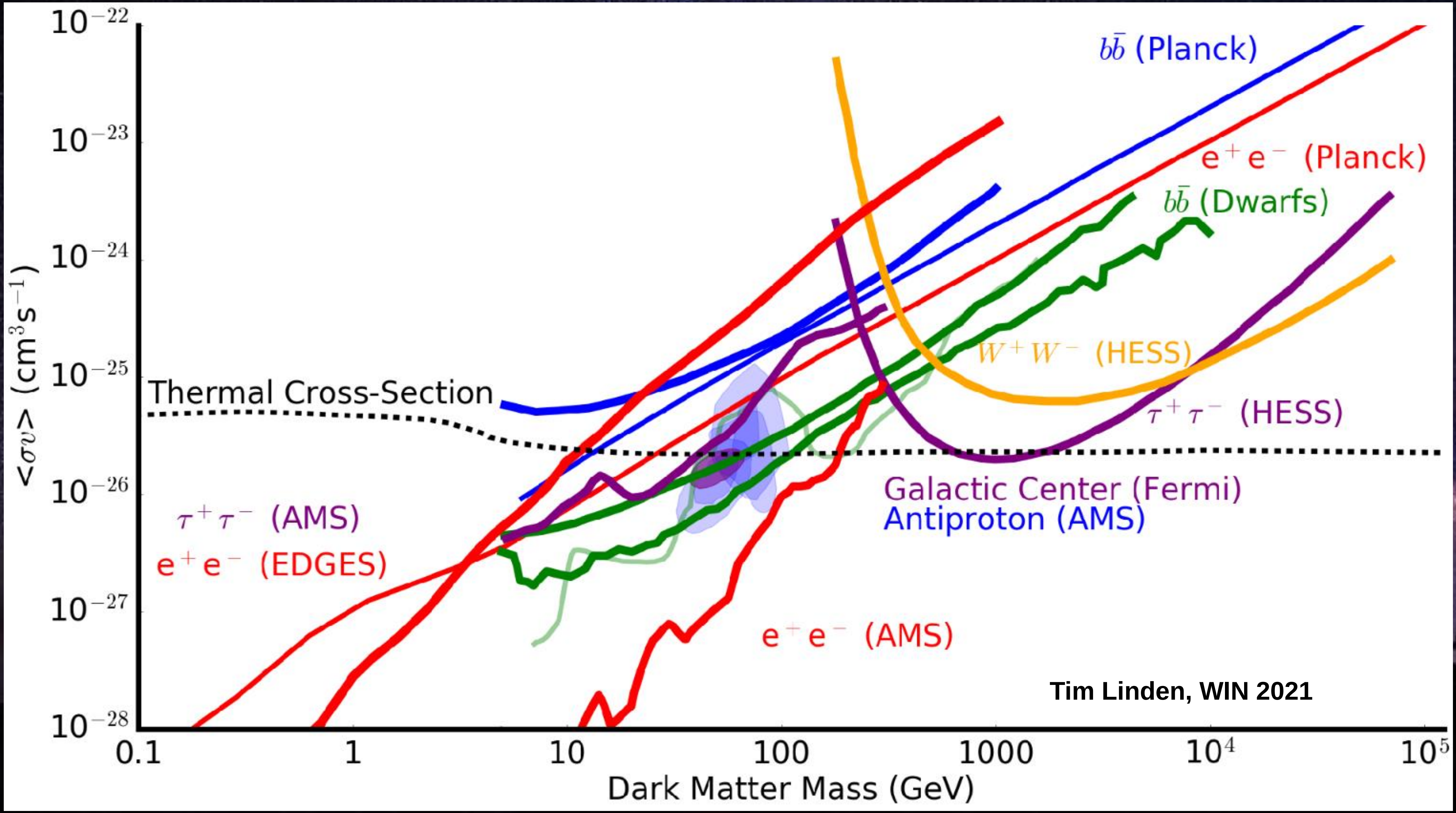
A SM Resonance Enhance $\overline{^3He}$



WIMPs annihilating could account for the detection of O(1) 3He events under optimistic assumptions at energies < 10 GeV.

AntiHelium4 challenging to explain in terms of dark matter!
Antistar, antimatter domain…

Conclusions



Conclusions

No conclusive evidence of DM signals has been found. Possible gamma-ray excess from the Galactic Center and AMS02 antiproton -> absorbed with a better treatment of the model systematics or the correlation between experimental systematics.

The major challenge is the modeling of the background and its associated systematics.

Future: not many experiment (GAPS..) specifically devoted to the indirect searches.

2023

Neutrino and gamma ray experiment from ground will increase limits.

Correlate a signal among multiple messengers.

Is the WIMP paradigm dead?

Backup slides

2023

Is the WIMP Paradigm Dead?

Huge impact from the direct search!

Simple WIMP models predict scattering rates with nuclei that exceed current bounds

An (Incomplete) List of Ways to Reconcile WIMP Dark Matter With All Current onstraints:

1) Co-annihilations between the dark matter and another state

2) Annihilations to W, Z and/or Higgs bosons; scattering with nuclei only through highly suppressed loop diagrams

3) Interaction which suppress elastic scattering with nuclei by powers of velocity or momentum

4) Dark matter that is lighter than a few GeV (relaxing direct constraints)

5) Departures from radiation domination in the early universe (early matter domination; late-time reheating, etc.) which result in the depletion of the dark matter's relic abundance

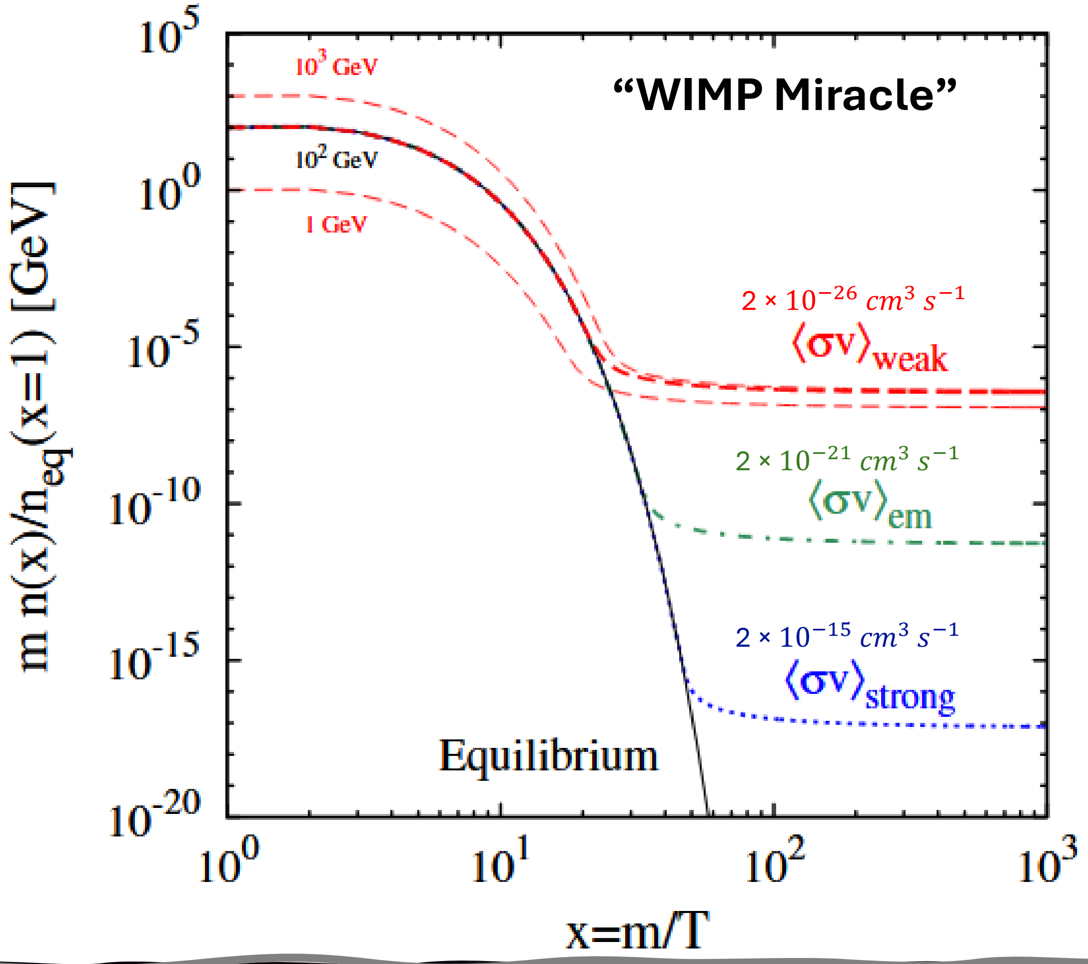
6) The dark matter annihilates to unstable non-Standard Model states (*ie*. hidden sector models)

Although these scenarios can be invisible to both underground detectors and colliders, many are testable with indirect searches

Dan Hooper, IDM 2024, L'Aquila

The WIMP paradigm

Steigman, Dasgupta, Beacom (2012; 1204.3622)



A stable particle species that was in equilibrium with the thermal bath in the early universe will be held near their equilibrium value until their production/ annihilation rate falls below the rate of Hubble expansion -> thermal freeze out

After the freeze out the relic abundancy is directly related to its annihilation cross section:

$$\Omega_X \sim 0.27 \times \left(\frac{2.2 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}}{\langle \sigma v \rangle}\right)$$

To account for the measured Dark Matter (DM) abundance, such a particle must annihilate through an interaction comparable in strength to the weak force and with mass in the scale from few tens of MeV from few tens of TeV

$\langle \sigma v \rangle$ thermally averaged product of the dark matter self-annihilation cross-section times the dark matter velocity

DM searches with radio

e± injected by Dark matter annihilating in the Large Magellanic Cloud.
Synchrotron emission searched by ASKAP telescope