Probing the sterile neutrino portal to Dark Matter with γ rays

Miguel G. Folgado

Based on:
Folgado, Gomez-Vargas, Rius and Ruiz de Austri (JCAP 1808 (2018) no.08, 002)
arXiv:1803.08934

Kavli IPMU, 26/10/2018.

Introduction

The current astrophysical experiments provide a new handle to test BSM physics:

- Dwarf spheroidal galaxies (dSph).
- Galactic Center γ-ray excess.

- Antiprotons to protons ratio.
- Positrons to electrons ratio.

Could this be new DM signals?

Sterile neutrino portal: Set up of the model

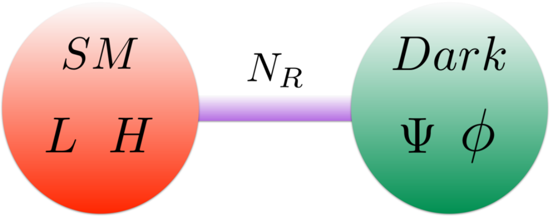


Figure: Escudero, Rius and Sanz (1607.02373)

$$\begin{aligned}\mathcal{L} &= \mu_H^2 H^\dagger H - \lambda_H (H^\dagger H)^2 - \mu_\phi^2 \phi^\dagger \phi - \lambda_\phi (\phi^\dagger \phi)^2 - \lambda_{H\phi} (H^\dagger H)(\phi^\dagger \phi) \\ &- \left(\phi \overline{\Psi}(\lambda_a + \lambda_p \gamma_5) N + Y \overline{L}_L H N_R + \mathrm{h.c.}\right)\end{aligned}$$

Sterile neutrino portal: Set up of the model

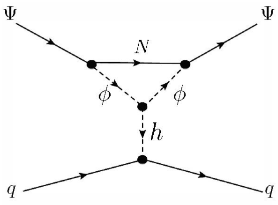
- In this model we have two particles in the hidden sector: The fermionic DM and the scalar mediator that allow the DM annihilation to Sterile Neutrinos.

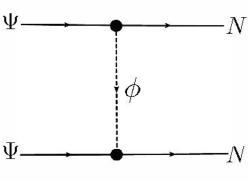
- The main feature of this model is that it connects the generation of neutrino masses and the DM.

- For any (M_ψ, M_N) in the ranges (1 - 3000) GeV we can always obtain the correct relic density using M_Φ and a perturbative coupling!!

$$\Omega h^2 \simeq \frac{10^{-37} cm^2}{\langle \sigma V \rangle} \longrightarrow \langle \sigma V \rangle \simeq 2.2 \times 10^{26} cm^3/s$$

Sterile neutrino portal: Set up of the model





- Direct detection at one loop. Depends on the Higgs portal term: $\lambda_{H\phi}.(H^\dagger H)\,(\phi^\dagger\phi)$
- Annihilation DM only depends on $\left(\phi\overline{\Psi}(\lambda_a + \lambda_p\gamma_5)N\right)$
- $\lambda_{H\phi}$ as small as we want to evade the Direct detection constrains.

Seesaw Mechanism

- Light neutrino masses are generated via TeV scale type I seesaw mechanism. The mass matrix in the basis (ν_α, N_s) is given by:

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & M_D \\ M_D^T & M_N \end{pmatrix} = U^* Diag(M_\nu, M) U^\dagger$$

- Where M_ν is the diagonal matrix with the three lightest eigenvalues of $\mathcal{M}_\nu$, of order M_D^2/M_N, and M contains the heavier ones, of order M_N.

$$\begin{pmatrix} \nu_\alpha \\ N_s \end{pmatrix}_L = U^* \begin{pmatrix} \nu_i \\ N_h \end{pmatrix}_L$$

- The mass eigenstates $n = (\nu_i, N_h)$ are related to the active and sterile neutrinos, (ν_α, N_s).

Seesaw Mechanism

- The unitary matrix U can be written as:

$$U = \begin{pmatrix} U_{\alpha i} & U_{\alpha h} \\ U_{si} & U_{sh} \end{pmatrix}$$

- At leading order in the seesaw expansion parameter, $O(M_D/M_N)$:

$$U_{\alpha i} = [U_{PMNS}]_{\alpha i} \qquad U_{\alpha h} = [M_D M_N^{-1}]^*_{\alpha h}$$

$$U_{si} = -[M_D M_N^{-1} U_{PMNS}]^*_{si} \qquad U_{sh} = I$$

- At this order the states N_h and N_s coincide.

Decay channels of the sterile neutrinos

- 3-body decays:

$$\Gamma(N \to \nu q\bar{q}) = 3AC_{NN}[2(a_u^2 + b_u^2) + 3(a_d^2 + b_d^2)]f(z)$$

$$\Gamma(N \to 3\nu) = AC_{NN}\left[\frac{3}{4}f(z) + \frac{1}{4}g(z,z)\right]$$

$$\Gamma(N \to lq\bar{q}) = 6AC_{NN}f(\omega,0)$$

$$\Gamma(N \to \nu l\bar{l}) = AC_{NN}(3(a_e^2 + b_e^2)f(z) + 3f(\omega) - 2a_e g(z,\omega))$$

- The functions $f(z)$, $f(w,0)$ and $g(z,w)$ can be found in Dittmar, Santamaria, Gonzalez-Garcia and Valle (Nucl. Phys. B 332 (1990) 1).

$$z = (M_N/M_Z)^2 \qquad \omega = (M_\omega/M_Z)^2$$

$$A = \frac{G_F^2 M_N^5}{192\pi} \qquad C_{ij} = \sum_{\alpha=}^{3} U_{\alpha i} U_{\alpha j}^*$$

Decay channels of the sterile neutrinos

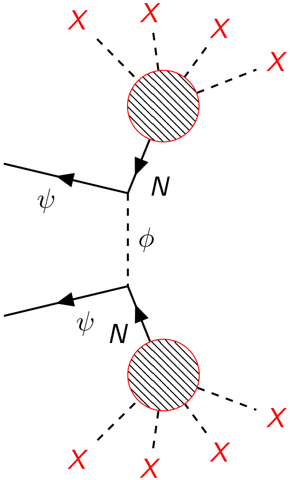
- If $M_N > M_W$ 2-body decays to SM particles are open:

$$\Gamma(N \to W^\pm l^\mp) = \frac{g^2}{64\pi}|U_{\alpha N}|^2 \frac{M_N^3}{M_W^2}\left(1 - \frac{M_W^2}{M_N^2}\right)^2 \left(1 + \frac{2M_W^2}{M_N^2}\right)$$

$$\Gamma(N \to Z\nu_\alpha) = \frac{g^2}{64\pi c_W^2}|C_{\alpha N}|^2 \frac{M_N^3}{M_Z^2}\left(1 - \frac{M_Z^2}{M_N^2}\right)^2 \left(1 + \frac{2M_Z^2}{M_N^2}\right)$$

$$\Gamma(N \to h\nu_\alpha) = \frac{g^2}{64\pi}|C_{\alpha N}|^2 \frac{M_N^3}{M_W^2}\left(1 - \frac{M_h^2}{M_N^2}\right)^2$$

Indirect signals



- After hadronization the final states of the process are:

$$X = \gamma, \bar{P}, e^{+}, ...$$

- How can we obtain this final spectra?
  - Sarah
  - SPheno
  - Madgraph
  - Pythia
  - MicrOMEGAs

Indirect signals from the model

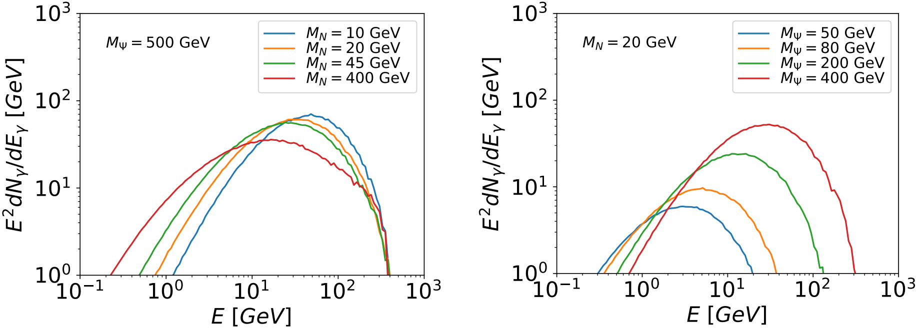
Uncharged particles:

- γ-rays
  - Galactic center excess.
  - Dwarf spheroidal galaxies.

Charged particles:

- Antiprotons ($\bar{p}$)
  - Antiproton excess.
- Positrons (e^{+})

γ-Spectrum of Neutrino Portal Model



- Variations in the DM and N masses induce changes in the shape of the spectrum.

Can the model fit the GCE?

Two sources for the GCE in our analysis:

$$\Phi = \Phi_{astro} + \Phi_{DM}$$

- $E > 10 GeV$: Extension of the Fermi bubbles.
- $E < 10 GeV$: DM annihilation.

- The spectral shape of the Fermi bubbles is described by a power law times an exponential cut off. We assume the same form for the astrophysical contribution to the GCE.

$$\Phi_{astro} = N E^{-\alpha} e^{-E/E_{cut}}$$

Can the model fit the GCE?

- For the DM component, the differential flux of photons from a window with size $\Delta\Omega$, is given by:

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma) = \frac{J}{8\pi M_{DM}^2} \sum_f \langle \sigma v \rangle_f \frac{dN_\gamma^f}{dE_\gamma}(E_\gamma)$$

In this equation J is the J-factor that encapsulates the information about the dark matter distribution:

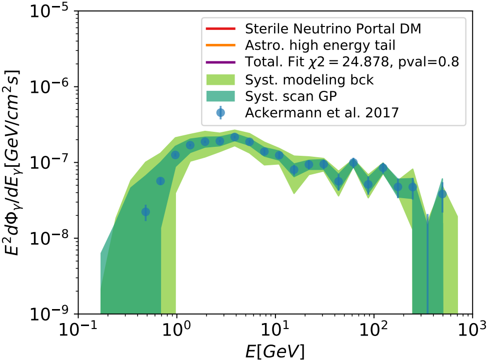
$$J = \int_{\Delta\Omega} d\Omega \int \rho_{DM}^2(s) ds \qquad \rho_\Psi(r) = \rho_s \left(\frac{r}{r_s}\right)^{-\gamma} \left(1 + \frac{r}{r_s}\right)^{-3+\gamma}$$

Can the model fit the GCE?

$$\chi^2 = \sum_{i,j} (\Phi_i^{obs} - \Phi_i^m) \Sigma_{i,j}^{-1} (\Phi_j^{obs} - \Phi_j^m) \qquad (1709.10429)$$

- For each point of the DM model, (M_ψ, M_N), we vary N, α, E_{cut} and J-factor for find the best fit in this point Φ_{best}^m and save χ^2_{best}.
- We create a set of 10^5 pseudo-random data normal distributed with mean at Φ_{best}^m according to $\Sigma_{i,j}^{-1}$.
- We compute χ^2 between Φ_{best}^m and each of the 10^5 data.
- We create a χ^2 distribution using this data.
- The integrated χ^2 distribution up to χ^2_{best} gives the p-value of the model.

Can the model fit the GCE?



- Two sources for the GCE:

$$\Phi = \Phi_{astro} + \Phi_{DM}$$

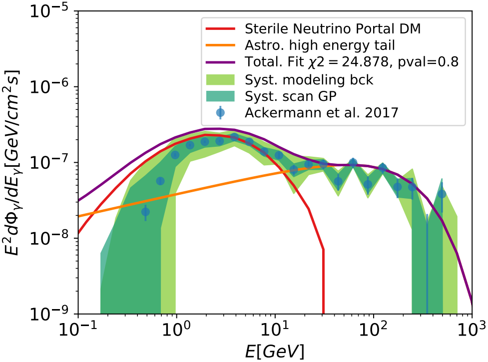
- Best fit point (M_ψ, M_N):

$$(55, 51)\ \text{GeV}$$

- Very impressive p-value:

$$P - value \simeq 0.8 \text{ !!}$$

Can the model fit the GCE?



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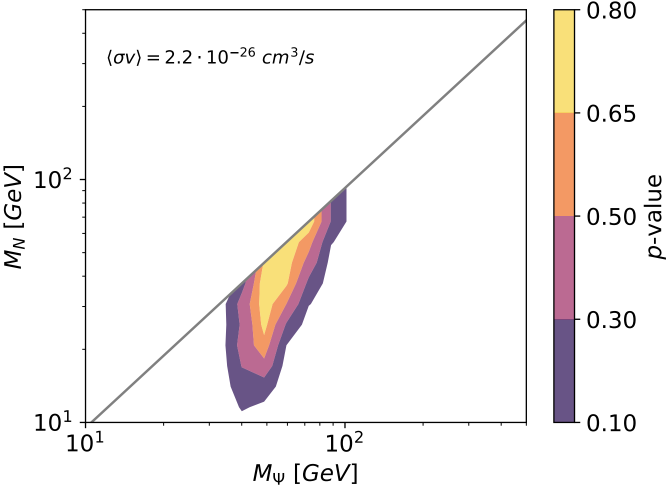


Dwarf spheroidal galaxies (dSphs)

- The GCE is not the only constraint that we can use over the γ-rays. No excess has been detected by Fermi-LAT from the dSphs.
- Test statistic (TS) to obtain 90% C.L. upper limits on the DM annihilation cross section.

gamLike v.1.0

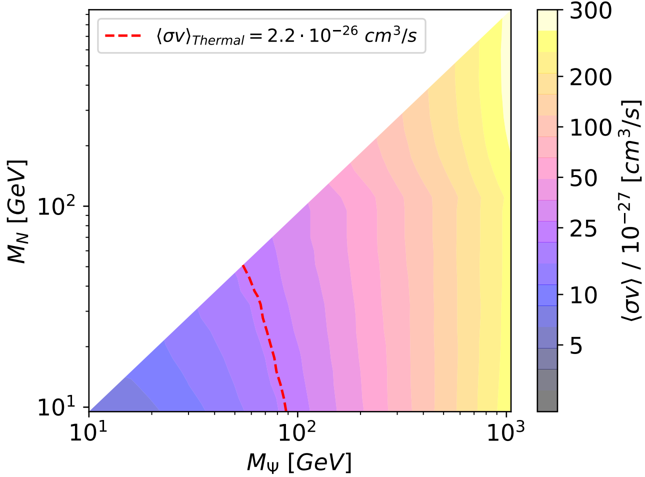
$$TS = -2\ln(\mathcal{L}_0/\mathcal{L})$$

$\mathcal{L}_0 \rightarrow$ No DM case

$\mathcal{L} \rightarrow (M_\psi,\, M_N)$ point

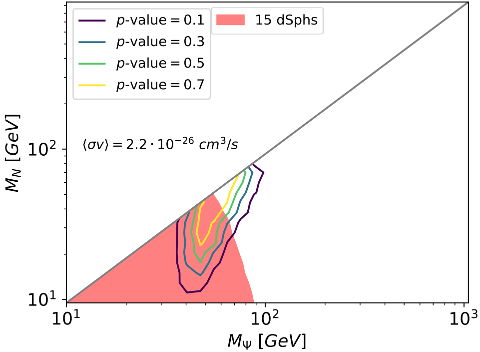
- If $TS > 2.71$ the parameter space point is excluded because it is not compatible with the background at 90% C.L.

Dwarf spheroidal galaxies (dSphs)



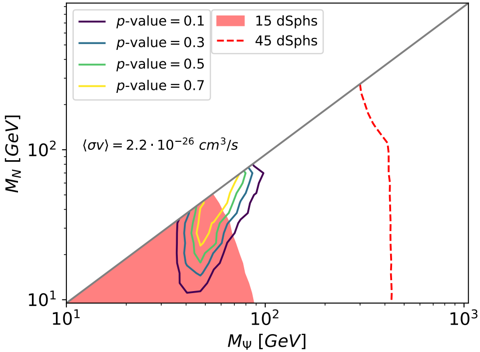
Is this new constraint compatible with the GCE fit?

- The dSphs sets a stringent limit which excludes DM masses below $\sim$ 50 GeV (90 GeV) for N masses near to 50 GeV (10 GeV).

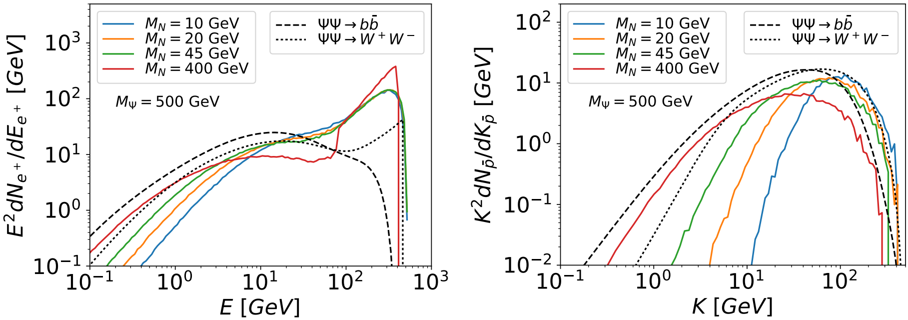


15 years Fermi-LAT prospects for dSphs

- 3 times more dSphs discovered (45 dSphs).
- Sensitivity increases as the square-root of the observation time.
- Constraints are expected to be improved by a factor of 5.



e^+ and $\bar{p}$ spectrum



- The shape of the e^+ and $\bar{p}$ spectra depends on the sterile neutrino and DM masses

Charge particles propagation

Based on Cirelli et al. (1012.4515)

Positrons

$$\frac{d\Phi_{e^\pm}}{dE}(E, r_\odot) = \frac{v_{e^\pm}}{8\pi b(E, r_\odot)} \left(\frac{\rho(r_\odot)}{M_\psi}\right)^2 \langle \sigma v \rangle \int_E^{M_\psi} dE_s \frac{dN_e^\pm}{dE}(E_s) I(E, E_s, r_\odot)$$

$I(E, E_s, r_\odot)$ is the generalized halo function and encodes the astrophysical information and $b(E, r_\odot)$ is the energy loss coefficient function.

Antiprotons

$$\frac{d\Phi_{\bar{p}}}{dK}(E, r_\odot) = \frac{v_{\bar{p}}}{8\pi} \left(\frac{\rho(r_\odot)}{M_\psi}\right)^2 R(K) \langle \sigma v \rangle \frac{dN_{\bar{p}}}{dE}(K)$$

The function R(K) encodes all the astrophysics of production and propagation.

Charge particles propagation

- Three propagation models: MAX, MED and MIN. R(K) and $I(E, E_s, r_\odot)$ depends on the propagation scheme.
- In our analysis we use the MED scheme.

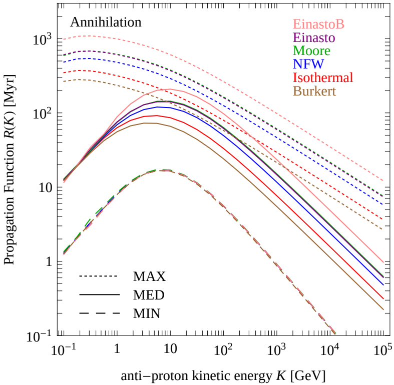
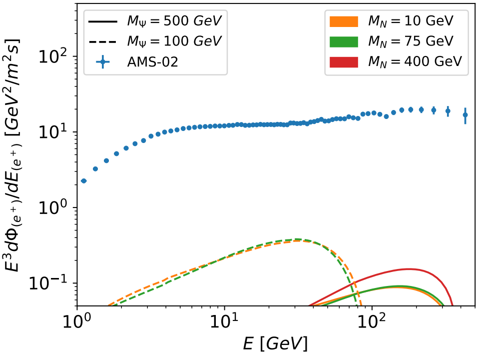


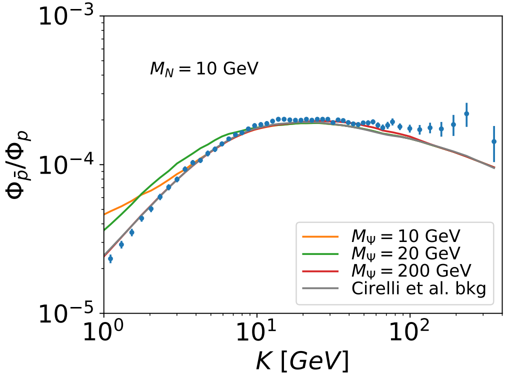
Figure: Cirelli et al. (1012.4515)

About e^+



- e^+ flux well below AMS-02 data.
- This model can not account for the observed e^+ flux

And maybe... $\bar{p}$?



- AMS-02 reports an anti-proton excess. There are many uncertainties in the propagation model. For this reason we have not fitted the excess.
- Even so, it provides a rough estimate of the constraint from $\bar{p}$.

Constraints from antiprotons

- Total flux given by our model:

$$\Phi_{\bar{p}}(K_i, M_\Psi, M_N) = \Phi_{\bar{p},bkg}(K_i) + \Phi_{\bar{p},\Psi}(K_i, M_\Psi, M_N)$$

where $\Phi_{\bar{p},bkg}(K_i)$ is calculated in 1504.04276.

- We calculate the ratio between this flux and the proton flux data $\Phi_p(K_i)$ from AMS-02.

- For each point of our parameter space (M_ψ, M_N) we construct the estimator:

$$\chi^2 = \sum_i \left[\frac{R(K_i) - \Phi_{\bar{p}}(K_i, M_\Psi, M_N))/\Phi_p(K_i)}{\sigma_i} \right]^2$$

Constraints from antiprotons

- χ_0^2 is the minimum chi-squared (only background-only case).
- We can exclude points in the parameter space (M_ψ, M_N) using the condition:

$$\chi^2(M_\Psi, M_N) - \chi_0^2 \leq 4$$

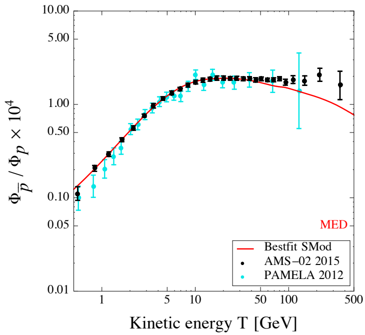
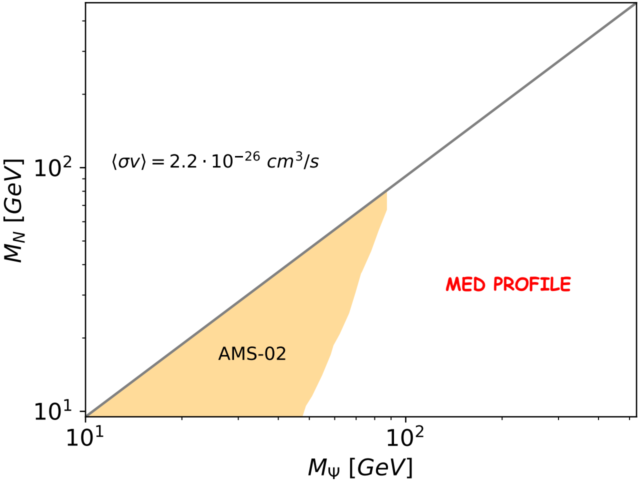


Figure: Giesen et al. 1504.04276.

Constraints from antiprotons



Combined results

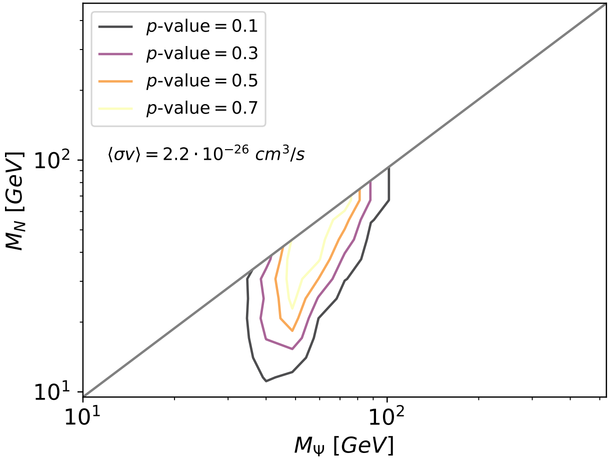
Turning to the initial question:

- Dwarf Spheroidal galaxies.
- Galactic Center γ-ray excess.

- Antiprotons.
- ~~Positrons~~.

Can the model reconcile all of these measurements?

Combined results



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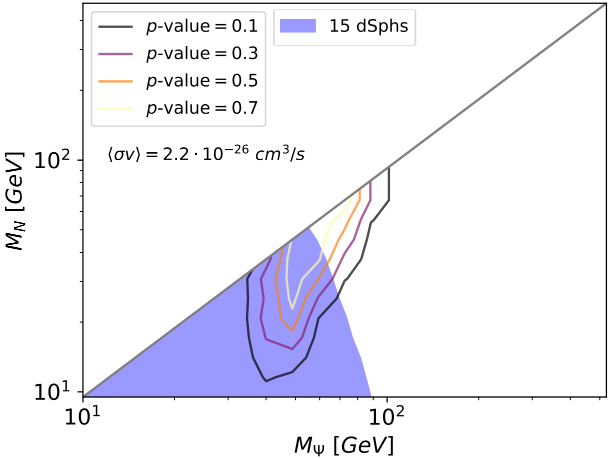

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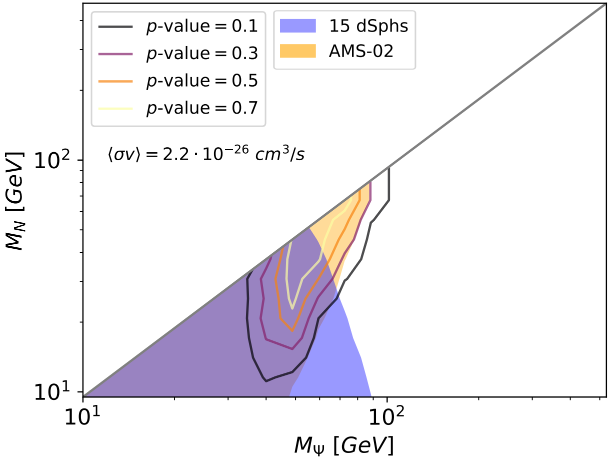

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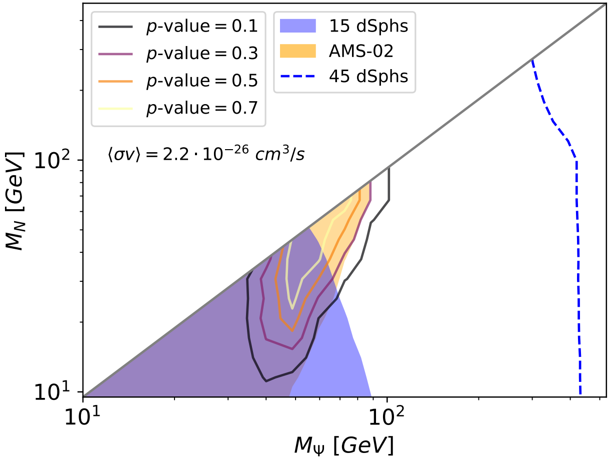

Summary

- The Fermi-LAT Collaboration confirms the existence of a γ-ray excess in the GC peaked at 3 GeV.
- Excellent fit to the GCE (p-value $= 0.8$) with the Sterile neutrino portal to DM.
- There is a sizeable GCE fit region allowed by the dSphs constraints.
- Using the MED propagation scheme we find that current antiproton data from AMS-02 already disfavours a large fraction of GCE fit region.
- The constraint derived of antiprotons is not conclusive, there are a lot of uncertainties in the antiproton background and the propagation model.