Limits on dark matter annihilation and decay from the CALET electron spectrum up to 7.5 TeV

18aW3-4

JPS annual meeting
on-line, 2024/3/18

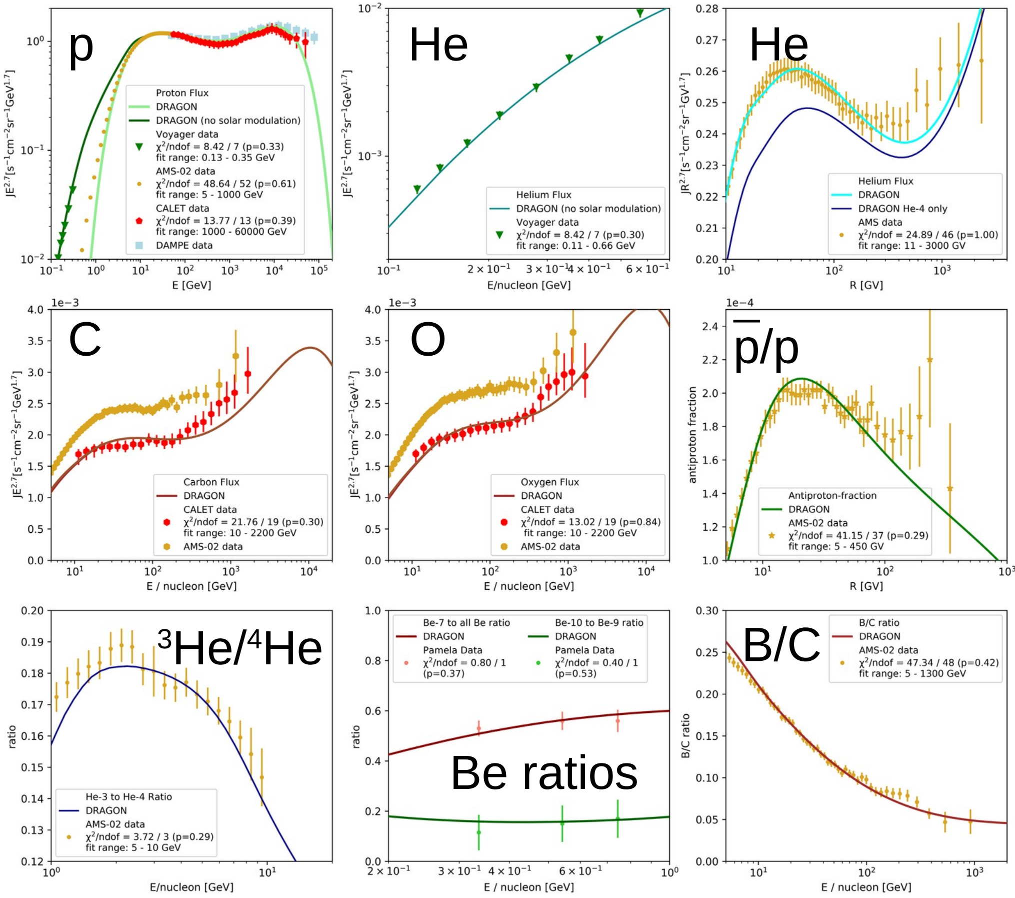
Holger Motz
Waseda University
Faculty of Science and Engineering
Global Center for Science and Engineering

Introduction

- Limits on dark matter annihilation and decay calculated based on CALET all-electron data combined with AMS-02 positron-only data from [PRL 122, 041102 (2019)].
- Individual SNR and pulsar samples combining known and randomly generated sources are used as the background model.
- Method and results based on ICRC2021 CALET data published in [PoS ICRC2023 1385]

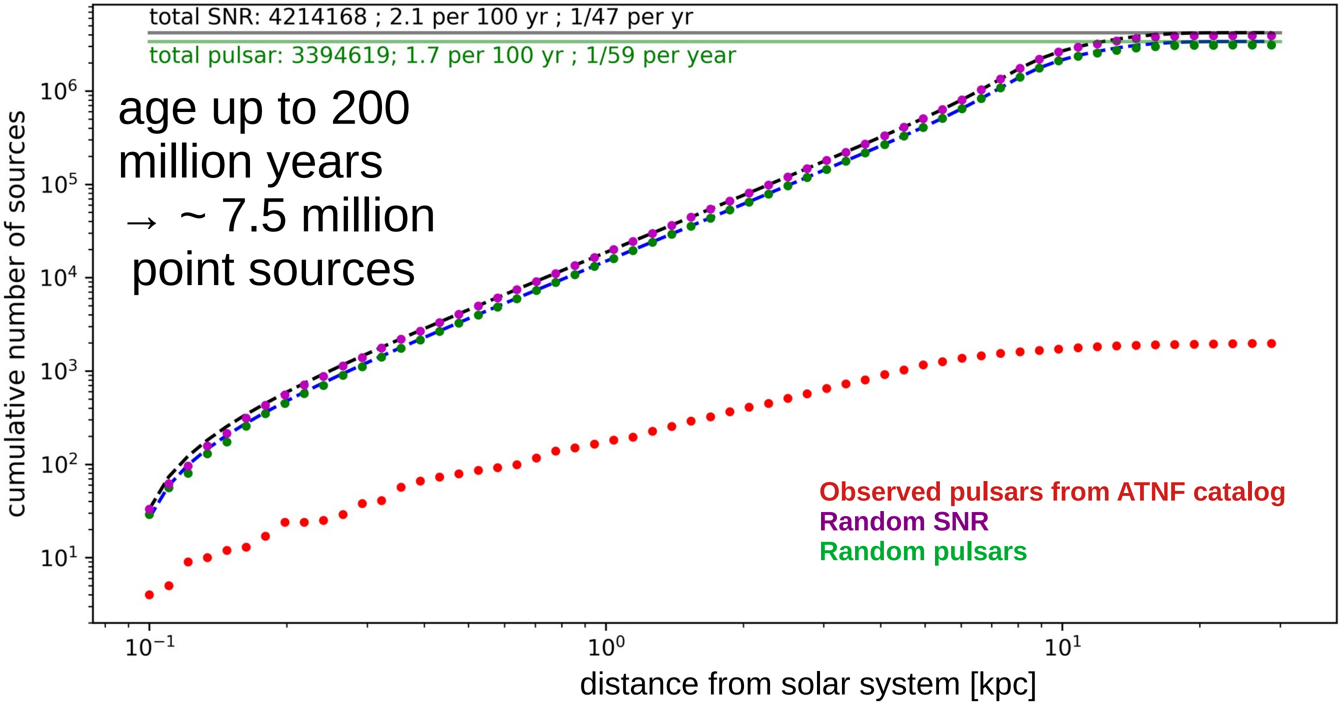
- New aspects in this presentation:
  - Using the latest CALET all-electron spectrum data from from 10.6 GeV to 7.5 TeV published in [PRL 131, 191001 (2023)]
  - Extend the all-electron spectrum below 10 GeV with AMS-02 data published in [Phys. Rep. 894, 1 (2021)]
  - Compare limits from different datasets (CALET+AMS-02 / CALET / AMS-02 all electron and AMS-02 positron only)

Propagation Model



- Calculation of nuclei spectra with DRAGON tuned to explain measurements of AMS-02, CALET and Voyager.
- A common injection spectrum for all primary nuclei species is assumed, structures (hardening, softening) in the observed spectra are due to propagation effects from rigidity and position dependence of diffusion coefficient.
- Secondary electron and positron component of background for the dark matter limit fit also taken from this DRAGON calculation.
- Reference: HM, A Cosmic-Ray Propagation Model based on Measured Nuclei Spectra, [POS ICRC2023 068]

Background: Individual Pulsars and SNR



For each of the studied samples, source properties are randomly generated (pulsars first → add SNR to each pulsar → add more SNRs without pulsar)

Kinetic energy (SN explosion, pulsar rotation)
$Q_{SNR} = 10^{51\pm1}$ erg, log-Gaussian spread
$Q_{pulsar} = 10^{49.3\pm1.01}$ erg , log-Gaussian spread, fit to energies from ATNF catalog pulsars, calculate energy as

$$Q_{pulsar} = \dot{Q}\, T^2 / \tau \quad ; \quad \tau = 10\, kyr$$

Release delay time (time CR are trapped in pulsar wind nebula) for pulsars up to 60 kyr in steps of 10 kyr (SNR: instant emission)

Known pulsars and associated SNR from ATNF catalog added, random sources in same distance and age bin removed if existing in the sample.

Spatial distribution and SN rate:

The interstellar environment of our galaxy, K. Ferriere, Rev.Mod.Phys. 73, 1031-1066 (2001) (same model as used in DRAGON for determining the propagation parameters)

Pulsar birth rate:

The galactic population of young γ-ray pulsar, Kyle P. Watters and Roger W. Romani, 2011 ApJ 727 123

Calculating the Flux at Earth from Pulsars and SNR

$$\phi(E) = \frac{Q_0 \eta}{\pi^{3/2} r_{dif}^3} E_0^{-\gamma} e^{-\frac{E_0}{E_{cut}}} \frac{b(E_0)}{b(E)} e^{-\frac{r^2}{r_{dif}^2}} \quad ; \quad r_{dif} = 2\sqrt{\int_E^{E_0} \frac{D(E')}{b(E')} dE'}$$

$$D(E) = D_{0(@sol)} \left(\frac{E}{E_0}\right)^{\delta_l} \left(1 + \left(\frac{E}{E_{bl}}\right)^{\frac{\delta_l - \delta}{s_l}}\right)^{s_l} \left(1 + \left(\frac{E}{E_{bh}}\right)^{\frac{\delta - \delta_h}{s_h}}\right)^{-s_h}$$

$b(E) = b_{IC}(E) + b_{SYN}(E)$ (IC takes Klein-Nishina effect into account)

source spectrum parameters: efficiency η, index γ, cut-off energy E_{cut}

source properties: total energy Q_0, distance r, diffusion time t_{dif}

propagation parameters: $D_0, \delta, \delta_l, \delta_h, E_{bl}, E_{bh}, s$

- Calculation method adopted from K. Asano et al. 2022 ApJ 926 5

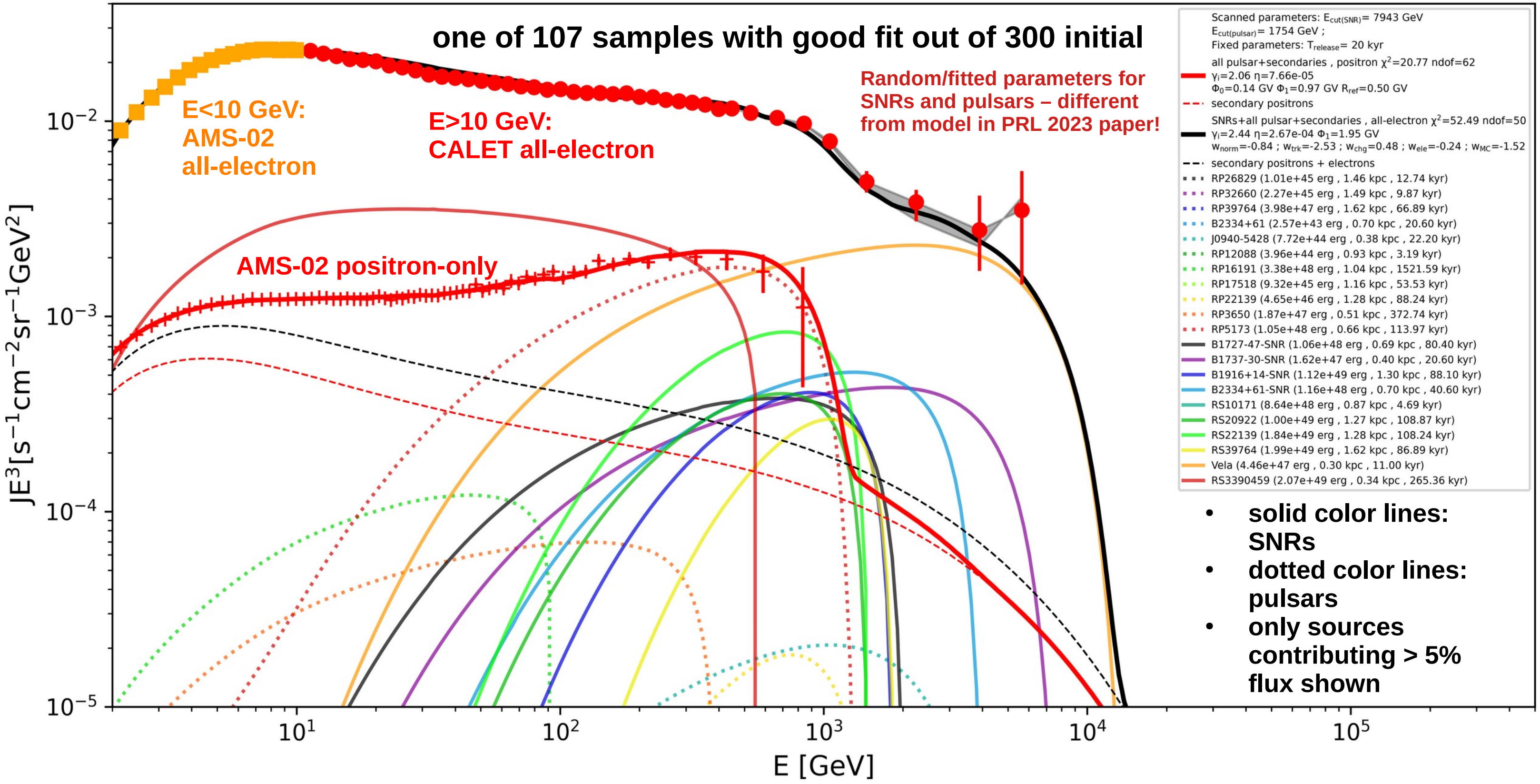
semi-analytic calculation for 7.5 million sources not feasible inside the fitting procedure

→ combined flux of all sources pre-calculated for several indices

→ interpolation used in the fitting procedure to quickly get the flux for any index value

→ injection spectrum cut-off energies are scanned parameters (10 bins per decade on log scale)

Fit to CALET and AMS-02



- Source spectrum index spread with Gaussian distribution (σ=0.033)
- Efficiency spread with log-Gaussian distribution (σ=0.33), max factor 10
- Distributions re-rolled until good fit (or 1000 attempts)
- Free parameters:
  - average SNR index $\gamma_{i(S)}$
  - average SNR efficiency η_S
  - average pulsar index $\gamma_{i(P)}$
  - average pulsar efficiency η_P
  - solar modulation (4)
  - weights for energy dependent systematic uncertainties of CALET spectrum (5)
- Scanned parameters:
  - pulsar cut-off $E_{cut(pulsar)}$
  - SNR cut-off $E_{cut(SNR)}$

Charge sign and rigidity depended solar modulation potential based on Ilias Cholis, Dan Hooper, Tim Linden Phys. Rev. D 93, 043016 (2016) “A Predictive Analytic Model for the Solar Modulation of Cosmic Rays”

$$\Phi = \Phi_0 + \Phi_{1\pm}\left(\frac{1+(R/R_0)^2}{\left((R/R_0)^3\right)}\right)$$

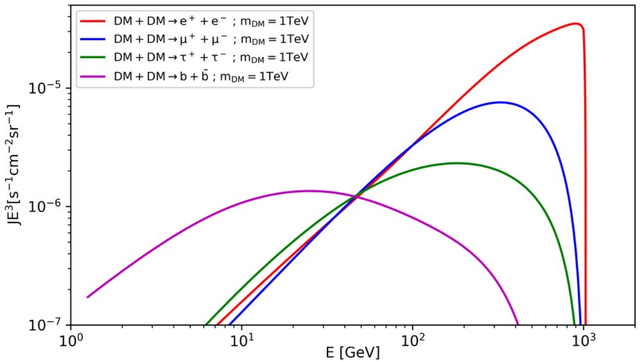
4 parameters:
Φ_0, Φ_{1+} (positive charge),
Φ_{1-} (negative charge), R_0

DM Signal Calculation

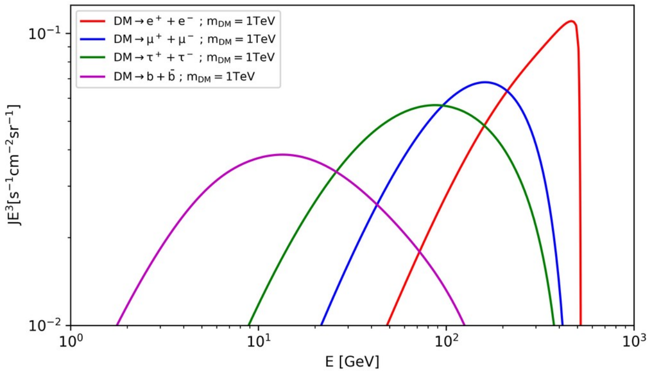
calculated channels:

Annihilation	Decay	Decay (Skyrmion)
DM+DM → e^++e^-	**DM → e^++e^-**	**DM → π^+ + e^-**
DM+DM → μ^++μ^-	**DM → μ^++μ^-**	**DM → π^+ + μ^-**
DM+DM → τ^++τ^-	**DM → e^++e^-**	**DM → π^+ + τ^-**
DM+DM → b+$\overline{\text{b}}$	**DM → b+$\overline{\text{b}}$**	

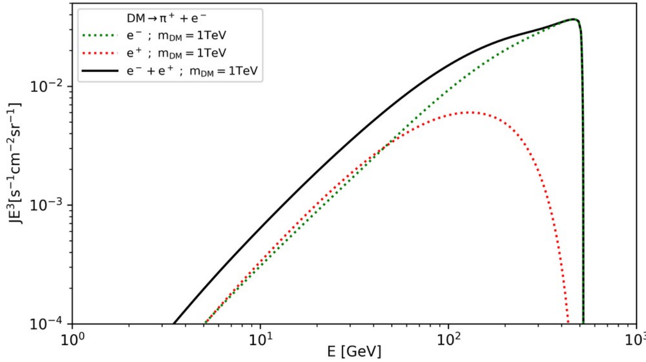
- Flux of electrons and positrons per annihilation or decay from decay of primary annihilation products calculated with PYTHIA
- Flux at Earth calculated with DRAGON assuming **0.3 GeV/cm³ local DM density** and NFW halo profile for a base cross section <σv>= 3×10^{-26} cm³/s or base lifetime of 3.3×10^{25} s :



annihilation



decay

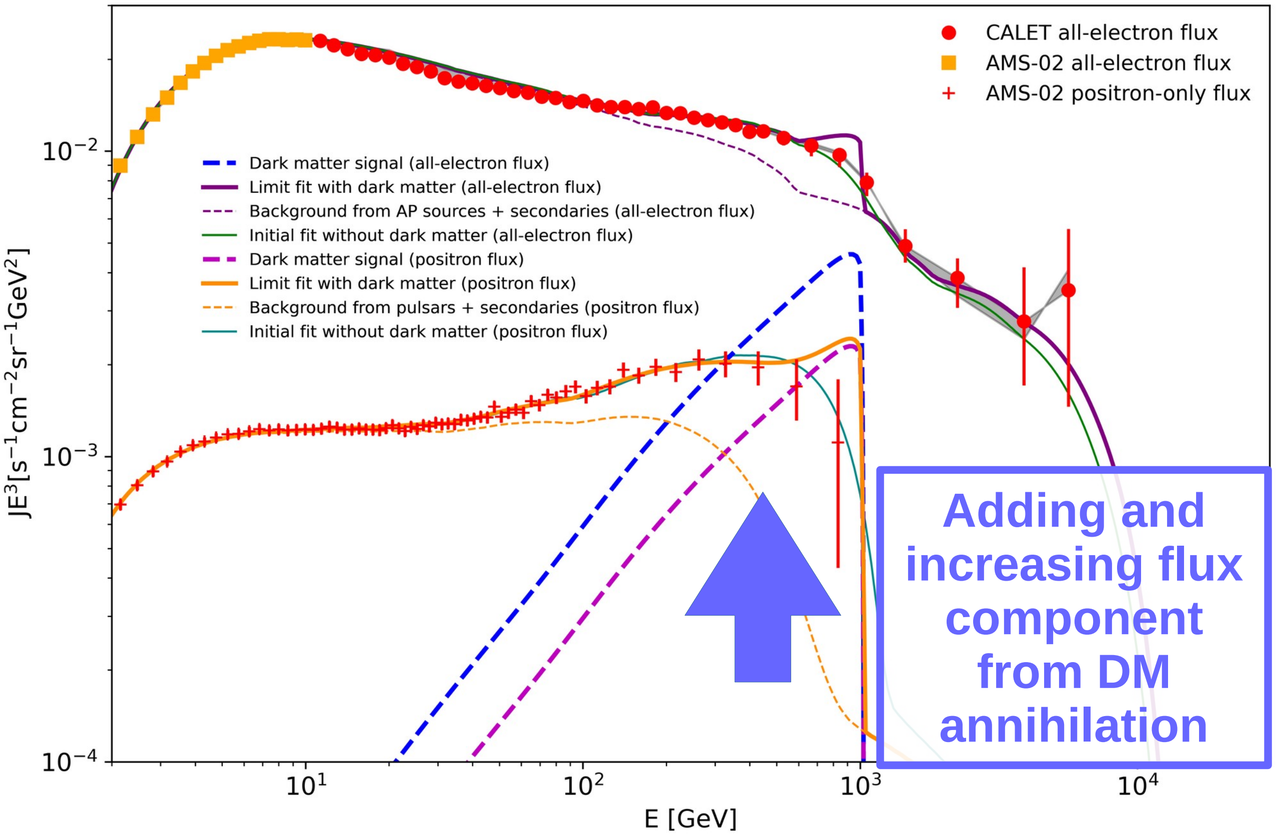


Possible signature of Topological Defect DM (Skyrmion)

- Hitoshi Murayama and Jing Shu. Topological Dark Matter. Phys.Lett. B, 686:162–165, 2010.
- Eric D'Hoker and Edward Farhi. The Decay of the Skyrmion. Phys. Lett. B, 134:86–90, 1984.

Limit Calculation

To derive a limit on DM annihilation/decay rate, the flux for a given DM mass and annihilation/decay mode is added to the base model, and the scalefactor increased in iteratively smaller steps, while adjusting the free parameters until:



Dark Matter
mass = 1000 GeV
cross section 95%CL limit:
$<\sigma v> = 4.24\ 10^{-24}\ cm^3/s$

Fit Quality
all-electron base: $\chi^2 = 52.5$
all-electron limit: $\chi^2 = 53.4$
positron-only base: $\chi^2 = 20.8$
positron-only limit: $\chi^2 = 23.7$
combined base: $\chi^2 = 73.3$
combined limit: $\chi^2 = 77.1$
difference: $\Delta\chi^2 = 3.8$

Limit (Base) Fit Values:

SNR parameters
$\gamma_{i(S)} = 2.44$ ($\gamma_{i(S)} = 2.44$)
$\eta_{(S)} = 0.026\%$ ($\eta_{(S)} = 0.027\%$)

pulsar parameters
$\gamma_{i(P)} = 2.01$ ($\gamma_{i(P)} = 2.06$)
$\eta_{(P)} = 0.006\%$ ($\eta_{(P)} = 0.008\%$)

solar modulation
$\Phi_0 = 0.12GV$ ($\Phi_0 = 0.14GV$)
$\Phi_{1(n)} = 2.02GV$ ($\Phi_{1(n)} = 1.95GV$)
$\Phi_{1(p)} = 0.99GV$ ($\Phi_{1(p)} = 0.97GV$)
$R_{ref} = 0.50GV$ ($R_{ref} = 0.50GV$)

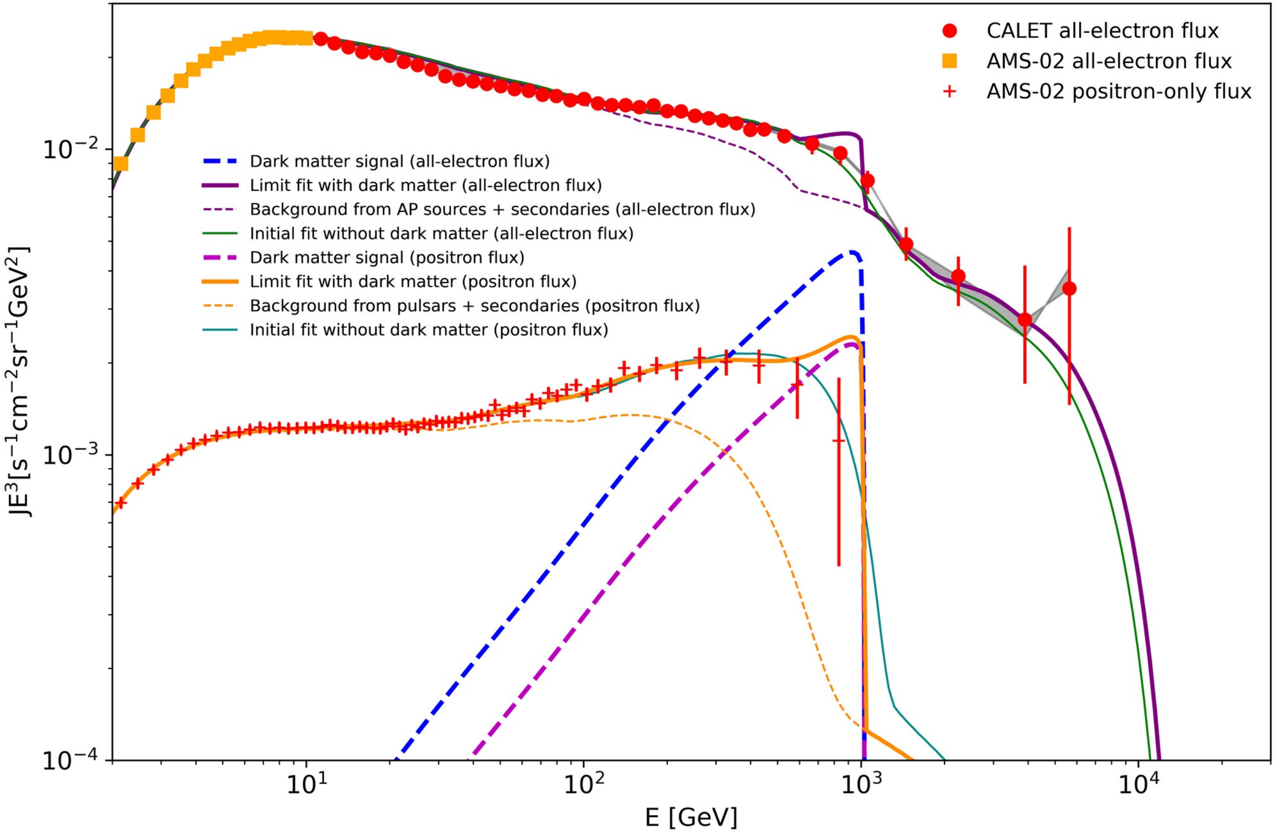
nuisance weights:
$w_{norm} = 0.98$ ($w_{norm} = 0.84$)
$w_{trk} = 2.30$ ($w_{trk} = 2.53$)
$w_{chg} = 0.39$ ($w_{chg} = 0.48$)
$w_{ele} = 0.48$ ($w_{ele} = 0.24$)
$w_{MC} = 1.29$ ($w_{MC} = 1.52$)

Relative Limit:
χ^2 increases by 3.841 compared to χ^2 of the base model, thus the addition of DM is disfavored at 95% CL (stricter but not conservative since base model is over-fitted - assumes the base model is true, which is not certain)

Absolute Limit:
χ^2 exceeds the 95% CL threshold for the fit's number of degrees of freedom, thus the whole model including the DM flux is excluded

Limit Calculation

To derive a limit on DM annihilation/decay rate, the flux for a given DM mass and annihilation/decay mode is added to the base model, and the scalefactor increased in iteratively smaller steps, while adjusting the free parameters until:



Dark Matter
mass = 1000 GeV
cross section 95%CL limit:
$<\sigma v> = 4.24\ 10^{-24}\ cm^3/s$

Fit Quality
all-electron base: $\chi^2 = 52.5$
all-electron limit: $\chi^2 = 53.4$
positron-only base: $\chi^2 = 20.8$
positron-only limit: $\chi^2 = 23.7$
combined base: $\chi^2 = 73.3$
combined limit: $\chi^2 = 77.1$
difference: $\Delta\chi^2 = 3.8$

Limit (Base) Fit Values:

SNR parameters
$\gamma_{i(S)} = 2.44$ ($\gamma_{i(S)} = 2.44$)
$\eta_{(S)} = 0.026\%$ ($\eta_{(S)} = 0.027\%$)

pulsar parameters
$\gamma_{i(P)} = 2.01$ ($\gamma_{i(P)} = 2.06$)
$\eta_{(P)} = 0.006\%$ ($\eta_{(P)} = 0.008\%$)

solar modulation
$\Phi_0 = 0.12GV$ ($\Phi_0 = 0.14GV$)
$\Phi_{1(n)} = 2.02GV$ ($\Phi_{1(n)} = 1.95GV$)
$\Phi_{1(p)} = 0.99GV$ ($\Phi_{1(p)} = 0.97GV$)
$R_{ref} = 0.50GV$ ($R_{ref} = 0.50GV$)

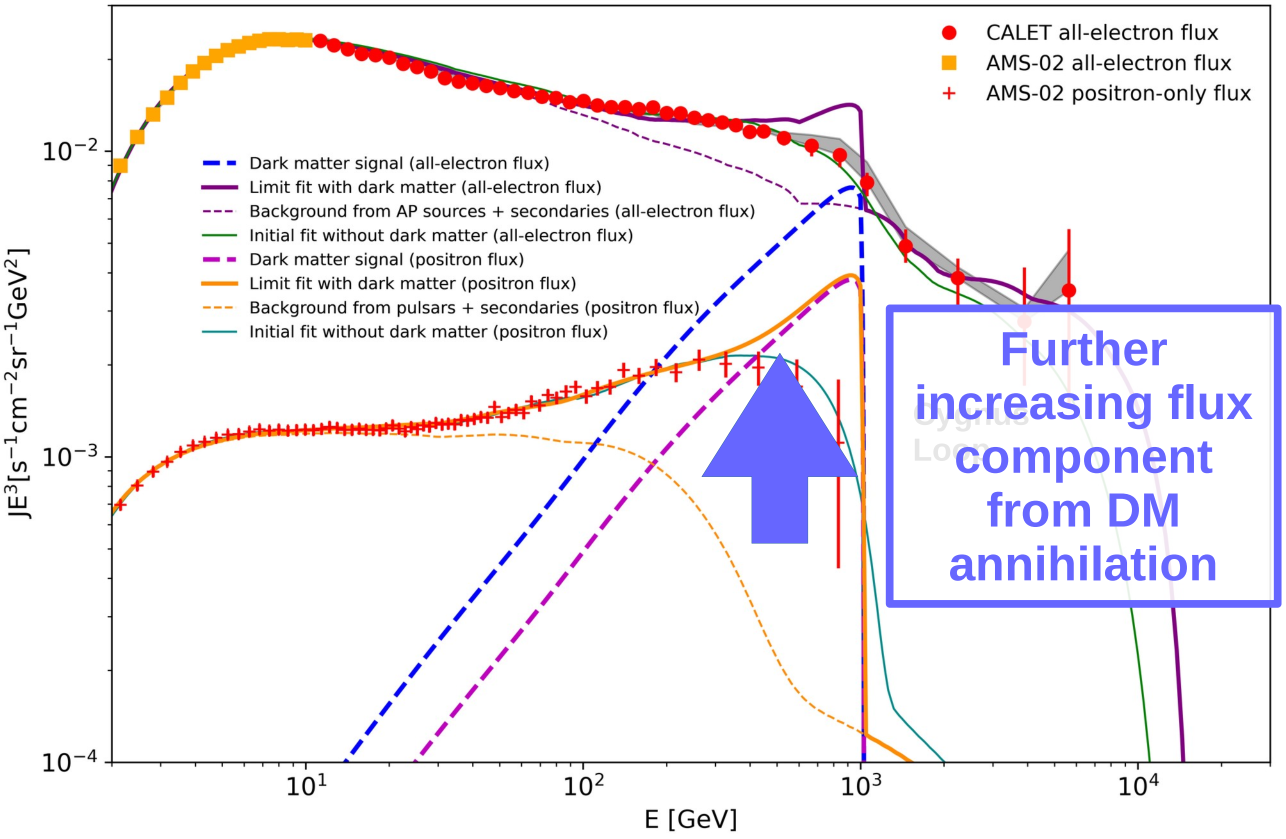
nuisance weights:
$w_{norm} = 0.98$ ($w_{norm} = 0.84$)
$w_{trk} = 2.30$ ($w_{trk} = 2.53$)
$w_{chg} = 0.39$ ($w_{chg} = 0.48$)
$w_{ele} = 0.48$ ($w_{ele} = 0.24$)
$w_{MC} = 1.29$ ($w_{MC} = 1.52$)

Relative Limit:
χ^2 increases by 3.841 compared to χ^2 of the base model, thus the addition of DM is disfavored at 95% CL (stricter but not conservative since base model is over-fitted - assumes the base model is true, which is not certain)

Absolute Limit:
χ^2 exceeds the 95% CL threshold for the fit's number of degrees of freedom, thus the whole model including the DM flux is excluded

Limit Calculation

To derive a limit on DM annihilation/decay rate, the flux for a given DM mass and annihilation/decay mode is added to the base model, and the scalefactor increased in iteratively smaller steps, while adjusting the free parameters until:



Dark Matter
mass = 1000 GeV
cross section 95%CL limit:
$<\sigma v> = 7.01\ 10^{-24}\ cm^3/s$

Fit Quality
all-electron base: $\chi^2 = 52.5$
all-electron limit: $\chi^2 = 95.6$
positron-only base: $\chi^2 = 20.8$
positron-only limit: $\chi^2 = 56.3$
combined base: $\chi^2 = 73.3$
combined limit: $\chi^2 = 152.0$
difference: $\Delta\chi^2 = 78.7$

Limit (Base) Fit Values:

SNR parameters
$\gamma_{i(S)} = 2.46$ ($\gamma_{i(S)} = 2.44$)
$\eta_{(S)} = 0.028\%$ ($\eta_{(S)} = 0.027\%$)

pulsar parameters
$\gamma_{i(P)} = 1.95$ ($\gamma_{i(P)} = 2.06$)
$\eta_{(P)} = 0.006\%$ ($\eta_{(P)} = 0.008\%$)

solar modulation
$\Phi_0 = 0.14GV$ ($\Phi_0 = 0.14GV$)
$\Phi_{1(n)} = 2.04GV$ ($\Phi_{1(n)} = 1.95GV$)
$\Phi_{1(p)} = 0.87GV$ ($\Phi_{1(p)} = 0.97GV$)
$R_{ref} = 0.50GV$ ($R_{ref} = 0.50GV$)

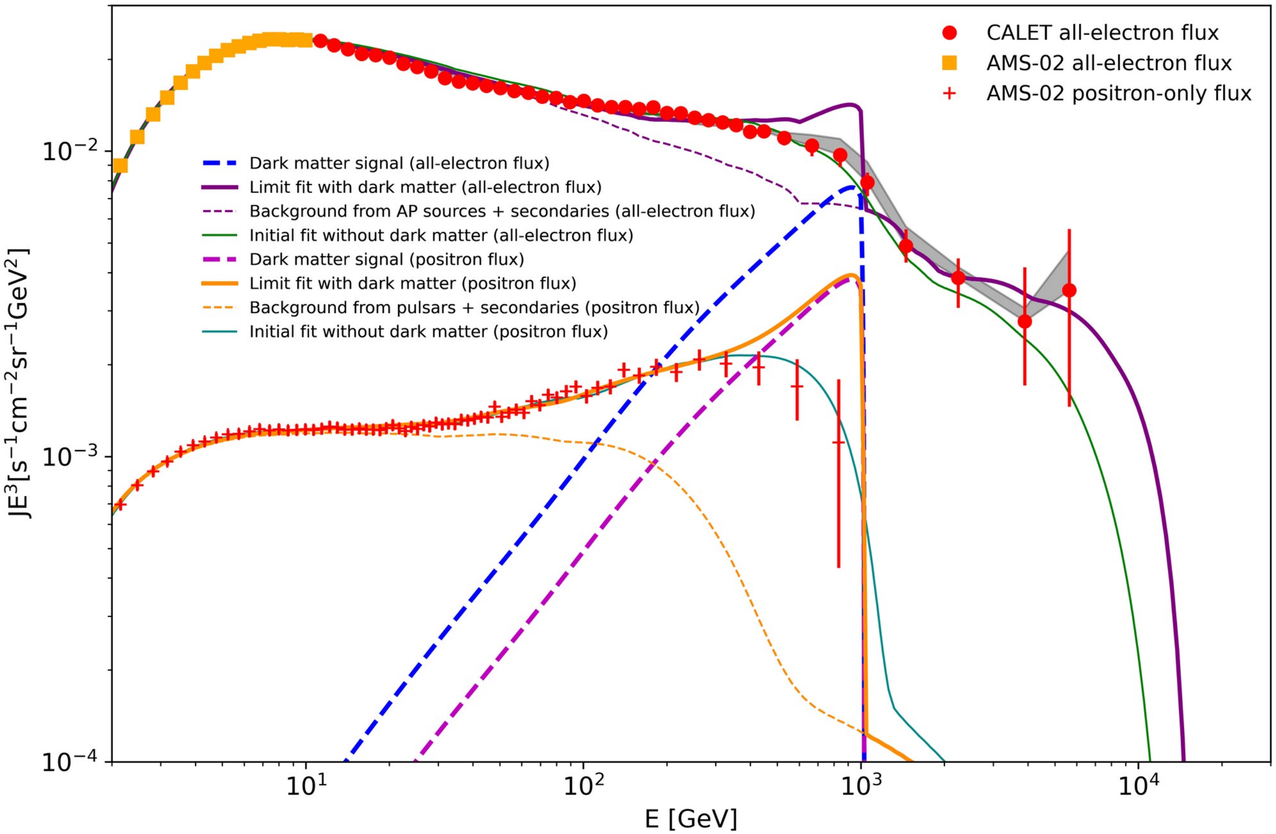
nuisance weights:
$w_{norm} = 1.36$ ($w_{norm} = 0.84$)
$w_{trk} = 1.79$ ($w_{trk} = 2.53$)
$w_{chg} = 0.54$ ($w_{chg} = 0.48$)
$w_{ele} = 1.46$ ($w_{ele} = 0.24$)
$w_{MC} = 1.17$ ($w_{MC} = 1.52$)

Relative Limit:
χ^2 increases by 3.841 compared to χ^2 of the base model, thus the addition of DM is disfavored at 95% CL (stricter but not conservative since base model is over-fitted - assumes the base model is true, which is not certain)

Absolute Limit:
χ^2 exceeds the 95% CL threshold for the fit's number of degrees of freedom, thus the whole model including the DM flux is excluded

Limit Calculation

To derive a limit on DM annihilation/decay rate, the flux for a given DM mass and annihilation/decay mode is added to the base model, and the scalefactor increased in iteratively smaller steps, while adjusting the free parameters until:



Dark Matter
mass = 1000 GeV
cross section 95%CL limit:
$<\sigma v> = 7.01\ 10^{-24}\ cm^3/s$

Fit Quality
all-electron base: $\chi^2 = 52.5$
all-electron limit: $\chi^2 = 95.6$
positron-only base: $\chi^2 = 20.8$
positron-only limit: $\chi^2 = 56.3$
combined base: $\chi^2 = 73.3$
combined limit: $\chi^2 = 152.0$
difference: $\Delta\chi^2 = 78.7$

Limit (Base) Fit Values:

SNR parameters
$\gamma_{i(S)} = 2.46$ ($\gamma_{i(S)} = 2.44$)
$\eta_{(S)} = 0.028\%$ ($\eta_{(S)} = 0.027\%$)

pulsar parameters
$\gamma_{i(P)} = 1.95$ ($\gamma_{i(P)} = 2.06$)
$\eta_{(P)} = 0.006\%$ ($\eta_{(P)} = 0.008\%$)

solar modulation
$\Phi_0 = 0.14GV$ ($\Phi_0 = 0.14GV$)
$\Phi_{1(n)} = 2.04GV$ ($\Phi_{1(n)} = 1.95GV$)
$\Phi_{1(p)} = 0.87GV$ ($\Phi_{1(p)} = 0.97GV$)
$R_{ref} = 0.50GV$ ($R_{ref} = 0.50GV$)

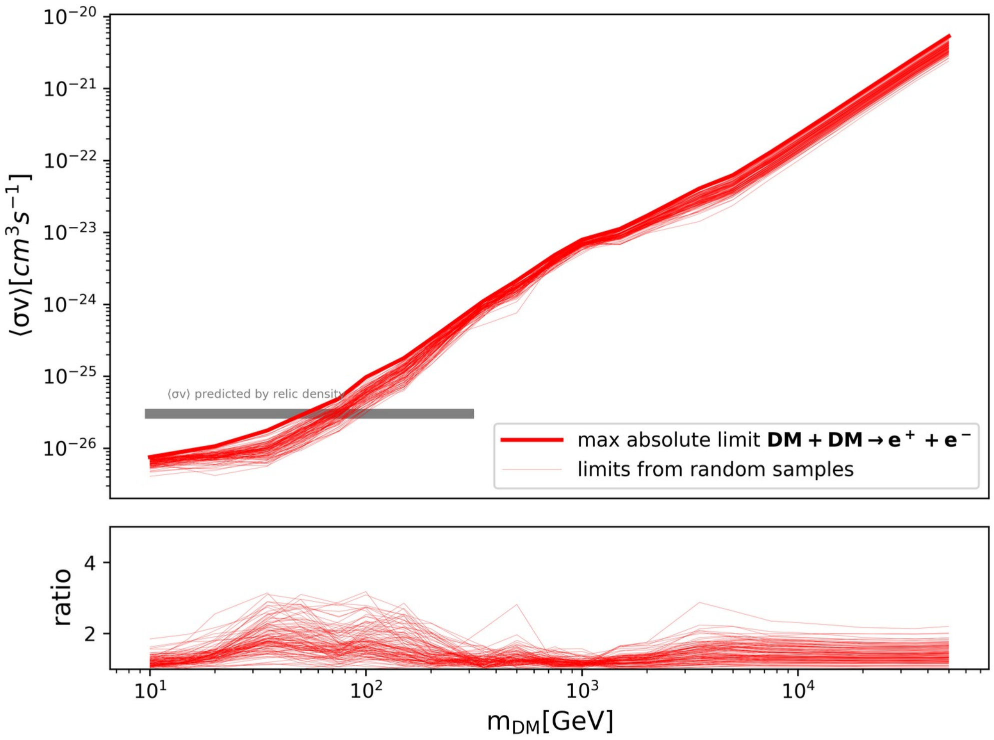
nuisance weights:
$w_{norm} = 1.36$ ($w_{norm} = 0.84$)
$w_{trk} = 1.79$ ($w_{trk} = 2.53$)
$w_{chg} = 0.54$ ($w_{chg} = 0.48$)
$w_{ele} = 1.46$ ($w_{ele} = 0.24$)
$w_{MC} = 1.17$ ($w_{MC} = 1.52$)

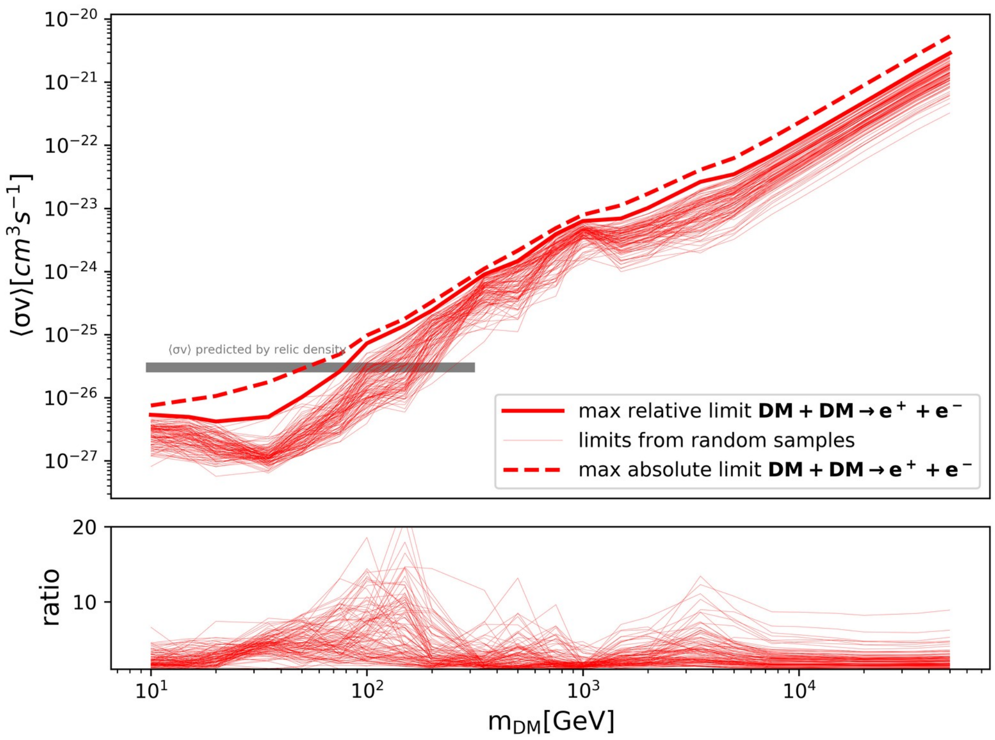
Relative Limit:
χ^2 increases by 3.841 compared to χ^2 of the base model, thus the addition of DM is disfavored at 95% CL (stricter but not conservative since base model is over-fitted - assumes the base model is true, which is not certain)

Absolute Limit:
χ^2 exceeds the 95% CL threshold for the fit's number of degrees of freedom, thus the whole model including the DM flux is excluded

Dependence on Background Variation

107 random SNR&pulsar distributions

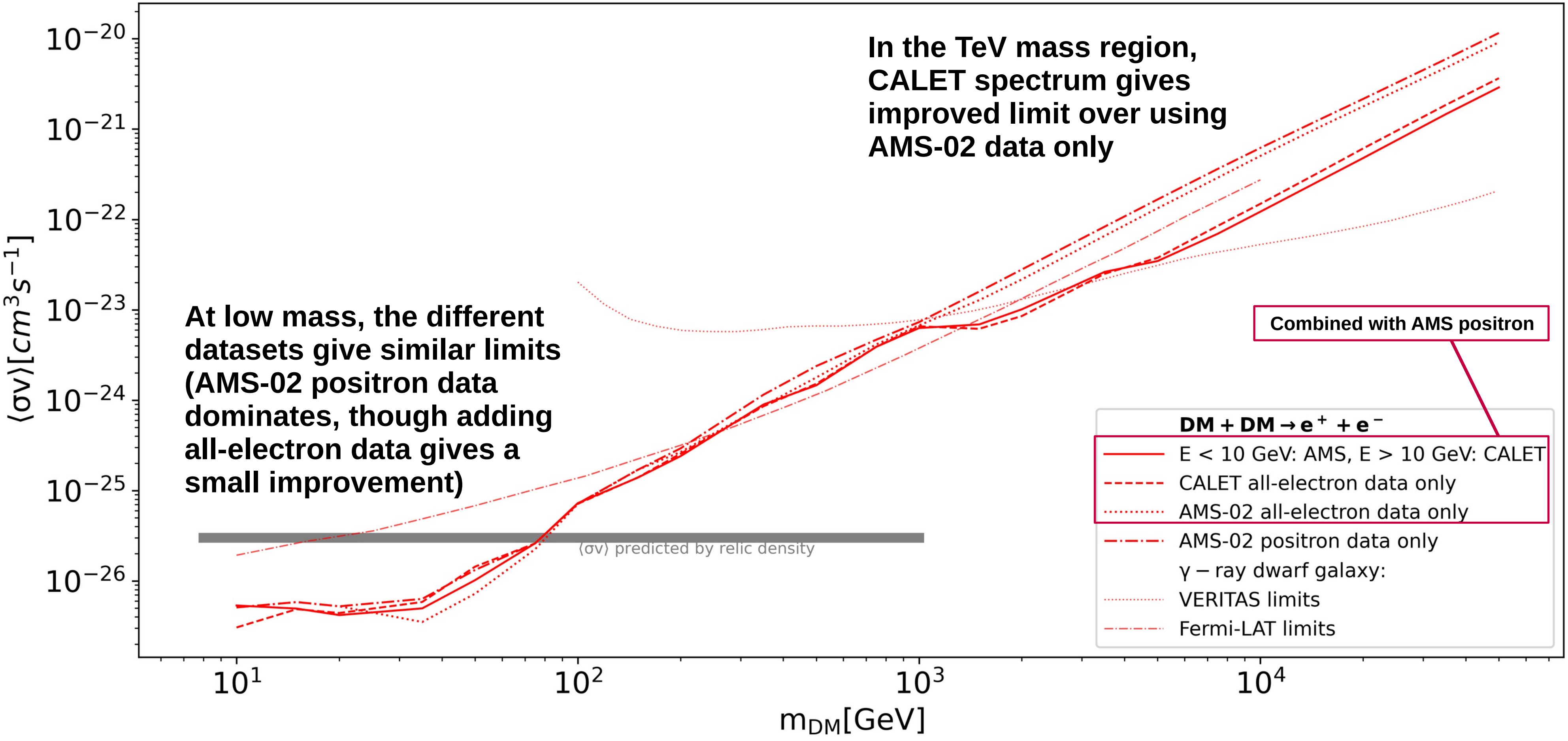




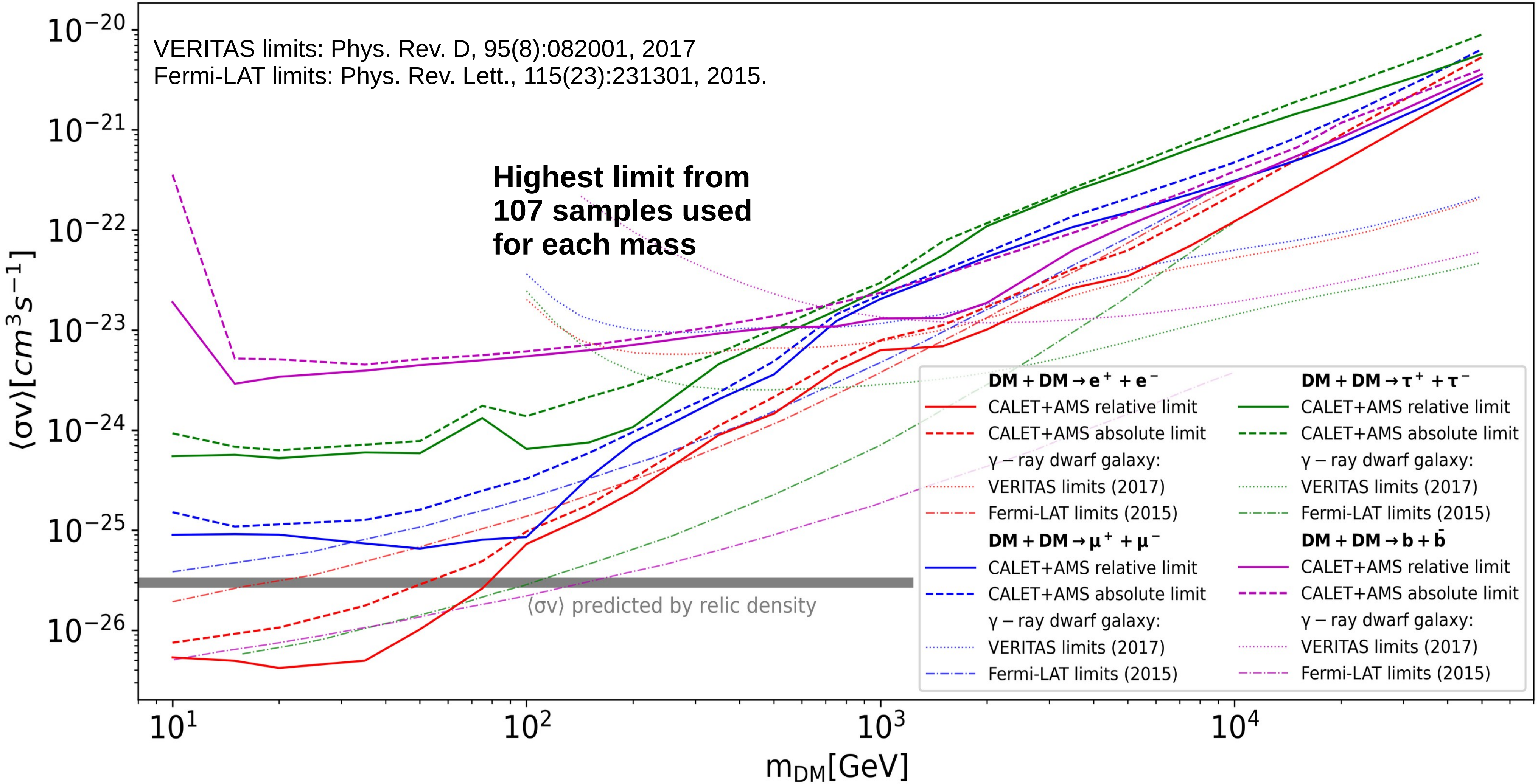
Absolute limits are less dependent on the background differences between samples

Relative limits change more sample by sample but the worst limit is still better than the absolute limit

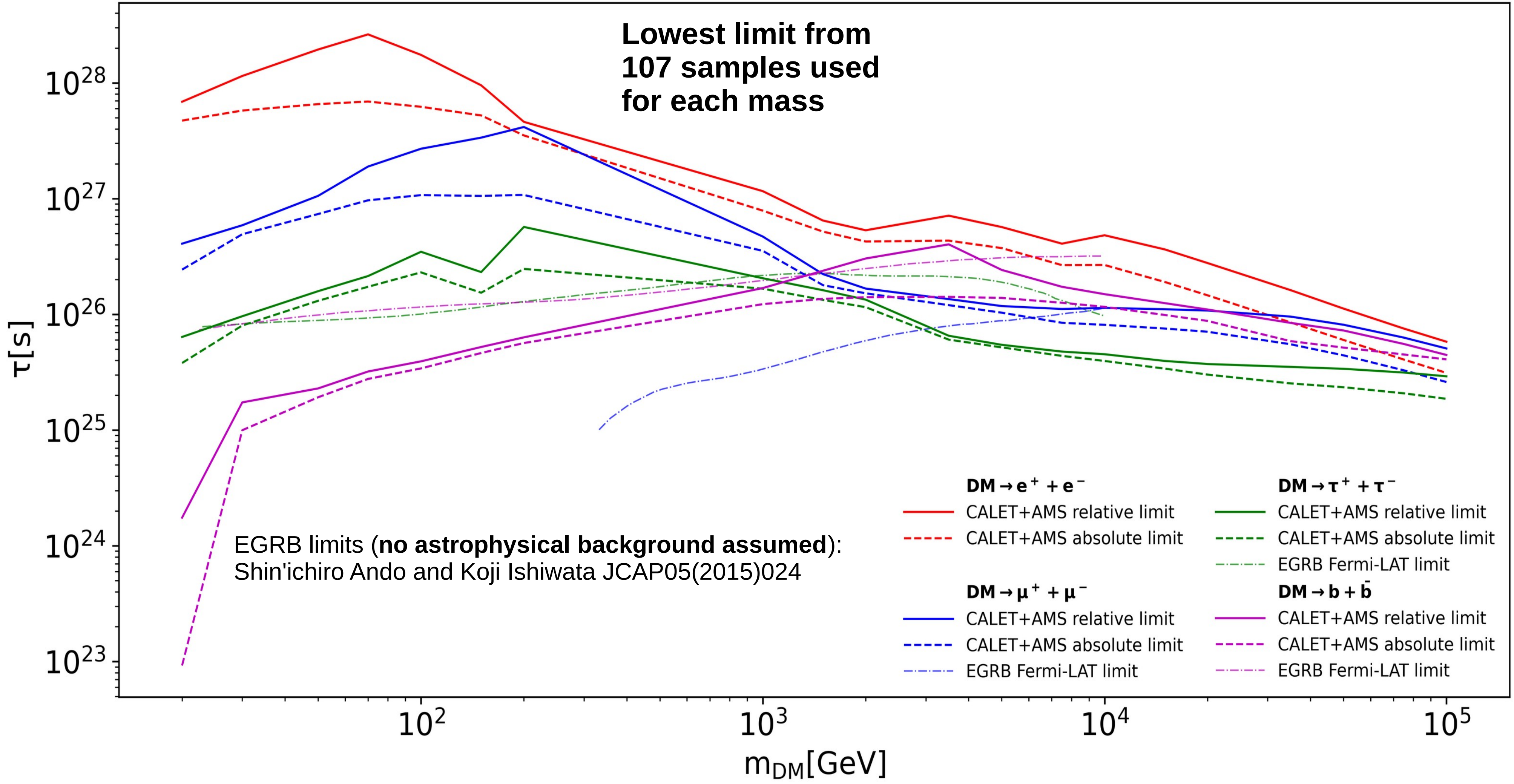
Comparison with other Datasets



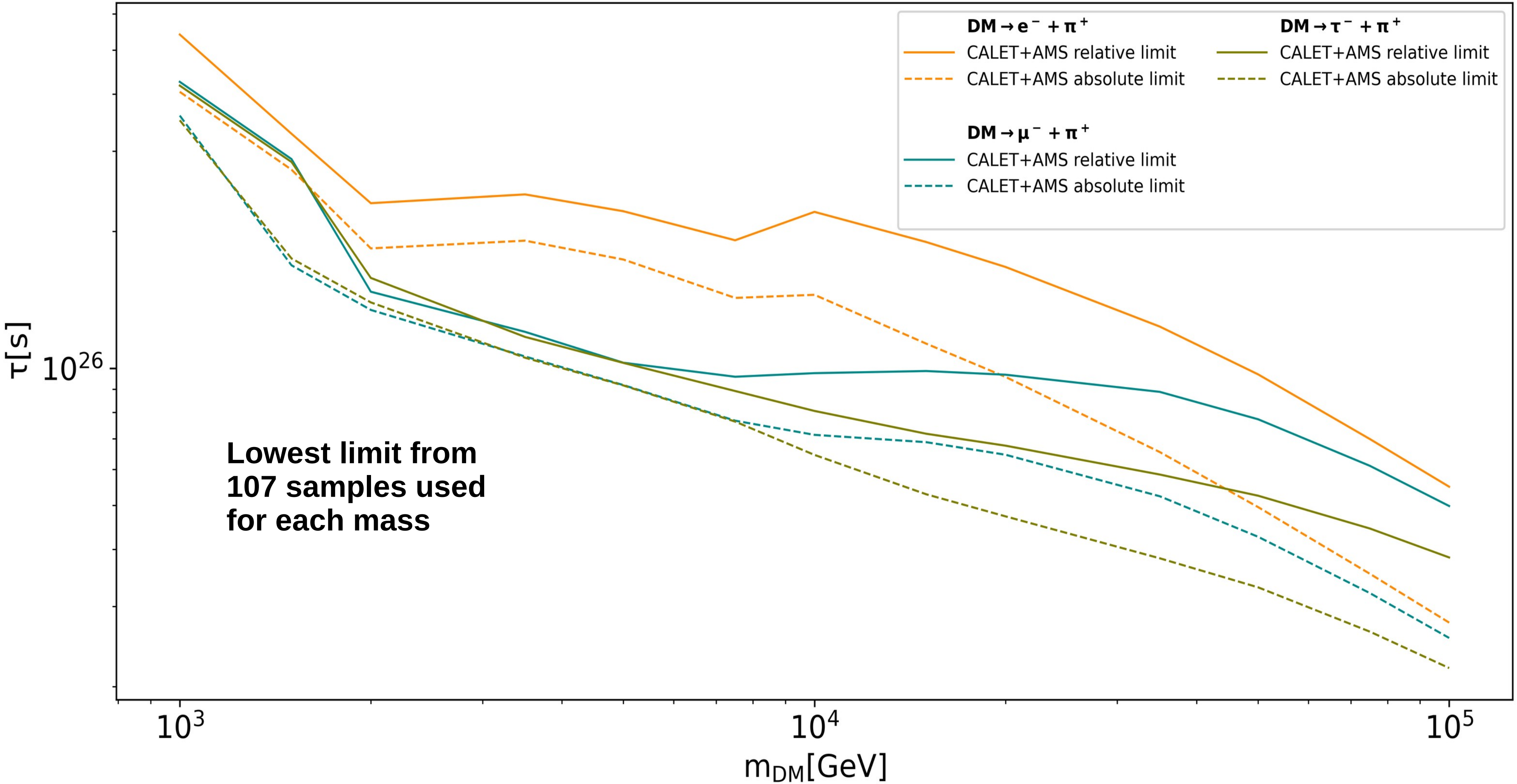
Limit Results (annihilation)



Limit Results (decay)



Limit Results (skyrmion decay)



Conclusions & Outlook

- From CALET all-electron and AMS-02 positron-only data, limits on DM lifetime (annihilation cross-section) have been calculated up to a DM mass of 100 TeV (50 TeV). These limits are comparable and, given the different sources of systematic uncertainty, complementing those from other messengers such as γ-rays and neutrinos.
- By using an astrophysical base model comprising random realizations of the individual SNR and pulsar sources within the galaxy, the effect of background variability and potential spectral structures from individual sources on the limits has been taken into account. Due to this, the presented stricter limits based on a relative χ^2 increase are reliable constraints.
- Comparing limits from different datasets, it is demonstrated that the CALET all-electron spectrum up to 7.5 TeV allows for significantly stricter limits in the TeV mass range than the AMS-02 all-electron spectrum up to 2 TeV, or only the AMS-02 positron spectrum.

This work is supported by JSPS KAKENHI Grant No. JP21H05463.