Dark Matter Limits from the CALET Electron+Positron Spectrum with Individual Astrophysical Source Background

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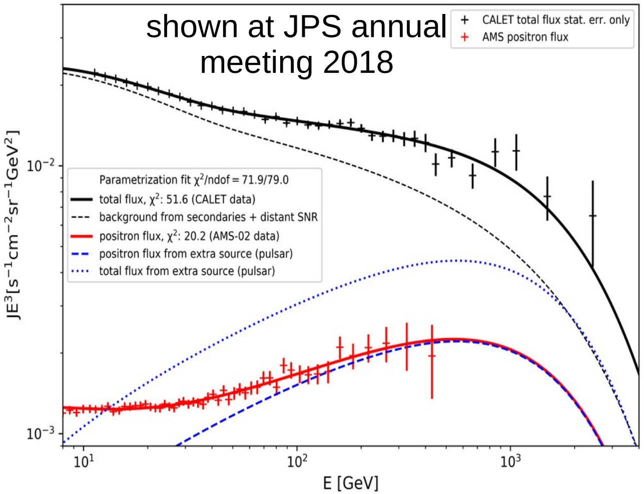
Overview

- **Product:** Limits on DM annihilation and decay from a combined analysis of:
  - CALET all-electron spectrum [ICRC 2021 (105)]
  - AMS-02 positron-only spectrum [M. Aguilar et al. Phys. Rev. Lett. 122, 041102]

- **Basic Concept:** Astrophysical base model which fits the data well → add flux from DM calculated with DRAGON and increase scale factor → limit on annihilation rate or lifetime when χ^2 exceeds a given threshold

- **Goals:**
  - Improve reliability by introducing a realistic background model based on individual astrophysical sources
  - Obtain stricter limits by using a relative χ^2 increase threshold, which could be considered reliable only if the variability of the limits with background is studied and the worst limit from a range of sampled cases taken.



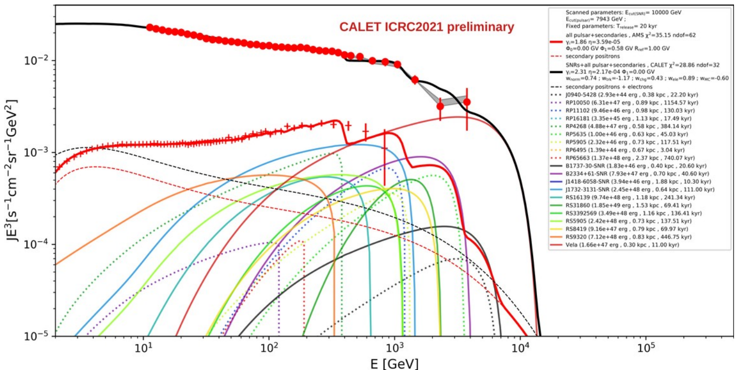
old background model:
power-law parametrization

$$\Phi_{ele} = C_e E^{-(\gamma_e - \Delta\gamma_e)} \left(1 + \left(\frac{E}{E_B}\right)^{\frac{\Delta\gamma_e}{s}}\right)^{s} \left(\frac{C_s}{C_e} E^{-(\gamma_s - \gamma_e)} + e^{-\left(\frac{E}{E_{cut_e}}\right)}\right) + C_{ex} E^{-\gamma_{ex}} e^{-\left(\frac{E}{E_{cut_{ex}}}\right)}$$

$$\Phi_{pos} = C_e E^{-\gamma_e} \left(\frac{C_s}{C_e} E^{-(\gamma_s - \gamma_e)}\right) + C_{ex} E^{-\gamma_{ex}} e^{-\left(\frac{E}{E_{cut_{ex}}}\right)}$$

$$\Phi_{tot} = \Phi_{ele} + \Phi_{pos}$$

new background model:
spectra fitted by overlapping flux from individually calculated SNR and pulsar point sources

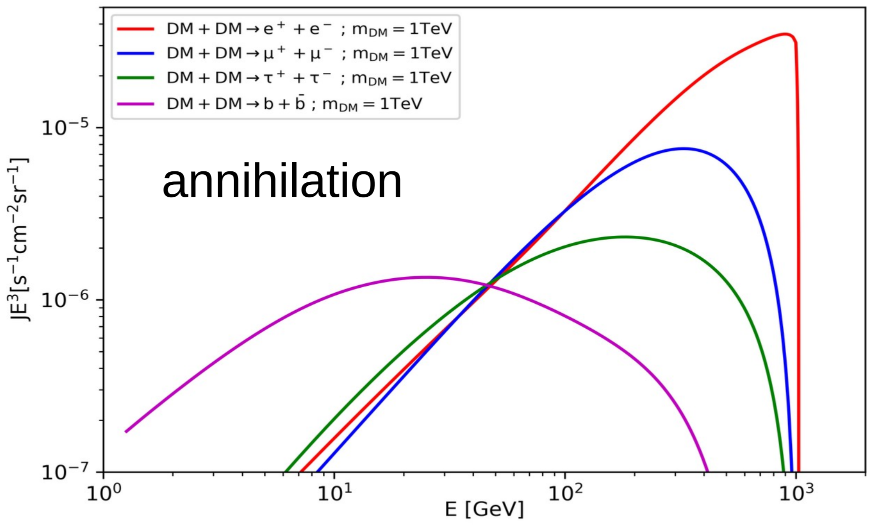


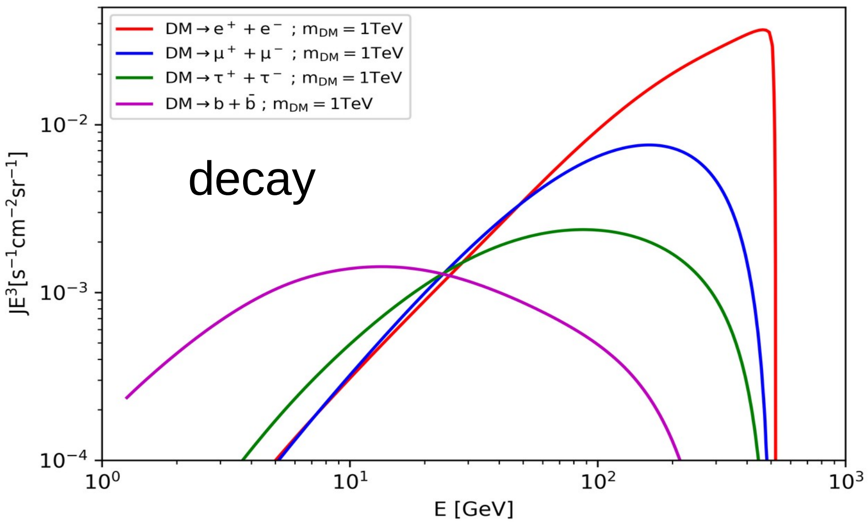
DM Signal Calculation

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+$\overline{b}$	**DM→ b+$\overline{b}$**	

- 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 10^{28} s :





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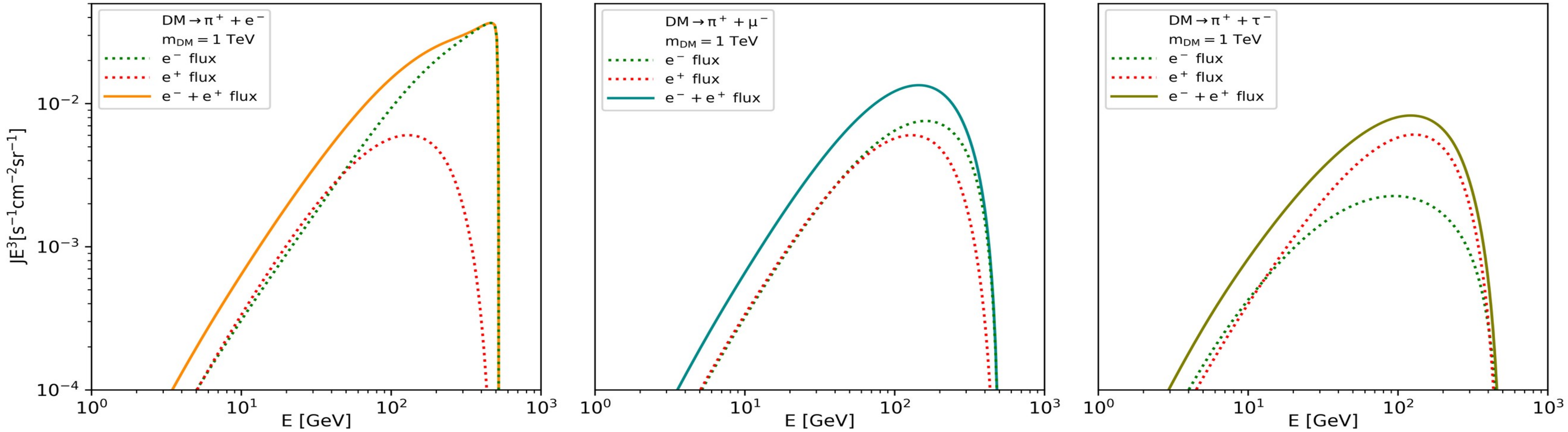
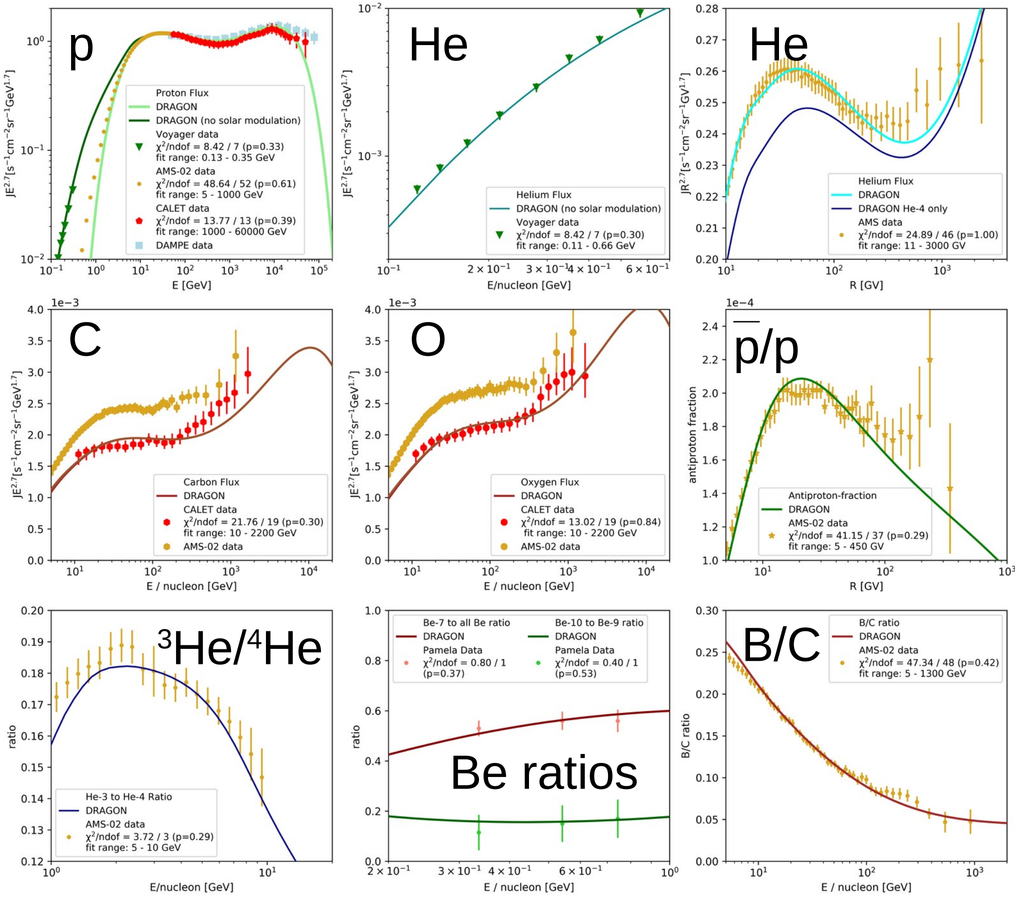
- π – lepton channels are a possible signature of topological defect DM (Skyrmion)
  - Hitoshi Murayama and Jing Shu. Topological Dark Matter. Phys.Lett. B, 686:162–165, 2010.
  - Eric D'Hoker and Edward Farhi. The Decay of the Skyrmion. Phys. Lett. B, 134:86–90, 1984.
- different spectra in e^+ and e^- → all-electron spectrum more sensitive to DM → π^+ + e^- than positron-only

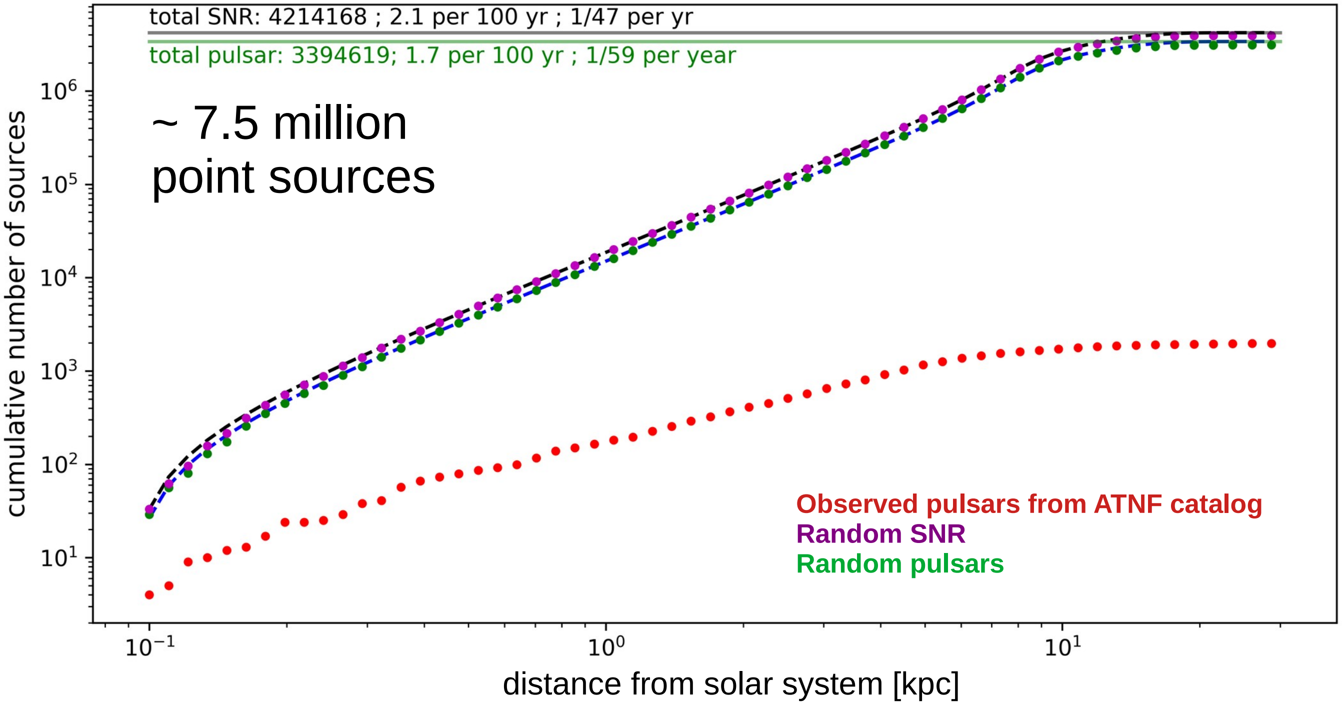


Propagation Model



- 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.
- For details, see “A Cosmic-Ray Propagation Model based on Measured Nuclei Spectra” (PCRD2-08 poster / proceedings)
- Secondary electron and positron component of background for the dark matter limit fit also taken from this DRAGON calculation.

Pulsar and SNR Distribution



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 model and secondary flux component

Pulsar birth rate:

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

- Random pulsar samples created with spatial distribution of Ferriere model, up to 200 Myr age
- Observed pulsars are added and replace random ones with similar distance and age if present
- SNRs are added at the same position and time as the pulsars, additional SNRs generated
- Pulsar initial rotation energy distribution log-Gaussian based on ATNF catalog $10^{49.3\pm1.01}$ erg
- SNR kinetic energy distribution: $10^{51\pm1}$ erg

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
- Details in “Interpretation of the CALET Electron+Positron Spectrum by Astrophysical Sources” (PCRD2-07 poster / proceedings)

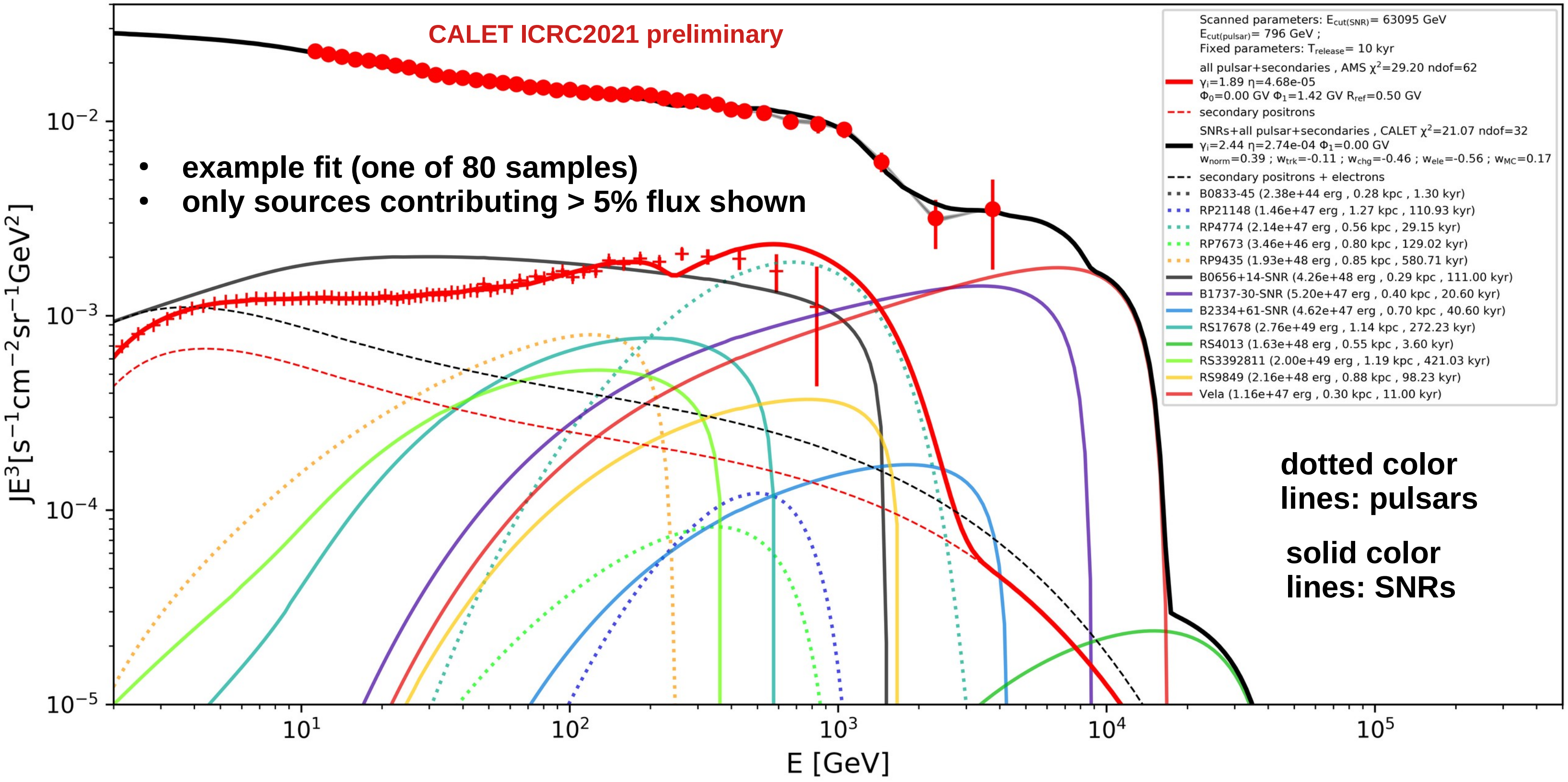
semi-analytic calculation for 7.5 million sources not feasible inside the fitting procedure

→ 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 of Base Model 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
- 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 $E_{cut(SNR)}$

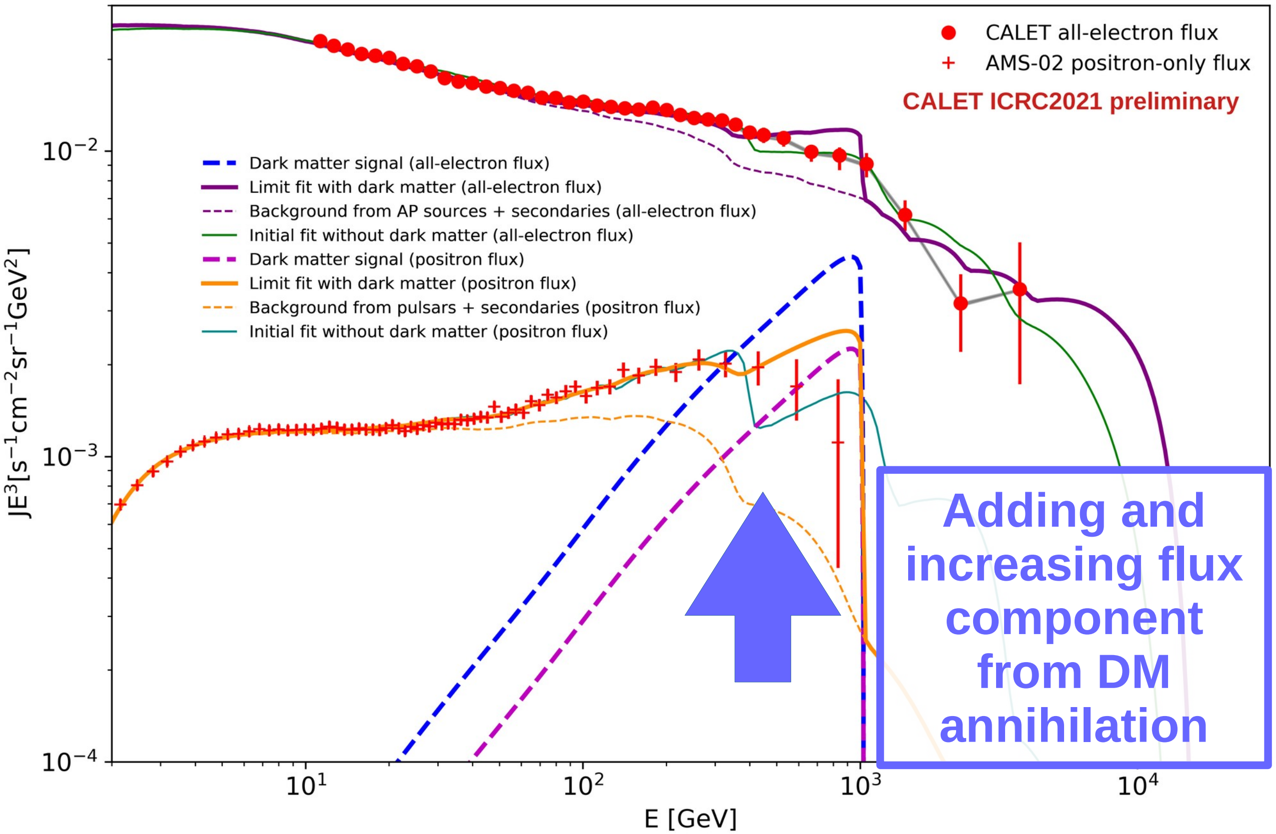
Charge sign and rigidity depended solar modulation potential based on Ilias Cholis, Dan Hooper, Tim Linden Phys. Rev. D 93, 043016 (2016) “A Predictive Analytic Model for the Solar Modulation of Cosmic Rays”

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

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

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:
$<\sigma v> = 4.16\ 10^{-24}\ cm^3/s$

Fit Quality
CALET base: $\chi^2 = 28.9$
CALET limit: $\chi^2 = 41.0$
AMS base: $\chi^2 = 35.1$
AMS limit: $\chi^2 = 26.8$
combined base: $\chi^2 = 64.0$
combined limit: $\chi^2 = 67.8$
difference: $\Delta\chi^2 = 3.8$

Limit (Base) Fit Values:

SNR parameters
$\gamma_{i(S)} = 2.33$ ($\gamma_{i(S)} = 2.31$)
$\eta_{(S)} = 0.023\%$ ($\eta_{(S)} = 0.022\%$)

pulsar parameters
$\gamma_{i(P)} = 1.88$ ($\gamma_{i(P)} = 1.86$)
$\eta_{(P)} = 0.004\%$ ($\eta_{(P)} = 0.004\%$)

solar modulation
$\Phi_0 = 0.00GV$ ($\Phi_0 = 0.00GV$)
$\Phi_{1(n)} = 0.00GV$ ($\Phi_{1(n)} = 0.00GV$)
$\Phi_{1(p)} = 0.71GV$ ($\Phi_{1(p)} = 0.58GV$)
$R_{ref} = 0.86GV$ ($R_{ref} = 1.00GV$)

nuisance weights:
$w_{norm} = 0.82$ ($w_{norm} = 0.74$)
$w_{trk} = 0.04$ ($w_{trk} = 1.17$)
$w_{chg} = 0.56$ ($w_{chg} = 0.43$)
$w_{ele} = 0.11$ ($w_{ele} = 0.89$)
$w_{MC} = 0.45$ ($w_{MC} = 0.60$)

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

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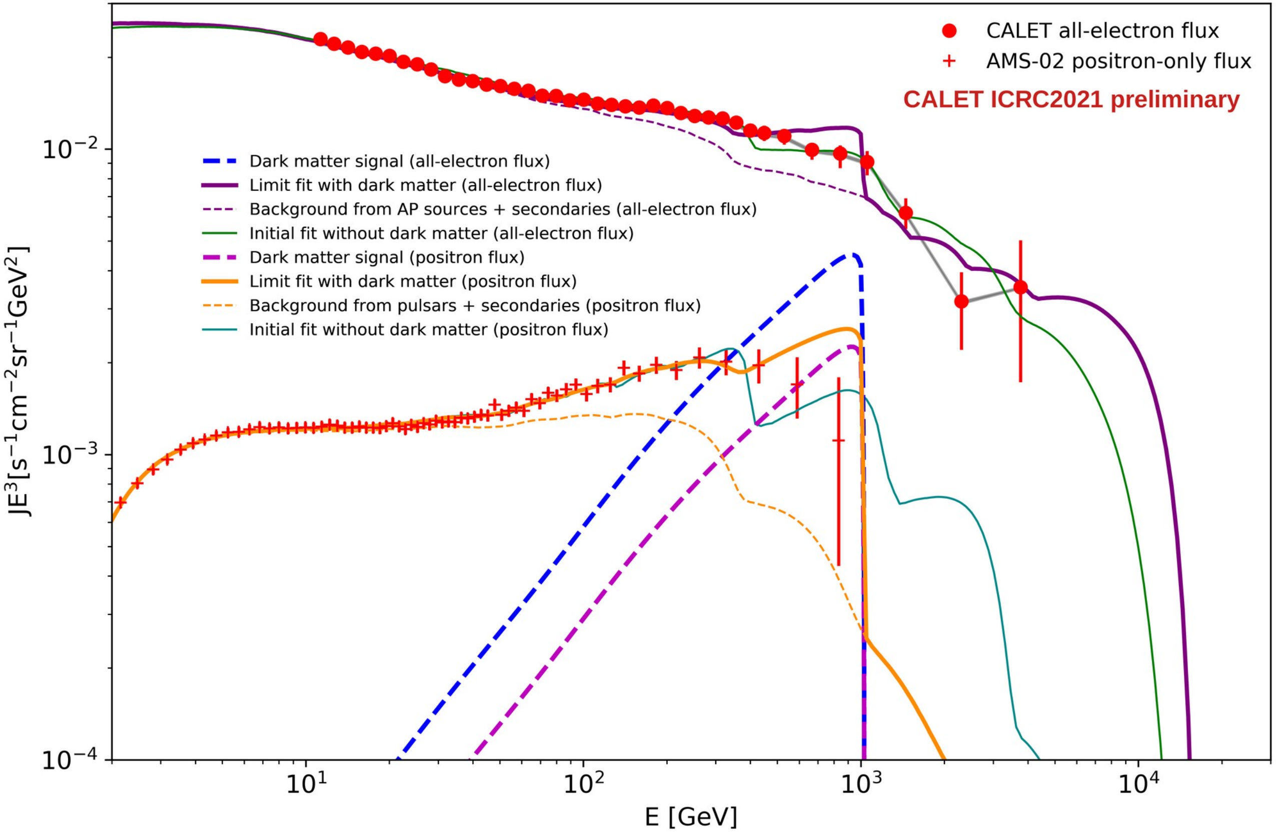

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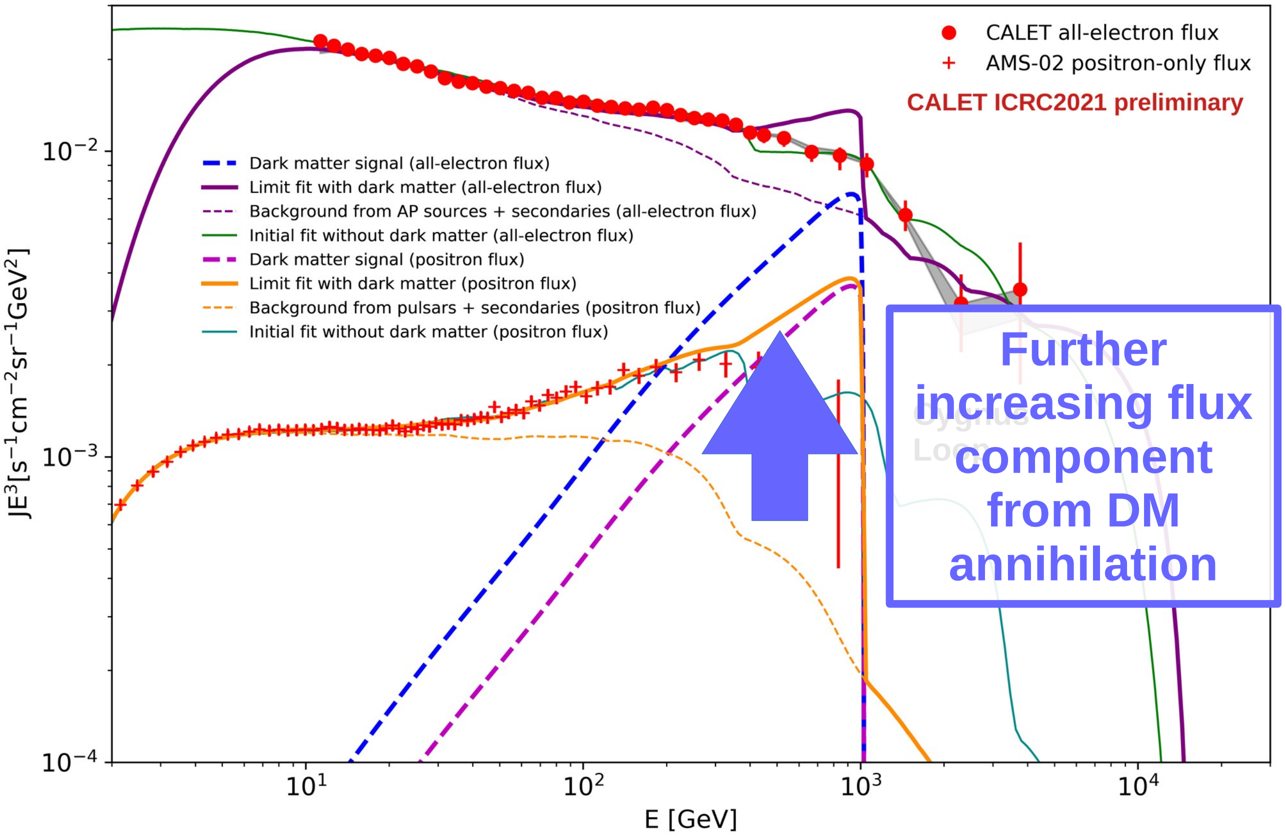

Dark Matter
mass = 1000 GeV
cross section 95%CL limit:
$<\sigma v> = 6.68\ 10^{-24}\ cm^3/s$

Fit Quality
CALET base: $\chi^2 = 28.9$
CALET limit: $\chi^2 = 75.9$
AMS base: $\chi^2 = 35.1$
AMS limit: $\chi^2 = 56.1$
combined base: $\chi^2 = 64.0$
combined limit: $\chi^2 = 132.1$
difference: $\Delta\chi^2 = 68.0$

Limit (Base) Fit Values:

SNR parameters
$\gamma_{i(S)} = 2.37$ ($\gamma_{i(S)} = 2.31$)
$\eta_{(S)} = 0.028\%$ ($\eta_{(S)} = 0.022\%$)

pulsar parameters
$\gamma_{i(P)} = 1.95$ ($\gamma_{i(P)} = 1.86$)
$\eta_{(P)} = 0.005\%$ ($\eta_{(P)} = 0.004\%$)

solar modulation
$\Phi_0 = 0.03GV$ ($\Phi_0 = 0.00GV$)
$\Phi_{1(n)} = 4.83GV$ ($\Phi_{1(n)} = 0.00GV$)
$\Phi_{1(p)} = 1.30GV$ ($\Phi_{1(p)} = 0.58GV$)
$R_{ref} = 0.50GV$ ($R_{ref} = 1.00GV$)

nuisance weights:
$w_{norm} = 0.63$ ($w_{norm} = 0.74$)
$w_{trk} = 0.78$ ($w_{trk} = 1.17$)
$w_{chg} = 1.98$ ($w_{chg} = 0.43$)
$w_{ele} = 0.54$ ($w_{ele} = 0.89$)
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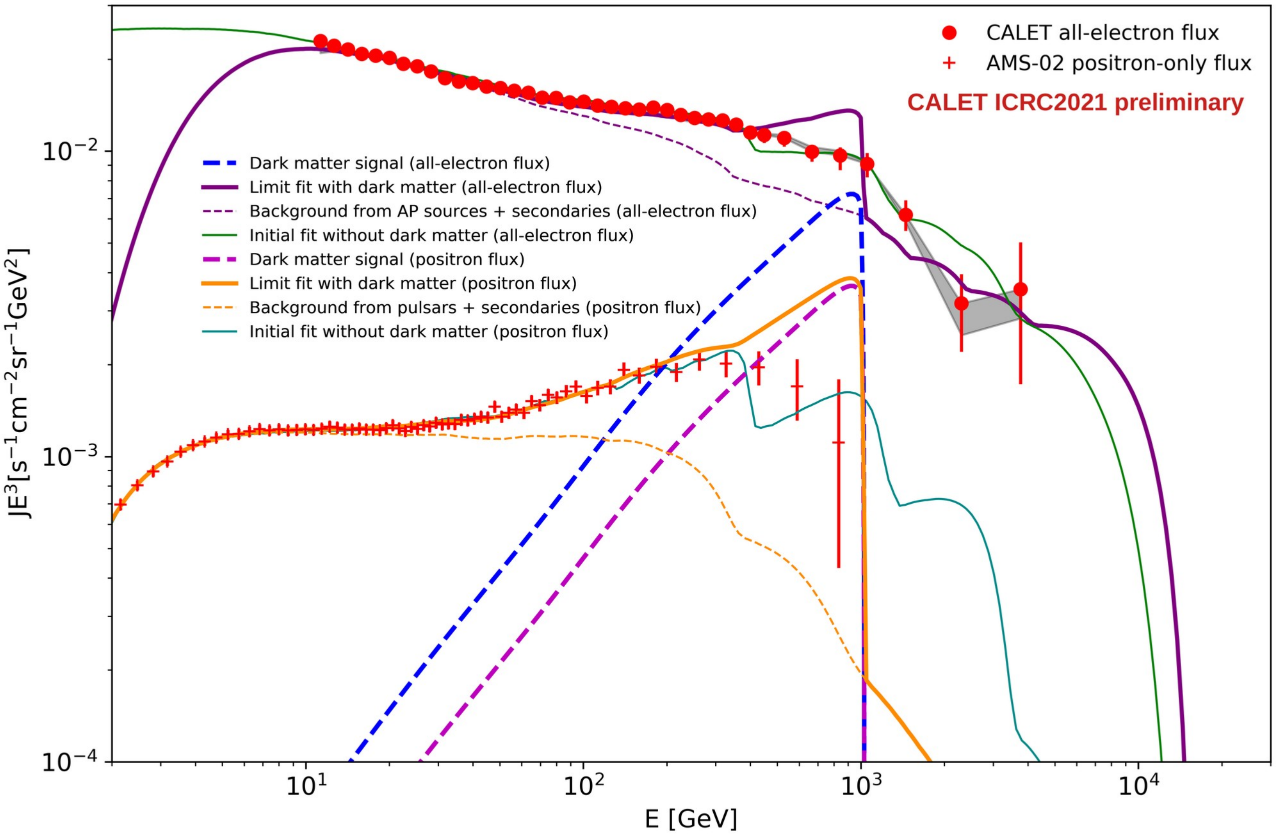

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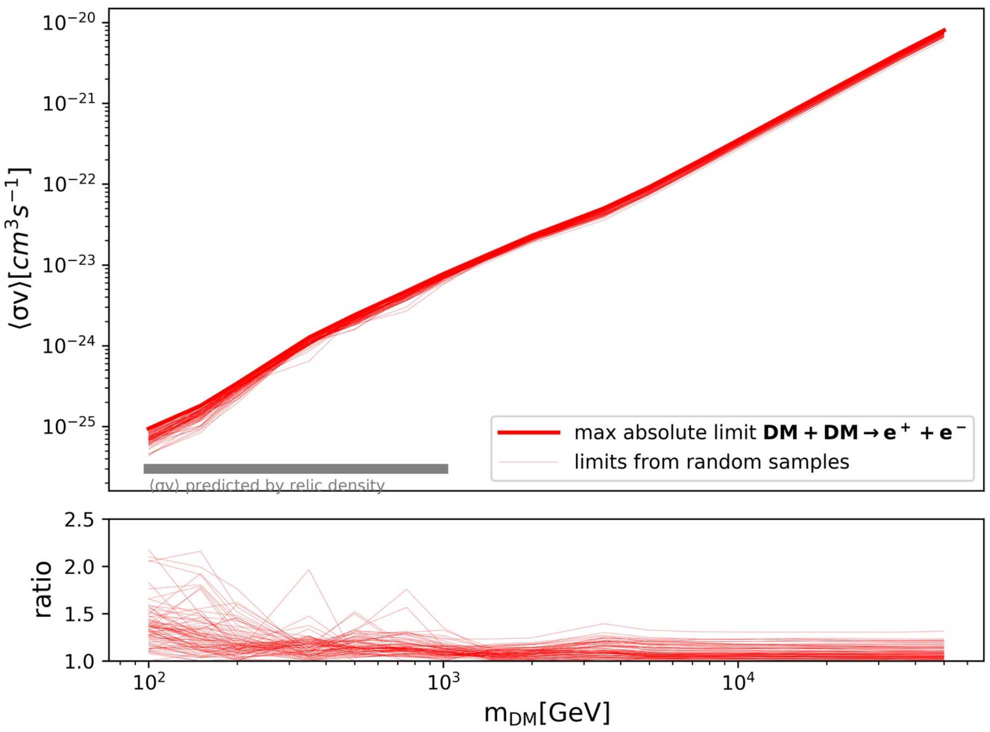
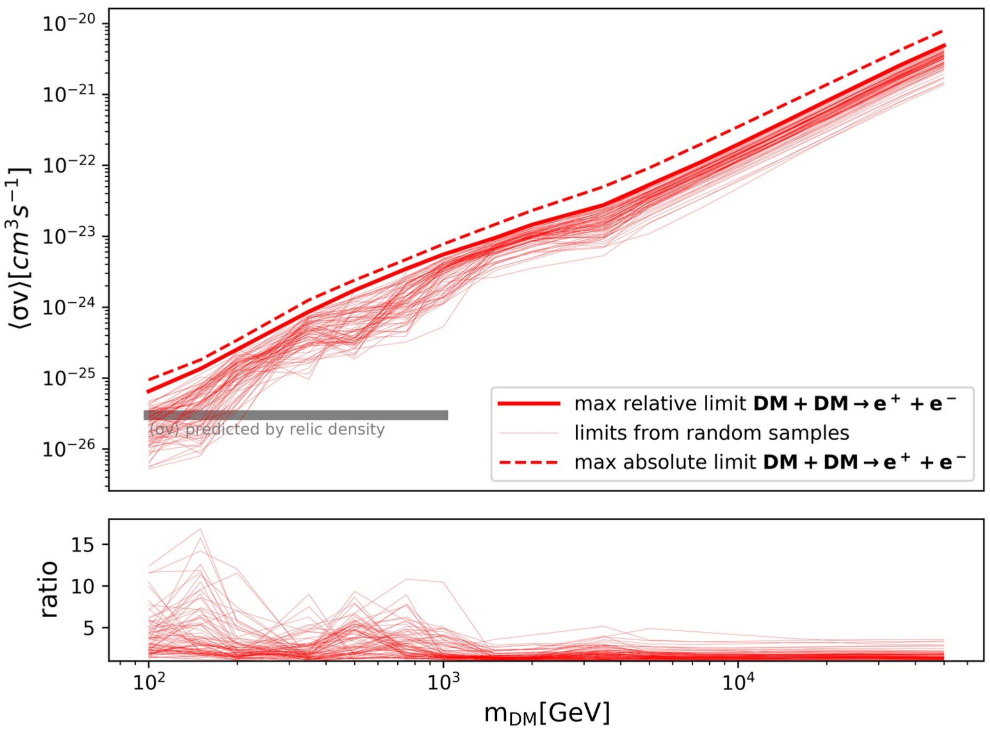
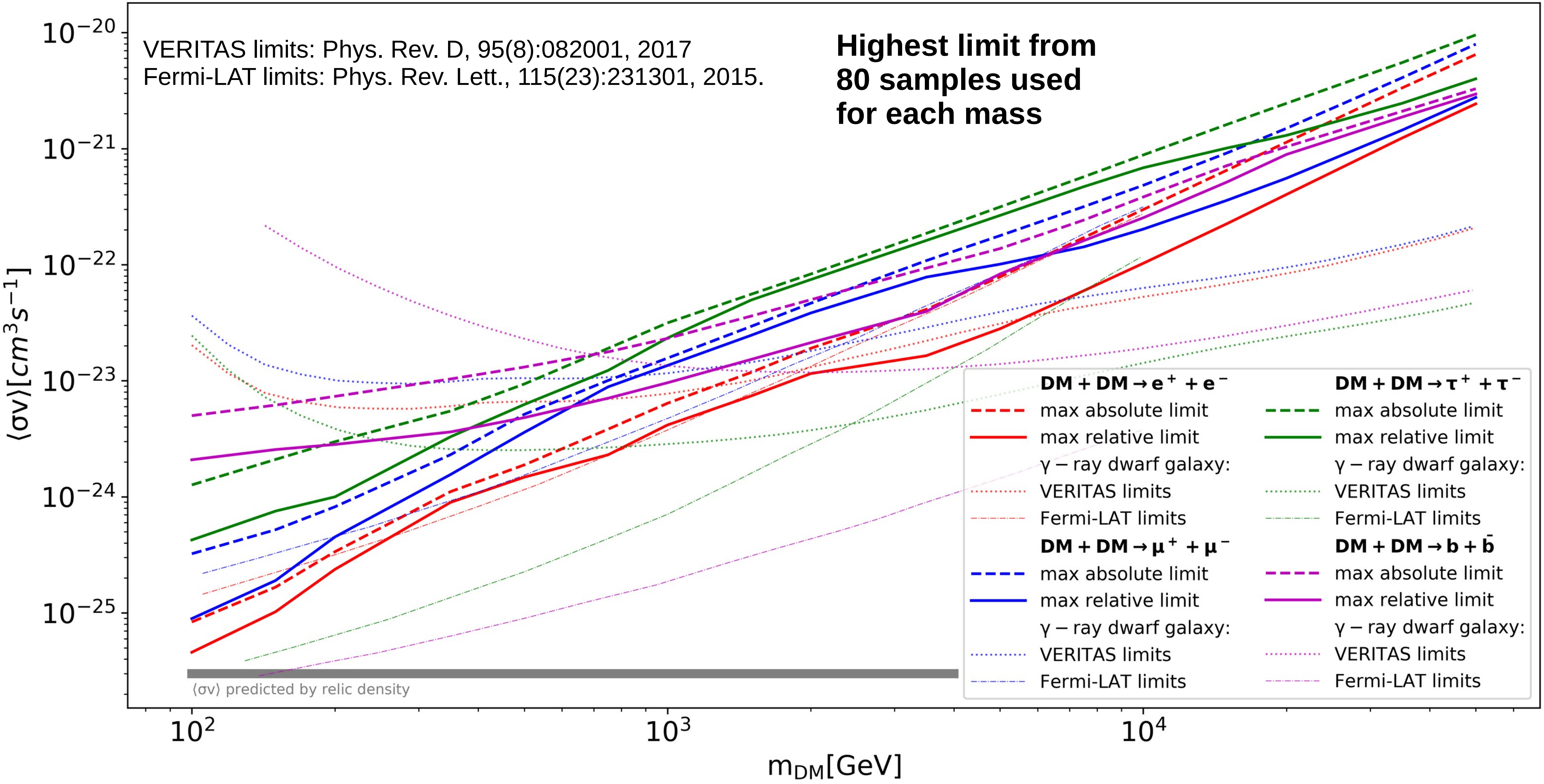
Dependence of Limits on Samples



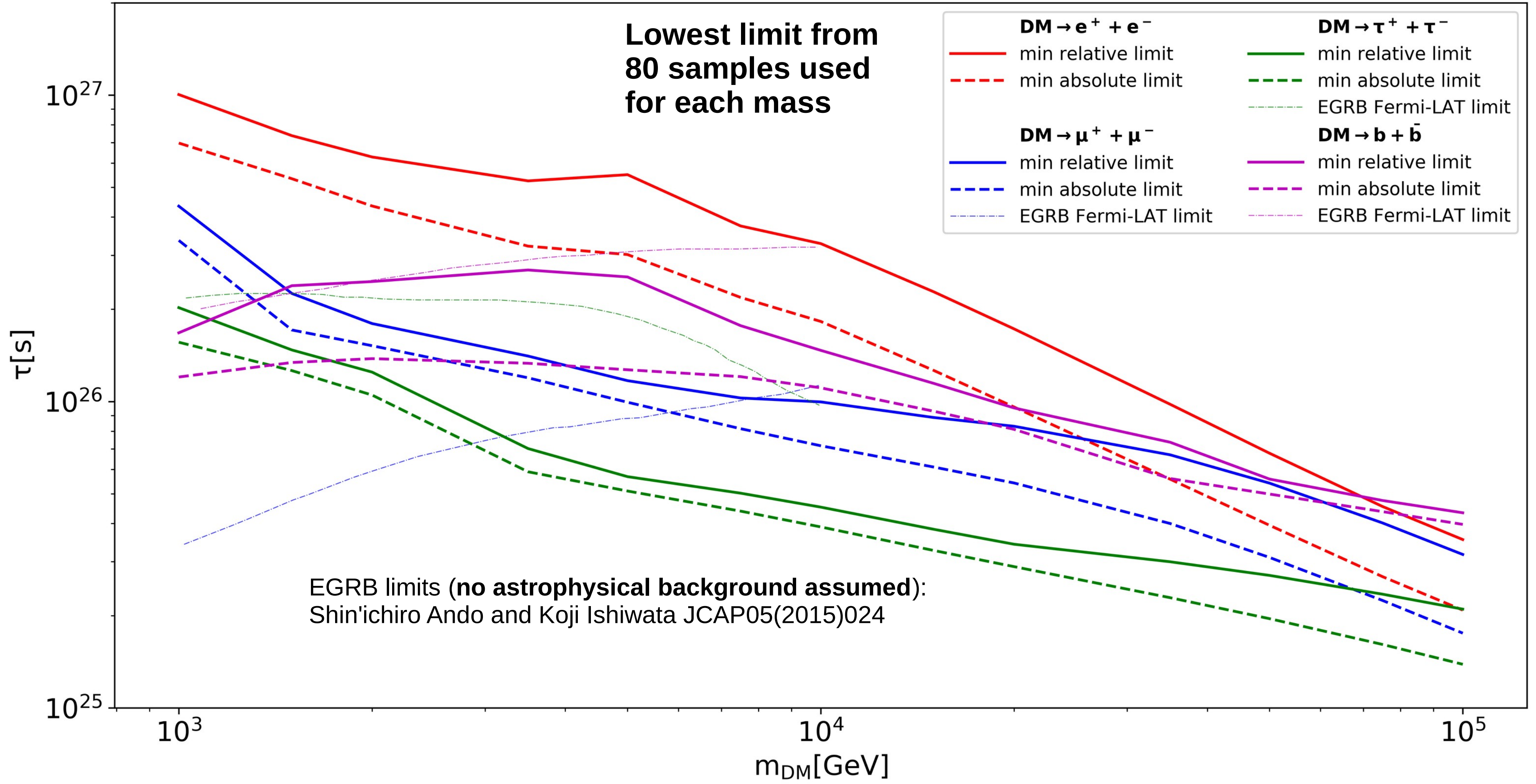


- The relative limit has a stronger dependence on the background variation than the absolute limit.
- The worst relative limit is lower (stricter) than the absolute limit.

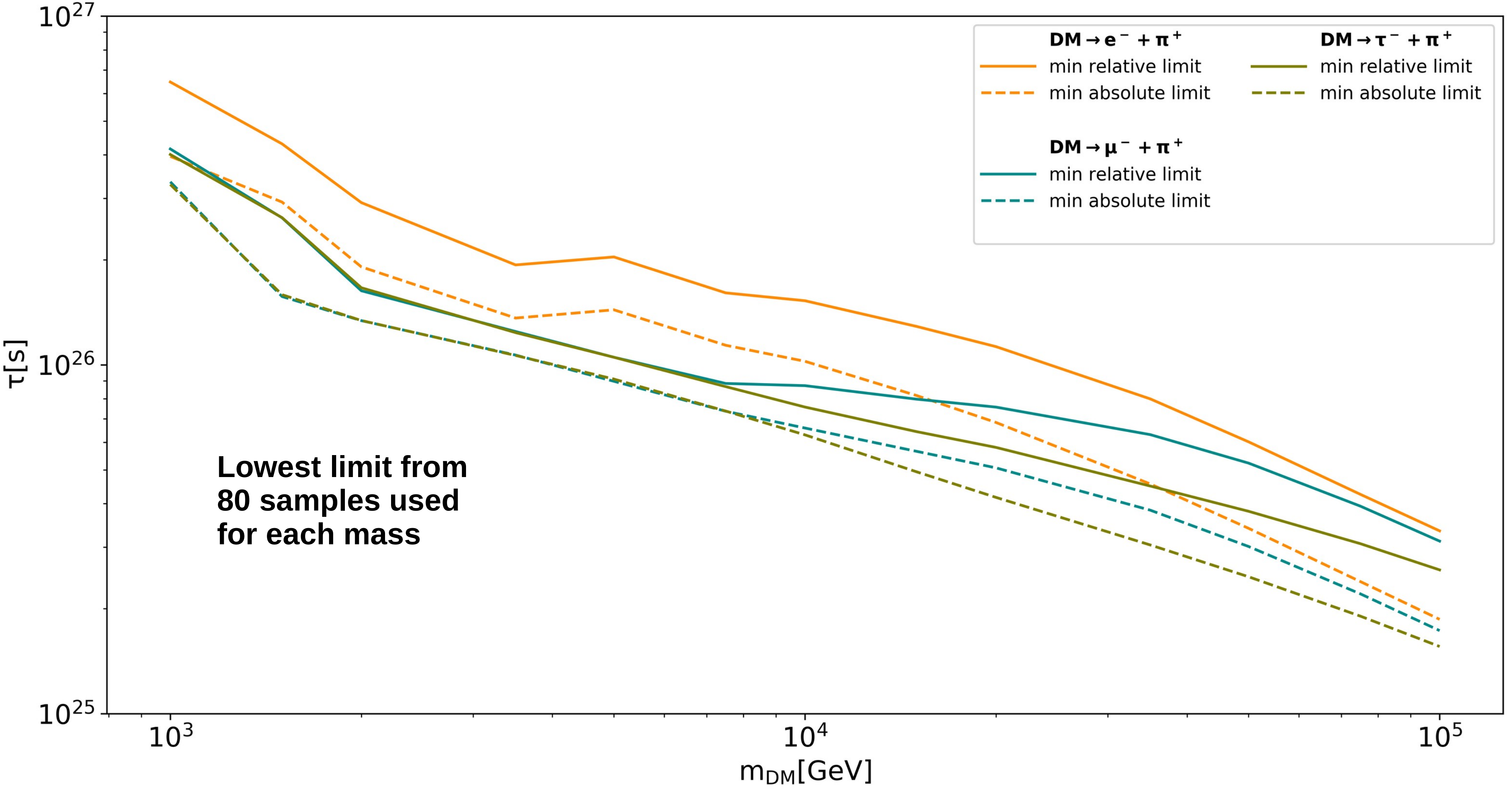
Limit Results (annihilation)



Limit Results (decay)



Limit Results (Skyrmion decay)



Conclusions

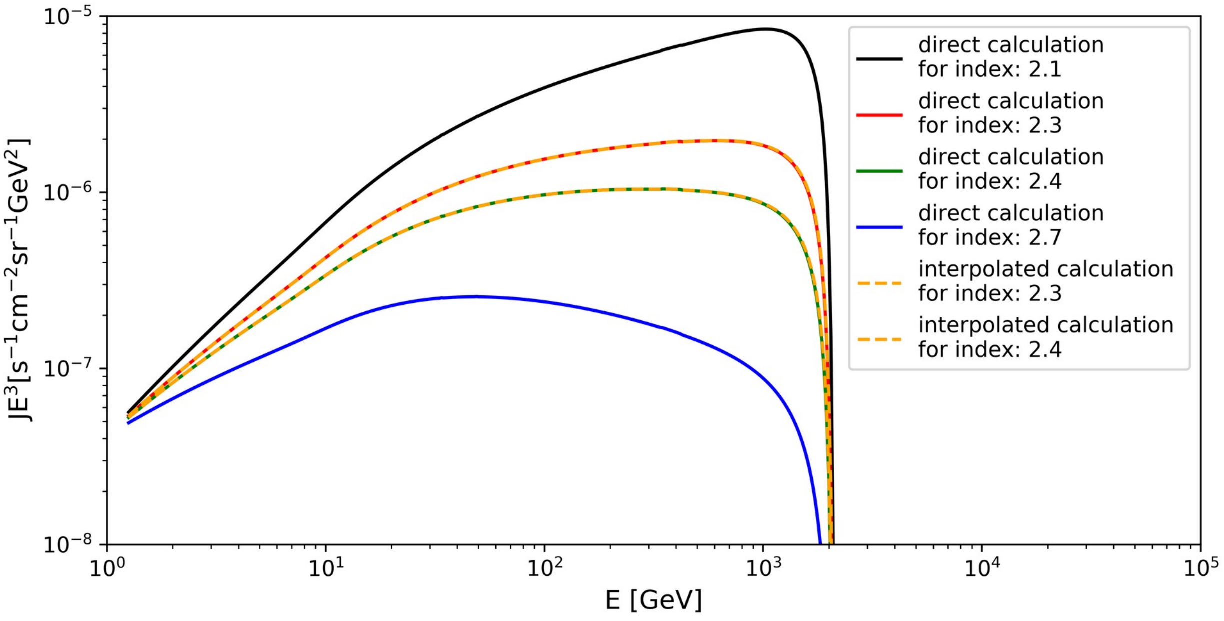
- From CALET all-electron and AMS-02 positron-only data, limits on DM lifetime (annihilation cross-section) have been calculated up to a DM mass of 100 TeV (50 TeV).
- These limits are comparable and, given the different sources of systematic uncertainty, complementing those from other messengers such 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.

We gratefully acknowledge JAXA's contributions to the development of CALET and to the operations onboard the International Space Station. The CALET effort in Italy is supported by ASI under Agreement No. 2013-018-R.0 and its amendments. The CALET effort in the United States is supported by NASA through Grants No. 80NSSC20K0397, No. 80NSSC20K0399, and No. NNH18ZDA001N-APRA18-0004. In Japan, this work is supported in part by JSPS Grant-in-Aid for Scientific Research (S) Grant No. 19H05608 and by JSPS Grant-in-Aid for Scientific Research (C) Grant No. JP21H05463.

Backup Slides

Spectrum Interpolation (Index)

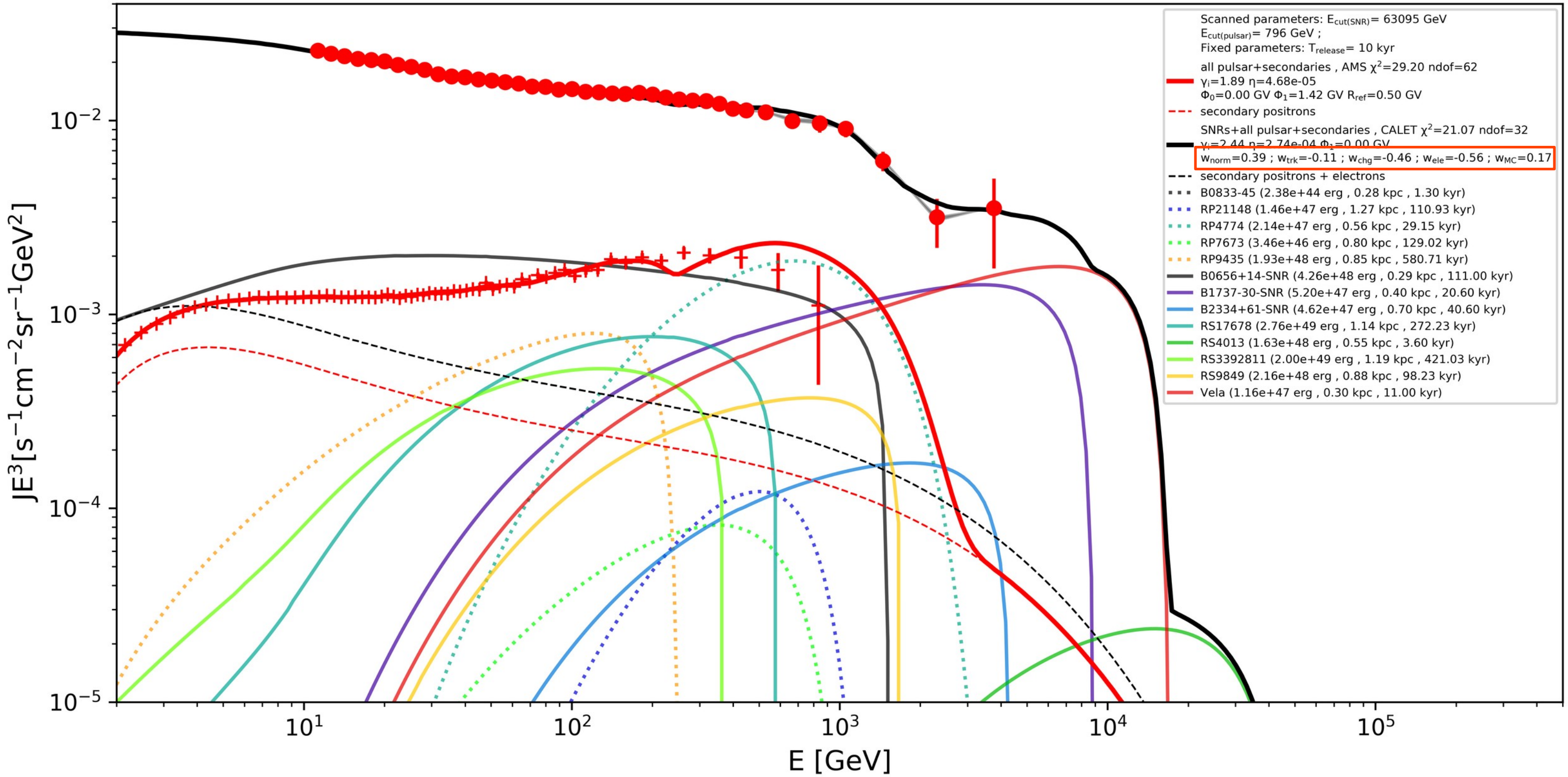
- Calculating the propagated spectrum for 7.5 million sources takes several minutes → not feasible to put this through a minimizer
- Solution: Calculate spectrum for selected values, compensate for the index difference and interpolate to get intermediate values:



$$F(\gamma)=\frac{\gamma_2-\gamma}{\gamma_2-\gamma_1}F(\gamma_1)\left(\frac{E}{GeV}\right)^{\gamma_1-\gamma}+\frac{\gamma-\gamma_1}{\gamma_2-\gamma_1}F(\gamma_2)\left(\frac{E}{GeV}\right)^{\gamma_2-\gamma}$$

Treatment of systematic errors

- The spectrum measured by CALET has systematic errors with known energy dependence
- Instead of adding the systematic error quadratically to the systematic error, the data is shifted systematically by the function Δ calculated in the same way as those in the S.M. of Phys. Rev. Lett. 120, 261102 (2018) with the normalization coefficients as fitted nuisance parameters
- The systematic uncertainties of Normalization, Tracking, Charge Selection, Electron Identification and Monte Carlo are fitted in this way,
- The squared weight of each uncertainty is added to the total χ^2 of the fit, while the fitting function is shifted as represented by the gray area.



$$\chi^2_{CALET} = \left(\sum_i \frac{\left(\phi_i + \sum_k \Delta_k w_k - J_i\right)^2}{\sigma_i^2} \right) + \sum_k w_k^2$$

i: data point index
k: uncertainty type index