Individual Astrophysical Sources as Background for Dark Matter Search with CALET

JPS annual meeting
on-line, 2023/3/24

24pW2-13

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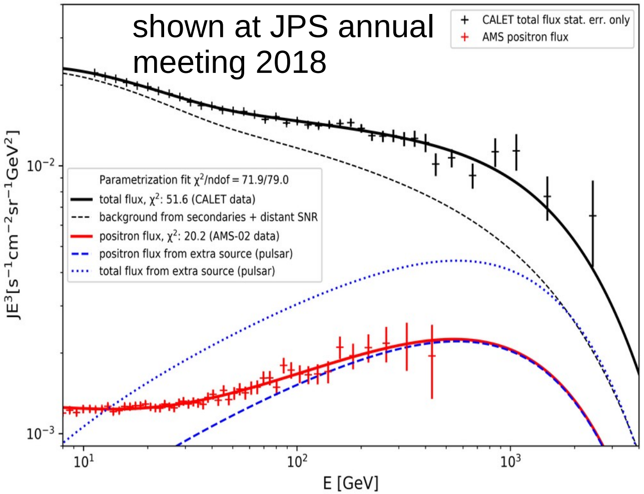
Overview

- **Product:** Limits on DM annihilation and decay from a combined analysis of the latest all-electron spectrum published by CALET [currently: S. Torii, Y. Akaike et al. POS ICRC 2021 (105)] and the positron-only spectrum from AMS-02 [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.

shown at JPS annual meeting 2018



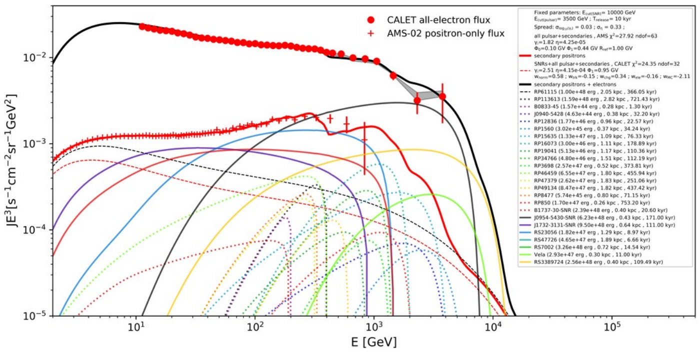
old background model:
power-law parametrization

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

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

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

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

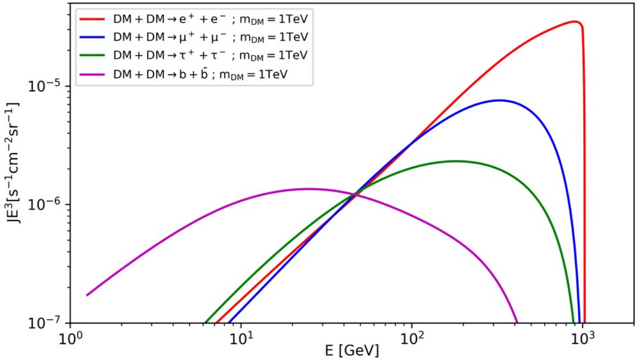


DM Signal Calculation

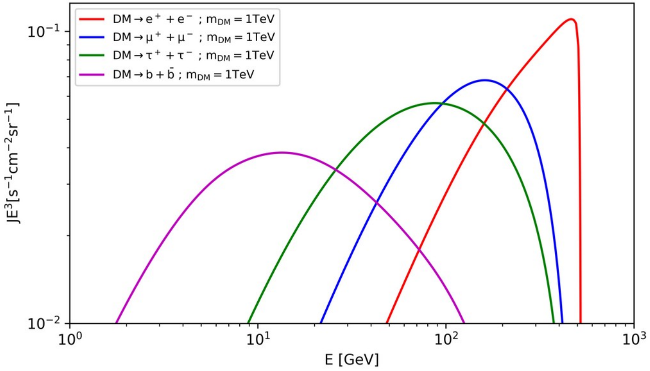
calculated channels:

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+$\overline{b}$**	

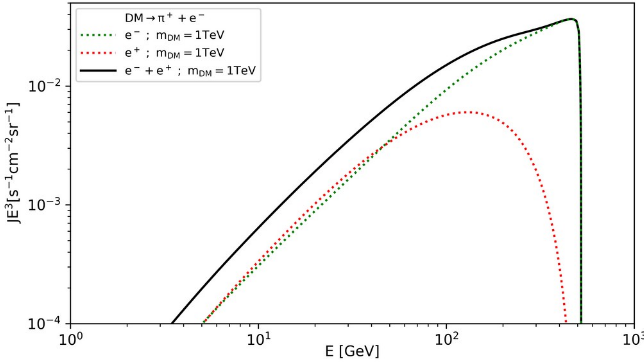
- Flux of electrons and positrons per annihilation or decay from decay of primary annihilation products calculated with PYTHIA
- Flux at Earth calculated with DRAGON assuming **0.3 GeV/cm³ local DM density** and NFW halo profile for a base cross section <σv>= 3×10^{-26} cm^3/s or base lifetime of 3.3×10^{25}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



annihilation



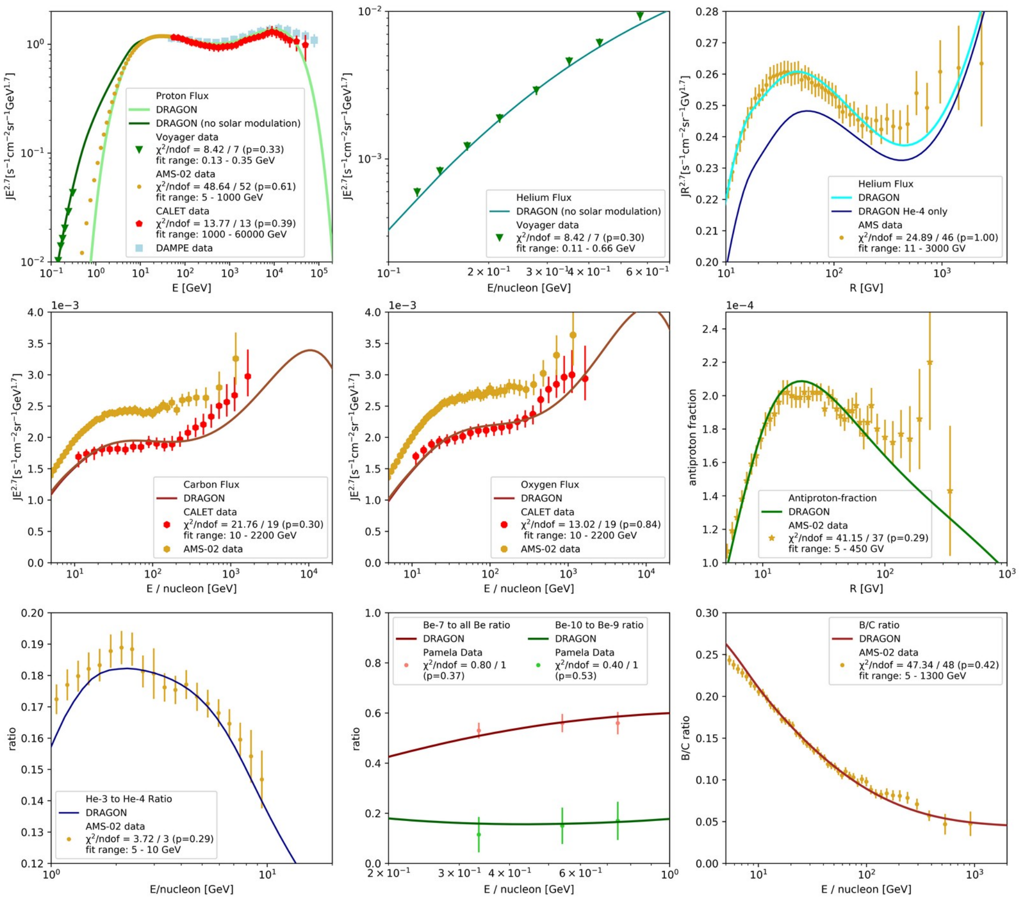
decay



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.

Propagation Model



secondary electron and positron component of background for the dark matter limit fit also taken from this DRAGON calculation

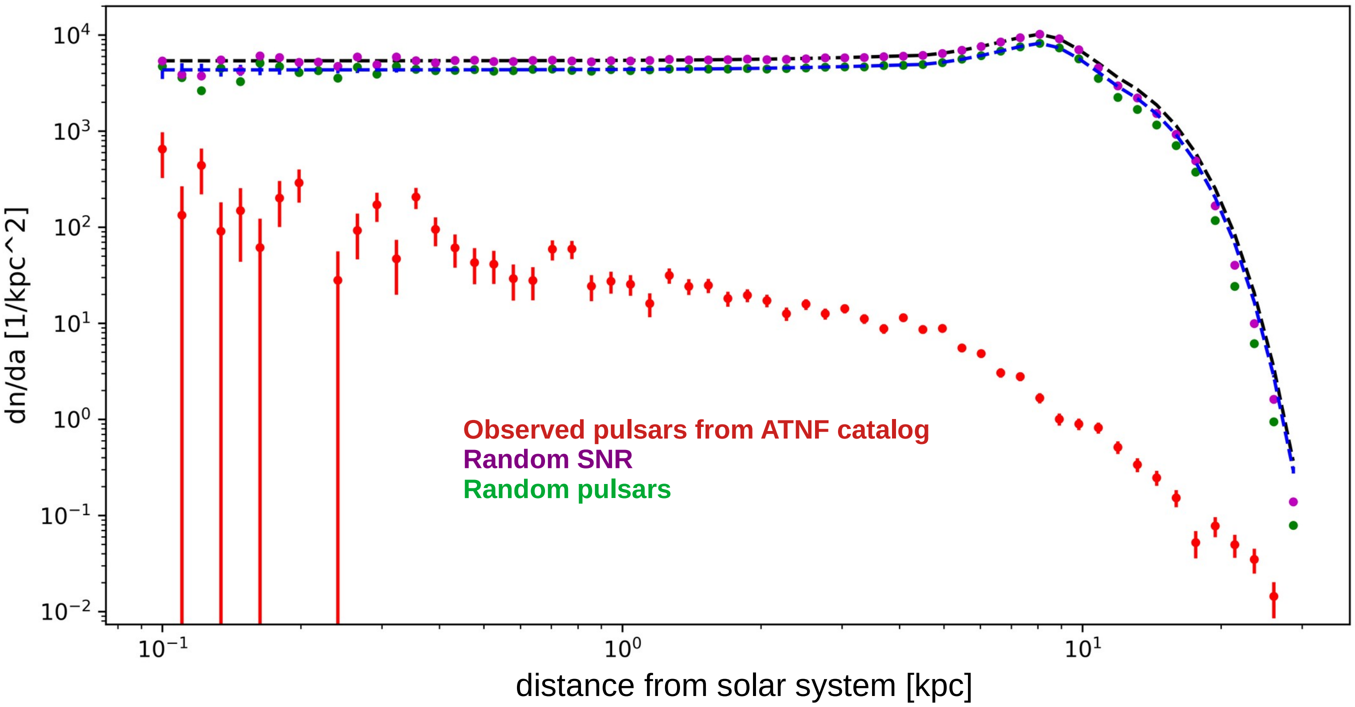
- Calculation of nuclei spectra with DRAGON tuned to explain data of AMS-02, CALET and Voyager
- Spectral changes of the nuclei spectra are modeled by two soft breaks in the slope of the diffusion coefficient, softening from δ_l to δ at R_{bl} with softness s_l , then hardening again to δ_h at R_{bh} with softness s_h
- Diffusion coefficient depends on position (exponential increase with galactic radius r, distance from galactic plane z) and rigidity:

$$D(r,z,D)=D_0 \max\left(e^{(r-r_n)/r_s},1\right)\max\left(e^{(z-z_n)/z_s},1\right)\left(\frac{R}{R_0}\right)^{\delta_l}\left(1+\left(\frac{R}{R_{bl}}\right)^{\frac{\delta_l-\delta}{s_l}}\right)^{s_l}\left(1+\left(\frac{R}{R_{bh}}\right)^{\frac{\delta-\delta_h}{s_h}}\right)^{-s_h}$$

- A common injection spectrum for all primary nuclei species is assumed, which is a power law with index γ_l below, and γ_i above the break at R_{bi} with softness s_{bi} , and with an exponential cut-off at R_{cut}

γ_l	R_{bi}	s_{bi}	γ_h	R_{cut}	w_{sa}
2.030	13.45GV	0.229	2.345	30.12TV	0.648kpc
D_0	r_s	z_s	δ_l	R_{bl}	s_l
$3.1\times10^{28}cm^2/s$	10.70kpc	4.50kpc	0.211	8.437GV	0.053
δ	R_{bh}	s_h	δ_h	v_a	
0.514	913.5GV	0.369	0.002	14.74 m/s	

Pulsar and SNR Distribution (differential)



Spatial distribution and SN rate:

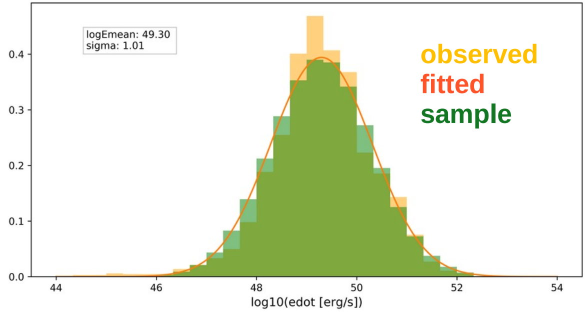
The interstellar environment of our galaxy, K. Ferriere, Rev.Mod.Phys. 73, 1031-1066 (2001)

→ same model as used in DRAGON for determining the propagation model and secondary flux component

Pulsar birth rate:

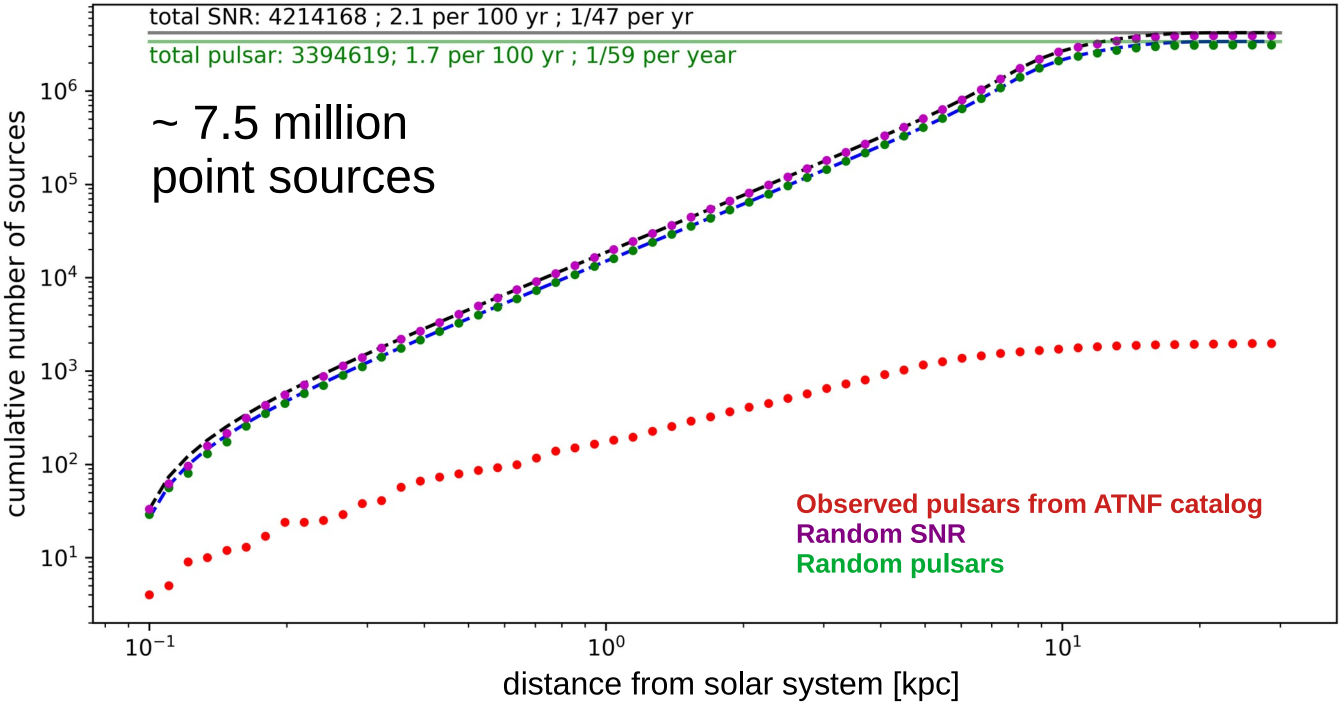
The galactic population of young γ-ray pulsar, Kyle P. Watters and Roger W. Romani, 2011 ApJ 727 123

pulsar energy distribution



- random pulsar samples created with spatial distribution of Ferriere SNR model, up to 200 Myr
- pulsar initial power distribution based on measured data (ATNF catalog)
- 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, then additional SNRs generated
- SNR total energy distribution is also log-Gaussian with average $10^{51\pm1}$ erg and cut at 5×10^{52} erg
- Vela is a special case with energy $1–2.5\times10^{51}$ erg (G. Dubner et al. APJ 116:813-822, 1998)

Pulsar and SNR Distribution (cumulative)



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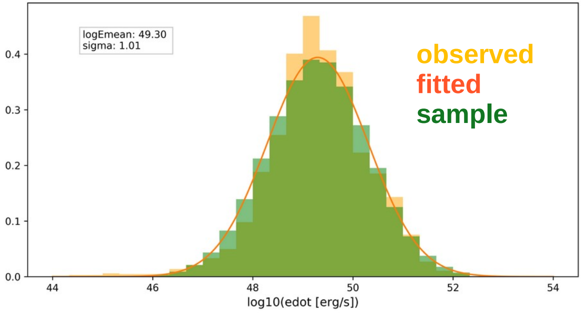

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Calculating the Flux at Earth from Pulsars and SNR

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

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

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

free parameters: efficiency η, index γ

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

total energy Q_0, cutoff energy E_{cut}, distance r,

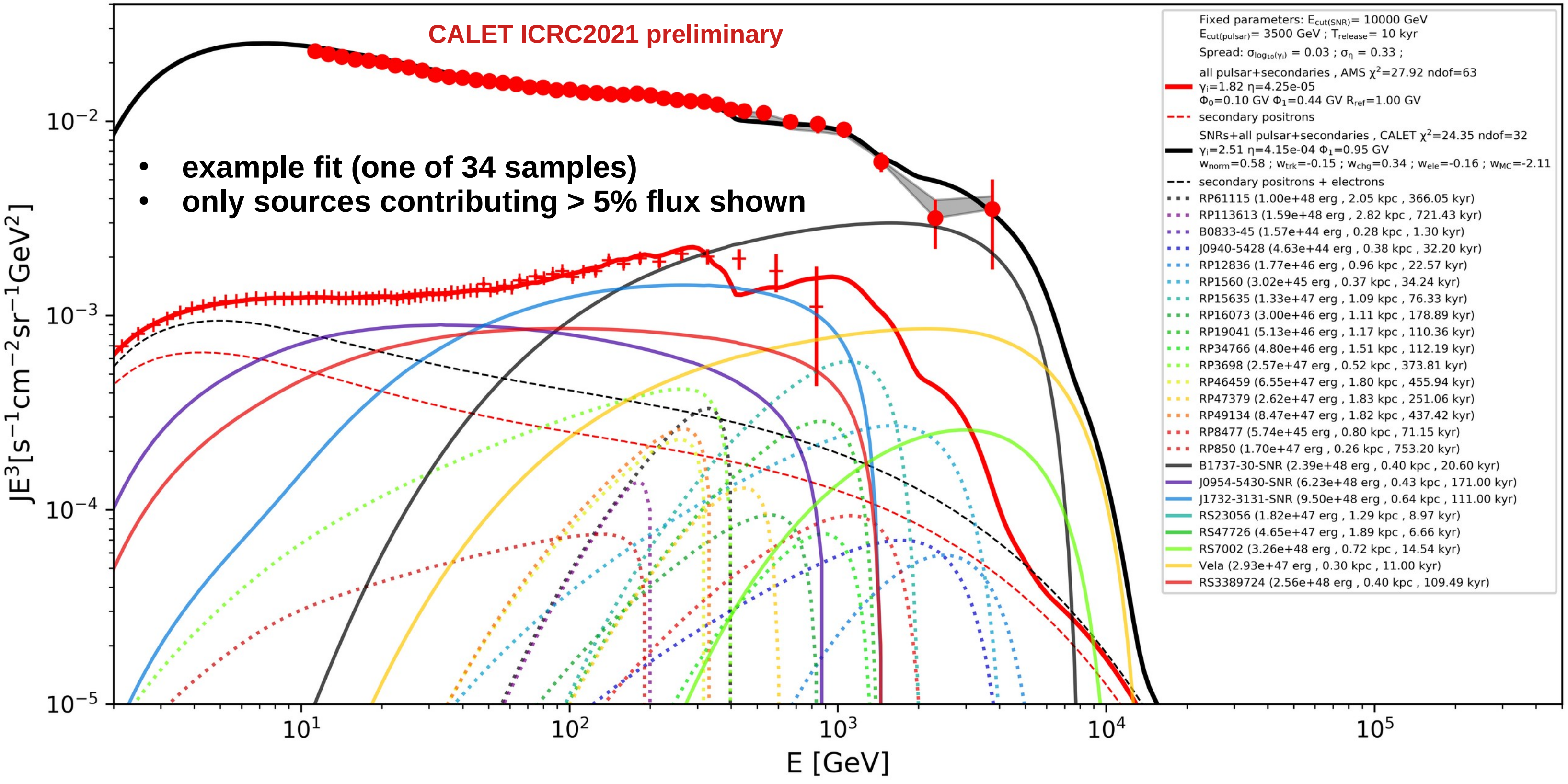
diffusion time $t_{dif}=$ age - release delay T_R

(random sampling / ATNF catalog)

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

Fit of Base Model to CALET and AMS-02



- Random source spectrum index spread with Gaussian distribution (σ=0.03)
- Free parameters:
  - average SNR index $\gamma_{i(S)}$
  - SNR efficiency η_S
  - average pulsar index $\gamma_{i(P)}$
  - pulsar efficiency η_P
  - solar modulation (4)
  - weights for energy dependent systematic uncertainties of CALET spectrum (5)
- 34 out of 100 samples gave a good fit to the data after 1000 trials of source spectrum index randomization

  → **suitable background model**

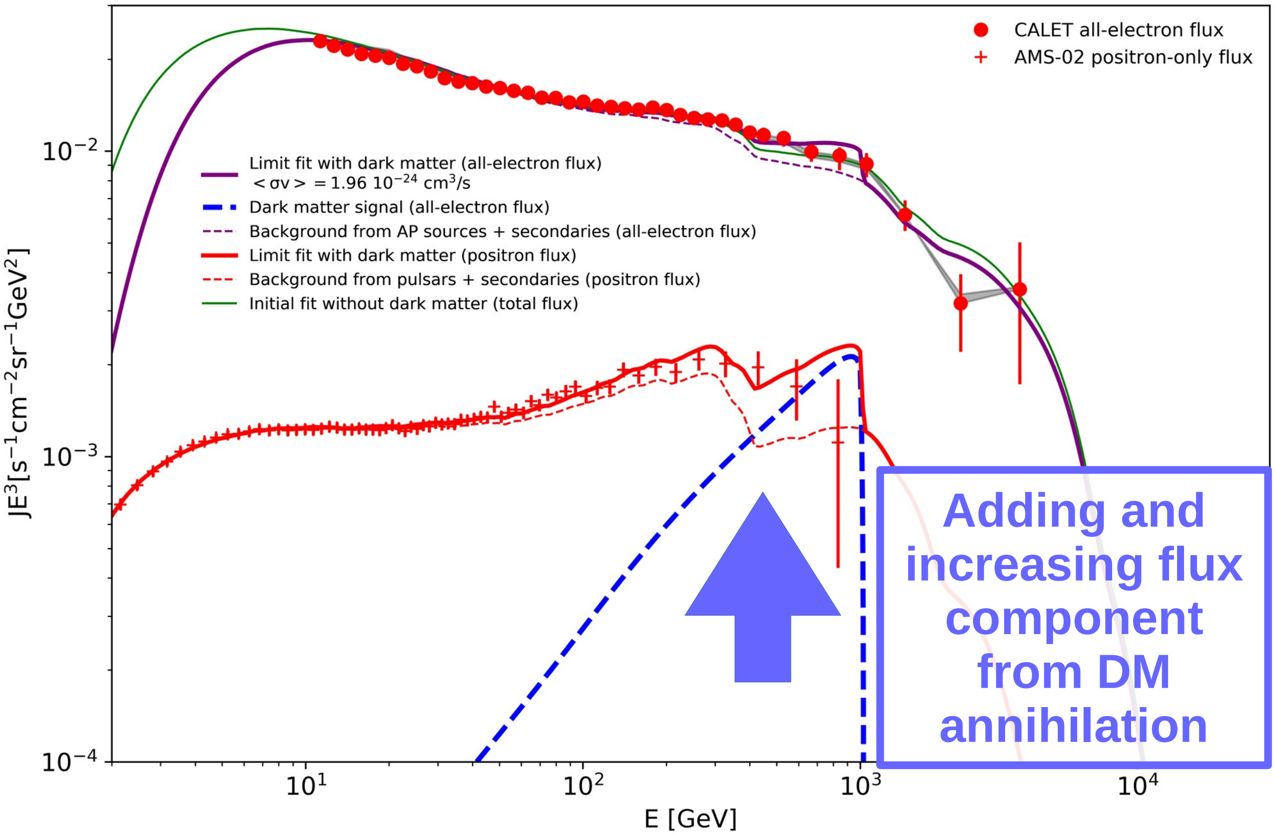
Charge sign and rigidity depended solar modulation potential based on Ilias Cholis, Dan Hooper, Tim Linden Phys. Rev. D 93, 043016 (2016) “A Predictive Analytic Model for the Solar Modulation of Cosmic Rays”

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

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:
$<\sigma v> = 1.96\ 10^{-24}$ cm^3/s

Fit Quality
CALET base: $\chi^2 = 24.35$
CALET limit: $\chi^2 = 27.15$
AMS base: $\chi^2 = 27.92$
AMS limit: $\chi^2 = 28.96$
combined base: $\chi^2 = 52.28$
combined limit: $\chi^2 = 56.11$
difference: $\Delta\chi^2 = 3.84$

Limit (Base) Fit Values:

SNR parameters
$\gamma_{i(S)} = 2.53$ ($\gamma_{i(S)} = 2.51$)
$\eta_{(S)} = 0.046\%$ ($\eta_{(S)} = 0.042\%$)

pulsar parameters
$\gamma_{i(P)} = 1.89$ ($\gamma_{i(P)} = 1.82$)
$\eta_{(P)} = 0.006\%$ ($\eta_{(P)} = 0.004\%$)

solar modulation
$\Phi_0 = 0.17$GV ($\Phi_0 = 0.10$GV)
$\Phi_{1(n)} = 2.46$GV ($\Phi_{1(n)} = 0.95$GV)
$\Phi_{1(p)} = 0.34$GV ($\Phi_{1(p)} = 0.44$GV)
$R_{ref} = 1.00$GV ($R_{ref} = 1.00$GV)

nuisance weights:
$w_{norm} = 0.57$ ($w_{norm} = 0.58$)
$w_{trk} = 0.31$ ($w_{trk} = 0.15$)
$w_{chg} = 0.73$ ($w_{chg} = 0.34$)
$w_{ele} = 0.31$ ($w_{ele} = 0.16$)
$w_{MC} = 1.76$ ($w_{MC} = 2.11$)

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:
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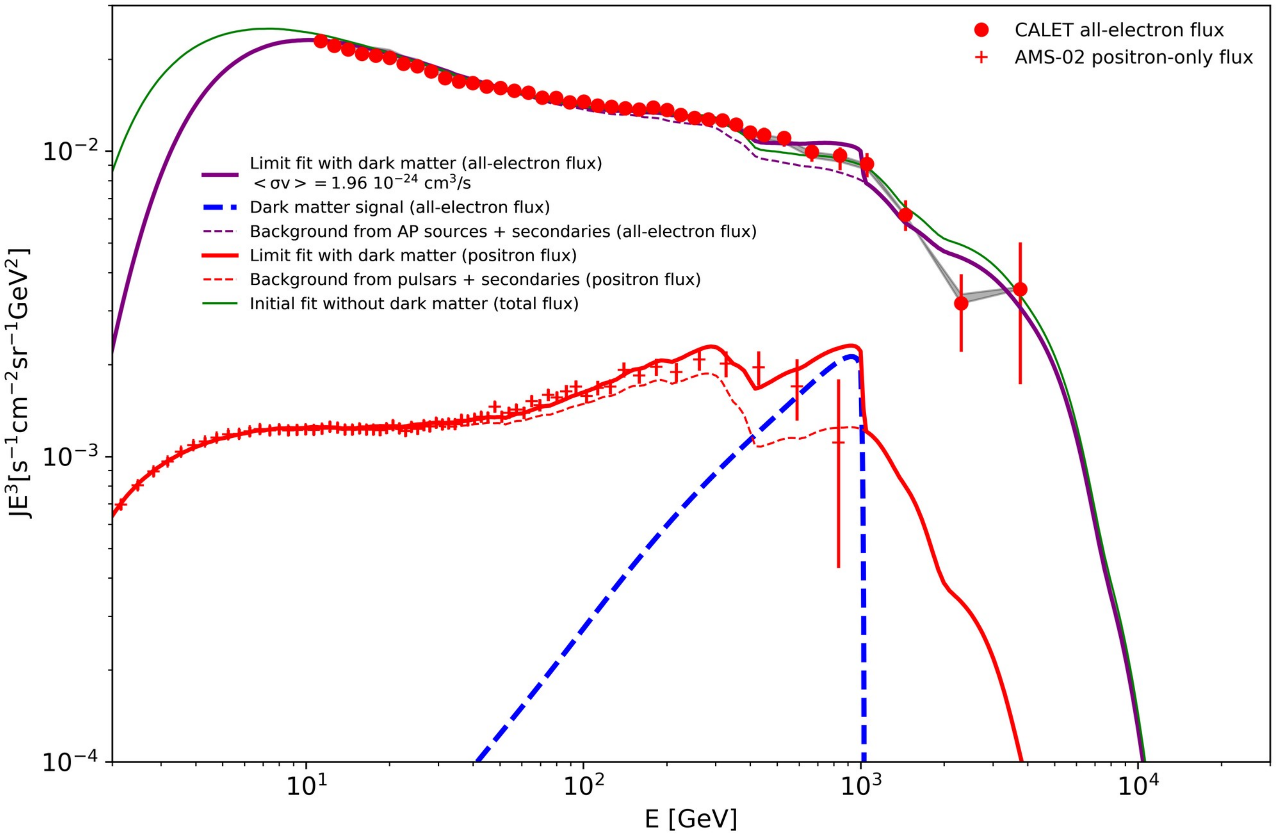

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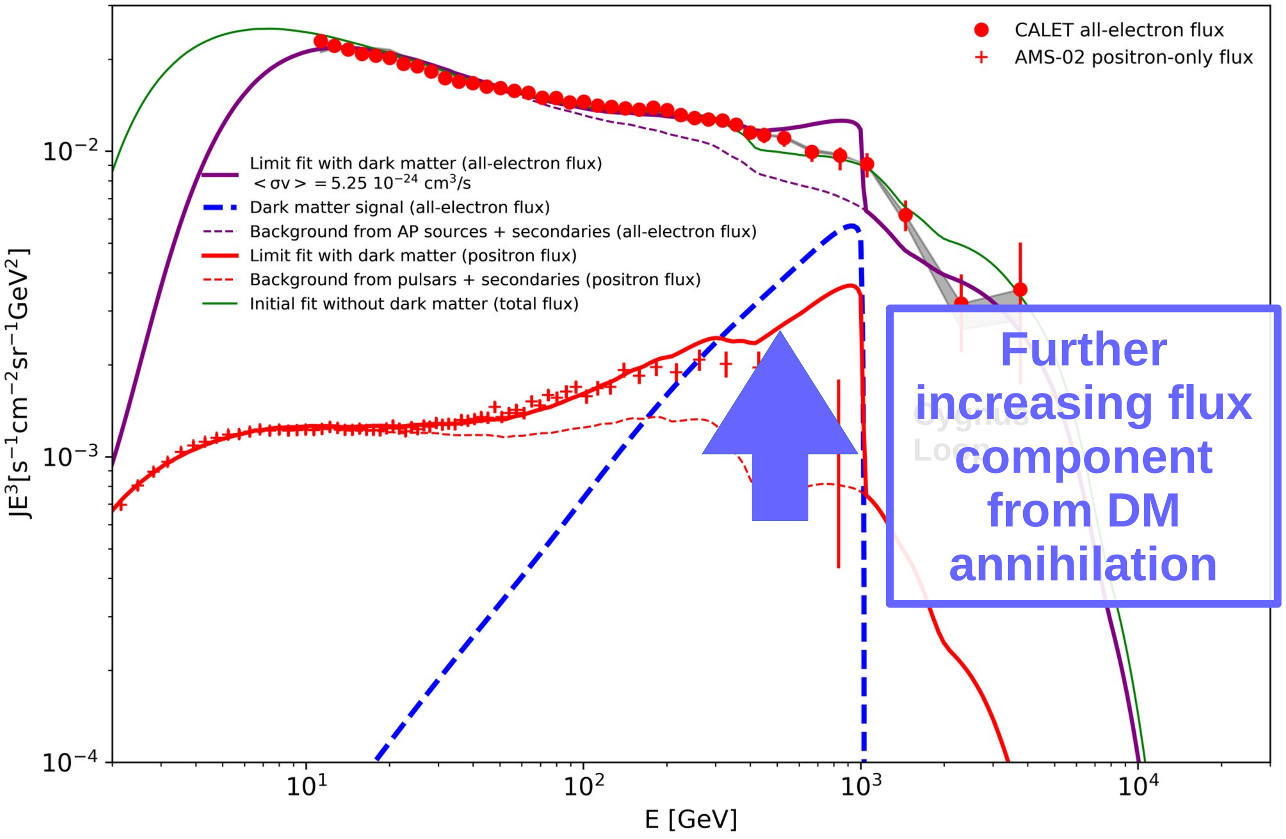

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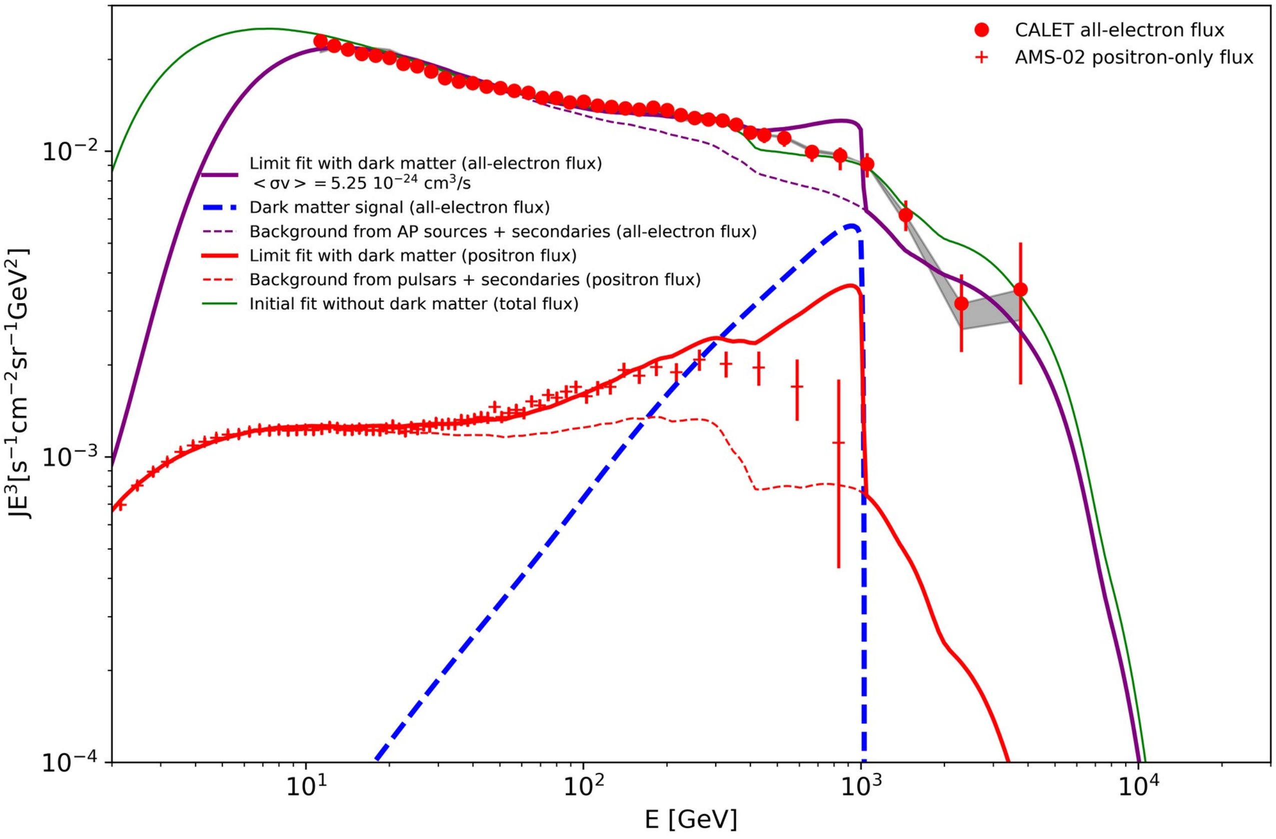

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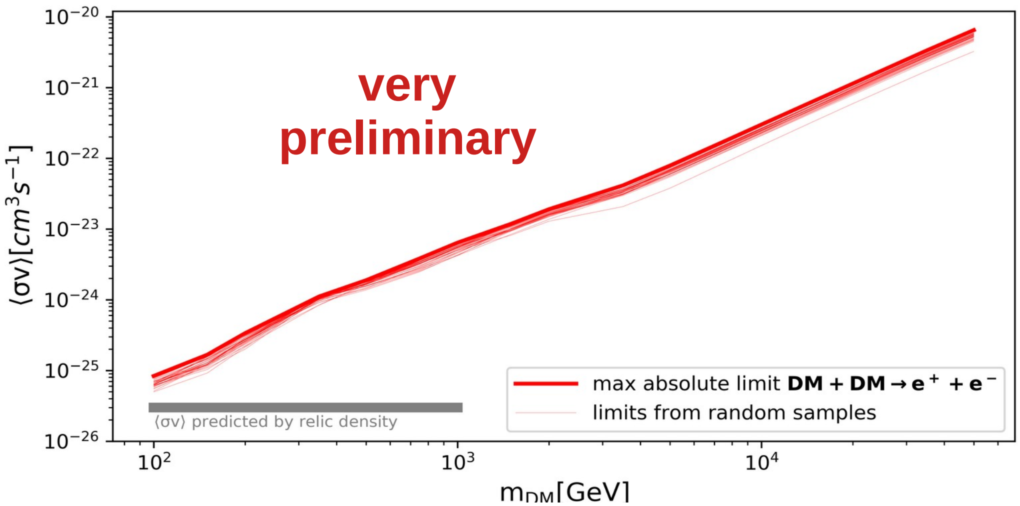
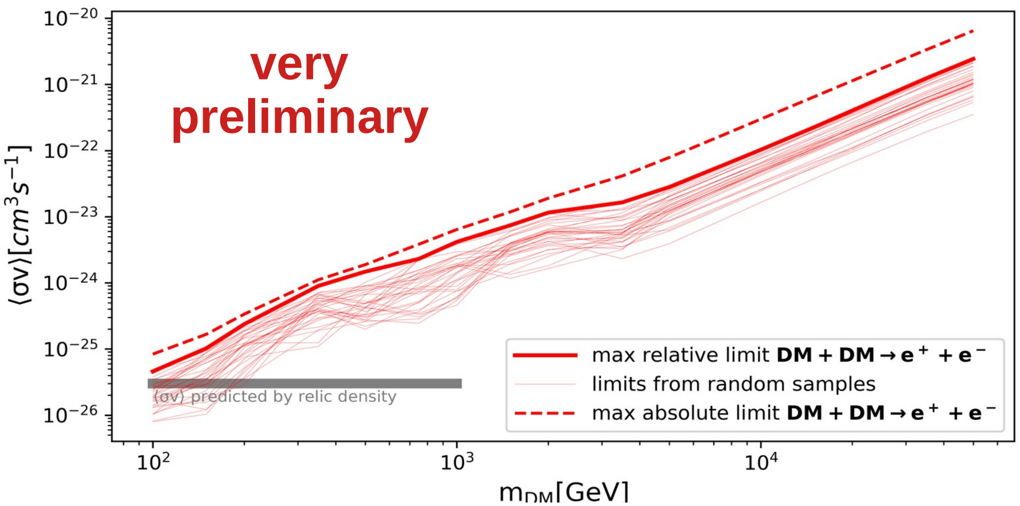
Dependence of Limits on Background Variation

based on the 34 random SNR&pulsar distributions processed so far

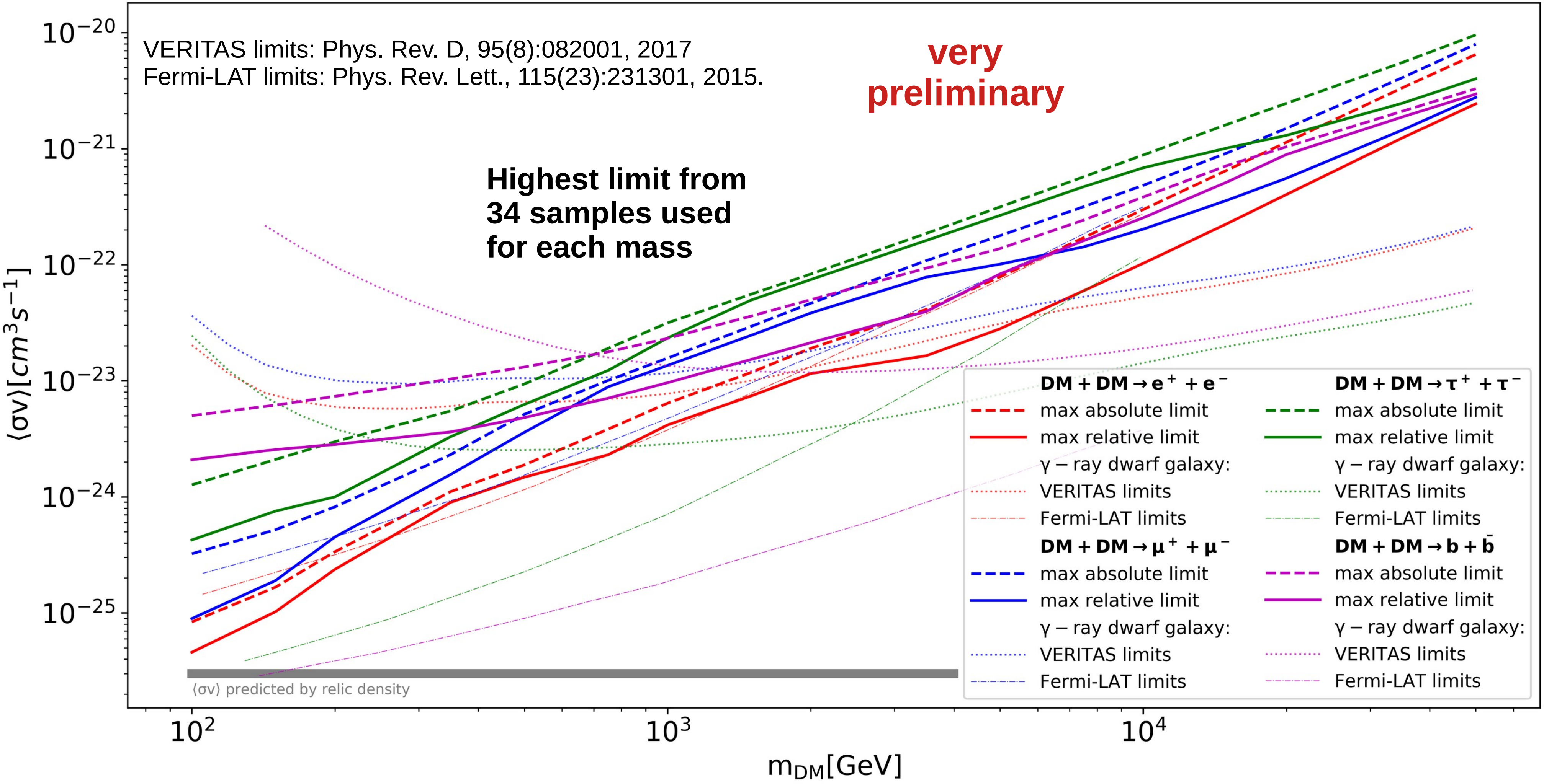




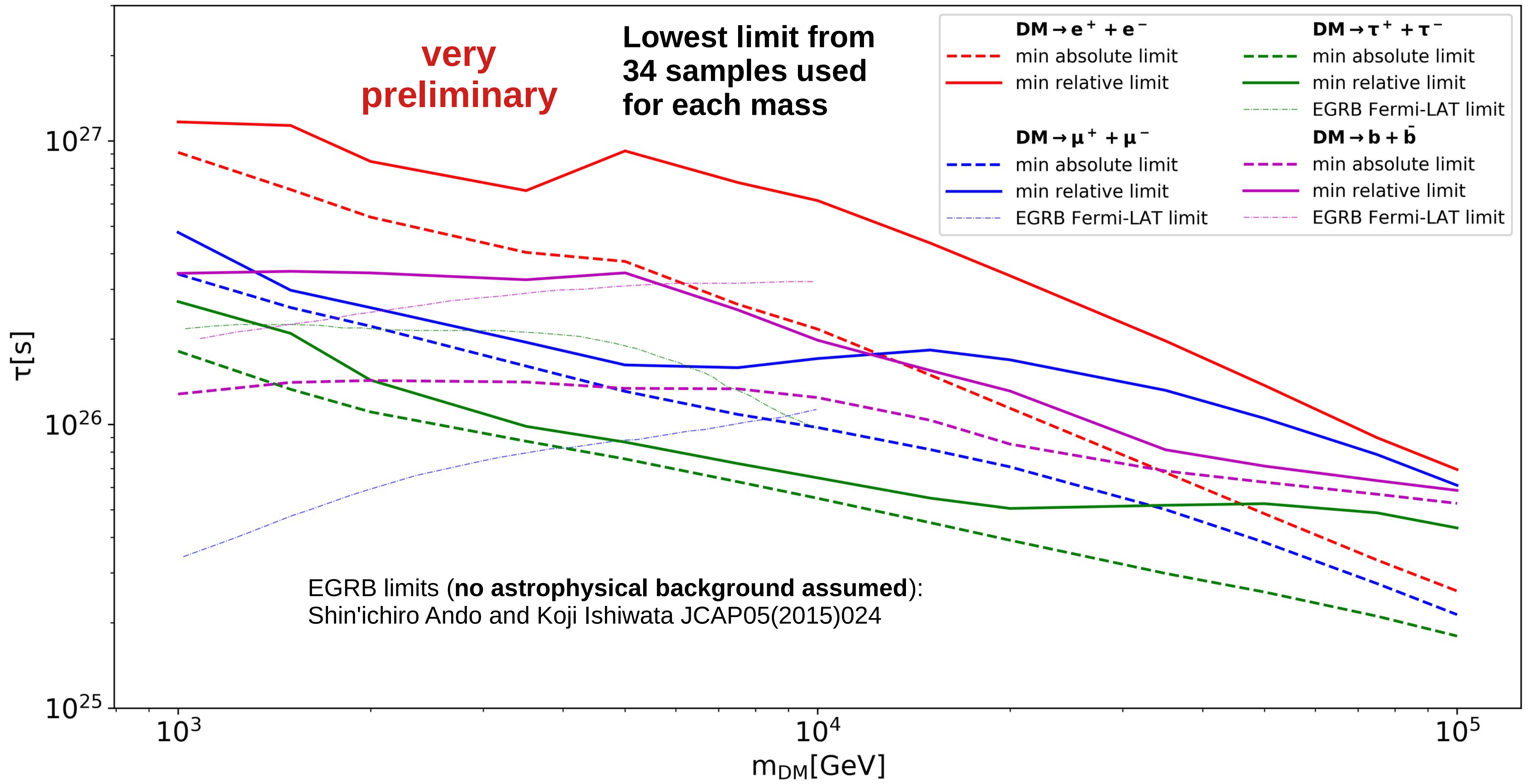
Absolute limits are almost independent of the background differences between samples

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

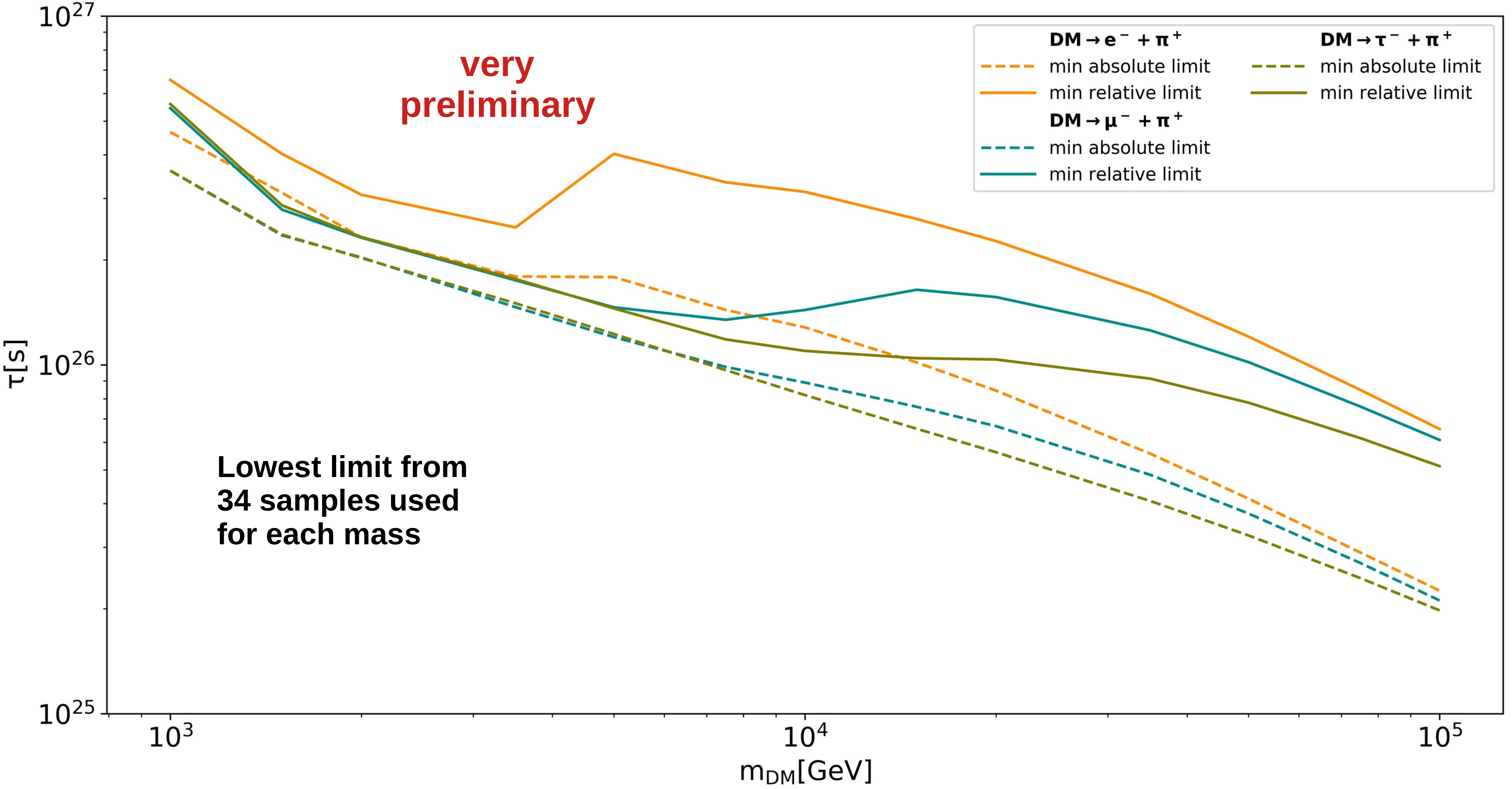
Limit Results (annihilation)



Limit Results (decay)



Limit Results (skyrmion decay)



Conclusions & Outlook

- A background model with all SNR and pulsar contribution treated as randomized individual source samples has been developed, allowing to study the influence of background structures on dark matter limits.
- Preliminary limits from a small number of samples have been calculated for various annihilation/decay channels with DM mass up to 100 TeV (annihilation: 50 TeV)

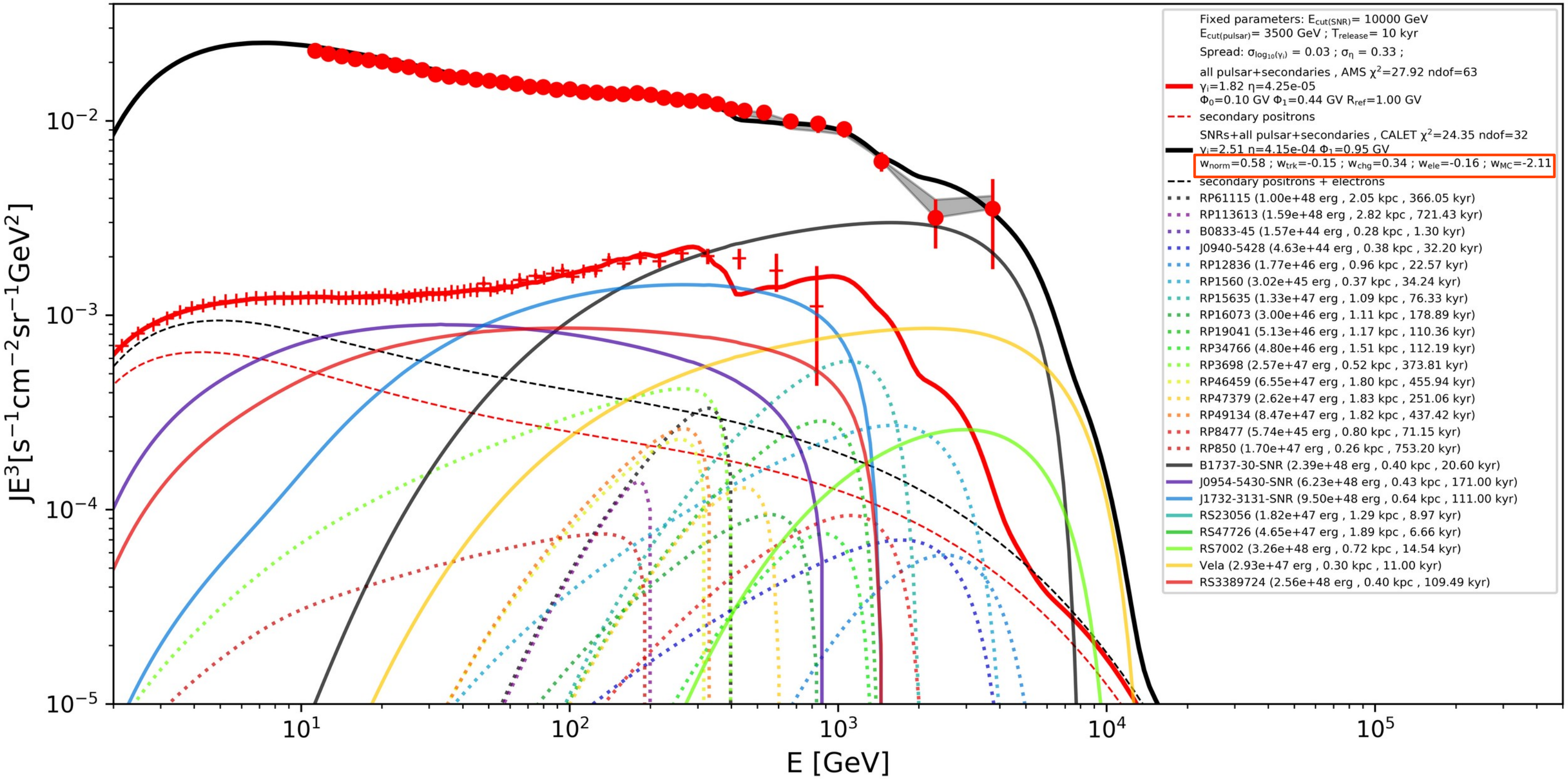
- Limits with the absolute χ^2 threshold definition are shown to be robust against background variation, while limits based on a relative χ^2 increase show a strong dependence → to use the stricter relative limits, the variability with background must be studied in detail → processing of many more samples necessary

The author gratefully acknowledges the support of the CALET collaboration team in making the preliminary results published at ICRC2021 available for use in this work. This work is supported by JSPS KAKENHI Grants No. JP21H05463 and No. JP21K03604.

Backup Slides

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.

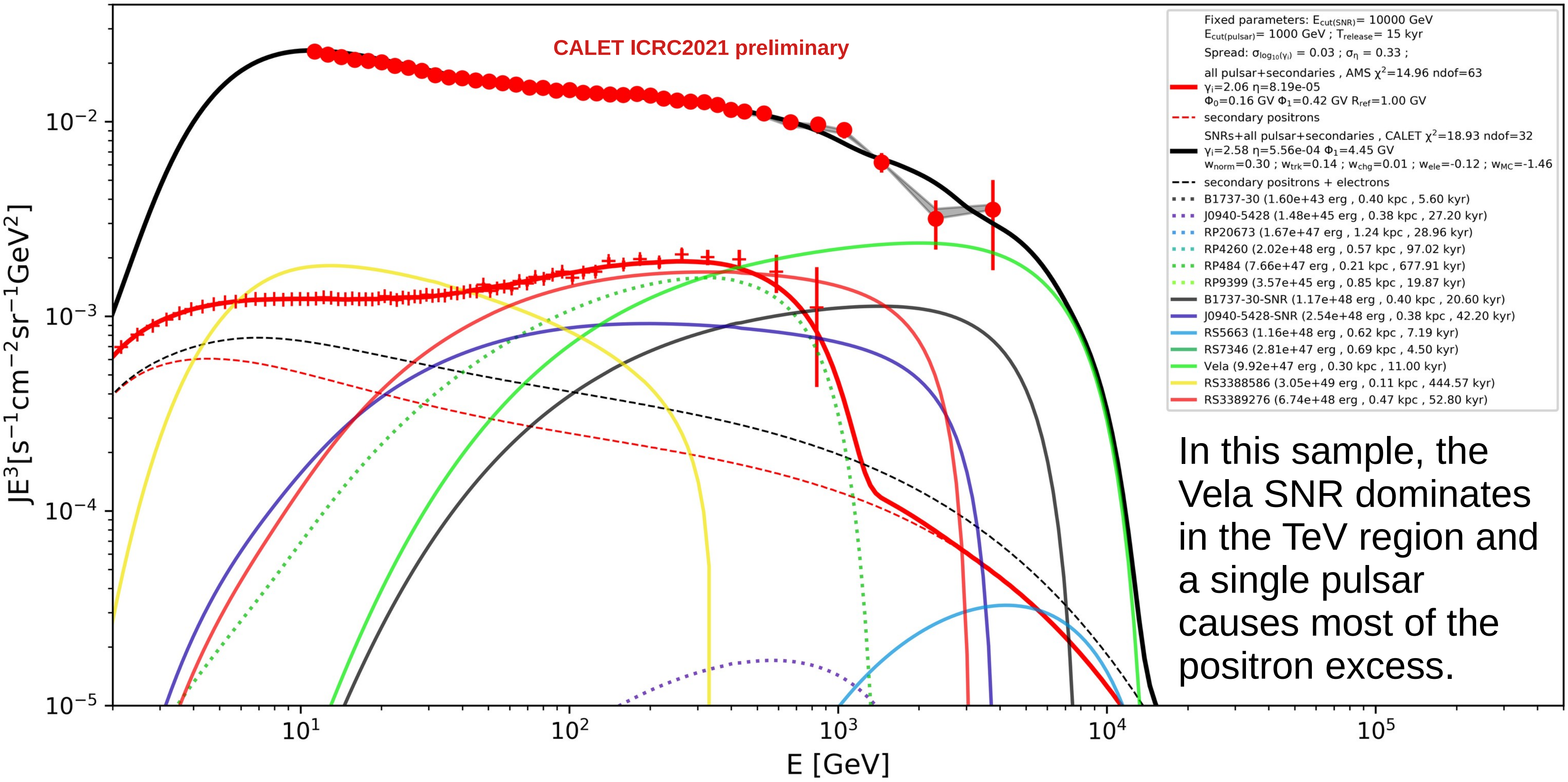


$$\chi^2_{CALET} = \left(\sum_i \frac{\left(\phi_i + \sum_k \Delta_k w_k - J_i\right)^2}{\sigma_i^2} \right) + \sum_k w_k^2$$

i: data point index
k: uncertainty type index

e.g. for this example base model fit, nuisance parameter weights contribute 4.95 to χ^2

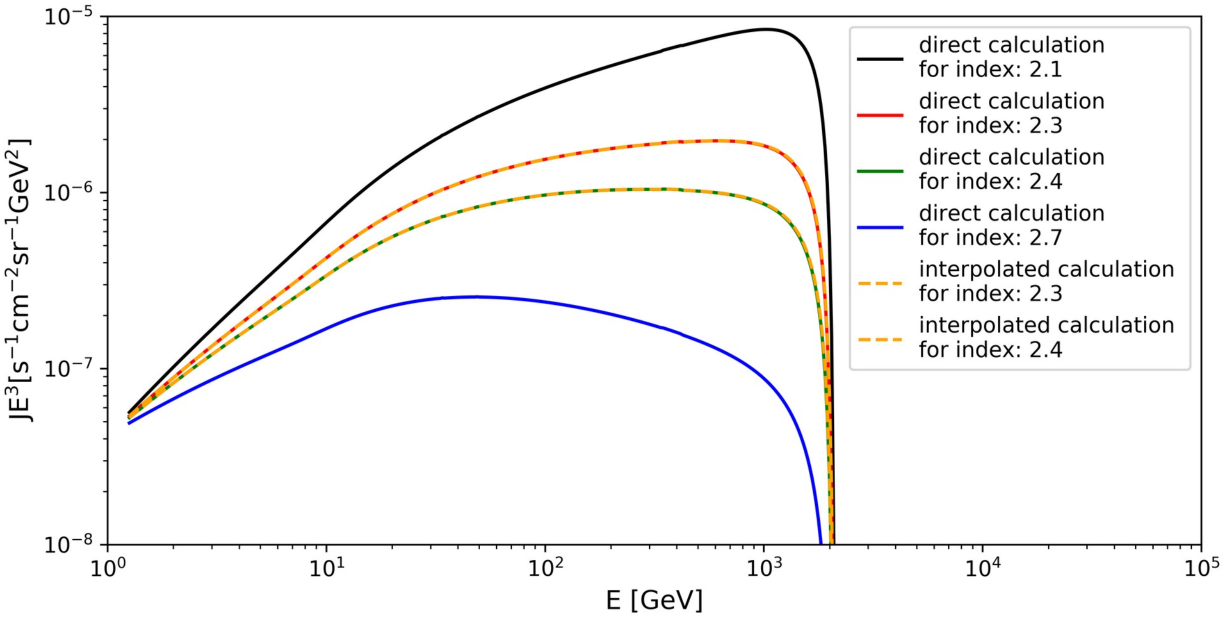
Another Sample



In this sample, the Vela SNR dominates in the TeV region and a single pulsar causes most of the positron excess.

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:



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