Dark Matter Interpretation of CALET Data

2nd Toyama International Symposium on
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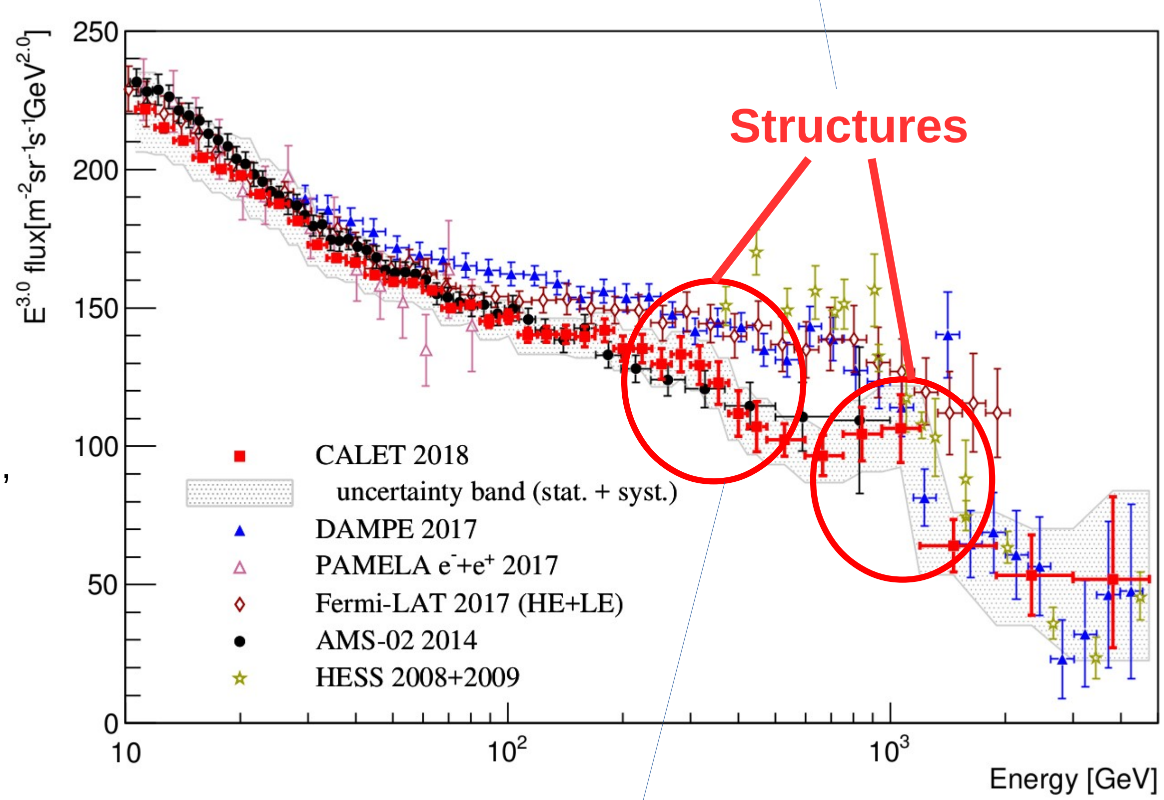
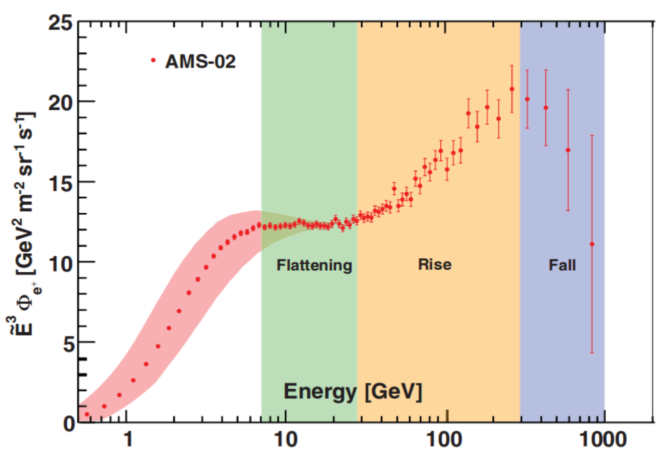
The electron + positron spectrum measured by CALET shows deviations from a single power law. We investigate their possible origin.



O. Adriani et al.
Phys. Rev. Lett. 120, 261102 (2018)

This feature could be linked to a common (electron+ positron) source causing the positron excess

CALET electron+poitron spectrum analyzed together with positron-only data from AM-02



AMS-02 Positron Flux up to 1 TeV

M. Aguilar et al.
Phys. Rev. Lett. 122, 041102 (2019)

Single Nearby Pulsar Model Fitted to CALET Electron+Positron and AMS-02 Positron-only Data

Before studying potential Dark Matter signatures, a base model following common assumptions* about the CR origin and sufficiently detailed to fit the CR spectra well, but with the minimal number of parameters is defined.

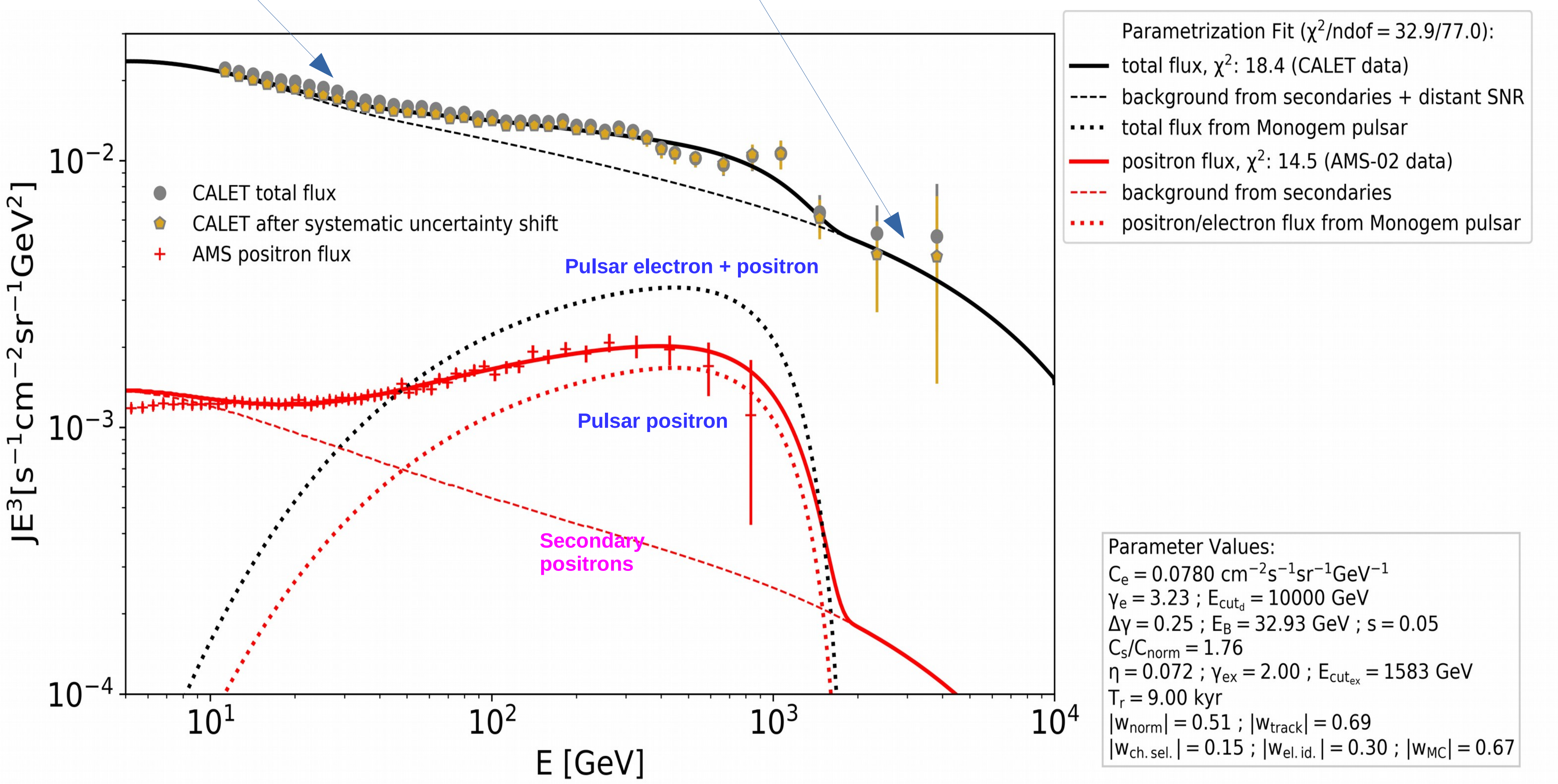
Based on the different level of knowledge about different components, different approaches are combined:
- parametrization of the local (propagated) spectrum for primary electrons
- result of numerical propagation calculation for secondaries
- analytic propagation of parametrized source spectrum for pulsar source

Primary electron spectrum with low-energy spectral break and exponential cut-off, secondary electrons, secondary positrons, extra pulsar source for positron excess

$$\Phi_{ele} = C_e E^{-(\gamma_e - \Delta\gamma_e)} \left(1 + \left(\frac{E}{E_B}\right)^{\frac{\Delta\gamma_e}{s}}\right)^s e^{-\left(\frac{E}{E_{cut_d}}\right)} + C_s \Phi_{s(e^-)} + \Phi_{ex} \quad ; \quad \Phi_{pos} = C_s \Phi_{s(e^-)} + \Phi_{ex} \quad ; \quad \Phi_{tot} = \Phi_{ele} + \Phi_{pos}$$

Smooth break in the **primary electron spectrum** required to model low energy part of the spectrum well

Exponential cut-off of **primary electron spectrum** from energy loss, not well constrained by data
→ fixed values of **$E_{cut(d)}$ = [2 TeV , 4 TeV , 10 TeV]**
studied as nuisance parameter (10 TeV case shown)



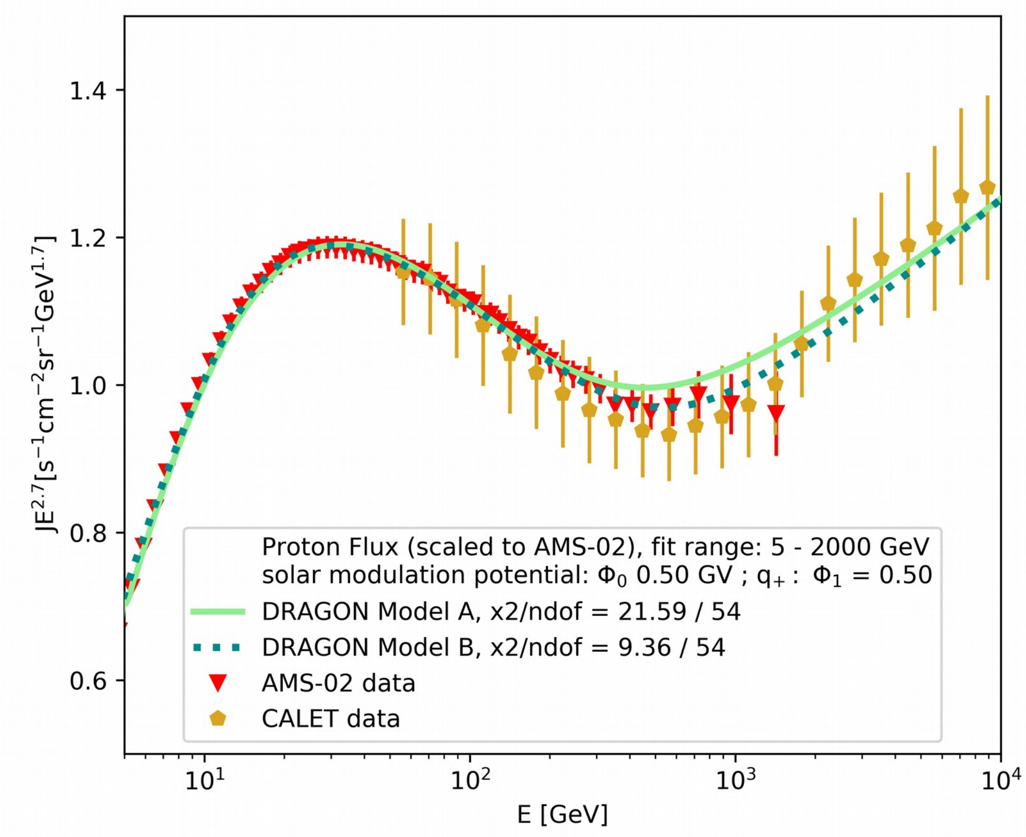
The combined model is fitted to **CALET data** and AMS-02 positron flux for E>10GeV

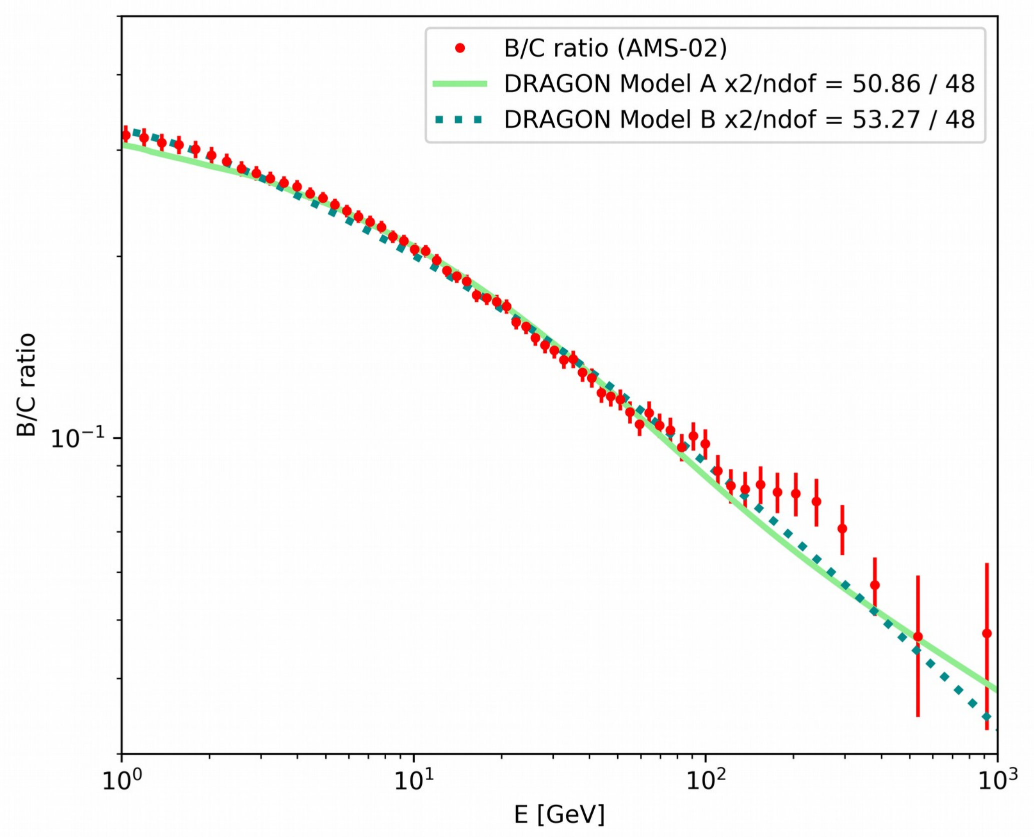
E<10 GeV: charge and time dependent solar modulation → not used in fitting
E>10 GeV: solar modulation included using force field approximation with potential for both charge signs Φ=[300 MV, 500 MV ,700 MV] treated as a nuisance parameter

* alternatives to the pulsar explanation of the positron excess are non-standard secondary production or specific Dark Matter models producing a very soft annihilation/decay spectrum with high boost factor. While these models are possible, they are very specific hypotheses and thus not viable as a flexible base model.

Details of the base model: Propagation

- Nuclei spectra independent of local source distribution
  → Propagation parameters tuned to explain nuclei measurements, most importantly proton flux and B/C ratio
- Using DRAGON to include conversion of nuclei in propagation
- Flux of secondary electrons and positrons interpolated and used in fitting with rescaling factor C_s as free parameter
- Propagation parameters consistently used also for pulsar and DM





Model A:	$D_0 = 1.1 \cdot 10^{28}\, cm^2/s \quad @\, 4\, GV$ $\delta = 0.62\, (R > 350\, GV \rightarrow 0.33)$ $L = \pm 3\, kpc$ $\gamma_i = 2.28$	Smooth break in the diffusion coefficient: $D = D_0 \left(\frac{R}{R_0}\right)^{\delta_l} / \left(1 + \left(\frac{R}{R_b}\right)^{\frac{\delta_l - \delta_h}{s}}\right)^s$	No break in injection spectrum needed Spiral arm width : 0.65 kpc (default: 0.3 kpc)
Model B:	$D_0 = 3.7 \cdot 10^{28}\, cm^2/s \quad @\, 4\, GV$ $\delta = 0.5$ $L = \pm 15\, kpc$ $\gamma_i = 2.36$ $v_a = 12\, km/s$	Smooth breaks in the injection spectrum at 12 GeV and 500 GeV: Index changes from 2.0 (below 12 GeV) to 2.36, then to 2.1 above 500 GeV	

- Two models representing fundamentally different concepts:
  - Low vs. high diffusion coefficient normalization → no vs. existing diffusive acceleration
  - Explanation of spectral hardening by change in diffusion coefficient index vs. change in the injection spectrum index

Details of the Base Model: Flux from Pulsars

- Information about position, age and spin-down rate of pulsars from astronomical observations
- Large uncertainty on the acceleration and escape mechanism of cosmic rays from pulsars (or their pulsar wind nebulae - PWN)

$\rightarrow$ use available information but keep parameters of injected cosmic ray spectrum free parameters in the global fitting:

Analytic solution of propagation equation for instantaneous point source (Green's function) [e.g. Eur. Phys. J. C. 76:229 (2016)] adapted to propagation model with break in diffusion coefficient

$$\phi_{pulsar} = \frac{Q_0 \eta}{\pi^{3/2} r_{dif}^3} E^{-\gamma} \left(1 - \frac{E}{E_{max}}\right)^{\gamma-2} e^{-\frac{E/E_{cut}}{1-E/E_{max}} - \frac{r^2}{r_{dif}^2}}$$

$$r_{dif} = 2\sqrt{\frac{D(E)\, t_{dif}}{1-\delta(E)} \frac{E_{max}}{E} \left[1 - \left(1 - \frac{E}{E_{max}}\right)^{(1-\delta(E))}\right]} \quad ; \quad E_{max} = \frac{1}{b_0 t_{dif}}$$

$$D(E) = D_0 \left(\frac{E}{E_0}\right)^{\delta_l} / \left(1 + \left(\frac{E}{E_b}\right)^{\frac{\delta_h - \delta_l}{s}}\right)^{s} \quad ; \quad \delta(E) = \frac{d[\log(D(E))]}{d[\log(E)]}$$

free parameters: efficiency η, index γ, cutoff energy E_{cut}

determined parameters: $D_0, \delta_l, \delta_h, E_B, s, b_0$ (from propagation model)

total energy Q_0, distance r, diffusion time t_{dif} (from ATNF catalog)

- Instantaneous release of the cosmic rays is assumed
- The diffusion time is equal to the age of the pulsar minus the duration for which the electrons and positrons are trapped in the PWN (T_R)
- T_R is optimized in the fitting by scanning in steps of 1 kyr
- Among nearby single pulsar candidates, the Monogem pulsar (J0659+1414) gives the best fit as the source of the positron excess and is thus selected as the default source

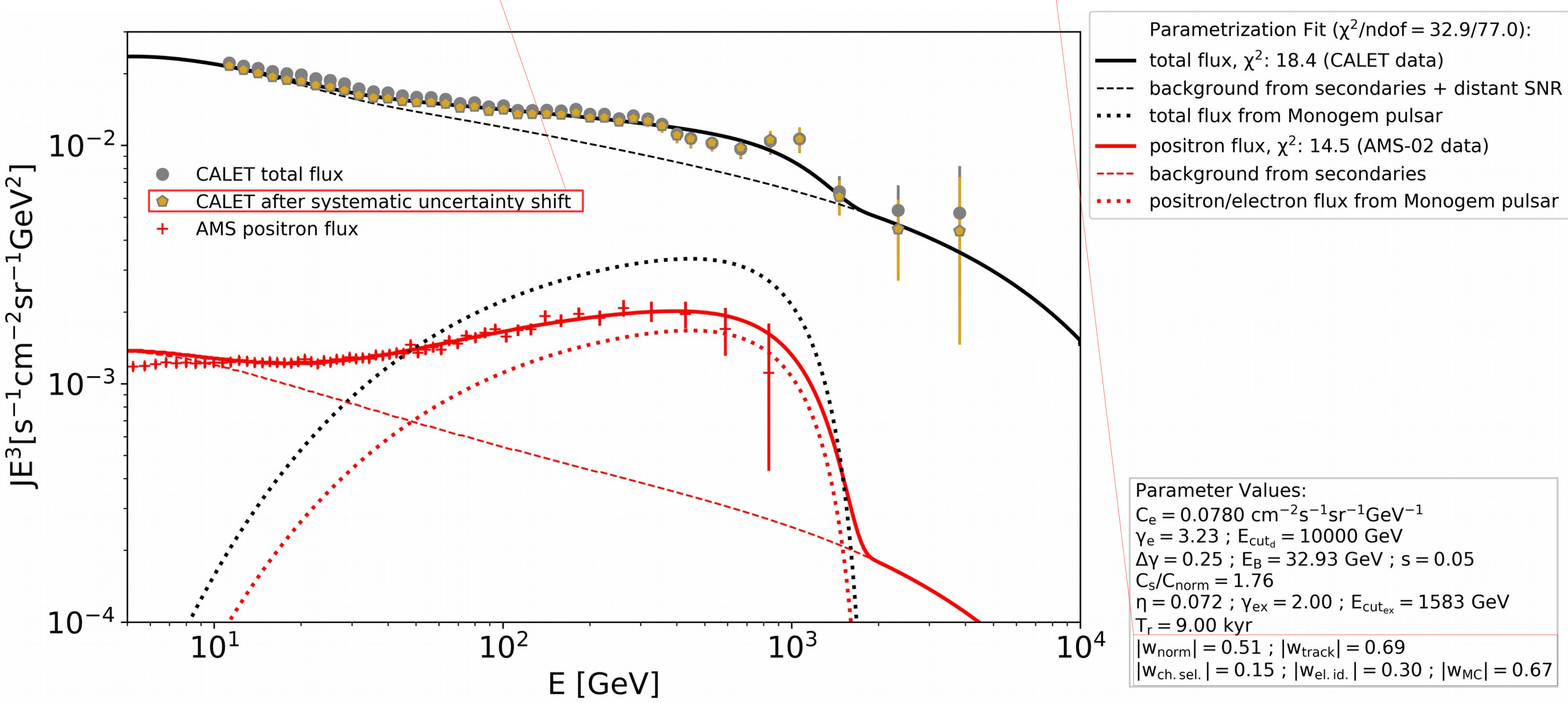
Details of the Base Model: Treatment of Systematic Errors

- The spectrum measured by CALET is subject to systematic errors with in some cases known energy dependence
- Instead of adding the systematic error quadratically to the systematic error, the data is shifted systematically by the function Δ given in the supplemental material of Phys. Rev. Lett. 120, 261102 (2018) with the normalization coefficients as fit 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:

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

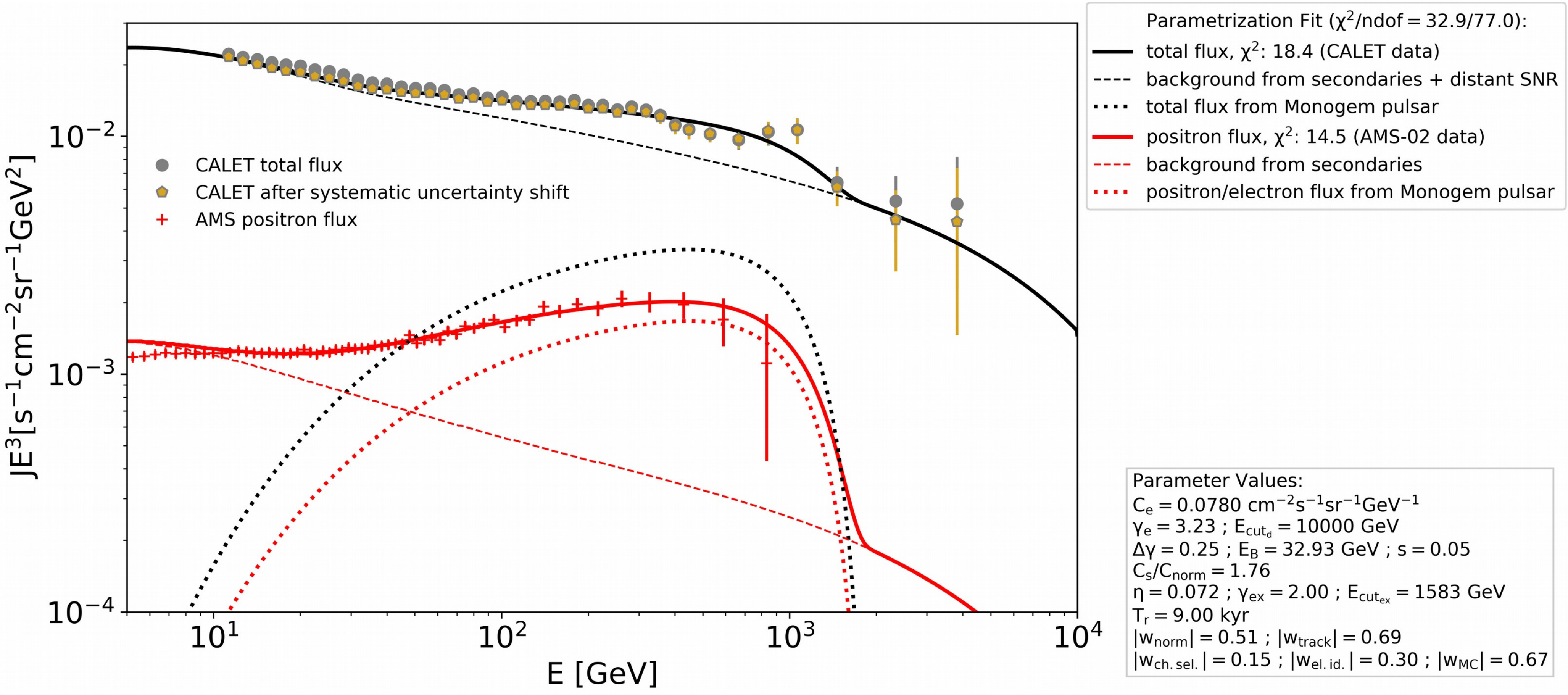
i: data point index
k: uncertainty type index



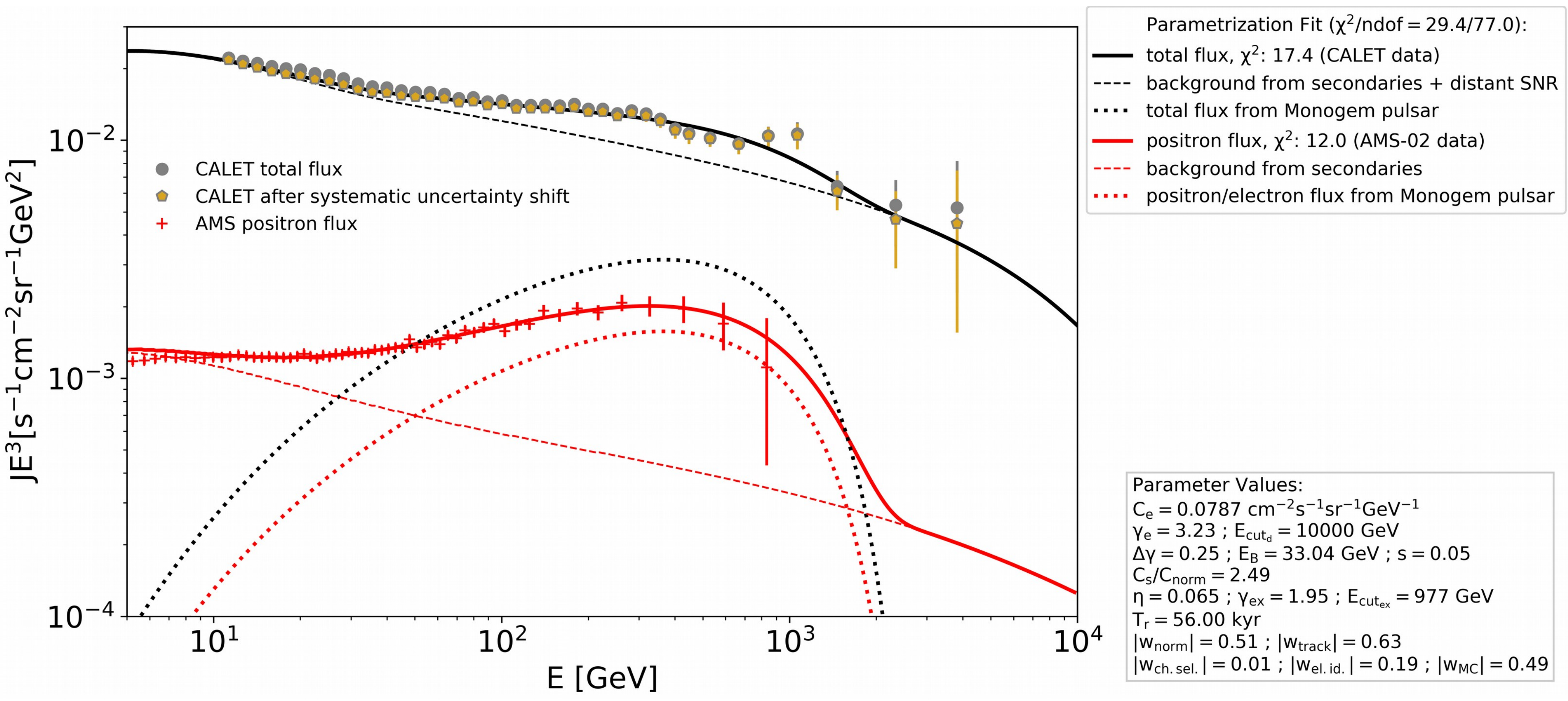
Uncertainties of Trigger and BDT (proton rejection) are added quadratically to statistical error since their energy dependence is not well known

Single Pulsar Base Model Best Fit

Propagation Model A:



Propagation Model B:



- For prop model A, the best fit is obtained with T_R = 9 kyr, while for model B T_R = 56 kyr yields lowest χ^2 .
- The best fit for both propagation models uses $E_{cut(d)}$ = 10 TeV, which is thus taken as the default case.
- The reduced χ^2 is in either case χ^2 /ndof ≈ 0.5, indicating that the base model already more than adequately describes the data.

Flux from Dark Matter and Addition to the Base Model

- Electron and positron flux from Dark Matter annihilation is calculated with DRAGON using propagation models A and B, with a NFW profile for the galactic halo for various Dark Matter Masses and annihilation channels, normalized to the relic density predicted annihilation of $3 \cdot 10^{-26}$ cm^3 s^{-1}

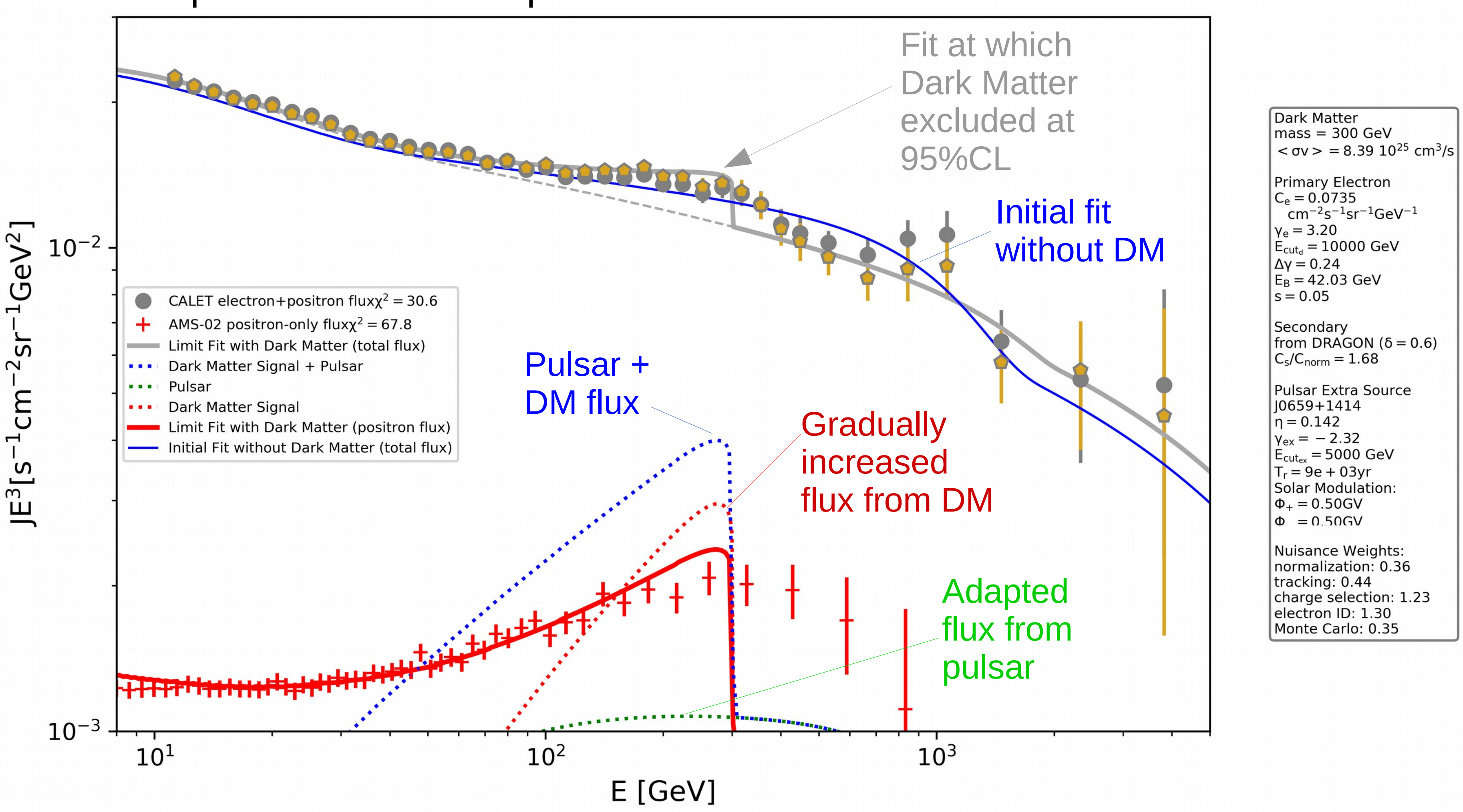
- The flux after propagation is added to the base model. A scale factor which can be associated with a potential boost in the annihilation due to halo substructures or Sommerfeld/Breit Wigner enhancement is applied.

- The boost factor is increased in steps while optimizing all free parameters of the fitting function

- If adding Dark Matter flux with a too large boost factor, the data does not match the resulting spectral feature → χ^2 increases

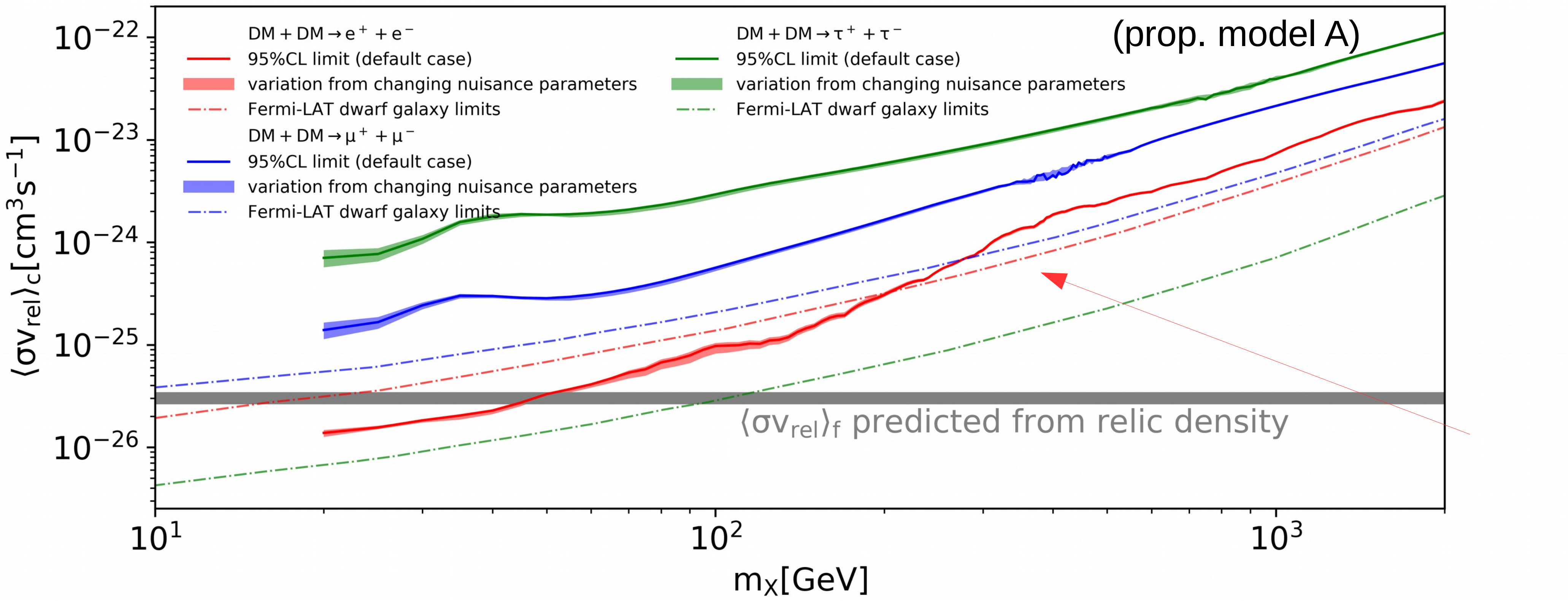
- The boost factor at which χ^2 reaches 95 % CL corresponds to a limit on the Dark Matter annihilation rate

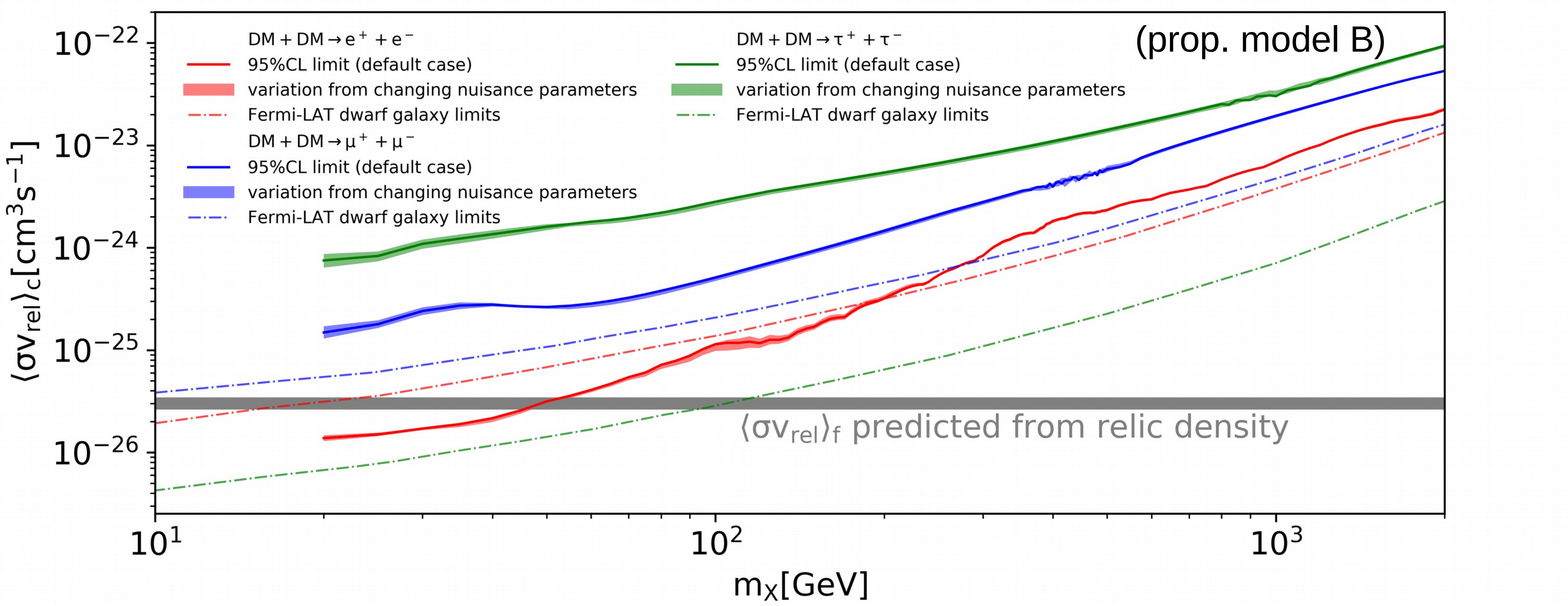
Example fits for electron+positron channel with 300 GeV Dark Matter mass



- By performing this limit-fitting procedure for many Dark Matter masses, limits as a function of Dark Matter mass are obtained.

Limits on Dark Matter Annihilation for Leptonic Annihilation Channels





- **Electron channel limit competitive with Fermi-LAT limit**

Fermi-LAT gamma-ray dwarf-galaxy limits taken from Phys. Rev. Lett. 115, 231301 (2015) (SM)

- **Result emphasize that Dark Matter search in the electron+positron spectra is complementary to search with gamma-rays:**
  - different sensitivity to annihilation channels (electron channel vs. tau-channel)
  - different target regions with different systematic uncertainties (galactic neighborhood vs. dwarf galaxies)
- **Shared regions show dependence on variation of nuisance parameters :**

$E_{cut(d)}$ [2TeV,4TeV,10TeV] , Φ [0.3GV,0.5GV,0.7GV]

A Dark Matter Candidate from a Flavor Dependent Gauge Symmetry Model

"Cosmic-Ray Signatures of Dark Matter from a Flavor Dependent Gauge Symmetry Model with Neutrino Mass Mechanism",
H.M., Hiroshi Okada, Yoichi Asaoka, and Kazunori Kohri
Publication in preparation

- We have investigated a model which explains neutrino mass by loop interactions through the Dark Matter candidate (scotogenic model).
- Breaking of $U_{e\text{-}\mu}$ symmetry gives mass to the Z' gauge boson which couples to the first two lepton generations
- The model is anomaly-free
- Depending on values of Yukawa coupling chosen, predicted lepton flavor violations are far below experimental limits
- Interaction with hadrons is determined by mixing of the new scalar fields with the SM Higgs and can be arbitrarily low → model not ruled out by direct Dark Matter detection and collider experiments (LHC)

Particle contents of the model:

New neutral Dirac fermions, lightest N is the DM candidate

Heavy neutrinos to give mass to two SM neutrinos via seesaw mechanism (one remains massless)

Breaks $U_{e\text{-}\mu}$ and gives mass to Z'

	SM fermions						New fermions				
Fermions	L_{L_e}	L_{L_μ}	L_{L_τ}	e_R	μ_R	τ_R	N_e	N_μ	N_τ	ν_{R_e}	ν_{R_μ}
$SU(3)_C$	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
$SU(2)_L$	**2**	**2**	**2**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
$U(1)_Y$	$-\frac{1}{2}$	$-\frac{1}{2}$	$-\frac{1}{2}$	-1	-1	-1	0	0	0	0	0
$U(1)_{e-\mu}$	1	-1	0	1	-1	0	1	-1	0	1	-1
Z_3	1	1	1	1	1	1	ω	ω	ω	1	1
Z_2	$+$	$+$	$+$	$+$	$+$	$+$	$+$	$+$	$+$	$-$	$-$

	VEV$\neq 0$	Inert		
Bosons	H	φ	η	S
$SU(2)_L$	**2**	**1**	**2**	**1**
$U(1)_Y$	$\frac{1}{2}$	0	$\frac{1}{2}$	0
$U(1)_{e-\mu}$	0	1	0	0
Z_3	1	1	ω	ω
Z_2	$+$	$+$	$+$	$-$

Tau-lepton has no charge for the new interaction mediated by Z'

N is stable and a Dirac particle

No weak interaction of new fermions and heavy neutrinos

Prevents Dirac neutrino mass at tree level

Standard model
New particles
New symmetries/charges
New symmetries/charges of new particles

The lightest N particle is designated as the Dark Matter candidate X

Phenomenology of the Dark Matter Candidate X

Since Z' only couples to the first two lepton generations, the branching ratios of the annihilation are as follows:

$$X+\bar{X}\rightarrow\frac{1}{3}e^{+}+e^{-}+\frac{1}{3}\mu^{+}+\mu^{-}+\frac{1}{3}\nu_{e,\mu}+\bar{\nu}_{e,\mu}$$

The annihilation cross section is velocity dependent, with a resonance around the pole

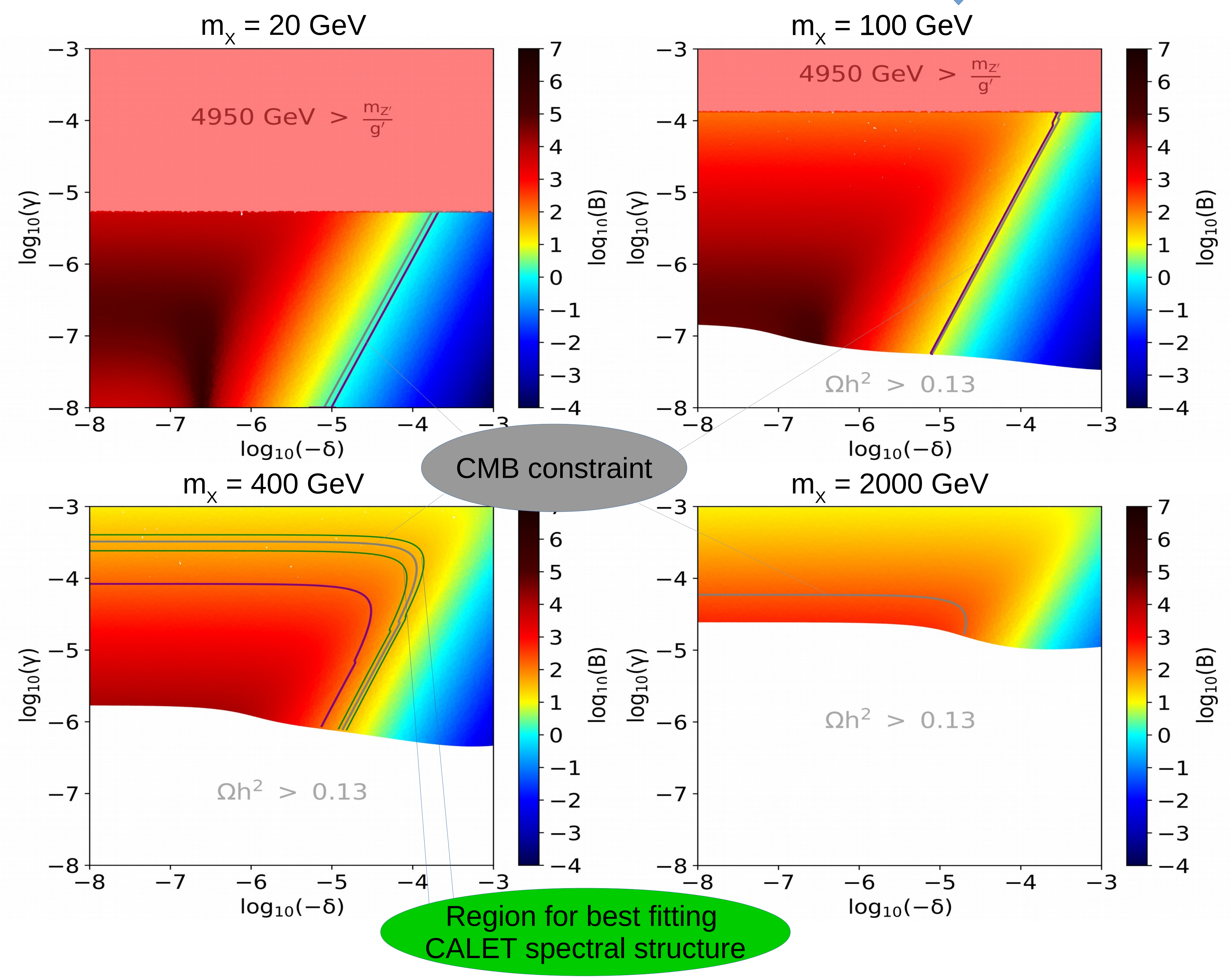
$$2m_X\approx m_{Z'}$$

Solutions yielding the correct relic density are only found around this pole.
Furthermore, Breit-Wigner enhancement can provide an additional boost factor B defined as the ratio of annihilation of X in the galactic halo ($v\sim10^{-3}$) compared to the generic WIMP with constant cross section $\langle\sigma v\rangle = 3\cdot10^{-26}\ \mathrm{cm}^3\ \mathrm{s}^{-1}$

B is determined by the width of the resonance $\gamma=\frac{\Gamma}{m_{Z'}}$

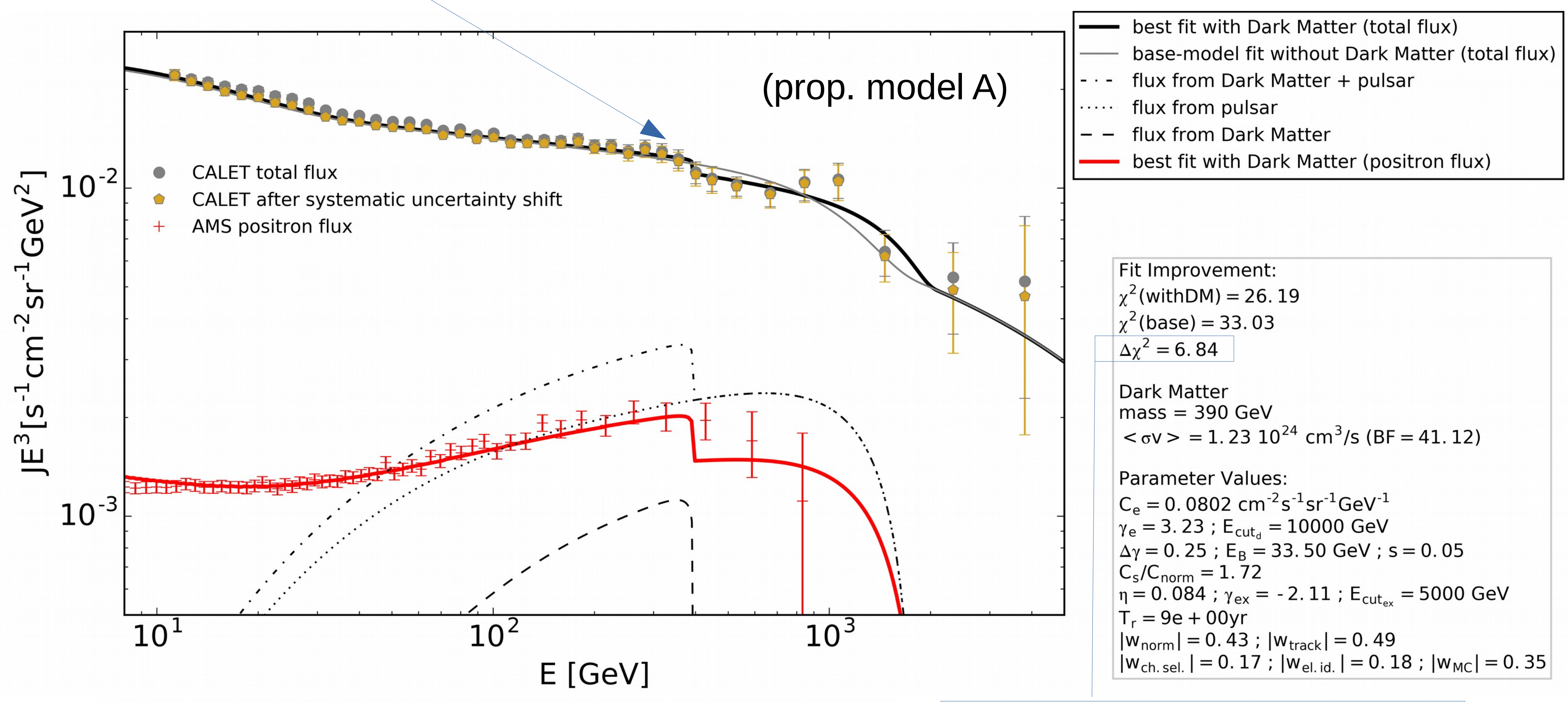
and the distance to the resonance $\delta=1-\frac{m_{Z'}^2}{m_X^2}$

Results of numerical analysis using micrOMEGAs

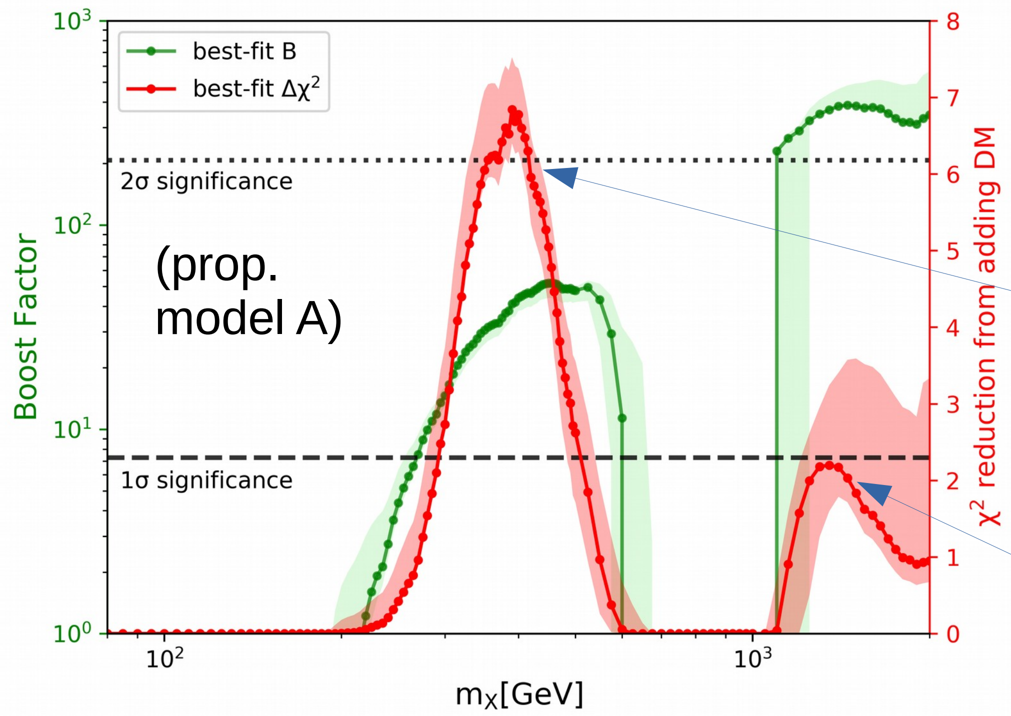


Association of a Structure in the CALET Spectrum with the Signature of Dark Matter Candidate X

Addition of the flux from annihilation of X (electron+muon channel) at mX ~ 400 GeV with a boost factor of ~ 40 improves the fit quality compared to the base model since the step-like structure near 400 GeV is better modeled than by the pulsar source alone.



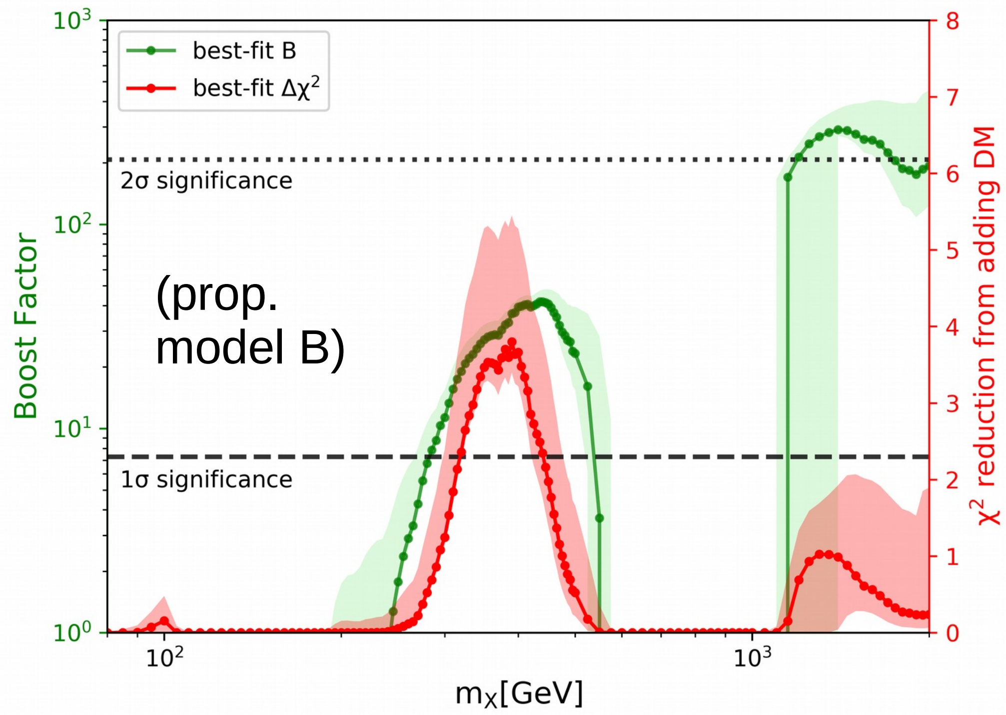
The largest fit improvement (reduction of χ^2) is found for m_X = 390 GeV (prop. model A)



The fit improvement exceeds the 2σ significance level for two additional free parameters (m_X and B)

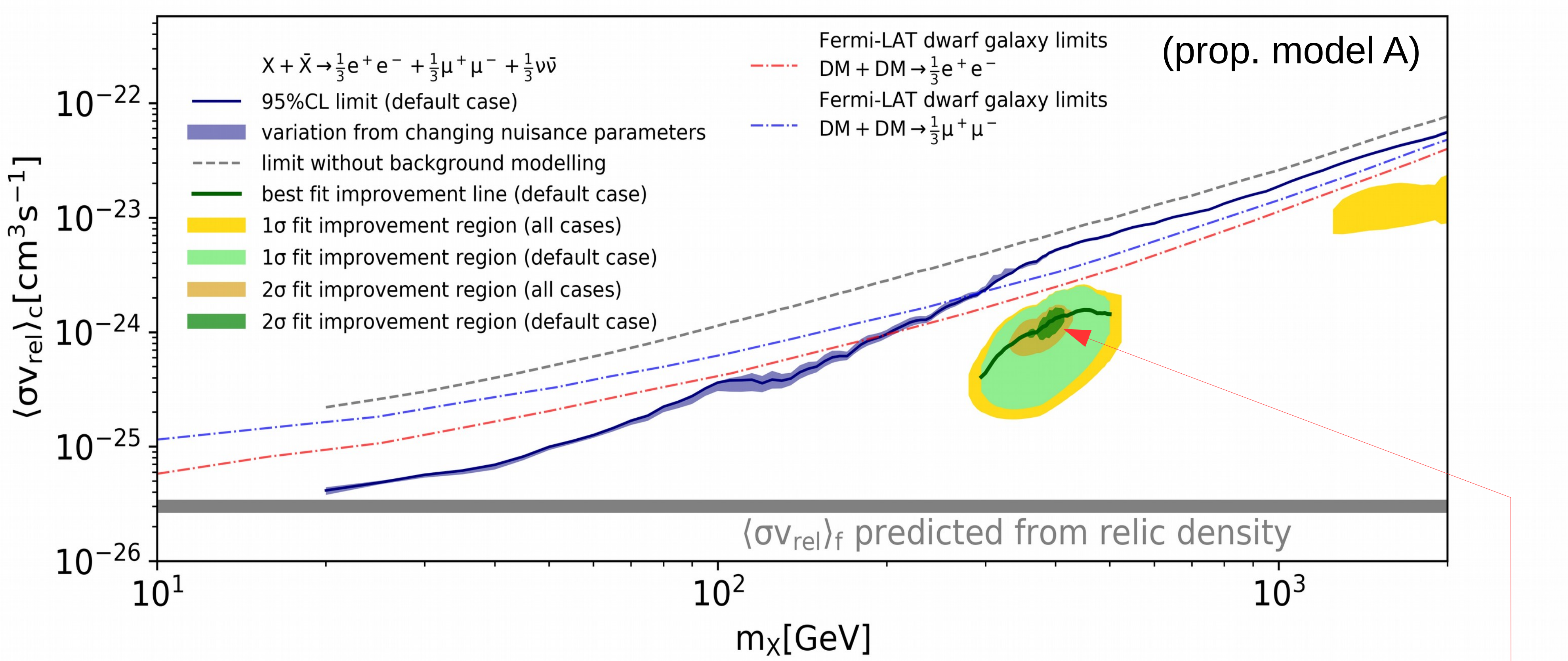
The improvement for fitting the structure near ~ 1 TeV is less significant:
- statistical error larger
- even more hard spectrum required to well match structure

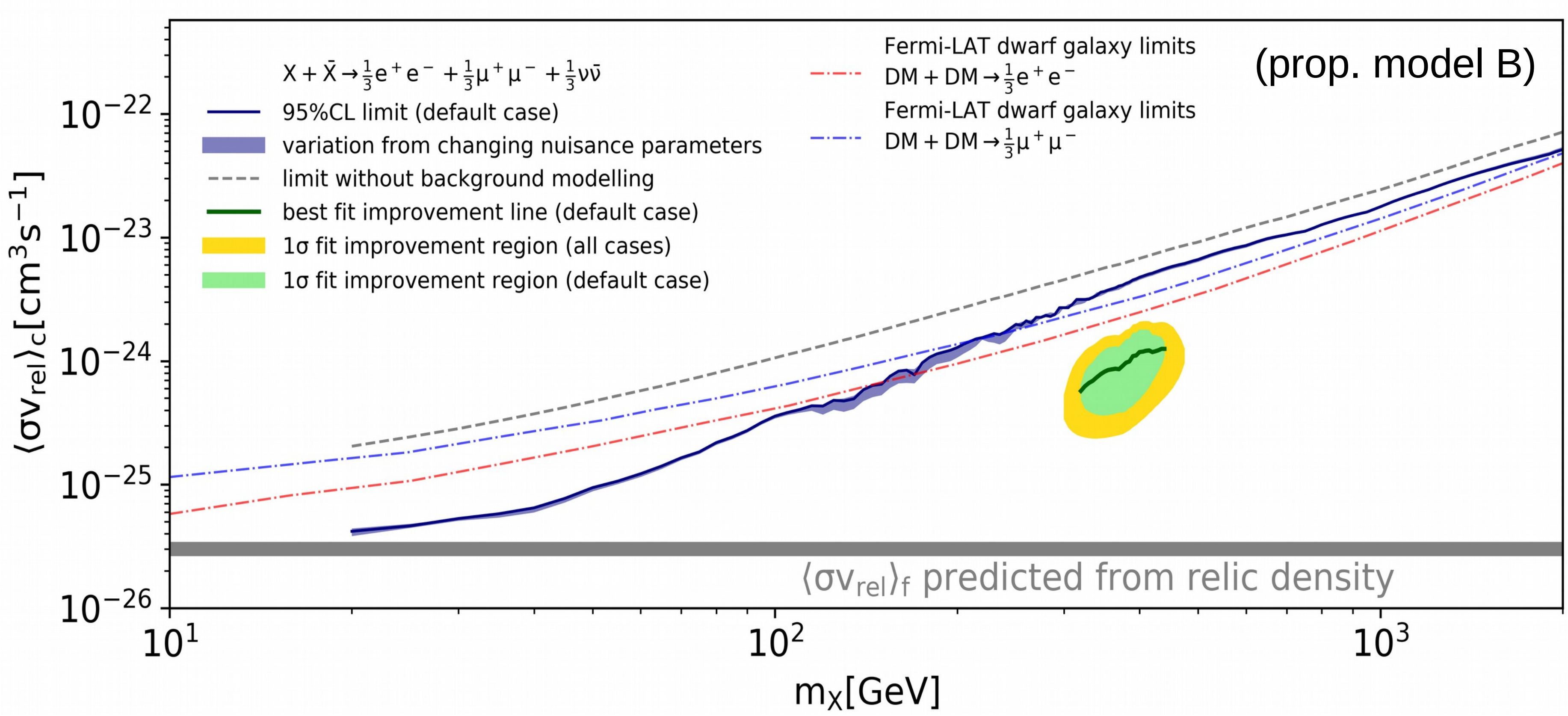
Shaded regions show effect of variation of nuisance parameters (Φ and E_{cut})



There is also an fit improvement for the case of prop. model B, but less compared to model A

Limits and Best-Fit Region for Dark Matter Candidate X





- For propagation model A, a region where the fit quality improves by 2σ exists around m_X = 400 GeV.
- The boundaries of this region are shown in the plot of m_X = 400 GeV on previous slide “Phenomenology of the Dark Matter Candidate X” as green lines → Part of the region is not excluded by the CMB anisotropy constraint.
- The best fit region is not excluded by Fermi-LAT dwarf-galaxy gamma limits, while the limits from CALET/AMS-02 are competitive with the Fermi-LAT limits

Summary and Conclusions

- Structures exist in the CALET spectrum which could be indication of individual astrophysical sources and/or signatures of Dark Matter
- A model with a single pulsar as source of the positron excess gives a good fit to the electron+positron CALET spectrum and the positron-only AMS-02 spectrum
- Limits on Dark Matter annihilation and decay from the CALET and AMS-02 spectra give a strong constraint on two-body annihilation of Dark Matter directly to electron+positron pairs complementary to gamma-ray measurements

- A GeV-TeV range WIMP-like DM candidate with flavor-dependent interaction only with electron and muon is theoretically viable and allowed by current experimental constraints
- The DM candidate is predicted in the framework of a scotogenic model at two-loop level, with two families of Dirac neutral fermions and Majorana fermions under gauge $U(1)_{e-\mu} \times Z_3 \times Z_2$. The Dirac fermion with lightest mass is our DM candidate running inside the neutrino loop.
- The correct relic density is obtained near a pole $2m_X \sim m_{Z'}$, with the annihilation cross section being velocity dependent, allowing for a significant boost factor by Breit-Wigner Enhancement.
- The flux from annihilation of X with branching ratios to electron and muon channel with a boost factor of ~ 40 matches well a spectral structure around 400 GeV in the CALET spectrum, improving the fit quality over the single pulsar base model significantly → **it is possible to associate the spectral structure with the signature of annihilation of the Dark Matter Candidate X.**