Interpretation of the CALET Electron+Positron Spectrum concerning Dark Matter Signatures

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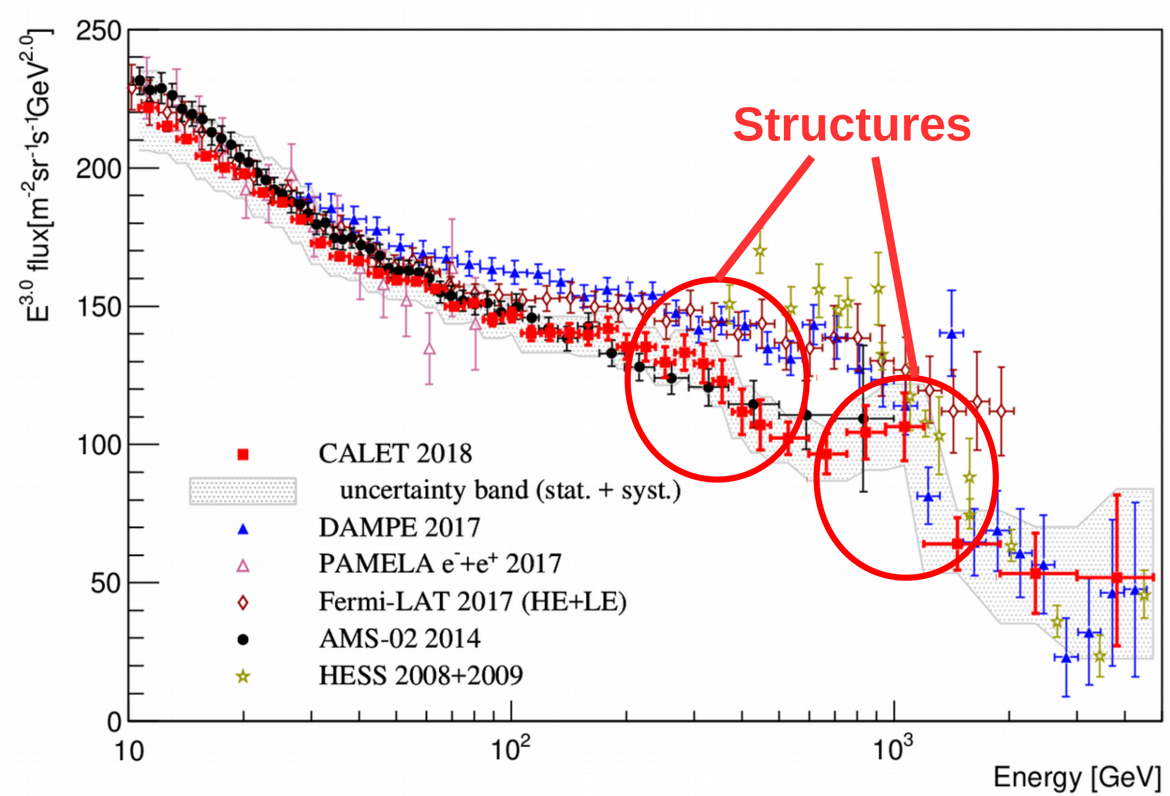
CALET Electron+Positron Spectrum



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

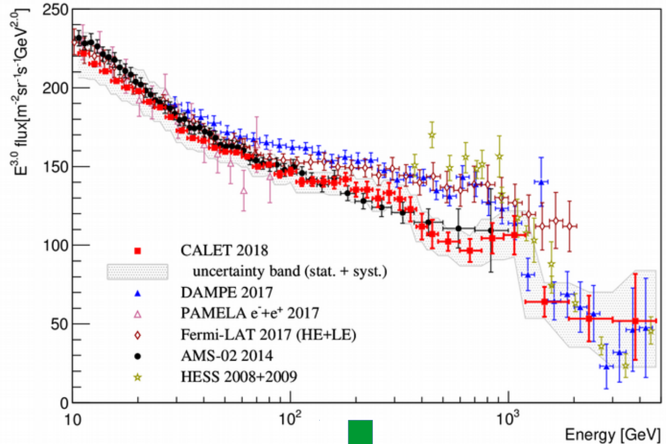
Interpretation of structures as Dark Matter signatures

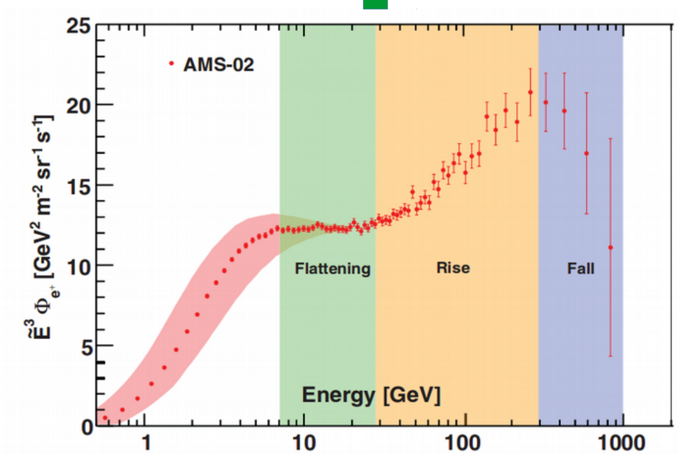
- Interesting speculation
- Allows to compare model with hints from other search methods → to be taken more seriously if finding agreement

Explanation of structures by astrophysical origin

- Refine background model for Dark Matter search, investigate if it impacts the constraints that can be set on Dark Matter properties (limits)

Background Model





AMS-02 Positron Flux up to 1 TeV

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

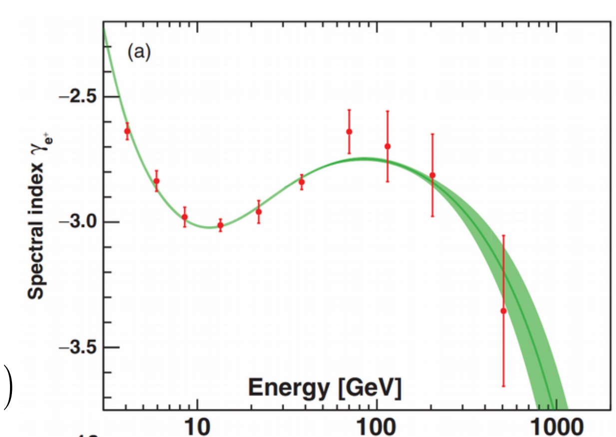
Error on energy converted to error on flux using the published power law index: $\sigma_{\Phi(E)}=\Phi(\sigma_E/E)(\gamma-1)$

Desired properties:

- Good fit with as few parameters as possible
- Physics motivated and variation of parameters should reflect uncertainty in physical processes
- Consider known features of the spectra such as the positron excess

  → assume pulsar(s) extra source as the most mundane option* to explain the excess

  → to constrain its properties, CALET $e^- + e^+$ data combined with AMS-02 e^+-only data



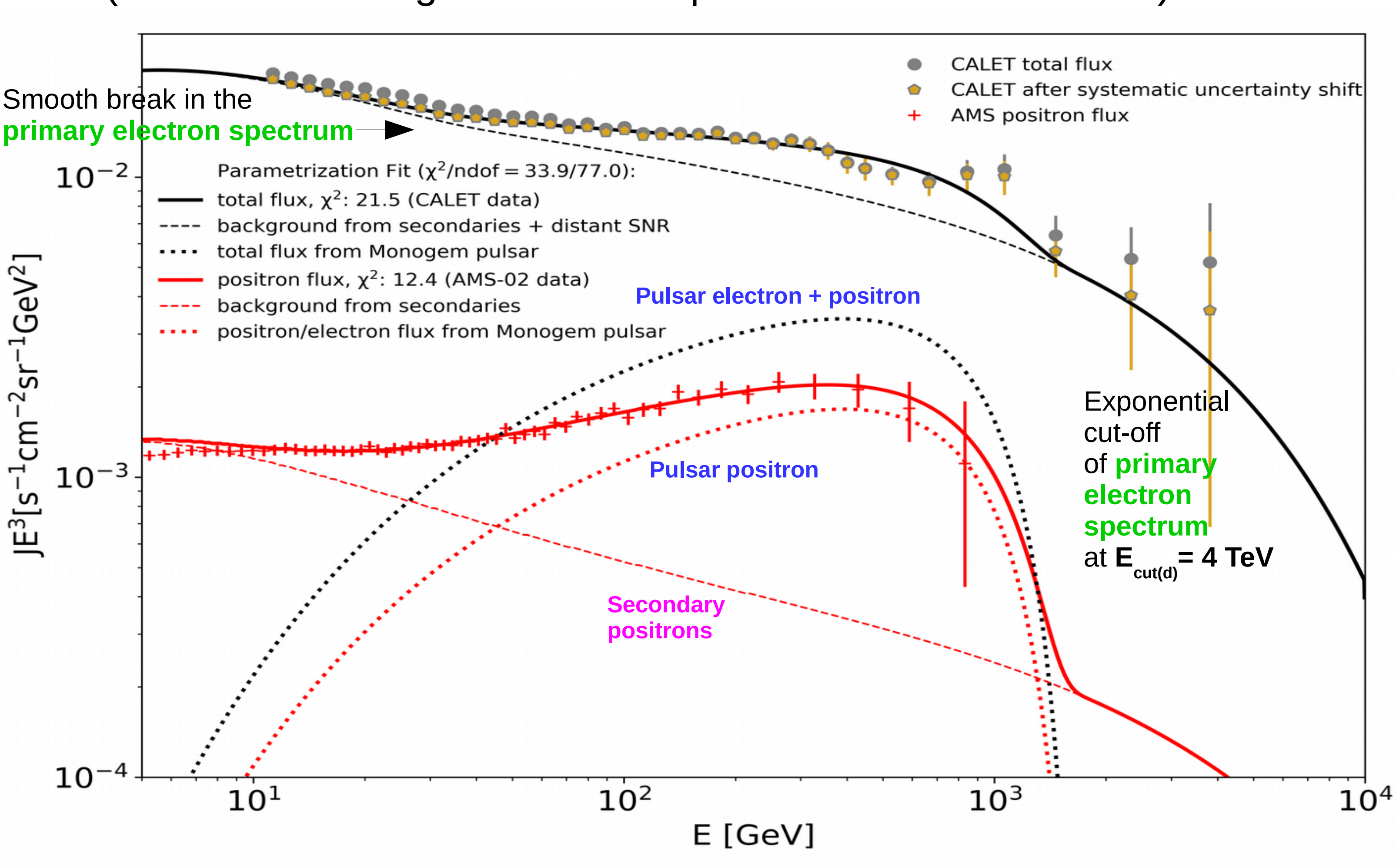
* compared to:
- DM-only origin of the positron excess
- more complicated secondary production in CR propagation than standard assumption

Model for the Local e^- & e^+ Spectra

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

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

- Fitted to **CALET data** and AMS-02 positron flux for E>10GeV (E<10 GeV: charge and time dependent solar modulation)



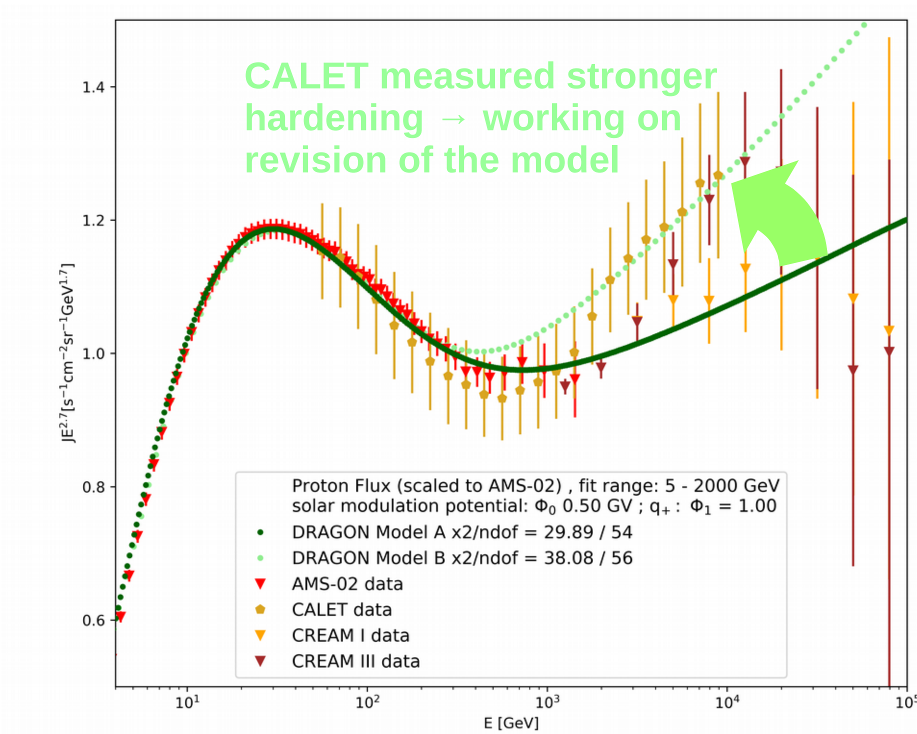
Solar modulation:
- force field approximation
- potential for both charge signs: Φ=500 MV

Parameter Values:
$C_e = 0.0714\ cm^{-2}s^{-1}sr^{-1}GeV^{-1}$
$\gamma_e = 3.19$; $E_{cut_d} = 4000$ GeV
$\Delta\gamma = 0.25$; $E_B = 35.64$ GeV
$s = 0.05$; $C_s/C_{norm} = 1.69$
$\eta = 0.066$; $\gamma_{ex} = 1.95$
$E_{cut_{ex}} = 1195$ GeV
$|w_{norm}| = 0.54$; $|w_{track}| = 1.16$
$|w_{ch.\,sel.}| = 0.11$; $|w_{el.\,id.}| = 0.32$
$|w_{MC}| = 0.82$

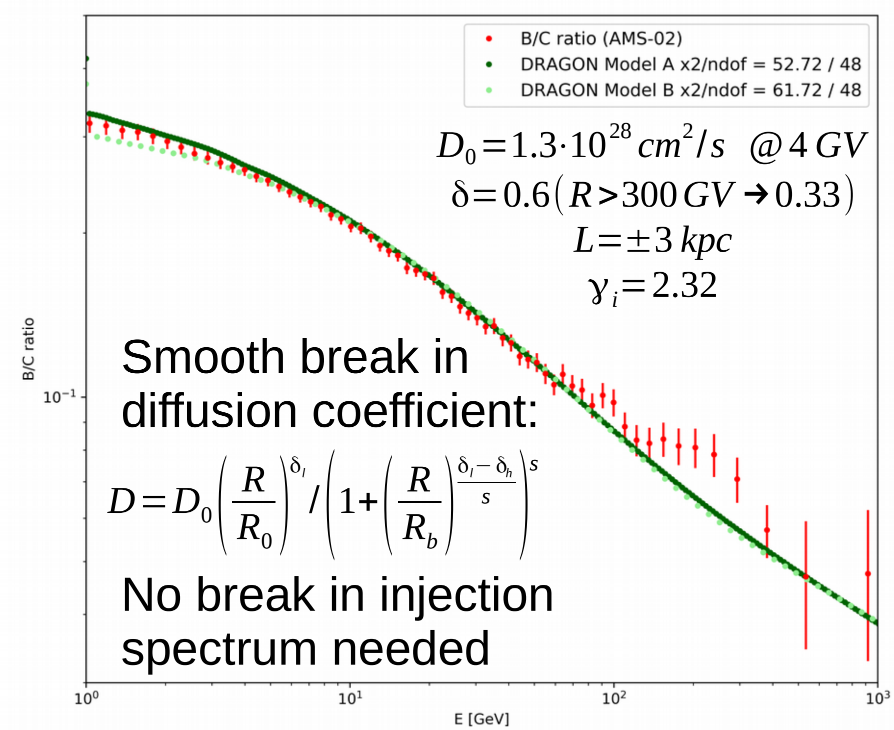
Propagation Model (Calculation with DRAGON)

- Nuclei spectra independent of local source distribution
  → Propagation parameters tuned to explain nuclei measurements

Proton Spectrum:



Boron/Carbon ratio:



- Flux of secondary electrons and positrons interpolated and used in fitting with rescaling factor C_s as free parameter in range [0.5 , 2.0]
- Propagation parameters consistently used also for pulsar and DM

Calculation of Flux from Pulsars

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)

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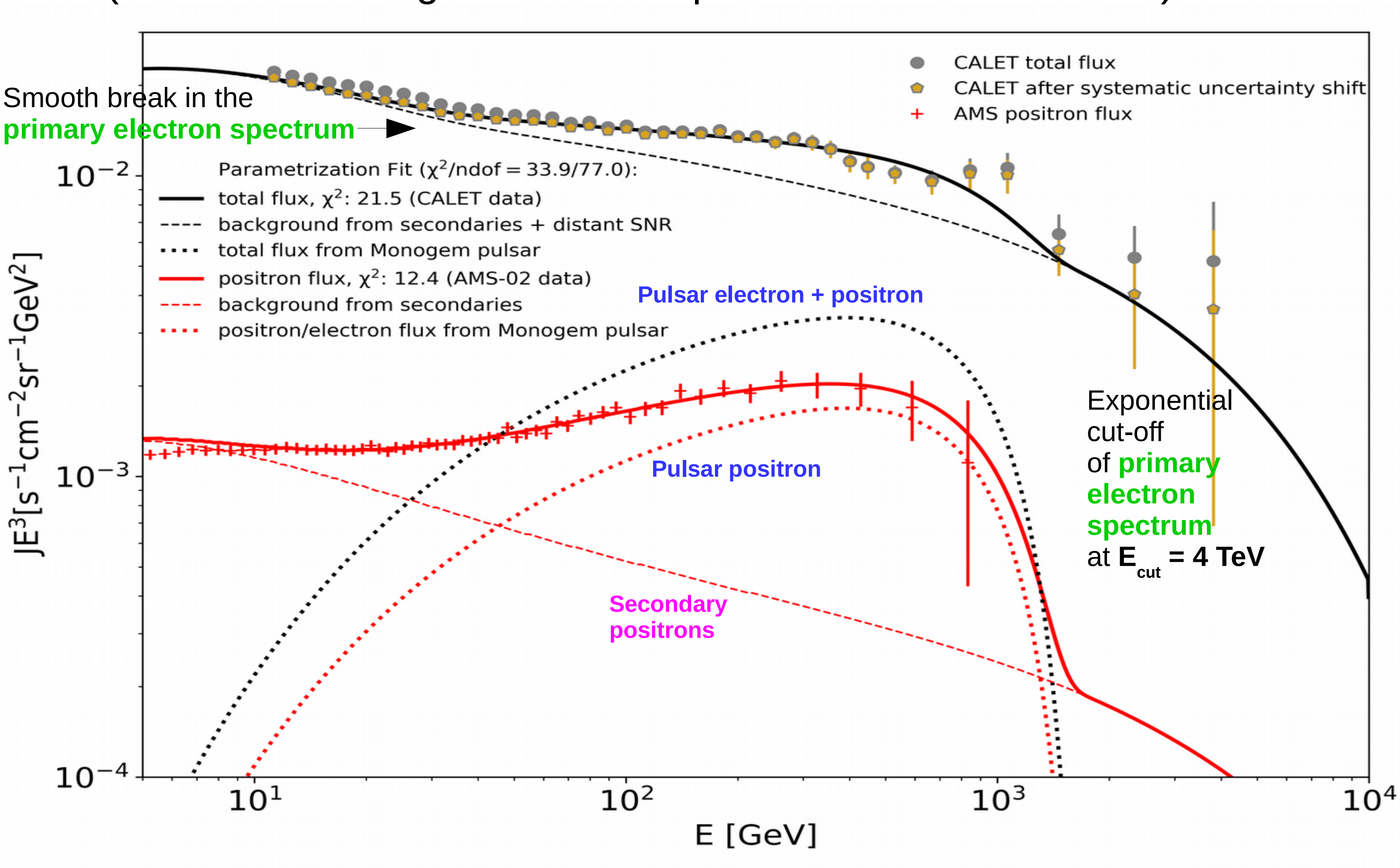

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Systematic Uncertainties as Fitted Nuisance Parameters

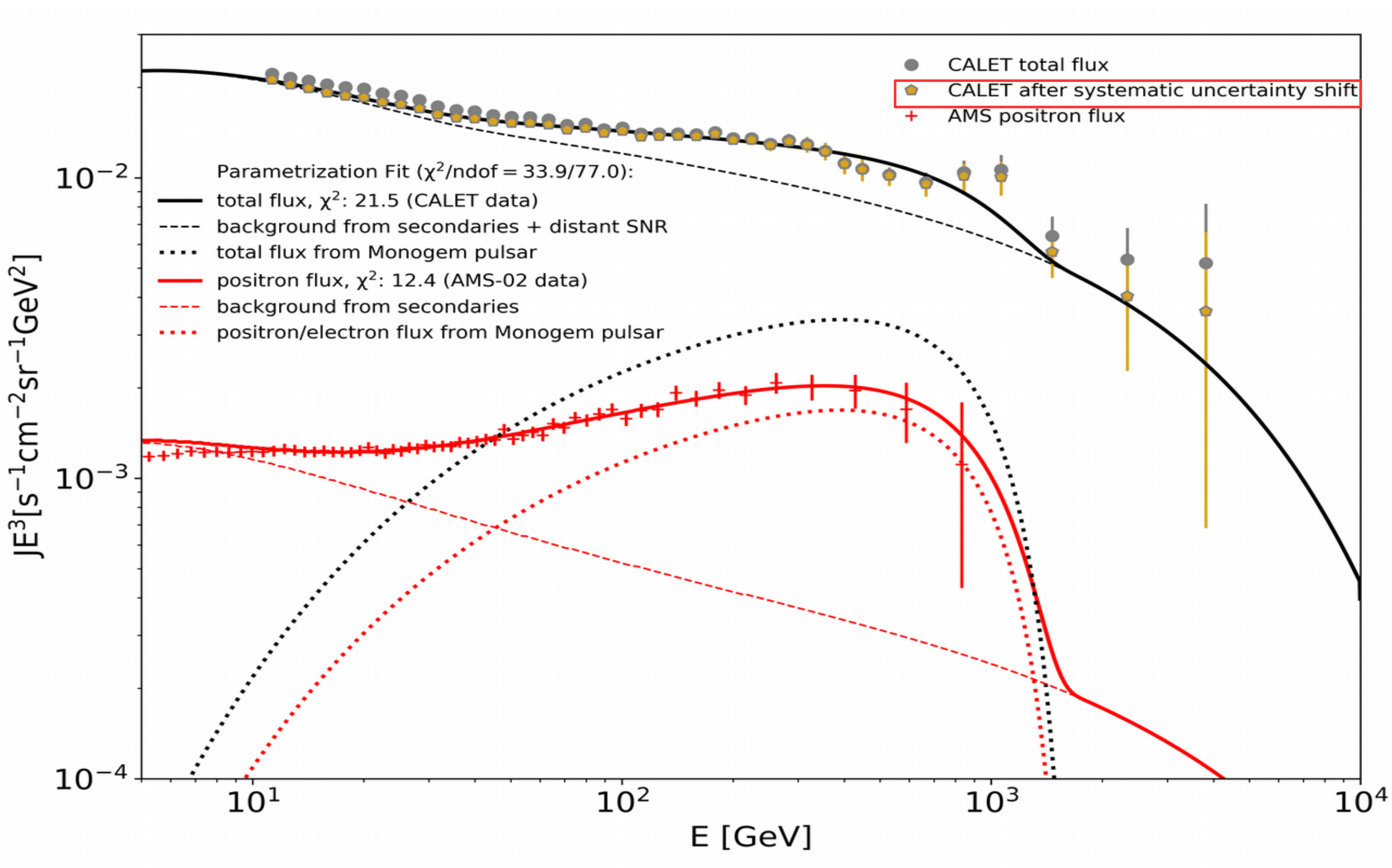
Systematic uncertainties with energy dependence listed in the paper's S.M.

- Normalization
- Tracking
- Charge Selection
- Electron Identification
- Monte Carlo

Systematic shift of fit function, squared weight of each uncertainty added to the total χ^2 of the fit:

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

i: data point index
k: uncertainty index



Uncertainties of Trigger and BDT (proton rejection) are still added quadratically to statistical error

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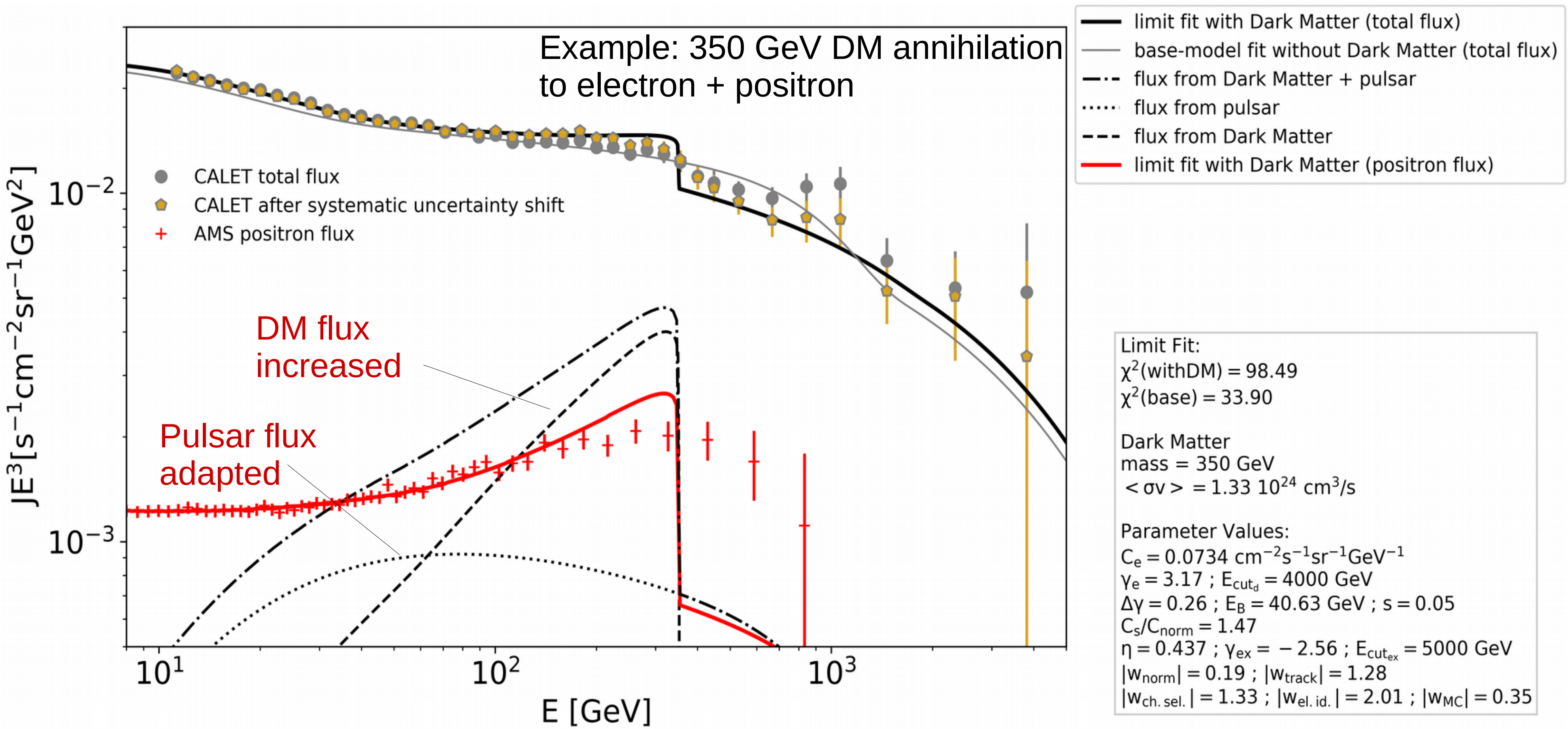
Nuisance parameter weights contribute 2.13 to χ^2

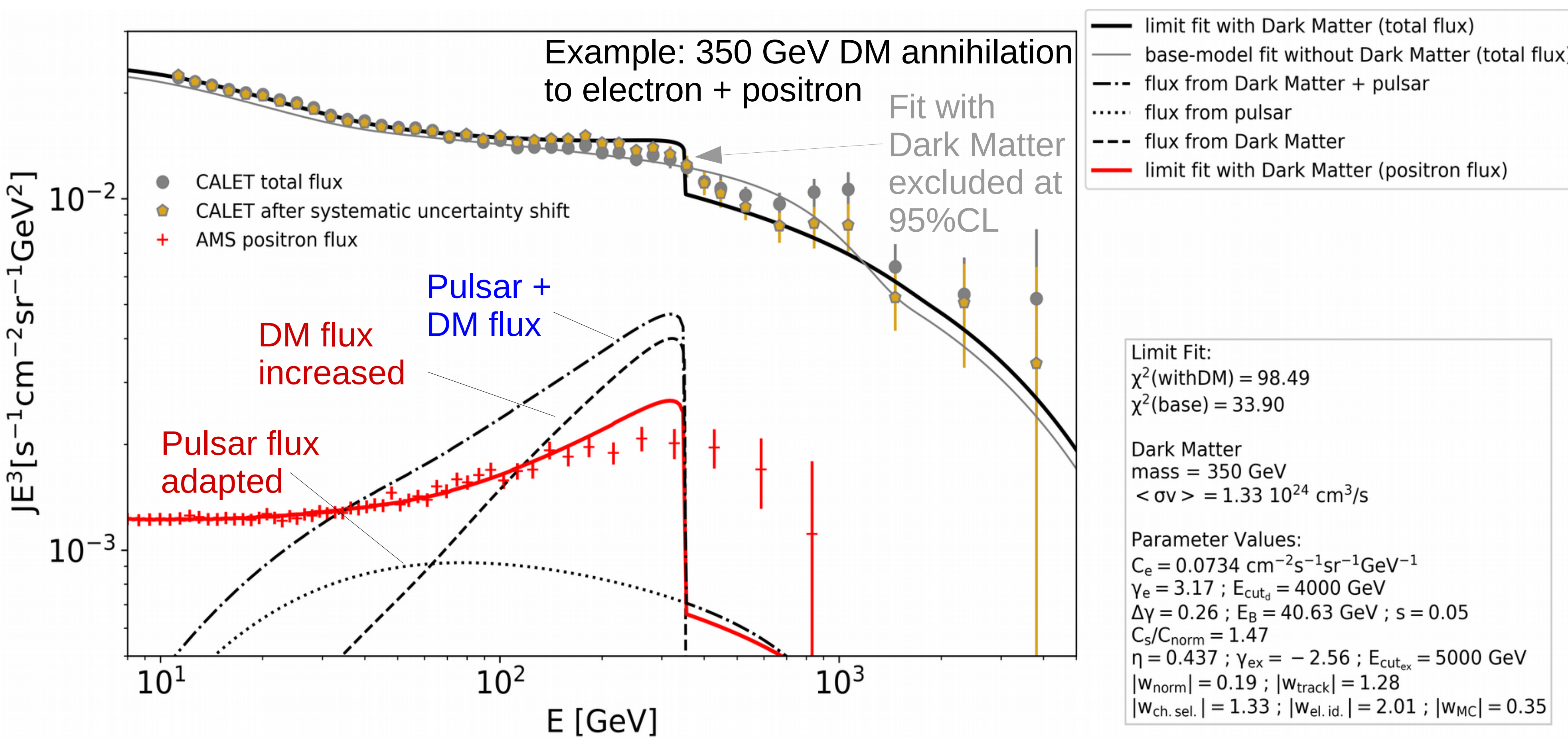
Adding Dark Matter

- Initial assumption that the Monogem pulsar is the reason for the positron excess
- Starting from this pulsar-only fit, flux from Dark Matter annihilation (calculated with PYTHIA, propagated with DRAGON using common propagation parameters, NFW profile, 0.3 GeV/cm^3 local density) is added and the boost factor increased while repeating the fit each time to adapt other parameters

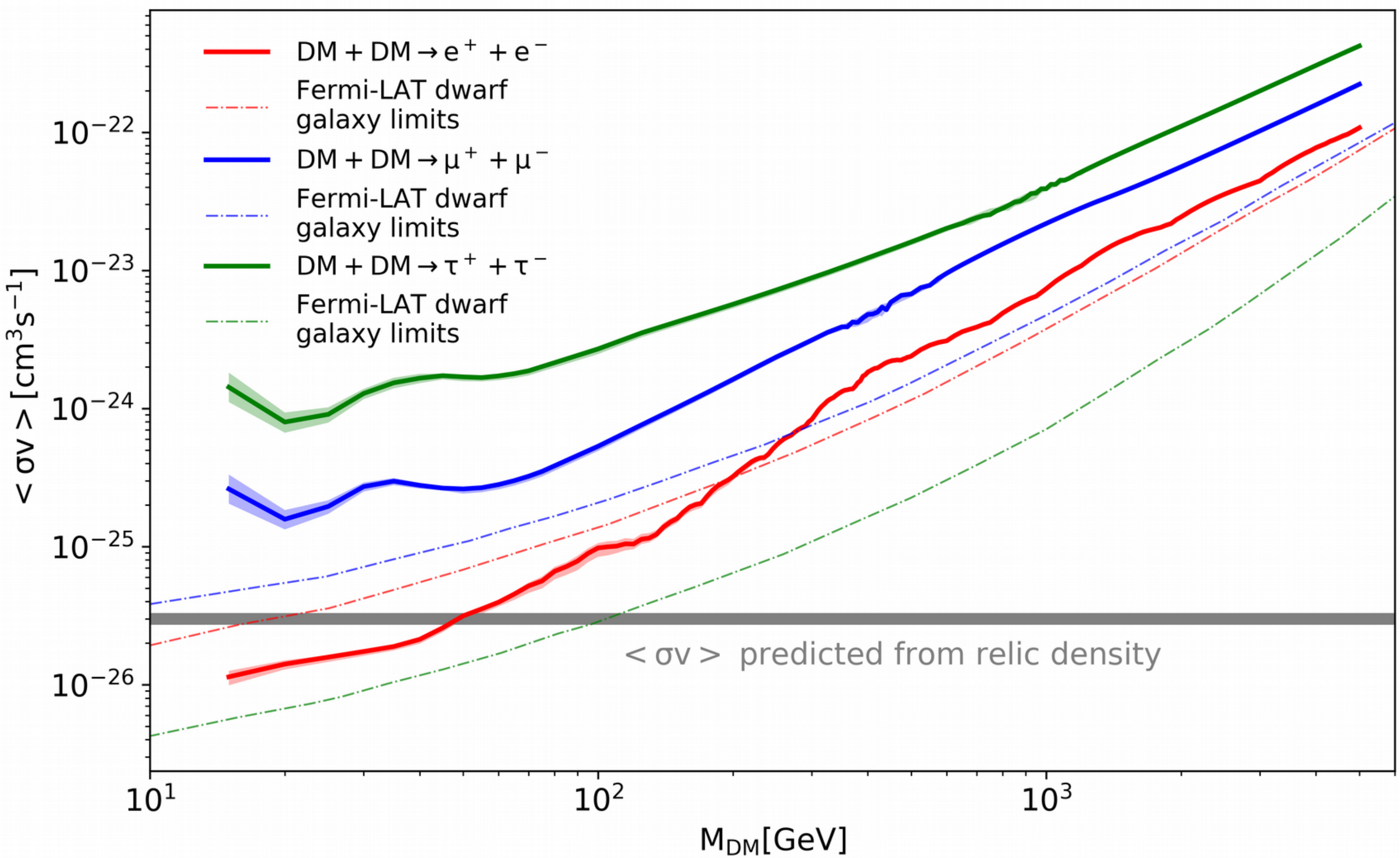


Adding (too much) Dark Matter

- If adding Dark Matter flux with large scale (boost) factor, the data does not match the resulting spectral feature → χ^2 increases
- Boost factor at which χ^2 reaches 95 % CL corresponds to a limit on the Dark Matter annihilation rate → repeat for many Dark Matter masses ...



Limits on Dark Matter Annihilation as a Function of Dark Matter Mass



Fermi-LAT limits from Phys. Rev. Lett. 115, 231301 (2015) (SM)

electron+positron complementary to gamma-ray search

→ different sensitivity to annihilation channels

→ different target region (galactic neighborhood vs. dwarf galaxies)

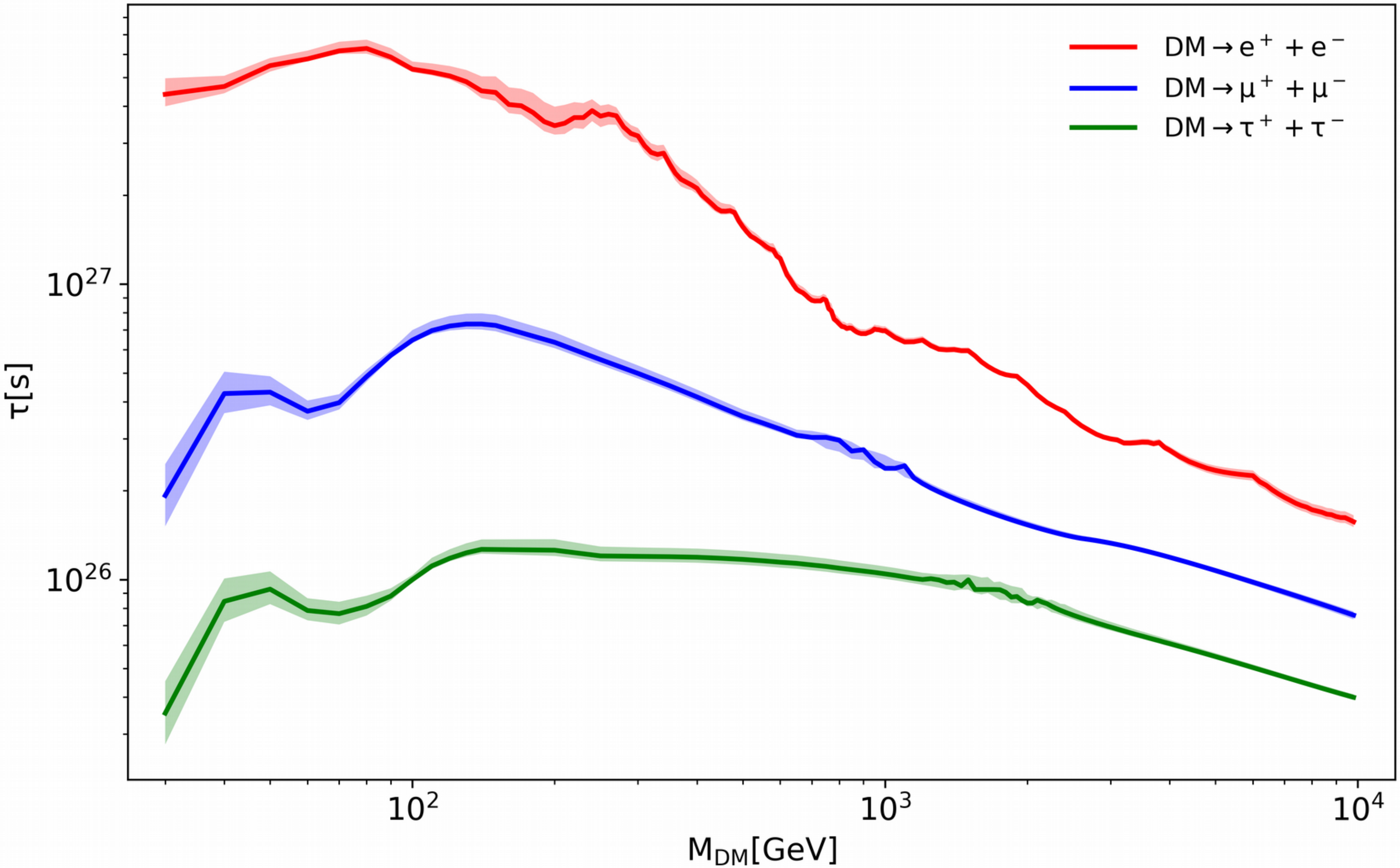
Shaded regions show dependence on nuisance parameters:

$E_{cut(d)}$ [2TeV,**4TeV**,10TeV]

Φ [0.3GV,**0.5GV**,0.7GV]

s [0.03,**0.05**,0.1]

Limits on Dark Matter Decay as a Function of Dark Matter Mass



Shaded regions show dependence on nuisance parameters:

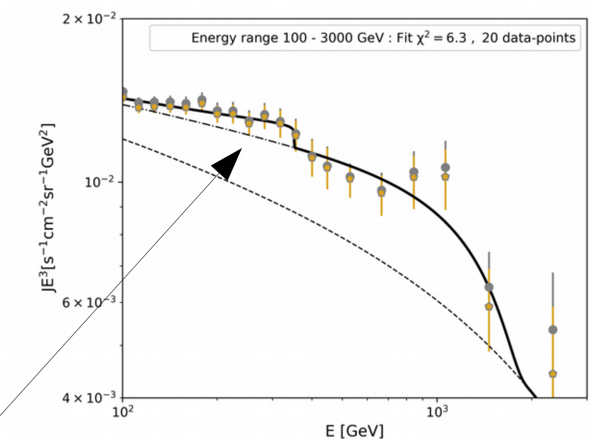
$E_{cut(d)}$ [2TeV,**4TeV**,10TeV]

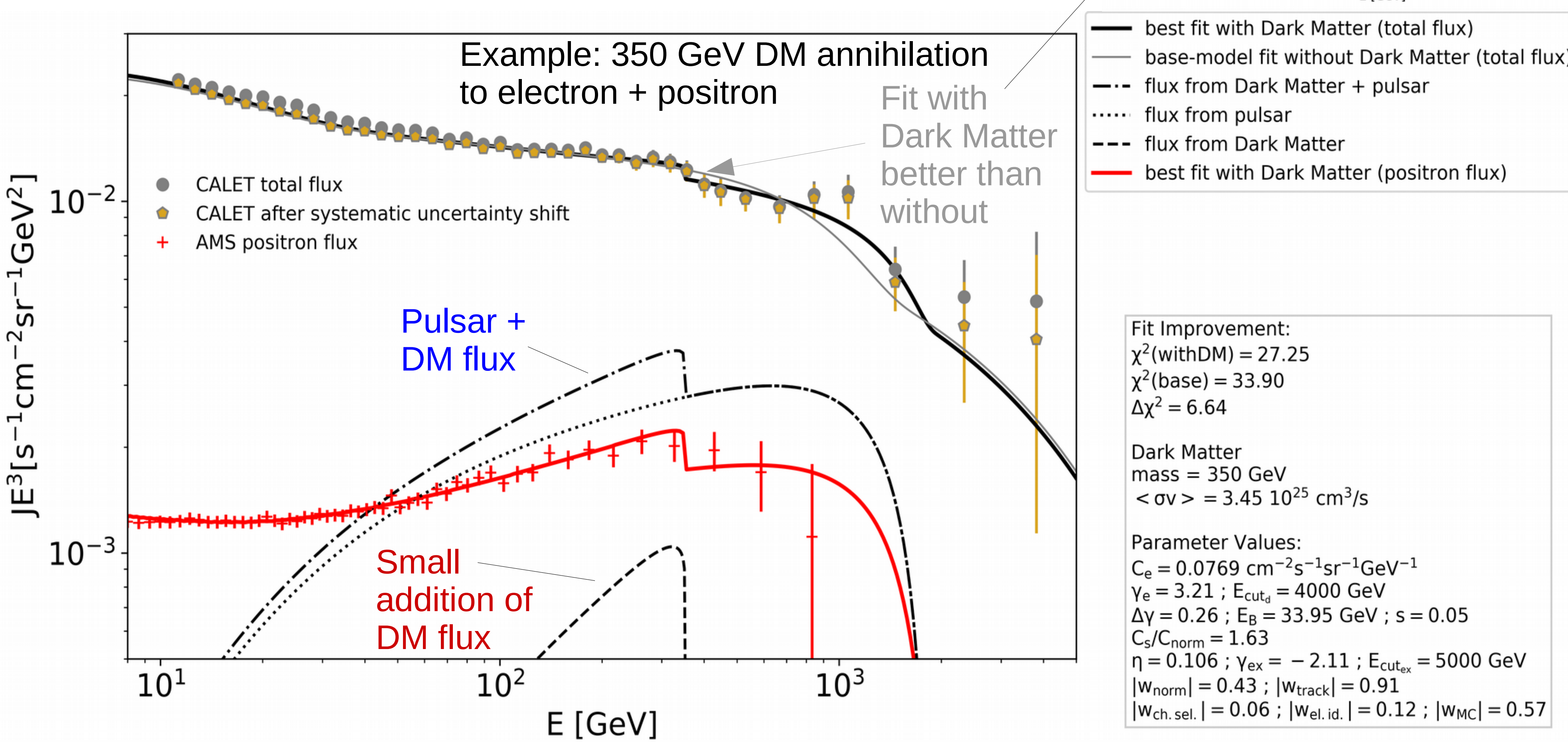
Φ [0.3GV,**0.5GV**,0.7GV]

s [0.03,**0.05**,0.1]

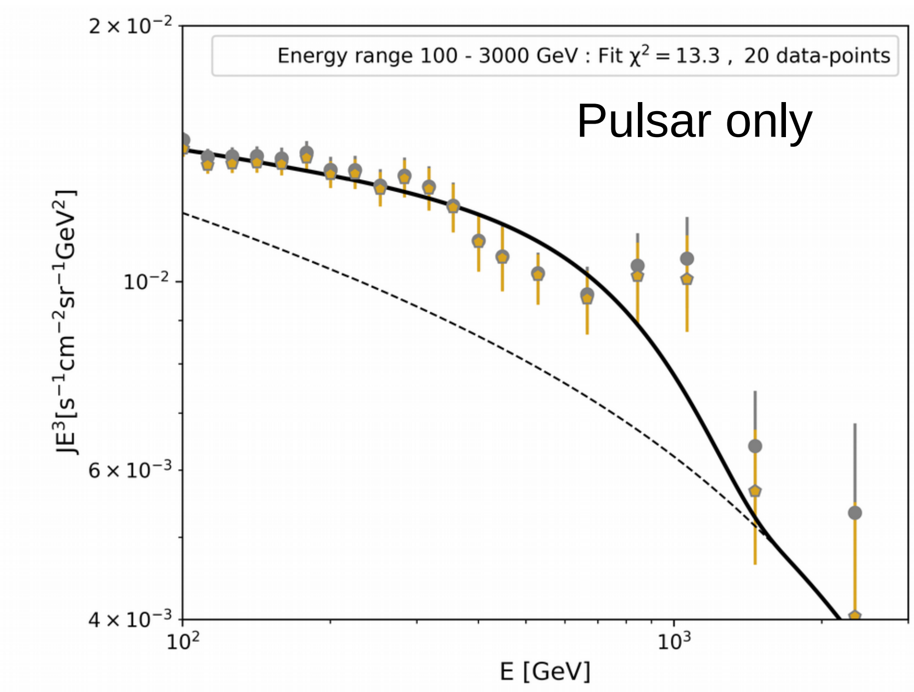
Adding (a bit of) Dark Matter

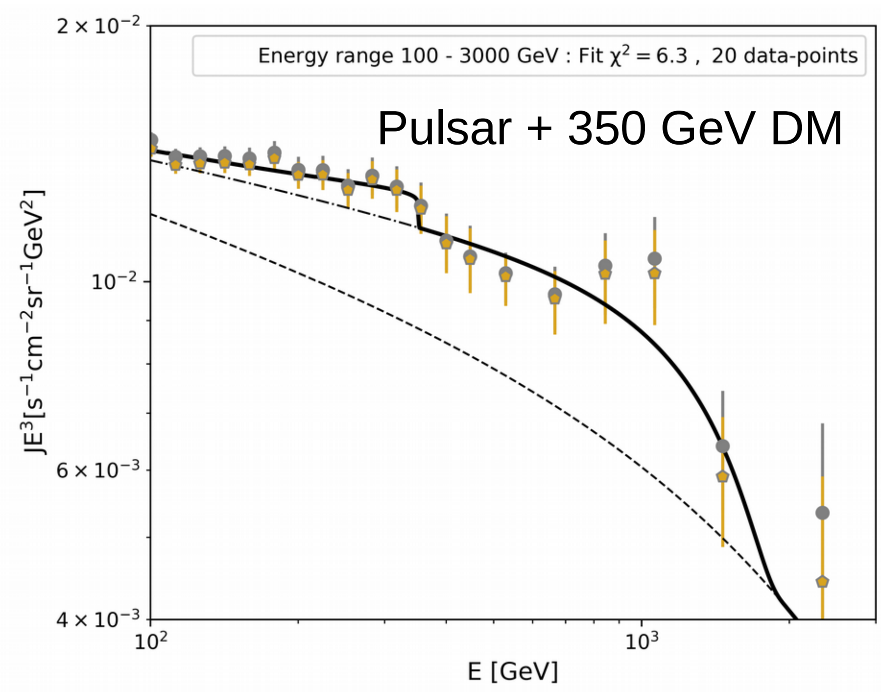
- χ^2 decreases initially before increasing → best fit **INCLUDING** Dark Matter signal
- Structure near 350 GeV better modeled





Fit Improvement by Modeling 350 GeV Step-like Structure with Dark Matter Signature

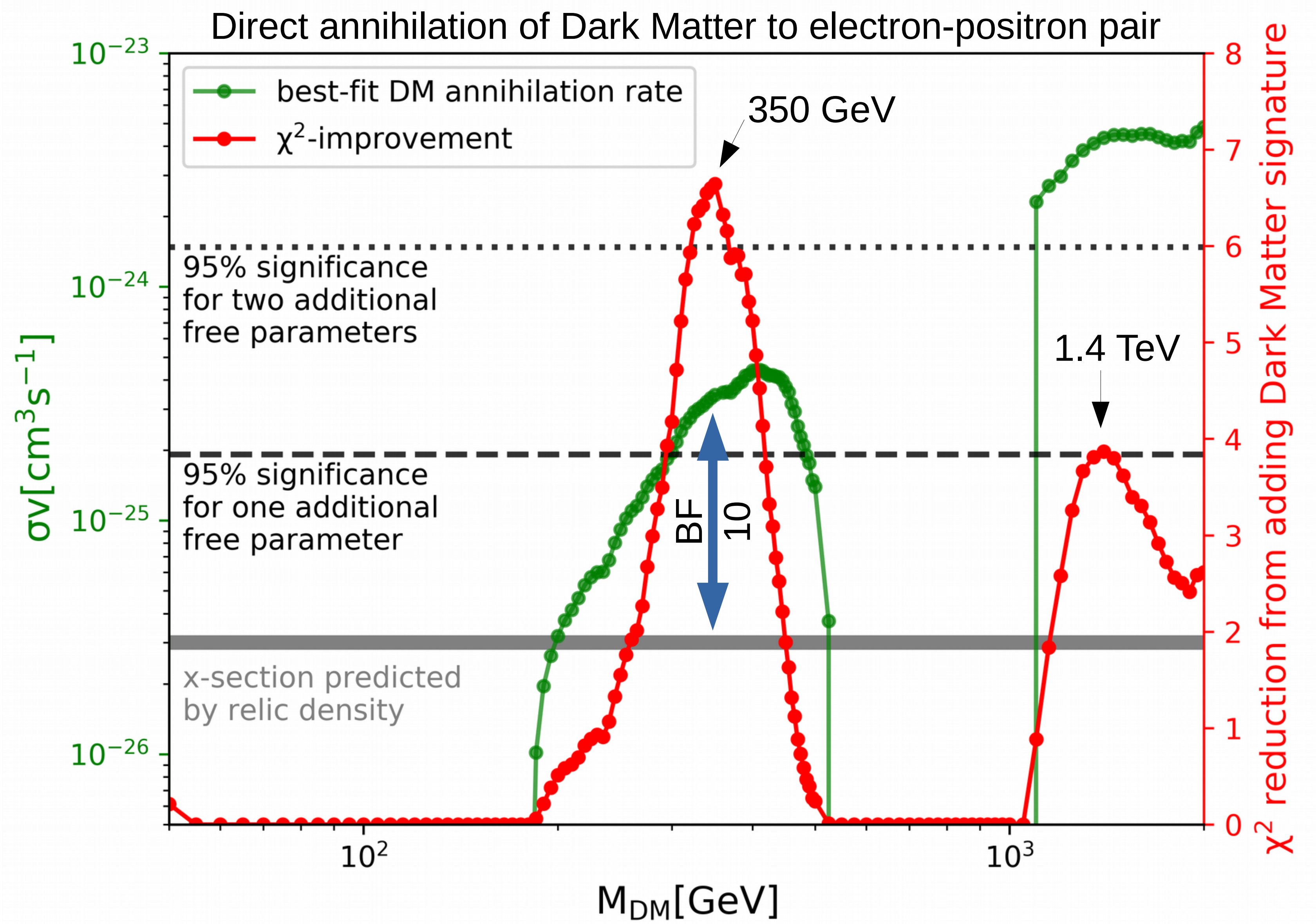




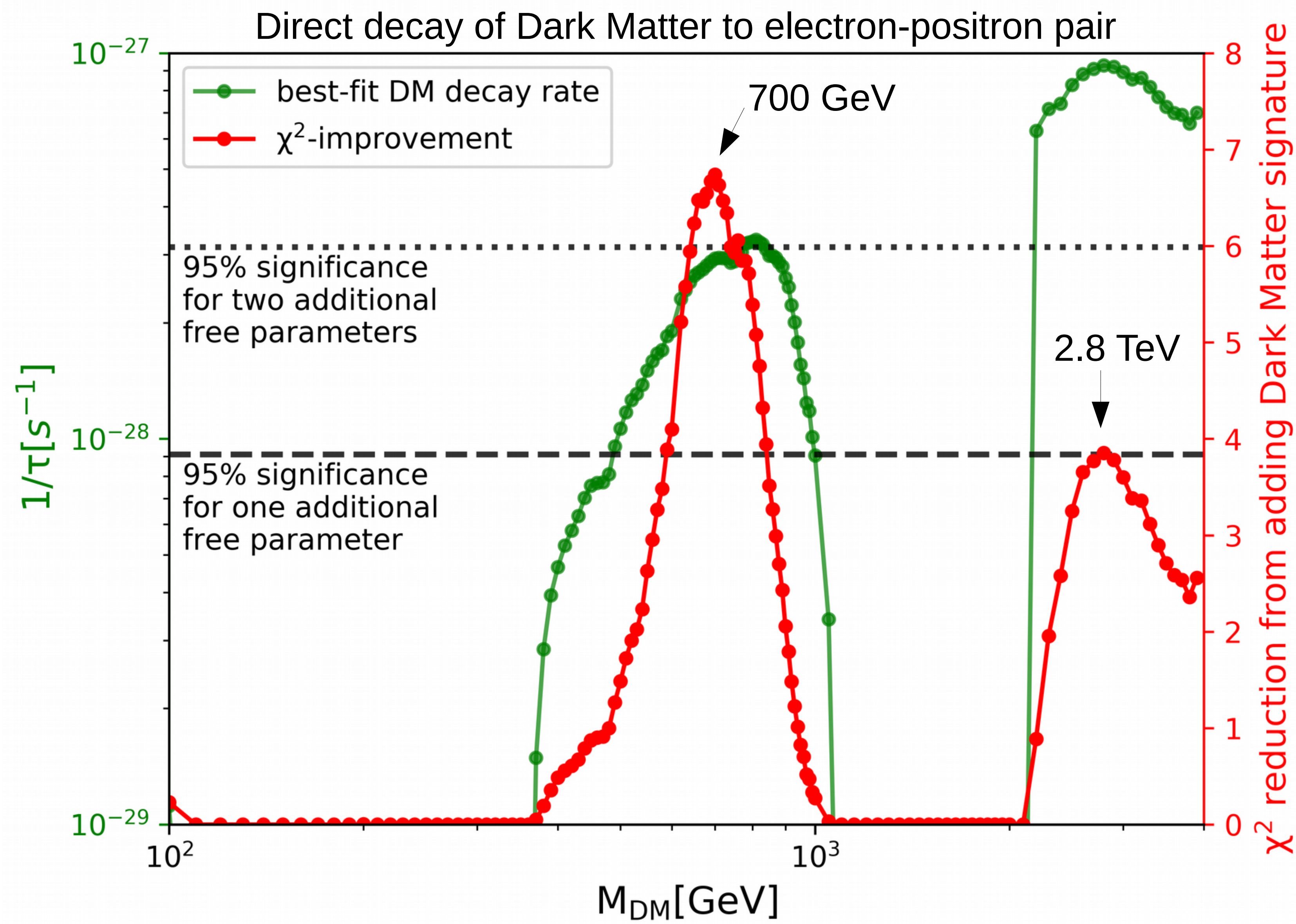
- χ^2 improvement compared to single pulsar case:

Full energy range (CALET & AMS-02 data) : $\Delta\chi^2 = 6.6$ (33.9 → 27.3)
100 GeV – 3 TeV (CALET data only) : $\Delta\chi^2 = 7.0$ (13.3 → 6.3)

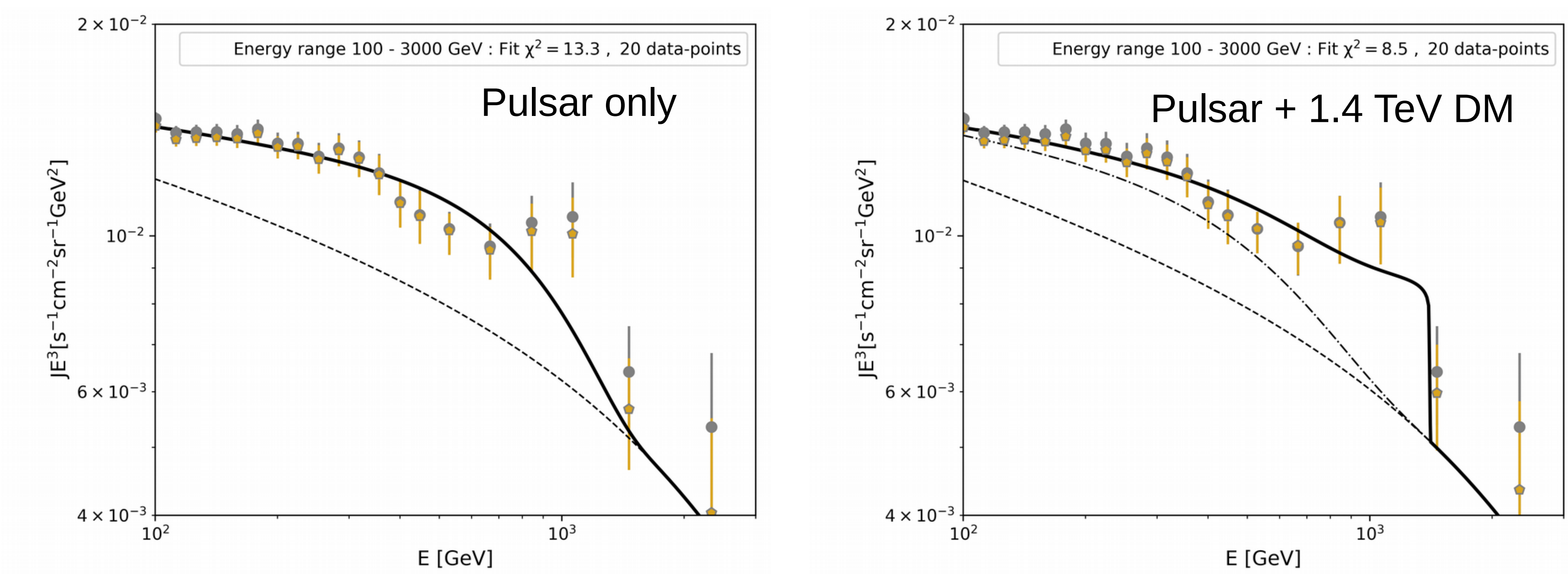
Fit Improvement and Best x-Section against Dark Matter Mass



Fit Improvement and Best Lifetime against Dark Matter Mass



Fit Improvement by Modeling ~ 1 TeV Step/Peak-like Structure with Dark Matter Signature



- χ^2 improvement compared to single pulsar case:

Full energy range (CALET & AMS-02 data) : $\Delta\chi^2$ = 3.9 (33.9 → 30.0)
100 GeV – 3 TeV (CALET data only) : $\Delta\chi^2$ = 4.8 (13.3 → 8.5)

The spectrum from DM annihilation to electron-positron pairs can't model this "peak" well, but significance anyway limited due so larger statistical errors

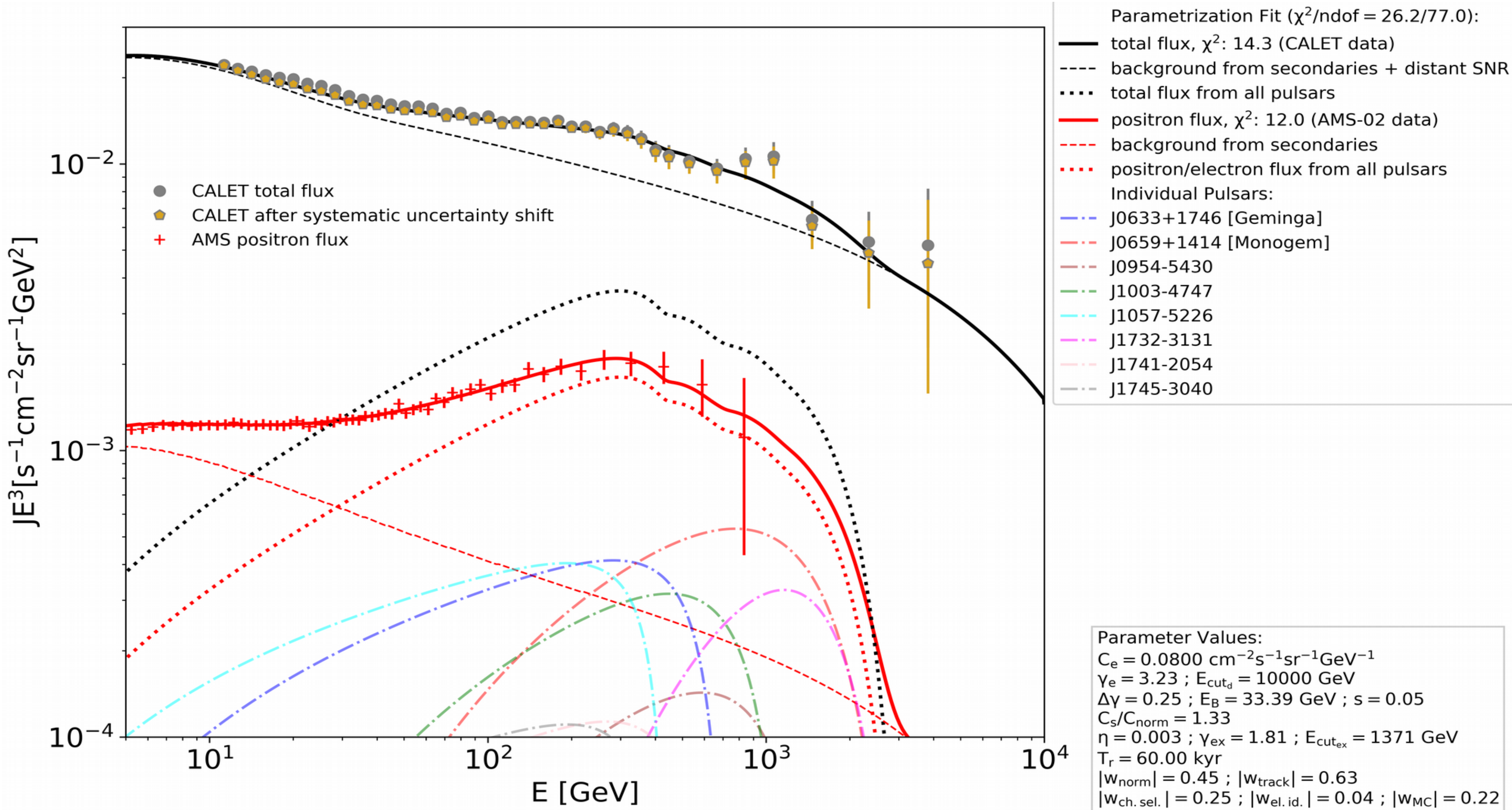
Refined Pulsar Model

- Accelerated particles may be trapped in pulsar wind nebula for the lifetime of the nebula, assumed to be up to ~ 10^5 years [e.g. Phys. Rev. D. 80.063005]

  → Introduce release time T_r as additional free parameter subtracted from the age of the pulsar to get time of cosmic ray propagation t_{dif}

- Calculate flux of all pulsars in ATNF catalog with age < 1 Myr and distance < 1 kpc (22 pulsars) scanning over power law index [1..3] and release time [0 .. 100 kyr]
- Select pulsars contributing more then 5% of total pulsar flux at any energy under any condition → 13 “relevant” pulsars used in fit
- Same free parameters (γ, η, E_{cut}, T_r) assumed for all pulsars, but initial energy, distance and age different (calculated from ATNF catalog data)

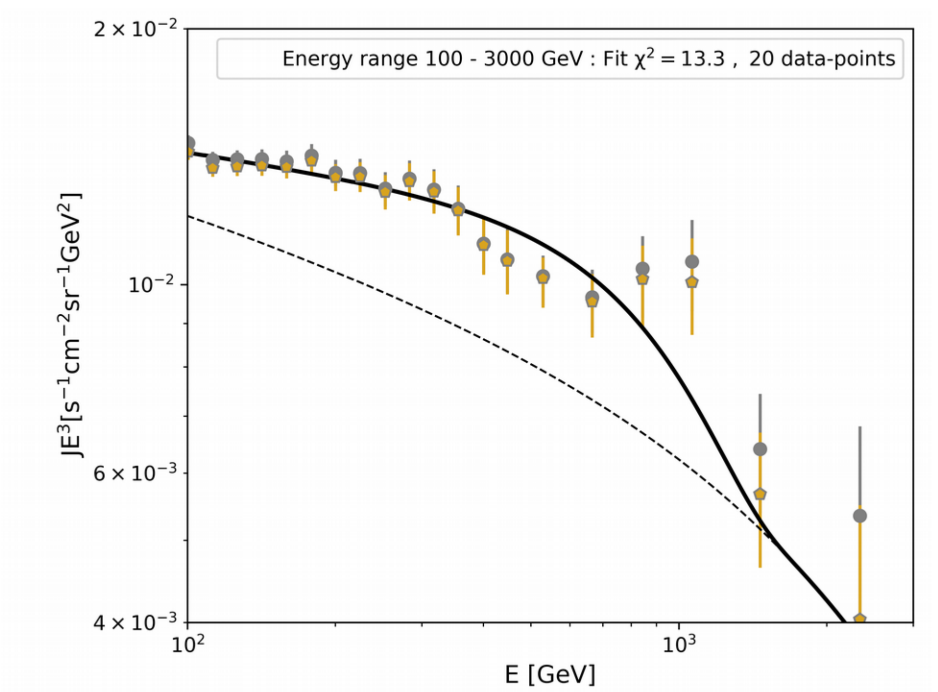
Best Fit Multi-Pulsar Model

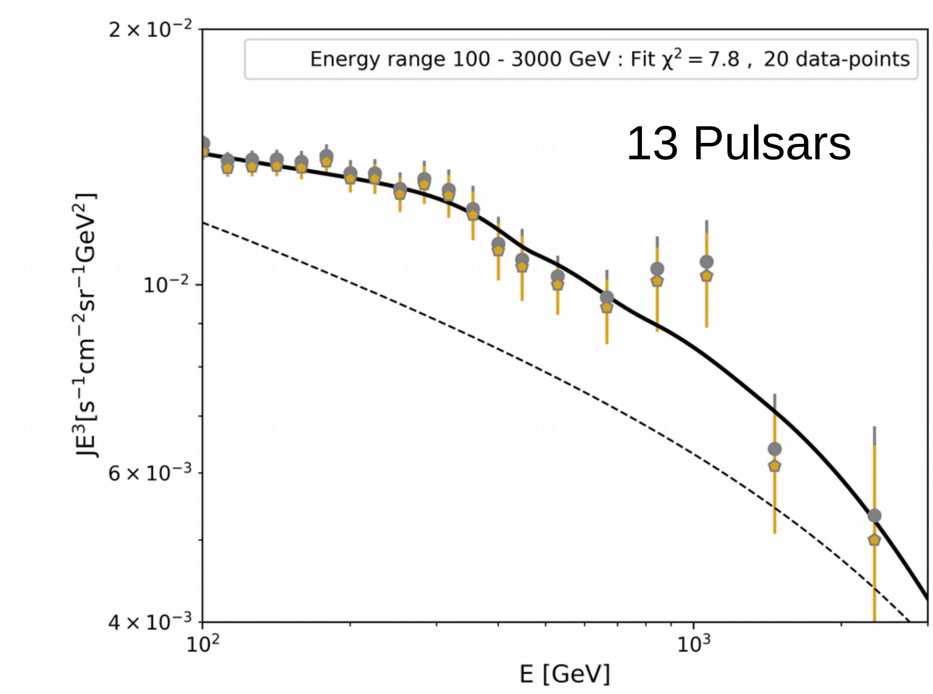


Scan T_r in steps of 1000 years → T_r ≥ 60 kyr

Scan over cutoff energy of primary e^- spectrum → $E_{cut(d)}$ 10 TeV

Fit Improvement by Modeling 350 GeV Step-like Structure with Multiple Pulsars



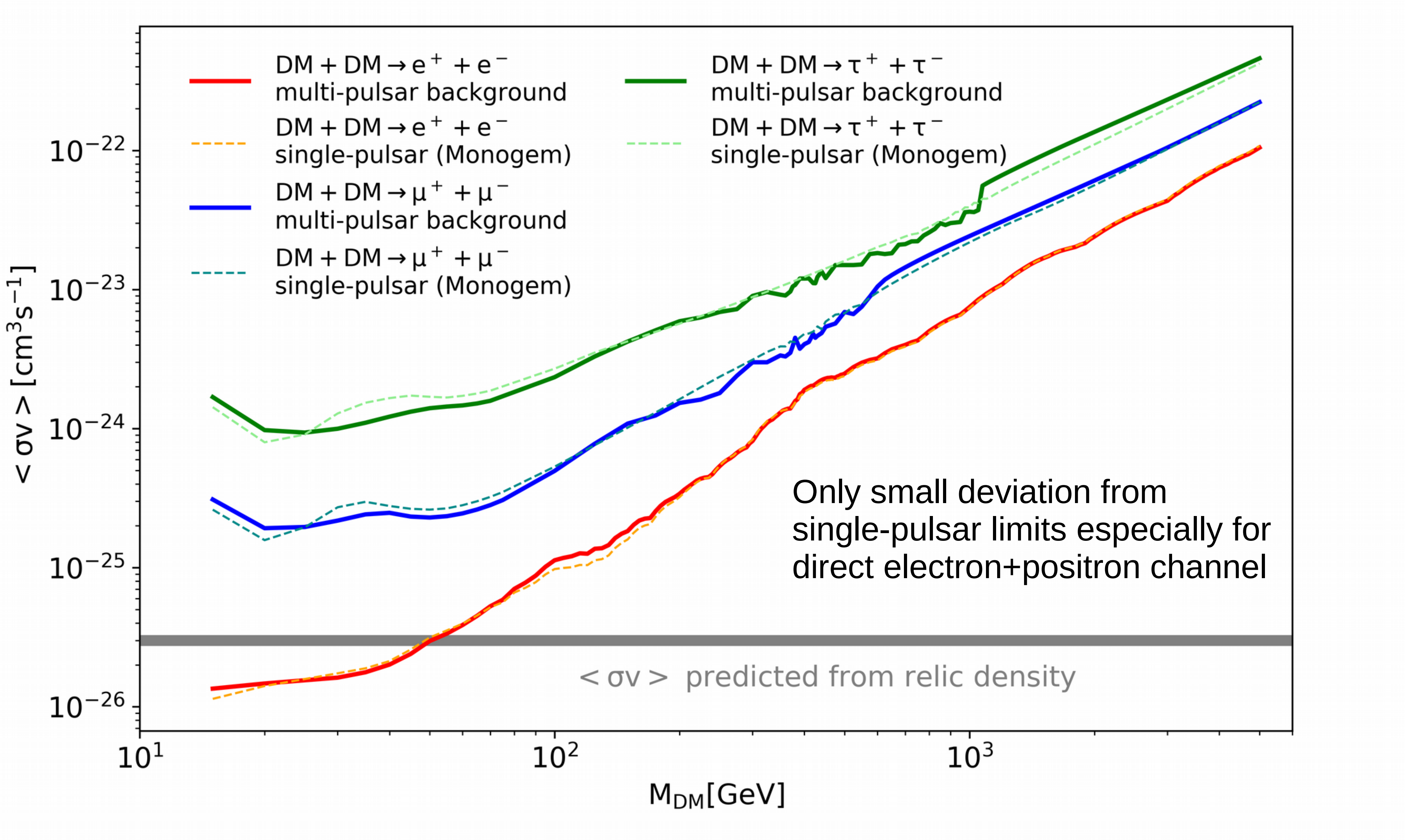


- χ^2 improvement compared to basic single pulsar case:

Full energy range (CALET & AMS-02 data) : $\Delta\chi^2 = 7.7$ (33.9 → 26.2)
100 GeV – 3 TeV (CALET data only) : $\Delta\chi^2 = 5.5$ (13.3 → 7.8)

Similar (slightly larger) improvement than for addition of Dark Matter

Limits on Dark Matter Annihilation with Multi-Pulsar Background



Summary, Conclusions and Outlook

- Structures exist in the CALET spectrum, a significant improvement of the fit quality can be achieved by modeling the step near 350 GeV:
  - By adding the predicted signal from Dark Matter annihilation into electron-positron pairs
  - By combining the flux from all known nearby pulsars with same injection parameters as the extra source causing the positron excess
- Limits on Dark Matter annihilation and decay from the CALET electron+positron spectrum give a strong constraint on two-body annihilation or decay of Dark Matter directly to electron+positron pairs complementary to gamma-ray measurements
- The limits change only slightly if using the multi-pulsar model as background instead of single pulsar model
- The observed structure is potentially statistically significant and could be a hint for the presence of individual local astrophysical sources (or Dark Matter ?)
- The variability in astrophysical background necessary to explain it does not invalidate the Dark Matter limits from using a simpler single-pulsar model
- Reduction of systematic errors and better understanding of their energy dependence expected to further increase the precision of the CALET measurement in the future, improving the limits and possibly the significance of structures (if real)

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