Evaluation of the CALET Cosmic-Ray Electron Spectrum with regard to Dark Matter

ダークマターの懇談会 2019
Waseda University

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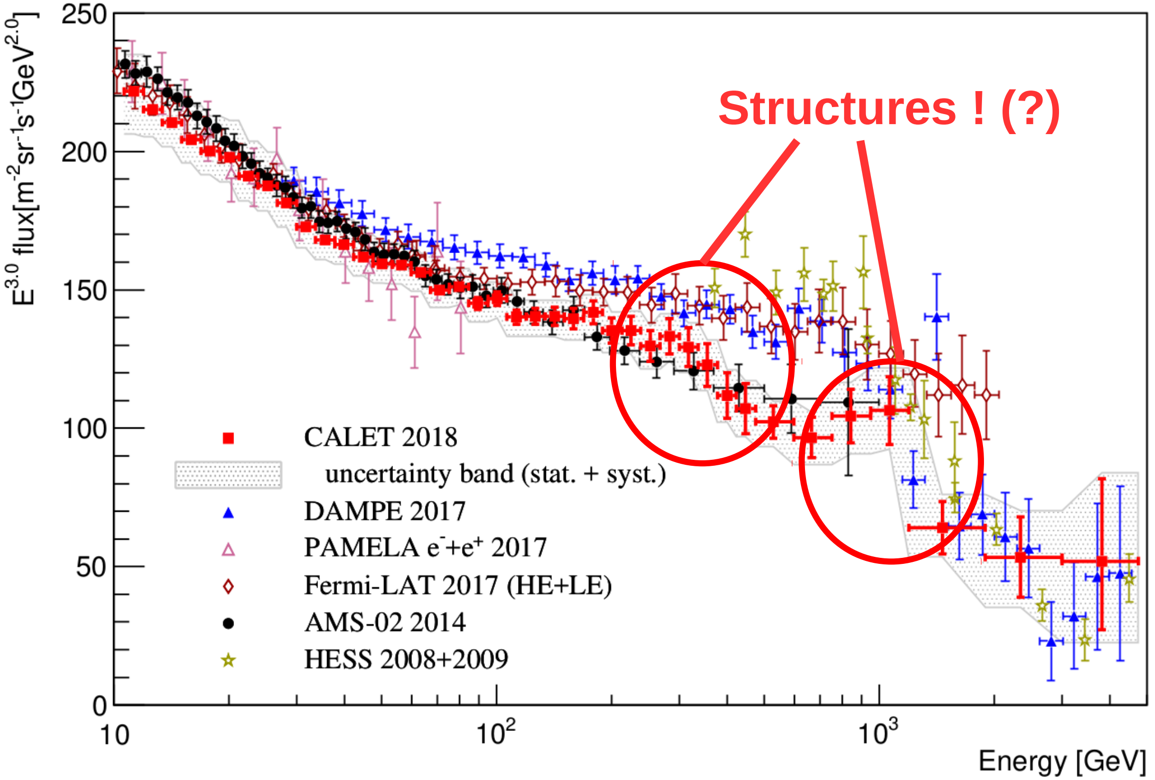
Dark Matter Search in Electron+Positron Cosmic Rays

- Basic Idea (as in most indirect DM search):
  - Background is astrophysical power law spectrum from stochastic acceleration
  - Signal is peaked due to cut off at (half) the mass of the dark matter particle from annihilation (decay)

  → Search for "structures" in the spectrum
- Complications:
  - Dark Matter spectrum softened by decay of primary annihilation (decay) products and propagation
  - Astrophysical background spectrum from multiple sources, deviation from power law due to escape mechanism and propagation effects possible

CALET Electron+Positron Spectrum



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

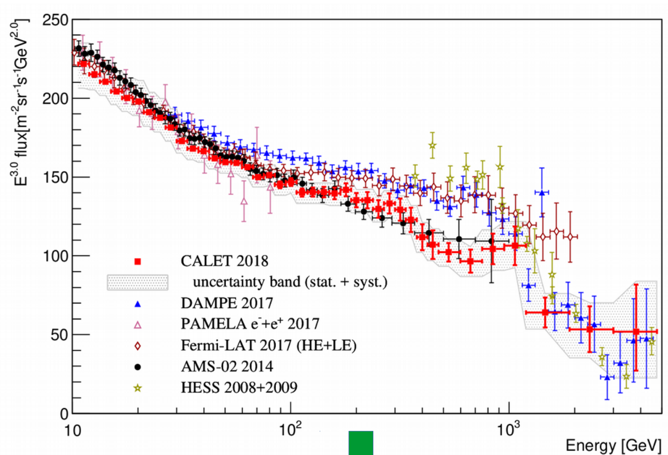
Interpretation of structures as Dark Matter signatures

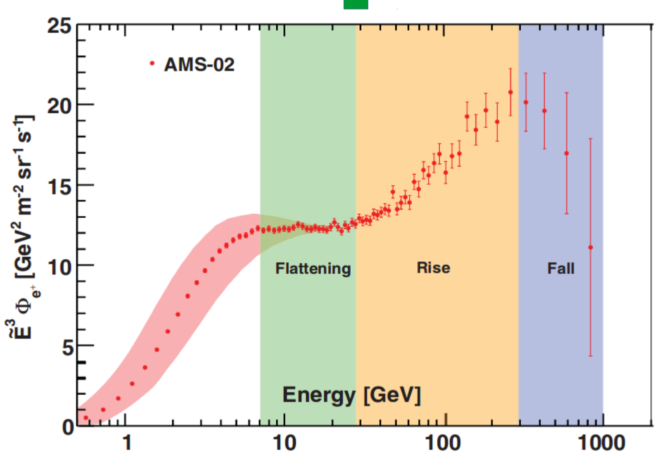
- Interesting speculation
- Allows to compare model with hints from other search methods → to be taken seriously if finding agreement

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



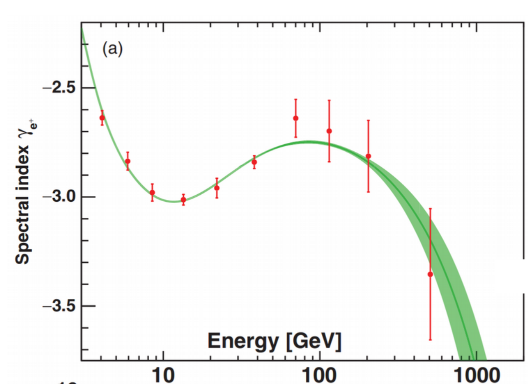


AMS-02 Positron Flux up to 1 TeV

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

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

- The background model should describe the data well (give a good fit) with as few parameters as possible
- It should be as much as possible physics motivated and variation of parameters should reflect uncertainty in physical processes
- It should take into account correlation with other results e.g. consider the source of the positron excess
  → assume pulsar(s) as mundane option*
  → to constrain their 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

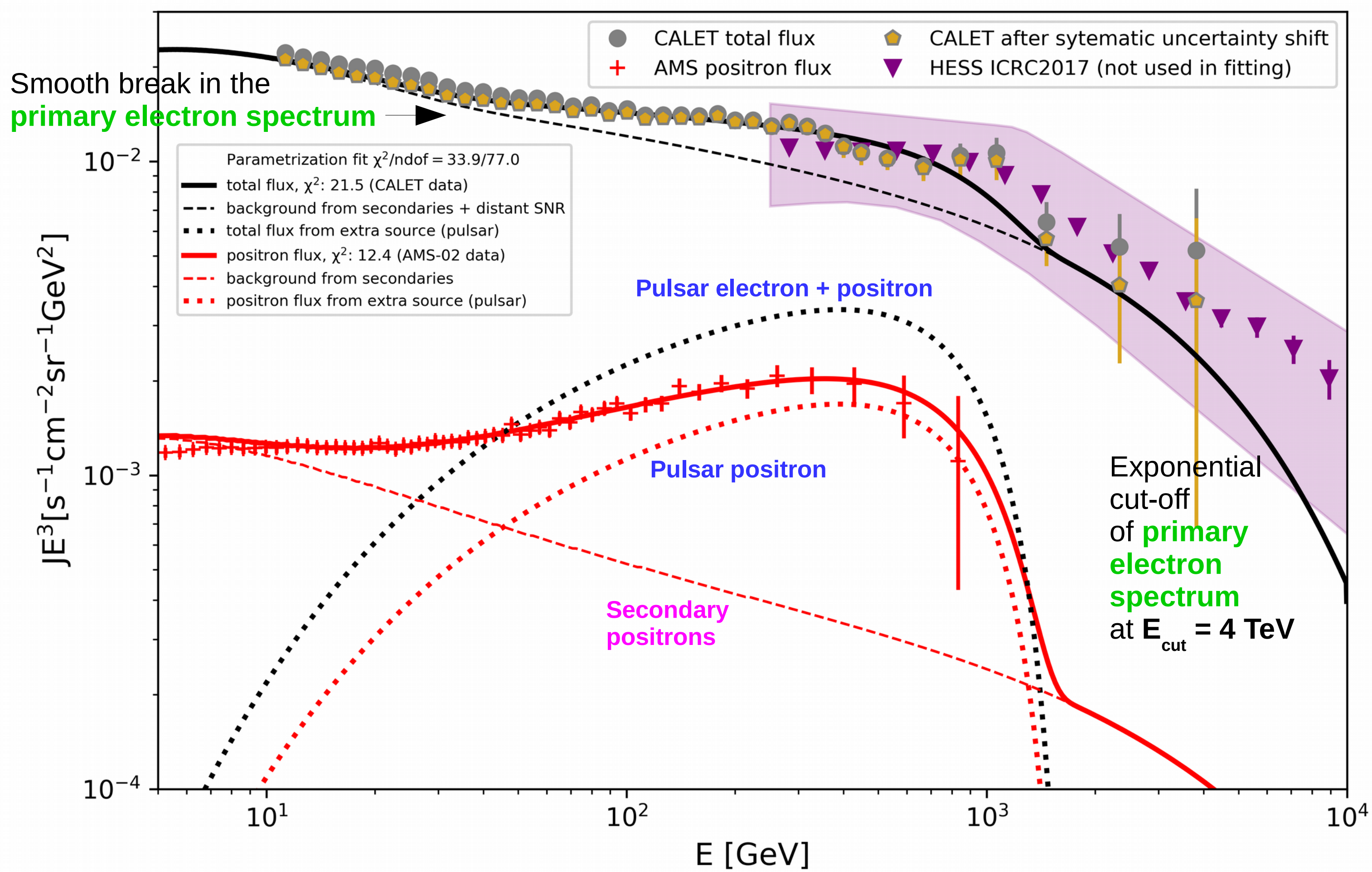
Model for the Local e^- & e^+ Spectra

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

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

- 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: 500 MV



Primary Electron
$C_e = 0.0714$ $cm^{-2}s^{-1}sr^{-1}GeV^{-1}$
$\gamma_e = 3.19$
$E_{cut_d} = 4000$ GeV
$\Delta\gamma = 0.25$
$E_B = 35.65$ GeV
$s = 0.05$

Secondary
from DRAGON ($\delta = 0.6$)
$C_s/C_{norm} = 1.69$

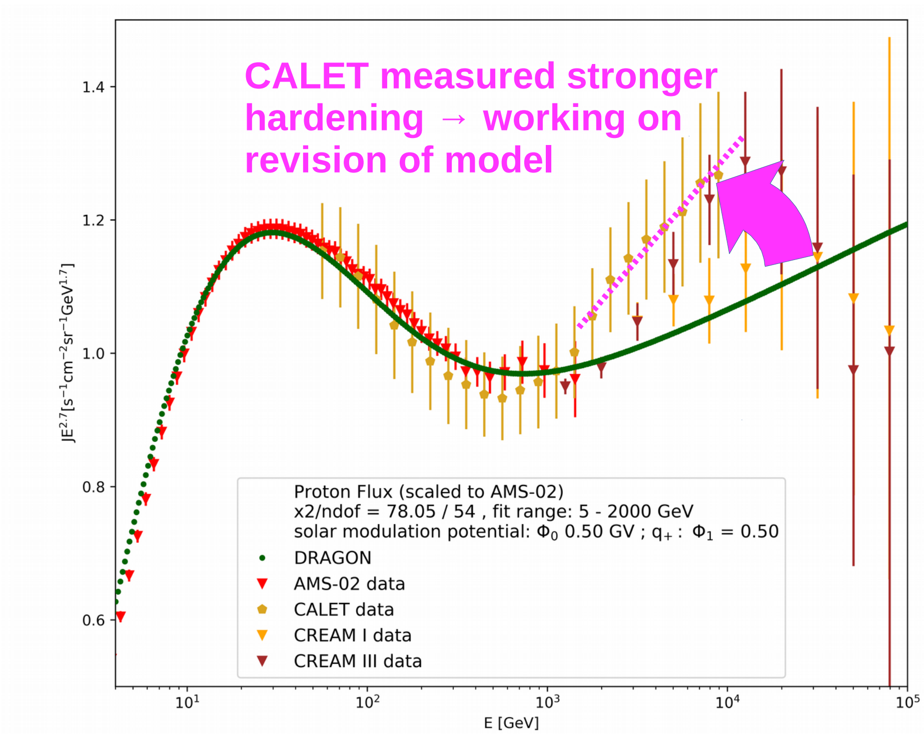
Pulsar Extra Source
J0659+1414 [Monogem]
$\eta = 0.066$
$\gamma_{ex} = 1.95$
$E_{cut_{ex}} = 1195$ GeV

Nuisance Weights:
normalization: 0.54
tracking: 1.16
charge selection: 0.11
electron ID: 0.32
Monte Carlo: 0.82

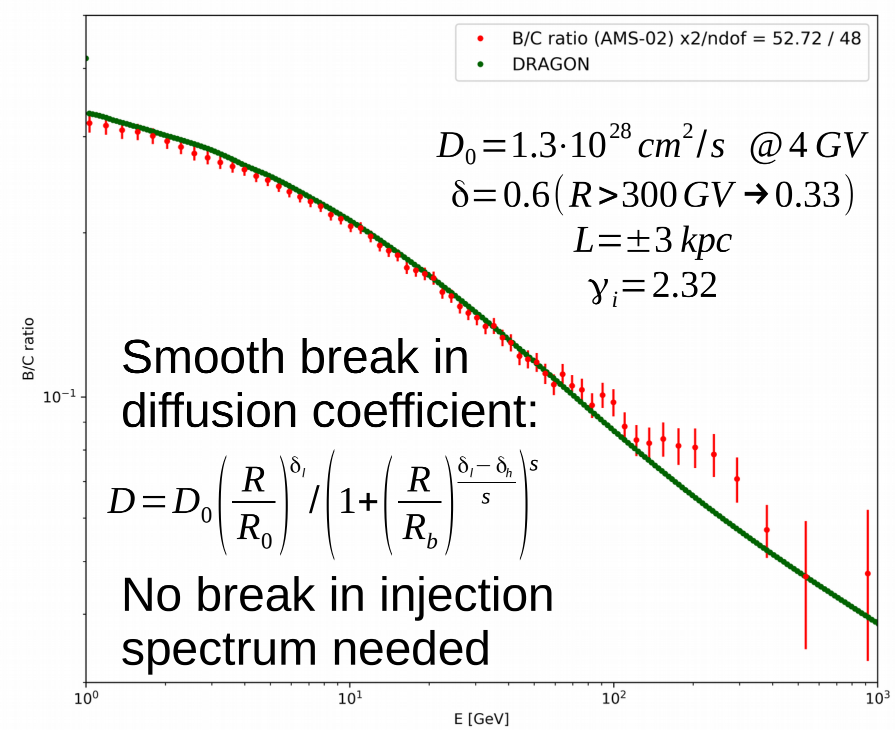
Propagation Model (Calculation with DRAGON)

- 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

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

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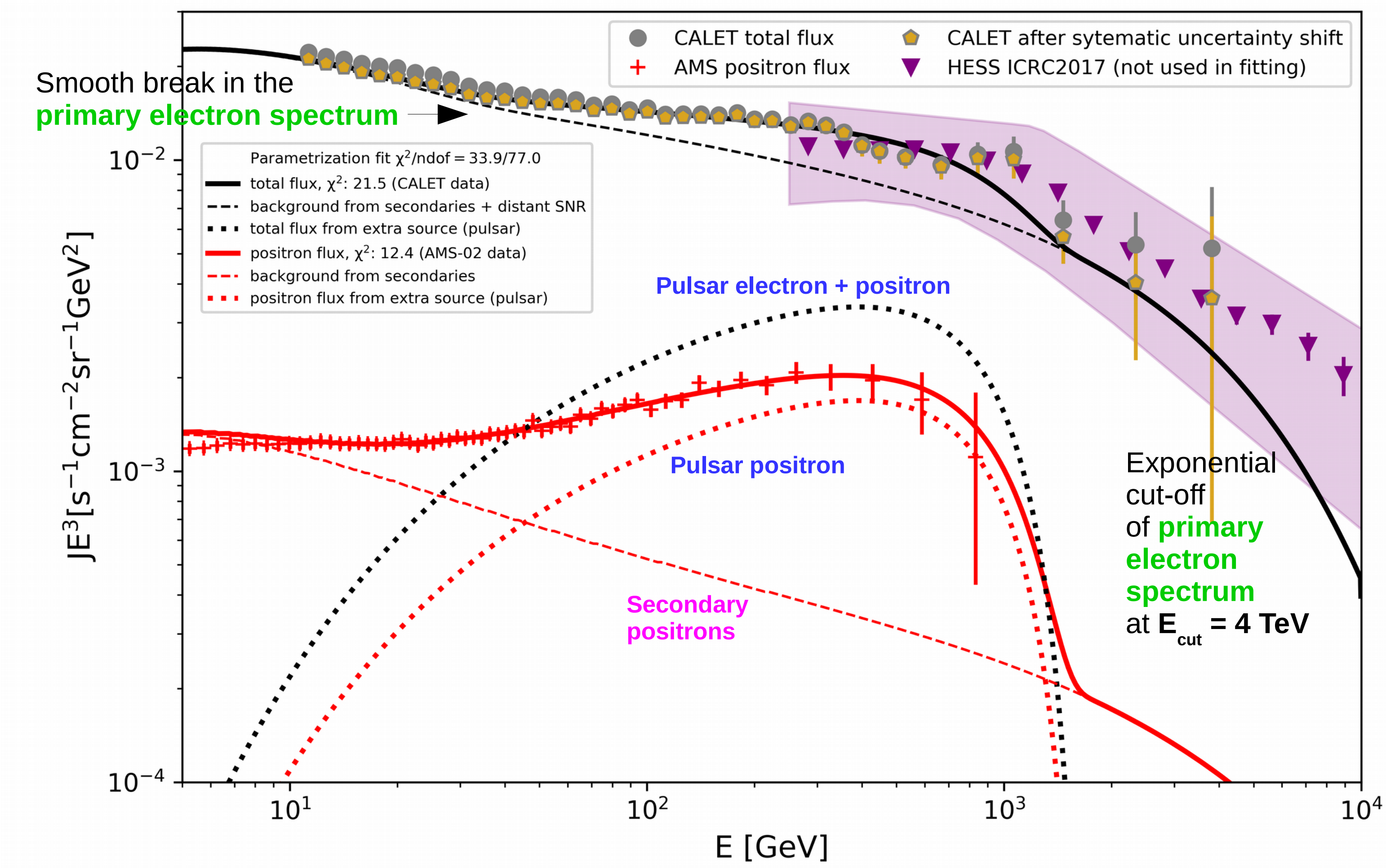

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Calculation of Flux from Pulsars

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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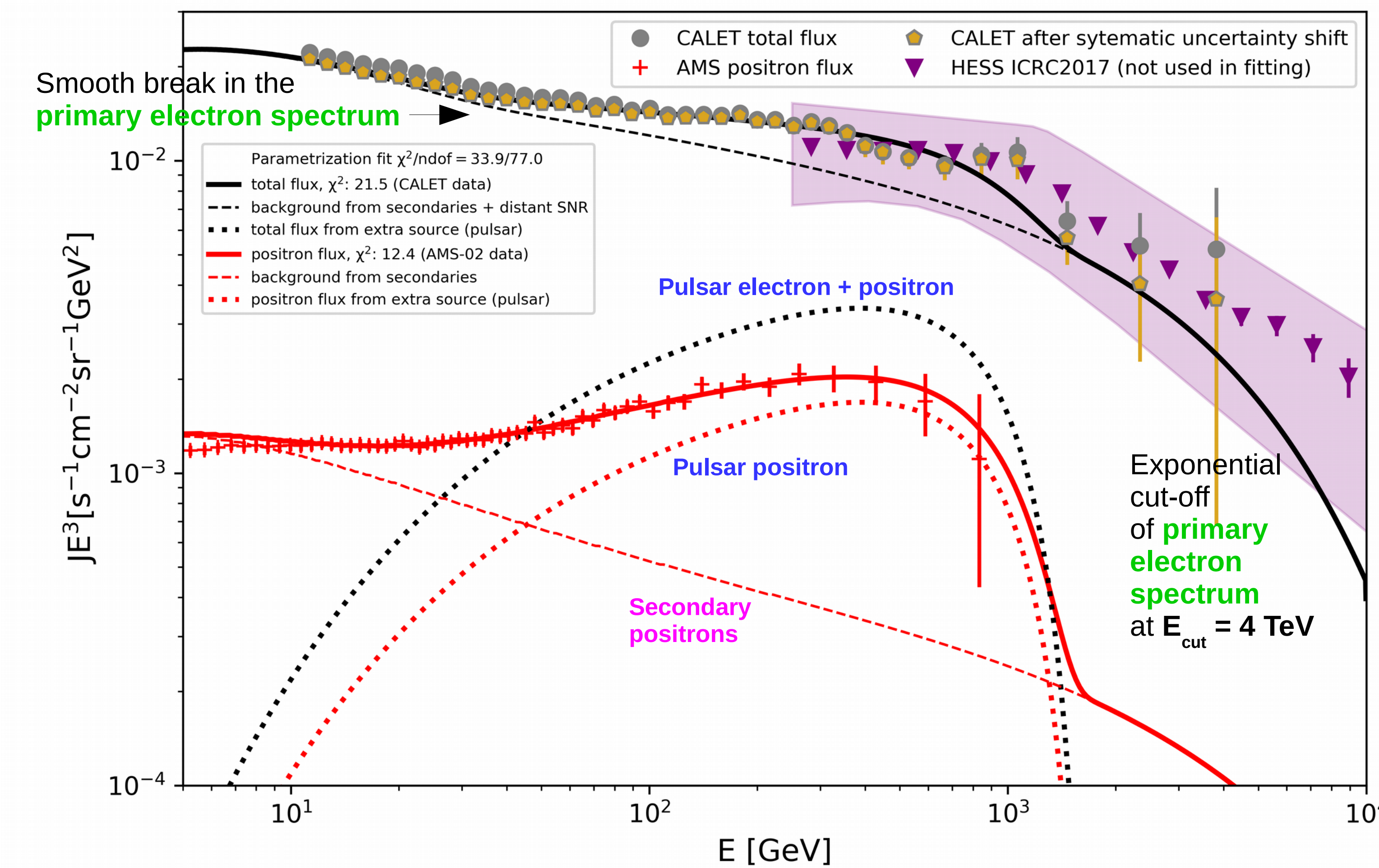

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Systematic Uncertainties as Fitted Nuisance Parameters

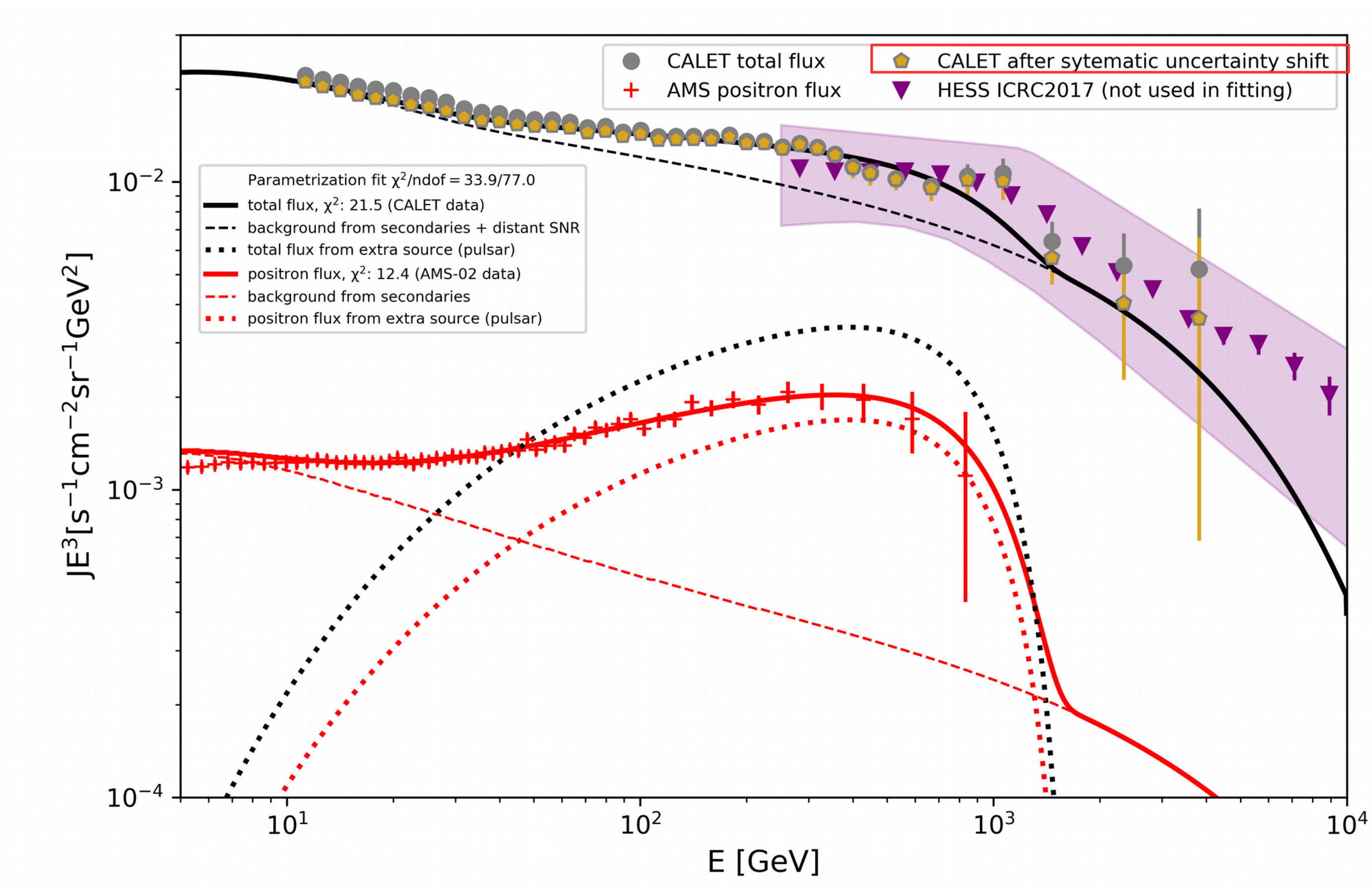
Systematic uncertainties with energy dependence listed in the paper's S.M.

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

Systematic shift of fit function, squared weight of each uncertainty added to the total χ² 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



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

Nuisance parameter weights contribute 2.13 to χ²

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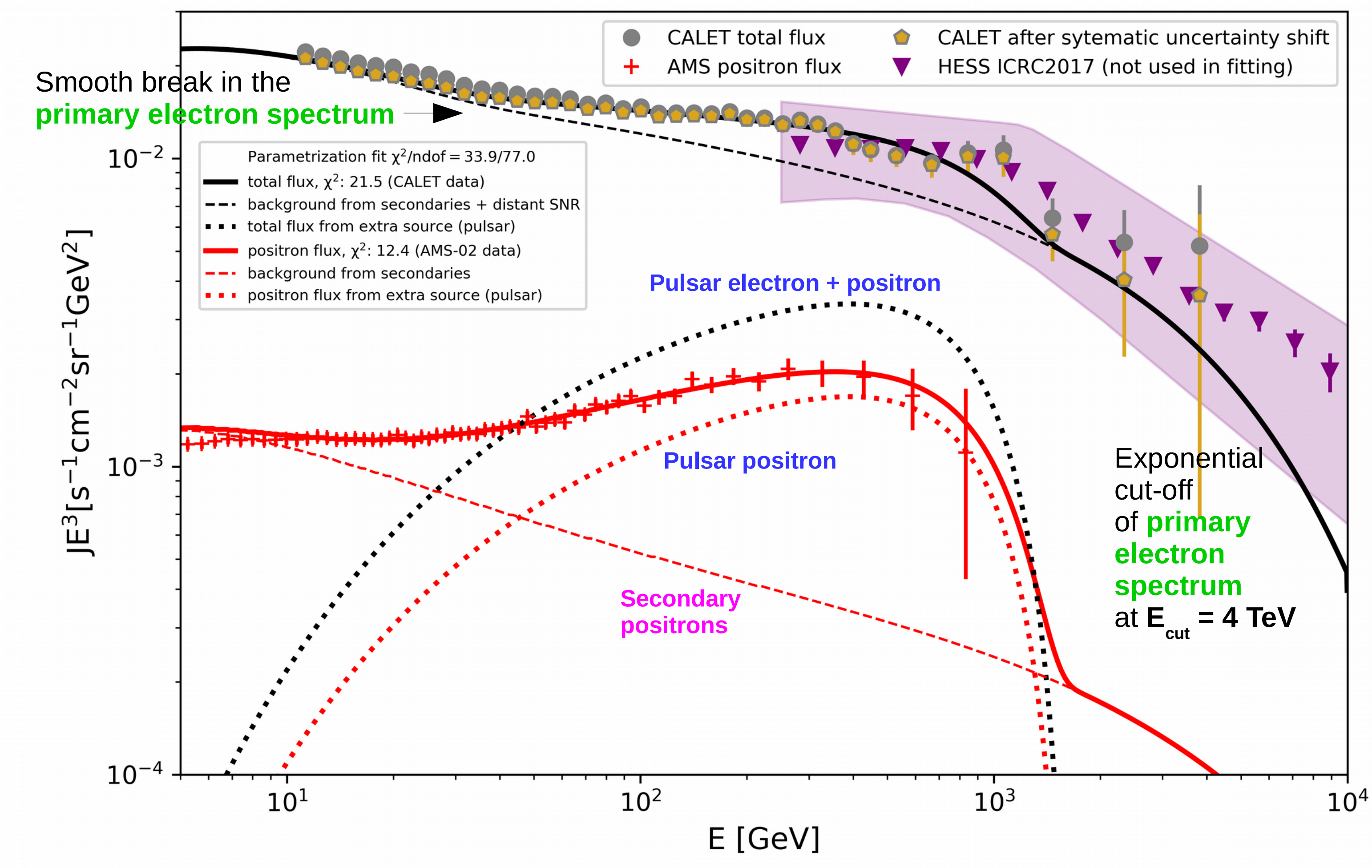

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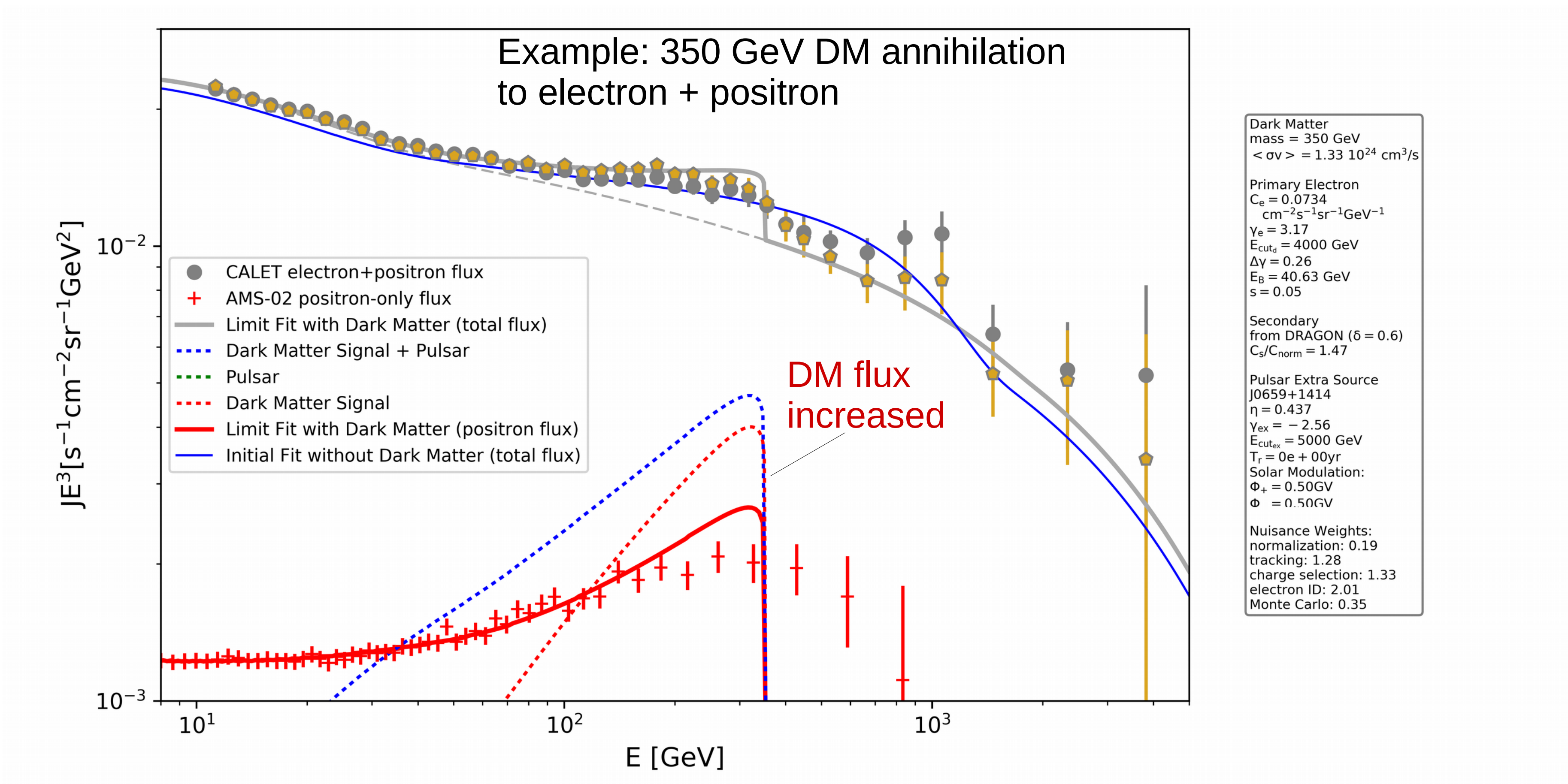
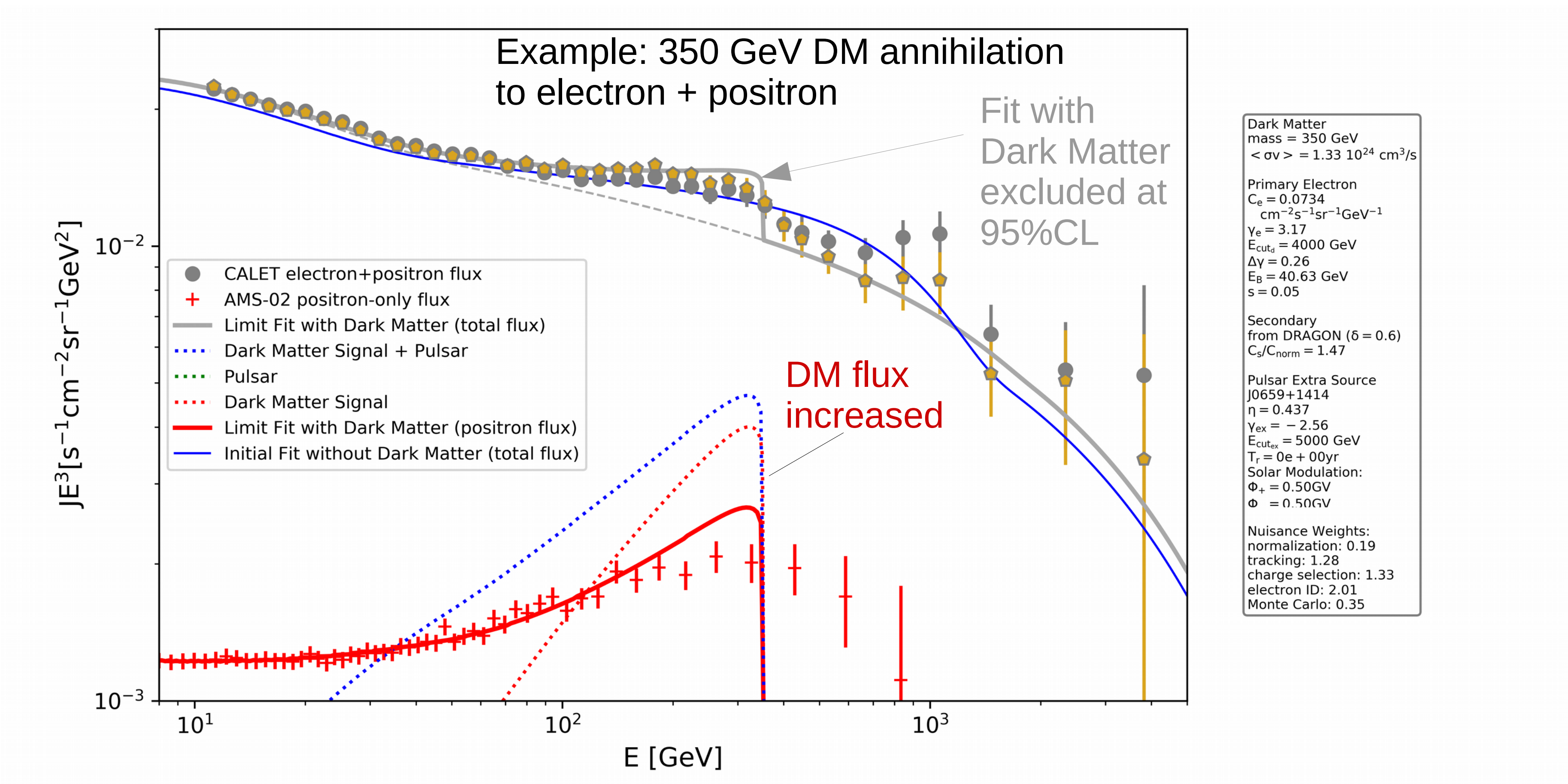
Adding Dark Matter

- 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

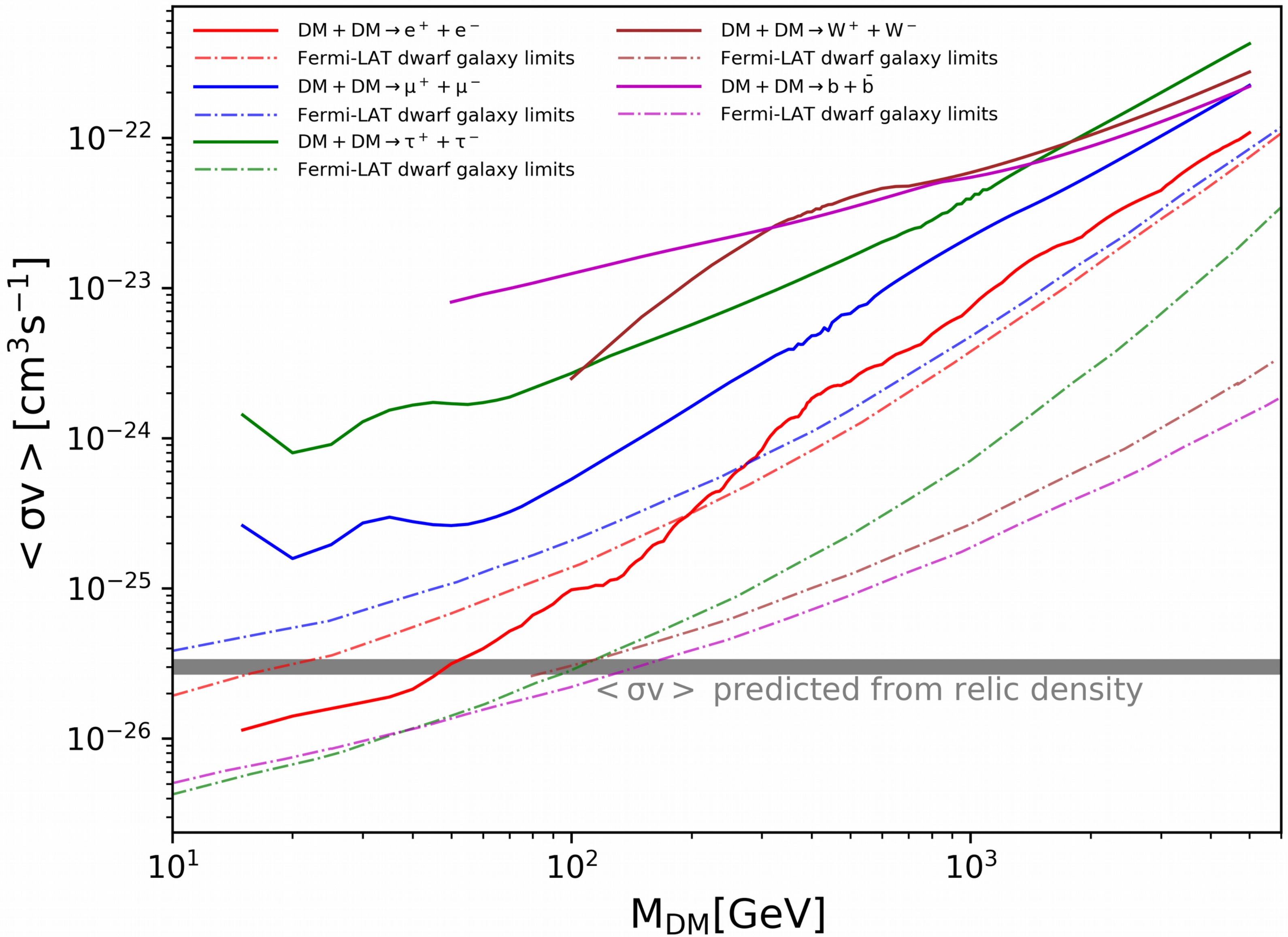


Adding (too much) Dark Matter

- 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



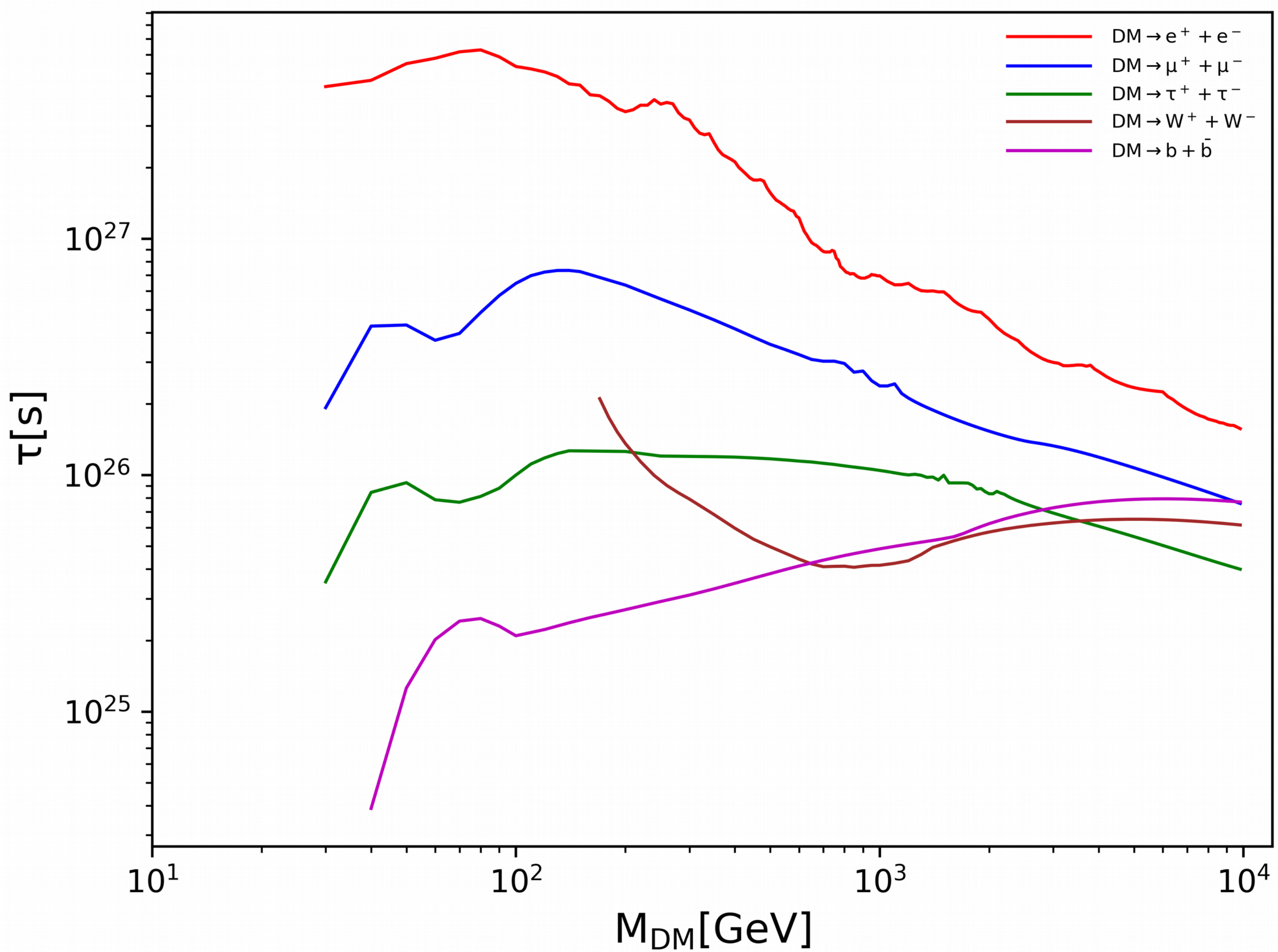
Fermi-LAT limits from Phys. Rev. Lett. 115, 231301 (2015) (SM)

electron+positron complementary to gamma-ray search

→ different sensitivity to annihilation channels

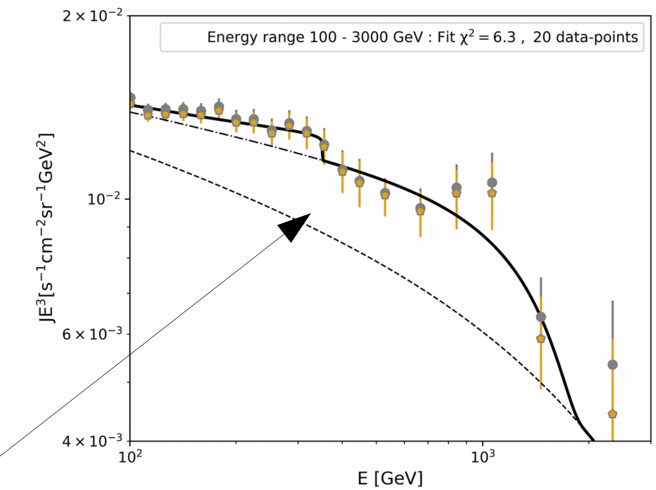
→ different target region (galactic neighborhood vs. dwarf galaxies)

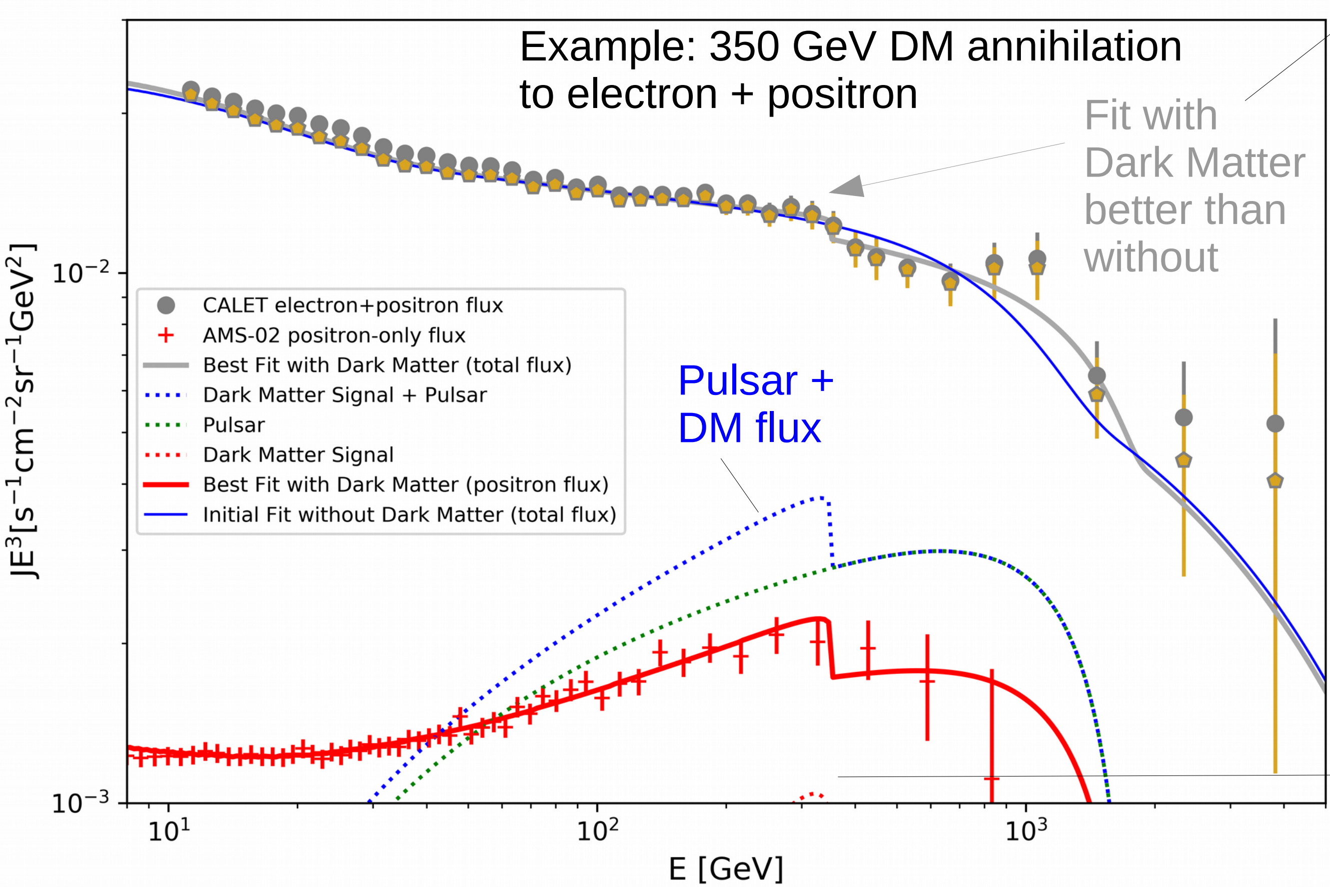
Limits on Dark Matter Decay as a Function of Dark Matter Mass



Adding (a bit of) Dark Matter

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





$\chi^2(DM) = 27.25$
$\chi^2(base) = 33.90$
$\Delta\chi^2 = 6.64$

Dark Matter
mass = 350 GeV
$<\sigma v> = 3.45\ 10^{25}\ cm^3/s$

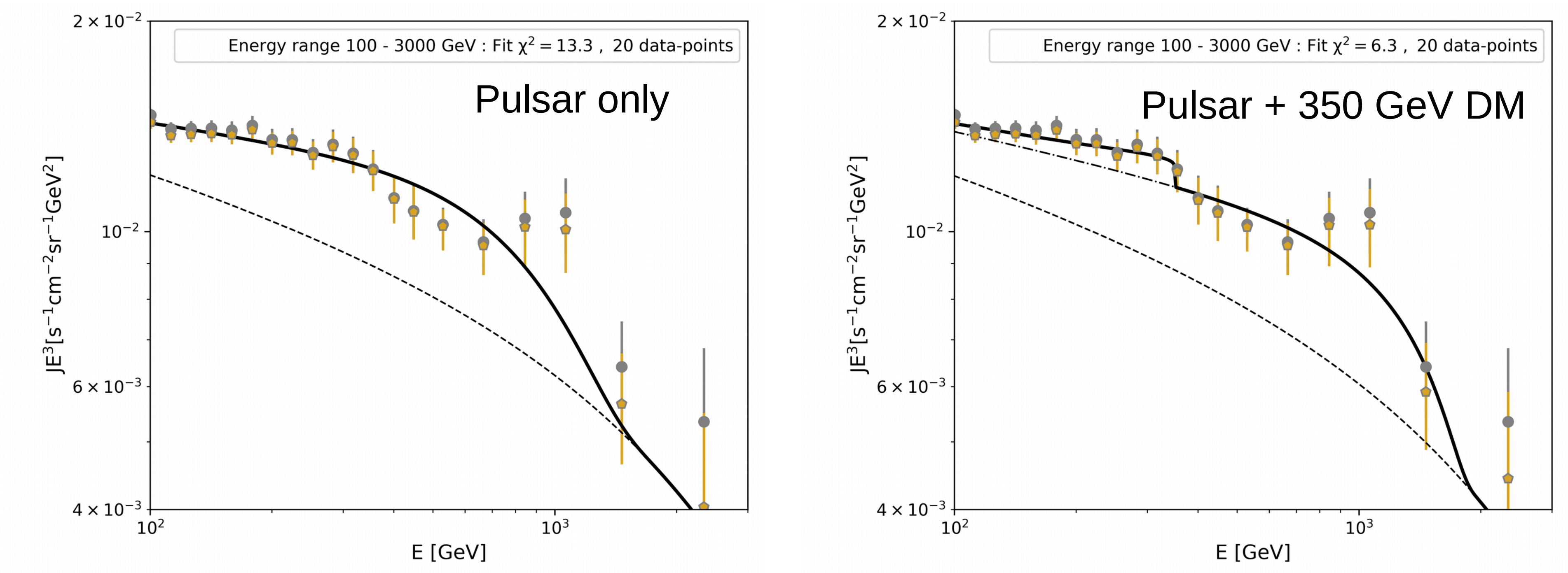
Primary Electron
$C_e = 0.0769$
$cm^{-2}s^{-1}sr^{-1}GeV^{-1}$
$\gamma_e = 3.21$
$\Delta\gamma = 0.26$
$E_B = 33.95$ GeV
$s = 0.05$
$E_{cut_d} = 4000$ GeV

Secondary
from DRAGON ($\delta = 0.6$)
$C_s/C_{norm} = 1.63$

Pulsar Extra Source
J0659+1414
$\eta = 0.106$
$\gamma_{ex} = -2.11$
$E_{cut_{ex}} = 5000$ GeV
$T_r = 0e+00yr$
Solar Modulation:
$\Phi_+ = 0.50GV$
$\Phi_- = 0.50GV$

Nuisance Weights:
normalization: 0.43
tracking: 0.91
charge selection: 0.06
electron ID: 0.12
Monte Carlo: 0.57

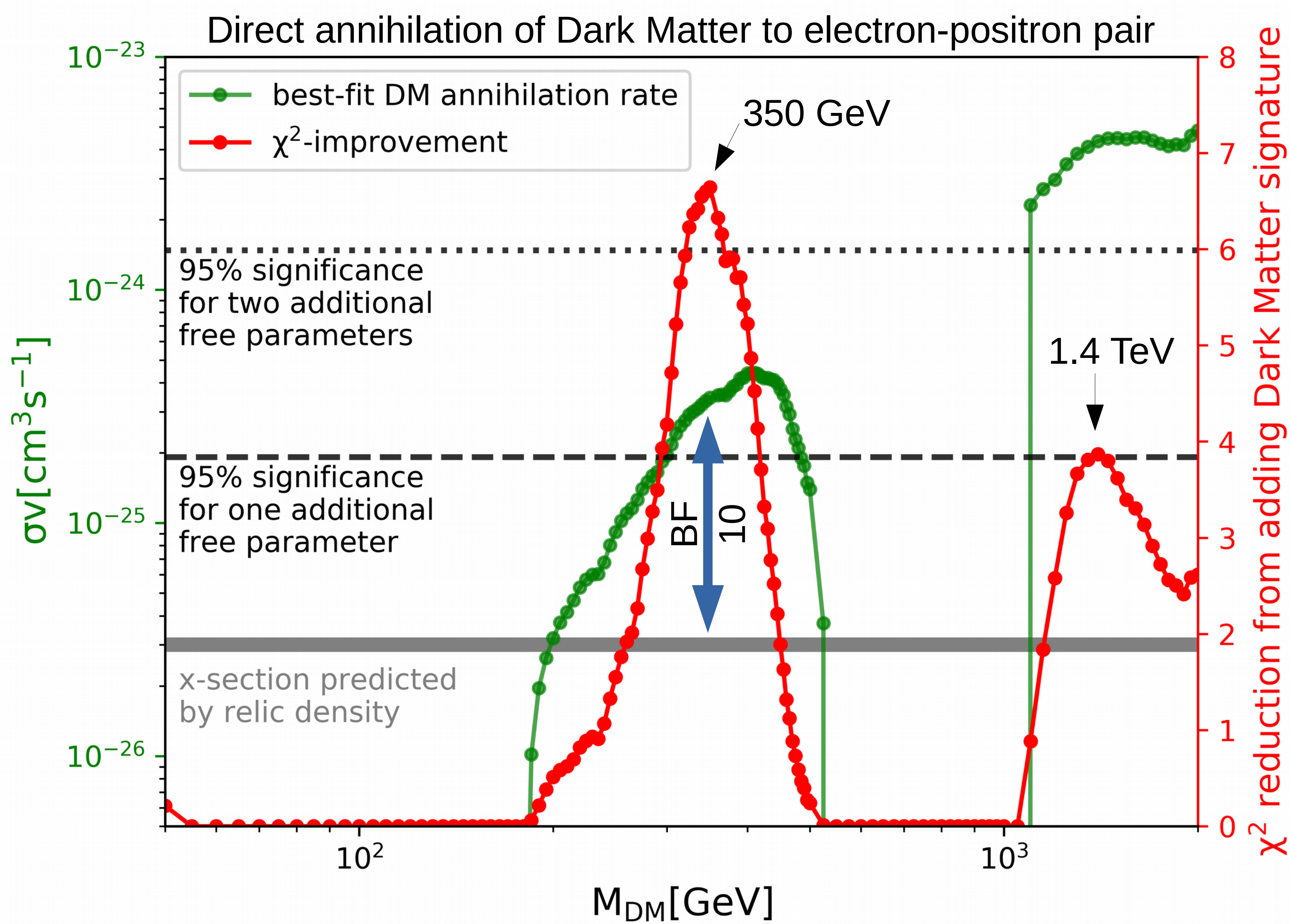
Fit Improvement by Modeling 350 GeV Step-like Structure with Dark Matter Signature



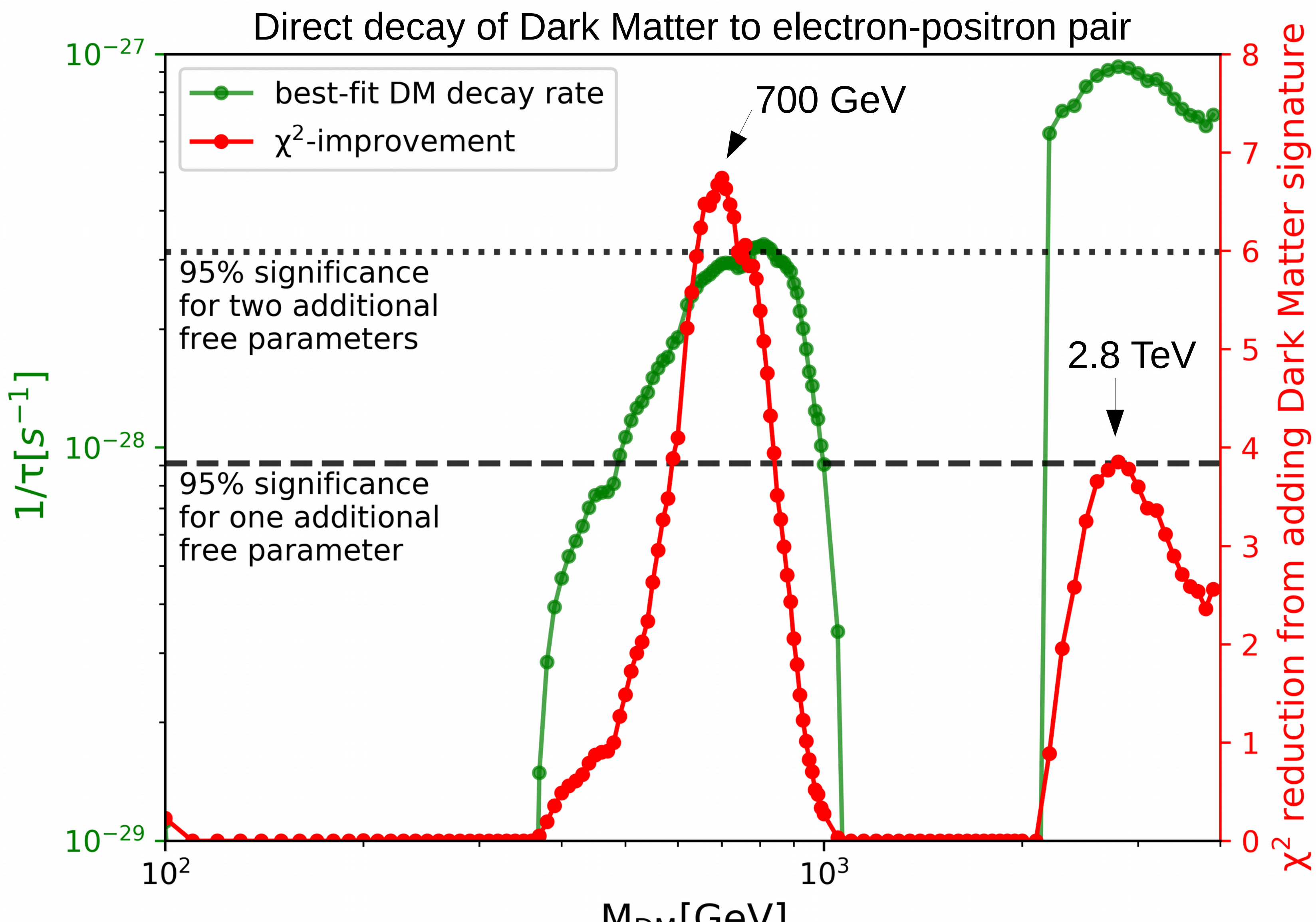
- χ^2 improvement compared to single pulsar case:

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)

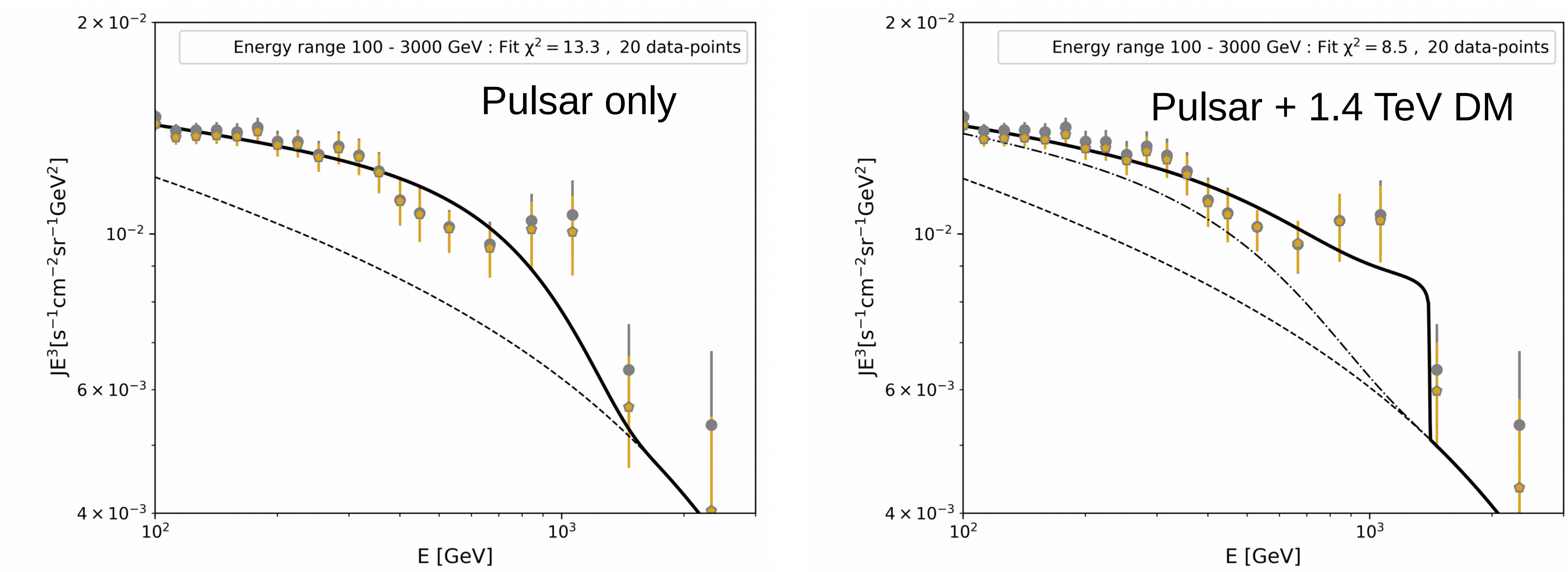
Fit Improvement and Best x-Section against Dark Matter Mass



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)

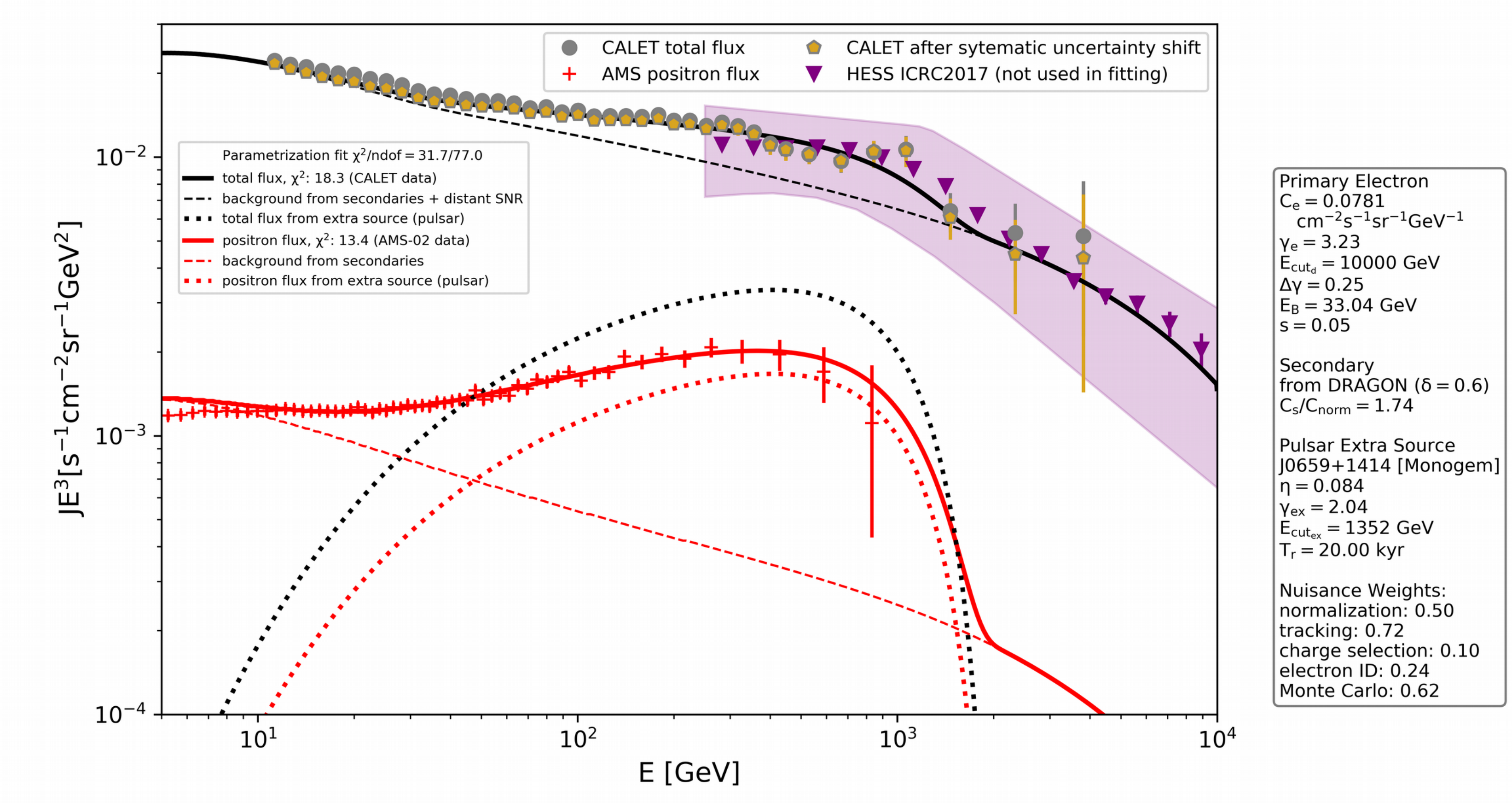
The spectrum from DM annihilation to electron-positron pairs can't model this "peak" well, but significance anyway limited due so larger statistical errors

Refining the Pulsar Model

- Accelerated particles may be trapped in pulsar wind nebula for the lifetime of the nebula, assumed to be up to ~ 100000 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}

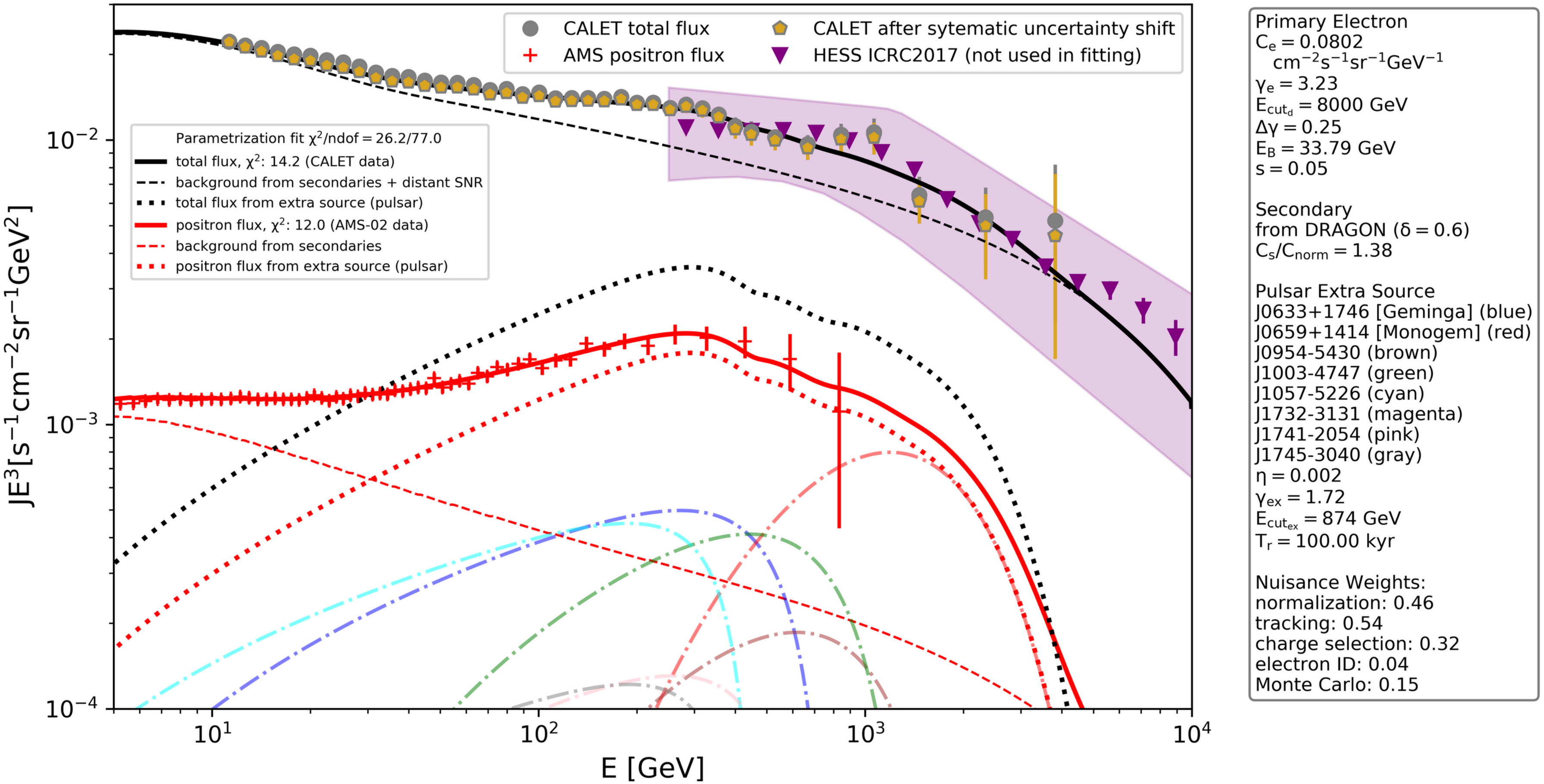
- Scan in steps of 1000 years → optimal value for Monogem: 20000 years
- Scan over cutoff energy of primary energy spectrum, best value 10 TeV



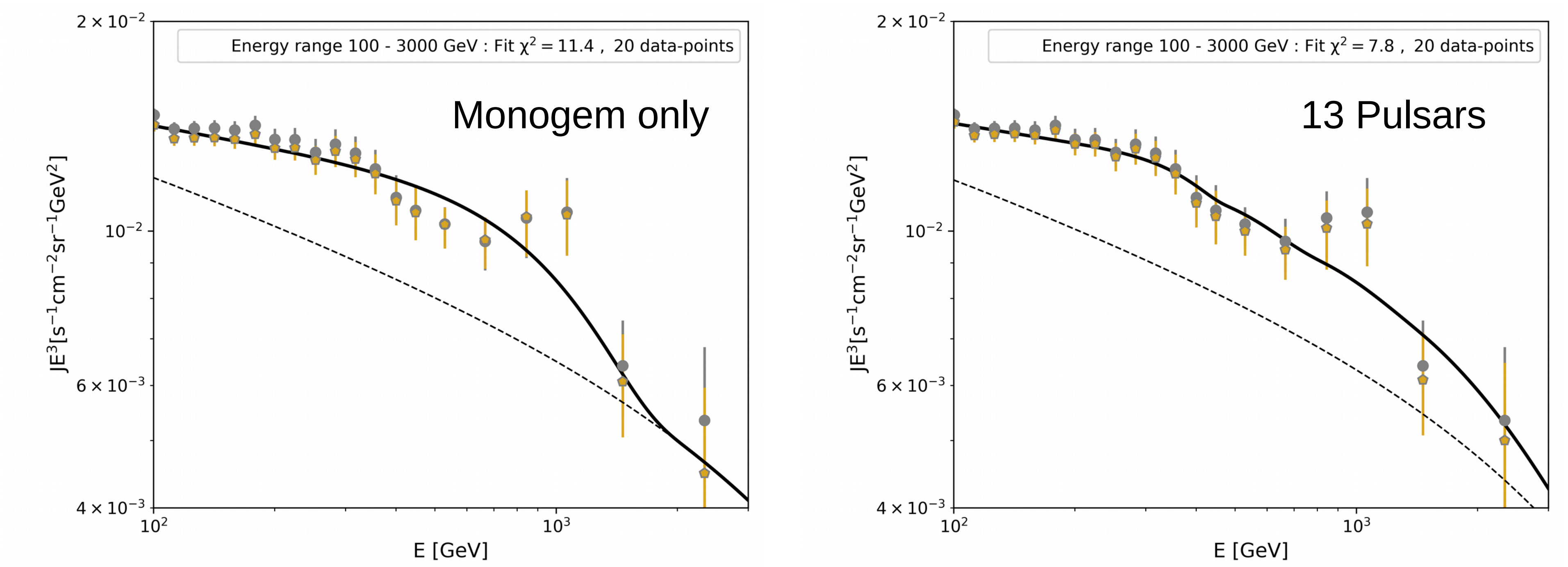
χ^2 improves by 2.2 from 33.9 to 31.7

Multi-Pulsar Model

- 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)



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

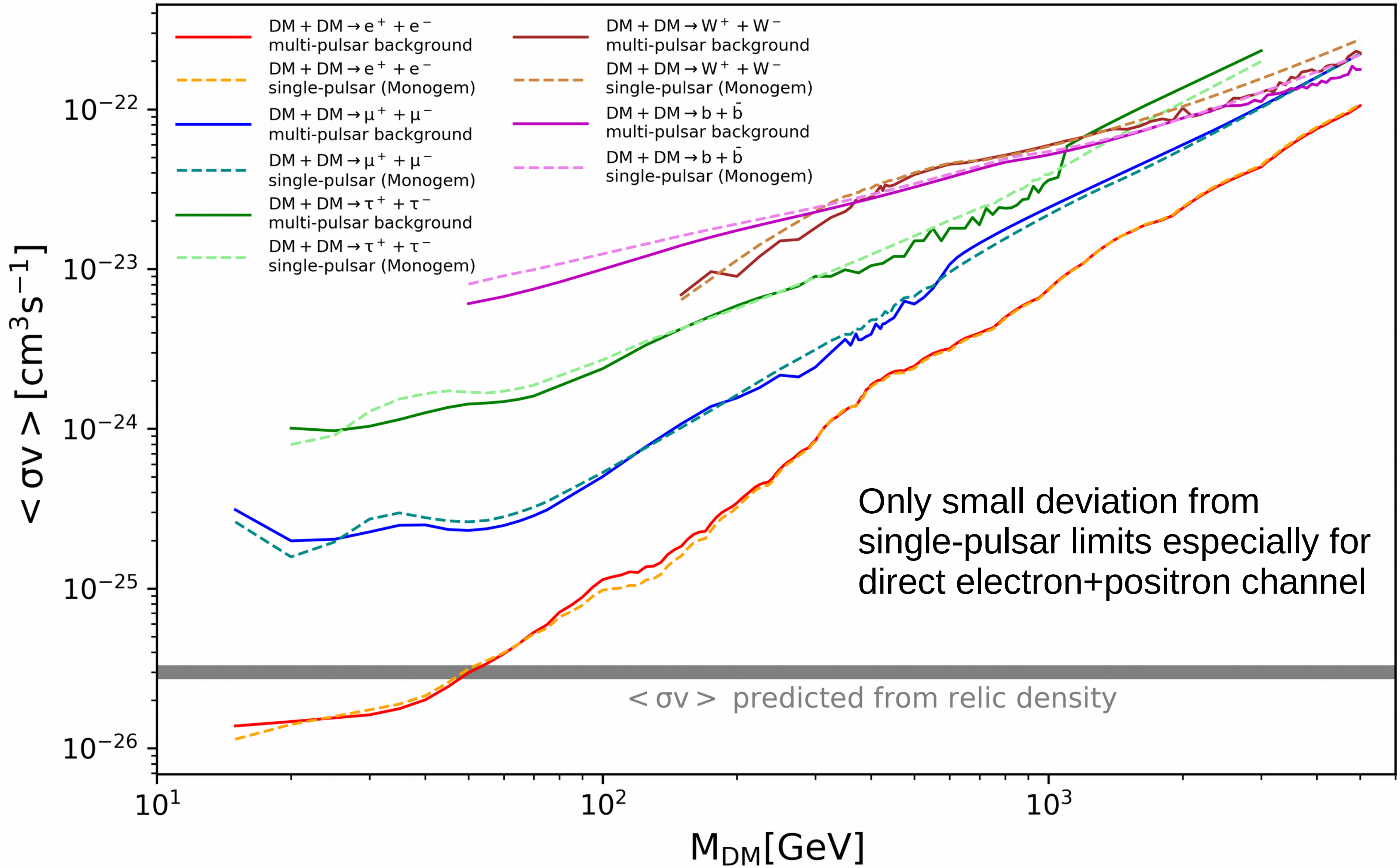


- χ^2 improvement compared to optimized single pulsar case:

Full energy range (CALET & AMS-02 data) : $\Delta\chi^2$ = 5.5 (31.7 → 26.2)
100 GeV – 3 TeV (CALET data only) : $\Delta\chi^2$ = 3.6 (11.4 → 7.8)

No additional free parameters
→ multiple pulsar model clearly favored over single pulsar (Monogem)

Limits on Dark Matter Annihilation with Multi-Pulsar Background



Variability of Background

- Why not vary the parameters of all the pulsars individually?
  - Technical: Fitting not feasible, since minimized function not constrained enough (no unique minimum)
  - Physical: Pulsar parameters should be assumed approximately equal with limited random variation for individual pulsars, not fine-tuned to hide the dark matter signal.
- To improve the limits on Dark Matter, the individual nearby sources of the astrophysical background (SNR and pulsars) and their parameters must be identified, a goal to which CALET contributes

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
- 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)

These results are part of the research outcome of Waseda University Grant for Special Research Projects No. 2019C-539