# Pulsars Do Not Produce Sharp Features in the Local Cosmic-Ray Electron and Positron Spectra

I. John & T. Linden
arXiv:2206.04699

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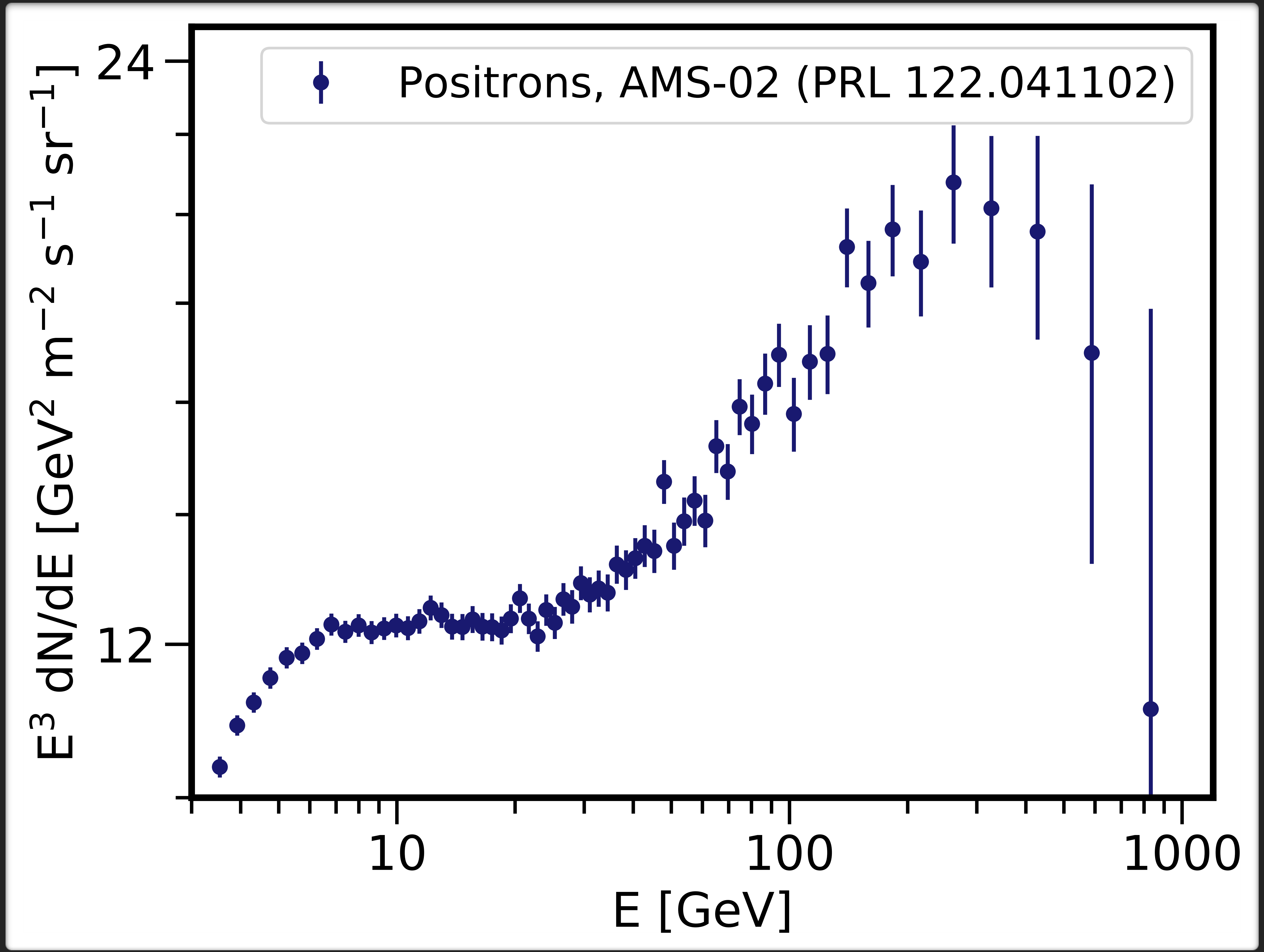
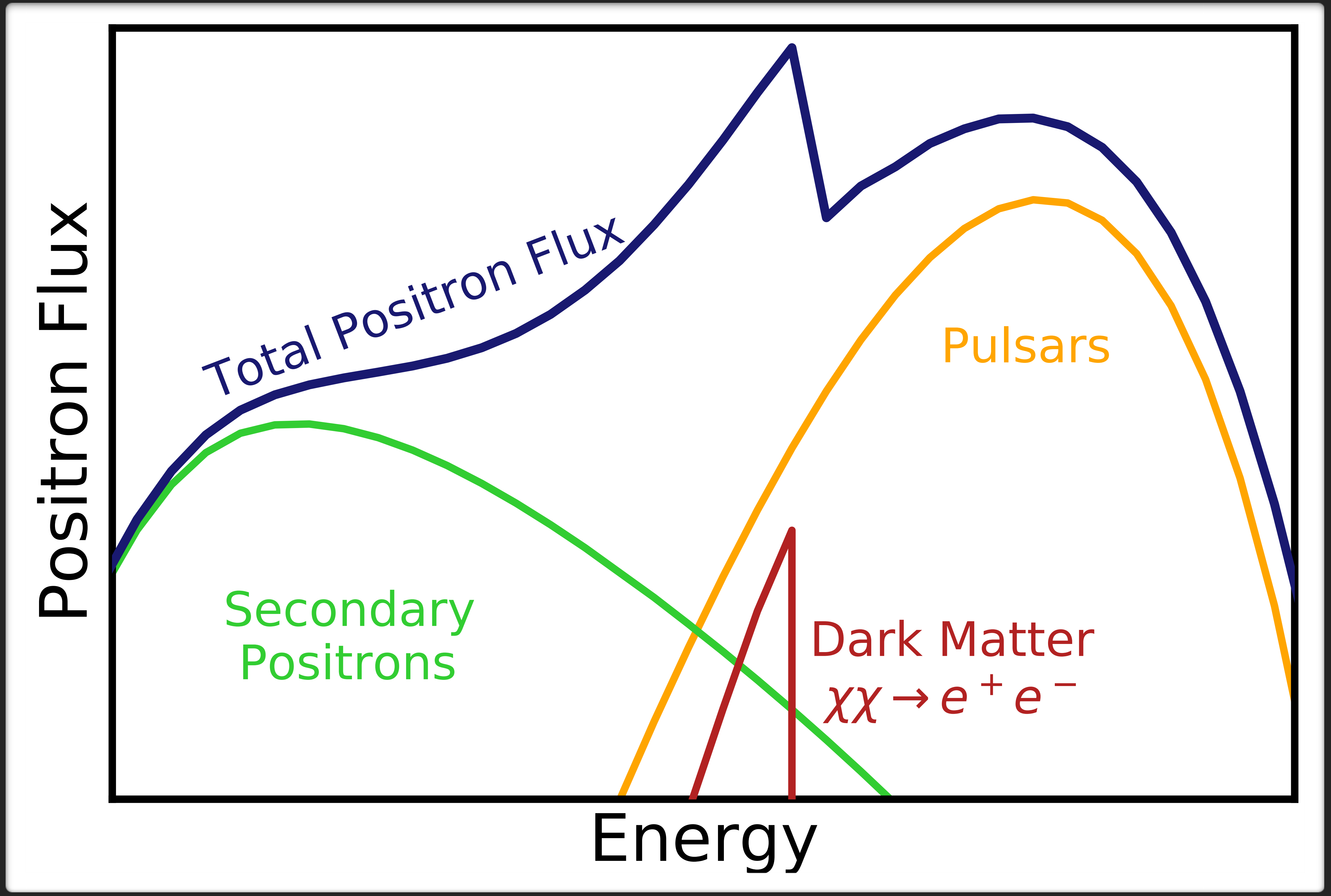
# Local Cosmic-Ray Positron Flux

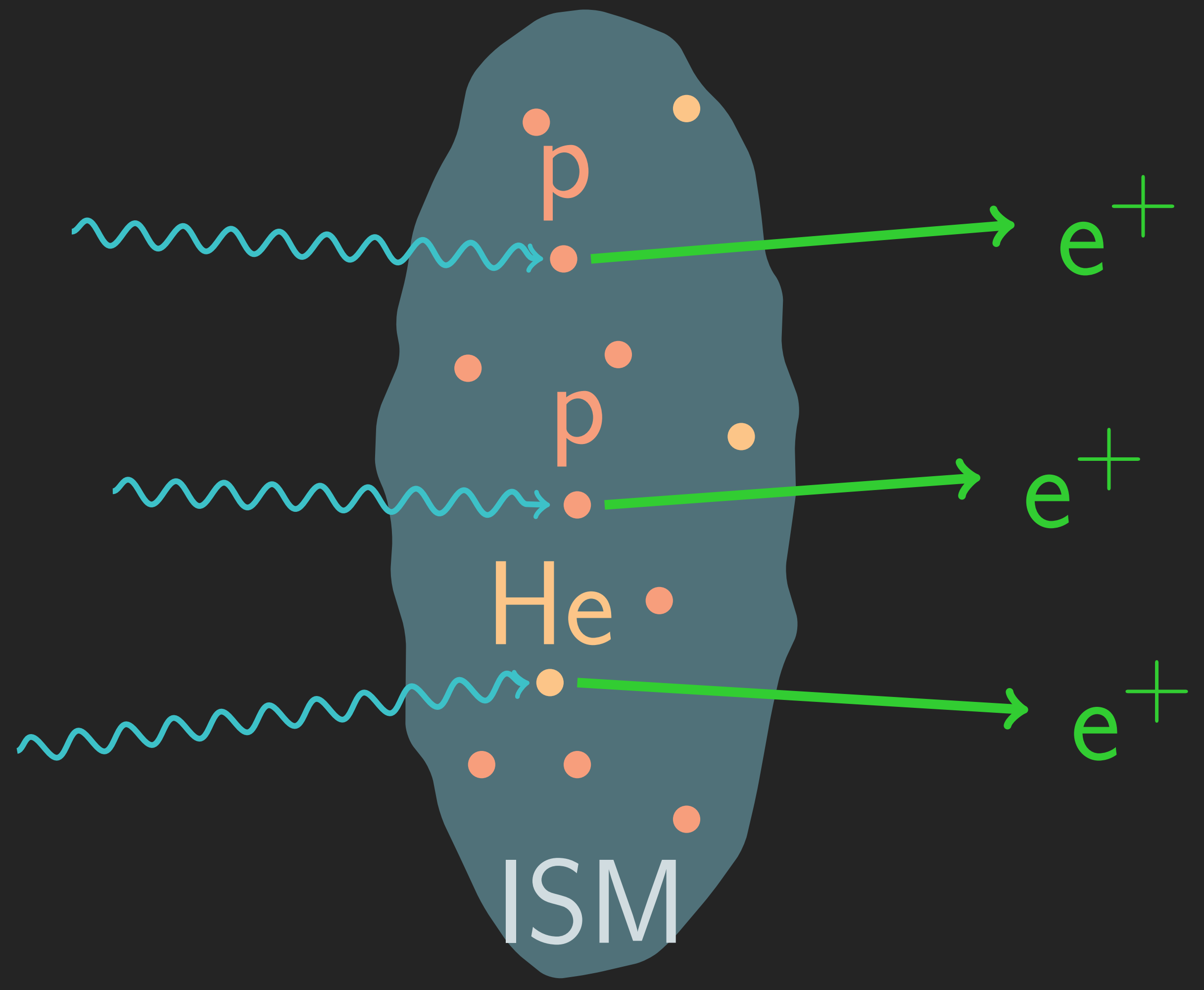
- Measured up to ~ 1 TeV
- Rises above ~ 20 GeV
- Spectrum is very smooth



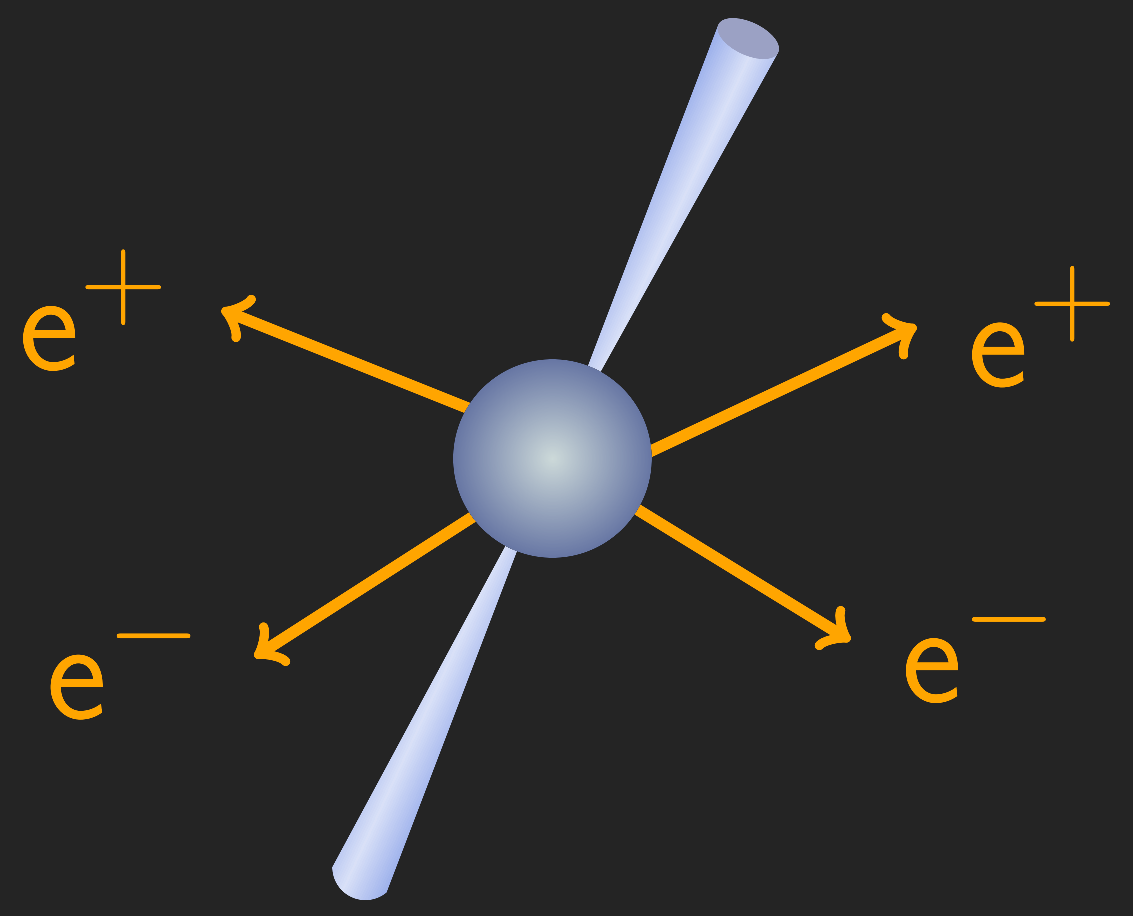
# Components of the Positron Flux



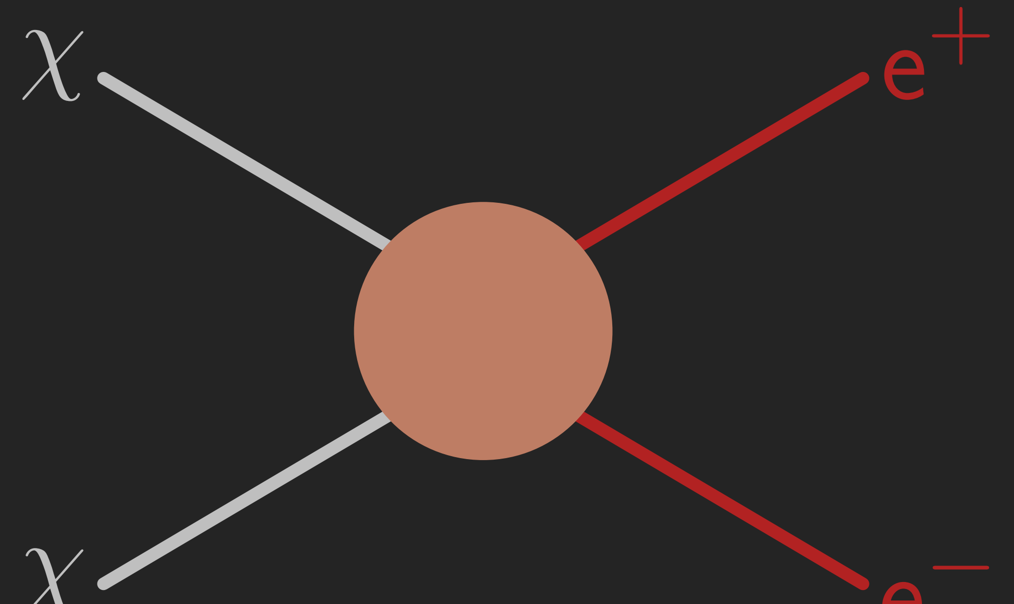
Secondary Production



Pulsars



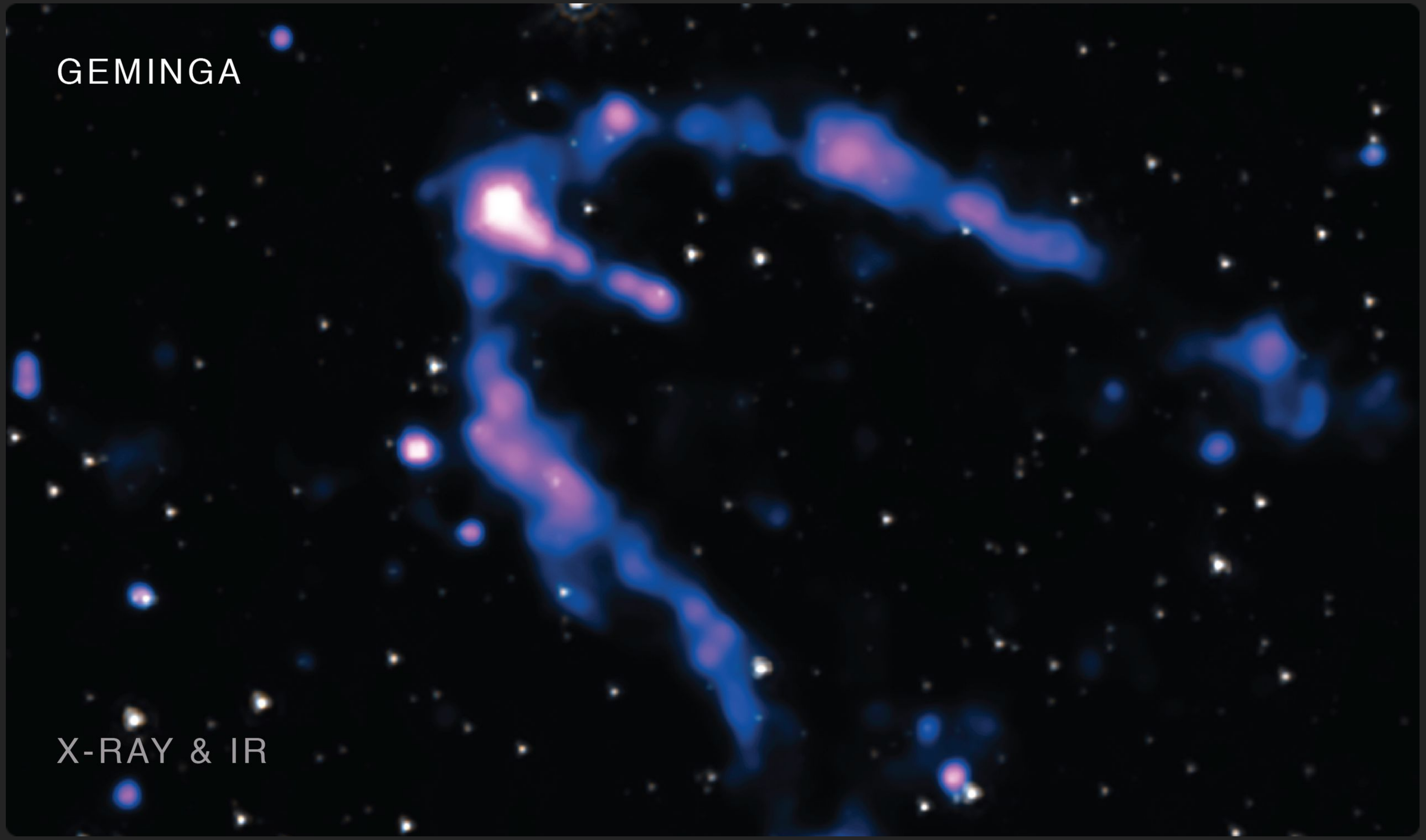
Dark Matter Annihilation

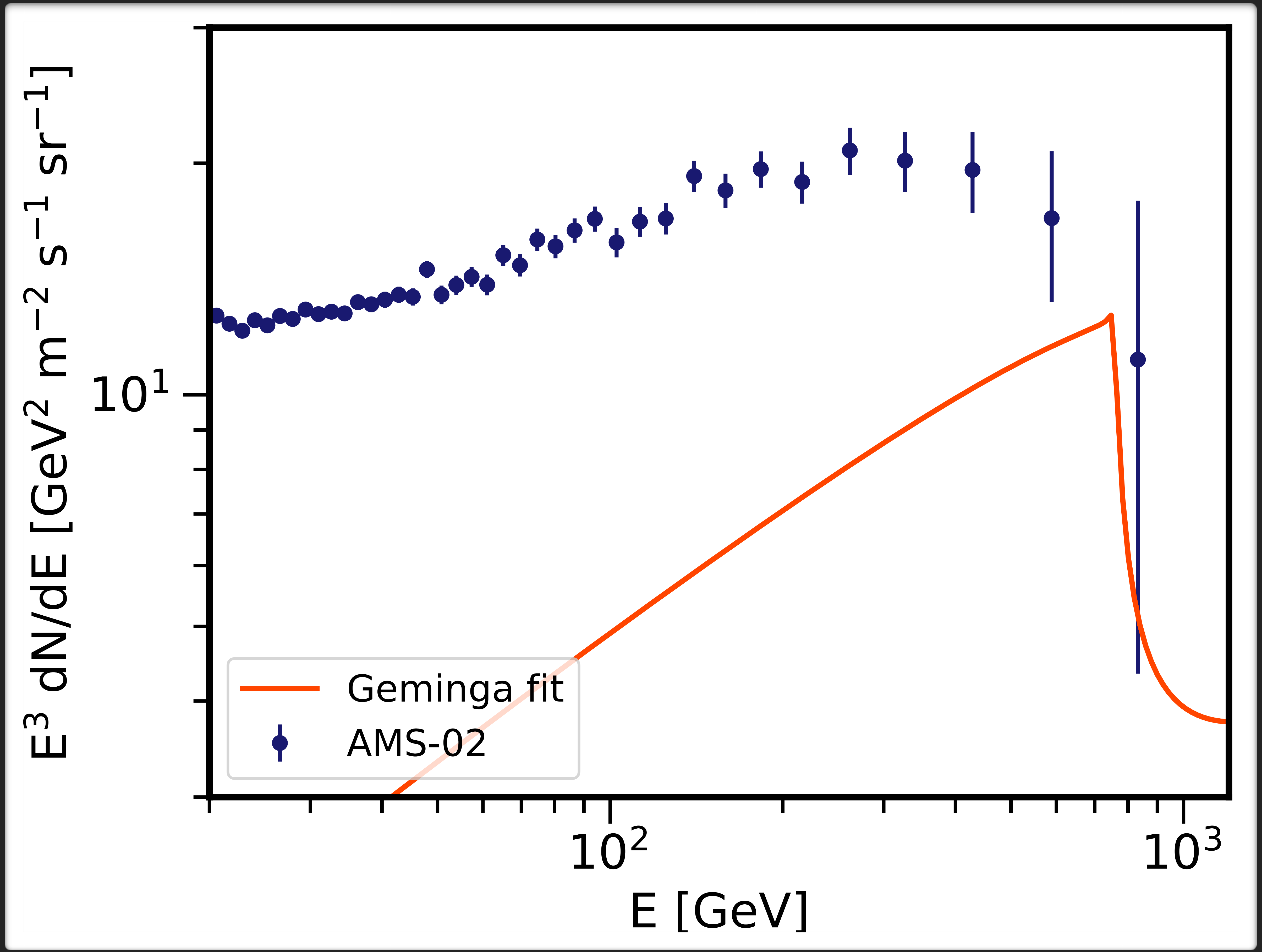


# Positron Spectrum of Individual Pulsars

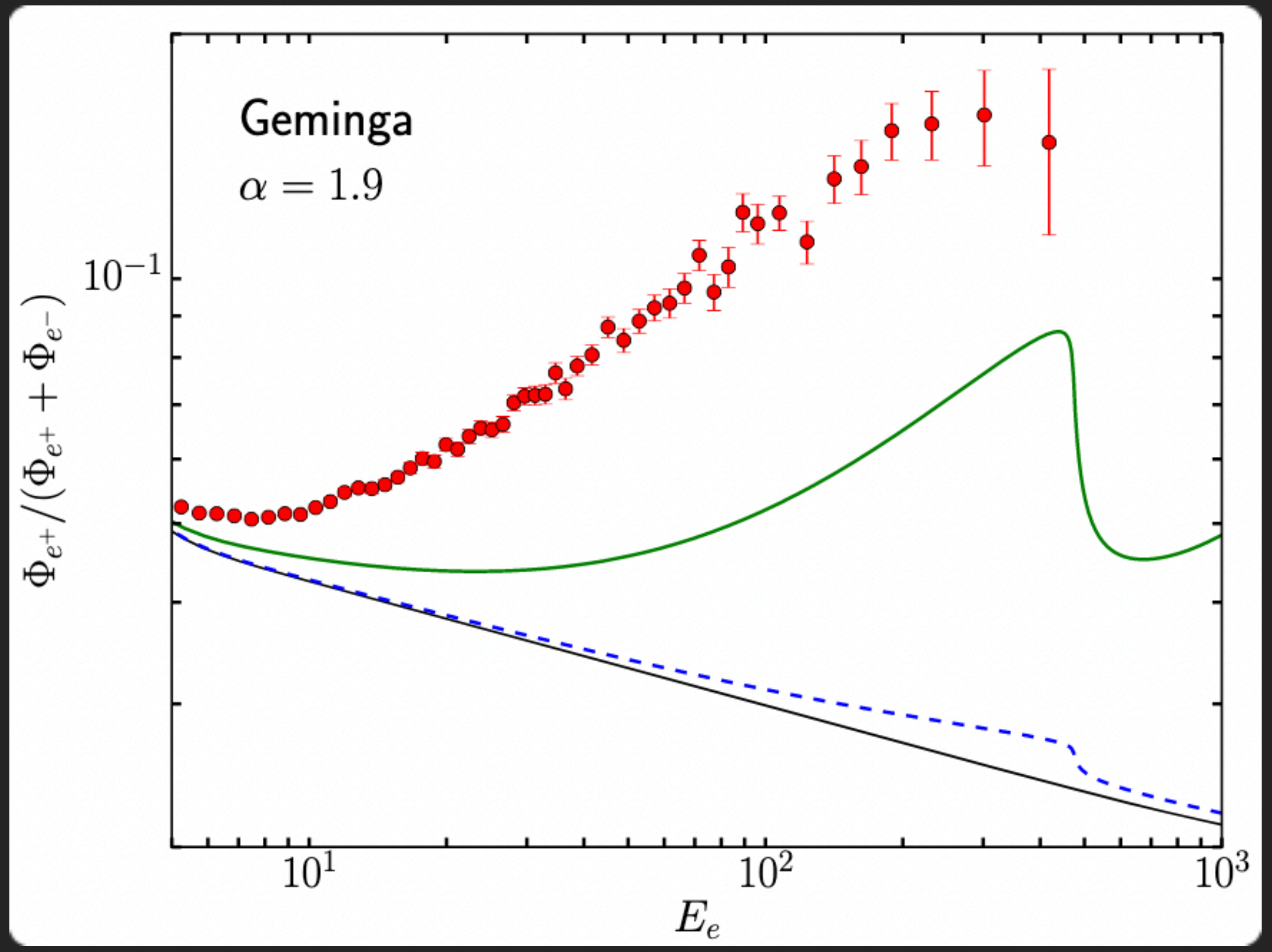
Template System: Geminga

- Middle-aged (~370 000 years)
- Nearby (~250 pc)

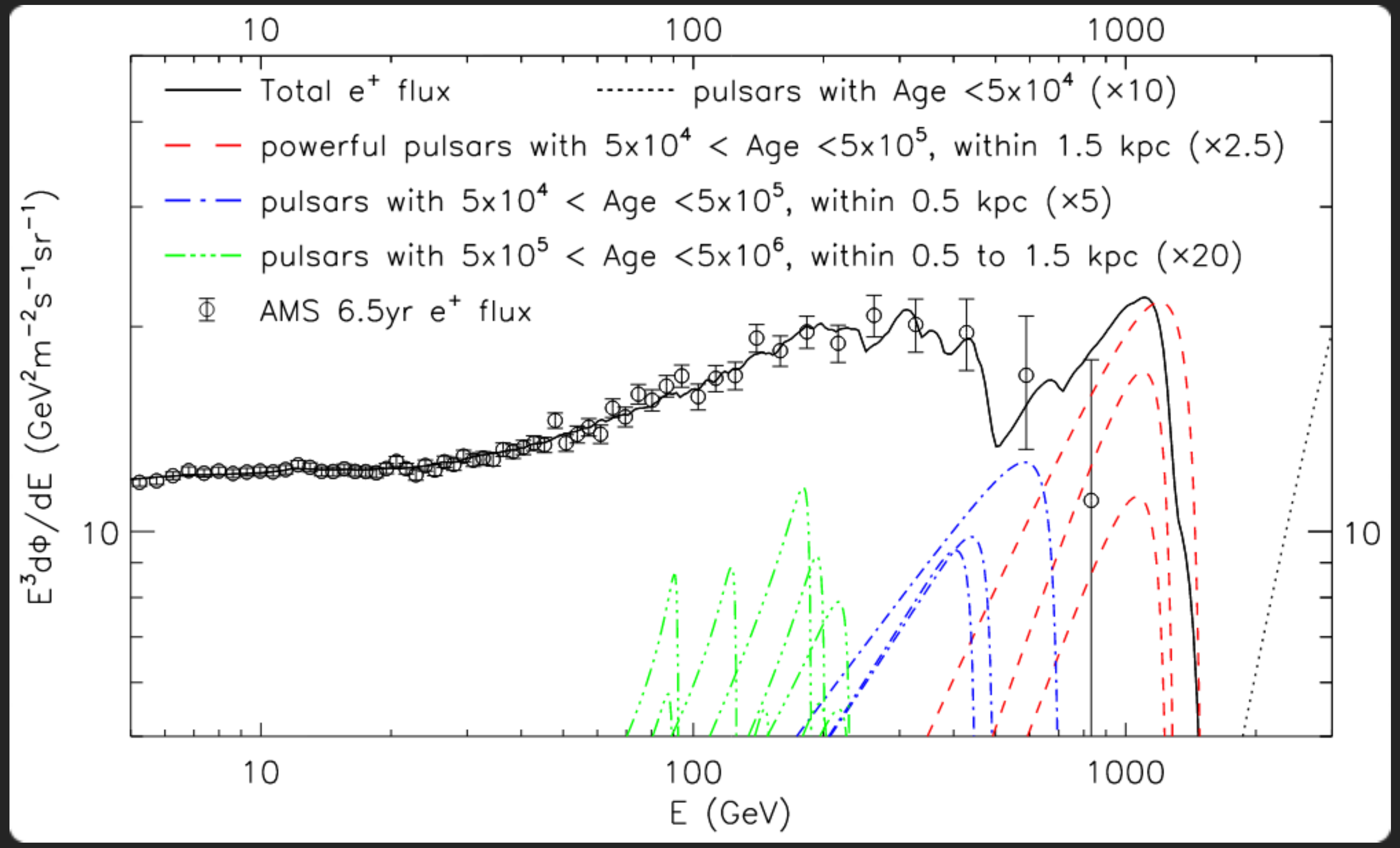




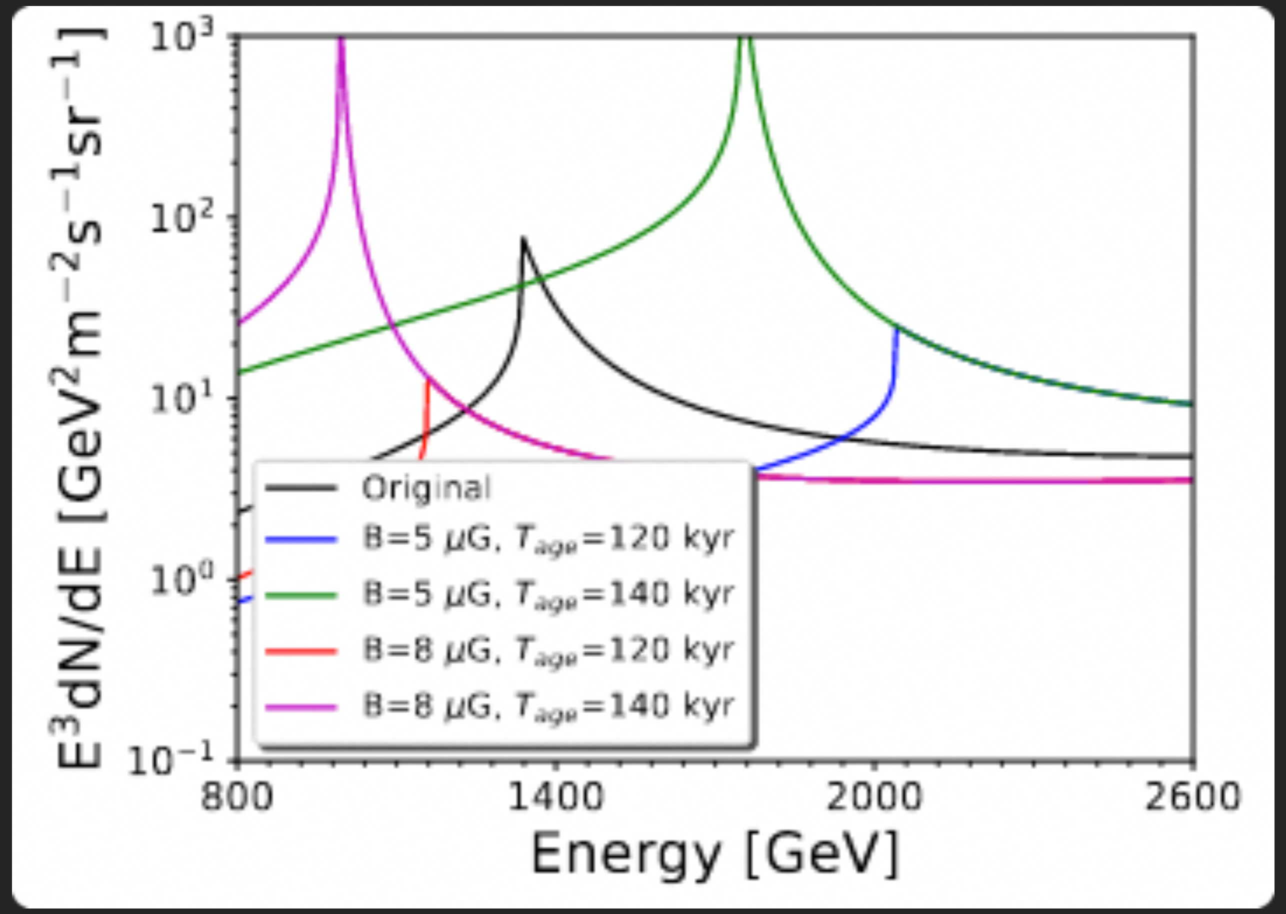
# Recent Papers Predict Sharp Features for Individual Pulsars



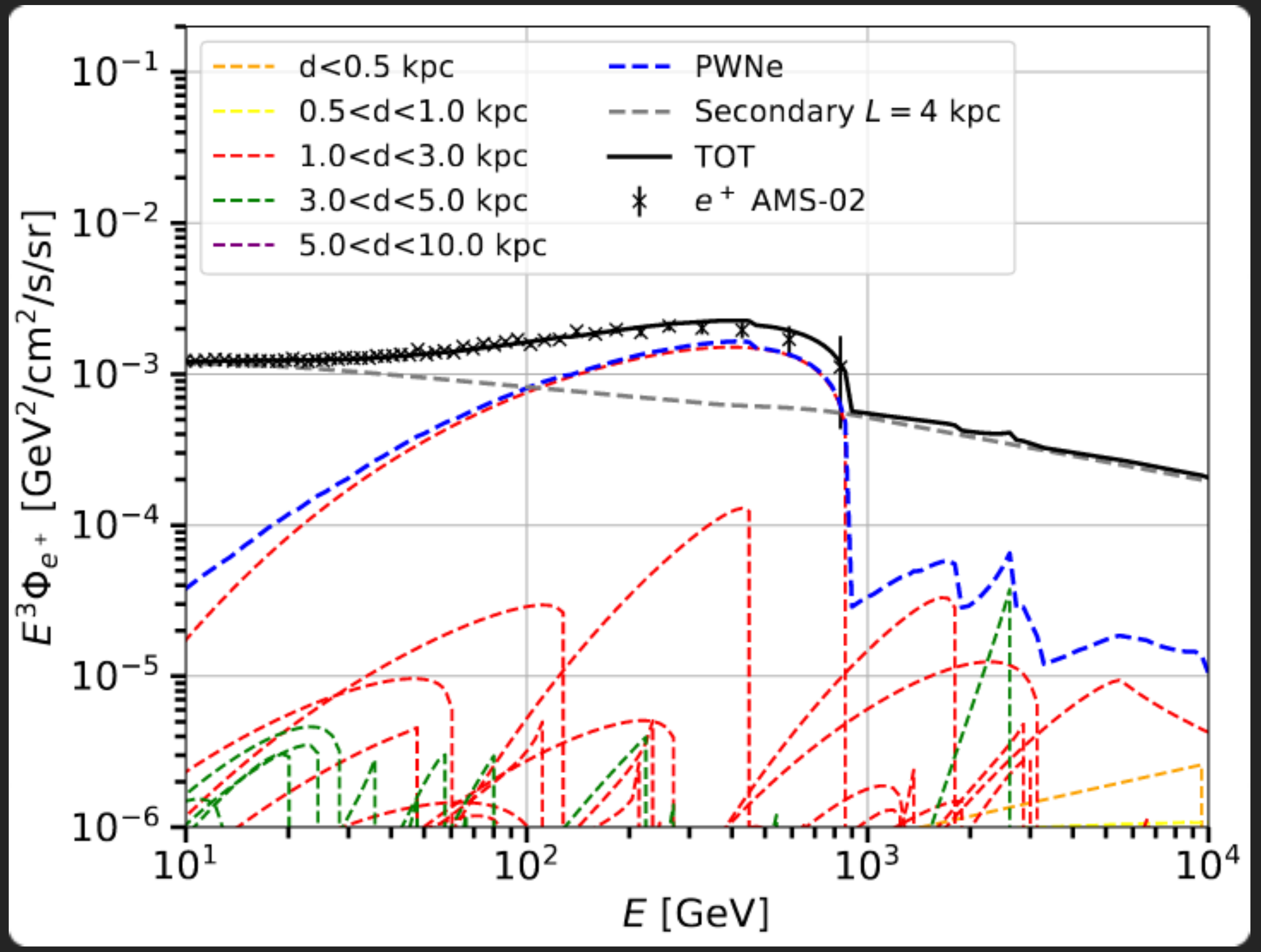
Hooper et al., arXiv:1702.08436



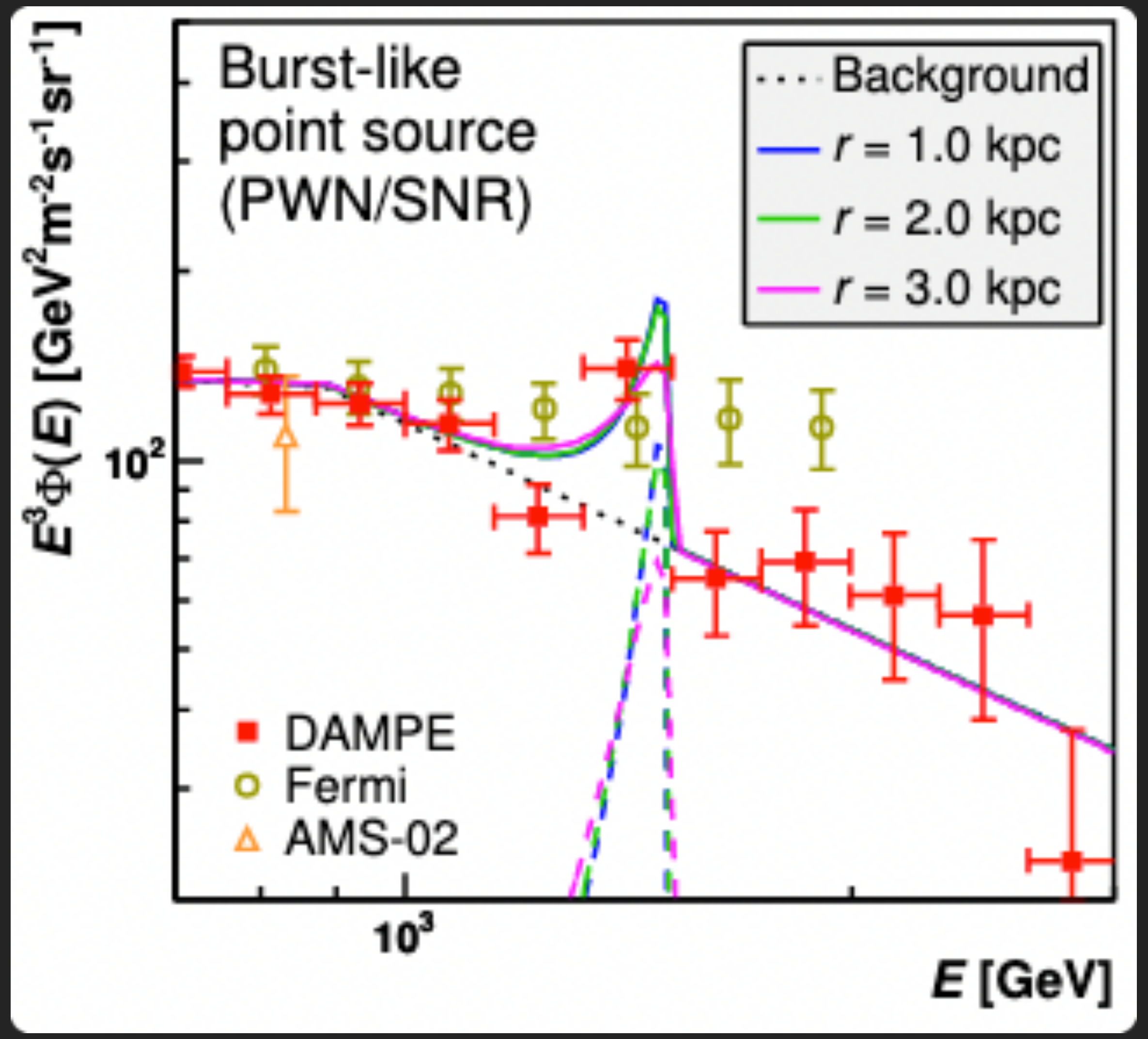
Cholis & Krommydas, arXiv:2111.05864



Bao et al., arXiv:2010.12170

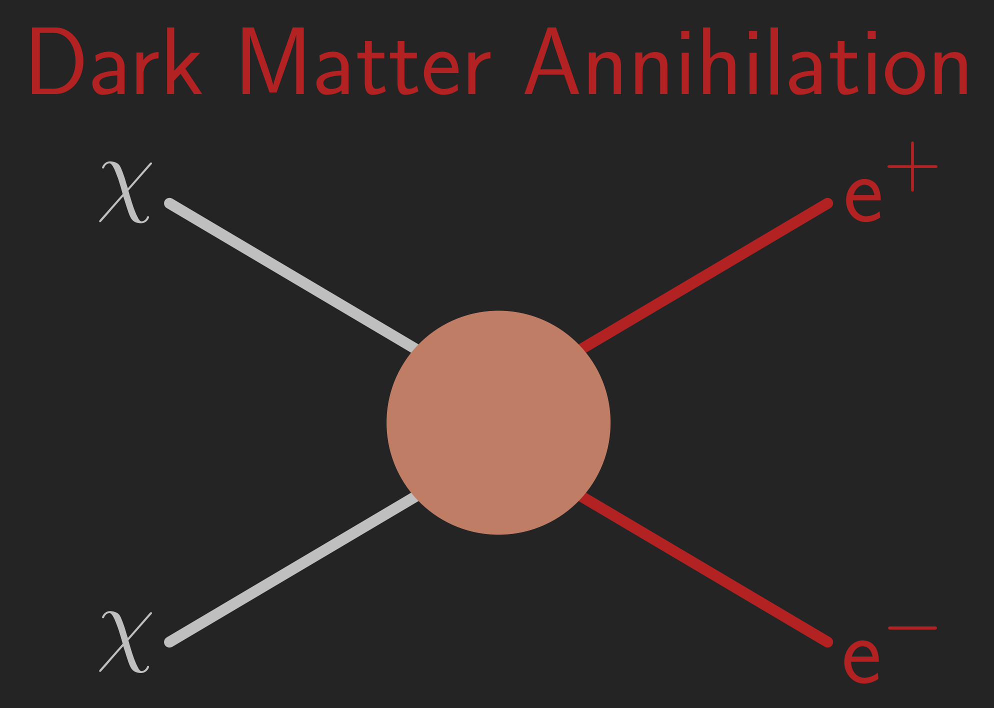


Orusa et al., arXiv:2107.06300

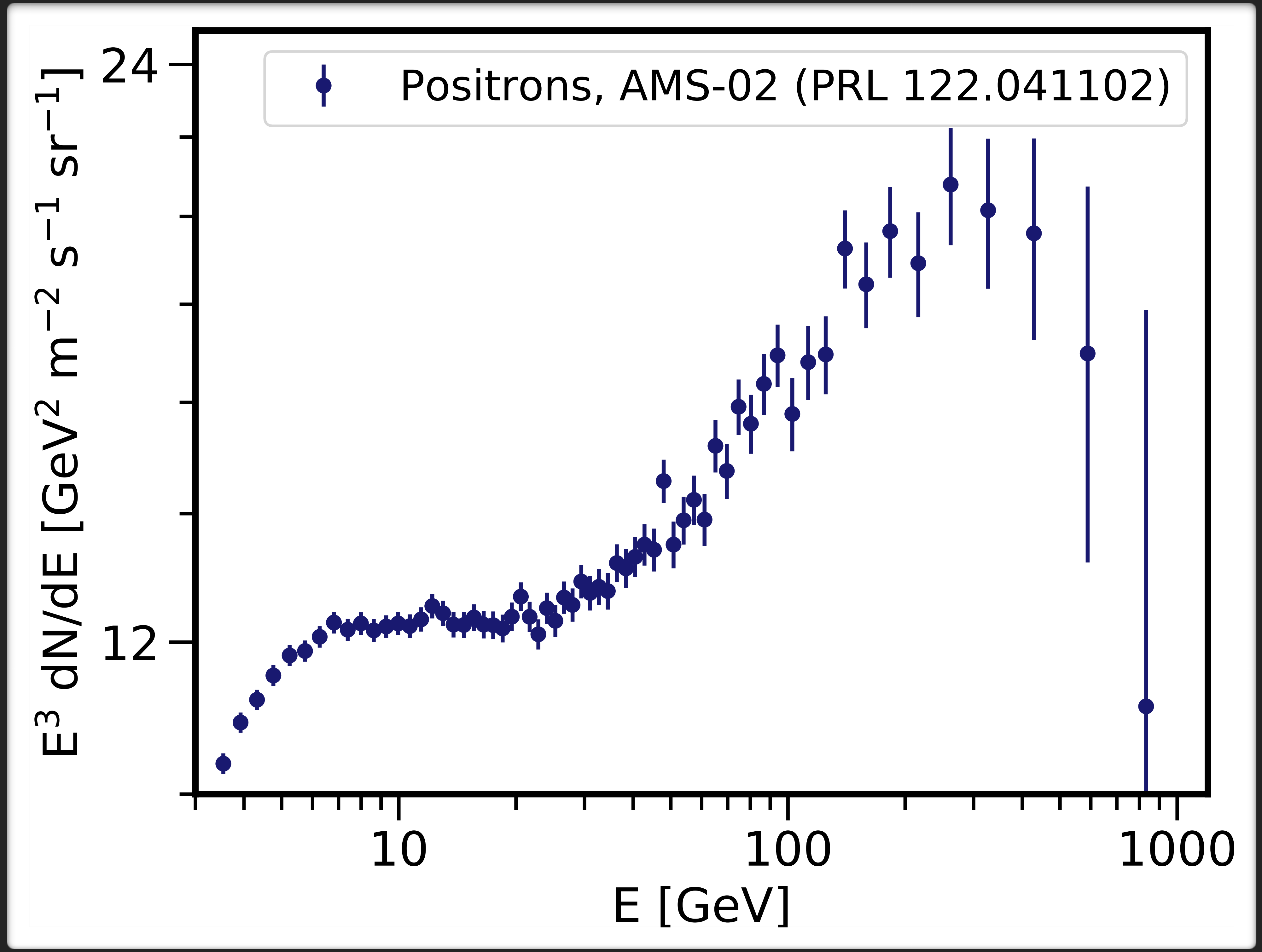


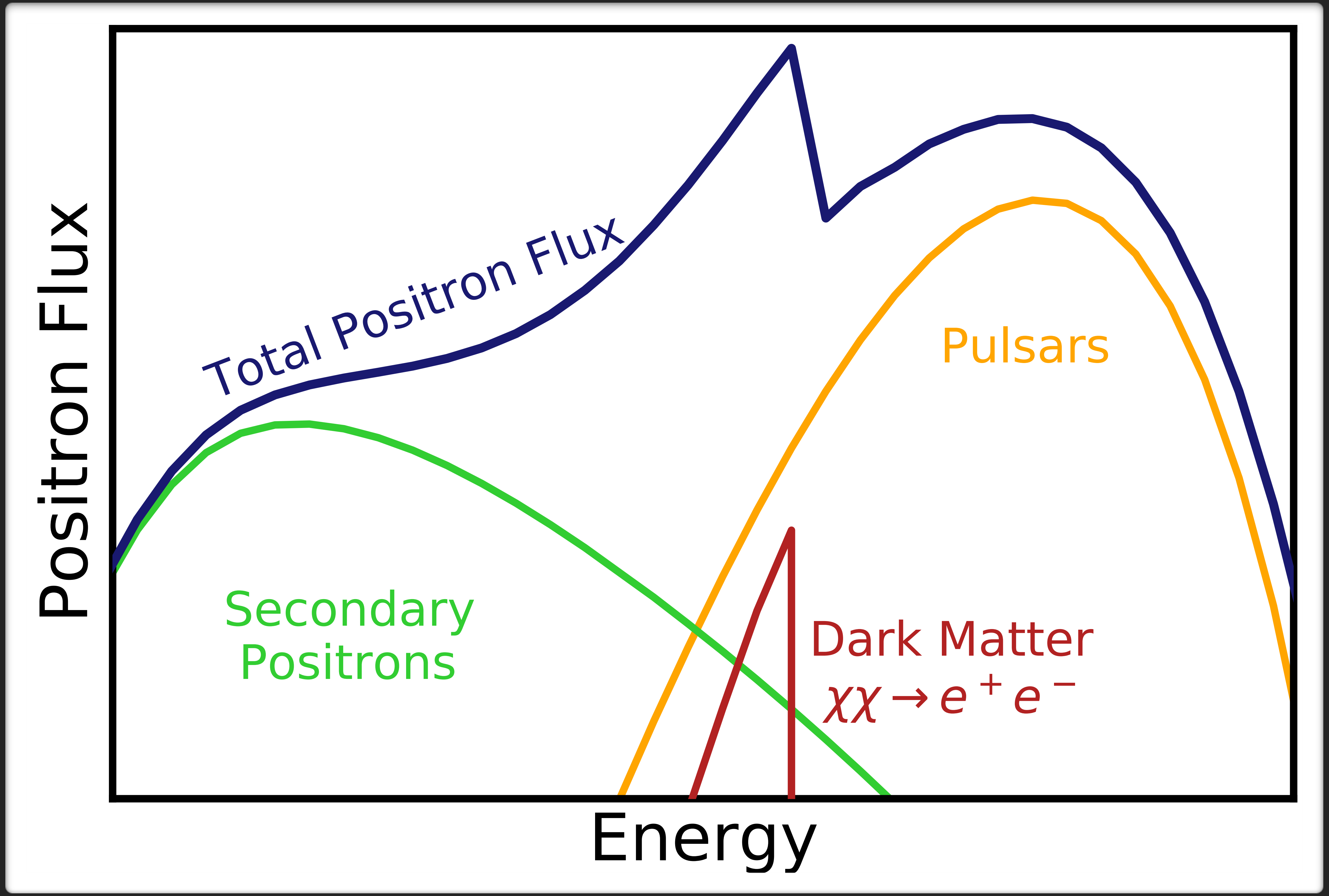
Huang et al., arXiv:1712.00005

# Sharp Spectral Features?



- AMS positron flux is very smooth
- Annihilating dark matter could produce sharp spectral features as well



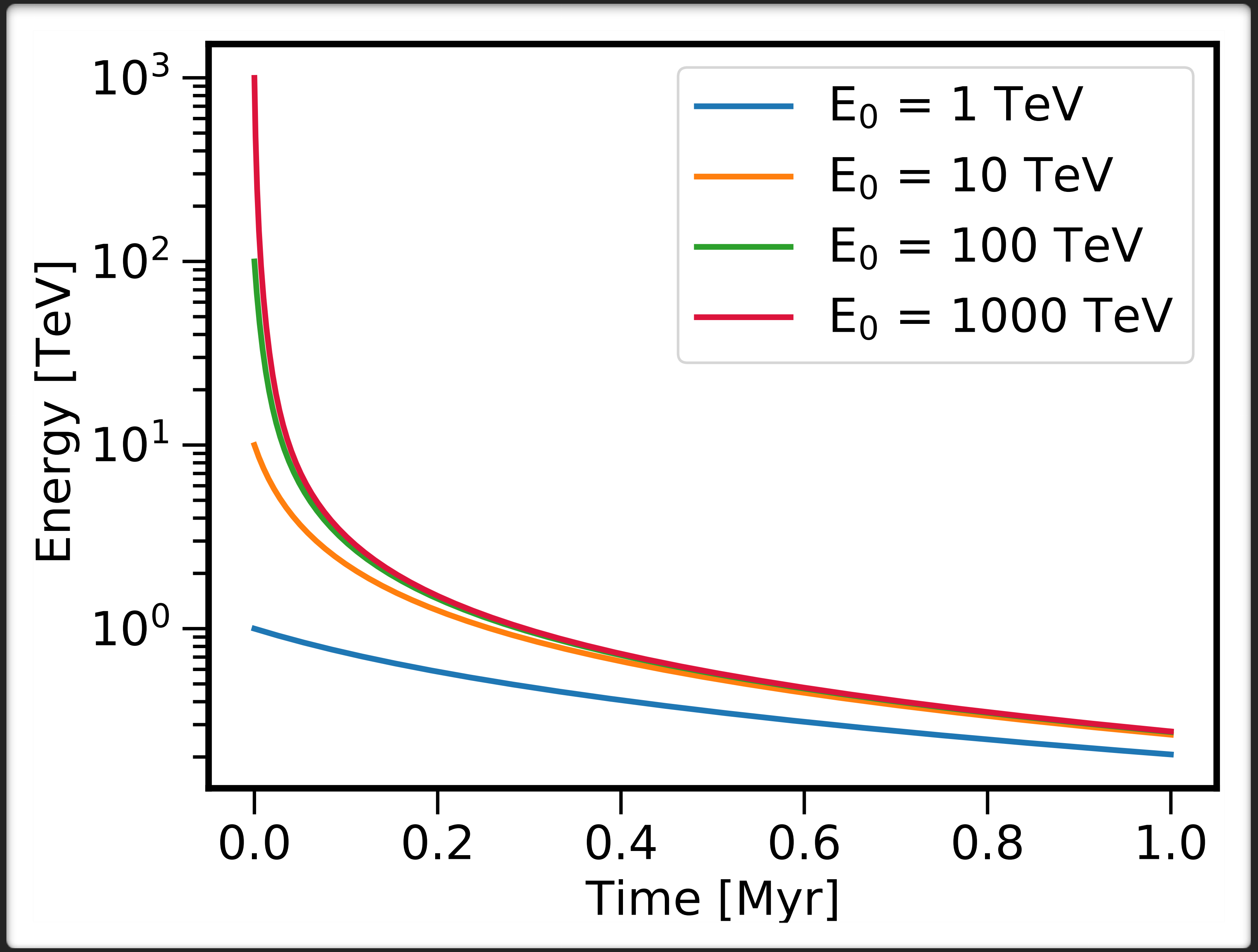


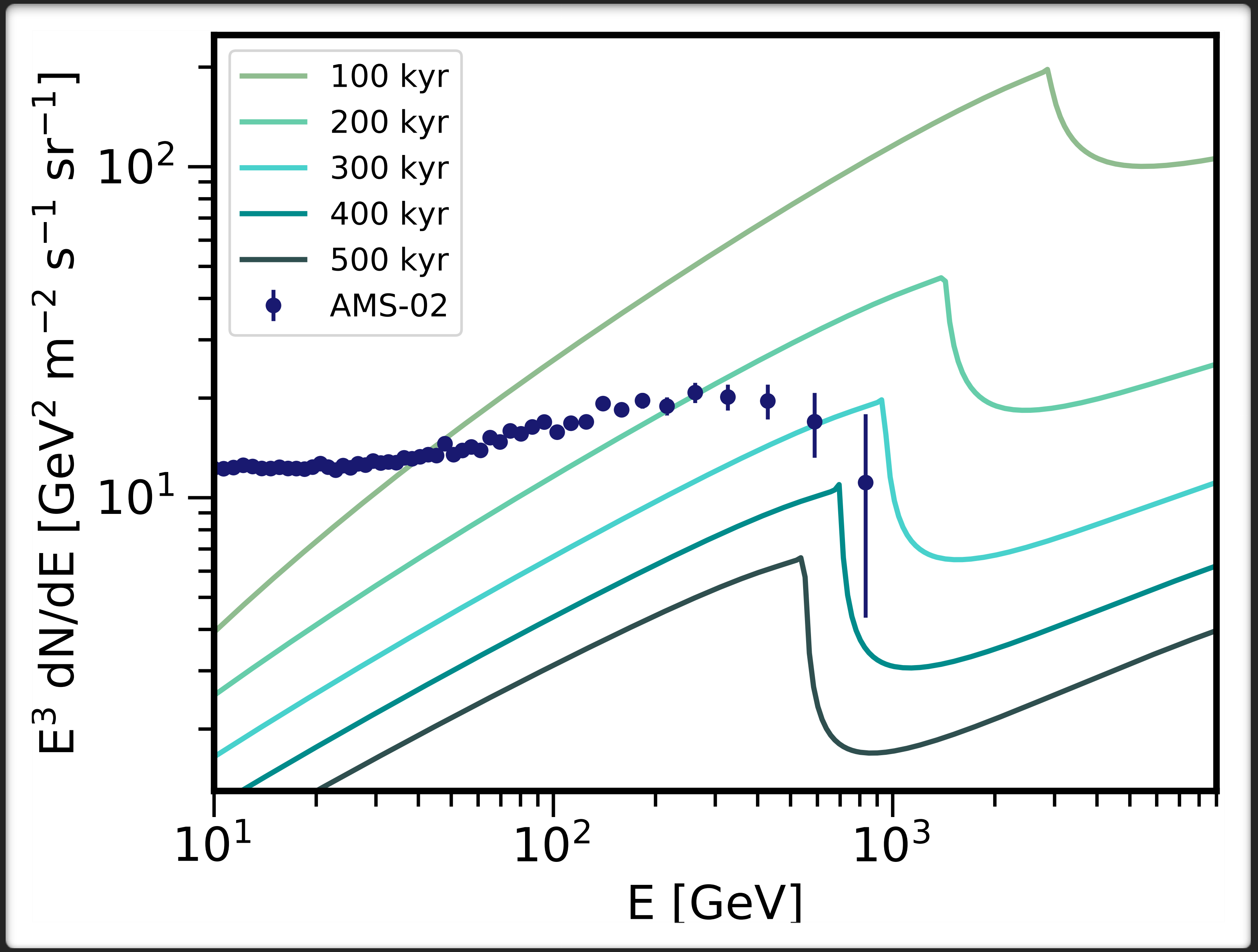
# Spectral Features From Pulsars

1. Large fraction of positrons are produced when pulsar is very young

2. High-energy positrons lose energy faster than low-energy positrons:
- To synchrotron radiation in magnetic fields
- To inverse-Compton scattering on ISRF photons

3. These initial positrons build up sharp feature in positron spectrum over time





# Cooling Mechanisms

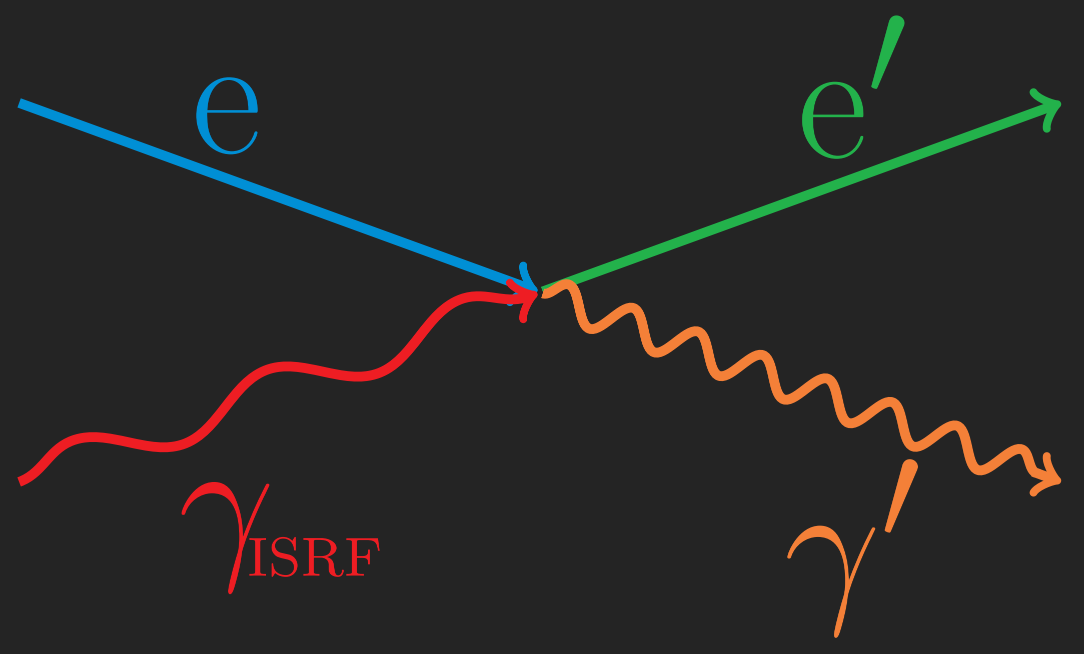
As positrons propagate through the Galaxy, they cool:

- Energy losses to synchrotron radiation in magnetic fields
- Energy losses to inverse-Compton scattering on ambient photons (Interstellar Radiation Field)
- Energy loss rate:

$$\frac{dE}{dt} = -\frac{4}{3}\sigma_T \left(\frac{E}{m_e}\right)^2 \left[\rho_B + \sum_i \rho_i(\nu_i) S(E, \nu_i)\right]$$

- Analytic approximations treat ICS as a continuous process
- But ICS is a stochastic process with catastrophic energy losses
  - Each positron only interacts with small number of photons
  - Energy transfer in each interaction differs greatly

## Inverse Compton Scattering



Interstellar Radiation Field:
- CMB photons
- IR radiation
- Starlight
- UV radiation

| | |
|---|---|
| $E$ | Electron energy |
| $\nu_i$ | Photon energy |
| $\sigma_T$ | Thomson cross section |
| $\rho_B$ | Magnetic field energy density |
| $\rho_i$ | ISRF energy densities |
| $S$ | Klein-Nishina suppression |

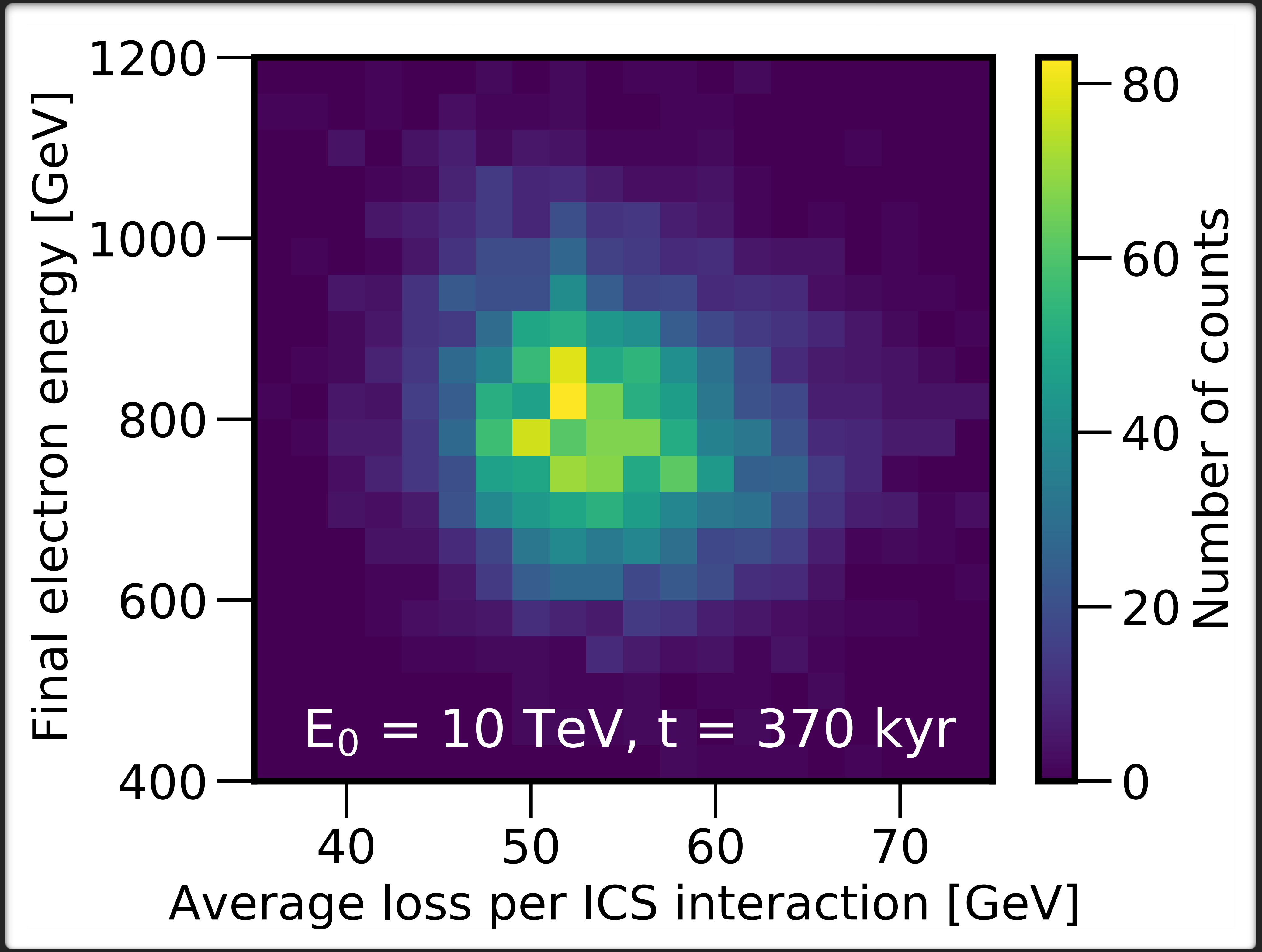
# Stochastic Inverse-Compton Scattering Model

1. Create positron with some initial energy
2. Evolve in time steps
    - Calculate synchrotron energy losses
    - Based on positron and photon energy, determine if ICS happens and at what photon energy
    - If ICS: Calculate energy loss and new positron energy
3. Repeat until current pulsar age is reached

# Stochasticity of Inverse-Compton Scattering

- Analytic calculation:
  - All positrons are treated the same way, cool down to exactly the same energy

- Stochastic ICS:
  - ICS interactions are rare (~120 interactions in 370 kyr)
  - Catastrophic energy losses (~10-100% of energy lost)
  - ~30% spread in final positron energy distribution



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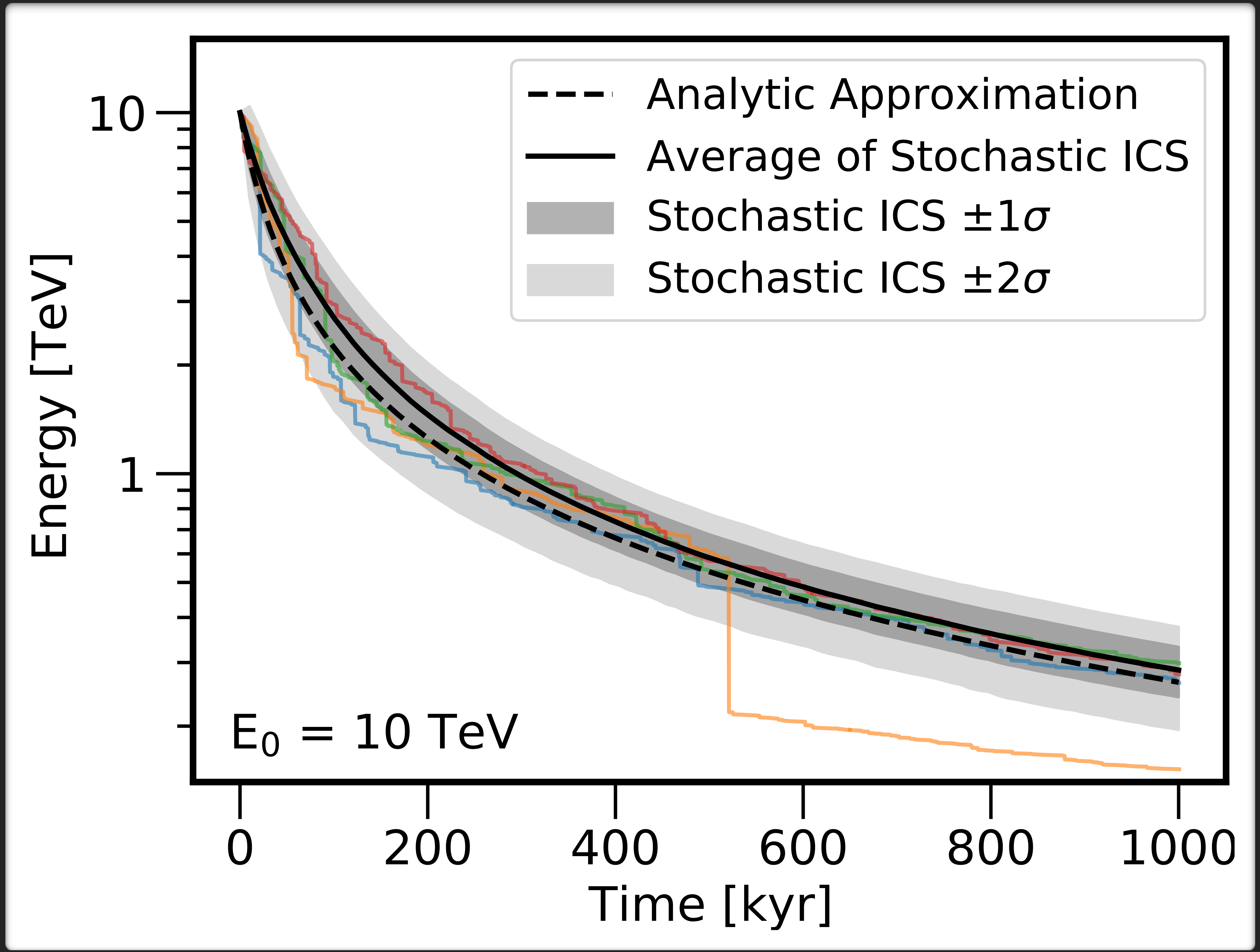
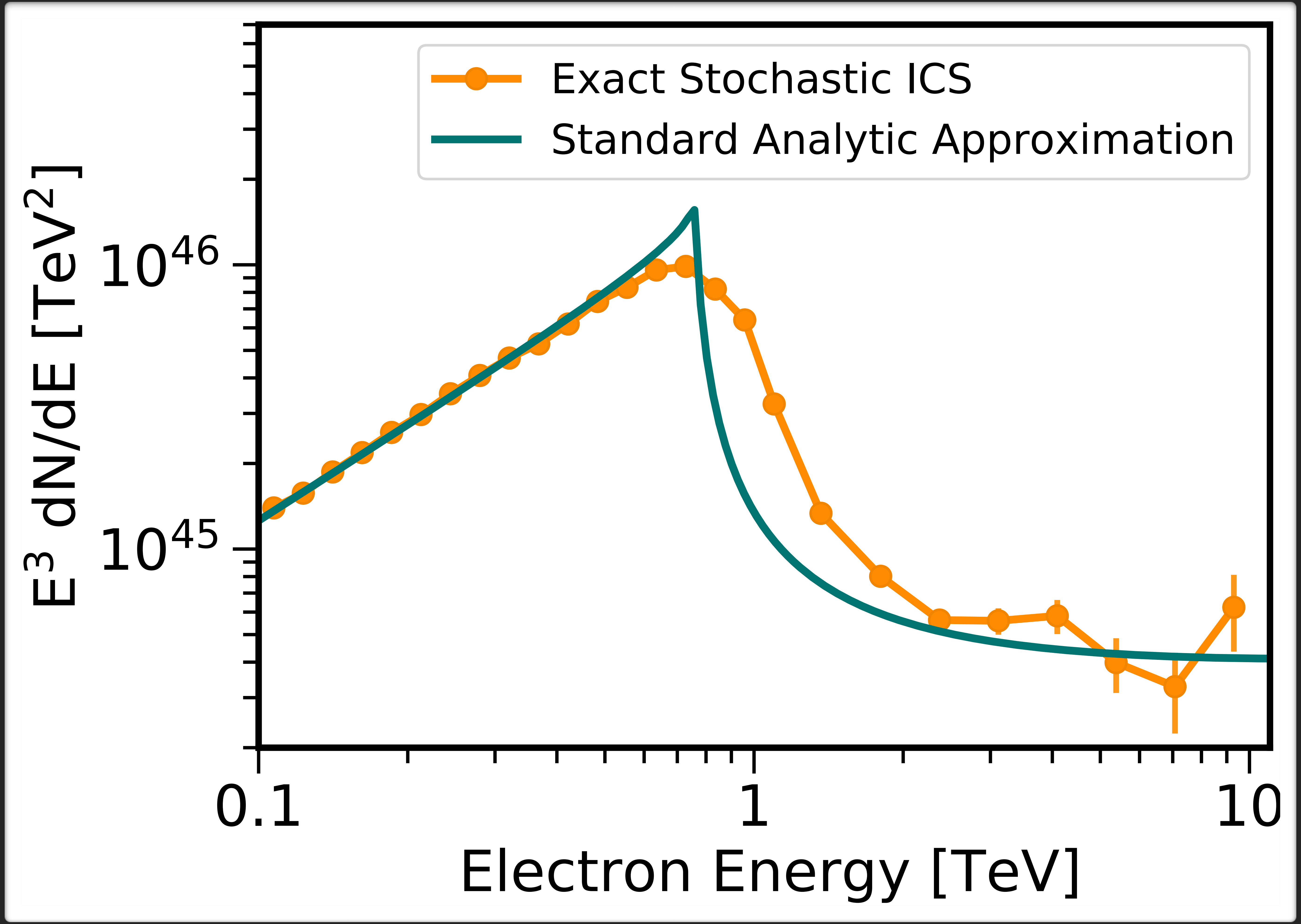


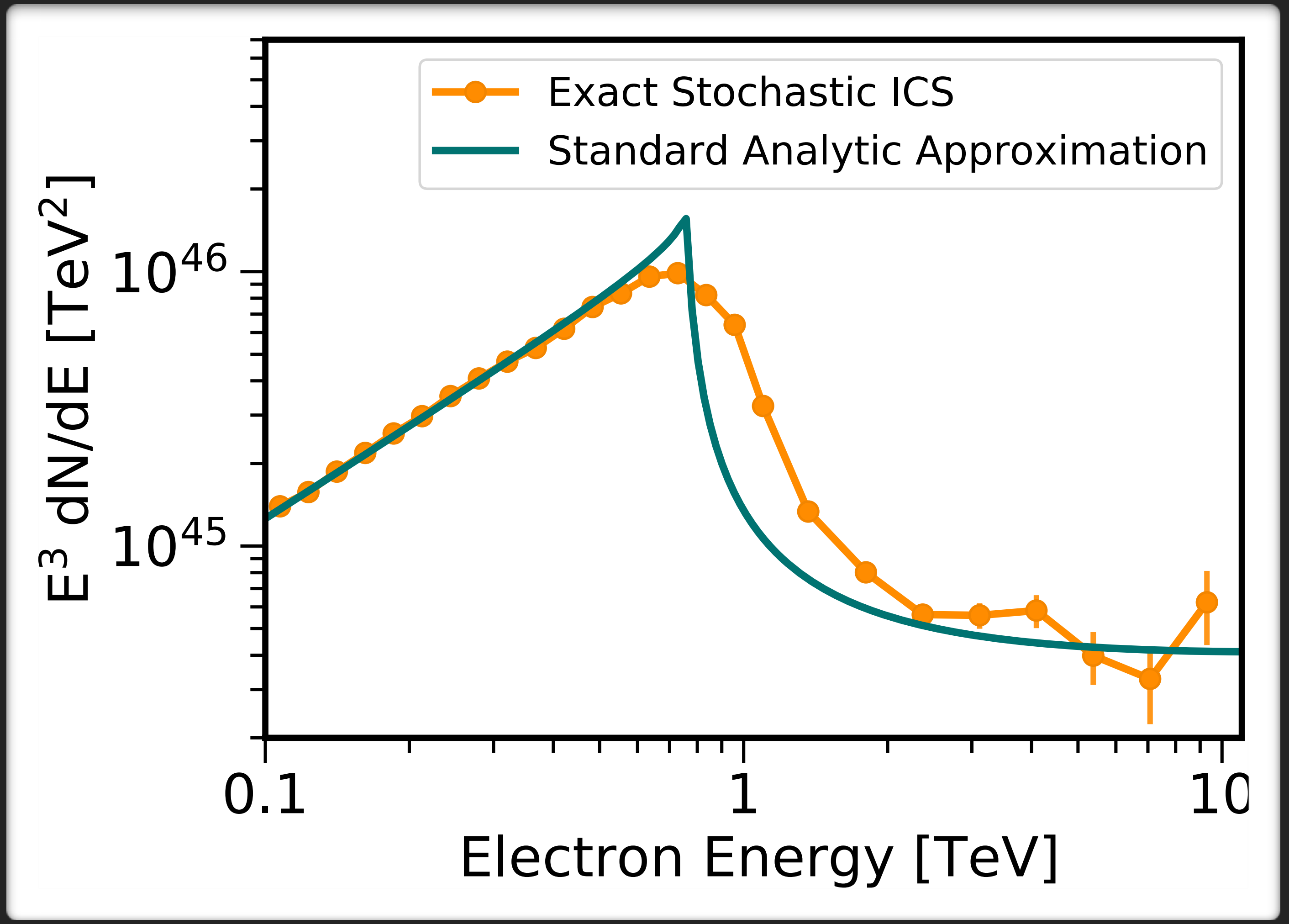
# Positron Spectrum of Individual Pulsars

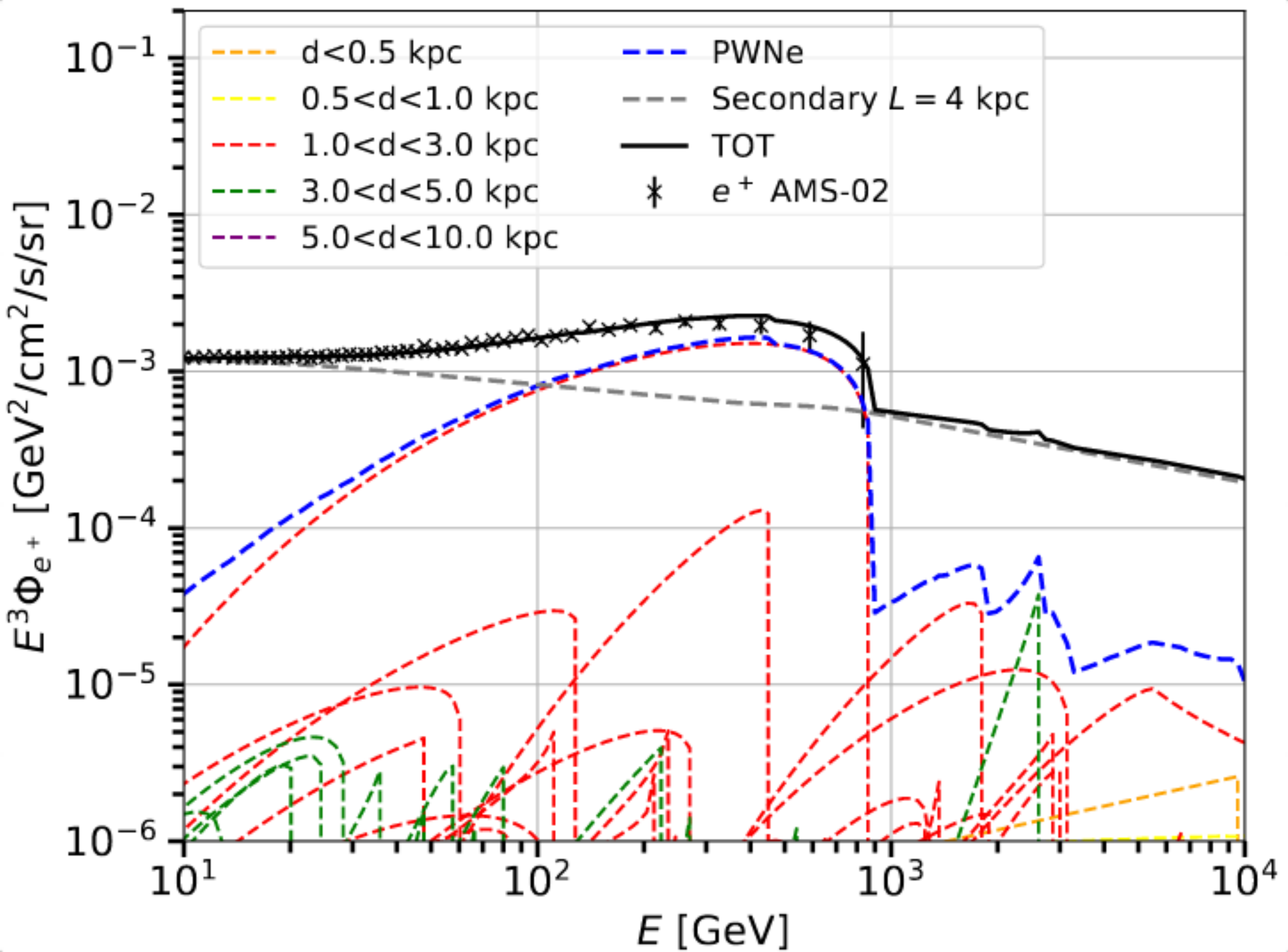


- Sharp spectral features introduced by analytic approximation are smoothened out by ~50% when correctly treating inverse-Compton scattering stochastically

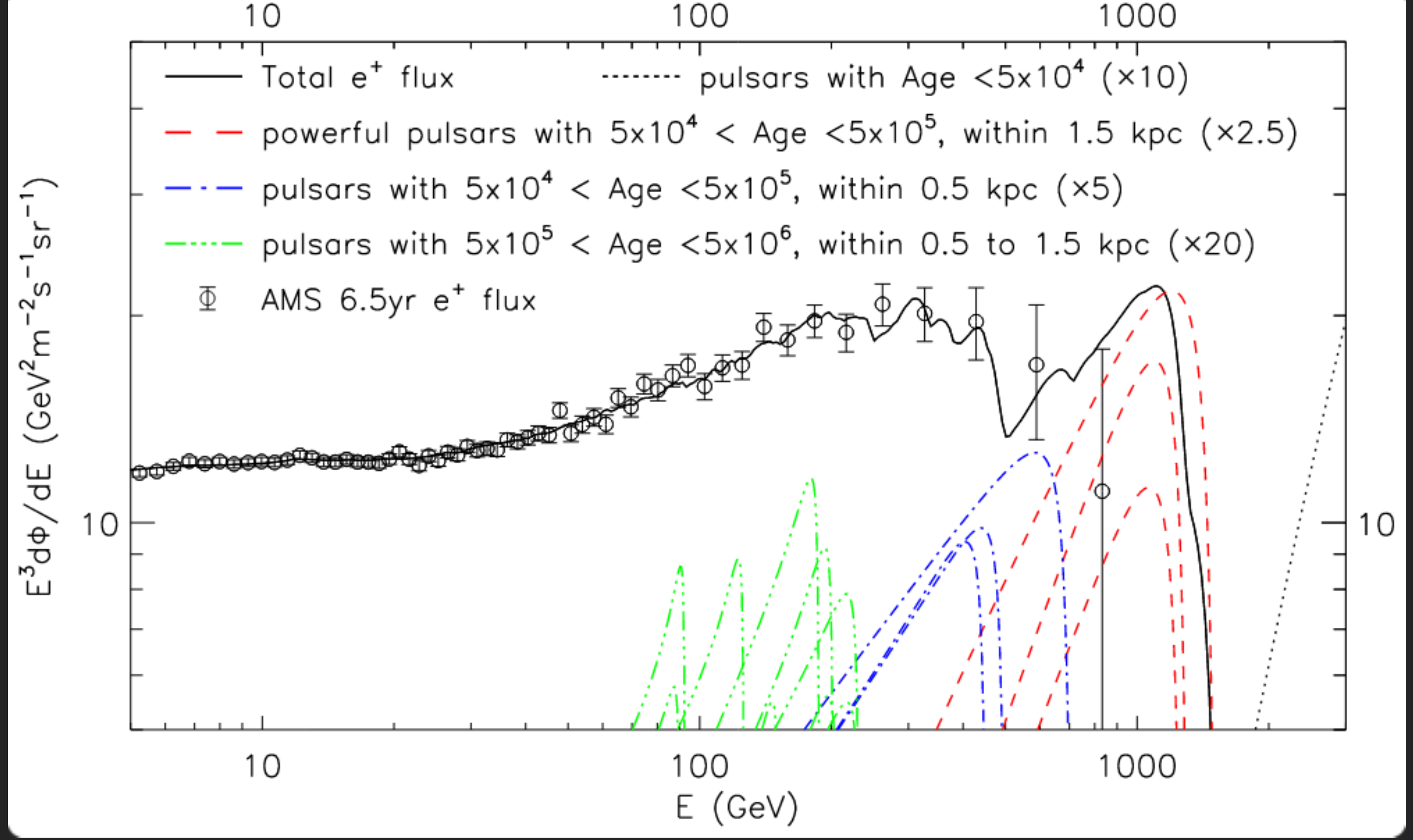
# Implications for Pulsar Models

- Pulsars do not produce sharp features
- Loosens constraints on pulsars
- Recent papers that fit pulsars to the positron data require large number of pulsars to wash out sharp features: Possibly only smaller number of pulsars needed to fit AMS-02 positron flux





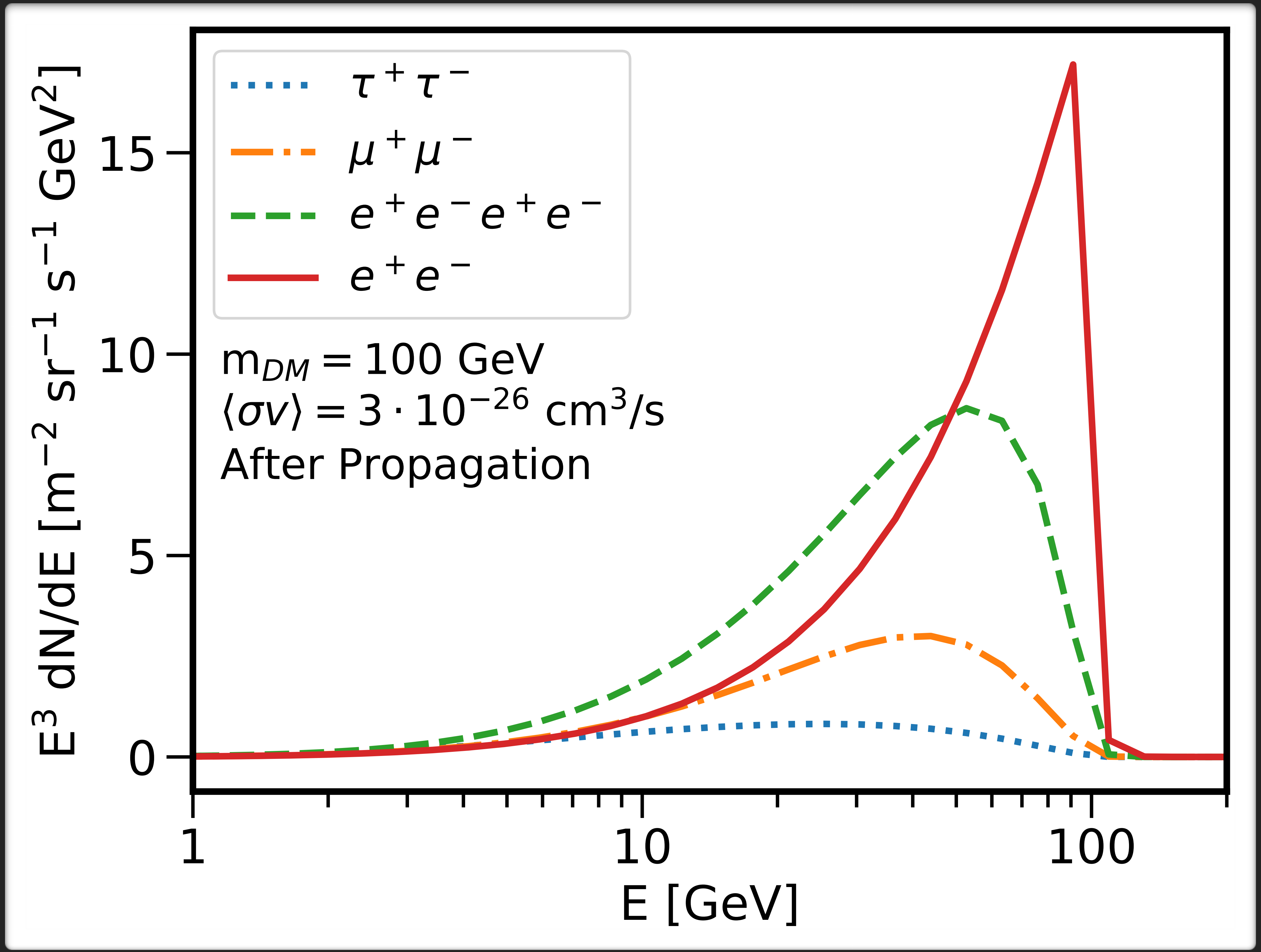
Orusa et al., arXiv:2107.06300

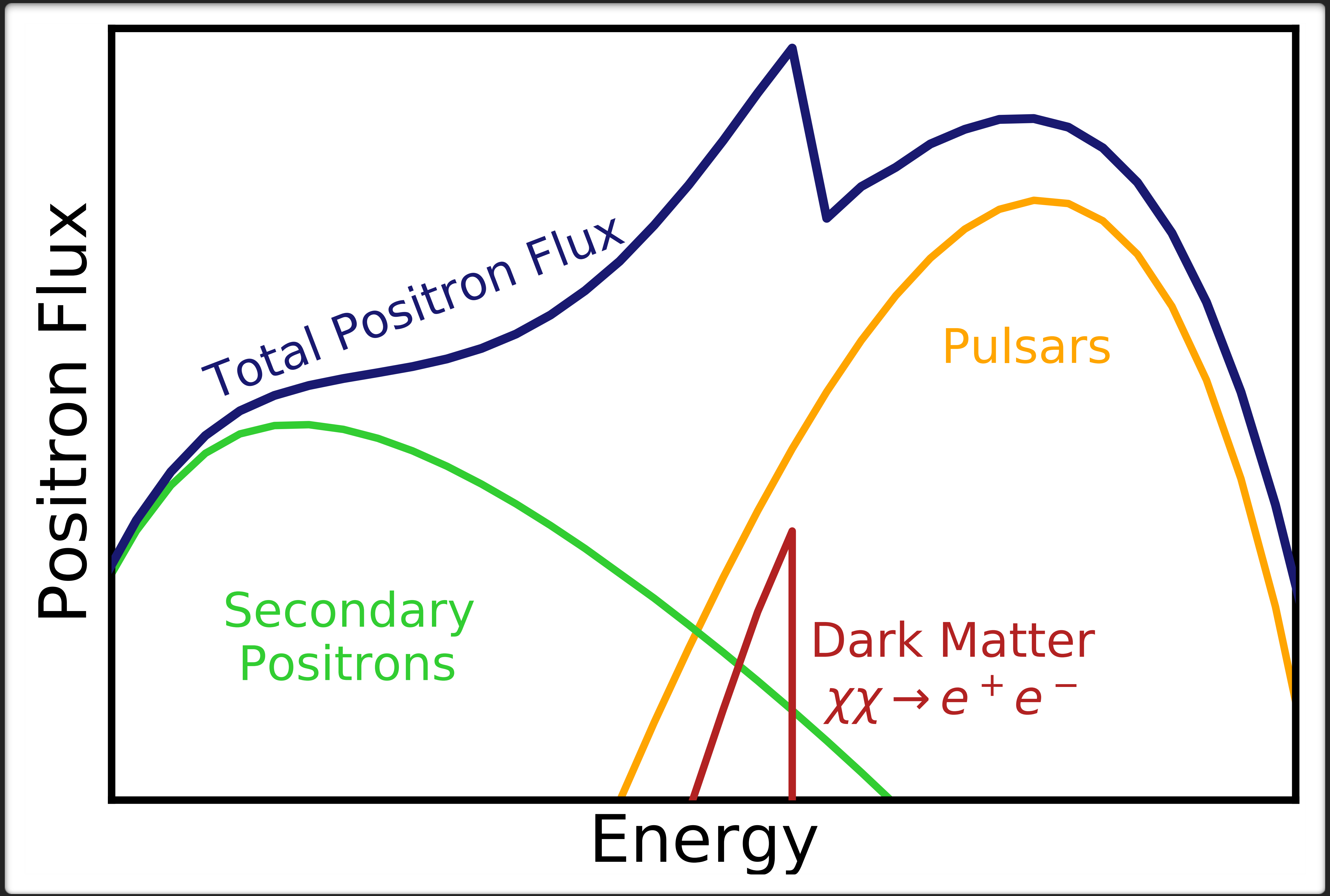


Cholis & Krommydas, arXiv:2111.05864

# Implications for Dark Matter

- Dark matter particles annihilating into leptonic final states produce sharp spectral features at dark matter mass
- Dark matter is the only known astrophysical mechanism that produces sharp spectral features





# Constraints on Dark Matter Models from Cosmic-Ray Positrons

I. John & T. Linden, arXiv:2107.10261

Aim: Model dark matter contribution to local cosmic-ray positron flux to constrain leptophilic dark matter

## Astrophysical Background Model

Pulsar model

- Spectrum: Hooper et al. arXiv:0810.1527
- Distribution: Lorimer et al. Mon. Not. Roy. Astron. Soc.372, 777

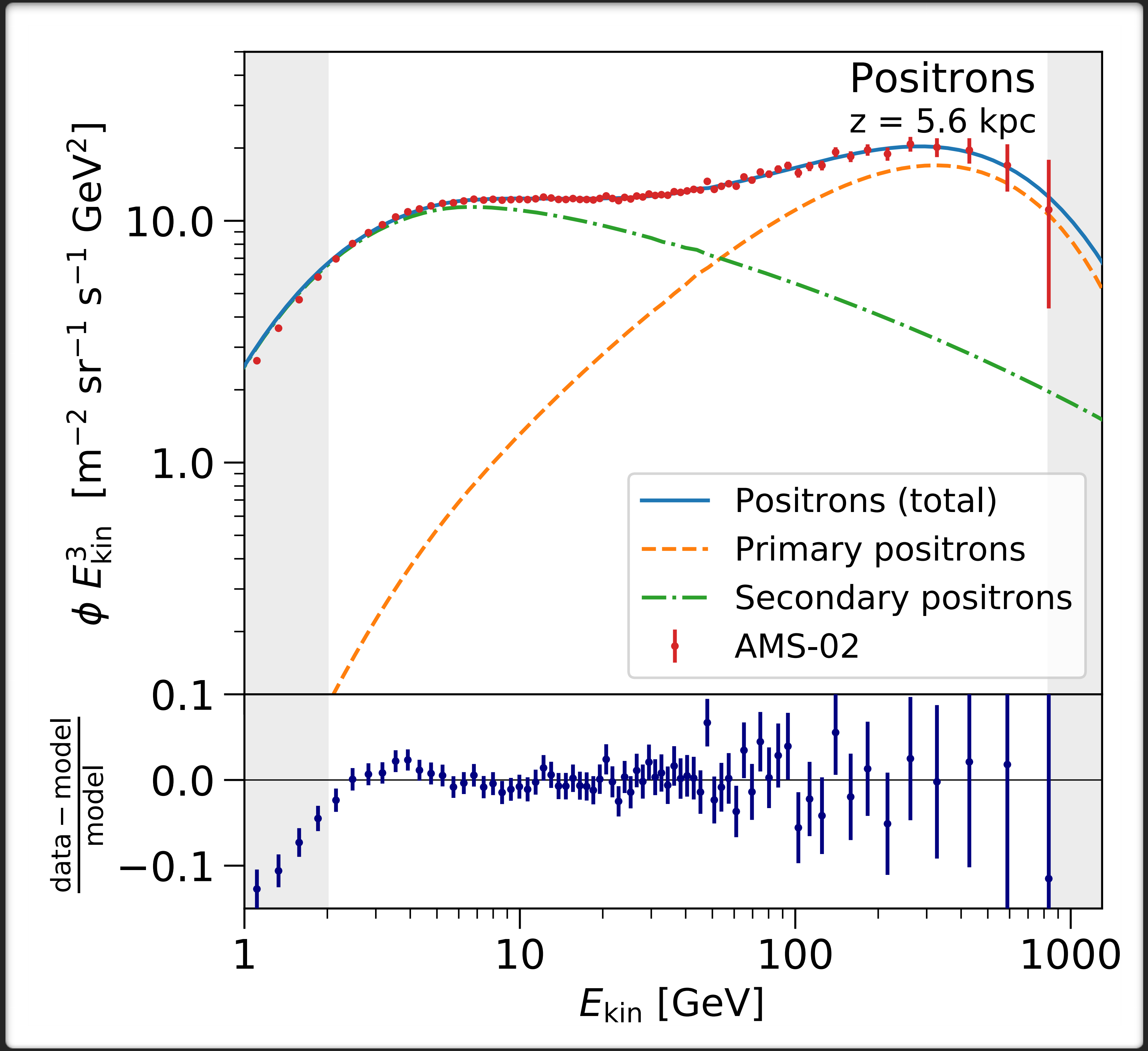
Simulation of cosmic-ray propagation using Galprop with many free parameters

New solar modulation model: time-, charge- and rigidity-dependent model (Cholis et al. arXiv:2007.00669)

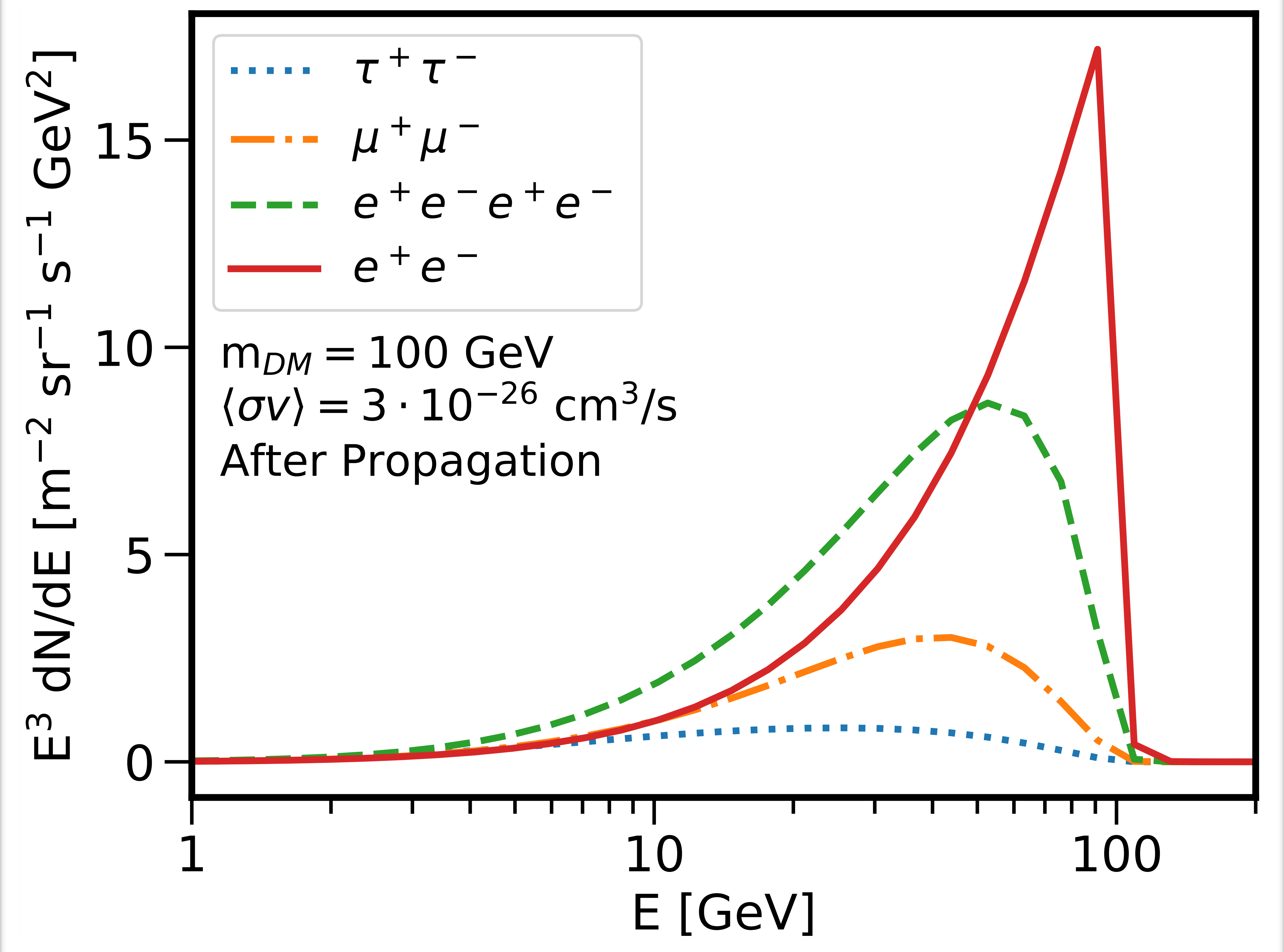
Fitting recent AMS-02 data for positrons, protons and Helium

# Constraints on Dark Matter Models from Cosmic-Ray Positrons

arXiv:2107.10261



Background model fits data to within a few percent $\left(\text{reduced } \chi^2 \sim 0.88\right)$



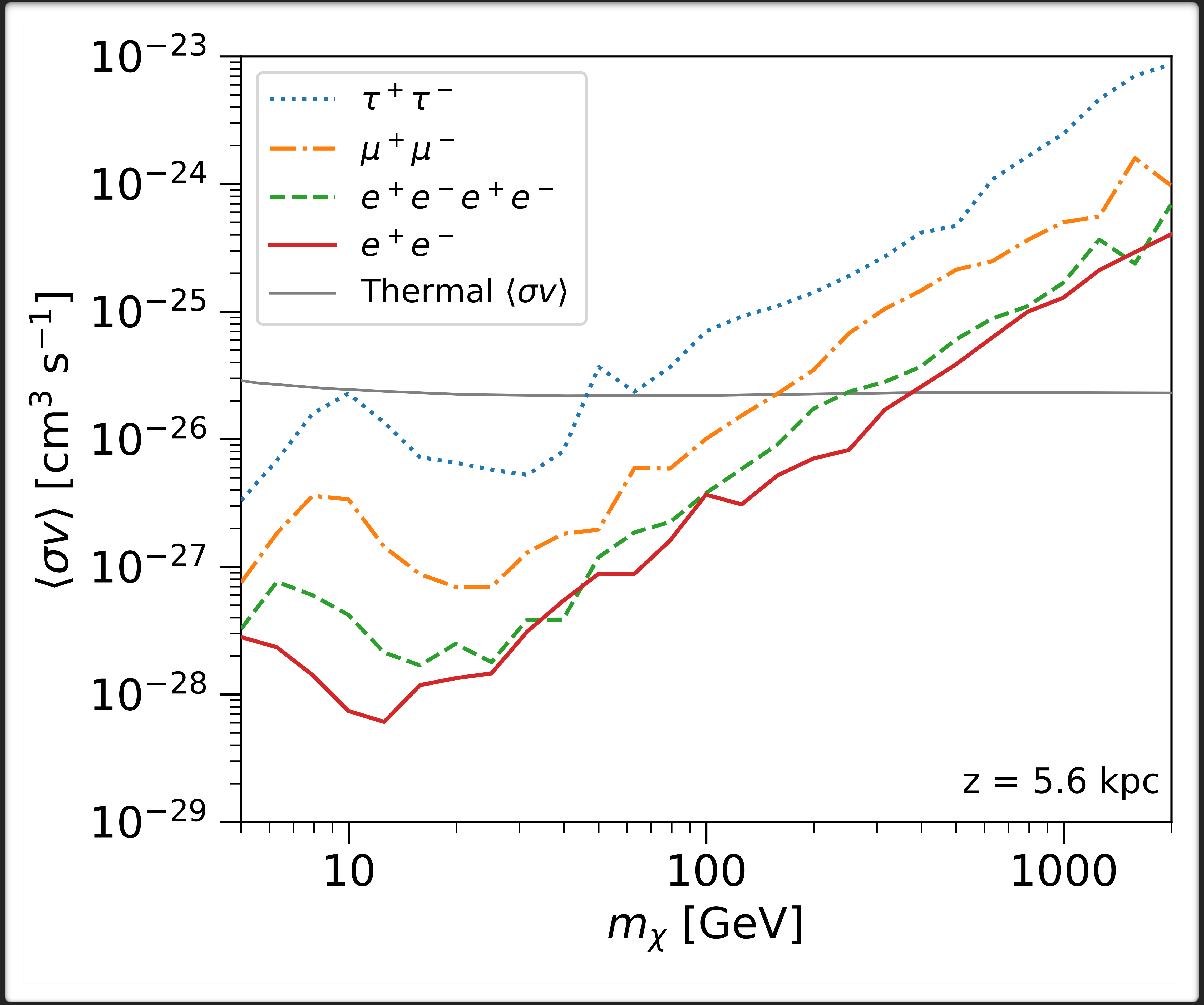
Add dark matter contributions to background model

# Constraints on Dark Matter Models from Cosmic-Ray Positrons

arXiv:2107.10261

- Four leptonic final states:
  - $\chi\chi \rightarrow \tau^+\tau^-$
  - $\chi\chi \rightarrow \mu^+\mu^-$
  - $\chi\chi \rightarrow e^+e^-$
  - $\chi\chi \rightarrow \phi\phi \rightarrow e^+e^-e^+e^-$, where $\phi$ is a light mediator

- Strongest constraints for $e^+e^-$ at $m_{DM} = 12$ GeV and $\langle\sigma v\rangle = 2.5 \times 10^{-29}$ cm$^3$/s, significantly below thermal cross section



Limits at 95% upper CL

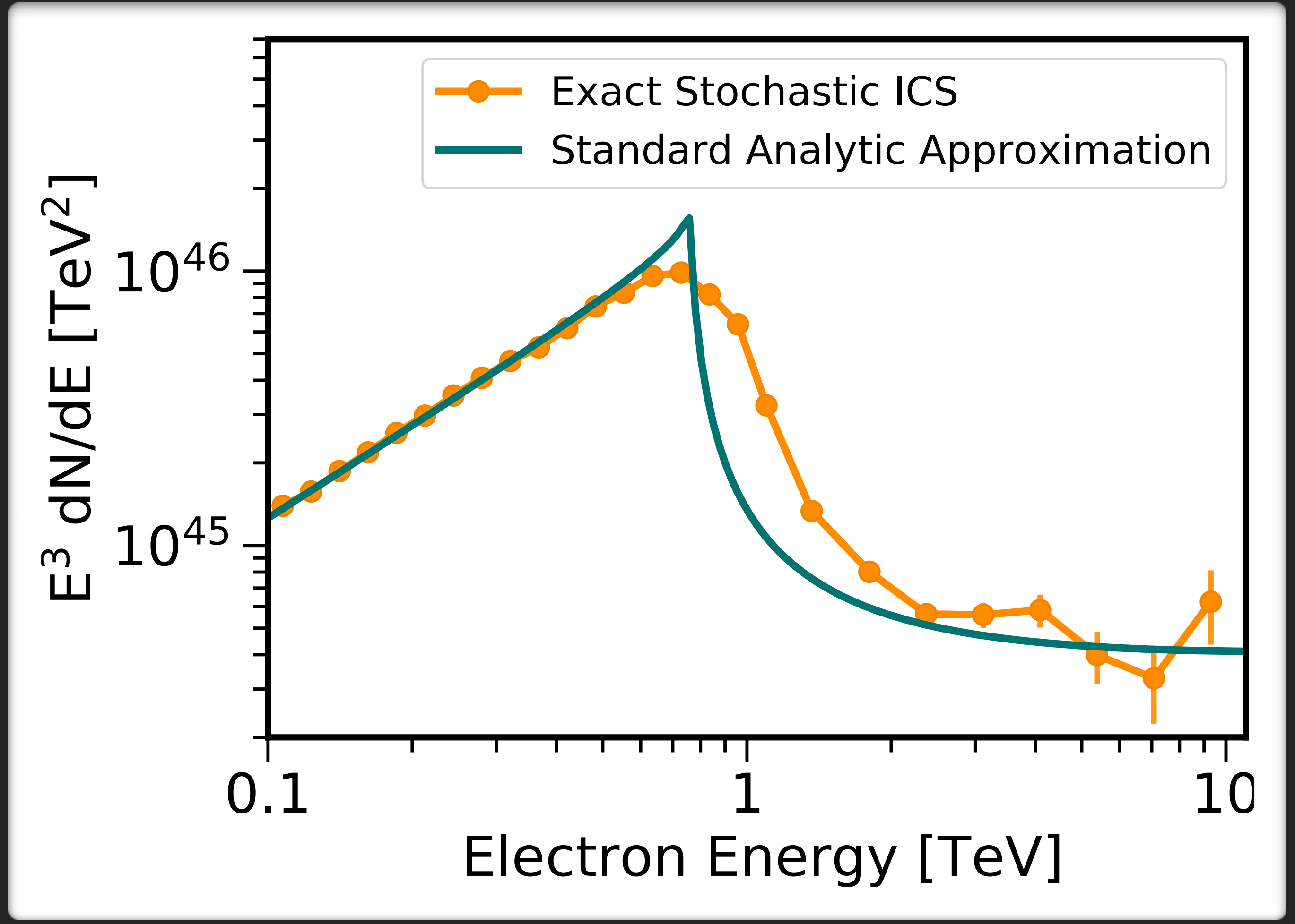
See also arXiv:1306.3983

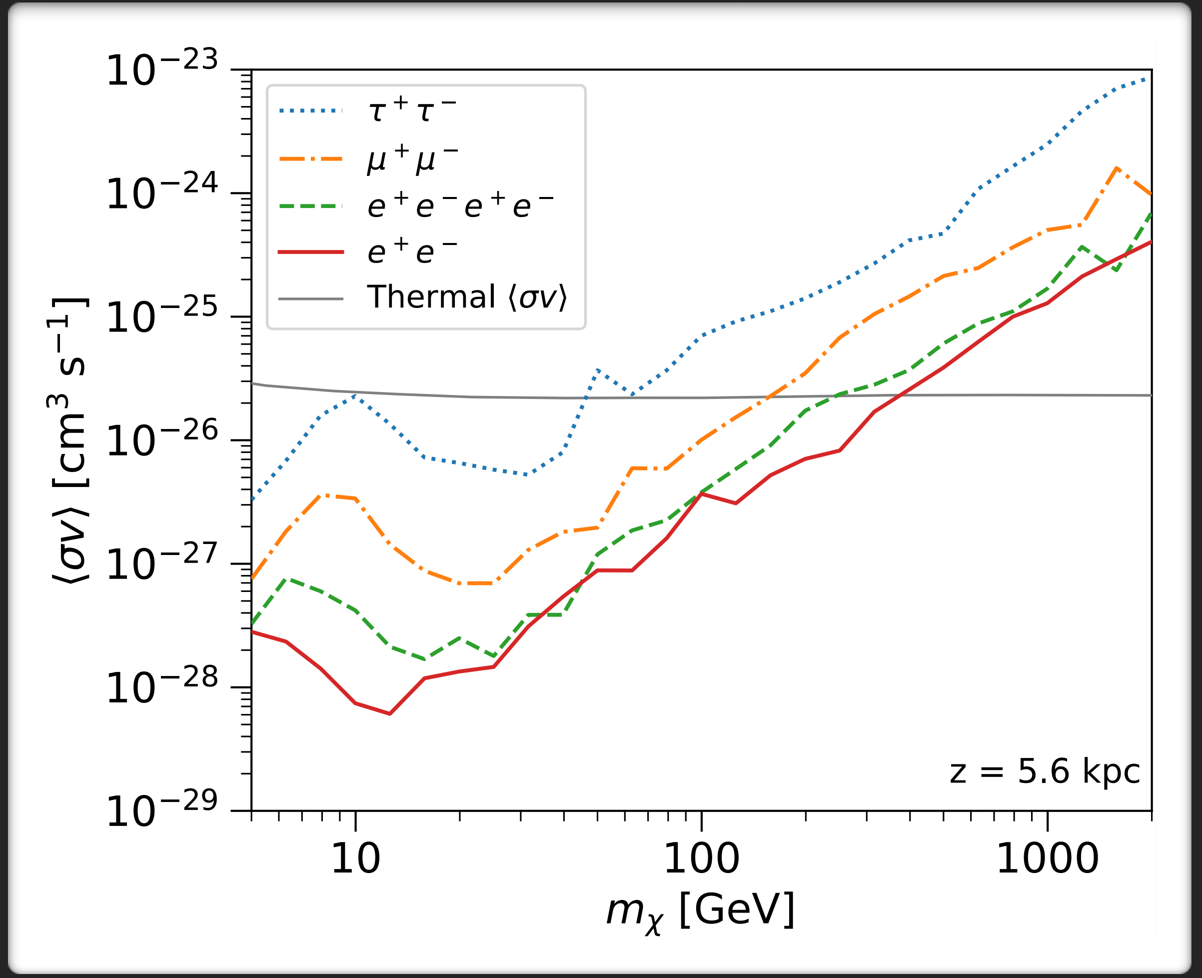
# Summary

We have proven that pulsars cannot produce sharp spectral features when inverse-Compton scattering is treated correctly stochastically.

This makes dark matter the only known potential source of sharp spectral features.

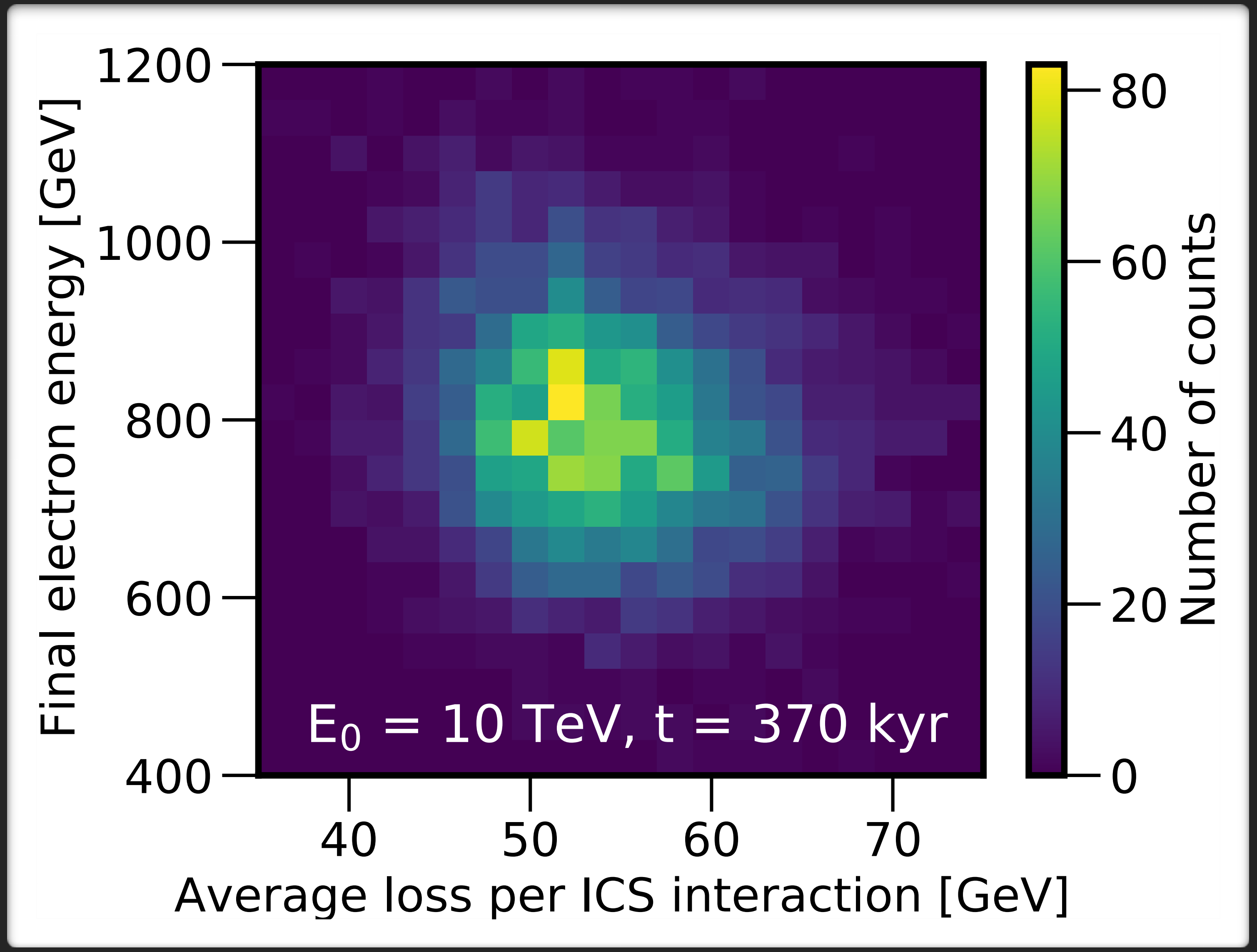
Cosmic-ray positrons strongly constrain models of dark matter annihilation into leptonic final states.

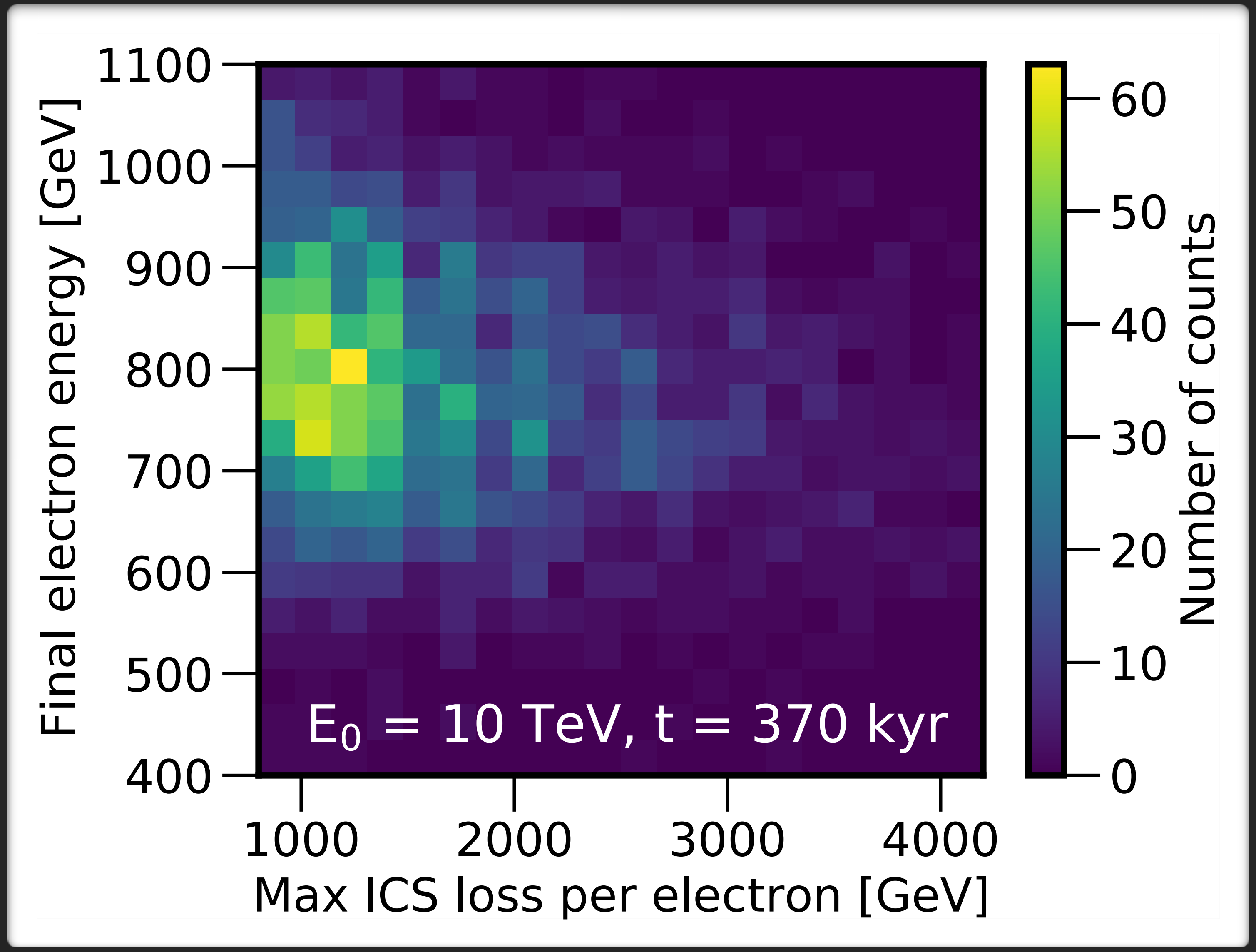


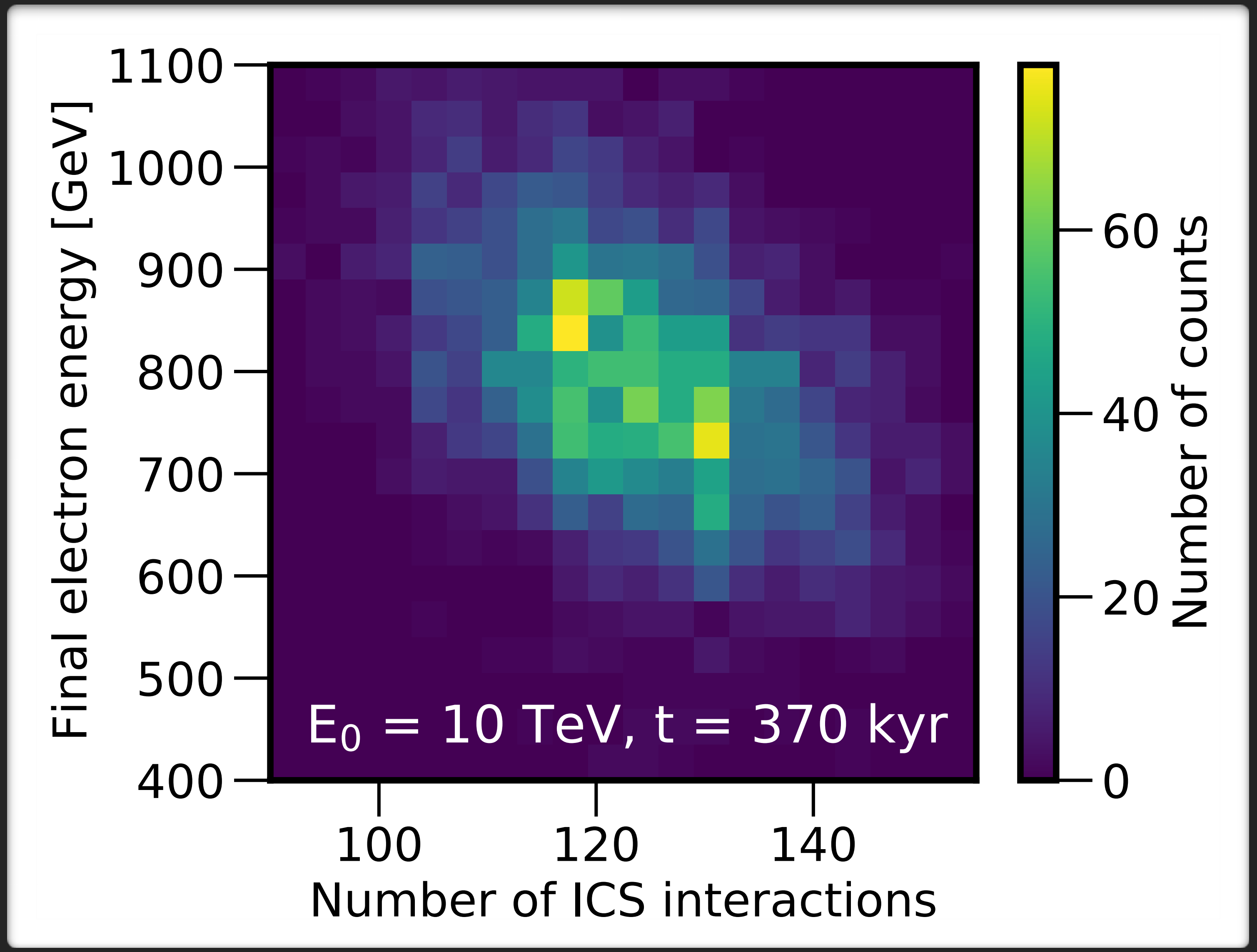


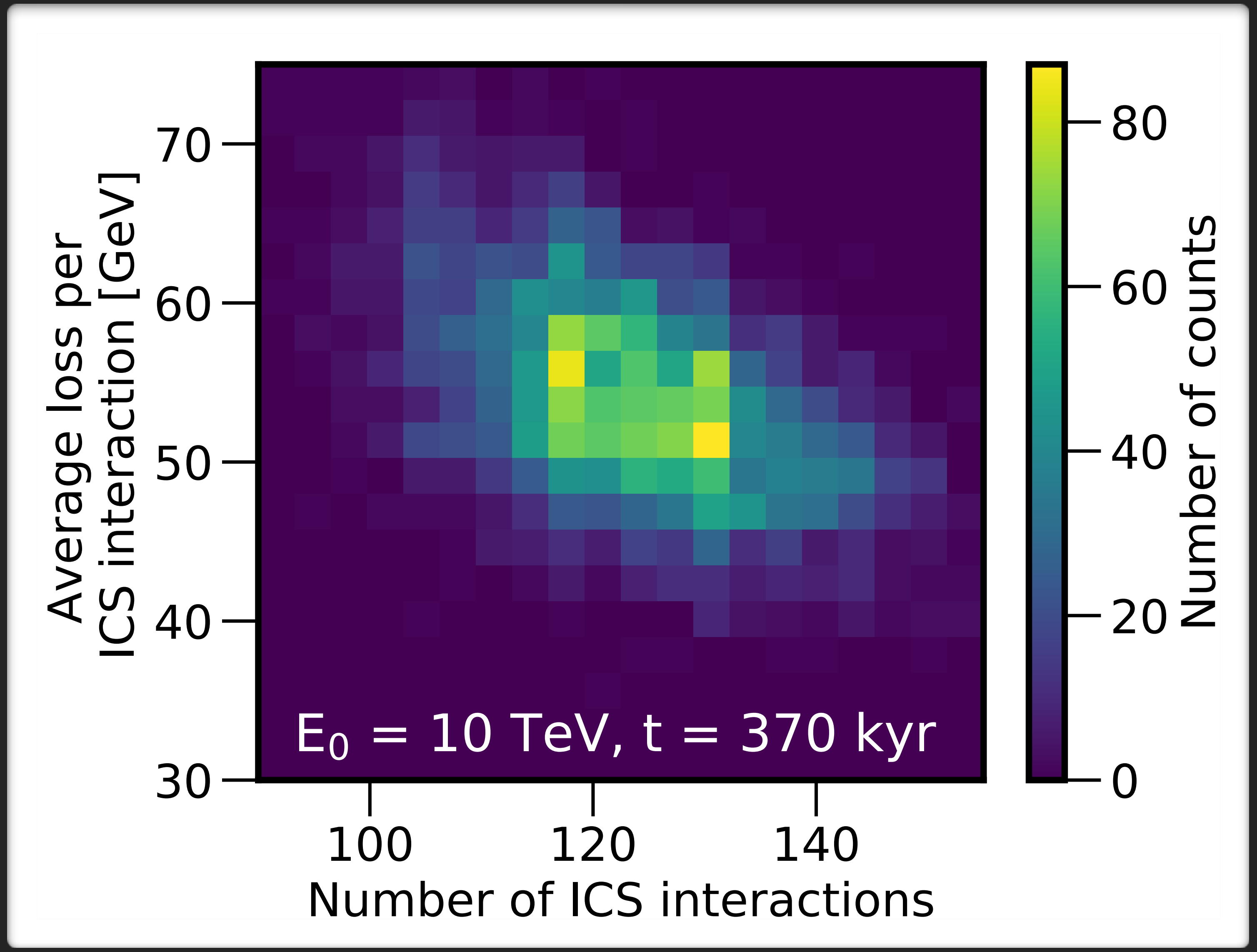
# Supplementary Slides

# Stochastic Inverse-Compton Scattering

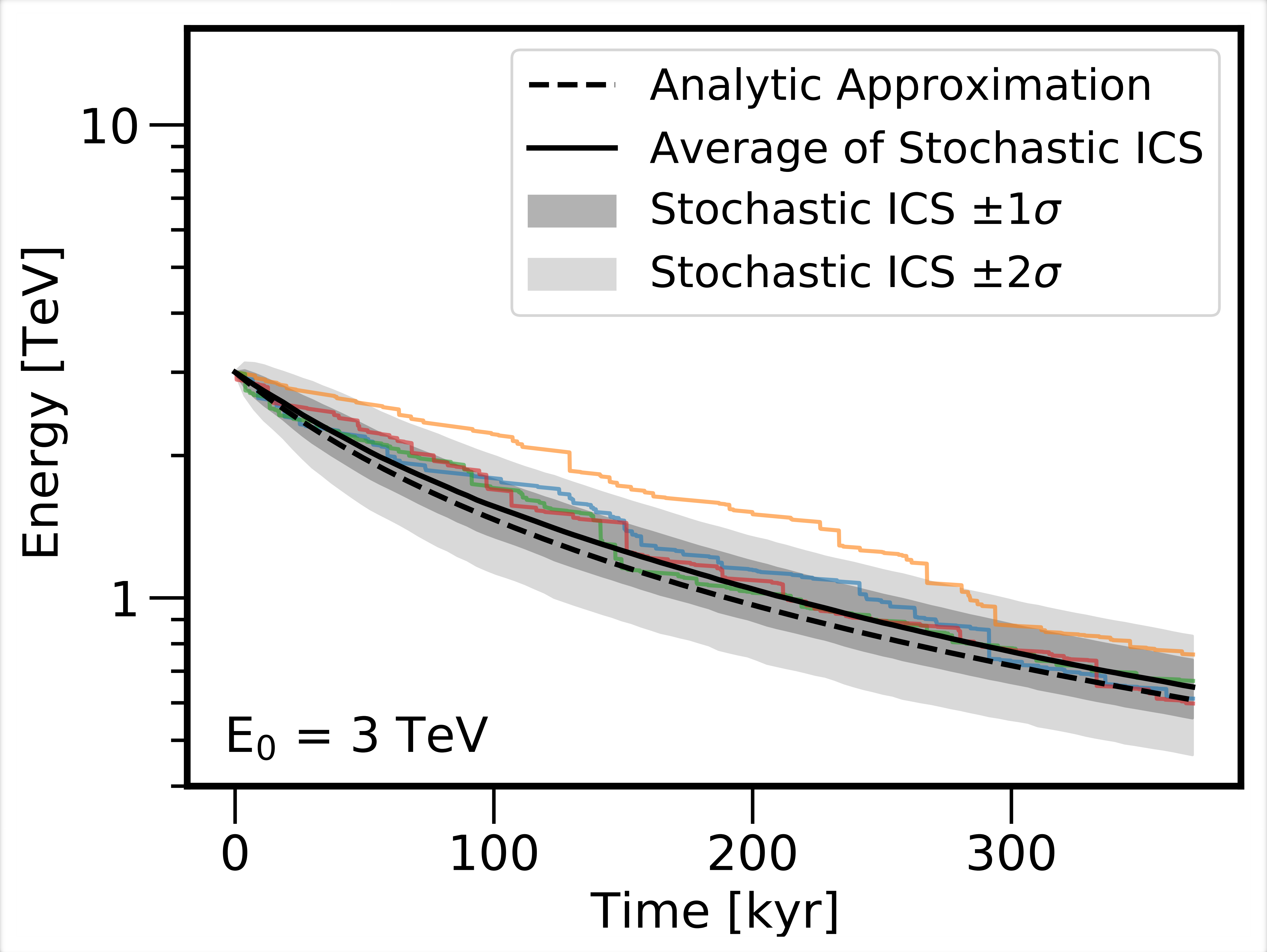




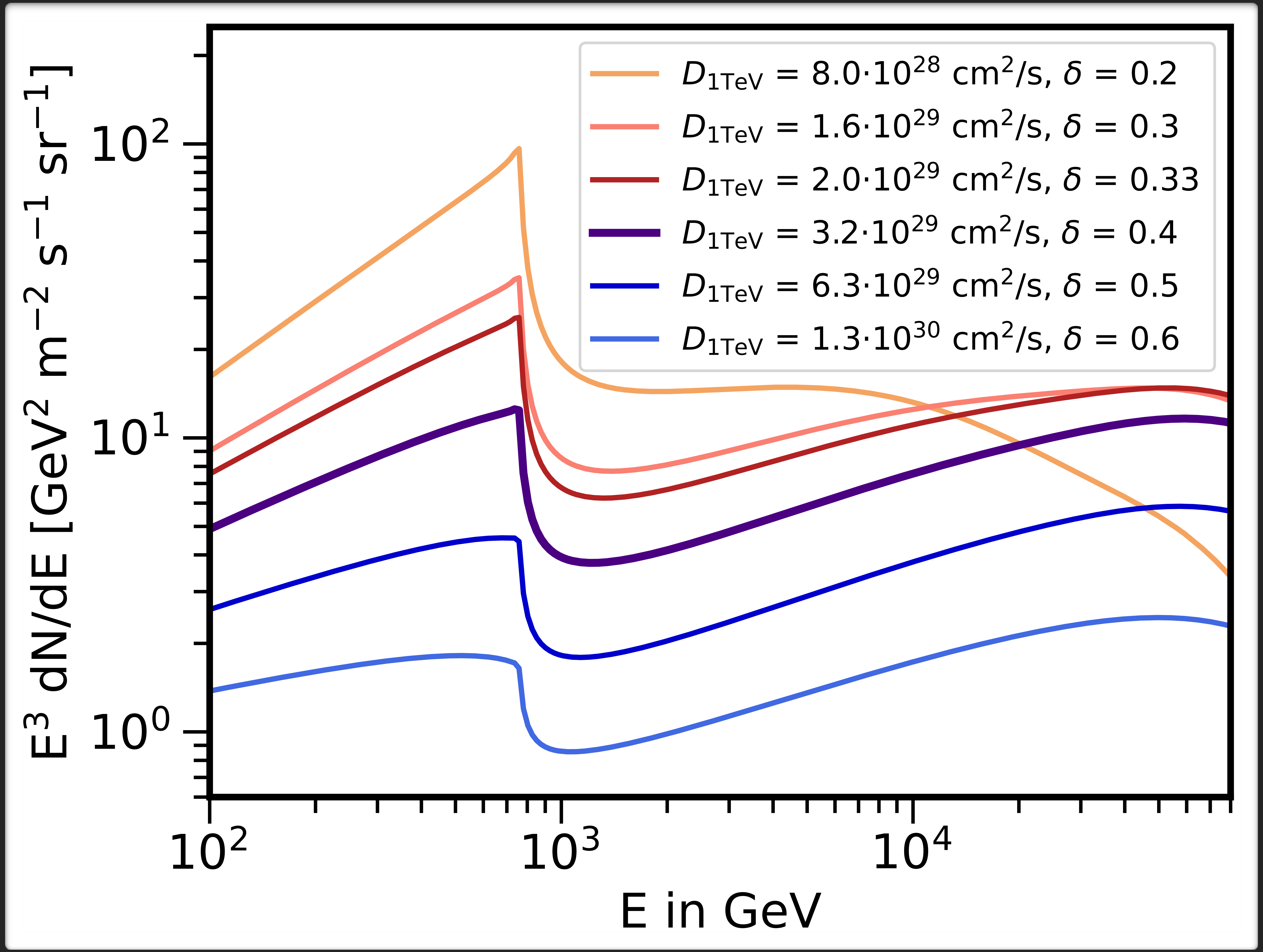




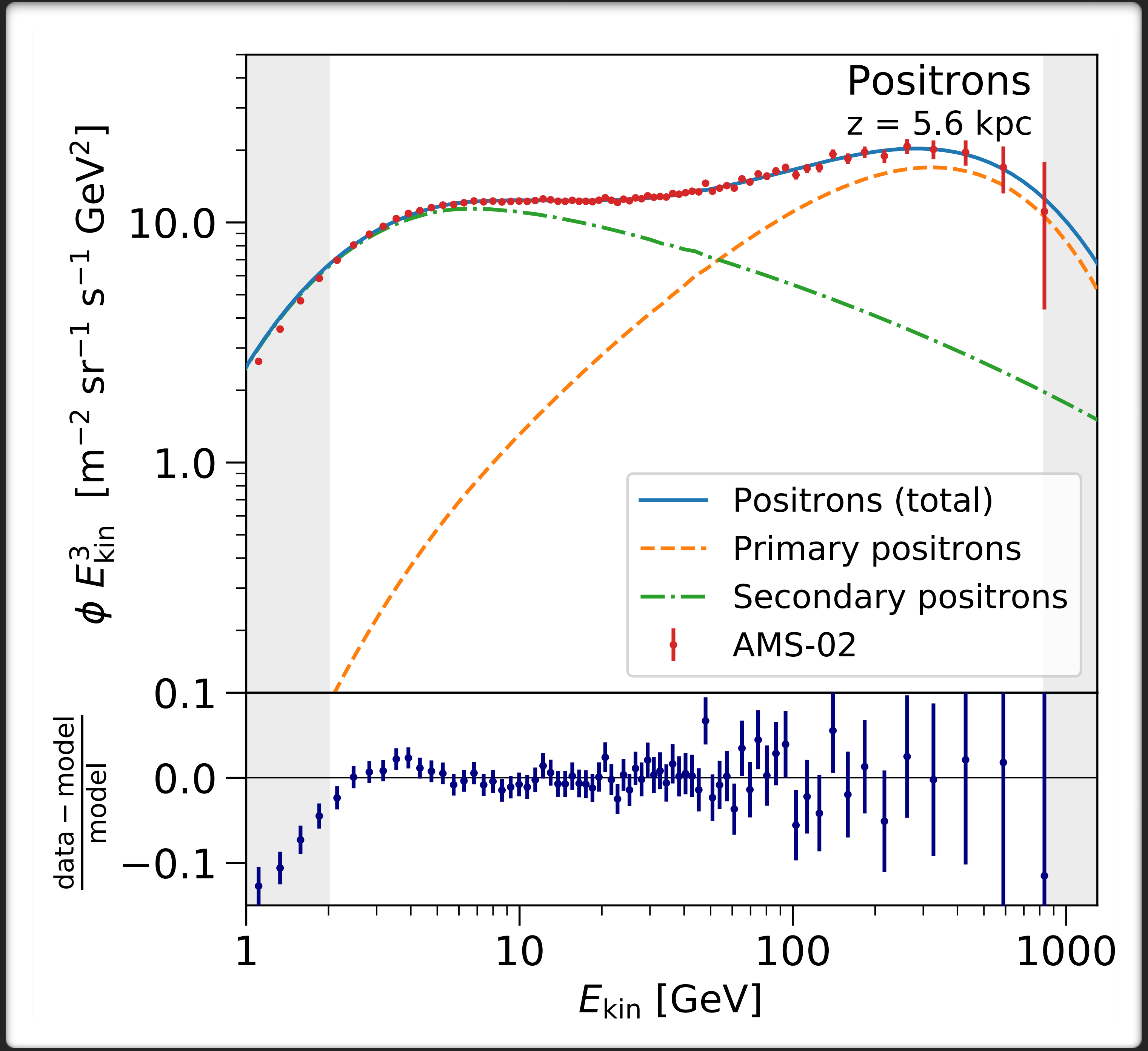
# Stochastic Inverse-Compton Scattering



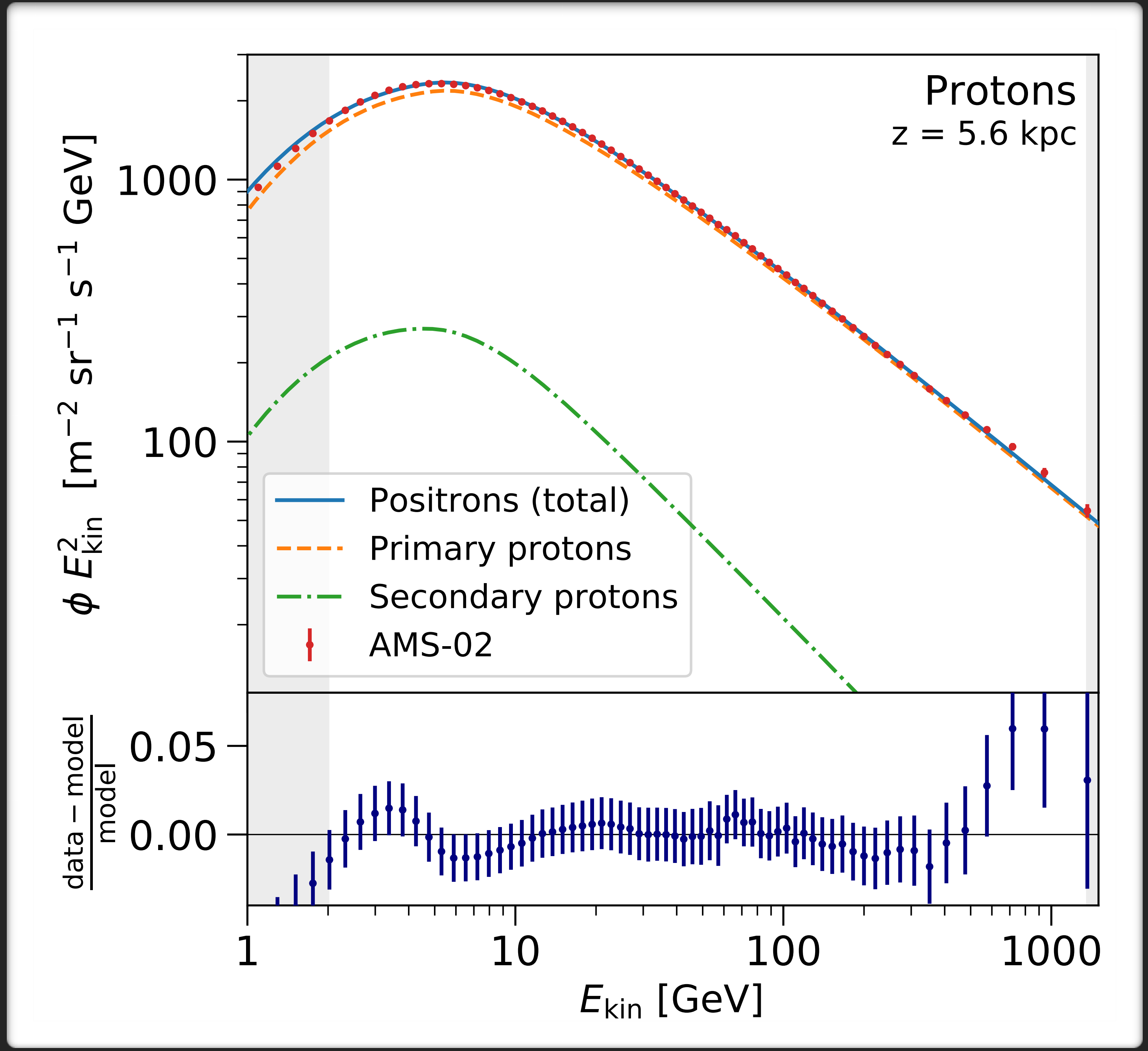
# Spectral Feature is Independent of Diffusion



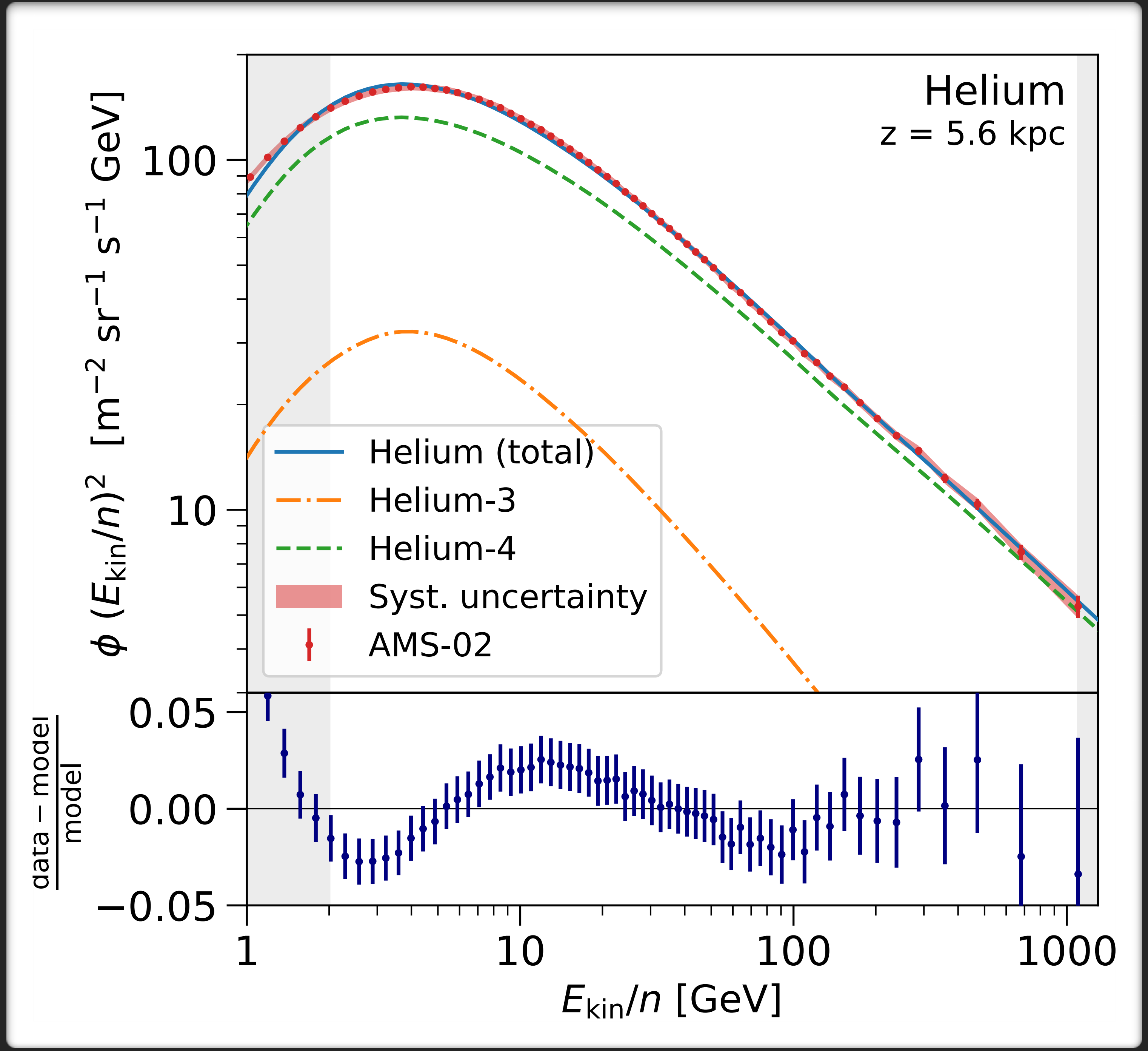
# Astrophysical Background Model



**Positrons:**
Reduced $\chi^2 = 0.88$
Degrees of Freedom: 49



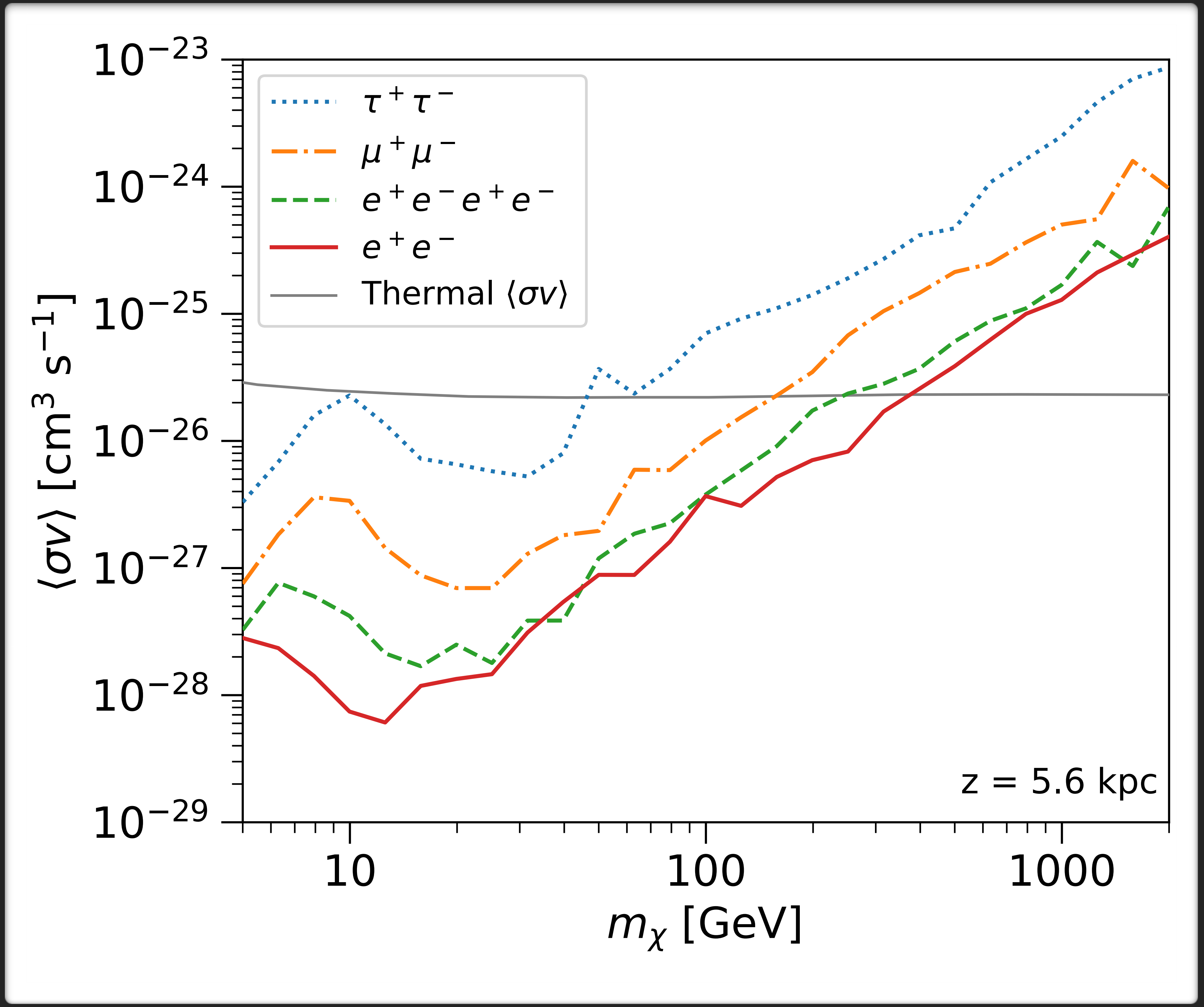
**Protons:**
Reduced $\chi^2 = 0.43$
Degrees of Freedom: 49



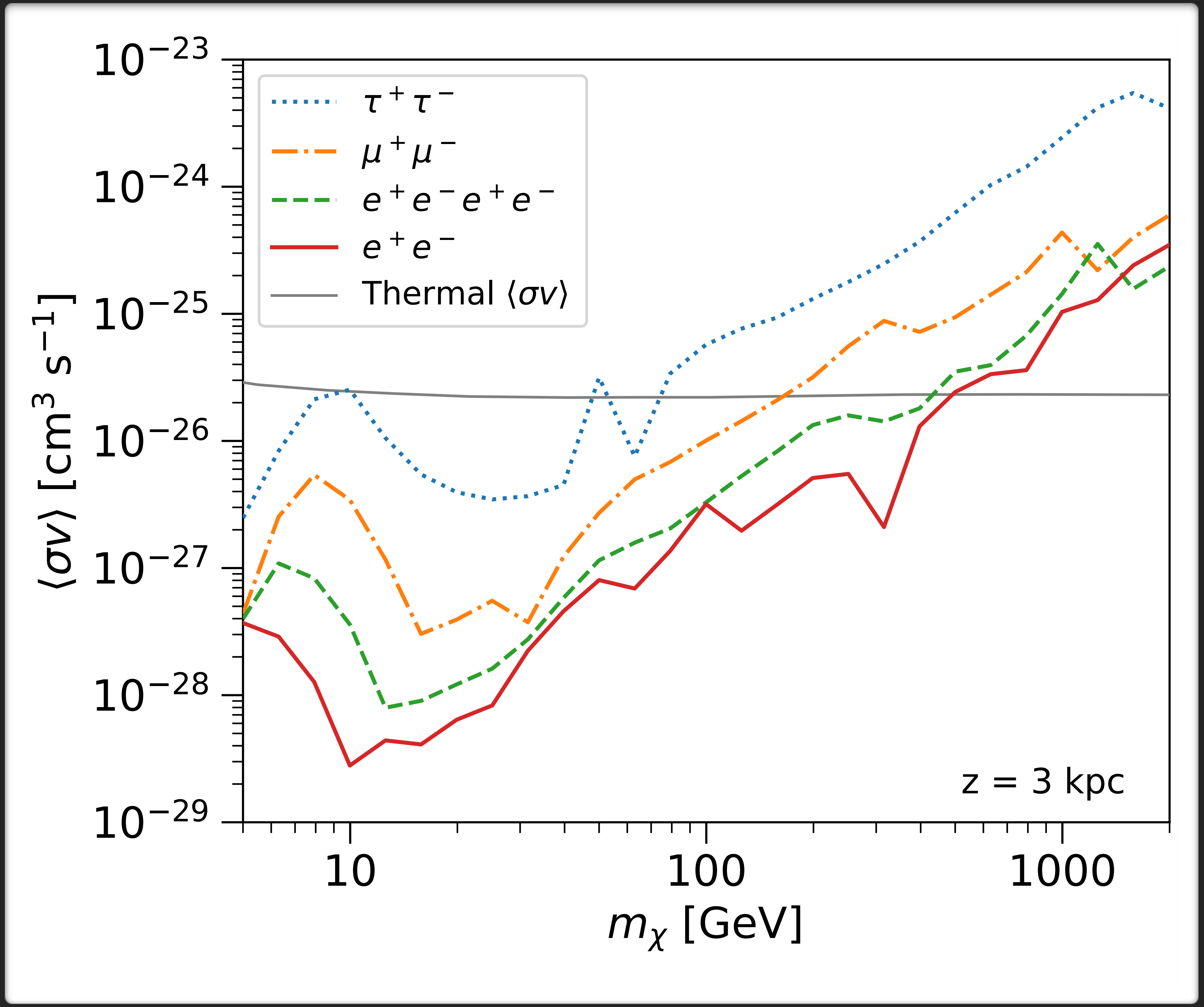
**Helium:**
Reduced $\chi^2 = 0.57$
Degrees of Freedom: 43

Total: Reduced $\chi^2 = 0.63$, Degrees of Freedom: 141

# Effect of Dark Matter Halo Height

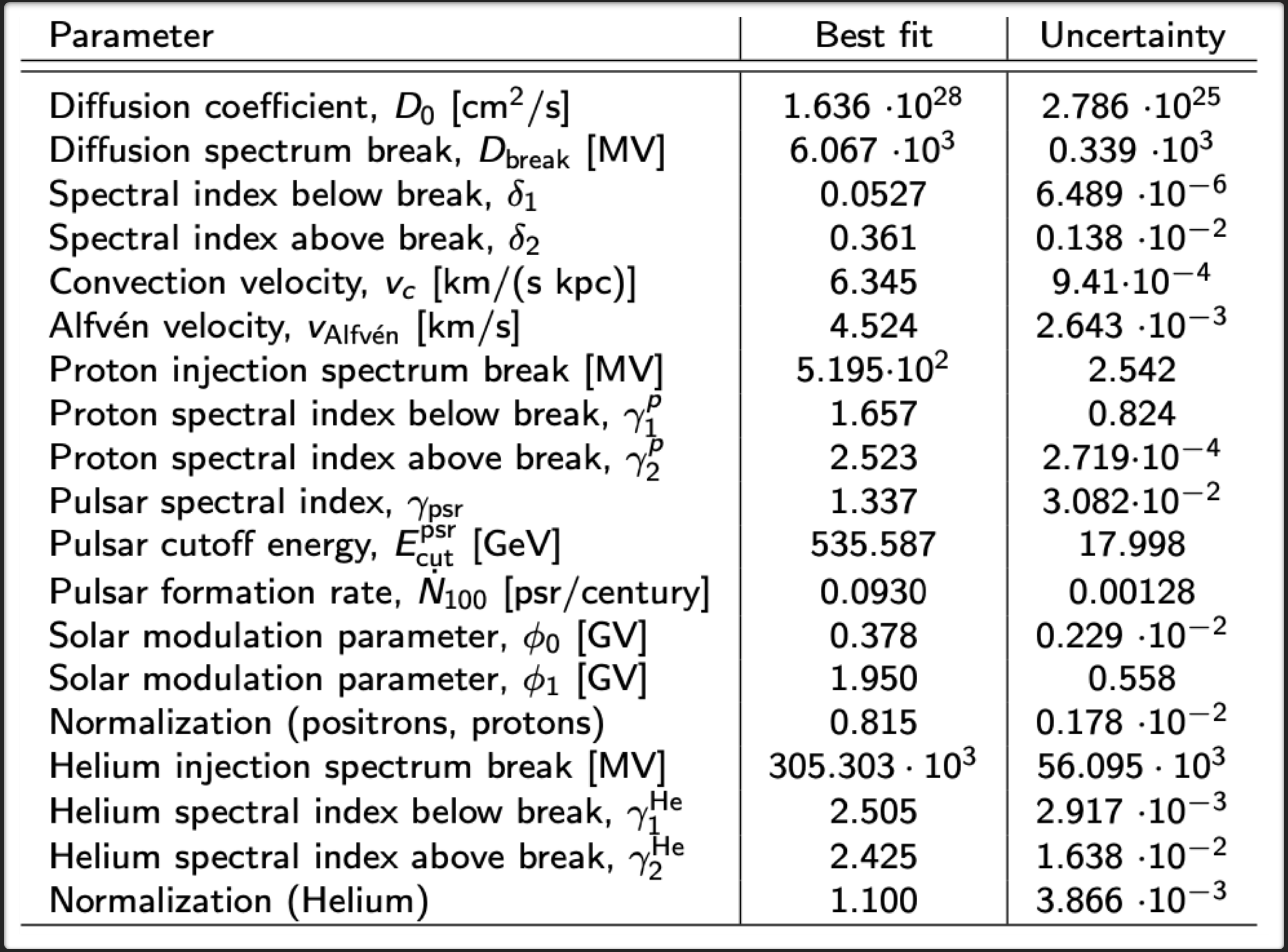


$z = 5.6$ kpc



$z = 3$ kpc

# List of Free Parameters for Background Model



| Parameter | Best fit | Uncertainty |
|---|---|---|
| Diffusion coefficient, $D_0$ [cm$^2$/s] | $1.636 \cdot 10^{28}$ | $2.786 \cdot 10^{25}$ |
| Diffusion spectrum break, $D_{\mathrm{break}}$ [MV] | $6.067 \cdot 10^{3}$ | $0.339 \cdot 10^{3}$ |
| Spectral index below break, $\delta_1$ | 0.0527 | $6.489 \cdot 10^{-6}$ |
| Spectral index above break, $\delta_2$ | 0.361 | $0.138 \cdot 10^{-2}$ |
| Convection velocity, $v_c$ [km/(s kpc)] | 6.345 | $9.41 \cdot 10^{-4}$ |
| Alfvén velocity, $v_{\mathrm{Alfvén}}$ [km/s] | 4.524 | $2.643 \cdot 10^{-3}$ |
| Proton injection spectrum break [MV] | $5.195 \cdot 10^{2}$ | 2.542 |
| Proton spectral index below break, $\gamma_1^p$ | 1.657 | 0.824 |
| Proton spectral index above break, $\gamma_2^p$ | 2.523 | $2.719 \cdot 10^{-4}$ |
| Pulsar spectral index, $\gamma_{\mathrm{psr}}$ | 1.337 | $3.082 \cdot 10^{-2}$ |
| Pulsar cutoff energy, $E_{\mathrm{cut}}^{\mathrm{psr}}$ [GeV] | 535.587 | 17.998 |
| Pulsar formation rate, $\dot{N}_{100}$ [psr/century] | 0.0930 | 0.00128 |
| Solar modulation parameter, $\phi_0$ [GV] | 0.378 | $0.229 \cdot 10^{-2}$ |
| Solar modulation parameter, $\phi_1$ [GV] | 1.950 | 0.558 |
| Normalization (positrons, protons) | 0.815 | $0.178 \cdot 10^{-2}$ |
| Helium injection spectrum break [MV] | $305.303 \cdot 10^{3}$ | $56.095 \cdot 10^{3}$ |
| Helium spectral index below break, $\gamma_1^{\mathrm{He}}$ | 2.505 | $2.917 \cdot 10^{-3}$ |
| Helium spectral index above break, $\gamma_2^{\mathrm{He}}$ | 2.425 | $1.638 \cdot 10^{-2}$ |
| Normalization (Helium) | 1.100 | $3.866 \cdot 10^{-3}$ |