

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

I. John & T. Linden

arXiv:2206.04699



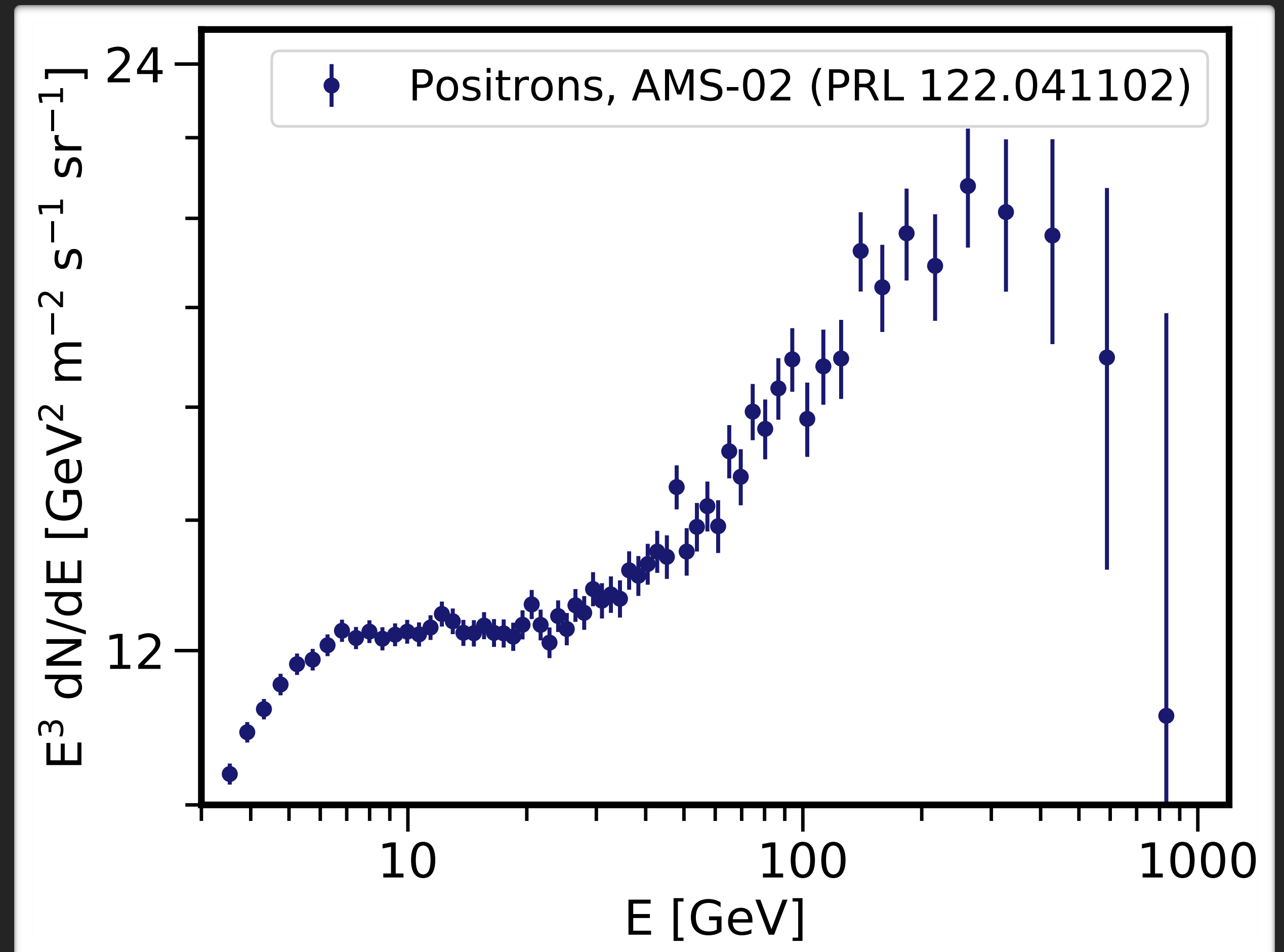
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27 July 2022

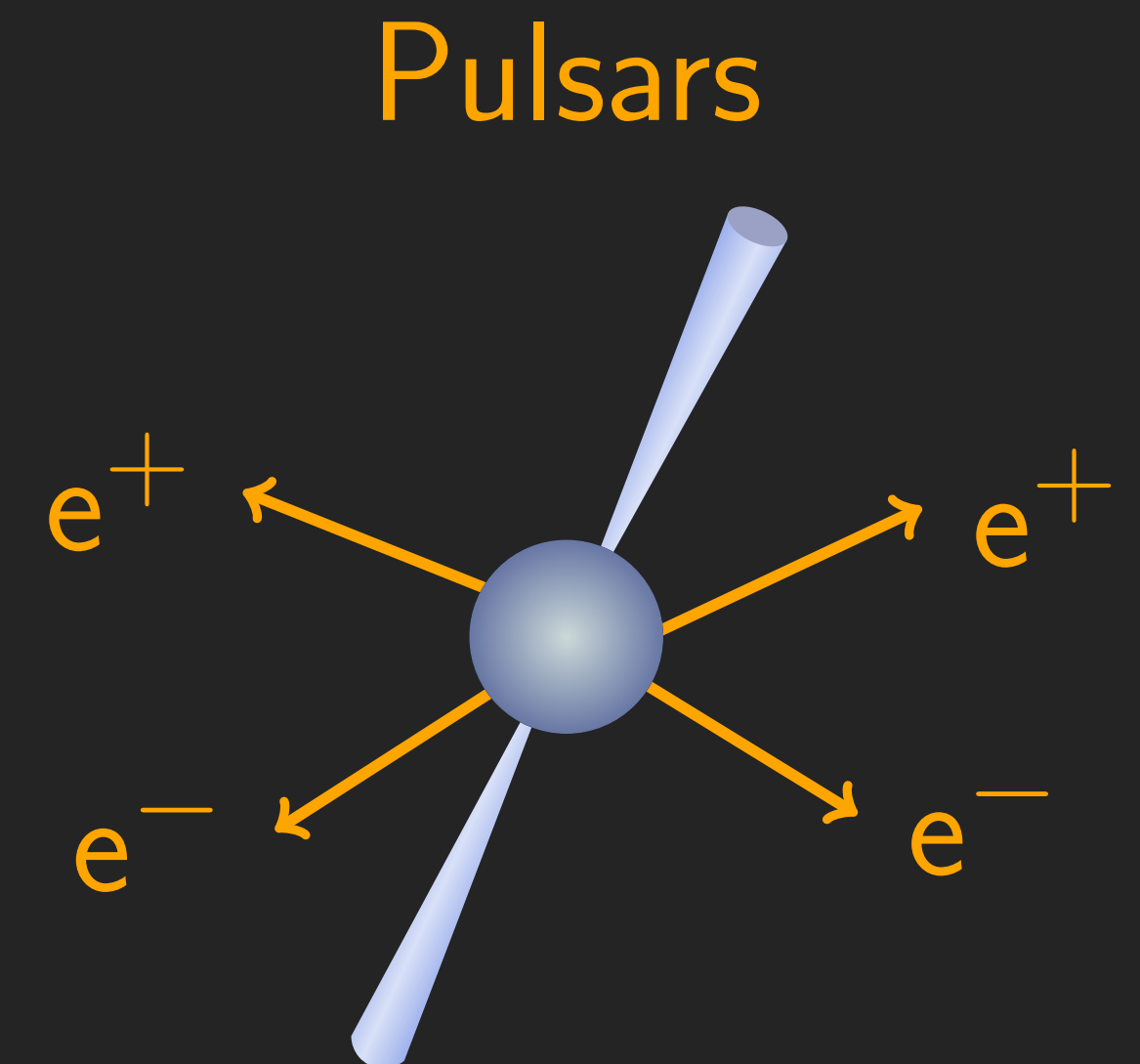
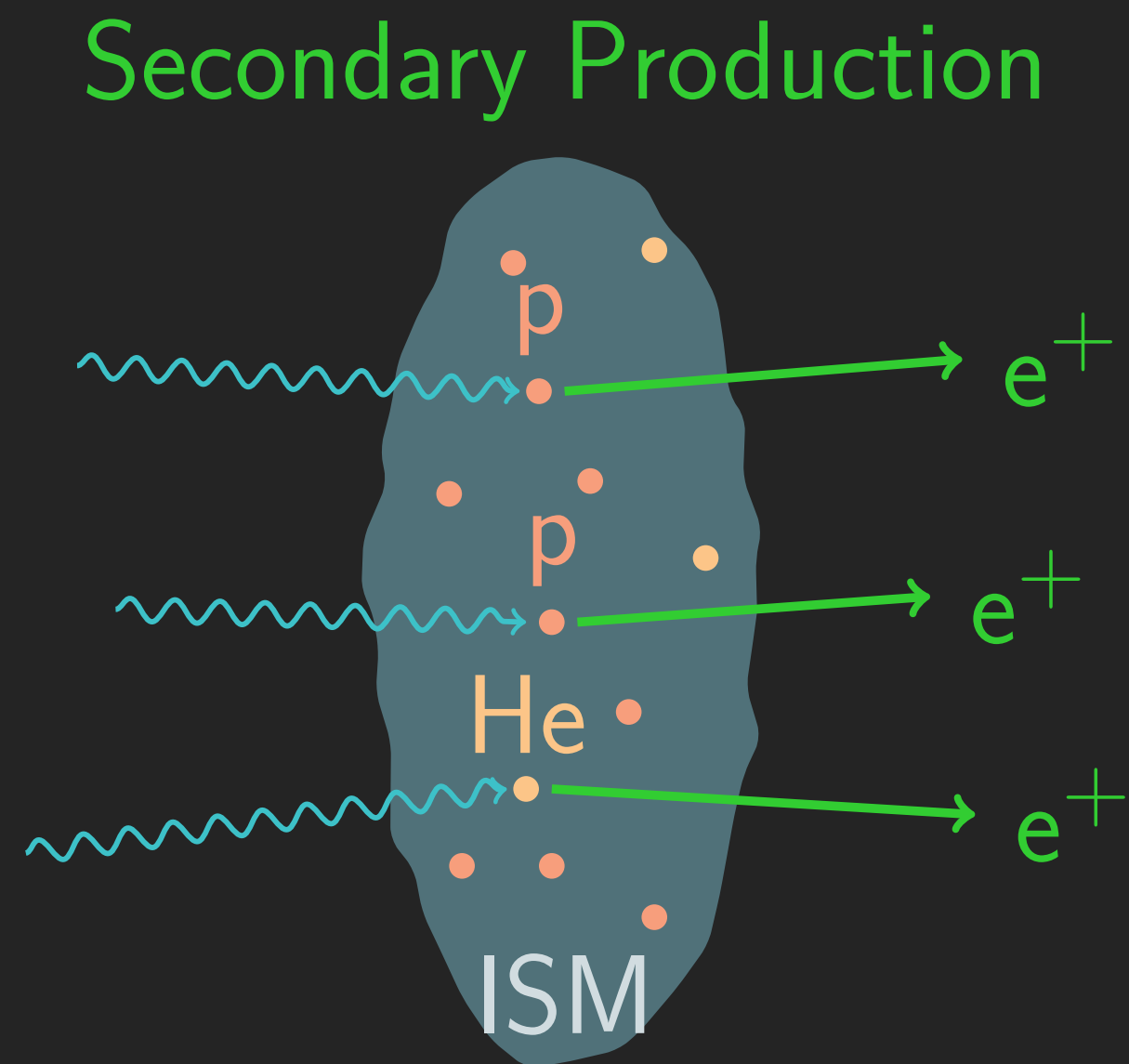
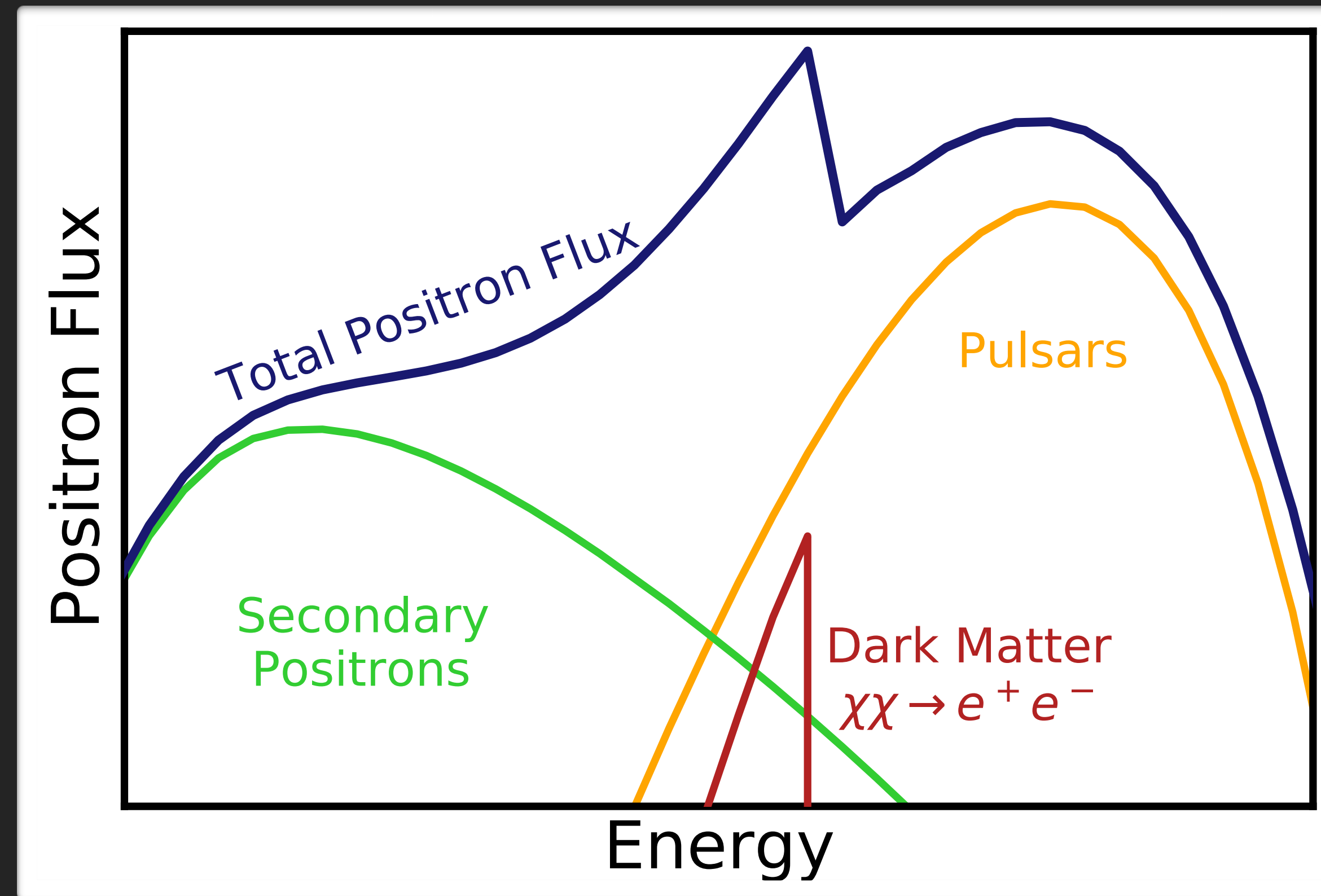


Local Cosmic-Ray Positron Flux

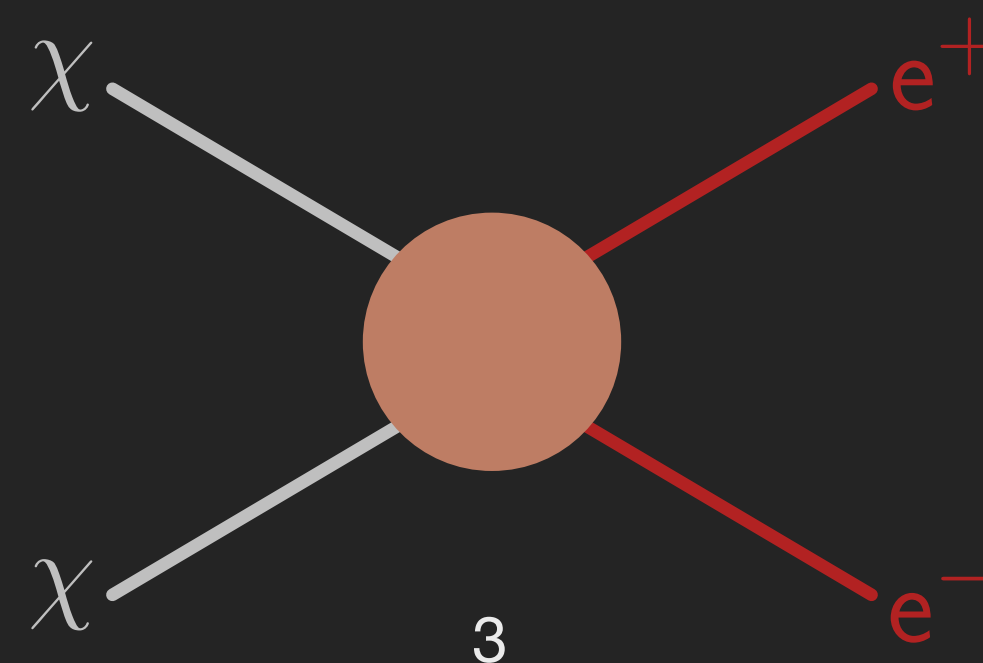
- Measured up to ~ 1 TeV
- Rises above ~ 20 GeV
- Spectrum is very smooth



Components of the Positron Flux



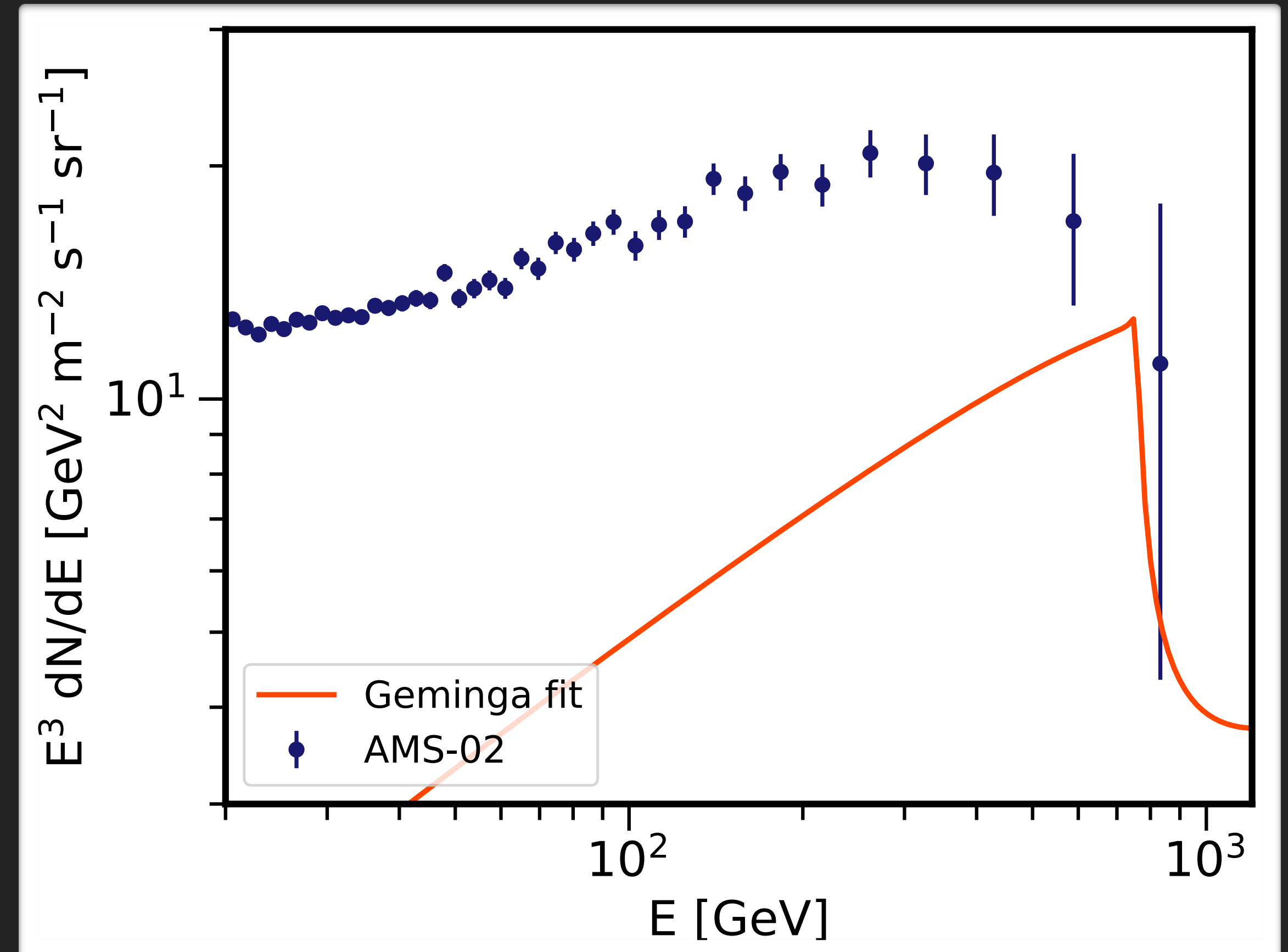
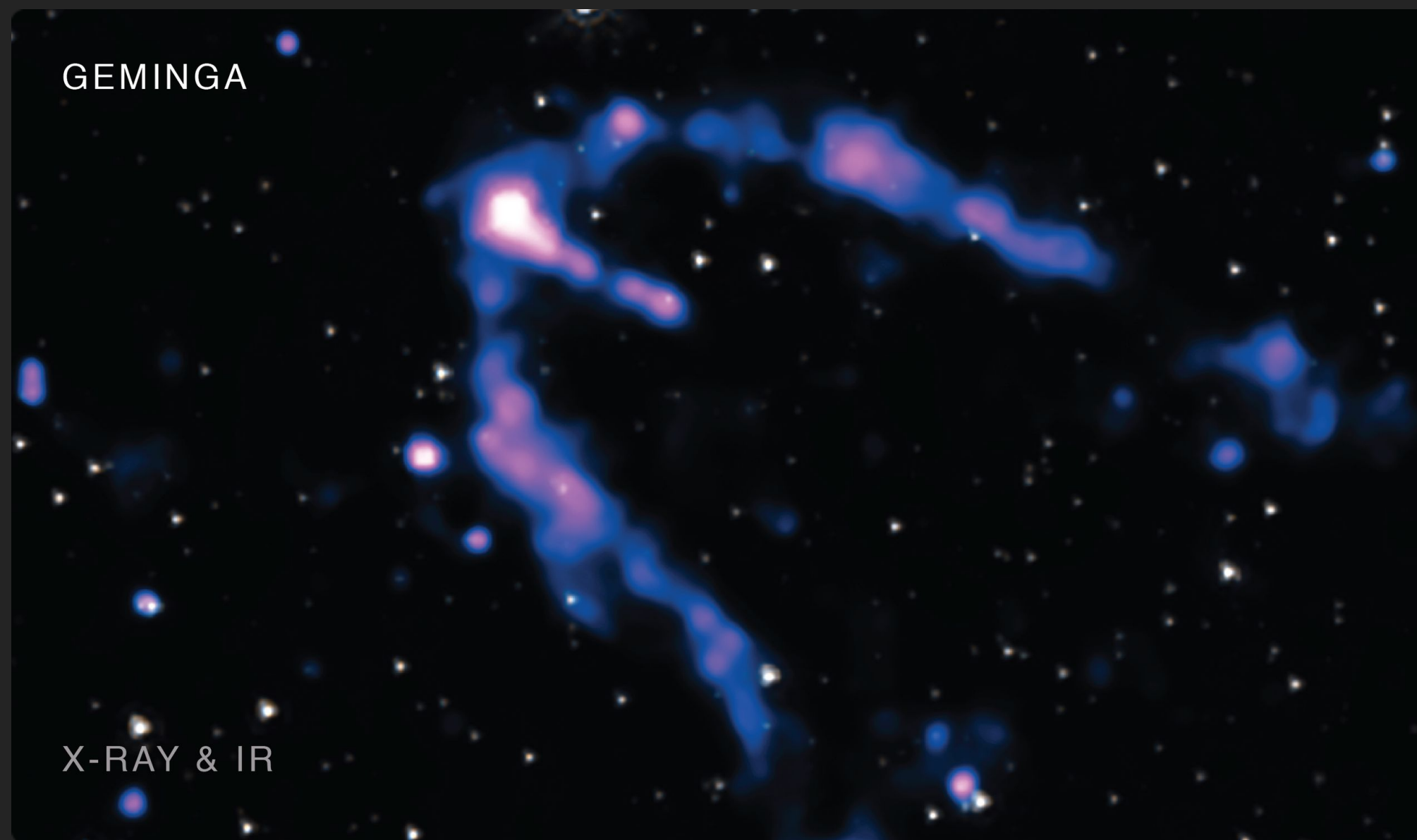
Dark Matter Annihilation



Positron Spectrum of Individual Pulsars

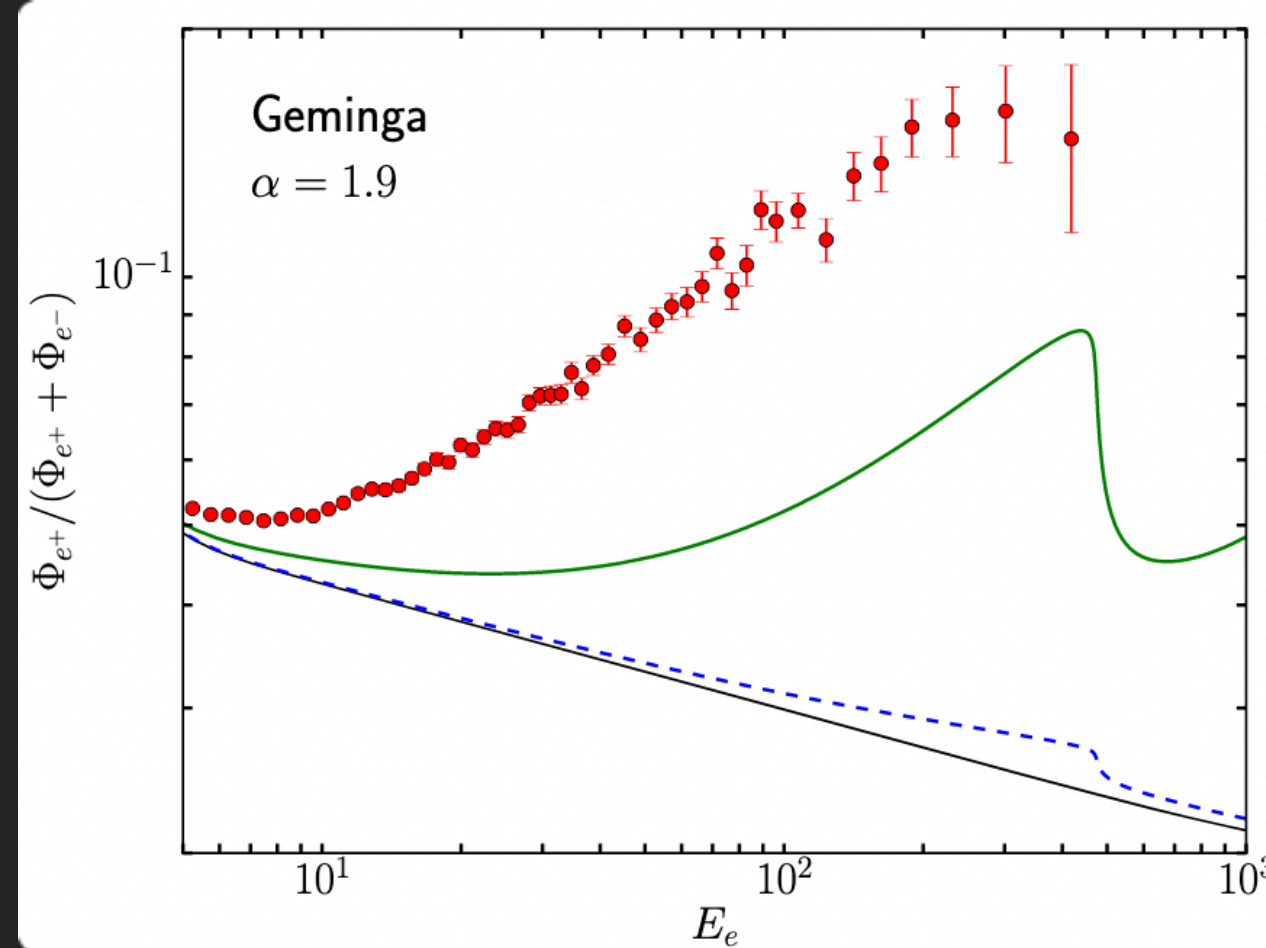
Template System: Geminga

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

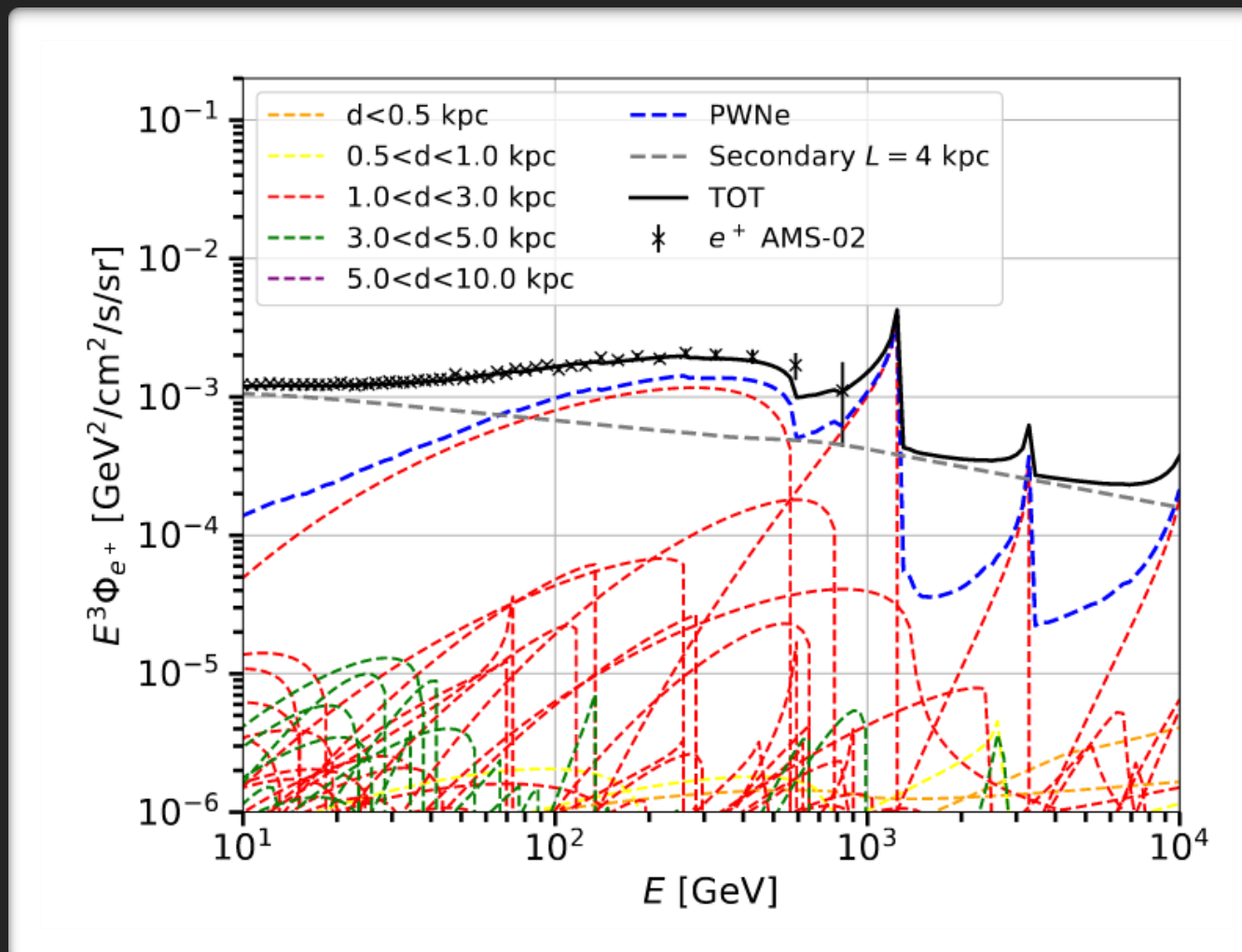


Analytic Model: Hooper et. al, arXiv:0810.1527

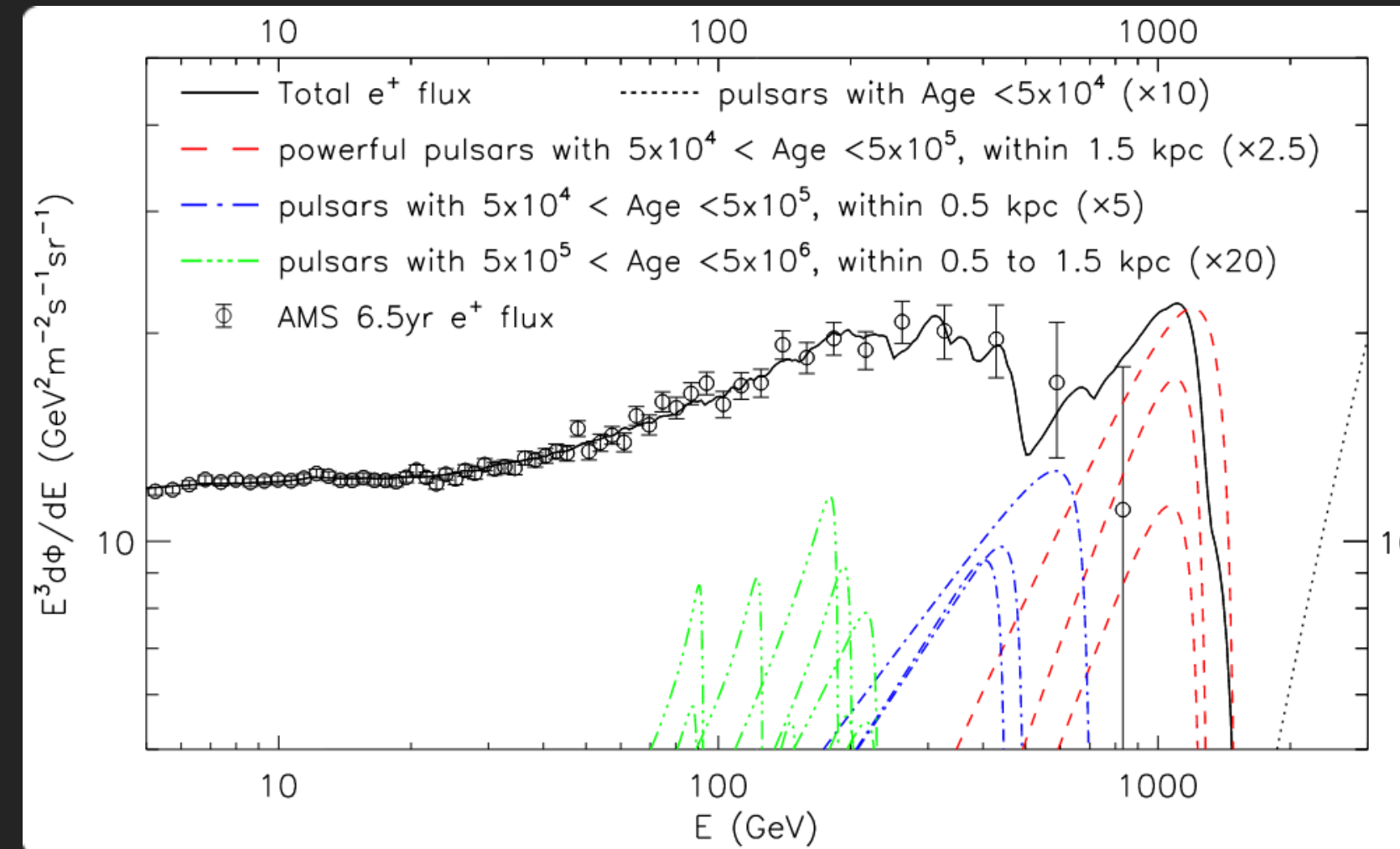
Recent Papers Predict Sharp Features for Individual Pulsars



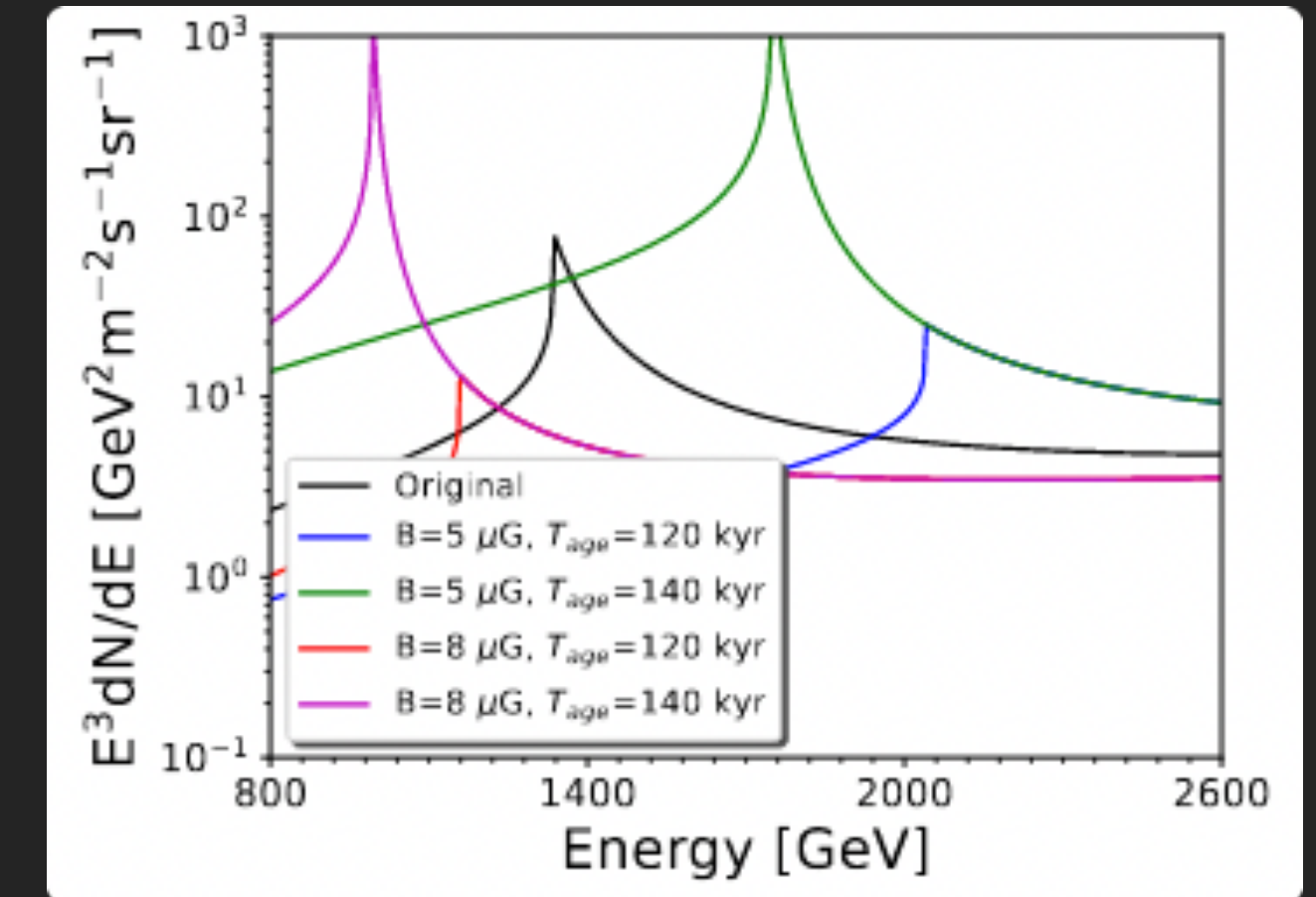
Hooper et al., arXiv:1702.08436



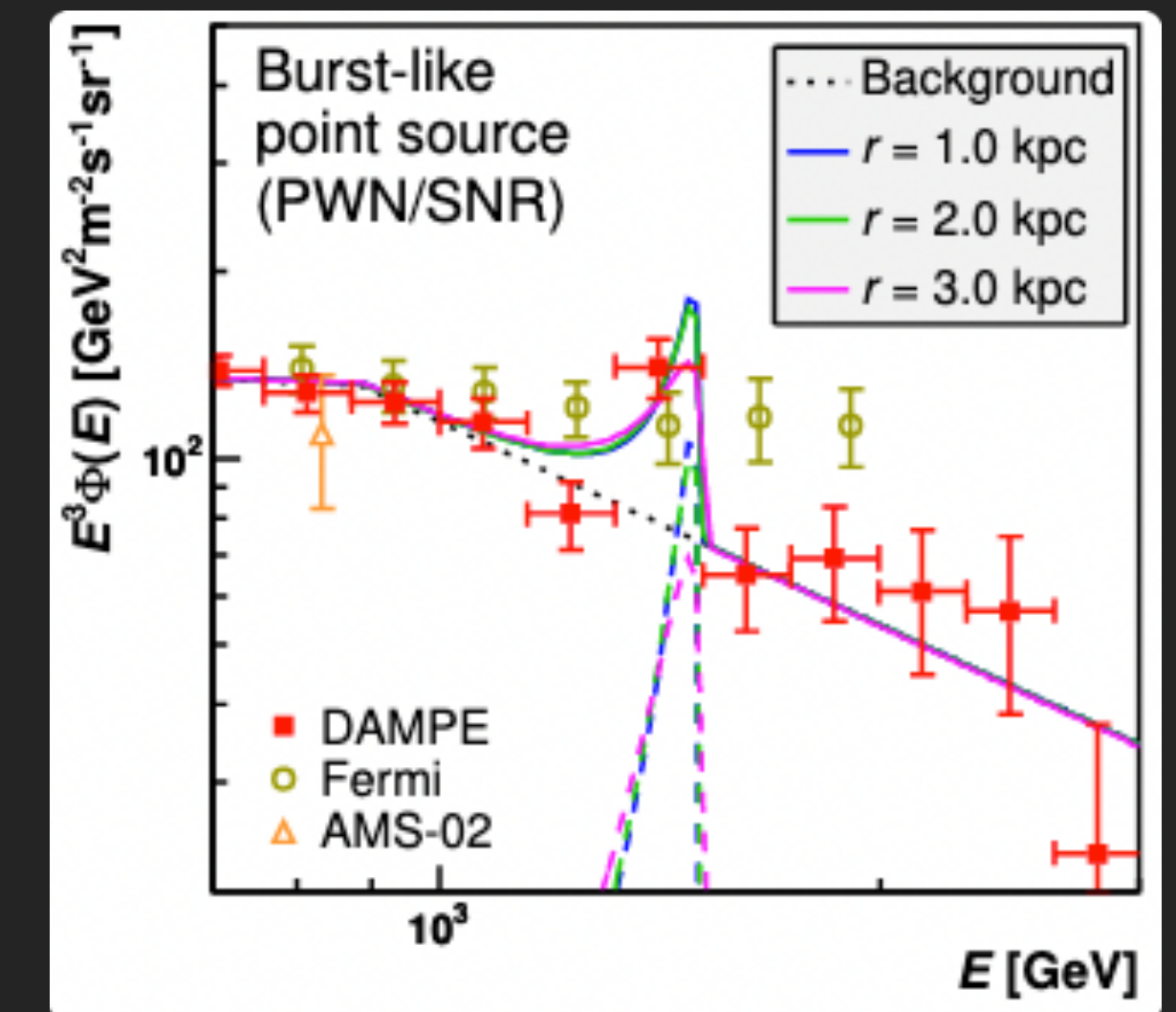
Orusa et al., arXiv:2107.06300



Cholis & Krommydas, arXiv:2111.05864



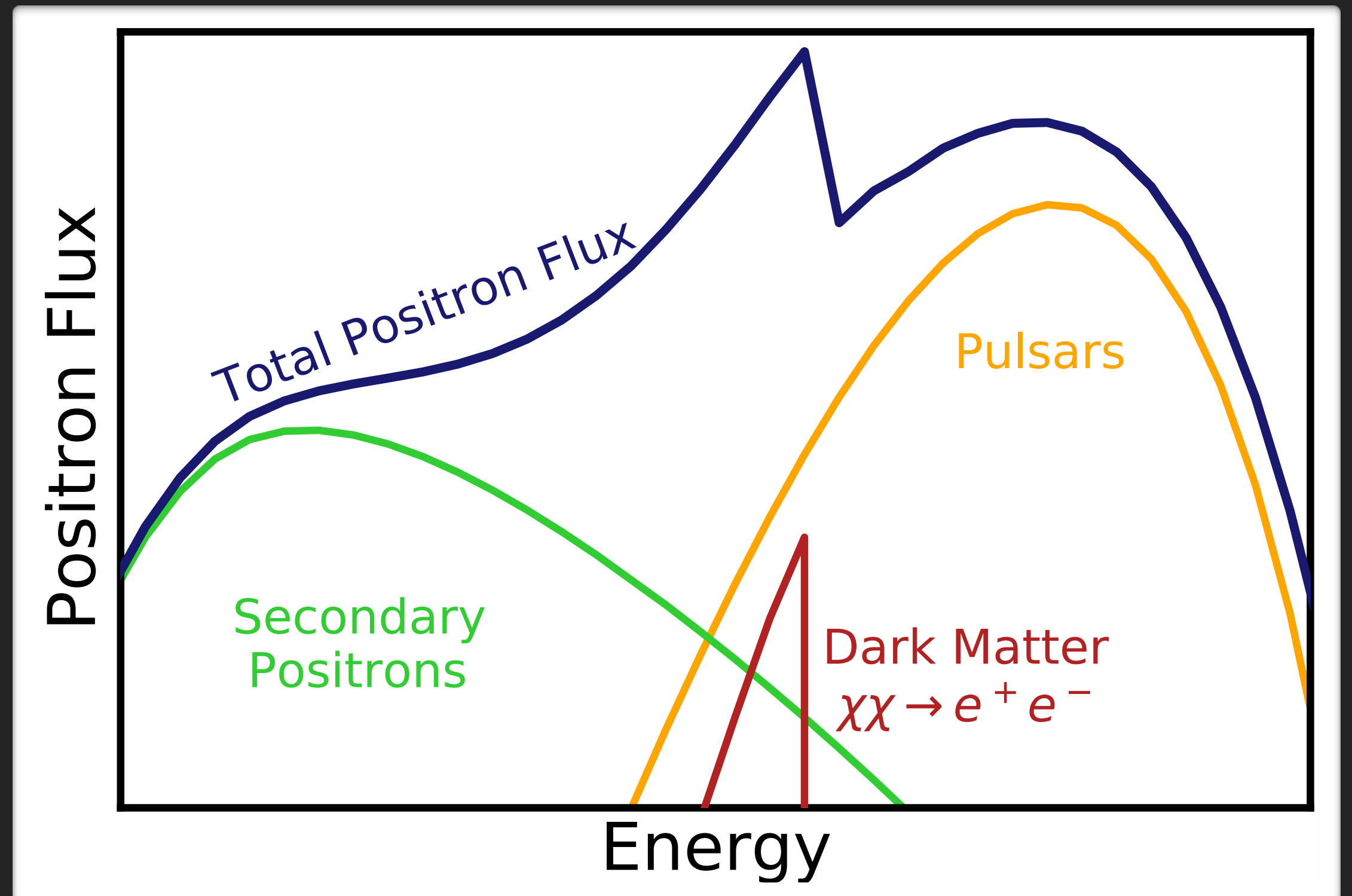
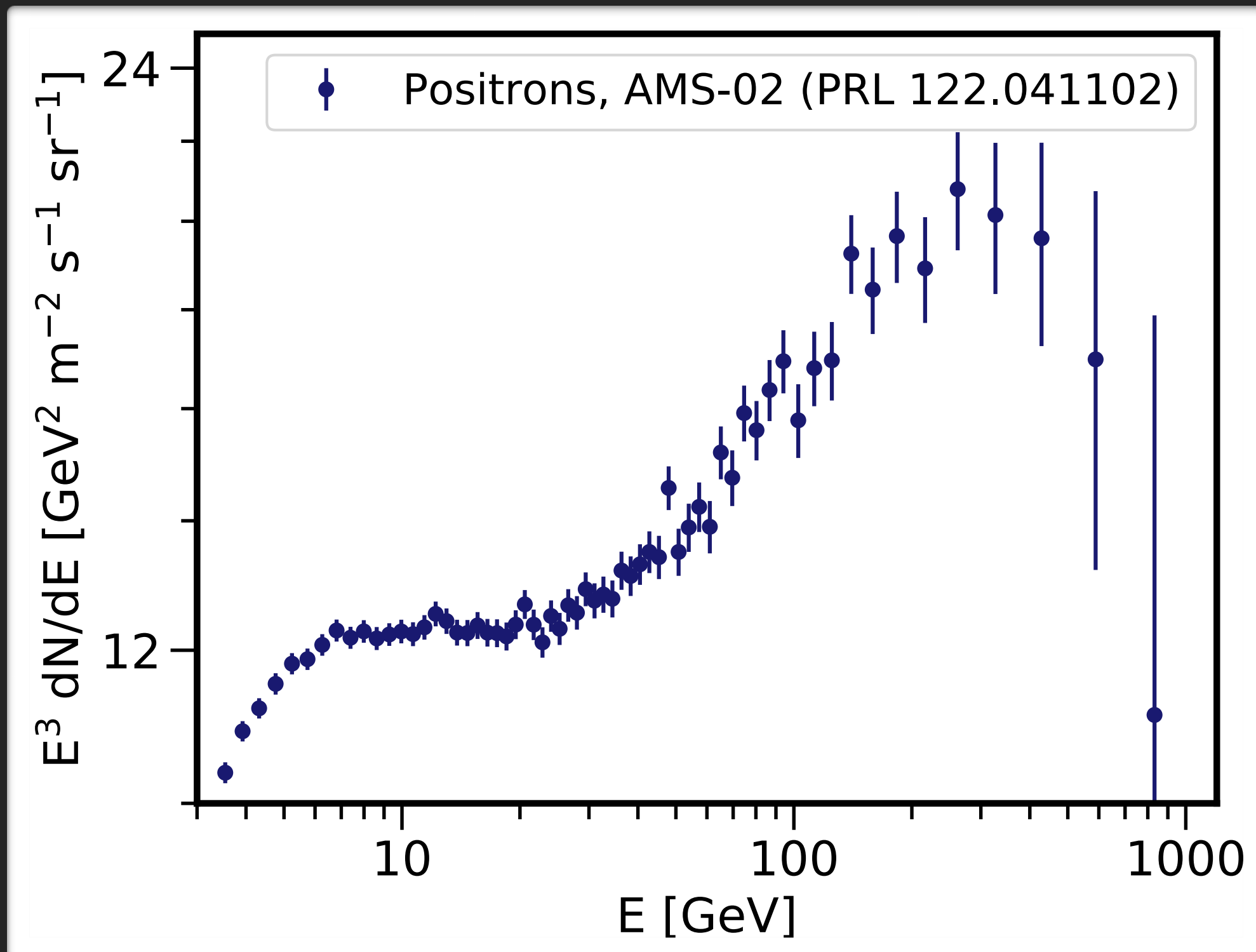
Bao et al., arXiv:2010.12170



Huang et al., arXiv:1712.00005

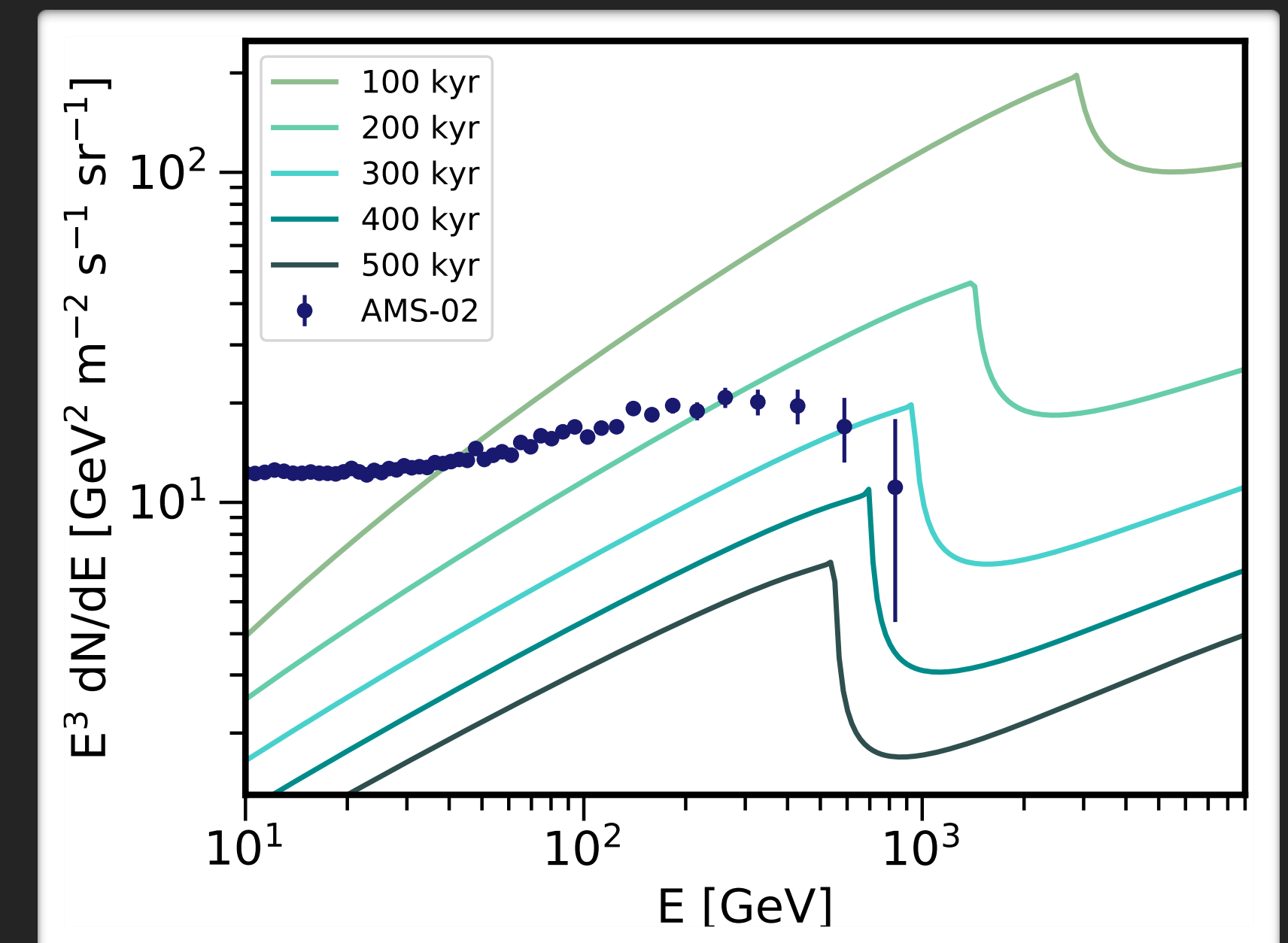
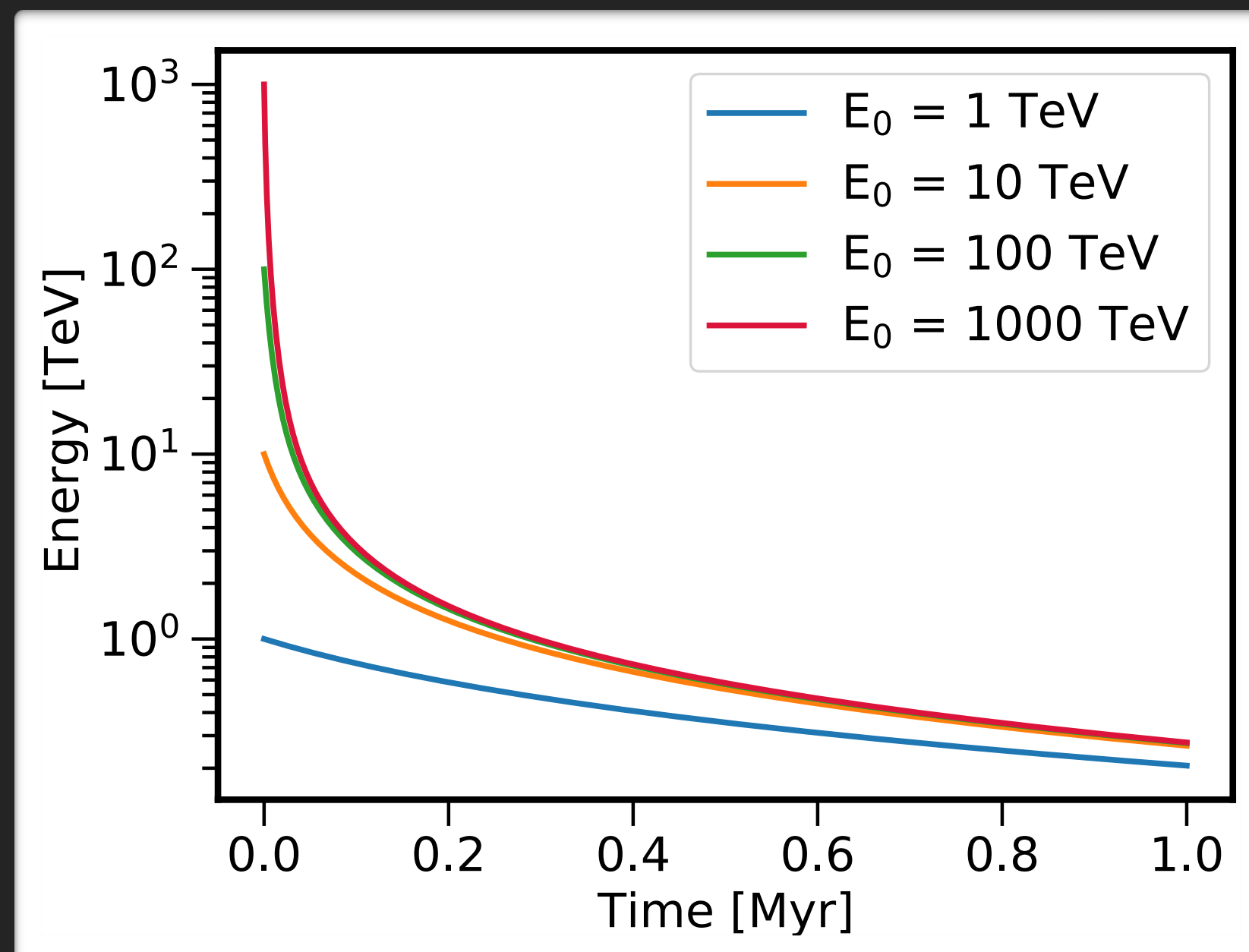
Sharp Spectral Features?

- AMS-02 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

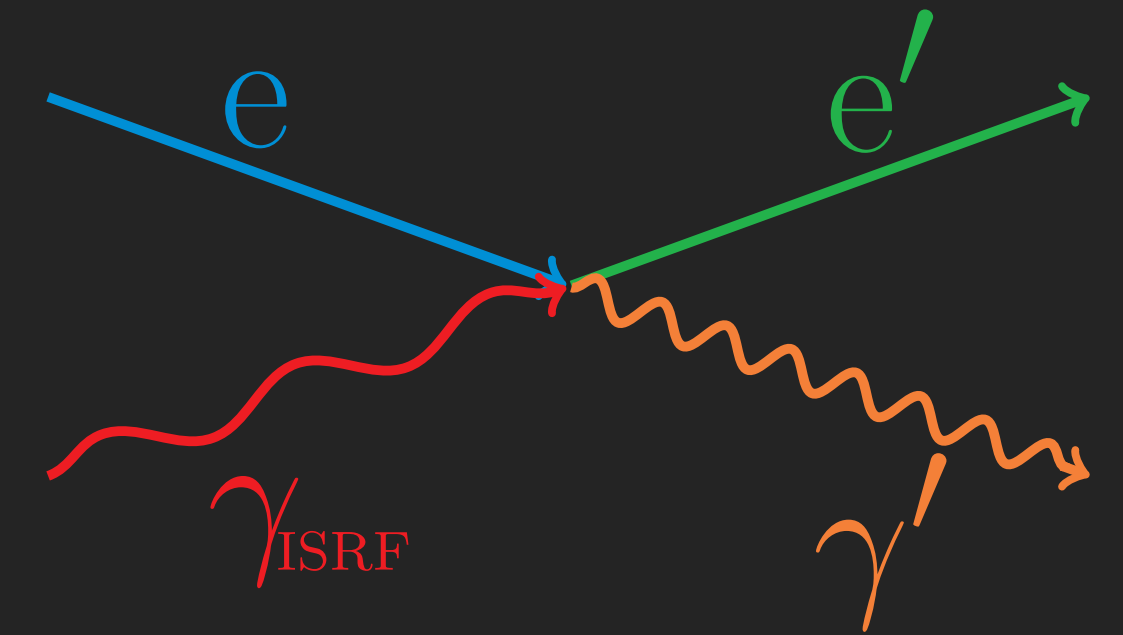
As positrons propagate through the Galaxy, they cool:

- 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

ν_i Photon energy

σ_T Thomson cross section

ρ_B Magnetic field energy density

ρ_i ISRF energy densities

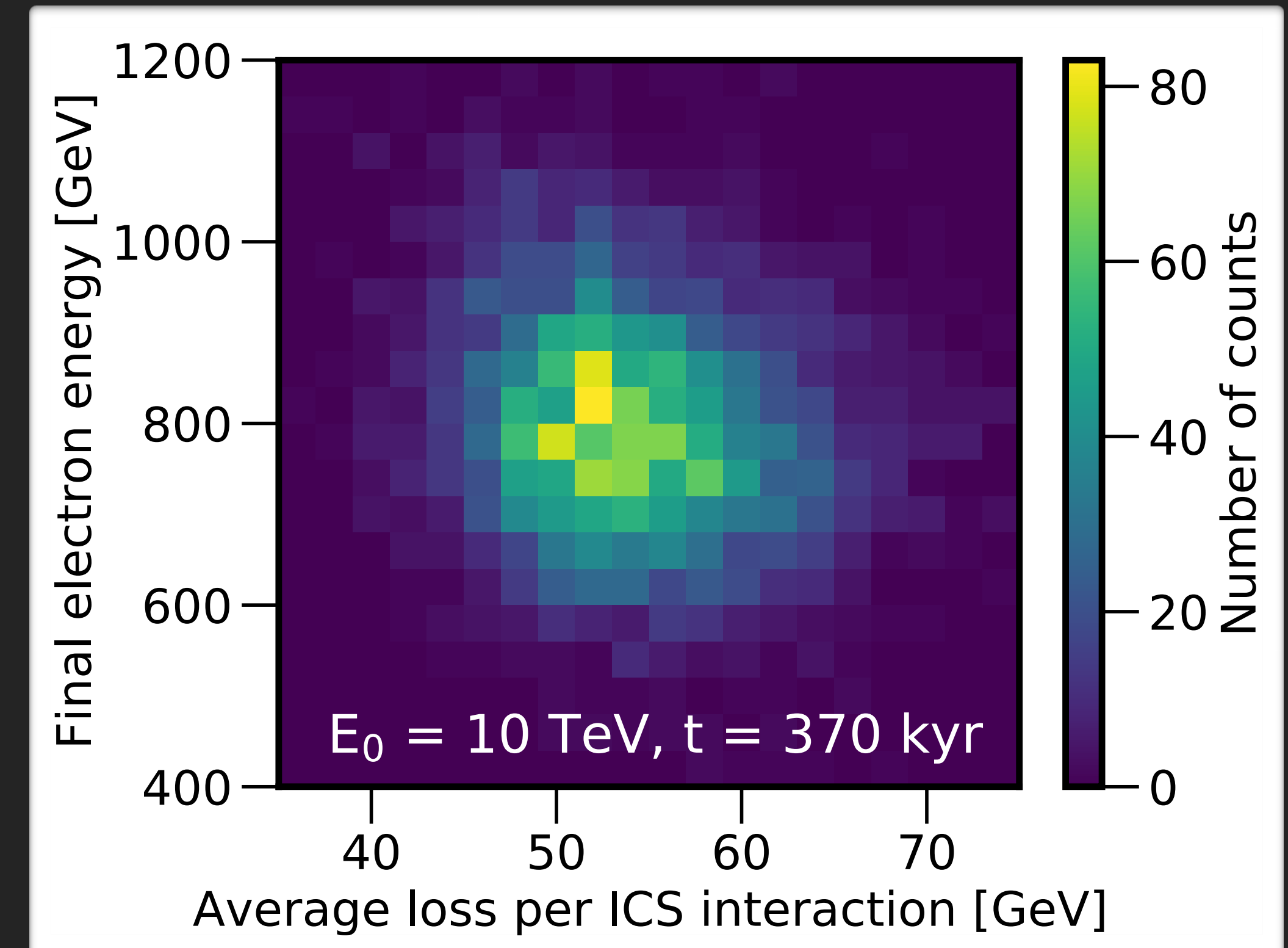
S Klein-Nishina suppression

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

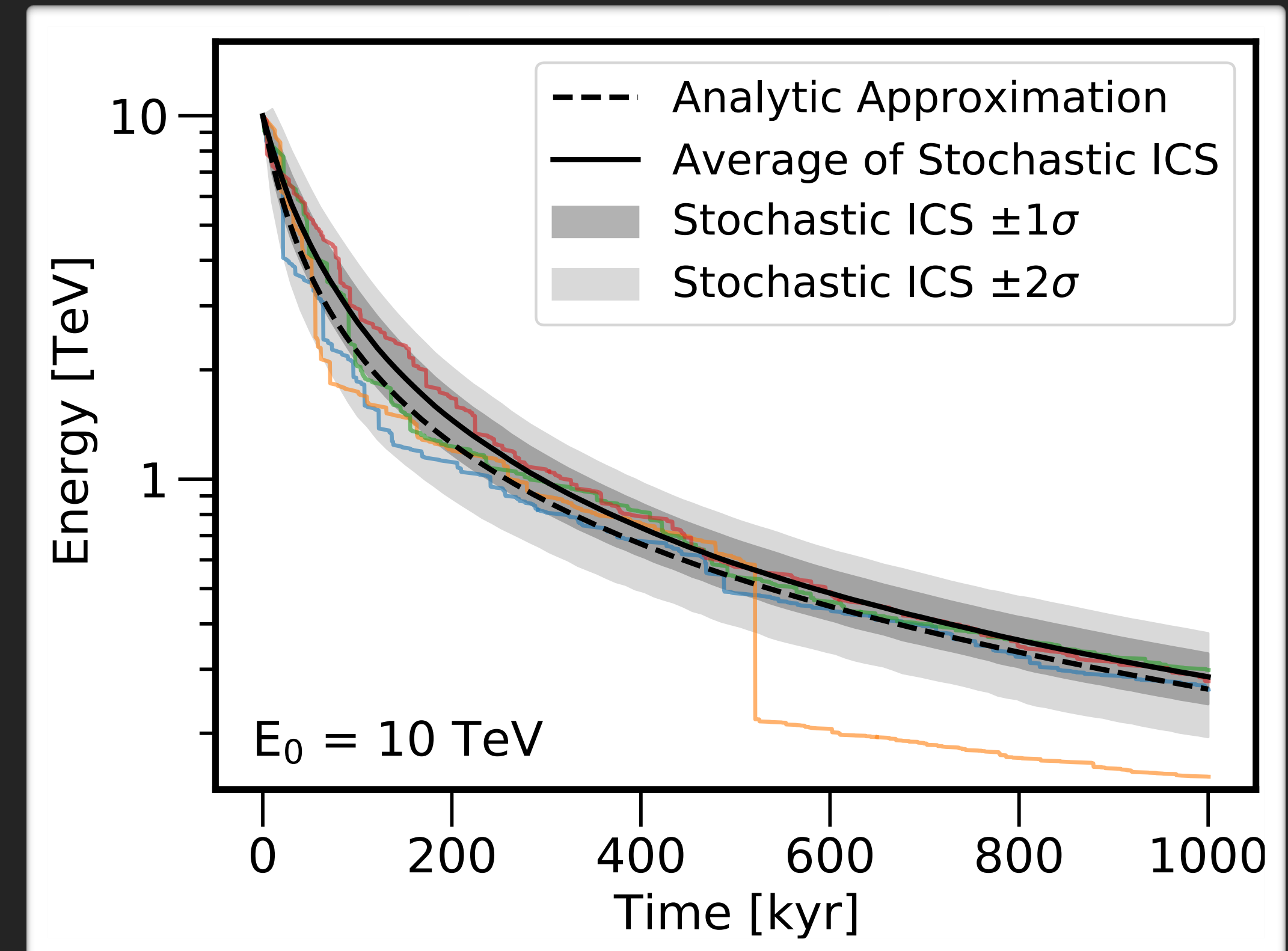
Stochasticity of Inverse-Compton Scattering

- **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

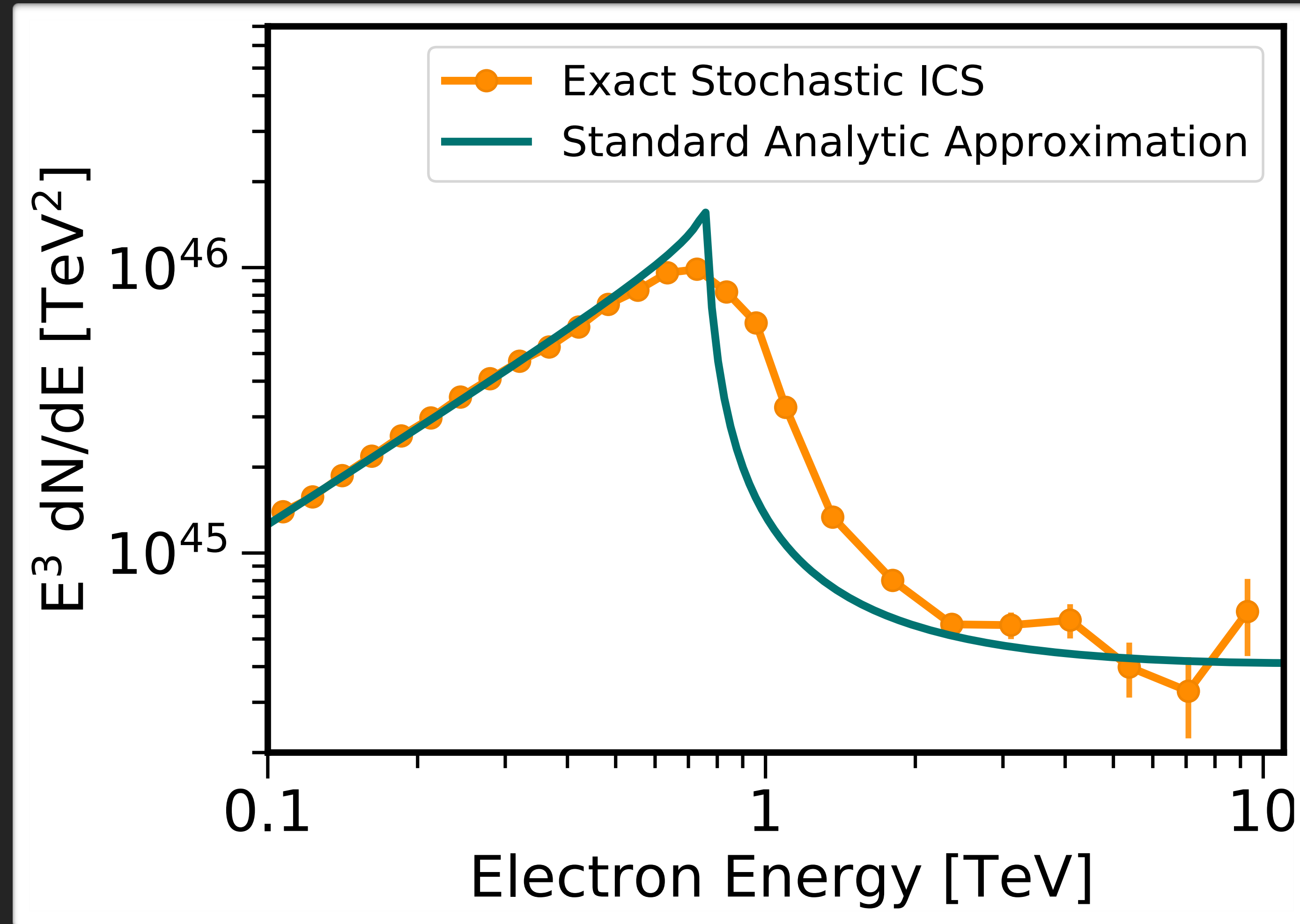


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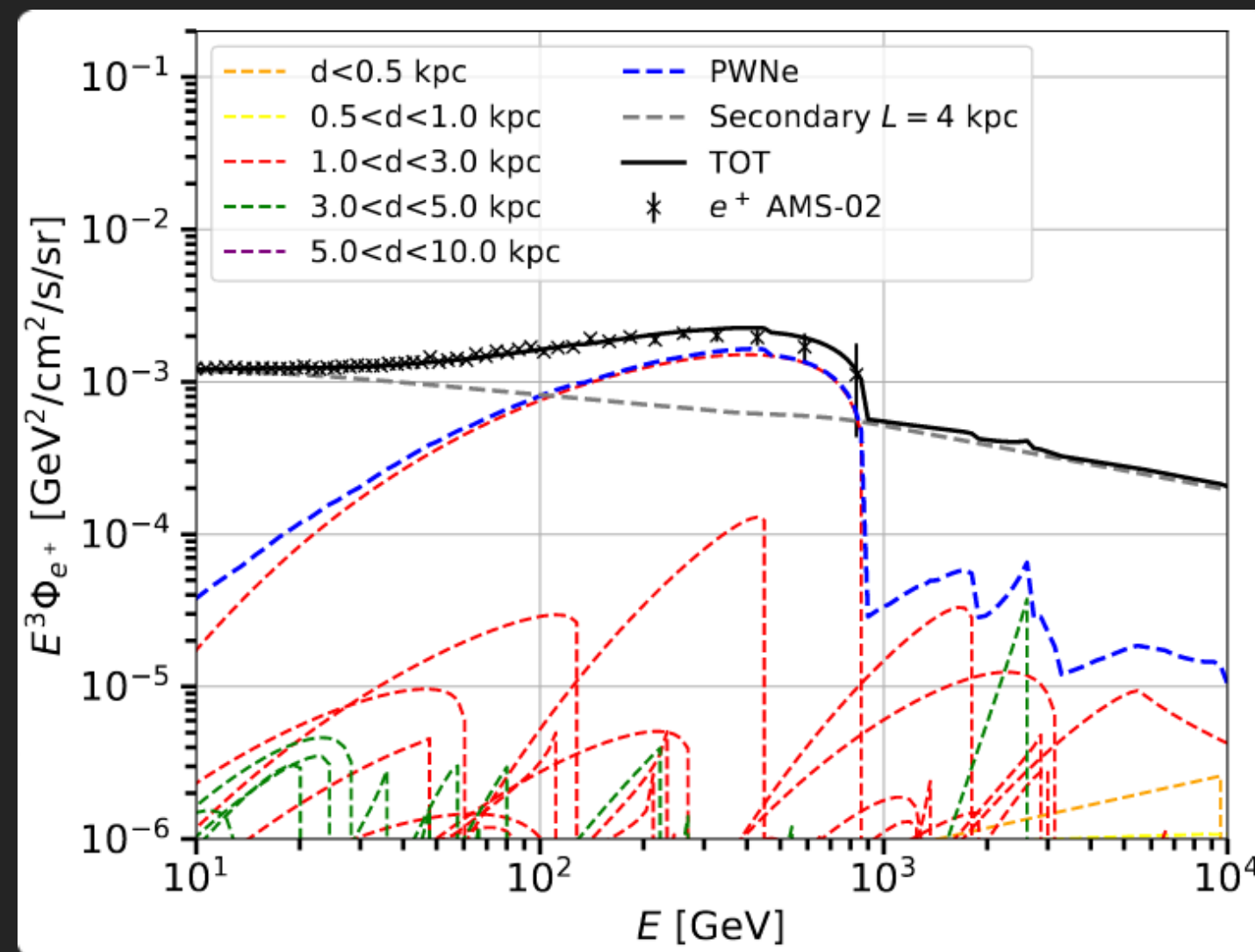
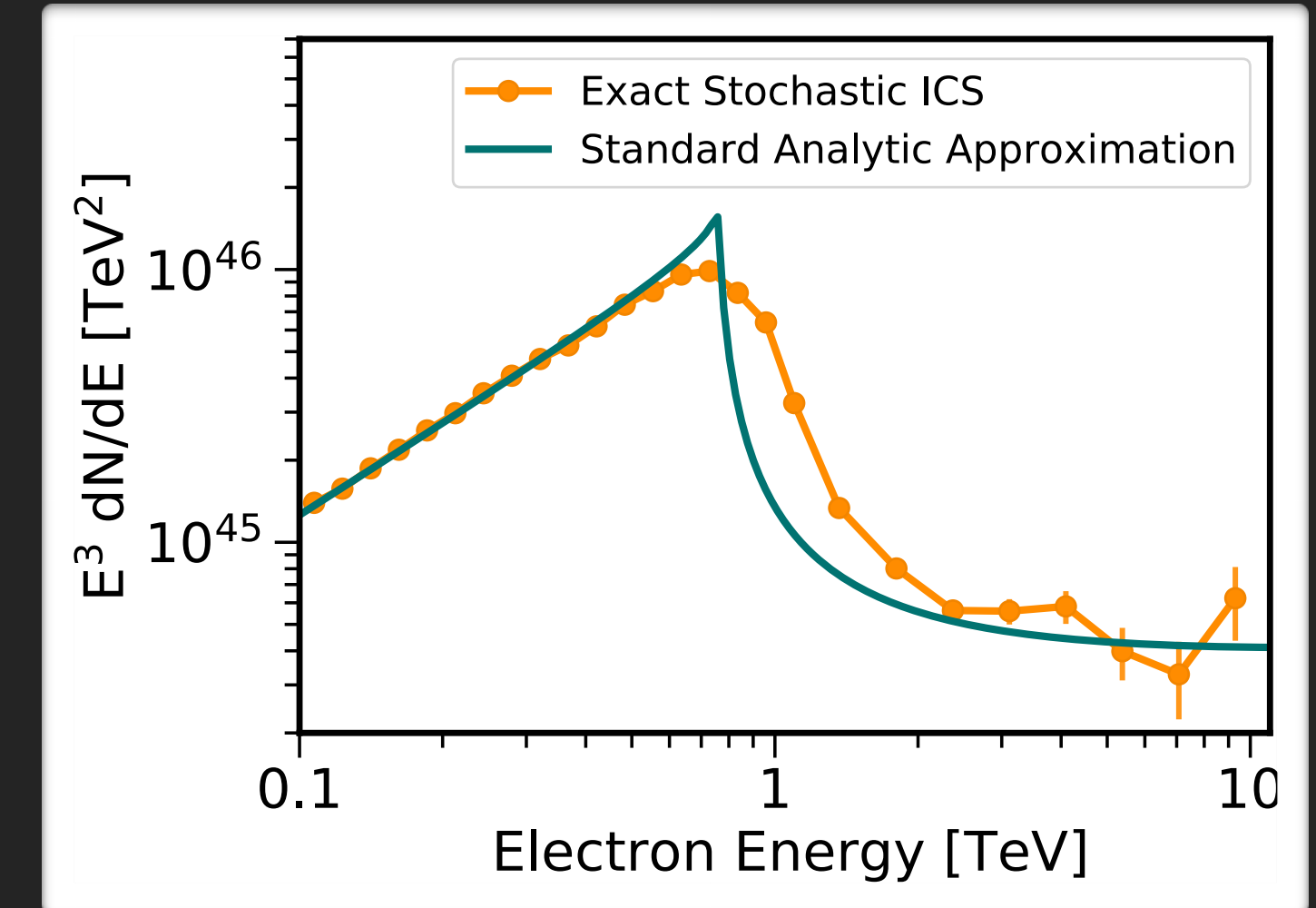
Positron Spectrum of Individual Pulsars



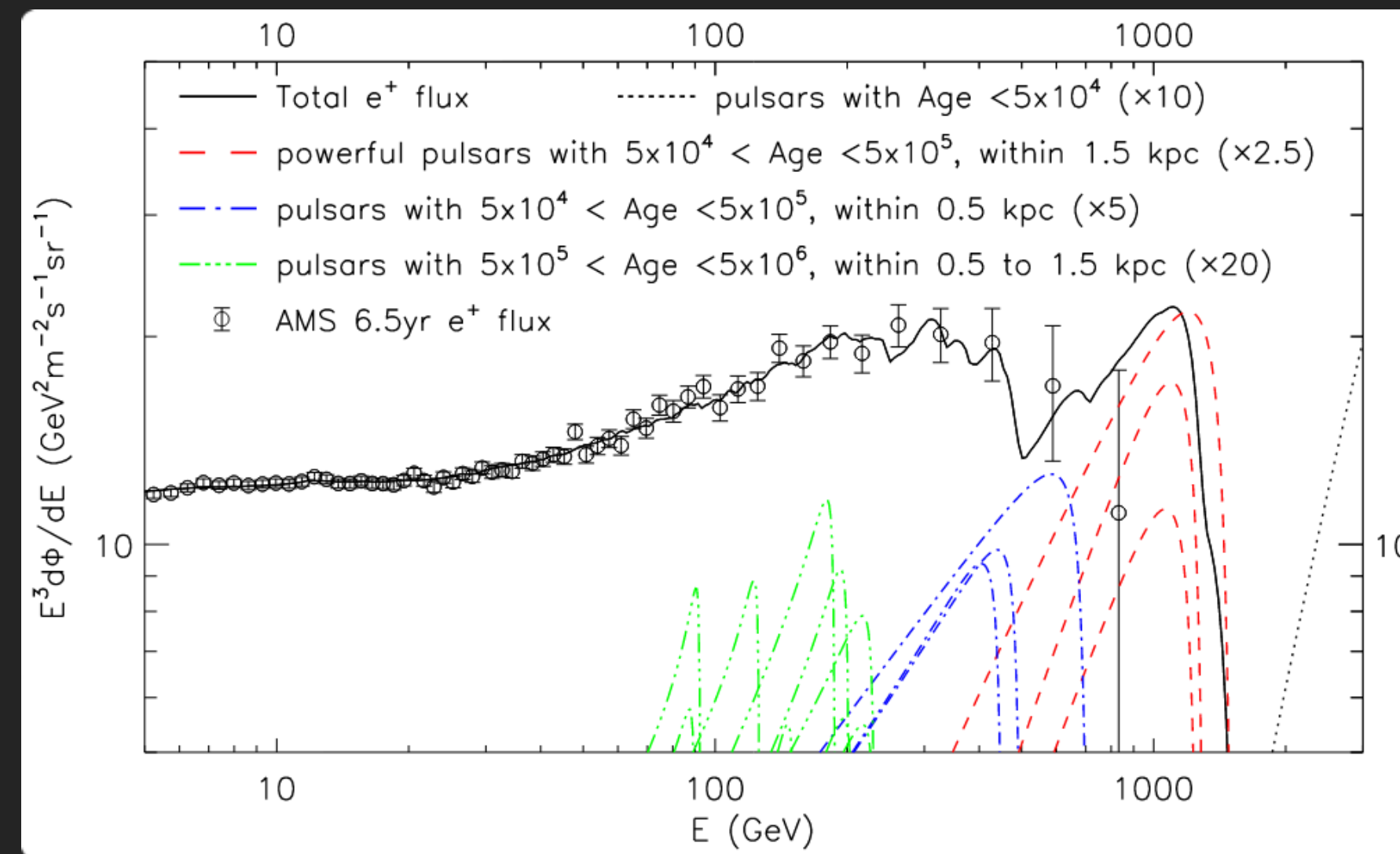
- Sharp spectral features introduced by analytic approximation are smoothed out by ~50% when correctly treating inverse-Compton scattering stochastically

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 below 500 GeV:
Possibly only smaller number of pulsars needed to fit positron flux



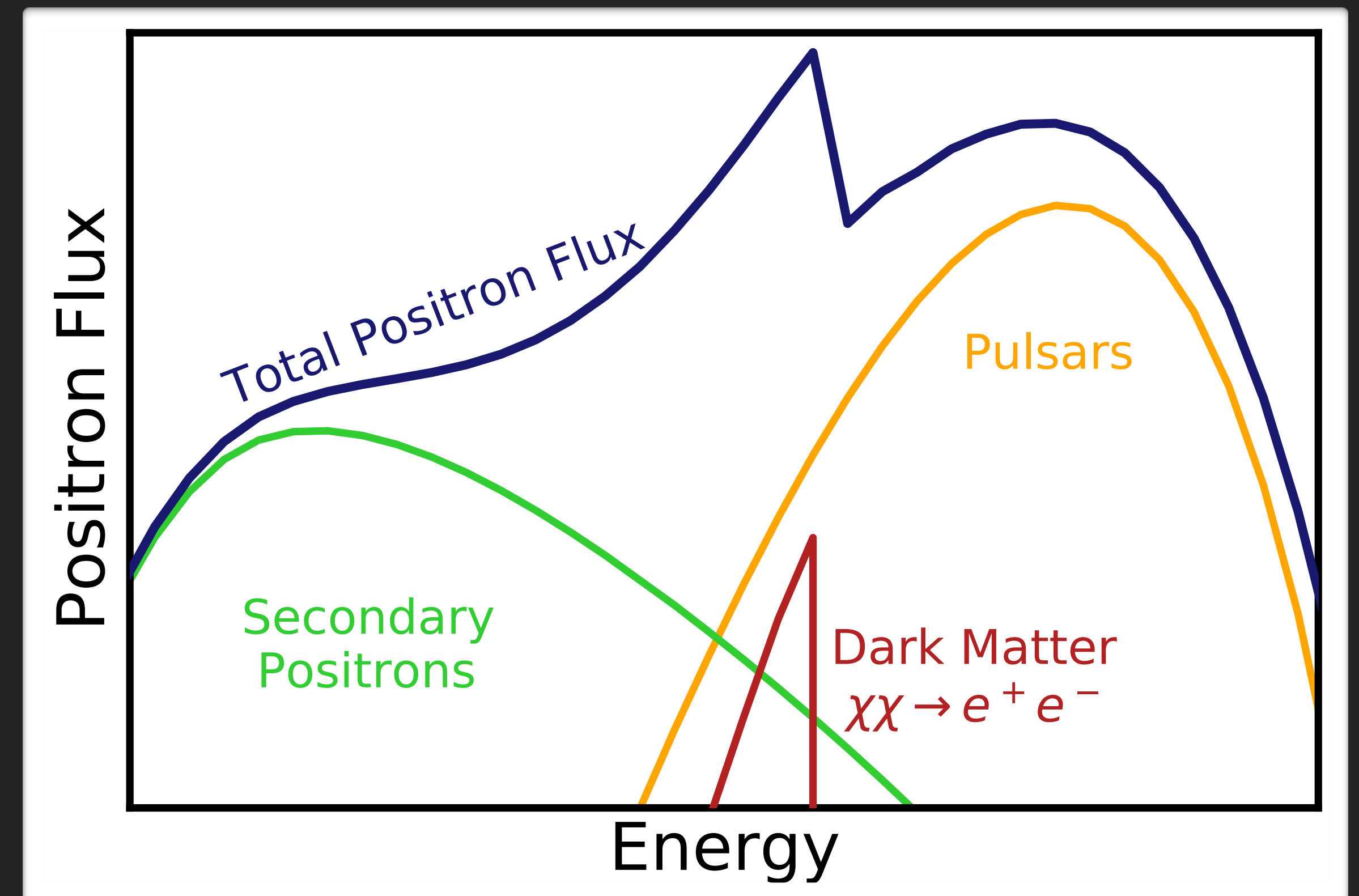
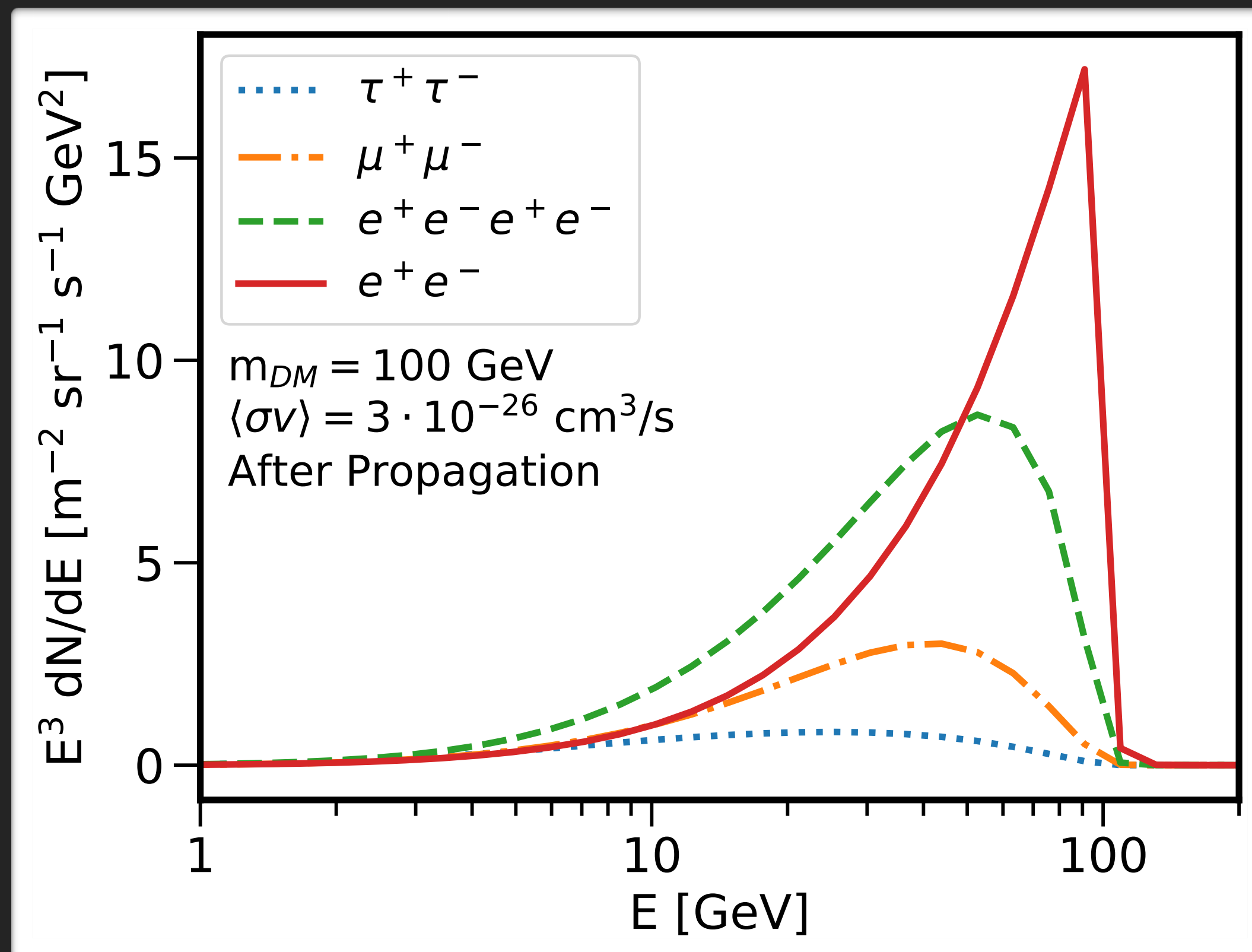
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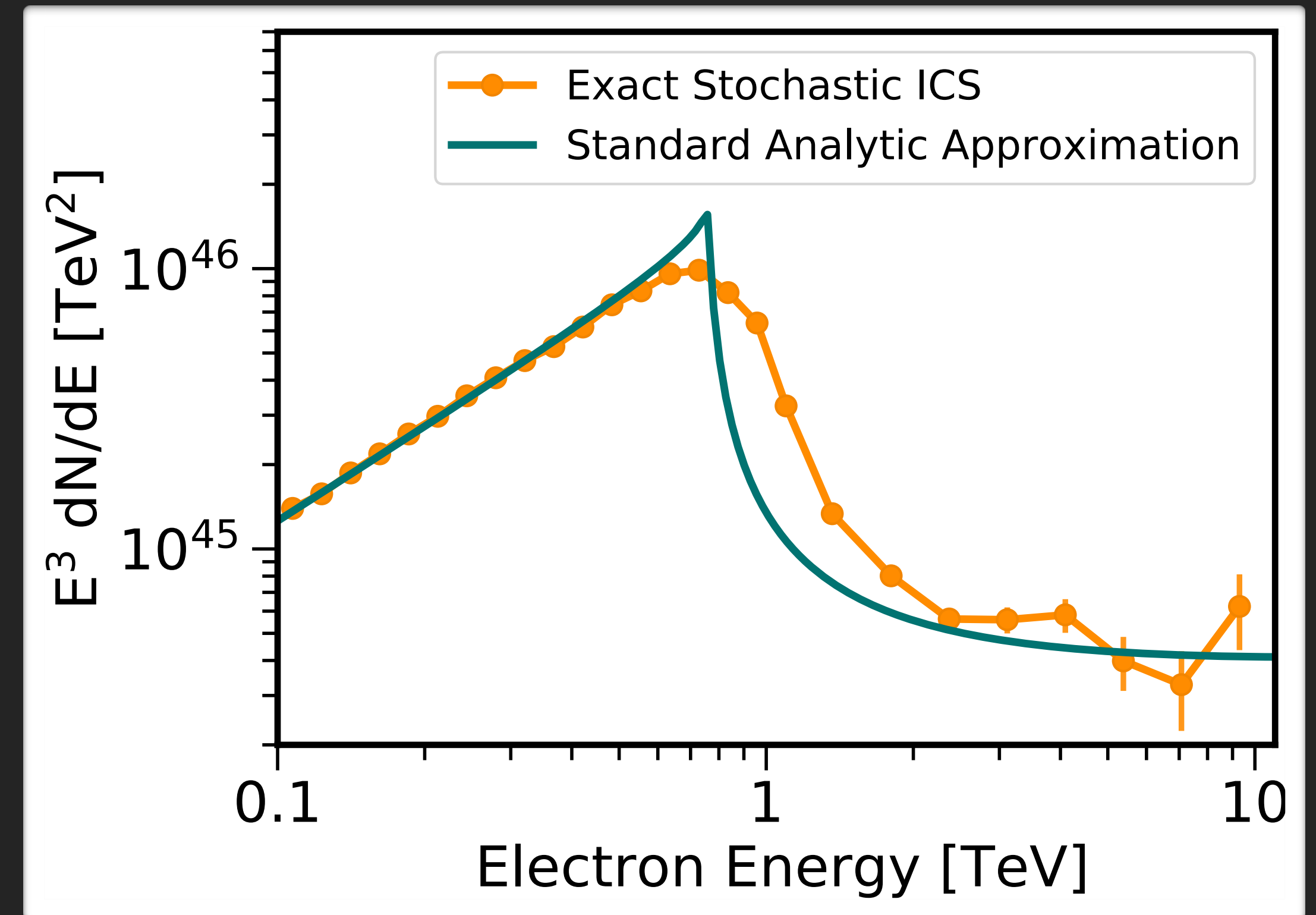
Implications for Dark Matter

- 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



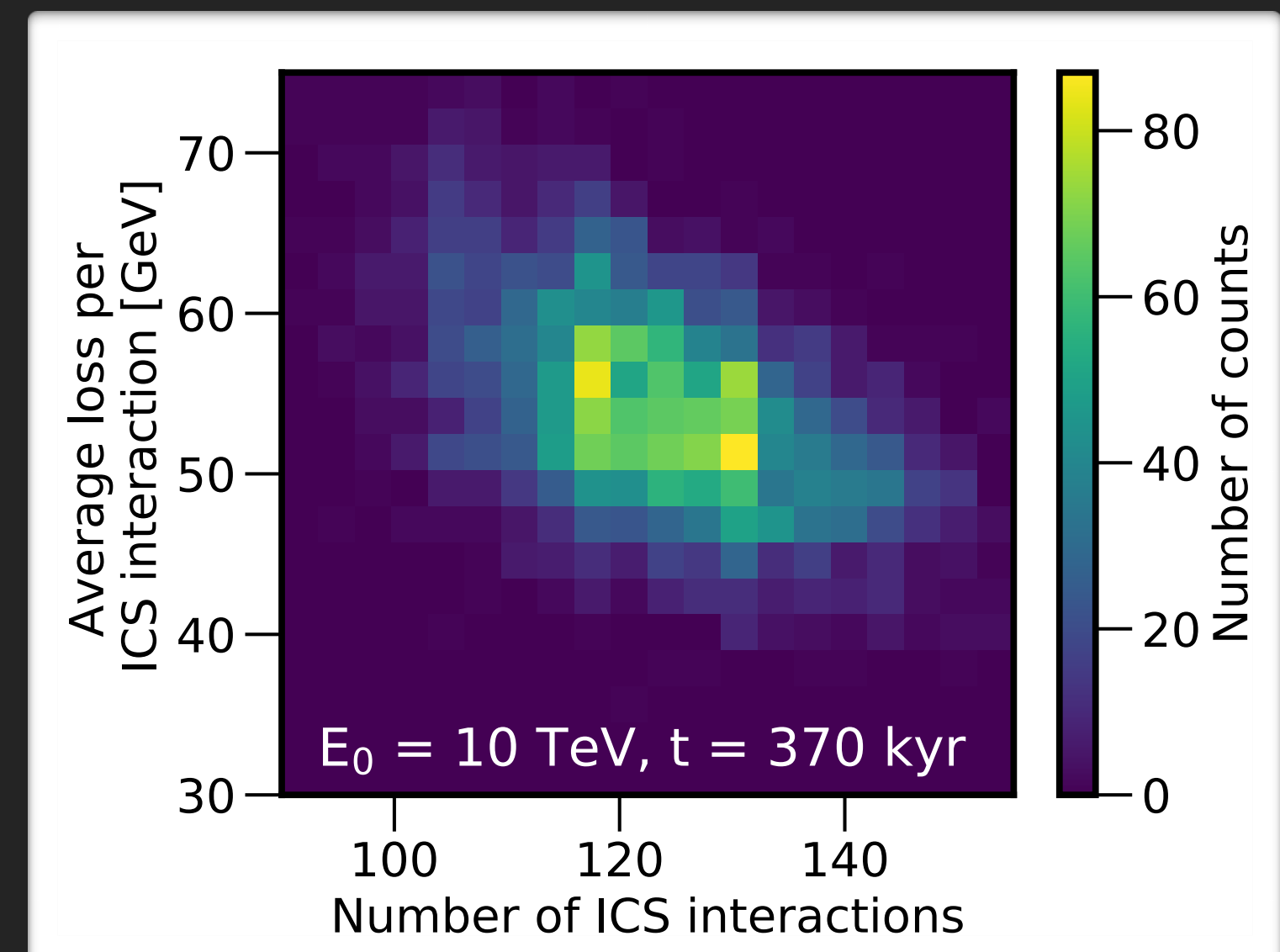
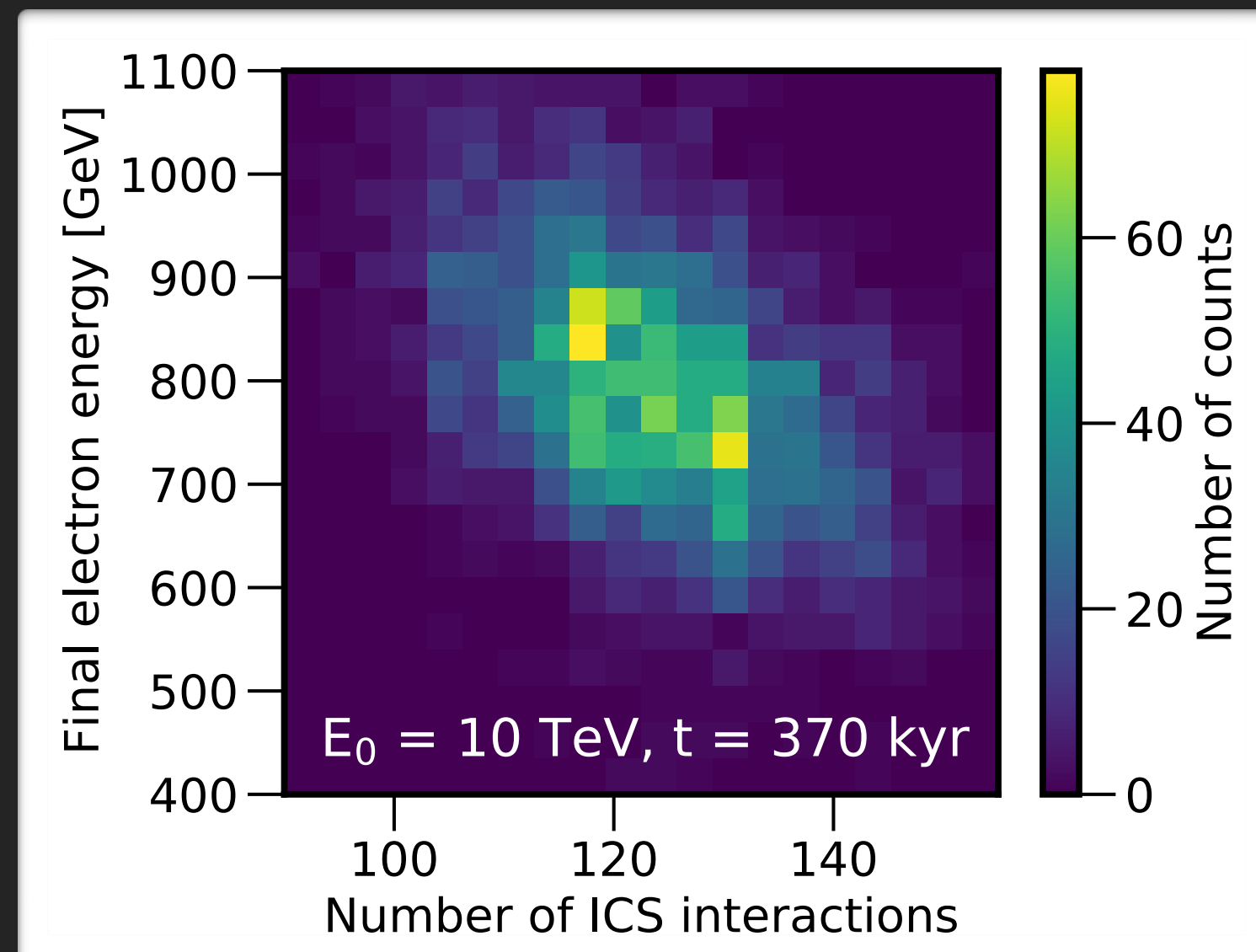
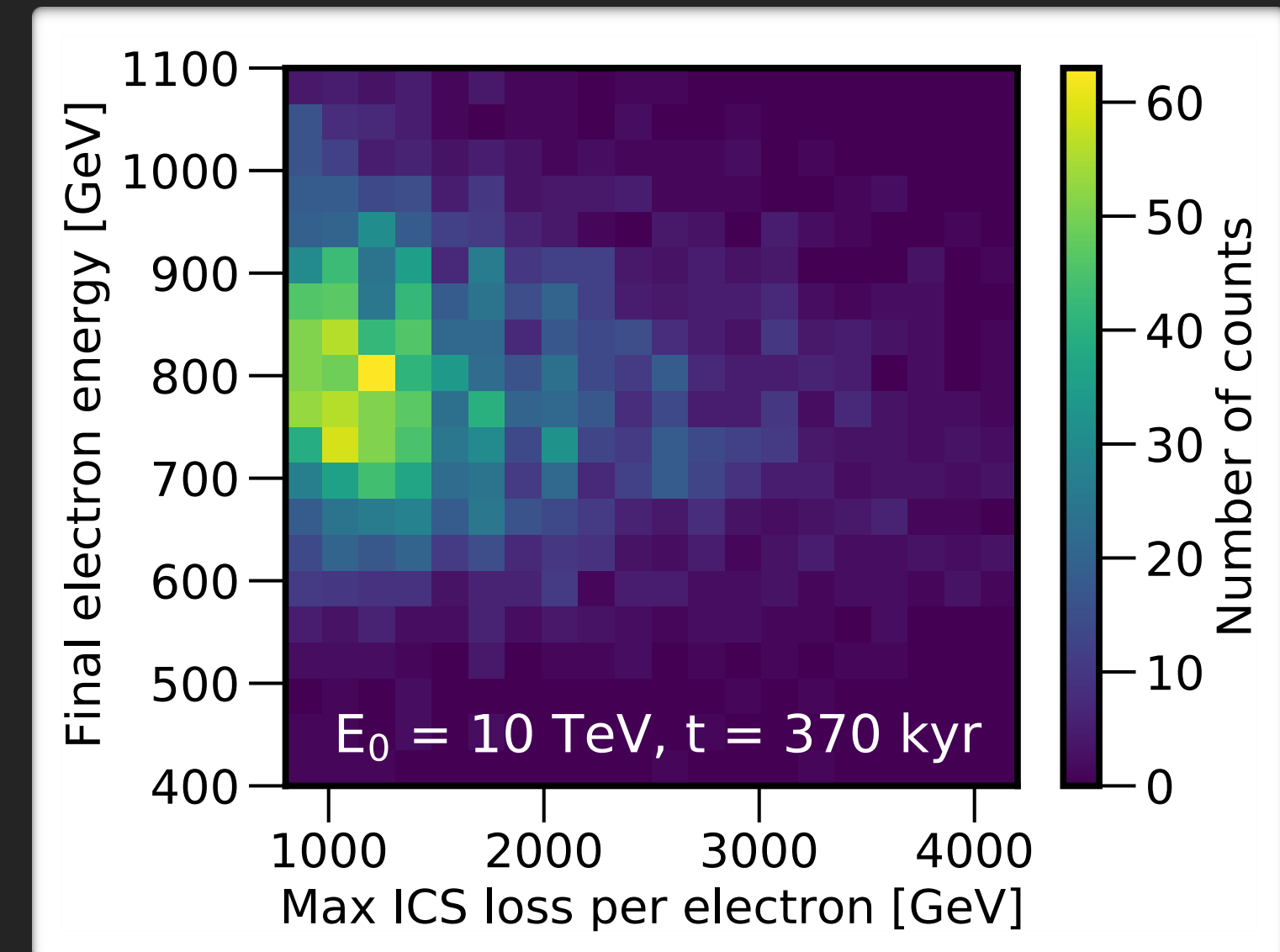
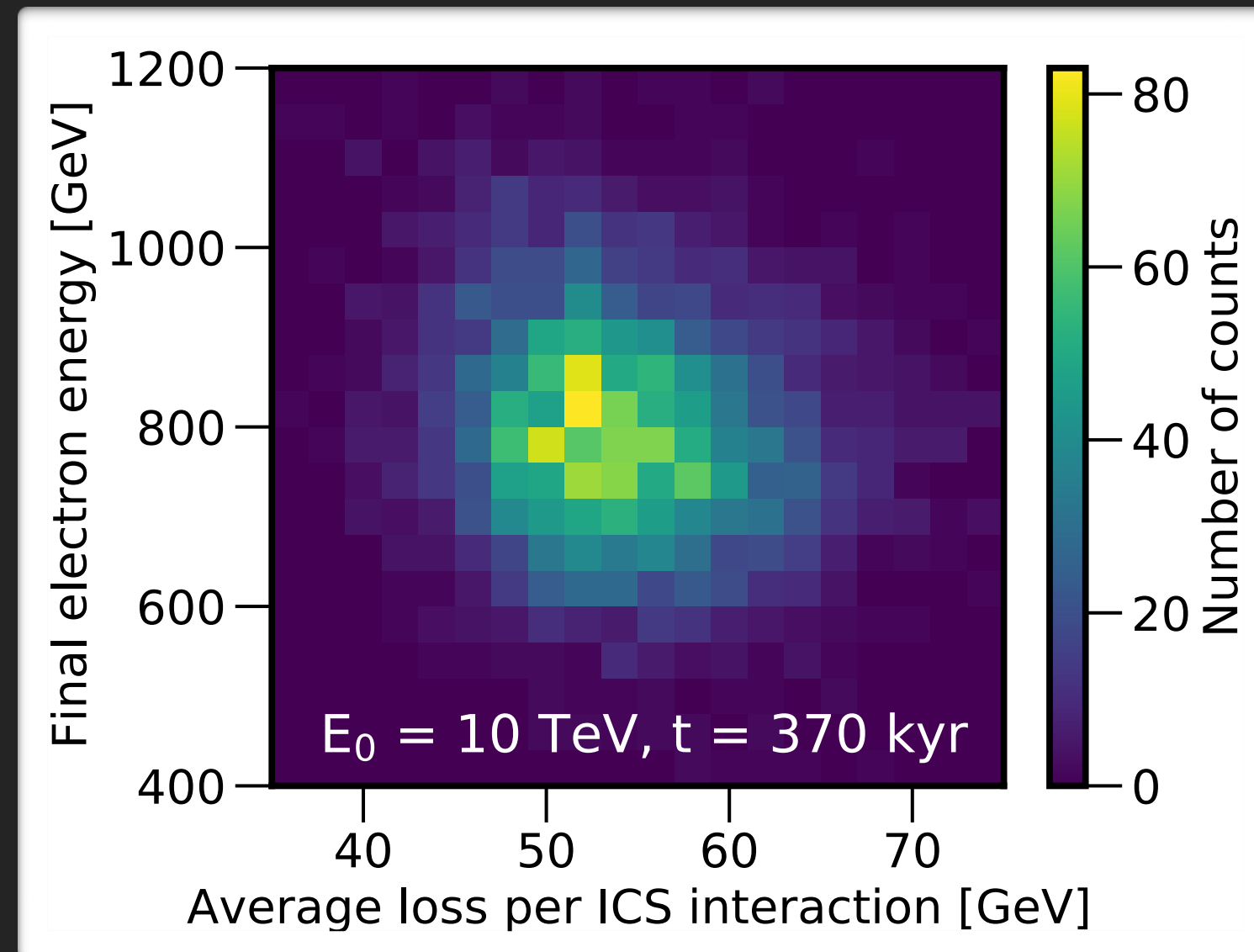
Summary

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

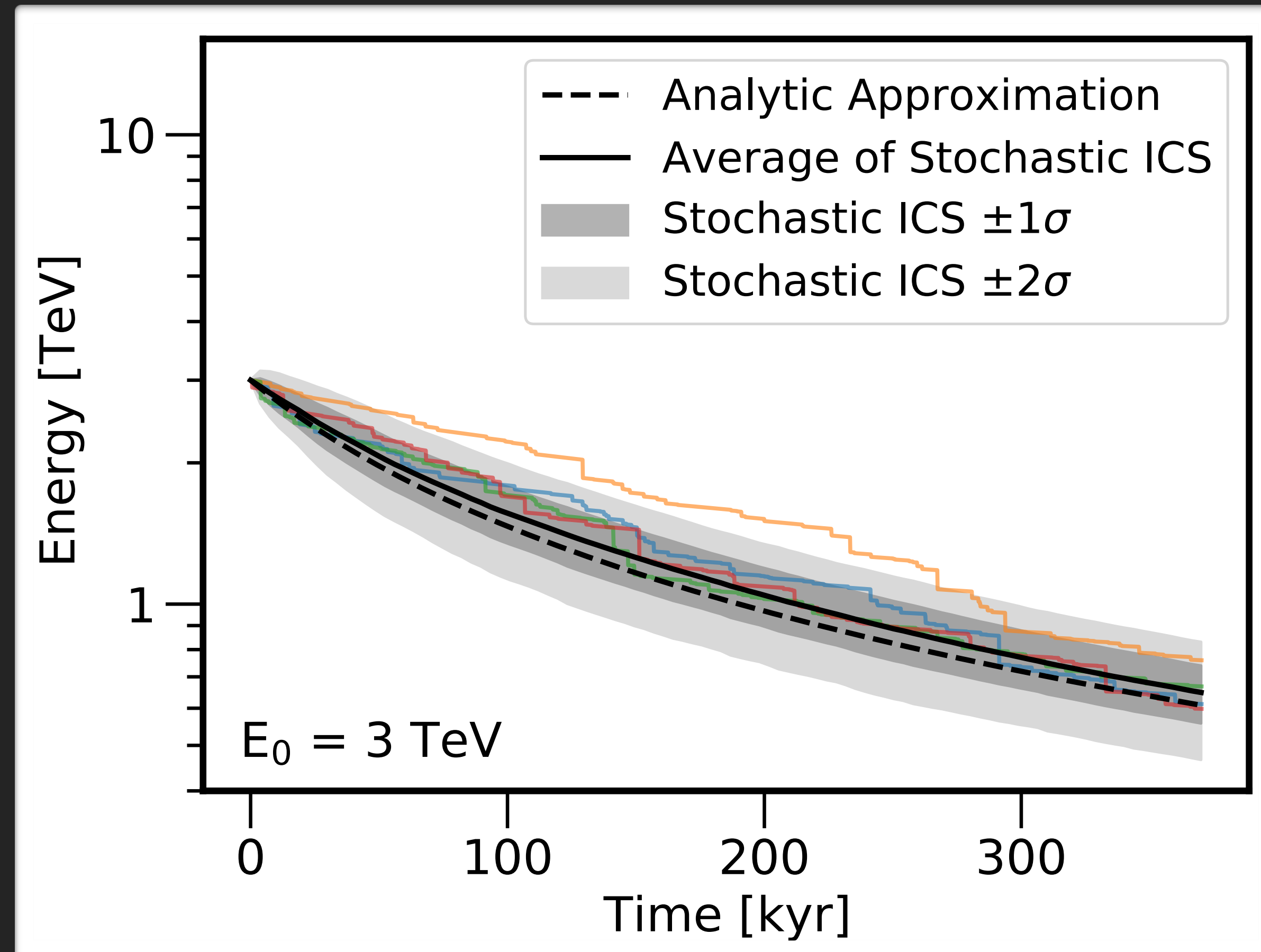


Supplementary Slides

Stochastic Inverse-Compton Scattering



Stochastic Inverse-Compton Scattering



Spectral Feature is Independent of Diffusion

