Pulsars do not Produce Sharp Features in the Cosmic-Ray Electron and Positron Spectra

I. John & T. Linden, arXiv:2206.04699

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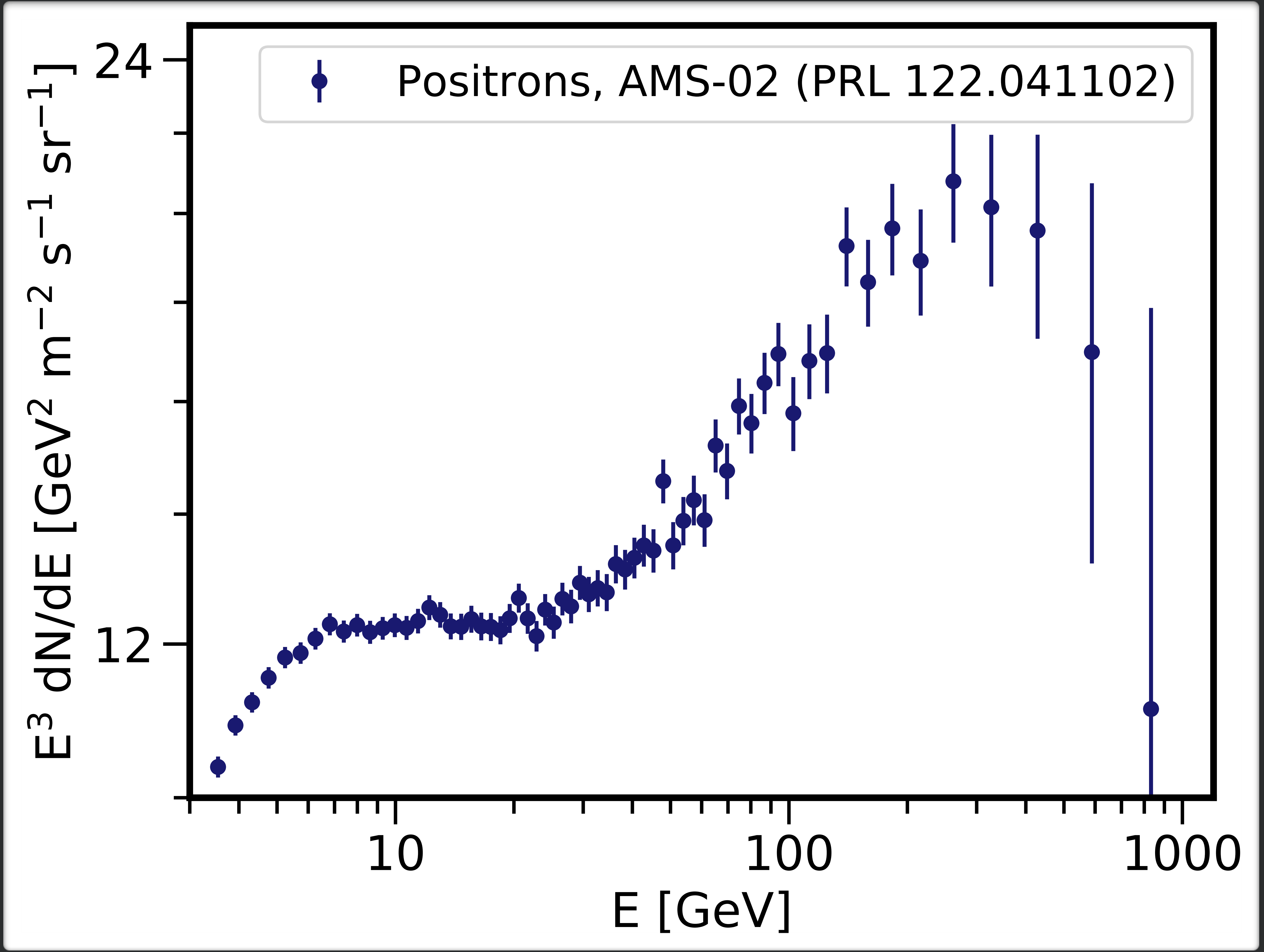
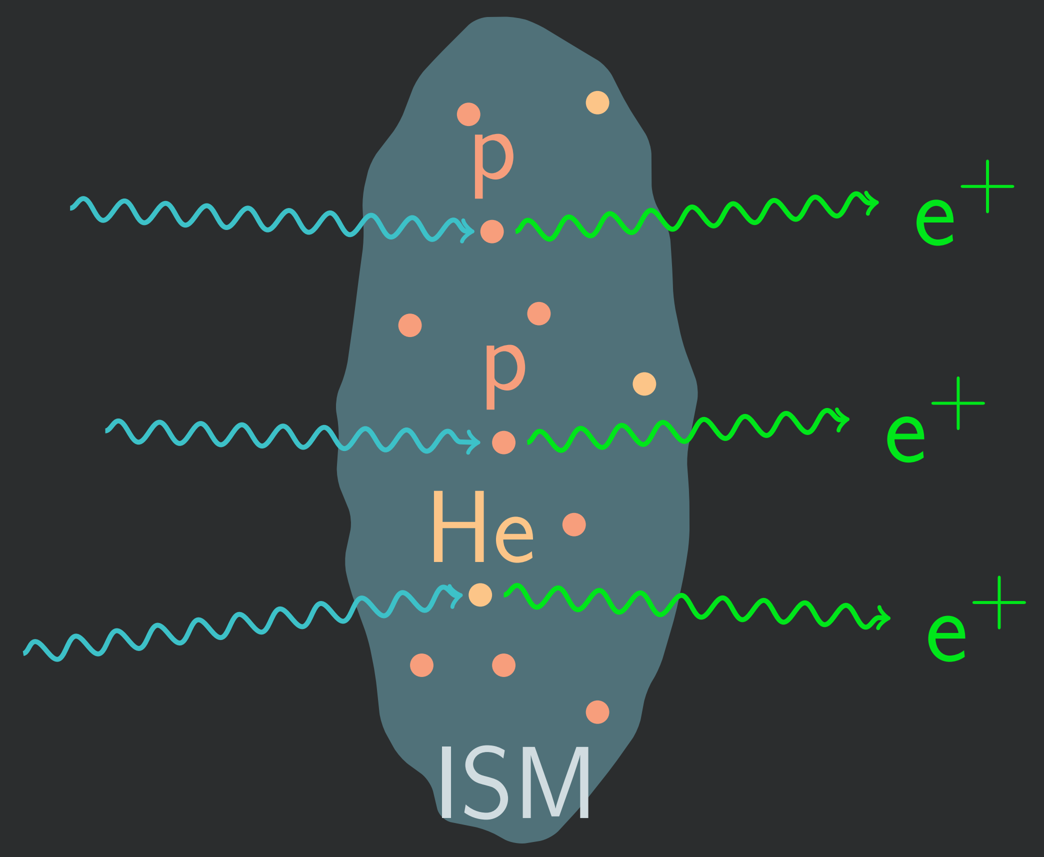
Local Cosmic-Ray Positron Flux

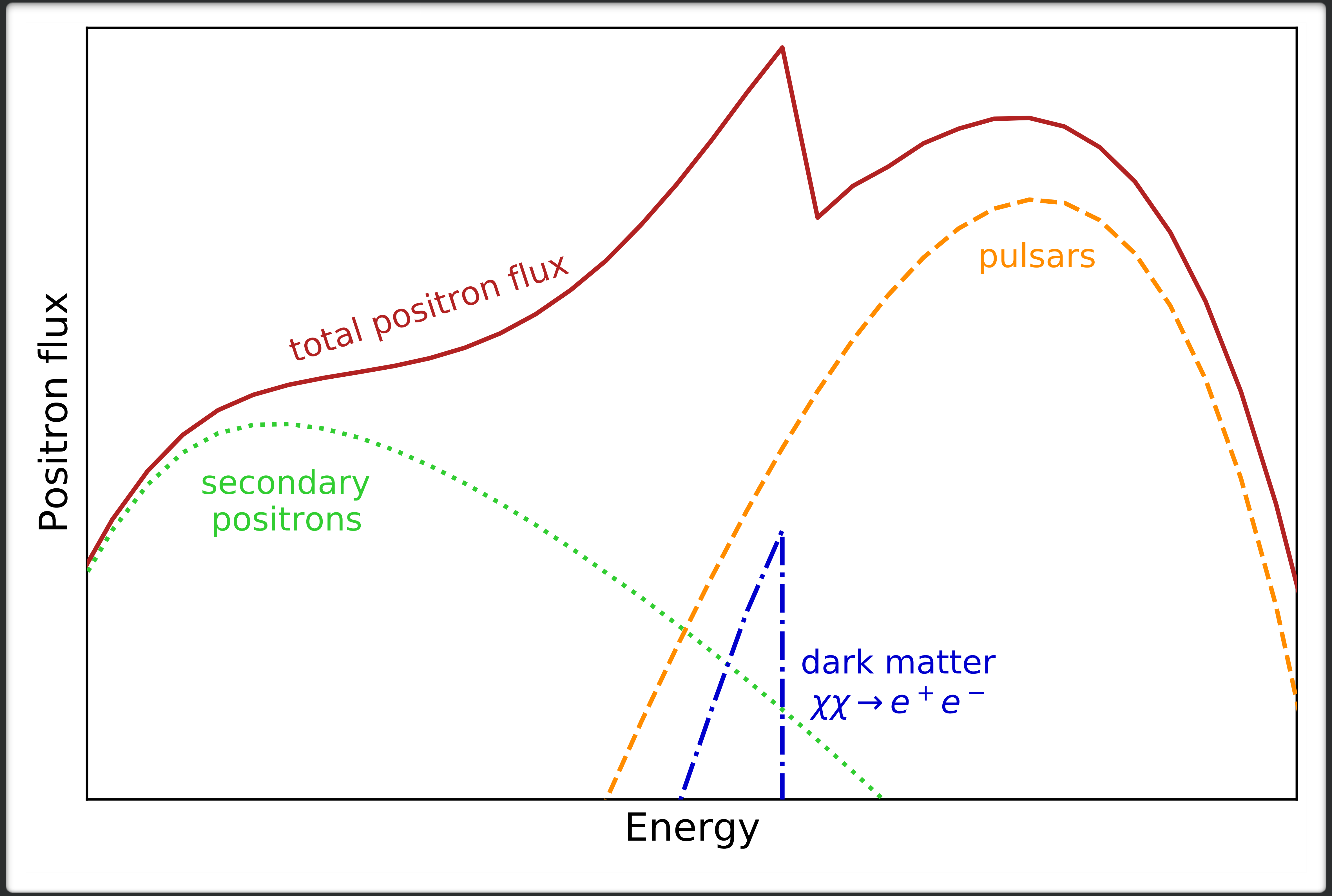
- Measured up to 1 TeV
- Rises above 20 GeV
- Spectrum is very smooth



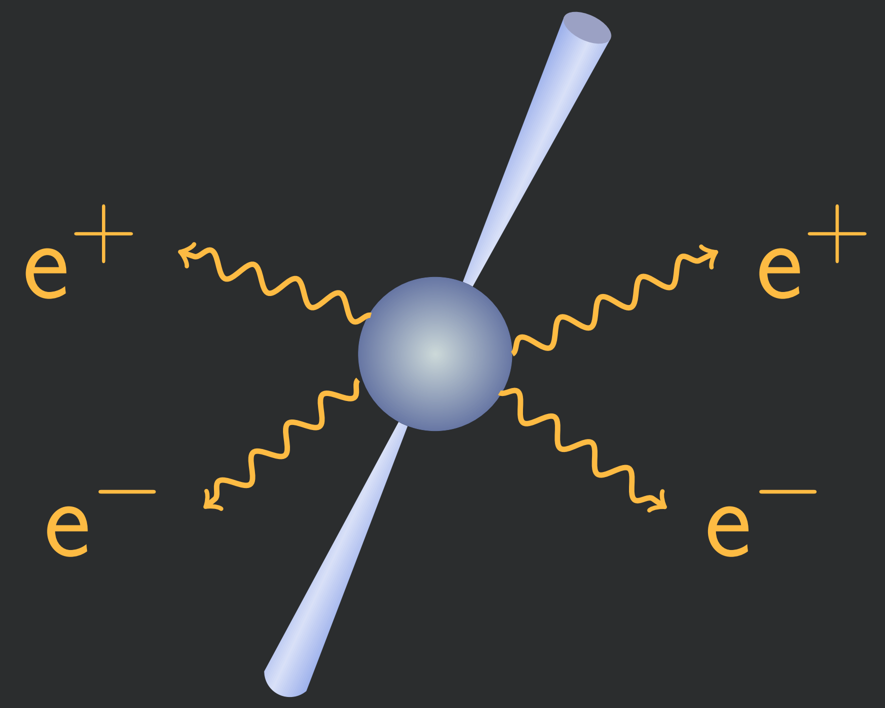
Components of the Positron Flux

Secondary production

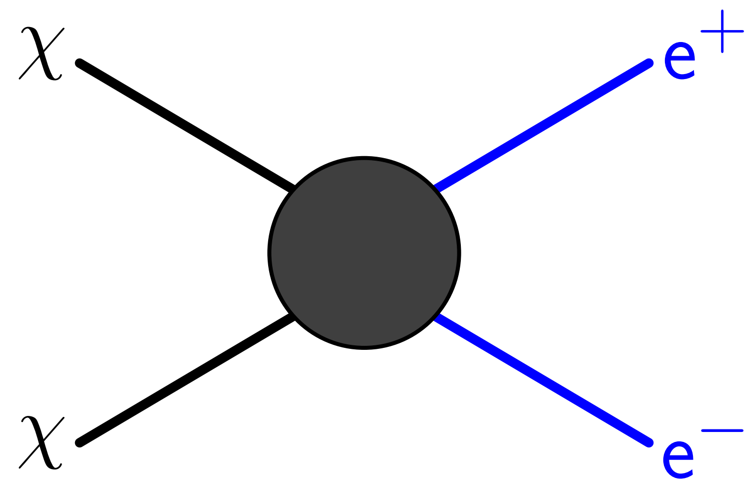




Pulsars

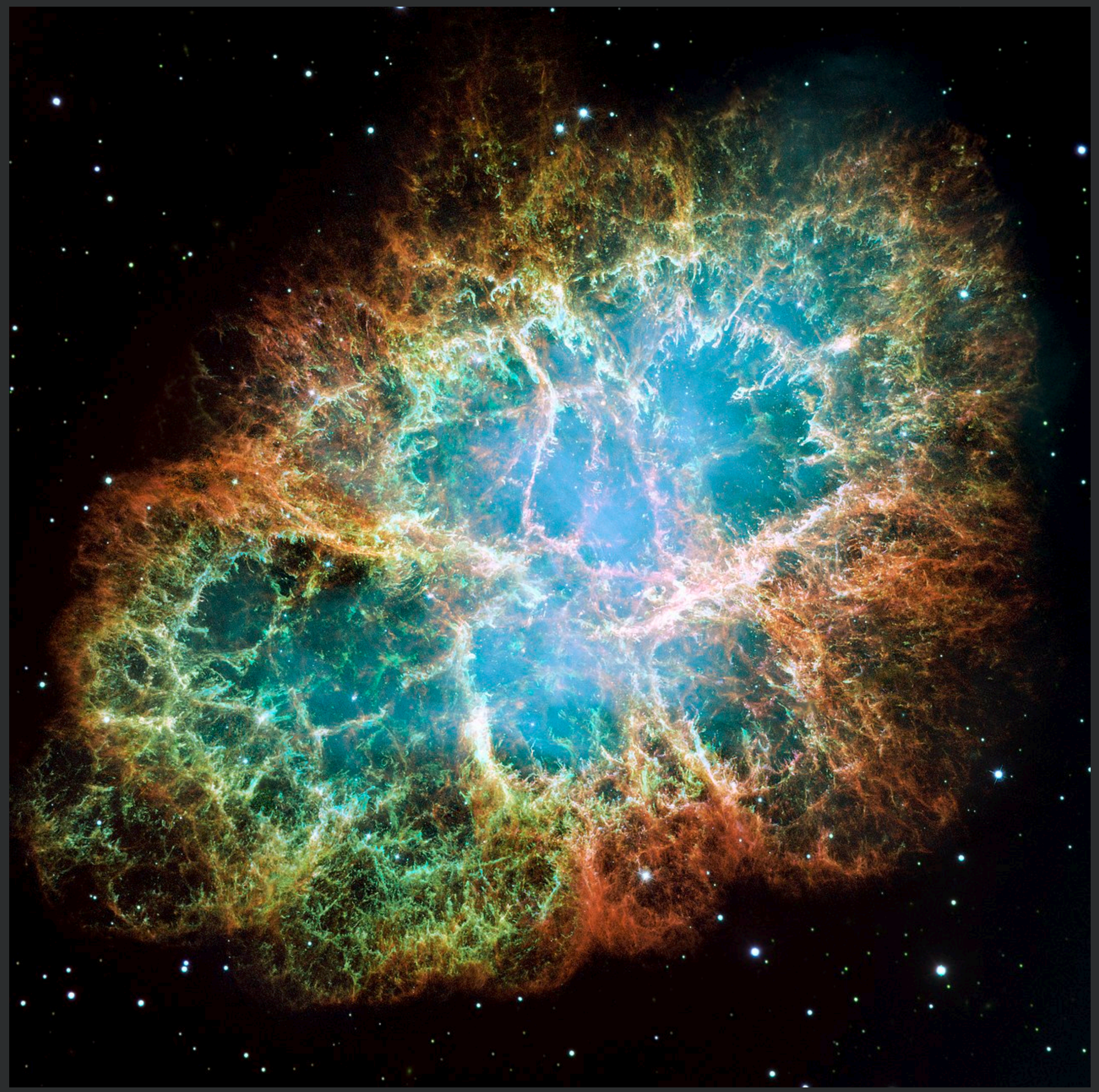


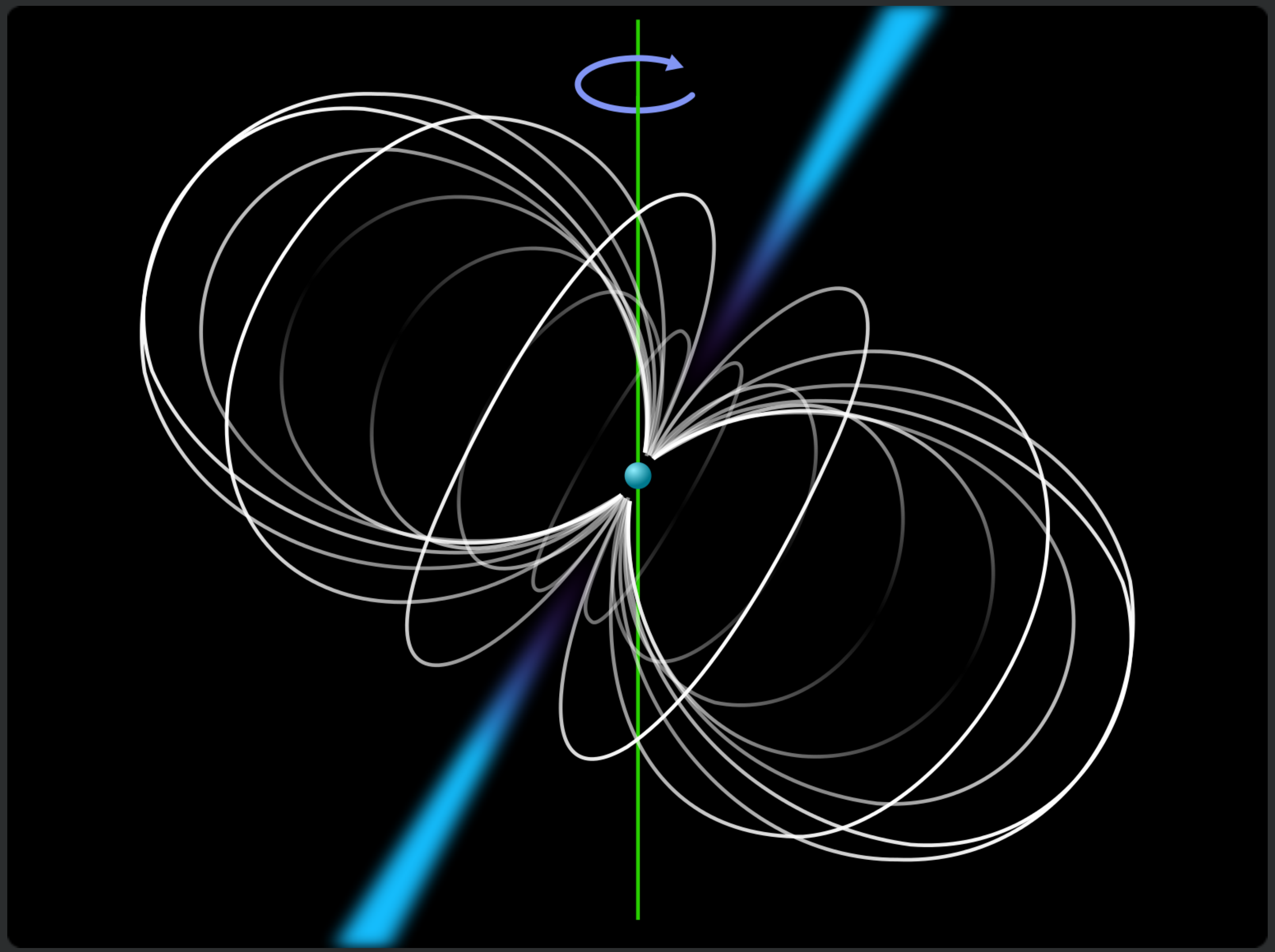
Dark matter annihilation



Pulsars

- Rapidly rotating neutron stars
- Convert spin-down power to electron-positron pairs
- Dominant contribution to the local CR positron flux from ~50 GeV to TeV energies

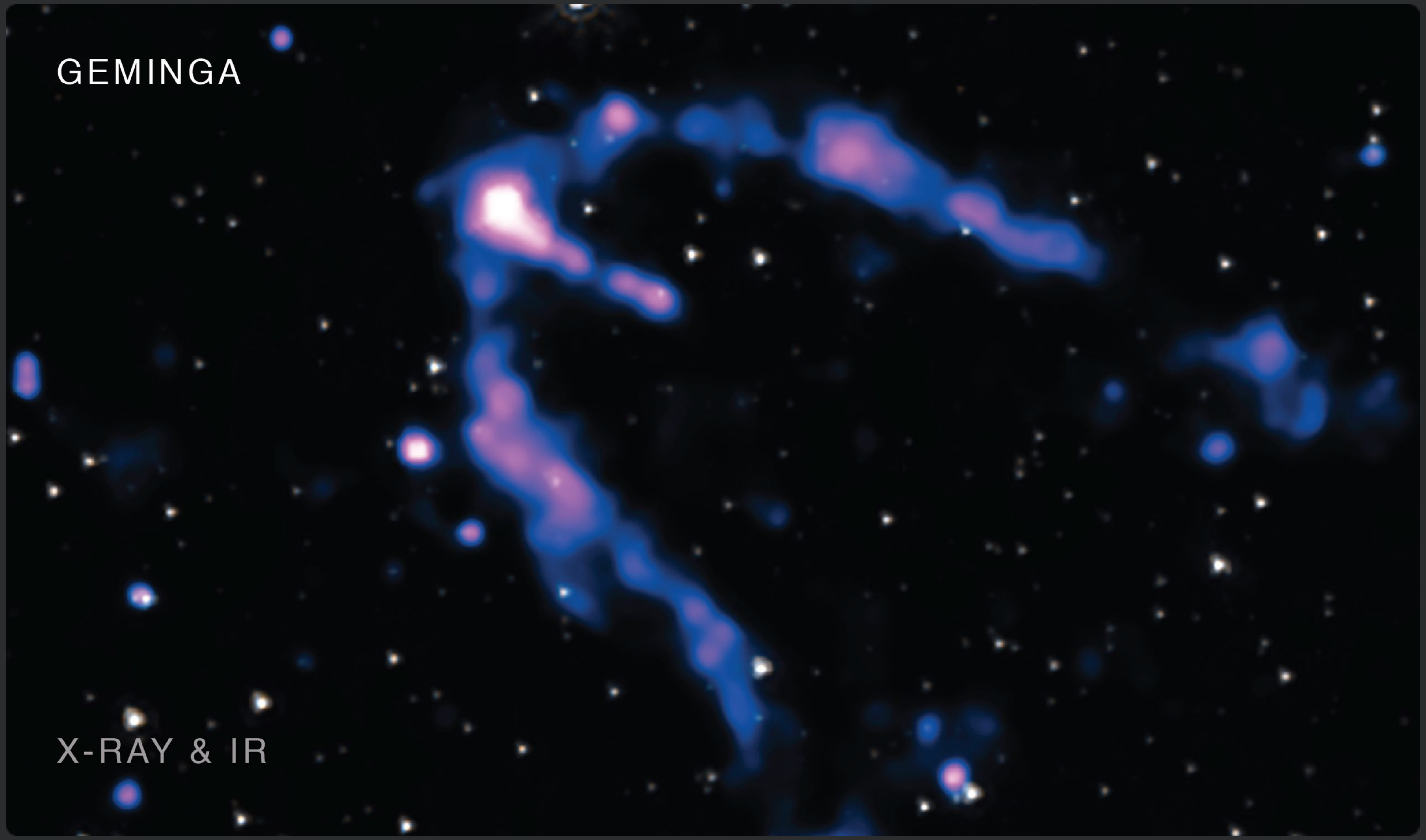


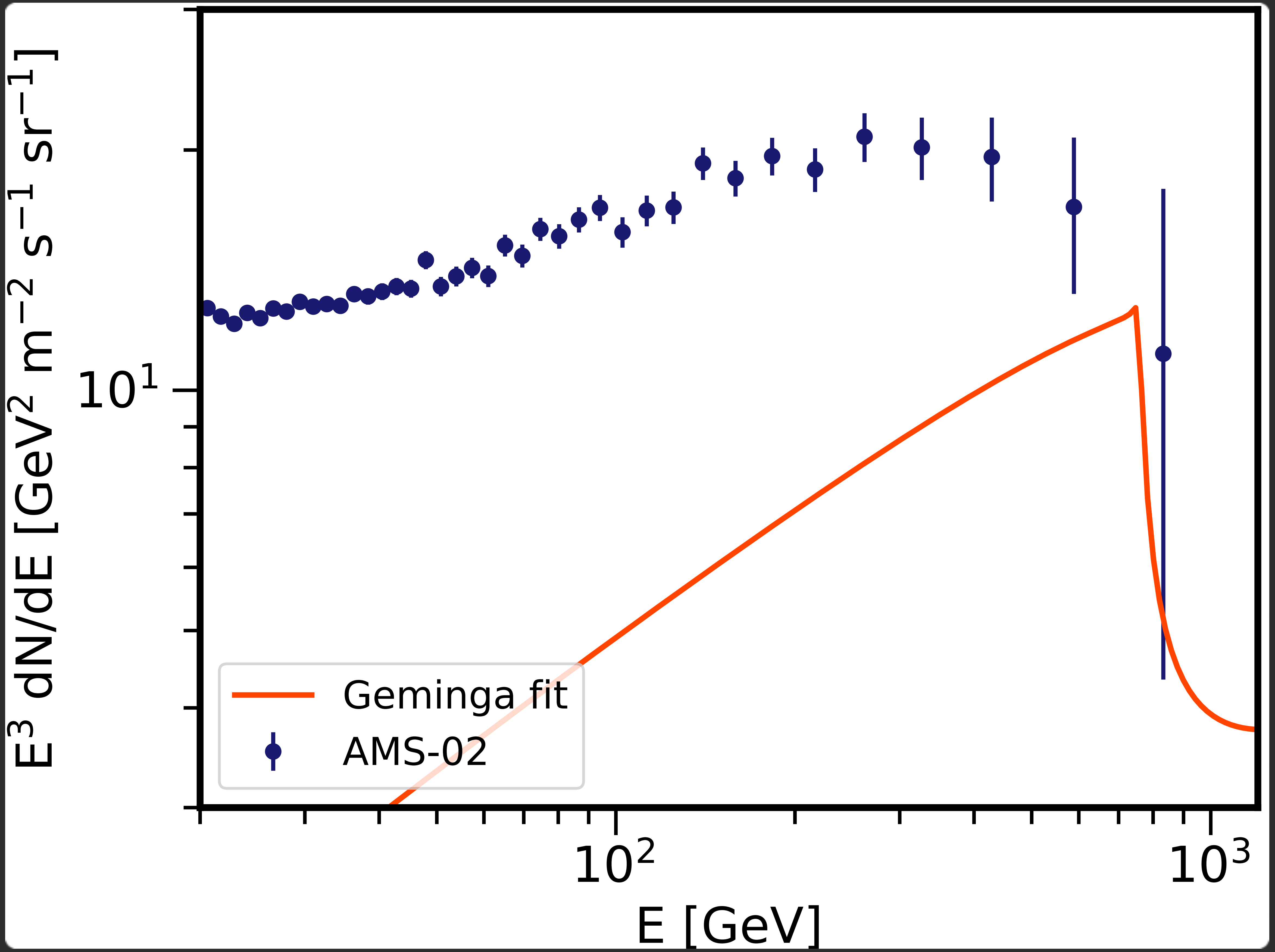


Positron Spectrum of Individual Pulsars

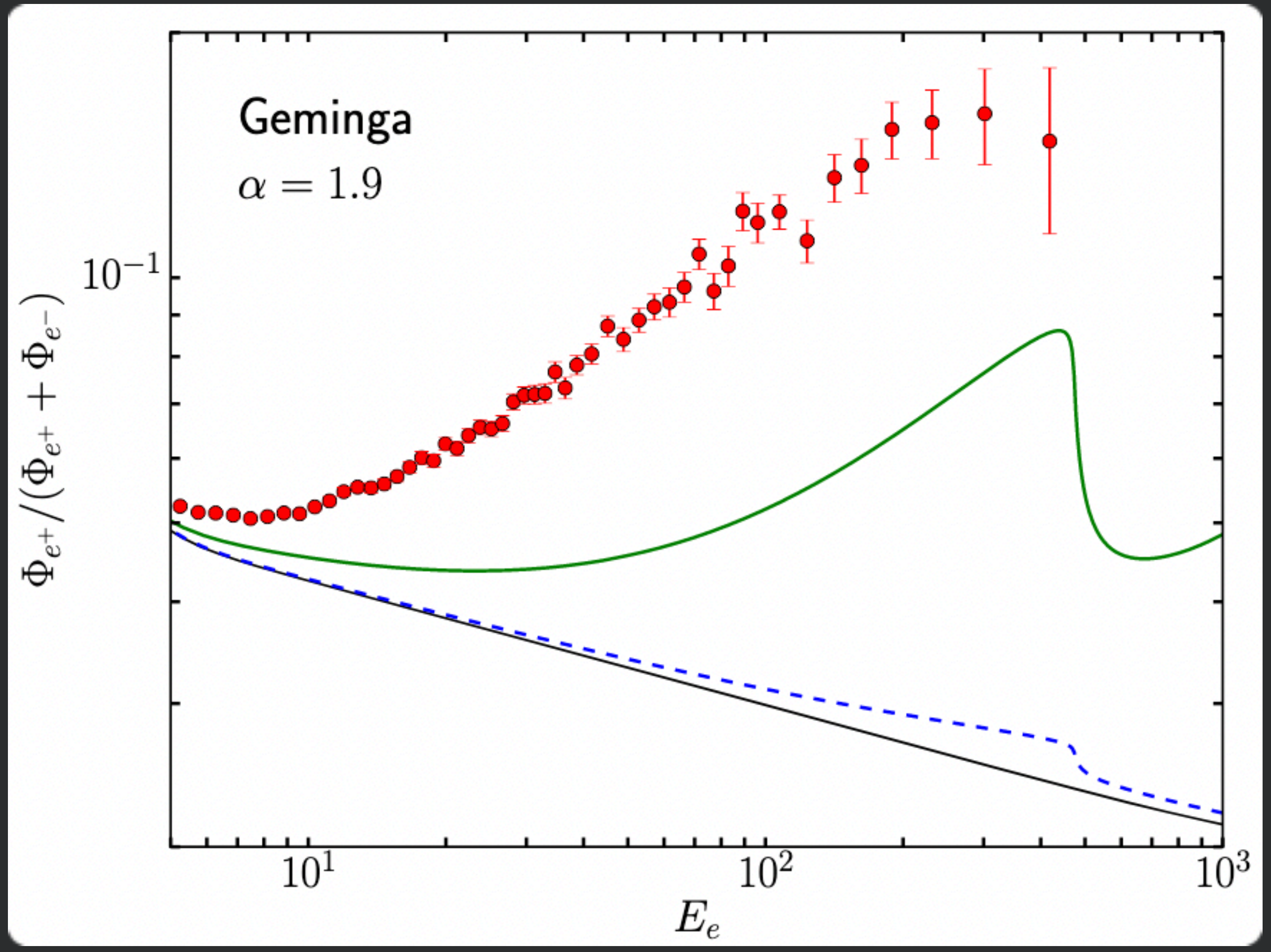
Template system: Geminga

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

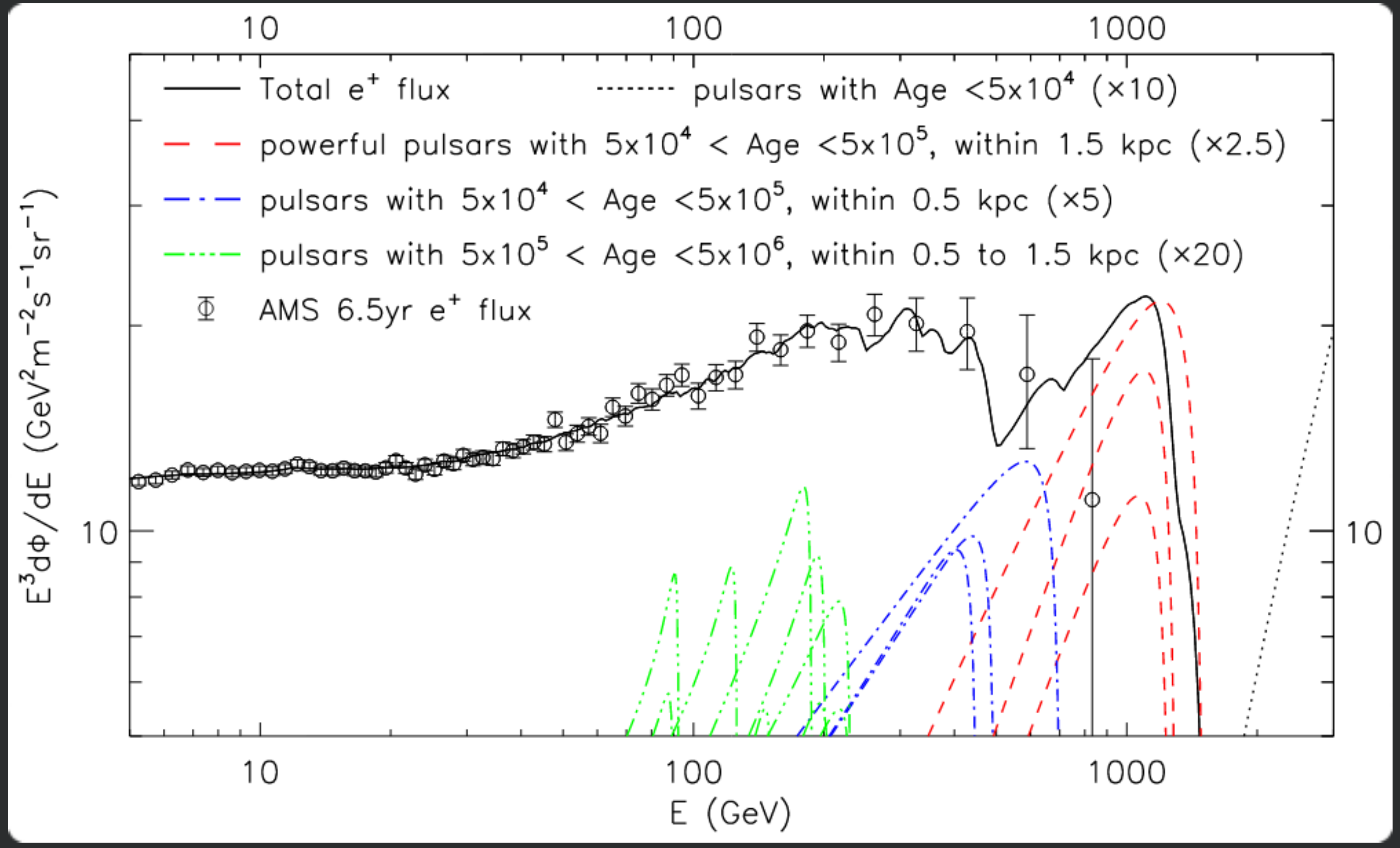




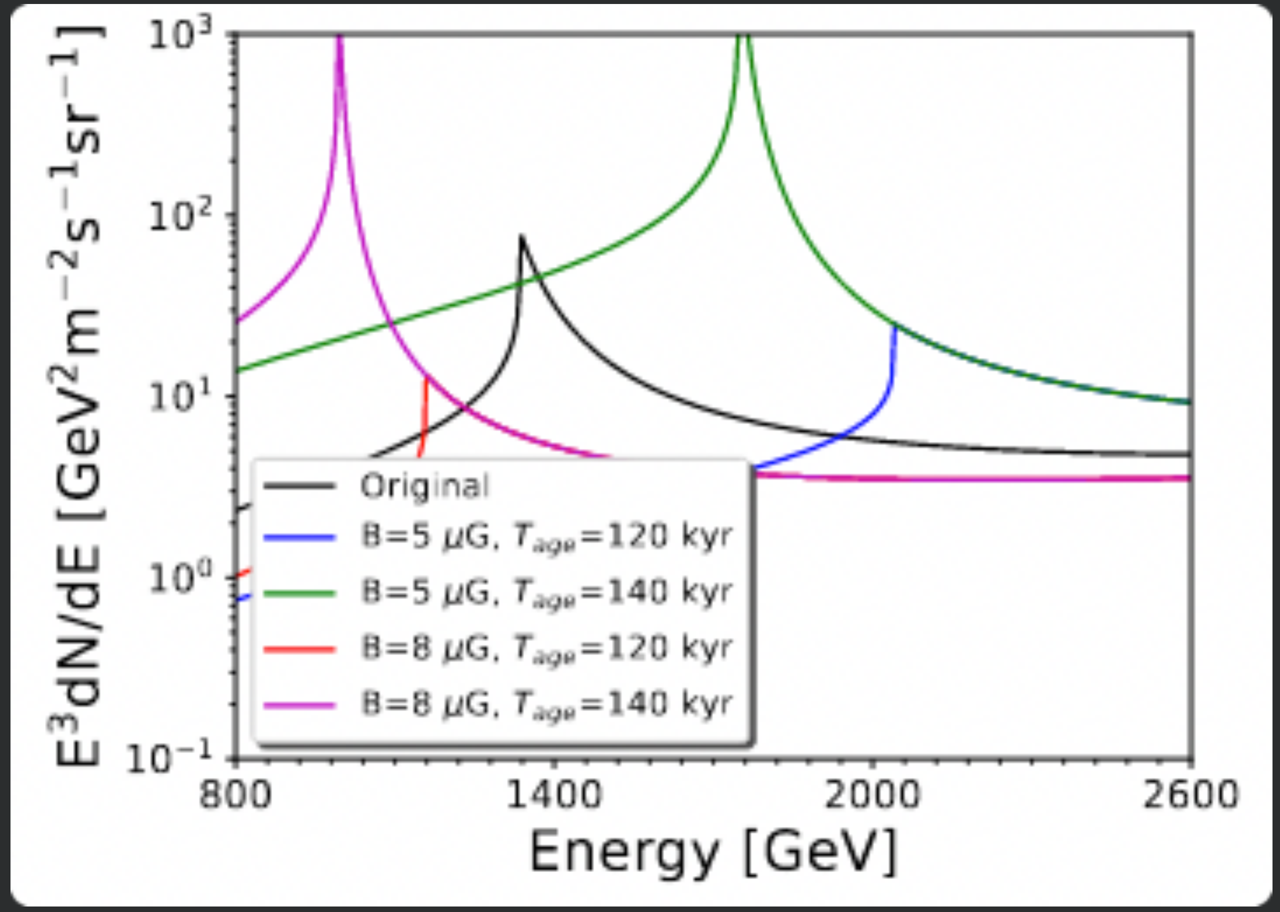
Recent Pulsar Papers Predict Sharp Features



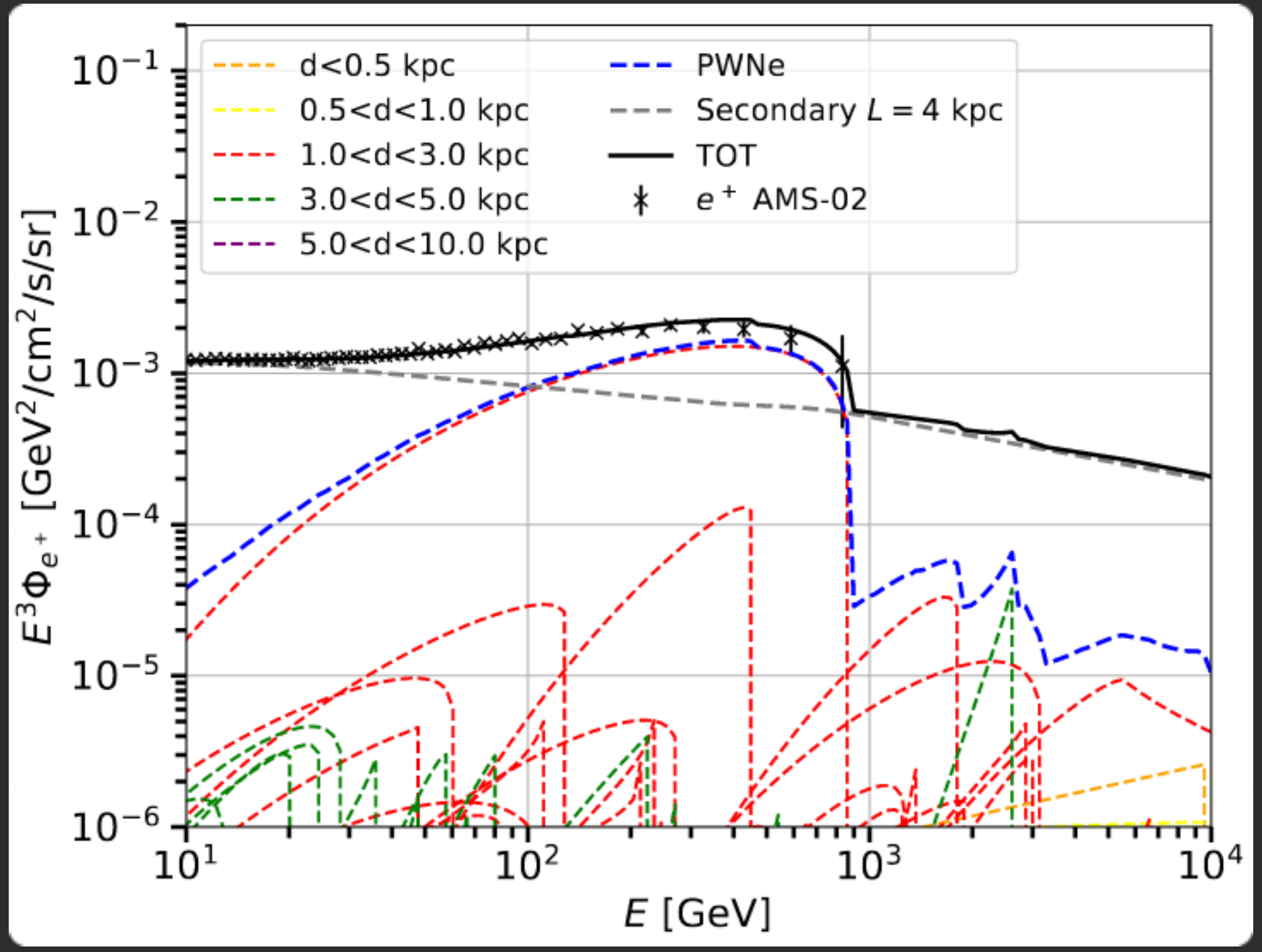
Hooper et al., arXiv:1702.08436



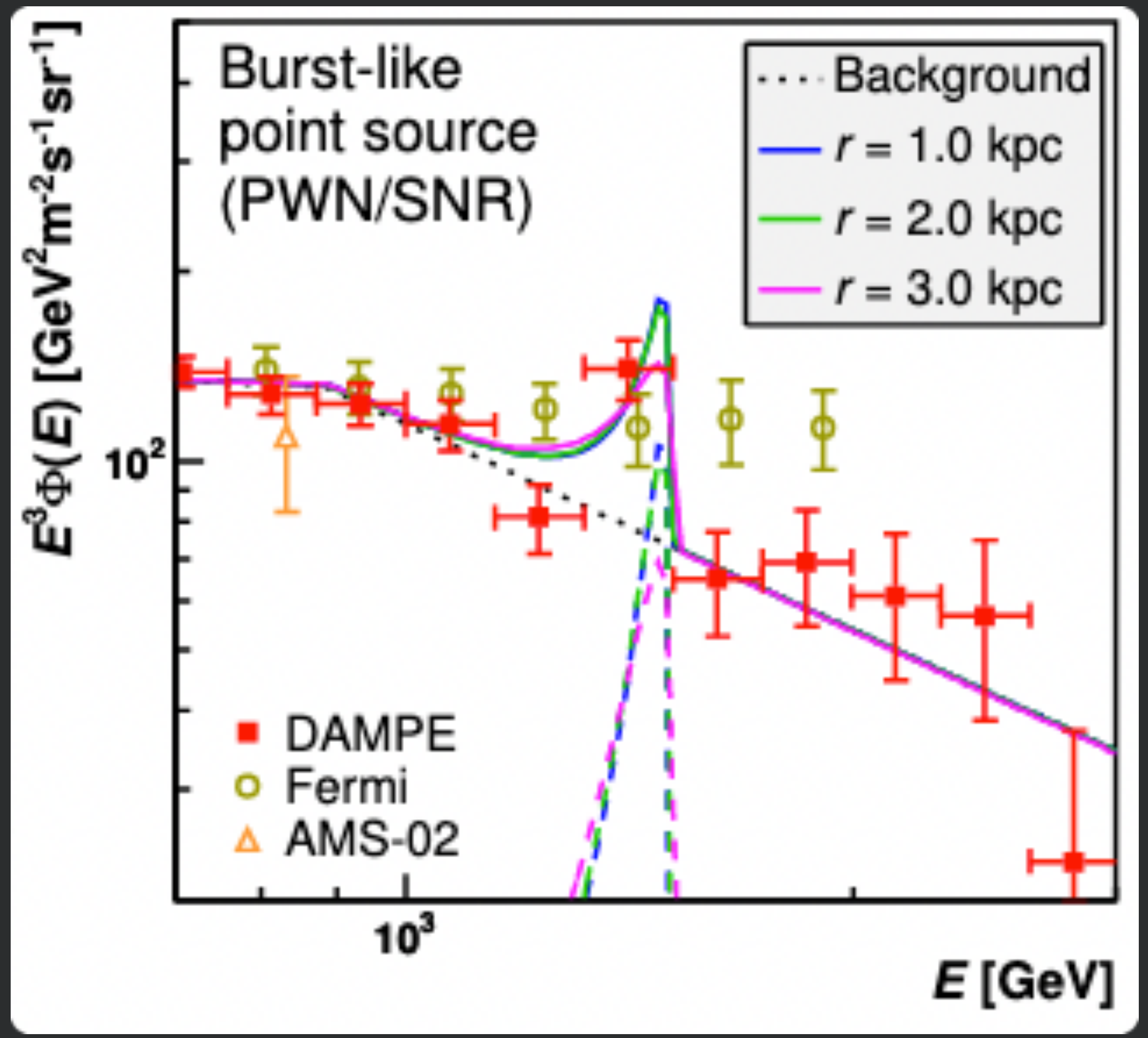
Cholis & Krommydas, arXiv:2111.05864



Bao et al., arXiv:2010.12170



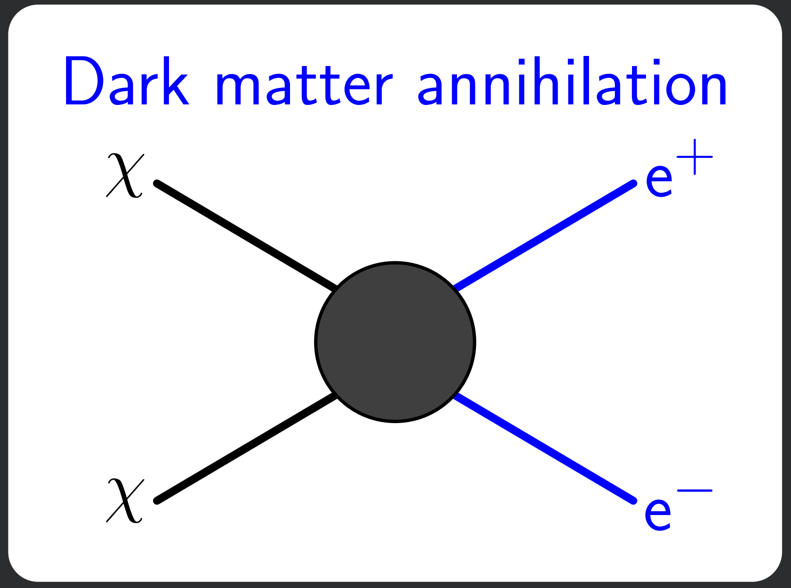
Orusa et al., arXiv:2107.06300

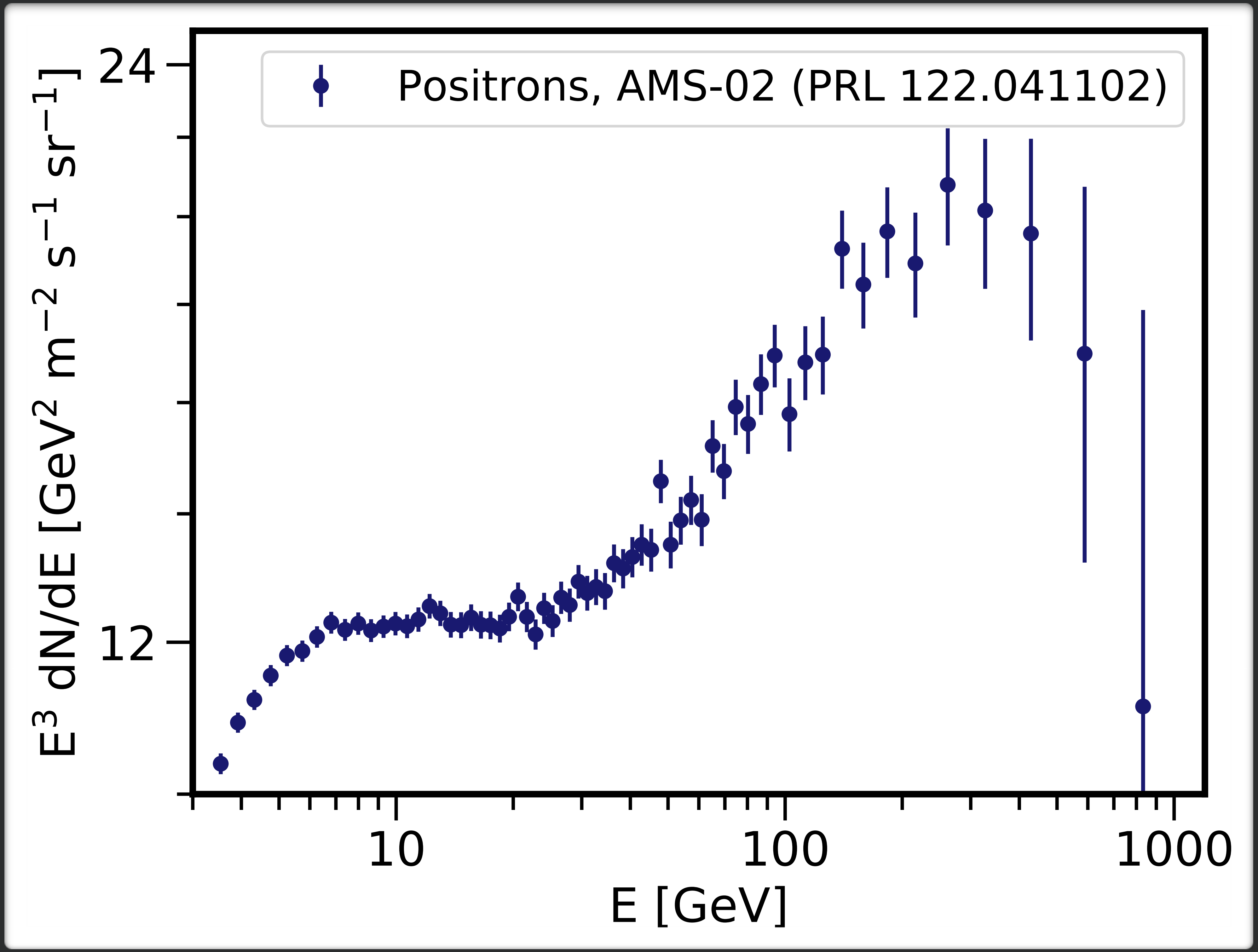


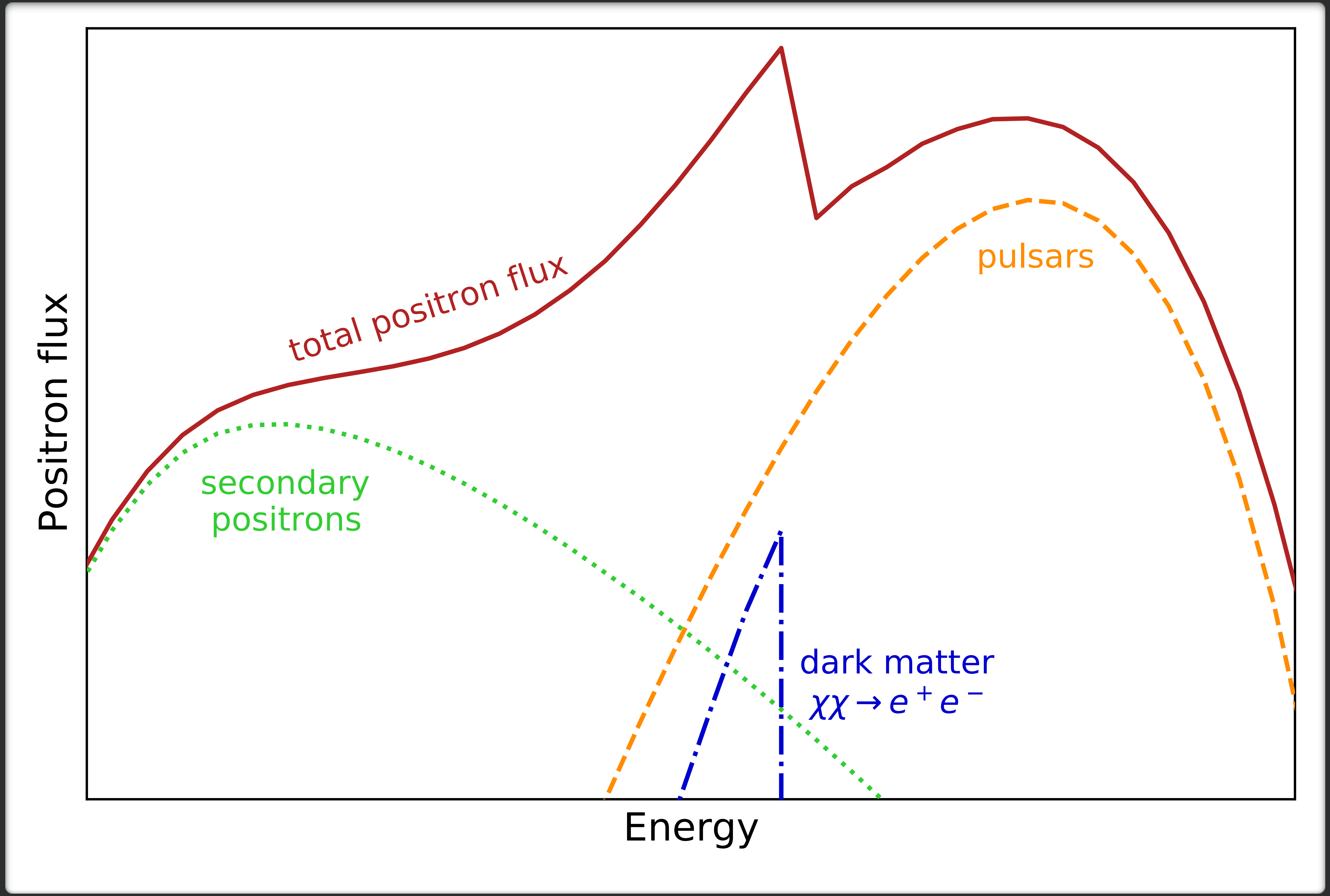
Huang et al., arXiv:1712.00005

Sharp Spectral Features?

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





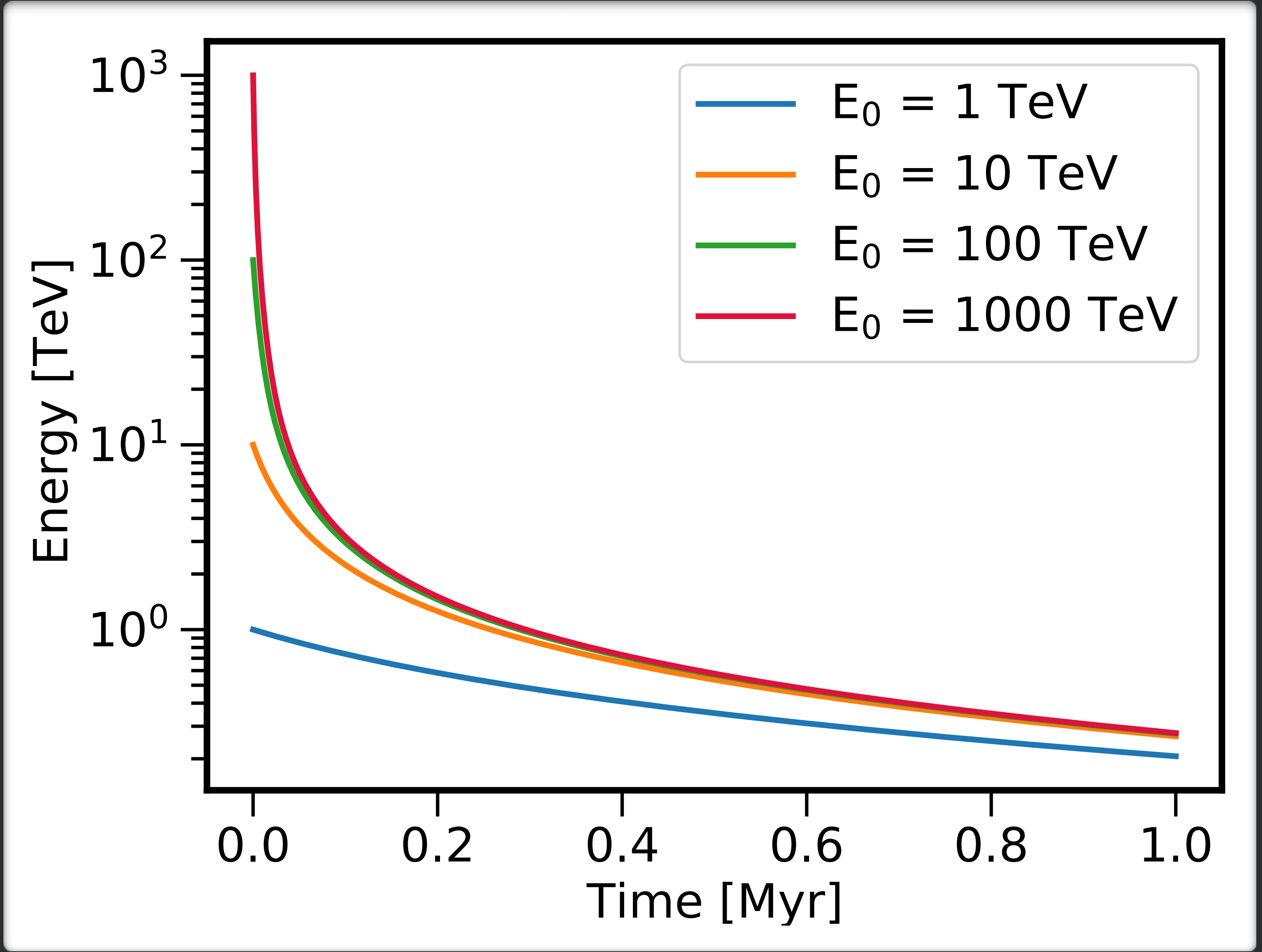


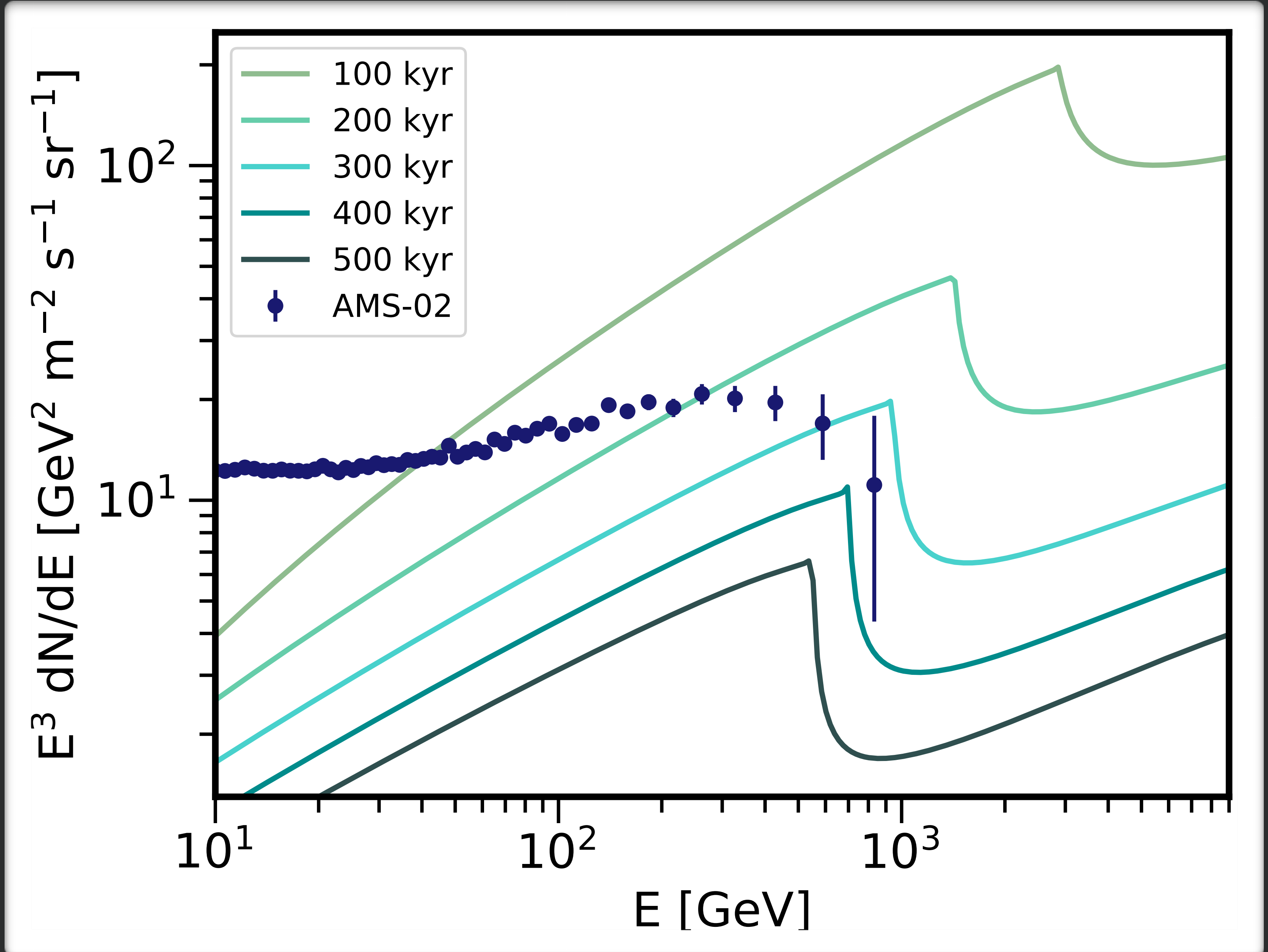
Spectral Features From Pulsars

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

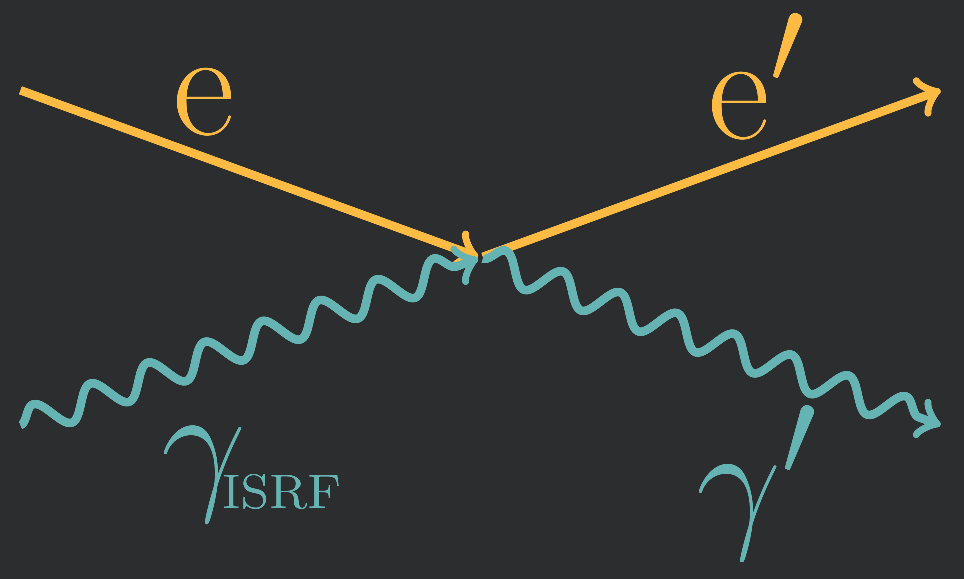
As positrons propagate through the Galaxy, they cool:

- 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

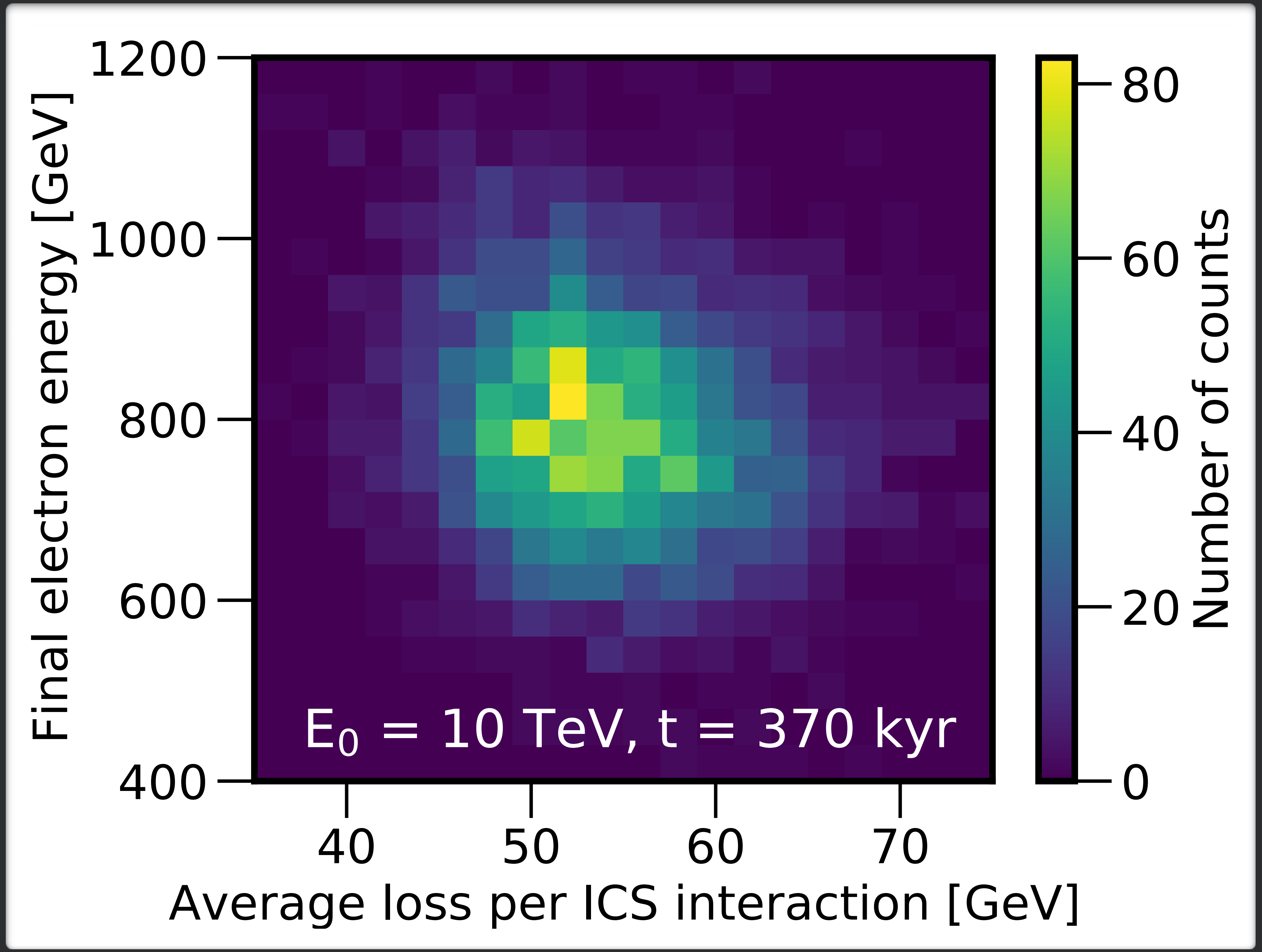
E Electron energy
ν_i Photon energy
σ_T Thomson cross section
ρ_B Magnetic field energy density
ρ_i ISRF energy densities
S Klein-Nishina suppression

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 electron 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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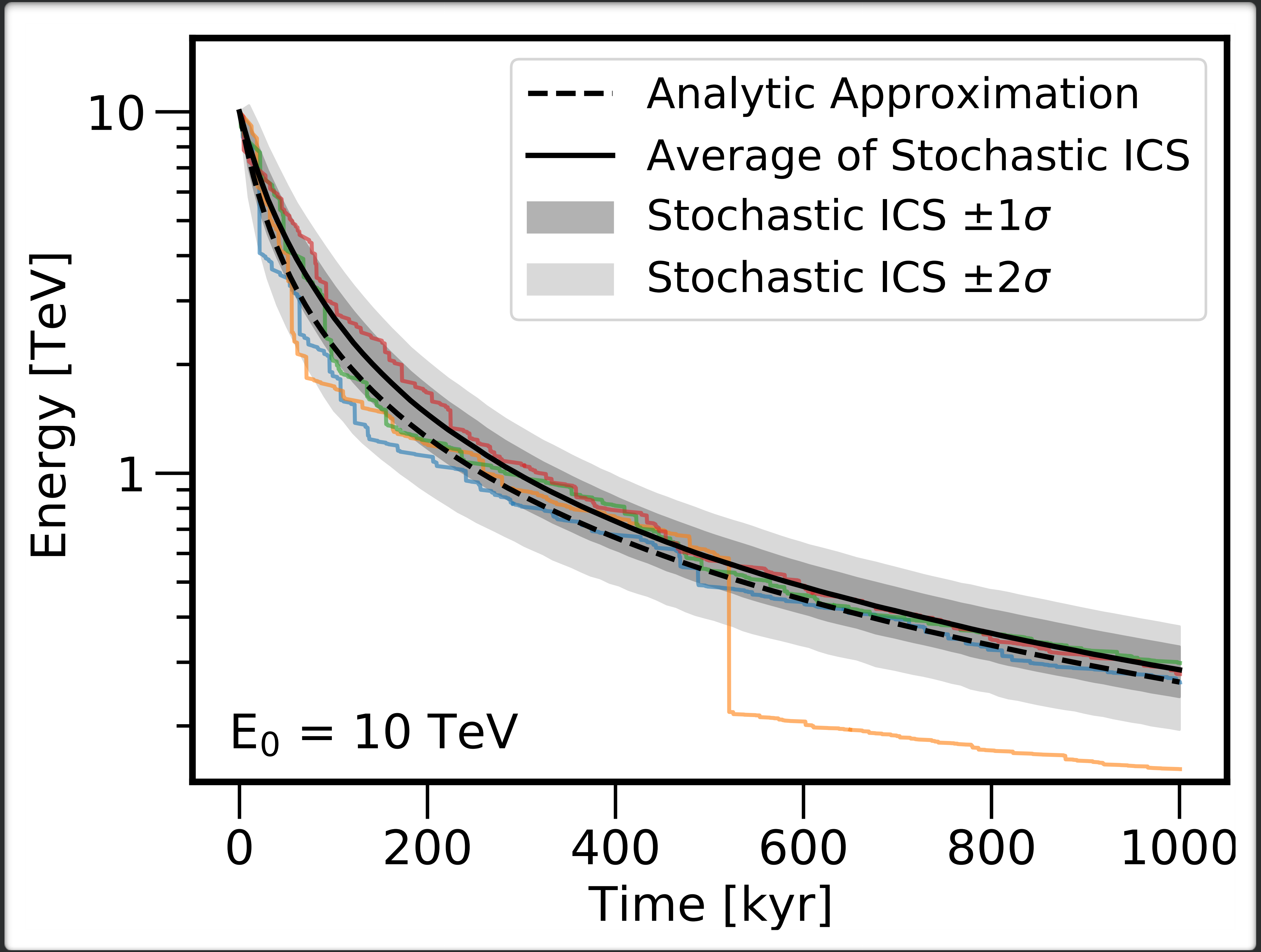
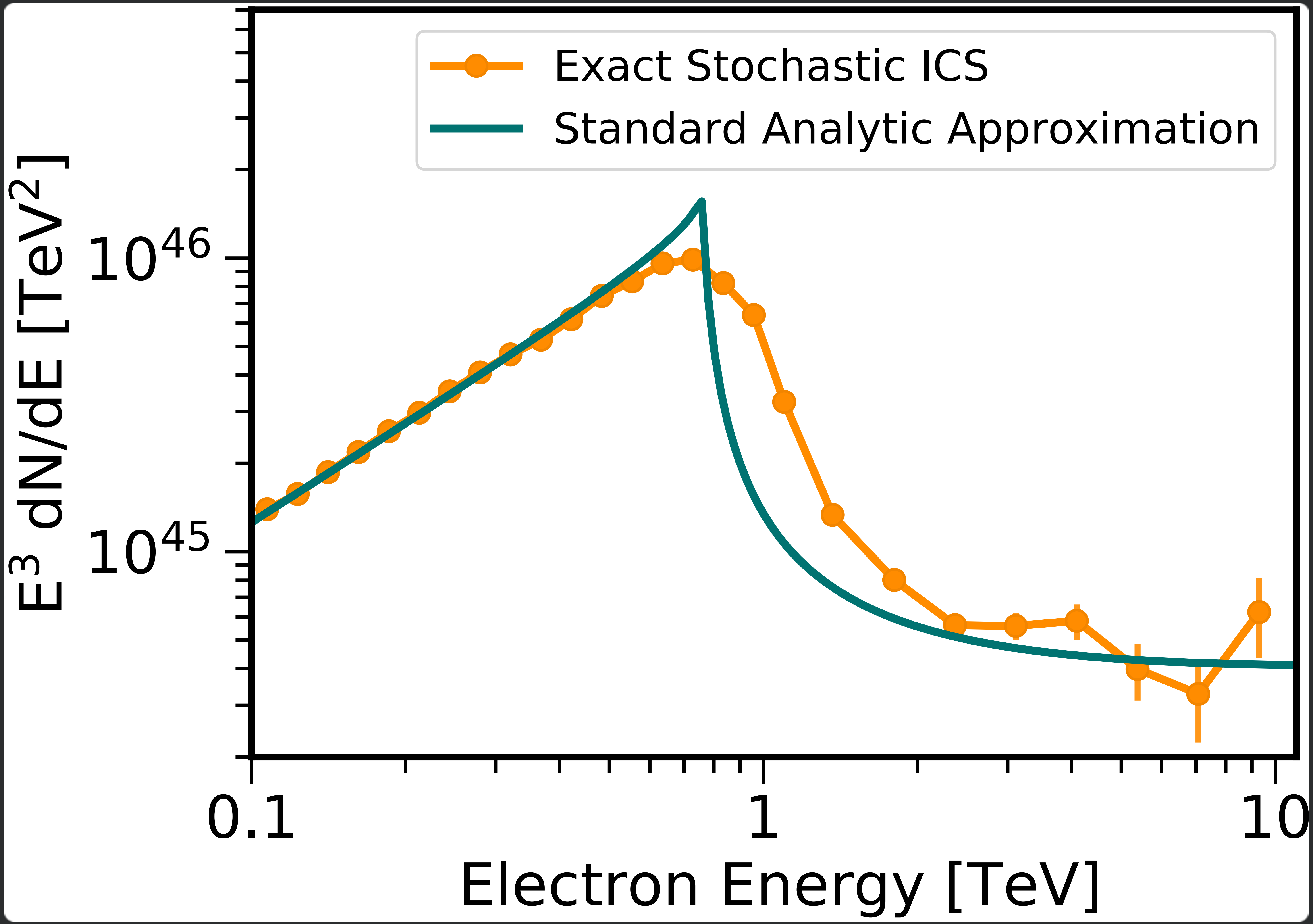


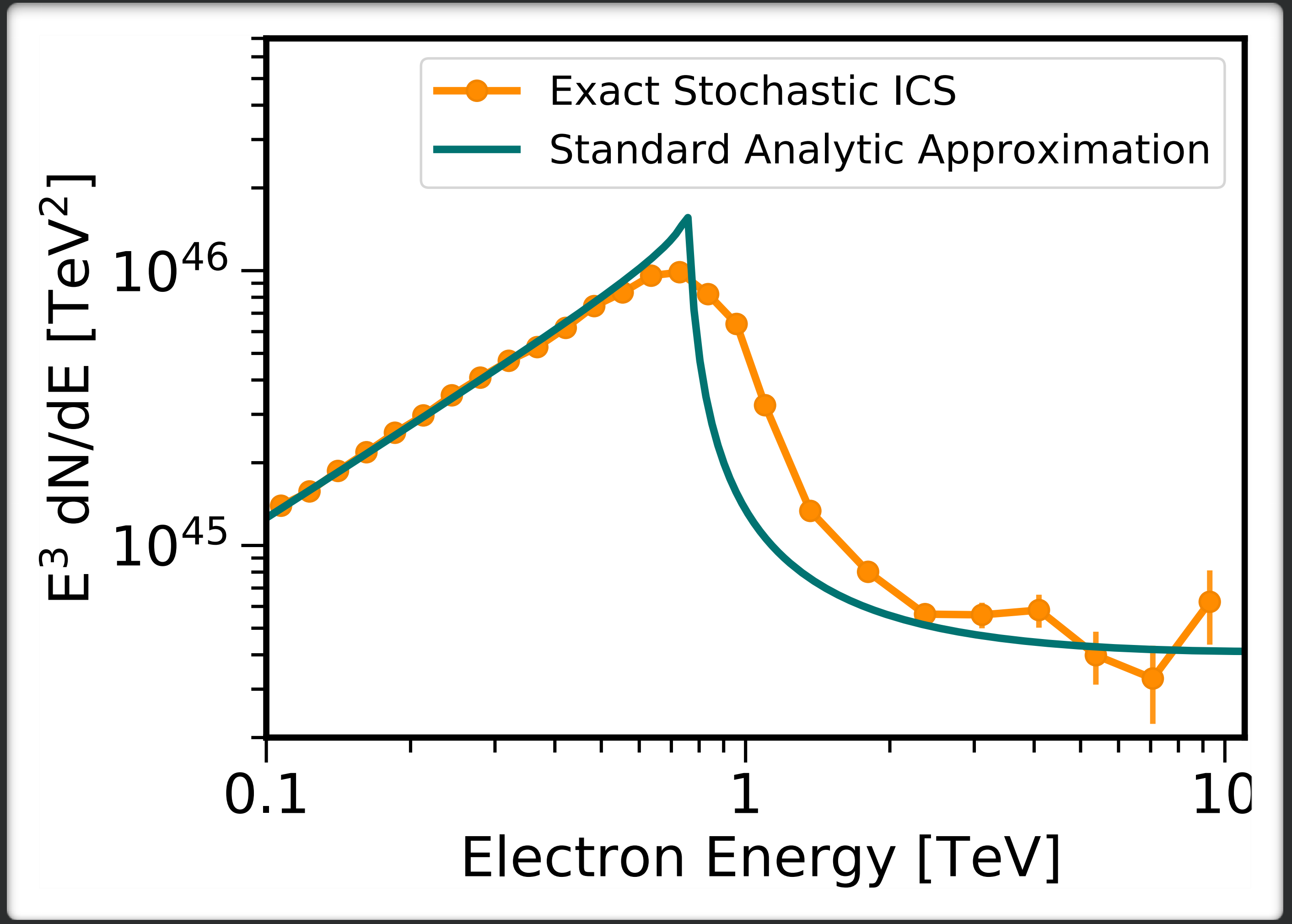
Pulsar Positron Spectrum

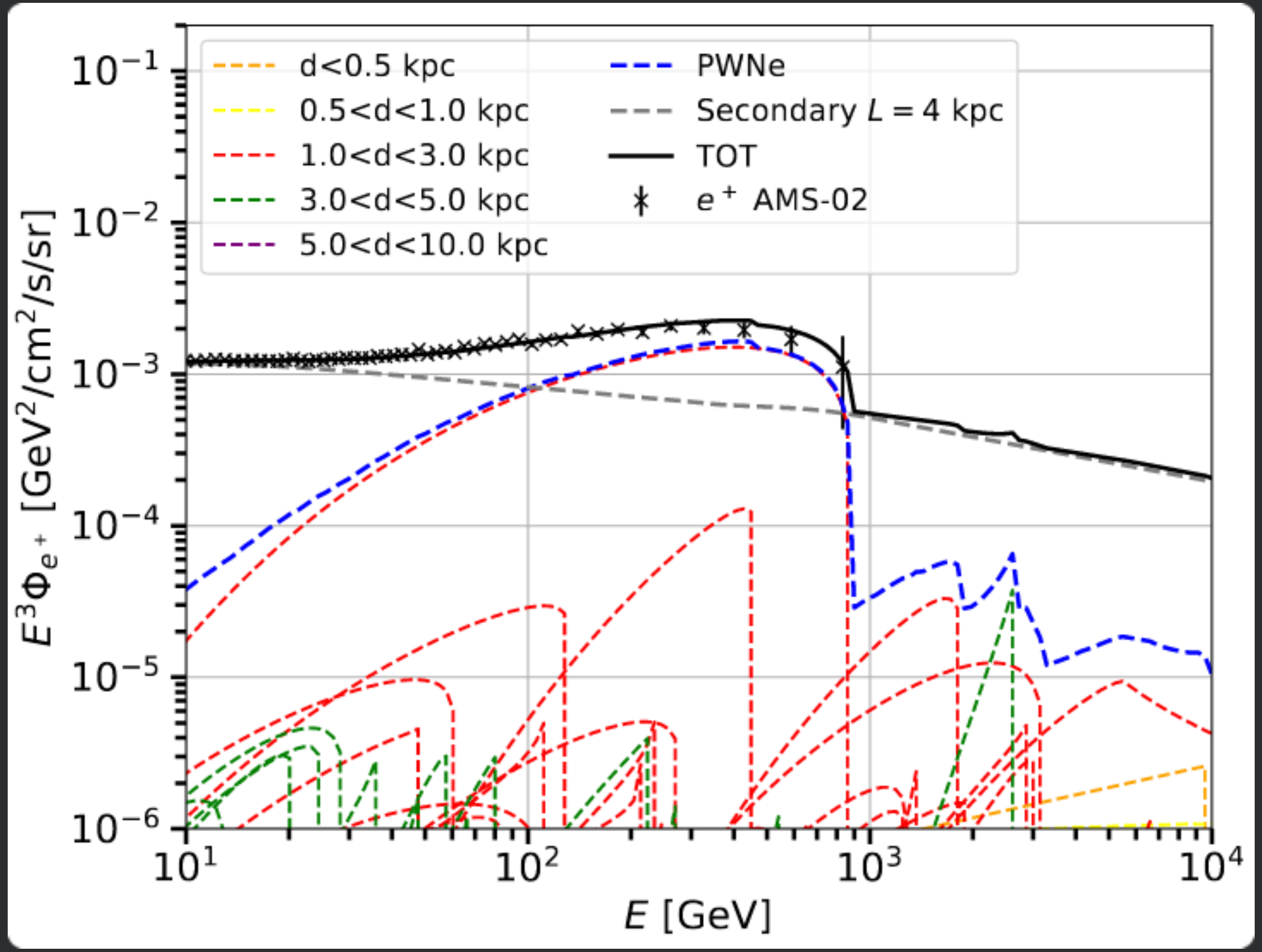


- Sharp spectral features introduced by analytic approximation are smoothened out by ~50% when correctly treating inverse-Compton scattering stochastically

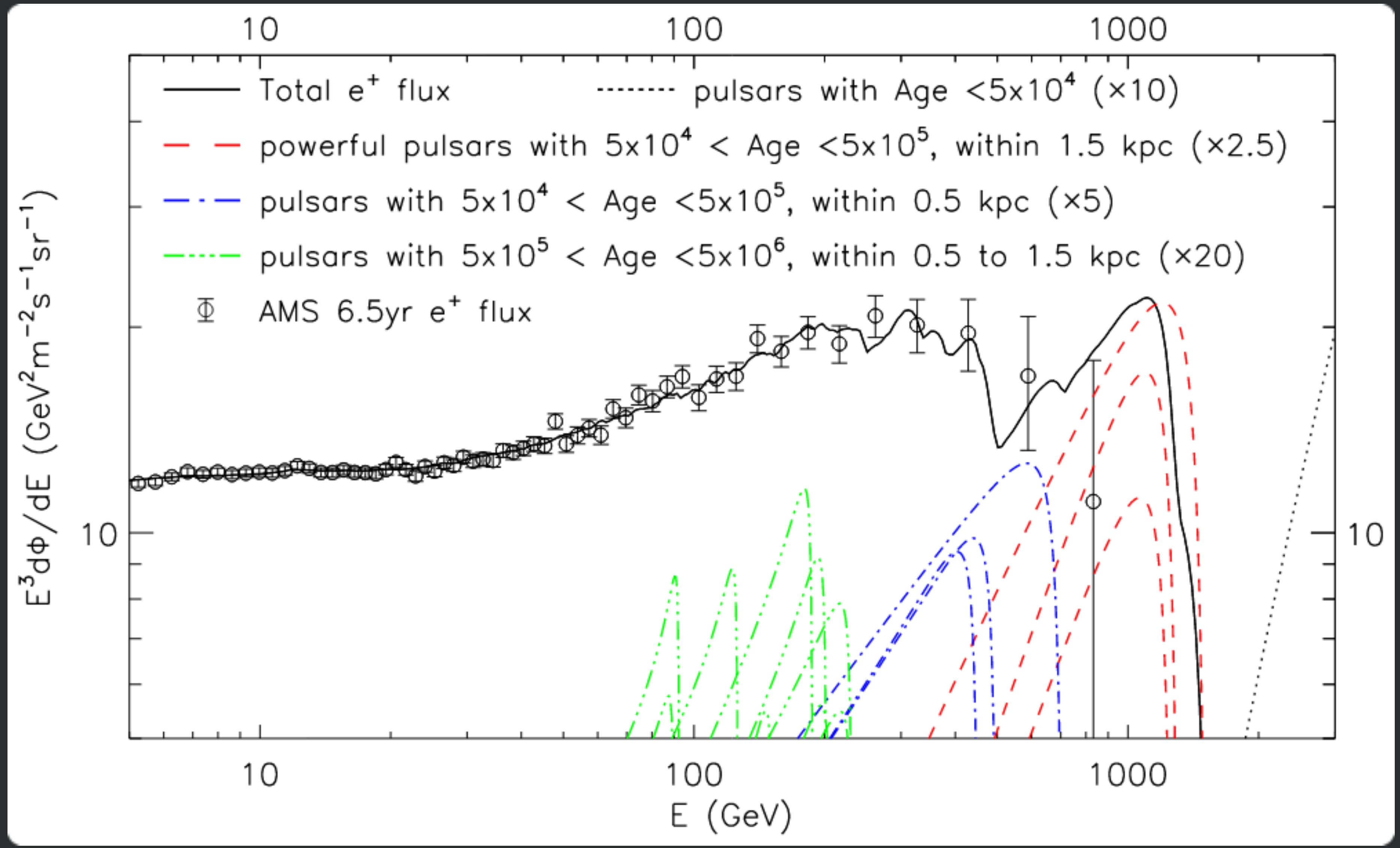
Implications for Pulsar Models

- 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





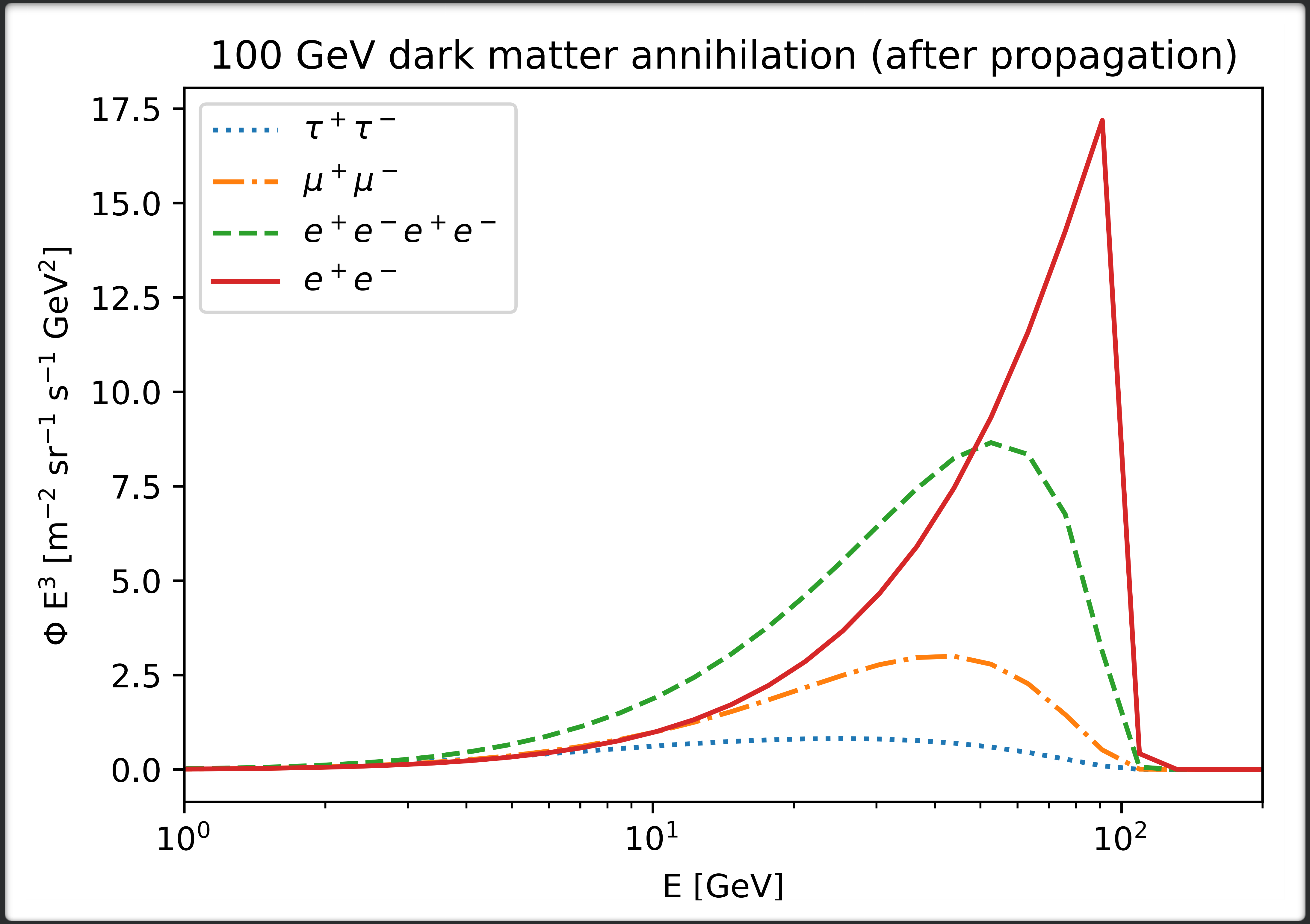
Orusa et al., arXiv:2107.06300

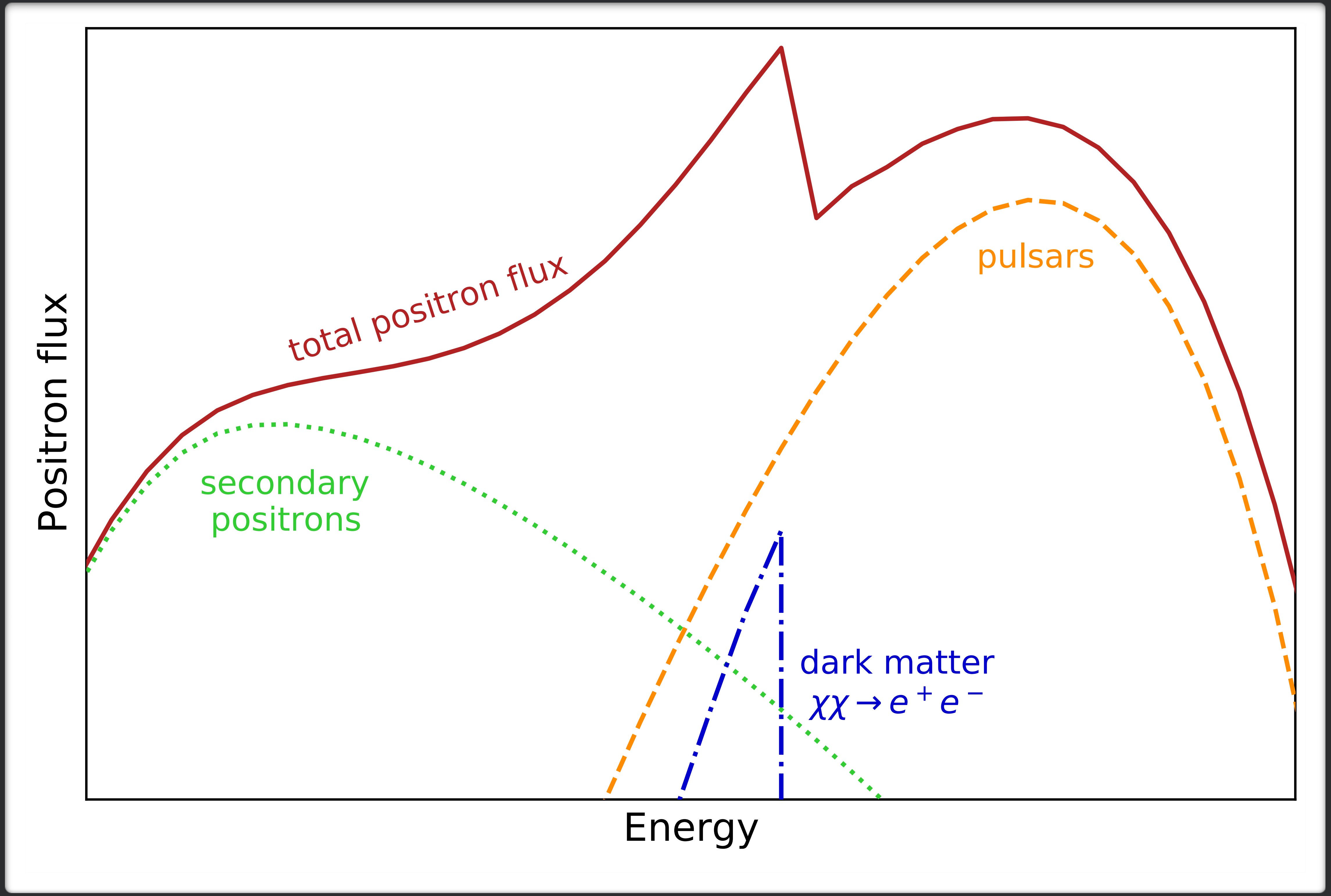


Cholis & Krommydas, arXiv:2111.05864

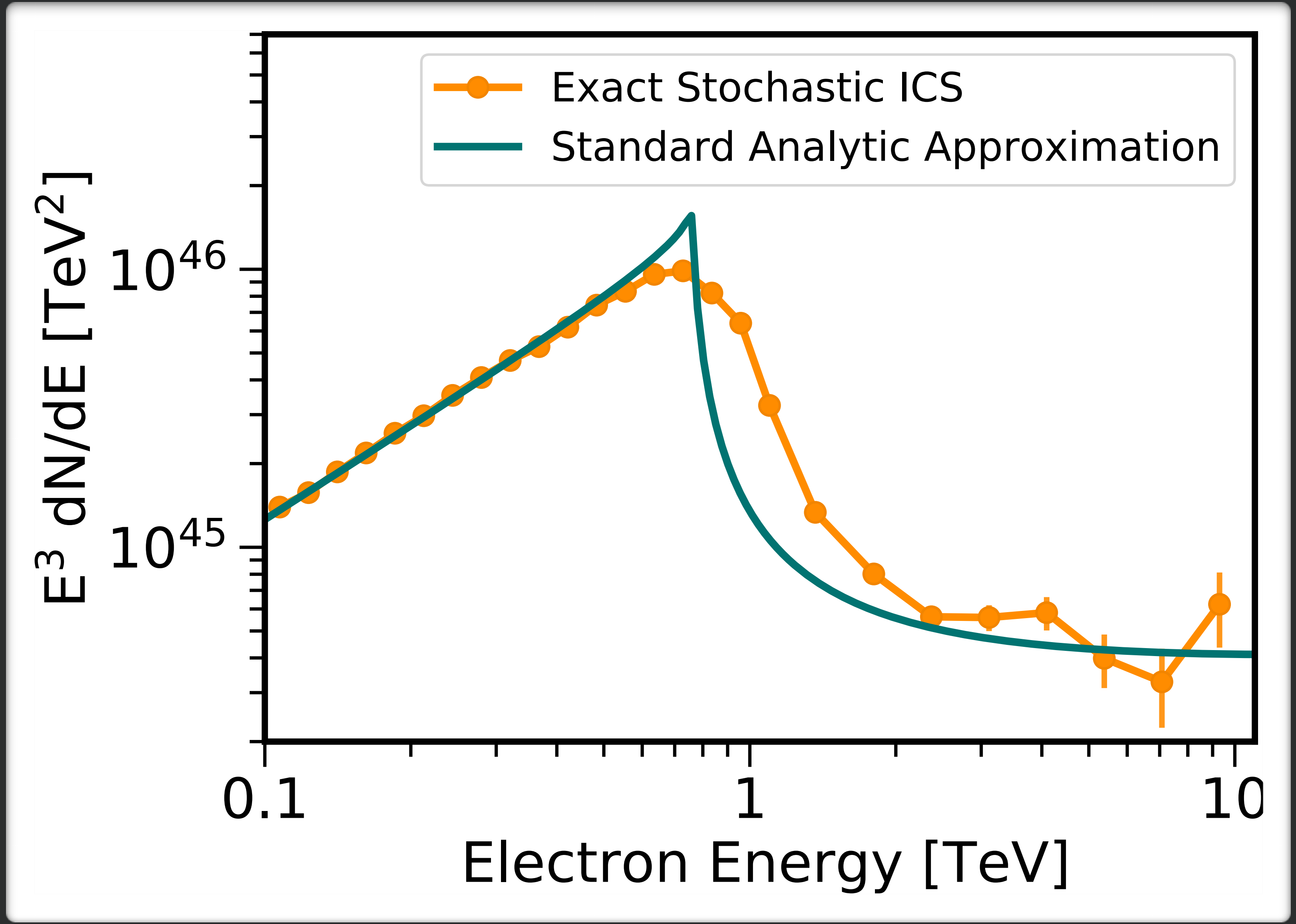
Implications for Dark Matter

- 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





Summary and Outlook



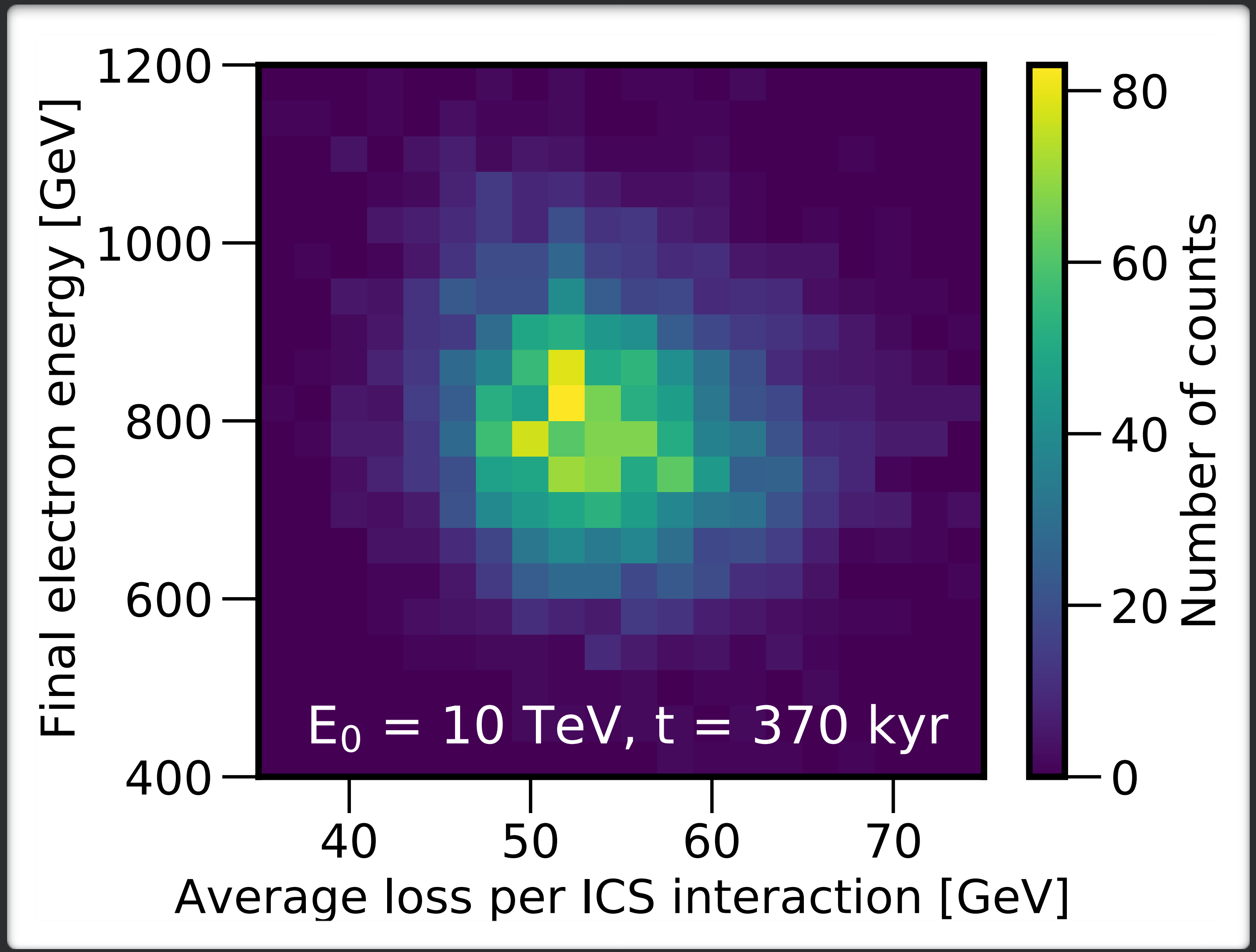
We have proven that pulsars cannot produce sharp spectral feature when inverse-Compton scattering is treated correctly stochastically.

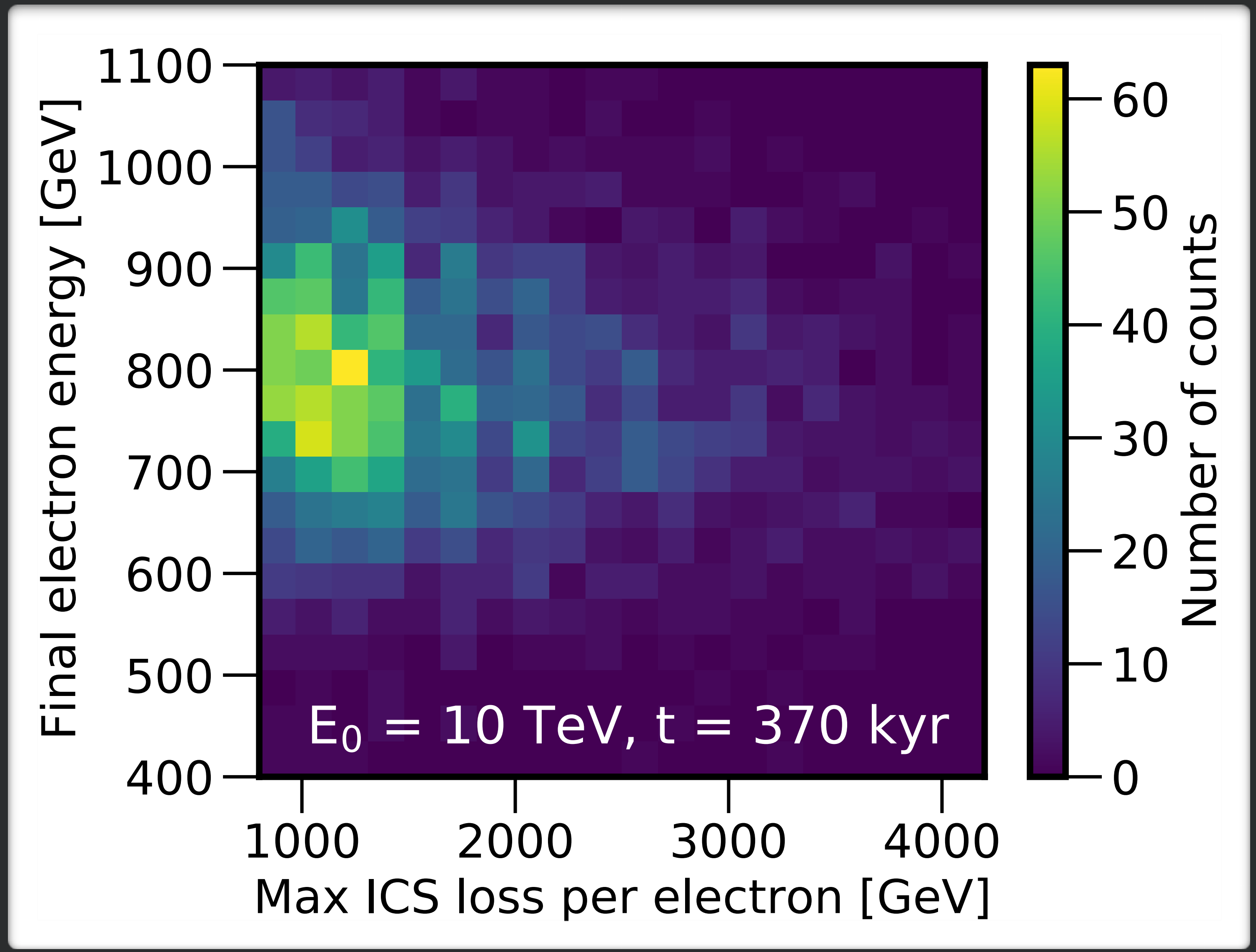
Next projects:

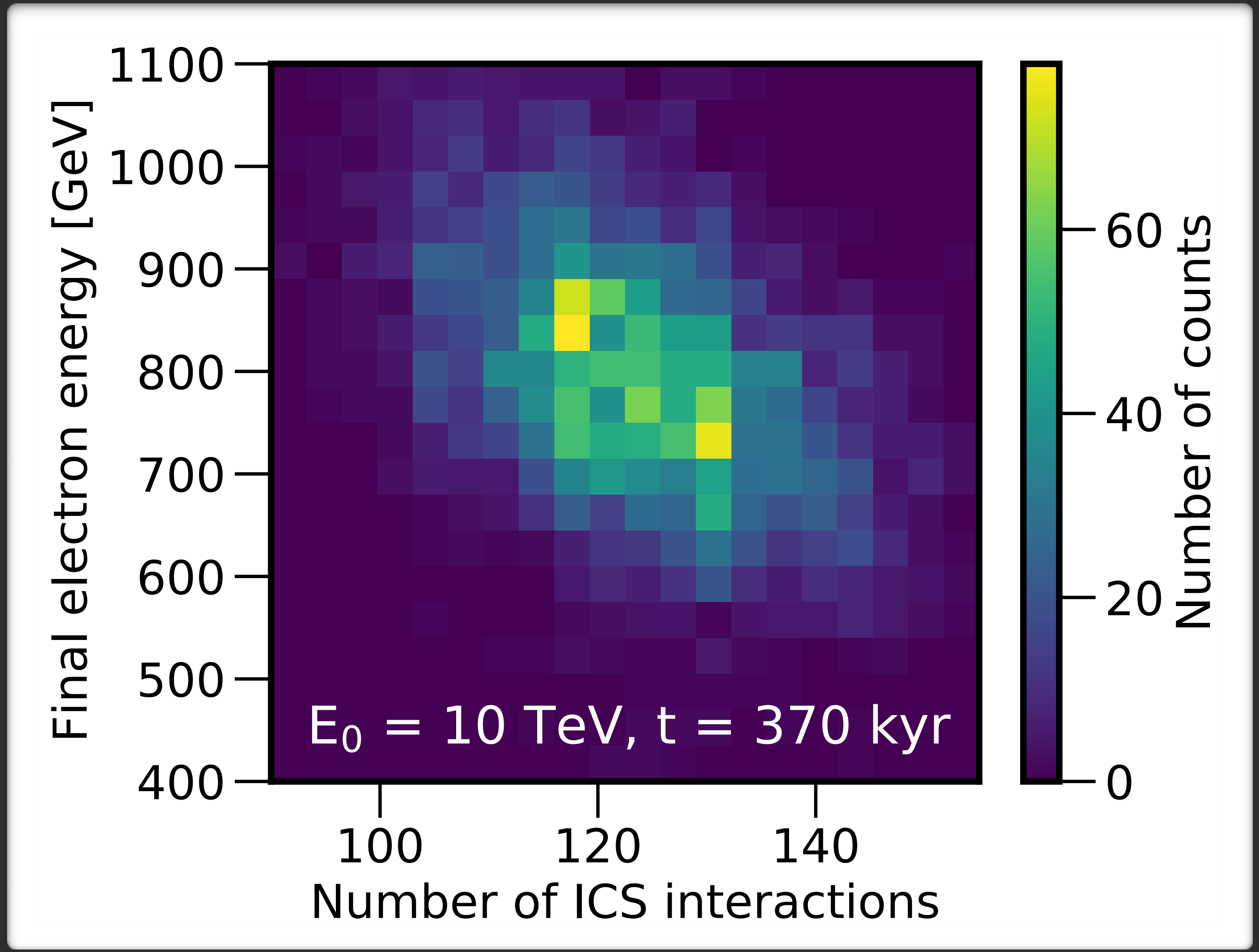
- Integrate stochastic ICS into full diffusion models
- Provide simple way of integrating stochastic ICS effects into large-scale pulsar models
- Investigate other mechanisms that smoothen out the spectral feature further, e.g. variations in the Interstellar Radiation Field

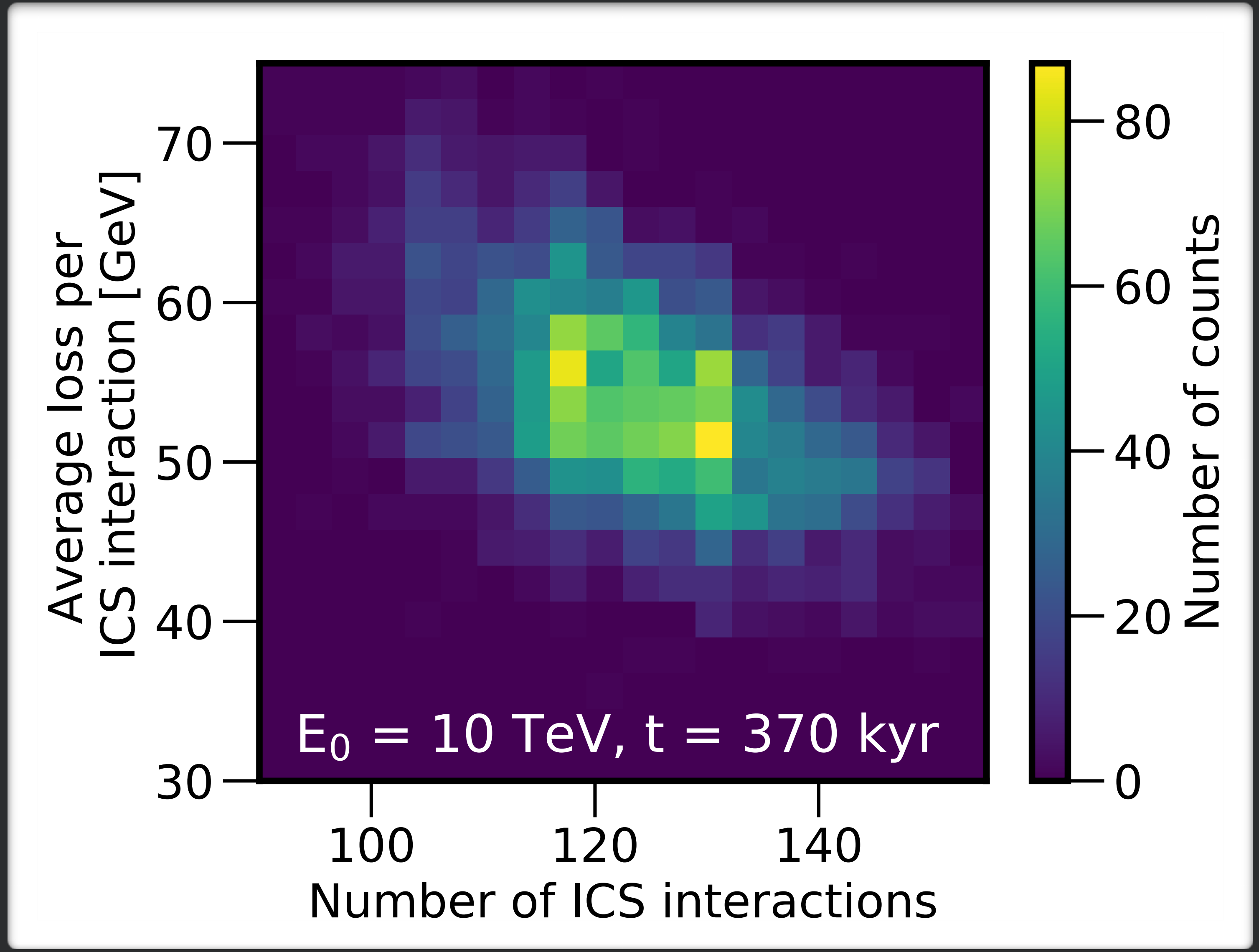
Supplementary Slides

Stochastic Inverse-Compton Scattering

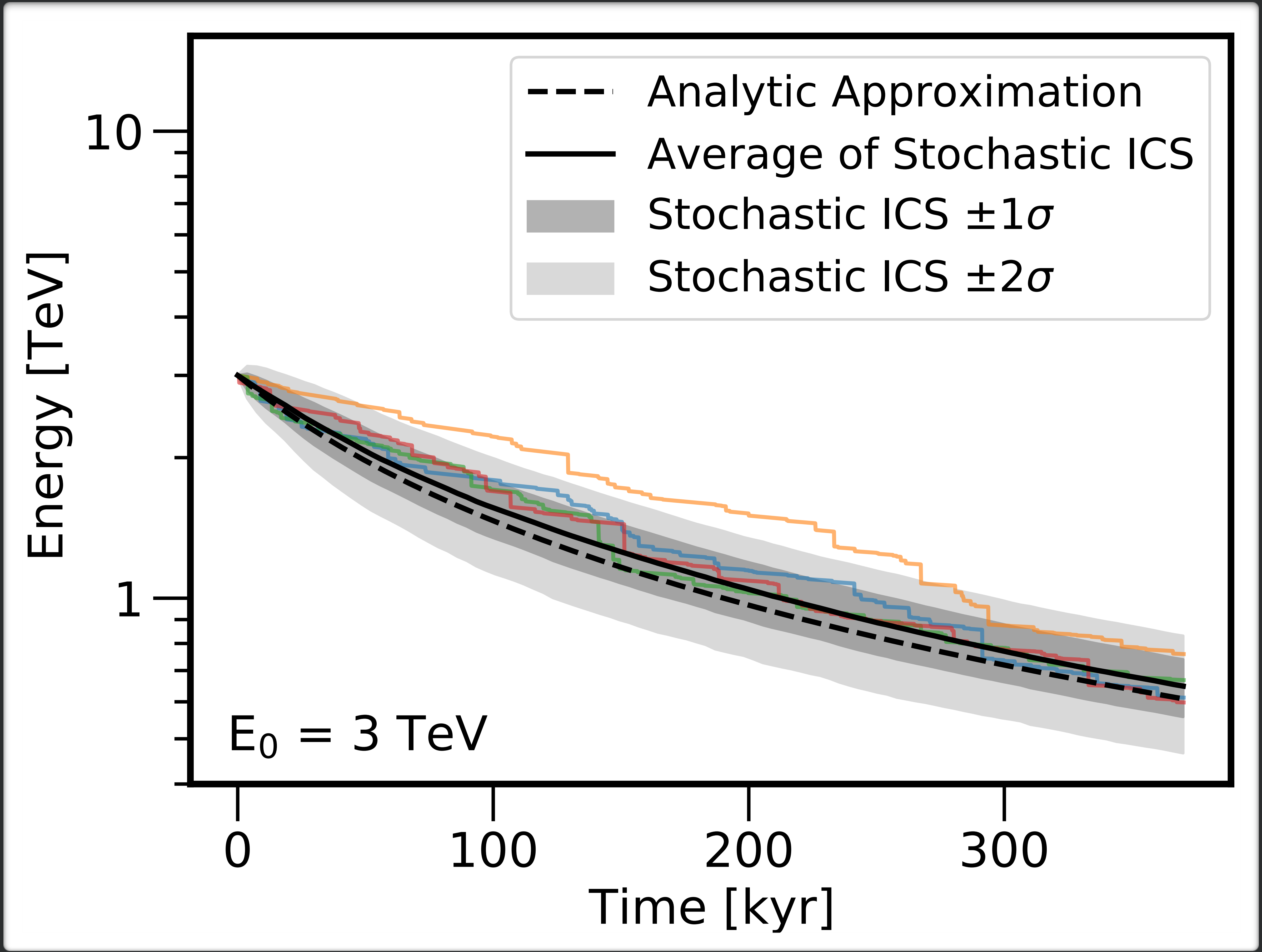








Stochastic Inverse-Compton



Spectral Feature is Independent of Diffusion