Spectral Features From Pulsars and Dark Matter in the Local Cosmic–Ray Electron and Positron Flux

arXiv:2107.10261 & arXiv:2304.07317

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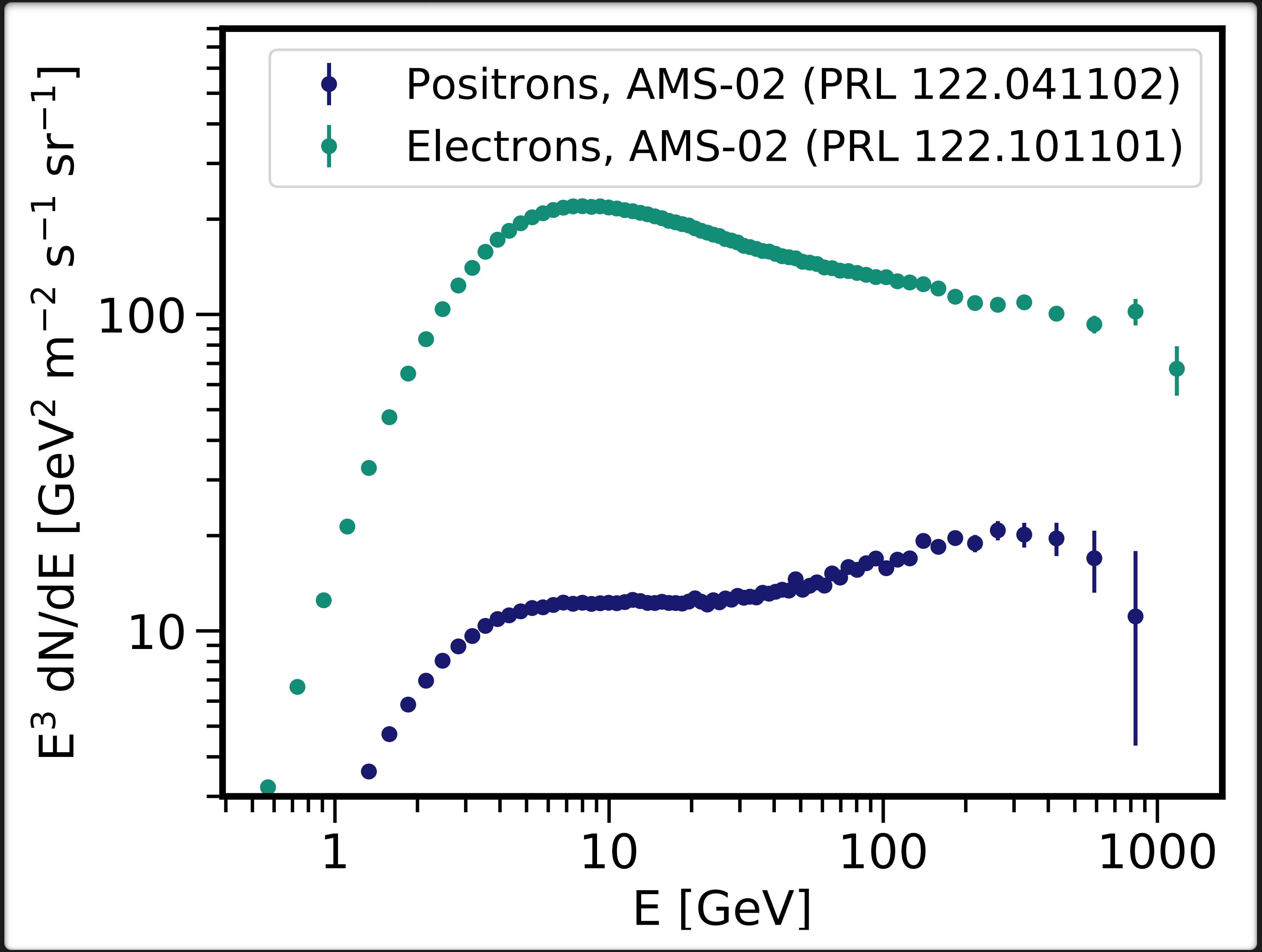
With Tim Linden

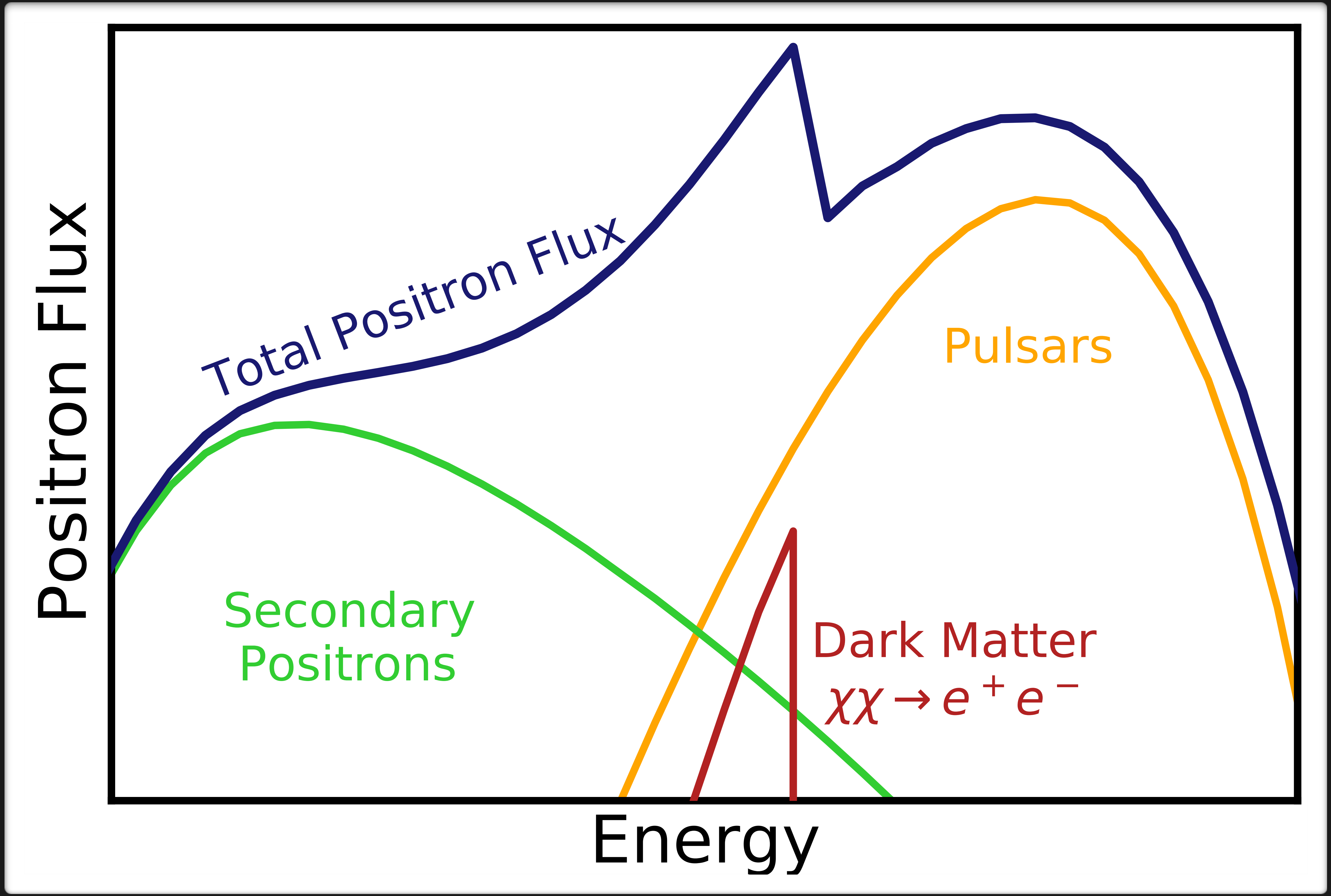
29 August 2023
Cosmology in Miramare

Cosmic–Ray Electrons and Positrons

Experimental



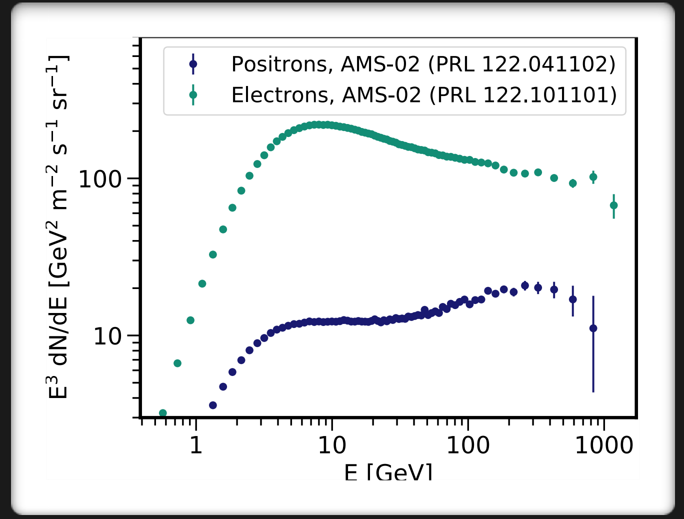
Modelling

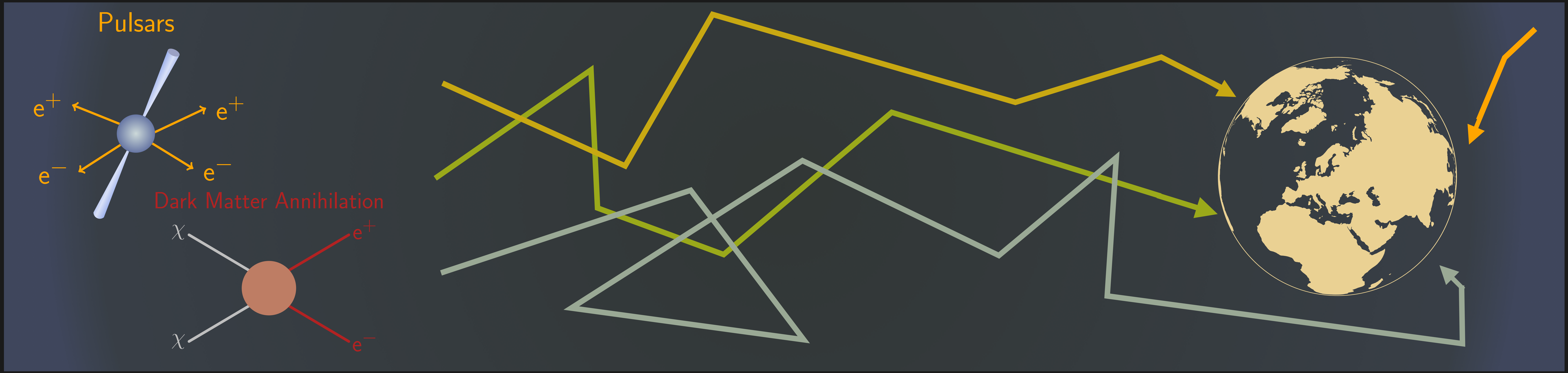


Propagation and Energy Losses

Positron source
e.g. pulsars or
dark matter

Propagation and
Energy Losses





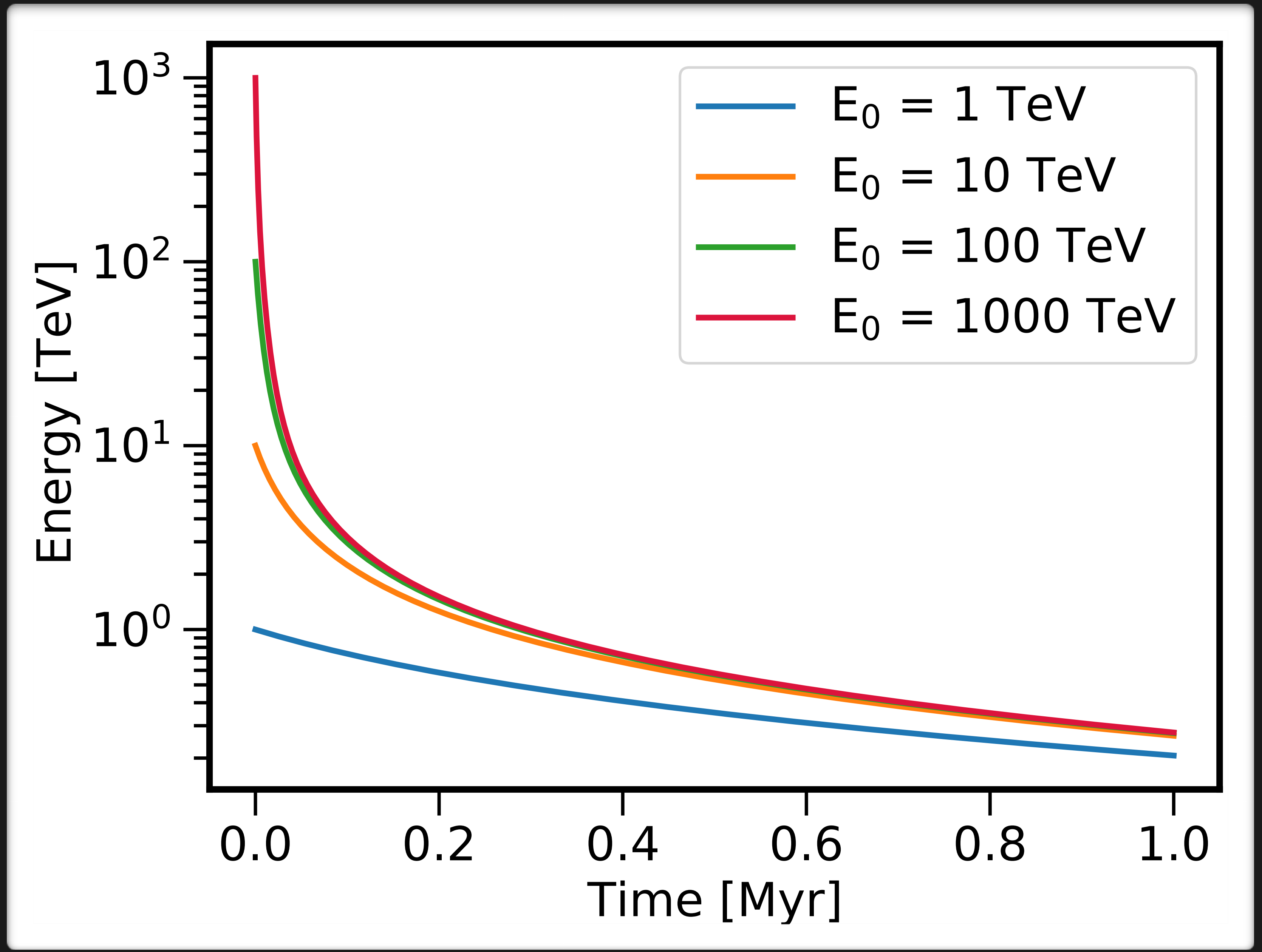
Synchrotron radiation
in magnetic fields

Inverse–Compton scattering
on ambient photons

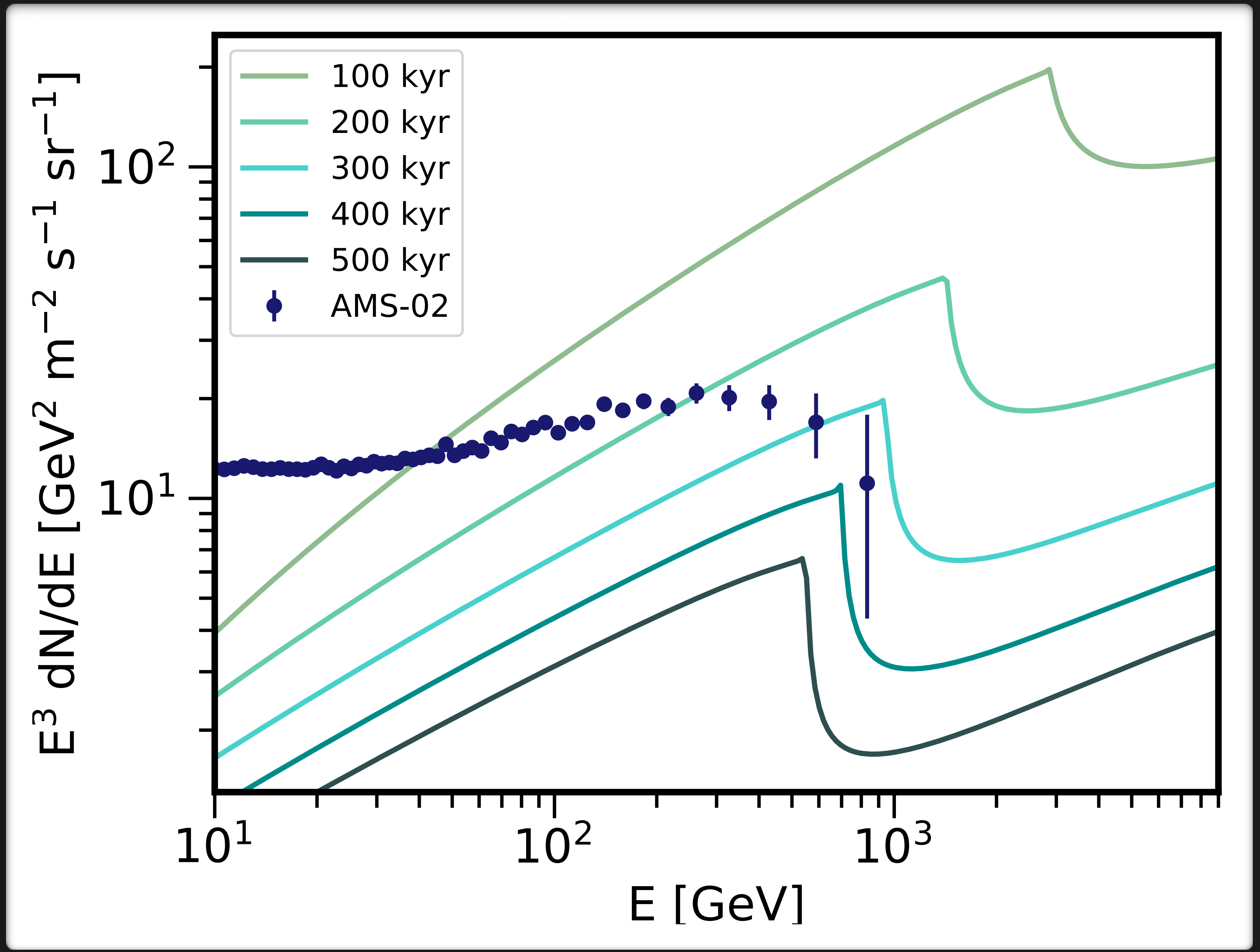
Spectrum of an Individual Pulsar

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

2. High-energy positrons lose energy faster than low-energy positrons

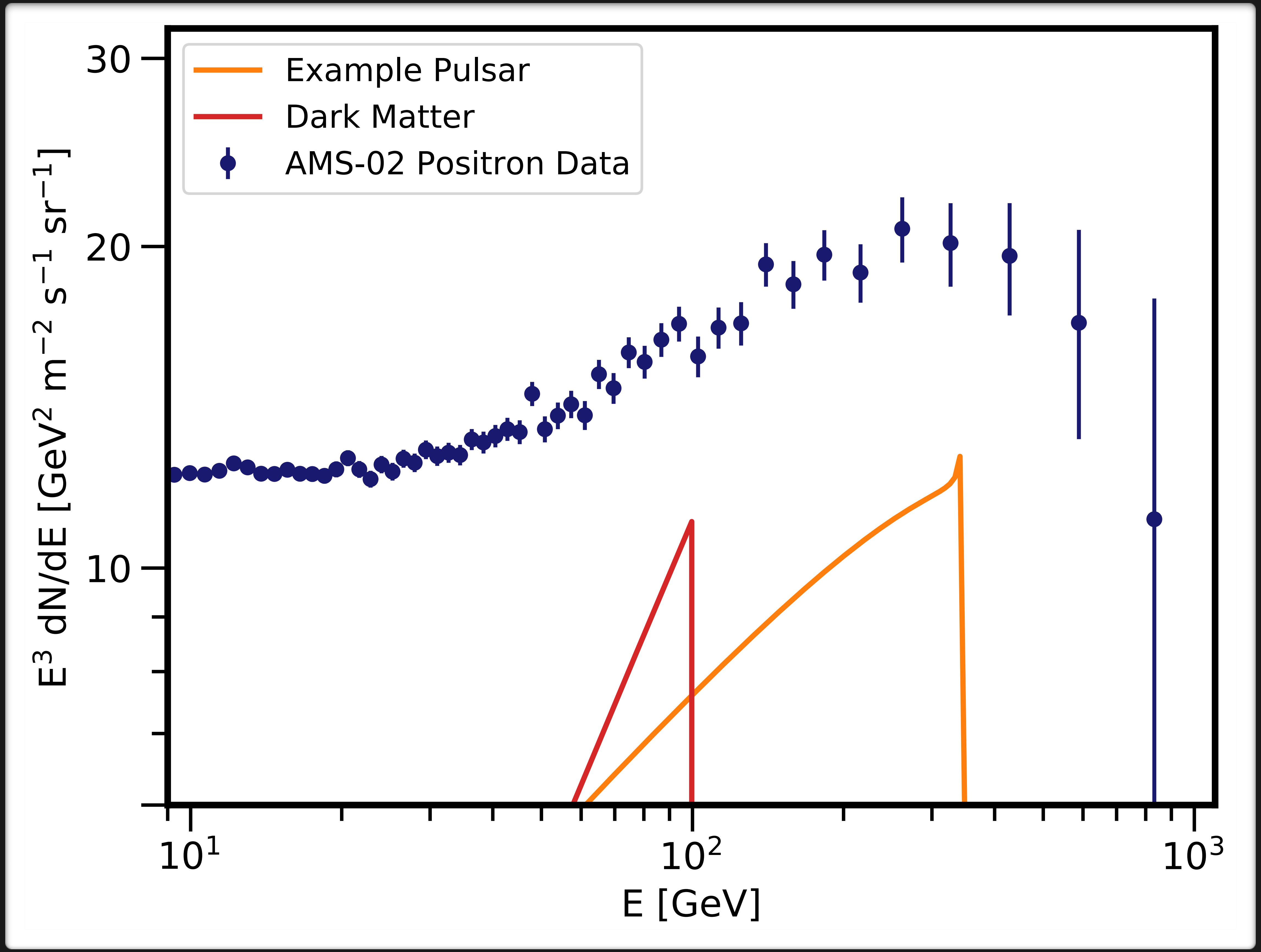


3. These initial positrons build up sharp feature in positron spectrum over time



Sharp Spectral Features?

- Annihilating dark matter would produce sharp spectral features
- Energy loss processes set up a tension of pulsar feature with dark matter



Energy Loss Rate

Continuous energy loss rate:

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

σ_T: Thomson cross section
E_e: Electron energy
m_e: Electron mass
u_i: ISRF photon energy density
ν_i: ISRF photon energy
S: Klein-Nishina suppression

Synchrotron radiation
in magnetic fields

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on ambient ISRF photons

Synchrotron Losses

Average energy loss per interaction:

$$E_{\text{crit}} \approx 0.06 \left(\frac{B}{1\ \mu\text{G}}\right)\left(\frac{E_e}{1\ \text{TeV}}\right)^2$$

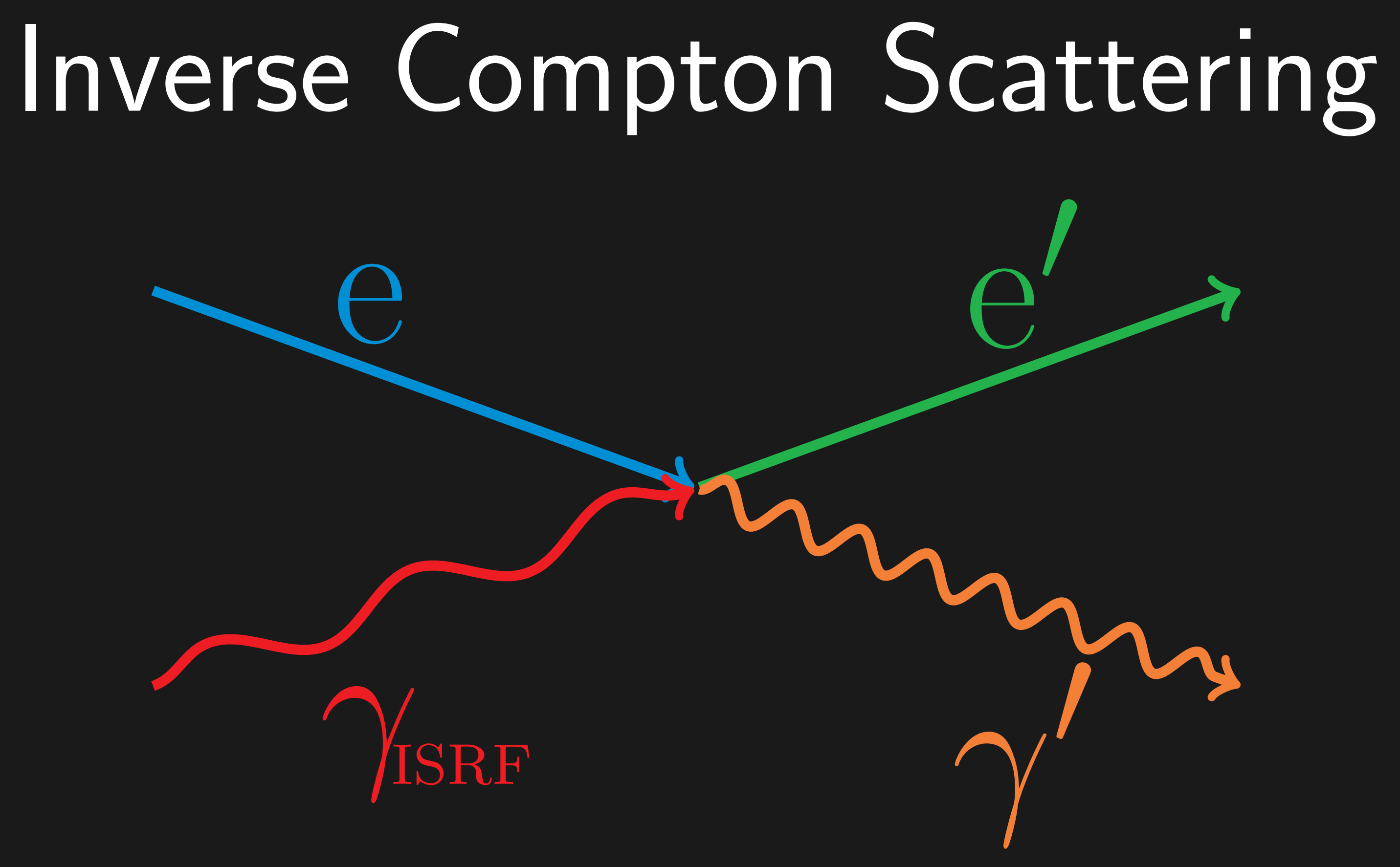
For typical magnetic field strength $B \sim 3\,\mu\text{G}$ and electron energy E_e = 100 TeV

$$\approx 1.8\ \text{keV}$$

Synchrotron losses are small and approximately continuous.

Inverse–Compton Scattering

High energy electrons scatter with photons of the interstellar radiation field



Interstellar Radiation Field (ISRF):

- CMB photons
- IR radiation
- Starlight
- UV radiation

$$\frac{dE_e}{dt} = -\frac{4}{3}\sigma_T c \left(\frac{E_e}{m_e}\right)^2 \sum_i u_i(\nu_i)\, S_i(E_e, \nu_i)$$

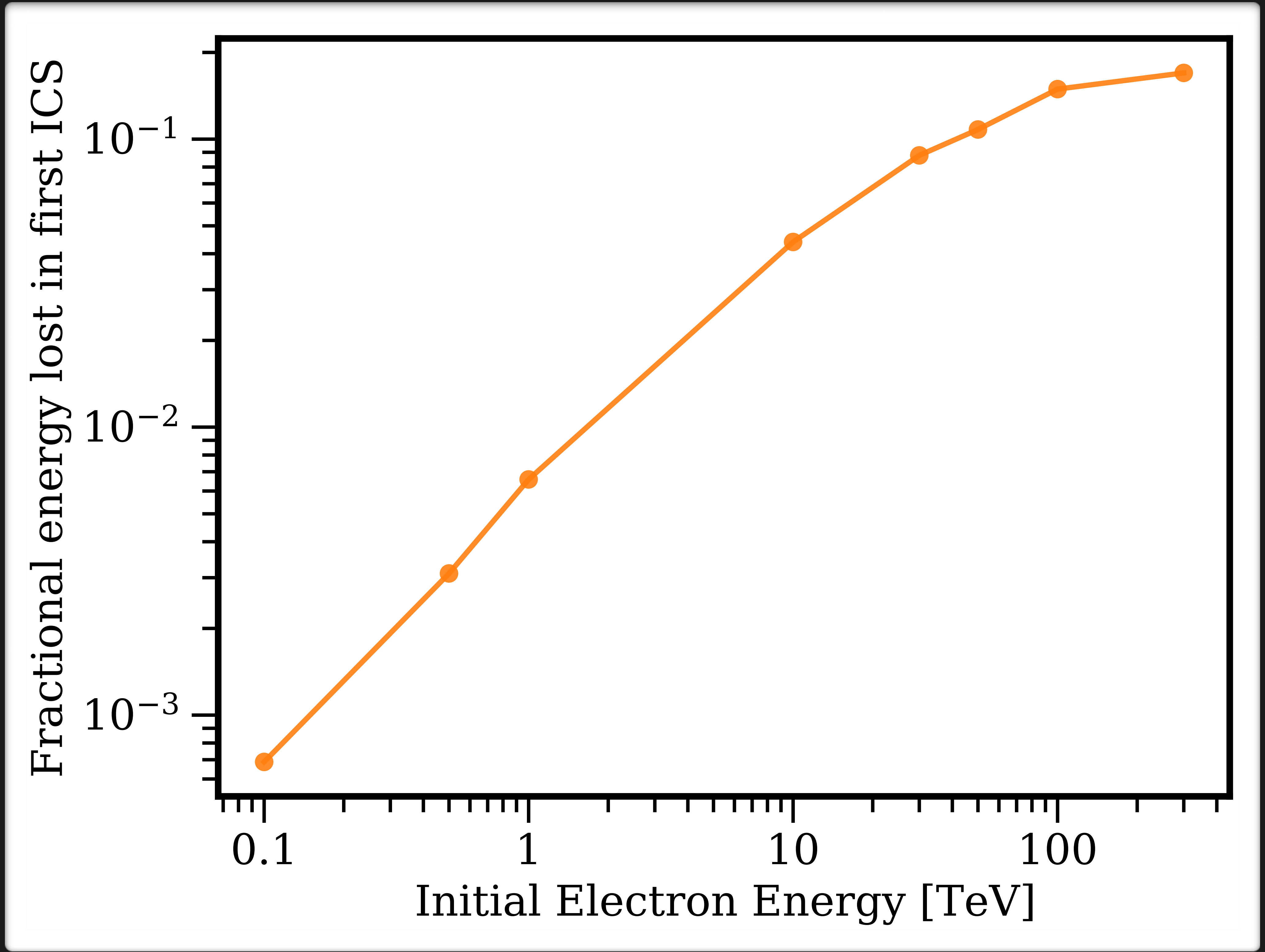
σ_T: Thomson cross section
E_e: Electron energy
m_e: Electron mass
u_i: ISRF photon energy densities
ν_i: ISRF photon energy

S_i: Klein–Nishina suppression

Inverse-Compton Scattering: Continuous Modelling Fails

Average energy loss per ICS interaction

$$\approx \begin{cases} \text{at } E = 1 \text{ TeV} & \rightarrow 0.007 \text{ TeV} \\ \text{at } E = 10 \text{ TeV} & \rightarrow 0.4 \text{ TeV} \\ \text{at } E = 100 \text{ TeV} & \rightarrow 10 \text{ TeV} \end{cases}$$



Modelling Energy Losses

Continuous energy loss rate:

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

Synchrotron radiation
in magnetic fields

Approximately continuous.

Inverse-Compton scattering
on ambient ISRF photons

ICS is a stochastic process
with catastrophic energy losses.

Stochastic Inverse–Compton Scattering Model

[I. John & T. Linden, arXiv:2107.10261]

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

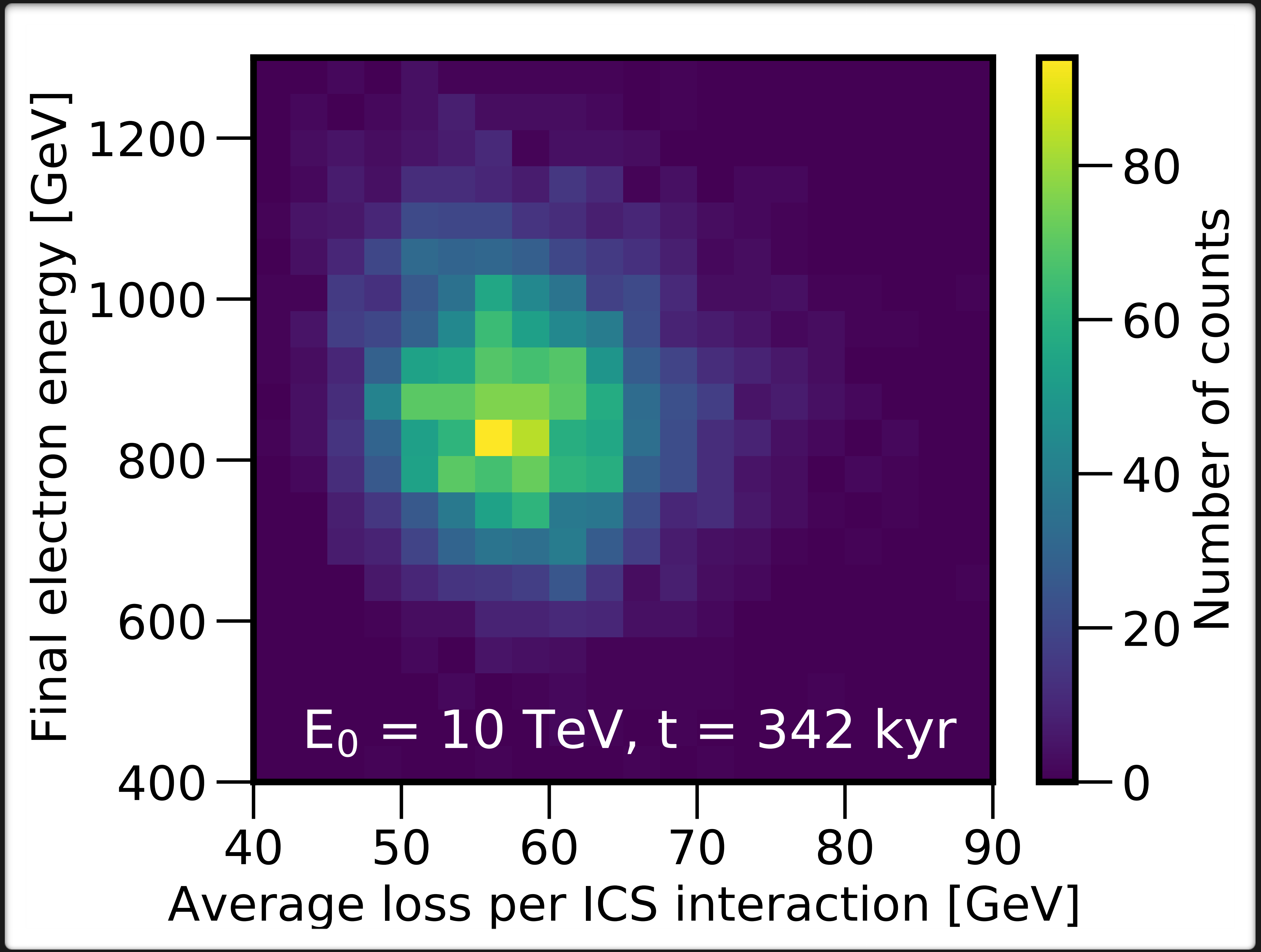
Stochasticity of Inverse–Compton Scattering

Stochastic ICS:

- ICS interactions are rare (~110 interactions in 342 kyr)
- Catastrophic energy losses (~10–100% of energy lost)
- ~30% spread in final positron energy distribution

Continuous calculation:

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

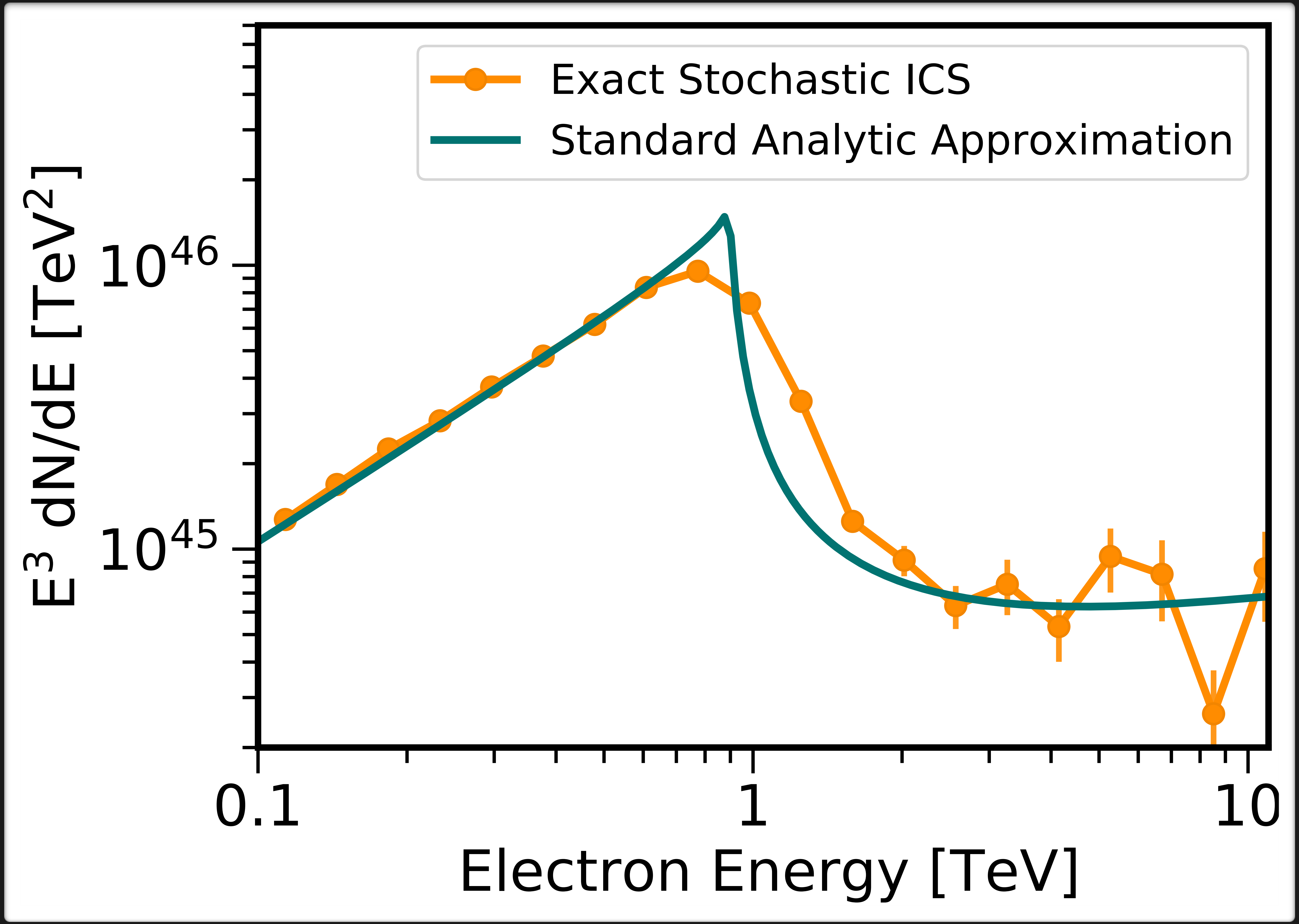


Positron Spectrum of Individual Pulsar

Example Pulsar: Geminga

Age: 342 kyr

Distance: 250 pc

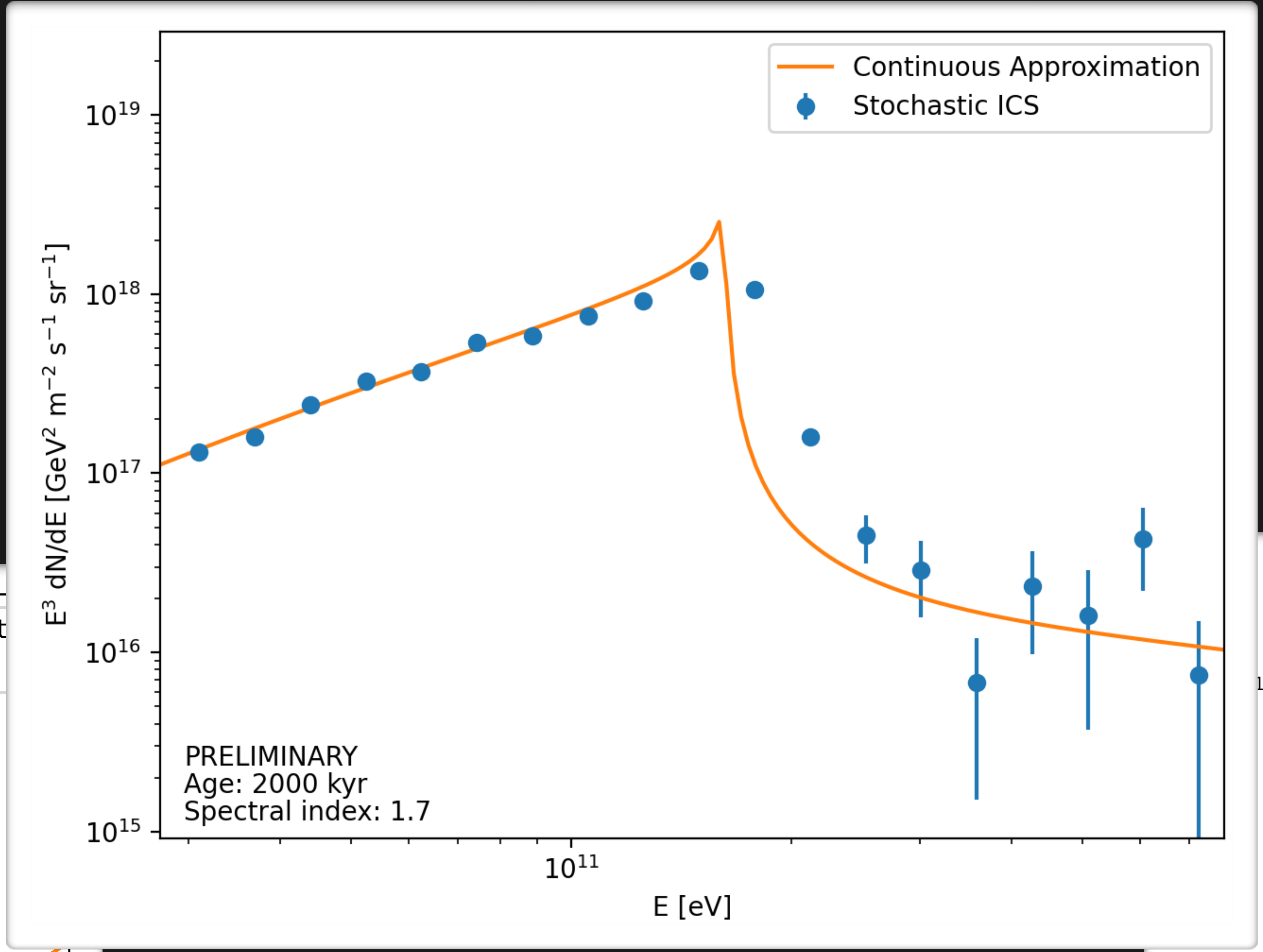


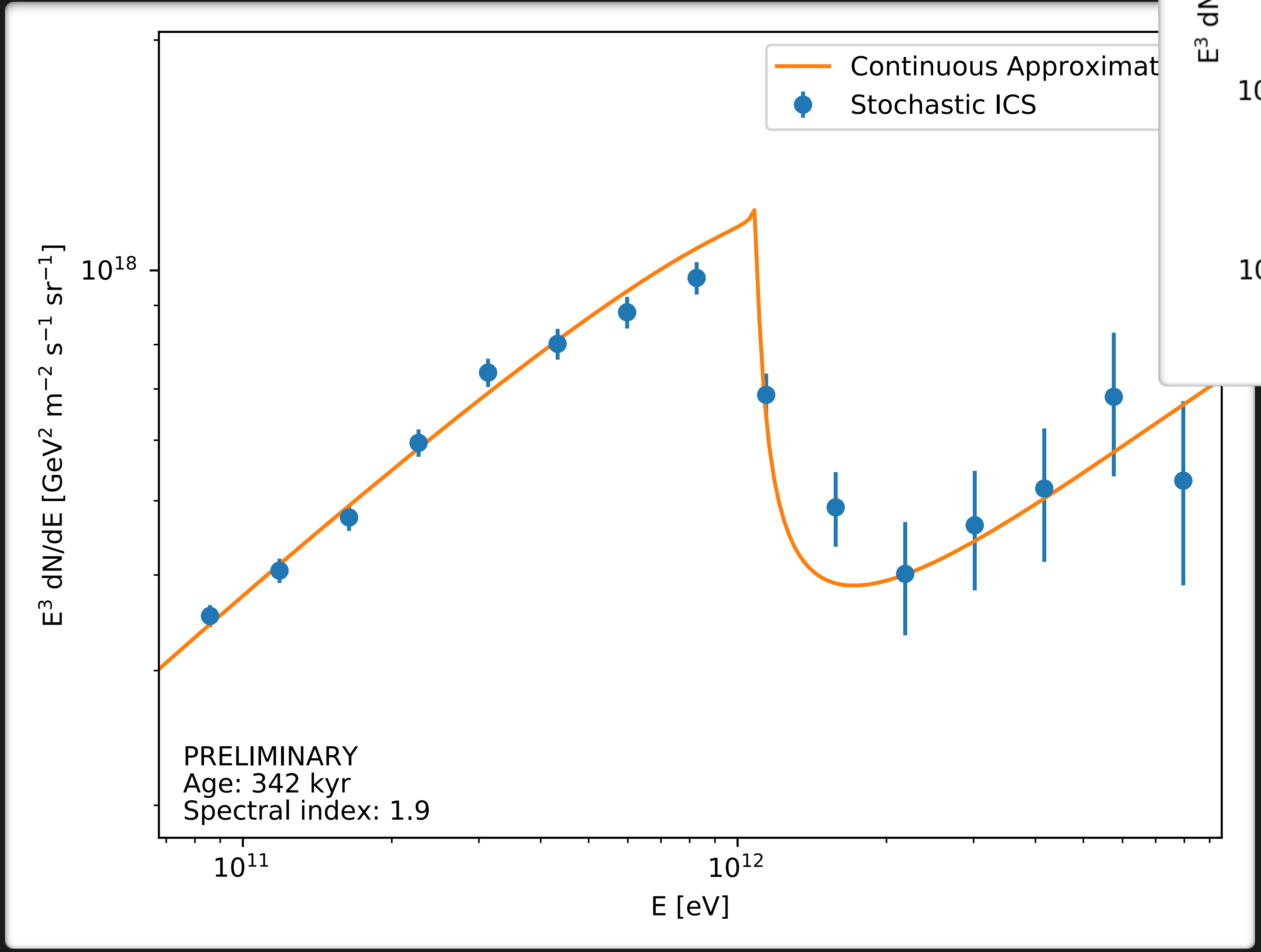
Analytic Model: Hooper et. al, arXiv:0810.1527

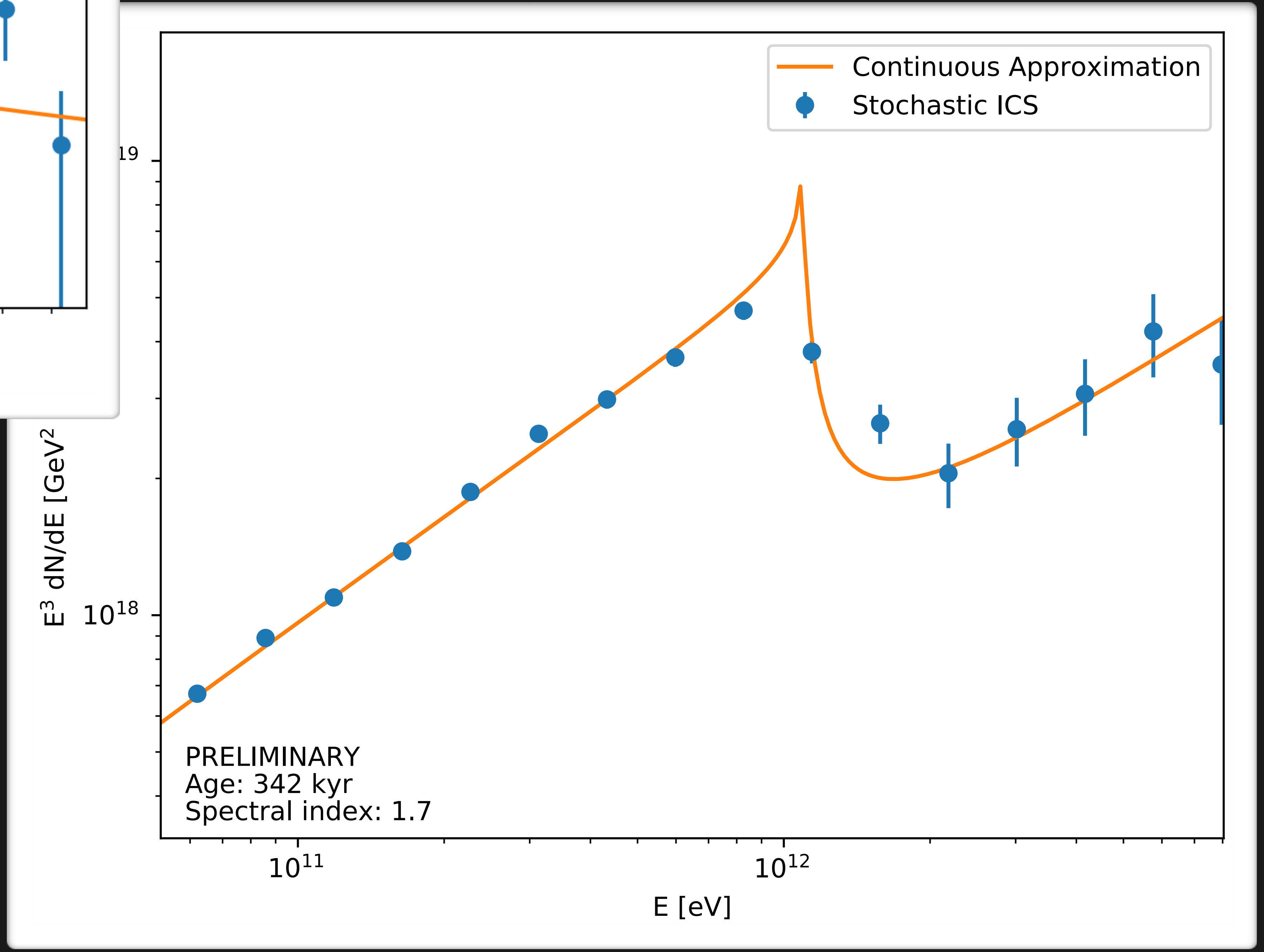
Sharp spectral features introduced by continuous approximation are smoothened out by ~50% when correctly treating inverse-Compton scattering stochastically

Work in Progress: Spectra For A Range of Pulsar Models

[I. John & T. Linden, arXiv:23xx.xxxx]





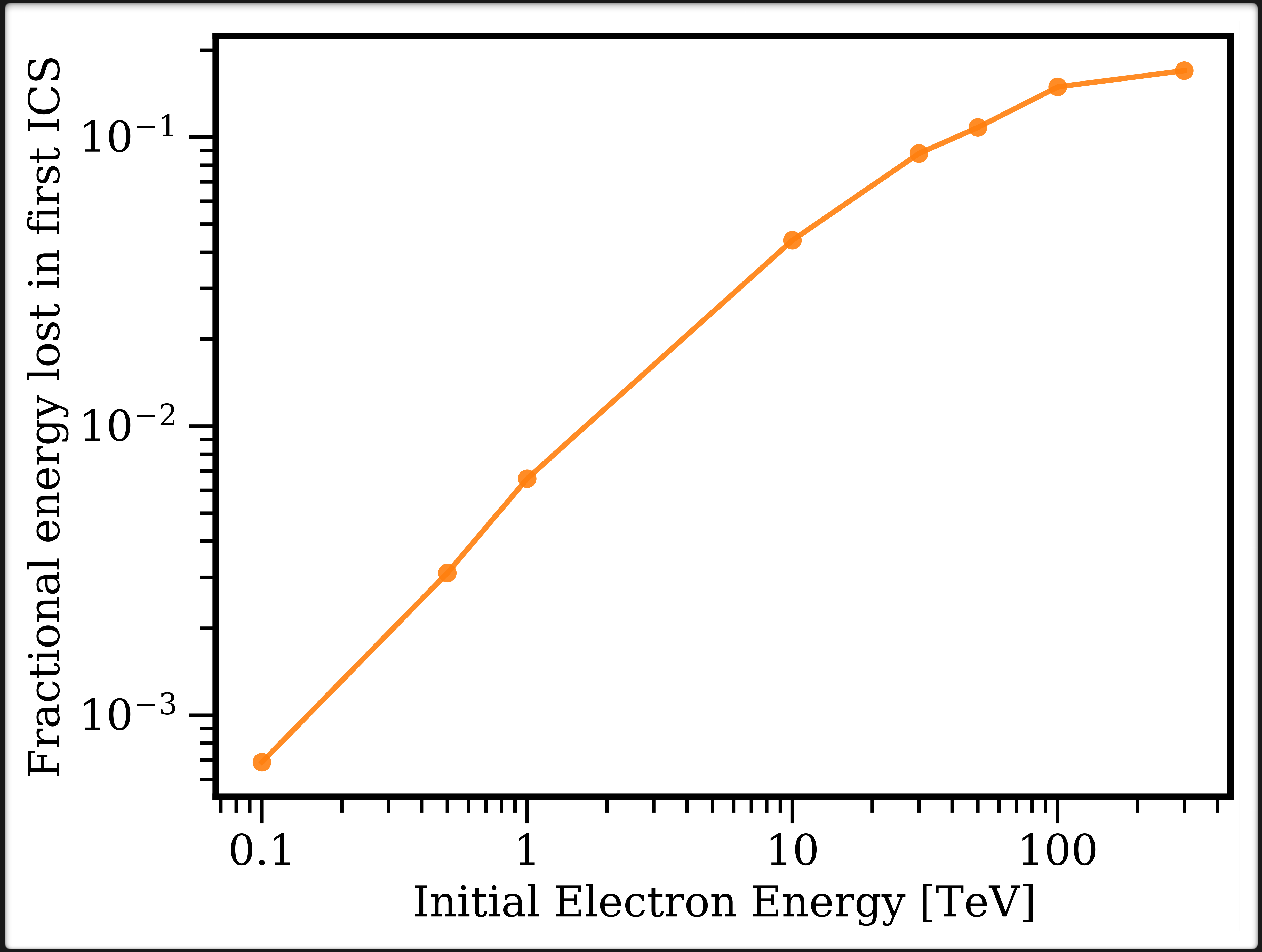


Positron Injection from Pulsars and Dark Matter

Pulsars		Leptophilic Dark Matter
Burst-like injection of e^+e^-	⟷	Continuous injection of e^+e^-
Distribution of e^+e^- injection energies (power law)	⟷	Sharply peaked e^+e^- injection energy (corresponding to dark matter mass)

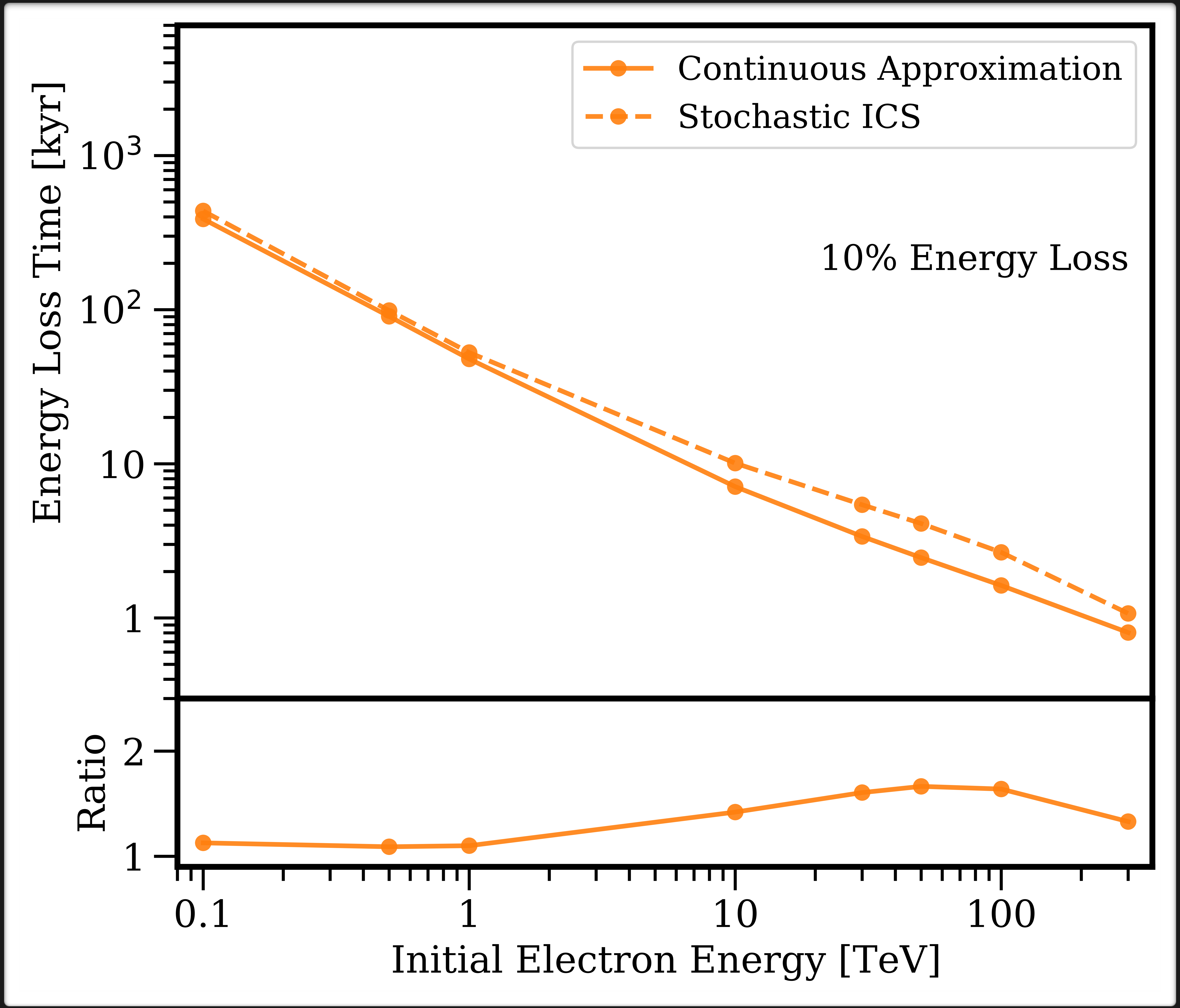
Catastrophic and Rare Inverse–Compton Scattering

[I. John & T. Linden, arXiv:2304.07317]



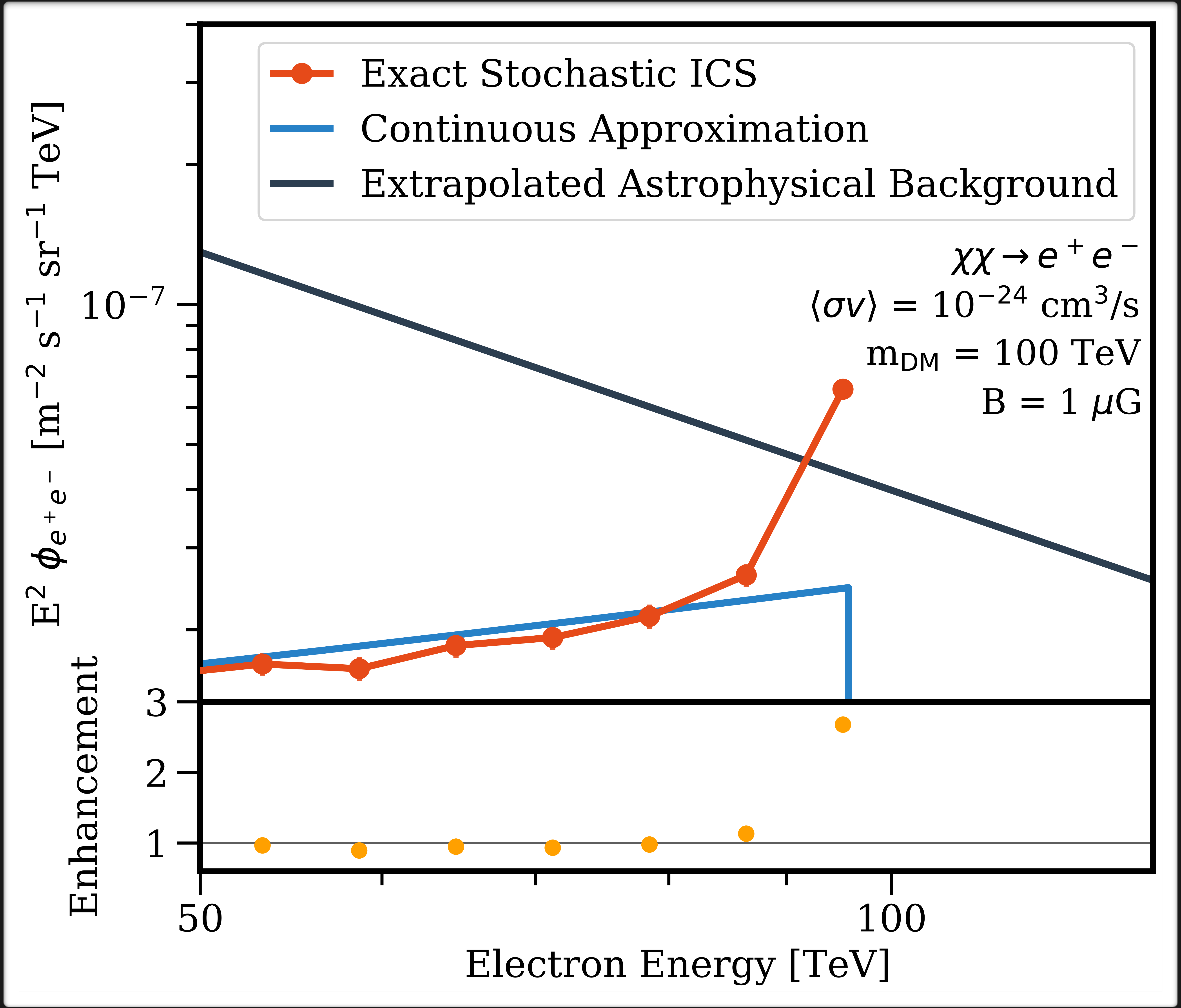
ICS interactions are rare, but take a large fraction of the energy in a single interaction, especially at high energies

Energy Loss Times



Energy losses happen slower in stochastic model than in continuous model

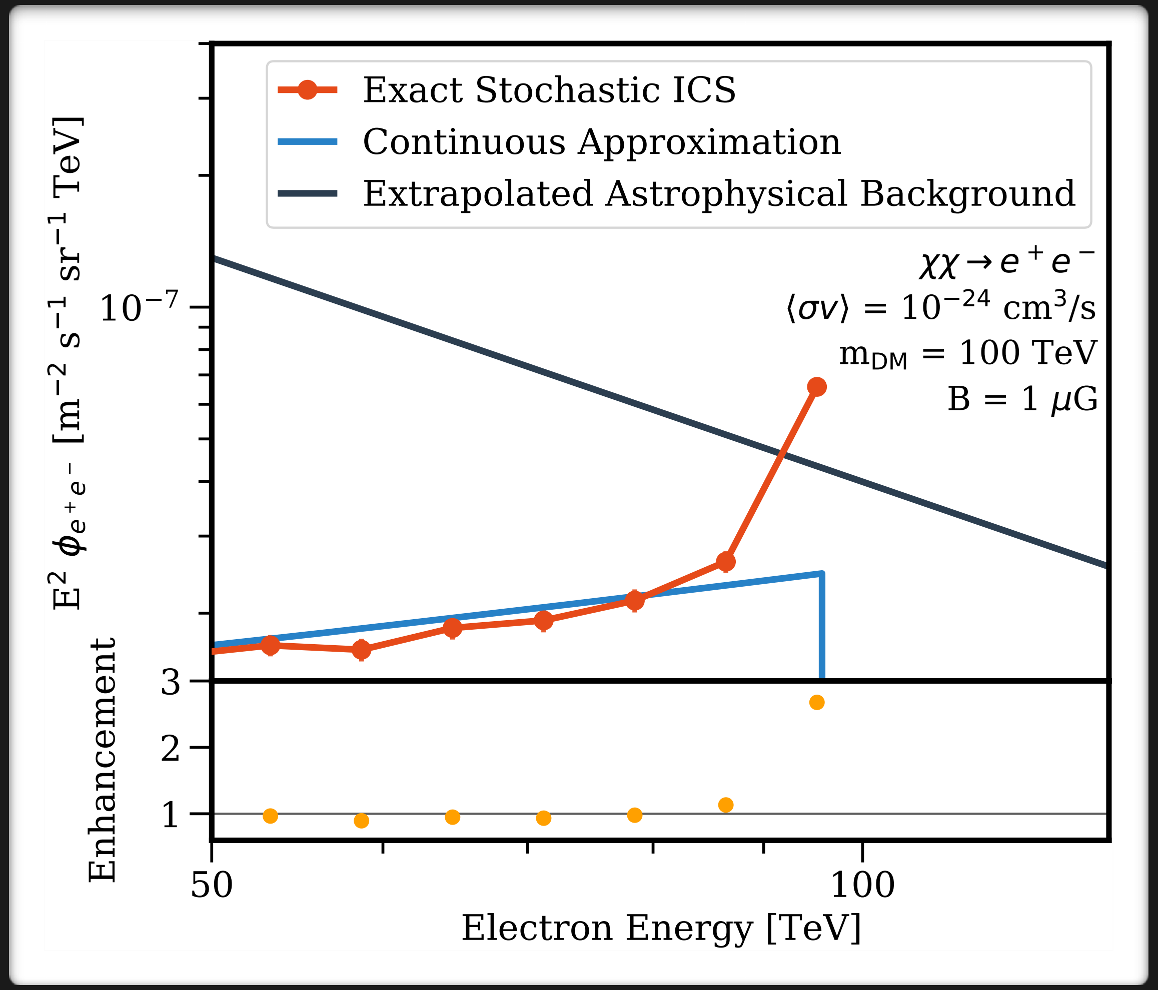
Enhancement of Dark Matter Signal

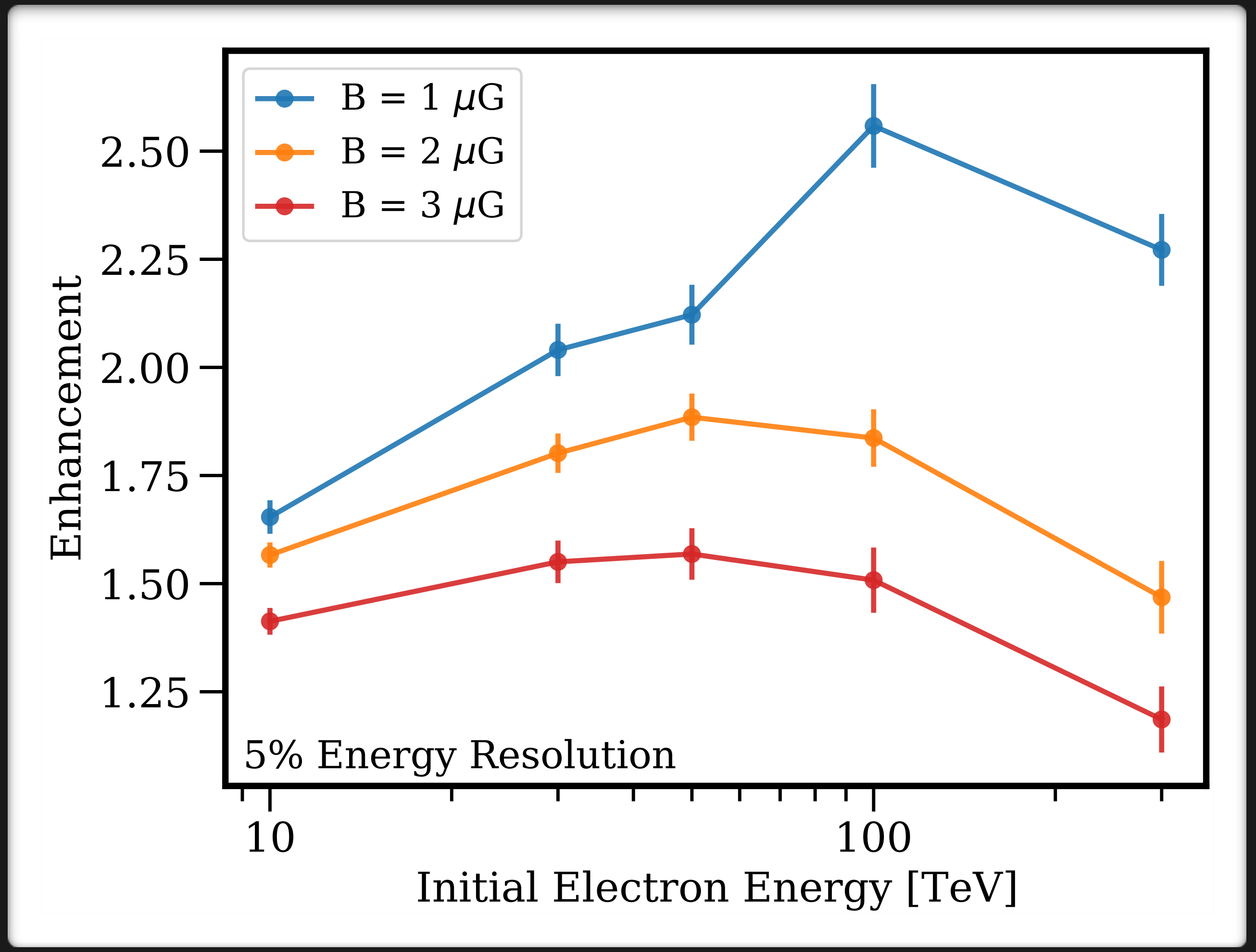


Near the dark matter mass, the spectral cutoff is enhanced by about a factor of 2.6

Increased Detectability: Dependence on Energy Resolution

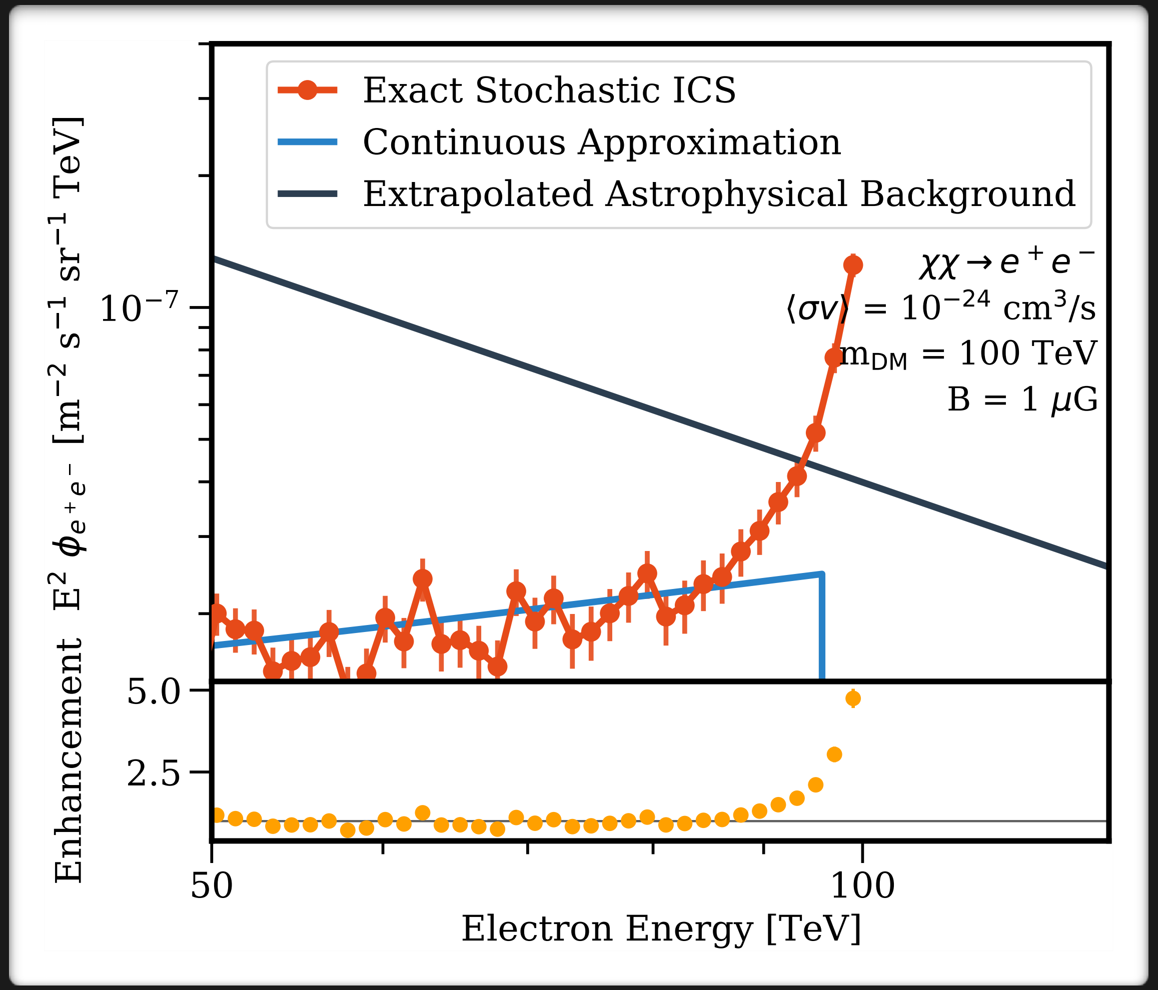
5 % energy resolution

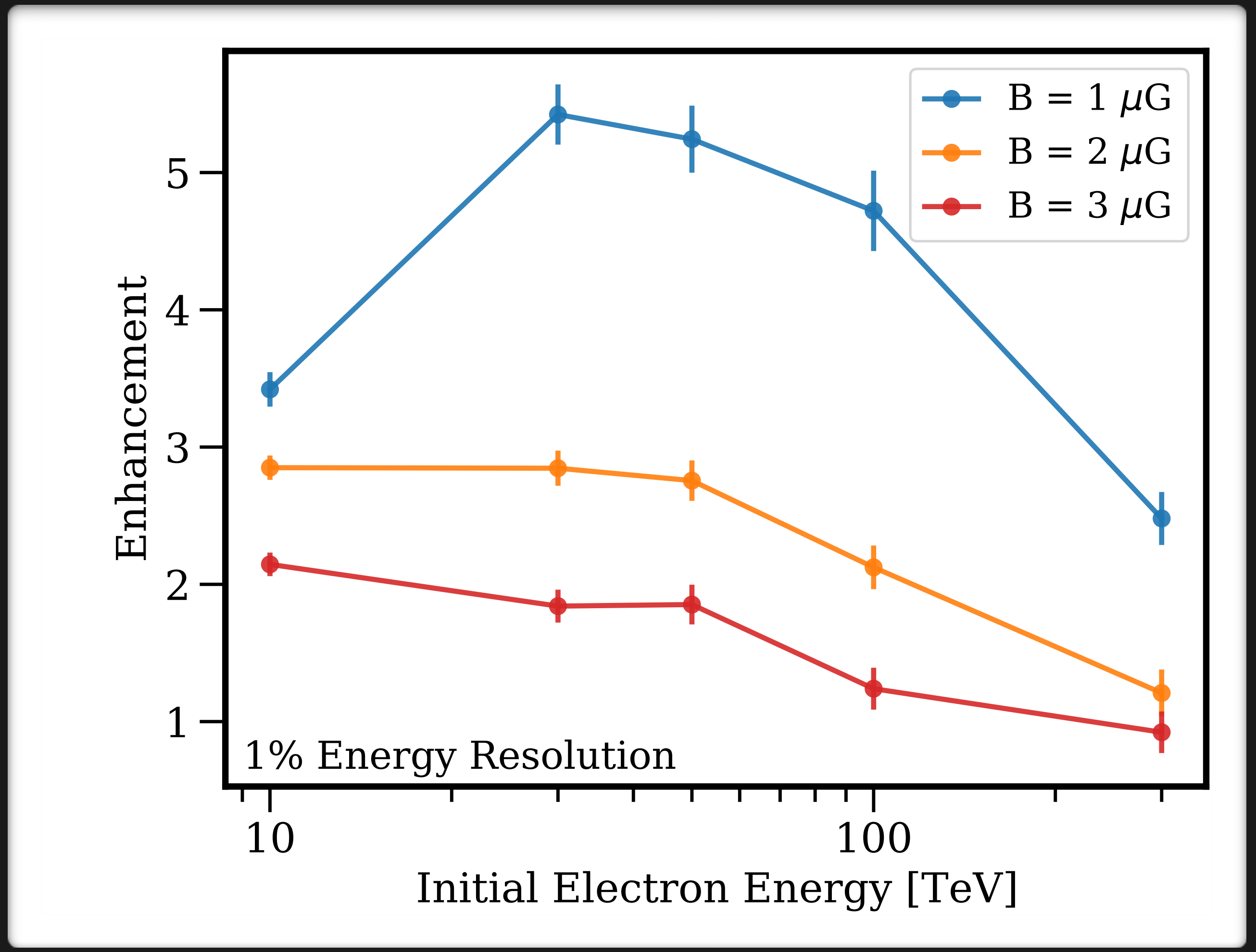




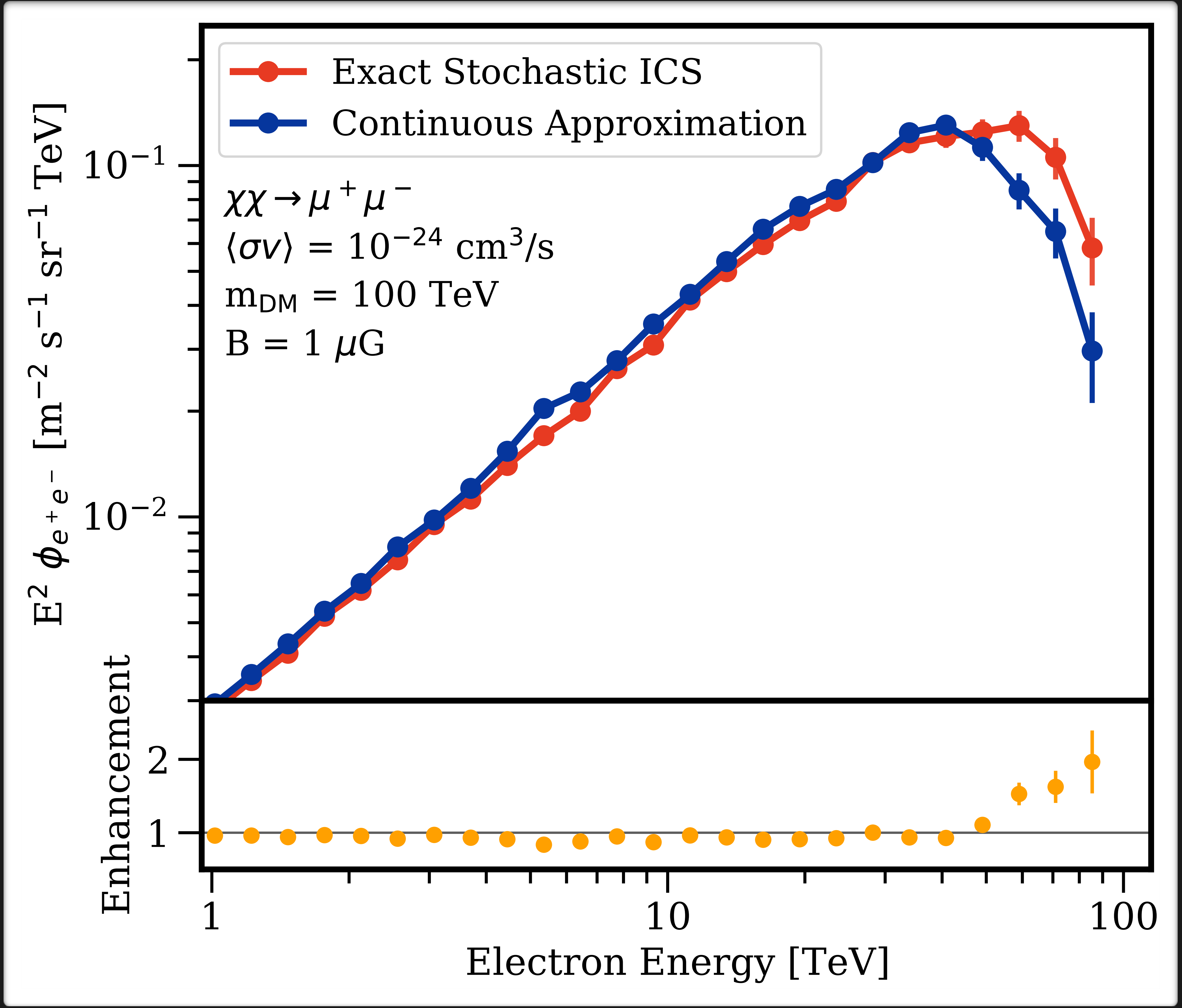
1 % energy resolution

Expected for e.g. HERD





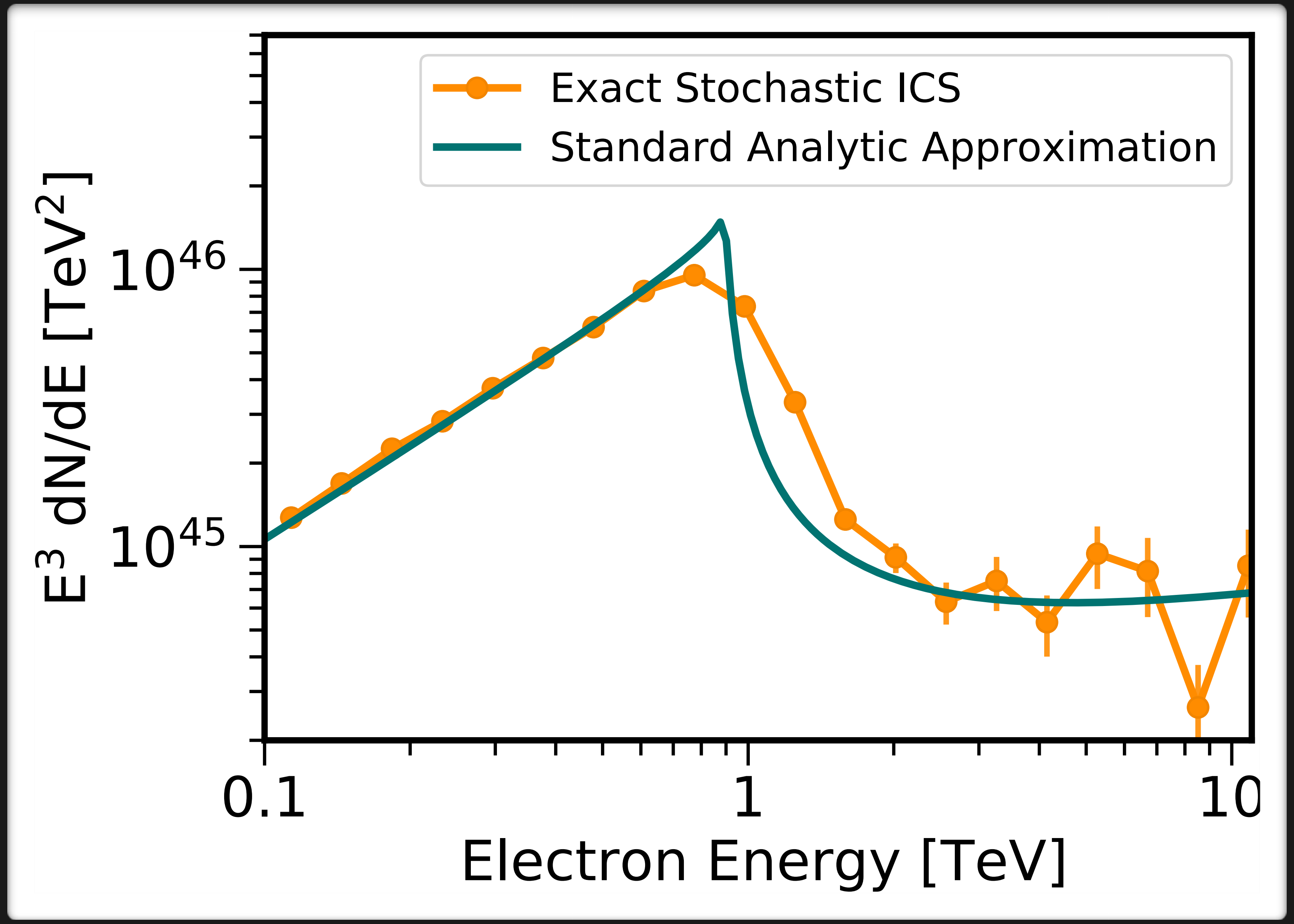
Dark Matter Annihilation into Muons



- Dark matter annihilates into $\mu^+\mu^-$ that subsequently decay into e^+e^-
- e^+e^- are injected at a distribution of energies
- Enhancement is smaller than in direct e^+e^- case
- Enhancement is further reduced for annihilations into $\tau^+\tau^-$ and other hadronic final states

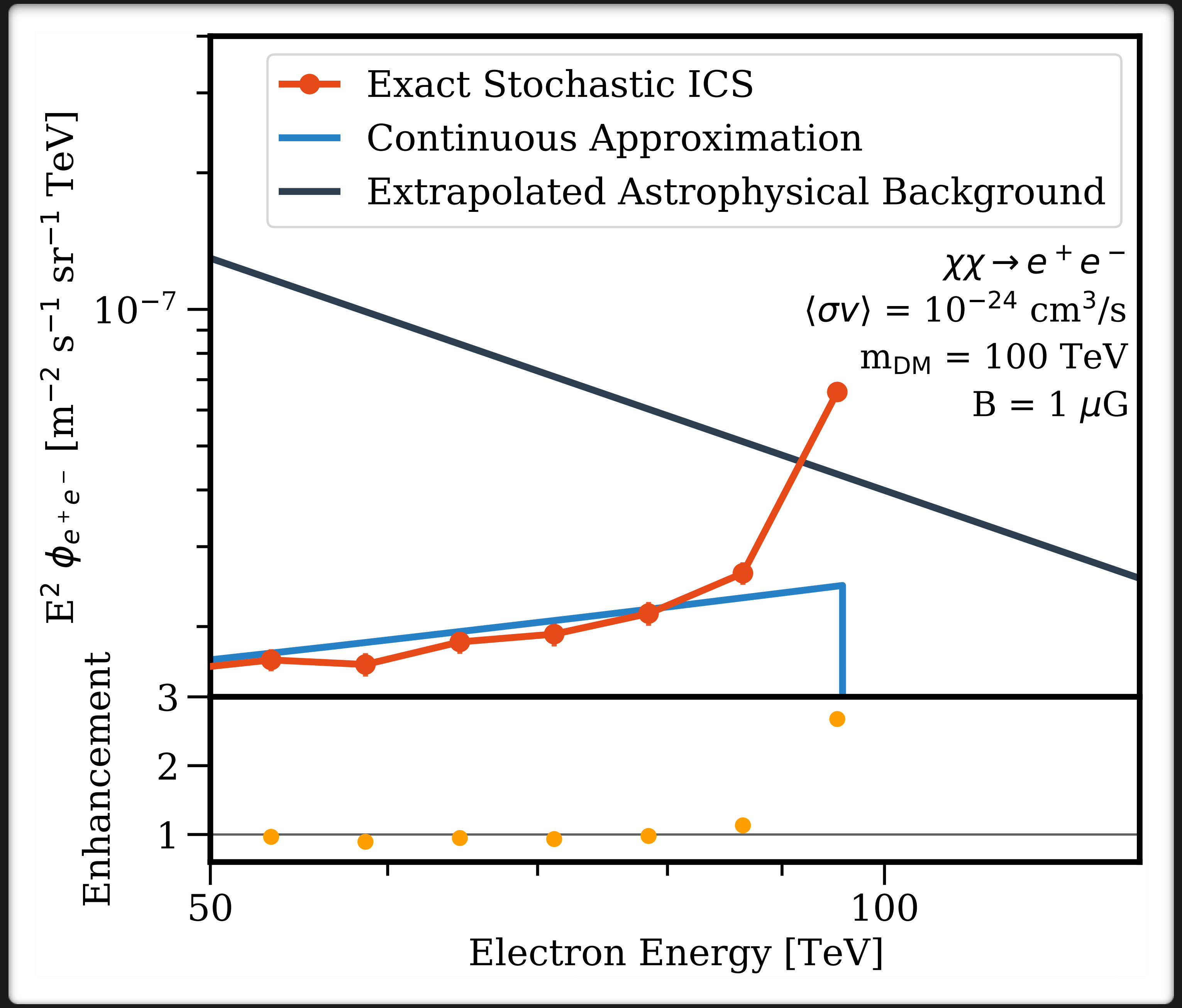
Implications of Stochastic ICS

Pulsars do not produce sharp spectral features



[arXiv:2107.10261]

Leptophilic dark matter signal is enhanced



[arXiv:2304.07317]

Dark matter is the only known astrophysical mechanism that can produce sharp spectral features in the e^+e^- flux.

Extra Slides

Stochasticity of Inverse–Compton Scattering

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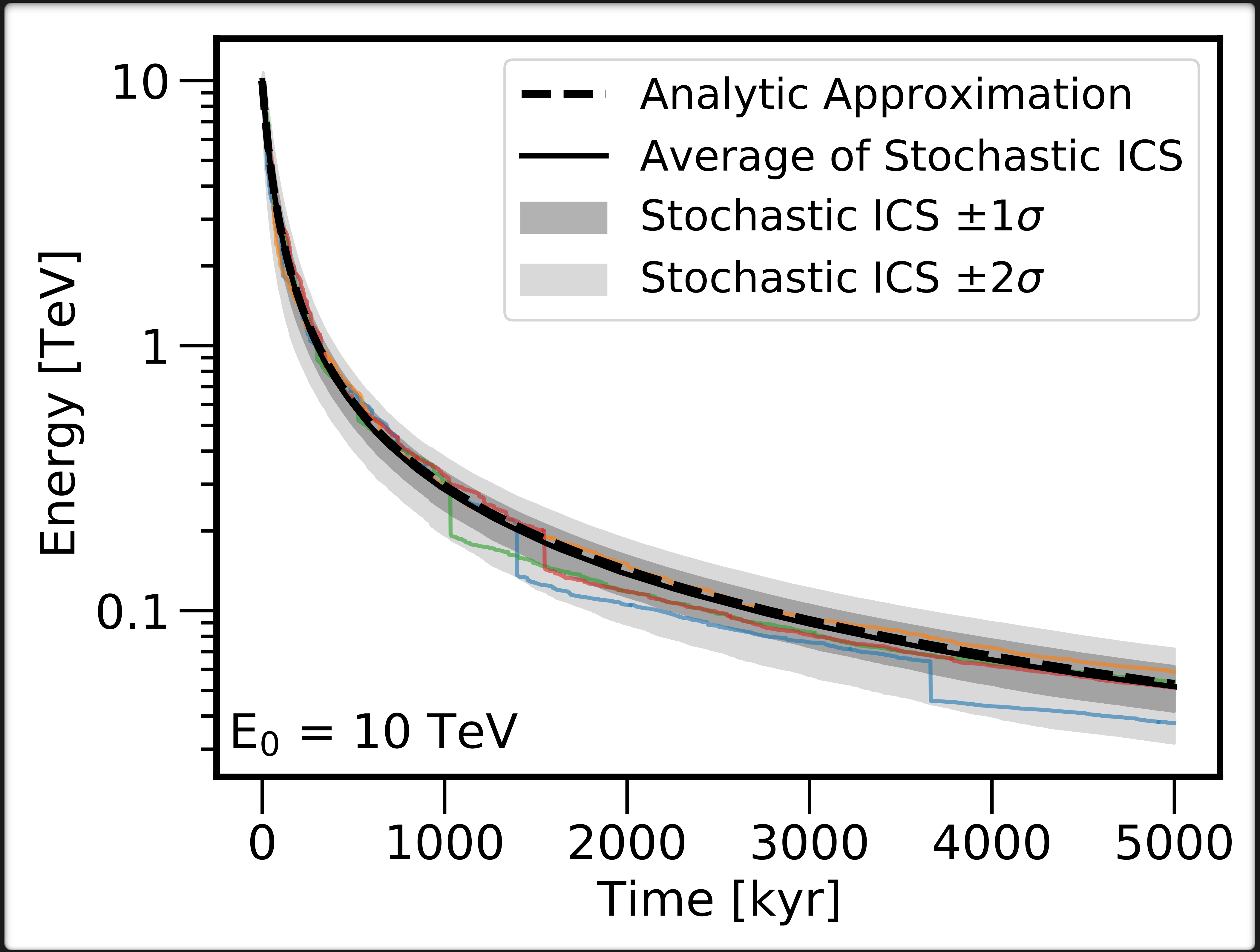
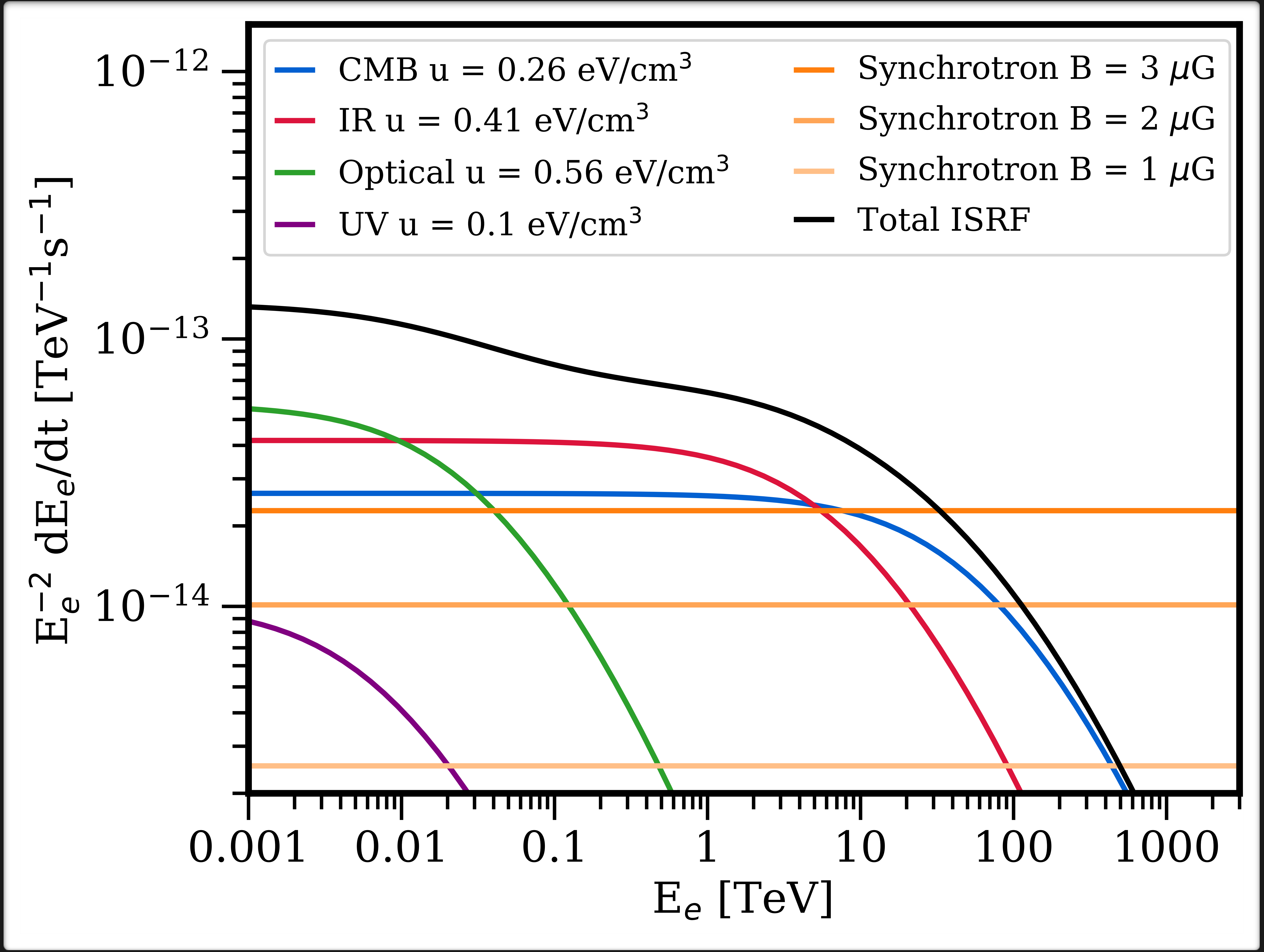


Continuous calculation:

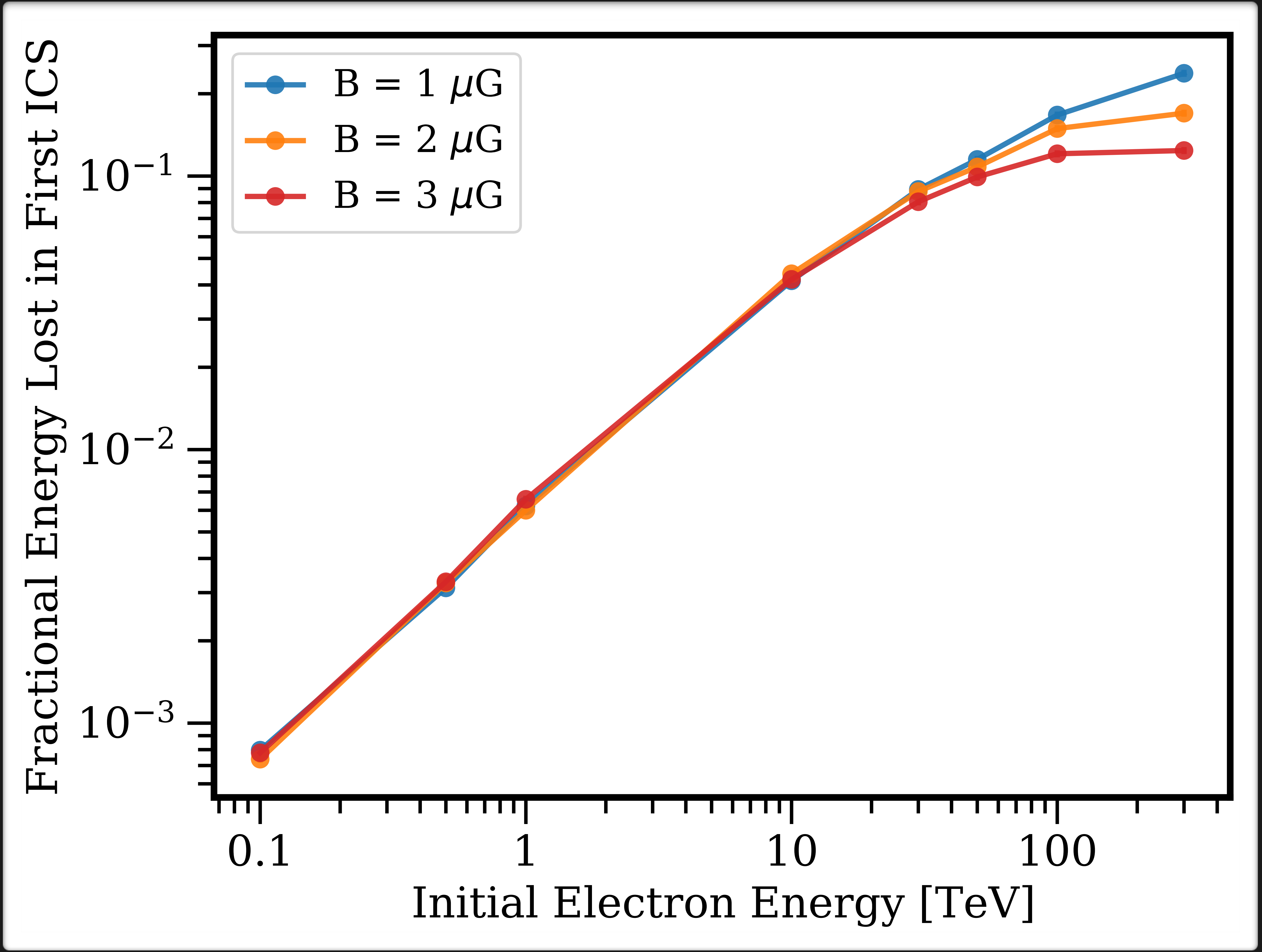
- All positrons are treated the same way, cool down to exactly the same energy

Interstellar Radiation Fields and Magnetic Fields



Inverse–Compton Energy Losses

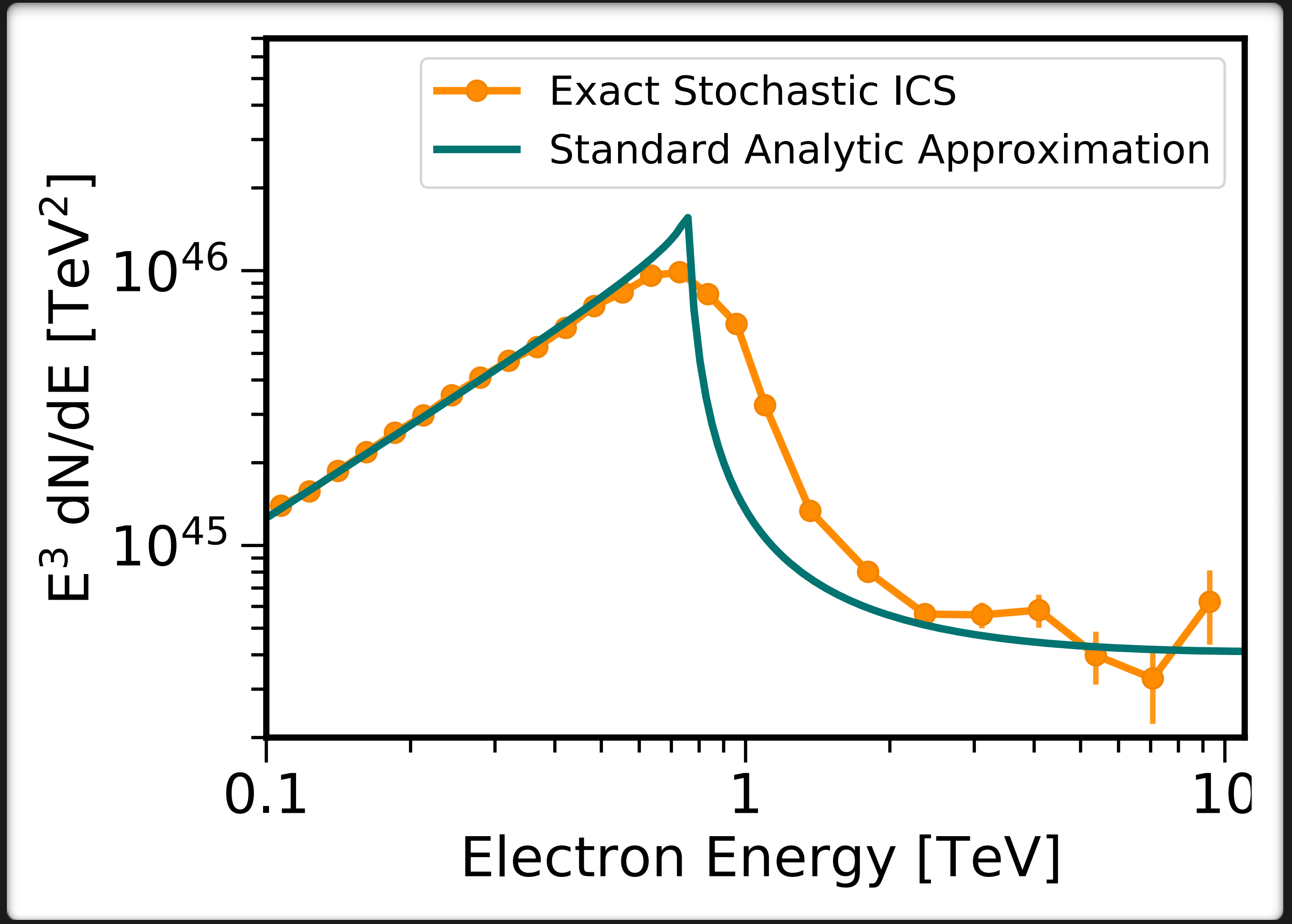
[I. John & T. Linden, arXiv:2304.07317]

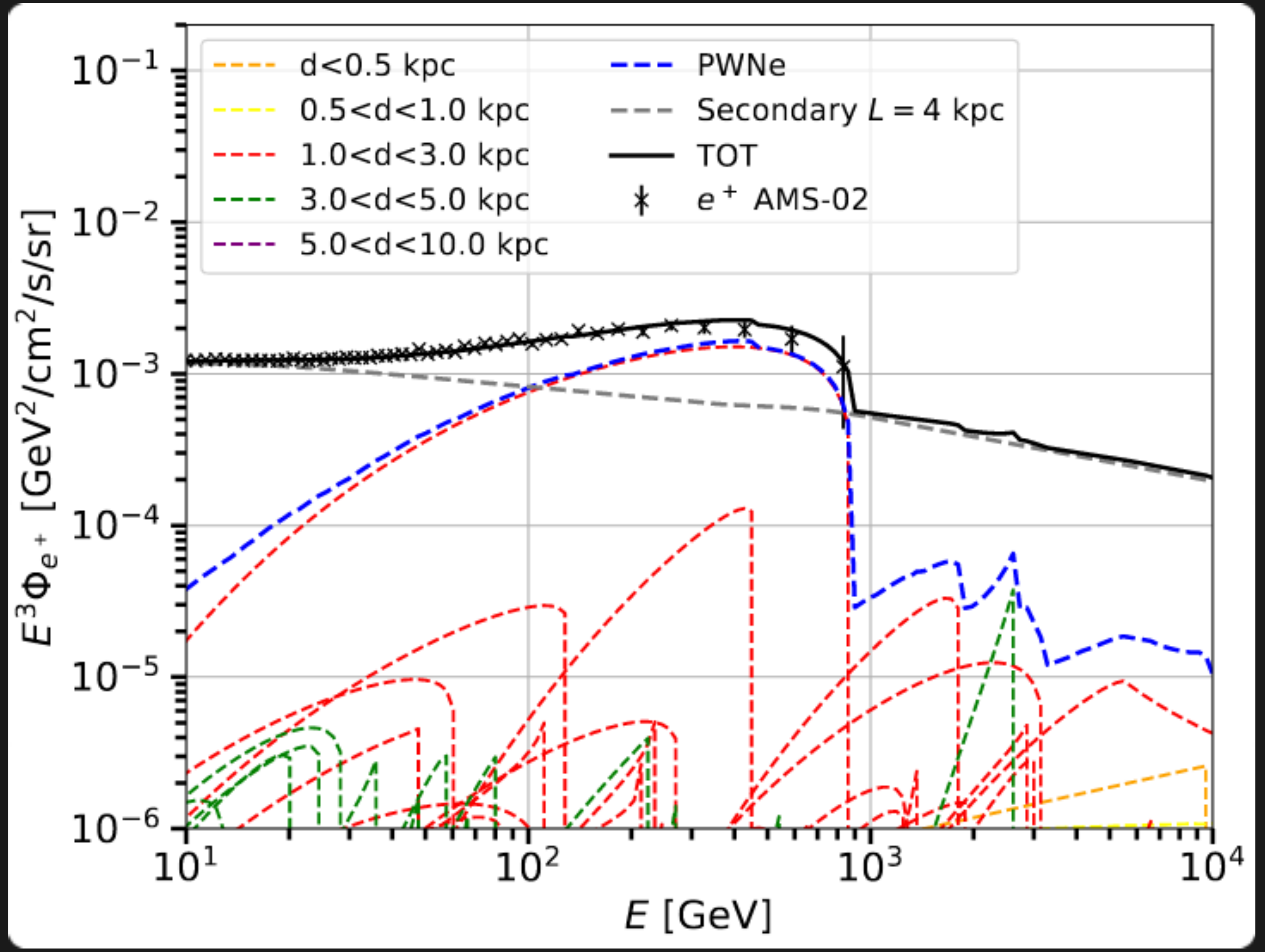


ICS interactions are rare, but take a large fraction of the energy in a single interaction, especially at high energies

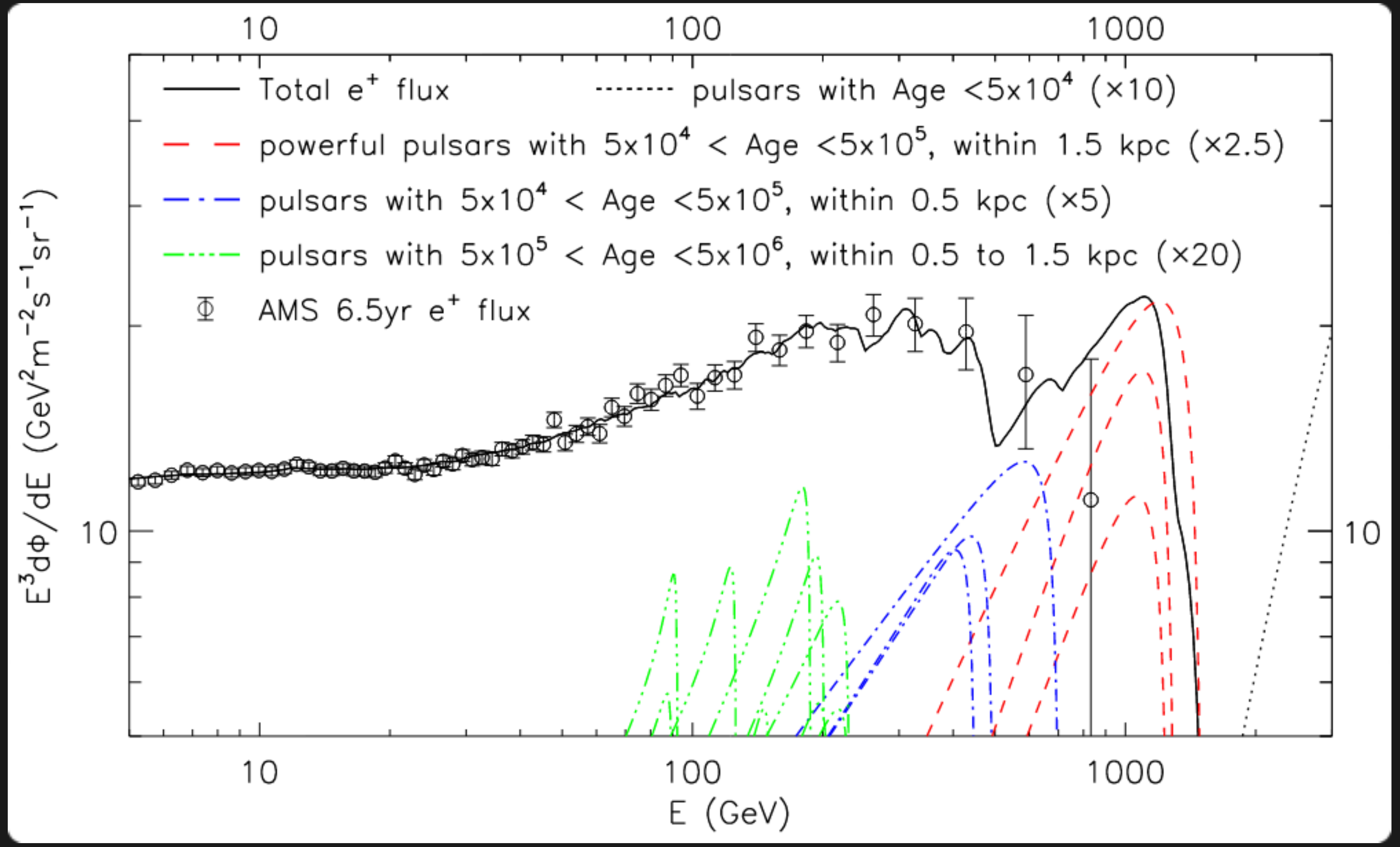
Implications for Pulsar Models

- Pulsars do not produce sharp features
- 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
- Loosens constraints on number of contributing pulsars





Orusa et al., arXiv:2107.06300



Cholis & Krommydas, arXiv:2111.05864