Production of high-energy neutrinos in binary-neutron-star merger events

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BNS merger environment

After the merger, a portion of the fall-back material can be shock-accelerated to high-energy cosmic rays with subsequent neutrino production.

$$E_{max} \sim A^{3/2} Z^{-3/2} \left(\frac{t}{10^3\, s}\right)^{5/12} \cdot 10^{17.5}\, eV$$

The thermal photon background is approximated with a black body photon field:

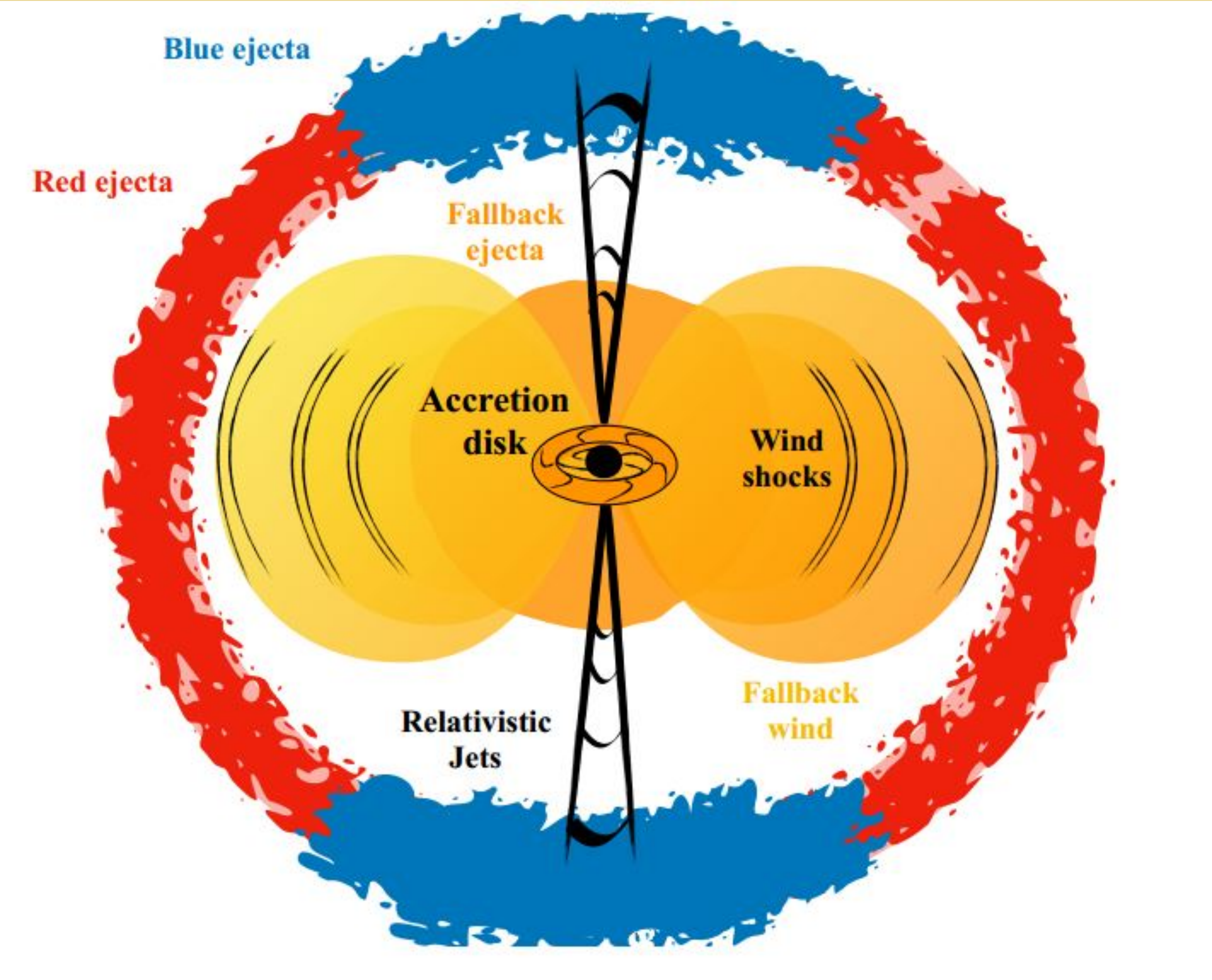
$$T = 10^8\, K \div 10^4\, K \qquad \log\left(\frac{t}{1\, s}\right) \simeq -\frac{1}{2}\log\left(\frac{T}{1\, K}\right) + 6$$

Non-thermal component:

$$n_{NT}(\epsilon) \simeq (7.2 \cdot 10^{41}\, eV^{-1}\, cm^{-3}) \left(\frac{1\, cm^3}{V}\right) \left(\frac{t}{1\, s}\right)^{2.21} \left(\frac{\epsilon}{1\, eV}\right)^{-1.6}$$

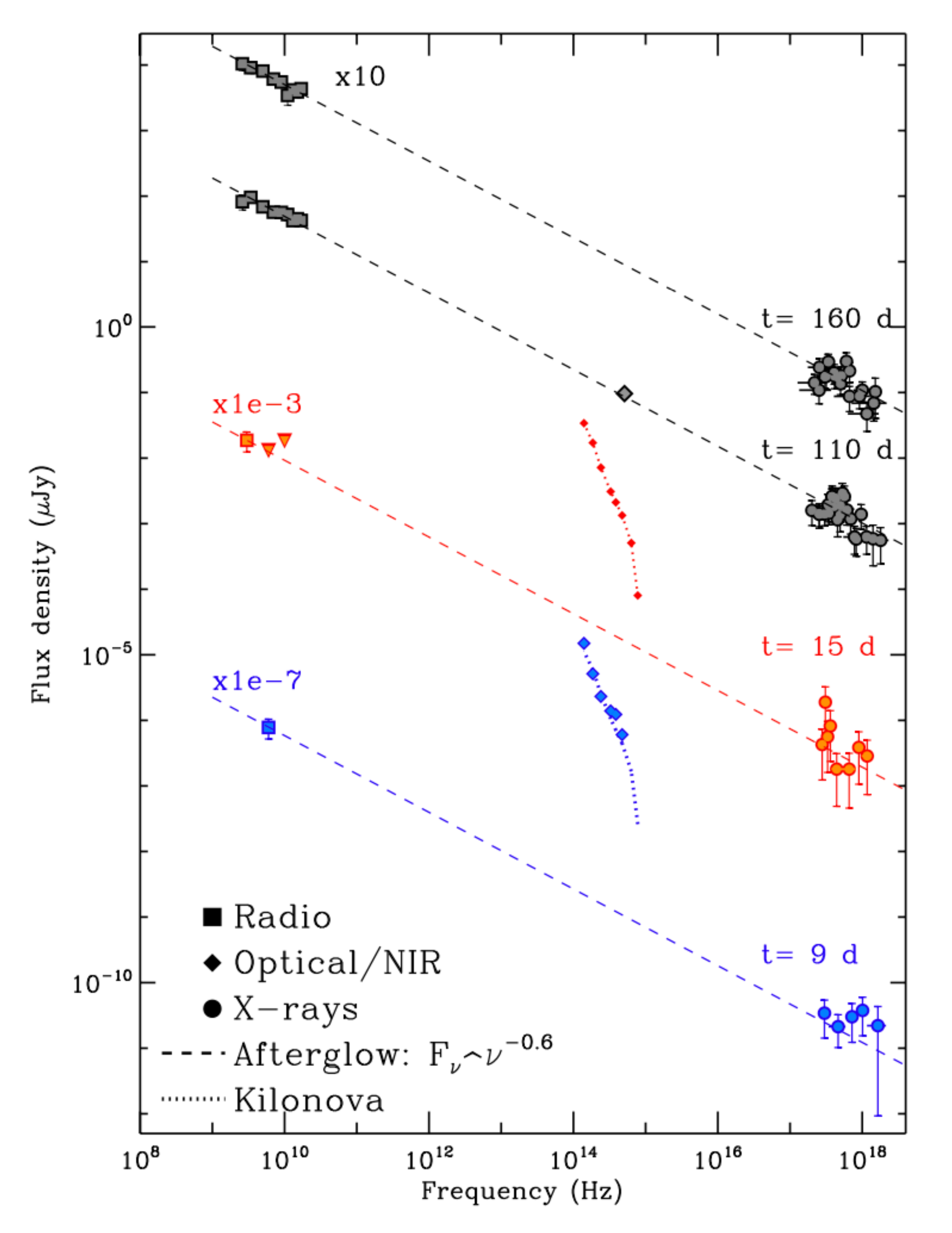
Spherical interaction environment:

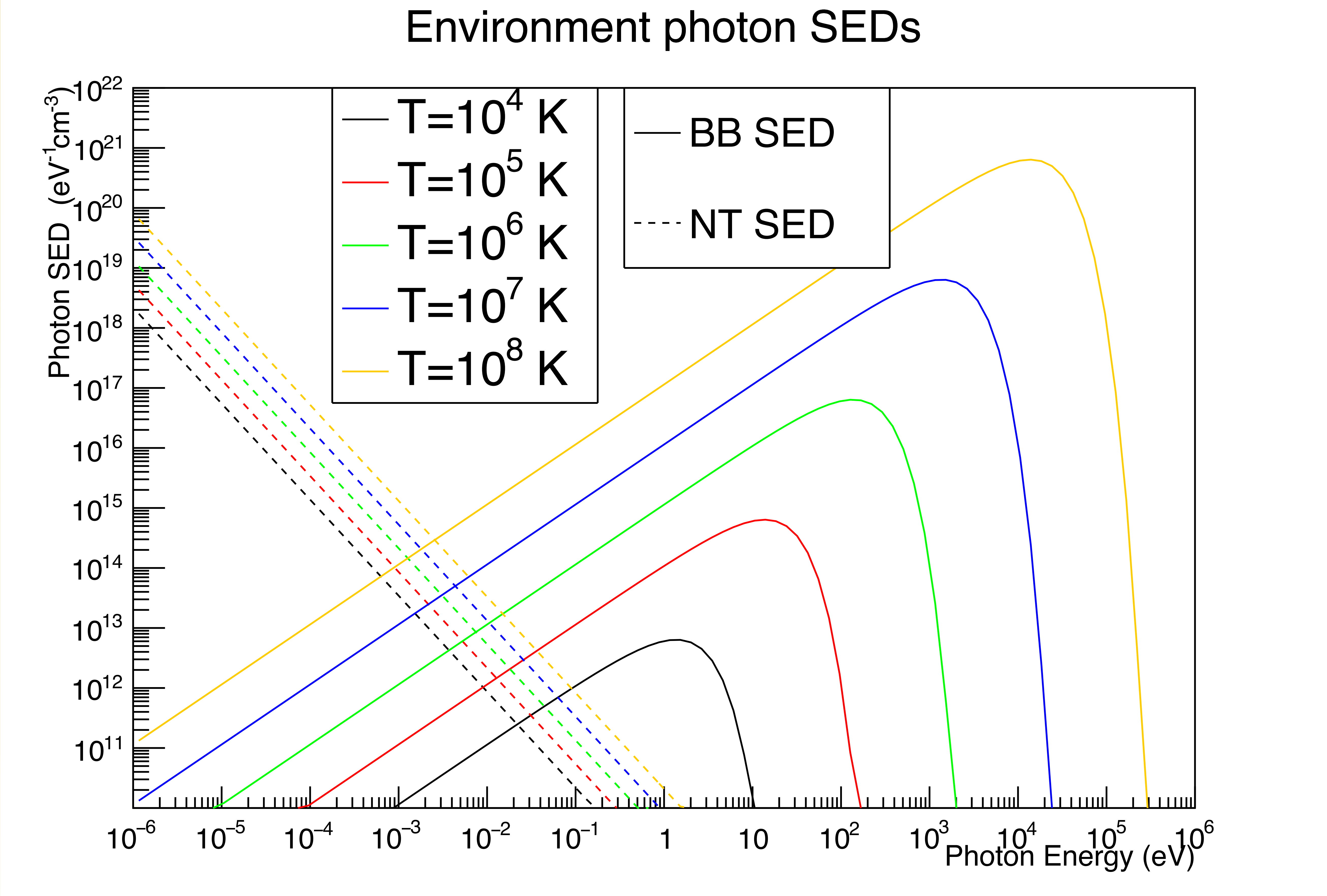
$$\lambda_{esc}(t) = c\beta_{ej} t \qquad \beta_{ej} \simeq 0.3$$



V. Decoene et al JCAP04(2020)045

BNS merger environment





R. Margutti et al 2018 ApJL 856 L18

BNS merger environment

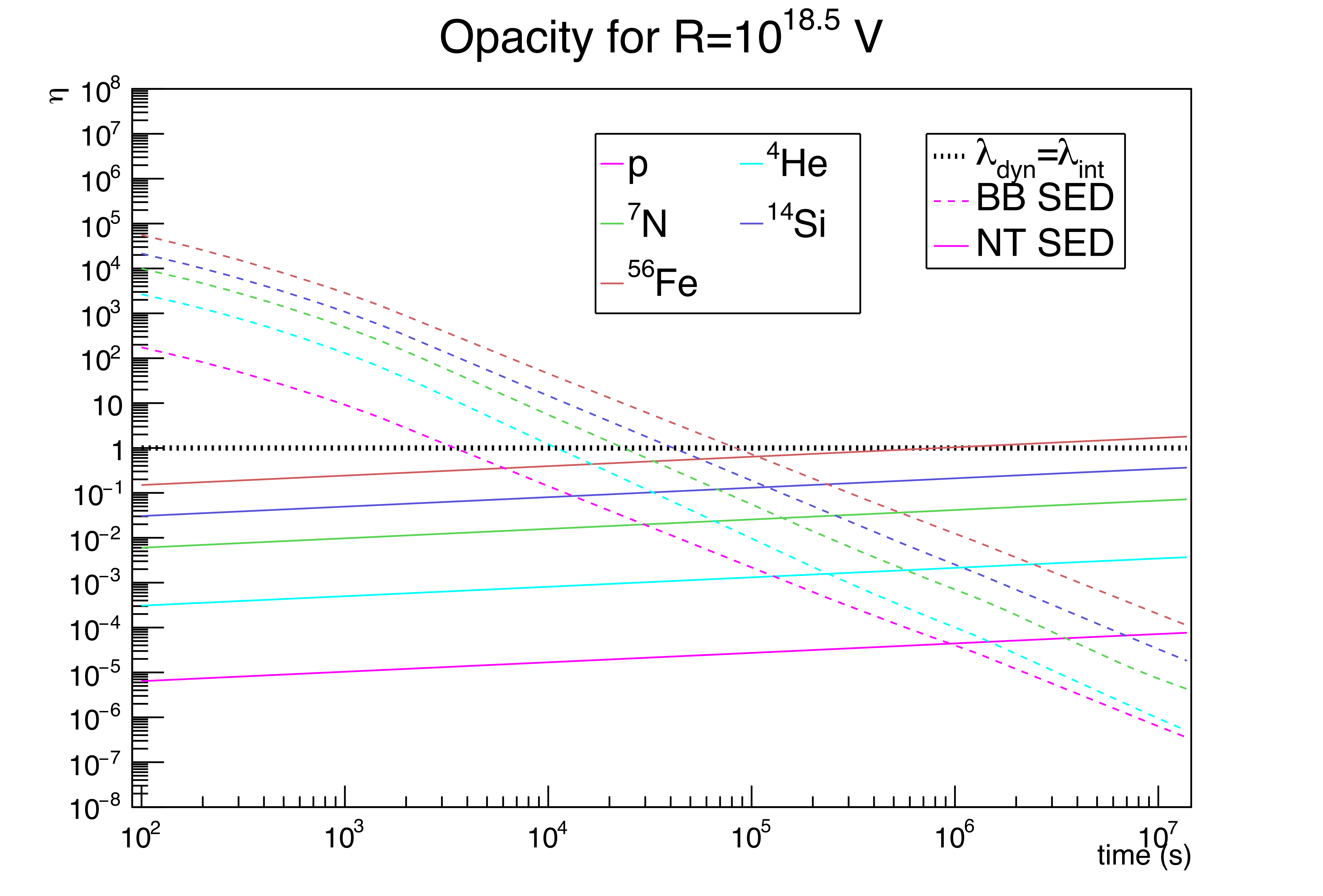
The interaction efficiency of the post-merger environment can be characterized by the opacity:

Photon SED: $n_j(\epsilon) \qquad j = BB, NT$

$$\eta_j(t) = \frac{\lambda_{esc}(t)}{\lambda_j(t)} = \frac{\sum_i \tau_{ji}^{-1}(t)}{\tau_{esc}^{-1}(t)}$$

The quantity $\tau_{ji}^{-1}(t)$ represents the interaction rate of the process I with the photon field j.

$$\tau_{ji}^{-1}(t) = \frac{c}{2\Gamma^2}\int_{\epsilon'_{th}}^{\infty} d\epsilon'\,\sigma_j(\epsilon')\epsilon' \int_{\epsilon'/2\Gamma}^{\infty} dx\, n_i(x) x^{-2}$$



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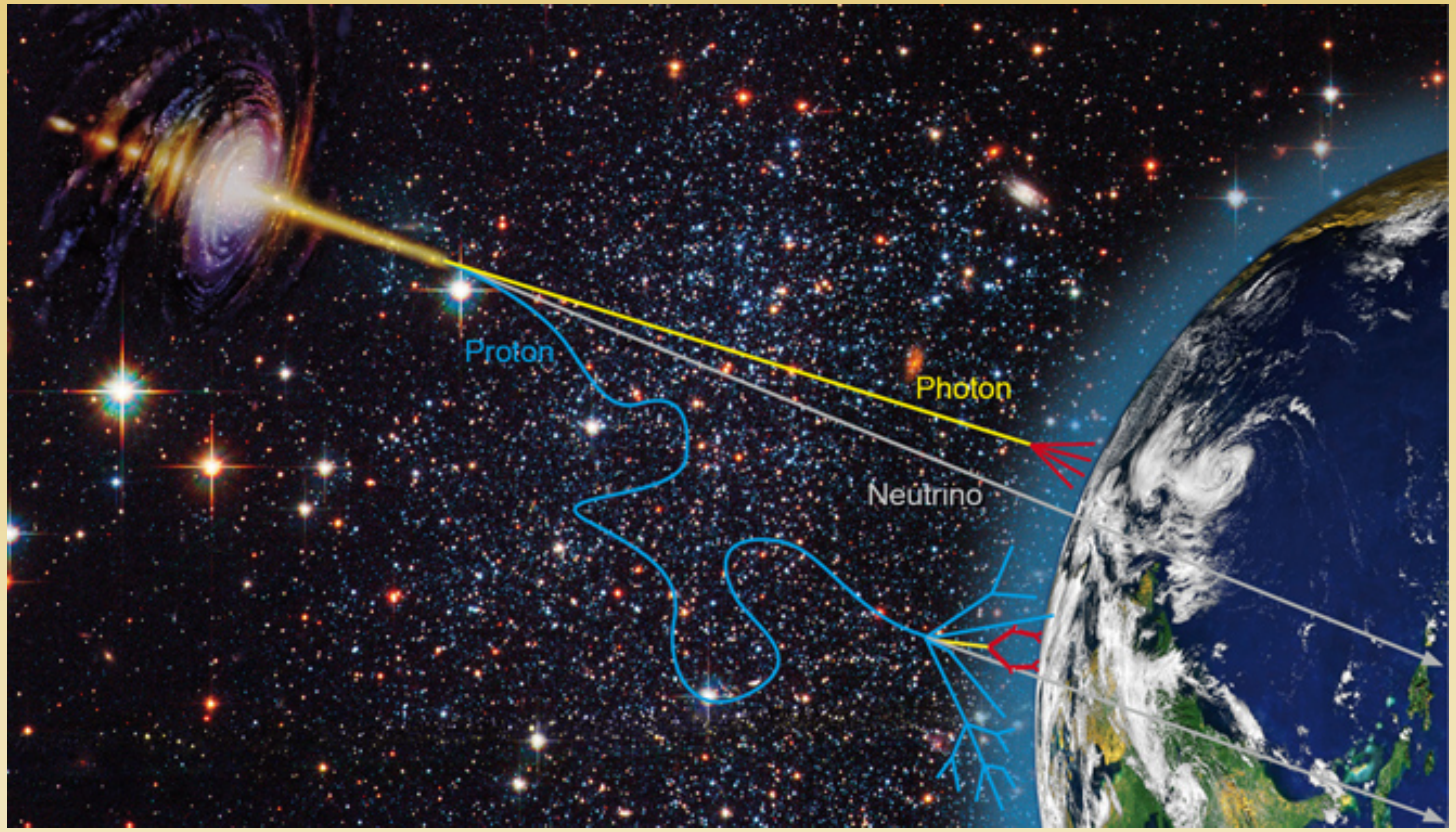
Monte Carlo simulations

SimProp v2r4

Monte Carlo code for the extragalactic propagation of UHECRs.

R. Aloisio et al JCAP11(2017)009



SimProp v2r4-Mod

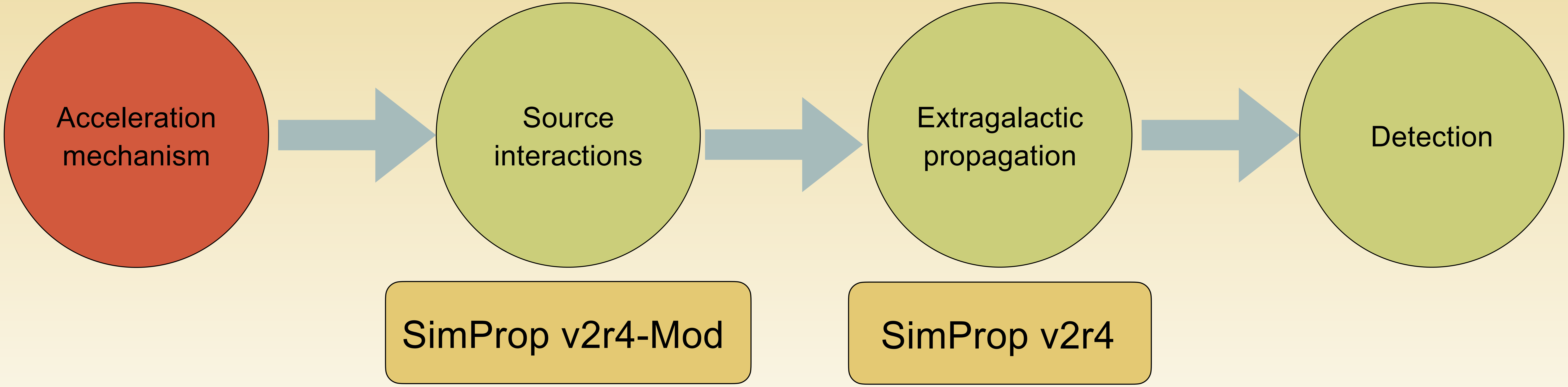
Monte Carlo code for the propagation of UHECRs within the source environment.

Photo-hadronic interactions between the injected nuclei and local photon fields.

Escape condition based on the comparison of the total interaction rate with the escape rate.

Monte Carlo simulations

Combination of several versions of the same code to study different phases of the “UHECR life”.



Simulations of source interactions

Source injection

We simulate the propagation of UHECRs within the source environment by using the modified Monte Carlo code SimProp v2r4-Mod.

The source environment is static in each simulation.

$$Fixed\ T \ \Rightarrow Fixed\ t \ \Rightarrow \ Fixed\ n_{BB}(\epsilon)\ \ and\ \ \lambda_{esc}$$

Injection of a pure composition of protons with energy spectrum:

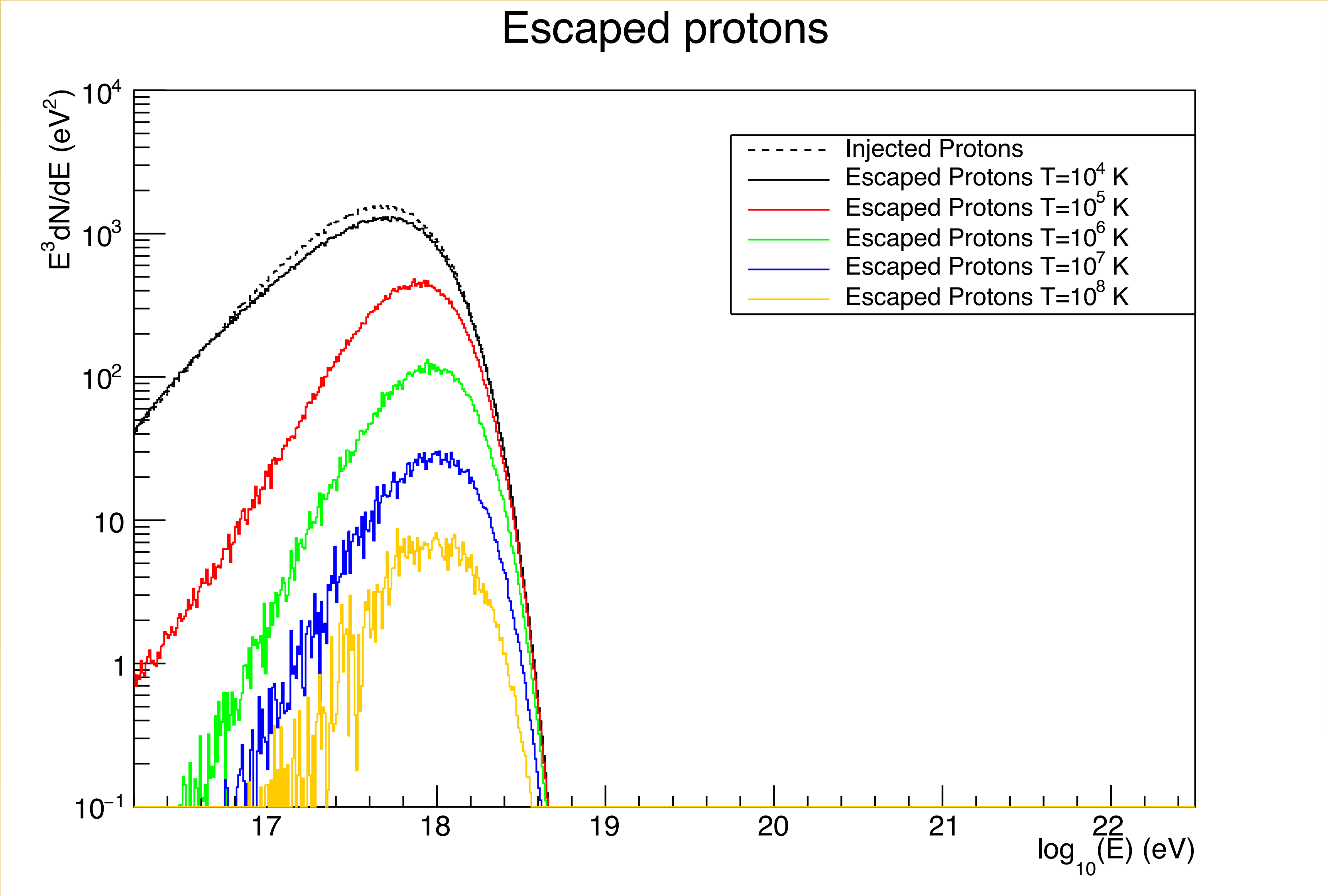
$$\frac{dN}{d\log E} = const. \quad , \quad 10^{14}\, eV \leq E \leq 10^{20}\, eV$$

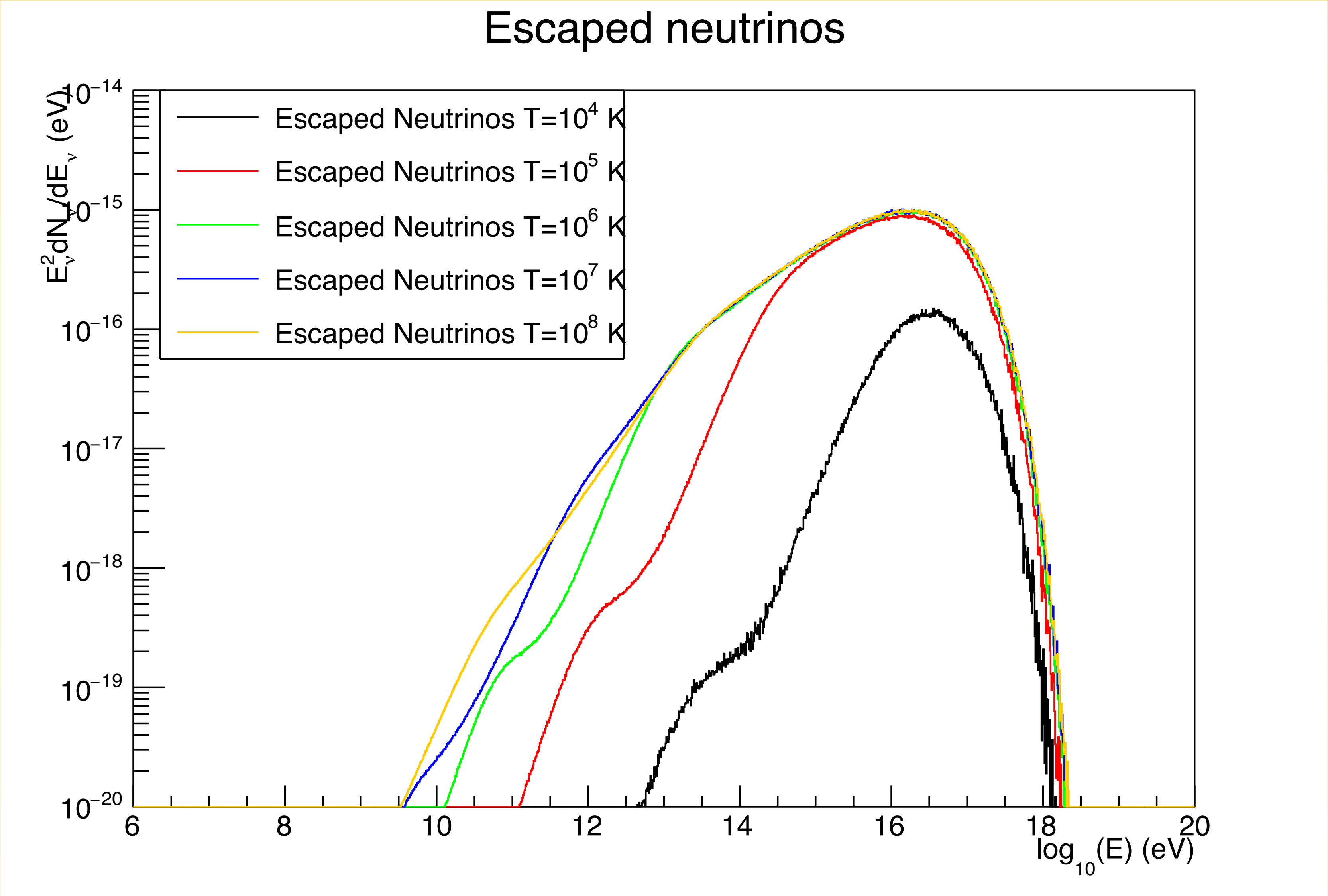
Post re-weighted injection

We re-weight the simulation output with an accelerated spectrum of the form:

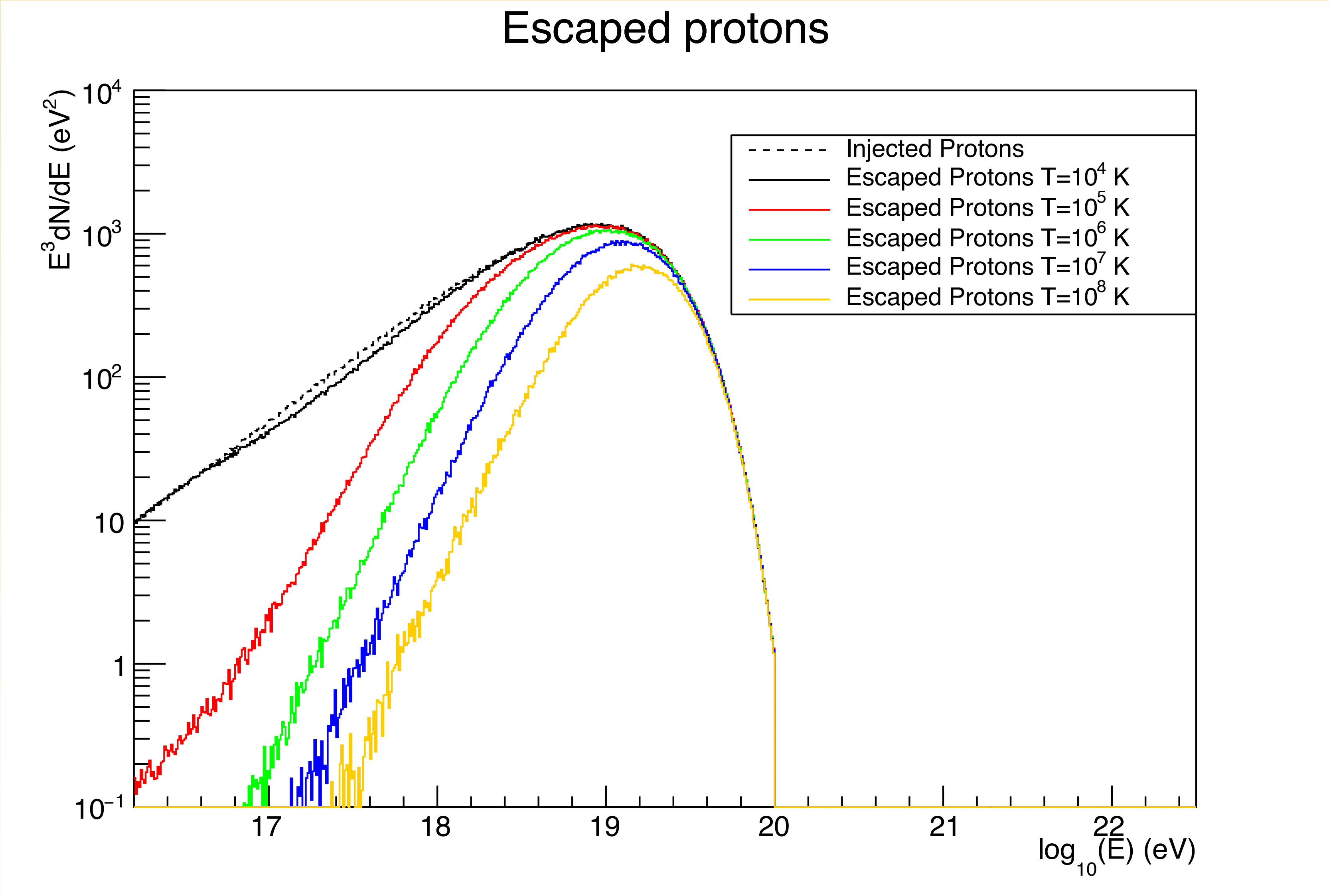
$$\frac{dN}{dE} \propto E^{-\gamma} \exp\left(-\frac{E/Z}{R_{max}}\right)$$

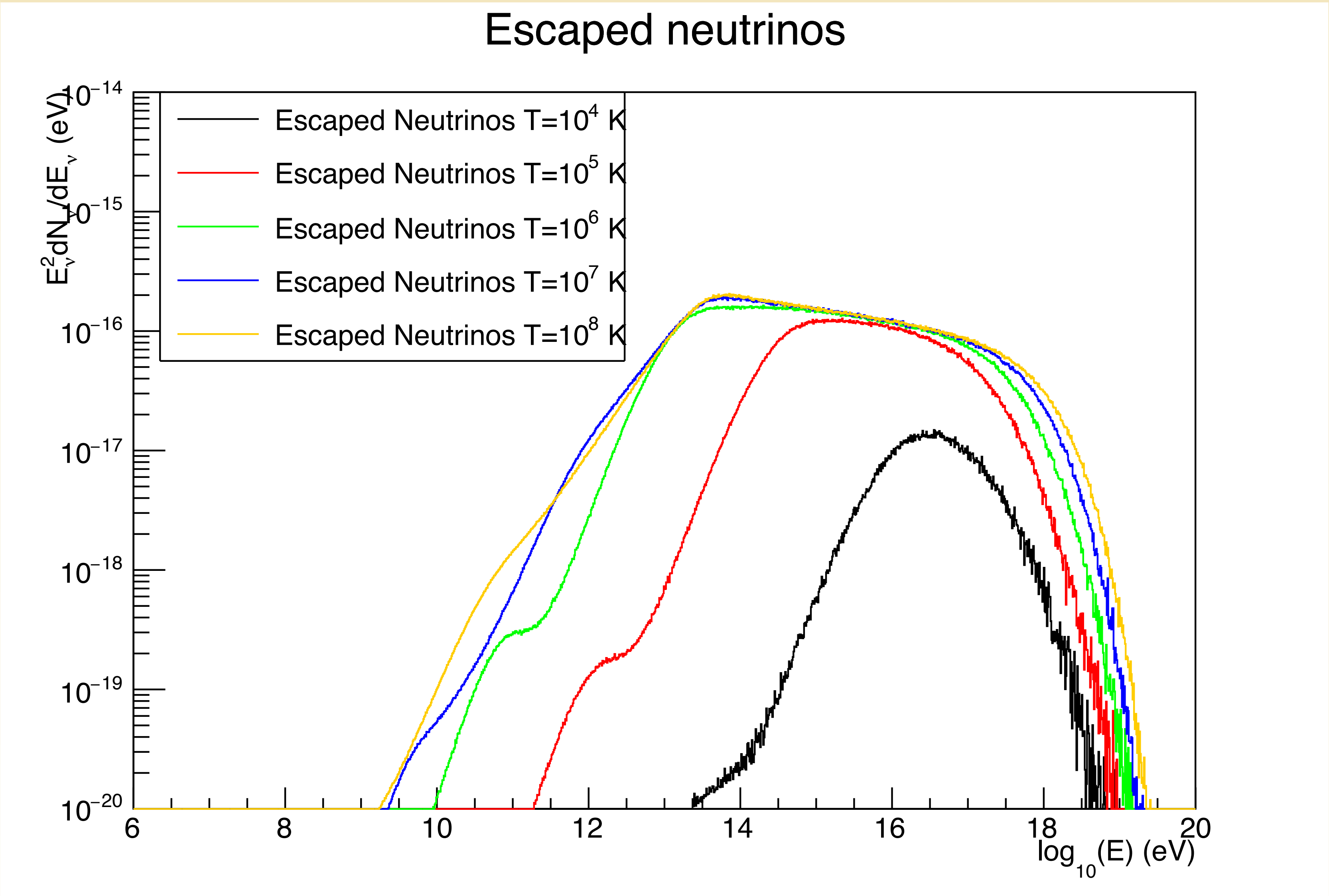
Simulations of source interactions





$\gamma = 1.5 \quad , \quad R_{max} = 10^{17.5}\,V$





$\gamma = 2.1 \quad , \quad R_{max} = 10^{19}\,V$

Simulations of extragalactic propagation

Extragalactic propagation

We use the in-source simulation output as an input for the extragalactic propagation.

We use the original SimProp v2r4 taking into account other source characterization parameters.

Different maximum temperature.

$$GW170817-like: \quad T = 10^6\,K \div 10^4\,K$$

$$Optimistic: \quad T = 10^8\,K \div 10^4\,K$$

Source cosmological evolution

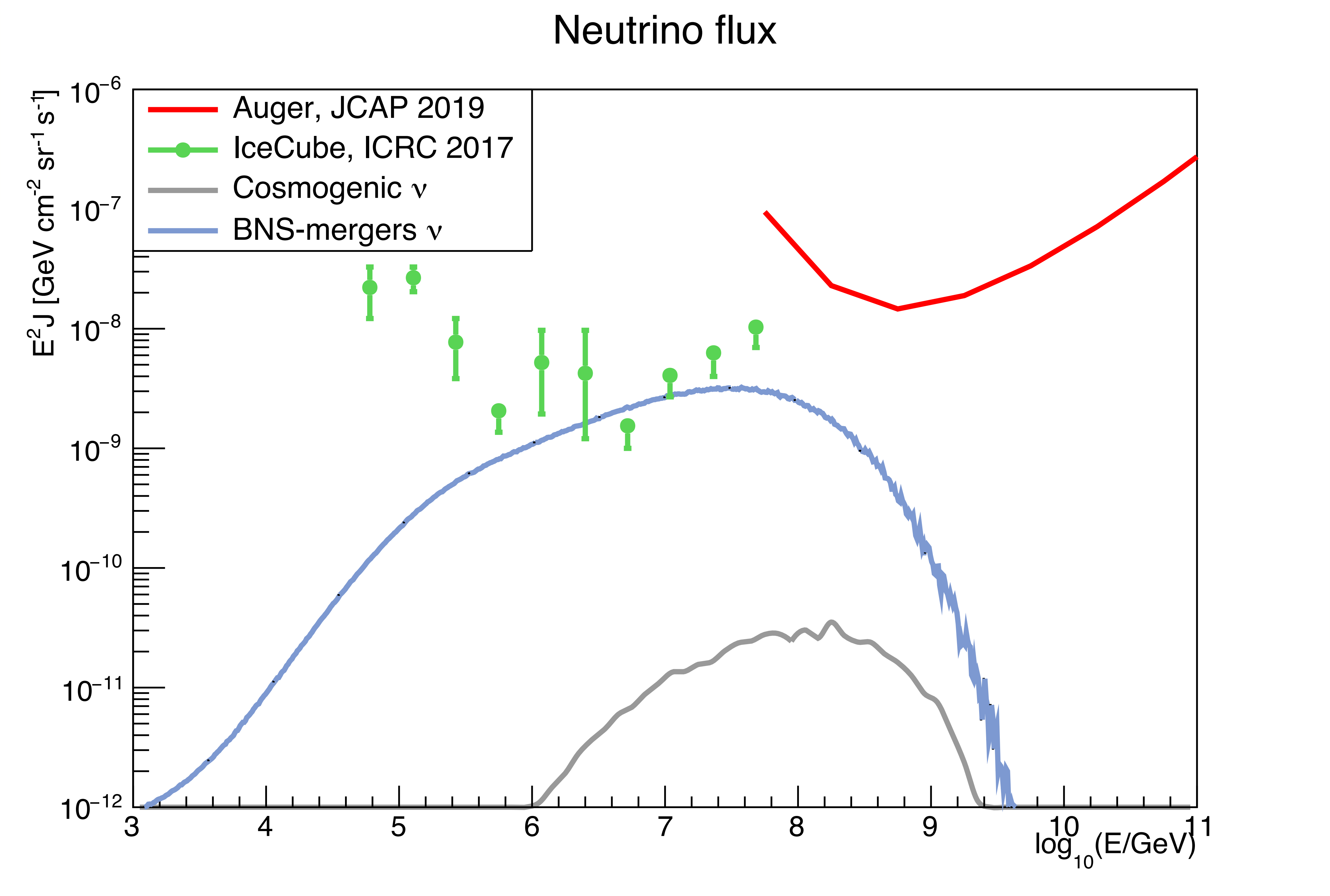
$$J_{inj}(E,z) = J_{inj}(E,z=0)\cdot(1+z)^m$$

Normalization

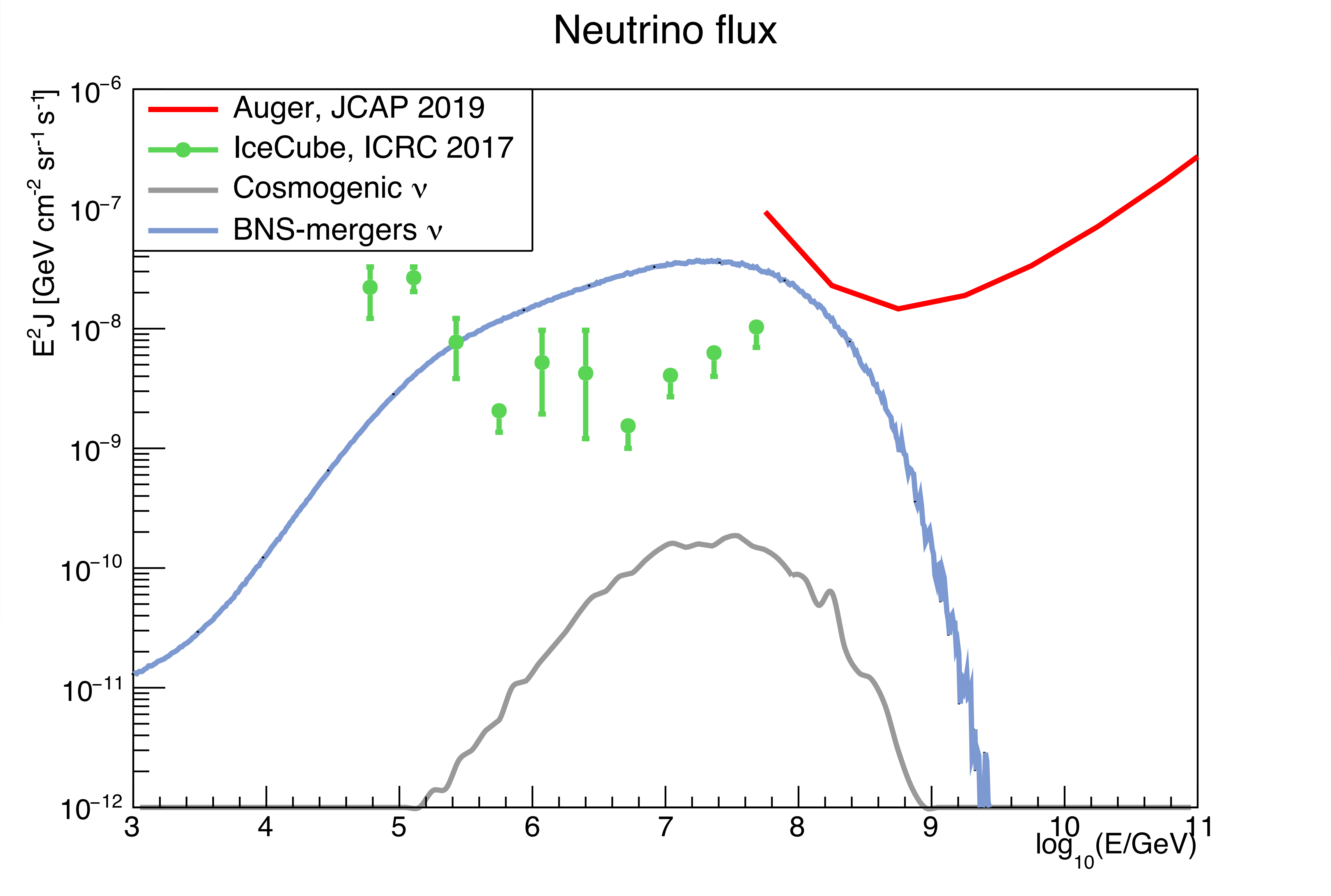
The UHECR flux normalized to the observed cosmic ray flux below the ankle

Neutrino flux

$Protons \quad , \quad \gamma = 1.5 \quad , \quad R_{max} = 10^{18.5}\,V \quad , \quad m = 0 \quad , \quad GW170817 - like$

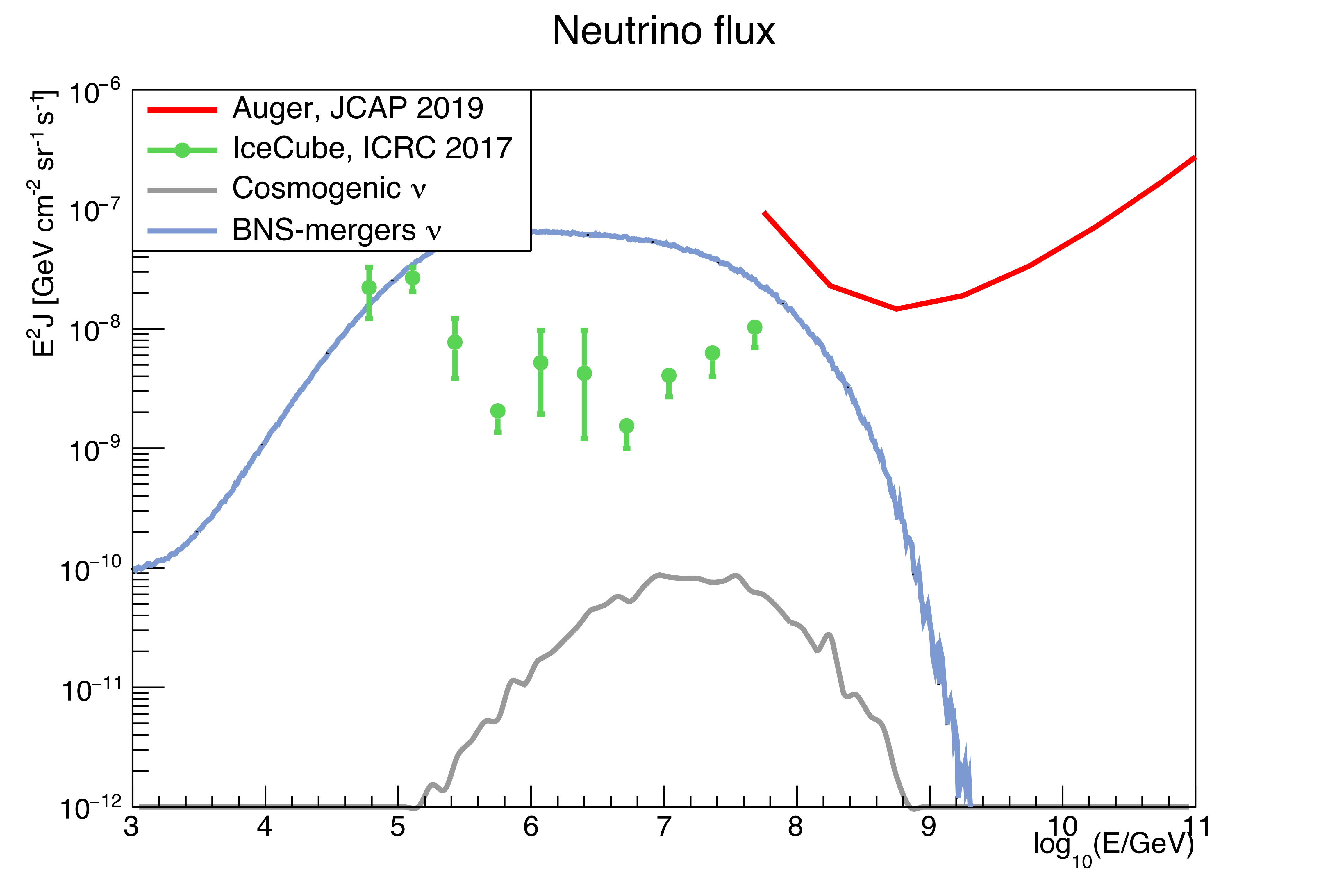


$Protons \quad , \quad \gamma = 1.5 \quad , \quad R_{max} = 10^{18}\,V \quad , \quad m = SFR \quad , \quad GW170817 - like$

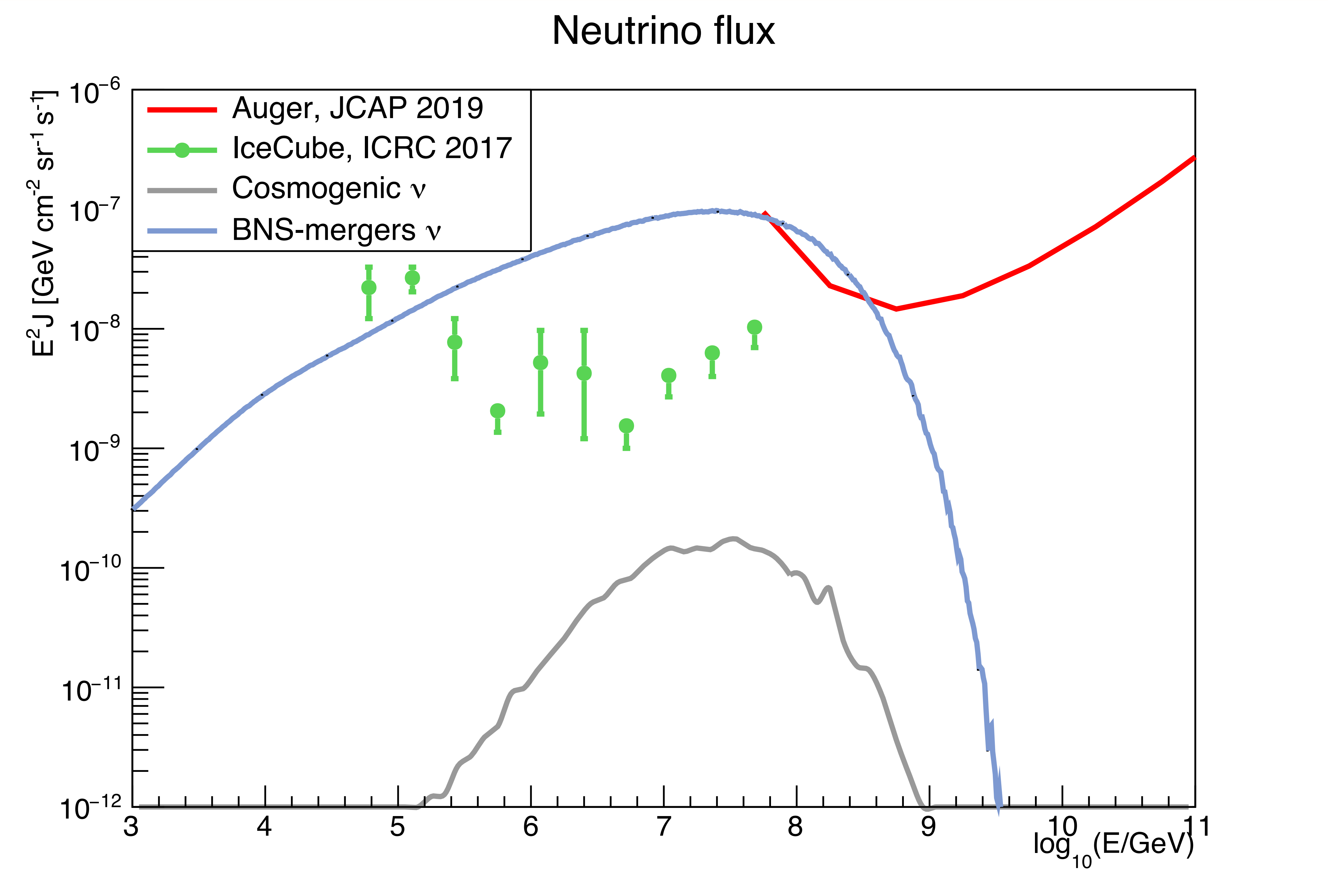


Neutrino flux

$Protons \quad , \quad \gamma = 2.1 \quad , \quad R_{max} = 10^{18}\,V \quad , \quad m = 0 \quad , \quad GW170817-like$



$Protons \quad , \quad \gamma = 1.5 \quad , \quad R_{max} = 10^{18}\,V \quad , \quad m = SFR \quad , \quad Optimistic$



Results and future developments

Results

Cosmogenic neutrinos cannot be responsible of the observed neutrino flux.

Sources located nearby our Galaxy and that do not reach too high temperatures could be favored to interpret the observed flux.

Regarding the cosmic rays acceleration mechanism, these sources are characterized by a hard spectral index and a large rigidity cutoff.

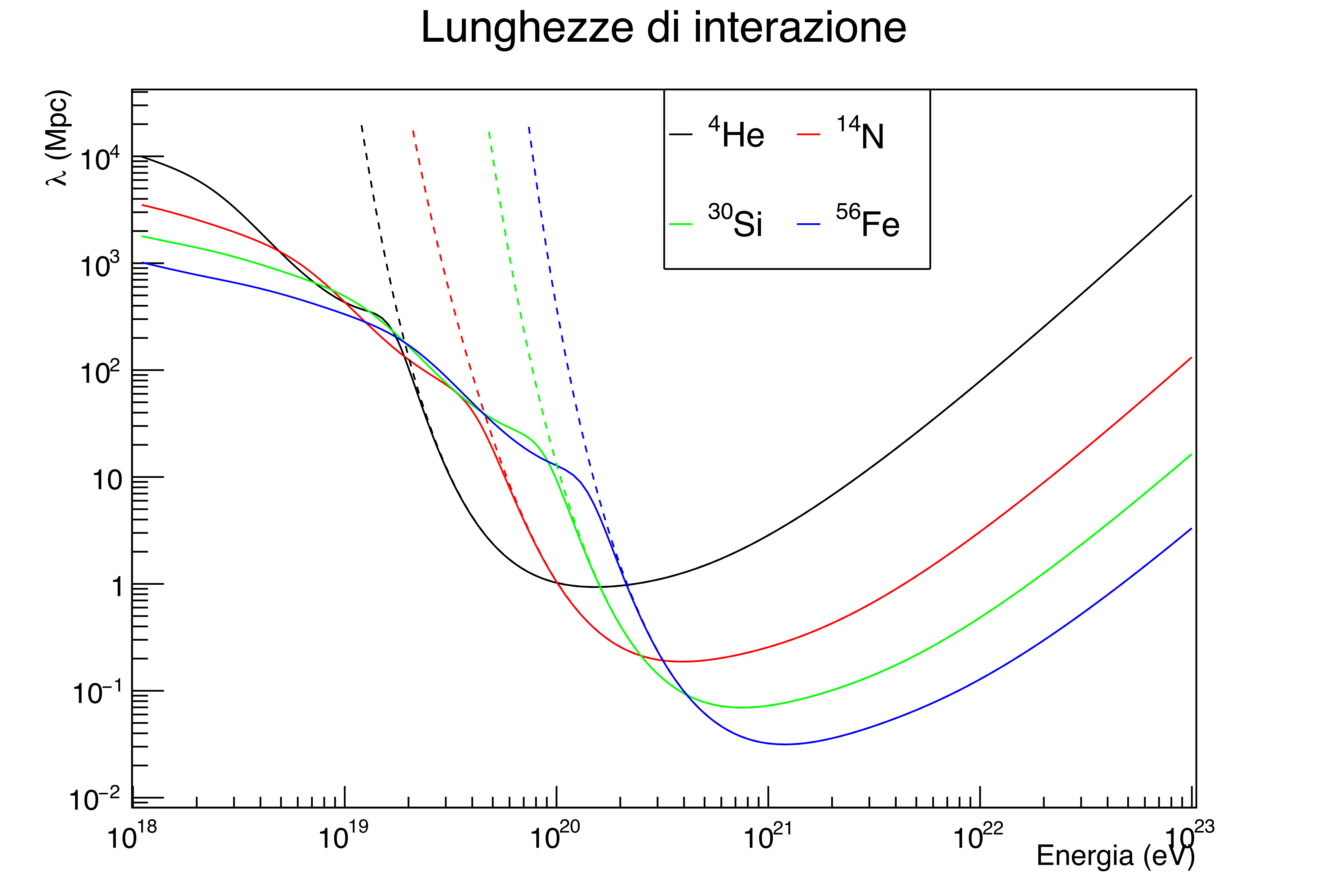
Future developments

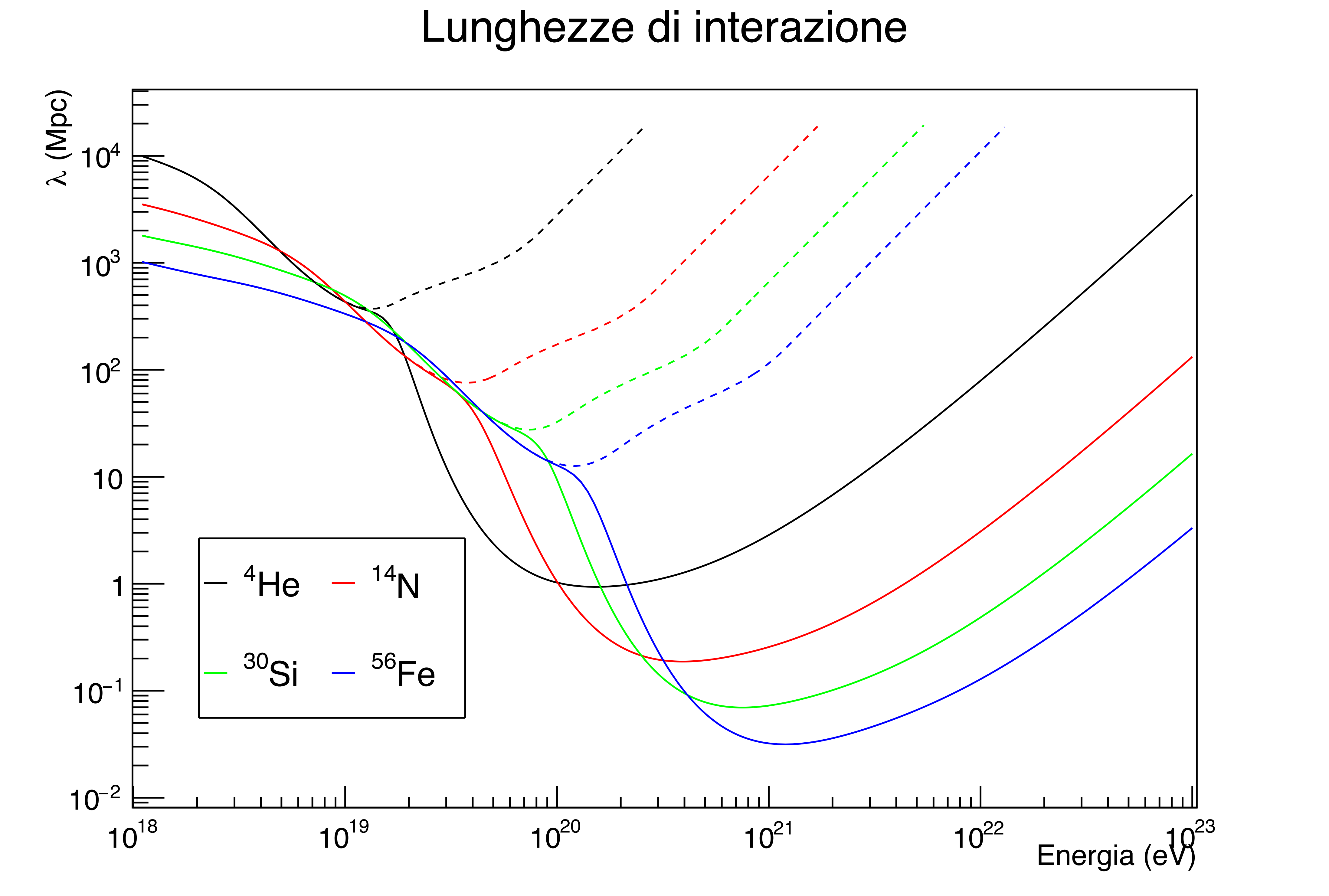
This analysis could be improved by considering the following new features:

mixed and heavier injected composition (interactions with the local non-thermal component), hadronic interactions, neutrino flavor oscillation during the extragalactic propagation and knowledge of the BNS-merger event density rate (more relaxed normalization).

Backup

Interaction lengths





Interaction rate

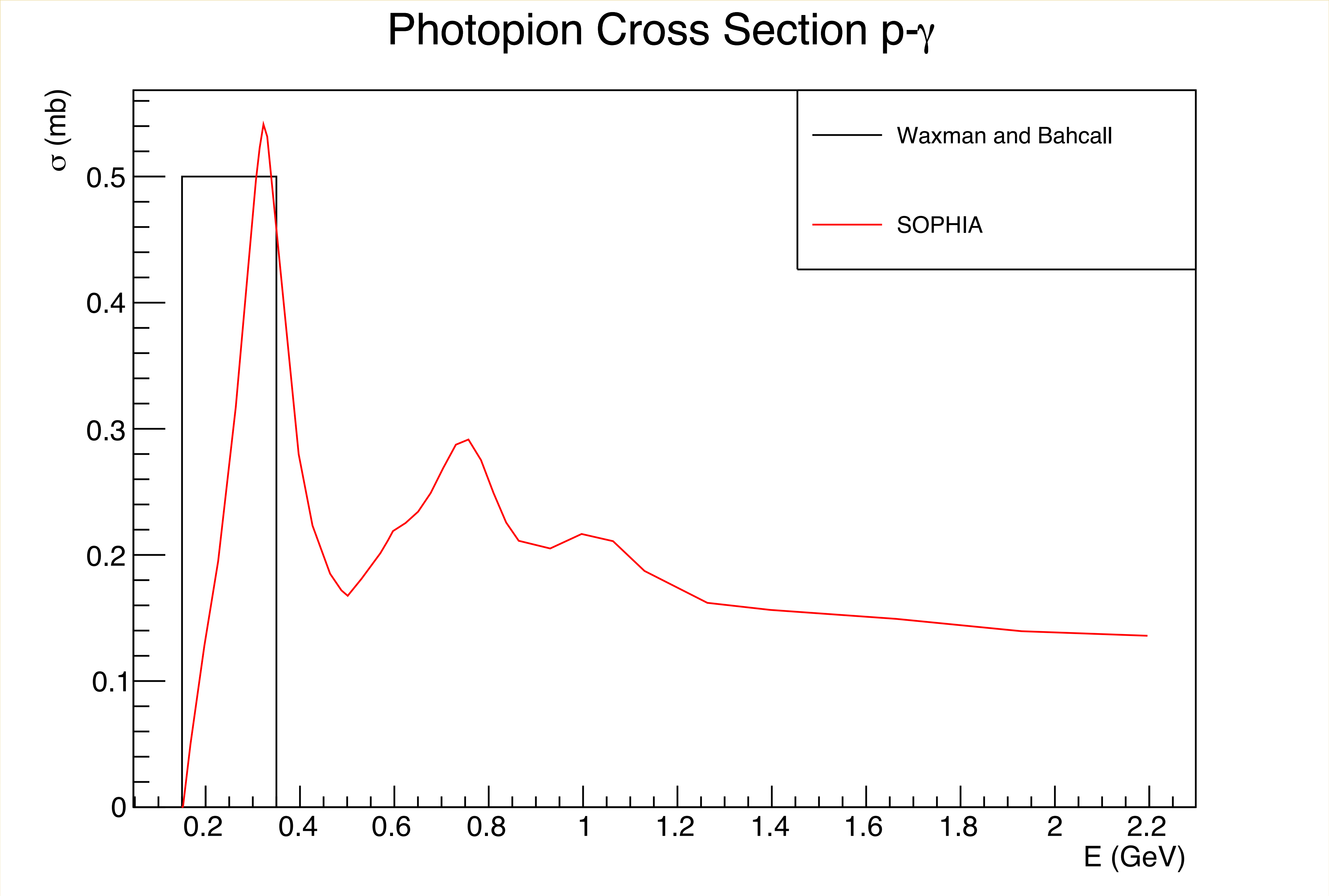
Constant cross section

$$\tau^{-1} \simeq \frac{c}{\pi^2(\hbar c)^3}\sigma_{p\gamma}(k_B T)^3 \cdot \mathcal{I}(\Gamma, T)$$

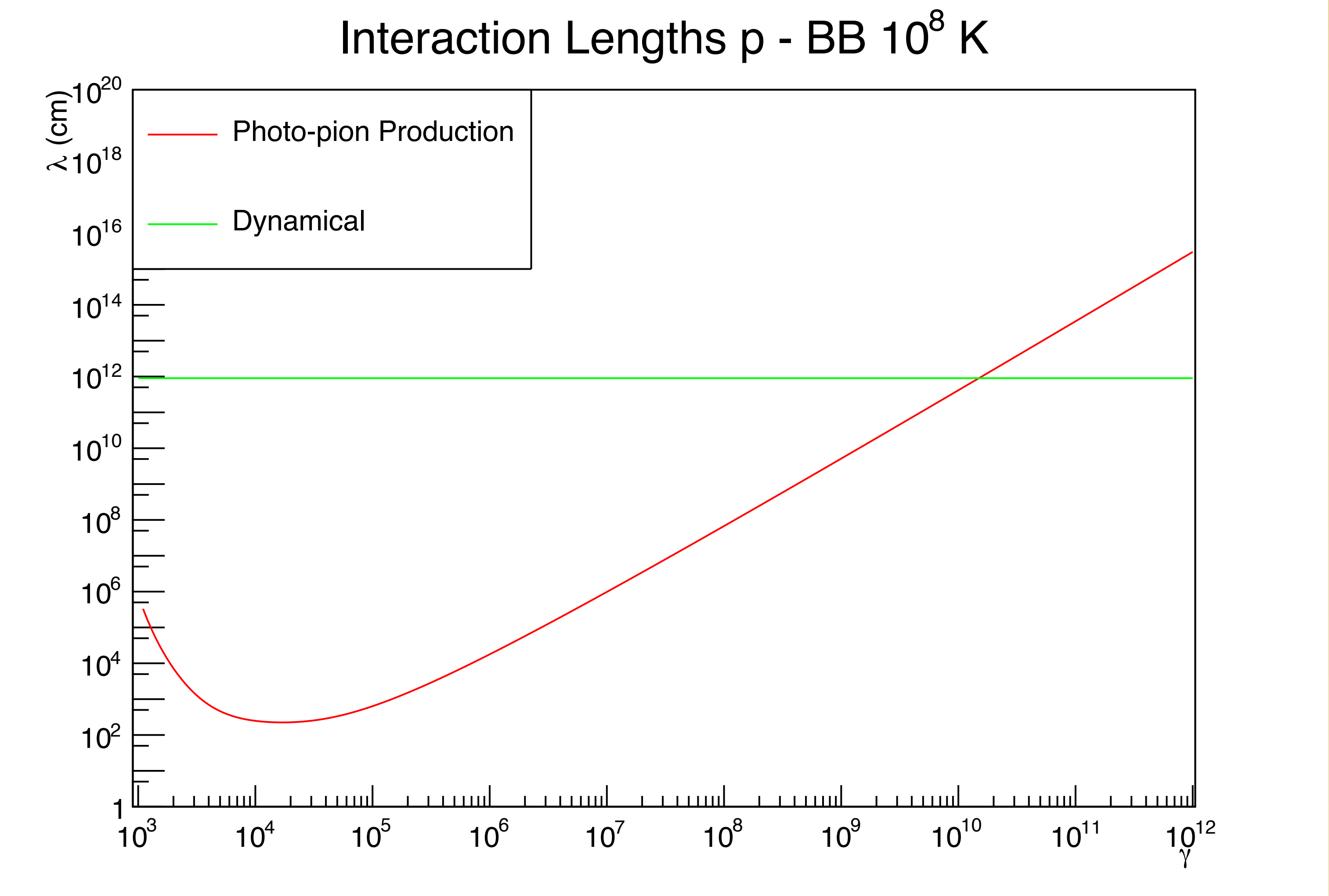
$$\mathcal{I}(\Gamma, T) = \int_r^\infty dx\, \frac{x^2 - r^2}{e^x - 1} \qquad r = \frac{\epsilon_\Delta}{2\Gamma k_B T}$$

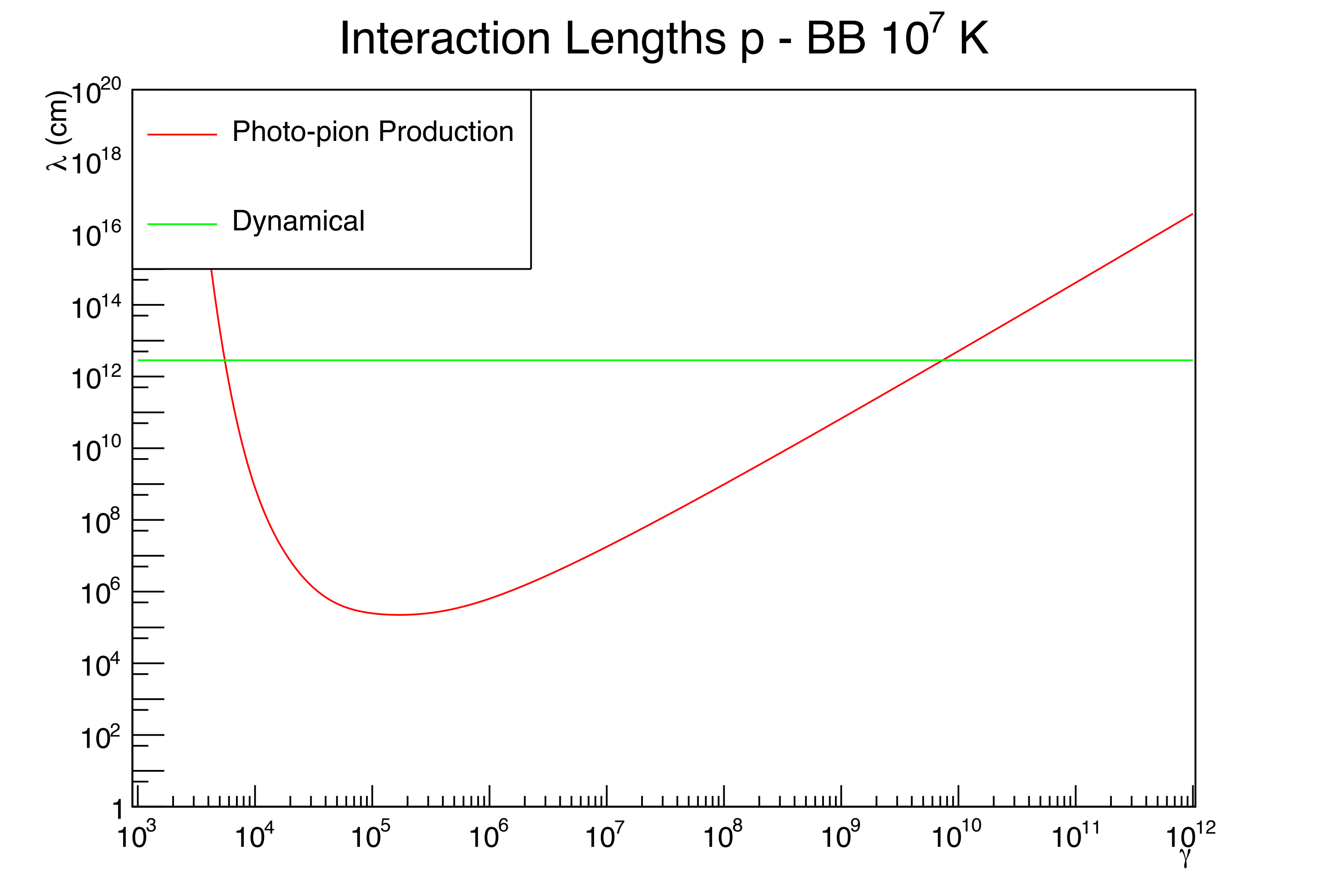
$$r \gg 1 \quad \Rightarrow \quad \Gamma(3)\zeta(3) + r^2\left(\ln(1 - e^{-r}) - \frac{1}{2}\right)$$

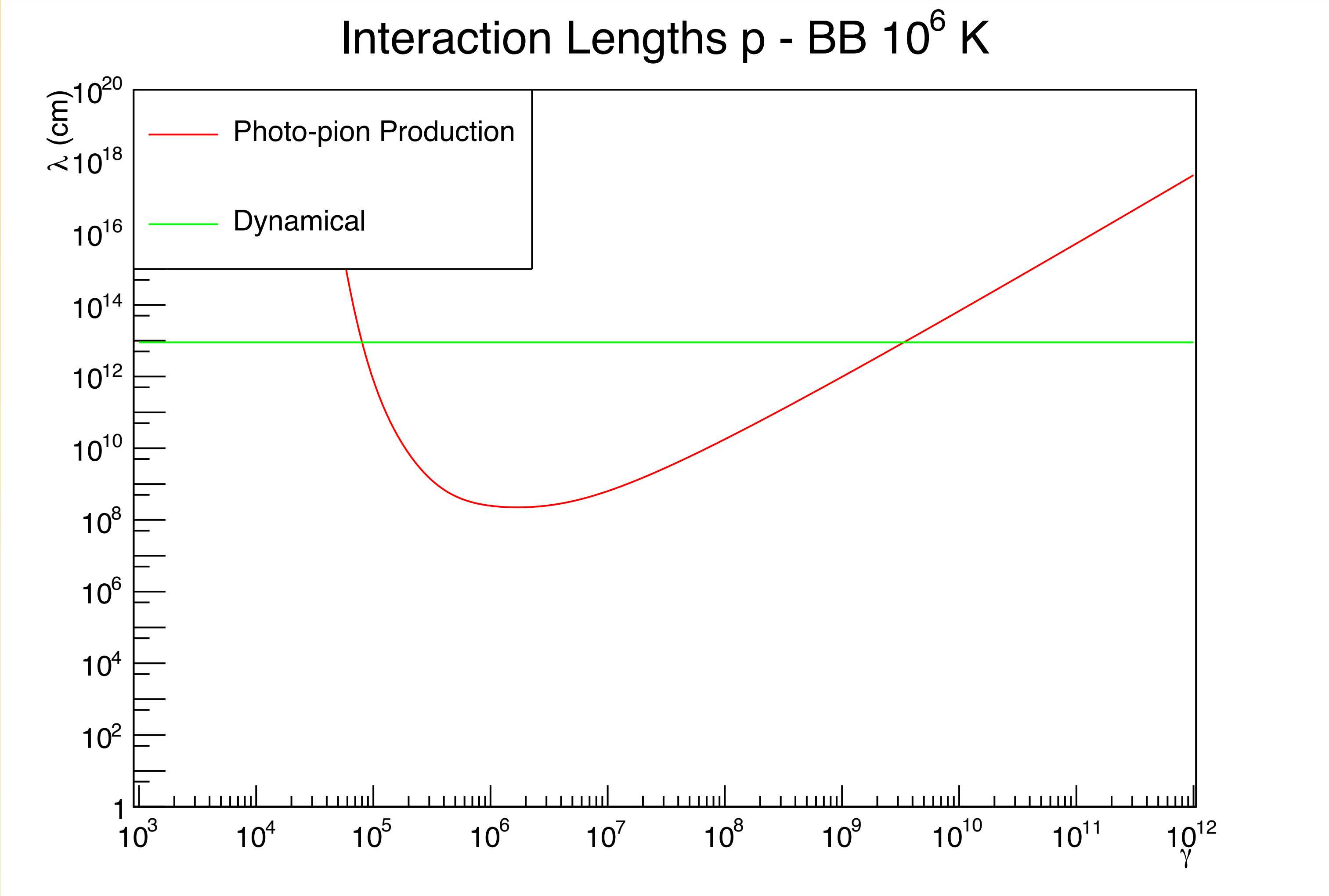
$$r \ll 1 \quad \Rightarrow \quad 2(1 + r)e^{-r}$$

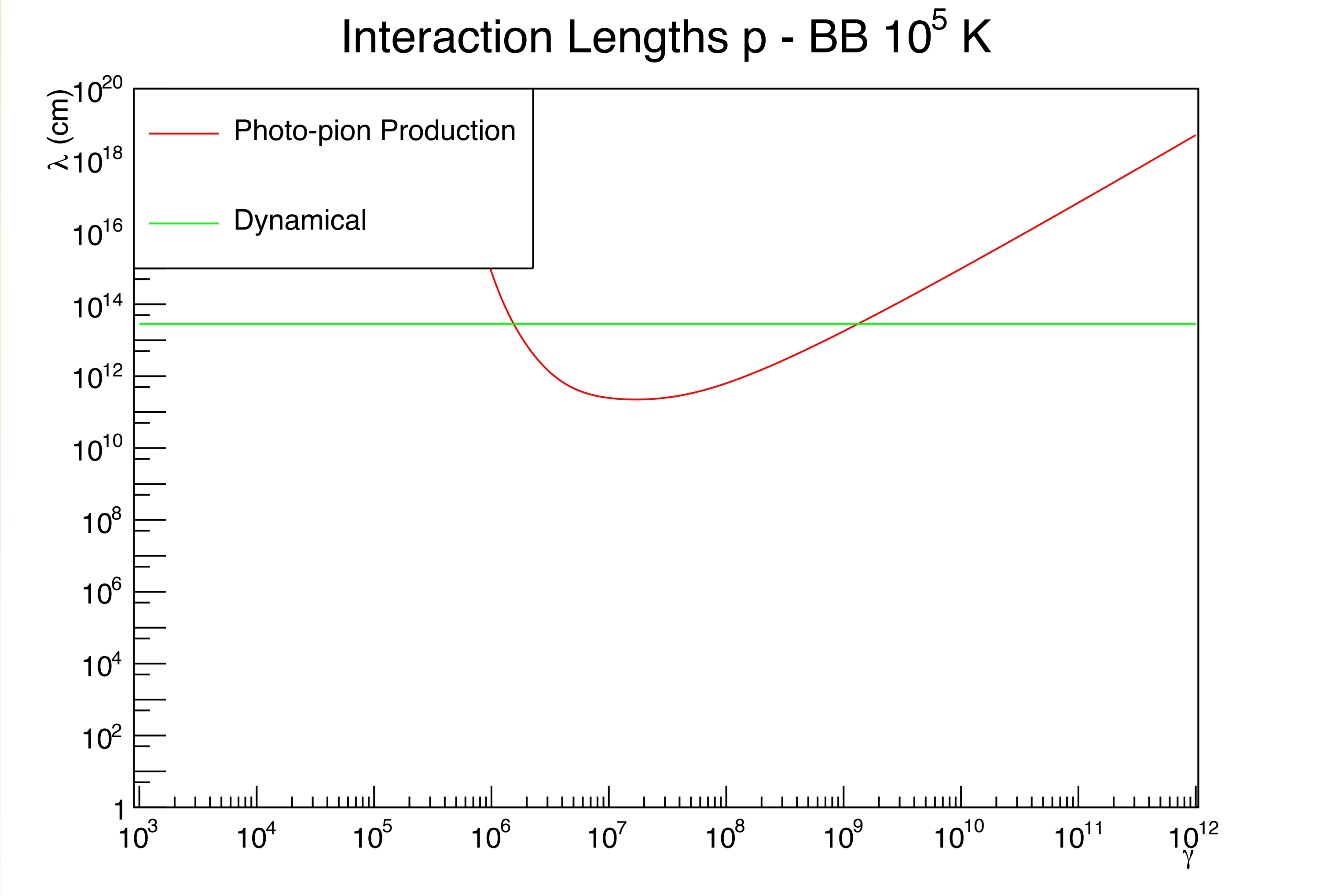


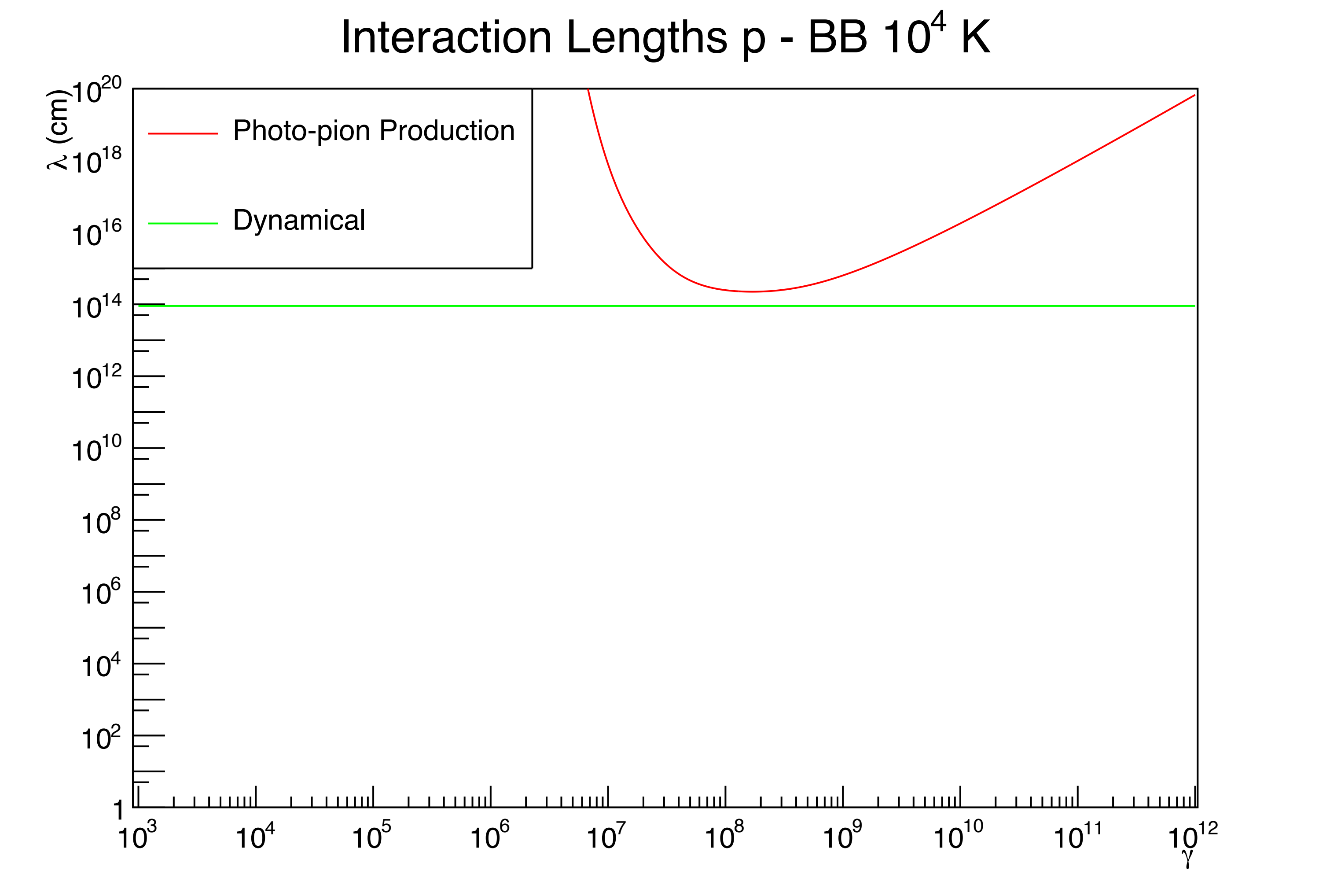
Proton escape



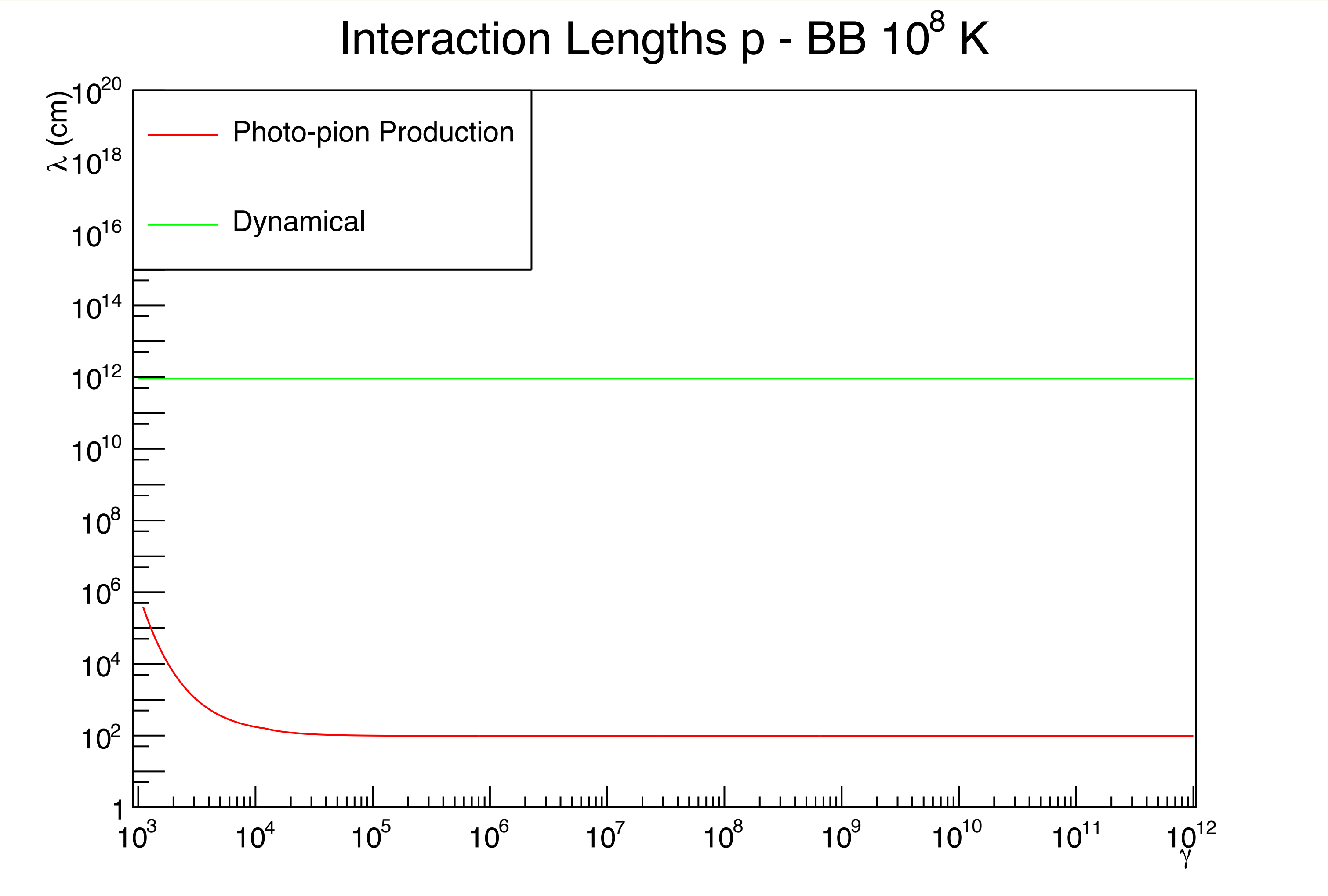


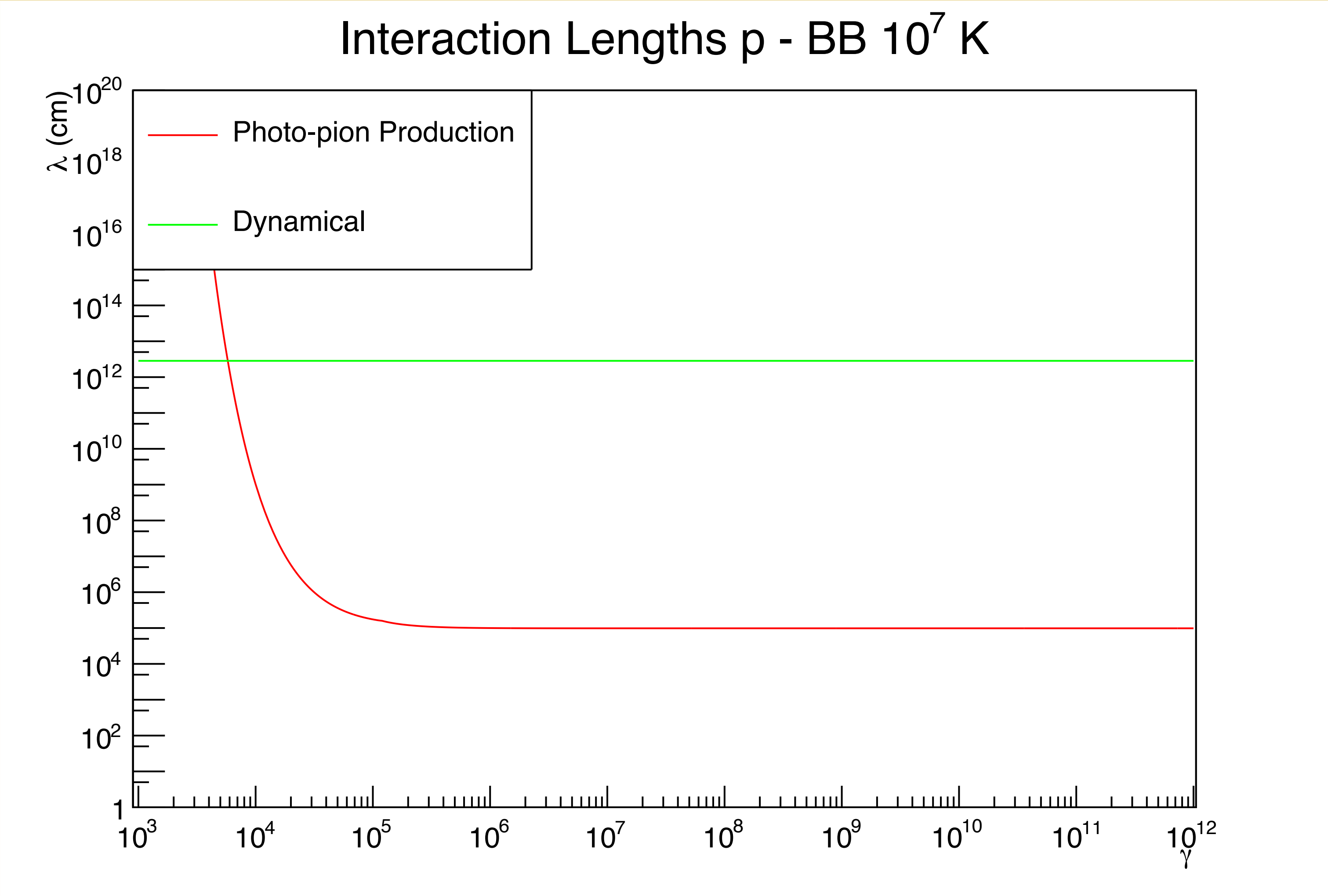


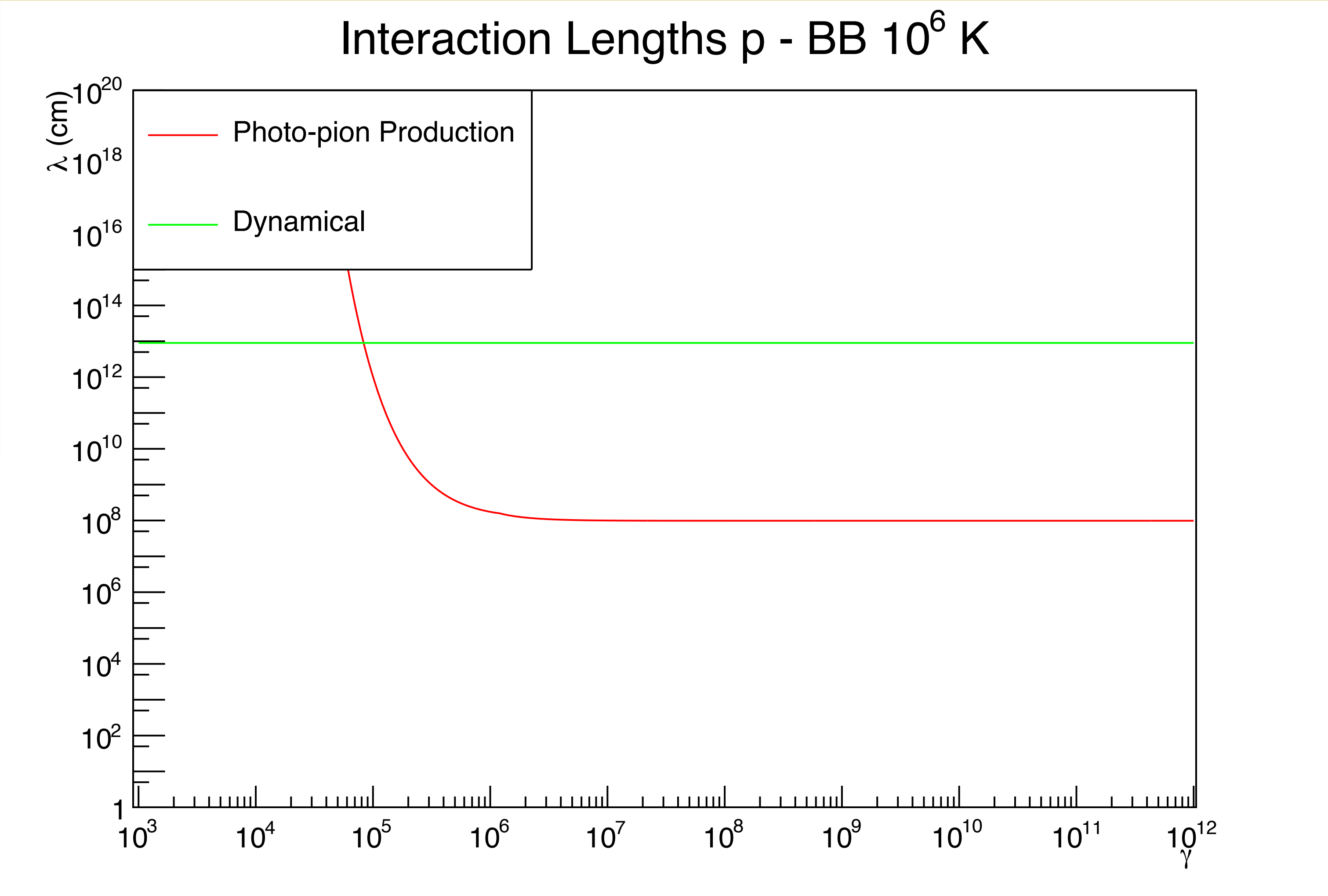


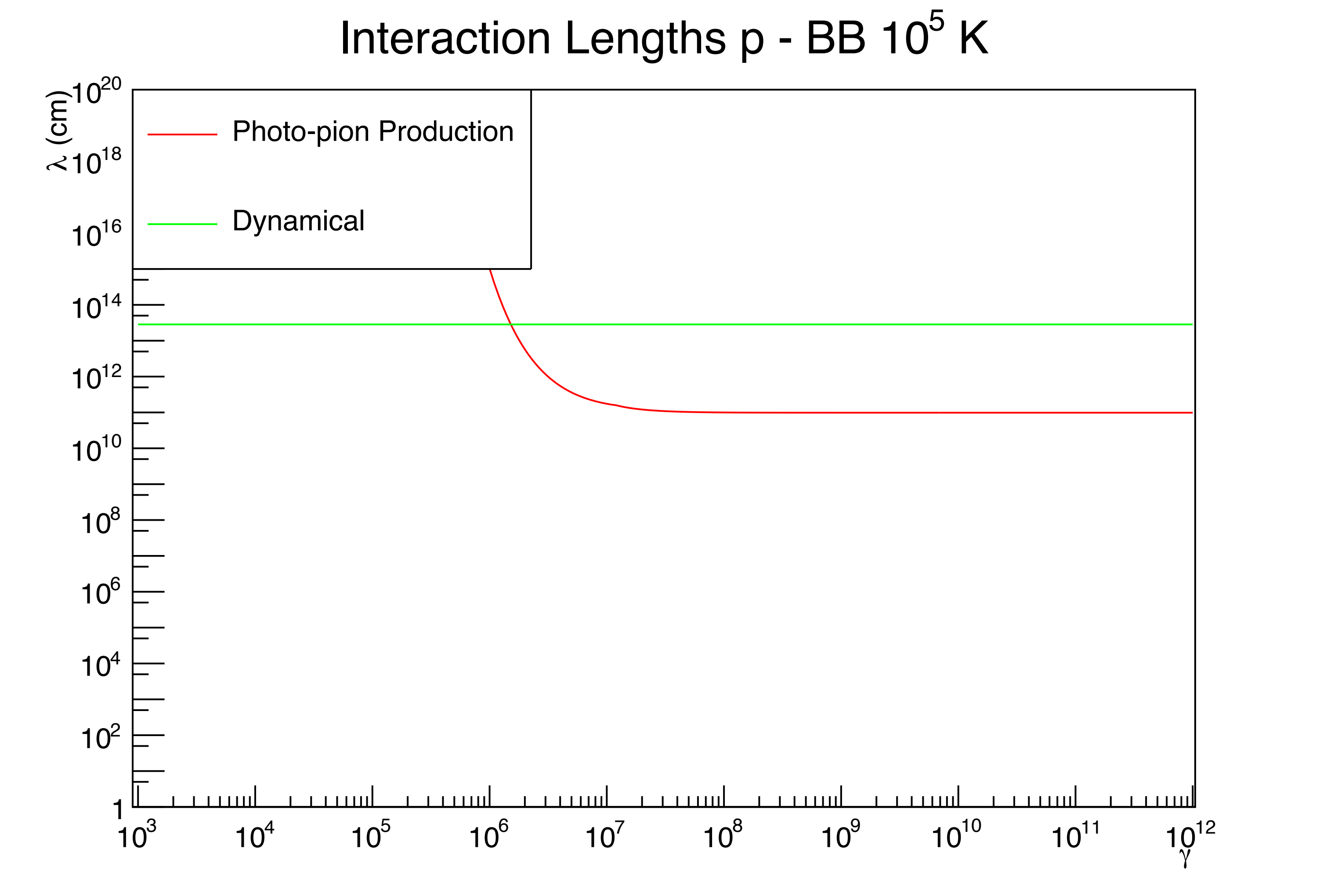


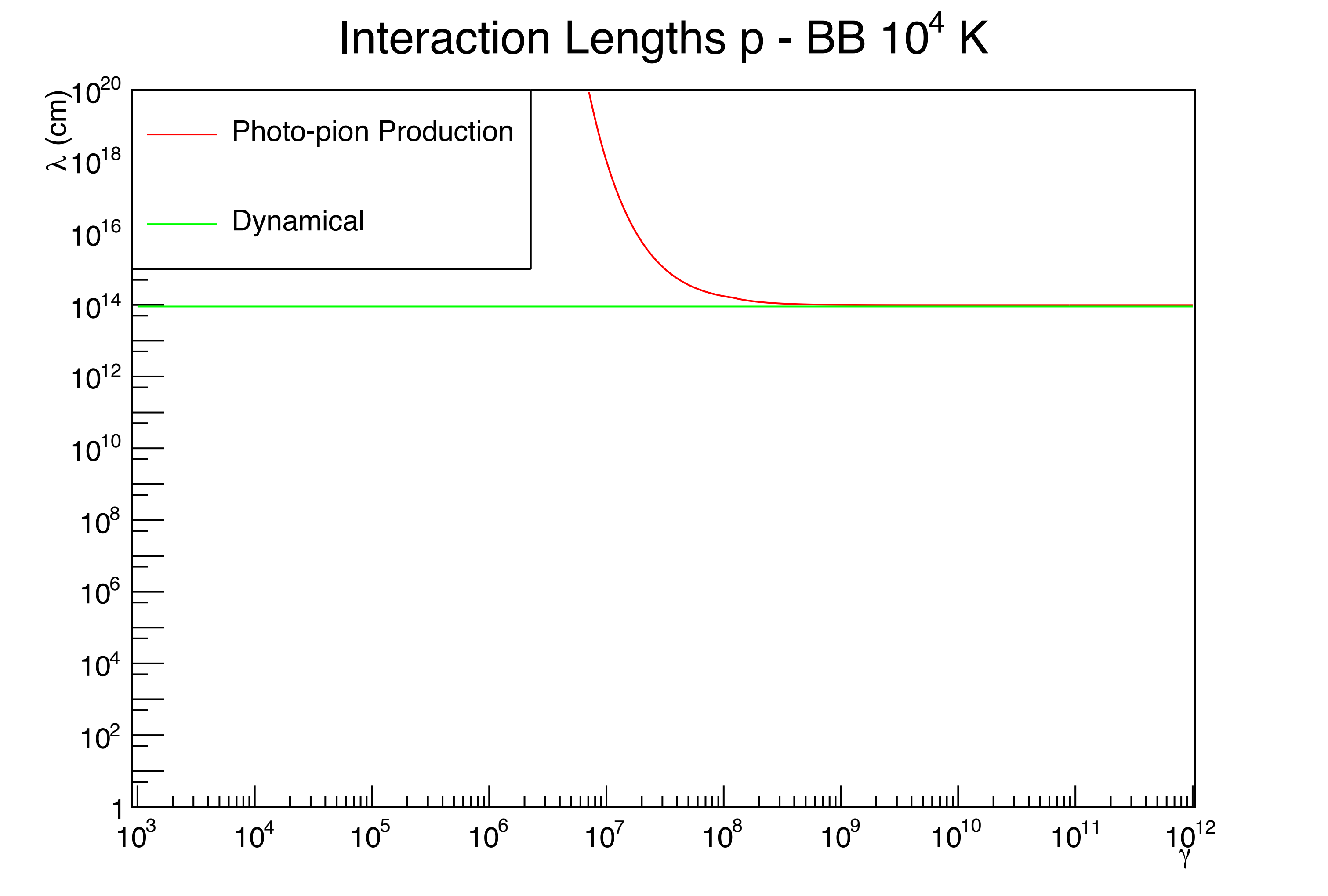
Proton escape - bis



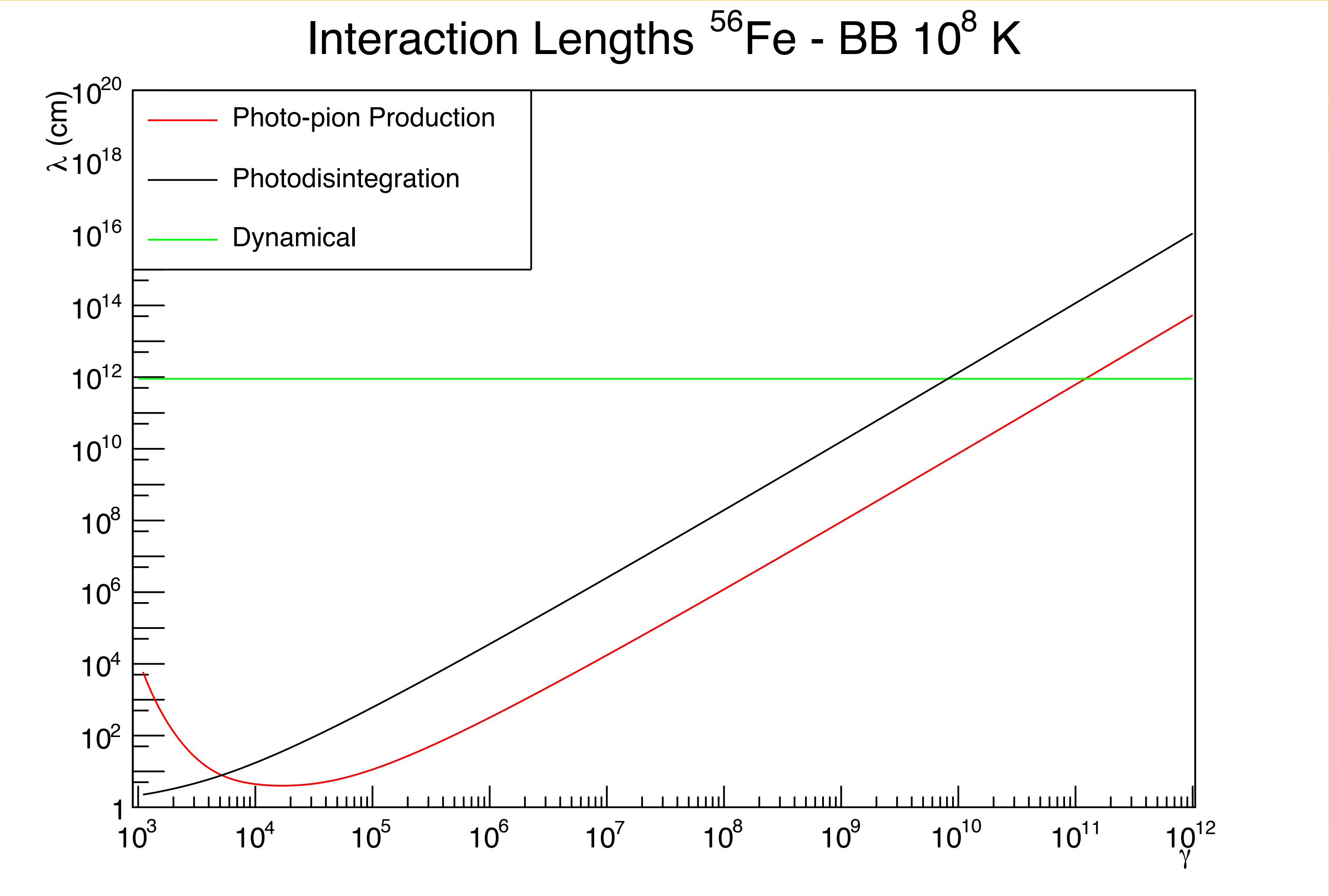


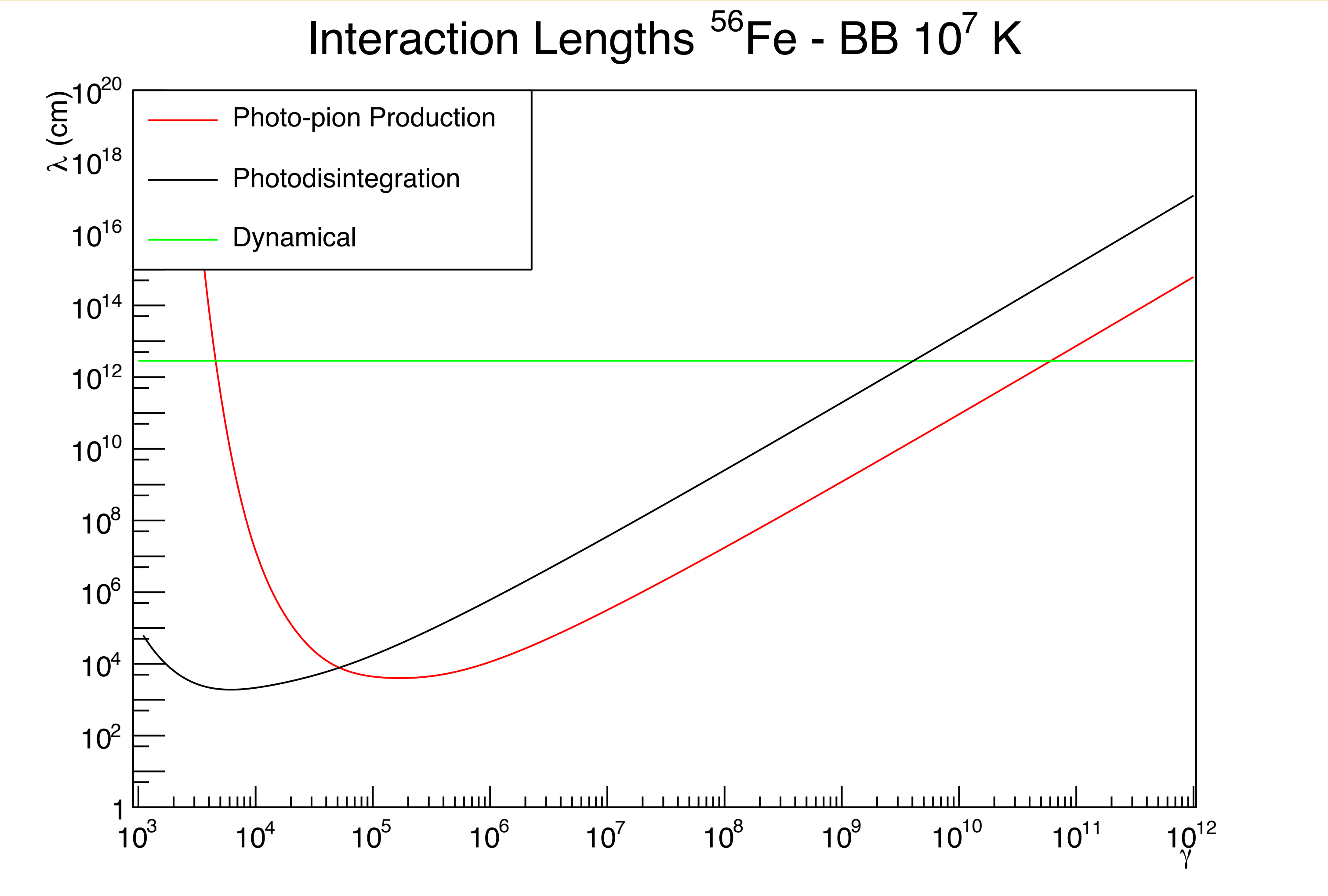


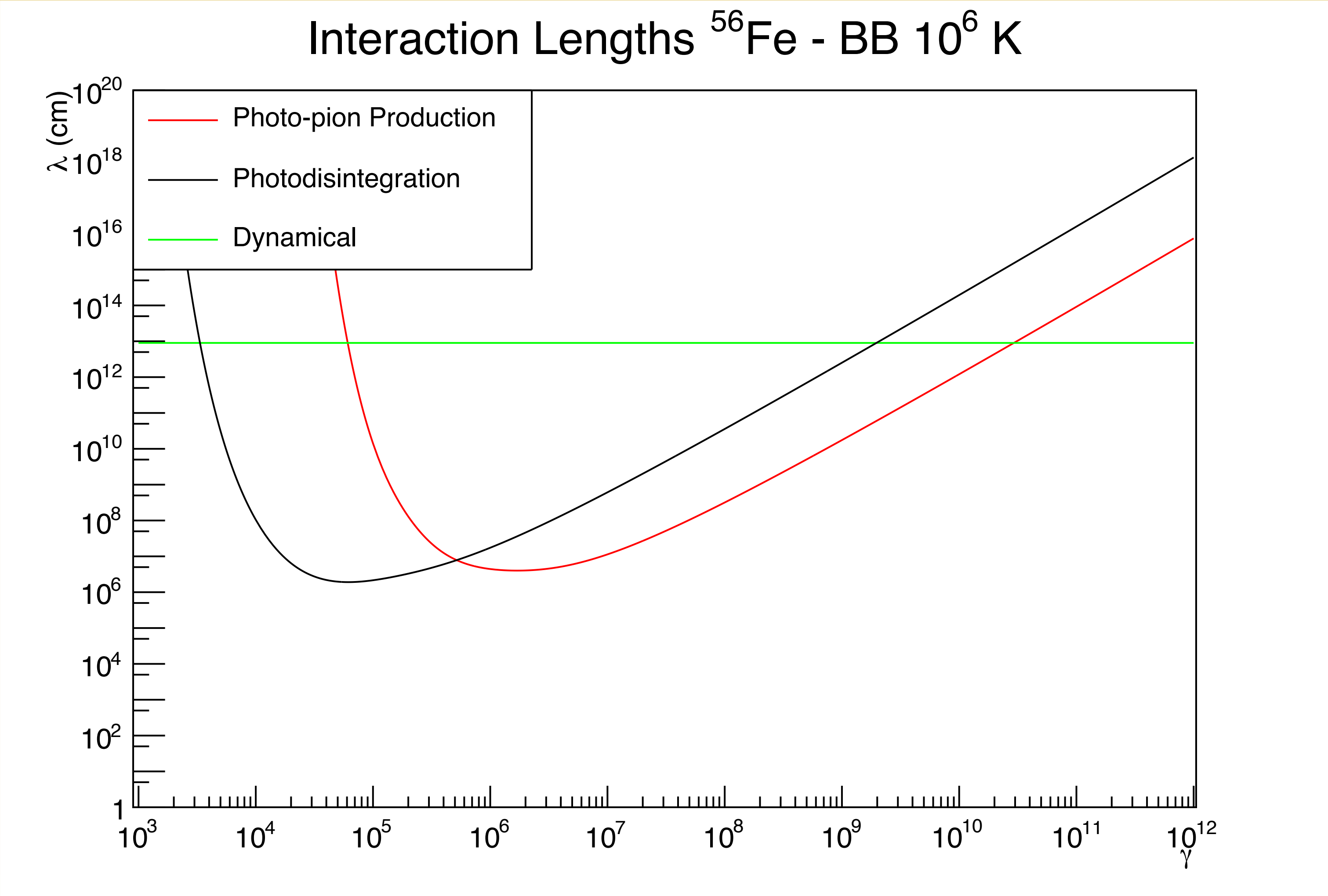


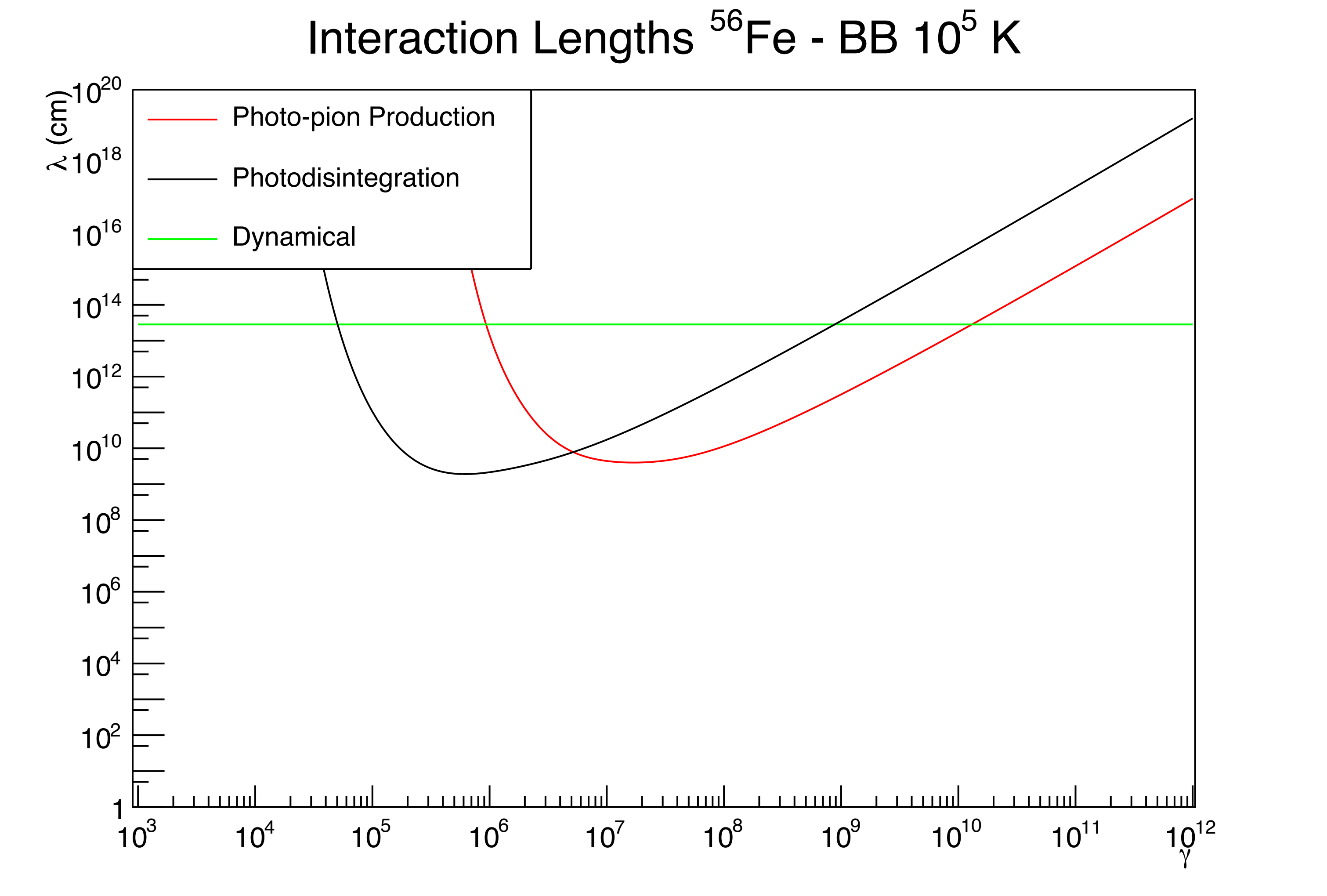


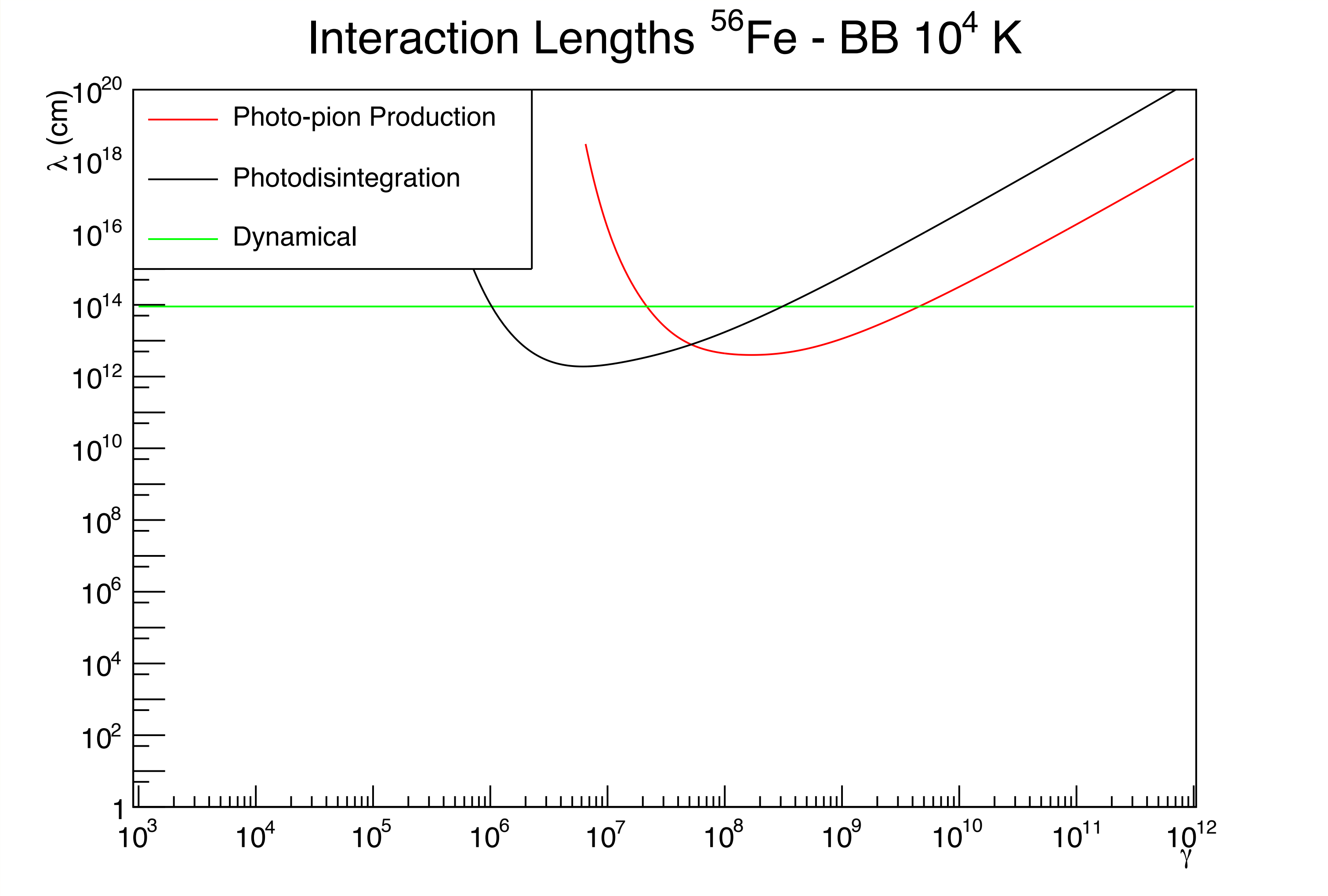
Iron escape


Interaction Lengths ^{56}Fe - BB 10^8 K
λ (cm)
Photo-pion Production
Photodisintegration
Dynamical
γ

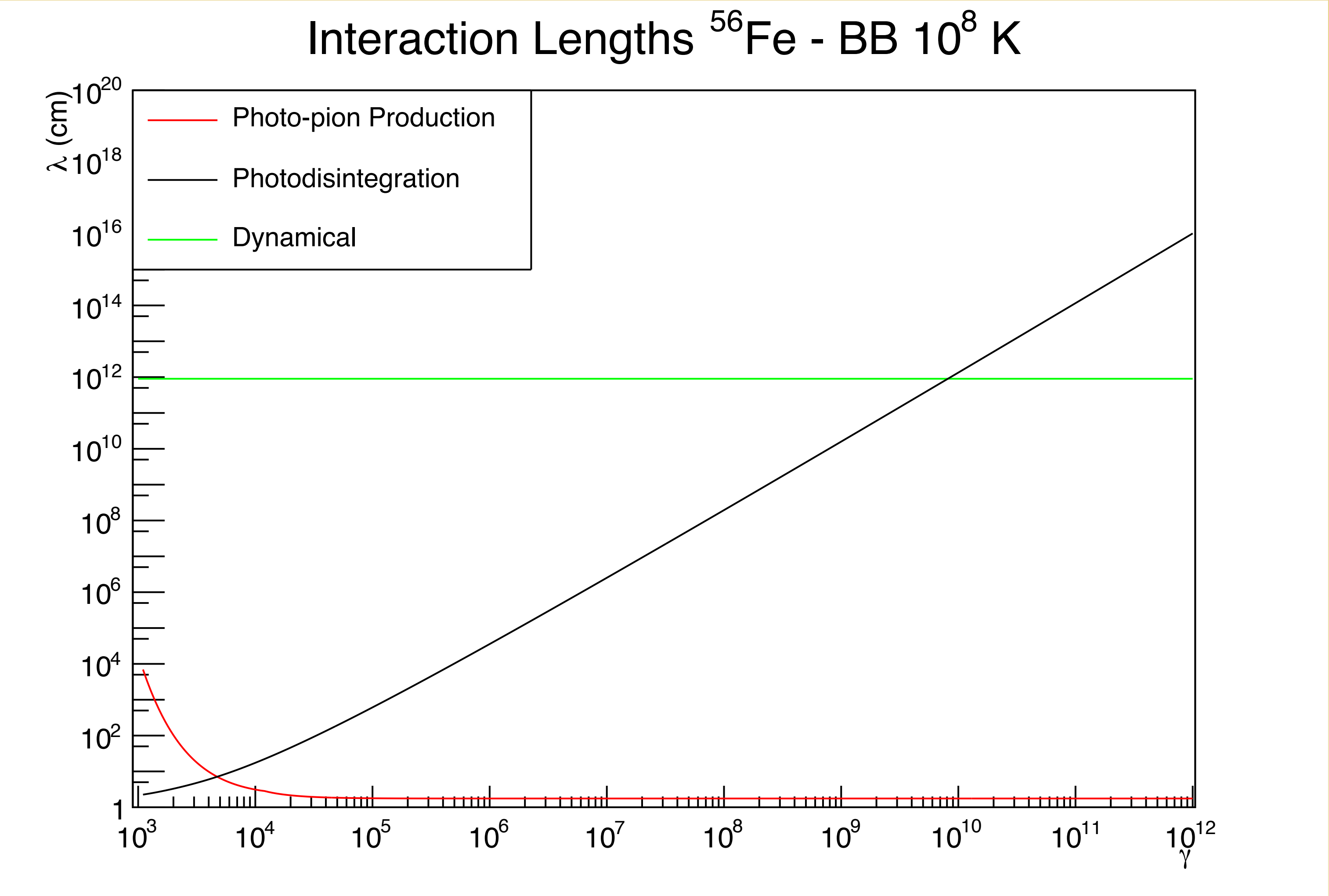

Interaction Lengths ^{56}Fe - BB 10^7 K
λ (cm)
Photo-pion Production
Photodisintegration
Dynamical
γ

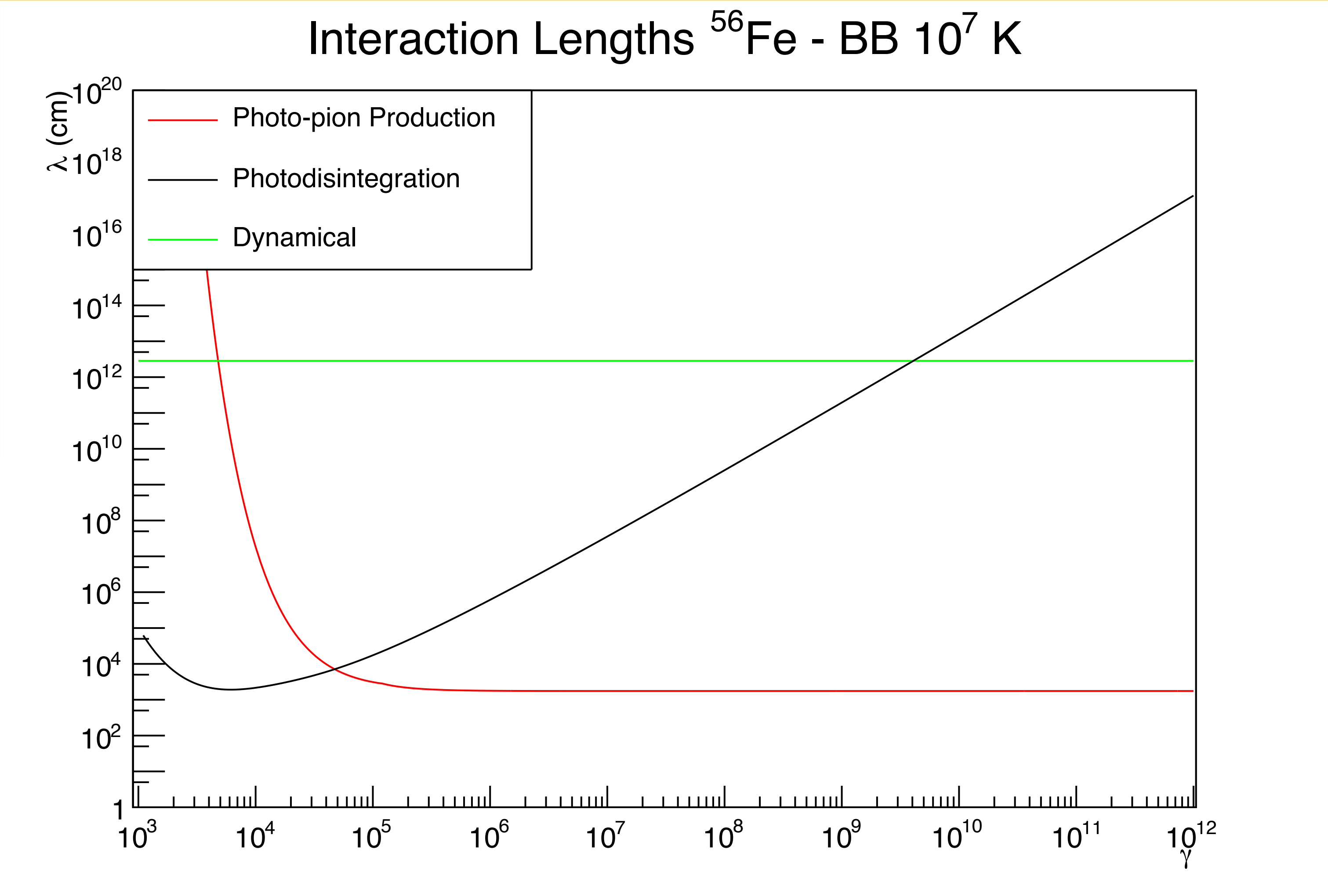

Interaction Lengths ^{56}Fe - BB 10^6 K
λ (cm)
Photo-pion Production
Photodisintegration
Dynamical
γ

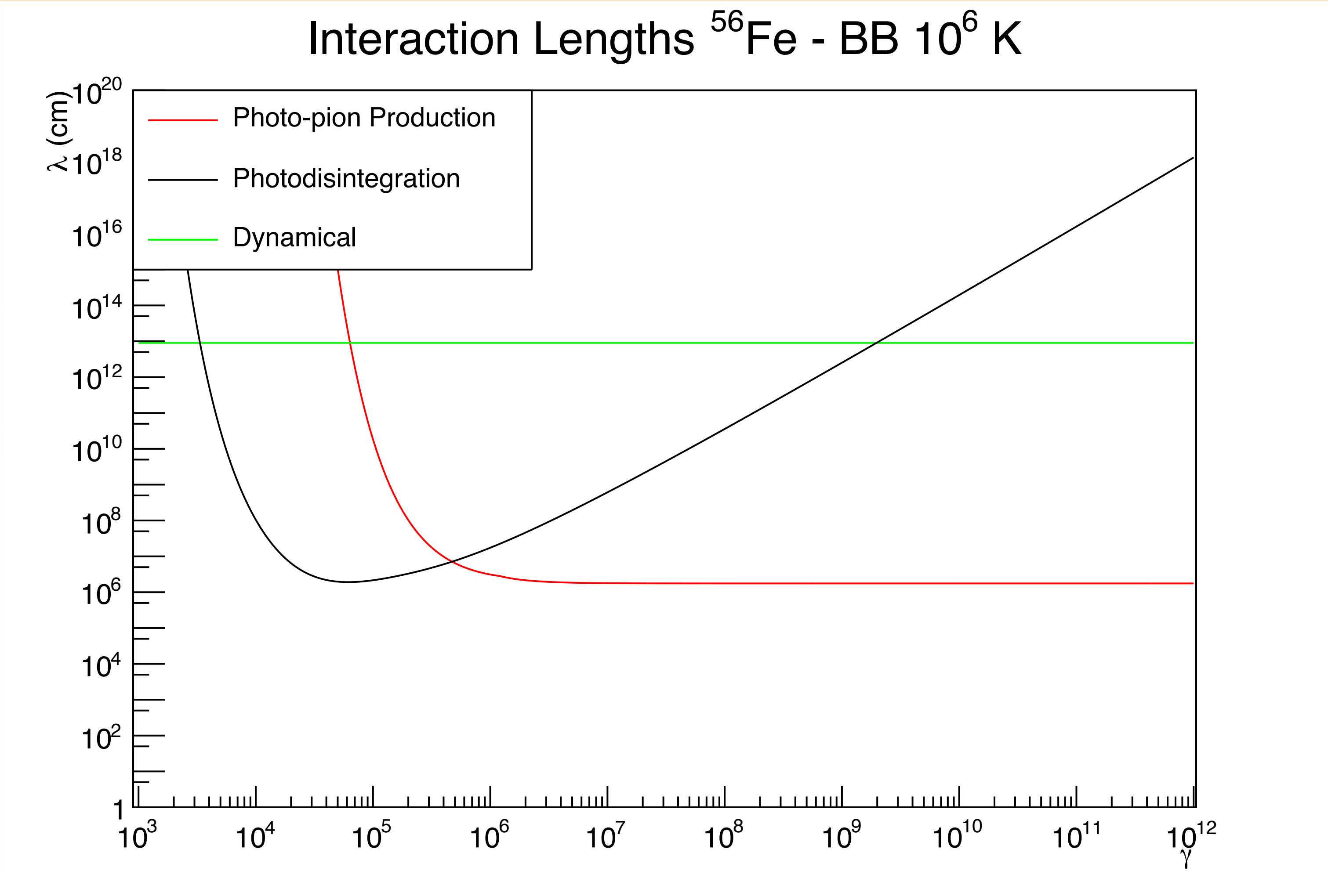

Interaction Lengths ^{56}Fe - BB 10^5 K
λ (cm)
Photo-pion Production
Photodisintegration
Dynamical
γ

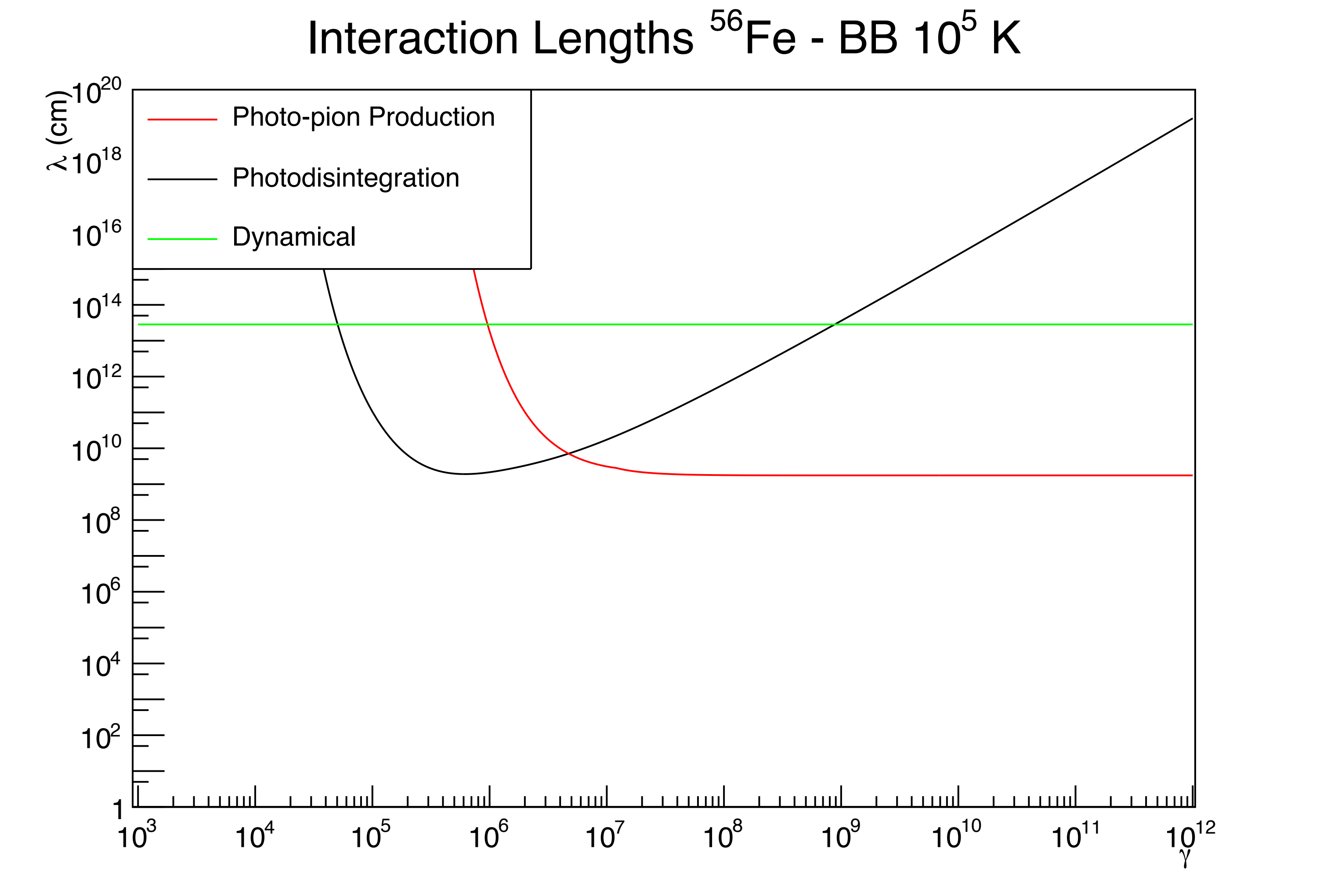

Interaction Lengths ^{56}Fe - BB 10^4 K
λ (cm)
Photo-pion Production
Photodisintegration
Dynamical
γ

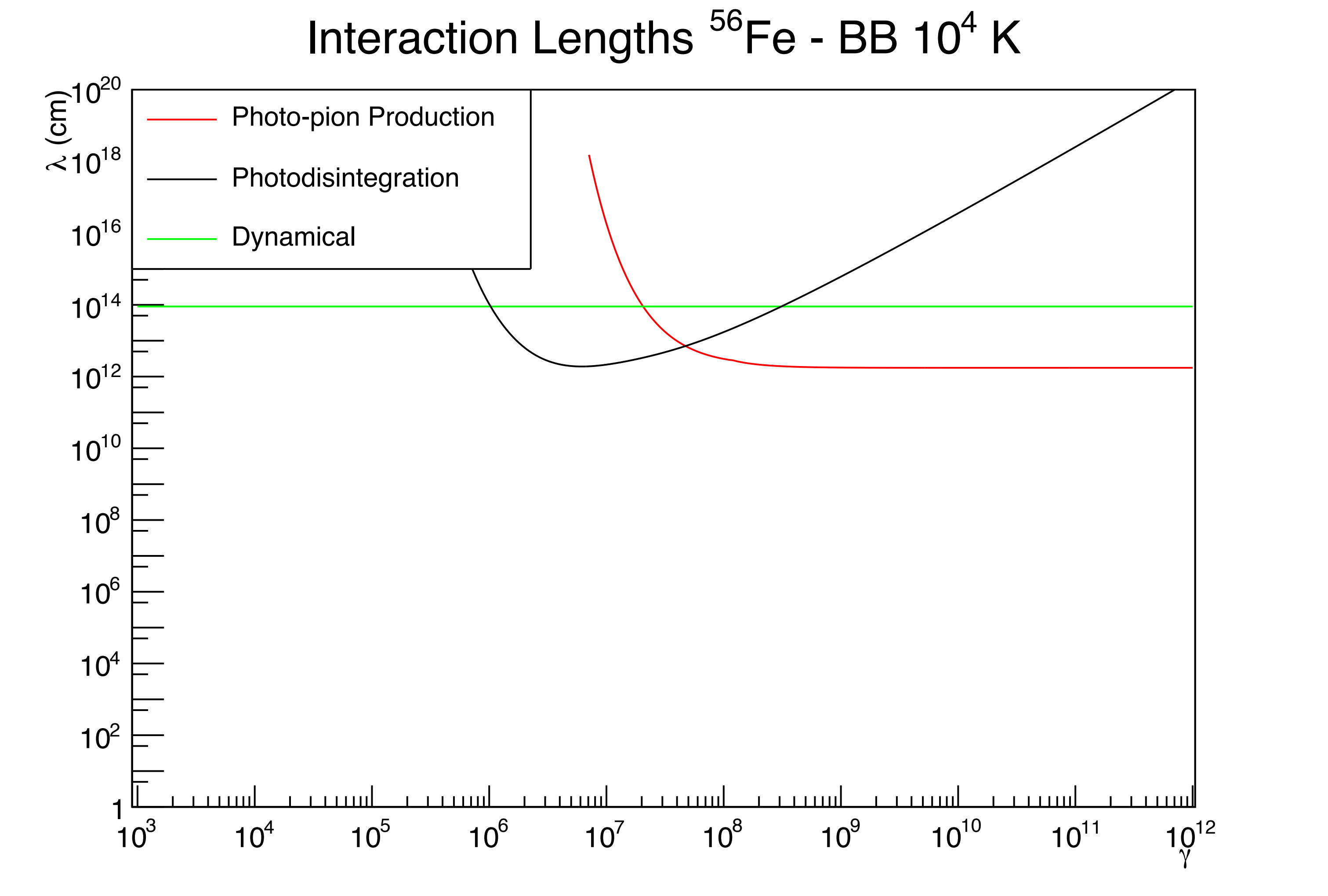
Iron escape - bis



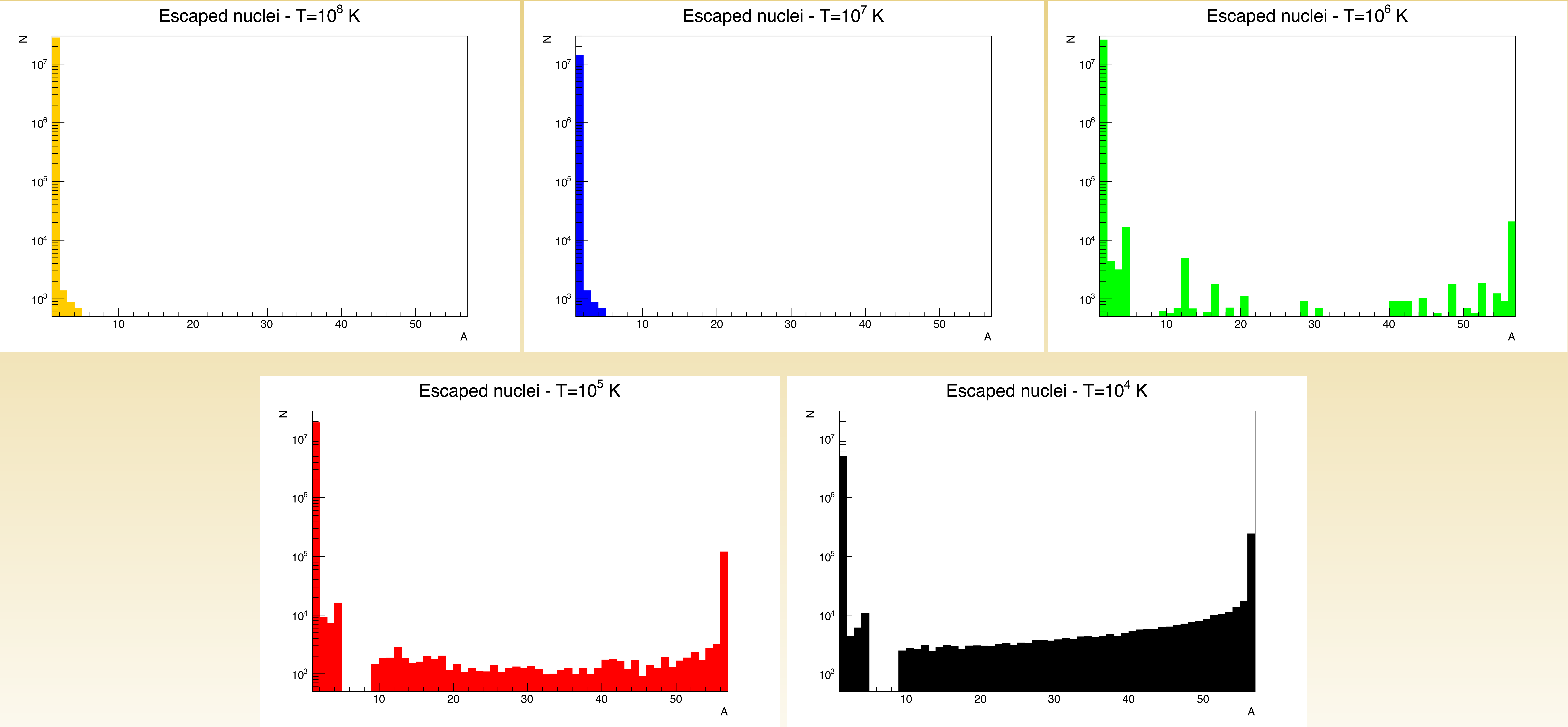




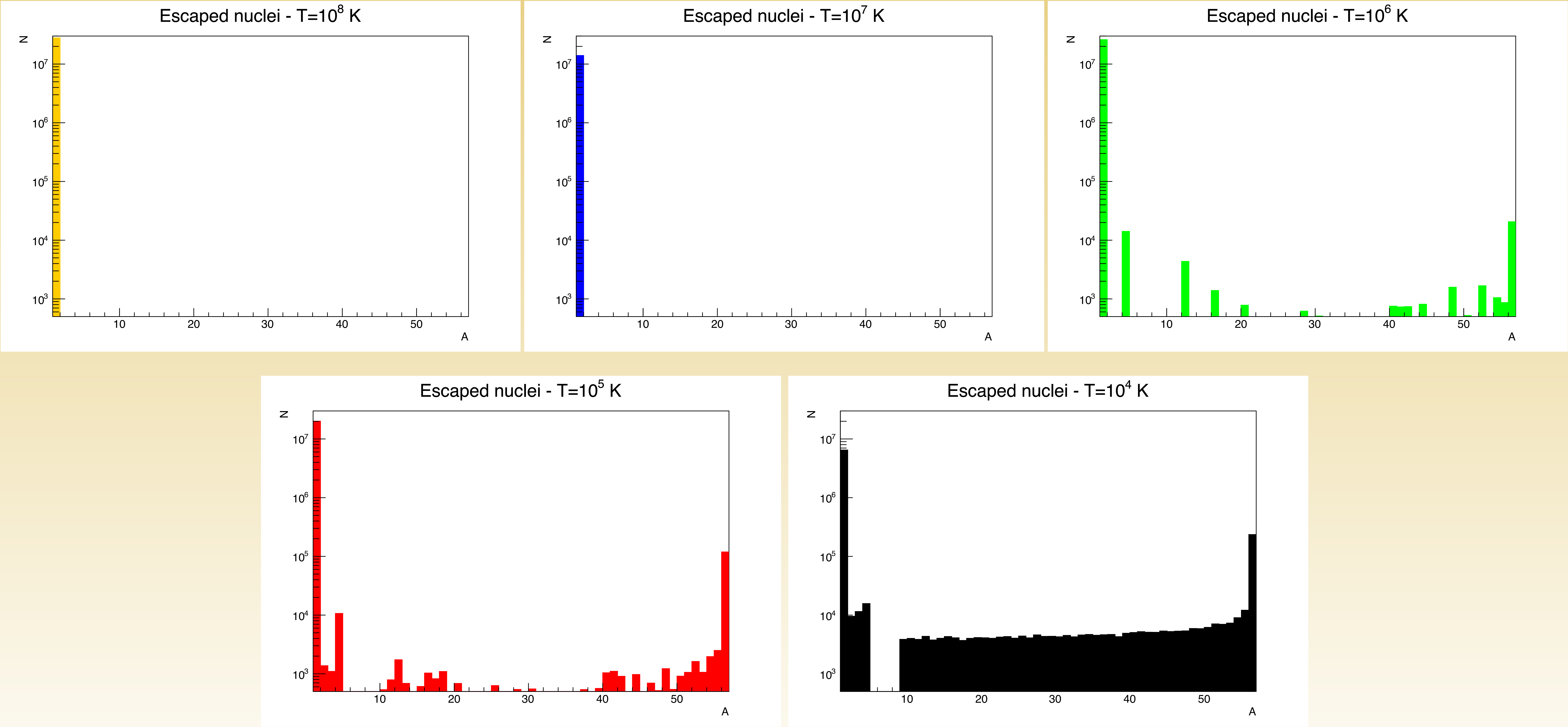




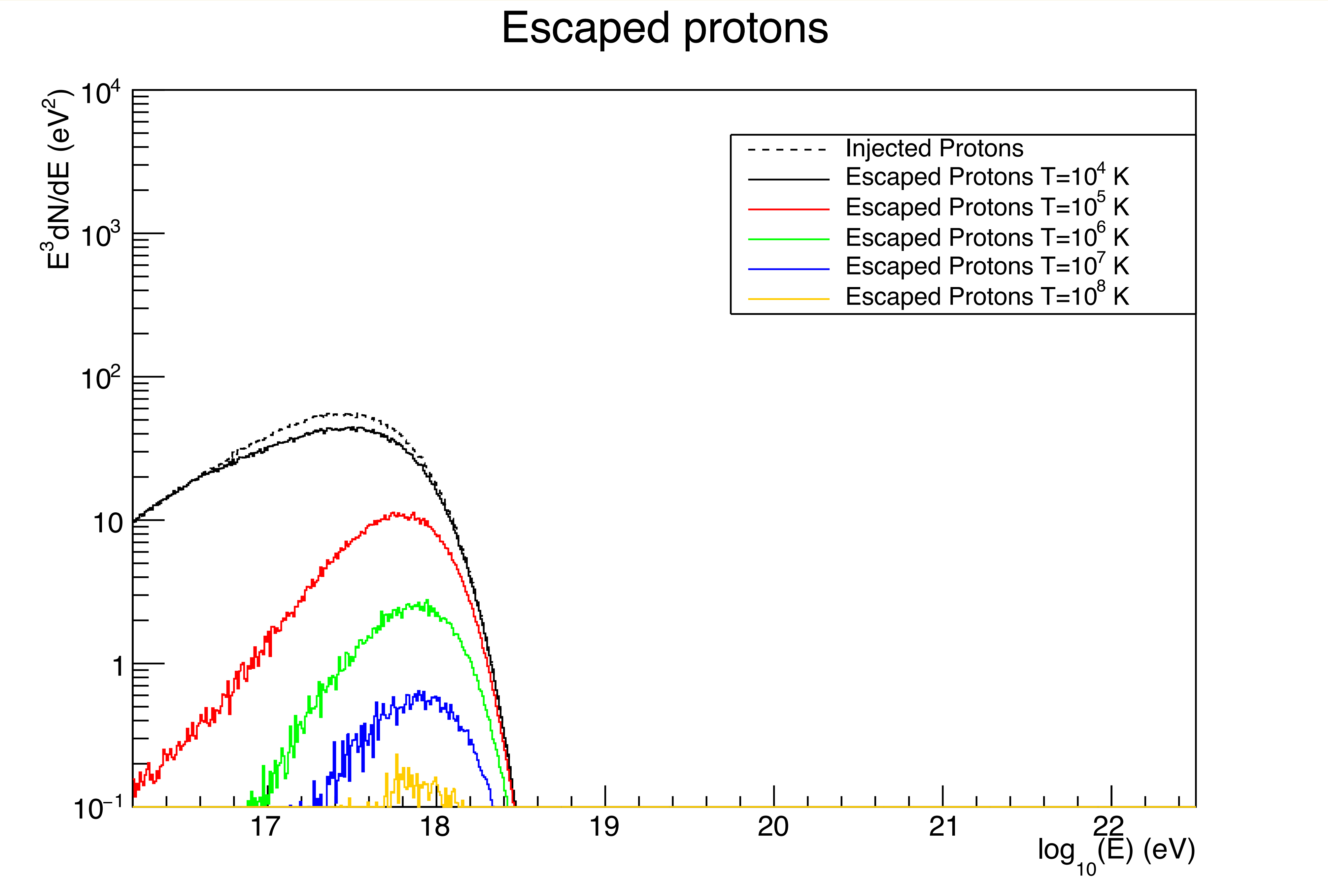
Fragmentation

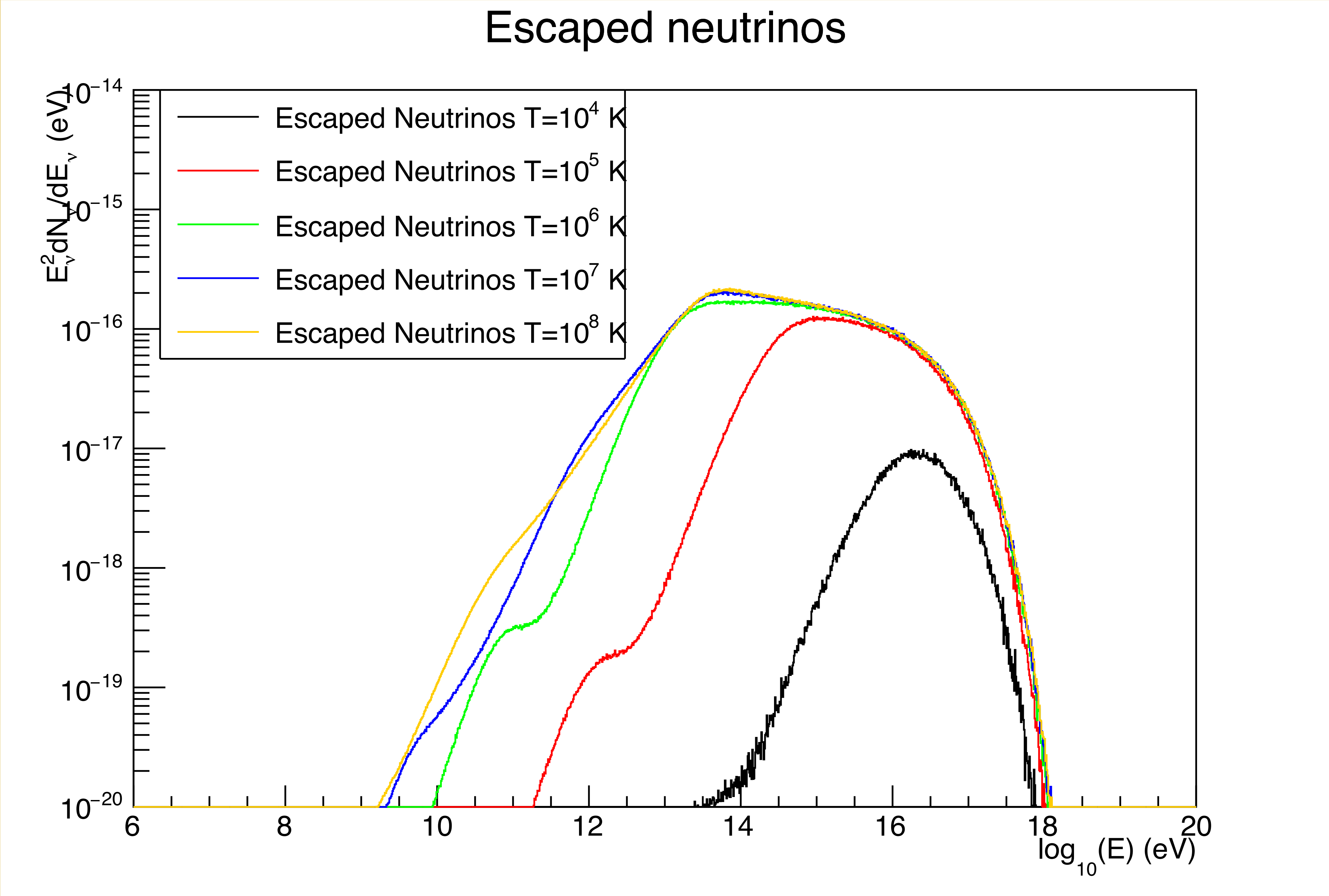


Fragmentation - bis



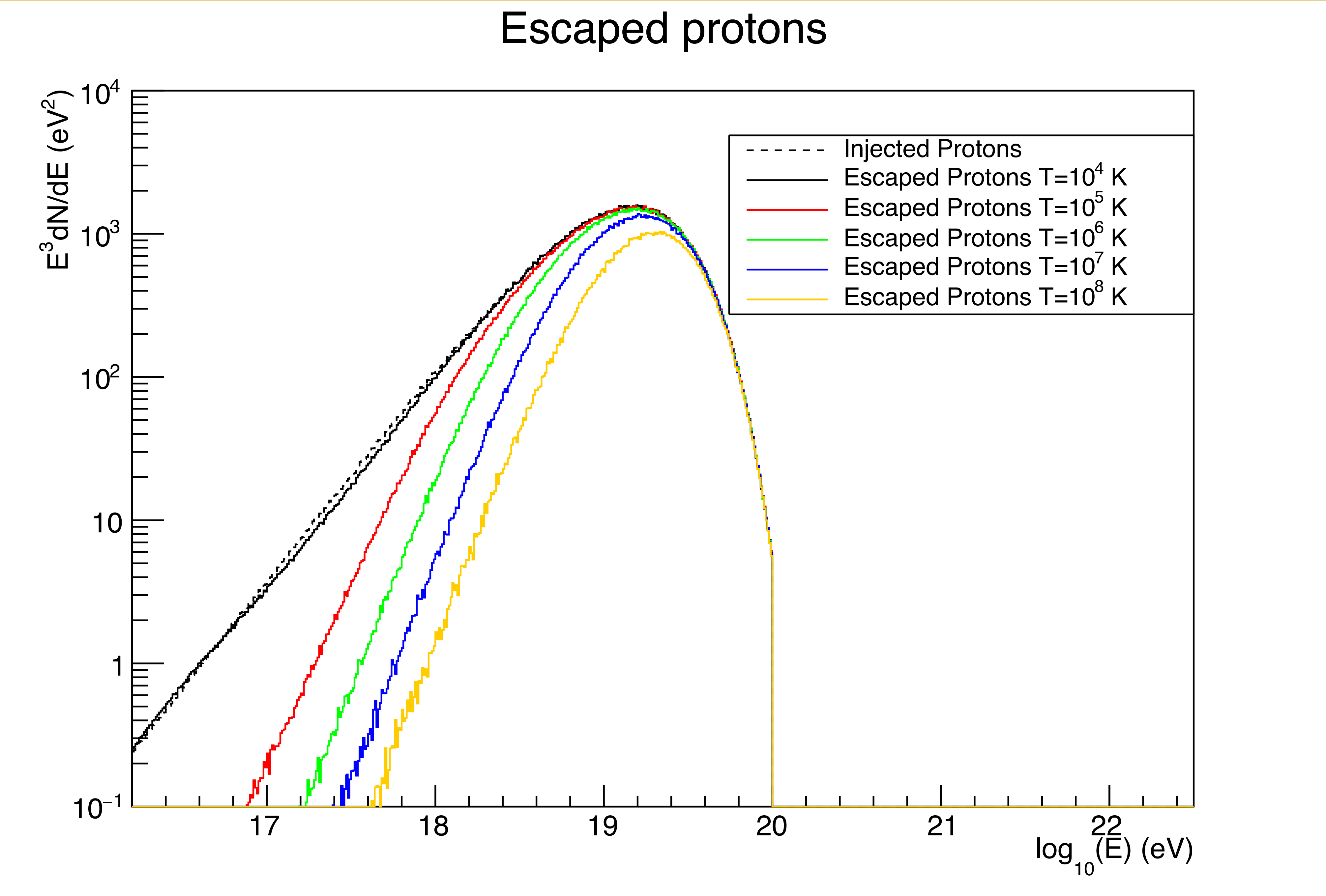
Simulations of source interactions - p

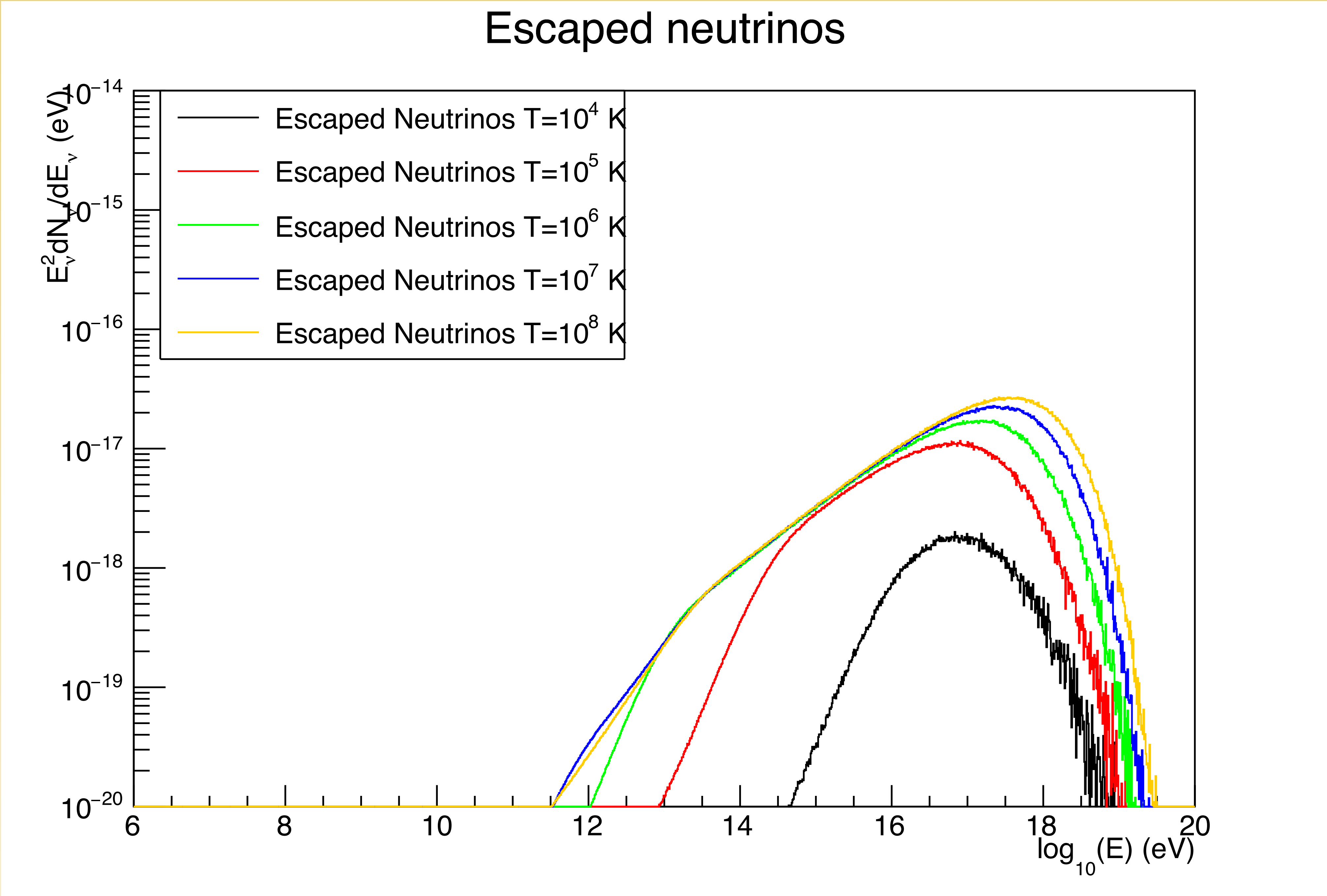




$$\gamma = 2.1 \quad , \quad R_{max} = 10^{17.5}\,V$$

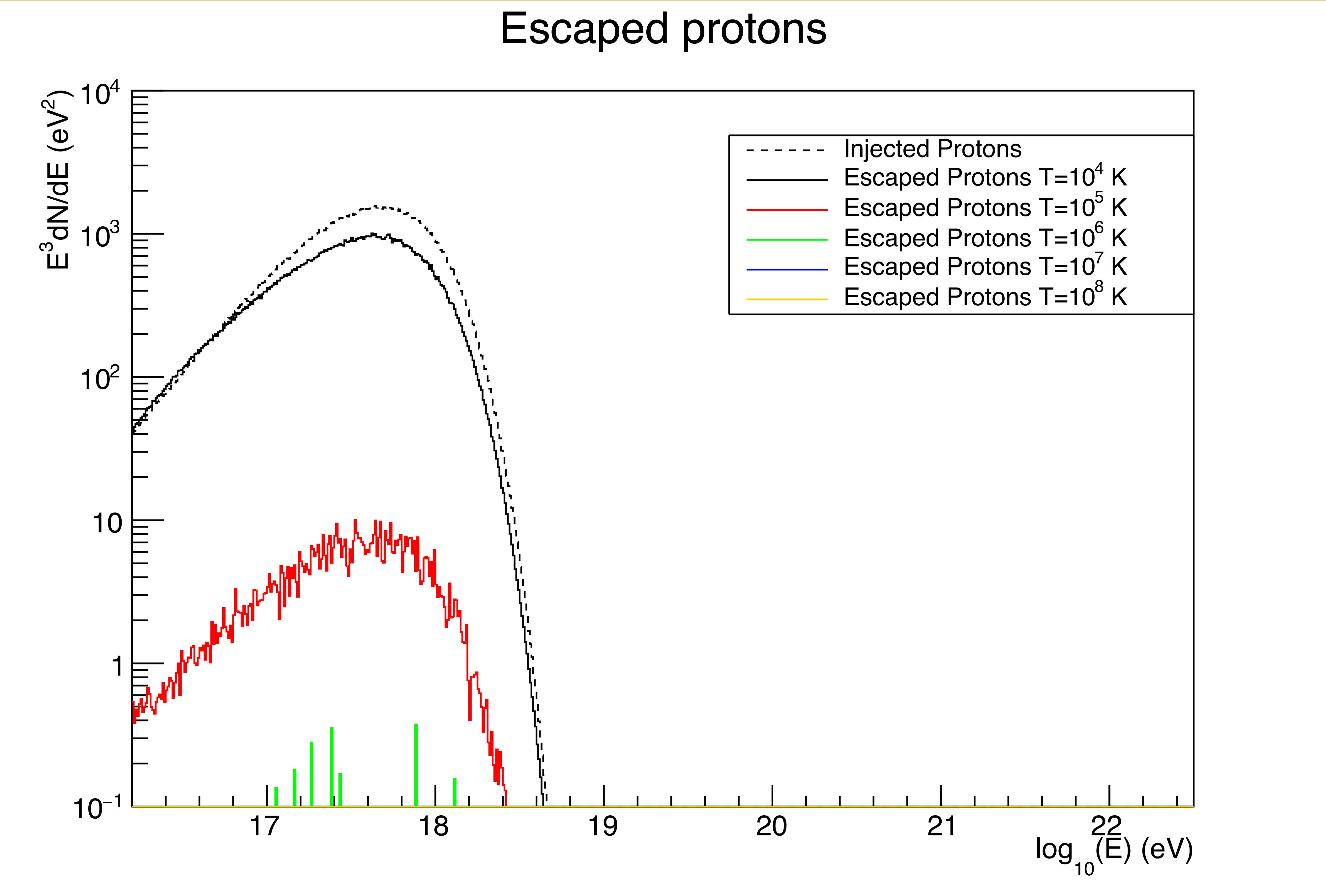
Simulations of source interactions - p

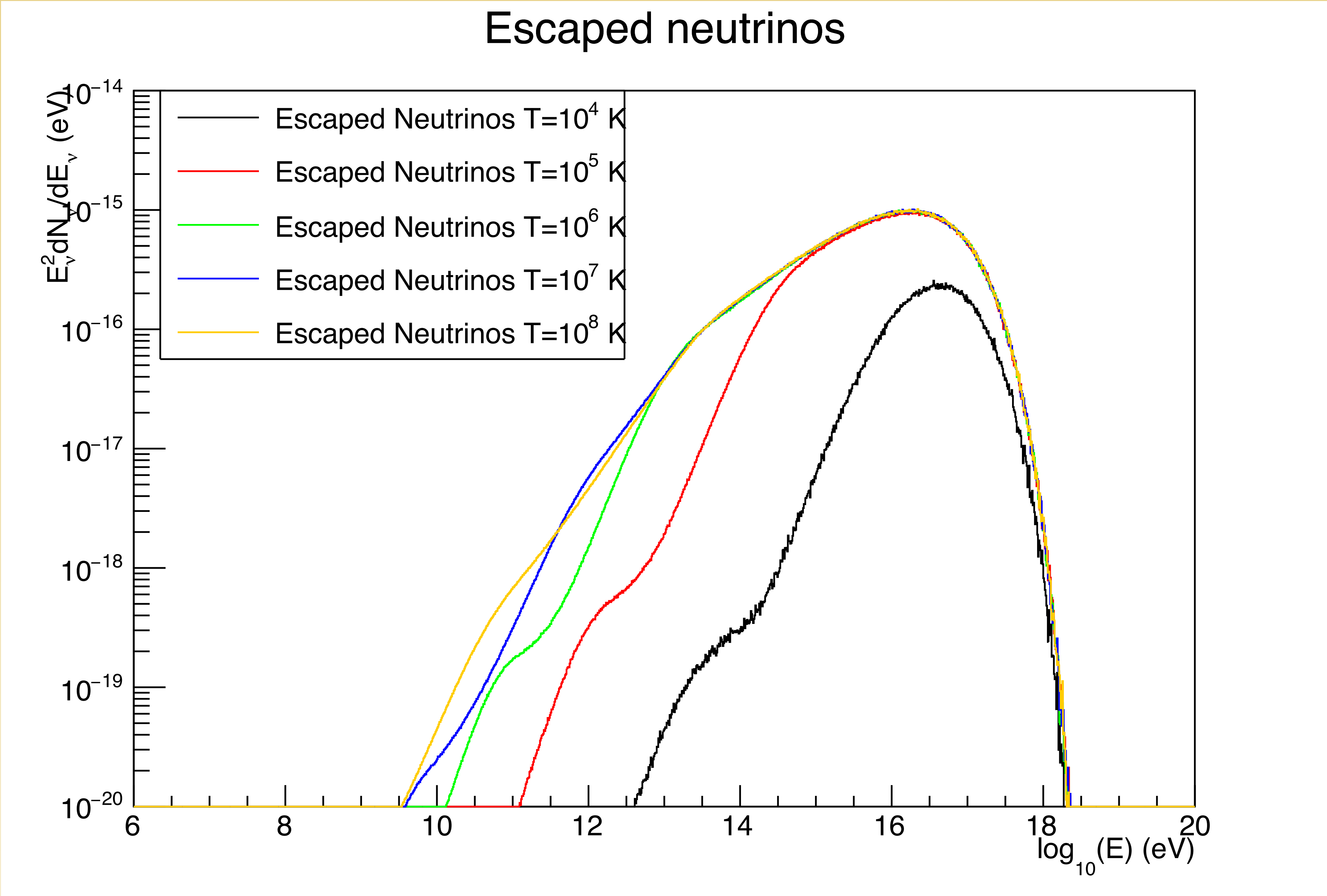




$$\gamma = 1.5 \quad , \quad R_{max} = 10^{19}\,V$$

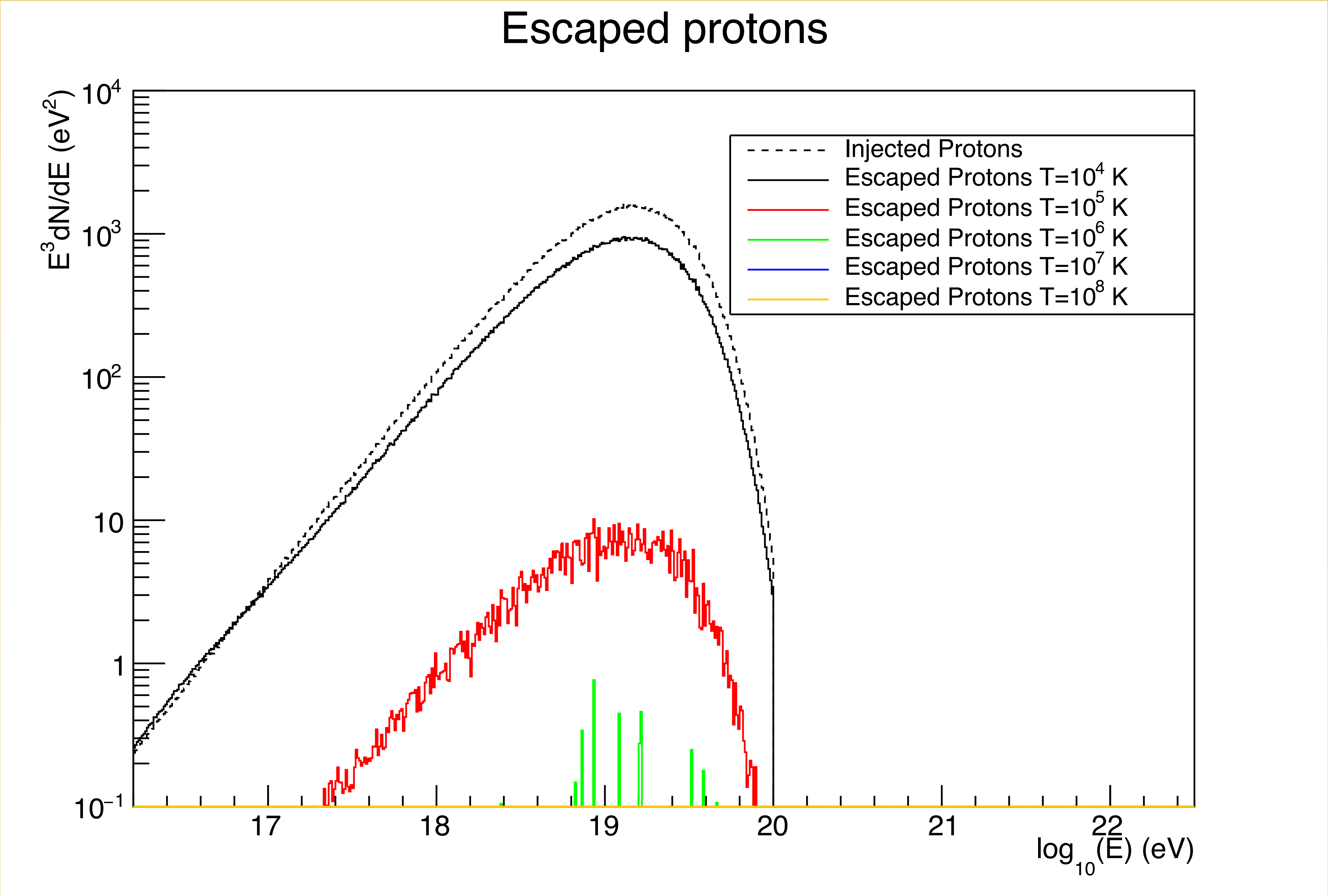
Simulations of source interactions - p

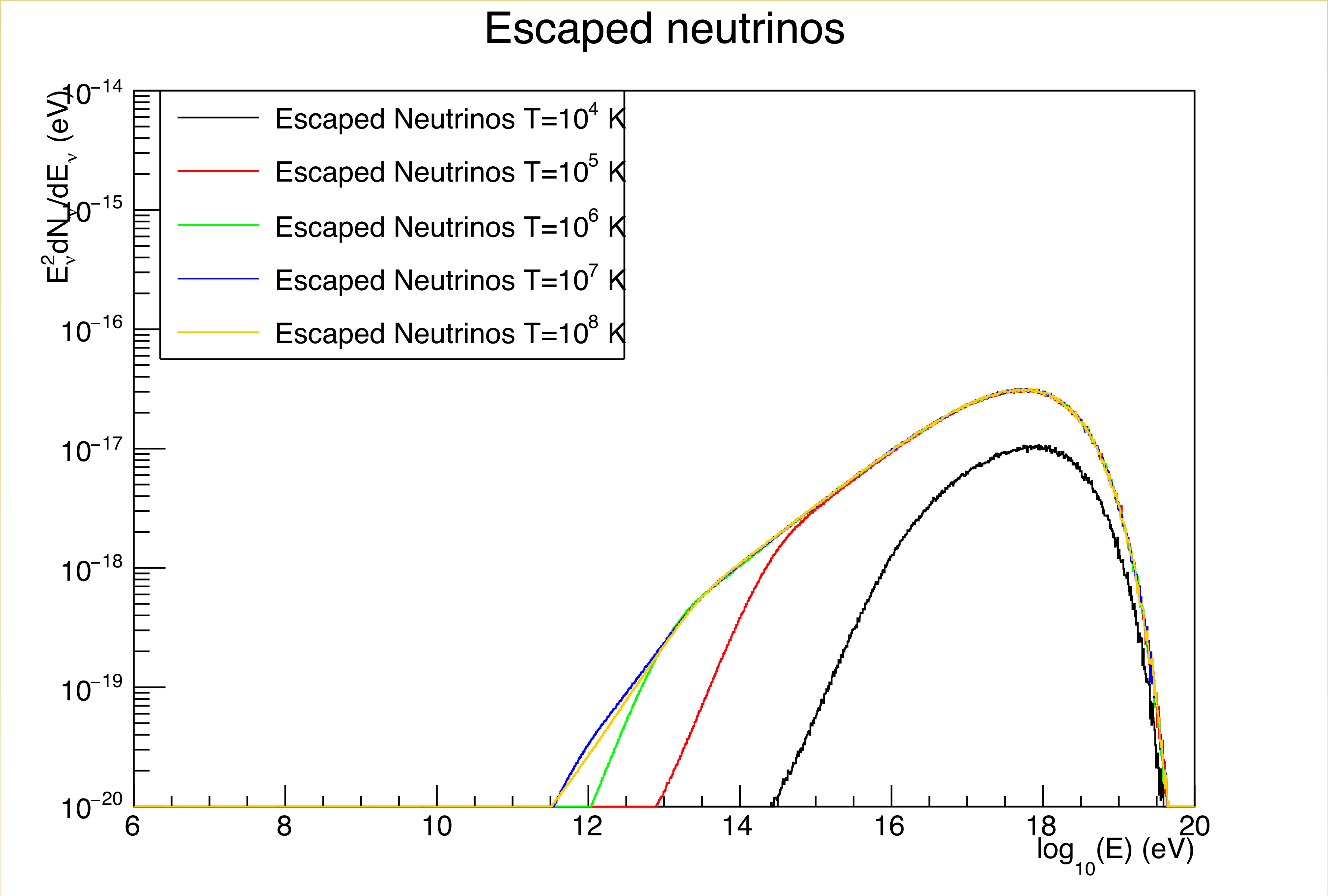




$$\gamma = 1.5 \quad , \quad R_{max} = 10^{17.5}\, V \quad , \quad Bis$$

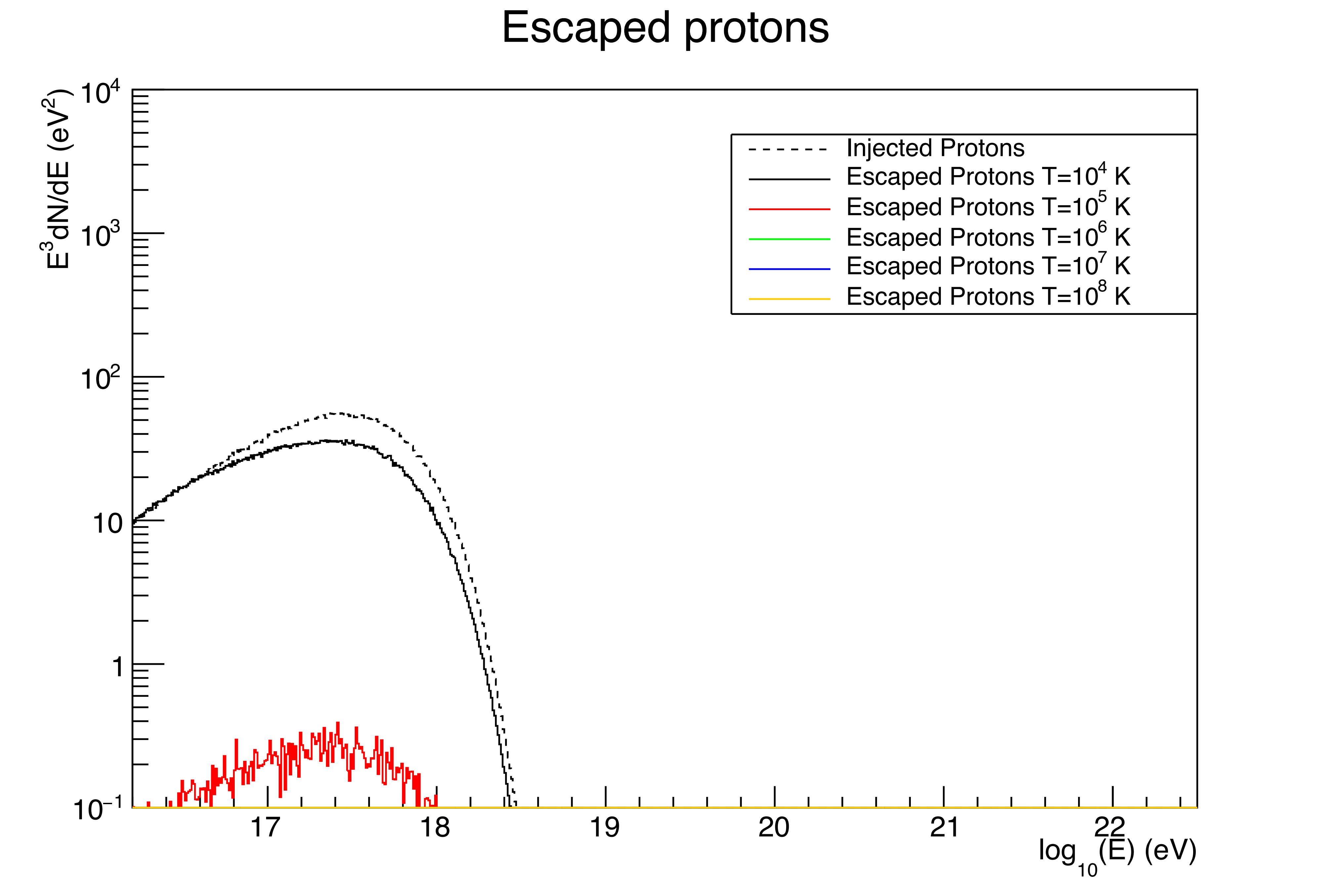
Simulations of source interactions - p

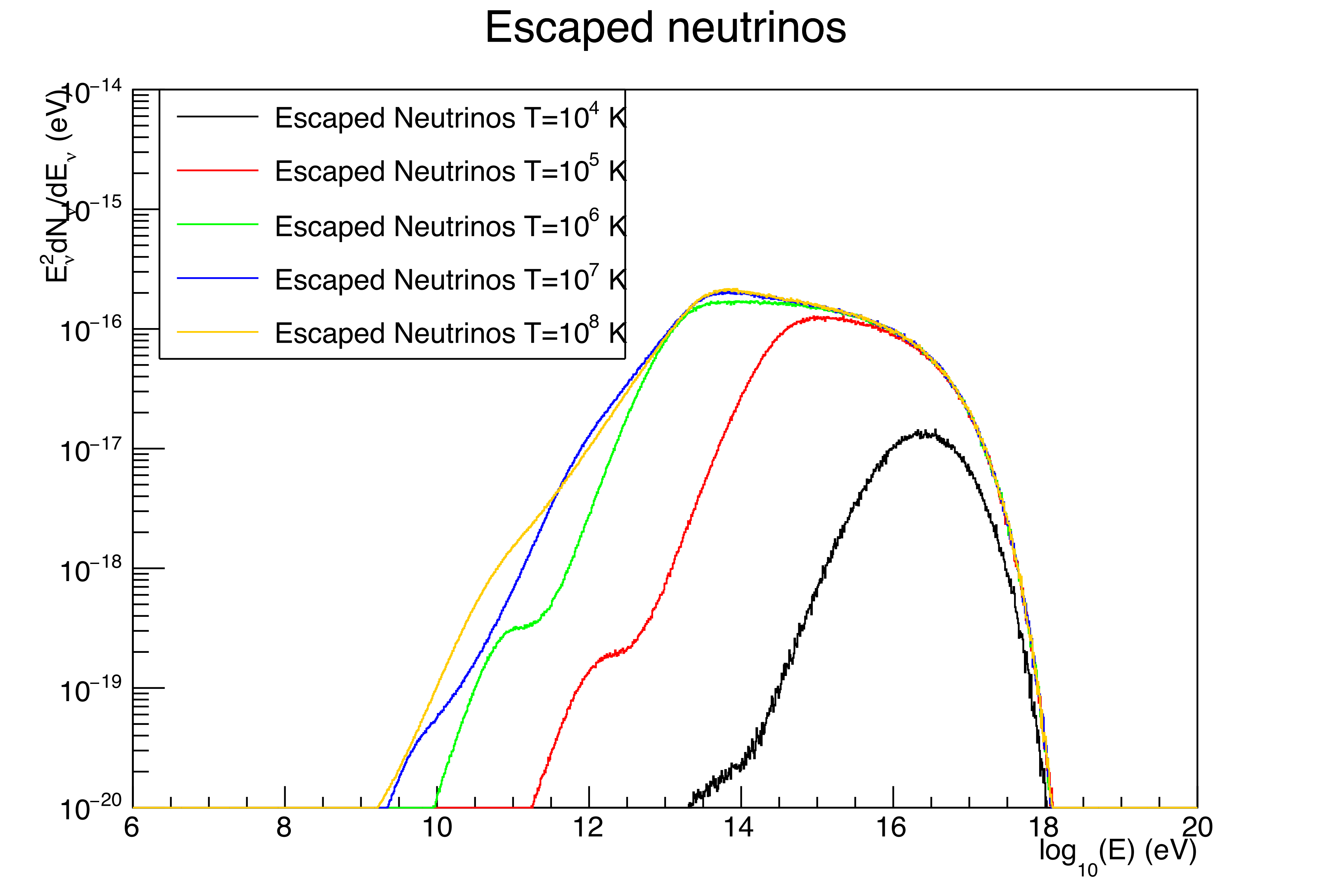




$$\gamma = 1.5 \quad , \quad R_{max} = 10^{19}\,V \quad , \quad Bis$$

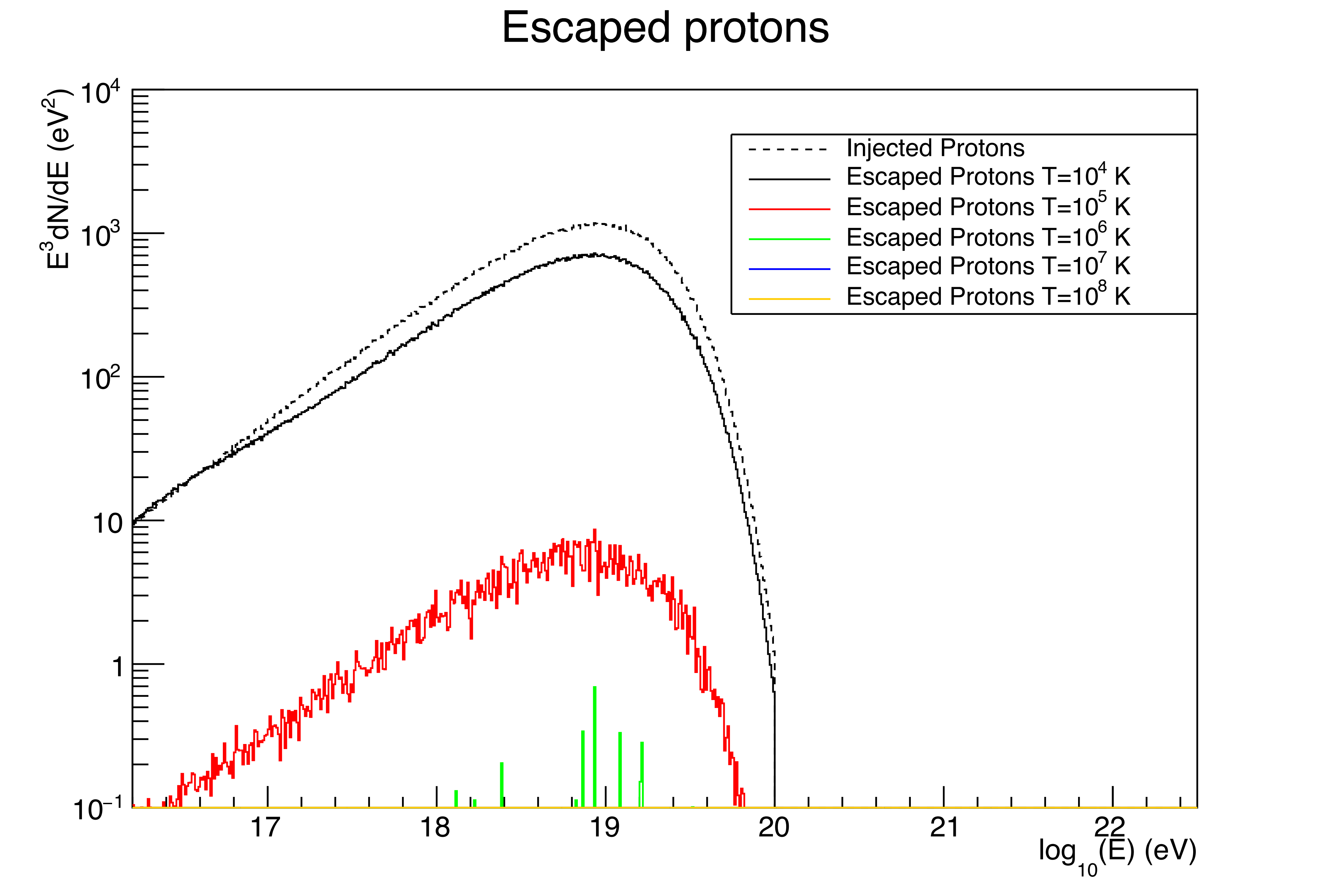
Simulations of source interactions - p

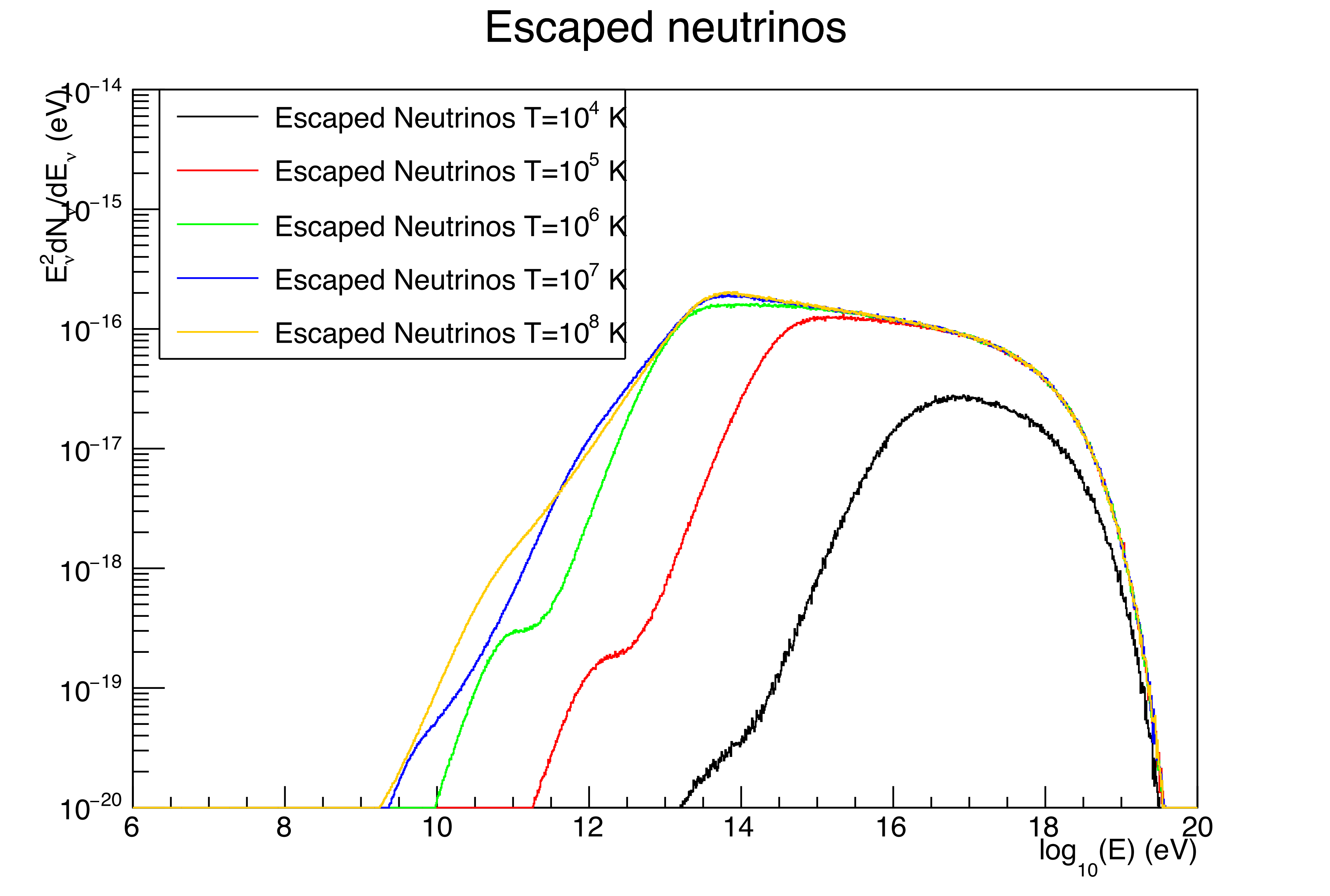




$$\gamma = 2.1 \quad , \quad R_{max} = 10^{17.5}\, V \quad , \quad Bis$$

Simulations of source interactions - p





$$\gamma = 2.1 \quad , \quad R_{max} = 10^{19}\,V \quad , \quad Bis$$

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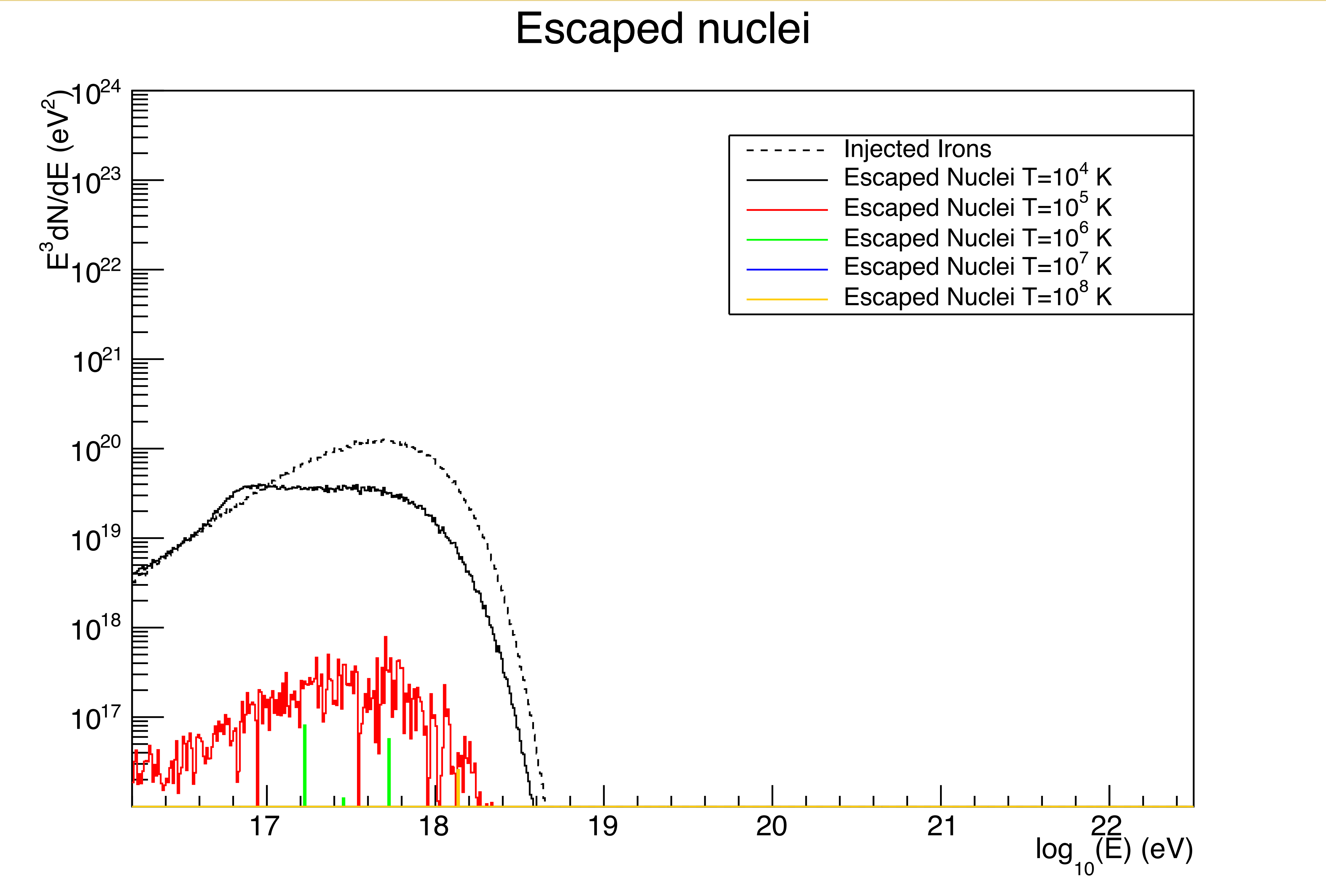
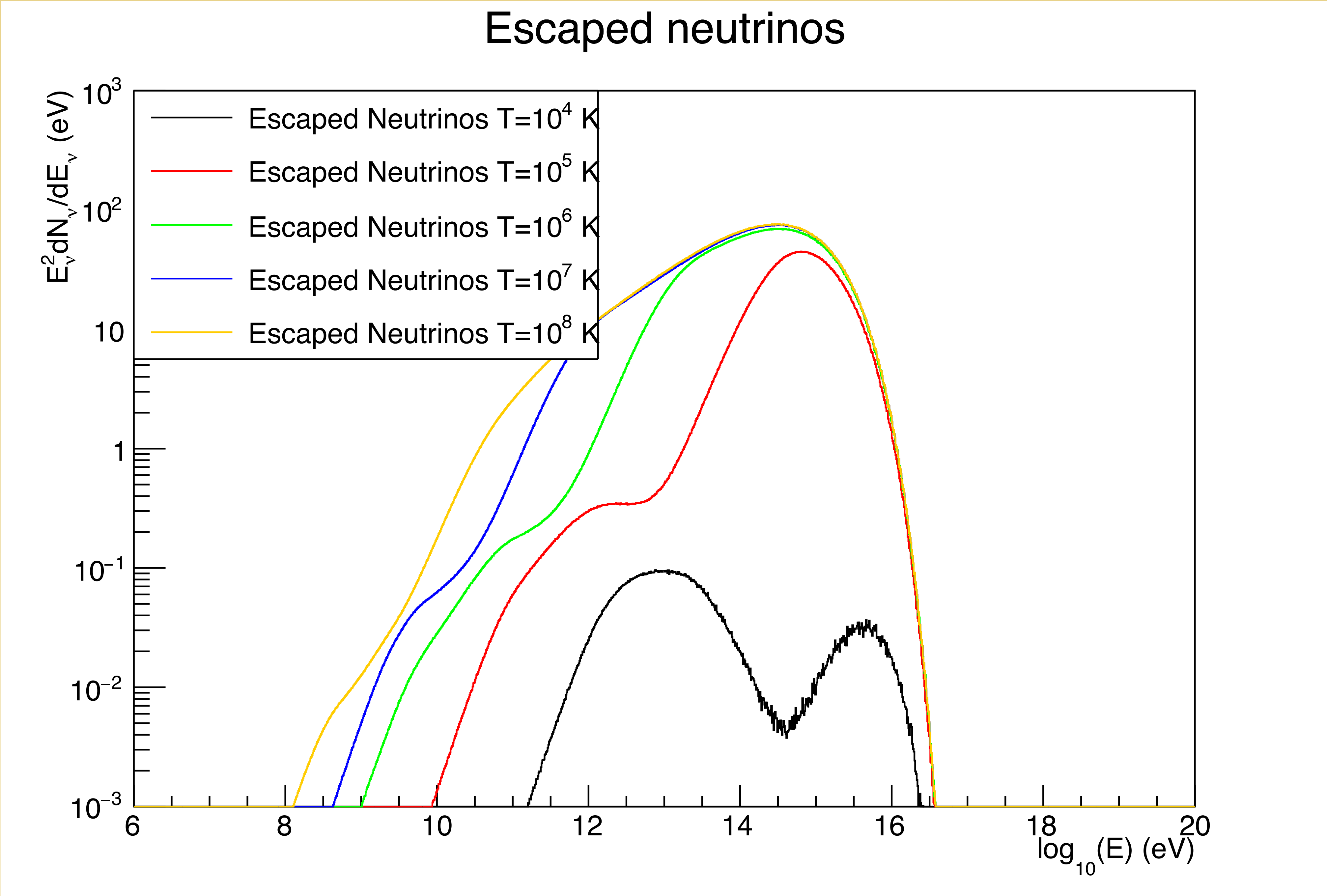
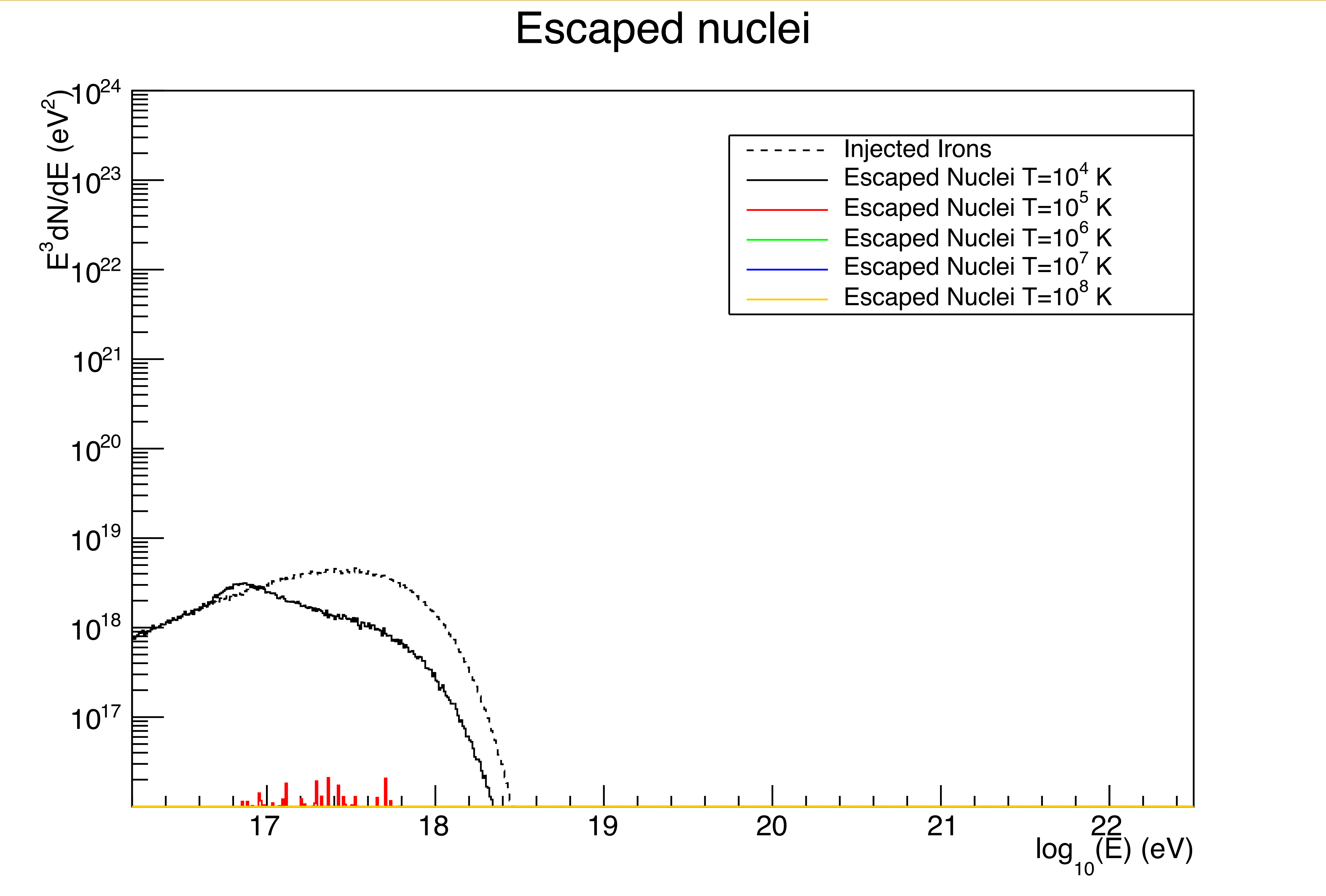
Simulations of source interactions - Fe

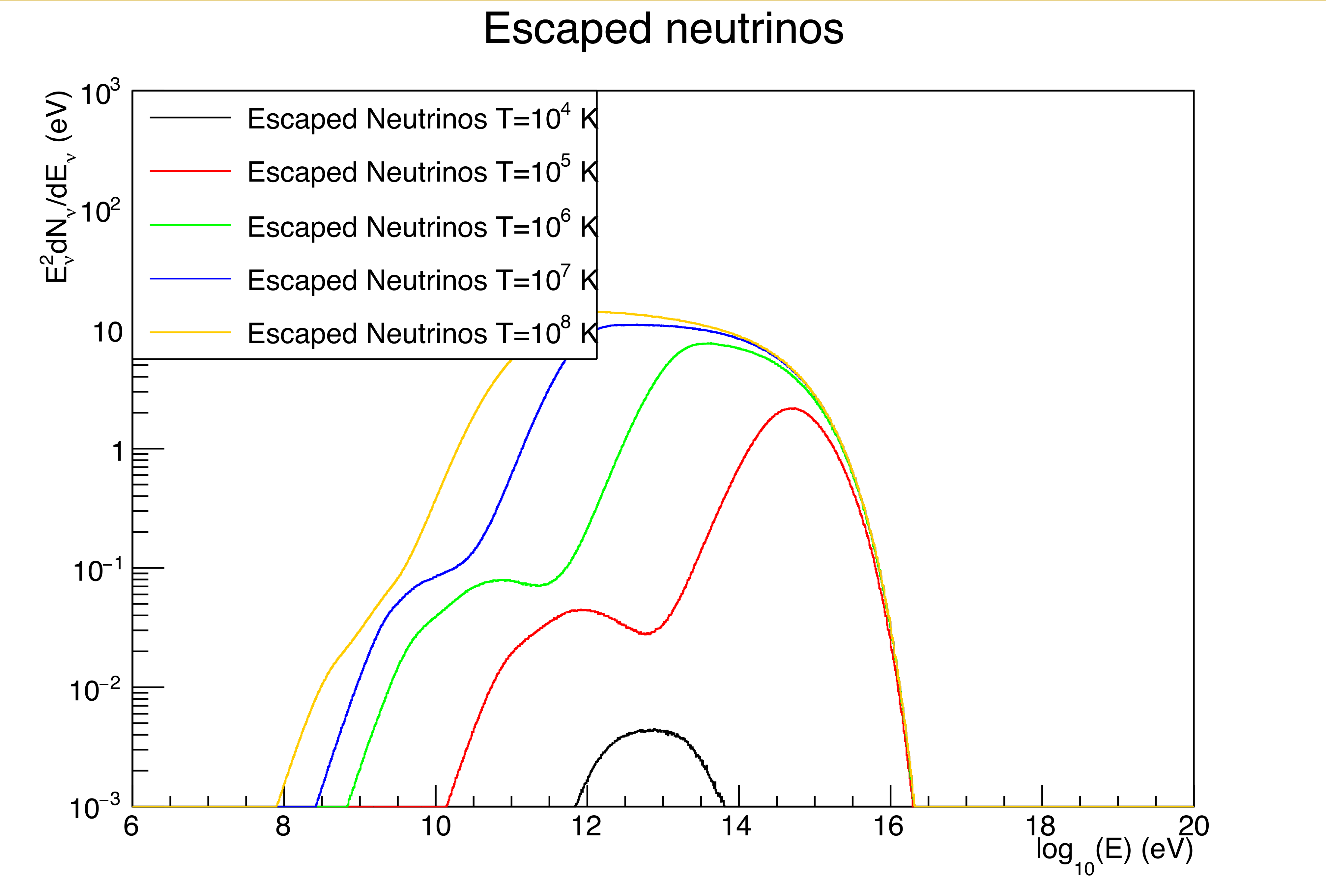




$$\gamma = 1.5 \quad , \quad R_{max} = 10^{17.5}\, V$$

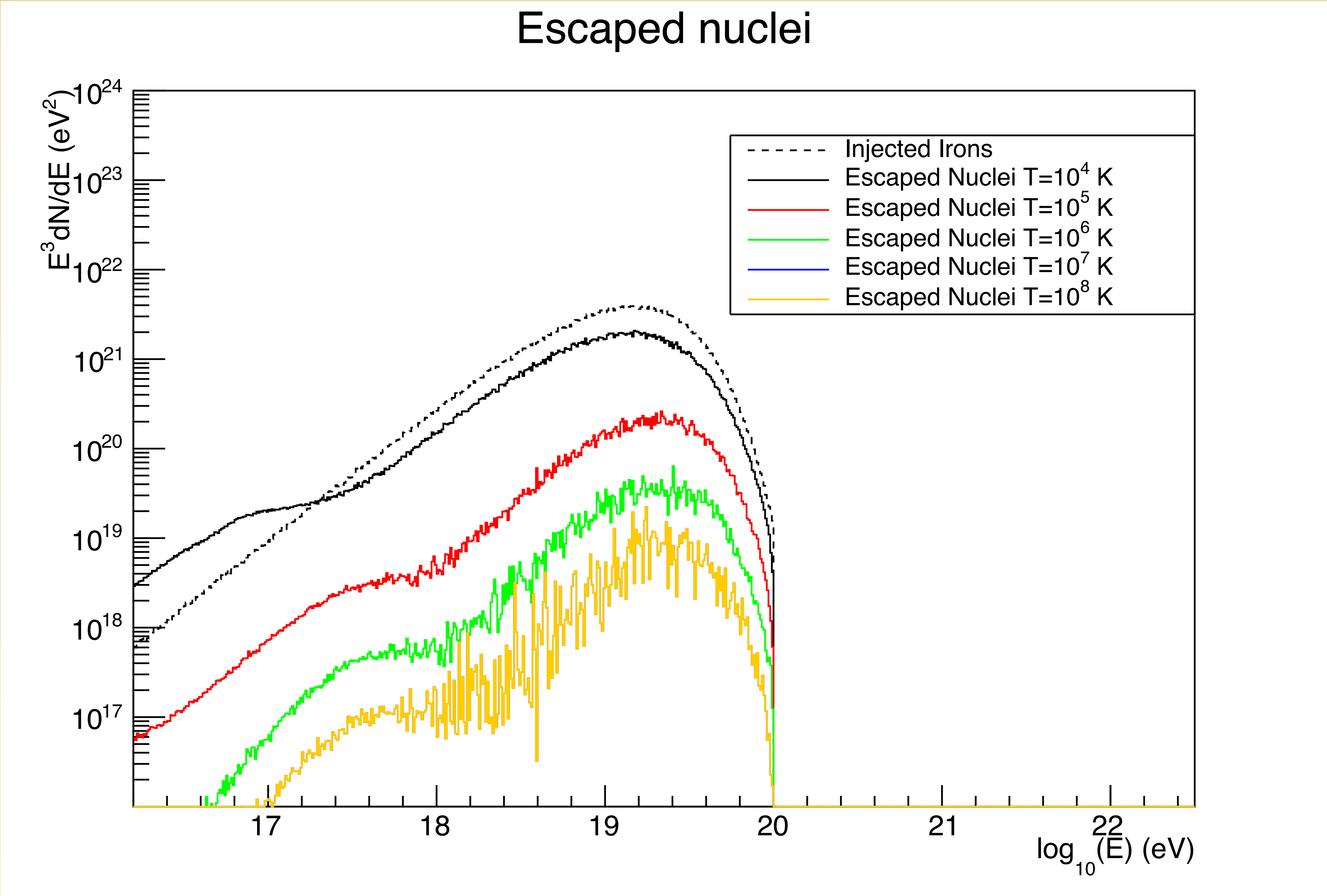
Simulations of source interactions - Fe

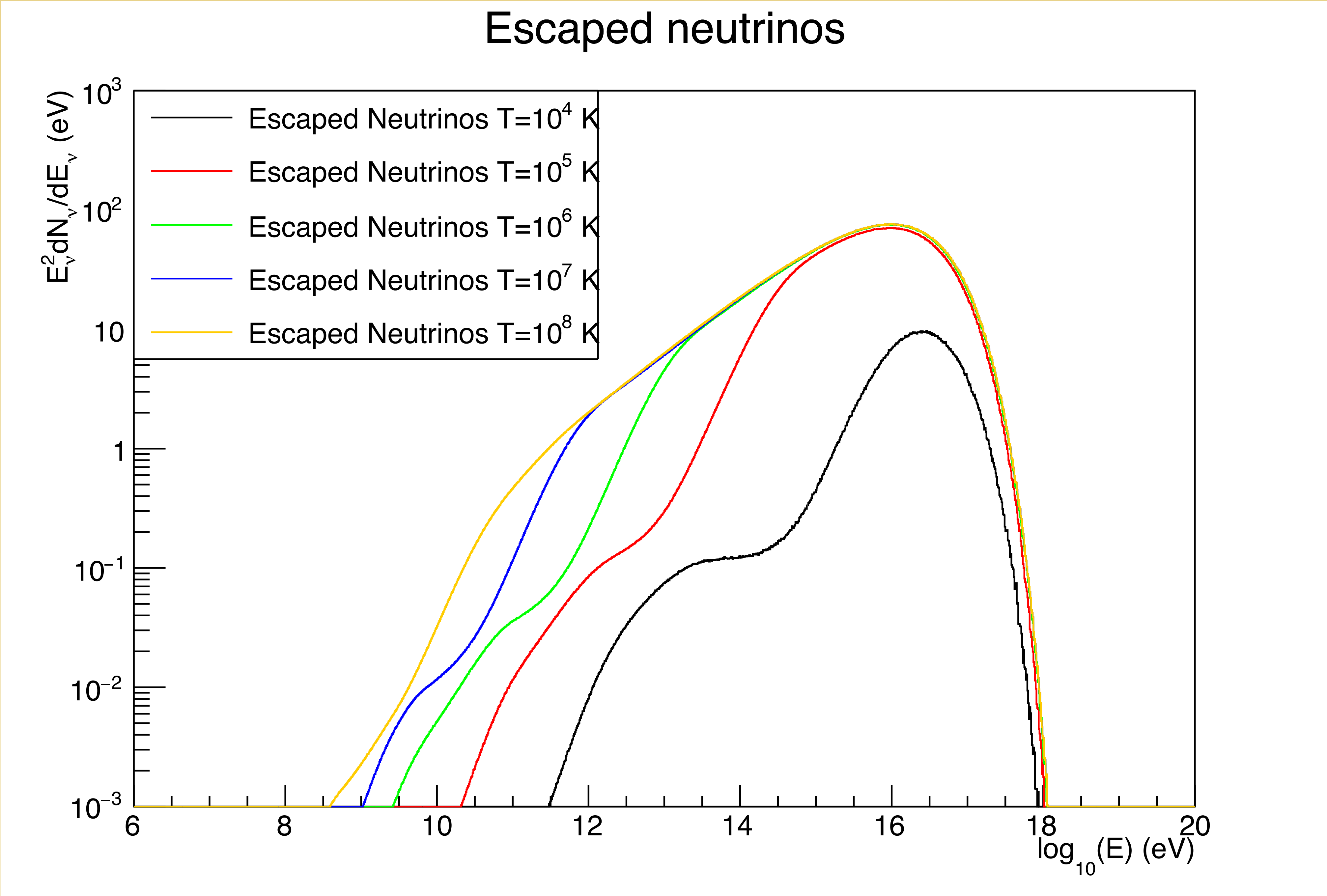




$$\gamma = 2.1 \quad , \quad R_{max} = 10^{17.5}\, V$$

Simulations of source interactions - Fe

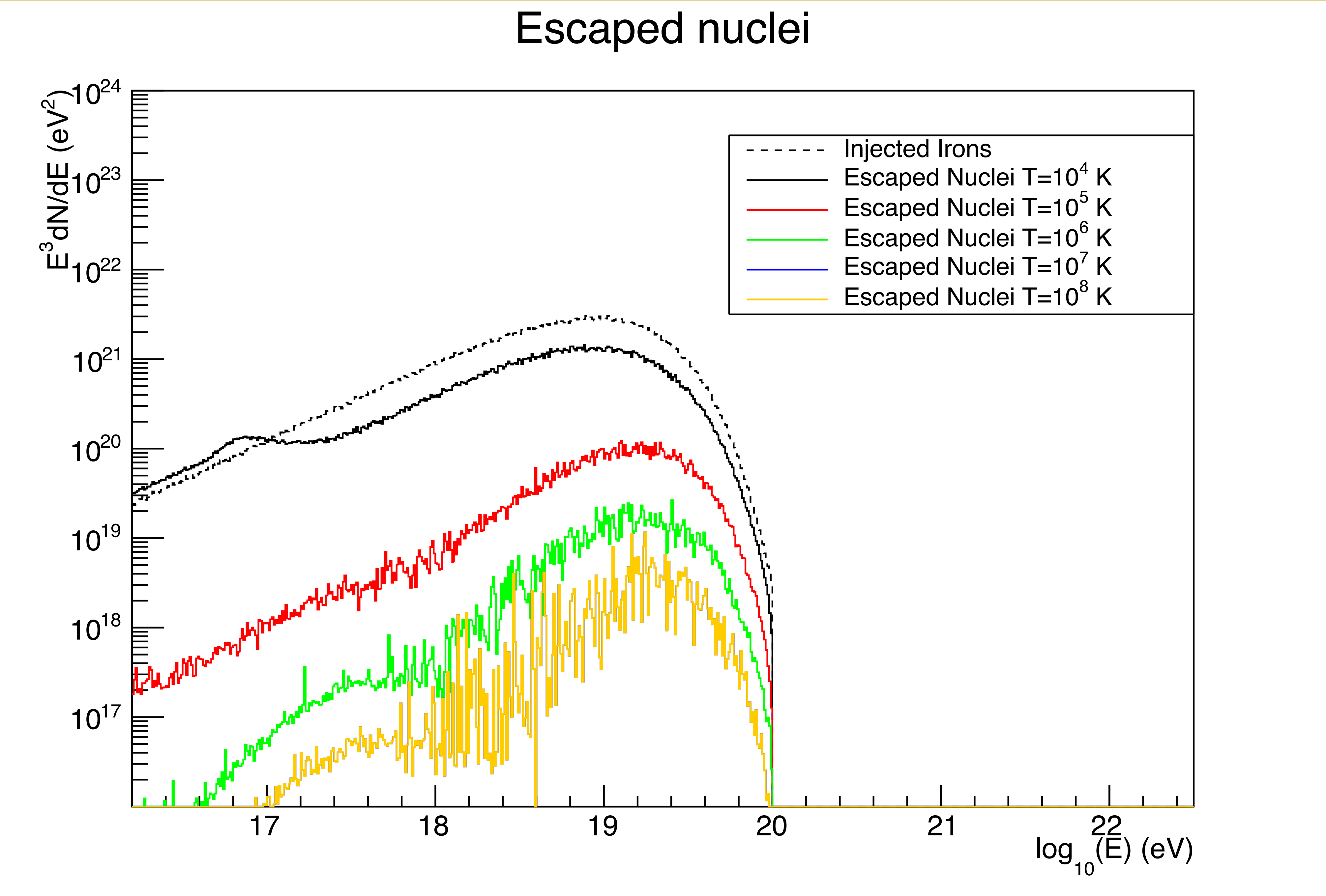


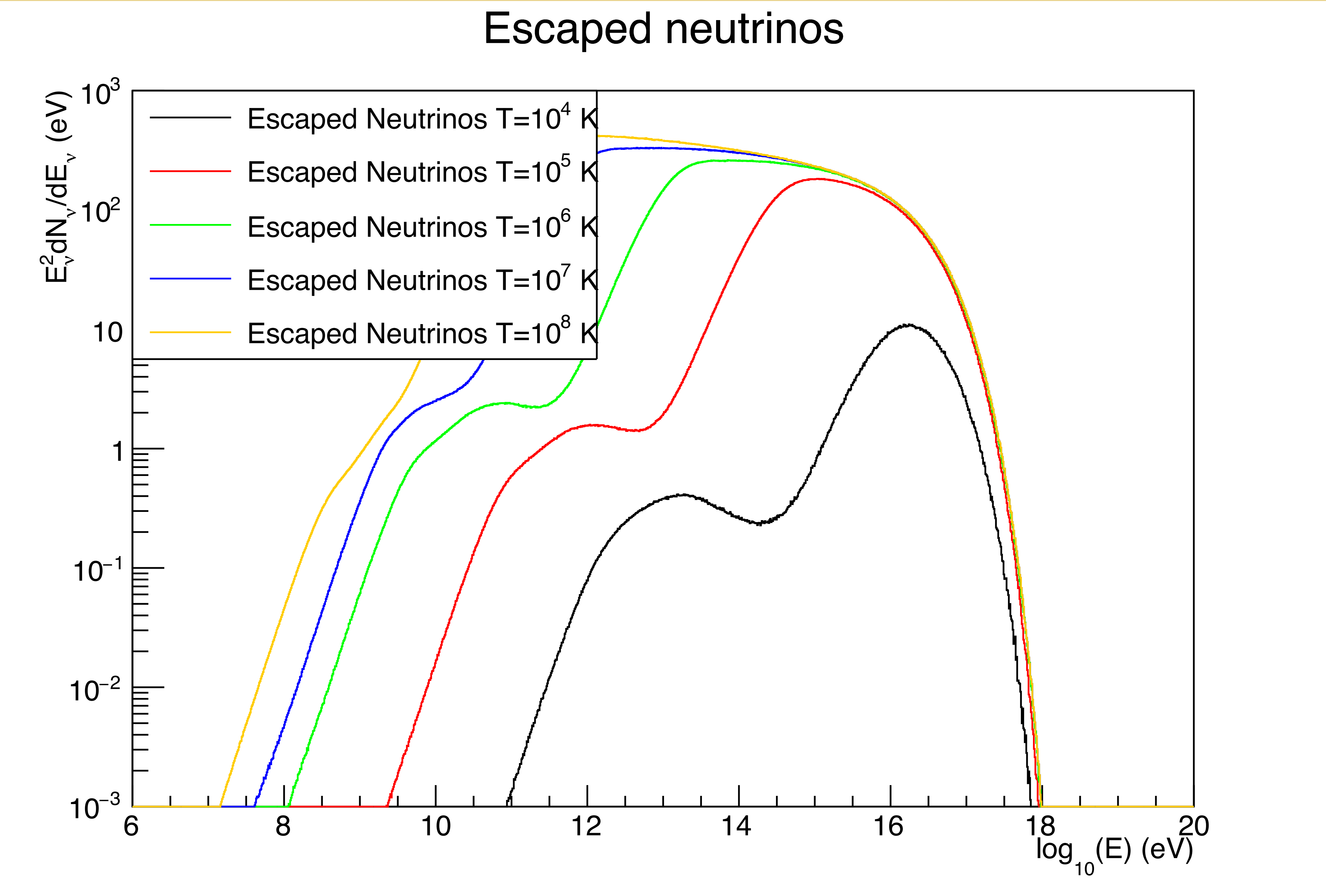


$$\gamma = 1.5 \quad , \quad R_{max} = 10^{19}\, V$$

PIERRE AUGER OBSERVATORY

Simulations of source interactions - Fe

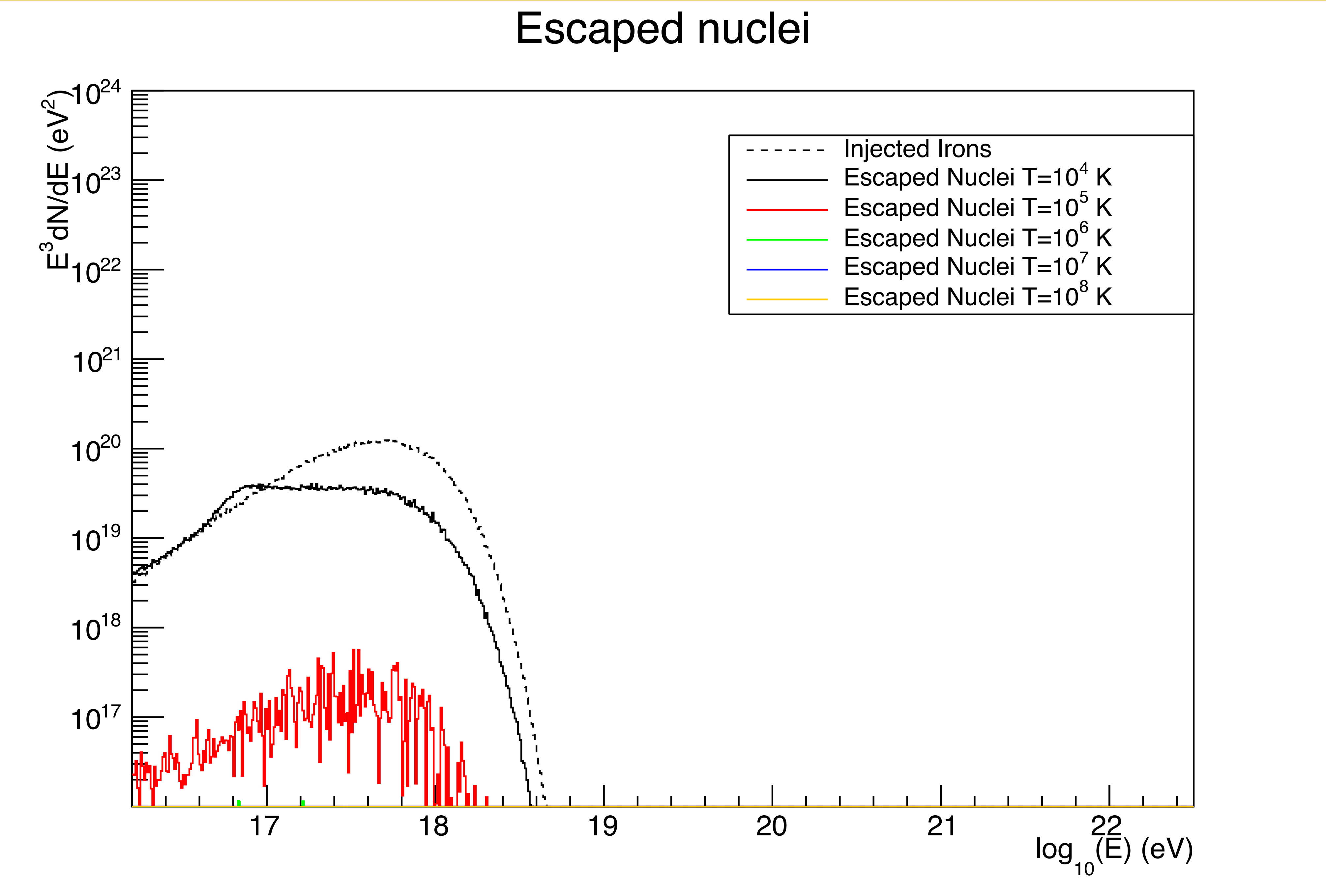


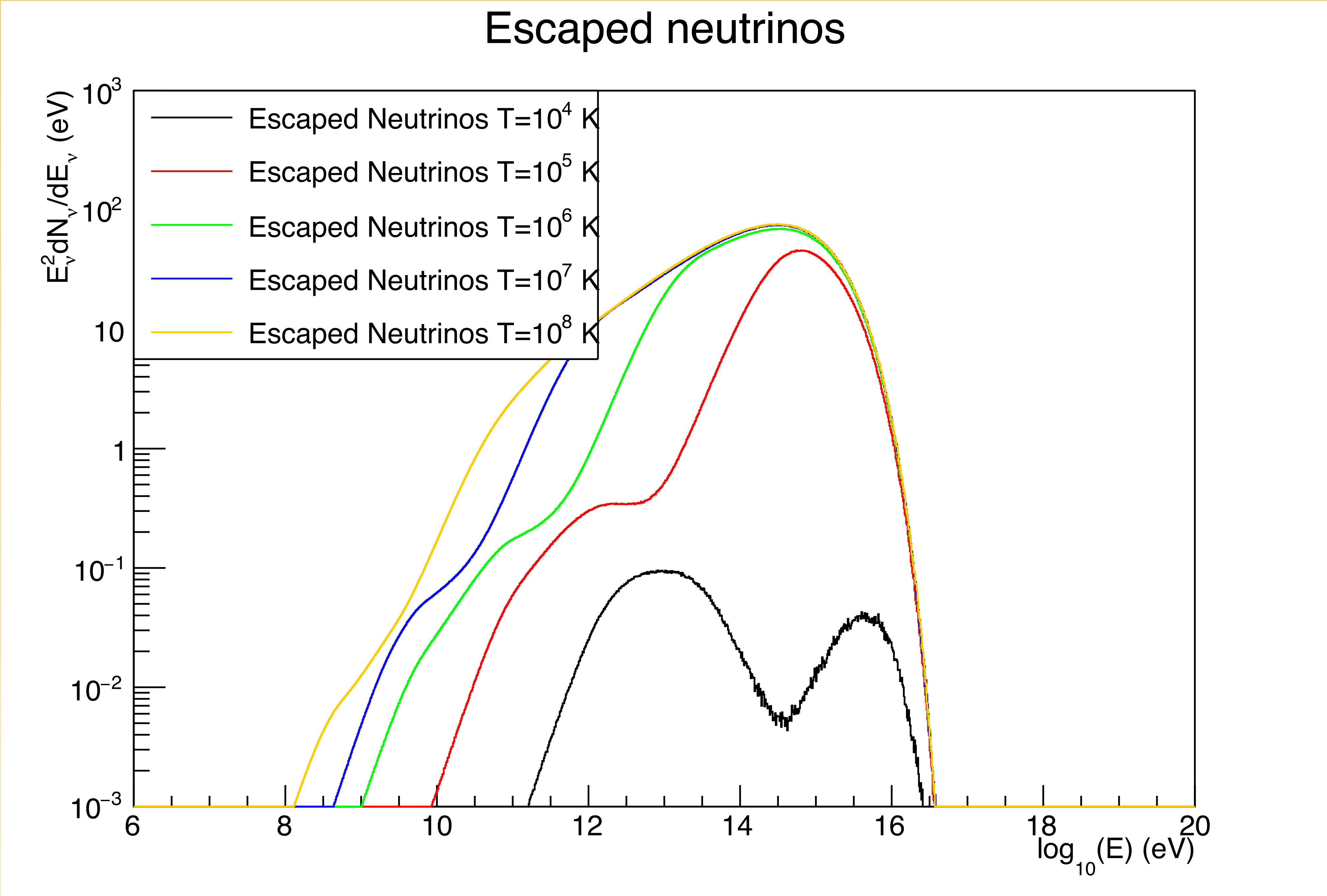


$$\gamma = 2.1 \quad , \quad R_{max} = 10^{19}\,V$$

PIERRE AUGER OBSERVATORY

Simulations of source interactions - Fe

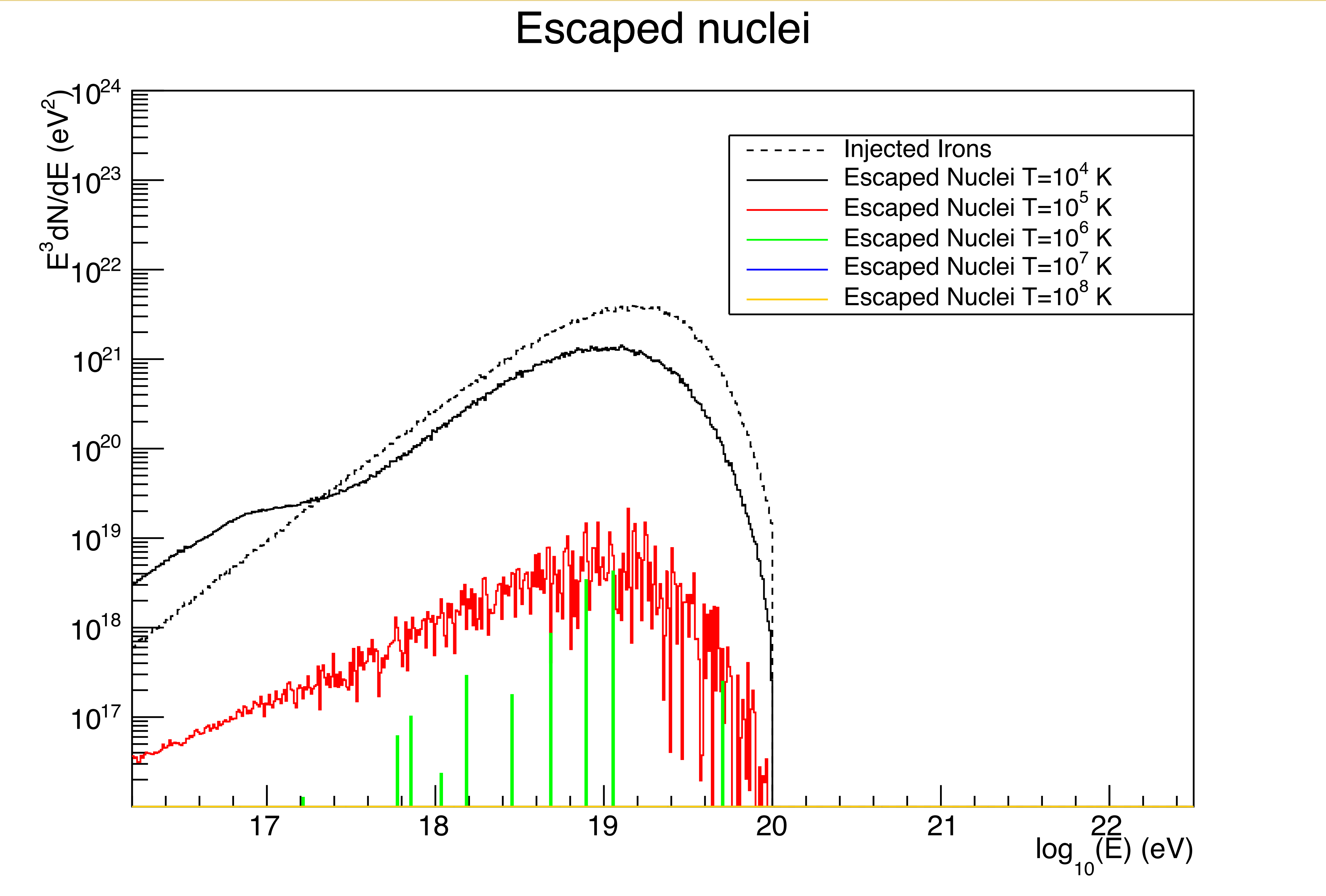


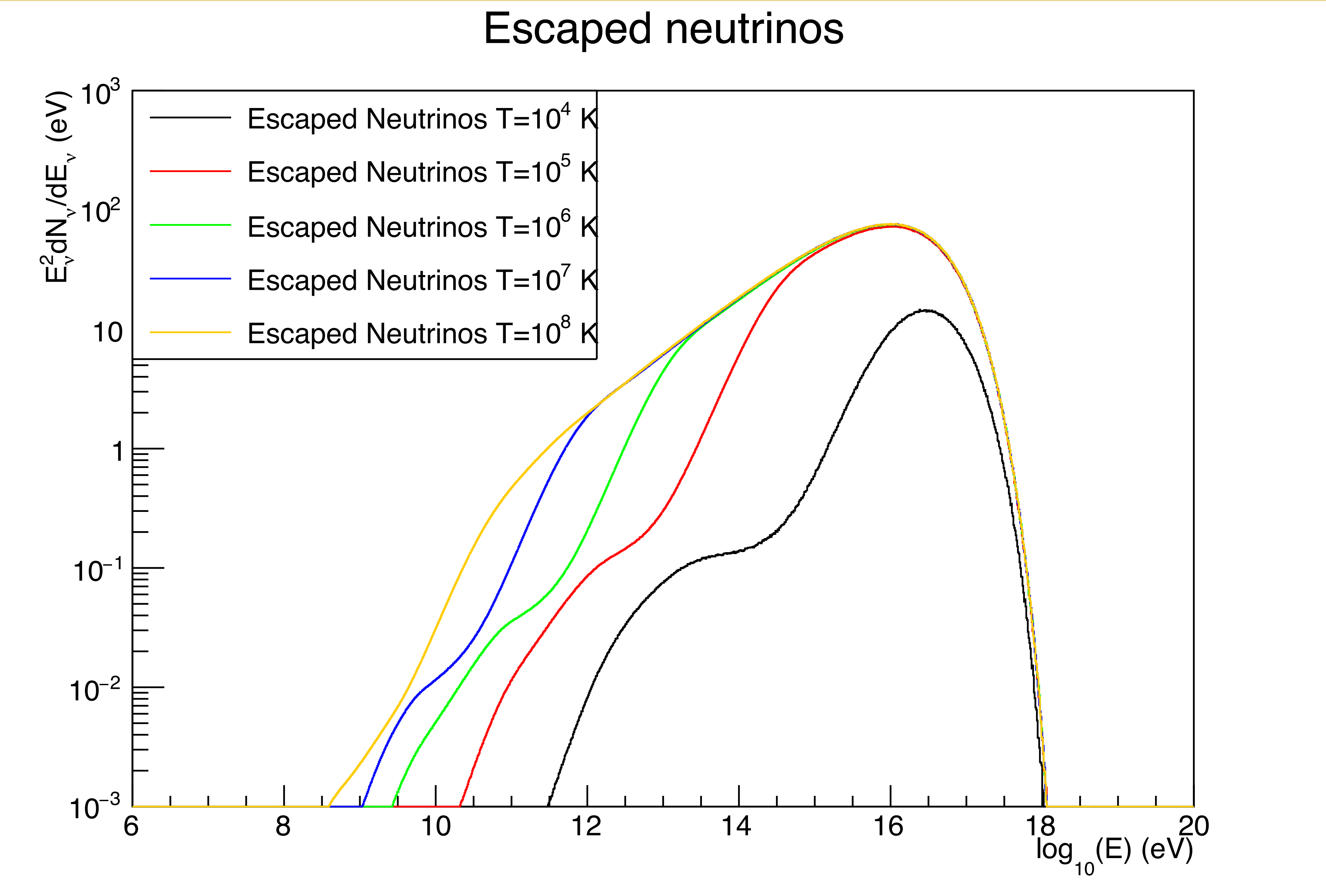


$$\gamma = 1.5 \quad , \quad R_{max} = 10^{17.5}\, V \quad , \quad Bis$$

PIERRE AUGER OBSERVATORY

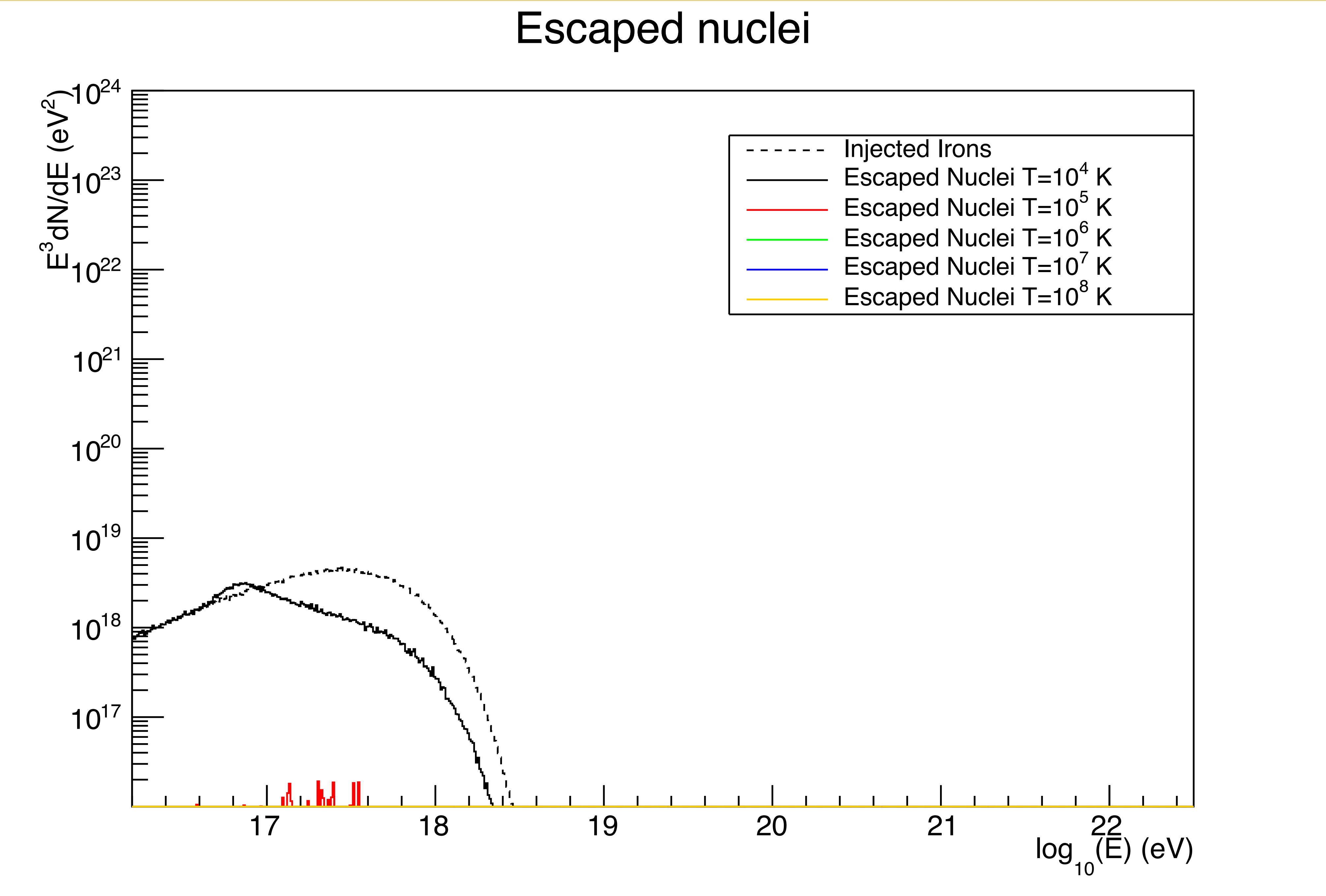
Simulations of source interactions - Fe

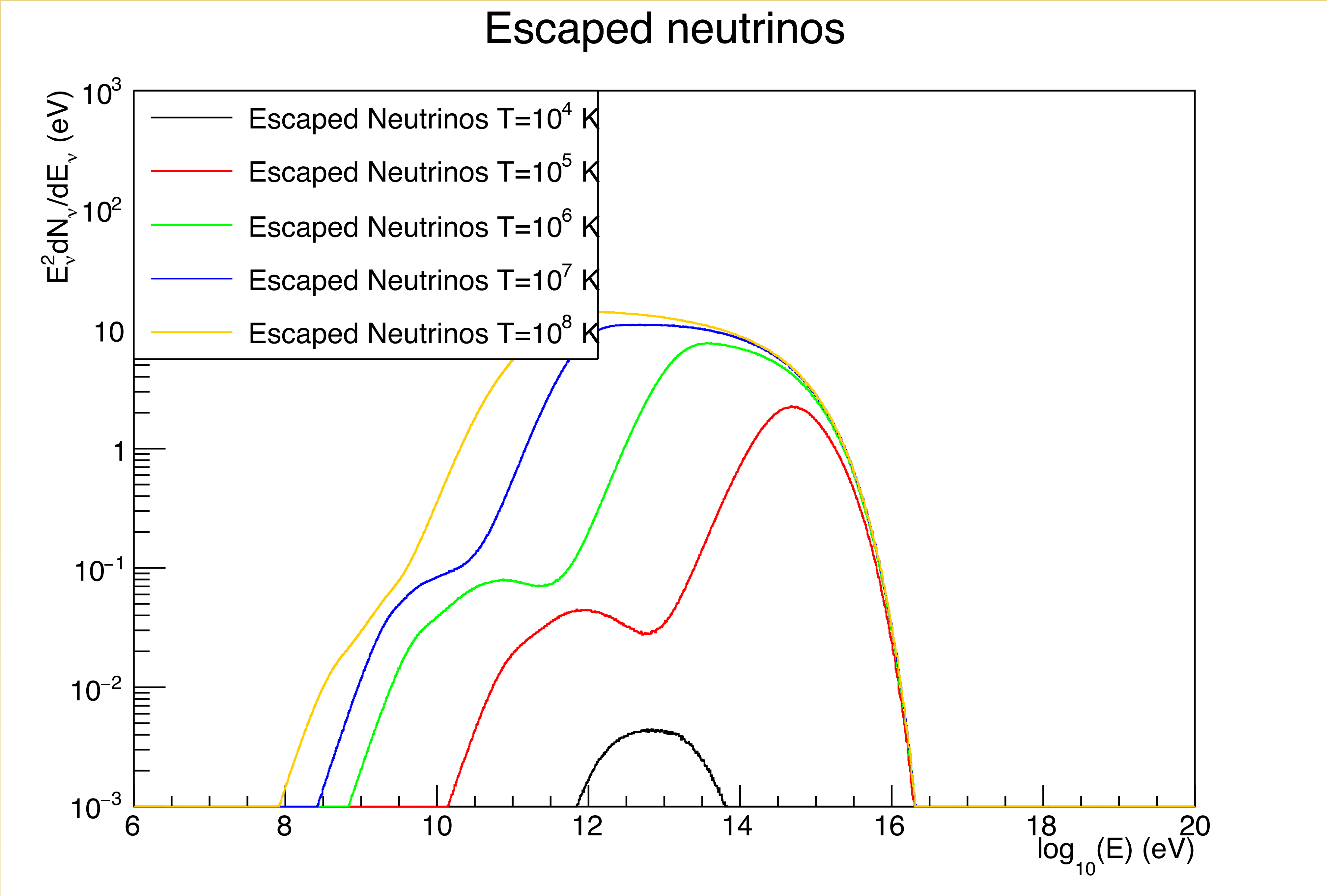




$$\gamma = 1.5 \quad , \quad R_{max} = 10^{19}\, V \quad , \quad Bis$$

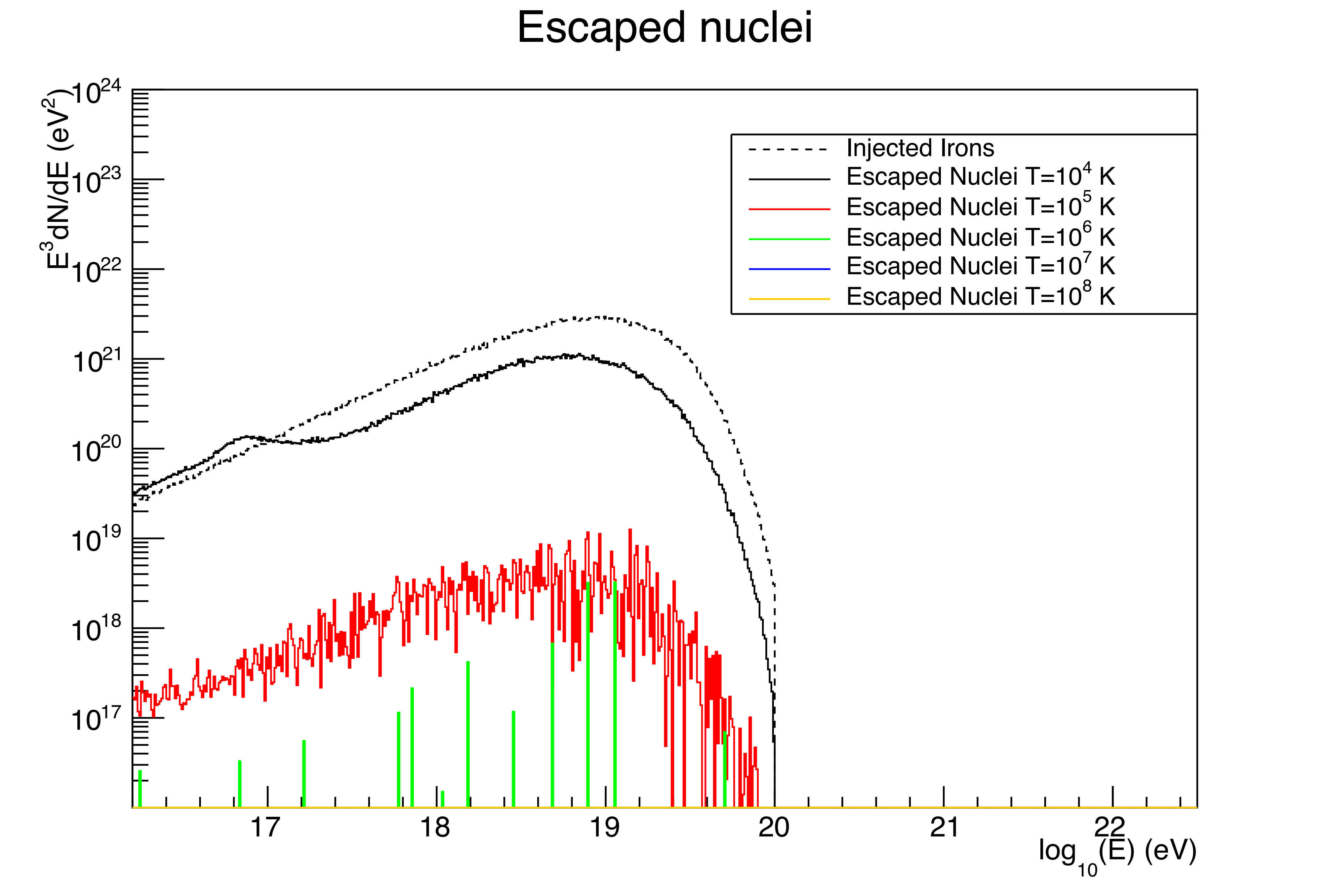
Simulations of source interactions - Fe

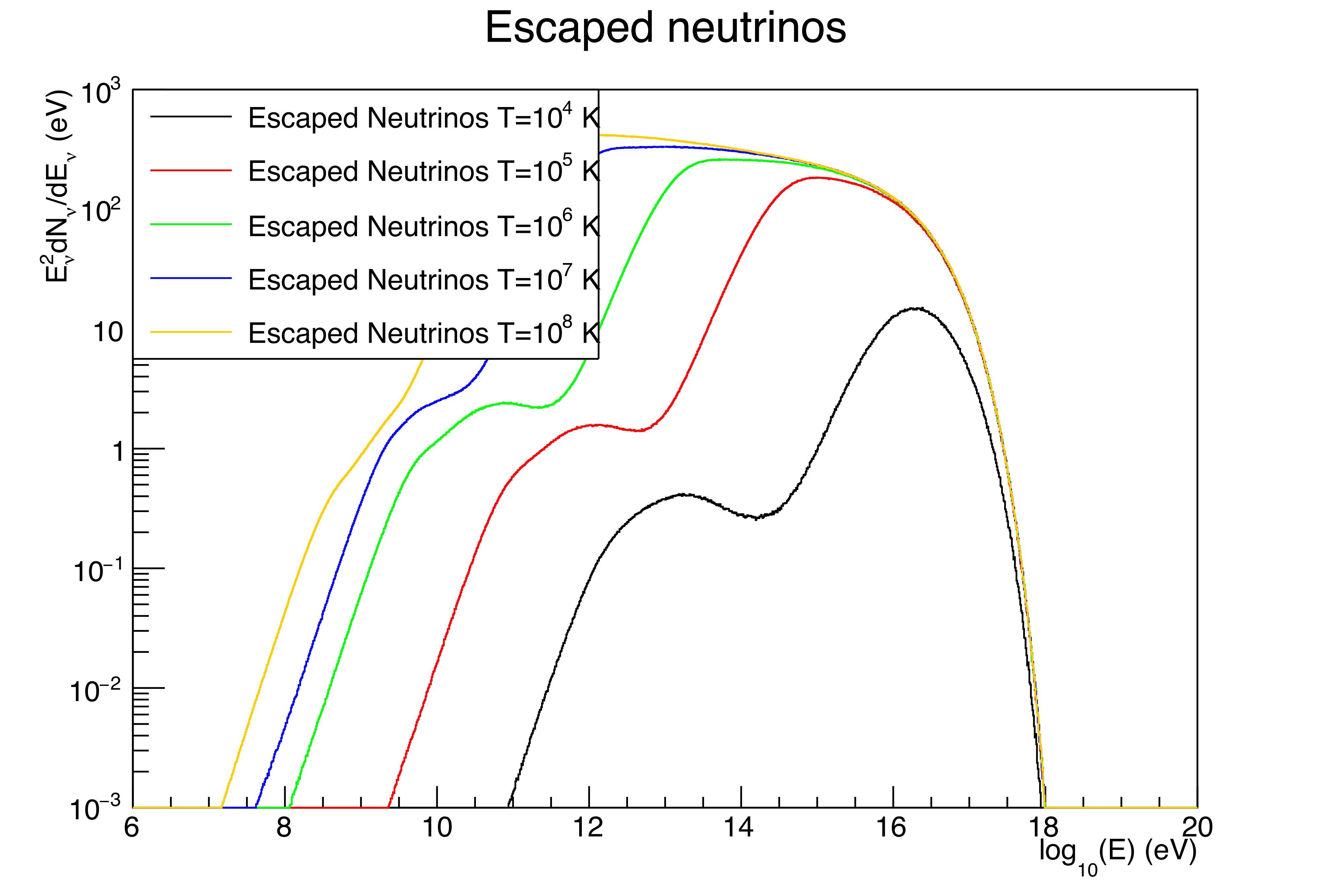




$$\gamma = 2.1 \quad , \quad R_{max} = 10^{17.5}\, V \quad , \quad Bis$$

Simulations of source interactions - Fe



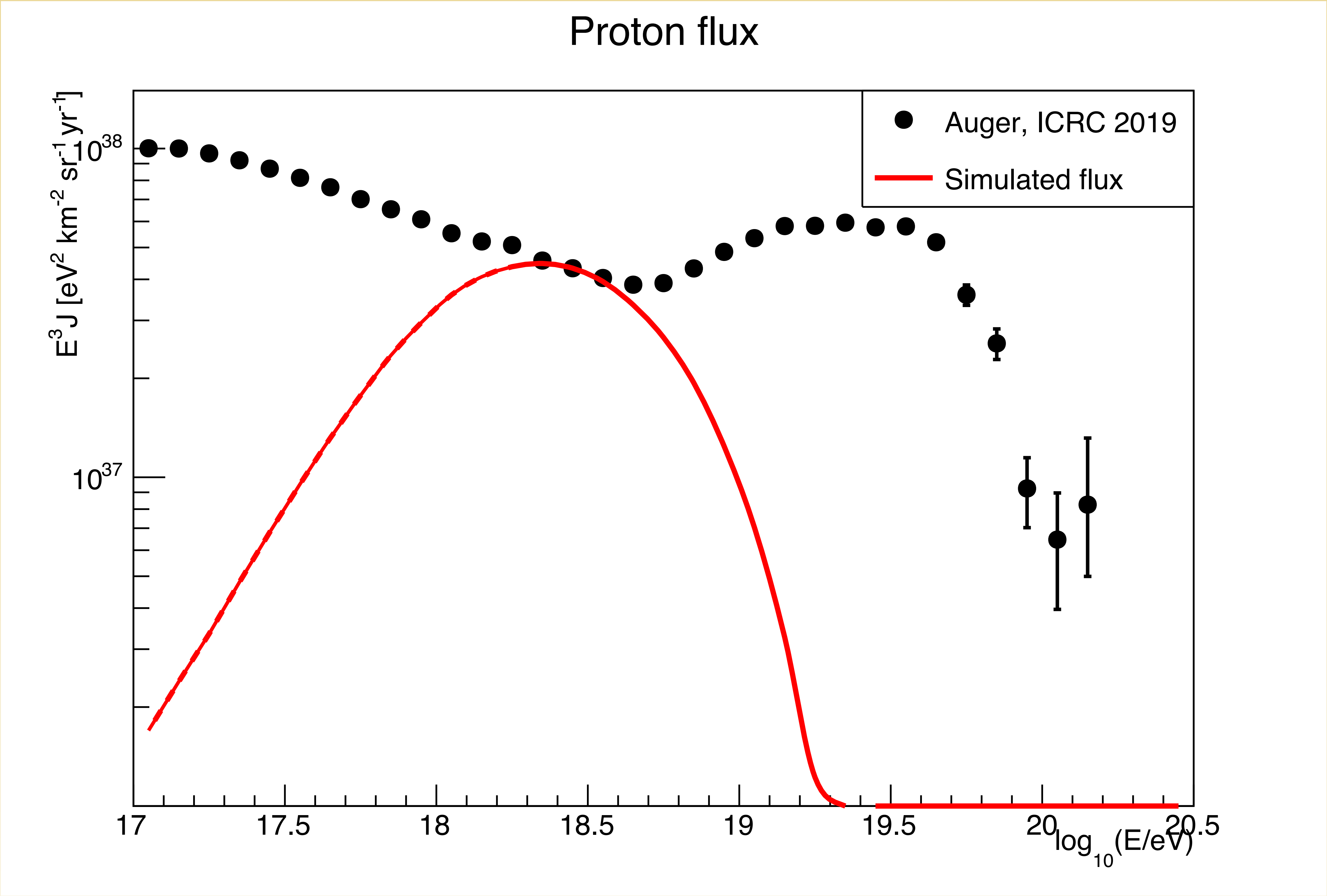


$$\gamma = 2.1 \quad , \quad R_{max} = 10^{19}\,V \quad , \quad Bis$$

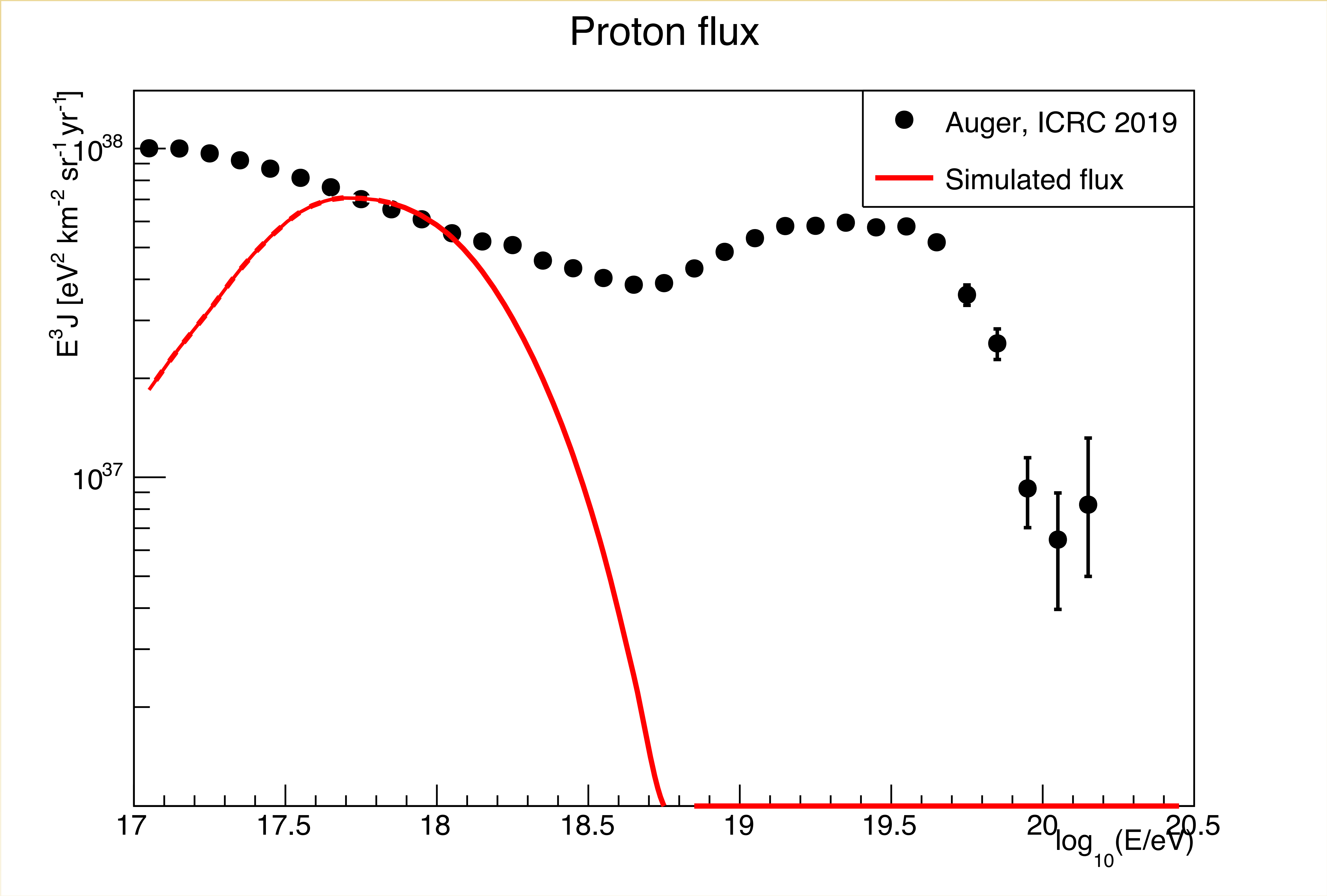
PIERRE AUGER OBSERVATORY

CR flux - p

$Protons \quad , \quad \gamma = 1.5 \quad , \quad R_{max} = 10^{18.5}\,V \quad , \quad m = 0 \quad , \quad GW170817-like$

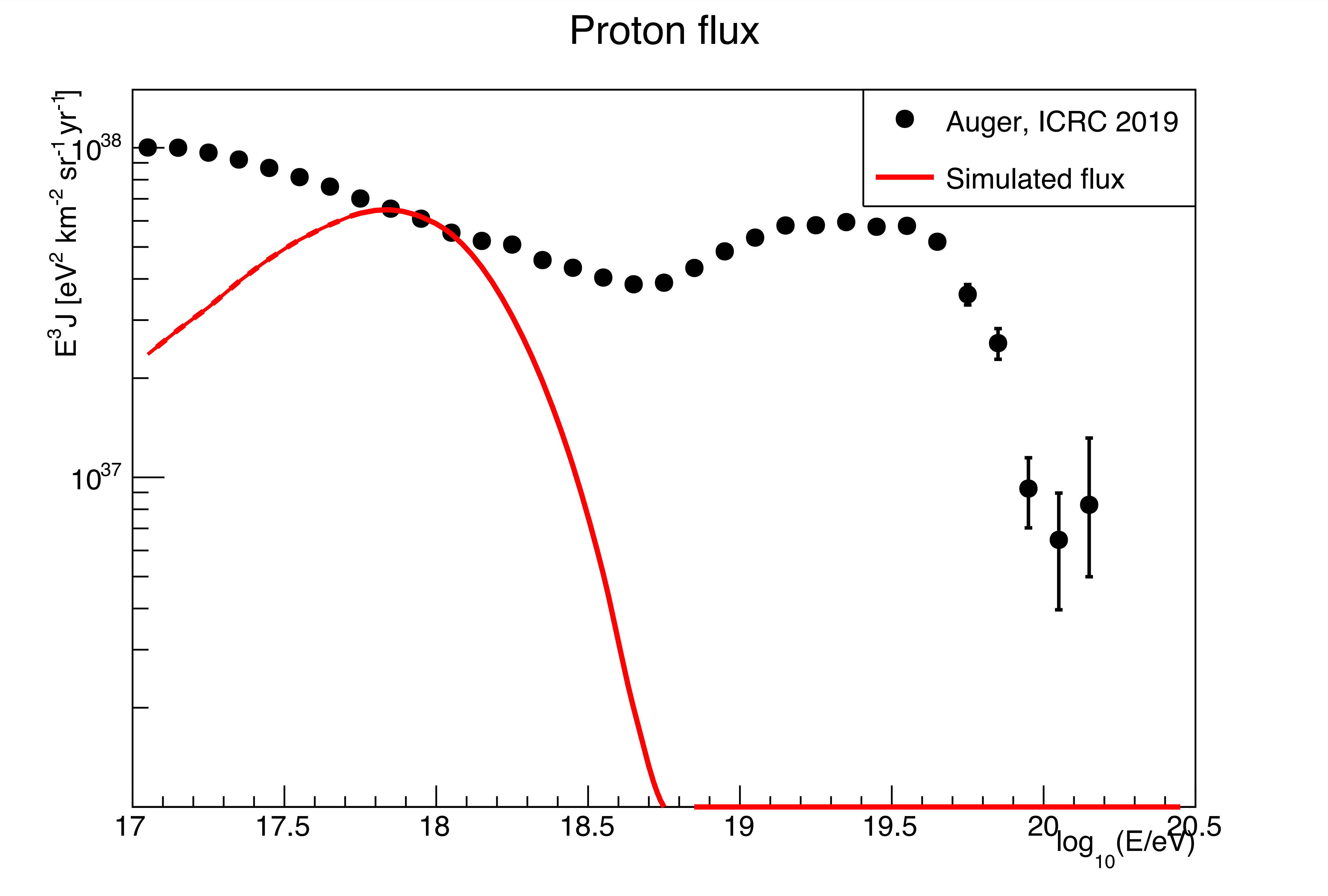


$Protons \quad , \quad \gamma = 1.5 \quad , \quad R_{max} = 10^{18}\,V \quad , \quad m = SFR \quad , \quad GW170817-like$

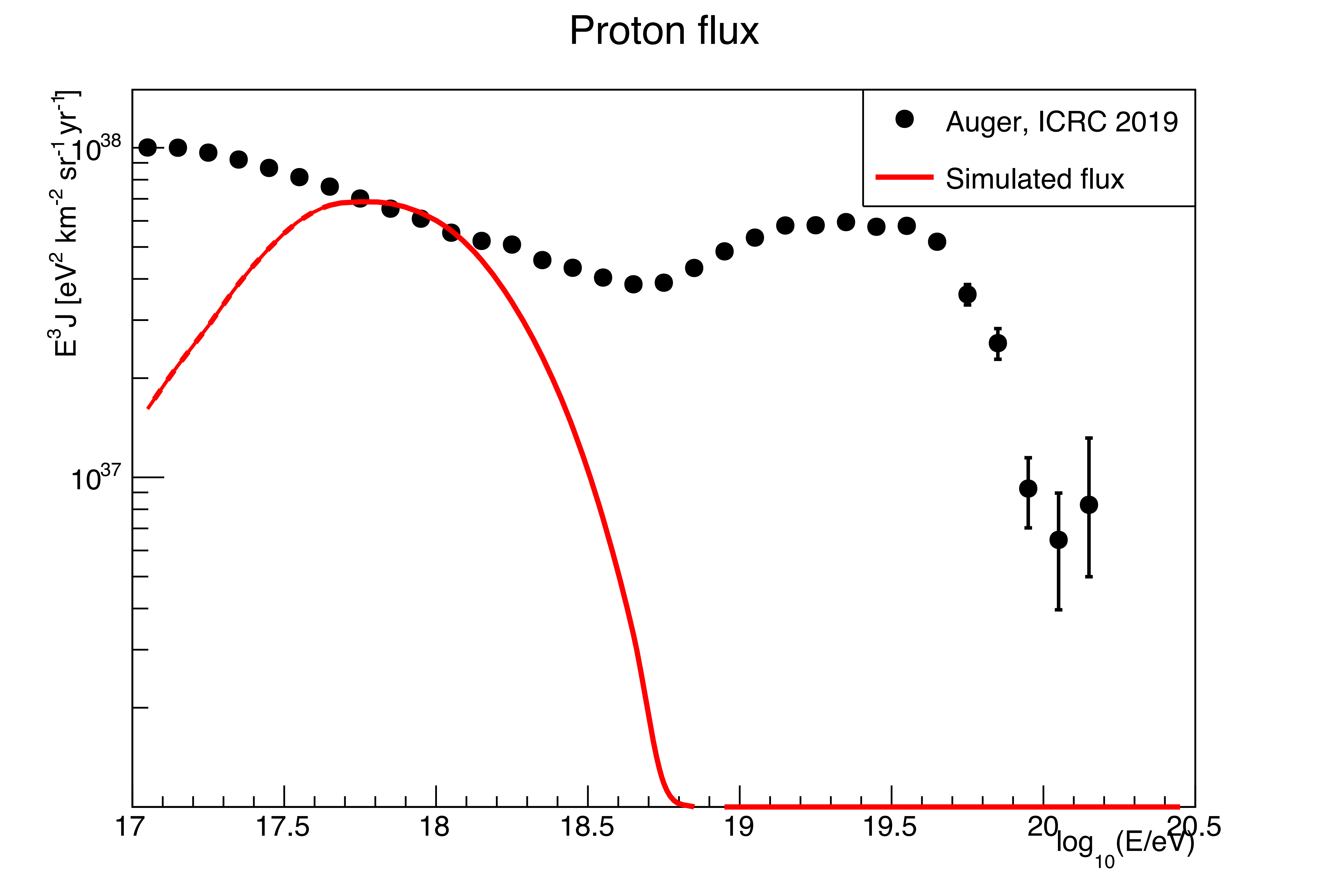


CR flux - p

$Protons \quad , \quad \gamma = 2.1 \quad , \quad R_{max} = 10^{18}\,V \quad , \quad m = 0 \quad , \quad GW170817-like$



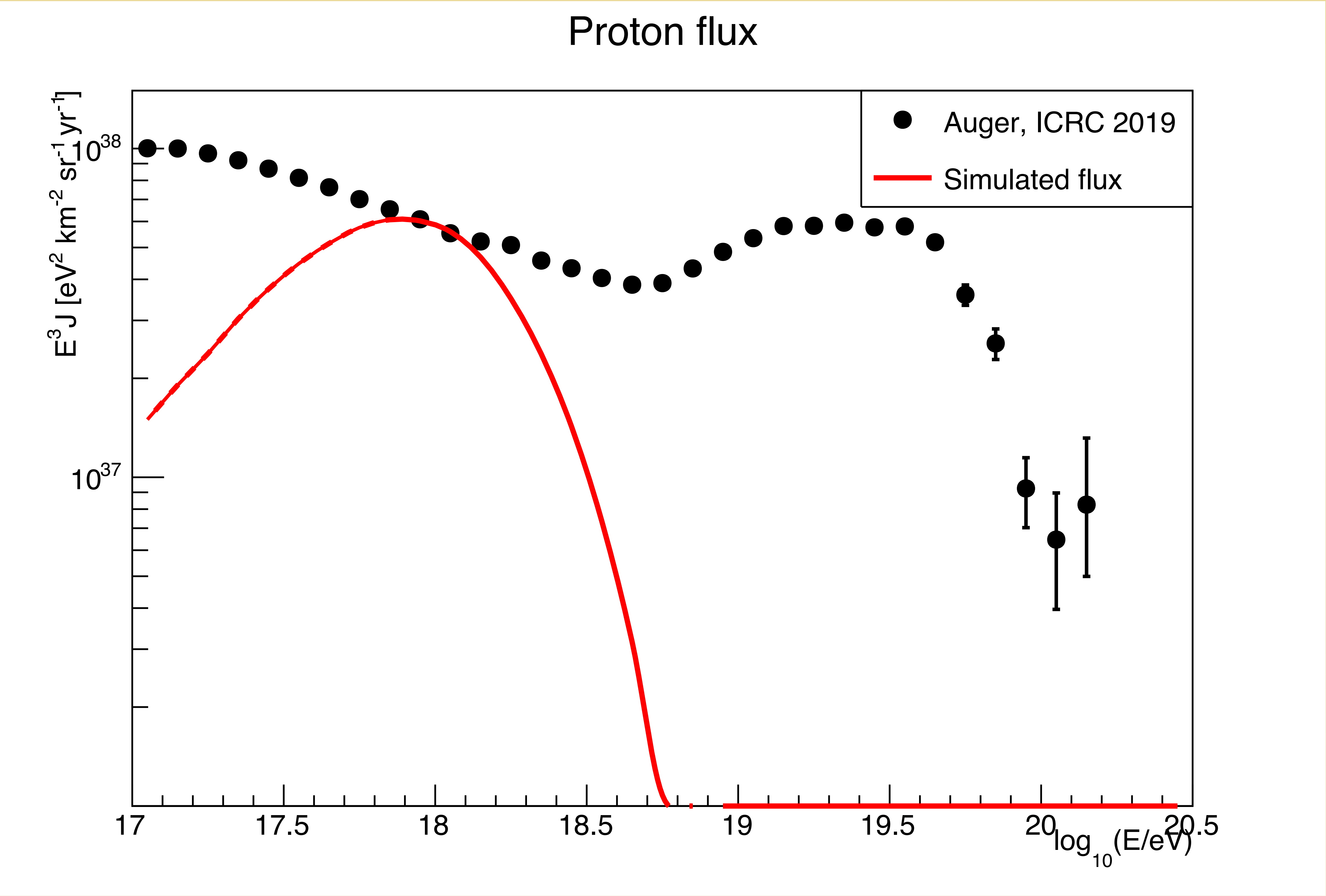
$Protons \quad , \quad \gamma = 1.5 \quad , \quad R_{max} = 10^{18}\,V \quad , \quad m = SFR \quad , \quad Optimistic$

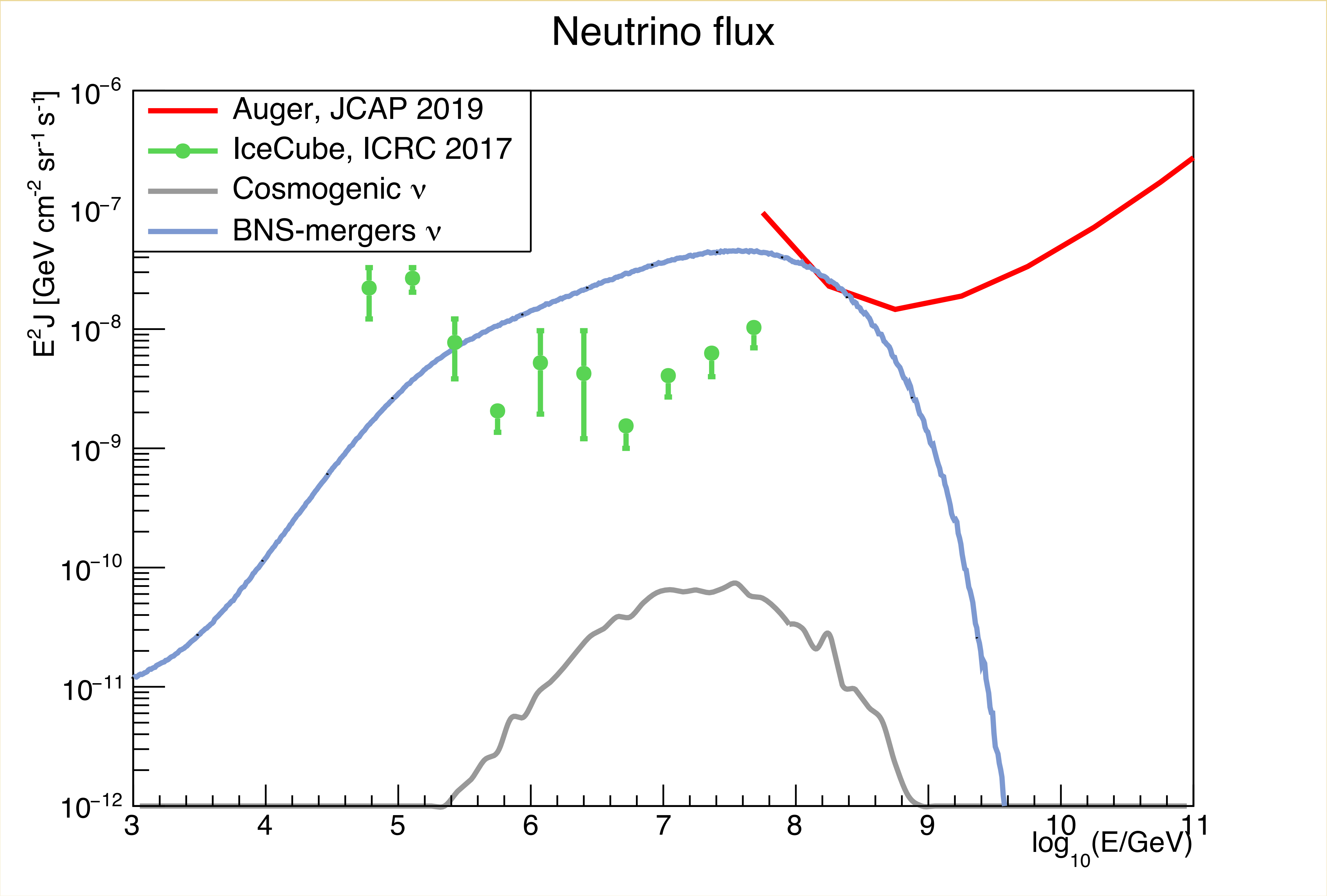


PIERRE AUGER OBSERVATORY

CR and neutrino flux - p

$$Protons \quad , \quad \gamma = 1.5 \quad , \quad R_{max} = 10^{18}\,V \quad , \quad m = 0 \quad , \quad GW170817-like \quad , \quad \sigma = constant$$





CR and neutrino flux - Fe

$$Irons \quad , \quad \gamma = 1.5 \quad , \quad R_{max} = 10^{18}\, V \quad , \quad m = 0 \quad , \quad GW170817 - like$$