From extragalactic to in-source simulations: SimProp for studying binary-neutron-starmergers as production sites of high-energy neutrinos

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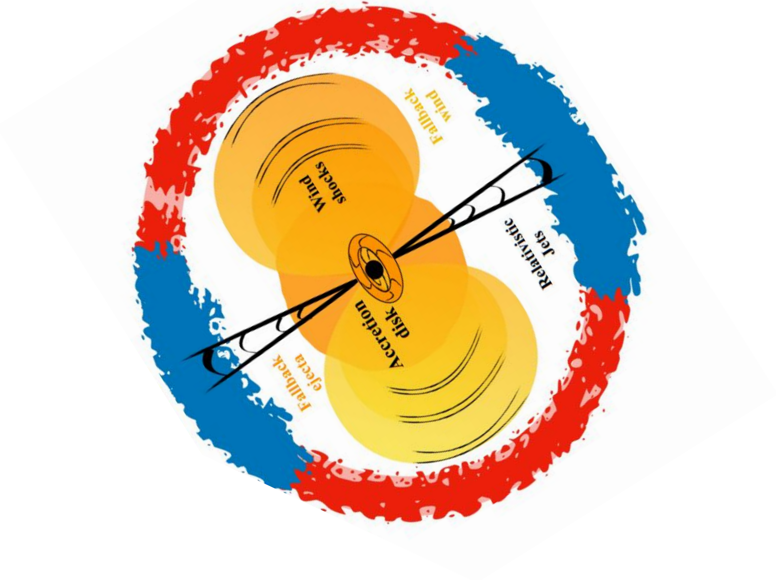
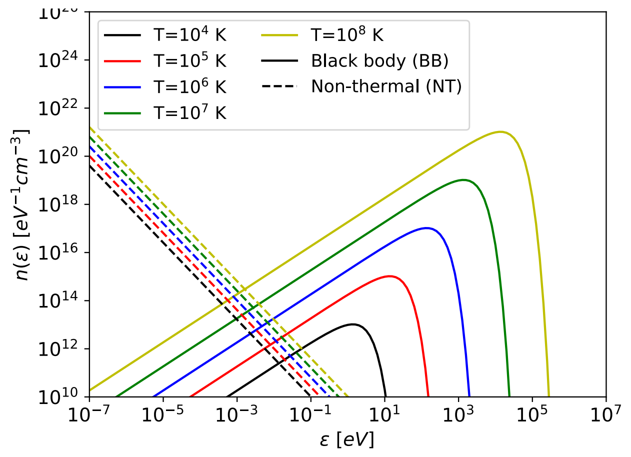
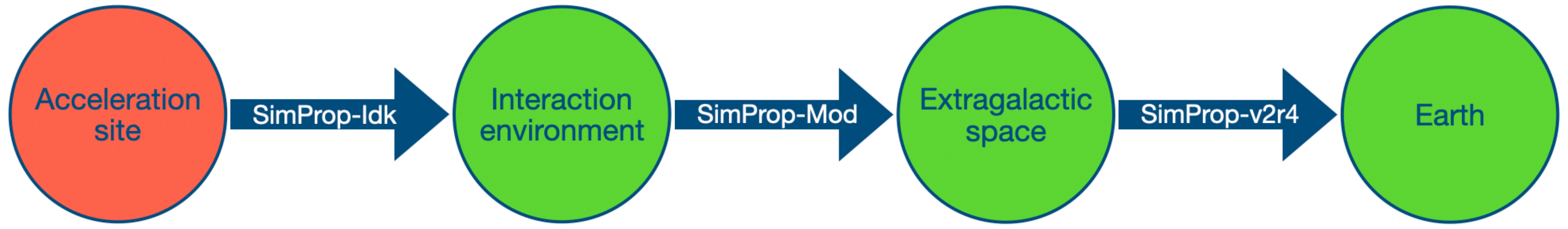
Outlook

- BNS-merger environment

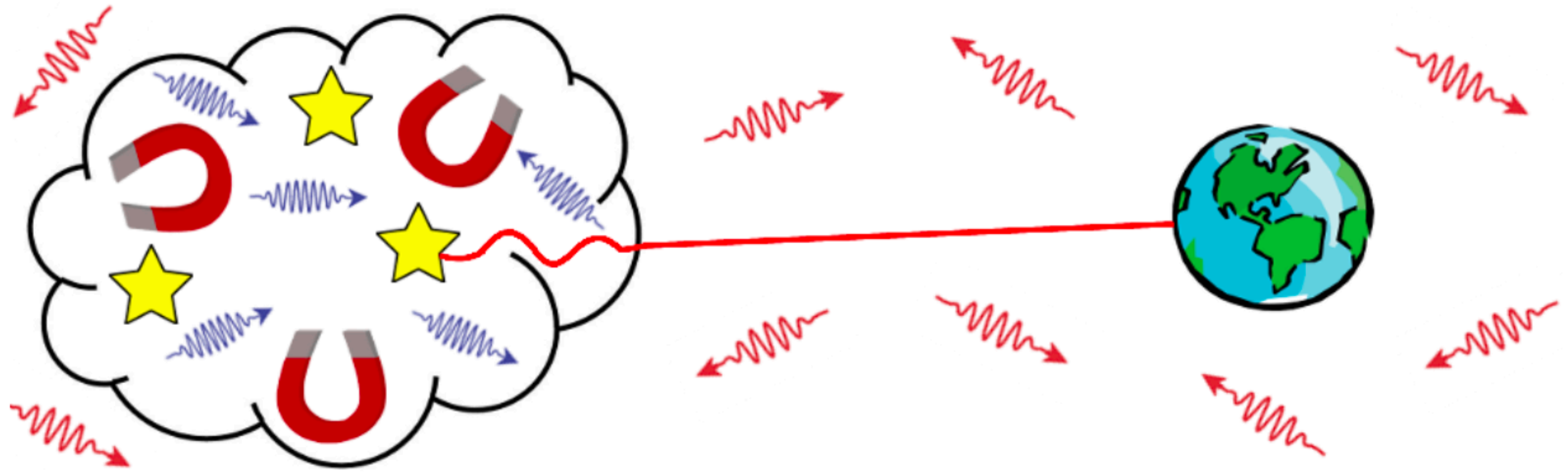




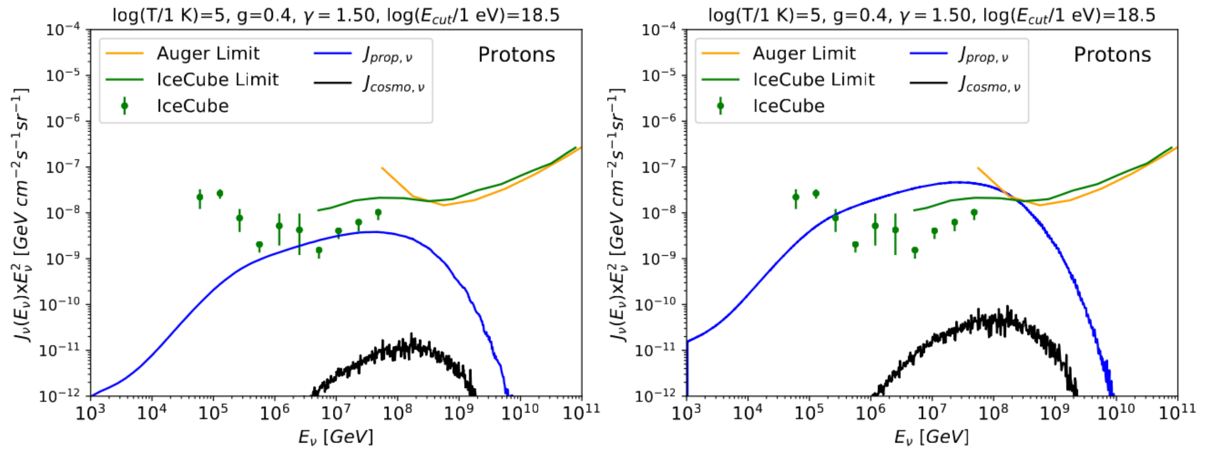
- SimProp *in-source*

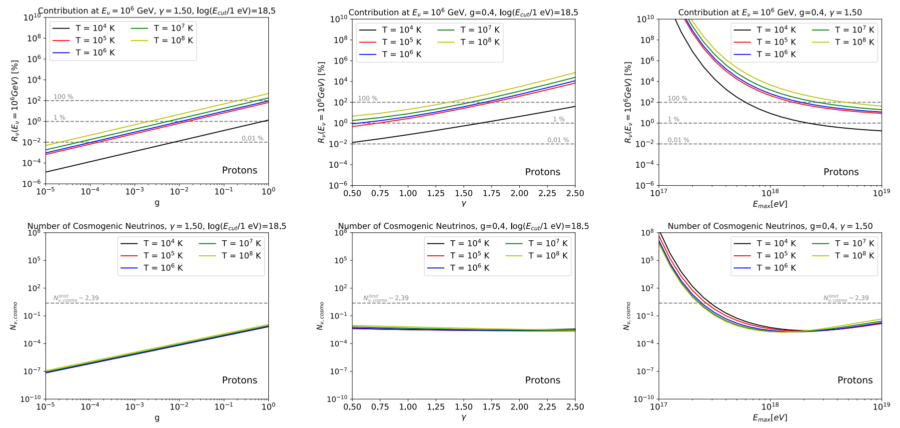


- Simulations and analysis setup

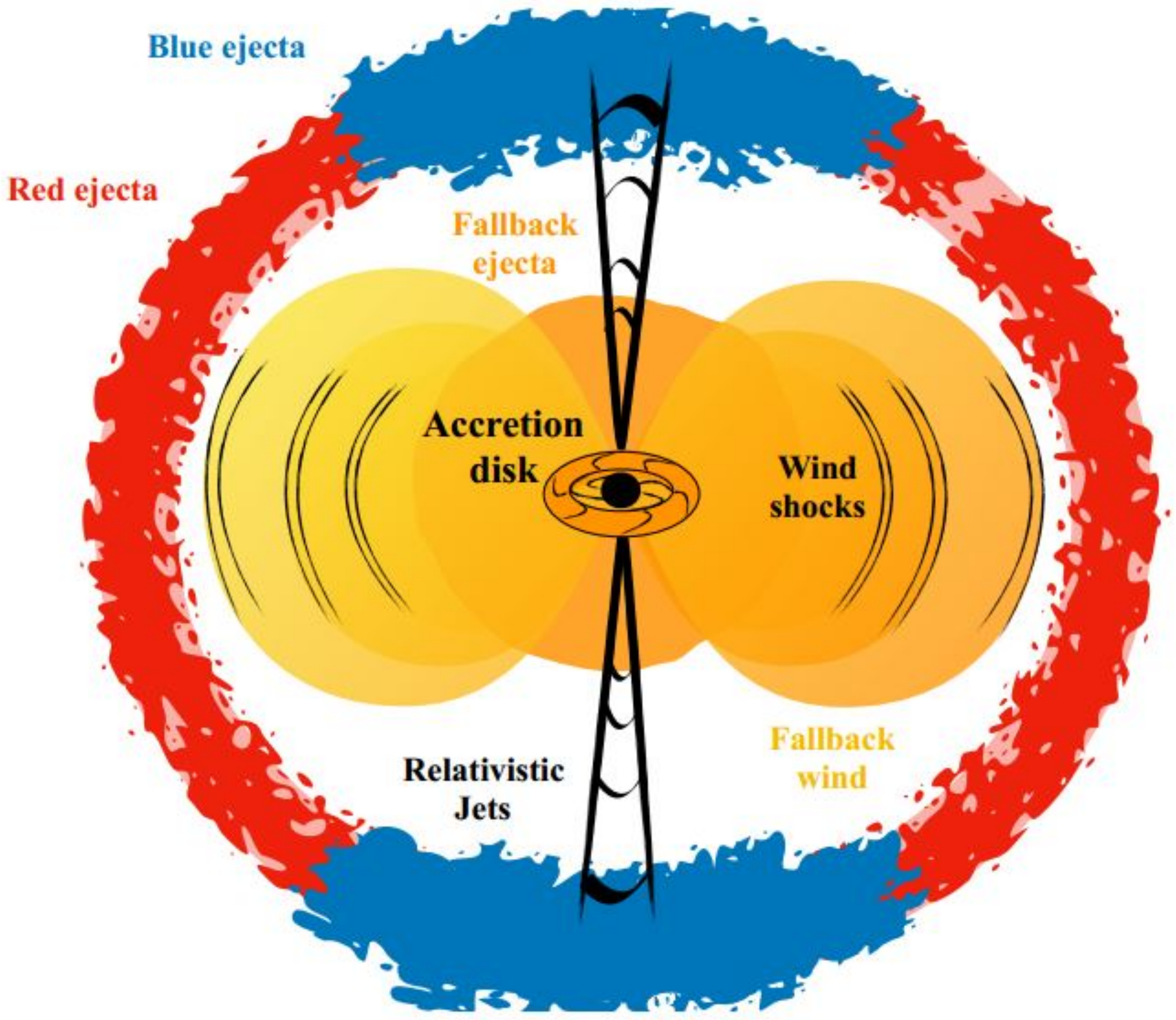


- Results





BNS-merger environment



V. Deconne et al, JCAP (2020)

- The probable end state of binary-neutron-star (BNS) mergers is a black hole (BH) with a relativistic jet.
- The formation of the jet gives rise to a short gamma-ray burst (GRB), which represents a site for the production of high-energy neutrinos.
- Part of the fallback outflow encounters the earlier ejected mass shell producing a shock-wave.

$$E_{max} \simeq 1.2 \cdot 10^{17} \left(\frac{A}{Z}\right)^{3/2} \left(\frac{t}{10^3\, s}\right)^{5/12} eV$$

- A thermal photon field is produced in the source environment by the nuclear decay of the unstable species synthesized in the ejecta by the merger.
- The photon emission can be modelled as a black-body photon field.
- Non-thermal component, mainly due to synchrotron emission.

BNS-merger environment

SEDs

$$n_{BB}(\epsilon) = \frac{1}{\pi^2(\hbar c)^3}\frac{\epsilon^2}{\exp(\epsilon/k_B T) - 1} \Rightarrow \rho_{BB} = 20\left(\frac{T}{1\,K}\right)^3 cm^{-3}$$

V. Deconne et al, JCAP (2020)

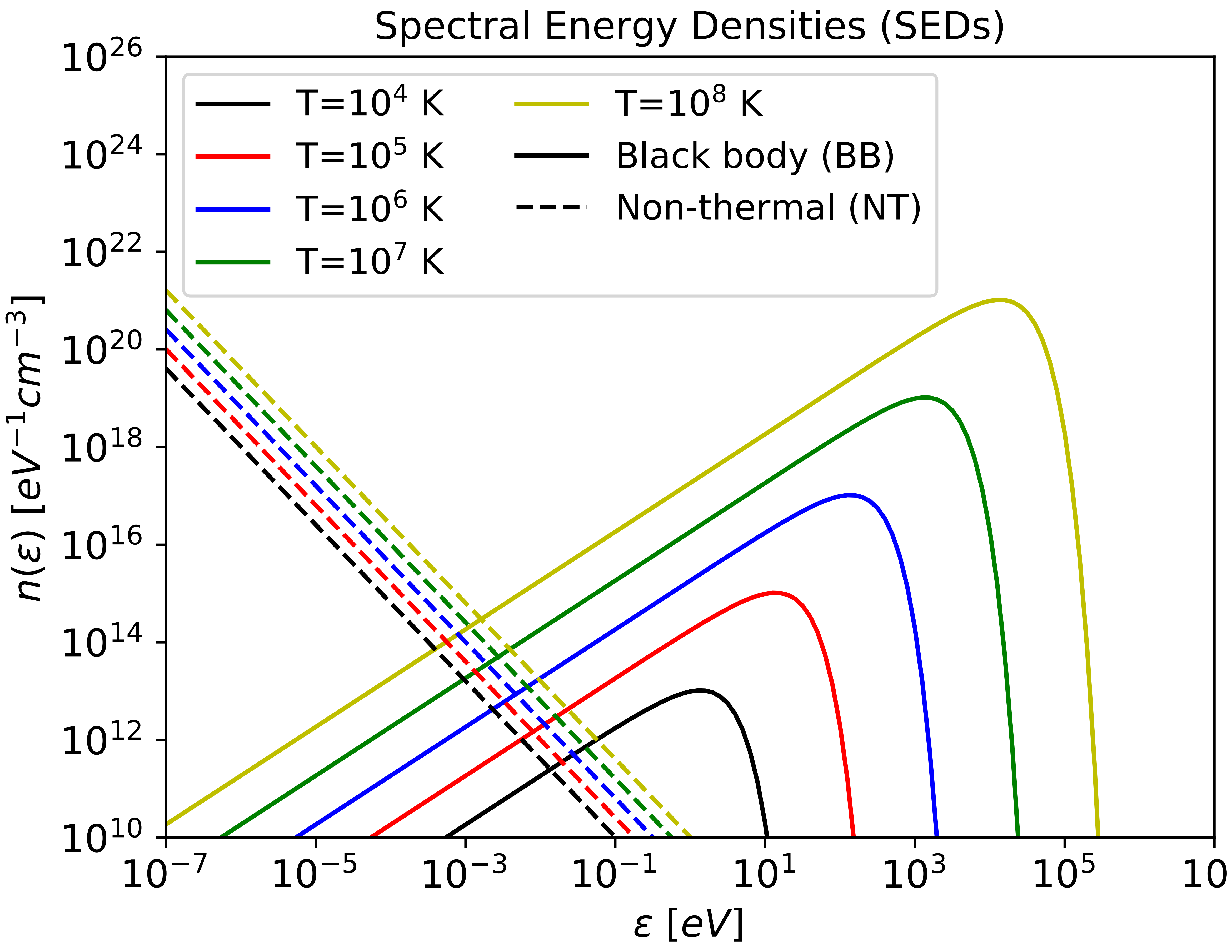
$$n_{NT}(\epsilon) = \left(1.2 \cdot 10^{42} eV^{-1} cm^{-3}\right)\left(\frac{V}{1\,cm^3}\right)^{-1}\left(\frac{t}{1\,s}\right)^{2.2}\left(\frac{\epsilon}{1\,eV}\right)^{-1.6}$$

R. Margutti et al, ApJL (2018)

Time-temperature

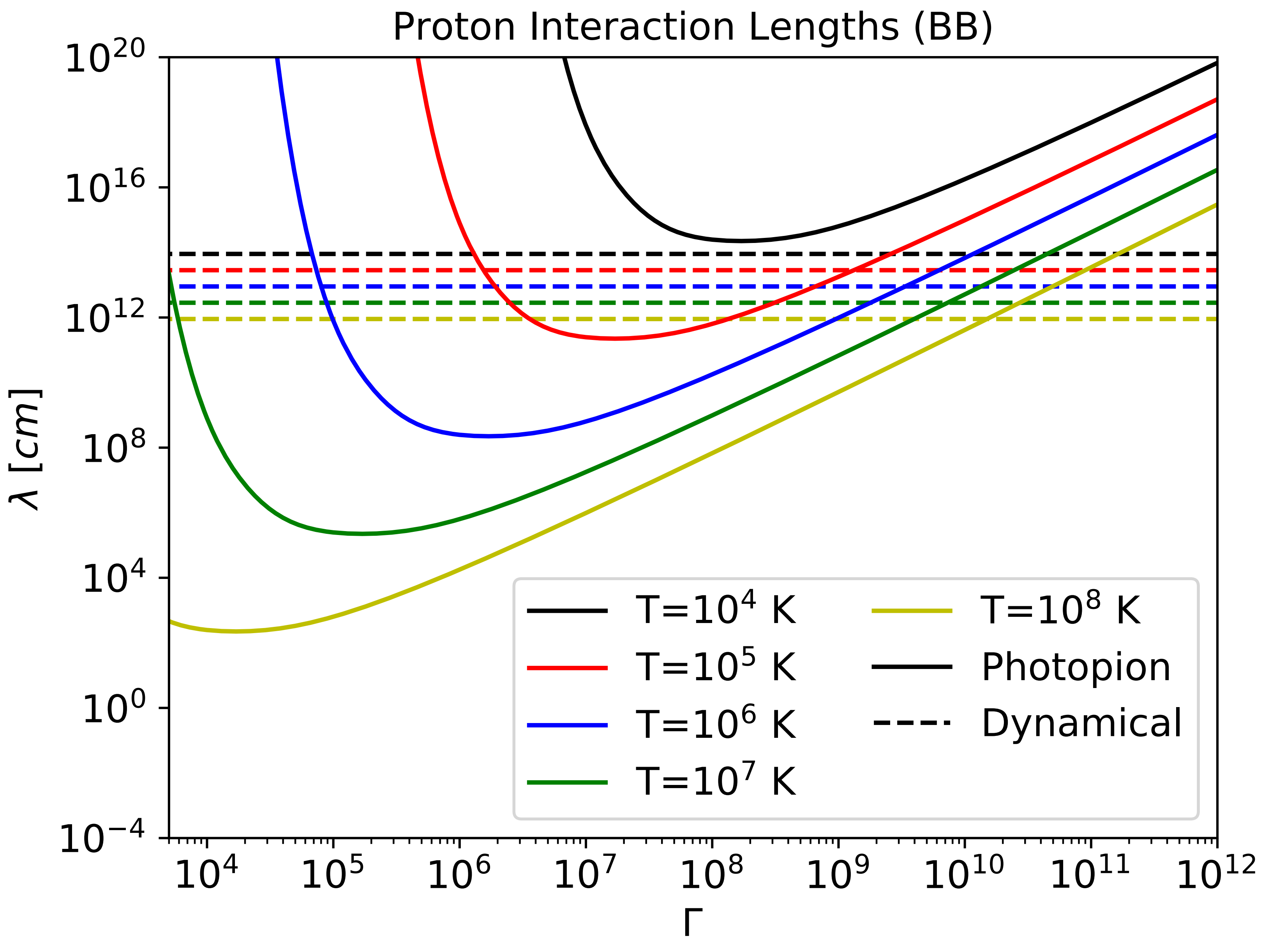
$$\log\left(\frac{t}{1\,s}\right) \simeq -\frac{1}{2}\log\left(\frac{T}{1\,K}\right) + 6$$

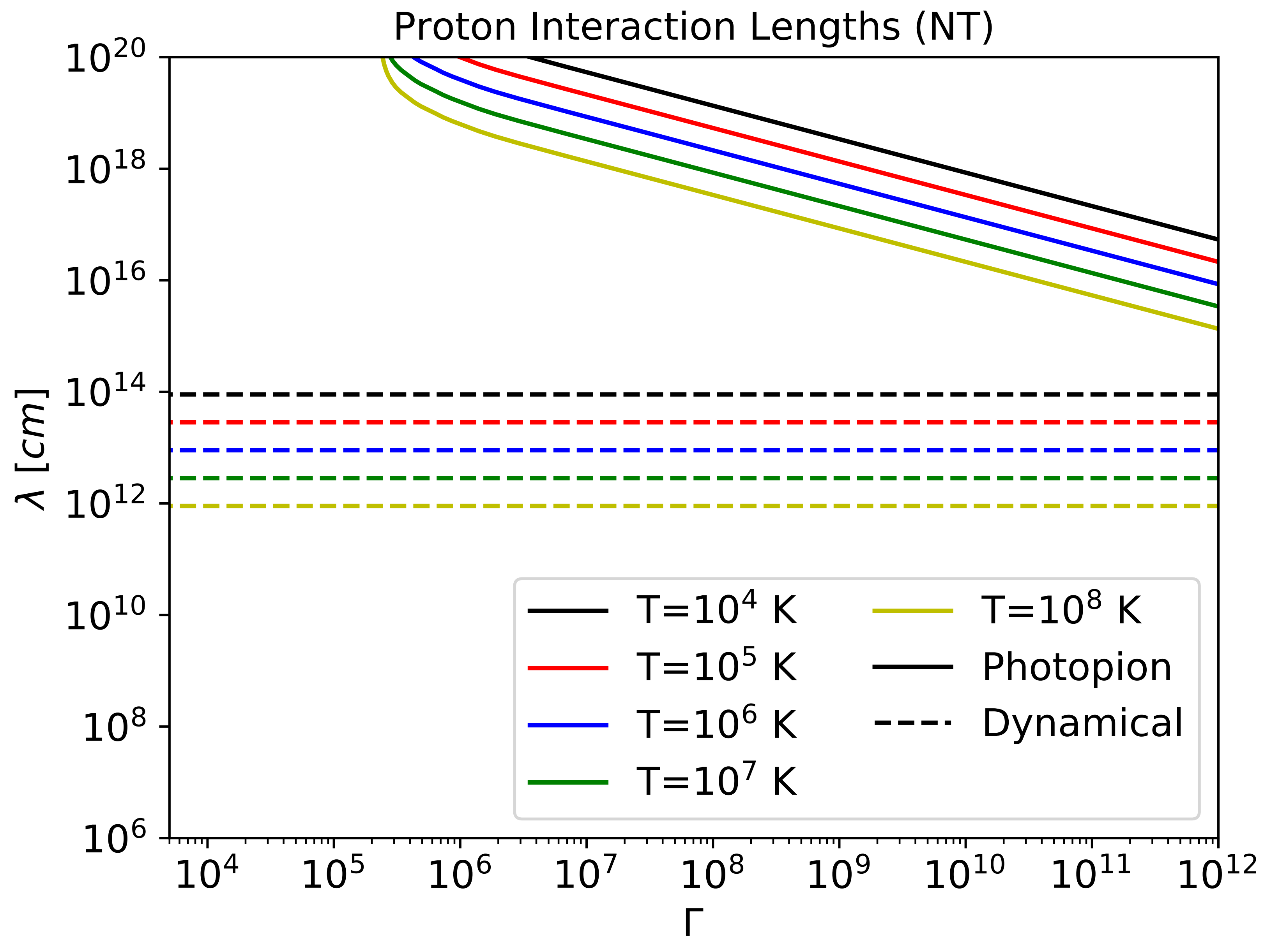
V. Deconne et al, JCAP (2020)

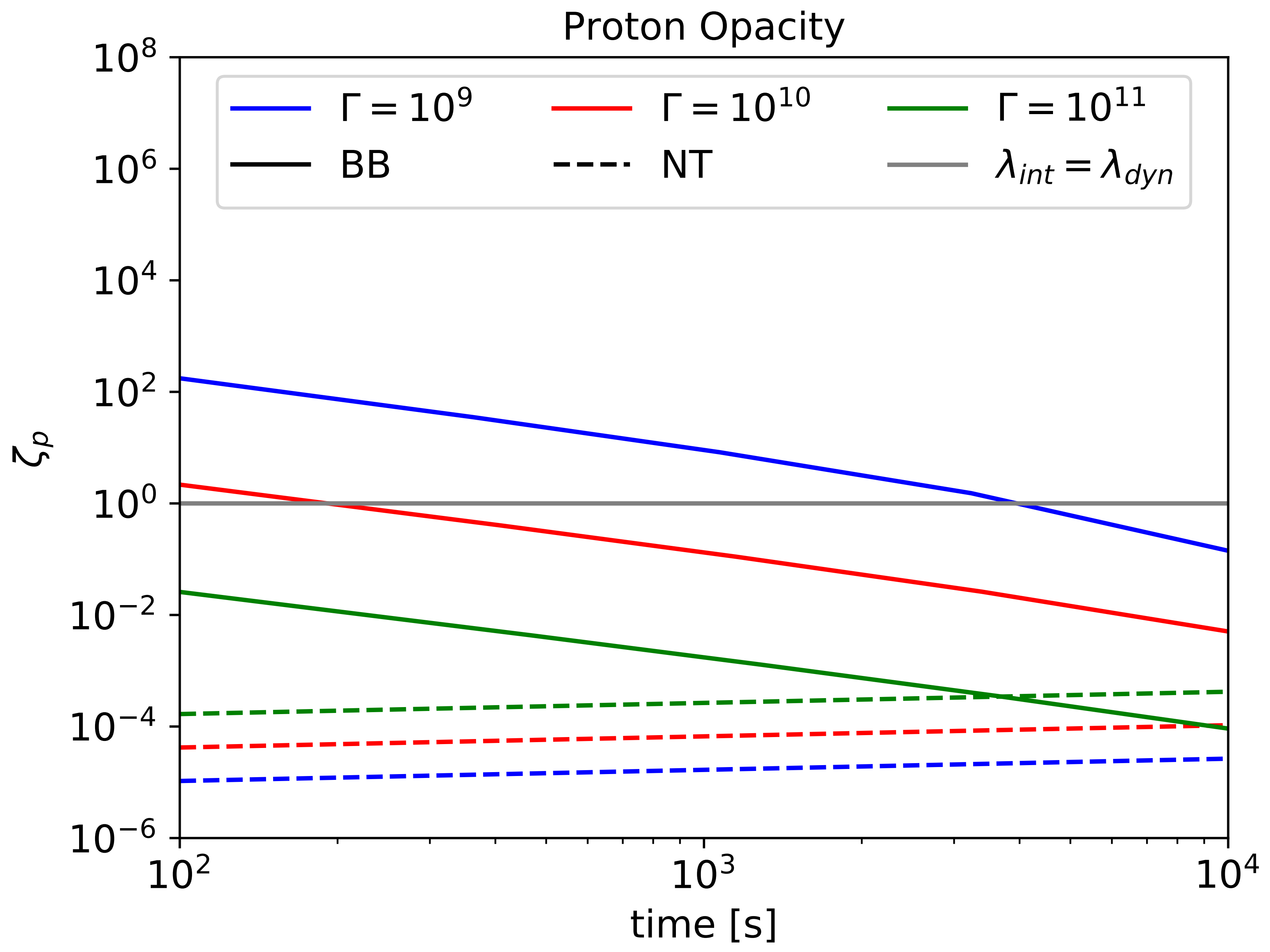


Photohadronic interactions

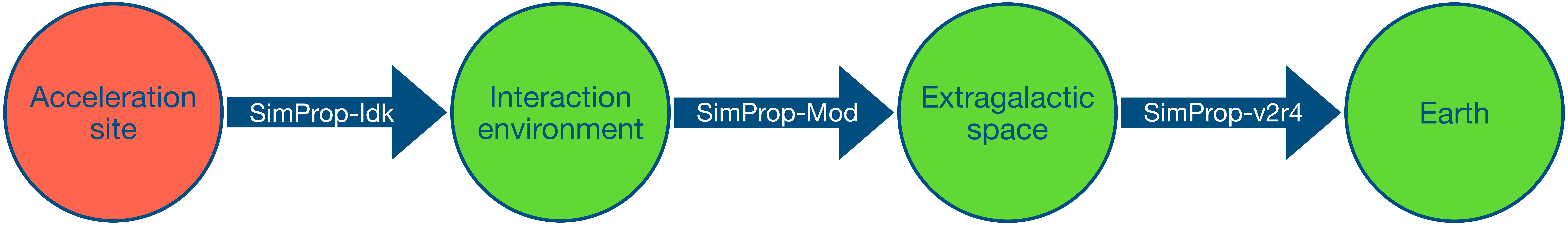
- Escape length: typical radius of the source $\lambda_{esc}(t) = \beta_{ej} c t$, $\beta_{ej} = 0.3$
- Source opacity: ratio of the escape length with the total interaction length $\zeta_A(\Gamma, t) = \frac{\lambda_{esc}(t)}{\lambda_A(\Gamma, t)}$







SimProp *in-source*



- SimProp-Mod: modified version of SimProp-v2r4 for the propagation of UHECRs within the source environment
  - Interactions: extragalactic photon fields replaced by local fields (only BB)
  - Escape: Monte Carlo comparison of the escape rate with the total interaction rate

R. Aloisio et al, JCAP (2017)

SimProp-Idk: SimProp *I don't know*

SimProp simulations and analysis

In-source simulations

- Fixed T or t corresponds to fixed source radius and local SEDs
- Injection of p or Fe with energy spectrum $dN/d\log E = const$, $10^{14}\, eV \leq E \leq 10^{20}\, eV$

Extragalactic simulations

- Propagation matrices for cosmological evolution m=0 and SFR

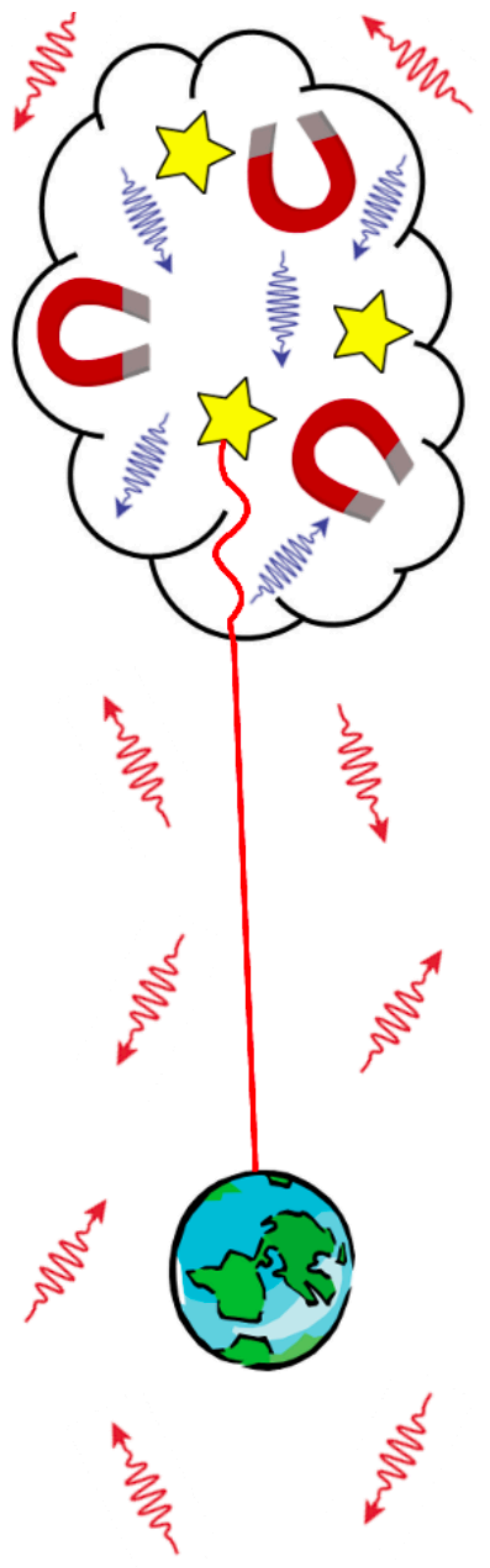
Analysis

- Source temperature $T = 10^8\, K, 10^7\, K, 10^6\, K, 10^5\, K, 10^4\, K$
- Accelerated spectrum $Q^A_{acc}(E) = Q^A_{0,acc}\left(\frac{E}{1\, EeV}\right)^{-\gamma} \exp\left(-\frac{E}{E_{cut}}\right)$

  $\gamma = 0.5,...,2.5 \;\; with \;\; \Delta\gamma = 0.25$

  $\log(E_{cut}/1\, eV) = 17.0,...,19.0 \;\; with \;\; \Delta \log(E_{cut}/1eV) = 0.1$
- Normalization $J_{prop}(E = 10^{18.5}\, eV) = g \cdot J_{exp}(E = 10^{18.5}\, eV)$ E.W. Mayotte et al, PoS ICRC2023

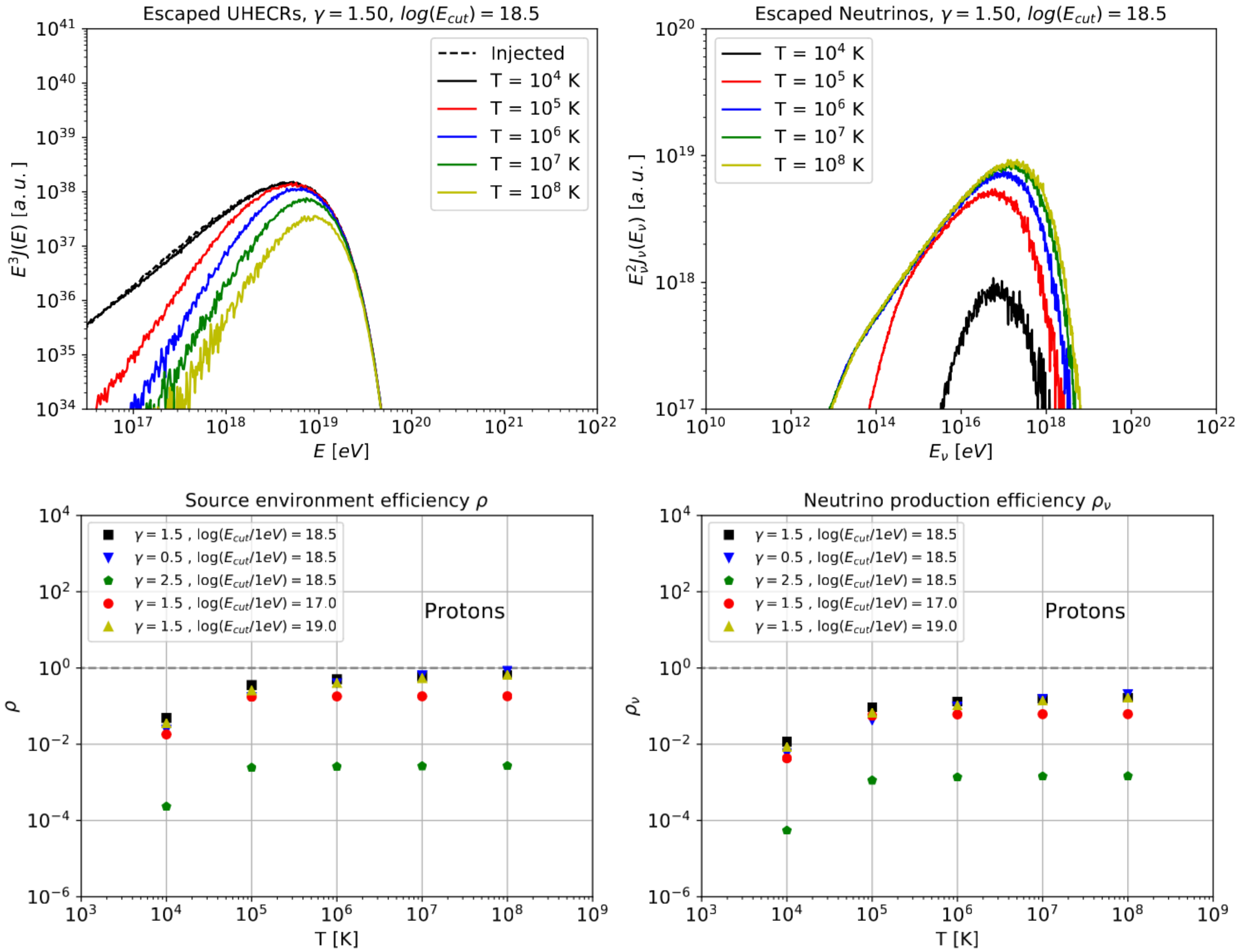
  $\log(g) = -5,...,0 \;\; with \;\; \Delta \log(g) = 0.1$



M. Unger at al, Phys.Rev.D (2015)

Source escape

Proton injection



- Emissivities

$$\mathcal{E}_{acc/esc} = \sum_A \int dE\, E\, Q^A_{acc/esc}(E)$$

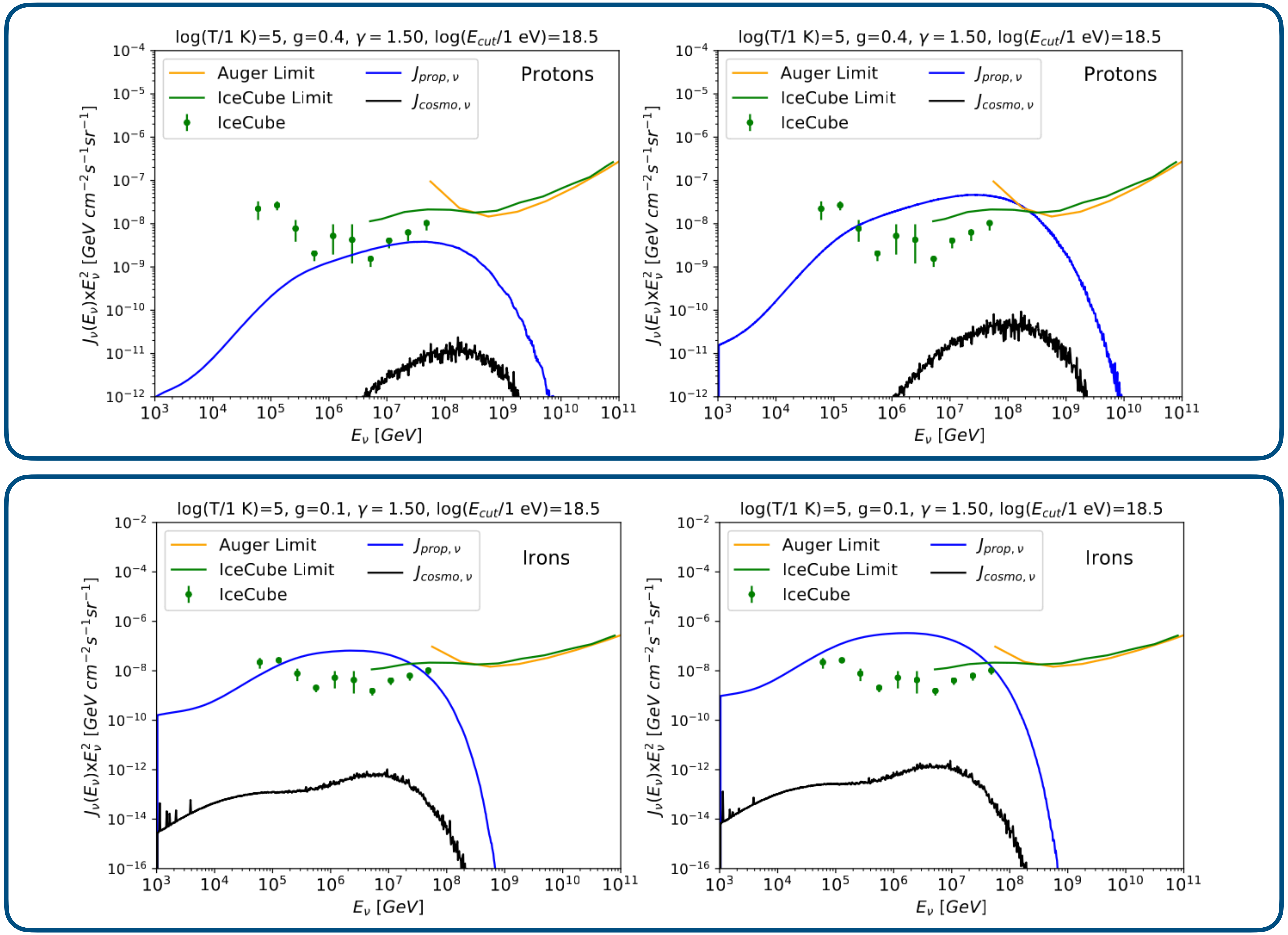
- Efficiency parameters

$$\rho = \frac{\mathcal{E}_{acc} - \mathcal{E}_{esc}}{\mathcal{E}_{acc}}$$

$$\rho_\nu = \frac{\mathcal{E}^\nu_{esc}}{\mathcal{E}_{acc}}$$

Propagated neutrinos

m=0



SFR

m=0

SFR

M. G. Aartsen et al, ICRC2017

A. Aab et al, JCAP (2019)

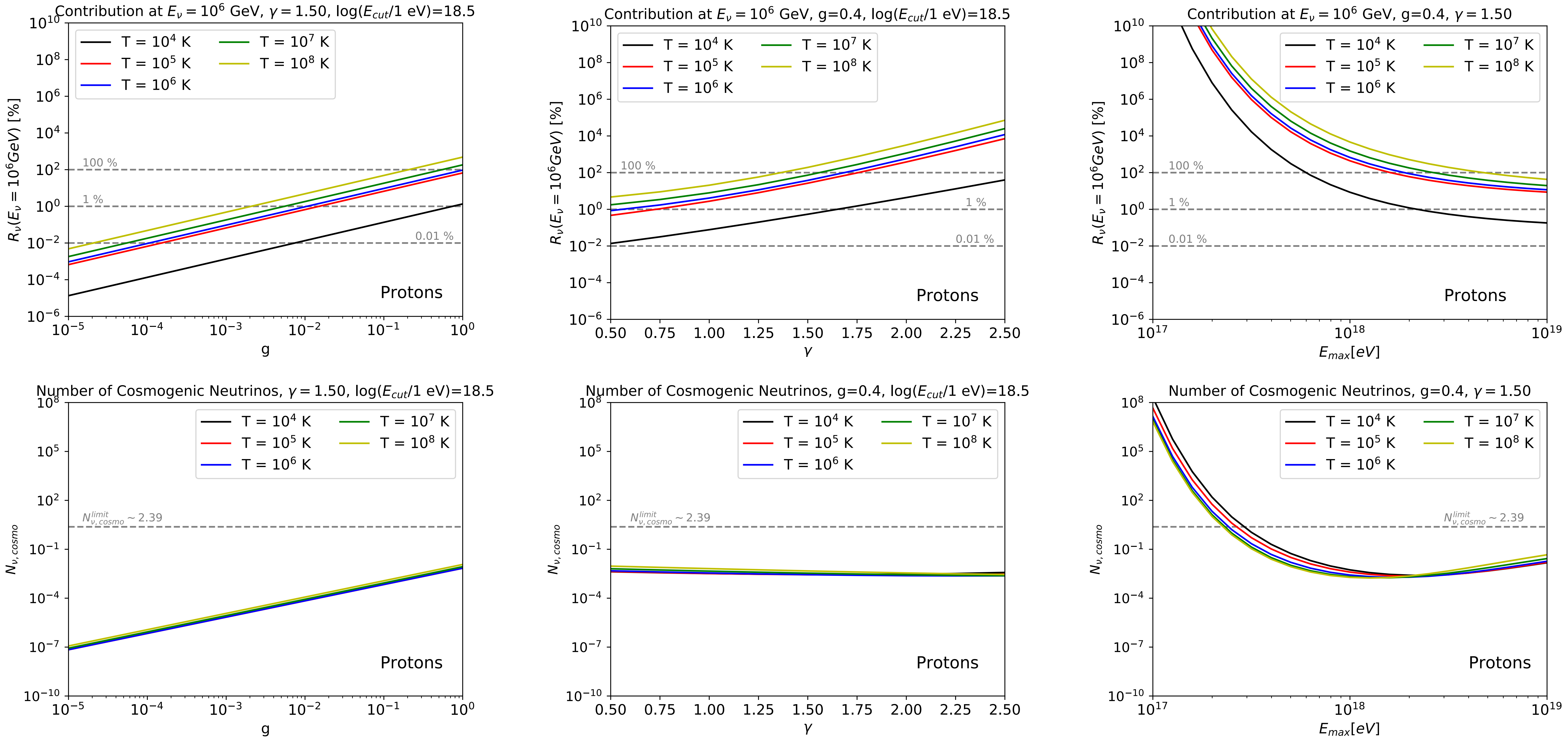
Neutrino *control quantities*

- Neutrino spectral ratio

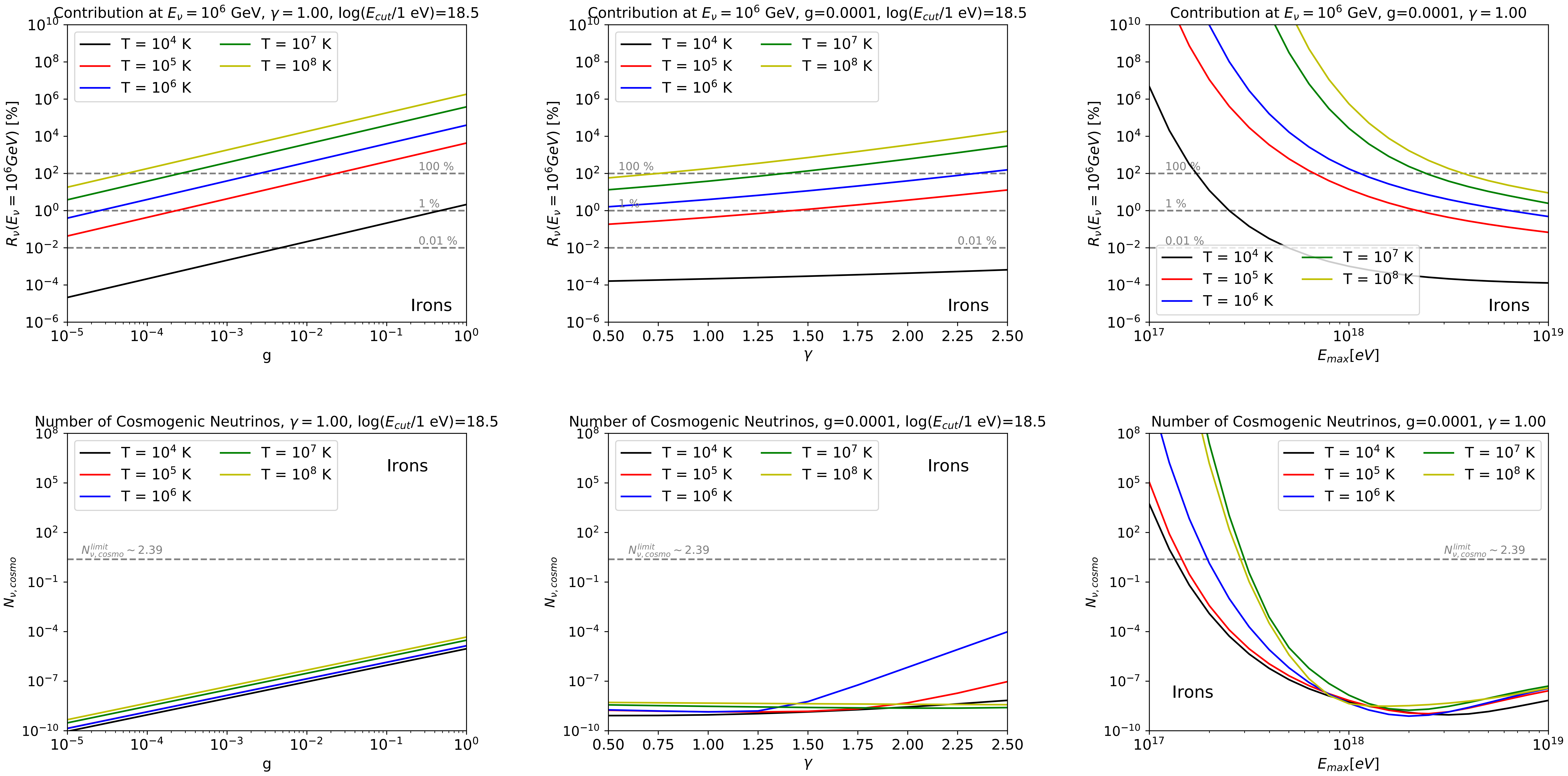
$$R_\nu(E_\nu = 10^6\,GeV) = \frac{J_{prop,\nu}(E_\nu = 10^6\,GeV)}{J_{IceCube}(E_\nu = 10^6\,GeV)}$$

- Number of cosmogenic neutrinos

$$N_{\nu,cosmo} = \int dE_\nu\, \mathscr{E}(E_\nu) J_{\nu,prop}(E_\nu)$$



Neutrino *control quantities*



Source density rate

- Emissivity at the acceleration

$$\mathcal{E}_{acc} = \mathcal{L}_{acc} n = E_{acc} \dot{n}$$

- Fallback luminosity

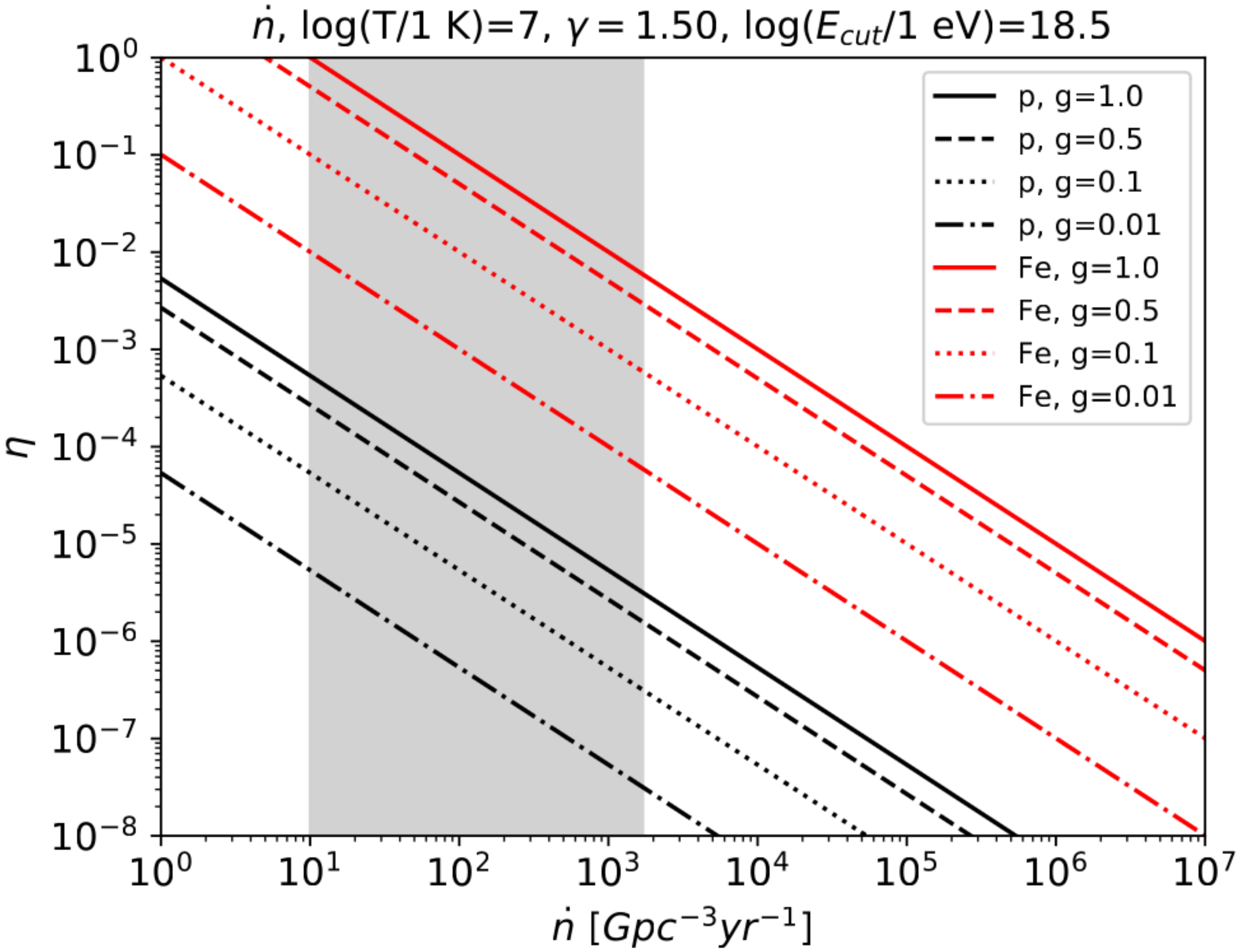
$$\mathcal{L}_{fb} = 1.3 \cdot 10^{43} \cdot \left(\frac{t}{10^3\, s}\right)^{-5/3} \; erg\, s^{-1}$$

- Baryonic loading

$$\mathcal{L}_{acc} = \eta \mathcal{L}_{fb}$$

- Baryonic loading vs source density rate degeneracy

$$\eta\, \dot{n} = \frac{\mathcal{E}_{acc}}{\mathcal{L}_{fb}\, t}$$



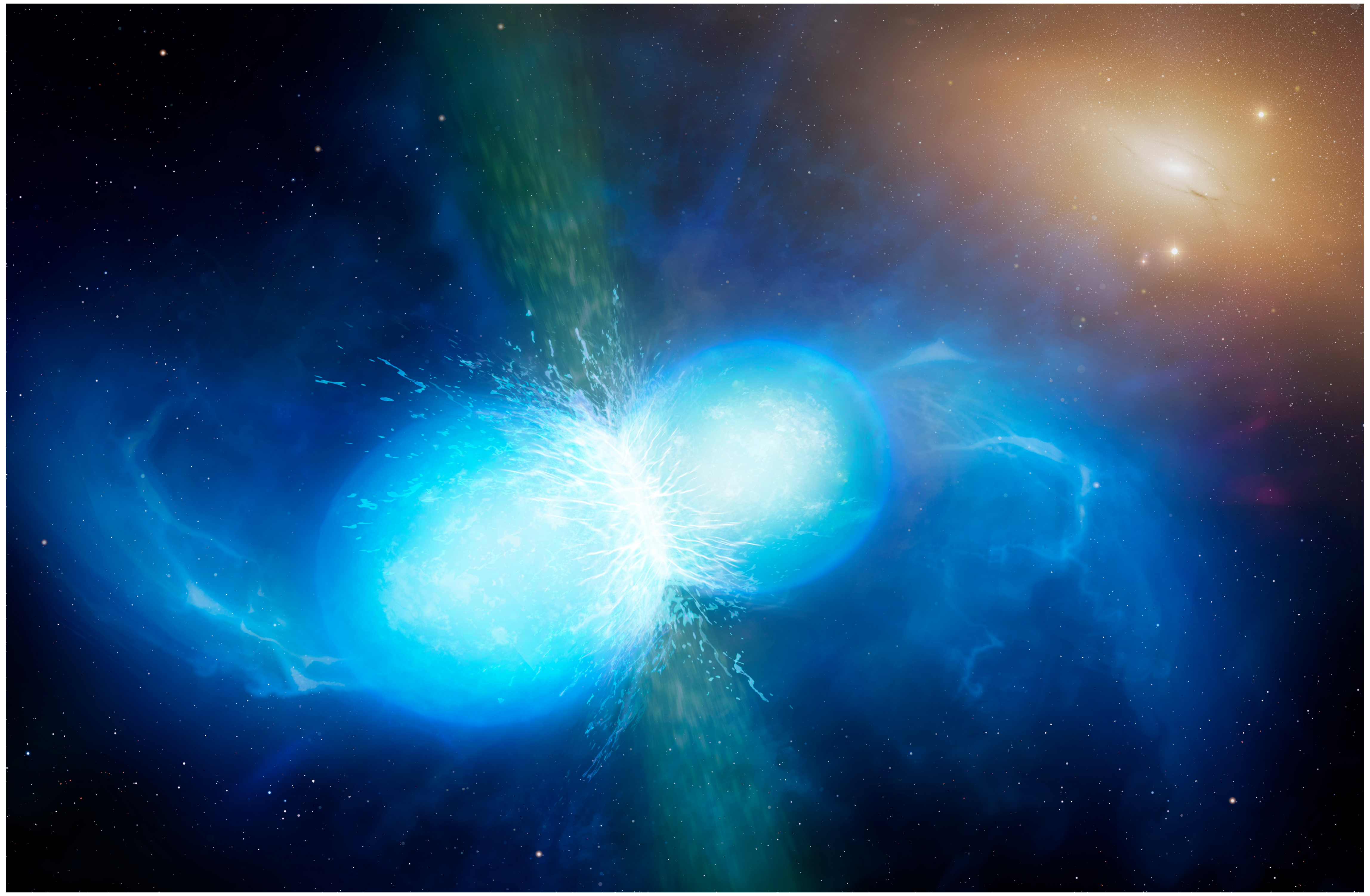
R. Abbott et al, Phys. Rev. X (2023)

Conclusions

- Only the black-body component of the source environment can trigger photohadronic interactions
- The fraction of cosmic rays energy converted into neutrinos saturates with temperature at values smaller than 10%
- Cosmogenic neutrinos cannot be responsible of the observed neutrino flux
- The high energy cutoff of the accelerated spectrum is constrained by the limits on the cosmogenic neutrinos

$$E_{cut} \gtrsim 10^{17}\, eV$$

- Cold sources (in particular for Fe) are required to be compatible with the observed data
- It is possible to constrain the baryonic loading given the event density rate



Backup slides

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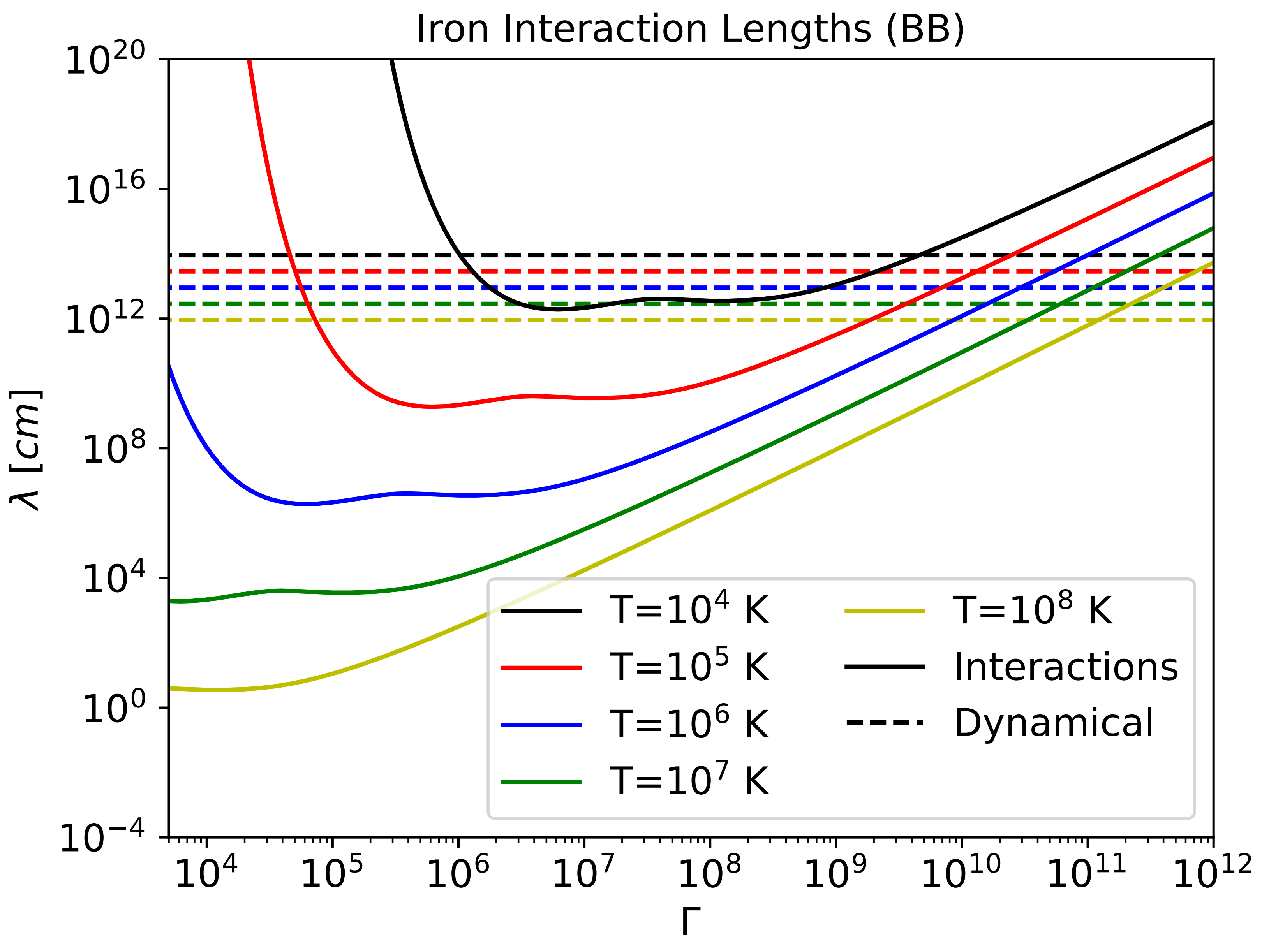

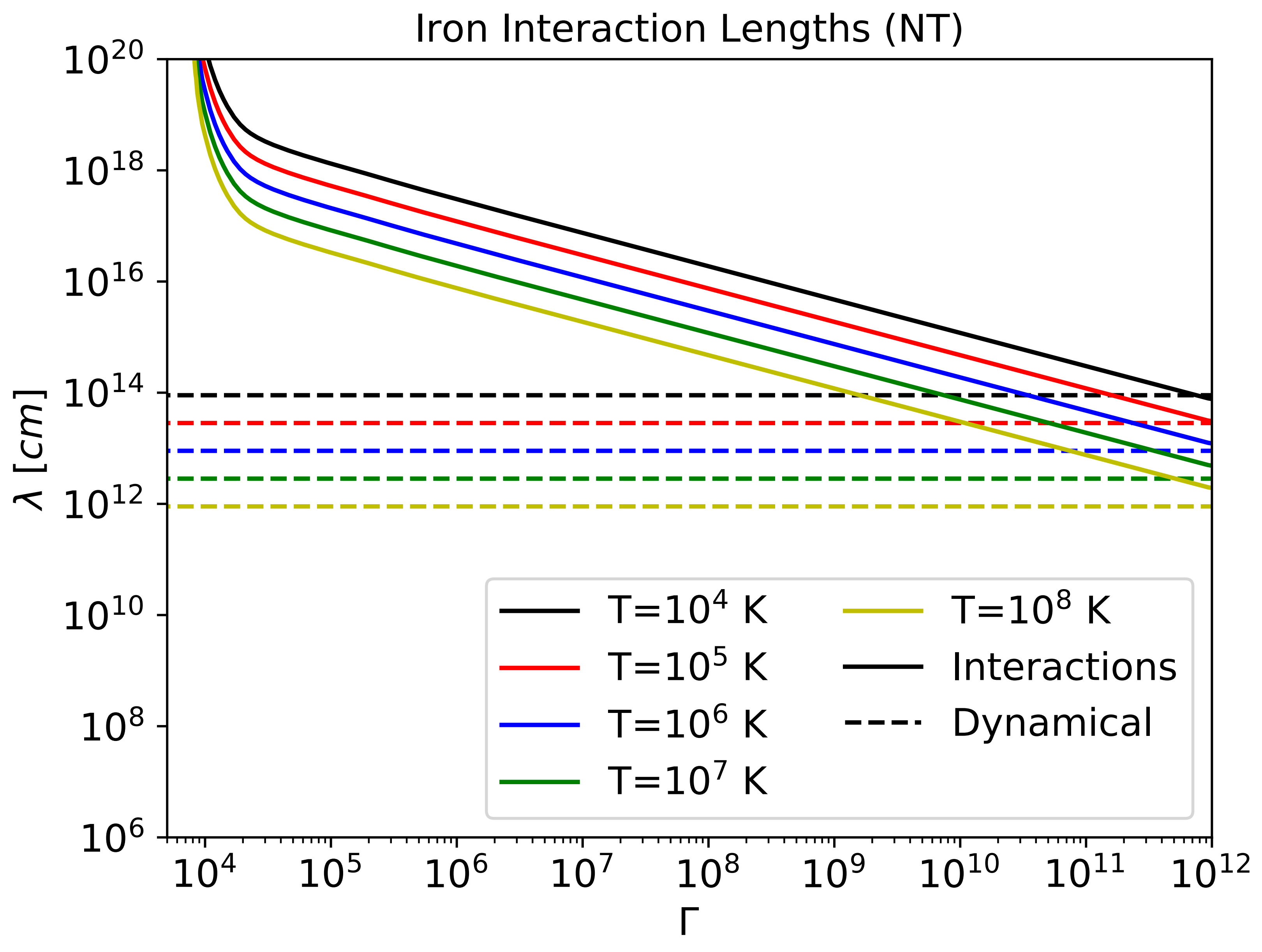

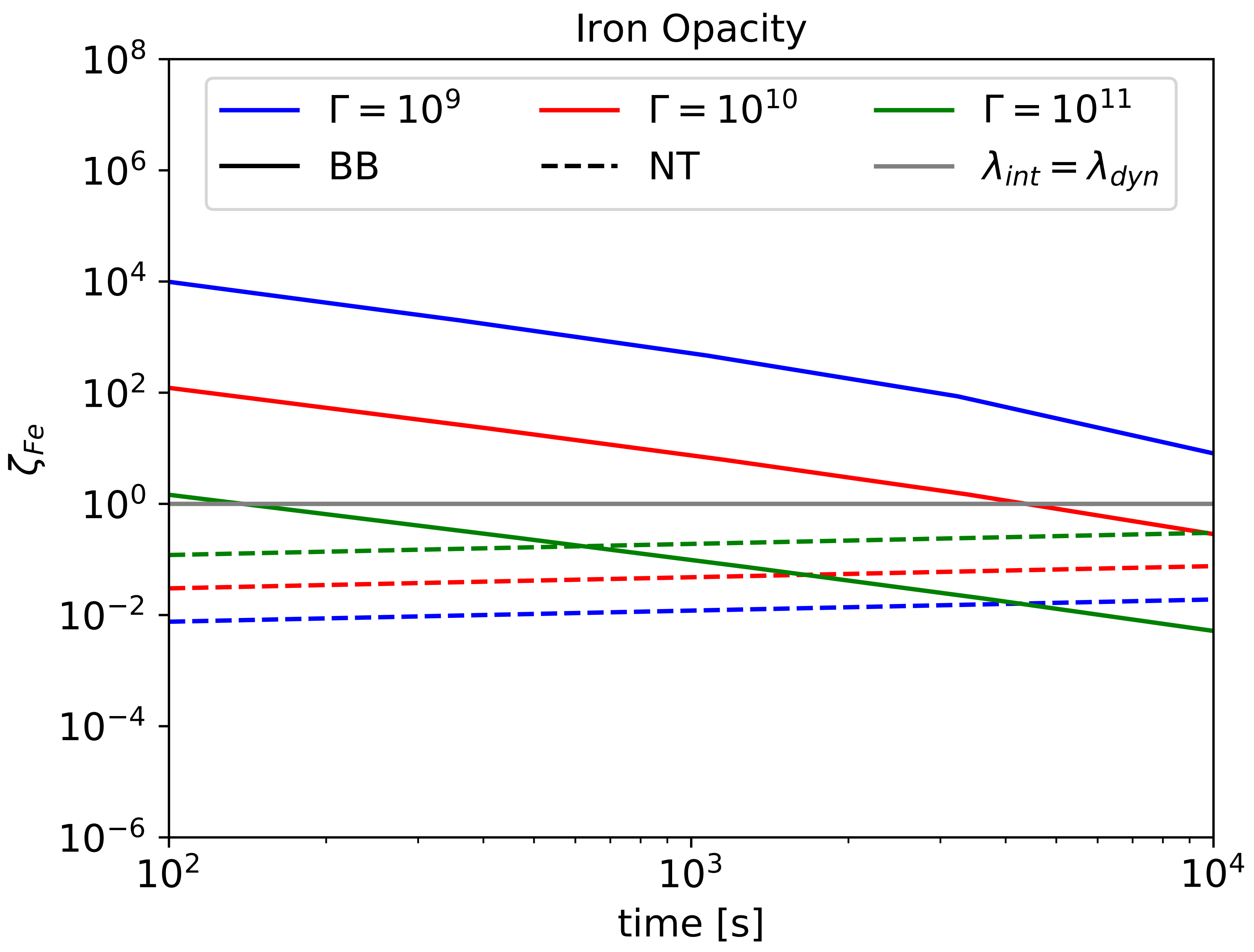

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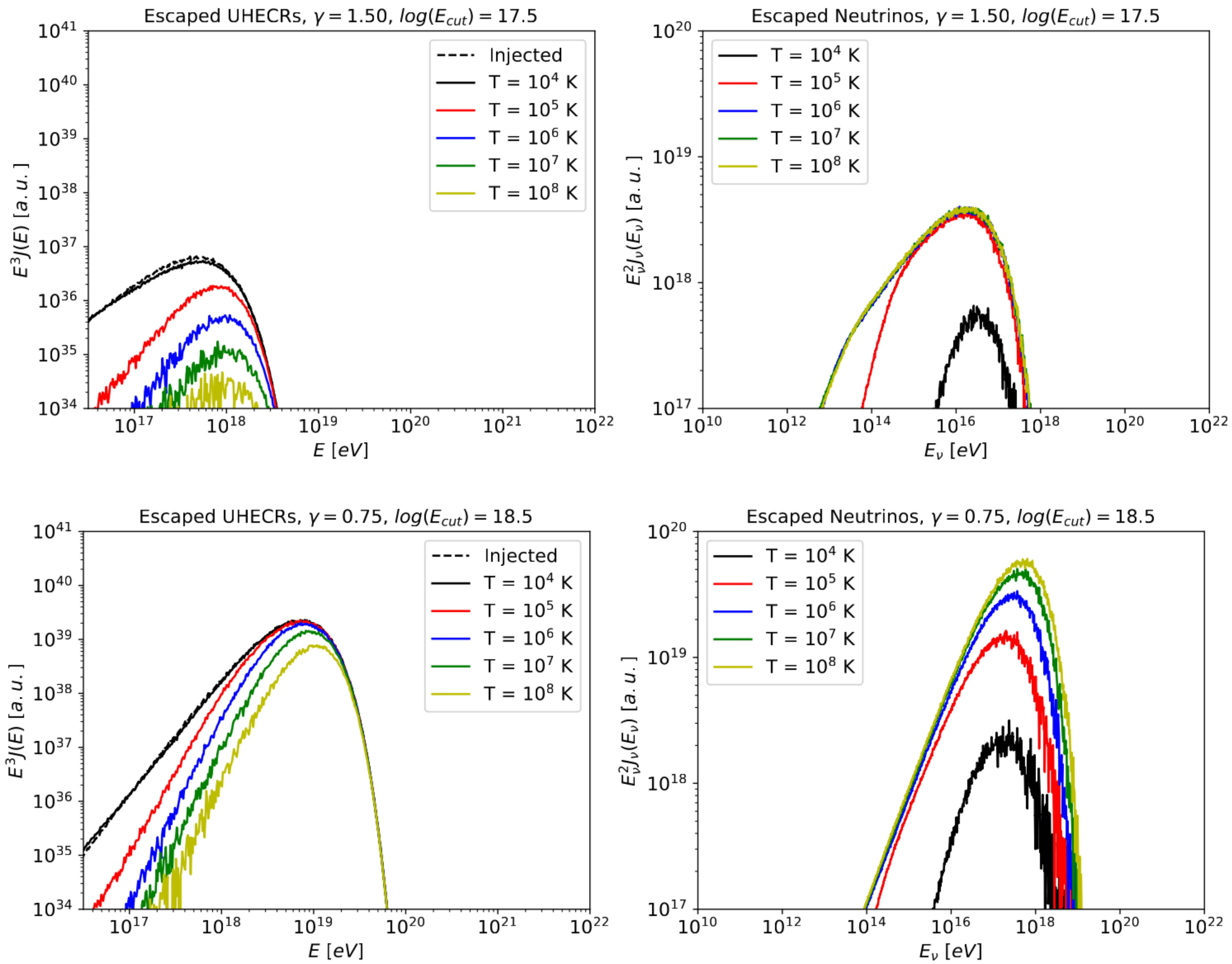

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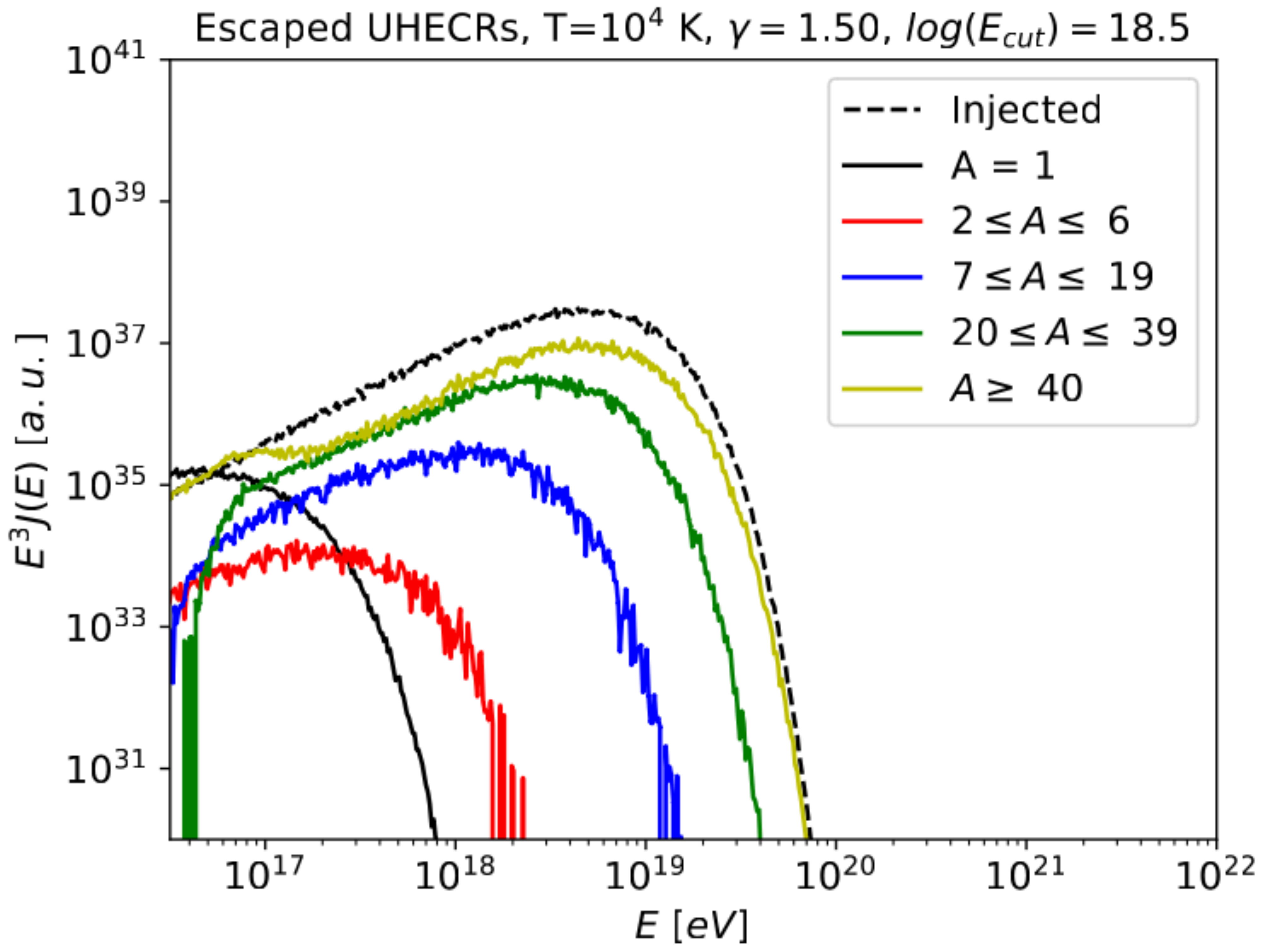

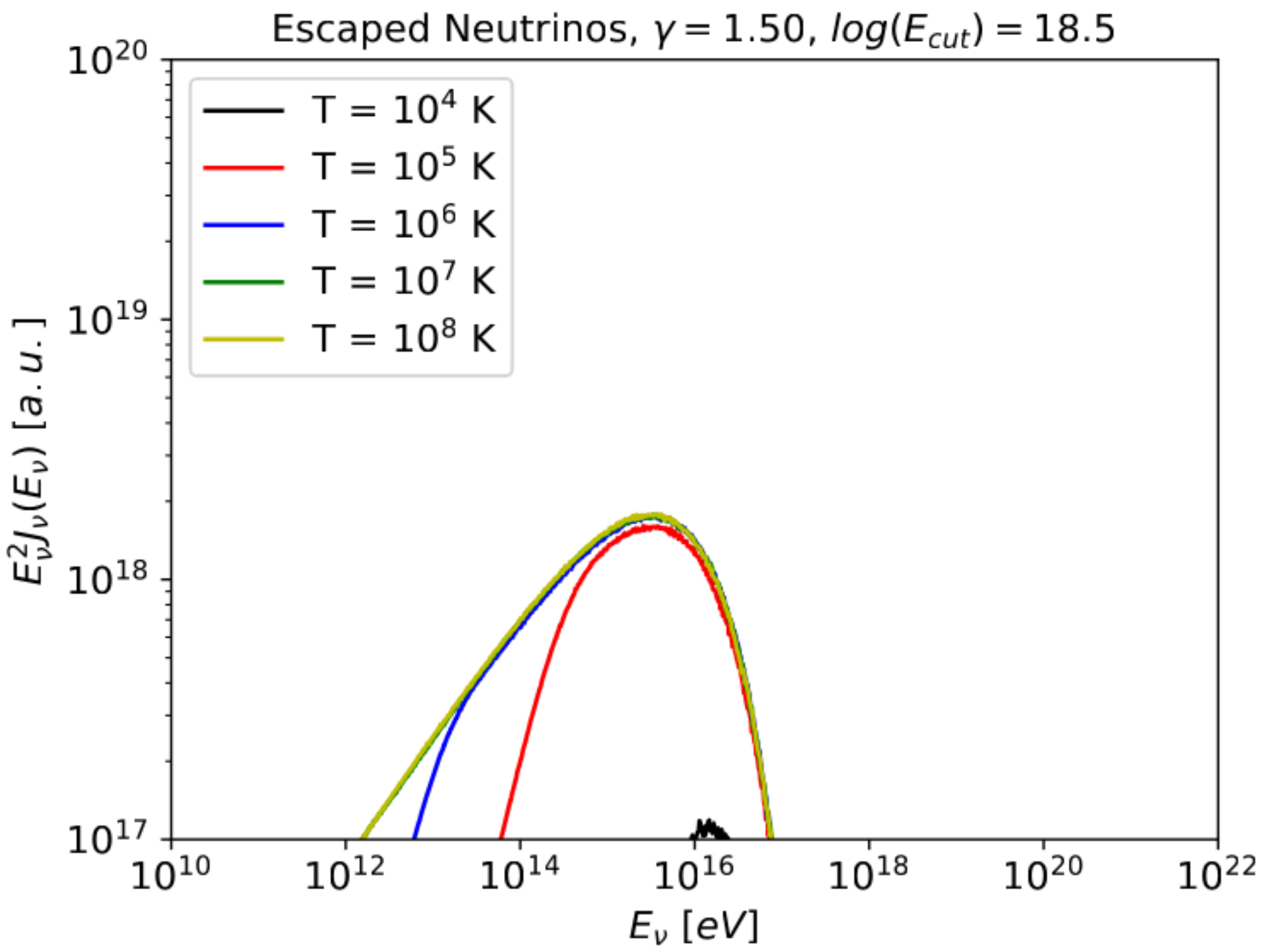

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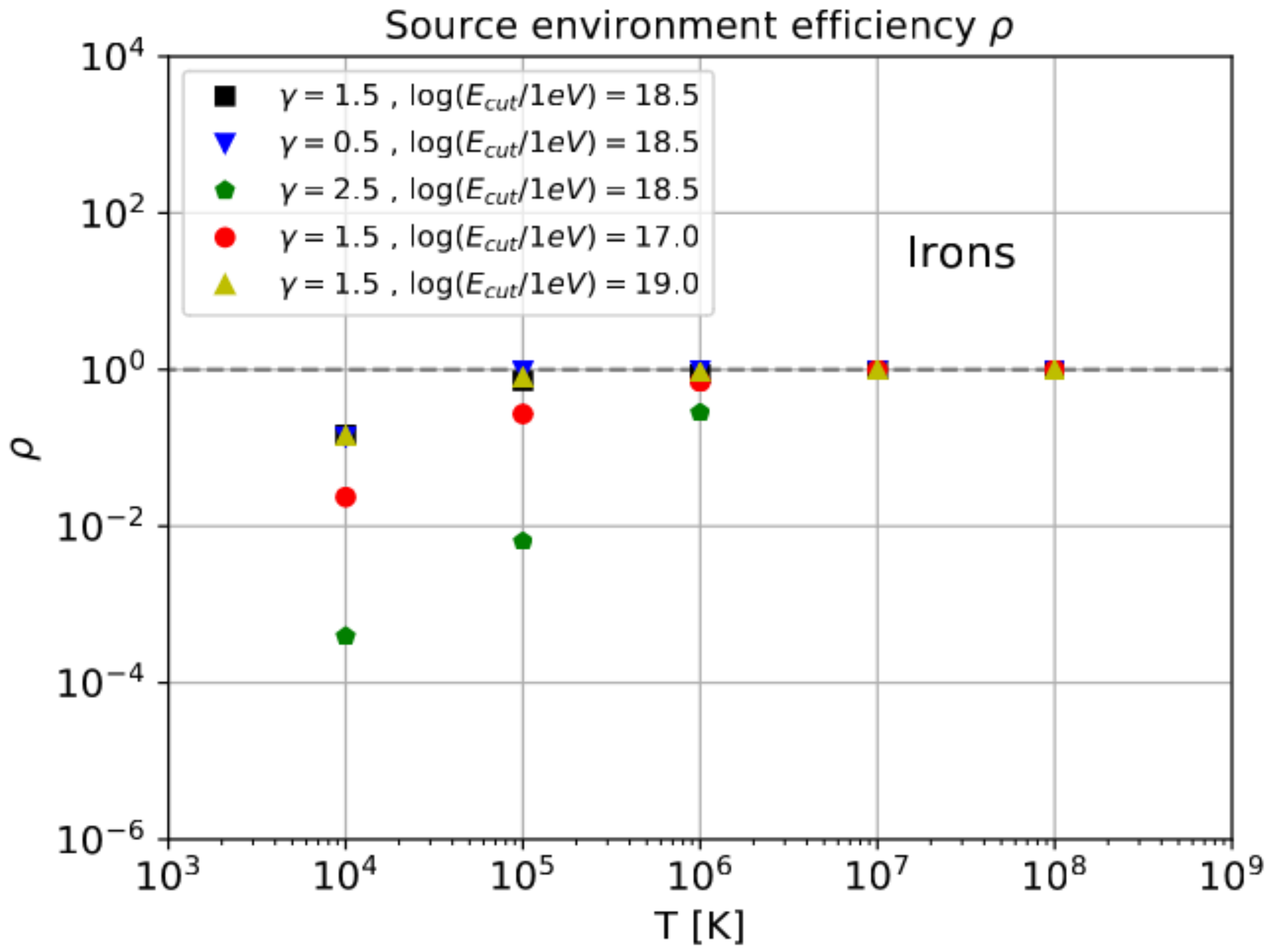

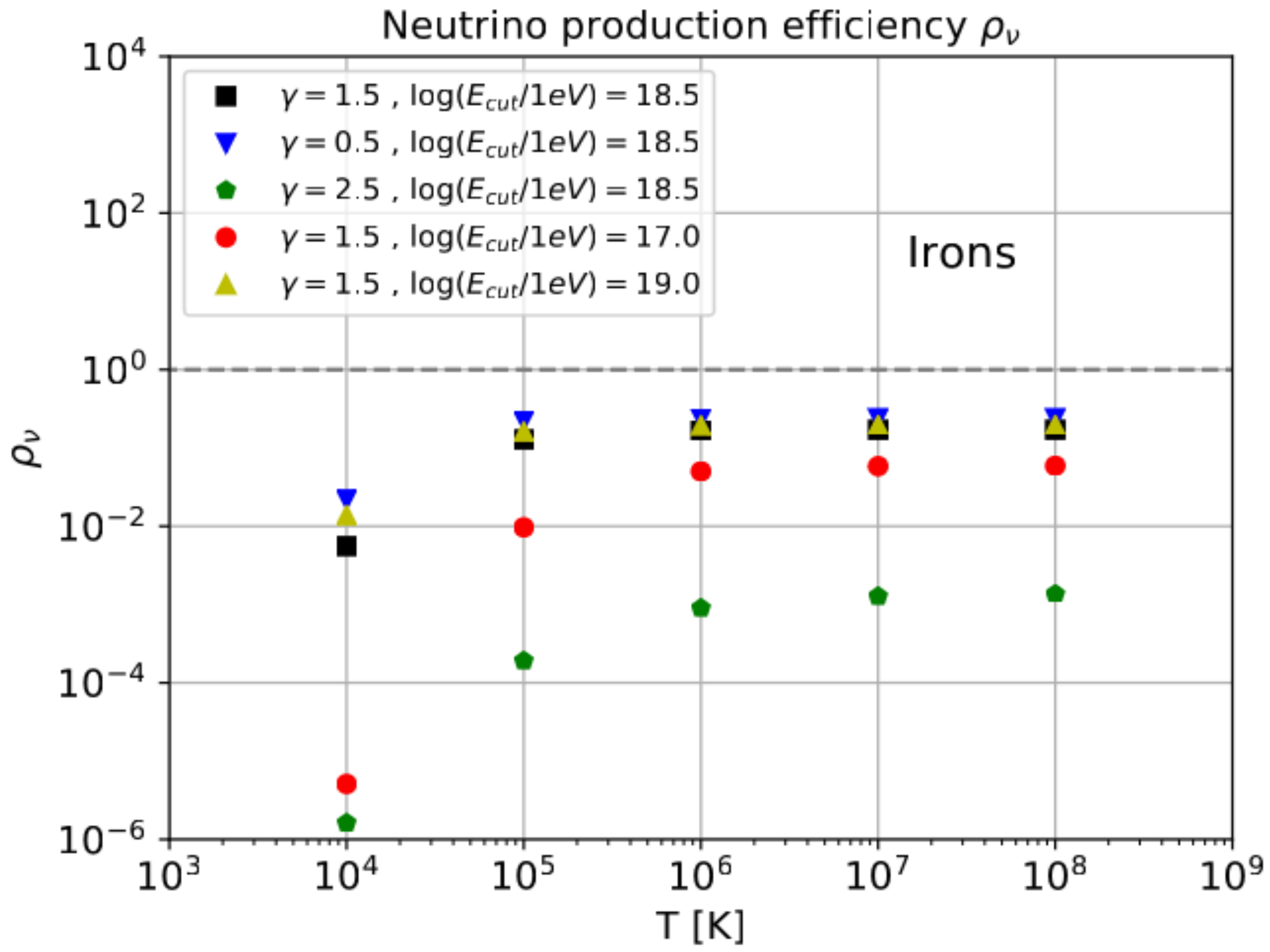

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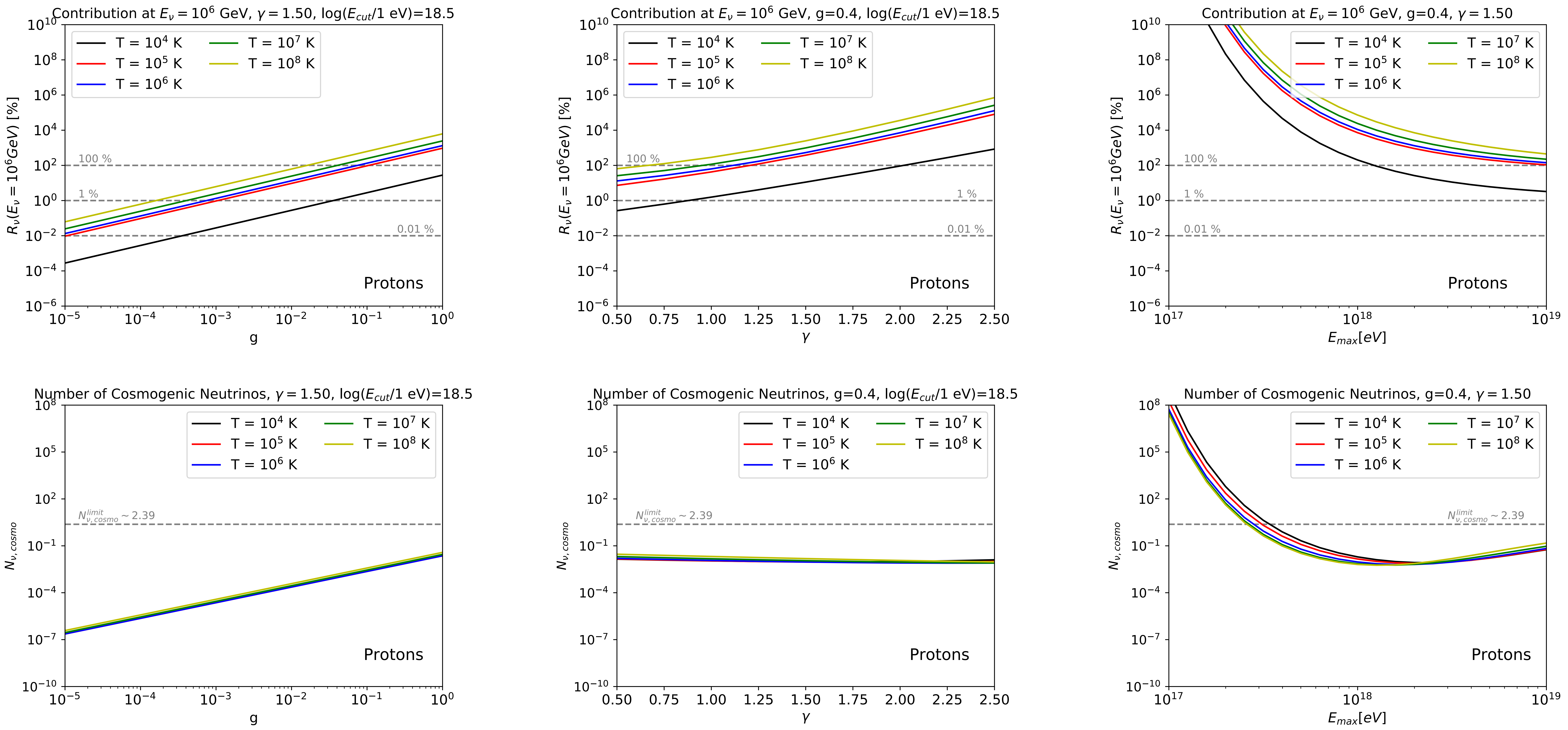

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