Neutrinos from Muon-rich Ultra-High Energy Electromagnetic Cascade

22nd International Symposium on Very High Energy Cosmic Ray Interactions

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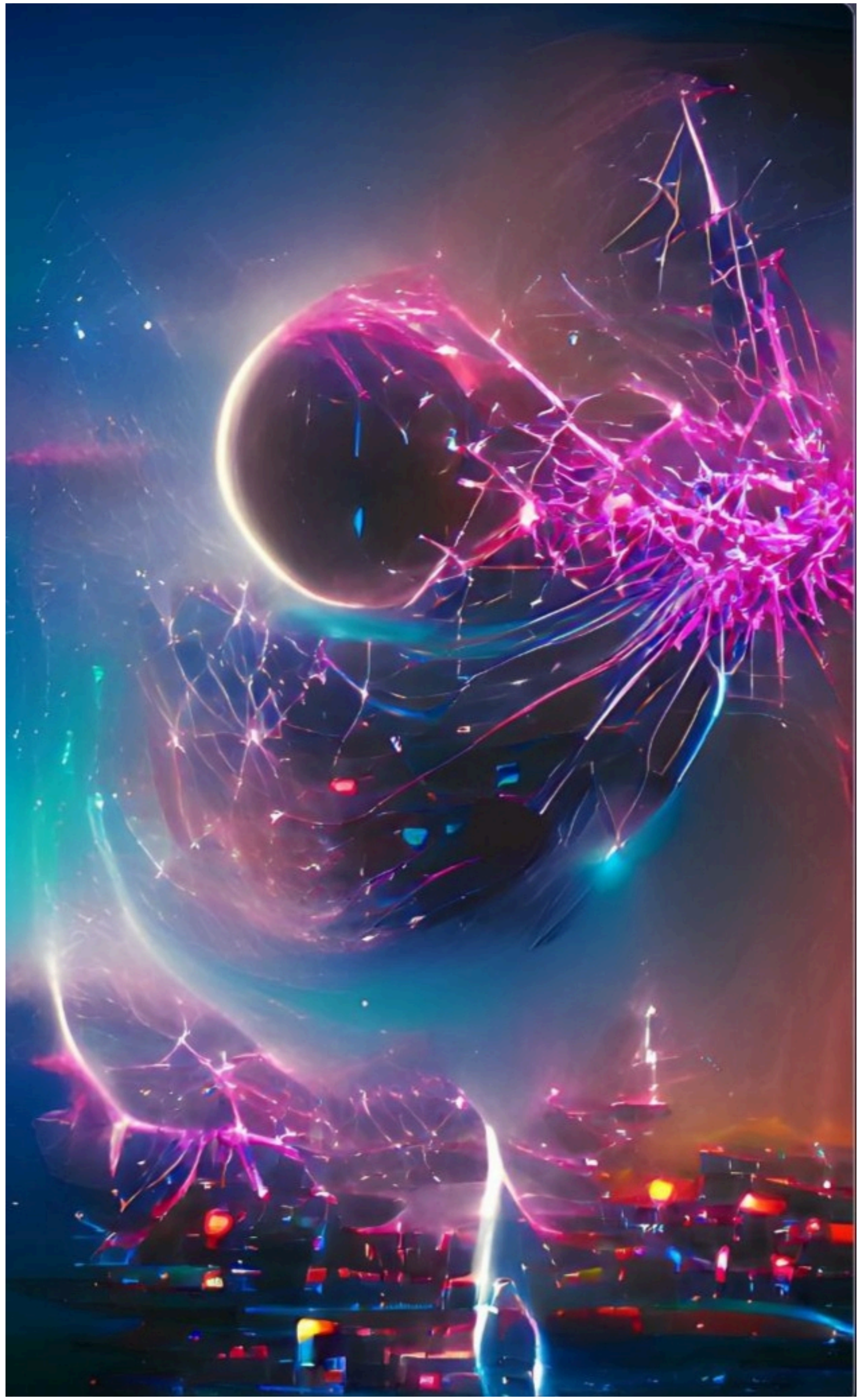

Picture by the application WOMBO

Outline

- **Electromagnetic Cascade Development**
  - **Commonly Considered Involved Processes**
  - **Inelasticity**
  - **Sub-leading Photon-Photon and Electron-Photon Interactions and Neutrinos**
- **MUNHECA Framework (A Monte Carlo Cascade Simulation)**
- **Results for the Relevant Cases**
  - **Propagation in Cosmic Distances**
  - **Astrophysical Sources**

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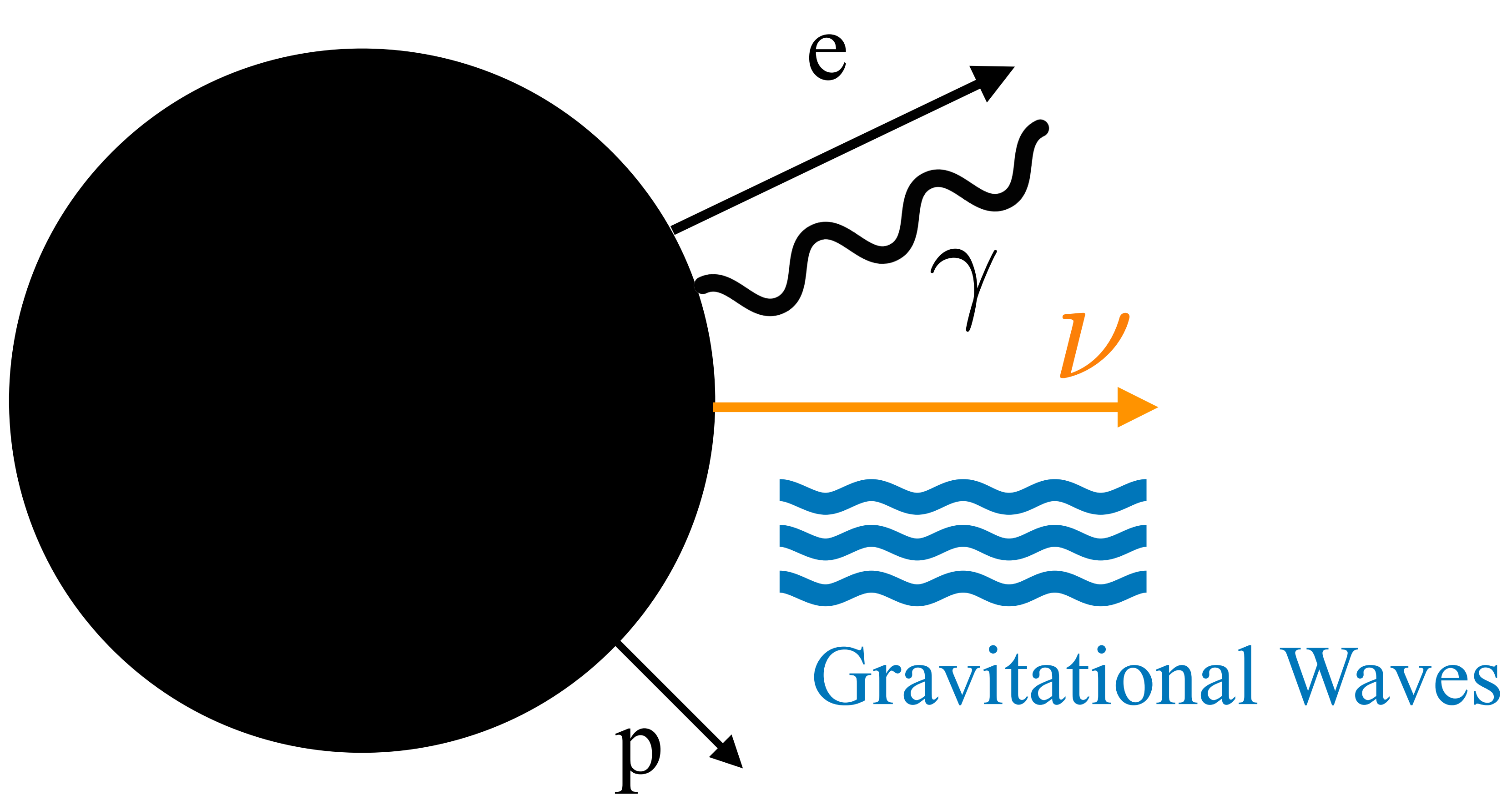
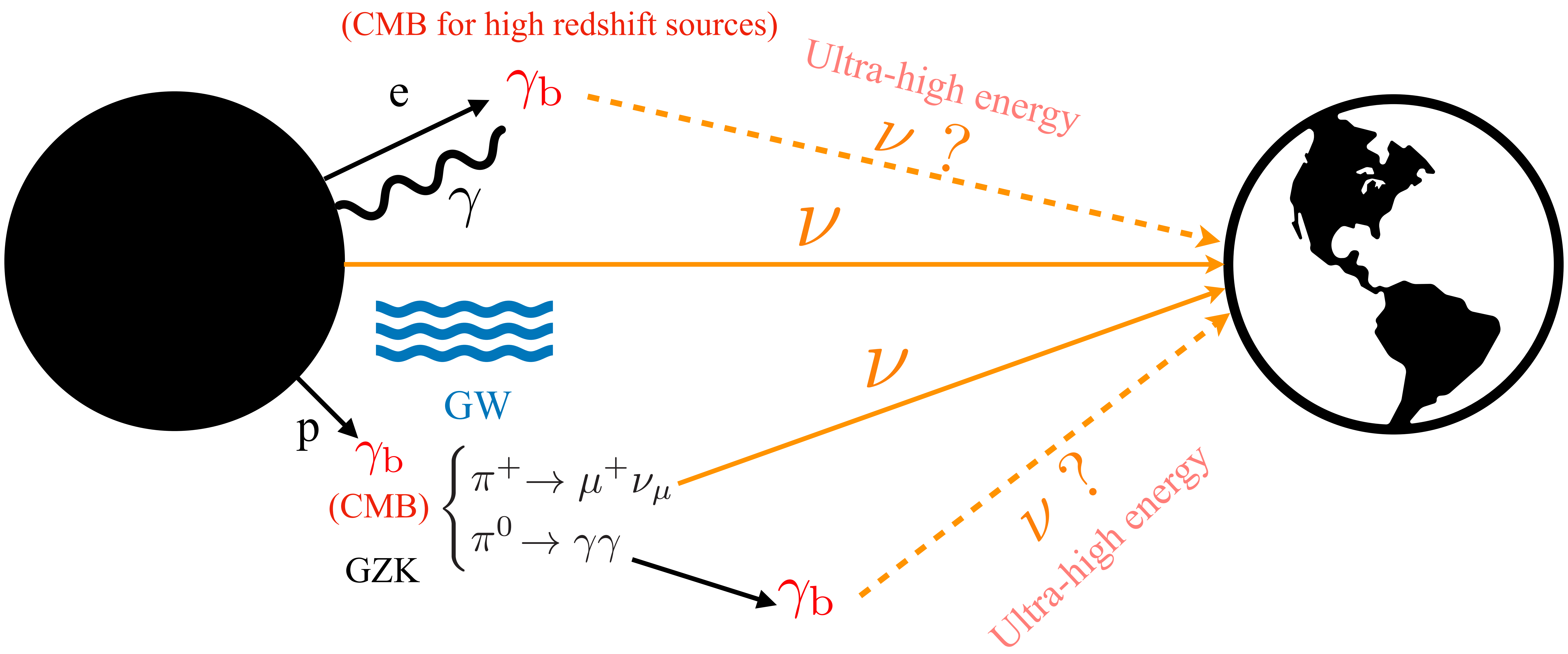
Messengers from Astrophysical Sources



Messengers from Astrophysical Sources

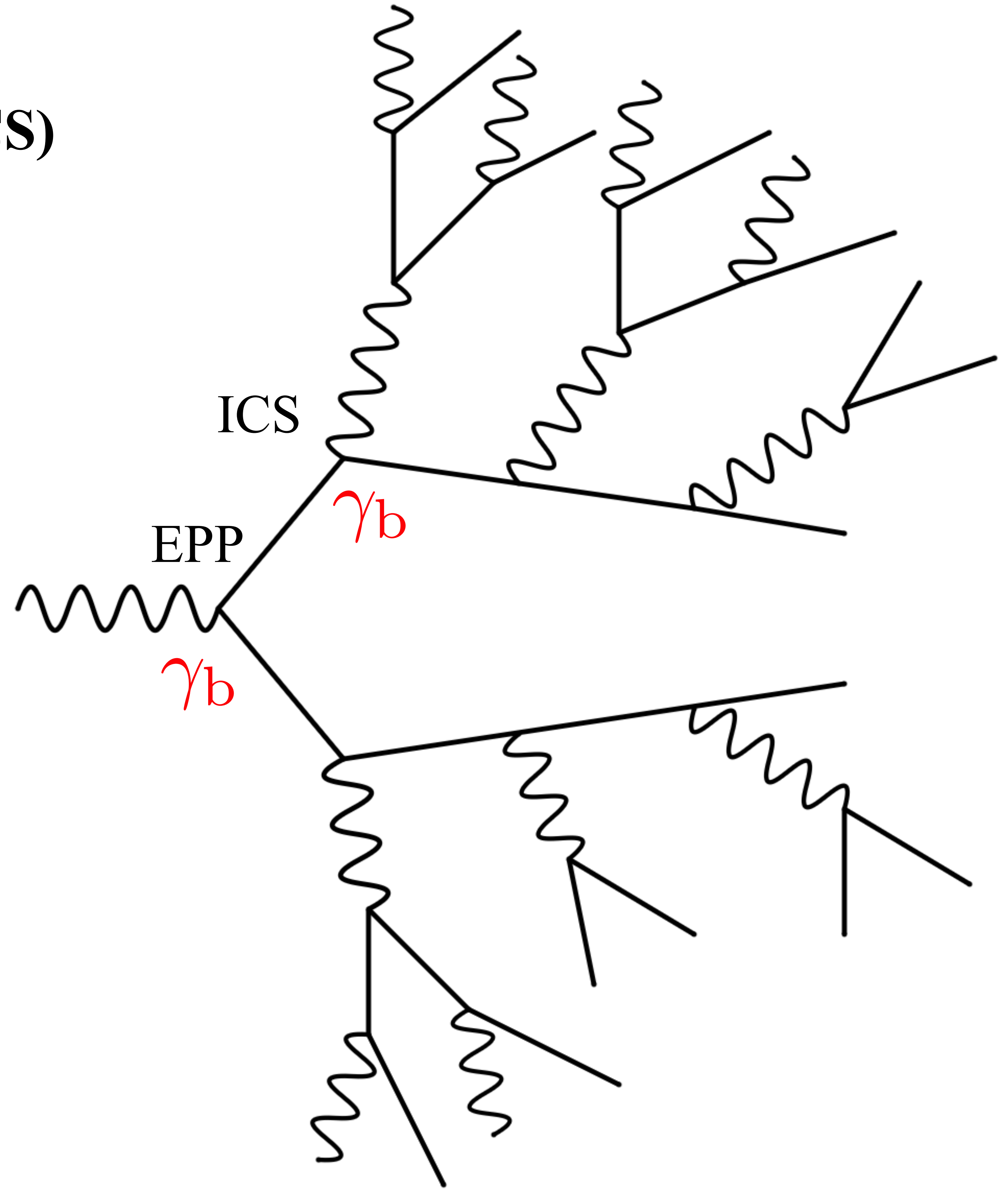


Electromagnetic Cascade: Remarked soon after the CMB discovery. (Cosmic ray conference in Soviet Union)
Has been scrutinized in V. S. Berezinsky and A. Y. Smirnov, Astrophys. Space Sci. 32, 461 (1975)
as a handle to probe cosmogenic neutrinos

Electromagnetic Cascade:

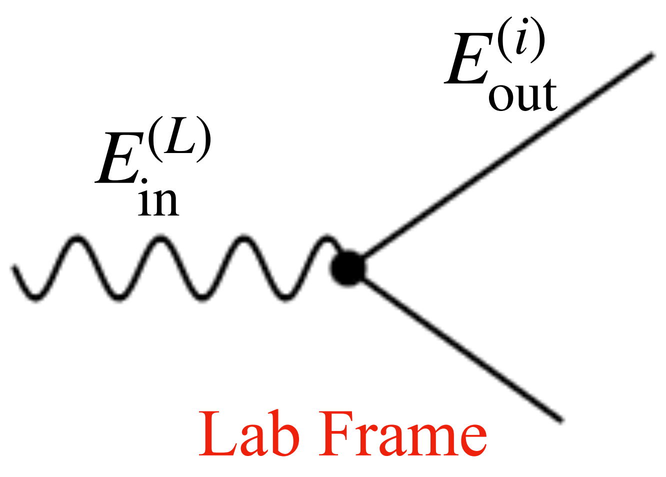
A successive iteration of electron pair production (EPP) and inverse Compton scattering (ICS)

$$\begin{cases} \gamma\gamma_{\rm b} \to e^- e^+ & \text{EPP} \qquad s = 4m_e^2 \ \text{(Threshold Energy)} \\ e\gamma_{\rm b} \to e\gamma & \text{ICS} \end{cases}$$



Inelasticity

The fraction of the incoming leading particle energy ($E_{\rm in}^{(L)}$) carried by outgoing particle i ($E_{\rm out}^{(i)}$)



$$\eta^{(i)}(s) = \frac{1}{\sigma}\int_0^{E_{\rm in}^{(L)}(s)} \frac{E_{\rm out}^{(i)}}{E_{\rm in}^{(L)}} \frac{{\rm d}\sigma}{{\rm d}E_{\rm out}^{(i)}} {\rm d}E_{\rm out}^{(i)}$$

EPP and ICS have high inelasticities

EPP: Head-on collision, $E_\gamma = 10^{20}$ eV, $\epsilon = 10^{-3}$ eV $\to \eta = 0.96$

ICS: Head-on collision, $E_e = 10^{20}$ eV, $\epsilon = 10^{-3}$ eV $\to \eta = 0.91$

At each sequence of EPP+ICS the leading particle emerges with energies close to the initial one

But at the UHE stage ($s \gtrsim 4m_\mu^2$) it will be more complicated

Other channels for $\gamma\gamma_{\rm b}$ and $e\gamma_{\rm b}$ will open up

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Sub-leading Photon-Photon Interactions

$\gamma\gamma_b$

$\xrightarrow{s > 16m_e^2}$ $e^-e^+e^-e^+$ Double pair production (DPP) $\sigma_{\rm DPP}^{\infty} \simeq 6.45\mu b$

One of the pairs takes almost all of the initial energy → $E_e = 0.77E_\gamma$, $E_e = 0.23E_\gamma$ — Re-assessed by `calcHEP`

$\xrightarrow{s > 4m_\mu^2}$ $\mu^-\mu^+$ Muon pair production (MPP) → $\mu^+ \to e^+\nu_e\bar{\nu}_\mu$, $\mu^- \to e^-\bar{\nu}_e\nu_\mu$; $E_\nu = 0.65E_\mu$, $E_e = 0.35E_\mu$

$\xrightarrow{s > 4m_\mu^2}$ $e^+e^-\mu^+\mu^-$ Electron-Pair Muon-Pair Production (EPMPP) → Re-assessed by `calcHEP`

→ Radiative Corrections to the interactions above

$\xrightarrow{s > 4m_{\pi^\pm}^2}$ $\pi^+\pi^-$ Charged Pion Pair Production (CPPP) → $\pi^\pm \to e^\pm\nu_\mu\bar{\nu}_\mu\nu_e(\bar{\nu}_e)$

$\xrightarrow{s > 4m_{\pi^0}^2}$ $\pi^0\pi^0$ Neutral Pion Pair Production (NPPP)

⋮

Question 1: What is the relevance of each of these interactions?

Question 2: What is the effect of these microphysics on the cascade development?

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Sub-leading Electron-Photon Interactions

$e\gamma_{\rm b} \longrightarrow e\mu^+\mu^-$ Electron Muon-Pair Production (EMPP)

Re-assessed by `calcHEP`

$\mu^+ \to e^+\nu_e\bar{\nu}_\mu$

$\mu^- \to e^-\bar{\nu}_e\nu_\mu$

$E_\nu = 0.65 E_\mu$

$E_e = 0.35 E_\mu$

$\longrightarrow ee^+e^-$ Electron Triplet Production (ETP) [Know as TPP]

Re-assessed by `calcHEP`

$\longrightarrow e + n\gamma$ Radiative Corrections (n-Compton Scattering)

Question 1: What is the relevance of each of these interactions?

Question 2: What is the effect of these microphysics on the cascade development?

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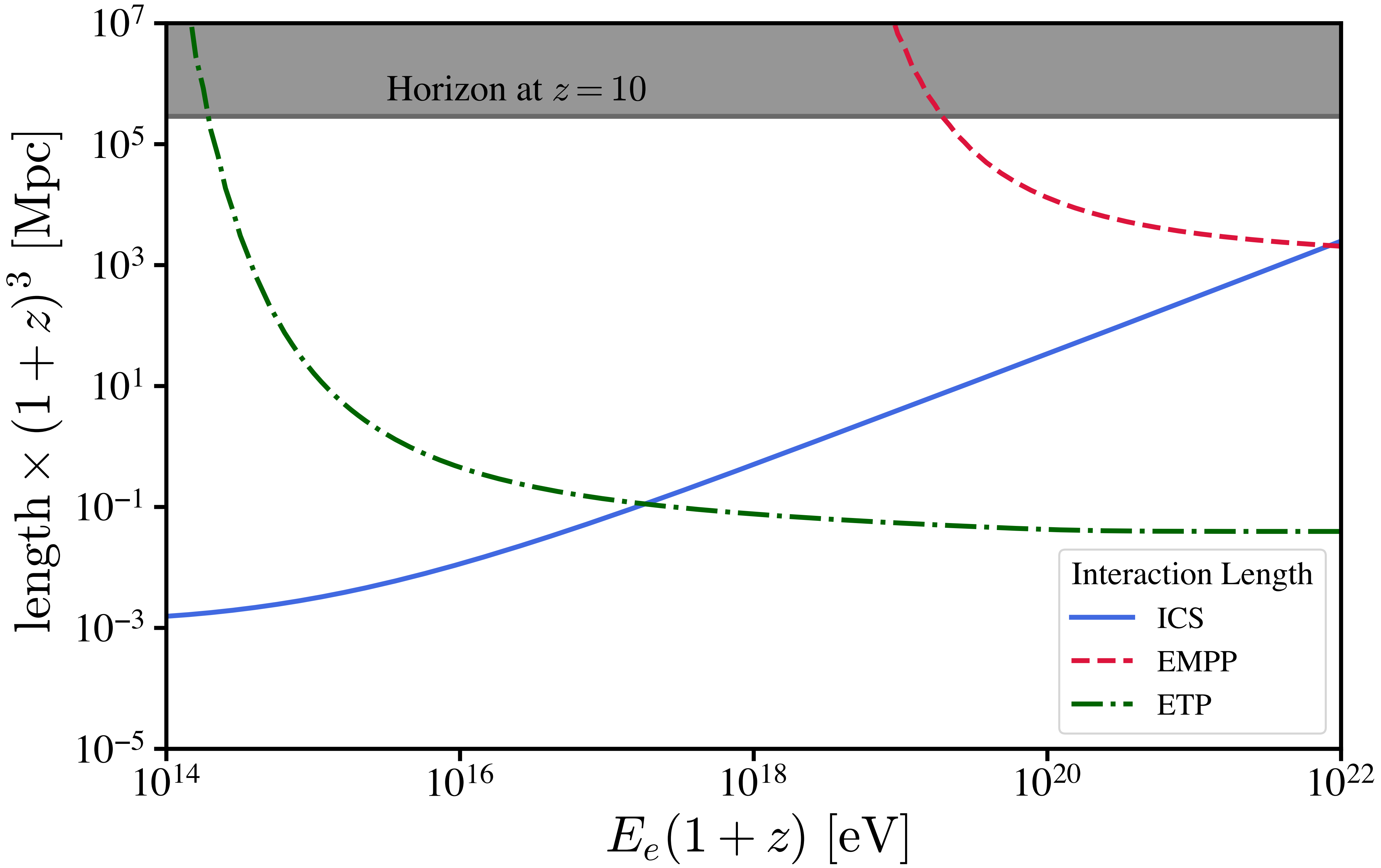
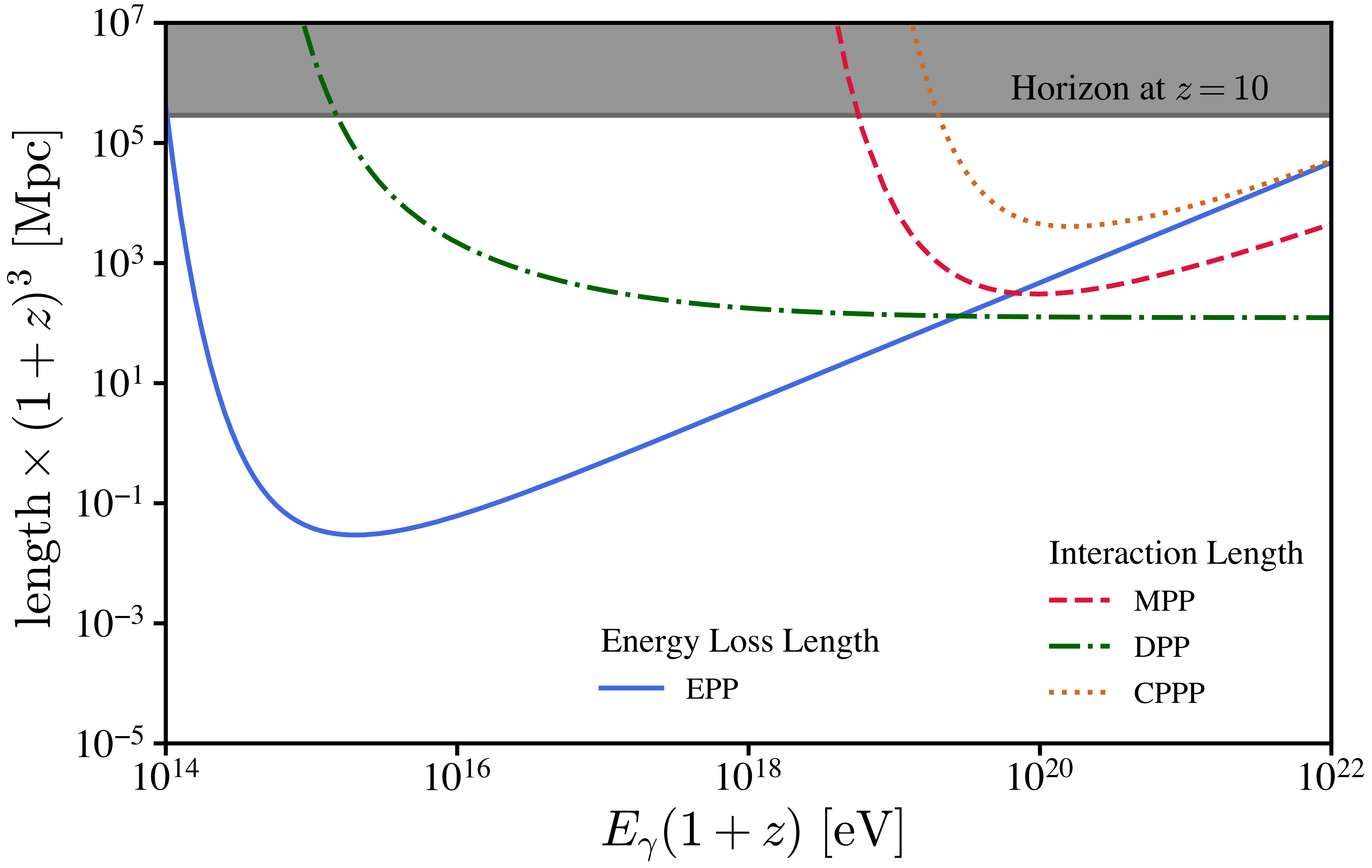
Answer 1: Comparing the lengths!

For Cosmological Distance Propagation ($z > 5$)
→ CMB is the only background photon field





CPPP for the first Born approximation

Interaction length (mean free path) $\lambda_i(E) = \dfrac{1}{\int \mathrm{d}\epsilon \int \mathrm{d}\mu\, P(\mu)\, n_{\mathrm{CMB}}(\epsilon)\, \sigma_i(s)}$

Energy loss length $\Lambda_i(E) = \dfrac{1}{\int \mathrm{d}\epsilon \int \mathrm{d}\mu\, P(\mu)\, n_{\mathrm{CMB}}(\epsilon)\, \sigma_i(s)\, [1 - \eta_i(s)]}$

$P(\mu) = (1 - \cos\theta)/2$ Flux Factor

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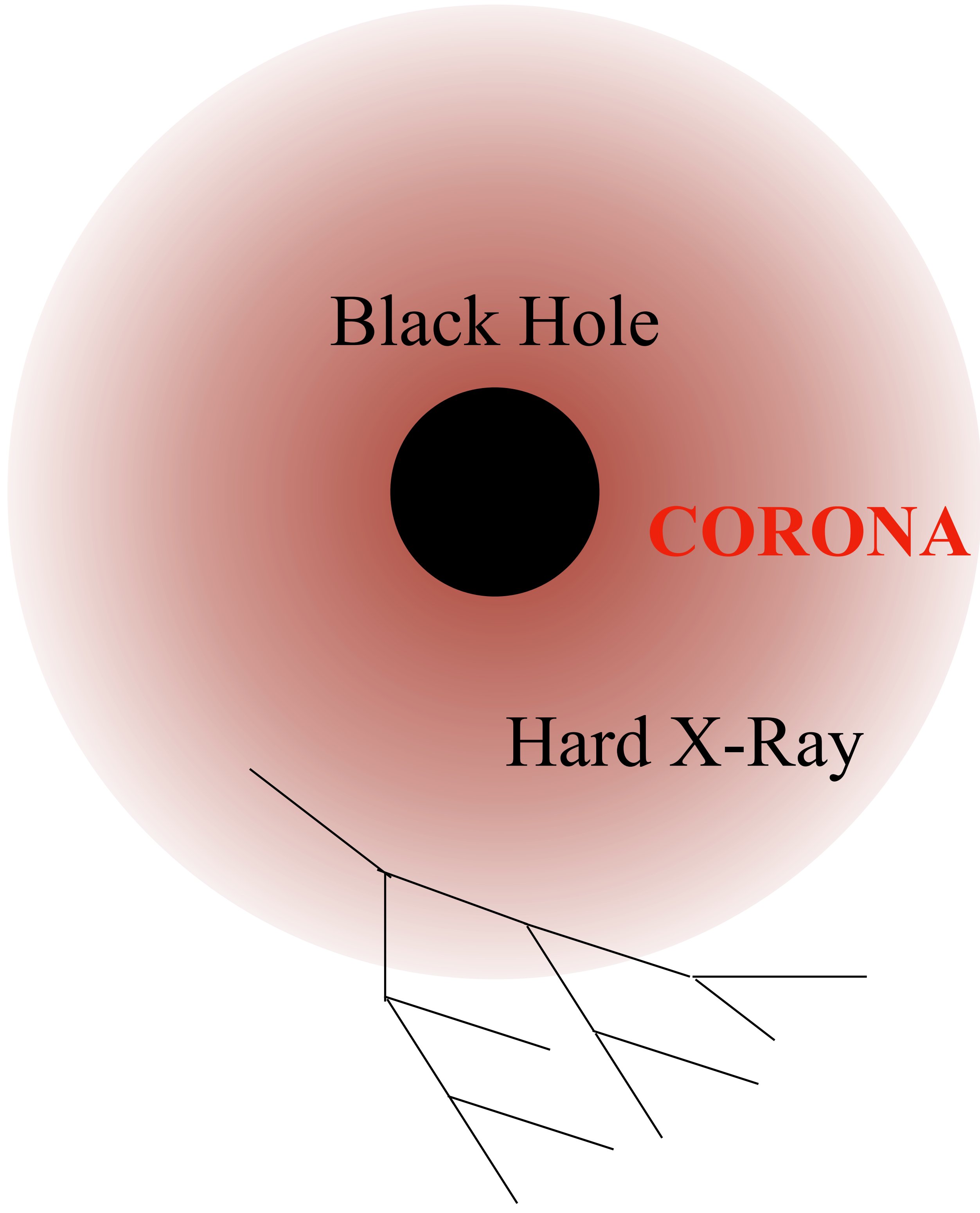
The cascade also can happen inside an astrophysical source

Although very model dependent!



$\gamma\gamma_b$
- EPP
- MPP
- DPP: **New numerical reassessment**
- CPPP: **First Born Approximation**

$e\gamma_b$
- ICS
- EMPP: **New numerical reassessment**

Stochastic Nature of the Process

↓

Monte Carlo Simulation

↓

MUNHECA

Python3 framework

- Cosmological Distances Propagation
- Inside Astrophysical Sources (A pure leptonic process for ν production)

MUons and **N**eutrinos in **H**igh-energy **E**lectromagnetic **CA**scades.
https://github.com/afesmaeili/MUNHECA.git

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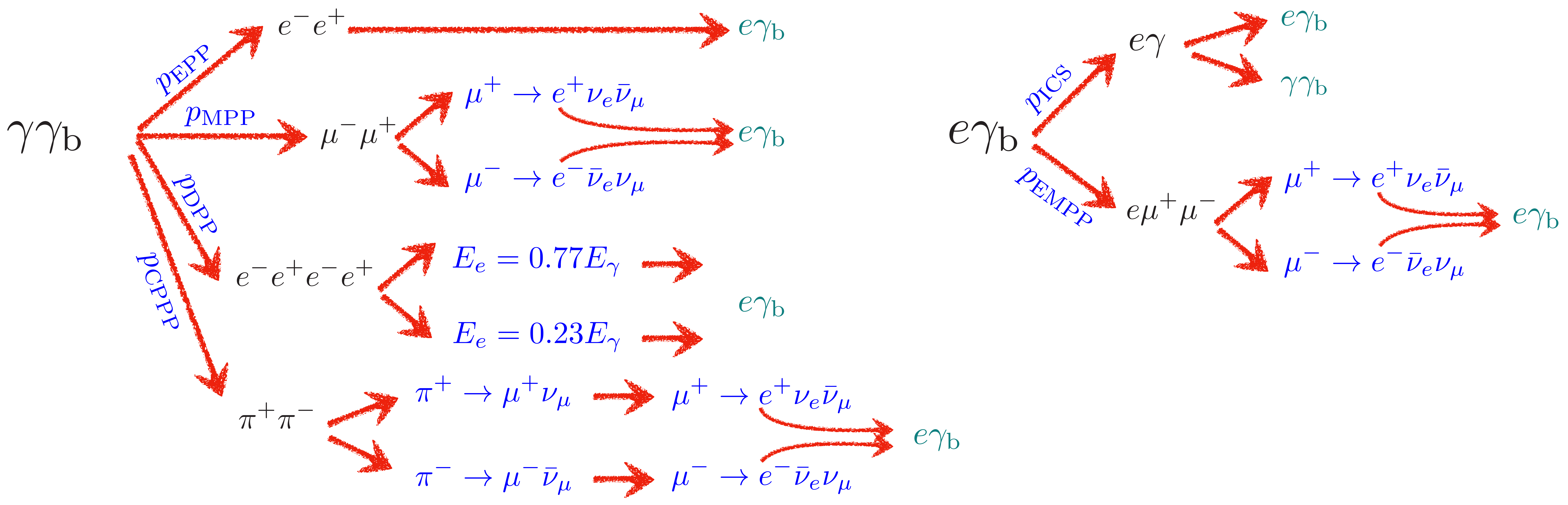


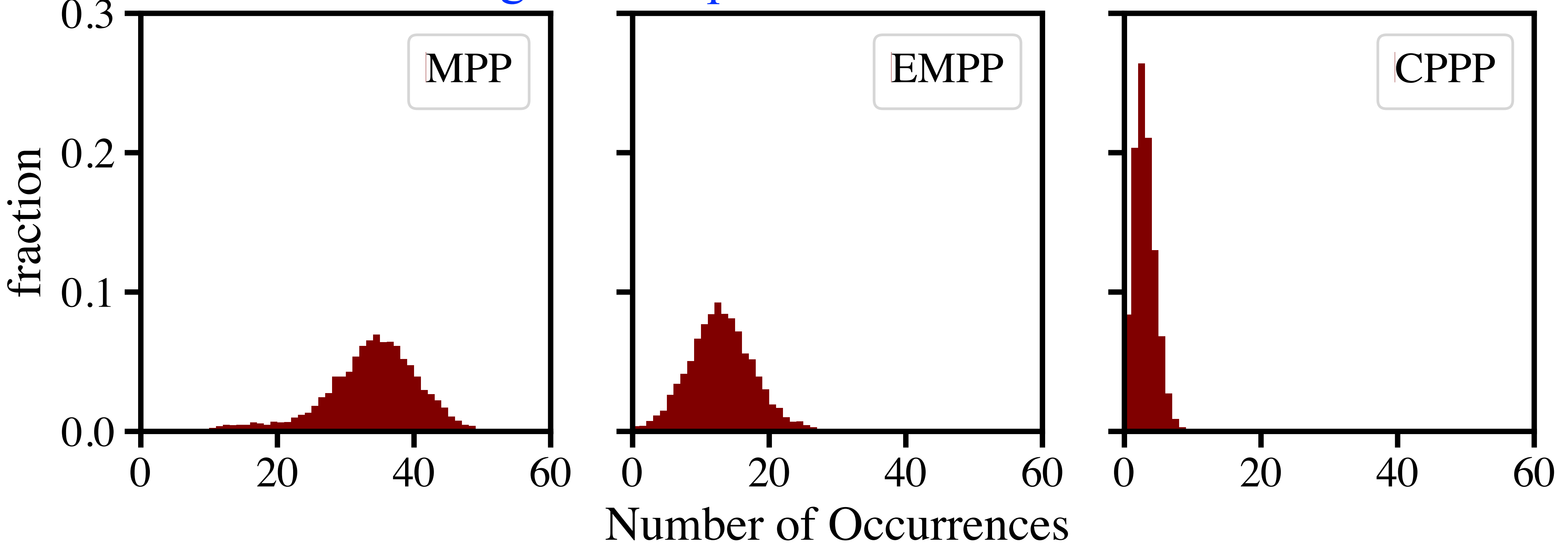
Probabilities are the ratio of the cross-sections

The Monte Carlo will be stopped at the "Break point" given by user!

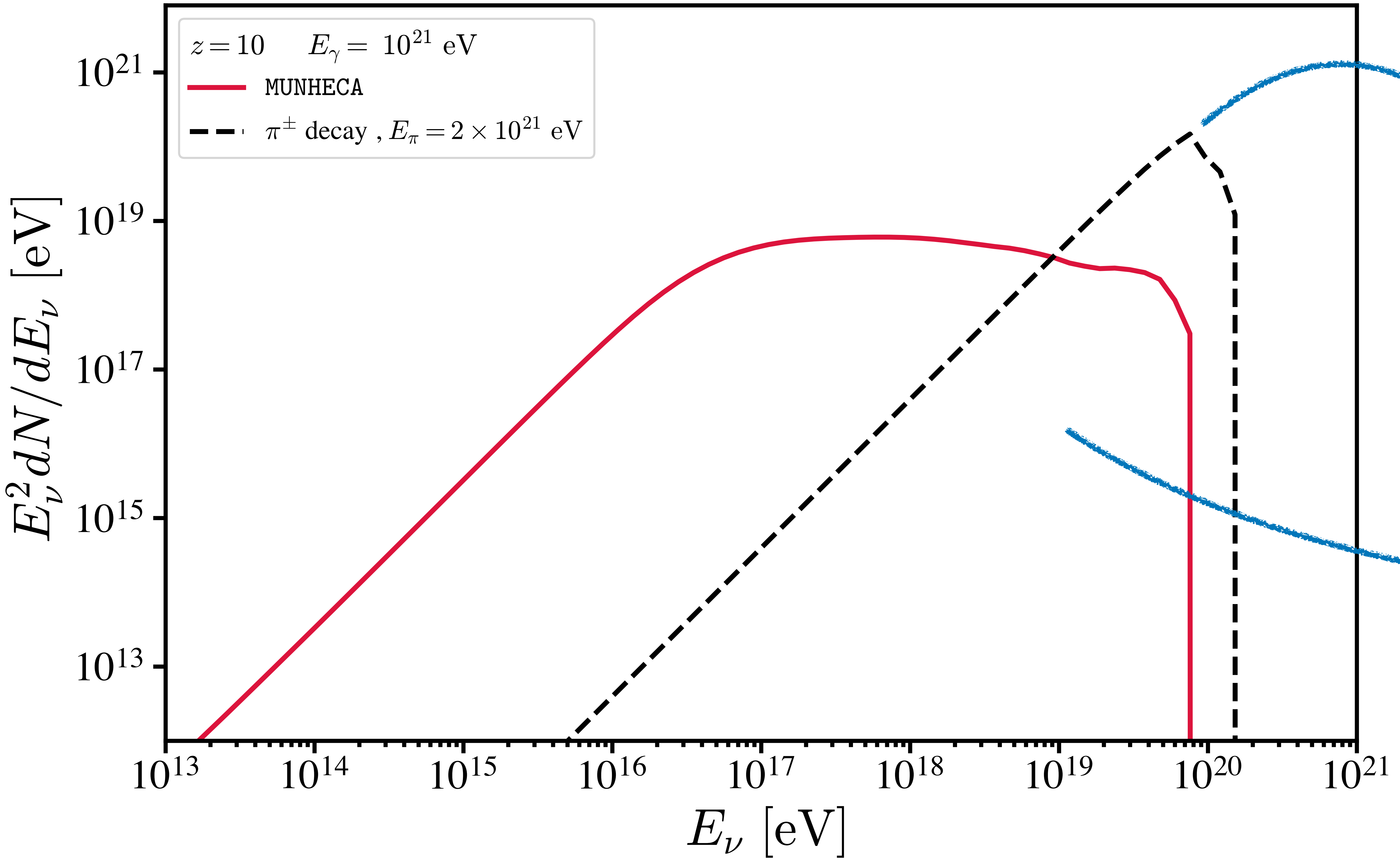
CASE 1: Cosmological Distances Propagation

Initial photon injection at redshift $z = 10$, $E_\gamma = 10^{21}$ eV

Number of neutrino generator processes occurrence in 5000 realizations



20 - 30 % of the leading photon energy
will be carried by the NEUTRINOS,
depending on the leading and background photon's energies



Monochromatic neutrino from $\pi^\pm \rightarrow \mu^\pm \nu_\mu(\bar{\nu}_\mu)$

Comparison to the conventional (Hadronic)
cosmogenic ν production scenario

Continuous neutrino spectrum from
$\mu^\pm$ decay of $\pi^\pm \rightarrow \mu^\pm \nu_\mu(\bar{\nu}_\mu)$

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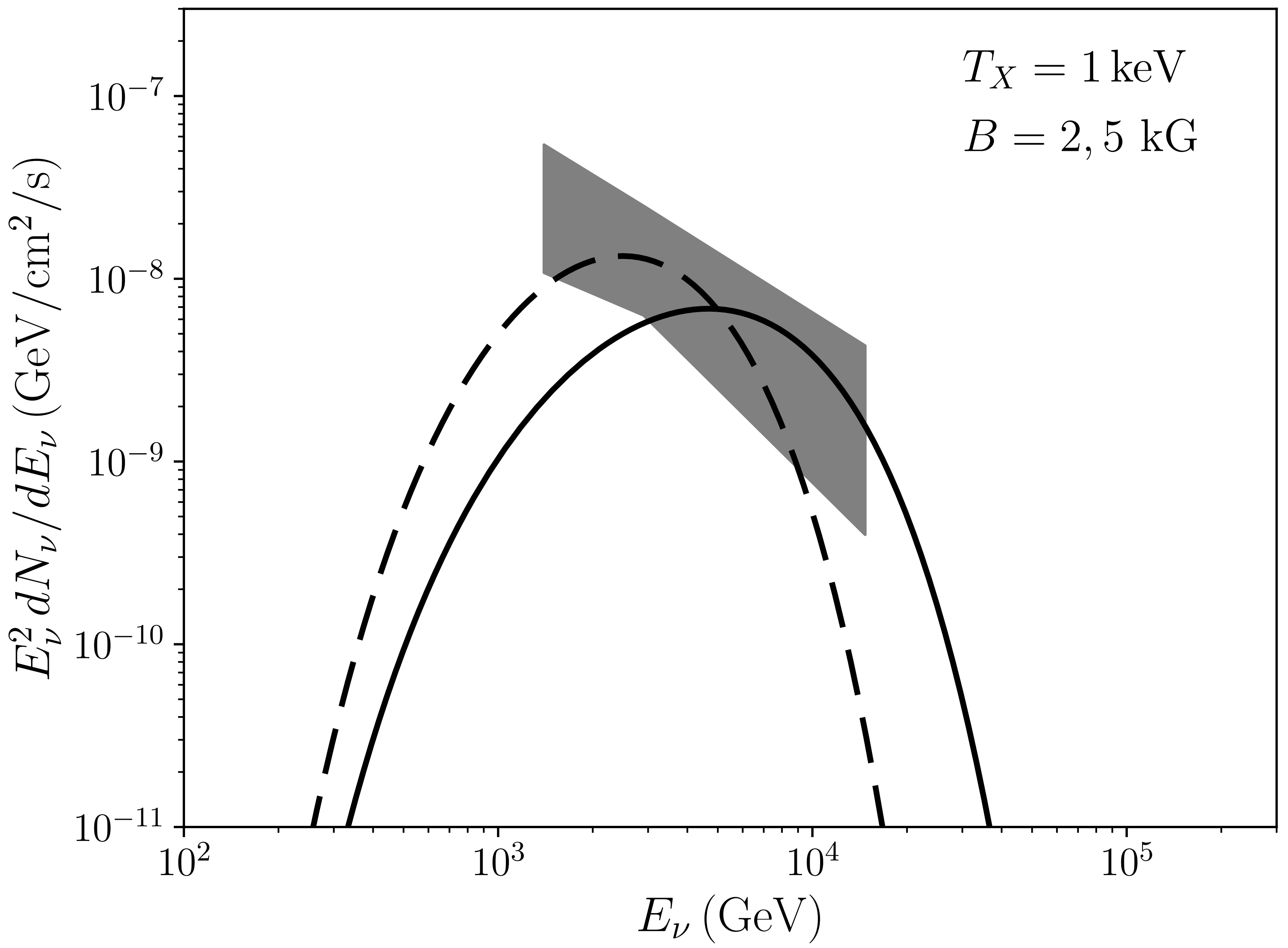
CASE 2: Leptonic Model For NGC1068

A Leptonic Model for Neutrino Emission From Active Galactic Nuclei

Dan Hooper[1,2,3*] and Kathryn Plant[4†]
[1] *Fermi National Accelerator Laboratory, Theoretical Astrophysics Department, Batavia, IL, USA*
[2] *University of Chicago, Department of Astronomy & Astrophysics, Chicago, USA*
[3] *University of Chicago, Kavli Institute for Cosmological Physics, Chicago, IL, USA and*
[4] *California Institute of Technology, Department of Astronomy, Pasadena, CA, USA*
(Dated: May 22, 2023)

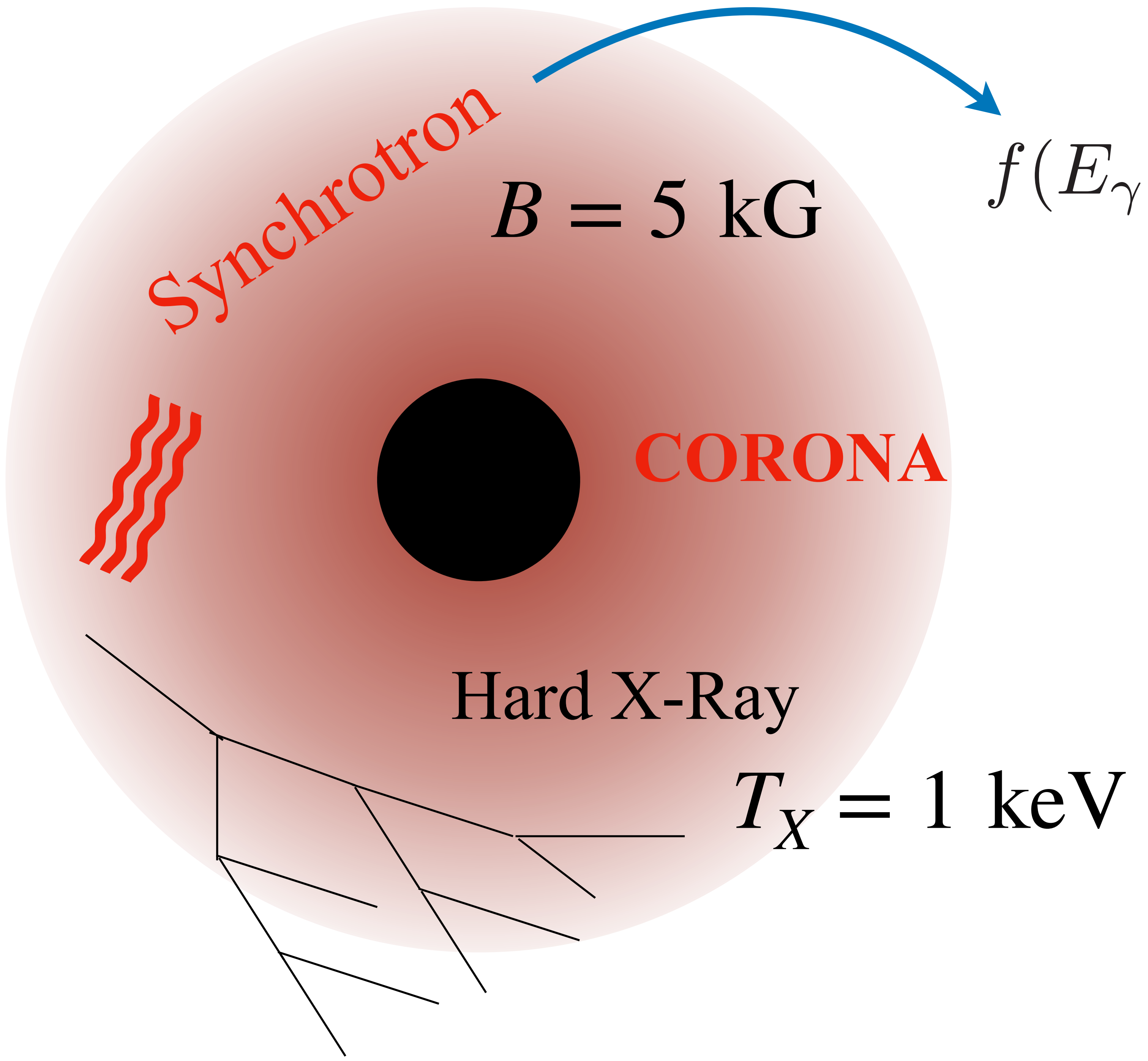
It is often stated that the observation of high-energy neutrinos from an astrophysical source would constitute a smoking gun for the acceleration of hadronic cosmic rays. Here, we point out that there exists a purely leptonic mechanism to produce TeV-scale neutrinos in astrophysical environments. In particular, very high-energy synchrotron photons can scatter with X-rays, exceeding the threshold for muon-antimuon pair production. When these muons decay, they produce neutrinos without any cosmic-ray protons or nuclei being involved. In order for this mechanism to be efficient, the source in question must produce very high-energy photons which interact in an environment that is dominated by keV-scale radiation. As an example, we consider the active galaxy NGC 1068, which IceCube has recently detected as a source of TeV-scale neutrinos. We find that the neutrino emission observed from this source could potentially be generated through muon pair production for reasonable choices of physical parameters.

https://arxiv.org/pdf/2305.06375.pdf



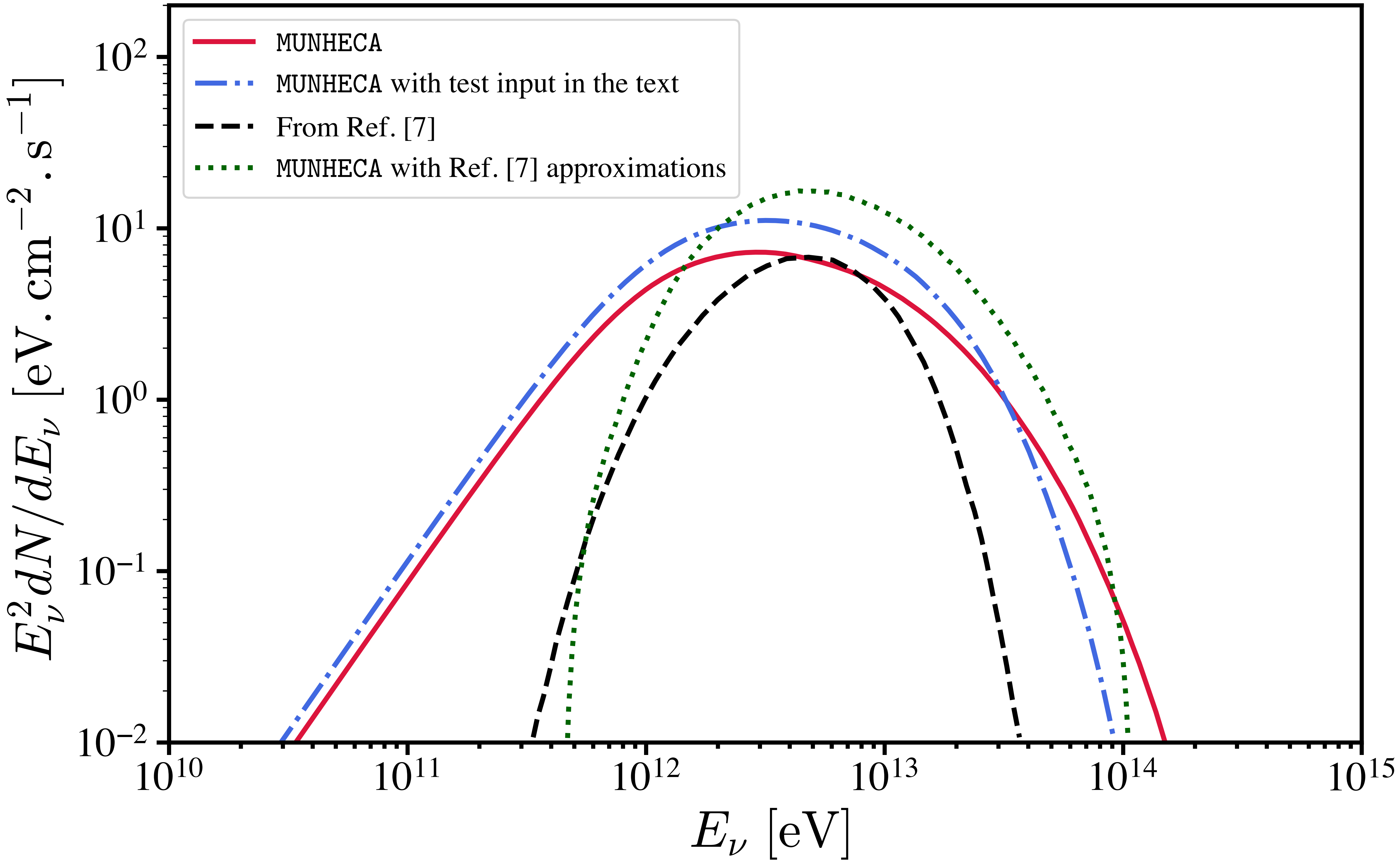
- DPP, CPPP and EMPP are NOT taken into account
- $\eta_{\text{MPP}} = 0.5$ is supposed
- Multiple muon production is neglected

CASE 2: Leptonic Model For NGC1068



$$f(E_\gamma) = E_\gamma^{-1.5} \exp\left[\sqrt{2\pi m_e^3 E_\gamma / eB} / (300\mathrm{TeV})\right]$$

The total power injected above 1 TeV is 1.2×10^{43} erg/s



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Recap and Conclusion:

- A pure leptonic process for ultra-high and high energy neutrino production ($s >$ muon production threshold)
- 20 - 30 % of the injected energy channels to neutrinos
- MUNHECA gives us this neutrino spectrum
- Detection: Upcoming experiments, e.g. GRAND and IceCube-Gen2

Future:

- Next Version of MUNHECA:
  - Full set of non-negligible hadronic processes
  - Magnetic field inside the astrophysical source
- SuperMassive Black Hole (SMBH)
- Super Heavy Dark Matter (SHDM)

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- A. Esmaeili, A. Capanema, A. Esmaili and P. D. Serpico, https://doi.org/10.1103/PhysRevD.106.123016

- A. Esmaeili , A. Esmaili and P. D. Serpico, arXiv: 2310.01510

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Thank you!

Back-up Slides

Neglected Processes:

ETP → In the CoM frame the electron will be scattered in the forward direction and the $e^{\pm}$ will be scattered backward.
Doing the Lorentz transformation from CoM to Lab frame, the backward pair takes $\mathcal{O}(10^{-5})$ fraction of the initial electron's energy.

Radiative Correction → According to the seminal paper R. J. Gould, Astrophys. J. 230, 967 (1979)
The sum of the amplitudes for these processes not only cures the infrared divergence in cross section but also cancels the apparent increase of double Compton scattering cross section at high energy, such that the total cross section of these processes only differs at the few percent level from the leading-order cross section of the single Compton scattering.

EPMPP → It's cross-section is 3 orders of magnitude less than the DPP

Inelasticity Calculation:

(*)

Usually we have the $\mathrm{d}\sigma/\mathrm{d}E$ in the CoM frame → Boost to the Lab Frame

For the interactions that we have considered $\frac{\mathrm{d}\sigma}{\mathrm{d}E_{\mathrm{out}}}\mathrm{d}E_{\mathrm{out}} = \frac{\mathrm{d}\sigma}{\mathrm{d}E^*_{\mathrm{out}}}\mathrm{d}E^*_{\mathrm{out}}$

And the Lorentz transformation can be approximated by $E_{\mathrm{out}} = E^*_{\mathrm{out}}\gamma_c(1 \pm \beta^*_{\mathrm{out}})$ → Forward/Backward

$\gamma_c = E_{\mathrm{out}}/\sqrt{s}$ velocity of the outgoing particle

As $\beta_{\mathrm{out}} \to 1$ → the inelasticity of the forward scattered particles:

$$\eta_+(s) = \frac{1}{\sigma}\int_0^{\sqrt{s}/2} \frac{2E^*_{\mathrm{out}}}{\sqrt{s}} \frac{\mathrm{d}\sigma}{\mathrm{d}E^*_{\mathrm{out}}} \mathrm{d}E^*_{\mathrm{out}}$$

For the backward scattered particles : $E_{\mathrm{out}} = E^*_{\mathrm{out}}\gamma_c(1-\beta^*_{\mathrm{out}}) = \frac{E^*_{\mathrm{out}}\gamma_c}{(\gamma^*_{\mathrm{out}})^2(1+\beta^*_{\mathrm{out}})} \simeq \frac{\gamma_c m^2}{2E^*_{\mathrm{out}}}$

$$\rightarrow \quad \eta_-(s) = \frac{1}{\sigma}\int_{\frac{m^2}{2\sqrt{s}}}^{\sqrt{s}/2} \frac{m^2}{2\sqrt{s}} \frac{1}{E^*_{\mathrm{out}}} \frac{\mathrm{d}\sigma}{\mathrm{d}E^*_{\mathrm{out}}} \mathrm{d}E^*_{\mathrm{out}}$$

Inelasticity Calculation:

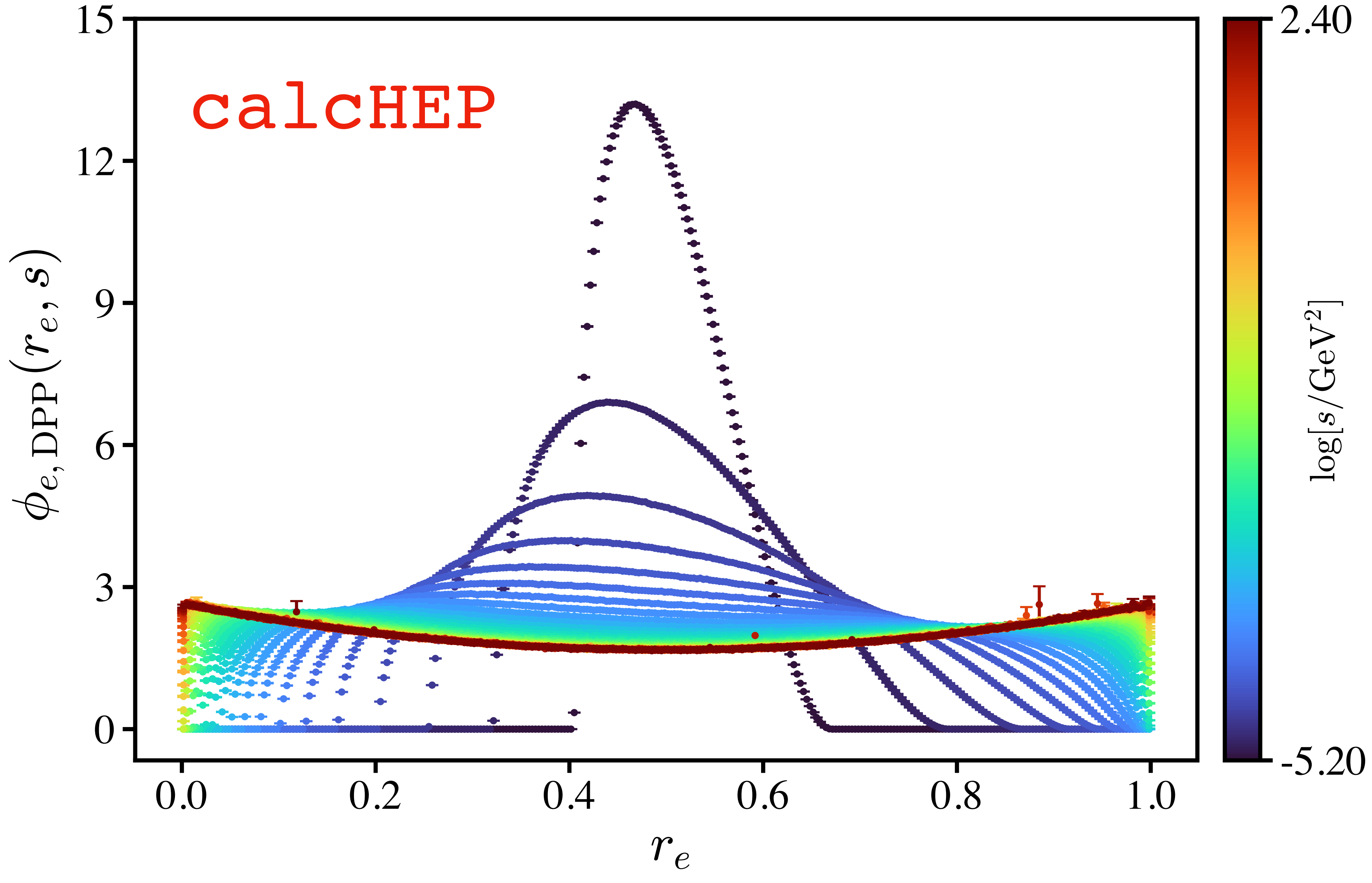
$$\frac{\mathrm{d}\sigma_\ell}{\mathrm{d}E^*}(s) = \frac{1}{\sqrt{s}}\,\phi_\ell(r_\ell, s)\sigma_{\text{tot}}(s)$$

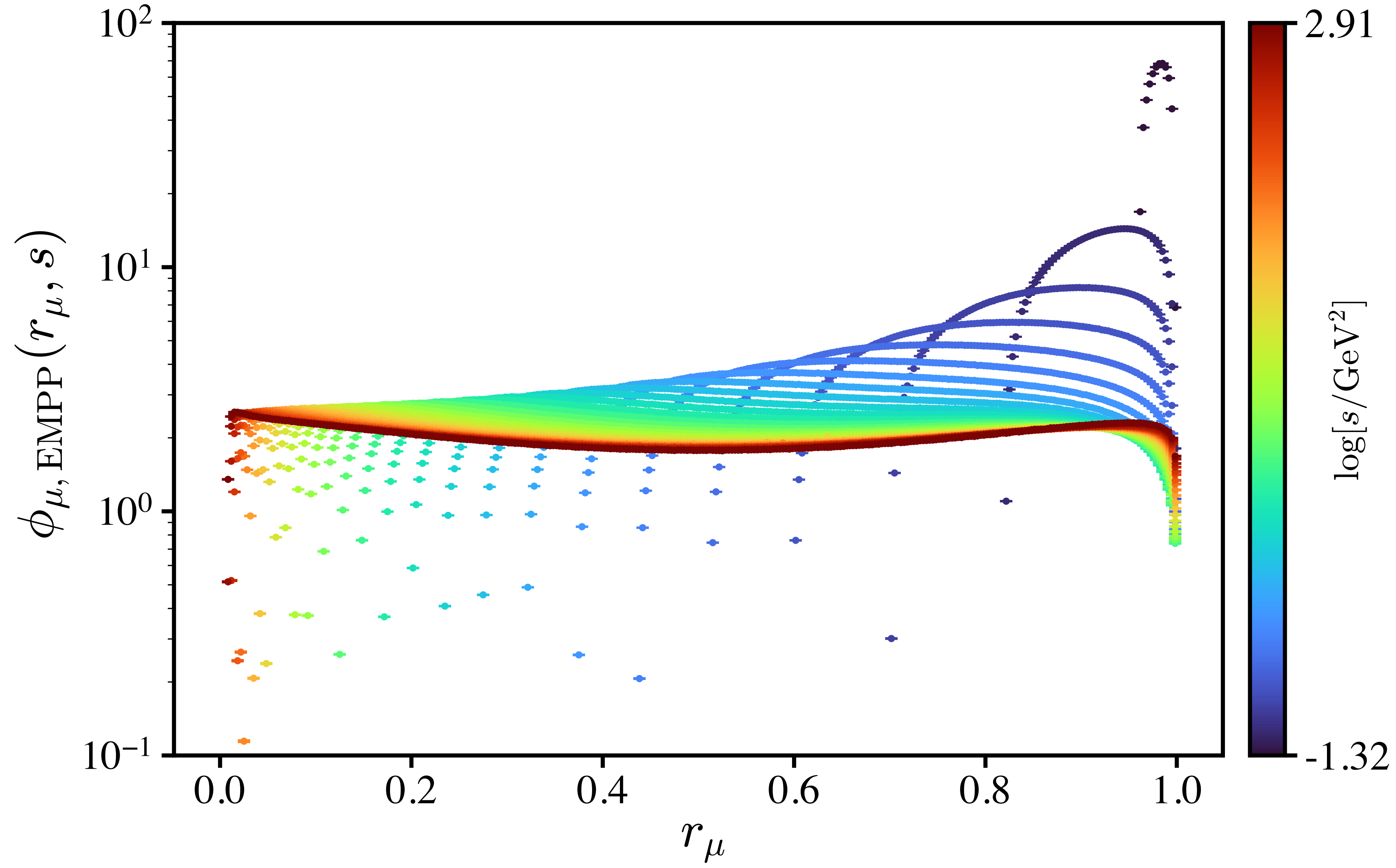
$$\int_0^1 \phi_\ell(r_\ell, s)\,\underset{\cdot}{\mathrm{r}}_\ell = 2$$ Probability Conservation

$$\sum_\ell \int_0^1 r_\ell \phi_\ell(r_\ell, s)\,\underset{\cdot}{\mathrm{r}}_\ell = 4$$ Energy Conservation

$$\eta_{\ell,+}(s) = \int_0^1 \frac{r_\ell}{2}\,\phi_\ell(r_\ell, s)\,\underset{\cdot}{\mathrm{r}}_\ell$$

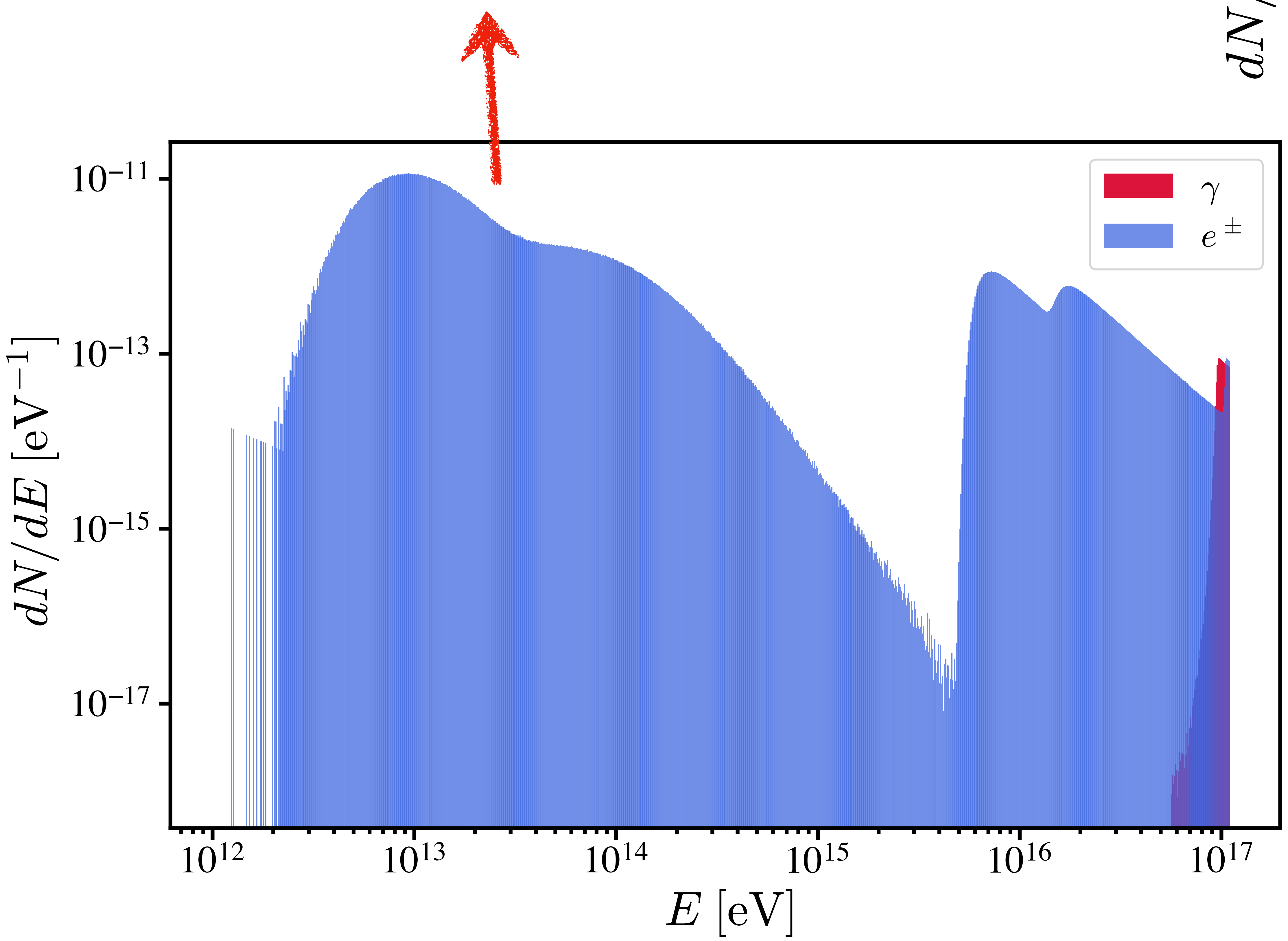
$$\eta_{\ell,-}(s) = \int_{\frac{m^2}{s}}^1 \frac{m^2}{2sr_\ell}\,\phi_\ell(r_\ell, s)\,\underset{\cdot}{\mathrm{r}}_\ell$$

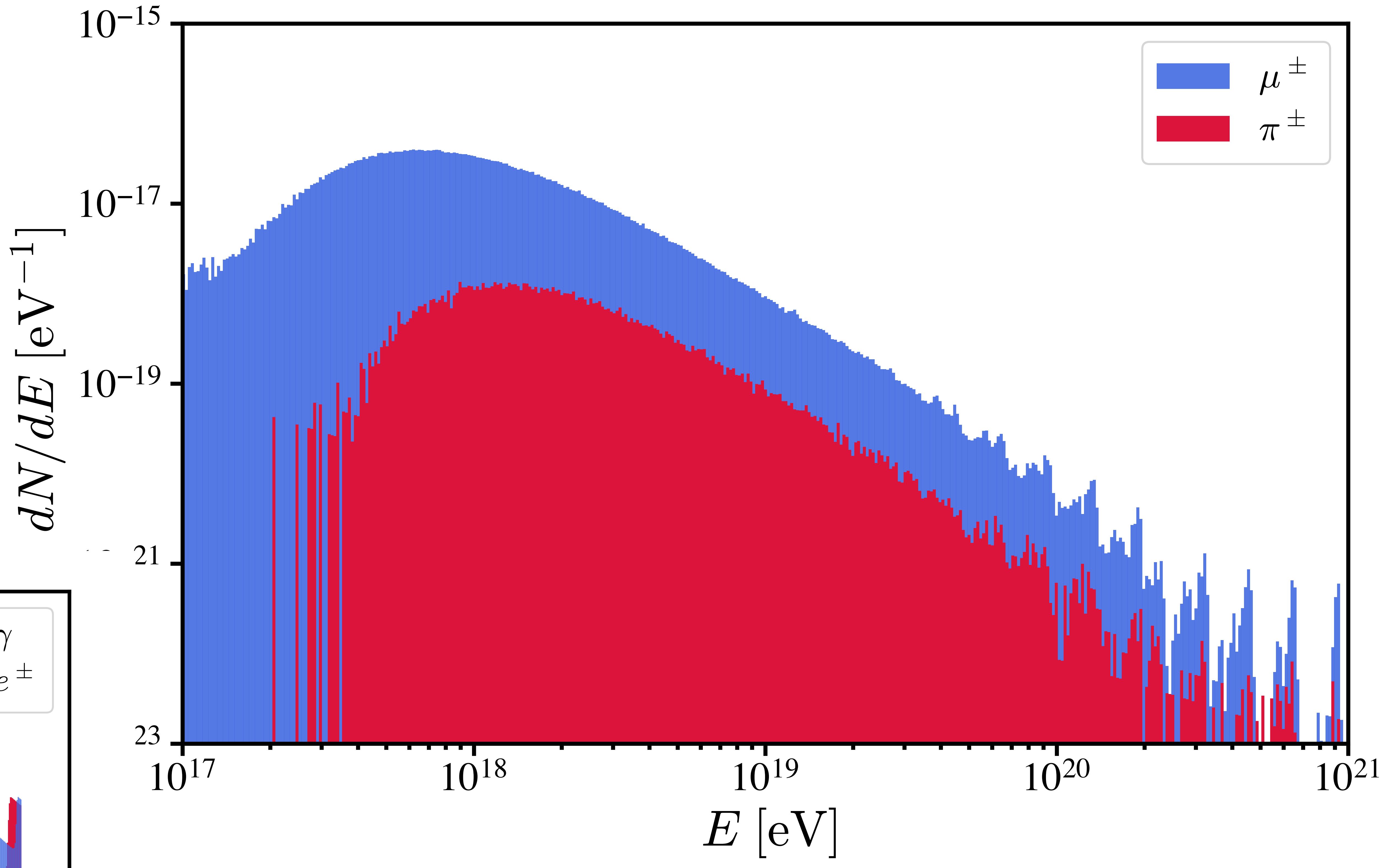




CASE 1: Cosmological Distances Propagation

The $e^{\pm}$ pair of DPP [backward scattered] which takes $\ll 1$ fraction of initial energy





Muon and Pion Spectra

Gamma-ray and Electron Spectra below the break point

Work — vi test.txt — 143×41

```
# Test file to run

# INTERACTIONS:

MPP: ON                                                                          #(ON / OFF)
DPP: ON                                                                          #(ON / OFF)
EMPP: ON                                                                         #(ON / OFF)
CPPP: ON                                                                         #(ON / OFF)

# BACKGROUND PHOTON FIELD: Source can be "CMB", "BlackBody" or "PowerLaw"

Source: CMB                                                                      #(CMB / BlackBody / PowerLaw)

# BLACKBODY DISTRIBUTION SETTING:

Temperature: 1.0e+3                                                              # [eV]
BB_E_min: 1e+0                                                                   # MINIMUM ENERGY FOR THE BLACKBODY DISTRIBUTION [eV]
BB_E_max: 4e+4                                                                   # MAXIMUM ENERGY FOR THE BLACKBODY DISTRIBUTION [eV]

# POWERLAW DISTRIBUTION SETTING:

PL_E_min: 1000                                                                   # MINIMUM ENERGY FIR THE POWERLAW DISTRIBUTION[eV]
PL_E_max: 1e+4                                                                   # MAXIMUM ENERGY FIR THE POWERLAW DISTRIBUTION[eV]
PL_index: 1.5                                                                    # POWERLAW INDEX (WITHOUT THE MINUS SIGN)

# HIGH-ENERGY PHOTON INJECTION:

Redshift: 10                                                                     # REDSHIFT OF THE SOURCE

INJ_Spectrum: Monochrome                                                         # HIGH-ENERGY SPECTRUM CHOICE CAN BE 'Monochrome' OR 'PowerLaw'


# INJECTION SPECTRUM SETTING - MONOCHROME:

E_gamma: 1e+20                                                                   # ENERGY OF THE INJECTED PHOTONS.
Number_of_photons: 5                                                             # NUMBER OF PHOTONS INJECTED (NUMBER OF MONTE CARLO REALIZATION
)


# INJECTION SPECTRUM SETTING - POWERLAW:
```

Work — vi test.txt — 143×41

```
# INJECTION SPECTRUM SETTING - MONOCHROME:

E_gamma: 1e+20                                                              # ENERGY OF THE INJECTED PHOTONS.
Number_of_photons: 5                                                        # NUMBER OF PHOTONS INJECTED (NUMBER OF MONTE CARLO REALIZATION
)


# INJECTION SPECTRUM SETTING - POWERLAW:

INJ_Emin: 1e+12                                                             # MINIMUM ENERGY OF THE INJECTED PHOTONS [eV]
INJ_Emax: 3e+14                                                             # MAXIMUM ENERGY OF THE INJECTED PHOTONS [eV]
INJ_SPEC_Index: 1.5                                                         # INDEX OF THE POWERLAW SPECTRUM
EXP_HIGH_CUTOFF: ON                                                         # IF YOU ARE SETTING AN EXPONENTIAL CUTOFF AT HIGH-ENERGY
EXP_LOW_CUTOFF: OFF                                                         # IF YOU ARE SETTING AN EXPONENTIAL CUTOFF AT LOW-ENERGY
ExpCut_HighEnergy: 3.16e+12                                                 # EXPONENTIAL CUTOFF HIGH-ENERGY [eV]
ExpCut_LowEnergy: 1e+19                                                     # EXPONENTIAL CUTOFF LOW-ENERGY [eV]
PHOTON_PER_BIN: 10                                                          # NUMBER OF PHOTONS PER BIN (UNIFORM SPECTRUM)
NUMBER_OF_BINS: 10                                                          # NUMBER OF BINS BETWEEN 'INJ_Emin' AND 'INJ_Emax'


BREAK_Energy: 1.1e+17                                                       # BREAKING ENERGY OF THE MONTE CARLO [eV]


# DESTINATION FILE NAME:

DESTINATION_DIR: test_E21EV_Z10                                             # DESTINATION FILE NAME IN /results/


# OUTPUT FILES FOR MONOCHROME INJECTION:

Muon_Output: muons_1                                                        # SET THE OUTPUT FILES NAMES WITHOUT FILE FORMAT (.txt , .csv ,
 ...)
Pion_Output: pions_1
Gamma_Output: gamma_hist_1
Electron_Output: electron_hist_1
Neutrino_Output: neutrinos_1
EMPP_Output: Number_of_EMPP_1
MPP_Output: Number_of_MPP_1
CPPP_Output: Number_of_CPPP_1
```