LeHaMoC: an open-source leptohadronic code for multi-messenger modeling

D. Karavola[1]†, S. I. Stathopoulos[1], M. Petropoulou[1,2,†], G. Vasilopoulos[1,2], K. Xyloportas[1]
[1]National & Kapodistrian University of Athens (Greece), [2]IASA (Greece)

Abstract

Recent associations of high-energy neutrinos with AGN have rekindled interest in leptohadronic models of radiation from astrophysical sources. The rapid growth in multi-messenger data acquisition highlights an emerging need for fast numerical models capable of application to large source samples. In this contribution, we introduce `LeHaMoC`, an open-source, versatile leptohadronic code. `LeHaMoC` is specifically designed for modeling time-variable, non-thermal emission from compact astrophysical sources, including blazar jets, AGN coronae, and gamma-ray bursts (GRBs). We showcase recent applications, such as blazar SED fitting using Bayesian inference techniques, modeling X-ray and γ-ray variability in blazars, and exploring high-energy neutrino associations. Additionally, we discuss its role in training deep neural networks - an essential step toward achieving more efficient computations and exploring larger parameter spaces.

Blazar Jet Emission

• **Bayesian fitting of stationary blazar SEDs.** Leptonic MCMC fitting (`emcee`) is feasible using reasonable computational resources, such as a high-performance desktop or workstation equipped with 32–64 CPU cores. Measurements and upper limits are included in the likelihood function calculation. An example is shown in Fig. 2.

• **Time-dependent modeling of blazar multi-wavelength variability.** The code supports user-defined time series for all parameters, either in tabulated or functional form. An example is displayed in Fig. 3.

• **Calculation of neutrinos and hadronic cascades.** The code computes secondary emission from hadronic cascades and its feedback on all relevant particle populations. Fig. 1 illustrates the decomposition of a leptohadronic SED into its constituent processes.

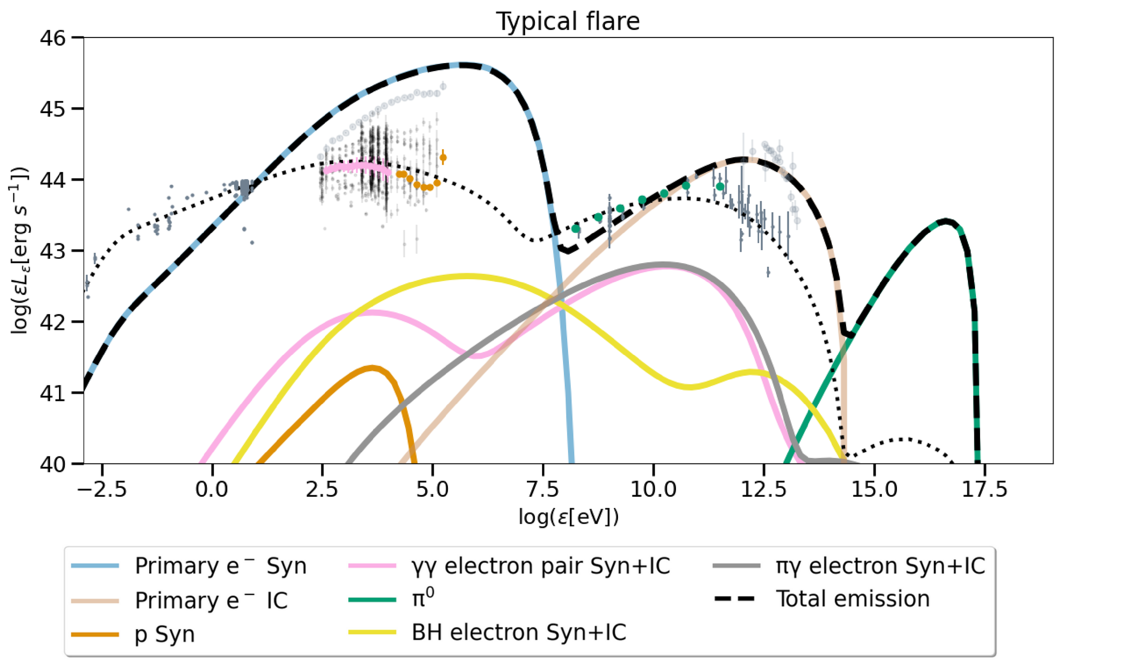

Figure 1: Lepto-hadronic model for an extreme X-ray flare of Mrk 501 (dashed black line). Colored lines show the hadronic cascade spectra [4].

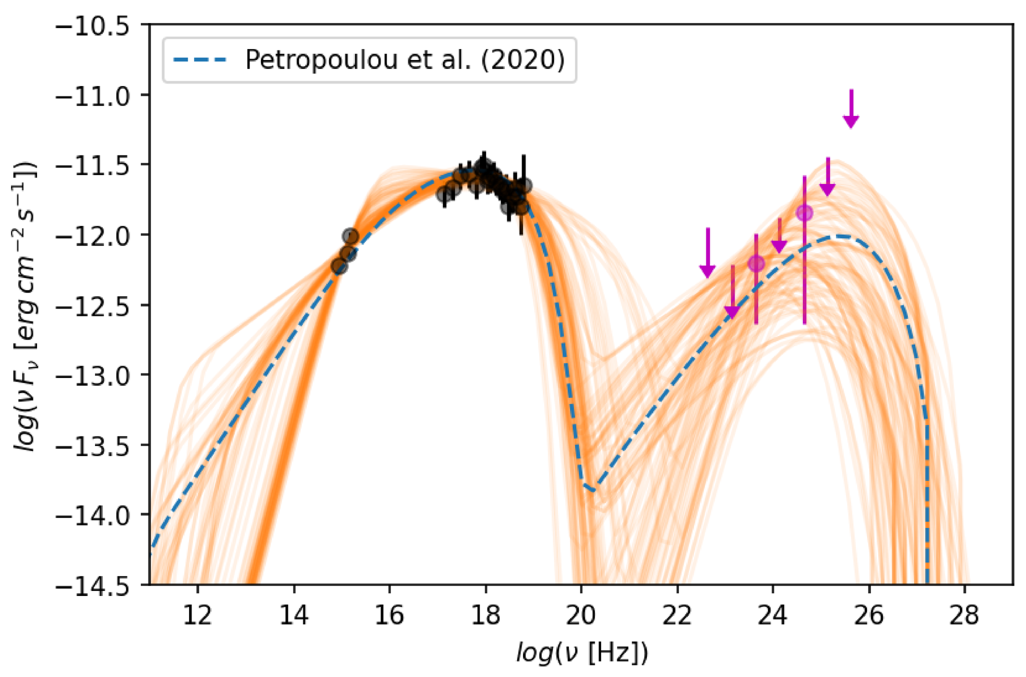

Figure 2: SED of extreme blazar 3HSP J095507.9+355101, which was tentatively associated with a neutrino alert (data from [5]). 100 SSC spectra from the posterior distributions of the MCMC fit are overplotted (orange lines). The SSC model from Petropoulou et al. [7] is also shown for comparison [8].

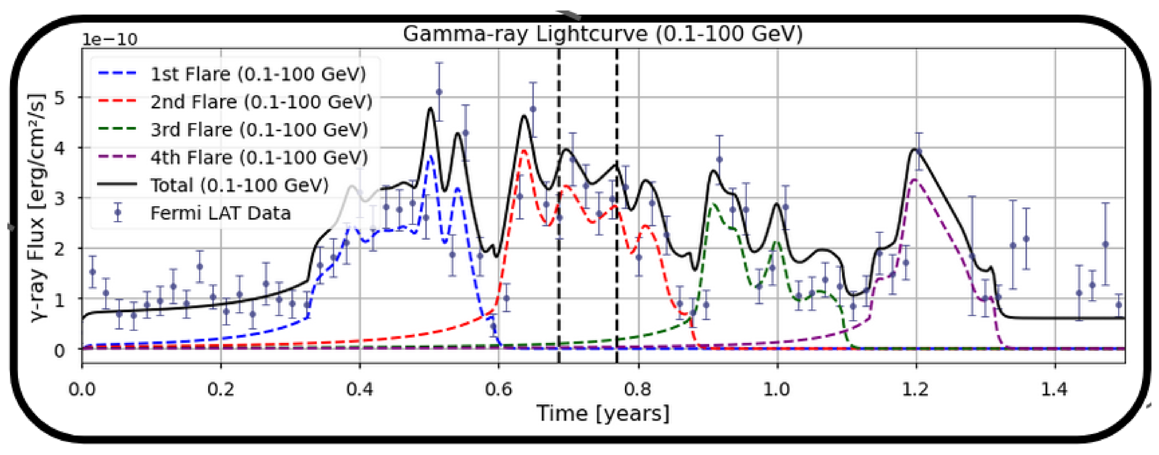

Figure 3: Time-dependent modeling of TXS 0506+056 based on its 7-day binned *Fermi*-LAT light curve. The particle injection luminosity is $\propto L_\gamma(t)$, as expected in the External Compton scenario (Stathopoulos et al., in prep).

GRB Emission

• **Time-dependent modeling of GRB emission.** The code is applicable to both the rapidly varying GRB prompt emission and the smoothly decaying afterglow, as all parameters can evolve with time. It also accounts for adiabatic expansion (density dilution and particle energy losses).

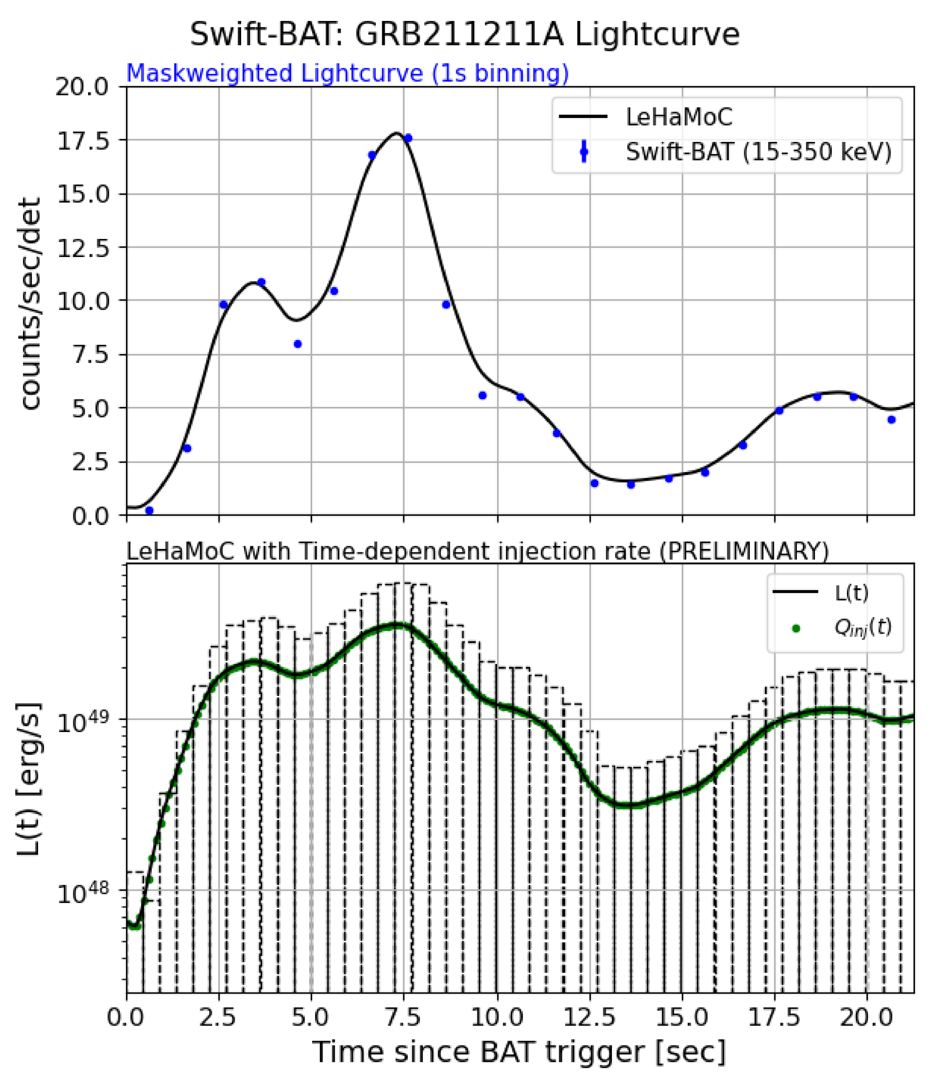

Figure 4: Prompt emission modeling of GRB 211211A using variable electron injection rate. GRB 211211A was detected by *Fermi*-GBM and *Swift*-BAT [6]. Its long duration ($\sim$ 1 min) and its brightness allow for a detailed study of its spectral and temporal evolution (Xyloportas et al., in prep.) *Top:* (Rescaled) numerical light curve (solid line) and 1-sec binned *Swift*-BAT light curve (markers). *Bottom:* The injection profile used in `LeHaMoC` (histogram) and the bolometric photon light curve (green line).

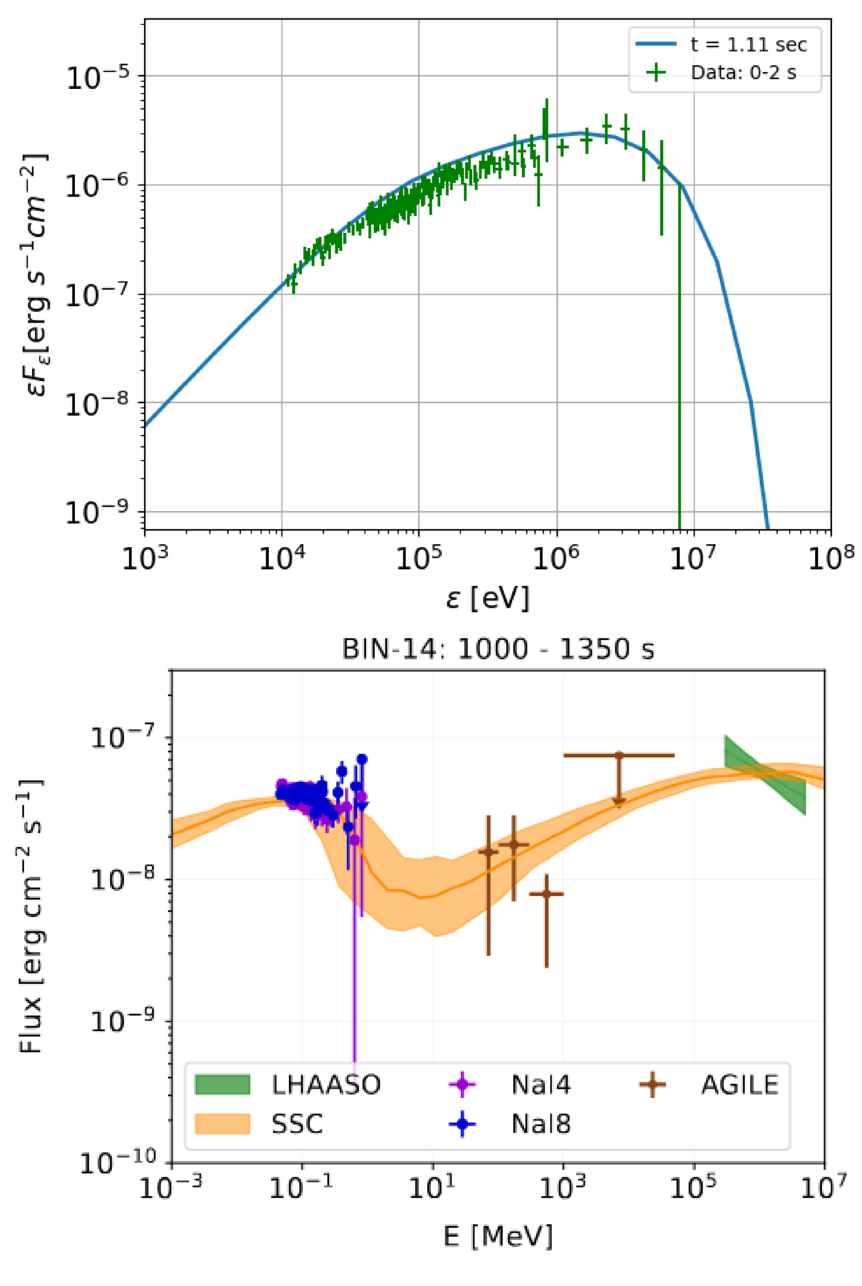

Figure 5: *Top:* Time-averaged spectrum of GRB 211221A during the 0-2 sec interval computed with `LeHaMoC` (solid line). Data are from Ref. [6]. *Bottom:* Afterglow SED of GRB 221009A for the time interval 1000 - 1350 s (post trigger). The SED is modelled with SSC and fitted using MCMC. Adopted from Ref. [1].

The Code

`LeHaMoC` is an open-source code written in Python [8]. Its performance is compared against that of other similar codes in [2]. It solves the Fokker-Planck equations of *photons, electrons, positrons, protons, and neutrinos* produced in a homogeneous magnetized source that may also be expanding. The code utilizes the Chang & Cooper method [3], a fully implicit difference scheme that allows fast computation of steady-state and dynamically evolving physical problems.

Neural Network Training

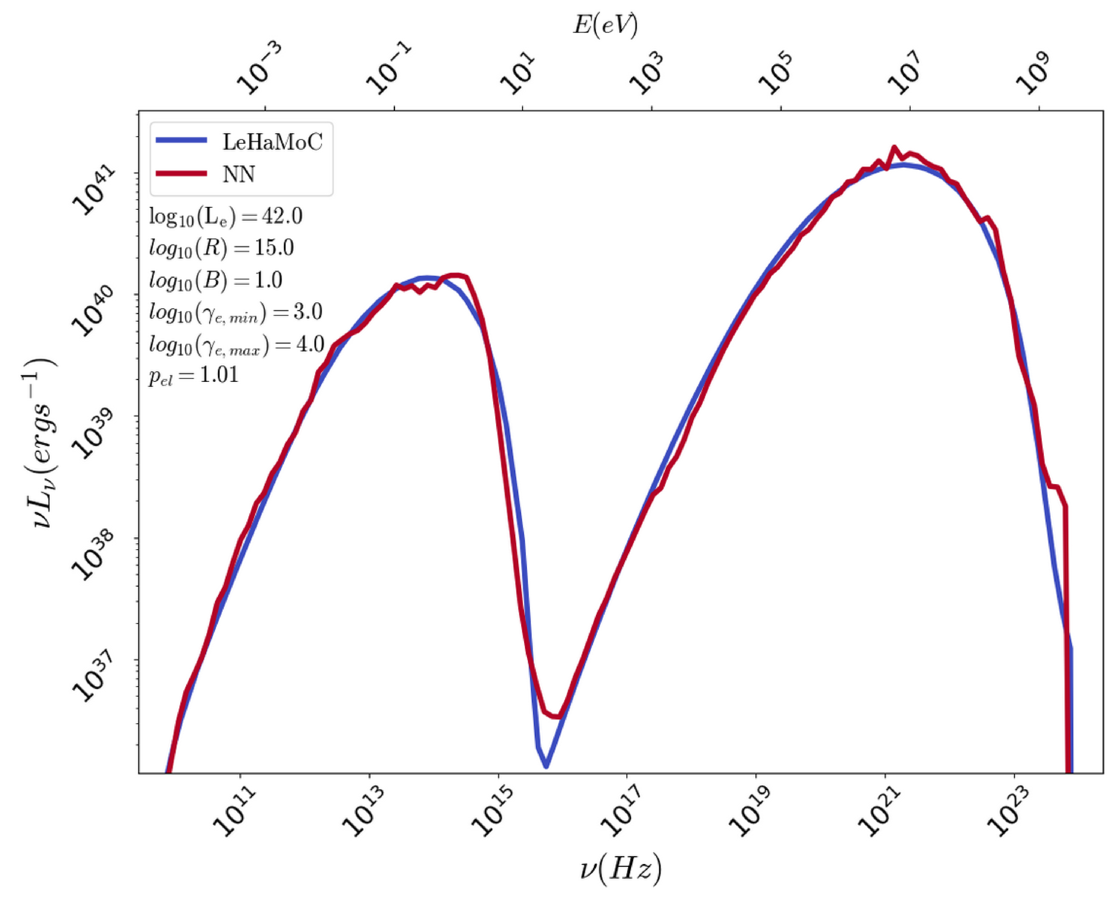

Figure 6: Example of simulated SED vs NN prediction.

NN features:

- trained on 10^5 SEDs, with only leptonic components
- GRU architecture
- 250 neurons/layer
- batch size of 32
- 500 epochs
- 6 hidden layers
- Uses 1st derivative

Conclusions & Future Work

What we offer:

• `LeHaMoC`: A simple and friedly to use open-source, versatile leptohadronic code.

• `github` repositories with examples on modeling and SED fitting usning MCMC [8] and NN [9].

• Interested in GRBs, time dependent problems etc? We are too, and `LeHaMoC` can do that as well.

Future Work:

• `LeHaMoC` is on constant develepment with improvements.

• NN training based on lepto-hadronic code currently on the way.

Feel free to use our codes in your studies and email us: mpetropo@phys.uoa.gr, stamstath@phys.uoa.gr

References

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LeHaMoC: `https://github.com/mariapetro/LeHaMoC`

NN first results: `https://github.com/tzavellas/blazar_ml`

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