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The blazar hadronic code comparison project

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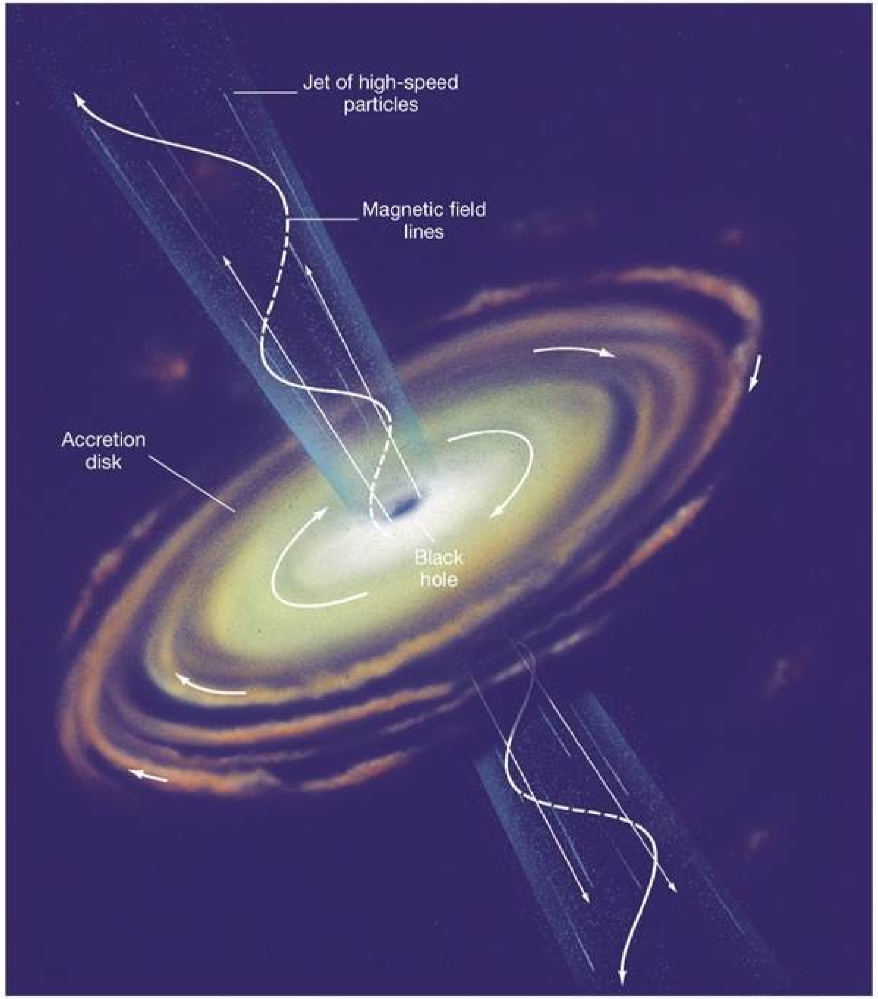

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Motivation

1. Answer one of the most essential open questions in physics: the **origin of cosmic rays**, especially their production and acceleration in the Universe.

2. Detection of **neutrinos** emitted by a particular source could help to distinguish between leptonic and hadronic scenarios, and uniquely identify cosmic ray accelerators in the Universe.

3. Up to date, no comparison between the different codes was performed, preventing an understanding of the underlying uncertainties in the numerical simulations. **We present results from the first comprehensive comparison of hadronic radiative transfer codes.**

Codes

→ **AM3** [1]: to study time-dependent, multi-wavelength, and multi-messenger signatures in AGNs as well as in prompt and afterglow phases of GRBs; computes evolution in time and energy of particle distributions for photons, electrons, positrons, protons, neutrons, muons, pions, and neutrinos.

→ **ATHEvA** [2,3,4]: time-dependent radiative transfer code, describing the evolution of relativistic particle distributions within a fixed spherical volume: protons, neutrons, electrons, positrons, photons, and neutrino. Designed to investigate electromagnetic cascades in linear and non-linear regimes, pair cascades in electrostatic gaps, radiative instabilities in relativistic plasmas, to simulate time-dependent events, i.e. flares, to model non-thermal radiation from AGNs and GRBs.

→ **B13** [5]: steady-state code to study AGN emission; evaluates equilibrium distributions of primary electrons/positrons and protons based on a balance of instantaneous injection of power-law distributions of relativistic particles with radiative and adiabatic losses as well as escape. Successfully employed to the modeling of *Fermi*-LAT detected blazars.

Codes

→ **LeHa-Paris** [6]: computes steady state photon and neutrino emission from a spherical plasmoid in the jet; primary electron and proton distributions are parameterized by broken power-law and the at-equilibrium distributions of secondary particles in the plasmoid are self-consistently computed from injection and cooling terms. Employed to study potential detection of TeV hadronic spectral features with CTA and to model emission from blazars.

Features	Codes			
	AM3	ATHEνA	B13	LeHA-Paris
steady state	✓	✓	✓	✓
time dependent	✓	✓	✗	✗
linear EM cascades	✓	✓	✓	✓
non-linear EM cascades	✓	✓	✗	✗

Main features of numerical codes and implementation of hadronic processes. Table credit: [7].

Codes

Physical Processes	Codes			
	AM3	ATHEνA	B13	LeHa-Paris
electron synchrotron radiation	✓	✓	✓	✓
synchrotron self-absorption	✓	✓	✓	✓
electron inverse Compton scattering	✓	✓	✓	✓
electron-positron annihilation	✓	✓	✓	✗
photon-photon pair production	✓	✓	✓	✓
triplet pair production	✗	✓	✗	✗
proton synchrotron radiation	✓	✓	✓	✓
proton inverse Compton scattering	✓	✗	✗	✗
proton-photon pair production	✓	✓	✓	✓
neutron-photon pion production	✓	✓	✗	✗
kaon synchrotron radiation	✗	✓	✗	✗
pion synchrotron radiation	✓	✓	✗	✗
muon synchrotron radiation	✓	✓	✗	✓

Physical processes employed in the numerical codes utilized in this work.
Table credit: [7].

Tests

1. Synchrotron self Compton (SSC) scenarios
   → no cooling
   → synchrotron cooling
   → γγ pair production (also with optically thick regime)
   → external inverse-Compton

2. Proton synchrotron
   → electron cooling / no cooling
   → generic case with grey-body photon field:
      → low compactness without proton cooling
      → high compactness with proton cooling
   → generic case with power-law photon field:
      → low compactness without proton cooling

Tests

→ SSC scenario with inverse Compton scatter occurring in **Thomson regime** (TH) and **Klein–Nishina regime** (KN).

→ General parameters:

Redshift: **$z = 0.01$**

PL distribution of injected e^- and p: **$\alpha_e = 1.9$**

Injection compactness: **$\log_{10}(l_{e,inj}) = -4.47$**

Radius of spherical emission region: **$R = 10^{15}$ cm**

Doppler factor: **$\delta = 30$**

Black hole mass **$M_{BH} = 10^8 M_\odot$**

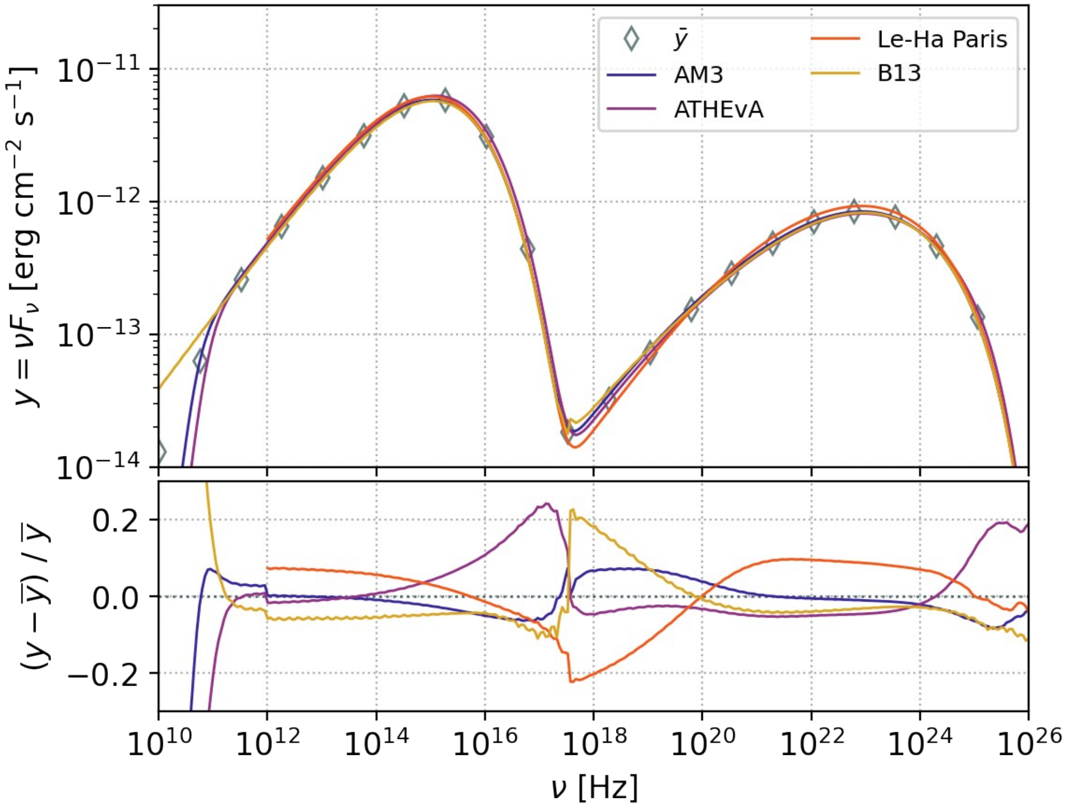
→ SSC scenario:

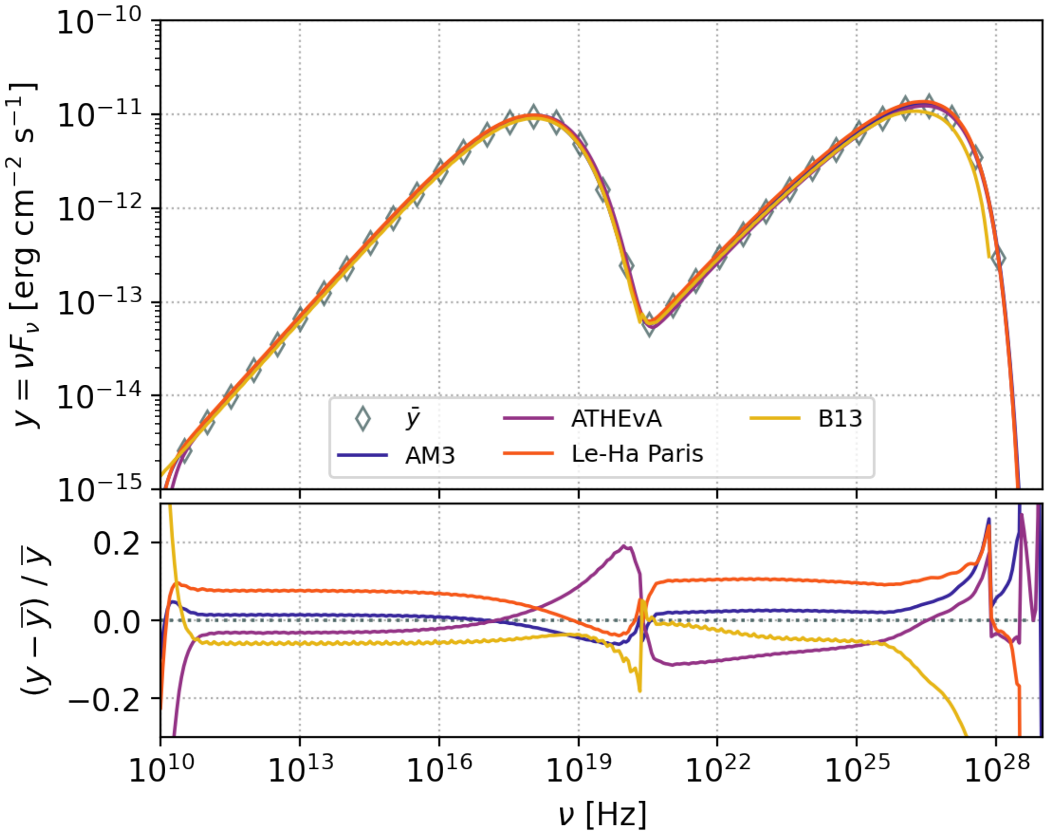
Magnetic field: **$B = 0.01$ G**

Minimum e^- Lorentz factor: **$\gamma_{e,\,min} = 1$**

Maximum e^- Lorentz factor: **$\gamma_{e,\,max} = 10^4$**

Leptonic comparison



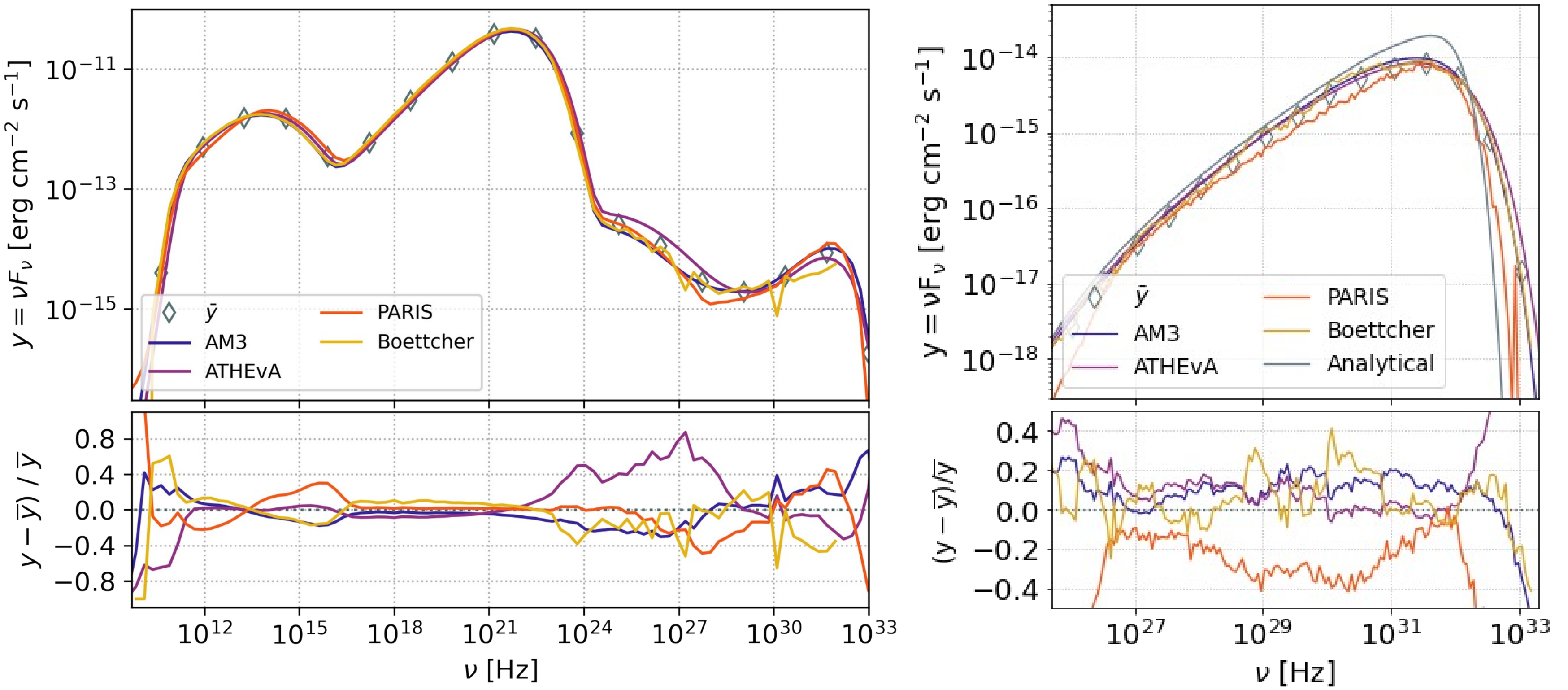


SEDs computed for the **SSC-TH** (left panel) **and SSC-KN** (right panel) **scenarios.** The mean model is shown with open diamonds, while the residuals are plotted at the bottom of each panel.

Hadronic comparison

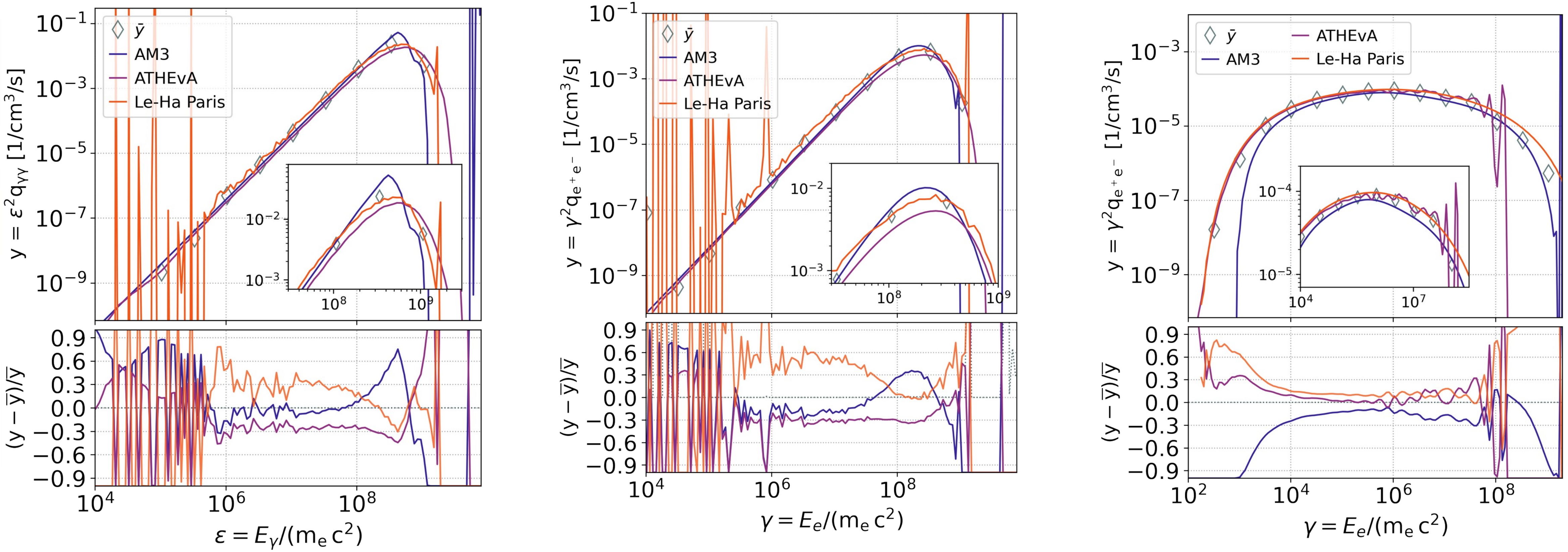
B = 10	
$\gamma_{e,\,min}$ = 1	
$\gamma_{e,\,max}$ = 10^3	
$\gamma_{p,\,min}$ = 1	
$\gamma_{p,\,max}$ = 10^8	
α_{ph} = 2	
ε_{max} = 0.1	
ε_{min} = 10^{-6}	

The parameters for the proton synchrotron scenario.



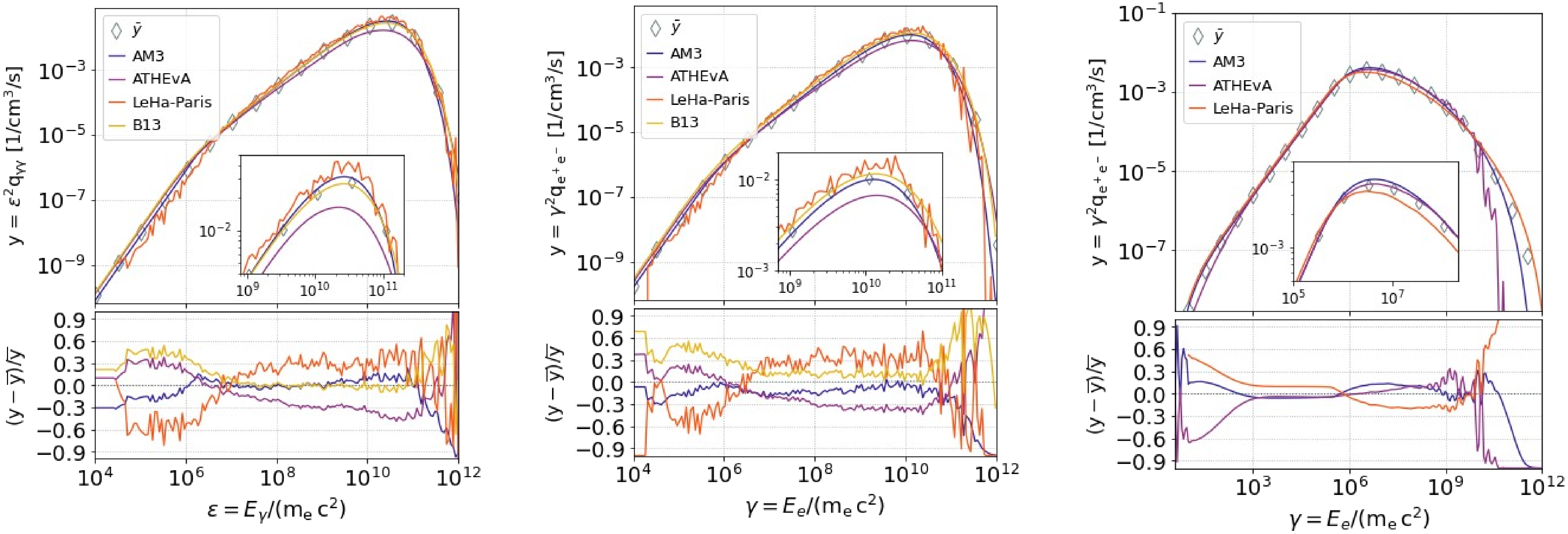
Left: SED computed for the **proton synchrotron scenario with cooling.** *Right:* Predicted **neutrino fluxes.** The mean model is shown with open diamonds, while the residuals are plotted at the bottom of each panel.

Hadronic comparison: spectra



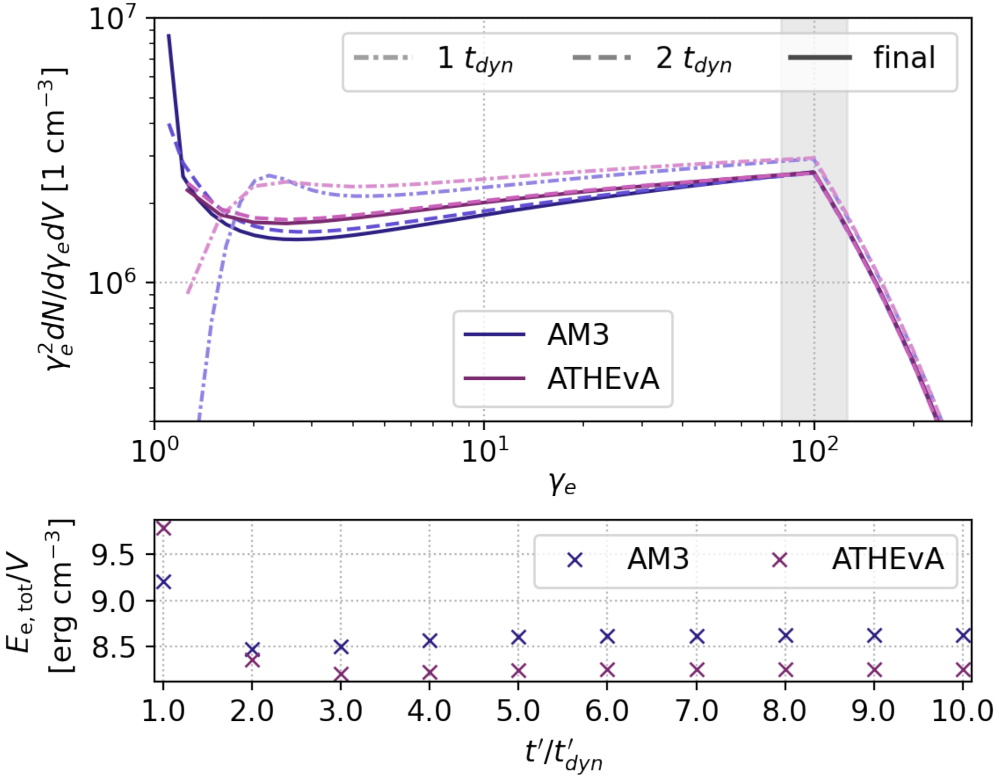
Production rates per unit volume of secondaries from **photopion production** (left and middle panels) and **photopair production** (right panel) for the case of a **quasi mono-energetic proton distribution interacting with a grey-body radiation field**. Inset panels show a zoom into the energy range around the peak of the curves.

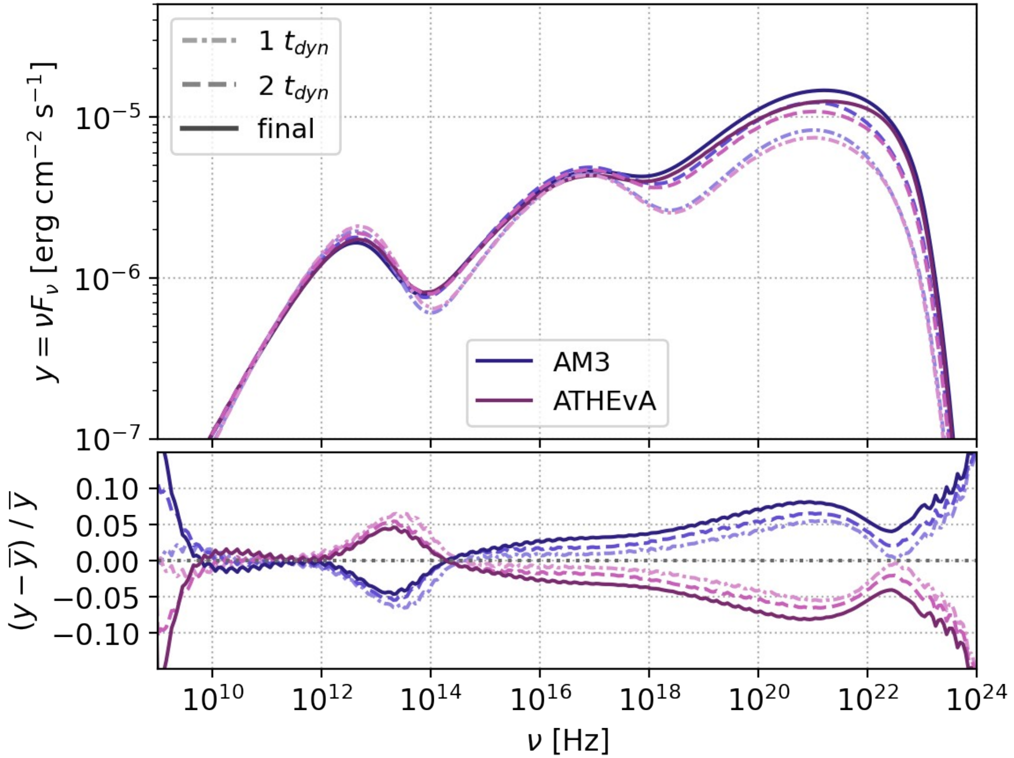
Hadronic comparison: rates



Production rates per unit volume of secondaries from **photopion production** (left and middle panels) and **photopair production** (right panel) for the case of a **power-law proton distribution interacting with a power-law radiation field**. Inset panels show a zoom into the energy range around the peak of the curves.

Non-linear SSC cooling





Left panel: **Electron energy distribution** computed using AM3 and ATHEvA for parameters leading to **inverse Compton catastrophe**. Thick solid lines show the steady-state distributions, while thin dash-dotted and dashed lines show the distributions after one and two dynamical times, respectively. The grey-shaded region indicates the energy range of injected electrons. The bottom panel shows the temporal evolution of the electron energy density. *Right panel:* The **corresponding photon spectral energy distributions** computed using AM3 and ATHEvA, with the residuals with respect to the mean shown in the bottom panel.

Conclusions

→The first extensive comparison of the outputs of lepto-hadronic blazar codes.

→ Good agreement between the studied codes in terms of spectral shapes.

→ Distortions at low-energy and high-energy cut-offs.

→ Visible spread in normalization for photo-meson interactions and Bethe-Heitler pair production (30-40%).

→ **Current status**: we are now finishing tests and finalizing the draft; we will also release all curves from our work.

Feel free to contact us if you are interested in the output of our work.

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Thank you for your attention!

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