ExHaLe-jet: Modeling blazar jets with an extended hadro-leptonic radiation code

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Abstract

Blazars emit across all electromagnetic wavelengths. While the so-called one-zone model has described well both quiescent and flaring states, it cannot explain the radio emission and fails in more complex data sets, such as AP Librae. In order to self-consistently describe the entire electromagnetic spectrum emitted by the jet, extended radiation models are necessary. Notably, kinetic descriptions of extended jets can provide the temporal and spatial evolution of the particle species and the full electromagnetic output. Here, we present the initial results of a newly developed hadro-leptonic extended-jet code: ExHaLe-jet. As protons take much longer than electrons to lose their energy, they can transport energy over much larger distances than electrons and are therefore essential for the energy transport in the jet. Furthermore, protons induce injection of additional pairs through pion and Bethe-Heitler pair production, which can explain a dominant leptonic radiation signal while still producing neutrinos. Here we discuss the differences between leptonic and hadronic dominated SED solutions, the SED shapes, evolution along the jet flow, and jet powers. We also highlight the important role of external photon fields, such as the accretion disk and the BLR.

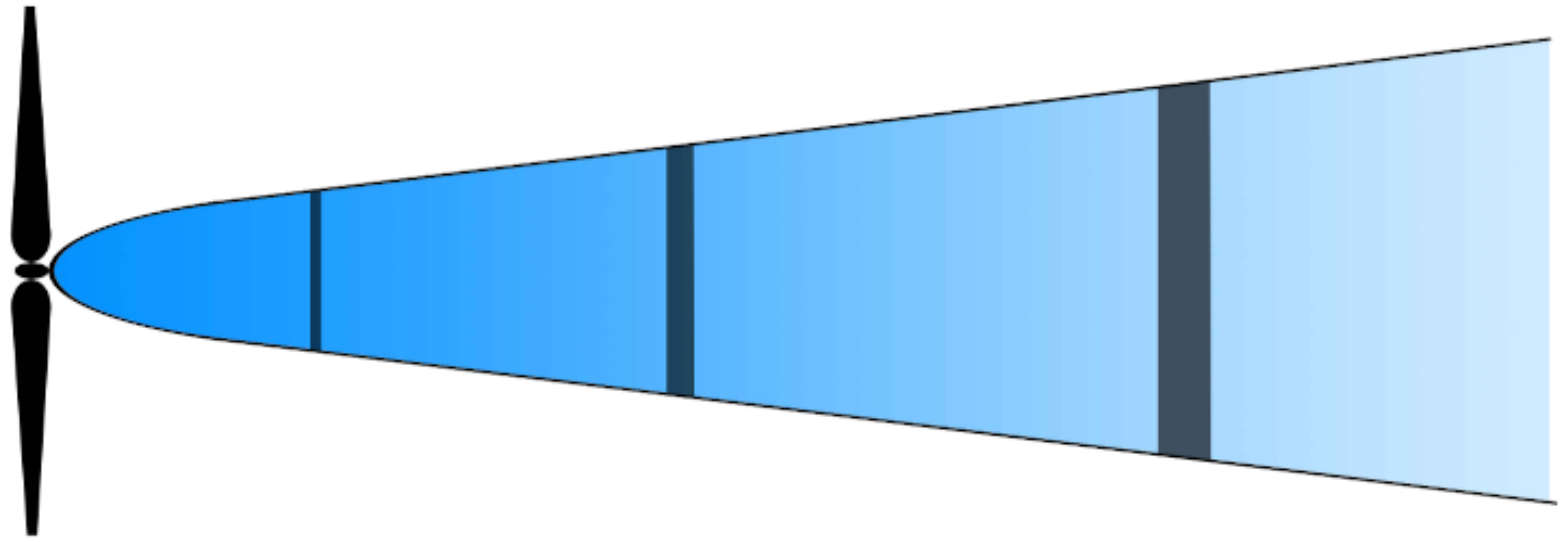


Figure courtesy of Jonathan Heil

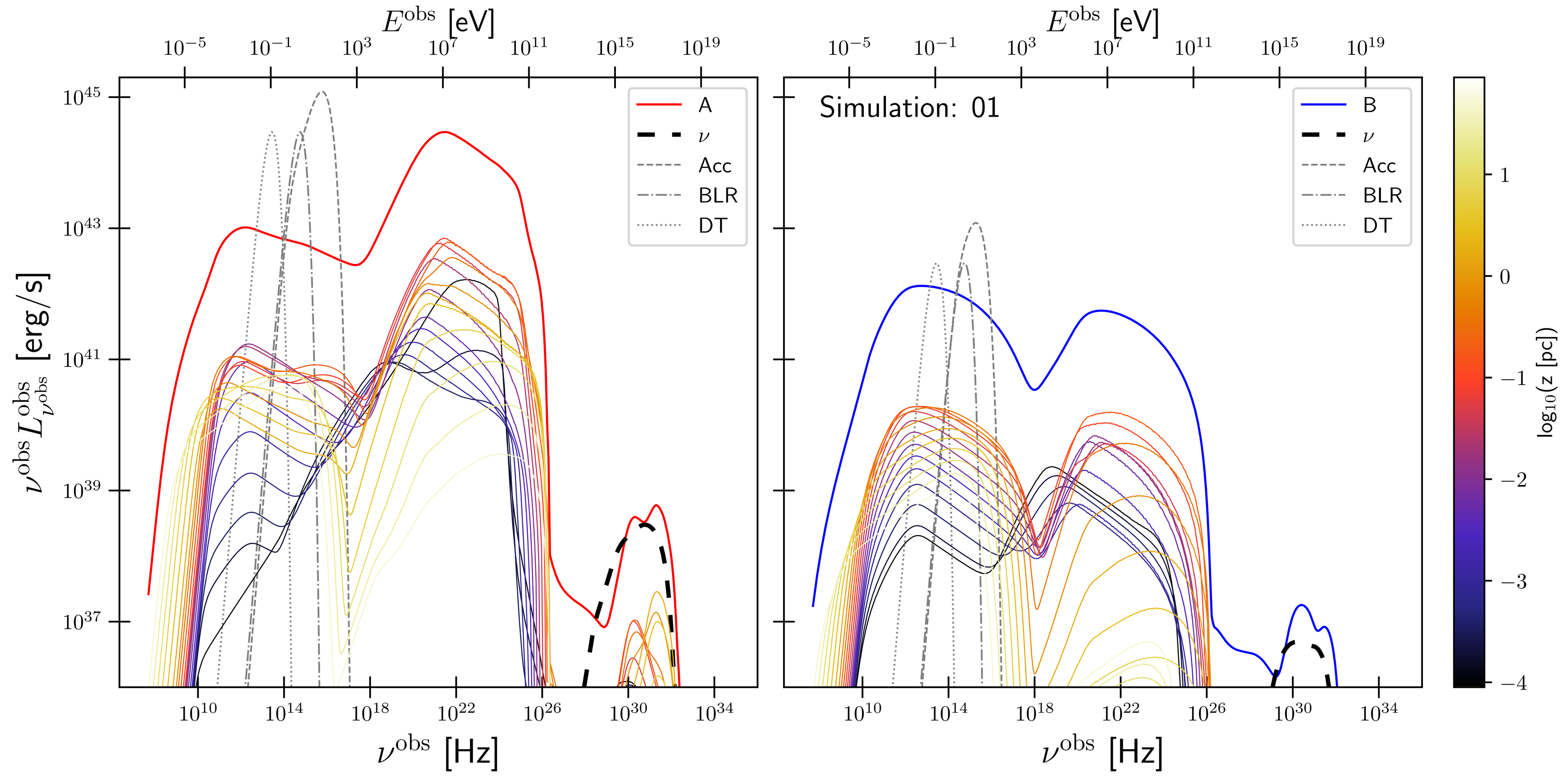
ExHaLe-jet

- Injection of primary proton and electron distributions, and magnetic field at the base of the jet
- Self-consistent evolution of particles and magnetic field along the jet flow
- Pre-set bulk flow pattern and geometry depending on distance z from the jet base:

$$\Gamma_b(z) \propto \sqrt{z} \text{ for } z \leq z_{acc} \quad ; \quad \Gamma_b(z) = \text{const for } z > z_{acc} \quad ; \quad R(z) \propto \tan\left[0.26/\Gamma_b(z)\right]$$

- The jet is cut into numerous slices (cf. dark regions in the sketch), wherein the Fokker-Planck equation is solved for all particles (protons, charged pions, muons, and electrons/positrons)
- For each slice, the radiation and neutrino output is derived
- Secondary electron/positron pairs are carried along the jet flow becoming primaries in the next slice
- Considered processes are synchrotron, pion production, Bethe-Heitler pair production, inverse Compton, and γ-γ pair production
- For particle-γ interactions, we consider all internal photon fields, and the external photon fields: Accretion disk, broad-line region (BLR), and dusty torus (DT)

Simulations with external fields



Distance evolution (color code) of the intrinsic total spectrum (red/blue solid) for simulation 01A (left) and 01B (right). Black dashed lines mark the total neutrino spectrum. In gray, the external fields.

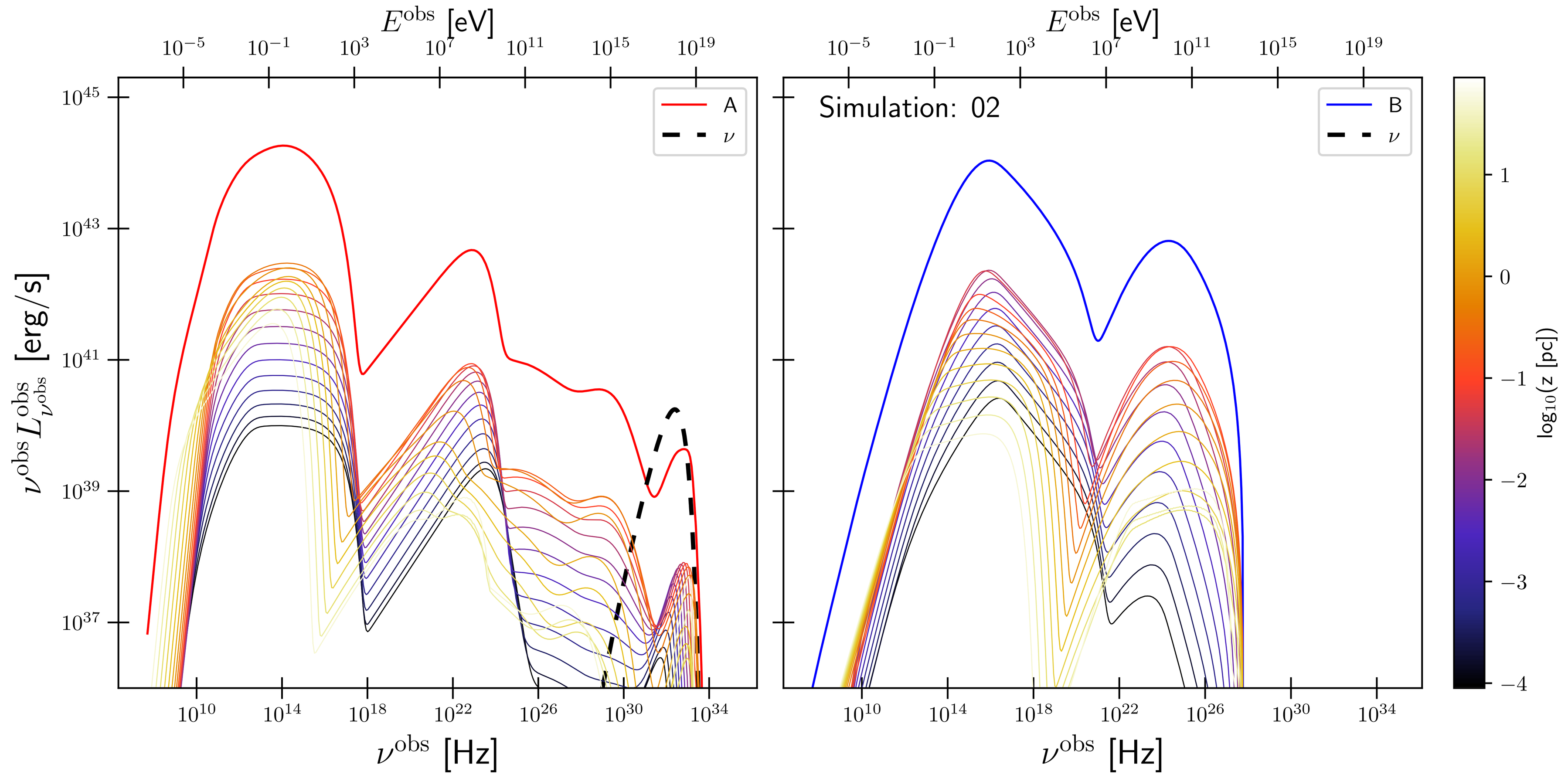
- The external fields are crucial for the simulation outcome:
  - **(i)** The γ rays dominate the electron-synchrotron emission in A, but not in B, due to different levels of secondary pair production (influenced by p-γ processes)
  - **(ii)** Most emission is produced between 0.01 and a few parsec in A, while it is between 0.1 and 1 parsec in B; related to the extension of the external photon fields
  - **(iii)** The neutral-pion bump (at frequencies $> 10^{30}$ Hz) shows a different spectral shape between A and B

Parameters

Simulation	01A	01B	02A	02B
Main γ-ray production process	EC	EC	P-Syn	SSC
Jet length	100 pc	100 pc	100 pc	100 pc
Acceleration zone length	1 pc	1 pc	1 pc	0.1 pc
Disk Eddington ratio	0.1	0.01	—	—
Max. Doppler factor	30	30	50	30
Initial magnetic field	50 G	50 G	70 G	30 G
Injection particle power	$10^{-5}\,L_{\rm edd}$	$10^{-5}\,L_{\rm edd}$	$2\times10^{-4}\,L_{\rm edd}$	$2\times10^{-6}\,L_{\rm edd}$
Initial proton to electron ratio	1	1	1	10^{-10}
Proton $\gamma_{\rm min}$ / $\gamma_{\rm max}$	2 / 2×10^{8}	2 / 2×10^{8}	2 / 2×10^{9}	2 / 2×10^{2}
Electron $\gamma_{\rm min}$ / $\gamma_{\rm max}$	100 / 2×10^{4}	100 / 2×10^{4}	100 / 2×10^{4}	10^{5} / 2×10^{6}
P & e spectral index	2.5	2.5	2.0	2.8
Total jet power	$2\times10^{-3}\,L_{\rm edd}$	$2\times10^{-3}\,L_{\rm edd}$	$0.03\,L_{\rm edd}$	$2\times10^{-4}\,L_{\rm edd}$

BLR and DT scale with Disk luminosity. No external fields in simulations 02A and 02B. No EBL absorption is considered.

Hadronic and SSC simulations



Distance evolution (color code) of the intrinsic total spectrum (red/blue solid) for the hadronic simulation (02A, left) and the SSC simulation (02B, right). Black dashed lines mark the total neutrino spectrum. No external fields are used.

- Hardonic solution (γ-rays dominated by p-synchrotron):
  - **(i)** Requires more extreme parameters and jet power
  - **(ii)** P-syn emitted mostly within 0.1 pc, while e-syn is mostly emitted beyond 0.01 pc with its peak shaped by (non-)cooling effects at large distances
  - **(iii)** The plateau beyond 1 TeV is synchrotron of secondary pairs, while the peak at $> 10^{30}$ Hz is the π^0-bump; these follow the proton distance evolution
- SSC solution:
  - **(i)** Synchrotron mostly emitted around 0.01 pc, while the SSC flux peaks around 0.1 pc (end of acc. zone)
  - **(ii)** SSC shows much stronger distance evolution than synchrotron

Summary

- We show first results of a newly developed extended hadro-leptonic jet code covering the most relevant processes
- Protons have typically an indirect, but important role by providing highly relativistic secondary particles (and neutrinos), while electrons produce the radiation
- A model with a significant p-synchrotron contribution requires more extreme parameter sets and jet powers
- The strength or absence of the external fields has a very strong impact on the jet evolution (radiation dominance, secondary production, distance evolution)
- No model produces sufficient neutrinos for a detection

Bibliography

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