The imprint of protons on the emission of extended blazar jets

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Abstract
Blazars – active galaxies with the jet pointing at Earth – emit across all electromagnetic wavelengths. The so-called one-zone model has described well both quiescent and flaring states, however it cannot explain the radio emission. In order to self-consistently describe the entire electromagnetic spectrum, extended jet 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 recently developed hadronic extended-jet code. 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 can inject additional leptons through pion and Bethe-Heitler pair production, which can explain a dominant leptonic radiation signal while still producing neutrinos. We will present a detailed parameter study and provide insights into the different blazar sub-classes.

Introduction

- In some blazars, the one-zone model fails; e.g., AP Librae can only be described through the addition of an extended component (for example the kpc-scale jet)

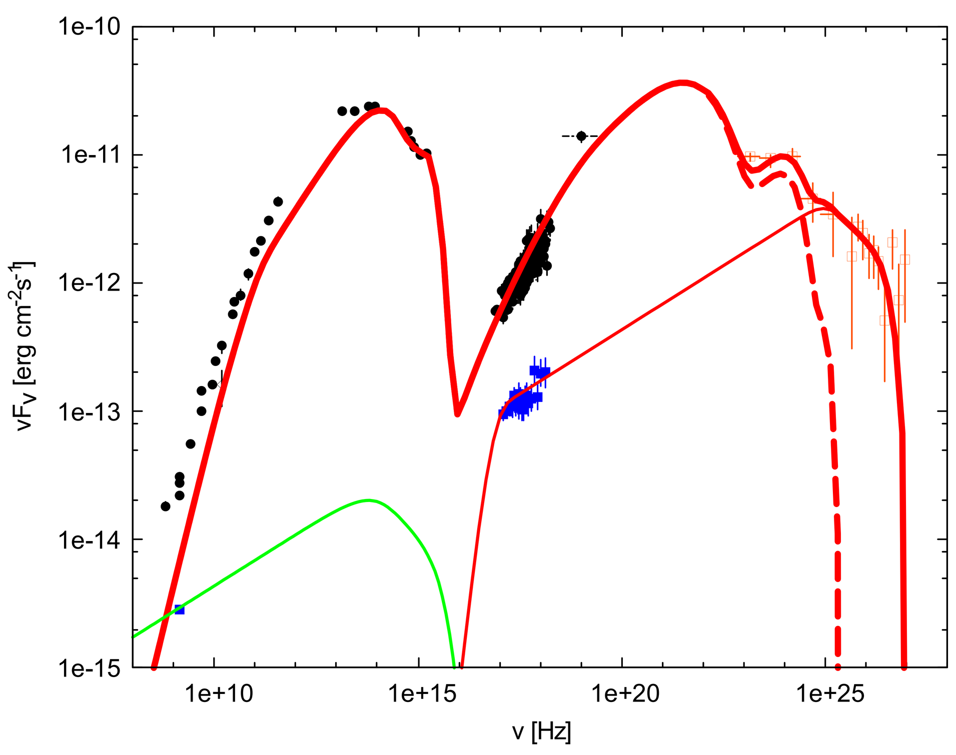


Figure from Zacharias&Wagner2016 showing the spectrum of AP Librae with a one zone-model (thick dashed), the kpc-jet contribution (synchrotron, thin green; IC/CMB, thin red), and the total (thick red).

- Such examples call for the development of extended jet models considering the radiation produced along the entire jet
- Different extended, leptonic models have been developed over the last years (e.g., Potter&Cotter2013, Zdziarski+2014, Lucchini+2019)
- The association of neutrinos with blazars (IceCube+2018) require the inclusion of hadronic processes
- The *Ex*tended *ha*dro-*le*ptonic jet code is the first step to produce such a model

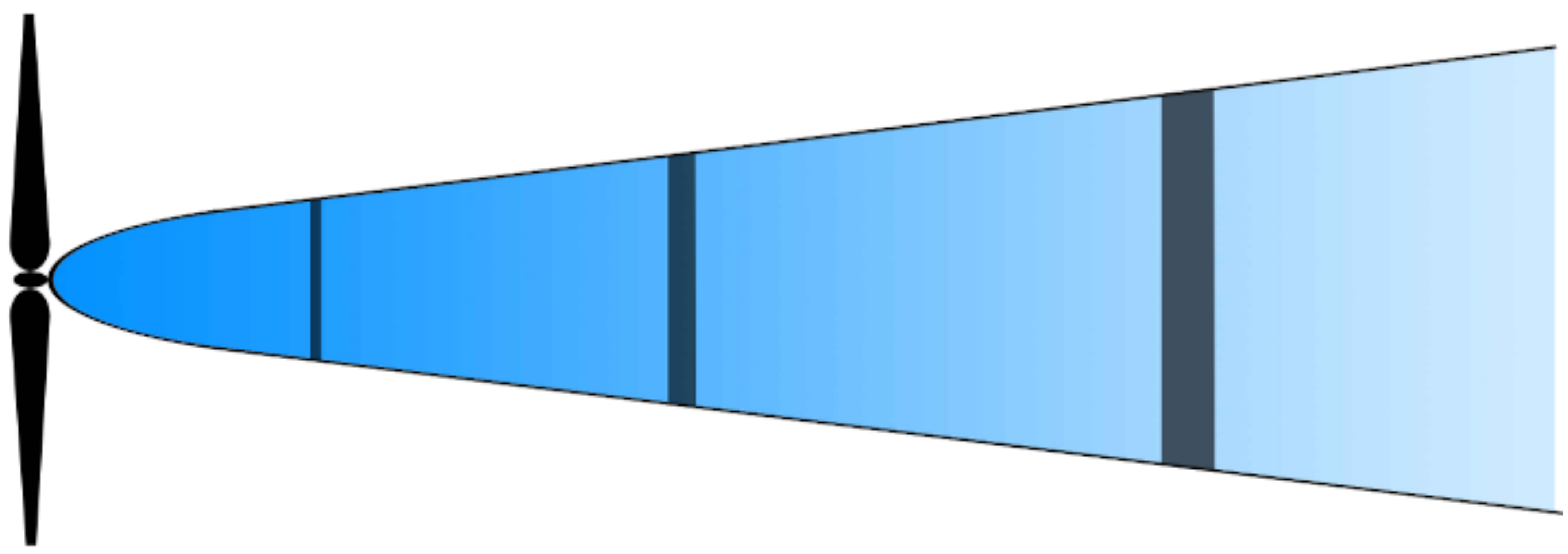


Figure courtesy of Jonathan Heil

ExHaLe-jet

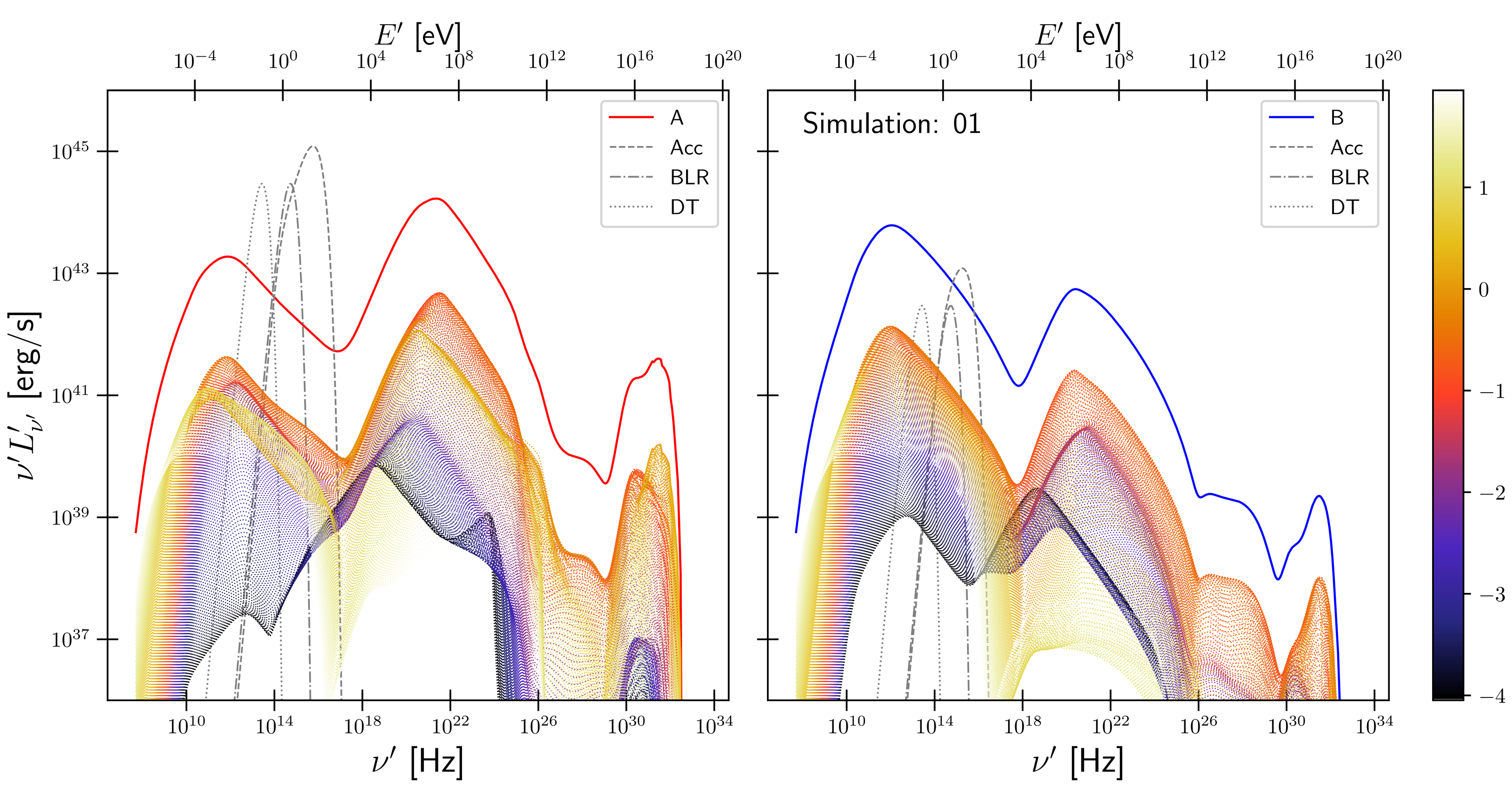
- Injection of a primary proton and electron distribution, and a magnetic field at the base of the jet
- Self-consistent evolution of particles and magnetic field along the jet flow
- Pre-set bulk flow pattern and geometry depending on distance z from the jet base (a parabolic acceleration region followed by a conical coasting region):

$$\Gamma_b(z) \propto \sqrt{z} \text{ for } z \le z_{acc} \quad ; \quad \Gamma_b(z) = \text{const for } z > z_{acc} \quad ; \quad R(z) \propto \tan 1/\Gamma_b(z)$$

- 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-photon interactions, we consider all internal photon fields, as well as the external photon fields: Accretion disk (AD), broad-line region (BLR), and dusty torus (DT)

Results

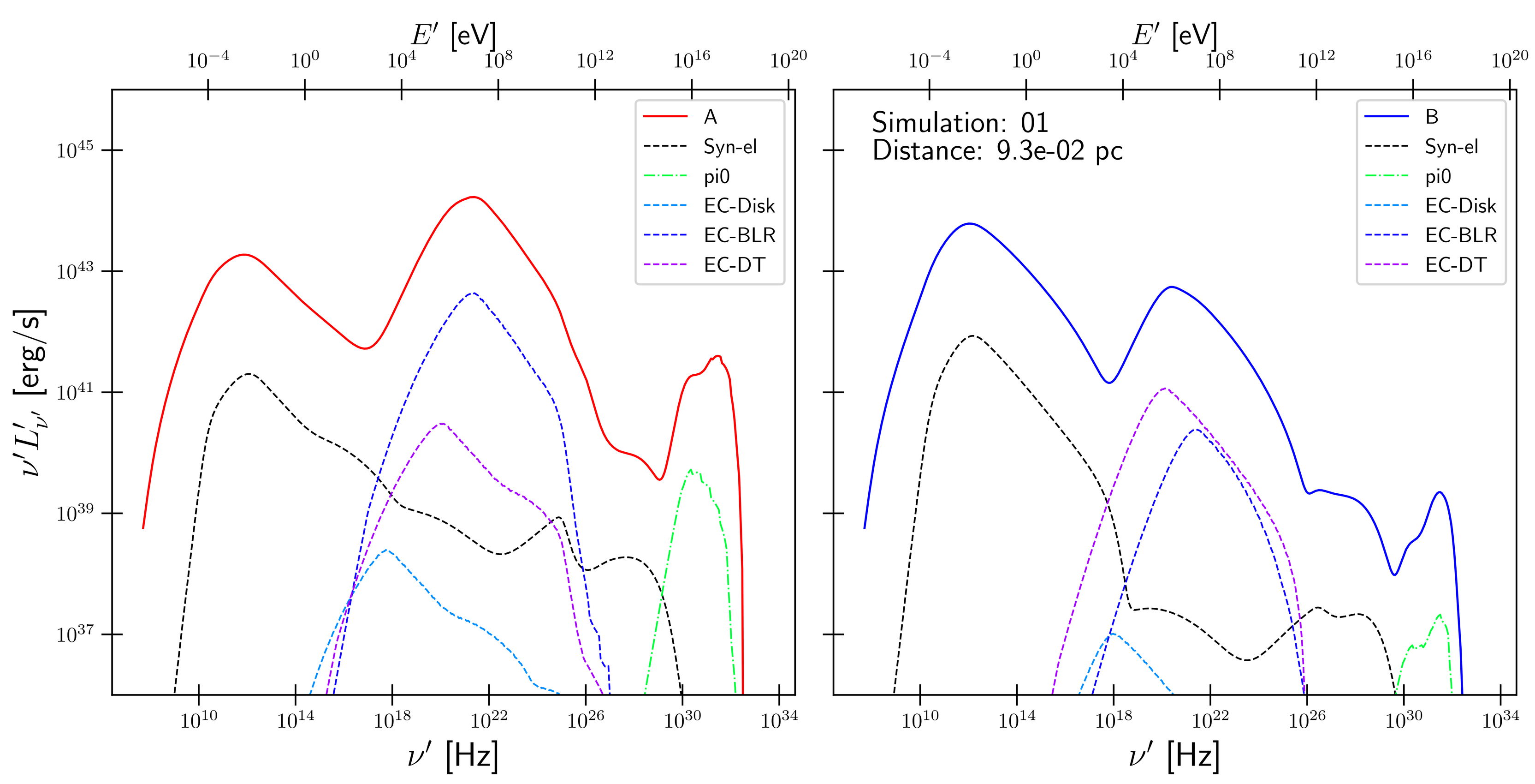
We show results for two simulations, which are only separated by the strength of the external fields, namely AD flux at 10% of $L_{\rm edd}$ (A), and at 0.1% of $L_{\rm edd}$ (B)



Distance evolution (color code) of the intrinsic total spectrum (red/blue solid) for simulation A (left, red) and B (right, blue). 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, while it is reversed in B
(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
(iii) The neutral-pion bump (at super-high frequencies) shows a different spectral shape between A and B



Same as left, but showing the jet's intrinsic radiative components at $z \sim 0.1$ pc from the black hole

- The γ rays in both simulations are dominated by electron emission: In A, they are dominated by IC/BLR, while in B it is a mixture of IC/BLR and IC/DT
- While direct proton emission is not visible for these parameters, the hadronically induced super-energetic pairs show a feature of electron synchrotron emission above 1 TeV

Summary

- We show first results of a newly developed extended hadro-leptonic jet code covering all relevant processes
- In the chosen parameter sets, protons have an important, indirect role by providing highly relativistic secondary particles (and neutrinos)
- The radiative output in these simulations is dominated by electron emission (synchrotron, external Compton)
- The strength of the external fields has a very strong impact on the jet evolution (radiation dominance, secondary production)

Bibliography

- M. Zacharias, et al., 2021, MNRAS, submitted
- M. Zacharias, S.J. Wagner, 2016, A&A, 588, A110
- W. Potter, G. Cotter, 2013, MNRAS, 429, 1189
- A. Zdziarski et al., 2014, MNRAS, 440, 2238
- M. Lucchini et al., 2019, MNRAS, 482, 4798
- IceCube Collaboratio et al., 2018, Science, 361, eaat1378

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