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Latest Updates in agnpy: Implementing hadronic processes and analyzing FSRQ data

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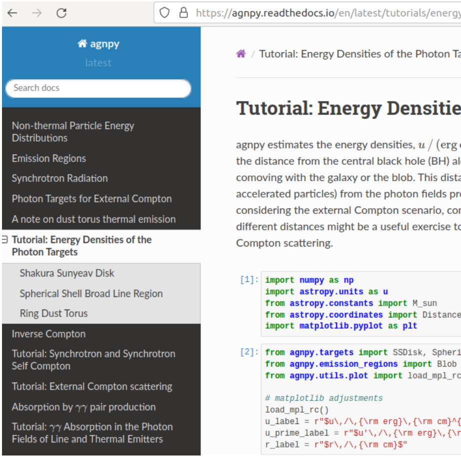
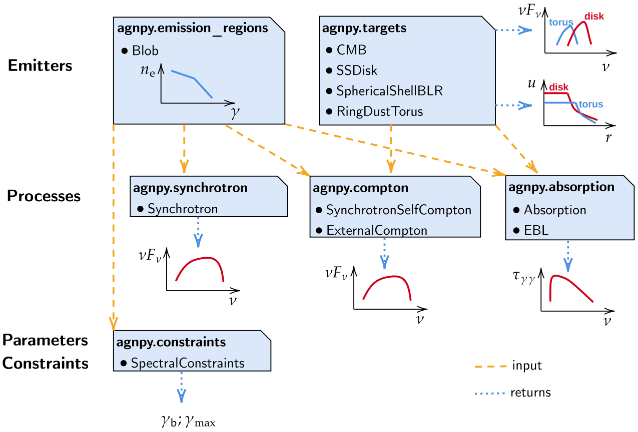
About agnpy

- agnpy - a Python open-source package for modelling the radiative processes in jetted active galaxies.
- Built on `NumPy`, `SciPy` and `astropy`.
- Well documented: `agnpy.readthedocs.io`



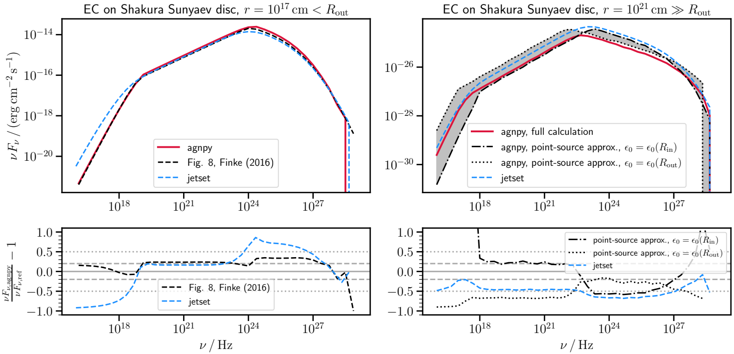
agnpy

- agnpy includes modules for modeling non-thermal emissions across various target environments from different AGN components.
- Enables the simulation of absorption effects.



agnpy and another modeling packages

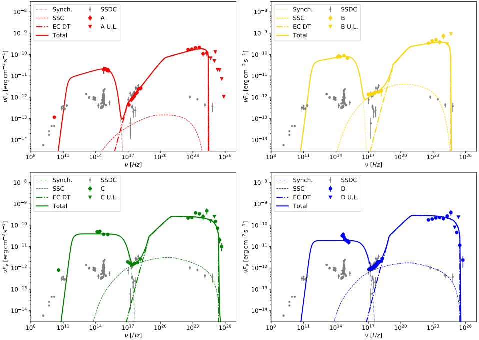
- Results have been validated against references and another modeling software, `jetset` , through internal consistency checks.
- Results vary 10-30% with respect to `jetset` and literature.



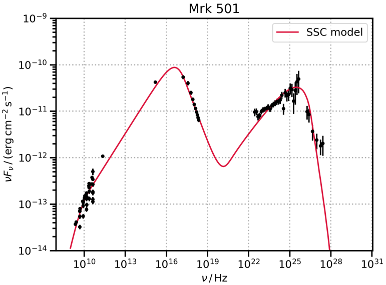
C. Nigro et al., A&A 660, A18 (2022).

Research publications using agnpy

According to NASA ADS, the agnpy paper was cited nine times.



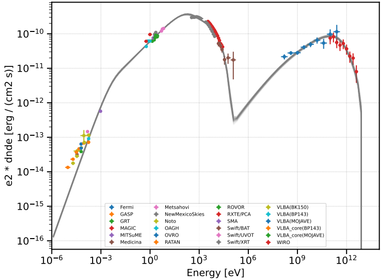
MAGIC Collaboration et al. (2021), FSRQ QSO B1420+326



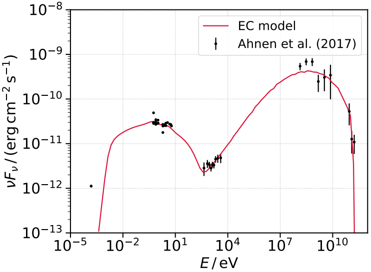
Albert et al. (2022). Mrk 501

Fitting

- The agnpy library includes Sherpa and Gammapy wrappers that enable fits of the broad-band spectral energy distribution (SED) using combinations of several radiative processes.
- Best-fit parameters for emission models through Monte Carlo Markov Chain (MCMC) method or χ^2 minimization.



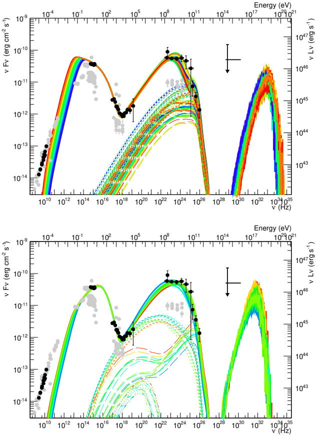
Fit of a broad-band SED of Mrk421 using MCMC [agnpy notebook]



Fit of a broad-band SED of PKS1510-089 [agnpy notebook]

From leptonic to hadronic interpretation

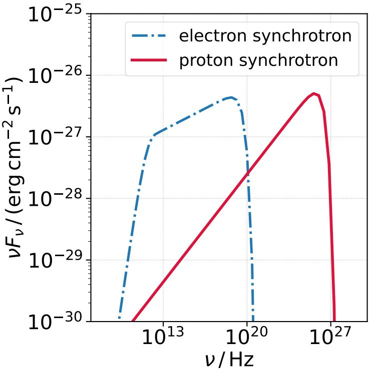
- The first version of the package allowed a fully leptonic interpretation of the source's SED.
- The high-energy emission from AGN and blazars can arise due to leptonic and hadronic processes.
- The evidence for multi-messenger photon and neutrino emission from the blazar TXS 0506+056 in 2017 reinforced interest in hadronic scenarios and modeling of blazars as cosmic rays acceleration sites and neutrino sources.



Proton synchrotron (up) and Lepto-hadronic (down) modeling of TXS 0506+056 [Cerruti et al.(2019)]

Synchrotron emission from relativistic protons

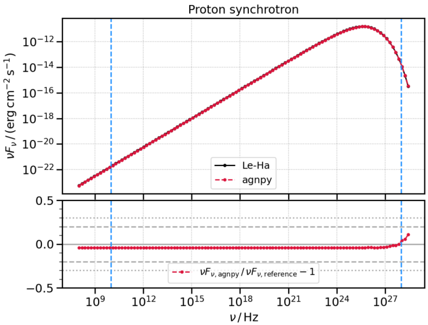
- Proton can also produce synchrotron radiation.
- The simplest process with hadron.
- Strong magnetic fields or high proton densities make proton synchrotron radiation relevant.
- Proton synchrotron can contribute to the high-energy SED peak, but for TeV γ rays $\sim 10^{20}$ eV proton are required.



Protons follow a PL spectrum with $p = 2.5, \gamma_{\min} = 10, \gamma_{\max} = 10^{11}$. $B = 1\,\mathrm{G}$

Proton synchrotron in agnpy

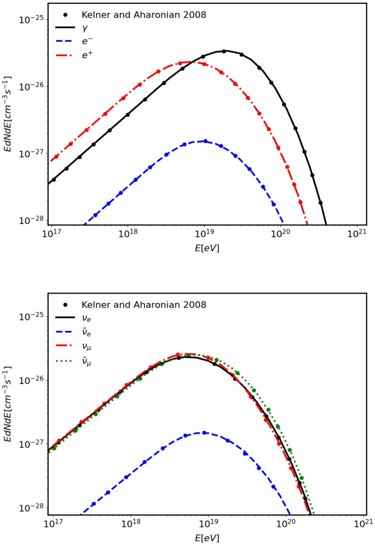
- The agnpy class `proton_synchrotron` allows the computation of the proton synchrotron spectrum, assuming the particles to be immersed in a random magnetic field.
- To validate the implementation, the results were compared with those obtained from the private code LeHa-Paris (Cerruti et al. 2015).



I. Viale et al., PoS ICRC2023, 1524

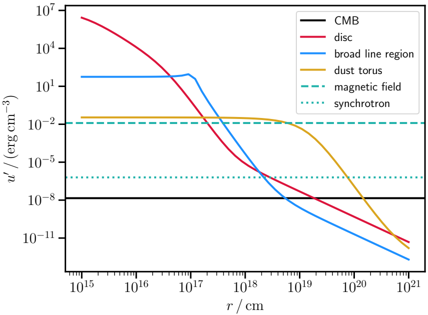
Photo-meson interactions

- A key hadronic process in the jet emissions of AGNs and blazars, leading to neutrino production.
- Interaction between a high-energy proton and a low-energy photon typically comes from the AGN's surrounding environment.
- Implemented in the agnpy.photo_meson class based on the analytical model from Kelner and Aharonoan 2008.
- On pull request in `github:agnpy`.



γ-ray absorption

- Pair production in the radiation field can cause a γ-ray cutoff in SED.
- The cutoff energy of the γ-rays is dependent on the distance r, from emission region to the black hole and the density of surrounding photons.
- agnpy computes γ absorption from e^+e^- pair production across multiple photon fields.



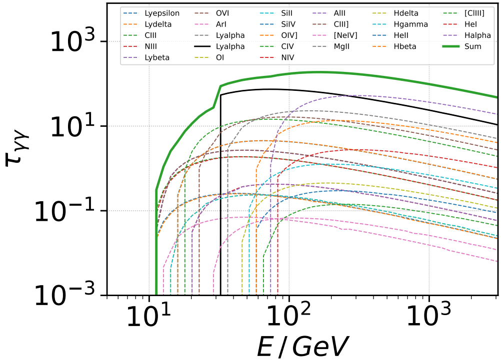
A&A 660, A18 (2022).

Broad-Line-Region (BLR) and Flat Spectrum Radio Quasars (FSRQs)

- The BLR is important for understanding the high-energy behavior of FSRQs.
- The BLR is a zone near the central black hole filled with fast-moving gas that interacts with particle jets leading to production or absorption γ-rays.
- The BLR optical depth might be computed within the stratified BLR model following Finke 2016. The BLR is modeled as a collection of concentric shells.

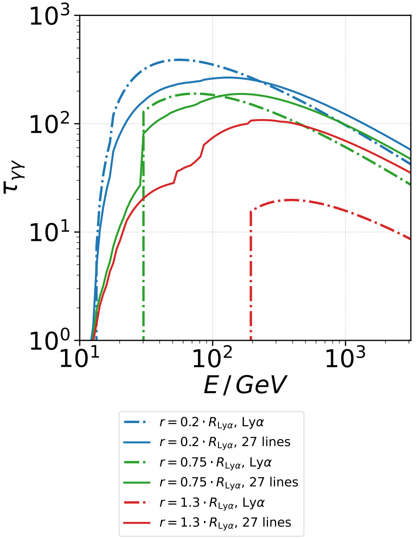
BLR model

- In agnpy a list of 27 typical lines are implemented.
- The luminosity and radius of a particular shell are obtained from a reference shell, following the scaling of the stratified BLR model.
- The absorption is often dominated by pair production with Lyα photons.



BLR model in agnpy

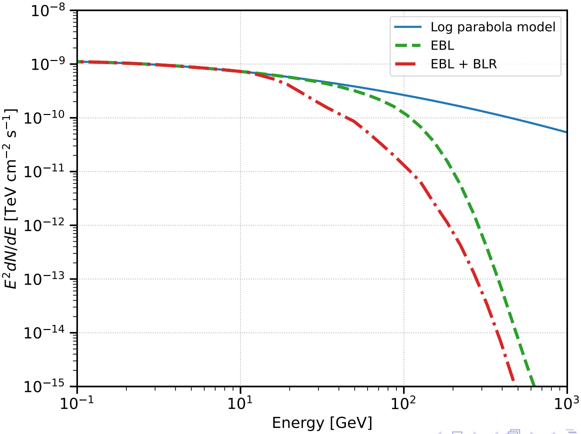
- The BLR is often simplified to consist of only Lyα.
- To consider multiple lines, an improvement in the integration method was needed because the previous approach was resource-hungry and led to numerical instabilities.
- This method uses CubePy, a fully vectorized package for multi-dimensional numerical integration.
- On pull request in `github:agnpy`.



Application to HE/VHE SED

Fitting the $\gamma - ray$ spectra of FSRQs during bright flares can identify absorption features that shed light on the r distance between the black hole and the emission region:

$$f(E, \theta, r, z) = f_{init}(E, \theta) \times exp[-(\tau_{\gamma\gamma}^{BLR}(E, r) + \tau_{\gamma\gamma}^{EBL}(E, z))]$$



Summary and future plan

- agnpy enables leptonic modeling and has recently begun incorporating hadronic processes.
- The library includes modules for considering absorption effects in the BLR.
- We are working to integrate support for photo-meson interactions, which are expected to be the primary sources of neutrinos in jetted AGN.
- Future plans include adding proton-proton interactions, Bethe-Heitler pair production, and more.
- Interested in developing agnpy? Join us!

Back-up

Photo-meson interactions

- Low-Energy Photons typically come from the AGN's surrounding environment.
- Examples include radiation from the Broad Line Region, the accretion disk, and the torus.
- Neutral and charged pions are produced and decay info γ-rays, positrons, and neutrinos.
- Spectrum of secondary particles obtained using Monte Carlo code SOPHIA.

Absorption

The $\gamma\gamma$ absorption for a photon field with specific energy density $u(\epsilon, \mu, \phi; l)$ is given by:

$$\tau_{\gamma\gamma}(\nu) = \int_r^{\infty} \mathrm{d}l \int_0^{2\pi} \mathrm{d}\phi \int_{-1}^{1} \mathrm{d}\mu \, (1 - \cos\psi) \int_0^{\infty} \mathrm{d}\epsilon \, \frac{u(\epsilon, \mu, \phi; l)}{\epsilon m_{\mathrm{e}} c^2} \, \sigma_{\gamma\gamma}(s), \quad (1)$$

Where:

- $\cos\psi = \mu\mu_s + \sqrt{1-\mu^2}\sqrt{1-\mu_s^2}\cos\phi$ is the cosine of the angle between the hitting and the absorbing photon;
- $u(\epsilon, \mu, \phi; l)$ is the energy density of the target photon field with ϵ dimensionless energy, (μ, ϕ) angles, l distance of the blob from the photon field;
- $\sigma_{\gamma\gamma}(s)$ is the pair-production cross section, with $s = \epsilon_1 \epsilon \, (1 - \cos\psi) \, / \, 2$ and $\epsilon_1 = h\nu \, / \, (m_e c^2)$ the dimensionless energy of the hitting photon.

Synchrotron emission from relativistic protons

- Proton can also produce synchrotron radiation.
- The simplest process with hadron.
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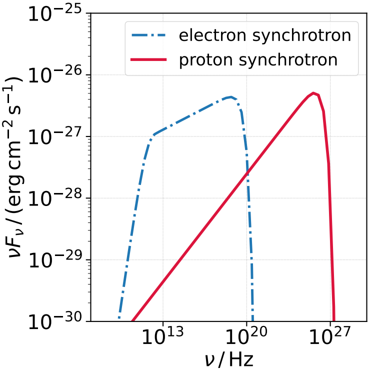

Electrons follow a PL spectrum with $p = 2.8, \gamma_{\mathrm{min}} = 100, \gamma_{\mathrm{max}} = 10^6$. Protons follow a PL spectrum with $p = 2.5, \gamma_{\mathrm{min}} = 10, \gamma_{\mathrm{max}} = 10^{11}$. $B = 1\,\mathrm{G}$