Exercise: A *pp* interaction model for NGC 1068

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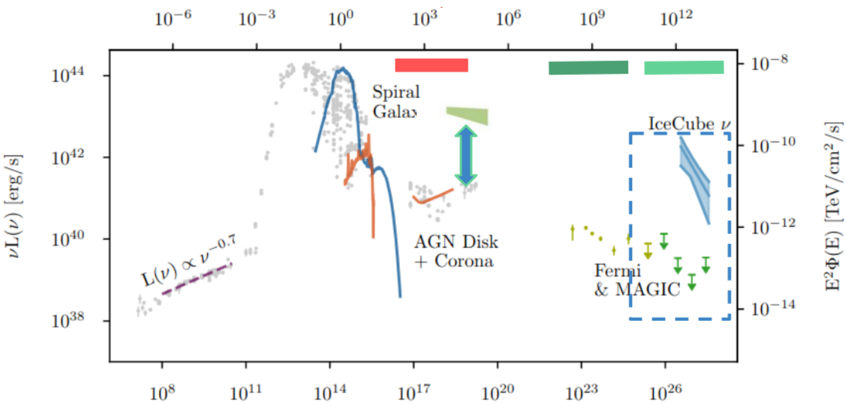

Figure 1: Photon and neutrino spectral energy distribution of galaxy NGC 1068. Adopted from Padovani et al. (2024), Nature Astronomy

You are at a conference when you hear about the neutrino emission from NGC 1068 ($d_L = 10.2$ Mpc, $M_{BH} = 10^7 M_\odot$) – see Fig. 1. You come up with the following interpretation: neutrinos are produced through *pp* interactions in a compact spherical region of the AGN core, which is optically thick to $\gamma\gamma$ pair creation. You write down the expression that relates the neutrino to the cosmic-ray (CR) proton luminosity:

$$E_\nu^2 \frac{dN_\nu}{dt dE_\nu} \approx \frac{1}{2} f_{pp} E_p^2 \frac{dN_p}{dt dE_p} \tag{1}$$

where $f_{pp} = (1 + t_{pp}/t_{esc})^{-1}$ is the *pp* efficiency (check the lecture slides).

1. Estimate the proton Lorentz factors $\gamma_{p,1}$ and $\gamma_{p,2}$ responsible for the neutrino emission that ranges from $E_{\nu,1} = 1$ TeV to $E_{\nu,2} = 10$ TeV. What is the slope s of the proton power-law distribution if $E_\nu^2 \Phi(E_\nu) \propto E_\nu^{-1.2}$?

2. If the protons escape from the neutrino production site, which has a radius $R = 100 R_S$, on a timescale R/c and the gas density is $n_{gas} = 10^9$ cm^{-3}, calculate f_{pp}. (You may use $\kappa_{pp} \approx 0.5$ and $\sigma_{pp} \approx 40\ mb$, and $R_S = 2GM/c^2$). Is the source optically thick to pp interactions?

3. Using Eq. (1) and the values from the previous questions, estimate the bolometric CR luminosity, L_p.

4. You hypothesize that $U_B = \epsilon_B U_{ph}$ where U_{ph} is the energy density of thermal radiation from the AGN core in a spherical region of radius R, and $\epsilon_B \leq 1$. Derive the following expression for the magnetic field strength in the neutrino production region:

$$B = B_0 \left(\frac{\epsilon_B}{0.1}\right)^{\chi_1} \left(\frac{L_{bol}}{10^{45}\ erg/s}\right)^{\chi_2} \left(\frac{M_{BH}}{10^7 M_\odot}\right)^{\chi_3} \left(\frac{R}{R_S}\right)^{\chi_4} \tag{2}$$

   and derive the values B_0 [G], $\chi_1, \chi_2, \chi_3, \chi_4$. You are given that the bolometric thermal luminosity from the AGN core is $L_{bol} \approx 10^{45}$ erg/s.

5. Insert the values you derived from the previous questions ($\gamma_{p,1}, \gamma_{p,2}, s, L_p, B$ for $R = 100\ R_S$) into the input file `Parameters.txt` of `LeHaMoC` and run the code with the following processes activated: (i) synchrotron radiation, (ii) pp interactions, and (iii) $\gamma\gamma$ pair production.

   - Compute the photon and neutrino spectra and compare with the observed ones. Plot also the proton and pair distributions. Comment on your results.
   - Compute the photon energy density from the electromagnetic cascade and compare it with U_{ph}.

6. Activate the inverse Compton scattering and repeat step 4. Do you see any differences? Yes, no, and why ?

7. Change the file `Parameters.txt` appropriately to account for the presence of coronal X-ray photons in the neutrino production site. The coronal radiation field is a power law $E_X^2 \Phi(E_X) \propto E_X^0$, extending from $E_{X,1} = 0.1$ keV to 100 keV with integrated luminosity $L_X = 10^{44}$ erg/s. Repeat steps 4-5 and comment on your findings.

8. Repeat steps 4-6 for a more compact corona $R = 10\ R_S$. What do you observe?