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GammaPBHPlotter: A public code for calculating the complete Hawking evaporation gamma-ray spectra from primordial black holes

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Summary

We present `GammaPBHPlotter`, a public Python package for calculating and plotting the Hawking radiation gamma-ray spectra of primordial black holes in the mass range of 5×10^{14} to 10^{18} grams. This tool allows users to compute the monochromatic and mass-averaged spectra of black holes over a range of parameters. We include the primary/direct Hawking emission, the secondary emission from the decay and hadronization of unstable particles, the final state radiation, and the in-flight annihilation gamma-ray emission components.

Statement of Need

Hawking radiation (Hawking, 1974) remains an unobserved property of black holes. As the temperature of black holes is inversely proportional to the square of their mass, conventional stellar mass black holes are expected to emit too little radiation to ever be detected. However, primordial black holes (PBHs) that could have formed from the collapse of primordial perturbations in the early universe can provide detectable signals (Carr et al., 2016). PBHs with mass less than 10^{14} grams would have evaporated via Hawking radiation long before the present age of the universe. Upcoming gamma-ray telescopes such as e-ASTROGAM (Tavani & others, 2018) and AMEGO-X (Caputo & others, 2022) will be sensitive enough in the MeV range to detect the Hawking spectra of PBHs lying between this lower bound and 10^{19} grams. We have developed `GammaPBHPlotter`, as an open source and user friendly means of simulating gamma-ray spectra produced from different PBH mass-distributions. By simulating in-flight annihilation, and final state radiation, this package additionally allows for more accurate and comprehensive simulations than existing software.

Hawking Spectra

Modeling the emission components

The gamma-ray spectrum of a PBH within the relevant mass range consists of four primary components; direct/primary Hawking radiation, secondary radiation, final-state radiation, and in-flight annihilation.

Direct Hawking radiation accounts for all kinematically allowed elementary particles formed at the event horizon (Hawking, 1974), including gamma-ray photons. Secondary radiation originates from the decay of unstable particles and contributes significantly at lower energies. We rely on `BlackHawk` (Arbey & Auffinger, 2021) to evaluate the gamma-ray primary and secondary spectral components. `BlackHawk` uses `PYTHIA` (Sjöstrand et al., 2015) for the

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modeling of the hadronization and decay processes leading to the secondary spectra. Final-state radiation originates from relativistic electrons and positrons and has a differential spectrum given by Eq.~,

$$\frac{dN_\gamma^{\mathsf{FSR}}}{dE_\gamma} = \frac{\alpha}{2\pi} \int dE_{e^+} \frac{dN_{e^+}}{dE_{e^+}} \left(\frac{2}{E_\gamma} + \frac{E_\gamma}{E_{e^+}^2} - \frac{2}{E_{e^+}} \right) \left[\ln \left(\frac{2E_{e^+} + (E_{e^+} - E_\gamma)}{m_{e^+}^2} \right) - 1 \right],$$

where $\alpha = 137.037$ is the fine structure constant, E_{e^+} is the kinetic energy of a given positron (e^+), E_γ is the energy of the emitted photon, $m_{e^+} = 0.511$ MeV is the rest mass of the electron, and $\frac{dN_{e^+}}{dE_{e^+}}$ the differential spectrum of emitted electrons/positrons. In addition to the previously mentioned components, gamma-rays can be produced through pair-annihilation of positrons with interstellar medium electrons. This is known as in-flight annihilation and its differential spectrum is (Keith et al., 2022),

$$\frac{dN_\gamma^{\mathsf{IA}}}{dE_\gamma} = \frac{\pi \alpha^2 n_H}{m_e} \int_{m_e}^{\infty} dE_{e^+} \frac{dN_{e^+}}{dE_{e^+}} \int_{E_{\min}}^{E_{e^+}} \frac{dE}{dE/dx} \frac{P_{E_{e^+} \to E}}{(E^2 - m_e^2)}$$

$$\times \left(-2 - \frac{(E + m_e)(m_e^2(E + m_e) + E_\gamma^2(E + 3m_e) - E_\gamma(E + m_e)(E + 3m_e))}{E_\gamma^2 (E - E_\gamma + m_e)^2} \right).$$

We take $n_H = 1\,\mathrm{cm}^{-3}$ as the density of interstellar medium hydrogen (and by extension electrons). E_{e^+} is again the initial positron total energy, E is the final positron total energy, dE/dx is the rate of positron energy lost per path via the Bethe-Bloch formula (Bethe & Ashkin, 1953), E_γ is the resulting photon energy from annihilation, and $P_{E_{e^+} \to E}$ is the probability of a particular positron of a given initial and final energy to decay. This probability matrix can be calculated as (Keith et al., 2022),

$$P_{E_{e^+} \to E} = \exp \left(-n_H \int_E^{E_{e^+}} \sigma_{\mathrm{ann}}(E') \frac{dE'}{dx} dE' \right),$$

where σ_{ann} is the cross section of annihilation for positrons of a given energy.

In Fig.~1, we give the individual gamma-ray spectral components as well as their sum for a PBH of mass 3×10^{15} grams.

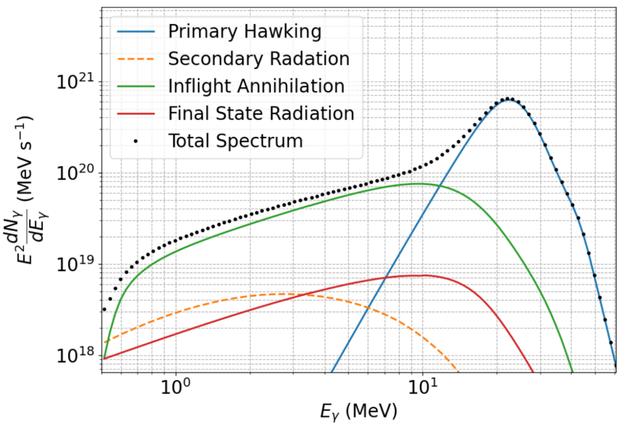

Figure 1: The total gamma-ray spectrum of a 3×10^{15} grams PBH as well as its components.

PBH Mass Distribution

Users can calculate the gamma-ray spectra from four types of PBH mass distributions. Those are, i) a monochromatic distribution with a mass to be set in the range of 5×10^{13} to 1×10^{19} grams, ii) a Gaussian distribution of PBH masses originating from a Gaussian distribution of density perturbations (Biagetti et al., 2021), iii) a more realistic non-Gaussian PBH mass distribution from (Biagetti et al., 2021) and iv) a log-normal distribution of PBH masses. In Fig.~2, we give the gamma-ray spectra from monochromatic and Gaussian PBH mass-distributions.

The total gamma-ray spectrum per PBH, from a PBH of mass 3×10^{15} grams (blue line) and from a Gaussian distribution of density perturbations leading to a distribution of a mean mass of 3×10^{15} grams. σ refers to the standard deviation of initial density perturbations (Biagetti et al., 2021).

Figure 2: The total gamma-ray spectrum per PBH, from a PBH of mass 3×10^{15} grams (blue line) and from a Gaussian distribution of density perturbations leading to a distribution of a mean mass of 3×10^{15} grams. σ refers to the standard deviation of initial density perturbations (Biagetti et al., 2021).

Software content

`GammaPBHPlotter` was written in `Python` version 3.9 and is capable of running on Windows, Linux, and Mac. The main code uses five modules in its routine. Those being `colorama` (Hartley, 2022), `NumPy` (Harris et al., 2020), `Matplotlib` (Hunter, 2007), `tqdm`, (Costa-Luis & developers, 2024) and `SciPy` (Virtanen et al., 2020). The package is available via PyPI and the archived release is cited as (Carlini & Cholis, 2025).

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