

Article

Ultra-High-Energy Cosmic Rays from Active Galactic Nuclei Jets: The Role of Supermassive Black Hole Growth and Accretion States

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Abstract: Jets emanating from active galactic nuclei (AGNs) represent some of the most formidable particle accelerators in the universe, thereby emerging as viable candidates responsible for the detection of ultra-high-energy cosmic rays (UHECRs). If AGN jets indeed serve as origins of UHECRs, then the diffuse flux of these cosmic rays would be dependent on the power and duty cycle of these jets, which are inherently connected to the nature of black hole accretion flows. In this article, we present our cosmological semi-analytic framework, *JET* (Jets from Early Times), designed to trace the evolution of jetted AGN populations. This framework serves as a valuable tool for predictive analyses of cosmic ray energy density and, potentially, neutrino energy density. By using *JET*, we model the formation and evolution of galaxies and supermassive black holes (SMBHs) from $z = 20$ to $z = 1$, incorporating jet formation and feedback mechanisms and distinguishing between various accretion states determined by the SMBH Eddington ratios. The implications of different SMBH growth models on predicting cosmic ray flux are investigated. We provide illustrative examples demonstrating how the associated diffuse UHECR fluxes at the source may vary in relation to the jet production efficiencies and the selected SMBH growth model, linking cosmological models of SMBH growth with astroparticle backgrounds.

Keywords: supermassive black holes; AGN jets; cosmic rays;



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1. Introduction

The origin of ultra-high-energy cosmic rays (UHECRs) with energies above 10^{17} eV, presumed to come from extragalactic sources, continues to be a subject of investigation. Several works have shown that UHERCs can play an important role in galaxy evolution [1–6], affecting the morphology and dynamics of molecular clouds in star-forming galaxies by depositing part of their energy into the interstellar medium (ISM) [7–10] and potentially driving gas outflows [11–13]. On an intergalactic scale, after escaping their galaxy of origin, they can interact with the warm-hot intergalactic medium present in filaments [14] and be transported around the cosmic web to other galaxies. For all these reasons, we believe that incorporating CR physics into cosmological models of galaxy evolution is of significant importance. The origin of cosmic rays, however, remains elusive, and there are considerable challenges in constraining source population models using ground-based observations of the CR flux [15–19]. The process of diffusive particle acceleration occurring behind the

shock fronts of supernovae (SNe) [20] as well as within the coronae of active galactic nuclei (AGNs) [21] may account for the acceleration of cosmic rays up to energies of $\sim 3 \times 10^{15}$ eV, potentially reaching up to 10^{17} eV for the heaviest nuclei when strong magnetic fields are present. This acceleration mechanism is insufficient, however, to account for the UHE tail of the CR spectrum, which extends up to $\sim 10^{20}$ eV. Relativistic jets in AGNs are often considered a viable site for UHECR acceleration due to their immense power (e.g., [22], and references therein), while alternative energetic phenomena, including gamma ray bursts and tidal disruption events, have also been considered as potential contributors [23–25]. Initial observations conducted by the Pierre Auger Collaboration appeared to support the AGN hypothesis, as they detected spatial anisotropies in the UHECR field that seem to align with the positions of AGN in the sky [26]; however, the statistical significance of these findings remains a topic of debate [27]. Observations carried out with Cherenkov telescopes such as HESS, MAGIC, and VERITAS, able to observe diffuse γ -ray fluxes, also suggest that active SMBHs can provide an origin for PeV and ultra-high-energy cosmic rays [28–30], confirming at the same time that SNe remnants alone are not sufficient to produce them [31,32].

Black hole jet activity, found in systems of both stellar-mass black holes in black hole X-ray binaries (BHXBs) and SMBHs in AGN, is associated with the accretion rate and therefore the type of accretion (see, e.g., [33]). For example, according to their hardness in X-ray spectra and total intensity, BHXBs exhibit jet activity at a low/hard state: when the X-ray spectrum is harder and the total intensity (and also the corresponding accretion rate) is lower. In contrast, the jet quenches when the system transits to a high/soft state: the X-ray spectrum is now softer and the total intensity is higher (e.g., [34,35]). Similar spectral states [36,37] and disk-jet couplings [38] have also been suggested for AGN systems. A typical threshold for state transition and jet suppression is when the Eddington ratio grows above $\lambda_{\text{ADAF,jet}} \sim 0.001\text{--}0.01$, where $\lambda \equiv \dot{M}/(\dot{M}_{\text{Edd}})$ and the Eddington accretion rate, $\dot{M}_{\text{Edd}}$, is related to the Eddington luminosity, L_{Edd} , with $\eta \dot{M}_{\text{Edd}} c^2 = L_{\text{Edd}}$, $\eta = 0.1$. Theoretically, below this ratio the central region is occupied by a radiatively inefficient geometrically thick and optically thin accretion flow (ADAF, advection-dominated accretion flow) [39–41]. When the Eddington ratio increases above $\lambda_{\text{ADAF,jet}}$, the accretion disc becomes optically thick, it can efficiently radiate away the accumulated energy, thus remaining cool and geometrically thin. The system enters in the thermal state and the jets are suppressed. At even higher accretion rates, for $\lambda_{\text{slim,jet}} \gtrsim 1$, the accretion becomes geometrically thick again because the photons are trapped inside the accretion flow, resulting in a slim disc (see, e.g., [42]). The magnetic extraction of rotational energy from black holes is thought to be responsible for the launching mechanisms of both ADAF jets and slim-disc jets. However, in the latter cases, the process can be more complex due to the significant influence exerted by radiation pressure (see, e.g., [43]). Despite the current incomplete understanding of the distinctions between these two types of jet, it is expected that the associated production of UHECRs from these jets may vary.

Ref. [44] (from now on referred to as PPW24) have modeled the historical activity of supermassive black hole jets from $z = 20$ to $z = 4$, encompassing a comprehensive range of halo masses while considering both types of jet: those operating at low accretion rates (ADAF jets) and those at high accretion rates (slim-disc jets). Two distinct accretion scenarios are evaluated: (1) super-Eddington model (sEDD; fiducial model in PPW24) and (2) Eddington-limited model (EDDlim; reference model in PPW24). Both scenarios effectively replicate the primary statistical properties of AGN and galaxies, as reported in $z \lesssim 7$; their predictions, conversely, differ substantially at higher redshifts and for black holes in the intermediate mass range $10^4 \lesssim M_{\text{bh}} \lesssim 10^6 M_{\odot}$, enabling us to potentially distinguish between the two black hole growth models.

This study investigates the predicted energy fluxes and spectral properties of UHECRs at the source by incorporating our cosmological model of galaxy and SMBH formation and evolution, as proposed in PPW24, with models for the production of cosmic rays in AGN jets. We examine two distinct models for the production of UHECRs: in the first model, UHECRs are exclusively generated by ADAF jets, whereas in the second model both ADAF and slim-disc jets produce UHECRs with the same efficiency. Furthermore, in contrast to PPW24, the cosmic evolution from $z = 20$ to $z = 1$ is modeled, along with a consideration of metallicity evolution. It is crucial to consider that the predicted UHECR spectrum is fundamentally dependent on the number density and power of the jetted AGN at specific redshifts, and consequently it is influenced by the associated uncertainties due to the limited constraints on jet properties at high redshifts. However, SMBH growth and feedback models during early epochs are expected to be constrained more effectively through the surveys conducted by current and forthcoming missions such as JWST [45], Laser Space Interferometer Antenna (LISA), and Advanced Telescope for High-energy Astrophysics (ATHENA).

The article is organized as follows: In Section 2, we recap the characteristics of the model, with a special focus on the features that are new with respect to the implementation in PPW24. In Section 3, we show our predictions for the main AGN and galaxy observables to make sure that our model is properly tuned. In Section 4, we introduce our formula for UHECR production in AGN jets and show the results with respect to different scenarios. We conclude with a summary and discussion in Section 5.

2. The *JET* Model for Galaxy and Black Hole Evolution

Our cosmological semi-analytic framework, *JET* (Jets from Early Times), finds its roots in the DELPHI cosmological framework [46–49], yet has been adapted to incorporate a model of jet formation (as already applied in PPW24) and to reach lower redshifts. In this section, we outline the primary characteristics of our model and present a comprehensive examination of the recent modifications implemented. For an overview of the parameters adopted in the model, see Table A1 in Appendix A.

2.1. Dark Matter Merger Tree

A dark matter merger tree of 120 halos with final masses $M_h = 10^9 - 10^{15} M_\odot$ is used for our semi-analytic model of galaxy evolutions and black hole growth. From $z = 20$ to $z = 1$, the merger trees are computed in time steps of 20 Myr and with a mass resolution of $10^9 M_\odot$. The number density of the final halos and their progenitors are assigned to be consistent with the Sheth–Tormen halo mass function (HMF [50]). Figure 1 shows that adopting a higher mass resolution does not pose a problem for the dark matter halo statistics. Merger trees, respectively with $10^8 M_\odot$ (red lines) and $10^9 M_\odot$ (green lines) mass resolutions, reproduce the theoretical Sheth–Tormen HMF (blue lines) equally well. The merger trees keep track of both halo mergers and dark matter accreted smoothly below the resolution mass threshold. New halos form with a dark matter mass just above the mass resolution threshold, and with a gas mass proportional to Ω_b/Ω_m . At each time step, beside receiving the contribution from mergers with other halos, each halo accretes dark matter and, proportionally, gas from the intergalactic space. The initial leaves of the merger trees at $z > 13$ are seeded with a $150 M_\odot$ stellar black hole (e.g., see [51–53] for a review on the formation channels of black hole seeds). It is worth pointing out that the final results are not significantly affected by implementing alternative seeding scenarios [47], since SMBH growth in such a model turns out to be self-regulated: higher-mass initial seeds will grow slower than lower-mass seeds, due to more feedback.

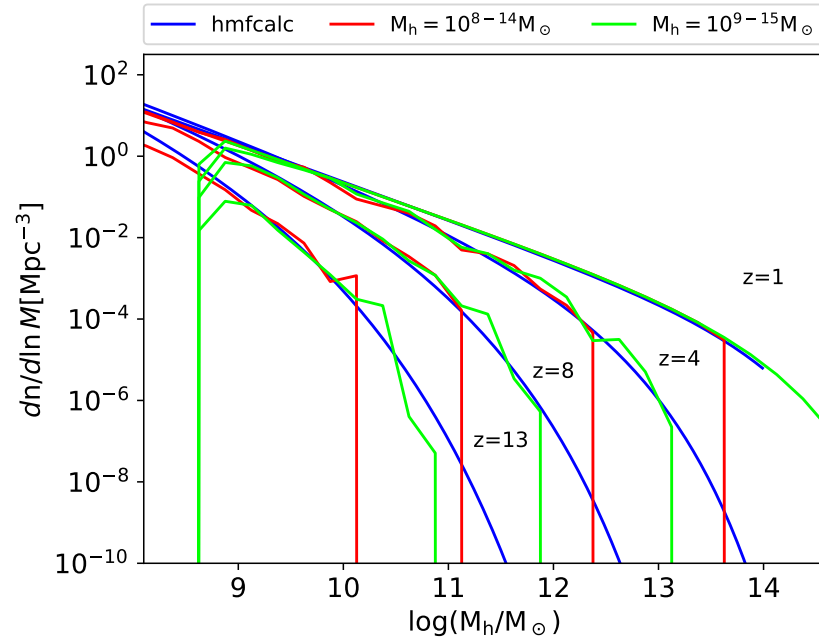


Figure 1. Merger trees at different redshift. The blue lines show the Sheth–Tormen halo mass function from the online published tool HMFcalc [54]. Red lines correspond to our merger trees from halos within the $10^8 - 10^{14} M_{\odot}$ mass range and a $10^8 M_{\odot}$ mass resolution, while green lines cover the $10^9 - 10^{15} M_{\odot}$ range with a $10^9 M_{\odot}$ mass resolution (used in this work).

2.2. Star Formation and the Gas Cycle

As described in PPW24, during each discrete temporal iteration, z , the variations in mass for the dark matter halo, hot and cold gas, black hole, stellar components, and the halo’s gaseous reservoir are calculated. Furthermore, it is assumed that an unresolved amount of dark matter and gas originating from intergalactic regions would contribute to each halo. The gas dynamics also includes the gas accreted from the IGM, and that ejected from the galaxy via feedback processes. Gas from the IGM (and the gas reservoir) can be accreted either cold, if the halo mass, M_h , is lower than a critical value, M_h^{crit} , or hot and cold if $M_h > M_h^{\text{crit}}$. Consistently with what was found in [55], however, at $z < 2$ halos more massive than M_h^{crit} can only accrete hot gas. The critical halo mass, which also defines the SMBH accretion model, as we will see in the corresponding subsection, is treated as a free parameter:

$$M_h^{\text{crit}}(z) = 10^{11.25} \Delta_z^{-3/8} M_{\odot}. \quad (1)$$

At each time step, part of the cold gas is turned into stars, and star formation feedback drives gas outflows into the gas reservoir. For more details on how the different gas phases and the stellar mass are tracked, we refer the reader to PPW24.

2.3. Metallicity Evolution

Stellar activity in galaxies produces metals that can then be ejected into the ISM and the gas reservoir. Stellar winds from AGB stars and SNe explosions are the main metal polluters, and to track the metallicity evolution we introduce two parameters, following the example set by [56]: $R(z)$ represents the fraction of stellar mass returned to the ISM in the form of gas during stellar evolution, while $p(z)$ is the fraction of stellar mass that is turned into metals and ejected into the ISM. In their work, ref. [57] computed these parameters for a Kennicutt initial mass function (IMF). Here, we re-compute the values of

these parameters for our fiducial IMF $\Phi(m)$, which corresponds to a Salpeter IMF within the $0.1 - 100M_{\odot}$ mass range, finding

$$R = \int_{0.1M_{\odot}}^{100M_{\odot}} (m - m_{\text{rem}}(m)) \Phi(m) d \ln m = 0.301 \quad (2)$$

and

$$p = \int_{0.1M_{\odot}}^{100M_{\odot}} p_Z(m) m \Phi(m) d \ln m = 0.018, \quad (3)$$

where $m_{\text{rem}}(m)$ is the mass of the remnant (white dwarf, neutron star, or black hole) of a star of mass m and $p_Z(m)$ is the fraction of the initial mass m of a star that is synthesised into metal and ejected. Both $m_{\text{rem}}(m)$ and $p_Z(m)$ are derived by interpolating the results from the stellar evolution calculations performed in [58,59]. The metal production rate then reads

$$\dot{M}_Z = p \dot{M}_*. \quad (4)$$

The new metals are injected into the cold gas mass component and are then proportionally exchanged between the cold gas, hot gas, stellar, and gas reservoir mass components.

2.4. Black Hole Growth and Feedback Model

As presented in detail in PPW24, our black hole accretion and feedback model depends on the host halo mass. Below the critical value $M_{\text{h}}^{\text{crit}}$, black holes can accrete only from the hot gas at the Bondi rate. Above $M_{\text{h}}^{\text{crit}}$, major mergers (with mass ratio ≥ 0.1) trigger episodes of fast accretion of cold gas:

- in the sEDD scenario, the accreted gas mass is limited to a fraction $f_{\text{av}}^{\text{bh}}$ (see Appendix A) of the total cold gas mass present in the galaxy;
- in the EDDlim scenario, the accreted gas mass corresponds to the minimum between the same fraction, $f_{\text{av}}^{\text{bh}}$, of the cold gas mass or the mass that the black hole would accrete by growing at the Eddington rate.

For both scenarios, the duration of the episode persists until the fraction of the cold gas mass, m_c , is reduced to a proportion, f_c , in relation to its value at the time of the merger. We write the mass accreted by the black hole at each time step as

$$\dot{M}_{\text{bh}} = \begin{cases} \dot{M}_{\text{bh}}^{\text{hot}} & \text{for } M_{\text{h}} < M_{\text{h}}^{\text{crit}} \\ \dot{M}_{\text{bh}}^{\text{hot}} + \dot{M}_{\text{bh}}^{\text{cold}} & \text{for } M_{\text{h}} > M_{\text{h}}^{\text{crit}} \end{cases}. \quad (5)$$

The inflow of hot gas towards the central black hole, on the other hand, is permitted continuously.

As specified in PPW24, it is assumed that radiative feedback lunched during cold gas accretion results in gas outflow and replenishes the gas reservoir, while jets, if they exist, can heat up the cold gas in the galaxy. The quasar luminosity, L_{bol} , is calculated according to the numerical simulation of the slim discs of [42] and fitted by [56]. The dimensionless black hole spin parameter is adopted to be $a = 0.5$ for all black holes. The jet can be launched when either the condition of the accretion rate, in terms of the Eddington ratio λ , is satisfied: $\lambda_{\text{Edd}} \leq \lambda_{\text{ADAF,jet}} = 0.01$ or $\lambda_{\text{Edd}} \geq \lambda_{\text{slim,jet}} = 1$. To estimate the electromagnetic extraction of black hole rotational energy as Blandford–Znajek jet power, we consider the theoretical estimation in [60]:

$$P_{\text{jet}} = 2.8 f(a) \left(\frac{\phi}{15} \right)^2 \dot{M}_{\text{bh}} c^2. \quad (6)$$

The above formula is related to the dimensionless magnetic flux, ϕ , and the black hole spin dependence, $f(a) = a^2 \left(1 + \sqrt{1 - a^2}\right)^{-2}$. For each black hole seed, a random value is chosen between $\phi = 1$ and $\phi = 50$. In the event of a black hole merger, the resulting ϕ corresponds to that of the black hole possessing the greatest mass. After the jet is launched, part of the jet energy, $f_{\text{jet}}^{\text{h}}$, heats up cold gas:

$$\dot{M}_{\text{heated}} = f_{\text{jet}}^{\text{h}} \frac{2 P_{\text{jet}}}{V_{\text{vir}}^2}. \quad (7)$$

3. The Galaxy and SMBH Populations

To guarantee that the model thoroughly represents the evolution of both galaxy and AGN populations through cosmic time, in this section we compare our results with observations. At the same time, we provide an overview of the main characteristics of the jetted AGN populations as forecasted by our model.

3.1. Star Formation and Black Hole Accretion Rates

Figure 2 shows the redshift evolution of the Eddington ratio, the cold gas fraction, and the specific star formation rate (in Myr^{-1}) for galaxies in halos of different masses. In particular, SMBHs in the sEDD model show short, early strong slim-disc jet bursts with $\lambda_{\text{Edd}} > 1$ that can temporarily quench both star formation and SMBH activity by heating the cold gas, until major mergers trigger new episodes. Later on, as the Eddington ratio decreases, the SMBH enters a prolonged ADAF jet phase with $\lambda < \lambda_{\text{ADAF,jet}} = 0.01$. On the other hand, SMBHs in the EDDlim case initially grow slower and galactic gas accretion from the IGM is able to compensate the feedback from the black hole and sustain continuous star formation activity in the early evolutionary phases. In this scenario, slim-disc jet bursts can last up to ~ 100 Myr and can be triggered multiple times by major mergers, before $\lambda < \lambda_{\text{ADAF,jet}}$ is satisfied and the SMBH enters the ADAF jet phase. In this case, we can have jet-induced quenching episodes at later epochs. For all considered quantities, the differences between the two scenarios become negligible at later epochs, and we expect this to reflect when looking at low-redshift population-wide statistical observables.

Figure 3 shows the redshift evolution of the cosmic star formation and black hole accretion rate densities (SFRD, BHARD) for different mass cuts. Overall, our results match the observations across the whole redshift range considered, the best agreement being achieved, respectively, for galaxies with $M_* > 10^{8.75} M_{\odot}$ and black holes with $M_{\text{bh}} > 10^7 M_{\odot}$. We also reproduce the correct redshift for the peak of stellar and black hole activity, at $z \sim 2$. In our model, this is caused by the combined effect of AGN jets emitted by SMBHs whose growth is now slowing down, with the Eddington ratio falling below $\lambda_{\text{Edd}} \leq 0.01$. These jets are capable of heating up most of the gas present in the galaxy. The second effect is that high-mass galaxies accrete most of the gas from the IGM in hot mode.

3.2. Black Hole Mass Function

Figure 4 displays the redshift evolution of the black hole mass function (BHMF) for both the sEDD (solid lines) and EDDlim (dashed lines) scenarios. In PPW2024, we showed that the two SMBH growth models produce markedly different SMBH populations in $z \gtrsim 7$, although they exhibit a tendency to converge as the redshift decreases. In this study, we validate this trend down to $z = 1$ and illustrate that both models are in agreement with the observational and theoretical findings of the BHMF at $z < 6-7$.

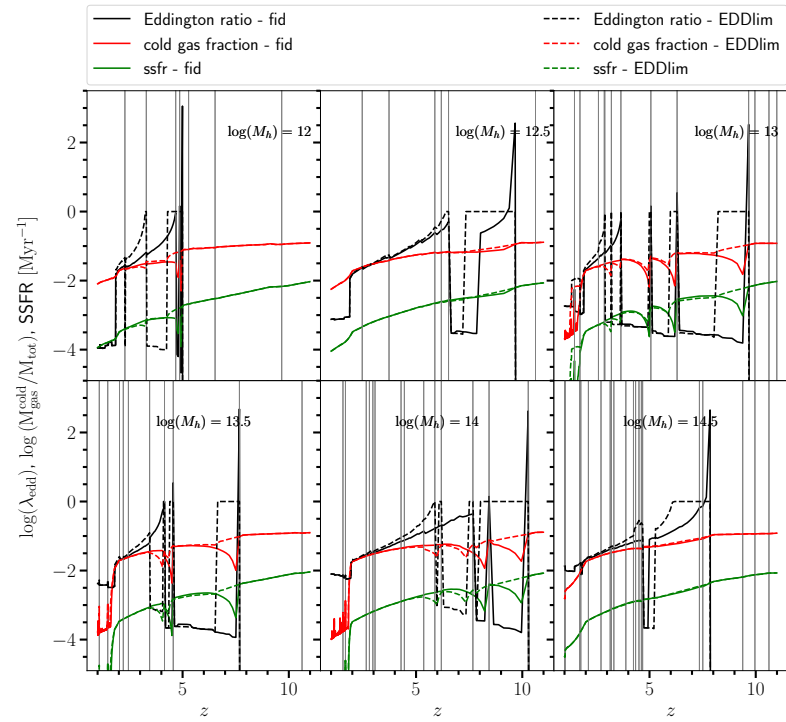


Figure 2. Redshift evolution for the cold gas fraction and specific star formation rate of galaxies, the Eddington ratio of their central SMBHs for halos of different masses. Grey vertical lines represent major mergers.

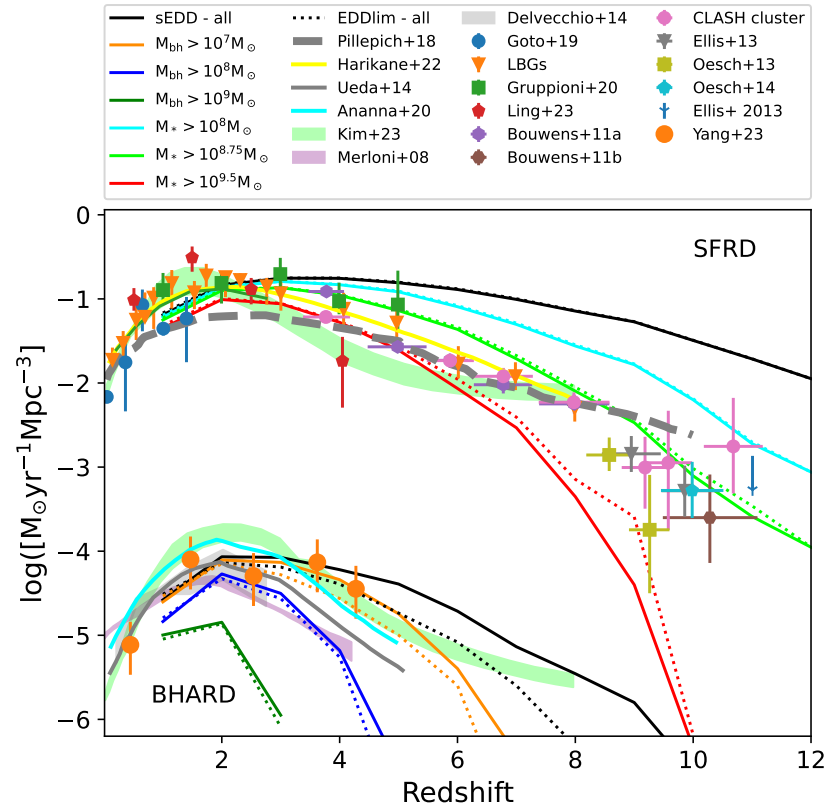


Figure 3. Cosmic SMBH accretion rate density and star formation rate density as a function of redshift for different BH and stellar mass cuts as specified in the legend. Solid lines represent the super-Eddington (sEDD) scenario, while dashed lines are for the Eddington-limited (EDDlim) case. Comparisons with several other observational and theoretical results are shown [61–76].

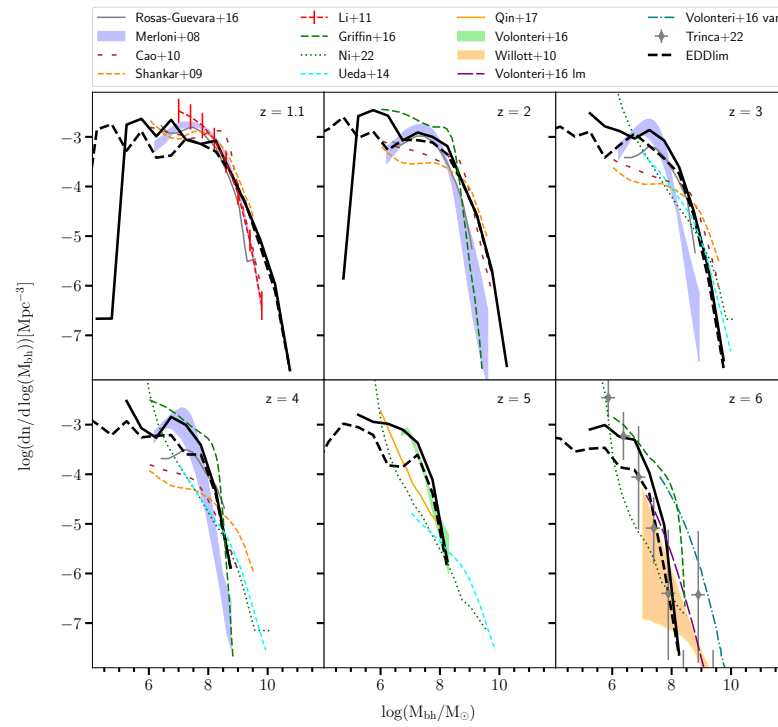


Figure 4. Redshift evolution of the black hole mass function for super-Eddington (sEDD, black solid lines) and the Eddington-limited (EDDlim, black dashed lines) cases. We also show the results of other observational and theoretical results for comparison [63,66,77–86].

3.3. Jet Activities During Cosmic Time

To examine the contribution of AGN jet activities, we compare AGN with jets (jetted AGN) to the entire AGN population. The AGN bolometric luminosity function, ϕ , based on the radiative output of the accretion disc, L_{qso} , is shown for our benchmark scenario (sEDD model) in Figure 5. Among jetted AGN, we further highlight that the population with their jet contribution belongs to ADAF jets. Note that the total jetted AGN populations consists of both sources with ADAF jets and slim-disc jets.

In general, jet activities become increasingly prevalent in high-luminosity bins as redshift decreases, whereas, at high redshift, the most luminous sources are associated with SMBHs in quasar mode, which characteristically lack jets. Slim-disc jets, originating from SMBHs undergoing super-Eddington accretion, predominate among high-luminosity jetted AGN at elevated redshifts. However, over time, there is a decrease in the average Eddington ratio of SMBHs, a trend corroborated by observational surveys. In particular, at $z \sim 1$, no SMBHs are accreting at super-Eddington rates. Furthermore, the gap observed in the luminosity function at high redshift is indicative of the bimodal distribution of the Eddington ratio, as previously identified in Figure 6 of PPW2024.

The AGN number densities as a function of redshift for different populations (AGN, all jetted AGN, and jetted AGN with ADAF jets) are presented in Figure 6. The evolution of the AGN number density is shown for different luminosity bins and for both the sEDD (solid lines) and the EDDlim (dashed lines) models, respectively. We note that the trends between the two growth models differ significantly at $z \gtrsim 7$, due to the different growth paths SMBHs undergo in the early stages of their evolution, as already shown in Figure 2. Jetted AGN dominate at low luminosities across all redshifts, while quasar-mode SMBHs are prevalent in the highest-luminosity bin and for $10^{43} < L_{\text{bol}} < 10^{47}$ erg/s at $z \lesssim 6-7$.

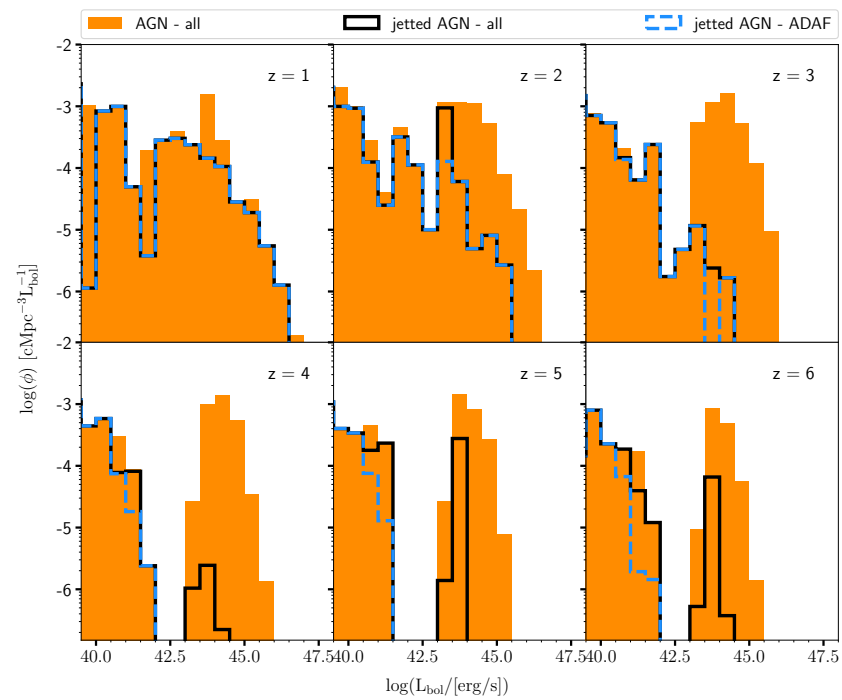


Figure 5. The AGN bolometric luminosity function, ϕ , across different redshifts for the sEDD model: it represents the expected number of AGNs found in a Mpc^3 per each bin of L_{bol} . The histograms filled in orange represent the AGN population, while the black solid lines and blue dashed lines denote the jetted AGN and ADAF-jetted populations, respectively.

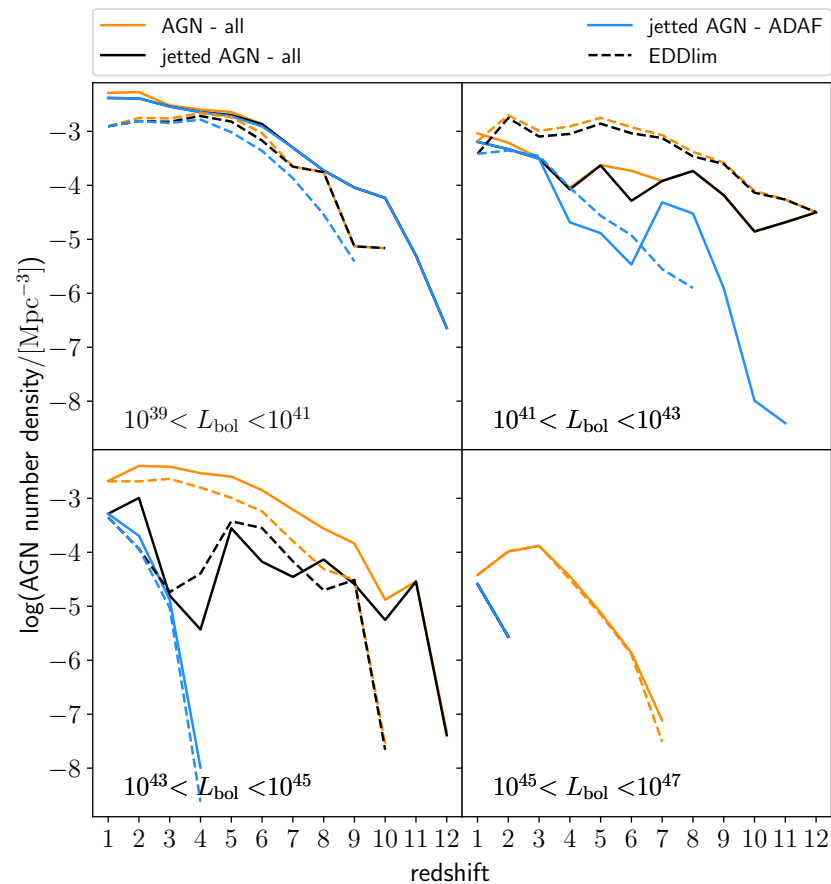


Figure 6. Evolution of the number densities of the total (solid blue line, jetted (dashed orange line) and ADAF-jetted (dotted green line) AGN populations as a function of redshift for different luminosity bins.

4. UHECR Source Spectra Associated with Jet Activities

To approach the question of how jet activities in different black hole growth models affect the evolution of UHECR background, we need to estimate the spectral energy distribution density of cosmic rays escaping from the jetted AGN systems and ejected into intergalactic space. We follow the work of [87] (see, e.g., [88] for a similar approach) and define

$$q(E) = \zeta_{\text{CR}} n_{\text{jet}} P_{\text{jet}} E^{-2} \Theta(E_{\text{max}} - E), \quad (8)$$

where Θ is the full Heaviside step function, the parameter ζ_{CR} is the fraction of the total jet power that goes into accelerating particles, and n_{jet} is the jet number density. In the formula, E_{max} is the maximum accelerating energy of a particle computed according to the Hillas criterion, and reads [87]

$$E_{\text{max}} = \mathcal{Z} e \left(6 \beta c^{-1} P_{\text{jet}} \right)^{1/2} \approx 2.7 \times 10^{20} \mathcal{Z} \beta (P_{\text{jet},45})^{1/2} \text{eV}, \quad (9)$$

where $P_{\text{jet},45} = P_{\text{jet}} / (10^{45} \text{erg s}^{-1})$, $\mathcal{Z}e$ is the particle charge, and β is the jet velocity in units of the speed of light (see, e.g., [89–91]). For a more thorough discussion of the shape of the injected CR spectrum, see also [92], where the distribution function for the energetic particles behind SN shocks is derived.

To incorporate the potential different UHECR production rates in jets with ADAF or slim disk, we further consider ζ_{CR} in Equation (8) for two different types of jet, as $\zeta_{\text{CR,ADAF}}$ and $\zeta_{\text{CR,slim}}$. We adopt $\beta = v_{\text{jet}}/c \approx 1$ and $\mathcal{Z} = 1$ ($\mathcal{Z} = 8$), assuming a pure Hydrogen (Oxygen) composition. The selected values presented in $\mathcal{Z}$ are intended to account for the uncertainties regarding the particle composition of UHECR (e.g., [93]). Recent measurements appear to challenge pure Hydrogen compositions, instead favoring multi-species models, especially at high energies [94,95].

Figure 7 shows the results for the evolution of the total emitted CR energy density for the super-Eddington (sEDD, solid lines) and Eddington-limited (EDDlim, dashed lines) models at different redshifts. Two instances of UHECR production rates are considered: (1) UHECRs are produced by all jetted AGN, with $(\zeta_{\text{CR,ADAF}}, \zeta_{\text{CR,slim}}) = (0.1, 0.1)$, as indicated by the black (for $\mathcal{Z} = 1$) and red (for $\mathcal{Z} = 8$) lines in the figure, and (2) UHECRs are produced only by the ADAF jet, with $(\zeta_{\text{CR,ADAF}}, \zeta_{\text{CR,slim}}) = (0.1, 0)$, as indicated by the grey (for $\mathcal{Z} = 1$) and yellow (for $\mathcal{Z} = 8$) lines in the figure. As expected, Oxygen (and generally heavier) nuclei would dominate the high-energy end of the spectrum. In addition, this analysis demonstrates that, when considering only the influence of ADAF jets, the energy density of the emitted UHECRs at $z \gtrsim 4$ corresponds to only 0.1–1% of the energy that would be emitted by slim-disc jets. This phenomenon arises because, as previously observed, slim-disc jets originating from super-Eddington sources predominantly prevail at high z , while ADAF jets are more common at lower redshift. The variance in UHECR spectra generated by ADAF jets between the sEDD and EDDlim models approximates an order of magnitude at $z \sim 3$, whereas no discernible discrepancy is observed at $z < 3$. Conversely, when considering contributions from all jets, a difference of one order of magnitude is evident in the spectra emitted by the two models at $z \sim 2$. The distinctions between the sEDD and EDDlim models become more pronounced at $z \gtrsim 8$.

Due to the uncertainties of the adopted parameters, it should be noted that our primary focus is not in the magnitude of the energy fluxes illustrated in Figure 7, but rather in elucidating the relative differences between the various models. Under the simplifying assumptions of this investigation, critical parameters such as jet power and the UHECR production rate, ζ_{CR} , are postulated. In fact, we assume that the jets are powered by magnetic extraction of the black hole rotational energy, and therefore their power depends on the black hole spin and the magnetic flux surrounding it, both of which are parameters

within our SMBH growth models PPW2024. More precise predictions could be achieved in the future with enhanced understanding of the physics related to these free parameters. Most of the models that track the evolution of the SMBH spin (e.g., [96–98]) follow the formalism developed in [99]. However, the resulting spin distribution strongly depends on the assumed BH accretion model and on the initial conditions. A more conservative approach, in this sense, would be considering upper and lower limits to the cumulative jet power by setting all BH spin parameters equal to, e.g., 0.15 and 0.998 [96]. According to Equation (6), this would result in a factor of ≈ 150 difference between the upper and lower limits of the jet power.

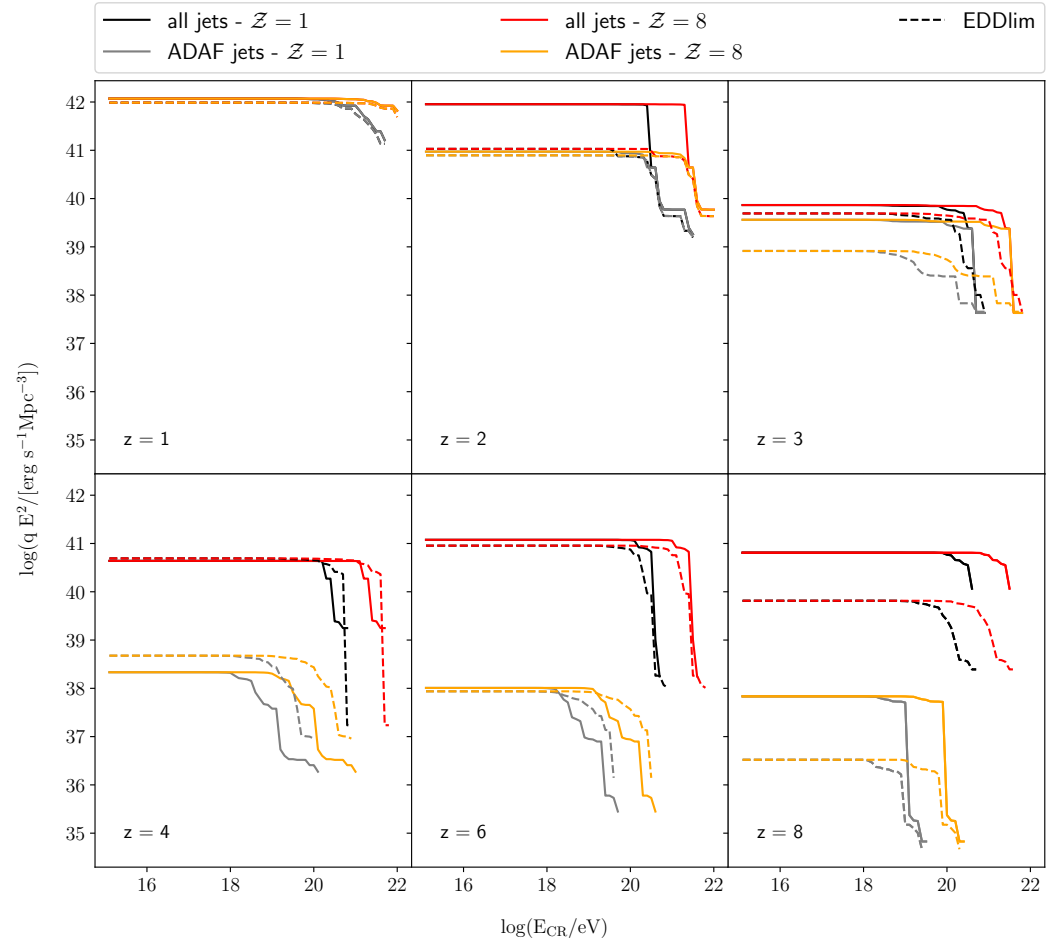


Figure 7. Evolution of the high-energy cosmic ray spectral energy density emitted at different redshift in the sEDD (dashed lines) and EDDlim (solid lines) scenarios. The results corresponding to different values of the atomic number Z —assuming pure Hydrogen (black and gray lines) or Oxygen (red and orange lines) compositions—are presented. The contribution to the total flux coming from ADAF jets, i.e., for $\lambda_E \leq 0.01$, as opposed to the slim-disc jets, defined for $\lambda_E \geq 1$, is also shown.

It is crucial to recognize that CRs experience energy loss during their propagation. Among the factors contributing to attenuation between their site of production and Earth, photohadronic ($p\gamma$) processes, particularly photo-pair production, are predominant in the energy loss of UHECRs. The interaction between UHECRs and cosmic microwave background photons establishes the Greisen–Zatsepin–Kuzmin (GZK) horizon [100,101], which restricts UHECRs from reaching Earth from distant sources as they dissipate energy prior to arrival. Moreover, the propagation length of cosmic rays decreases with increasing redshift (see, e.g., [14,102]), suggesting that the disparity in the UHECR spectrum sEDD and EDDlim models at high redshift could instead manifest itself in variations within other

particle constituents as they degrade in energy. For example, our framework allows for the estimation of the diffuse neutrino background contributed by AGNs, for given models of neutrino production within AGN jets (e.g., [103]).

5. Summary and Implications

In this study, we explore and demonstrate the role of AGN jets as potential sources of extragalactic UHECRs. We present the cosmological semi-analytic framework, *JET*, to model the evolution of jetted AGN populations and their connection to UHECR fluxes. Our framework provides a comprehensive approach to understanding the formation and evolution of galaxies, SMBHs, and their associated jet phenomena from $z = 20$ to $z = 1$. By incorporating jet formation mechanisms, black hole accretion states, and feedback processes into a cosmological context, *JET* enables predictions of the diffuse UHECR densities under different SMBH growth models.

Our results highlight several key insights for the connection between UHECR and AGN jets, as itemized below.

- Dependence on accretion types: the nature of AGN jets and their efficiencies are strongly influenced by the accretion states of SMBHs, as determined by their Eddington ratios. The UHECR production rate for the different jets (and therefore the accretion types), as considered in our parameter ξ_{CR} , is a major source of uncertainty.
- Dependence of jet duty cycles and feedback: the duty cycles of AGN jets, shaped by SMBH accretion histories, significantly impact the predicted UHECR flux at the source. Feedback effects further regulate the evolution of SMBHs and their host galaxies, leading to differences in the emitted cosmic ray energy densities.
- Dependence of SMBH growth models: different SMBH growth scenarios, such as the sEDD and EDDlim models considered in this work, lead to varying predictions for the UHECR background.

Furthermore, since the production of neutrinos and gamma rays is linked to the UHECR processes, such as proton–proton (pp) or photohadronic ($p\gamma$) interactions, the implications of our findings are not solely restricted to the theoretical predictions concerning cosmic rays but also encompass neutrino and gamma ray fluxes. In particular, the relative flux between UHECR, neutrinos, and gamma rays is associated with the prevailing interactions. Although the high redshifts of UHECR are unable to reach Earth owing to attenuation, the assessment of the diffuse neutrino background originating from AGN jets can be furthered through an understanding of neutrino production within these jets. This study reveals a direct connection between cosmological models of SMBH growth, AGN jet formation, and astroparticle backgrounds, thereby providing a framework for interpreting observational data in the realm of multi-messenger astrophysics. Further theoretical inquiries are necessary to explore these dependencies more comprehensively.

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Data Availability Statement: The data underlying this paper, which have been produced by our model, are available on reasonable request to the corresponding author.

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Appendix A

For completeness of information, we list in Table A1 the free parameters of the model, tuned to reproduce the statistical AGNs and galaxy observables shown in the paper. See PPW2024 for more details on their defining equations. $\Delta_z = [\Omega_m(1+z)^3 + \Omega_c]^{1/3}$.

Table A1. Model parameters, description, and default values.

Parameter	Description	Value
f_{cold}	fraction of the gas mass accreted onto the galaxy as cold	0.4
f_*	star formation efficiency cap	0.02
f_*^w	fraction of SN energy that couples to the gas	0.1
M_h^{crit}	critical halo mass for BH growth and cold accretion	$10^{11.25} \Delta_z^{-3/8} M_\odot$
M_{mm}	halo mass ratio defining major mergers	0.1
$f_{\text{av}}^{\text{bh}}$	fraction of cold gas mass that BH can accrete	0.00003
f_c	limiting cold gas fraction for quasar accretion	0.6
f_{qso}^w	fraction of BH energy that couples to the gas	0.003
f_{jet}^w	fraction of jet energy that drives outflows	0.003
f_{jet}^h	fraction of jet energy that heats up the gas	0.01

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