

REVIEW ARTICLE

Active galactic nuclei – the physics of individual sources and the cosmic history of formation and evolution

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Received November 20, 2012; accepted January 17, 2013

In this paper we give a brief review of the astrophysics of active galactic nuclei (AGNs). After a general introduction motivating the study of AGNs, we discuss our present understanding of the inner workings of the central engines, most likely accreting black holes with masses between 10^6 and $10^{10} M_{\odot}$. We highlight recent results concerning the jets (collimated outflows) of AGNs derived from X-ray observations (Chandra) of kpc-scale jets and γ -ray observations of AGNs (Fermi, Cherenkov telescopes) with jets closely aligned with the lines of sight (blazars), and discuss the interpretation of these observations. Subsequently, we summarize our knowledge about the cosmic history of AGN formation and evolution. We conclude with a description of upcoming observational opportunities.

Keywords active galactic nuclei (AGNs), black hole accretion, relativistic jets, cosmological evolution

PACS numbers 98.54.-h, 98.54.Cm, 98.54.Gr, 98.62.Js, 98.62.Nx

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supermassive black holes (SMBHs) of a few million to a few billion solar masses. Whereas it seems likely that all galaxies contain one or more supermassive black holes [1, 2], the black holes in AGNs give rise to spectacular observational consequences because they accrete matter and convert the gravitational energy of the accreted matter (and possibly also the rotational energy of the black hole) into mechanical and electromagnetic energy. A few of the most salient motivations for the study of AGNs are:

- **AGN taxonomy:** AGNs are among the brightest extragalactic sources and account for a large fraction of the electromagnetic energy output of the Universe, motivating their taxonomy and statistical characterization. The study of AGNs in the nearby Universe shows that the diversity of AGNs can be understood as resulting from observing a smaller number of basic AGN types from different viewing angles (see Section 3.1).
- **Accretion physics:** AGNs are powered by the accretion of magnetized plasma. Studies of AGN accretion flows complement studies of other accretion flows in astrophysics: accretion onto protostars and stars, accretion onto compact stellar remnants

1 Motivation

Active galactic nuclei (AGNs) are galaxies that harbor

(neutron stars and stellar mass black holes), and the accretion that powers gamma-ray bursts. One goal of the studies of AGN accretion flows is to provide a physical explanation of the different types of AGNs and their states in terms of the nature of their accretion flows and environments (see Section 3.3).

- **Role in eco-systems:** AGNs play an important role for galactic and galaxy cluster eco-systems, i.e., their mechanical and electromagnetic power contributes to the heating of the interstellar and intracluster medium, and thus influences the star formation of the host systems (see Section 2.4).
- **History through cosmic time:** Deep radio, IR, optical and X-ray observations of AGNs have provided us with a wealth of information about the cosmic history of the formation and growth of supermassive black holes and the evolution of AGNs. Related areas of research are to clarify the role of AGNs in re-ionizing the intergalactic medium, and to explain the correlation between black hole masses and the properties of the host galaxy observed in the local Universe (see Sections 4 and 5).
- **Fundamental physics:** On the most fundamental level, AGNs allow us to test the theory of general relativity (GR). GR's no-hair theorem states that Kerr (and more generally Kerr–Newman) solutions are the only stationary, axially symmetric vacuum solutions of the Einstein equations with an event horizon. Testing if astrophysical black holes are Kerr black holes thus constitutes a powerful test of GR in the observationally poorly constrained strong-gravity regime [3].
- **Astroparticle physics:** AGNs are astroparticle physics laboratories. A few examples: The TeV γ -ray emission from AGNs tells us that they can accelerate particles to $>\text{TeV}$ energies and AGNs might even be the sources of Ultra High Energy Cosmic Rays. The studies of the broadband emission from AGNs allows us to perform time resolved studies of the particle acceleration processes. AGN observations can also be used to constrain Lorentz Invariance violations (e.g. Ref. [4]), and to set upper and lower limits on extragalactic magnetic fields (see the discussion in Refs. [5, 6]).
- **AGNs as beacons at cosmological distances:** The emission from AGNs can be used to study the properties of objects, diffuse matter, and radiation fields that are located between us and the AGNs. High-resolution spectra of high-redshift, low-metallicity quasar absorption line systems have been used to constrain the relative abundance of

the light elements produced during the epoch of the Big Bang Nucleosynthesis [7]. Measurements of the Gunn–Peterson optical depths of high-redshift quasars constrain the re-ionization history of the intergalactic medium [8]. X-Ray Absorption lines constrain the abundance and properties of warm-hot intergalactic medium [9]. The study of the GeV and TeV γ -ray energy spectra of blazars can be used to constrain the energy spectrum of the infrared and optical Extragalactic Background Light [10].

The discussion in this paper is limited to recent results concerning the properties and inner workings of AGNs, and does not cover the research that uses AGNs as probes of the intervening medium. In Section 2 we discuss observations of AGN jets and their interpretation. In Section 3 we describe observations of the AGN cores, as well as models of AGN accretion and jet formation. We review recent results concerning the cosmic history of black hole accretion in Section 4, and trigger of black hole growth in Section 5. We conclude with a brief description of upcoming observational opportunities afforded by present and upcoming experiments in Section 6.

2 AGN jets on pc, kpc and Mpc scales

2.1 Morphology of radio galaxies

Some of the gravitational energy of the material accreted by AGNs is converted into heat and electromagnetic radiation inside the accretion disk and is radiated away by the accretion disk. Some of the material processed through the accretion disk escapes the accretion system as collimated (jets) and uncollimated (winds) outflows. The event horizon of a non-rotating Schwarzschild black hole is two times the gravitational radius:

$$r_g = \frac{GM_{\text{BH}}}{c^2} \approx 1.48 \frac{M_{\text{BH}}}{10^8 M_\odot} 10^{13} \text{ cm} \quad (1)$$

Approximately 10%–20% of AGNs are radio loud (radio to optical spectral index >0.35 , see e.g. Refs. [13, 14]), and show bright extended radio features with sizes up to ~ 1 Mpc (3.08×10^{24} cm). The AGN phenomenon thus spans ~ 11 orders of magnitudes in size scales.

The first jet of an SMBH was observed in the optical: in 1918, Curtis wrote about the object M 87 in the Virgo cluster [17]: “A curious straight ray lies in a gap in the nebulosity in p.a. 20° , apparently connected with the nucleus by a thin line of matter.” It was not before 1963 that the extragalactic nature of quasars (quasi-stellar objects, a type of AGNs) was established when Schmidt



Fig. 1 Comparison of the morphologies of an FRI radio galaxy (M84, *left panel*) and an FRII radio galaxy (3C 175, *right panel*). M84 is a massive elliptical galaxy in the Virgo cluster. The false-color composite image shows the Very Large Array 4.9 GHz image of the radio galaxy in red [11], the Chandra 0.5–2 keV image of hot galaxy gas in blue [12], and a Sloan Digital Sky Survey optical image in yellow and white. The radio galaxy has a projected diameter of ≈ 12 kpc. The Very Large Array 4.9 GHz image of 3C 175 ($z = 0.768$) shows a well-collimated jet, and two hot spot complexes typical for FRII radio galaxies. The projected distance between the two hotspots at the two ends of the radio galaxy is ≈ 370 kpc. Credits for the left panel: X-ray (NASA/CXC/MPE/A.Finoguenov et al.); Radio (NSF/NRAO/VLA/ESO/R.A.Laing et al); Optical (SDSS). The right image is a courtesy of NRAO/AUI.

measured the redshift $z = 0.158$ of the radio source 3C 273 [18]. We now know that radio-loud galaxies come in two qualitatively different types (see Fig. 1): Fanaroff–Riley Class I (FRI) sources have center-brightened outflows and Fanaroff–Riley Class II (FRII) exhibit an edge-brightened morphology. Whereas the separation of the regions of highest radio brightness of FRI sources are smaller than half the size of the radio source, those of FRII sources are larger than half the size of the radio source. FRI sources are less powerful than FRII sources, with 1.4 GHz luminosities below and above $5 \times 10^{25} \text{ W}\cdot\text{Hz}^{-1}$, respectively.

The observations of AGNs with single-dish and interferometric radio telescopes and with optical telescopes have provided us with detailed information about the morphology of radio-loud AGNs. As an example, Fig. 2 shows radio and optical images of M 87 with various resolutions, zooming in from an image of radio lobes blown by the central engine into the intrachuster gas to the inner jet imaged with a resolution of a few $10 r_g$. One distinguishes between the unresolved radio-core (which is likely to coincide with the location of the SMBH), the well collimated jet (which transports energy away from the SMBH), jet knots (locations of increased energy dissipation), hotspots and hotspots complexes (where the jet impinges on the ambient medium and most of the mechanical jet energy is dissipated in strong shocks), and lobes of radio-emitting plasma.

Radio-interferometric (and sometimes optical) observations of some AGNs reveal jet features moving with apparent motions exceeding the speed of light. Such

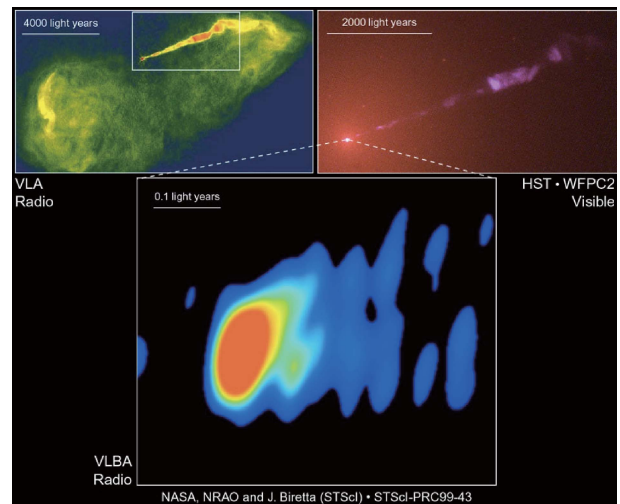


Fig. 2 Images of the radio galaxy M87 at the center of the Virgo galaxy cluster at different spatial scales and in different wavelengths. The Very Large Array radio image (*top left*) side shows the kpc-scale jet inflating radio lobes. The Hubble Space Telescope optical image (*top right*) shows the structure of the kpc-scale jet. The Very Long Baseline Array image (*bottom center*) shows the sub-pc scale jet very close to the black hole. Credits: National Radio Astronomy Observatory/National Science Foundation, NASA and John Biretta (STScI/JHU), National Radio Astronomy Observatory/Associated Universities, Inc.

“superluminal” motion can be explained by a near-alignment of the jet with the line of sight combined with highly-relativistic motion of the radio plasma. Photons emitted over a certain time interval reach the observer in a shortened time span as the plasma travels almost with the speed of light and thus stays closely behind photons emitted towards the observer. The apparent velocity can

then exceed the speed of light.

If we denote the jet plasma velocity with $v = \beta_j c \approx c$ (c being the speed of light), we can introduce the bulk Lorentz factor of the plasma with

$$\Gamma_j = (1 - \beta_j^2)^{-1/2} \quad (2)$$

Emission from the jets is red or blue-shifted by the relativistic Doppler factor

$$\delta_j = \frac{1}{\Gamma_j(1 - \beta_j \cos \theta)} \quad (3)$$

with θ being the angle between the jet axis and the line of sight as measured in the observer frame. A detailed study of a statistically complete, flux-density-limited sample of 135 compact radio sources with the Very Long Baseline Array (VLBA) and the Metsähovi Radio Observatory reveals relativistic motion with bulk Lorentz factors Γ_j between 1 and ~ 40 [20].

2.2 X-ray and gamma-ray observations of kpc-scale jets

The Chandra X-ray observatory discovered X-ray emission from the kpc-scale jets and hotspots of a large number of radio-loud AGNs [21]. The XJET web-site¹⁾ lists the detection of X-ray emission associated with the jets from ~ 120 AGNs. The origin of the X-ray emission is still somewhat uncertain, especially for the higher-power

FR II-type sources.

For the low-power FRI-type sources, the X-ray emission from the kpc-jets can in most cases be explained as synchrotron emission from $\sim \text{TeV}$ electrons gyrating in $10\text{--}1000 \mu\text{G}$ magnetic fields. As electrons lose their energy on time scales of years, the X-ray bright spots imply in-situ particle acceleration. Well resolved jets show X-ray bright knots, sometimes spread over the extension of the jet (Fig. 3). The hypothesis of a synchrotron origin of the X-rays is supported by the rapid time variability of the X-ray flux from the knots of the M87 jet [21], the radio to X-ray energy spectra which allow modeling with a single synchrotron component with a monotonic softening of the energy spectrum from the radio to the X-ray band (Fig. 4, left panel), and the relative morphologies of the radio, optical and X-ray emission.

For the higher-power FR II-type sources, the radio to X-ray energy spectrum can often not be described with a single synchrotron component as the radio, optical and X-ray observations imply a significant hardening of the energy spectrum between the optical and the X-ray band (Fig. 4, right panel). The presently favored explanation of the X-ray emission is that it originates as inverse-Compton emission of mildly relativistic ($\sim \text{MeV}$) electrons embedded in a highly relativistic plasma moving with a bulk Lorentz factor $\Gamma \sim 10$. In the co-moving reference frame of the jet plasma (primed variables), the

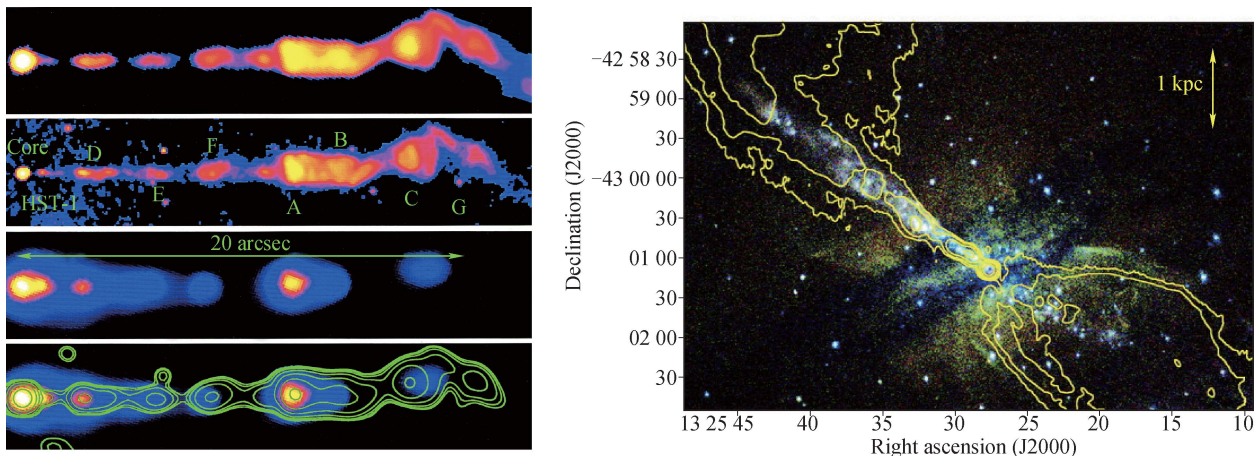


Fig. 3 Multiwavelength images of the radio galaxies M87 (left panel) and Cen A (right panel). The left image shows from top to bottom the 14.435 GHz Very Large Array (VLA) image, the Hubble Space Telescope Camera image in the F814W filter, and the Chandra X-ray (keV) image; the bottom panel shows the Chandra image overlaid with contours of the Hubble Space Telescope image smoothed to match the Chandra by spread function. The Hubble Space Telescope and Very Large Array images use a logarithmic color scale, and the X-ray image uses a linear scale. The portion of the jet shown in the image has a projected length of ≈ 1.6 kpc. The right image shows a false-color image of the radio galaxy Centaurus A as seen by Chandra [color image: 0.4–0.85 keV (red), 0.85–1.3 keV (green), and 1.3–2.5 keV (blue)] and the VLA at 5 GHz [contours at $7 \times (1, 4, 16, \dots) \text{ mJy} \cdot \text{beam}^{-1}$]. The portion of the northern X-ray jet has a projected length of ≈ 3 kpc. The left panel is reproduced from Ref. [15], Copyright © 2002 American Astronomical Society, and the right panel is reproduced from Ref. [16], Copyright © 2007 American Astronomical Society.

¹⁾ <http://hea-www.harvard.edu/XJET/>

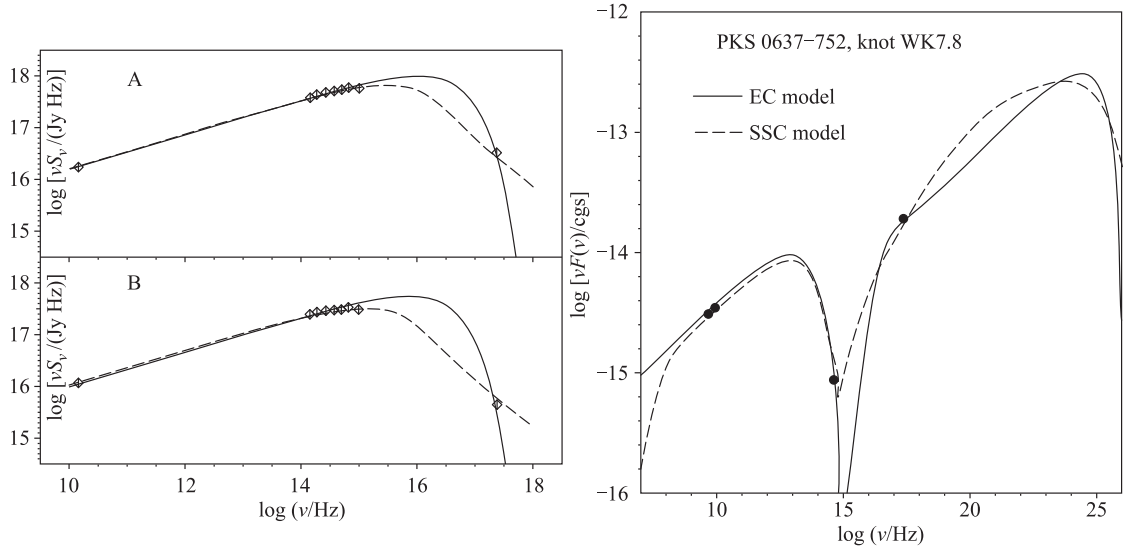


Fig. 4 Spectral energy distribution of two knots of the M87 jet (*left panel*, see the left upper-center panel of Fig. 3 for the labels of the knots). The radio, optical and X-ray flux points can be explained with a single population of non-thermal electrons (and/or positrons) with an energy spectrum that softens monotonically with energy. The dashed and dotted lines show synchrotron models. The right panel presents the spectral energy distribution of the knot WK7.8 of the quasar PKS 0637-752 that shows evidence for two emission components, one component extending from radio to optical and another one extending from X-rays to gamma-rays. The authors favor the inverse Compton/CMB model (*solid line*) over the SSC model (*dashed line*) as the former requires less power than the latter ($3 \times 10^{48} \text{ erg.s}^{-1}$ compared to $> 10^{49} \text{ erg.s}^{-1}$). The left panel is reproduced from Ref. [15], Copyright © 2002 American Astronomical Society, and the right panel is reproduced from Ref. [19], Copyright © 2000 American Astronomical Society.

mean frequency of cosmic microwave background (CMB) photons is

$$\nu'_{\text{CMB}} = (1+z) \Gamma_j \nu_0 \quad (4)$$

and the CMB energy density is

$$u'_{\text{CMB}} \approx (1+z)^4 \Gamma_j^2 u_{\text{CMB},0} \quad (5)$$

with the local present day values $\nu_0 \approx 1.6 \times 10^{11} \text{ Hz}$ and $u_{\text{CMB},0} \approx 4 \times 10^{-13} \text{ erg.cm}^{-3}$. The boosting of the mean energy and energy density proportional to Γ_j and Γ_j^2 , respectively, explains the presence of a relatively strong inverse-Compton component in the X-ray band. The inverse-Compton/CMB model predicts an increase of the X-ray to radio brightness proportional to the energy density of the CMB which scales with $(1+z)^4$. The data indeed show such a trend for a small sample of sources (Fig. 5). However, the model faces several problems: for some of the sources the inverse-Compton/CMB model implies very small viewing angles and thus large physical source diameters on the order of hundreds of Mpc [22]; furthermore, for some jets, the model parameters imply a rather high jet power ($\sim 10^{48} \text{ erg.s}^{-1}$) [23]. With regards to jet models, the most interesting implication of the inverse-Compton/CMB model is the relativistic motion of the jet plasma at $\sim \text{kpc}$ distances from the SMBH. An alternative explanation for the observed X-ray emission is synchrotron emission from an addi-

tional high-energy electron population [22]. However, in this case, the peak position of the second emission component at $\gg \text{keV}$ -energies remains unexplained.

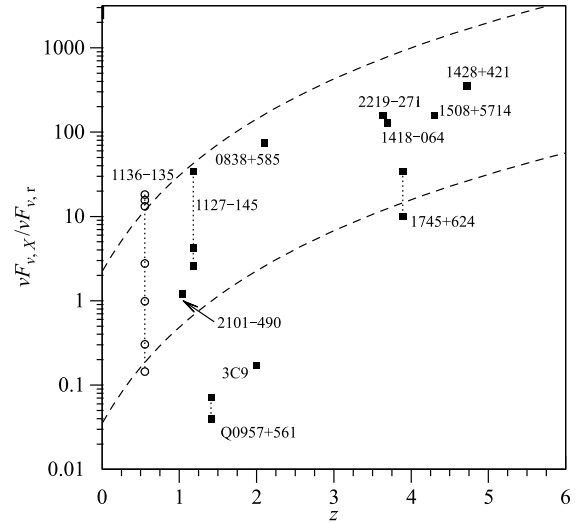


Fig. 5 Ratio of the X-ray and radio fluxes of high-redshift ($z > 1$) jets discovered with Chandra, following [26]. For the nearby source PKS 1136135 at $z = 0.5$ the spread of the $z < 1$ jet population is shown. The data indicate that the ratio follows approximately the $(1+z)^4$ -behavior predicted by the inverse-Compton/CMB model, albeit with a large spread (Courtesy of C. C. Cheung, 2012).

The Fermi LAT has recently detected emission from the core, and the northern and southern lobes of the ra-

dio galaxy Cen A [24, 25]. The emission can be explained as inverse-Compton emission from electrons scattering photons of the CMB and maybe also higher-frequency photons. Whereas the synchrotron radio emission traces the combined properties of the radio-emitting electrons and the magnetic field strength, the inverse-Compton emission in the γ -ray band traces the high-energy electrons more directly. The combined data can also be used to set an upper limit on the magnetic field B in the lobes of $B < 1 \mu\text{G}$. It would be extremely interesting to obtain a γ -ray image with a substantially improved signal-to-noise ratio.

2.3 Composition of AGN jets

It is quite remarkable that we are still uncertain about the composition of AGN jets. One of the reasons is the dominance of non-thermal continuum emission from jets leading to a lack of detected lines that give away the nature of the jet plasma. Theoretical considerations suggest that the energy and momentum of the jets is initially (at distances of a few $10 r_g$) dominated by electromagnetic energy (Poynting flux). At larger distances (on the order of a few 100 or 1000 r_g) the electromagnetic energy is transferred to particles. The particles carrying the energy might be electrons and positrons or Interstellar Medium (ISM) processed through the accretion disk and/or entrained along the way. The jet may entrain additional ISM as it propagates, leading to a decrease of Γ_j with distance from the central engine.

For Flat Spectrum Radio Quasars (FSRQs), Sikora and Madejski argued that jets with $\Gamma_j \sim 10$ cannot be dominated by cold pairs at their bases, as the inverse-Compton emission from the pairs scattering UV-radiation from the accretion disk would give rise to an unobserved soft X-ray emission component [27] (see also Refs. [28, 29]).

2.4 AGN feedback

Several X-ray observatories (first *ROSAT*, later Chandra and *XMM-Newton*) discovered large “cavities” in the hot X-ray bright gas of elliptical galaxies, galaxy groups, and galaxy clusters associated with the radio lobes of AGNs [30, 31] (see also Fig. 6). The cavities are caused by AGNs inflating bubbles of radio plasma which displaces the hot X-ray bright interstellar or intracluster medium. One can use these cavities to constrain the composition of the radio plasma in the cavities. For galaxy clusters, the intra-cluster medium (ICM) pressure is well constrained by the spectroscopic X-ray images of the ICM. One can estimate the $p dV$ work required to inflate the bubbles. Combining

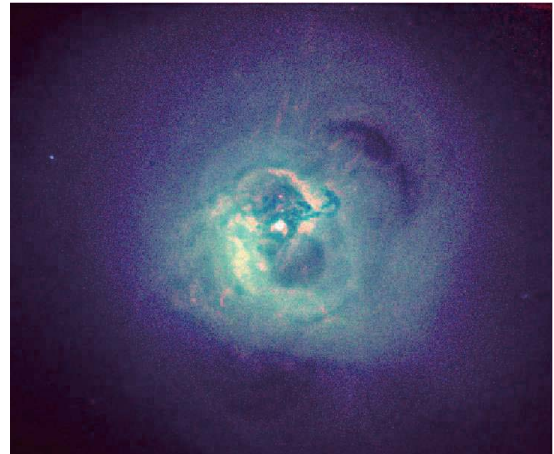


Fig. 6 A Chandra X-ray image of the Perseus galaxy cluster showing the emission from the hot ICM. The X-ray brightness clearly shows two cavities carved out by the radio plasma from the central radio galaxy NGC 1275. The ripples in the brightness distribution are explained as the result of sound waves propagating through the ICM. The opposite ends of the two radio bubbles are at a projected distance of ≈ 65 kpc, and the bright ICM emission has a projected diameter of ≈ 360 kpc (from Ref. [32]). Credits: NASA/CXC/IoA/A.Fabian et al..

this work with an estimate of the ages of the cavities (assuming they rise at the local sound speed), one can estimate the power required to inflate the bubbles of radio gas. Comparing the latter with the broadband radio power one can estimate the ratio k of the total jet power divided by the power carried by non-thermal electrons responsible for the observed radio emission. Such studies show $k \sim 100$ (Fig. 7) and indicate the presence of

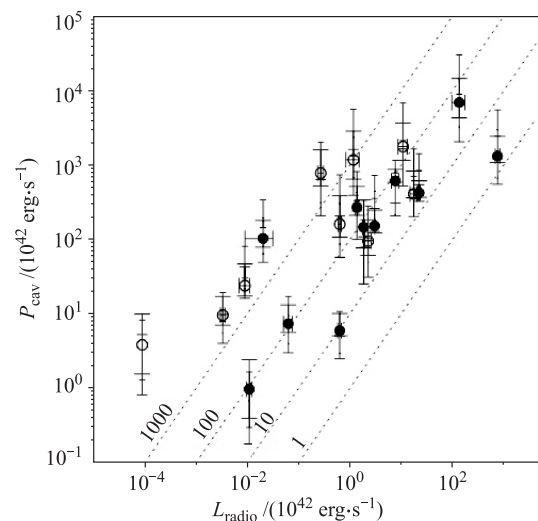


Fig. 7 The power required to blow cavities into the ICM as function of the power in the electrons that emit the observed radio emission. The former power exceeds the latter by an average factor on the order of 100 (diagonal lines), indicating that the energy density of the radio plasma in the cavities is dominated by a “dark component” that has not yet been detected. Reproduced from Ref. [34], Copyright © 2008 American Astronomical Society.

“dark” pressure-contributing components (non-thermal low-energy electrons, non-thermal protons, or magnetic field). Although AGN jets seem to have sufficient power to balance the radiative (Bremsstrahlung) cooling of the intracluster gas and to explain the lack of cold gas and freshly formed stars at the centers of galaxy clusters, the role of AGNs in heating the ICM is not well established [33]. The jet power may not be transformed efficiently into ICM heat, and other processes (i.e., efficient heat conduction owing to anisotropic transport properties) may dominate the heating of cluster cores.

2.5 Magnetohydrodynamic simulations of jets

The basic theoretical framework that is currently used to explain the observational appearance of radio-galaxies was introduced in the 1970s [35–38]. However, the predictive power of analytical jet models is limited owing to the non-linear processes taking place as jets propagate through the ambient medium. Recently, it has become possible to study jets with relativistic 3-D hydrodynamic (HD) and magnetohydrodynamic (MHD) codes (see e.g. Refs. [39, 40] and references therein). The simulations can reproduce the observed morphologies of radio sources rather well. Combined analytical and numerical studies show that certain ingredients can increase the stability of jets, i.e., magnetic fields, steep pressure gradients, a high density contrast between jet and external medium, fast motion, or a sheath/shear velocity outflow around the jet (e.g. Ref. [41] and references therein). The codes use the one-fluid approximation and do not model the microscopic effects occurring in the astrophysical plasmas in detail. Particle in cell (PIC) simulations can shed light on some of the processes occurring when relativistic flows propagate through ambient media (e.g. Ref. [42]).

3 Emission from the central regions of AGNs

3.1 Overview of emission components

The radio, infrared, optical, UV, X-ray and γ -ray observations of AGNs can be explained with a single model of the central AGN region. In this paradigm, the different types of AGN result from different viewing angles towards the symmetry axis, and from the absence or presence of certain components [43]. We briefly explain the most important emission components and their interpretation (see also Fig. 8):

- **Emission from the accretion disk:** In some AGNs, emission from the accretion disk itself may

have been detected. The feature, often referred to as the Big Blue Bump, can extend from the (AGN-frame) optical/UV band to the soft X-ray band and is believed to be thermal emission from the accretion disk (e.g. Refs. [44, 45]).

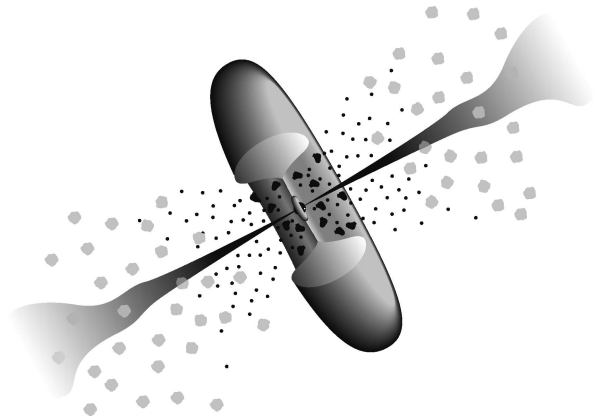


Fig. 8 The figure shows a sketch of the central engine of an AGN and highlights several components that can explain most of the observed properties of AGNs (not to scale; example lengths in parentheses). The central black hole (for an $M = 10^8 M_\odot$ black hole, the Schwarzschild radius is $R_S = 3 \times 10^{13}$ cm) is surrounded by an accretion disk ($\sim (1\text{--}30) \times 10^{14}$ cm); a hot corona above the accretion disk probably plays a role in producing hard X-rays. The broad emission lines originate in clouds orbiting above the disk (at $\sim (2\text{--}20) \times 10^{16}$ cm). A thick dusty torus (inner radius $\sim 10^{17}$ cm) or a warped accretion disk obscures the broad-line region (BLR) when the AGN is seen from the side; narrow lines are produced in clouds much farther from the central source ($10^{18}\text{--}10^{20}$ cm). Radio jets (extending from $\sim 10^{15}$ cm to several times 10^{24} cm) emanate from the region near the black hole in the case of radio loud AGNs. The image does not show the broad and narrow absorption line producing winds. The launching region of the broad absorption line producing winds is uncertain. The narrow absorption line winds are believed to be launched at distances of $\sim 10^{18}$ cm from the central engine at about the same distance from the central engine as the NLR clouds. Reproduced from Ref. [43], Copyright © 1995 Astronomical Society of the Pacific.

The accretion disk is partially covered by a corona of hot – yet still thermal – material. The hot corona Comptonizes some of the emission producing a high-energy tail extending into the hard X-ray regime. Alternative explanations of the origin of the hard X-ray emission include a hot inner flow (e.g. Refs. [46, 47]), the “lamp-post model” of an X-ray source illuminating the accretion disk from above (e.g. Refs. [48, 49]), and a structured multi-layer corona [50].

In the X-ray spectra of some AGN one detects a broad X-ray emission line at ~ 6.4 keV in the AGN rest frame. The line is believed to be fluorescence Fe K- α emission of iron atoms in the inner accretion disk excited by the hard X-rays from a source above the disk (e.g. Refs. [51–54]). Its shape results

from the gravitational redshift incurred by photons climbing out of the black holes gravitational well, and the blue and redshift from the relativistic motion of the disk material. The analysis of the line shape can be used to measure the black hole spin. For the Seyfert galaxy MCG6-30-15, the analysis of the Fe K- α line shape indicates a spin per unit mass of $a > 0.987$ in dimensionless units, close to the theoretical maximum value [55].

Radio interferometric observations at 230 GHz have recently achieved sufficiently good resolutions to resolve the accretion disk of Sgr A*, the $4.5 \times 10^6 M_\odot$ SMBH at the center of the Milky Way [56]. The radio emission is polarized cyclo-synchrotron emission.

- **Continuum emission from the inner jet:** Under favorable conditions, the accretion leads to the formation of a highly relativistic collimated jet. The make-up of the jet is not well constrained, but is believed to change from magnetic-field-dominated close to the central engine to particle (electron and positron, or ions and electrons) dominated at $> \text{pc}$ distances. Shocks in the jet (e.g. from re-collimation of the jet or plasma instabilities) or reconnection leads to the acceleration of electrons to GeV and TeV energies (Lorentz factors up to a few times 10^6). The electrons emit low-energy synchrotron emission and high-energy inverse-Compton emission. The latter comes from the electrons scattering synchrotron photons (synchrotron self-Compton (SSC) emission) or external photons (external Inverse Compton (EIC) emission), such as BLR photons or photons from upstream or downstream regions of the jet. The continuum emission holds information about the innermost jet regions and can be used for time-dependent studies of particle acceleration processes.
- **Emission lines from clouds:** Some AGNs exhibit narrow and/or broad emission lines emitted by rather cold clouds of interstellar material orbiting the black holes at different distances [57]. The broad line region (BLR) clouds have distances on the order of 10 light days from the SMBH; the narrow line region (NLR) clouds orbit the SMBH at distances of a few hundred parsecs. The line centroids can be used to measure the redshifts and thus the distances of AGNs. Observations of the BLR emission and the continuum emission from the accretion disk can be used to estimate the mass of the central black hole based on reverberation mapping [58, 59]. The technique combines the widths of the BLR lines (which constrain the orbital veloci-

ties of the emitting clouds) with measured time lags between variations of the continuum flux from the accretion disk and the BLR flux. As the BLR emission stems from reprocessing the continuum flux, the time lag can be used to estimate the distance of the BLR clouds from the central engine. The information about the velocity of the BLR clouds and the distance of the BLR clouds from the SMBH constrain the orbital parameters of the BLR clouds and thus the black hole mass. The technique can be used for AGNs which are so far away that stellar orbits close to the black hole cannot be resolved. Two classical papers used the line luminosities as estimators of the accretion rate and studied the correlation of line luminosities with the kinematic power of the jet. Rawlings and Saunders [60] estimated the jet power based on the energetics of the radio lobes and correlated the estimated jet power with the [O III] NLR luminosities. The authors found a significant correlation between these two quantities for a sample of radio galaxies. Celotti *et al.* [61] found a similar correlation between the BLR luminosities and jet luminosities from very-long-baseline interferometry (VLBI) observations of radio loud AGNs (see also Refs. [62, 63]).

- **Torus and winds:** Some of the differences between observational AGN classes can be explained by the presence of a dusty ~ 1 pc diameter torus which can obscure accretion disk and BLR emission from view and emits reprocessed emission from the central engine in the infrared [64, 65]. At the inner edge of the torus, the AGN continuum emission destroys the dust, ionizes the atoms and creates the material making up the BLR and X-ray obscuring clouds. The presence of blue-shifted broad (BAL) and narrow (NAL) absorption lines in the optical, UV, and X-ray regime show evidence for fast AGN outflows or winds [66]. While the NAL outflows are believed to be launched at $\sim \text{pc}$ distances from the central engine and are largely radiatively driven, the location and the driving mechanism of the fast ($0.2 c$) BAL outflows are still highly uncertain.

At larger viewing angles, the gas torus conceals the BLR and only narrow lines are observed, resulting in Type-2 Seyferts, and narrow line FRI and FRII galaxies. Closer to the line of sight, the torus does not obscure the BLR anymore and the AGNs appear as Type-1 Seyferts, radio quiet quasi-stellar objects (QSOs), and broad line steep spectrum radio quasars (SSRQs) and FSRQs. For viewing angles $< 10^\circ$, the relativistically beamed non-thermal continuum emission from the relativistic jet

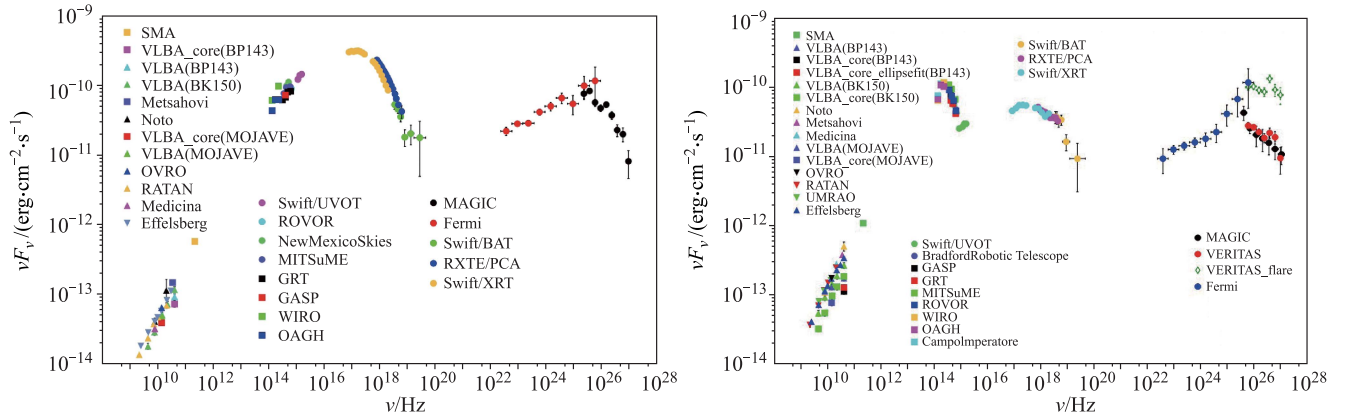


Fig. 9 Broadband spectral energy distribution of the HSP blazars Mrk 421 (*left panel*, data taken between January 19, 2009 and June 1, 2009) and Mrk 501 (*right panel*, data taken between March 15, 2009 and August 1, 2009). Reproduced from Ref. [73] (*left panel*) and Ref. [74] (*right panel*), Copyright © 2011 American Astronomical Society.

dominates and the object is a blazar. BL Lac objects are a sub-class of blazars either without detected emission lines or with lines with a rest-frame equivalent width smaller than $5 \text{ \AA}$ [67, 68]. Recently, this classification scheme has been criticized on the grounds that it introduces strong selection effects [69, 70].

3.2 Recent blazar observations with the Fermi space telescope and imaging atmospheric Cherenkov telescopes

In recent years γ -ray astronomy has made spectacular progress. The space-borne Fermi Large Area Telescope (LAT) [71] and ground-based Imaging Atmospheric Cherenkov Telescopes (IACTs) [72] achieve sensitivities of about $10^{-12} \text{ erg-cm}^{-2} \cdot \text{s}^{-1}$. The Fermi LAT covers the 100 MeV–300 GeV energy range. With its large field of view ($\sim 2.4 \text{ sr}$) it is well suited to monitor the entire sky on a regular basis. IACTs cover the 50 GeV–30 TeV energy range. With large detection areas on the order of 10^5 m^2 they are well suited to measure short-term ($< 1 \text{ min}$) flux and spectral variability. Between Fermi and the ground-based Cherenkov telescopes, it has become possible to sample the complete inverse Compton emission component of many blazars (Fig. 9).

The γ -ray telescopes detect mostly blazars and make it possible to study the properties of AGN jets on short time scales. In the following we use the abbreviations LSP, ISP and HSP to denote low synchrotron peaked ($\nu_{\text{peak}}^S < 10^{14} \text{ Hz}$), intermediate synchrotron peaked ($10^{14} \text{ Hz} < \nu_{\text{peak}}^S < 10^{15} \text{ Hz}$), and high synchrotron peaked ($\nu_{\text{peak}}^S > 10^{15} \text{ Hz}$) blazars. In the earlier literature, the reader will often find the abbreviations LBL, IBL, and HBL. These names denote the BL Lac subclasses of LSP, ISP, and HSP blazars, respectively.

The large sample of blazars detected by the Fermi-LAT can be used to study the cosmic evolution of blazars

as well as the intrinsic properties of blazars. The cosmic evolution of blazars depends on the cosmic evolution of SMBHs, the accretion history of these SMBHs, and the history of the radiative efficiency of the accreting SMBHs. The recently published second Fermi LAT AGN catalog [75] lists 1017 sources with an AGN association, and a “clean sample” of 886 sources with unambiguous AGN counterparts. The latter sample includes 395 BL Lacs, 310 FSRQs, 157 candidate blazars of unknown type, eight misaligned AGNs, four narrow-line Seyfert 1 galaxies, ten AGNs of other types, and two starburst galaxies. The redshift distribution (dN/dz) of detected BL Lacs peaks at $z \approx 0.2$ and extends to $z = 1.5$; the distribution of FSRQs peaks at $z \approx 1.1$ and extends to $z = 3.2$.

Ajello *et al.* used a complete sample of FSRQs detected during Fermi’s first year of operation to study the luminosity function (LF) and its cosmic evolution [76]. The FSRQ number density grows up to luminosity dependent redshifts of between 0.5 and 2.0 and declines thereafter. The sources show an “inverted evolution” with lower power sources peaking at lower redshifts (later times) than their higher-power counterparts (Fig. 10, left panel). The authors study the rest-frame spectral energy distribution (SED, energy flux per logarithmic energy interval, $E^2 dN/dE$) of the sources and find that the peak of average SEDs determined for different luminosity bins is independent of the AGN luminosity (Fig. 10, right panel). The earlier detection of a luminosity-hardness correlation (sometimes referred to as the “blazar sequence”) [77, 78] may have resulted from selection effects. Combining the inferred SED shapes with the LF, the authors predict that FSRQs contribute $\sim 10\%$ to the isotropic Fermi γ -ray background. Assuming that the jet Bulk Lorentz factors Γ_j follow a power law distribution $dN/d\Gamma_j \propto \Gamma_j^k$ over the range from 5 to 40 and

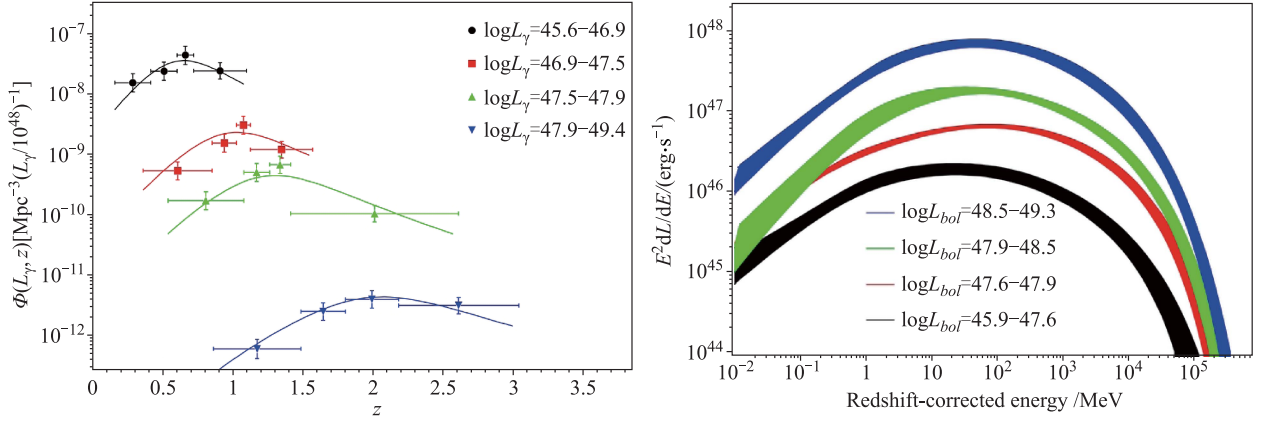


Fig. 10 Left panel: Space density of Fermi-LAT detected FSRQs for different luminosity classes indicate an “inverted hierarchy” with higher (lower) luminosity objects peaking at higher (lower) redshifts. Right panel: Average rest-frame spectral energy distributions for four FSRQ luminosity classes. The bands show the 1σ confidence level regions (from Ref. [76]). The data do not indicate a correlation of the energy at which the spectral energy distribution peaks and the γ -ray luminosity. Reproduced from Ref. [76], Copyright © 2012 American Astronomical Society.

that the γ -rays originate as SSC emission, the authors can derive the distribution of intrinsic jet luminosities $\mathcal{L}$ from the distribution of apparent luminosities L (for SSC emission, $L \propto \delta_j^p \mathcal{L}$ with $p = 4$). The analysis implies a power law index k of -2.0 ± 0.7 , a mean Lorentz factor of the Fermi-detected FSRQs of ≈ 12 , that most sources are seen from within 5° of the jet axis, and that the detected γ -ray loud FSRQs represent 0.1% of the unbeamed parent population. The distribution of L_j is in good agreement with those inferred from radio observations on pc-scales [20]. The finding may imply that both, the radio and the γ -ray emission comes from $\sim$ pc-distances from the central engines, or, that the jet Lorentz factors are the same at the scales probed by the radio and γ -ray observations.

Ghisellini *et al.* studied the correlation between the BLR luminosity L_{BLR} and the γ -ray luminosity L_γ , both measured in units of the Eddington accretion rate, and find a correlation albeit with a large scatter [29]. The result reinforces the earlier finding that accretion rate (and thus L_{BLR}) and jet power (proportional to L_γ) are correlated, but shows that it is even valid when both are normalized to the mass of the black hole.

Giommi *et al.* reported on a Monte Carlo study that shows that selection effects can strongly affect the outcomes of BL Lac and FSRQ studies [70]. Their work indicates that selection effects alone can produce an apparent correlation between the peak energy of the synchrotron SED and the luminosity of the sources. The analysis suggests that powerful BL Lac-type objects may exist, but cannot be identified as such owing to the relative weakness of the lines. In their model, all sources are qualitatively the same, but are identified as different sources owing to the relative strength of several basic emission components, i.e., the Doppler boosted radiation from the

jet, the emission from the accretion disk, the BLR, and the light from the host galaxy. The authors suggest that – using the standard definitions – BL Lacs and FSRQs may not be the beamed versions of FRI and FRII, respectively. Ghisellini *et al.* offered a definition of BL Lacs and FSRQs based on the broad line region luminosity in units of the Eddington luminosity ($L_{\text{BLR}}/L_{\text{Edd}}$ below and above 5×10^{-4} , respectively) [69], which might result in a cleaner identification of the beamed versions of FRI and FRII galaxies.

IACTs and the Fermi LAT have been used for extensive multiwavelength campaigns. For HSP blazars, the broadband SEDs (e.g. Refs. [79, 80]) and fast flux variability [81–84] imply very high relativistic Doppler factors δ_j [Eq. (3)] on the order of 50. The broadband SEDs can largely be fit with one-zone SSC models (e.g. Refs. [85, 86]) with notable exceptions (e.g. Refs. [87, 88]). Snapshot and time-dependent modeling indicates particle dominated emission zones with electron and positron energy densities $u_{e+/-}$ exceeding the magnetic field energy density $u_B = B^2/(8\pi)$ by typical factors of ~ 100 [79, 85]. Models with additional target photon fields (and with additional degrees of freedom) make it possible to fit the data closer to equipartition ($u_{e+/-} \sim u_B$) [89, 90].

LSP and ISP blazars seem to require EIC models. Abdo *et al.* discussed the broadband SEDs of 48 γ -ray bright Fermi blazars [91]. The authors find that one-zone SSC models cannot fit the SEDs of most LSP and ISP (low frequency peaked BL Lac objects and FSRQs) sources (see also Ref. [92]).

Broadband observations promise to give insights into the mechanisms responsible for the observed flares. There is good evidence for a correlation of the radio and > 100 MeV γ -ray luminosities of statistical samples of blazars

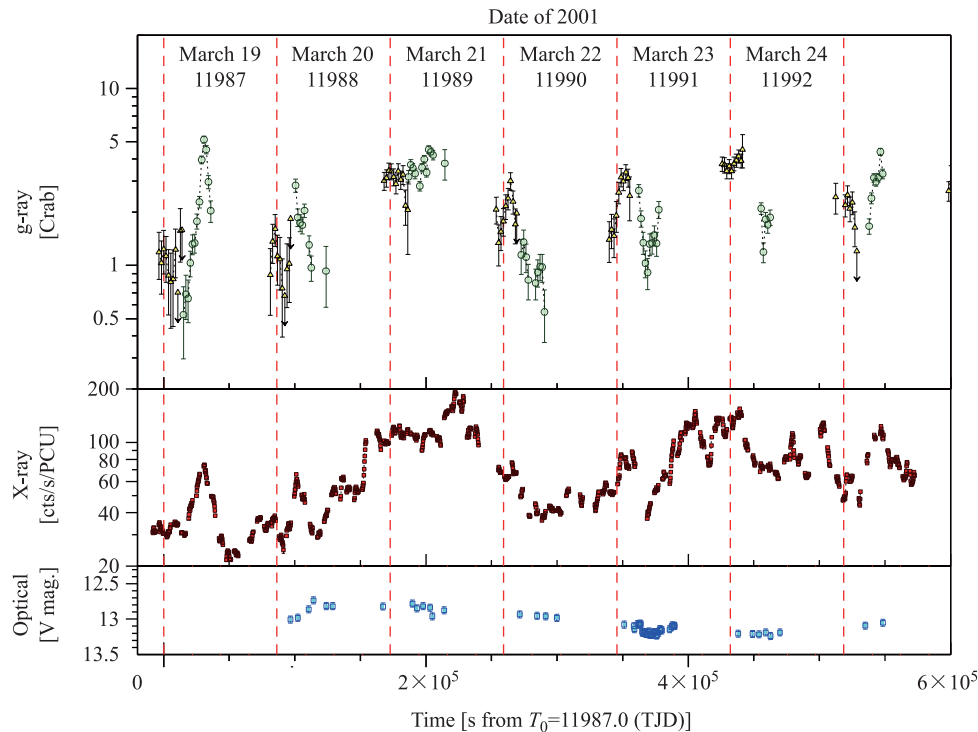


Fig. 11 Results from 2001 Rossi X-ray Timing Explorer (RXTE) 2–4 keV X-ray and Whipple (*full symbols*) and HEGRA (*open symbols*) γ -ray observations of Mrk 421 in the year 2001 (from Ref. [93]). IACTs achieve excellent sensitivities on short time scales owing to their large collection areas. Careful study of the light curves shows that the X-ray and TeV γ -ray fluxes are correlated for some flares but not for all. Reproduction of the figure with kind permission of the authors.

[92, 94, 95, 96], and to some degree of the X-ray and VHE (Very High Energy, >100 GeV) γ -ray fluxes of HSP blazars (e.g. Fig. 11 and Refs. [93, 97]). Marscher *et al.* [98] and Abdo *et al.* [99] reported the detections of correlated polarization swings and γ -ray flares. Unfortunately, the interpretation of some of the data is rather ambiguous as the sources exhibit a wide range of different behaviors; as a consequence, the statistical significance of the observed features is often rather limited. Unambiguous conclusions would require the observation of a statistical sample of sources with dense sampling in the temporal and waveband domains over many years.

The continuum emission from blazars is most commonly explained in the framework of electron and possibly positron acceleration in internal or external collisionless shocks. The accelerated leptons radiate synchrotron radio to X-ray and inverse-Compton X-ray to gamma-ray emission. Unfortunately, attempts to verify that Fermi-type acceleration energizes the leptons based on observations of predominantly clockwise or counterclockwise loops in the flux vs. spectral index plane (e.g. Ref. [100]) failed due to the rather chaotic behavior of the observed sources (e.g. Refs. [101, 102]).

Some authors considered hadronic models in an attempt to explain the γ -ray emission from blazars, but such models require the acceleration of protons to $> 10^{18}$

eV energies and magnetic fields typically on the order of ~ 50 G with very high energy densities to accelerate and confine the protons [103–107].

3.3 Models of the accretion flow and jet formation

A satisfactory model of the central engines of AGNs should explain (i) how matter and magnetic fields are transported towards the accretion disks of the SMBHs; (ii) which types of accretion disks occur in nature and how they work; (iii) which physical mechanisms are responsible for accretion disk state transitions and flares; (iv) how the individual emission components are produced, (v) how jets form, transform, accelerate and/or decelerate at different distances from the SMBHs; (vi) how AGNs interact with their environment. The question of how matter and magnetic fields move towards the central engine (the feeding problem) will not have a simple answer as it will depend on the cosmic epoch and the type and evolutionary state of the host (a single galaxy or a galaxy inside a galaxy cluster). The main challenge is to explain how the matter can shed all but a tiny fraction of its initial angular momentum while it goes through different phases and moves from $\sim$ kpc distances to the accretion disk (e.g. Refs. [40, 108]). One of the open questions concerns the feeding of magnetic

fields with a preferred polarity into the accretion flow, as such magnetic fields can suppress plasma instabilities in the disk, and can explain the presence of a strong single polarity magnetic field in the surrounding of the black hole, i.e., in the plunging region between the event horizon and the innermost circular stable orbit (ISCO). Such magnetic fields are required in some models of accretion and jet formation.

Accretion disks transform gravitational energy of matter into electromagnetic and mechanical energy. Shakura and Sunyaev introduced a model for a geometrically thin (with a thickness H at radius r such that $H(r)/r \ll 1$), optically thick accretion disk [109]. Assuming that the disk matter orbits the black hole on circular geodesics, that there is no torque at the ISCO, that the disk radiates away all the dissipated energy, and that no heat is transported in radial direction, the radial structure of the disk is entirely determined by mass, energy, and angular momentum conservation [109, 110]. Using a prescription for the viscosity of the disk, the horizontal disk structure can be inferred. Although it was suspected that magnetic turbulence caused by the differential rotation of the accretion disk material was responsible for the viscosity, it was only in 1991 that Balbus and Hawley identified the magneto-rotational instability (MRI) as the driving instability based on numerical simulations [111].

A number of authors discussed alternative accretion flows. Ichimaru described a two-state model to explain two qualitatively different emission states of the X-ray binary Cygnus X-1 [146]. Whereas the high-soft state corresponds to the geometrically thin, optically thick radiatively efficient accretion disk of Shakura & Sunyaev, the low-hard state corresponds to a geometrically thick, optically thin radiatively inefficient accretion flow (RIAF). In the latter case, a thermal instability of the disk plasma develops when dissipative heating exceeds the radiative cooling causing the disk to puff up. Narayan *et al.* discussed a self-similar geometrically thick RIAF flow, the advection dominated accretion flows (ADAFs), in which the gas orbits the black hole with a velocity well below that of Keplerian orbits [112]. The authors remarked that such flows can form for low accretion rates when the flow is optically thin, or for very high accretion rates when the flow is optically thick and the cooling time of the plasma is much longer than the accretion rate. Variations of ADAFs include convection-dominated accretion flows (CDAFs) [113, 114], and advection-dominated inflow-outflow solutions (ADIOSs) [115, 116].

The jet is probably launched by the combined effect of thermal pressure, centrifugal forces, and the Blandford–Znajek process. The latter involves the conversion of the rotational energy of a black hole spinning in the magnetic

field anchored in the accretion disk into electromagnetic energy [117]. In the presence of a favorably shaped outflow channel (formed by a geometrically thick accretion disk or by a less collimated wind), the flow can accelerate owing to magnetic pressure gradients. Energy conservation dictates that the terminal Lorentz factor of the jet obeys $\Gamma_j^\infty < \sigma_0$ with σ_0 being the magnetization (ratio of electromagnetic to particle energy densities) at the base of the jet, so that $\sigma \gg 1$ is required to explain $\Gamma_j^\infty \gg 1$.

We would like to know which accretion flows occur in nature, which flow properties lead to the observed phenomenology, and how the observed jets form. Attempts in this direction include the identification of the radio quietness and loudness (the absence or presence of a jet) with geometrically thin and geometrically thick accretion flows, respectively. Some authors explain the difference between BL Lacs and FSRQs by invoking radiatively inefficient (with weak BLR emission) accretion flows for the former and radiatively efficient (strong BLR emission) accretion flows for the latter sources. Unfortunately, none of these associations is firm at the time of writing.

Recently it has become possible to employ 2D and 3D general relativistic magnetohydrodynamic (GRMHD) simulations with sufficient resolution to test some of the assumptions underlying the analytical and semi-analytical models. Most simulations neglect radiative transfer of heat owing to computational limitations. Such simulations have been used, for example, to test the assumption of zero torque at the ISCO (and zero energy dissipation of the disk plasma within the ISCO). The results indicate that the zero-torque approximation introduces rather small errors, i.e., it underestimates the emitted luminosity by $\sim 5\%$ [118, 119]. McKinney *et al.* studied rather thick ($H/r \sim 0.3$) accretion flows with large-scale dipole and quadrupole magnetic fields and obtained two interesting results [40]: (i) The structure of the accreted magnetic field is decisive for the formation of a collimated relativistic outflow; an accretion disk with a dipole magnetic field geometry does produce a jet, but disks fed by plasma without an ordered magnetic field or with higher moment magnetic field geometries do not (see also Refs. [120, 121]); (ii) Somewhat unexpectedly, the jets are stable even though the toroidal component of the magnetic field that accelerates the jets could disrupt the flow owing to helical kink and screw modes. Several effects – including gradual shear, stabilizing sheaths, or sideways expansion – may be responsible for stabilizing the outflow.

As ordered magnetic fields are needed for the production of jets, McKinney *et al.* employed 3D GRMHD simulations to study a geometrically thick flow supplied with

strongly magnetized plasma [40]. They found that for rapidly spinning black holes toroidal magnetic fields can lead to large patches of single-polarity poloidal magnetic fields threading the black hole enabling the transformation of rotational energy of the black hole into Poynting flux energy. Strong poloidal magnetic fields build up in the inner region of the disk and compress it into a geometrically thin accretion flow in which the strong poloidal magnetic field suppresses the MRI. As mentioned above, further studies are needed to understand which accretion flows are actually realized in nature.

4 The cosmic history of black hole accretion

Most current black hole formation models tell us that the first black hole seeds emerged at $z \gtrsim 15$. While the exact mechanism is not known, there are several prevailing theories (see the comprehensive reviews by Rees [122] and Volonteri [123] for more details). One possibility is that the first black holes were the remnants of the first generation of stars (Population III stars) that resulted from the gravitational collapse of primordial ultra-low metallicity gas. These black holes formed at $z \sim 20$ and have typical masses $\sim 100\text{--}1000 M_\odot$. This scenario has problems explaining the very high masses, of $\sim 10^9 M_\odot$, estimated for supermassive black holes in $z > 6$ optically-selected quasars [128, 129]. Alternatively, the first black holes could have formed directly as the result of gas-dynamical processes. It is possible for metal-free gas clouds with $T_{\text{vir}} \gtrsim 10^4 \text{K}$ and suppressed H_2 formation to collapse very efficiently [126], possibly forming massive black hole seeds with $M \sim 10^4\text{--}10^5 M_\odot$ as early as $z \sim 10\text{--}15$. If instead the UV background is not enough to suppress the formation of H_2 , the gas will fragment and form “normal” stars in a very compact star cluster. In that case, star collisions can lead to the formation of a very massive star, that will then collapse and form a massive black hole seed with mass $\sim 10^2\text{--}10^4 M_\odot$ [127].

Given the current typical masses of $10^{6\text{--}9} M_\odot$, most black hole growth happens in the AGN phase [128, 129]. With typical bolometric luminosities $\sim 10^{45\text{--}48} \text{erg}\cdot\text{s}^{-1}$, AGN are amongst the most luminous emitters in the Universe, particularly at high energies and radio wavelengths. These luminosities are a significant fraction of the Eddington luminosity—the maximum luminosity for spherical accretion beyond which radiation pressure prevents further growth—for a $10^{8\text{--}9} M_\odot$ central black hole. A significant fraction of the total black hole growth, $\sim 60\%$ [130], happens in the most luminous AGN (quasars) which are likely triggered by the major merger of two massive galaxies, as it is discussed in Section 5.

In the quasar phase, which lasts $\sim 10^8$ years, the central supermassive black hole can gain up to $\sim 10^7\text{--}10^8 M_\odot$, so even the most massive galaxies will have only a few of these events over their lifetime. Further black hole growth, mostly in low-luminosity (low Eddington rate) AGN, is likely due to stochastic accretion of cold gas, mostly in spiral galaxies [131].

According to the AGN unification paradigm [43, 132], a large fraction of these sources, $\sim 75\%$ locally, are heavily obscured by optically and geometrically thick axisymmetric material, which explains many of the observed differences among different types of active galaxies. In addition, luminosity [133] and cosmic epoch [134] play a significant role. One constraint on the fraction of obscured AGN and its evolution comes from the spectral shape of the extragalactic X-ray “background” (XRB). Thanks to deep X-ray observations at $E \lesssim 10 \text{keV}$ performed by Chandra and *XMM-Newton*, a very large fraction of the X-ray background, $\sim 80\%$, has been resolved into point sources [135], the vast majority of them AGN [136]. Several studies, the first of them ~ 20 years ago [137], have used a combination of obscured and unobscured AGN to explain the spectral shape and normalization of the X-ray background with overall good results. The latest AGN population synthesis models [138, 139] assume an average ratio of obscured to unobscured AGN of $\sim 3:1$ locally, increasing towards lower luminosities and higher redshifts, as well as a fraction of Compton-thick sources (CT ; $N_H > 10^{24} \text{cm}^{-2}$) of $\sim 5\%\text{--}10\%$, consistent with the value observed at higher energies, $E = 10\text{--}100 \text{keV}$, of $\sim 5\%$ by *INTEGRAL* in the local Universe [138, 140], lower by factors of ~ 3 than expectations of previous population synthesis models [141, 142].

Direct black hole mass measurements, either through stellar or gas dynamics, are available only for a few nearby galaxies. However, thanks to the tight correlation between the mass of the supermassive black hole and other properties (such as velocity dispersion), it has been possible to estimate the black hole mass function at $z \simeq 0$ [143–146]. This is commonly done starting from the observed galaxy luminosity or velocity function and assuming either a constant black hole to stellar mass ratio [143] or the $M\text{--}\sigma$ relation [145]. Both the overall shape of the black hole mass function and the integrated black hole mass density, which can only be computed at $z \simeq 0$, can be used to infer properties of the AGN population. This was first used in the so-called “Soltan’s argument” [129], which says that the intrinsic bolometric AGN luminosity, L , is directly linked to the amount of mass accreted by the black hole, $\dot{M}_{\text{acc}}$:

$$L = \varepsilon \dot{M}_{\text{acc}} c^2$$

where ε is the accretion efficiency and c is the speed of light. A typical value assumed for the efficiency is $\sim 10\%$ [129, 145].

Recent comparisons of the black hole mass function to the distribution inferred from the observed AGN luminosity indicate that the average efficiency is 8%, the Eddington ratio is $\sim 50\%$, and the average lifetime of the visible AGN phase is $\sim 10^8$ years [145, 146]. By studying the black hole mass distribution at the high mass end, $M > 10^9 M_\odot$, Natarajan and Treister [147] found that the observed number of ultra-massive black holes is significantly lower than the number density inferred from the AGN hard X-ray luminosity function. They concluded that this is evidence for an upper limit to the black hole mass, which can be explained by the presence of a self-regulation mechanism.

The observed black hole mass density at $z \simeq 0$ obtained by integrating the black hole mass function, ranges from 2.9×10^5 [144] to $4.6^{+1.9}_{-1.4} \times 10^5 M_\odot \text{Mpc}^{-3}$ [145]; more recently, Shankar *et al.* found $(3.2\text{--}5.4) \times 10^5 M_\odot \text{Mpc}^{-3}$ [148]. For comparison, integrating the AGN hard X-ray LF, including the number of Compton-thick AGN constrained by *INTEGRAL* and Swift/BAT observations, Treister *et al.* obtained a value of $4.5 \times 10^5 M_\odot \text{Mpc}^{-3}$, perfectly consistent with the observed value, indicating that at least locally, X-ray detected AGN can account for most or all of the black hole growth [138]. A comparison between the observed black hole mass density at $z \simeq 0$ and the value derived from integrating the AGN luminosity function is shown in Fig. 12.

At higher redshifts, the black hole mass density at $z \sim 1\text{--}3$ can be derived from the Chandra observations of X-ray detected AGN and luminous infrared galaxies at $z \sim 2$ [130]. Upper limits to the observed black hole mass density at $z > 7$ were obtained from X-ray stacking at the position of high-redshift galaxy candidates in the Chandra Deep Field South by Ref. [149]. Although a strong detection at $z \sim 6$ was reported [149], it was recently questioned by other authors [150, 151]. In the following, we treat the detection as an upper limit. The measurements can be compared to the expectations derived from black hole growth models. In particular, we use as a comparison the results in Refs. [152], [153] and [154]. Two “seed” formation models are considered: those deriving from population-III star remnants (Pop III), and from direct collapse models (D.C.). In this scheme, the central black holes accumulate mass via accretion episodes that are triggered by galaxy mergers. Accretion proceeds in one of two modes: self-regulated or un-regulated. For each black hole in these models we know its mass at the time when the merger starts (M_{in}), and we set the final mass through the self-regulated or un-regulated prescription.

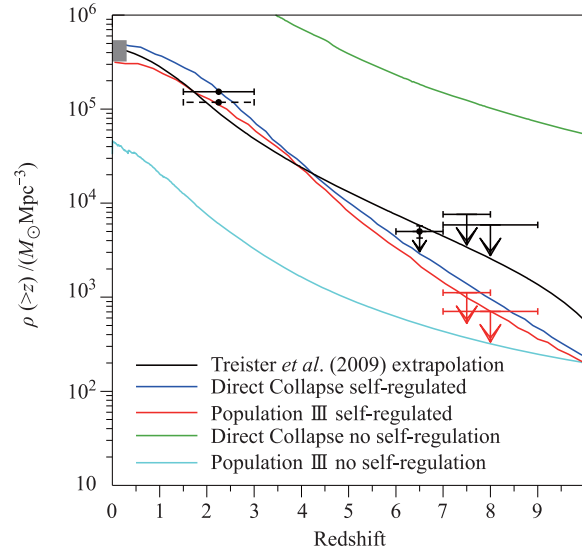


Fig. 12 Total accreted mass by supermassive black holes per cubic megaparsec as a function of redshift. The gray rectangle shows the range of values allowed by observations of $z \simeq 0$ galaxies [148]. The data points at $z \sim 2$ correspond to the values obtained from Chandra observations of X-ray detected AGN and luminous infrared galaxies [130], while the upper limits at $z > 6$ show the results described in Ref. [149] (red and black data points from the observed-frame soft and hard X-ray band observations respectively). The black solid line shows the evolution of the total accreted mass per proper volume element inferred from the extrapolation of AGN luminosity functions measured at lower redshifts [138]. We over-plot the predictions of black hole and galaxy evolution models [123] for non-regulated growth of Population-III star remnants (cyan line) and direct-collapse seeds (green). The red and blue lines show the predicted BH mass density if self-regulation is incorporated.

These two models differ by the amount of mass an SMBH accretes during a given accretion phase. As it can be seen in Fig. 12, models that do not incorporate the effects of self-regulation in black hole growth are grossly inconsistent with the available observational data.

While a clear picture of the history of black hole growth is emerging, significant uncertainties still remain. In particular, while the spectral shape and intensity of the extragalactic X-ray background have been used to constrain the AGN population, the number of heavily obscured accreting supermassive black holes beyond $z \sim 1$ is not properly bounded. Infrared and deep X-ray selection methods have been useful in that sense, but have not provided a final answer, due to confusion with star-forming galaxies in the infrared and the effects of obscuration in X-rays. At higher redshifts, the situation is even more unclear, and only a few, very rare, high luminosity quasars are known. Unless high-redshift AGN luminosity functions are pathological, these extreme sources do not represent the typical growing black holes in the early Universe. As a consequence, and in spite of recent advances [149, 155], the formation mechanism for the first

black holes in the Universe is still unknown.

5 What triggers black hole growth?

While it is clear now that most galaxies contain a super-massive black hole in their center, only a small fraction of these black holes are AGNs. This indicates that black hole growth is most likely episodic, with each luminous event lasting $\sim 10^7$ – 10^8 years [156]. An obvious question is: What triggers these black hole growth episodes?

Major galaxy mergers provide a good explanation, since, as simulations show, they are very efficient in driving gas to the galaxy center [157], where it can be used as fuel for both intense circumnuclear star formation and black hole growth. Indeed, a clear link between quasar activity and galaxy mergers has been seen in intensely star-forming galaxies like ultra-luminous infrared galaxies (ULIRGs) and in some luminous quasars (e.g. Ref. [158]). In contrast, many AGN are clearly not in mergers or especially rich environments [159]. Instead, minor interactions [160], instabilities driven by galaxy bars [161] and other internal galaxy processes might be responsible for these lower activity levels. Understanding the role of mergers is further complicated by the difficulty of detecting merger signatures at high redshifts.

In order to reconcile these potentially contradictory observations, it has been suggested that the AGN triggering mechanism is a function of luminosity and/or redshift [162, and others]. More recently, Hopkins and Hernquist [163] used five indirect tests to conclude that the triggering mechanism is strongly luminosity-dependent and more weakly redshift-dependent, so that only the most luminous sources, which are preferentially found at $z > 2$, are triggered by major mergers [163]. Thanks to results from large AGN surveys, which now include heavily-obscured IR-selected sources, and recent deep high-resolution observations carried out with the *Hubble* WFC3 detector, it is now possible to obtain reliable morphological information even for high- z , low luminosity sources.

To measure the fraction of AGN hosted by a galaxy undergoing a major merger as a function of luminosity and redshift, Treister *et al.* compiled information from AGN samples selected from X-ray, infrared and spectroscopic surveys [164]. They studied data from 10 independent surveys, which include 874 AGN, spanning a wide range in luminosities, $3 \times 10^{42} < L_{bol}(\text{erg}\cdot\text{s}^{-1}) < 5 \times 10^{46}$, and redshift, $0 < z < 3$. The goal of their work is to determine the physical mechanism(s) that provoked the AGN activity identified in these surveys. Only visual morphological classifications have been used, as they are

the reliable option to determine if a galaxy is experiencing a major merger [165]. The fraction of AGN linked to galaxy mergers in these samples has been computed by dividing the number of AGN in which the host galaxy has been classified as an ongoing merger or as having major disturbances by the total number of AGN. Figure 13 shows the fraction of AGN showing mergers as a function of bolometric luminosity, which increases rapidly, from $\sim 4\%$ at $10^{43} \text{ erg}\cdot\text{s}^{-1}$ to $\sim 90\%$ at $10^{46} \text{ erg}\cdot\text{s}^{-1}$.

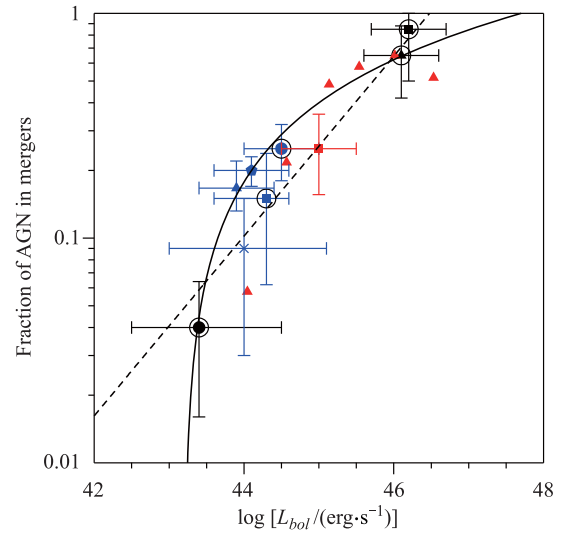


Fig. 13 Fraction of AGN showing mergers as a function of the AGN bolometric luminosity. Colors indicate AGN selection method (red: infrared, blue: X-rays, black: optical) (from Ref. [164]). Encircled symbols show samples at $z < 1$. Solid line shows a fit to the data assuming a linear dependence of the fraction on $\log(L_{bol})$, while the dashed line assumes a power-law dependence.

The spectral shape and intensity of the X-ray background can tell us about the average properties of the AGN population. Using the models of Ref. [138] with the AGN luminosity function of Ref. [166] and the luminosity dependence of the fraction of AGN triggered by major mergers, we can estimate their contribution to the background radiation in X-rays. In Fig. 14 we show separately the contributions to the X-ray background from AGN triggered by secular processes and major mergers, which contribute nearly equally to the X-ray background. This is because most of the X-ray background comes from $z < 1$ sources (e.g. Ref. [138]), where AGN activity due to secular processes is relatively more important. This is particularly true at $E > 10 \text{ keV}$, where AGN emission is roughly unaffected by obscuration. Because of the luminosity dependence of the fraction of obscured AGN (e.g. Ref. [167]), AGN triggered by secular processes are relatively more obscured than those attributed to major galaxy mergers, which explains the different spectral shapes in Fig. 14 and the fact that AGN triggered by

mergers are more important at $E < 5$ keV. We note that a population of high-luminosity heavily-obscured quasars likely associated with major mergers have been reported by Ref. [130] and others. These sources are mostly found at $z \sim 2$ and show evidence of very high, Compton thick, levels of obscuration. Hence, these sources do not contribute significantly to the X-ray background radiation at any energy.

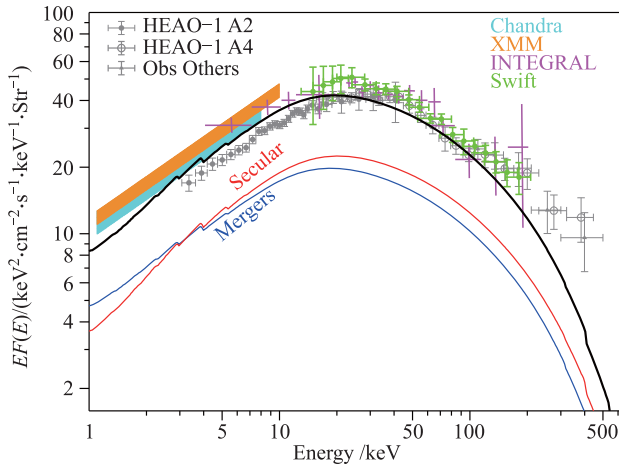


Fig. 14 Spectral energy distribution of the extragalactic X-ray background, as a function of observed-frame energy. Observational data points are summarized in Ref. [138]. Merger-triggered AGN (blue line) contribute roughly equal amounts of light as black hole growth (red line). Most of the X-ray background emission comes from $z < 1$ [138], hence the relative importance of secularly-triggered AGN. The extragalactic background light from higher redshift AGN peaks in the optical/UV and is dominated by luminous, merger-triggered AGN. The spectral shapes of the merger and secular contributions are slightly different since the fraction of obscured sources is a function of luminosity.

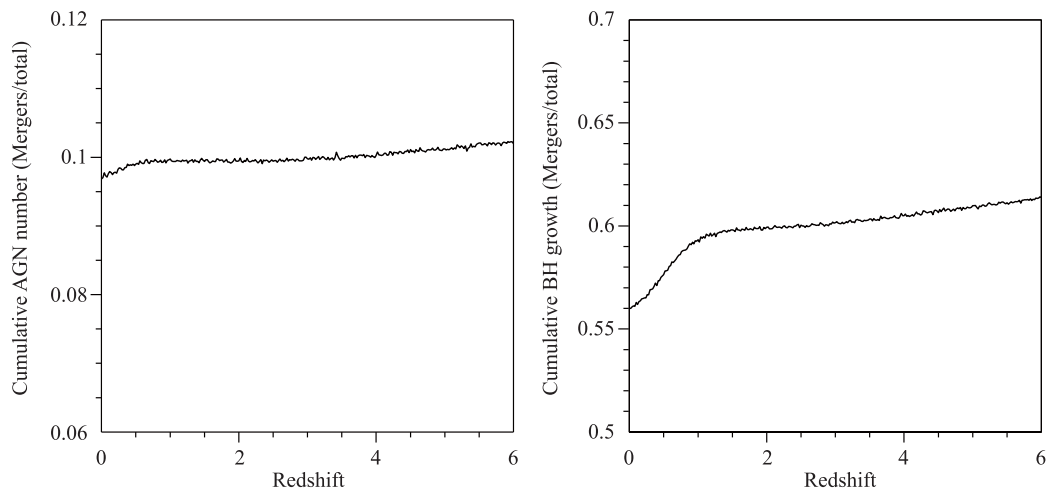


Fig. 15 Left panel: Cumulative number of merger-triggered AGN relative to the total number of AGN as a function of redshift (from Ref. [164]). While secularly-triggered AGN vastly outnumber those triggered by major mergers, by about a factor of ~ 10 , the latter are on average significantly more luminous, thus explaining why they constitute $\sim 60\%$ of black hole accretion. Right panel: Cumulative fraction of black hole accreted mass in AGN triggered by mergers as a function of redshift, assuming a constant efficiency for converting mass to light. Black hole accretion is dominated by merger-triggered AGN at all redshifts but especially at $z > 1$. At $z \sim 1$, the much lower gas and merger fractions lead to a dominance of secular processes in AGN accretion.

In Fig. 15 we show, as a function of redshift, the amount of black hole growth and number of AGN triggered by major galaxy mergers relative to those associated with secular processes. As can be seen and was previously reported (e.g. Ref. [130]), black hole growth occurs mostly in accretion episodes triggered by major galaxy mergers, although secular processes are still important. This is particularly true at $z \gtrsim 2$, where there is $\sim 60\%$ more black hole growth in merger-triggered AGN than in those growing via secular processes. At lower redshifts, there are relatively fewer galaxy mergers and so secular processes become slightly more important. Furthermore, at lower redshifts dry mergers become more common than gas-rich major mergers [168]. Since the availability of gas is a critical factor in determining the black hole accretion rate, this further explains why major mergers are relatively more important at high redshifts. It is interesting to note that the diminishing role of mergers coincides with the decline in the space density of black hole growth and with the observed decline in the cosmic star formation rate [169], i.e., cosmic downsizing. Integrated over the whole cosmic history, to $z = 0$, 56% of the total black hole growth can be attributed to major galaxy mergers.

In terms of numbers, the population is strongly dominated by secularly-triggered AGN. Indeed, as can be seen in Fig. 15, $\sim 90\%$ of AGN at all redshifts are associated with secular processes. This explains the conclusions of previous studies, mostly based on X-ray surveys (e.g. Refs. [170, 171, 172]) of moderate luminosity AGN, which found that normal disk-dominated galaxies constitute the majority of the AGN host galaxies. We conclude

that while most AGN are triggered by secular processes, most of the black hole growth, particularly at high redshifts, can be attributed to intense accretion episodes linked to major galaxy mergers.

6 Outlook

The recent progress in our understanding has come from a fleet of telescopes and from the possibility to test accretion disk, jet, and particle acceleration models with numerical codes. On the observational side, we expect further progress from several observatories; for example:

- **mm and sub-mm radio emission:** the Atacama Large Millimeter Array (ALMA) will revolutionize our understanding of galaxy evolution. Sources of mm and sub-mm emission traced by ALMA include thermal emission of the warm/cold dust, which traces star formation, synchrotron radiation associated with relativistic particles and free-free radiation from HII regions. In particular, CO rotational transition lines have been used to trace the spatial distribution, kinematics, temperature and mass of the molecular gas [173]. The sensitivity of ALMA will allow for the detection of luminous IR galaxies ($L_{\text{IR}} > 10^{11} L_{\odot}$), which have been found to often host a heavily-obscured AGN [174], up to $z \sim 10$. Furthermore, with ALMA it will be possible to study separately the molecular dust surrounding the central black hole and those in star forming regions in the host galaxy. Due to their limited sensitivity and angular resolution, currently-available mm/sub-mm telescopes are not ideal to study star-forming regions even in nearby galaxies. This will dramatically change thanks to ALMA, which will have orders of magnitude better sensitivity and HST-like angular resolution. The first call for ALMA observations was released on March 31, 2011, for observations starting on September 30, 2011. It is expected that the complete array will be in full operation in 2013. The superb spatial resolution and sensitivity of ALMA will allow the identification of the optical/near-IR counterpart of the mm-sub-mm sources. Furthermore, ALMA will directly provide the redshift of the mm-sub-mm sources through the detection of CO rotational transition lines, up to very high redshifts. Combining these new data with existing multiwavelength information will finally allow us to complete the census of supermassive black hole growth since the epoch of cosmic re-ionization.

Using (sub-)mm observatories around the world for very long baseline interferometry, it should be possible to achieve angular resolutions on the order of $20 \mu\text{as}$ [175]. Such angular resolutions, corresponding to a few gravitational radii of the SMBHs in the Milky Way and in the nearby radio galaxy M87, may allow us to observe the shadow of these two SMBHs. The measurements would provide direct evidence for the presence of an event horizon; furthermore, they would allow us to measure the Sgr A* and M87 SMBH spins, and to perform rough tests of GR in the strong gravity regime.

- **Hard X-rays:** launched in June 2012, NuSTAR is the first focusing hard X-ray (5–80 keV) X-ray mission, reaching flux limits ~ 100 times fainter than *INTEGRAL* or *Swift*/BAT observations and comparable to Chandra and *XMM-Newton* at lower energies. During the first two years of operations, NuSTAR observes, as part of the guaranteed time program, two extragalactic fields: the ECDF-S and the central 1 deg^2 part of COSMOS, for a total of 3.1 Msec each. These deep high-energy observations will enable us to obtain a nearly complete AGN survey, including heavily-obscured Compton-thick sources, up to $z \sim 1.5$ [176]. A similar mission, ASTRO-H [177], will be launched by Japan in 2015. Both missions will provide angular resolutions $\lesssim 1'$, which in combination with observations at longer wavelengths will allow for the detection and identification of most growing supermassive black holes at $z \sim 1$. Balloon-borne hard X-ray polarimeters [178, 179] might succeed to measure the polarization of the hard X-ray emission from bright AGN jets. The observations could shed light on the magnetic field structure in HSP blazars and could distinguish between an SSC and EIC origin of the inverse-Compton emission of LSP and ISP sources [180].
- **γ -rays:** the VERITAS array of IACTs has been upgraded in summer 2012 to observe the northern $> 100 \text{ GeV}$ γ -ray sky with a 30% improved sensitivity. The HESS Collaboration announced first light observations with a large 600 m^2 Cherenkov telescope in July 2012 which will enable observations down to energies of 50 GeV. Together with the Fermi LAT and MAGIC, these experiments will scrutinize the γ -ray sky with unprecedented sensitivity. Long-term monitoring programs enabled by Fermi LAT's quasi-continuous sky coverage and multiwavelength campaigns with all the γ -ray telescopes will clarify the existence or non-existence broadband flux and spectral correlations giving us

more detailed information about the properties of AGN jets at their bases.

Other experiments, currently in the proposal stage, could revolutionize our understanding of AGNs, including a *LISA*-type space-based gravitational wave mission (tests of GR, insights into the formation and growth of SMBHs from SMBH spin measurements, e.g. Ref. [181]), an *IXO*-type high-throughput soft X-ray observatory (measurement of the spins of a sample of SMBHs through Fe K- α observations) [182], a *GEMS*-type high-sensitivity X-ray polarimeter (geometry of accretion disk coronae and magnetic field structure in jets) [183], and the next-generation Cherenkov Telescope Array (time resolved observations of blazars and mapping of the γ -ray emission from radio galaxies) [184].

Acknowledgements H. Krawczynski acknowledges support from NASA (Grant No. NNX10AJ56G), and the Office of High Energy Physics of the US Department of Energy. E. Treister received partial support from Center of Excellence in Astrophysics and Associated Technologies (PFB 06) and from FONDECYT grant 1120061. The authors thank A. McCollum for help with the references. Special thanks go to Dan Harris and Anca Parvulescu and to the editors Bing Zhang and Peter Meszaros for carefully reading the manuscript and providing excellent comments.

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