Proceedings of CONF-CIAP 2026 Symposium: International Conference on Atomic Magnetometer and Applications
DOI: 10.54254/2753-8818/2026.HZ27962

Supermassive Black Hole Spin: Probing the Extremes of Relativity in the Universe

Minghim Gao

STFA Leung Kau Kui College, Hong Kong, China
ivankdzga@gmail.com

Abstract. The spin of supermassive black holes (SMBHs) is a fundamental parameter that impacts accretion phenomena, jet physics, and also the co-evolution of black holes and galaxies. In this paper, we assess the recent state of observed SMBH spin from current observational techniques, including X-ray reflection spectroscopy, thermal continuum fitting, gravitational wave detection, and horizon-scale observations from very-long-baseline interferometry. For each, we outline the theoretical underpinnings, observations required for the spin measurement, and the complications of each method. Spin estimates are important in order to use as diagnostics of black hole characteristics, but to understand relativistic effects in the strong gravitational field, and as potential tests of general relativity, for example, through frame-dragging, or the Kerr metric. Relativistic jets powered by high-SP SMBHs are thought to occur through mechanisms such as the Blandford-Znajek process, which has implications for AGN feedback and star formation in host galaxies. Thus, the spin parameter also includes important information regarding a black hole's accretion and merger history. In addition, we anticipate new observatories (LISA, ATHENA, and next-generation Event Horizon Telescope arrays) will be able to provide the greatest level of precision spin measurements. In this paper, we will explore the theoretical, observational aspects of spin measures, and future opportunities. This combined understanding of spin will demonstrate the importance of the spin parameter to black hole physics and its implications in other areas.

Keywords: Supermassive black holes, Spin, Accretion disks, Relativistic jets, Galaxy evolution

1. Introduction

Supermassive black holes (SMBHs) which range in mass from millions to billions of solar masses, lie at the center of every galaxy. They are important and often studied in astrophysics as they govern their surroundings and influence the evolution of galaxies on a large-scale. Therefore, understanding the properties of SMBHs is a requisite to understand the processes that shape the universe. The known attributes of a black hole include the mass, charge, and spin of the object. While mass and charge are generally considered straightforward to acquire, spin is less clear-cut. Therefore, it often evokes more fascination within the astrophysics community. The spin of a SMBH retains information about the formation process, addition of matter through either accretion or mergers, and

© 2025 The Authors. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/).

DOI: 10.54254/2753-8818/2026.HZ27962

the relativistic effects predicted by Einstein's General Relativity [1]. Spin also determines the structure of spacetime at the event horizon and modulates radiative efficiency during accretion which is essential to the launching mechanism for spacecrafts [2].

Moreover, there is growing evidence that SMBH spin is strongly linked to galaxy evolution. The angular momentum of a black hole might play a role in feedback processes which controls star formation activity and alters the growth of structure on cosmic scales. As a result, it is not only a project in black hole astrophysics, but it also has potential implications to answer cosmological questions about galaxy formation and evolution.

This paper aims to address some basic questions on supermassive black hole (SMBH) spin. First of all, how does SMBH spin form and evolve? For example, spin evolution is related to black hole's accretion history and merger history as coherent accretion is likely to spin up a black hole to high or maximal values effectively. While chaotic and iterative accretion or mergers with randomly oriented spins may lead to lower spins or even misaligned ones [1].

Knowing both the accretion and merger process allows for our understanding the black hole's growth history. Second, what does a measurement of SMBH spin allow us to glean about the extremes of general relativity? The spin parameter directly affects the geometry of spacetime near the event horizon, changing the position of the innermost stable circular orbit (ISCO), and enabling a series of frame-dragging effects [3]. If we can measure spin accurately, it allows us to test general relativity in the strong-field regime. Finally, how does spin influence high-energy processes and any observable signatures? High-spin SMBHs can produce relativistic jets, as is possible through Blandford–Znajek process [2]. Spin also influences the emission spectra of accretion disks and alters the nature of black hole shadows — these spins allow for a broad range of observable signatures across the electromagnetic spectrum [4,5].

This paper contains a discussion of the theoretical background, observational methods, and astrophysical implications of SMBH spin. It first discusses spin in the context of general relativity, including how spin is produced and evolves (Section 2). Then the author summarizes the main observational methods for studying spin, including X-ray spectroscopy, gravitational wave signals, and black hole shadow images (Section 3). The following sections discuss the implications of spin for relativistic physics (Section 4), galaxy co-evolution (Section 5), and opportunities for future spin-focused investigations of the universe. Since SMBH spin has been, and continues, to be an important area of study in contemporary astrophysics, the author hope to show the fundamental role that SMBH spin has in astrophysics, including opportunities for studying some of the most extreme physical environments that humans know of.

2. Theoretical foundations of supermassive black hole spin

2.1. Spin in the framework of general relativity

Black holes are characterized through the Kerr metric in general relativity. The Kerr metric is an extension of the Schwarzschild solution to cases including rotation. The Kerr metric describes a rotating black hole by mass and spin, which dramatically changes the structure of spacetime around it [3]. As a parameter ranges from 0 (non-rotating) to 1 (maximal spin), it controls the way gravitational effects are distributed around the black hole.

Spin affects the geometry of several important regions of spacetime around the black hole. It changes the size and shape of the event horizon and ergosphere (a region outside of the event horizon in which frame dragging is so strong an object never can remain stationary), as well as the radius of the innermost stable circular orbit (ISCO), identifying the boundary of stable matter

DOI: 10.54254/2753-8818/2026.HZ27962

accretion [3]. As spin increases, ISCO radius decreases, allowing matter to orbit closer to the black hole and radiate energy with a greater efficiency. These relativistic alterations affect energy extraction and observational signatures significantly.

2.2. Formation of SMBH spin

The spin state of a supermassive black hole provides a valuable record of the formation and growing history. The supermassive black hole spin can vary over time through accretion, which is the main process for accretion. During coherent (longish) periods of accretion, the material is presented for a long length of time with the same specific angular momentum, leading to large spin values. When a supermassive black hole undergoes chaotic (episodic) accretion, this is characterized by short (random) bursts of accretion that produce lower (and often misaligned) spinning black holes [1].

The merger of supermassive black holes also changes their spin. The final spin state of the remnant from a merger process is a product of the initial spin of the parent black holes, the mass ratio of the parents, and the alignment of the parents' angular momentum [1]. During the merger process there is some degree of angular momentum transfer, and these angular momentum dynamics can work to either increase or decrease the spin of the remnant.

The spin of a supermassive black hole may also depend on some population-level effects. There are effects associated with black hole mass, as well as astrophysical conditions to include the geometry of the accretion, or the presence of magnetic field. The interplay of these properties is important to have an understanding of in order to understand values of black hole spin evolutionary lineages completely.

2.3. Spin’s role in astrophysical processes

Not only has spin changed the structure of spacetime, but its principle is also fundamental in a lot of high-energy astrophysics processes. One of the most recognizable roles of spin is its ability to produce relativistic jets. For example, the Blandford–Znajek process is a theoretical method for extracting rotational energy from the black hole and launch a jet [2].The ergosphere is the region of a rotating black hole where the rotational energy can be extracted via magnetic fields, creating jets that can travel beyond the host galaxy.

Spin also controls the efficiency of accretion disks as a spinning black hole can allow matter to orbit closer, which will enhance the radiative efficiency of accretion [6]. In turn, burning that higher efficiency rate means more luminous and energetic emissions, as is observed in active galactic nuclei. Therefore, spin plays a role not only in the dynamic processes of the matter around the black hole, but also in regard to the more and more energetic output observed within the jets and within the jets' end-state. These interactions can play a significant role in how human observe and describe the universe across the electromagnet spectrum.

3. Observational techniques for measuring SMBH spin

Assessing the spin of supermassive black holes (SMBHs) is a major objective in modern astrophysics as spin carries important information regarding black hole growth, relativity, and the energetics of accretion. Because of the extreme conditions at the event horizon (elastic limit and several physical constraints), it is not possible to directly measure spin, and astronomers often have to rely on indirect observational methods of spin, which use spin's effect on electromagnetic and gravitational wave signals to infer spin. Here the author explores the main methods currently

DOI: 10.54254/2753-8818/2026.HZ27962

employed to determine SMBH spin, including a review of their theoretical bases, techniques for obtaining spin values and limitations of each method.

3.1. X-ray spectroscopy

X-ray spectroscopy, especially the analysis of the relativistically broadened Fe Kα line, is one of the most common ways to measure SMBH spin. The Fe Kα line is usually emitted at 6.4 keV through fluorescent emission in the innermost regions of the accretion disk. When measured, the line shows severe broadening and asymmetry from gravitational redshift, Doppler boosting, and relativistic beaming and distortion.

The broadening and distortion are fundamentally related to the location of the innermost stable circular orbit (ISCO), which is dependent on the spin of the black hole. Higher spins imply a smaller ISCO, leading to stronger relativistic effects. Fitting the obtained spectra with models of relativistic disk reflection facilitate spin measurements with high precision [4]. Current and future X-ray observatories, such as Chandra, XMM-Newton, and NuSTAR, provide ever-increasing observational data with spin estimates from a large sample of active galactic nuclei (AGNs) demonstrating that this remains a popular technique in estimating SMBH spin [7].

3.2. Continuum fitting method

An alternative method for spin measurement is to study the thermal continuum emission from geometrically thin, optically thick, accretion disks. This method is called the continuum fitting method, and it can discern the spectral shape of the disk's emission, particularly the peak temperature and emitted flux of the disk, relative to the ISCO radius. The ISCO, as derived from the black holes spin, is also well constrained by the set of spectral parameters.

It is important to note that continuum fitting accurately quantifies the spin parameter if the mass of the black hole, the distance from the black hole, and the disk inclination angle are known in advance. The method also assumes a canonical disk structure and that spectra from other non-thermal emission processes did not contaminate the process. Although continuum fitting is predominantly applied to measure spins of stellar-mass black holes, it has been applied to SMBHs in their AGN state with positive results, although it does remain compromised to the degree in which any of the assumptions of the continua fitting are invalid [6].

3.3. Gravitational wave observations

The emergence of gravitational wave astronomy has created an exciting new pathway for studying the spin of black holes. The gravitational waveforms produced by mergers of supermassive black holes (SMBHs) contain information about the spins of the original black holes and the remnant. The spin parameters, including the magnitude of the spins and their orientation, affect the inspiral, merger, and ringdown process.

While directly detecting SMBH mergers by gravitational waves remains an ultimate goal for future observatories, the ongoing efforts from Pulsar Timing Arrays (PTAs) and the future launch of the Laser Interferometer Space Antenna (LISA) will help facilitate this type of measurement of SMBH spins [8]. This technique adds a new tool to constrain SMBH spin in systems that are faint or lurking underneath obscuring electromagnetic emission, a potentially population that may be large.

DOI: 10.54254/2753-8818/2026.HZ27962

3.4. VLBI and imaging techniques

Recent advancements in very-long-baseline interferometry (VLBI) have made it possible to image black hole shadows and offer a new means of measuring spin. The Event Horizon Telescope (EHT) has obtained detailed images of black hole at the center of M87 and will image Sgr A* in the Milky Way.

Spin influences the shape and asymmetry of the black hole shadow primarily through frame-dragging and the geometry and orientation of the accretion flow. By comparing the images from observation with simulations with various spin values, information about the magnitude and direction of the spin can be inferred. Additionally, spin affects the jet and emission structure of the surrounding area, which also provides additional information for imaging [5].

3.5. Multi-wavelength observations

A solid comprehension of SMBH spin often necessitates the integration of information over different wavebands, a process that is more effective than studying each waveband separately. For example, X-ray spectroscopy only provides information about the form of inner accretion disk, while radio observations provide a layout of the structure and energy of relativistic jets that are believed to be powered by spin. Optical and infrared observations provide extra context and piece together general properties about host galaxies and the accretion state of each object. Using diverse datasets of numerous wavebands helps to correct they measurements to reflect spin and potentially allows us to check spin measurements against each other on the same sources. Additionally, with the rise of multi-messenger astronomy, which combines electromagnetic signals with gravitational wave signatures, we further expand the possibility to view SMBH spin as a whole. The interconnections derived from multi-messenger approaches is something we expect to see more in the next era of high-precision black hole studies.

4. Relativistic physics and extremes of spin

The spin of a supermassive black hole (SMBH) encodes information about its history and surroundings. SMBH spin also acts as a natural analogue for studying relativistic phenomena in the strong field regime of general relativity. Indeed, the spin of a rapidly spinning black hole severely distorts spacetime in its immediate vicinity. This distortion can have effects that are distinctively relativistic and do not appear in other astrophysical contexts. This section will investigate how does SMBH spin provide ways for us to test fundamental physics, helps extract energy from black holes and demonstrates extreme relativistic behaviour [2,3].

4.1. Testing general relativity with SMBH spins

SMBHs offer us a natural laboratories through which we can explore the effects of general relativity in a regime of extreme gravity. One universal prediction for general relativity is frame dragging, which occurs when a rotating mass drags the spacetime around with it. The frame dragging effect (also referred to as Lense–Thirring precession) is maximized in and around a rapidly spinning black hole [3]. Observations of the precession of the inner accretion disk, the wobble of relativistic jets, and also the quasi-periodic oscillations are possible observable mechanisms to search for frame dragging effects. The key is to find some way of measuring spin so as to begin tests of the Kerr metric describing the spacetime geometry of a rotating and uncharged black hole. When we measure

DOI: 10.54254/2753-8818/2026.HZ27962

spin in a high-spin system, if it deviates from the Kerr metric, this could suggest new physics or some structural change in the black hole's environment after correcting for relativity.

4.2. Spin and energy extraction

A major consequence of black hole spin is the possibility of extracting rotational energy from the black hole itself. There have been several theoretical methods proposed for extracting this energy, most notably the Penrose process and the Blandford–Znajek mechanism [2].

The Penrose process allows for energy extraction through the interaction of particles that occur in the ergosphere of a spinning black hole. The Blandford–Znajek mechanism, has been considered within the astrophysical context because it can demonstrate how the spin energy of the black hole is accessed through the magnetic fields linking to the accretion disk. This is what produces powerful relativistic jets along the rotation axis of the black hole, which is observable in quasars, blazars and radio galaxies, and for some time, the strength of the associated brightness and orientation was thought to be intimately related to the spin of the SMBH.

Some observational evidence exists that supports the assertion of spin-driven outflows as some of the observed systems have high jet power relative to their actual accretion rate [6]. This collectively provides a case for why spin is important and may be an essential driver for some of the most energetics phenomena in the universe.

4.3. Spin as a probe of extreme relativistic phenomena

The influence of spin applies to different relativistic properties calculated near the event horizon. Spin will modify the redshift of emitted radiation, change the structure of photon orbits, and affect the time dilation experienced near the black hole. All of these properties will modify observable spectral and variability characteristics of accreting SMBHs in observable ways [4].

Moreover, spin also has implications for the origin of high-energy astrophysical transients, such as gamma-ray bursts and active galactic nucleus (AGN) jets are powered, at least in part, by spin processes. High-spin SMBHs in the early Universe may also explain the rapid formation of the first quasars, and their extreme luminosities [1].

5. Implications for galaxy and black hole co-evolution

In the last two decades, observational and theoretical evidence has demonstrated a strong link between SMBHs and the galaxies they are in, showing that spin is an important tracer of black hole growth and energetic feedback. In this section, we will address how spin connects to accretion history, feedback processes, and the formation of large scale cosmic structures.

5.1. Tracing accretion and merger history

The spin of a SMBH is a direct record to a black hole's previous accretion, mergers, and the black hole growth process. Coherent accretion tends to build spins of black holes up to nearly maximal spin. Chaotic accretion with random inflow of gas and randomly oriented angular momentum tends toward low or moderate spins due to the cancellation of angular momentum [1].

In the case of galaxy mergers, the spins of the merged binary black holes depends on the mass ratio and spins of the black holes that merged. Numerical relativity has shown that binary black hole mergers can lead to a broad variety of spin states, including re-alignment of spin directions and spins mobs with multiple spin downs, depending upon the orientations of the spins, directions, and mass

DOI: 10.54254/2753-8818/2026.HZ27962

ratios of the merging black holes [8]. Therefore, measuring SMBH spins across a sample of many galaxies is informative about the relevant modes of black hole growth over cosmic history. There is an association between high spins and long accretion episodes, and low spins may reflect history with chaotic fueling and black hole mergers.

5.2. Feedback and regulation of star formation

Spin is fundamentally connected to the regulation of galaxy growth via AGN feedback. Black holes with high spin can launch relativistic jets and winds, propagating energy and momentum into the surrounding interstellar, intergalactic medium, which are capable of heating or ejecting gas from the center of a galaxy, thereby suppressing star formation and changing the thermodynamic state of the surrounding environment of the host galaxy [2].

This feedback process is frequently included in cosmological simulations to match the properties of observed massive galaxies — the curves of star forming galaxies and tight scaling relations between black hole mass and the properties of their host galaxies' bulges (e.g. the M–σ relation). Spin-dependent feedback mechanisms, especially those based on the Blandford–Znajek process, may provide one explanation as to why some galaxies evolve from blue, star forming to red, quiescent elliptical galaxies [6].

Furthermore, spin-aligned jets can prelocate into environments much larger than the host galaxy when it drive them into the host galaxy, interfering in the evolution of galaxy groups and clusters via mechanical heating of the intracluster medium. Thus, SMBH spin providing a natural connection between the microphysics of accretion and the macroscopic evolution of galaxies and large-scale structure.

5.3. Evolution across cosmic time

The co-evolution of SMBHs and galaxies inherently occurs over time. Quasars viewed at redshifts $z > 6$ show SMBHs with masses of $>10^9$ solar masses only ~1 billion years after the Big Bang. Describing their growth requires rapid and efficient accretion which may be able to occur with large spin values that will also allow for greater radiative efficiency, converting mass into energy [1].

Over cosmic time, the average spin of the SMBH population is expected to evolve with the changes in accretion modes and merger rates. SMBHs in the early universe may have had coherent accretion because of the volume of cold gas present that likely contributed to higher angular momentum black holes. In the later universe, chaotic accretion and dry mergers will likely produce a larger dispersion in the spin values.

In order to understand this co-evolution we will need to measure spin populations, model spin-dependent feedback, and test behaviour against galaxy formation. As observational facilities continue to advance, particularly in X-ray [4], gravitational wave signals [8], or even high-resolution Nichols imaging facilities [5], we will see the ability to advance the tracking of SMBHs co-evolving with their host across cosmic time.

6. Conclusions

Over the next several years, significant advancements in the study of supermassive black hole (SMBH) spin can be expected, with both observational advancements and theoretical improvements. The author believes that upcoming X-ray observatories (e.g. ATHENA and XRISM) will substantially advance the spin measurement field through improving our ability to measure

DOI: 10.54254/2753-8818/2026.HZ27962

relativistically broadened iron lines and thermal emission from accretion disks, which will substantially improve the uncertainties in spin (due to the improvements in systematic errors). The author also expects that the Event Horizon Telescope (EHT) and planned upgrades, will allow us to take sharper images of the black hole shadows and measure the spin via comparison of relativistic models with the observations. LISA, or the Laser Interferometer Space Antenna, will generate unprecedented data, generating gravitational wave observations from merging SMBHs. Specifically, LISA will provide access to spin measurements on a wider and more diverse collection of black holes throughout cosmic time. The improvements made in the study of black hole spin will likely also be aided by improvements in our observational capabilities and a better understanding of our own place in the universe. Theoretical studies of spin are also benefitting from rapid developments in numerical relativity and magnetohydrodynamic (MHD) simulations, which can develop advanced modeling and integrate more realistic physics (i.e., magnetic reconnection, radiation pressure, particle acceleration, etc.). The studies of simulations, observation datasets, and the emerging modern statistical and machine learning data analysis can all contribute to answering the many unresolved questions, unknowns, and uncertainties about interpretations of spin values. There are theoretically interpretations about spin in addition to black hole spin values being important for how black holes act and evolve across cosmic history.

References

[1] Gammie, C. F., Shapiro, S. L., & McKinney, J. C. (2004). Black hole spin evolution. The Astrophysical Journal, 602(1), 312–319.
[2] Blandford, R. D., & Znajek, R. L. (1977). Electromagnetic extraction of energy from Kerr black holes. Monthly Notices of the Royal Astronomical Society, 179(3), 433–456.
[3] Bardeen, J. M., Press, W. H., & Teukolsky, S. A. (1972). Rotating black holes: Locally nonrotating frames, energy extraction, and scalar synchrotron radiation. The Astrophysical Journal, 178(1), 347–370.
[4] Reynolds, C. S. (2014). Measuring black hole spin using X-ray reflection spectroscopy. Space Science Reviews, 183(1–4), 277–294.
[5] Event Horizon Telescope Collaboration. (2019). First M87 Event Horizon Telescope Results. I: The Shadow of the Supermassive Black Hole. The Astrophysical Journal Letters, 875(1), L1.
[6] McClintock, J. E., Narayan, R., & Steiner, J. F. (2014). Black hole spin via continuum fitting and the role of spin in powering transient jets. Space Science Reviews, 183(1–4), 295–322.
[7] Fabian, A. C., Zoghbi, A., Ross, R. R., Uttley, P., Gallo, L. C., Miniutti, G., ... & Young, A. J. (2009). Broad line emission from iron K- and L-shell transitions in the active galaxy 1H0707–495. Nature, 459(7245), 540–542.
[8] Sesana, A. (2013). Prospects for multiband gravitational-wave astronomy after LISA. Classical and Quantum Gravity, 30(24), 244009.