Survey for Observations related to Black Holes

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Abstract: **In this paper presents a survey of key observational findings related to black hole (BH) thermodynamics and radiation. It examines landmark measurements that support the theoretical framework of BH evaporation and entropy, as well as observational missions that have captured indirect signatures of these phenomena. Furthermore, the study explores potential mechanisms through which BHs may interact with their environment, including scenarios that imply possible information exchange.**

Keywords: **Astronomical observations, <u>BH</u>, Event horizon, Gravitational wave, Hawking Radiation, Jets.**

I. PHYSICS OF BH (CLASSICAL AND QUANTUM ASPECT)

A BH is a cosmic object characterized by a significant gravitational field that not even light can escape from its grasp. Its so called surface, known as the event horizon (EH), marks the boundary beyond which the escape velocity surpasses the speed of light the ultimate speed limit in the universe. Once matter or radiation crosses this boundary, it cannot return. BHs are broadly classified into two well documented categories. Stellar mass BHs, ranging from a few to several dozen times the mass of our Sun, are scattered throughout the Milky Way. In contrast, supermassive BHs ranging had wide range of solar masses reside in the cores of most large galaxies, including our own. Astronomers have also proposed the existence of intermediate mass BHs, believed to weigh between 100 and over 10,000 solar masses, though they remain less well understood.

Stellar mass BHs typically originate from the collapse of massive stars exceeding 20 solar masses, once they deplete the nuclear fuel in their cores. This collapse leads to a powerful supernova explosion that ejects the outer layers of the star.

However, if the remaining core mass exceeds roughly $3M_{\odot}$, as its goes complete to collapse into a BH. While the formation mechanisms of supermassive BHs are still largely unknown, their presence dates back to the earliest epochs of galaxy formation. Once formed, BHs grow by accreting infalling material, including gas from nearby stars and even other BHs.

The method adopted by astronomers in observing space objects depends on detecting the radiation emitted by those objects. As BH gravitational field is very strong that need special process.

Blandford and Znajek process

The Blandford Znajek process[1,2], illustrated in Fig.1, describes the extraction of energy and angular momentum from a rotating BH. This mechanism requires the electromagnetic field surrounding the BH to be altered by magnetospheric currents. In order to sustain these currents, the electric field must remain unscreened. As a result, the vacuum electric field generated within the ergosphere by distant sources must contain a non-screened component. The most widely accepted

mechanism for enabling this is an $e^{\pm}$ pair cascade triggered by strong electric and radiation fields. Since the ergosphere

induces rotation in the magnetosphere within it, the resulting outward flux of angular momentum leads to the extraction of energy from the BH.
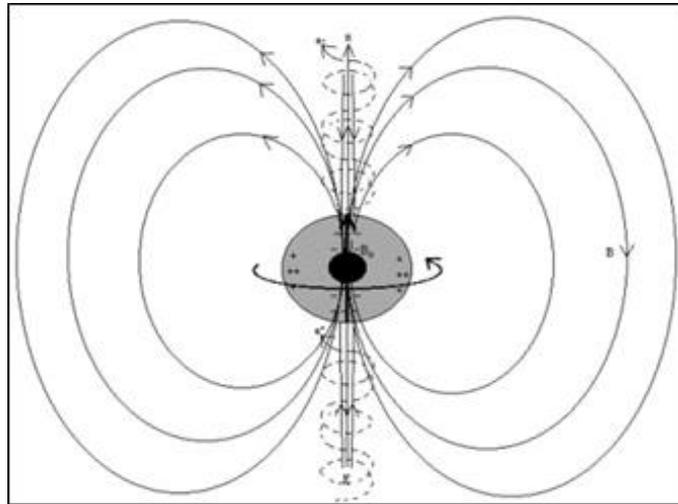
Gravity vs Radiation pressure for BH.

Penrose process

The Penrose process[3,4] demonstrates that energy can be extracted from a rotating BH. This mechanism exploits the ergosphere a region of spacetime surrounding the BH that is dragged by the BH's rotation at such extreme rates that, from the perspective of an external observer, any object within this region is compelled to co rotate with the BH.
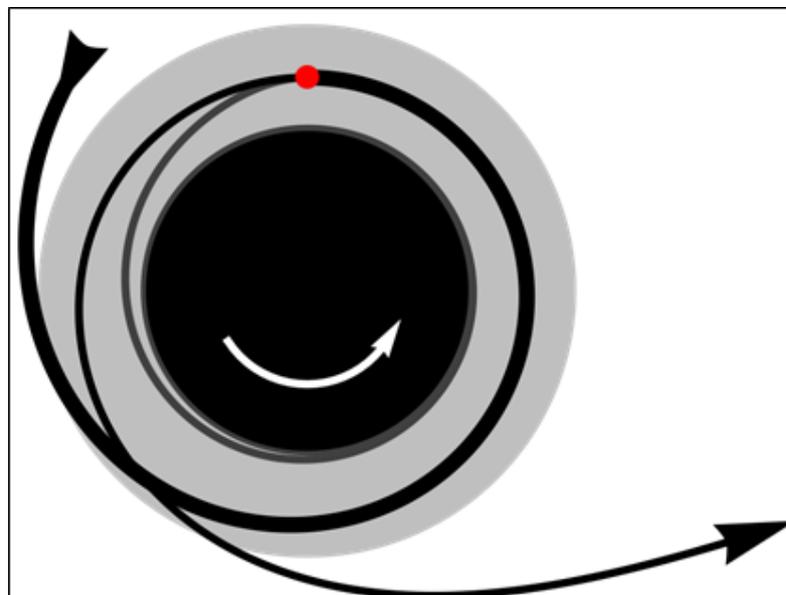

Trajectories of bodies in a Penrose process.

In the process illustrated in Fig.2, a test body enters the ergosphere (depicted as the gray region). At its closest approach to the BH (marked by the red dot), the body ejects a portion of its mass backward as propellant. Due to the frame dragging effect, both the main body and the ejected propellant appear to continue moving forward from the perspective of a distant observer, although at different velocities. The propellant, having lost energy, follows a trajectory (thin gray line) that leads it toward the EH (represented by the black disk). Meanwhile, the remaining part of the body gains additional energy and escapes along a separate path (thin black line), ultimately carrying away more energy than the total initial energy, thereby extracting energy from the BH.
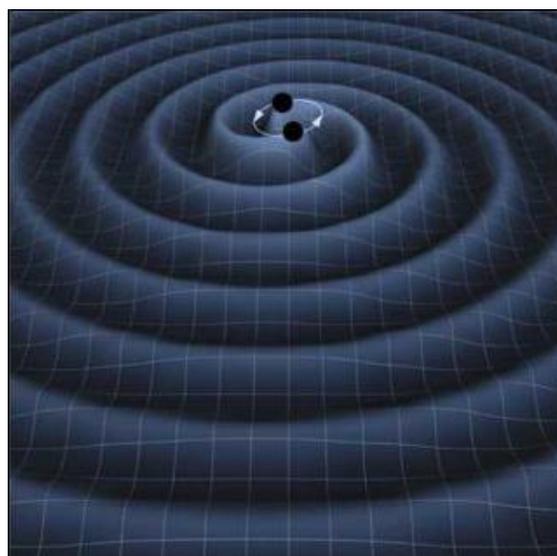
Hawking radiation

Hawking radiation[5,6] arises as a consequence of the Unruh effect and the application of the equivalence principle to BH horizons. Near the EH, a stationary observer must undergo constant acceleration to avoid falling into the BH. According to the Unruh effect, such an accelerating observer perceives a thermal bath of particles emerging from the local acceleration horizon, momentarily escaping before falling back in. The requirement of local thermal equilibrium leads to a consistent extension of this thermal bath to asymptotic infinity, implying a finite temperature as measured by distant observers. As a result, a fraction of these particles are not reabsorbed and instead escape to infinity as outgoing Hawking radiation, as illustrated in Fig.3.
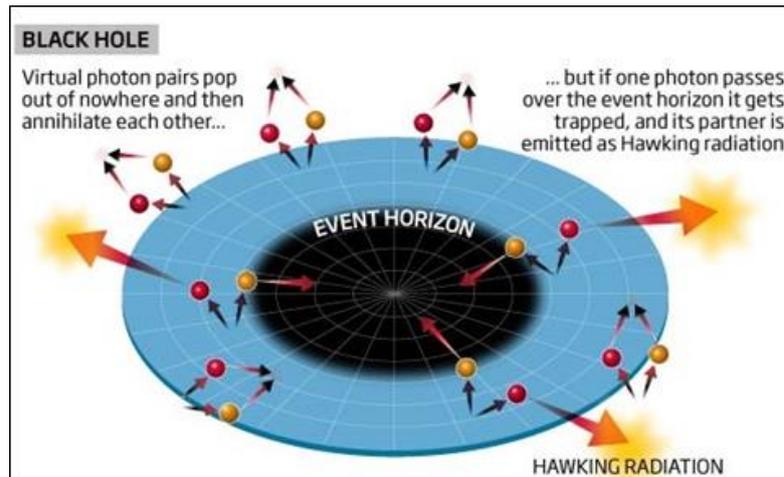

Hawking radiation.

Gravitational waves (GWs)

In Einstein's general theory of relativity (GR)[7,8], gravity is described as a manifestation of spacetime curvature, which arises due to the existence of mass and energy. The greater the mass confined within a given region of space, the more pronounced the curvature at its boundary. As massive objects move through spacetime, they dynamically alter this curvature to reflect their new positions. Under certain conditions, accelerating masses can produce disturbances in the curvature that propagate outward at the speed of light in the form of waves. These disturbances are known as GWs, as illustrated in Fig.5.

GWs of merger BH.

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BH event horizon

The EH is the boundary surrounding a BH beyond which nothing, not even light, can escape. It defines the region from which no causal signal can reach an external observer, making it the point of no return for infalling matter and radiation.
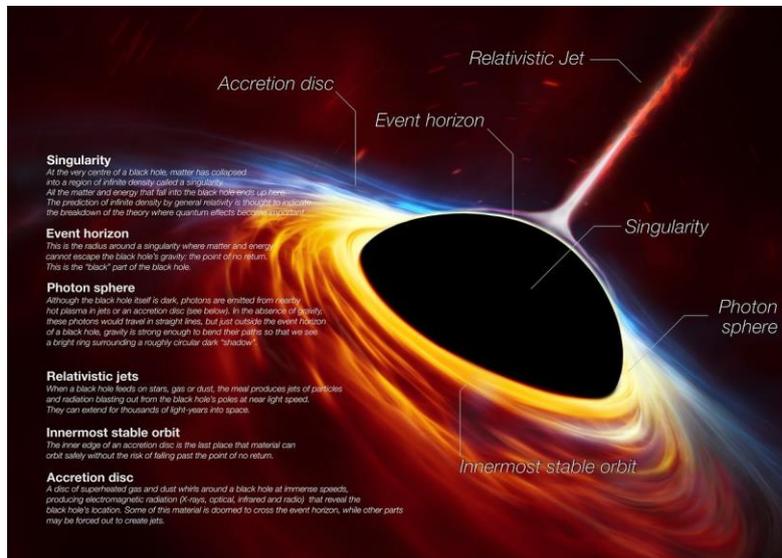
BH EH.

For a non-rotating (Schwarzschild) BH, the EH is located at the *Schwarzschild radius*:

$$r_s = \frac{2GM}{c^2}$$

where:

- G is the gravitational constant,
- M is the mass of the BH,
- c is the speed of light.

In the case of a rotating (Kerr) BH, the radius of the EH depends on both the mass M and the angular momentum per unit mass $a = J/Mc$.

- The EH has no locally observable features; an infalling observer crossing it experiences no physical discontinuity.
- It is a causal boundary, not a material surface.
- The *surface gravity* on the horizon is related to the BH's temperature and plays a central role in Hawking radiation.

The EH's area is directly proportional to the BH's entropy, known as the Bekenstein-Hawking entropy:

$$S_{BH} = \frac{k_B A}{4\ell_P^2}$$

where:

- A is the area of the EH,
- k_B is Boltzmann's constant,

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- ℓ_P is the Planck length.

This relationship underpins the thermodynamic description of BHs and connects gravity with quantum theory. The EH plays a critical role in the BH information paradox. According to Hawking's theory, BHs emit thermal radiation that appears uncorrelated with the infalling matter. This leads to a potential loss of information, which challenges the unitarity of quantum mechanics and raises deep questions about the fate of information in BH evaporation.

- **Apparent horizon**: Depends on the observer and may differ from the EH in dynamical spacetimes.

- **Trapped surface**: A surface where outgoing light rays converge, indicating the presence of strong gravity and potential horizon formation.

- **Killing horizon**: In stationary spacetimes, this coincides with the EH and is associated with a Killing vector field.

The EH is a foundational concept in BH physics. It defines the causal structure of spacetime near a BH and is essential to our understanding of gravitational collapse, quantum information loss, and the thermodynamic behavior of BHs. According to these processes, we can say that astronomers have been studying BHs through two ways:

A. Indirect observations of BHs.

B. Direct observations of BHs.

II. INDIRECT OBSERVATIONS OF BHS (BH JETS)

Radiation and astrophysical jets are produced as a result of several extreme physical processes occurring near BHs. Firstly, the immense tidal forces in the vicinity of a BH cause nearby infalling matter to be heated to temperatures of millions of degrees. Additionally, some of the material orbiting very close to the EH may be ejected outward instead of being accreted. Through the Blandford–Znajek process, these hot, energetic particles can generate both radiation and highly collimated astrophysical jets.

These jets can be broadly classified into two categories[9]:

- **High-energy, superthermal particles:** These produce collimated plasma jets observable across various electromagnetic bands radio, X-ray, and gamma-ray (γ-ray). Such jets can stretch across many light-years into intergalactic space.

- **Relativistic, nonthermal particles:** These particles undergo synchrotron and inverse Compton radiative losses as they interact with ambient magnetic fields or background radiation fields.

Physics of BH jets

Supermassive BHs located at the centers of some active galaxies are known to produce powerful jets composed of radiation and high energy particles traveling at nearly the speed of light. These jets originate as matter from the surrounding environment such as gas and dust is drawn inward by the BH's intense gravitational field and spirals toward the EH. However, rather than all of this material being accreted, a small fraction becomes highly energized and is expelled along the BH's rotational axis in the form of two narrow, oppositely directed jets. These relativistic jets are thought to be responsible for some of the fastest-moving particles in the Universe, known as cosmic rays. In certain cases, the jets extend beyond the host galaxy itself, ending in enormous radio lobes located far from the galactic center. When observed with radio telescopes, these galaxies often exhibit structures resembling dumbbells.

Astrophysical jets provide highly favorable conditions for particle acceleration. They are often supersonic and capable of generating strong shock waves. Additionally, they contain regions characterized by velocity shear, turbulence, and strong magnetic fields each of which plays a crucial role in accelerating particles to relativistic energies. In such environments, particles can gain energy through various mechanisms, including scattering in turbulent plasma, crossing shock fronts, traversing shear layers, or interacting with magnetic reconnection zones.

The energy gain of charged particles in these settings is commonly attributed to motion through an induced electric field described by $\vec{u} \times \vec{B}$, where $\vec{u}$ is the bulk plasma velocity and $\vec{B}$ is the magnetic field. Under appropriate conditions, the

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energy acquired by particles can be offset by their escape from the acceleration site, leading to a power-law energy spectrum. The emergence of such a spectrum, however, typically requires specific and finely tuned physical conditions.

Observations related to BH jets

Observational aspects of astrophysical jets[9] are:

Radio emission

Images of jetted sources in the radio band provide valuable insights into the mechanisms of particle acceleration. The study of radio emissions offers critical information about the physical regions responsible for generating the observed radiation and allows for a direct connection between these regions and various radio emission parameters[10], such as:

- **Luminosity:** The total energy emitted by the source in all directions per unit time.

- **Spectral index:** A parameter that quantifies how the radiative flux density varies with frequency, indicating the underlying particle energy distribution.

- **Morphology:** The physical shape and structure of the radio source, which helps in classifying the emission region and understanding the dynamics of jet propagation.

Synchrotron spectra

Synchrotron radiation is the most universal observational signature of astrophysical jets[9], which is produced by relativistic charged particles (electrons) spiraling around magnetic field lines. The exact spectral characteristics of the observed synchrotron emission depend on several key factors:

- **The energy distribution of the charged particles (electrons):** Determines the shape and intensity of the emitted spectrum.

- **The observing waveband:** Different wavebands (radio, optical, X-ray, etc.) probe different parts of the electron energy distribution.

- **The number of distinct radiating charged particles (electrons) populations:** Multiple electron populations can superimpose different spectral components.

- **The bulk Lorentz factor of the emitting plasma:** Affects the observed frequency and intensity through relativistic beaming and Doppler boosting.

- **Absorption effects:** Whether or not the emission undergoes self-absorption or other absorption processes can significantly alter the observed spectrum.

Gamma ray emission

Gamma ray (γ ray)[9] can be produced through both leptonic and hadronic interaction mechanisms. In the leptonic scenario,

high energy γ ray emission arises from inverse Compton scattering, where relativistic electrons transfer energy to lower-energy photons. These target photons may originate from various radiation fields, including the cosmic microwave background (CMB), thermal emission from the accretion flow, or even the charged particles (electrons) own synchrotron radiation. In the latter case, where electrons upscatter their self generated synchrotron photons, the process is known as synchrotron self Compton (SSC).

What we get from BH jets observations

BH jets serve as powerful tools for probing the nature of BHs and their surrounding environments. By studying these jets, researchers can gain deeper insight into the physical properties of BHs and their broader role in the evolution of galaxies and the Universe. Powerful relativistic jets launched by supermassive BHs offer a means to investigate the structure and dynamics of the accretion disks surrounding them, the configuration and strength of the magnetic fields involved, and even the spin of the BHs themselves[11,12], as illustrated in Fig.6.
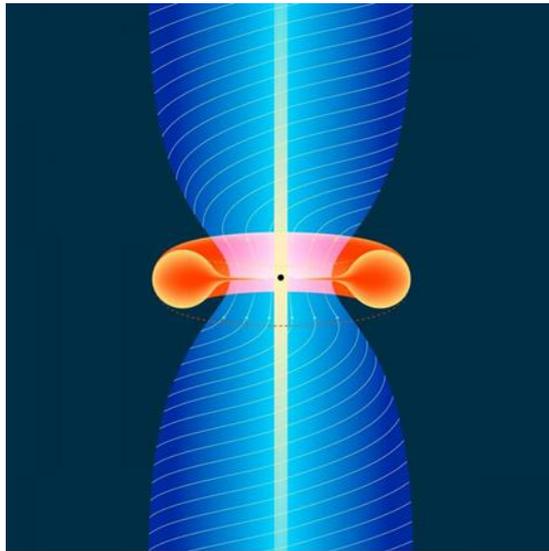
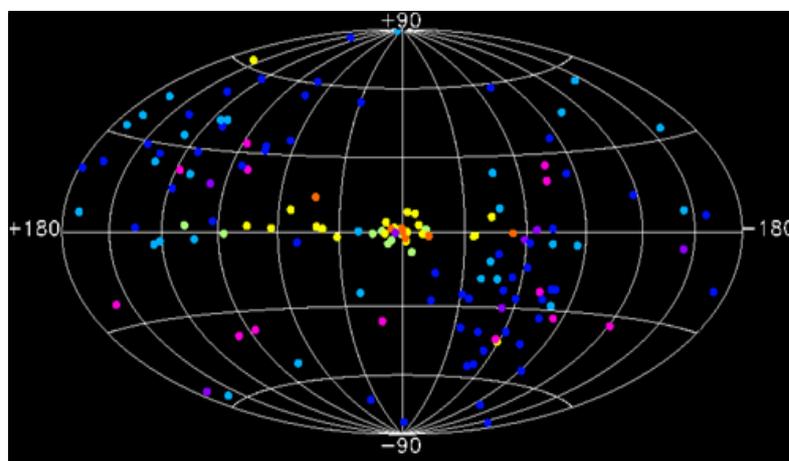*The accretion disk of supermassive BH is shown in red color and emits jets that shown as vertical beams[12].*

BH jets observation missions

In order to study the jets coming from BHs, there must be observatories that can monitor X ray, γ ray, and radio waves, which represents evidence of BH jets.

The BeppoSAX Mission

BeppoSAX[13] was a major mission of the Italian Space Agency, conducted in collaboration with the Netherlands Agency for Aerospace Programs. It was launched on April 30, 1996, from Cape Canaveral and remained operational for six years, during which it observed 130 transient X-ray sources, as shown in Fig.7.

BeppoSAX[14,15] was the first X-ray astronomy mission equipped with a scientific payload capable of covering more than

three decades of energy, ranging from 0.1 to $300\,\mathrm{keV}$. It featured a relatively large effective area, where medium energy

resolution, and imaging capabilities in the 0.1–$10\,\mathrm{keV}$ range. This broad energy coverage, combined with the inclusion of wide-field instruments designed to detect transient phenomena, allowed these sources to be promptly followed up with narrow-field instruments. As a result, BeppoSAX offered an unprecedented opportunity to study the broadband spectral behavior of various classes of X-ray sources.

Sky galactic map of 130 transients X ray stars showed by BeppoSAX Wide Field Cameras its mission.

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A large collaboration, BeppoSAX observational program given the results[16] aimed at studying the 0.1–$200\ keV$ spectral properties of newly discovered X-ray novae, which are expected to harbor BH candidates. The spectral and temporal characteristics observed during the outburst phase do not resemble those typically associated with X-ray novae hosting either BHs or neutron stars. However, the properties of the source during its quiescent phase remain puzzling. Radio jets associated with the source may offer critical insights into its true nature. Specifically, the velocity of the radio jets has been proposed as a potential distinguishing feature for identifying the nature of the compact object. In the case of BHs, these jets are expected to travel at speeds approaching the speed of light, making jet velocity a promising diagnostic tool for differentiating BHs from other compact objects.

Atacama Pathfinder Experiment (APEX)

Located at an altitude of 5100 meters on the Chajnantor Plateau in Chile's Atacama Desert, APEX[17] is a pioneering 12-meter instrument designed to operate at millimeter and submillimeter wavelengths. APEX enables astronomers to explore

the cold Universe regions dominated by gas, dust, and celestial objects with temperatures ($-273.15°C$). At the core of APEX lies LABOCA (Large APEX BOlometer CAmera), one of the largest bolometer cameras in the

world, consisting of 295 individual bolometers. These highly sensitive detectors are capable of measuring extremely small amounts of energy emitted by cold astronomical sources. To achieve such sensitivity, the bolometers must be

cooled dawn to less than 0.3 degrees above absolute zero. This is accomplished by housing LABOCA in a high-vacuum cryostat system that uses both liquid nitrogen and liquid helium to reach and maintain operational temperatures near absolute zero.

Thanks to these advanced features, LABOCA and APEX are exceptionally well suited to complement the Atacama Large Millimeter/submillimeter Array (ALMA) in probing the cold Universe. Their combined observational power provides astronomers with fascinating and detailed images, as illustrated in Fig.8.

Centaurus constellation appear as radio galaxy showing the jets with lobes go out of the central surround 1.

APEX has revealed the strongest link to date between the most intense bursts of star formation during the early Universe and the massive galaxies observed in the present day, as shown in Fig.9. A likely explanation for the abrupt cessation of these starbursts is the emergence of supermassive BHs, which may play a key role in regulating or quenching star formation in their host galaxies.
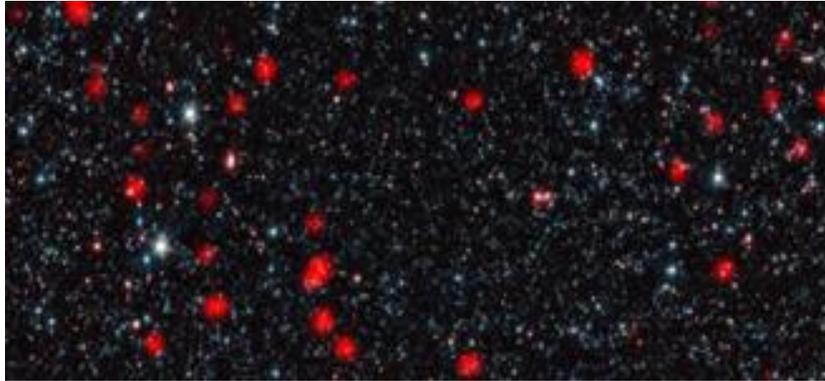
Centaurus constellation appear as radio galaxy showing the jets with lobes go out of the central surround 2.

Rossi X ray Timing Explorer Mission (RXTE)

RXTE[18,19] satellite provided insights into the extreme environments surrounding white dwarfs, neutron stars, BHs, and other X-ray-emitting celestial objects. During its 16 years of operation, RXTE far exceeded its initial scientific objectives, leaving behind a rich legacy of data that continues to benefit the astronomical community. The observatory's instruments were capable of detecting variations in X-ray emission over timescales ranging from microseconds to months, and across a broad energy range from $2\,\text{keV}$ to $250\,\text{keV}$. For context, the energy of a typical dental X-ray is approximately $60\,\text{keV}$. This wide temporal and spectral coverage made RXTE an invaluable tool for studying high-energy astrophysical phenomena in remarkable detail.
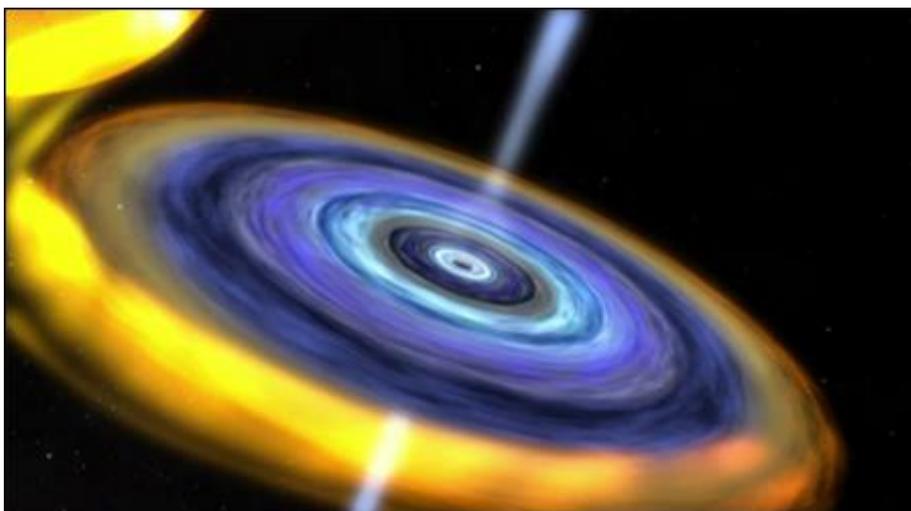
Centaurus constellation appear as radio galaxy showing the jets with lobes go out of the central surround 3.

The X ray signals was detected[20,21] from hot gas in the rapidly accretion disks around BHs. These observations will help astronomers understand how BHs re direct some of this gas into oppositely directed jets of matter moving at nearly the speed of light.How these jets form deep in the disk, just outside the BH is an open question, but the phenomenon occurs in binaries containing lower mass BHs, as shown in Fig.10, as well as for supermassive BHs centered at galaxies. RXTE[22,23] giving the first observational evidence of frame-dragging in the vicinity of a BH, an effect predicted by Einstein's GR, which shown in Fig.11.
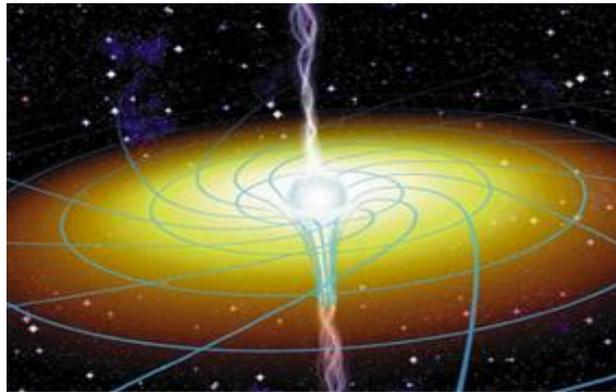
Frame dragging as expected from GR.

Chandra Observatory

Start July 23, 1999, the Chandra Observatory has served as the leader of NASA's missions for X-ray astronomy, joining the fleet of Great Observatories. The Chandra Observatory[24,25] is a space-based telescope specifically designed to detect the emissions of X-ray from extremely hot regions of the Universe, including supernova remnants, galaxy clusters, and the accretion environments surrounding BHs.

As Earth's atmosphere absorbs X-rays, Chandra work from a highly elliptical orbit that takes it up to an altitude of

$139,000\,\text{km}$ ($86,500$ miles), far above the atmospheric interference. The mission is managed by the Smithsonian Astrophysical Observatory (SAO) in Cambridge, Massachusetts, which hosts the Chandra X-ray Center. The Center is responsible for satellite operations, data processing, and global scientific data distribution. Additionally, it maintains a comprehensive public website for disseminating scientific discoveries and supporting an educational outreach program.
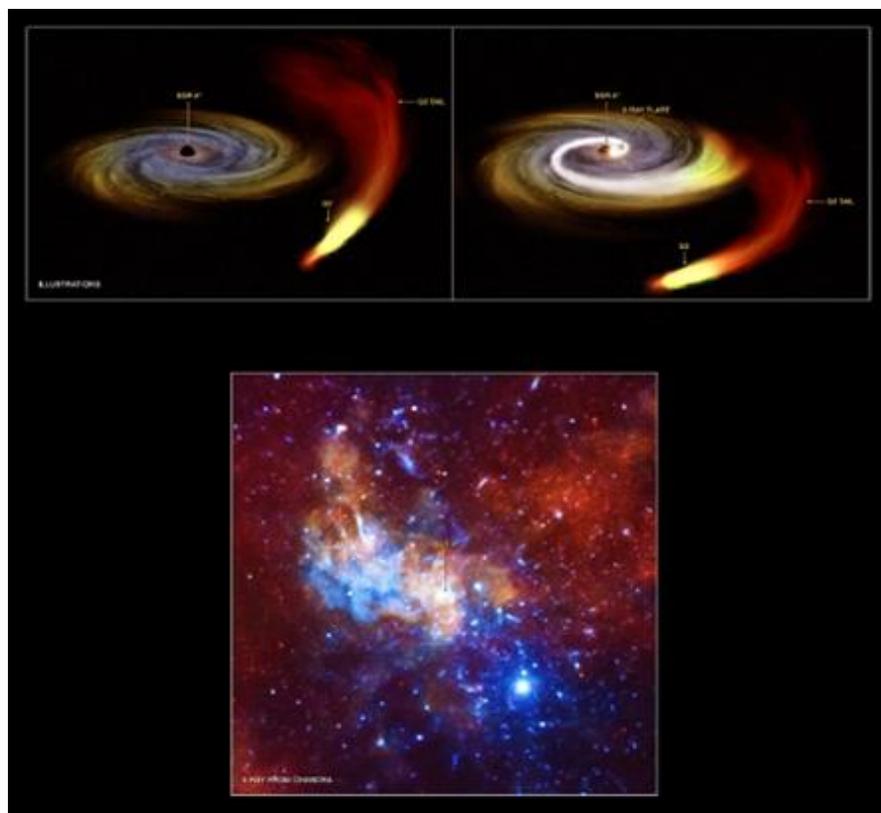
Sagittarius A^*: Milky Way's BH Shows Signs.

Important study of BHs at the center of our Milky Way galaxy. Known as Sagittarius A^*, this BH is about $4 * 10^6 M_\odot$, as the behavior and history of this BH was given by Chandra[26,27]. Because of the nature of the center of our Milky Way (fill with thick clouds of dust and gas), the Optical telescopes cannot see through it, as shown in Fig 12. However, the highly velocity (near speed of light) of this components, they produce X rays that penetrate this cover. Chandra after short time from its launching separate the X-ray emissions from the surrounding hot gas and nearby compact sources. Chandra's data[28] of Sagittarius A^* showing the measured energy output and flaring from Sagittarius A^*. The variations in the X ray was rapidity indicates that they are occurring near the EH, or point of no return, around the BH, and the X ray low intensity suggests that Sagittarius A^* is a juvenile BH. Unusual long jet of particles coming from a supermassive BH belong to the early universe[29,30] had been discovered by using Chandra. If confirmed, it would be a remarkable most distant supermassive BH about 12.7 billion light years was detected, these data will help to explain how the suppermassive BHs formed at early time. A quasar named PSO J352.4034 15.3373 (PJ352 15 for short) represent source of these jets, which located at the center of a young galaxy. "PJ352 15" is one of the two most powerful quasars detected in radio waves in the first 10^9 year after the big bang, and its mass is larger than $10^9 M_\odot$. The photons detected from this jets were emitted when the universe was only $0.98 * 10^9$ years old. At this point, the intensity of the CMB from the big bang was greater than it is today. As charged particles (electrons) in the jet go away from the BH nearly at the speed of light, they move through and collide with photons making up the CMB, boosting the photons energy up to the X ray range. In this scenario, the X rays are remarkable brightness compared to radio waves, as shown in Fig 13. This agrees with the observation that the large X ray jet feature has no emission of energy in radio band.

Detecting 'Ripples' From BH's X Ray using Chandra X Ray Observatory.

How supermassive BHs (SMBHs) were able to grow so rapidly to reach enormous masses during the early epochs of the Universe remains one of the most compelling open questions in modern astrophysics. Despite their intense gravitational pull and ominous reputation, BHs do not inevitably consume everything that approaches them. Matter orbiting a BH within an accretion disk must first lose angular momentum and energy before it can spiral inward and cross the EH the boundary beyond which nothing can escape.

Magnetic fields play a center role in this process. They can exert a braking effect on the rotating disk by powering relativistic jets, which serve as an efficient mechanism for the removal of angular momentum and energy. This loss of energy allows material to move inward more efficiently, thereby accelerating the growth of the BH. Understanding these mechanisms is essential for explaining how SMBHs attained their massive sizes so early in cosmic history.

W. M. Keck Observatory (Keck Observatory)

From the summit of Maunakea in Hawaii, astronomers worldwide utilize the Keck Observatory[31–33] to explore the Universe with unprecedented power and precision. The twin Keck Observatory telescopes are among the most scientifically productive optical and infrared telescopes in the world. Each telescope features a primary mirror 10 meters in diameter, composed of 36 hexagonal segments that function together as a single monolithic reflective surface. Despite weighing approximately 300 tons, each telescope operates with nanometer-level precision.

Maunakea's location in the middle of the Pacific Ocean provides unique observational advantages. Hawaii Island is surrounded by huge area of thermally stable ocean, and the 13,796 foot summit of Maunakea stands isolated, with no nearby mountain ranges to disturb the upper atmosphere. In addition, the region suffers minimal light pollution, and for much of the year, the skies above Maunakea remain clear, calm, and dry. These conditions make it one of the best astronomical observing sites on Earth, offering exceptional "seeing" for ground-based telescopes.

*Keck I and Keck II Pointed to the BH at the center of Milky Way galaxy.*

The enormous BH is having an unusually large interstellar gas and dust. The researchers[34,35] analyzed more than $13 * 10^3$ observations of the BH from 133 nights since 2003, as shown in Fig 14. The images were gathered by the Keck Observatory and the European Southern Observatory's in Chile. The team found that the area just outside the BH's the point of no return was twice as bright as the next brightest observation.

The IllustrisTNG project

The IllustrisTNG is a series of large scale cosmological magnetohydrodynamical simulations focused on modeling the formation of galaxy and its evolution. The goal of TNG is to uncover the physical mechanisms that participate in galaxy formation, to determine the time and how galaxies evolve into the entities observed in the Universe today, and to provide theoretical expectations for current and future observational programs.

These simulations utilize numerical techniques that incorporate a comprehensive set of physical processes, including gravity, hydrodynamics, star formation, BH physics, and magnetic fields. The simulations are executed using powerful supercomputers. TNG is the successor to the original *Illustris* simulation and represents the culmination of several years of collaborative development.

The project consists of three primary simulation runs, each differing in volume and resolution: **TNG50**, **TNG100**, and **TNG300**, corresponding to cubic volumes of approximately 50, 100, and 300 Mpc per side, respectively. These runs enable the study of galaxy formation across a wide dynamic range of environments and mass scales.
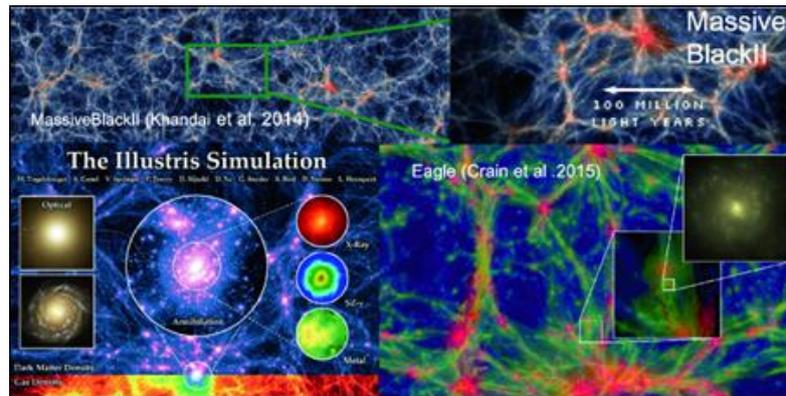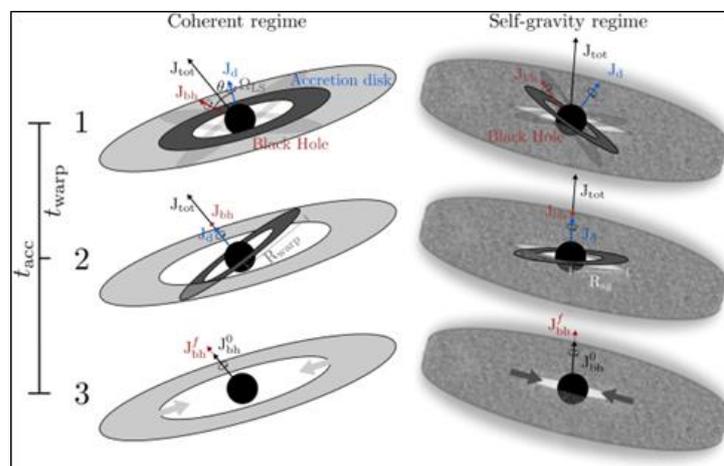
Collage images from a set of simulations able to show the formation of galaxy in a uniform cosmological volume.

Supermassive BH feedback is widely believed to be a primary mechanism responsible for the suppression of star formation—also known as quiescence—in fraction of galaxies, as illustrated in Fig.15. In this study, we examine how relations (depends on observations) between specific star formation rate ($sSFR$), stellar mass (M_{star}), and BH mass (M) are influenced by the physics of BH feedback within the formation model of galaxy.

We employ the *IllustrisTNG* simulation suite[36–38], focusing on the TNG100 along with 10 model variations that modify parameters related to BH feedback. Analyzing central galaxies at redshift $z = 0$ with $M_{star} > 10^{10} \, M_{\odot}$, we find that the $sSFR$ begins to decline sharply when the energy realized from BH driven kinetic winds at low accretion rates exceeds the gravitational binding energy of gas compare to the galaxy stellar radius. This marks a critical M threshold, above which galaxies transition from predominantly star-forming to predominantly quiescent.

As a consequence, the fraction of quiescent galaxies as a function of M_{star} is hugely depends to both the normalization of the M–M_{star} relation and the M threshold for quiescence in the IllustrisTNG framework. Compering these model predictions to observations of 91 central galaxies with dynamically measured BH masses, and used it in IllustrisTNG showing successfully reproduces the observed trend that quiescent galaxies host more massive BHs, the observational data reveal a broader scatter in M at fixed M_{star}, and a smoother decline in $sSFR$ with increasing M_{BH}, as shown in Fig.16.

Schematic illustration of the spin evolution model.

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Hubble Space Telescope (Hubble)

The *Hubble*[39–41] is a large, space based observatory that has significant remarkable in the modern astronomy since its launch and ejected by the Space Shuttle *Discovery* in 1990. Positioned above Earth's atmosphere, far from atmospheric distortions, Hubble offers a clear image of the Universe. Over its more than 30 years of operation, Hubble was used to observe most distant galaxies and stars ever seen, as well as planets in our own solar system.

Hubble's capabilities have significantly expanded over time due to the installation, as these upgrades and the replacement of aging components have greatly extended the telescope's operational lifespan. Hubble is sensitive to a wide range of wavelengths, from the ultraviolet through the visible spectrum and into the near infrared. This wide spectral range has enabled Hubble to deliver breathtaking photos of stars, galaxies, and other cosmic phenomena images that have revolutionized our understanding of the cosmos.

During its mission, Hubble has made more than $1.5 * 10^6$ observations, resulting in over $19 * 10^3$ peer reviewed scientific publications. Its discoveries are featured in every modern astronomy textbook. The telescope has tracked many astronomical events like captured galaxies in the process of merging, investigated supermassive BHs, and looked more

than $13.4 * 10^9$ light-years into the past helping to unravel the history of the expanding Universe.

Astronomers estimate that approximately $1 * 10^8$ BHs reside within the Milky Way[42–44], yet an isolated BH had never been directly identified until recently. After six years of precise monitoring, Hubble provided direct evidence for a solitary BH float through interstellar space, achieved through a highly accurate mass measurement of the otherwise invisible object. Previously, BH masses were inferred either using statistics or through gravitational interactions in binary systems or galactic centers.

This newly detected stellar-mass BH lies roughly $5 * 10^3$ light-years away, in the Carina Sagittarius spiral arm of the Milky Way. Unlike most known BHs, which are found in binary systems, this object is truly isolated. Its discovery suggests that the nearest isolated stellar-mass BH could be as close as 80 light years from Earth relatively nearby, considering that Proxima Centauri, the nearest star, is a little over 4 light-years away.

Isolated BHs originate from rare, massive stars fewer than one in a thousand in the galaxy that are at least $20M_\odot$. When such a star explodes as a supernova, the asymmetry in the blast can impart a kick to the resulting BH, sending it hurtling through space like a cosmic cannonball. Because BHs emit no light, they cannot be imaged directly. However, their gravitational influence can bend and amplify light from background stars a phenomenon known as gravitational microlensing.

Ground-based observatories target the brightness of huge number of stars in the dense fields toward the bulge of Milky Way's located at its center, searching for sudden brightening events caused by massive foreground objects passing between Earth and the star. Hubble is then used to follow up on the most promising candidates. As shown in Fig. 17, the warping of spacetime by a BH causes the light from a background star to momentarily brighten and shift in position, providing a unique method to detect and measure otherwise invisible BHs.
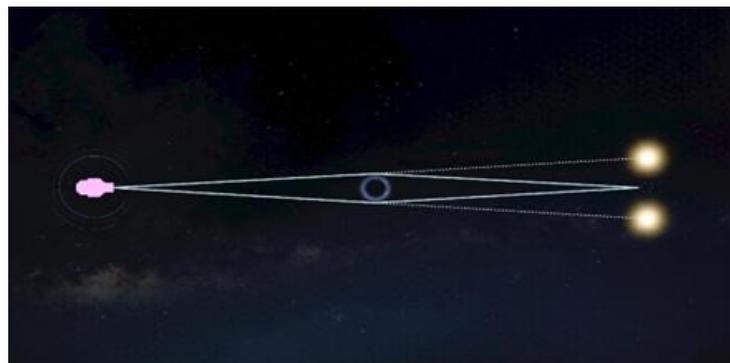
Schematic illustration of gravitational microlensing.

The phenomenon of *gravitational microlensing* is used to study astronomical objects, with approximately $3 * 10^4$ microlensing events observed within our galaxy to date. Among these, the evidence of a forefront BH stands out due to its unique observational characteristics. The extreme gravitational field of a BH stretches the lensing event time significantly often lasting over 200 days much longer than typical stellar lensing events.

Furthermore, if the intermediate object were a forefront star, it would cause a unsettled color shift in the observed star radiation due to blending between the foreground and background stars. However, in the case of the BH event under study, no such color change was observed, further supporting the absence of a luminous lensing object. To confirm this, the Hubble was utilized to precisely measure the deflection of the background of star's position due to the gravitational field of the lensing BH.

Hubble's astrometric capabilities enabled detection of an image displacement on the order of one 10^{-3} arcsecond , this technique, known as *astrometric microlensing*, provided key constraints on the lensing object's distance, mass, and velocity. The deflection amount caused by the BH's warping of spacetime allowed Sahu and his team[45] to estimate a mass

of approximately 7 solar masses for the invisible compact object.

Their analysis concluded that the object's mass lies within the range of 1.6 to $4.4 \, M_\odot$. At the upper end of this interval, the object would clearly be a stellar-mass BH, while at the lower end, it could instead be a neutron star. The measurement was particularly challenging due to the presence of an unrelated bright star located very close angularity to the lensed source.

Stellar mass BHs are studied briefly since 1970; however, all previous mass measurements were limited to systems in which the BH is part of a binary. In such systems, gas from the companion star accretes onto the BH, heating to extreme temperatures and emitting X-rays a key observational signature. This latest detection represents the first dynamical mass measurement of an *isolated*, non-interacting BH using microlensing.
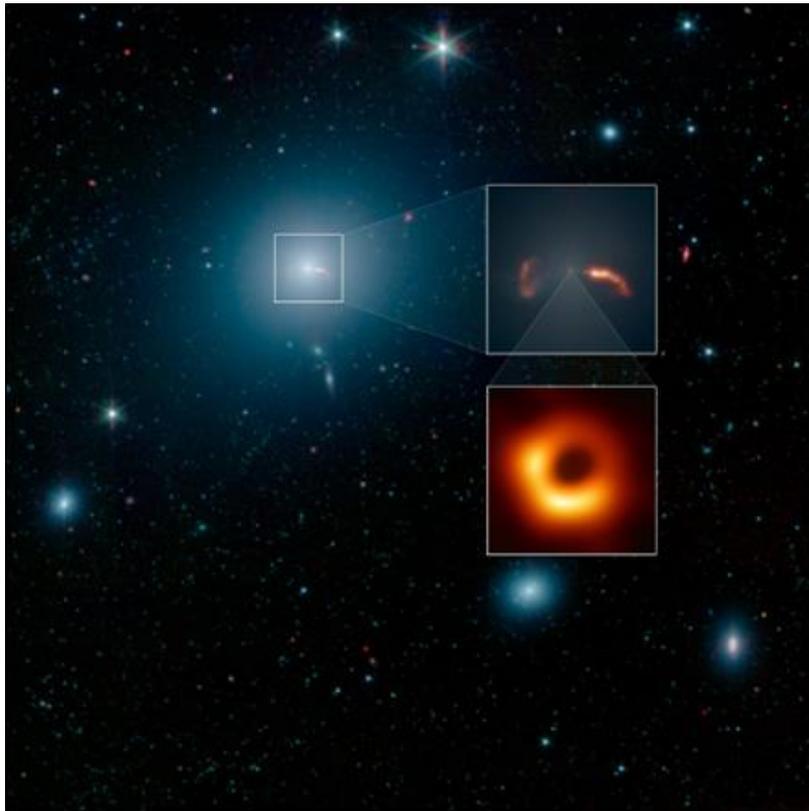
Spitzer Space Telescope Spitzer

Spitzer[46,47] has been unveiled the deepest images yet captured, revealing distant cosmic objects including supermassive BHs that remain hard to be observe in even the most sensitive observations from telescopes working at different wavelengths. Among the newly detected sources, seven are believed to belong to the long explore population of *missing* supermassive BHs, which are hypothesized to have powered the luminous cores of the older active galaxies. These discoveries are illustrated in Fig.18.

Distant Eruption as BH Destroys Star.

The discovery represents a major milestone in the comprehensive identification of X-ray sources[48] detected in one of the most important astronomical surveys ever conducted. This investigative breakthrough relied on the integrated capabilities of NASA's three orbiting Great Observatories the Hubble, Chandra, and the Spitzer[49–51]. Each mission is sensitive to a different region of the electromagnetic spectrum: Chandra observes high energy X-rays, Hubble captures visible light, and Spitzer operates in the infrared. The synergy among these instruments provides a more complete and nuanced picture of the universe than any single observatory could achieve alone, as illustrated in Fig.19.

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Spitzer Space Telescope giving infrared image of galaxy M87*, a magnified look at the galaxy's central regions, and the EH Telescope's enormously zoomed in radio image of the galaxy's central BH.

All three Great Observatories Hubble, Chandra, and Spitzer conducted observations reaching out to distances of up to

$13 * 10^9$ light-years, targeting a small part of the southern celestial hemisphere containing more than $1 * 10^4$ galaxies. This cooperation effort, known as the Great Observatories Origins Deep Survey (GOODS), aimed to study the formation of galaxy and the growth of BHs in the primordial universe. Within this survey, Chandra detected over 200 X-ray sources, most of which are showing a promise to be supermassive BHs located in the centers of juvenile galaxies. These X-rays are produced by hot gas accreting onto the BHs.

Hubble's Advanced Camera for Surveys (ACS) revealed optical counterparts for nearly all of these X-ray sources, identifying the host galaxies around the BHs. However, seven X-ray sources remained mysterious, with no optical galaxies detected. Several hypotheses were proposed to explain these "missing" hosts: they could be enshrouded by dense dust clouds that obscure all optical light, composed of very old and red stellar populations, or potentially represent some

of the most distant BHs ever discovered possibly as far as $13 * 10^9$ light-years. In the latter case, the optical light from these galaxies would have been redshifted into the far-infrared range due to cosmic expansion.

To resolve this mystery, astronomers turned to Spitzer, which work in infrared band that up to 100 times longer than those of Hubble. The first infrared images from Spitzer[46,47] revealed the characteristic infrared brightness from host galaxies associated with all seven previously undetected X-ray BHs (see Fig.18). This marked the first time all galaxies surrounding *Chandra*-detected BHs in the GOODS field had been successfully identified.

Among the sources identified by Koekemoer and collaborators, three galaxies exhibited extremely red colors, indicative of high infrared brightness. Data from Spitzer, combined with shorter wavelength infrared observations from the Very Large Telescope (VLT) at the European Southern Observatory, suggest that these galaxies may be heavily dust obscured and possibly much far than other known dusty galaxies. Intriguingly, some of the other objects show very different infrared colors, suggesting diverse origins or evolutionary stages.

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In a related study using the same Spitzer dataset, researchers focused on a subsection of the GOODS field that had also aimed to target the most deepest images in optical range known as Hubble Ultra Deep Field. These images, obtained using

Hubble's ACS and Near Infrared Camera and Multi-Object Spectrometer (NICMOS), reach sensitivies more than 5 times softer than the original GOODS survey. Yet, even at these extraordinary depths, two of the 17 Spitzer selected galaxies remained completely undetected in optical range, while the others were only faintly visible. This finding underscores the power of infrared observations to unveil ancient and dust-enshrouded galaxies that optical telescopes cannot detect.

Fermi γ ray Space Telescope

The Universe hosts a wealth of exotic and awe-inspiring phenomena capable of producing energy at nearly unimaginable scales. Among these are supermassive BHs, colliding neutron stars, and relativistic jets of hot gas all of which are sources

of γ-ray radiation, the highest energetic form of electromagnetic radiation, with energies $1 * 10^9$ of times higher than those of visible light. These phenomena raise fundamental questions: What physical mechanisms are responsible for such extreme energy outputs? How do these events impact their surrounding cosmic environments? And how can studying these high energy processes deepen our understanding of the Universe's behavior and structure?

The Fermi γ-ray Space Telescope[52–54], formerly known as the *γ-ray Large Area Space Telescope* (GLAST), is designed to explore this high energy frontier. With its advanced instrumentation, Fermi enables astronomers to investigate how BHs typically associated with accreting matter can also launch jets of particles at relativistic speeds. In parallel, physicists are utilizing Fermi's observations to probe subatomic particles at energy levels far exceeding those attainable in terrestrial particle accelerators. Moreover, cosmologists are harnessing data from Fermi to understand the conditions of the early Universe and its evolutionary history. In doing so, the mission is significantly enhancing our understanding of high energy astrophysics and the cosmos at large.


GWs from Monster BHs.

Our universe can be represent as a chaotic sea of GW, as shown in Fig 20. The Fermi, provides crucial indirect constraints on the GW background. Pulsars, the rapidly rotating remnants of massive stars, act as highly stable cosmic clocks. Any passage of a GW between a pulsar and Earth would perturb spacetime along the line of sight, leading to minuscule advances or delays in the arrival times of pulses. By precisely monitoring these times of arrival over many years,

correlated deviations across multiple pulsars can be used to identify a GW signal. The Fermi detects γ rays from pulsars, which are less susceptible to dispersion and scattering by the interstellar medium than radio waves, yielding cleaner timing measurements. An international team[55,56] examined over a decade of Fermi pulsar data for such timing variations, which would be expected if long wavelength GWs from orbiting supermassive black hole binaries were present. Although no such signal was detected, the results place stringent upper limits on the GW amplitude in the probed frequency range.

LOFAR space survey

The design of the LOw Frequency ARray (LOFAR) endows it with exceptional capabilities as a survey instrument. Its individual dipole antennas are inherently sensitive to a wide part of the visible sky, and the dipole arrays collectively offer

an extraordinarily wide field of view covering hundreds of square degrees particularly at the lowest frequencies accessible to LOFAR. As a result, LOFAR is well suited for large-scale sky surveys. The telescope has already completed, or is actively conducting, several major survey programs, including the Multifrequency Snapshot Sky Survey (MSSS)[57], the LOFAR Two metre Sky Survey (LoTSS) wide-area and deep-field campaigns[58], the LOFAR LBA Sky Survey (LoLSS)[59], and the ongoing WEAVE LOFAR spectroscopic follow-up survey[59].
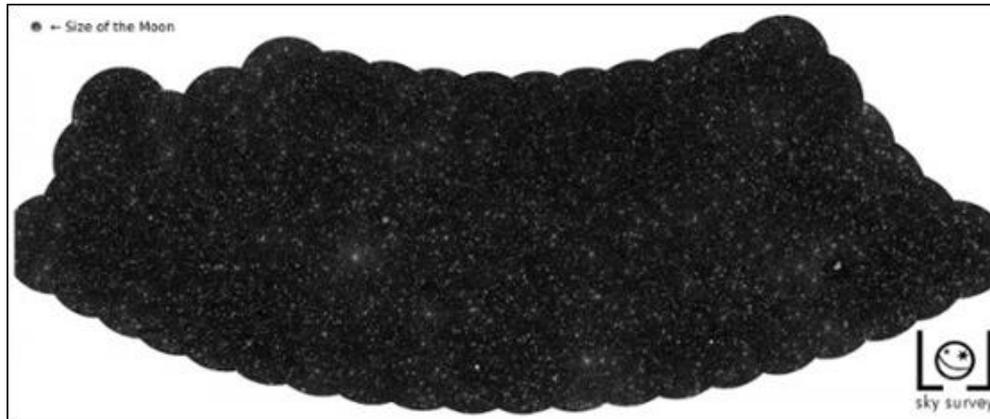

25,000 supermassive BHs. as white dot is showing supermassive BH in its own galaxy.

The LOFAR space survey has produced a captivating new image of the sky, revealing what appears to be a field of white dots scattered across a dark background. However, these dots are not stars, suns, or moons; rather, they represent supermassive BHs emitting radio waves from the centers of distant galaxies, as illustrated in Fig.21. The objective of this survey is to construct a comprehensive "BH map" of the universe, charting the distribution of these enigmatic and powerful objects across cosmic space. This image underscores the vast and largely unexplored population of BHs that populate the distant universe.

MeerKAT radio telescope

The MeerKAT radio telescope[60,61] consists of an array of 64 interconnected receptors. Each receptor comprises the complete antenna system, including the main reflector, sub-reflector, and all associated receivers, digitizers, and supporting electronics. The spatial configuration of these receptors is optimized according to the scientific goals of the observatory. A total of 48 receptors are densely clustered within a central core region approximately 1 km in diameter. The array's maximum baseline the greatest separation between any two receptors extends to 8 km, providing high angular resolution necessary for detailed imaging of astronomical radio sources.
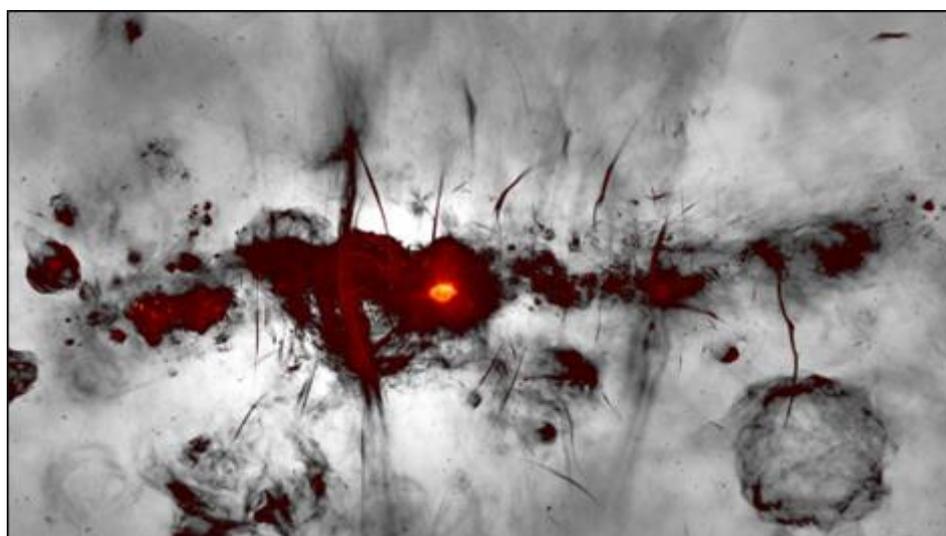
MeerKAT radio telescope image.

The South African Radio Astronomy Observatory (SARAO) released a new MeerKAT telescope image of the center of our Galaxy[62,63], revealing radio emission from this region with a novel clarity and depth, as shown in Fig.22. The image captures a wealth of radio emitting phenomena, including eruptive stars, star-forming regions, and the turbulent

environment surrounding the supermassive BH estimated to contain $4 * 10^6 M_\odot$ located approximately $25 * 10^3$ light-years from Earth at the Galactic center. Unlike optical and infrared observations, which are hindered by intervening dust, radio waves penetrate this obscuration, allowing MeerKAT to uncover structures that would otherwise remain hidden. Thanks to its innovative design, high sensitivity, and advantageous geographic location, MeerKAT has succeeded in producing this remarkable image. The data reveal new supernova leftovers expanding shells of gas and dust left behind by the explosive deaths of massive stars including a rare, nearly perfect spherical example. Additionally, the image provides the most detailed view to date of the enigmatic radio filaments, linear features unique to the Galactic center whose origins remain a subject of active investigation.

III. DIRECT OBSERVATIONS OF BH

Direct Observations of BHs refer to evidence collected by astronomers that reveals the presence or properties of BHs through measurements that are as close as possible to "seeing" the BH or its immediate environment. Observations try to detect GWs and imaging the EH of BH will give direct evidence of BH and characterization of its properties.

Characterization of GWs from BHs

GWs are ripples in the fabric of spacetime predicted by Einstein's GR[7,8,64–66]. They provide a direct observational window into the dynamics of compact astrophysical objects, such as BHs. The detection of GWs from binary BH mergers by LIGO and Virgo has opened a new era in astrophysics and gravitation, allowing the study of strong field gravity in a previously inaccessible regime. The study of GWs not only enhances our understanding of astrophysical BHs but also provides a testing ground for fundamental questions in gravitation, quantum information, and spacetime structure. As detectors improve in sensitivity, they may offer critical insights into the interplay between classical and quantum descriptions of BHs.

In the case of BH binaries, gravitational radiation is emitted as the system evolves through three stages:

1. **Inspiral**: Two BHs orbit each other and gradually lose energy through GW emission.

2. **Merger**: The BHs coalesce into a single, highly distorted BH.

3. **Ringdown**: The final BH settles into a stationary Kerr state, emitting quasinormal mode (QNM) radiation.

Each stage produces a distinct GW signature that encodes information about the system:

- **Masses and spins** of the initial BHs.

- **Final mass and spin** of the remnant BH.

- Possible evidence for deviations from classical GR.

Measuring QNMs allows for:

- Testing the no hair theorem.

- Constraining alternative theories of gravity.

- Probing the structure of spacetime near the EH.

Gravitational wave observations can potentially shed light on the BH information paradox. For instance:

- Deviations from expected QNM patterns could signal new physics or information recovery mechanisms.

- Quantum corrections near the horizon may lead to *gravitational wave echoes*, delayed secondary pulses after the main ringdown.

- Precise measurements of merger and ringdown phases can constrain the nature of the BH interior and horizon structure.

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GW Observational Observations for BHs

The direct detection of GWs has inaugurated a new era in BH astrophysics[67–69], allowing for the observation of phenomena previously hidden from electromagnetic telescopes. A number of ground based and space based observatories have played, and will continue to play, a crucial role in detecting and analyzing the GWs emitted by BH systems. Gravitational wave astronomy has become an indispensable tool in BH physics. The synergy between current and future observational missions will not only deepen our understanding of BH populations and evolution but also provide novel insights into the fundamental nature of gravity, quantum information, and spacetime.
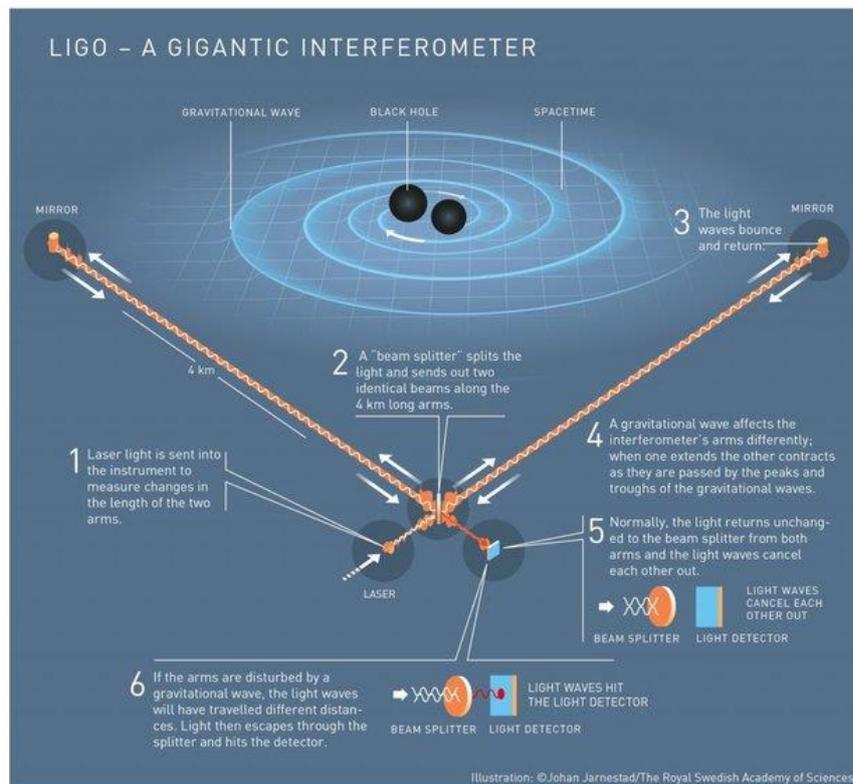
GWs of BH observation[70].

LIGO is the first observatory to directly detect GWs. It consists of two detectors located in the United States:

• LIGO Hanford Observatory in Washington.

• LIGO Livingston Observatory in Louisiana.

In 2015, LIGO made the historic first detection of GWs (GW150914), originating from the merger of two stellar mass

BHs. LIGO operates in the frequency range $\sim 10\,\mathrm{Hz}\,1\,\mathrm{kHz}$, which is optimal for detecting binary mergers involving stellar mass BHs and neutron stars.

Virgo Interferometer

Located in Italy, Virgo is a European gravitational wave detector that collaborates with LIGO. Joint observations by LIGO and Virgo have allowed for:

• Improved source localization on the sky.

• Better parameter estimation for BH and neutron star mergers.

• Increased detection confidence.

KAGRA is an underground gravitational wave observatory in Japan. It is the first GW detector to incorporate cryogenically cooled mirrors, reducing thermal noise. Its inclusion enhances the global detector network (LIGO–Virgo–KAGRA), increasing sensitivity and sky coverage.

LISA is a planned space based gravitational wave observatory developed by ESA and NASA. Scheduled for launch in the 2030s, LISA will detect low frequency GWs in the range of $\sim 10^4\,Hz\,1\,Hz$, making it particularly suited for observing:

- Mergers of supermassive BHs.

- Extreme mass ratio inspirals (EMRIs).

- Galactic binary systems.

LISA will open a new observational window on BH dynamics in the early universe and test GR in strong field regimes over long timescales.

The Einstein Telescope and Cosmic Explorer are proposed next generation ground based detectors that will greatly extend the sensitivity and frequency range of current observatories. Key goals include detecting BH mergers at cosmological distances ($z > 10$), exploring the formation and growth of primordial BHs and, providing detailed tests of the BH no hair theorem and quantum gravity signatures.

Gravitational wave observatories contribute to resolving the BH information paradox by enabling precise measurement of BH parameters and dynamic, searching for anomalies in ringdown signals or gravitational wave *echoes* possible signatures of new physics beyond GR and, constraining models of quantum gravity and spacetime structure near the horizon.

Physics of the BH EH

The EH of a BH is a critical surface in spacetime beyond which no causal signals or information can escape to an external observer. It marks the boundary between regions of spacetime that are causally disconnected from future null infinity. Understanding the physics of the EH is essential to grasp the foundational aspects of BH thermodynamics, quantum information, and the information paradox. The EH is more than a geometric boundary it is a physical and thermodynamic surface that encapsulates many of the conceptual challenges at the intersection of GR, quantum theory, and information science. Any resolution of the BH information paradox must grapple with the detailed physics of the EH and its quantum structure.

Geometric Definition

The EH is a *null hypersurface* defined globally as the boundary of the causal past of future null infinity, $\mathcal{J}^+$. Unlike an apparent horizon, the EH is a global feature of the spacetime manifold and depends on its entire causal structure.

Characterization of the BH EH

The EH of a BH is one of its most defining features. It represents a boundary in spacetime separating regions where escape to infinity is possible from those where it is not[8,65,66,71]. The characterization of the EH involves both local and global geometrical, causal, and thermodynamic aspects. The characterization of the EH unites several fundamental ideas in geometry, causality, and thermodynamics. It serves not only as a mathematical boundary but also as a physical surface that encodes profound insights about gravity and quantum information. A complete understanding of BH physics must include both classical properties of the horizon and their quantum modifications.

BH EH observations missions

The EH Telescope (EHT) captures light from a BH using a limited number of telescopes positioned across the globe[72–74]. After collecting this data, scientists must still construct an image a process known as imaging. The light gathered offers partial insights into the BH's structure, but because it comes from only a few locations, significant portions of the image remain missing. To address this, specialized imaging algorithms are used to fill in the gaps and reconstruct a complete picture.
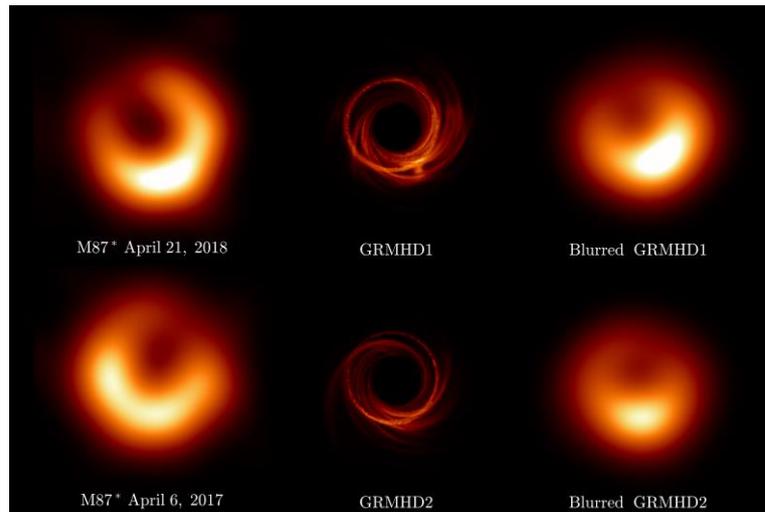
BH EH of $M87^*$ in 2017 and 2018.

Given the extent of the missing data, one might wonder how an image can be formed at all. To understand this, imagine the data collected by the EHT as musical notes in a song. Each pair of telescopes produces a measurement similar to a single musical tone. The pitch of that tone depends on the distance between the telescopes as seen from the BH's direction the greater the distance, the higher the pitch. By combining these tones, or measurements, and using advanced algorithms, scientists can piece together an image, much like reconstructing a melody from a few notes.

IV. COMPARISON BETWEEN DIFFERENT TYPES OF BH OBSERVATIONS

BHs have been studied through various observational channels, each providing unique insights into their physical properties and behavior. The following table summarizes the main types of observations, associated instruments, the physical quantities they measure, and their relevance to the BH information paradox.

Key Results from Major BH Observational Missions

- **Observation Type: GWs**
  - **Mission / Instrument:** LIGO Virgo (GW150914)
  - **Key Measurement:** Binary BH merger: initial masses, spin, final mass
  - **Notable Result:** $m_1 = 35.6\,M_\odot$, $m_2 = 30.6\,M_\odot$, final mass $= 63.1\,M_\odot$, spin $a \approx 0.69$

- **Observation Type: EH Imaging**
  - **Mission / Instrument:** EHT 2019 (M87)
  - **Key Measurement:** Shadow diameter, BH mass
  - **Notable Result:** Angular diameter $= 42 \pm 3\,\mu\text{as}$, mass $= (6.5 \pm 0.7) \times 10^9\,M_\odot$

- **Observation Type: Stellar Motion Tracking**
  - **Mission / Instrument:** GRAVITY @ VLT (S2 orbit / Sgr A^*)
  - **Key Measurement:** Schwarzschild precession of orbit
  - **Notable Result:** Precession $\approx 12.1'$ per orbit, mass of Sgr $A^* = 4.1 \times 10^6\,M_\odot$

- **Observation Type: X ray Spectroscopy**
  - **Mission / Instrument:** Chandra / NuSTAR
  - **Key Measurement:** Broad iron $K\alpha$ line profiles
  - **Notable Result:** Detected relativistic broadening near ISCO, spin estimates typically $a > 0.9$ for some AGNs

REFERENCES

[1] Penrose, R. & Floyd, R. M. Extraction of rotational energy from a black hole. *Nature Physical Science* **229**, 177–179 (1971).

[2] Blandford, R. D. & Znajek, R. L. Electromagnetic extraction of energy from kerr black holes. Monthly Notices of the Royal Astronomical Society 179, 433–456 (1977).

[3] Frolov, V. P. & Zelnikov, A. Introduction to Black Hole Physics. (OUP Oxford, 2011).

[4] Penrose, R. & Floyd, R. M. Extraction of rotational energy from a black hole. *Nature Physical Science* **229**, 177–179 (1971).

[5] Williams, R. K. Extracting x rays, γ rays, and relativistic e- e+ pairs from supermassive kerr black holes using the penrose mechanism. *Physical Review D* **51**, 5387 (1995).

[6] Hawking, S. W. Black hole explosions? *Nature* **248**, 30–31 (1974).

[7] DeWitt, B. Quantum gravity: The new synthesis in general relativity, edited by SW hawking and w. *Israel, CUP, Cambridge* (1979).

[8] Einstein, A. & Rosen, N. On gravitational waves. *Journal of the Franklin Institute* **223**, 43–54 (1937).

[9] Schutz, B. *A First Course in General Relativity*. 186 (Cambridge university press, 2022).

[10] Matthews, J. H., Bell, A. R. & Blundell, K. M. Particle acceleration in astrophysical jets. *New Astronomy Reviews* **89**, 101543 (2020).

[11] Fanaroff, B. L. & Riley, J. M. The morphology of extragalactic radio sources of high and low luminosity. *Monthly Notices of the Royal Astronomical Society* **167**, 31P–36P (1974).

[12] Ghisellini, G., Tavecchio, F., Maraschi, L., Celotti, A. & Sbarrato, T. The power of relativistic jets is larger than the luminosity of their accretion disks. *Nature* **515**, 376–378 (2014).

[13] Nokhrina, E. E. The correlation between the total magnetic flux and the total jet power. *Frontiers in Astronomy and Space Sciences* **4**, 63 (2017).

[14] Boella, G. *et al.* BeppoSAX, the wide band mission for x-ray astronomy. *Astronomy and Astrophysics Supplement Series* **122**, 299–307 (1997).

[15] Frontera, F. *et al.* Spectral and temporal behavior of the black hole candidate XTE J1118+ 480 as observed with BeppoSAX. *The Astrophysical Journal* **592**, 1110 (2003).

[16] Frontera, F. The key role of BeppoSAX in the GRB history. *Rendiconti Lincei. Scienze Fisiche e Naturali* **30**, 171–184 (2019).

[17] Frontera, F. *et al.* Observations of new black hole candidates with BeppoSAX. in *Exploring the gamma-ray universe* vol. 459 187–190 (2001).

[18] Lutz, D. *et al.* The LABOCA survey of the extended chandra deep field south: Two modes of star formation in active galactic nucleus hosts? *The Astrophysical Journal* **712**, 1287 (2010).

[19] Morgan, E., Remillard, R. & Greiner, J. RXTE observations of QPOs in the black hole candidate GRS 1915+ 105. *The Astrophysical Journal* **482**, 993 (1997).

[20] Sobczak, G. J. *et al.* Complete RXTE spectral observations of the BlackHole x-ray nova XTE J1550–564. *The Astrophysical Journal* **544**, 993 (2000).

[21] Wilms, J., Nowak, M. A., Dove, J. B., Fender, R. P. & Di Matteo, T. Low-luminosity states of the black hole candidate GX 339–4. I. ASCA and simultaneous radio/RXTE observations. *The Astrophysical Journal* **522**, 460 (1999).

[22] Miller, J. M. *et al.* Evidence of black hole spin in GX 339–4: XMM-newton/EPIC-pn and RXTE spectroscopy of the very high state. *The Astrophysical Journal* **606**, L131 (2004).

[23] Cui, W., Zhang, S. & Chen, W. Evidence for frame-dragging around spinning black holes in x-ray binaries. *The Astrophysical Journal* **492**, L53 (1997).

[24] Morsink, S. M. & Stella, L. Relativistic precession around rotating neutron stars: Effects due to frame dragging and stellar oblateness. *The Astrophysical Journal* **513**, 827 (1999).

[25] Weisskopf, M. C., Tananbaum, H. D., Van Speybroeck, L. P. & O'Dell, S. L. Chandra x-ray observatory (CXO): overview. *X-ray optics, instruments, and missions iii* **4012**, 2–16 (2000).

[26] Weisskopf, M. *et al.* An overview of the performance and scientific results from the chandra x-ray observatory. *Publications of the Astronomical Society of the Pacific* **114**, 1 (2002).

[27] Baganoff, F. K. *et al.* Chandra x-ray spectroscopic imaging of sagittarius a* and the central parsec of the galaxy. *The Astrophysical Journal* **591**, 891 (2003).

[28] Marrone, D. *et al.* An x-ray, infrared, and submillimeter flare of sagittarius a. *The Astrophysical Journal* **682**, 373 (2008).

[29] Ponti, G. *et al.* Fifteen years of XMM–newton and chandra monitoring of sgr A^*: Evidence for a recent increase in the bright flaring rate. *Monthly Notices of the Royal Astronomical Society* **454**, 1525–1544 (2015).

[30] Connor, T. *et al.* Enhanced x-ray emission from the most radio-powerful quasar in the universe's first billion years. *The Astrophysical Journal* **911**, 120 (2021).

[31] Wang, F. *et al.* Revealing the accretion physics of supermassive black holes at redshift z 7 with chandra and infrared observations. *The Astrophysical Journal* **908**, 53 (2021).

[32] Nelson, J. E., Mast, T. S. & Faber, S. M. The design of the keck observatory and telescope. *Keck observatory report* **90**, 1–44 (1985).

[33] Wizinowich, P. L. *et al.* The WM keck observatory laser guide star adaptive optics system: overview. *Publications of the Astronomical Society of the Pacific* **118**, 297 (2006).

[34] Nelson, J. E. & Gillingham, P. R. Overview of the performance of the WM keck observatory. *Advanced Technology Optical Telescopes V* **2199**, 82–93 (1994).

[35] Do, T. *et al.* Unprecedented near-infrared brightness and variability of sgr a. *The Astrophysical Journal Letters* **882**, L27 (2019).

[36] Yang, J., Wang, F., Fan, X., *et al.* A luminous z= 7.5 quasar hosting a 1.5 billion solar mass black hole. *arXiv preprint arXiv:2006.13452* (2020).

[37] Terrazas, B. A. *et al.* The relationship between black hole mass and galaxy properties: Examining the black hole feedback model in IllustrisTNG. *Monthly Notices of the Royal Astronomical Society* **493**, 1888–1906 (2020).

[38] Weinberger, R. *et al.* Supermassive black holes and their feedback effects in the IllustrisTNG simulation. *Monthly Notices of the Royal Astronomical Society* **479**, 4056–4072 (2018).

[39] Zinger, E. *et al.* Ejective and preventative: The IllustrisTNG black hole feedback and its effects on the thermodynamics of the gas within and around galaxies. *Monthly Notices of the Royal Astronomical Society* **499**, 768–792 (2020).

[40] Ford, H. C. *et al.* Advanced camera for the hubble space telescope. in *Space telescopes and instruments v* vol. 3356 234–248 (SPIE, 1998).

[41] Koekemoer, A. M. *et al.* The cosmos survey: Hubble space telescope advanced camera for surveys observations and data processing. *The Astrophysical Journal Supplement Series* **172**, 196 (2007).

[42] Scoville, N. *et al.* COSMOS: Hubble space telescope observations. *The Astrophysical Journal Supplement Series* **172**, 38 (2007).

[43] Andrews, J. J. & Kalogera, V. Constraining black hole natal kicks with astrometric microlensing. *The Astrophysical Journal* **930**, 159 (2022).

[44] Lam, C. Y. *et al.* An isolated mass-gap black hole or neutron star detected with astrometric microlensing. *The Astrophysical Journal Letters* **933**, L23 (2022).

[45] Sahu, K. C. *et al.* An isolated stellar-mass black hole detected through astrometric microlensing. *The Astrophysical Journal* **933**, 83 (2022).

[46] Dominik, M. & Sahu, K. C. Astrometric microlensing of stars. *The Astrophysical Journal* **534**, 213 (2000).

[47] Martínez-Sansigre, A. *et al.* The obscuration by dust of most of the growth of supermassive black holes. *Nature* **436**, 666–669 (2005).

[48] Rosario, D. J. *et al.* An accreting supermassive black hole irradiating molecular gas in NGC 2110. *The Astrophysical Journal Letters* **875**, L8 (2019).

[49] Gelino, D. M., Gelino, C. R. & Harrison, T. E. Spitzer observations of black hole low-mass x-ray binaries: Assessing the non-stellar infrared component. *The Astrophysical Journal* **718**, 1 (2010).

[50] Lacy, M. *et al.* Obscured and unobscured active galactic nuclei in the spitzer space telescope first look survey. *The Astrophysical Journal Supplement Series* **154**, 166 (2004).

[51] Rieke, G. H. *The Last of the Great Observatories: Spitzer and the Era of Faster, Better, Cheaper at NASA*. (University of Arizona Press, 2006).

[52] Wilson, R. Spitzer space telescope: An operational learning experience. in *SpaceOps 2008 conference* 3389 (2008).

[53] Atwood, W. *et al.* The large area telescope on the fermi gamma-ray space telescope mission. *The Astrophysical Journal* **697**, 1071 (2009).

[54] Michelson, P. F., Atwood, W. B. & Ritz, S. Fermi gamma-ray space telescope: High-energy results from the first year. *Reports on Progress in Physics* **73**, 074901 (2010).

[55] McEnery, J. E., Michelson, P. F., Paciesas, W. S. & Ritz, S. Fermi gamma-ray space telescope. *Optical Engineering* **51**, 011012–011012 (2012).

[56] Bailes, M. *et al.* Gravitational-wave physics and astronomy in the 2020s and 2030s. *Nature Reviews Physics* **3**, 344–366 (2021).

[57] Domcke, V. & Garcia-Cely, C. Potential of radio telescopes as high-frequency gravitational wave detectors. *Physical review letters* **126**, 021104 (2021).

[58] Heald, G. *et al.* The LOFAR multifrequency snapshot sky survey (MSSS)-i. Survey description and first results. *Astronomy & astrophysics* **582**, A123 (2015).

[59] Shimwell, T. *et al.* The LOFAR two-metre sky survey-i. Survey description and preliminary data release. *Astronomy & Astrophysics* **598**, A104 (2017).

[60] Gasperin, F. de *et al.* The LOFAR LBA sky survey-i. Survey description and preliminary data release. *Astronomy & Astrophysics* **648**, A104 (2021).

[61] Booth, R. & Jonas, J. An overview of the MeerKAT project. *African Skies, Vol. 16, p. 101* **16**, 101 (2012).

[62] Jonas, J. & Team, M. The MeerKAT radio telescope. *MeerKAT science: on the pathway to the SKA* 1 (2016).

[63] Heywood, I. *et al.* The 1.28 GHz MeerKAT galactic center mosaic. *The Astrophysical Journal* **925**, 165 (2022).

[64] Yusef-Zadeh, F. *et al.* Statistical properties of the population of the galactic center filaments: The spectral index and equipartition magnetic field. *The Astrophysical Journal Letters* **925**, L18 (2022).

[65] Eddington, A. S. The propagation of gravitational waves. *Proceedings of the Royal Society of London. Series A, Containing Papers of a Mathematical and Physical Character* **102**, 268–282 (1922).

[66] Hartle, J. B. *Gravity: An Introduction to Einstein's General Relativity*. (Cambridge University Press, 2021).

[67] Papapetrou, A. *Lectures on General Relativity*. 134–135 (Springer Science & Business Media, 2012).

[68] Abbott, B. P. *et al.* Observation of gravitational waves from a binary black hole merger. *Physical review letters* **116**, 061102 (2016).

[69] Raidal, M., Vaskonen, V. & Veermäe, H. Gravitational waves from primordial black hole mergers. *Journal of Cosmology and Astroparticle Physics* **2017**, 037 (2017).

[70] Nitz, A. H. & Wang, Y.-F. Search for gravitational waves from high-mass-ratio compact-binary mergers of stellar mass and subsolar mass black holes. *Physical Review Letters* **126**, 021103 (2021).

[71] Martin-Delgado, M. A. The new SI and the fundamental constants of nature. *European Journal of Physics* **41**, 063003 (2020).

[72] Hawking, S. W. Black holes in general relativity. *Communications in Mathematical Physics* **25**, 152–166 (1972).

[73] Broderick, A. E., Loeb, A. & Narayan, R. The event horizon of sagittarius a. *The Astrophysical Journal* **701**, 1357 (2009).

[74] Akiyama, K. *et al.* First M87 event horizon telescope results. IV. Imaging the central supermassive black hole. *The Astrophysical Journal Letters* **875**, L4 (2019).

[75] Collaboration, E. H. T. *et al.* First M87 event horizon telescope results. I. The shadow of the supermassive black hole. *arXiv preprint arXiv:1906.11238* (2019).