Chapter 10

Active Galactic Nuclei (AGN)

CO §28

Every sufficiently massive galaxy is thought to harbour a super massive black hole (SMBH, BH for black hole) in its centre. Evidence for the presence of an SMBH with mass $M_{\rm BH} \approx 4 \times 10^6 {\rm M}_\odot$ at the centre of the Milky Way galaxy, from the motion of stars in the vicinity of the BH, is especially convincing, as is the recent detection of an SMBH with mass $M_{\rm BH} \approx 6.4 \times 10^9 {\rm M}_\odot$ in the centre of galaxy M87, though the detection of its 'shadow'. The origin of these SMBHs is presently unclear. However, they can grow in mass by mergers with other SMBHs (during a galaxy-galaxy merger) or through accretion of gas through an *accretion disc*. Energetic phenomena in and around the accretion disc turn SMBHs into the most luminous objects in the Universe, displaying a rather baffling variety of phenomena from extremely luminous radio sources to optically luminous quasars. The generic name for an accreting SMBH that emits copious radiation is 'Active Galactic Nucleus'- or AGN for short. It is becoming clear that such AGN can dramatically affect their host galaxy, suppressing or indeed preventing star formation.

10.1 Discovery

Radio waves from outside the solar system were first detected by Jansky in 1933, who also correctly identified the physical process that generates them - synchrotron radiation[1] - yet the source of the emission was unknown. Following-up from this, Hey et al., 1946 reported strong radio-emission emanating from the direction of Cygnus - later identified as coming from the AGN now called 'Cygnus A'. Synchrotron spectra are power-laws therefore there is little information in the spectrum about the nature of the source. A more systematic investigation of what caused this radiation was made possible by the 'third Cambridge all-sky radio-survey' (3C) published by Edge et al., 1959 and refined by Bennett 1962 . Identifying optical counterparts (*i.e.* optical sources at the exact same position in the sky as the radio source) allowed detailed study of the sources of radio emission, heralding the era of AGN studies.

10.2 Observational manifestations of AGN

Although originally discovered by their radio-emission, AGN display a baffling variety of observational manifestations. For some AGN, light is detected from the radio over IR and optical-UV to X-rays to gamma rays. It is thought that this light is produced by gas accreting onto the SMBH through an accretion disc, but many details remain to be understood.

Figure 10.1 shows two famous examples. The top left panel is a radio image taken by the VLA of Cygnus-A. Notice the two very extended radio-lobes, and the thin 'jet' of emission that connects them to the bright source in the centre. The bright source is the central BH, located at the centre of a galaxy (which you can't see in this radio image). Notice also the shear scale of the lobes, with the image extending over 150 kpc, 5 times the diameter of the MW's disc.

The top right panel shows the quasar 3C273, indicated by an arrow. At a distance of 740 Mpc, this quasar appears almost equally bright as the MW foreground star next to it, even though this solar luminosity star is much closer, at a distance of ~ 0.5 kpc - implying the luminosity of 3C272 is $\sim 2 \times 10^{12} L_\odot$ - or about 100 times the luminosity of the MW. The most luminous quasar currently known has $L \sim 4 \times 10^{14} L_\odot$ - or 10^4 times as bright as the MW!

The bottom left panel is a deep X-ray image taken by the Chandra telescope. Visible in this image are two clusters of galaxies detected in X-rays

[1]The radiation emitted by electrons on helical trajectories when moving through a magnetic field.

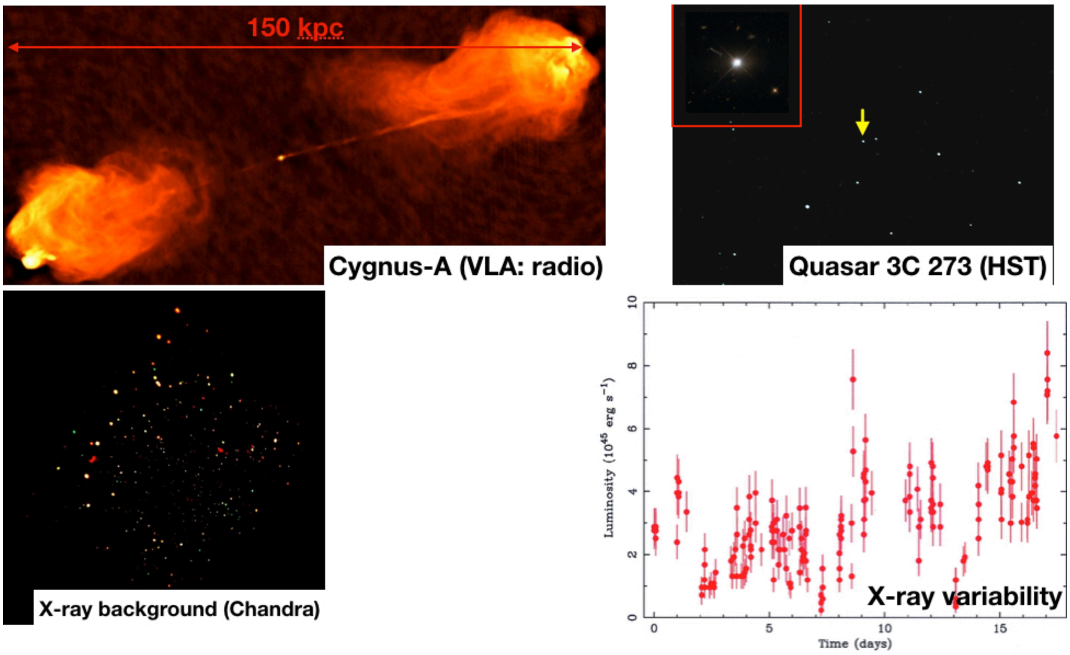

Figure 10.1: Manifestations of AGN and cartoon of the central engine. *Top left panel:* Cygnus A, the brightest radio source in the sky located outside our galaxy, as imaged with the *Very Large Array*. *Top right panel* (main panel): the optical AGN, quasar 3 C273, does not look very impressive in this optical image, until you realise that the distance to 3C273 is about750 Mpc, yet it appears approximately equally bright as the MW foreground star next to it. Assuming this star has the luminosity of the Sun and is at a distance of 1/2 kpc the shows that 3C273 has a luminosity of about $4 \times 10^{12} L_\odot$ or ~ 100 times the total luminosity of the MW. The inset in red shows an HST image of 3C273. *Bottom left panel*: The *Chandra deep field* X-ray image of the sky. The two red objects are clusters of galaxies, all others are AGN that are emitting hard X-rays. *Bottom right panel:* Time variation of the X-ray luminosity of AGN PHL1092, from Brandt '99.

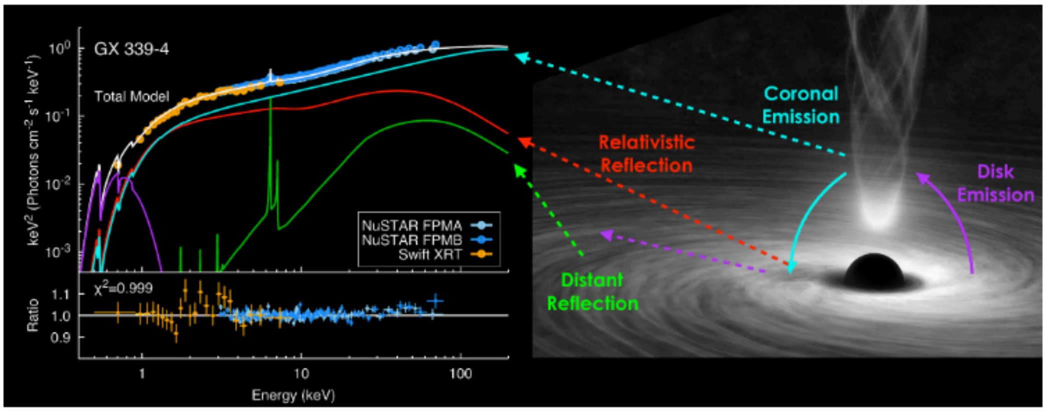

Figure 1: (*left:*) The *Swift* and *NuSTAR* spectrum of the BHXB GX 339−4 during its 2017 outburst, fitted with a Compton continuum (blue); relativistic reflection (red); distant reflection (green); and thermal disk emission (violet). The lower panel shows the fit residuals (García et al. in prep.) (*right:*) Schematic representation for the origin of the spectral components in an accreting black hole. The disk's thermal emission (violet) is Compton scattered into a power-law (blue) by electrons in a hot and compact corona. A fraction of this component illuminates the disk thereby generating the relativistic reflection component (red arrows), as well as a distant reflection component (green). These models are commonly used to constrain the black hole spin, among other important parameters. Adapted from original artwork by NASA/JPL-Caltech/R. Hurt (IPAC).

Figure 10.2: Taken from Garcia '19

(the two reddish objects), and hundreds of unresolved X-ray sources: these are AGN emitting X-ray. The bottom right panel shows that the X-ray luminosity of AGN PHL1092 is **highly variable** in time, with order of unity variations in luminosity occurring over time scales of order of hours or less.

10.3 Central engine of AGN

The rapid variability detected in the X-rays is in fact very surprising. Indeed, it implies that *the size of the AGN engine is of order of light hours*[2]. This argument is based on *causality:* an object that varies on a time-scale t must have an extent smaller than $\sim ct$ - if not, the time-variation would be smoothed out over time and hence smaller in amplitude. The order unity variation in the X-rays on time-scale of $\sim$ hours therefore implies that the engine is of order of light hours - or smaller. How can an object be so small

[2]For comparison, light takes ≈ 1.3 light hours to cover the distance Sun-Saturn.

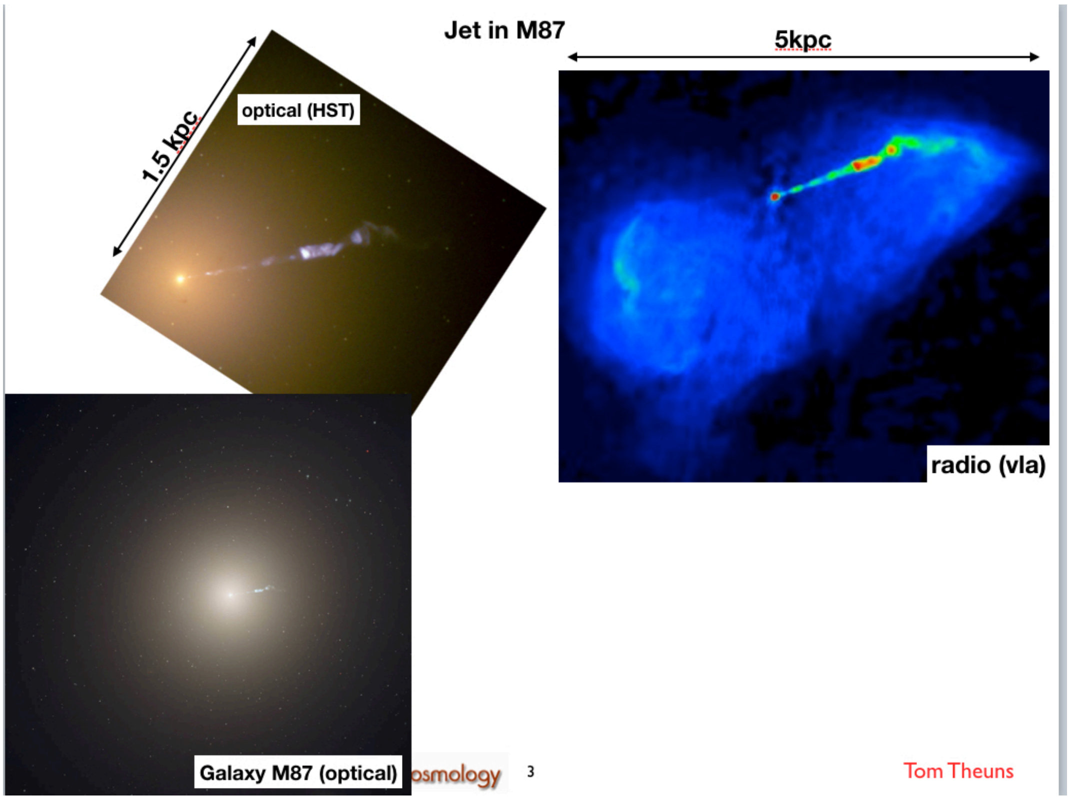

Figure 10.3: Illustrating the jet in galaxy M87. *Bottom panel:* optical image of the galaxy M87 - the central galaxy in the Virgo galaxy cluster. *Top left panel:* HST image in optical light of the jet in M87, tracing the jet all the way to the centre of the galaxy. *Top right panel:* radio image of M87. Notice how the jet is bright in the radio, and seems to 'feed' the radio 'fuzz' surrounding the galaxy.

be *so* luminous[3]?

The ultimate source AGN energy is gravity: gravitational energy is converted into radiation. This should surprise you, since you may recall from the stars' part of this course that the Kelvin-Helmholtz time-scale[4] of the Sun is only ~ 30 Myr. Gas falling towards the SMBH enters an *accretion disc* - because of its angular momentum - and over many orbits slowly spirals in. How this results in the observed spectrum - which extends from radio to gamma rays - is complex, not universally agreed, and not suitable for a first intro to AGN. However if you're interested, do read the next paragraph.

The (nearly) Keplerian disc heats the gas thermally, basically because of its differential rotation and the presence of viscous forces in the disc. This implies that the further in, the hotter the disc. The spectrum of the disc is then a sum of the spectra of each ring in the disc, each approximately a Black Body spectrum. Combined, this results in a broad spectrum of emission peaking around 1 keV, and is thought to be the origin of the optical-UV emission for AGN. Hot electrons above the disc scatter optical-UV photons[5] creating a power-law of high-energy photons - these are observed as X-rays and gamma rays, see also Fig. 10.3. This figure also illustrates the *jet* - a narrow energetic beam that is thought to be launched due to magnetic fields in the disc and which feeds extended radio-lobes.

10.3.1 Making light of gravity: Eddington limited accretion

The[6] basic mechanism that powers AGN is the conversion of gravitational energy into light. To describe this, consider an object of mass $M_{\rm BH}$ (a super massive black hole) accreting mass at a rate $\dot{M}$. If all the rest mass of the accreting gas were converted into radiation, then the luminosity of the object would be[7] $L = \dot{M}c^2$. It is thought that AGN come close to radiating at this

[3]Recall, some AGN have luminosities op to $\sim 10^4$ times the combined luminosity of all stars in the MW.

[4]The time it would take the Sun to radiation all its gravitational energy at its current luminosity.

[5]Through Thomson scattering's relativistic version called Compton scattering - discussed in the L1 lectures.

[6]'Making light of gravity' was the title of Martin Rees' birthday conference. Martin Rees, together with Donald Lynden-Bell, were the first to point to gravity as the ultimate source of AGN power.

[7]Using Einstein's famous $E = Mc^2$ equation.

maximum efficiency, therefore we write

$$L = \eta\, \dot{M}\, c^2\,; \quad \eta \approx 0.1\,. \tag{10.1}$$

The radiative efficiency η is estimated from considerations of the last stable circular orbit around a black hole[8]. The value of $\eta = 0.1$ is much higher than the energy efficiency of *stars* since Hydrogen fusion only manages a meagre efficiency of 0.007, as shown in the Stars section of this course.

Curiously, the mass of the black hole does *not* increase as $\dot{M}_{\rm BH} = \dot{M}$. Indeed, the luminosity is so high[9] that we cannot neglect the 'mass loss' associated with this luminosity - the energetic photons carry energy and hence mass away. The correct relation is then

$$\dot{M}_{\rm BH} = \dot{M} - \frac{L}{c^2} = (1-\eta)\,\dot{M} = \frac{1-\eta}{\eta}\frac{L}{c^2}\,. \tag{10.2}$$

When in a steady state, this accretion rate is limited by the *Eddington limit*. Consider a spherical shell of gas around the BH. This shell feels gravity exerted (mostly) by the black hole pulling the gas inward. But radiation streaming through the shell pushes the shell away due to radiation pressure. If the radiation pressure is too large, the net force is outward, and the black hole can no longer accrete. To compute this maximum luminosity - called the 'Eddington luminosity'- we equate the gravitational force to the force exerted by the radiation pressure[10].

For simplicity we consider a shell consisting of Hydrogen gas with number density n (neglecting other elements) which is fully ionised (by the ionising radiation of the black hole). The shell is at distance r from the BH and has thickness dr, with $dr \ll r$. Its mass density $\rho = m_{\rm H}\, n$, the volume of the shell is $4\pi r^2 dr$, and hence the (inward) gravitational force (neglecting self gravity) is

$$F_{\rm G} = \frac{G\, M_{\rm BH}\, (4\pi r^2\, dr)\, \rho}{r^2}\,. \tag{10.3}$$

[8] In Newton mechanics, circular orbits around a point mass are stable - but this is no longer the case in general relativity when the radius of the orbit is close to the event horizon. The value of $\eta = 0.1$ quoted in the text applies to a Schwarzschild - or non-spinning - black hole.

[9] Again use $E = M\, c^2$. A large luminosity effectively means that the total energy of the object is decreasing rapidly - meaning its mass is decreasing.

[10] Recall the identical derivation in the *Stars* part of this course

The (energy) flux impinging on the shell at distance r is $F_{\rm E} = L/(4\pi r^2)$. Since a photon of energy E has momentum E/c, this corresponds to a momentum flux of $F_{\rm p} = L/(4\pi r^2\,c)$. To calculate the radiation pressure we need to know the interaction cross section of the radiation with the matter. One interaction process is Thomson scattering of photons off electrons, with the wavelength independent Thomson cross section, $\sigma_T = 6.625\times 10^{-29}$ m^2. The force on a single electron is thus $F_{\rm p}\,\sigma_T$, which, multiplying with the number of electrons in the shells yields the radiation force on the shell as

$$F_{\rm L} = \frac{L}{4\pi r^2\,c}\,\sigma_T\,(4\pi\,r^2\,dr)\,n\,. \tag{10.4}$$

Setting $F_{\rm G} = F_{\rm L}$ yields the expression for the Eddington luminosity,

$$L_{\rm Edd} = \frac{4\pi G\,M_{\rm BH}\,c\,m_{\rm H}}{\sigma_T} \approx 3.3\times 10^{12}\,\frac{M_{\rm BH}}{10^8\,M_\odot}\,L_\odot\,. \tag{10.5}$$

Given the extremely high luminosities we observed for AGN, values of $10^{12}L_\odot$ or more, shows that the black holes that power bright AGN have masses of order $10^8\,M_\odot$, a conclusion first reached by Lynden-Bell (1969)

10.3.2 Growth of black holes - Salpeter time

Once a seed black hole exists, it can grow in mass through accretion and merging with other black holes, shining as an AGN as described above. How black hole seeds form is unclear: they may simply be remnants of massive stars ending their lives as black hole remnants, or may form through a completely different route, for example direct collapse of a gas cloud.

The Eddington luminosity also limits the rate at which a BH can grow as follows. Suppose the BH always accretes at its maximum rate, *i.e.* has luminosity $L = L_{\rm Edd}$. Substituting Eq. (10.5) into Eq. (10.2) yields

$$\dot M_{\rm BH} = \frac{1-\eta}{\eta}\frac{M_{\rm BH}}{\tau_S}\,;\quad \tau_s = \frac{c\sigma_T}{4\pi G m_h} \approx 4.5\times 10^8{\rm yr}\,. \tag{10.6}$$

Solving the differential equation for $M_{\rm BH}$ shows that the mass grows exponentially in time, $M_{\rm BH} = M_{\rm BH}(t=0)\exp(t/t_S)$, with a characteristic time $t_s = \eta/(1-\eta)\tau_S$ called the **Salpeter time**.

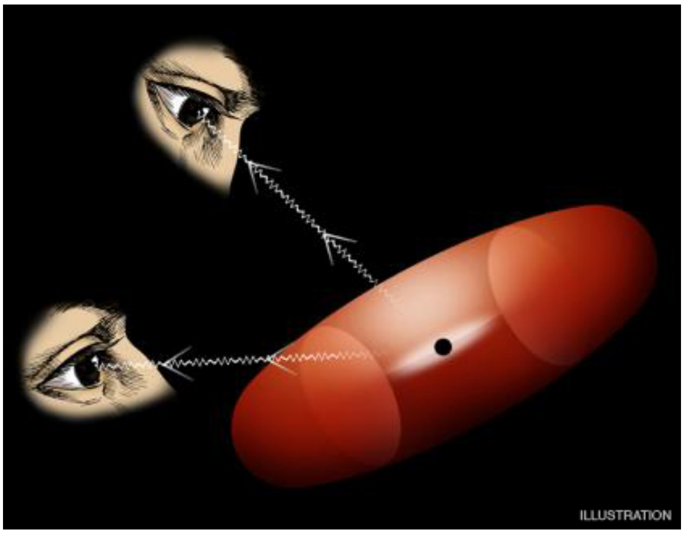

Figure 10.4: Depending on the orientation of the observer with respect to the torus of gas surrounding the black hole, the AGN may look different. Seen from above, the observer sees very close to the centre and may see an optically bright source - a QSO. Seen from the side, optical/UV light gets obscured and the observer does not see a QSO. Figure credit: Chandra observatory.

The mass of the SMBH in the most distant AGN currently known[11], ULAS J1342+0928, is estimated to be $M_{\rm BH} \approx 8 \times 10^8 \rm M_\odot$. This AGN is observed at a redshift of $z = 7.45$, at which point the age of the Universe was only 0.7 Gyr. Assuming this BH continuously accreted at its Eddington rate and that the seed formed at the time of the Big Bang - both quite unlikely - its seed mass was at least $\sim 670 \rm M_\odot$ - suggesting whatever seeds a SMBH is *much* heavier than a stellar remnant[12]. See the workshop for exercises on this aspect of BH growth.

10.3.3 Unification schemes

If mass accretion powers AGN, why is there such a variety of observational manifestations of the AGN activity? It is thought that the accretion disc is surrounded by a bigger structure in the shape of a doughnut - called a 'torus'. The presence of this torus may change our view of an AGN, depending on its orientation compared to our sightline to the AGN, as illustrated in Fig. 10.4. For example, when observing the AGN nearly perpendicular to the plane of the torus, we have a direct view of the accretion disc and hence can detect the optical/UV light emitted and infer the presence of a QSO. But if our sightline is more edge on, then the torus may obscure the optical light. However that still does not explain why some AGN have huge extended radio lobes and others don't. We still have much to understand!

10.4 Evidence for super massive black holes in galaxies

Only a small fraction of galaxies hosts an AGN. In the local Universe, $\approx 1\%$ or so of massive galaxies hosts a bright AGN, with around 10-20% showing some evidence for weak AGN activity. However, all these massive galaxies do host a SMBH. Clearly this requires that most SMBH are not active at any one time - the SMBH is not active because it is starved of gas. Feed the SMBH some gas and the SMBH will light up and become an AGN. It seems very likely that galaxies then go through relatively short phases where their SMBH is active and prolonged phases were it is not, with the active phase typically 100 times shorter than the inactive phase to obtain the 1% AGN duty cycle.

The evidence that galaxies host a SMBH even when the AGN is off is based on dynamics - basically observing large speeds for objects getting close to the centre, where they are accelerated by the gravitational attraction of the SMBH.

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[11] Your lecturer used to hold the record for the discovery of the most distant known AGN, ULASJ112001.48+064124.3, at a redshift of $z = 7.09$.

[12] And if the BH accreted at less than its maximum rate or formed later in time, then the seed mass must, of course, have been even higher.

10.4.1 The Milky Way's SMBH

Evidence for the presence of a SMBH in the MW is exquisite. Recording the positions of stars in the centre of the MW over many years, it became possible to reconstruct the orbits of these stars, see Fig. 10.5. The observed speeds of several 1000 km s^{-1} and the large measured accelerations require the presence of a very massive object - a SMBH with mass $\sim 4 \times 10^6 \mathrm{M}_\odot$. These observations were done in the IR, since otherwise the stellar light would be absorbed by the dust in the MW's disc - and hence not observable to us.

One of these stars - called 'S2' - ventured so close to the SMBH in 2018 that it was possible to measure gravitational redshift of H and He lines in its spectrum - that is, photons emitted by the star losing measurable amounts of energy and hence changing their wavelengths having to climb out of the gravitational potential of the SMBH. The loss of energy means that the wavelengths shift to longer wavelengths - to the red, hence 'gravitational redshift'.

10.4.2 The 'shadow' of the black hole in M87

Black holes are called black since 'not even light can escape from them'- more accurately, the escape speed from their event horizon is equal to the speed of light. Light emitted from within the event horizon cannot escape.

The presence of the SMBH distorts ('bends') space-time around it, so that from the point of view of a distant observer even the path of light appears curved. In the most extreme case, light can orbit the SMBH. This is an extreme instance of 'gravitational lensing' discussed in the next chapter. The scale at which extreme lensing occurs is of order of the Schwarzschild radius (event horizon) of the BH,

$$R_S = \frac{2GM}{c^2} \approx 126\,\frac{M}{6.4 \times 10^9 \mathrm{M}_\odot}\,\mathrm{AU}\,, \tag{10.7}$$

where the numerical value uses the mass of the SMBH in M87. At M87's distance, $d \approx 16.4$ Mpc, the angle[13] under which we see R_S is $\theta = R_s/d \approx 10^{-5}$ arc sec.

Given this the tiny angular extent, it would seem impossible to resolve M87's event horizon. However, this is exactly what the 'Event Horizon Telescope' managed, using Very Long Baseline Interferometry combining several

[13] Or approximately maximal angular extent of Durham cathedral - as seen from Saturn!

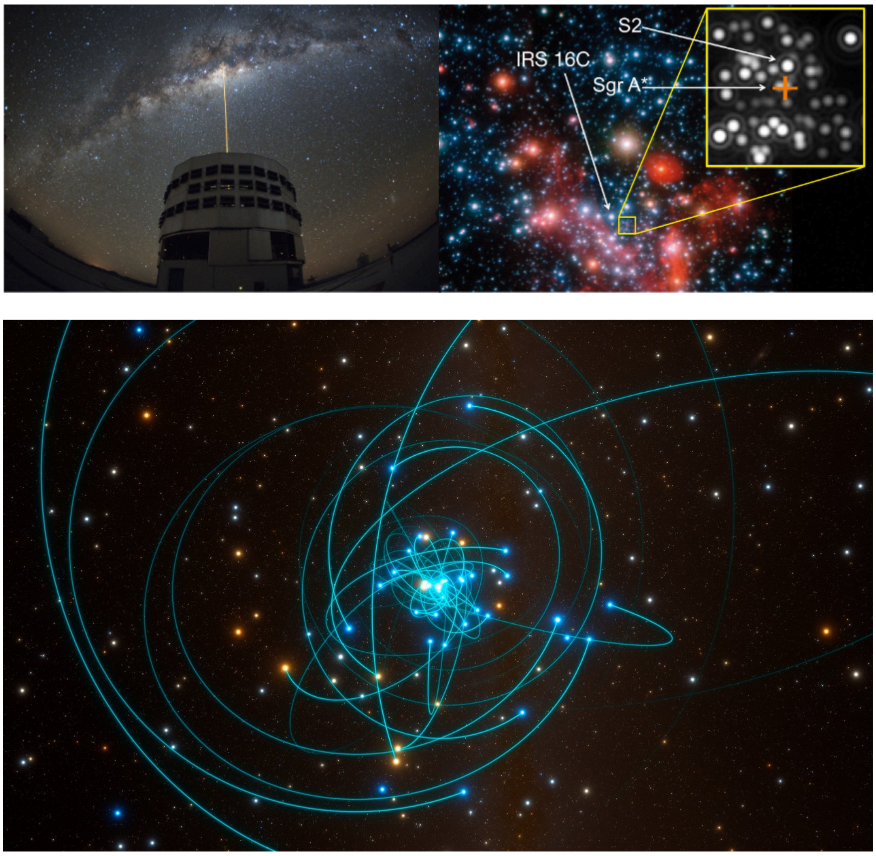

Figure 10.5: *Top left panel:* ESO's VLT telescope firing its laser to enable adaptive optics to correct for atmospheric seeing. *Top right panel:* VLT's IR image of the centre of the MW. The object labelled 'Sgr A' is the MWs SMBH - it is barely detectable in the IR. The bright sources in the inset are massive stars orbiting Sgr A; star 'S2' is also indicated. *Bottom panel:* reconstructed orbits of stars around Sgr A over the past 26 years. From ESO's *Messenger*.

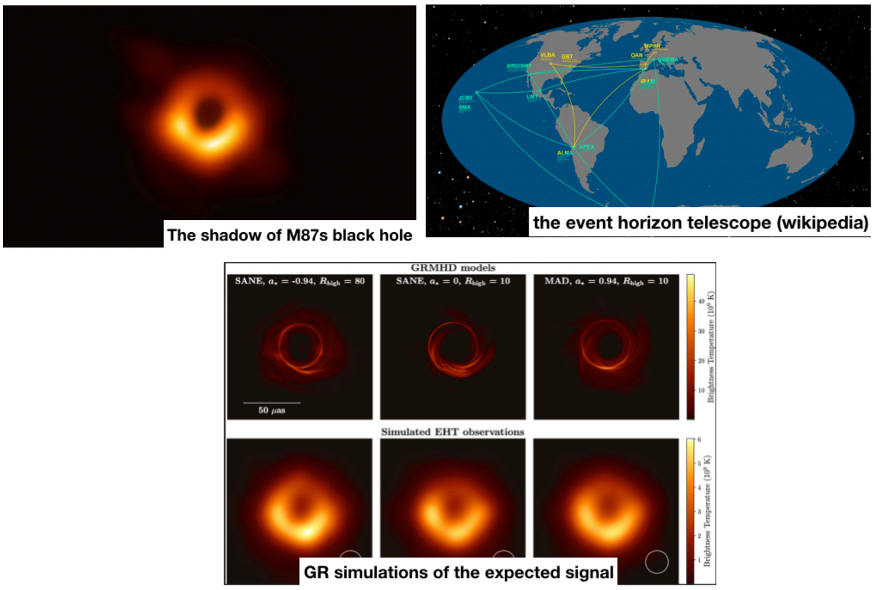

Figure 10.6: *Top left panel:* light with wavelength ≈ 1 mm detected from the immediate vicinity of M87's SMBH by the Event Horizon Telescope. *Top right panel:* radio dishes that make-up the telescope. *Bottom panel:* simulations of the expected light taking into account relativistic effects close to the event horizon, for different values of the BH's spin (left to right). The intrinsic signal is shown in the top row, the signal taking into account the telescope resolution and sensitivity is shown in the bottom row. From The event horizon telescope.

radio telescopes across earth. Observing at a wavelength of $\lambda \approx 1$ mm, they detected a ring of light around M87, see Fig. 10.6. Taking the earth's diameter, D, as the baseline yields an angular resolution of $1.2\lambda/D \approx 2 \times 10^{-5}$ arc seconds at a wavelength of $\lambda = 1$ mm, meaning the telescope can resolve scales of order R_S. This astonishing feat shows convincingly that the object in the centre of M87 is really a black hole - that is, a relativistic object with an event horizon [14].

10.4.3 SMBHs in other galaxies

The techniques used to identify the SMBH in the MW and M87 cannot be applied to more distant galaxies. Evidence for SMBHs in them is of course less convincing and comes from other observations.

- The gravity of the BH affects orbits of stars close to it. Even if individual orbits cannot be measured, this does lead to an enhanced stellar density close to the SMBH - a 'cusp' (rapid increase) of the surface brightness. This can be detected in nearby galaxies using HST imaging.

- *Maser* emission. A maser is the microwave equivalent of a laser[15]. It may already be surprising that maser emission occurs naturally in the ISM of galaxies. Sometimes, the maser emission originates close to the centre, allowing us to measure the mass of the central concentration (SMBH) orbited by the masering gas.

- Similar to maser emission, it is possible to estimate the mass of the BH from the line-widths of emission lines originating close to the BH. Assuming the large widths of these lines is due to the orbital motion of the emitting gas allows us to infer the black hole mass[16]

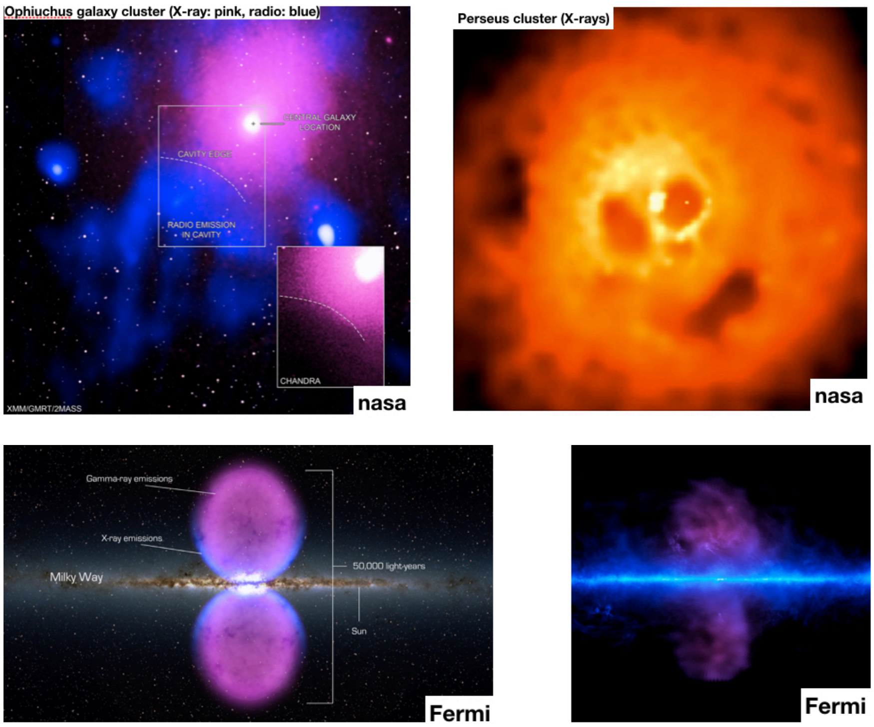

Figure 10.7: *Top left panel:* giant shocks detected in the Ophiuchus galaxy cluster. The energy required to create these shock is estimated at 5×10^{61} ergs equivalent to 5×10^{10} simultaneously supernova explosions - motivating the press to call this the biggest explosion since the Big Bang. *Top right panel:* X-ray image of the Persues cluster of galaxies. The large dark patches in the X-rays (resembling eye sockets of a skull) are due to the hot X-ray gas being displaced by relativistic particles injected by the AGN. *Bottom left panel:* cartoon of the gamma ray bubbles detected above and below the plane of the Milky Way by the Fermi satellite. These 'Fermi' bubbles are likely relics of past AGN activity of the MWs SMBH. *Bottom right panel:* actual Fermi data.

10.5 Impact of AGN on their host galaxy

The large amounts of energy that AGN inject into their surroundings is thought to affect the host galaxy. Exactly how this happens is currently not well understood - probably the jet inflates radio bubbles, filling them with relativistic particles, and these bubbles prevent gas from cooling. With no more gas able to cool, the galaxy cannot make any more stars. Examples of giant cavities created by AGN in the hot gas of cluster of galaxies - where they are visible due to the *absence* of the hot X-ray gas- are shown in Fig. 10.7. With AGN activity being prevalent in galaxies with mass $\geq 10^{10.5}\mathrm{M}_\odot$, this might explain the rapid drop in galaxies more massive than this that we noticed in Fig. 9.3: when the SMBH can turn into an AGN, the galaxy stops making stars. More speculative, this is probably also why massive galaxies tend to be elliptical: the SMBH they host prevents star formation when it switches to the 'AGN-on' state.

The SMBH in the Milky Way is thought to be a puny version of the energetic beasts seen in the top panels of Fig. 10.7. The bottom panels shows the striking Fermi bubbles, detected in gamma rays, that are thought to be relics of past activity of Sgr A - the SMBH in the MW.

[14] The other convincing evidence for the existence of black holes comes from the detection of gravitational waves emitted during the merging of stellar mass black holes. A discovery too exciting not to at least mention here.

[15] Light amplification by stimulated emission radiation

[16] Note unlike measuring the enclosed mass of the Milky Way from the observed rotation curve.