Chapter 15

Observational Evidence for Black Holes

By definition an isolated black hole should be a difficult object to observe directly. However, if black holes exist they should often be accreting surrounding matter and interacting gravitationally with their environment, and this is potentially observable. Thus, although the direct observation of a natural black hole is difficult and the production of a black hole in a laboratory is far beyond any present technology (unless the behavior of gravity at very short distances is fundamentally different from what we have observed so far), we have very strong reasons to believe that black holes exist and are being observed indirectly.

15.1 Observation of Stellar Black Holes

We have very strong reasons to believe that black holes exist and are being observed indirectly because of

1. Unseen massive companions in binary star systems that are
   - Strong sources of X-rays
   - Probably too massive to be anything other than black holes.
2. The centers of many galaxies where
   - Masses inferred by virial theorem methods (or even direct measurement of individual star orbits in the center of the Milky Way) are far too large to be accounted for by any simple hypothesis other than a supermassive black hole.
   - In many cases there is direct evidence of an enormous energy source in the center of the galaxy.

We shall now summarize some of the reasons why the first class of observations give us strong confidence that black holes, or at least objects that have many of the features of black holes, exist.

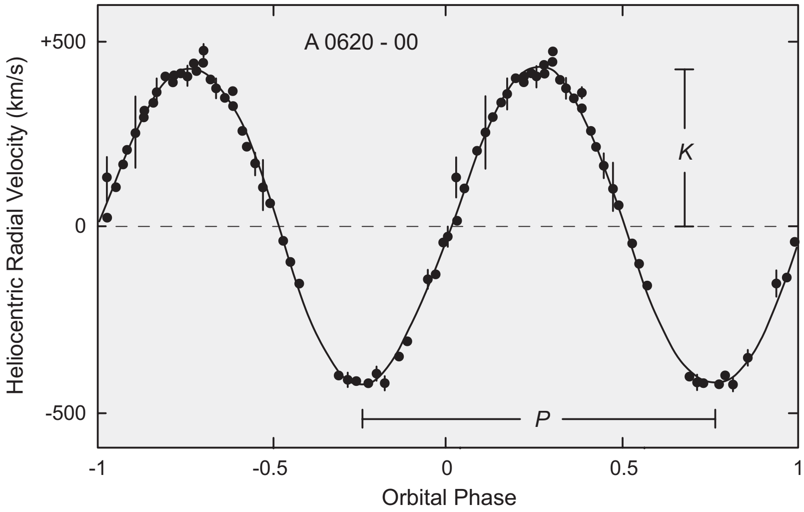


Figure 15.1: Velocity curve for the black hole binary candidate A 0620–00.

15.1.1 Black Hole Masses in X-ray Binaries

From Kepler's laws, the mass function $f(M)$ for the binary may be related to the radial velocity curve (Fig. 15.1) through

$$
\begin{aligned}
f(M) &= \frac{(M\sin i)^3}{(M+M_{\rm c})^2} = \frac{PK^3}{2\pi G} \\
&= 0.1036\left(\frac{P}{1\ \rm day}\right)\left(\frac{K}{100\ \rm km\ s^{-1}}\right)^3 M_\odot
\end{aligned}
$$

where

- K is the semiamplitude and P the period of the radial velocity.
- i is the tilt angle of the orbit
- $M_{\rm c}$ is the mass of the companion star.
- M is the mass of the black hole

Table 15.1: Some black hole candidates in galactic X-ray binaries

X-ray source	Period (days)	$f(M)$	$M_{\rm c}(M_\odot)$	$M(M_\odot)$
Cygnus X-1	5.6	0.24	24–42	11–21
V404 Cygni	6.5	6.26	$\sim$0.6	10–15
GS 2000+25	0.35	4.97	$\sim$0.7	6–14
H 1705–250	0.52	4.86	0.3–0.6	6.4–6.9
GRO J1655–40	2.4	3.24	2.34	7.02
A 0620–00	0.32	3.18	0.2–0.7	5–10
GS 1124–T68	0.43	3.10	0.5–0.8	4.2–6.5
GRO J0422+32	0.21	1.21	$\sim$0.3	6–14
4U 1543–47	1.12	0.22	$\sim$2.5	2.7–7.5

Because the angle i is often not known, the measured mass function places a lower limit on the mass of the unseen component of the binary if the mass of the companion star is known. The mass of the companion can often be estimated reliably from systematic spectral features.

Table 15.1 illustrates some candidate binary star systems where a mass function analysis suggests an unseen companion too massive to be a white dwarf or neutron star. We assume these to be black holes.

15.1.2 Example: Cygnus X-1

The first strong case found, and most famous stellar black hole candidate, is called Cygnus X-1 (the first X-ray source discovered in the constellation Cygnus).

1. In the early 1970s an X-ray source was discovered in Cygnus and designated Cygnus X-1.
2. In 1972, a radio source was found in the same general area and identified optically with a blue supergiant star called HDE226868. Correlations in radio activity of HDE226868 and X-ray activity of Cygnus X-1 implied that the two were probably components of the same binary system.
3. Doppler measurements of the radial velocity of HDE226868 and other data confirmed that it was a member of a binary with a period of 5.6 days.
4. Detailed analysis showed that the X-ray source was fluctuating in intensity on timescales as short as 1/1000 of a second.
    - Signals controlling the fluctuation are limited light speed, which implies that the X-ray source must be very compact, probably no more than hundreds of kilometers in diameter.
    - The compact size, orbital perturbation on HDE226868, and strong X-ray emission, indicate that Cygnus X-1 is a compact object (white dwarf, neutron star, or black hole, with the latter two possibilities more likely).

5. The mass of the blue supergiant HDE226868 was estimated from known properties of such stars (it is a spectrum and luminosity class O9.7Iab star).
    - This, coupled with a mass function analysis, can be used to estimate the mass of the unseen, compact companion.
    - These estimates are uncertain because the geometry (tilt of the binary orbit) can only partially be inferred from data.
    - However, all such estimates place a lower limit of about 5–6 $M_\odot$ on the unseen companion and more likely indicate a mass near 10 $M_\odot$.
6. Since we know of no conditions that would permit a neutron star to exist above about 2–3 solar masses (or a white dwarf above about 1.4 solar masses), we conclude that the unseen companion must be a black hole.

Although this chain of reasoning is indirect, it builds a very strong case that Cygnus X-1 contains a black hole.

15.2 Supermassive Black Holes in the Cores of Galaxies

Many observations of star motion near the centers of galaxies indicate the presence of large, unseen mass concentrations. The most direct is for our own galaxy.

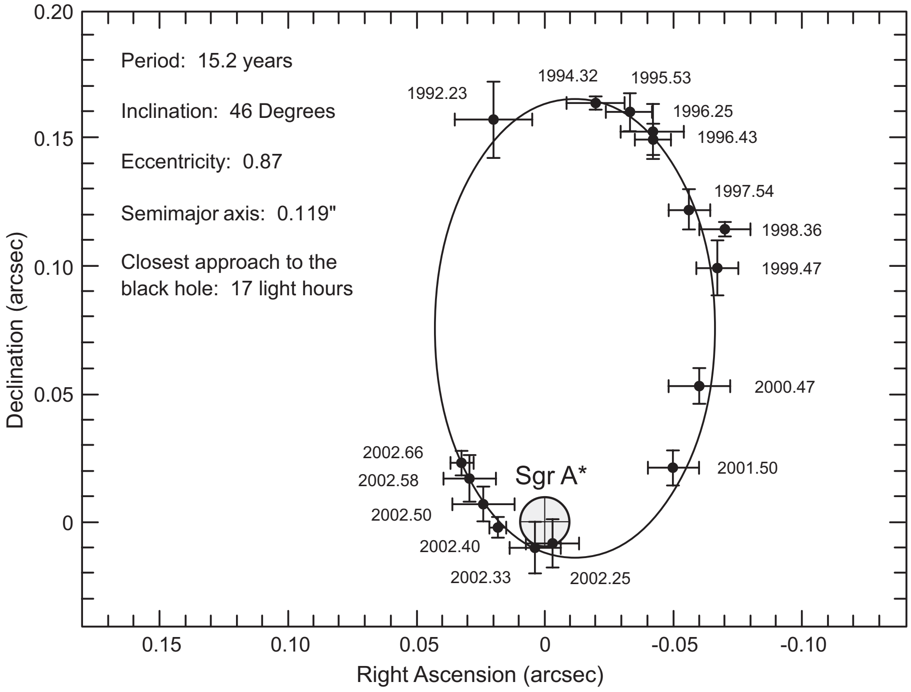


Figure 15.2: Orbit of the star S2 near the radio source SGR A*.

15.2.1 The Black Hole at the Center of the Milky Way

The star denoted S2 is a 15 solar mass main sequence star that orbits in the vicinity of the strong radio source SGR A*, which is thought to lie very near the center of the Milky Way.

- The orbit has been measured precisely using adaptive optics and speckle interferometry at near-IR wavelengths (penetrate dust).
- The orbit of S2 is shown in Fig. 15.2, with dates shown in fractions of a year beginning in 1992.
- The orbit corresponds to the projection of the best-fit ellipse with SGR A* at a focus. The closest approach for the orbit corresponds to a distance of about 17 light hours from SGR A*.

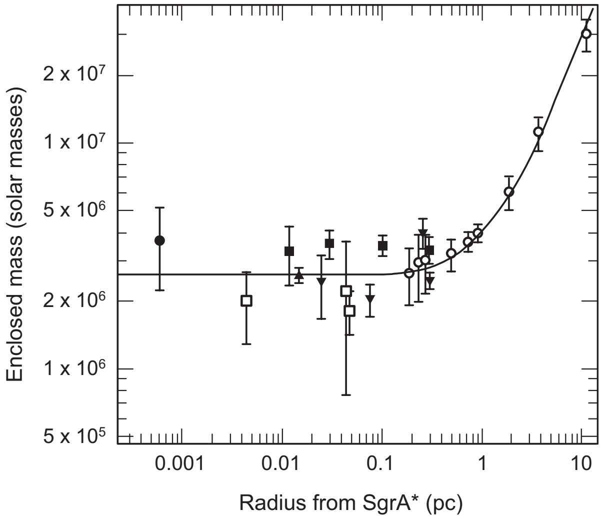


Figure 15.3: Mass distribution near Sag A* as inferred from stellar motion.

- From detailed fits to the Kepler orbit of S2, the mass inside the orbit of the star is estimated to be $2.6 \times 10^6 M_\odot$ (see Fig. 15.3).
- From the size of the orbit, this mass is concentrated in a region that cannot be much larger than the Solar System, with little luminous mass in that region.
- By far the simplest explanation is that the radio source SGR A* coincides with a nearly 3 million solar mass black hole.
- The innermost point in Fig. 15.3 is derived from the observed elliptical orbit for the star S2 that comes within 17 light hours of the black hole
  - This distance is still well outside the tidal distortion radius for the star (which is about 16 light minutes).
  - It is about 2100 times larger than the event horizon.
  - At closest approach the separation from the black hole is not much larger than the radius of the Solar System.

15.2.2 The Water Masers of NGC 4258

The galaxy NGC 4258 (also called M106) is an Sb spiral visible through a small telescope, but its nucleus is moderately active and it is also classified as a Seyfert 2 Active Galactic Nucleus (AGN). It lies in the constellation Canes Venatici (very near the Big Dipper) at a distance of around 20 Mpc. This makes it one of the nearest AGNs.

- A set of masers has been observed in the central region of the galaxy. (Masers are the microwave analog of a visible-light laser.) The maser emission in NGC 4258 is due to clouds of heated water vapor, so these are termed water masers.
- Because masers produce sharp spectral lines (allowing precise Doppler shifts), and because microwaves are not strongly attenuated by the gas and dust near the nucleus of the galaxy, observation of the water masers has permitted the motion of gas near the center to be mapped very precisely using the Very Long Baseline Array (VLBA).

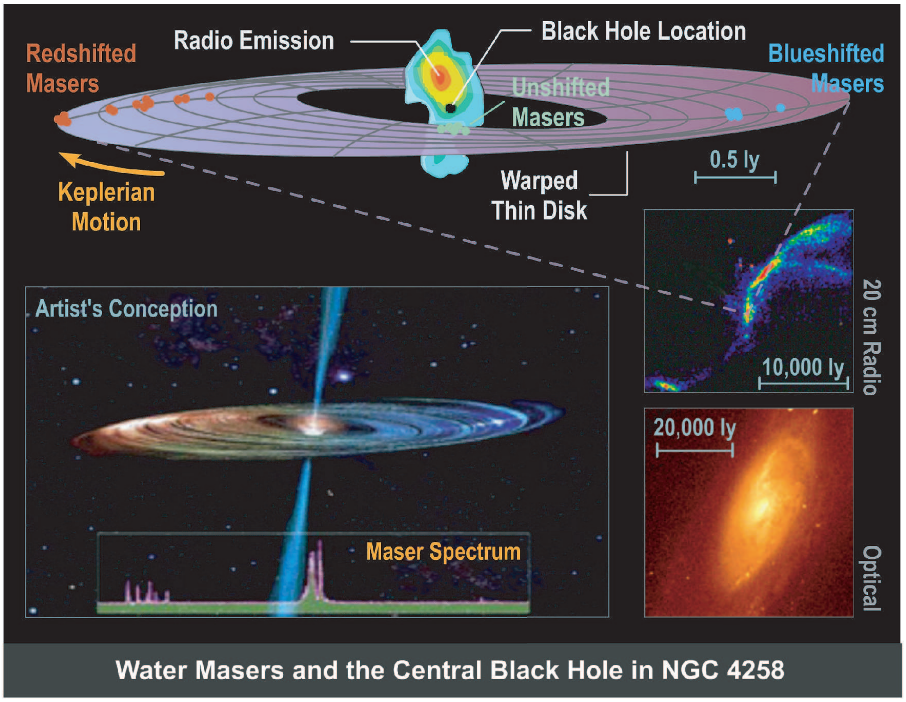
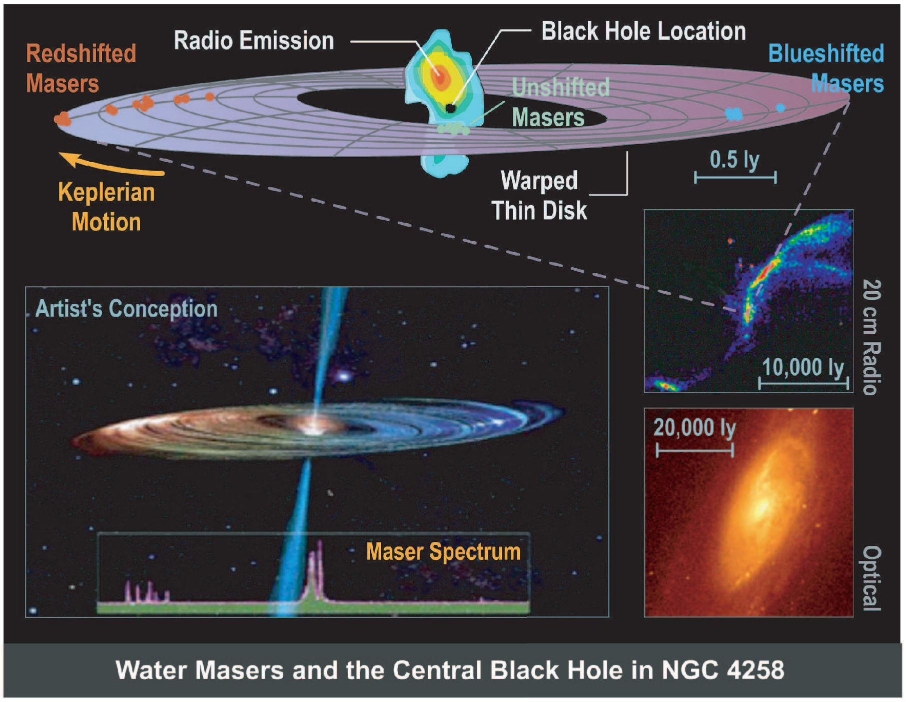


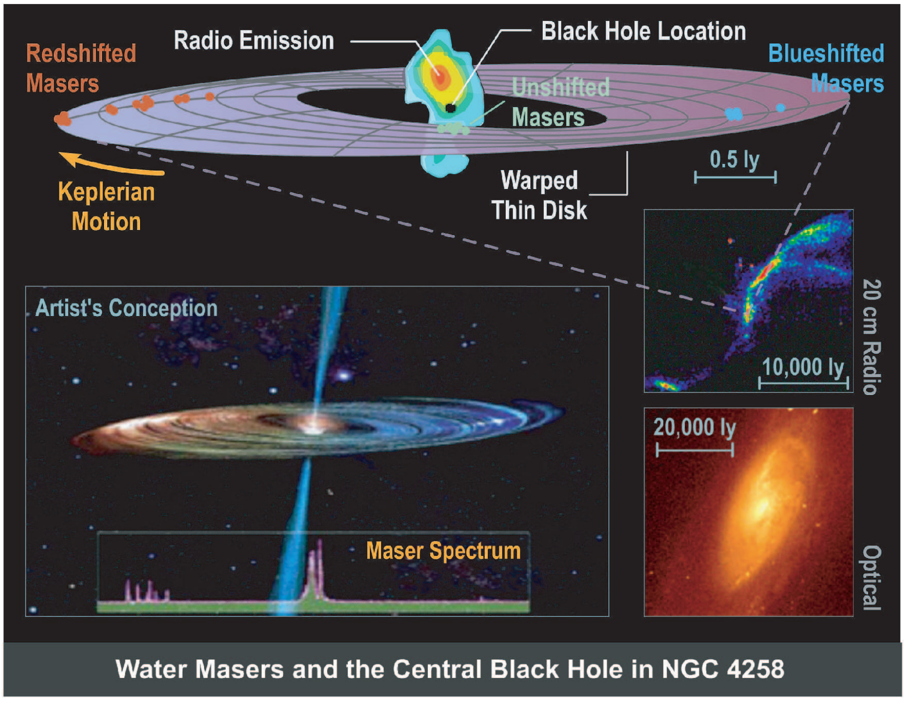
Figure 15.4: Water masers in NGC 4258 and evidence for a central black hole.

Water maser emission from the central region of NGC 4258 implies (Fig. 15.4).

- The masers are mapped with a precision of better than 1 milliarcsecond and their radial velocities indicate bulk motion of the gas within several light years of the core at velocities approaching 1000 km s^{-1}.
- In Fig. 15.4 masers approaching us (blue shift) are shown in blue, masers receding from us (red shift) are shown in red, and those with no net radial velocity are shown in green. From this we may infer the general rotation of the gas disk, as indicated by the arrow labeled “Keplerian motion”.



- The masers are embedded in a thin, warped, dusty, molecular gas disk revolving around the core.
- The motion of the masers is Keplerian → masers in orbit around a large mass that is completely contained within all their orbits.
- The mass obtained is approximately $3.5 \times 10^6 \, M_\odot$.
- Measured mass and measured size of region enclosed by maser orbits implies minimum density of $10^8 \, M_\odot$ per cubic light year.
  - 10,000 times more dense than any known star cluster.
  - If such a star cluster existed, calculations indicate that collisions of the stars would cause the stars of the cluster to drift apart or mutually collapse to a huge black hole.
  - Only plausible explanation is a supermassive black hole.



- The nucleus of the galaxy produces radio jets that appear to come from the dynamical center of the rotating disk and are approximately perpendicular to it (see fig).

- The position of the radio jets and precise location of the center of the disk determines the location of the central black hole engine within the uncertainty of the black circle shown in the figure.

  - This black circle denotes the uncertainty in location of the black hole, not its size.
  - The black circle is about 0.05 ly in diameter, but a supermassive black hole would have an event horizon hundreds of times smaller than this.

These results taken together make NGC 4258 one of the strongest cases known for the presence of supermassive black hole engines at the cores of active galactic nuclei.

15.2.3 Virial Methods and Central Masses

For distant galaxies we have insufficient telescopic resolution to track individual stars but we may still learn something about the mass contained within particular regions by observing the average velocities of stars in that region.

- On conceptual grounds, we may expect that the larger the gravitational field that stars feel, the faster they will move.
- This intuitive idea may be quantified by using the virial theorem to show that the mass M responsible for the gravitational field in which stars move in some spherical region of radius R is given by

  $$M \simeq \frac{5R\sigma_{\mathrm{r}}^2}{G},$$

  where the radial velocity dispersion

  $$\sigma_{\mathrm{r}}^2 = \langle v_{\mathrm{r}}^2 \rangle \equiv \frac{1}{3N}\sum_{i=1}^{N} v_i^2$$

  can be determined by averaging over the squares of radial velocity fields determined from Doppler-shift measurements.

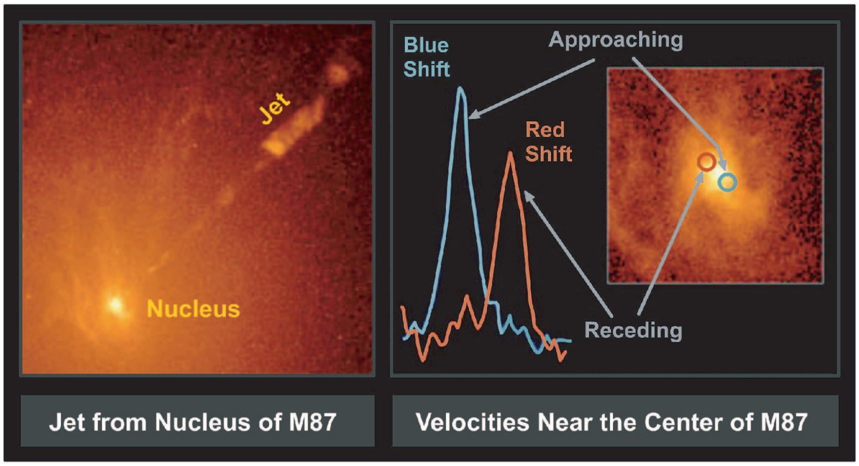
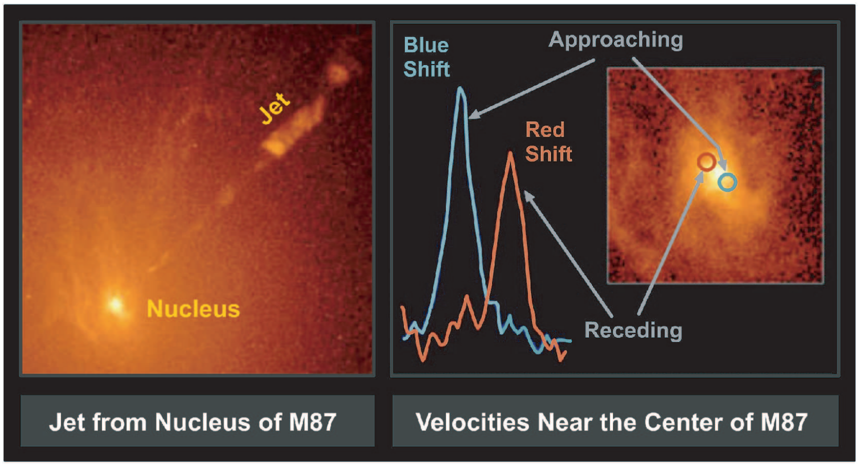


Figure 15.5: Evidence for a central black hole in the galaxy M87.

15.2.4 Evidence for a Supermassive Black Hole in M87

The left portion of Fig. 15.5 is a Hubble Space Telescope image showing the center of the giant elliptical radio galaxy M87.

- The diagonal line emanating from the nucleus in the left image is a jet of high-speed electrons—a synchrotron jet—approximately 6500 light years (2 kpc) long.
- This is what would be expected for matter swirling around the supermassive black hole, with part of it falling forever into the black hole and part of it being ejected in a high-speed jet.
- The right side of Fig. 15.5 illustrates Doppler shift measurements made on the central region of M87 that suggest rapid motion of the matter near the center.



- The measurement was made by studying how the light from the disk is redshifted and blueshifted by the Doppler effect.
- The gas on one side of the disk is moving away from Earth at a speed of about 550 kilometers per second (redshift). The gas on the other side of the disk is approaching the Earth at the same speed (blueshift).
- These high velocities suggest a gravitational field produced by a huge mass concentration at the center of M87.
- By applying the virial theorem to the measured radial velocities we infer that approximately 3 billion solar masses are concentrated in a region at the galactic core that is only about the size of the Solar System.
- This inferred mass is far larger than could be accounted for by the visible matter there and the simplest interpretation is that a 3 billion solar mass black hole lurks in the core of M87.

15.3 Summary: A Strong But Circumstantial Case

The evidence cited in this chapter is not yet iron-clad proof of the existence of black holes.

- The defining characteristic of a black hole is an event horizon.
- No known black hole candidates are near enough to permit imaging an angular region the size of an event horizon with present instrumentation.
- (However, angular resolution sufficient to resolve the event horizon of the Milky Way's suspected central black hole appears at least technically feasible on a 2-decade timescale.)

Nevertheless, data on X-ray binary systems and on the motions of stars and other objects in the central region of our galaxy and other nearby ones provide extremely strong circumstantial evidence for the existence of black holes (or at least of objects very much like black holes).