Why are we so sure that black holes are real, and that we have found them?

"Extraordinary claims require extraordinary evidence." – Attributed to Carl Sagan

(1) "We know that neutron stars exist, and black holes are pretty close!"

This isn't a strong argument. Just because it's plausible doesn't mean it must exist. Horses are almost unicorns, and we know that horses exist, but this doesn't imply that unicorns must exist.

(2) To hold up against collapse, a neutron star with a mass of greater than 3 Suns would have to be made of material that's infinitely strong. Indeed, nuclear theory predicts how strong neutron star material should be: a realistic neutron star should collapse, if it had a mass greater than 2.7 $\pm$ 0.3 Suns.

Can we find a compact object with a mass we can prove is greater than 3 Suns?

We measure mass of stars (and black holes) with Kepler's Third Law, from the strength of gravity as they orbit each other. From Kepler's third law, $m = a^3/P^2$ (m = mass in Suns; a = semi-major axis or orbital separation in AU; P = orbital period in years). This is done by getting spectra of the binary star system all around the orbit, and measuring **how much the stars' gravity pull each other** around by measuring the Doppler shift. This is similar to how we detect planets around other stars, by measuring how their gravity pulls their parent stars around.

The compact star in the binary star system Cygnus X-1 for many years (from 1971 to 1992) was hailed as the most likely black hole candidate, but the case wasn't decisive. Mass estimates were in the range of 10 Suns, but they were only estimates. The problem was astronomers couldn't measure the other properties of the system (in particular the orbital separation, or a), well enough to be sure.

(3) V404 Cygni: In 1994, Jorge Casares, Phil Charles, and Tim Naylor (Oxford) got spectra to measure the masses of both stars in V404 Cygni, a binary system in which there had been a nova eruption. They found that one star is a K giant. The other, which emits X-rays, is compact, and has a **mass function of 6.0 $\pm$ 0.4 Suns**—definitely a black hole. There are now at least 59 similar black holes in binary star systems known.

(4) **Event horizons (not) seen**: In 1997, Ramesh Narayan and Mike Garcia (Harvard) showed that binary star systems containing black holes are systematically fainter than similar star systems containing neutron stars. Why? Because they have something black in them—the event horizon.

(5) **Direct imaging of M87***: the Event Horizon Telescope, a millimeter-wave long-baseline interferometer, has directly imaged the black hole in the elliptical galaxy M87. It's black, and it looks like a hole.

(6) **N6946-BH1 disappears**: *Hubble Space Telescope* observations of a red supergiant star with a mass of 25 Suns apparently showed it to collapse directly into a black hole, without even a supernova explosion.

(7) **Gravitational microlensing** events observed with *Hubble Space Telescope* have revealed single black holes moving through space, as they pass in front of dense star fields.

All this so far is indirect evidence. Can we show black holes exist more directly?

(8) **Spectral lines in galaxy centers** are distorted in ways like those predicted if they contained black holes with masses of millions to billions of Suns. Masers (which are natural microwave lasers) in the gas around these supermassive black holes allow precise measurements of velocities, which prove compactness.

(9) **Gravitational waves** were discovered in 2015 by the Laser Interferometer Gravitational-Wave Observatory (LIGO). Many events since observed fit predictions by Einstein's General Theory of Relativity of what gravitational waves from pairs of merging black holes and neutron stars should look like.

(10) **Time slowing down**: In 1997, a NASA spacecraft first timed how, waves in gas falling into a black hole get longer, as predicted by Einstein's general theory of relativity. This is basically watching a clock fall into a black hole, and seeing the second hand go slower as it falls.

(11) **Frame dragging**: In 2019, how V404 Cygni drags space around it as it spins was observed. This is like how ice cubes swirl around when stirring a drink, but instead of the drink, space itself was swirling.

The Mass Function:

Why astrononmers stopped arguing (in the early '90s) about whether black holes exist.

$$f(M_1) = \frac{{M_1}^3 \sin^3 i}{M_1 + M_2} = \frac{P{K_2}^3 \sin i^3}{2\pi G}$$

$$f(M_2) = \frac{{M_2}^3 \sin^3 i}{M_1 + M_2} = \frac{PK^3 \sin i^3}{2\pi G}$$

where:

M_1 = mass of the more massive body (the black hole)
M_2 = mass of companion (the normal star)
i = the inclination of the orbit

and:

P = the orbital period
G = the gravitational constant
$K \sin i$ = the companion's orbital amplitude, from the Doppler effect.

$K \sin i$ = the amplitude of the radial velocity curve.

$$\frac{\lambda(observed) - \lambda(rest)}{\lambda(rest)} = \frac{v}{c}.$$

Note that:

P_{orb} and $K_2 \sin i$ are both **observed** quantities.

This is therefore a secure way of finding $f(M_1)$,

— and —

$f(M_1)$ is the minimum mass that M_1 can have.

Casares, Charles, & Naylor (1992) found that V404 Cygni
(previously known as Nova Cygni 1938)
has $f(M_1) = 6.0 \pm 0.1\ M_{Sun}$!

Maximum mass a neutron star can have is $3.0 \pm 0.3\ M_{Sun}$.

V404 Cyg is therefore probably really a black hole!