Observational evidence

Black holes

Despite its invisible interior, a black hole can reveal its presence through interaction with other matter.

A black hole can sometimes be inferred by tracking the movement of a group of stars in a region of space which looks “empty”.

Alternatively, one can observe X-ray emission from gas falling into a relatively small black hole, from a companion star. This gas spirals inwards, heats up to a high temperature and emits radiation that can be detected.

These kinds of observations have led to the consensus that black holes do exist in the Universe. They are, in fact, the conservative explanation for many phenomena.

Cygnus X1

Cygnus X-1, is a well known galactic X-ray source. It was discovered in 1964 during a rocket flight and is one of the strongest X-ray sources seen from Earth.

Cygnus X-1 was the first X-ray source that was widely thought to be a black hole and it remains one of the most studied candidates.

In this system a normal star orbits a “dark” companion. From the orbital motion, one can constrain the mass of the unseen object. It is now estimated to have a mass equal to 8.7 solar masses.

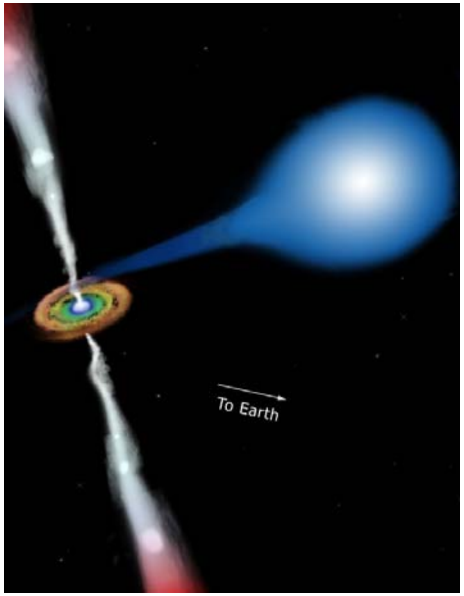
Since the maximum mass of white dwarfs is about 1.4 solar masses and neutron stars should have a maximum mass less than 3 solar masses, this is strong indications that Cygnus X-1 is a black hole.

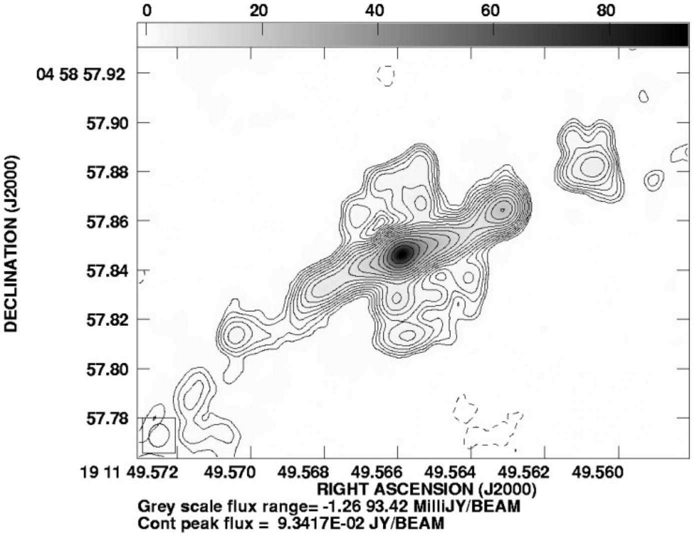
Cygnus X-1 was the subject of a bet between Stephen Hawking and Kip Thorne in 1974, with Hawking betting that it was not a black hole. He conceded in 1990.

SS433

SS 433 is one of the most exotic star systems in the sky. It is an X-ray emitting binary system, most likely containing a black hole.

Estimates suggest that the mass of the black hole is equal to 16 solar masses.



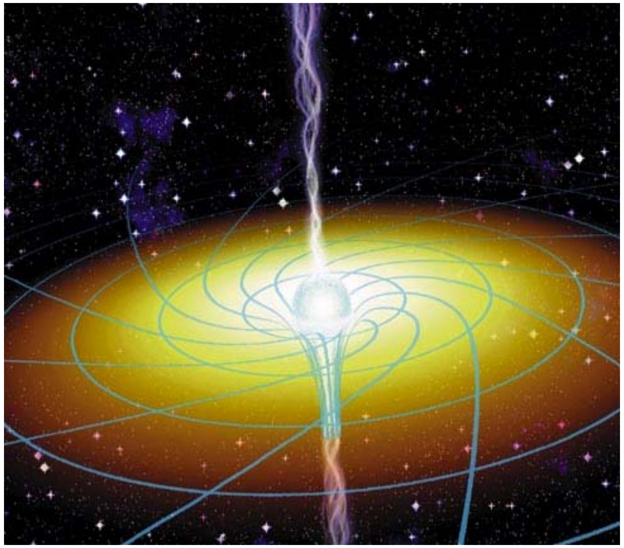


Discovered in 1978, SS 433 was the first “microquasar”.

The material in the jets travels at 26% of the speed of light.

Accretion is a fundamental process in astronomy: Gravity collects matter to make stars, galaxies, and galaxy clusters, and the resulting energy powers the radiation we see.

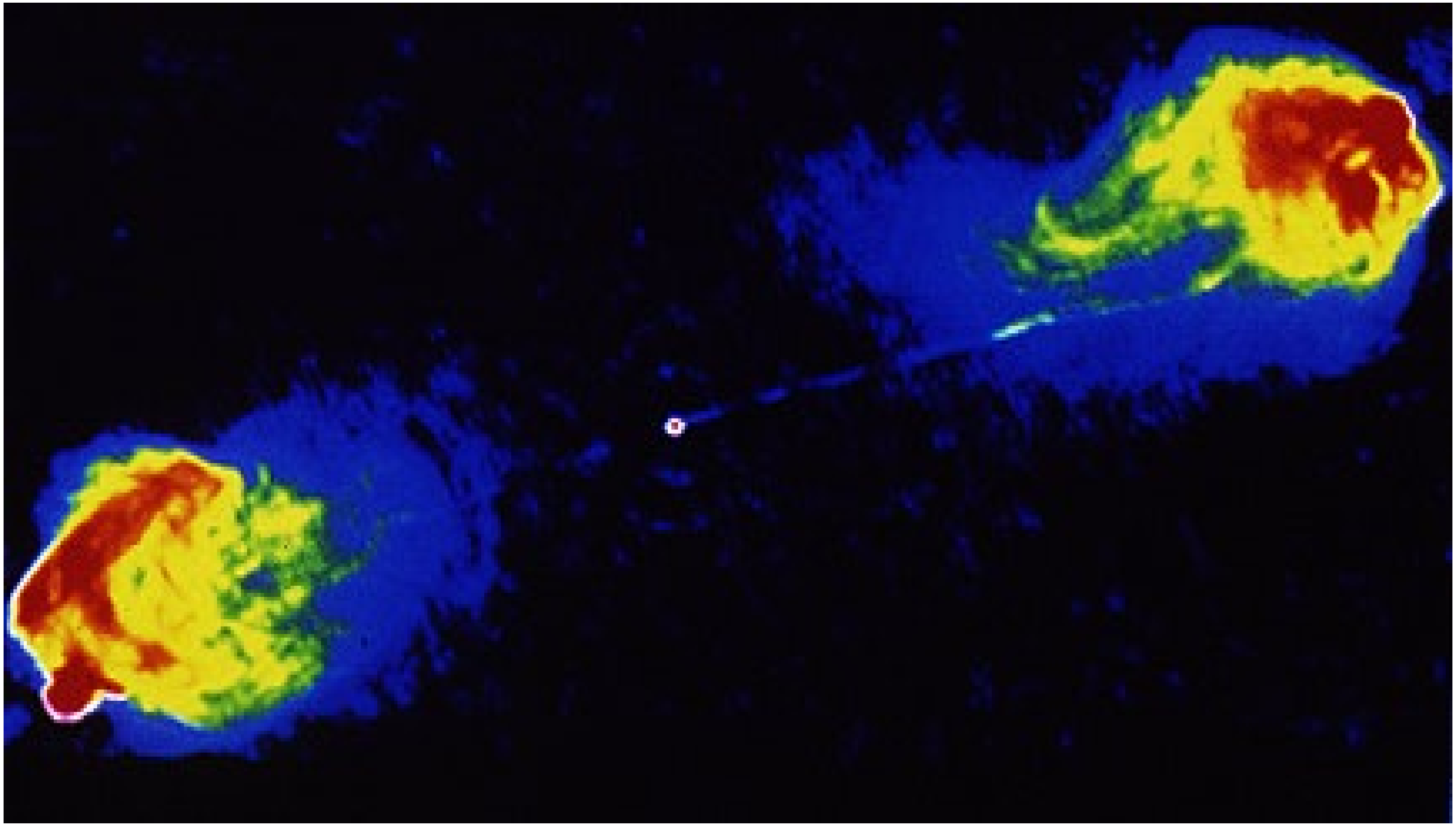
There is strong evidence that accretion tends to be accompanied by outflows, in objects ranging from proto-stellar disks to supermassive black holes in the centres of galaxies. The most spectacular of these outflows are the relativistic jets seen in active galactic nuclei, and more locally in microquasars and pulsars. SS433 is a unique laboratory for studying these phenomena.



A rotating black hole drags the surrounding spacetime along with it.

When the black hole interacts with a magnetised accretion disk the field is twisted and highly relativistic particles are generated.

This could explain the observed jets.



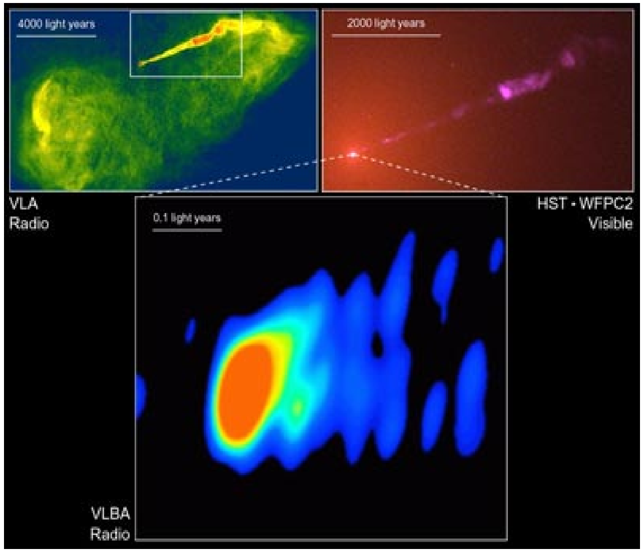
Cygnus A is one of the loudest radio objects in the sky. It is an active galaxy with two highly collimated jets. The jets extend many times the size of the host galaxy.

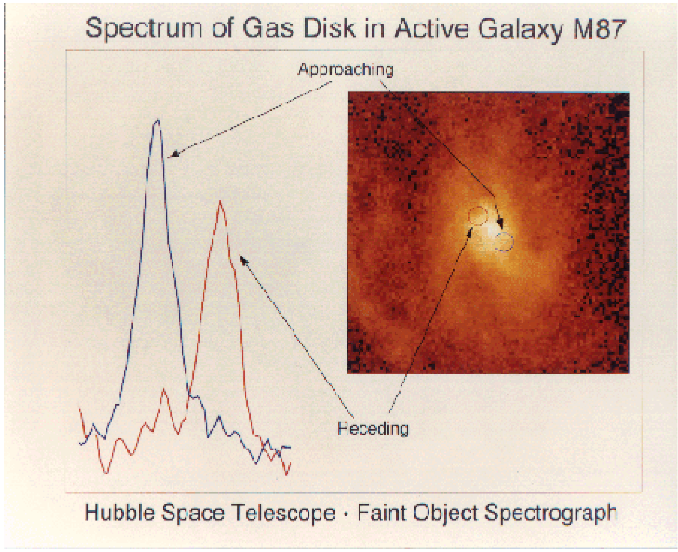
M87

M87 is an active galaxy. In the core is a spiral-shaped disk of hot gas.

Using spectra taken from opposite sides one can infer the rotation and size of the disk. This way one can weigh the invisible object at the centre.

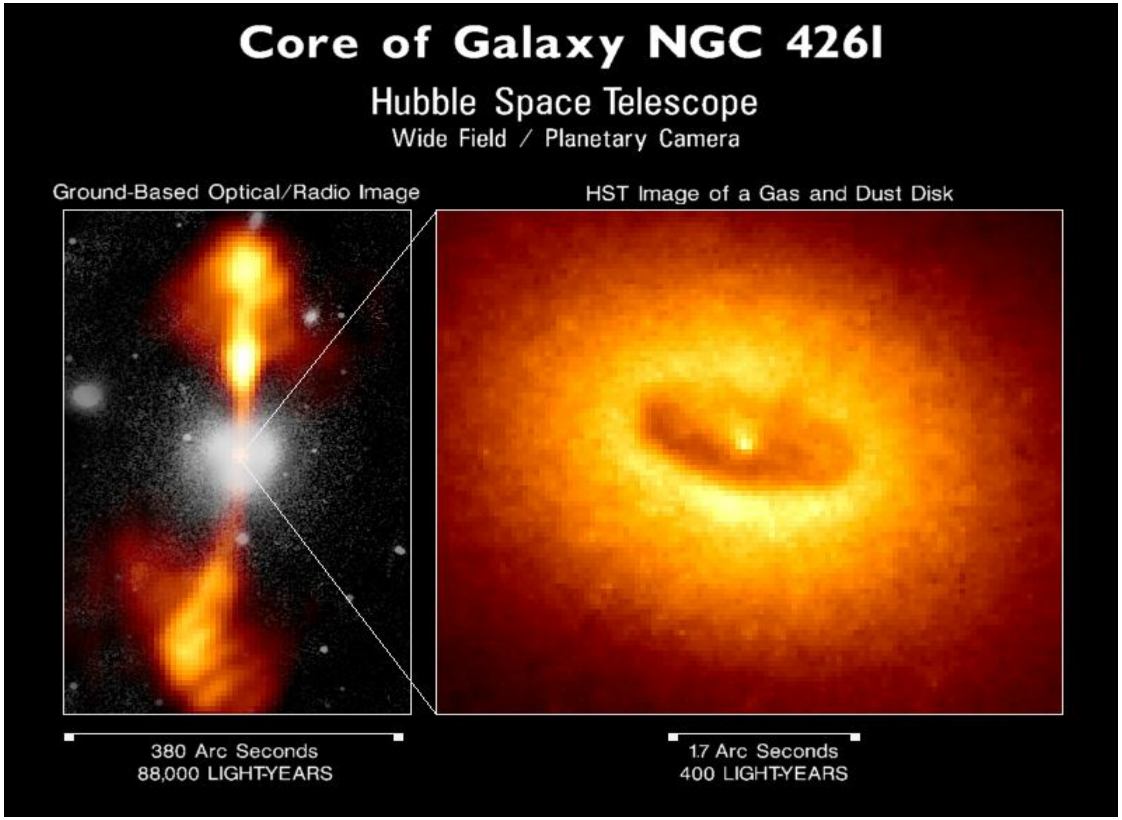
Although the object is no bigger than our solar system it weighs three billion times as much as the sun.





NGC4261

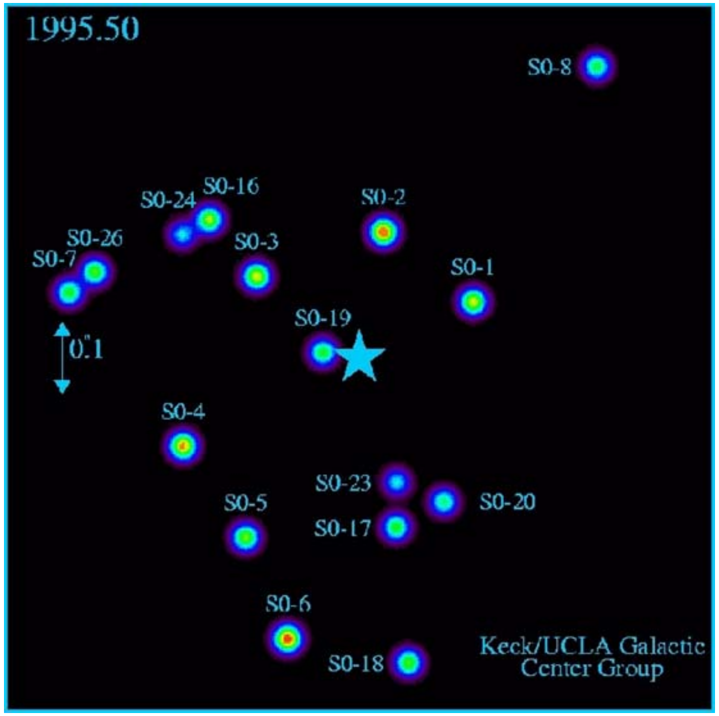
NGC4261 is another active galaxy with a disk in the centre. In this case the black holes if found to weigh one billion times as much as the sun.



Milky way

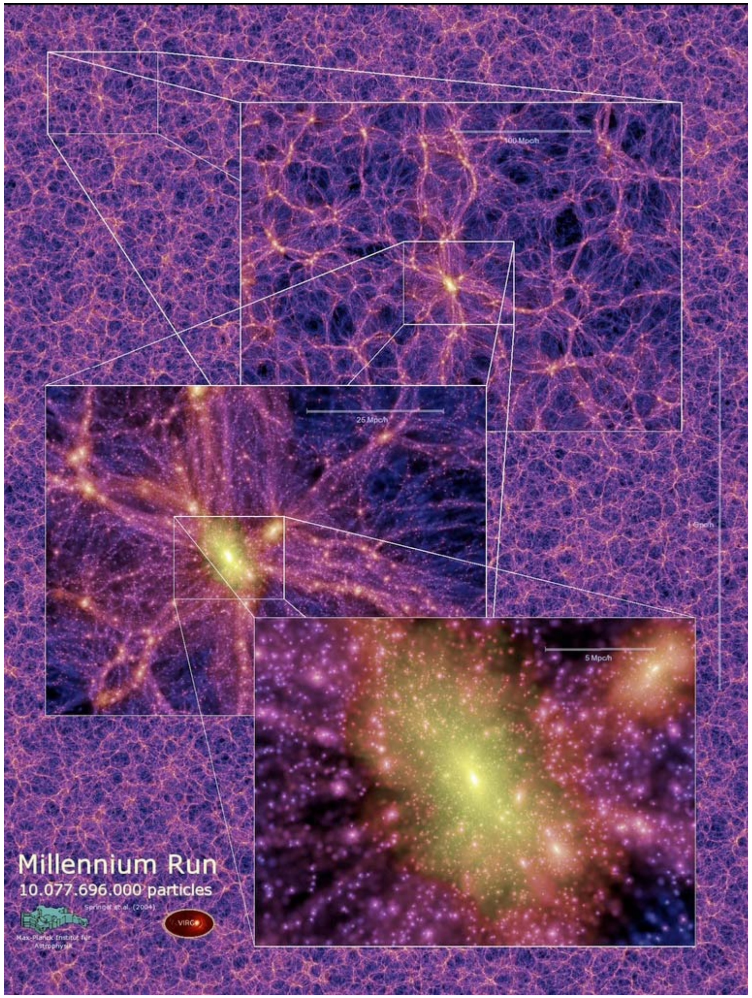
Our own galaxy provides some of the strongest evidence for the existence of supermassive black holes.

Orbits of stars near the galactic centre, Sagittarius A*, indicate the presence of a black hole with mass 4 million times that of the sun.



… if any other luminous bodies should happen to revolve about them we might still perhaps from the motions of these revolving bodies infer the existence of the central ones. Michell 1784

How do they form?



In the standard scenario, structures in the Universe build up hierarchically through repeated mergers.

If all galactic bulges have black holes, then massive binaries provide a natural evolutionary stage .

By finding such binaries we may be able to probe the cosmological growth of black holes and structure in the Universe.

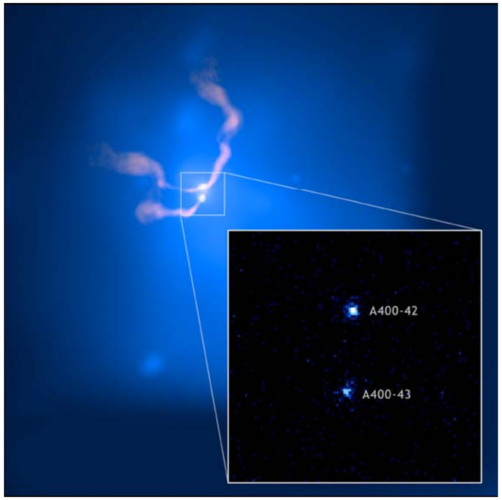
This is a key problem in modern astrophysics.

Supermassive binaries?

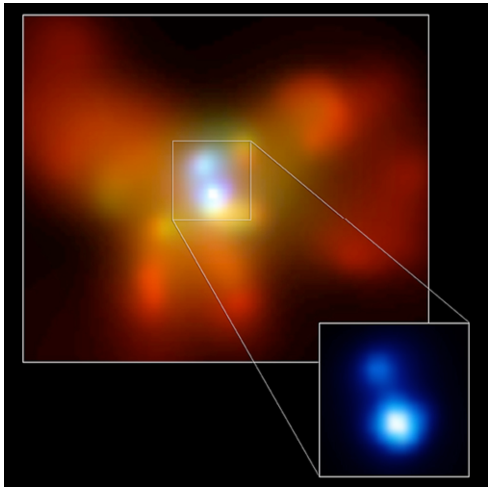
Massive black holes must build up very rapidly. The most extreme example so far is provided by SDSS 1148+5251 at redshift $z = 6.4$. Luminosity implies a black hole mass ~ $(2\text{-}6) \times 10^9\ M_o$.

This would be comparable to the largest black hole we see at $z \sim 0$, but at a time when the Universe was less than 10^9 years old.

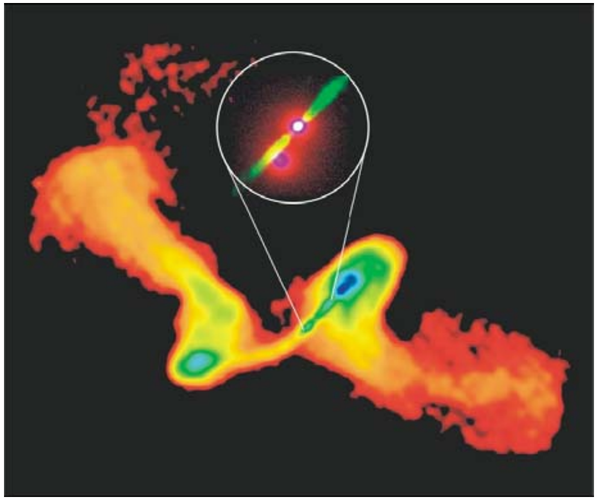
To explain this we need rapid accretion or multiple mergers.



Abell 400, separation ~ 7600 pc
(X-ray: NASA Radio:NRAO/VLA/NRL)



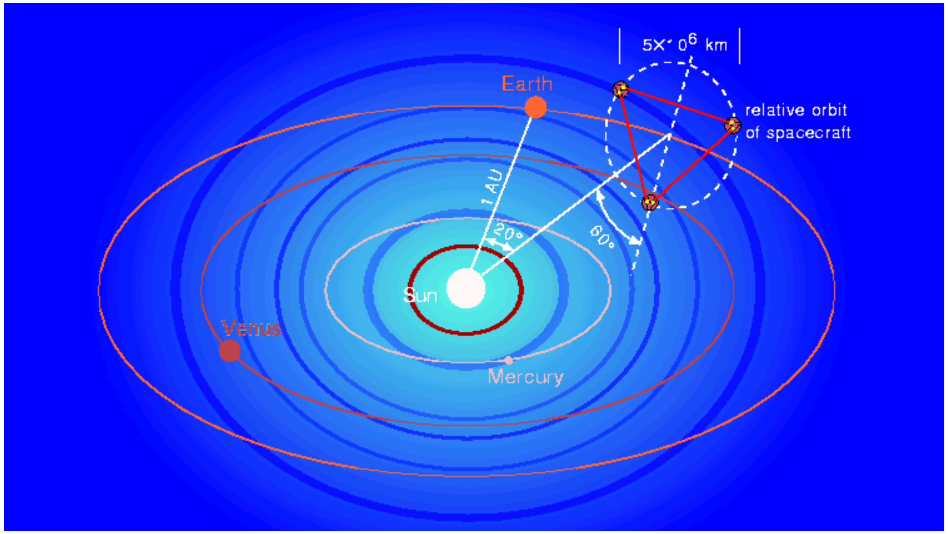
NGC 6240, separation ~ 1000pc
(NASA)



Post-merger?
(NRAO/AUI)

An interferometer in space

Merging supermassive black holes would be very strong gravitational-wave sources. But the radiation is emitted at low frequencies where ground based observations are prohibited by seismic noise.



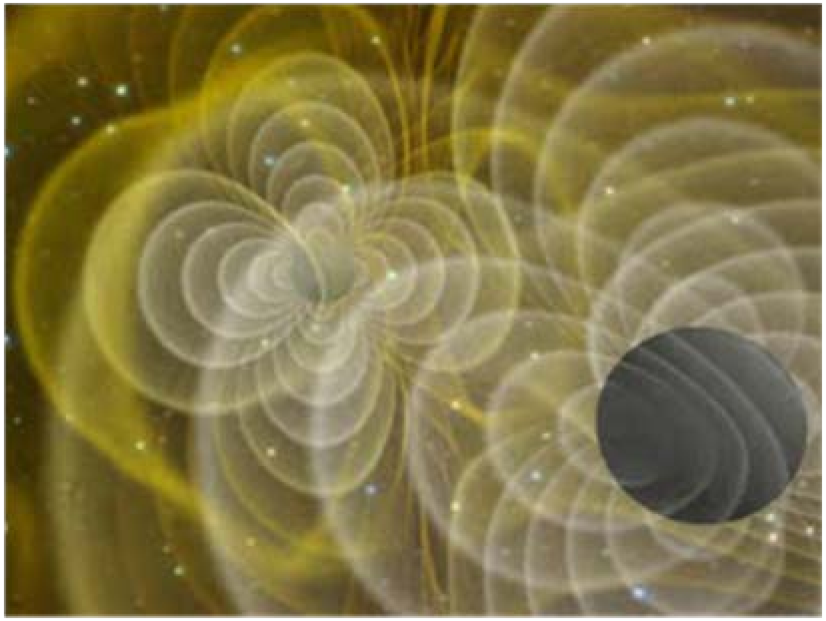
To observe such systems we need a detector in space.

LISA is a space-based interferometer with baseline of 5 million kilometers (!). It is planned for launch as a joint ESA-NASA mission around 2020.

By studying comparable mass mergers we can measure;
–the merger history throughout cosmic time.
–black hole properties to unprecedented precision.

Colliding black holes

In order to detect these gravitational-wave signals and extract as much information as possible, we need reliable theoretical models.



In the last few years there have been major advances in this area of research.

Simulations of colliding black holes are now carried out on the largest available supercomputers.