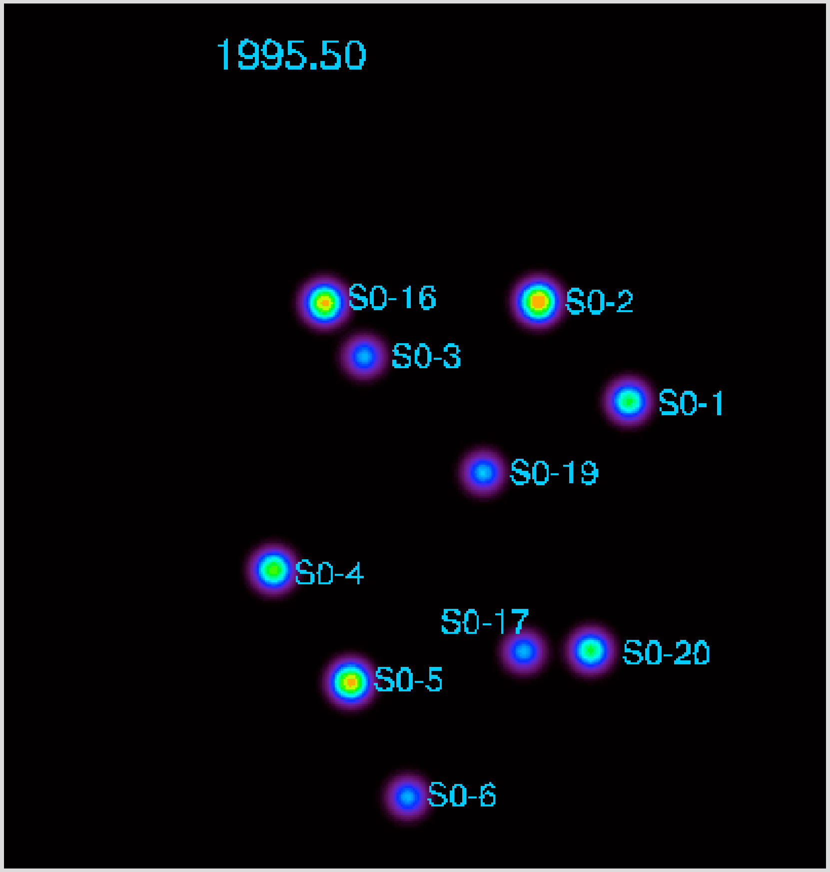
Evidence for black holes in galactic nuclei

Strongest evidence from our own Galactic center
Observe individual stars orbiting an unseen companion with a mass of around 3 x 10^6 Solar masses.



Closest approach of this star to the focus of the ellipse (the `black hole' position) is 130 AU.

Derived position of the black hole coincides with a radio and X-ray source, which varies on short timescales.

Can we `prove' the unseen mass is a black hole? No, but can demonstrate that if it's not a black hole it must be something even weirder…

A (very) dense cluster of stars

Suppose we packed 3×10^6 Solar masses of stars into a sphere of radius $r < 130$ AU. Is this stable?

First assume they are Solar mass stars, moving at velocity v. Average time for a given star to collide with another star is:

$$t_{collision} \approx \frac{1}{n \sigma v}$$

…where $\sigma = \pi (2R_*)^2$ is the cross-section for a physical collision and n is the number density of stars.

Estimate these quantities:

$$n = \frac{N_*}{\frac{4}{3}\pi r^3} = \frac{3\times 10^6}{\frac{4}{3}\pi\left(130\times 1.5\times 10^{13}\,\mathrm{cm}\right)^3} \approx 9\times 10^{-41}\,\mathrm{cm}^{-3}$$

$$\sigma = \pi (2R_*)^2 \approx 6\times 10^{22}\,\mathrm{cm}$$

$$v \approx \sqrt{\frac{GM_{enclosed}}{r}} \approx 4.5\times 10^{8}\,\mathrm{cm s}^{-1}$$

Using these numbers, find $t_{collision}$ ~ 10 years!

A super-dense cluster of ordinary stars would collide almost instantaneously (of course, we could also *see* such a cluster)…

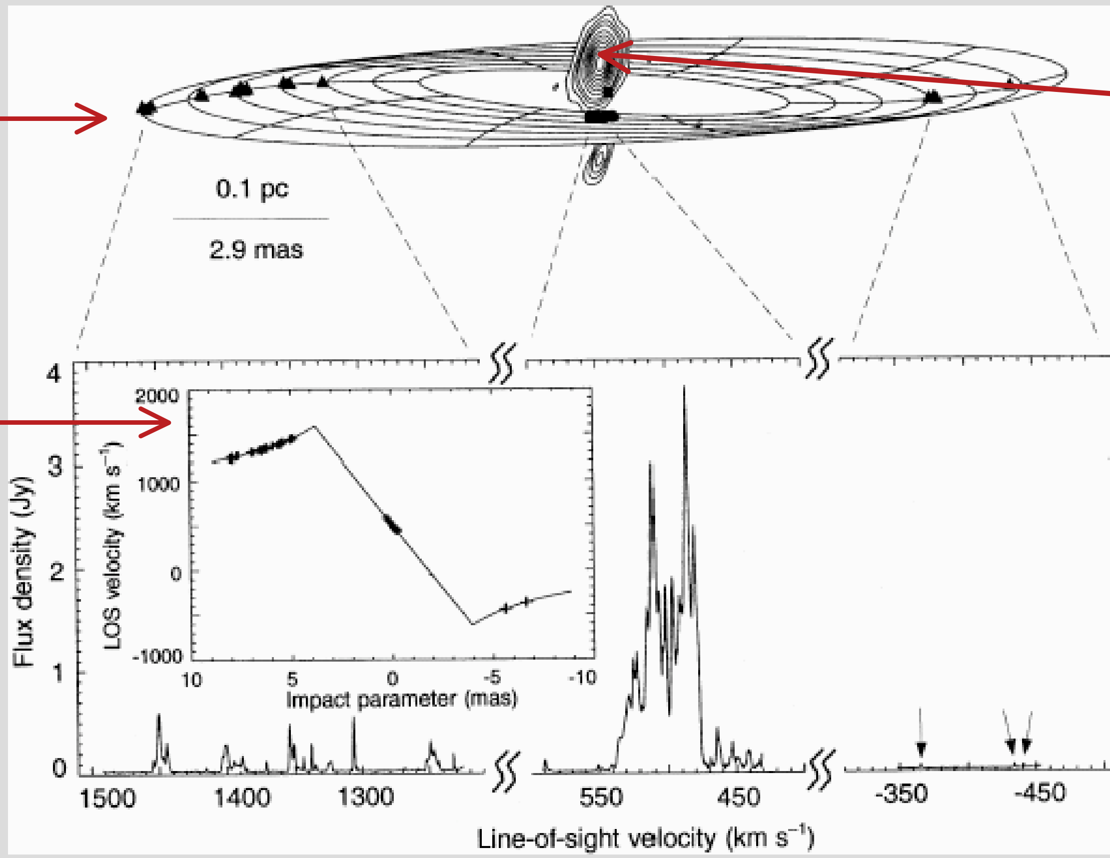
NGC4258

Next best evidence for a black hole in the galaxy NGC 4258
Observe the positions and velocities of **water masers** in a thin gas disk orbiting the black hole

Thin disk

Rotation curve

Jet



Rotation curve of the maser spots is accurately Keplerian - ie consistent with a single central point mass of:

$$M_{BH} = (3.9 \pm 0.1) \times 10^7 M_{sun}$$

…most accurately measured black hole mass

Maser emission extends from 0.16 pc to 0.28 pc - close enough that non-black hole explanations are difficult

Also, NGC 4258 is an AGN

Unfortunately, only a small fraction of AGN have observable water masers in their disks, and of those that do, this example is much the best…

Most black hole masses are derived from less accurate methods:

Gas disk kinematics

Measure the velocity of gas disks in the nucleus, correct for inclination, and assume Keplerian motion. Then use:

$$M = \frac{rv^2}{G}$$

…to estimate mass from observed radius and velocity

Works well, but less accurate because:

- Measurements are made much further from the black hole (~100 pc)
- Gas disk may have more complex motions (eccentricity, pressure support)

Stellar kinematics

If the velocity dispersion in the galaxy is σ, black hole will dominate motion of stars with a radius r_{BH}, the black hole's **sphere of influence**, given by:

$$\sqrt{\frac{GM_{BH}}{r_{BH}}} = \sigma \quad \Rightarrow \quad r_{BH} = \frac{GM_{BH}}{\sigma^2}$$

Subtler effects on stellar orbits outside this radius

If we can measure the velocities of stars within the sphere of influence (from spatially resolved spectra), expect to see increase in stellar velocities due to presence of black hole

⇒ use detailed galaxy models to derive mass.

This is very difficult in practice

e.g. consider a black hole of mass 10^8 M_{sun}, at the center of a galaxy with velocity dispersion σ = 200 km/s

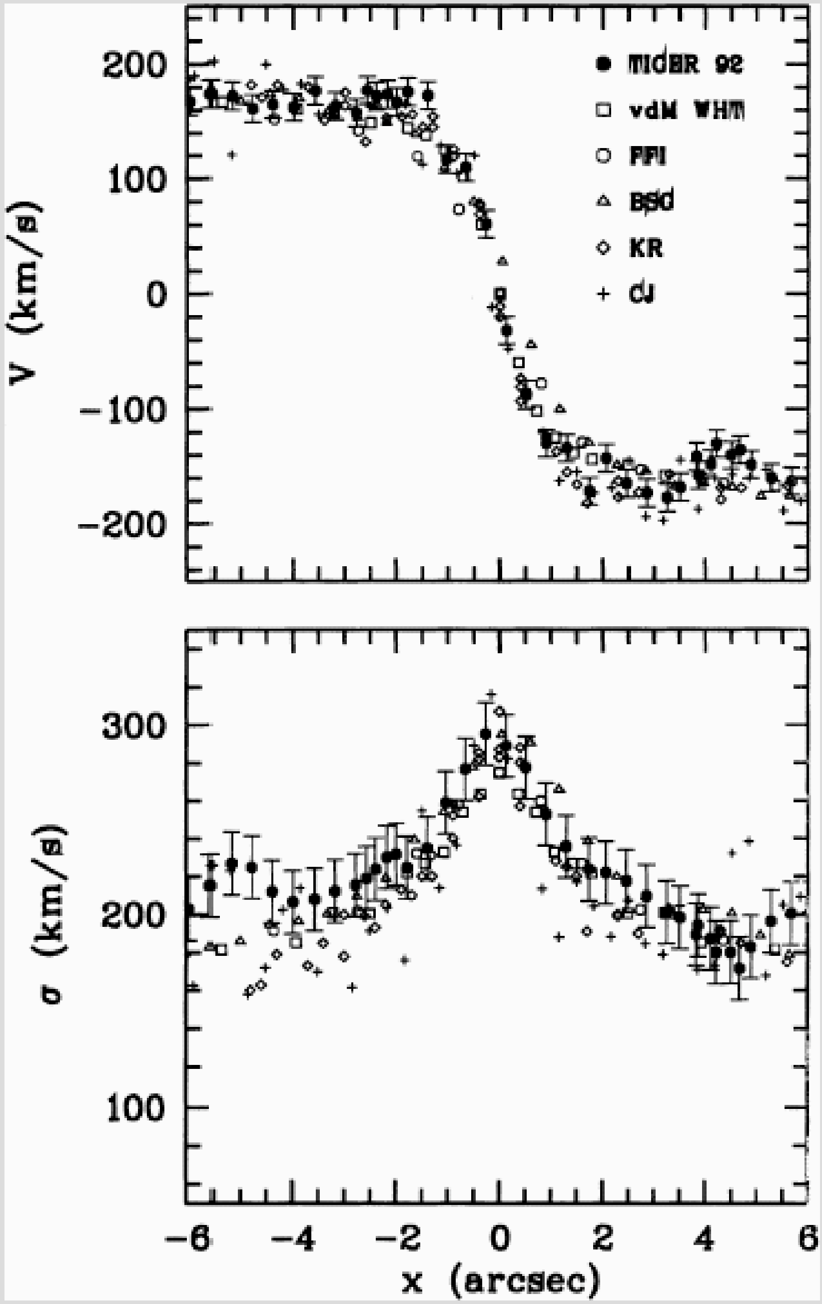
Sphere of influence is r_{BH} = 11 pc

For a galaxy in the Virgo cluster (distance 16 Mpc), the angular size of the sphere of influence is 0.14 arcseconds

Feasible for nearby galaxies, and requires HST resolution.

Rotation curve

Velocity dispersion

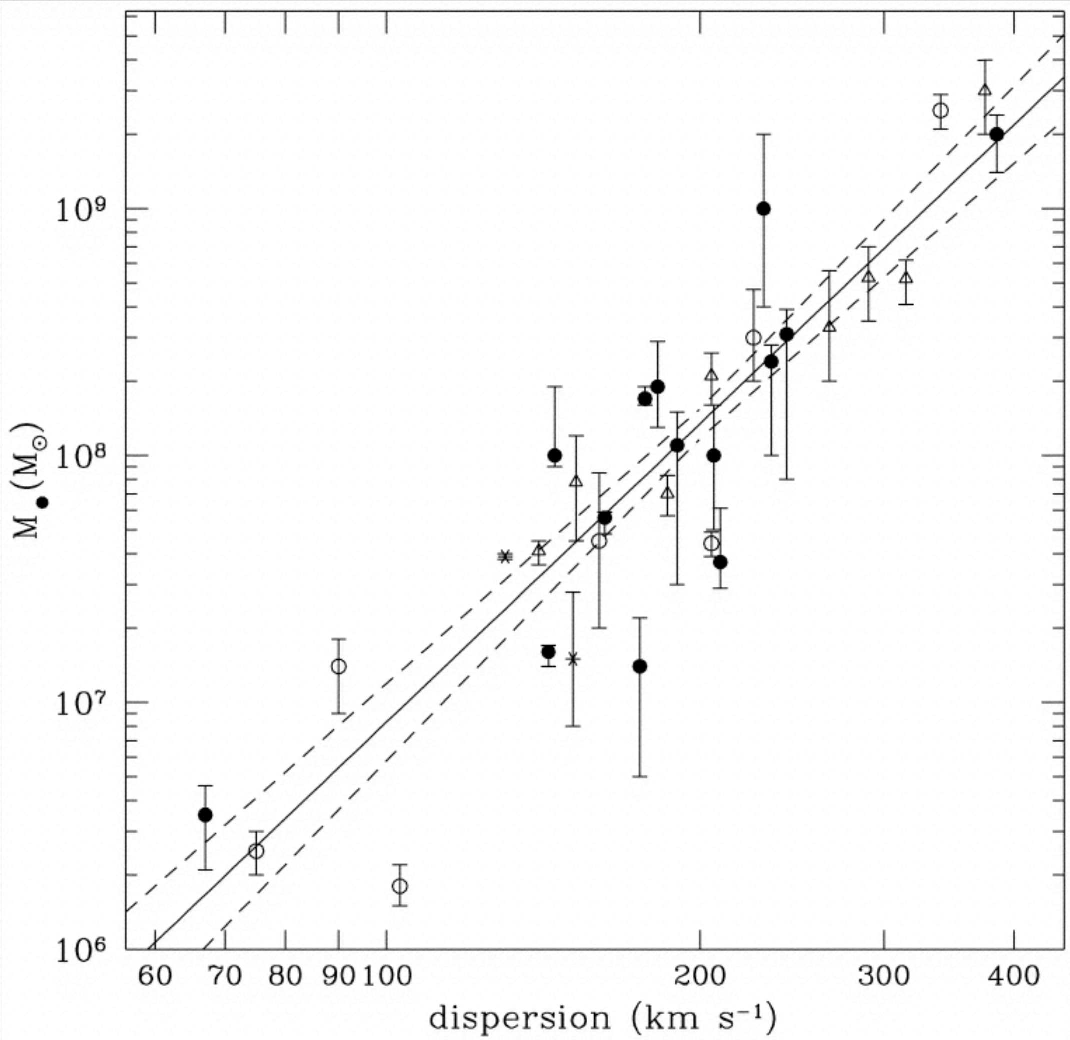


NGC 3115

Reasonably `easy' galaxy - close (10 Mpc) with evidence for a massive black hole of 10^9 Solar masses

Clear rise in the velocity dispersion, but only within central arcsecond

The M-σ relation



Plot the derived black hole mass against the velocity dispersion of the galaxy

Find that: $M_{BH} = C\sigma^4$ where C is a constant

Recall Faber-Jackson law: $L \sim \sigma^4$

Implies black hole mass *roughly* proportional to luminosity of the bulge

This relationship has apparently very little scatter