OBSERVATIONS OF STELLAR-MASS BLACK HOLES & THE GALACTIC CENTER

PROBLEM SET #6 ON WEBWORK – DUE WEDNESDAY, 11/6 AT MIDNIGHT

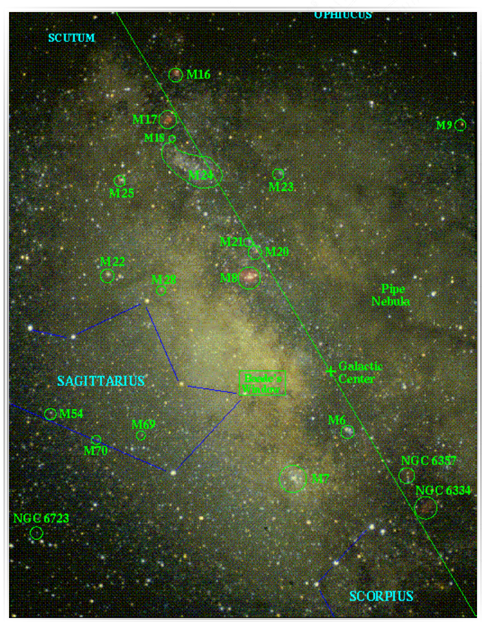
HALLOWEEN EXTRA CREDIT!

OBSERVATIONS OF STELLAR-MASS BLACK HOLES & THE GALACTIC CENTER

Results for stellar-mass black holes: two almost-certain examples

- Cygnus X-1
- GRO J1655-40

The center of the Milky Way galaxy: compelling evidence for a 4.2 million solar-mass black hole



Wide-angle photo and overlay key of the Sagittarius region of the Milky Way, showing the effect of obscuration by dust clouds. The very center of the Milky Way lies behind particularly heavy dust obscuration (Bill Keel, U. Alabama)

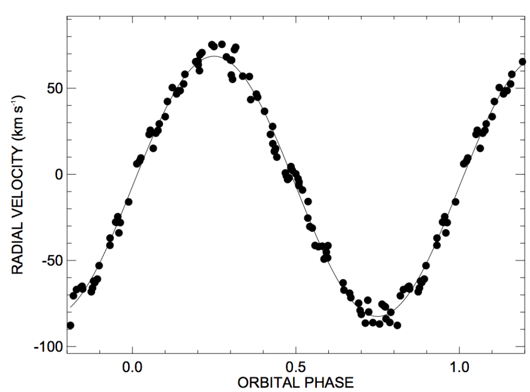
DISCOVERY OF "STELLAR" BLACK HOLES: CYGNUS X-1

Cygnus X-1 (a.k.a. Cygnus XR-1) is the second-brightest X-ray source in the sky.

- Its X-ray brightness varies dramatically on time scales of 0.001 s: the X-ray object must be about 0.003 ls (940 km) in circumference.
- Essentially at the same position as the X-ray source is a bright star that appears to be in orbital motion. No other visible star nearby exhibits orbital motion; the bright star's companion is invisible. Other stars like it are not bright in X-rays. It is thus reasonable to assume that the bright star's invisible companion is the X-ray source.
- The star and the invisible companion are too close together for telescopes to **resolve** them from our distance.

CYGNUS X-1

- Orbital parameters of the bright star (HDE 226868): distance of 7300 ly, revolution period of 5.6 days, orbital circumference of $1.8{\times}10^8$ km, mass of about $40M_\odot$.
- The tilt of the orbit has been determined with difficulty (and not with great accuracy): the rotation axis makes an angle of about 27° with respect to our line of sight (Miller-Jones et al., 2021).
- Applying these inputs to Newton's laws of motion, a mass between 19 and $23M_\odot$ is derived for the invisible companion; most probable value is $21.2M_\odot$ (Miller-Jones et al., 2021). A black hole?

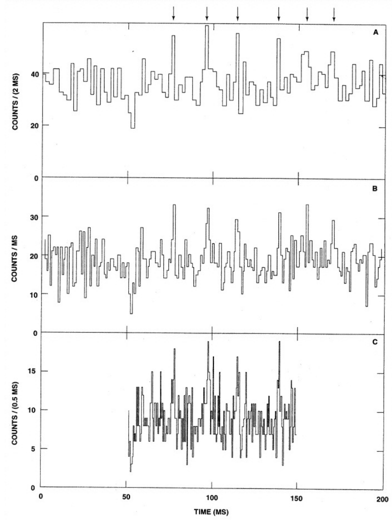


Measured orbital motion of HDE 226868 (Gies et al. 2003)

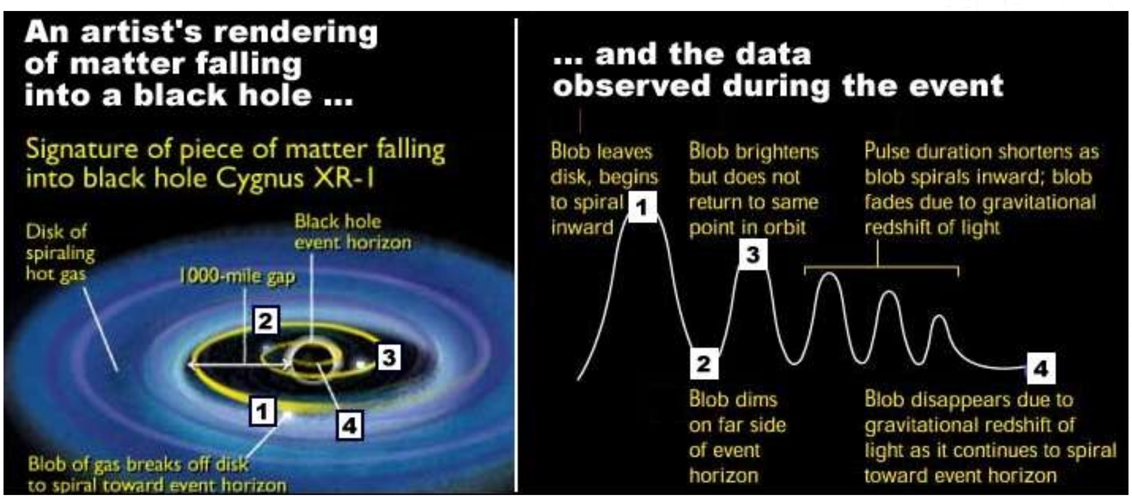
"DEATH SPIRALS" IN CYGNUS X-1: THE EVENT HORIZON?

Occasionally, Cyg X-1 emits short bursts of light seen at ultraviolet wavelengths, in the form of a train of pulses that dies off toward the end. One such burst, seen with the Hubble Space Telescope by Dolan (2001), is shown on the right.

- Pulse period close to orbital period near innermost stable orbit
- Are we seeing material falling from an unstable orbit and passing through the horizon once per orbit?



"DEATH SPIRALS" IN CYGNUS X-1: THE EVENT HORIZON?



CYGNUS X-1: SUMMARY

- Too small, too X-ray bright, and too faint at visible wavelengths to be a $21.2M_{\odot}$ star.
- Far too massive to be a white dwarf or neutron star
- Evidence of orbit instability, **and of an event horizon**, on precisely the scales expected for a $21.2M_{\odot}$ black hole

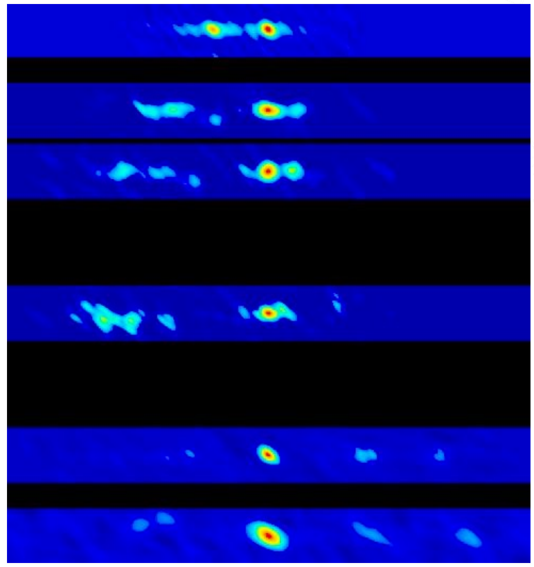
The simplest, and least exotic, interpretation of the observations is that Cygnus X-1 consists of a $40M_{\odot}$ star and a $21.2M_{\odot}$ black hole in orbit around each other.

(Stephen Hawking, who used to assert that Cyg X-1 does not contain a black hole, conceded his celebrated bet with Kip Thorne on this subject; see Thorne's book, pg. 315.)

DISCOVERY OF "STELLAR" BLACK HOLES: GRO J1655-40

GRO J1655-40 (a.k.a. Nova Scorpii 1994) is an X-ray transient source discovered by NASA's *Compton* Gamma-Ray Observatory (GRO) in 1994.

- Rapidly-variable emission in its X-ray bursts: the X-ray object is a few hundred km around.
- The X-ray source has a stellar companion, a star rather like the Sun (about $1.1M_{\odot}$); the X-ray source and the visible star revolve around each other with a period of 2.6 days. Their distance from us is measured to be 10,000 ly (Jonker & Nelemans 2004).
- A stroke of luck: it is an **eclipsing** system, so the orbit is known to be tilted edge-on to our line of sight.
- Therefore, we know the mass of the X-ray bright companion rather accurately: it must be between 5.5 and $7.9M_{\odot}$, with a most probable value of $7.0M_{\odot}$ (Shahbaz et al. 1999).
- Also has radio jets with motions close to the speed of light!



GRO J1655-40

Two jets, perpendicular to the plane of the orbit, with ejection speed $0.92c$.

Radio images: R. Hjellming & M. Rupen, NRAO

GRO J1655-40 SPINS

We expect it to spin, but now we can demonstrate this:

A $7M_{\odot}$ black hole has a horizon circumference of 130 km, and if it does not spin, its innermost stable orbit circumference is 390 km. Material in this orbit will circle the black hole **314 times per second**.

- However, the X-ray brightness of GRO J1655-40 has been seen to modulate **450 times per second** for long stretches of time (Strohmayer 2001).
- Nothing besides very hot material in a stable orbit can do this so reproducibly at this frequency.
- Therefore, there are stable orbits closer to the black hole than they could be if it did not spin.

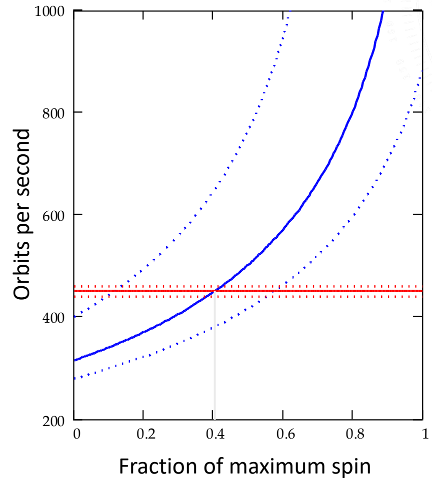
GRO J1655-40 SPINS

Most probably, the black hole in GRO J1655-40 is spinning at about 40% of its maximum rate. Within the uncertainties, the spin rate lies in the range 12%-58% of maximum; zero spin is quite improbable.

In blue: innermost stable orbits per second for a $7.0M_{\odot}$ black hole, with uncertainties

In red: measured orbits per second, with uncertainties

(by Tod Strohmayer, with the Rossi X-ray Timing Explorer)

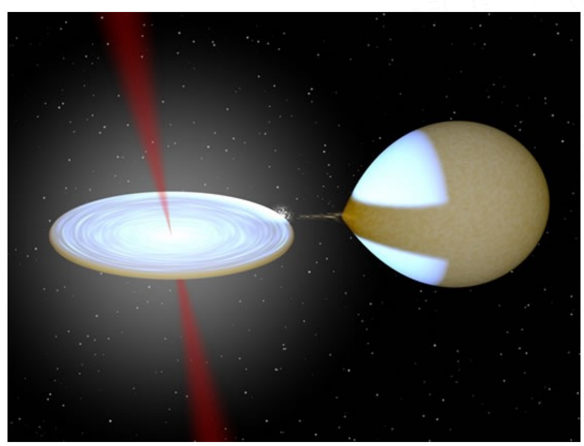


GRO J1655-40: SUMMARY

The invisible companion object:

- X-ray bright
- Too small to be a white dwarf star
- Too massive to be either a white dwarf or a neutron star
- Associated with ejecta traveling at 92% of the speed of light
- Associated with orbital frequencies appropriate for a spinning black hole

These properties make GRO J1655-40 more likely to harbor a black hole than most other objects we know.



Artist's conception of GRO J1655-40

DISTINCTIVE FEATURES THAT INDICATE THE PRESENCE OF A BLACK HOLE

Observe **two or more** of these features to “find” a black hole:

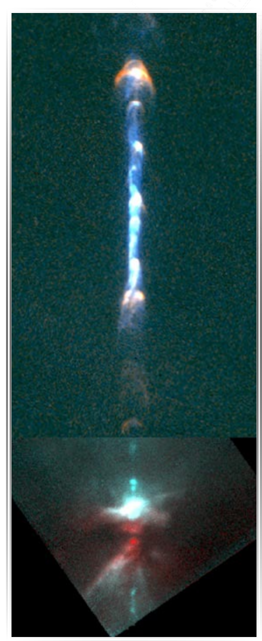
- **Gravitational deflection of light** by an amount requiring black hole masses and sizes
- **X-ray and/or γ-ray emission** from ionized gas falling into the black hole
- **Orbital motion of nearby stars or gas clouds** that can be used to infer the mass of (perhaps invisible) companions: a mass too large to be a white dwarf or neutron star might correspond to a black hole.
- **Motion close to the speed of light** or apparently greater than the speed of light (“superluminal motion”)
- **Extremely large luminosity** that cannot be easily explained by normal stellar energy generation
- Direct observation of a large, massive **accretion disk**

IS THERE A BLACK HOLE THERE?

HH 111 (HST images by Reipurth et al. 1999):

- Starlike object obscured by dusty disk
- Luminosity is $9.6{\times}10^{34}$ erg/s
- Shines mostly at visible and infrared wavelengths
- Twin jets, each 24 ly long, of material flowing out from the central object at 500 km/s

How many black hole characteristics does HH 111 have?

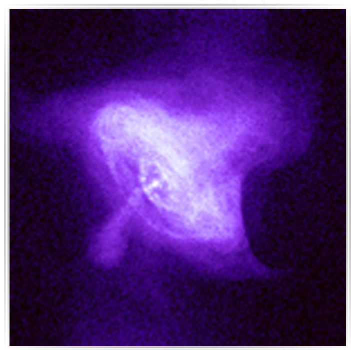


IS THERE A BLACK HOLE THERE?

PSR 0531+21 (*Chandra* X-ray Observatory image):

- Starlike object with luminosity 10^{30} erg/s surrounded by a very hot disk
- Brightest at radio and X-ray wavelengths
- Twin jets
- Surrounding material flowing outwards at several hundred km/s
- Brightness oscillates extremely regularly: 30 pulses per second

How many black hole characteristics does PSR 0531+21 have?



BLACK HOLES IN GALAXY NUCLEI

Why might we expect to find black holes in the centers of galaxies?

- Densest part of the galaxy since birth: there are many more stars per cubic light year – and presumably, many more of every other kind of object, too.
- The galactic garbage can: as objects further out in the galaxy occasionally collide, material (or objects) released in the collision tends to fall into the galactic center.

Starlight from the Milky Way: visible (top) and near-infrared (bottom), the latter from the NASA COBE satellite.

ORBITAL MOTION & THE CENTER OF THE MILKY WAY, SAGITTARIUS A WEST

The center of the Milky Way is obscured by interstellar dust; it cannot be seen at visible through longer X-ray wavelengths.

- It is bright at infrared and radio wavelengths, and **hard** (short-wavelength) X-rays, which are transmitted through the dust.
- The name Sagittarius A indicates that it is the brightest radio source in the constellation Sagittarius (abbreviated Sgr). It was also the first extraterrestrial object discovered at radio frequencies, by Karl Jansky in 1933.

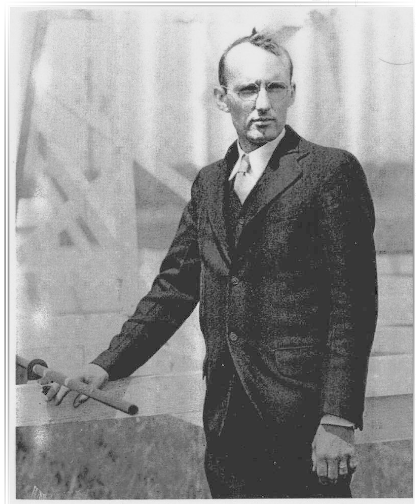
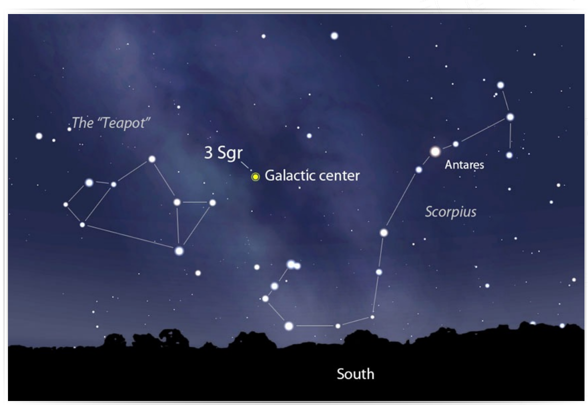


FIG. 1—Karl Guthe Jansky, about 1933.

ORBITAL MOTION & THE CENTER OF THE MILKY WAY, SAGITTARIUS A WEST

Within the central 10 ly, we find a dense cluster of stars, a bright, compact radio source, and a swirl of gas clouds.

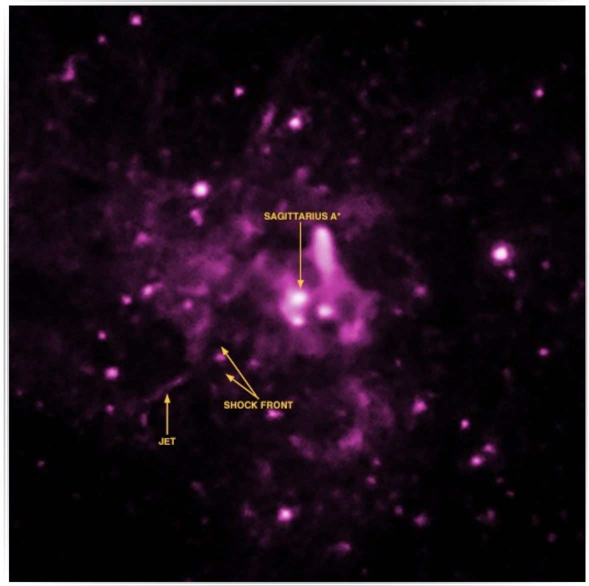
- The small, bright radio source (Sagittarius A* = **Sgr A***) resembles the objects at the centers of quasars, but it has a much smaller luminosity.
- Sgr A* lies **precisely** at the center of our Galaxy – at the place about which everything in the galaxy revolves.



*Where to find Sgr A**

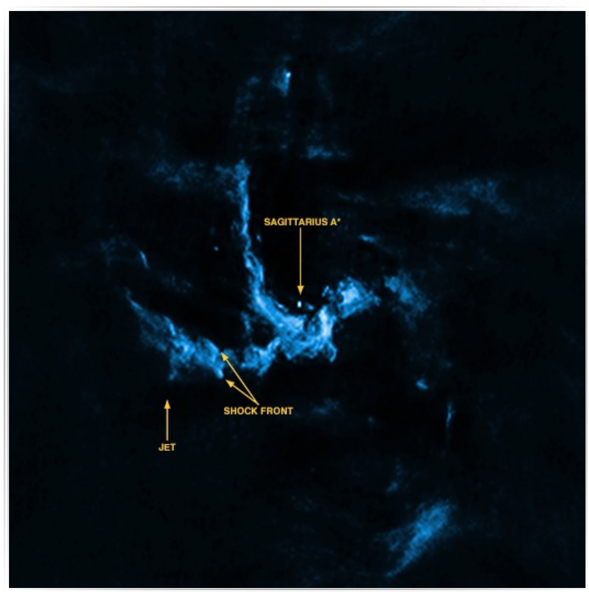
X-RAY IMAGE OF THE CENTRAL 6.5 LY OF SGR A WEST

Sgr A* is the brightest starlike object in the center of the image. By Li et al. (2013) with the *Chandra* X-ray Observatory (CXC).



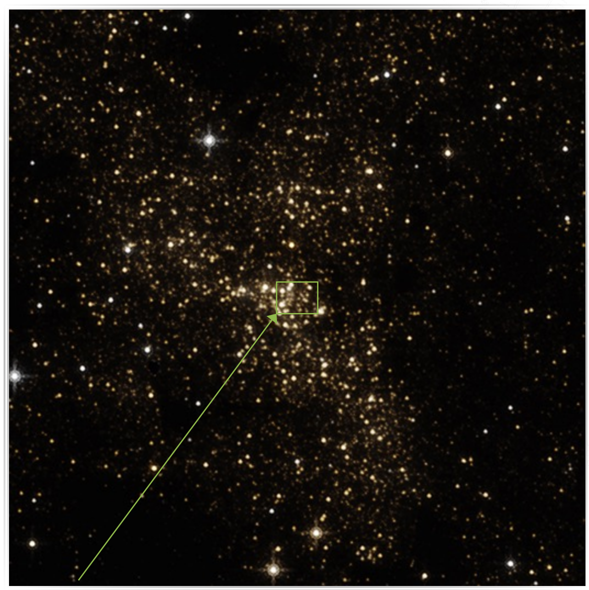
RADIO IMAGE OF THE CENTRAL 6.5 LY OF SGR A WEST

Sgr A* is the bright point in the center of this image by Li et al. (2013) taken with the NRAO Very Large Array (VLA).



NEAR-INFRARED IMAGE OF THE CENTRAL 6 LY OF SGR A WEST

Sgr A* does not appear in this image, as it is drowned out by the light of all the stars (NASA/STScI).

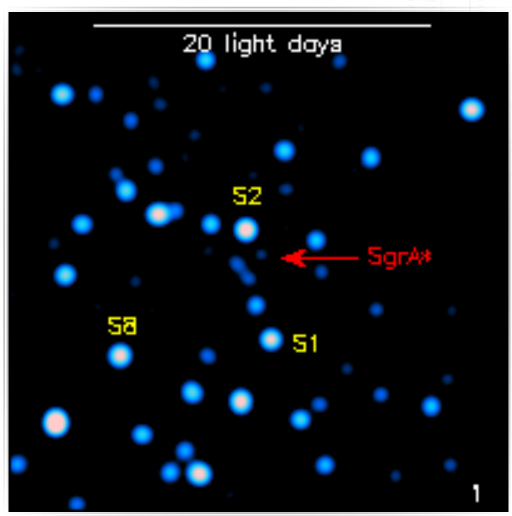


Area in next image

NEAR-INFRARED IMAGE SEQUENCE OF THE CENTRAL 30 LIGHT-DAYS OF SGR A WEST

Adaptive-optical imaging has made it possible to finally see Sgr A* at infrared wavelengths.

Most of the infrared light it emits comes in the form of short “flares,” as in this image sequence.



Genzel et al. (2003); see also Ghez et al. (2004) and http://www.mpe.mpg.de/ir/GC

ORBITAL MOTION & THE CENTER OF THE MILKY WAY, SAGITTARIUS A WEST

Over the course of the last four decades, astronomers have measured velocities related to orbital motion about the center for many objects that lie within the central few light years of the Galaxy:

- Doppler shifts in the spectra of gas clouds
- Doppler shifts in the spectra of stars
- **Proper motions** of stars (motion across the sky, perpendicular to the line of sight)

From the orbital-motion velocities, it is possible to calculate the **mass enclosed** by each orbit in much the same way as calculating the mass of one star from the spectrum of another orbiting star.

ORBITAL MOTION & THE CENTER OF THE MILKY WAY, SAGITTARIUS A WEST

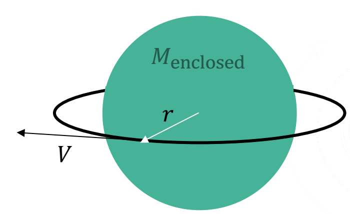
In this case, the conversion of the Doppler-shift velocities into enclosed mass is simpler than it is for binary stars, since the mass enclosed by orbits around the Galactic center is so much larger than the mass of individual orbiting objects that we can presume the center of the orbit to stay fixed.

The math (provided only for those curious; not on any exam):

$$F = ma$$

$$\frac{GmM_{\text{enclosed}}}{r^2} = m\frac{V^2}{r}$$

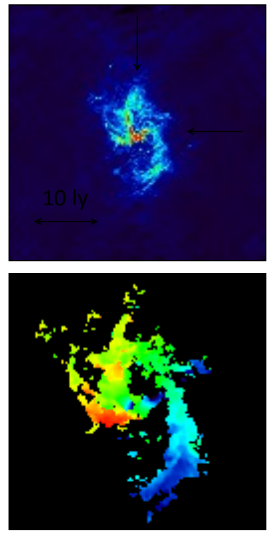
$$M_{\text{enclosed}} = \frac{rV^2}{G}$$



GAS CLOUDS IN ORBIT AROUND SGR A*

At radio wavelengths, most of the bright objects near Sgr A* are gas clouds in orbit around Sgr A*.

- In the top false-color radio-wave image, Sgr A* appears as a small white dot (follow the arrows). The "swirls" are streamers and clouds of ionized gas in orbit about the Galactic center.
- The lower image is a color code of the speed of the ionized gas along our line of sight. Red = receding at about 200 km/s; blue = approaching at about 200 km/s.

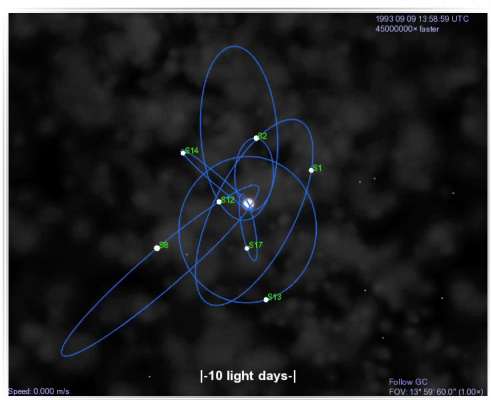


Data: Roberts & Goss (1993), using the NRAO VLA

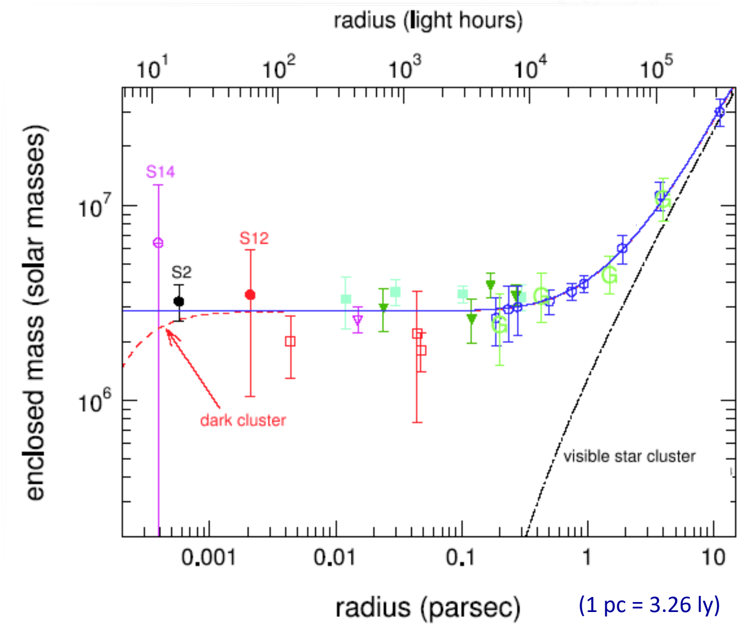
STELLAR MOTIONS CLOSE TO SGR A*

The brightest stars in the central 10 light-days of the Milky Way, as seen in infrared wavelengths over the course of fifteen years.

- Note the high speeds (over 5000 km/s) and close approach to Sgr A* by some of the stars.
- One has an orbital period of only 15.2 years and passes within 124 Earth-Sun distances of the black hole.



From the MPE group (Genzel et al.)



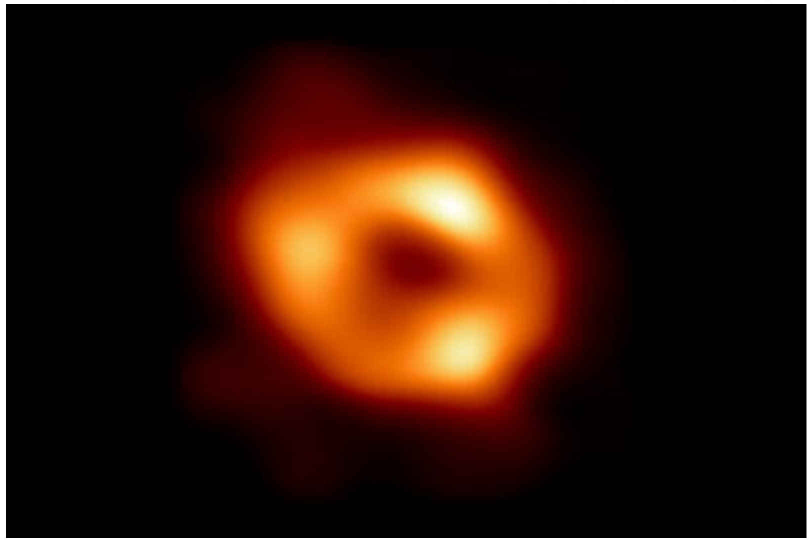
ORBITAL MOTION & THE CENTER OF THE MILKY WAY

Summary of the results from stellar and gas-cloud Doppler shifts and proper motions (Schödel et al. 2003).

ORBITAL MOTION & THE CENTER OF THE MILKY WAY

Results:

- The stellar and gas-cloud Doppler shifts get larger the closer the stars or cloud is to Sgr A*.
- The stellar proper motions are generally larger the closer the star is to Sgr A*.
- If the stellar cluster were all that were there (no massive black hole), the velocities from Doppler shifts or proper motions would decrease toward zero as you looked closer to the center because there would be less and less mass enclosed by the stellar orbits.
- If there were a massive black hole, the enclosed mass derived from the stellar orbits of smaller and smaller size would approach the black hole's mass.



SGR A* WITH THE EHT

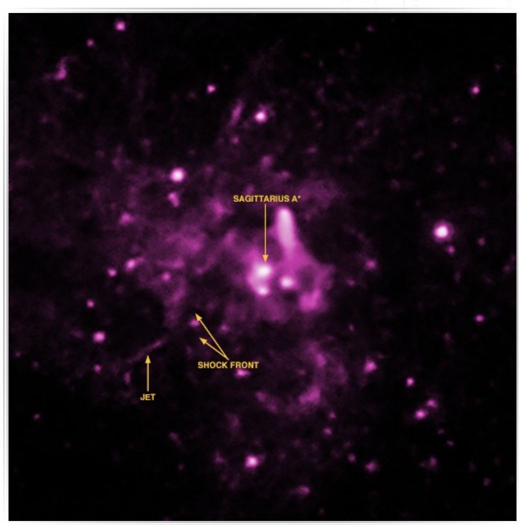
The first direct visual evidence of the presence of a supermassive black hole at Sgr A*, this is an image of the hot, ionized material in one of the smallest orbits around the black hole's horizon.

Comparing the image with simulations gives a mass of $4.0^{+1.1}_{-0.6}\times10^{6}M_{\odot}$ (EHT 2022).

THE BLACK HOLE AT THE CENTER OF THE MILKY WAY

The evidence is compelling: **there is a black hole at the center of the Milky Way,** its mass is $(4.154 \pm 0.014)\times10^{6}M_{\odot}$, and it spins at about 25% of its maximum rate.

- Presumably, the radio and X-ray components of Sgr A* are the outermost and innermost parts of the accretion disk around the black hole.
- The near-infrared flares probably also arise from the innermost, hottest part of the disk, with the quasiperiodic oscillations coming from the innermost stable orbit.
- Only the faintest of jet remnants are seen, though.



THE BLACK HOLE AT THE CENTER OF THE MILKY WAY

Some follow-up questions:

If Sgr A* contains a massive black hole, why is it so much fainter than those in quasars?

- Most of the answer: At the moment, there does not happen to be enough accrete-able material in the neighborhood of Sgr A*'s black hole to provide a quasar-like luminosity. This would also explain the lack of jets.
- It is also not quite massive enough for quasar-size luminosity, as we will see next lecture.

Stellar-mass black holes, like those in Cygnus X-1 and GRO J1655-40, were formed by the gravitational collapse of dead stars. There are no million-solar-mass stars; how did the black hole in Sgr A* form?

- We do not yet know for sure – this question describes one of the most active research areas in astronomy – but it may have formed small, in the normal fashion, and have grown by swallowing material slowly during the long life of our Milky Way Galaxy ($\sim 1.2{\times}10^{10}$ years old).