Downtown Milky Way

you can always go…

Richard Edgar, Learners @ Wind Crest, Nov 11, 2020
RichardJEdgar.github.io for course materials, slides, resources.

- Gravity theories:

- Isaac Newton, building on the work of Kepler on planetary orbits. The plague shut down Cambridge and he went home, invented calculus to describe the motion of the moon, and postulated gravity as a force between all objects in the universe. (What have you been doing with your pandemic time??)

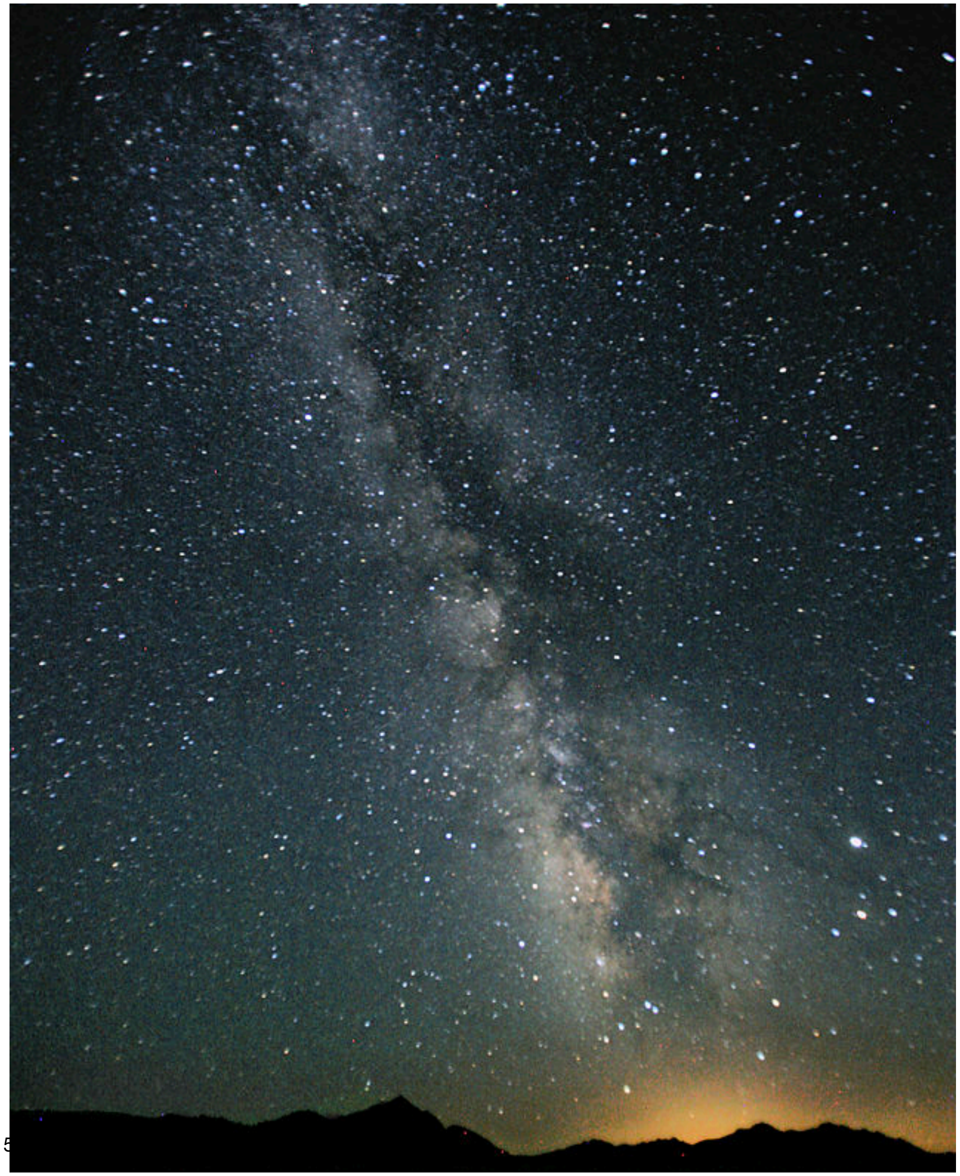
- Albert Einstein's General Theory of Relativity picks up where Newton left off: mostly in the strong field regime. It's difficult to test, but passes every test people have come up with.

- Mordechai Milgrom's various "modified Newtonian Dynamics" theories… haven't caught on.


?
LATCH
YTIVARG.

The Milky Way Galaxy

- There’s a band of light, zillions of stars, stretching across the night sky. It’s a little hard to figure out what shape it is because we’re in it.
- The Greeks called it γαλαξίας κύκλος, *galaxias kuklos*, the milky circle, hence our word Galaxy.
- Let’s take a brief tour of our Galaxy, a look at others, and then go downtown.

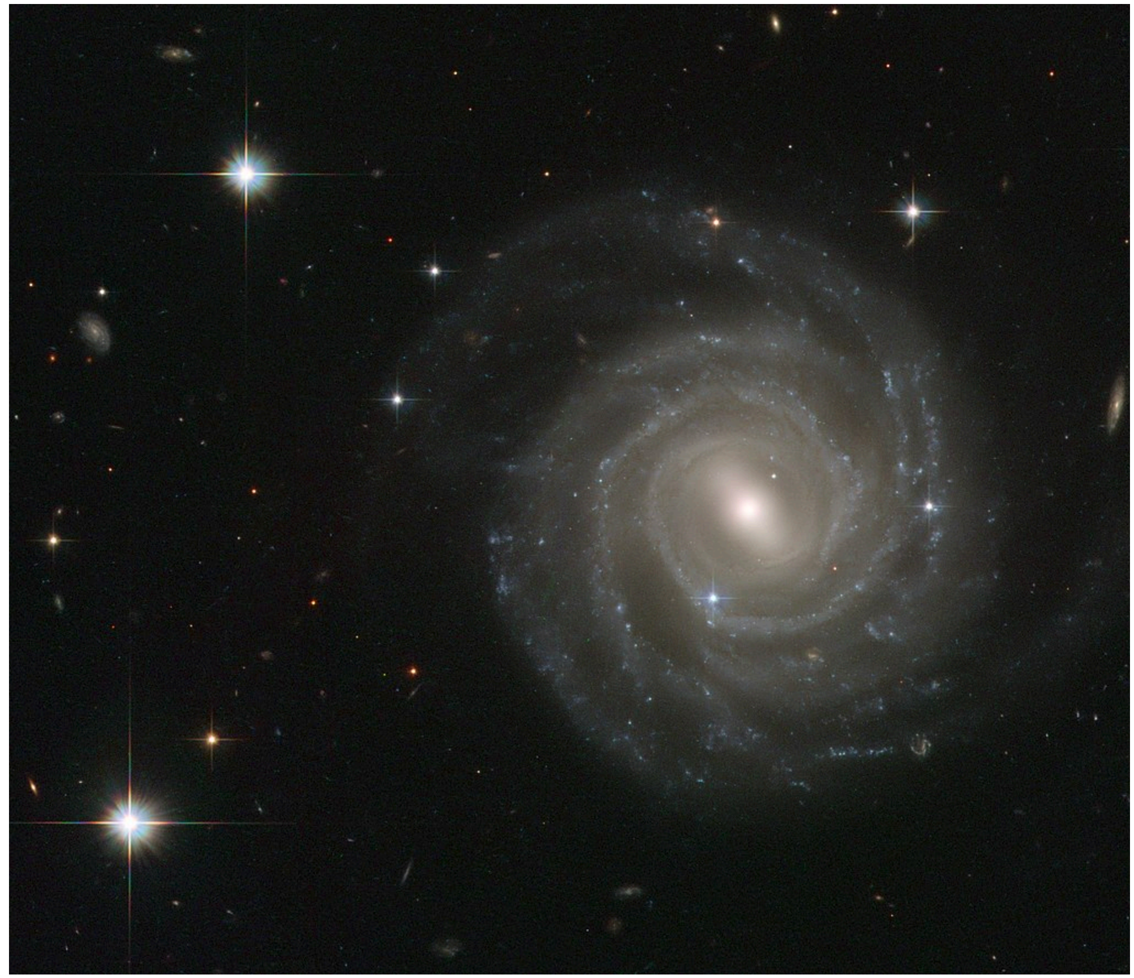


Flat (like a vinyl record)

- The Galaxy is flat like a phonograph record. Imagine replacing the label with an orange.
- We're about 2/3 of the way out.
- We look at it edge-on.
- Stars tend to be arranged in a spiral pattern (not as tightly wound as a record).
- For younger audiences I explain here what a record is.

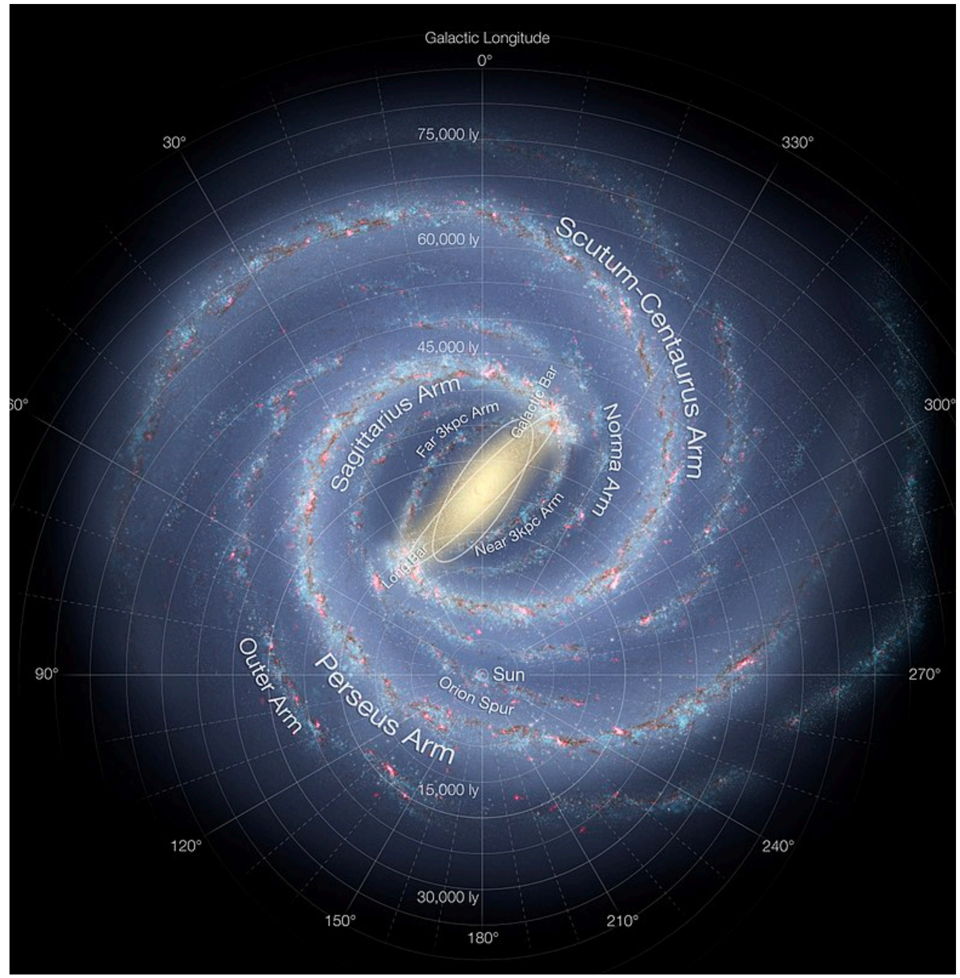
A similar galaxy

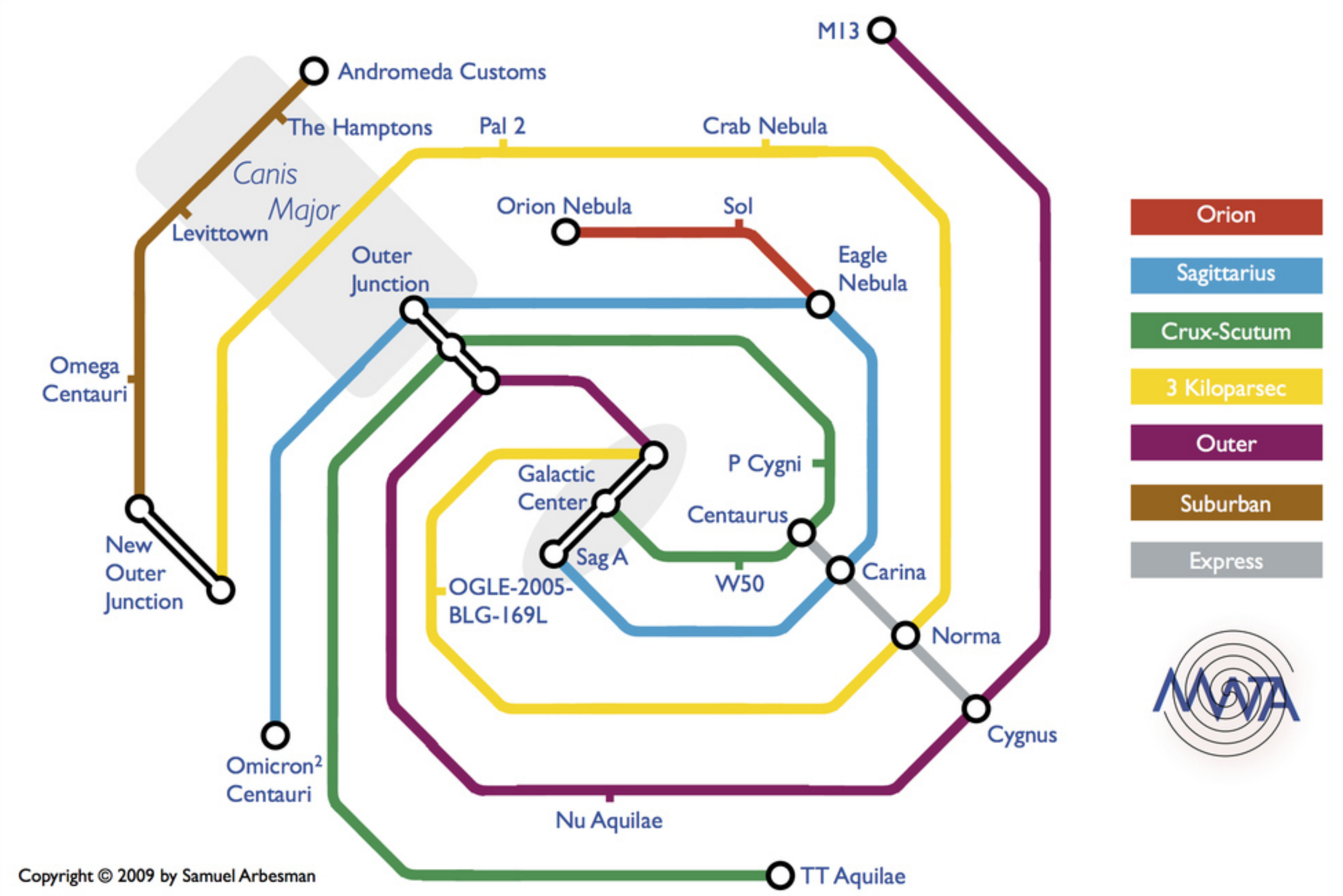
- This is a Hubble image of the galaxy UGC 12158, thought to be similar to the Milky Way.
- Note the spiral arms
- Note also the bar sticking out of the nucleus
- If this were the Milky Way, the Sun might be near the center of the frame.
- The star images with spikes are foreground. Ignore them.



A map of the Milky Way

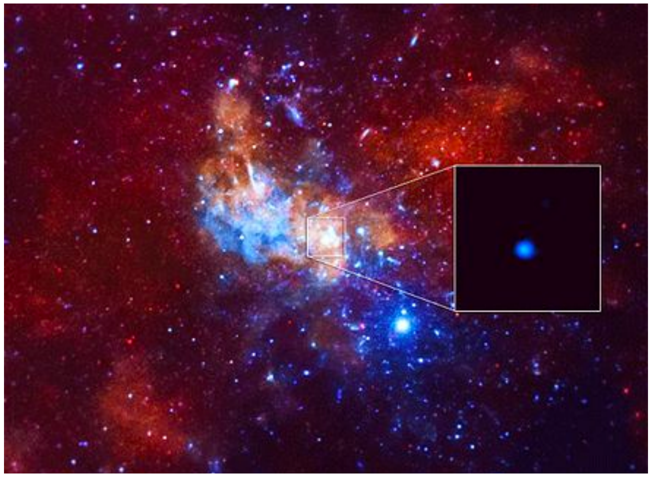
- Many radio measurements of hydrogen and star-forming regions give velocities and (some) distances
- The center of the Galaxy is about 27k light-years away from us.
- Stars revolve around the center; we're moving about 220 km/sec to the left in this diagram.
- Stars move through the spiral arms as they orbit.





Milky Way Transit Authority

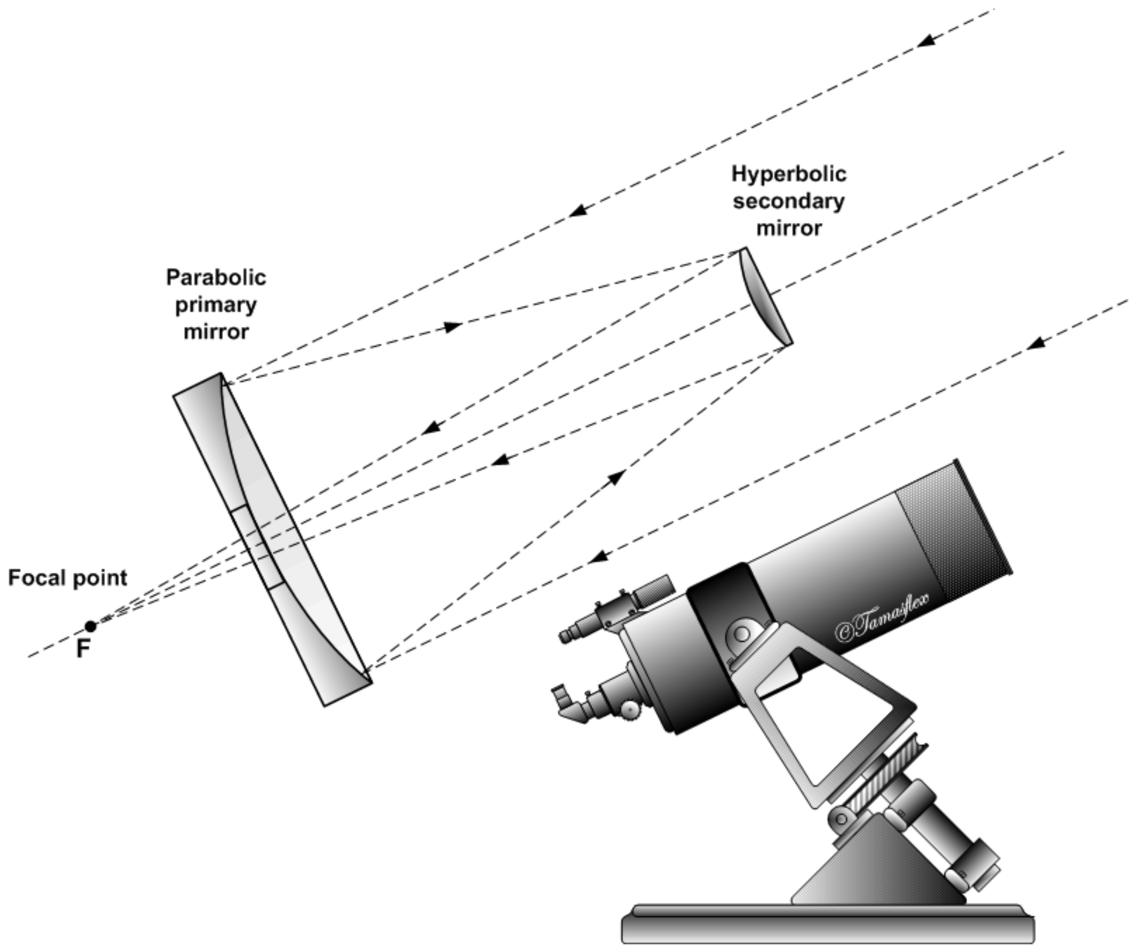
- How much stuff is there in the Galaxy?
- Typically we answer such questions using observations of velocities, and what we know about gravity, by counting stars, by adding up all the light.
- There are something like 100 billion stars in our Galaxy, more of them closer to the center than we are. There's also a fair amount of gas and dust. Some of it is in clouds, forming new generations of stars (e.g. Orion).
- There's quite a lot of dust along our line of sight to the Galactic Center.
- It must be observed in the radio, infrared or x-ray.
- There's a weird radio source called Sagittarius A* (A-star) or Sgr A* for short, at the geometrical center of the Galaxy.



- We’d like much sharper images of the Galactic Center, particularly in the infrared, where we can track red giant stars.

- Andrea Ghez of UCLA with colleagues, set out to compensate for the bright sky in the infrared, and the tendency of images to move around and fuzz out during long exposures needed to detect individual stars at this distance.

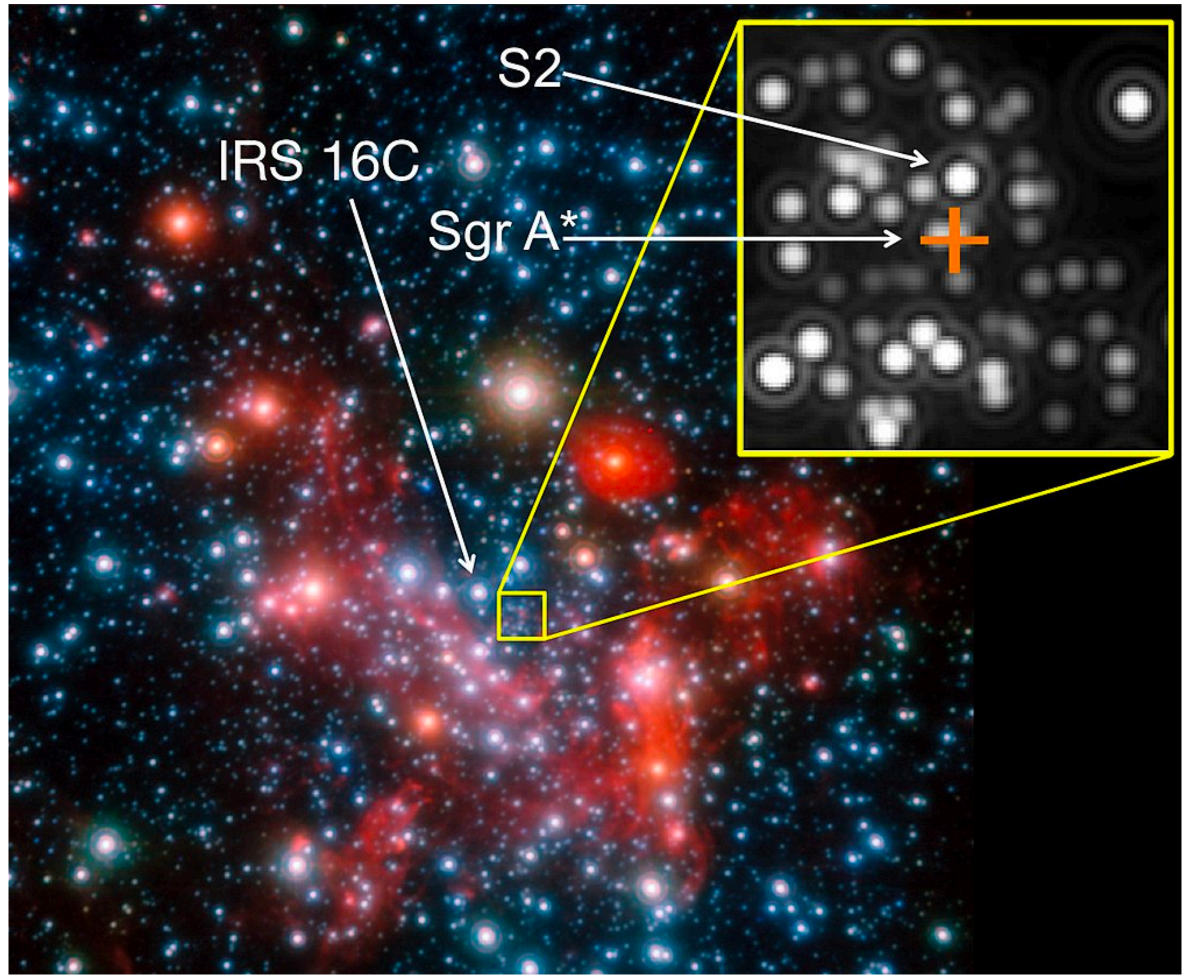
- Using natural, and then artificial laser-based “guide stars” and some clever electronics to detect wave fronts, they figured out how to tip & tilt the secondary mirror in their telescopes in real time to sharpen up the images.



- Sharpness of the image is limited by wavelength divided by telescope size (aperture).
- It’s further blurred by “seeing” caused by air turbulence.
- Seeing can be fixed to some extent by adaptive optics (making an optimal image of another star in the field).

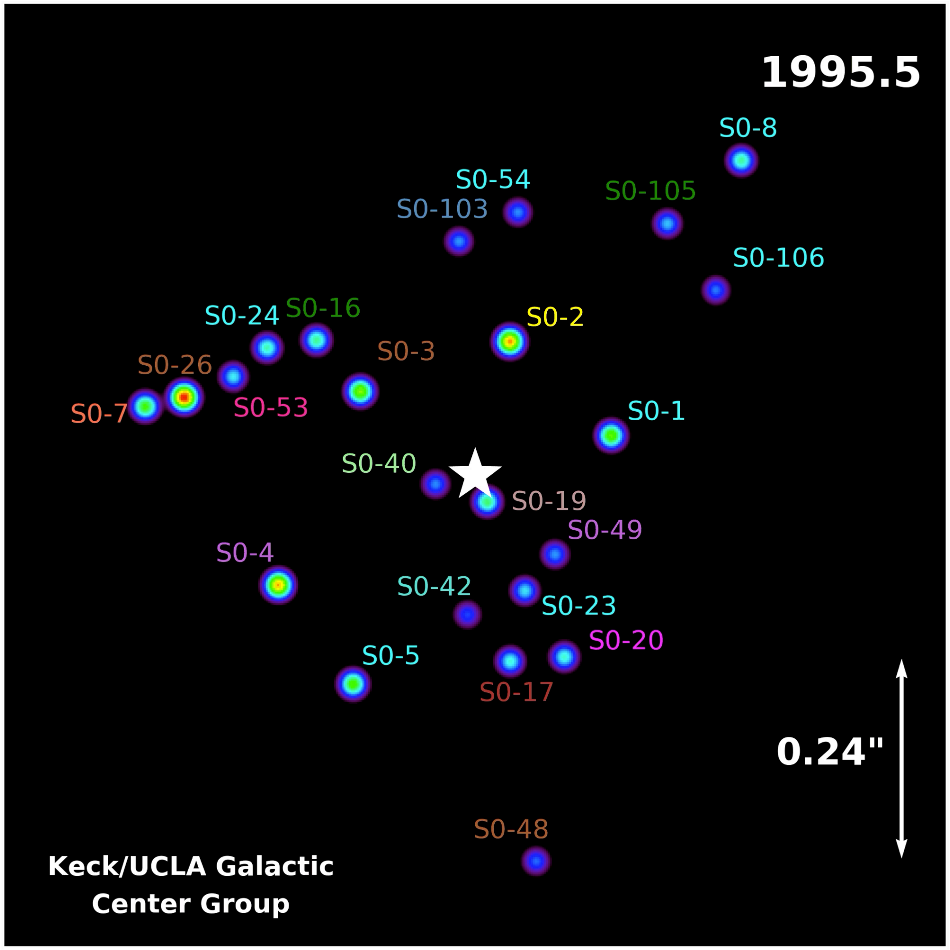
With adaptive optics…

- Individual stars can be picked out.
- Of special interest is star S2 which orbits the Galactic center in about 16 years.
- We can use Kepler's and Newton's laws to compute the mass of the central object.
- The answer is about 4.3 million times the mass of the sun.



25 year movie

- Sgr A* is marked with the star.
- The star S2 (S0-2) starts out above the central object.
- Watch how it speeds up as it gets closer to the central object.
- Several other stars in the picture are doing similar things.
- Credit to Andrea Ghez's group at UCLA and Keck Observatory (in Hawaii)

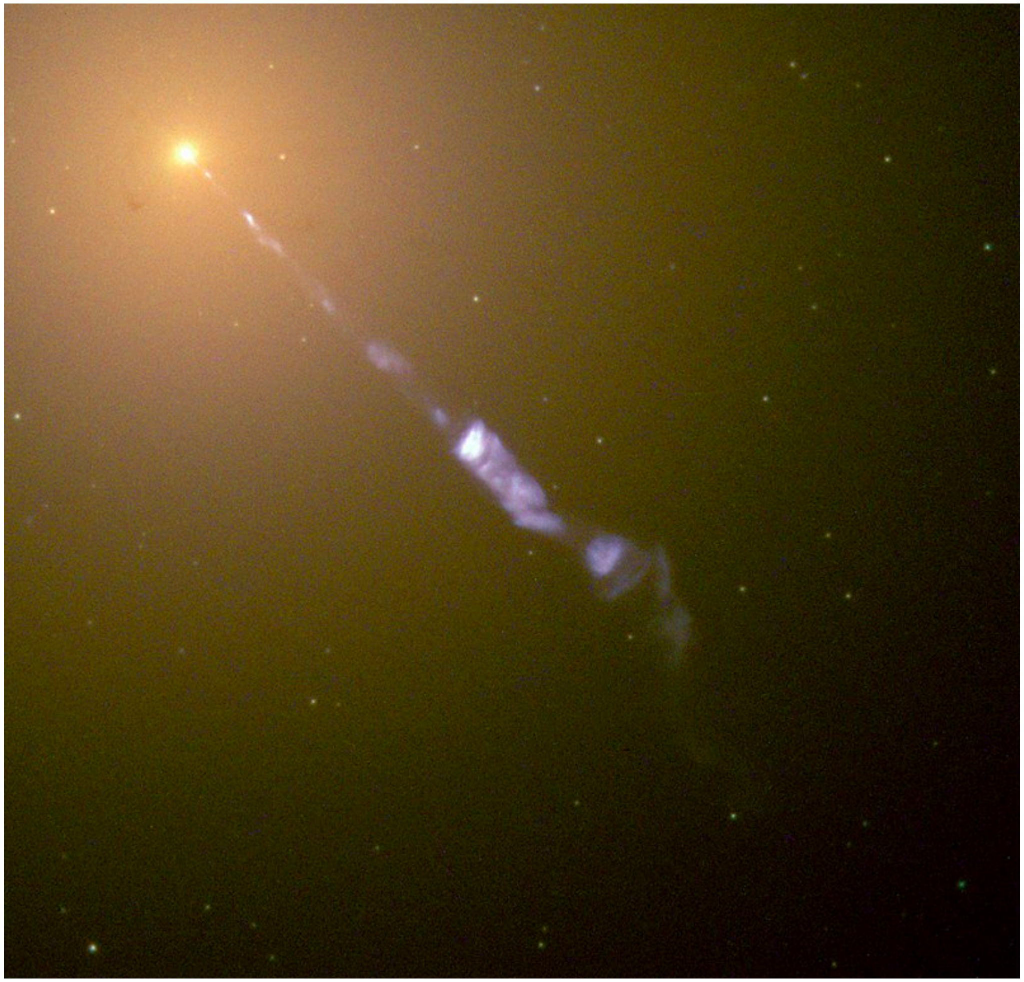


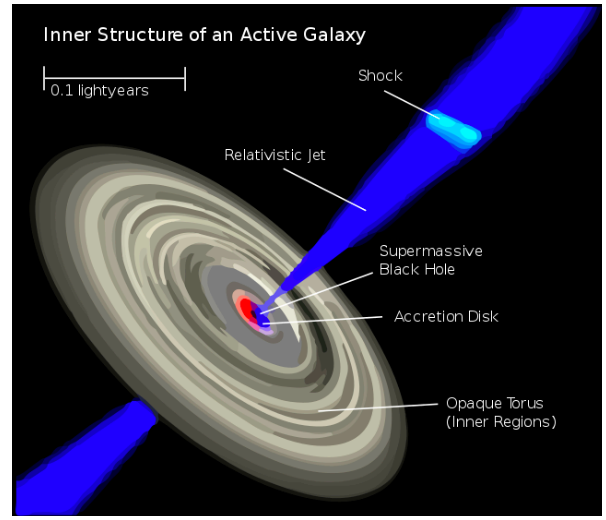
- Note the scale bar on the video: 0.24 arc seconds.
- On an exceptional night without adaptive optics, the atmosphere smears out images to about half an arc second. This measurement would be unthinkable in such circumstances.
- For this research program covering 25 years plus instrument development time, Andrea Ghez, UCLA, and Reinhard Genzel (Max Plank Institute for Extraterrestrial Physics in Munich) shared half the 2020 Nobel Prize in Physics. The other half went to Roger Penrose, a theorist at Oxford.
- For more animations from the Galactic Center research:
- http://www.astro.ucla.edu/~ghezgroup/gc/animations.html


NOBELPRISET I FYSIK 2020
THE NOBEL PRIZE IN PHYSICS 2020
KUNGL. VETENSKAPS-AKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES
Photo: Penrose Institute
Photo: Max Planck Institute for Extraterrestrial Physics
Photo: Christopher Dibble, UCLA
Roger Penrose
Reinhard Genzel
Andrea Ghez
"för upptäckten att bildandet av svarta hål är en robust förutsägelse av den allmänna relativitetsteorin"
"for the discovery that black hole formation is a robust prediction of the general theory of relativity"
"för upptäckten av ett supermassivt kompakt objekt i Vintergatans centrum"
"for the discovery of a supermassive compact object at the centre of our galaxy"

- It turns out that large (millions to billions of solar mass) black holes are very common in the cores of galaxies. Most big galaxies have one. Some (probably mergers) have more than one.
- Black holes, even the monster ones are physically small objects (astronomically speaking).
- The “Event Horizon” from inside which nothing emerges (no light, no information, no matter) is given by the Schwarzschild Radius, and depends only on the mass:
- $R_s = 2GM / c^2$
- If M is one solar mass, R_s is 2.95 km.
- Sgr A* has R_s of 12 million km. Earth is 150 million km from the sun.

- Black holes are black, that is, invisible. Anything that falls on them is lost, including light.
- Since they're physically small, it's difficult to drop matter directly in; typically anything falling in has some sideways motion. If you're trying to feed a lot of stuff to a black hole, most of it spends some time in a disk in orbit around the black hole. Friction in the disk heats the material to very high temperatures. These "Accretion Disks" are often x-ray and radio sources as well as optical.
- They can vary on short time scales since they're not large (light travel time across the disk is short).
- Sometimes such a disk spits out a jet of high energy material at near light speed perpendicular to the disk.
- Stars passing too close can be tidally disrupted.





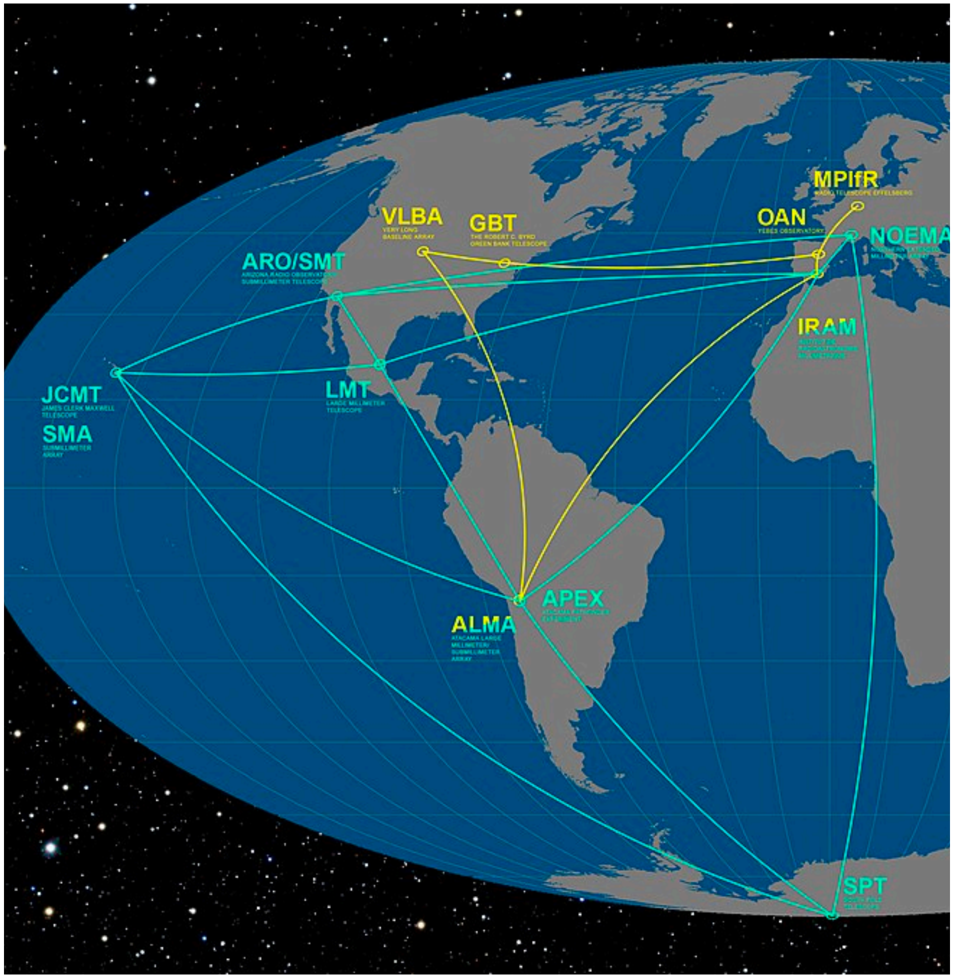
- Image of M87 in the Virgo Cluster of galaxies
- Diagram shows jet and accretion disk. Black hole in the very center.

Part of the Virgo cluster of galaxies. Lots of them are spirals, but M-87 in the upper left is an Elliptical galaxy.

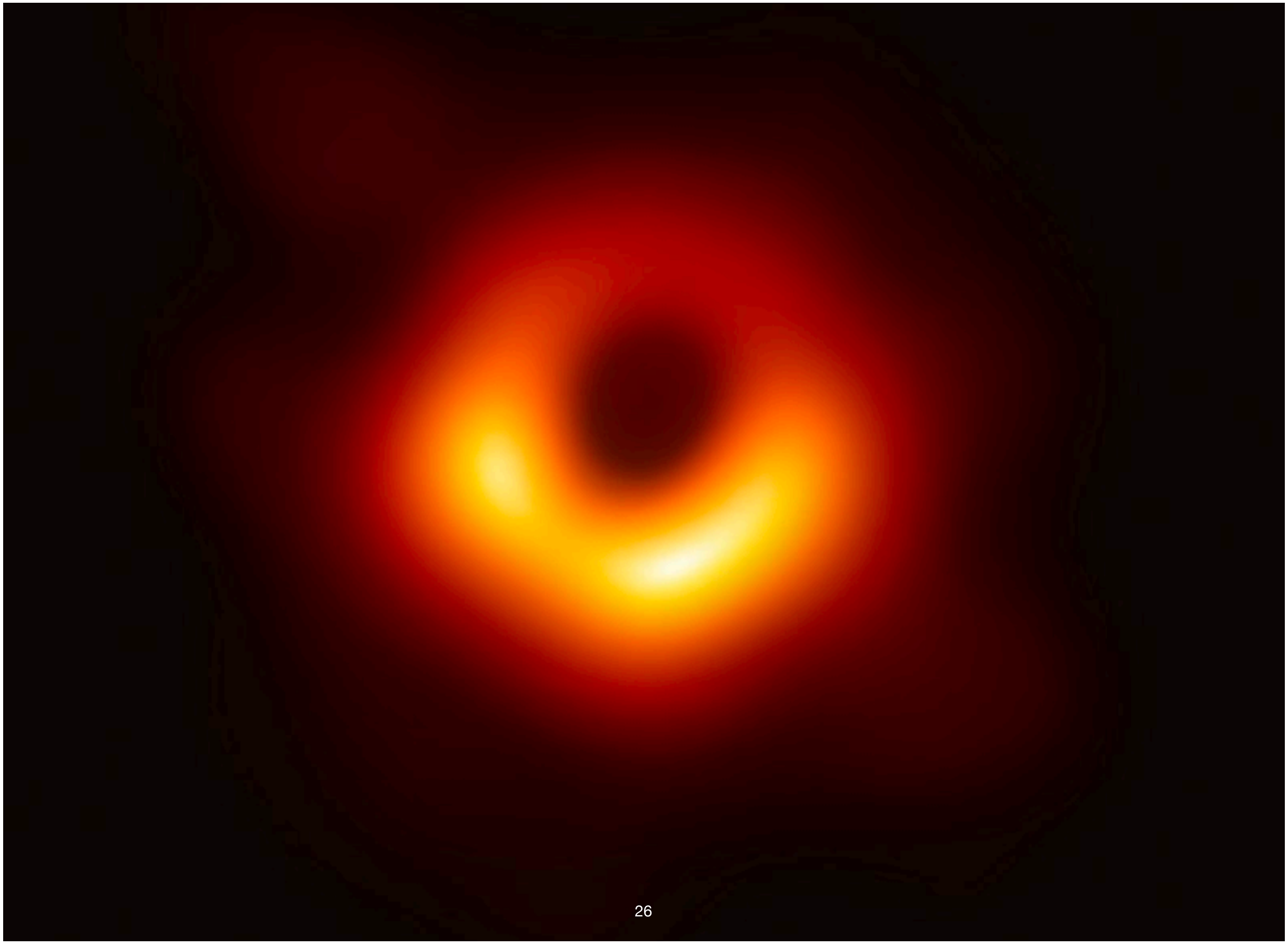
Previous slide showed the jet coming from the black hole in its nucleus.

- It would be interesting to image the immediate surroundings of a black hole.
- Diffraction limits sharpness of images, and goes as wavelength over telescope diameter. There’s no hope with a monolithic telescope.
- In radio, we can record the waveforms, and use multiple telescopes together, combining their signals to make images as sharp as could be done with a telescope as large as the separation between the antennas. “Interferometry”
- If antennas are spread around the world, we can use the earth’s diameter of 12,000 km. At a wavelength of under a millimeter (frequencies in THz, or 1000s of GHz), the math works out.
- Enter the “Event Horizon Telescope” using mm-wave radio telescopes all over the earth to simultaneously observe large, “nearby” black holes.

- Previous slide: the Atacama Large Millimeter Array (ALMA) in Chile.
- Right: Locations of participating observatories in the Event Horizon Telescope project.
- Two viable targets: Sagittarius A* (central object in our galaxy) and the nucleus of M-87, a thousand times more distant, but also a thousand times larger (M~6 Billion solar masses).
- Also observes non-black hole targets.



- Event Horizon Telescope teams all observed Sgr A* and M-87* every April for several years.
- Data from the South Pole Telescope on hard drives waited to be flown out of Antarctica the following October/November (polar springtime).
- Signals combined in computers in Massachusetts, and analyzed by three separate subgroups who didn't talk to each other at all.
- Sgr A* results are still pending. I imagine some of the stuff along the line of sight may have interfered with the signal in ways that are hard to correct.
- The sightline to M-87 is mostly empty, intergalactic space.
- M-87* image is spectacular (and apparently changes from year to year).

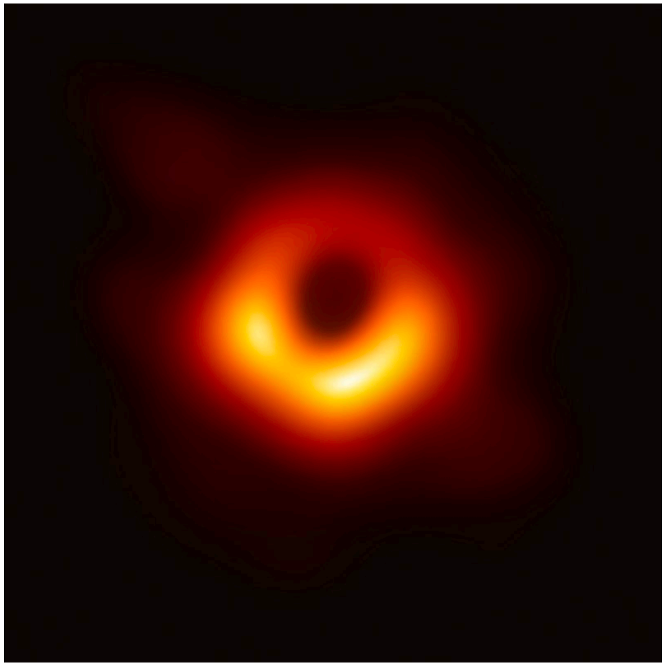


- What we’re seeing is the disk of stuff around the black hole at the center of galaxy M-87, and the shadow of the black hole’s event horizon.

- Our line of sight is almost perpendicular to the disk; the jet seen at larger scales is coming almost right toward us.

- Image released Apr 2019.

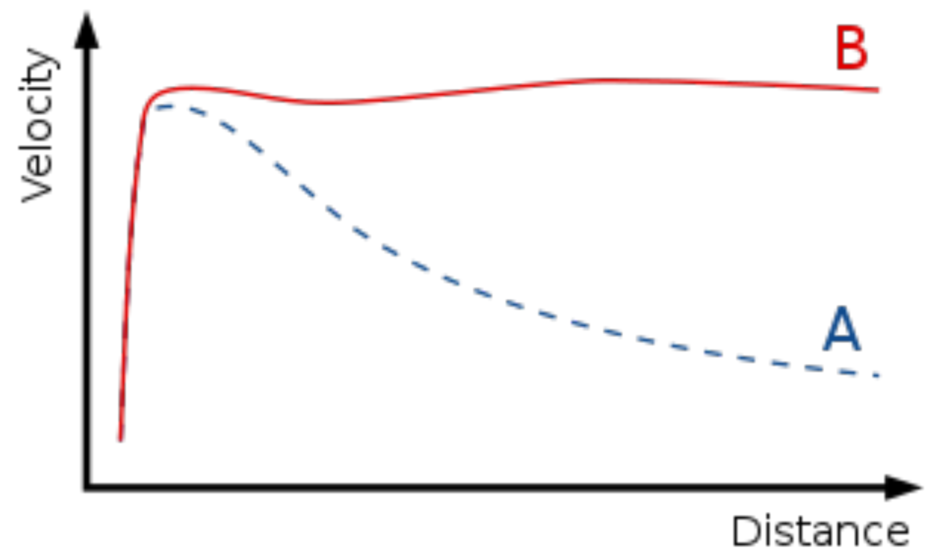
- Collaboration includes 300 scientists at 60 institutions



- From here, I'd like to go on two small side trips:
- Structure of galaxies and clusters of galaxies, and what is Dark Matter anyway? With credit to Vera Rubin (1928-2016) who should have won the Nobel Prize for making it so obvious that the establishment had to take notice.
- Clusters of galaxies, and in particular x-ray observations, which show very different things than optical observations do.

Gravity

- Stars and gas in a galaxy orbit their center of mass (and the black hole there).
- If the mass is spread out like the light is, you'd expect the speeds of the stars in their orbits to decrease as you observe farther out. (curve A)
- Spoiler: nope!
- Vera Rubin found curve B.



- Vera Rubin overcame institutional sexism (e.g. first woman to observe at Mt. Palomar, arranging for her own bathroom facilities).
- Worked at Carnegie Institution w/Kent Ford.
- Careful observations of star velocities toward/away from earth (Döppler effect) in galaxy UGC 2885 and others traced out curve B above.
- There must be a flattened oval distribution of mass that’s not emitting light, to make the orbits work. “Dark Matter.”

- Everything we know about dark matter:
- It exerts gravitational forces at the scale of galaxies and clusters of galaxies (and the universe as a whole).
- um…

- What could it be?
- Cosmologists tell us it can't be made of neutrons & protons.
- Some other kind of exotic elementary particles? So-called Weakly Interacting Massive Particles (WIMPs) have been searched for and not found (so far).
- Black holes left over from the formation of the universe? Stellar-mass black holes would pass directly between us and background stars, creating a "gravitational lens" and amplifying their light. MAssive Compact Halo Objects (MACHOs) are also not there in the quantity required.
- Much smaller objects would be common enough that we'd see them go by.
- Or maybe there's something wrong with the weak-field limit of gravity theories. Cue Milgrom and MOND (see slide 2).

- This is a rather unsatisfactory state of affairs.
- We can study ordinary matter using its interactions with light.
- We can do a little more with gravitational radiation (tune in next time) and neutrinos. Plus meteors and sample return missions in the solar system.
- Current models of the universe have 5% as normal matter, 29% as dark matter, and the other 69% of the energy as the energy of expansion of the universe.
- People are tinkering with theories and making new and different observations, some of them very hard, but nothing seems to be happening.

- Next time, a grab bag of stuff I haven't had time for yet.
- Gravitational waves, merging black holes & neutron stars.
- More about the sun, space weather, the heliosphere, and the boundary between that and interstellar space. What's out there between the stars?
- Pretty pictures taken in multiple wavelength bands by Hubble, the Chandra X-ray Observatory, and other instruments.
- A little about exoplanets (planets orbiting other stars). See Feb 2020 course on my website for six weeks on that topic.
- Other suggestions?
- Some summing up: learning to read science journalism.