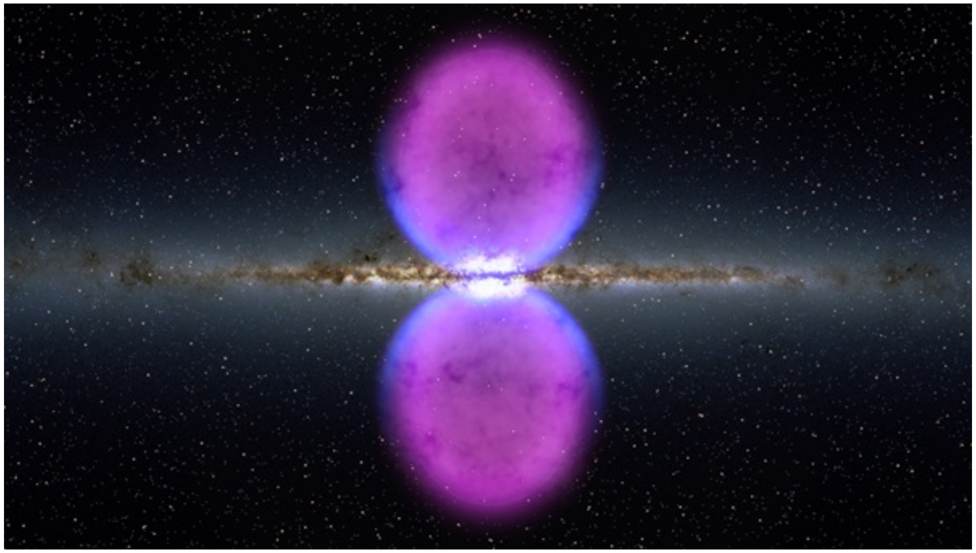
# [15] The Galactic Center (3/27/18)

## Upcoming Items

1. Welcome back!
2. Homework #4 due next Tuesday.
3. Second midterm in two weeks!
4. Read Ch. 20.1 for next class and do the self-study quizzes

## "I'm forever blowing bubbles" (that are detected with Fermi)

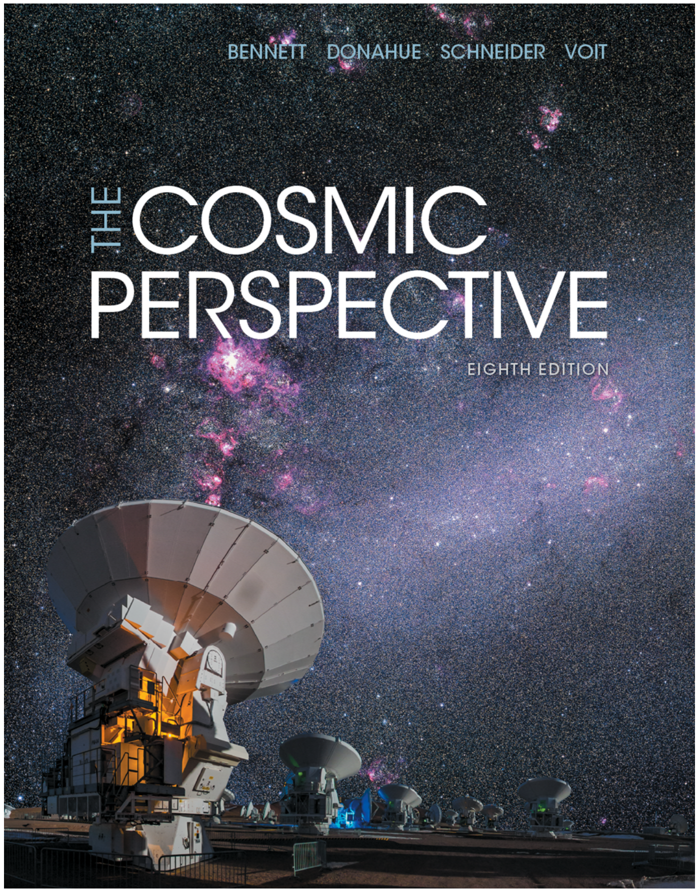


# LEARNING GOALS

Ch. 19.4

*For this class, you should be able to…*

- … *summarize the observational evidence for the existence of a supermassive black hole at the center of the Milky Way, and explain why the observations are difficult to obtain;*
- … *predict the mass of a supermassive black hole based on the motions of stars and/or gas clouds in orbit around it.*



# Some new items

- I have put up practice problems related to both the first midterm and your upcoming midterm on Files->practice
  These are only related to derivations; we'll have the usual mix of definitions and qualitative questions as well
- I will now post a draft of the slides for a class by the day before a class (e.g., Thursday's is up now). I won't have slides with any questions for you; those will be a surprise ☺
- Mike says you did a good job on the calculus problem for the last homework. Well done!
- I ***strongly*** suggest that you talk with the tutors (or TAs or me!) about derivations and use of calculus, not just about homeworks
  E.g., go through my derivations and practice problems with tutors; you can definitely do the math, but anyone can use experience in setting up the problems; tutors can help!

# Any astro questions?

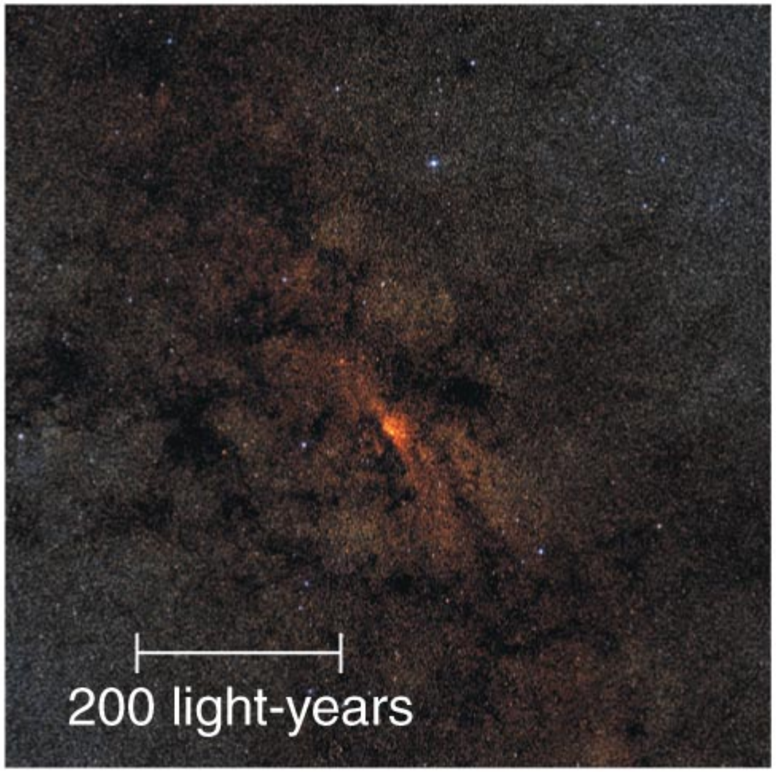
# The Galactic Center

- We can only see the galactic center at wavelengths that can get through the dust in the galactic disk: radio, infrared, and X-ray.
- The center of the Milky Way almost certainly contains a supermassive black hole.
  - The orbits of individual stars around Sgr A* provide an excellent measurement of its mass ($4\times10^6\,M_\odot$) and compactness.

# The Center of our Galaxy

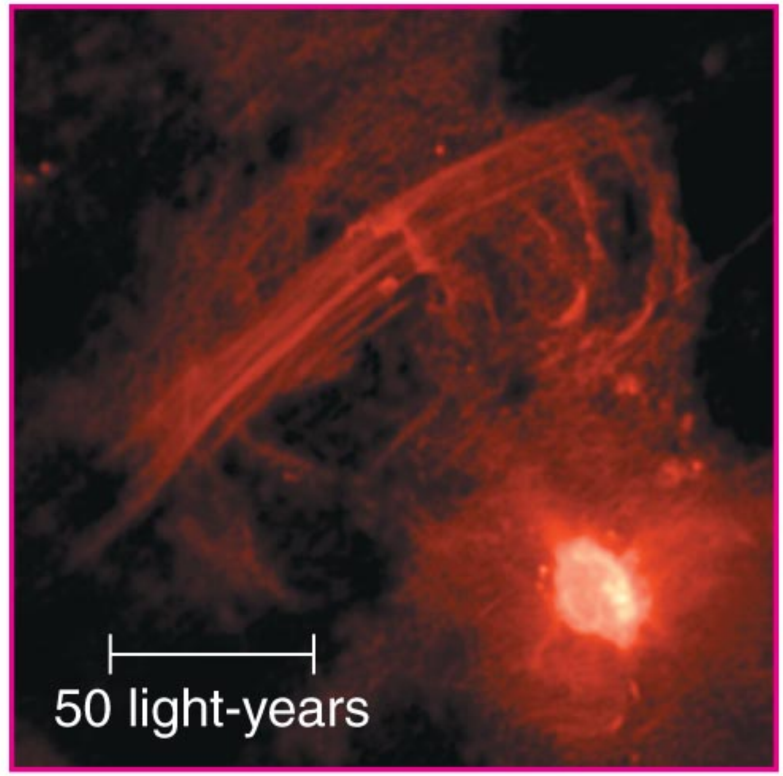
- Cannot see center of our galaxy in optical light: dust produces 30 magnitudes of extinction!
- Need to look in radio, IR, or X ray to penetrate dust.
- In radio & X ray, there is a compact source of energy at precise center of Milky Way…long suspected that this was black hole.

## Infrared light from center

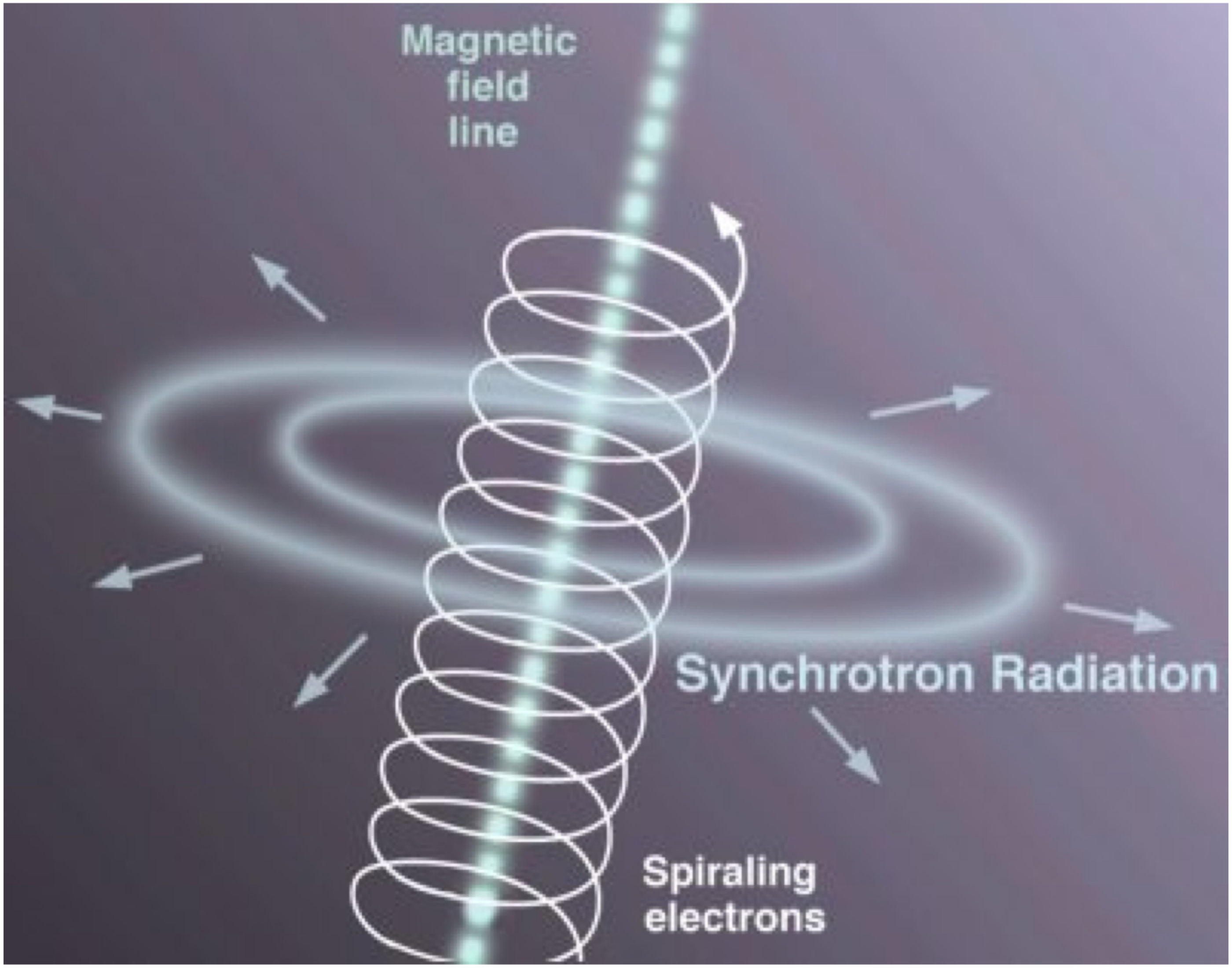



**a** This infrared image shows stars and gas clouds within 1000 light-years of the center of the Milky Way.

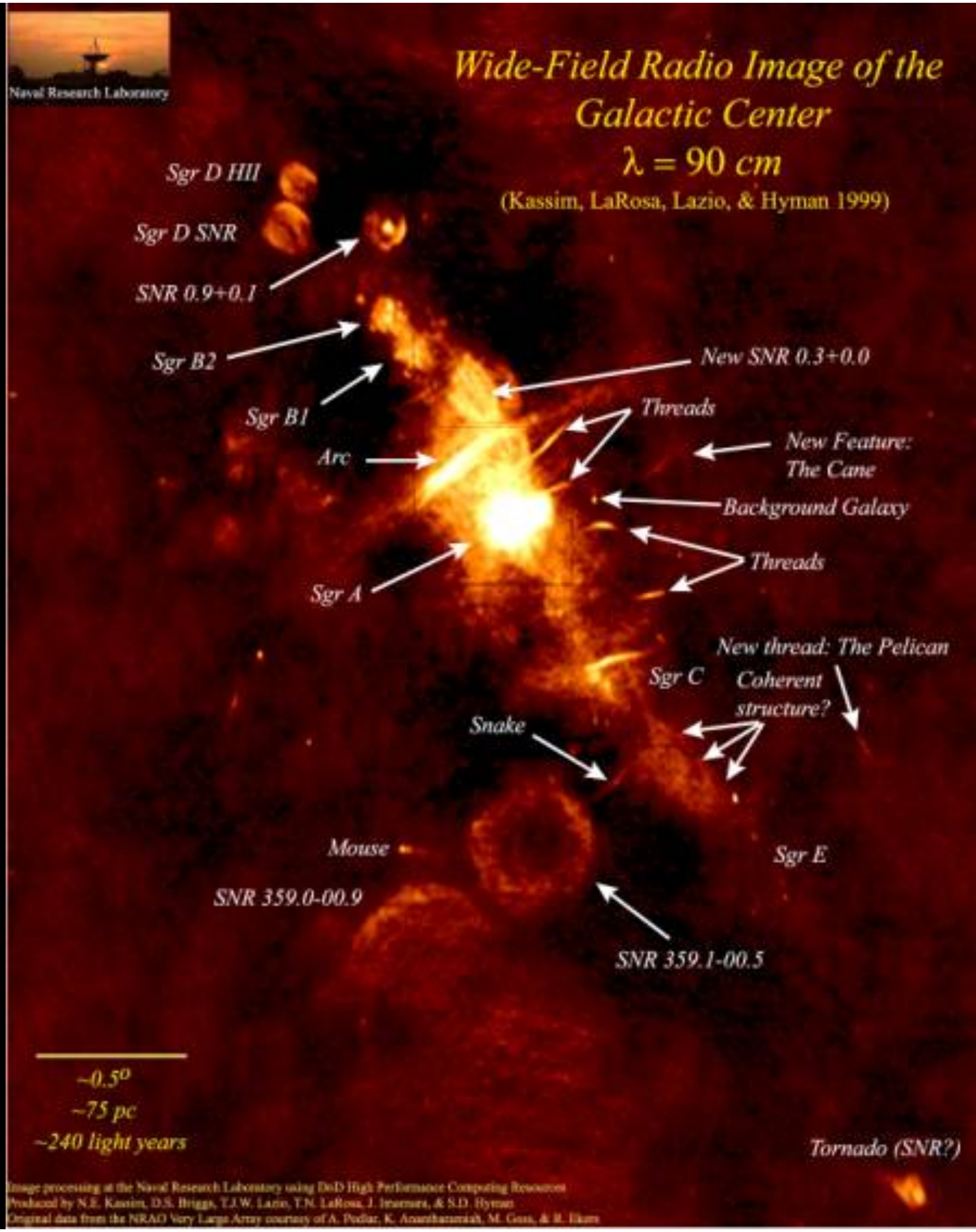
## Radio emission from center



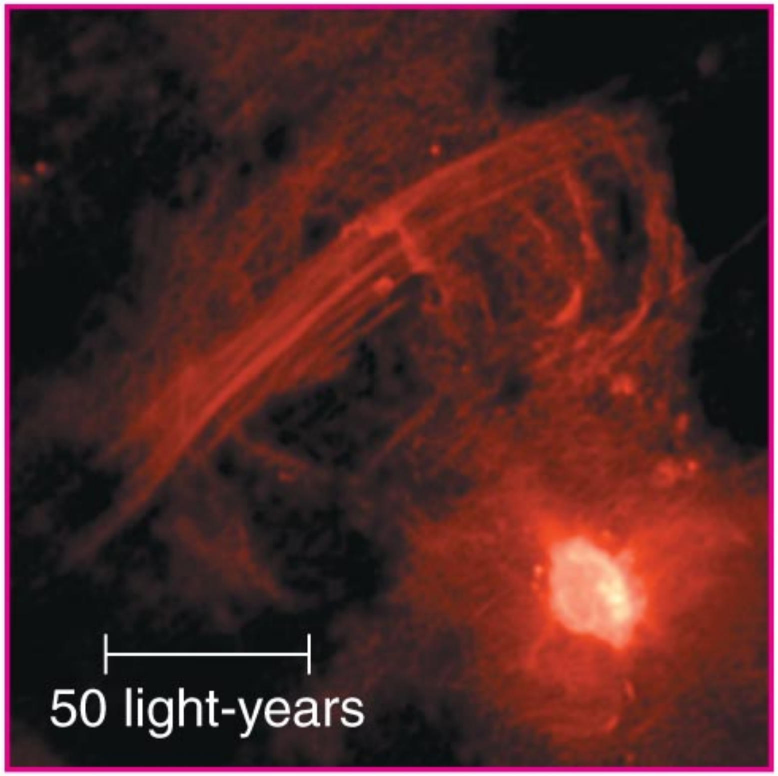

**b** This radio image shows vast threads of emission tracing magnetic field lines near the galactic center.




- Relativistic electrons spiraling along magnetic field lines will emit *synchrotron radiation* at all frequencies.

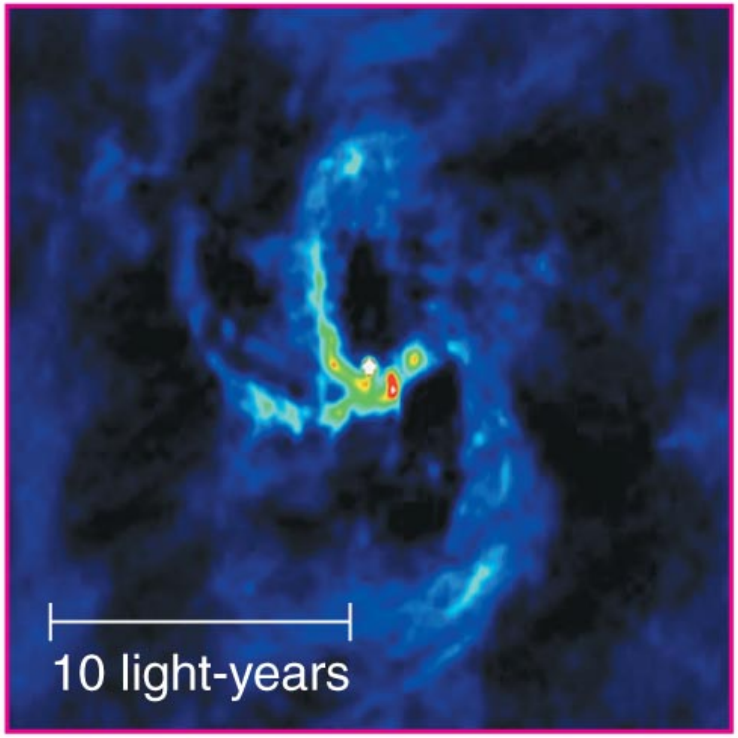

Naval Research Laboratory
Wide-Field Radio Image of the Galactic Center
λ = 90 cm
(Kassim, LaRosa, Lazio, & Hyman 1999)
Sgr D HII
Sgr D SNR
SNR 0.9+0.1
Sgr B2
Sgr B1
New SNR 0.3+0.0
Threads
New Feature: The Cane
Arc
Background Galaxy
Threads
Sgr A
New thread: The Pelican
Sgr C
Coherent structure?
Snake
Mouse
Sgr E
SNR 359.0-00.9
SNR 359.1-00.5
~0.5°
~75 pc
~240 light years
Tornado (SNR?)
Image processing at the Naval Research Laboratory using DoD High Performance Computing Resources
Produced by N.E. Kassim, D.S. Briggs, T.J.W. Lazio, T.N. LaRosa, J. Imamura, & S.D. Hyman
Original data from the NRAO Very Large Array courtesy of A. Pedlar, K. Anantharamaiah, M. Goss, & R. Ekers

## Radio emission from center




**b** This radio image shows vast threads of emission tracing magnetic field lines near the galactic center.

## Swirling gas near center

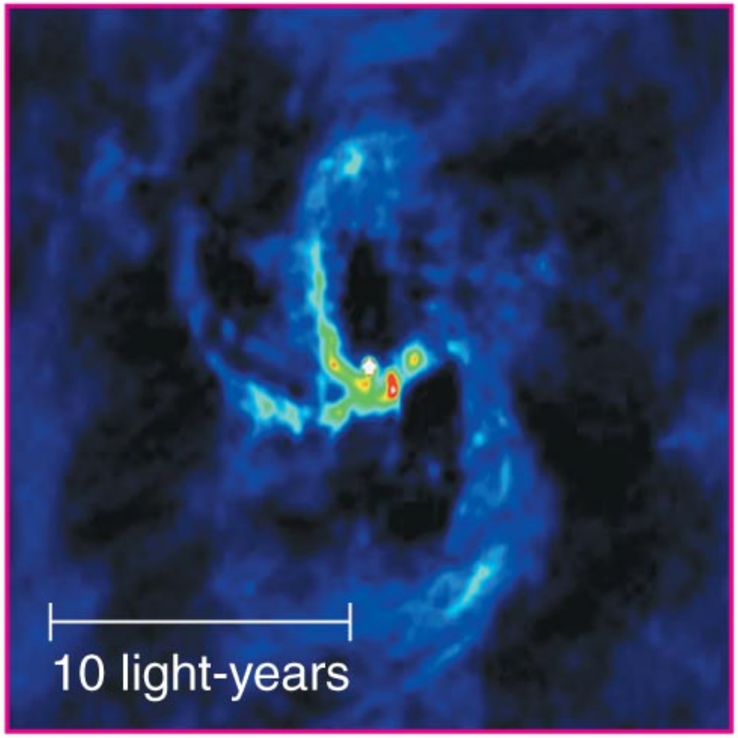



**c** This radio image zooms in on gas swirling around the radio source Sgr A* (white dot), suspected to contain a very massive black hole.

# How do we search for a massive black hole?

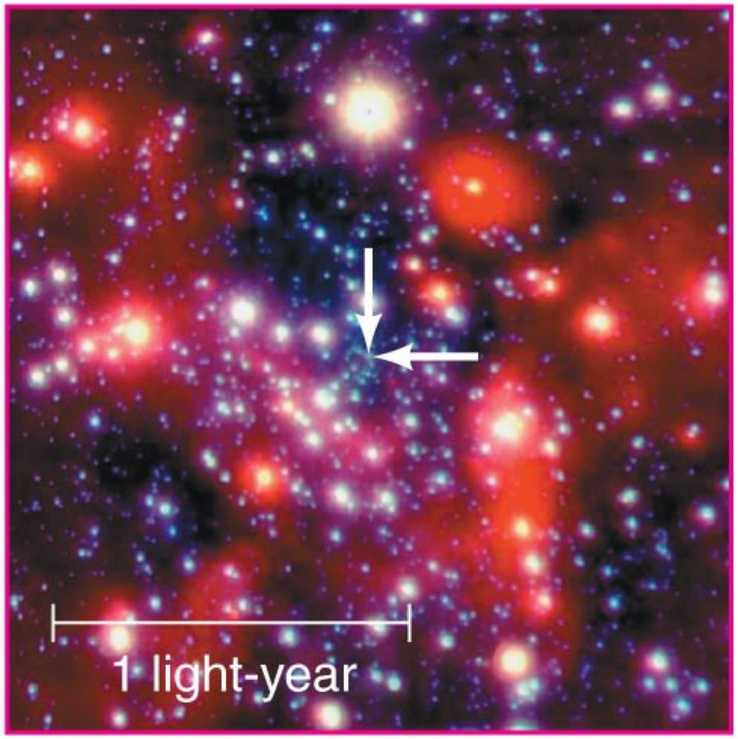
- Most direct way to search for a black hole is to look for the influence of its gravitational field on nearby stars and gas.
- Dramatic evidence came from IR observations…
  - In IR, see dense cluster of young stars within central light year.
  - Can see these stars move on orbits about an unseen mass at the galactic center.
  - The central object is both extremely massive and extremely compact: a black hole is the only viable option (unless there is something seriously wrong with our understanding of physics).
  - Remember, if we had many stellar-mass objects instead of one massive object, they would throw each other out in thousands of years
  - If it was instead dark matter particles, then those particles would have been thrown out by gravitational interactions with stars

## Swirling gas near center




**c** This radio image zooms in on gas swirling around the radio source Sgr A* (white dot), suspected to contain a very massive black hole.

## Orbiting stars near center



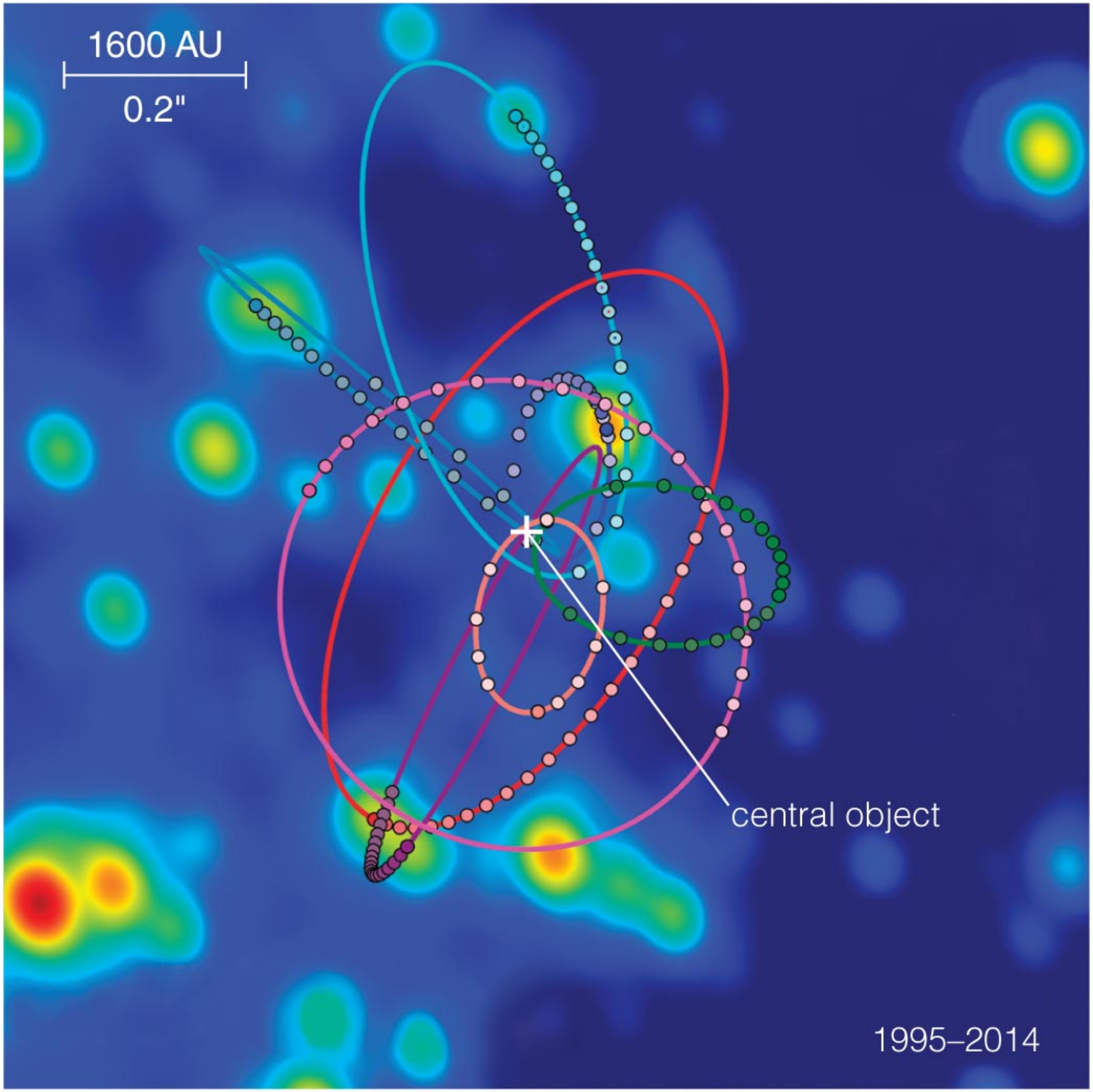

**d** This infrared image shows stars within about 1 light-year of Sgr A*. The two arrows point to the precise location of Sgr A*.

# How massive is the Milky Way's central black hole?

- Suppose stars/gas are orbiting the black hole (but some distance from it), and we can actually observe their motion (measure semimajor axis $a$ and period $P$), then

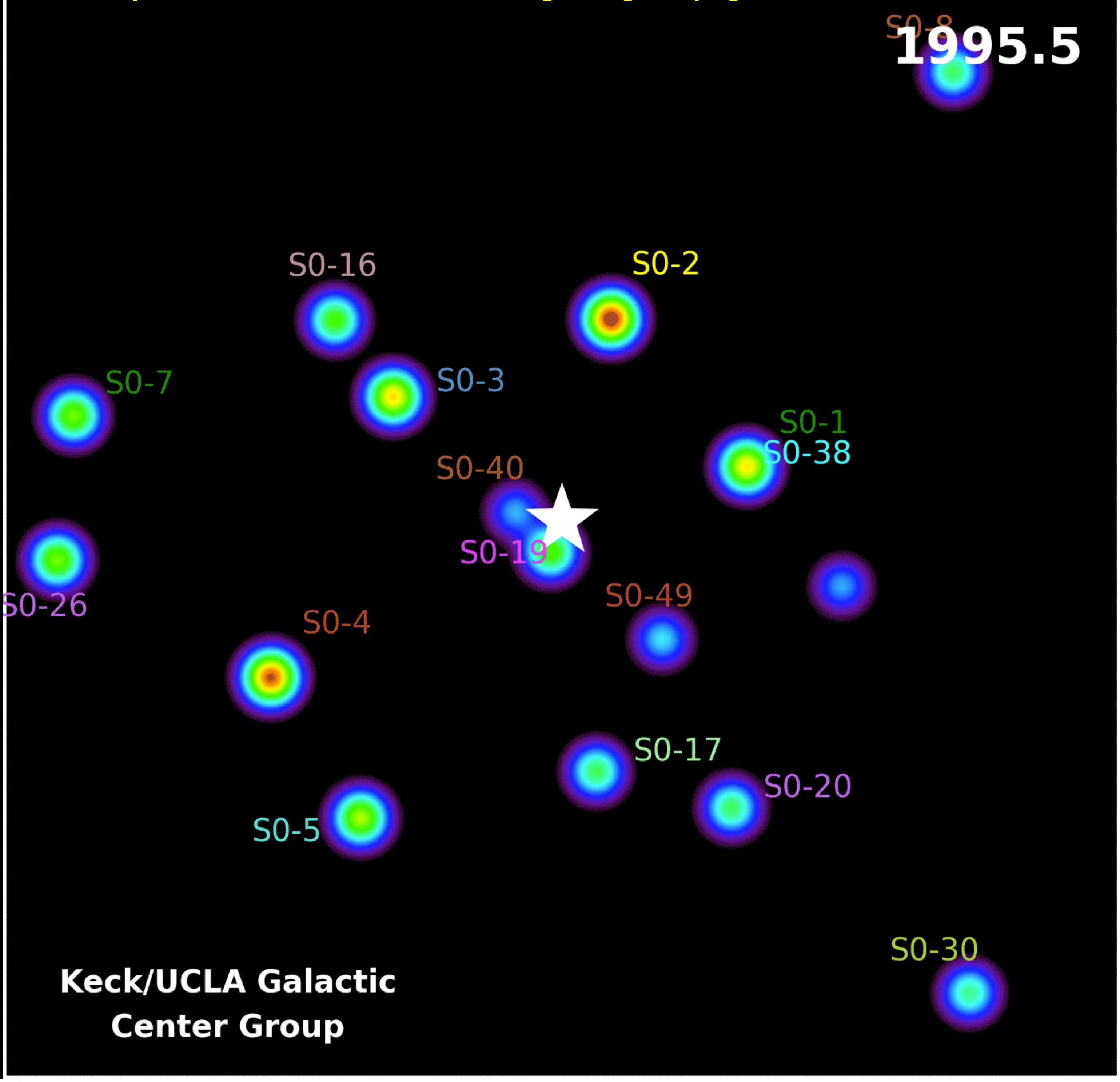
$$M \cong \left(\frac{4\pi^2}{G}\right)\left(\frac{a^3}{P^2}\right).$$

- Group questions:
  1. Why can we use Newtonian formulae?
  2. When would we expect this formula to break down?
  3. What are the complications of measuring $a$?
  4. Are there other ways than orbits that we can establish that a supermassive black hole is in the center of a galaxy?



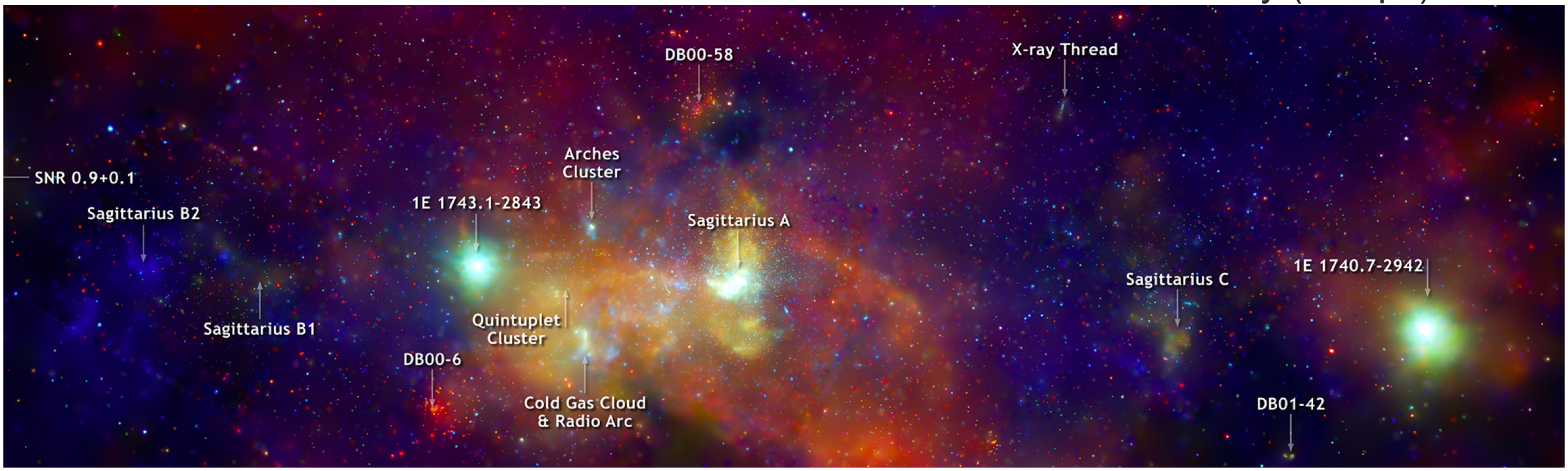

- Stars appear to be orbiting something massive but invisible… a *black hole*!
- Orbits of stars indicate a mass of about **4.3 million $M_{\odot}$ within a radius of 40 AU**.

http://www.astro.ucla.edu/~ghezgroup/gc/animations.html

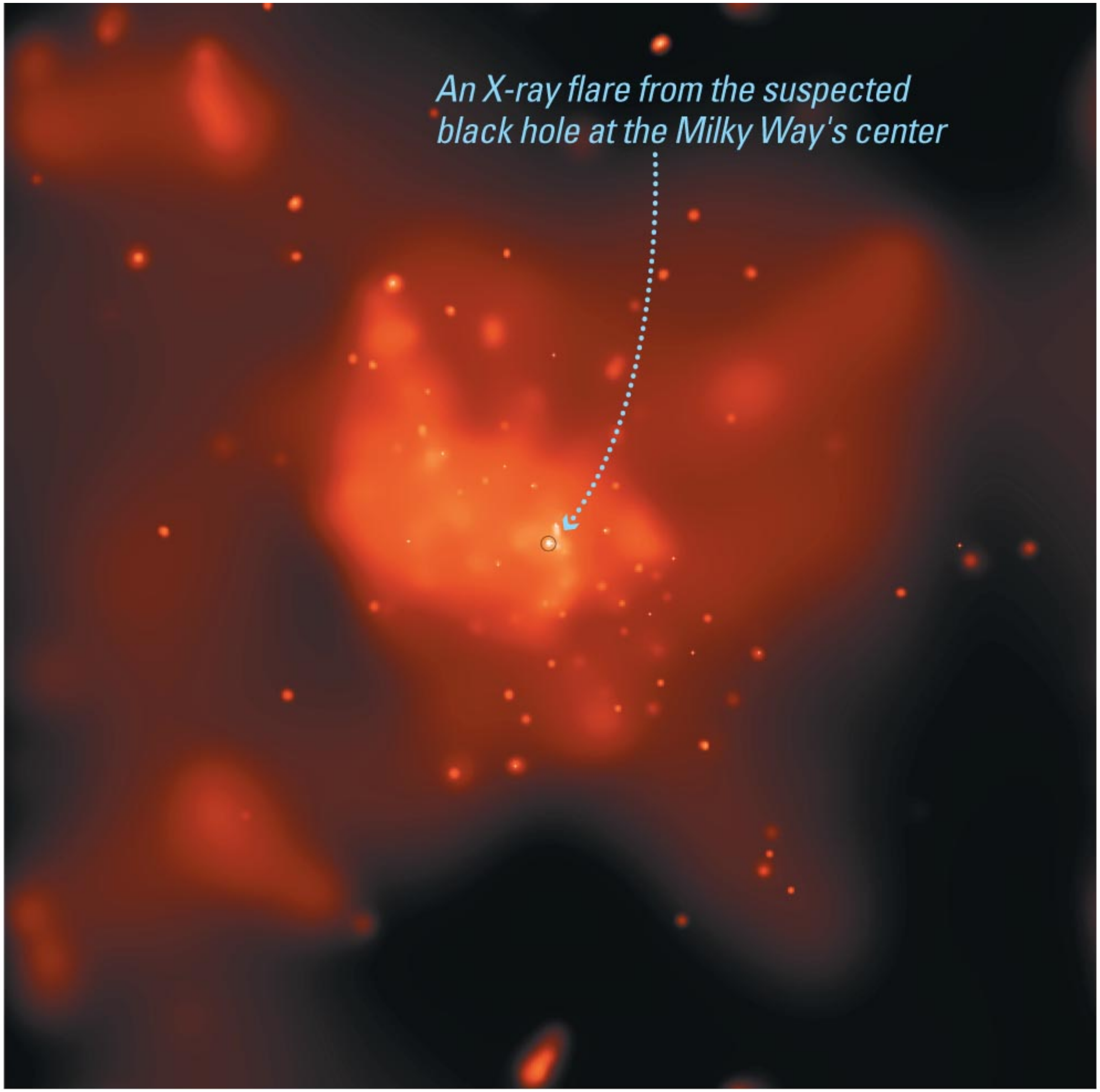


# X rays in the Galactic Center

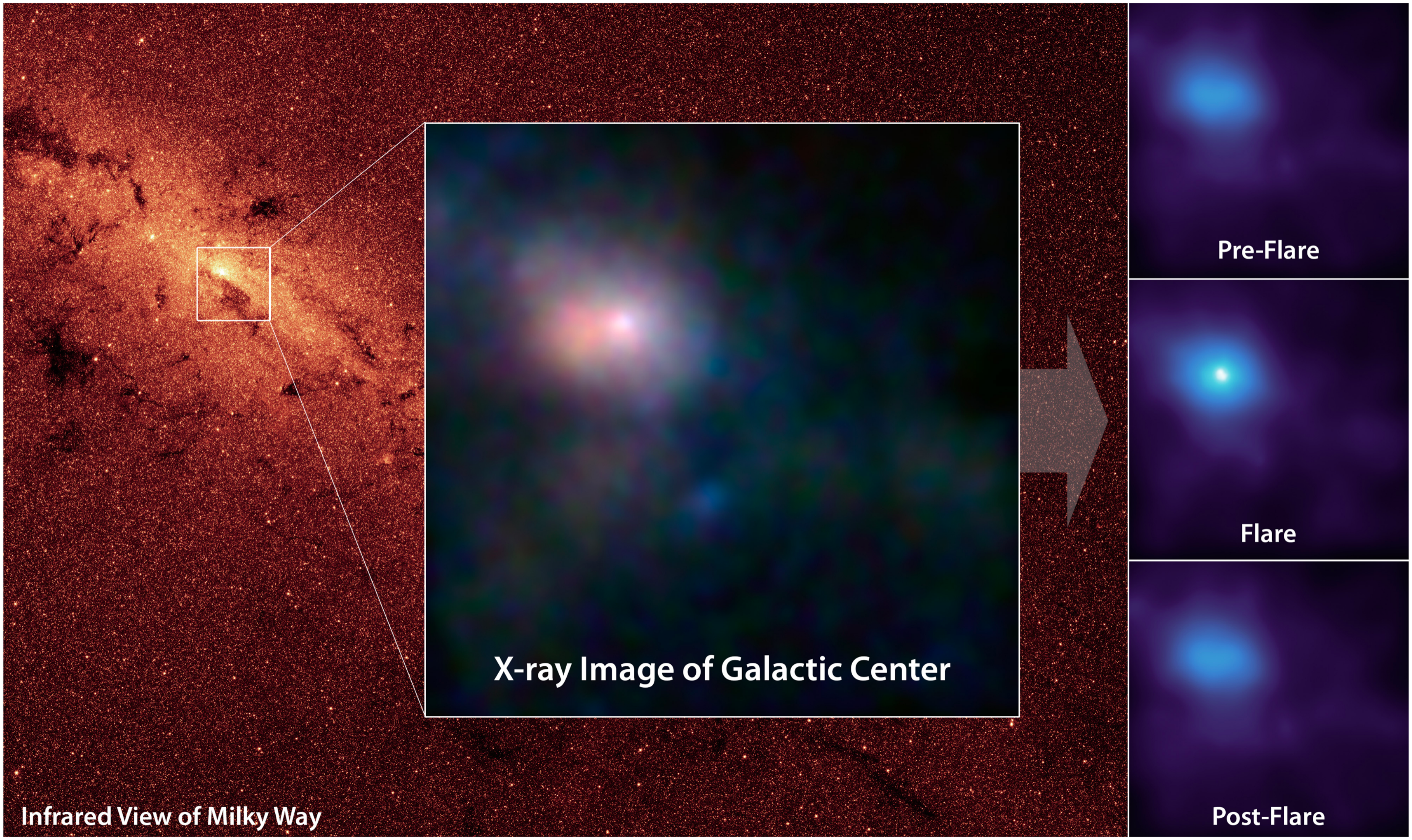
View: 900 ly (300 pc) across



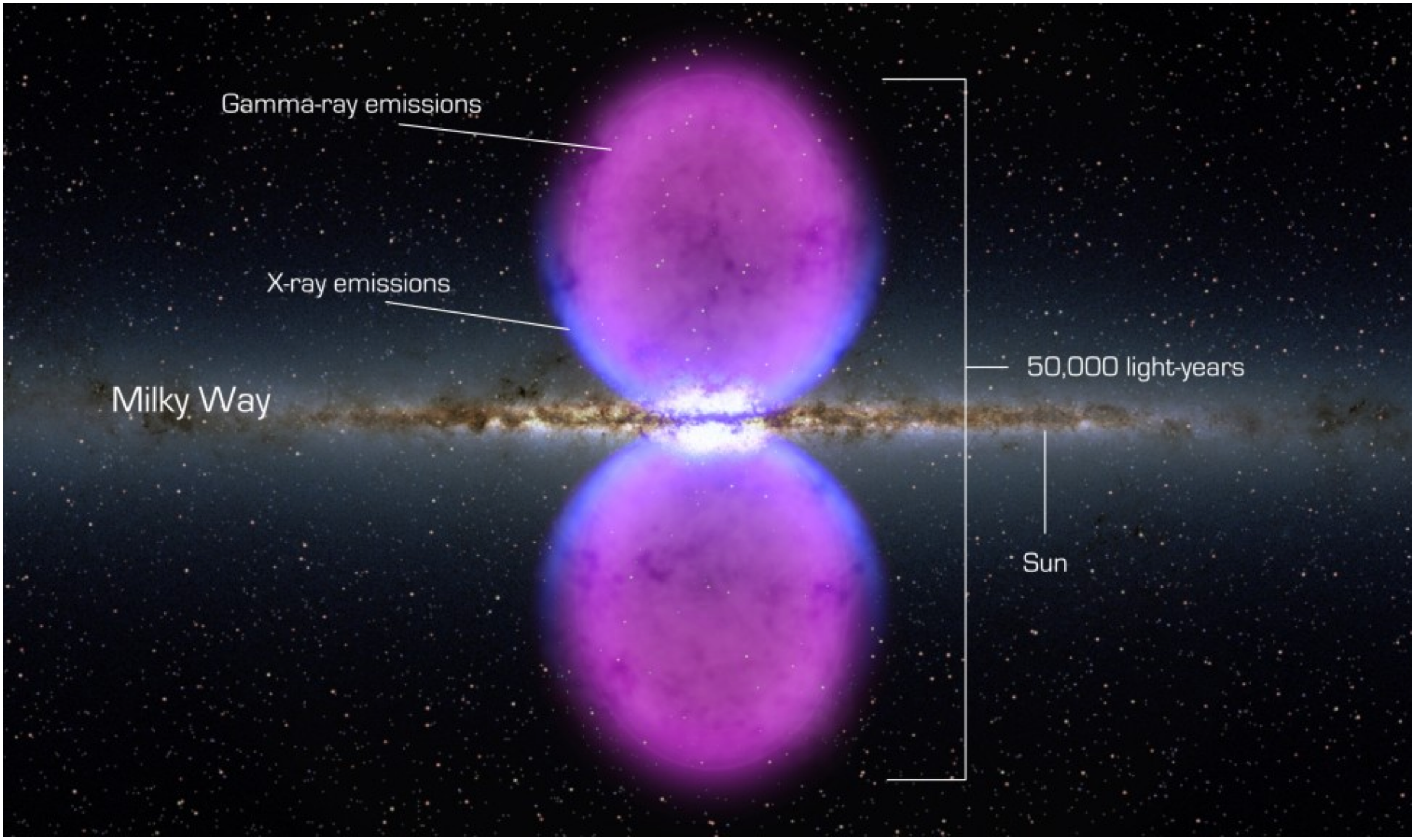

- Diffuse X-ray light shows gas heated by supernova explosions and other winds/outflows.
- Point source X-ray emission shows accreting compact objects in binary systems (i.e., X-ray binaries).




- X-ray flares from galactic center suggest that tidal forces of suspected black hole occasionally tear apart chunks of matter about to fall in.




- Recent observations with NuSTAR pinpoint an X-ray flare centered on the supermassive black hole (Sgr A*).

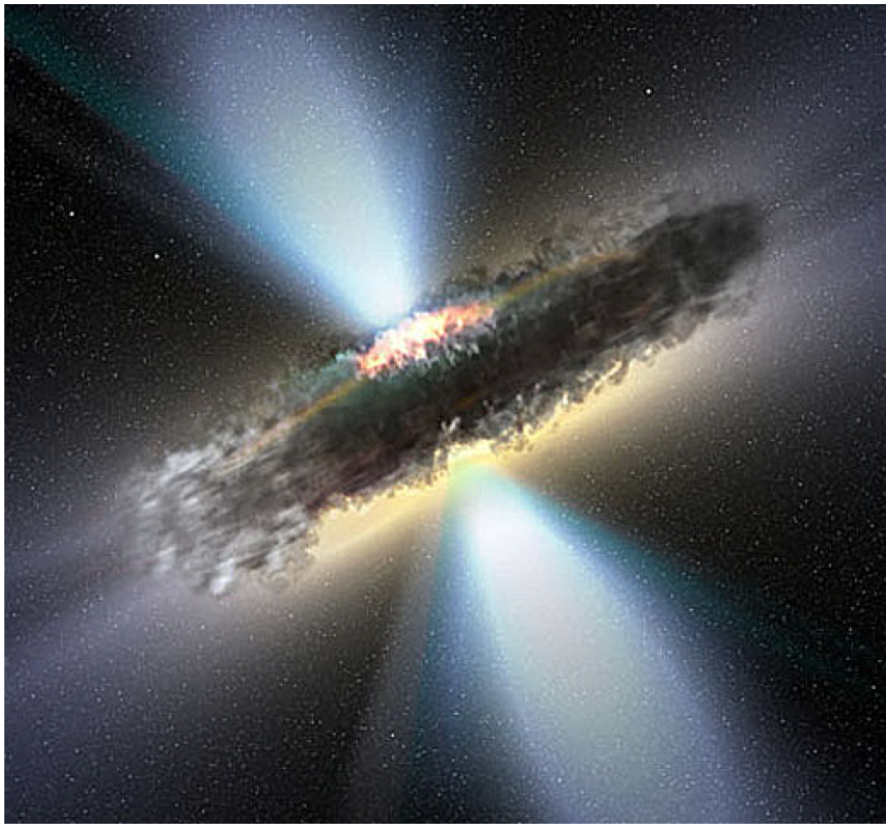



- Gamma ray observations show *huge* bubbles of emission coming from the center of the galaxy: the Fermi Bubbles.
- Origin unknown!  (Maybe result of stars consumed by SMBH?)

# Possible origins of the Fermi Bubbles

Galactic winds (supernovae)

Supermassive black hole jets



Post from former grad student: astrobites.org/2013/01/22/no-jets-in-the-galactic-center/

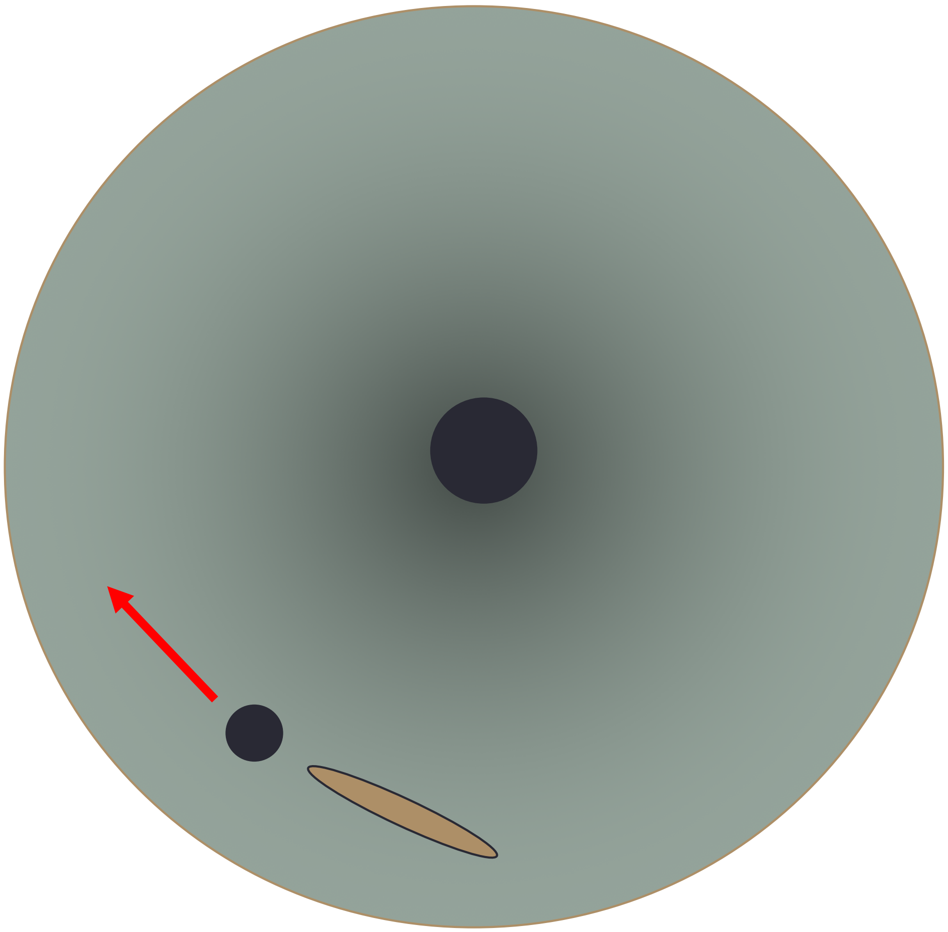
# SPECIAL TOPIC

Supermassive Black Hole Mergers

# Was there a recent black hole merger in our galactic center?

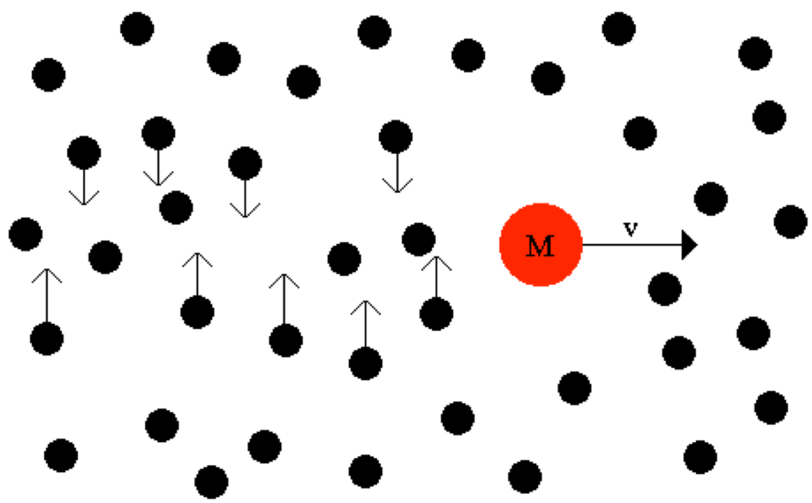
- The accretion of a satellite galaxy with an intermediate-mass black hole (IMBH) at its center could explain some odd characteristics in the center of the Milky Way.
- The hypothesis:
  - Tidal forces strip off most of the stars from the satellite as it falls in.
  - The smaller black hole stirs up material around the galactic center.
    - Some material falls into our supermassive black hole, which emits energy as jets and forms the Fermi bubbles.
    - Tidal compression of gas allows stars to form; explains why there are many young stars near the galactic center.
  - Gravitational interactions with the two black holes eject low-mass stars; explains lack of old stars near the galactic center and observations of “hypervelocity stars” in the halo.

# What about the black holes themselves?

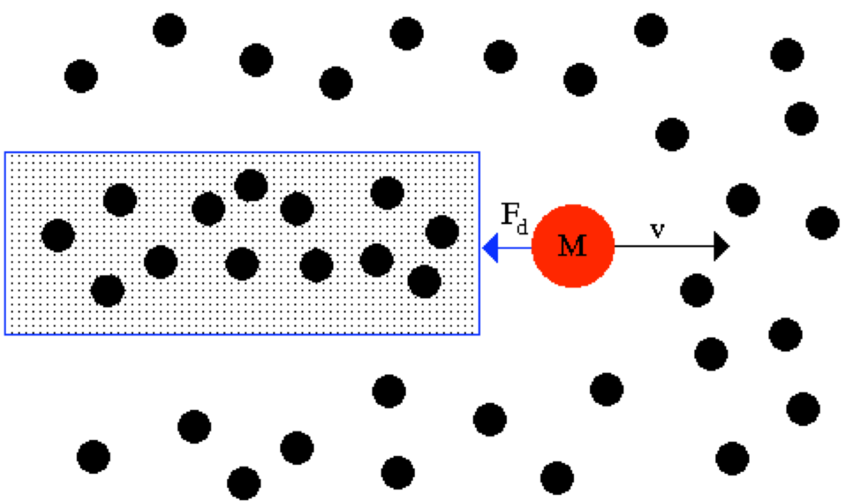


- The intermediate mass black hole sinks towards the center due to a process known as *dynamical friction.*
  - The black hole leaves a “wake” of stars and gas in its trail…the gravitational tug of this wake removes energy and angular momentum from the black hole’s orbit.

consider a mass, M, moving through a uniform sea of stars. Stars in the wake are displaced inward.

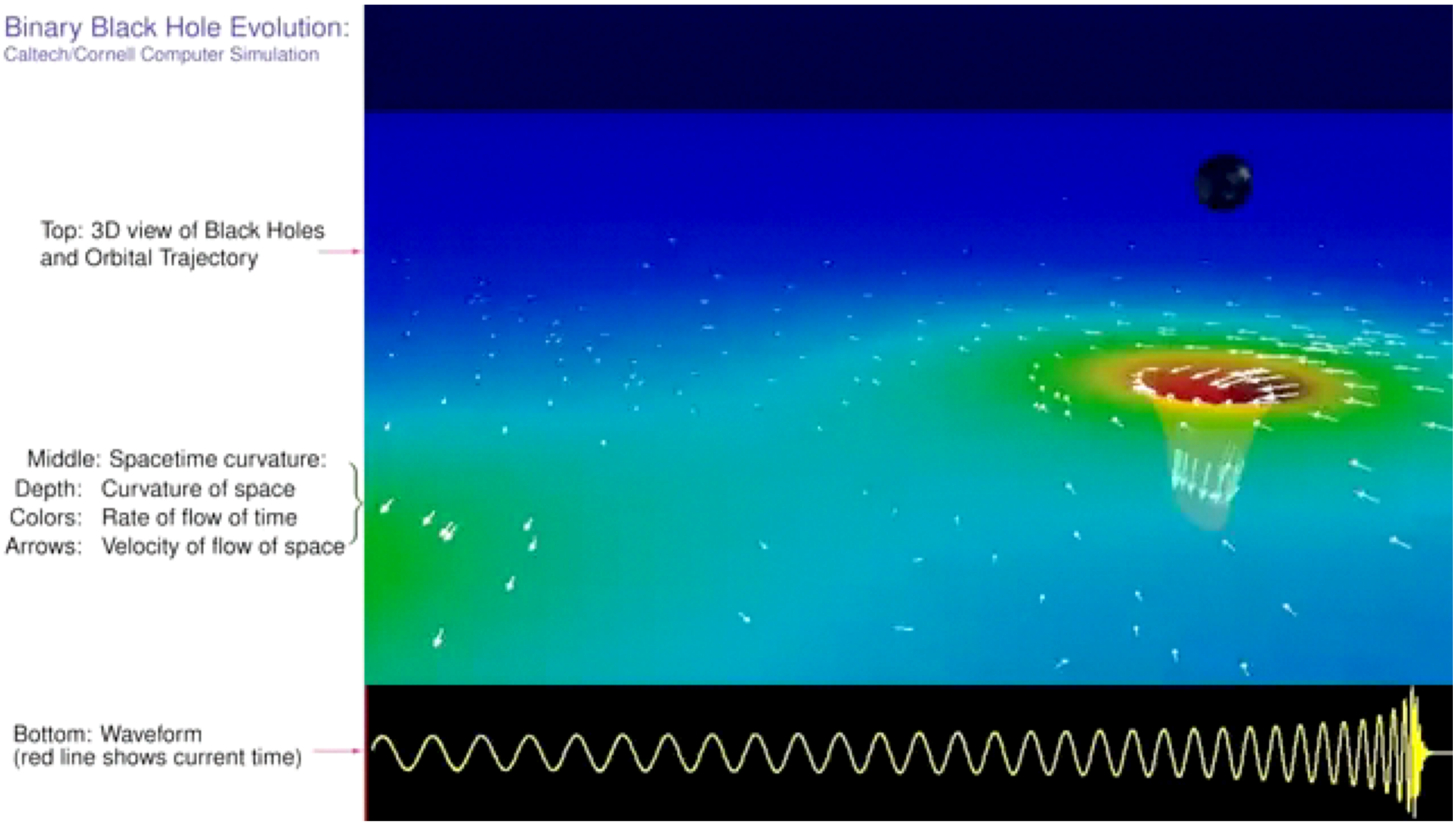



this results in an enhanced region of density behind the mass, with a drag force, $F_d$ known as dynamical friction



# The "Final Parsec Problem"

- Eventually, the intermediate mass black hole gets close enough that only the gravitational field of our supermassive black hole matters…they form a *binary black hole*. What then?
  - Dynamical friction continues to operate, causes binary to shrink.
  - Once black holes are about ~1 pc apart, this process may become ineffective (why?).
  - But *somehow*, binary continues to shrink...
  - Once black holes are about 0.01 pc apart, the *gravitational waves* that they are producing become effective at removing energy and angular momentum from the orbit in a reasonable timescale.
  - As black holes get close, they move faster, they emit stronger gravitational waves, and the binary shrinks at a faster rate.
  - Eventually, the black holes merge…


Binary Black Hole Evolution:
Caltech/Cornell Computer Simulation
Top: 3D view of Black Holes and Orbital Trajectory
Middle: Spacetime curvature:
Depth: Curvature of space
Colors: Rate of flow of time
Arrows: Velocity of flow of space
Bottom: Waveform
(red line shows current time)

# Supermassive black hole mergers

- This particular event would have happened billions of years ago…too late for us to observe it.
- Could we observe similar events in other galaxies?
  - For a brief time, the power output from a merging black holes **exceeds that of all of the stars in the observable universe combined!**
  - But this energy is released as gravitational waves (small disturbances in space-time)…
  - Need a detector like ESA's eLISA (Evolved Laser Interferometric Space Antenna), to launch in 2034.
    - LISA Pathfinder launched in September 2015.