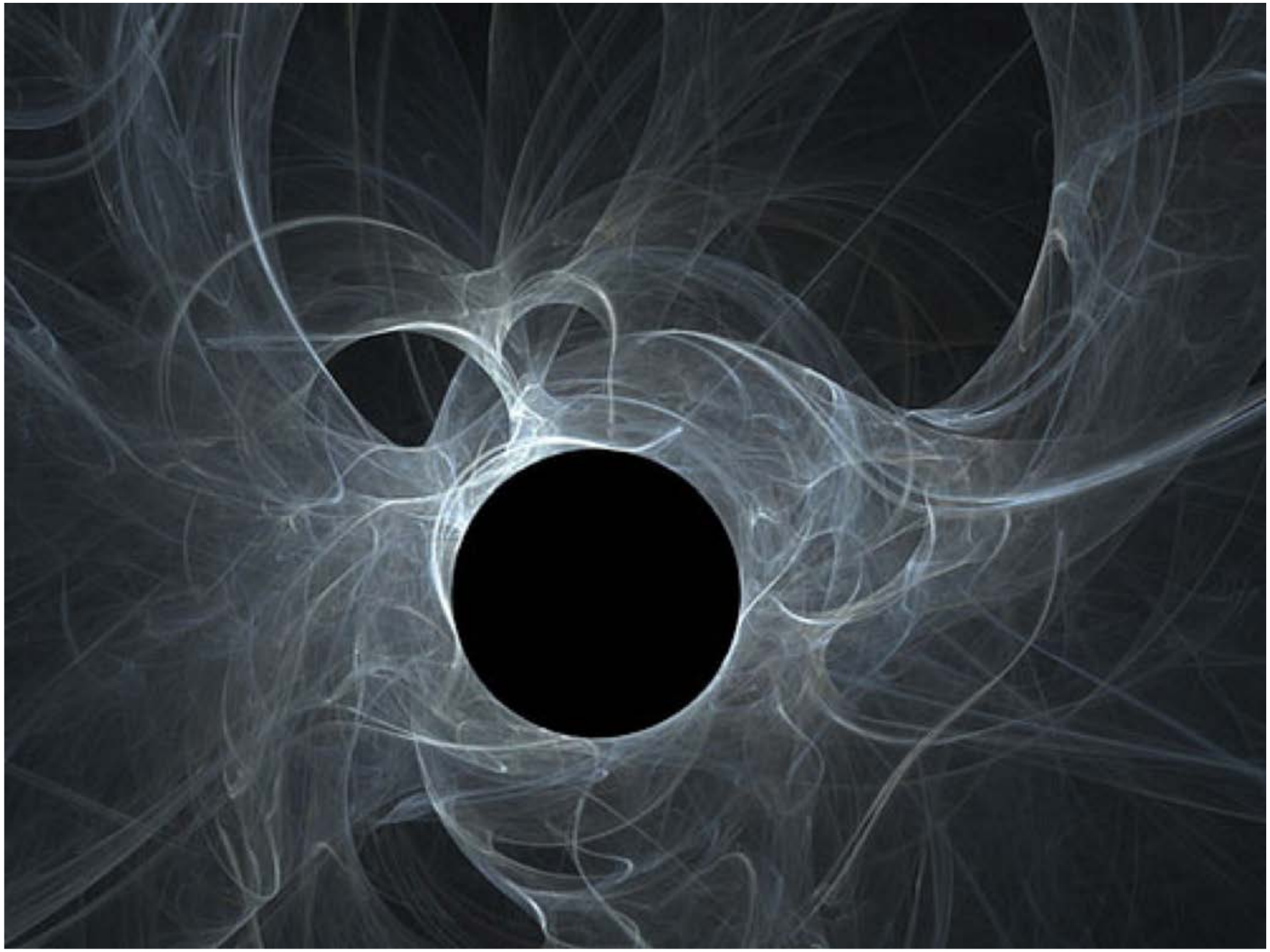
# Black Holes in Hibernation



# Black Holes in Hibernation

Only about 1 in 100 galaxies contains an active nucleus. This however does not mean that most galaxies do no have SMBHs since activity also requires a supply of fuel.

Typically a galactic nucleus needs a supply of about 1 $M_{\odot}$ per year to power a quasar or Seyfert galaxy.

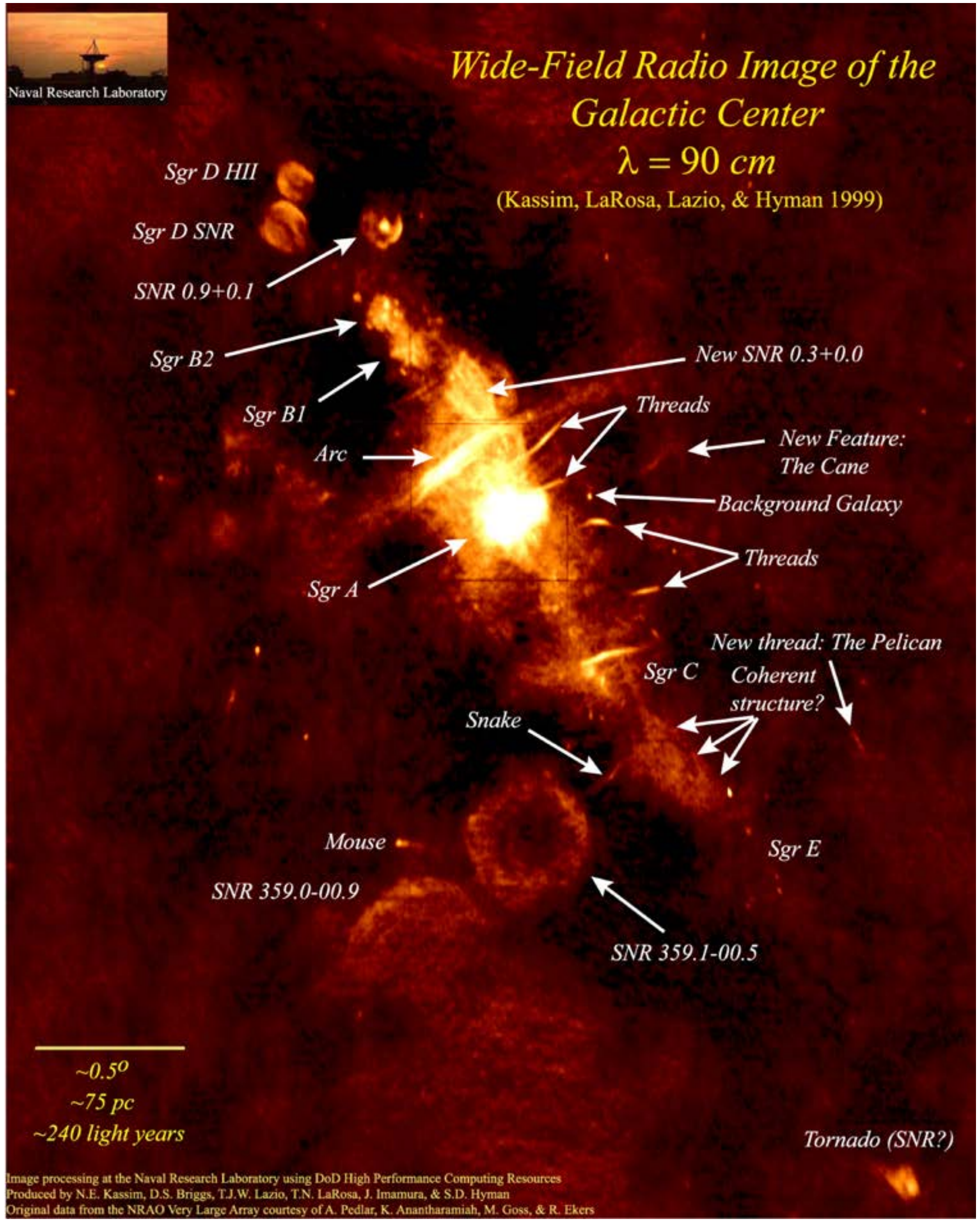
Objects with powerful jets may need less accretion to maintain the jets, however, without a supply of accretion the rate of SMBH's spin may slowly decline.

The masses of SMBH's in the centers of galaxies turn out to be correlated with the properties of the host galaxies indicating a link with the epoch of galaxy formation in the past.

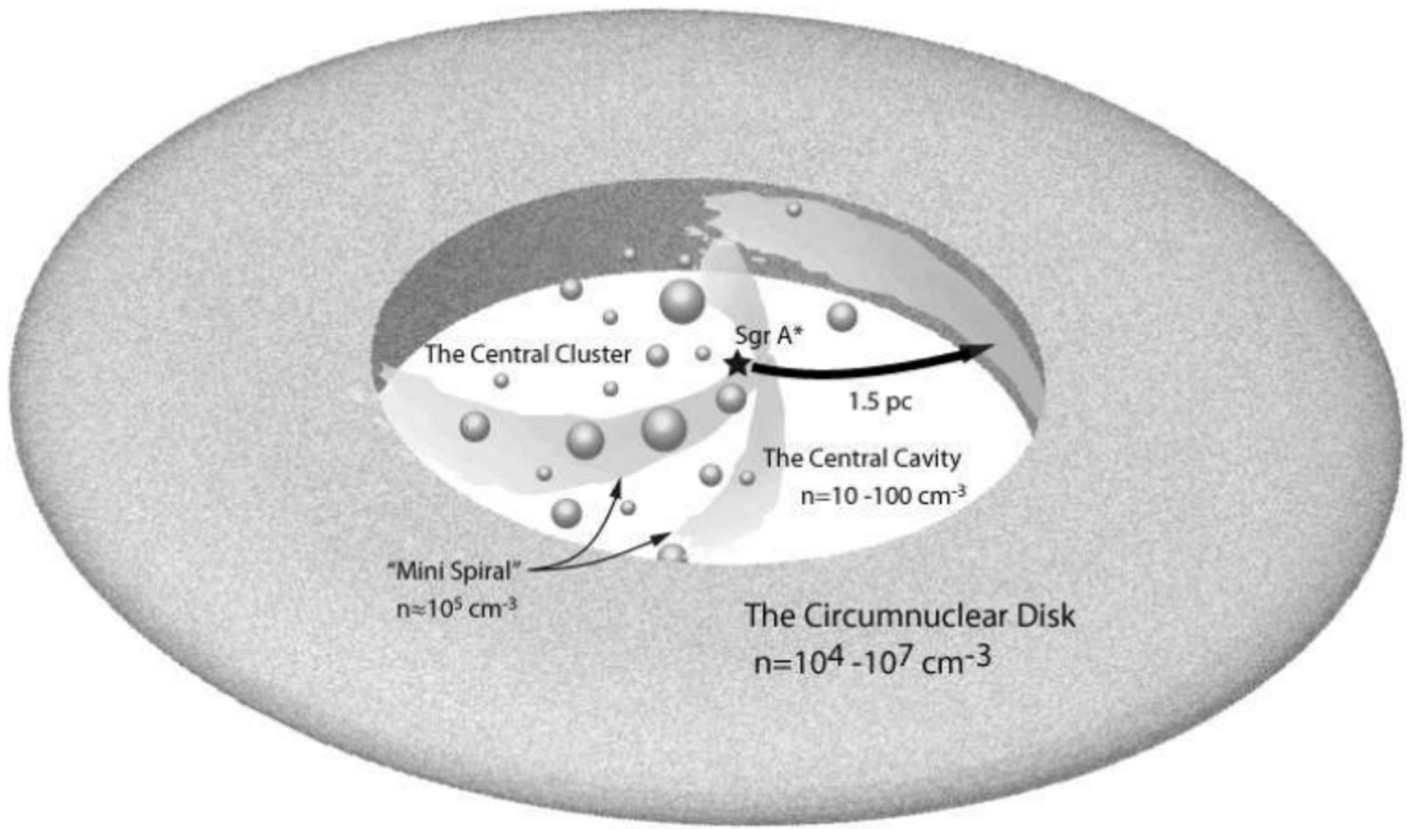
An infrared image of the central region of the Milky Way shows a dense concentration of stars.

The image covers about 4 light years on a side; the central black hole is located at the center of the rectangle.

# Galactic Center



# Galactic Center

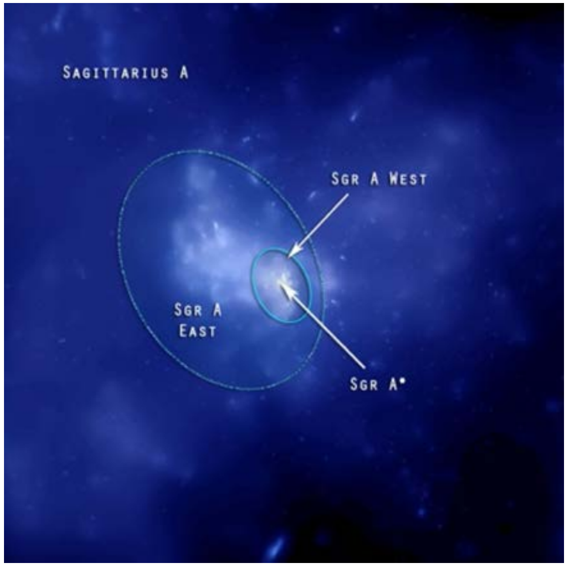



Schematic view of the central few parsecs of the galaxy (central molecular zone), showing the central black hole, Sgr A*, stars in the central star cluster, and the circumnuclear disk which contains dense molecular clouds.
The ring is inclined some 20 degrees with respect to the Galactic plane and rotates at about 110 km/s. The ring has very sharp boundaries implying a recent violent event like a supernova may have recently occurred.

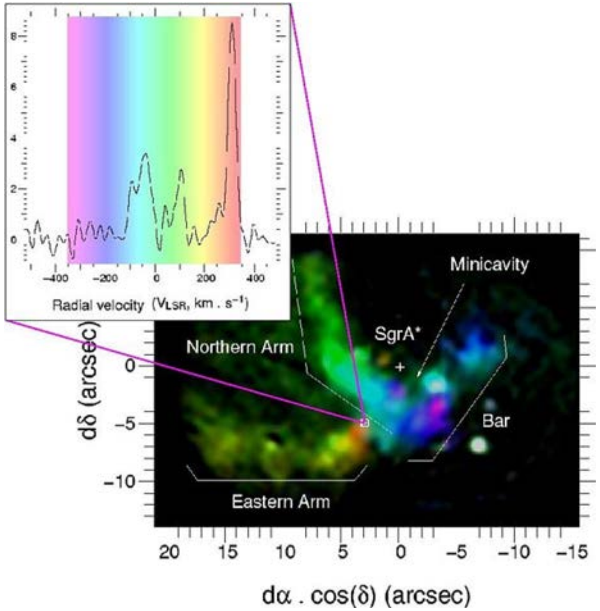
# Galactic Center

**Sgr A East** is 25 light-years in width and has the attributes of a **supernova remnant** from an explosive event that occurred between 35,000 and 100,000 BCE.

**Sgr A West** has the appearance of a three-arm spiral, from the point of view of the Earth. The apparent spiral is made of several dust and gas clouds, which orbit and fall onto Sagittarius A* at velocities as high as 1,000 km/s. The surface layer of these clouds is ionized. The source of ionization is the **population of massive stars OB stars** that also occupy the central parsec.




The central parsec around Sagittarius A* contains thousands of stars. Although most of them are old red main-sequence stars, the Galactic Center is also rich in massive stars. Astronomers have found a population of more than a 100 very young (O, B) stars close to the Galactic Center. They seem to have all been formed in a single star formation event a few million years ago.



# Black Holes in Hibernation

To penetrate the dust and gas near the center of our galaxy astronomers typically observe this region in the infrared.

Infrared images show that the **density of stars** increases dramatically near the nucleus of a galaxy.

In our galaxy the density of stars near the sun is ~ 0.006 stars per cubic light-year

Near the center of our galaxy the density is ~$10^6$ stars per cubic light-year

# Black Holes in Hibernation

To improve the spatial resolution of the IR observations of the galactic center astronomers employed two methods:

1. Lining up and stacking together thousands of very short exposures. This reduced the effects of atmospheric turbulence.

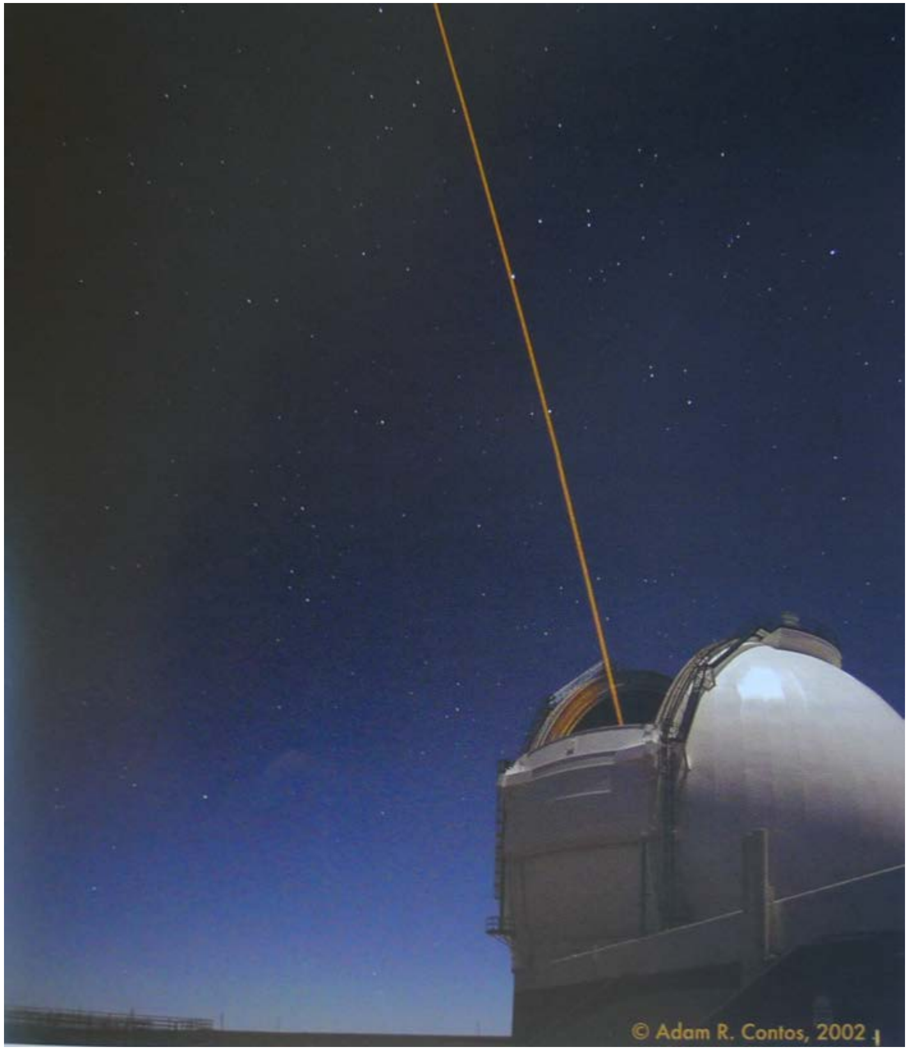
2. Using adaptive optics. With adaptive optics the distorted and flickering image of a star is compared to every few milliseconds to the point-like appearance it would have with the absence of turbulence. The telescopes mirrors are slightly deformed in real time to compensate.

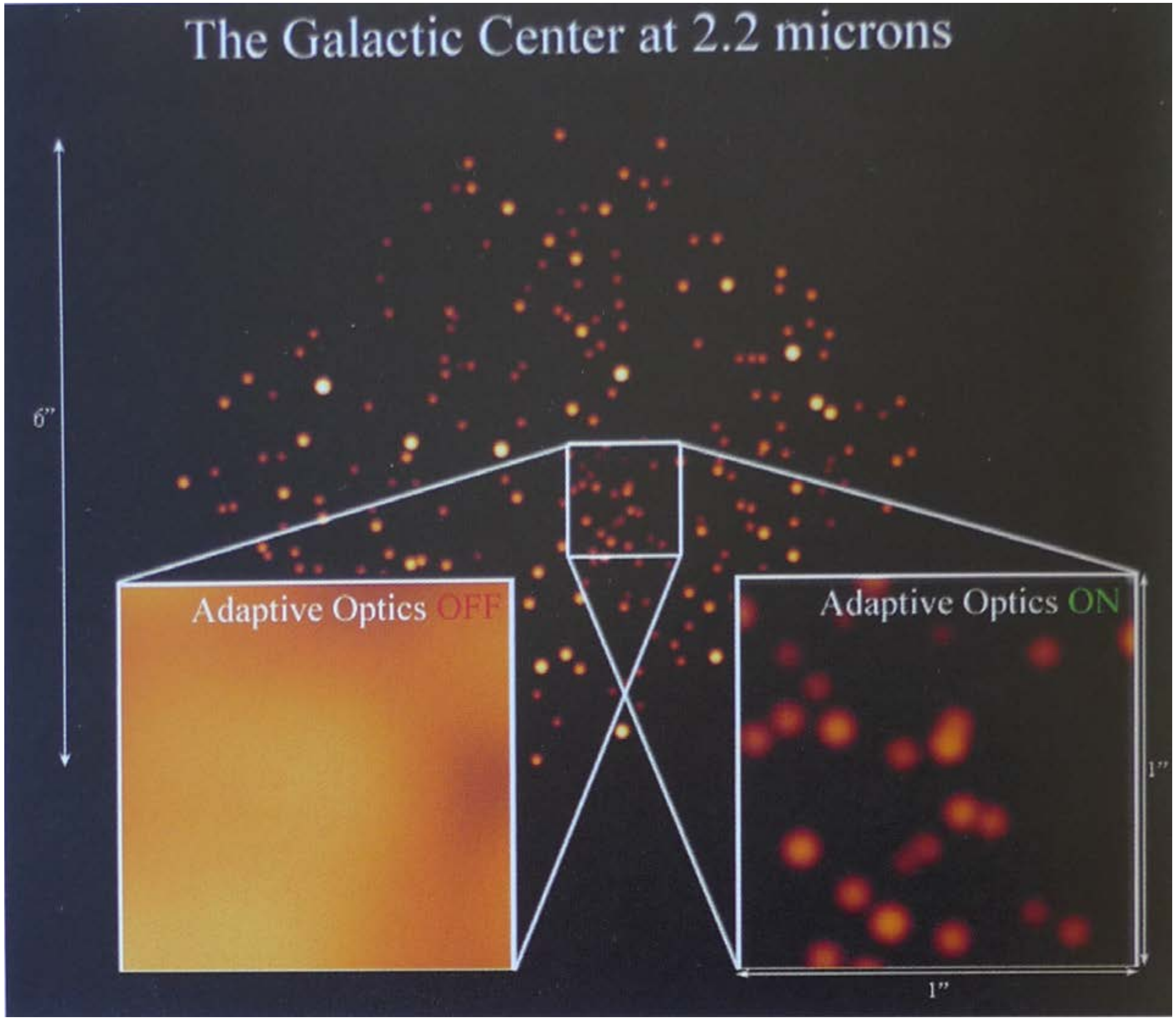
Reinhard Genzel and Andrea Ghez mapped the orbits of stars close to the galactic center and showed that it must contain a supermassive black hole with a mass of about $4 \times 10^6\ M_{\odot}$.

One does not need to use a real star to monitor atmospheric turbulence.

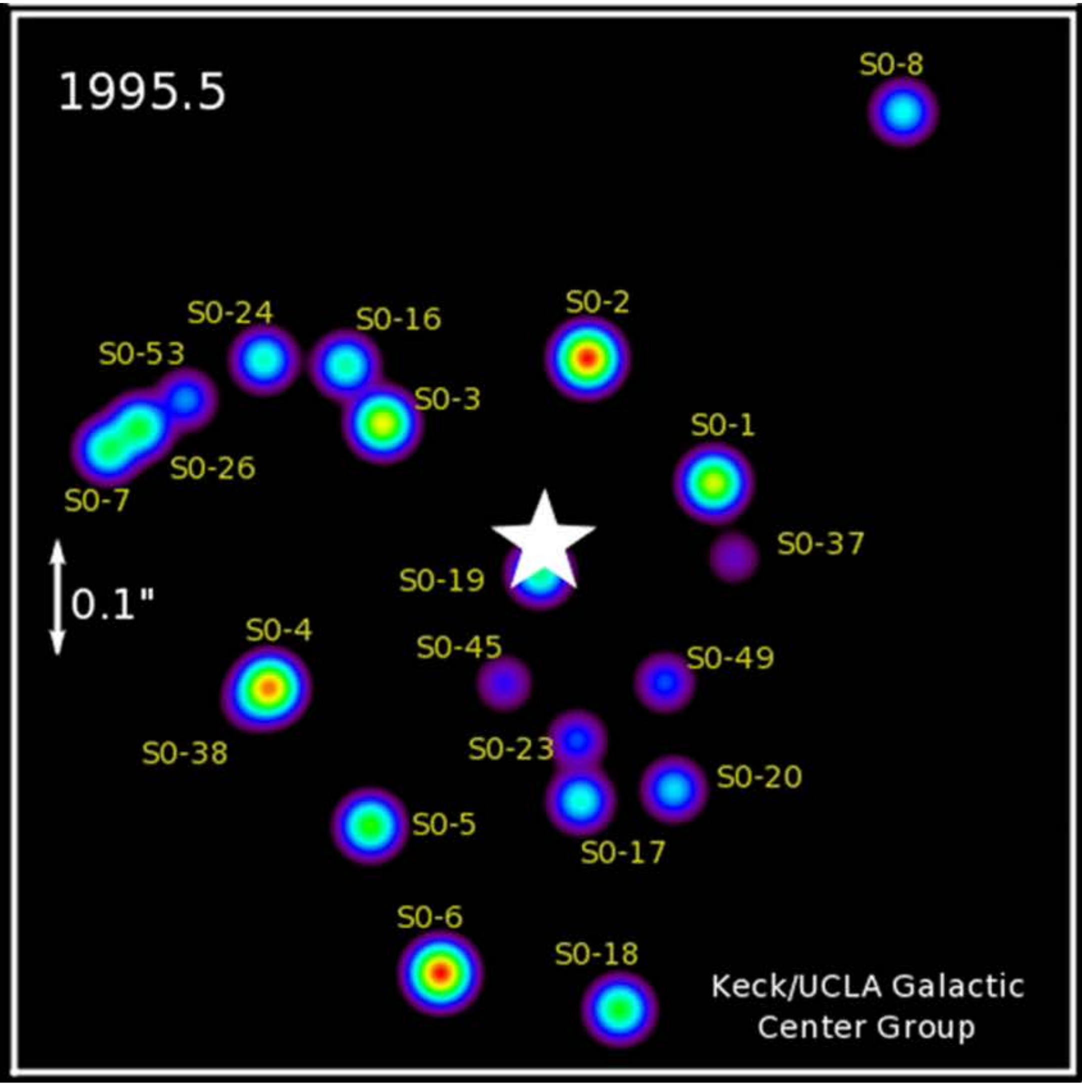
In the photo a laser beam from the 10m Keck Telescope is reflected by sodium atoms (Na) in the upper atmosphere producing an artificial guide star.

Adaptive Optics observations of the galactic center leave no doubt that a SMBH lies at the center. One of the stars orbiting around the SMBH has a speed of about 12,000km/s and its point of closest approach is about 1000 $R_s$.






An example of the dramatic improvement of the ability of the Keck Telescopes to discern individual stars in the Galactic center when adaptive optics is used.




Observations over more than a decade have enabled the Ghez and Genzel groups to trace the orbits of individual stars around Sgr A*, providing incontrovertible evidence for a SMBH. Distance to Sgr A*~ 26,000 ly, $M_{BH} \sim 4.2 \times 10^6 M_\odot$.

# Supermassive Black Hole in NGC 4258

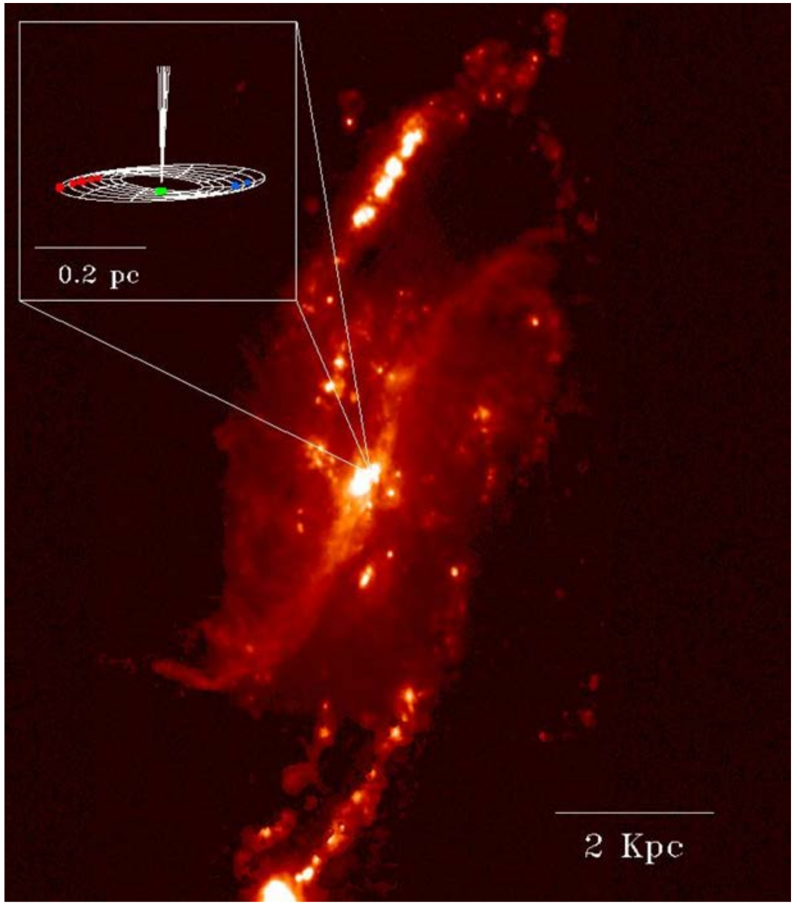
NGC 4258 is a spiral Seyfert II active galaxy with a weak radio jet (distance ~ 24 million ly).

The **mass and distance** to the SMBH of NGC 4258 comes from measurements of emission from water molecules in gas clouds orbiting very near the nucleus.

The water molecules in clouds of gas that orbit the SMBH emit powerful microwave radiation.

These sources of stimulated spectral line radiation are called **masers**.

Maser = *m*icrowave *a*mplification by *s*timulated *e*mission of *r*adiation.




Optical $H_\alpha$ image of NGC 4258

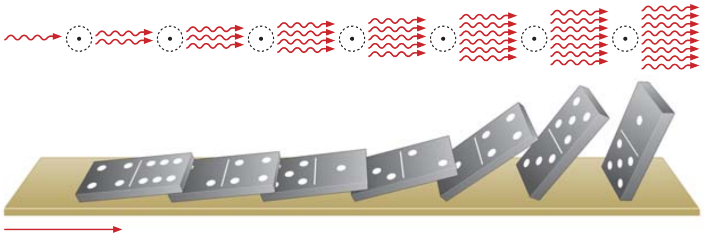
# Water Masers in NGC 4258

**Spectral emission lines** are produced during the de-excitation of an atom or molecule from a certain energy to a lower energy level.

Typically a **water molecule in an excited state** will jump to the lower energy level at random emitting a photon of a specific wavelength.

There is a way, however, to **stimulate the molecule to transition** to the lower level. If light from exactly the same wavelength passes by the molecule it can stimulate the molecule to emit right away.

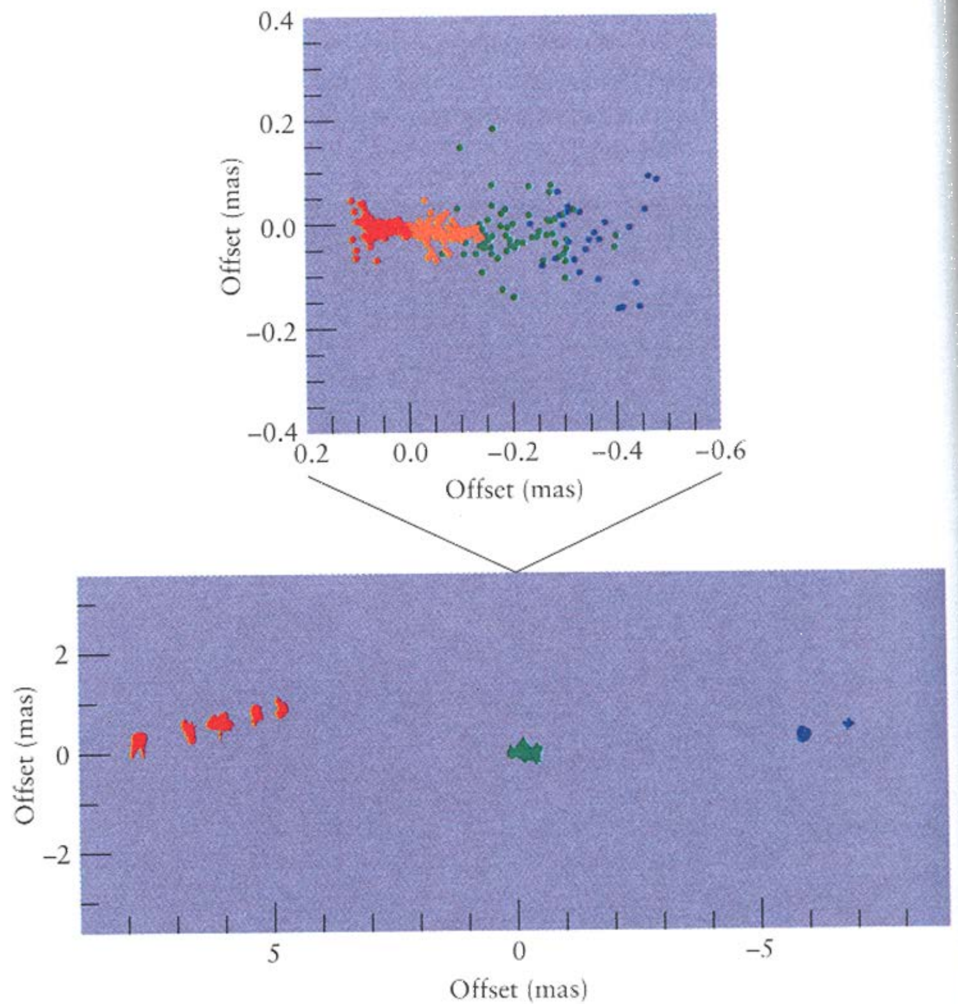
Imagine a large group of water molecules all in an excited state at the same time. Once one begins to de-excite it will cause all the other ones to almost simultaneously de-excitate producing a **maser**; an intense beam of microwave radiation at ~ 22 GHz.



# Water Masers in NGC 4258

By using the VLBA to obtain the precise locations of the masers and using the Doppler effect to get their velocities astronomers can map out the velocity of clouds in the accretion disk of NGC 4258.

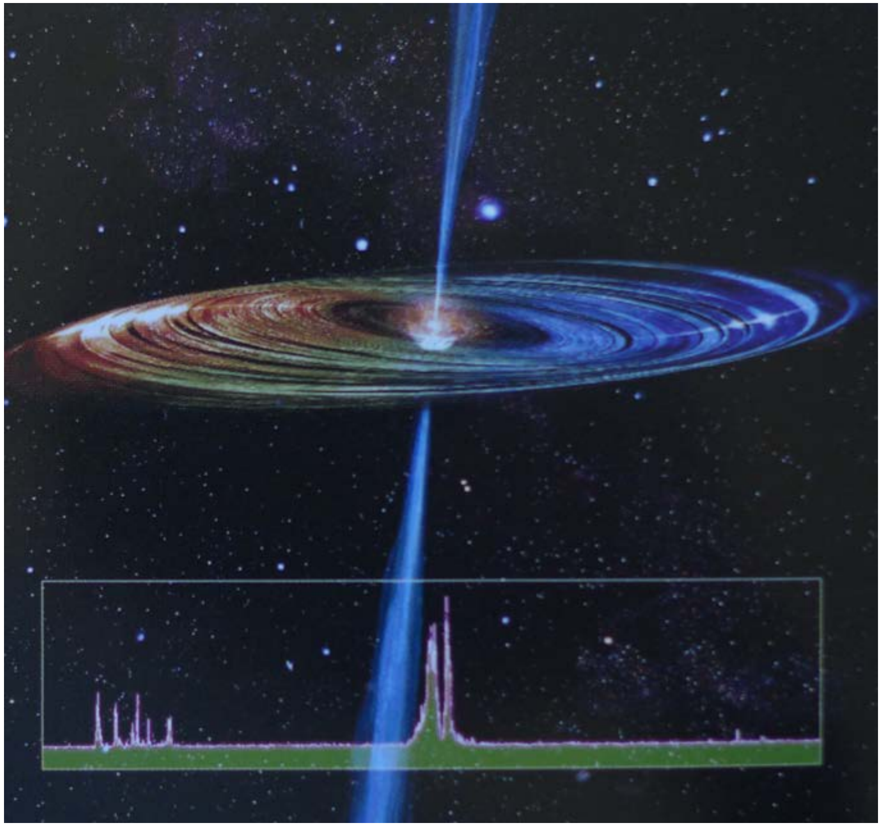
The red dots indicate masers in the disk moving away from us and blue dots moving towards us. The disk of NGC 4255 is viewed almost edge on.



# Water Masers in NGC 4258

The center of NGC 4258 harbors a thin disk that we observe almost edge on; the graph at the bottom shows the Doppler shifted emission lines coming from various discrete molecular clouds.

These molecular clouds contain water molecules that are acting like masers.



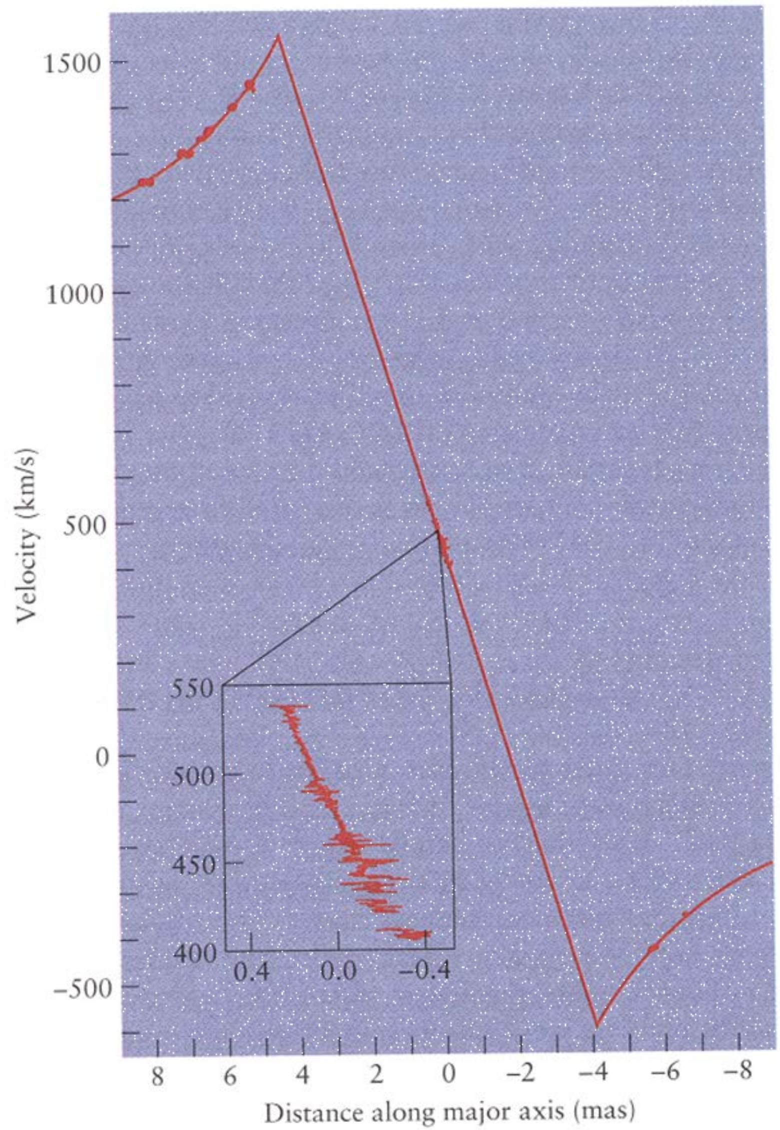
# Velocity Profile of Masers in NGC 4258

This is a plot of the **velocities of the masers** in the disk of NGC 4258 as a function of their distance from the center of the galaxy.

The entire galaxy is moving away from us at about 500 km/s.

The continuous line shows what Newton's theory would predict if the gas in the disk were orbiting under the influence of a $36 \times 10^6 M_\odot$ central object.

The disk has an inner edge with a velocity of about 1080 km/s. Outside the edge the velocity drops off as $1/\sqrt{R}$ as expected by Newton's Law.



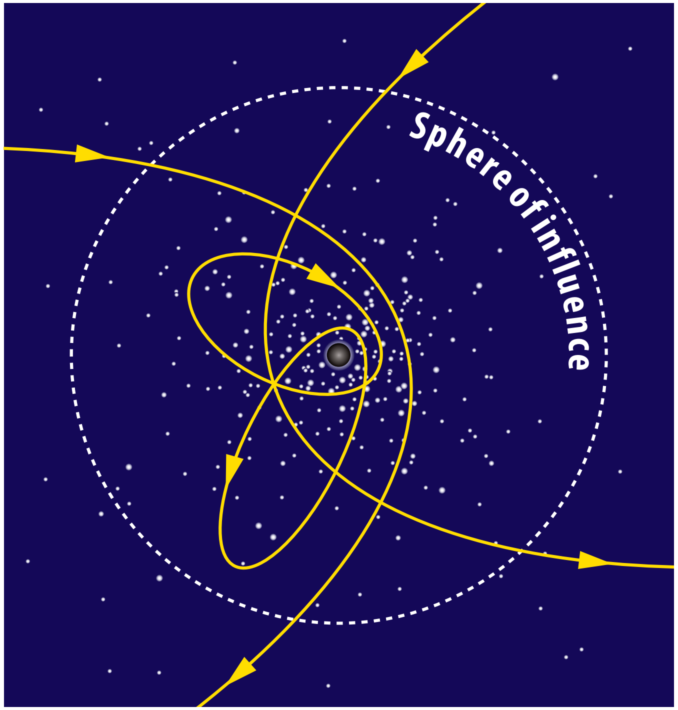
# A SMBHs Sphere of Influence

Stars in a galactic nucleus move in random directions.

A SMBH has a **sphere of influence** within which the black holes gravity significantly affects the motion of stars.

**sphere of influence** : the radius at which the gravity on a star from the hole is stronger than the gravity from all the other stars combined.

$r_{sphere}$ may be > $10^6$ times larger than the event horizon.



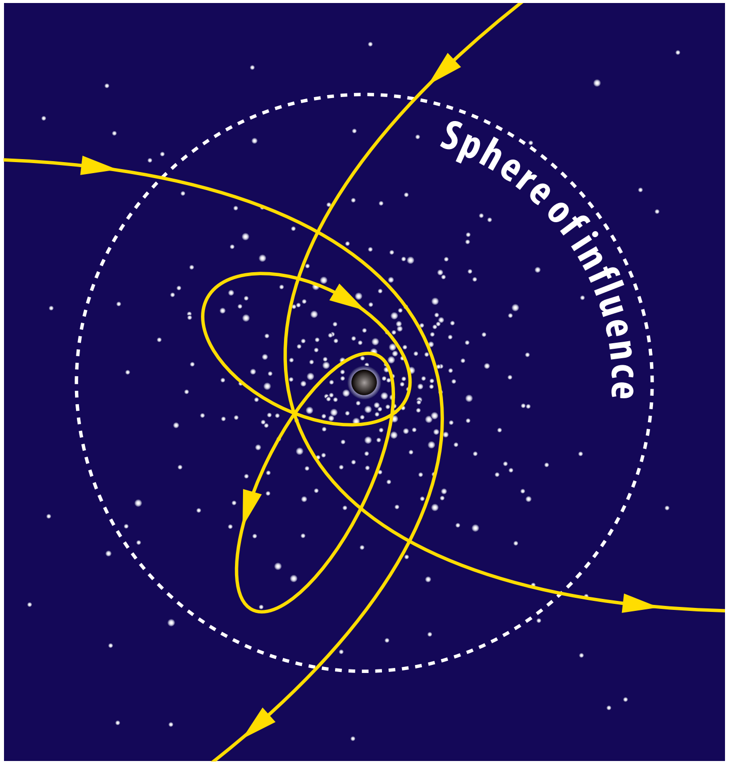

$$r_{sphere} \propto \frac{M_{BH}}{v^2}$$

# Signatures of the Presence of a SMBH

A SMBH makes its presence in a galaxy by:

1. Leads to an increase in the velocities of stars near the galactic nucleus.

2. Increases the number density of stars near the BHs sphere of influence.



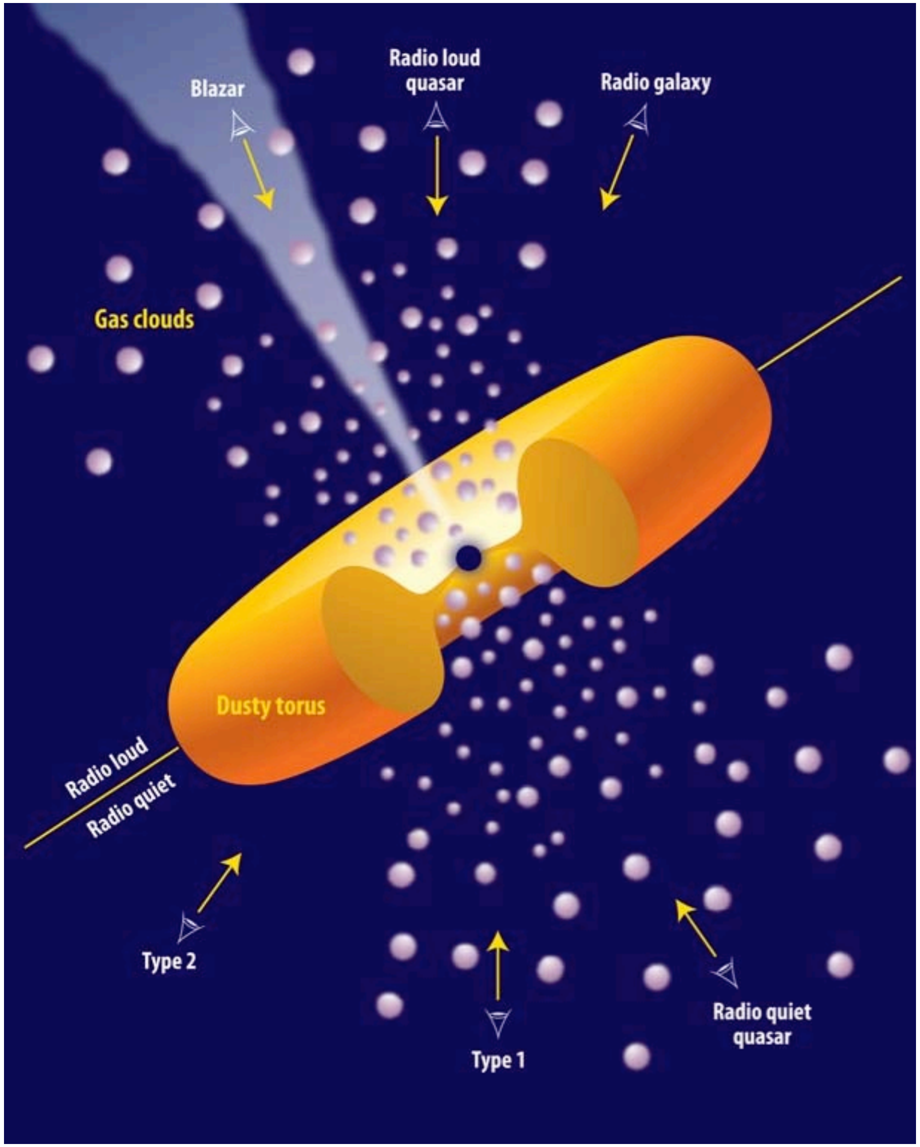
# Determining BH Masses in AGN

The BH mass in an AGN is given by the virial equation :

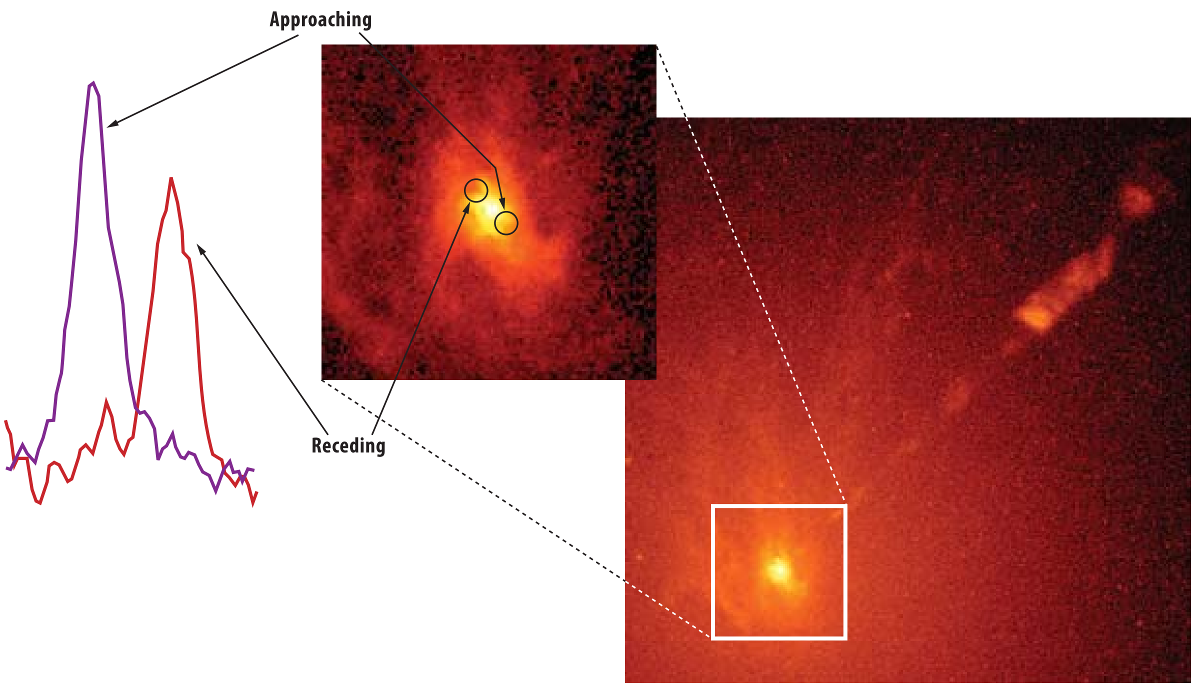
$$M_{BH} = \frac{fR\Delta v^2}{G} \propto \frac{fL^{\gamma}\Delta v^2}{G}$$

Where $f$ is a scale factor ~ 1 that depends on the broad line region (BLR) geometry, $R$ is the distance between the BLR and ionizing source as inferred from reverberation mapping and $\Delta v$ is the emission-line width.

Observations show that $R \propto L^{\gamma}$, where L is the AGN's continuum luminosity. The AGNs luminosity can therefore be used as a surrogate for R in the $M_{BH}$ equation.


Blazar
Radio loud
quasar
Radio galaxy
Gas clouds
Dusty torus
Radio loud
Radio quiet
Type 2
Type 1
Radio quiet
quasar

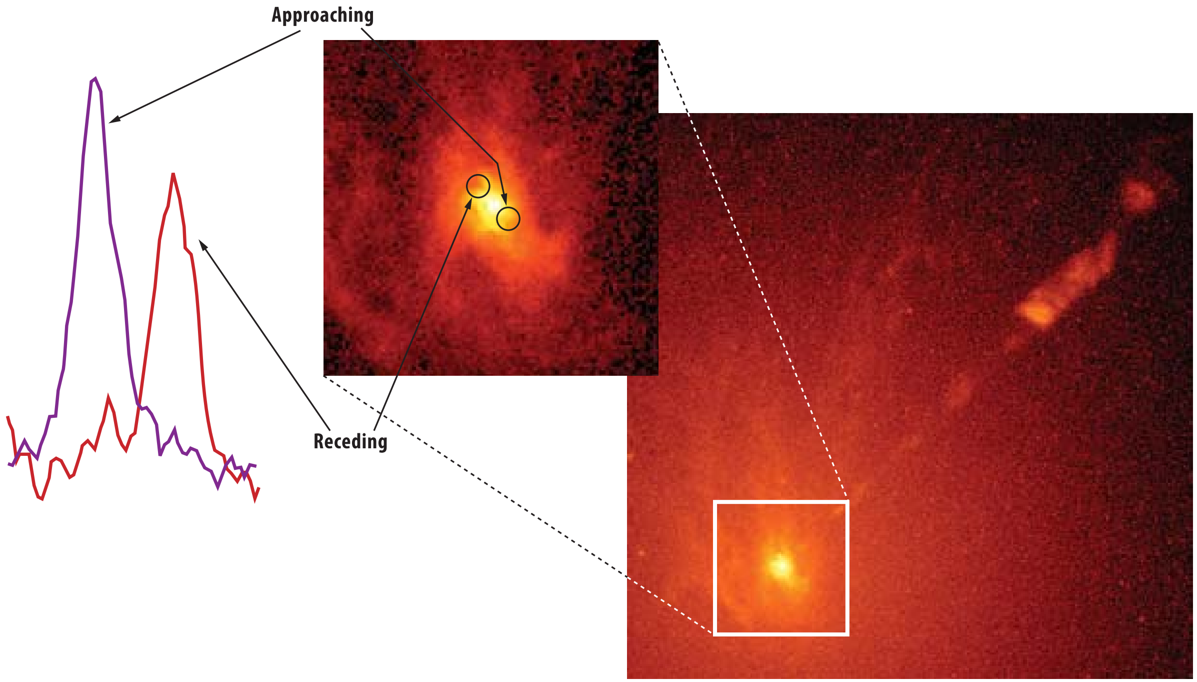
# A Black Hole Census




Hubble image of **glowing gas of material orbiting the nucleus** of the giant elliptical galaxy **M87**. The glowing gas is about 60 ly from the core. The Doppler shifted lines indicate that the gas is rotating at a speed of ~ 750 km/s.

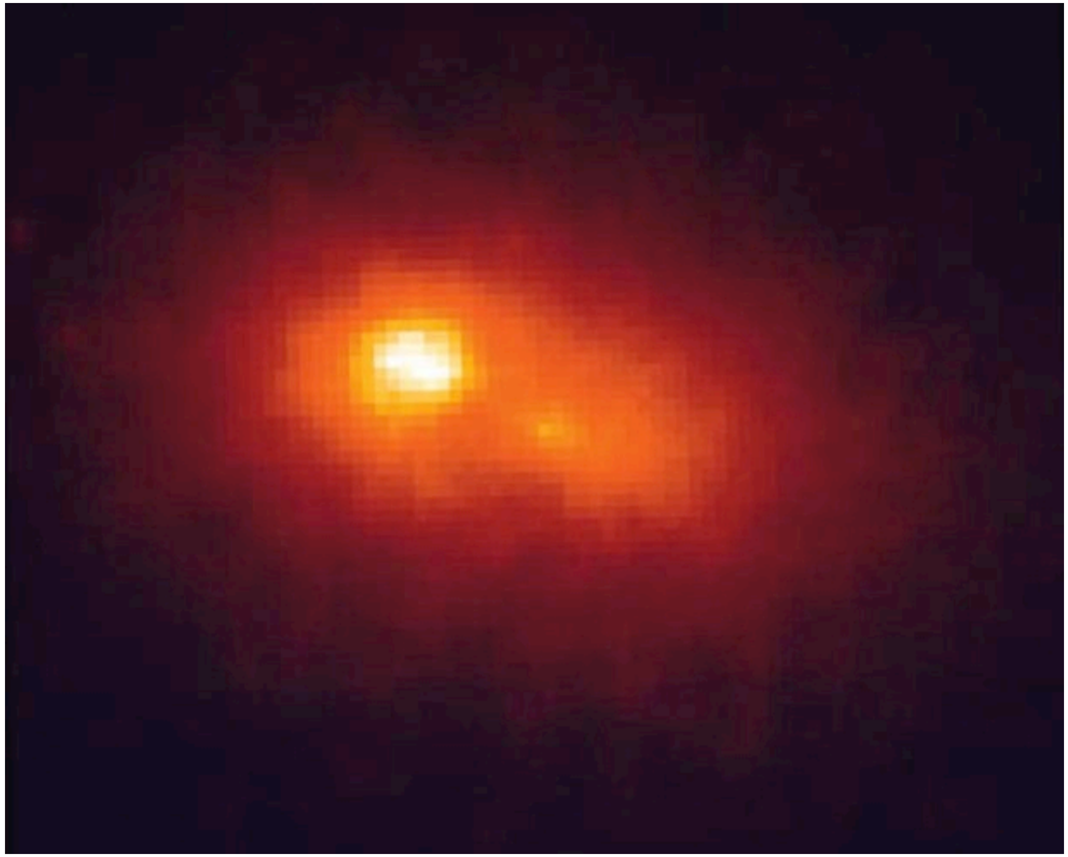
$G = 6.7 \times 10^{-11} m^3\ kg^{-1}\ s^{-2}$, $M_\odot = 2 \times 10^{30}$ kg, 1 ly = $9.461 \times 10^{15}$ m

# A Black Hole Census




Hubble image of **glowing gas of material orbiting the nucleus** of the giant elliptical galaxy **M87**. The glowing gas is about 60 ly from the core. The Doppler shifted lines indicate that the gas is rotating at a speed of ~ 750 km/s. The central mass required to keep gas in orbit at that speed is $2.4 \times 10^9\ M_\odot$.
Recent estimates, however, place the mass at $6.4 \times 10^9\ M_\odot$

# A Black Hole Census



Hubble image of the central region of the Andromeda galaxy (M31) in visible light. The stars form an eccentric disk around the SMBH ($M_{BH} \sim 140 \times 10^6\ M_\odot$). The black hole is located closer to the fainter of the two peaks in the light distribution.

# Black Hole Mass and Galaxy Bulge Mass

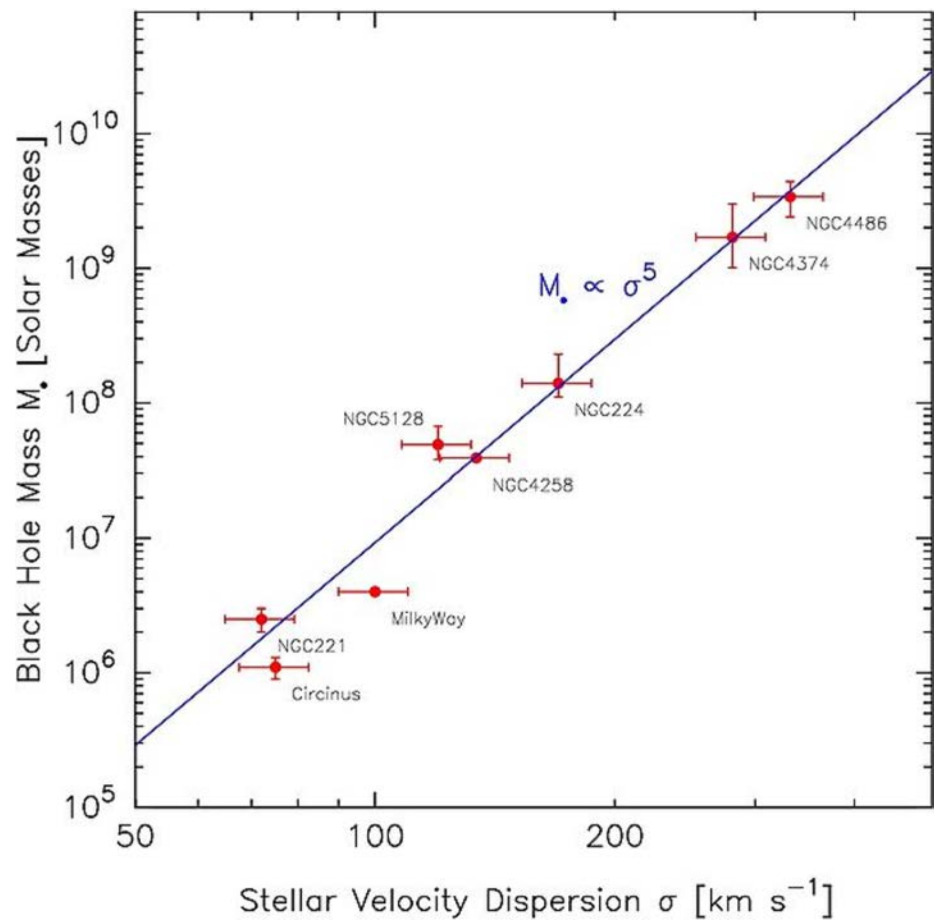
Observations in the 1990s had demonstrated a possible empirical relationship between **galaxy luminosity and black hole mass** but this relationship had larger scatter (*Magorrian Relation)*.

The mean ratio of black hole mass to bulge mass is believed to be approximately 0.1% , i.e., a bulge of one billion solar masses contains a black hole of approximately one million solar masses.

# Black Hole Mass – Velocity Dispersion Relation

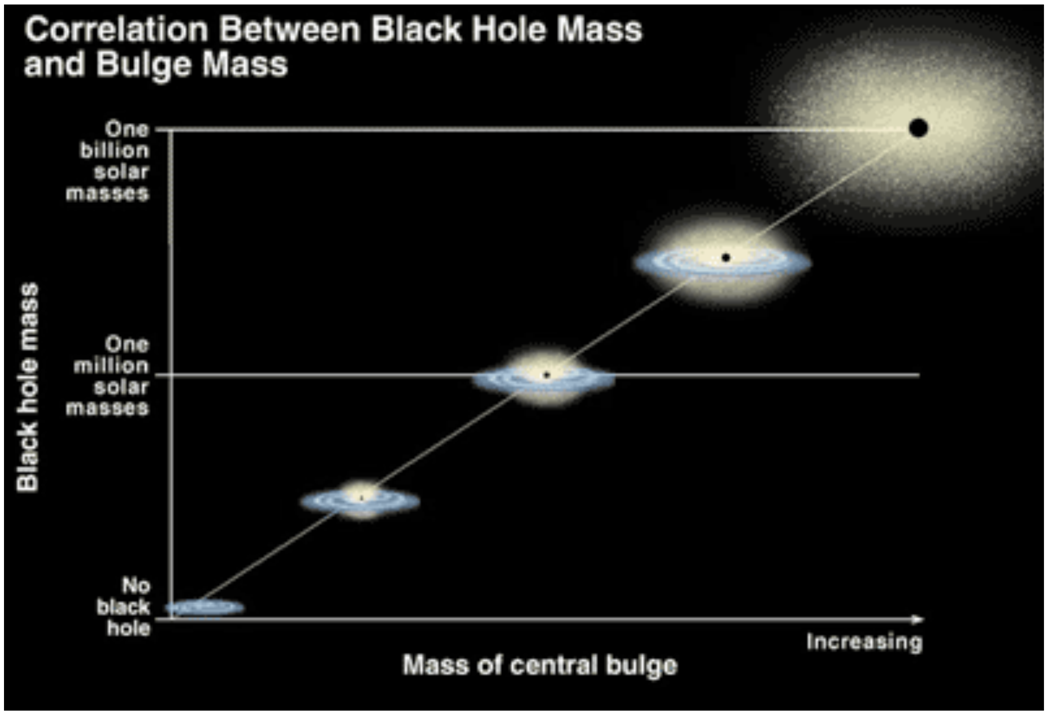
The $M_{BH}$-σ relation is an empirical correlation between the stellar velocity dispersion σ of a galaxy bulge and the mass M of the supermassive black hole at the galaxy's center.

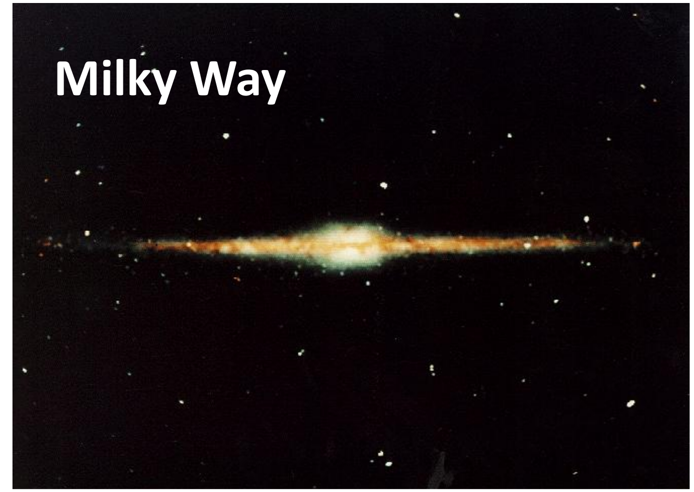
$$\sigma = \frac{1}{\sqrt{N}} \left[ \sum_{i=1}^{N} \left( \mathrm{v}_i - \langle \mathrm{v} \rangle \right)^2 \right]^{1/2}$$




$$M_{BH} \propto \sigma^{\alpha}, \ \alpha \approx 5$$

# The influence of black hole winds and jets on their environments




# Black Holes with Low Accretion Rates

Low accretion rates in black holes are found in environments that are gas poor.

The luminosity of an AGN due to accretion is:

$$L_{accretion} = \frac{G\dot{m}M}{R} = \eta(\dot{m})c^2, \text{ where } \dot{m} = \frac{dM}{dt} \text{ is the accreton rate.}$$

For a black hole $\eta \sim 0.06\text{-}0.42$

SgrA* appears to have a luminosity much lower than what is expected for its accretion rate.

## Numerical Simulations of Accretion Flows

- (**Advection Dominated Accretion Flow** ) ADAF

$L < 0.001\ L_{Edd}$ e.g. Sadowski+ 2016

- Radiatively Efficient Flows result in a geometrically thin disk

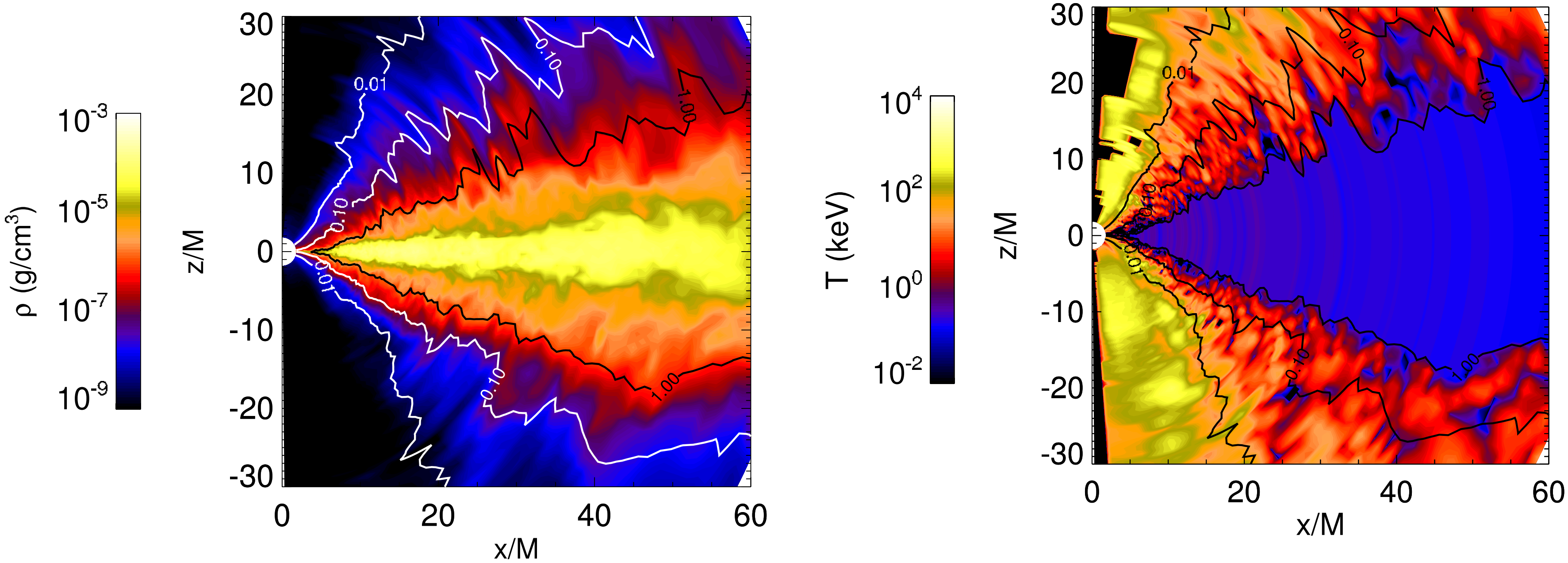
$0.001L_{Edd} < L < L_{Edd}$ e.g. Noble+ 2011; Kulkarni+ 2011; Penna+ 2012; Sadowski+ 2016.

- super-Eddington accretion disks (Slim Disks)

$L > L_{Edd}$

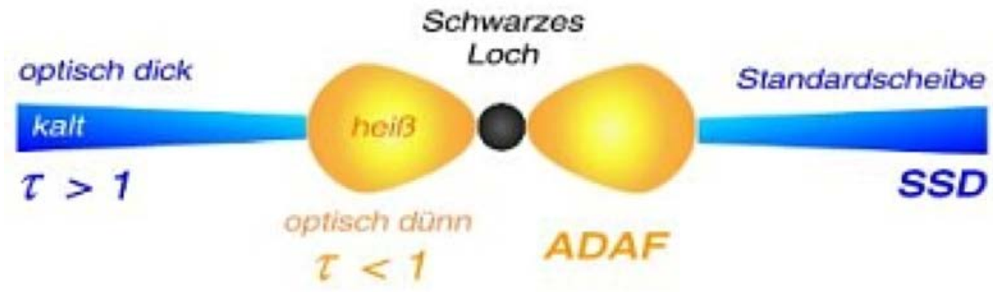
# Numerical Simulations of Accretion Flows

**GRMHD simulations for $M_{BH} = 10M_{\odot}$, $L=0.1L_{Edd}$, Schnittman+2013**




**Fluid density profile** | **Electron temperature in the Corona**

# Black Holes with Low Accretion Rates

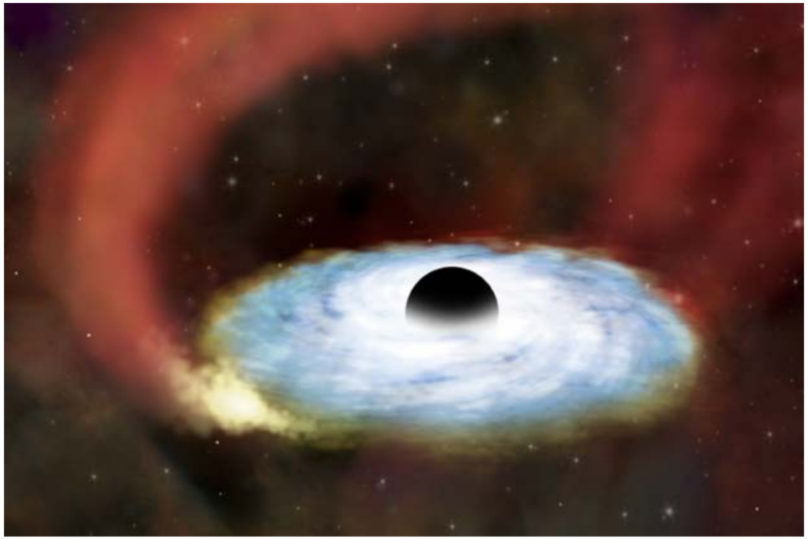



According to the **Advection Dominated Accretion Flow** model (ADAF) at low accretion rates the disk puffs up, cannot radiate efficiently and is very hot.

The spectrum of an ADAF is close to that of a power-law. Because of their low efficiency, ADAFs are much less luminous than normal thin disks.

SgrA* may have an ADAF explaining its low luminosity.

# Fueling a Black Hole by Tidal Disruption



A star is ripped apart by the tidal forces of a massive black hole (left panel). Part of the stellar debris is then accreted by the black hole (middle panel). This causes a luminous flare of radiation which fades away as more and more of the matter disappears into the black hole

# Fueling a Black Hole by Tidal Disruption

Tidal disruption of stars is thought to be a mechanism of fueling quasars. For this mechanism to work (make quasars luminous) the star needs to be disrupted but not swallowed completely by the black hole.

A star of mass density $\rho_*$ approaching a massive body of mass density $\rho_{BH}$ and radius R must reach at least a distance from the body of $r_R$, where $r_R$ is the Roche limit for it to be tidally disturbed. The Roche limit is given by:

$$r_R = 2.4\left(\frac{\rho_{BH}}{\rho_*}\right)^{1/3} R$$

For a star approaching a black hole to be disrupted but not swallowed by the hole its Roche limit must be larger than the Schwarzschild radius, $r_R > R_s$. This then places an upper limit on the mass of the Black Hole for fueling by tidal disruption of:

$$M < 5 \times 10^8 \rho_*^{-1/2} M_{solar}$$

$\rho_*$ is the density of the star in gr/cm$^3$.

# Fueling a Black Hole by Tidal Disruption

$$r_R = 2.4\left(\frac{\rho_{BH}}{\rho_*}\right)^{1/3} R_s$$

$$r_R > R_s = \frac{2\mathrm{GM_{BH}}}{\mathrm{c}^2} \Rightarrow \mathrm{M_{BH}} < \frac{r_R \mathrm{c}^2}{2\mathrm{G}} = \frac{2.4\left(\frac{\rho_{BH}}{\rho_*}\right)^{1/3} R_s \mathrm{c}^2}{2\mathrm{G}} \Rightarrow$$

$$\mathrm{M_{BH}} < \frac{2.4\left(\frac{M_{\mathrm{BH}}}{\frac{4}{3}\pi R_S^3}\right)^{1/3} R_s \mathrm{c}^2}{2G\rho_*^{1/3}} = \frac{2.4\left(\frac{M_{\mathrm{BH}}}{\frac{4}{3}\pi}\right)^{1/3} \mathrm{c}^2}{2G\rho_*^{1/3}} \Rightarrow \mathrm{M_{BH}^{2/3}} < \frac{2.4\left(\frac{4}{3\pi}\right)^{1/3} \mathrm{c}^2}{2G\rho_*^{1/3}}$$

$$\mathrm{M_{BH}} < \left[\frac{2.4\left(\frac{4}{3\pi}\right)^{1/3} \mathrm{c}^2}{2G\rho_*^{1/3}}\right]^{3/2} = \mathrm{C}\rho_*^{-1/2}, \text{where } \mathrm{C} = 5 \times 10^8 \ \mathrm{M_{solar}}$$

# Fueling a Black Hole by Tidal Disruption

A **powerful X-ray outburst** was detected from the center of the galaxy RXJ1242-11, a billion light-years from Earth. The center of the galaxy suddenly flared up in X-rays yet in the visible it did not show any activity.

Astronomers believe that a doomed star came too close to a giant black hole and as it neared the enormous gravity of the black hole, **the star was stretched by tidal forces** until it was torn apart.

The X-ray outburst, was caused by gas from the destroyed star that was heated to millions of degrees Celsius before being swallowed by the black hole. The energy liberated in this process is equivalent to that of a supernova.

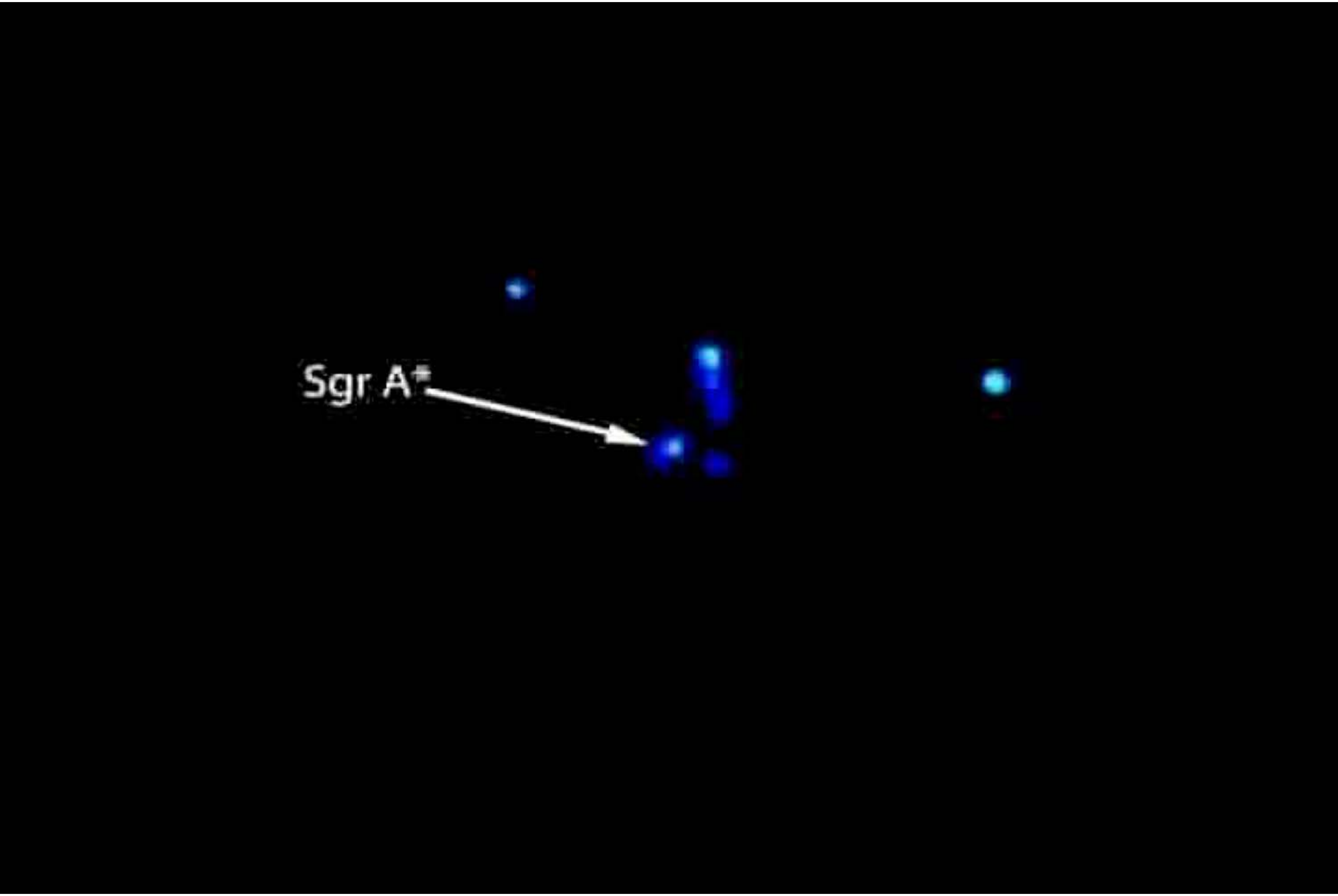
# Fueling a Black Hole by Tidal Disruption

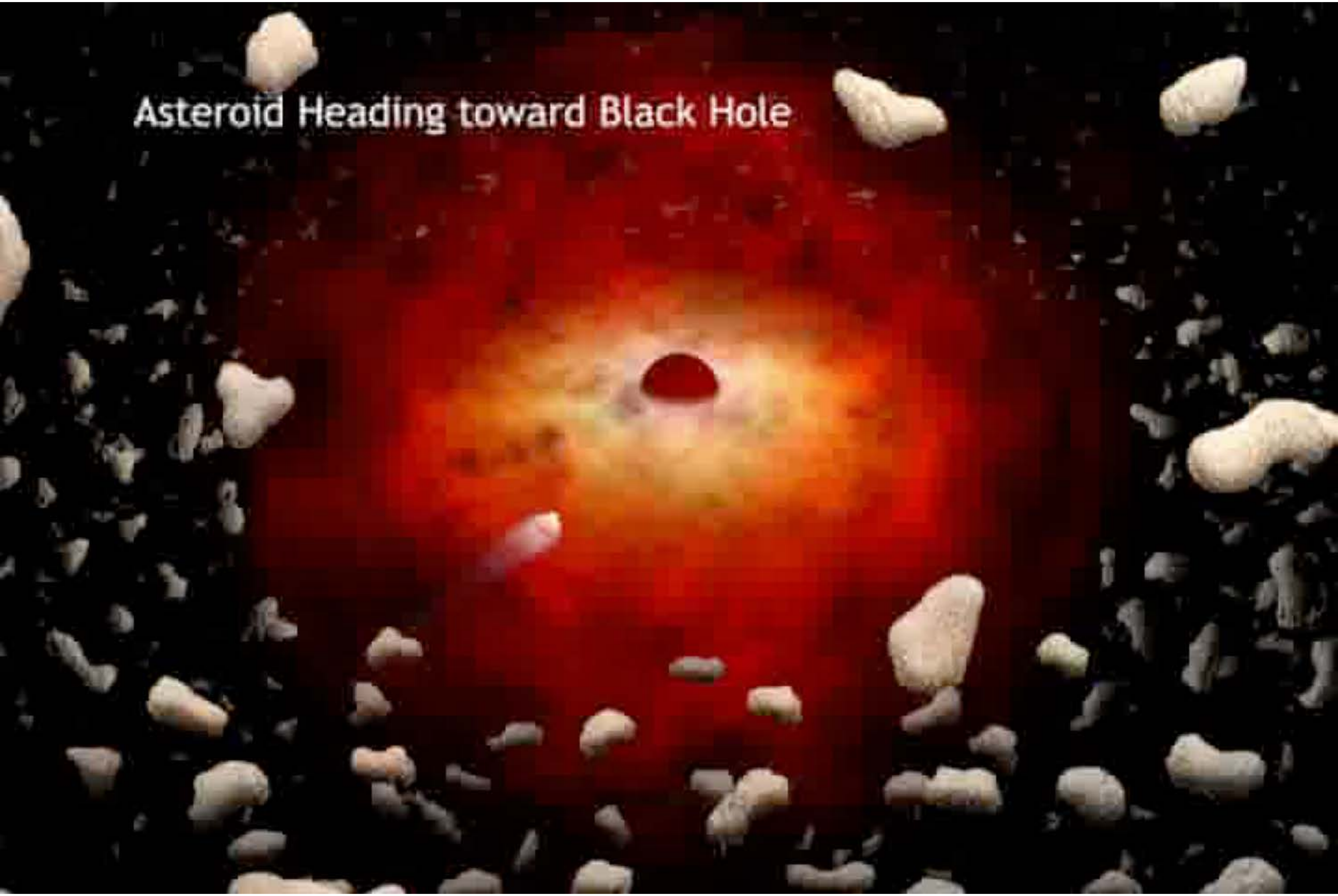
Sagitarius A*

What are the **chances of a tidal disruption happening in Sgr A* ?** Astronomers estimate that these events happen only about **once every 10,000 years**, so the chances are low. However observed X-ray flares in SgrA* may be caused by asteroids being tidally disrupted.

If our Galactic Center's black hole were to tear a star apart, the resulting X-ray source would easily outshine every other X-ray source in the sky besides the Sun, frying the instruments aboard the X-ray satellites *Chandra* and *XMM*!

The center of the Milky Way would become a hundred billion times brighter in X-rays than it is now.


Sgr A*


Asteroid Heading toward Black Hole