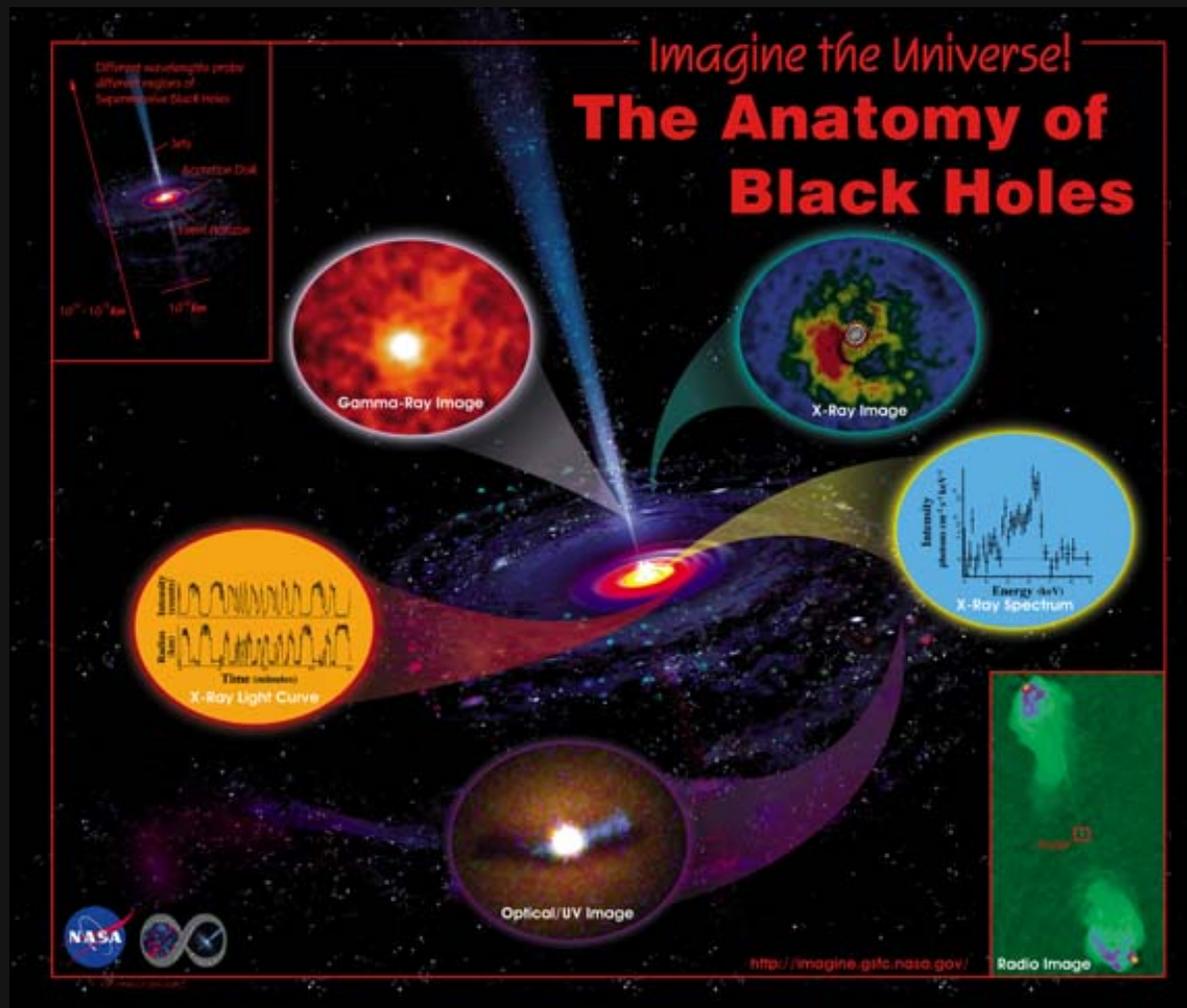


# Black Holes in a Different Light

Dr. Jim Lochner (NASA/GSFC)



# Outline

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- Why Teach Black Holes?
- If Black Holes Are Black, How Do We See Them?
  - Getting to Know Your X-ray Binary
- How Do We Know They are Black Holes?
- Are There Any Web Resources Available?

# *Concepts in Teaching Black Holes*

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- The escape velocity of light from a star depends upon the star's mass and radius.
- Gravity is a basic force of nature created between objects that have mass.
- The speed of light, 300,000 km/s, is the universal "speed limit."
- The laws of motion and gravitation are utilized to study the effects of black holes on their immediate environment.

# *Content Standards for Grades 9-12:*

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(From: *National Science Education Standards*, National Academy Press, 1998.)

Black Holes touch on topics in:

- Motions and Forces
- Conservation of Energy and Increase in Disorder
- Interactions of Matter and Energy
- The Origin and Evolution of the Universe

# ***Standards Used in Teaching About Black Holes***

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(From: *Benchmarks for Science Literacy*, American Association for the Advancement of Science, Oxford University Press, 1993. )

By the end of Grade 12, students should know that:

Increasingly sophisticated technology is used to learn about the universe. **Visual, radio, and x-ray telescopes collect information from across the entire spectrum of electromagnetic waves**; computers handle an avalanche of data and increasingly complicated computations to interpret them; space probes send back data and materials from the remote parts of the solar system; and accelerators give subatomic particles energies that simulate conditions in the stars and in the early history of the universe before stars formed.

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If Black Holes are Black,  
How do We See Them ?

# *What You Need to Know ...*

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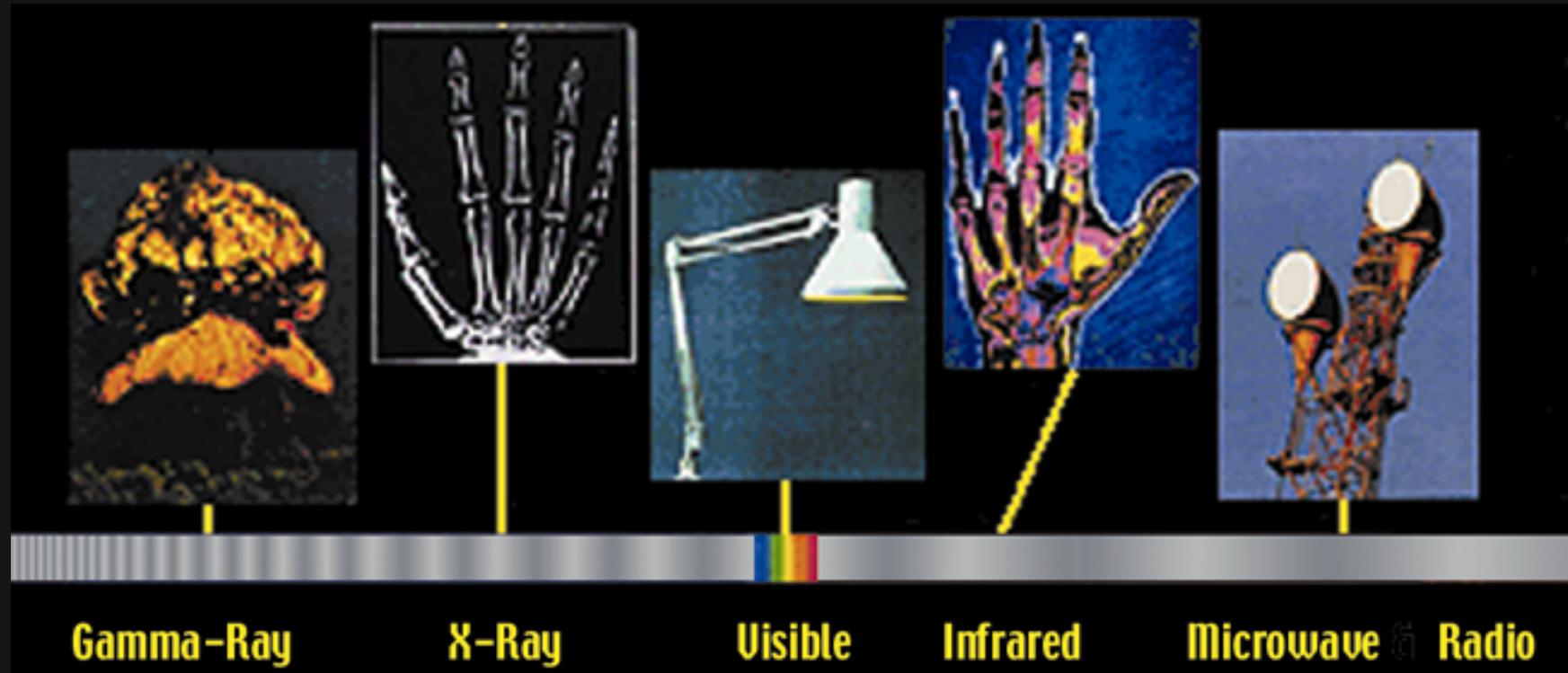
## Black Holes Come in Two Sizes:

- “Stellar Mass”
  - 5 - 20 times the mass of the sun
  - Result from supernova explosion of massive star
- Massive (“Active Galaxies”)
  - Millions times the mass of the sun
  - Lie in centers of galaxies

Make that Three Sizes (more later ...)

# *EM Spectrum*

## Electromagnetic Spectrum



# *Optical*

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Optical images peer into central regions of other galaxies.



# Optical

- Material swirls around central black hole.
- Gas near black hole heats up to UV and X-ray temperatures.
- This heats surrounding gas, which glows in the optical.



**Circinus Galaxy**

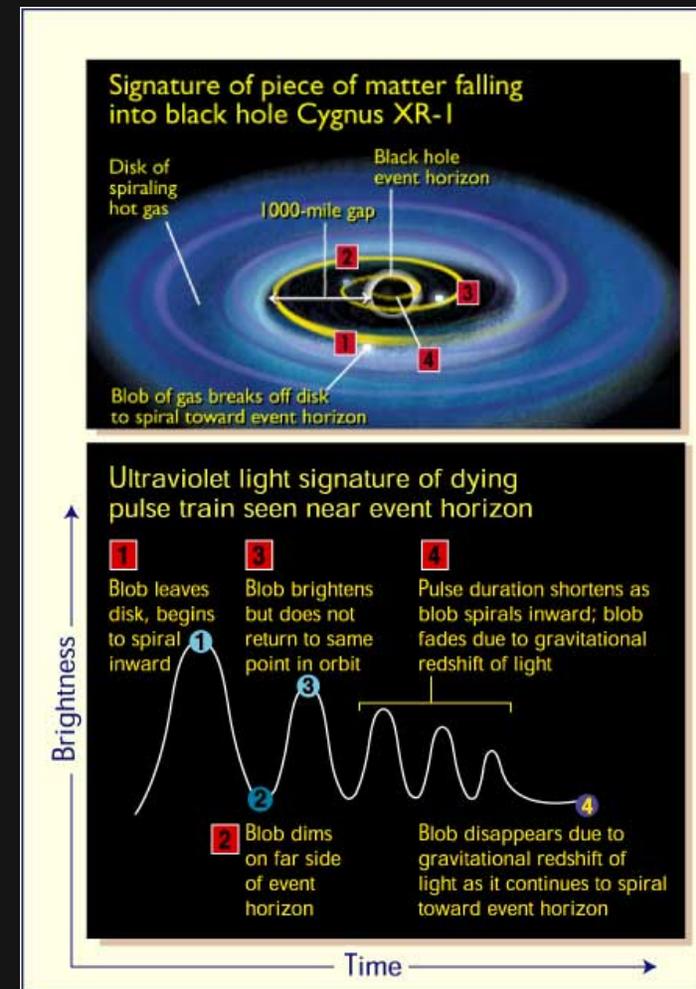
**Hubble Space Telescope • WFPC2**

NASA and A. Wilson (University of Maryland) • STScI-PRC00-37

# Ultraviolet

## Seeing Matter Disappear

- Hubble observed pulses of UV light emitted by material as it fell into a black hole.
- Pulses arise from material orbiting around intense gravity of the black hole.
- Light pulses, lasting 0.2 s, are red-shifted from X-ray to UV, as they fall into gravity of the black hole.



# Radio

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Radio tells us about motions of particles in magnetic fields.

Using many radio dishes allows us to see small details



A portion of the Very Large Array, Socorro NM

# *Radio Jets from Black Holes*

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Many black holes emit jets.

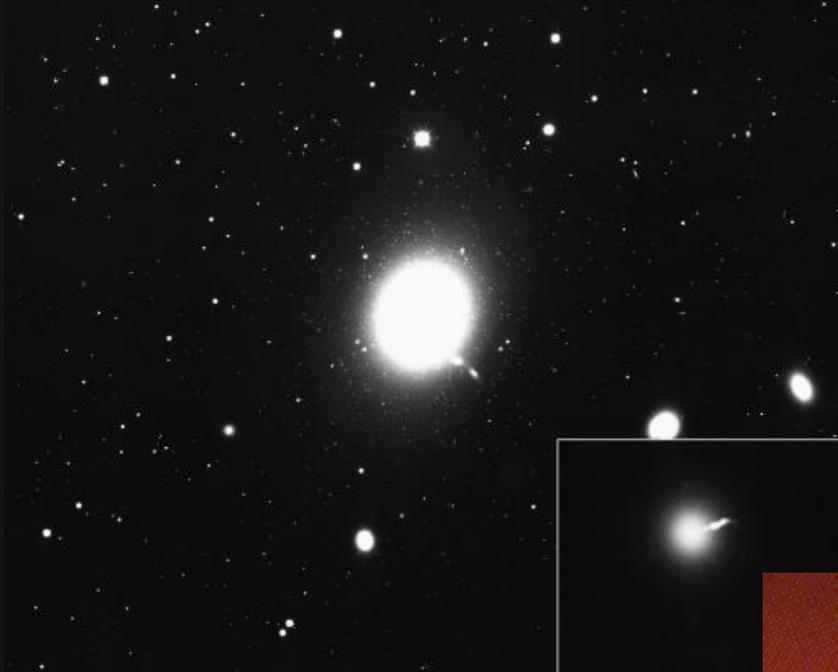
- Material in jet moving at  $0.9c$ .
- Jet likely composed of electrons and positrons.

Magnetic fields surrounding black hole expel material and form the jet.

- Interaction of jet material with magnetic field gives rise to Radio emission.

# *M87 - An Elliptical Galaxy*

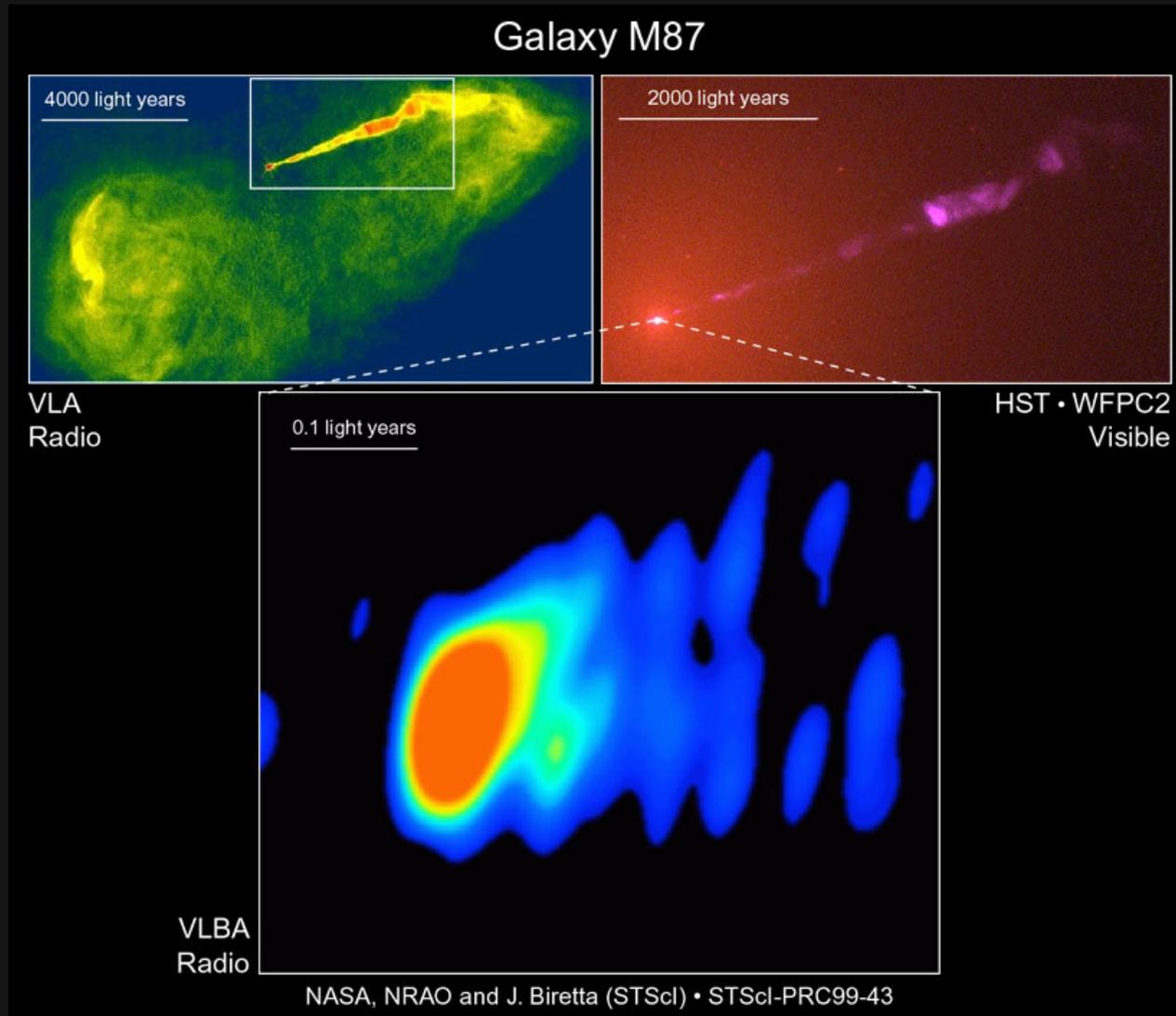
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With a curious feature

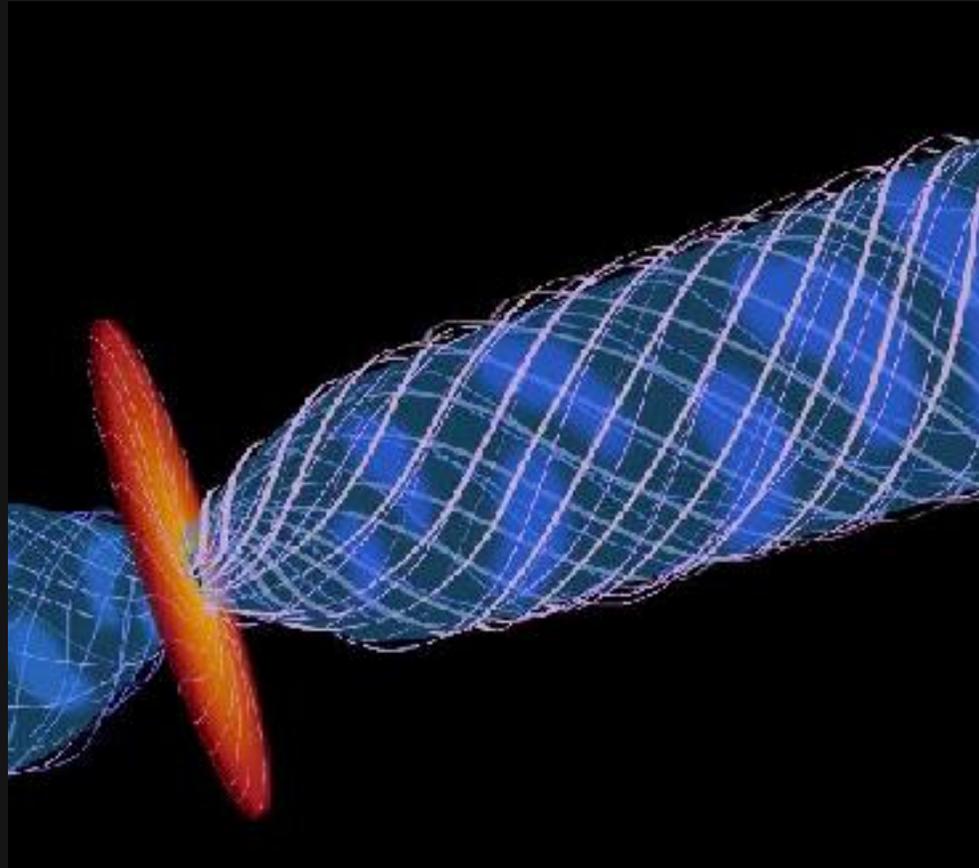


# Radio shows the origin of the Jet



# *Our picture of what's happening*

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Magnetic field from surrounding disk funnels  
material into the jet

# X-ray

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X-rays reveal high temperatures and highly energetic phenomena.

- Current satellites include Chandra X-ray Observatory, XMM, and Rossi X-ray Timing Explorer

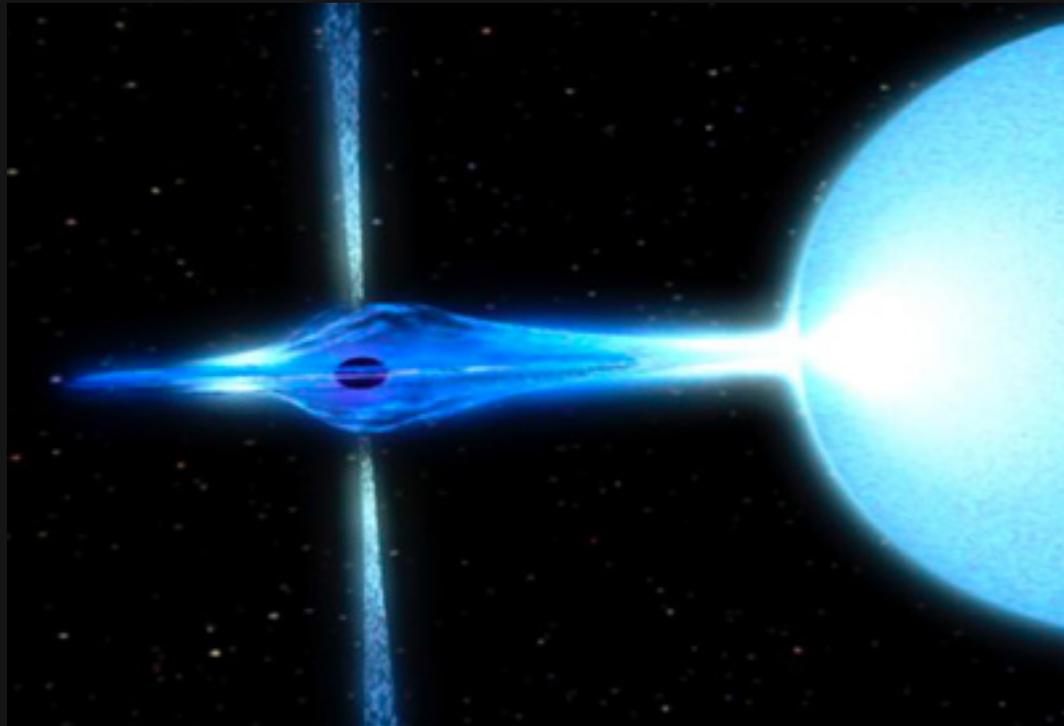


Chandra X-ray Observatory

# *X-rays from Black Holes*

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In close binary systems, material flows from normal star to black hole. X-rays are emitted from disk of hot gas swirling around the black hole.



# *Power of Accretion*

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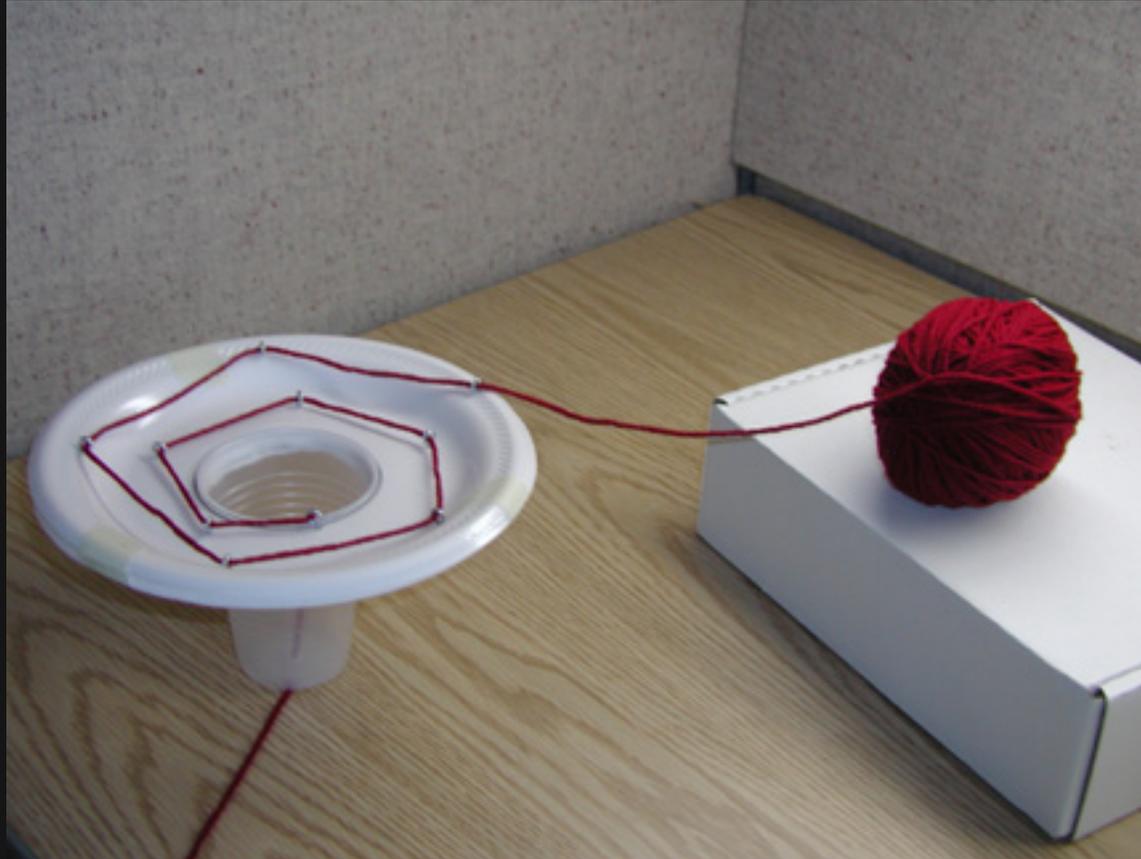
Material in Disk gains energy as it falls into black hole.

- Gravitational energy is converted to kinetic energy.
  - Kinetic Energy is converted to heat and x-rays.

Up to 42% of the mass of infalling material is converted into energy.

- That's  $10^{38}$  erg/s ! (100,000x more than sun)

# *Getting to Know your X-ray Binary*



The Groovy X-ray Binary Model

# *How Well Do Know your X-ray Binary ?*

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What force causes material to be pulled toward the black hole ?

**Gravity**

Why is there a disk surrounding the black hole ?

**Gas flows according to rotational motion from orbit of star**

What happens to the mass of the black hole as it takes in material from the companion ?

**Black hole mass increases**

How much material is it ? (alot or a little ?)

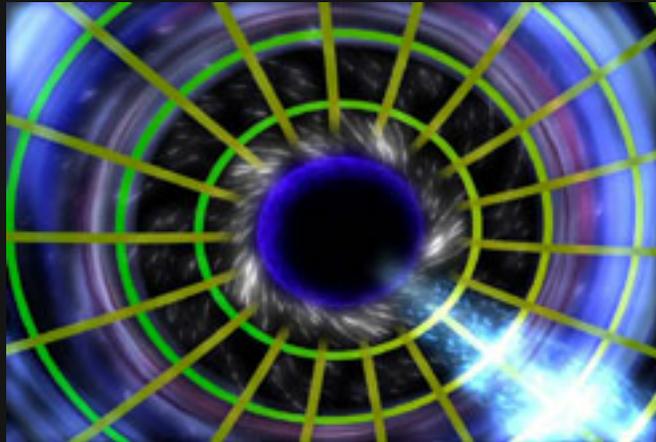
**A little (compared to mass of Companion Star)**

What makes it possible for us to “see” the black hole ?

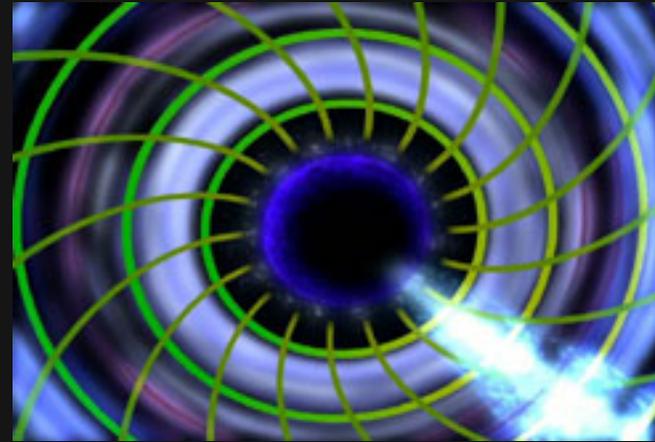
**The disk emits X-rays**

# *X-ray: A Rotating Black Hole*

We expect everything in the Universe to rotate. Non-rotating black holes are different from rotating ones.



Non-rotating black hole

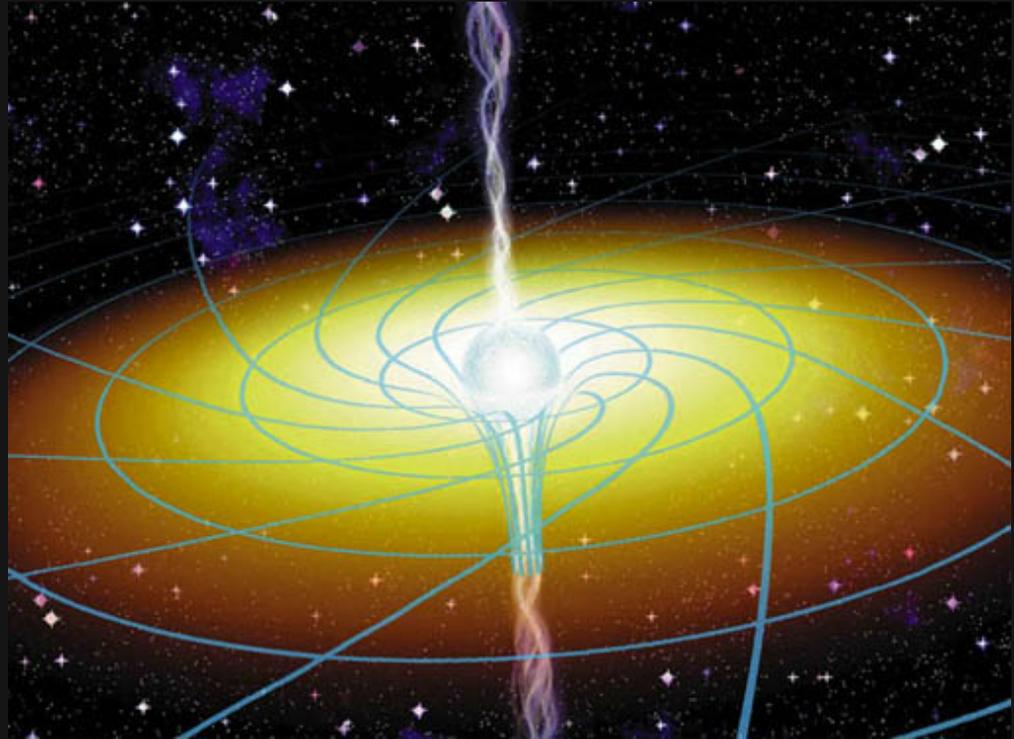


Rotating black hole

In GRO J1655-40, a 2.2 ms period was discovered. This implies an orbit that is too small to be around a non-rotating black hole. This means the black hole is rotating.

# *X-ray: Frame Dragging*

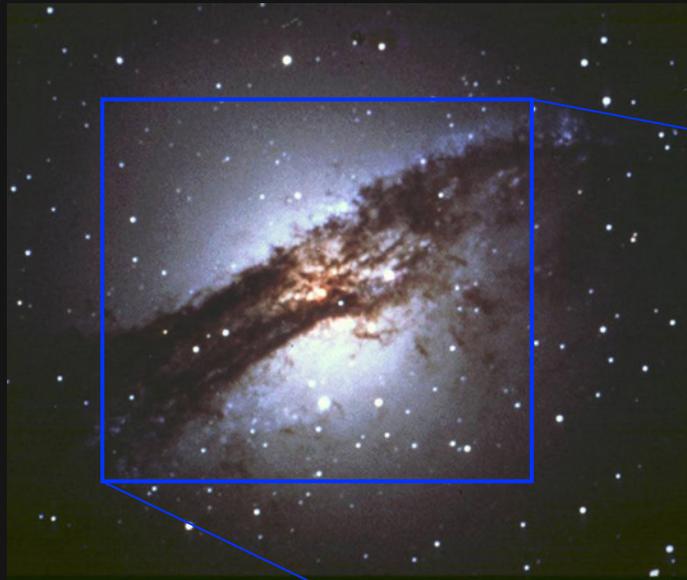
- Detection of a period in GRO J1655-40 due to precession of the disk.
- This precession period matches that expected for frame dragging of space-time around the black hole.



Credit: J. Bergeron, Sky & Telescope Magazine

# *X-ray: Jets*

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Optical image of Cen A

Cen A is known to be a peculiar galaxy with strong radio emission.

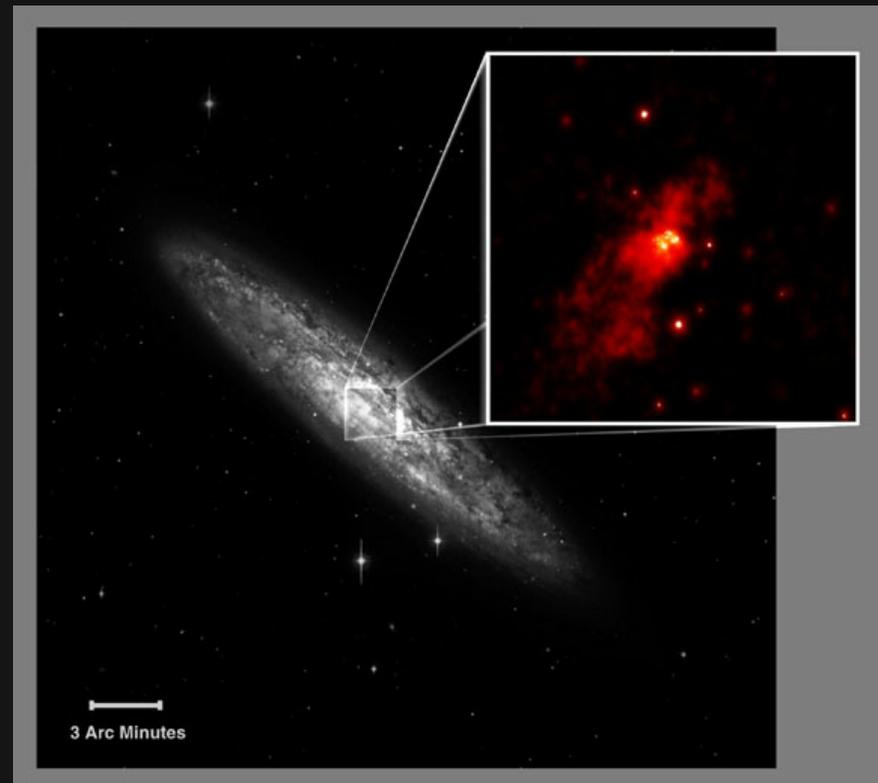


Chandra image of Cen A

But it is also a strong X-ray emitter, and has an X-ray jet.

# *X-ray: Mid mass black holes*

- Black Holes with masses a few hundred to a few thousand times the mass of the sun have been found outside the central regions of a number of galaxies.
- Often found in Starburst galaxies.
- May be precursors to Active Galaxies.



Optical and X-ray images of NGC 253

# *Gamma ray*

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Gamma Rays reveal the highest energy phenomena

Jets in active galaxies emit gamma-rays as well as radio.



Compton Gamma-Ray Observatory

# *Gamma ray*

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## Active Galaxies

### Seyferts - viewing the jet sideways

- Gamma rays are extension of thermal emission seen in X-ray.

### Blazars - looking down the jet

- Highly variable gamma-ray luminosity
- Gamma rays arise from lower energy photons gaining energy from fast moving electrons in the jet.

# Different views of same phenomena



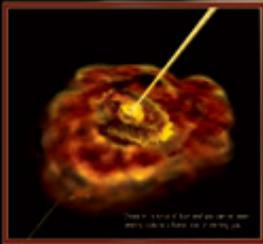
## ACTIVE GALAXIES



### Zooming In On The Galaxy



The long view of an active galaxy is dominated by the glow of light emitted by dust in the spiral arms of the galaxy, surrounding the central black hole.



Here is a view of dust and gas orbiting the central black hole, and the jet.



The nucleus is the source of the energy that powers the phenomena we see.

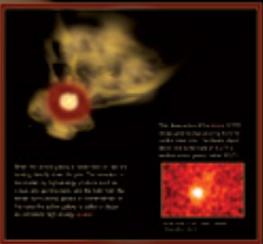
**What we see depends on the angle we see it.**

An active galaxy is one in which a tremendous amount of energy is emitted from the nucleus. Active galaxies take many forms, some have exquisitely bright nuclei pouring forth high-energy photons, others have high-energy nuclei but appear to be surrounded by a more-or-less "normal" galaxy, while others have long, narrow jets or beams of matter streaming out from the center. All these different flavors of galaxies may represent the same kind of object seen at different viewing angles. Discussed here is a generic model for the nucleus of an active galaxy, which contains a supermassive but invisible black hole - the engine that powers the phenomena we see.

© 2005 NASA and the European Space Agency

### Different Views Of The Galaxy

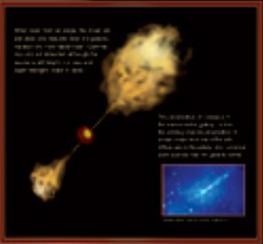
Viewing along the jet



**Blazar**

When the central engine is seen at an angle directly facing us, the galaxy is called a blazar. The nucleus is the source of the energy that powers the phenomena we see. The galaxy is seen edge-on, and the jet is pointing directly at us. The galaxy is seen edge-on, and the jet is pointing directly at us. The galaxy is seen edge-on, and the jet is pointing directly at us.

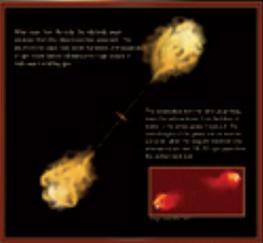
View 45° to jet



**Seyfert**

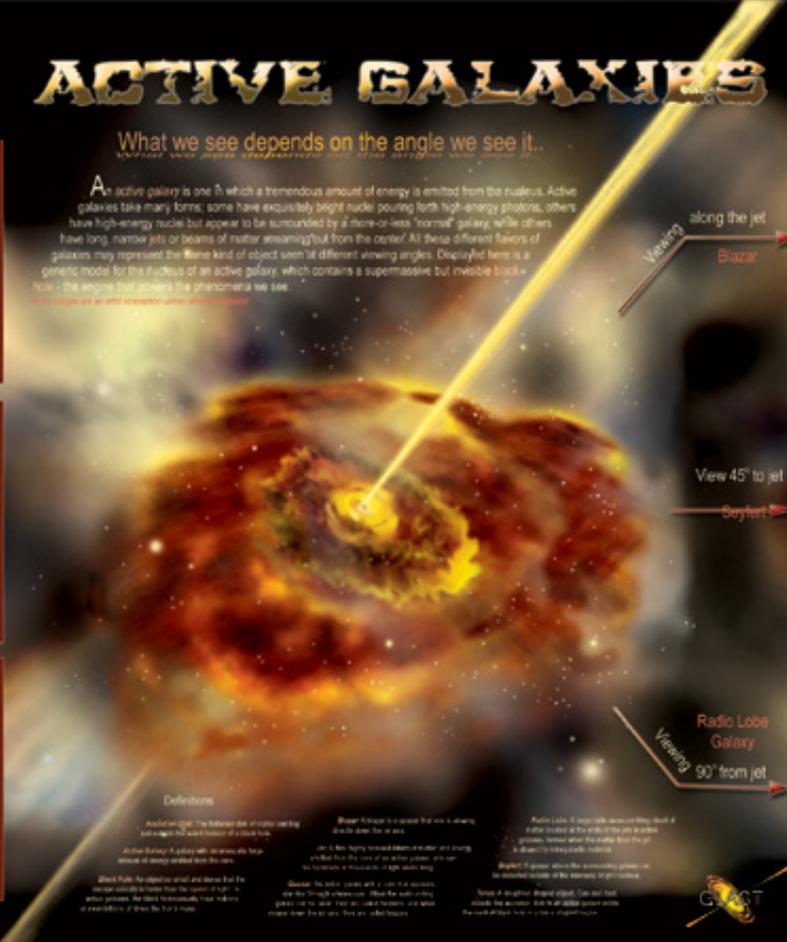
When the jet is seen at an angle, the galaxy is called a Seyfert galaxy. The nucleus is the source of the energy that powers the phenomena we see. The galaxy is seen at an angle, and the jet is pointing away from us. The galaxy is seen at an angle, and the jet is pointing away from us. The galaxy is seen at an angle, and the jet is pointing away from us.

Viewing 90° from jet



**Radio Lobe Galaxy**

When the jet is seen from the side, the galaxy is called a radio lobe galaxy. The nucleus is the source of the energy that powers the phenomena we see. The galaxy is seen face-on, and the jet is pointing away from us. The galaxy is seen face-on, and the jet is pointing away from us. The galaxy is seen face-on, and the jet is pointing away from us.



### Definitions

Active Galaxy: The fastest rate of energy output per unit mass of any kind of object in the universe.

Active Nucleus: A galaxy with an unusually large amount of energy emitted from the core.

Black Hole: An object so small and dense that the escape velocity is greater than the speed of light. It is a region of space where the gravitational pull is so strong that nothing can escape from it.

Blazar: A galaxy in which the jet is pointing directly at us.

Seyfert: A galaxy in which the jet is pointing away from us at an angle.

Radio Lobe: A large volume of space containing a high density of particles, often a plasma, that is held together by magnetic fields.

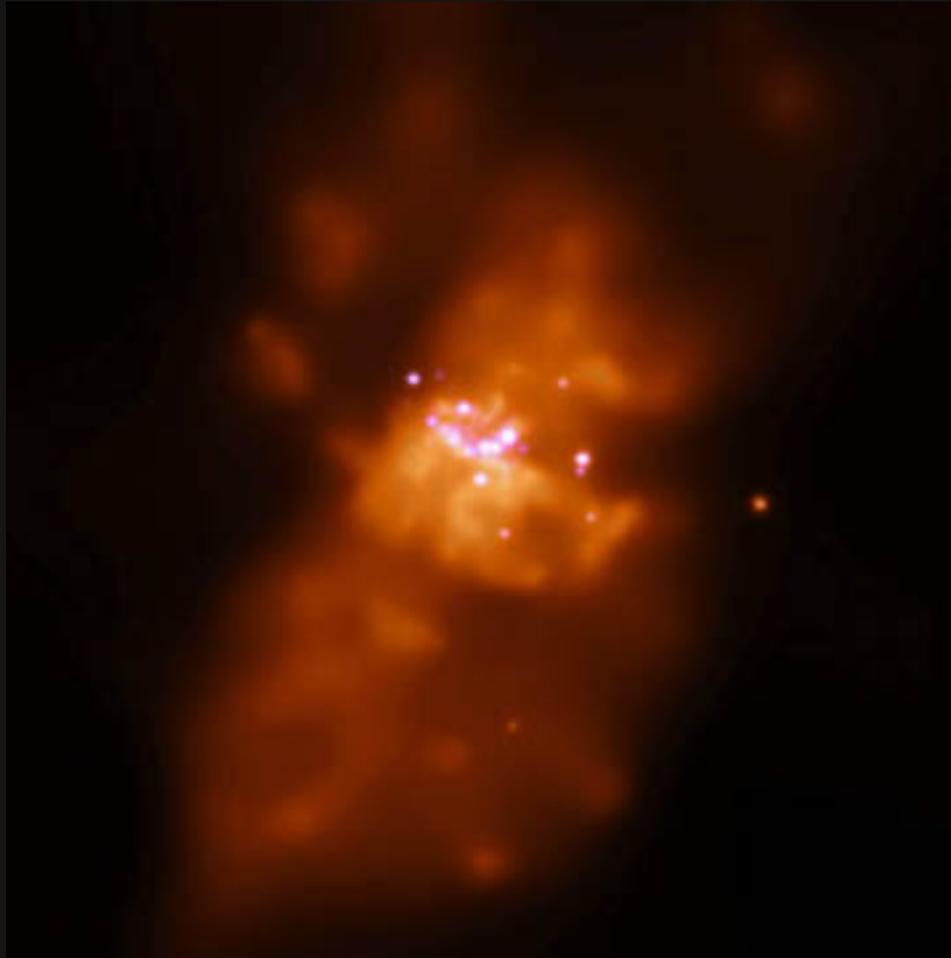
Radio Lobe Galaxy: A galaxy in which the jet is pointing away from us at an angle, and the jet is pointing away from us.

Blazar: A galaxy in which the jet is pointing directly at us.

Seyfert: A galaxy in which the jet is pointing away from us at an angle.

# *How do we know they are black holes?*

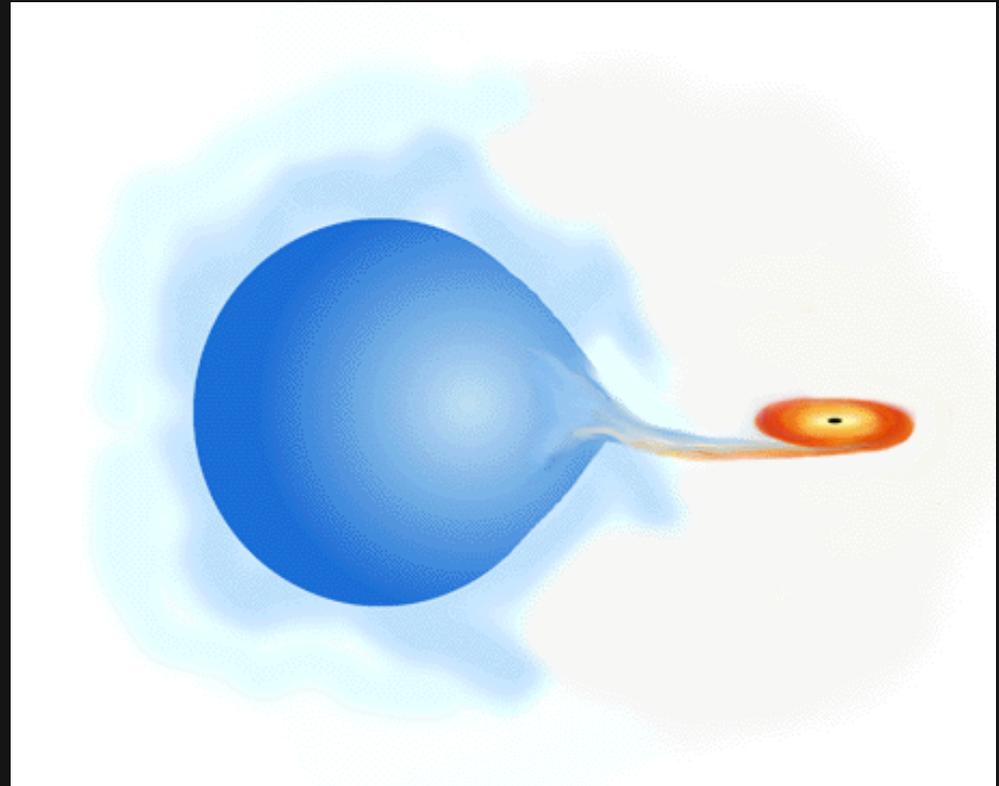
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Middle mass black holes

# *Black Holes in Binary Star Systems*

- Black holes are often part of a binary star system - two stars revolving around each other.
- What we see from Earth is a visible star orbiting around what appears to be nothing.
- We can infer the mass of the black hole by the way the visible star is orbiting around it.
- The larger the black hole, the greater the gravitational pull, and the greater the effect on the visible star.

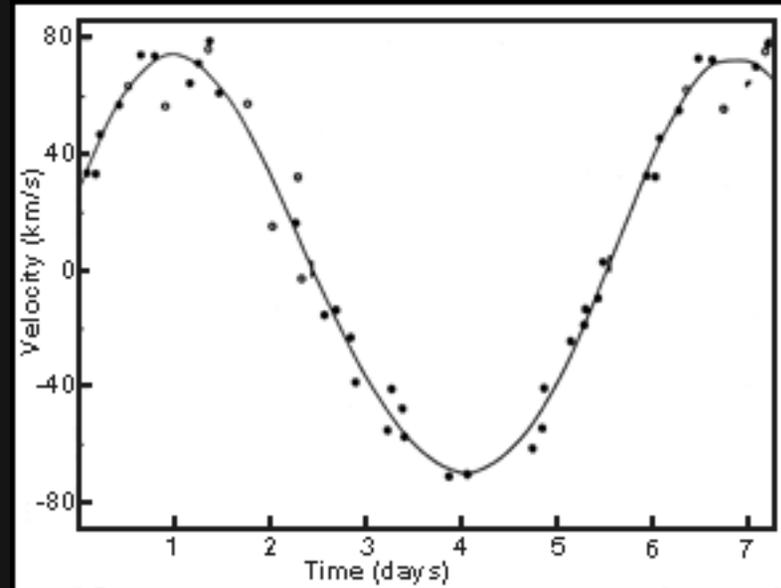


Chandra illustration

# Velocities give us Mass

- Gravitational effect of Black Hole on Companion star is measured through the orbital velocity of the Companion.
- What's the connection ?

$$\frac{(m_{bh})^3 \sin^3 i}{(m_c + m_{bh})^2} = \frac{(v_c)^3 P}{2\pi G}$$



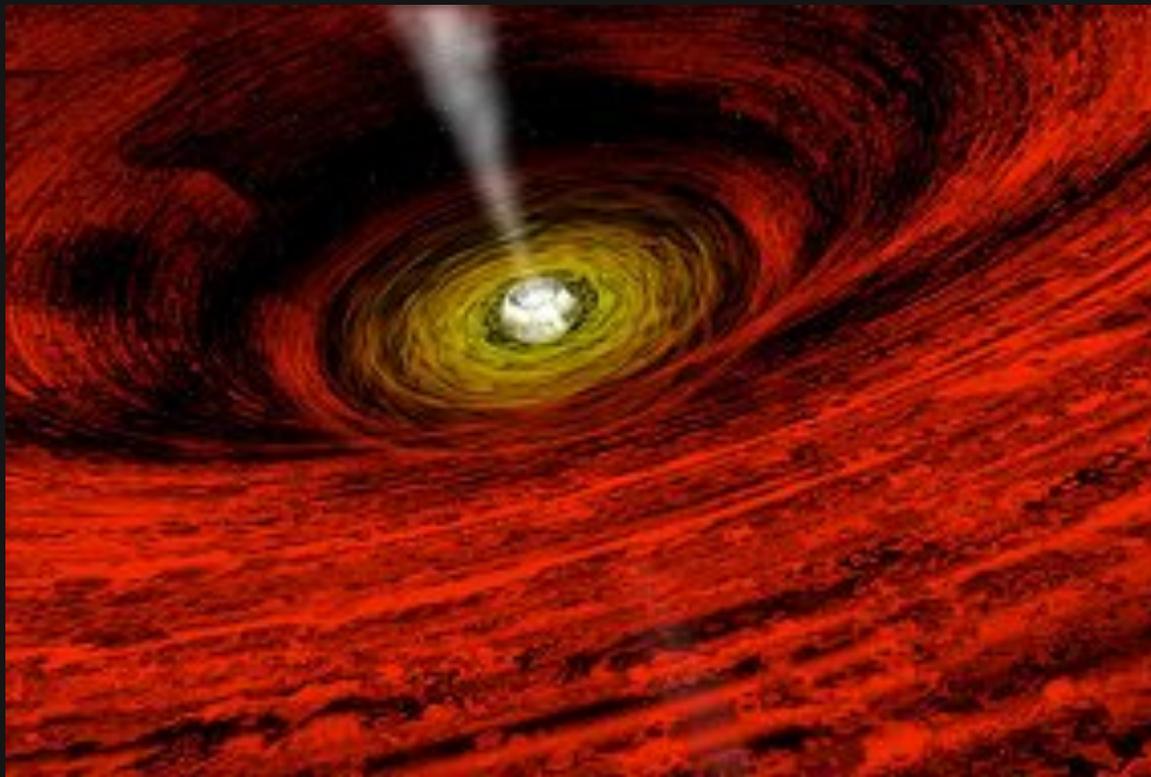
***Orbital Velocity of Optical Companion Star in Cygnus X-1***

# *Supermassive Black Holes*

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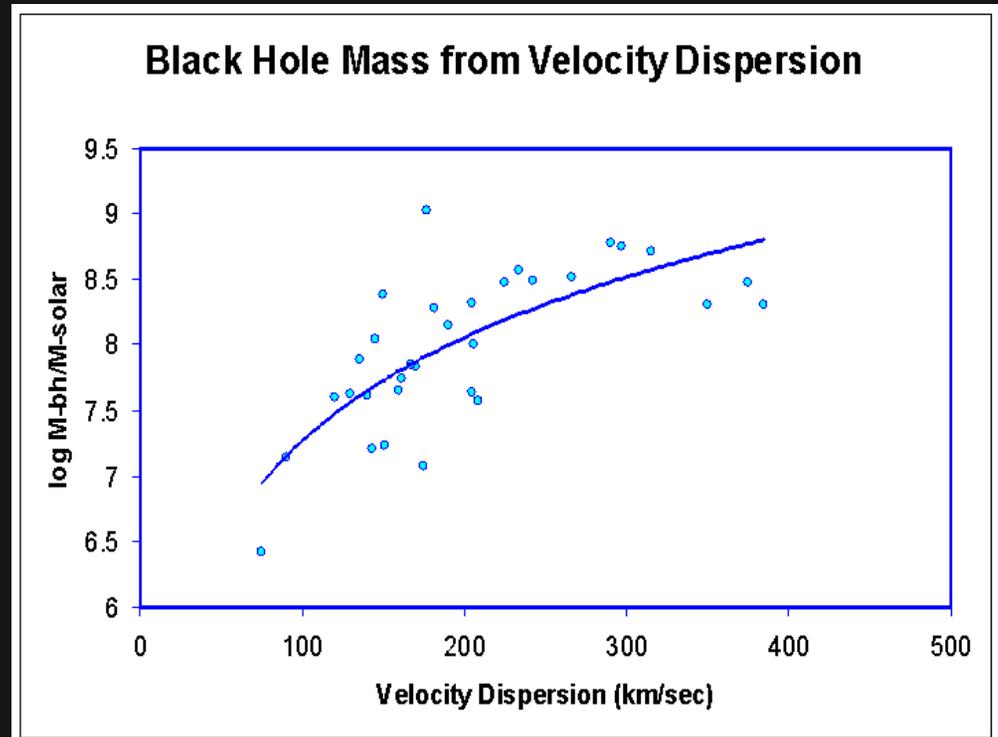
Stars near the center of a galaxy have varied speeds and directions of their orbital motions - that is termed their “*velocity dispersion.*”

The cause of all this chaotic behavior appears to be a super-massive black hole that lurks at the galactic center!



# Masses of Supermassive Black Holes

- Hubble Space Telescope can precisely measure the speed of gas and stars around a black hole.
- It discovered a correlation between a black hole's mass and the average speed of the stars in the galaxy's central bulge.
- The faster the stars are moving, the larger the black hole.



# Web Resources, page 1

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Imagine the Universe – “An Introduction to Black Holes”

[http://imagine.gsfc.nasa.gov/docs/science/known\\_11/black\\_holes.html](http://imagine.gsfc.nasa.gov/docs/science/known_11/black_holes.html)

Amazing Space – “The Truth About Black Holes”

<http://amazing-space.stsci.edu/>

Hubble Space Telescope Institute

[http://hubble.stsci.edu/news\\_and\\_views/cat.cgi.black\\_holes](http://hubble.stsci.edu/news_and_views/cat.cgi.black_holes)

Adler Planetarium - “Astronomy Connections - Gravity and Black Holes”

<http://www.adlerplanetarium.org/education/ac/gravity/index.html>

Gravity Probe B <http://einstein.stanford.edu/>

## Web Resources, page 2

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### Constellation X-ray Observatory

[http://constellation.gsfc.nasa.gov/ga/black\\_holes.html#what](http://constellation.gsfc.nasa.gov/ga/black_holes.html#what)

### Imagine the Universe: “You be the Astrophysicist” - Determine the Mass of Cygnus X-1

<http://imagine.gsfc.nasa.gov/YBA/cyg-X1-mass/intro.html>

### Imagine the Universe – “Taking a Black Hole for a Spin”

[http://imagine.gsfc.nasa.gov/docs/features/movies/spinning\\_blackhole.html](http://imagine.gsfc.nasa.gov/docs/features/movies/spinning_blackhole.html)

### Starchild – “Black Holes”

[http://starchild.gsfc.nasa.gov/docs/StarChild/universe\\_level2/black\\_holes.html](http://starchild.gsfc.nasa.gov/docs/StarChild/universe_level2/black_holes.html)

### “Virtual Trips to Black Holes and Neutron Stars”

[http://antwrp.gsfc.nasa.gov/htmltest/rjn\\_bht.html](http://antwrp.gsfc.nasa.gov/htmltest/rjn_bht.html)

# Web Resources, page 3

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## Universe! – “Voyage to a Black Hole”

<http://cfa-www.harvard.edu/seuforum/explore/blackhole/blackhole.htm>

## Falling Into a Black Hole

<http://casa.colorado.edu/~ajsh/schw.shtml>

## Massive Black Hole Information Center

<http://arise.jpl.nasa.gov/arise/infocenter/info-center.html>

## Everything you need to know about Black Holes

<http://www.astro.keele.ac.uk/workx/blackholes/index3.html>

## Black Holes in a Different Light (this presentation)

<http://imagine.gsfc.nasa.gov/docs/teachers/blackholes/blackholes.html>