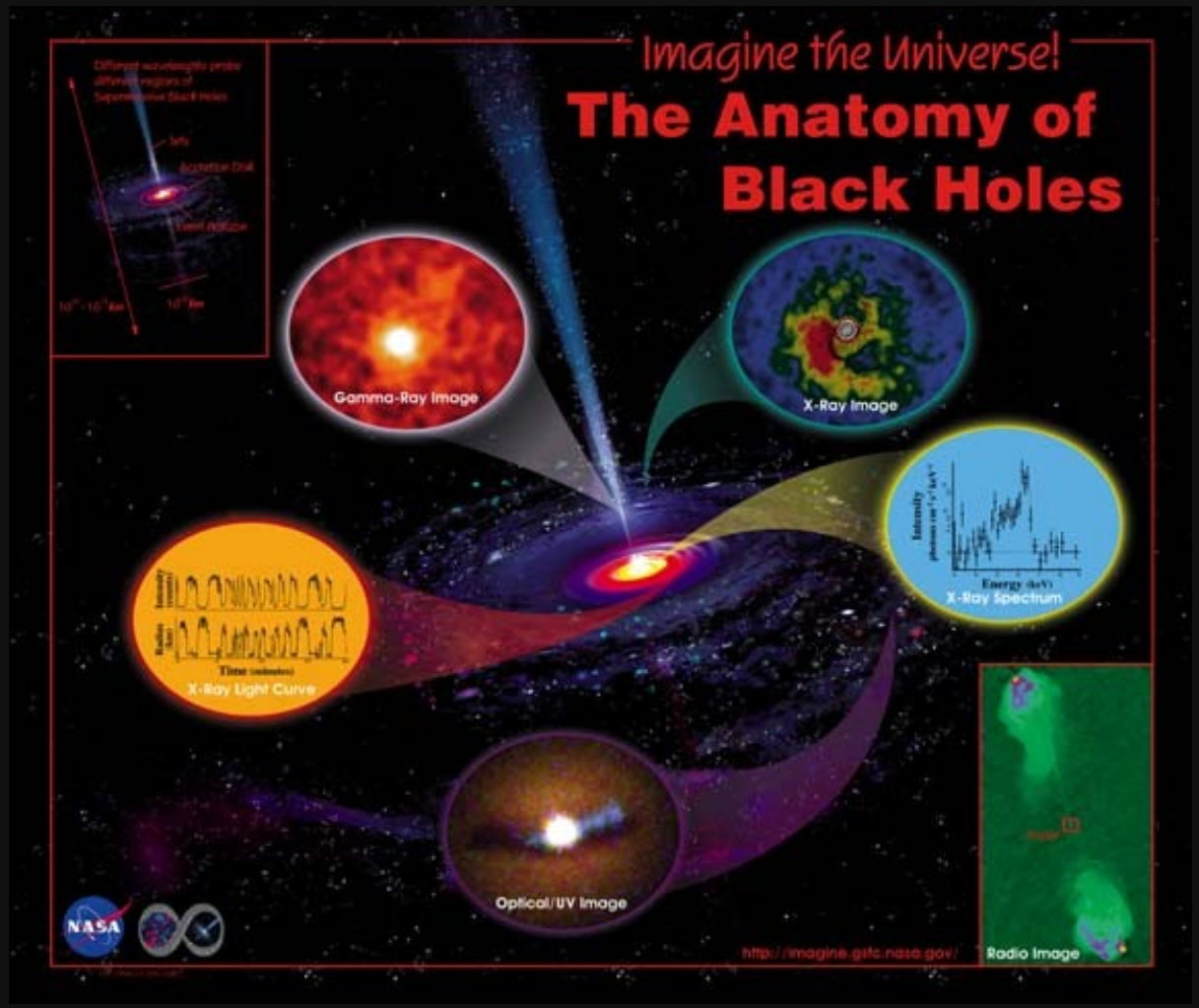
Black Holes in a Different Light

Dr. Jim Lochner (NASA/GSFC)



Outline

- 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

- 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:

(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

(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.

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

What You Need to Know ...

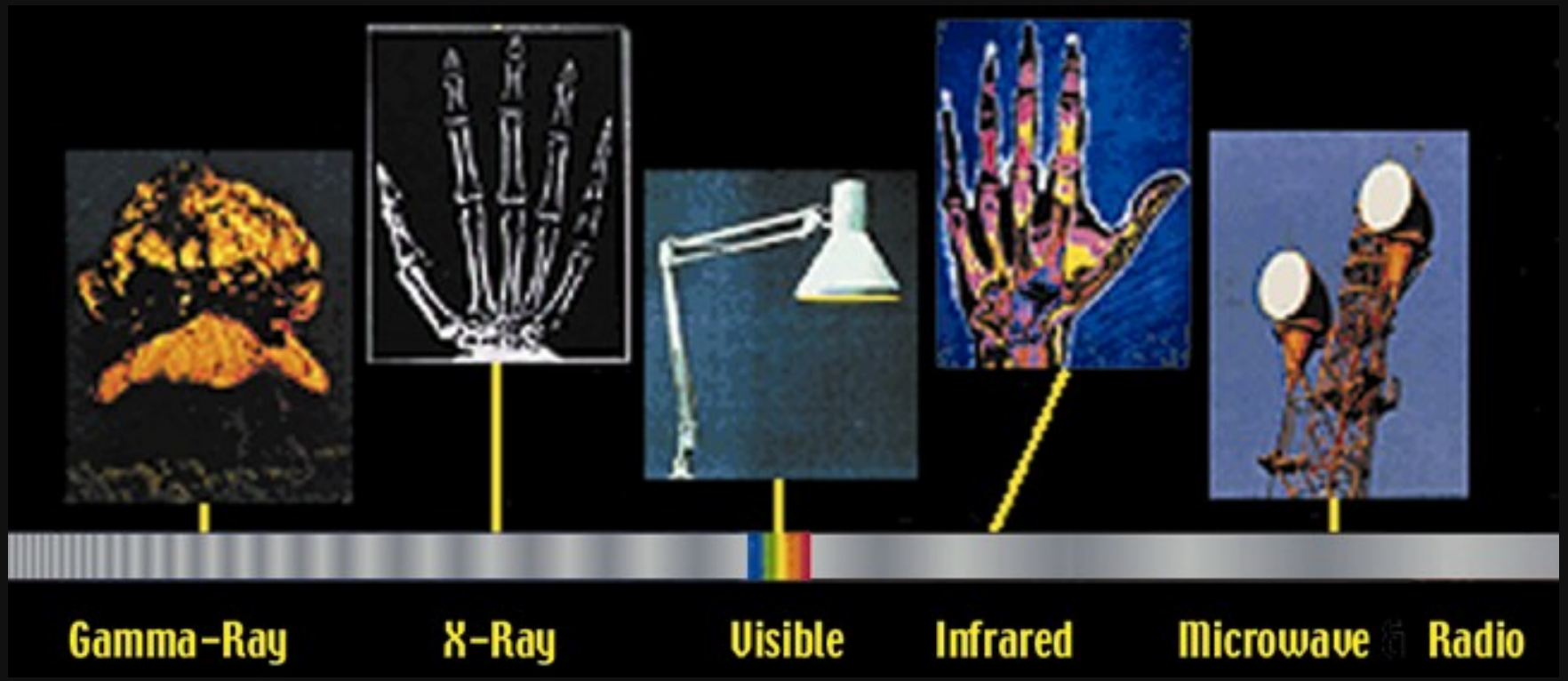
Black Holes Come in Two Sizes:

- "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

Optical images peer into central regions of other galaxies.

Optical

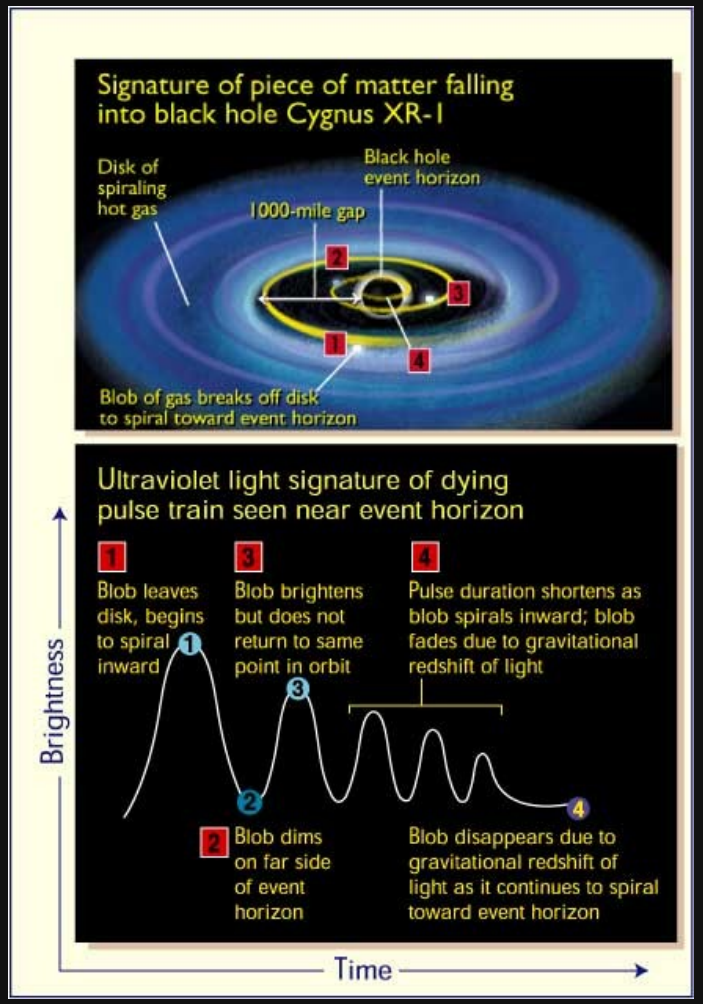
- Material swirls around central black hole.
- Gas near black hole heats up to UV and X-ray temperatures.
- This heats surrounding gas, which glows in the optical.

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

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

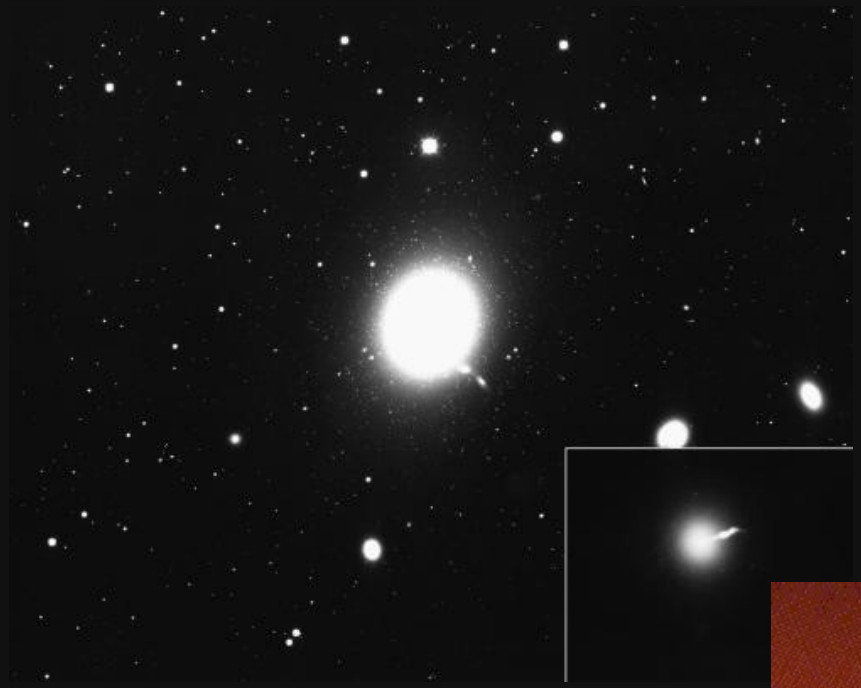
Many black holes emit jets.

- 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.

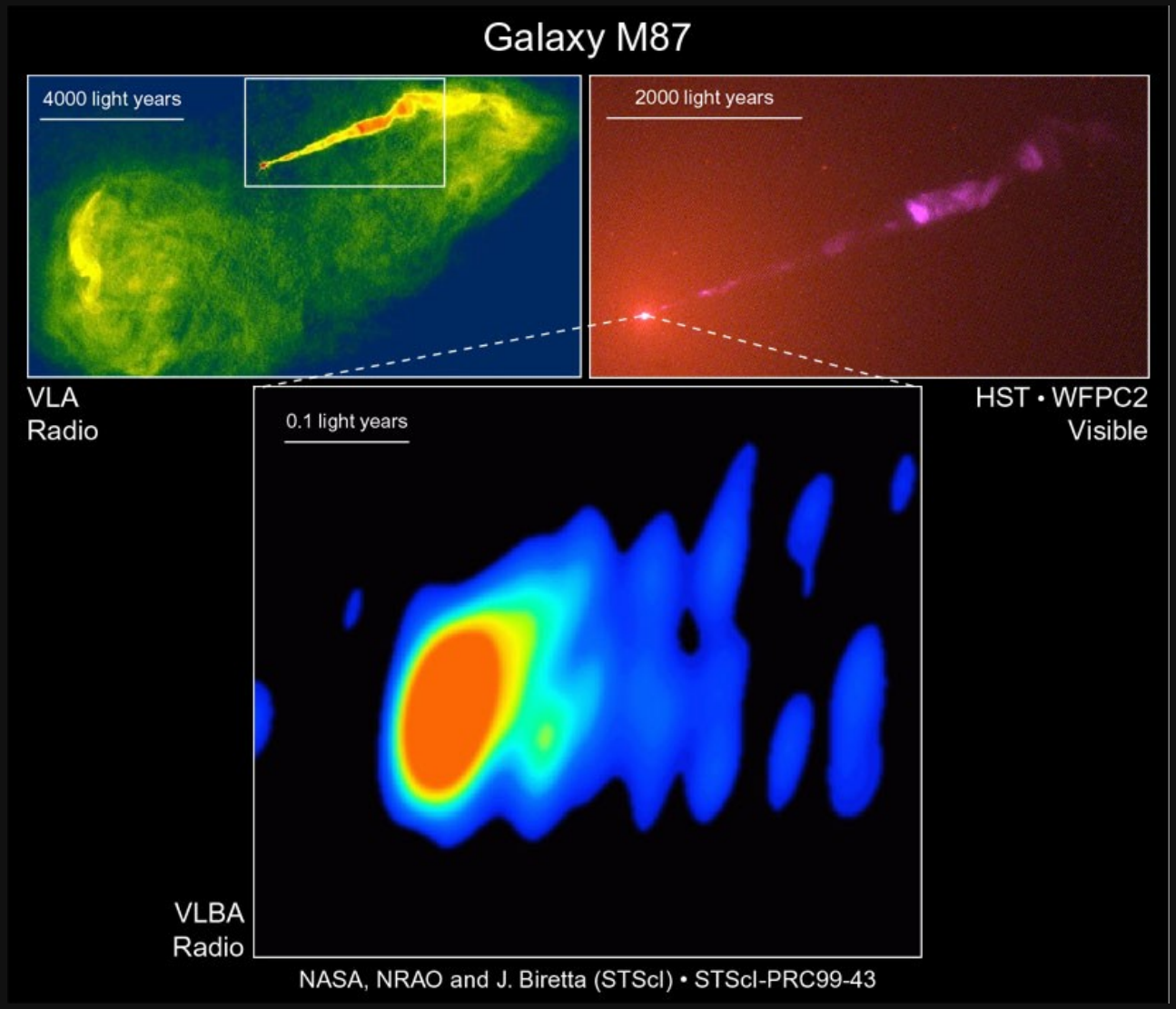
- Interaction of jet material with magnetic field gives rise to Radio emission.

M87 - An Elliptical Galaxy

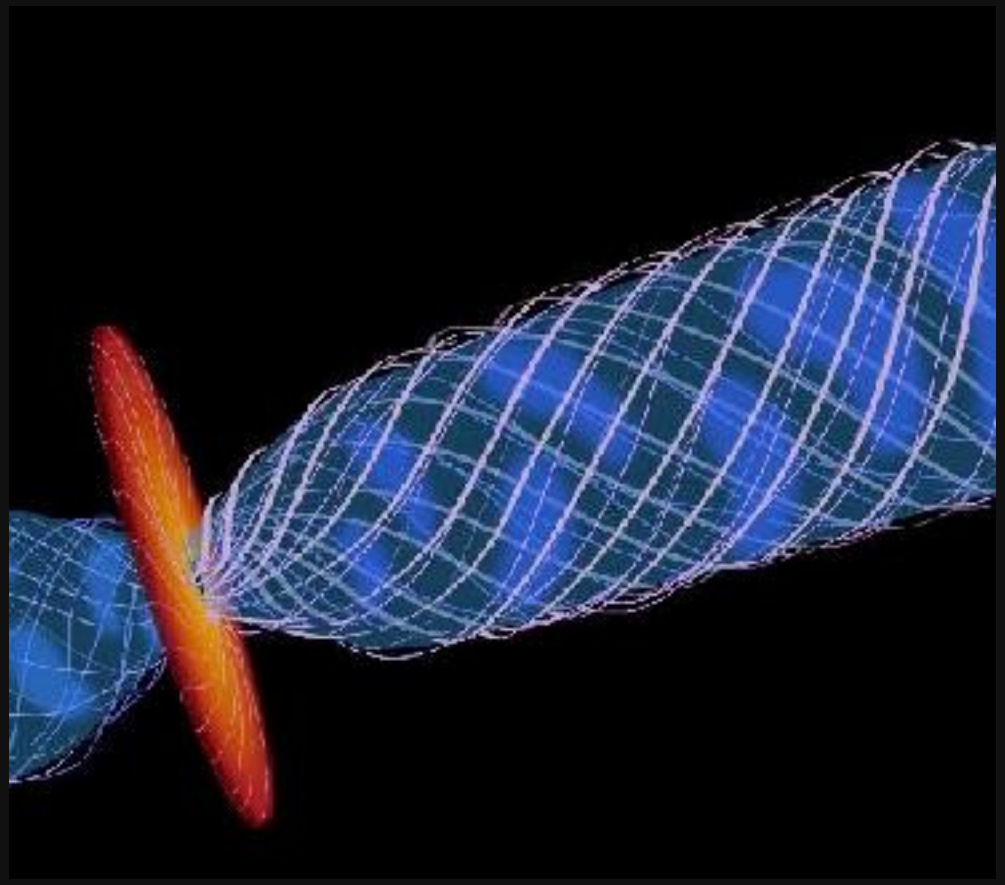


With a curious feature

Radio shows the origin of the Jet



Our picture of what's happening



Magnetic field from surrounding disk funnels material into the jet

X-ray

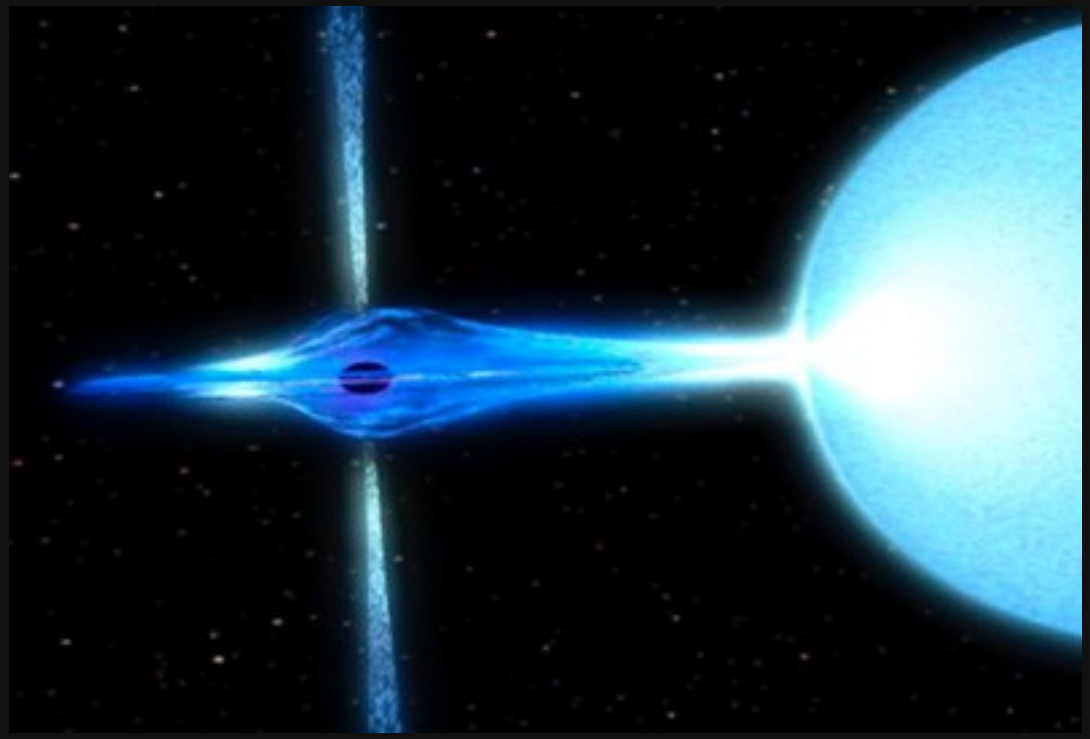
X-rays reveal high temperatures and highly energetic phenomena.

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

Chandra X-ray Observatory

X-rays from Black Holes

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

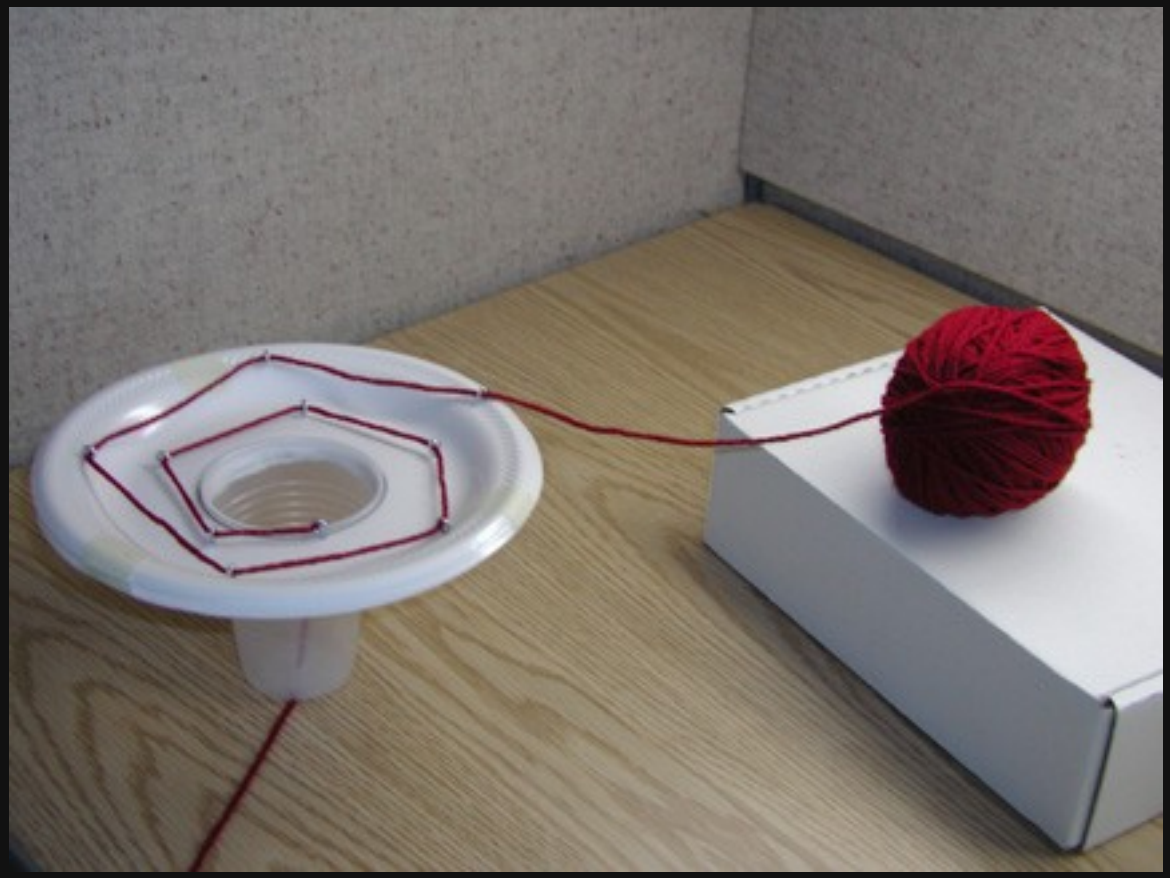
Material in Disk gains energy as it falls into black hole.

- 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 ?

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 ?)

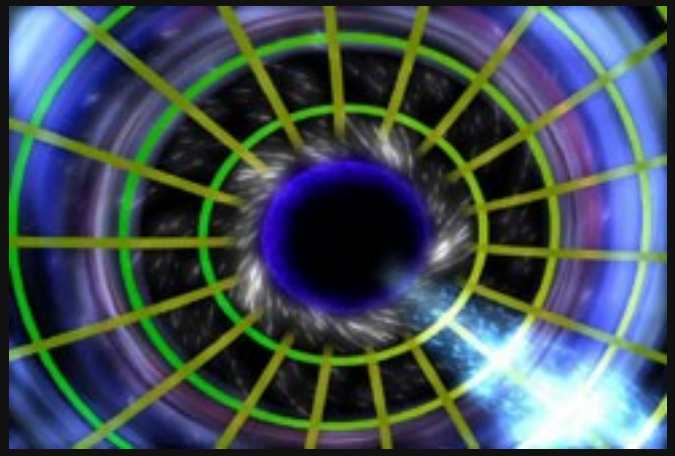
A little (compared to mass of Companion Star)

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

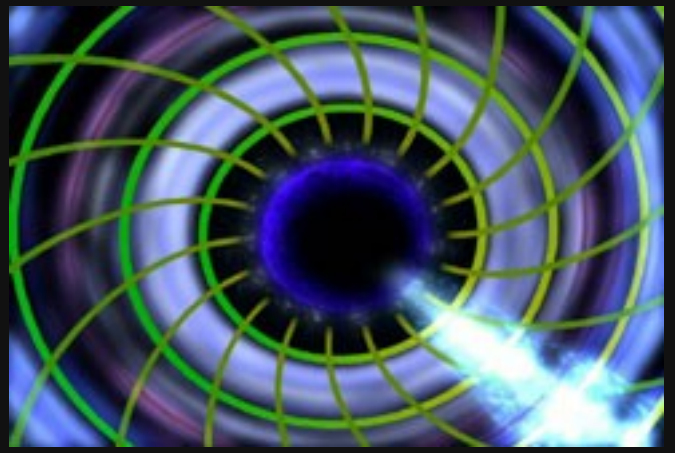
The disk emits X-rays

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



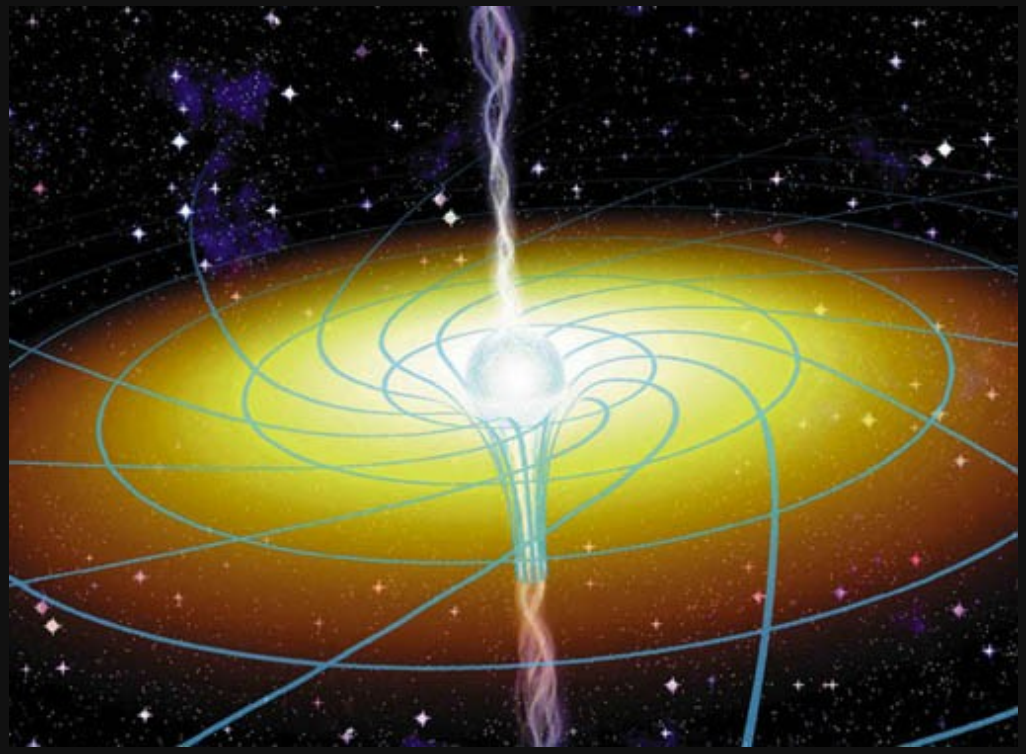
Rotating black hole

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

Optical image of Cen A

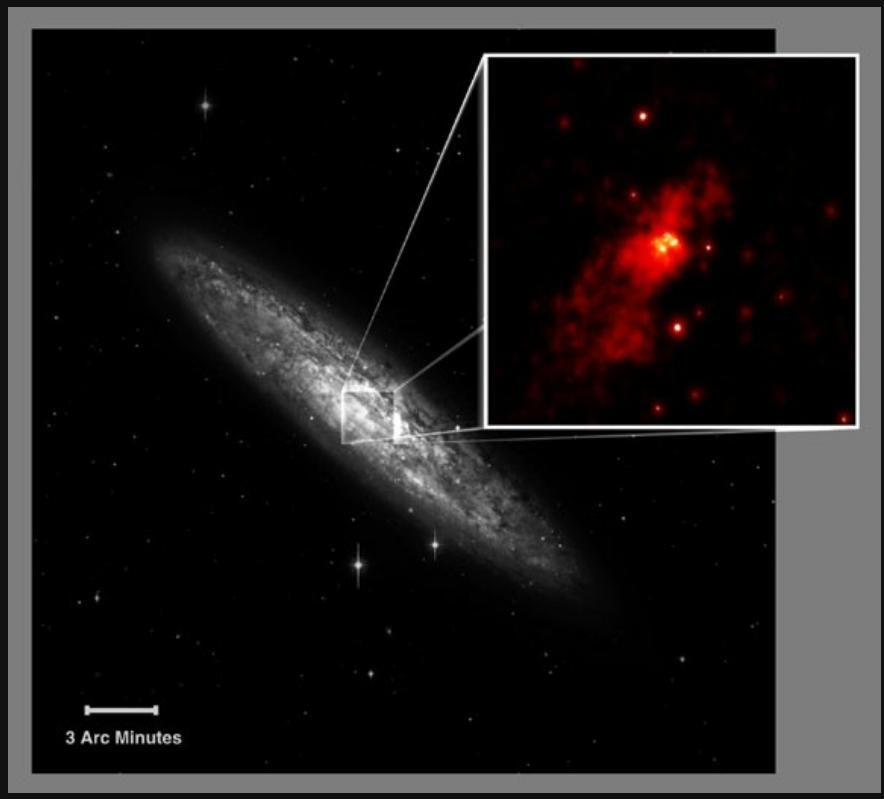
Cen A is known to be a peculiar galaxy with strong radio emission.

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

Gamma Rays reveal the highest energy phenomena

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

Compton Gamma-Ray Observatory

Gamma ray

Active Galaxies

Seyferts - viewing the jet sideways

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

Blazars - looking down the jet

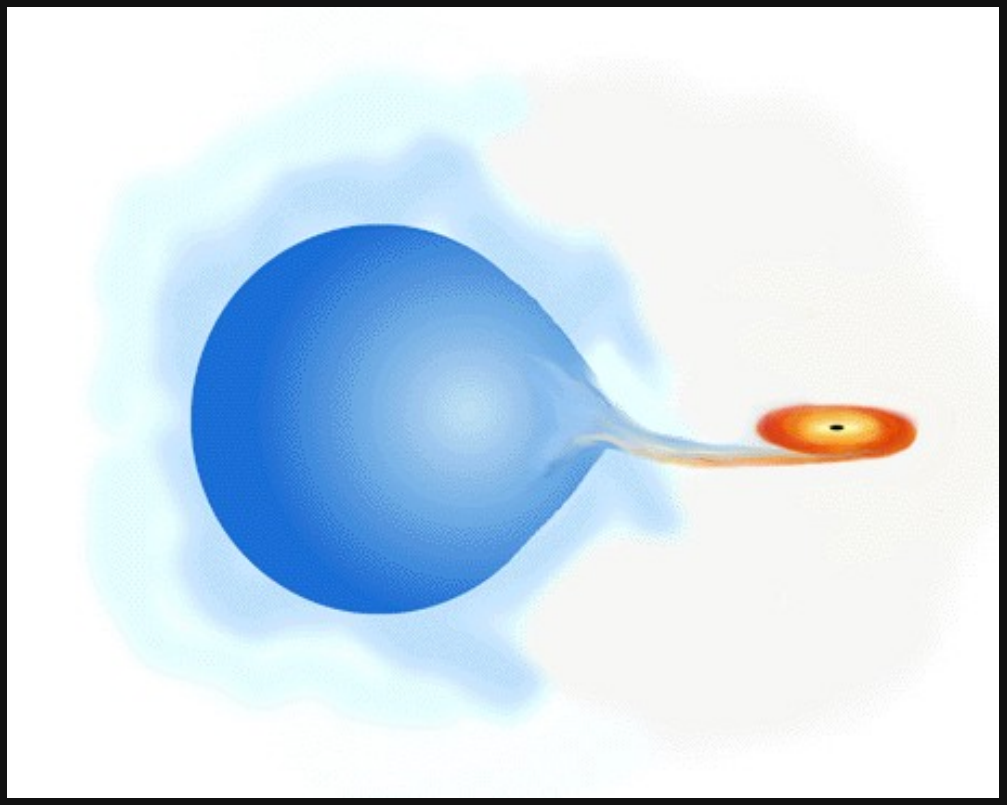
- Highly variable gamma-ray luminosity
- Gamma rays arise from lower energy photons gaining energy from fast moving electrons in the jet.

Different views of same phenomena

How do we know they are 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.

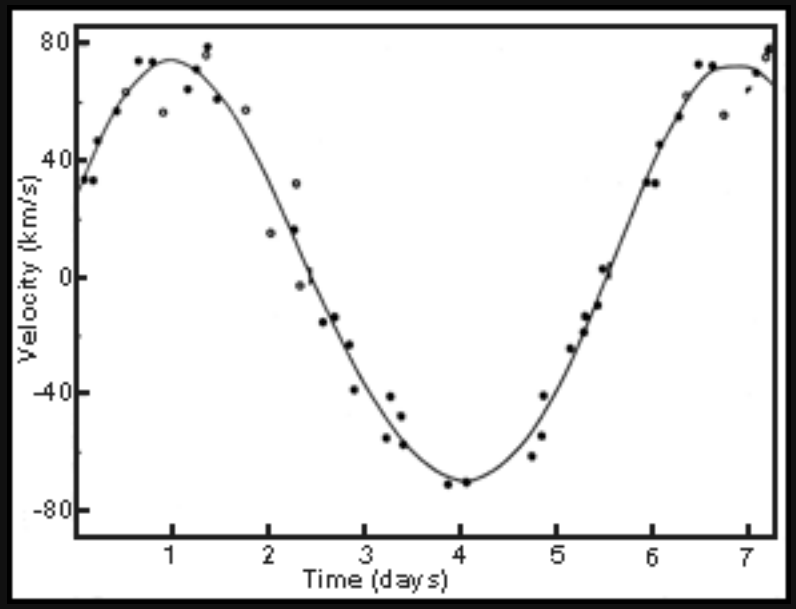


Chandra illustration

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 ?

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

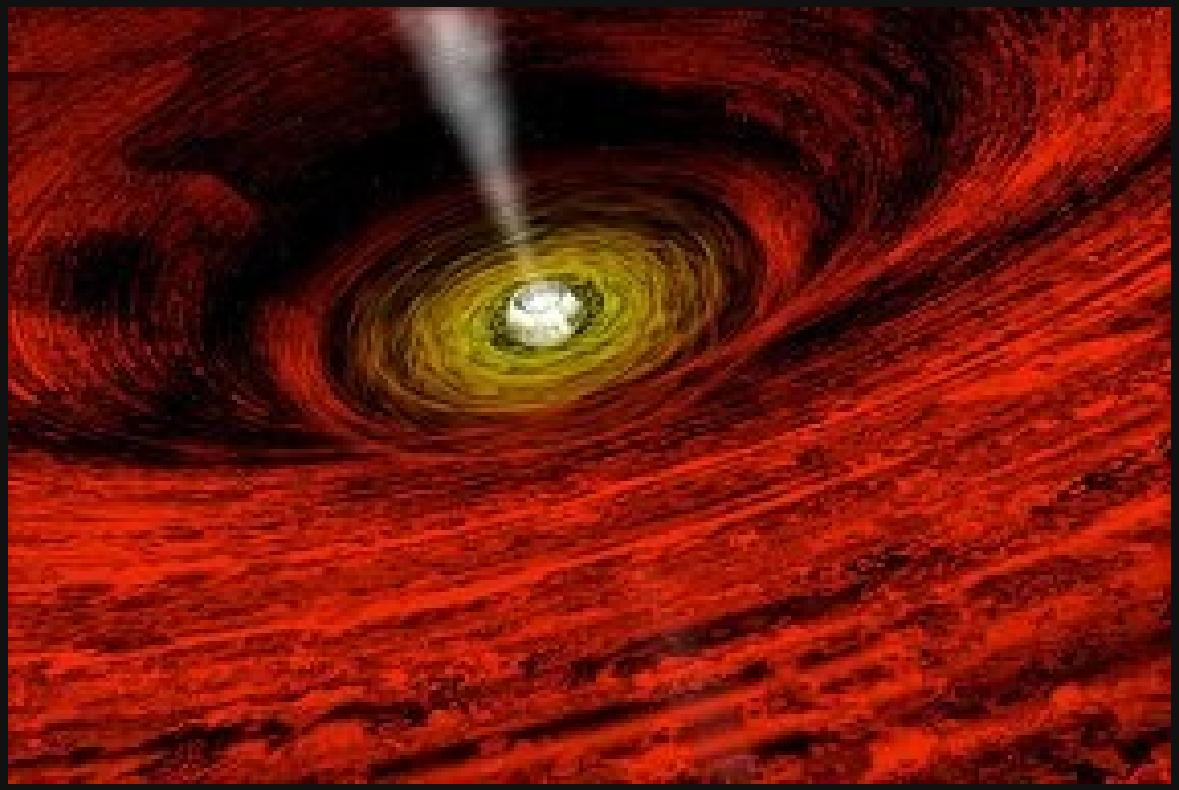


Orbital Velocity of Optical Companion Star in Cygnus X-1

Supermassive Black Holes

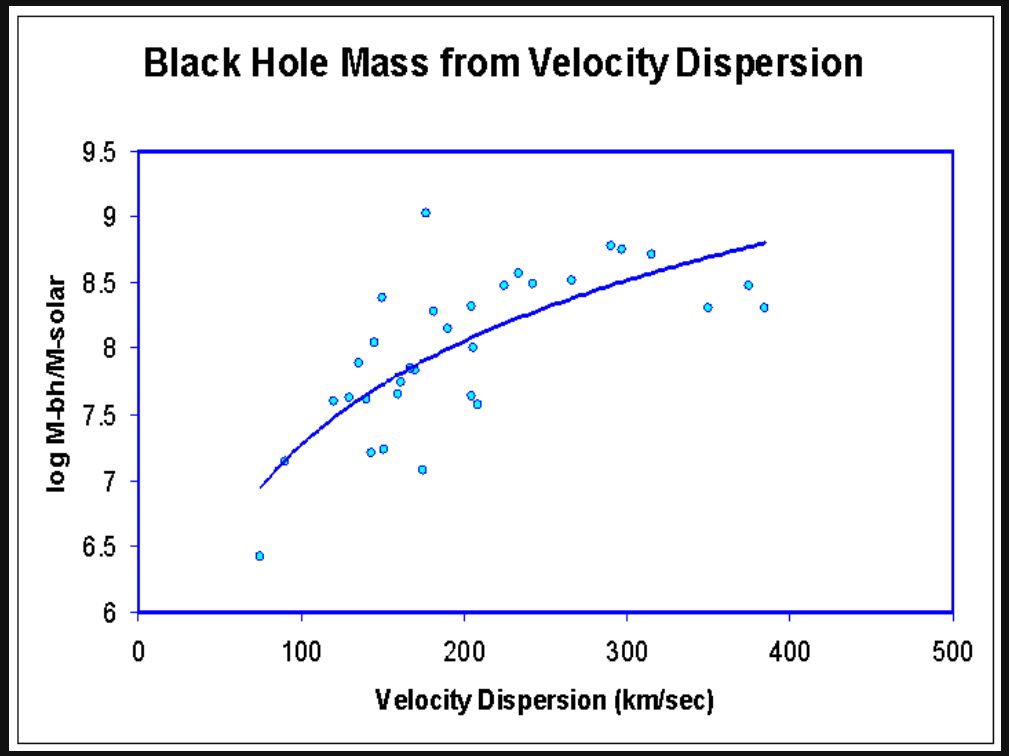
Stars near the center of a galaxy have varied speeds and directions of their orbital motions - that is termed their "*velocity dispersion.*"

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

Imagine the Universe – “An Introduction to Black Holes” http://imagine.gsfc.nasa.gov/docs/science/know_l1/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

Adler Planertarium - “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

Constellation X-ray Observatory
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

Starchild – "Black Holes" 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

Web Resources, page 3

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