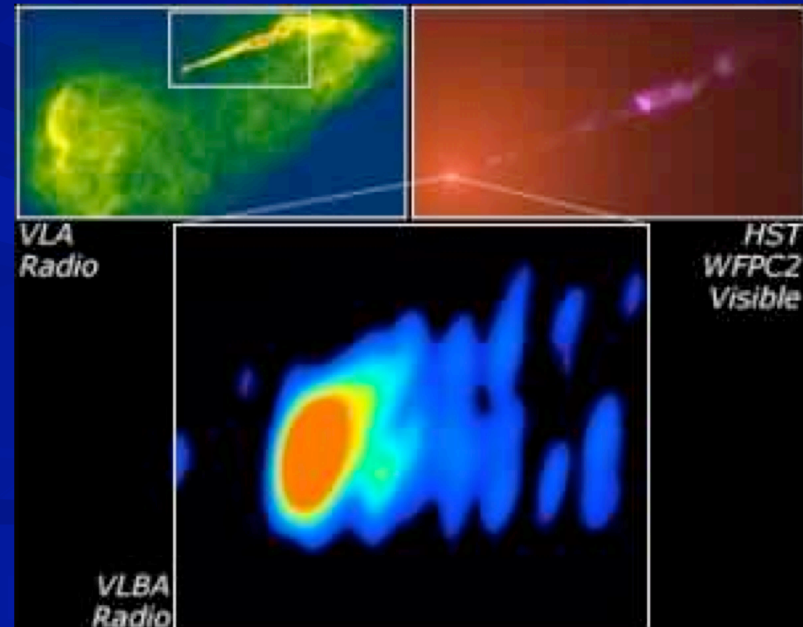
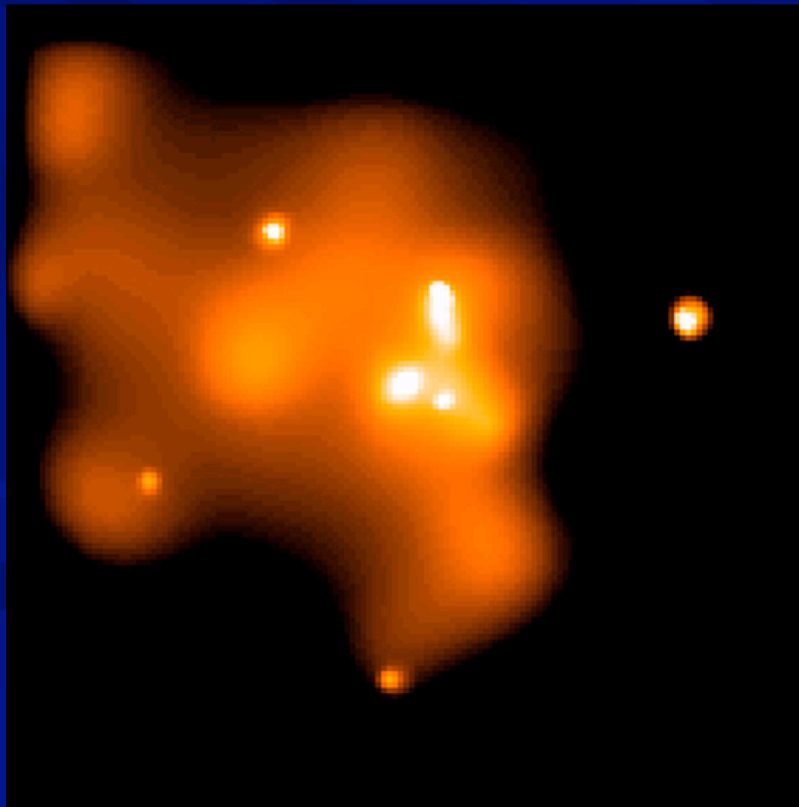


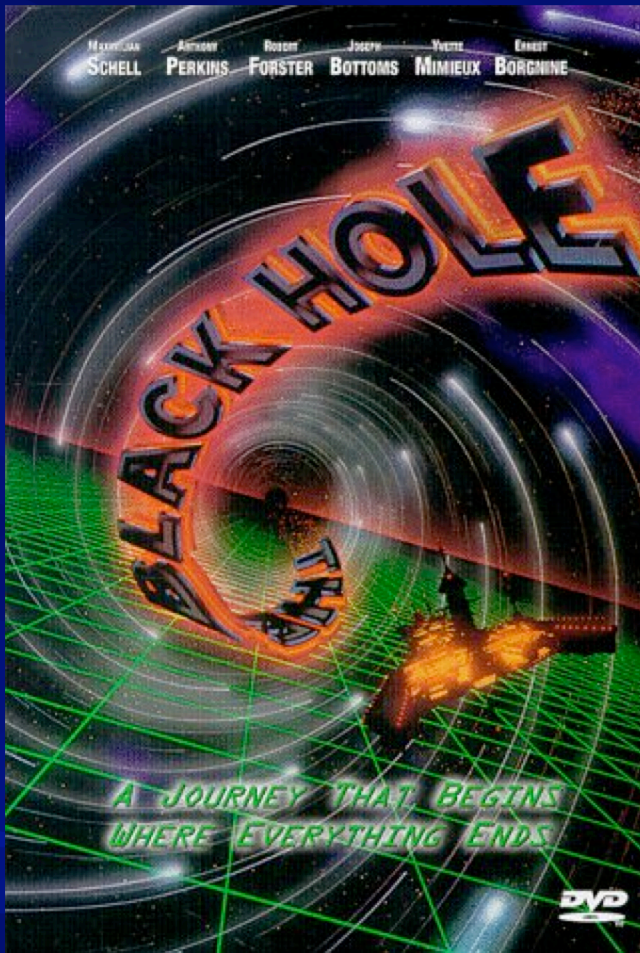
# Black Holes

Monsters Lurking at the Centers of Galaxies

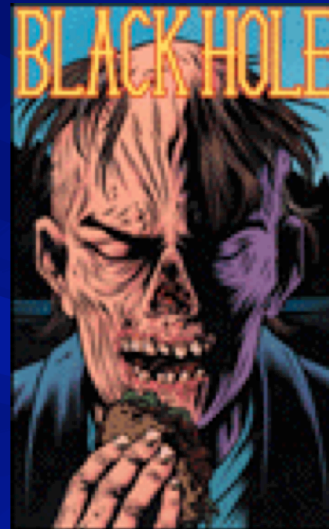
Eliot Quataert (UC Berkeley)



# Science Fiction

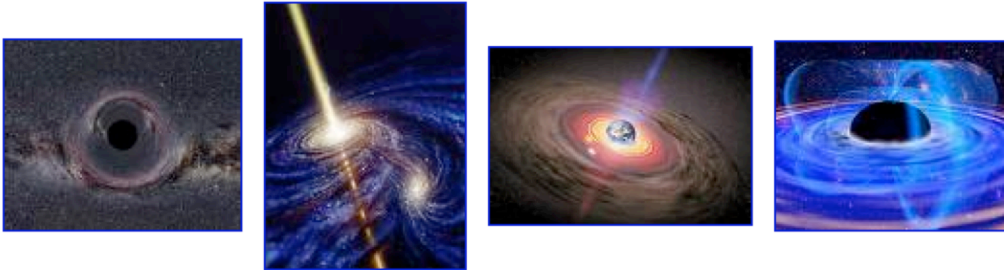


**“A Journey That Begins  
Where Everything Ends”**



**“Infinite Space,  
Infinite Terror”**



[Advanced Search](#)  
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### [Black hole](#) - Wikipedia, the free encyclopedia

Simulated view of a **black hole** in front of the Milky Way. The **hole** has 10 solar masses and is viewed from a distance of 600 km. [1] ...

[en.wikipedia.org/wiki/Black\\_hole](http://en.wikipedia.org/wiki/Black_hole) - 267k - [Cached](#) - [Similar pages](#)

### [BLACK HOLES](#) by Ted Bunn

List of questions that explore the basic properties of **black holes** (such as what happens when you fall in, or how a **black hole** evaporates).

[cosmology.berkeley.edu/Education/BHfaq.html](http://cosmology.berkeley.edu/Education/BHfaq.html) - 38k - [Cached](#) - [Similar pages](#)

### [HubbleSite: Black Holes: Gravity's Relentless Pull](#)

**Black Holes:** Gravity's Relentless Pull. Information, virtual journeys, and simulations about **black holes** from the Space Telescope Science Institute.

[hubblesite.org/explore\\_astronomy/black\\_holes/](http://hubblesite.org/explore_astronomy/black_holes/) - 15k - [Cached](#) - [Similar pages](#)

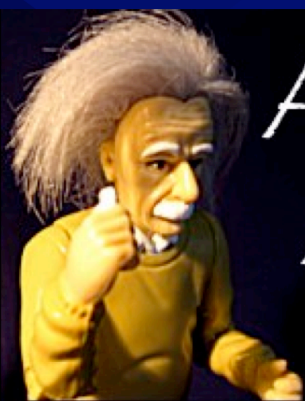
Sponsored Links

#### [Black Hole](#)

Prices Slashed. Today Only.  
Free UPS Shipping  
[spinellinutrition.com](http://spinellinutrition.com)

#### [Death by Black Hole \\$17](#)

And Other Cosmic Quandaries  
By Neil deGrasse Tyson. Hardcover  
[www.amazon.com](http://www.amazon.com)



# Albert Einstein Action Figure



"Cover me. I'm going in there," cried Albert, tossing aside his slide rule.

Sgt. Randell grabbed Einstein by the elbow patch of his tweed jacket. "Please, Professor. Don't do it. You're too valuable."

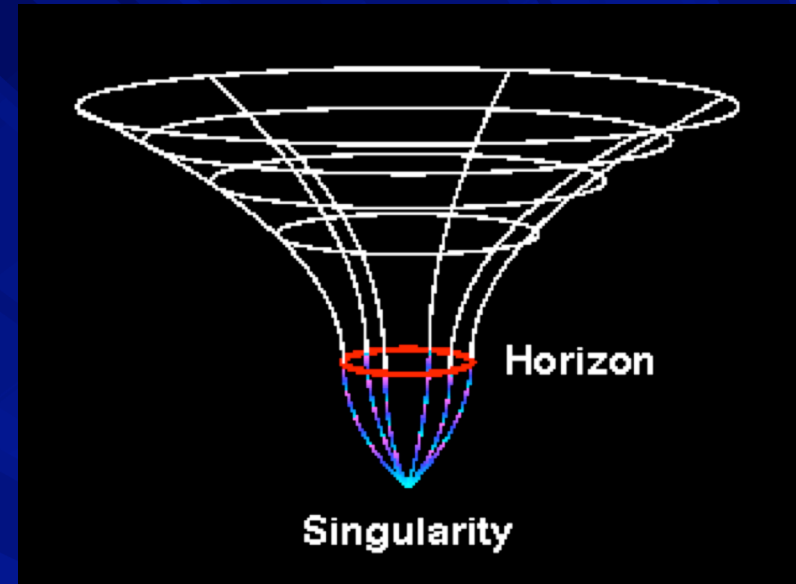
"I can't leave those men behind, Sergeant. Without loyalty, my theory of relativity is meaningless."

Einstein yanked his arm free and charged the German machine gun nest. Sgt. Randell stared at the suede patch that had come loose in his hand. "There goes one stupid genius," he muttered.

**This is just one of the many scenarios you can act out with the genuine Albert Einstein Action Figure. This 5-1/2" figure captures the world's most famous genius in all his frumpy glory. Albert is fully pose able, and features a huge shock of gray hair atop his head.**



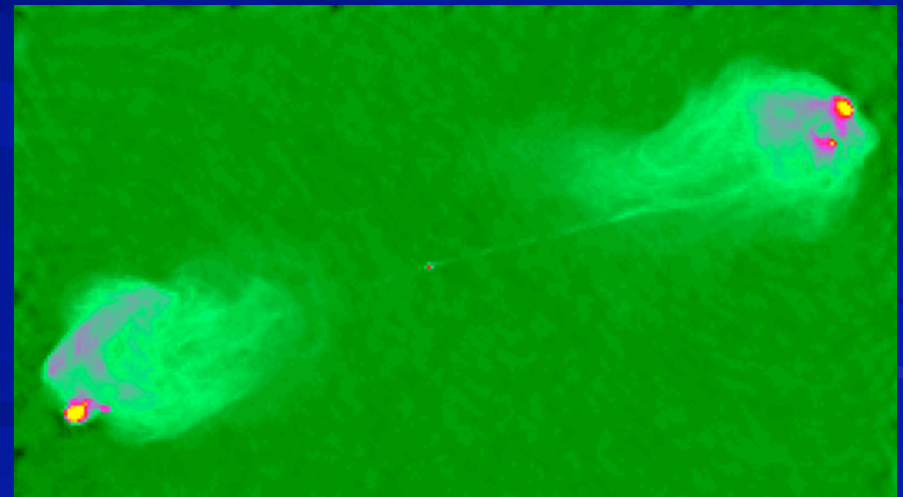
- What is a black hole?



- Do BHs exist in Nature?  
– **YES!**

- How are they found?

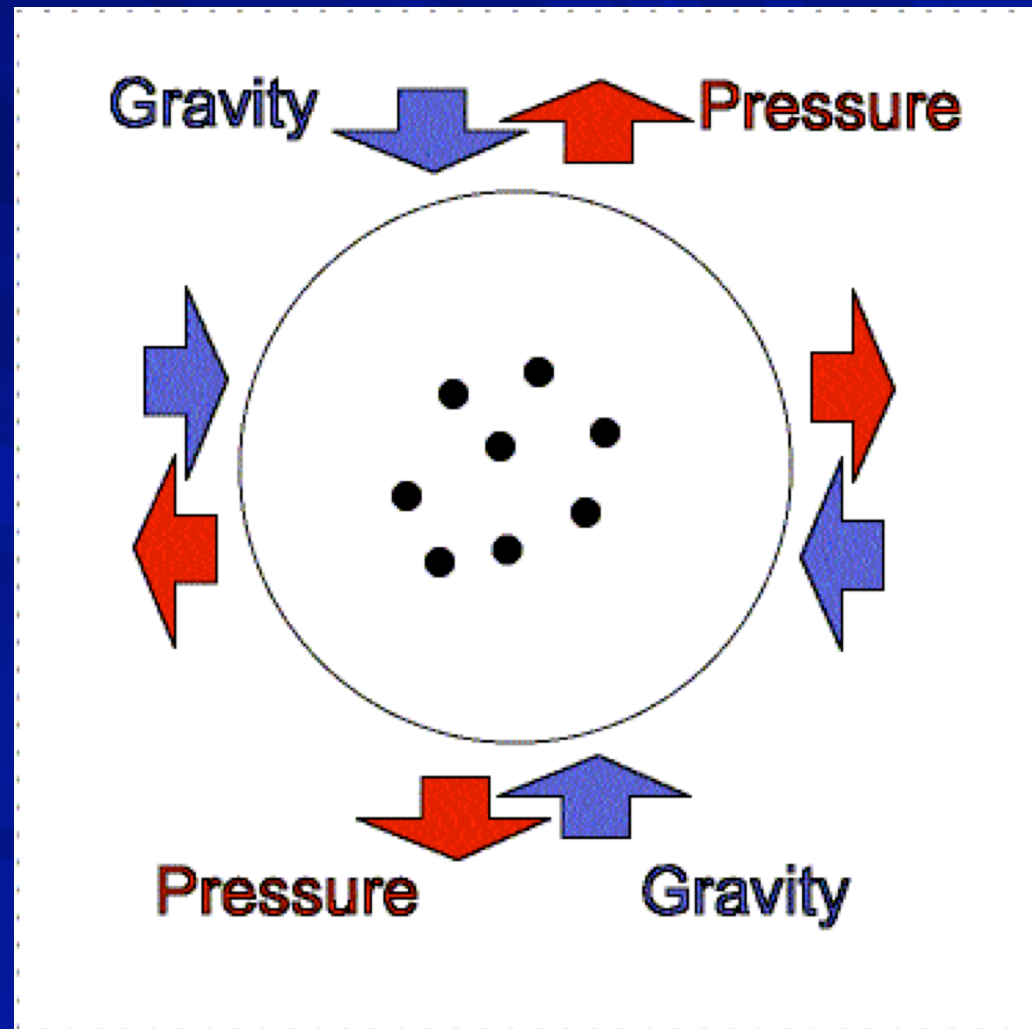
- What do they look like?



# First, Something Simpler: Stars Pressure Balances Gravity



The Sun





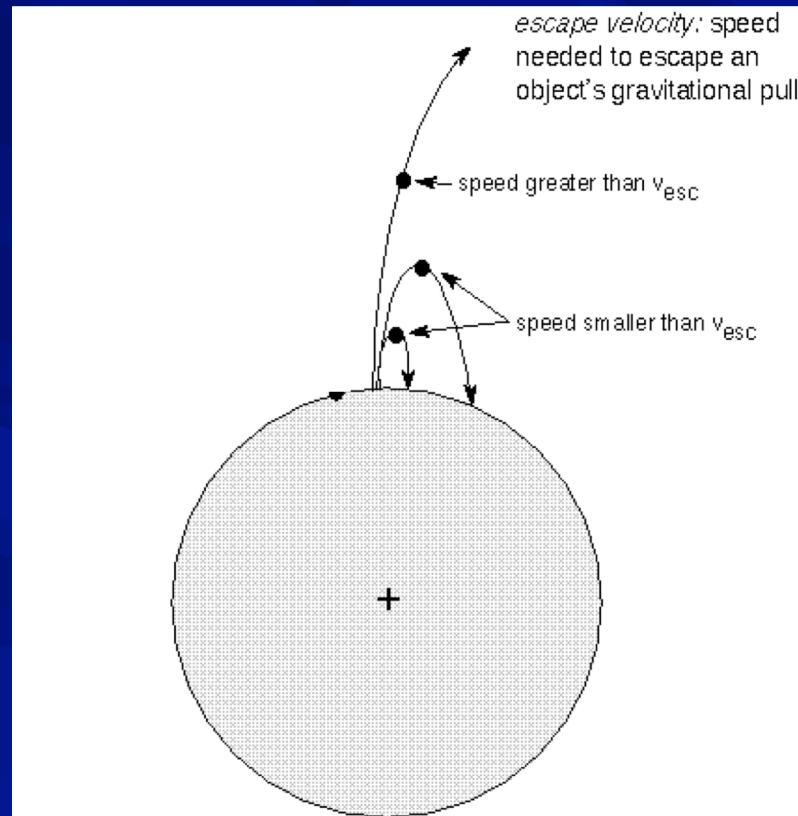
# Eluding Gravity's Grasp

## Escape Velocity

$$V_{esc} = \sqrt{\frac{2GM}{R}}$$

Mass  $M$   
Radius  $R$

Speed Needed To  
Escape An Object's  
Gravitational Pull



Earth:  $V_{esc} = 27,000$  miles/hour (11 km/s)  
Sun:  $V_{esc} = 1.4$  million miles/hour (600 km/s)

# “Dark Stars”

John Michell (1783) & Pierre-Simon Laplace (1796)

Speed of light  $\approx$  1 billion miles/hour  
( $\sim 3 \times 10^5$  km/s  $\sim$  foot/ns)

What if a star were so small,  
escape speed  $>$  speed of light?

**A star we couldn't see!**

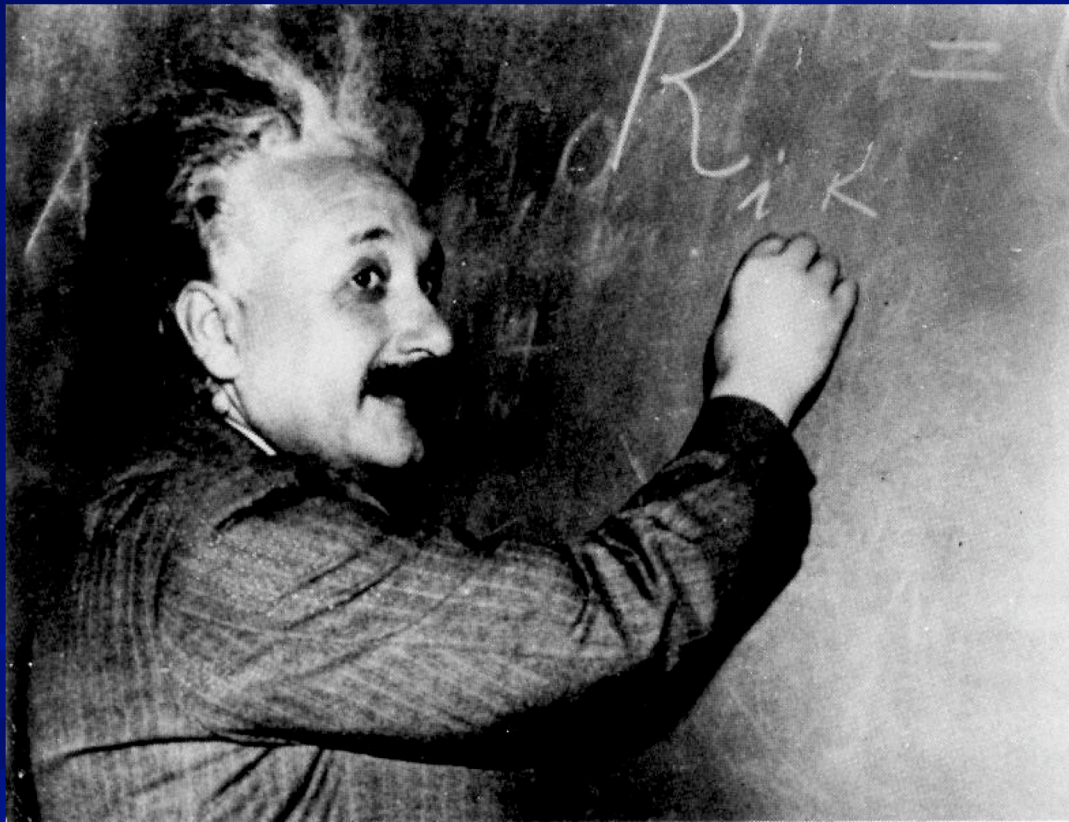
$V_{\text{esc}}$  = speed  
of light  $\Rightarrow$

Earth mass:  $R \approx 1$  inch

Solar mass:  $R \approx 2$  miles



**1915: General Relativity, Einstein's Theory of Gravity**  
**1916: Schwarzschild's Discovery of BHs in GR**  
**BHs only understood & accepted in the 1960s**  
**(Term "Black Hole" coined by John Wheeler in 1967)**

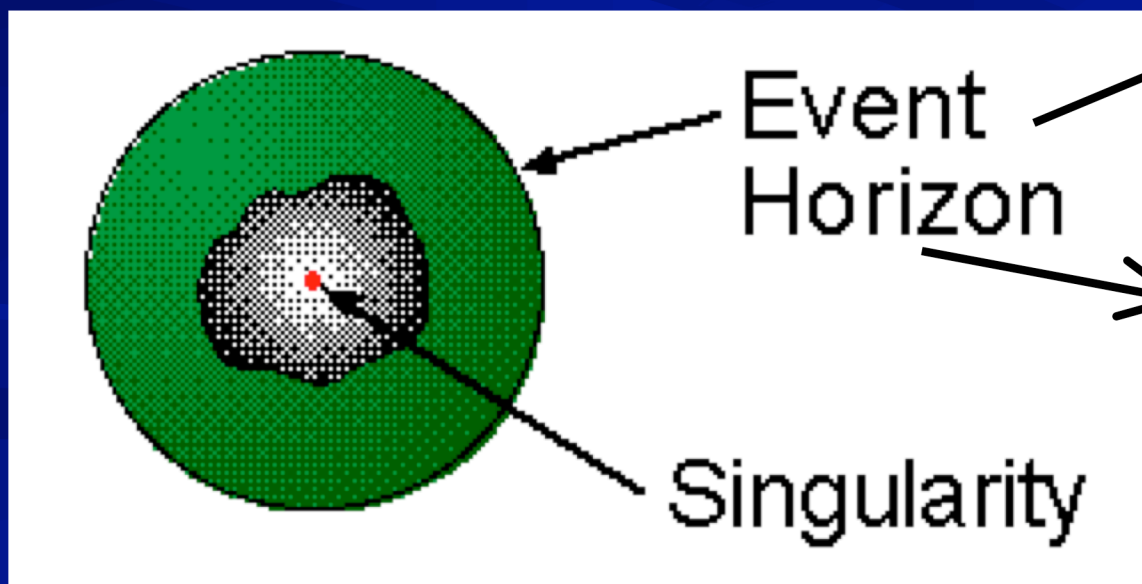


**Albert Einstein**

**Karl Schwarzschild**

# Black Holes in GR

If an object is small enough, gravity overwhelms pressure and the object collapses. Gravity is so strong that nothing, not even light, can escape.



“Radius” of a BH

≈ 2 miles for a solar mass

≈ 1 inch for an Earth mass

**NOT** a solid surface

All Mass at the Center  
(GR not valid there)



# Dispelling the Myths ...

- BHs are **NOT** cosmic vacuum cleaners: only inside the horizon is matter pulled inexorably inward
- Far away from a BH, gravity is **no different** than for any other object with the same mass ( $F = Gm_1m_2/r^2$ )
- If a BH were to replace the sun, the orbits of planets, asteroids, moons, etc., would be **unchanged** (though it would get really really cold).



# How do we find BHs in Nature?



"It's black, and it looks like a hole.  
I'd say it's a black hole."

Sidney Harris

**“It’s black, and it looks like a hole.  
I’d say it’s a black hole.”**

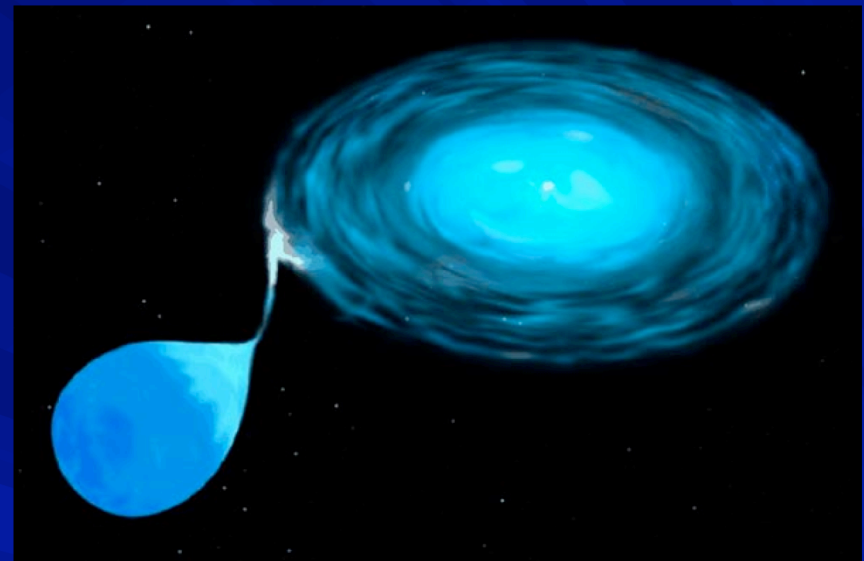


# Where are BHs Found?



## Centers of Galaxies

1 **BIG** BH per galaxy  
million-billion x mass of sun  
formation not fully understood  
(tied to galaxy formation)



## The Death of Stars

**millions** of 'little' BHs per galaxy ( $\sim 10 M_{\text{sun}}$ )  
 $\approx 20$  found as "X-ray binaries"  
formed by collapse of a massive star  
(after nuclear fusion ceases)

# The Milky Way Galaxy: ~ 100,000 light-years across

Scale: Size of Solar System: 0.01 light-years  
Typical Distance btw. Stars: 1 light-year



Total mass (dark matter):  $10^{12} M_{\text{sun}}$   
Mass in stars:  $10^{11} M_{\text{sun}}$





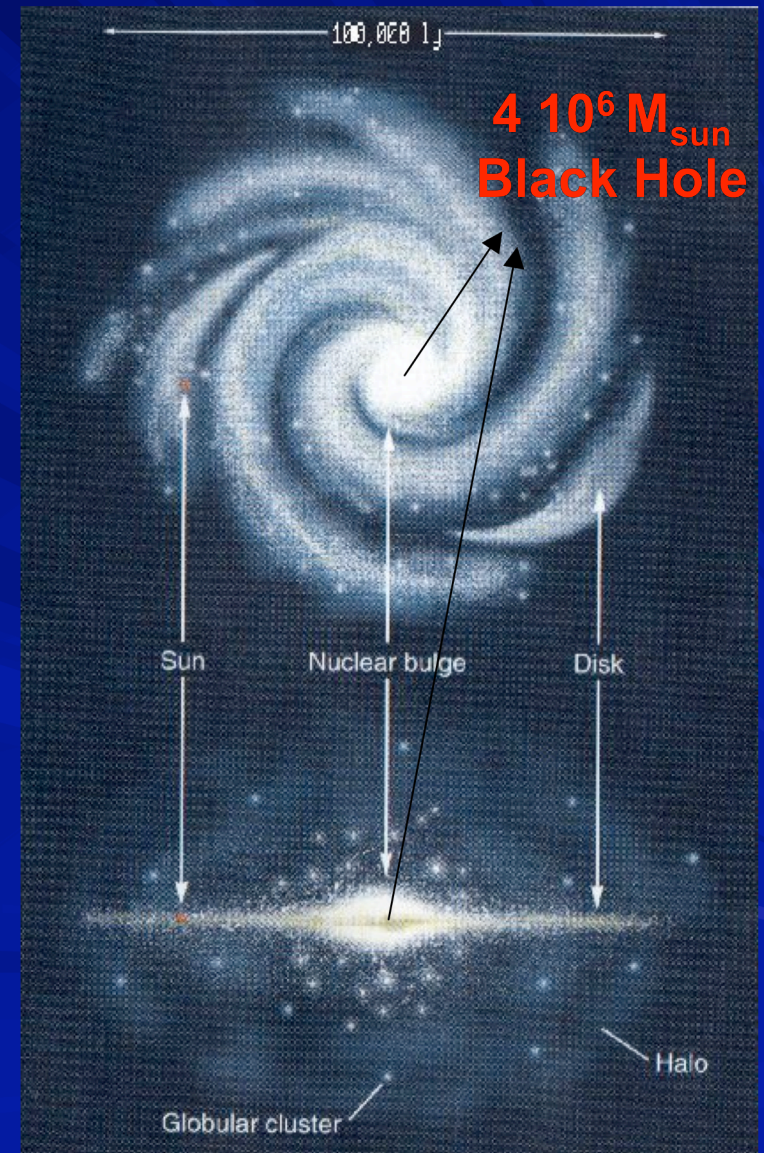
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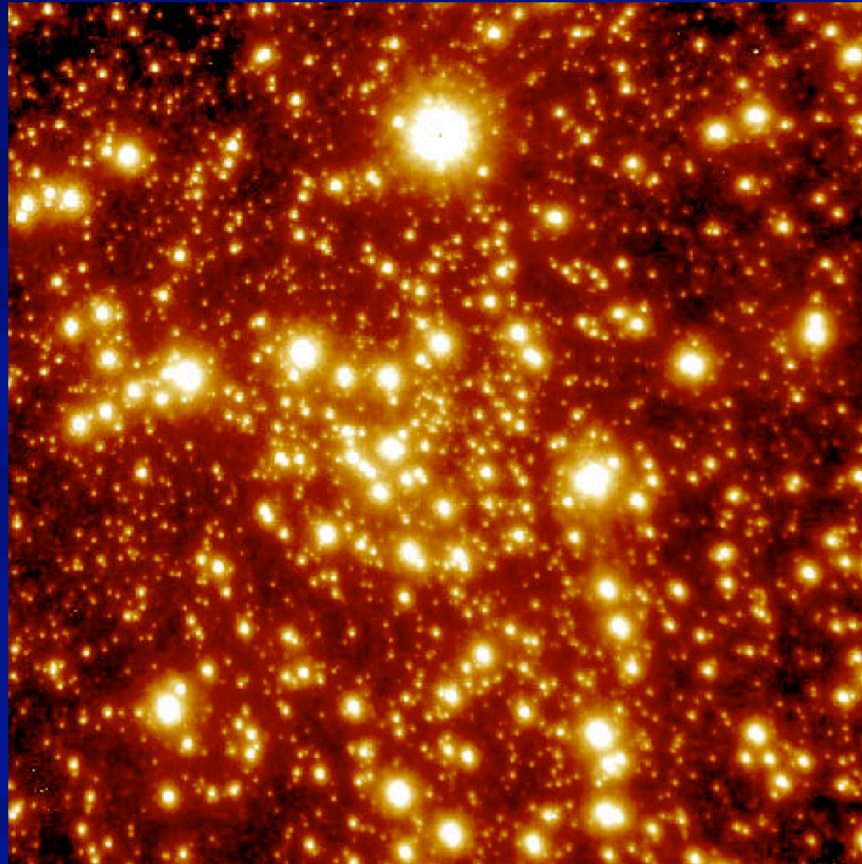
Total mass (dark matter):  $10^{12} M_{\text{sun}}$   
Mass in stars:  $10^{11} M_{\text{sun}}$

Central Black Hole Mass: 4 million  $M_{\text{sun}}$   
(also ~ millions of little  $10 M_{\text{sun}}$  BHs)



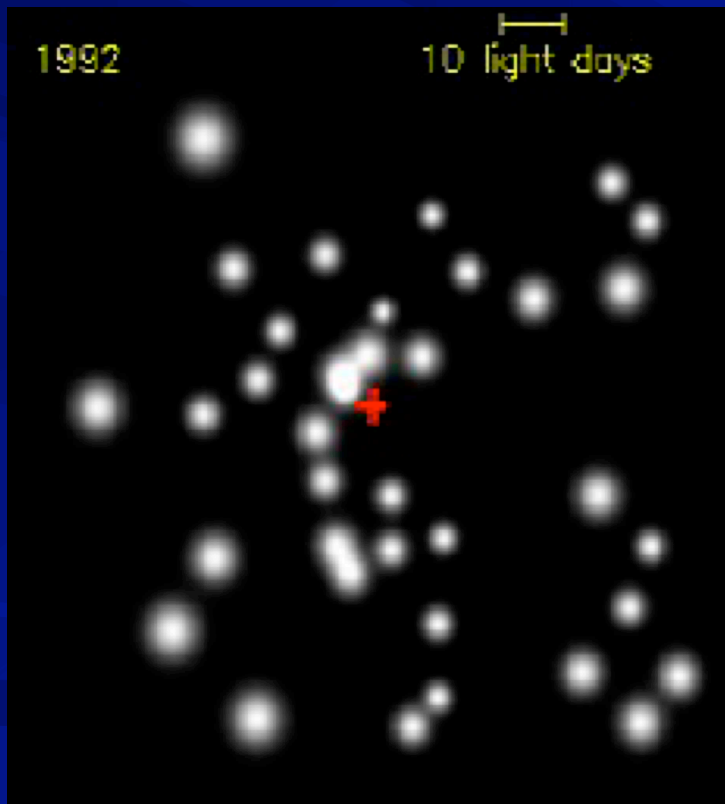


# Stars in the Central Light-Year of the Galaxy



Keep Zooming In ...

# Evidence for a Massive BH at the center of our Galaxy



Genzel et al (also Ghez et al.)

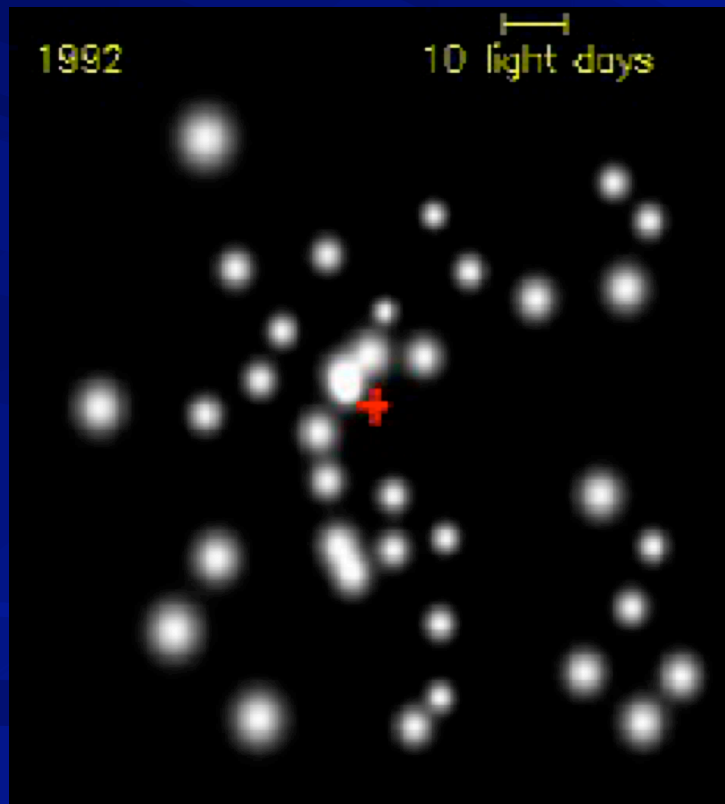
10 light-days  $\approx$  size of solar system

**Motion of stars  
at the center  
of the Milky  
Way over the  
past  $\sim$  15 yrs**

**closest star (so far!)  
min distance  $\sim$  500 x horizon  
max vel  $\approx$  12000 km/s  $\approx$  0.04 c**

<http://www.mpe.mpg.de/ir/GC/index.php>  
<http://www.astro.ucla.edu/~jlu/gc/>

# Evidence for a Massive BH at the center of our Galaxy



Genzel et al (also Ghez et al.)

**Velocities & Orbits  
of Stars  $\Rightarrow$  Mass**

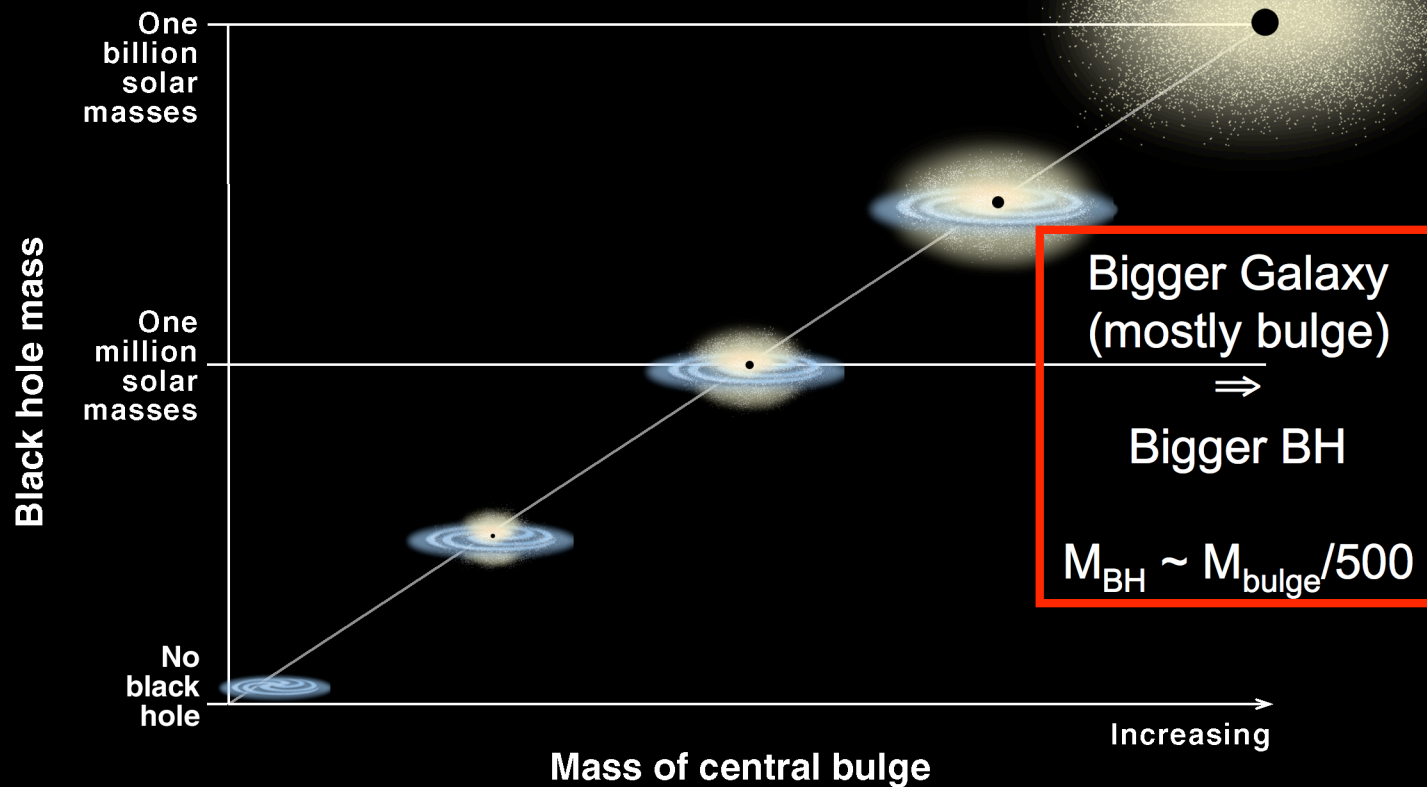
**BH in our Galaxy  
weighs in at  
4 MILLION  
SOLAR MASSES**

10 light-days  $\approx$  size of solar system

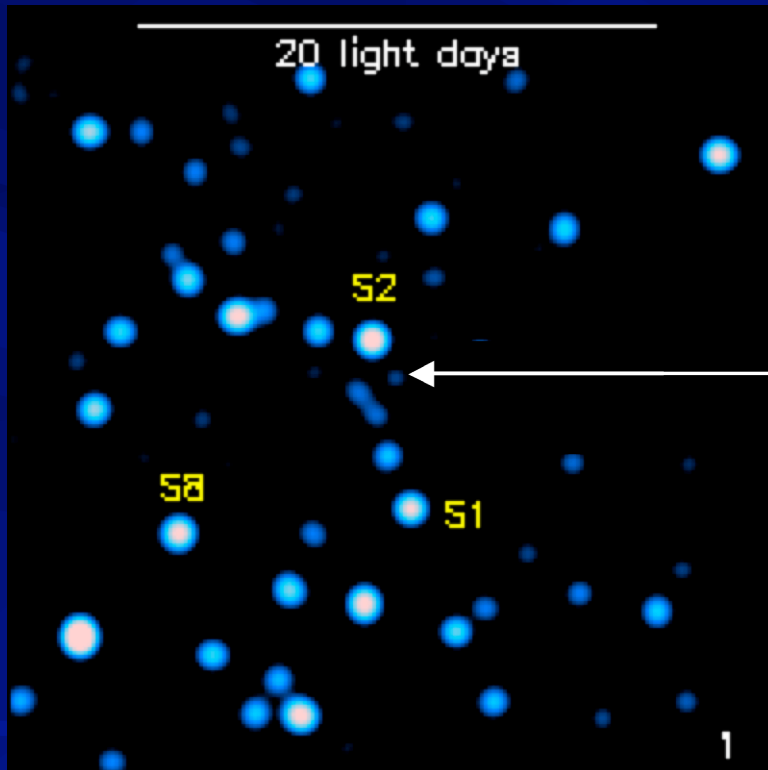


# Black Holes in Every Galaxy

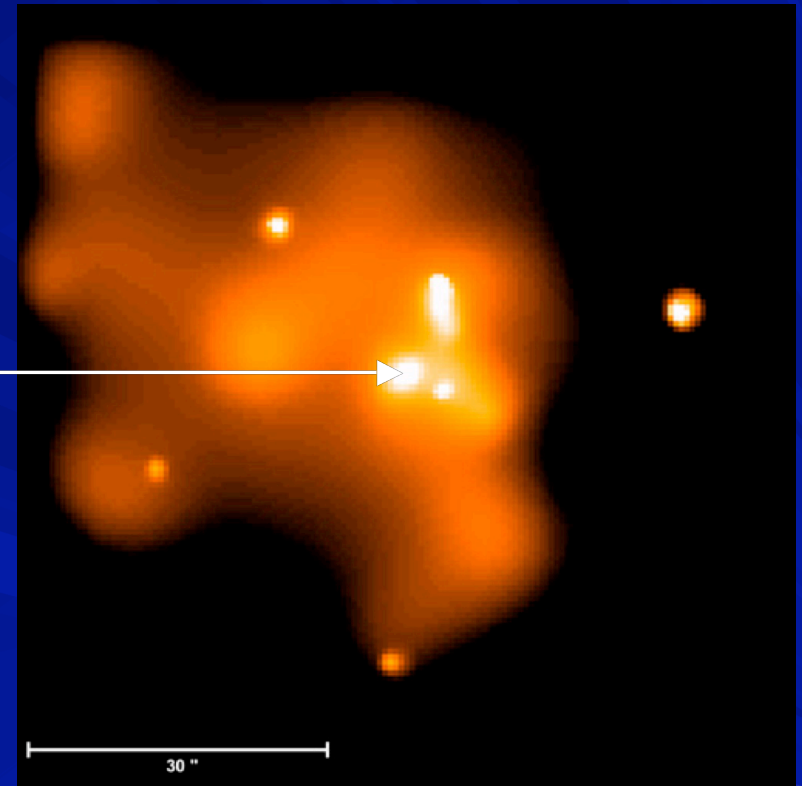
Correlation Between Black Hole Mass and Bulge Mass



# Shedding Light on BHs: Gas Falling Into a Black Hole (Accretion)



Infrared Image

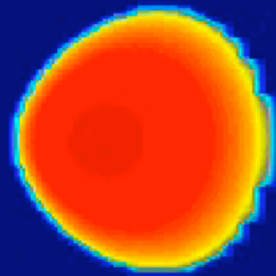


X-ray Image

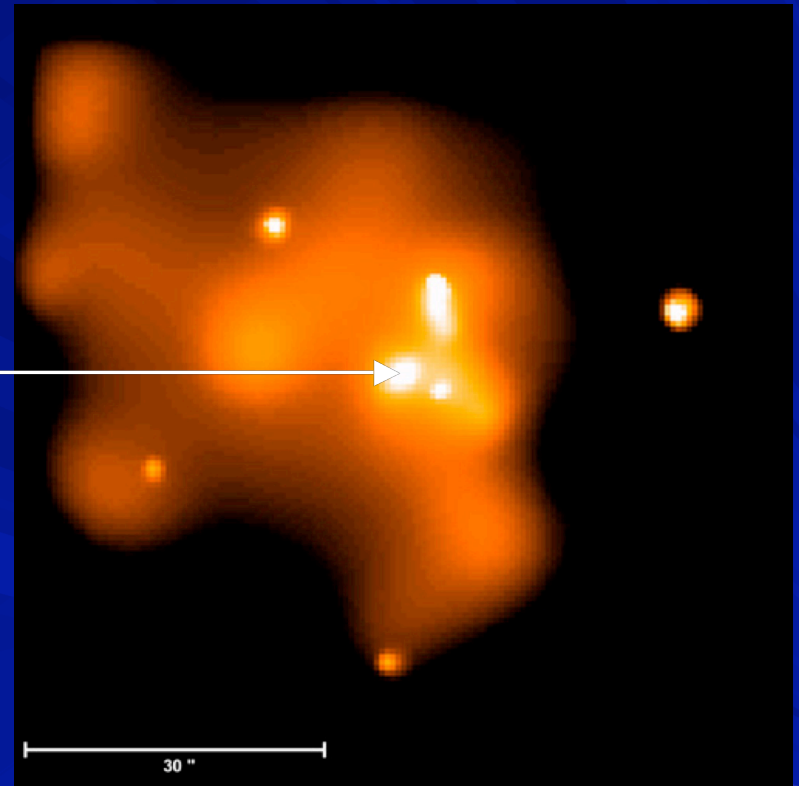
Gas falling into a BH gets *very hot* and emits *lots of light*

Accretion is how we "see" a black hole

# Shedding Light on BHs: Gas Falling Into a Black Hole (Accretion)



— BH —→



X-ray Image

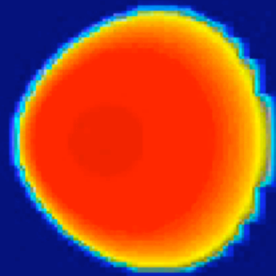
Simulation of Gas Falling into a Black Hole  
(red = dense gas; blue = low density)

**Gas falling into a BH gets very hot and emits lots of light**

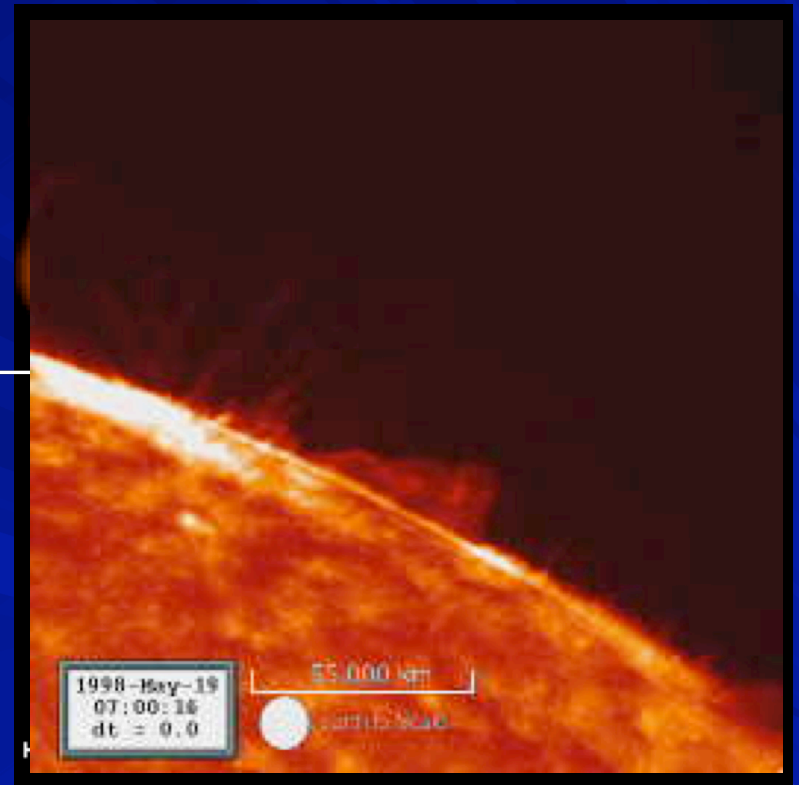
**Accretion is how we “see” a black hole**



# Shedding Light on BHs: Gas Falling Into a Black Hole (Accretion)



— BH —



Simulation of Gas Falling into a Black Hole  
(red = dense gas; blue = low density)

Analogy: Solar Flare

**Gas falling into a BH gets very hot and emits lots of light**

**Accretion is how we “see” a black hole**

# The Next Frontier: Towards the Horizon ...



# The Next Frontier: Towards the Horizon ...

- The BH at the Center of our Galaxy is the largest on the sky!
- can be directly imaged during the next ~ 10 yrs (in the radio using interferometry)

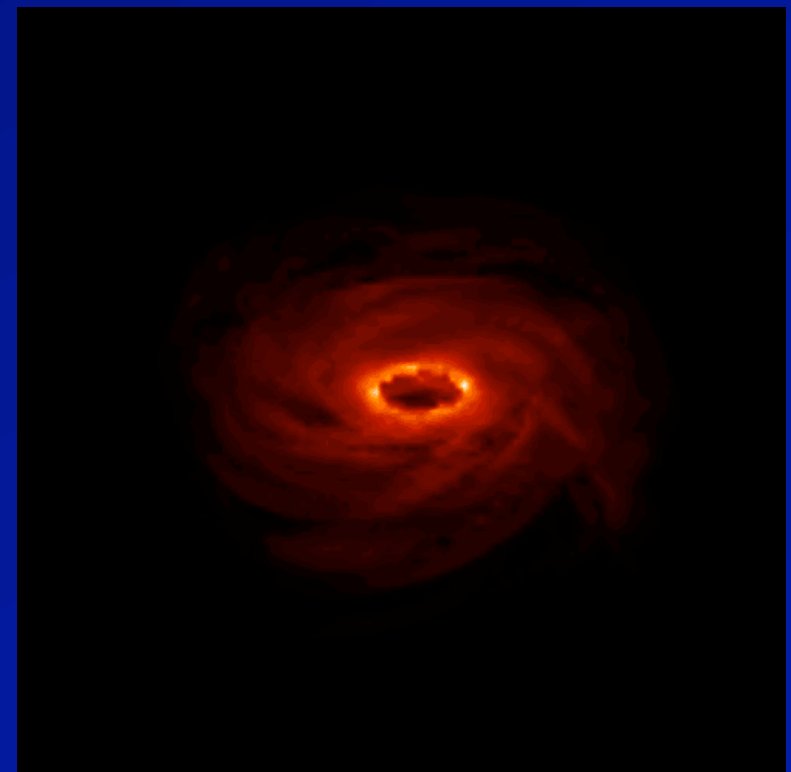




# The Next Frontier: Towards the Horizon ...

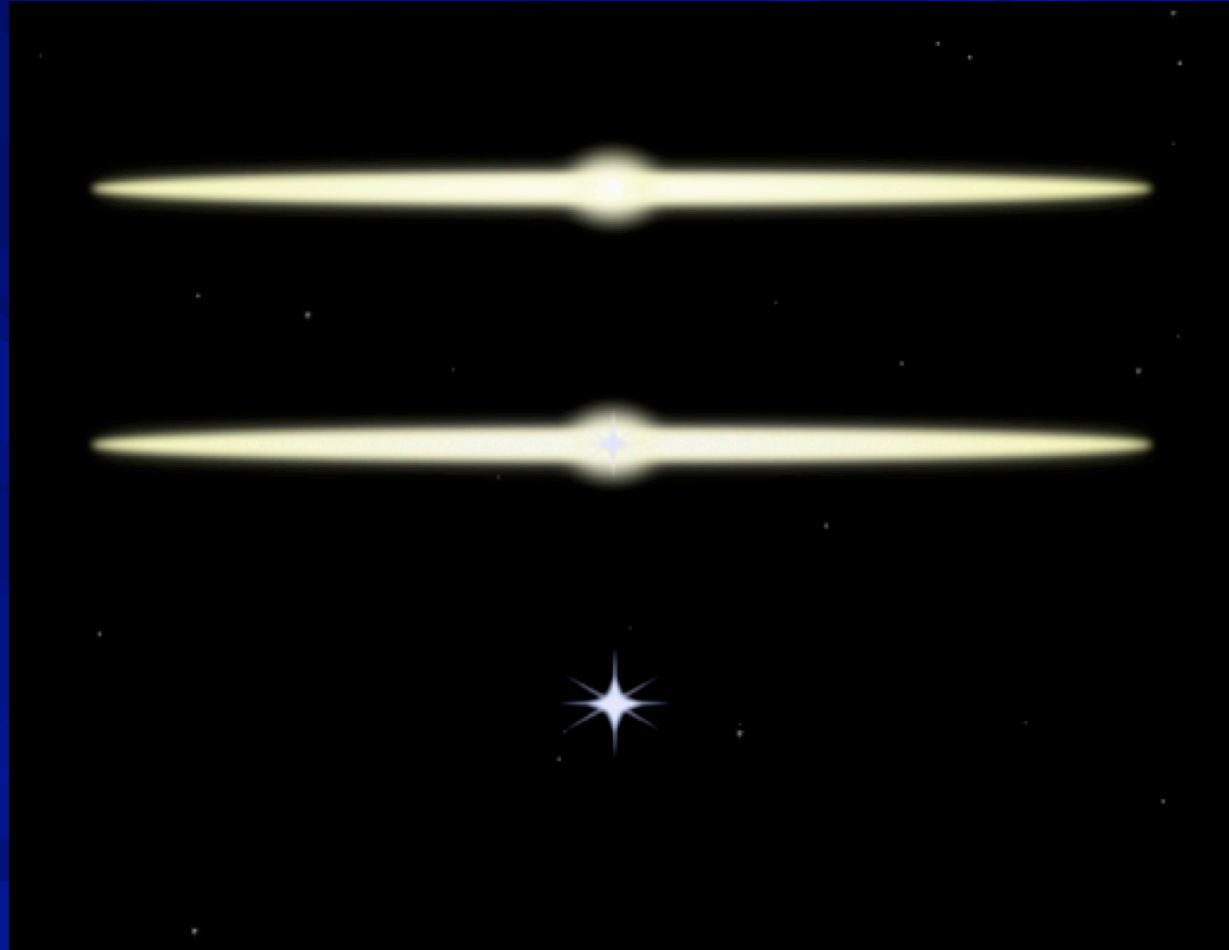
- The BH at the Center of our Galaxy is the largest on the sky!
- can be directly imaged during the next ~ 10 yrs (in the radio using interferometry)

“Ring of Fire”



# Many Varieties of Massive BHs

↓  
Brightness of Central Black Hole

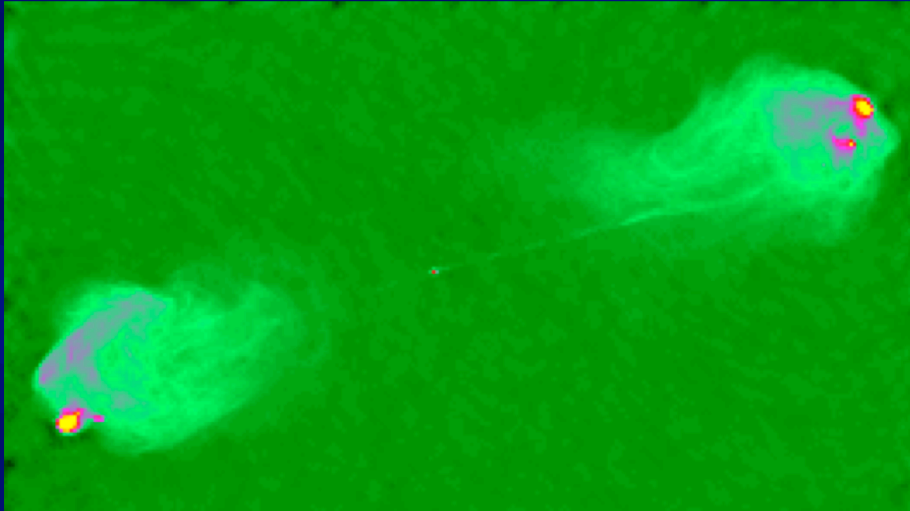


Our  
Galaxy

BHs Spend Most of their Time Faint and Unobtrusive  
(Like Ours), But Occasionally Light Up

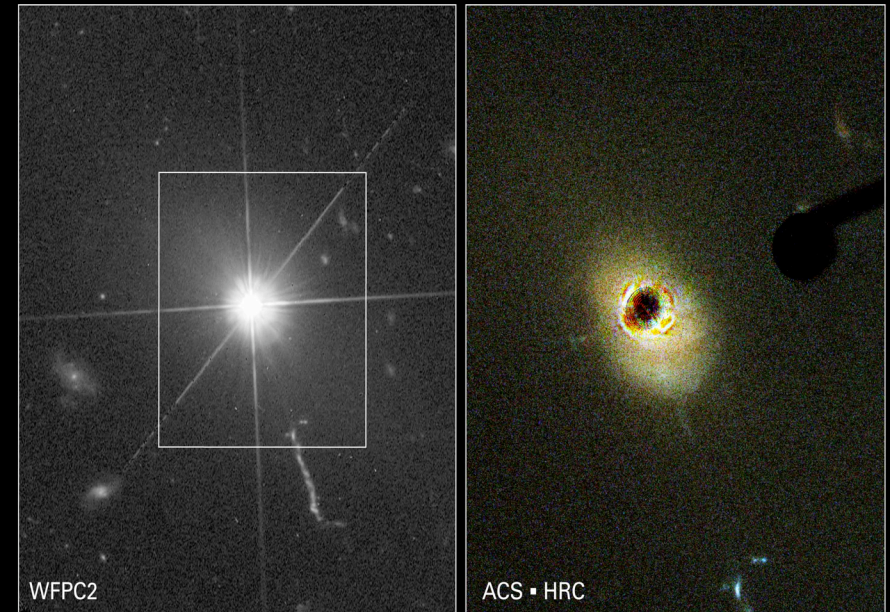
# “Active Galactic Nuclei”

radio image



**The BH ejects beams (“jets”) of matter & energy far outside its host galaxy into the surrounding universe**

**The BH produces so much radiation and outflows that it dramatically modifies how its host galaxy forms**



**Quasar 3C 273**

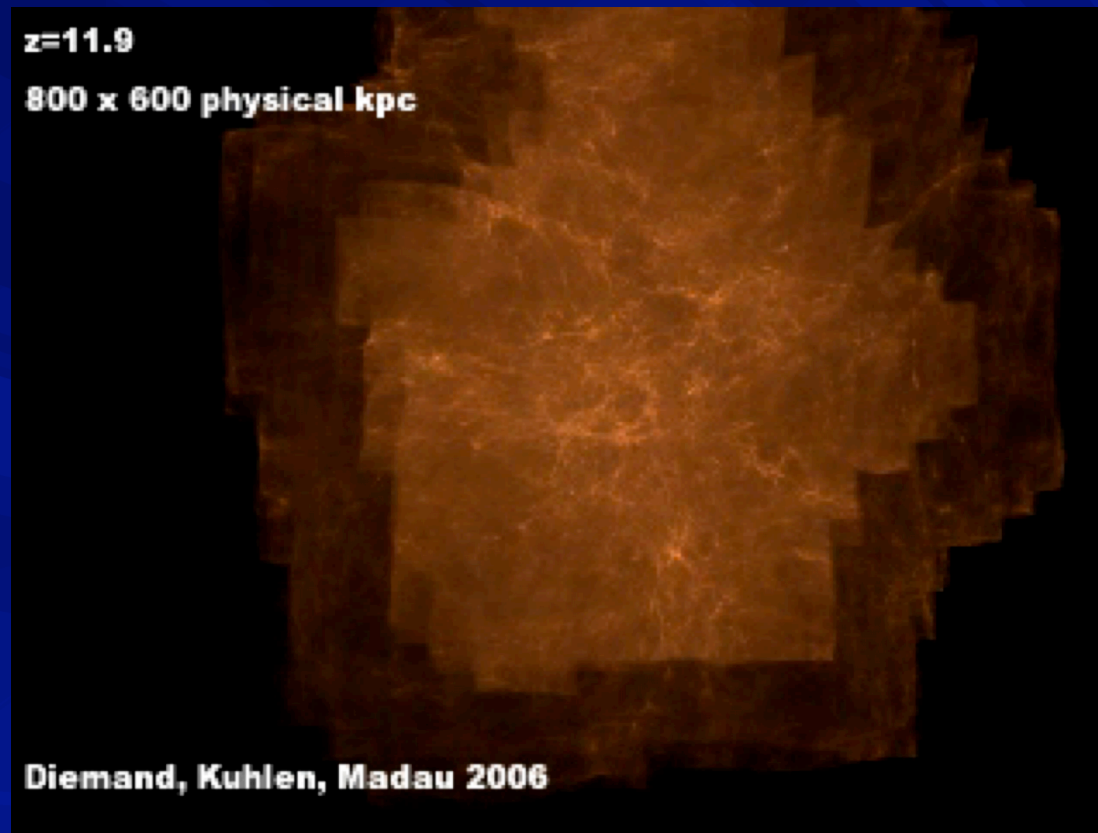
Hubble Space Telescope • ACS HRC Coronagraph

NASA, A. Martel (JHU), the ACS Science Team, J. Bahcall (IAS) and ESA • STScI-PRC03-03

**The BH can outshine all of the stars in its host galaxy!**

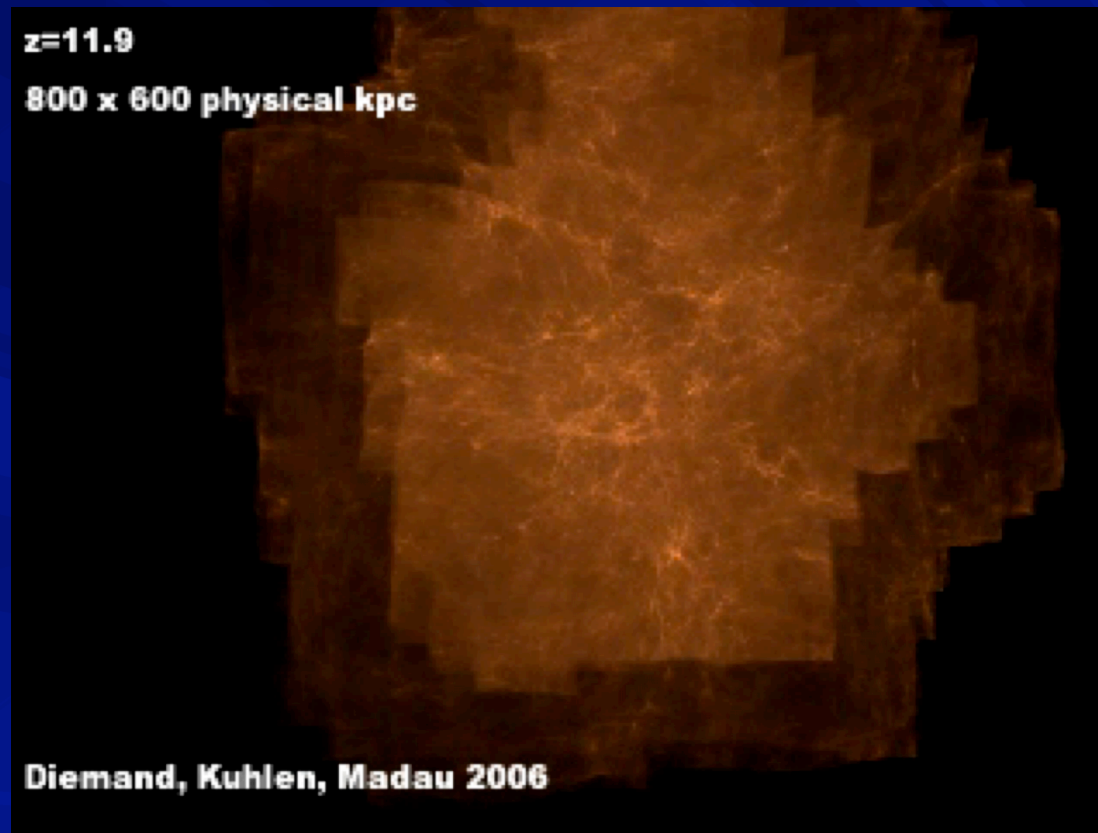


# The Growth of Structure in the Universe



Simulation of the Growth of Dark Matter in a Milky-Way-like Galaxy By Mergers/Collisions with Other Galaxies

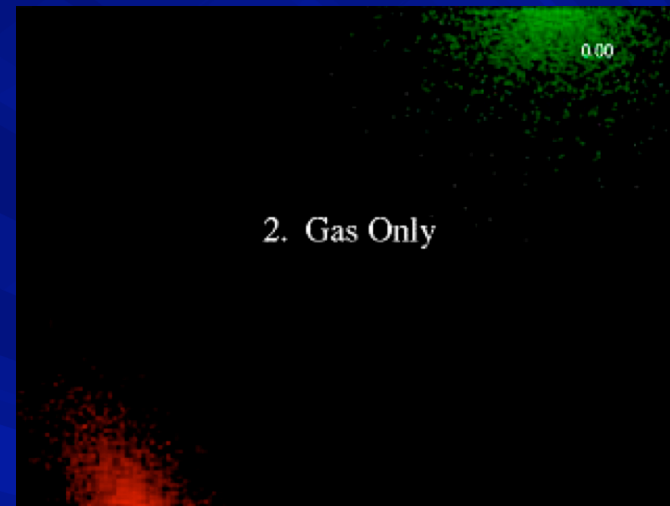
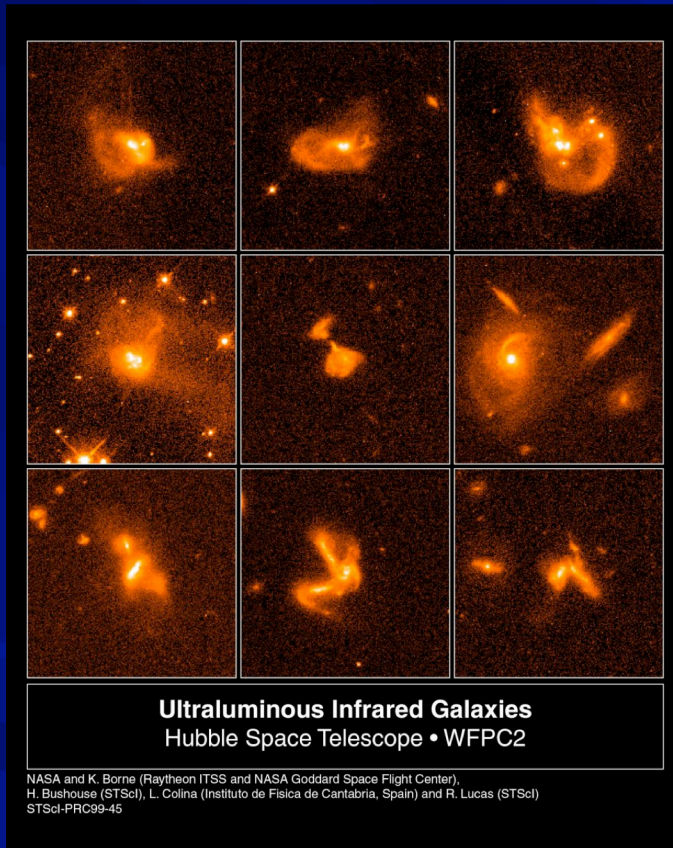
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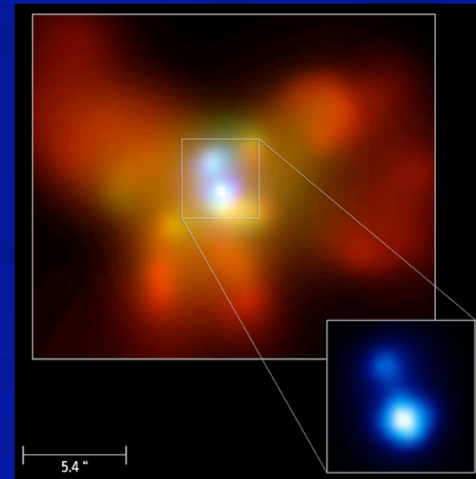
Simulation of the Growth of Dark Matter in a Milky-Way-like Galaxy By Mergers/Collisions with Other Galaxies

# Stirring up Nuclear Activity

- Galaxies grow by colliding w/ other Galaxies  $\Rightarrow$  gas flows to the center  $\Rightarrow$  Growth of Big BHs at the Centers of Galaxies



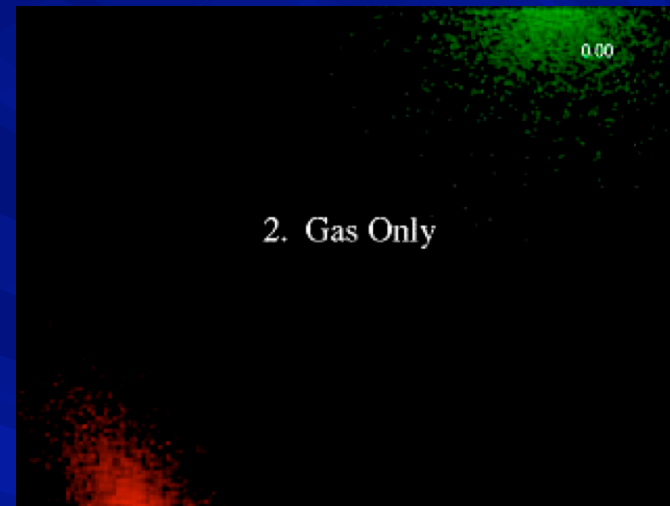
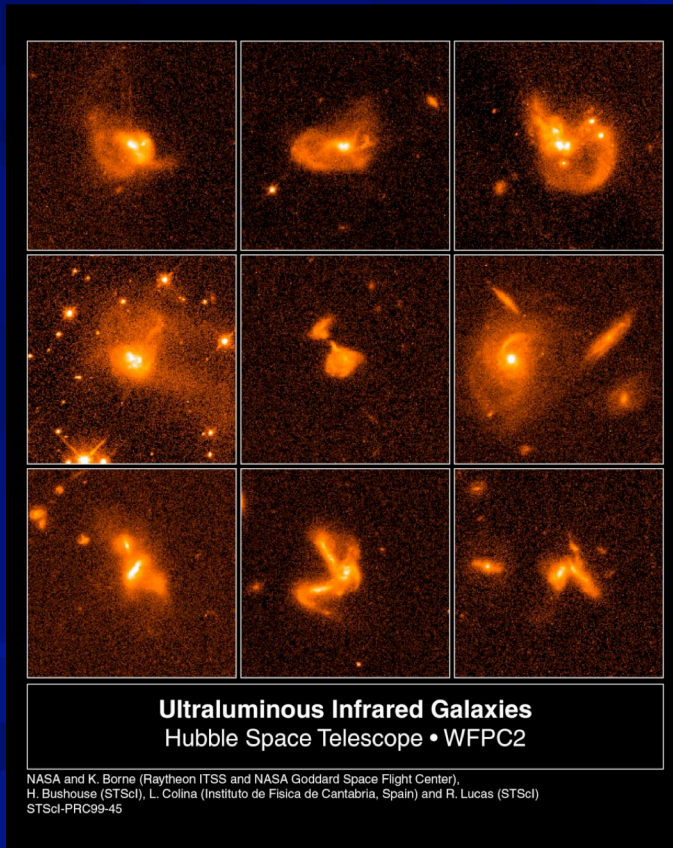
Josh Barnes



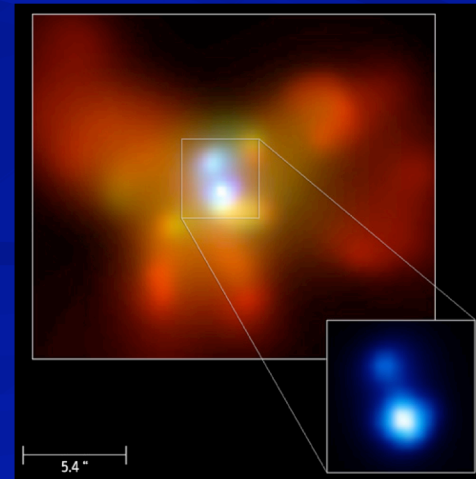


# Stirring up Nuclear Activity

- Galaxies grow by colliding w/ other Galaxies  $\Rightarrow$  gas flows to the center  $\Rightarrow$  Growth of Big BHs at the Centers of Galaxies



Josh Barnes



# The Moral of the Story ...

- **Physicists said that Black Holes **could** exist**
  - the ultimate victory of gravity over all other forces
- **Astronomers find that BHs **do** exist**
  - 1 **Big** BH per galaxy (~ million-billion solar masses)
  - millions of little BHs per galaxy (~ solar mass)
- **BHs produce the most energetic phenomena in the universe & play a key role in the formation of galaxies**
  - BHs are “seen” via the light produced by infalling gas & via the gravitational pull that they exert on nearby objects

# Good References

- Gravity's Fatal Attraction (Begelman & Rees)
- Black Holes & Time Warps: Einstein's Outrageous Legacy (Thorne)
- <http://cosmology.berkeley.edu/Education/BHfaq.html>
- [http://en.wikipedia.org/wiki/Black\\_hole](http://en.wikipedia.org/wiki/Black_hole)
- Info on the BH in our Galaxy
  - <http://www.mpe.mpg.de/ir/GC/index.php>
  - <http://www.astro.ucla.edu/~jlu/gc/>