Part 3: Galaxies and the Universe

Tuesday, March 22 Reading: Chapter 12.1 — 12.3
- Our Galaxy = The Milky Way

Thursday, March 24 Reading: Chapter 13.1 — 13.2
- Galaxies: types, properties, clusters of galaxies, dark matter

Tuesday, March 29 Reading: Chapters 13.3, 15
- Galaxies: formation, evolution; distance scales; expansion of the Universe

Thursday, March 31 Reading: Chapter 12.4, 14
- Galaxies: active galaxies and quasars; supermassive black holes

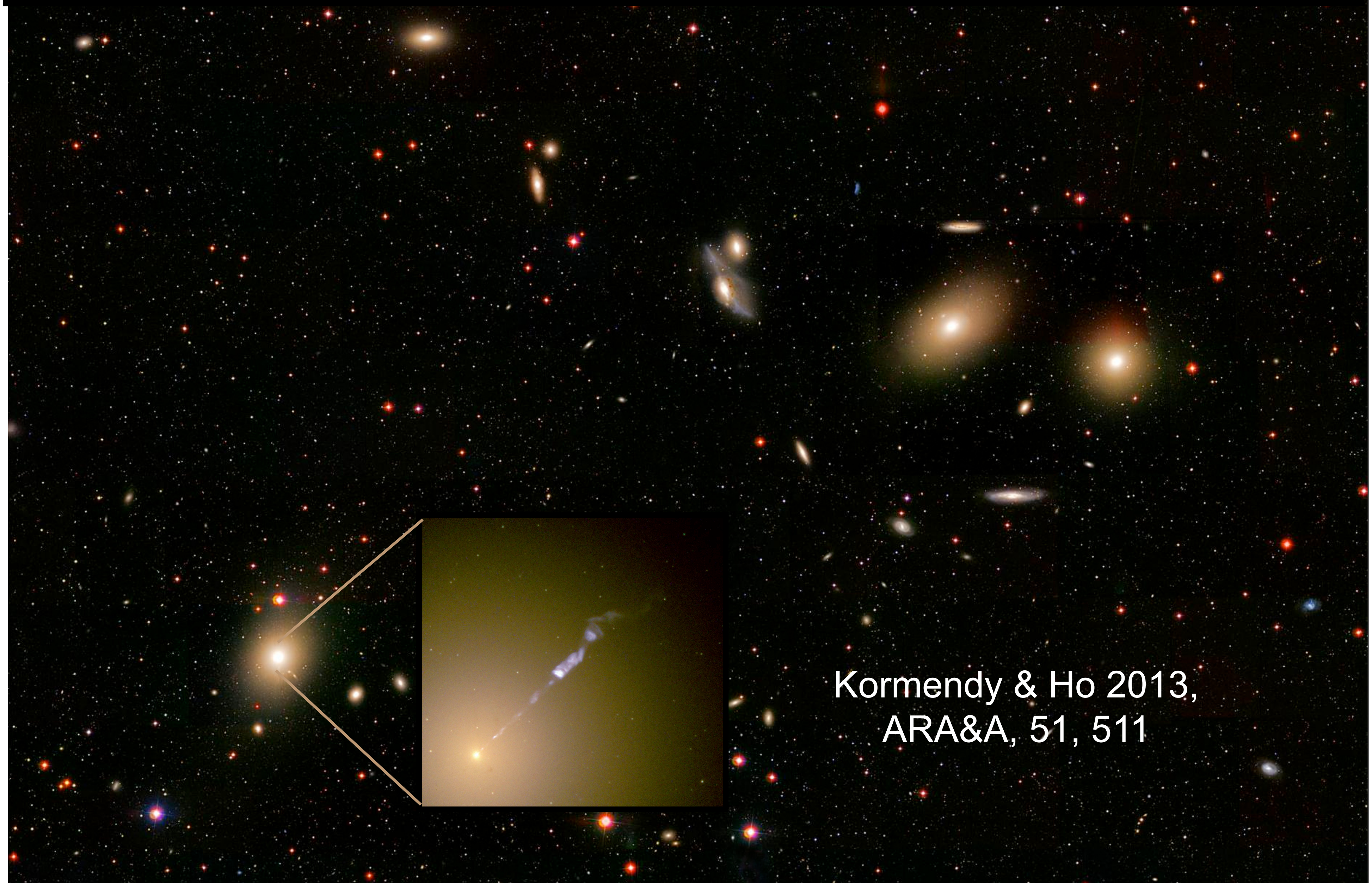
Monday, April 4 TA's help session for HW3: 3 to 5 PM in WCH 1.120

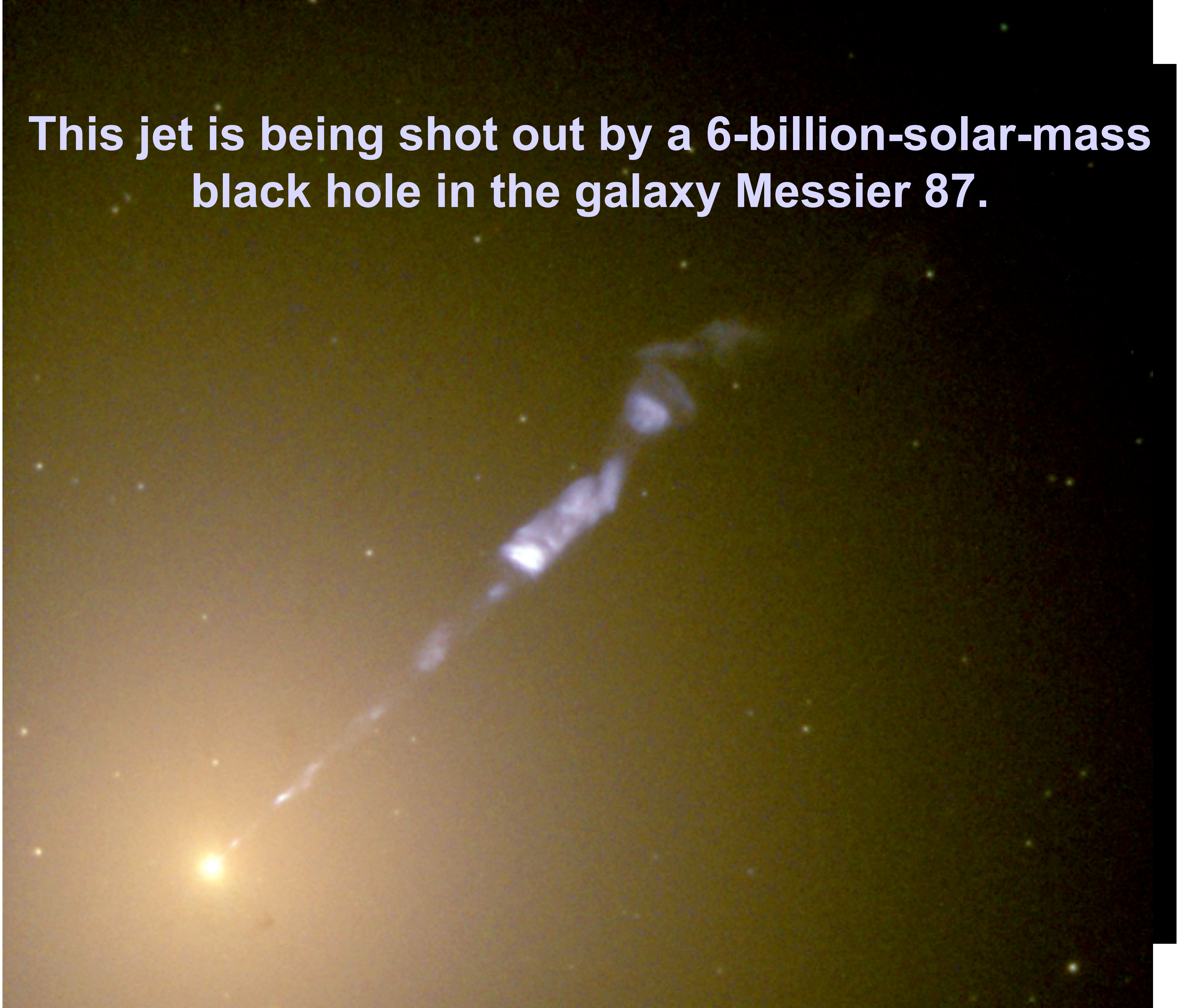
Tuesday, April 5 Reading: Chapter 15; HW 3 due
- Cosmology: Big Bang ➡ background radiation; formation of structure

Wednesday, April 6 Help session: 4 to 6 PM in Welch 2.224

Thursday, April 7 Exam 4

Monsters in Galactic Nuclei: Supermassive Black Holes and Galaxy Evolution

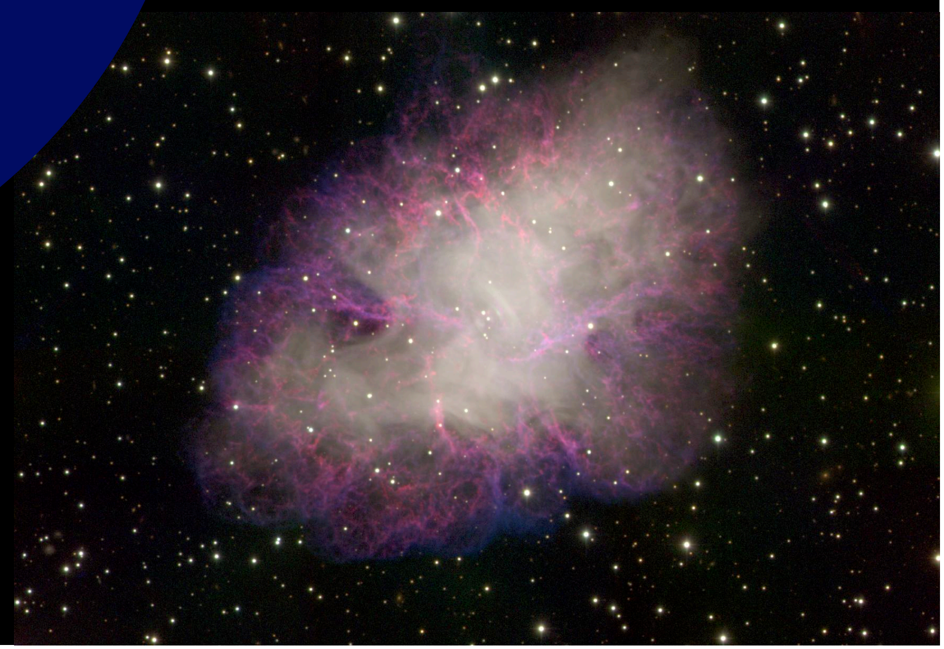



This jet is being shot out by a 6-billion-solar-mass
black hole in the galaxy Messier 87.

Two Types of Black Holes

Black holes with masses of a few Suns are well understood.

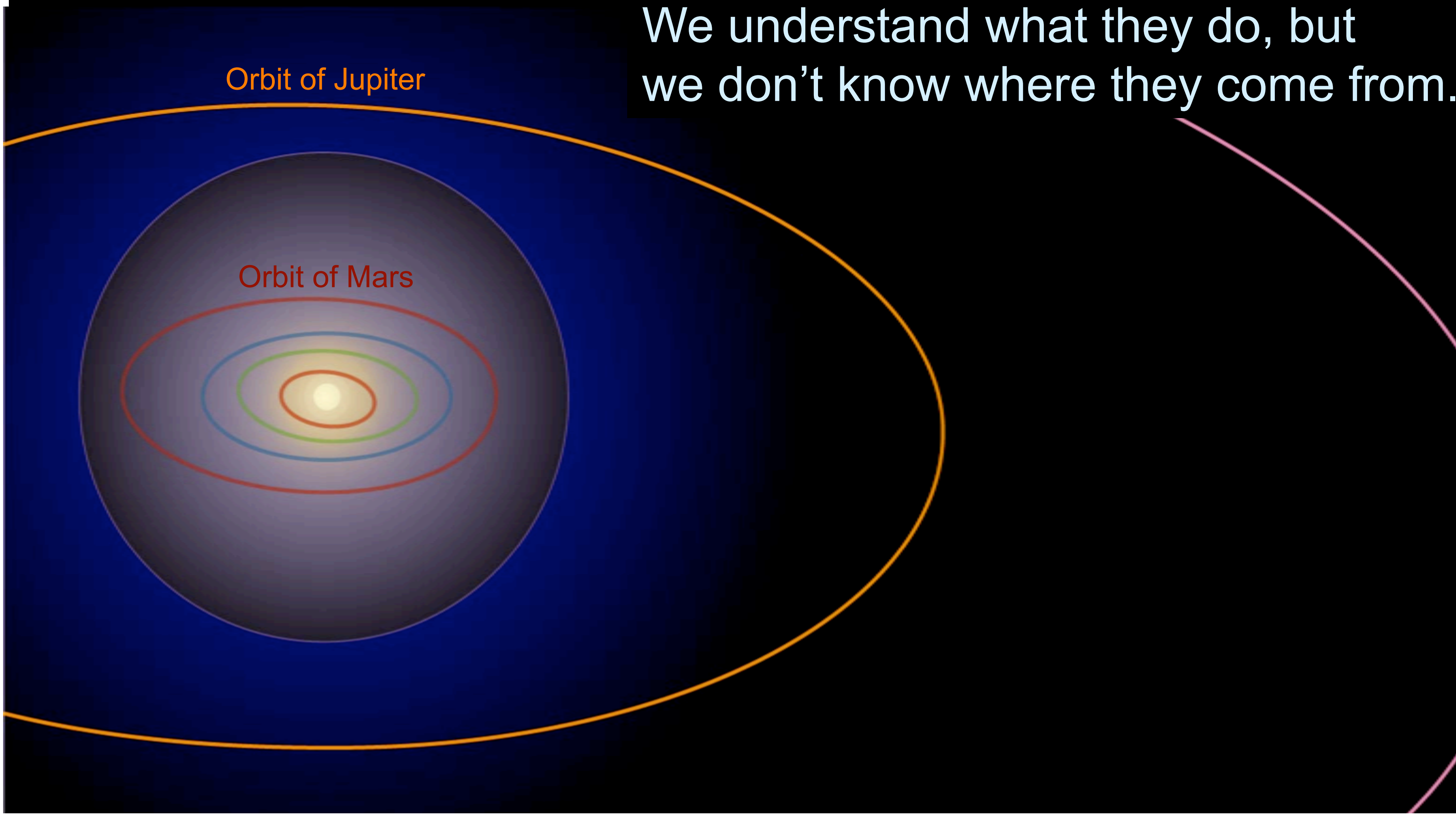
The most massive stars turn into such black holes when they die in supernova explosions.



Two Types of Black Holes

Supermassive black holes with masses of a million to a few billion Suns live in galactic centers.

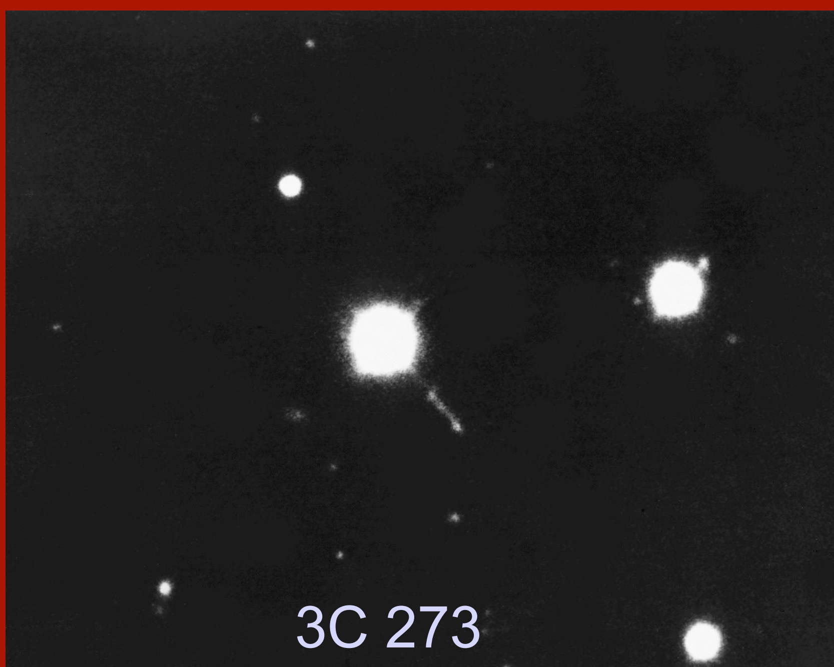
We understand what they do, but we don't know where they come from.

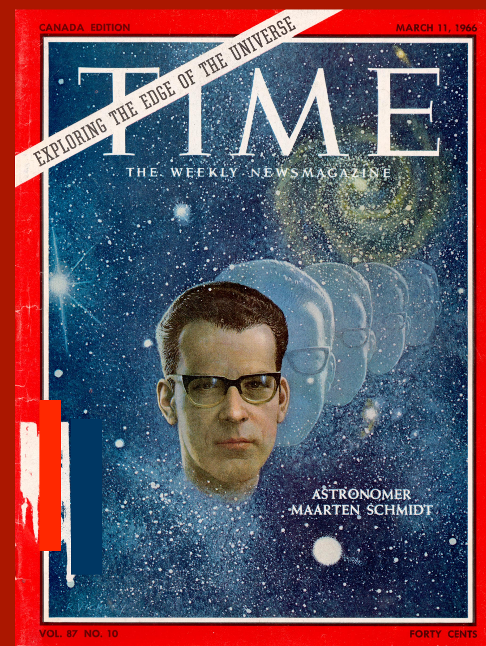


The Discovery of Quasars

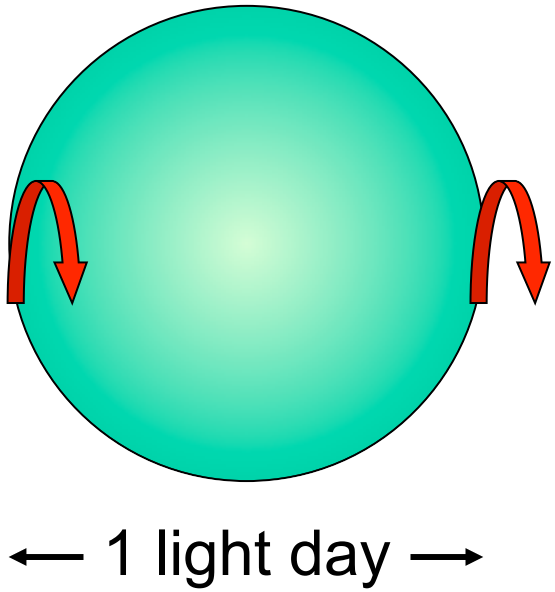
The 1963 identification by Maarten Schmidt of the radio source 3C 273 as a 13th magnitude “star” with a redshift of 16 % of the speed of light came as a huge shock. The Hubble law of the expansion of the Universe tells us that 3C 273 is one of the most distant objects known. It must be enormously luminous — more luminous than any galaxy.

The energy requirements for powering quasars were the first compelling argument for black hole engines.

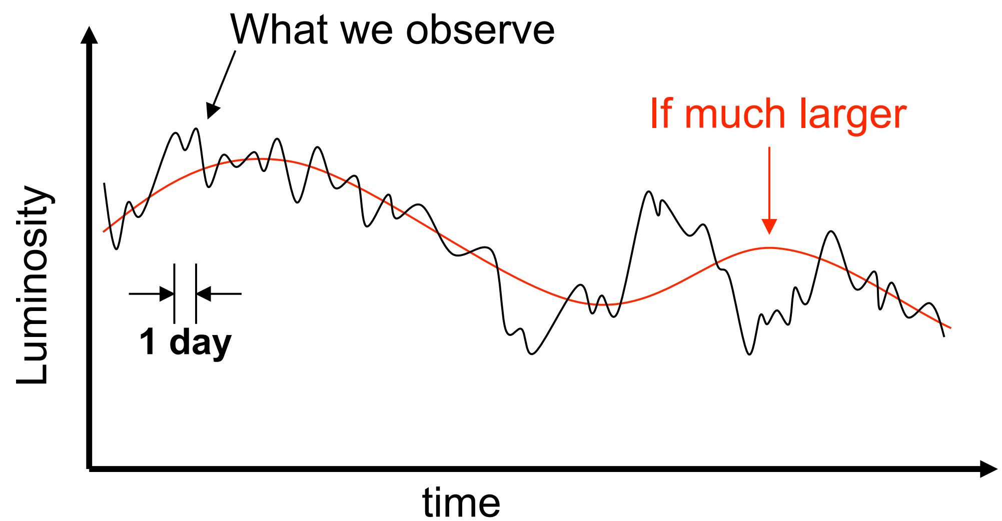




An object cannot vary much faster than the light travel time across it.

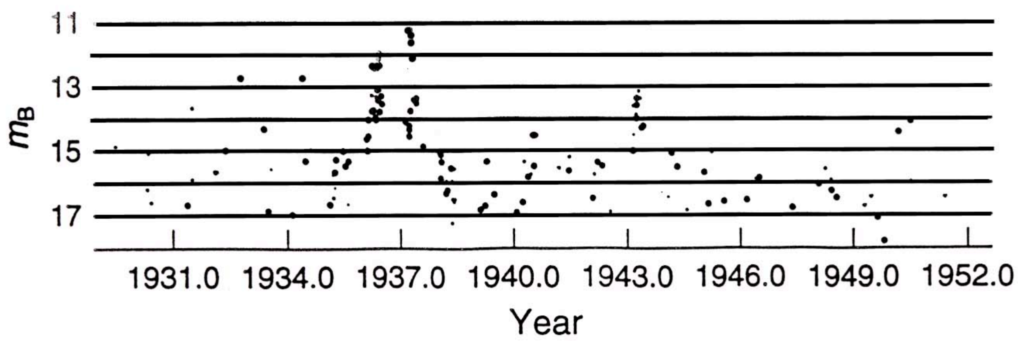


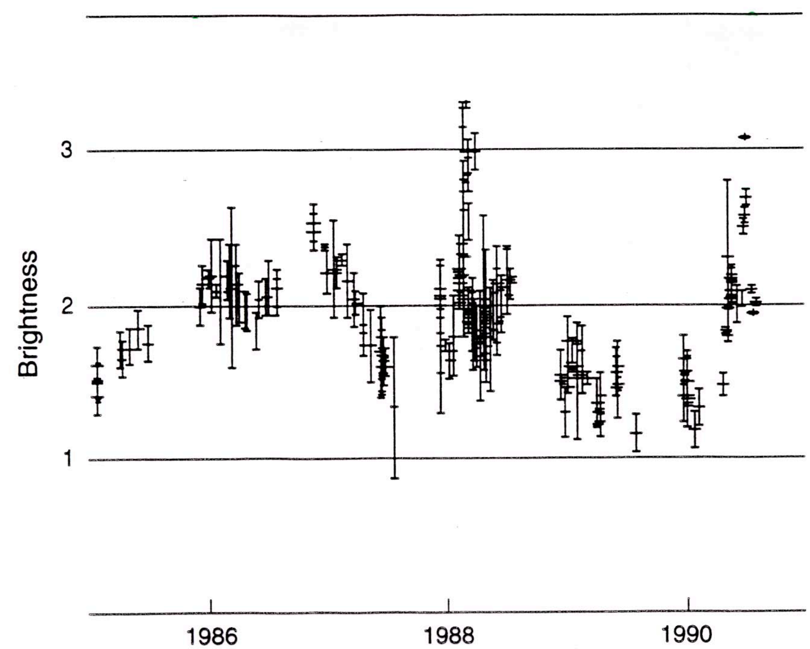
1 light day ≈ 26 billion km
≈ 2 × diameter of Solar System



Quasars Are Tiny

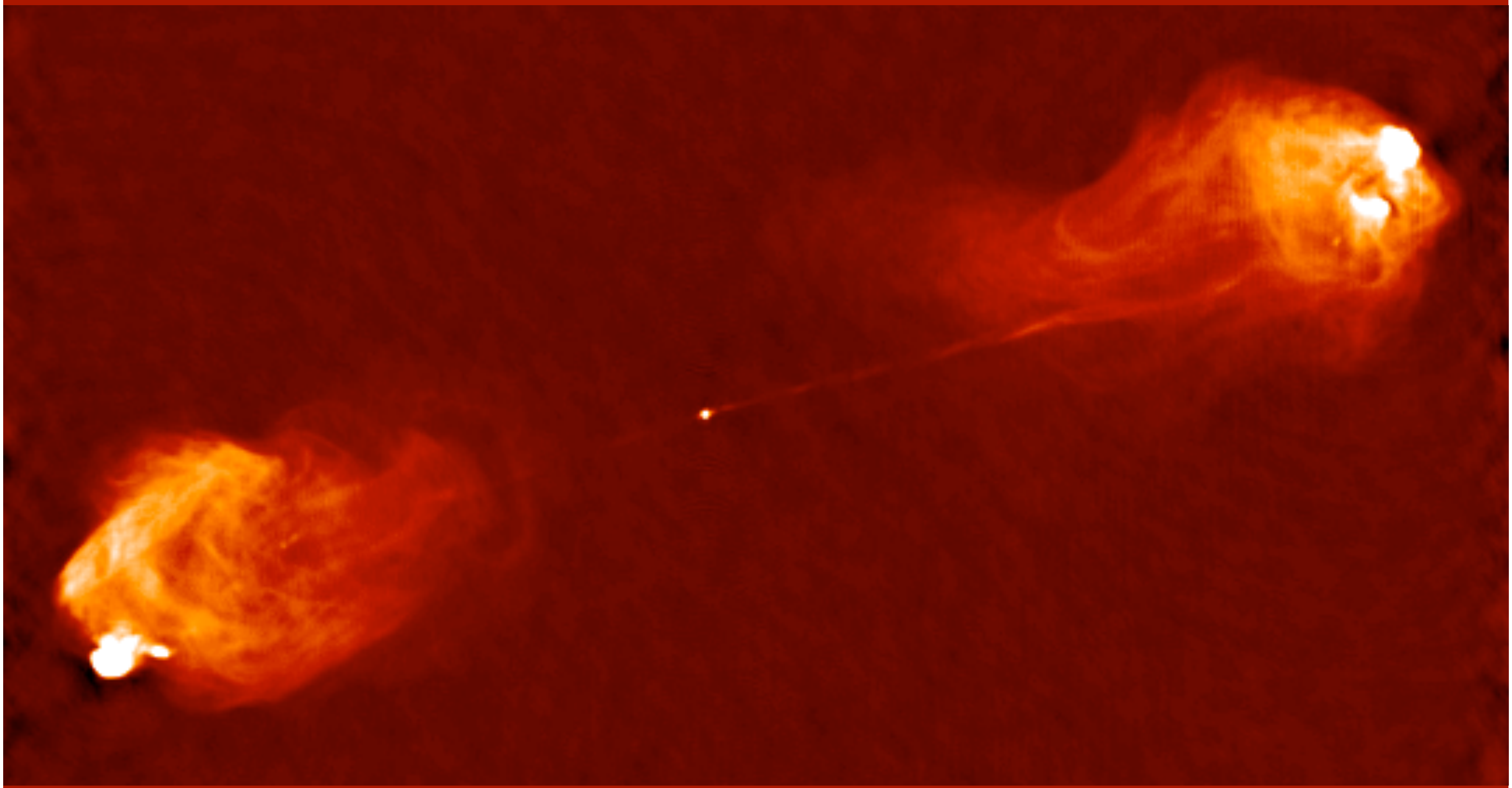
Some quasars vary in brightness in only a few days. But the luminosity cannot change by a lot in less time than it takes light to travel across the source. Therefore all the light from a typical quasar must come from a region the size of the Solar System!
How could such a huge luminosity come from such a small volume? Ideas included swarms of supernovae, supermassive stars, and supermassive black holes.
After a brief Darwinian struggle between theories, black holes won.





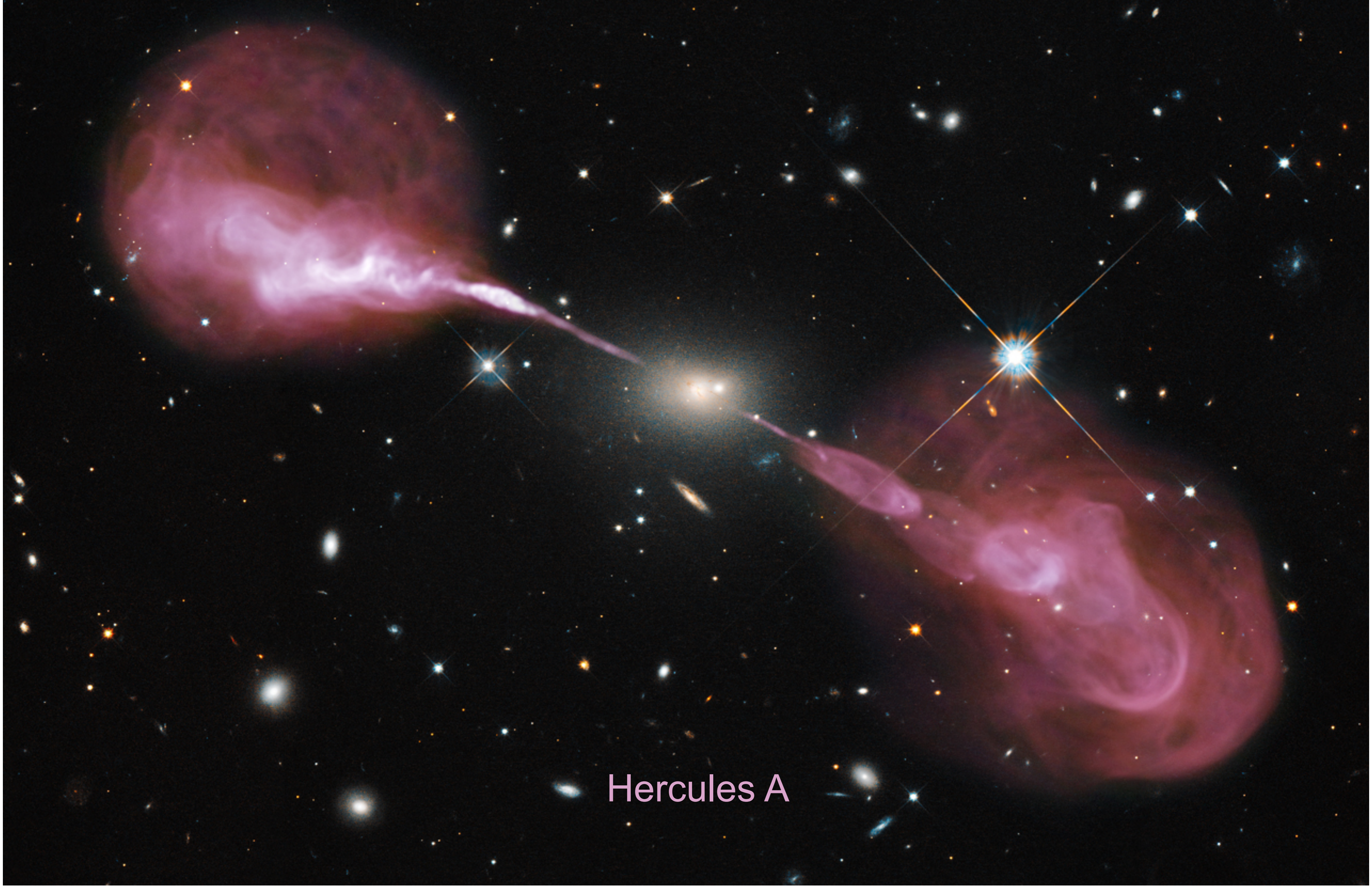
In X-rays, 3C 279 and some other quasars vary on timescales of hours!

Many radio galaxies and quasars have jets that feed lobes of radio emission



Cygnus A

Many radio galaxies and quasars have jets that feed lobes of radio emission



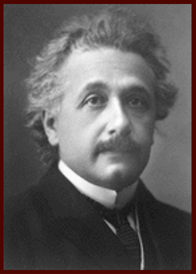
Hercules A

Supermassive Black Holes as Quasar Engines

Let's try to explain quasars using nuclear reactions like those that power stars:

- The total energy output from a quasar is at least the energy stored in its radio halo ≈ 10^{54} Joule.

  - Via $E = mc^2$, this energy "weighs" 10 million Suns.



- But nuclear reactions have an efficiency of only 1 %.
- So the waste mass left behind in powering a quasar is 10 million Suns / 1 % ≈ 1 billion Suns.
- Rapid brightness variations show that a typical quasar is no bigger than our Solar System.
- But the gravitational energy of 1 billion Suns compressed inside the Solar System ≈ 10^{55} Joule.

"Evidently, although our aim was to produce a model based on nuclear fuel, we have ended up with a model which has produced more than enough energy by gravitational contraction. The nuclear fuel has ended as an irrelevance."

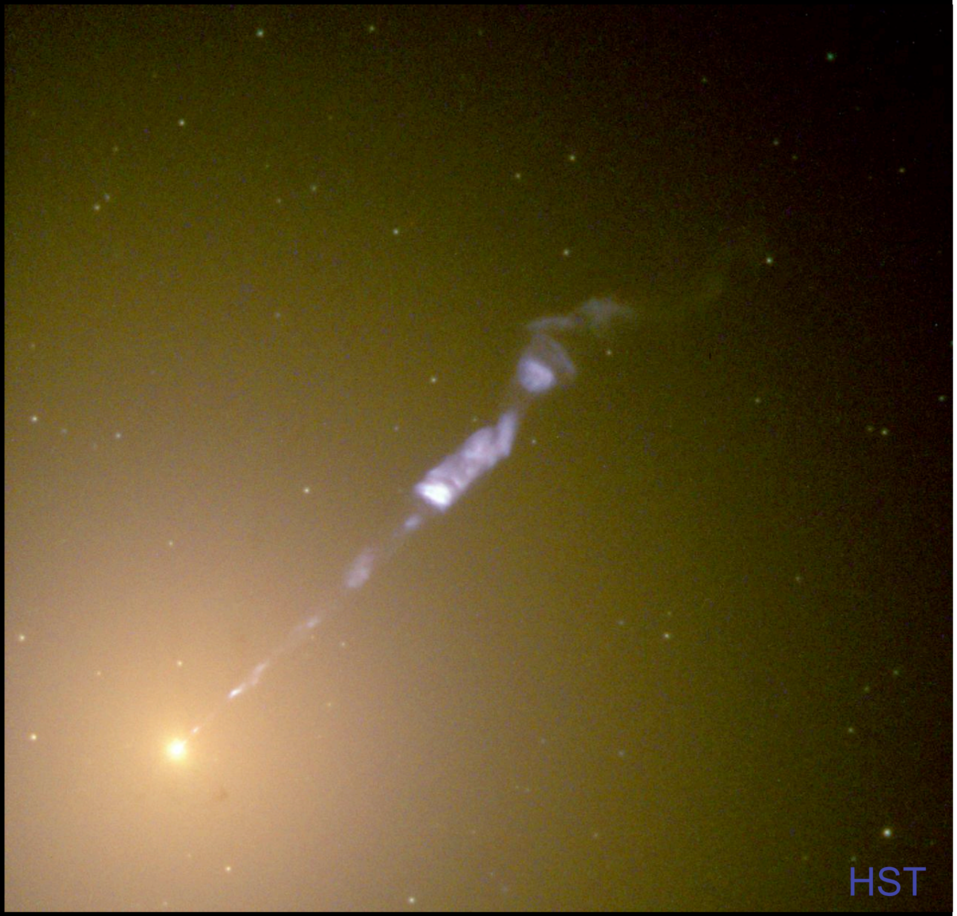
Donald Lynden-Bell (1969)

This argument convinced many people that quasar engines are supermassive black holes that swallow surrounding gas and stars.

Why Jets Imply Black Holes — 1

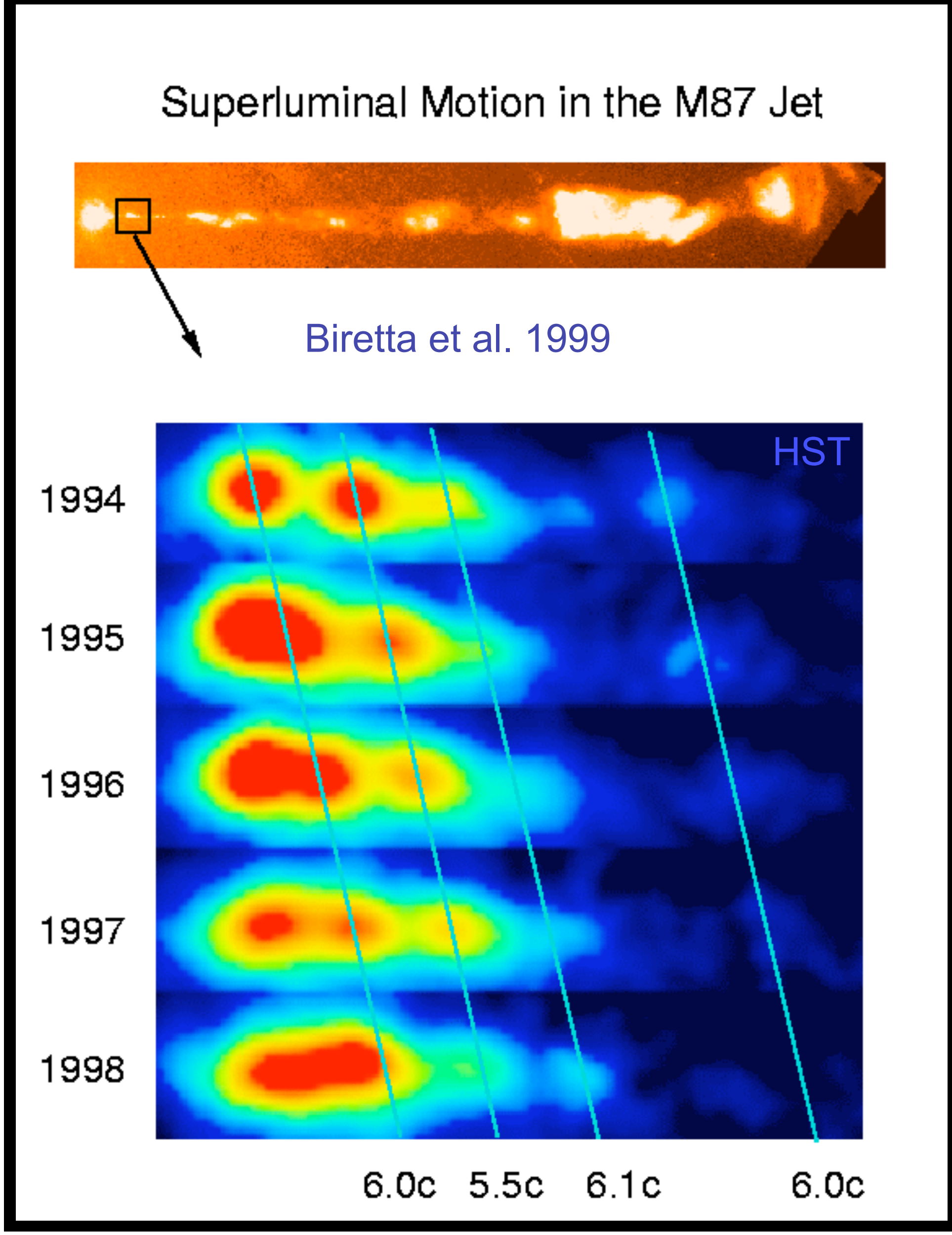
Jets remember ejection directions for a long time.
This argues against energy sources based on many objects (supernovae).
It suggests that the engines are rotating gyroscopes - rotating black holes.

Why Jets Imply Black Holes — 2



Jet knots move at almost the speed of light.
This implies that their engines are as small as black holes.
This is the cleanest evidence that quasar engines are black holes.

Why Jets Imply Black Holes — 2

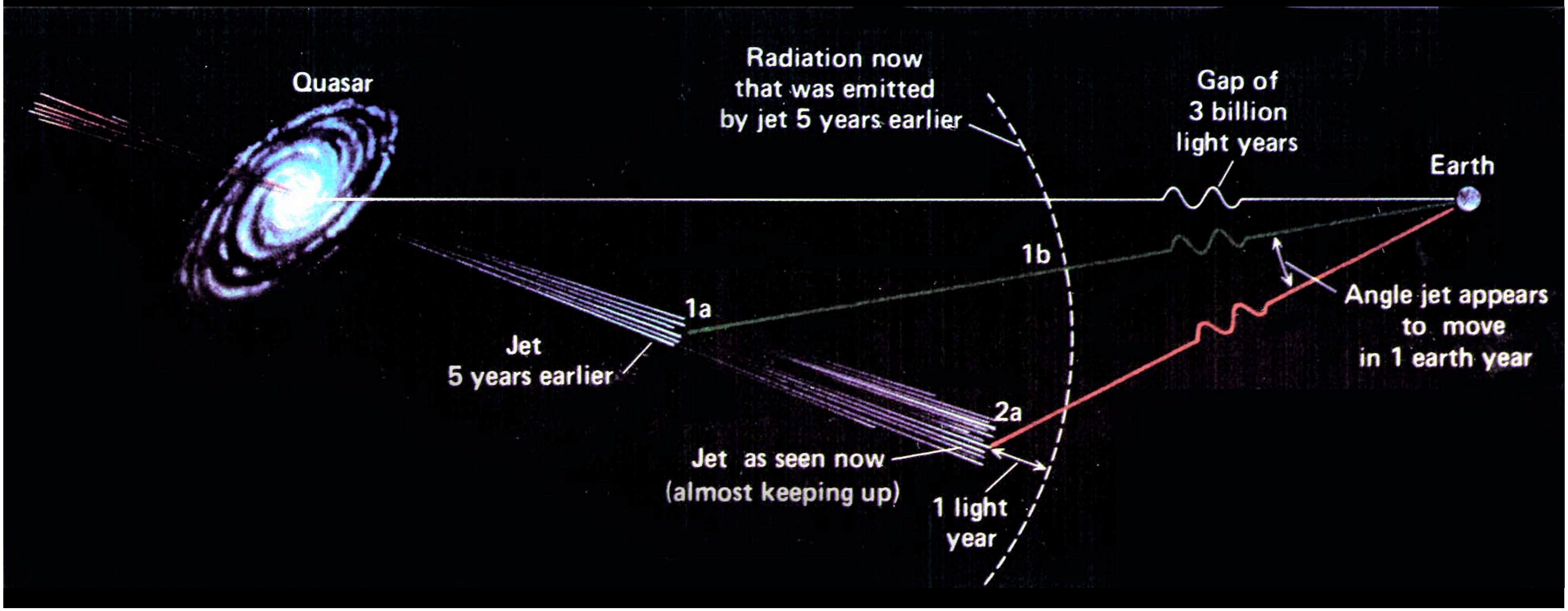


Jet knots in M 87 look like they are moving at 6 times the speed of light (24 light years in 4 years).

This means that they really move at more than 98 % of the speed of light.

Faster-than-light <u>apparent speed</u> implies that the <u>true speed</u> ≈ speed of light.

The light emitted from point 2a is only 1 year behind the light emitted 5 years earlier at point 1a. Billions of years later, when we see this light, it looks like the jet took only 1 year to move a distance that really required 5 years. We think that the jet is moving faster than it really is moving. For true speeds close to the speed of light, the jet looks like it is moving faster than the speed of light.



Supermassive Black Holes as Quasar Engines

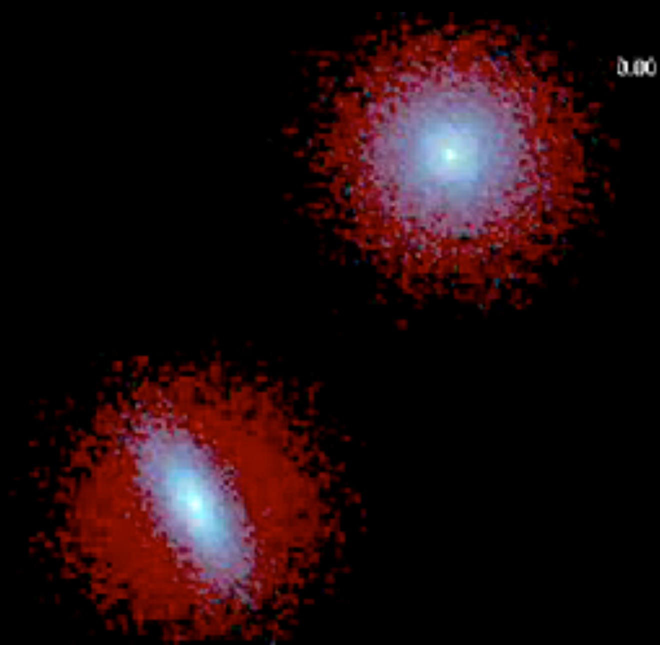
The huge luminosities and tiny sizes of quasars can be understood if they are powered by black holes with masses of a million to a few billion Suns.

Gas near the black hole settles into a hot disk, releasing gravitational energy as it spirals into the hole.

Magnetic fields eject jets along the black hole rotation axis.

A black hole lights up as a quasar when it is fed gas and stars.

How do you feed a quasar ?



One answer:
Galaxy collisions and mergers dump gas into the center.

PROBLEM

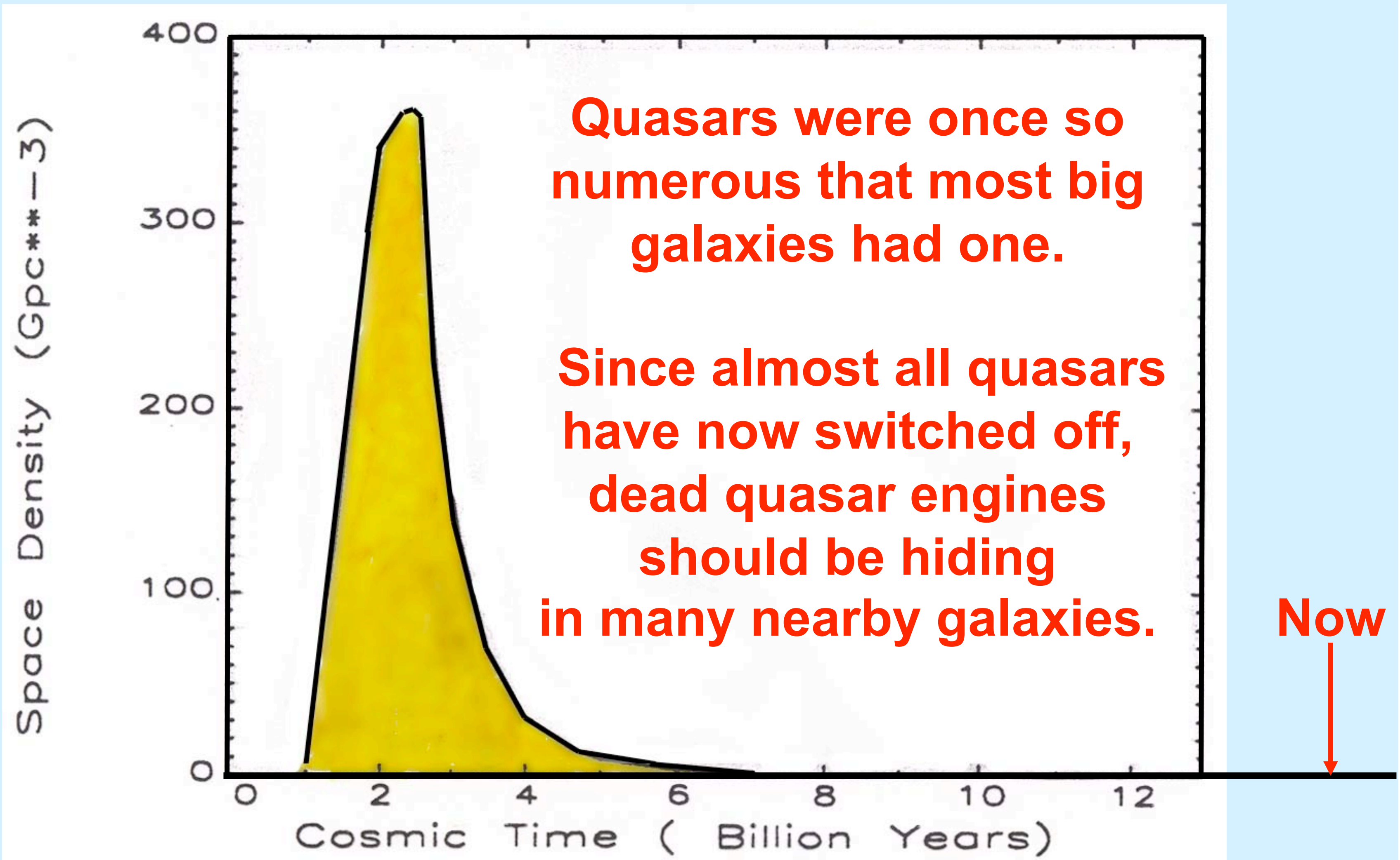
People believe the black hole picture.
They have done an enormous amount of work based on it.

But for many years there was no direct evidence that supermassive black holes exist.

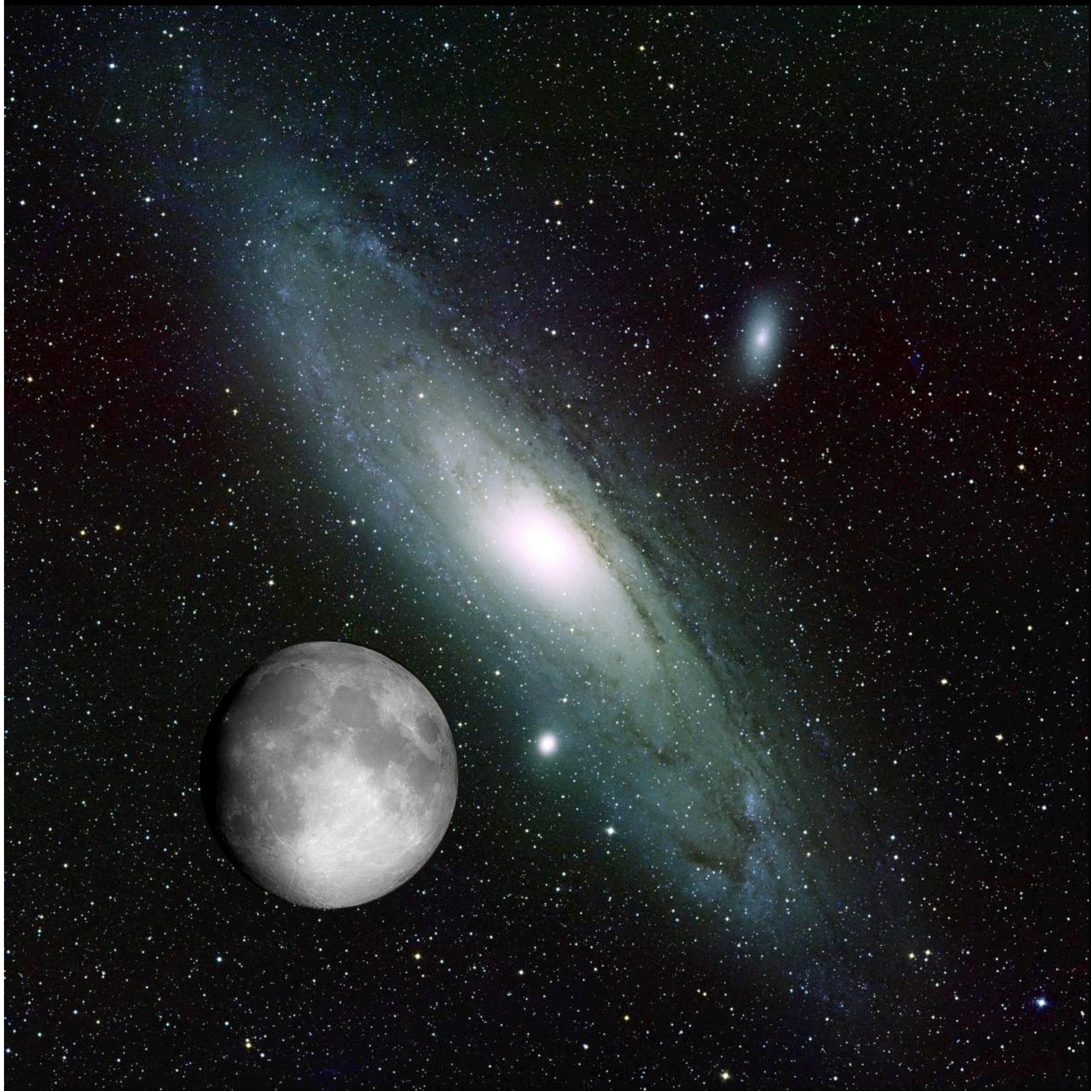
So the search for supermassive black holes became a very hot subject.

Danger: It is easy to believe that we have proved what we expect to find. So the standard of proof is very high.

The Quasar Era Was More Than 10 Billion Years Ago



The Search For Supermassive Black Holes



The first convincing dynamical evidence for a supermassive black hole was found in 1988 in the Andromeda Galaxy by Alan Dressler & Douglas Richstone using the Palomar 200" telescope and by John Kormendy using the Canada-France-Hawaii Telescope.


Canada-France-Hawaii-Telescope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5
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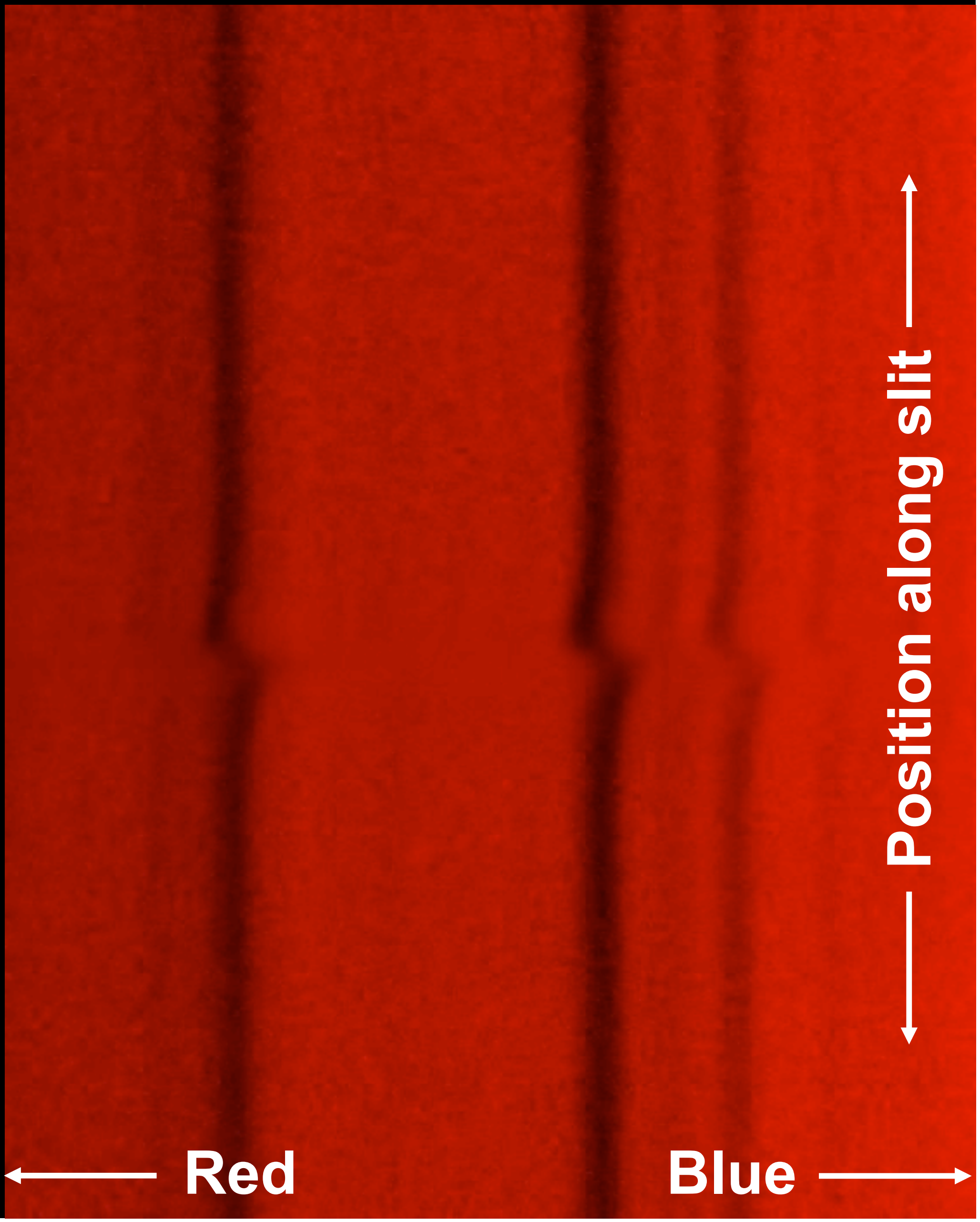
M 31: Black Hole Mass = 215 Million Suns

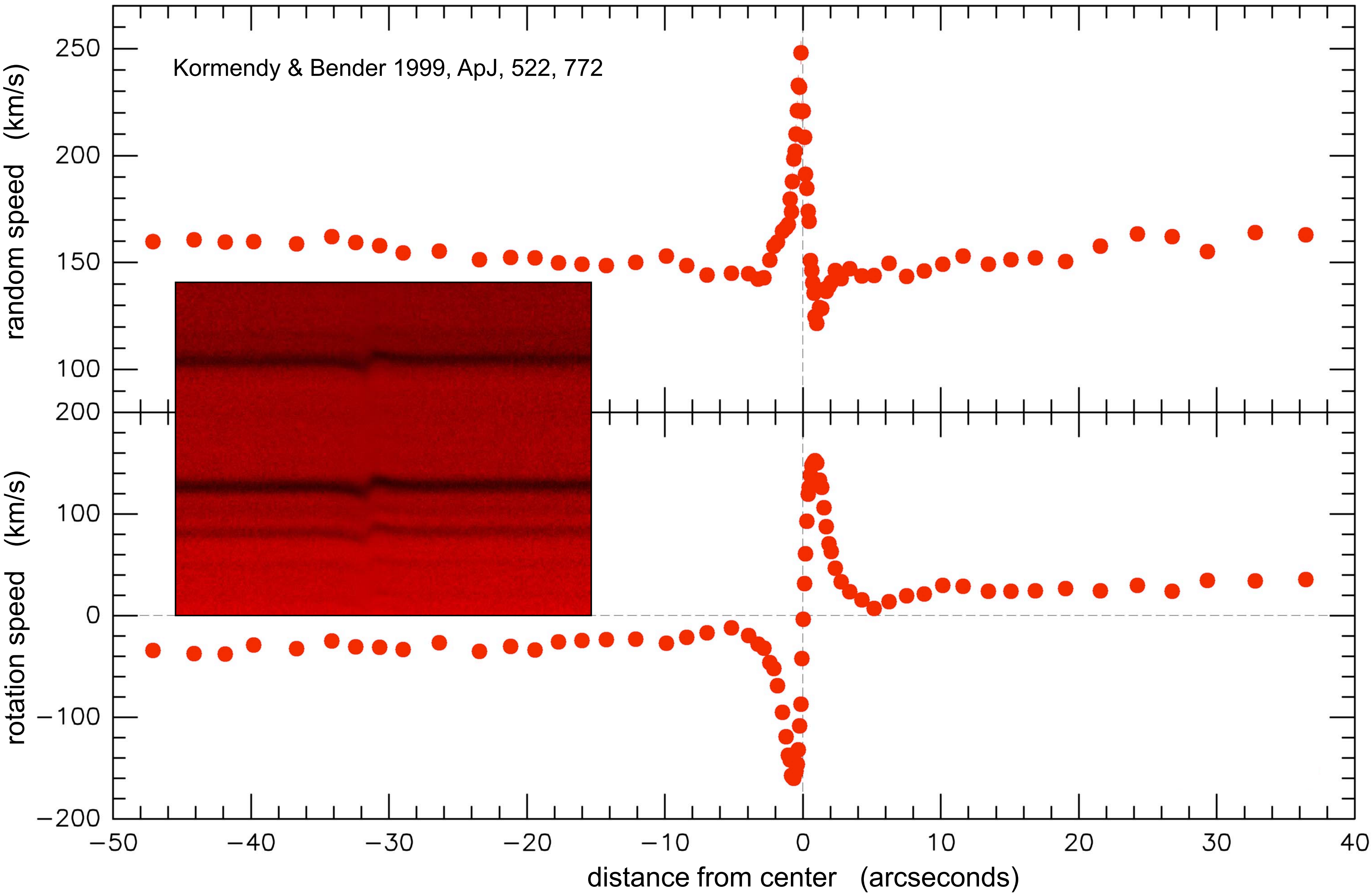
M 31 on spectrograph slit

Spectrum of M 31

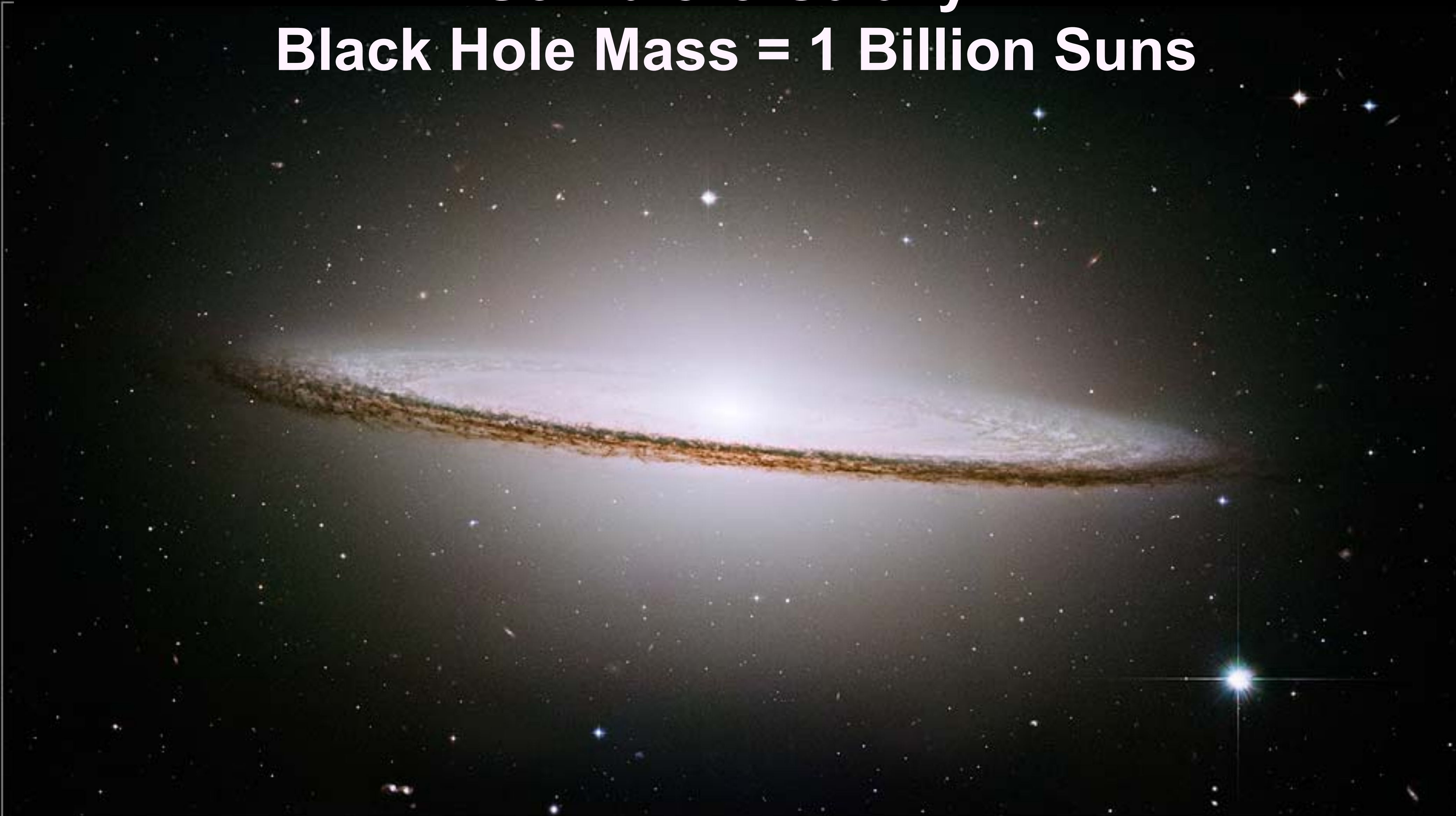
The brightness variation of the galaxy has been divided out.
The zigzag in the lines is the signature of the rapidly rotating nucleus and central black hole.



M 31: Black Hole Mass = 215 Million Suns



Sombrero Galaxy:
Black Hole Mass = 1 Billion Suns



Sombrero Galaxy:
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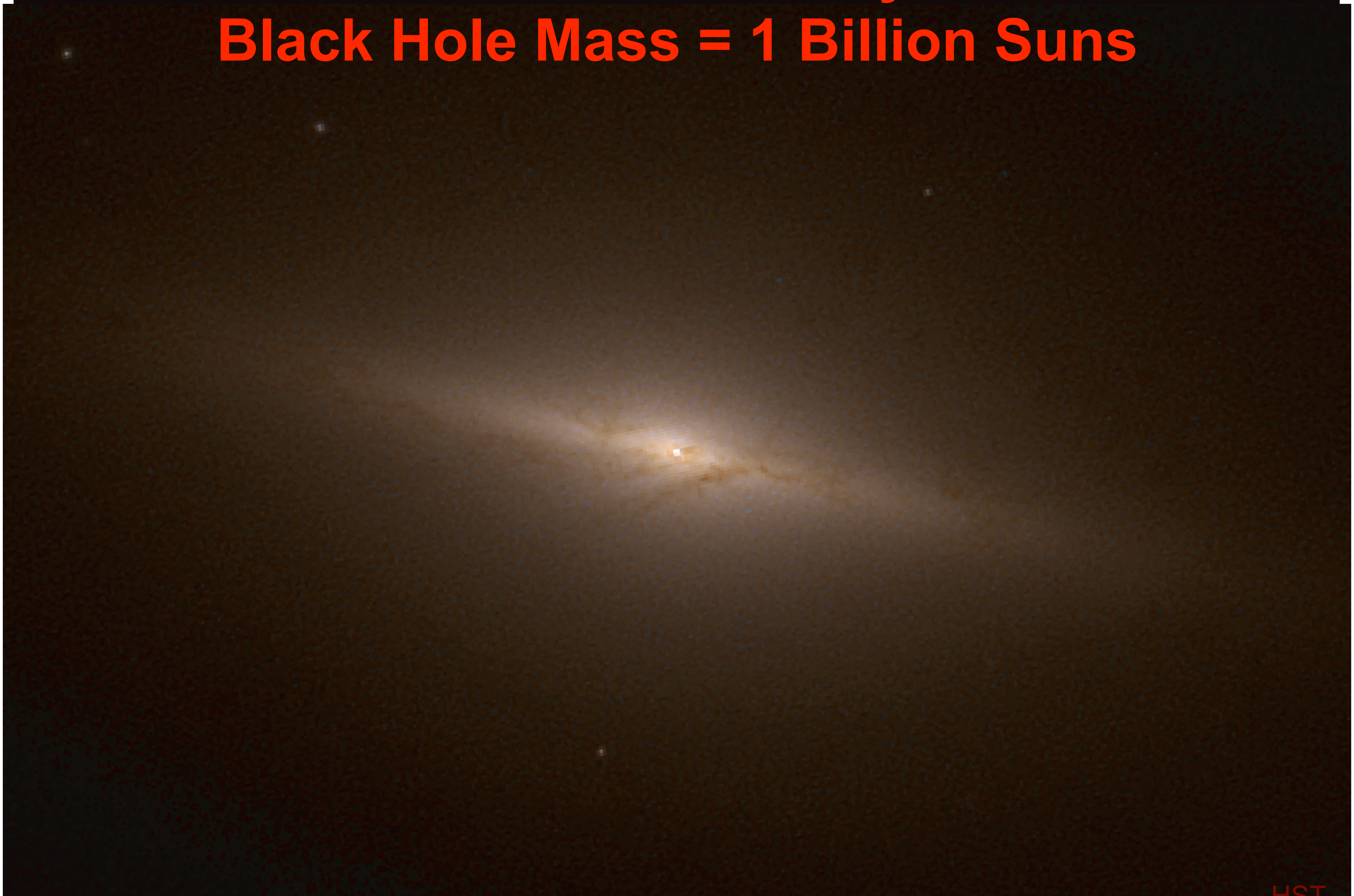

Sombrero Galaxy:
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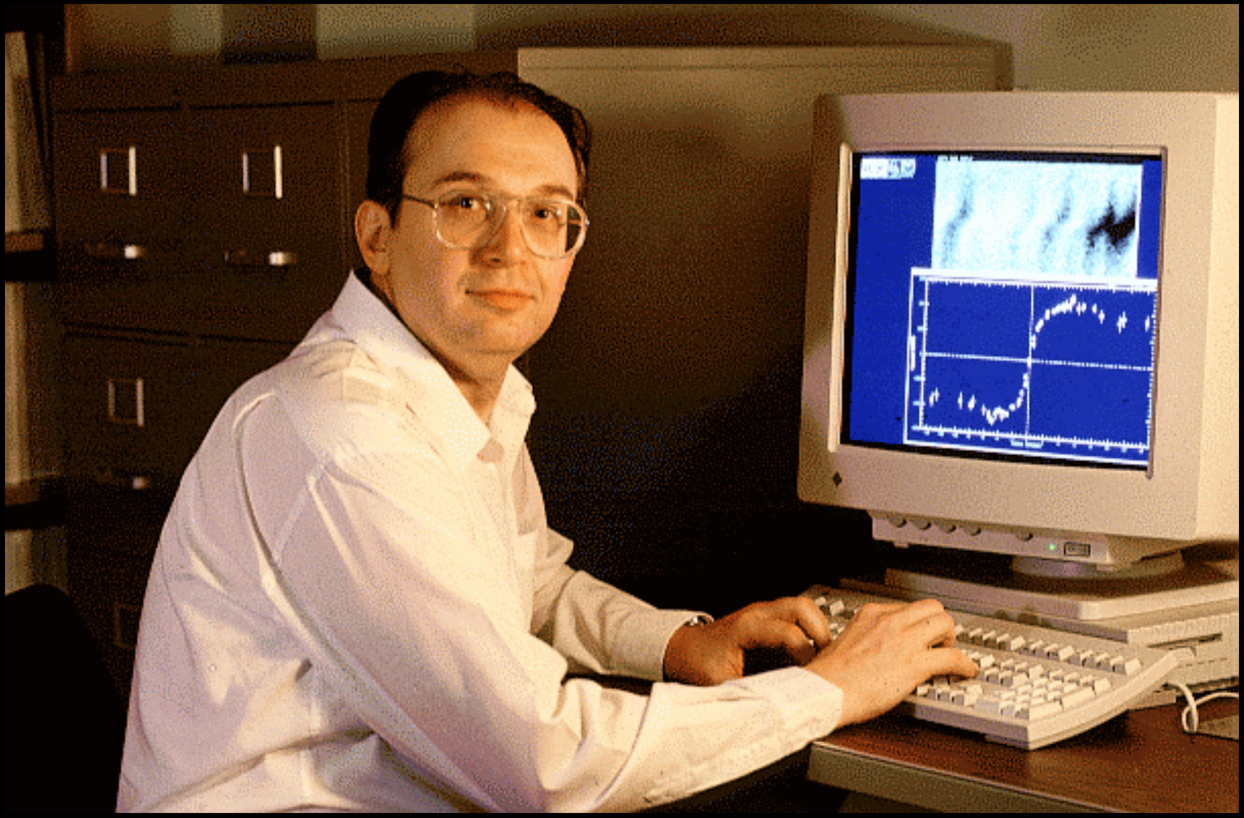
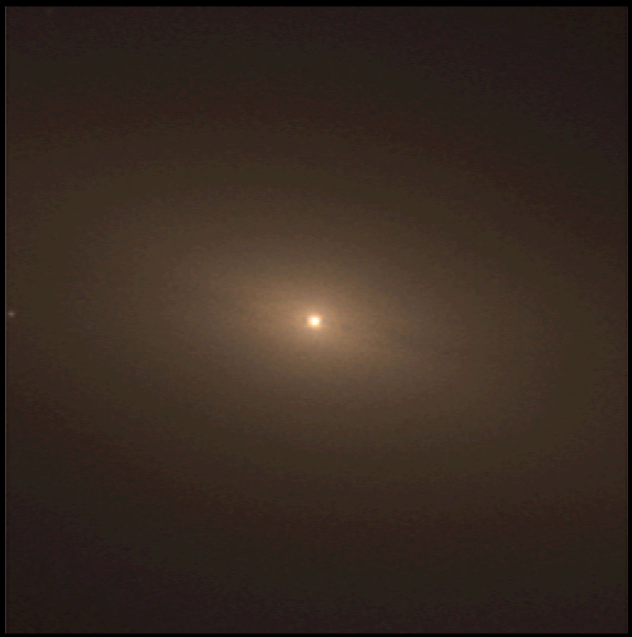


NGC 3115: Black Hole Mass = 1 Billion Suns

NGC 3115: Black Hole Mass = 1 Billion Suns

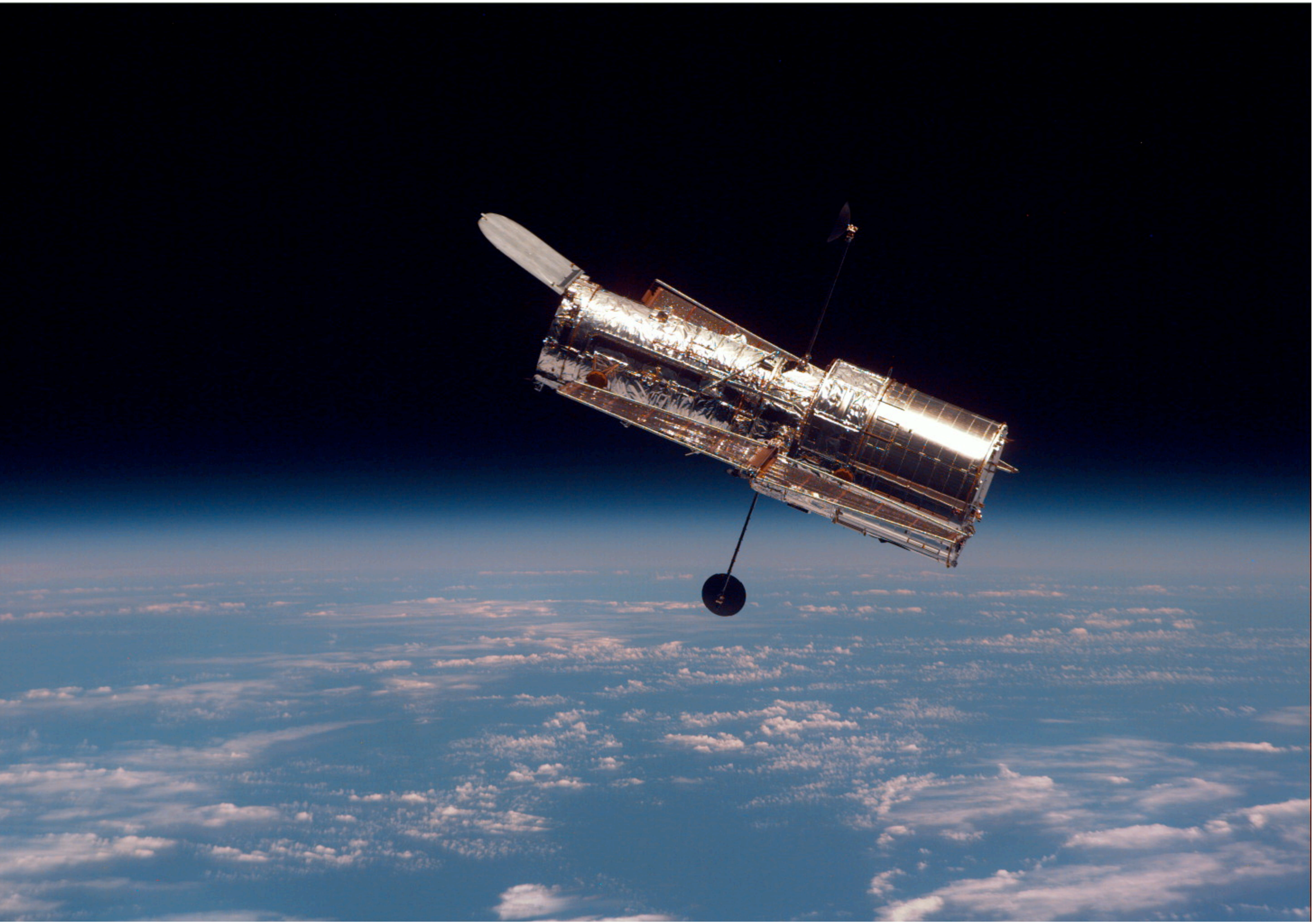


NGC 3115 has a bright central cusp of stars like we expect around a black hole.

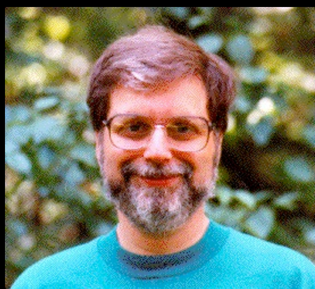
Stars in this nuclear cluster move at about 1000 km/s.

But: if the nucleus contained only stars and not a black hole, then its escape velocity would be 350 km/s. Stars moving at 1000 km/s would fly away.

This shows that the nucleus contains a dark object of mass 1 billion Suns.

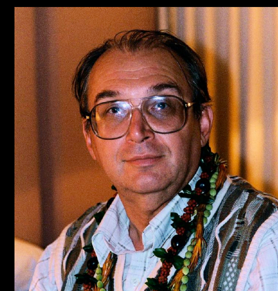


The Nuker Team


Doug Richstone


Sandra Faber


Karl Gebhardt


John Kormendy

Additional Nukers
Gary Bower
Carl Grillmair
Luis Ho
John Magorrian
Jason Pinkney
Kayhan Gültekin


Alan Dressler


Scott Tremaine


Ralf Bender


Tod Lauer


Alex Filippenko


Richard Green

Thanks Also To STIS Team Members
Gary Bower
Mary Beth Kaiser
Charlie Nelson

BH Census (early 2000s)

Galaxy	Distance (million ly)	Black Hole Mass (million Suns)
Milky Way	0.028	4
M 31	2.3	100
M 32	2.3	3
M 81	12.7	68
NGC 3115	32	1000
NGC 4594	32	1000
NGC 3379	34	100
NGC 3377	37	100
NGC 1023	37	39
NGC 3384	38	14
NGC 4697	38	120
NGC 7457	43	3
NGC 4564	49	57
NGC 4342	50	300
NGC 4486B	50	500
NGC 4742	51	14
NGC 4473	51	100
NGC 4649	55	2000
NGC 2778	75	20
NGC 3608	75	110
NGC 7332	75	15
NGC 821	78	50
NGC 4291	85	250
NGC 5845	85	320

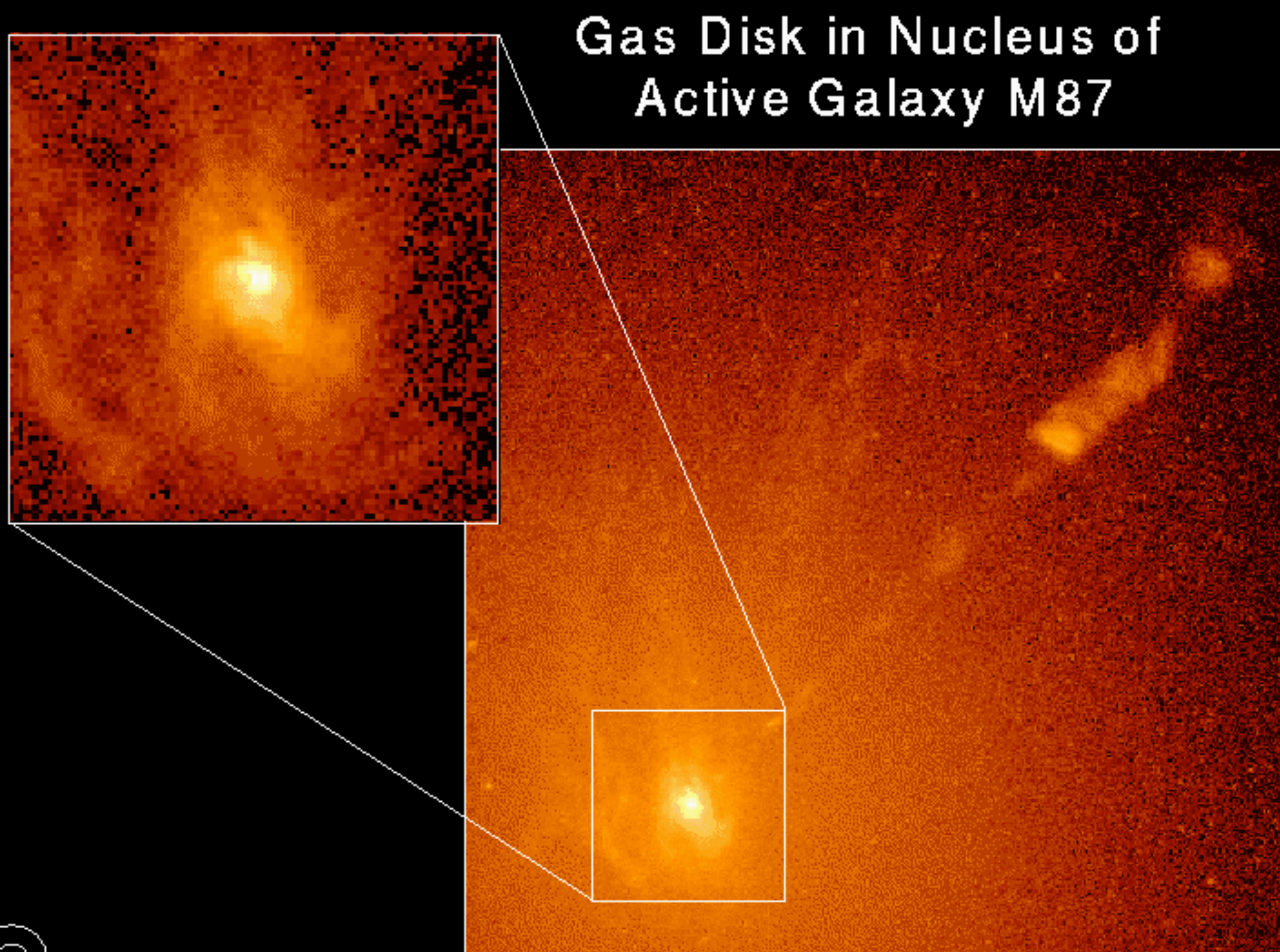
Galaxy	Distance (million ly)	Black Hole Mass (million Suns)
NGC 5128	6.5	200
NGC 2787	42	71
M 87	52	2500
NGC 4350	55	600
NGC 4459	55	73
NGC 4596	55	78
NGC 4374	60	1000
IC 1459	95	200
NGC 4261	104	540
NGC 7052	192	330
NGC 6251	345	600
NGC 4945	12.1	1
NGC 4258	23	42
NGC 1068	49	17

Kormendy et al.
Gebhardt et nuk.
STIS GTO Team

Some measurements of BH masses are corrected in Kormendy & Ho 2013.

We now have discovered 85 BHs via spatially resolved stellar and gas motions (Kormendy & Ho 2013, ARA&A, 51, 511)

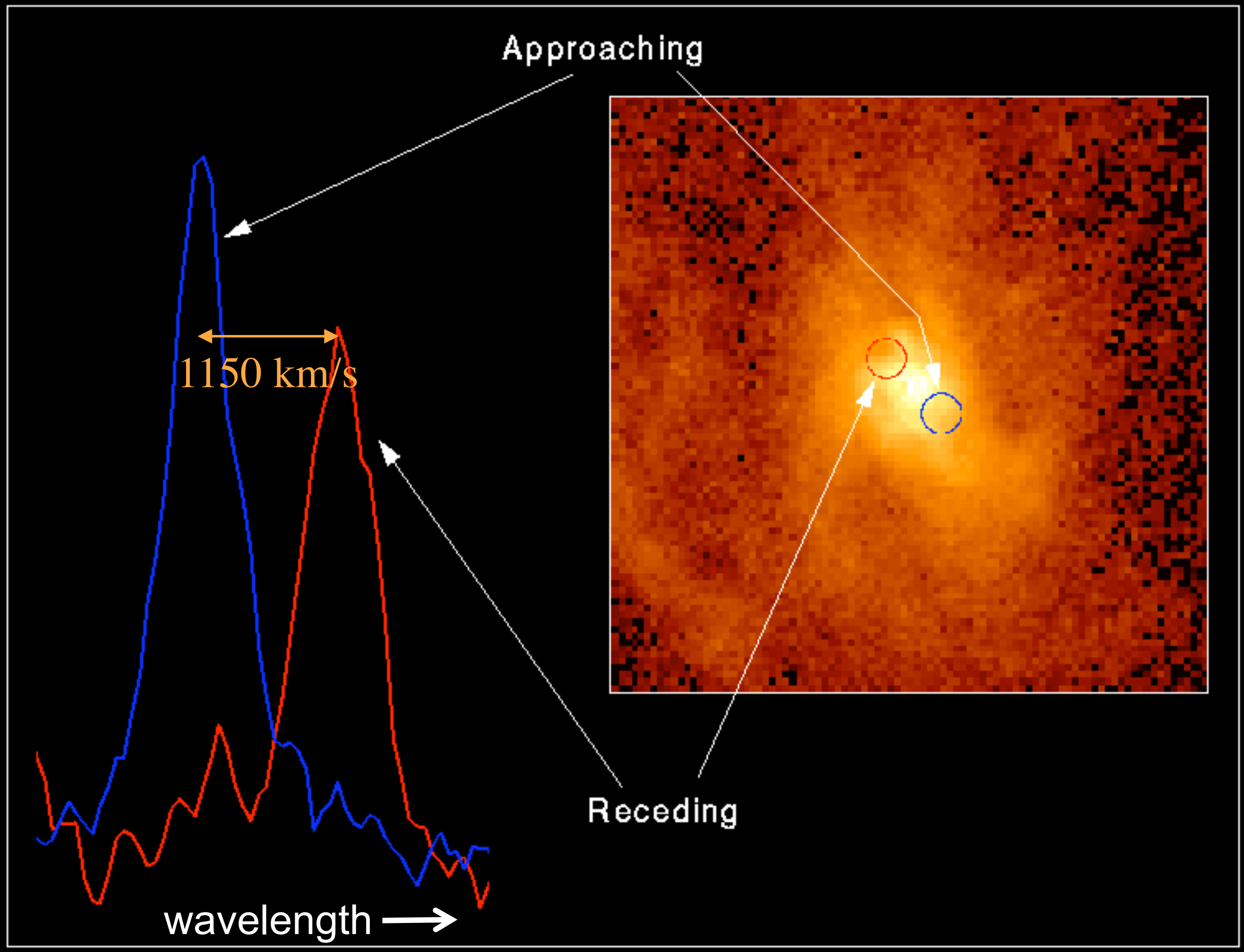
M 87: Black Hole Mass = 6.2 Billion Suns



M 87 was observed with Hubble by Harms, Ford, and collaborators.

SPACE TELESCOPE SCIENCE INSTITUTE

Spectrum of Gas Disk in Active Galaxy M87



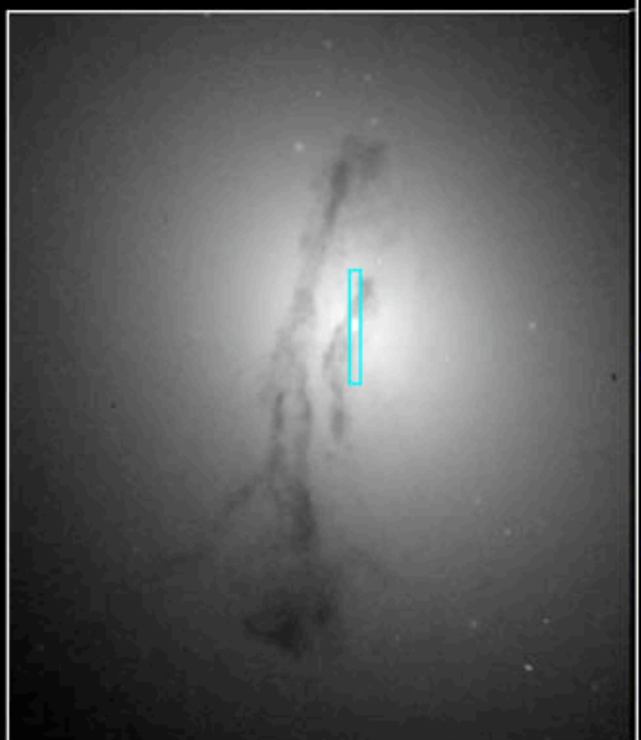
From the difference in Doppler shifts seen on opposite sides of the center, the disk rotates at almost 600 km/s.

This + motions of the stars implies a black hole of mass 6.2 billion Suns.

M 84: Black Hole Mass = 1 Billion Suns

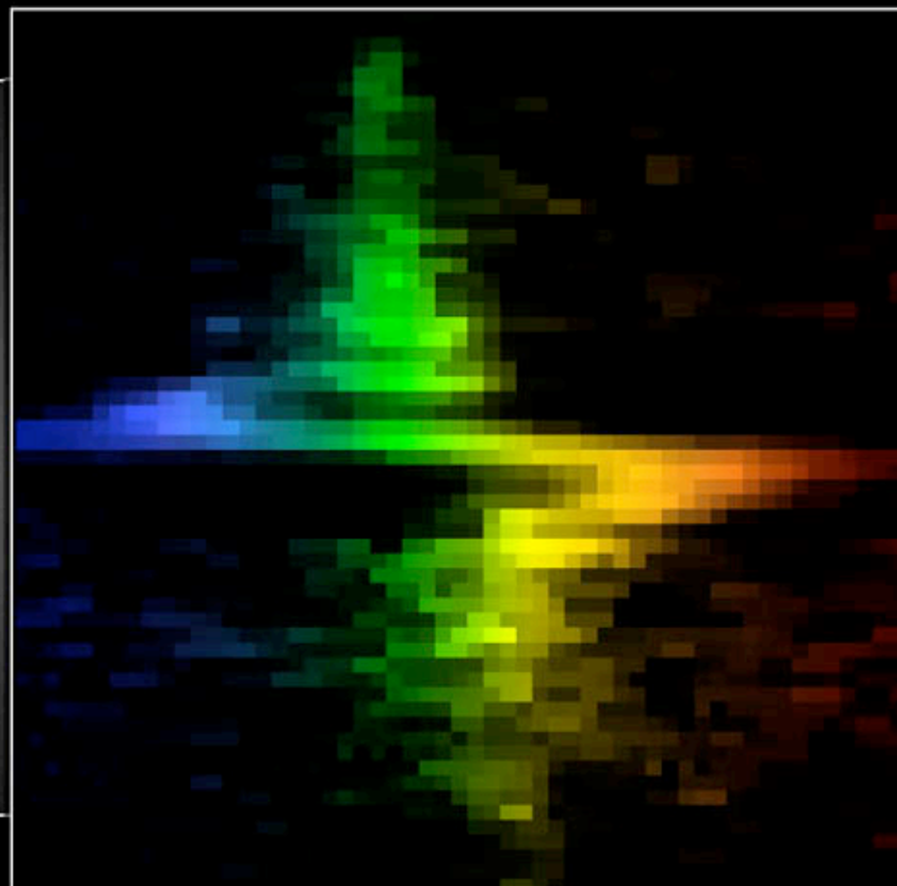
The Space Telescope Imaging Spectrograph provided spectacular data on black holes.

Galaxy M84 Nucleus



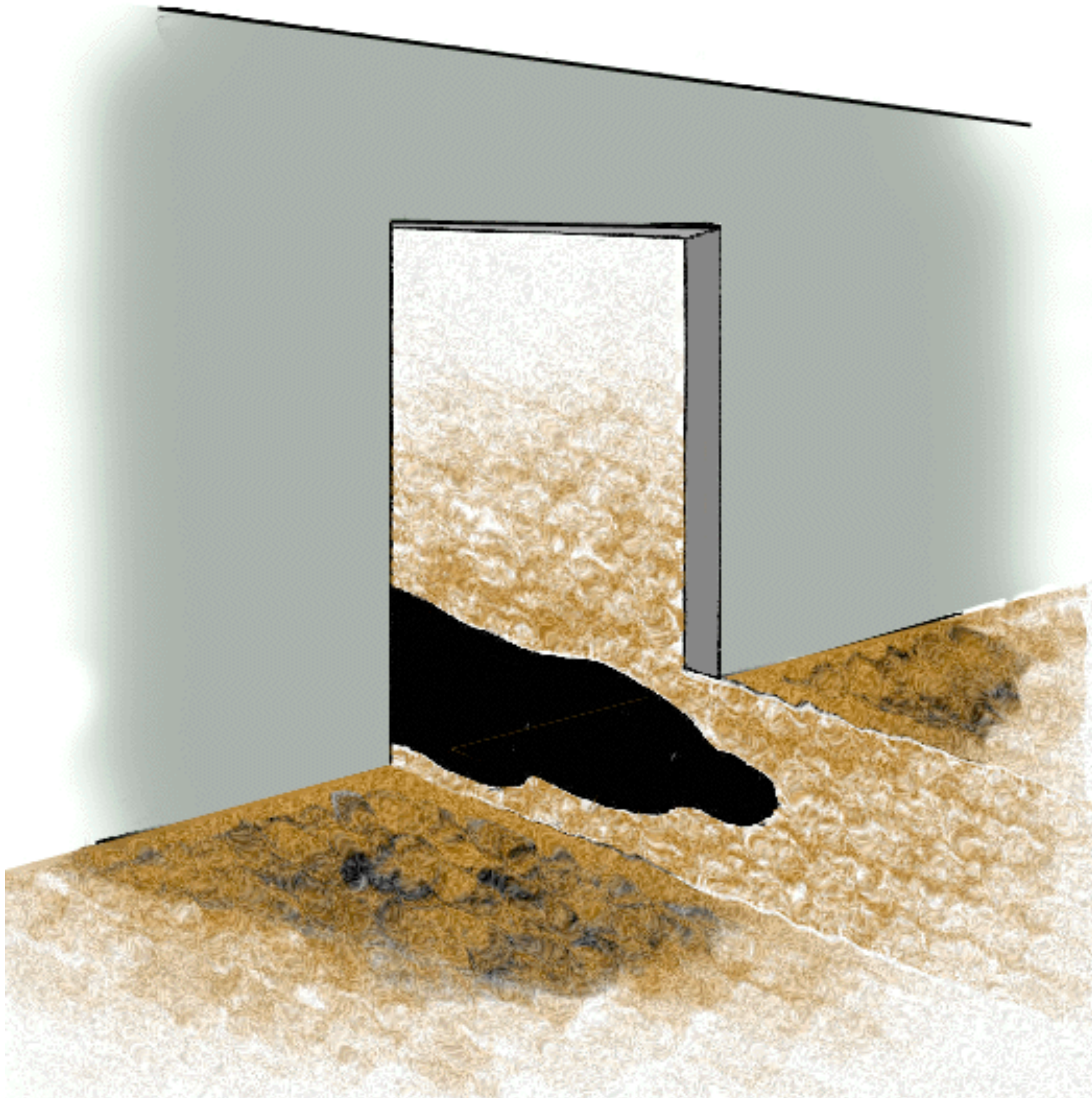
WFPC2

Hubble Space Telescope



Bower et al. 1998, ApJ, 492, L111

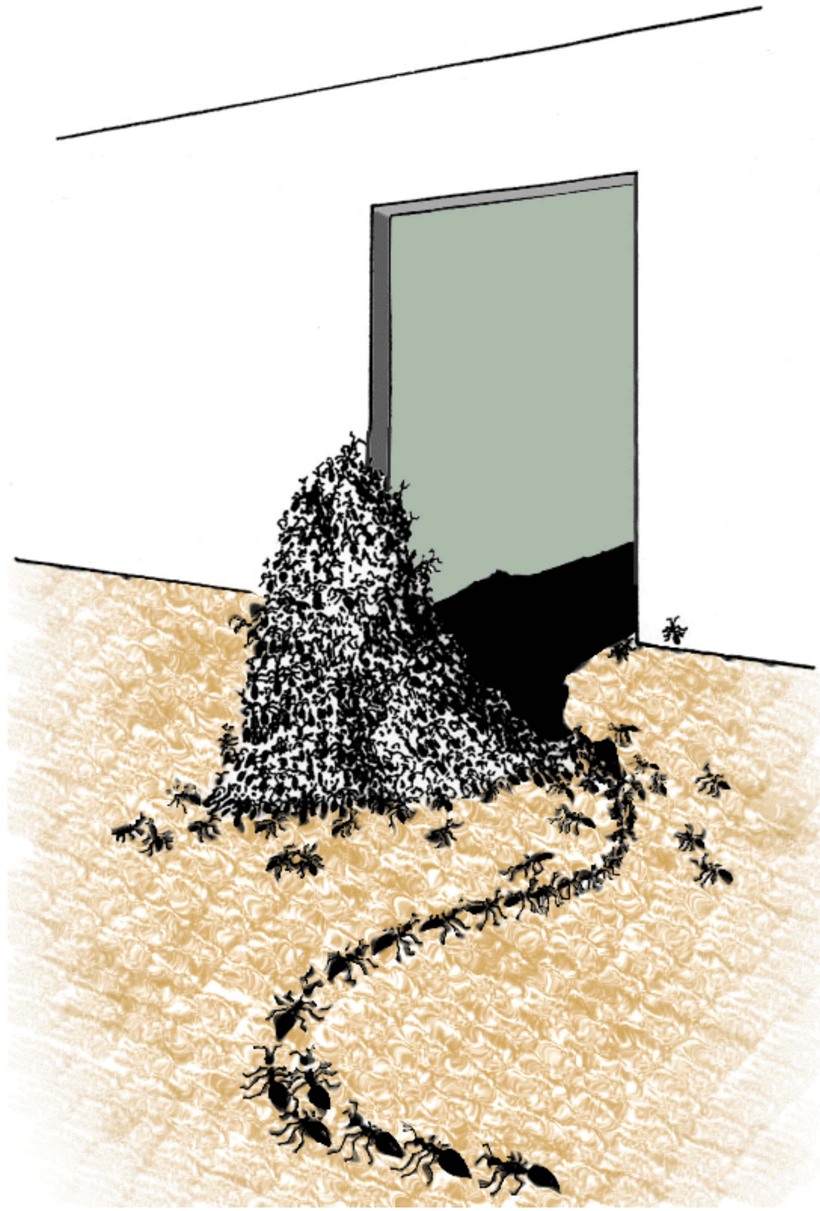
We observe only a shadow of the dark object — its gravitational effect on ordinary stars and gas.



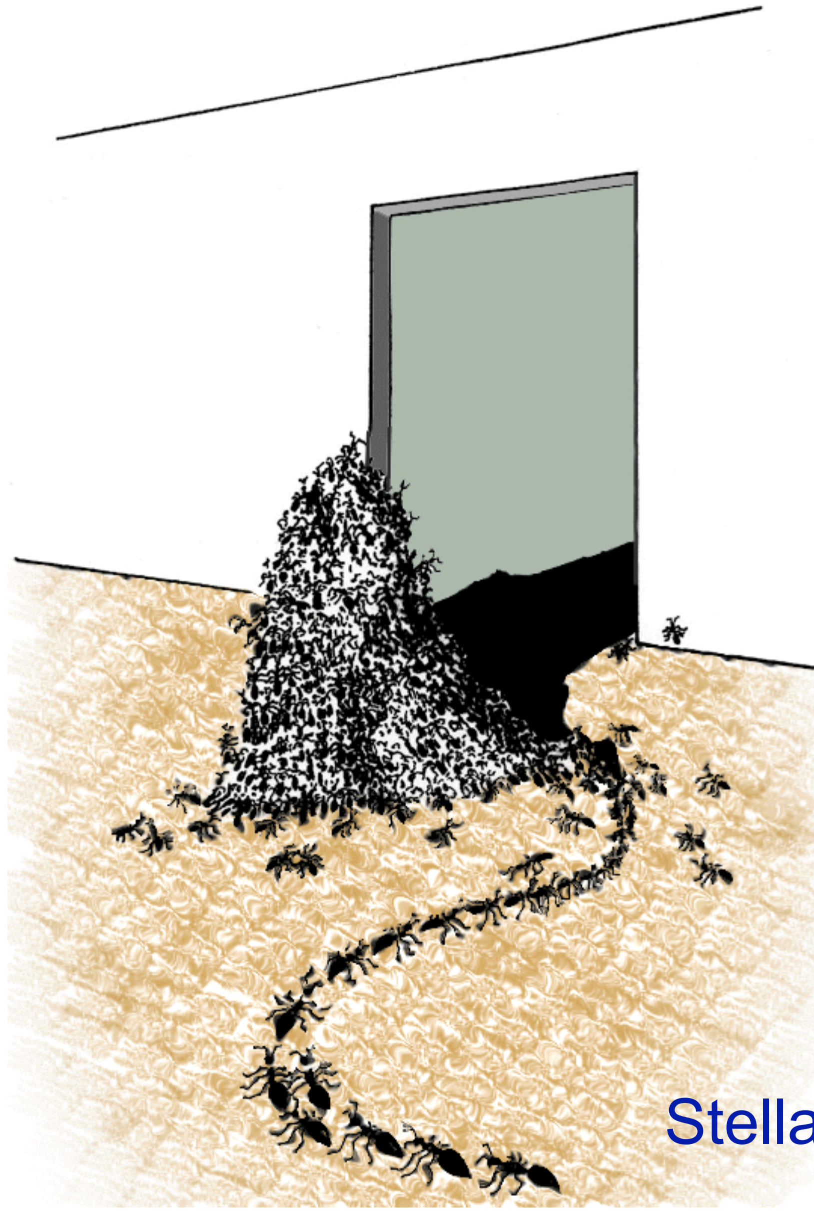
Are we detecting one object?

Or two?

Or many?



Could we be detecting a cluster of dark stars?

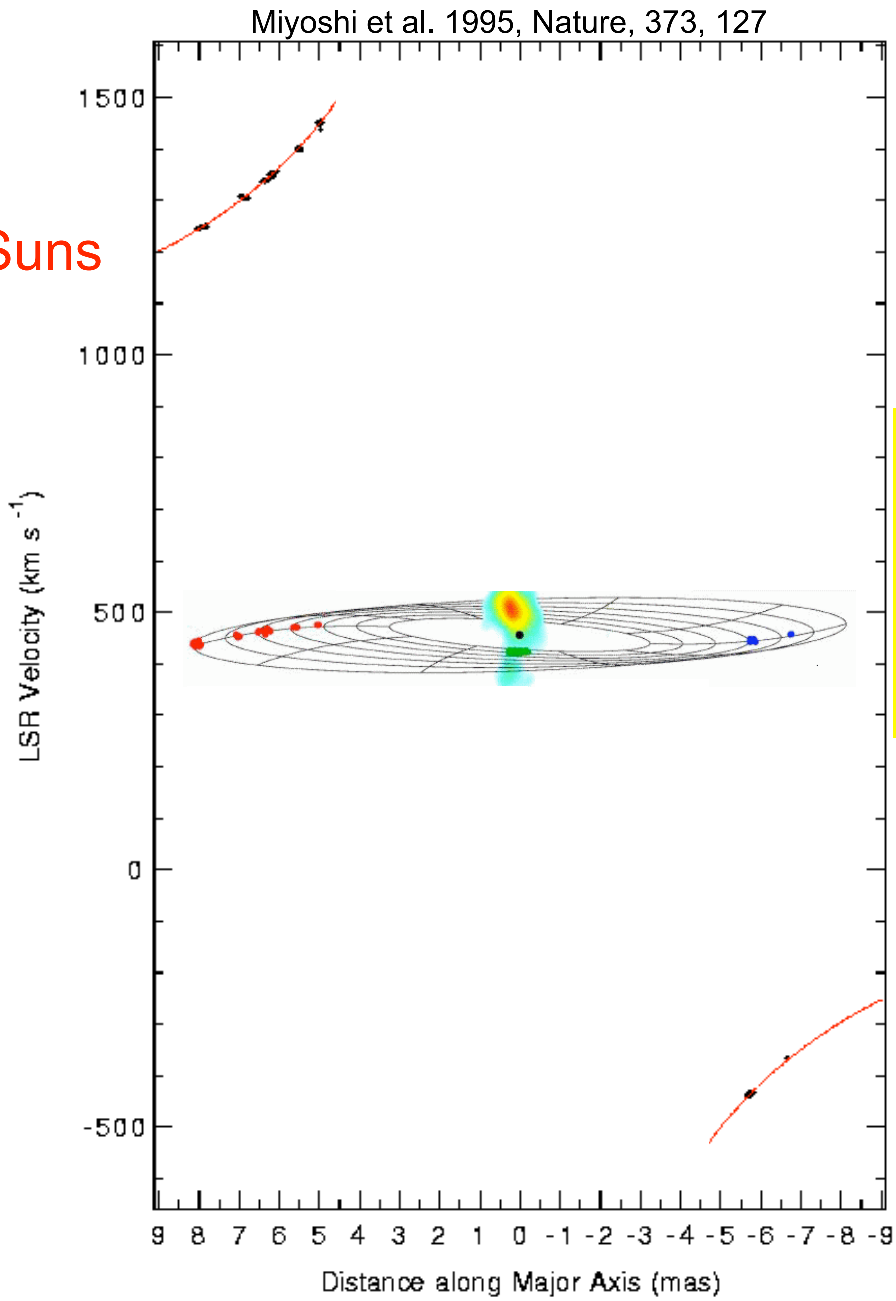


Possibilities

Brown dwarfs
White dwarfs
Neutron stars
Stellar-mass black holes

NGC 4258: Black Hole Mass = 38 Million Suns

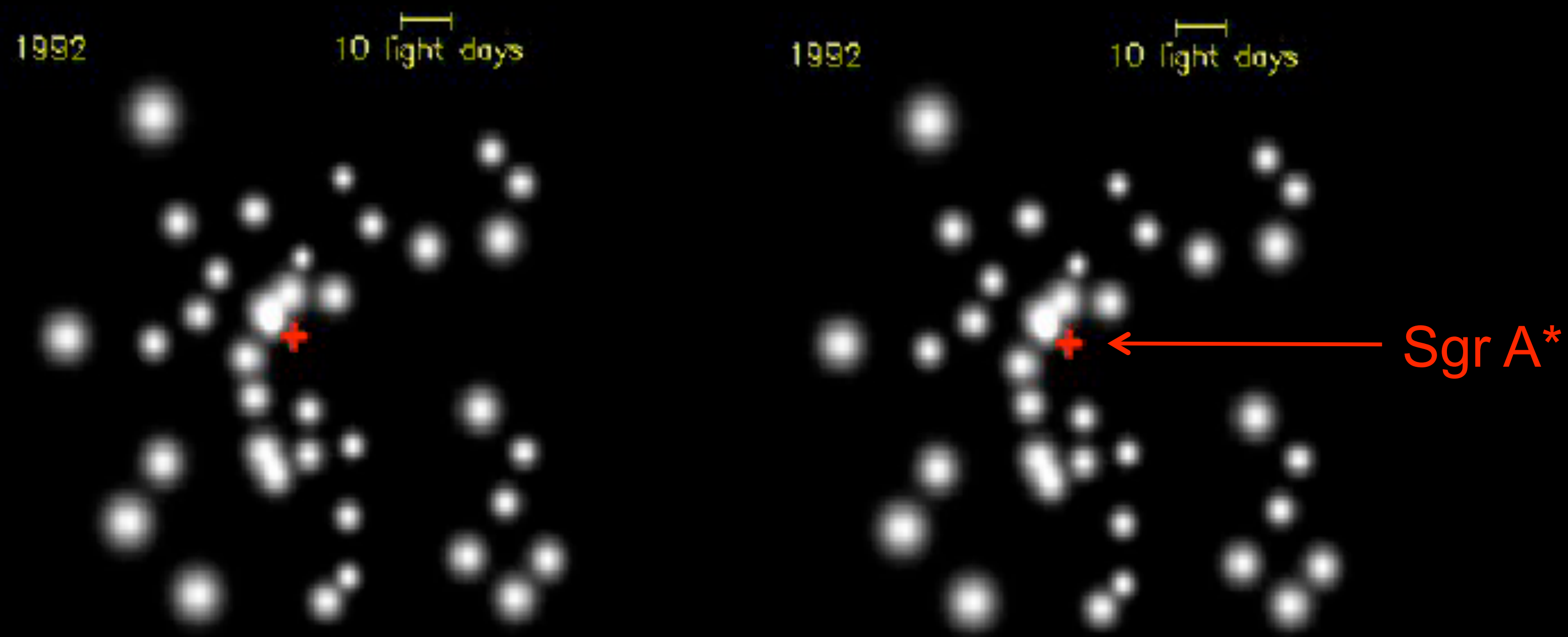
NGC 4258:
M● = 38 Million Suns



The accurately Keplerian rotation curve shows that all of the mass is in such a small volume at the center that alternatives to a black hole (failed stars or dead stars) are ruled out.

This is one of the best black hole candidates.

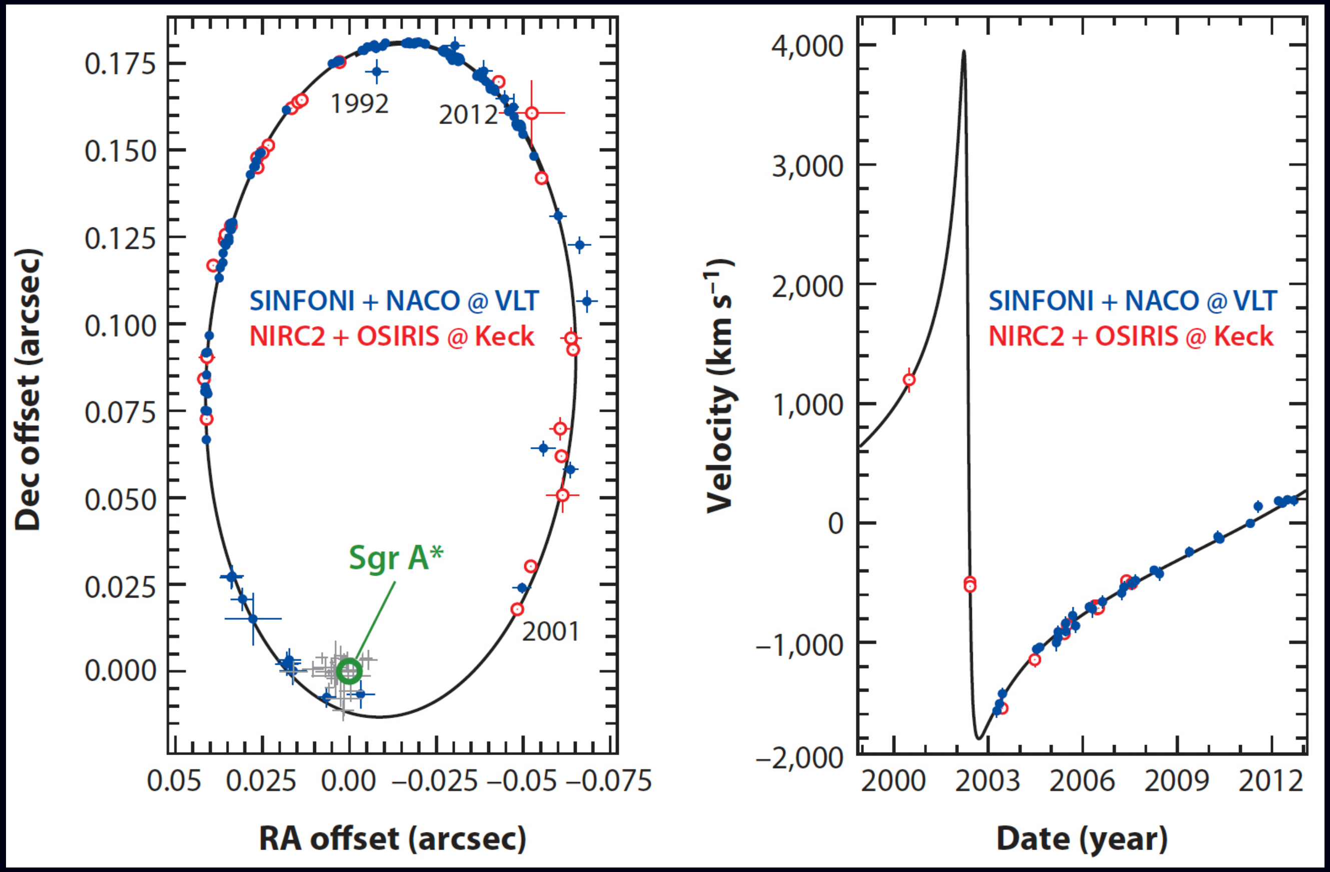
Our Galaxy: Black Hole Mass = 4.3 Million Suns



Reinhard Genzel, Andrea Ghez, and their collaborators have measured motions of stars as large as 5000 km/s in the dense cluster of stars that surrounds the Galactic center radio source Sgr A*.

Again, the dark mass at Sgr A* is so small in size that dark cluster alternatives to a supermassive black hole are excluded.

We are seeing the Galactic center rotate in our lifetimes!

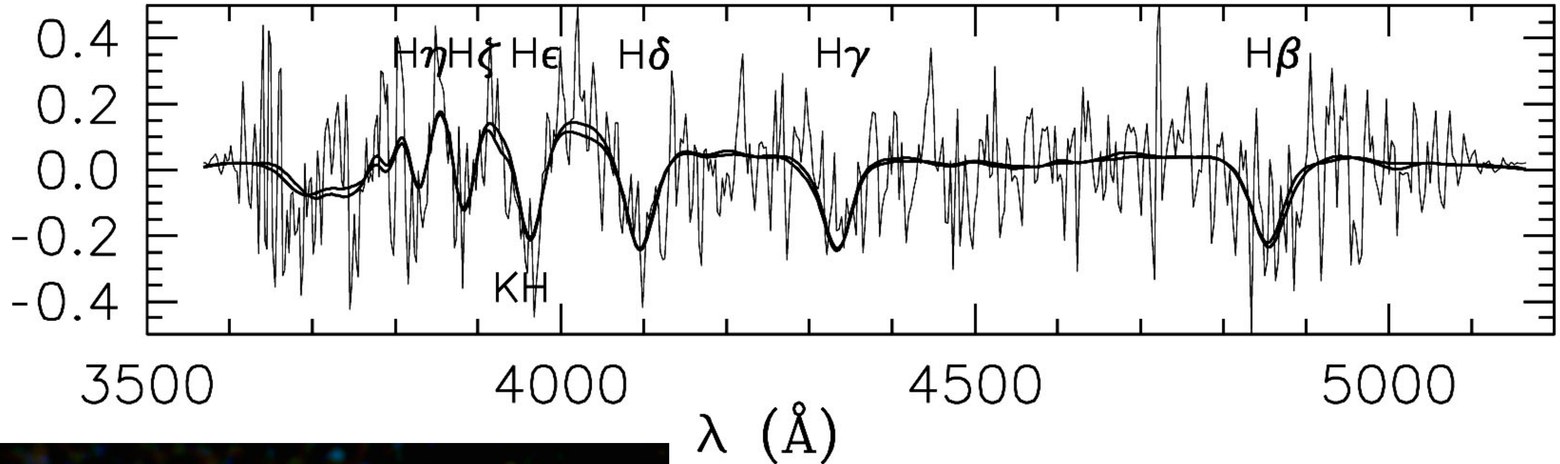


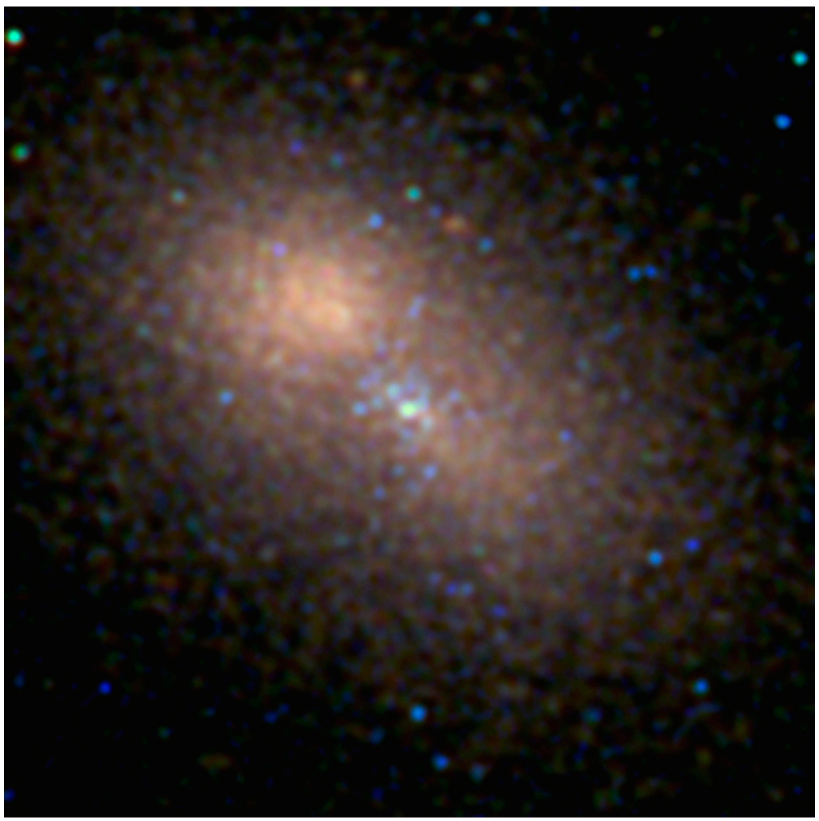
Schödel et al. (2002, Nature, 496, 649) followed star S0-2 through 2/3 of an orbit.
It came closest to the black hole in 2002 -- within 124 AU = 17 light hours of the black hole.
This is about 1700 times the radius of the black hole.

We have now (2016) seen this star go through more than one complete orbit.
Several other stars have been followed through complete orbits. Each star gives is the black hole mass. The existence and mass of the black hole are beautifully confirmed.

Artist's View of the Andromeda Galaxy's Nucleus

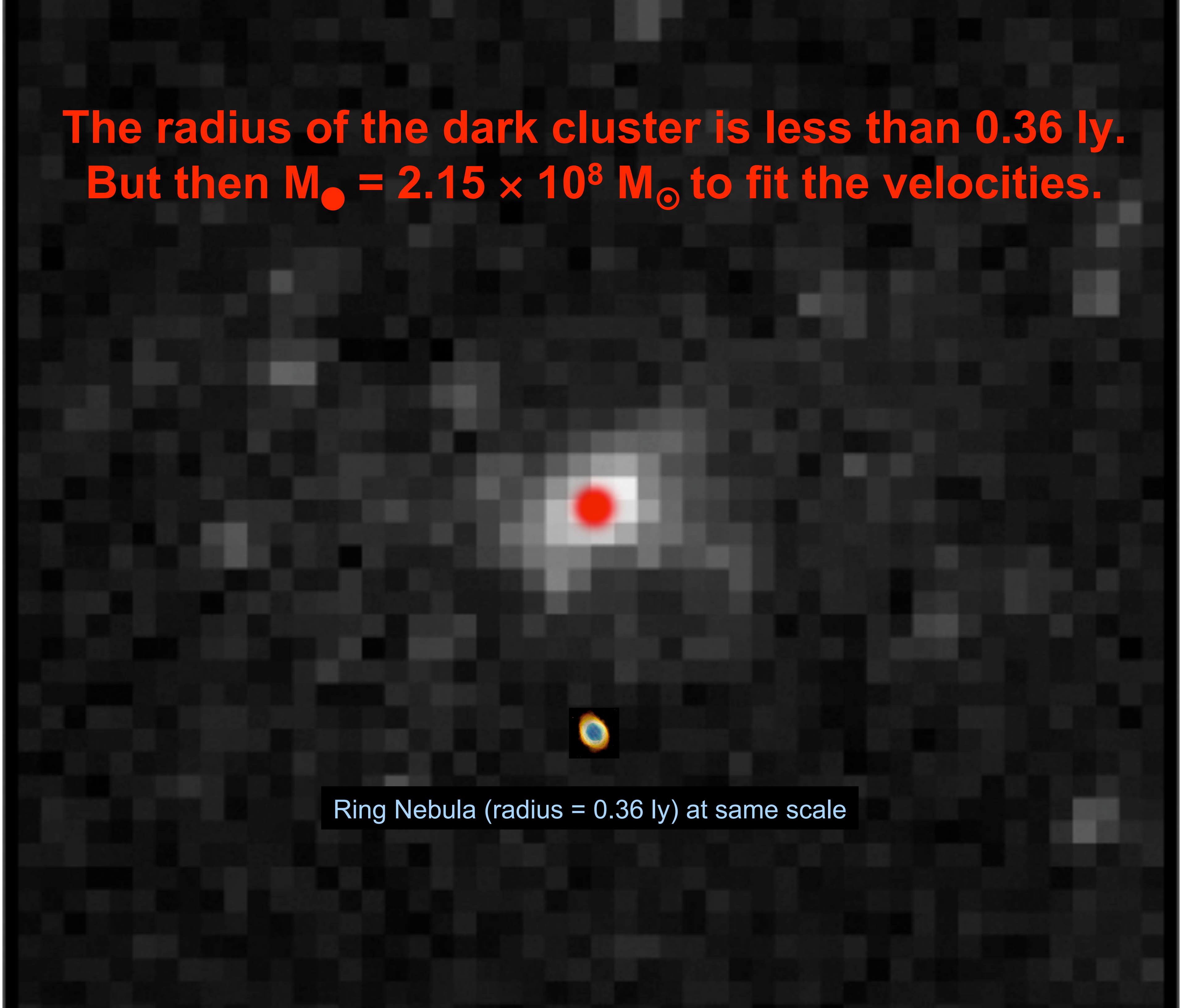
The blue cluster in M31 rotates at 1800 km s^{-1} at 0.05″





Any dark cluster alternative to a supermassive black hole in M 31 must be smaller than 0.03 arcsec in radius.

The radius of the dark cluster is less than 0.36 ly.
But then $M_\bullet = 2.15 \times 10^8 M_\odot$ to fit the velocities.



M31 becomes the third galaxy in which dark cluster alternatives to a black hole are ruled out.

The dynamically detected central dark object must be a black hole

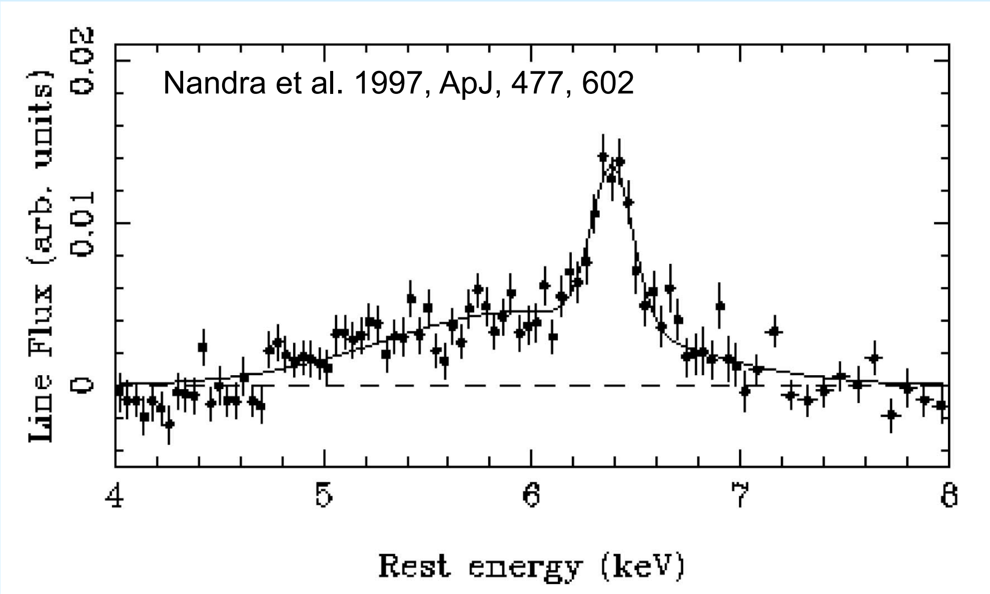
(http://chandra.as.utexas.edu/~kormendy/m31stis.html).

Have we discovered black holes in galactic nuclei?

Probably.

Other alternatives are very implausible.

But: Absolute proof requires that we see velocities of almost the speed of light from near the surface of the black hole.

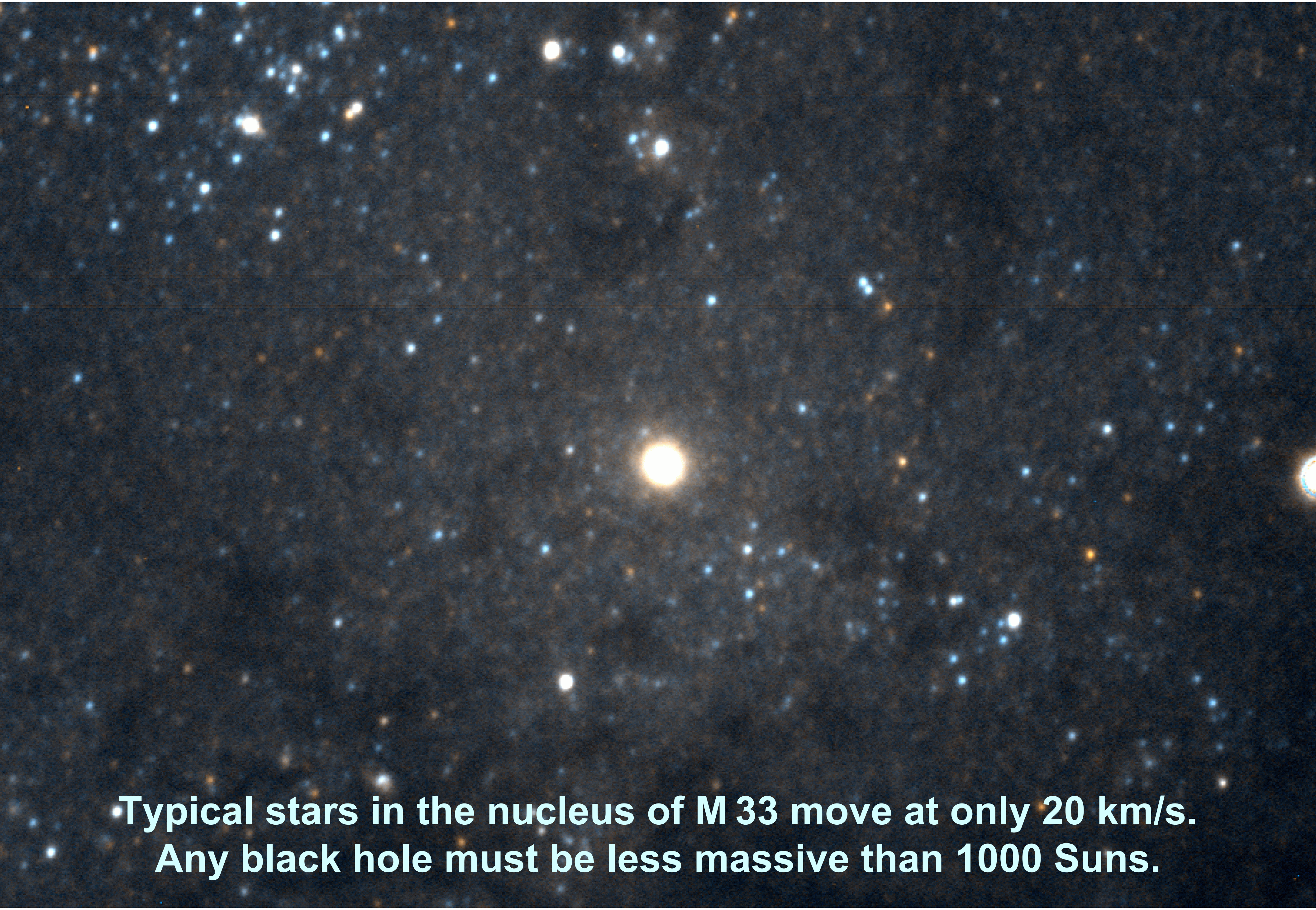


X-ray observations of Seyfert galaxies show spectral lines as wide as 100,000 km/s.

This is 1/3 of the speed of light.


← GLENMONT 2
BLACK HOLE →

The bulgeless galaxy M 33 does not contain a black hole.


Typical stars in the nucleus of M 33 move at only 20 km/s.
Any black hole must be less massive than 1000 Suns.

NGC 4395 is a bulgeless Sm galaxy that contains a BH of mass $(3.6 \pm 1.1) \times 10^5\ M_\odot$

(Peterson et al. 2005, ApJ, 632, 799 via reverberation mapping).

A bulge is not necessary equipment for BH formation

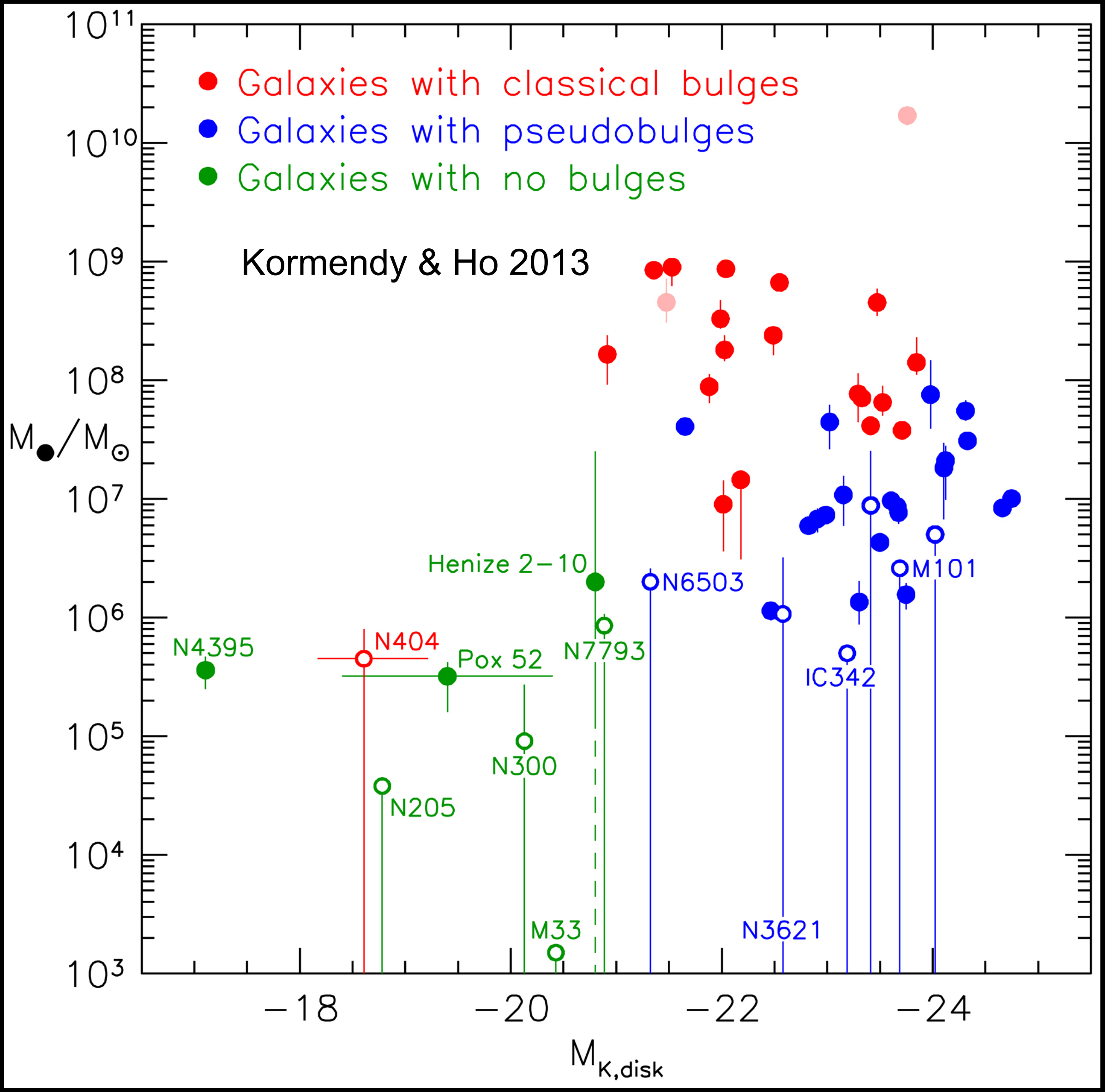
(Greene & Ho 2007, Ho 2008 ARA&A, Desroches & Ho 2009).

But BHs in bulgeless galaxies do not correlate with their hosts

(see also Greene + 2008, 2010).

Black holes do not correlate with galaxy disks.

(Kormendy & Gebhardt 2001, 20th Texas Symp., AIP, 363 ; Kormendy et al. 2011, Nature, 469, 374).



Conclude: Every galaxy that contains a bulge component also contains a black hole.

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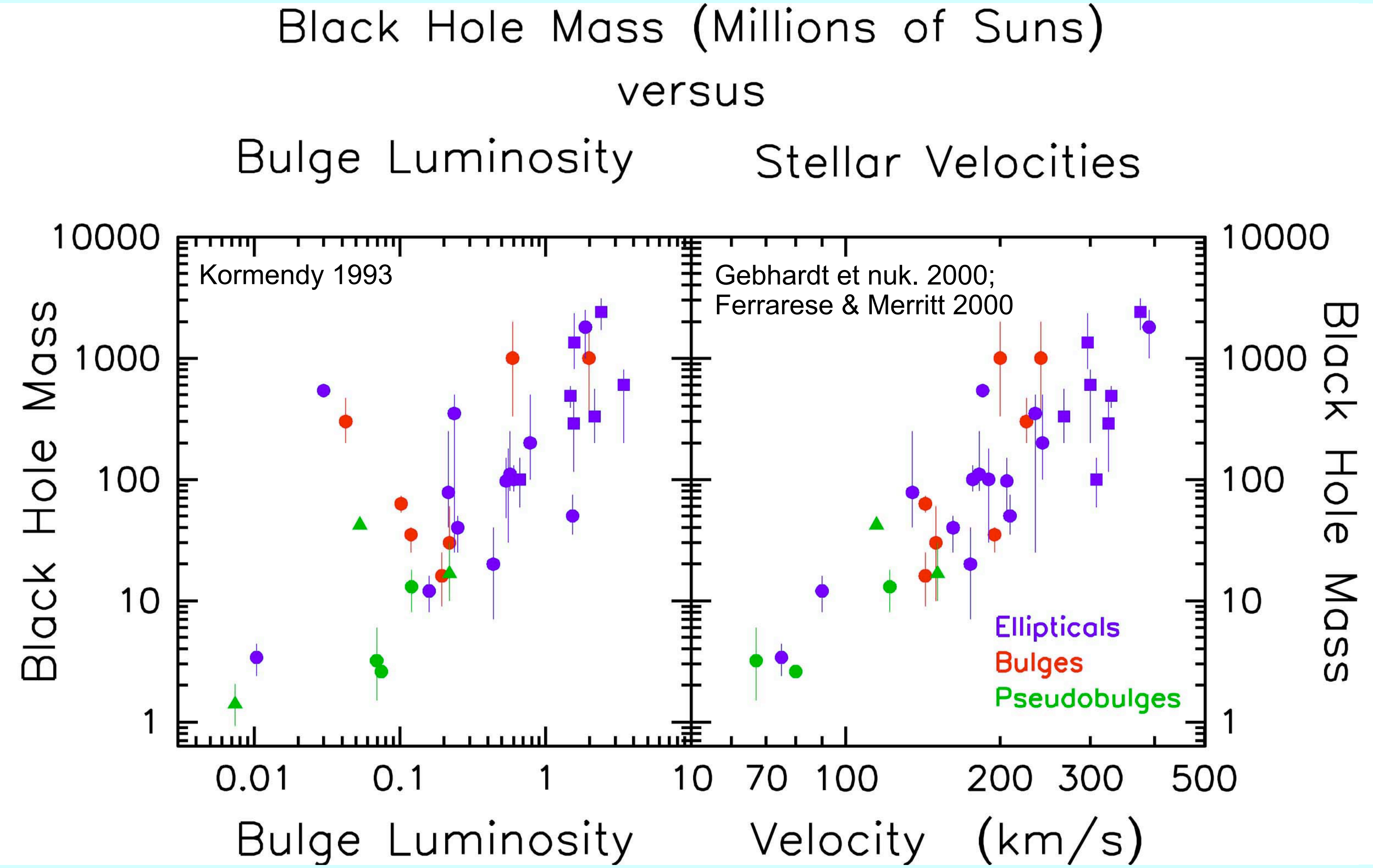
Conclude: Every galaxy that contains a bulge component also contains a black hole.

No bulge ⇒ sometimes no black hole.

When bulgeless galaxies do contain a black hole, then the its mass does not correlate with disk mass.



Bigger black holes live in bigger galaxy bulges.

Bigger black holes live in bulges in which the stars move faster.

Revised BH–Host Galaxy Correlations

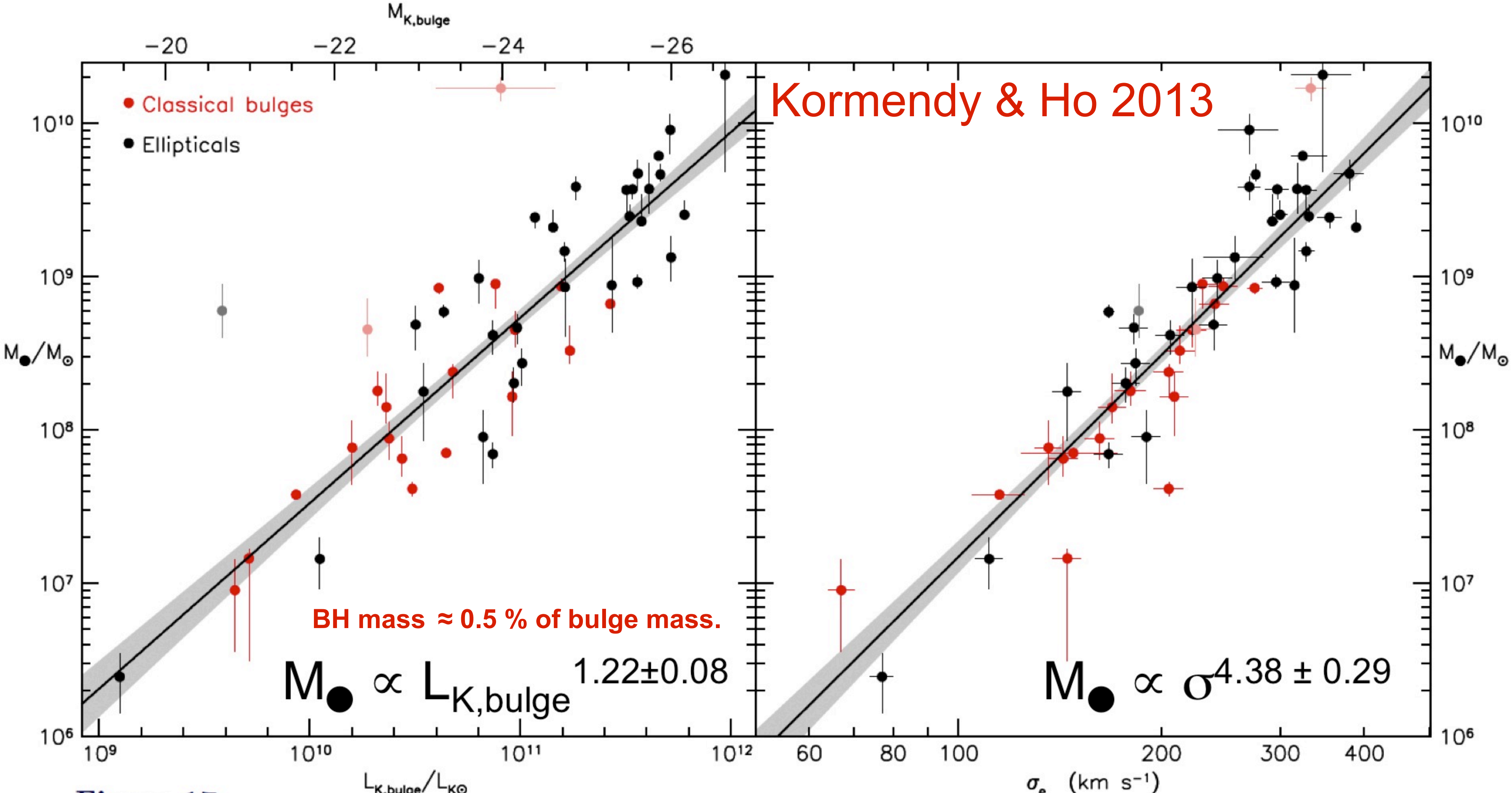


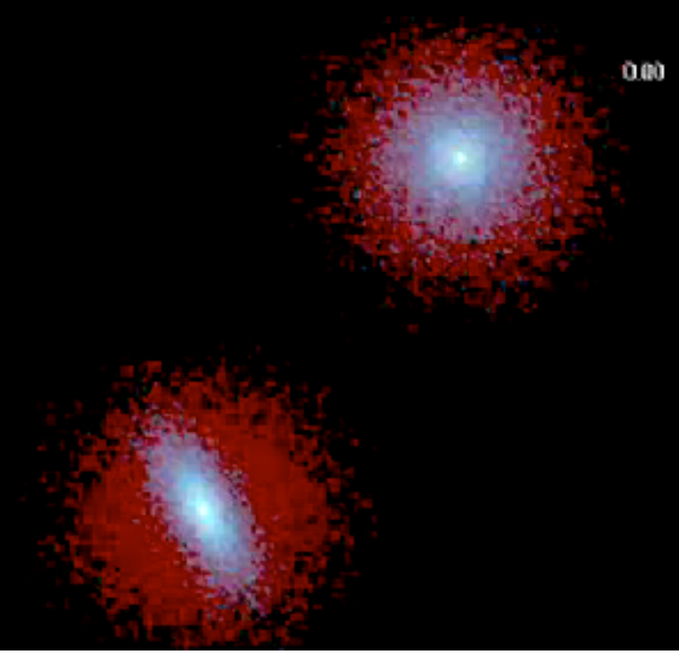
Figure 17

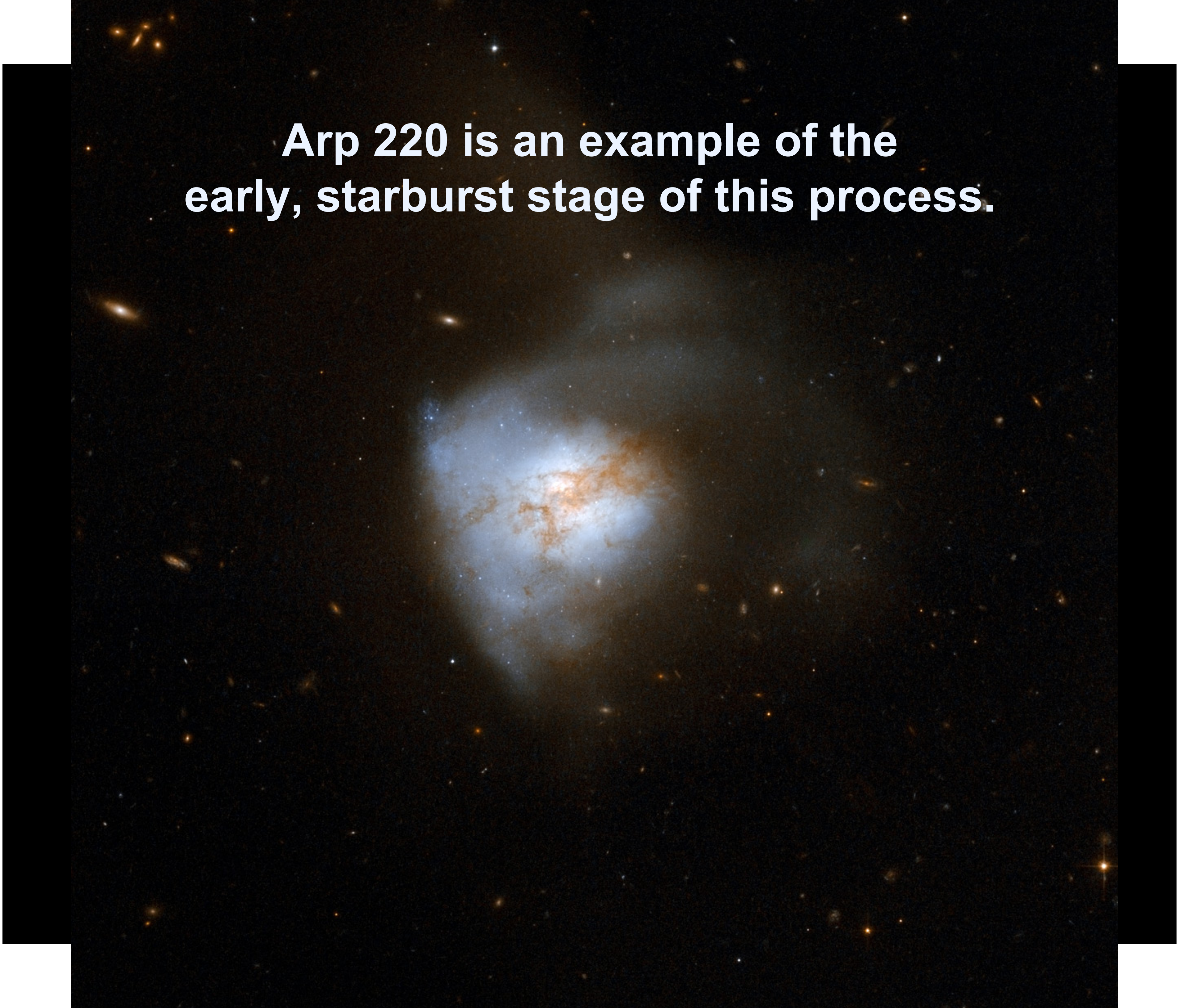
The $M_\bullet$–$M_{K,bulge}$ and $M_\bullet$–σ_e correlations with symmetric (Tremaine et al. 2002) least-squares fits (Equations 2 and 3) and the 1σ range of the fits (*gray shading*). Here we give equal weight to all the points. Fits that use the individual $M_\bullet$ measurement errors (Equations 4 and 5) are almost identical. Among the plotted points, all fits omit the BH monsters (*points in light colors*), $M_\bullet$ values determined from ionized gas rotation curves without taking line widths into account (NGC 4459 and NGC 4596), and the two highest-$M_\bullet$ ellipticals (NGC 3842 and NGC 4889).

Conclusion:
Black holes help to control
the formation of bulges via mergers, but, although they are
found in some disks,
they do not affect the
evolution of disks.

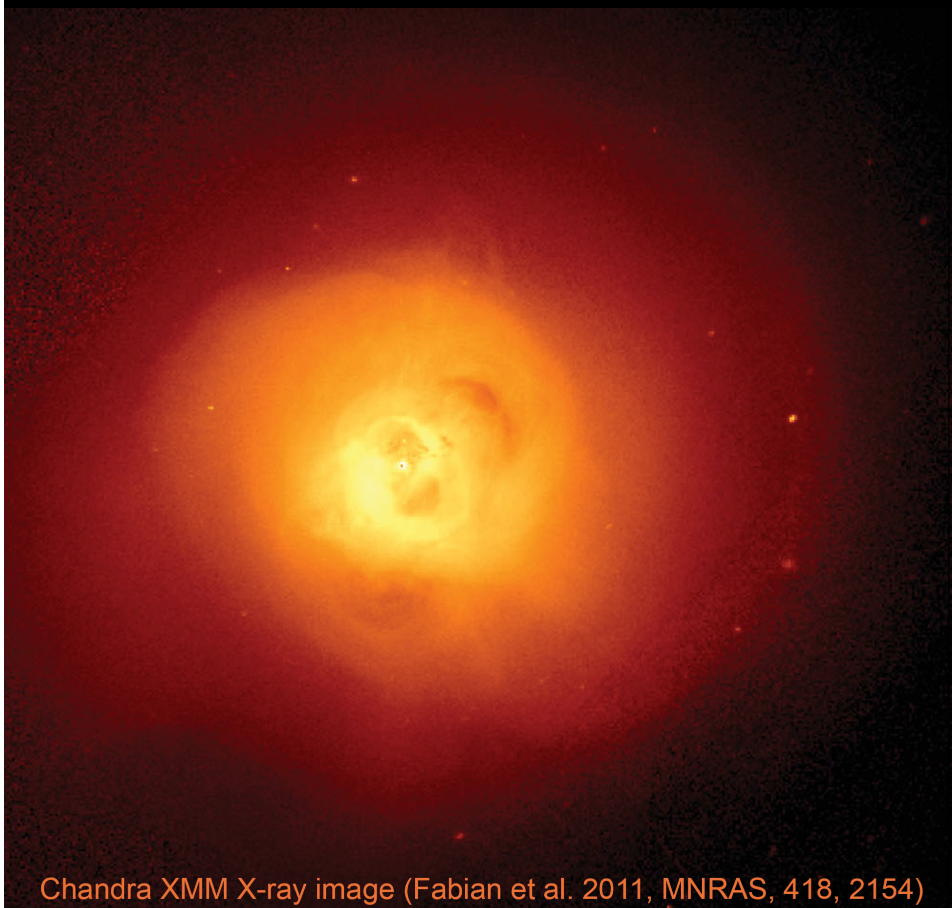
Ellipticals are formed when galaxies collide and merge.
Any disks in the progenitors are scrambled into elipticals.
Cold gas in the progenitors falls toward the center,
makes a starburst there,
and feeds the central black hole.

The resulting energy output from the (mini)quasar
helps to switch off star and galaxy formation.




Arp 220 is an example of the
early, starburst stage of this process.

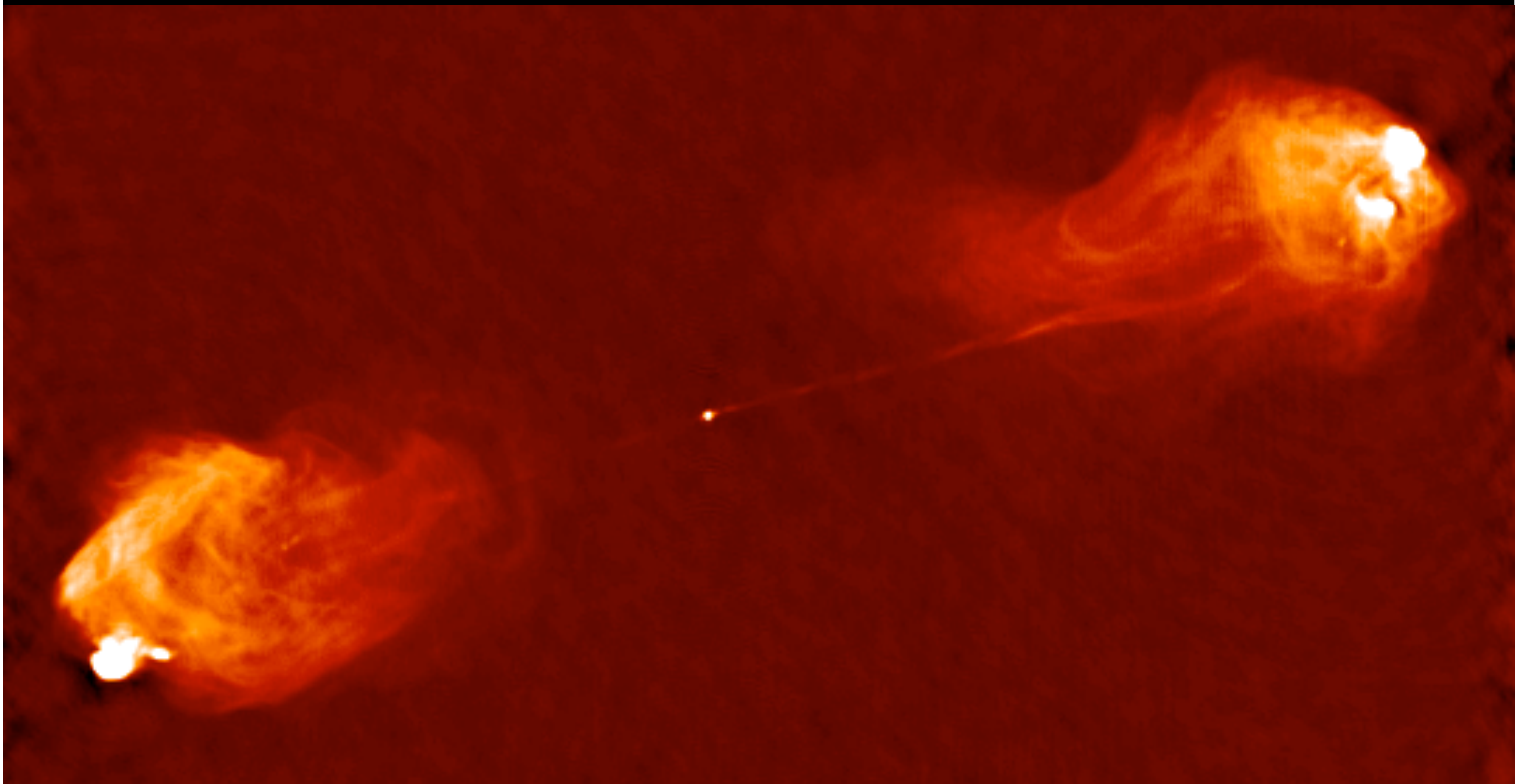
NGC 1275 is an example of the mature stages of this process: its miniquasar keeps million-degree gas that fills the Perseus galaxy cluster hot.



X-ray gas prevents star formation

Visible light picture

Cygnus A radio jets show one way that hot gas is kept hot.



CONCLUSION

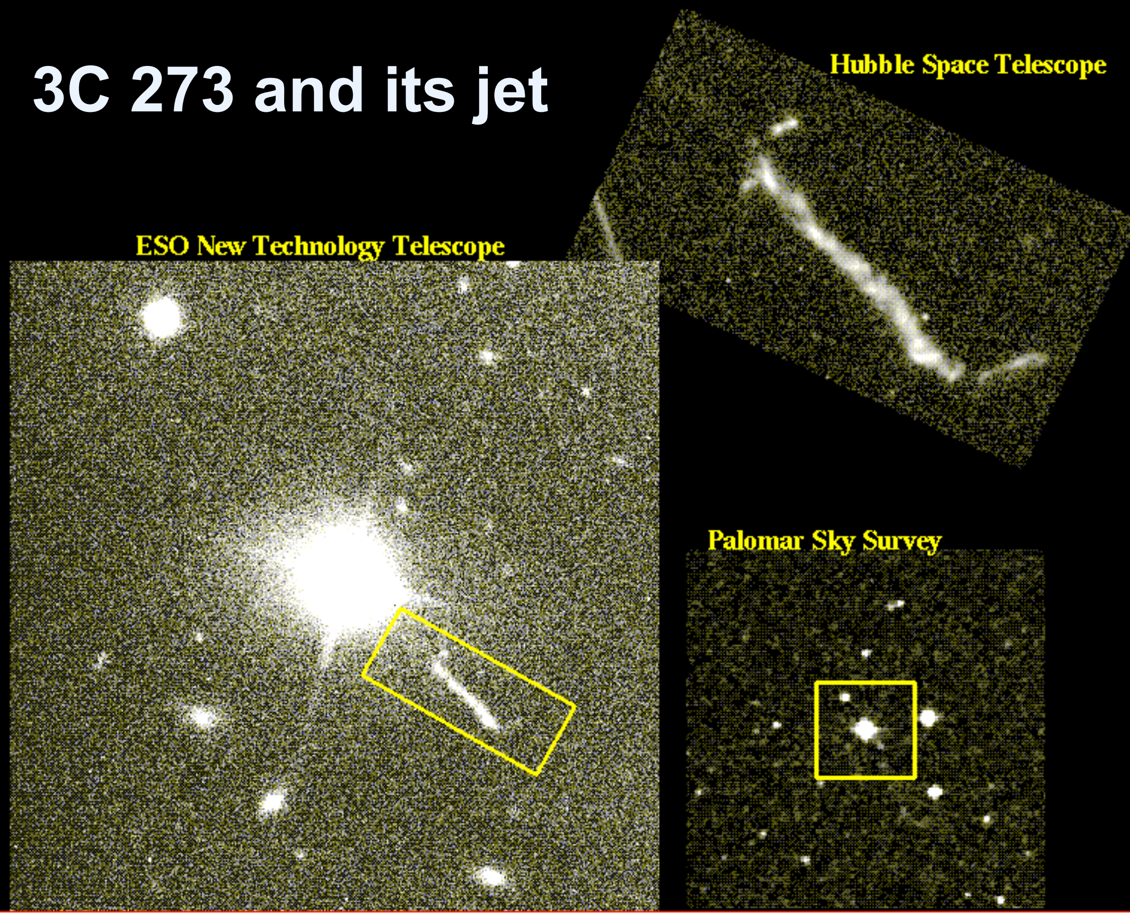
The formation of bulges in mergers + starbursts
and
the growth of their black holes,
when they shone like quasars,
happened together.

This unifies
two major areas of
extragalactic research:
quasars
and
galaxy formation.

Black Hole Conclusions

Measured black hole masses are just right to explain the energy output of quasars.

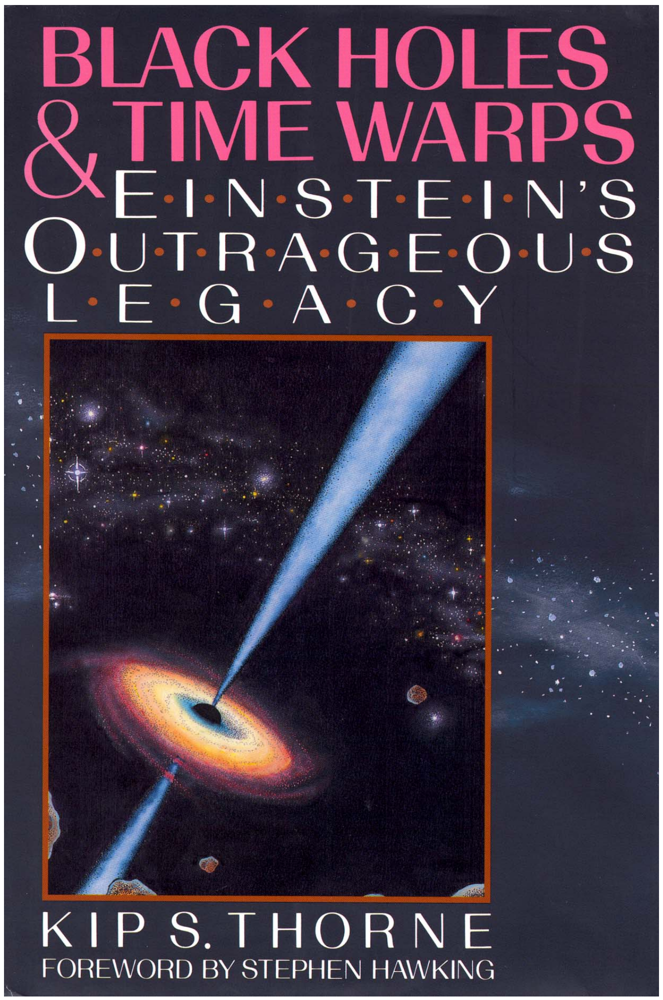
3C 273 and its jet



Supermassive Black Holes

For more information about supermassive black holes,
see http://chandra.as.utexas.edu/bhsearch.html
and especially the "review article for the general public" there.

For more information about black holes in general, I recommend:



Kip Thorne,
Feynman Professor of
Physics Emeritus at Caltech,
produced the movie
Interstellar.