Hot Science Cool Talks

UT Environmental Science Institute

18

Supermassive Black Holes: Galaxy Monsters

Dr. John Kormendy

April 19, 2002

Supermassive Black Holes in Galactic Nuclei

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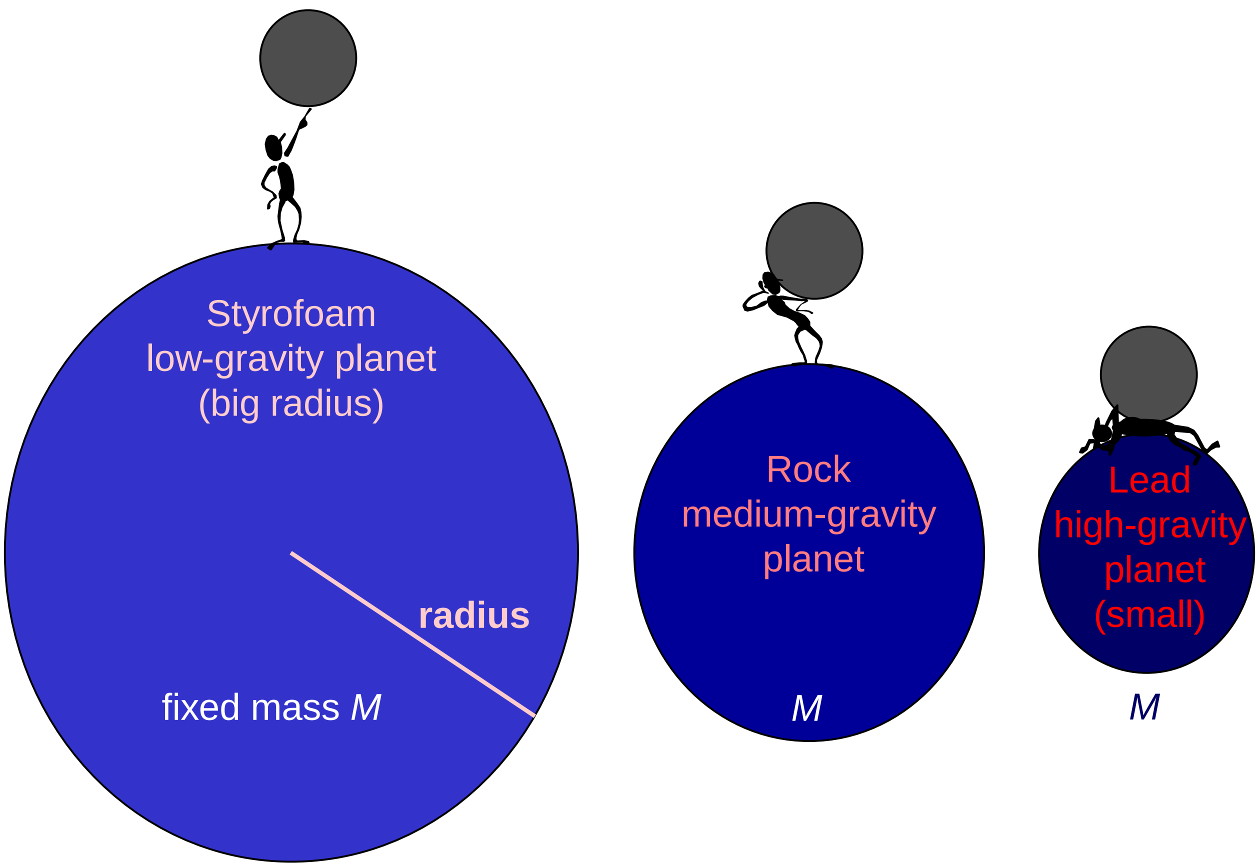
ESI Environmental Science Institute
UNIVERSITY OF TEXAS AT AUSTIN

What are black holes?
Why are we looking for them?
The search for supermassive black holes
Supermassive black holes and galaxy formation

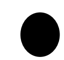
Black Hole

Suppose we squeeze a planet of fixed mass *M* into smaller and smaller volumes.

The surface gravity gets bigger as you make the planet smaller.
Surface gravity is proportional to $1/\text{radius}^2$.



$$\text{radius} = \frac{2GM}{c^2}$$



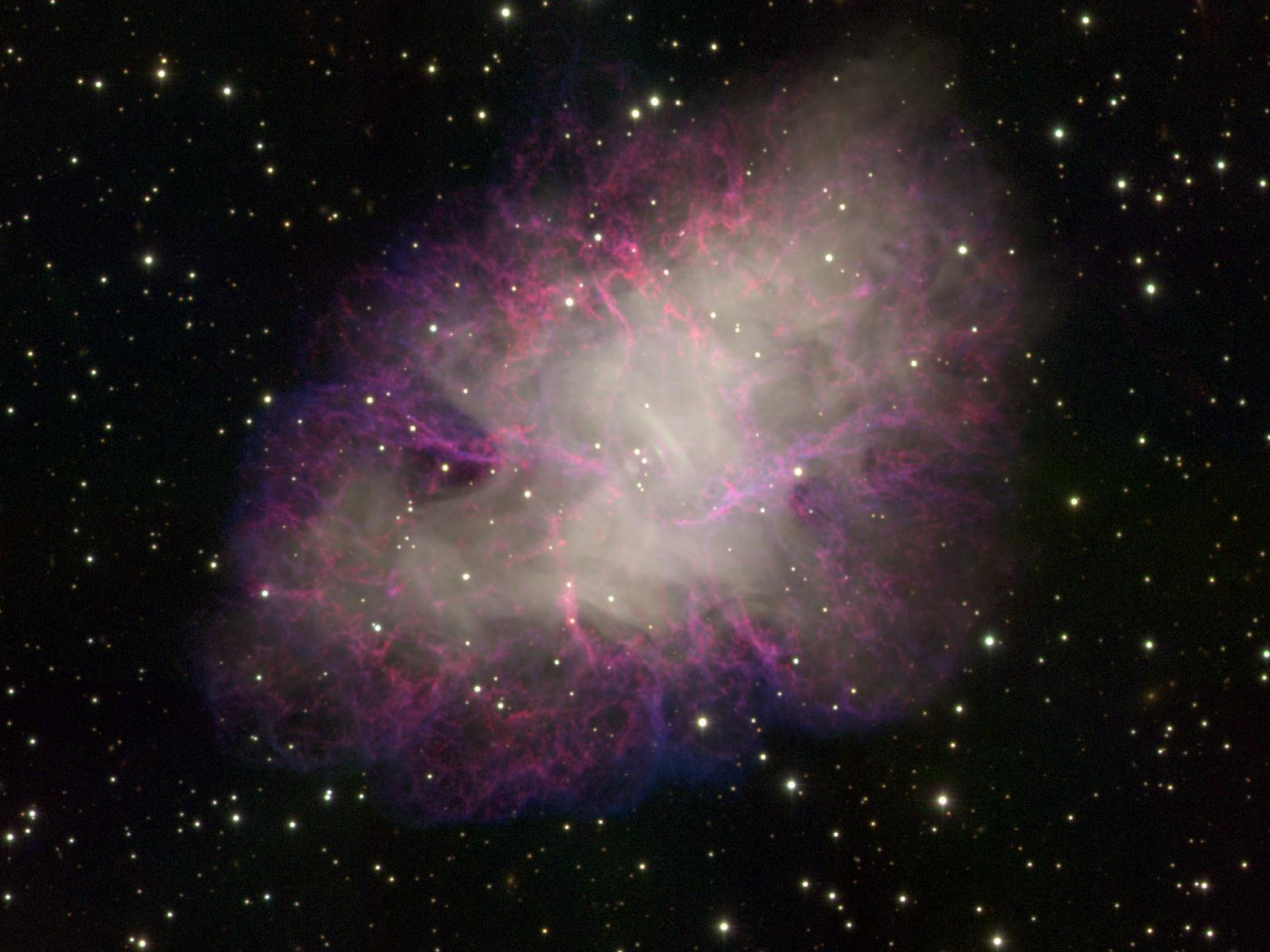
A black hole is so small
that its surface gravity is so high
that nothing can escape,
not even light.

To turn the Earth into a black hole,
we would have to squeeze it into the size of a grape.

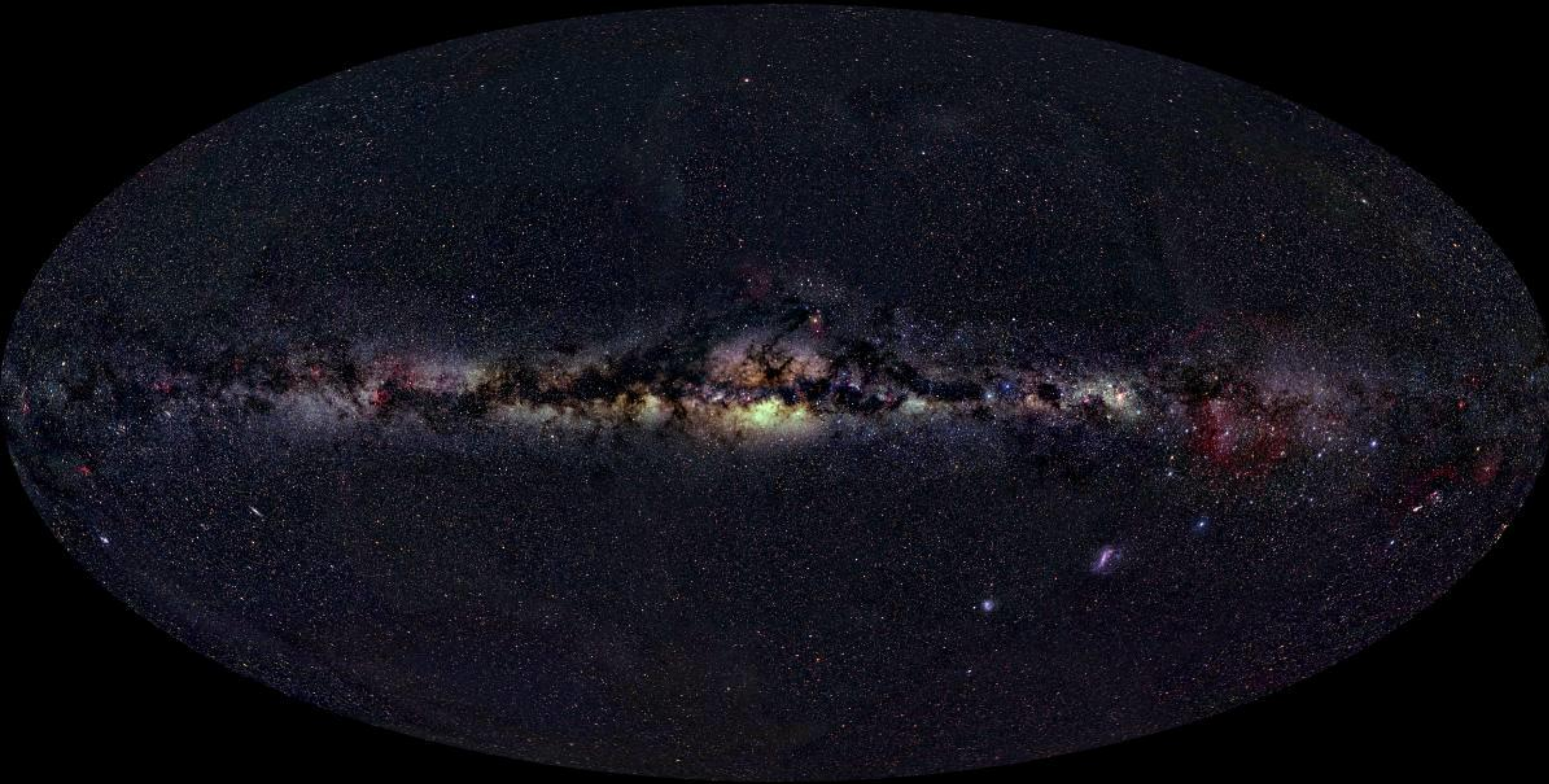
Two Types of Black Holes

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.



Our Galaxy



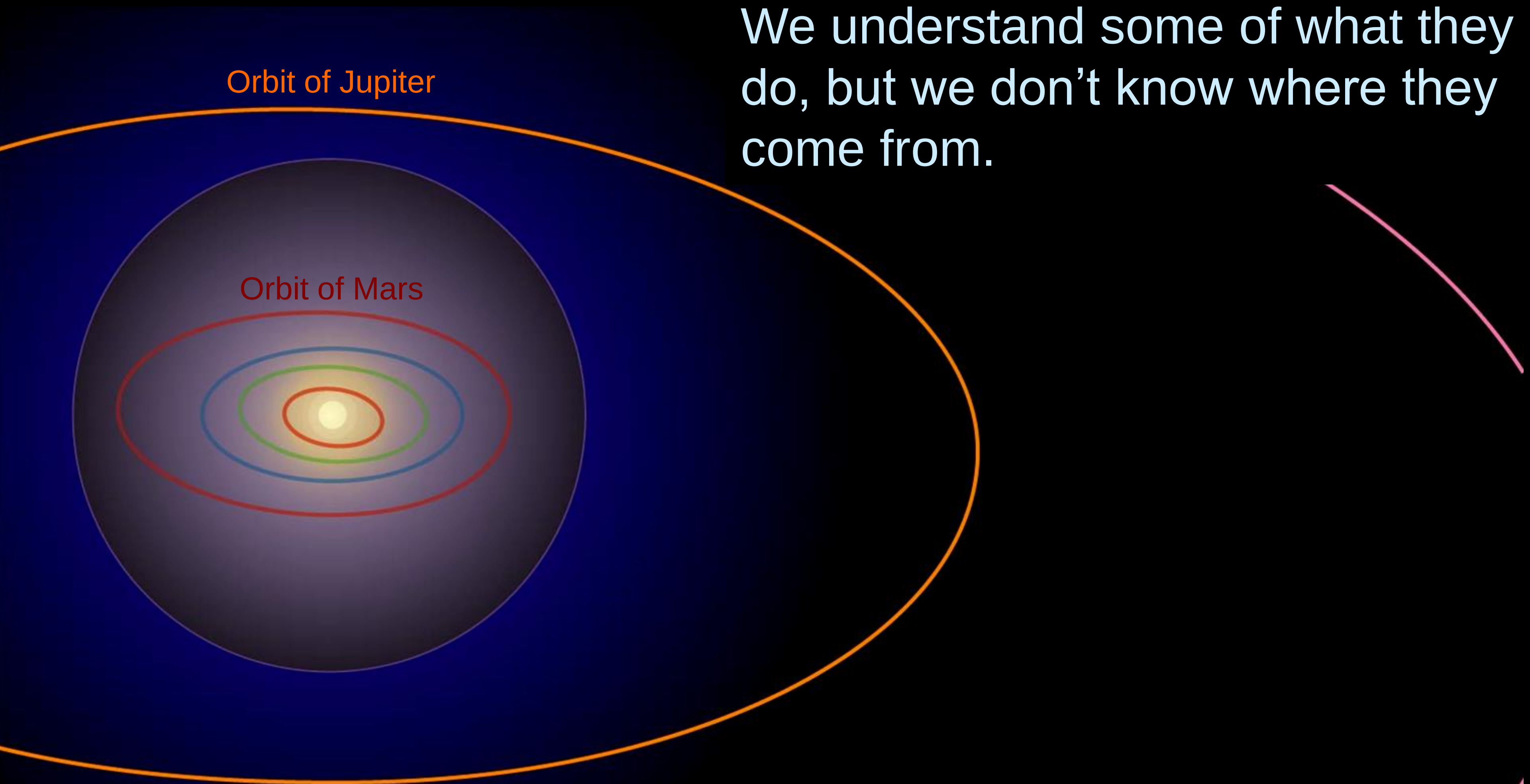
These are millions of stellar-mass black holes — dead stars — scattered throughout the disk of our Milky Way galaxy.

Sombrero Galaxy:
Black Hole Mass = 1 Billion Suns

Two Types of Black Holes

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

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

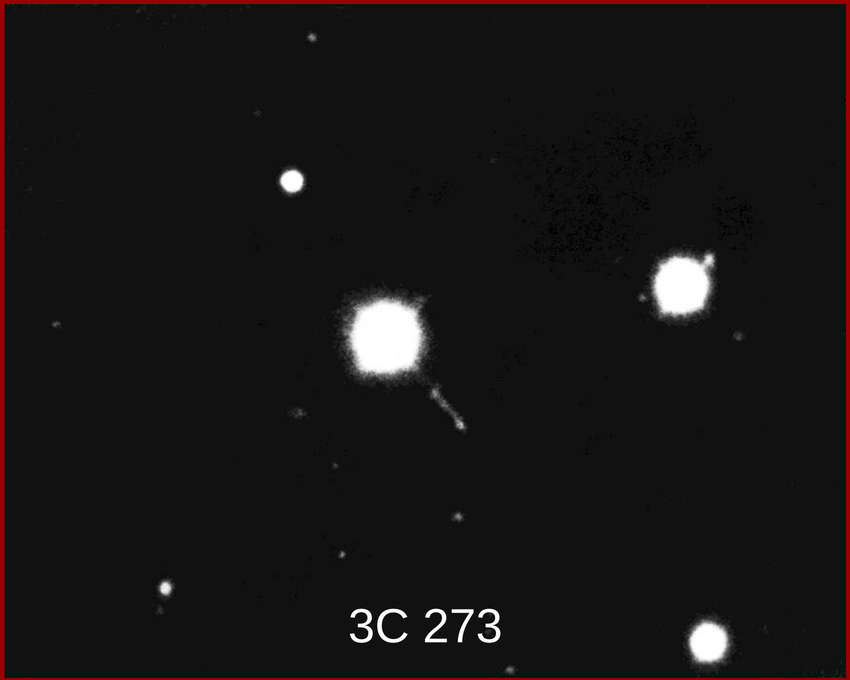


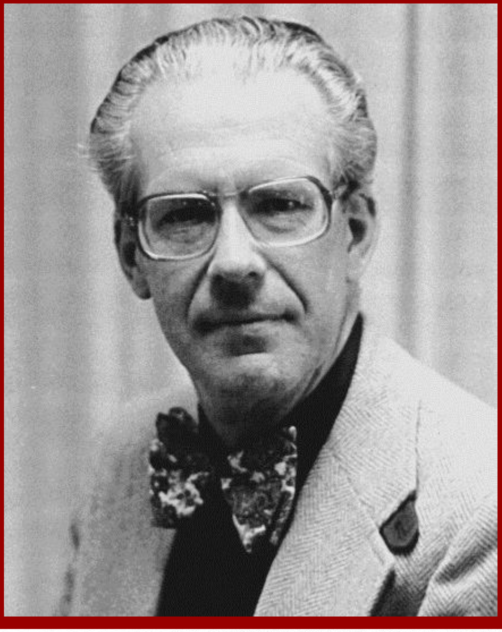
The Discovery of Quasars

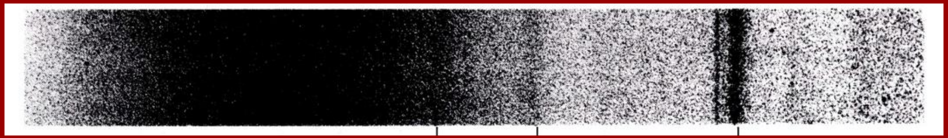
The identification by Maarten Schmidt (1963, Nature, 197, 1040) of the radio source 3C 273 as a 13th magnitude "star" with a redshift of 16 % of the speed of light was a huge shock. The Hubble law of the expansion of the Universe implies that 3C 273 is one of the most distant objects known. It must be enormously luminous.

Quasars — violently active galactic nuclei — are the most luminous objects in the Universe, more luminous than any galaxy.

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







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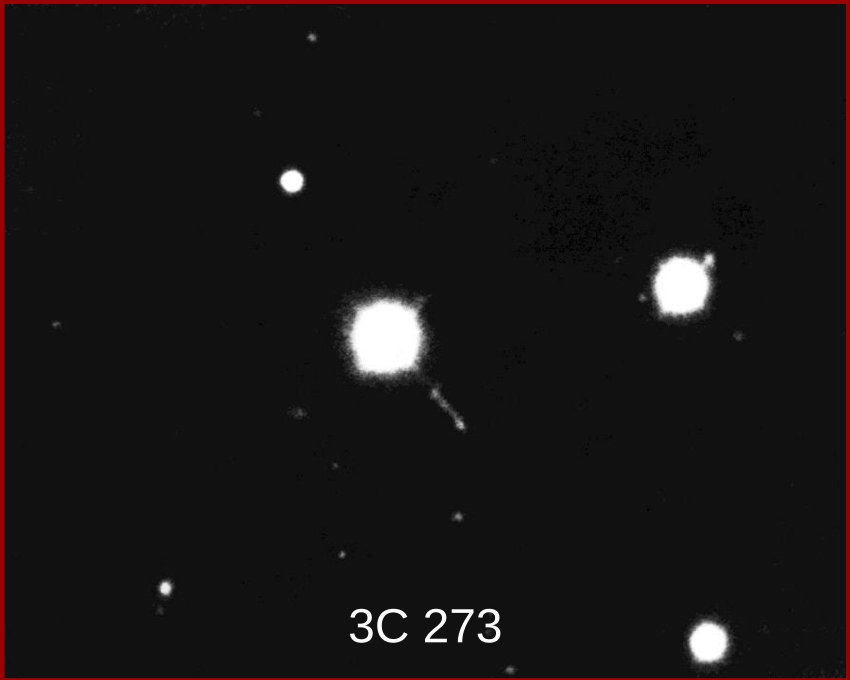
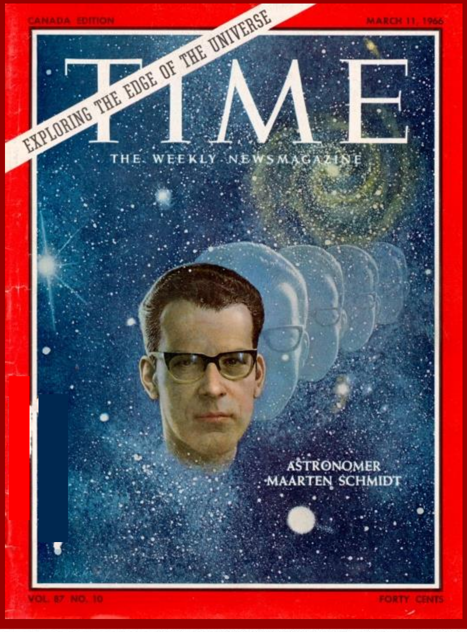
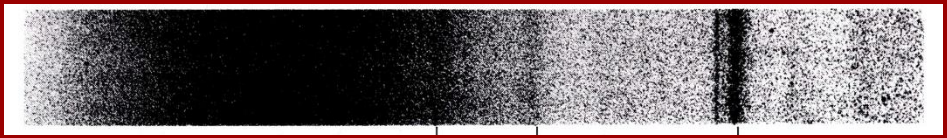
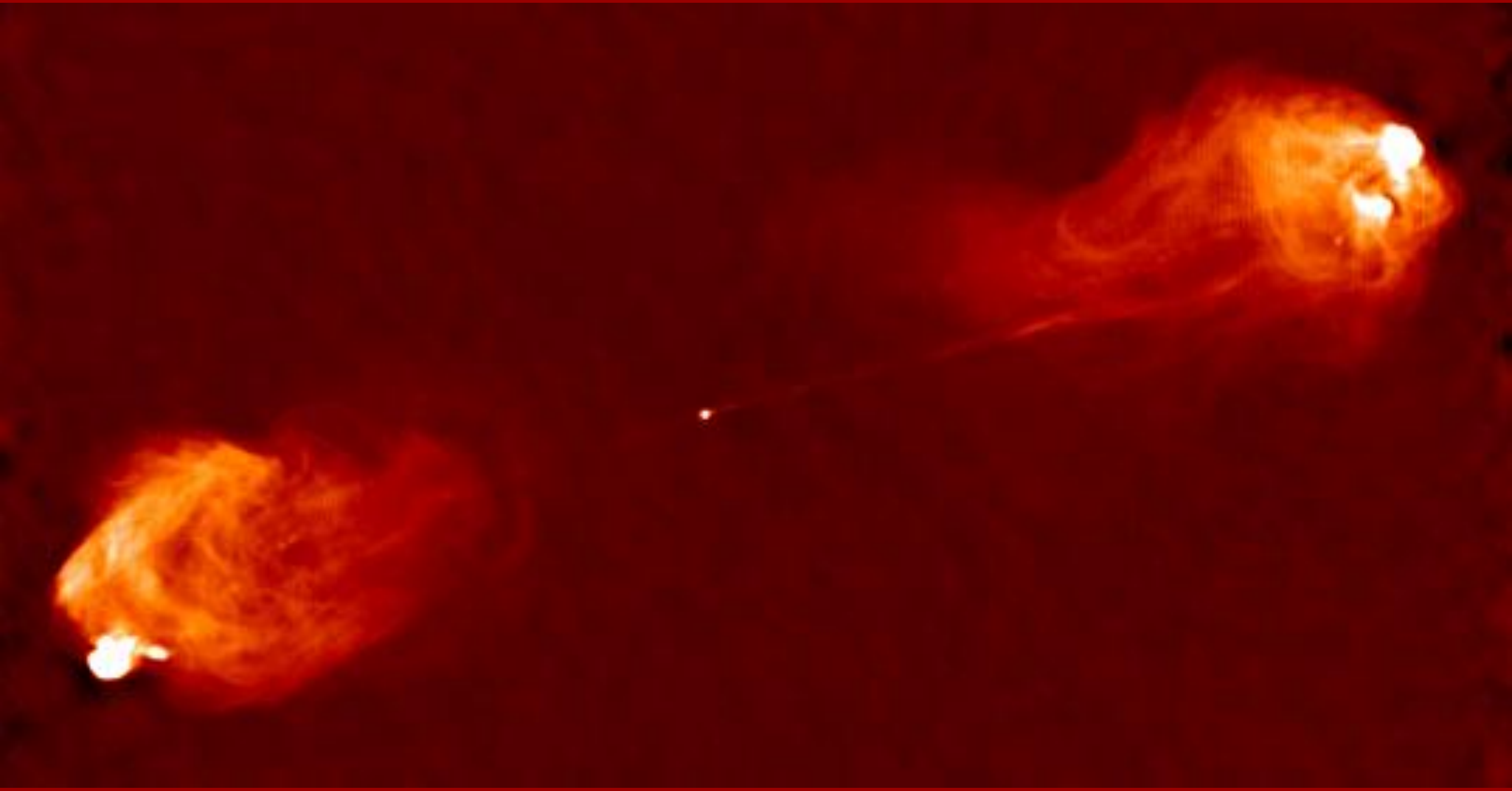






Many radio galaxies and quasars have jets that feed lobes of radio emission



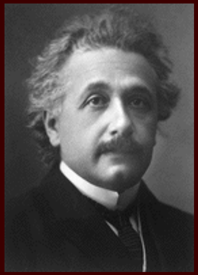
Cygnus A

Supermassive Black Holes as Quasar Engines

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

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

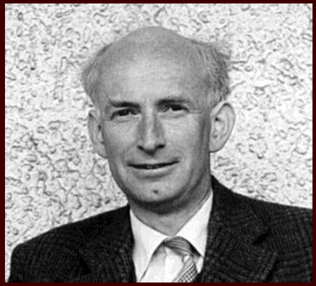
- Via $E = mc^2$, this energy "weighs" 10 million Suns.



- 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.

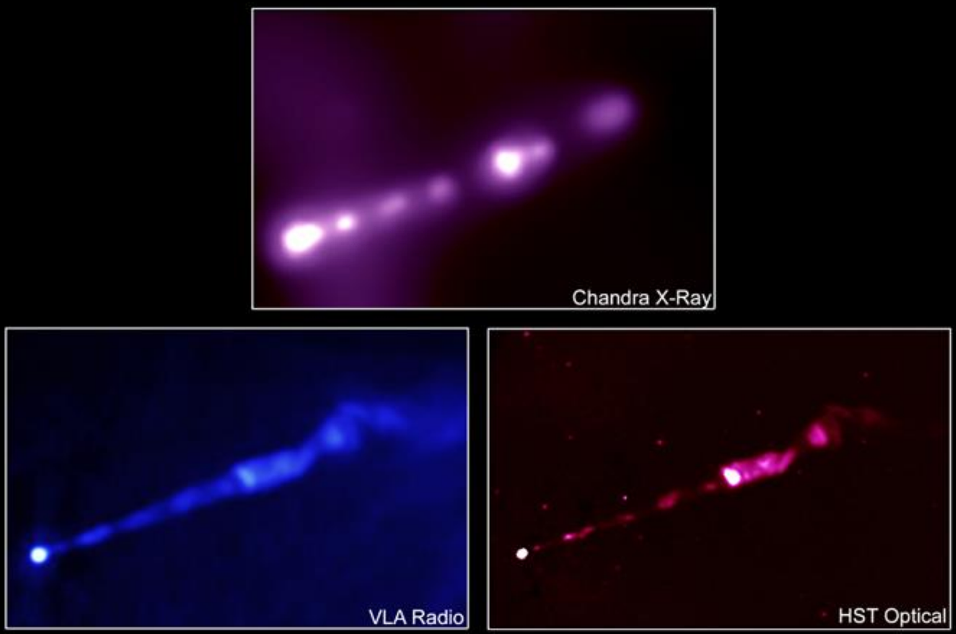
"Evidently, although our aim was to produce a model based on nuclear fuel, we have ended up with a model which has produced more than enough energy by gravitational contraction. The nuclear fuel has ended as an irrelevance."

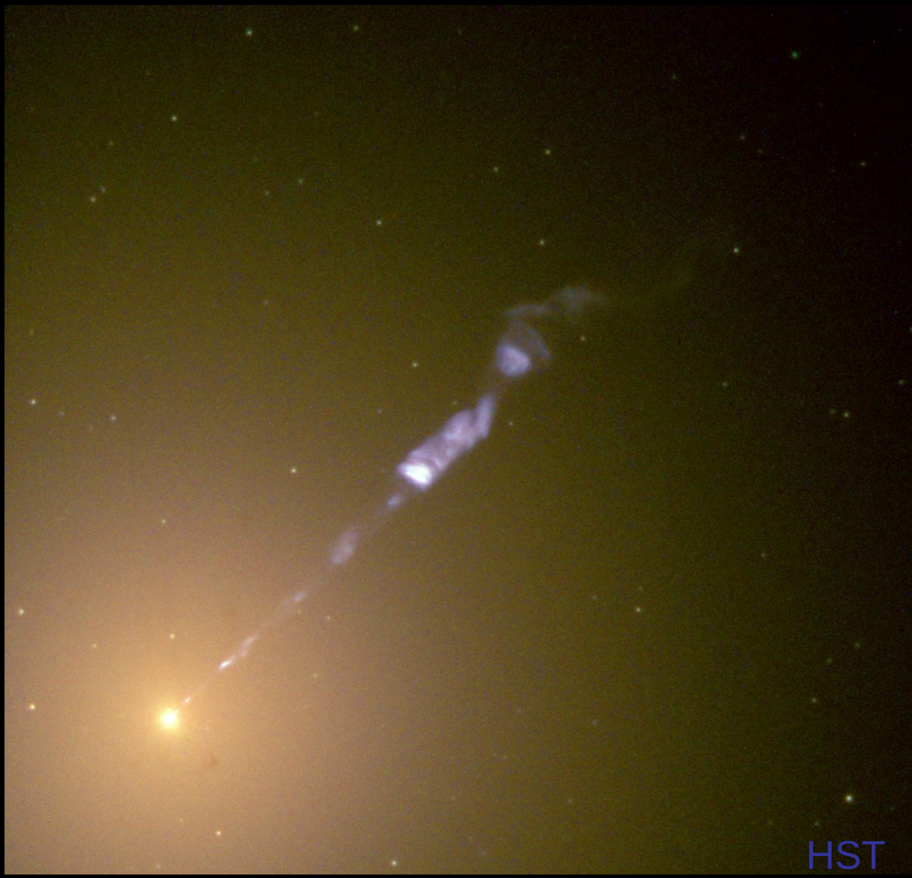
Donald Lynden-Bell (1969)



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

Why Jets Imply Black Holes — 1



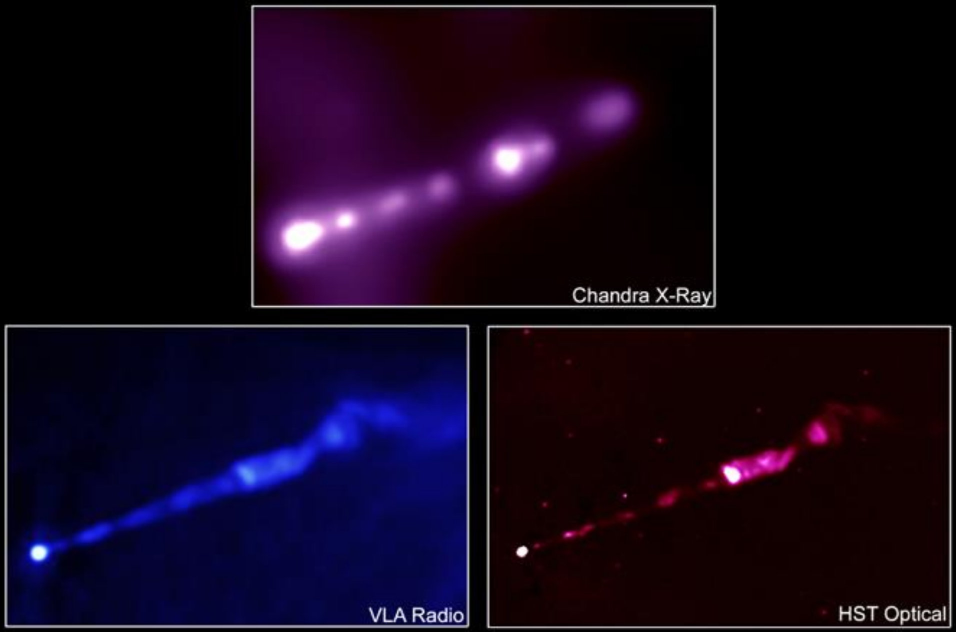


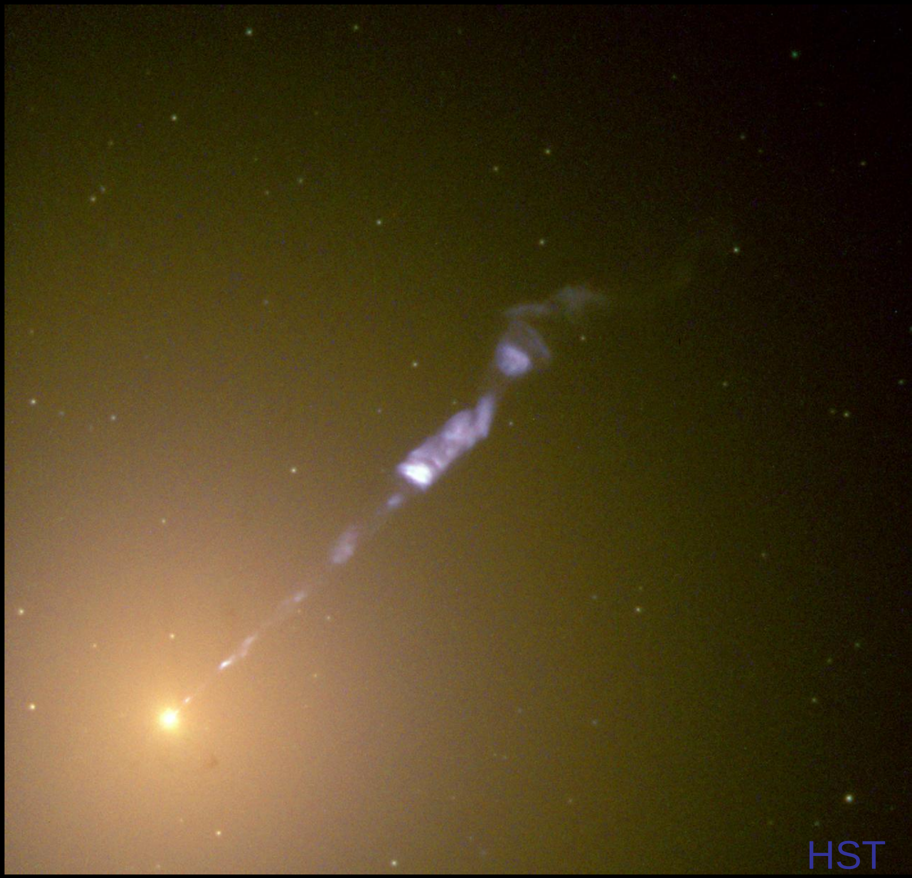
Jets remember ejection directions for a long time.

This argues against energy sources based on many objects (supernovae).

It suggests that the engines are rotating gyroscopes - rotating black holes.

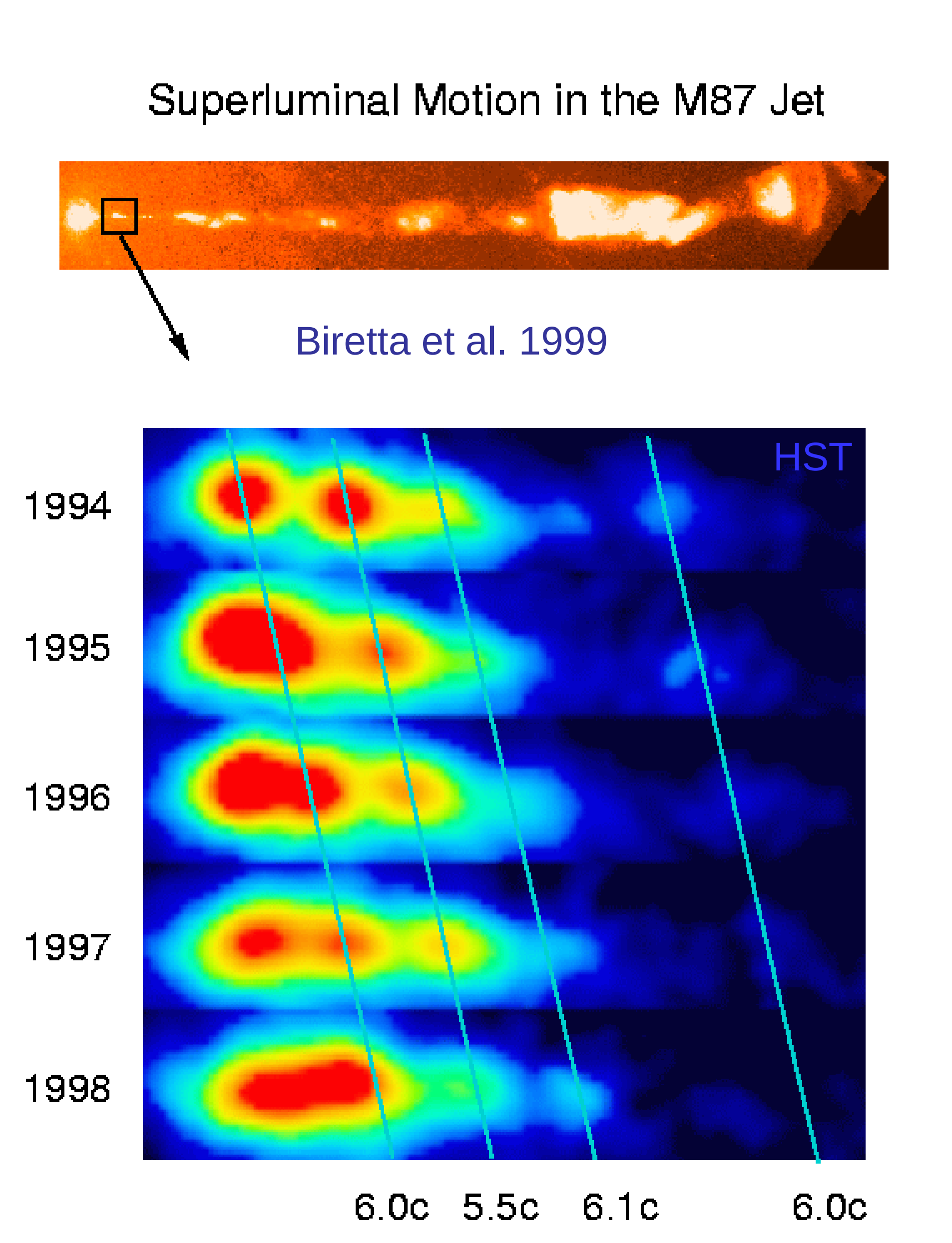
Why Jets Imply Black Holes — 2





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.

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 ?

Simulation:
Josh Barnes

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

PROBLEM

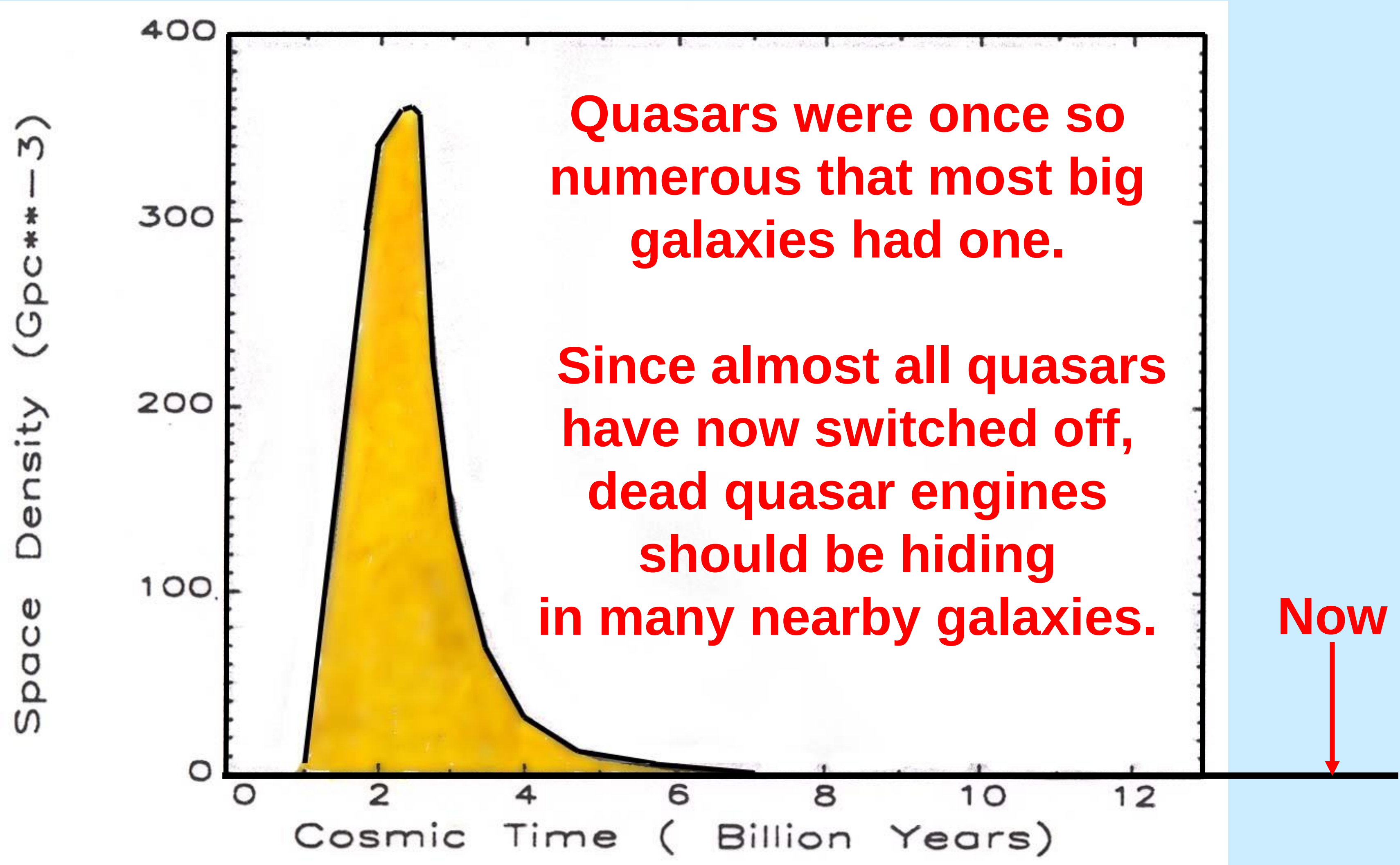
People believe the black hole picture.
They have done an enormous amount of work based on it.

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

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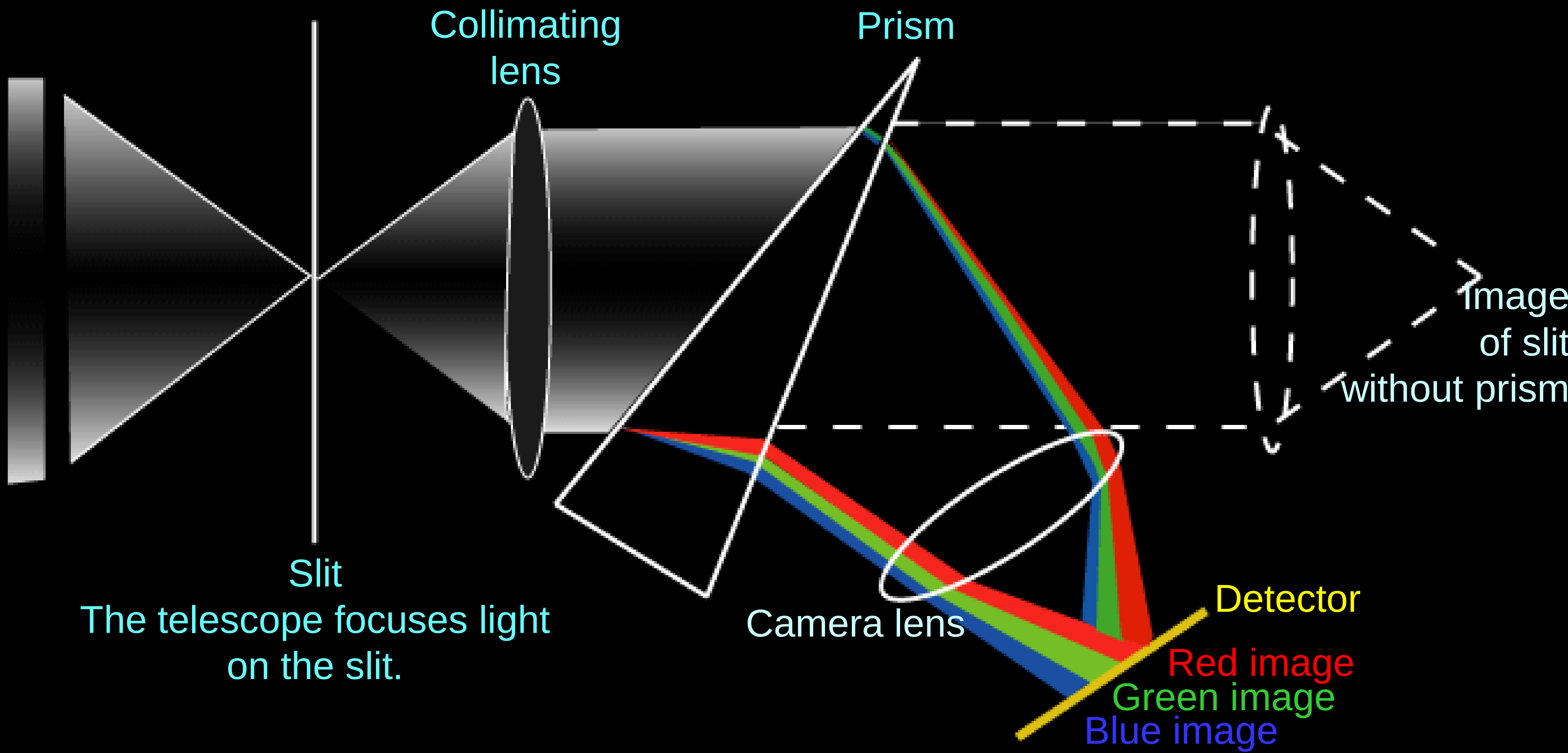
Canada-France-Hawaii-Telescope


OBSERVERS MANUAL
HP 1000
CFHT

Simple Spectrograph

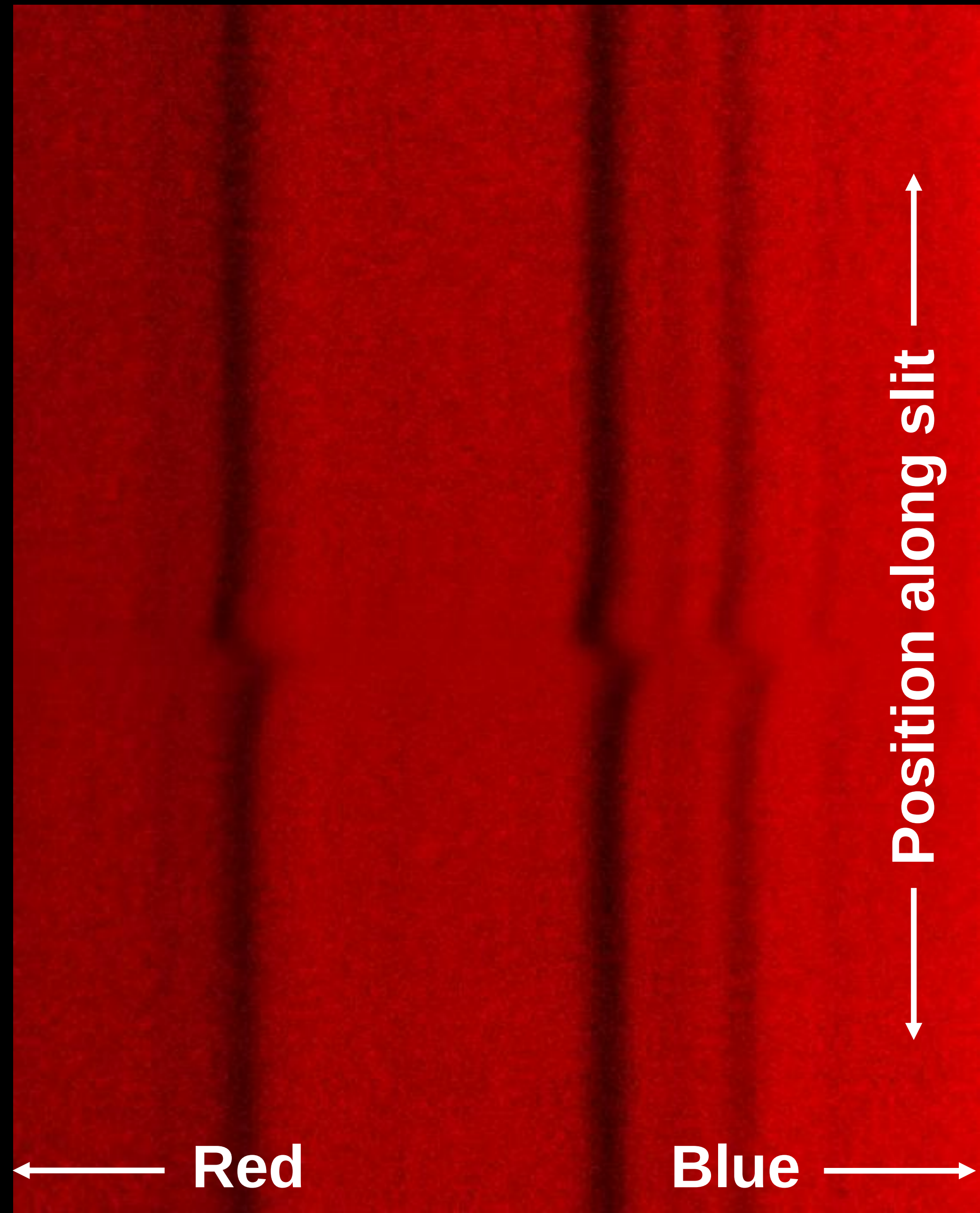


M 31: Black Hole Mass = 40 Million Suns

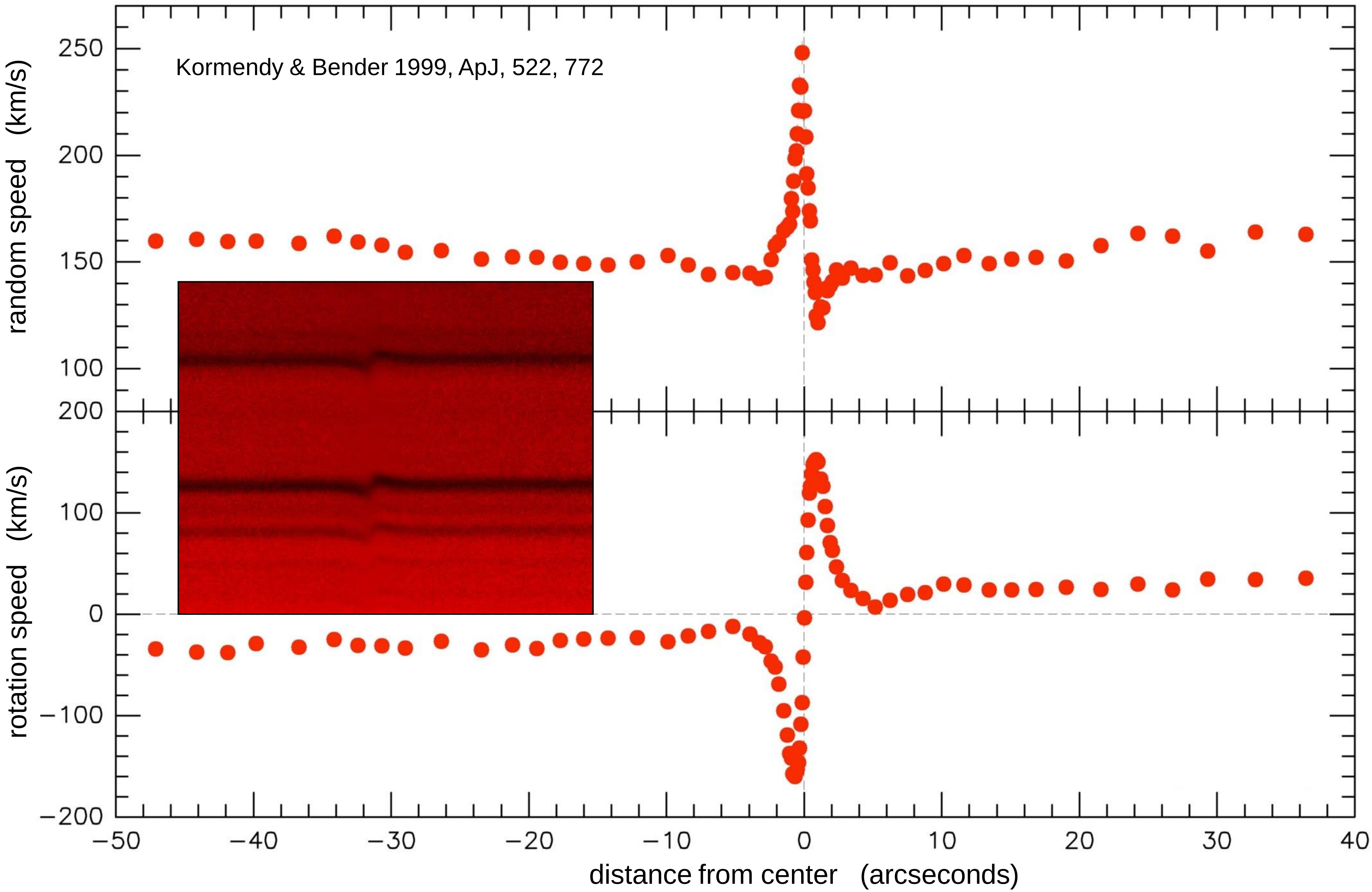
M 31 on spectrograph slit

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 = 40 Million Suns



M 31: Black Hole Mass = 40 Million Suns

Distance ≈ 2.5 x 10^6 light years (ly) $\Rightarrow$ scale = 82 arcsec / 1000 ly.

Observe rotation velocity V ≈ 160 km/s at radius r = 1 arcsec.

Mass: Balance centripetal acceleration and gravity:

$$mV^2/r = GMm/r^2 \quad \Rightarrow \quad M = V^2\, r\, /\, G\ ,$$

where M = central ("black hole") mass;
m = mass of orbiting star;
G = Gravitational constant;
$= 6.673 \times 10^{-8}\ cm^3 / g\, s^2$.

Approximate mass

$$V^2\, r\, /\, G \approx \frac{(160\ km/s)^2\ (10^5\ cm\ /\ km)^2\ (1\ arcsec)\ \ (9.47 \times 10^{17}\ cm/ly)}{(6.673 \times 10^{-8}\ cm^3\ g^{-1}\ s^{-1})\ (\ 1.99 \times 10^{33}\ g/\ M_\odot)\ (82\ arcsec\ /\ 1000\ ly)}$$

$= 22 \times 10^6\ M_\odot$. This is an underestimate because it does not include the effects of projection or random velocities.

M 31: Black Hole Mass = 40 Million Suns

NGC 3115: Black Hole Mass = 1 Billion Suns

NGC 3115: Black Hole Mass = 1 Billion Suns

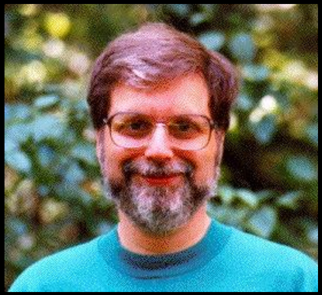
NGC 3115 has a bright central cusp of stars like we expect around a black hole.

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.

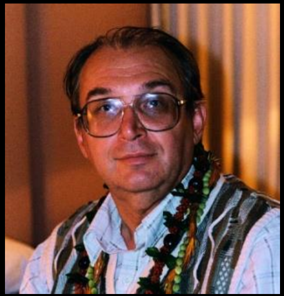
The Nuker Team



Doug Richstone

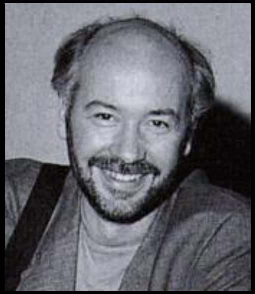
Sandra Faber

Karl Gebhardt



John Kormendy

Alan Dressler



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Alex Filippenko

Richard Green

Additional Nukers

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Luis Ho
John Magorrian
Jason Pinkney
Tod Lauer
Scott Tremaine

Thanks Also To
STIS Team Members

Gary Bower
Mary Beth Kaiser
Charlie Nelson

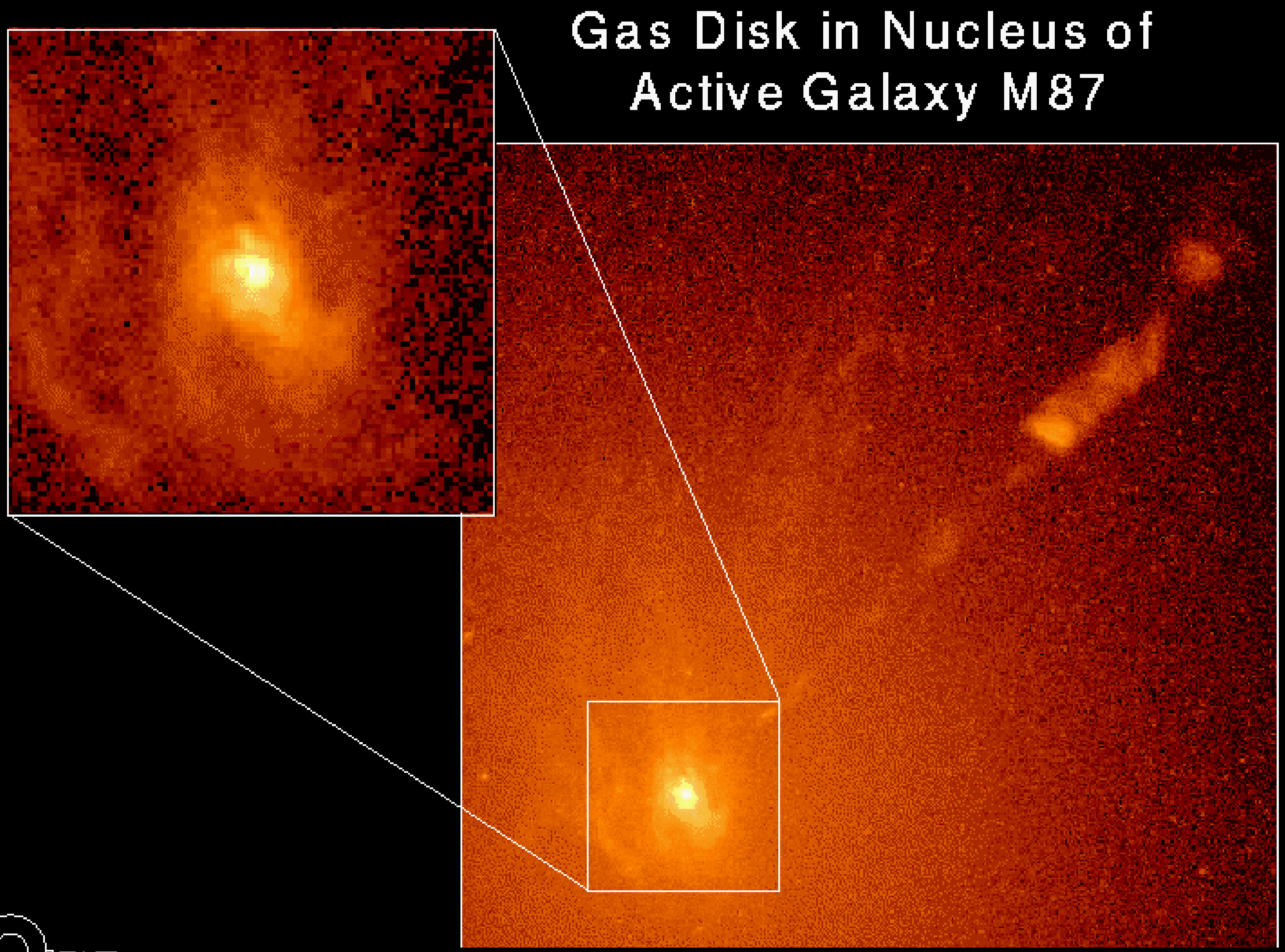
Black Hole Census — April 2002

Galaxy	Distance (million ly)	Black Hole Mass (million Suns)
Milky Way	0.028	3
M 31	2.3	40
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

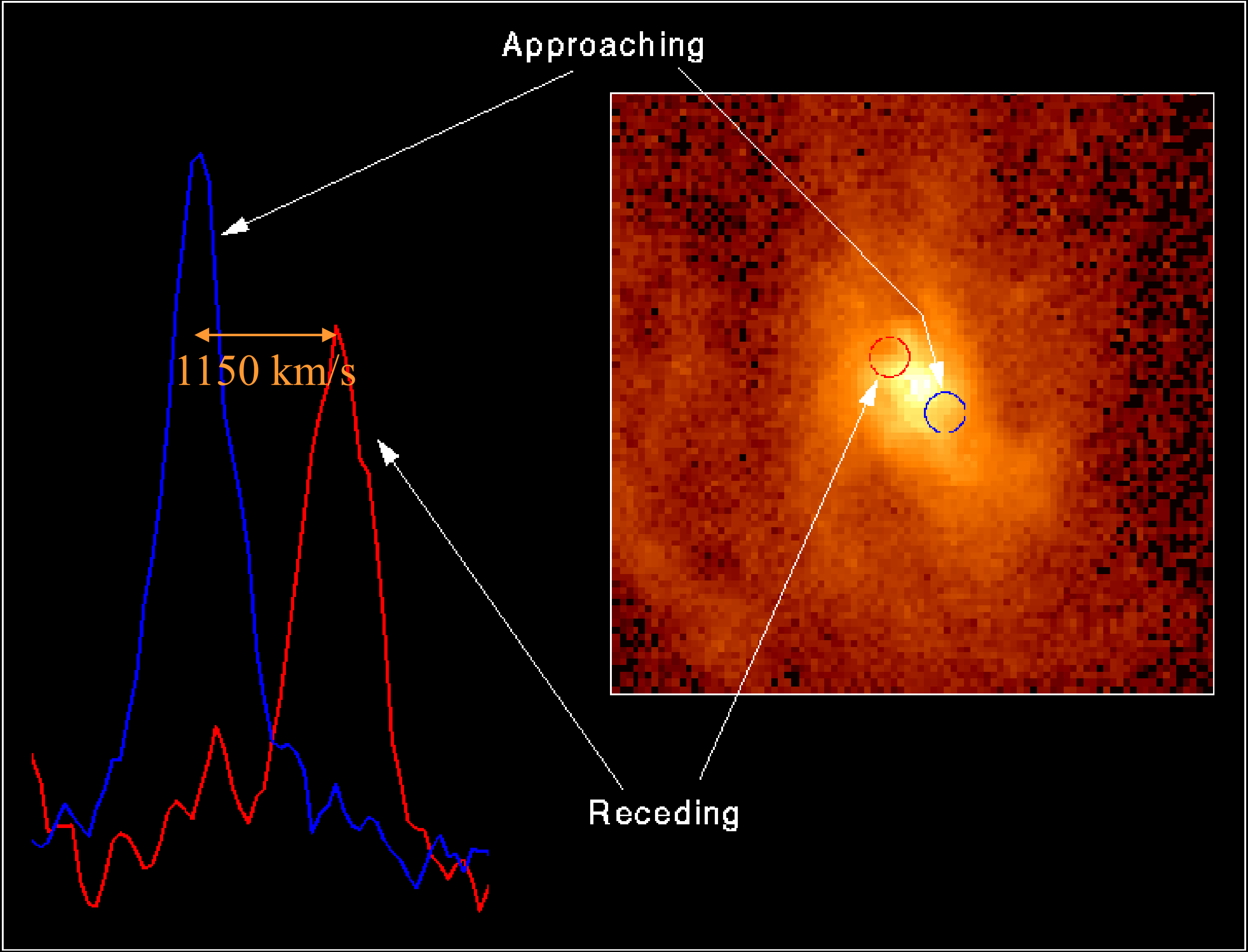
M 87: Black Hole Mass = 2.5 Billion Suns



SPACE TELESCOPE SCIENCE INSTITUTE

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

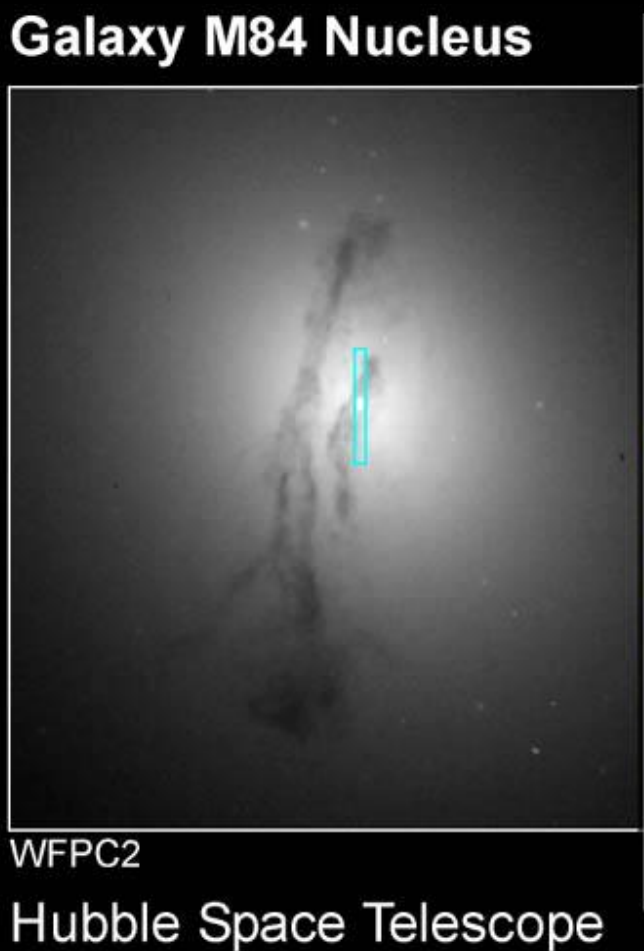
Spectrum of Gas Disk in Active Galaxy M87

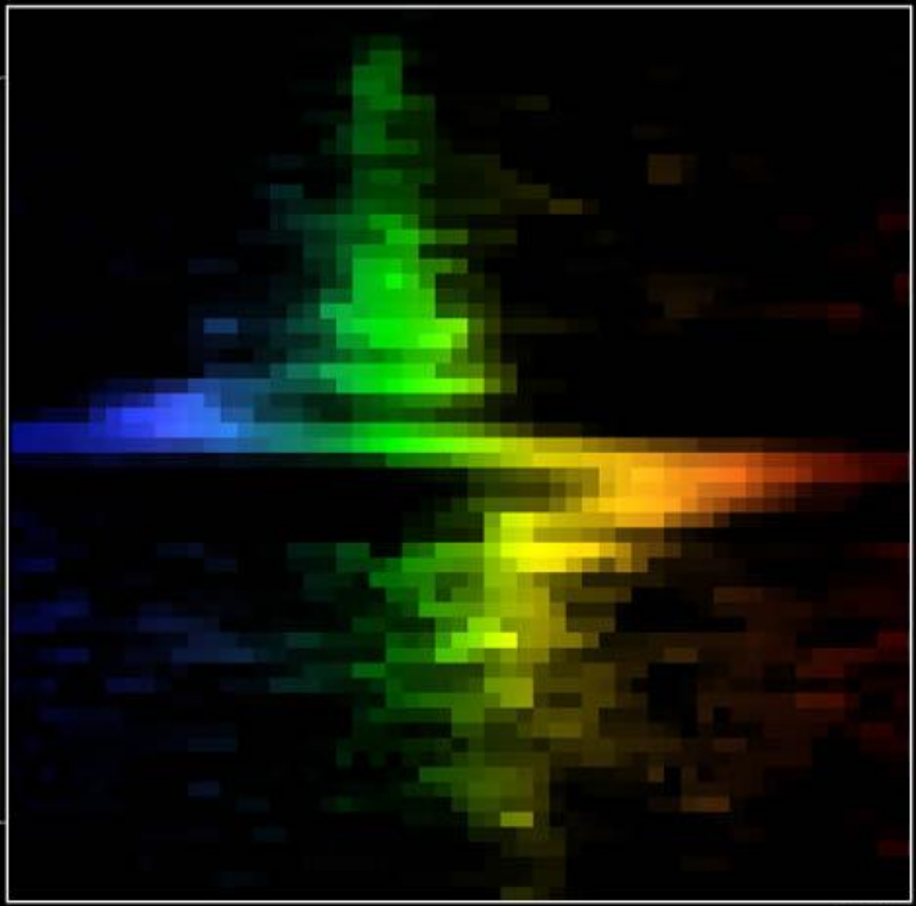


From the difference in Doppler shifts seen on opposite sides of the center, the disk rotates at almost 600 km/s.
This implies a black hole of mass 2.5 billion Suns.

M 84: Black Hole Mass = 1 Billion Suns

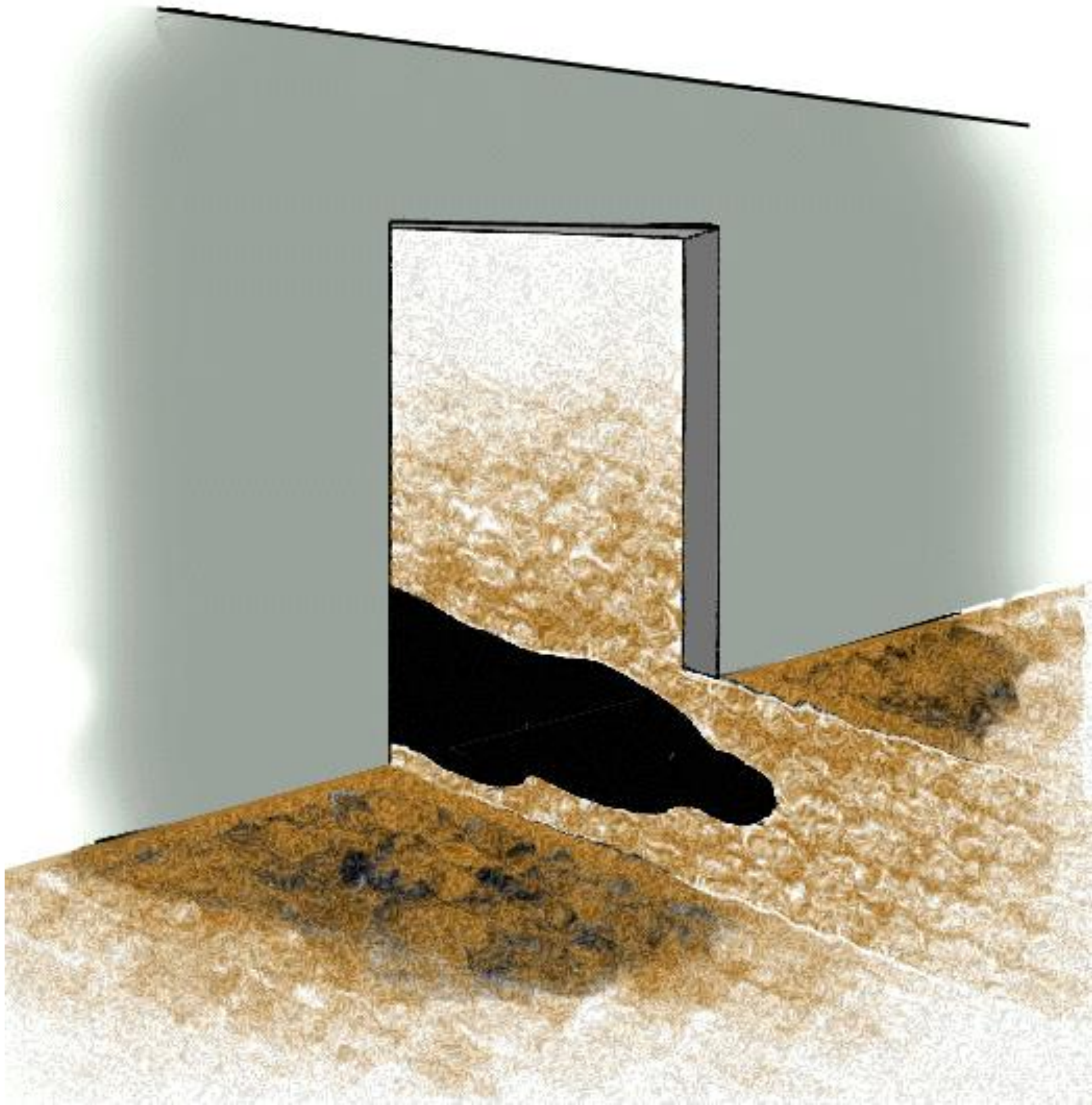
The Space Telescope Imaging Spectrograph
is providing spectacular new data on black holes.





Bower et al. 1998, ApJ, 492, L111

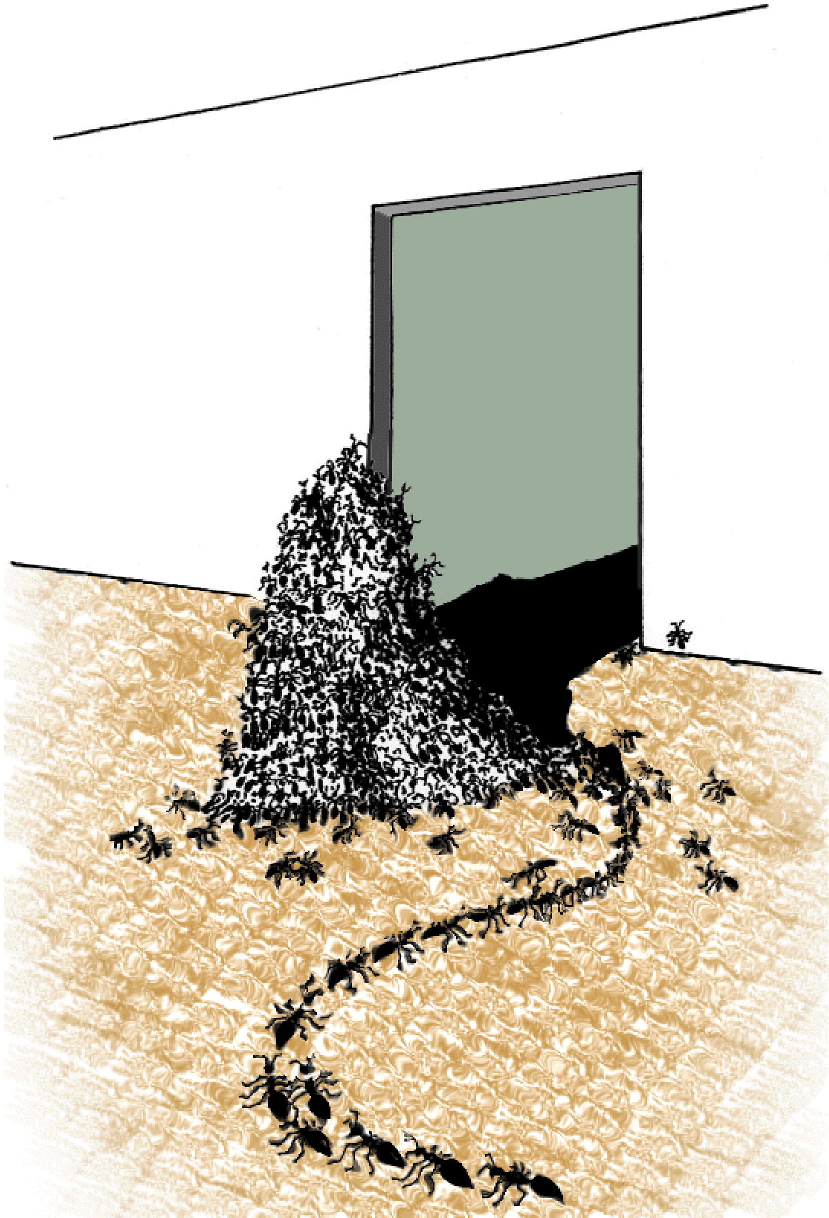
We observe only a shadow of the dark object — its gravitational effect on ordinary stars and gas.



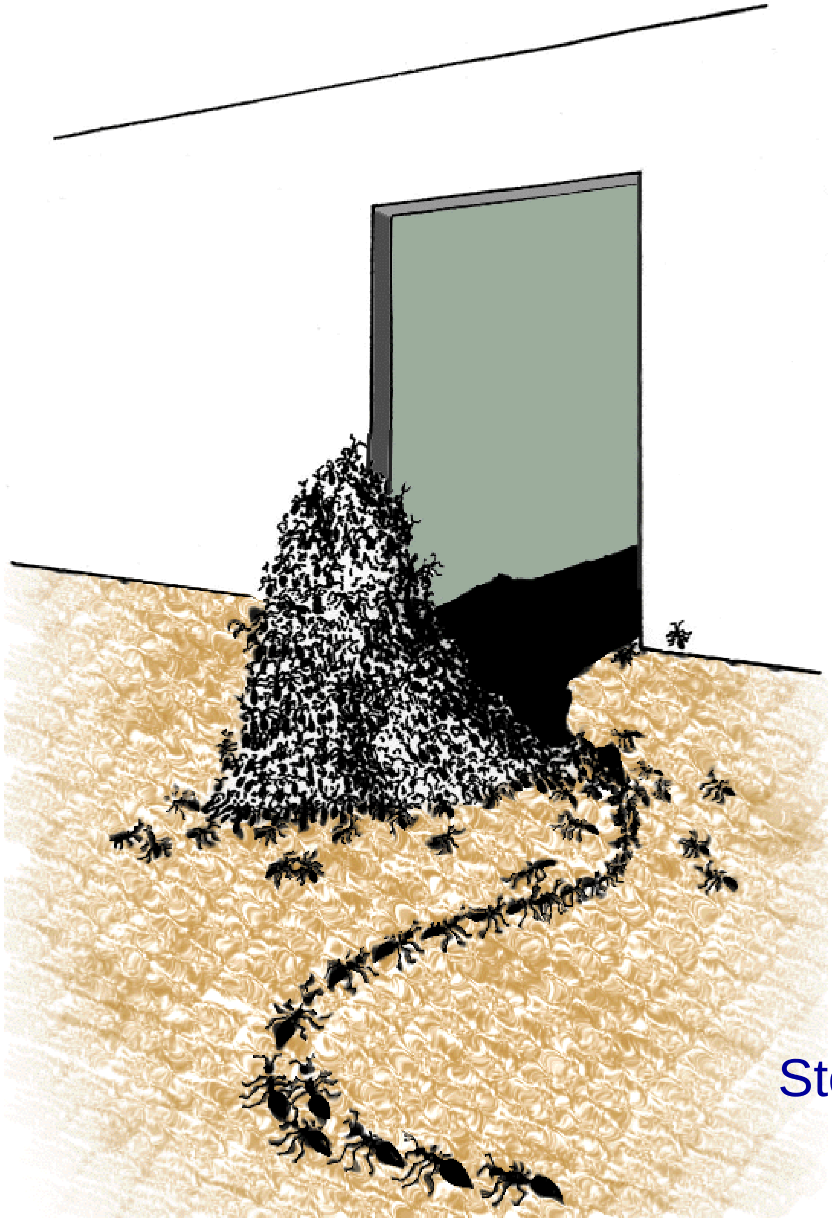
Are we detecting one object?

Or two?

Or many?



Could we be detecting a cluster of dark stars?

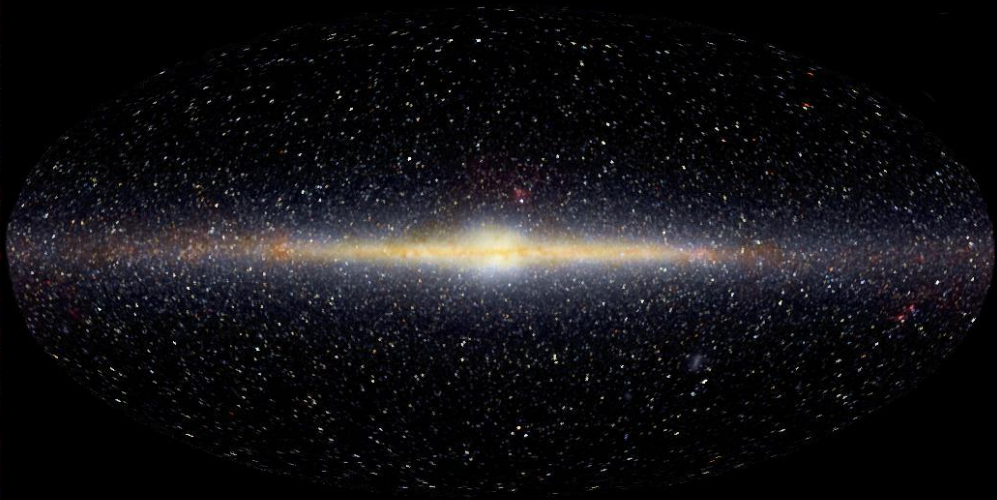


Possibilities

Brown dwarf stars
White dwarf stars
Neutron stars
Stellar-mass black holes

NGC 4258: Dark Mass = 42 Million Suns

Our Galaxy: Dark Mass = 3 Million Suns



We can measure the rotation of these two galaxies especially close to the center.

The dark mass is in such a small volume at the center that alternatives to a black hole (failed stars or dead stars) are ruled out.

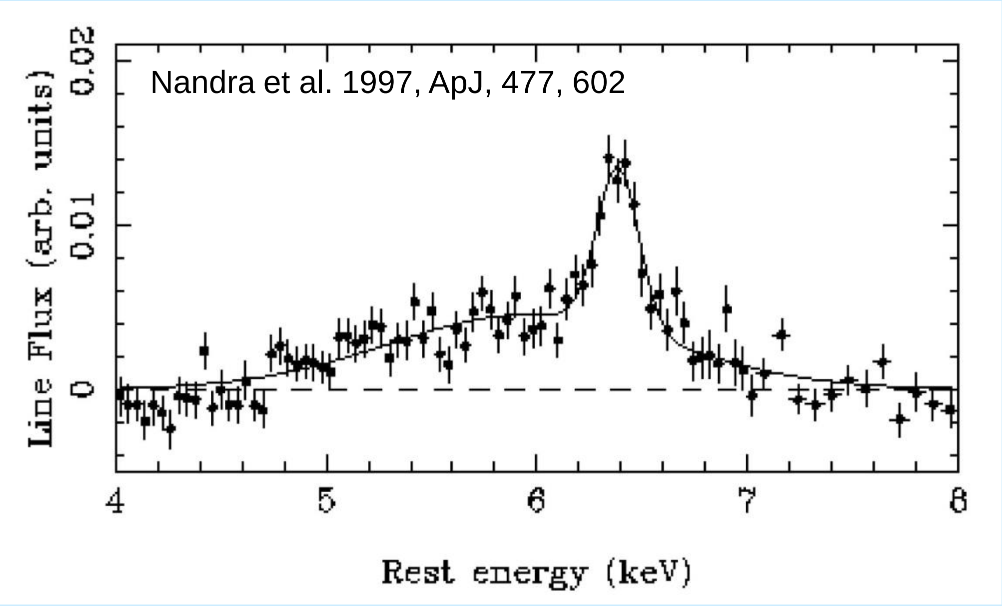
These are the best black hole candidates.

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.

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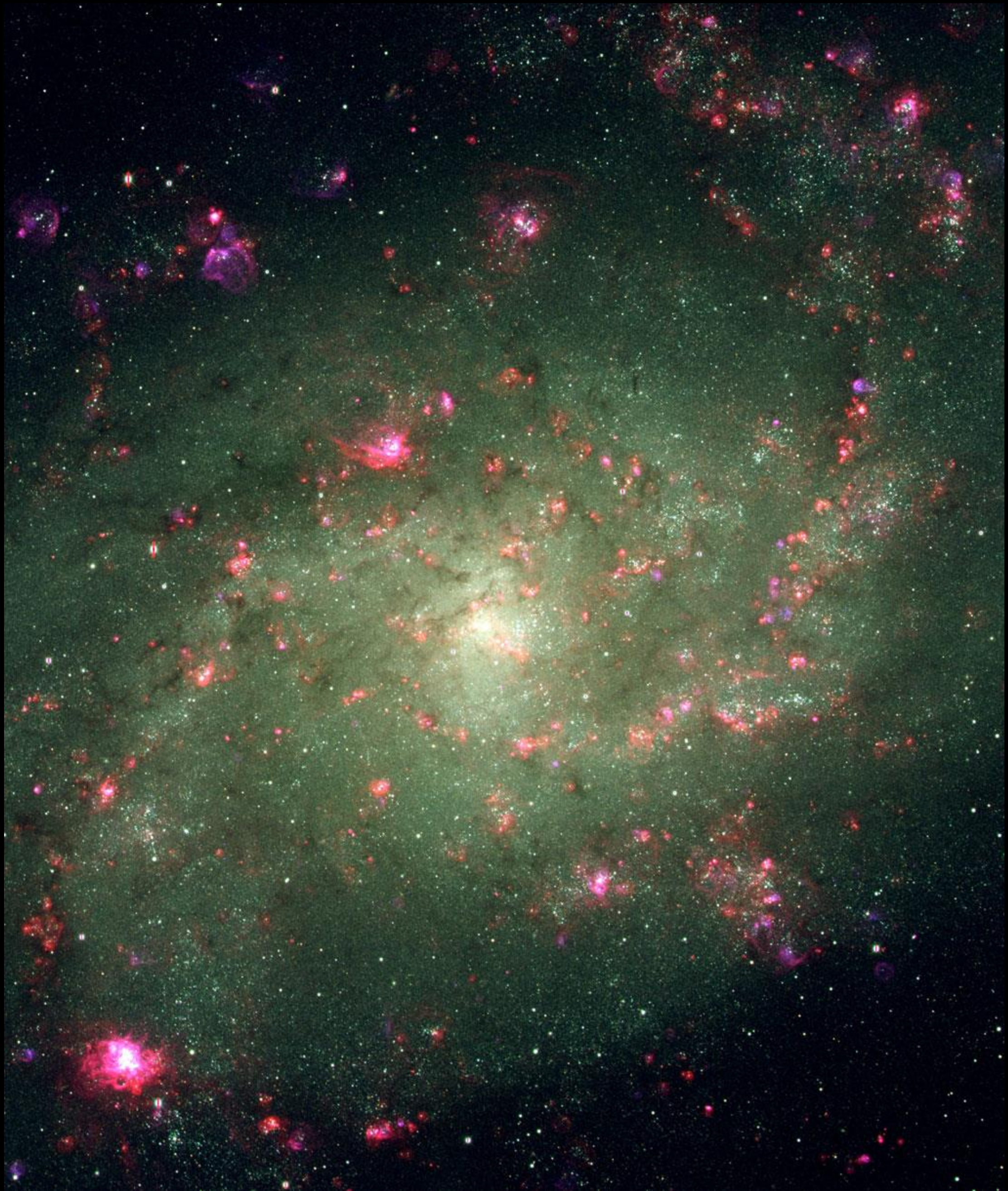
The bulgeless galaxy M 33 does not contain a black hole.




Typical stars in the nucleus of M 33 move at only 21 km/s.
Any black hole must be less massive than 1500 Suns.

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

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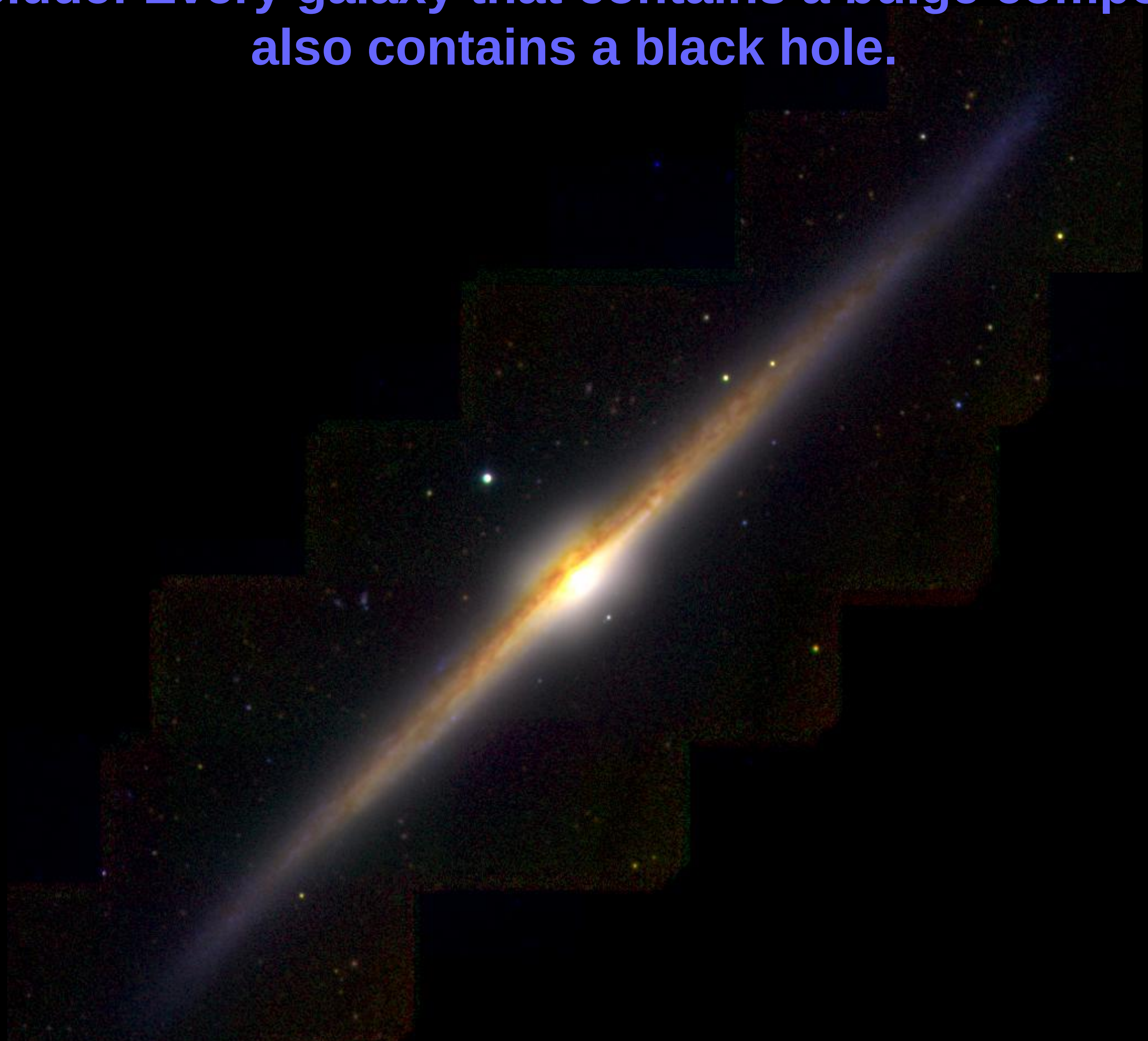
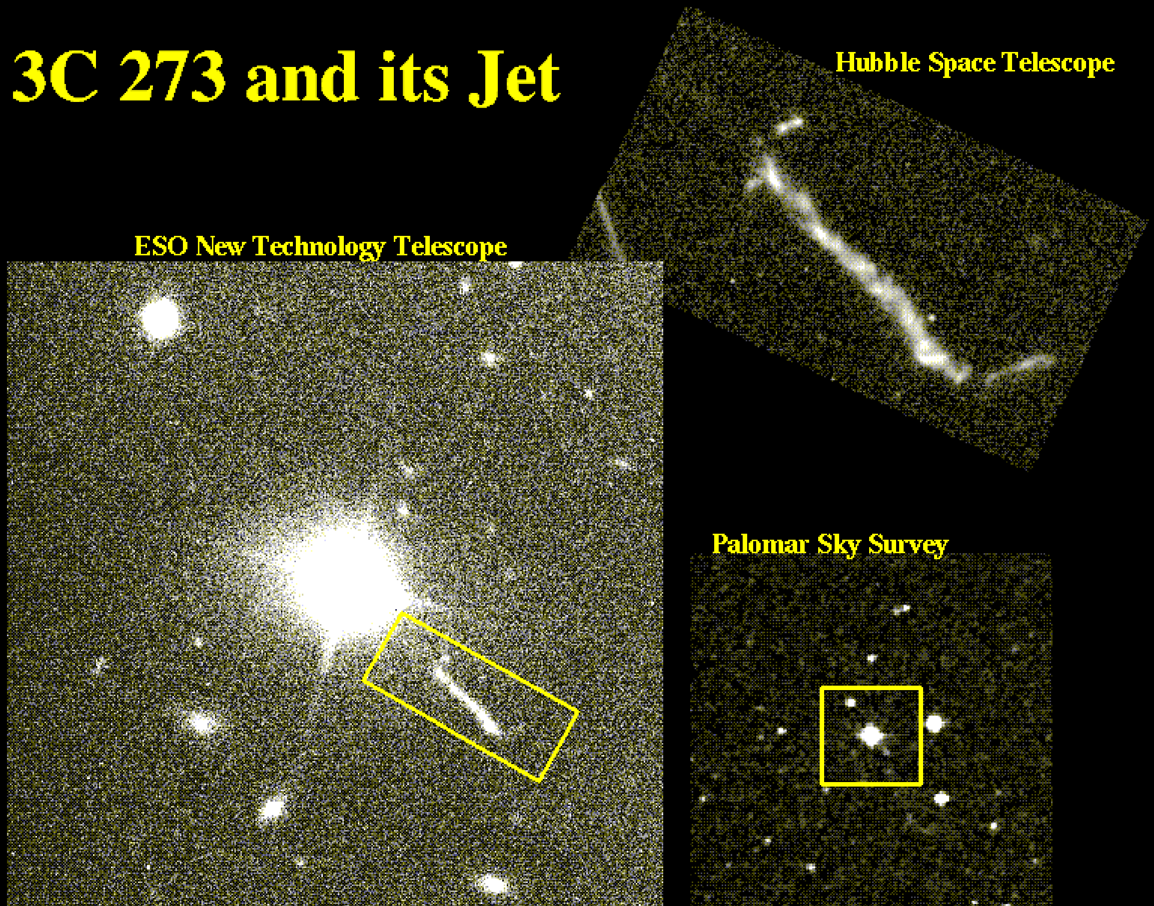


No bulge ⇒ no black hole.

Black Hole Conclusions

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



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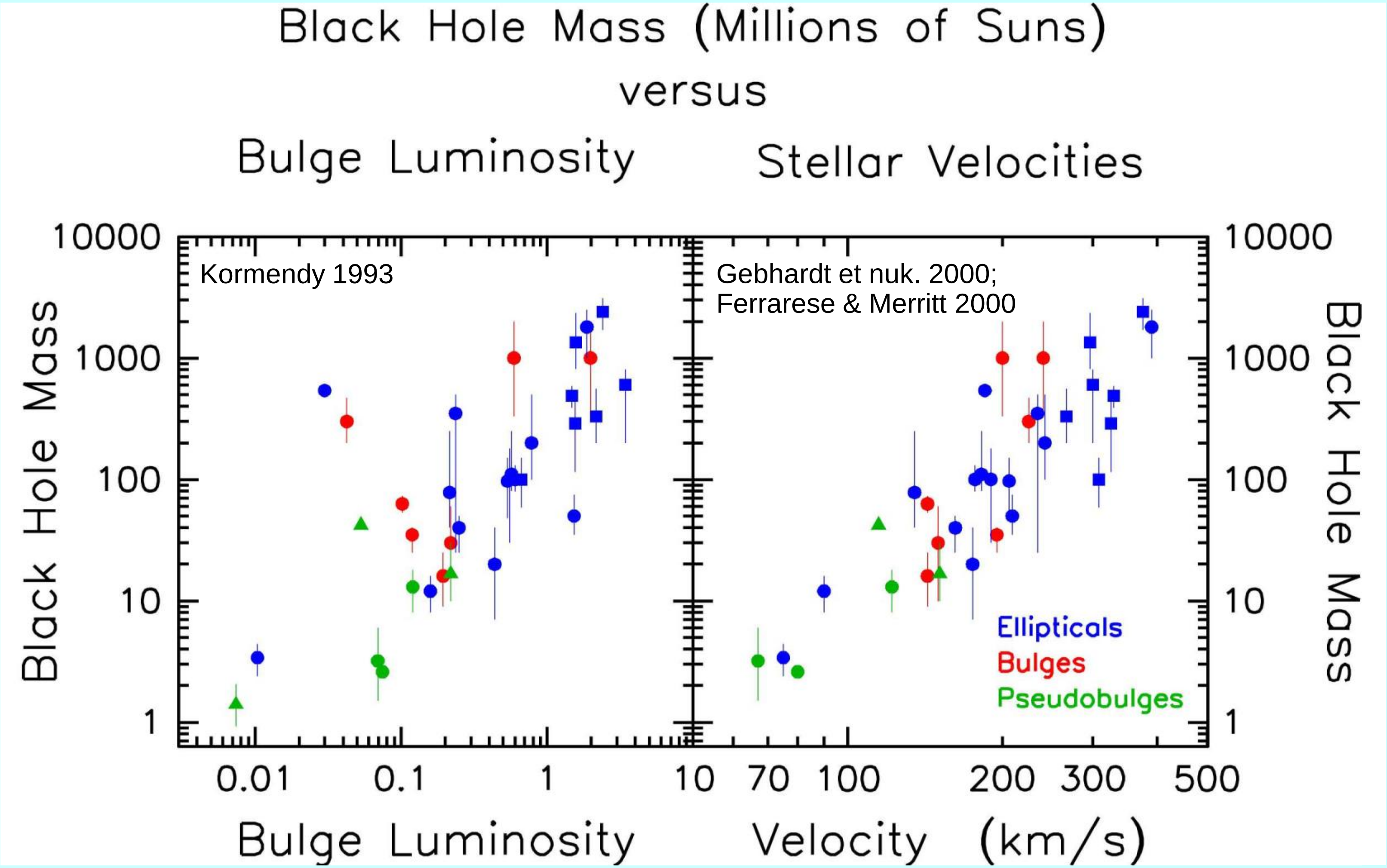
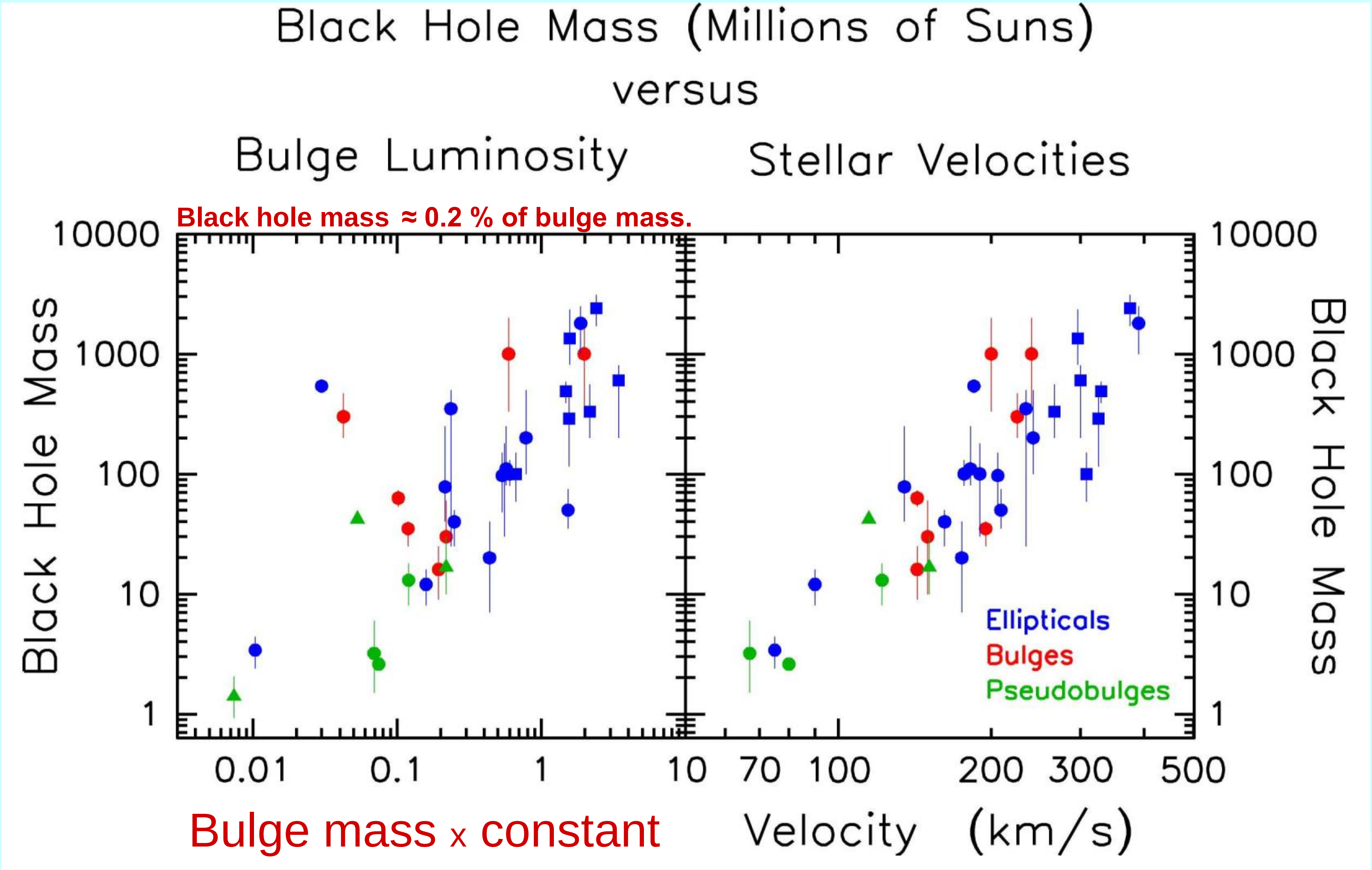


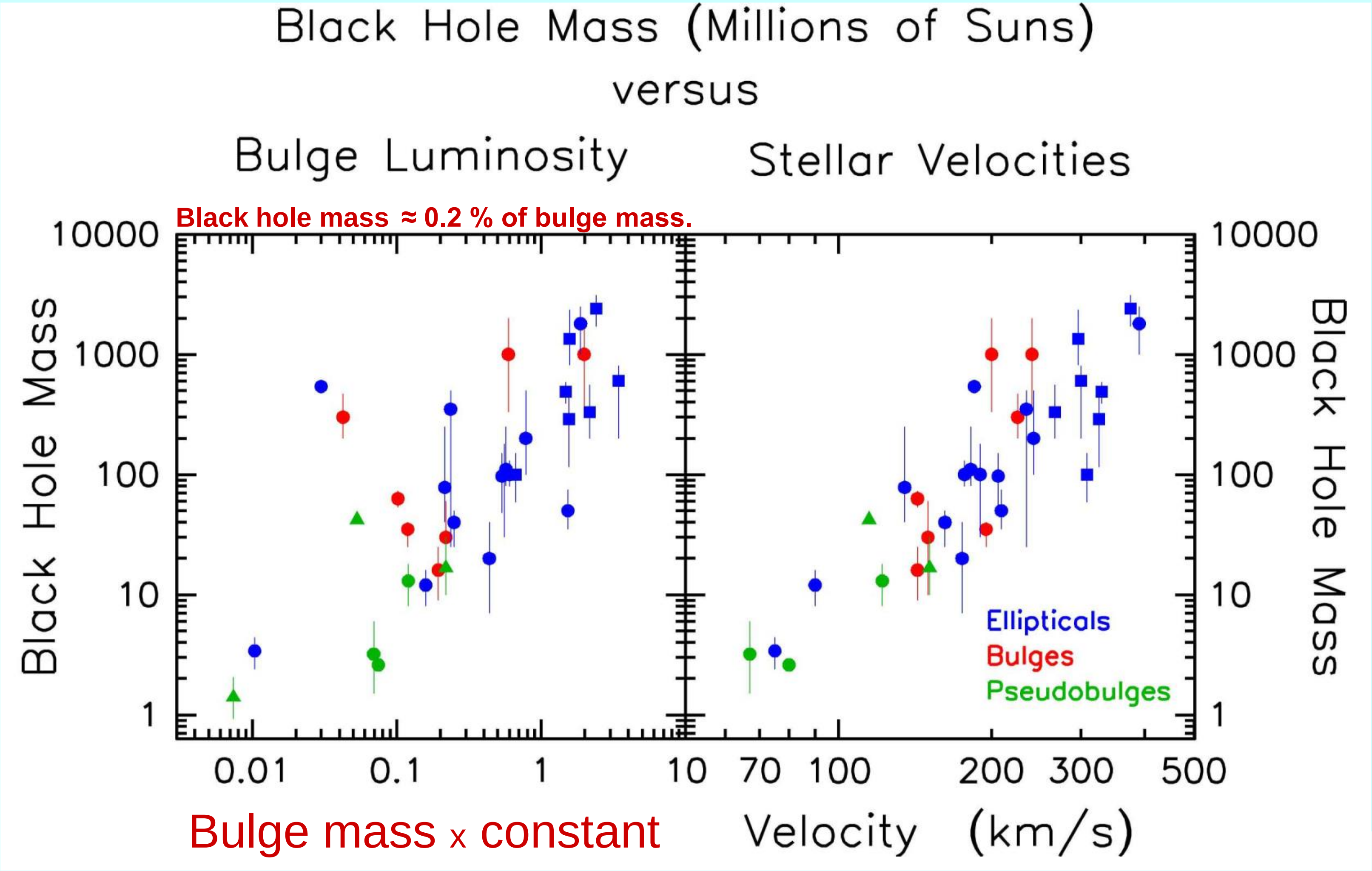
Bigger black holes live in bigger galaxy bulges.

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



These diagrams contain almost the same information, because galaxy mass is measured by stellar velocity. What is new in the right panel?

Answer: how much the bulge collapsed when it formed.



Black hole mass is more connected with how much a bulge collapsed than with how big the bulge is. So there is a close connection between black hole growth and bulge formation.

CONCLUSION

The formation of bulges
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.

Hubble Deep Field

The Future

<u>**Short-term**</u>

It should be possible to derive black hole masses for thousands of quasars and other active galaxies

and

probe the growth of black holes as the Universe evolved.

<u>**Long-term**</u>

Gravitational wave astronomy

THANKS

To Mr. And Mrs. Curtis Vaughan for endowing the Curtis T. Vaughan Centennial Chair in Astronomy.

To my wife Mary for putting up with an astronomer husband.

To Pamela Gay for her help with this presentation.

To the Nuker team and especially Karl Gebhardt for many years of fruitful collaboration.

Dr. John Kormendy

Department of Astronomy

Dr. John Kormendy is a professor at the University of Texas at Austin. His research interests include the search for black holes in galactic nuclei, elliptical galaxies and bulges of disk galaxies, dark matter, and secular evolution in galaxy structure.