# Introduction to Black Hole Astrophysics I

Giovanni Miniutti
with the help of Montserrat Villar Martin

CENTRO DE ASTROBIOLOGÍA

Nov 2016 – IFT/UAM

STRONGGRAVITY
EU FP7-SPACE research project 312789 2013 - 2017

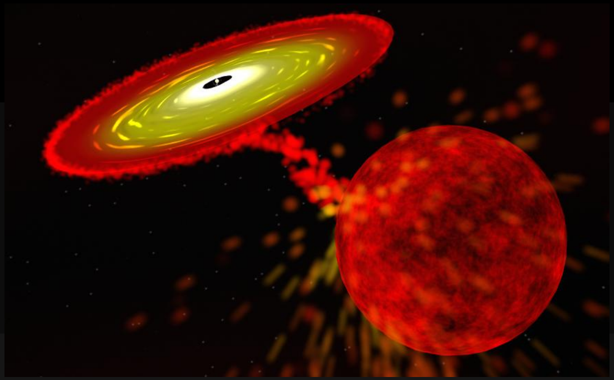
SEVENTH FRAMEWORK PROGRAMME

# Outline of the 3 lectures-course

## Lecture 1

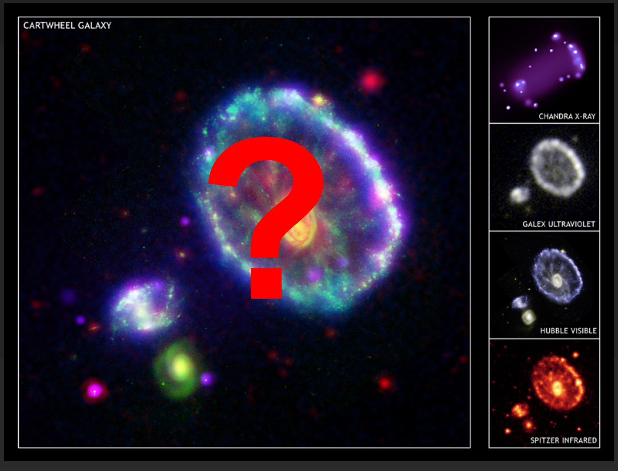
- The different flavors of astrophysical BHs
- Observational evidence for astrophysical BHs:
  - BHs in binary systems
  - The Milky Way super-massive BH (SMBH): the case of Sgr $A^*$
  - SMBHs in other galaxies

# Black Holes



**Stellar-mass (~10 solar masses)**
The most massive stars end their lives leaving nothing behind their ultra-dense collapsed cores which we can observe when accreting from a companion star [X-ray binary]

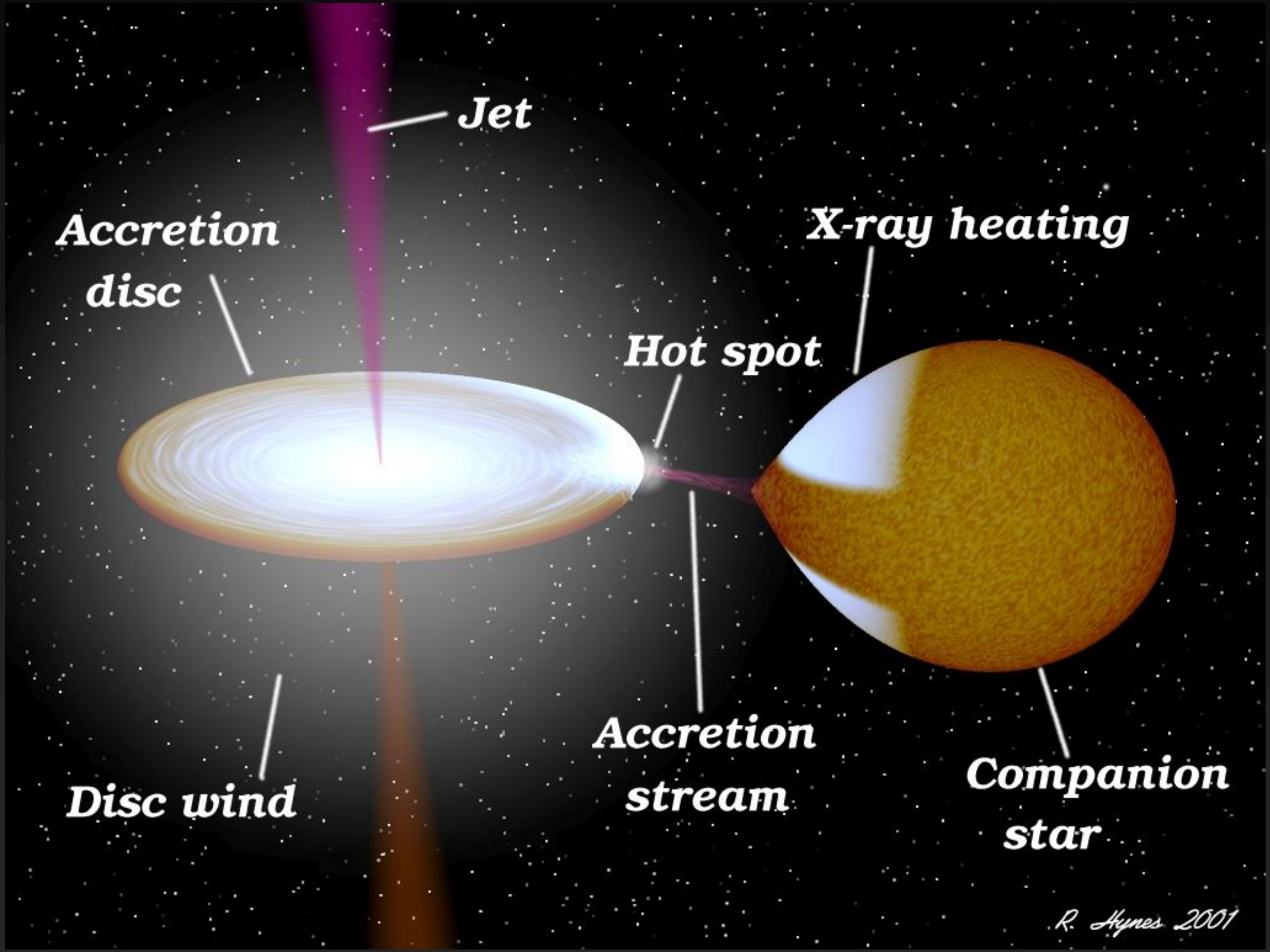
**Super-massive ($10^6$-$10^9$ solar masses)**
The centers of galaxies contain giant black holes, which we can observe when accreting the surrounding matter / gas [AGN]



**Intermediate-mass ($10^2$ – $10^4$ solar masses)**
A new class of recently-discovered black holes could have masses on the order of hundreds or thousands of stars although the debate is open [ULX ?]

# Black Holes: observational evidences (some)

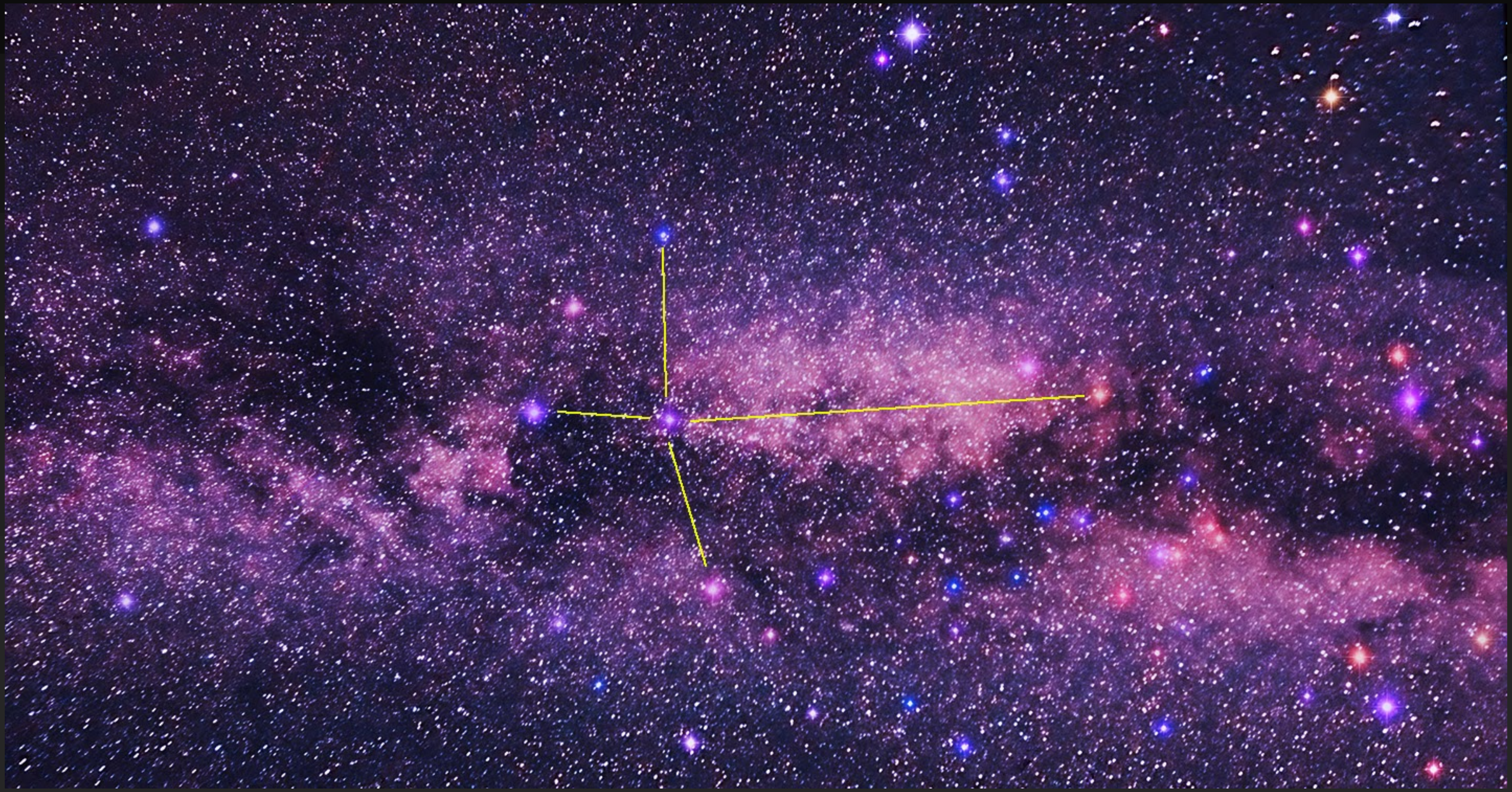
Stellar-mass (~10 solar masses)



# Black Holes: observational evidences (some)

## Stellar-mass (~10 solar masses)

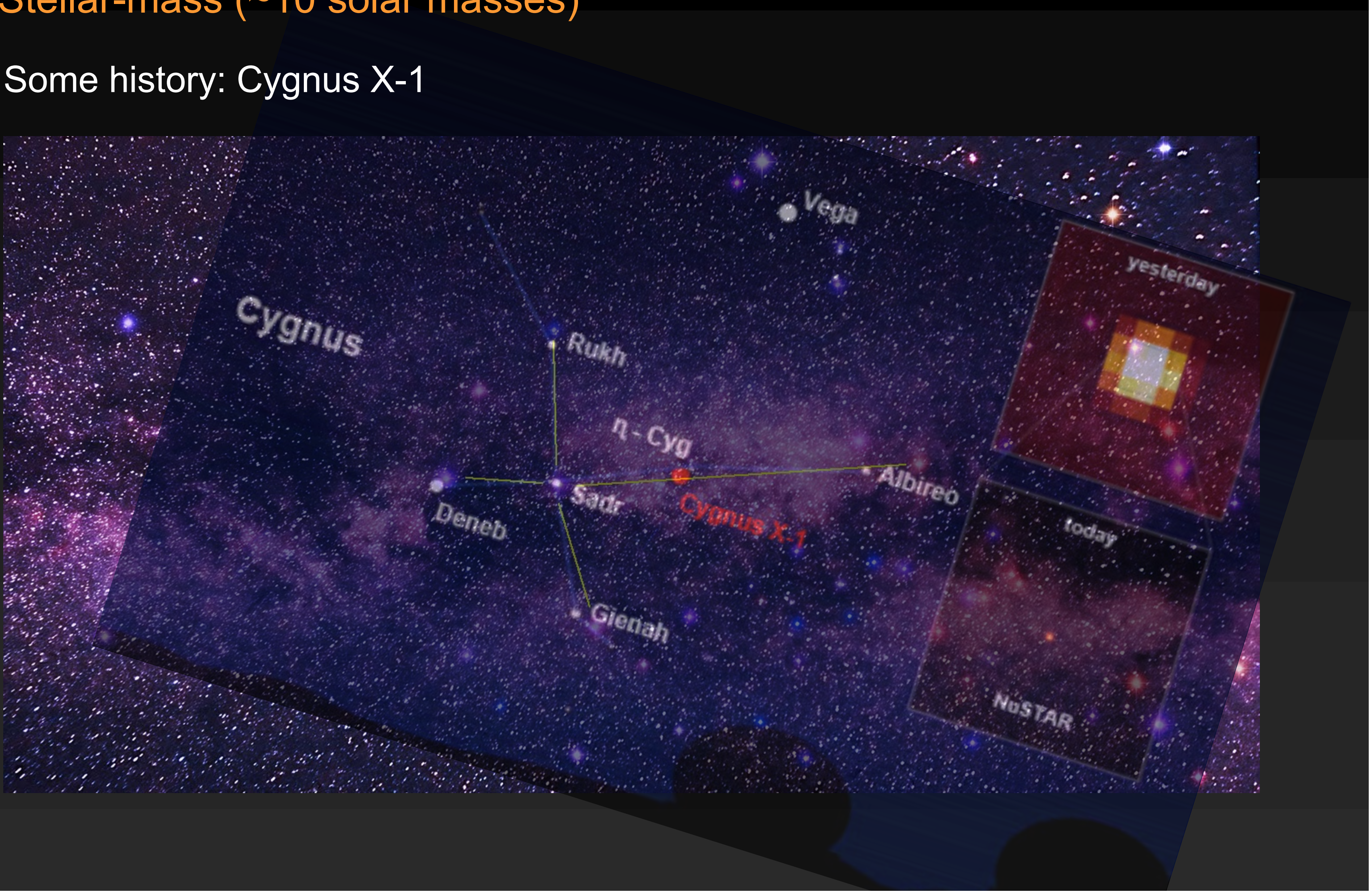
Some history: Cygnus X-1



# Black Holes: observational evidences (some)

## Stellar-mass (~10 solar masses)

Some history: Cygnus X-1



# Black Holes: observational evidences (some)

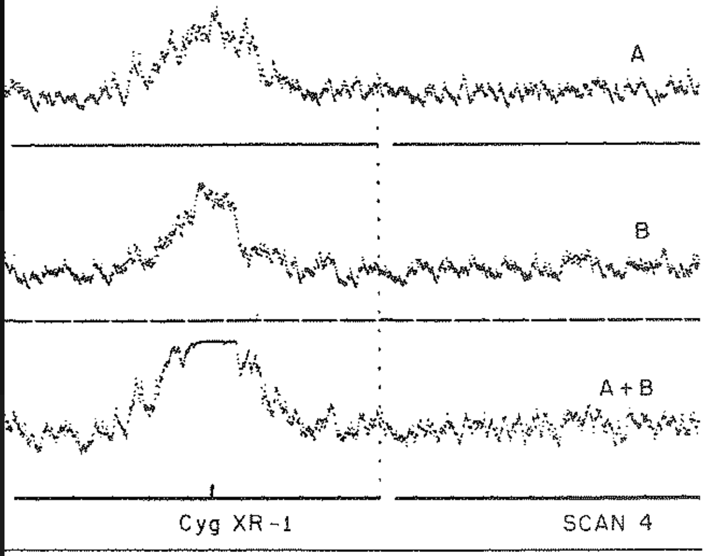
## Stellar-mass (~10 solar masses)

Some history: Cygnus X-1

1964 – a bright X-ray source was discovered from X-ray detectors launched on rockets

# Black Holes: observational evidences (some)

## Stellar-mass (~10 solar masses)



Some history: Cygnus X-1

1964 – a bright X-ray source was discovered from X-ray detectors launched on rockets

1970 – NASA launches the Uhuru satellite which leads to the discovery of about ~300 previously unknown X-ray sources

1970s - Uhuru observations of Cyg X-1 detected very fast variability (fluctuations in the X-ray emission on timescales < 1 s)

# Black Holes: observational evidences (some)

## Stellar-mass (~10 solar masses)

Some history: Cygnus X-1

1964 – a bright X-ray source was discovered from X-ray detectors launched on rockets

1970 – NASA launches the Uhuru satellite which leads to the discovery of about ~300 previously unknown X-ray sources

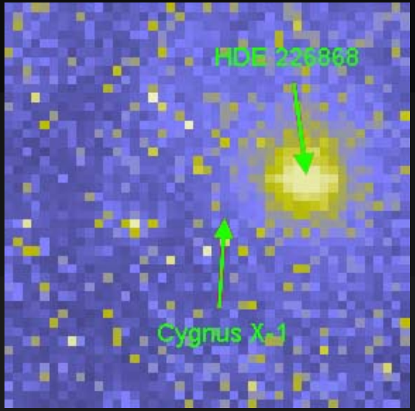
1970s - Uhuru observations of Cyg X-1 detected very fast variability (fluctuations in the X-ray emission on timescales < 1 s)

1971 – Radio emission was detected, and an accurate position was obtained for Cyg X-1 (X-ray telescopes have generally poor angular resolution)

# Black Holes: observational evidences (some)

## Stellar-mass (~10 solar masses)

Some history: Cygnus X-1



1964 – a bright X-ray source was discovered from X-ray detectors launched on rockets

1970 – NASA launches the Uhuru satellite which leads to the discovery of about ~300 previously unknown X-ray sources

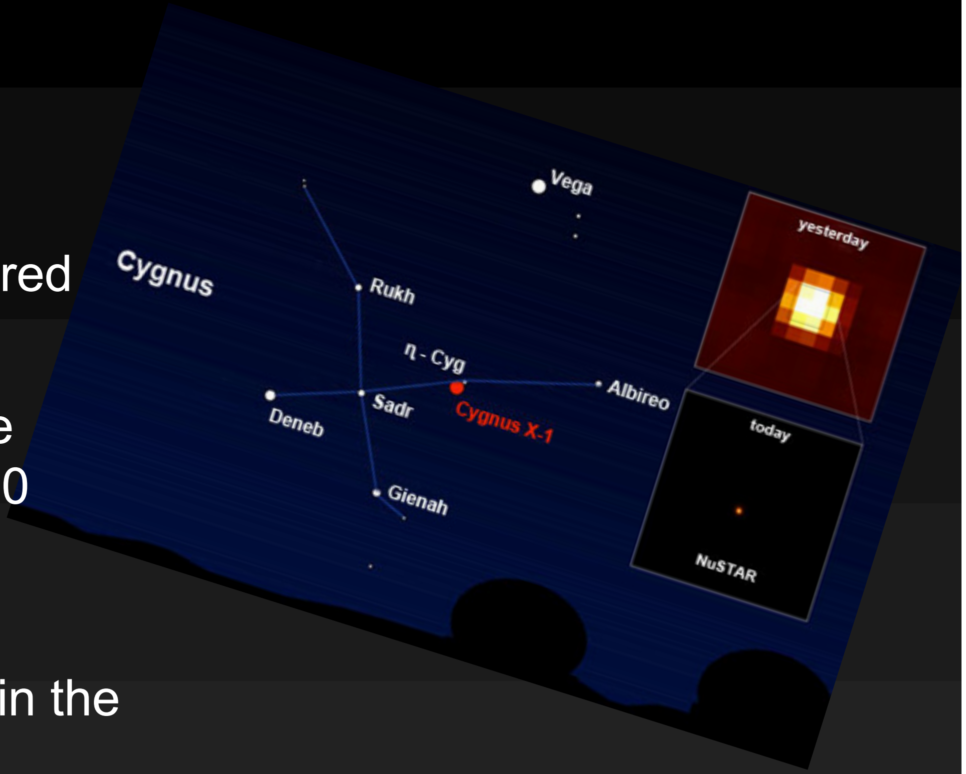
1970s - Uhuru observations of Cyg X-1 detected very fast variability (fluctuations in the X-ray emission on timescales < 1 s)

1971 – Radio emission was detected, and an accurate position was obtained for Cyg X-1 (X-ray telescopes have generally poor angular resolution)

→ an optical counterpart was found (the supergiant star HDE 226868). It is impossible for supergiant stars to emit the amount of X-rays that were observed

# Black Holes: observational evidences (some)

## Stellar-mass (~10 solar masses)



Some history: Cygnus X-1

1964 – a bright X-ray source was discovered from X-ray detectors launched on rockets

1970 – NASA launches the Uhuru satellite which leads to the discovery of about ~300 previously unknown X-ray sources

1970s - Uhuru observations of Cyg X-1 detected very fast variability (fluctuations in the X-ray emission on timescales < 1 s)

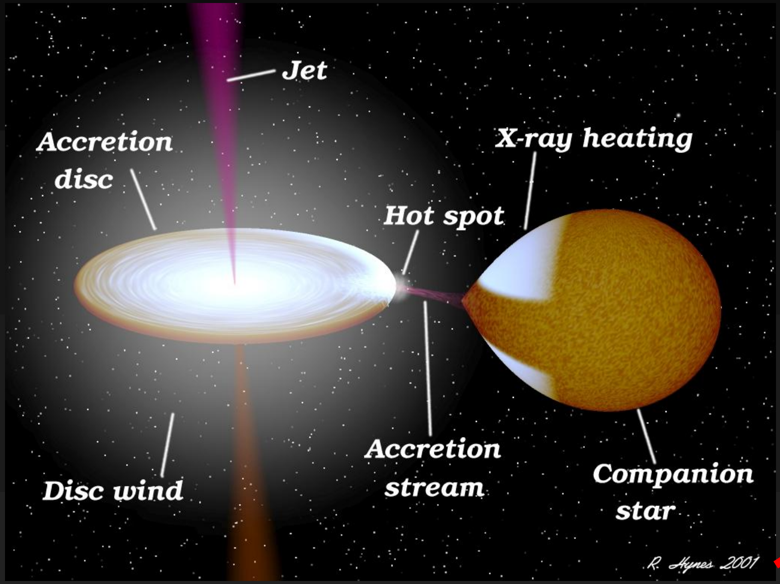
1971 – Radio emission was detected, and an accurate position was obtained for Cyg X-1 (X-ray telescopes have generally poor angular resolution)

→ an optical counterpart was found (the supergiant star HDE 226868). It is impossible for supergiant stars to emit the amount of X-rays that were observed

→ HDE 2268686 must have a companion capable of heating gas to the millions of degrees that are necessary for X-ray production

# Black Holes: observational evidences (some)

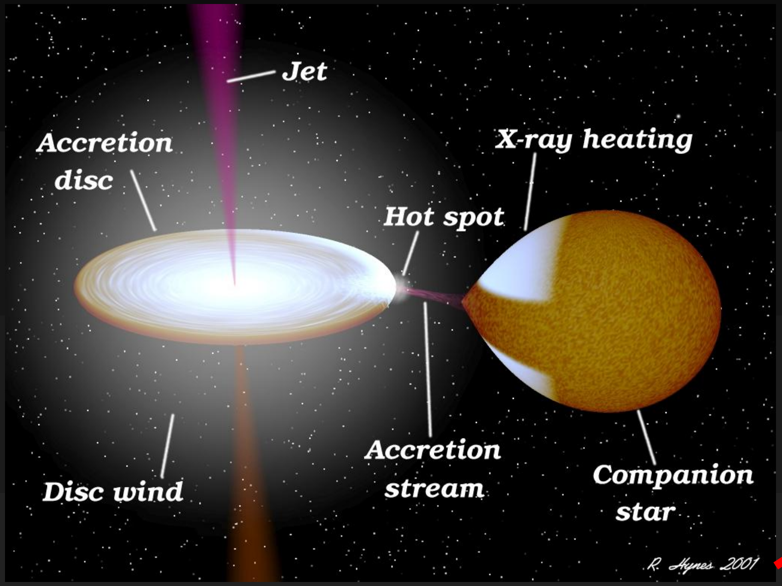
## Stellar-mass (~10 solar masses)

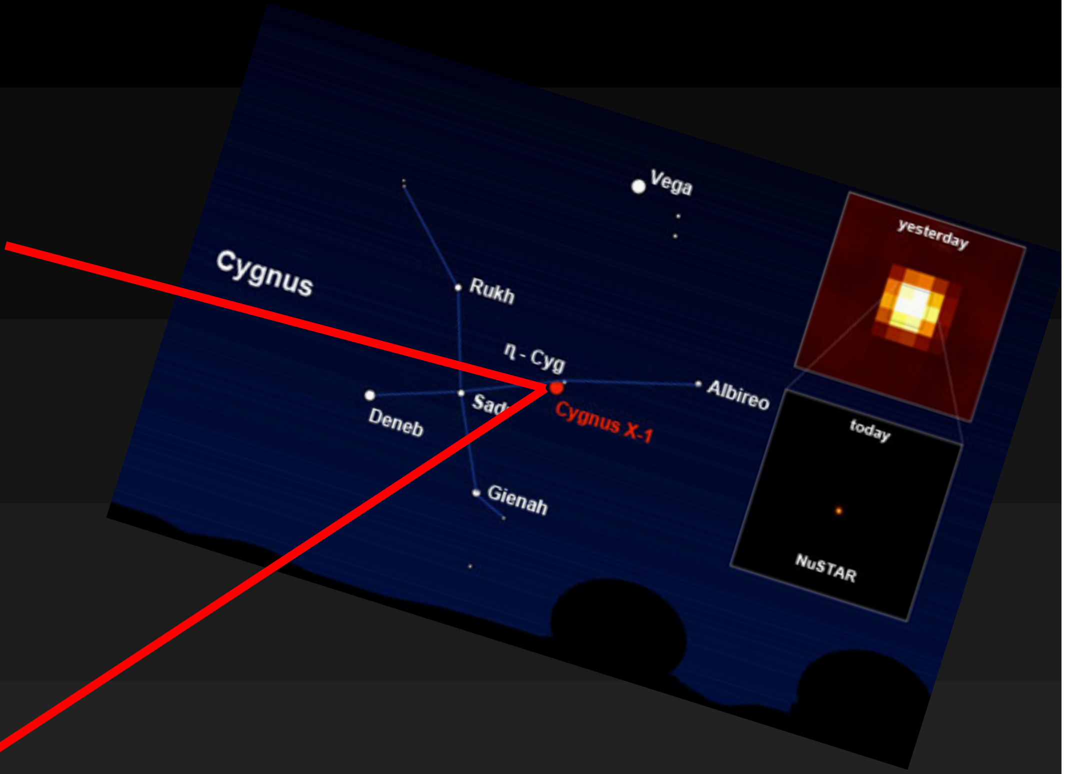


Many other X-ray sources at the position of normal stars have been detected afterwards. They were all identified with binary systems in which one of the two members is an accreting compact object

# Black Holes: observational evidences (some)

## Stellar-mass (~10 solar masses)





Many other X-ray sources at the position of normal stars have been detected afterwards. They were all identified with binary systems in which one of the two members is an accreting compact object

The challenge became then that of identifying (at least some of) these compact objects as BHs accreting gas and matter from their companion star and releasing vast amounts of energy in X-rays

# Black Holes: observational evidences (some)

## Stellar-mass (~10 solar masses)

The binary system is composed by a normal star loosing matter which is accreted onto a compact “invisible” object via a thin disc (the accretion disc)

How can we know about the nature of the compact dark object ? In principle, the dark companion to the satr could be a WD, a NS or a BH

So the question is: are there binary systems where we can be sure that the companion to the standard, visible star is a BH ?

# Black Holes: observational evidences (some)

## Stellar-mass (~10 solar masses)

The binary system is composed by a normal star loosing matter which is accreted onto a compact “invisible” object via a thin disc (the accretion disc)

How can we know about the nature of the compact dark object ? In principle, the dark companion to the satr could be a WD, a NS or a BH

So the question is: are there binary systems where we can be sure that the companion to the standard, visible star is a BH ?

We rely on the following maximum masses that are absolute upper limits for WDs and NSs

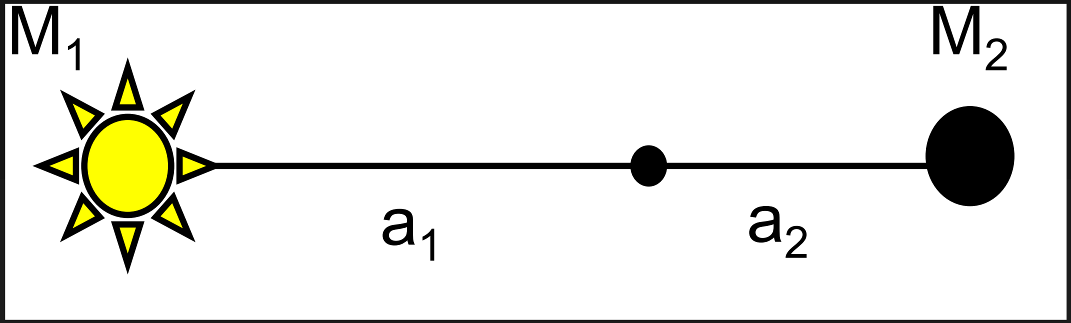
$$M_{\max}^{WD} \cong 1.5 M_{sun} \qquad M_{\max}^{NS} \leq 2.5 M_{sun}$$

if the mass of the compact object exceeds the maximum mass of a NS, we can be reasonably sure that we are dealing with a BH

# Black Holes: observational evidences (some)

## Stellar-mass (~10 solar masses)

how do we measure the mass of a dark companion in a binary system ?



$$\begin{cases} a = a_1 + a_2 \\ M_1 a_1 = M_2 a_2 \end{cases}$$

$$a = \frac{M_1 + M_2}{M_2} a_1$$

and considering Kepler's 3° law

$$G \frac{M_1 + M_2}{a^3} = \left( \frac{2\pi}{P} \right)^2$$

# Black Holes: observational evidences (some)

## Stellar-mass (~10 solar masses)

$$a = \frac{M_1 + M_2}{M_2} a_1$$

$$G \frac{M_1 + M_2}{a^3} = \left( \frac{2\pi}{P} \right)^2$$

By combining the two expressions, one derives

$$G \frac{{M_2}^3}{(M_1 + M_2)^2 {a_1}^3} = \left( \frac{2\pi}{P} \right)^2$$

which relates the unknown mass $M_2$ to the mass of the primary star $M_1$ as well as to the orbital period $P$ and to the star-center of mass separation $a_1$

# Black Holes: observational evidences (some)

Stellar-mass (~10 solar masses)

$$G\frac{M_2^{\,3}}{(M_1+M_2)^2 a_1^{\,3}}=\left(\frac{2\pi}{P}\right)^2$$

However, there are still too many unknowns in the equation

We must find a way to measure observationally the orbital period P and the separation $a_1$

# Black Holes: observational evidences (some)

## Stellar-mass (~10 solar masses)

$$G\frac{{M_2}^3}{(M_1+M_2)^2{a_1}^3}=\left(\frac{2\pi}{P}\right)^2$$

However, there are still too many unknowns in the equation

We must find a way to measure observationally the orbital period P and the separation $a_1$

This can be achieved if we have information about the velocity of one of the two components of the binary system because

$$v_1=\frac{2\pi}{P}a_1\sin i$$

# Black Holes: observational evidences (some)

## Stellar-mass (~10 solar masses)

$$f(M_1, M_2, i) = \frac{(M_2 \sin i)^3}{(M_1 + M_2)^2} = \frac{P v_1^3}{2\pi G}$$

This is the so-called mass function

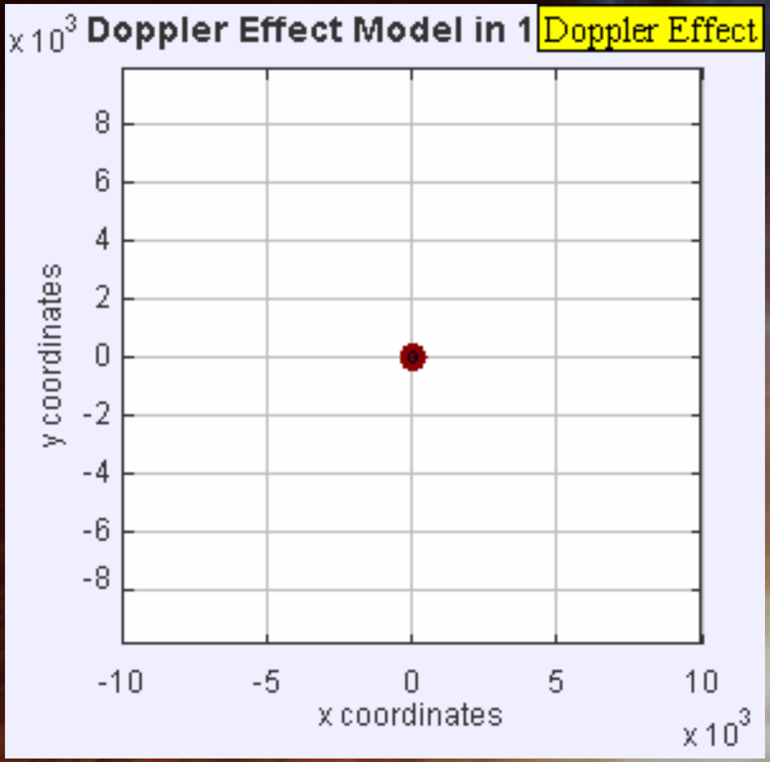
Moreover, looking at the l.h.s. of the equation, it is obvious that f = f ( $M_1$, $M_2$, i ) always satisfies

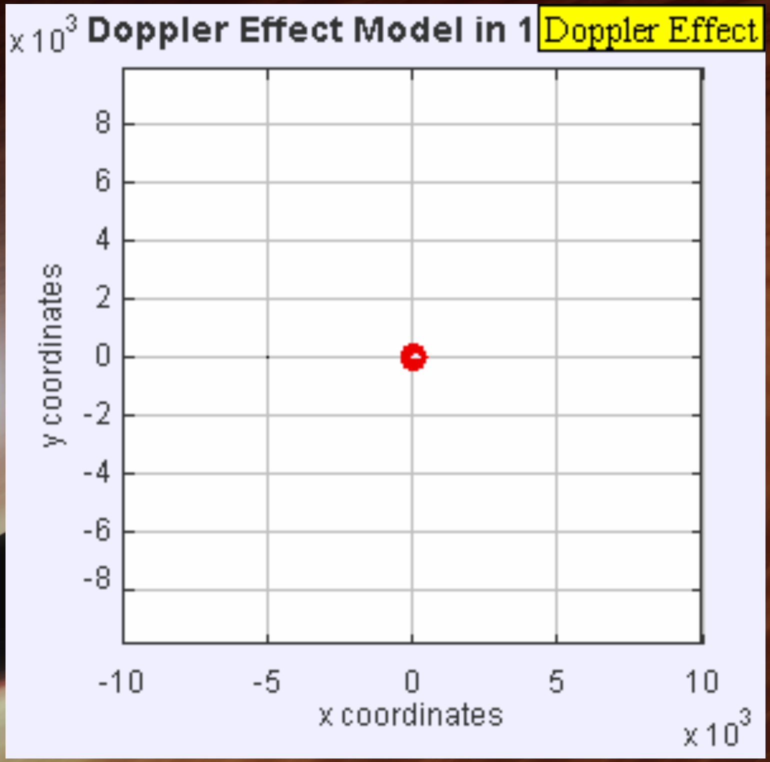
$$f(M_1, M_2, i) = \frac{(M_2 \sin i)^3}{(M_1 + M_2)^2} = \frac{P v_1^3}{2\pi G} \le M_2$$

The mass function is a lower limit on the mass of the dark object

# AGUJEROS NEGROS REALES: CYGNUS X-1

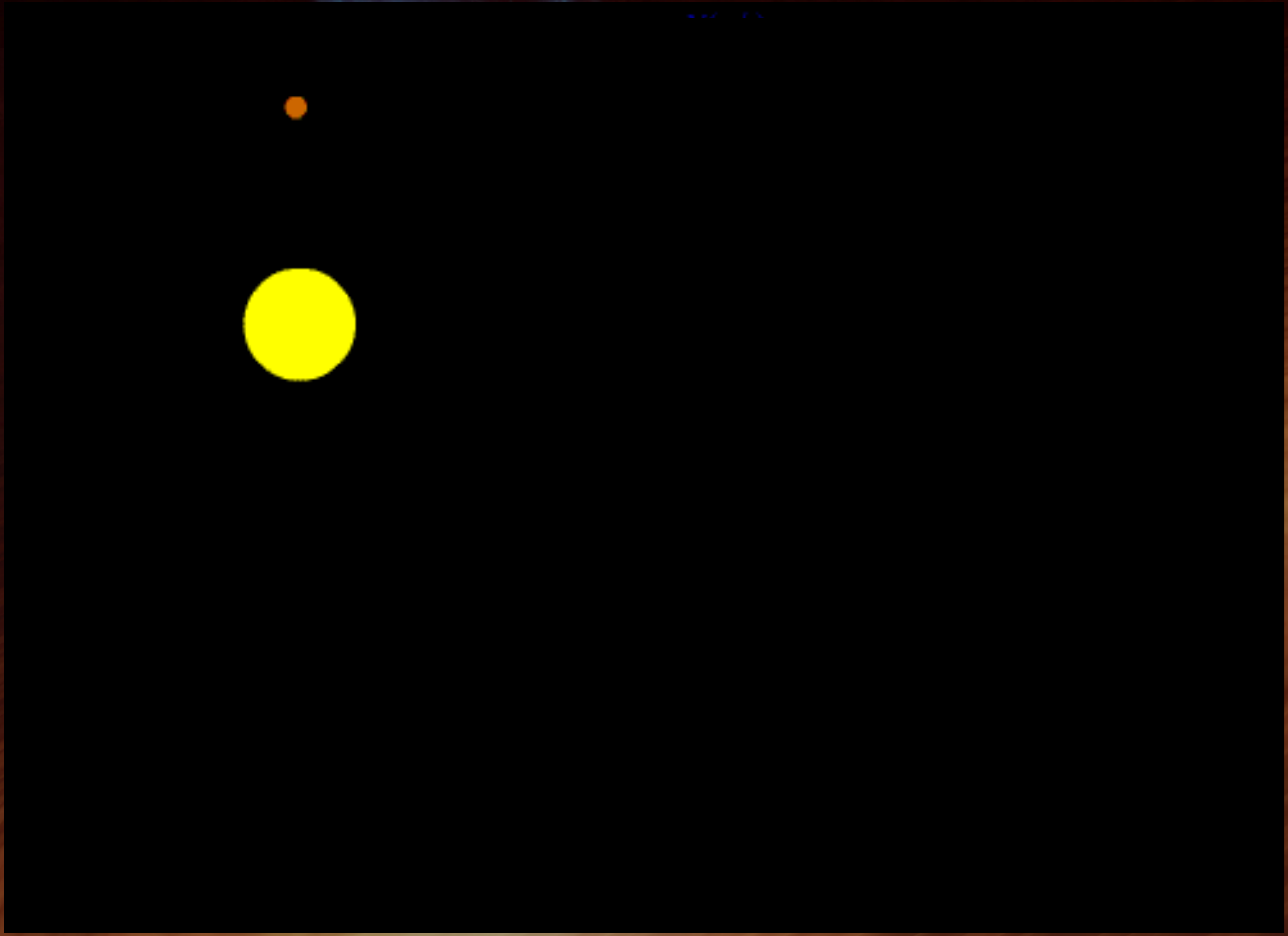
## Efecto Doppler



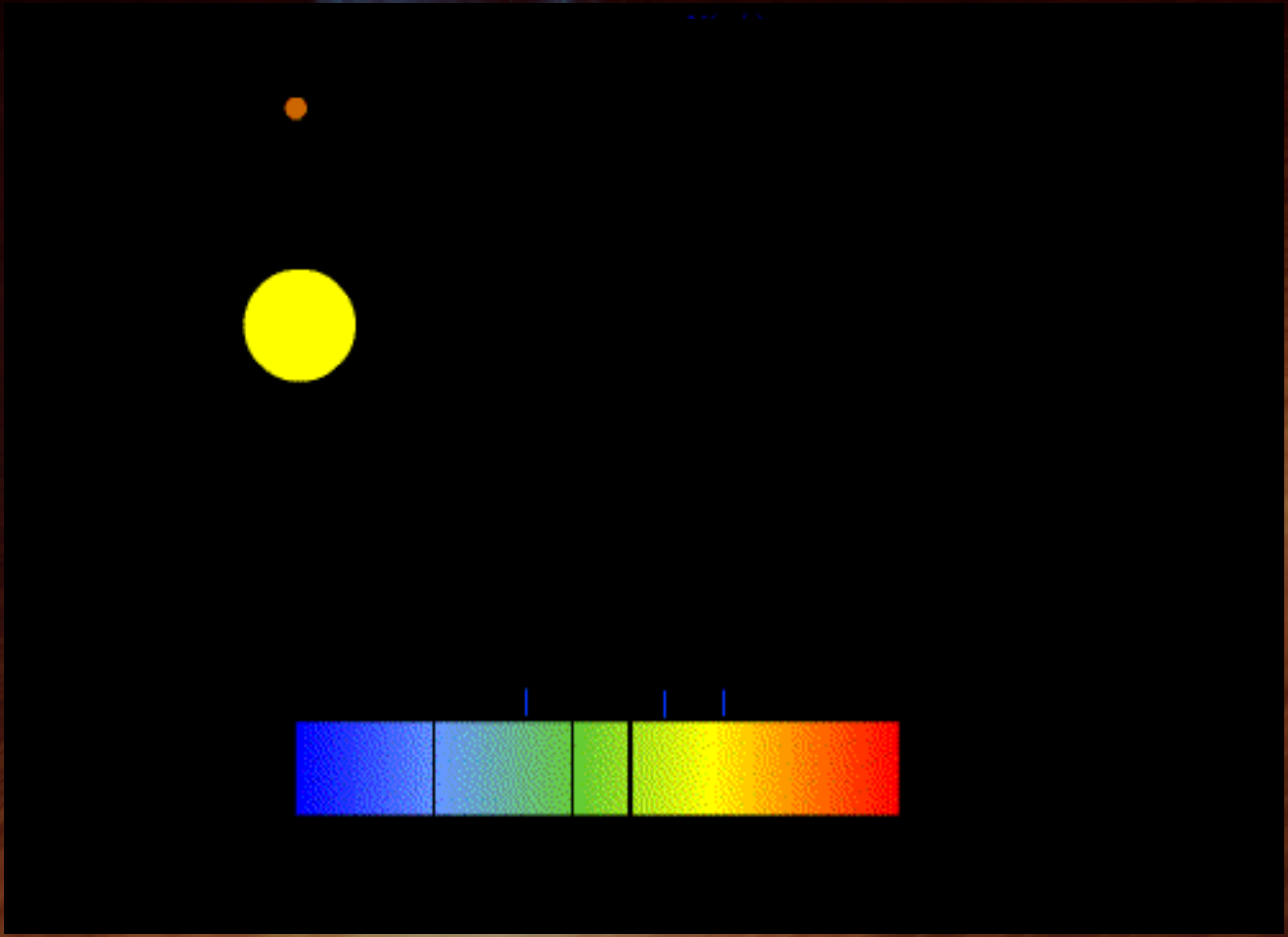


Si la fuente se mueve hacia nosotros, medimos una energía mayor
Si la fuente se aleja de nosotros, medimos una energía menor

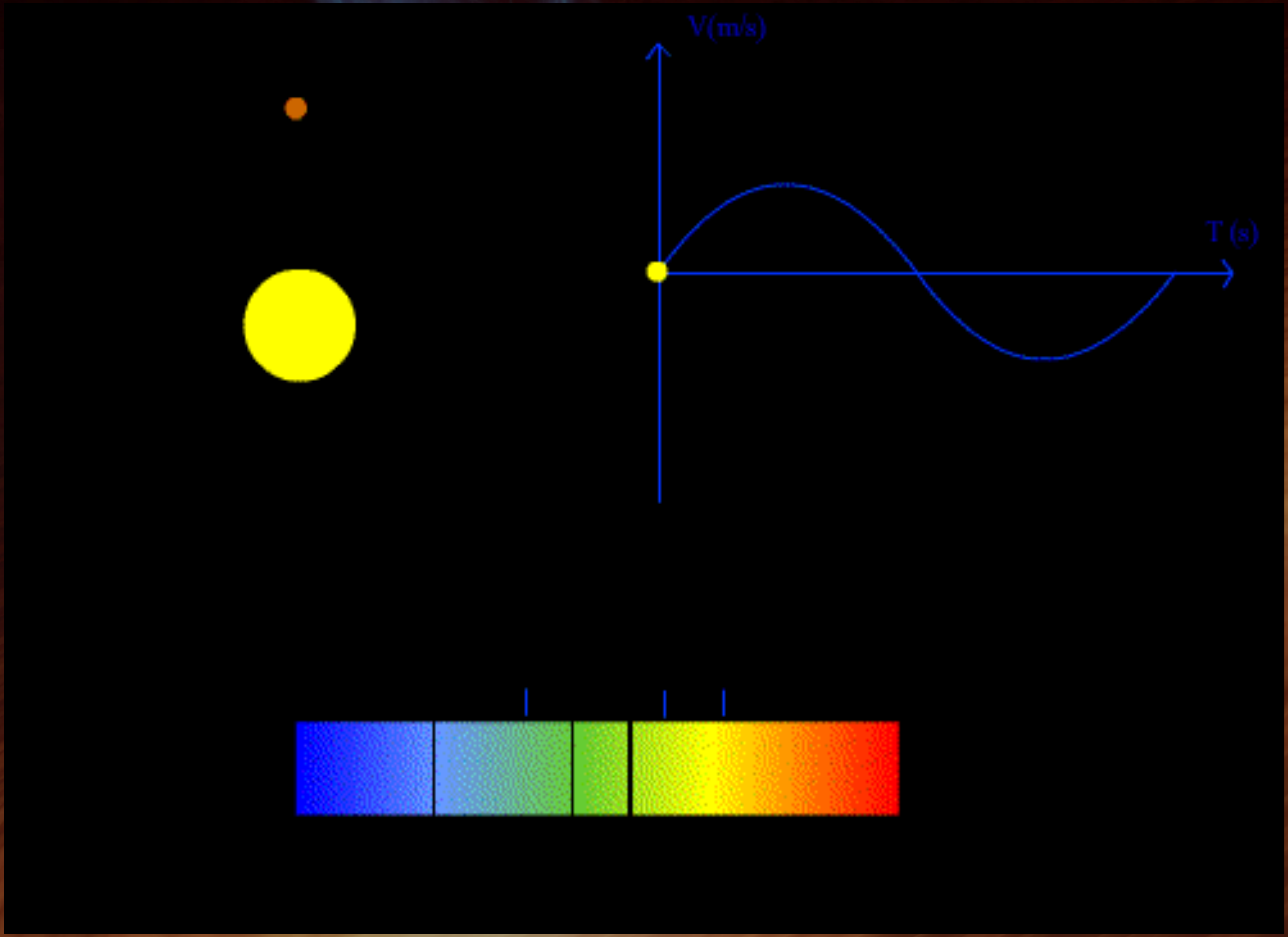
# AGUJEROS NEGROS REALES: CYGNUS X-1



# AGUJEROS NEGROS REALES: CYGNUS X-1



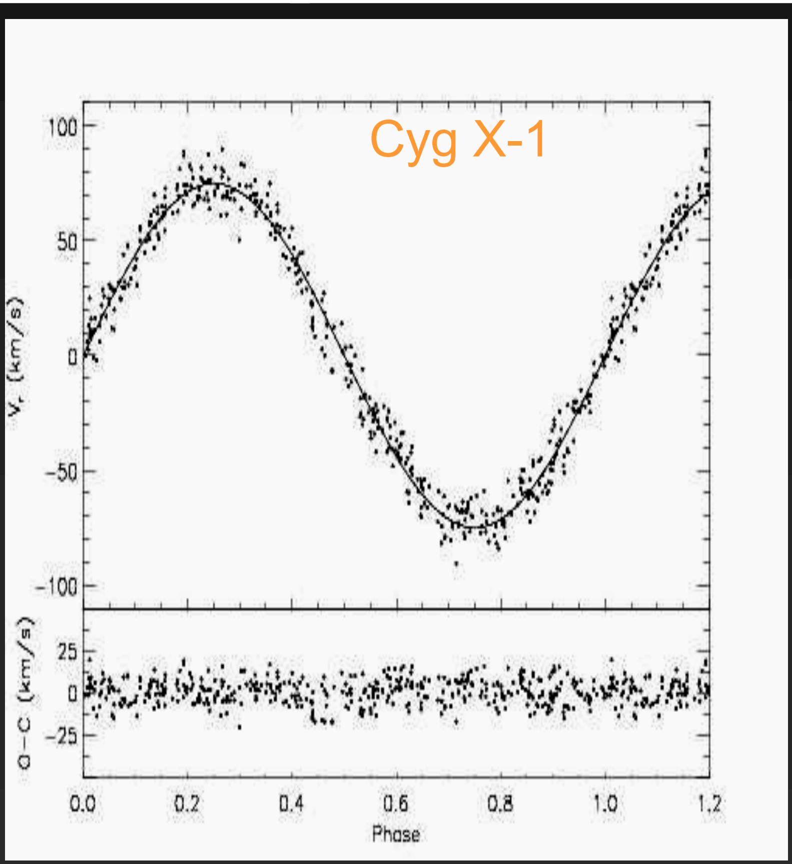
# AGUJEROS NEGROS REALES: CYGNUS X-1

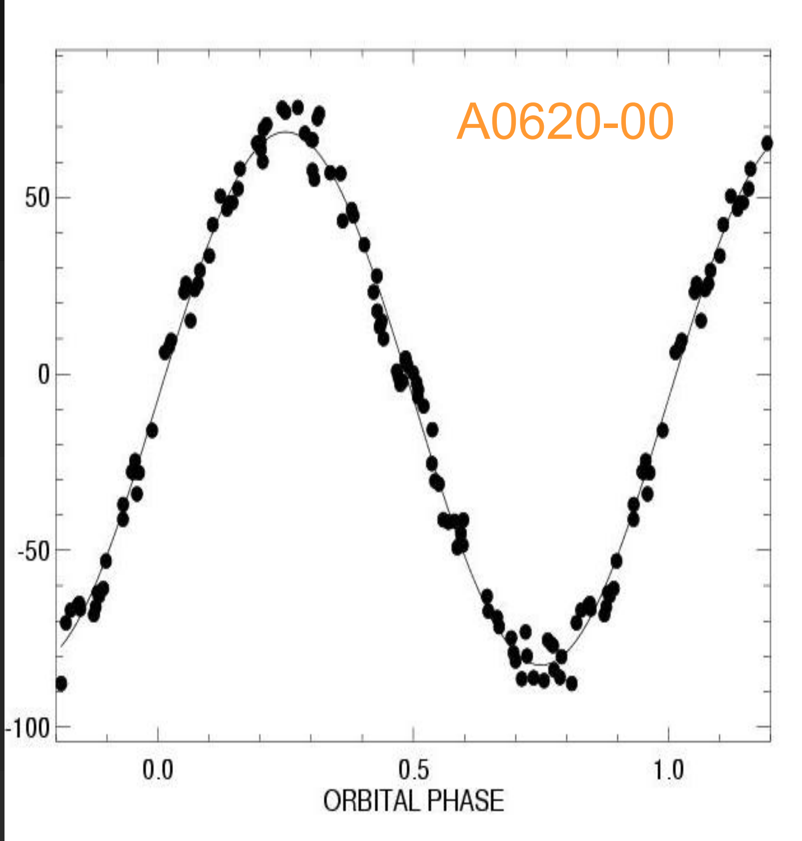


# Black Holes: observational evidences (some)

Stellar-mass (~10 solar masses)

$$f(M_1,M_2,i) = \frac{(M_2 \sin i)^3}{(M_1+M_2)^2} = \frac{P v_1^3}{2\pi G} \le M_2$$

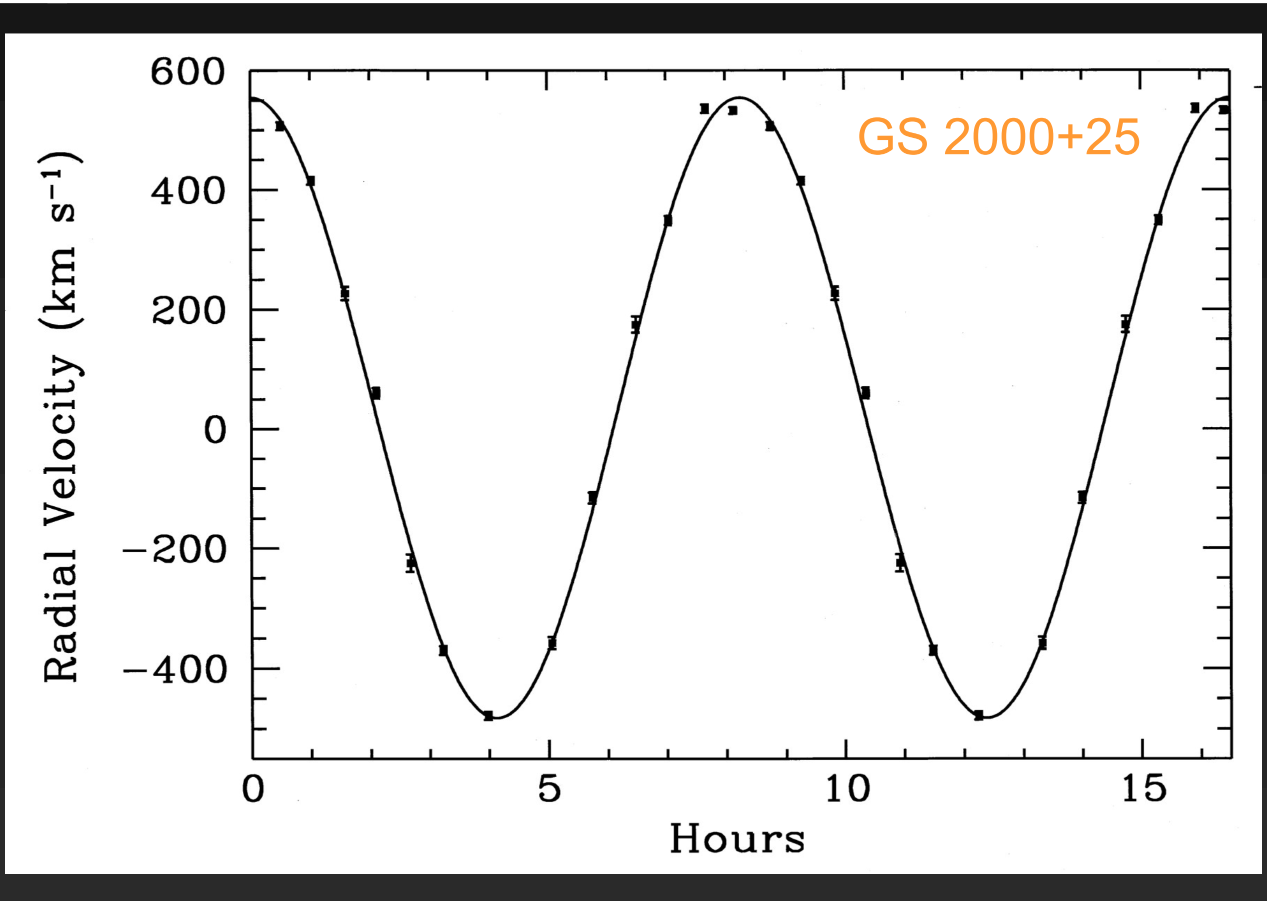




# Black Holes: observational evidences (some)

Stellar-mass (~10 solar masses)

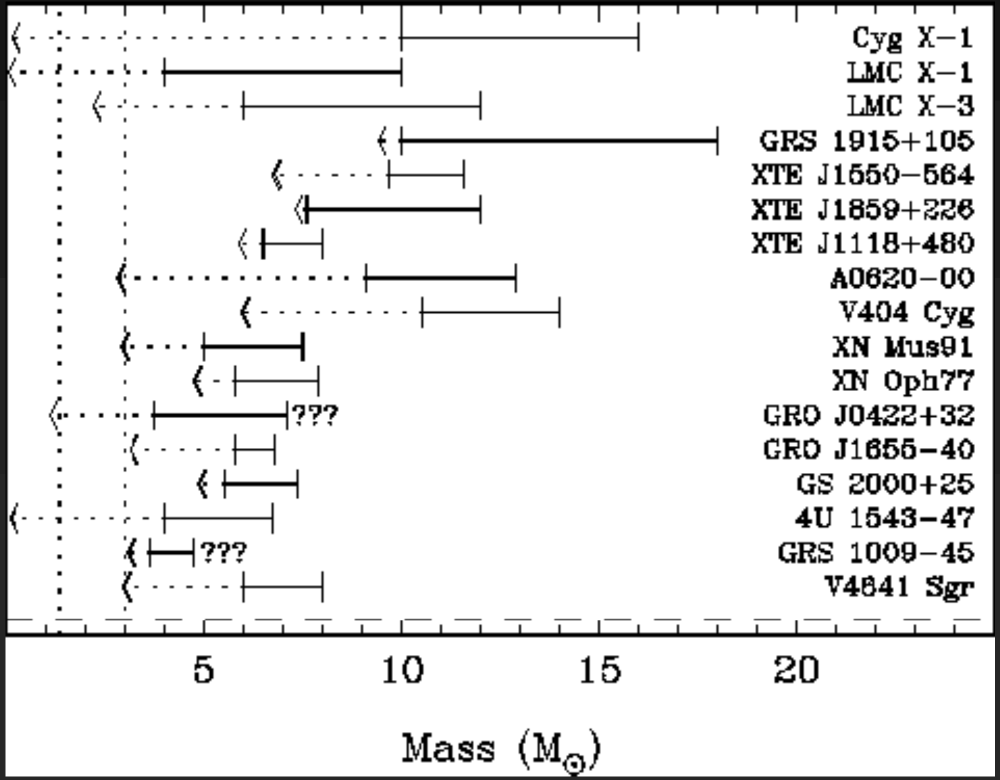
$$f(M_1, M_2, i) = \frac{(M_2 \sin i)^3}{(M_1 + M_2)^2} = \frac{P v_1^3}{2\pi G} \leq M_2$$

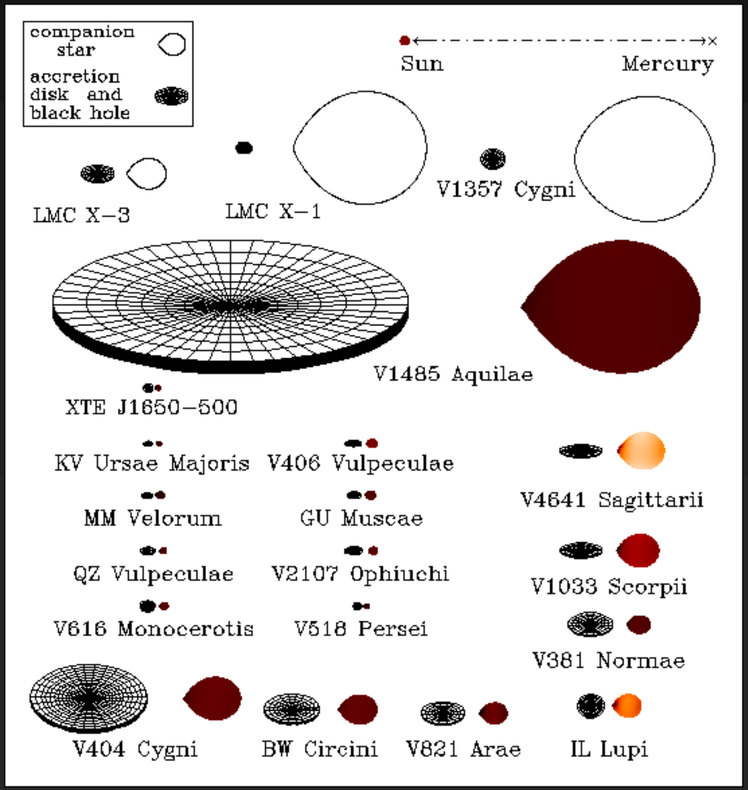


# Black Holes: observational evidences (some)

## Stellar-mass (~10 solar masses)

We now have about 24 dynamically confirmed BHs in binary systems (and a similar number of BH strong candidates) with masses in the range of 5-30 $M_{sun}$

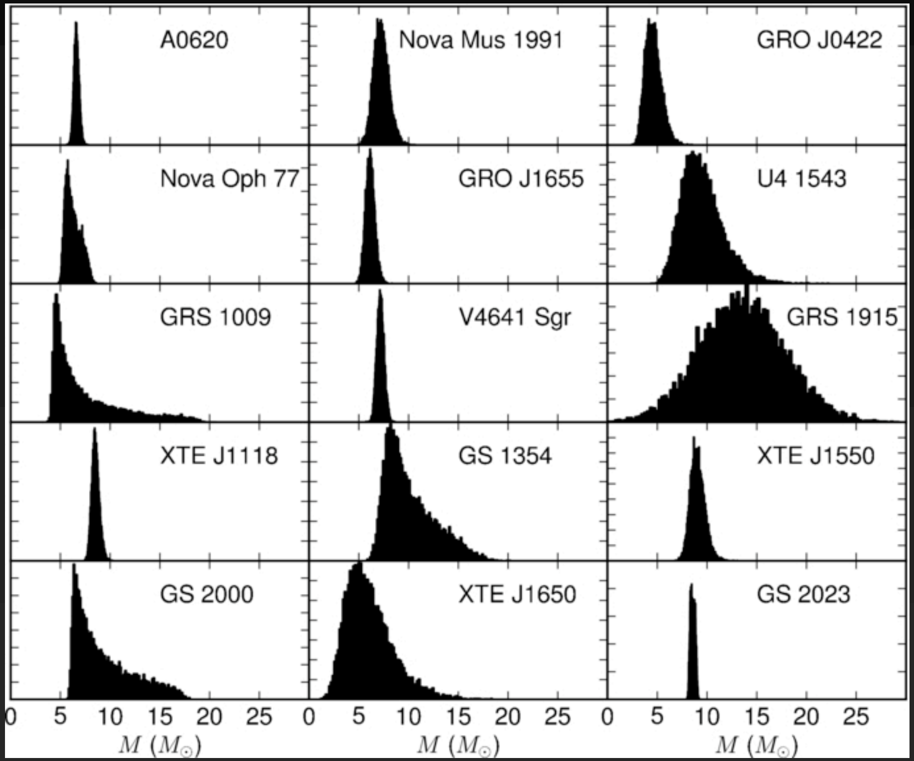




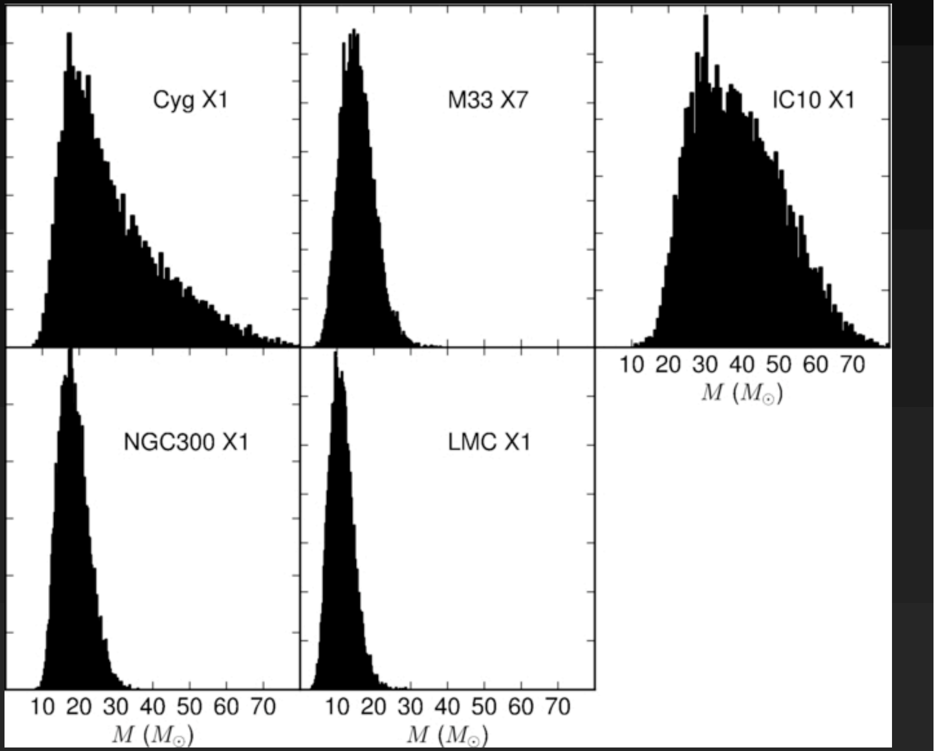
# Black Holes: observational evidences (some)

## Stellar-mass (~10 solar masses)

Relatively few systems, uncertainties on actual masses are large



LMXB
(older stellar population < 3 $M_{sun}$)



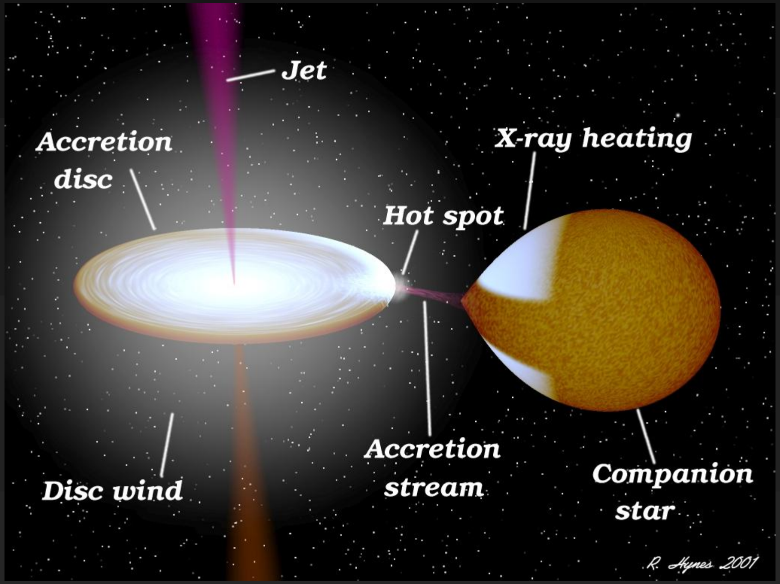
HMXB
(recent star formation and > 10 $M_{sun}$)

# Black Holes: observational evidences (some)

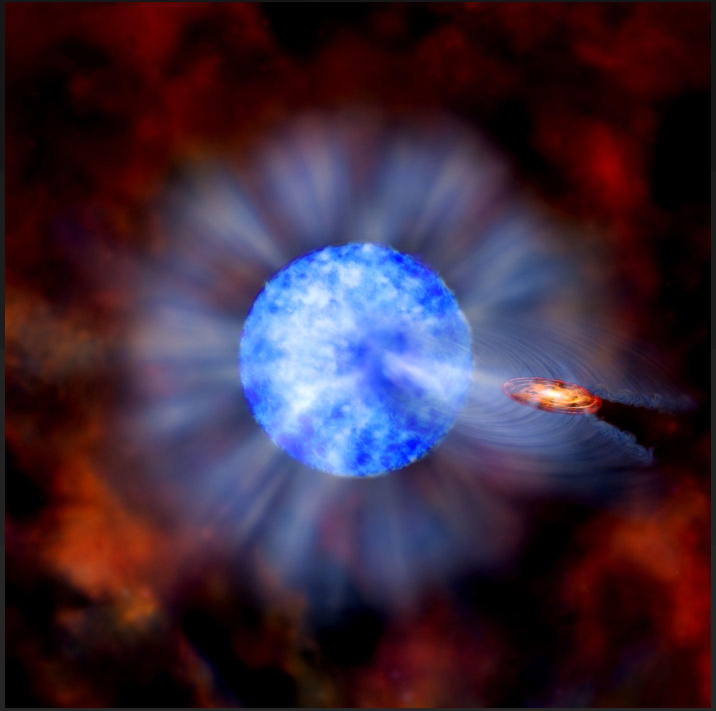
## Stellar-mass (~10 solar masses)

only Roche lobe

Winds + Roche lobe



LMXB
(older stellar population < 3 $M_{sun}$)



HMXB
(recent star formation and > 10 $M_{sun}$)

# Black Holes: observational evidences (some)

## Stellar-mass (~10 solar masses)

As per LMXB (accreting always via Roche lobe overflow) BH likely represent about 30 % of the overall population which is dominated by NS

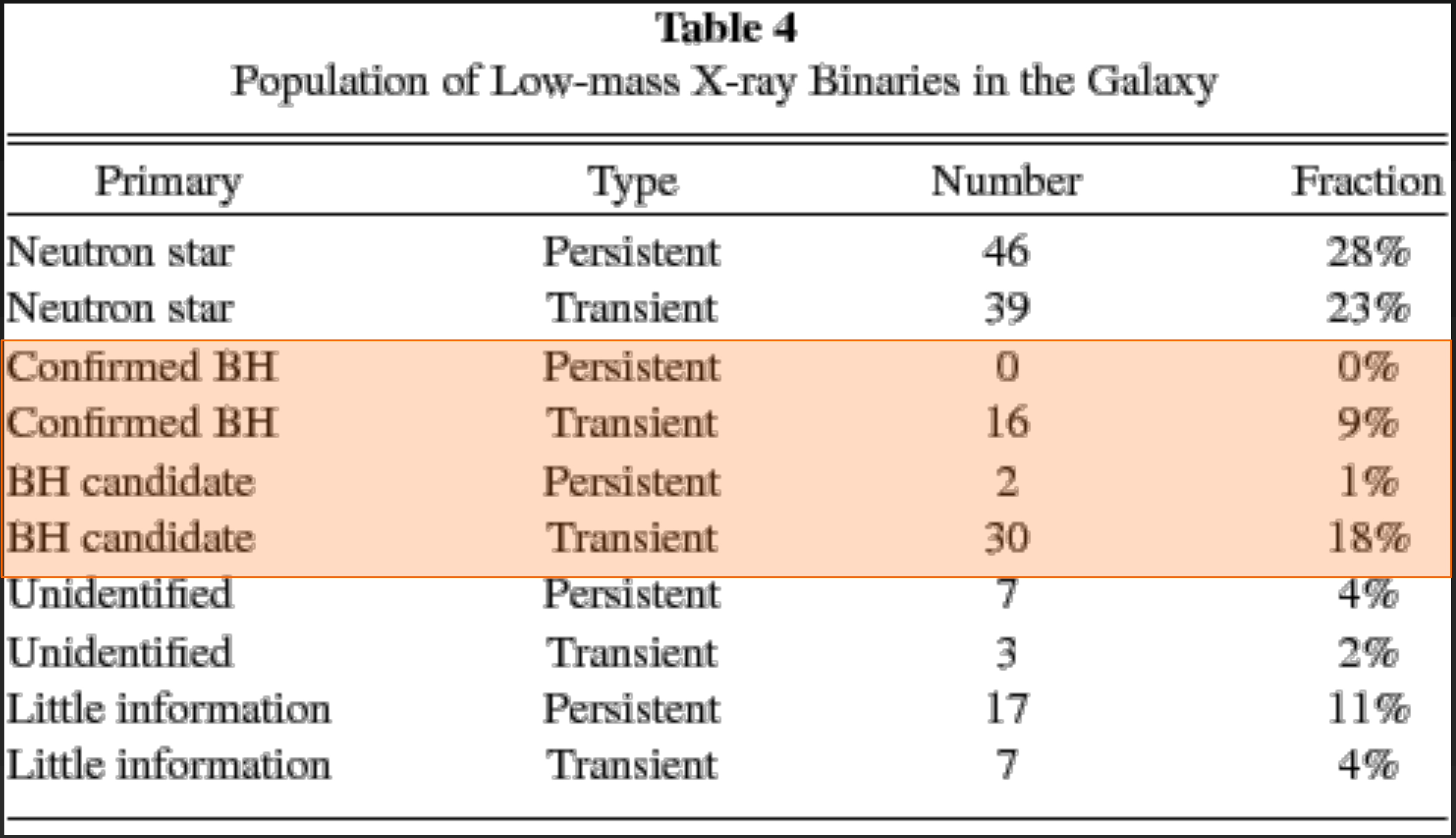


**Table 4**

Population of Low-mass X-ray Binaries in the Galaxy

| Primary | Type | Number | Fraction |
|---|---|---|---|
| Neutron star | Persistent | 46 | 28% |
| Neutron star | Transient | 39 | 23% |
| Confirmed BH | Persistent | 0 | 0% |
| Confirmed BH | Transient | 16 | 9% |
| BH candidate | Persistent | 2 | 1% |
| BH candidate | Transient | 30 | 18% |
| Unidentified | Persistent | 7 | 4% |
| Unidentified | Transient | 3 | 2% |
| Little information | Persistent | 17 | 11% |
| Little information | Transient | 7 | 4% |

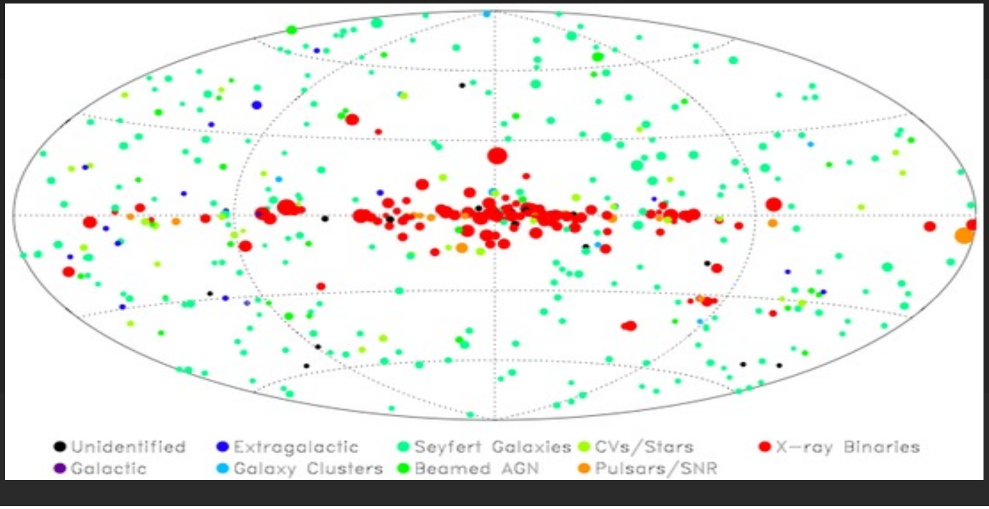
# Black Holes: observational evidences (some)

## Stellar-mass (~10 solar masses)

Most are transient, i.e. mass transfer (and therefore accretion) from the companion star only occurs at intervals, giving rise to accretion and to outbursts of emission (mostly X-rays) following which the system settles down to quiescence for long periods

Current estimates imply that the few tens of BH observed so far in the Mily Way as X-ray binaries are representative of a population of few hundreds millions of BHs scattered throghout the Galaxy

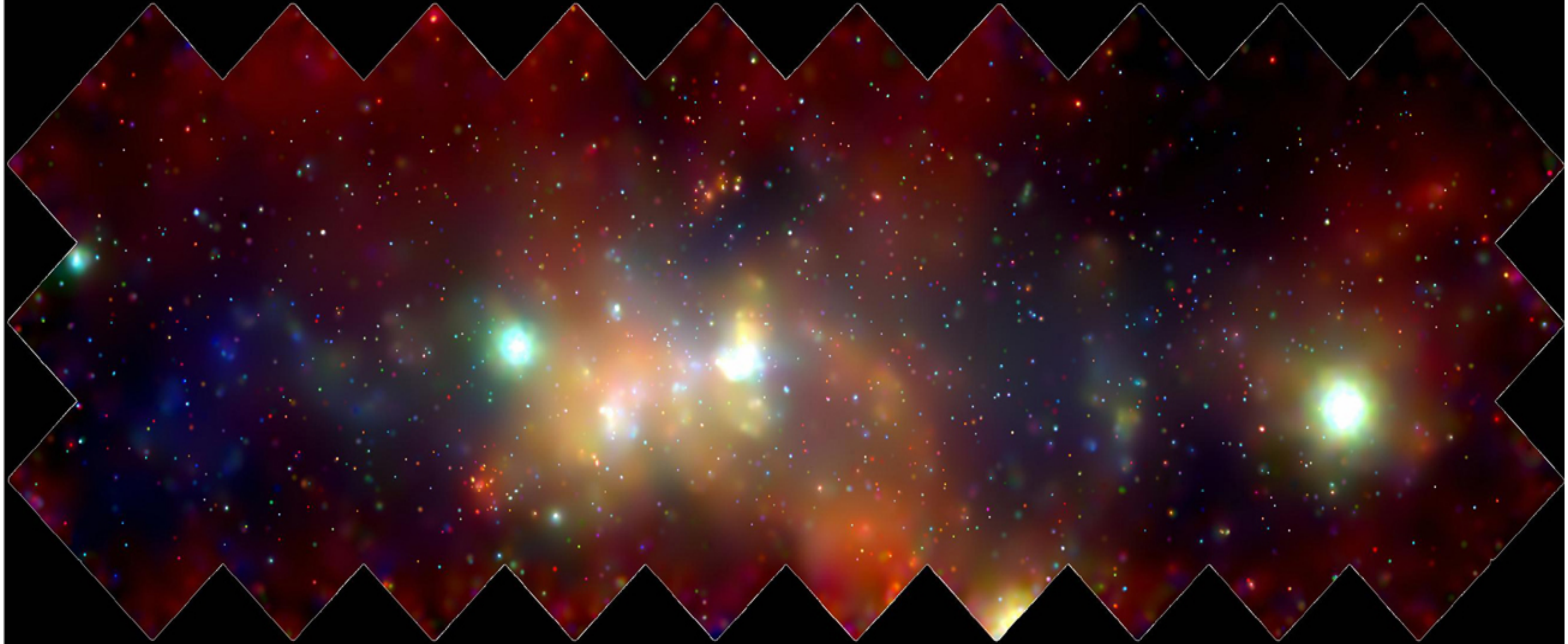
They then should represent a few per cent of the baryonic Galactic mass



# Black Holes: observational evidences (some)

## Supermassive (~ $10^6$-$10^9$ solar masses)

SMBHs are found in the center of galaxies, let’s first have a look nearby



Chandra (X-ray observatory) image of the Galactic center region (Milky Way)

# Black Holes: observational evidences (some)

## Supermassive (~ $10^6$-$10^9$ solar masses)

The cenral region of the Milky Way galaxy is a very crowded place comprising several components

Cluster of young and evolved stars
Diffuse hot gas
Dust
Supernova remnant(s)
Many X-ray point sources
and … a compact radio source: Sgr $A^*$

At a distance of only ~ 8 kpc it is by far the closest galactic nucleus and it is thus a unique laboratory to study galactic centers in general

However, observationally it is a very challenging place because of confusion (very crowded) and dust/gas extinction, so severe that only 1 out of ~ $10^{12}$ optical photons is transmitted and can be detected on Earth

The situation is better in the radio, IR and X-ray regions of the EM spectrum

# Black Holes: observational evidences (some)

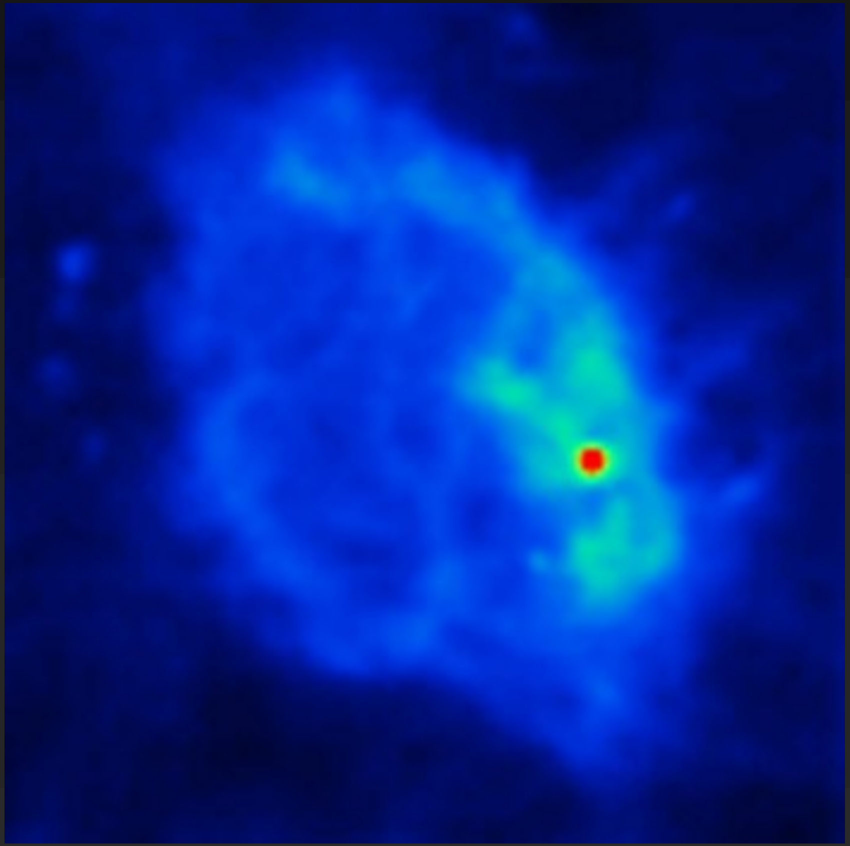
## Supermassive (~ $10^6$-$10^9$ solar masses)

Sgr A* - a compact radio source discovered in 1974
The * indicates that the source is compact and it was introduced to distinguish it from the extended radio emission (known as Sgr A West) surrounding it

# Black Holes: observational evidences (some)

## Supermassive (~ $10^6$-$10^9$ solar masses)

Sgr A$^*$ - a compact radio source discovered in 1974
The * indicates that the source is compact and it was introduced to distinguish it from the extended radio emission (known as Sgr A West) surrounding it



# Black Holes: observational evidences (some)

## Supermassive (~ $10^6$-$10^9$ solar masses)

Sgr A* - a compact radio source discovered in 1974
The * indicates that the source is compact and it was introduced to distinguish it from the extended radio emission (known as Sgr A West) surrounding it

It was realized relatively soon that the diffuse gas surrounding Sgr A* is in fact rotating around it or, in other words, that the motion of the diffuse gas has Sgr A* as its dynamical center

Moreover, the radio source was observed to be both compact and variable, ruling out the cumulative emission of a number of sources (or extended gas emission on small scales)

In order to know whether Sgr A* is the true dynamical center of the Milky Way one should measure its proper motion:

It is constant in time
It is consistent with 220 km/s

which is nothing else than the rotation of our Solar System in the galaxy

# Black Holes: observational evidences (some)

## Supermassive (~ $10^6$-$10^9$ solar masses)

Once Galactic rotation is removed, Sgr $A^*$ proper motion is consistent with 0 km/s

Hence it is highly likely the dynamical center of the Milky Way

The most remarkable results on the nature of the radio source come from the analysis of the motions of nearby stars

The idea is that by studying the detailed motions of nearby stars one can

1 - Verify that the radio source Sgr $A^*$ is truly the dynamical center of the Milky Way
2 - Estimate its mass (and, coupling with the inferred radio size, its density)

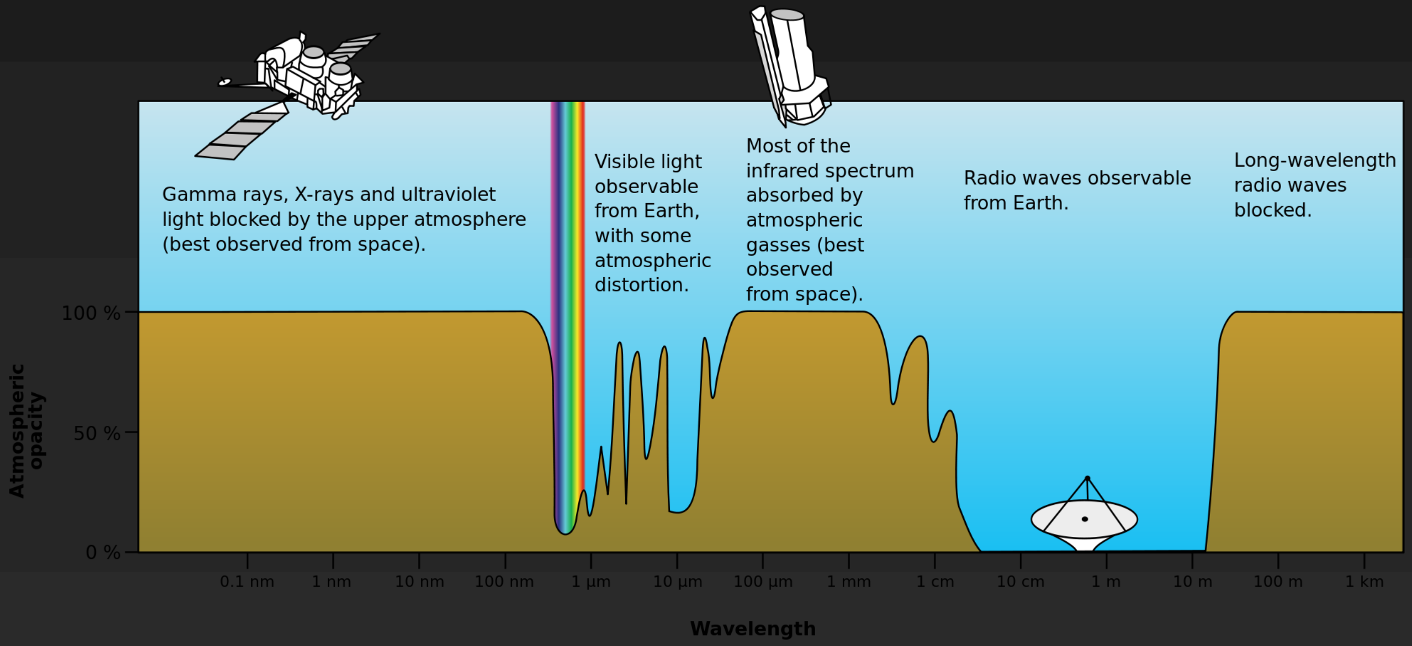
The proximity of the Galactic center (8 kpc) makes it a unique lab for such studies

# Black Holes: observational evidences (some)

## Supermassive (~ $10^6$-$10^9$ solar masses)

Star motions are good tracers of the gravitational potential because, unlike gas, they are not much affected by non-gravitational forces

Problem 1 – Stars emit mostly in the optical/UV, but the Galactic center extinction only allows 1:$10^{12}$ photons to be transmitted ! Then, other wavelengths are necessary, such as IR. IR are mostly absorbed in the Earth atmosphere, but one can use one of the IR atmospheric windows, e.g. the K-band @ 2.2 μm



# Black Holes: observational evidences (some)

## Supermassive (~ $10^6$-$10^9$ solar masses)

Star motions are good tracers of the gravitational potential because, unlike gas, they are not much affected by non-gravitational forces

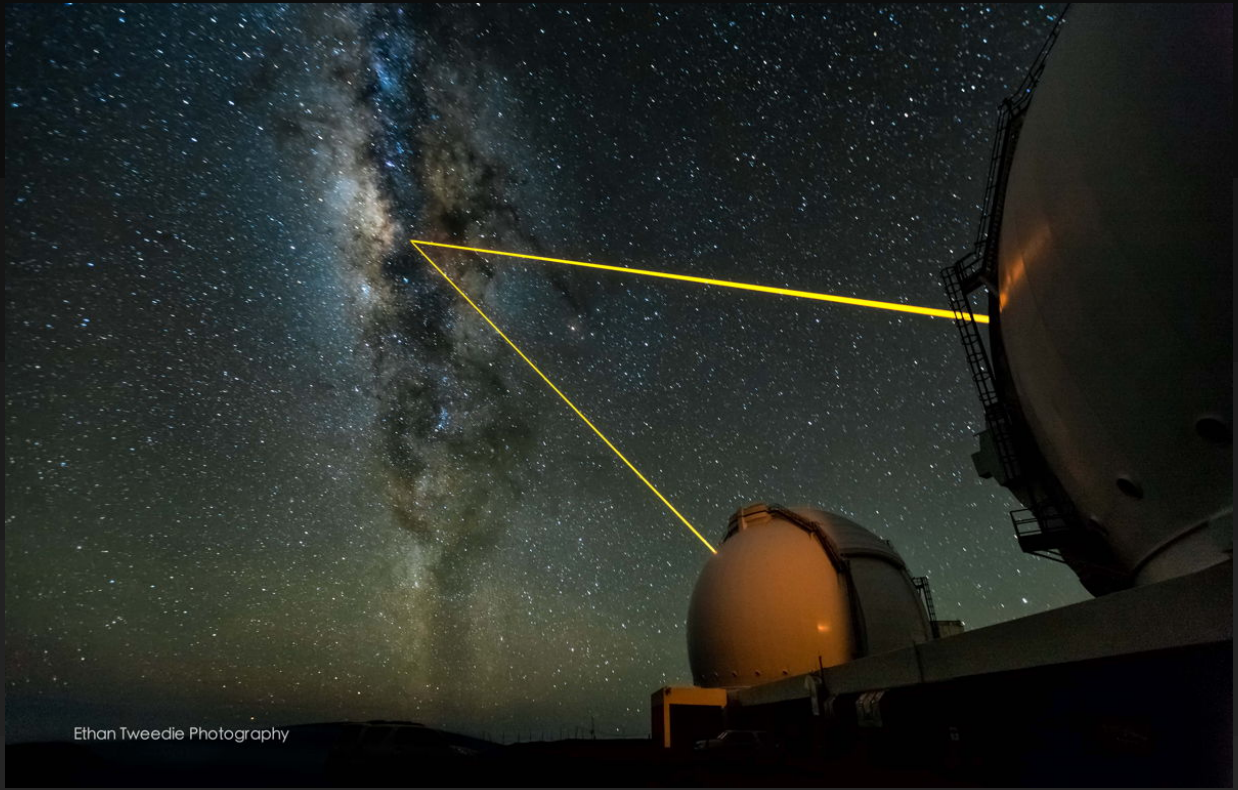
Problem 1 – Stars emit mostly in the optical/UV, but the Galactic center extinction only allows 1:$10^{12}$ photons to be transmitted ! Then, other wavelengths are necessary, such as IR. IR are mostly absorbed in the Earth atmosphere, but one can use one of the IR atmospheric windows, e.g. the K-band @ 2.2 μm

Problem 2 – the field is very crowded, there is a need for extremely high angular resolution if individual stars are to be followed in their motion

One needs big telescopes ($\theta \sim \lambda / D$) and a system which allows to limit the atmospheric distortions (adaptive optics)

# Black Holes: observational evidences (some)

## Supermassive (~ $10^6$-$10^9$ solar masses)

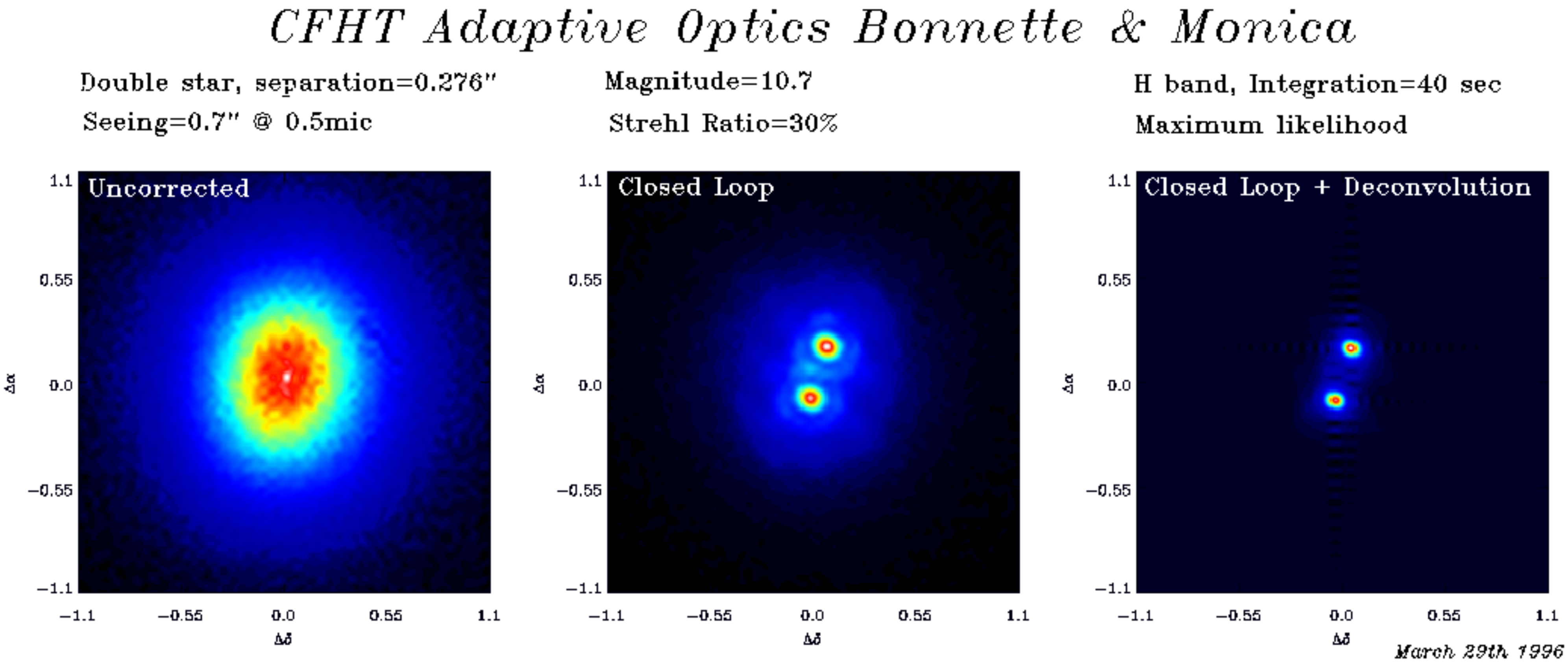


In this case, for example, the 10m Keck telescopes

The laser beam creates an artificial source in the atmosphere that is used to correct the mirror shape to get rid (as much as possible) of atmospheric seeing and increase the angular resolution (adaptive optics)

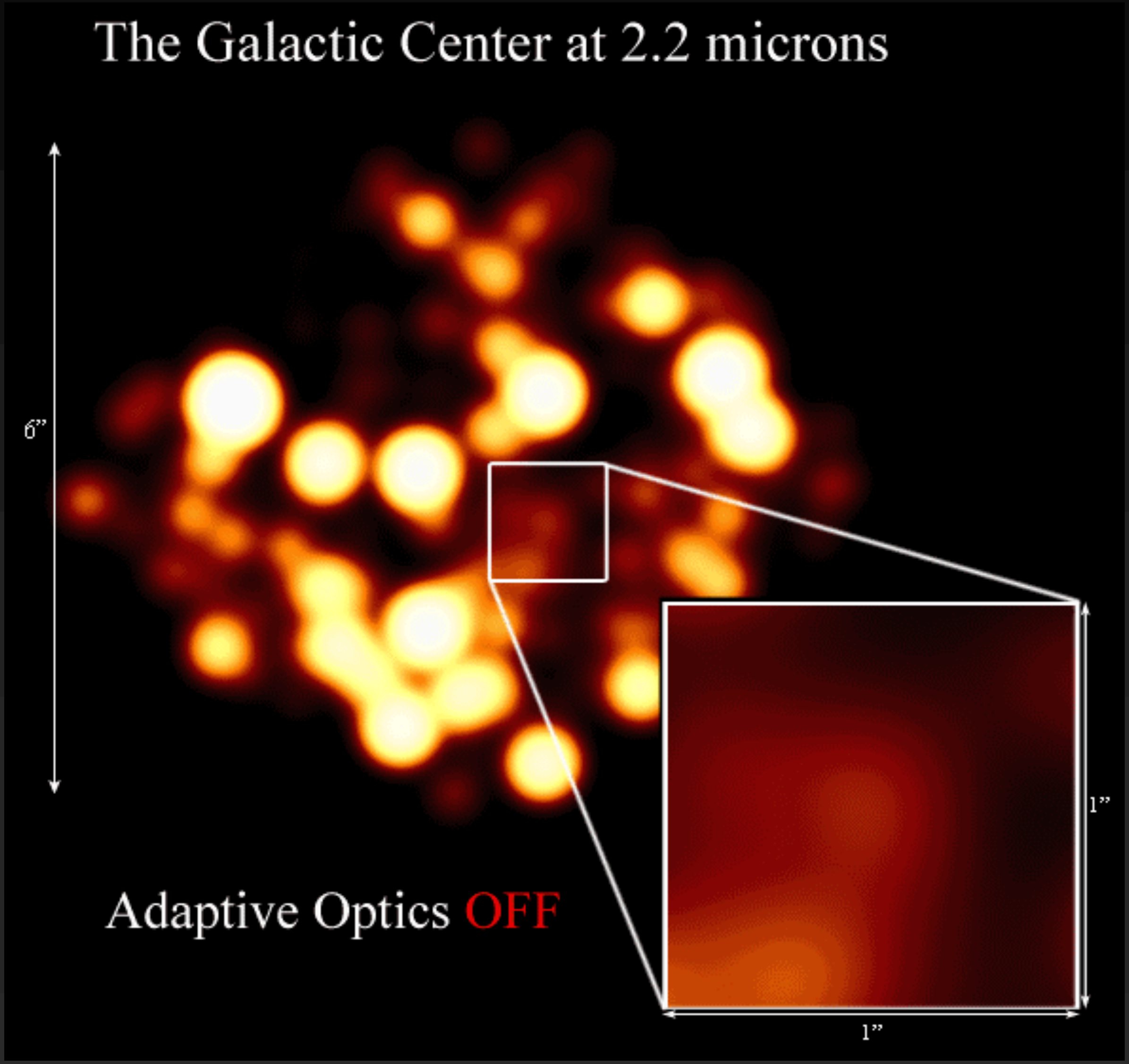
# Black Holes: observational evidences (some)

Supermassive (~ $10^6$-$10^9$ solar masses)



# Black Holes: observational evidences (some)

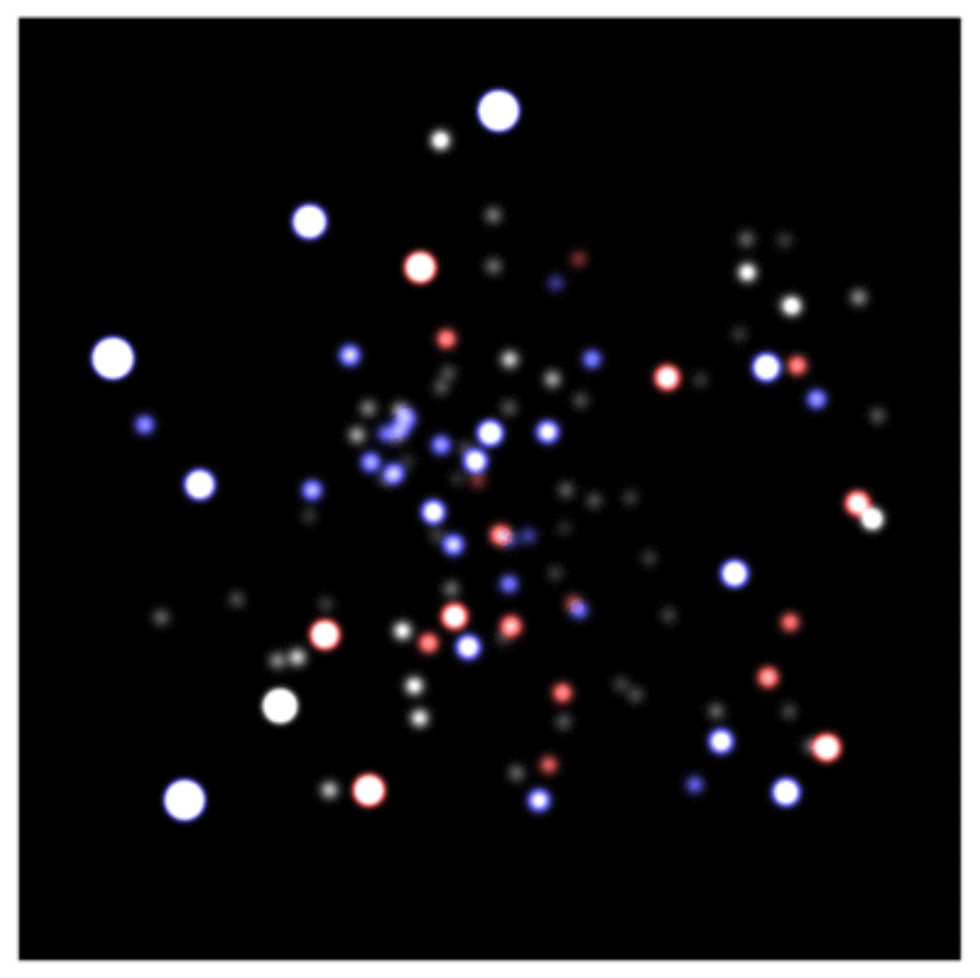
Supermassive (~ $10^6$-$10^9$ solar masses)



# Black Holes: observational evidences (some)

## Supermassive (~ $10^6$-$10^9$ solar masses)

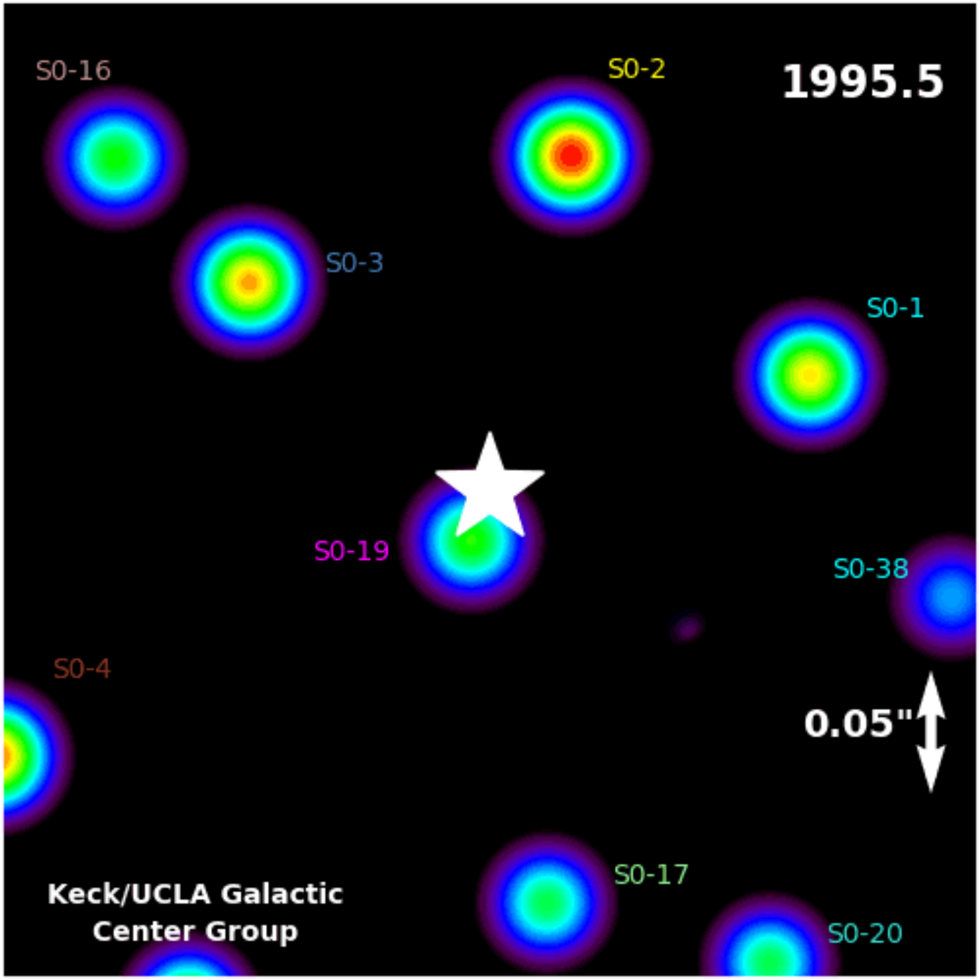
With this machinery in place, we can have a look at the very innermost region close to Sgr A$^*$ with repeated observations over several years



# Black Holes: observational evidences (some)

## Supermassive (~ $10^6$-$10^9$ solar masses)

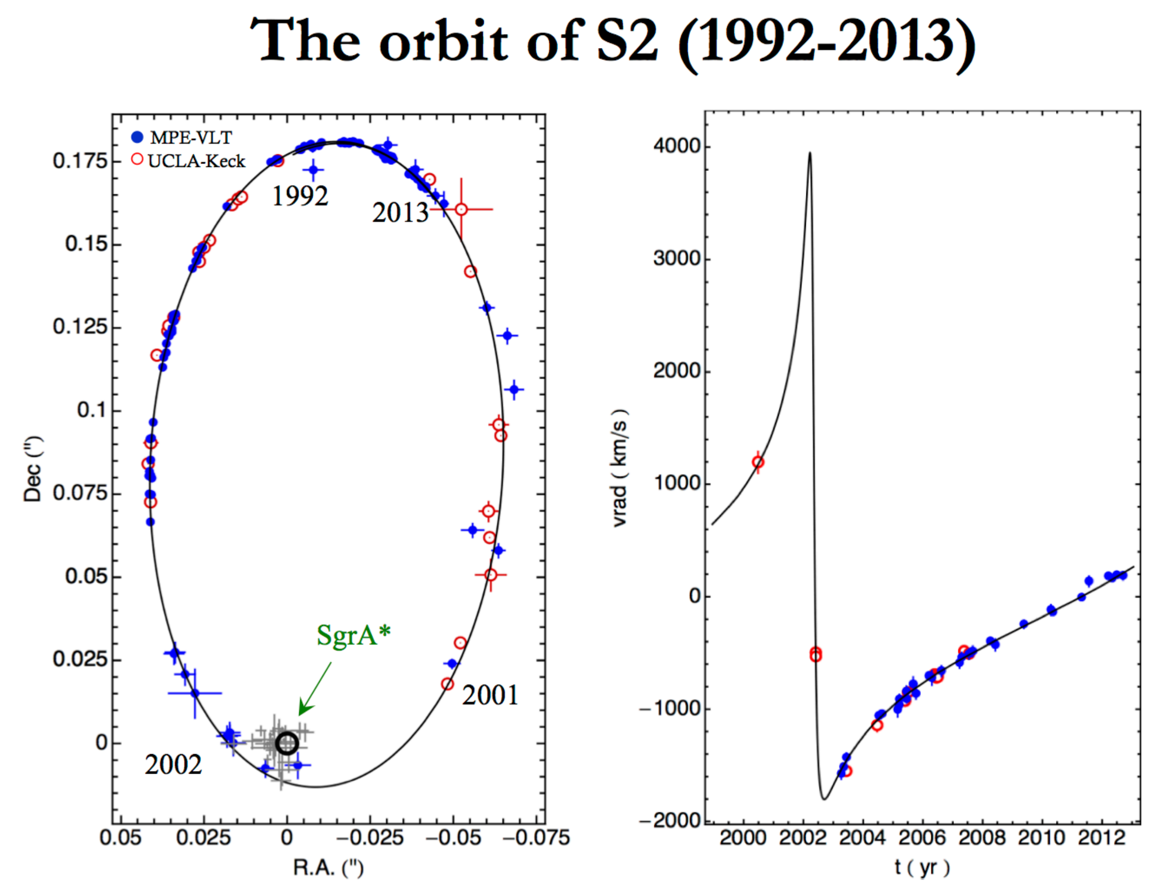
With this machinery in place, we can have a look at the very innermost region close to Sgr A$^*$ with repeated observations over several years



# Black Holes: observational evidences (some)

## Supermassive (~ $10^6$-$10^9$ solar masses)

One star (S2) has proven particularily useful in this game

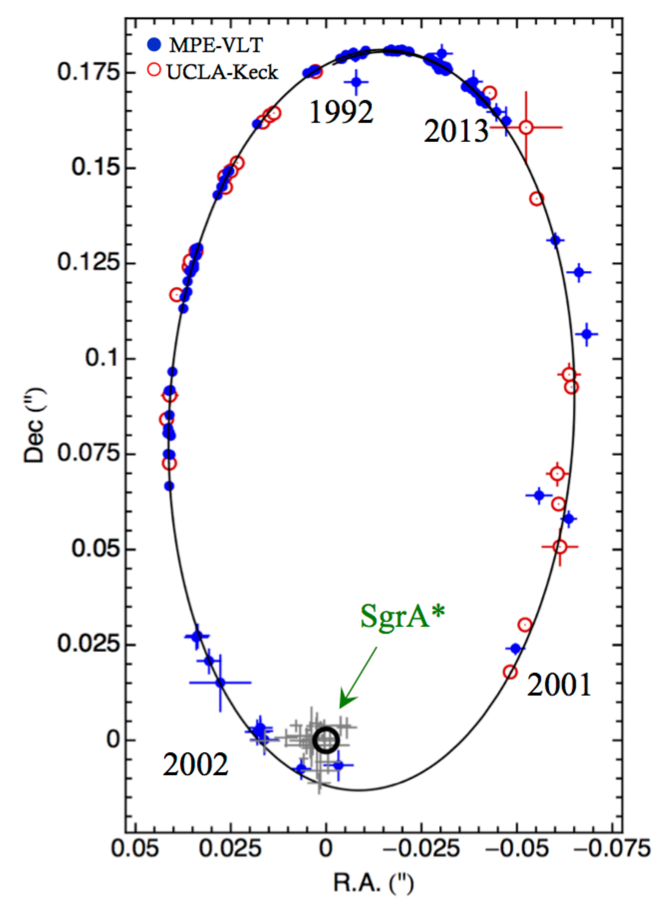


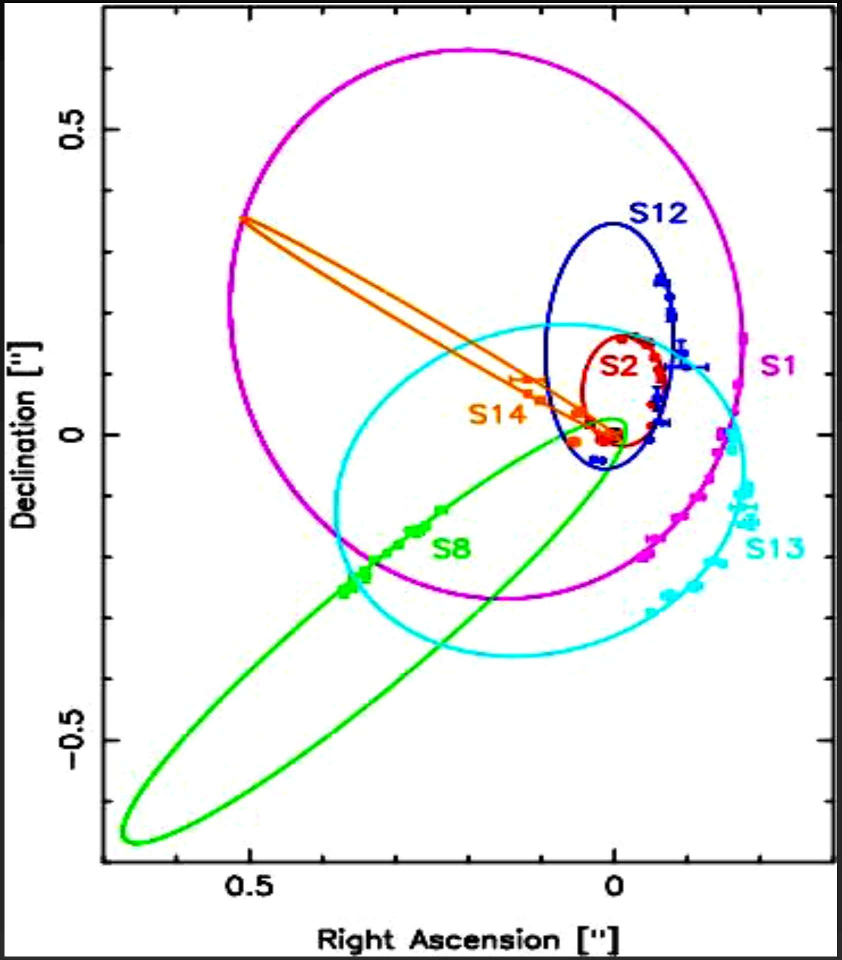
The orbit of S2 (1992-2013)

# Black Holes: observational evidences (some)

## Supermassive (~ $10^6$-$10^9$ solar masses)

Although it is not the only one orbiting Sgr A*





# Black Holes: observational evidences (some)

Supermassive (~ $10^6$-$10^9$ solar masses)

Having the full orbit of S2 (as well as partial orbits of other nearby stars) all orbital parameters can be easily computed and Kepler's laws can be aplied to derive the mass of the central mass

4-4.5 millions of solar masses

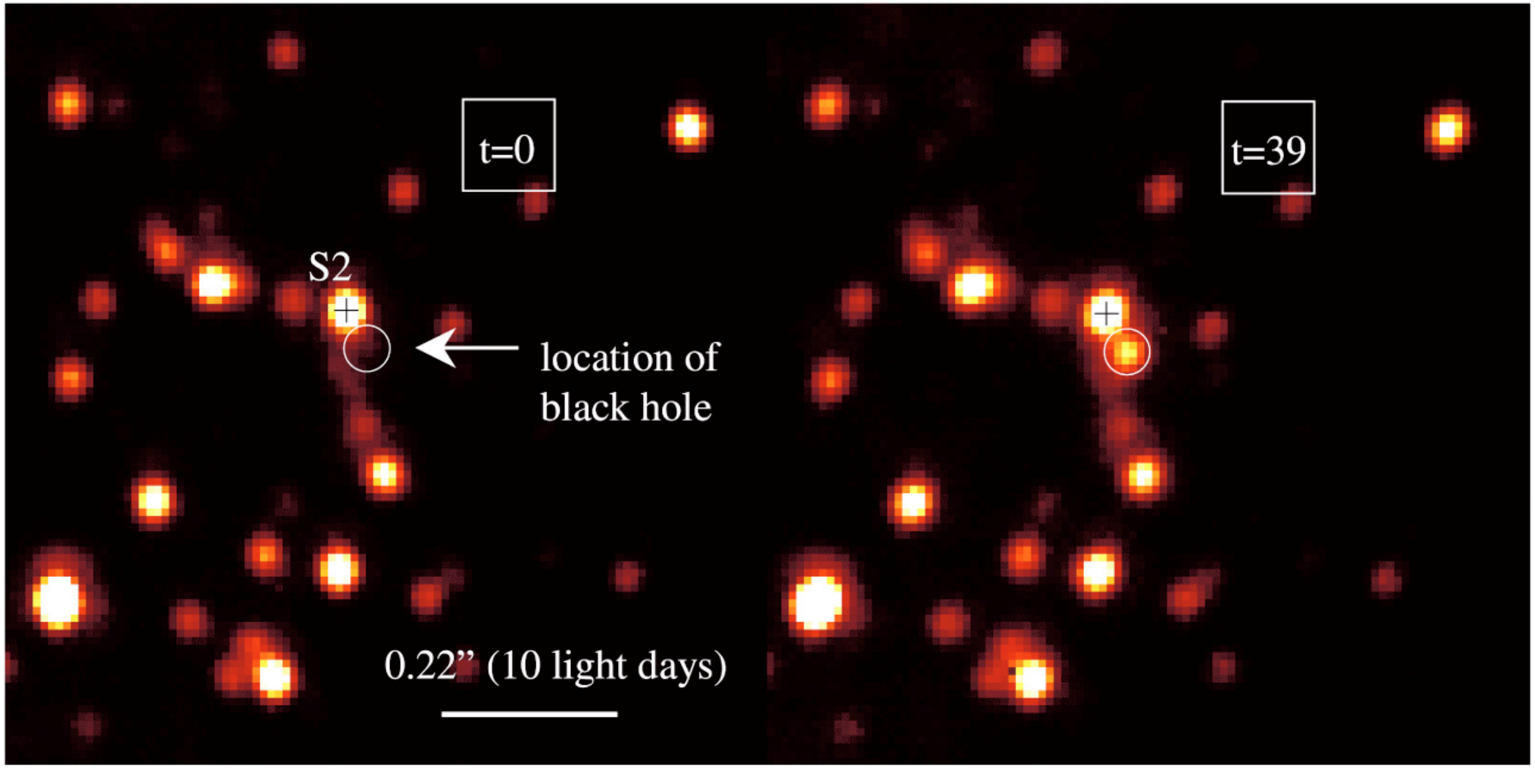
The closest approach of S2 and other stars limit the size to < 6.3 light-hours

The corresponding density rules out with extremely good confidence any possible concentration of such large mass in such a small volume other than a BH

The existence of a SMBH of ~$4 \times 10^6$ $M_{sun}$ at the center of the Milky way is universally accepted

# Black Holes: observational evidences (some)

Supermassive (~ $10^6$-$10^9$ solar masses)



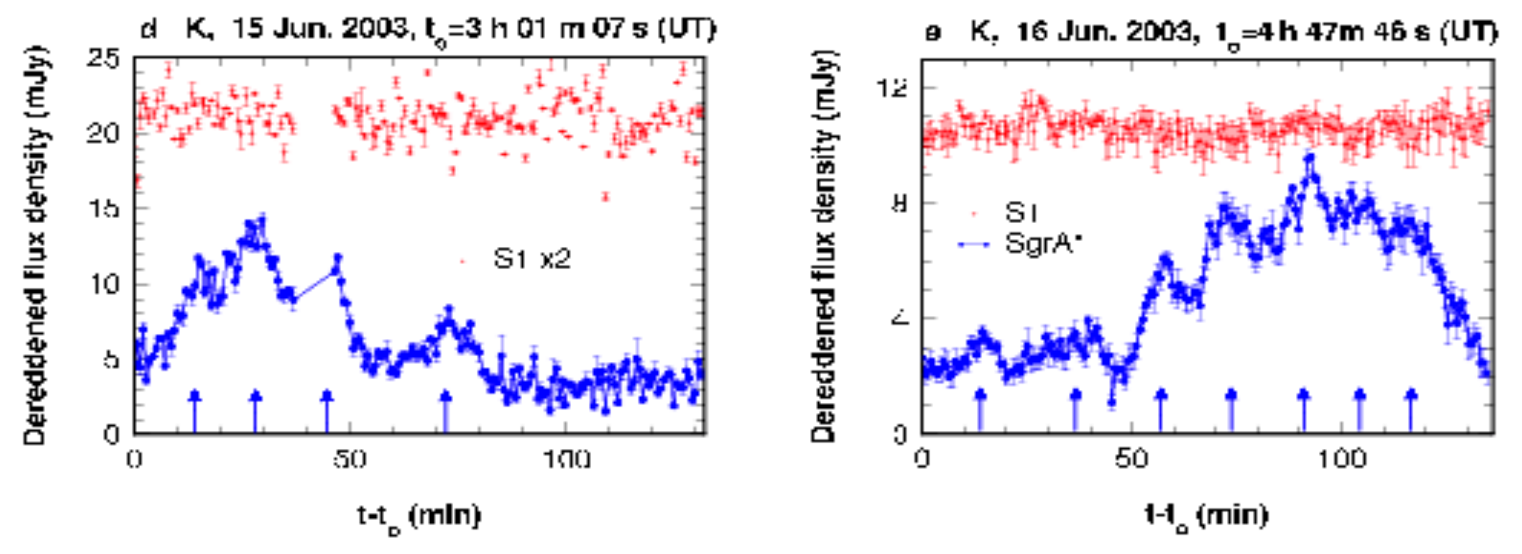
Near-IR Flare from Galactic Centre (VLT YEPUN + NACO)

ESO PR Photo 29a/03 (29 October 2003)

© European Southern Observatory

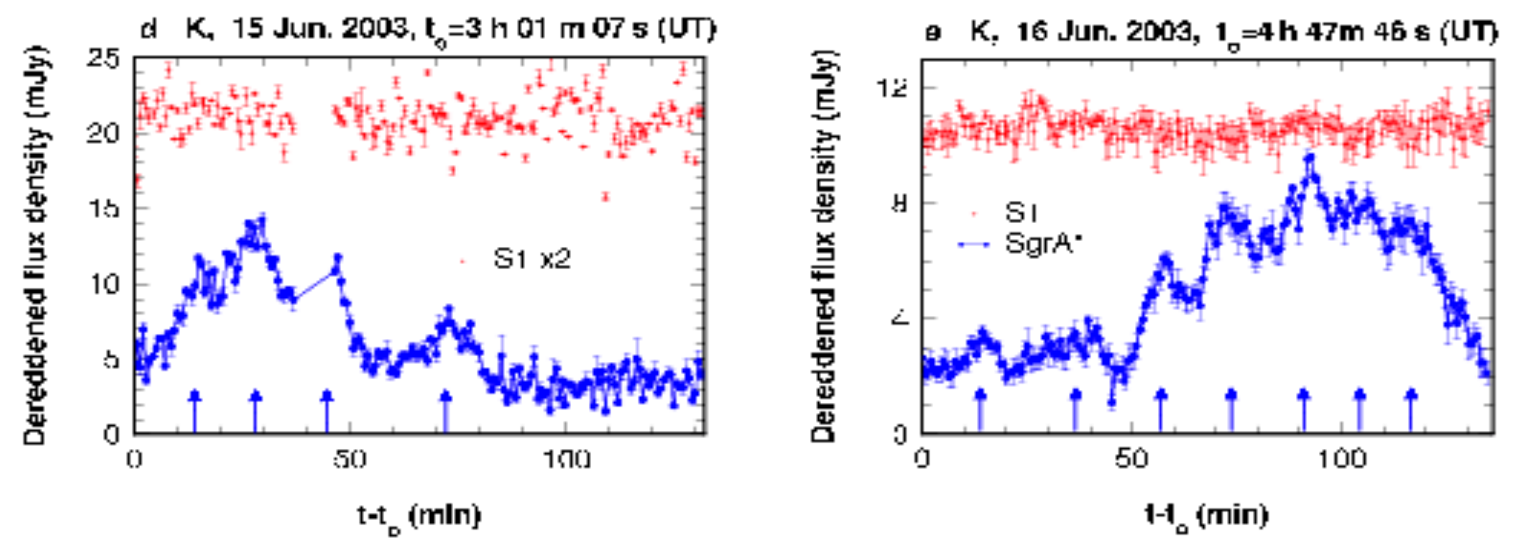
# Black Holes: observational evidences (some)

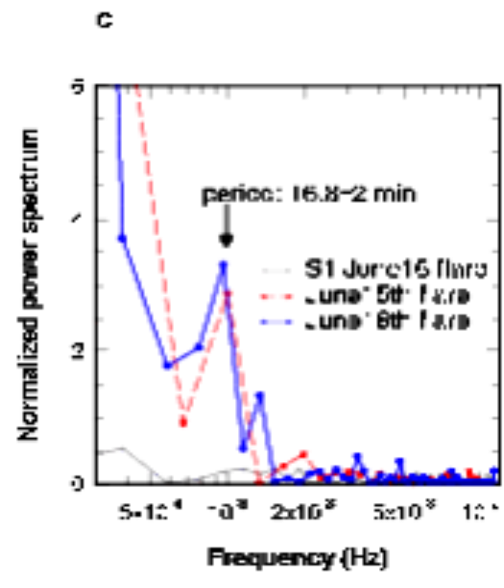
## Supermassive (~ $10^6$-$10^9$ solar masses)



# Black Holes: observational evidences (some)

## Supermassive (~ $10^6$-$10^9$ solar masses)





Fast variability (~ 1 min) combined with the estimated BH mass strongly suggests a size of only few $R_g = GM/c^2$ (horizon of Kerr BH)

A possible periodicity of the order of 1 ks is also detected in the IR data

# Black Holes: observational evidences (some)

## Supermassive (~ $10^6$-$10^9$ solar masses)

If we (tentatively) associate the detected period to an orbital timescale on the accretion disc

$$T = 310\,(a + r^{3/2})\,M_7 \text{ sec} \cong 102\,(a + r^{3/2}) \text{ sec}$$

In order to be of the order of the dected period, the term in parenthesis must be of the order of 10

# Black Holes: observational evidences (some)

## Supermassive (~ $10^6$-$10^9$ solar masses)

If we (tentatively) associate the detected period to an orbital timescale on the accretion disc

$$T = 310\,(a + r^{3/2})\,M_7\ \mathrm{sec} \cong 102\,(a + r^{3/2})\ \mathrm{sec}$$

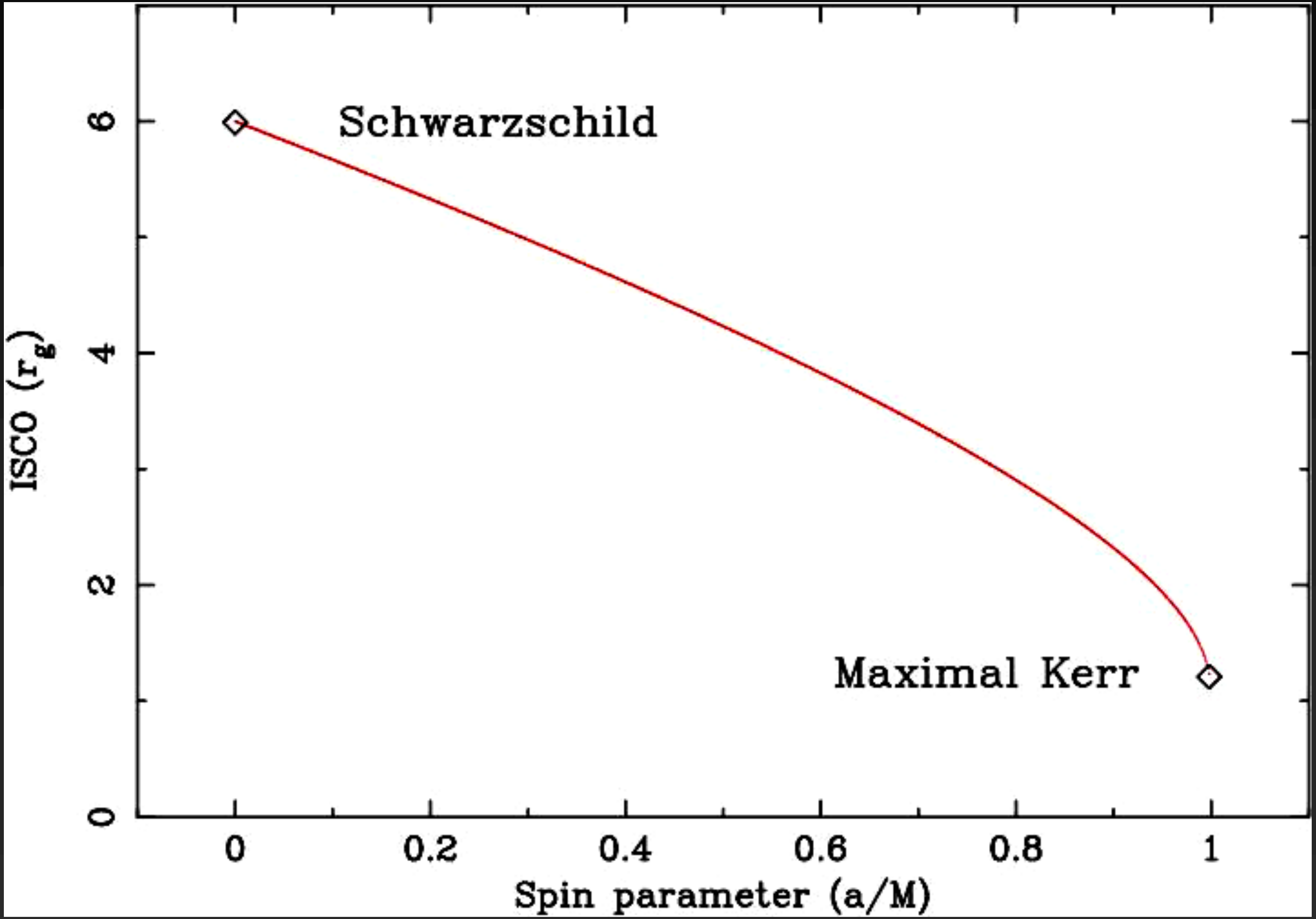
In order to be of the order of the dected period, the term in parenthesis must be of the order of 10

GR predicts the existence of an innermost stable circular orbit (ISCO) around BHs

Its radius only depends on BH spin

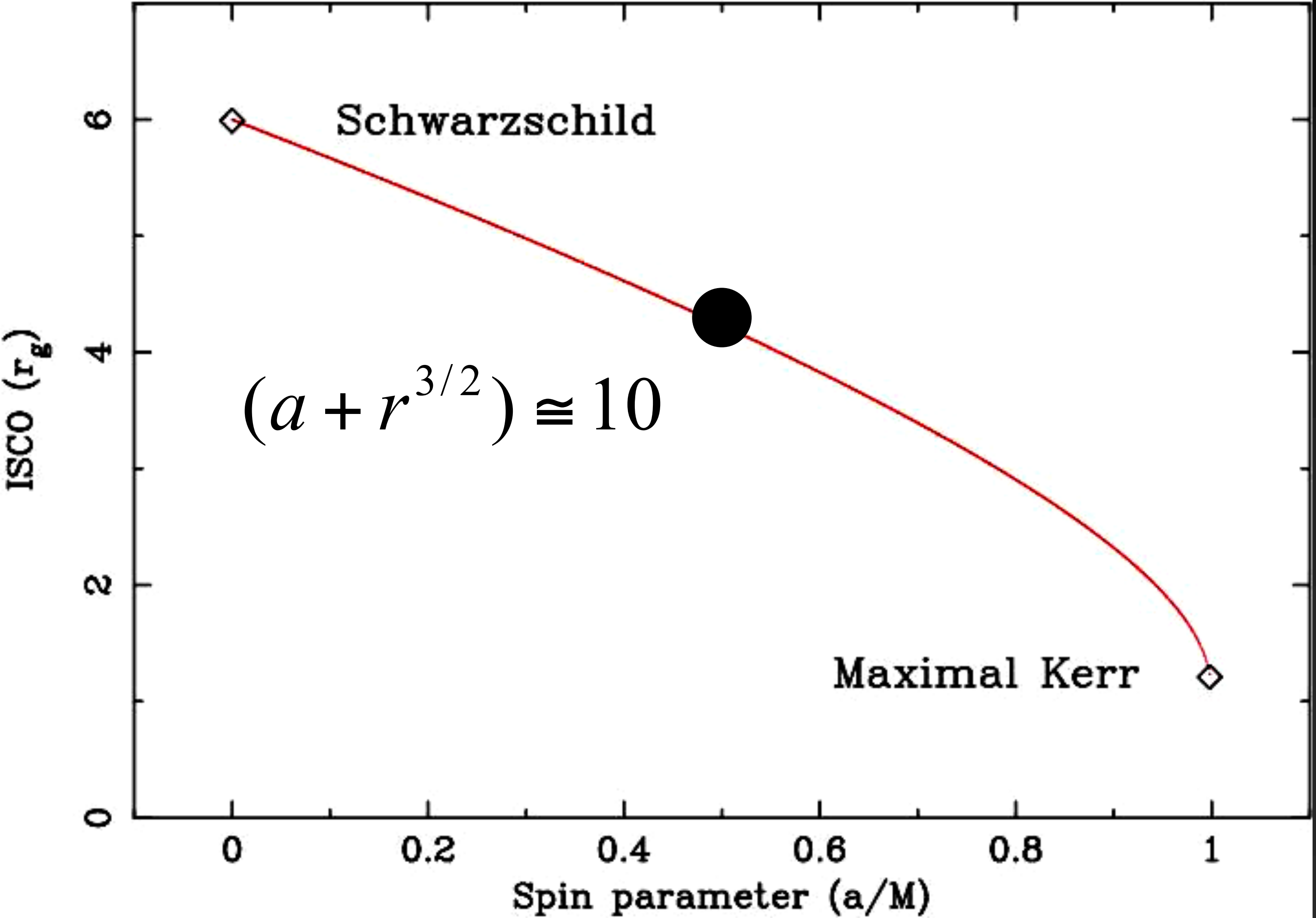
# Black Holes: observational evidences (some)

Supermassive (~ $10^6$-$10^9$ solar masses)



# Black Holes: observational evidences (some)

Supermassive (~ $10^6$-$10^9$ solar masses)



$$(a + r^{3/2}) \cong 10$$

# Black Holes: observational evidences (some)

## Supermassive (~ $10^6$-$10^9$ solar masses)

Due to angular resolution limitations, we cannot resolve the motion of individual stars close to the centers of other distant galaxies

However, stellar dynamics at relatively larger distances from the center can still be used to infer whether the motions imply the existence of a central dark concentration of mass

We still need high angular resolution, and in this case the best way is to get rid of atmospheric seeing problems going directly out of the atmosphere, i.e. using telescope on satellites

The Hubble Space Telescope is the natural instrument to use

# Black Holes: observational evidences (some)

## Supermassive (~ $10^6$-$10^9$ solar masses)

The observational signatures of a central concentration of mass are quite clear

1 – a central cusp in the velocity dispersion of stars

2 - a Keplerian (or nearly so) rotation curve

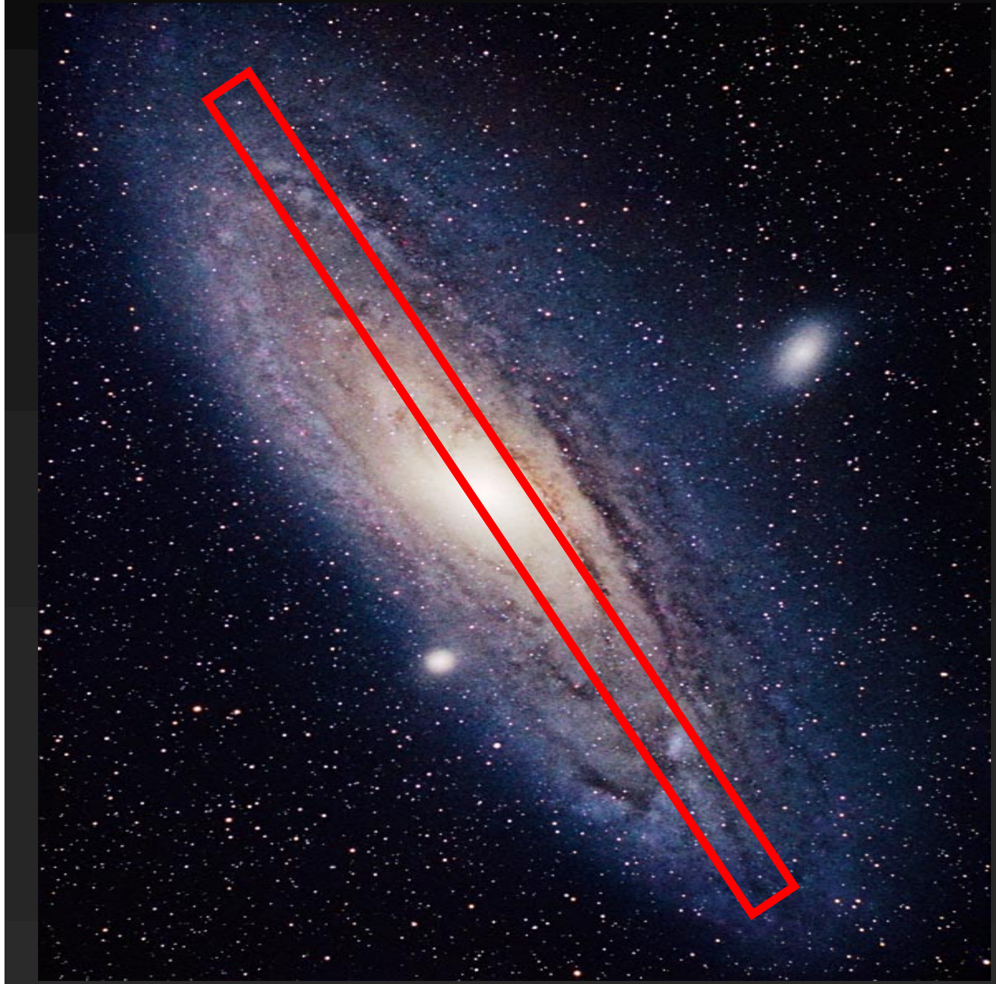
As seen for X-ray binaries, velocities can be determined from the Doppler shift of some distinctive stellar lines (in this case we use optical/UV lines from the HST detectors)

The observational goal is then to obtain the velocity distribution of stars as a function of the distance from the galaxy center

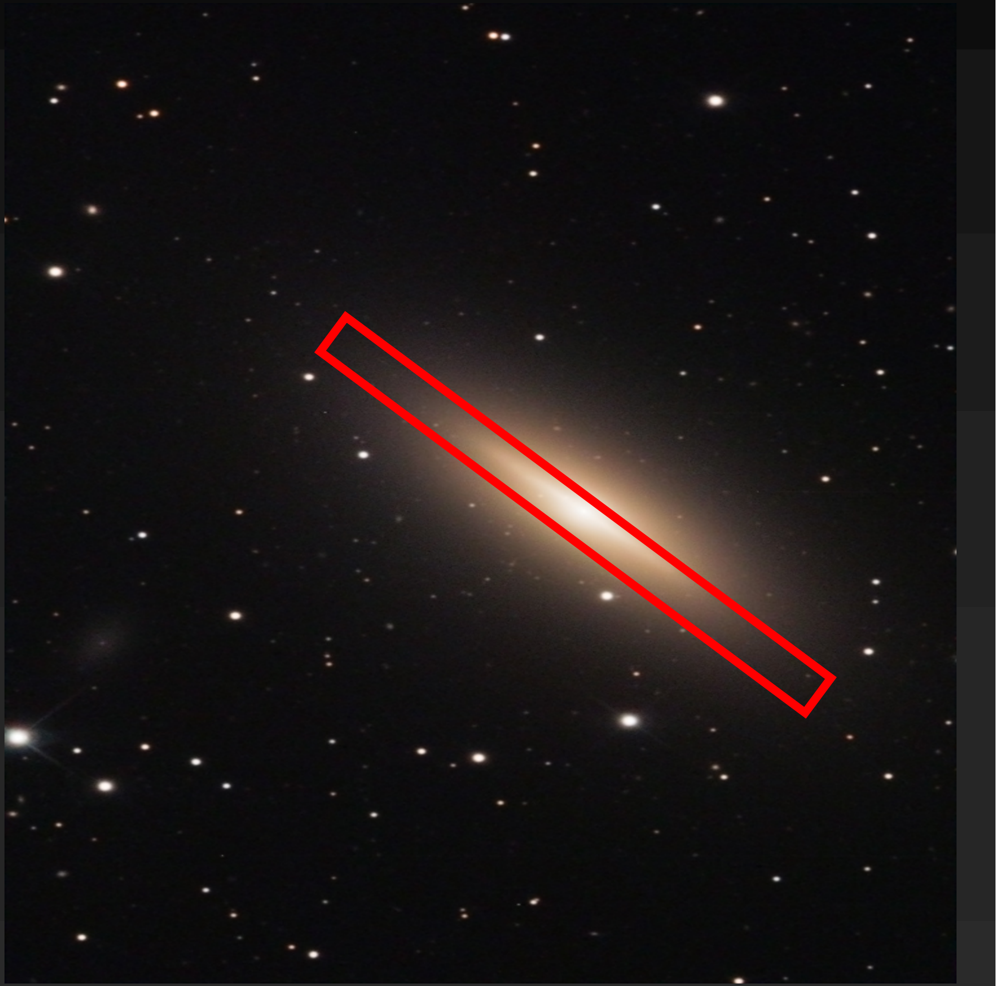
# Black Holes: observational evidences (some)

Supermassive (~ $10^6$-$10^9$ solar masses)

M 31 (Andromeda)



NGC 3115



# Black Holes: observational evidences (some)

## Supermassive (~ $10^6$-$10^9$ solar masses)

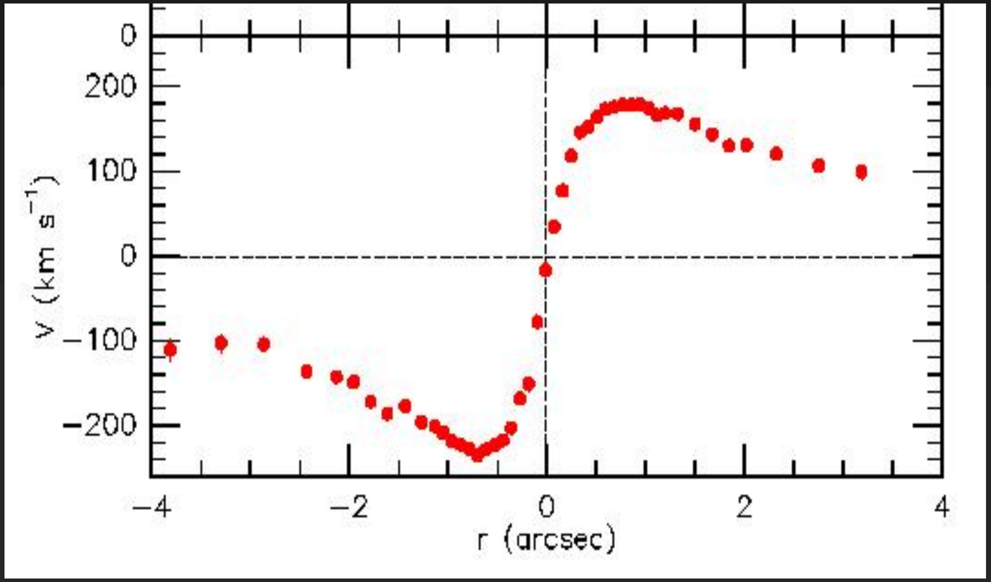
M 31 (Andromeda)

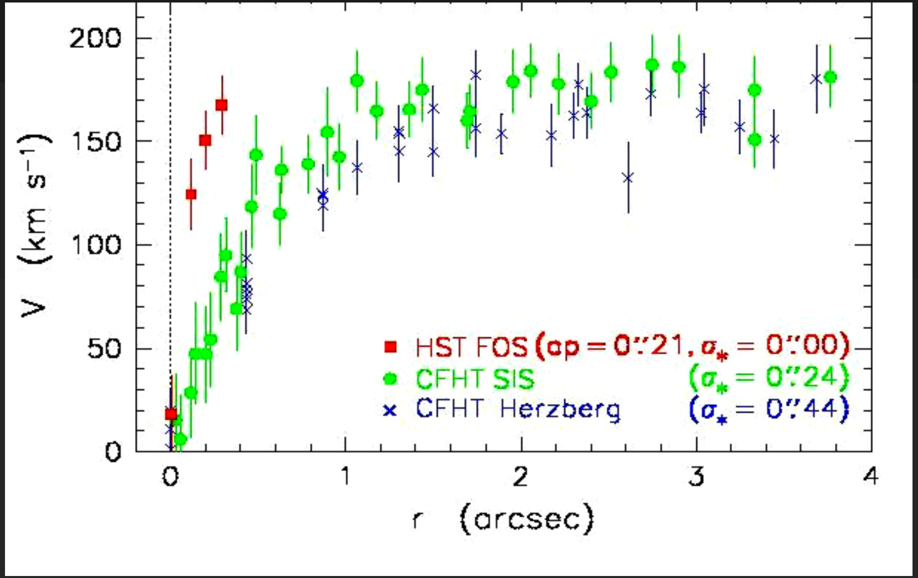
NGC 3115

The rotation curves are Keplerian to a high degree in both cases and they imply a central concentration of mass of the order of

~ $10^9$ $M_{sun}$

~$3x10^7$ $M_{sun}$





# Black Holes: observational evidences (some)

## Supermassive (~ $10^6$-$10^9$ solar masses)

In other cases we do not have the resolution to resolve any individual star and we have to rely on gas motions

This is more ambiguous because gas is not an extremely good tracer of the gravitational potential (at least not as good as stars) simply because of possible competing efects (e.g. radiation pressure or other effects)

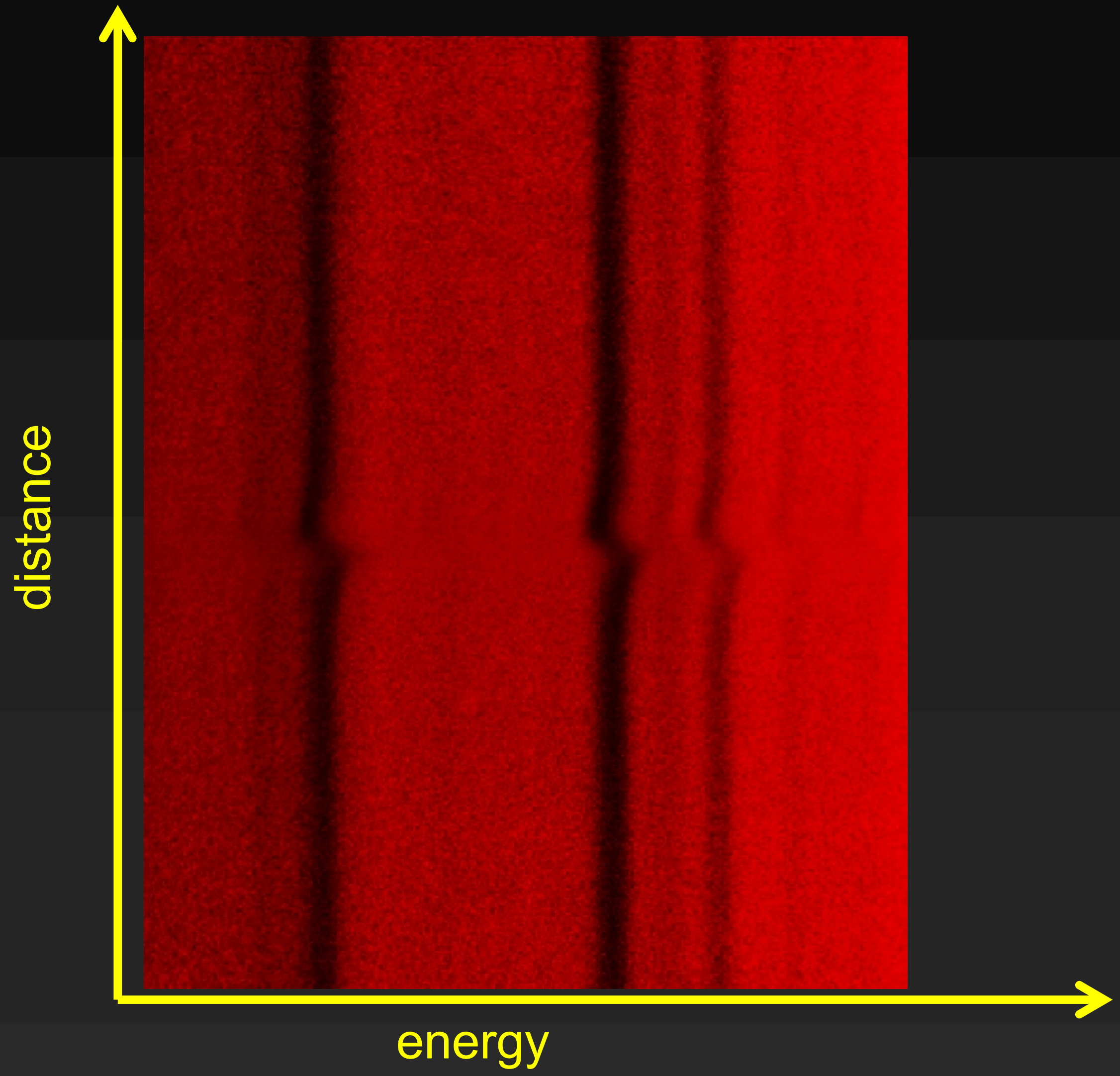
However, it is clear that if the gas motion turns out to be Keplerian to a good degree, this means that gravity dominates on all other possible forces affecting the gas motion

Again, gas dynamics can be studies in a few cases with the HST in good enough detail

# Black Holes: observational evidences (some)

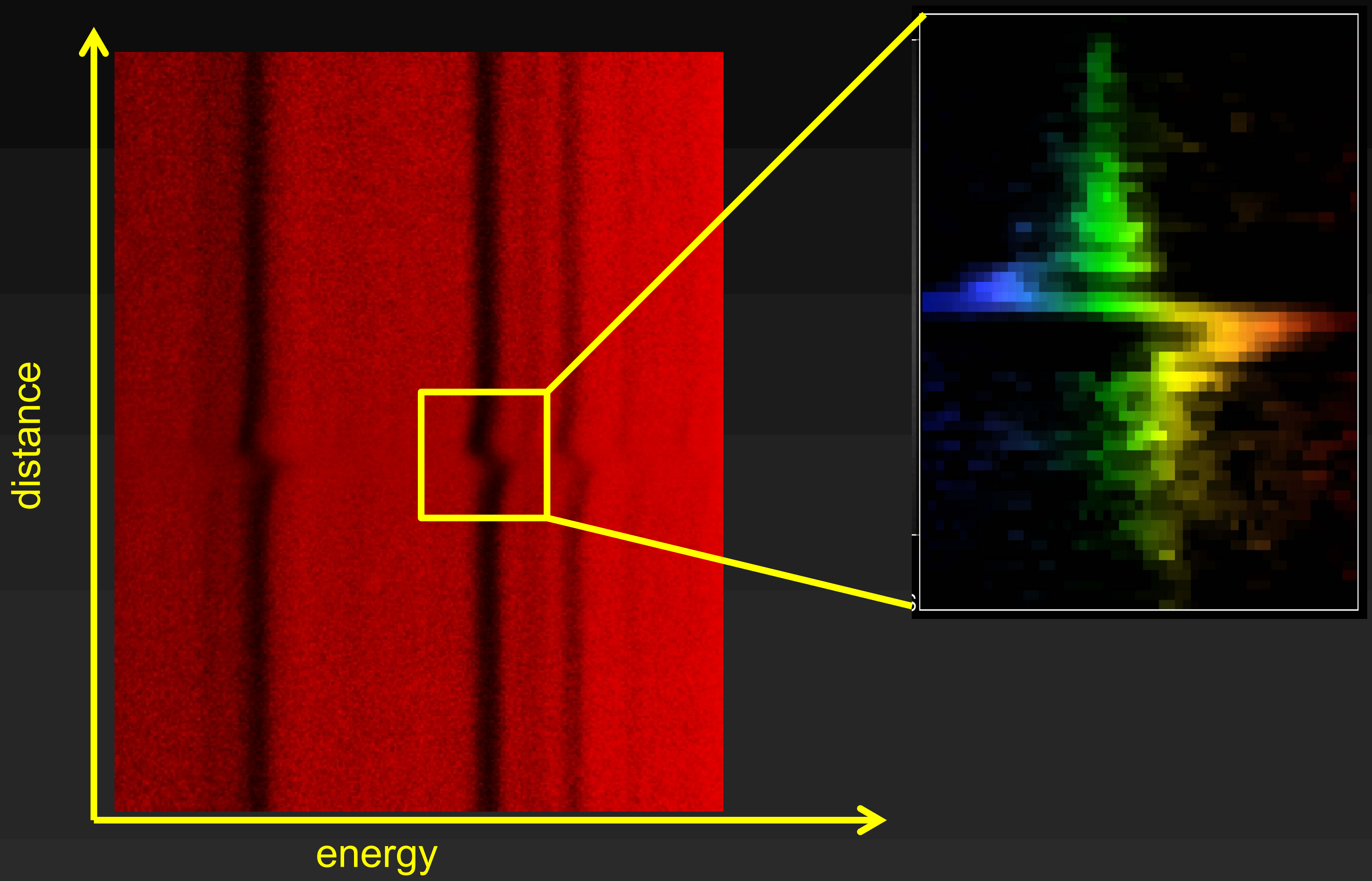
Supermassive (~ $10^6$-$10^9$ solar masses)

M84



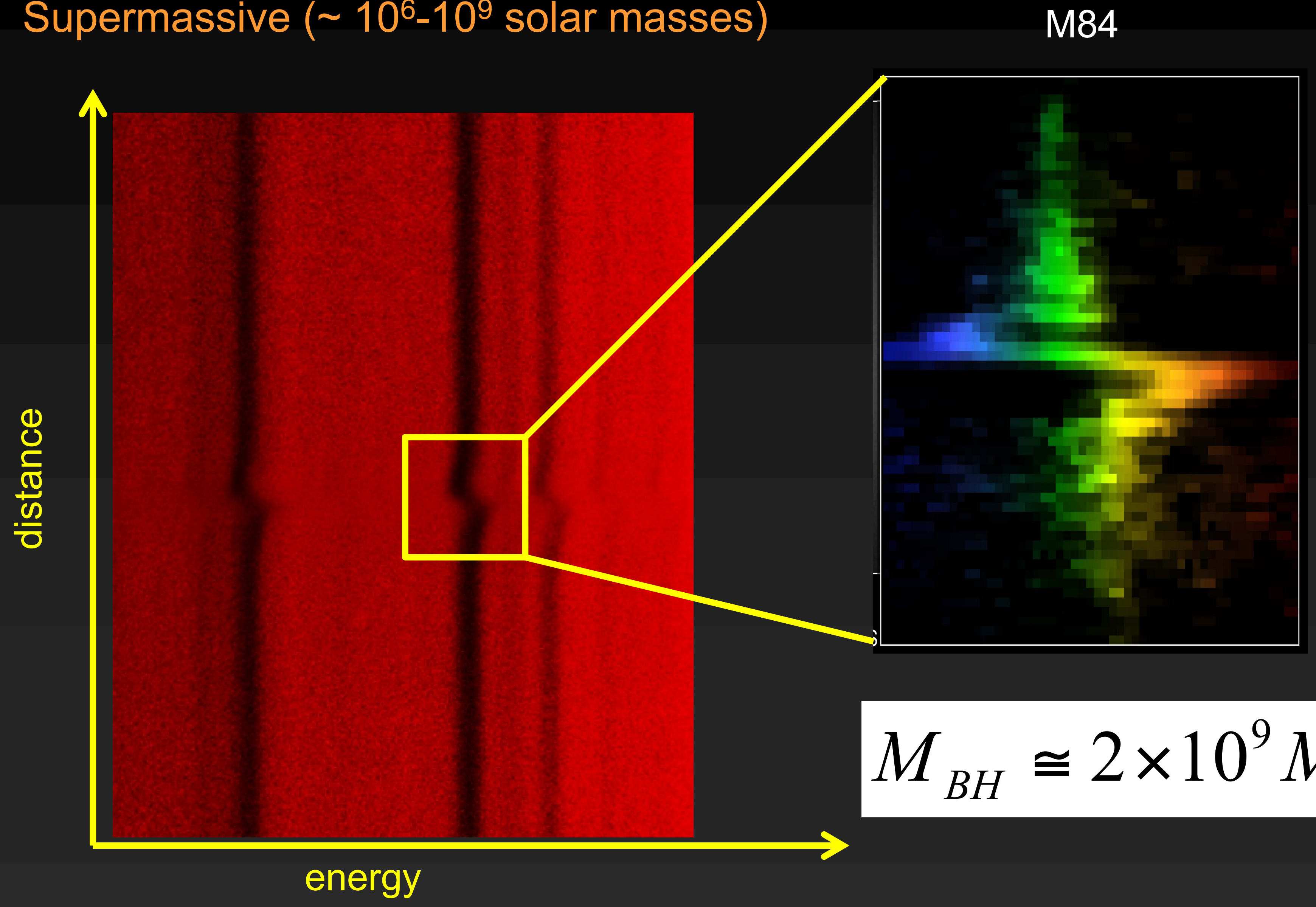
# Black Holes: observational evidences (some)

Supermassive (~ $10^6$-$10^9$ solar masses)



# Black Holes: observational evidences (some)

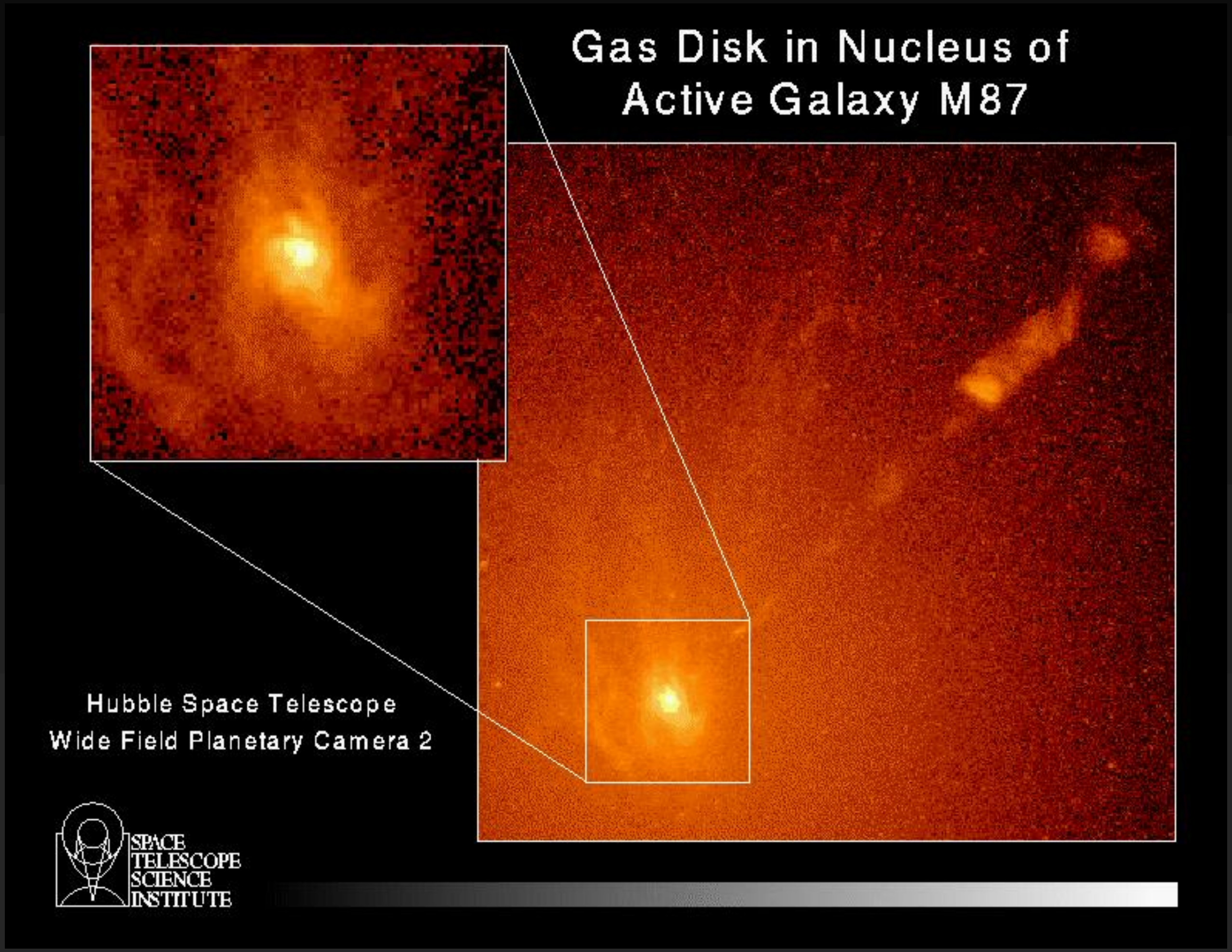
Supermassive (~ $10^6$-$10^9$ solar masses)



$$M_{BH} \cong 2\times10^9\,M_{sun}$$

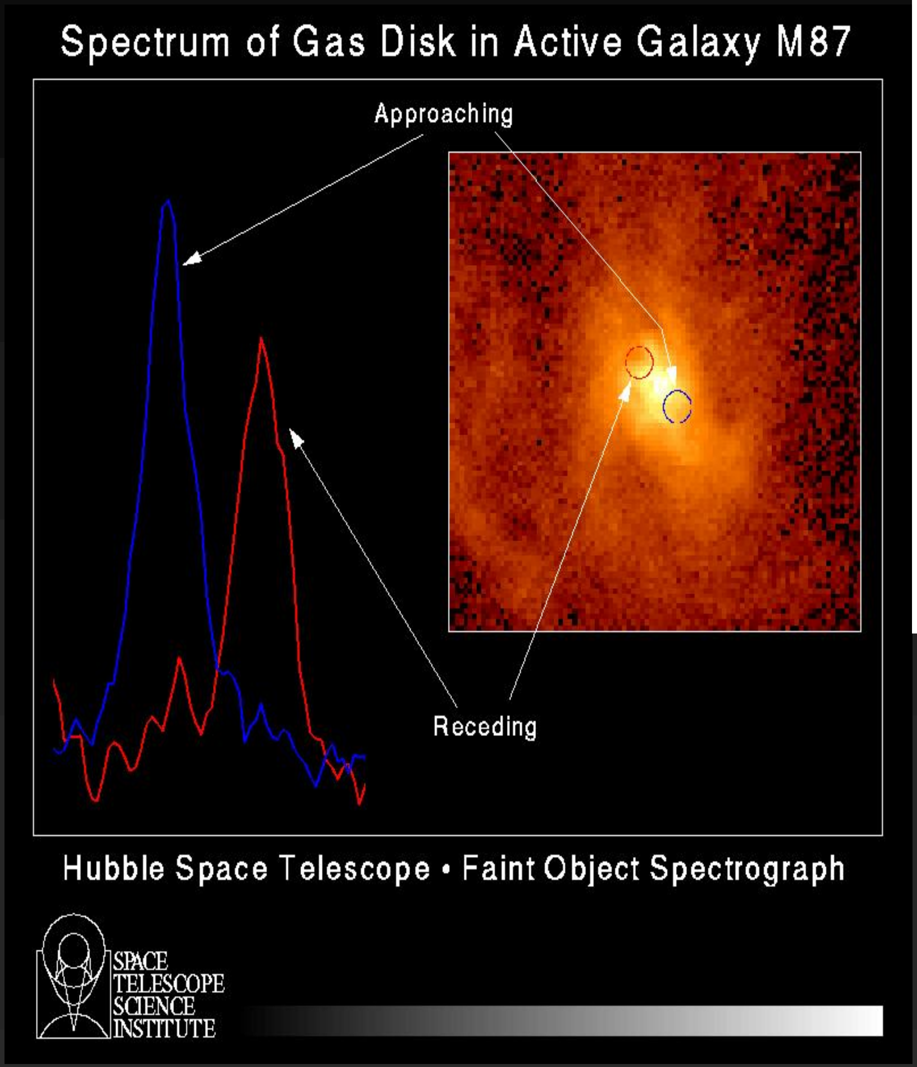
# Black Holes: observational evidences (some)

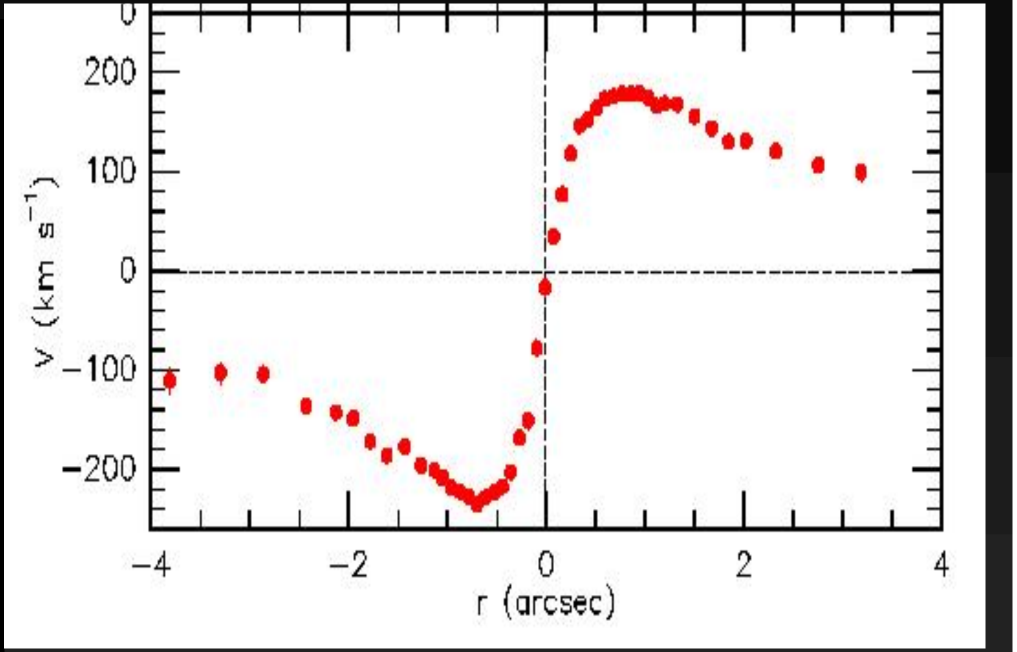
Supermassive (~ $10^6$-$10^9$ solar masses)



# Black Holes: observational evidences (some)

Supermassive (~ $10^6$-$10^9$ solar masses)



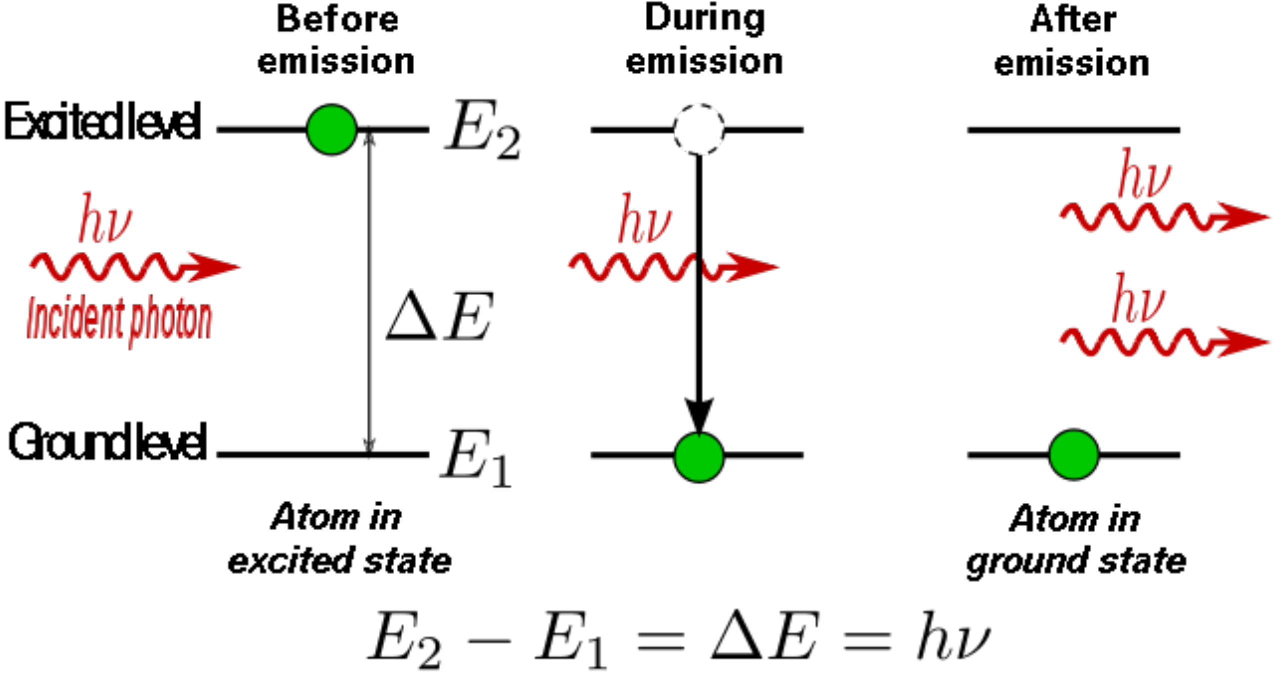


$$M_{BH} \cong 3\times10^{9} M_{sun}$$

# Black Holes: observational evidences (some)

## Supermassive (~ $10^6$-$10^9$ solar masses)

The 2nd-best case for a SMBH (after the GC one) comes from the galaxy NGC 4258 via the study of a water magamaser (i.e. stimulated emission) in the radio



$$E_2 - E_1 = \Delta E = h\nu$$

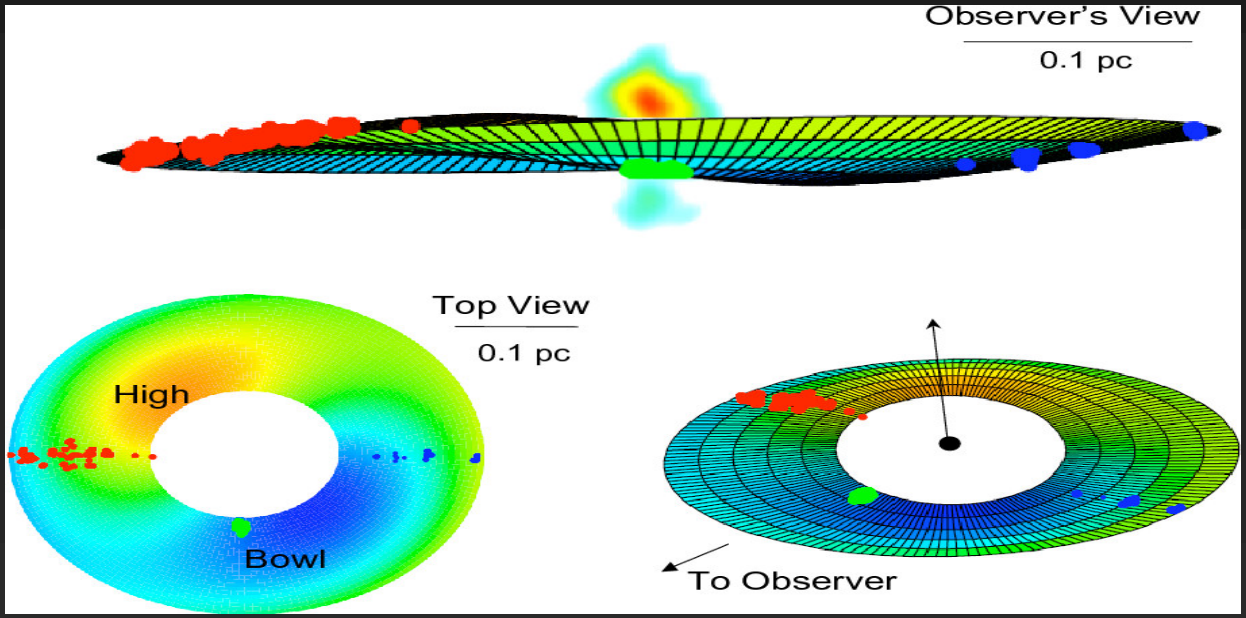
# Black Holes: observational evidences (some)

## Supermassive (~ $10^6$-$10^9$ solar masses)

The 2nd-best case for a SMBH (after the GC one) comes from the galaxy NGC 4258 via the study of a water magamaser (i.e. stimulated emission) in the radio

Very high angular resolution ( < 0.001" ) can be achieved using radio interferometry (higher resolution than with the HST which has ~ 0.05")

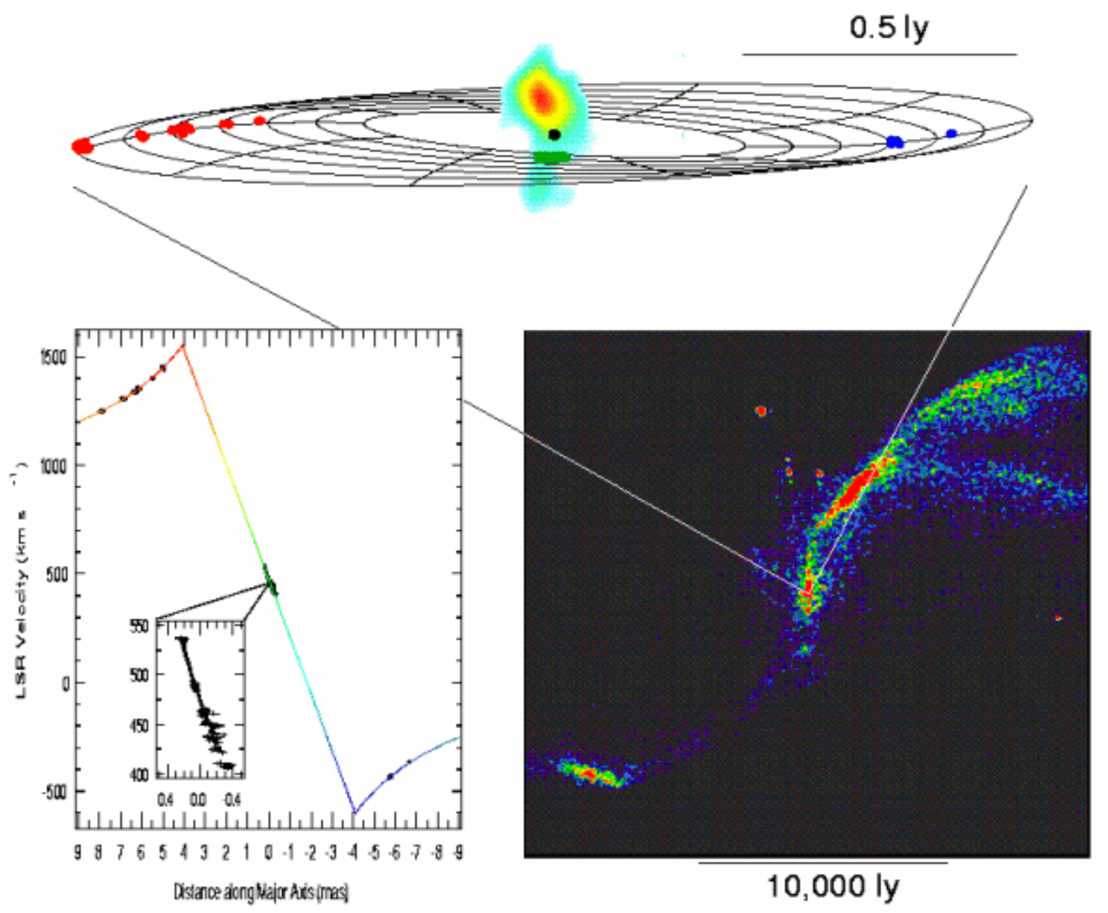
The main result is that the maser molecules are distributed in a distorted/warped disc around a radio source



# Black Holes: observational evidences (some)

## Supermassive (~ $10^6$-$10^9$ solar masses)

Velocities are Keplerian to an excellent degree



This means that all maser emitters orbit a mass that is completely contained within their orbits

A mass of $3.6 \times 10^7$ $M_{sun}$

is enclosed in such a small volume that, as in the GC case, any other reasonable alternative to a SMBH can be ruled out

# Black Holes: observational evidences (some)

## Summary

BHs are predicted as an inevitable endpoint of stellar evolution for massive stars

X-ray sources in binary systems have been discovered starting from the first X-ray observations (mid 60s and 70s)

Dynamical studies of these systems have provided highly convincing evidence for the existence of about 24 stellar-mass BH in X-ray binaries in the Milky Way, with masses in the typical range of 5 to 30 solar masses, plus a comparable number of very strong candidates (and many are now being discovered in nearby galaxies as well)

# Black Holes: observational evidences (some)

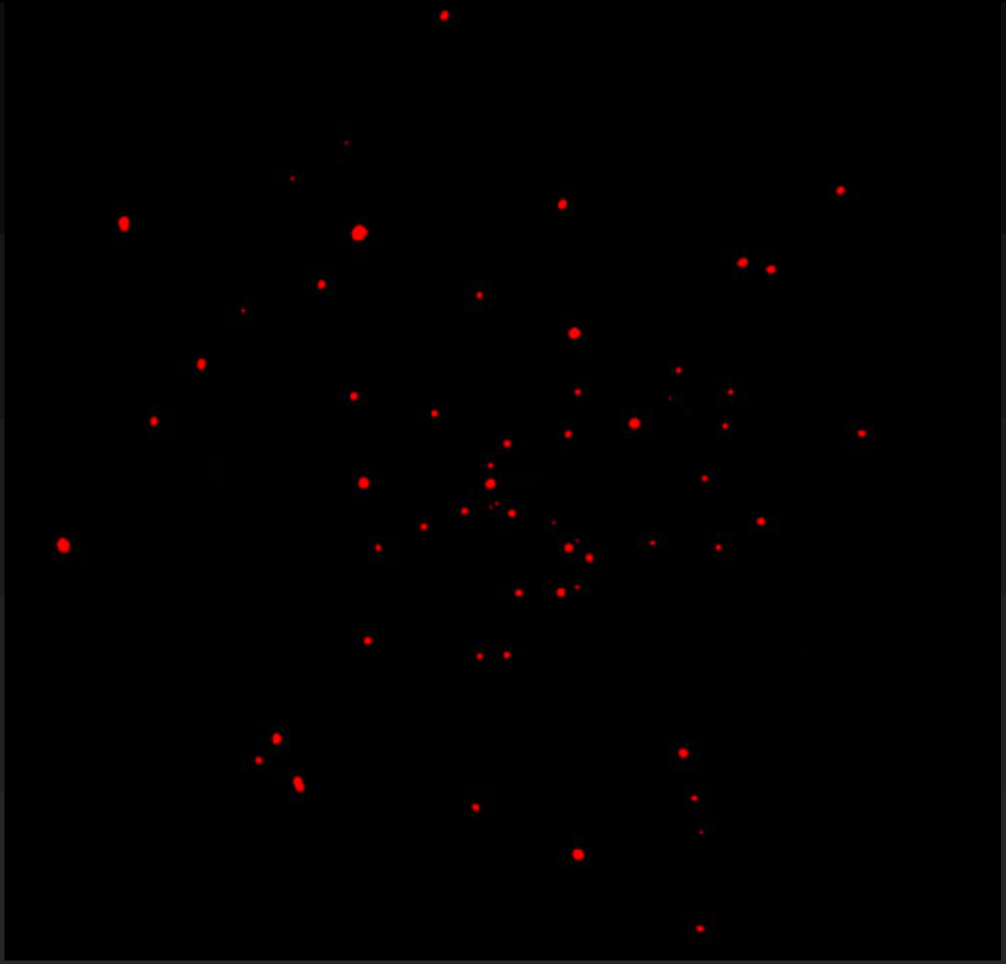
## Summary

NOAO / AURA / NSF/ T. Boroson

Like our own Milky Way, M74 is a majestic spiral

# Black Holes: observational evidences (some)

## Summary



NASA/CXC / U. Michigan / J. Liu et al.

X-ray observations reveal the presence of hundreds of X-ray sources in the field

These are all accreting sources on compact objects (WDs, NSs and BHs)

# Black Holes: observational evidences (some)

## Summary

NASA / CXC / U. Michigan / J. Liu et al.
NOAO / AURA / NSF / T. Boroson

Composite optical + X-ray image

# Black Holes: observational evidences (some)

## Summary

BHs are predicted as an inevitable endpoint of stellar evolution for massive stars

X-ray sources in binary systems have been discovered starting from the first X-ray observations (mid 60s and 70s)

Dynamical studies of these systems have provided highly convincing evidence for the existence of about 25 stellar-mass BH in X-ray binaries in the Milky Way, with masses in the typical range of 5 to 30 solar masses, plus a comparable number of very strong candidates (and many are now being discovered in nearby galaxies as well)

The Milky Way harbors a SMBH of about 4-4.5 millions solar masses in its center and the closest approach of stars rule out other possible “dark masses”

Any time we have looked at the center of other galaxies (stellar/gas velocities) we have discovered large concentrations of central masses of the order of $10^6$ to $10^9$ solar masses → all galaxies most likely harbor a SMBH in their nucleus (and hundreds of millions of stellar-mass BHs, only a few of which shining when accreting from a companion star in a binary system)