Galaxy Formation and Evolution

Lecture 12:
AGNs and
Supermassive Black Holes

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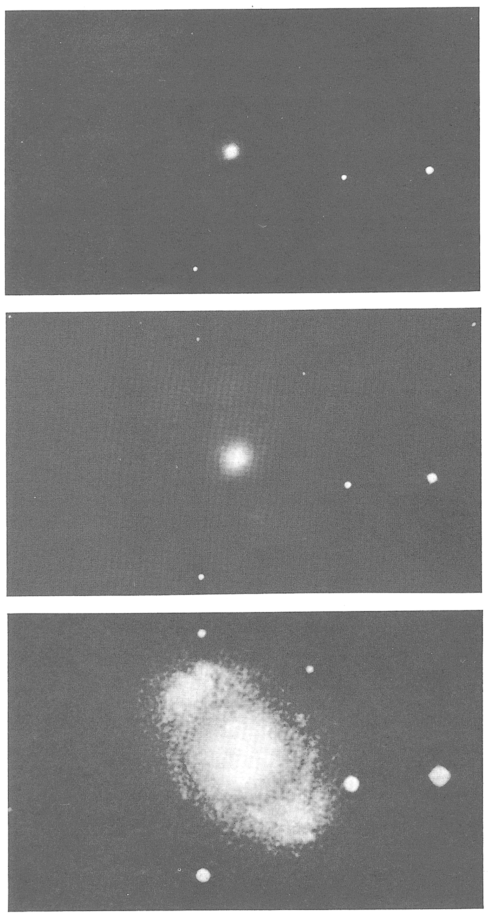
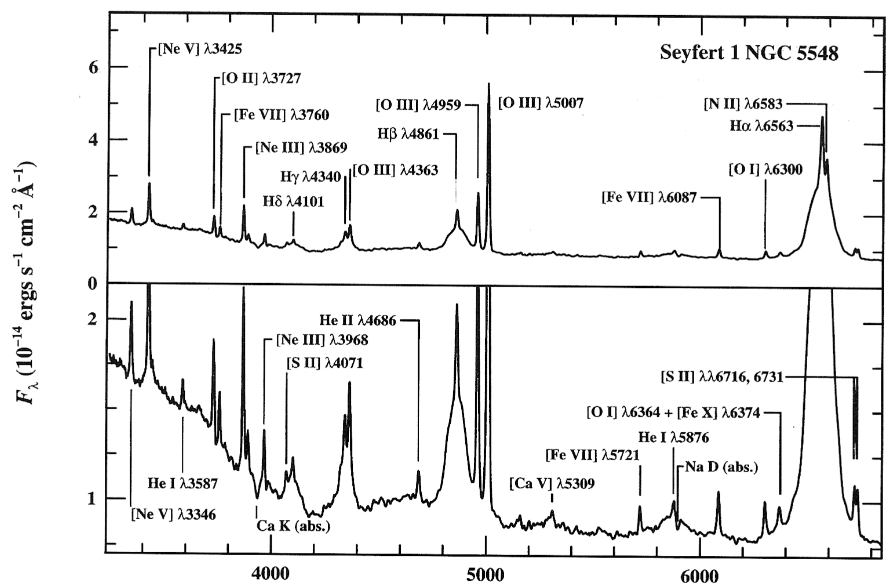
Seyfert Galaxies

Optical images



Optical spectra

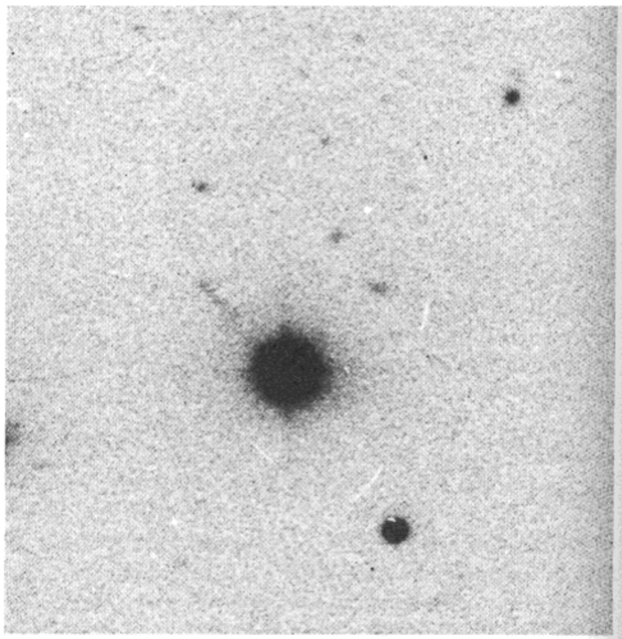


Seyfert (1943)

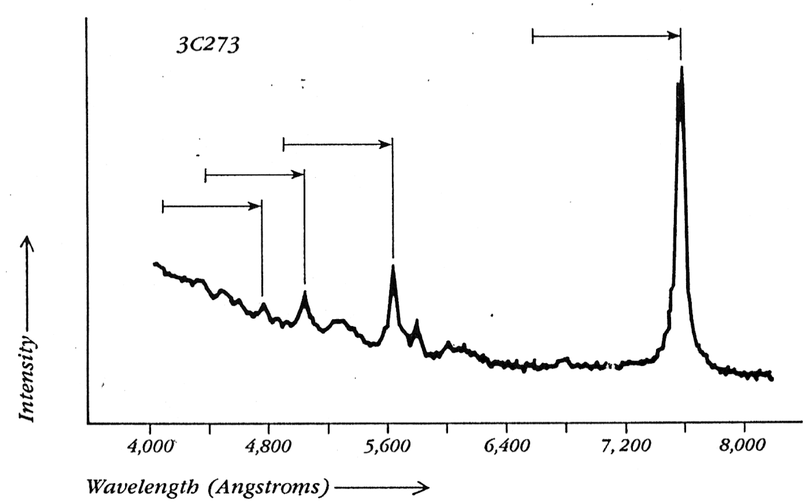
The discovery of the quasar 3C273

(Schmidt 1963)

Optical image

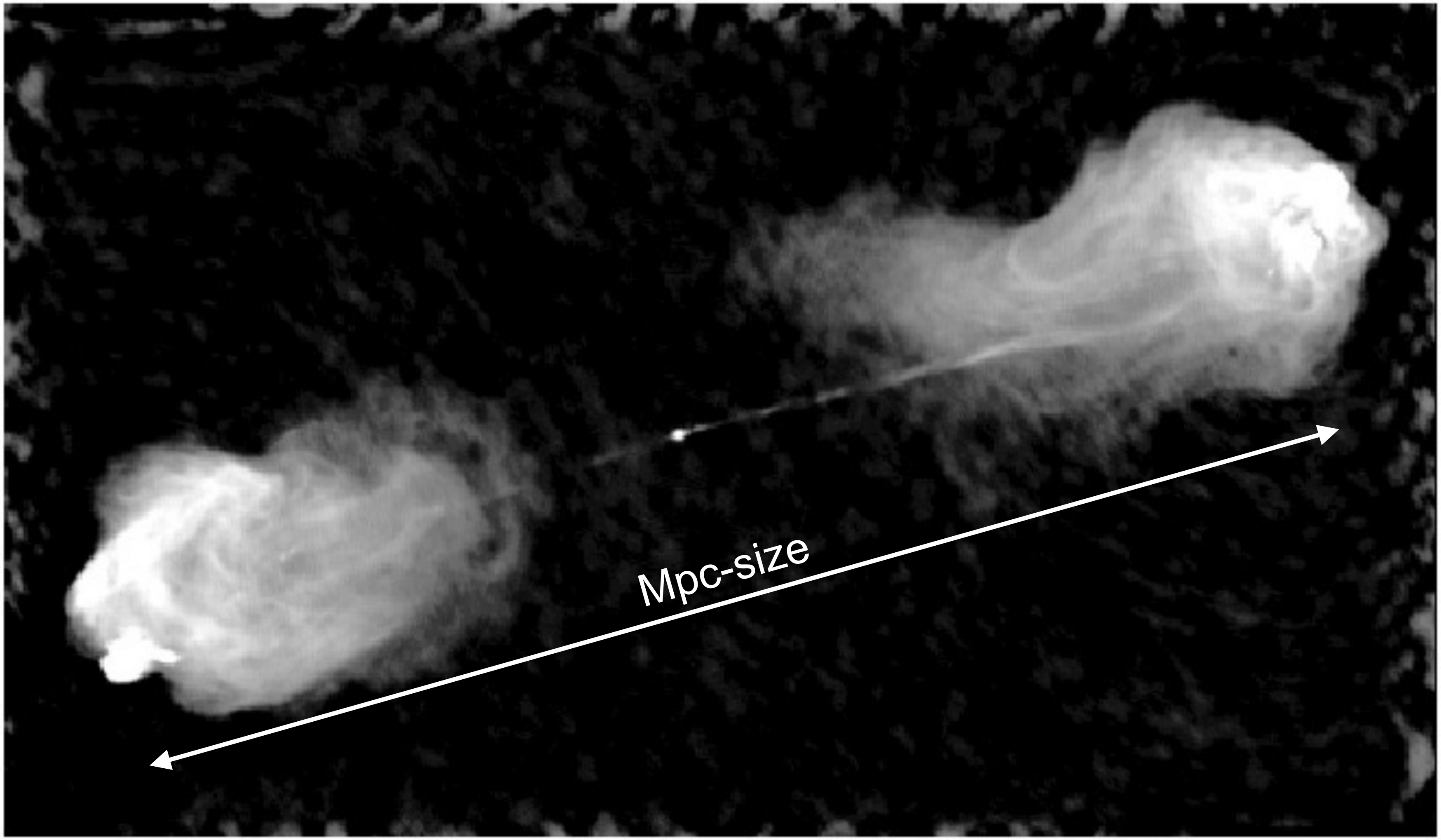


Optical spectrum z=0.158

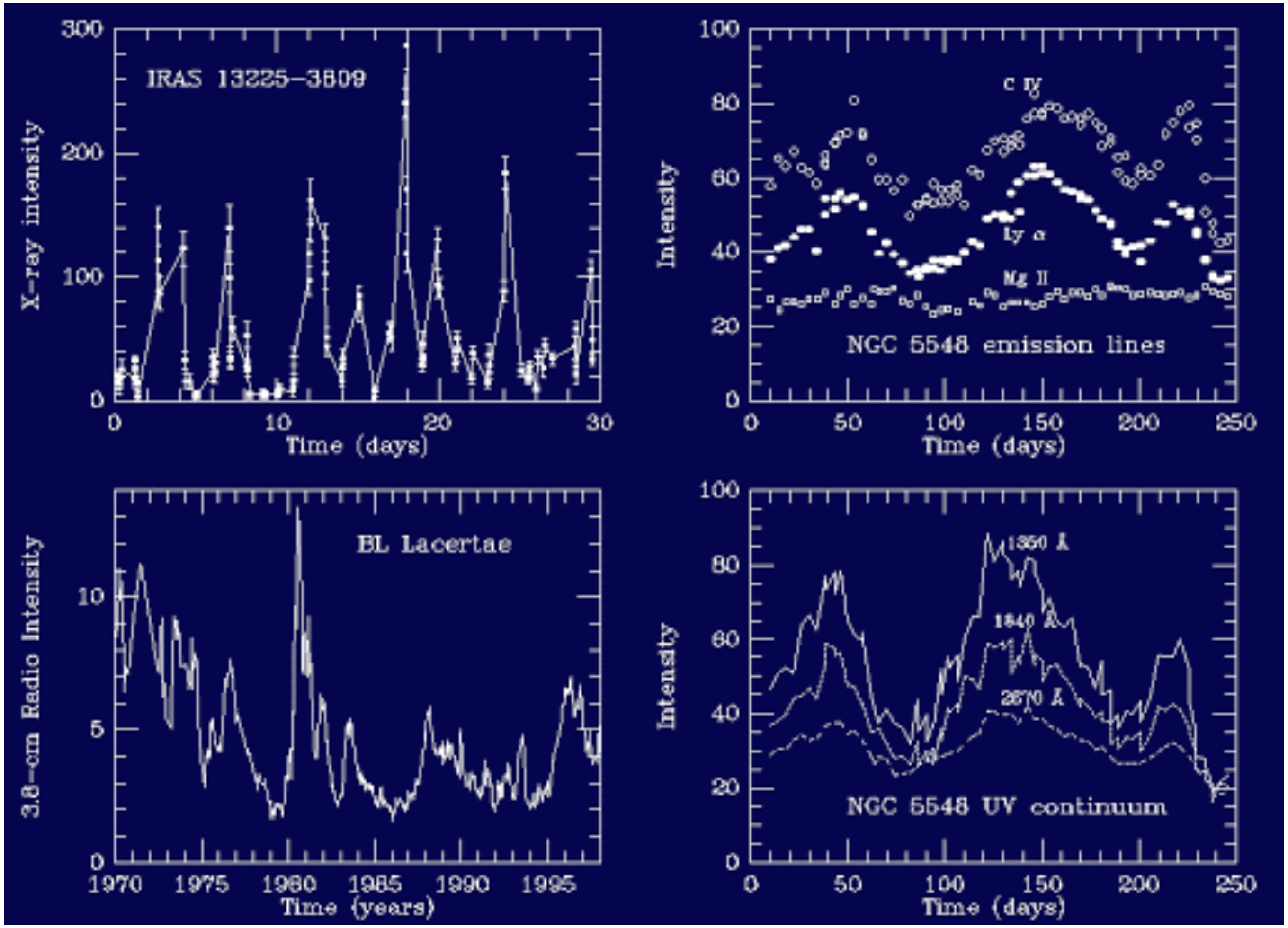


At the distances estimated from the redshifts of the emission lines, quasars have a luminosity 10 - 10,000x the integrated light of all the stars in the Milky way.

VLA image of Cygnus A

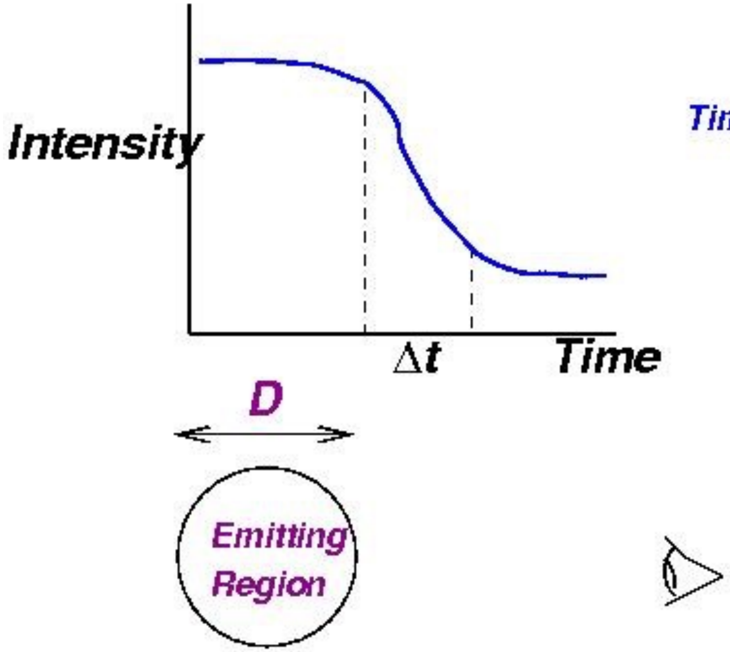


AGN Variability



The luminosity of AGN vary on all timescales, from days to years. Daily variations imply a small "central engine".

Variability and the size of the emitting region



Timescale for variability:
Δt

Time taken for information about physical disturbance causing brightening/fading to cross emitting region at speed of light:

$$\Delta t = \frac{D}{c}$$ (light crossing time & variability timescale)

$$\Rightarrow \quad D \sim c\,\Delta t$$ (estimate of size of region)

e.g. AGN/Quasars: $\Delta t \sim$ 1 day – 1year
$D \sim$ 1light day – 1 light year

Active nuclei: key characteristics

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- Large luminosities (1 - 10,000 galaxies)

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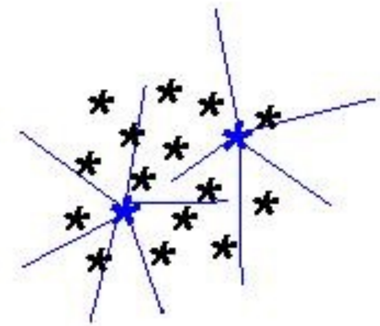
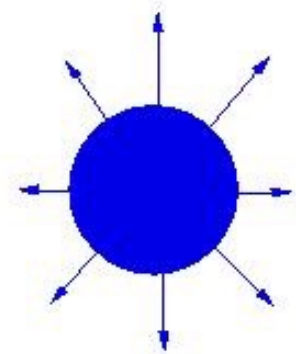
- Small size of emitting region (< 1 light year)
- Large lifetimes (1 - 100 million years)
- Ability to produce highly collimated jets

Energy Sources for AGN/Quasars

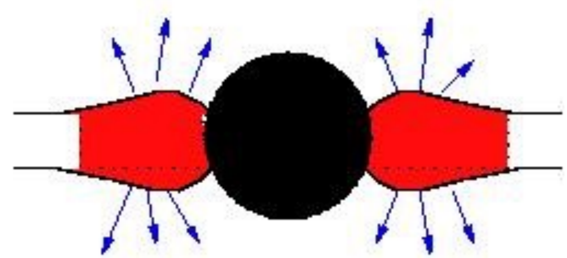
1. Central cluster of massive ($M^{*} > 20 \times M_{sun}$) stars which explode as supernovae.



2. Central supermassive star ($M^{*} > 10^{6} \times M_{sun}$)



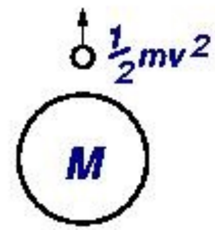
3. Central super-massive black hole ($10^{6} < M_{bh} < 10^{10} M_{sun}$)



What are black holes?

Black holes are objects in which the gravitational field is so strong that nothing can escape, not even light.

Michell (1783)
Laplace (1796)



Simple Newtonian approximation

For escape:

Particle kinetic energy > |Grav. potential energy|

Limit: $\frac{1}{2} m v_e^2 = \frac{GMm}{r}$

$$\Rightarrow \quad r = \frac{2GM}{v_e^2}$$

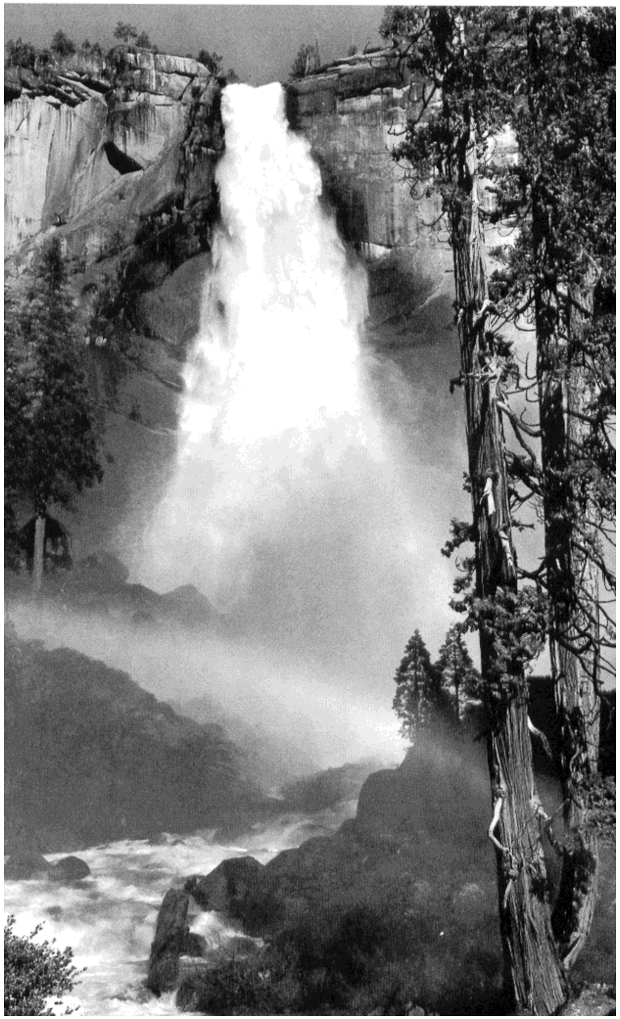
Set $v_e = c$ $\Rightarrow$ $\boxed{r_s = \frac{2GM}{c^2}}$

Schwarzschild Radius: the radius of the event horizon of a black hole of mass M.

e.g. M(Earth) $\Rightarrow$ $r_s = 1$ cm

M(Sun) $\Rightarrow$ $r_s = 3$ km

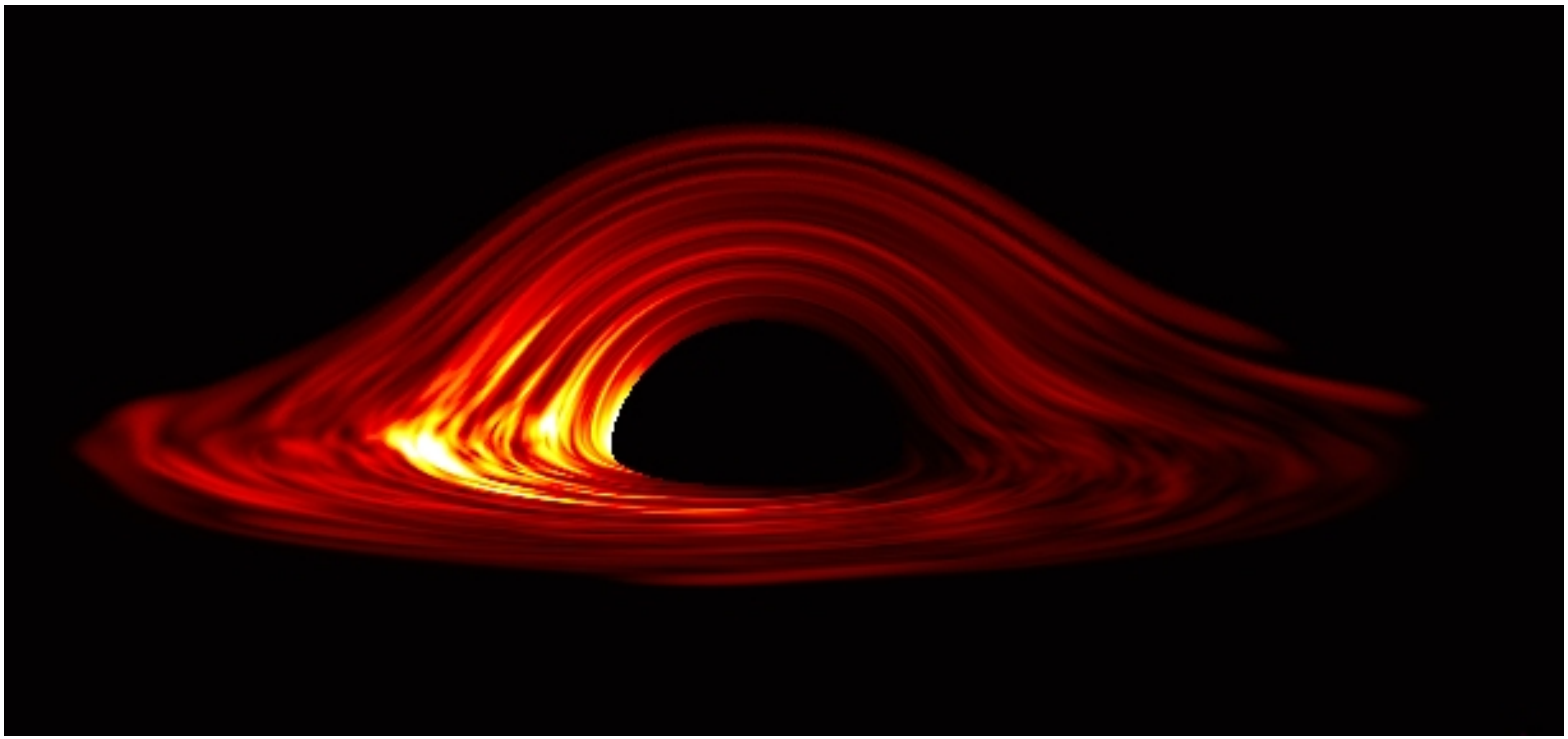
Gravitational energy generation around black holes



The release of gravitational energy when material falls close to the event horizon of a super-massive black hole is equivalent to 10 - 30% of the rest mass energy ($0.1 - 0.3 \times Mc^2$).

This is ~10x more efficient than nuclear fusion ($0.007 \times Mc^2$)!

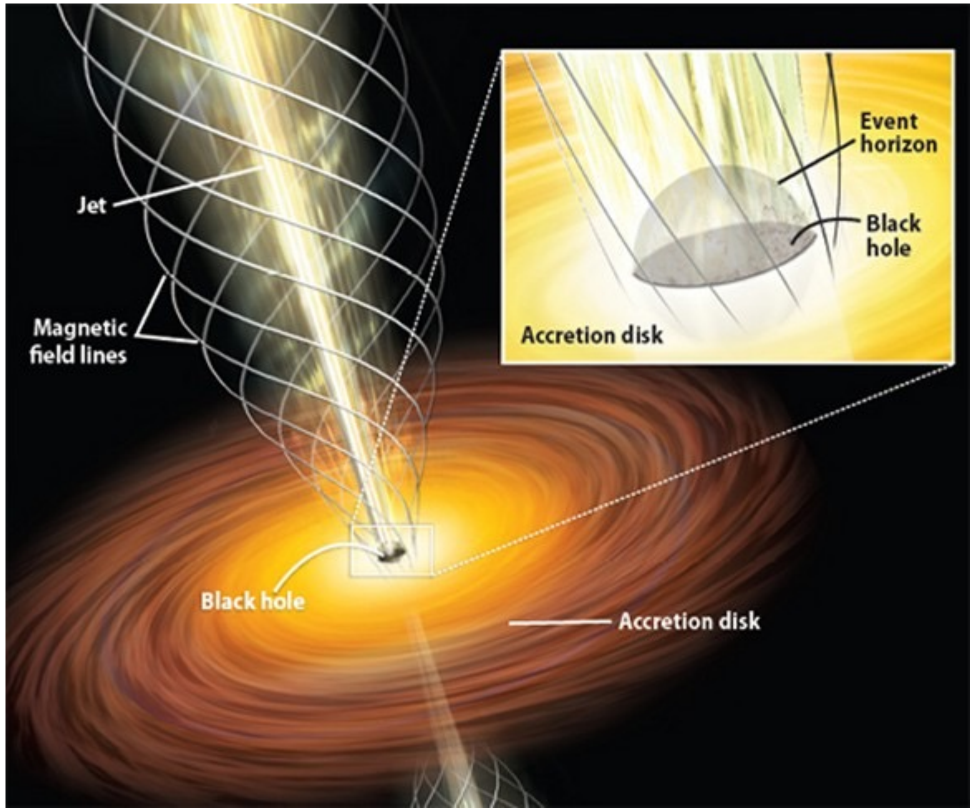
Supermassive black holes: the energy source for active galactic nuclei



Armitage and Reynolds (2003)

$$L_{BOL} = \eta \dot{M} c^2 ; \eta \sim 0.1 - 0.3$$

Generation of jets by spinning black holes



As material accreted, the black hole and accretion disk become threaded by a magnetic field. The spin of the black hole then tangles the magnetic field into a spiral pattern. Electrons caught in the “net” will be accelerated outwards in jet by their interaction with rapidly moving magnetic field lines.

Evidence of Supermassive Black Holes

We can place a lower limit on the mass of the black hole via the Eddington limit. Recall that the Eddington limit is the maximum luminosity that an accreting system of mass M can have before the outward photon pressure overcomes gravity (and thus stop accretion):

$$L_{\rm Edd} = \frac{4\pi G M m_p c}{\sigma_T}$$

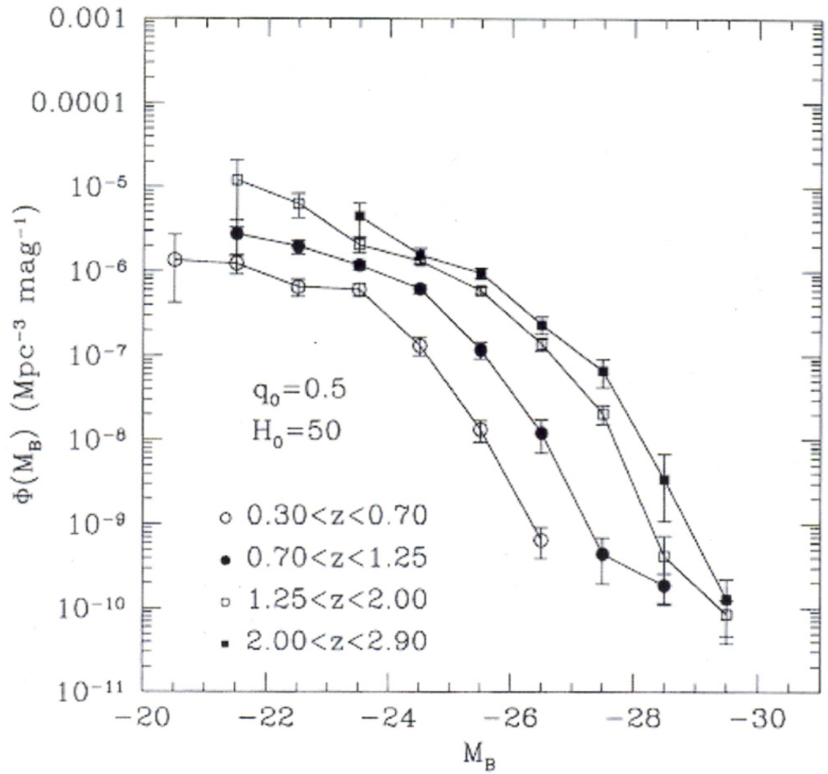
Which corresponds to: $$L_{\rm Edd} = 1.3 \times 10^{38} \left(\frac{M}{\rm M_\odot}\right) {\rm erg\ s}^{-1}$$

Meaning that a 5×10^{45} erg/s AGN must have a black hole mass of *at least*:

$$5 \times 10^{45}/1.3 \times 10^{38} \approx 4 \times 10^7\ {\rm M_\odot}$$

Which is vastly more massive than a stellar-mass black hole.

The Soltan argument I: why we should expect to find massive black holes in most galaxies



By integrating the luminosity function of AGN at a particular redshift and making a bolometric correction, we get the total light emitted by AGN per unit vol. at that redshift, then by integrating over all redshifts we estimate the total light emitted by AGN per unit vol. over history of Universe.

The Soltan argument II: why we should expect to find massive black holes in most galaxies

- Black holes grow through the accretion of material, and the accretion of material generates light that we see as AGN ($L_{BOL} = \eta \dot{M} c^2 ; \eta \approx 0.1$)

  ➔ the integrated bolometric luminosities of all the AGN in a co-moving volume integrated over all redshifts gives an estimate of the total mass density in black holes at the current epoch ($\rho_{bh} \sim 5 \times 10^5\ M_\odot\ Mpc^{-3}$)

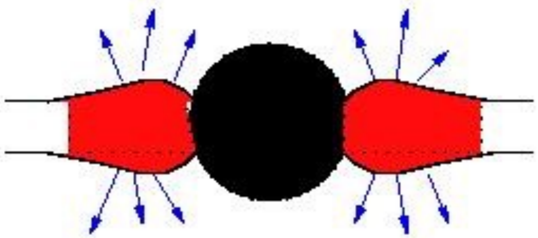
- This is similar to the measured local black hole density obtained from M_{bh} vs σ relation using the σ values measured for nearby galaxies by SDSS ($\rho_{bh} \sim 2.5 \times 10^5\ M_\odot\ Mpc^{-3}$)

- Dividing by the number density of massive galaxies in local Universe ($\sim 0.01\ Mpc^{-3}$) then gives the average black hole mass per massive galaxy ($\sim 2 - 5 \times 10^7\ M_\odot$)

Soltan (1982)

Black Holes: how do we detect them?

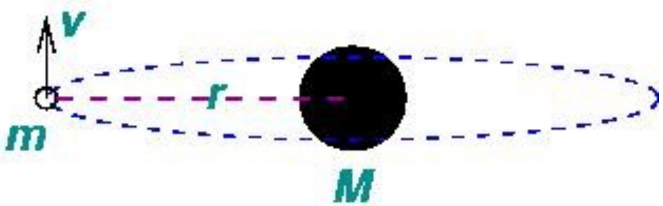
1. Heating effect



2. Motions of test particles

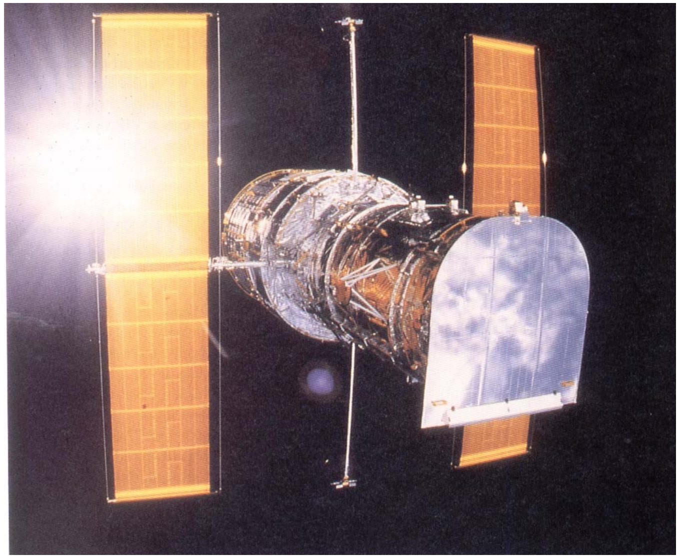
$$\frac{mv^2}{r} = \frac{GMm}{r^2}$$

$$\Rightarrow \boxed{M_{bh} = \frac{v^2 r}{G}}$$



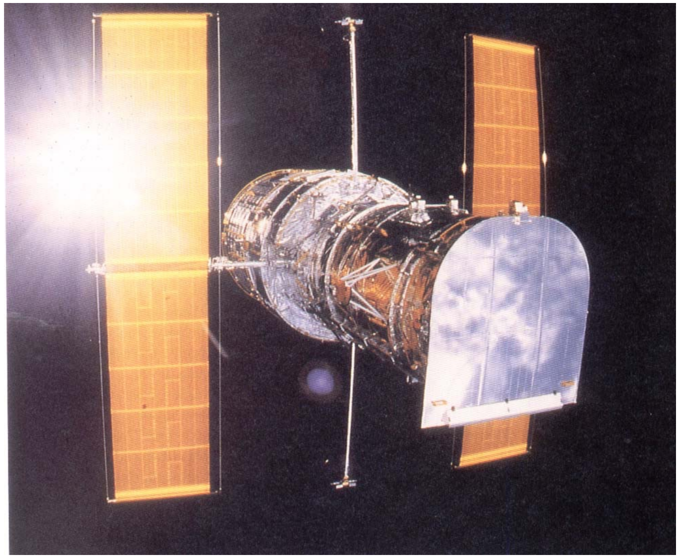
Test particles can be used to "weigh" the black hole if v, r are known.

Hubble Space Telescope Capabilities



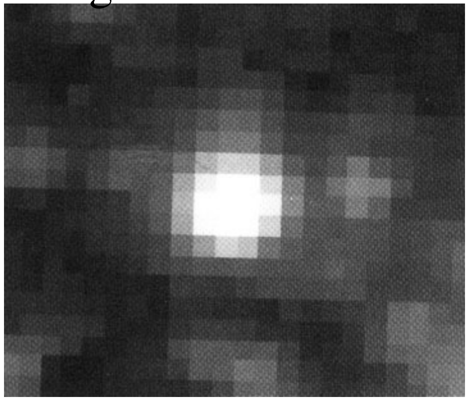
HST in orbit

Hubble Space Telescope Capabilities



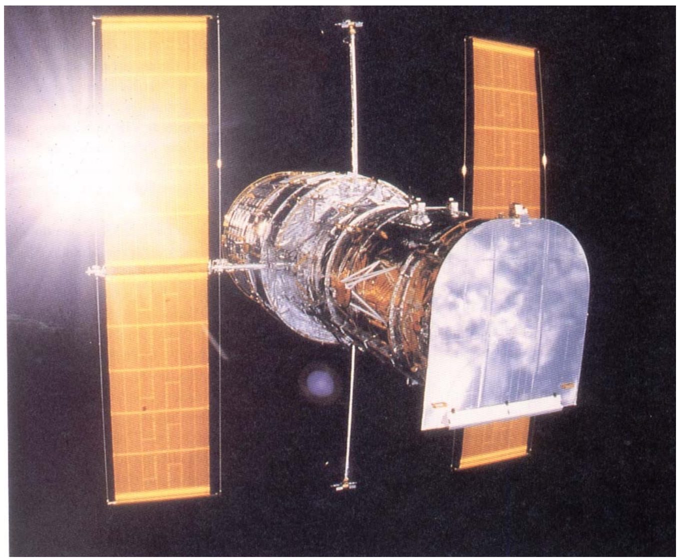
HST in orbit

Images of star cluster



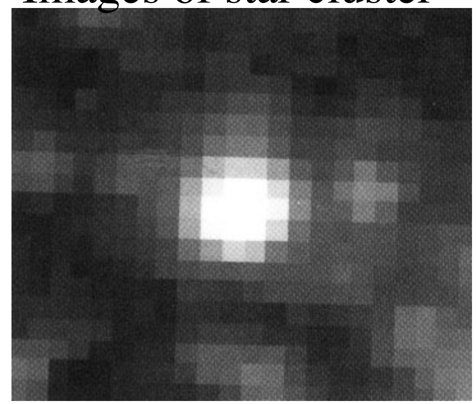
From ground

Hubble Space Telescope Capabilities

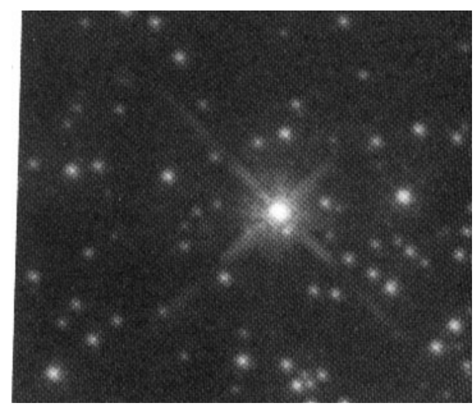


HST in orbit

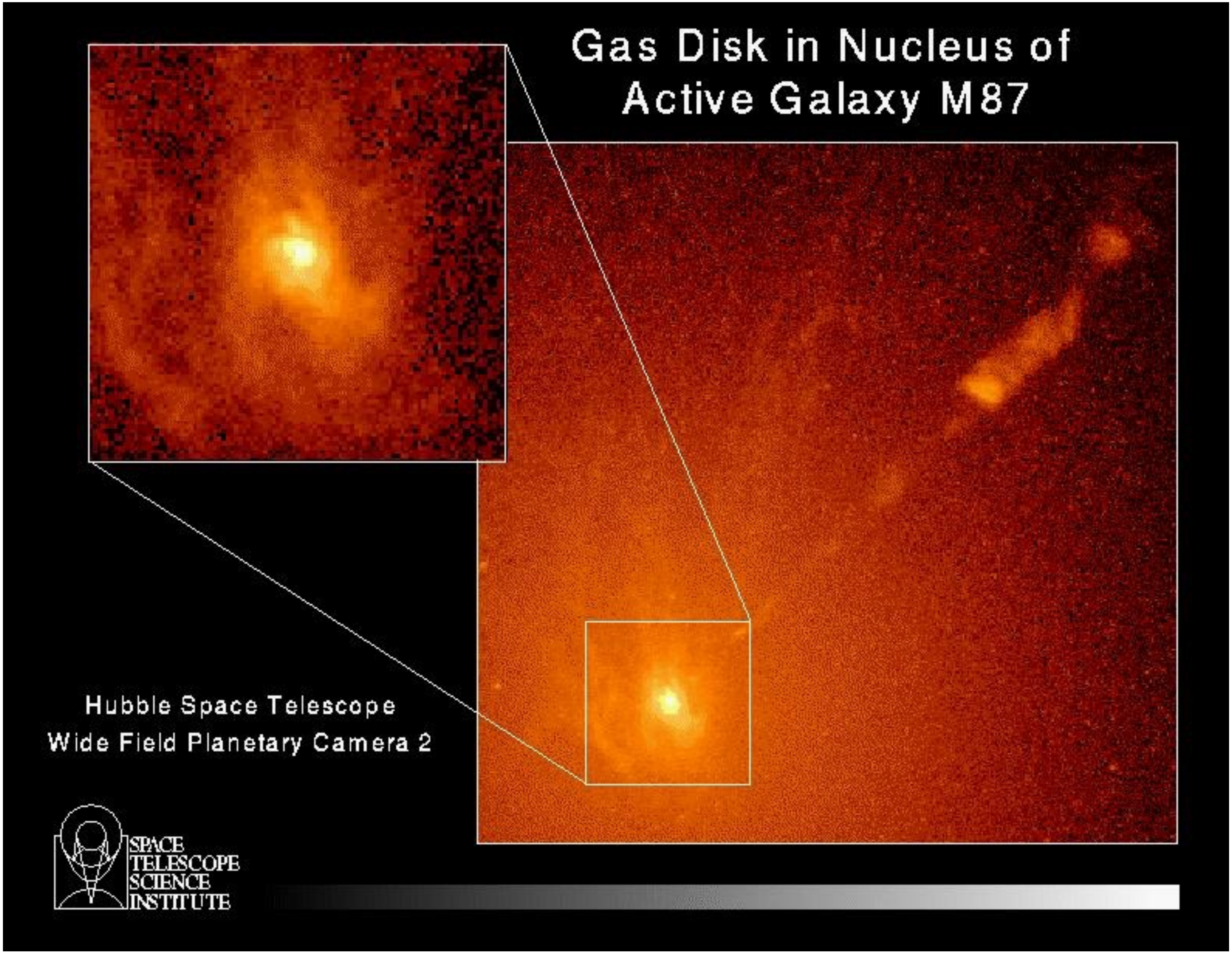
Images of star cluster



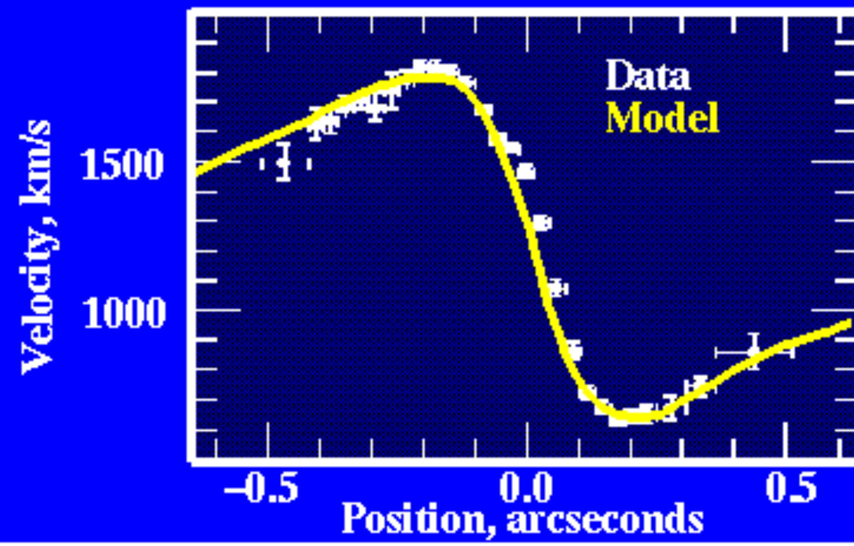
From ground



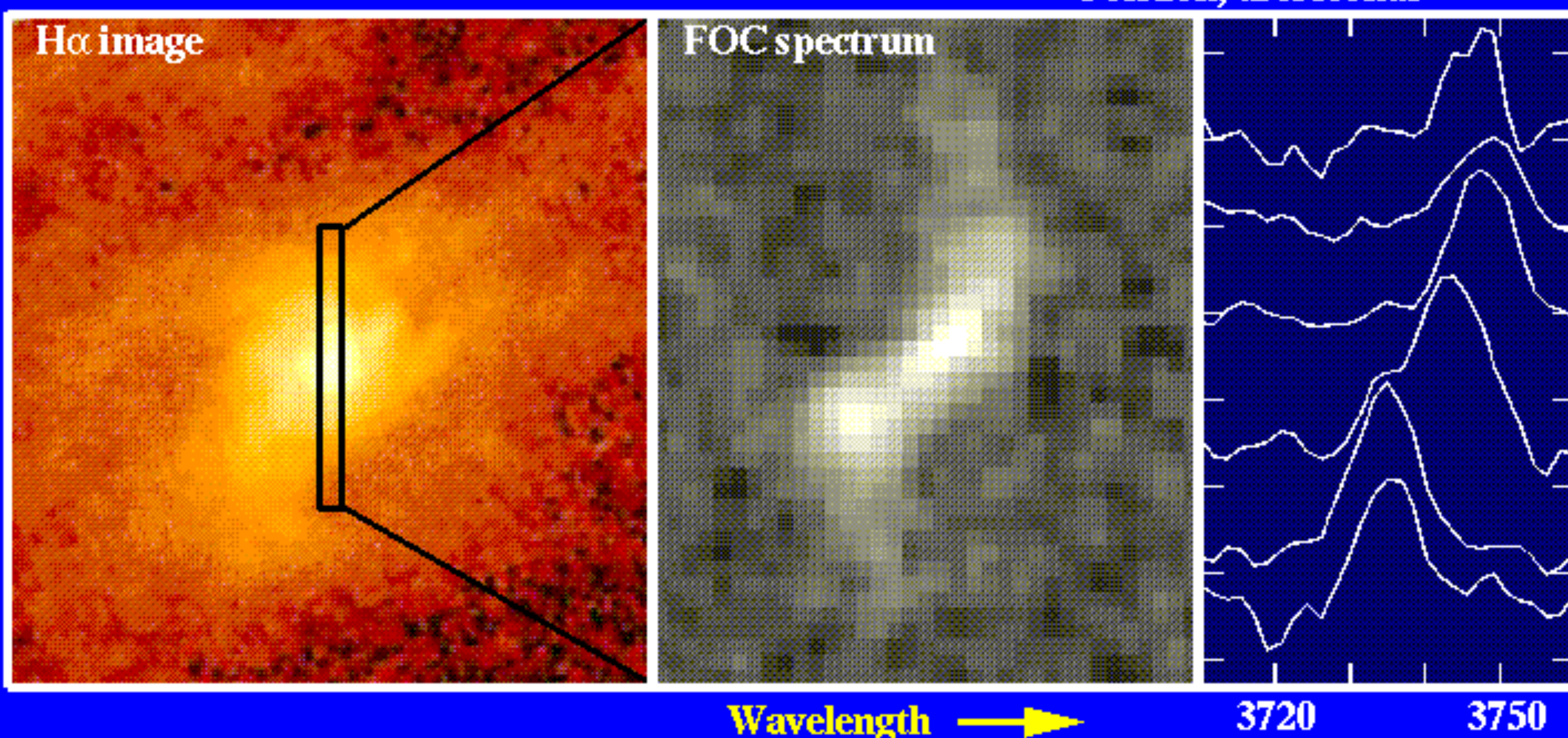
From HST

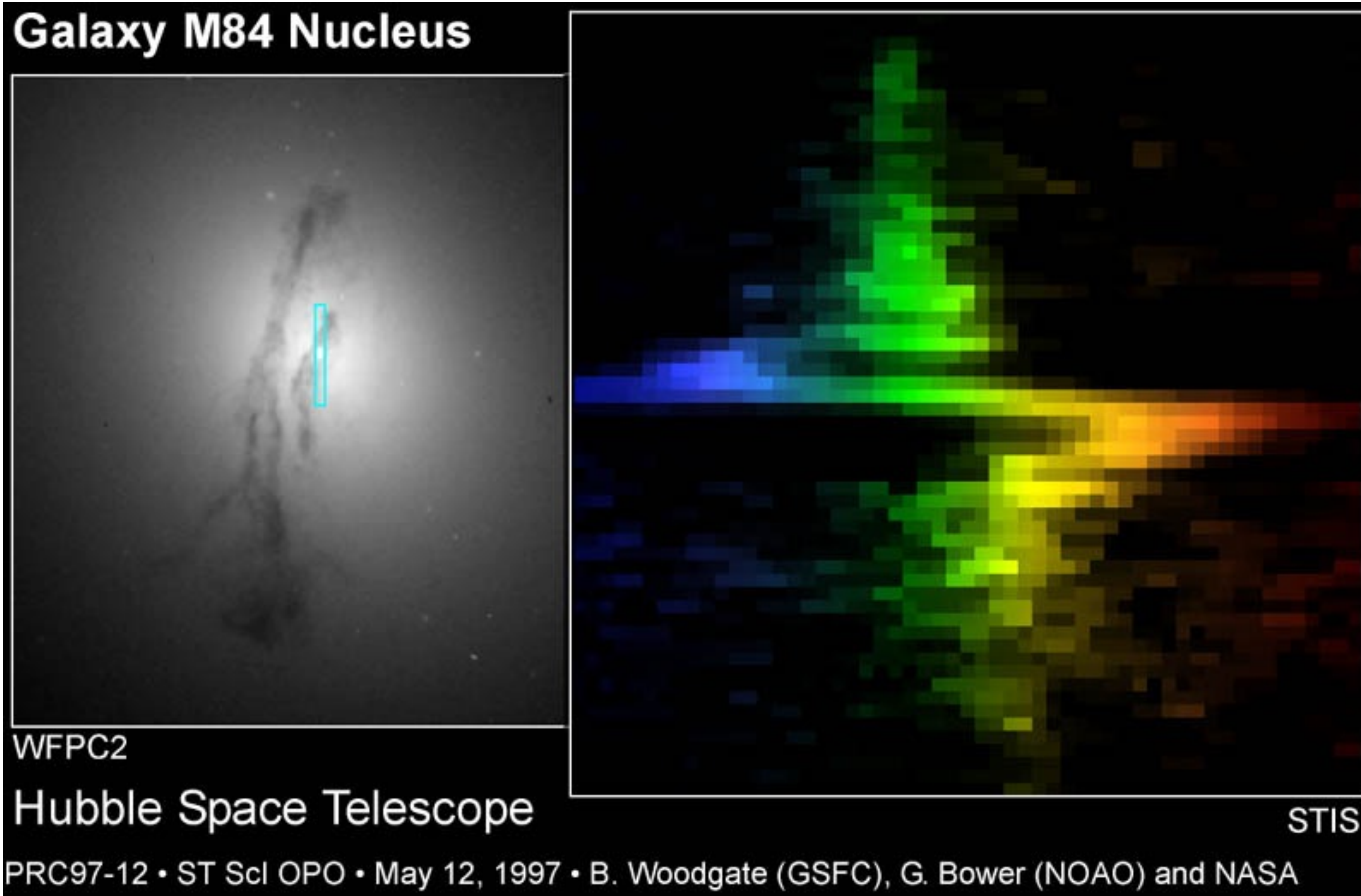

Gas Disk in Nucleus of
Active Galaxy M87
Hubble Space Telescope
Wide Field Planetary Camera 2
SPACE
TELESCOPE
SCIENCE
INSTITUTE

Velocity Profiles in the M87 Core



Model: central mass 3.2×10^9 solar masses



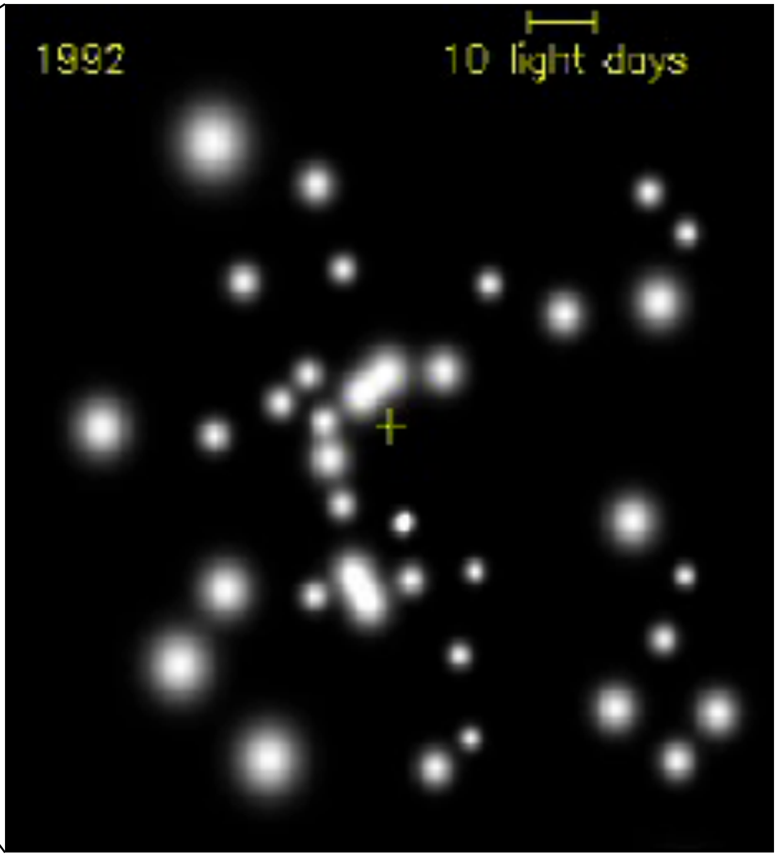

Galaxy M84 Nucleus
WFPC2
Hubble Space Telescope
STIS
PRC97-12 • ST ScI OPO • May 12, 1997 • B. Woodgate (GSFC), G. Bower (NOAO) and NASA

Observations of the centre of the Milky Way

Wide field optical image
of the Galactic Centre

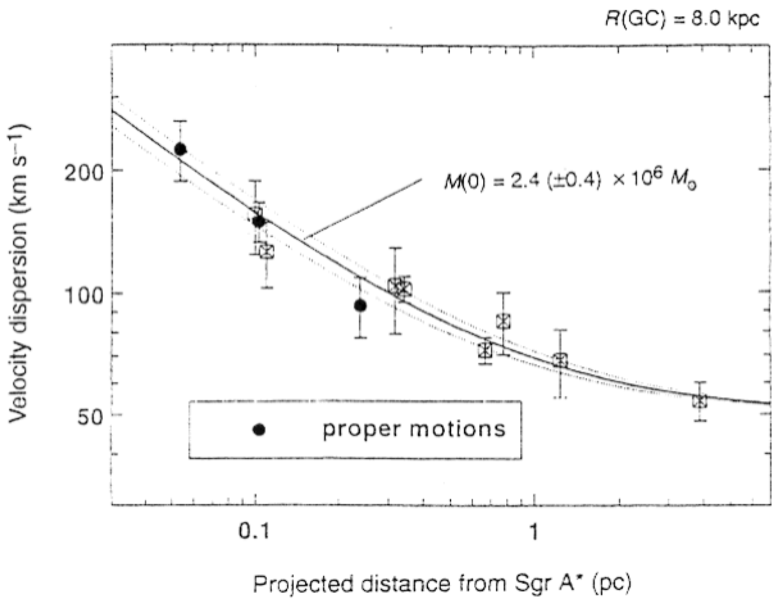
Observations of the centre of the Milky Way

Wide field optical image of the Galactic Centre

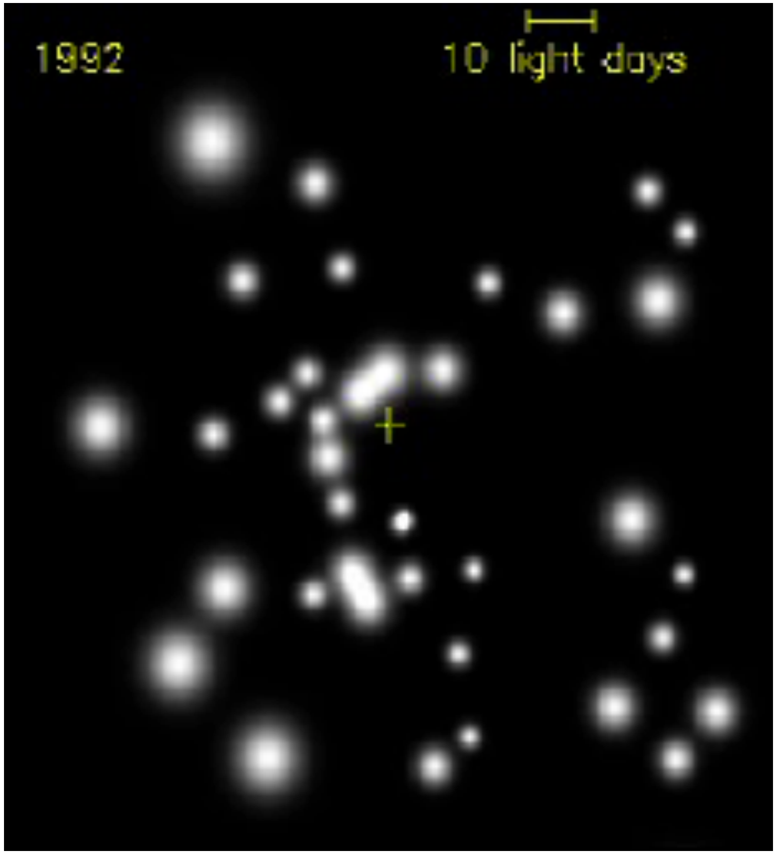


High resolution infrared image
Genzel et al. (2003)

Observations of the centre of the Milky Way

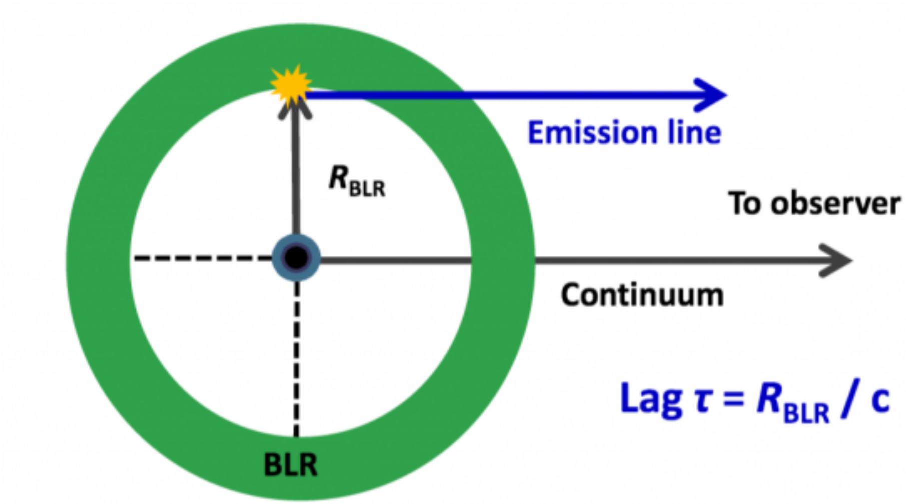


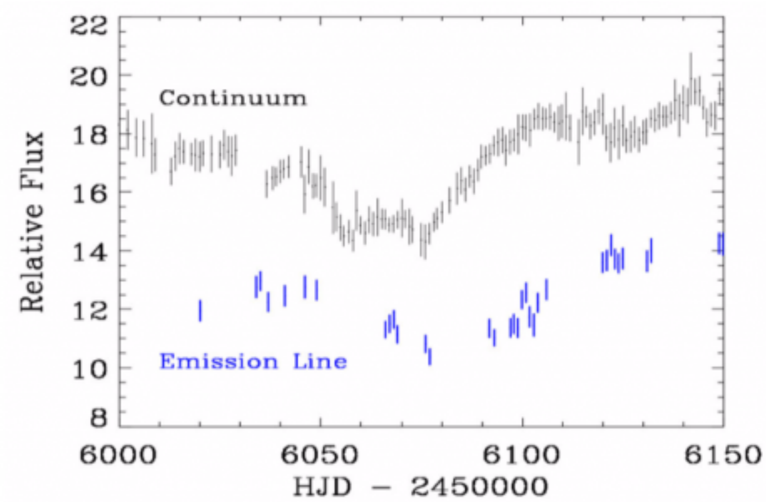
$M_{bh} = (4.3+/-0.4)x10^6\ M_{sun}$

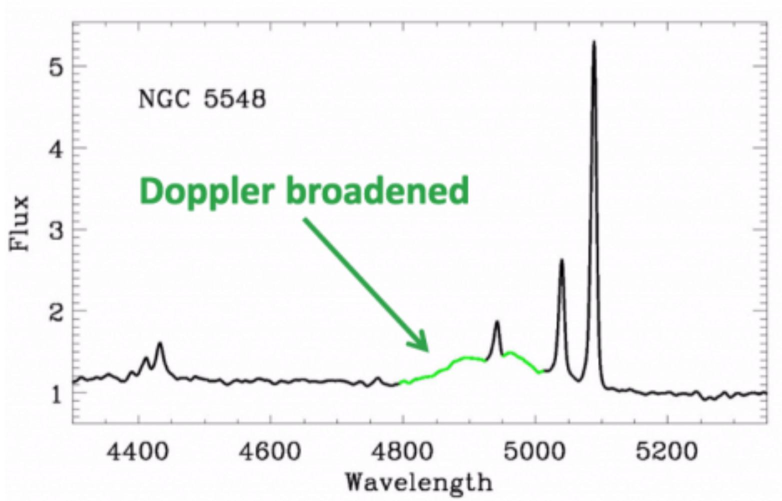


High resolution infrared image
Genzel et al. (2003)

Reverberation Mapping







Reverberation mapping allows us to measure the mass of the black hole via the time lag between brightness variations in the continuum and broad lines.

From width of lines　　From time-lag

$$M = \frac{v^2 r}{G}$$

Black Holes in Normal Galaxies

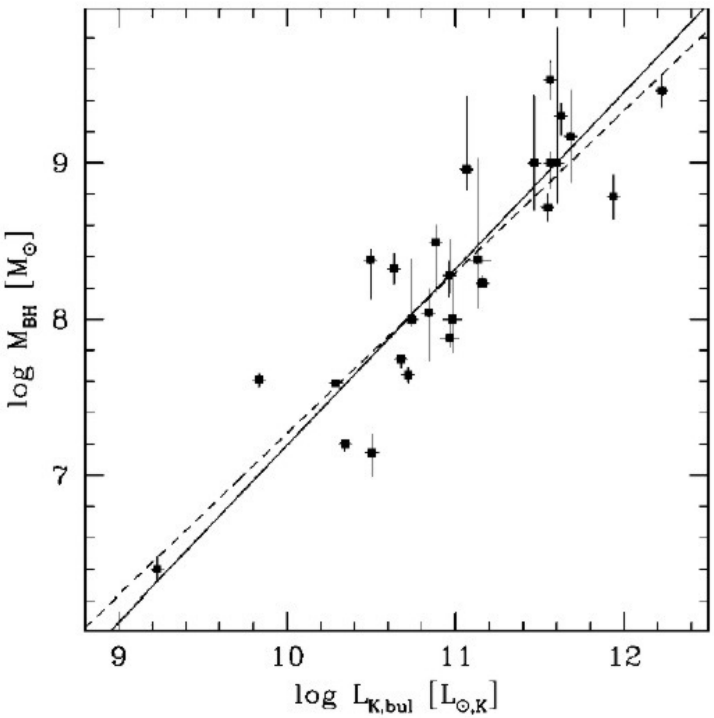
- Using the HST clear evidence for large masses (1×10^6 -- 3×10^9 M_{sun}) has been found in the central regions of several normal (non-active) galaxies in the local Universe.
- The matter in the nuclear regions appears to be dark:

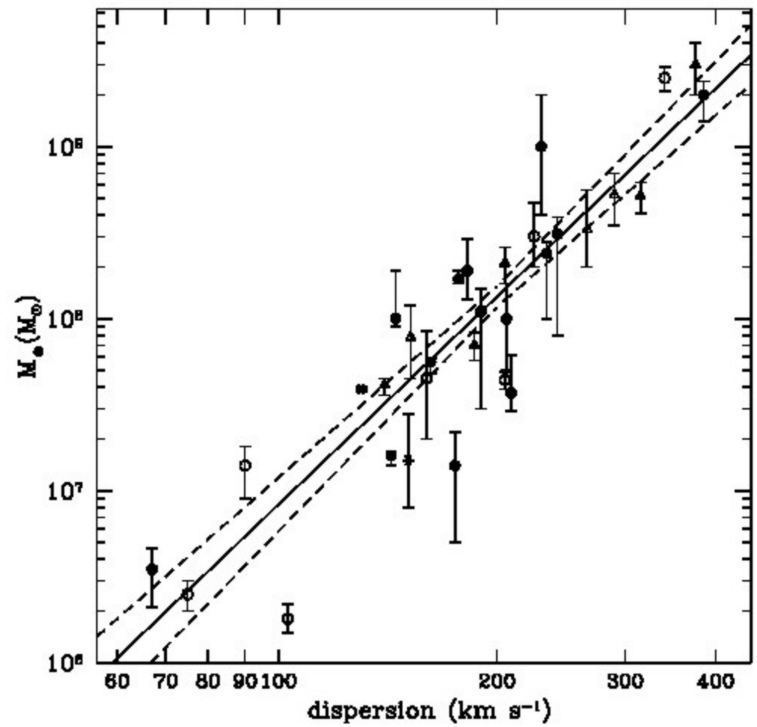
  $M/L \sim 30 - 150\ (M/L)_{sun}$ for galaxy cores

  ($M/L \sim 1 - 10\ (M/L)_{sun}$ for stellar systems)

  ---> Good evidence for super-massive black holes in most massive galaxies
- The masses of the black holes correlate with the masses of the bulges of the host galaxies

Correlations between black hole mass and bulge properties





M_{bh} →

L_{bulge} →

Velocity dispersion →

Marconi & Hunt (2003)

Tremaine et al. (2004)

Lecture 12: learning outcomes

- Knowledge of the general properties of AGN: high nuclear luminosities; compact energy generation regions; long lifetimes; jets
- Understanding of why accretion of material by black holes is the most plausible energy generation mechanism for AGN
- Knowledge of the evidence for supermassive black holes in the nuclei of nearby galaxies