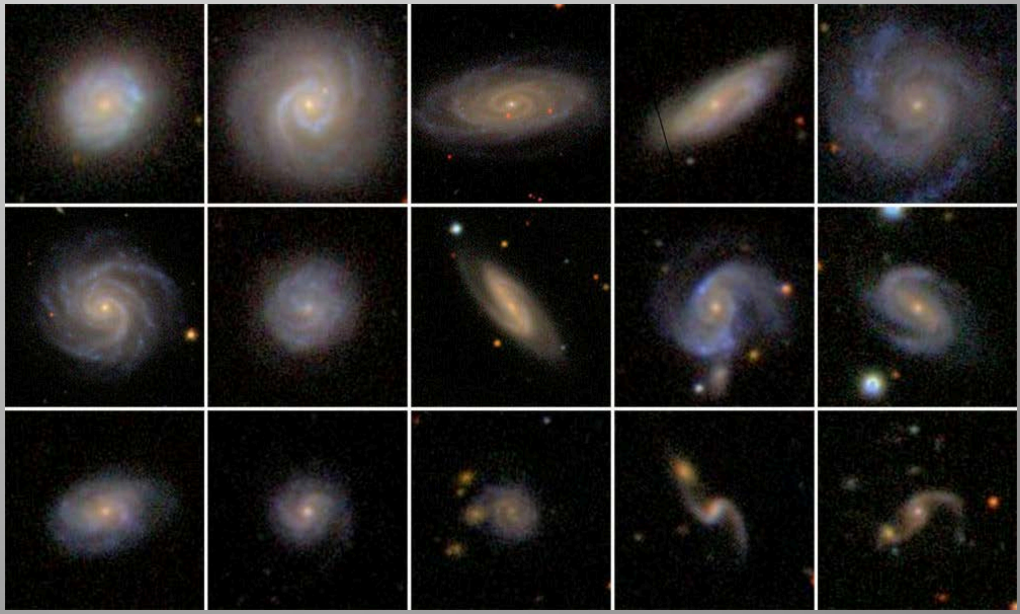
Active Galactic Nuclei

- How were they discovered?
- How common are they?
- How do we know they are giant black holes?
- What are their distinctive properties?

Active Galactic Nuclei

- for most galaxies the luminosity is dominated by starlight
- for a few % (higher fraction in the past) the nucleus of the galaxy is very bright

These are *Active Galactic Nuclei (AGN)*



Active Galactic Nuclei

Numerous different types of AGN:

- Seyfert galaxies
- Quasars
- Blazars
- Radio galaxies
- …

Different observed properties: *all* thought to be powered by disk accretion on to a central supermassive black hole

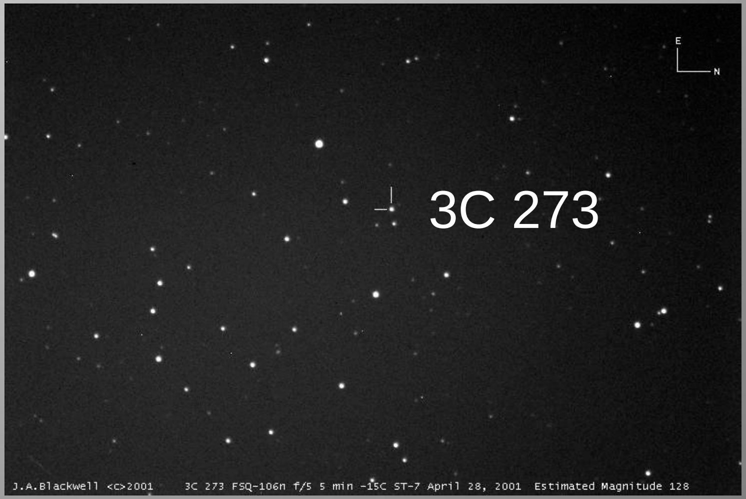
Quasars

First radio surveys of the sky done in 1950s

Many bright radio sources out of the plane of the Galaxy were found to coincide with star-like objects on photographic plates

Named “Quasi-stellar radio sources” (quasars)

Nature initially a mystery

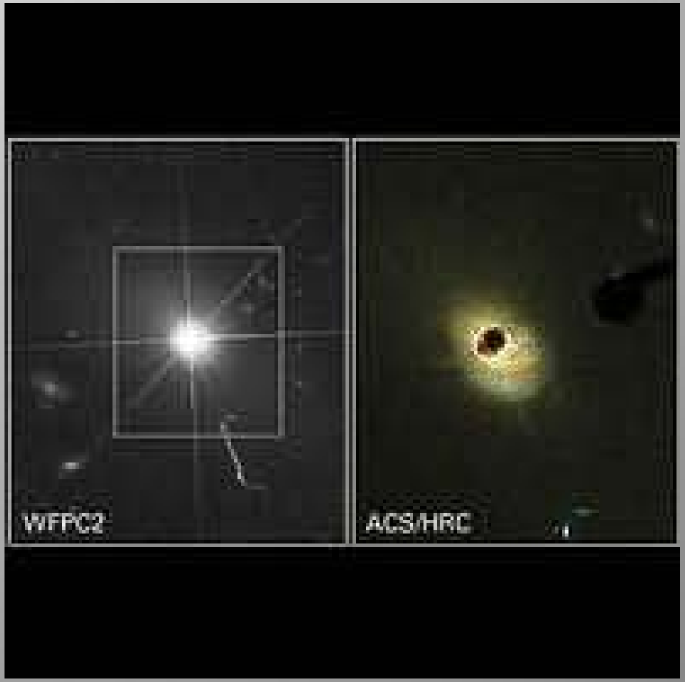


Quasars

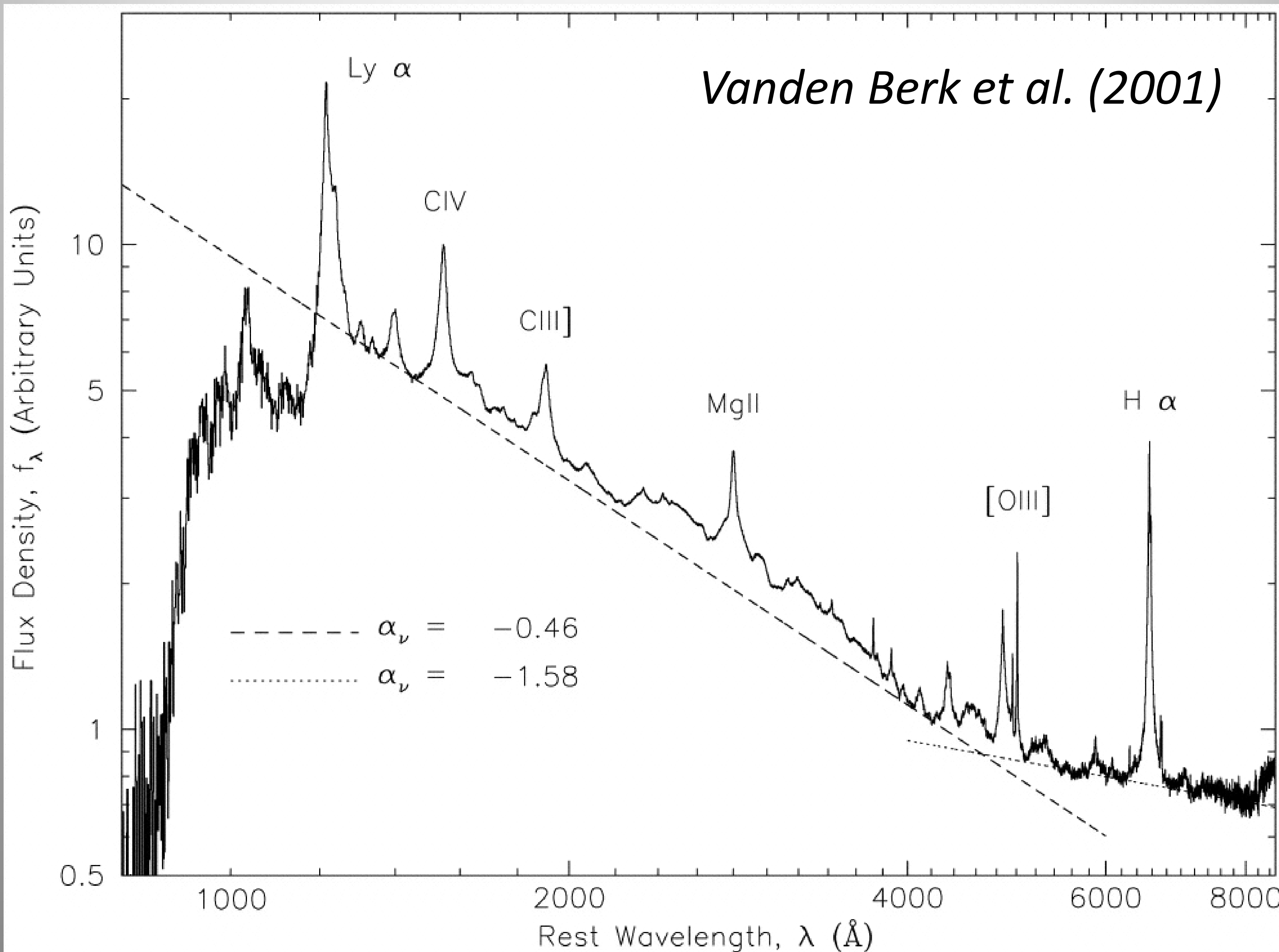
Mystery was solved when it was realized that quasars were very distant objects, whose spectra were red shifted by the expansion of the Universe

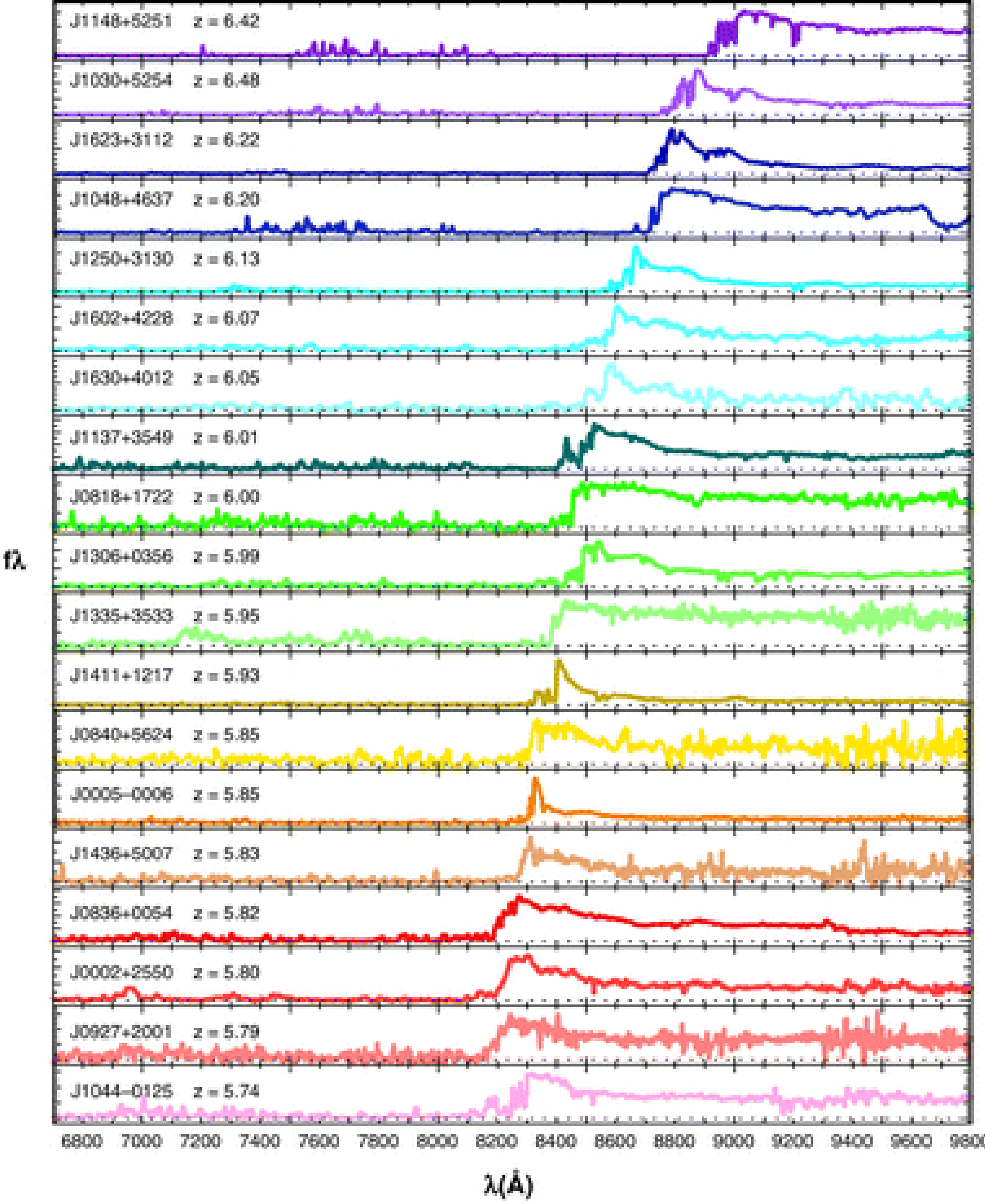
If a source emits light at wavelength λ_{emit},
and it is observed at λ_{obs},
define redshift z:

$$z = \frac{\lambda_{obs}}{\lambda_{emit}} - 1$$



Spectrum of a “typical” quasar





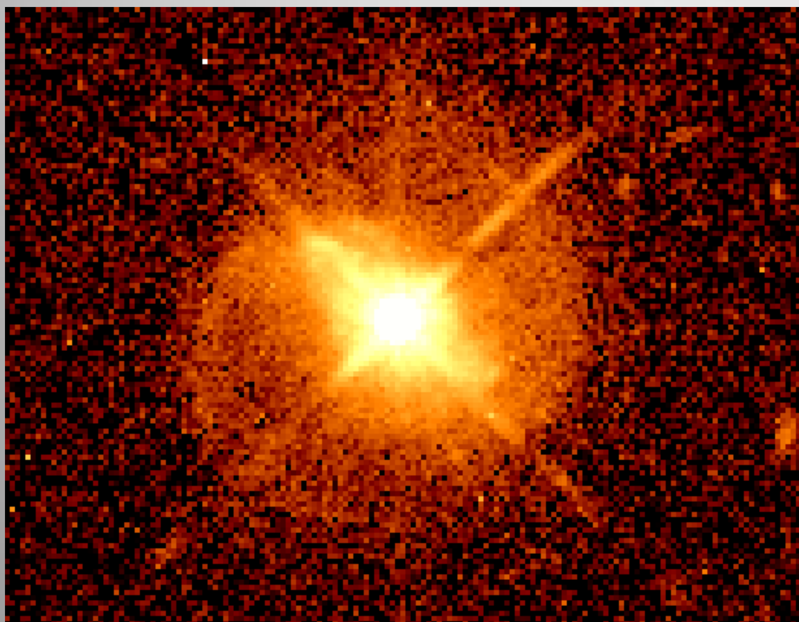
Fan X, et al. 2006.
Annu. Rev. Astron. Astrophys. 44:415–62

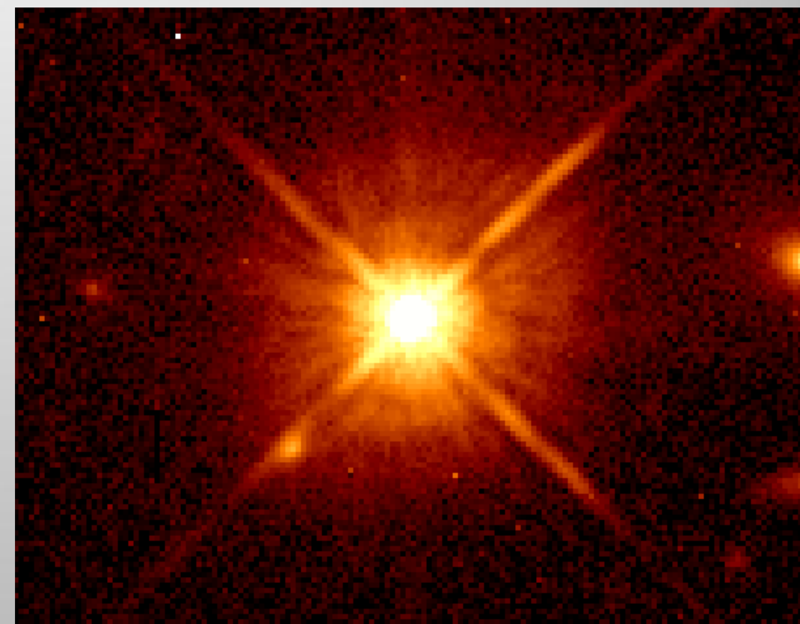
In an expanding Universe, redshift is a measure of distance: more distant quasars have higher redshift

Quasars

Large distance implies a very high luminosity: emission from the point source in the nucleus vastly outshines rest of the galaxy!

Quasars

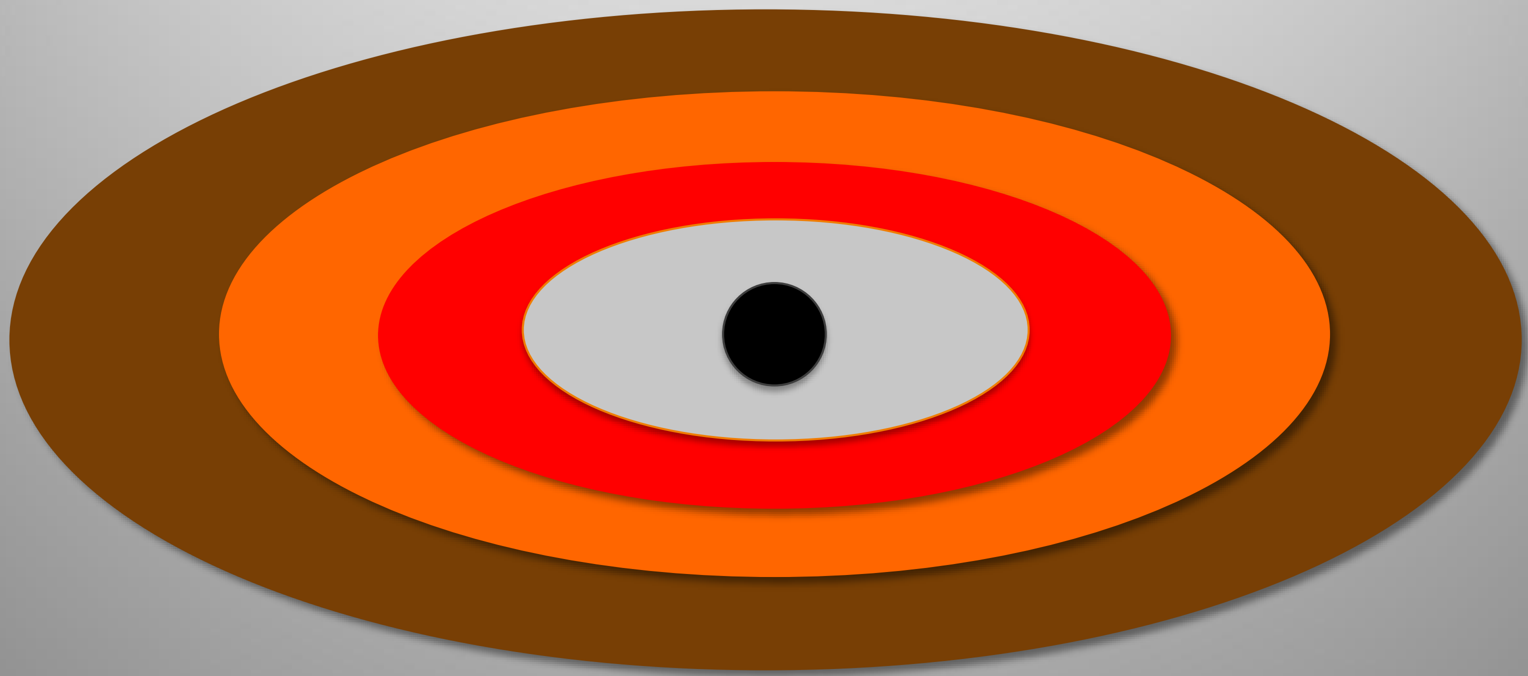




Hubble Space Telescope images
of quasars and host galaxies

Quasars

Interpret high luminosity as due to disk accretion of gas on to a supermassive black hole



Accretion rate $\dot{M}$ - kg s^{-1} (or Solar masses per year)

Quasars

Conversion of rest mass of accreting gas to radiated energy is about 10% for disk accretion on to a black hole, i.e. for 1 kg accreted get:

$$E = 0.1\,\mathrm{kg} \times c^2$$

of energy in the form of radiation

Generally, luminosity:

$$L = \varepsilon \dot{M} c^2 \approx 0.1 \dot{M} c^2$$

↑ radiative efficiency of accretion

Quasars

To get an observed luminosity of:

$$L \approx 0.1\dot{M}c^2 \approx 5.7\times10^{38} \text{ Watts}$$

Quasars must swallow gas at a rate of ~1 Solar mass per year

$$\dot{M} = \frac{2\times10^{30} \text{ kg}}{3.16\times10^{7} \text{ s}} = 6.3\times10^{22} \text{ kg s}^{-1}$$

… or 1 Earth mass every 90 seconds

Quasars

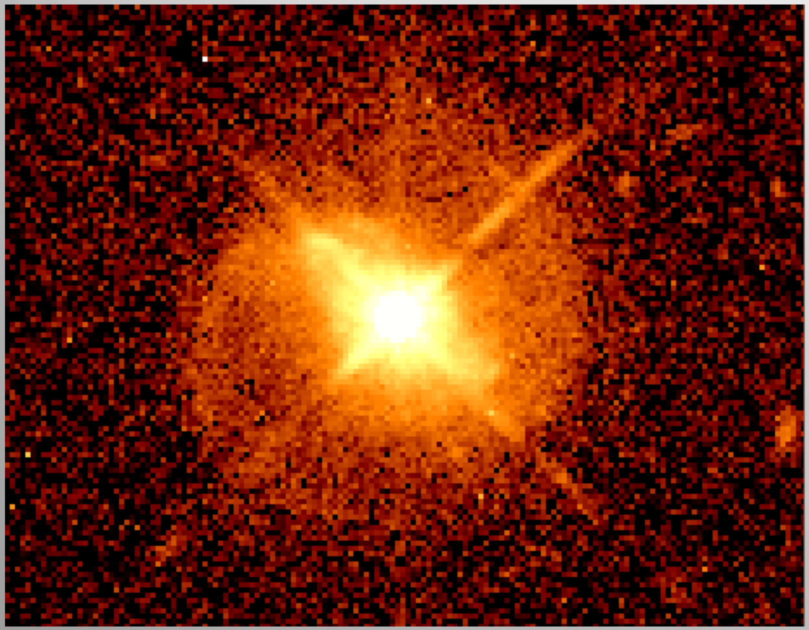
$$L \approx 0.1\dot{M}c^2 \approx 5.7 \times 10^{38} \text{ Watts}$$

Compare to luminosity of Sun, 3.8×10^{26} Watts

Luminosity from the accreting black hole is equal to 1.5 trillion (1.5×10^{12}) stars like the Sun!

Consequence of the high efficiency of black hole accretion vs nuclear fusion (10% vs 0.7%)

Quasars



Hard even to see the stars in the galaxy: the nucleus is so bright

DO WE HAVE INDEPENDENT PROOF THAT QUASARS ARE MASSIVE BLACK HOLES?

YES, TWO ARGUMENTS…

QUASARS MUST BE MASSIVE

1) 1% of galaxies seen as quasars IMPLIES:

EITHER

2) All galaxies swallow 1 solar mass/yr for 100 million years (1% of age of Universe)

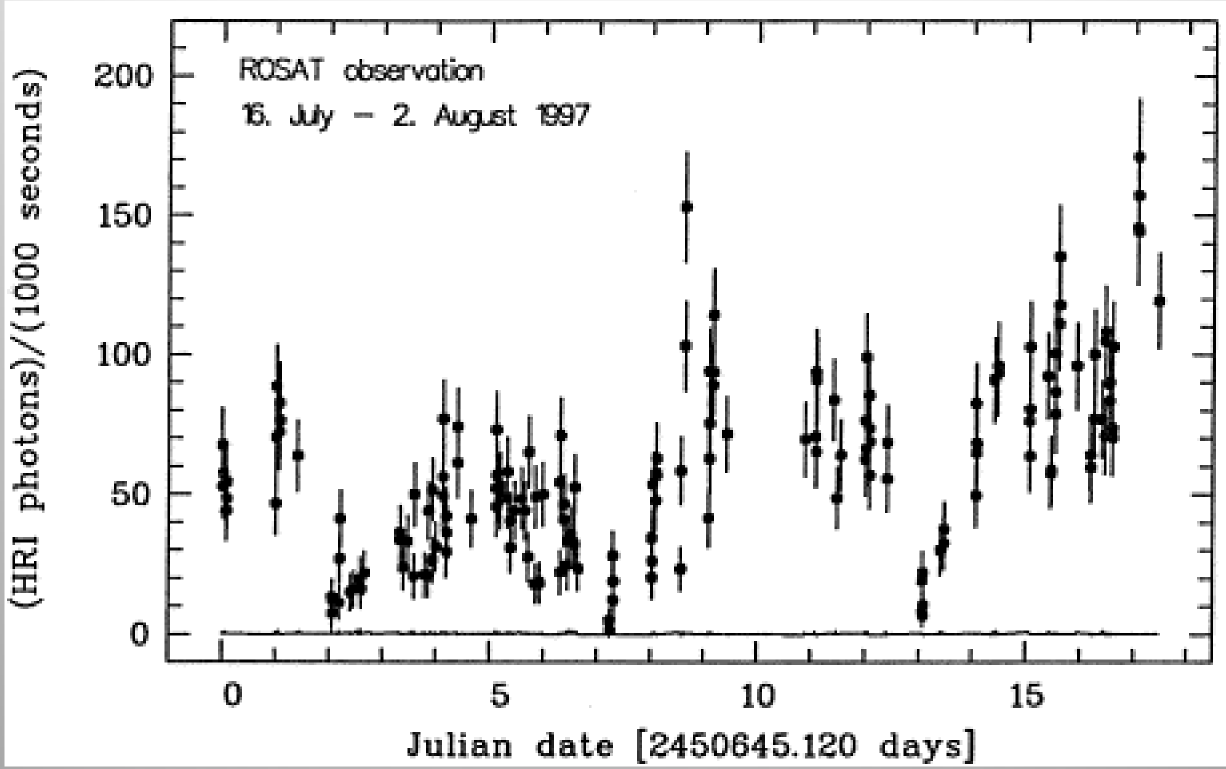
OR

3) 1 in 100 galaxies swallow 1 solar mass/yr for 10 billion years

THEREFORE

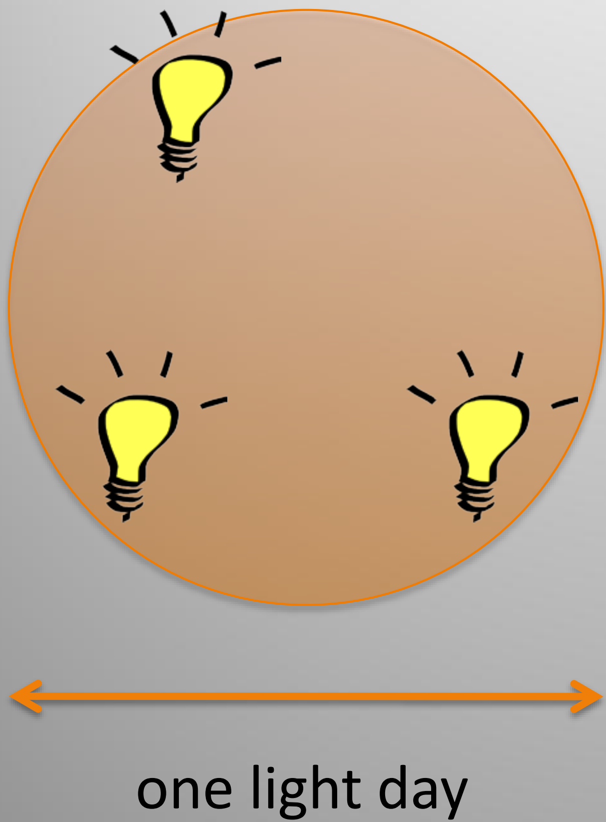
4) Whatever is in a quasar contains between 100 million and ten billion solar masses

QUASARS MUST BE COMPACT



Quasars (and other AGN, this is a Seyfert) are seen to vary on time scales of a day or less

Maximum size from variability



For a source of size one light day, fastest time for a signal to cross the source is one day

Don't expect to see coordinated variations on less thaN 1 day time scale

Maximum size from variability

Observe variability on 1 day time scale

Infer quasars are less than 1 light day across

$L \sim (24 \times 3600\ s) \times 3 \times 10^8\ ms^{-1}$

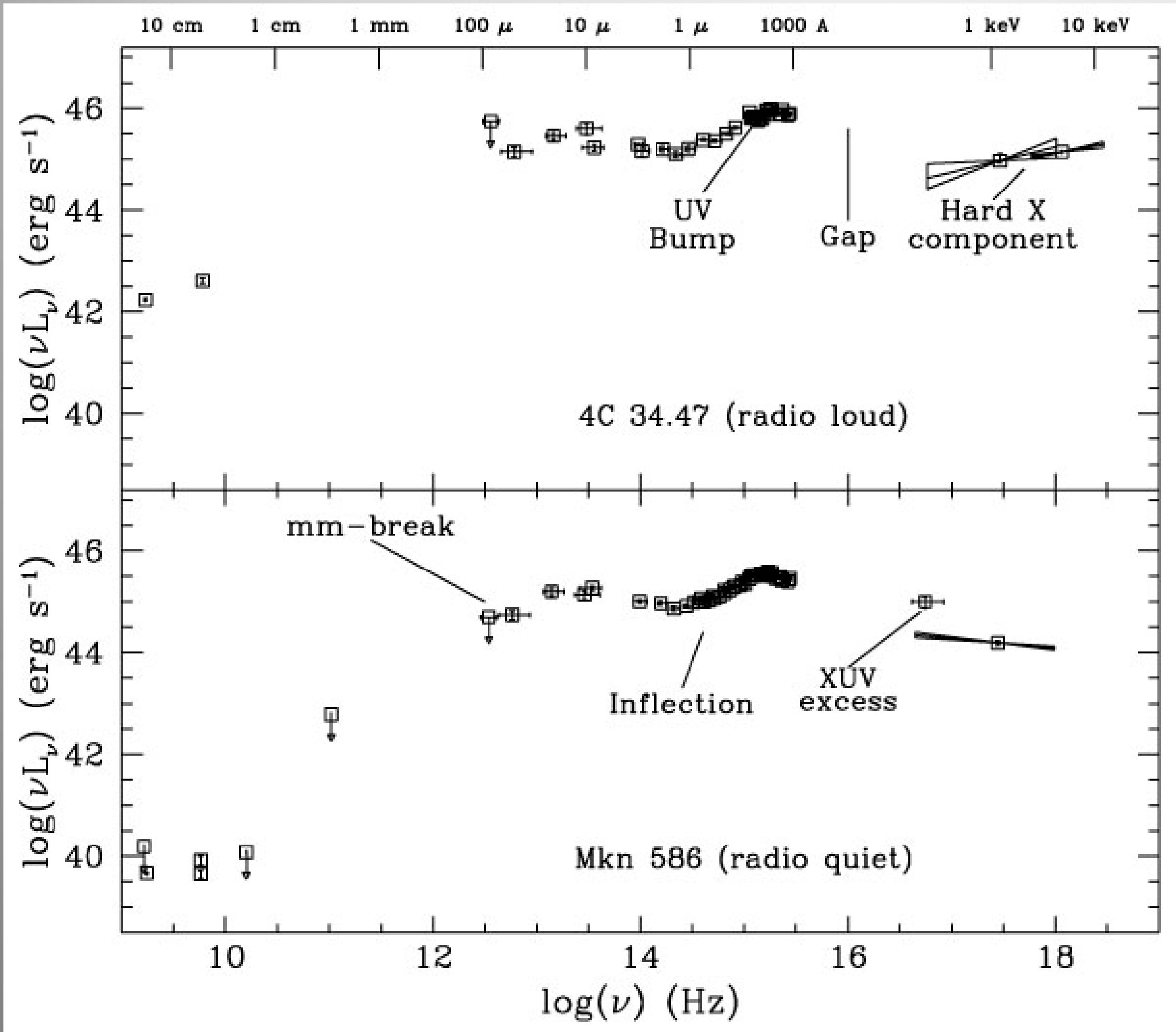
$= 2.6 \times 10^{13}\ m = 170 \times$ radius of Earth orbit

⇨ luminosity of a whole galaxy originates from region ~size of the Solar System!

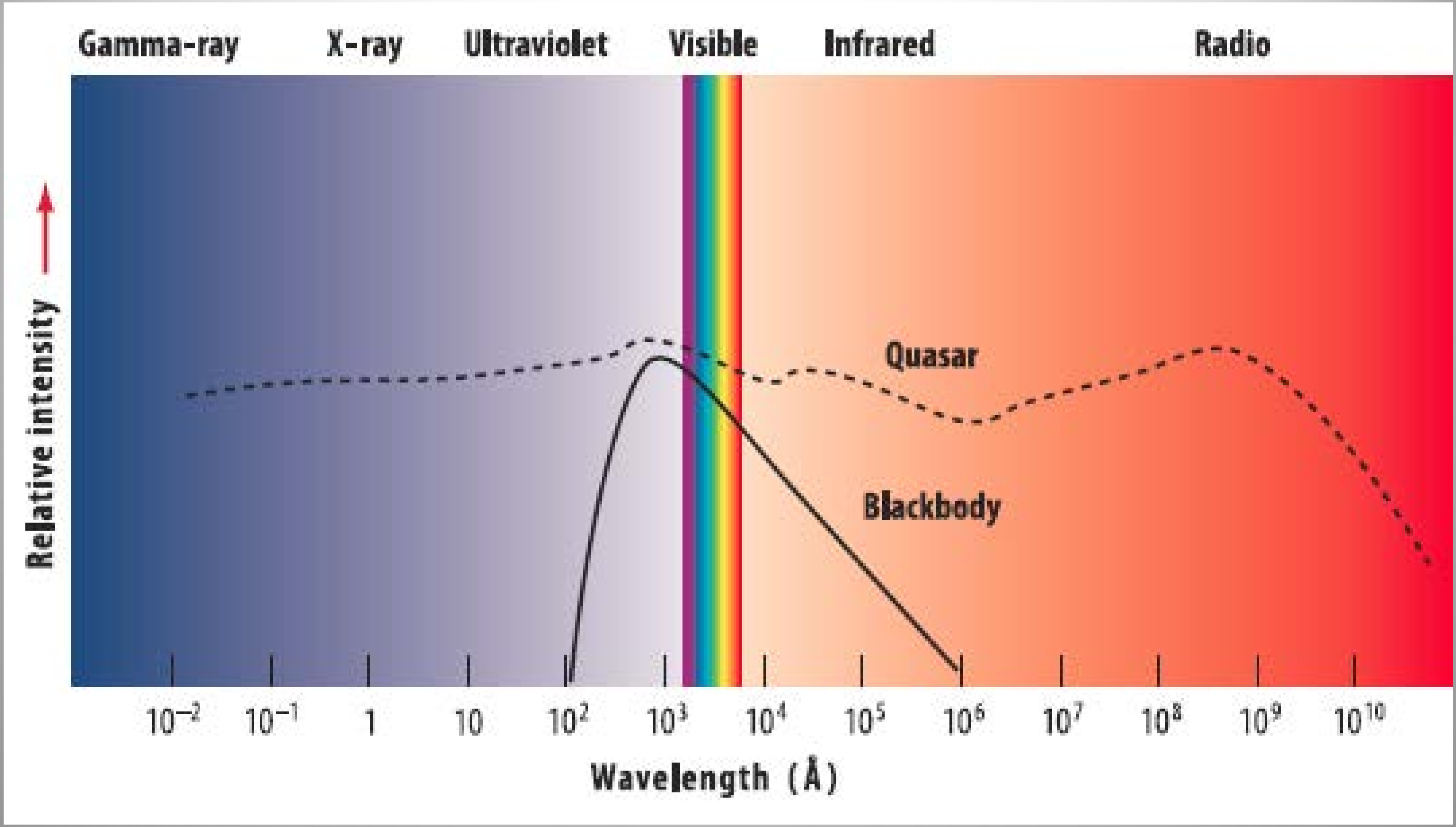
QUASARS ARE BILLION SOLAR MASS BLACK HOLES AT THE CENTERS OF GALAXIES, SWALLOWING MATTER AT A HIGH RATE

QUASARS PUT OUT A LOT OF RADIATION AT ALL WAVELENGTHS

Radiation from Quasars



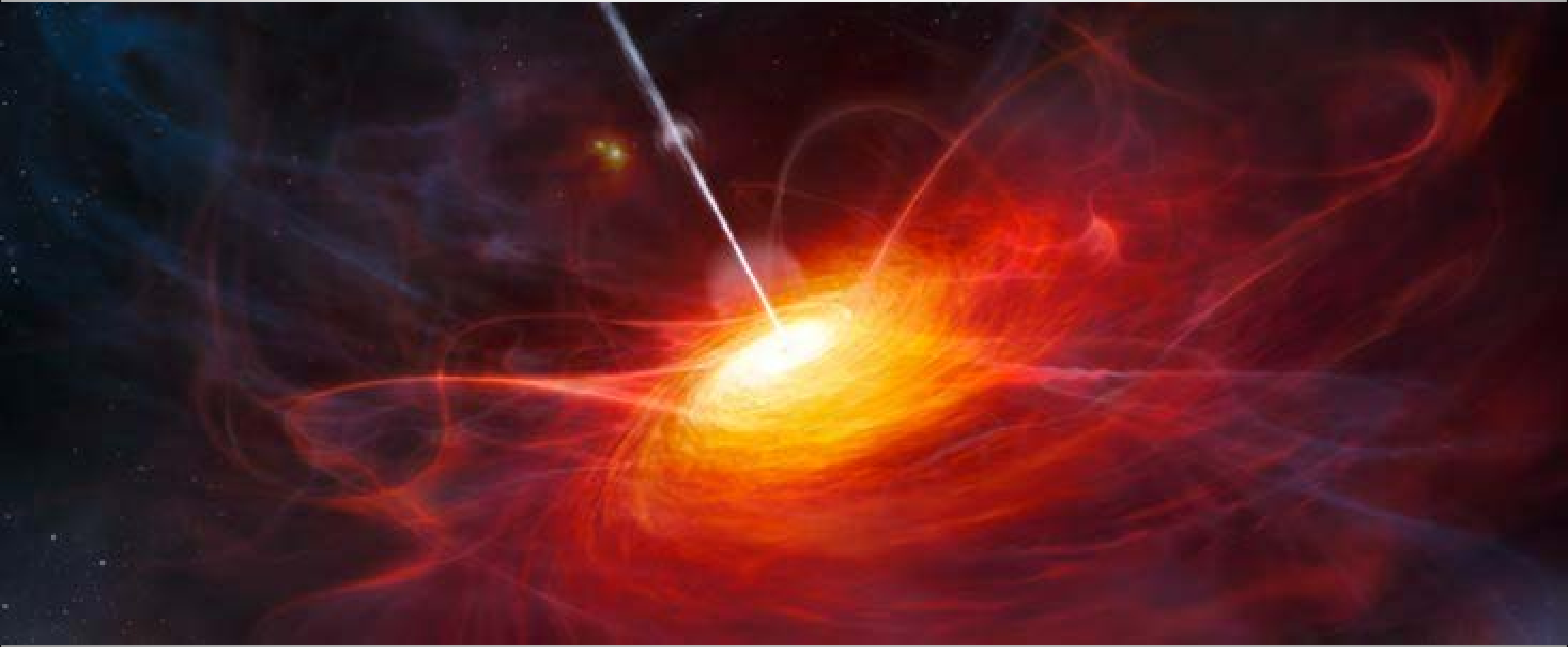
Emit most energy in UV and optical light, but also shine brightly across the whole electromagnetic spectrum



THERMAL: PEAK AT PREFERRED WAVELENGTH

NONTHERMAL: N0 PREFERRED WAVELENGTH

Quasars

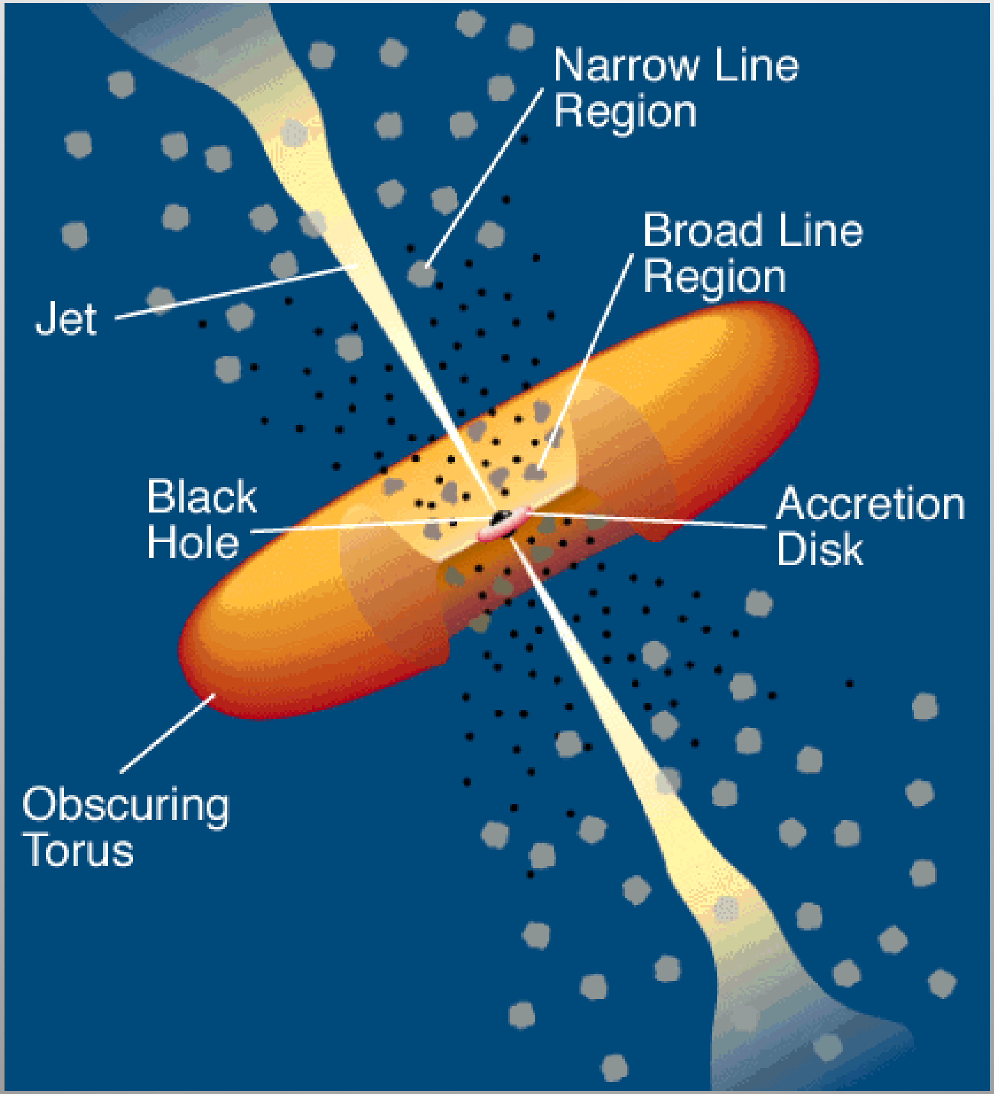


Luminosity from hot gas in the accretion disk, also from a *jet* possibly powered by black hole spin energy

Why do different AGN look different?

- Viewing direction?
  - Face-on vs. edge-on disk
  - Thick donut ("torus") of gas can completely block nucleus: AGN only seen in reflection
- High vs. Low Power (relative to mass of BH)?
  - High power: thin opaque disk, lots of dense gas clouds
  - Low power: thick transparent disk
- Jet or no jet?
  - pointed toward us or not?

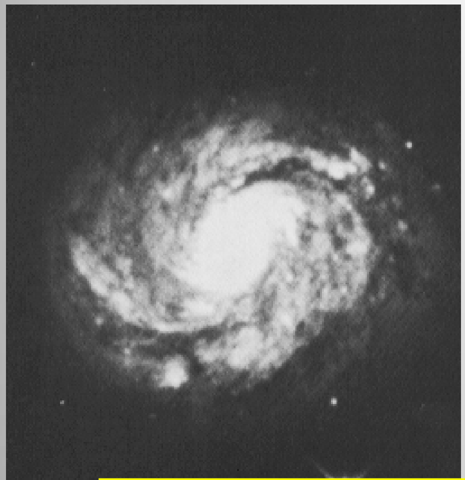
Schematic of an AGN

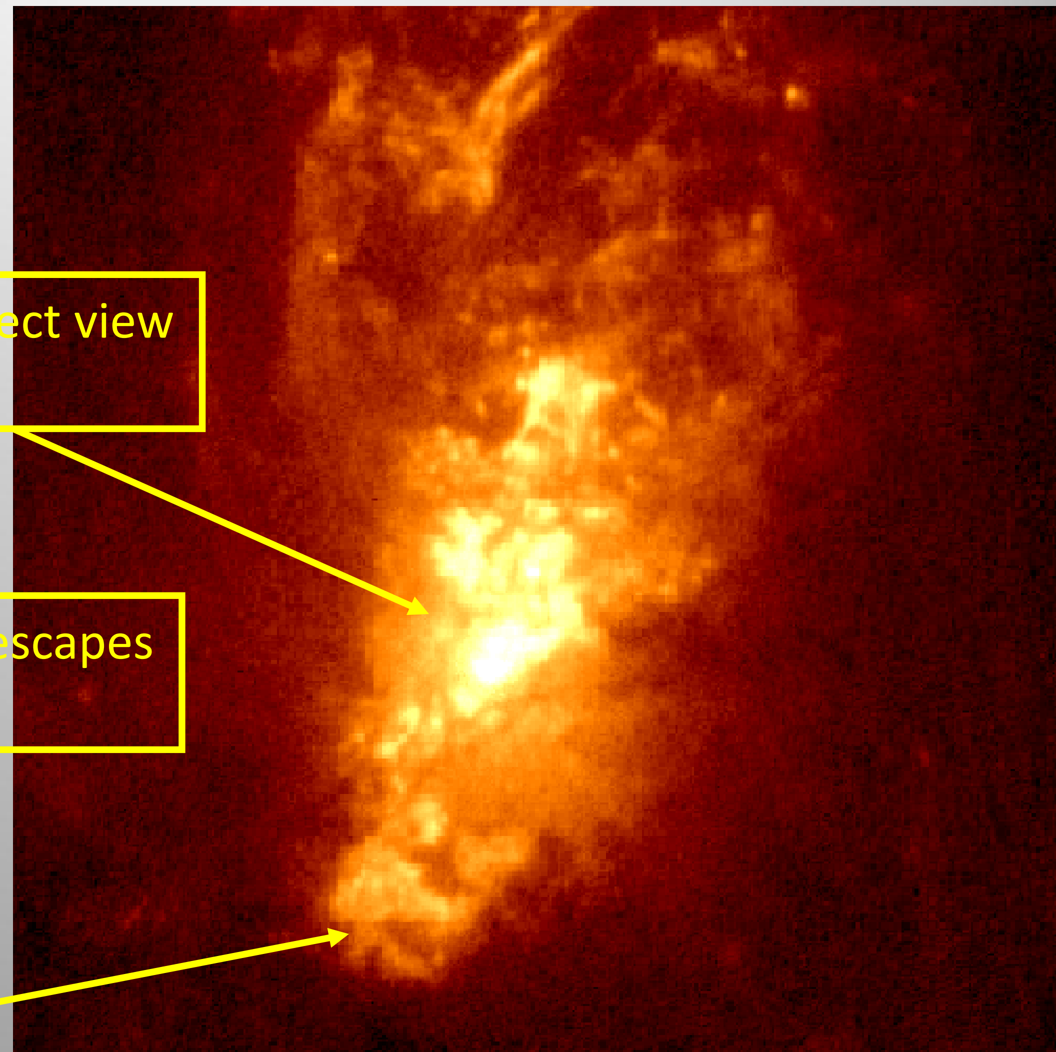


C.M. Urry and P. Padovani

NGC 1068: An Obscured AGN

…seen in reflection





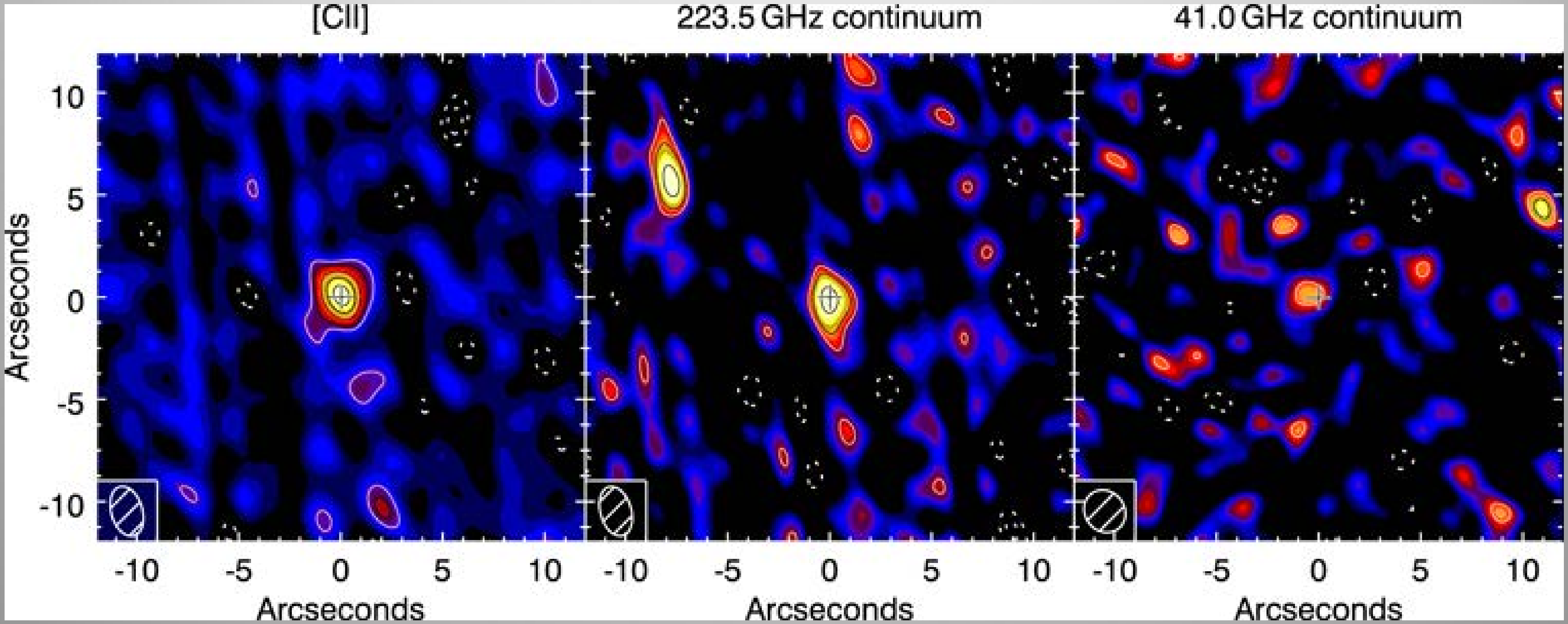
This bright cloud has a direct view of the intense nucleus

Radiation and (possibly) a wind escapes through a cone-shaped funnel

Nucleus is hidden in here

WHEN DID QUASARS FORM?

Most distant quasar known (z=7.54)



Bañados et al. 2017

A mystery:

- at $z = 7.5$, time since the Big Bang was ~700 million years
- very few galaxies had formed by that time
- how did a billion Solar mass black hole grow that large in the time available?