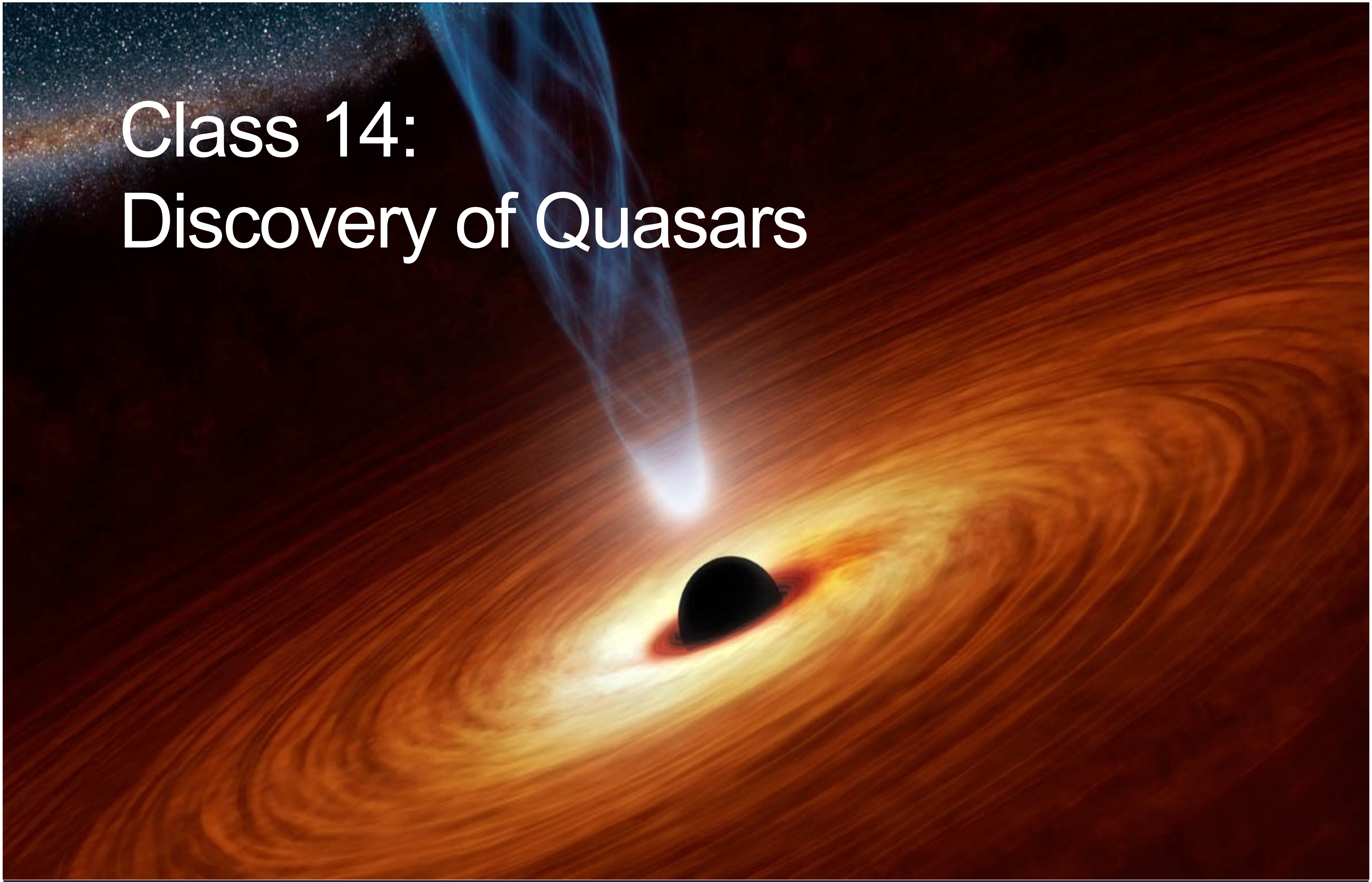
Class 14: Discovery of Quasars



ASTR350 Black Holes (Spring 2022)

Cole Miller

Next class (Tues, Mar 15): midterm!

- In class
- We will seat you; sorry about that, but we need an organized way to fit all students into this classroom
- Material will be from the start of the course through and including today's class
- Will be a mix of calculational questions and short-response involving understanding of the material
- Closed book and closed notes. Phones must be off and put away; a visible phone risks an honor code violation
- You will need a calculator
- Good luck!

RECAP

- Taking stock…
  - Part I : Physics of Black Holes
    - Physics from Newton to Einstein
    - Special and General Relativity
    - Schwarzschild and Kerr Black Holes
  - Part II : Stellar mass black holes
    - Black holes as the end points of massive stellar evolution
    - X-ray binary systems and accretion disks
    - Gamma-ray bursts

RECAP

Last time…

Gamma-Ray Bursts

Long detective story…occur randomly over sky - rate ~few per day, hard to identify in other wavebands

Very luminous- outshine all other gamma-ray sources in sky for a few seconds

Long GRBs – massive star supernovae-

Short GRBs – merging NSs or NS+BH

both types produce black holes

Can be detected at very large distances

Not ALL stellar mass black holes are produced by GRBs

This class

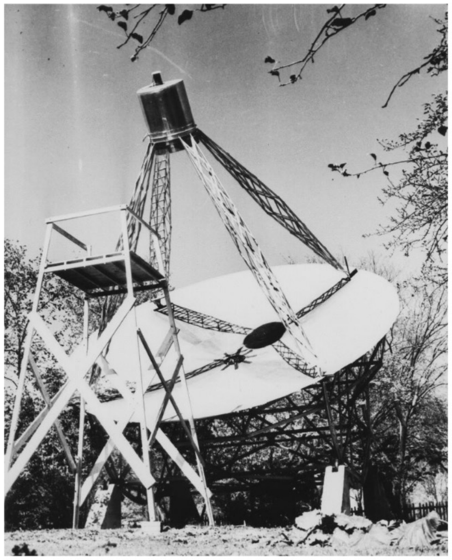
- Part III : Supermassive Black Holes!!
  - form in a very different way than stellar mass black holes
  - accretion powered, very luminous

- Today :
  - Discovery of quasars
  - Initial characterization and initial arguments for existence of supermassive black holes

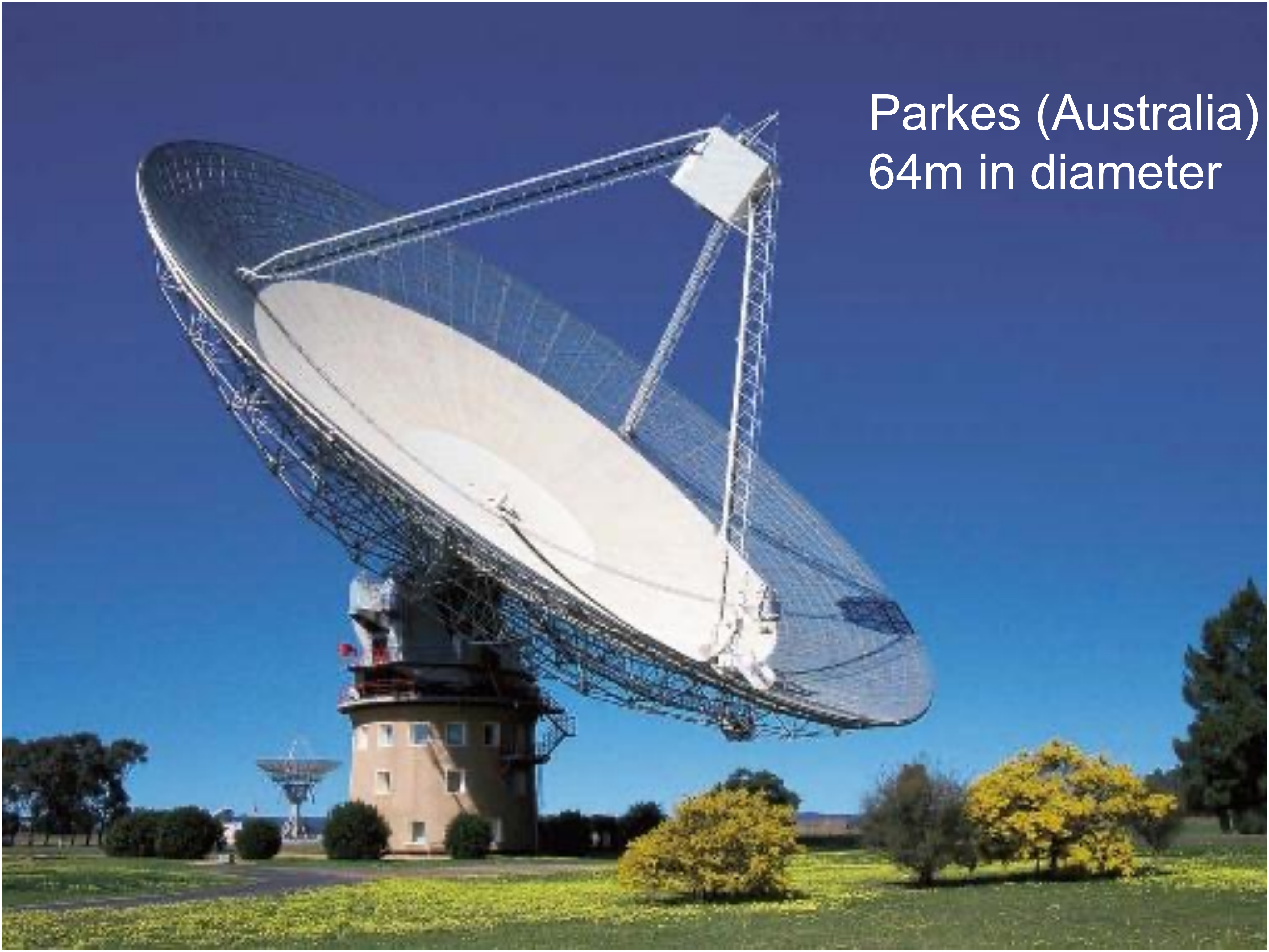
Radio Sources

- What do we mean by "radio sources"?
  - Discovery by Karl Jansky "Radio Waves from Outside the Solar System”, published in 1933, but his findings, were largely ignored for many years.
  - Only follow-up by amateur Grote Reber

Reber’s telescope 1937



for ~15 years these were 'just' objects
in the sky that emitted signals detected
in the radio band (~100's of Mhz (Megahertz)
FM radio is 88-108 Mhz)
with no understanding of what properties they
had


Parkes (Australia)
64m in diameter

Radio Telescopes

Radio telescopes are very different in design and construction from optical telescopes

Much larger (biggest is 500m diameter)- 2 major types are single dishes (see above) and interferometers (VLA below)

I : Quasi-Stellar Objects (QSOs)

- 1959 : Radio astronomers at Cambridge publish their 3rd Cambridge Catalogue
  - Contains about 470 *radio* sources
  - Used a radio "interferometer" consisting of 4 linked radio telescopes separated by about 1.5km operating with radio wavelengths of 1.89m (159MHz)-see previous slide
  - Ability to localize object on sky limited by the diffraction limit…

angular resolution of telescope θ

$$\theta \approx 70^0 \times \frac{\lambda}{D}$$

Wavelength of radiation

Diameter of telescope

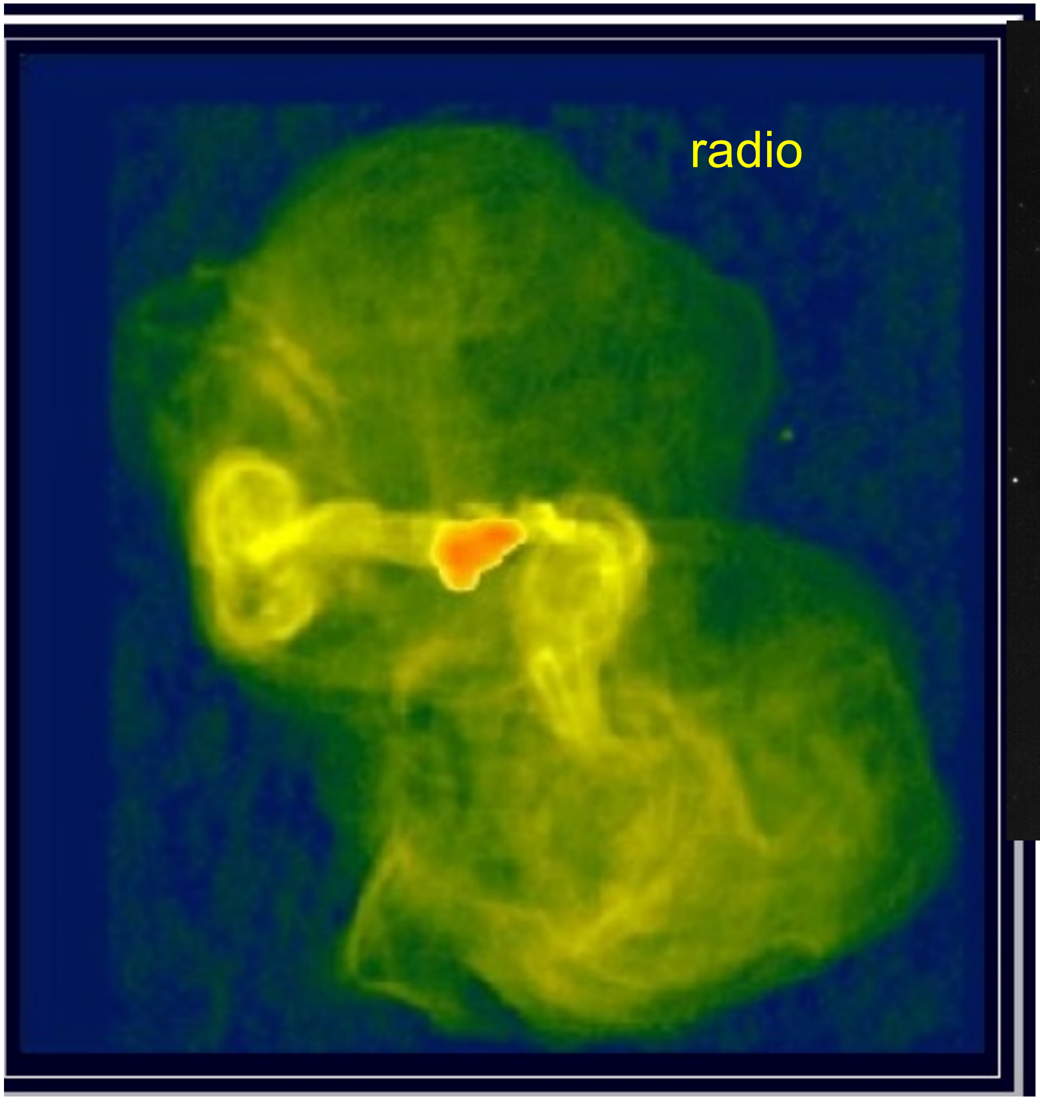
  - So, for D=1.5km and λ=1.88m we have a resolution of about 0.09 degrees=5.4 arc min. *Not very good!*

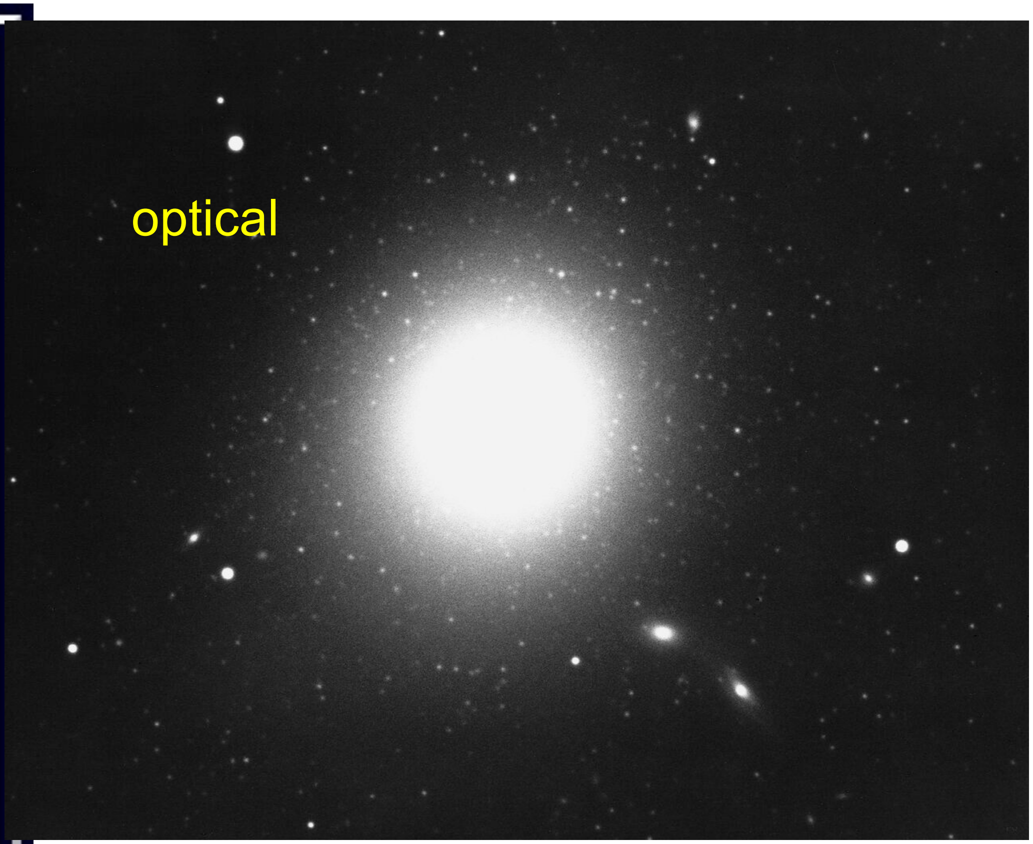
Cambridge One-Mile Radio Telescope

Radio Sources –

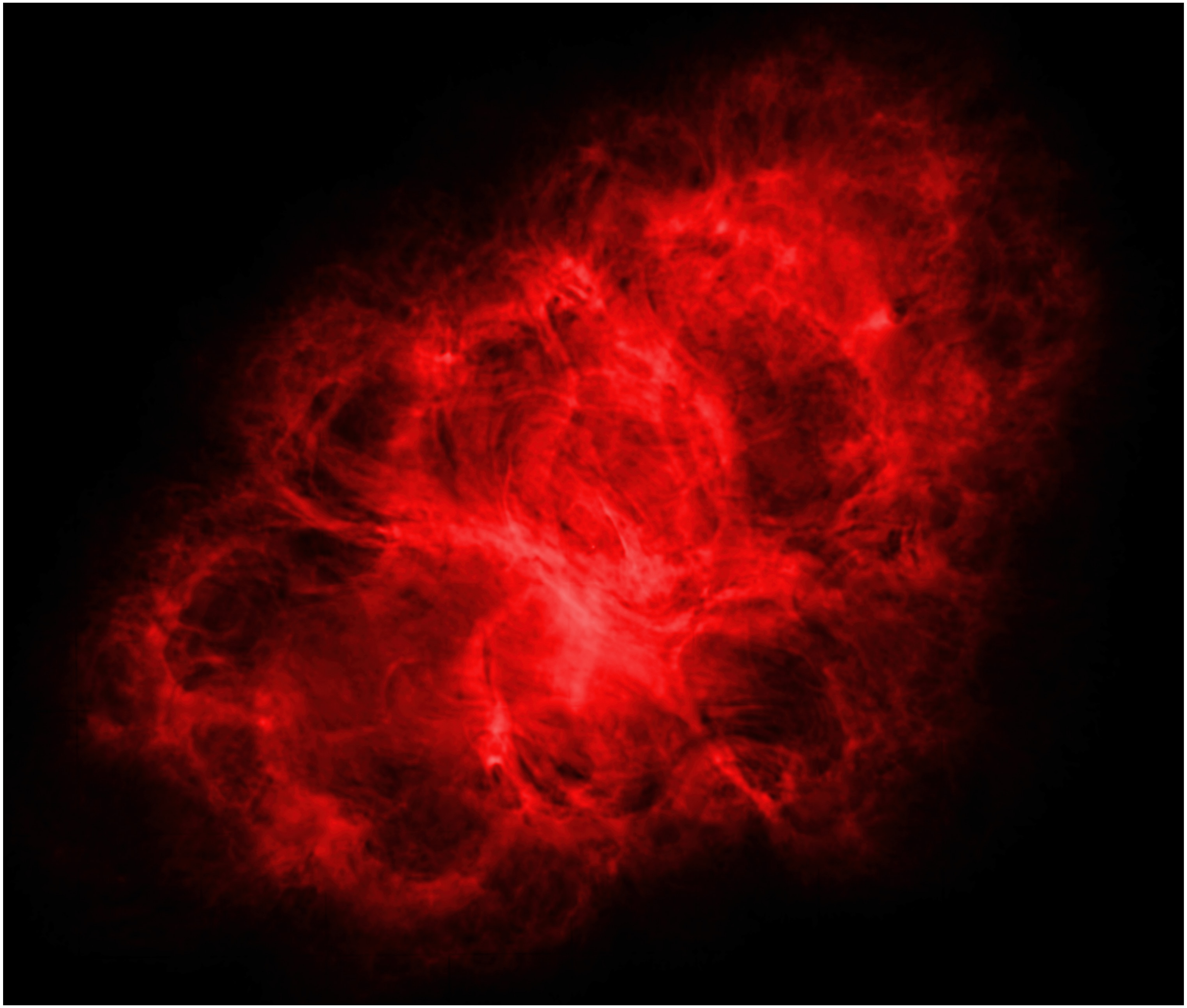
- This was a major event in the history of astronomy
  - For the first time astronomical sources were discovered by a technique other than optical astronomy
- This led rapidly to x-ray, gamma-ray, infra-red and now gravitational wave astronomy
- Seeing the universe with ***'new'*** eyes
- However
  - the types of telescopes in these other wavelength bands are very different and totally new technologies and observational techniques had to be invented!
  - As well as an understanding of what physical processes produced the radio emission

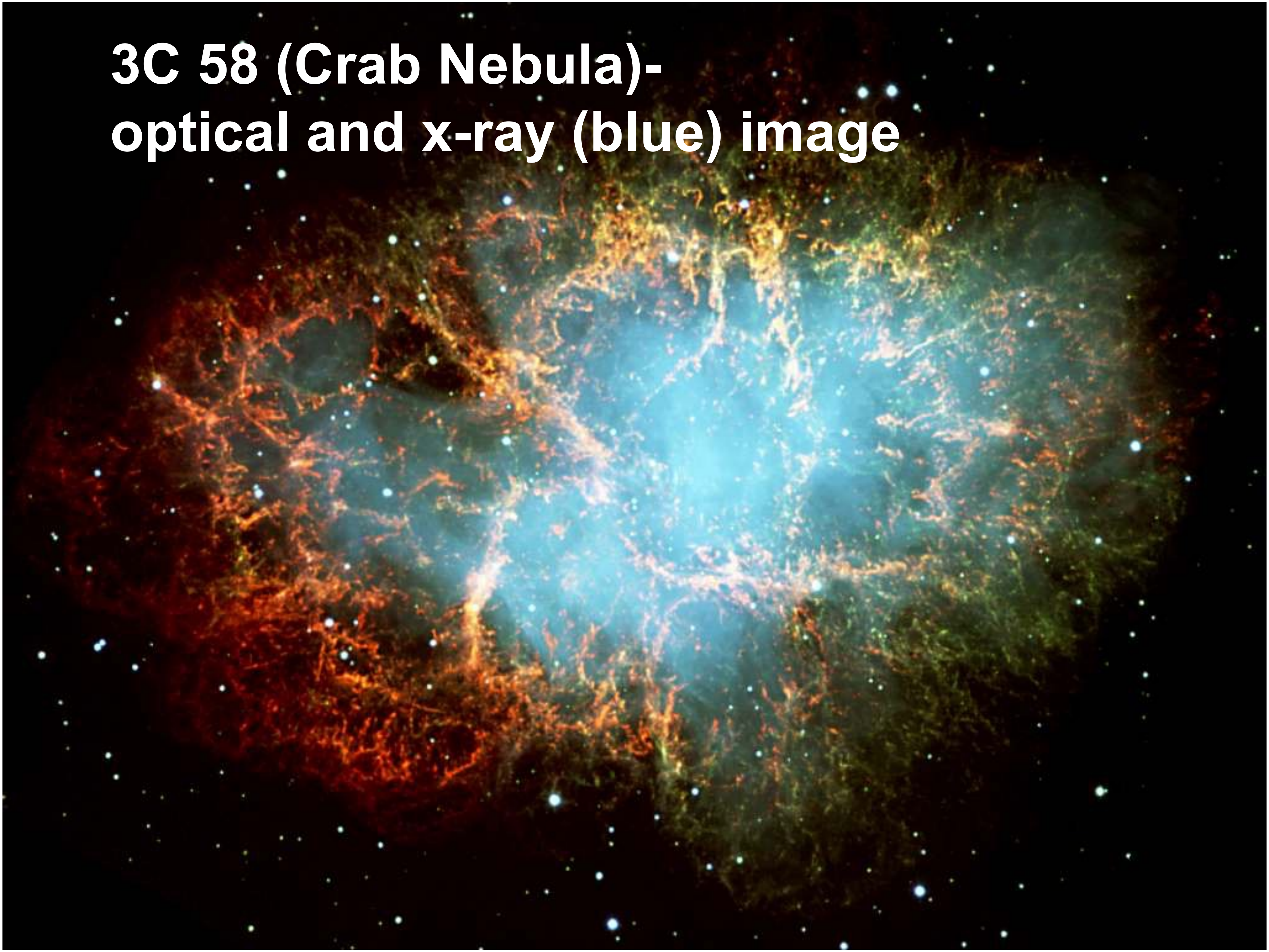
Optical and Radio Images of M87





3C 58 (Crab Nebula)- radio image



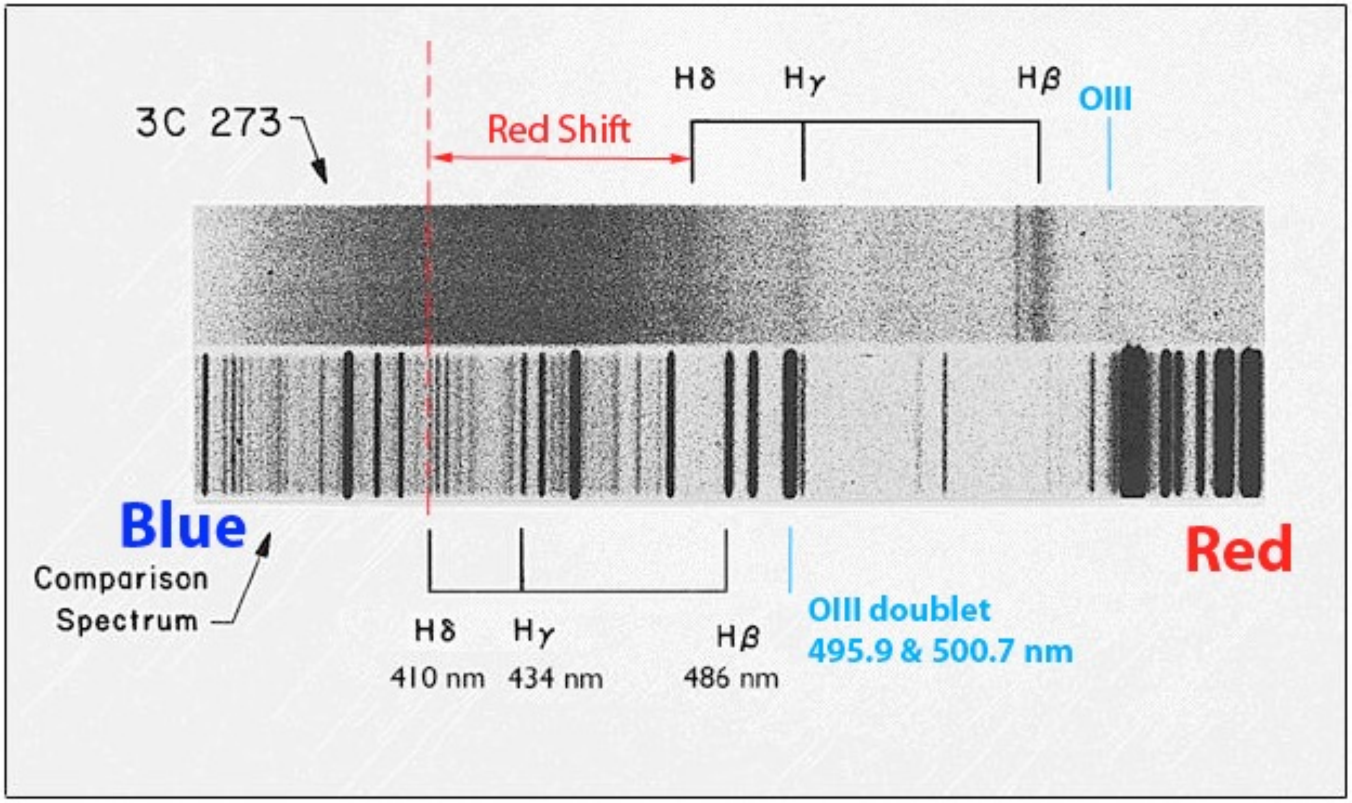

3C 58 (Crab Nebula)-
optical and x-ray (blue) image

How Did They "Identify" the Sources?

- Accurate measurements of the position of some sources were made from sites on the east and west coasts of New Zealand and on the east coast of Australia.
- The technique employed was to observe the sources at rising or setting, with an aerial on a high cliff overlooking the sea. These observations allow the path of a source above the horizon to be plotted, and the time of its rising and setting-and hence its celestial co-ordinates-to be determined.
- Only a few objects were identified this way since this was not accurate enough for most radio sources

3C273 : the first quasar

- 14th magnitude object at location derived from lunar occultation- called it a **Quasi-Stellar Radio Source (Quasar)**
- M. Schmidt took optical spectra… found **unique spectrum-lots of lines but at unusual wavelengths**
- **Big leap was realizing the lines are normal but highly redshifted and thus far away**



3C273 : the first active galactic nucleus

  - Schmidt realized that the spectrum implied an “extreme” redshift corresponding to v~50,000km/s- (1/6th the speed of light)
- Recall Hubble’s Law
  - A given galaxies is receding from us with a ***velocity, V_{shift}, that is proportional to their distance, D, from us.***

$$V_{shift} = H_0 D$$

  - The proportionality constant, H_0, is called the Hubble constant and is directly connected to the Big Bang and the subsequent expansion of the Universe.

Let's apply Hubble's Law to 3C273

- Modern value for Hubble constant:
  - H_0=68 km/s/Mpc (notice unusual units)
- So, for V_{shift}=50,000km/s, we get D=735 Mpc (2.2×10^{22} km)
- Since 3C273 is quite bright, this means that it must be **tremendously luminous**… 10^{39}W or more
- Compare with the total power output of our entire galaxy… about 10^{37}W-**3C273 is a hundred times brighter than even a very luminous galaxy would appear at a distance of 2 billion light years**

What produces these lines?

Using simple Newtonian calculation
V_{width}~200(M_7/r)$^{1/2}$ km s^{-1} at r pc. where M_7 is the mass of the BH in units of 10^7 solar masses

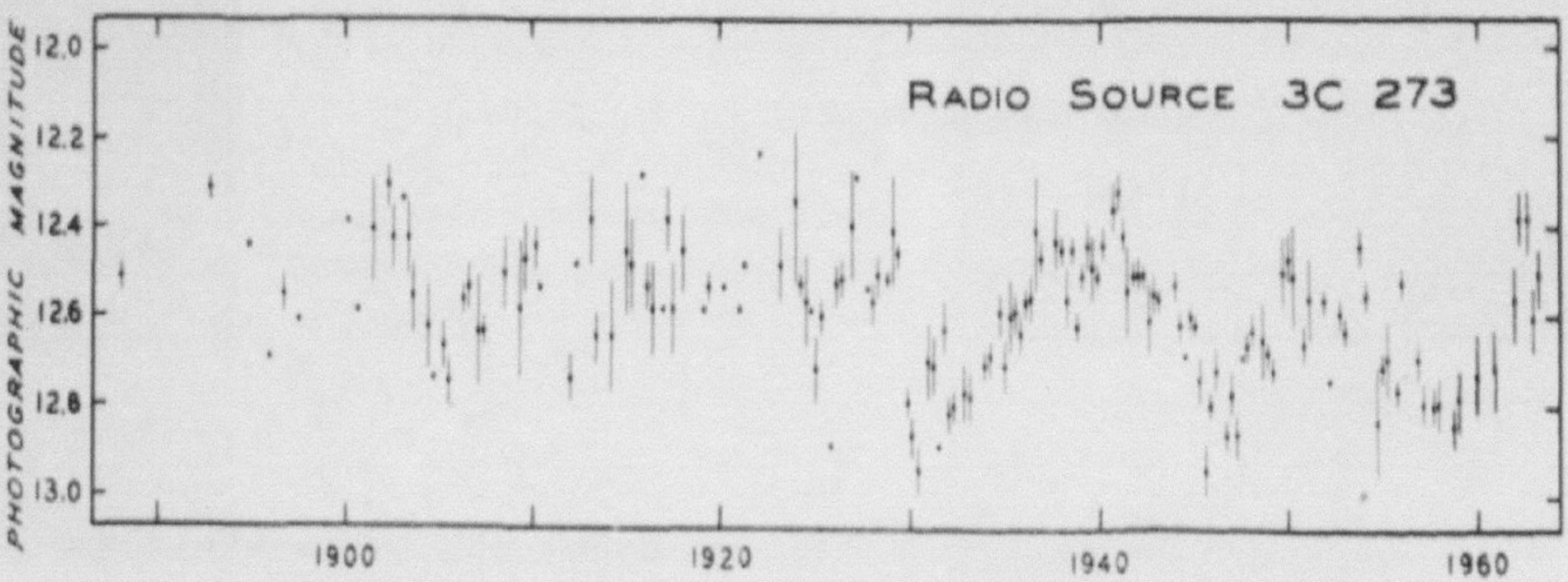
So if V_{width}~200km/sec and r= 1pc M=$6x10^9$Msun
or if we know the mass of the BH is 10^6Msun then
r=.0017pc=$1.7x10^2 R_{sch}$
(Remember R_{Sch}=$2GM/c^2$)=10^{-6}pc M_7)

So immediately know lots of gas is being 'excited' close to a massive object !!!

Variability

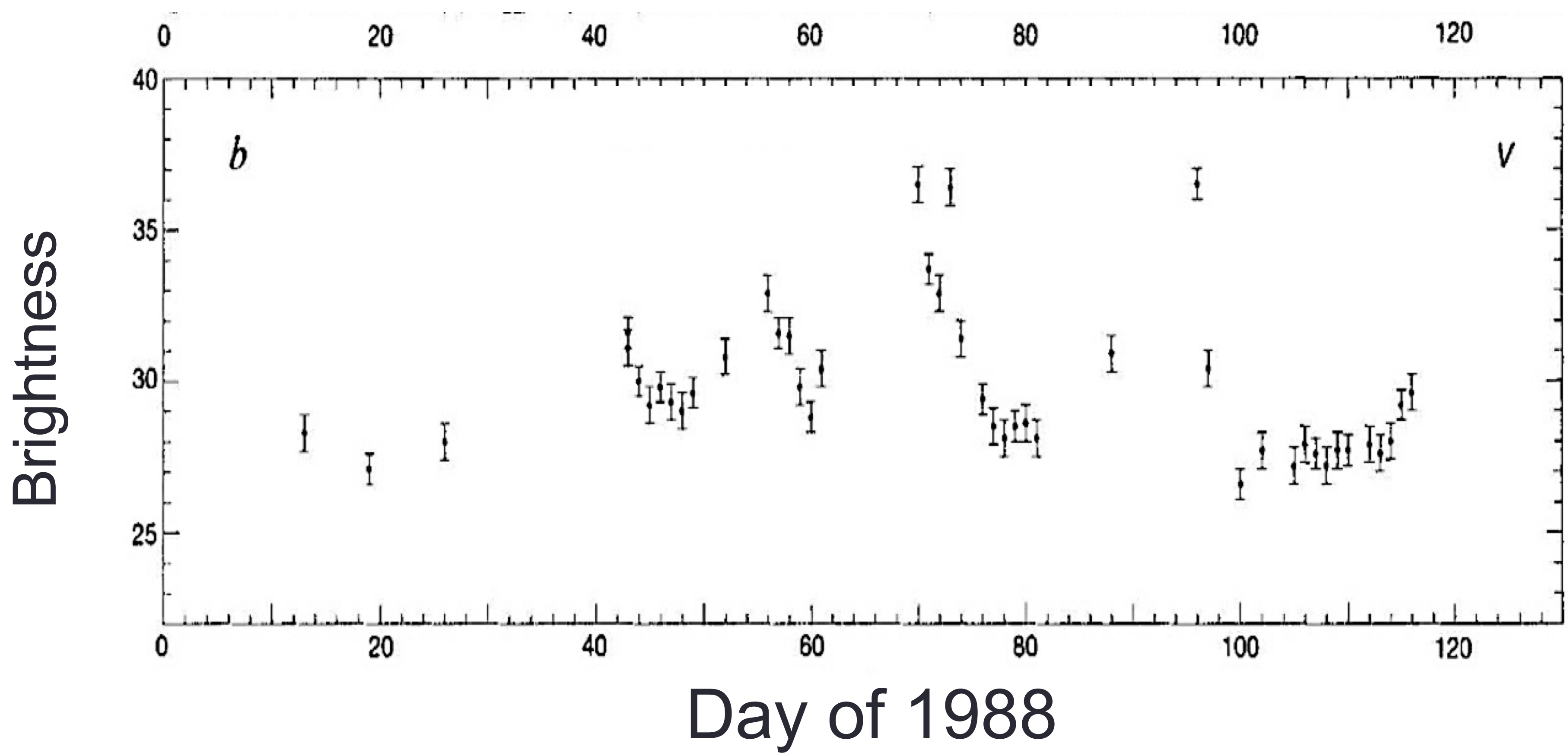
- Also found continuum to be **highly variable** on time scales of weeks in early data (1963)
- Using simple arguments, size <cδt (where δt is the time for the intensity to change significantly)- so 1 week variability corresponds to ~2×10^{14}m (100x distance of Saturn from the Sun)

Dr. Smith and Dorrit Hoffleit of Yale Observatory have checked thousands of photographs from a dozen observatories ("Sky and Telescope," June, 1963, page 311). This latest plot includes plates for recent years from Sonneberg Observatory.



Modern Optical Variability Data

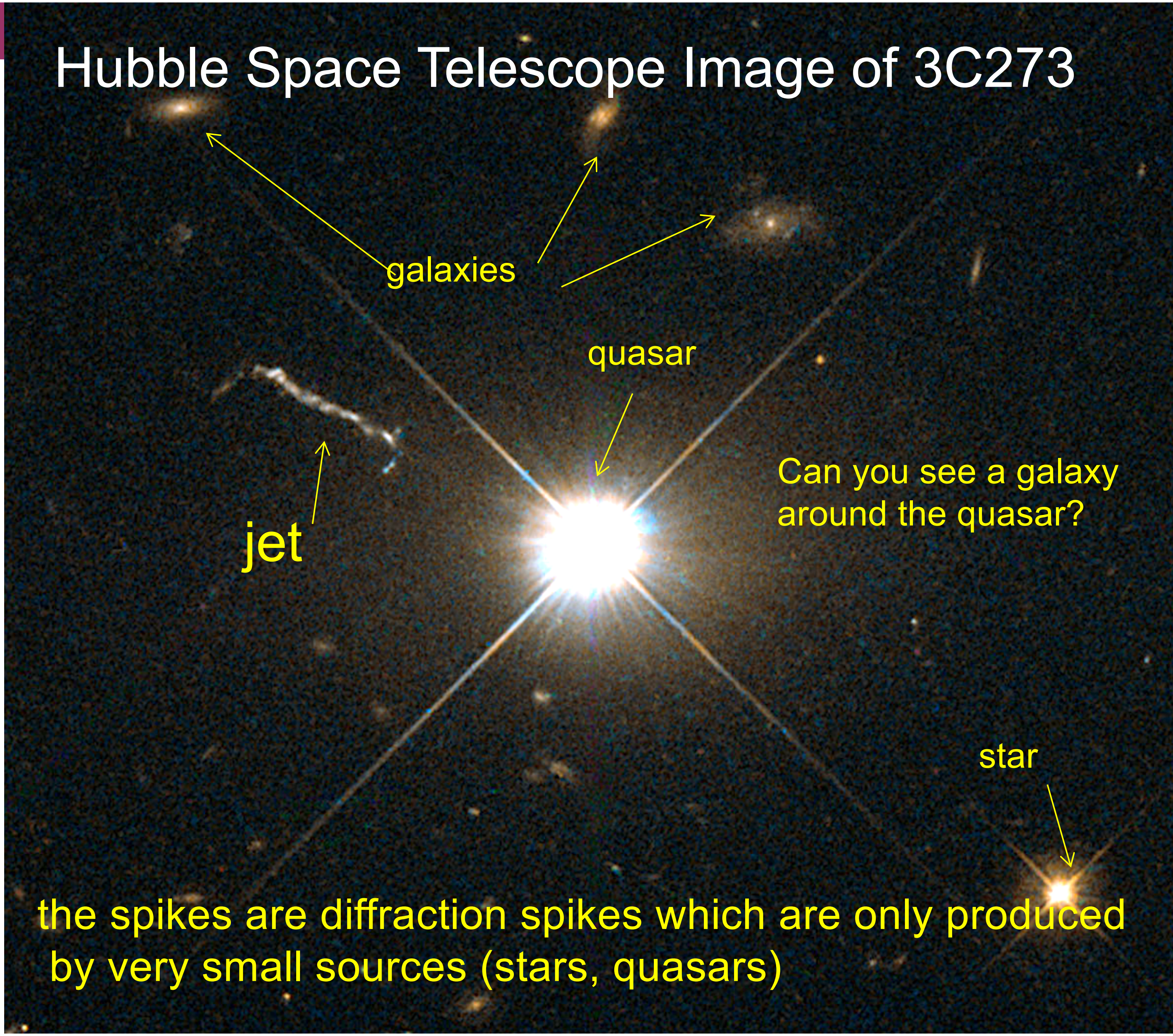
- Also found to be **highly variable** on time scales of days
- As we will see later many AGN are much more variable (higher amplitude and faster)

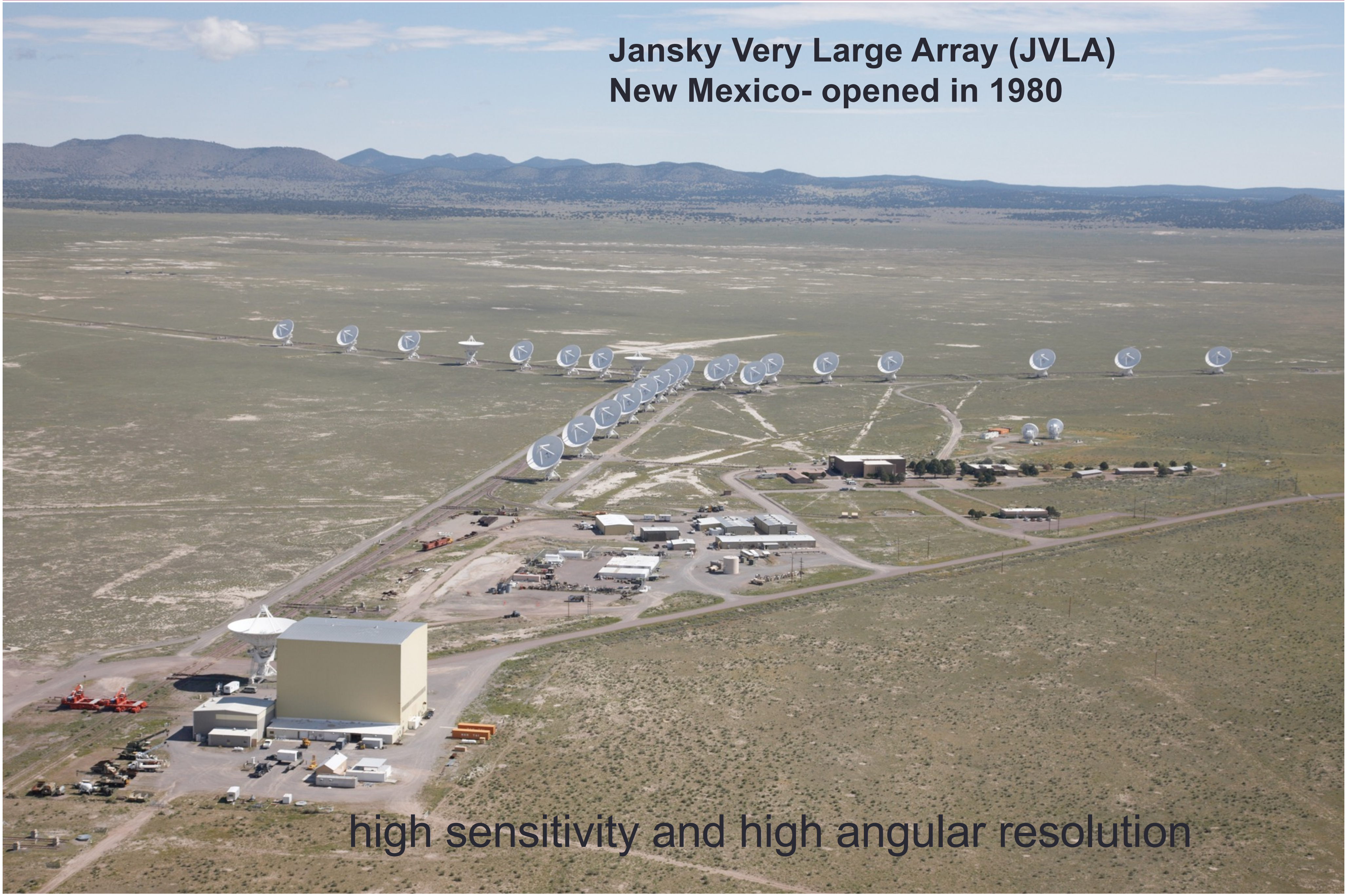


How Amazing These Objects Are

- To quote from Greenstein (1963)
  - Perhaps the most astonishing thing about 3C 273 and 3C 48 is that they do not look like distant objects. An ordinary bright galaxy at a distance of four billion light-years has a visual magnitude of 20 to 22 and can be observed only with the largest telescopes. The visual magnitude of 3C 48 is 16; of 3C 273, 13.... It is mystifying how 3C 273 and 3C 48 can be so far away and look so bright.....
  - In any event, we have encountered a most baffling group of astronomical objects. Whether fundamental new processes lie behind their brilliant but ephemeral appearance, or whether our imaginations are still too limited, remains for the future to determine.

Hubble Space Telescope Image of 3C273




Jansky Very Large Array (JVLA)
New Mexico- opened in 1980
high sensitivity and high angular resolution

Better Positions

- Over the next few years new techniques (radio interferometry) provided positions of tens of arcseconds- allowing accurate optical counterparts to be identified

Despite Being the Most luminous Objects in Universe, Optical Quasars are Usually Small, Faint, and Inconspicuous

Despite many years of study before the 1960's quasars had not been found

Using 1950's optical telescopes they are small, faint and unless you know their properties, hard to find

It was as the optical counterparts to radio sources that quasars were first found.

II : Decoding the mystery of QSOs

- What does this all mean?
- Rapid variability…
  - Source must be very small
  - Hour-timescale variability ➔ source few x AU or smaller
- So, we need something that is very efficient and very small…
  - What about black hole accretion?
  - First conference on quasars

  Sky_and_Telescope_February1964_Texas_Symposium_article.pdf

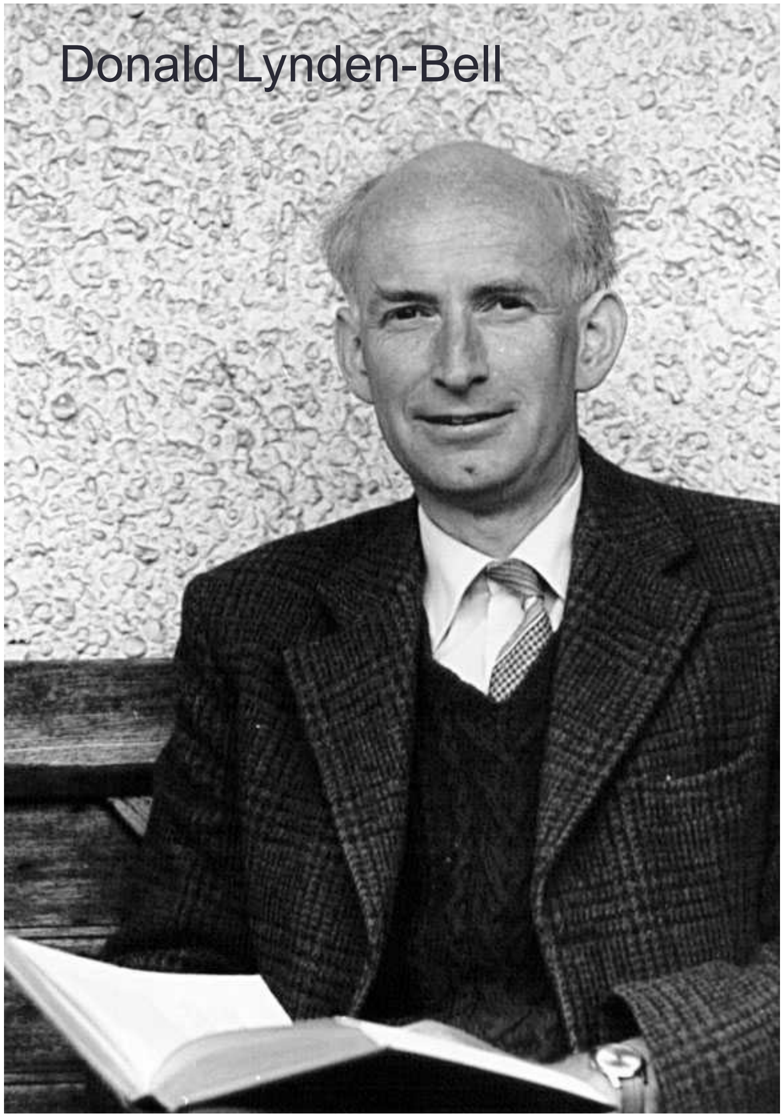
Quasars as Accreting Black Holes

In 1969, Donald Lynden-Bell became the first to suggest that supermassive black holes in the cores of galaxies might generate the enormous energy put out by quasars

1969 Nature Publishing Group

NATURE, VOL 223, AUGUST 16, 1969

Galactic Nuclei as Collapsed Old Quasars



Accretion of Matter Onto a Black Hole

- Define the efficiency of accretion through the following equation:

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

Luminosity — efficiency — Mass flow rate into BH

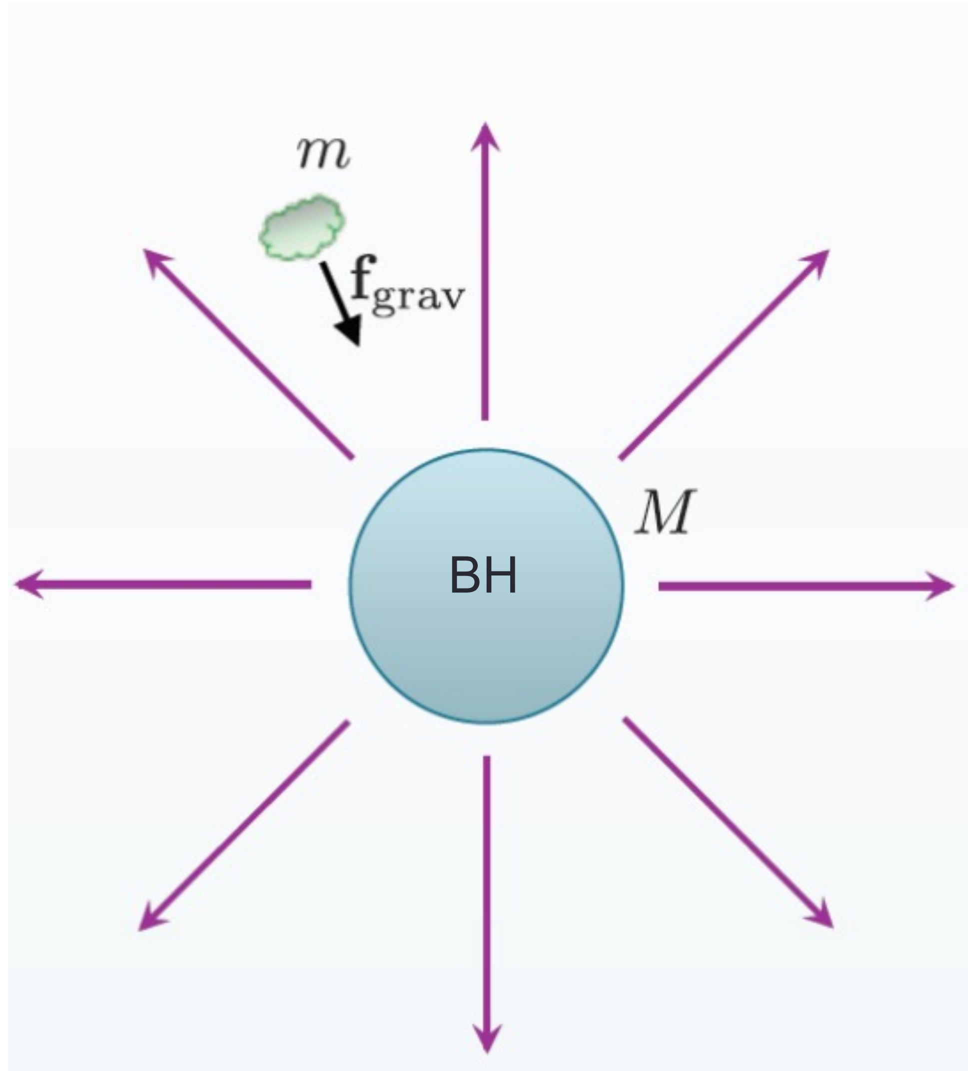
- Non-spinning hole… efficiencies can reach 6%
- Rapidly spinning hole… can reach 40%
- So, can fuel 3C273 with as little as 0.6 solar masses per year! **IF we can convert mass into energy**

Eddington Limit

Matter is falling in, pulled by gravity

As it falls in it gets hot (conversion of kinetic energy to heat) and emits lots of radiation

The radiation pushes against the infalling matter limiting how much can fall in



Not So Quick Dr....

- Outflowing radiation exerts tremendous outward pressure…
  - For material to still flow inwards, this radiation pressure must be overwhelmed by gravity
  - For a given black hole mass, there is a maximum luminosity after **which radiation blows system apart**

$$L_{\max} \approx 1.4 \times 10^{31} \left(\frac{M_{BH}}{M_{Sun}} \right) W$$

Eddington Limit

  - **So, since 3C 273 has L=10^{39}W, need at least a $10^8 M_{sun}$ black hole!**
  - Example of an active galactic nucleus (AGN). Approximately 1-10% of galaxies are AGN.

III : Some Big Questions

- What powers the quasar?
  - How is mass converted into energy?- Next lecture on accretion disks

- Future lectures
  - Where did these black holes come from?
    - how are supermassive black holes formed and grow
  - How and to what degree does an AGN influence its surrounding?
    - do black holes influence their host galaxies?
  - Are these 'really' the black holes predicted by general relativity?
    - testing general relativity