Radio waves from space

Astronomy at the longest wavelengths

Matt Bothwell

Lecture topics

- Background: the history of radio astronomy
- What is in the radio sky?

Astronomy beyond the optical

- Astronomy is the oldest science, but for >95% of history has been entirely optical
- Modern astronomy is multi-wavelength
- Radio astronomy was the first time astronomy went ‘beyond optical’.

Electricity + Magnetism = ?

- 1861 — James Clerk Maxwell, Scottish physicist
- Formulated **Maxwell's Equations**, describing electricity and magnetism

Electricity + Magnetism = ?

$$\nabla \cdot \mathbf{D} = \rho$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}$$

Electricity + Magnetism = ?

Electricity + Magnetism = ?

$$\begin{aligned}
\nabla \cdot \mathbf{D} &= \rho \\
\nabla \cdot \mathbf{B} &= 0 \\
\nabla \times \mathbf{E} &= -\frac{\partial \mathbf{B}}{\partial t} \\
\nabla \times \mathbf{H} &= \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}
\end{aligned}$$

Electricity + Magnetism = ?

Electric field leaving volume proportional to charge inside

$$\nabla \cdot \mathbf{D} = \rho$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}$$

Electricity + Magnetism = ?

Electric field leaving volume proportional to charge inside

No magnetic monopoles

$$\nabla \cdot \mathbf{D} = \rho$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}$$

Electricity + Magnetism = ?

Electric field leaving volume
proportional to charge inside

$$\nabla \cdot \mathbf{D} = \rho$$

No magnetic
monopoles

$$\nabla \cdot \mathbf{B} = 0$$

Electromotive force in a
circuit
depends on magnetic flux
enclosed

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}$$

Electricity + Magnetism = ?

Electric field leaving volume proportional to charge inside

$$\nabla \cdot \mathbf{D} = \rho$$

No magnetic monopoles

$$\nabla \cdot \mathbf{B} = 0$$

Electromotive force in a circuit
depends on magnetic flux enclosed

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}$$

Changes in electric current
depend on magnetic field

Electricity + Magnetism = Waves?

Physicists already knew the ‘wave equation’:

$$\frac{\partial^2 u}{\partial t^2} = c^2 \frac{\partial^2 u}{\partial x^2}$$

Electricity + Magnetism = Waves?

Physicists already knew the 'wave equation':

$$\frac{\partial^2 u}{\partial t^2} = c^2 \frac{\partial^2 u}{\partial x^2}$$

With some mathematical manipulation,
Maxwell's equations re-arrange to

$$\mu_0 \epsilon_0 \frac{\partial^2 E}{\partial t^2} = \frac{\partial^2 E}{\partial x^2} \qquad \mu_0 \epsilon_0 \frac{\partial^2 B}{\partial t^2} = \frac{\partial^2 B}{\partial x^2}$$

… the wave equation!

Electricity + Magnetism = Waves?

So, electric and magnetic fields travel in waves!

How fast?

$$\frac{\partial^2 u}{\partial t^2} = c^2 \frac{\partial^2 u}{\partial x^2} \qquad \mu_0 \epsilon_0 \frac{\partial^2 E}{\partial t^2} = \frac{\partial^2 E}{\partial x^2}$$

$$c = \frac{1}{\sqrt{\mu_0 \epsilon_0}}$$

$$= 2.9979 \times 10^8 \text{ m s}^{-1}$$

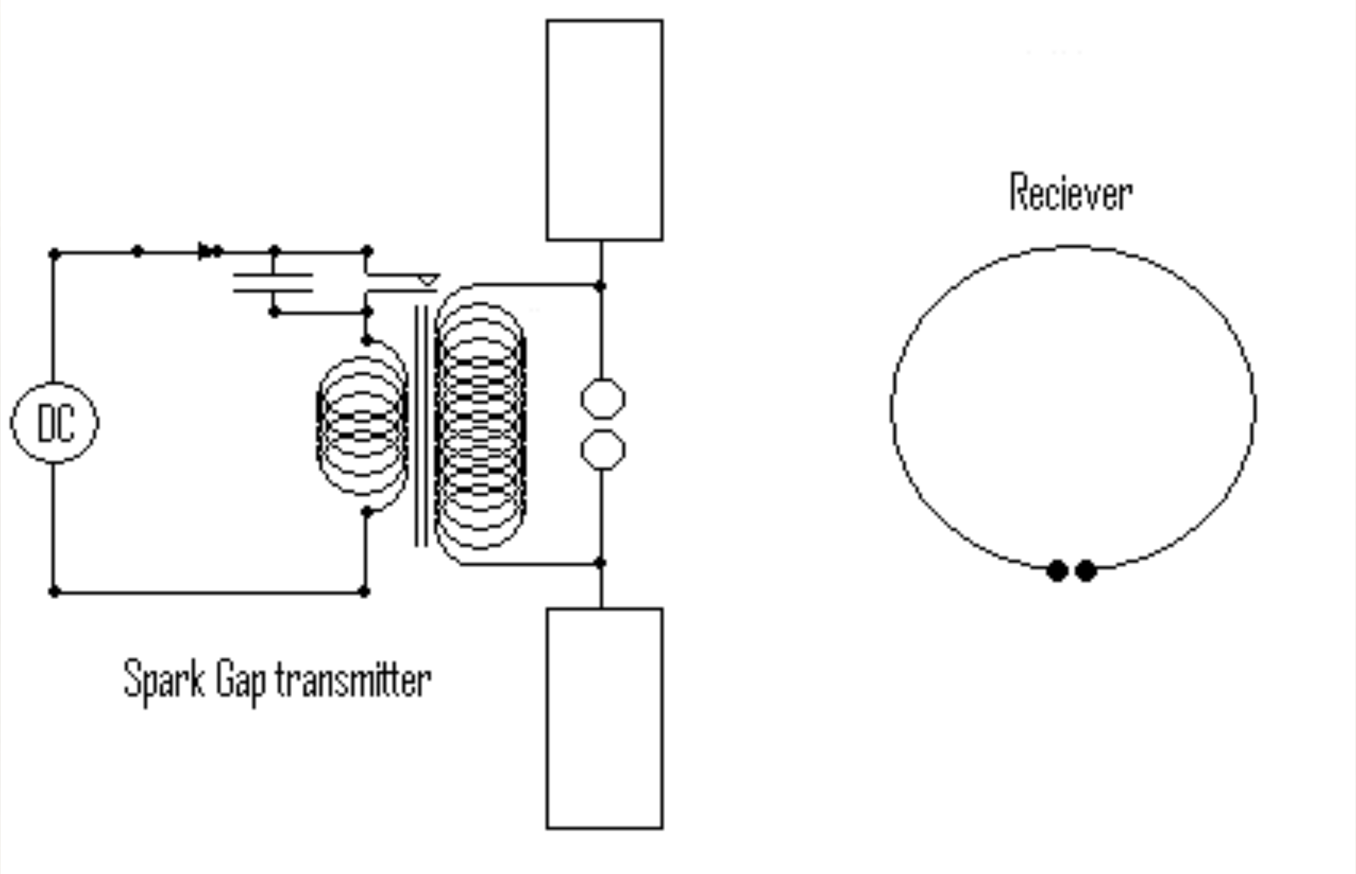
Light is an electromagnetic wave…

So, there should be other types of electromagnetic wave, at other wavelengths.

This discovery paved the way to the existence of radio astronomy

1887 – Hertz checks Maxwell's predictions

"Hertzian Waves"

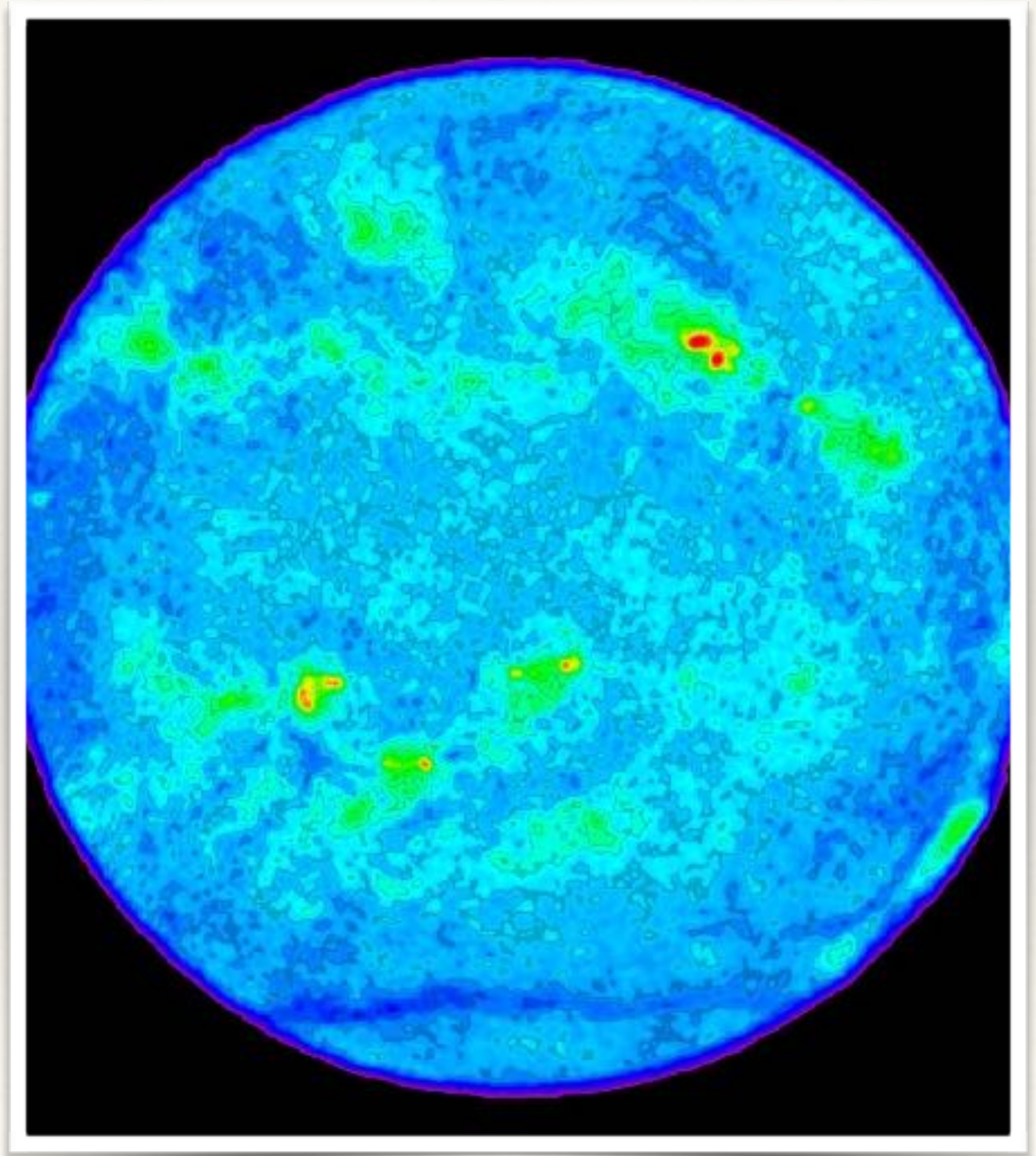


Discovered EM waves, wavelength ~60cm.

Hertz: "This has no practical purpose"

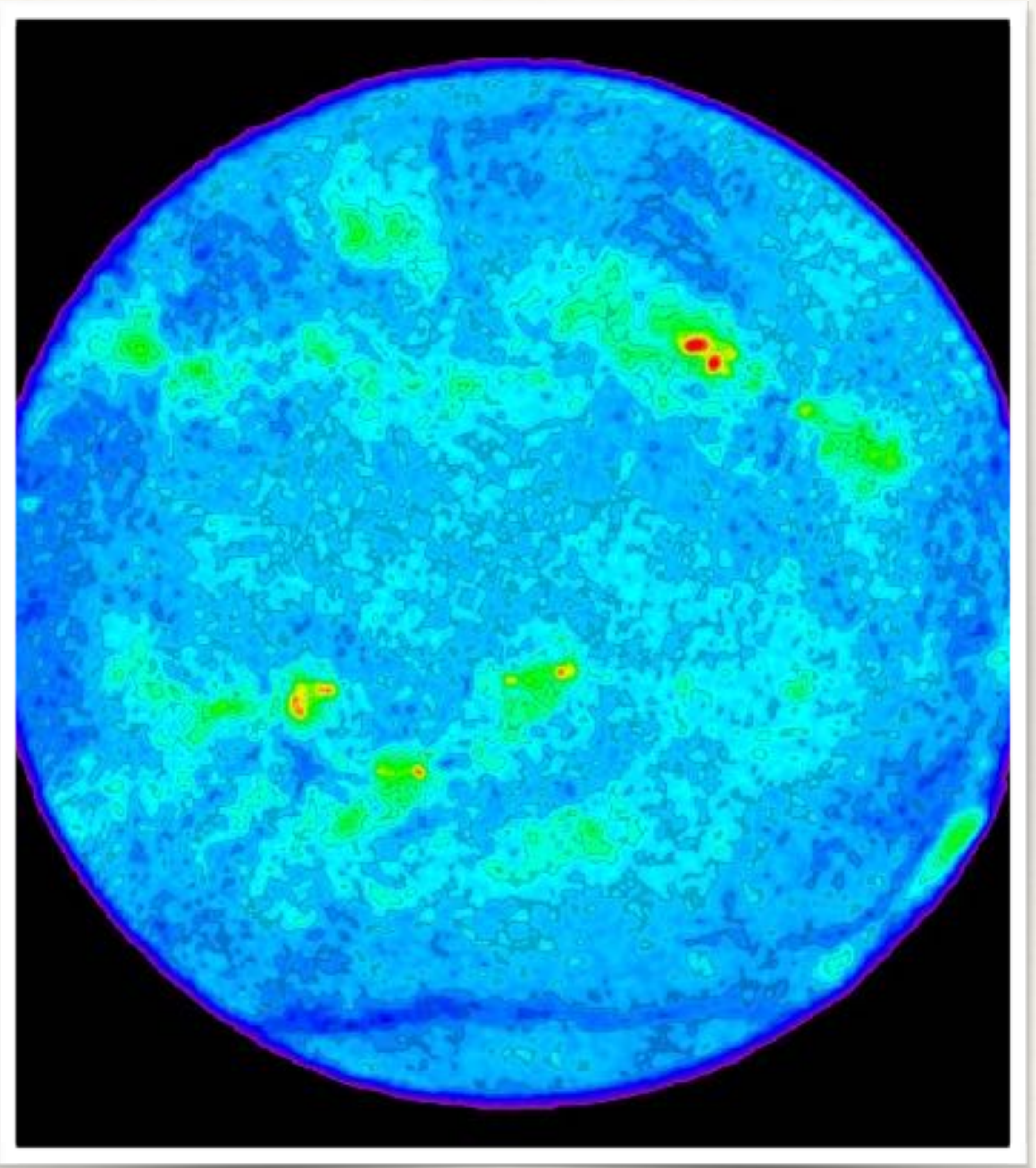
Can we see the Sun?

- Thomas Edison (1890) tried to detect the Sun (using millions of tonnes of magnetite ore as the core of an induction coil) and failed.



Can we see the Sun?

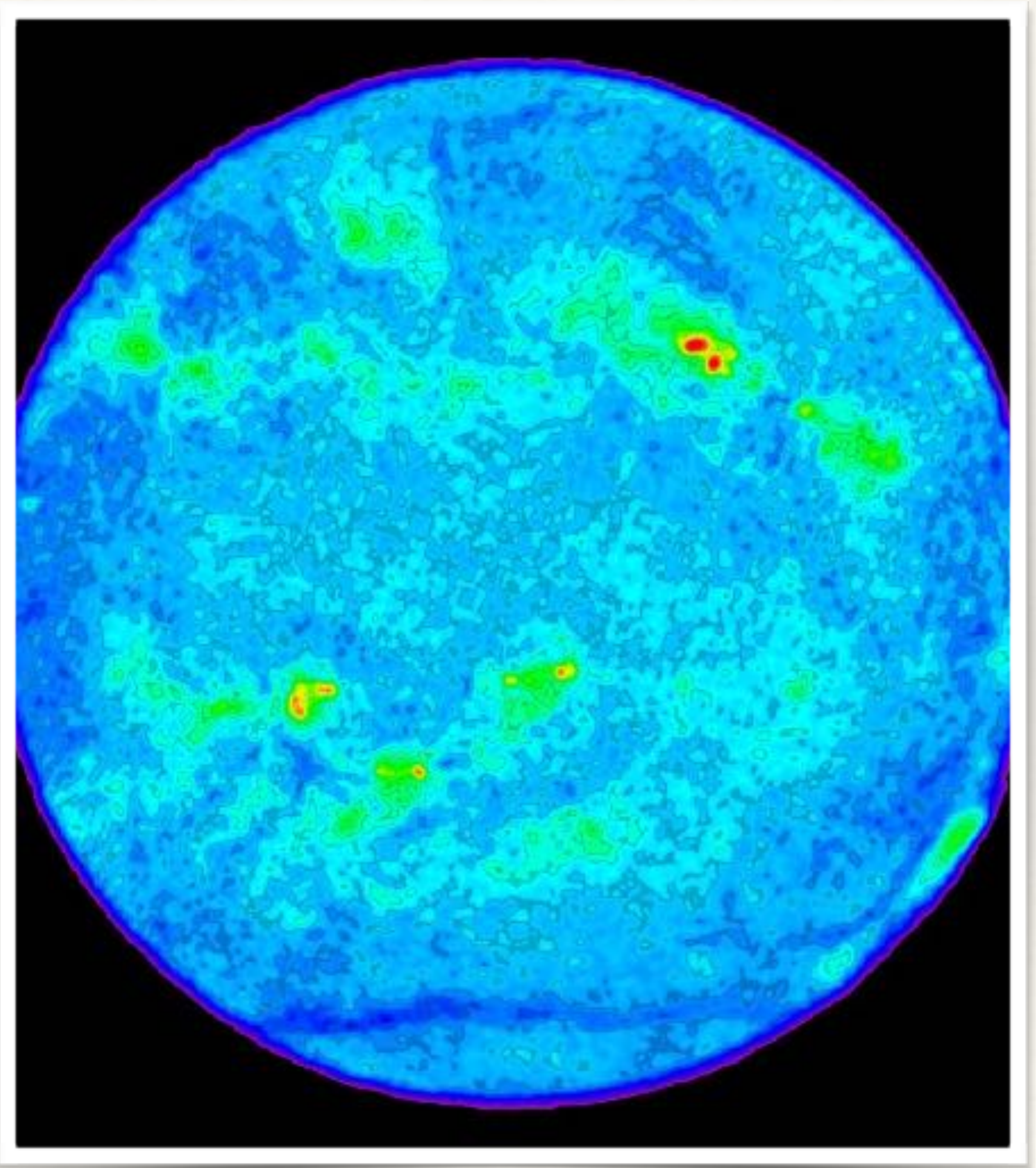
- Thomas Edison (1890) tried to detect the Sun (using millions of tonnes of magnetite ore as the core of an induction coil) and failed.
- Oliver Lodge (1894) got close… but wasn't sensitive enough:



Can we see the Sun?

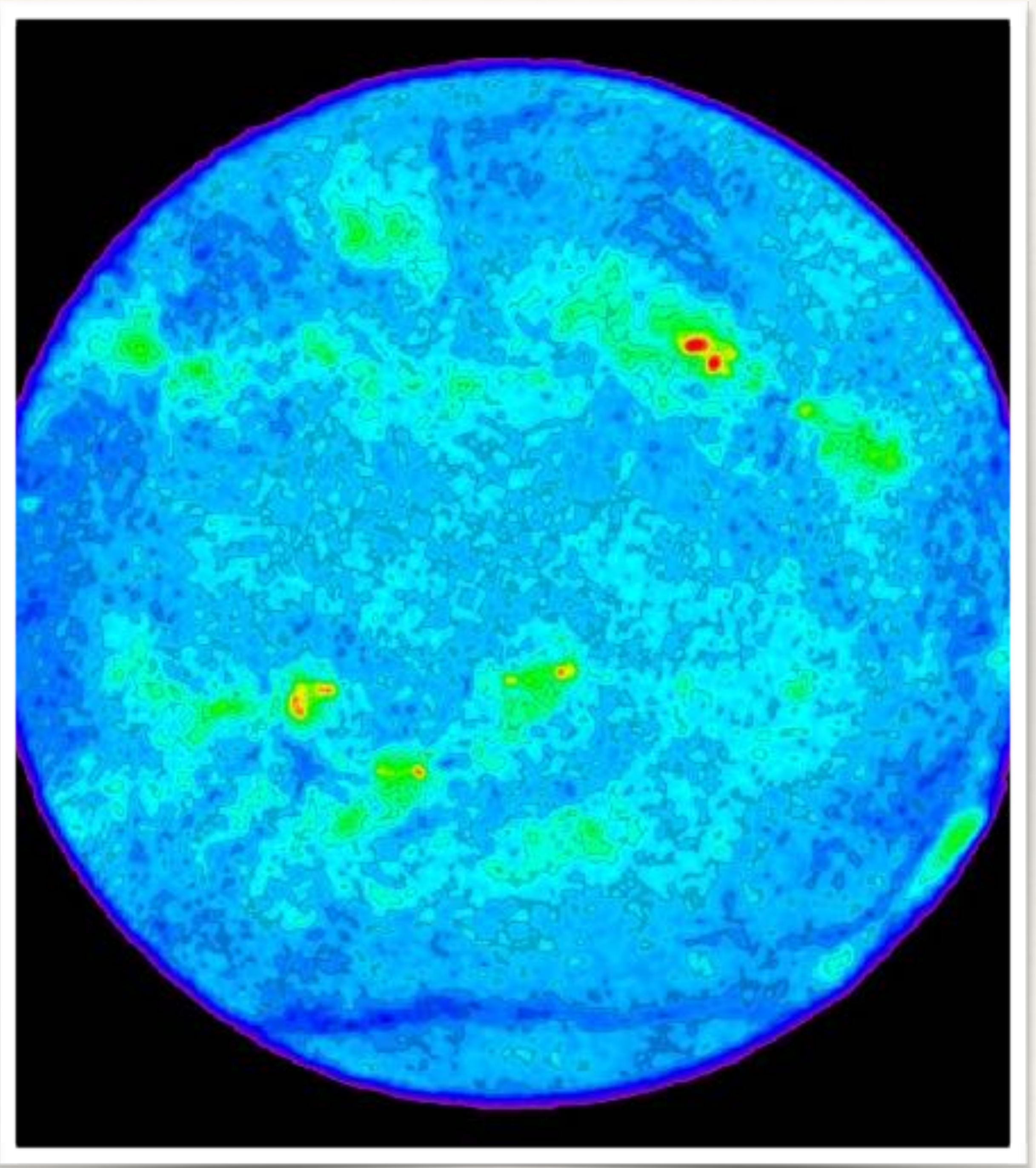
- Thomas Edison (1890) tried to detect the Sun (using millions of tonnes of magnetite ore as the core of an induction coil) and failed.
- Oliver Lodge (1894) got close… but wasn't sensitive enough:

> Tried sunshine today on coherer… couldn't swear to proper sun effect.. May be intermittent or weak



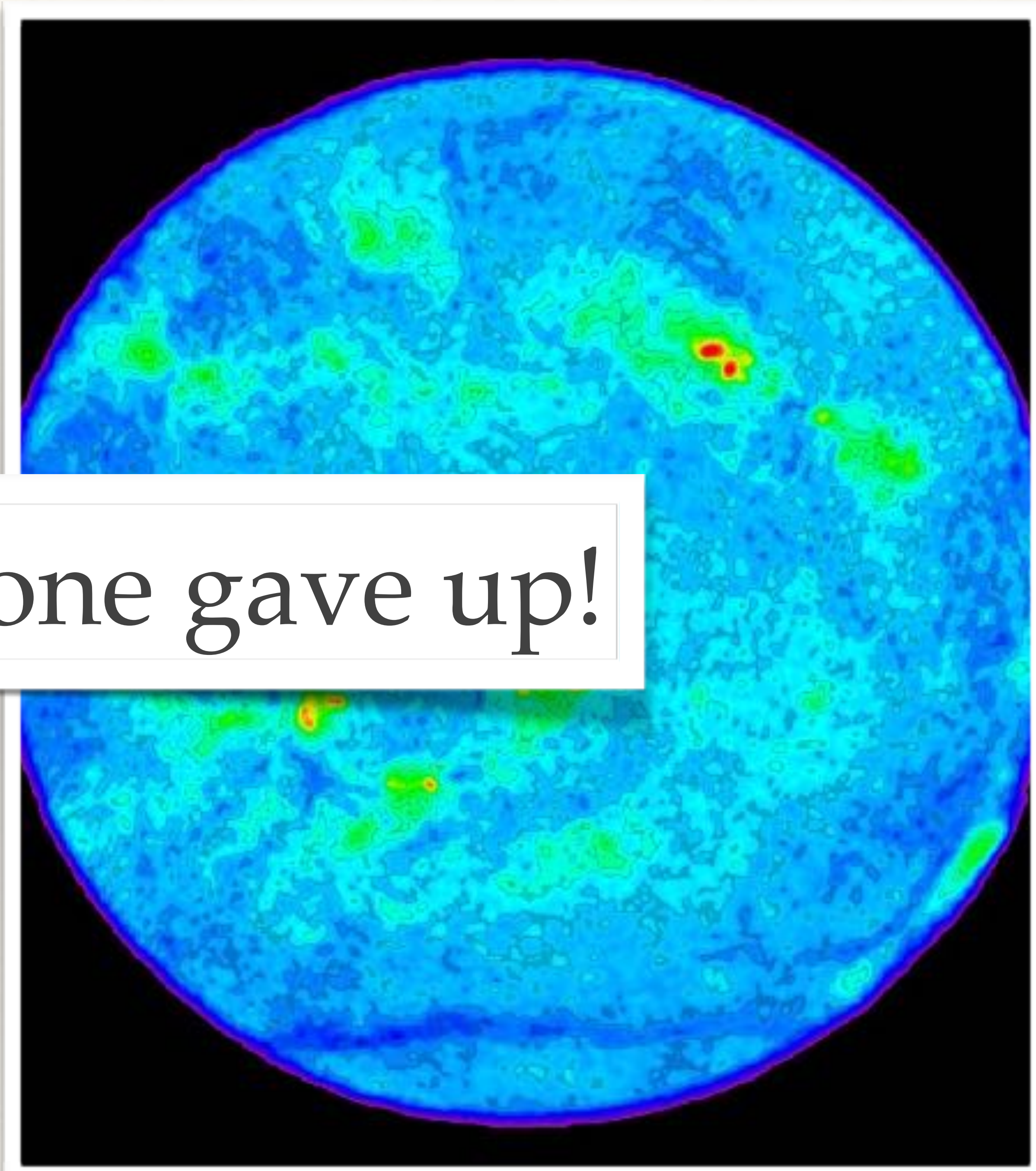
Can we see the Sun?

- Thomas Edison (1890) tried to detect the Sun (using millions of tonnes of magnetite ore as the core of an induction coil) and failed.
- Oliver Lodge (1894) got close… but wasn't sensitive enough:
- Charles Nordmann tried (1902), from Mont Blanc at 3100m… no result.



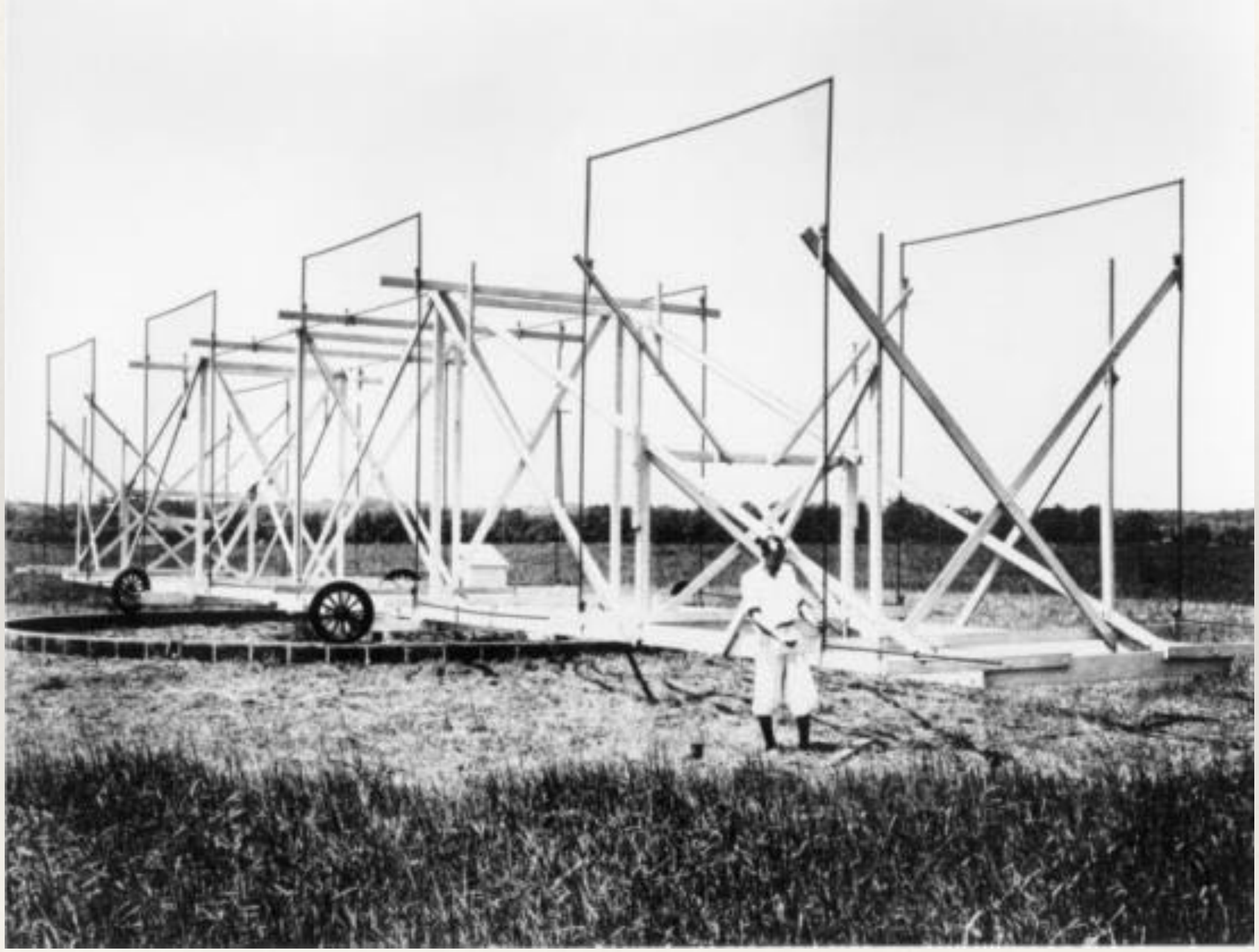
Can we see the Sun?

- Thomas Edison (1890) tried to detect the Sun (using millions of tonnes of magnetite ore as the core of an induction coil) and failed.
- Oliver Lod
  but wasn't sensitive enough:
- Charles Nordmann tried (1902), from Mont Blanc at 3100m… no result.



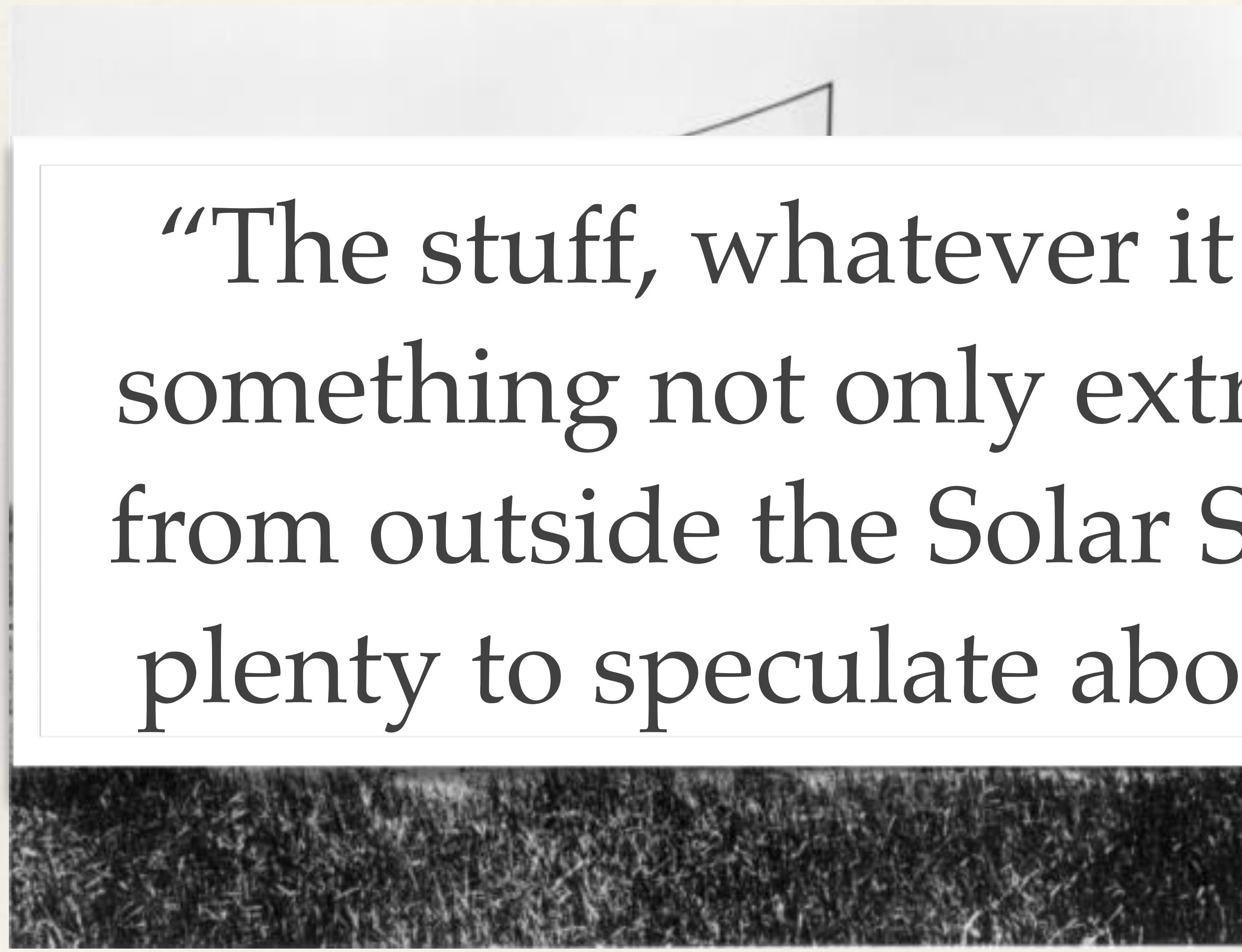
Then… everyone gave up!

1935- Jansky detects… something



- Karl Jansky, “father of Radio Astronomy”, worked for Bell Labs
- Discovered ‘hiss-type static’ at 20Mhz, which varied — almost, but not quite — on a 24 hour period.

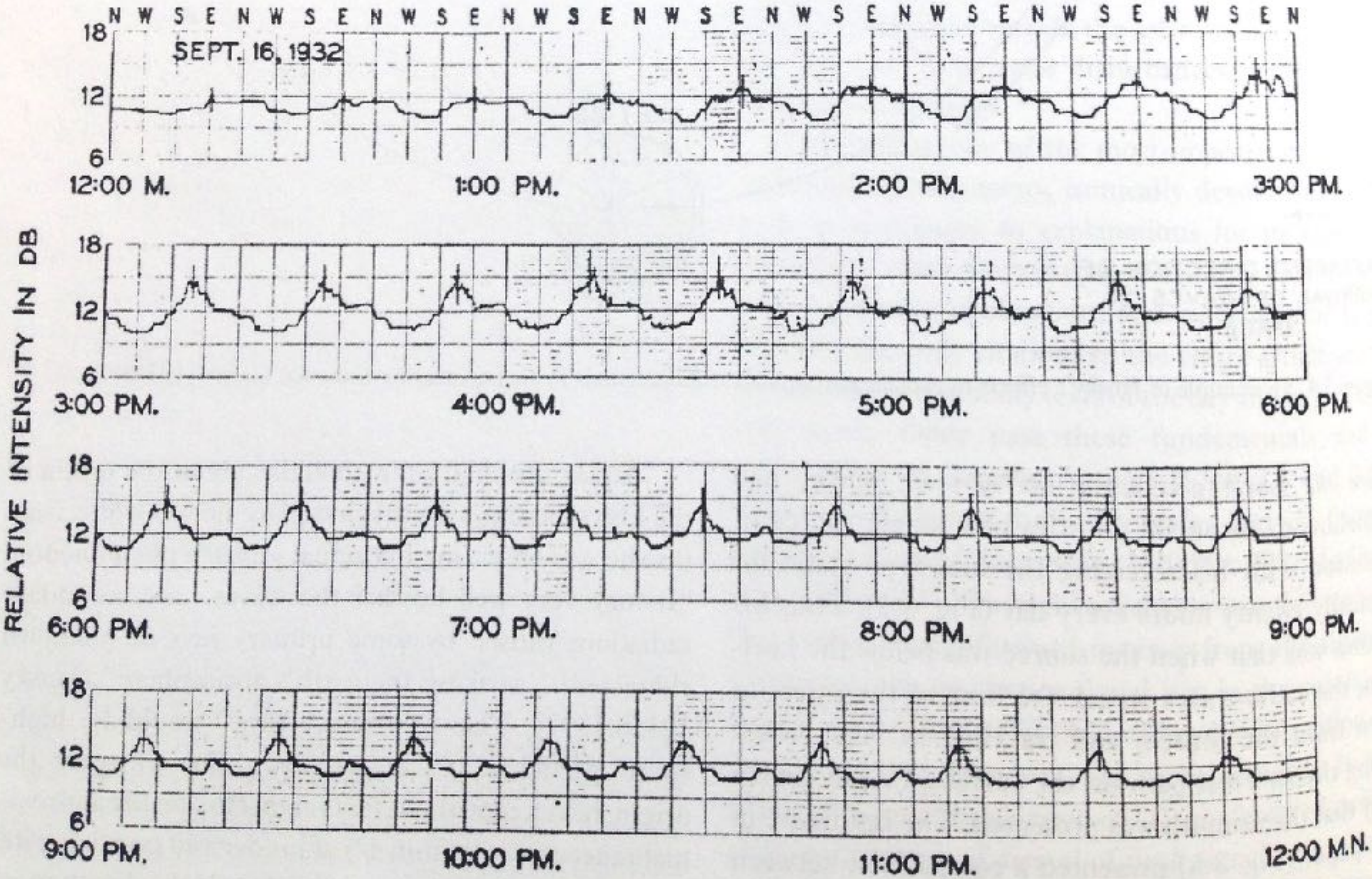
1935- Jansky detects the Galactic centre



- Karl Jansky, “father of

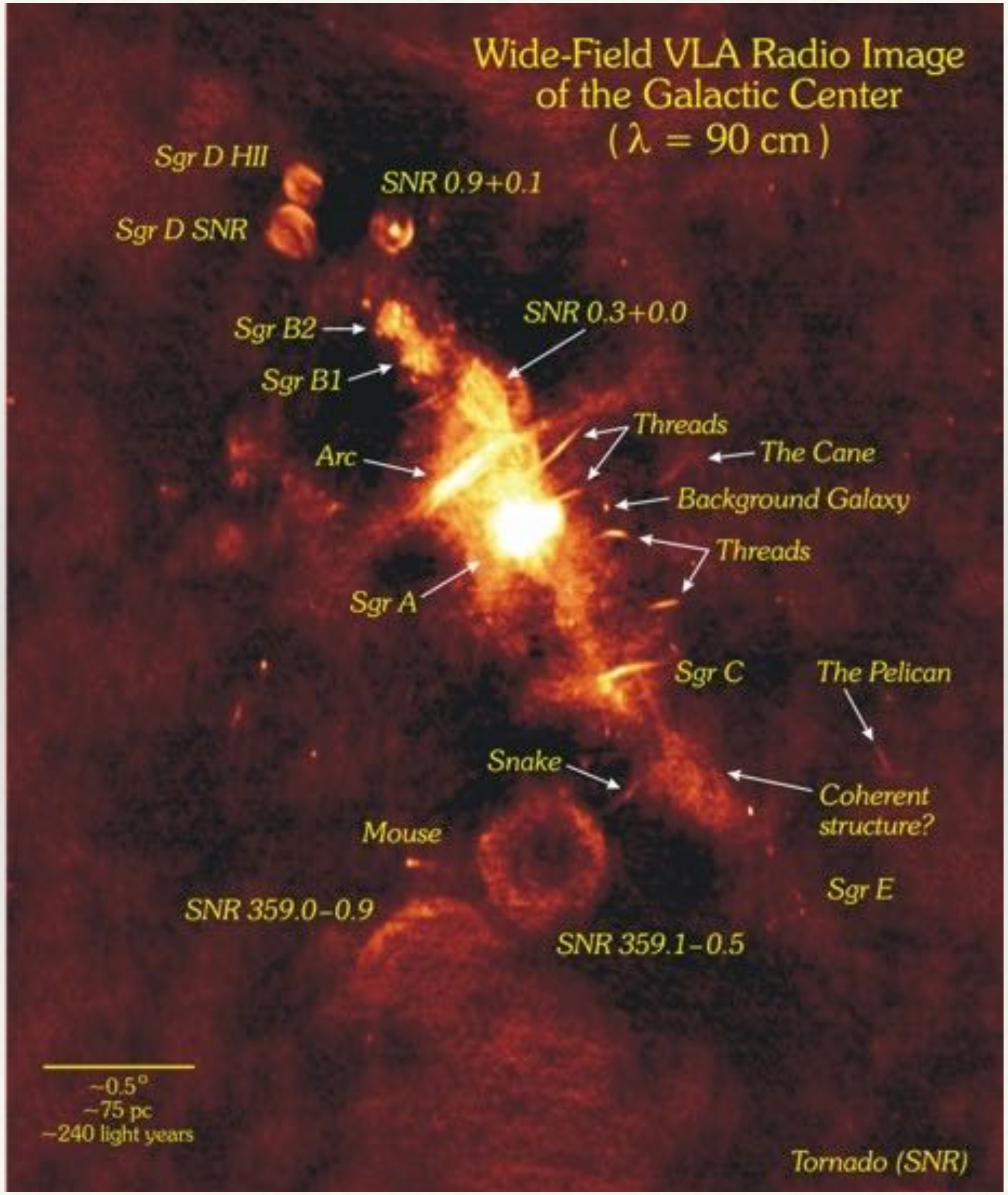
> “The stuff, whatever it is, comes from something not only extraterrestrial, but from outside the Solar System… there’s plenty to speculate about, isn’t there?”

— on a 24 hour period.



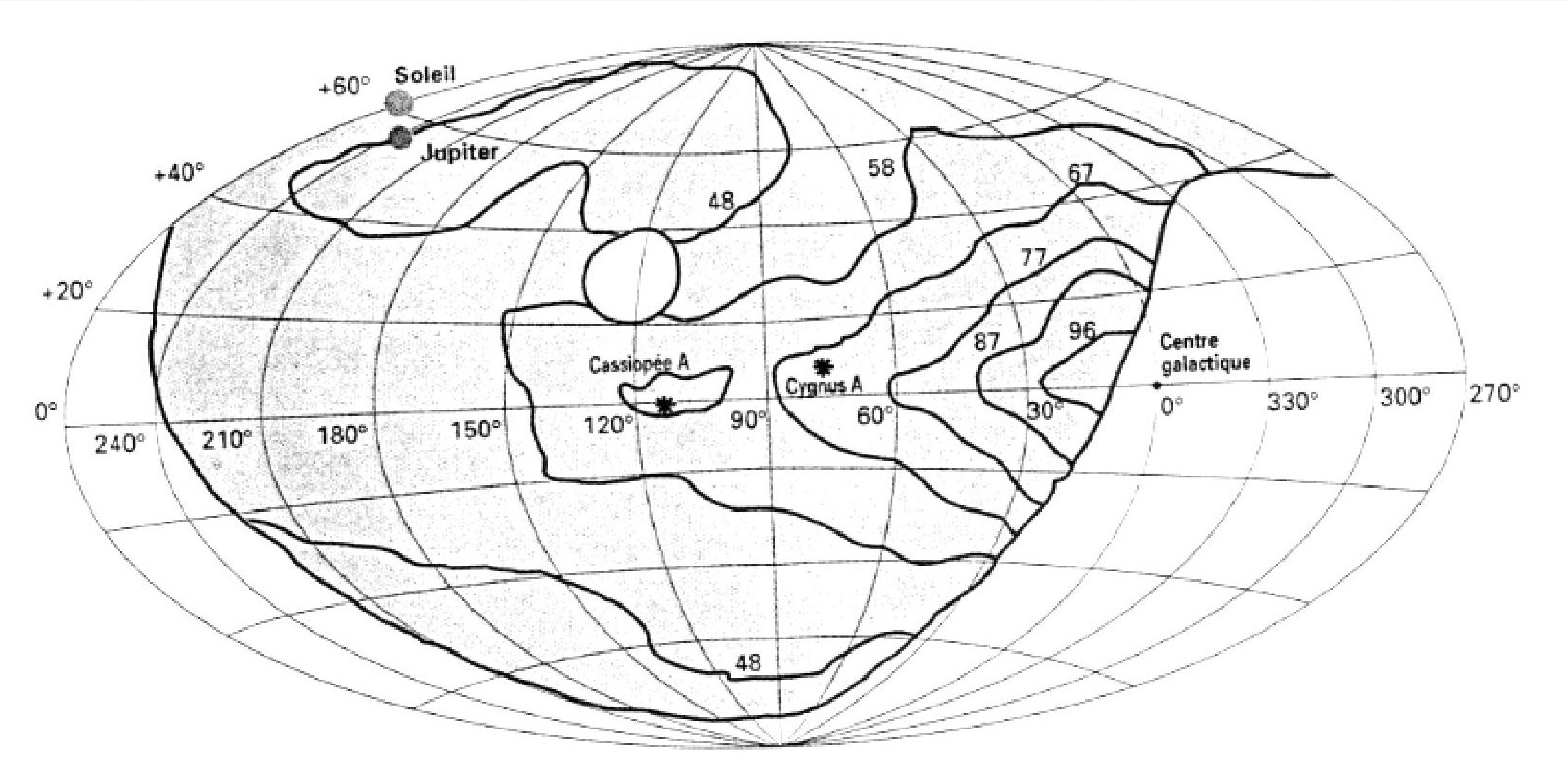
SEPT. 16, 1932
RELATIVE INTENSITY IN DB
N W S E N W S E N W S E N W S E N W S E N W S E N W S E N W S E N W S E N
18
12
6
12:00 M.
1:00 PM.
2:00 PM.
3:00 PM.
4:00 PM.
5:00 PM.
6:00 PM.
7:00 PM.
8:00 PM.
9:00 PM.
10:00 PM.
11:00 PM.
12:00 M.N.

1935- Jansky detects… the Galactic centre

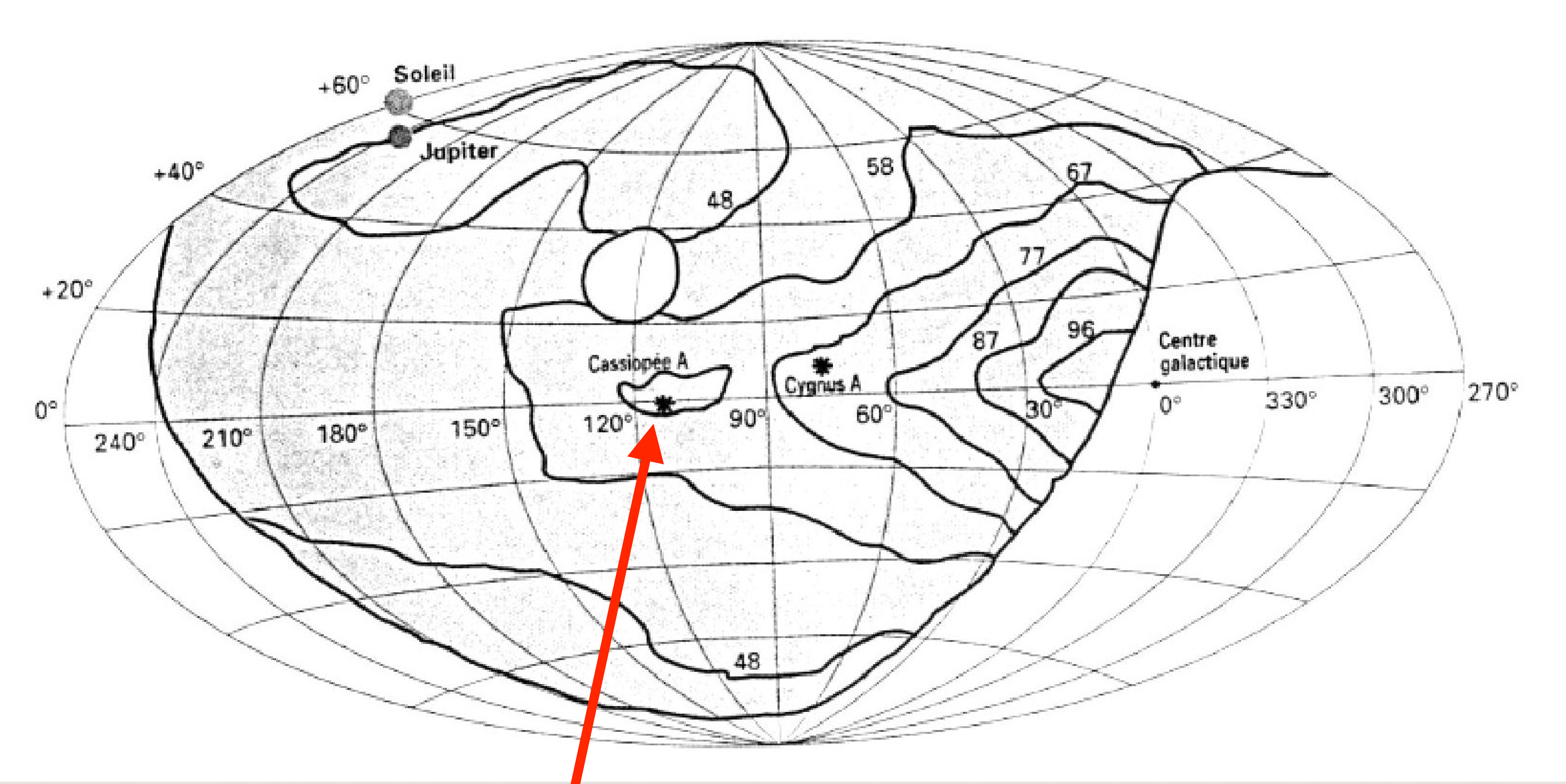


Radio astronomy blossoms

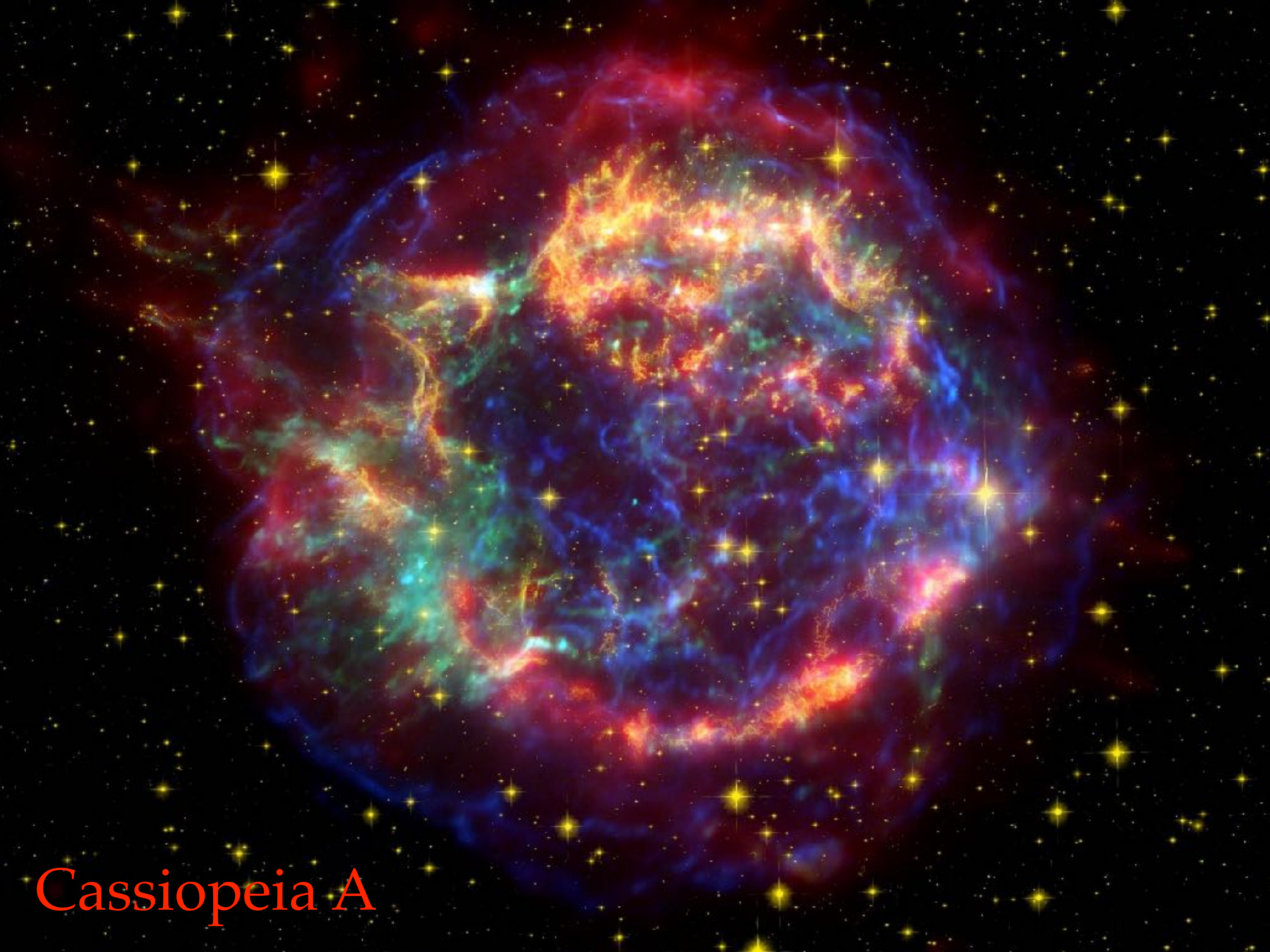
- Grote Reber (1911 - 2002) single-handedly developed radio astronomy in the 30's and 40's
- Jansky worked at Bell Labs… Grote Reber built the largest radio dish in the world in his Chicago back yard.

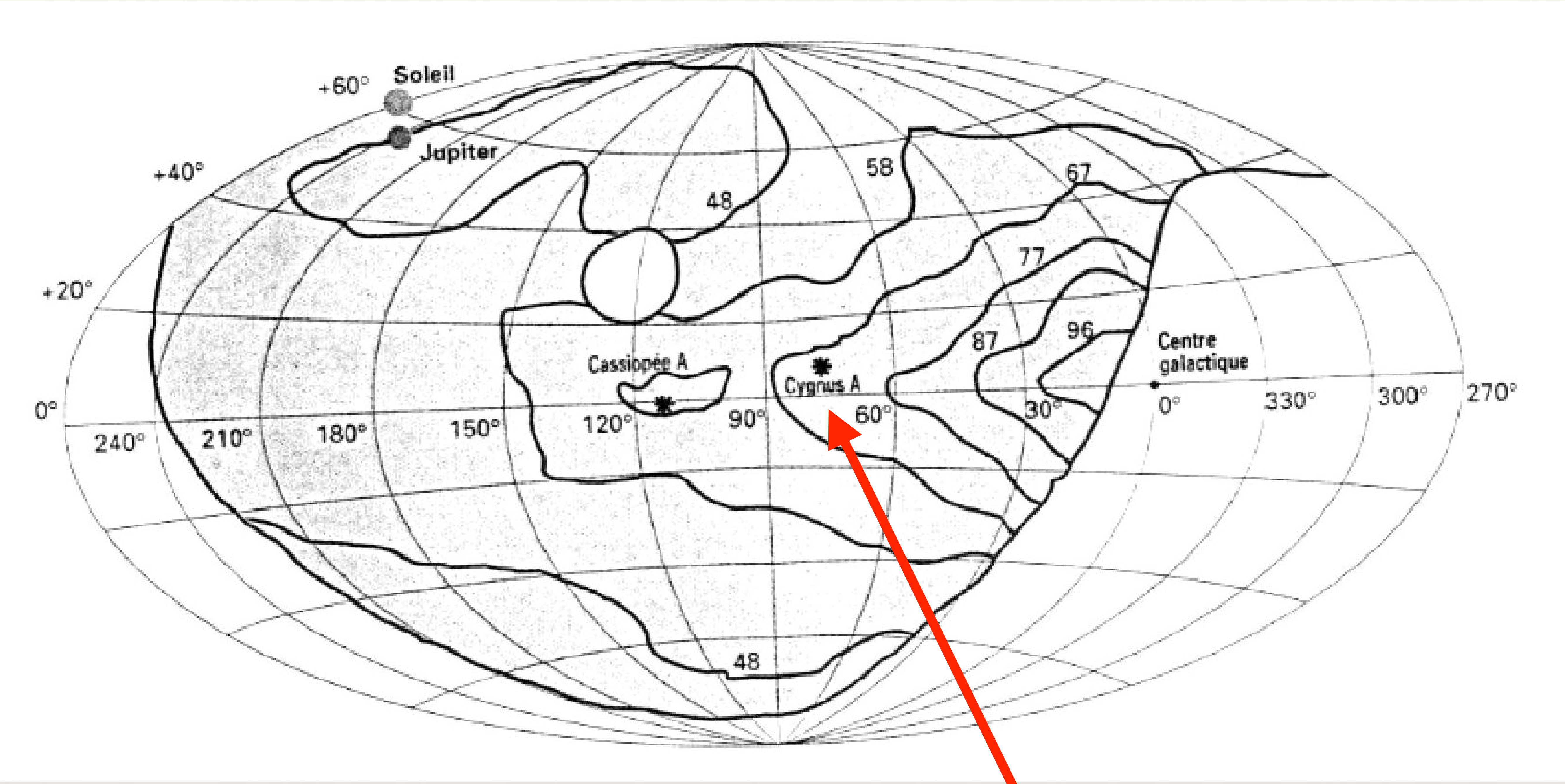


Grote Reber's map of the radio sky at 160 Mhz

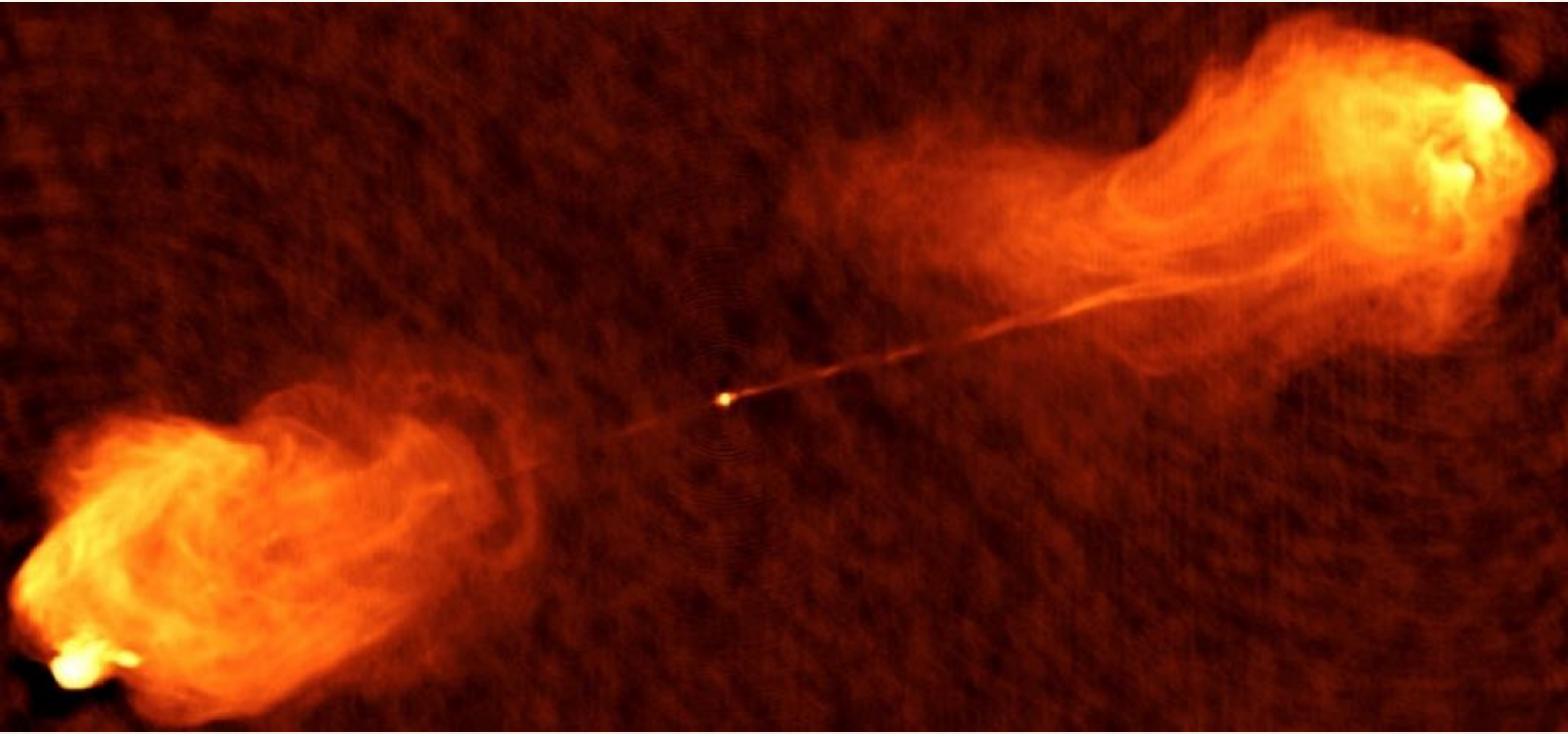


Cassiopeia A


Cassiopeia A


Soleil
+60°
Jupiter
+40°
+20°
0°
240°
210°
180°
150°
120°
90°
60°
30°
0°
330°
300°
270°
48
58
67
77
87
96
48
Cassiopée A
Cygnus A
Centre galactique

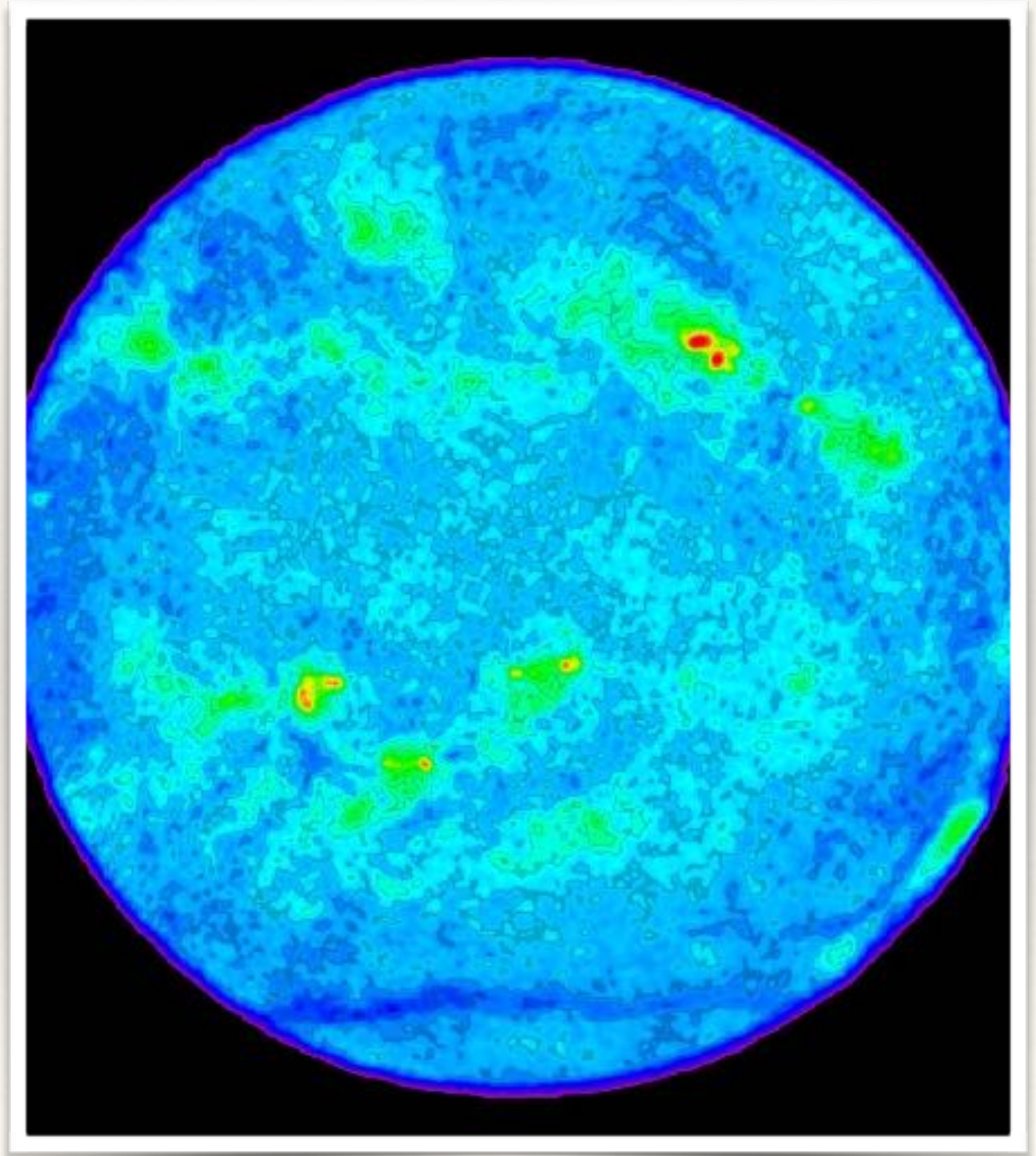
Cygnus A

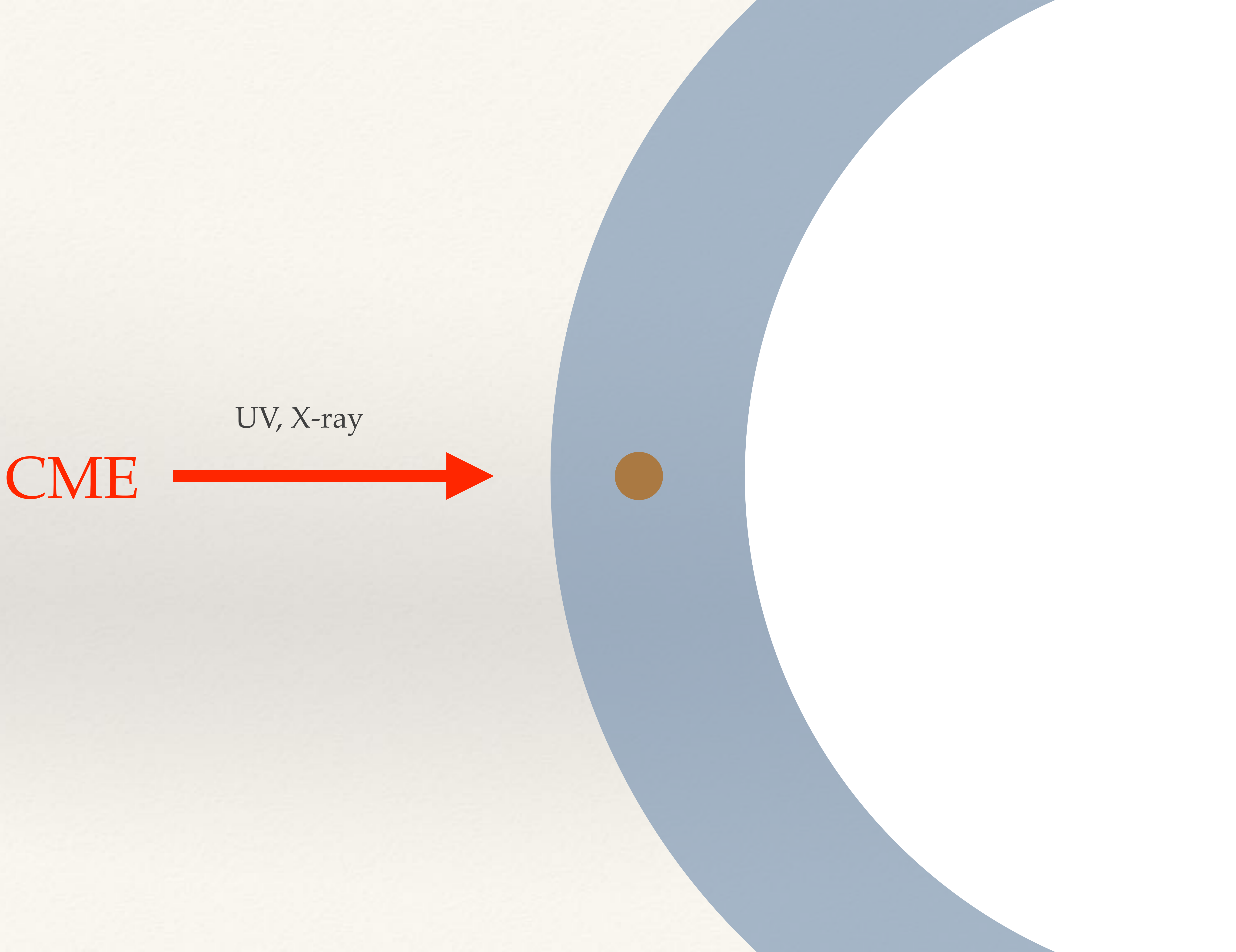


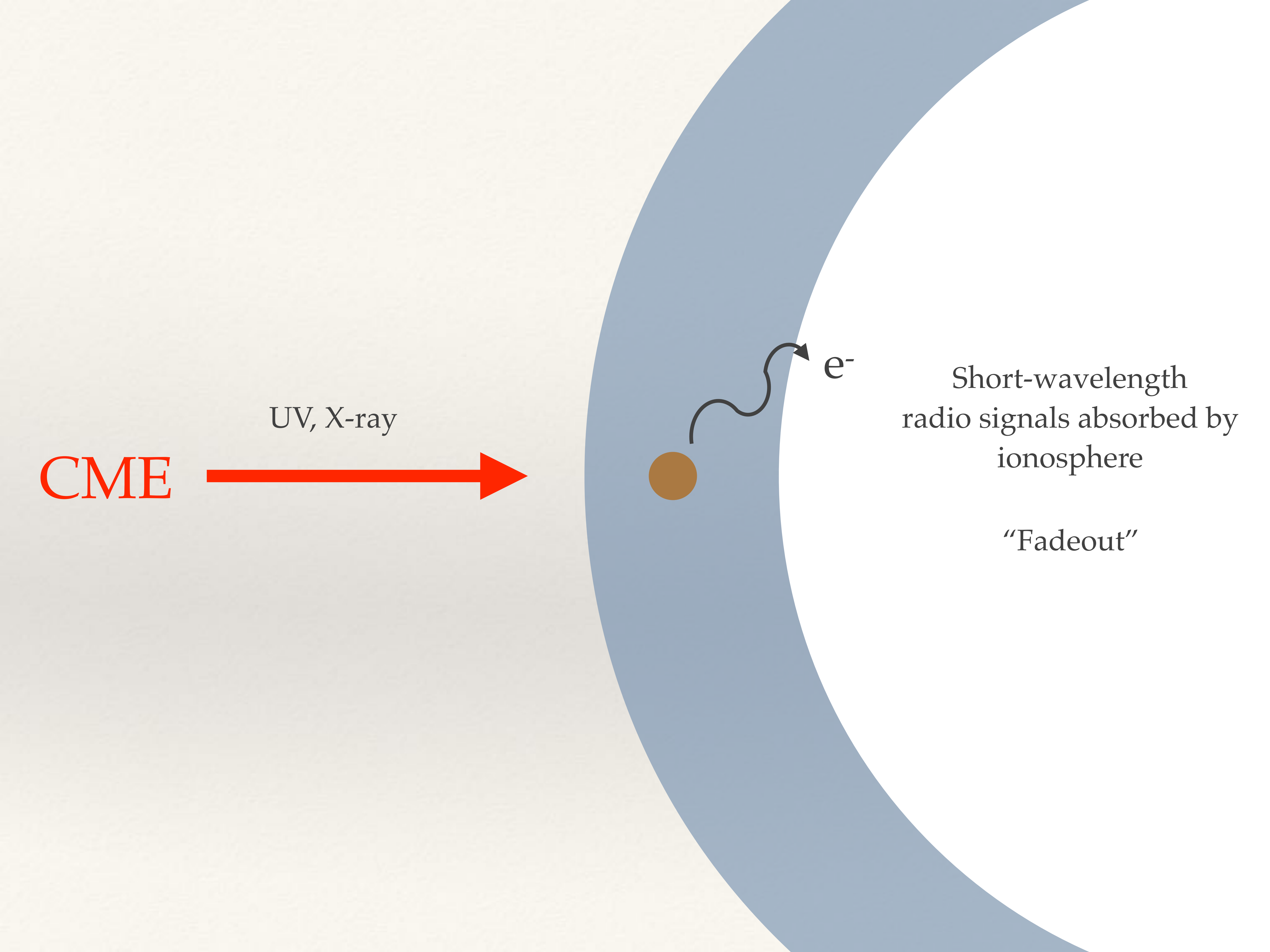
Cygnus A

Sun finally detected… by accident

- During WWII, radio technology developed due to Radar (**RA**dio **D**etection **A**nd **R**anging)
- In 1942, two German battle cruisers passed undetected through the Channel — British radar was jammed…
- Investigators found excessive radio noise over all frequencies, only during daylight hours

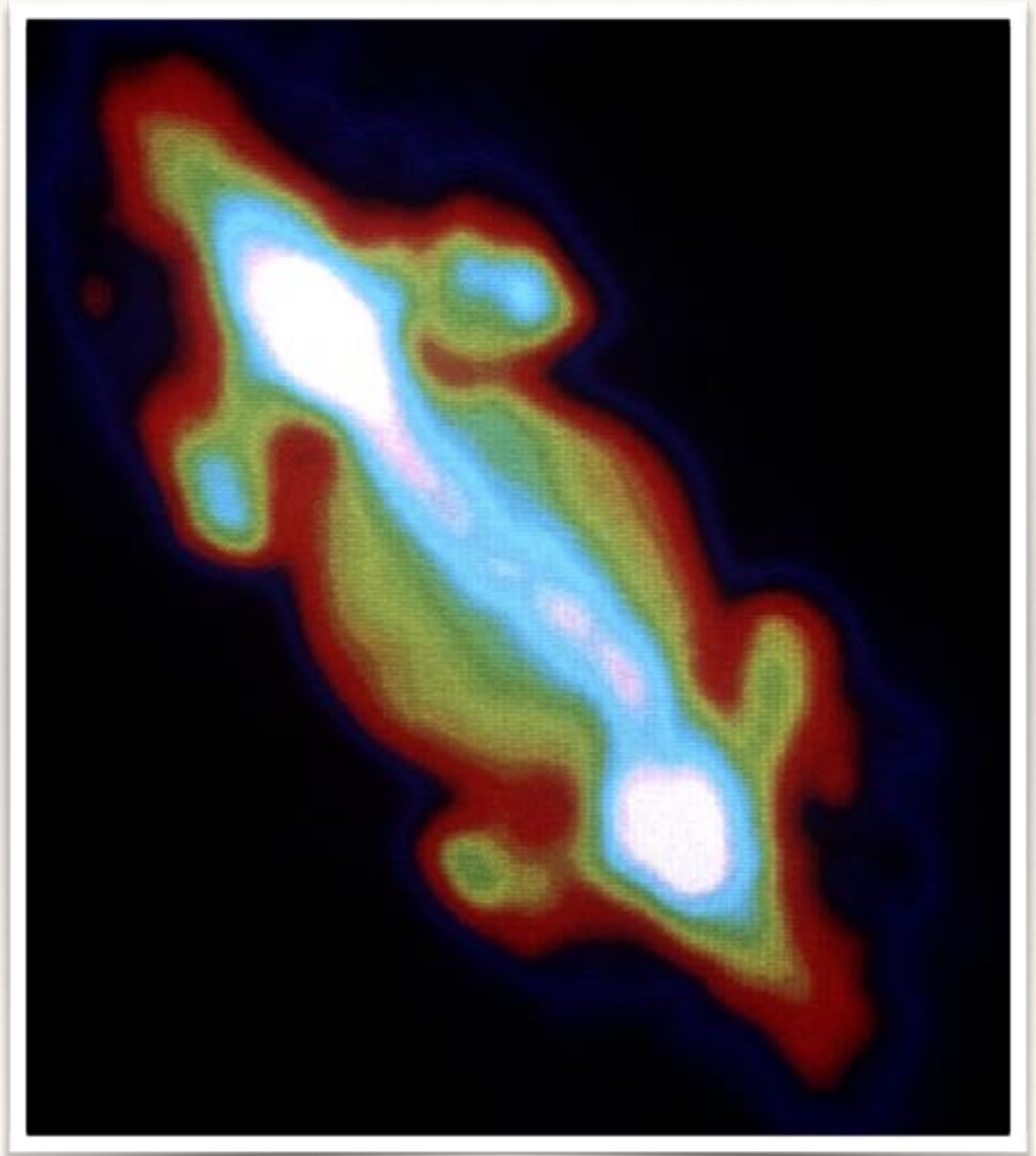



UV, X-ray
CME


CME
UV, X-ray
e-
Short-wavelength
radio signals absorbed by
ionosphere
"Fadeout"

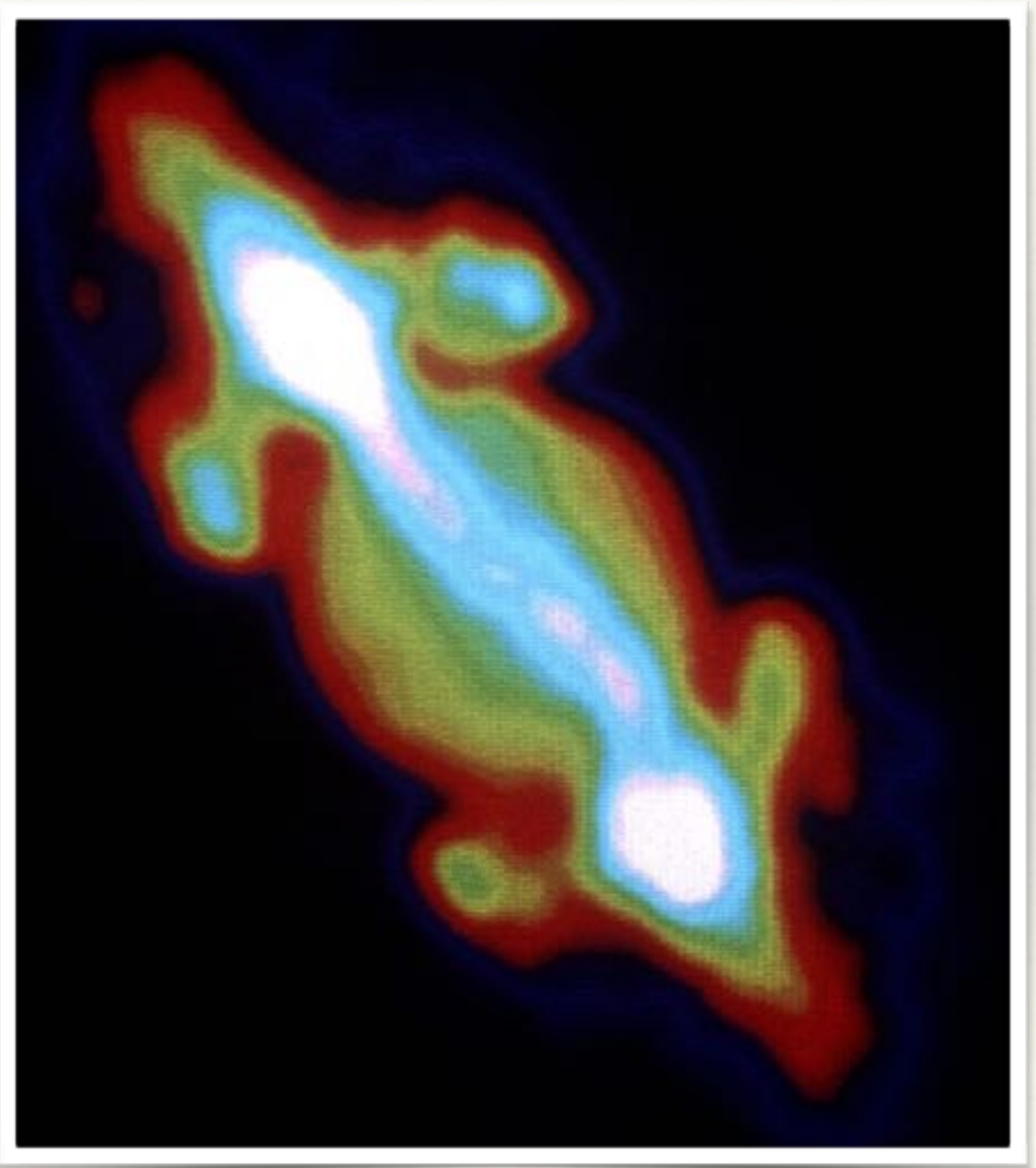
Farther afield…

- Astronomers expected thermal radio emission from planets (all objects >0K emit thermal radiation)
- Jupiter found to emit radio bursts (similar to the Sun) at 20 Mhz!
- Strong, non-thermal emission (70,000 K at 200 Mhz)



Radio bursts from Jupiter

- Jupiter found to have a magnetic moment 18000 times stronger than Earth
- Caused by:
- (1) metallic Hydrogen in Jupiter's interior
- (2) Plasma eruptions from Io (~1 tonne per second)



‘Radio stars’

‘Radio stars’

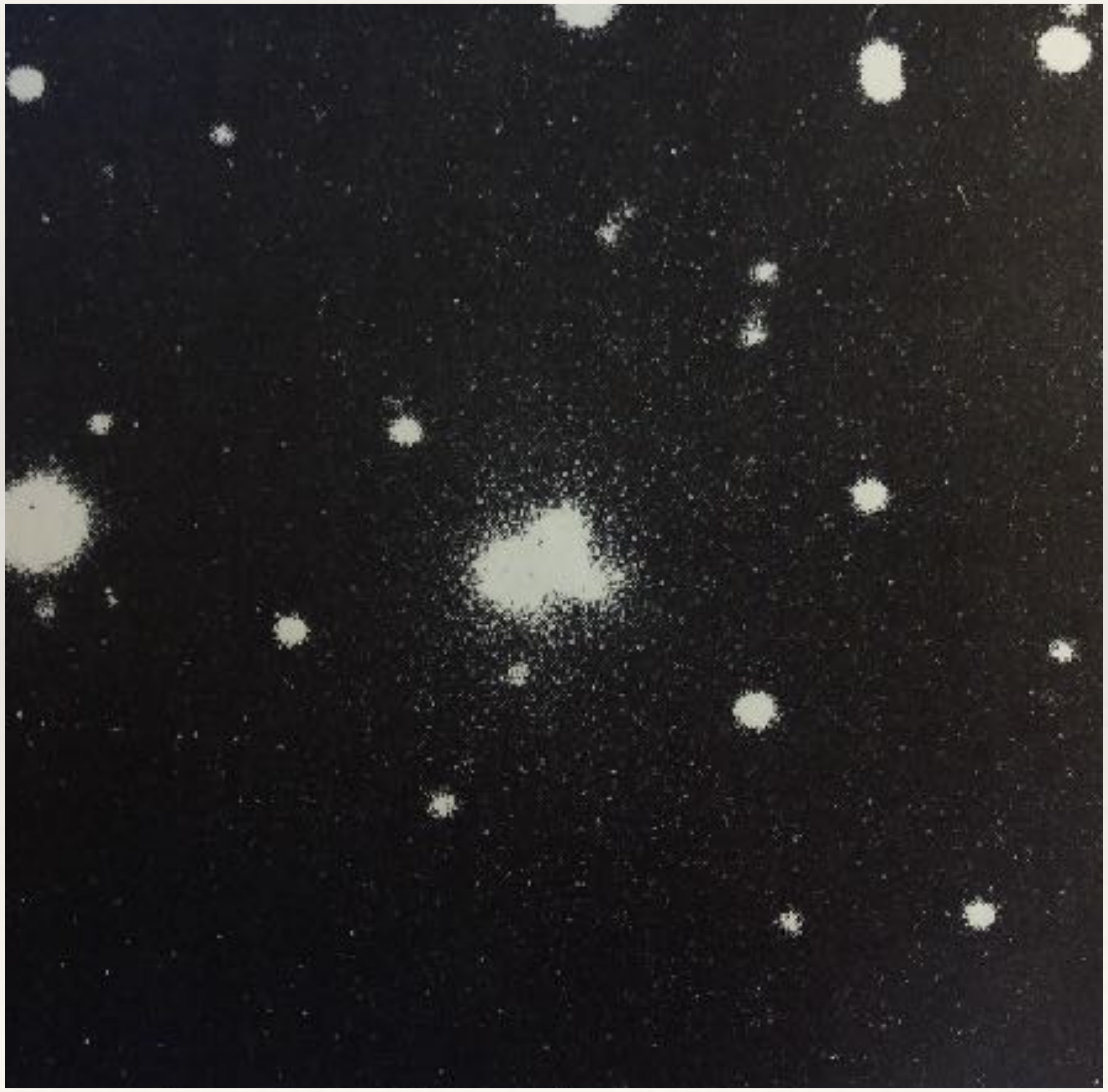
A few discrete radio sources were identified optically… the vast majority were, at first, totally mysterious

> “Distance suggestions have ranged from comets (0.1pc) to extragalactic structures (>100,000)”

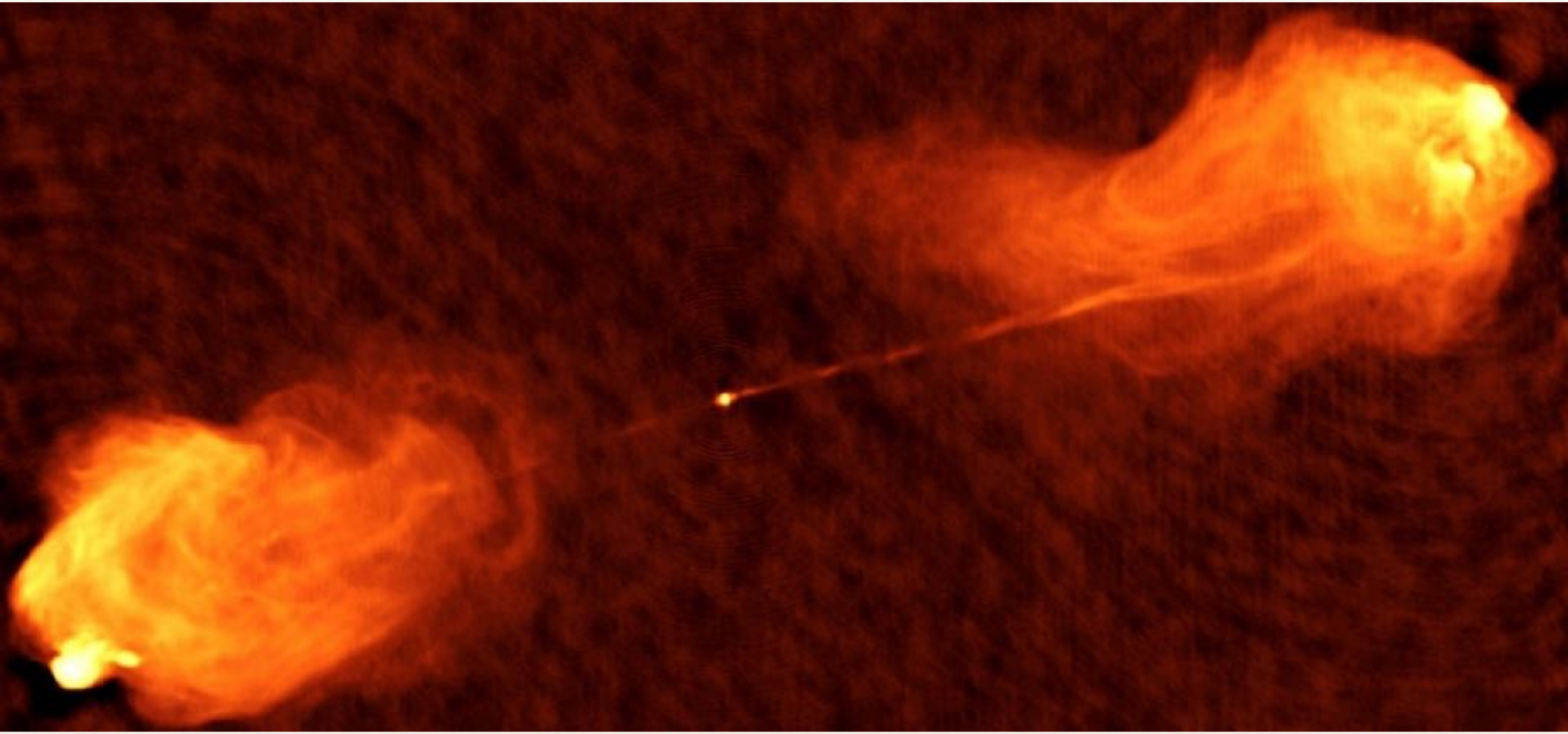
- Van de Hulst, 1951

‘Radio stars’

How to address issue? Optical followup!



Cyg A



Cygnus A

‘Radio stars’

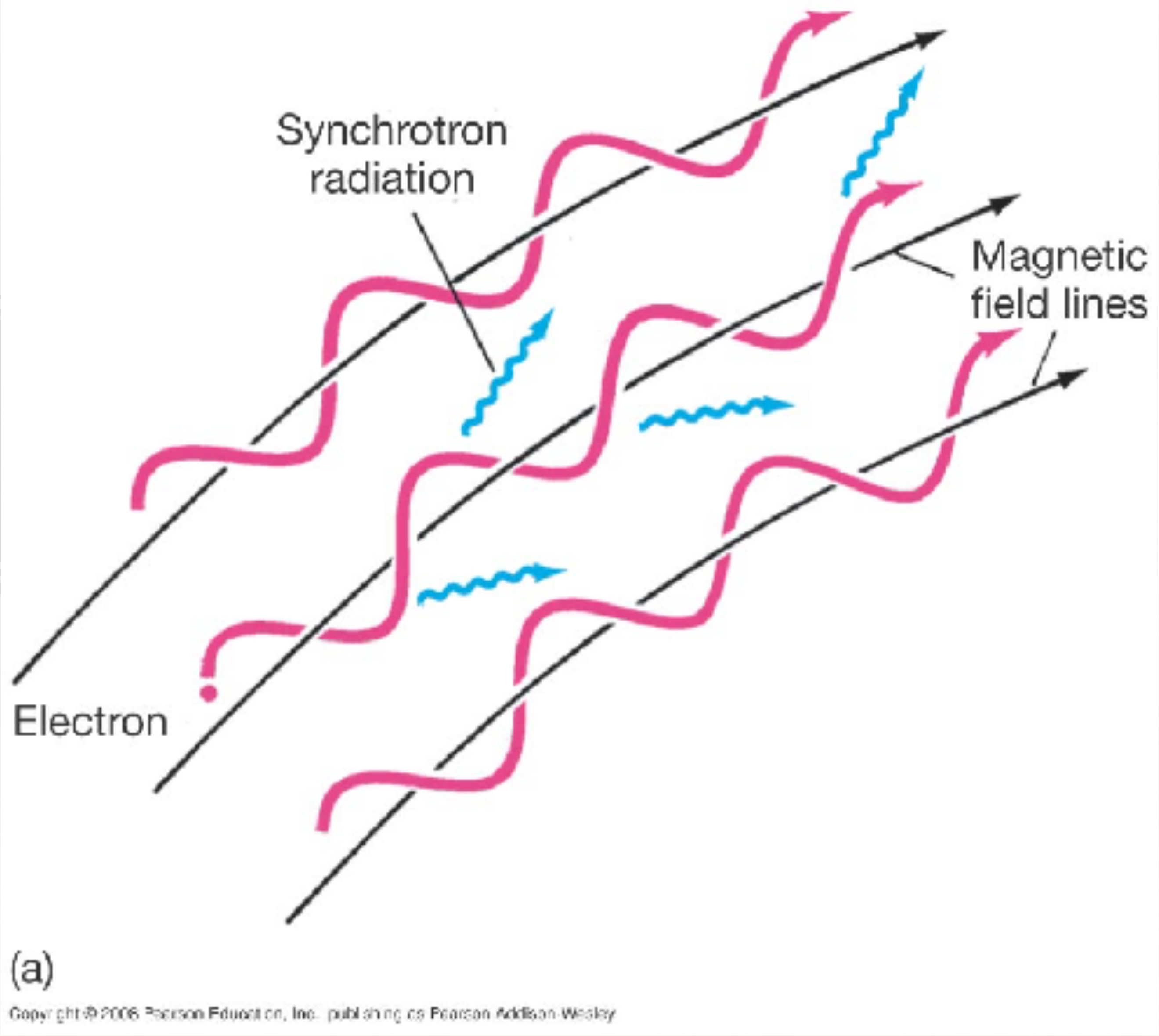
Velocity of radio stars showed that many were extragalactic (Cyg A has cz~15,000 km/s)

This implied a radio power over a million times that of the Milky Way

People found this hard to believe, because we didn’t have a mechanism that could produce such radio power)

‘Radio stars’

Answer: Synchrotron Radiation



‘Radio stars’

Answer: Synchrotron Radiation

“Radio stars” turned out to be a mix of radio galaxies and pulsars, powered by synchrotron radiation

(More about these later)

Further afield still… mapping the Galaxy

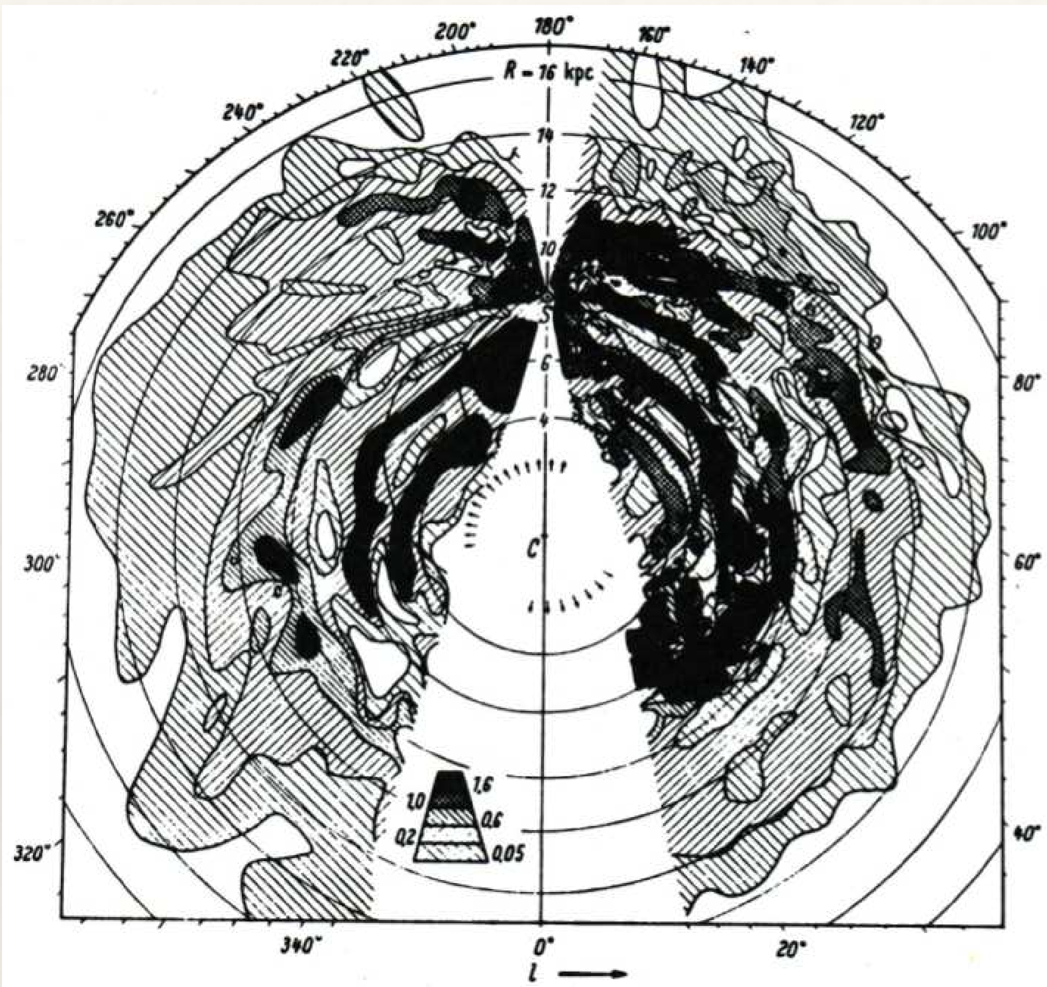
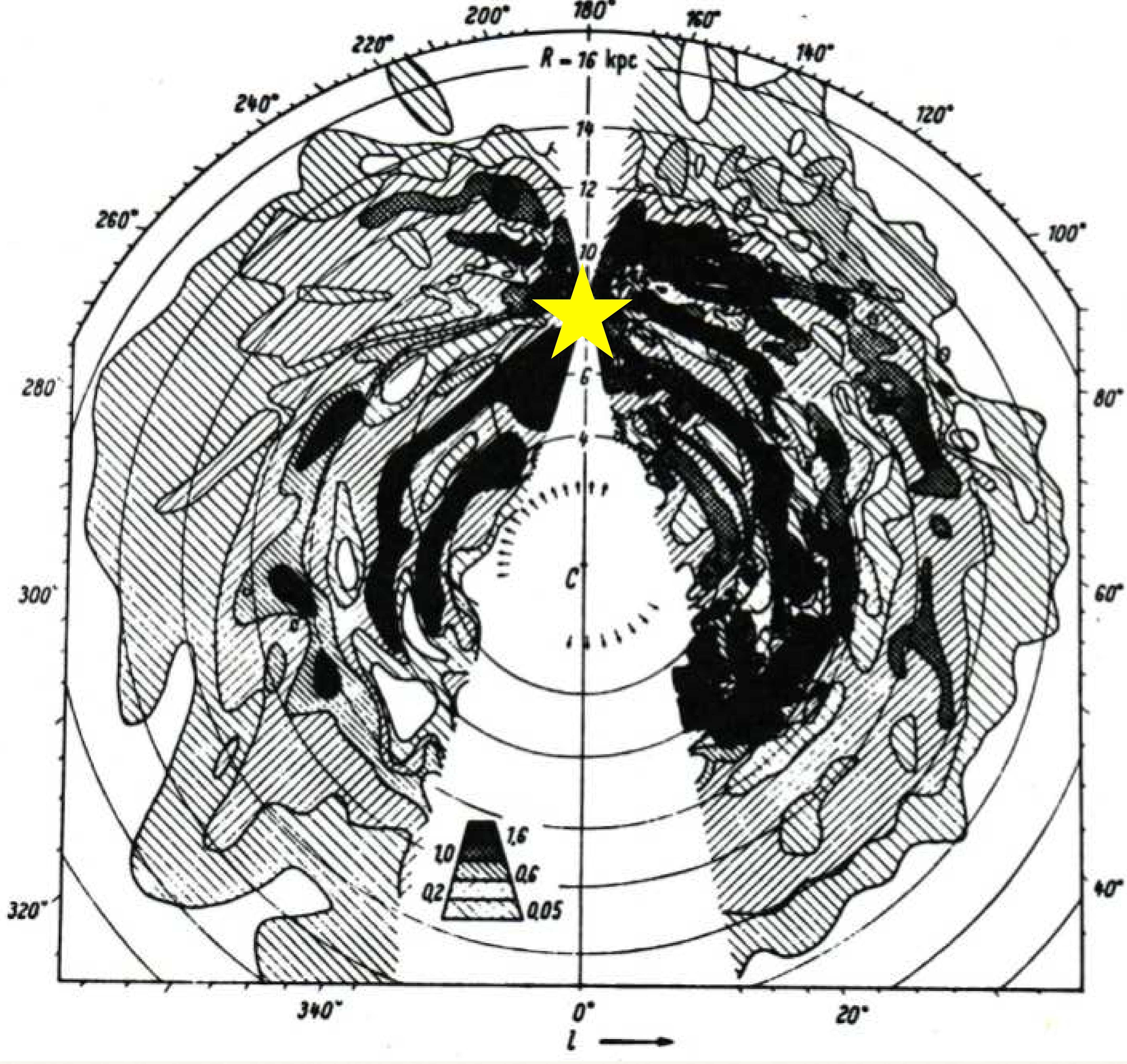


Fig. 1. Map of neutral atomic hydrogen (21-cm line) published by Oort (1959); figure taken from the text book Scheffler & Elsässer (1992). The Sun is in the upper part of the plot at 8 kpc.

1950s, early 1960s

Jan Oort maps atomic hydrogen

Discovers Milky Way spiral structure



180°
200°
160°
220°
140°
240°
120°
260°
100°
280°
80°
300°
60°
320°
40°
340°
0°
20°
R = 16 kpc
14
12
10
6
4
C
1,6
1,0
0,6
0,2
0,05
l

Radio telescope design

- The optical ‘band’ is roughly 400nm - 700nm
- By comparison, the ‘radio band’ spans >7 decades — from ~**1cm** (‘ultra high frequency’, 10s of GHz) -> **10,000m** (’low frequency’ 30 KHz)
- No single radio telescope design can be efficient for all of radio astronomy!

Why ‘antennas’?

- Radio photons are pretty wimpy
- Photon energy, $E=h\nu$
- E.g., optical photon, 600nm wavelength…
- Energy = 2 eV (1 eV = 1.6×10^{-19} J)
- Radio photon, 1m wavelength…
- Energy = 0.000001 eV!

Why 'antennas'?

- Radio photons are pretty wimpy
- I
- F
- F
- Radio photon, 1m wavelength…
- Energy = 0.000001 eV!

'Photon counting' doesn't work!
Need to think about measuring the electric field instead

Two main classes of radio telescope

Dipoles

Dishes

Dipoles are (relatively) simple

Dipoles operate at low frequency (= long wavelength, > 1m)

Two main classes of radio telescope

Dipoles

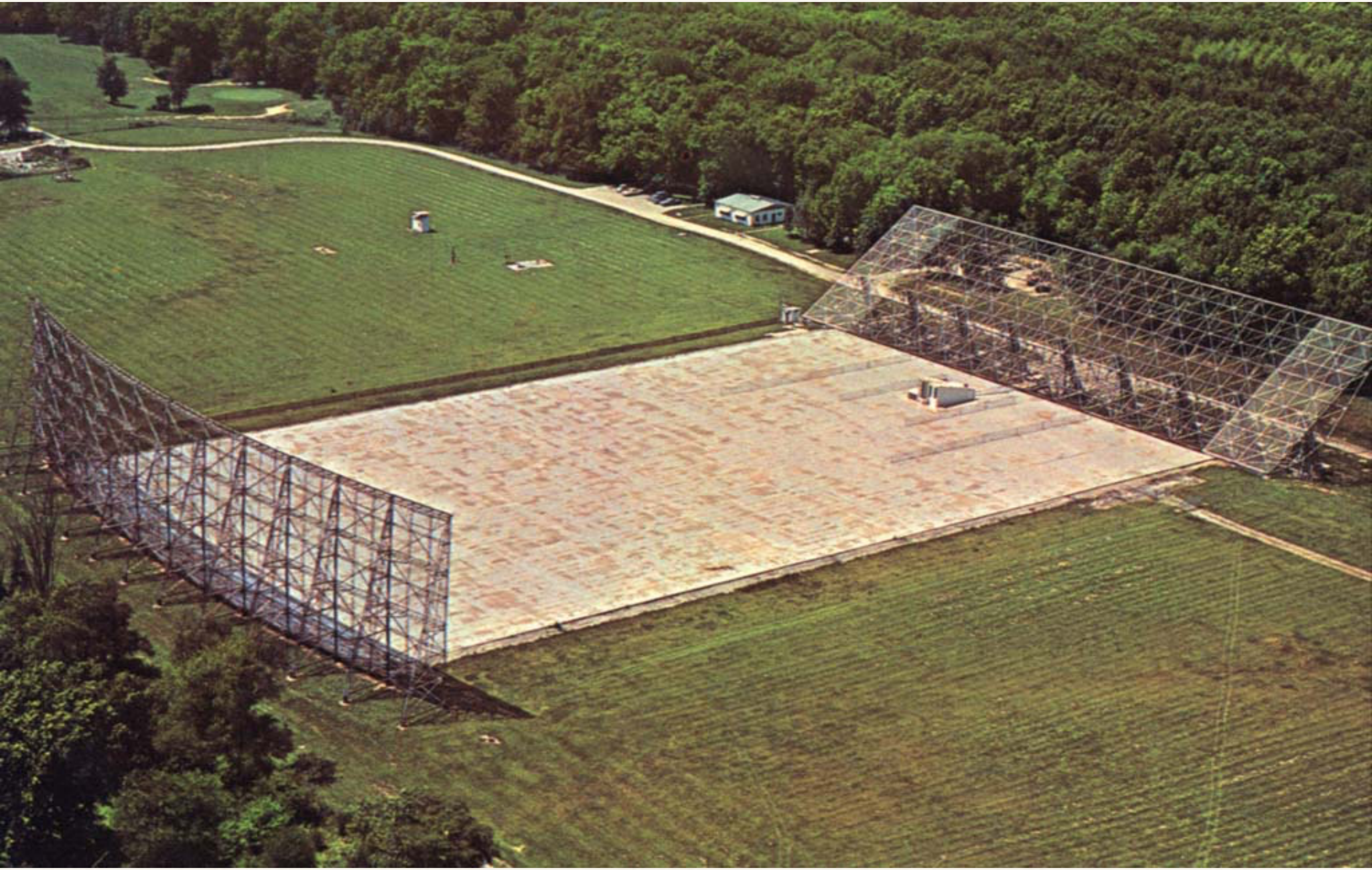
Dishes

Dishes (AKA parabolic telescopes)
Used at high frequencies
Boundary between dish and dipole is ~300 MHz
This will shift to higher frequencies as technology improves

Cambridge
1 Mile Telescope

Manchester
Lovell Telescope

Other weird telescope designs…



What is in the radio sky?

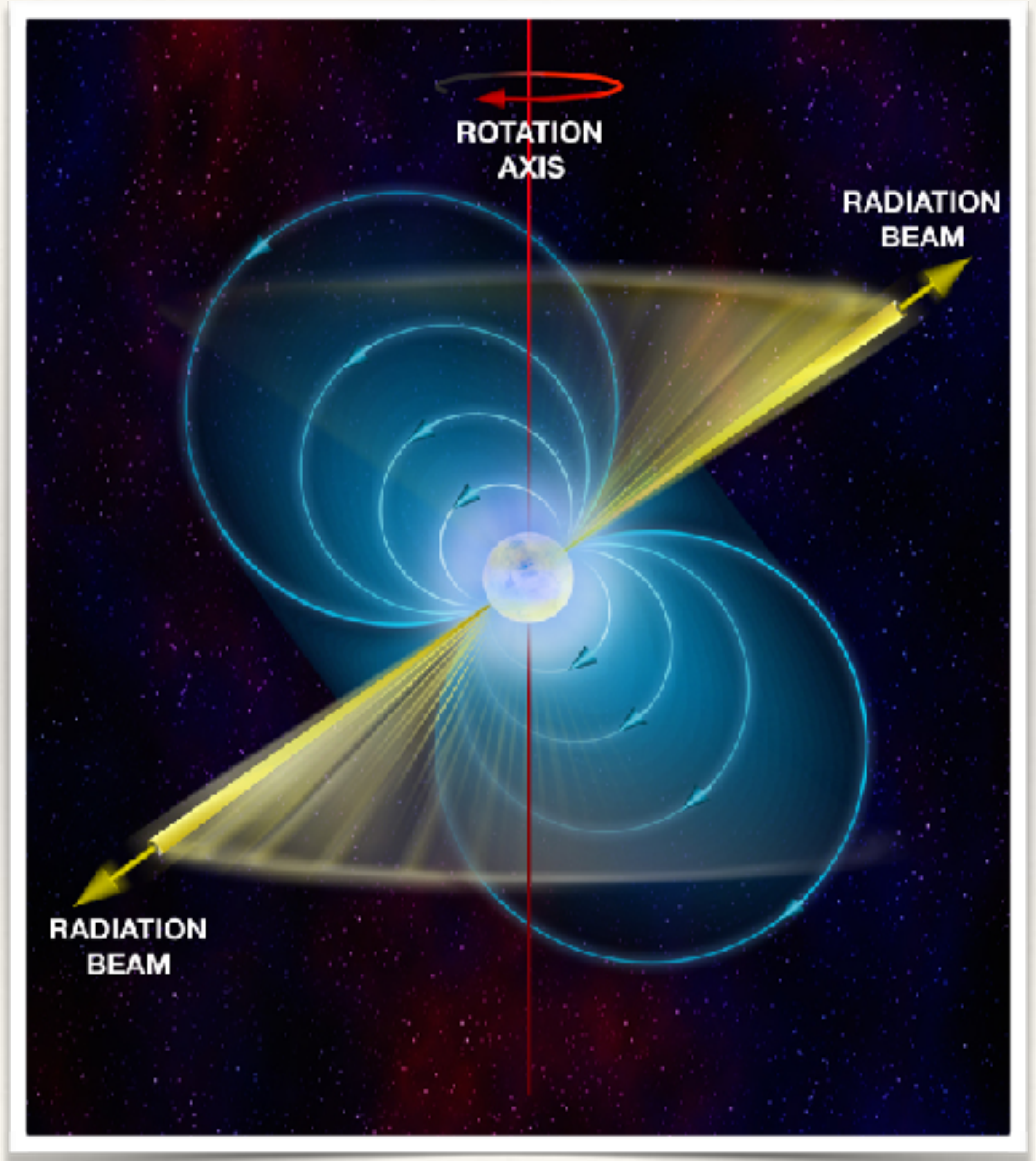
- Pulsars
- Atomic hydrogen
- Radio emission from galaxies

What is in the radio sky?

- Pulsars
- Atomic hydrogen
- Radio emission from galaxies

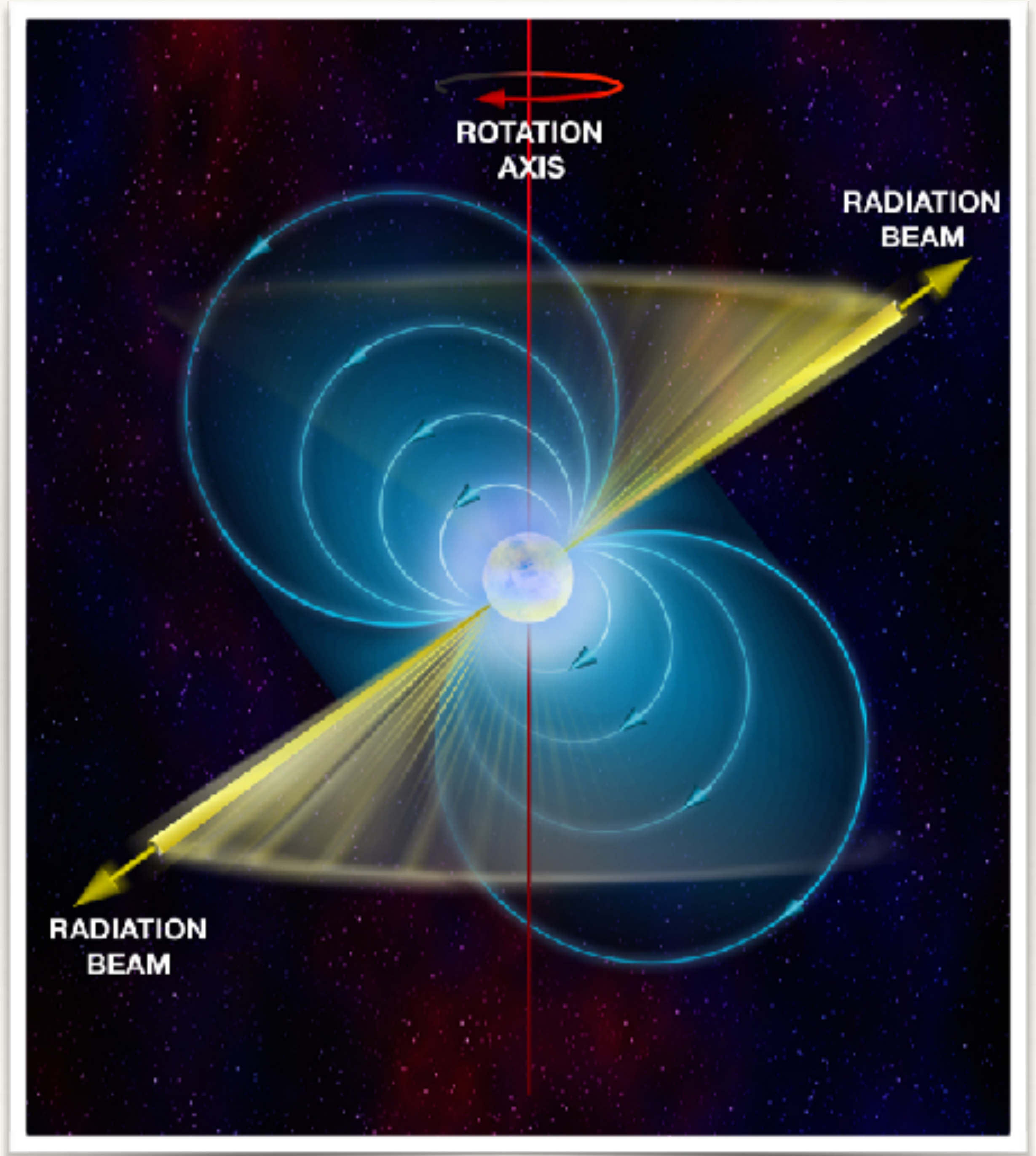
Pulsars: recap

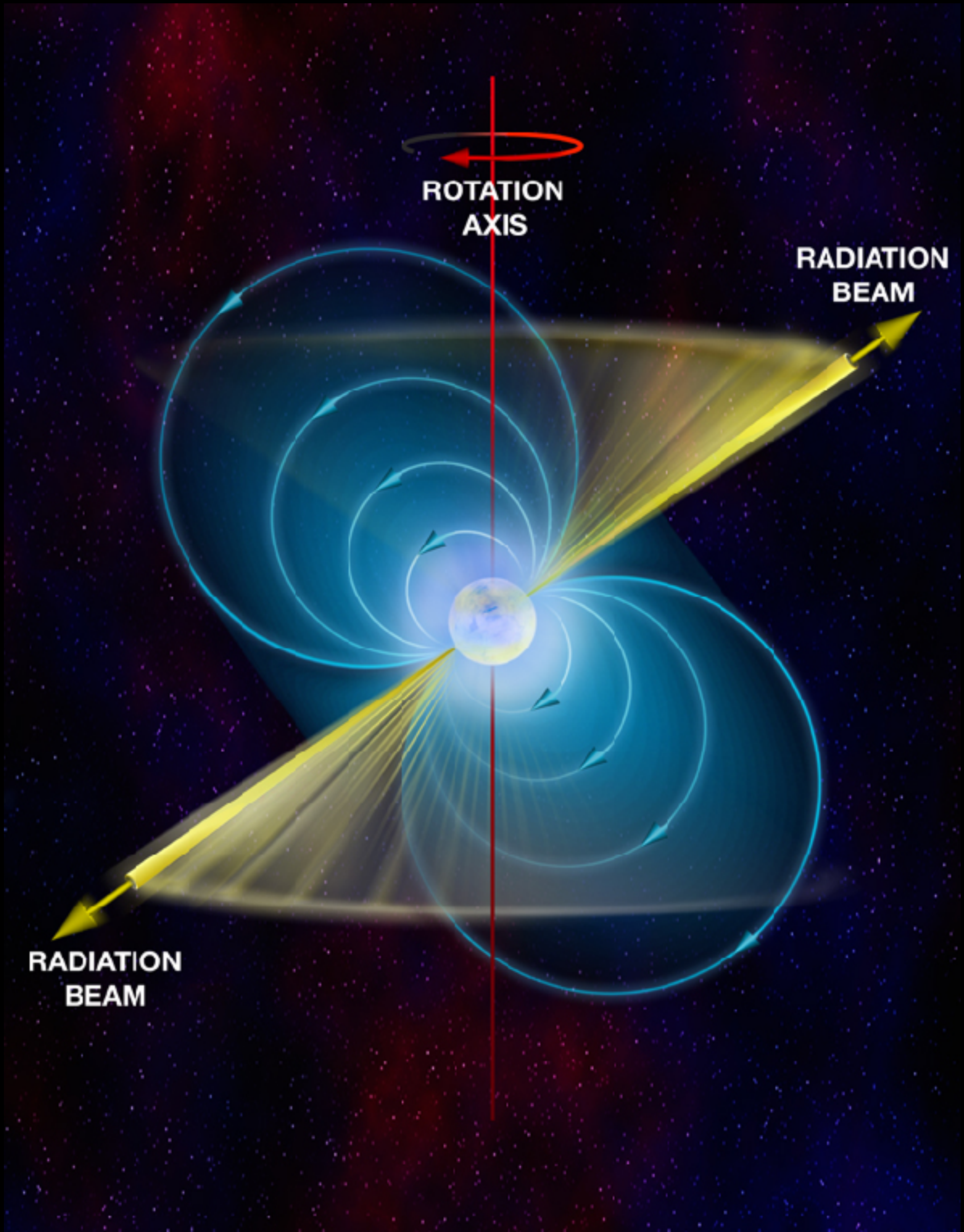
- Pulsars are rapidly spinning Neutron Stars
- Formed from the supernova of a massive (8-15 M_sun) star
- Held up by neutron degeneracy pressure
- Intense magnetic field produces **synchrotron radiation**



Pulsars: recap

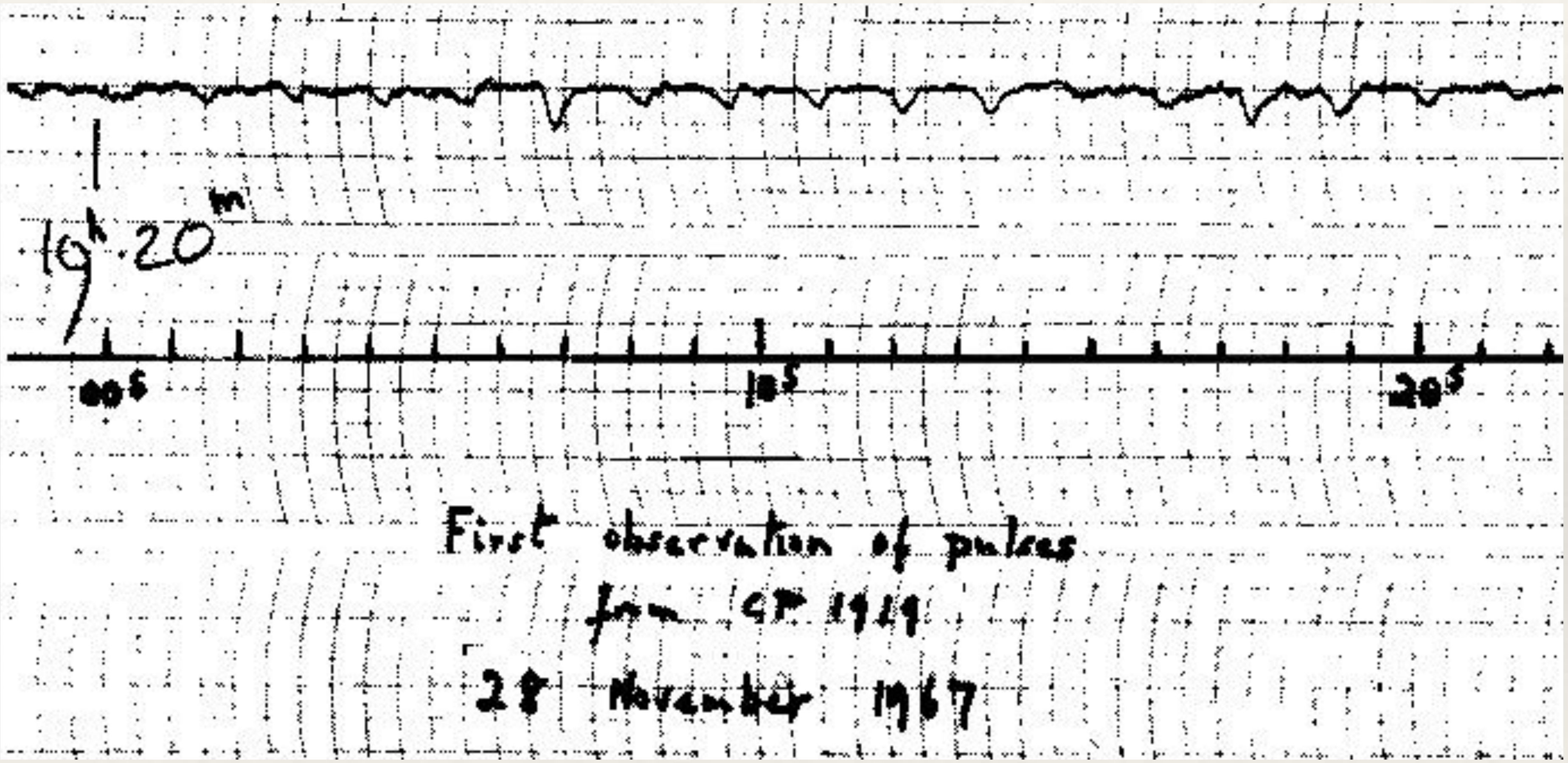
- When a massive star collapses, its core shrinks from ~10^6 km down to ~10 km. Reduction in radius of a factor 10^5
- Magnetic flux increase goes like radius^2 — a factor of 10^{10}
- A field of B~**100 G** becomes **10^{12} G** after collapse!




ROTATION
AXIS
RADIATION
BEAM
RADIATION
BEAM


JOY DIVISION
UNKNOWN PLEASURES

Pulsars



19h 20m
00s
10s
20s
First observation of pulses
from CP 1919
28 November 1967

Pulsars

We can see how fast these are spinning — what does this tell us?

Pulsars

We can see how fast these are spinning — what does this tell us?

A star with mass M and radius R rotates with angular velocity

$$\Omega = 2\pi / P$$

Pulsars

We can see how fast these are spinning — what does this tell us?

A star with mass M and radius R rotates with angular velocity

$$\Omega = 2\pi/P$$

Two opposing forces: gravity and centrifugal force.

To stay bound, gravity must win!

$$\Omega^2 r < \frac{GM}{r^2}$$

Pulsars

$$\Omega^2 r < \frac{GM}{r^2} \qquad \Omega = 2\pi/P$$

$$\frac{4\pi^2}{P^2} r < \frac{GM}{r^2}$$

$$P^2 > \frac{4\pi^2 r^3}{GM}$$

$$P^2 > \left(\frac{4}{3}\pi r^3\right)\frac{3\pi}{GM}$$

Pulsars

$$P^2 > \left(\frac{4}{3}\pi r^3\right)\frac{3\pi}{GM}$$

Density = Mass / Volume

$$\rho = M \left(\frac{4}{3}\pi r^3\right)^{-1}$$

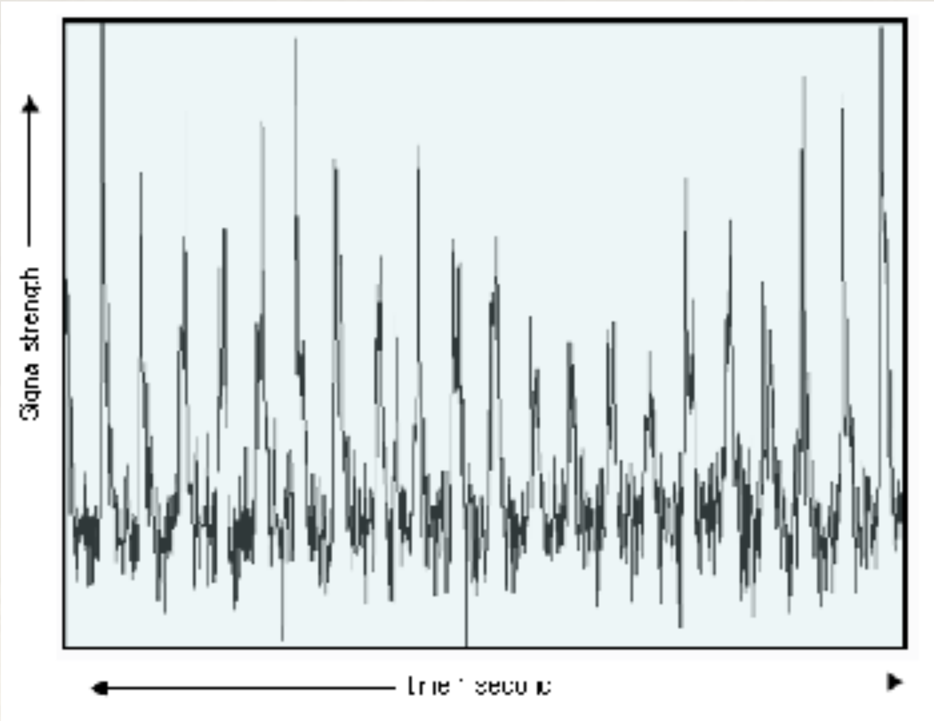
$$P^2 > \frac{3\pi}{G\rho}$$

or $$\rho > \frac{3\pi}{GP^2}$$

Pulsars

$$\rho > \frac{3\pi}{GP^2}$$

For a given period, there is a minimum density that will allow the spinning object to remain gravitationally bound



The crab pulsar has a period of 0.033 seconds…

Pulsars

$$\rho > \frac{3\pi}{(6.67 \times 10^{-11}\ \mathrm{m}^3\ \mathrm{kg}^{-1}\ \mathrm{s}^{-2})(0.033\ \mathrm{s})^2}$$

$$\rho > 1.3 \times 10^{14}\ \mathrm{kg\ m}^{-3}$$

Pulsars

$$\rho > \frac{3\pi}{(6.67 \times 10^{-11}\ \mathrm{m^3\ kg^{-1}\ s^{-2}})(0.033\ \mathrm{s})^2}$$

$$\rho > 1.3 \times 10^{14}\ \mathrm{kg\ m^{-3}}$$

This density is far greater than electron degeneracy can produce

Must be a **Neutron Star** (Baade & Zwicky, 1934)

Pulsars

Pulsars are some of the most important objects in the radio sky

Pulsars are `the Universe's gift to physics'

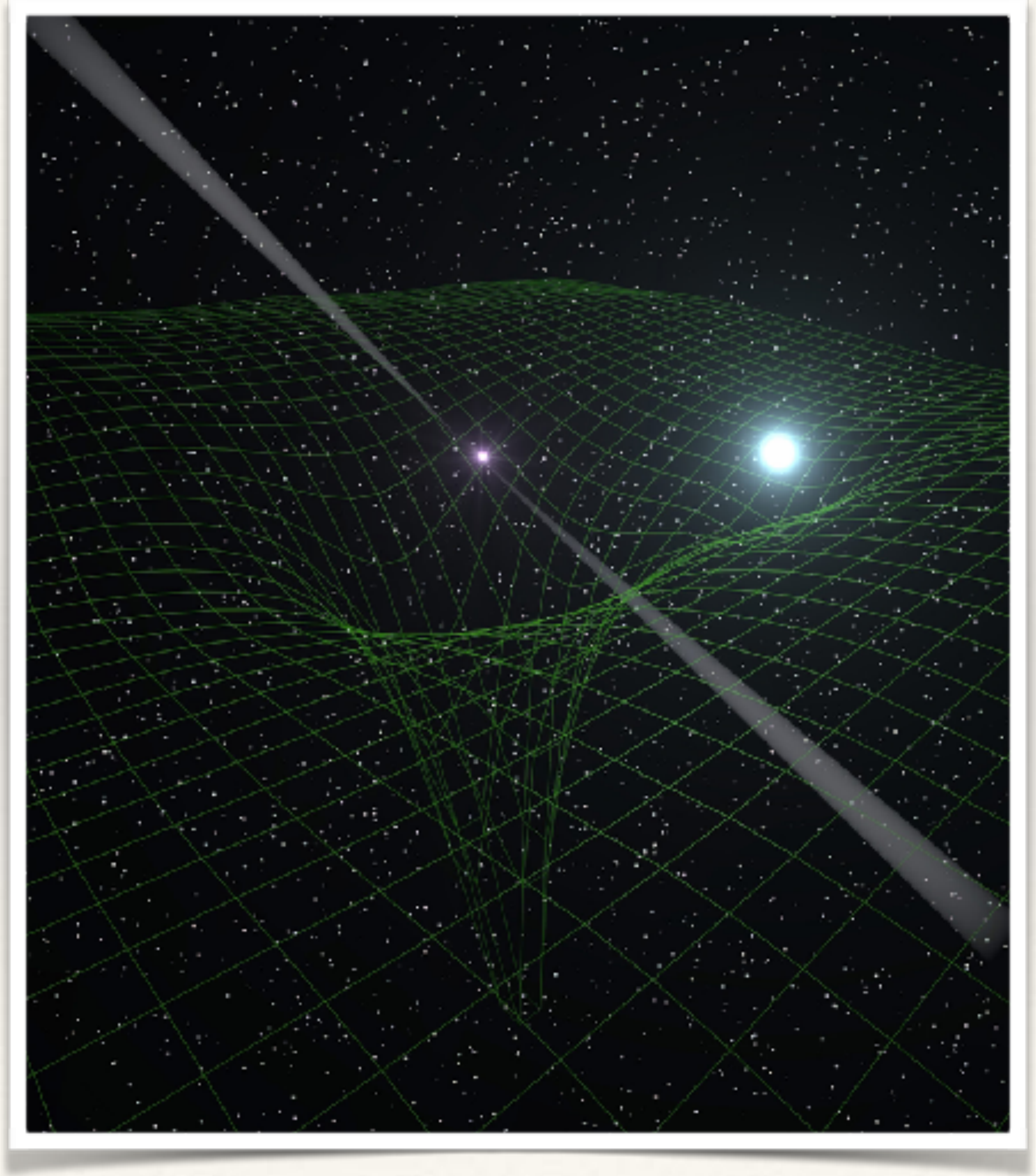
(according to the National Radio Astronomy Observatory)

(1) "Stress test" GR in extreme gravitational environments

(2) Sources of gravitational waves??

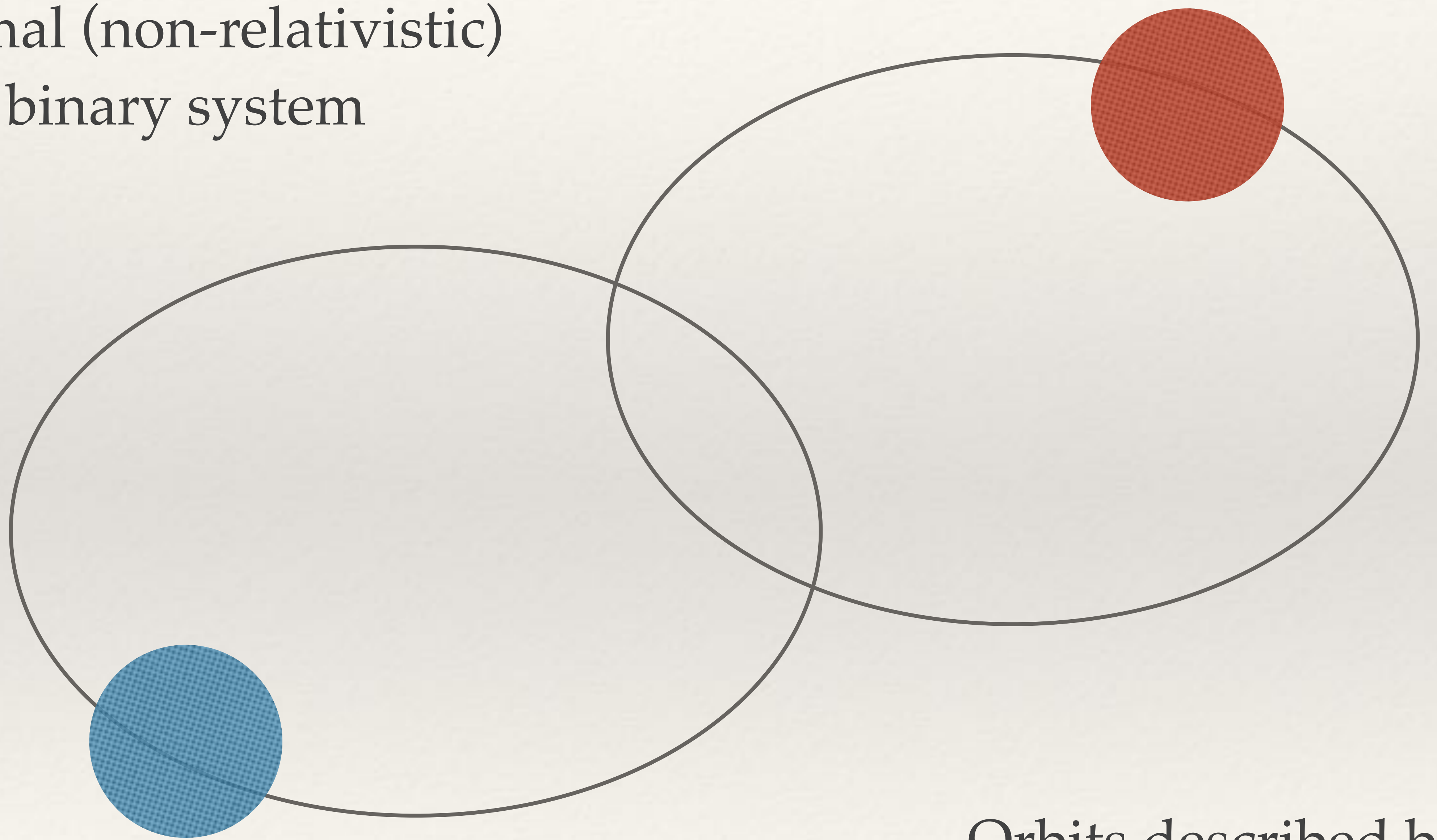
Pulsars as GR laboratories

- GR is hard to test under normal conditions — requires VERY strong gravity for effects to be measurable
- Binary pulsars are effectively point source masses in VERY strong gravitational fields
- Ideal candidates for testing GR!



Pulsars as GR laboratories

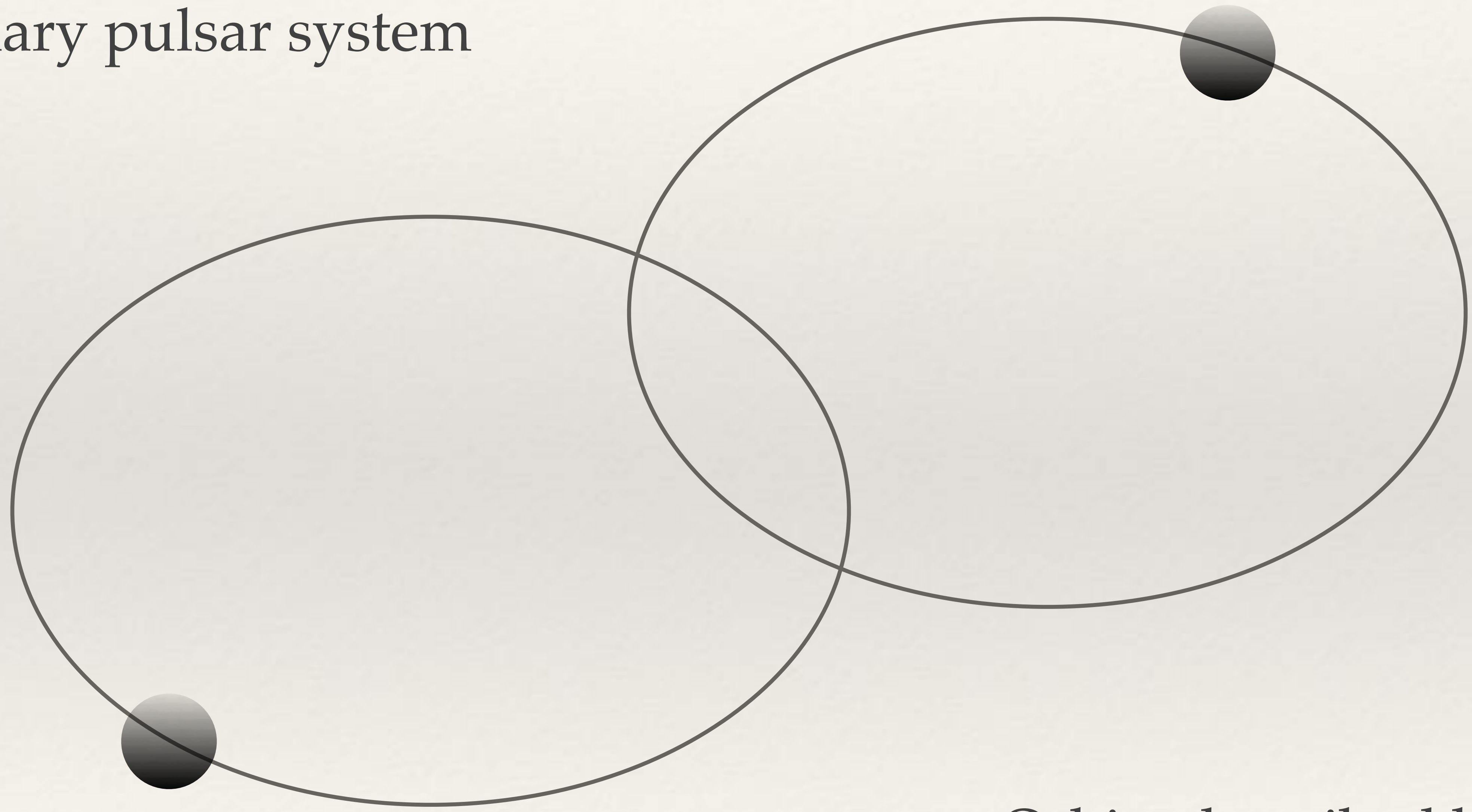
Normal (non-relativistic) binary system



Orbits described by 'Keplerian parameters'

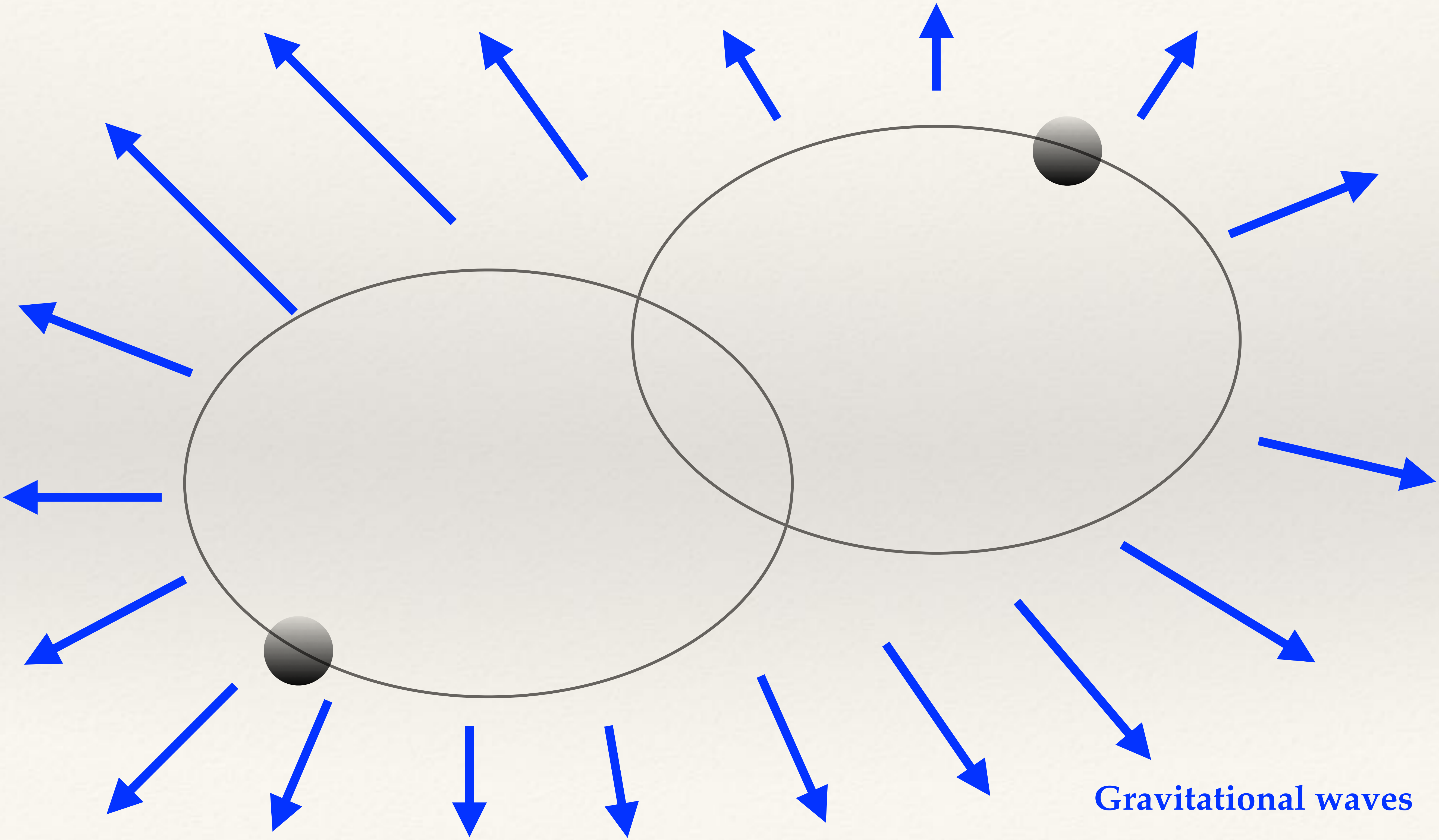
Pulsars as GR laboratories

Binary pulsar system



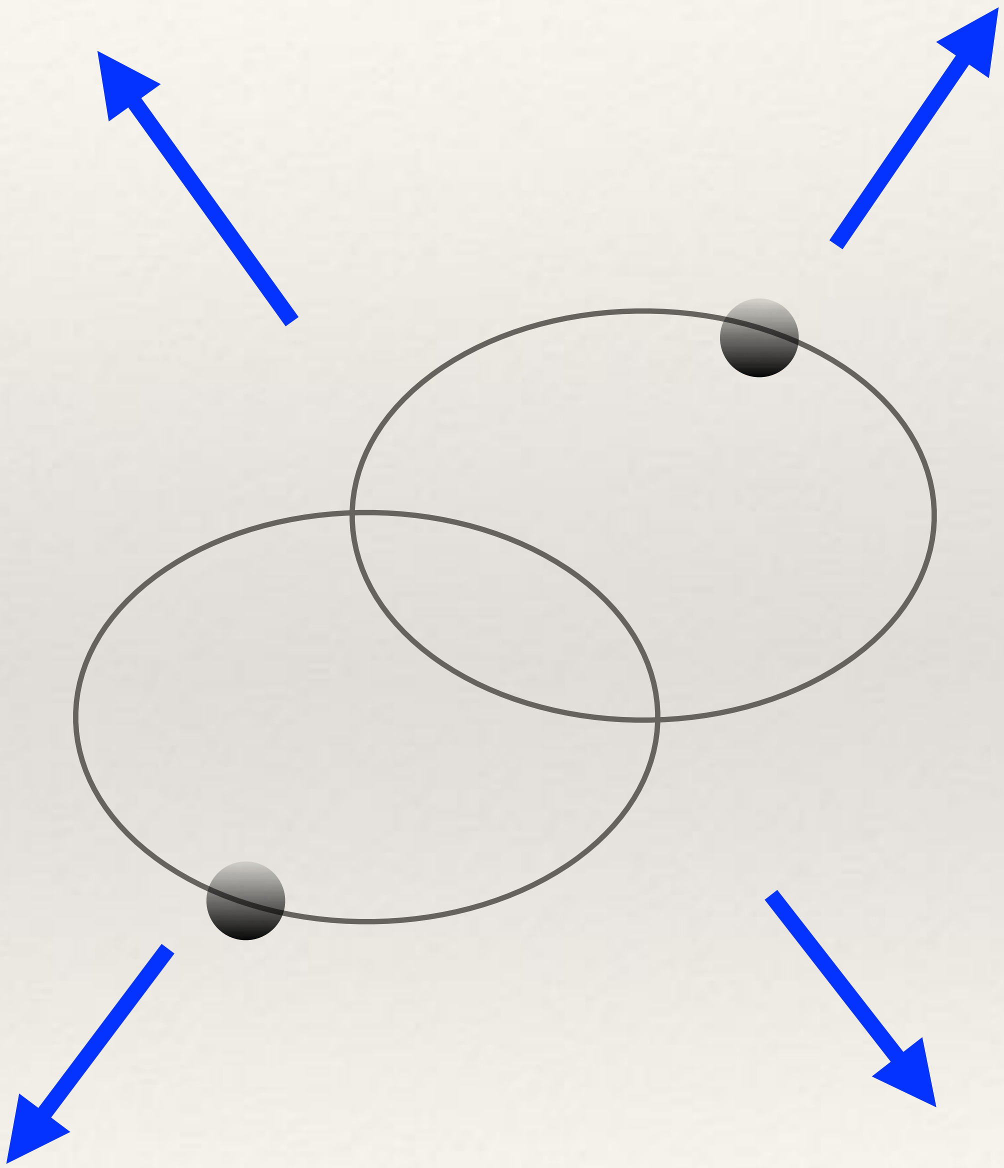
Orbits described by
'Post-Keplerian parameters'

Pulsars as GR laboratories



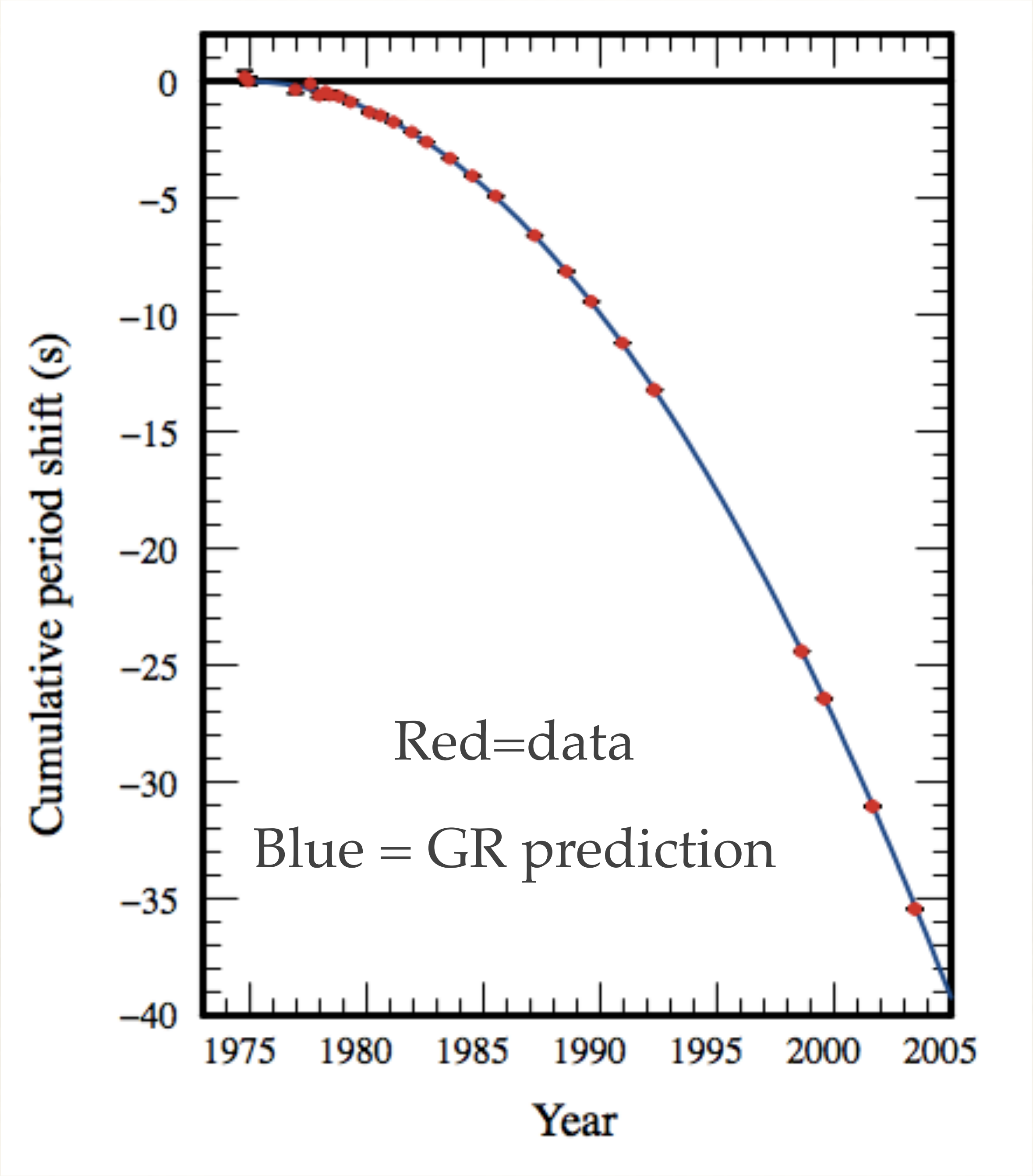
Pulsars as GR laboratories

- Gravitational wave radiation carries energy away from the system
- This will cause orbital decay: a reduction of the orbital period
- We can measure this, and compare to the predictions made by GR



Pulsars as GR laboratories

- I.e., PSR1913 + 16, with a period of 59ms (0.059 s)
- Orbit is decaying by 75 micro-seconds per year (measured with Arecibo!)
- Compares almost exactly with the prediction from GR (0.997 ± 0.002). Accurate to within <0.5%!



Pulsars as GR laboratories

- The SKA will discover essentially **all** visible pulsars (20,000)
- Allow for the most robust tests of GR
- Maybe even the holy grail — a black hole + neutron star binary

Pulsars as GR laboratories

Can these gravitational waves be detected 'directly' on large scales?

The SKA will be the world's most advanced **Pulsar Timing Array**

Relies on pulsars being the most accurate clocks in existence:

Pulsars as GR laboratories

Can these gravitational waves be detected ‘directly’ on large scales?

The SKA will be the world’s most advanced **Pulsar Timing Array**

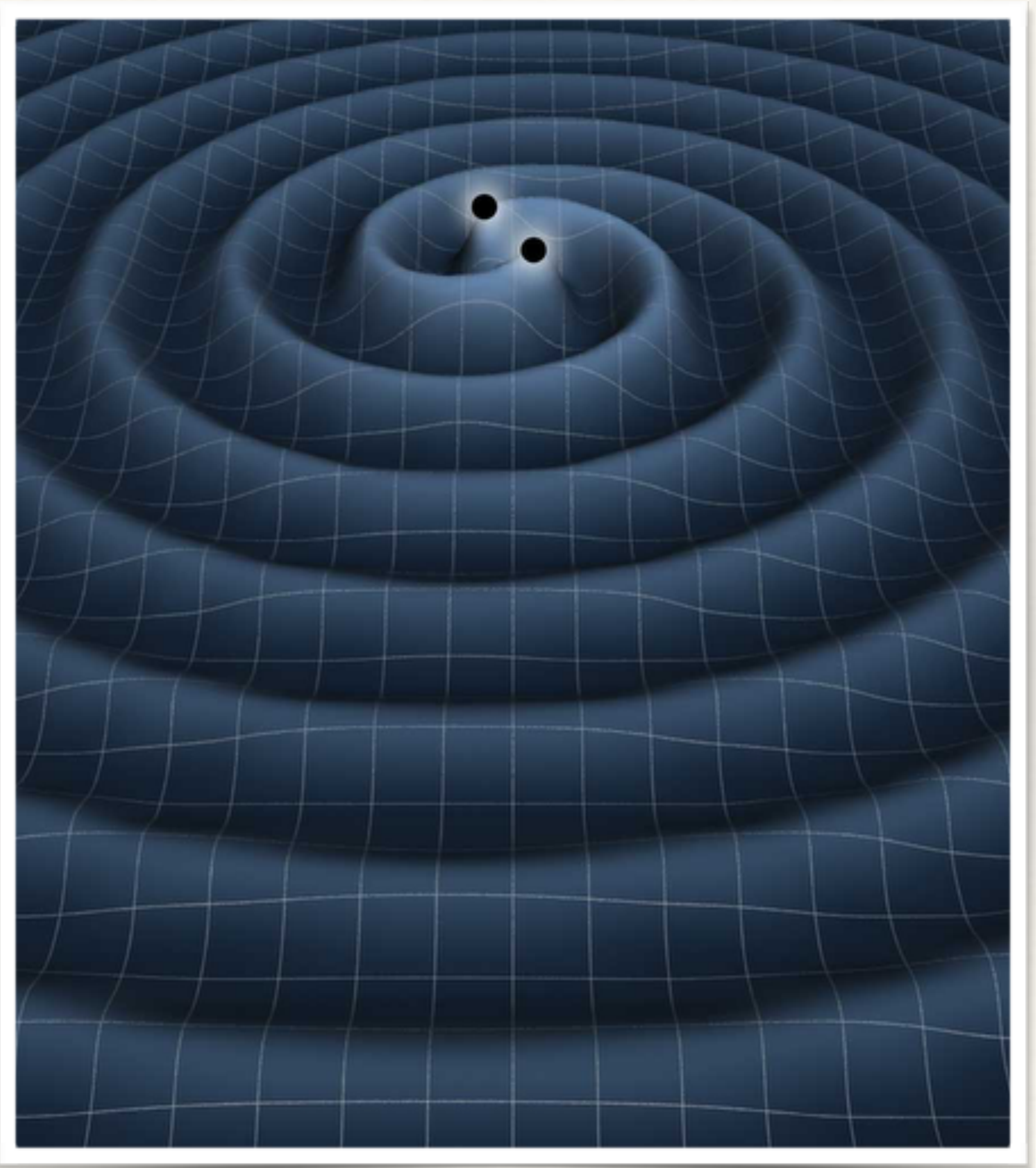
Relies on pulsars being the most accurate clocks in existence:

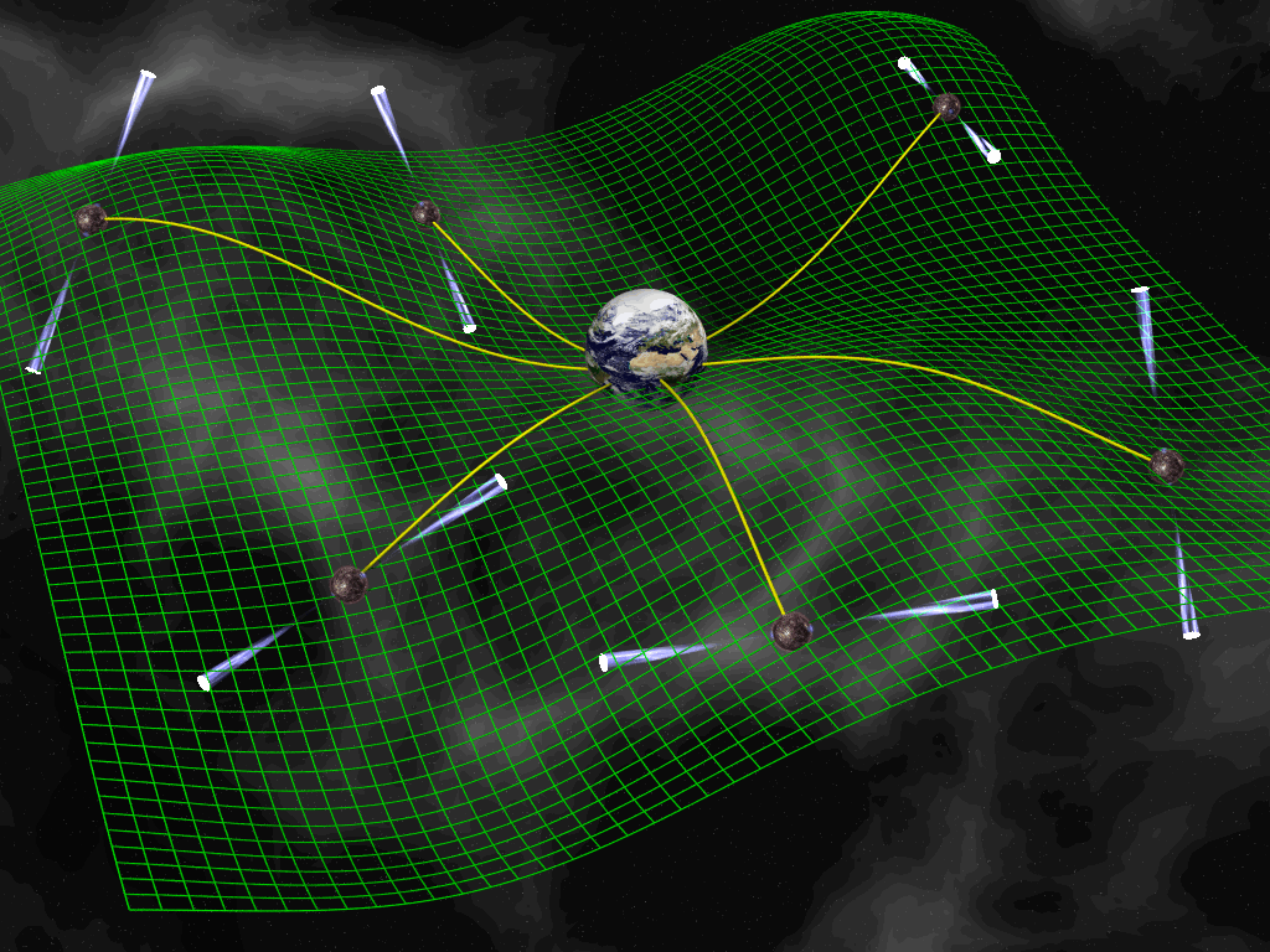
The measured period of the millisecond pulsar PSR B1937+21 is 1.5578064688197945 +/- 0.0000000000000004 milliseconds!

Accurate to within 10^{-18} s !

Pulsars as GR laboratories

- Idea: pairs of merging super-massive black holes (SMBHs) will cause a background of low-frequency gravitational waves throughout the Universe
- As these waves wash through the Universe, they will cause pulsars to change their spin slightly
- By simultaneously measuring the spin of many, many pulsars, we may detect these gravitational waves



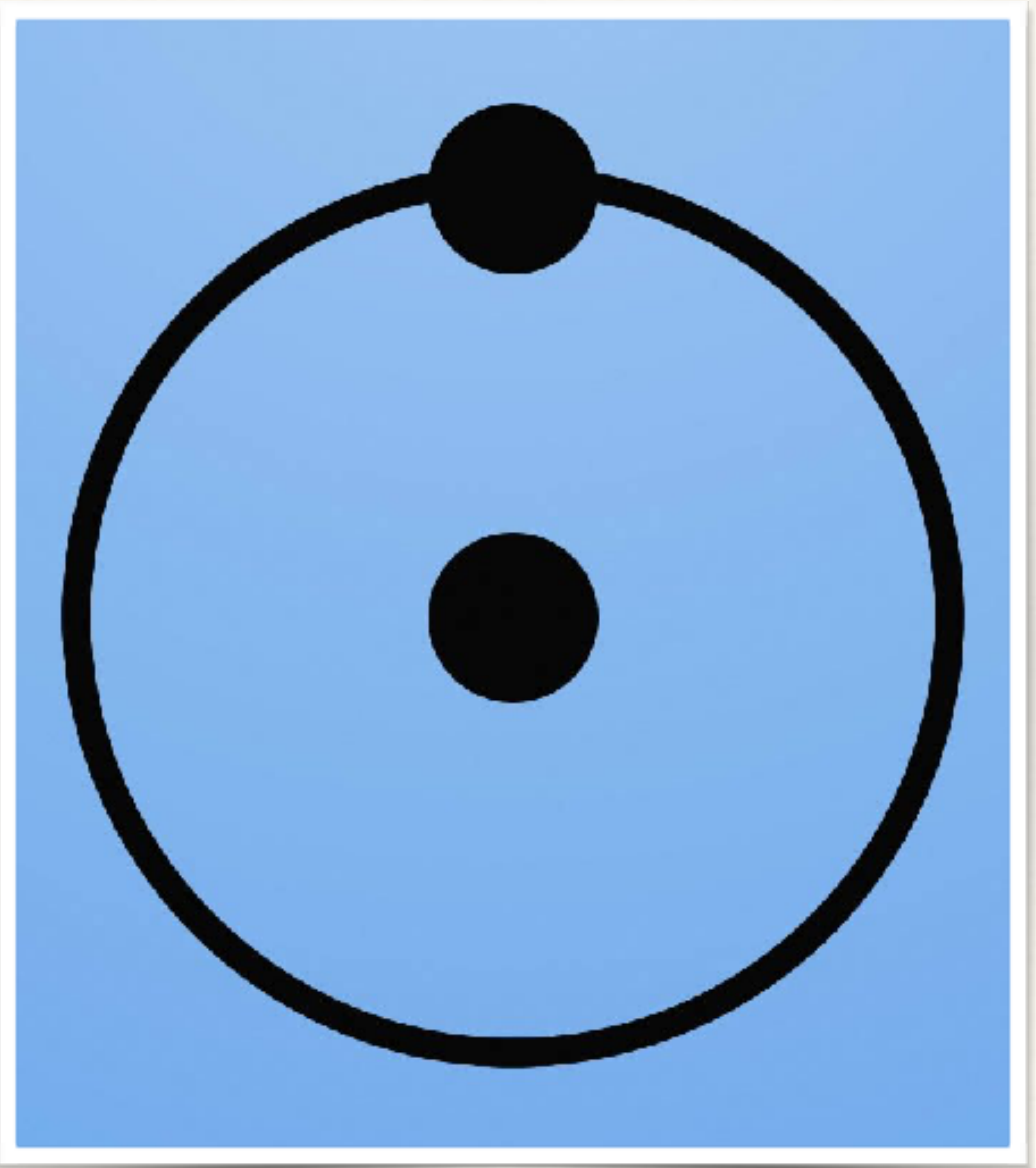


What is in the radio sky?

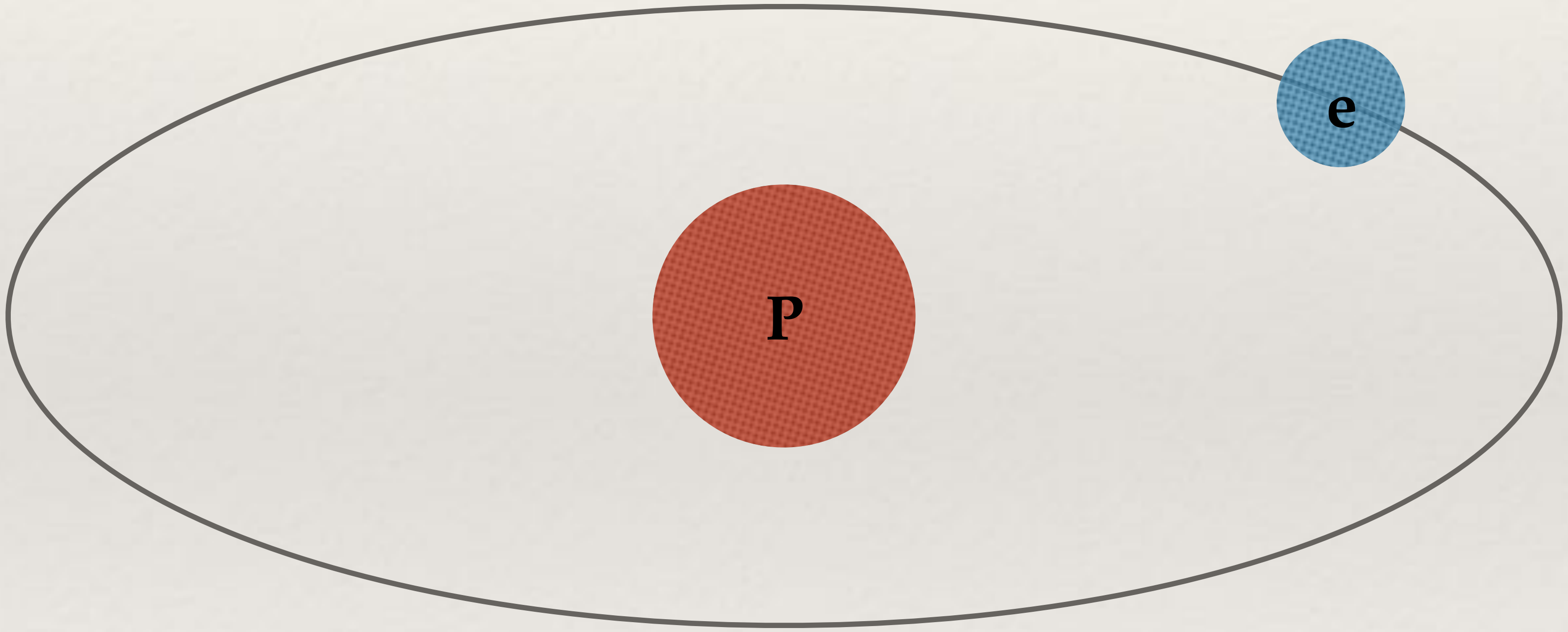
- Pulsars
- Atomic hydrogen
- Radio emission from galaxies

Neutral atomic hydrogen

- Hydrogen is the most common substance in the Universe (~75% of all baryons)
- In 1942, van de Hulst predicted that there would be a form of line emission from hydrogen atoms

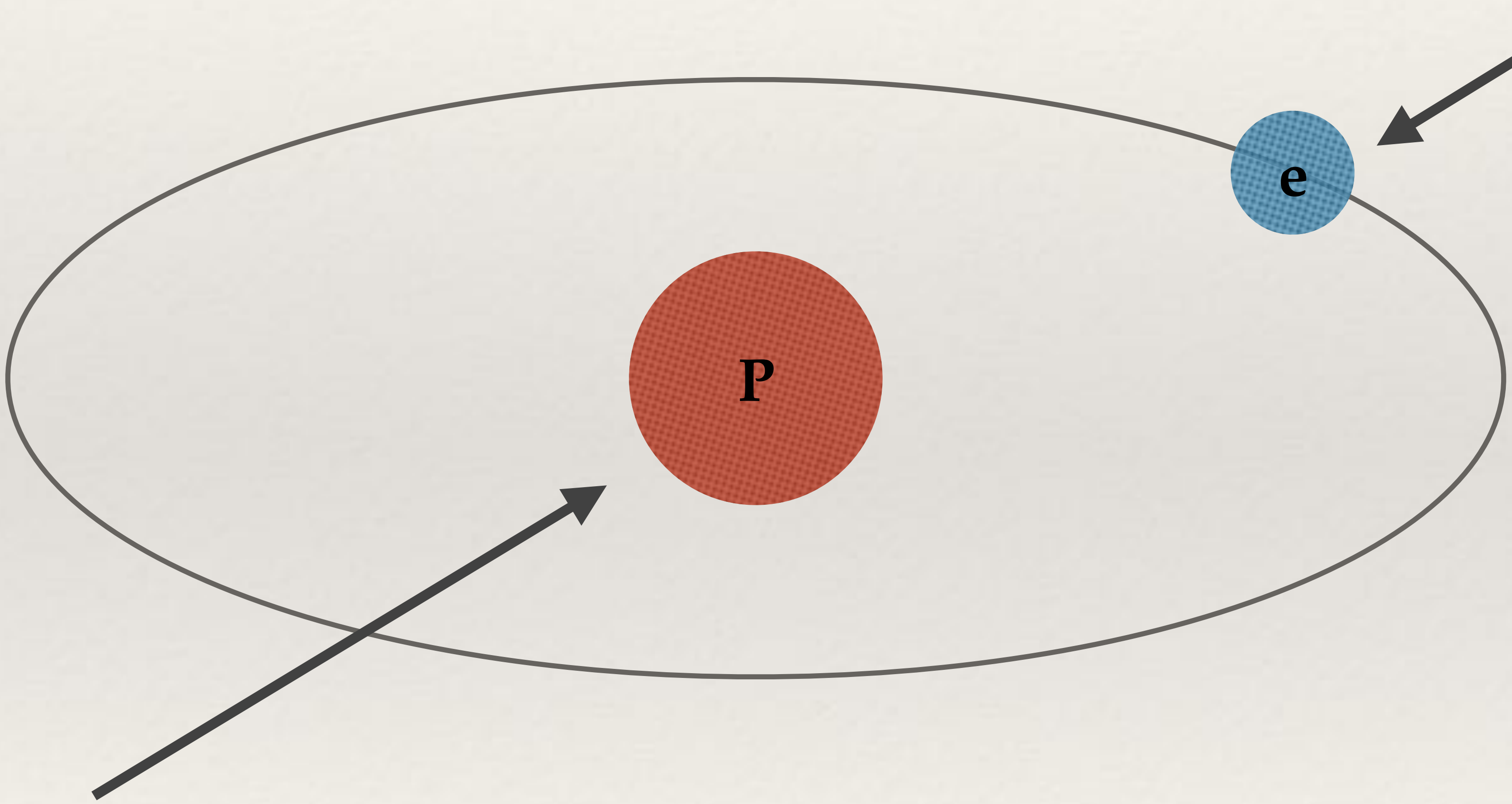


Neutral atomic hydrogen



Neutral atomic hydrogen

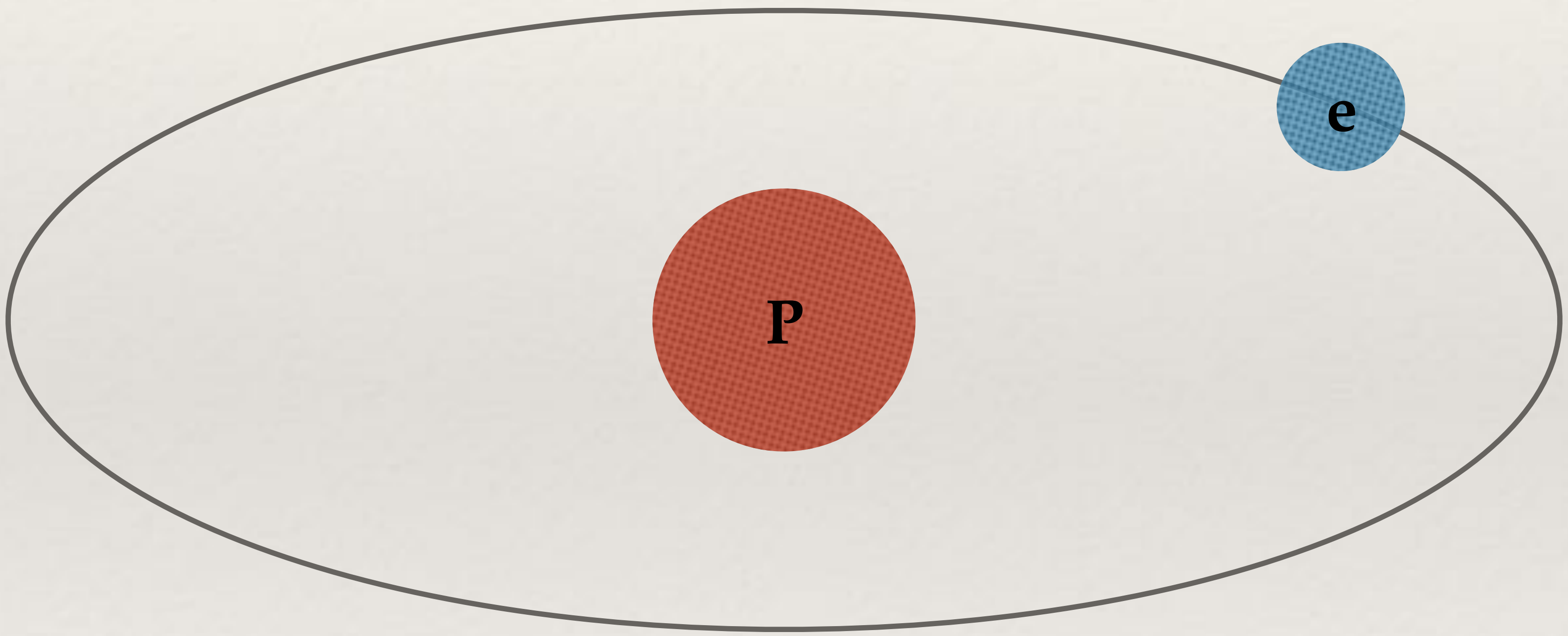
Electrons are Fermions,
spin = 1/2



Protons are made of quarks,
but are still fermions with spin = 1/2

Neutral atomic hydrogen

Two possible spin states for the atom:

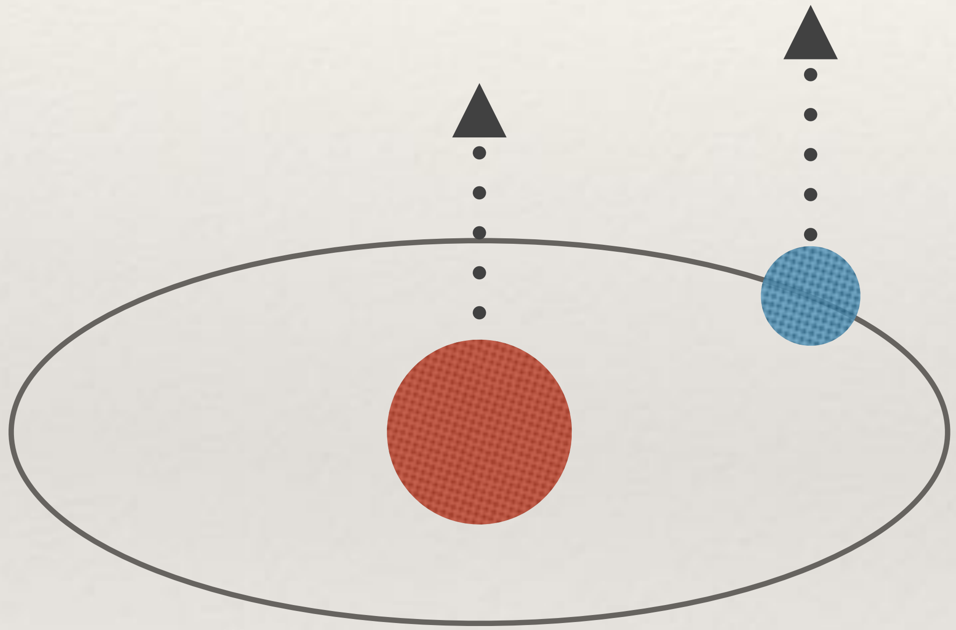


Neutral atomic hydrogen

Two possible spin states for the atom:

Neutral atomic hydrogen

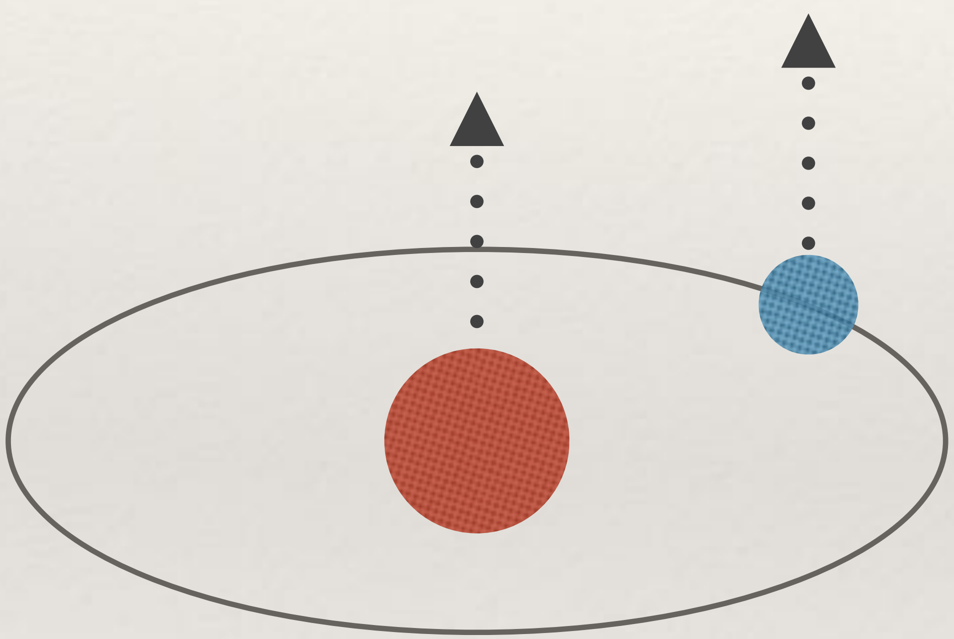
Two possible spin states for the atom:



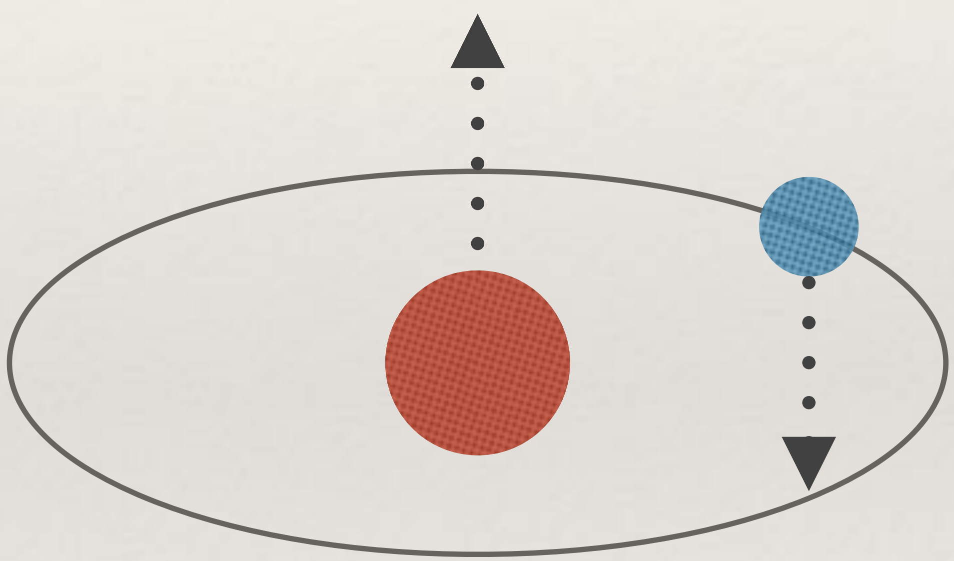
Spin parallel

Neutral atomic hydrogen

Two possible spin states for the atom:



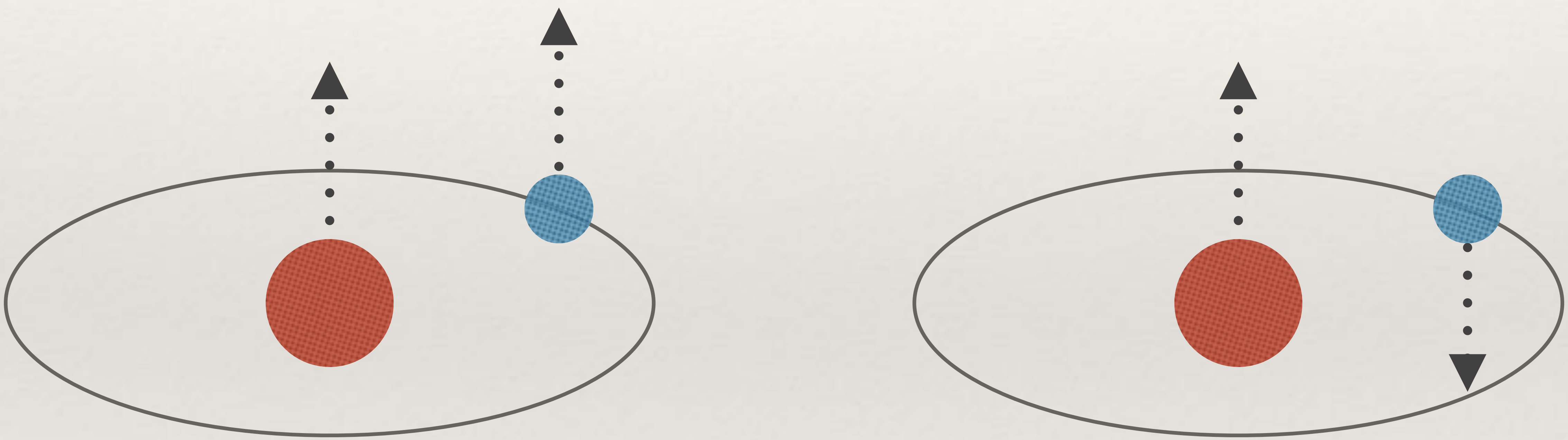
Spin parallel



Spin anti-parallel

Neutral atomic hydrogen

Two possible spin states for the atom:



Spin-parallel state has slightly higher energy

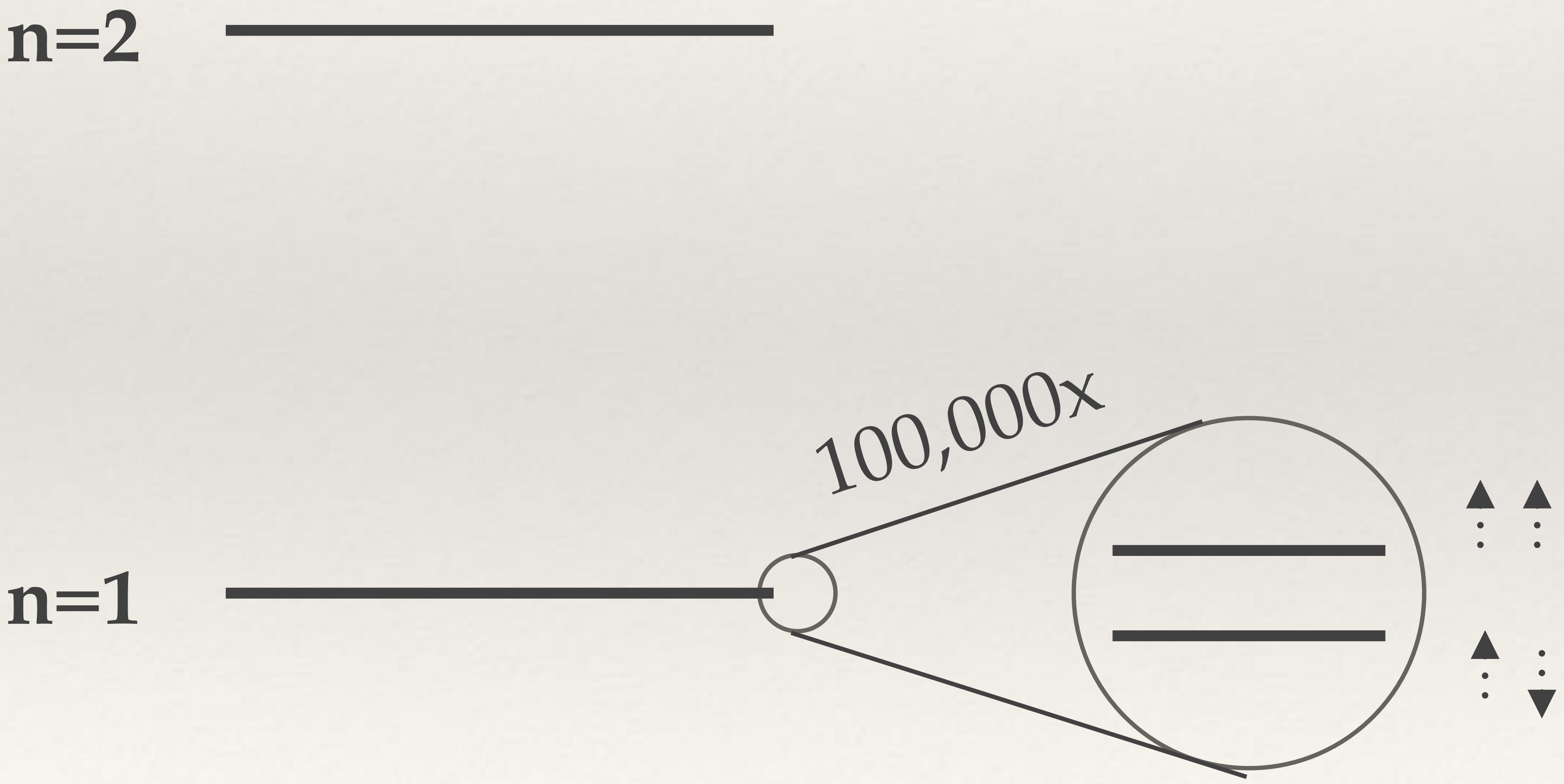
So, 'flipping' to the anti-parallel state is favourable, and will emit a photon with energy equal to the difference between the two states

Neutral atomic hydrogen

This transition is called 'hyperfine structure'

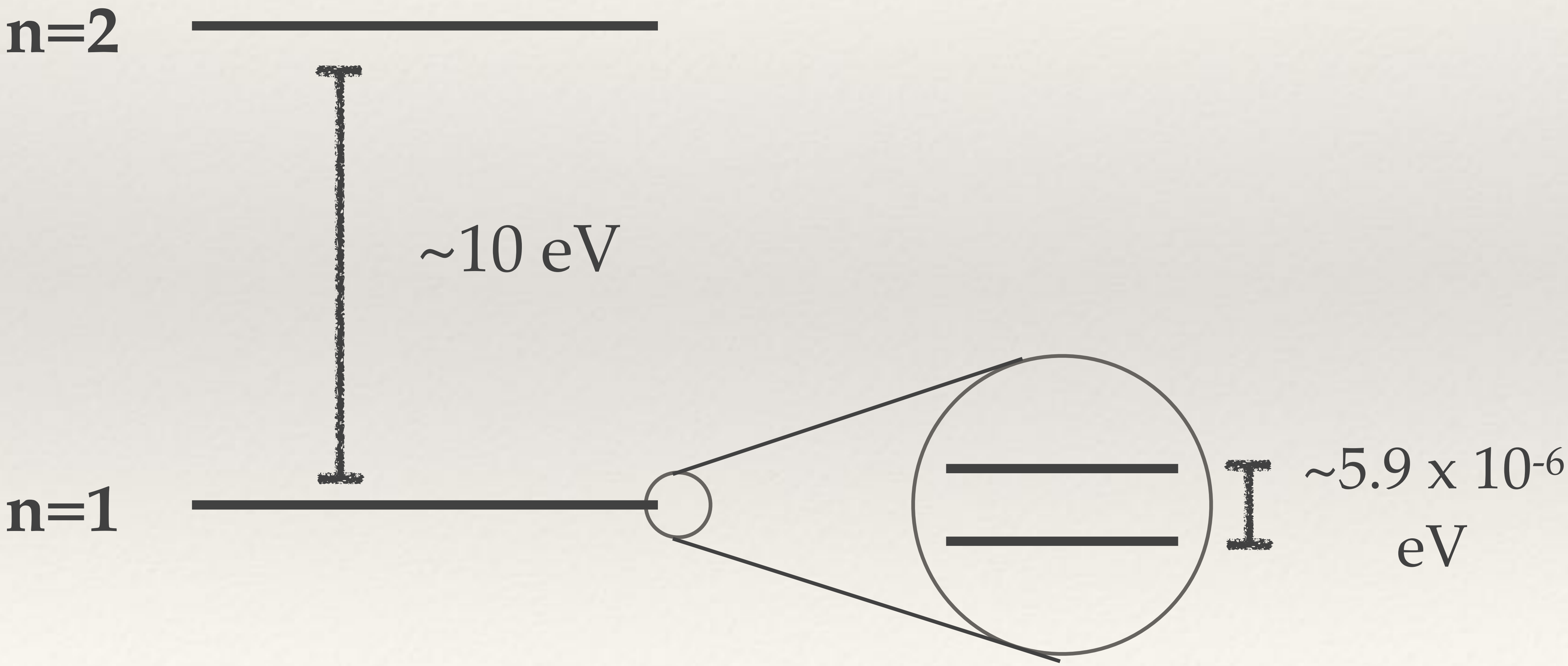
Neutral atomic hydrogen

This transition is called 'hyperfine structure'



Neutral atomic hydrogen

This transition is called 'hyperfine structure'



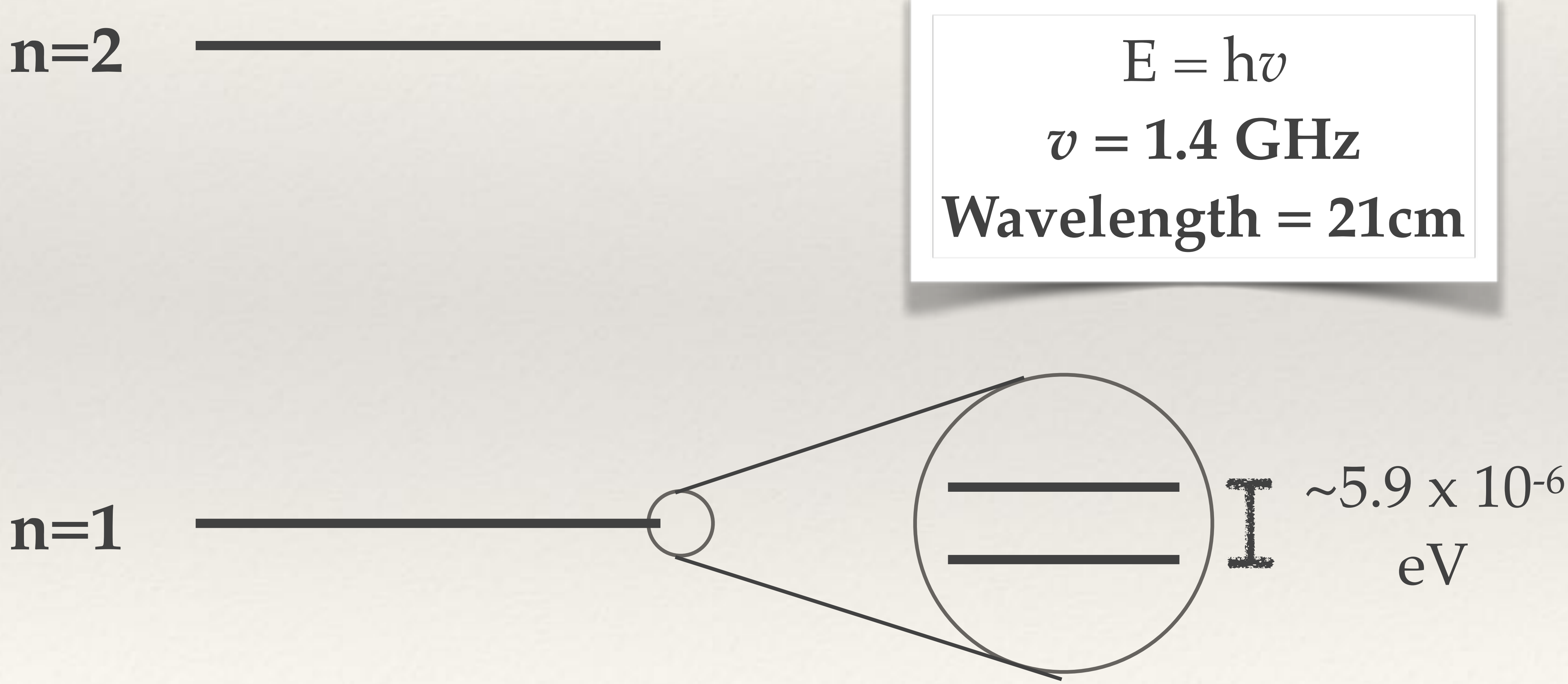
Neutral atomic hydrogen

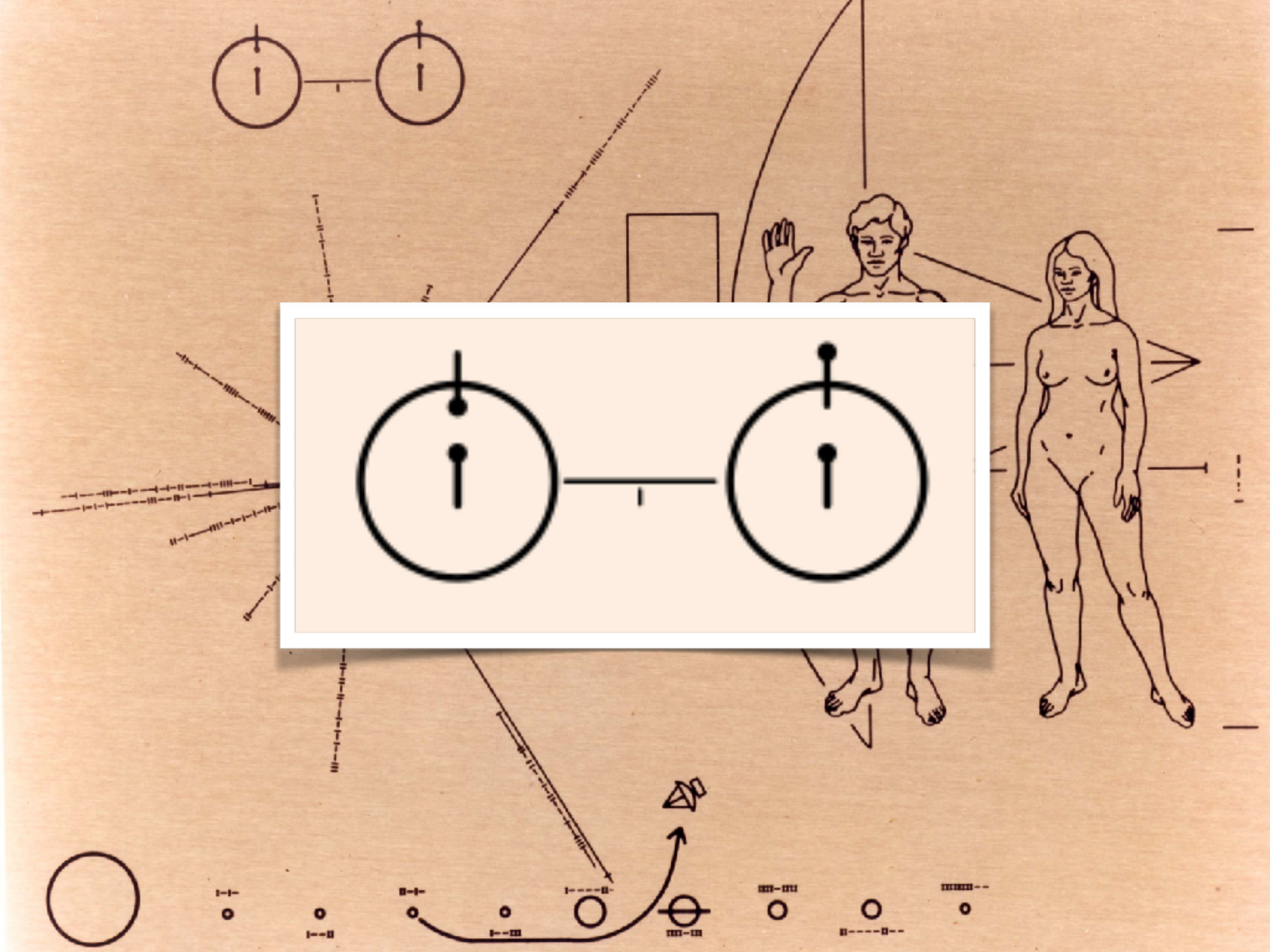
This transition is called 'hyperfine structure'

$E = h\nu$

ν = 1.4 GHz

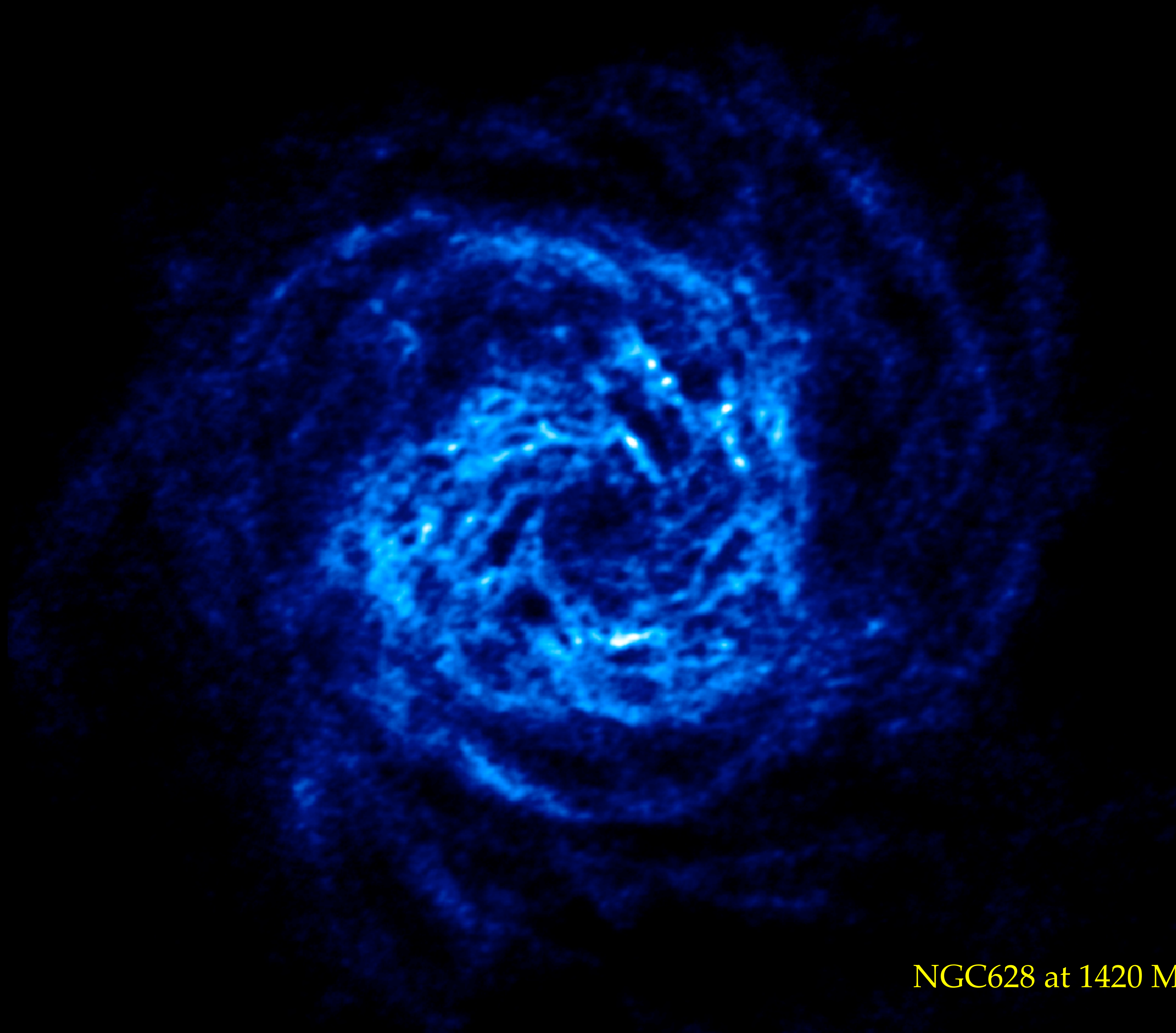
Wavelength = 21cm





NGC628 in optical

NGC628 in optical



NGC628 at 1420 MHz

Neutral atomic hydrogen

How much HI is there?

$$M(\mathrm{HI}) = 2.36 \times 10^5 \ \mathrm{f} \ \mathrm{D}^2$$

Neutral atomic hydrogen

How much HI is there?

$$M(\mathrm{HI}) = 2.36 \times 10^5 \ \mathrm{f} \ \mathrm{D}^2$$

HI mass, in units of 'solar masses'

Flux in 21cm line

Distance to galaxy, in Mpc

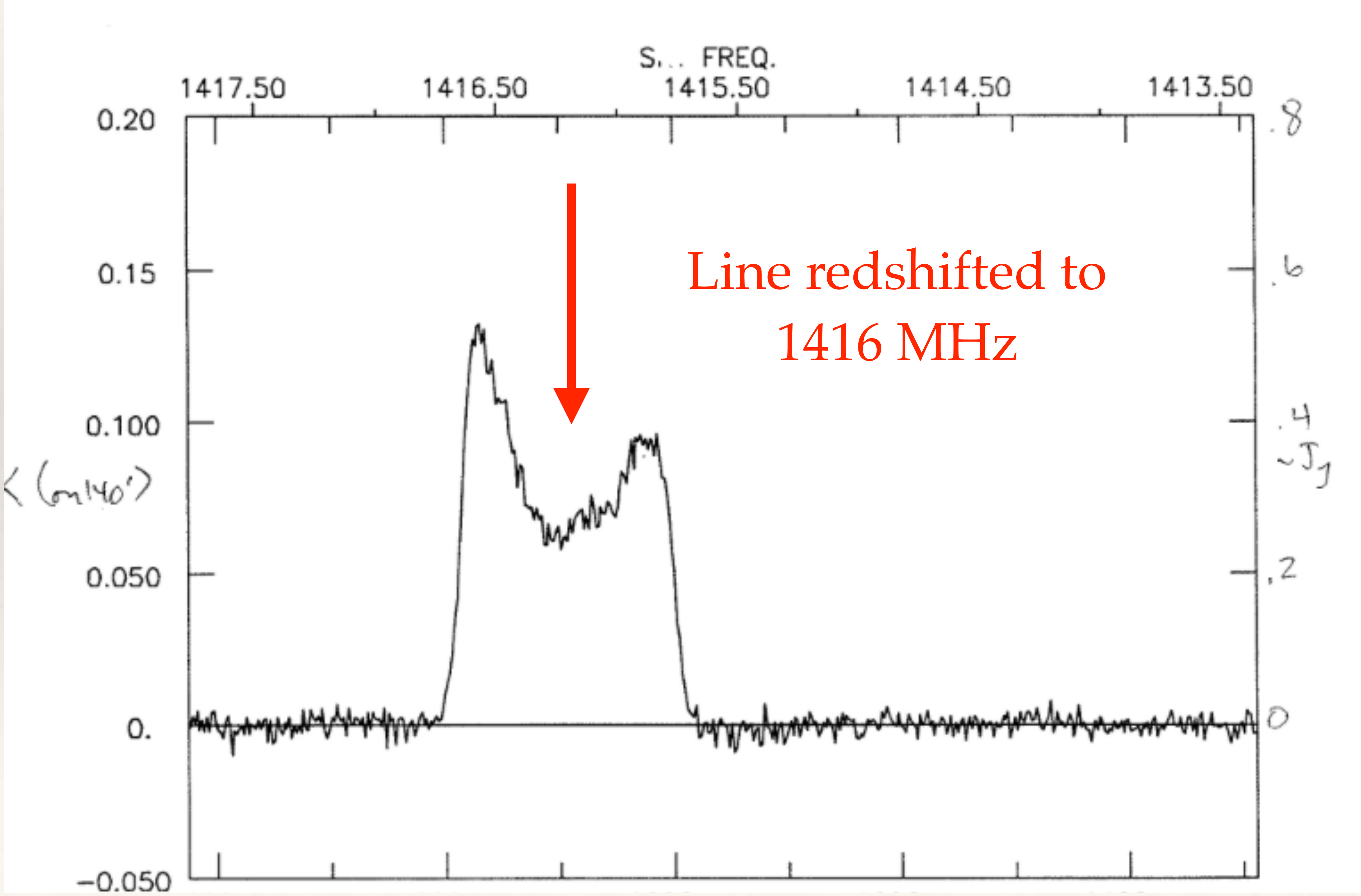
Neutral atomic hydrogen

How much HI is there?

The 140 foot telescope at Green Bank observed HI in the galaxy UGC 11707

Neutral atomic hydrogen

How much HI is there?



Neutral atomic hydrogen

How much HI is there?

UGC 11707 has **2.5 billion solar masses** of atomic hydrogen:
more HI than stars!

Observations of HI at 21cm are a major way of examining the Universe

What is in the radio sky?

- Pulsars
- Atomic hydrogen
- Radio emission from galaxies

What is in the radio sky?

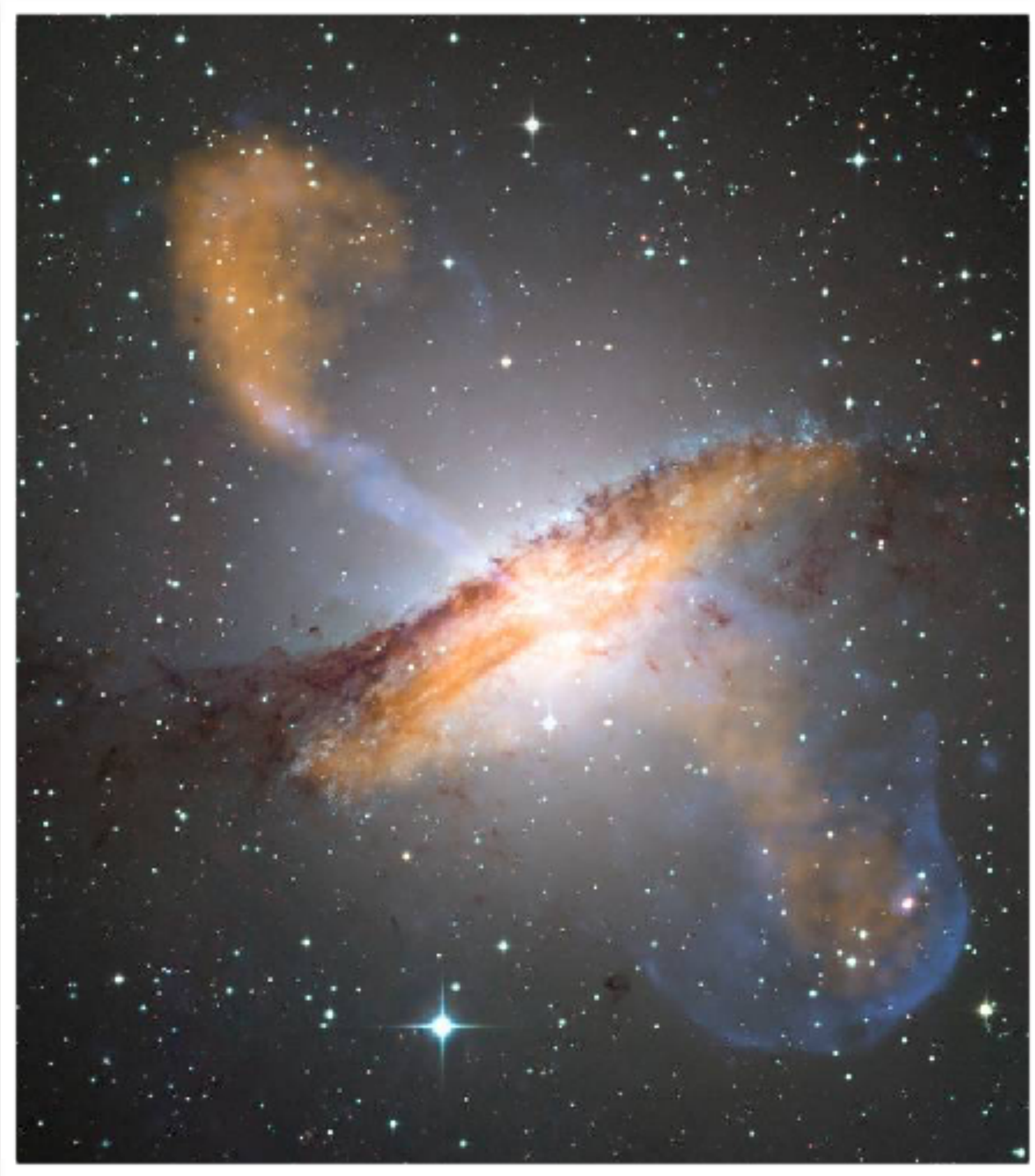
- Pulsars
- Atomic hydrogen
- Radio emission from galaxies

Active galaxies

Normal galaxies

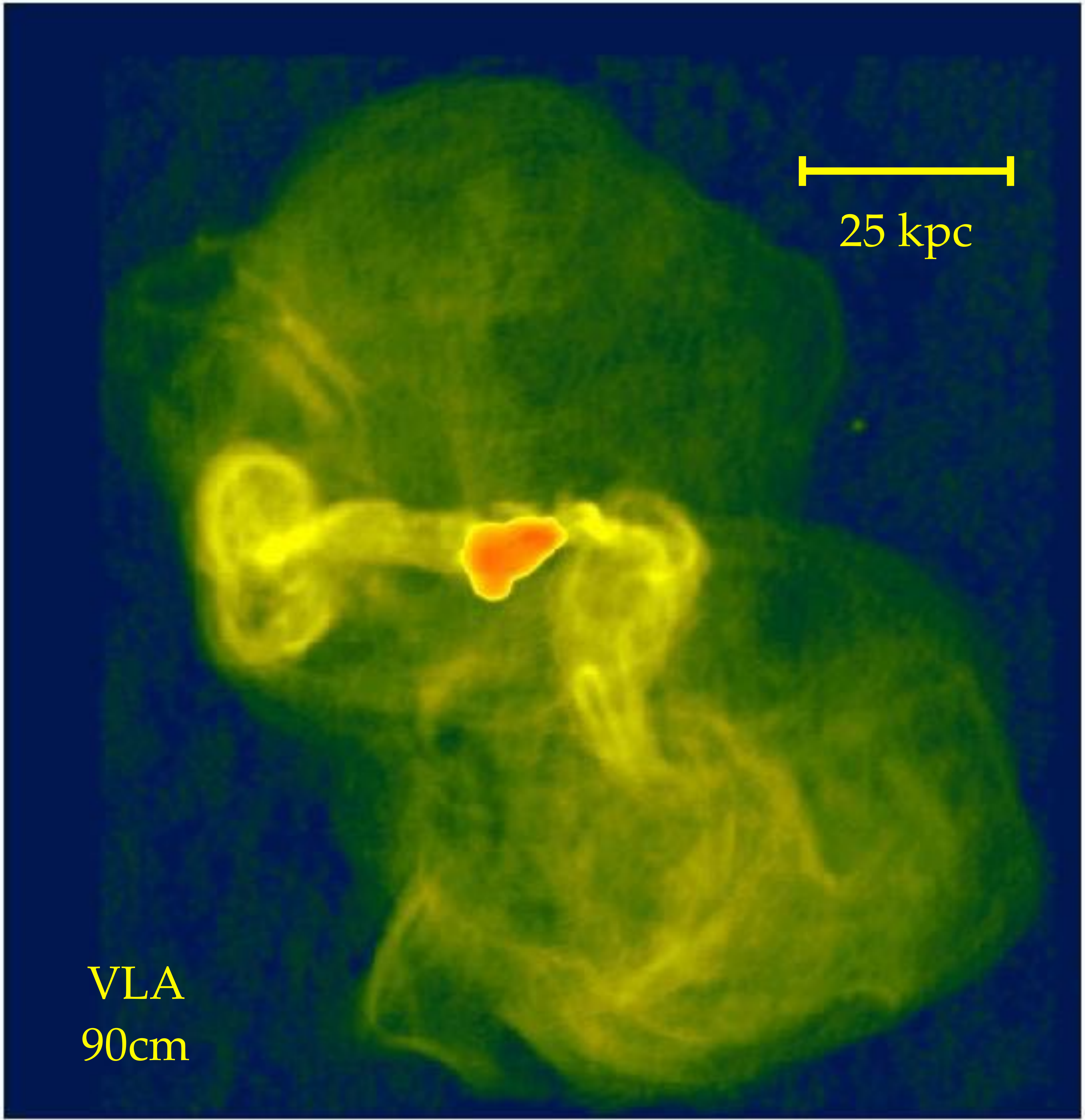
Radio emission from active galaxies

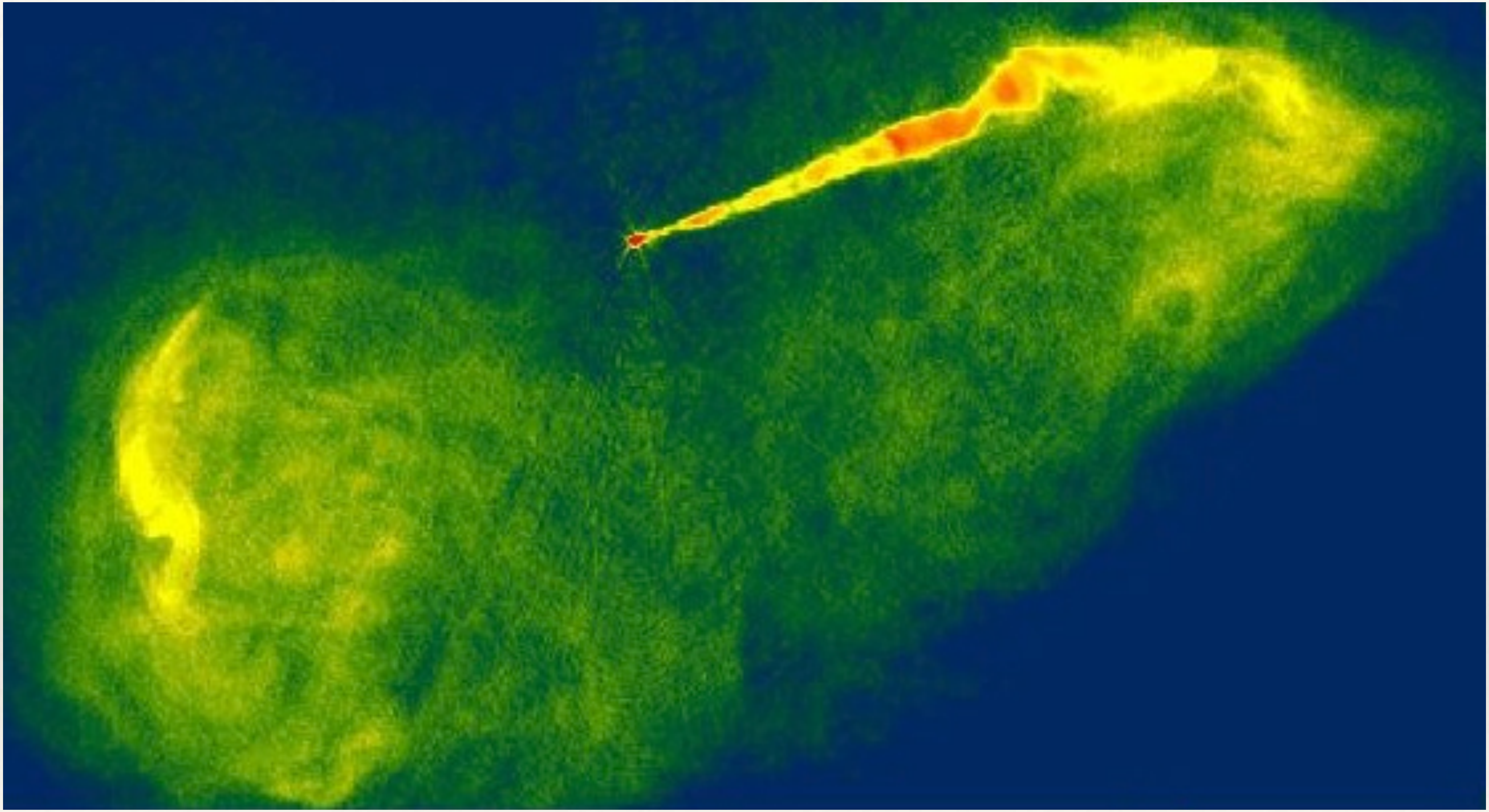
- Type of active galaxy (galaxy with central super-massive black hole).
- Known as AGN — Active Galactic Nuclei
- Radio emission powered by Synchrotron

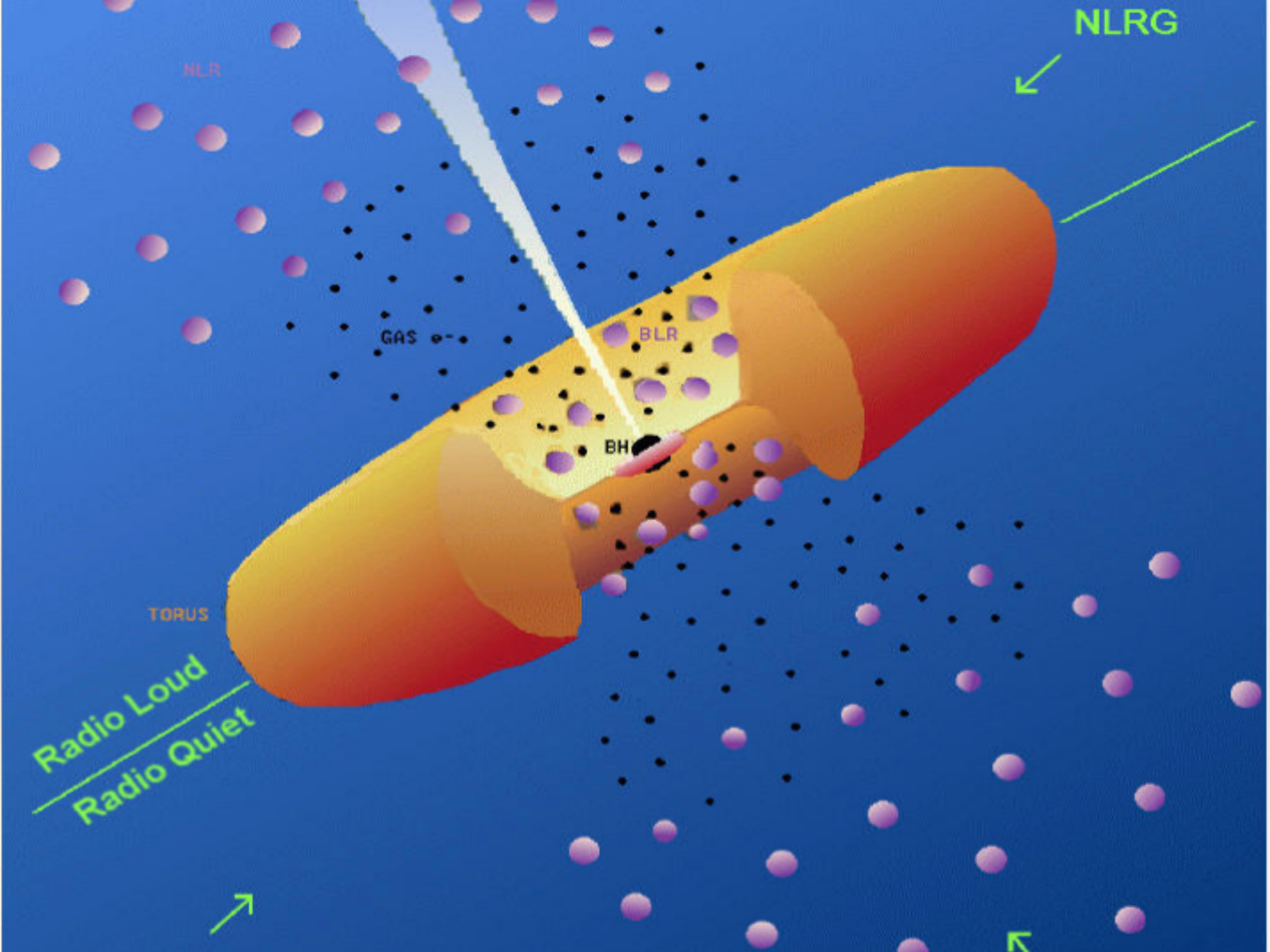


VLA
5 GHz

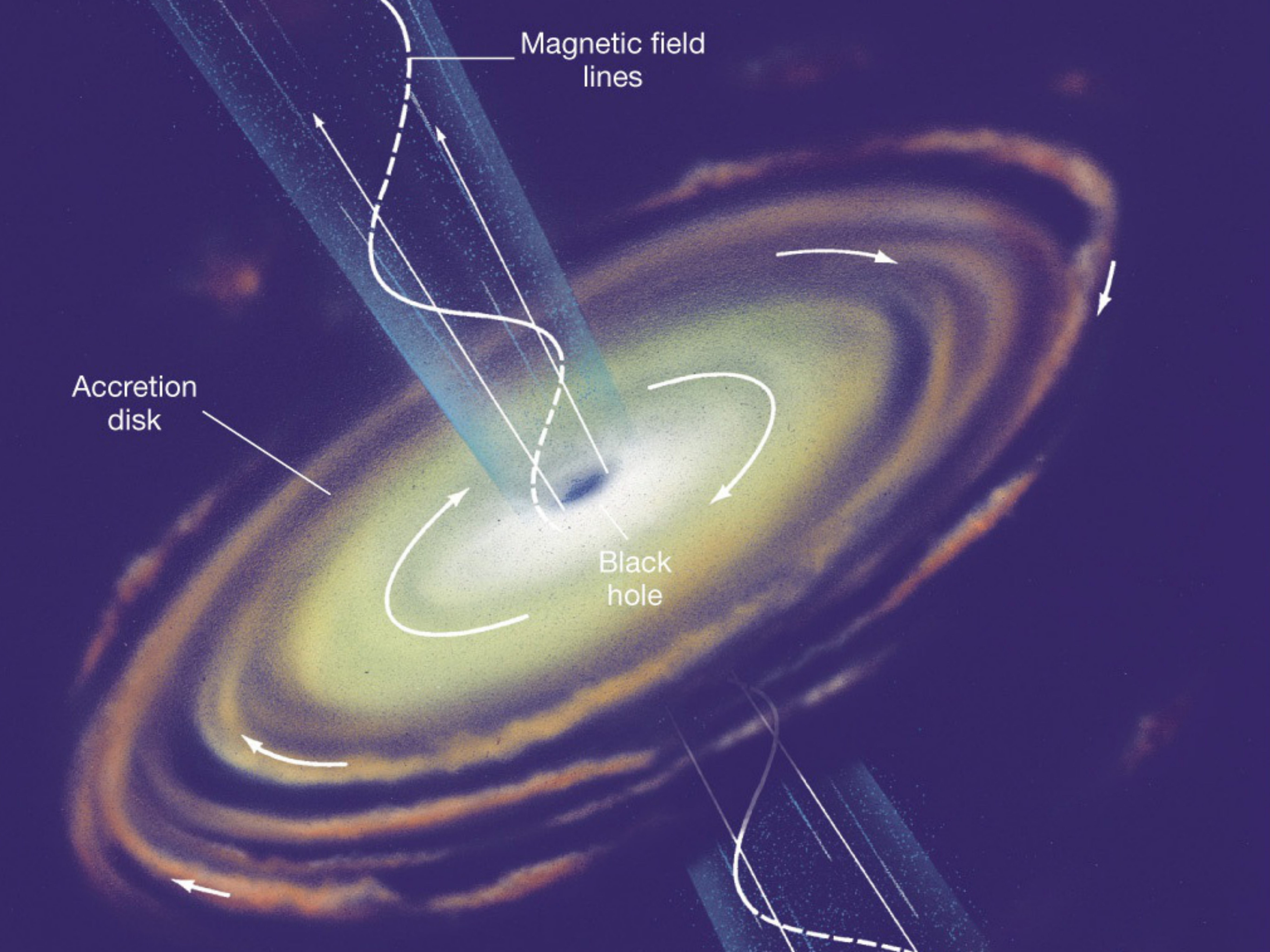
Parkes
5 GHz


25 kpc
VLA
90cm



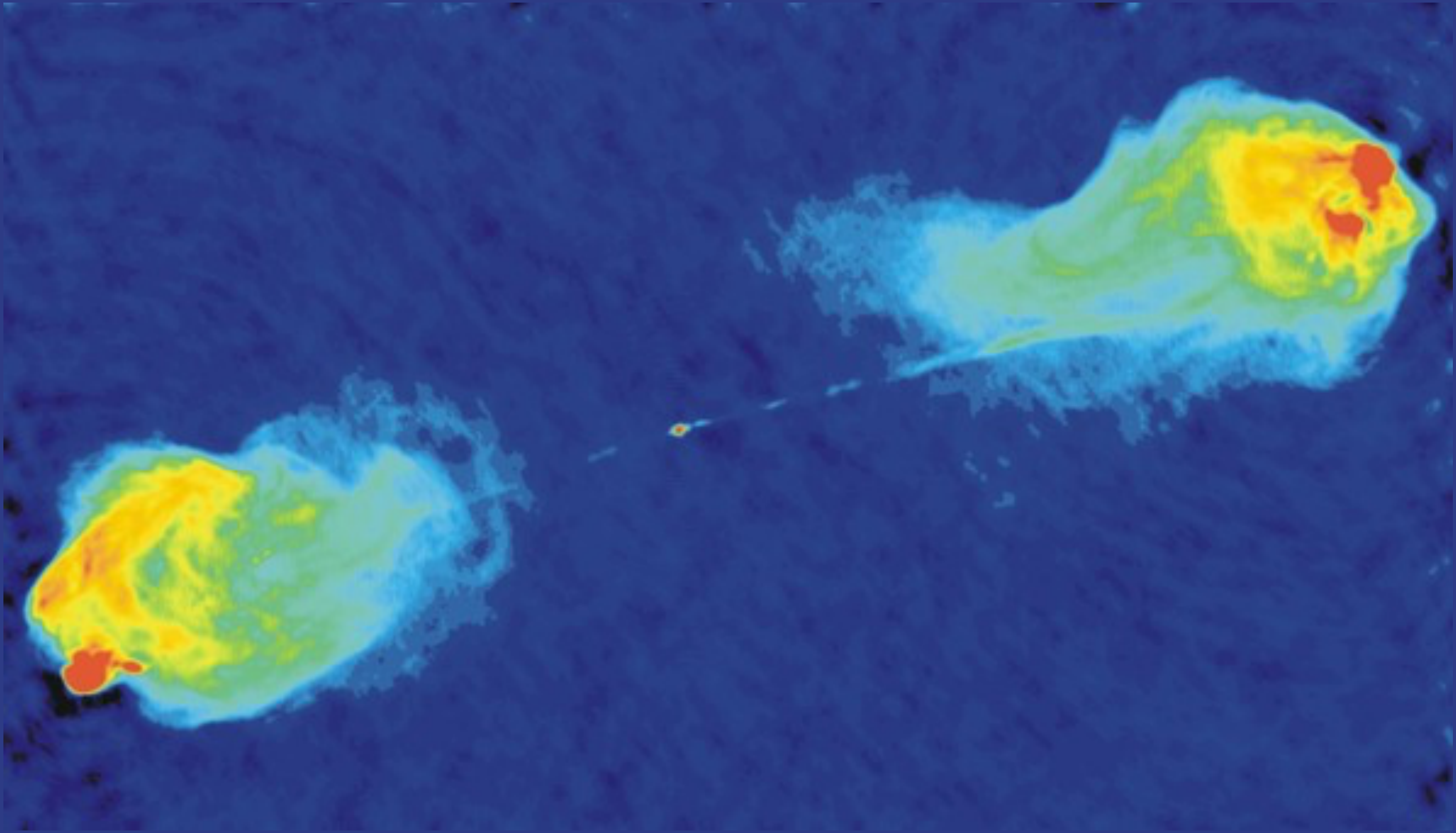


NLRG
NLR
GAS e-
BLR
BH
TORUS
Radio Loud
Radio Quiet



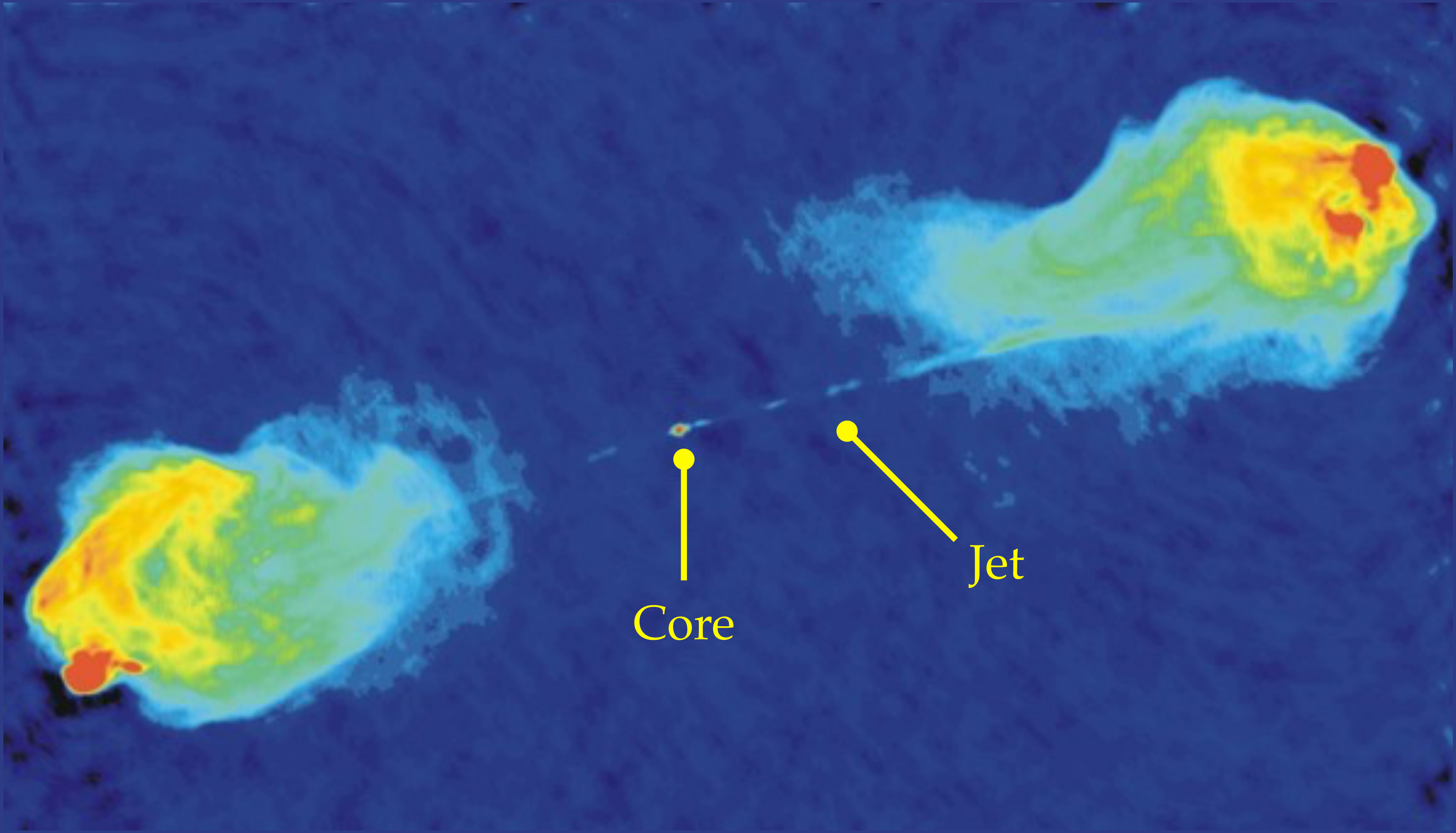
Magnetic field lines
Accretion disk
Black hole

Cygnus A



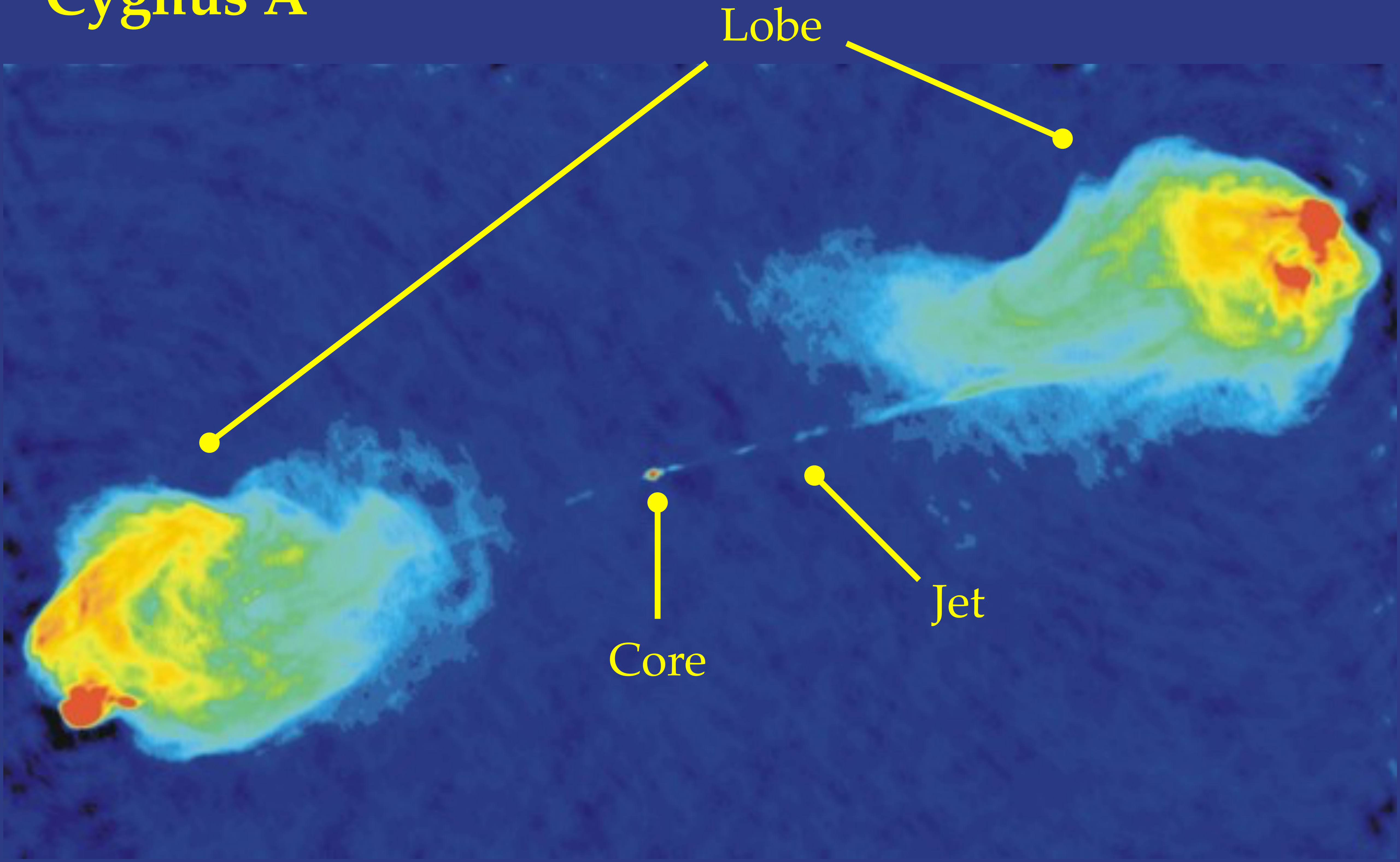
'Typical' radio galaxy

Cygnus A



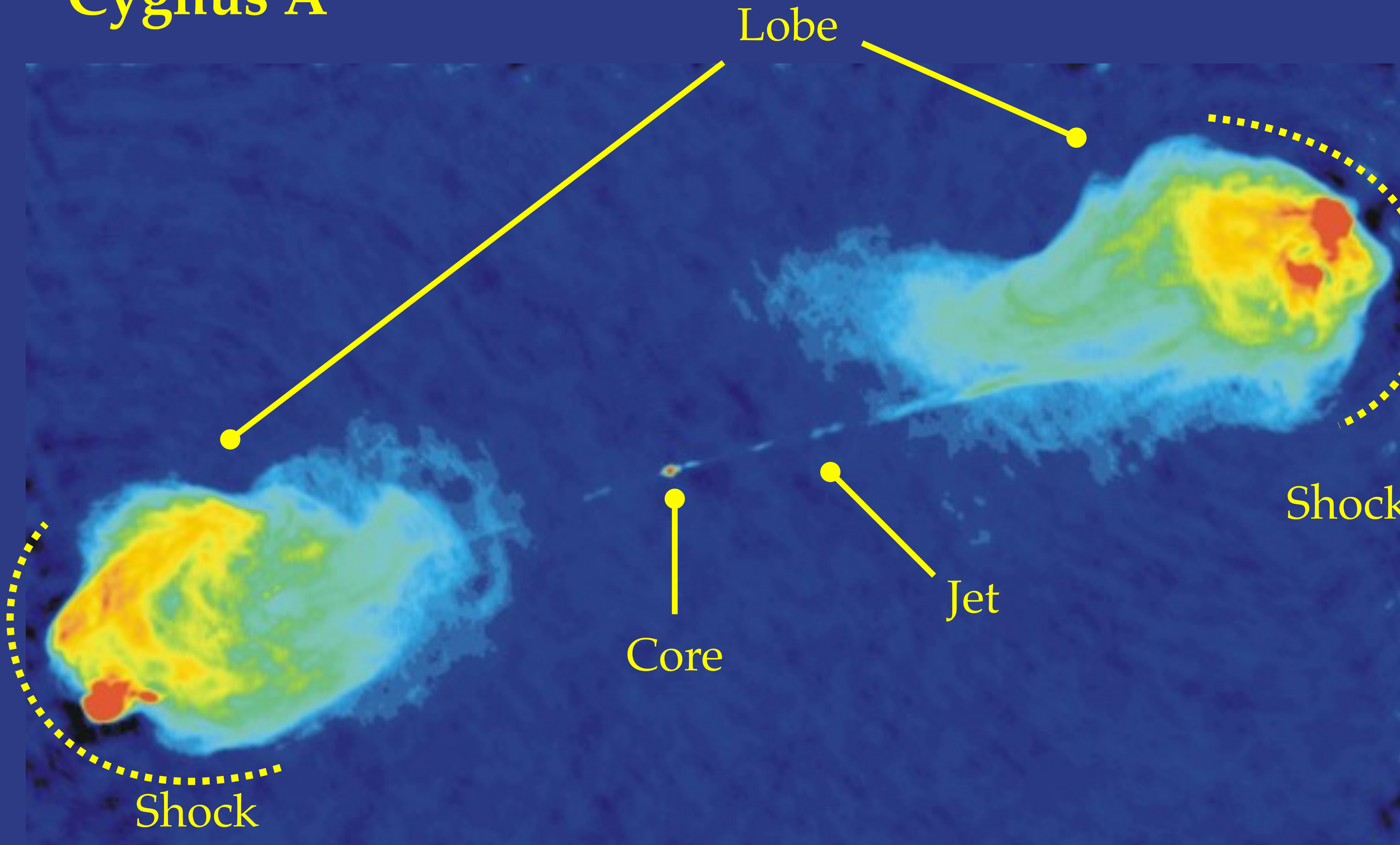
'Typical' radio galaxy

Cygnus A



‘Typical’ radio galaxy

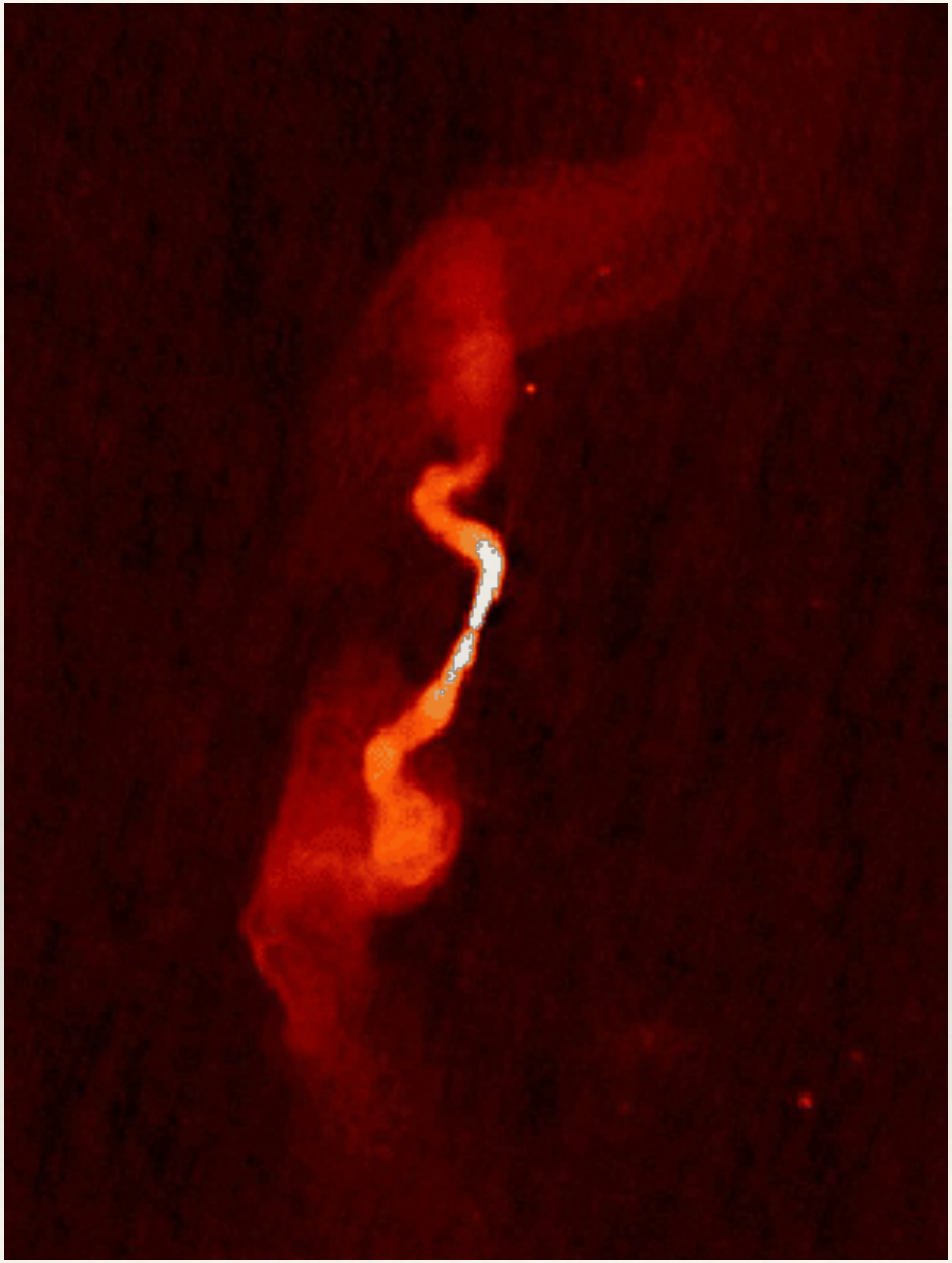
Cygnus A



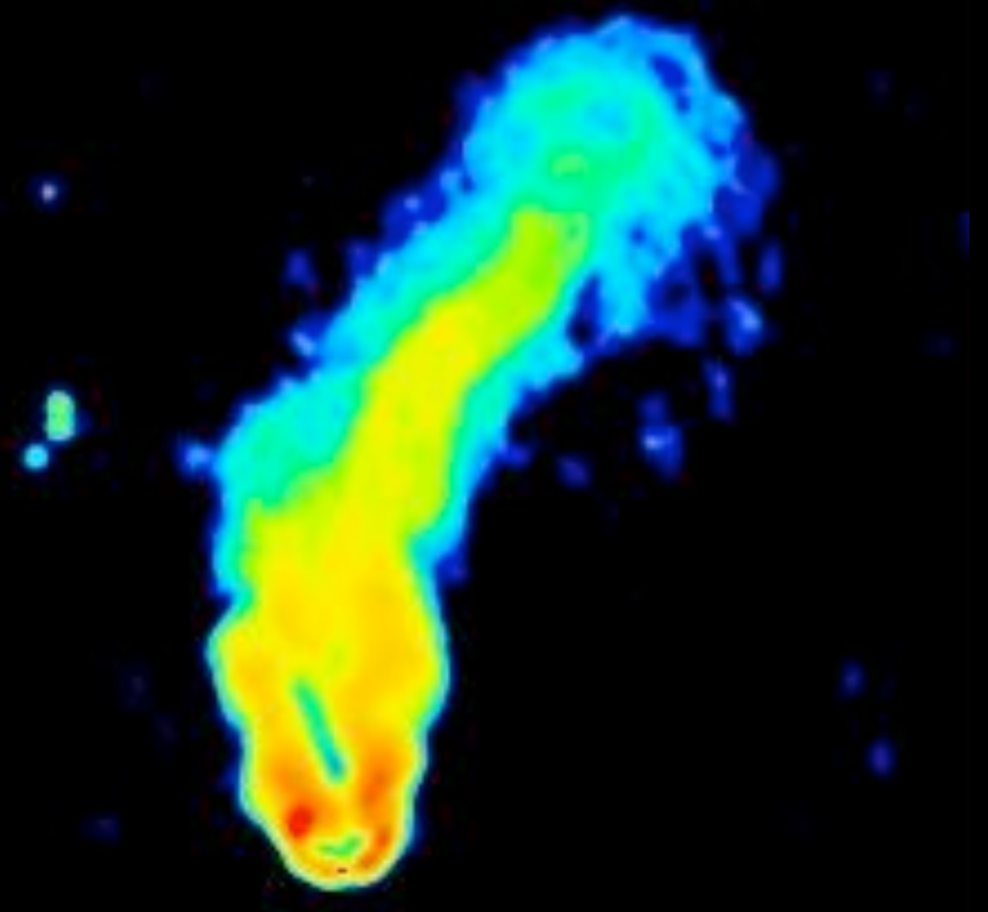
'Typical' radio galaxy

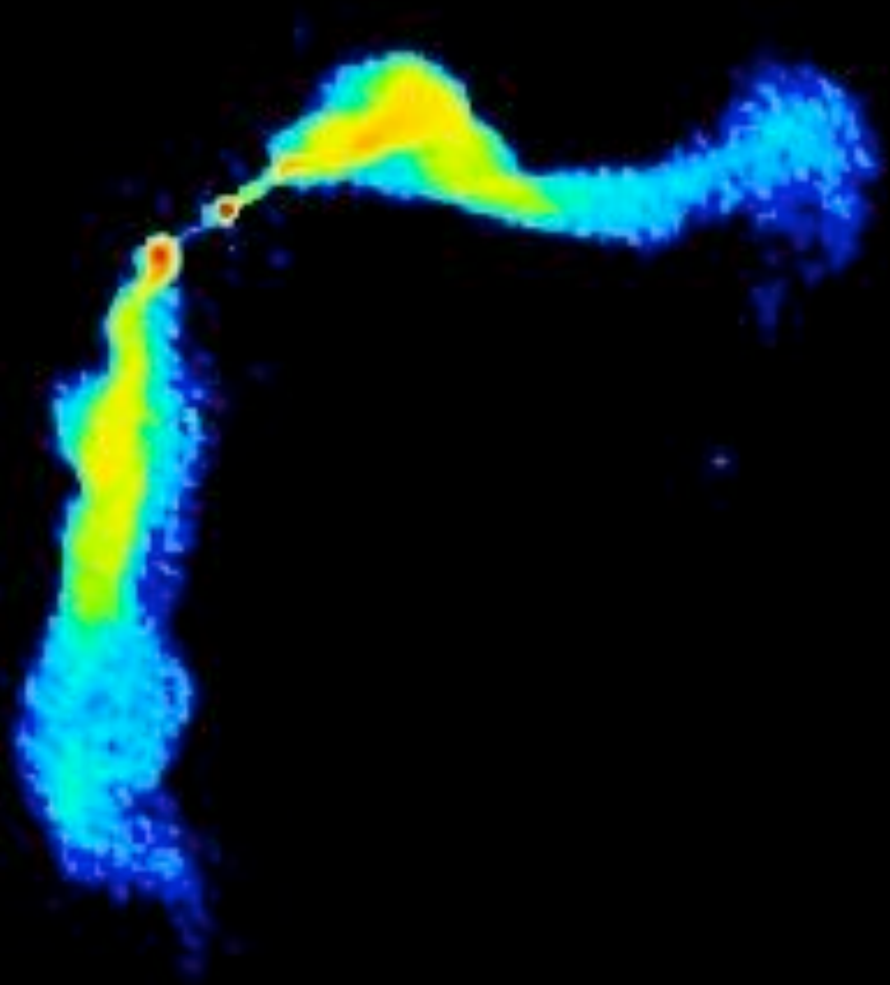
Jets can distort depending on environment

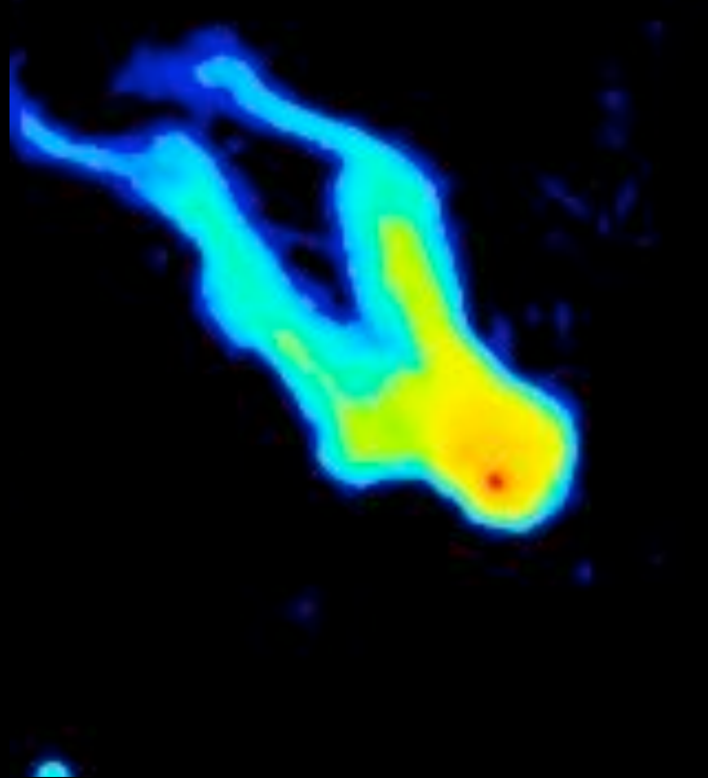
Here, the jets of galaxy 3C 31 (observed at ~20cm) are distorting due to interaction with cluster gas



Other examples of disturbed jet morphology…

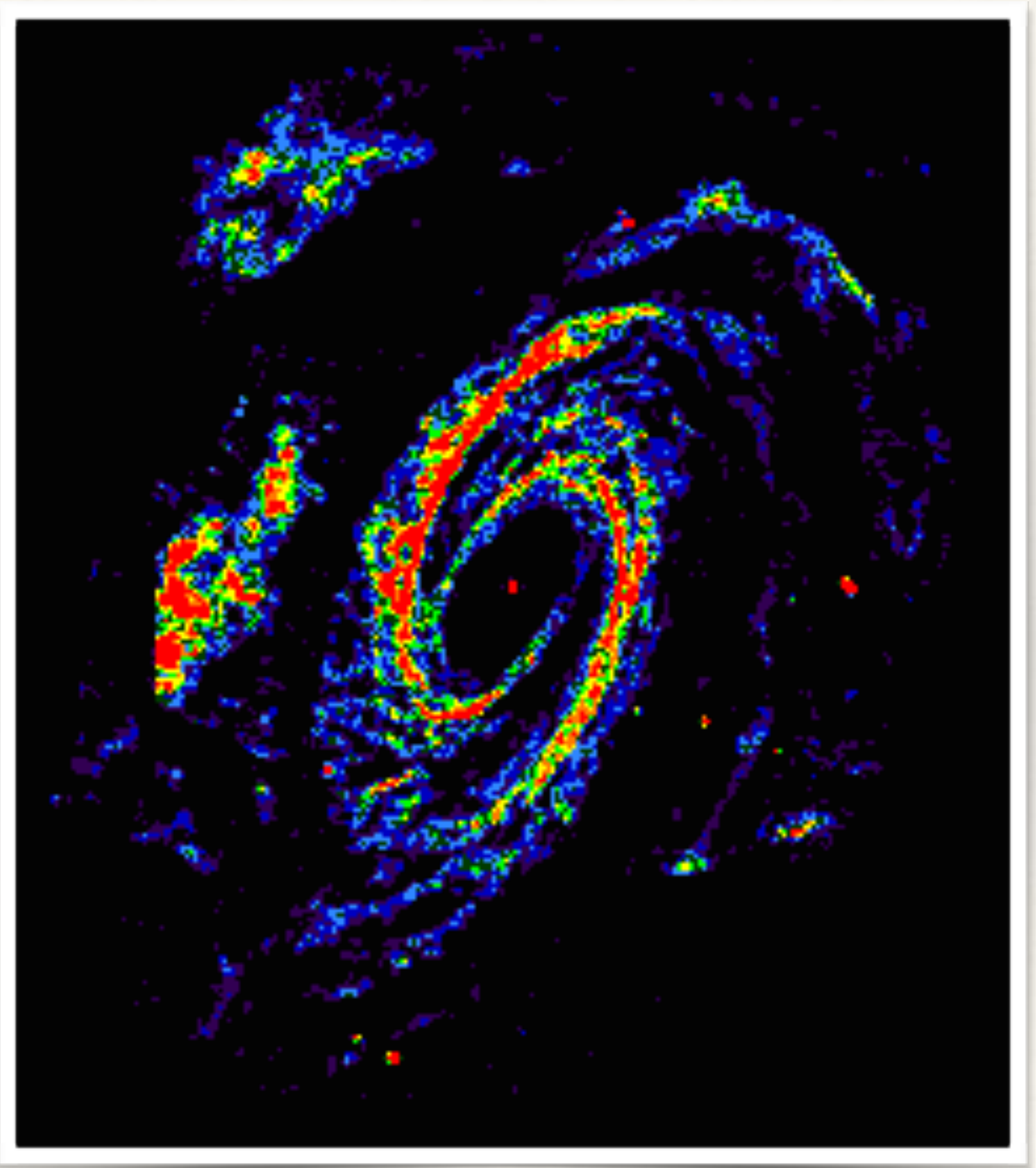






Radio emission from normal galaxies

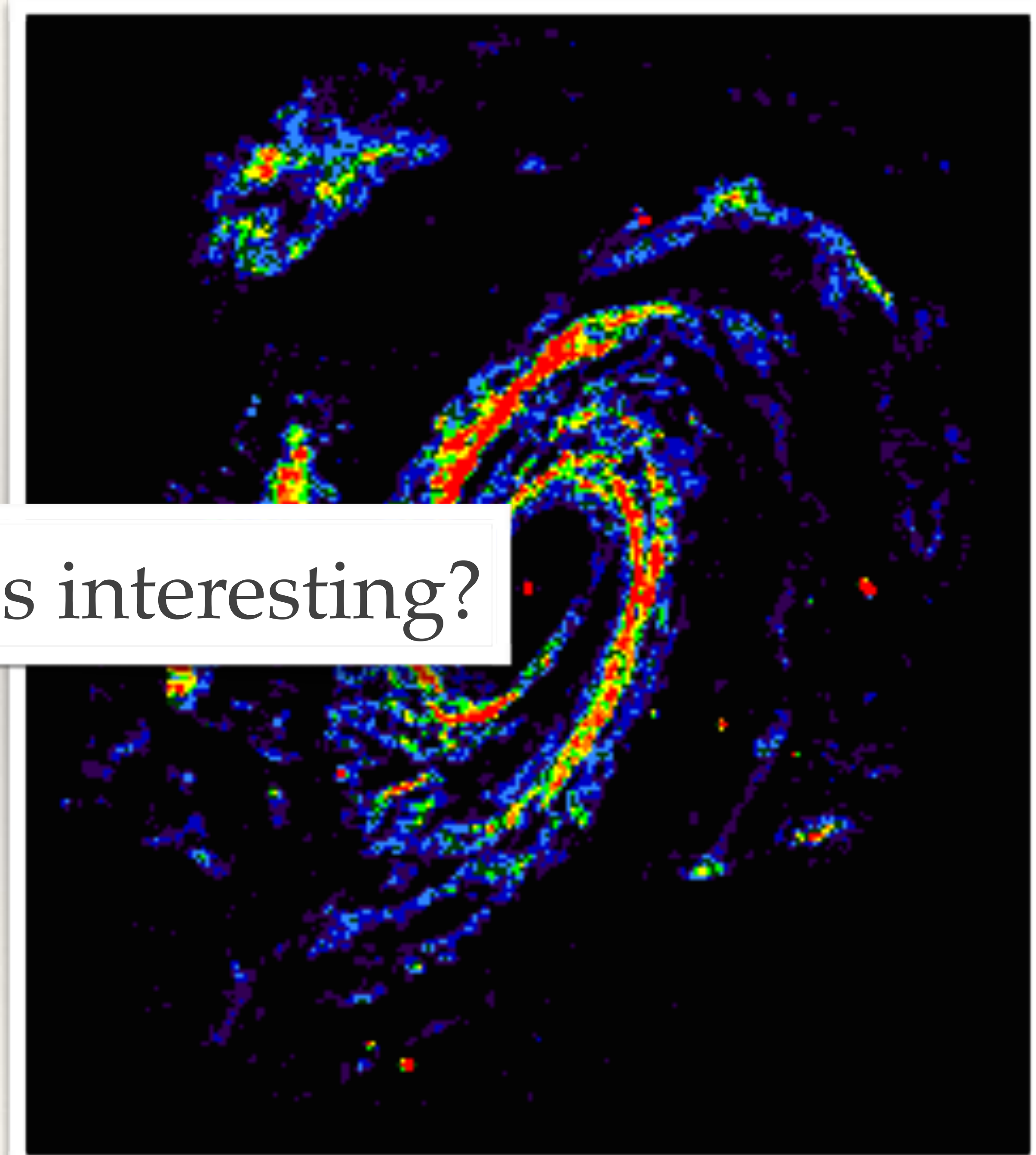
- Normal galaxies also produce radio emission — not related to the central black hole
- No jets — radio waves coming from the galaxy as a whole…
- Radio emission from synchrotron radiation from cosmic ray electrons (+positrons)



Radio emission from normal galaxies

- Normal galaxies also produce radio emission — not related to the central black hole
- No jets — radi… from the galaxy…
- Radio emission from synchrotron radiation from cosmic ray electrons (+positrons)

So… why is this interesting?



Radio emission from normal galaxies

Radio waves are an excellent way to measure the `star formation rate' of galaxies

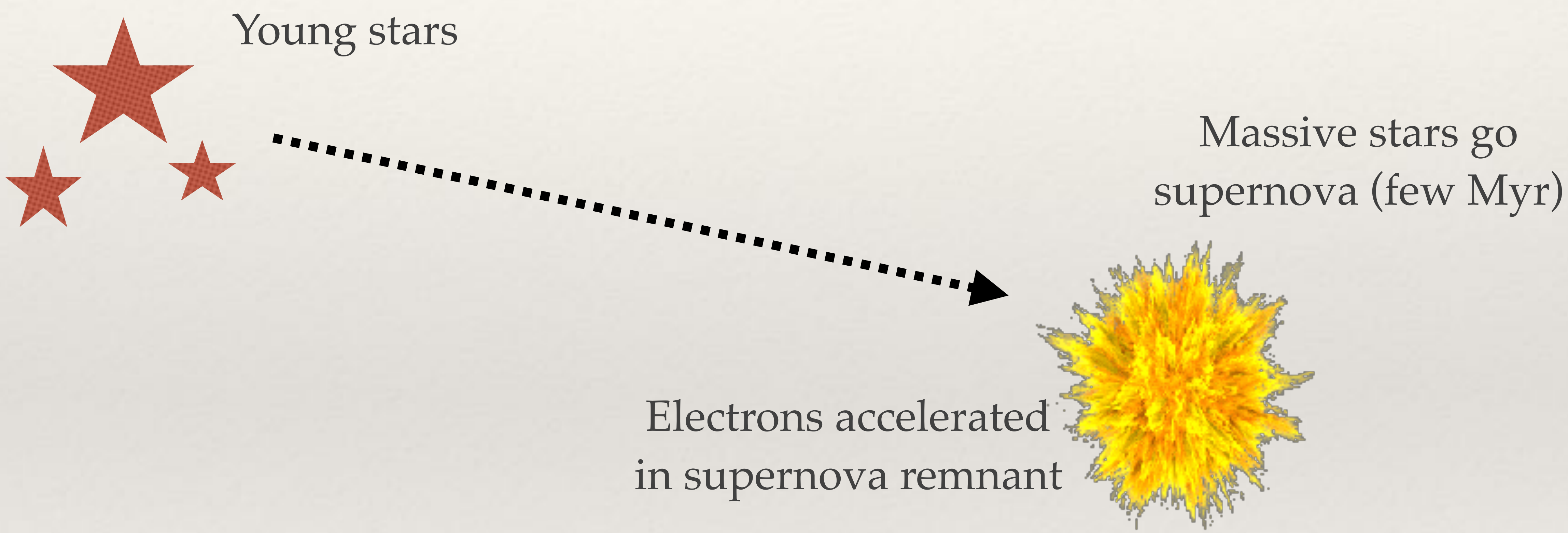
Radio emission from normal galaxies

How does this work?

Young stars

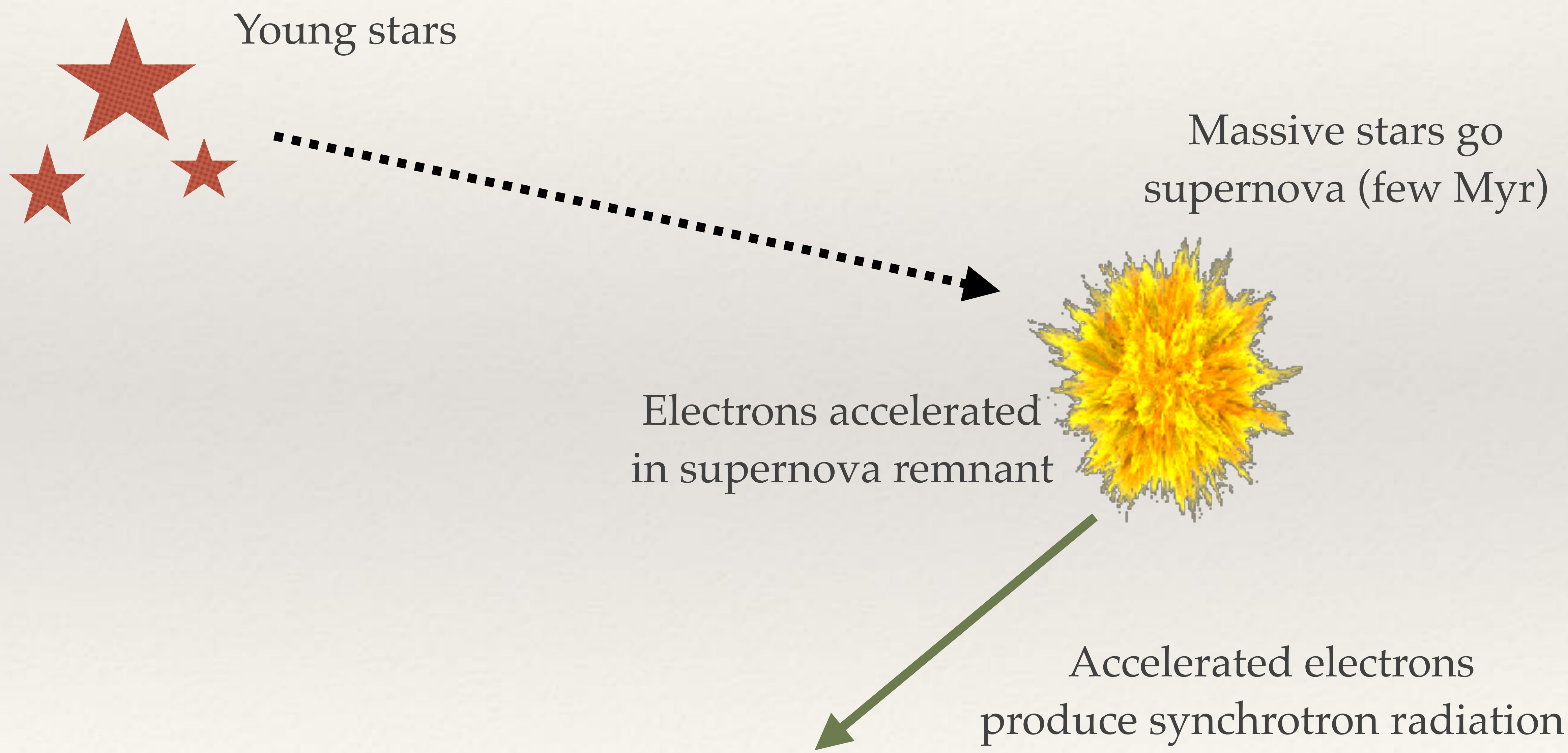
Radio emission from normal galaxies

How does this work?



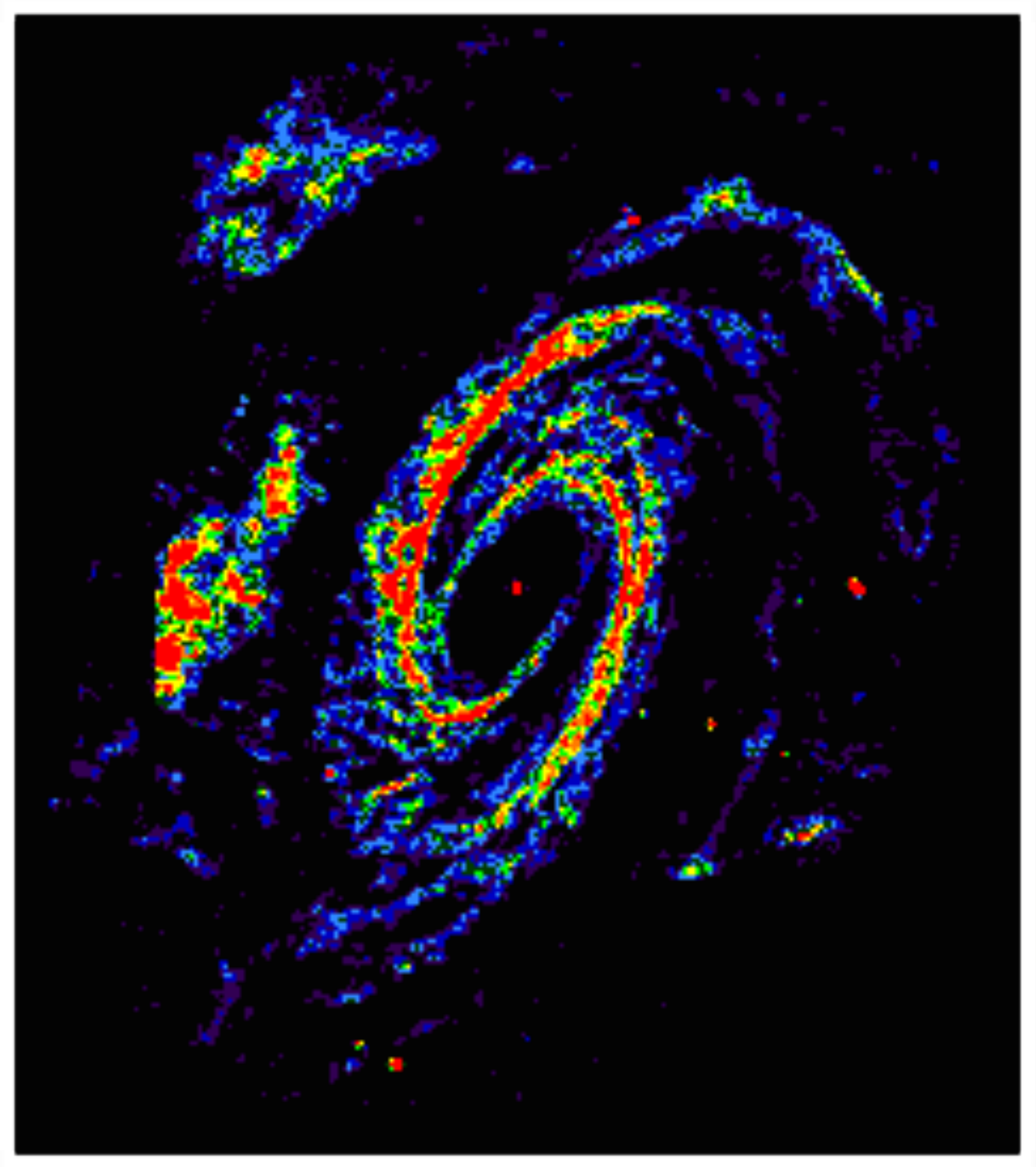
Radio emission from normal galaxies

How does this work?



Radio emission from normal galaxies

Radio emission from normal galaxies is a very useful + widely used star formation rate indicator



Radio astrophysics: Take Home Points

- Pulsars — radio observations to constrain period. Can be used to infer (+ directly measure??) gravitational waves
- Atomic hydrogen line at 21cm (1420 MHz)
- Radio galaxies: FRI, FRII
- Radio emission from galaxies as star formation tracer