Radio astronomy (II): What is in the radio sky?

Astrophysics of Radio Astronomy

Matt Bothwell

What is in the radio sky?

- Pulsars
- Atomic hydrogen
- Radio emission from galaxies

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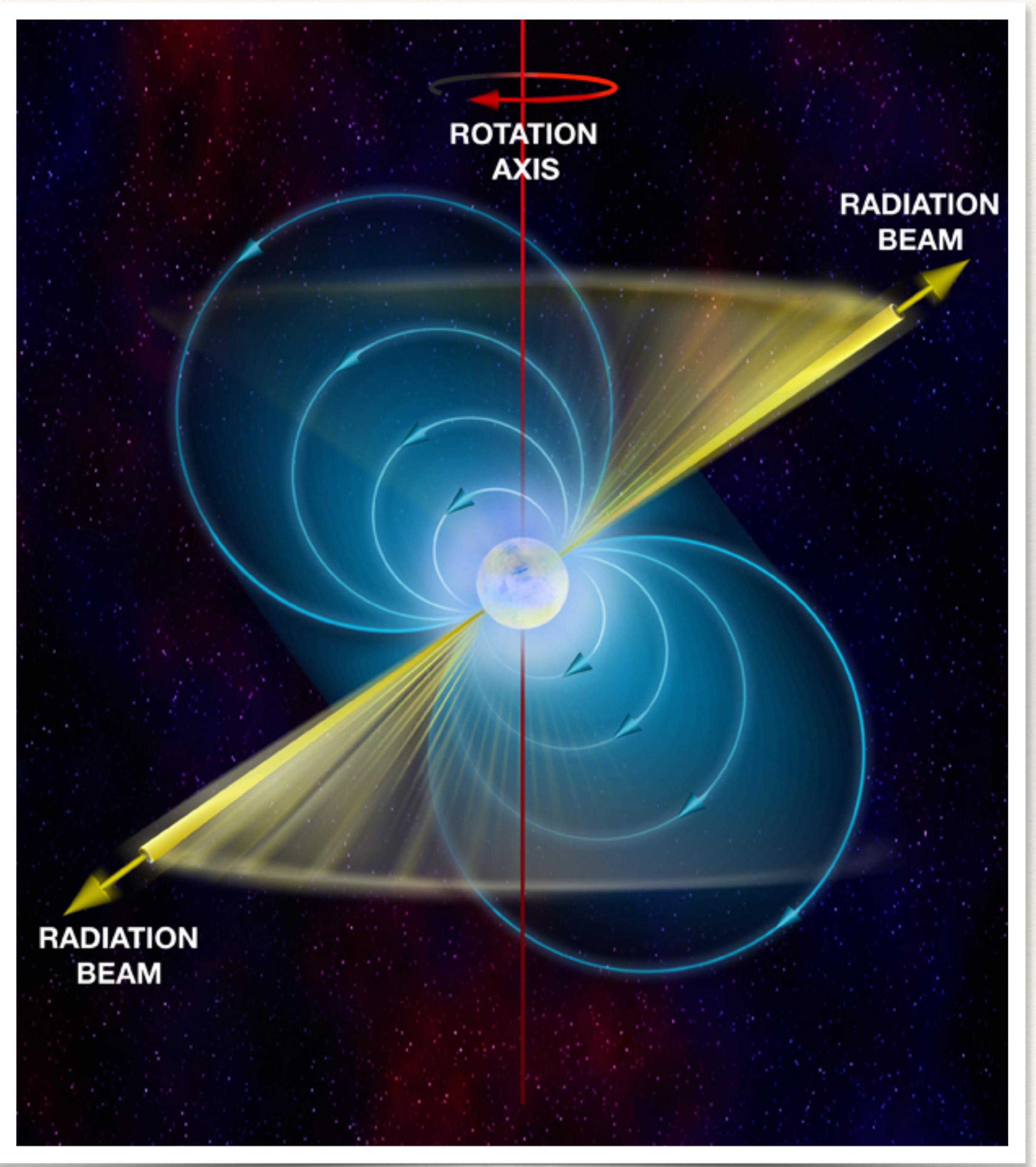
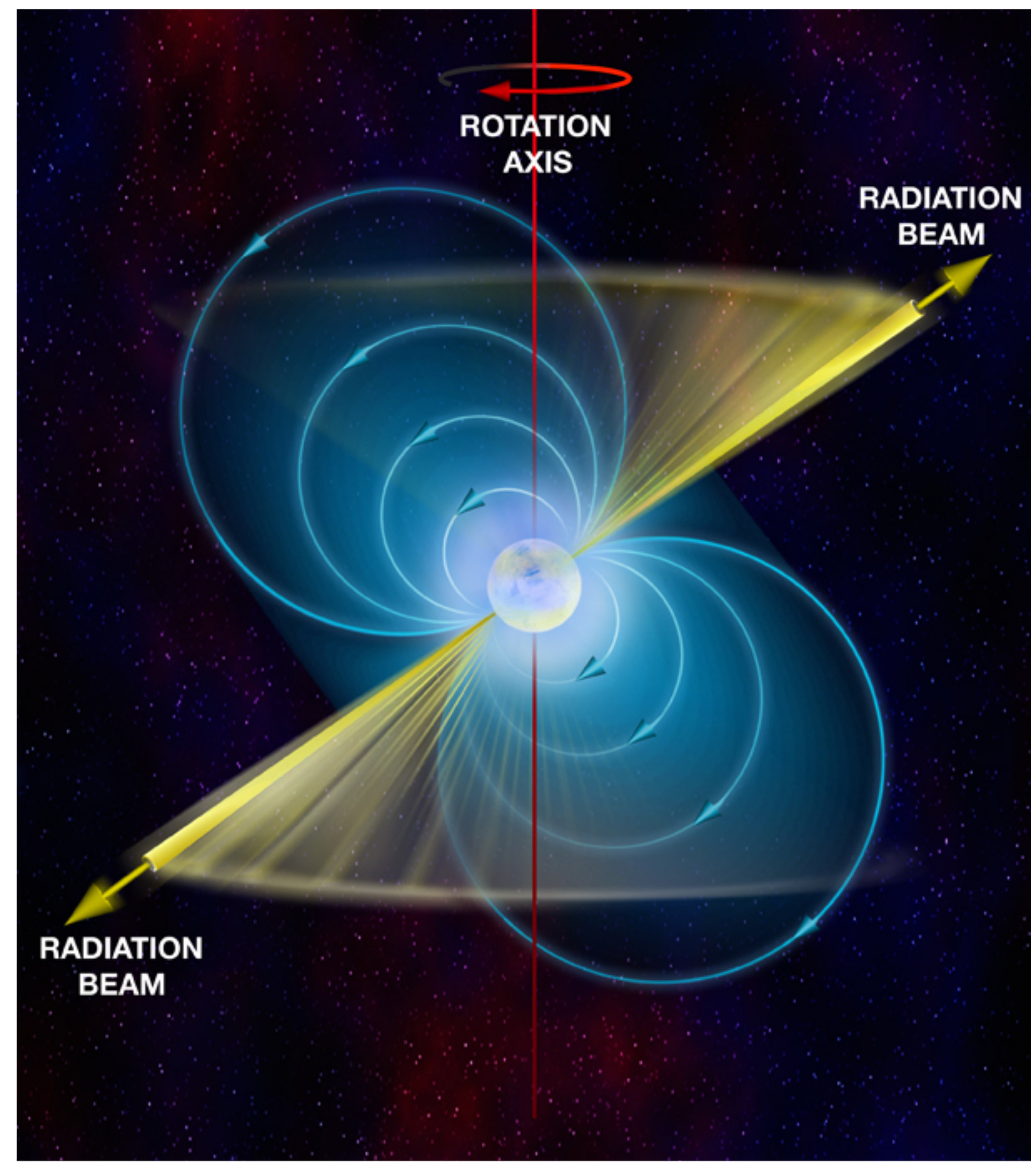
Pulsars: recap

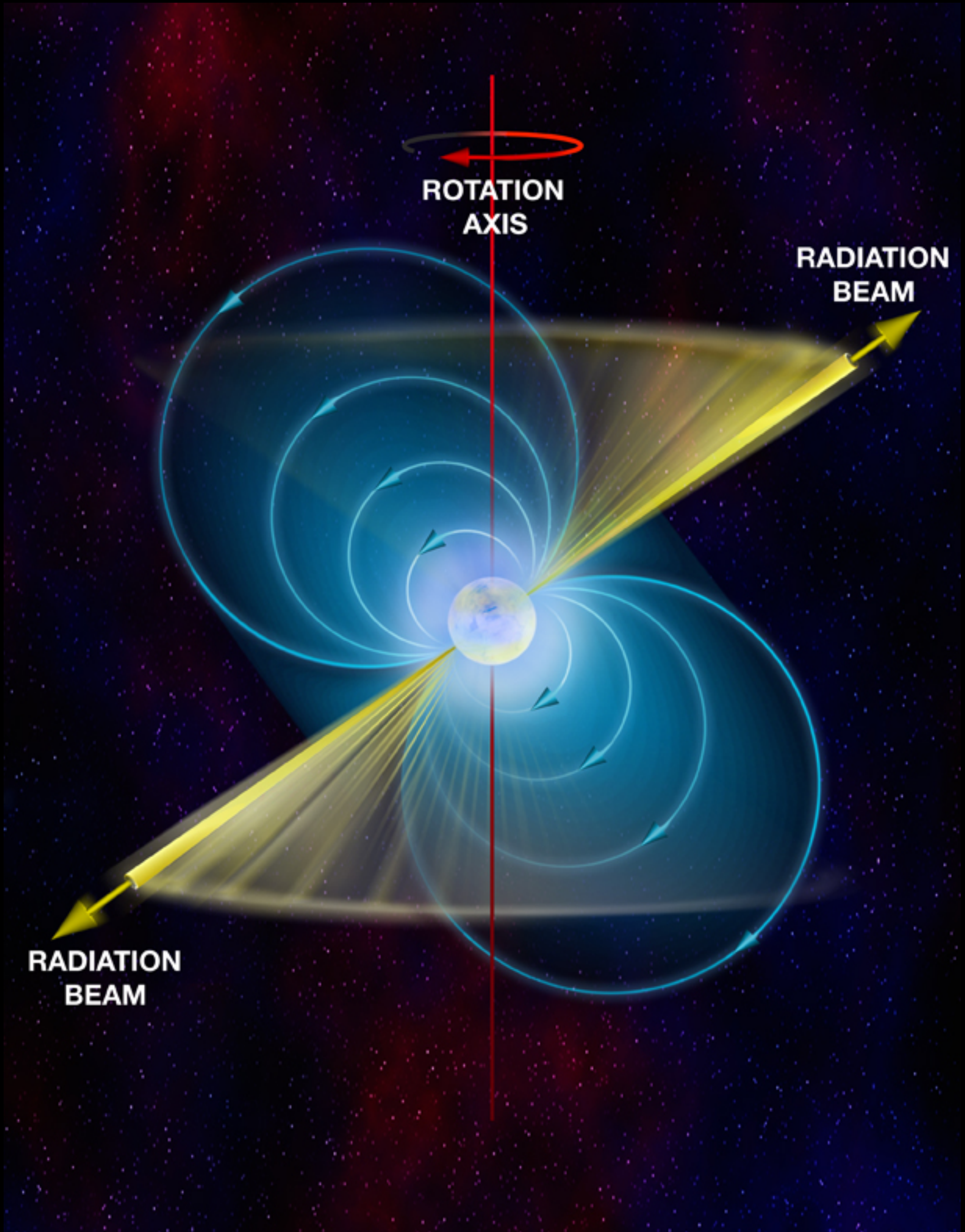
- Pulsars are rapidly spinning Neutron Stars
- Formed from the supernova of a massive (8-15 M_sun) star
- Held up by neutron degeneracy pressure
- Intense magnetic field produces **synchrotron radiation**



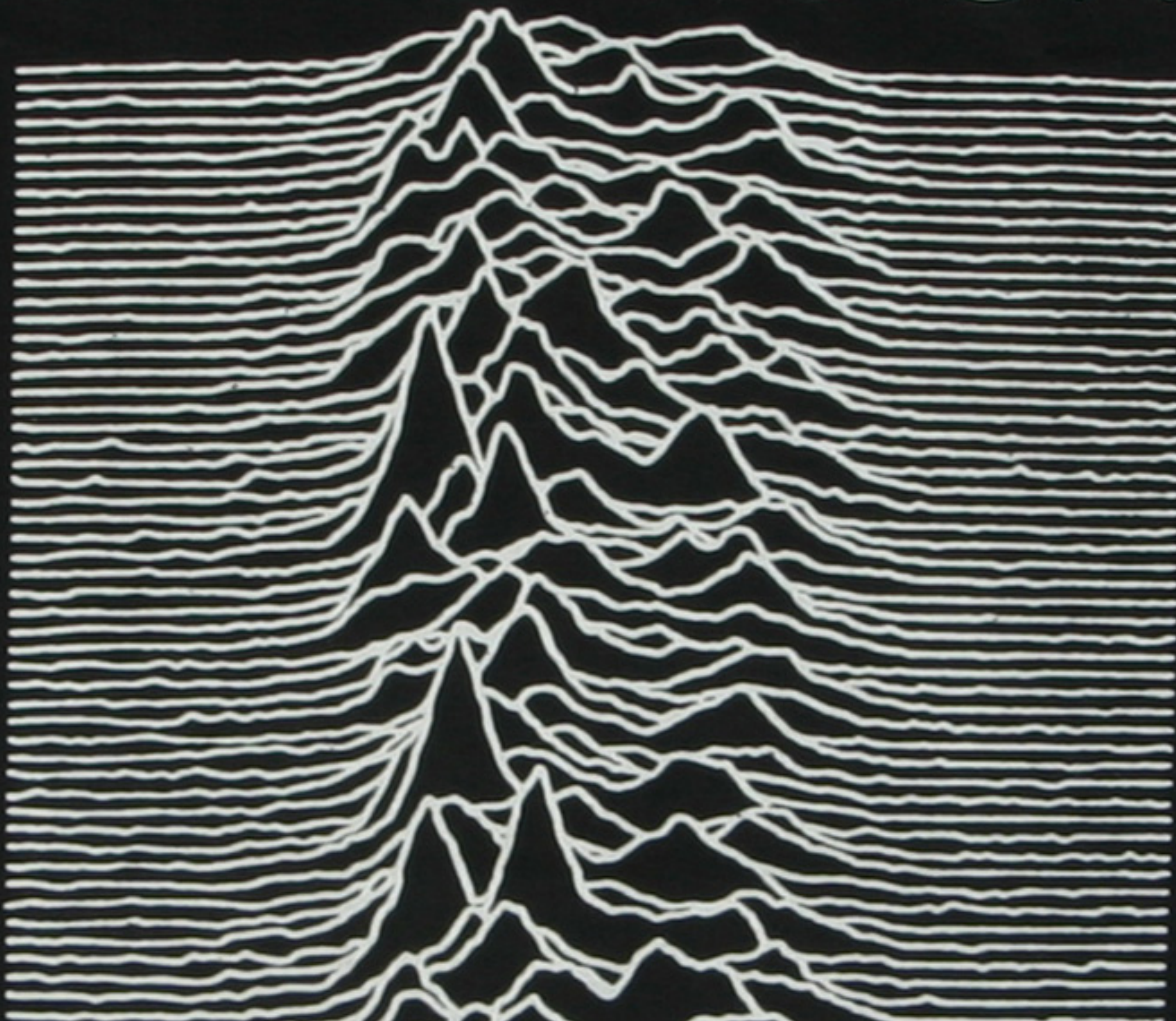
Pulsars: recap

- 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!



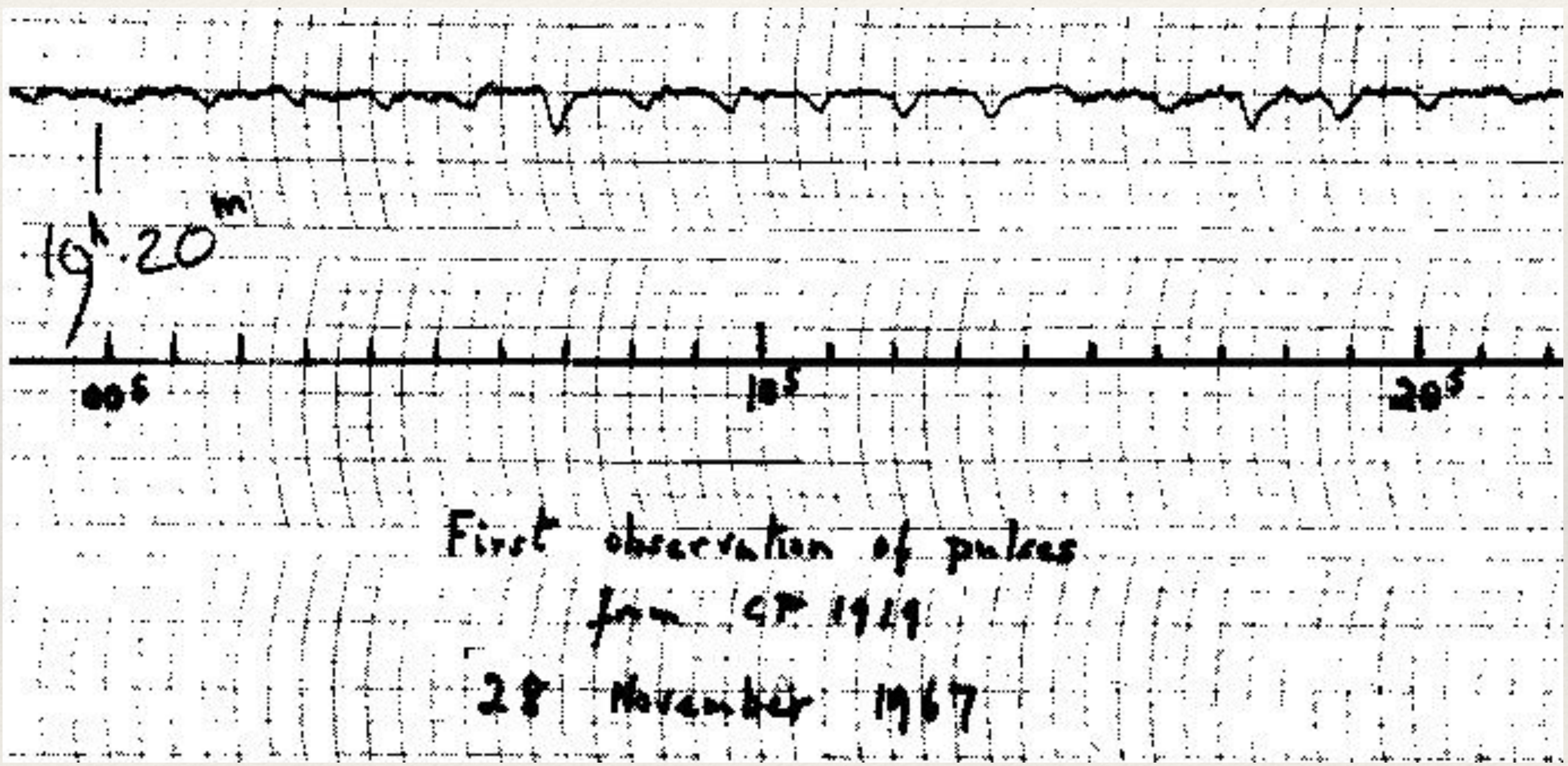

ROTATION
AXIS
RADIATION
BEAM
RADIATION
BEAM

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

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

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

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

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

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

Pulsars

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

Density = Mass / Volume

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

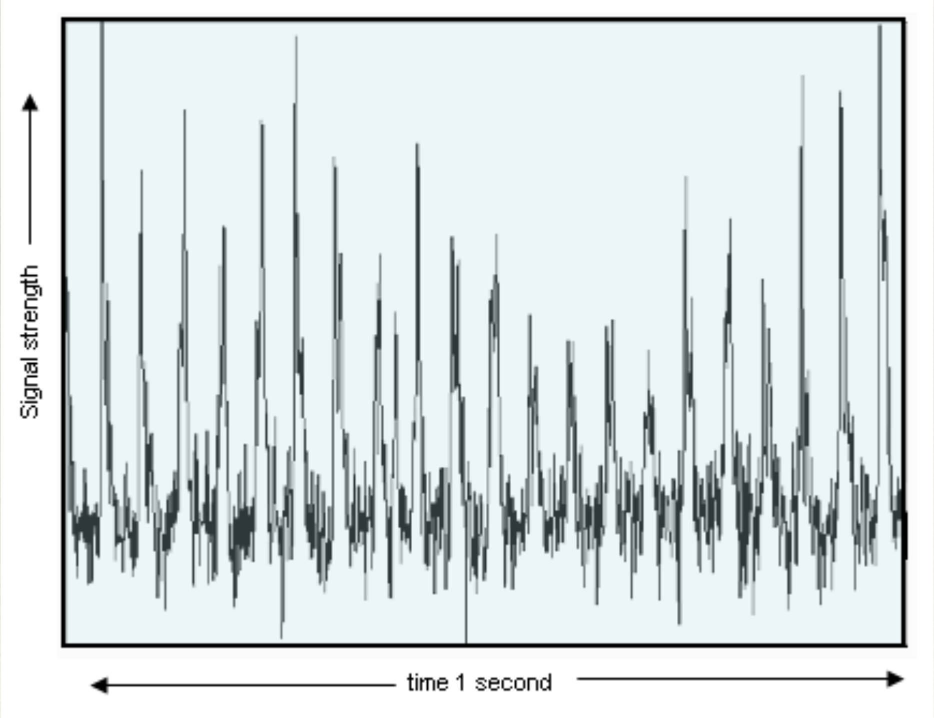
$$P^2 > \frac{3\pi}{G\rho}$$

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

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

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

Pulsars

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

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

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'

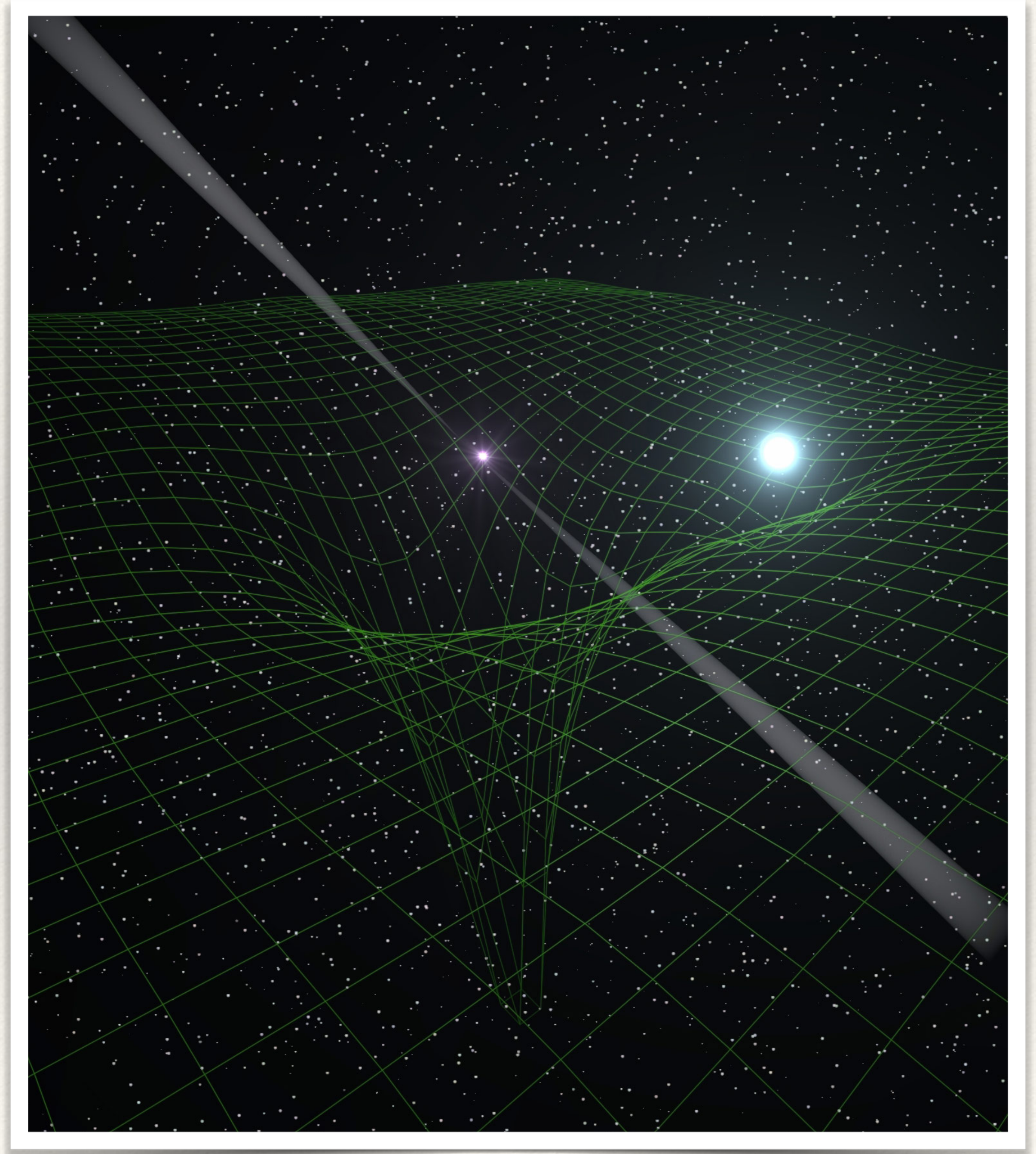
(according to the National Radio Astronomy Observatory)

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

(2) Sources of gravitational waves??

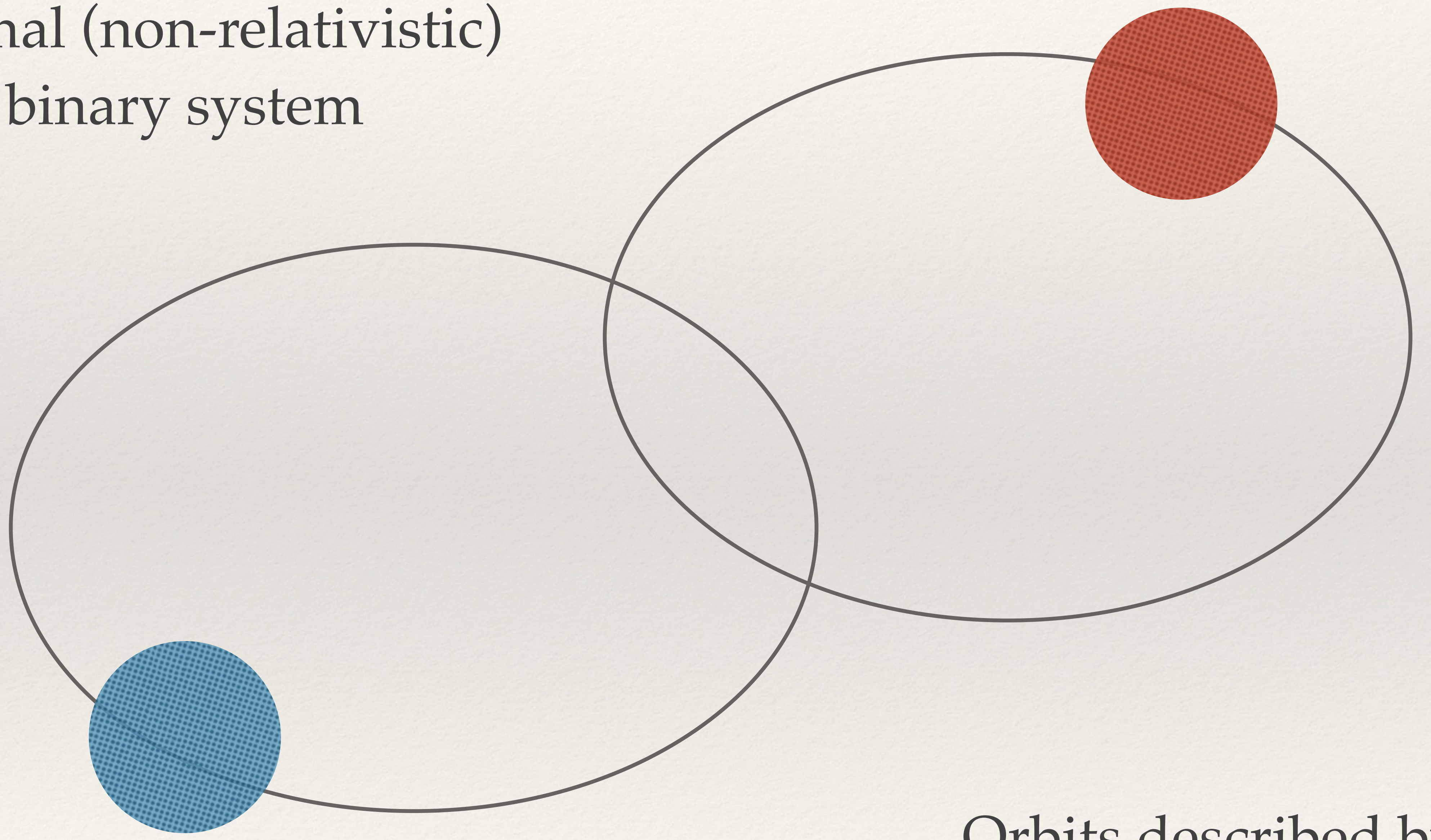
Pulsars as GR laboratories

- 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

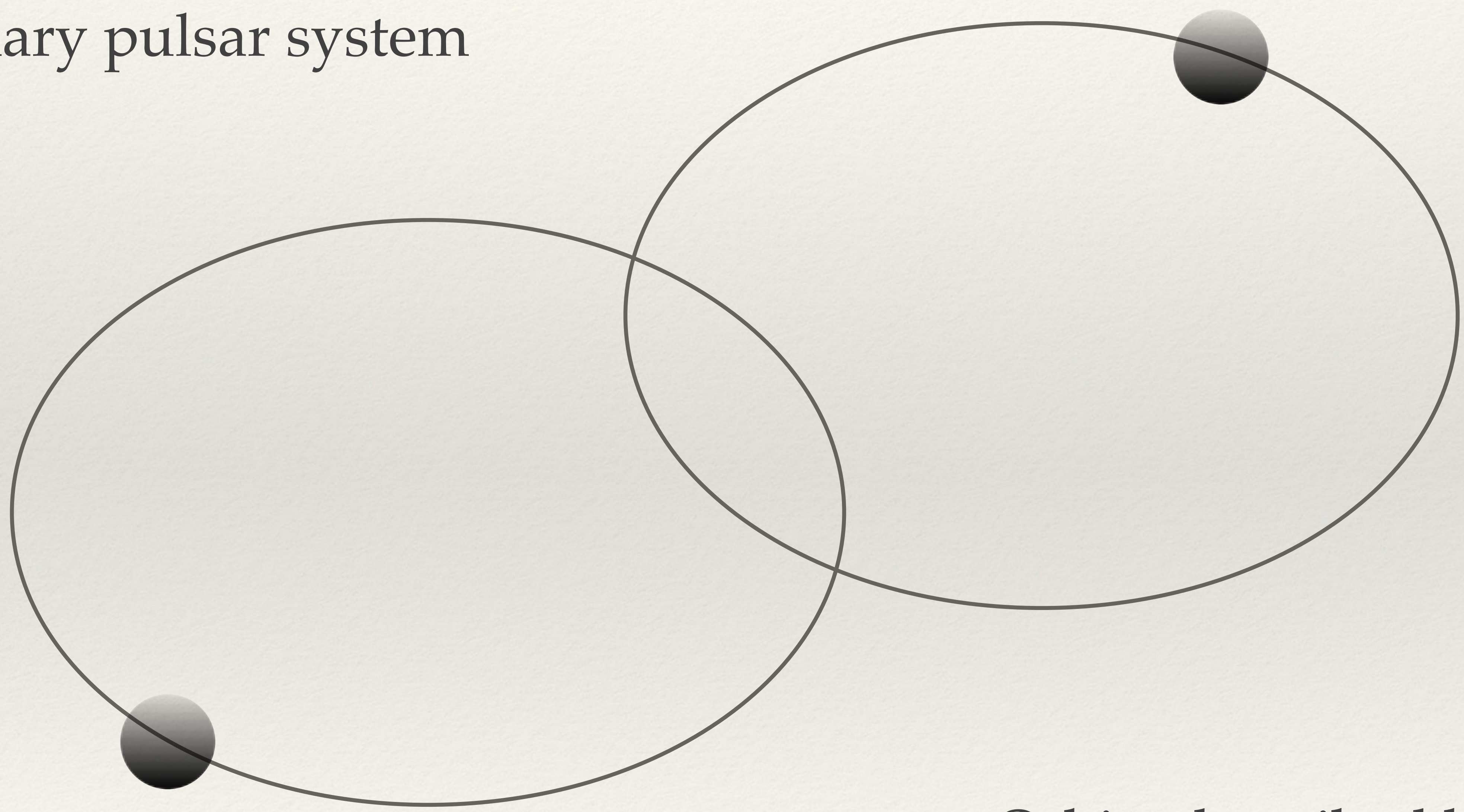
Normal (non-relativistic)
binary system



Orbits described by
'Keplerian parameters'

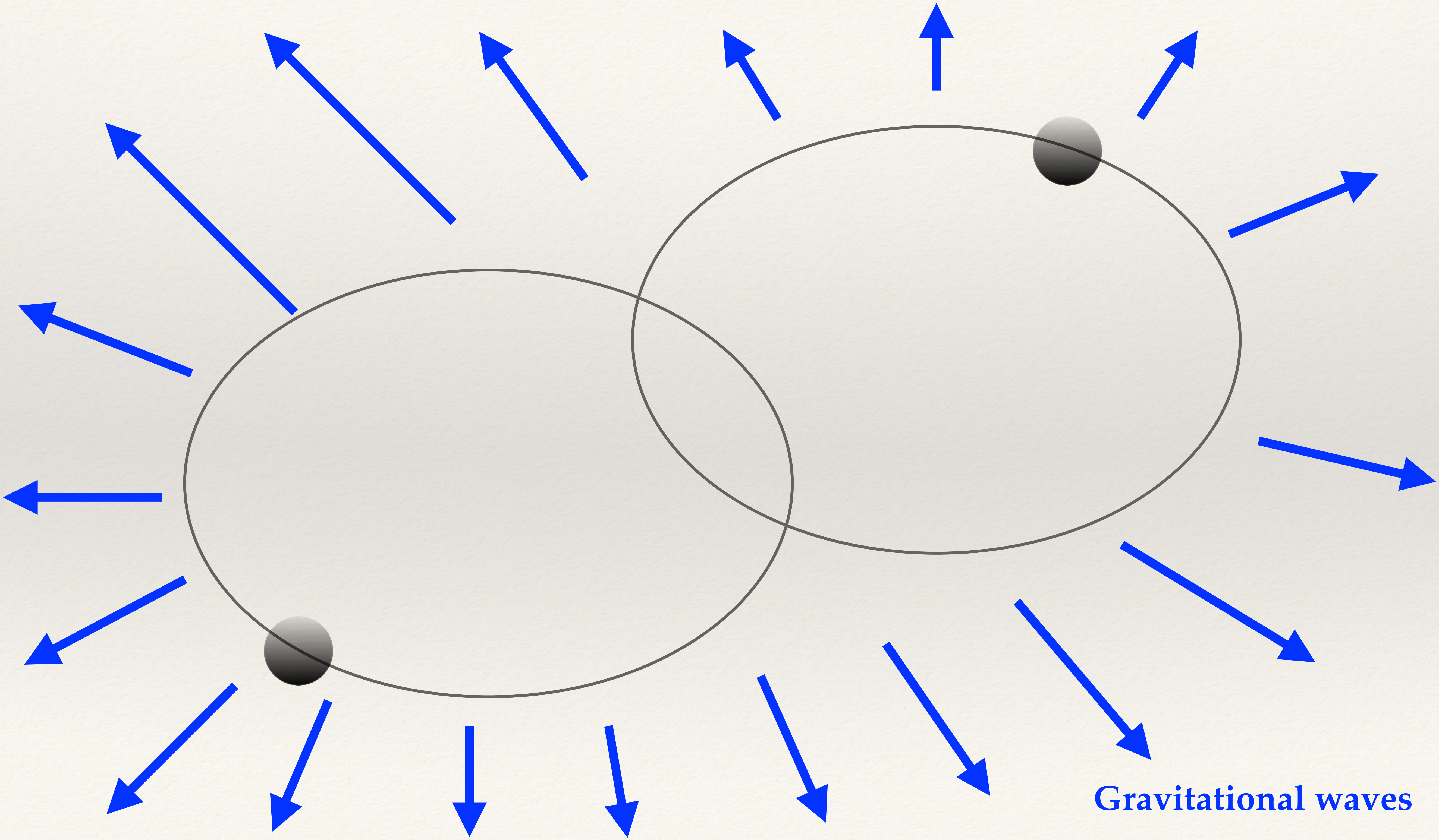
Pulsars as GR laboratories

Binary pulsar system



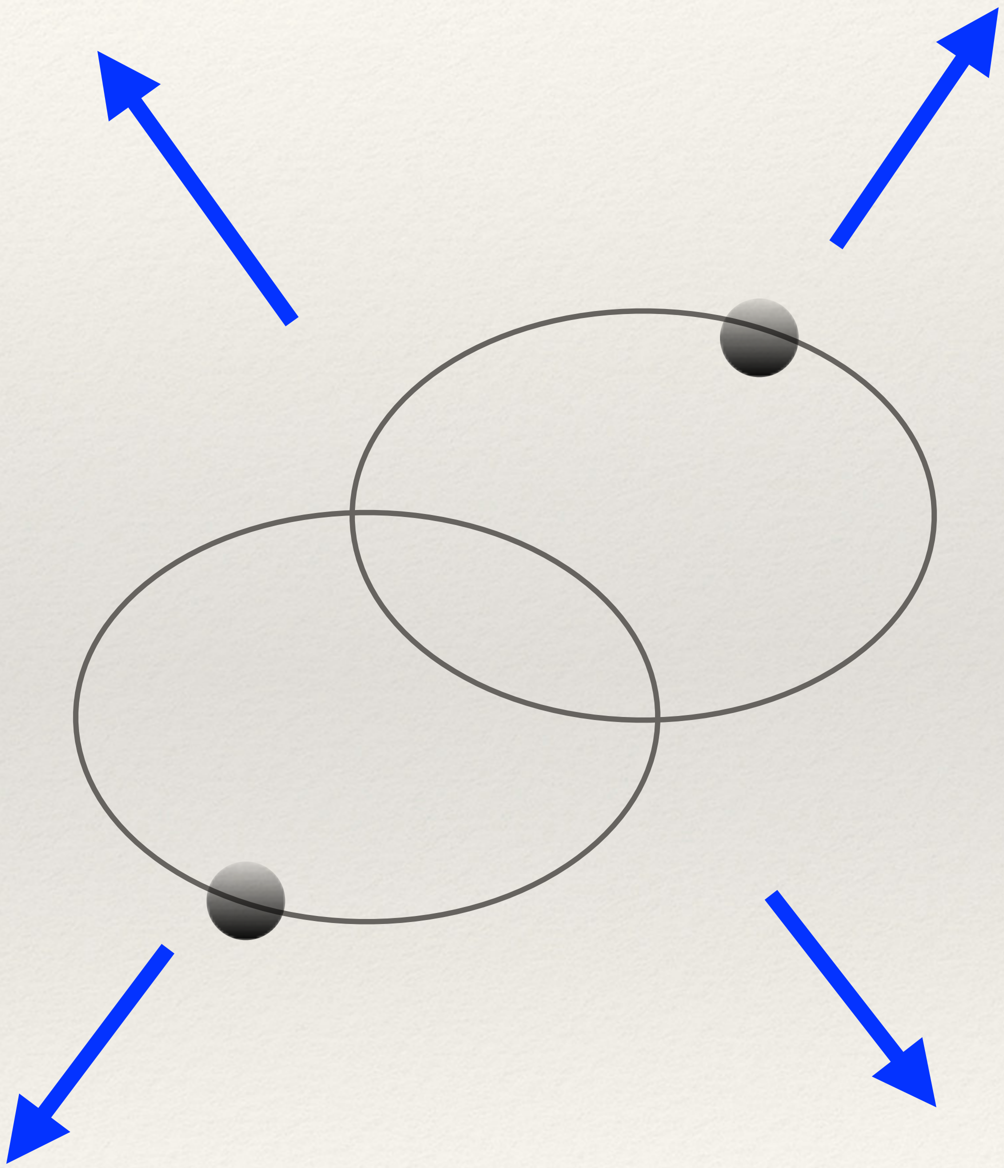
Orbits described by
'Post-Keplerian parameters'

Pulsars as GR laboratories



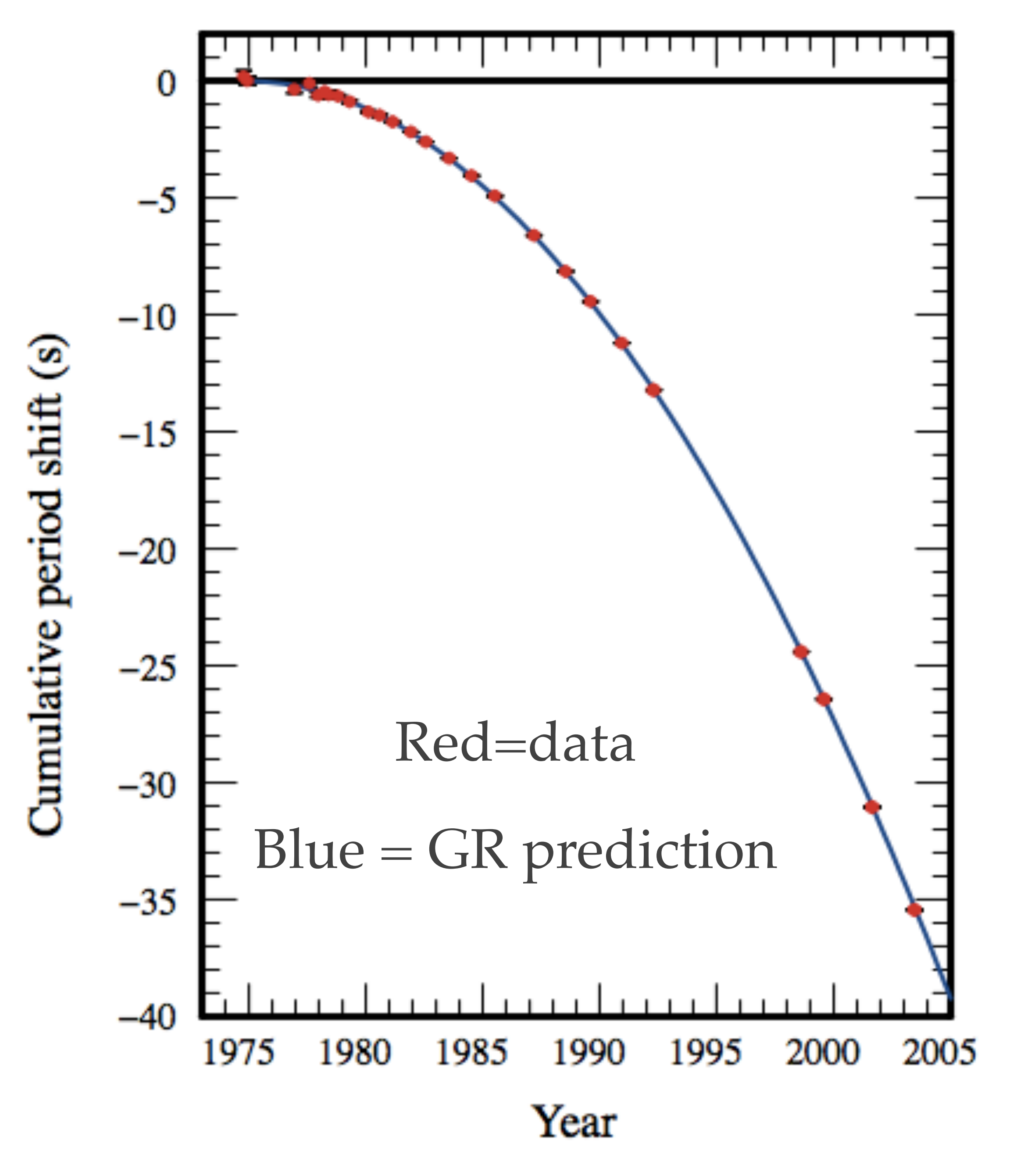
Pulsars as GR laboratories

- 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'?

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'?

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

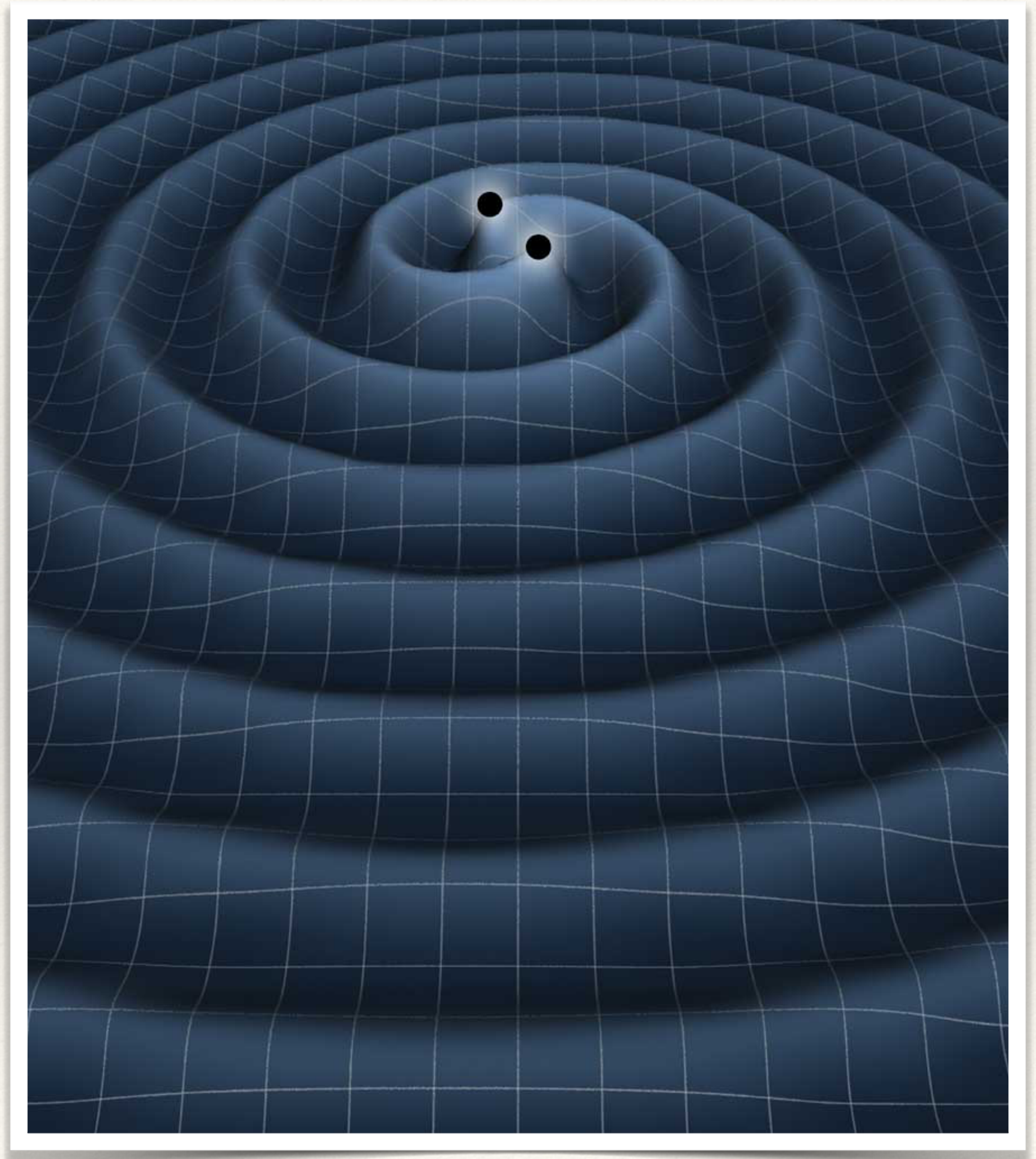
Relies on pulsars being the most accurate clocks in existence:

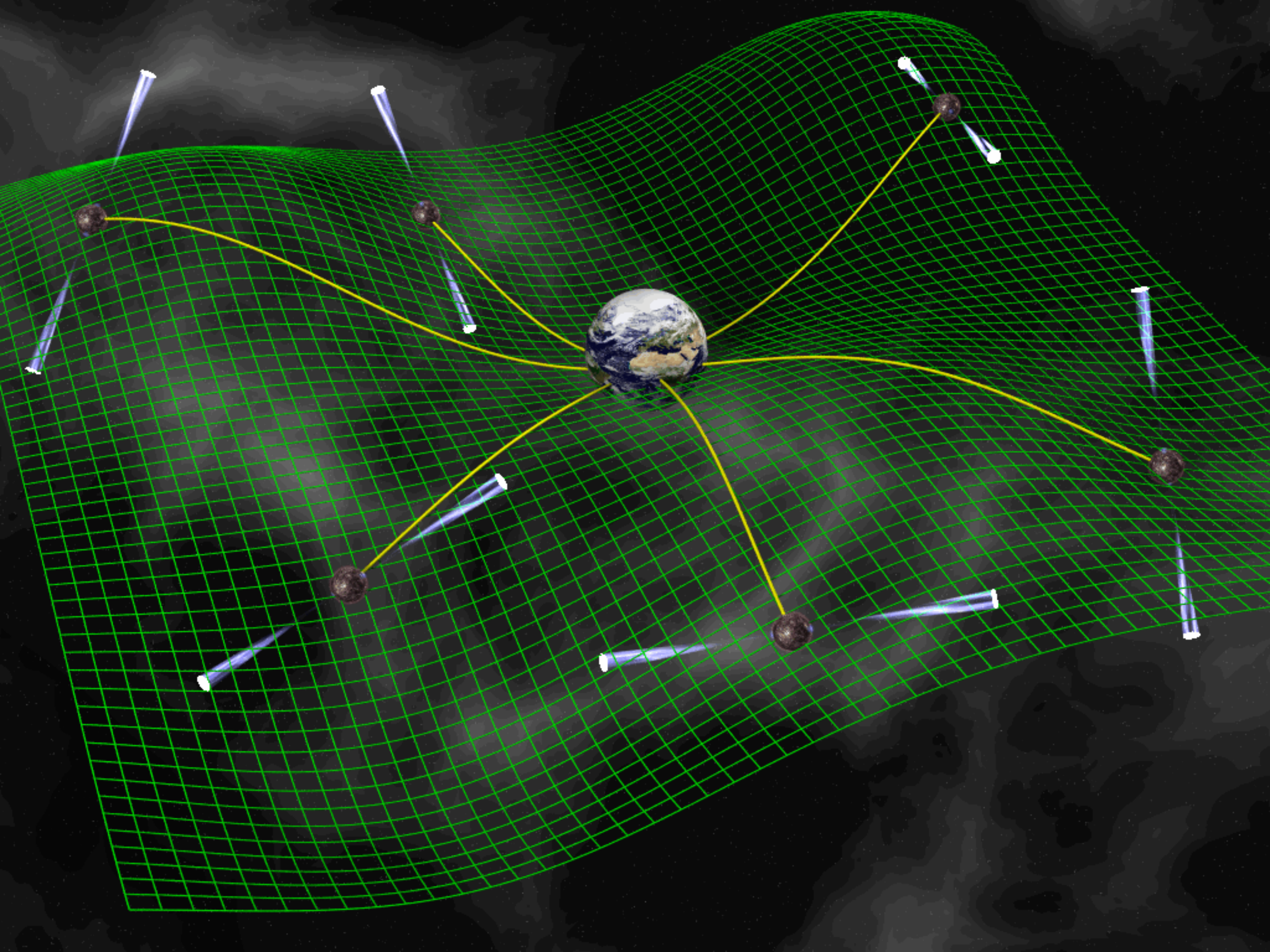
The measured period of the millisecond pulsar PSR B1937+21 is 1.5578064688197945 +/- 0.0000000000000004 milliseconds!

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



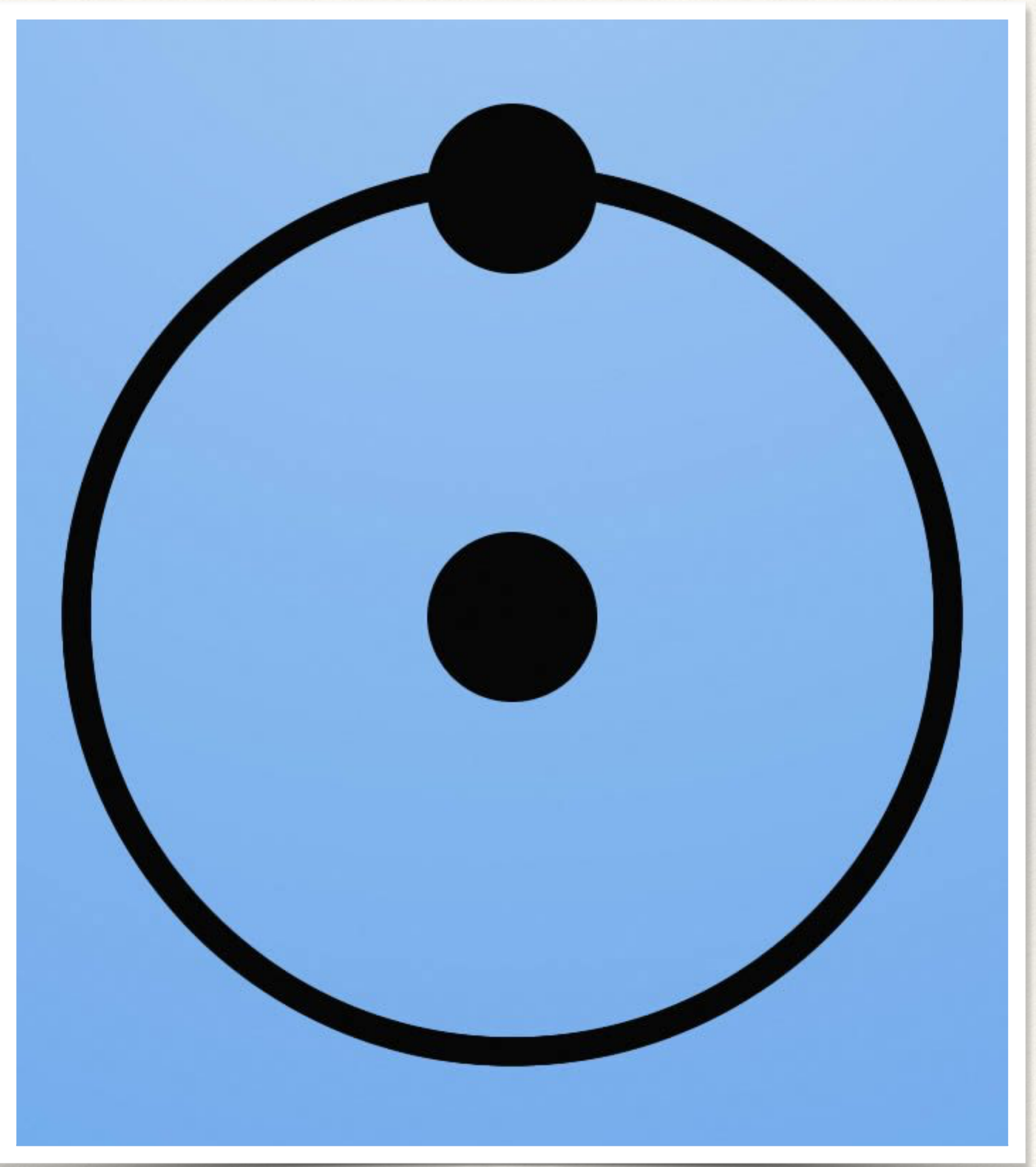


What is in the radio sky?

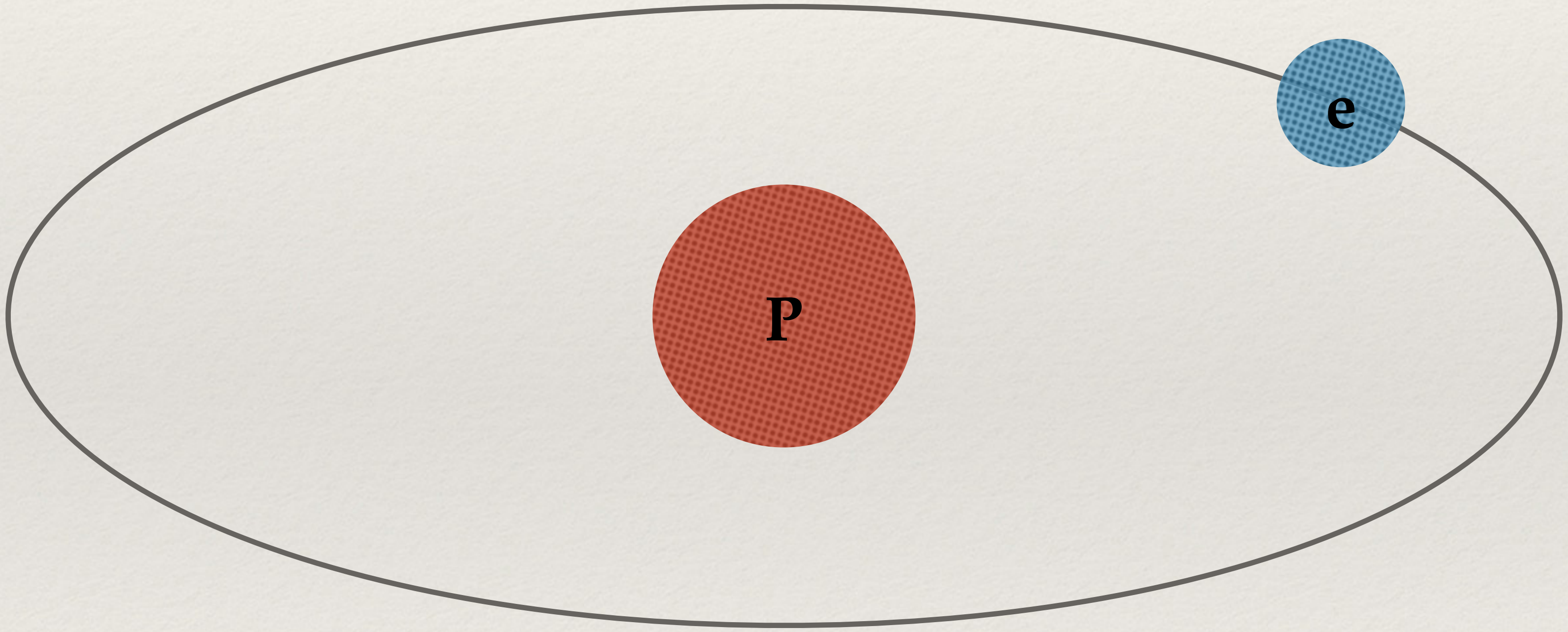
- Pulsars
- Atomic hydrogen
- Radio emission from galaxies

Neutral atomic hydrogen

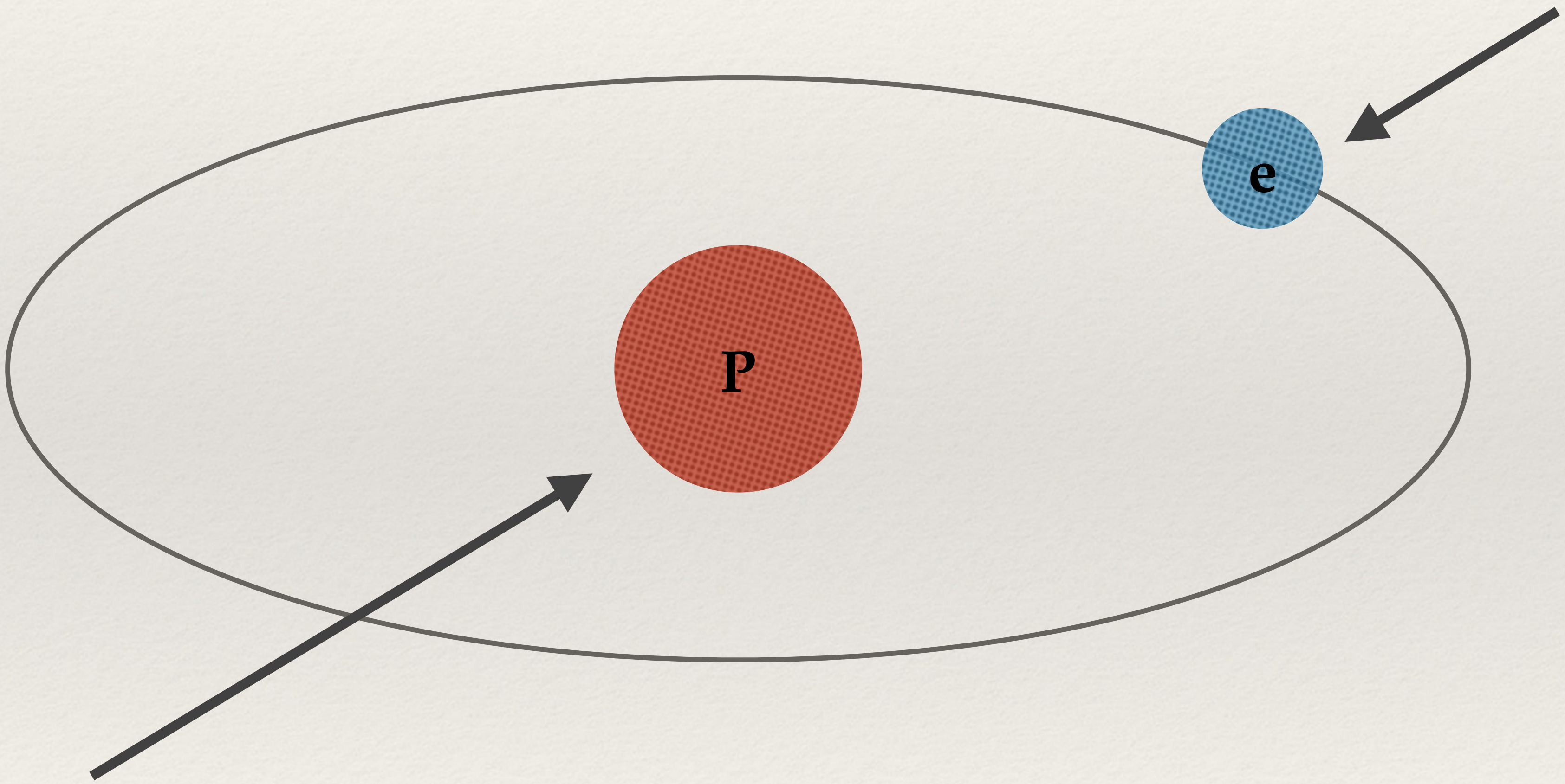
- Hydrogen is the most common substance in the Universe (~75% of all baryons)
- In 1942, van de Hulst predicted that there would be a form of line emission from hydrogen atoms



Neutral atomic hydrogen



Neutral atomic hydrogen

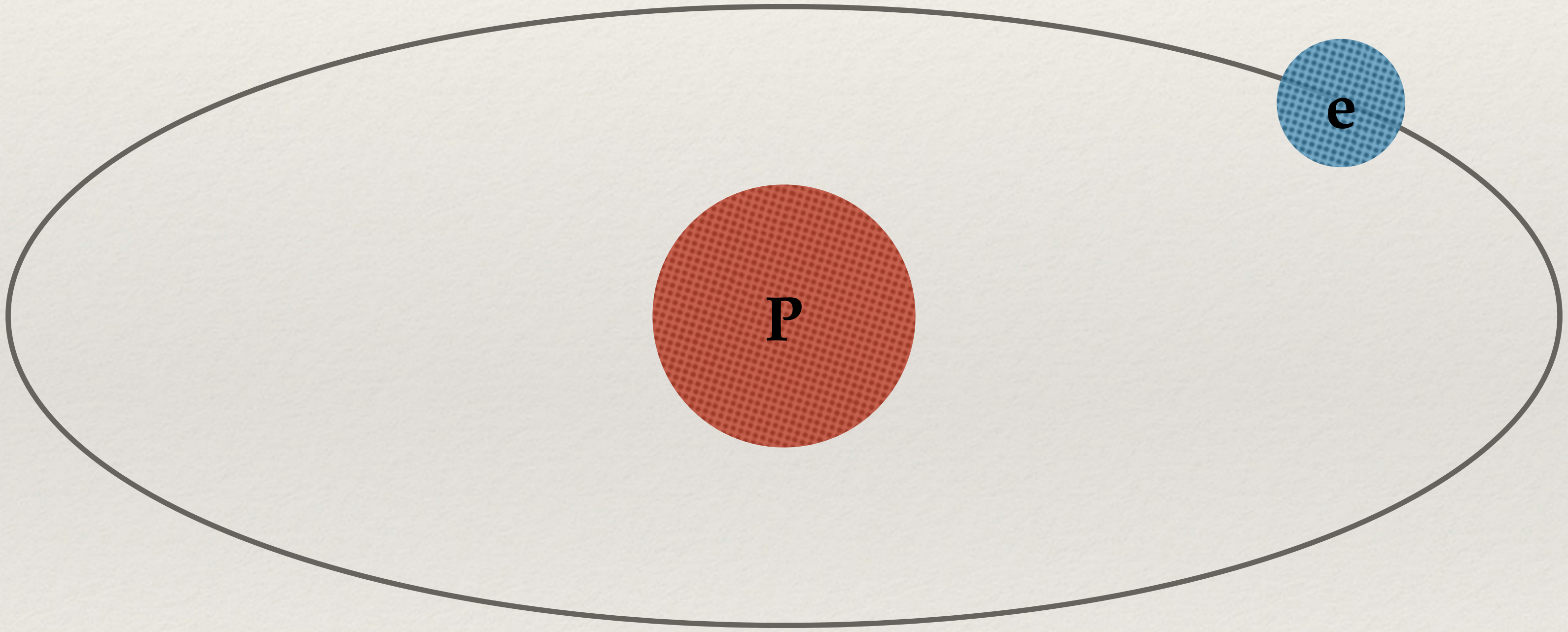


Electrons are Fermions,
spin = 1/2

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

Neutral atomic hydrogen

Two possible spin states for the atom:

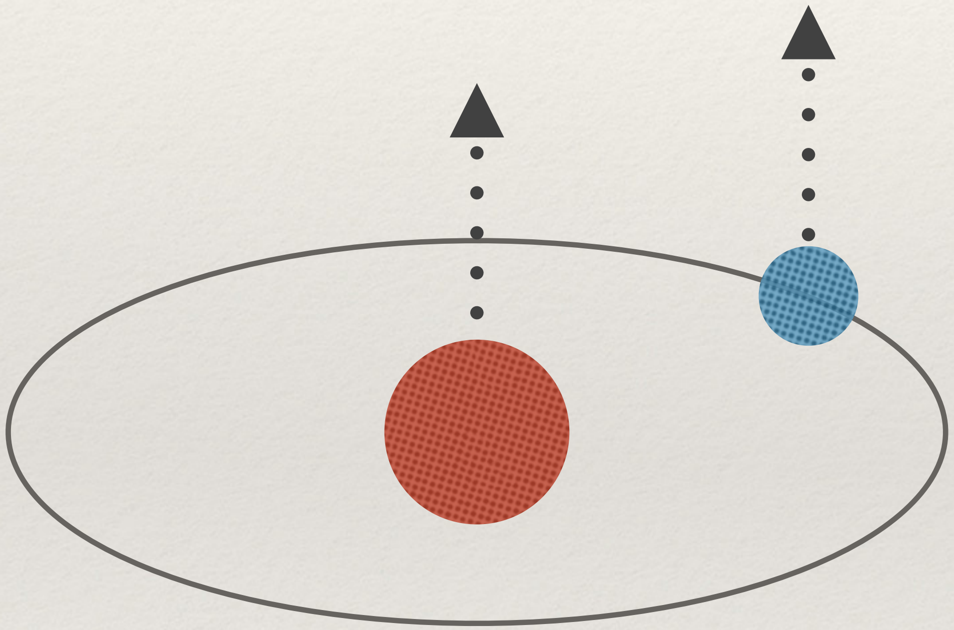


Neutral atomic hydrogen

Two possible spin states for the atom:

Neutral atomic hydrogen

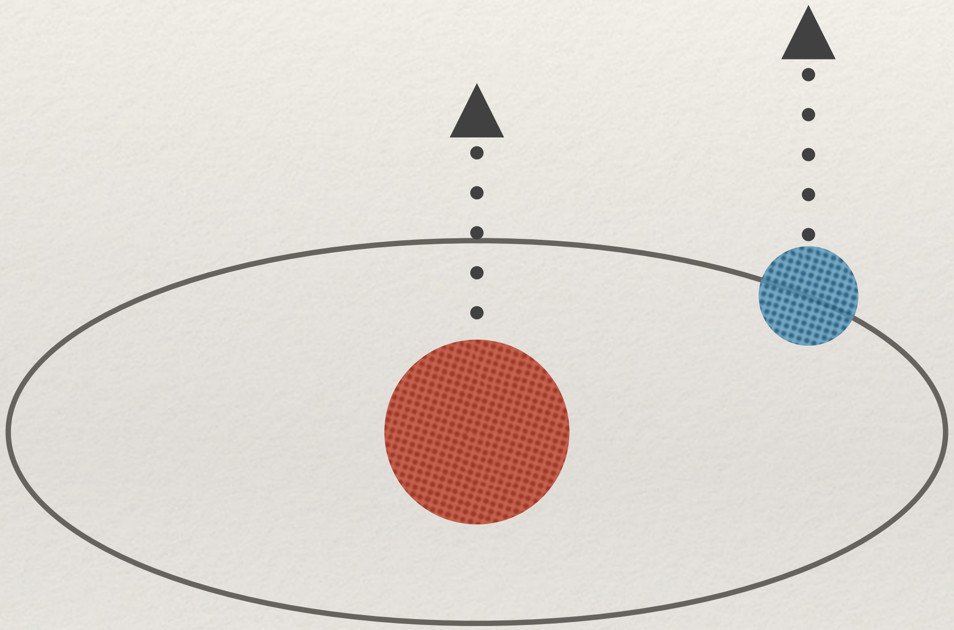
Two possible spin states for the atom:



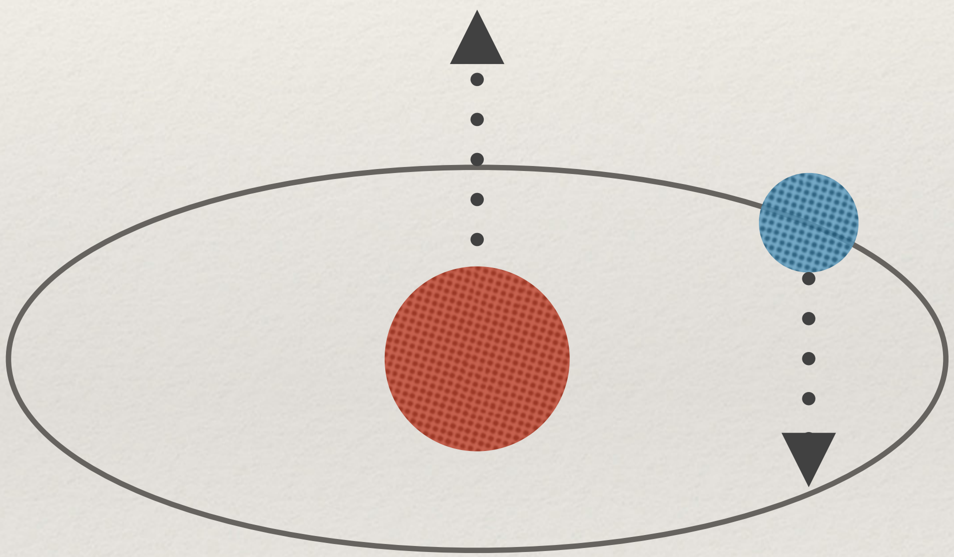
Spin parallel

Neutral atomic hydrogen

Two possible spin states for the atom:



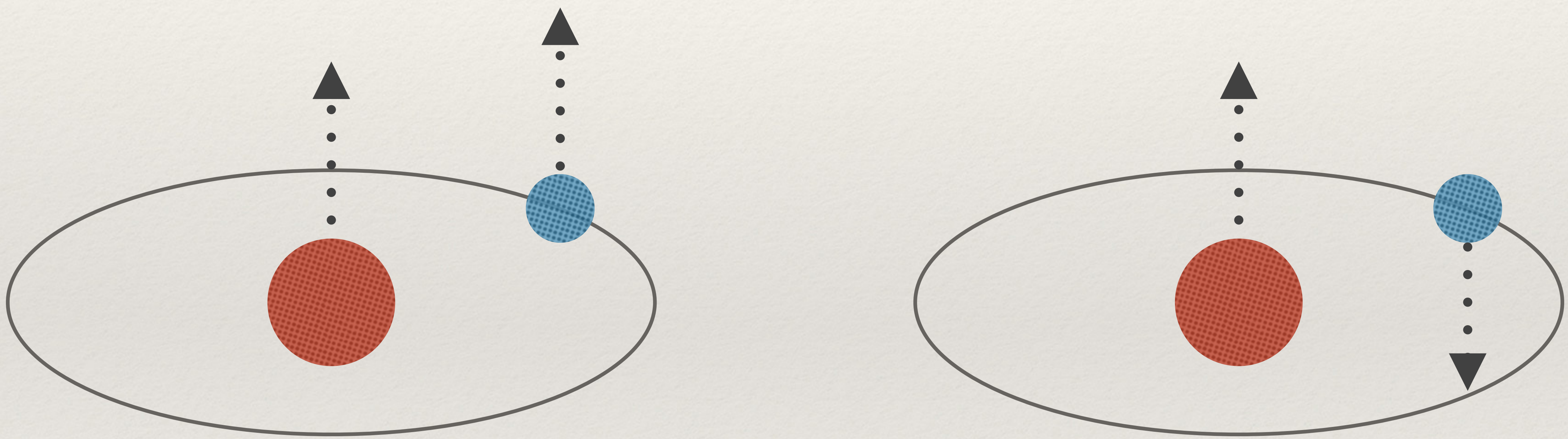
Spin parallel



Spin anti-parallel

Neutral atomic hydrogen

Two possible spin states for the atom:

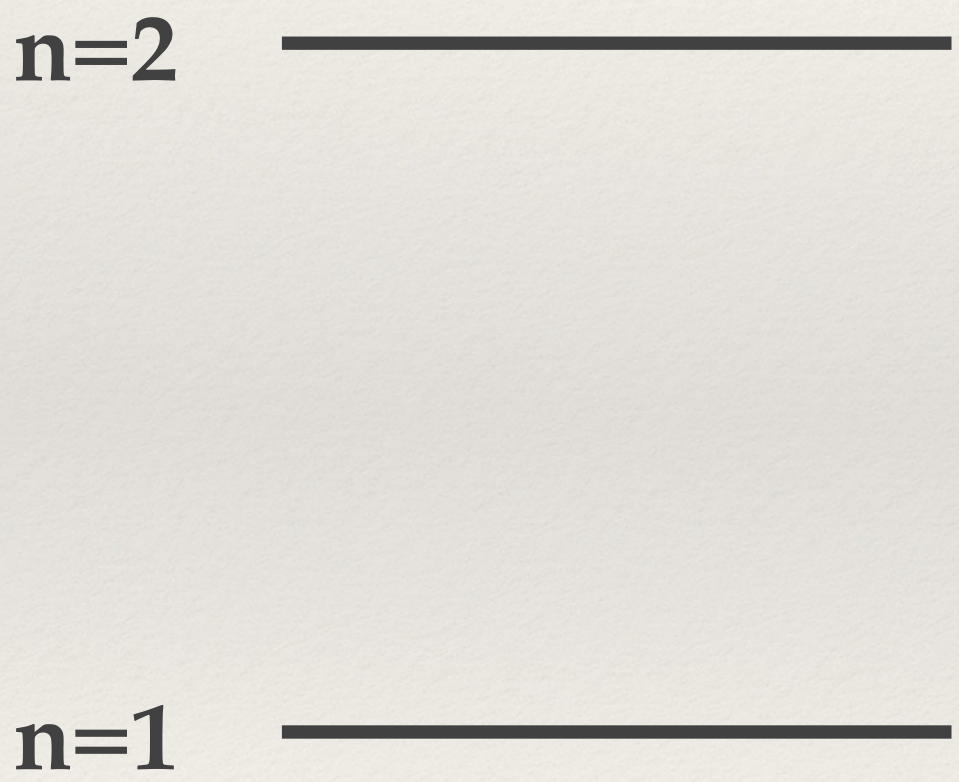


Spin-parallel state has slightly higher energy

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’



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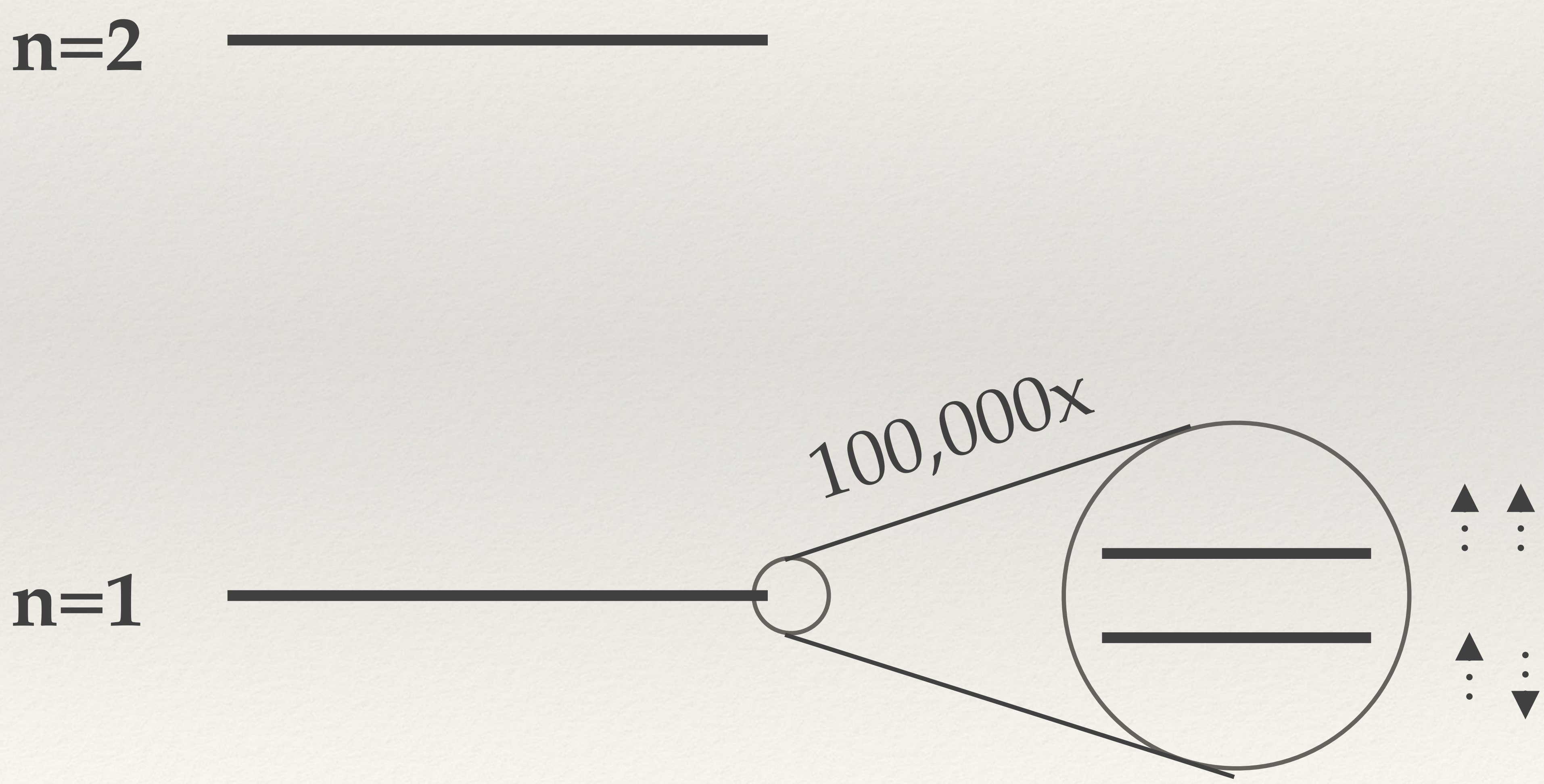

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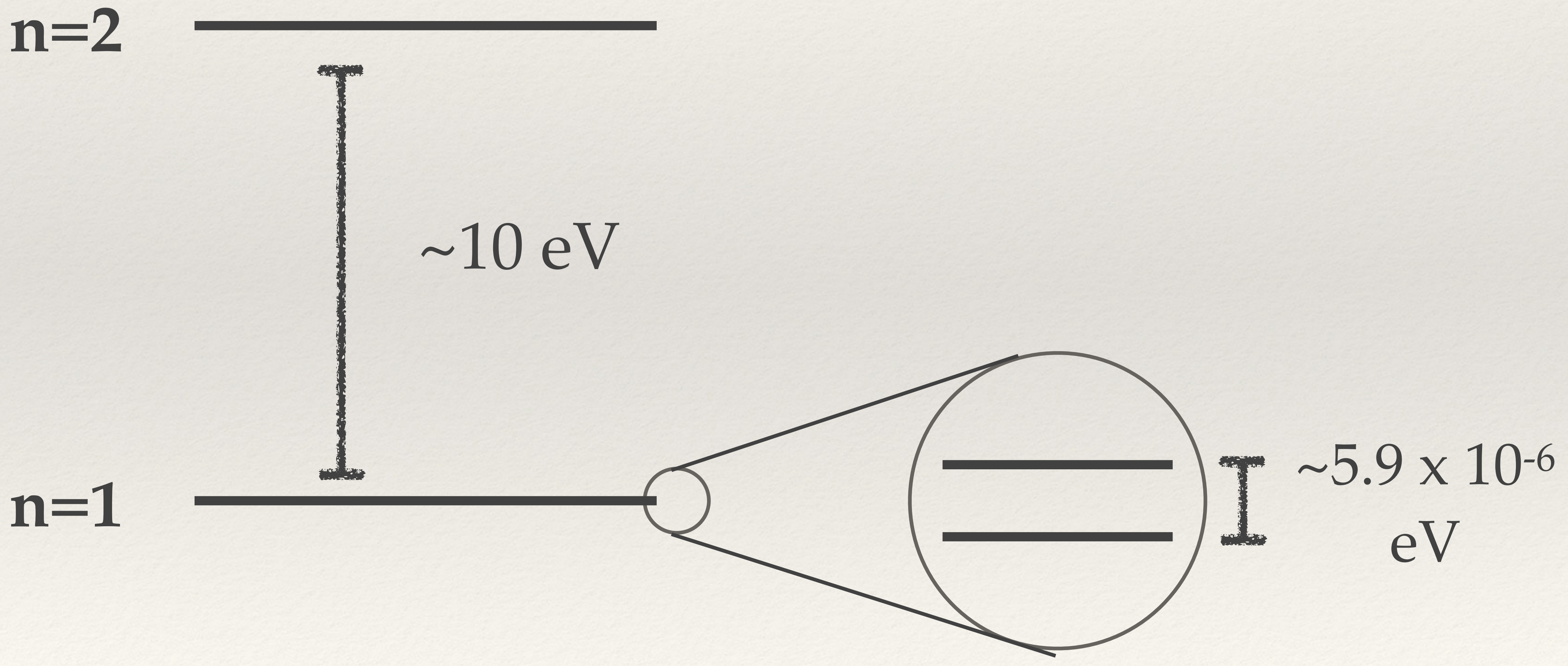


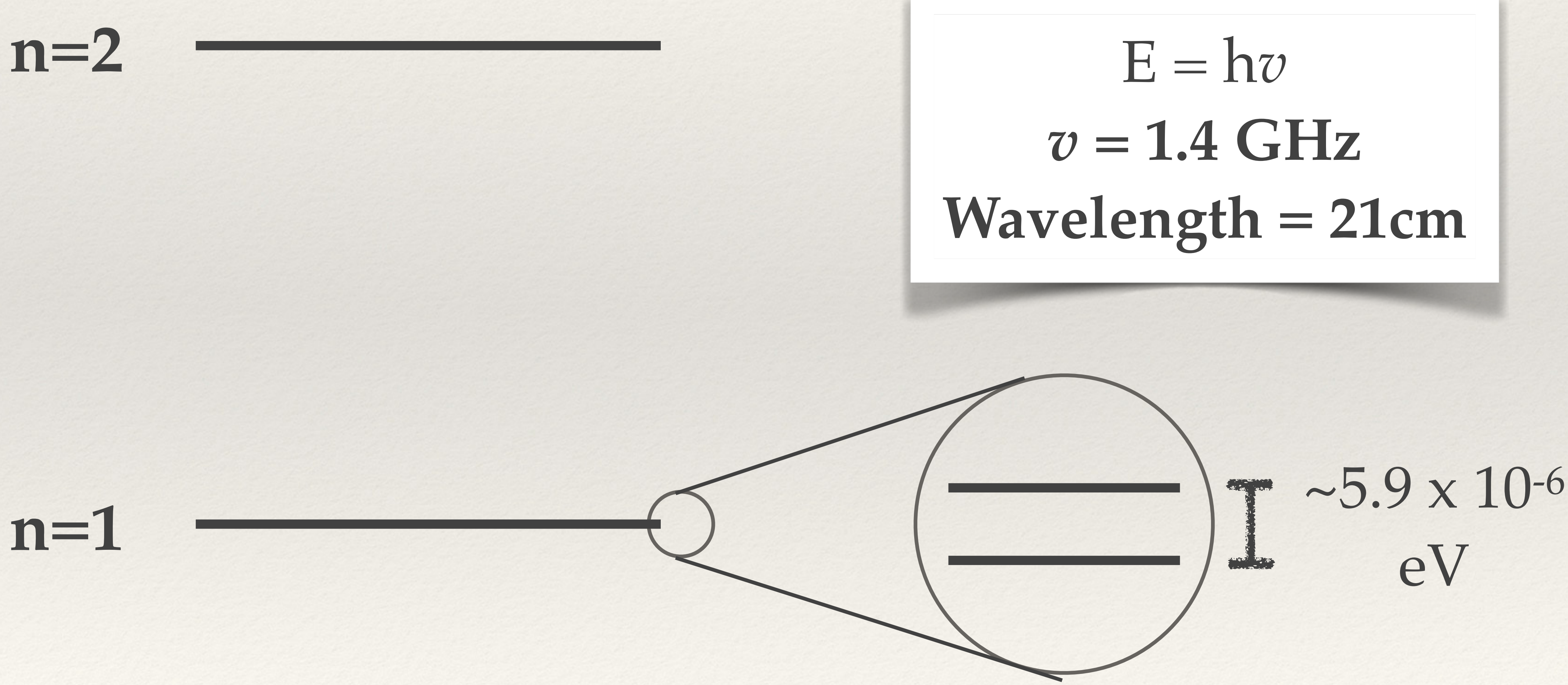
Neutral atomic hydrogen

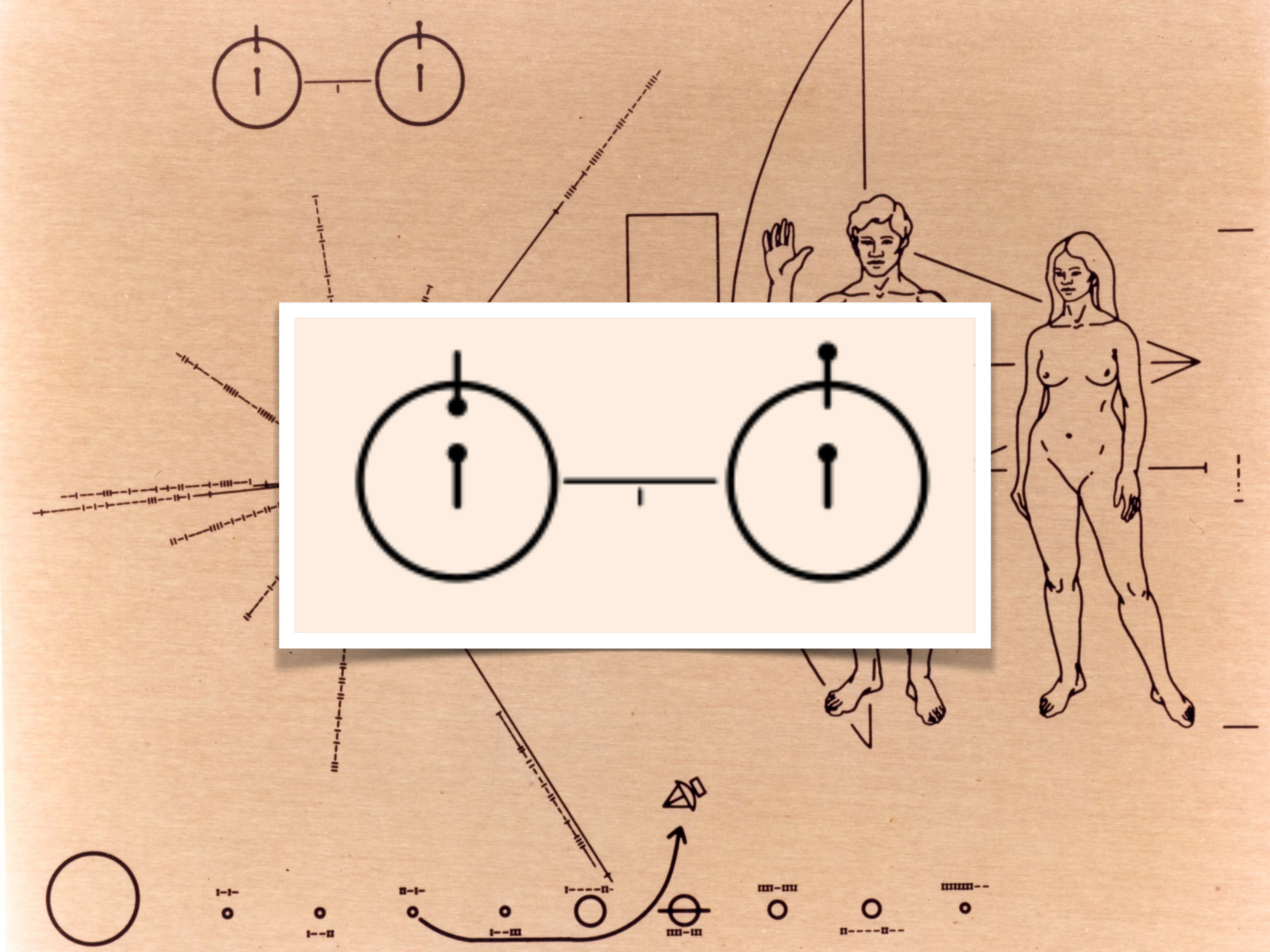
This transition is called 'hyperfine structure'

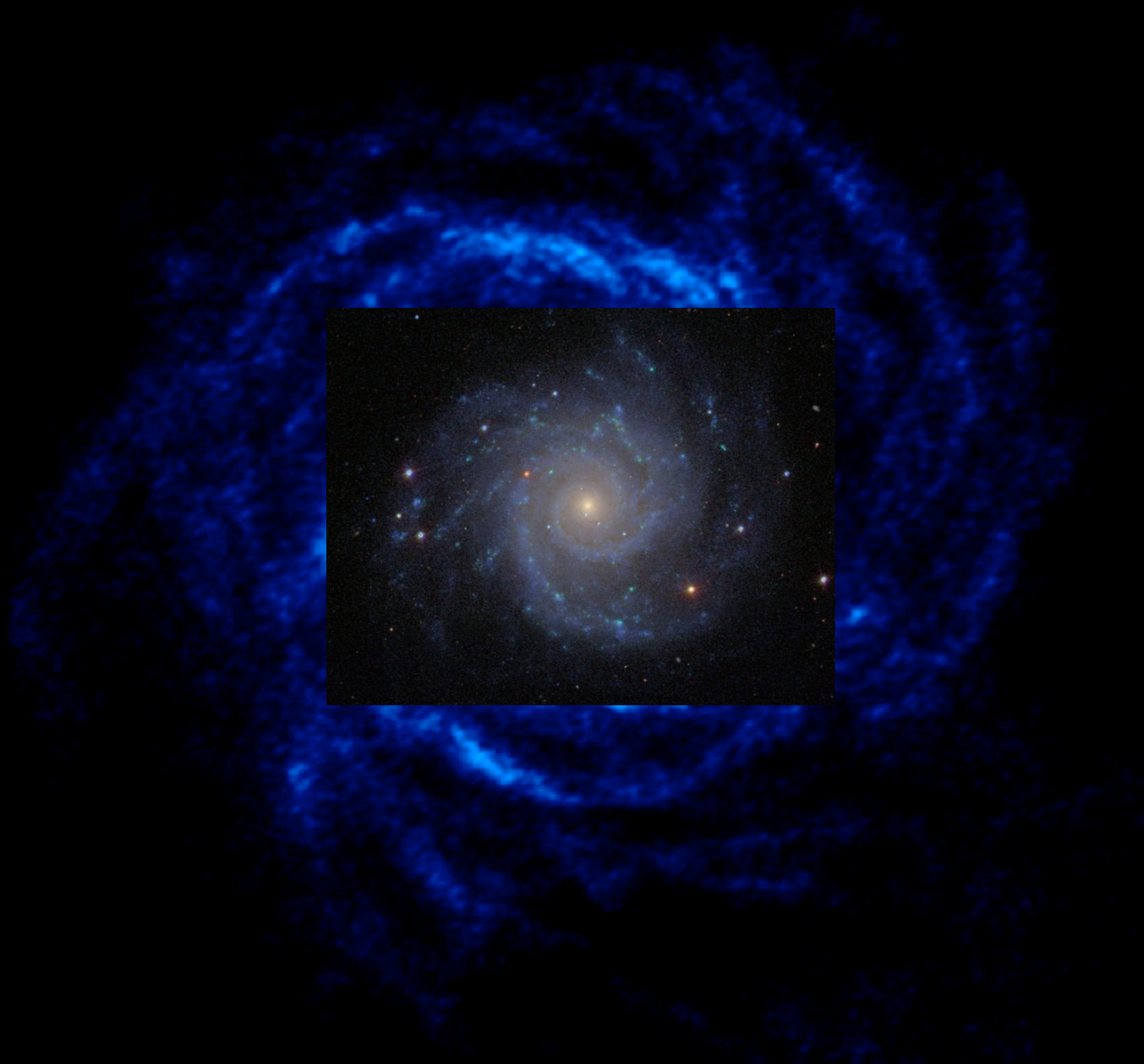
$E = h\nu$

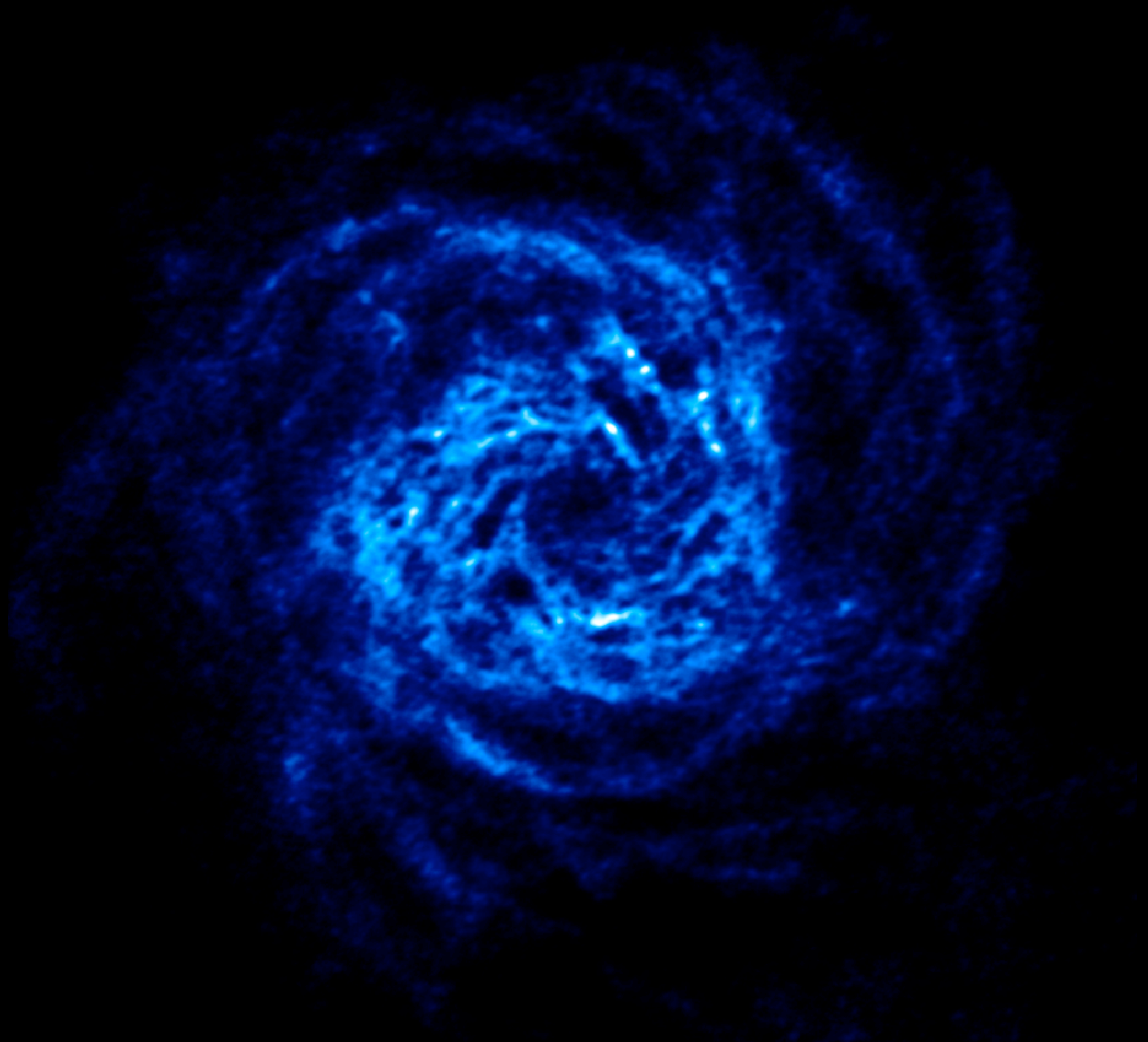
ν = 1.4 GHz

Wavelength = 21cm









Neutral atomic hydrogen

How much HI is there?

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

Neutral atomic hydrogen

How much HI is there?

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

HI mass, in units of 'solar masses'

Flux in 21cm line

Distance to galaxy, in Mpc

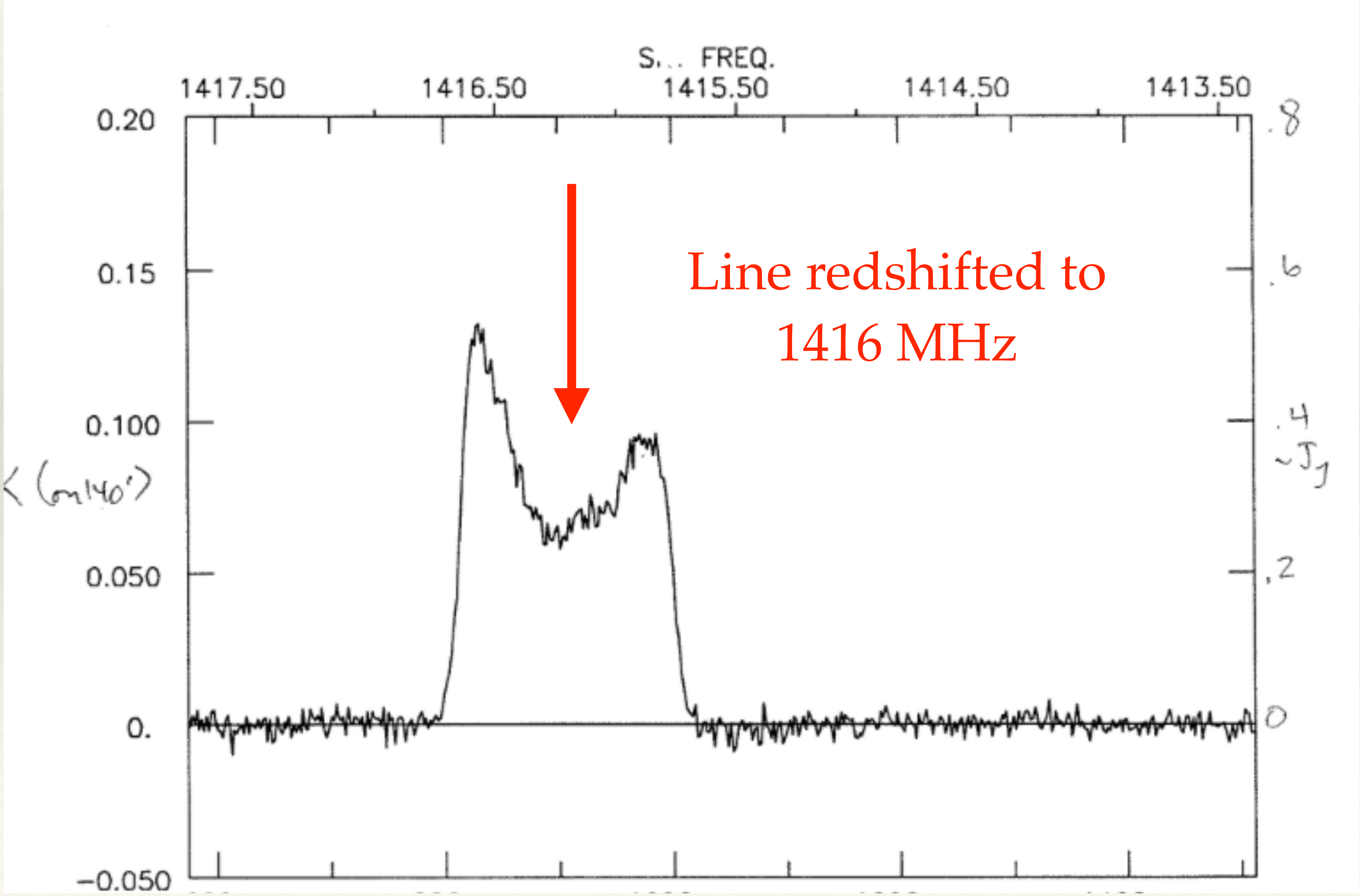
Neutral atomic hydrogen

How much HI is there?

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

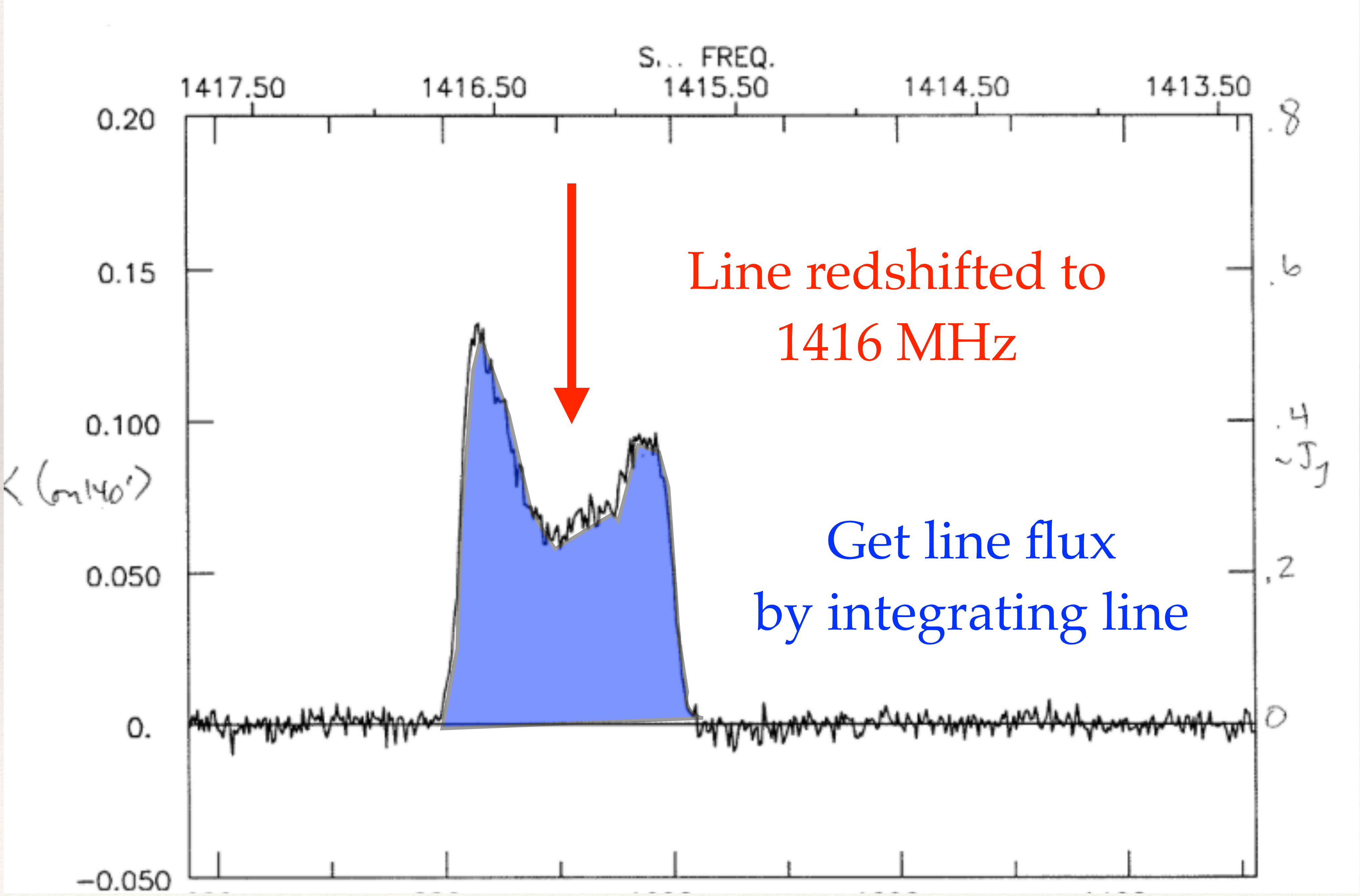
Neutral atomic hydrogen

How much HI is there?



Neutral atomic hydrogen

How much HI is there?



Neutral atomic hydrogen

How much HI is there?

Line at 1420 MHz redshifted to 1416 MHz

$$\frac{v}{c} = (1 - \frac{\nu_{\rm obs}}{\nu_{\rm rest}})$$

$$v = 2.99 \times 10^8 \text{ m/s } (1 - \frac{1416 \text{ MHz}}{1420 \text{ MHz}})$$

$$v = 890 \text{ km s}^{-1}$$

Neutral atomic hydrogen

How much HI is there?

$$v = 890 \text{ km s}^{-1}$$

$$v = H_0 \text{D}$$

Hubble's Law

$$\text{D} = \frac{890 \text{ km/s}}{72 \text{ km/s/Mpc}} = 12.4 \text{ Mpc}$$

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

$$\text{M(HI)} = 2.36 \times 10^5 \ (70) \ (12.4)^2 = 2.5 \times 10^9 \text{ M}_\odot$$

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?

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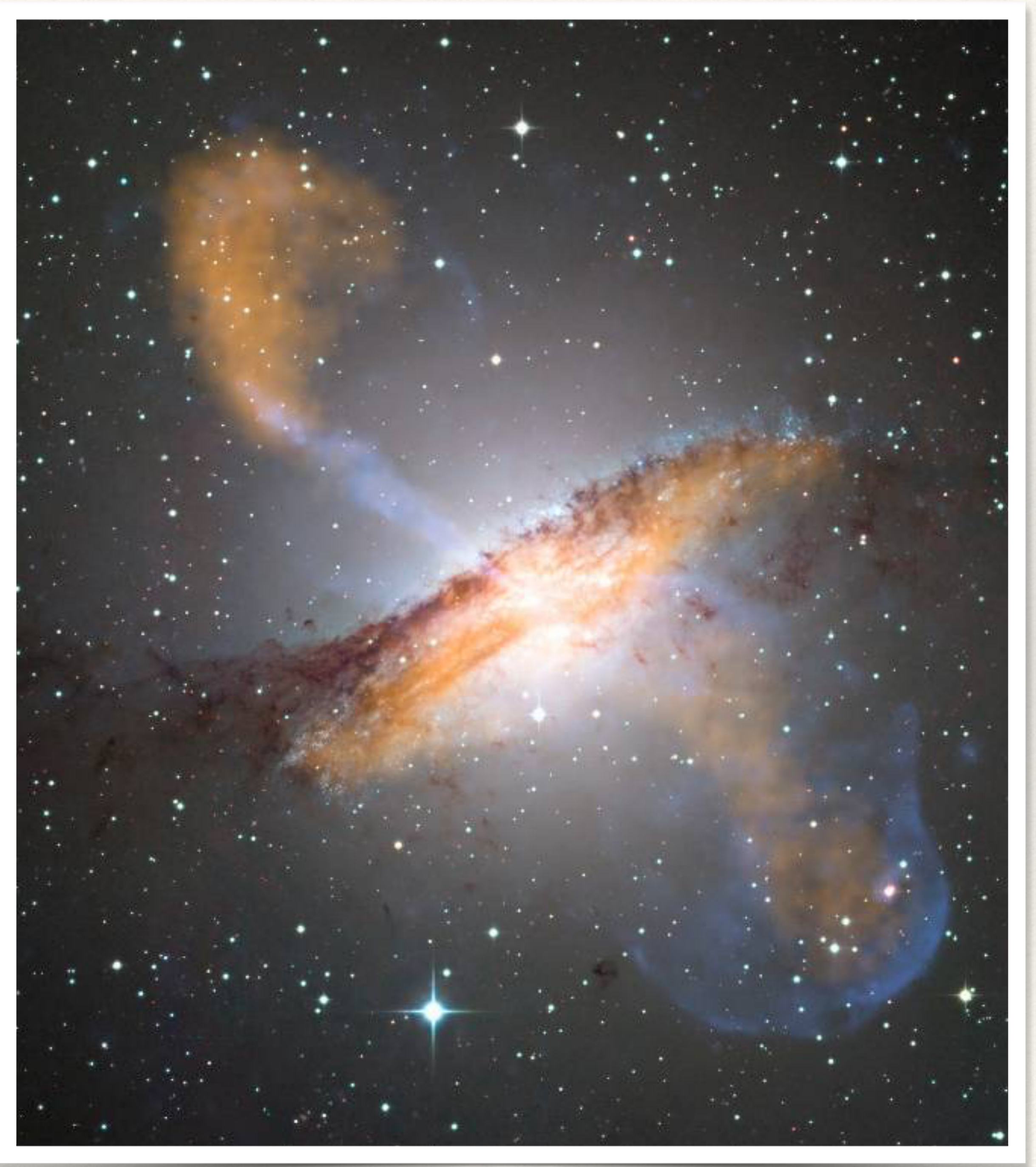
Active galaxies

Normal galaxies

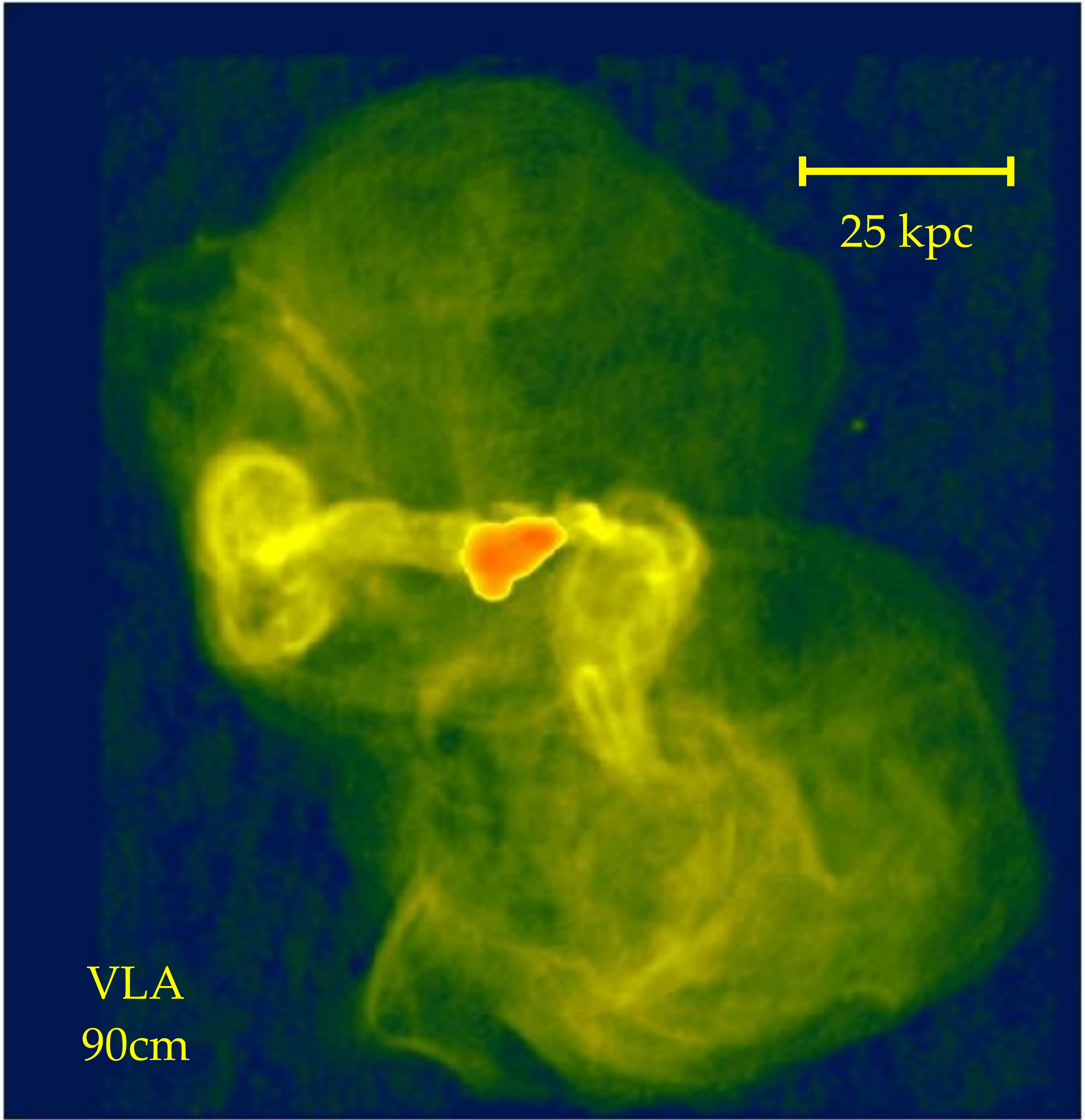
Radio emission from active galaxies

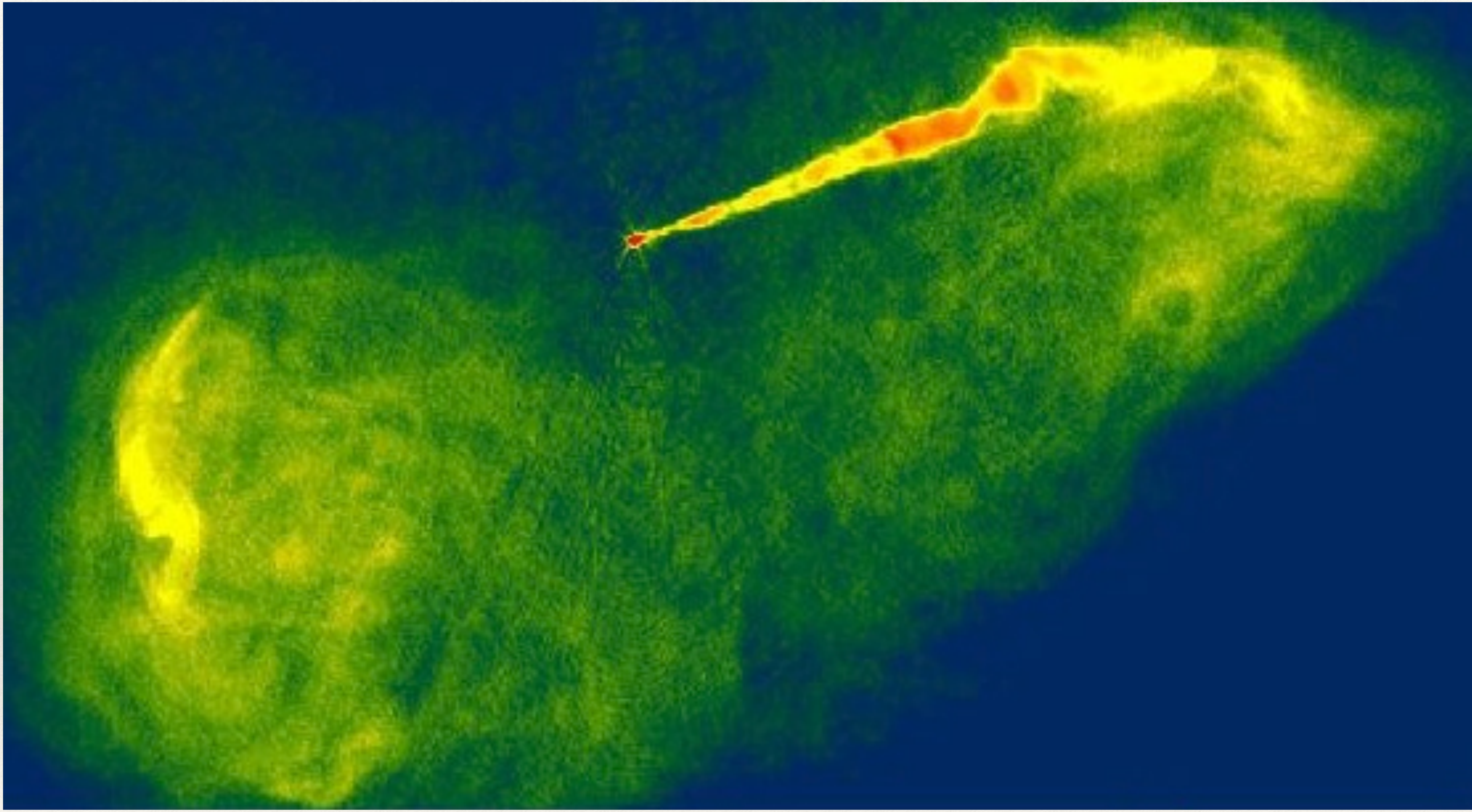
- Type of active galaxy (galaxy with central super-massive black hole).
- Known as AGN — Active Galactic Nuclei
- Radio emission powered by Synchrotron

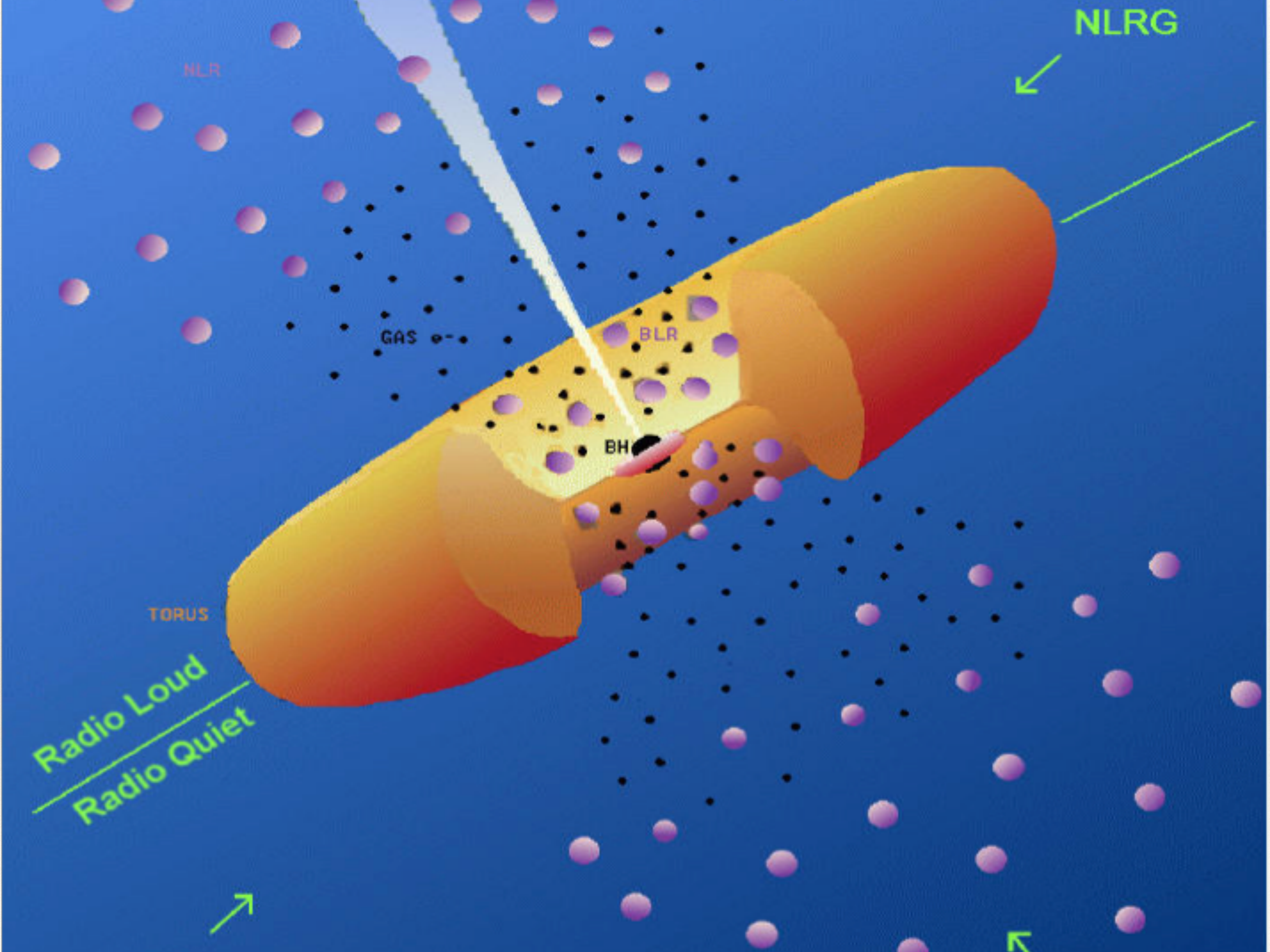


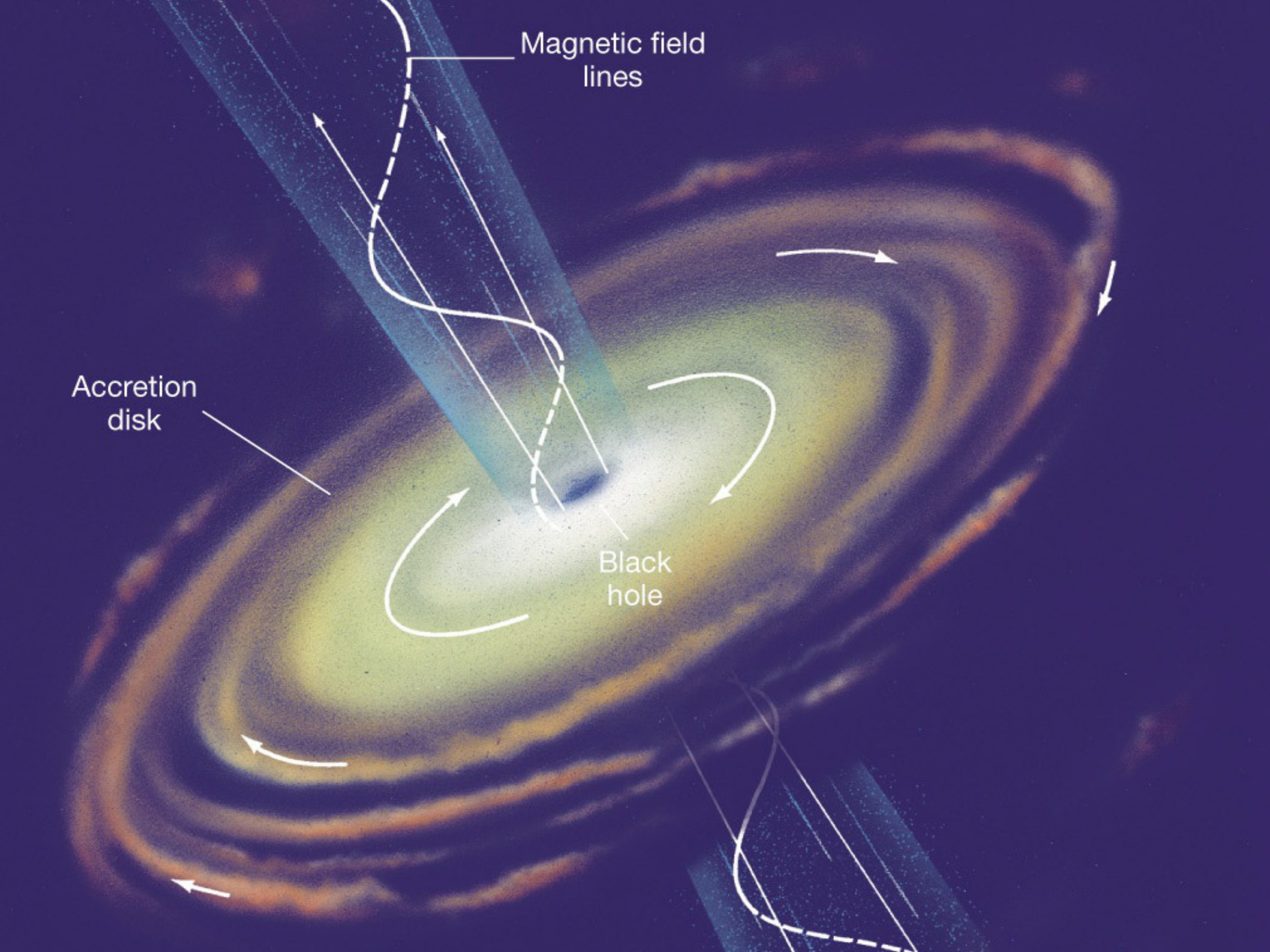
VLA
5 GHz

Parkes
5 GHz

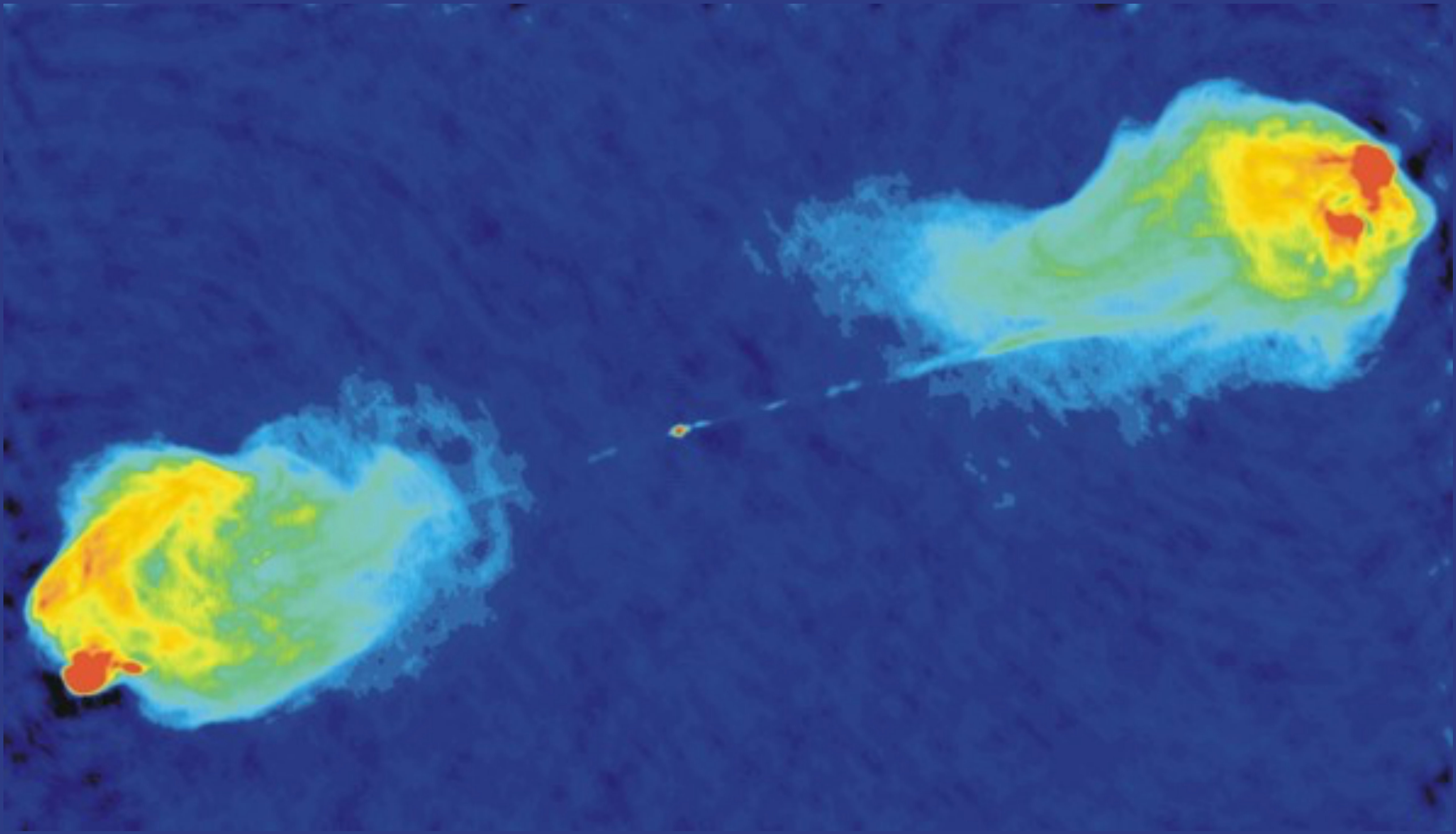

25 kpc
VLA
90cm




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

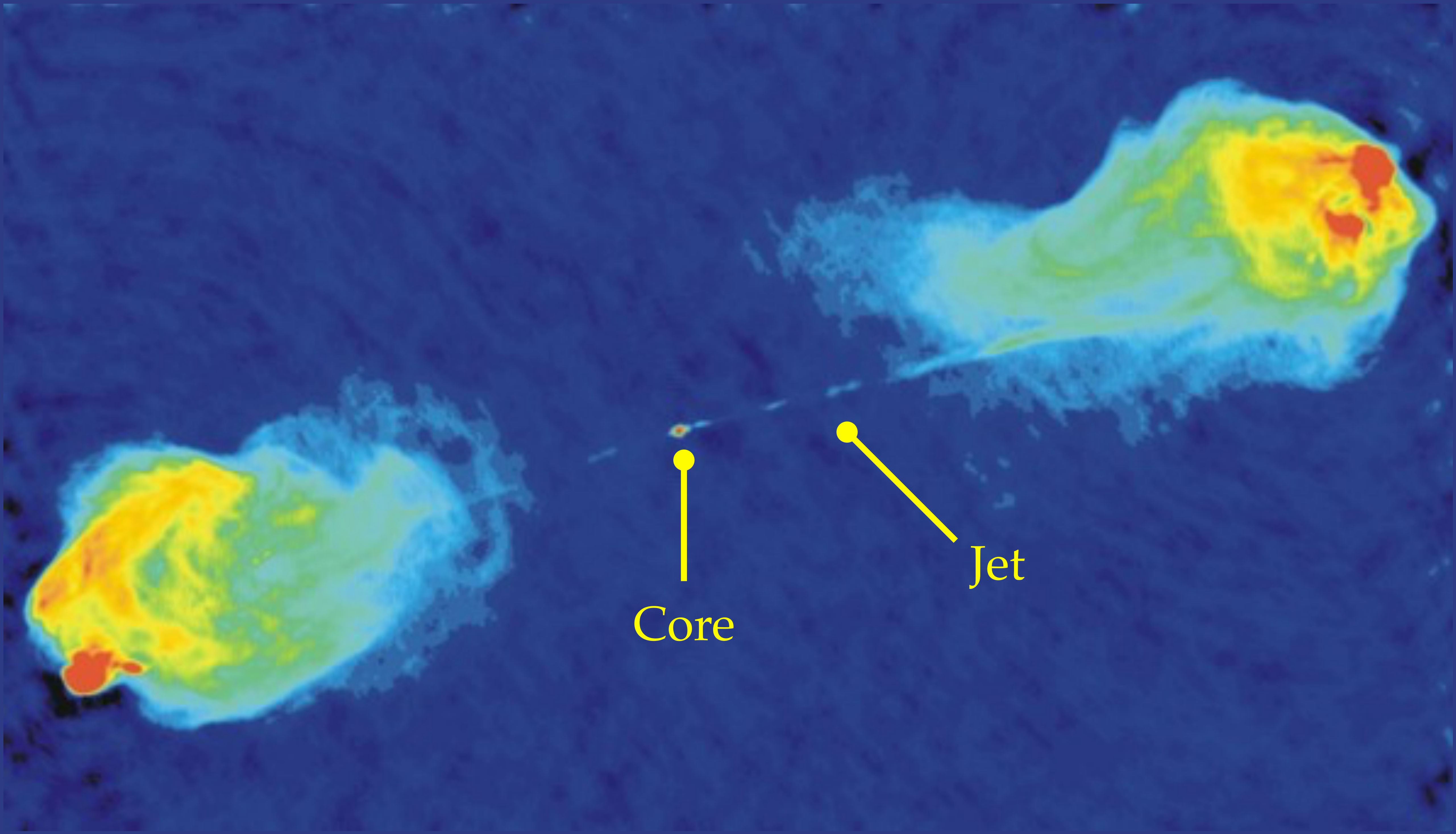

Magnetic field lines
Accretion disk
Black hole

Cygnus A



‘Typical’ radio galaxy

Cygnus A



'Typical' radio galaxy

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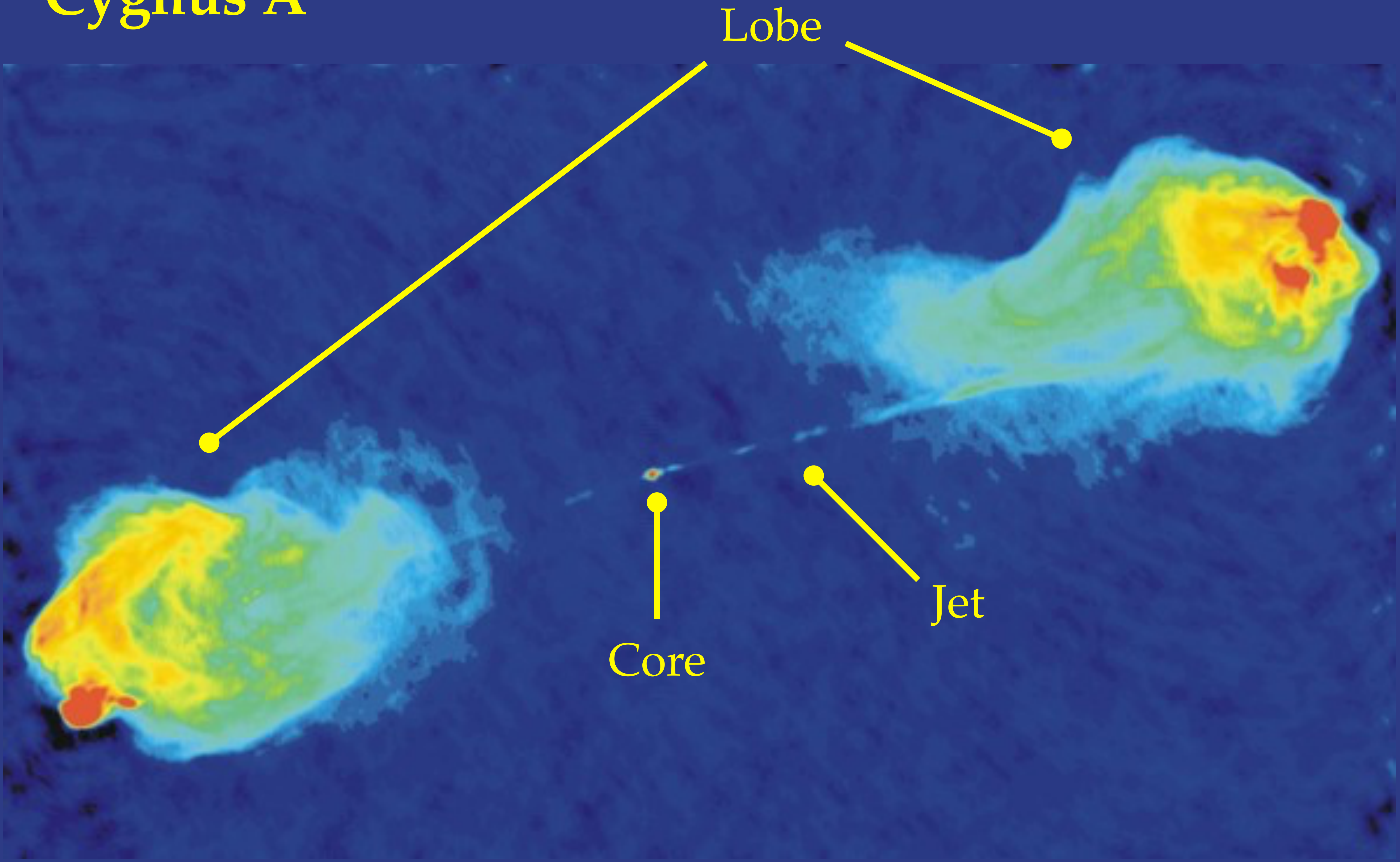
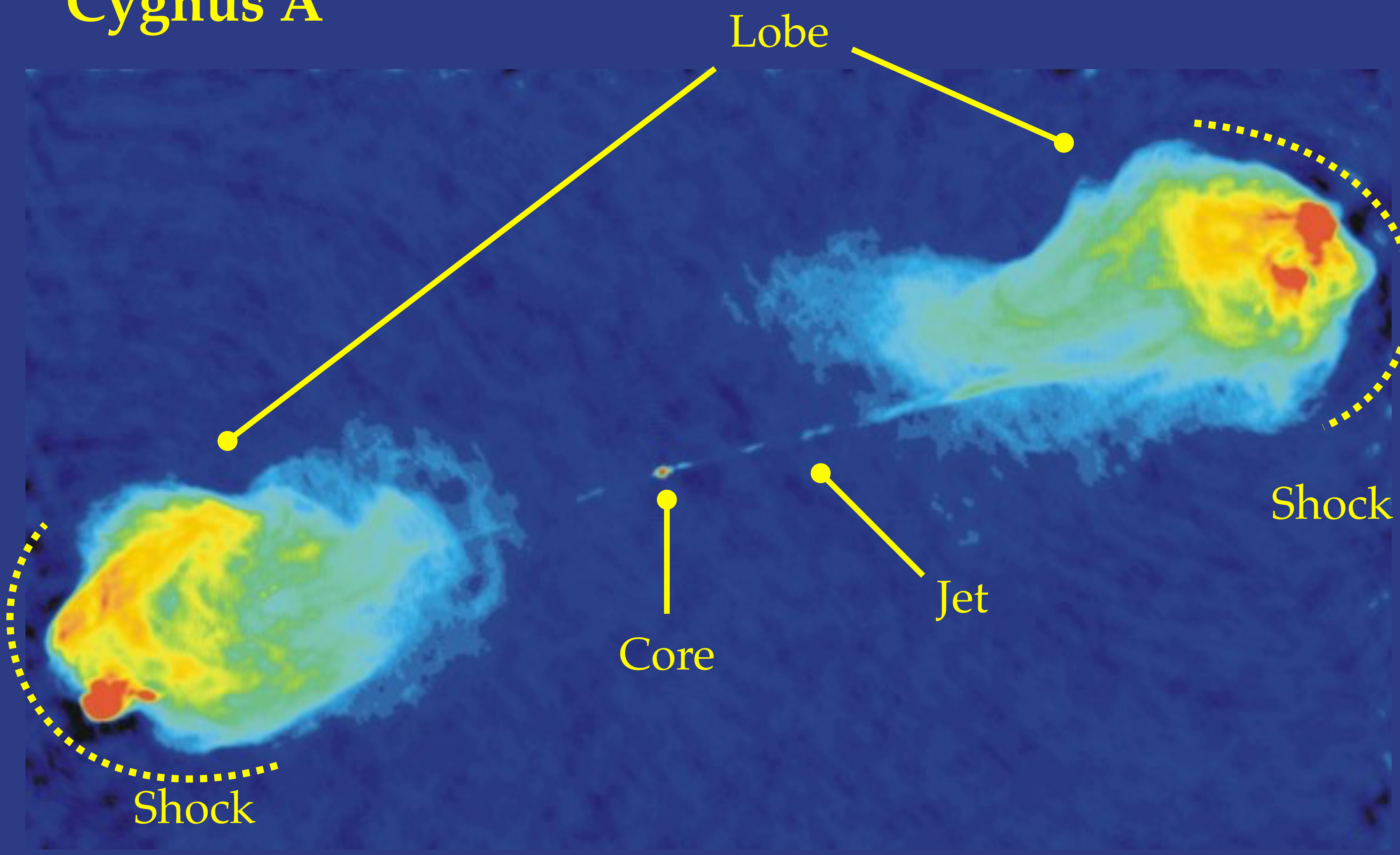


‘Typical’ radio galaxy

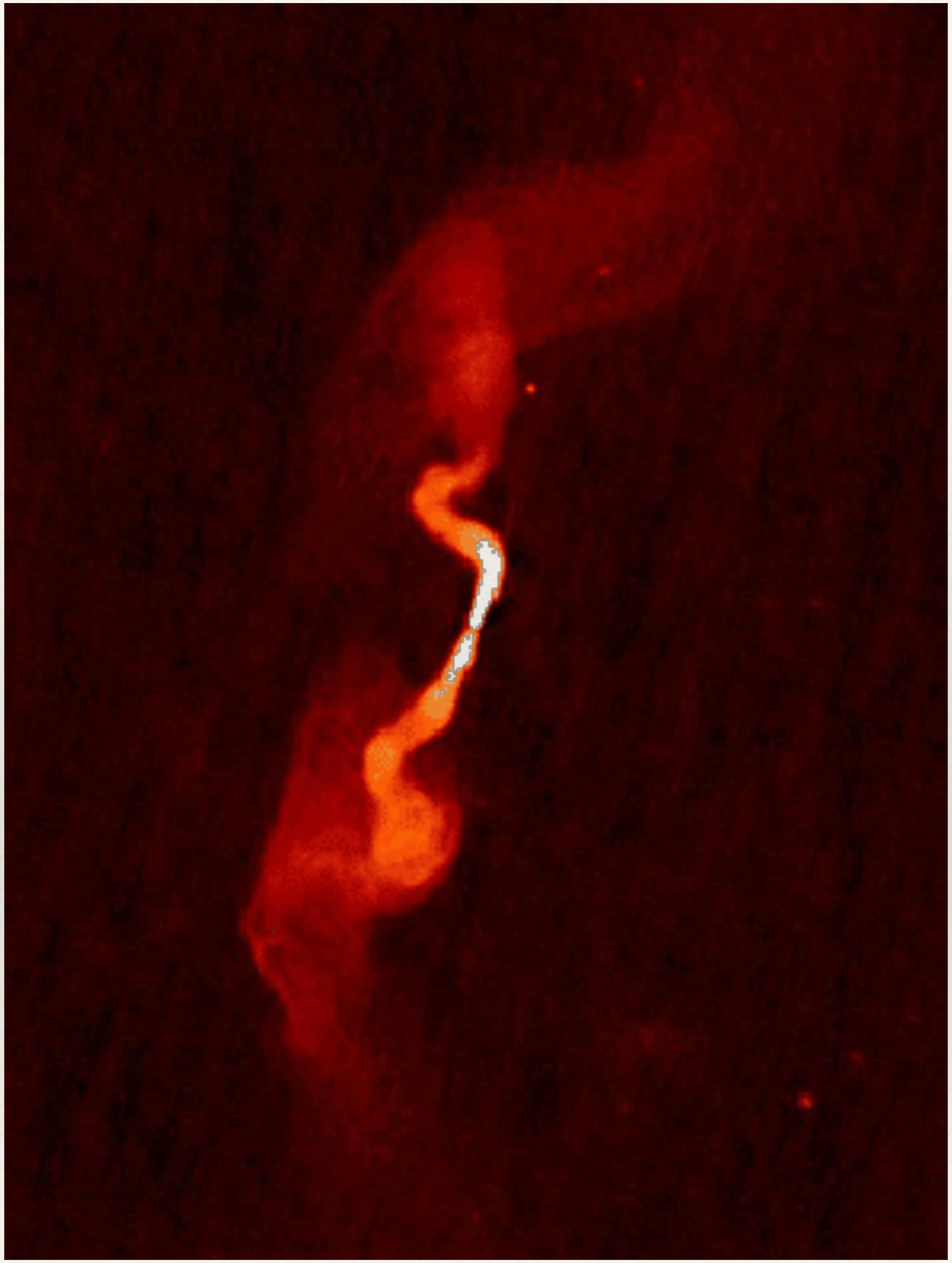
Cygnus A



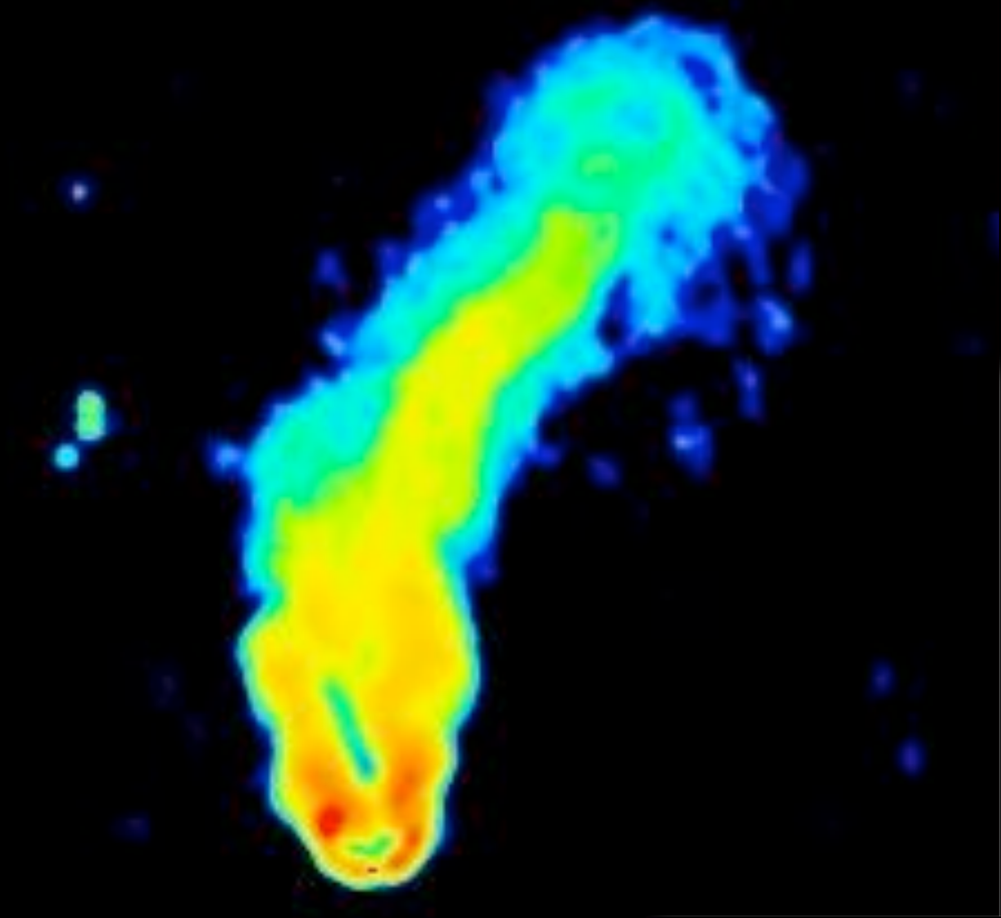
'Typical' radio galaxy

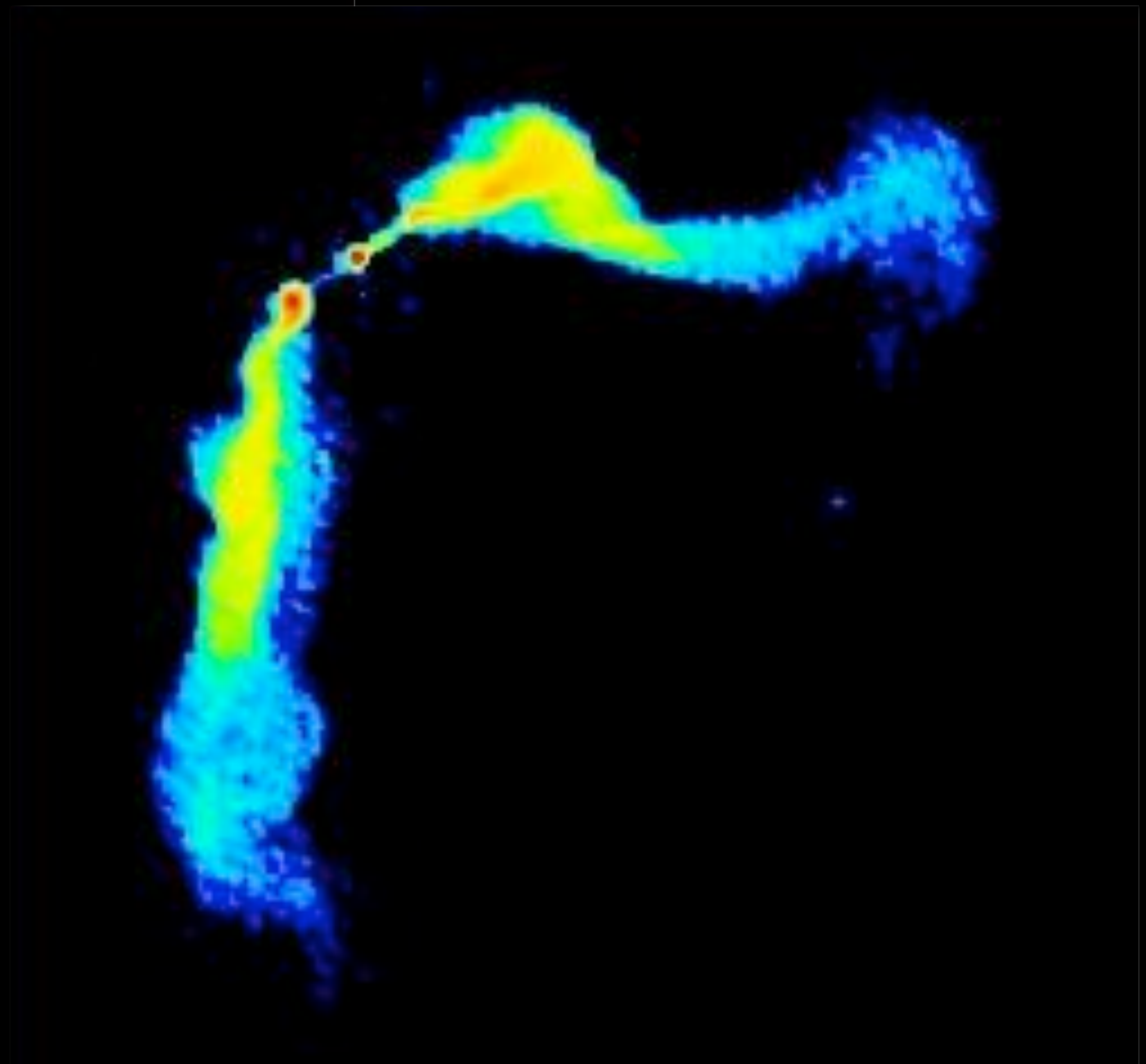
Jets can distort depending on environment

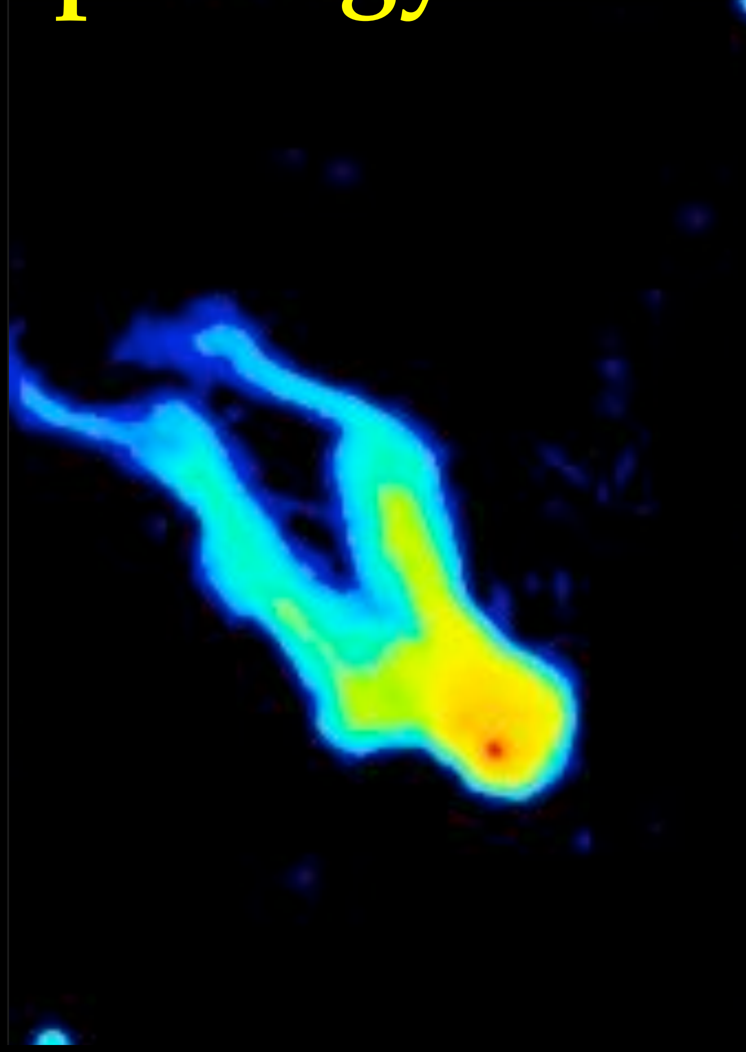
Here, the jets of galaxy 3C 31 (observed at ~20cm) are distorting due to interaction with cluster gas



Other examples of disturbed jet morphology…

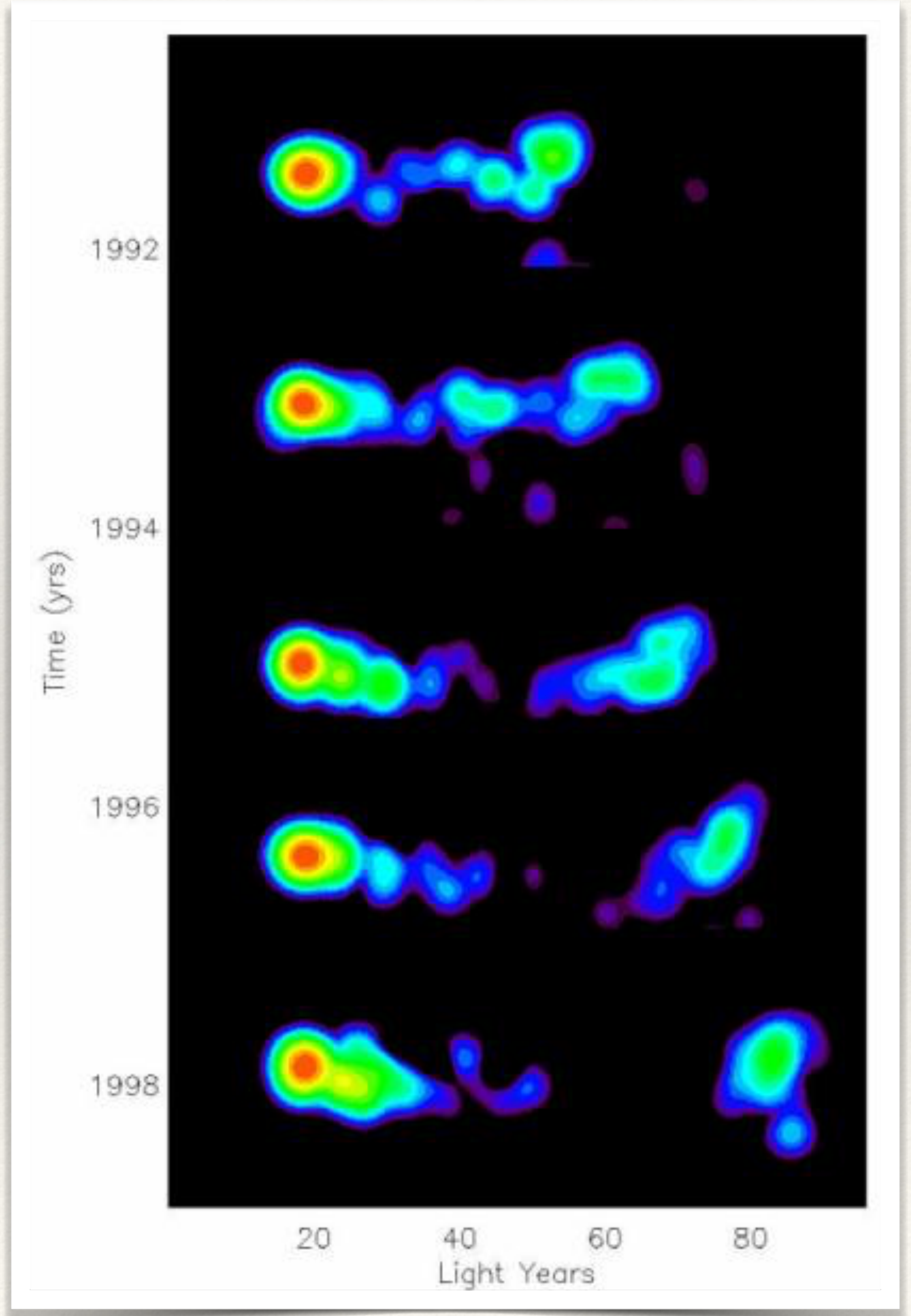






Radio galaxies: faster than light??

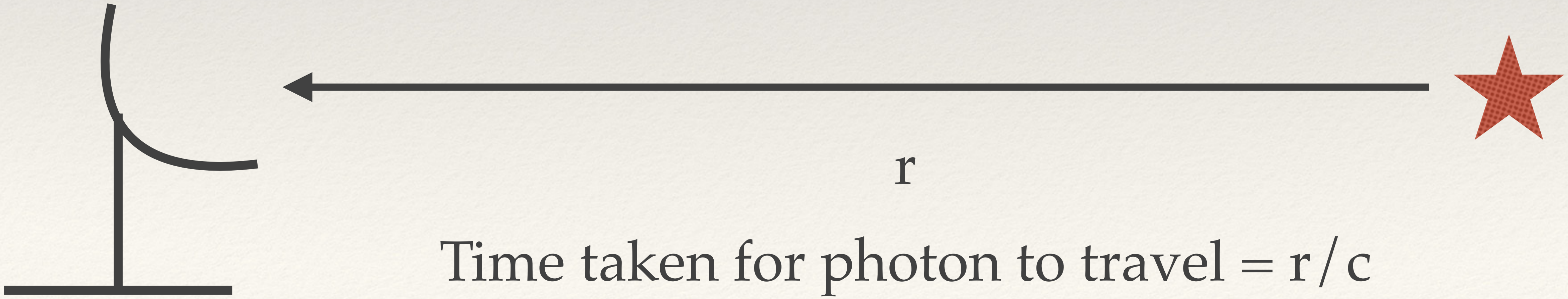
- Discovered in the 1970s, radio jets seemed to be travelling faster than light…
- 3C 279 (right)… bright spot seems to have travelled ~25 light years between 1991 and 1998



Radio galaxies: faster than light??

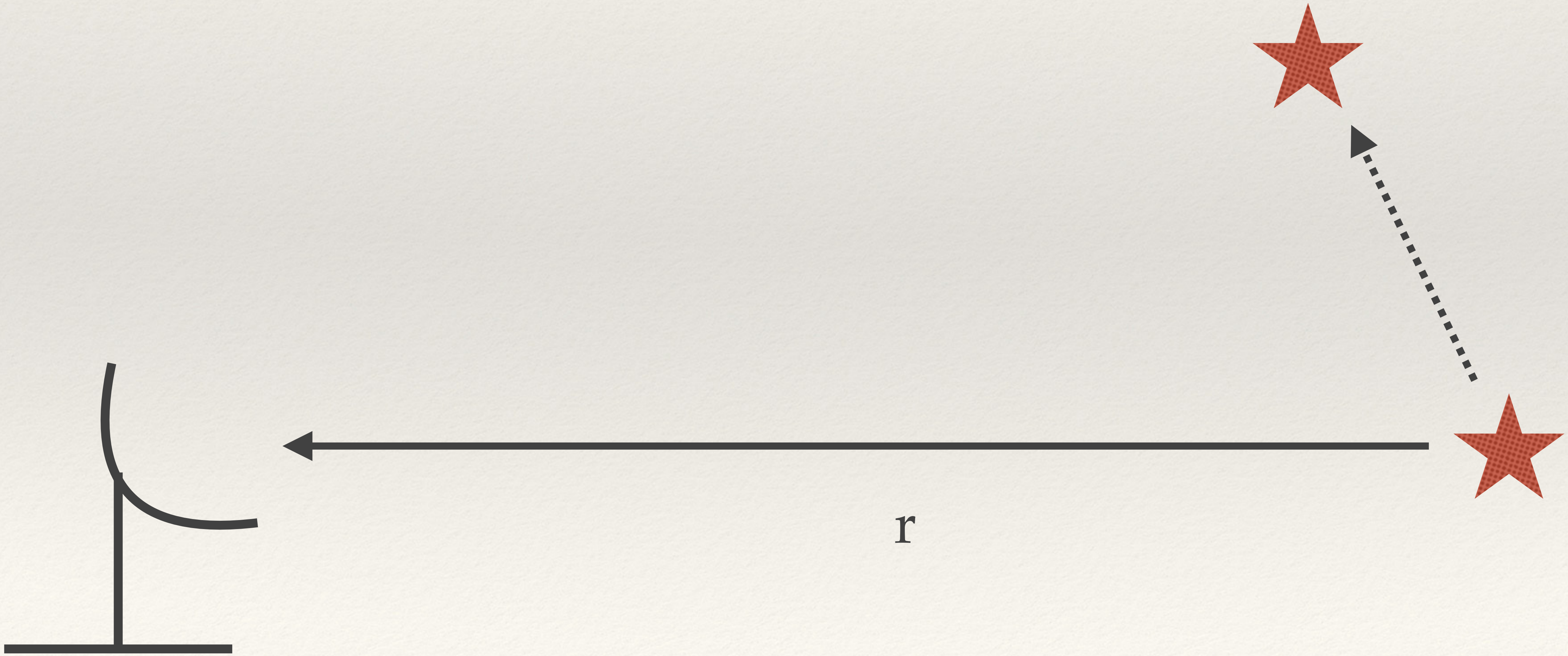
Actually a projection illusion caused by the high speeds!

Radio galaxies: faster than light??

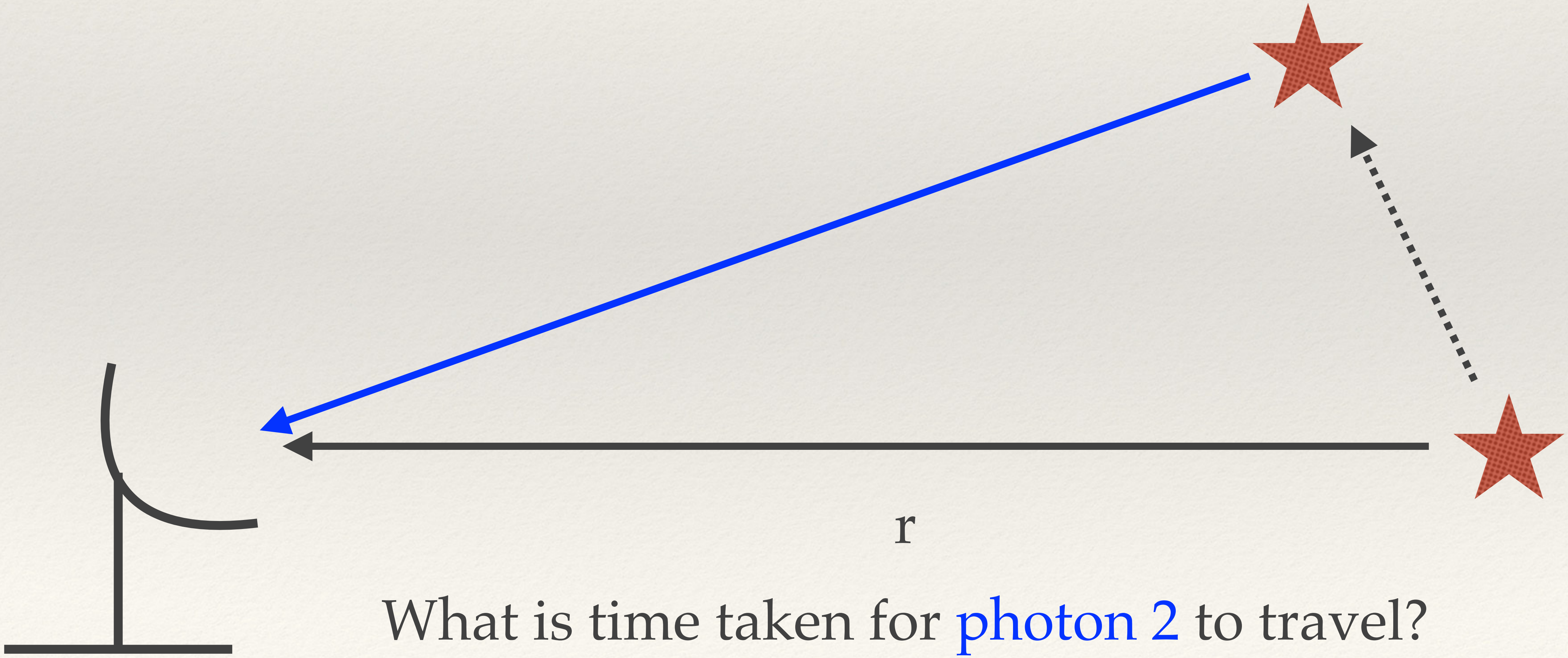


Time taken for photon to travel = r / c

Radio galaxies: faster than light??

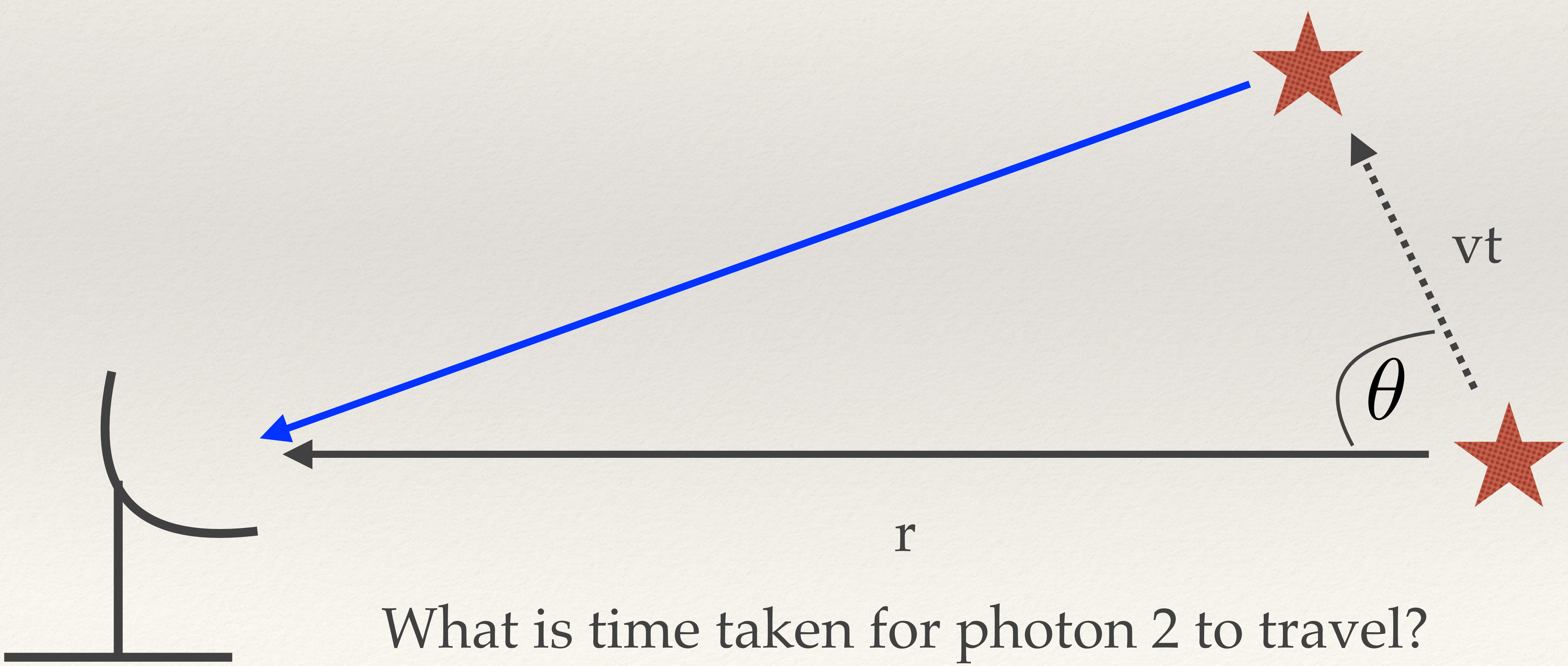


Radio galaxies: faster than light??



What is time taken for photon 2 to travel?

Radio galaxies: faster than light??

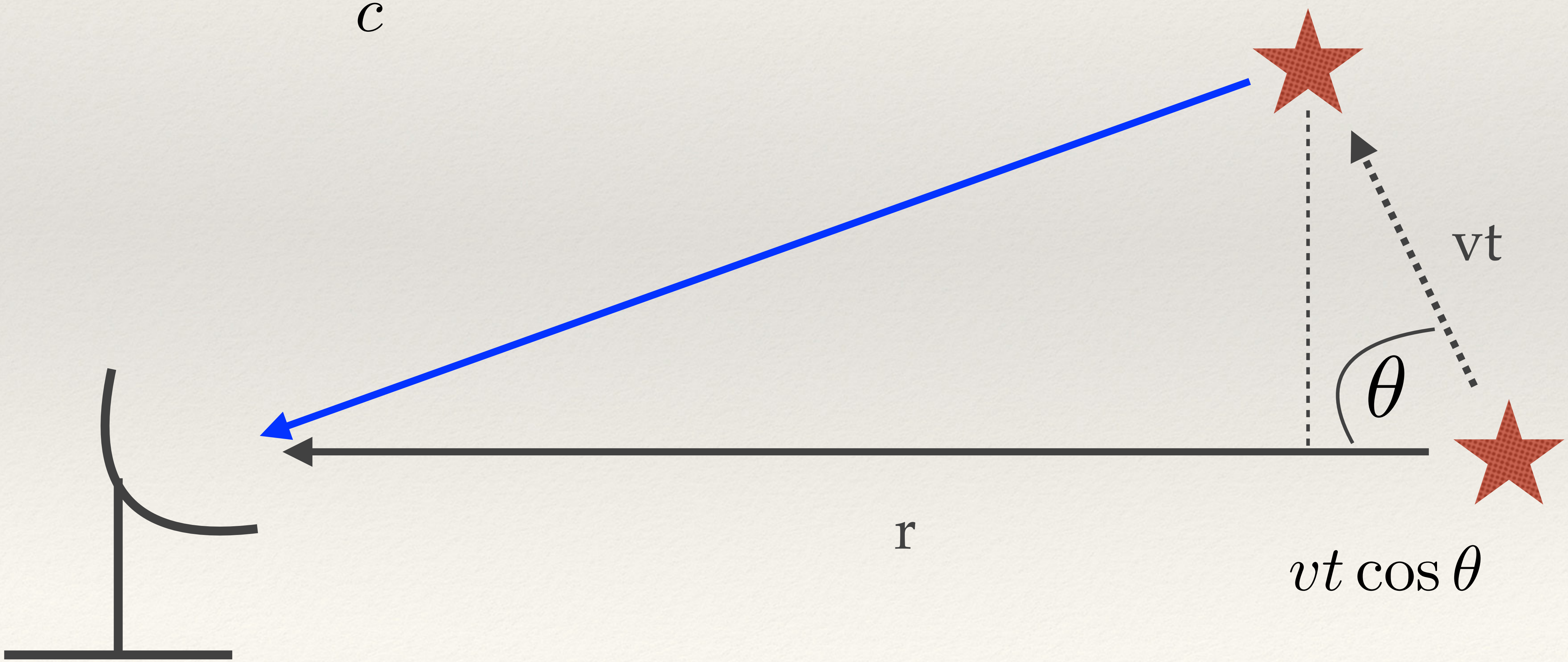


What is time taken for photon 2 to travel?

Radio galaxies: faster than light??

Time for photon 2 to arrive=

$$\frac{r - vt\cos\theta}{c} + t$$

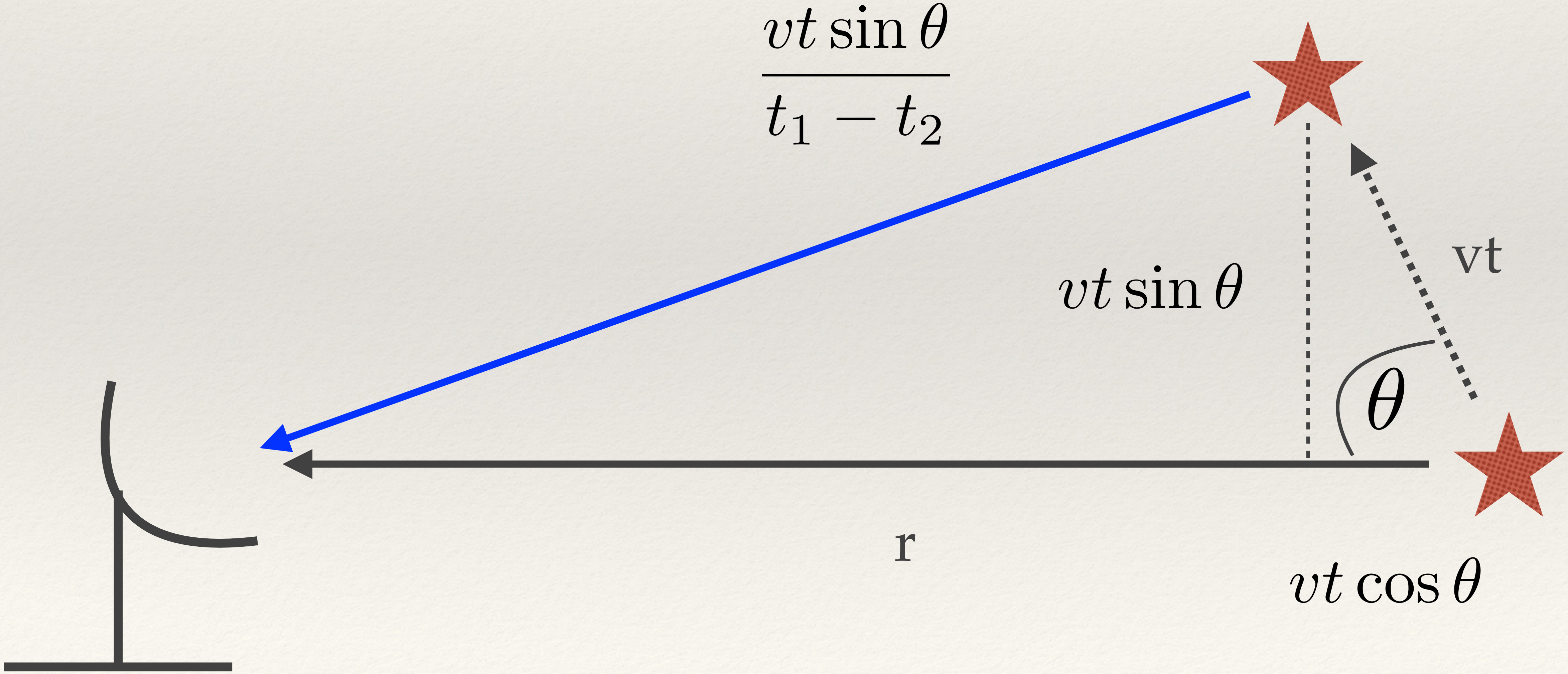


Radio galaxies: faster than light??

So, what is the apparent velocity (according to the observer on Earth)?

= apparent distance travelled / time taken

$$\frac{vt\sin\theta}{t_1 - t_2}$$



Radio galaxies: faster than light??

So, what is the apparent velocity (according to the observer on Earth)?

$$v_{\text{apparent}} = \frac{vt\sin\theta}{t_2 - t_1}$$

$$t_1 = \frac{r}{c}$$

$$t_2 = \frac{r - vt\cos\theta}{c} + t$$

$$\begin{aligned} t_2 - t_1 &= \frac{r - vt\cos\theta}{c} + t - \frac{r}{c} \\ &= t - \frac{vt\cos\theta}{c} \\ &= t\left(1 - \frac{v\cos\theta}{c}\right) \end{aligned}$$

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Putting numbers in… a jet travelling at 0.99c (they are fast!), coming from an object moving at an angle of 10 degrees

$$v_{\text{apparent}} = \frac{(0.99)(3 \times 10^8 \text{ m/s})(\sin 10^o)}{1 - (0.99 \ \cos 10^o)}$$

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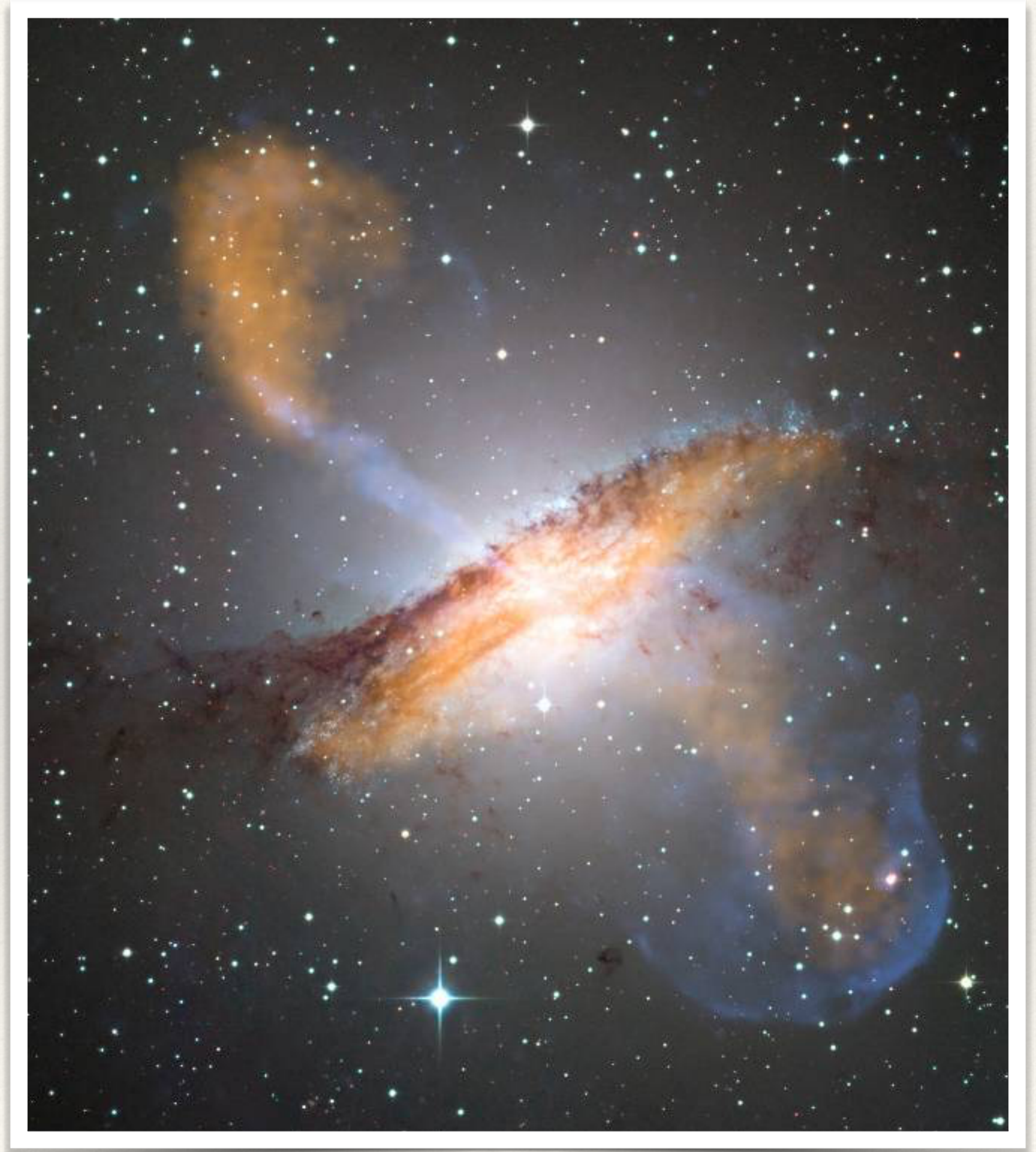
$$v_{\text{apparent}} = \frac{(0.99)(3 \times 10^8 \text{ m/s})(\sin 10^o)}{1 - (0.99 \ \cos 10^o)} = 2.06 \times 10^9 \text{ m/s}$$

Radio galaxies

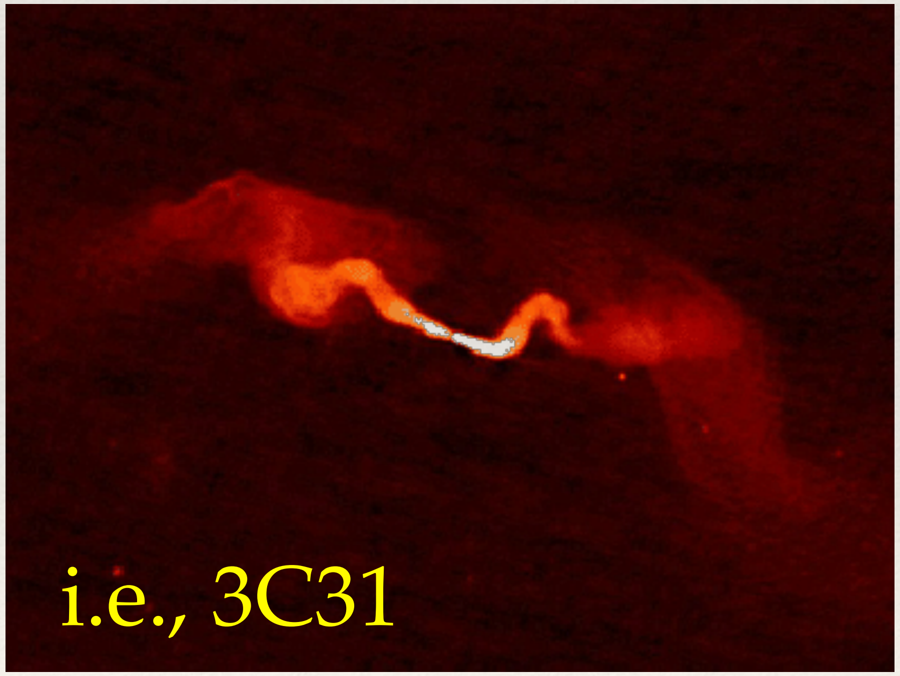
- Radio galaxies come in two categories, based on the 1974 classification by Bernie Fanaroff and Julia Riley (here in Cambridge!)
- The Fanaroff-Riley classification has two types: FR-I and FR-II



Radio galaxy classification

FR-I

Luminosity *decreases* away from the central galaxy

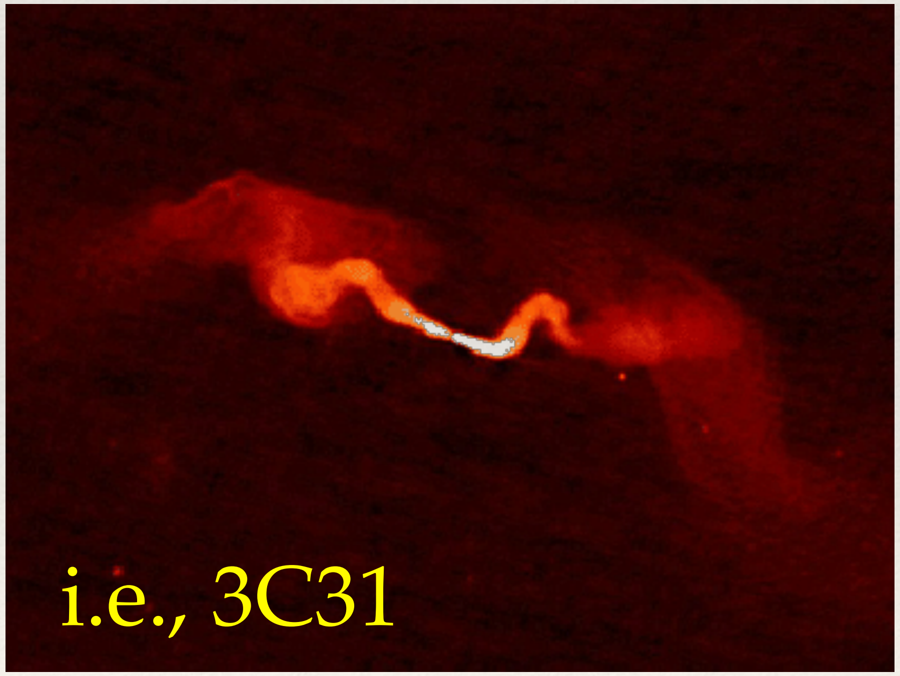


FR-II

Radio galaxy classification

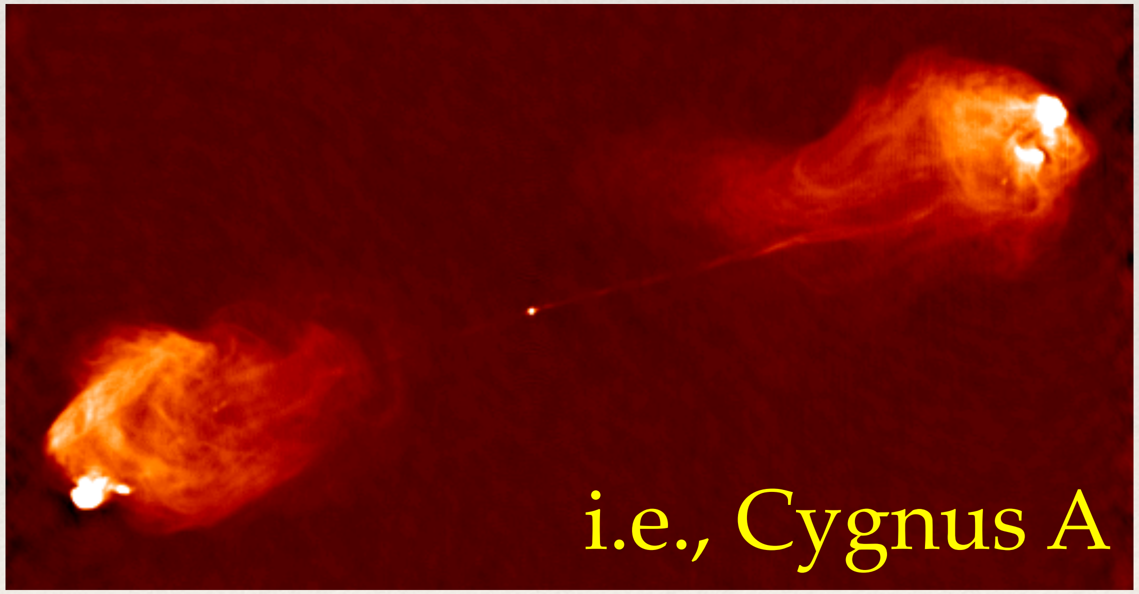
FR-I

Luminosity *decreases* away from the central galaxy



FR-II

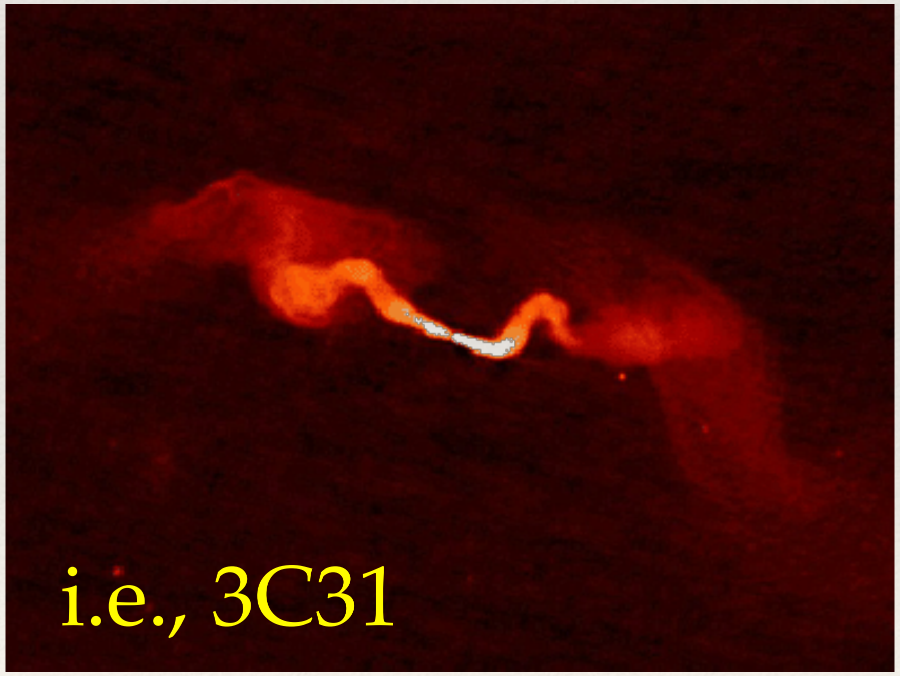
Luminosity *increases* away from the central galaxy, lobes terminate in 'hot spot'



Radio galaxy classification

<u>FR-I</u>

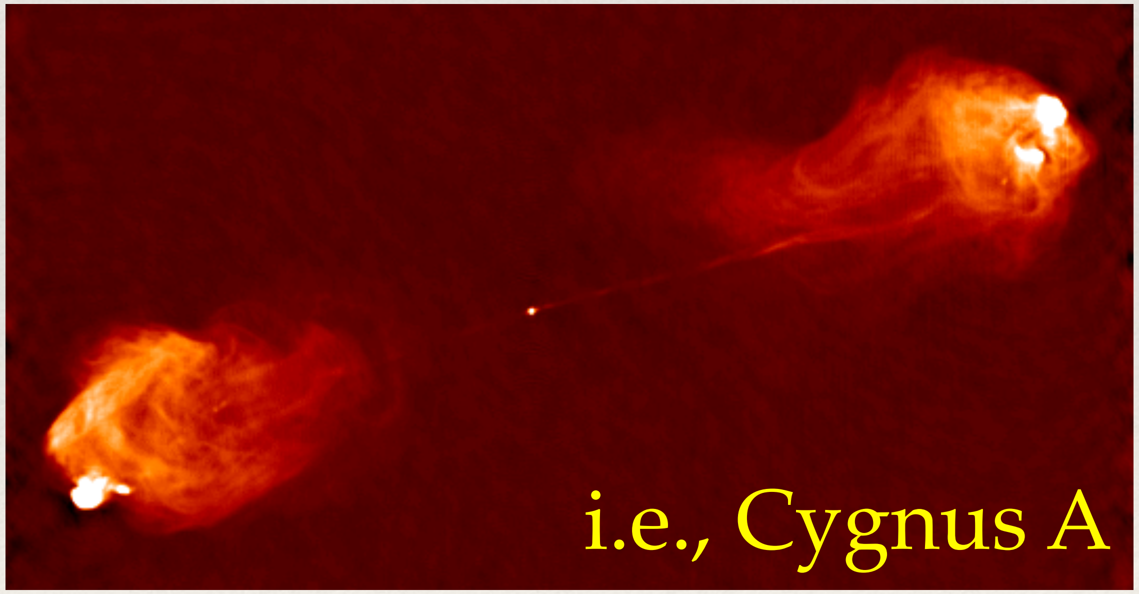
Luminosity *decreases* away from the central galaxy



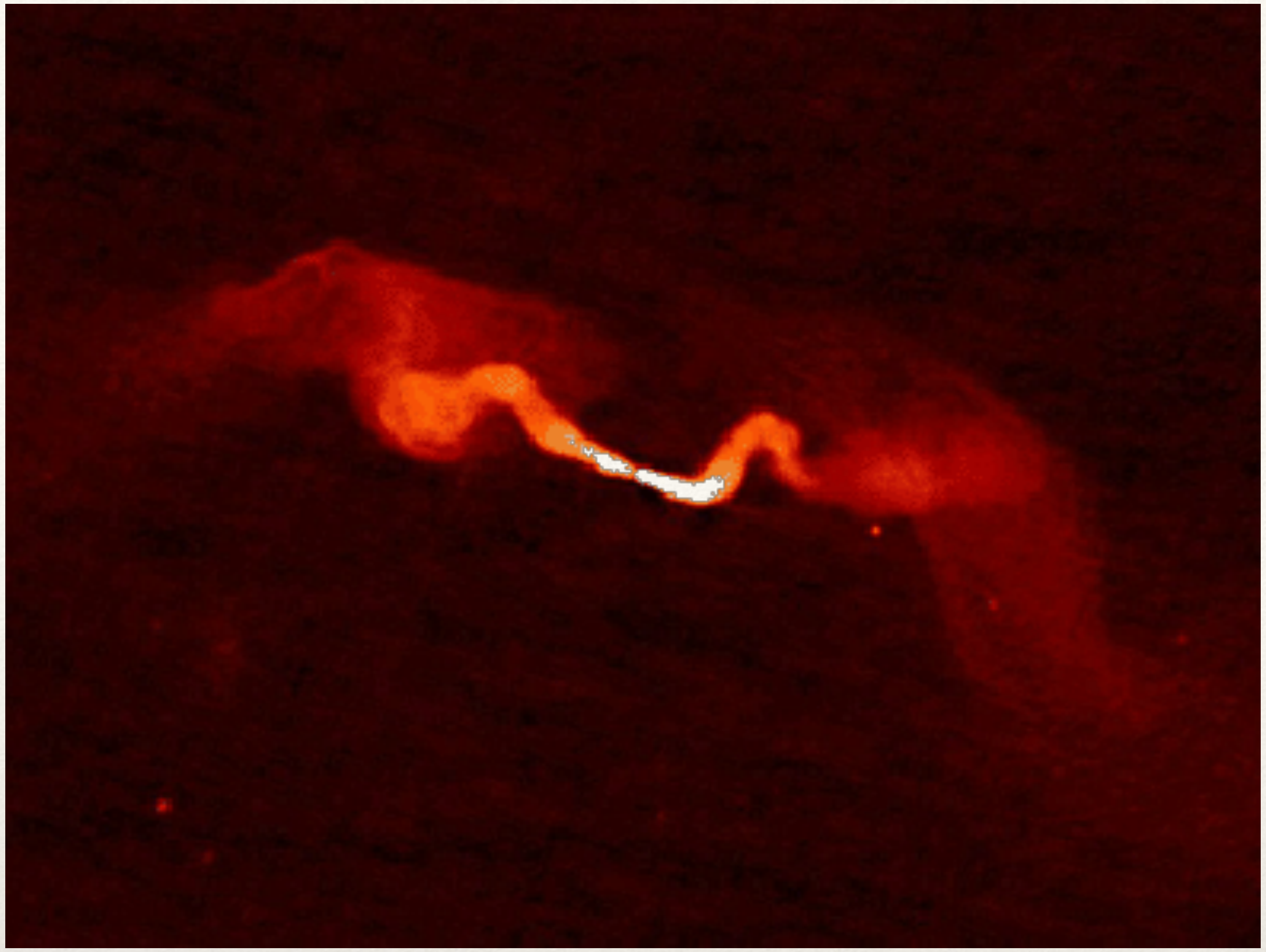
Low radio luminosity

<u>FR-II</u>

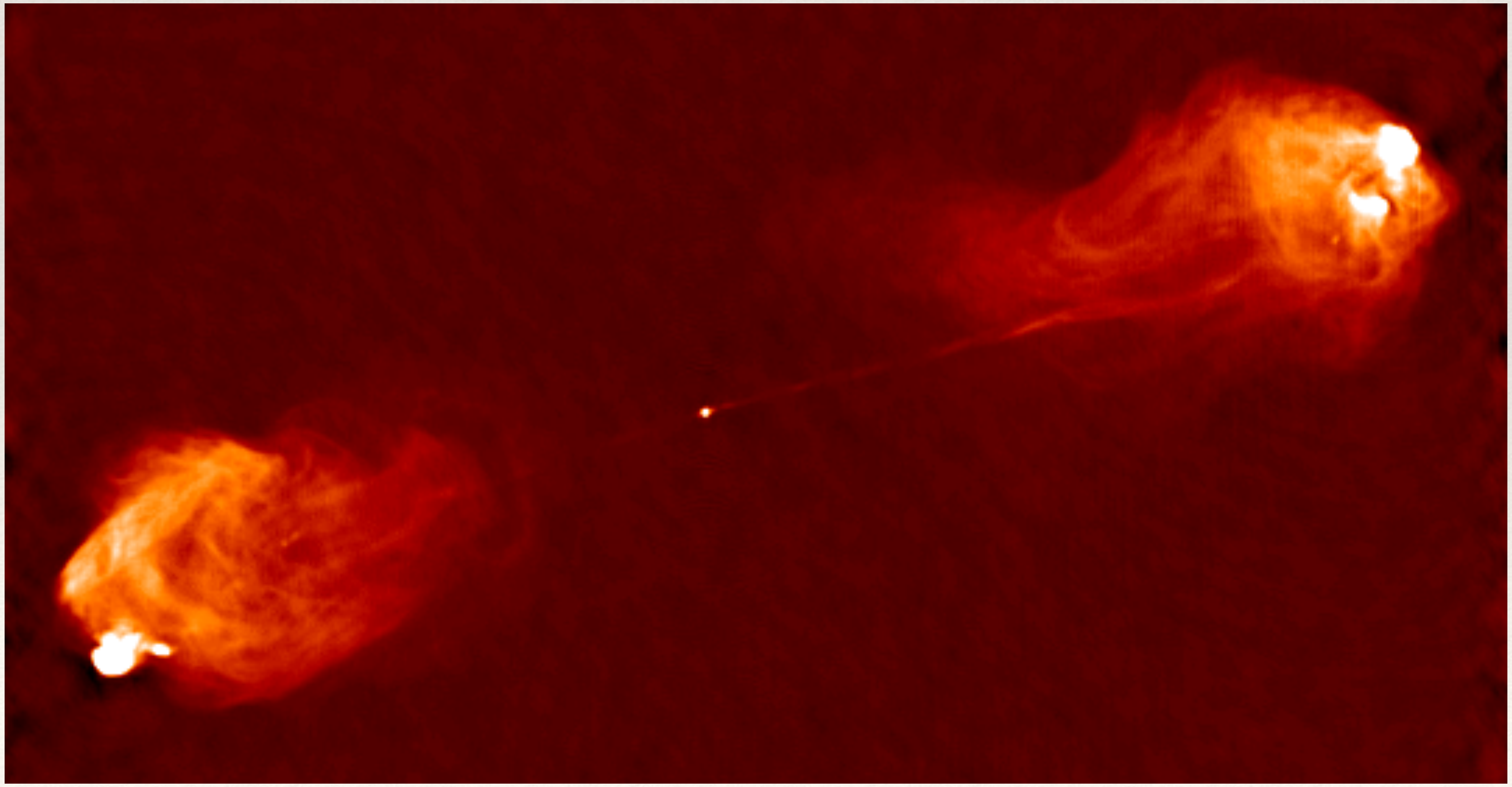
Luminosity *increases* away from the central galaxy, lobes terminate in 'hot spot'



High radio luminosity



FR-I



FR-II

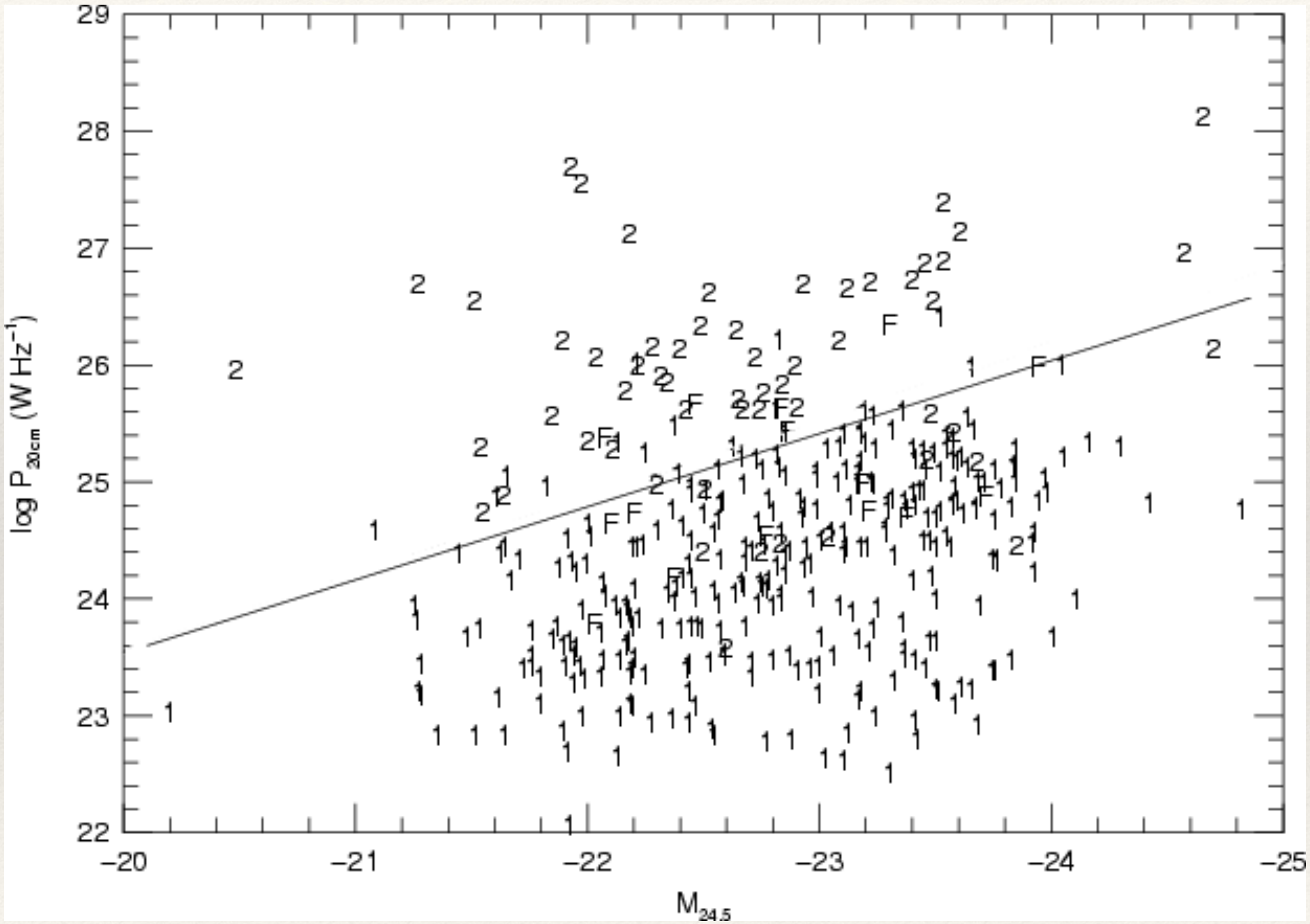
Radio galaxy classification

So, what causes the devision into FR-I and FR-II types?

Some clues…

1. **Radio luminosity** (FR-Is are generally less luminous)
2. **Host galaxy luminosity** (at fixed radio luminosity, hosts of FR-Is are more luminous
3. **Environment** (FR-Is are typically in dense environments)

Radio galaxy classification



Owen & Ledlow (1994)

Radio galaxy classification

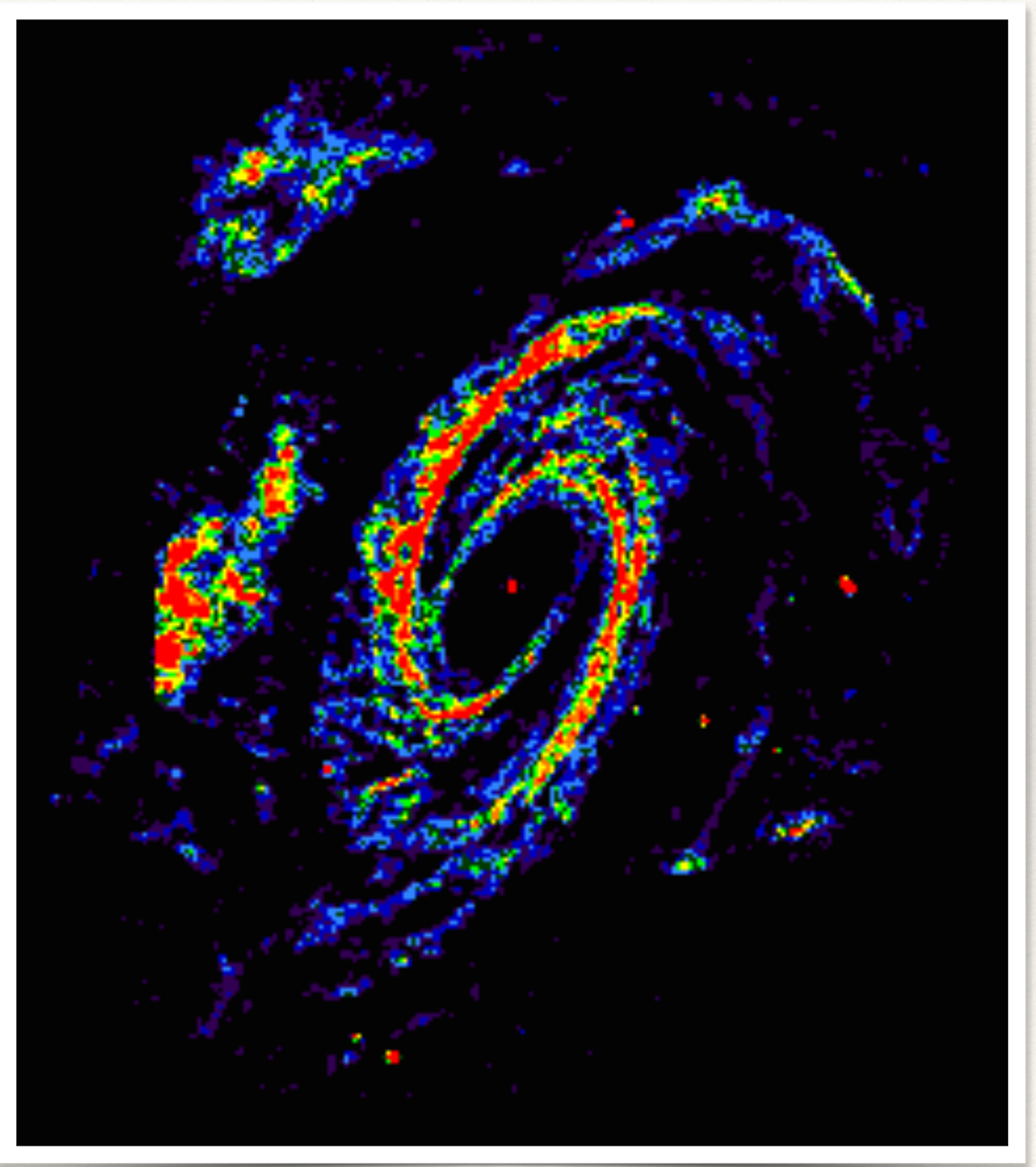
So, what causes the devision into FR-I and FR-II types?

Seems that all radio jets start the same (highly relativistic), then a combination of lower power and richer environments decelerate FR-Is to sub-relativistic speeds on kpc scales

FR-IIs, on the other hand, are powerful and unimpeded

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)



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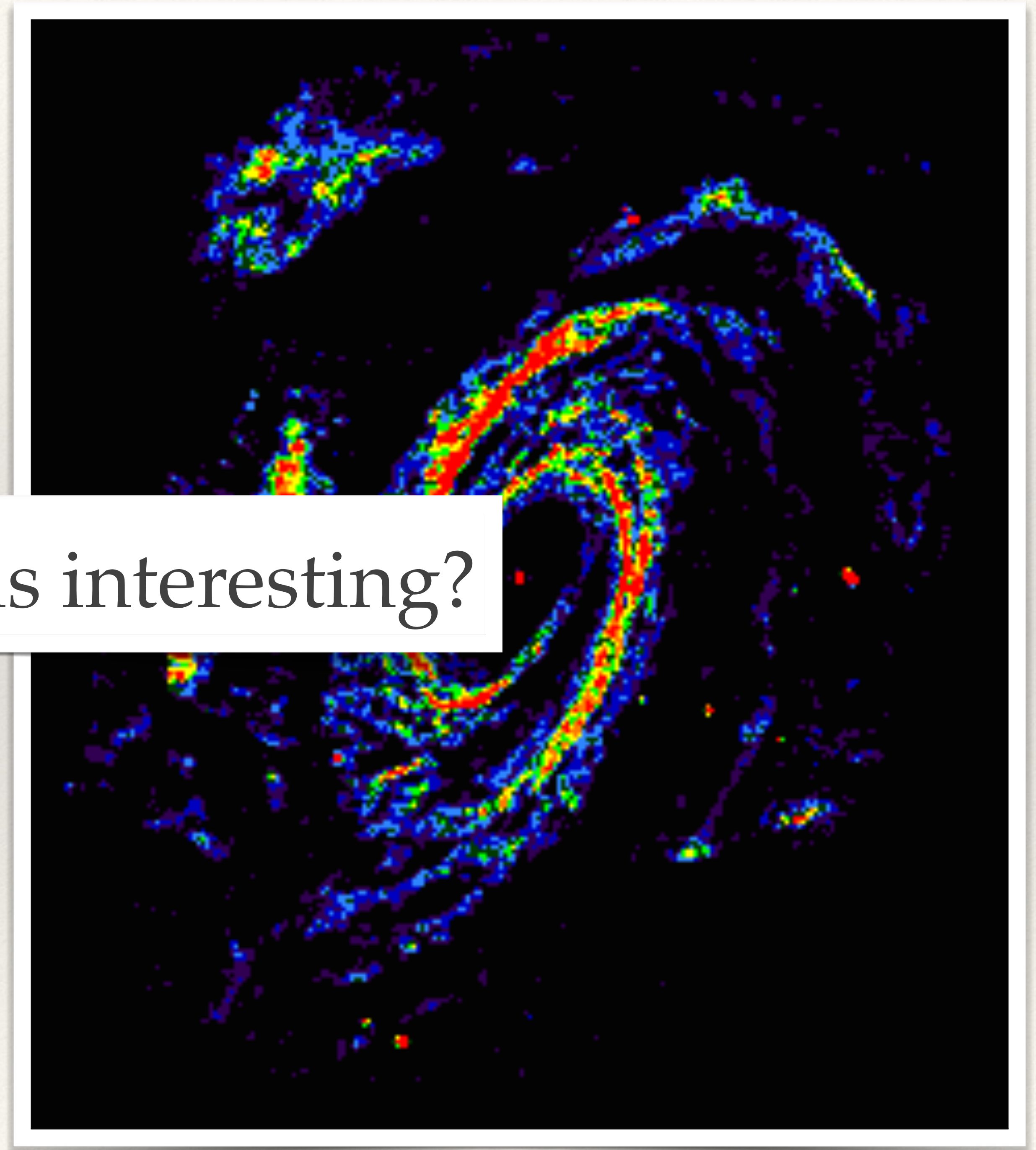


So… why is this interesting?

Radio emission from normal galaxies

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

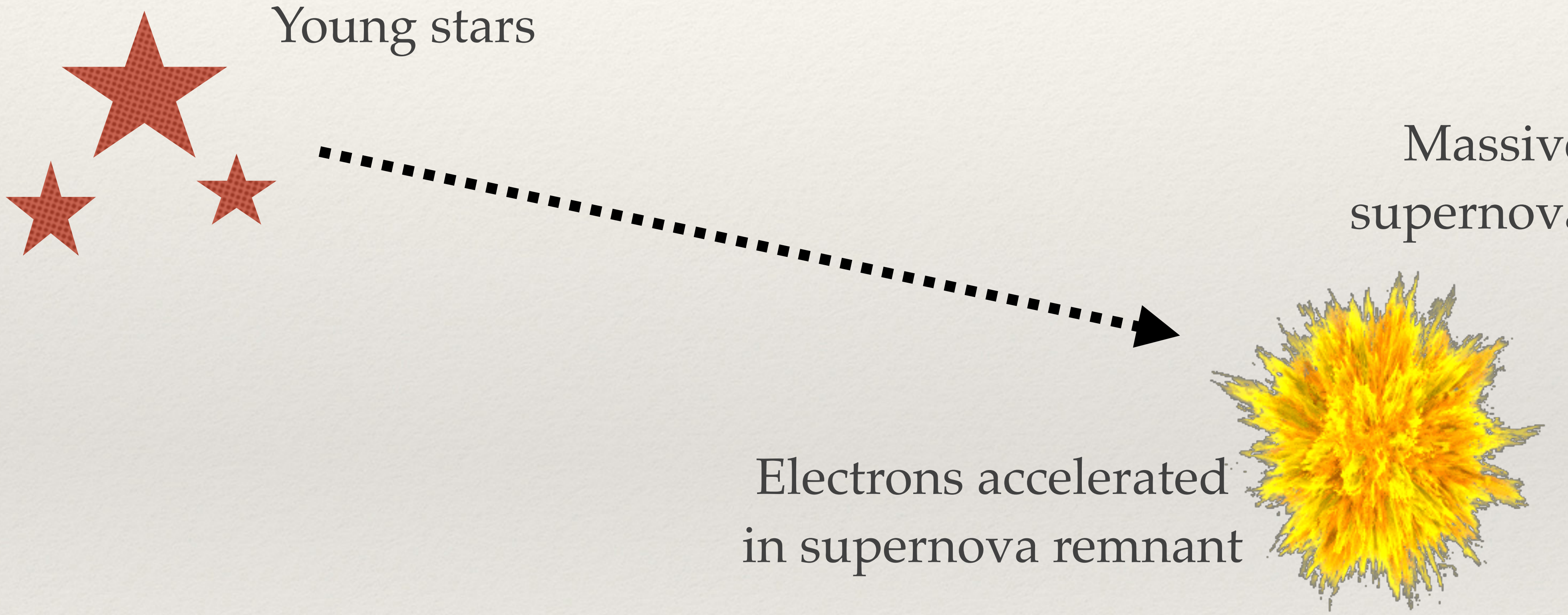
Radio emission from normal galaxies

How does this work?

Young stars

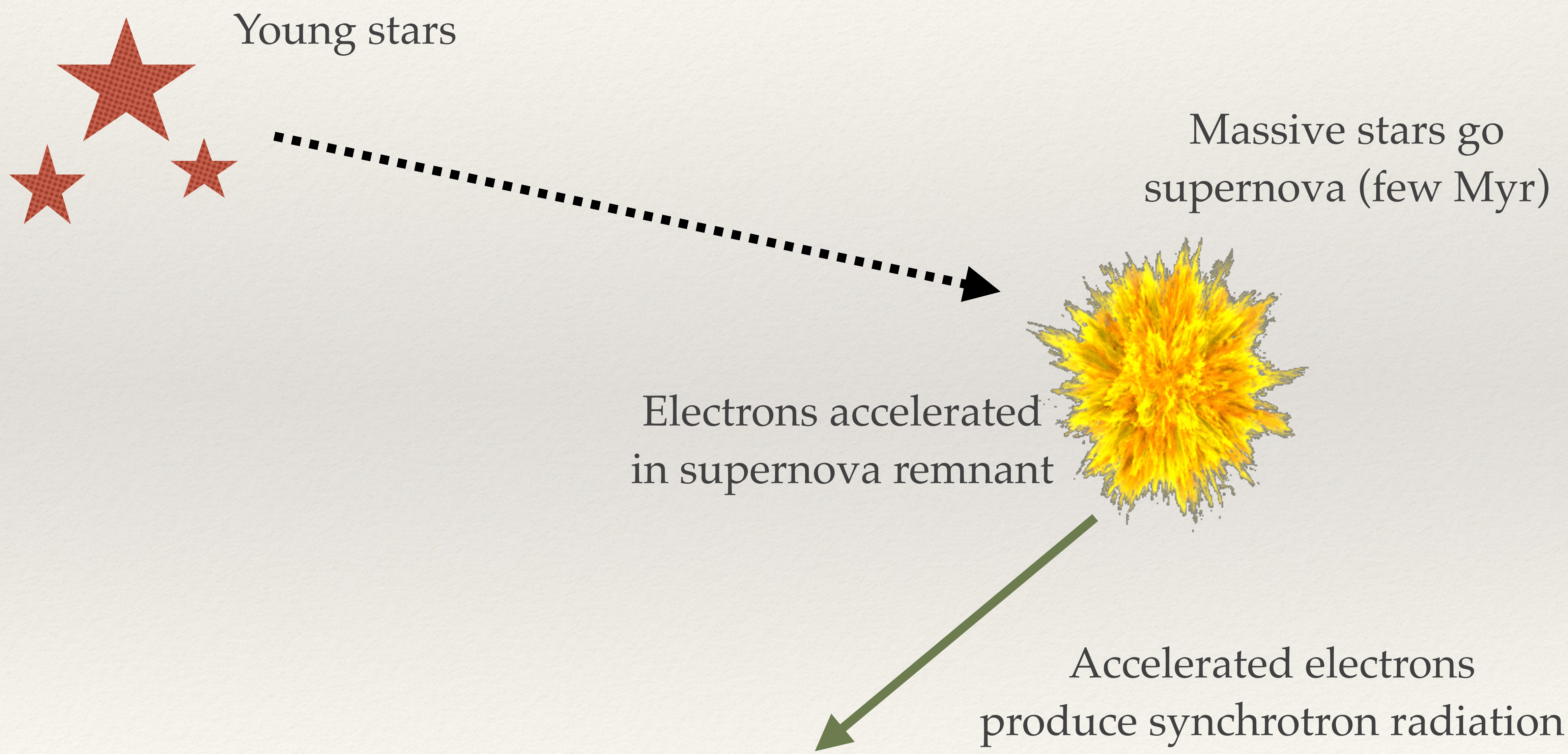
Radio emission from normal galaxies

How does this work?



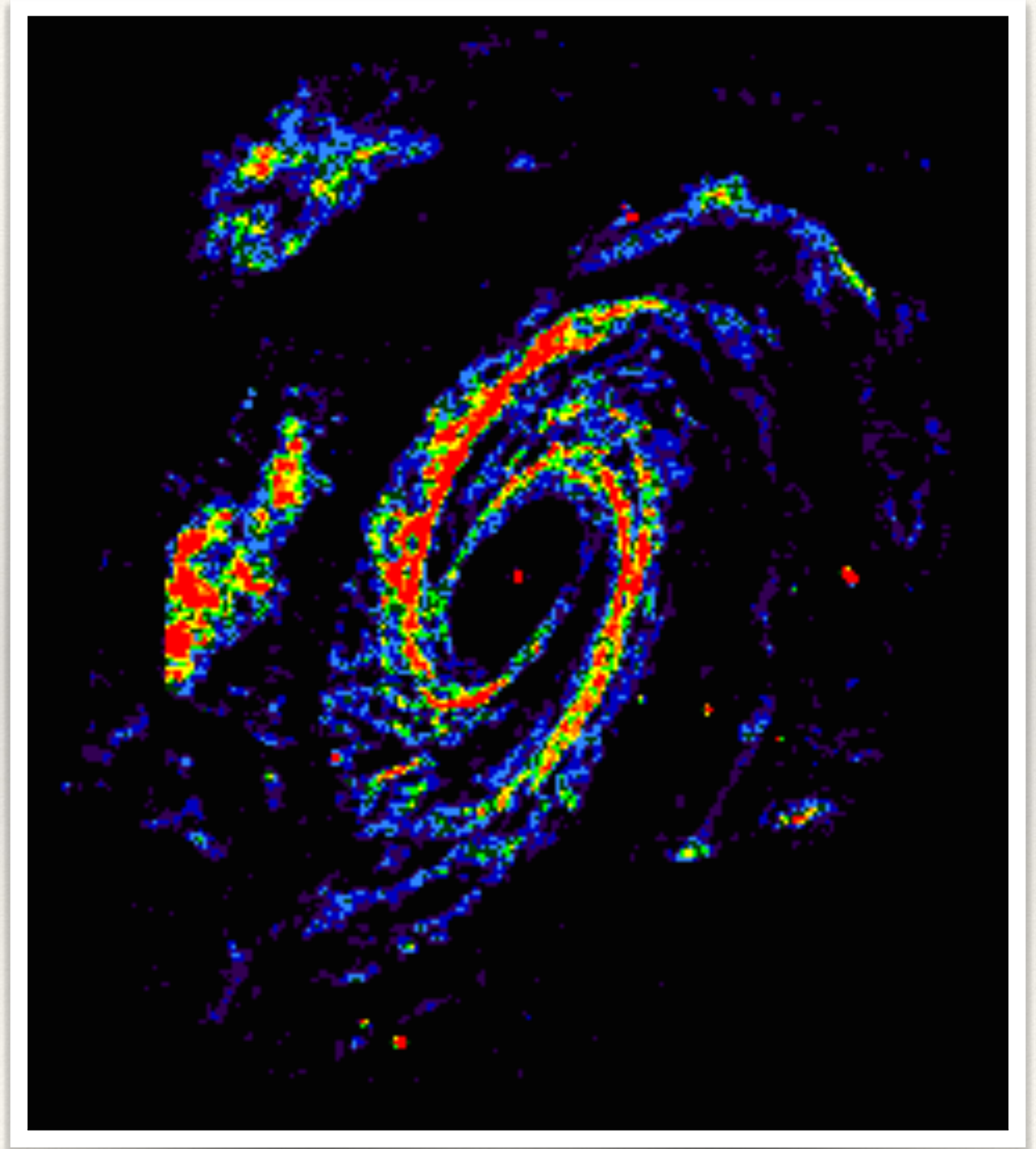
Radio emission from normal galaxies

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