Radio astronomy (I): Measuring the radio sky

History and techniques of Radio Astronomy

Dr Matt Bothwell

Topics

- Background: the history of radio astronomy
- Single aperture radio dishes
- Interferometry

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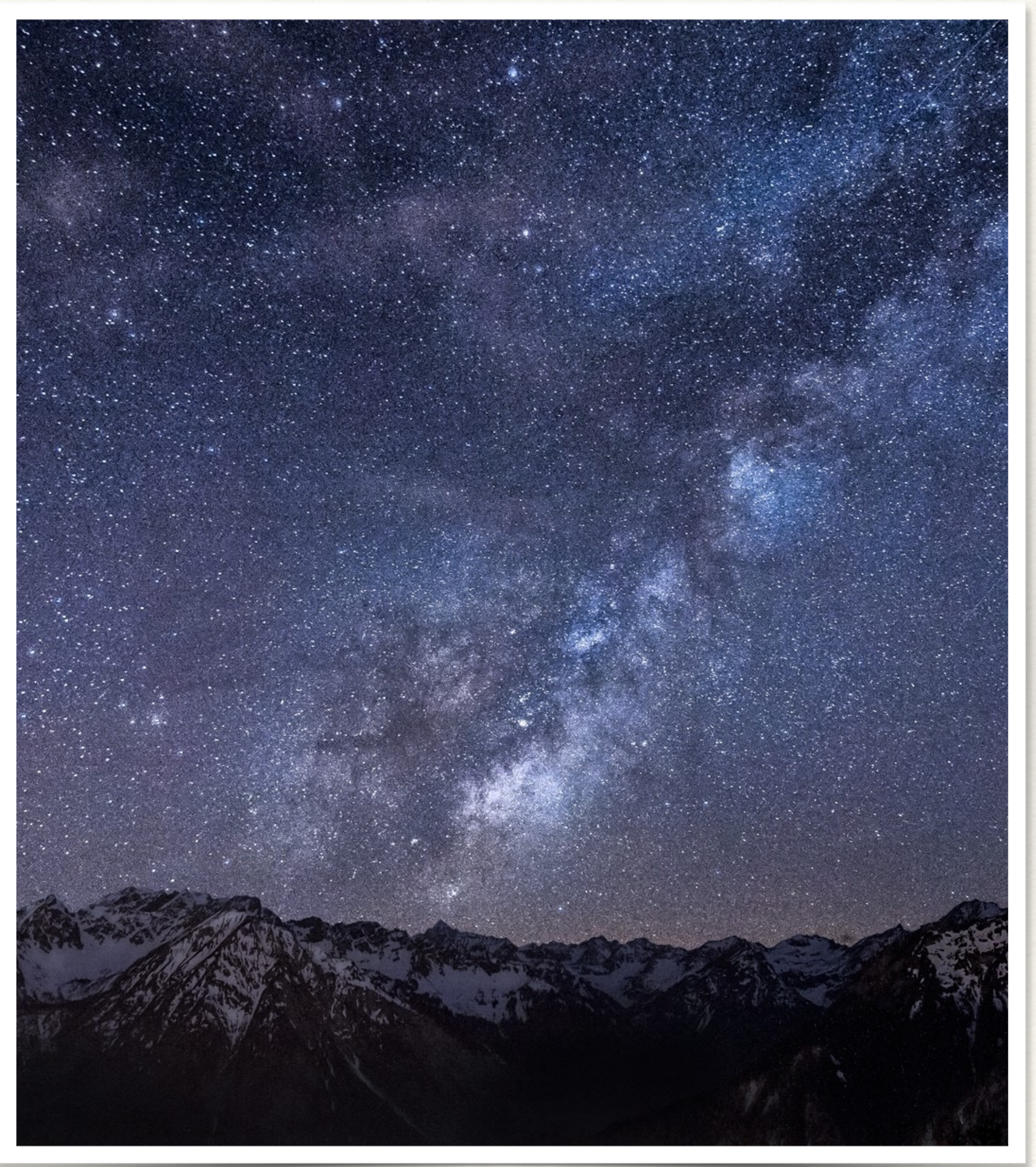
Astronomy beyond the optical

- 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 = ?

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$$
\begin{aligned}
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\end{aligned}
$$

Electricity + Magnetism = ?

Electric field leaving volume proportional to charge inside

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No magnetic
monopoles

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No magnetic monopoles

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

Electromotive force in a circuit
depends on magnetic flux enclosed

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

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

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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?

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

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

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

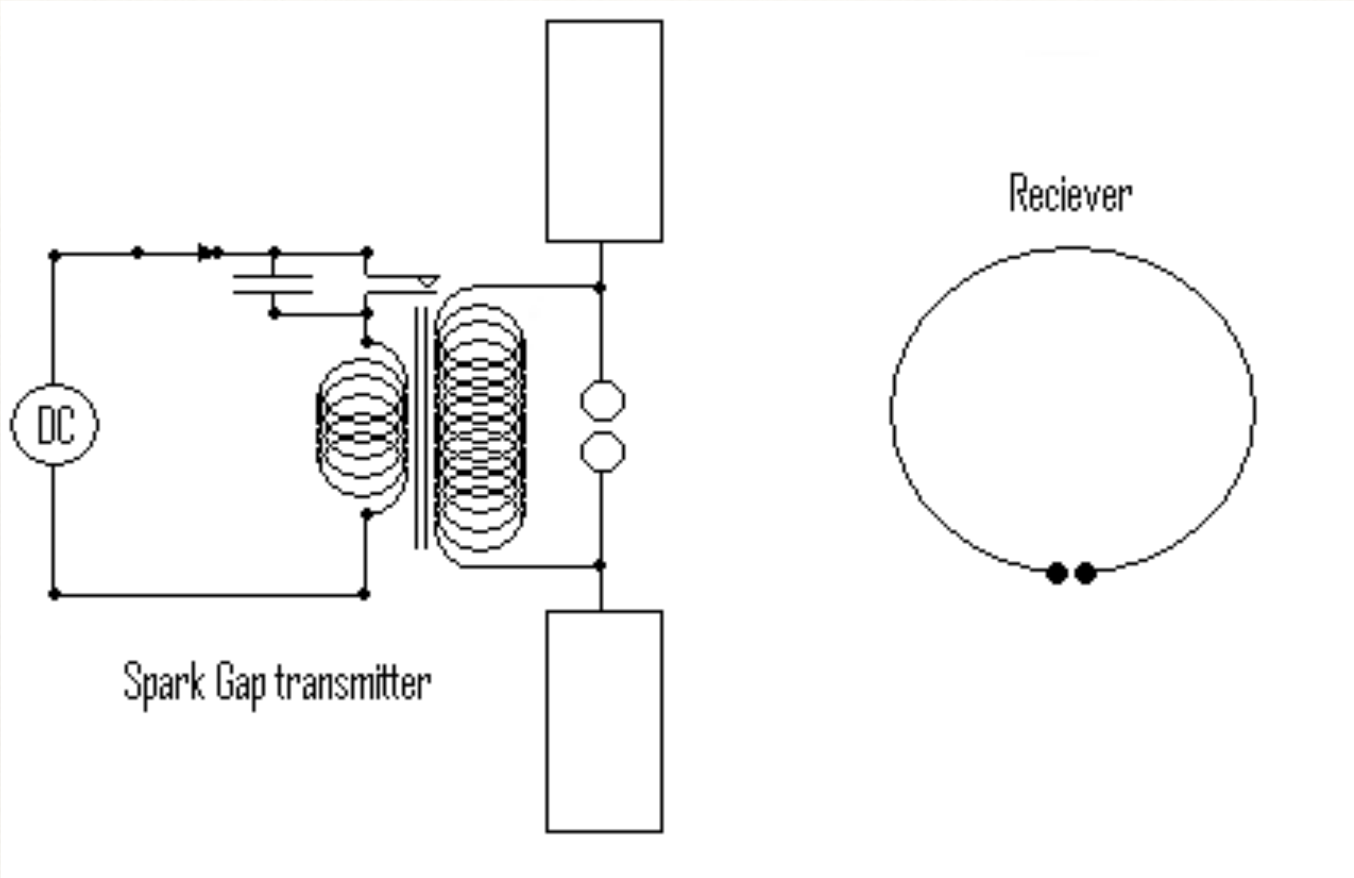
Light is an electromagnetic wave…

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"

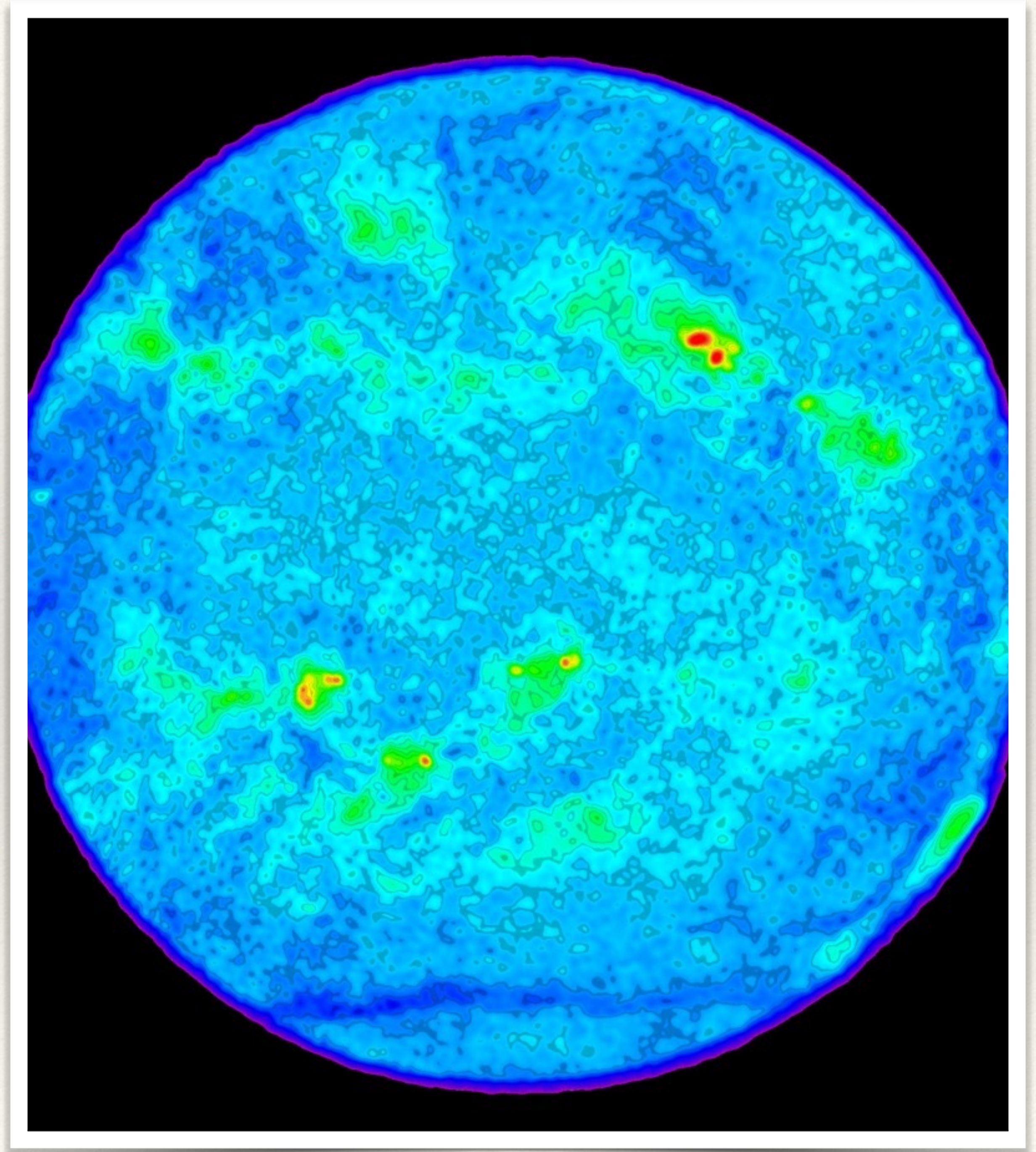


Discovered EM waves, wavelength ~60cm.

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.



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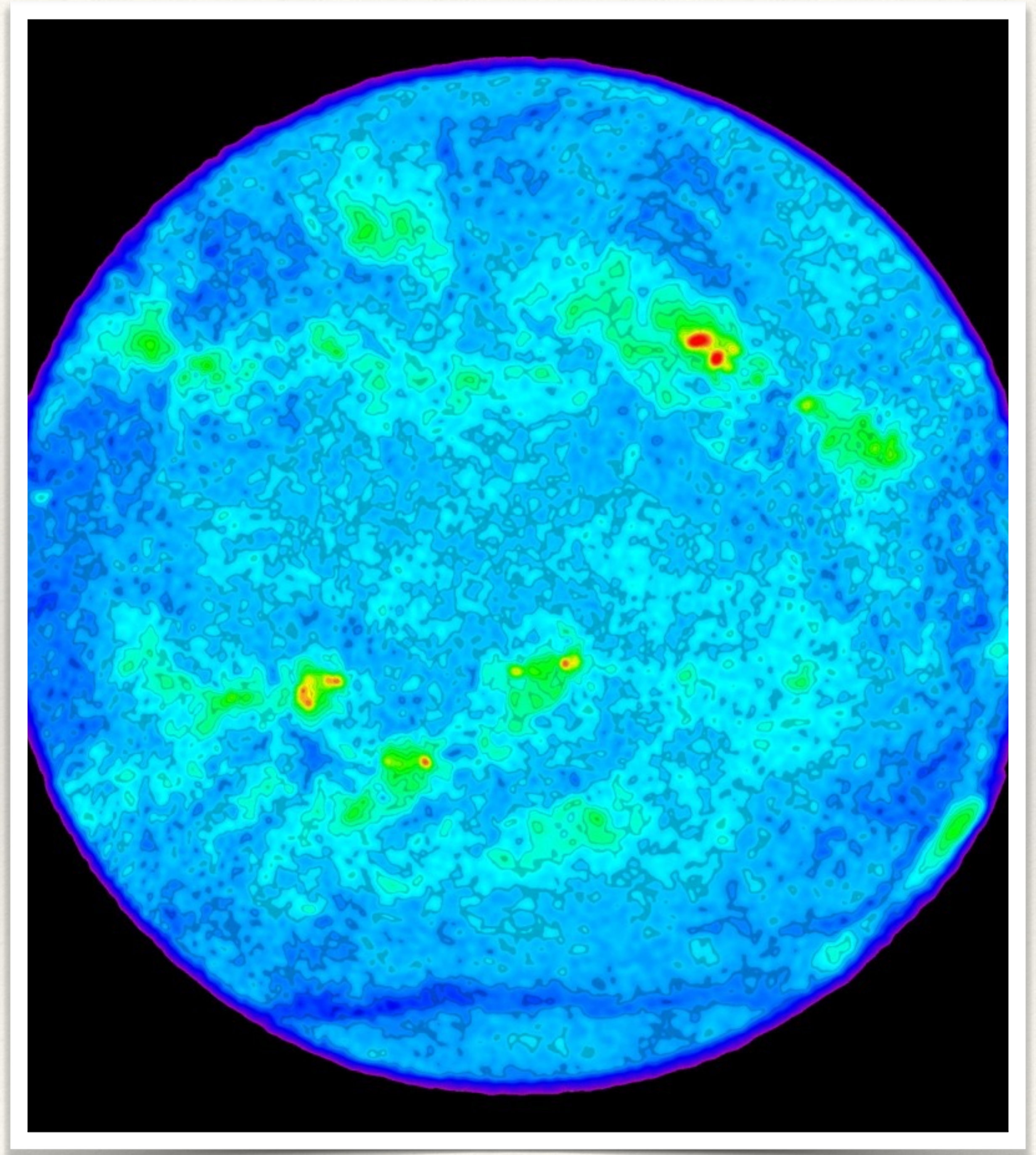

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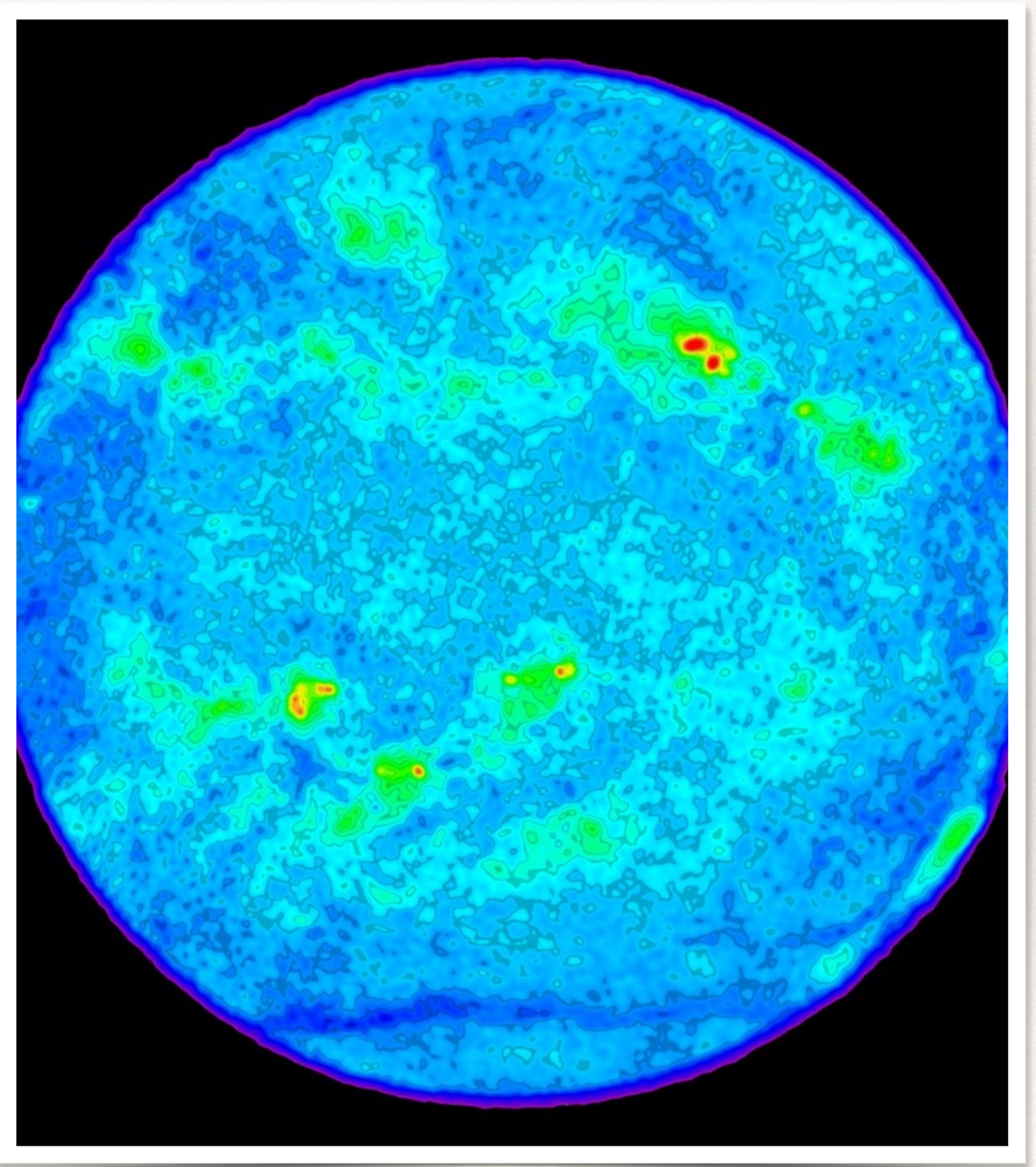
> Tried sunshine today on coherer… couldn't swear to proper sun effect.. May be intermittent or weak



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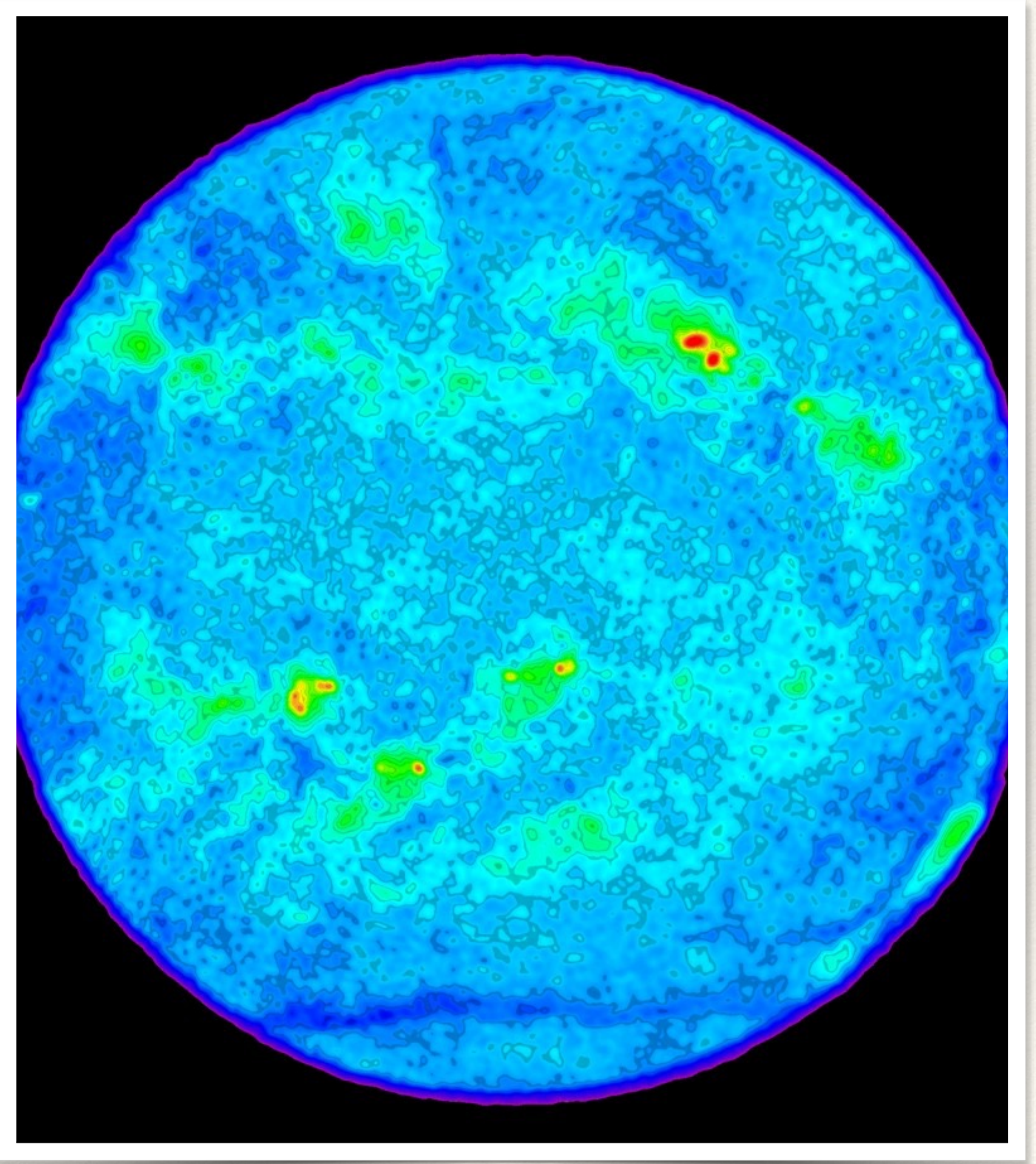

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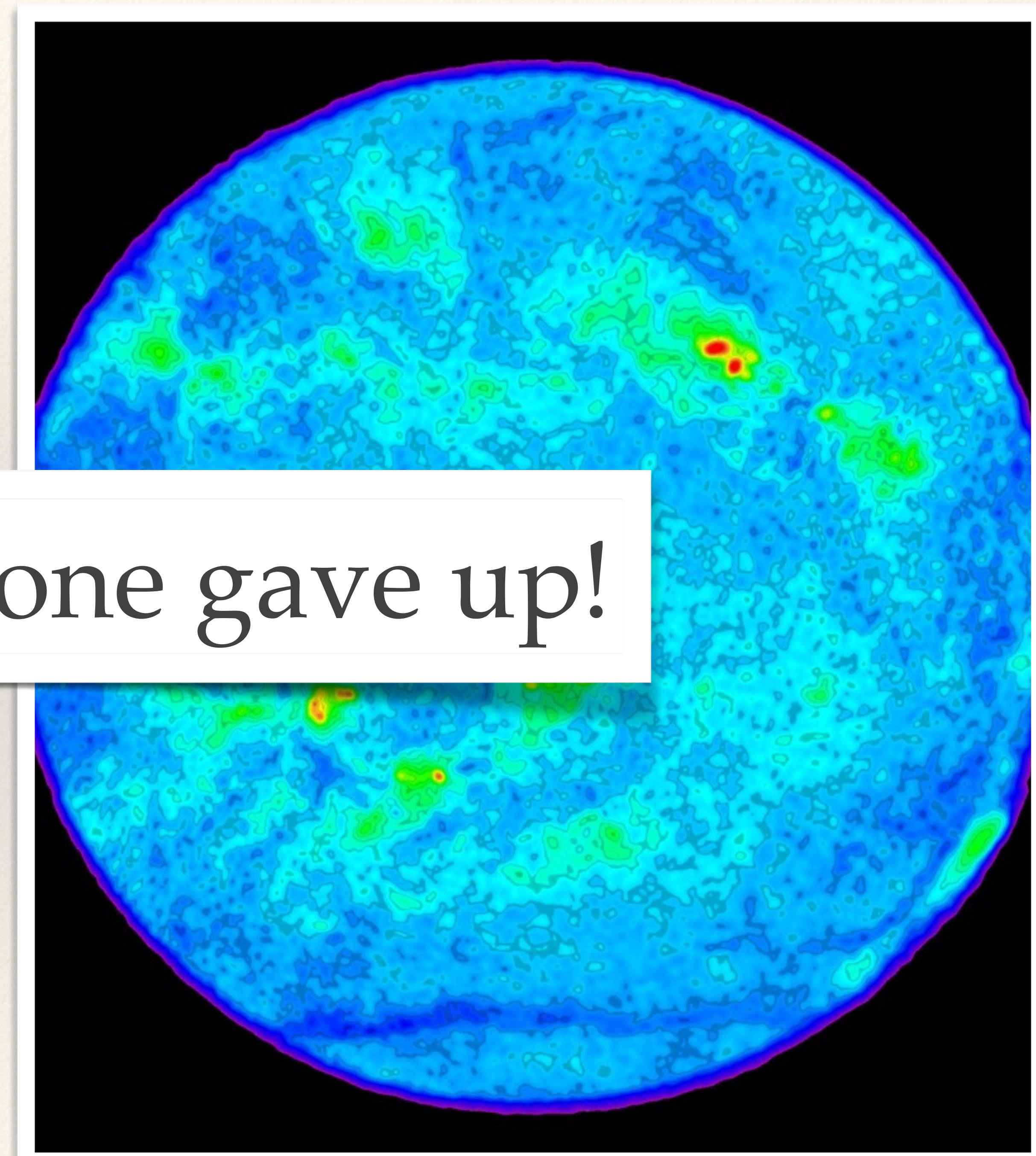
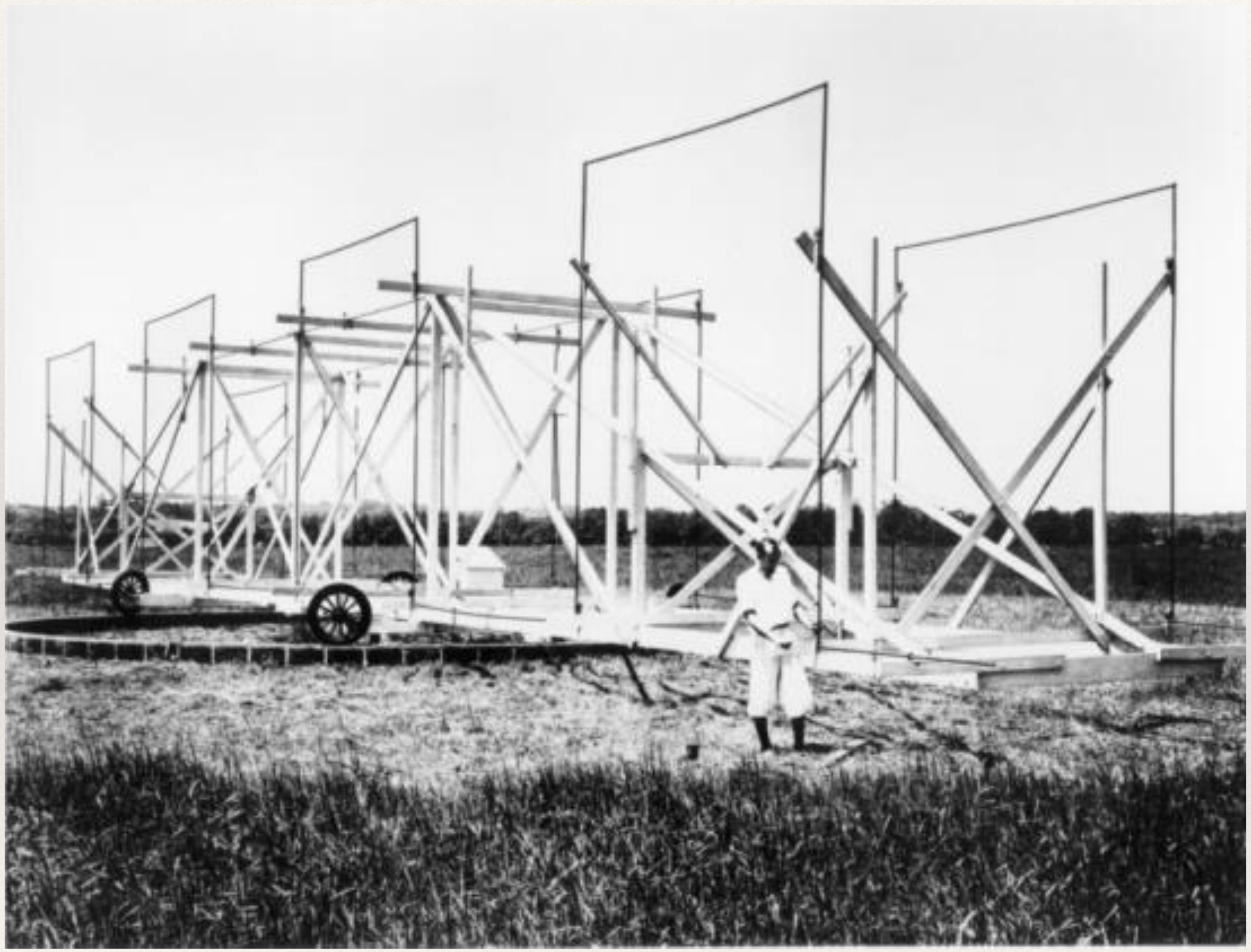


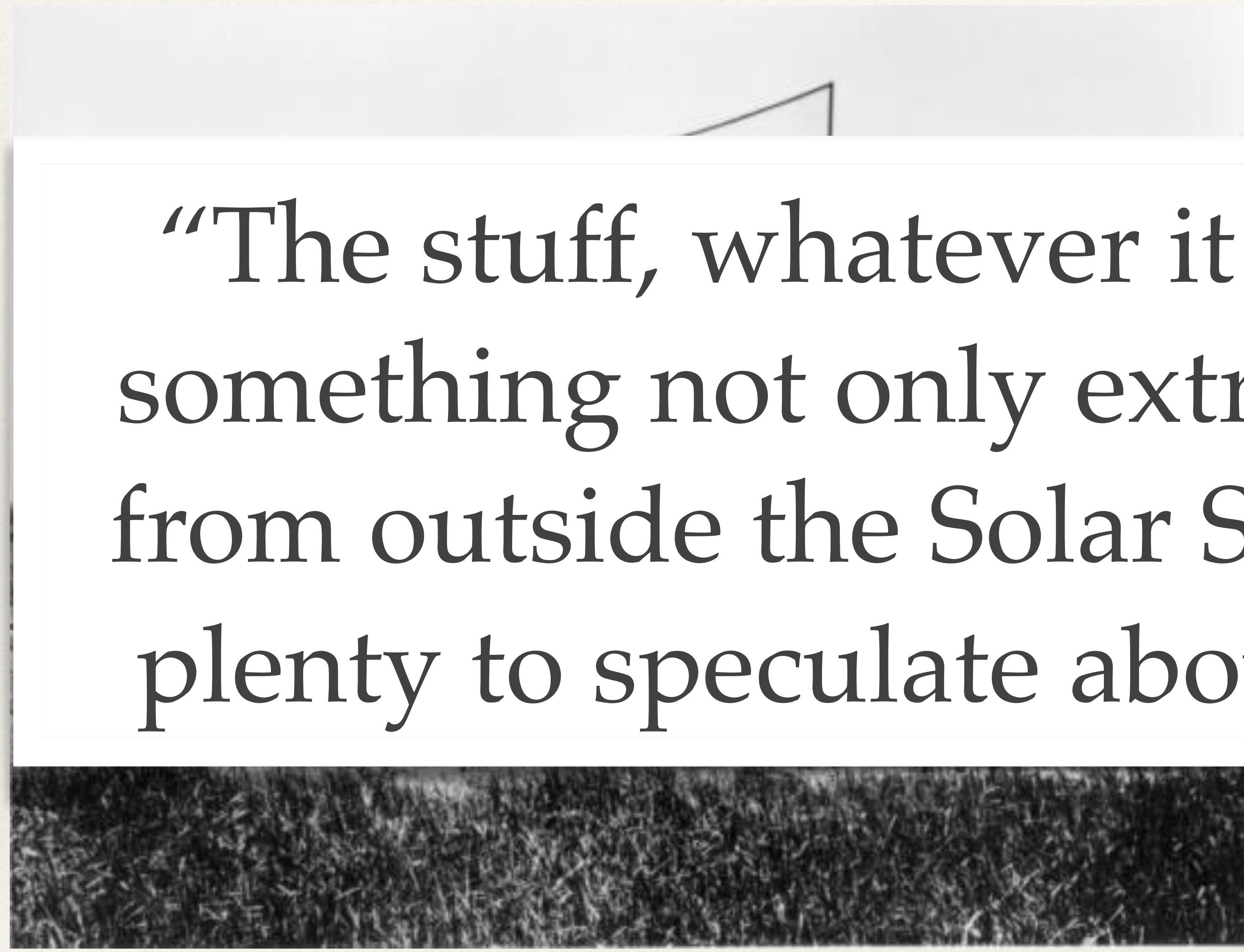
Then… everyone gave up!

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.

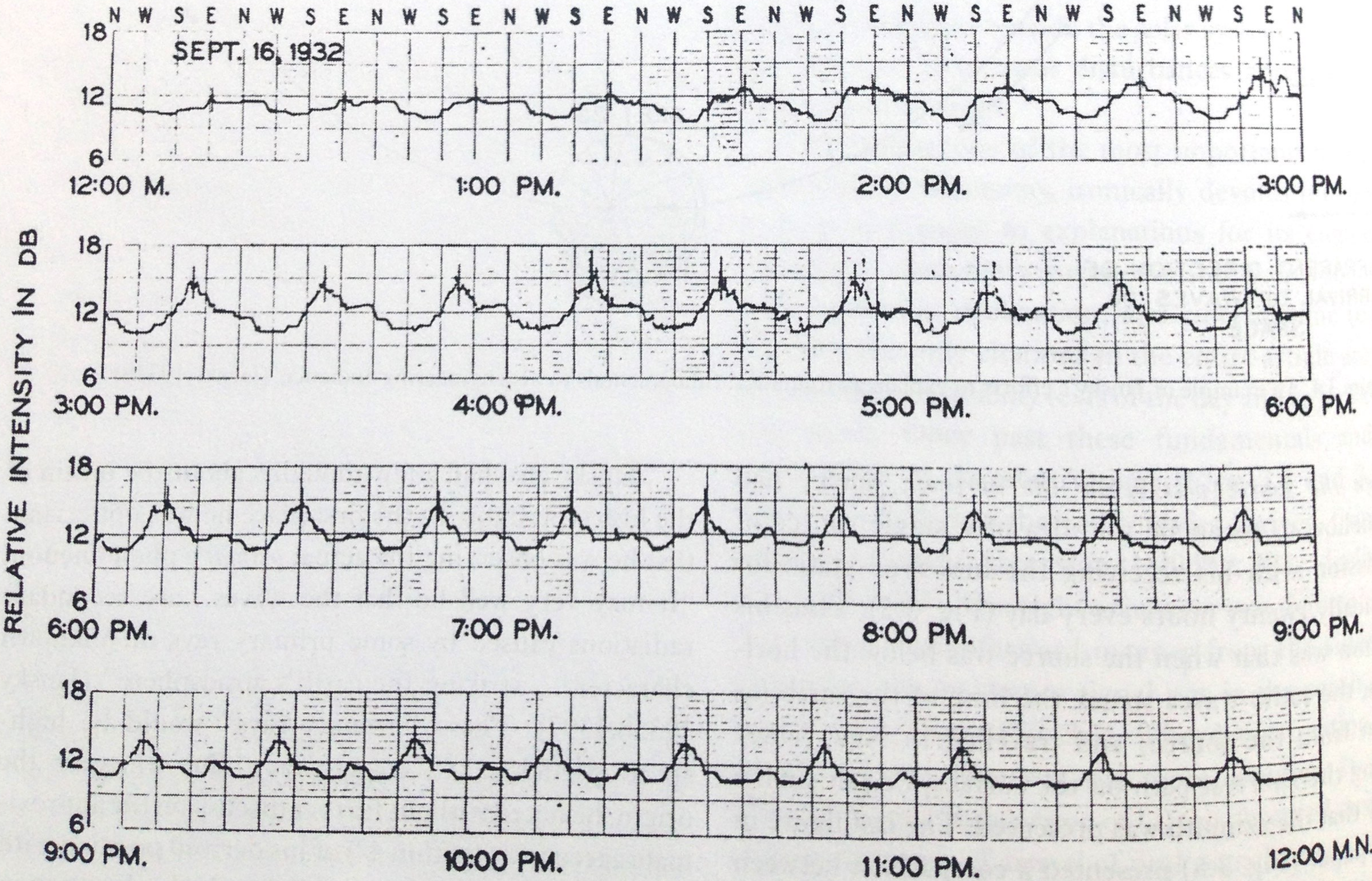
1935- Jansky detects the Galactic centre



- Karl Jansky, "father of

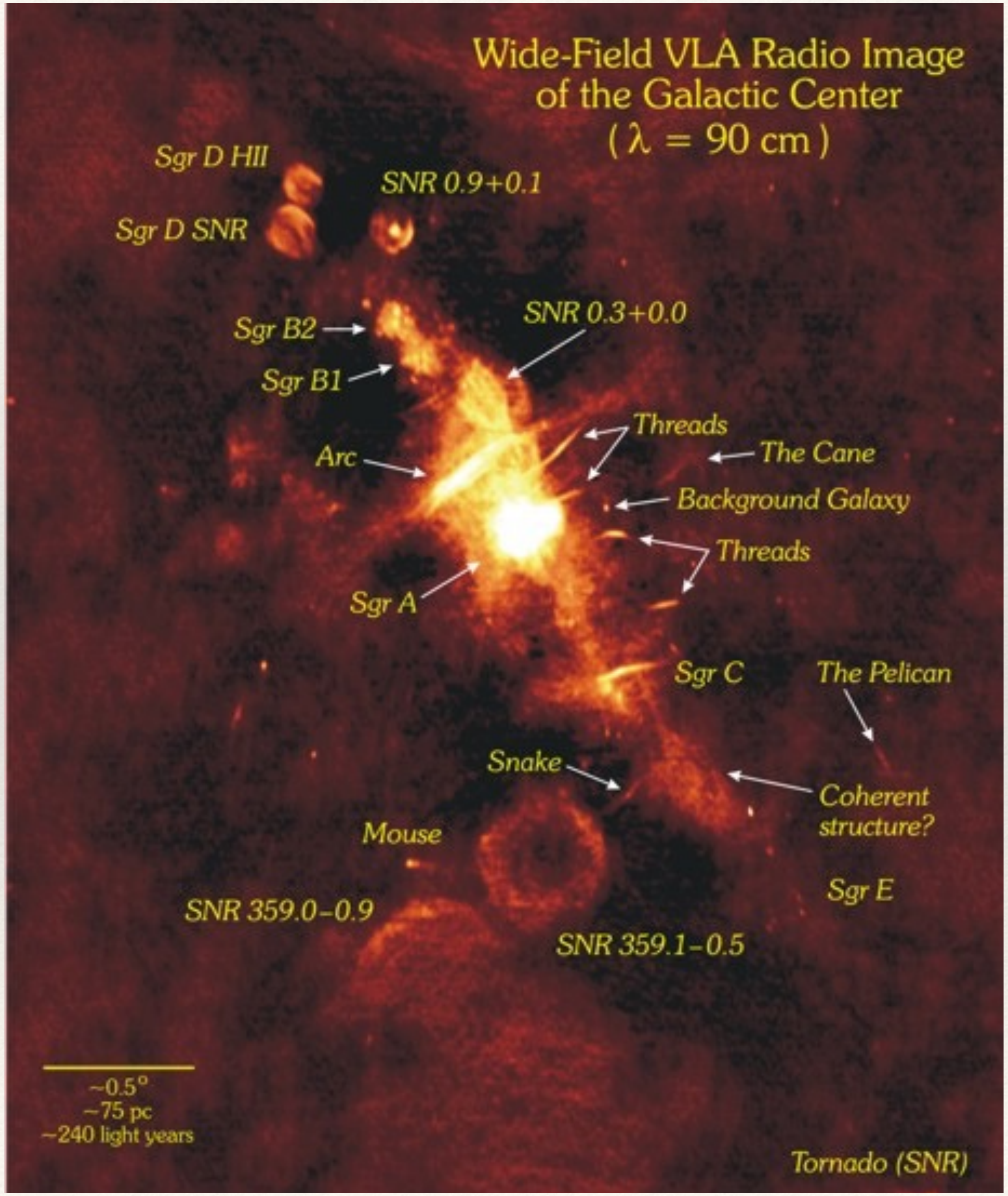
  — on a 24 hour period.

"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?"



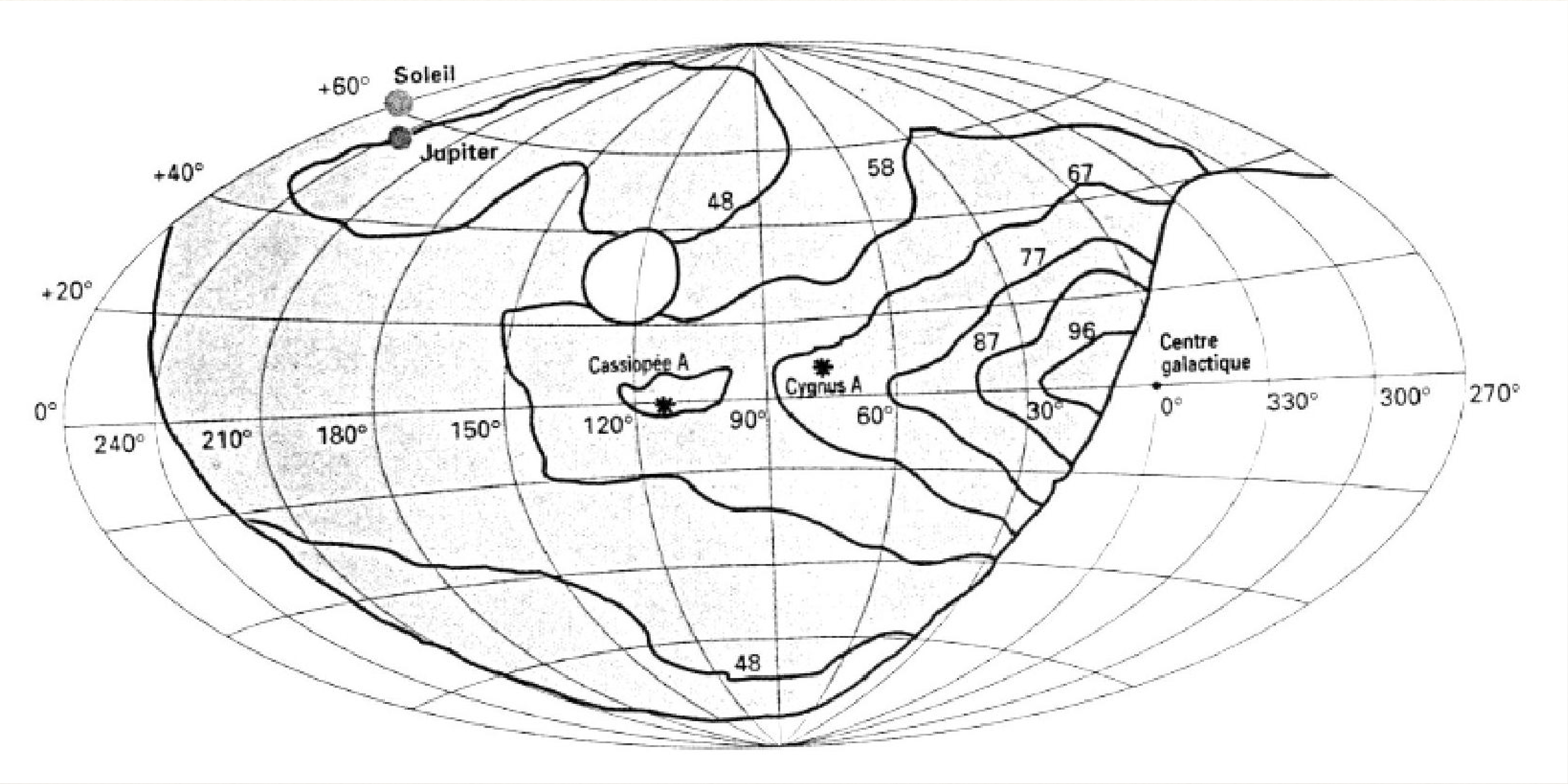
N W S E N W S E N W S E N W S E N W S E N W S E N W S E N W S E N W S E N
SEPT. 16, 1932
RELATIVE INTENSITY IN DB
18
12
6
12:00 M.
1:00 PM.
2:00 PM.
3:00 PM.
4:00 PM.
5:00 PM.
6:00 PM.
7:00 PM.
8:00 PM.
9:00 PM.
10:00 PM.
11:00 PM.
12:00 M.N.

1935- Jansky detects… the Galactic centre

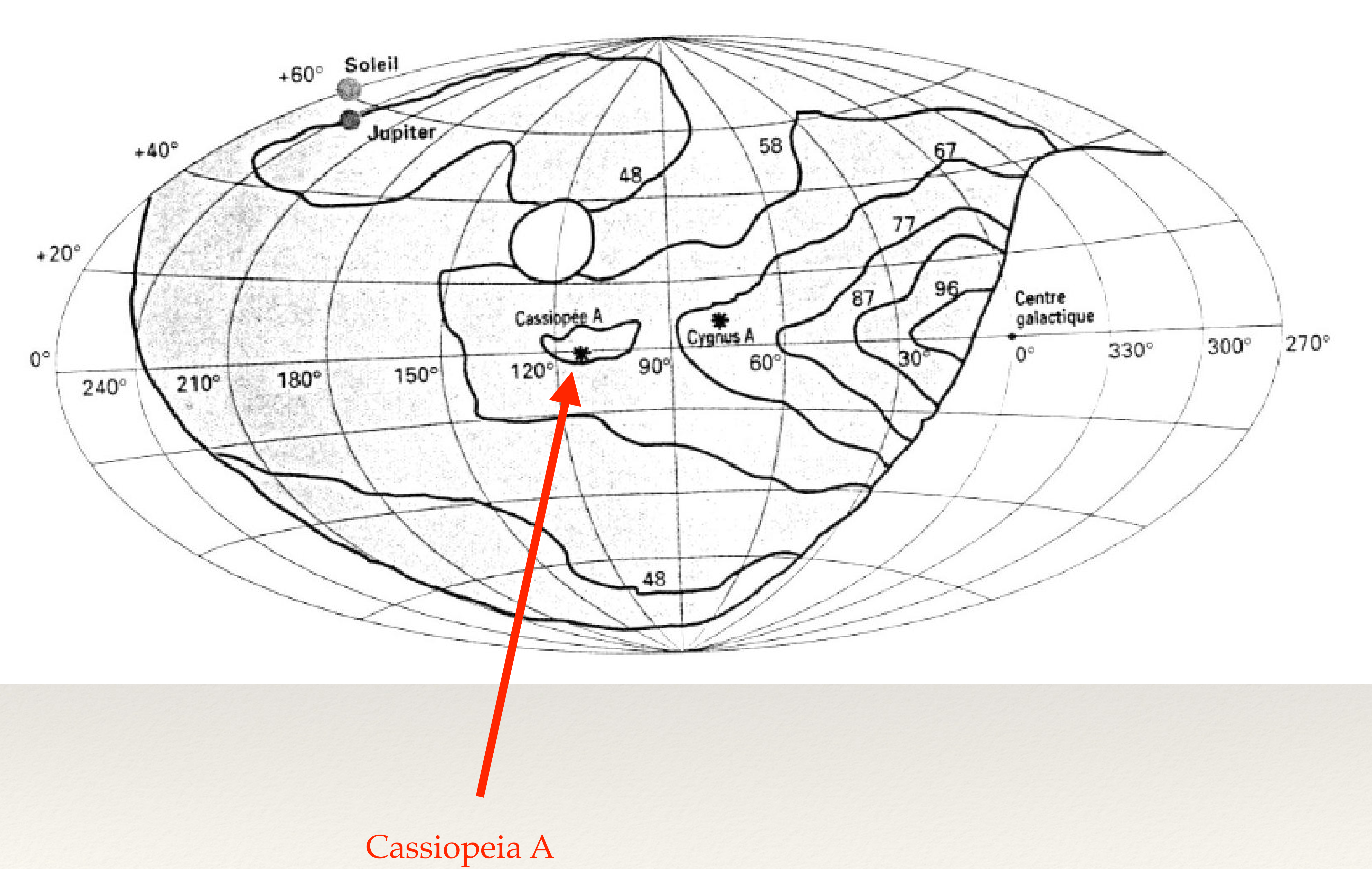


Radio astronomy blossoms

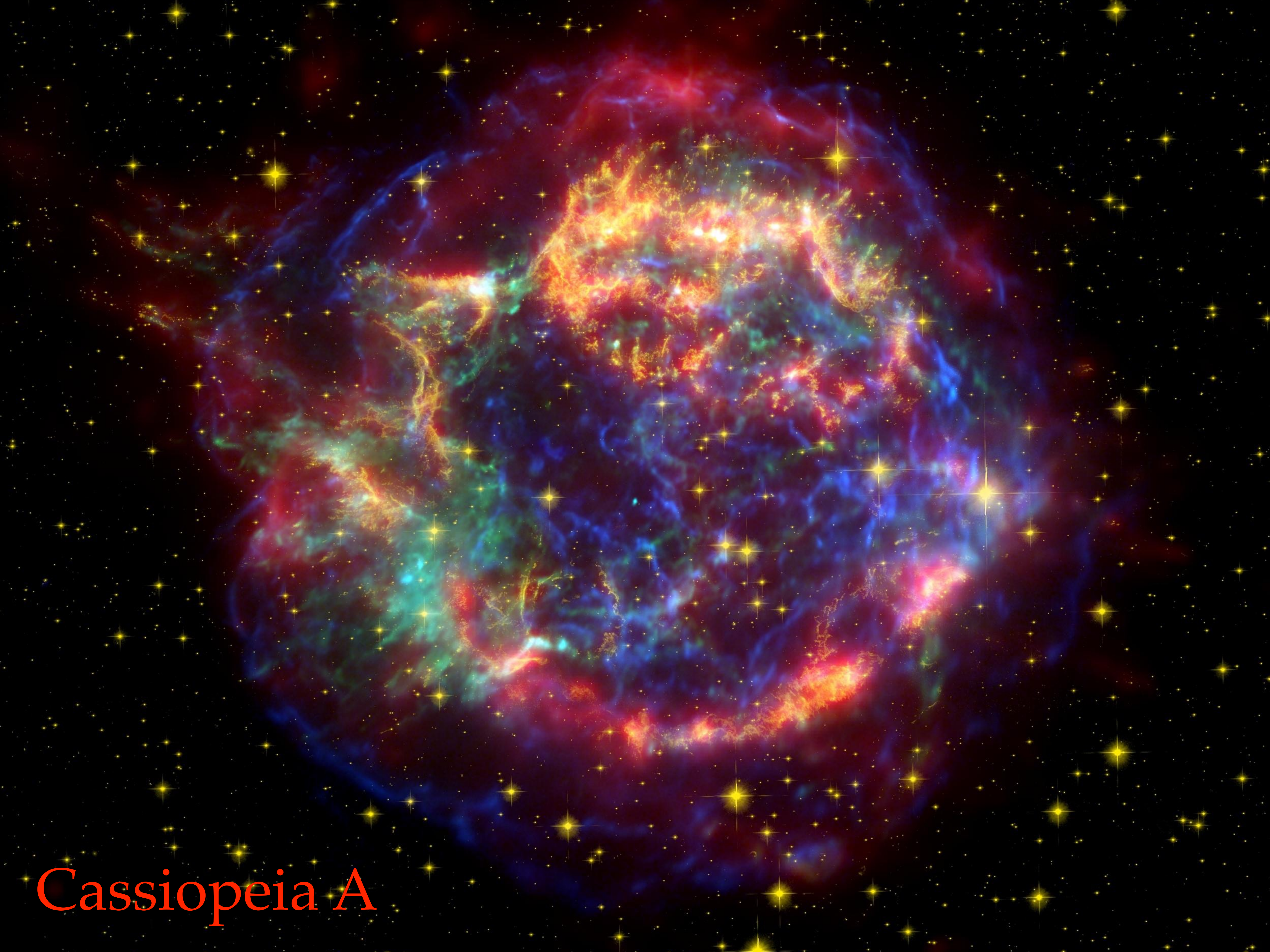
- Grote Reber (1911 - 2002) single-handedly developed radio astronomy in the 30's and 40's
- Jansky worked at Bell Labs… Grote Reber built the largest radio dish in the world in his Chicago back yard.

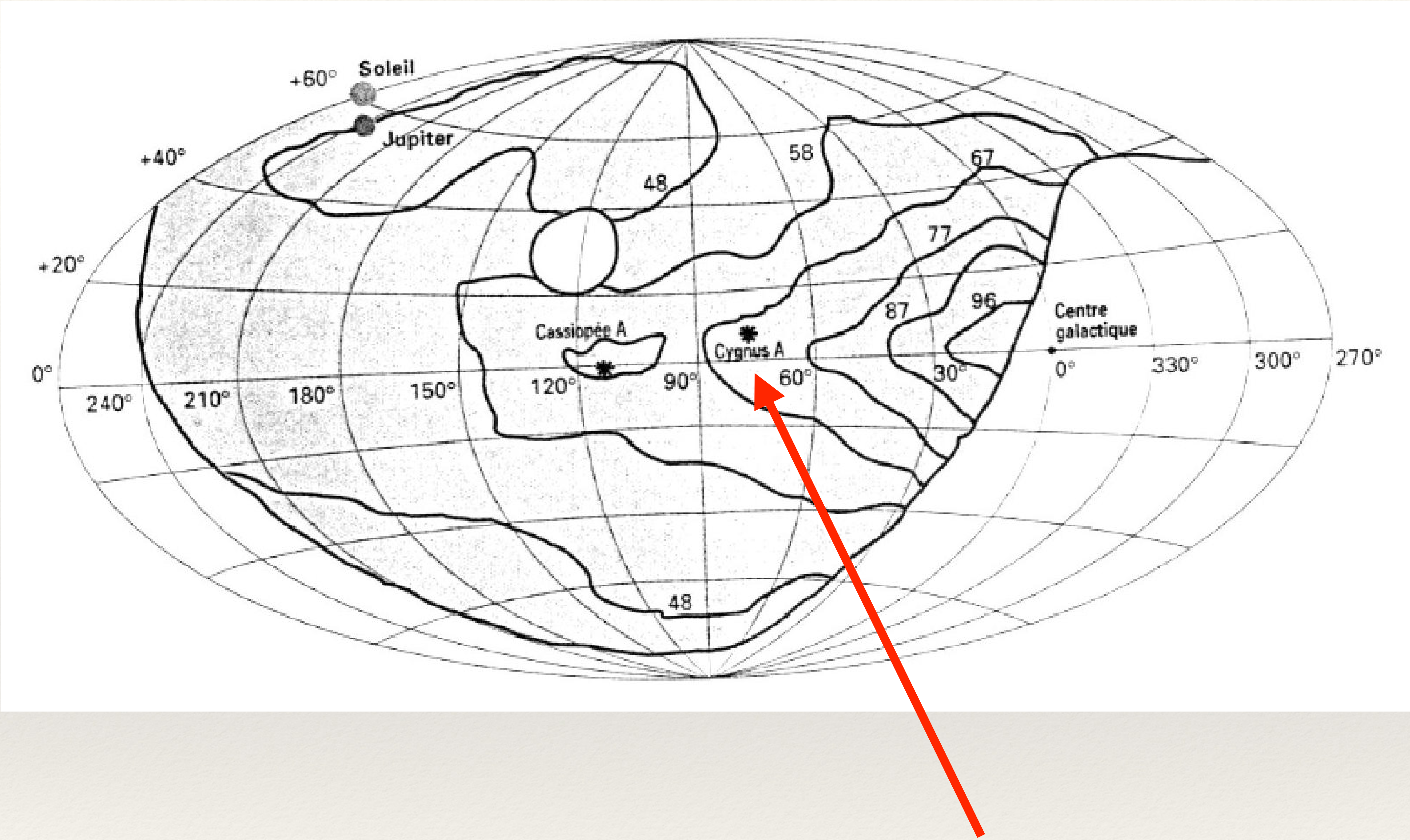


Grote Reber’s map of the radio sky at 160 Mhz



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


Cassiopeia A



Soleil
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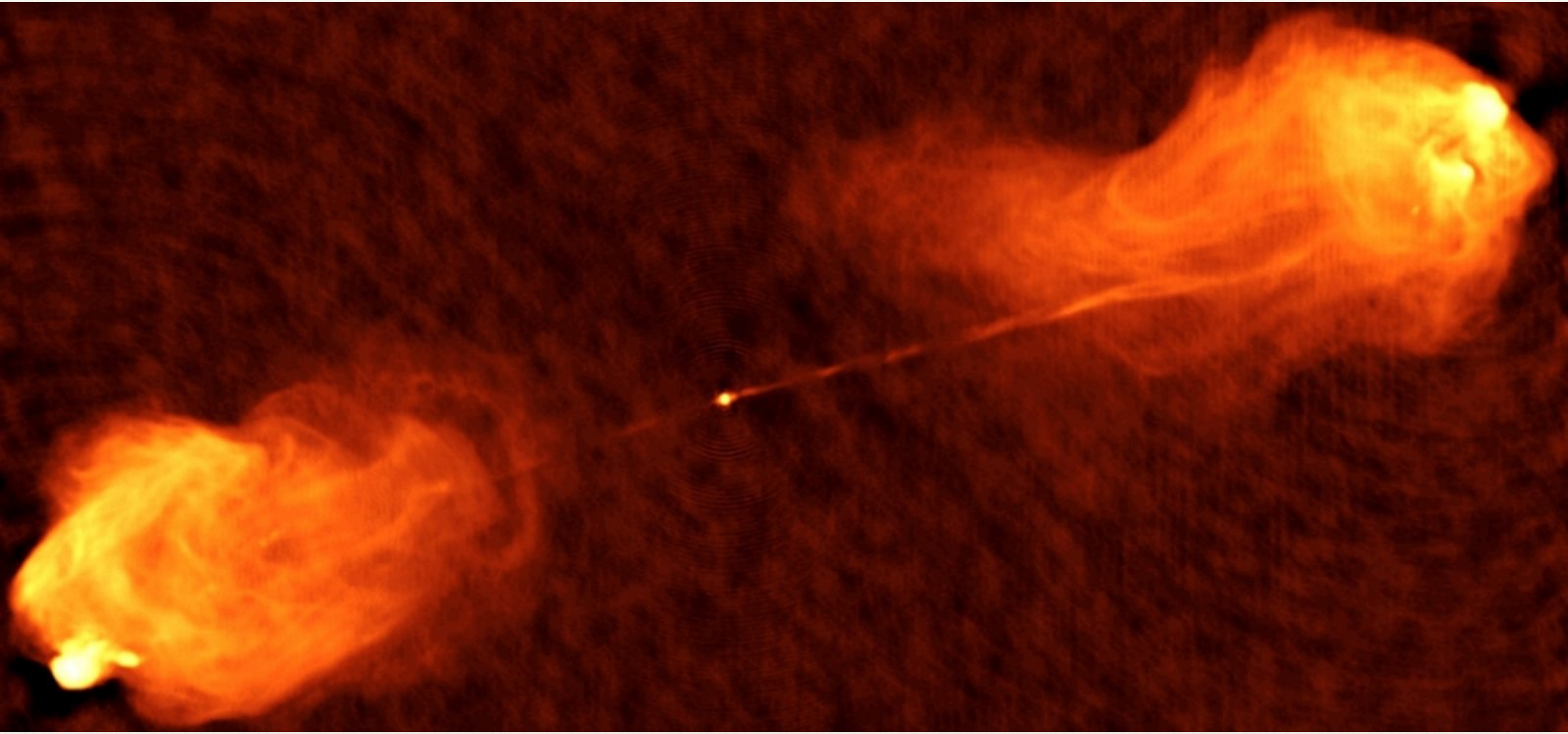
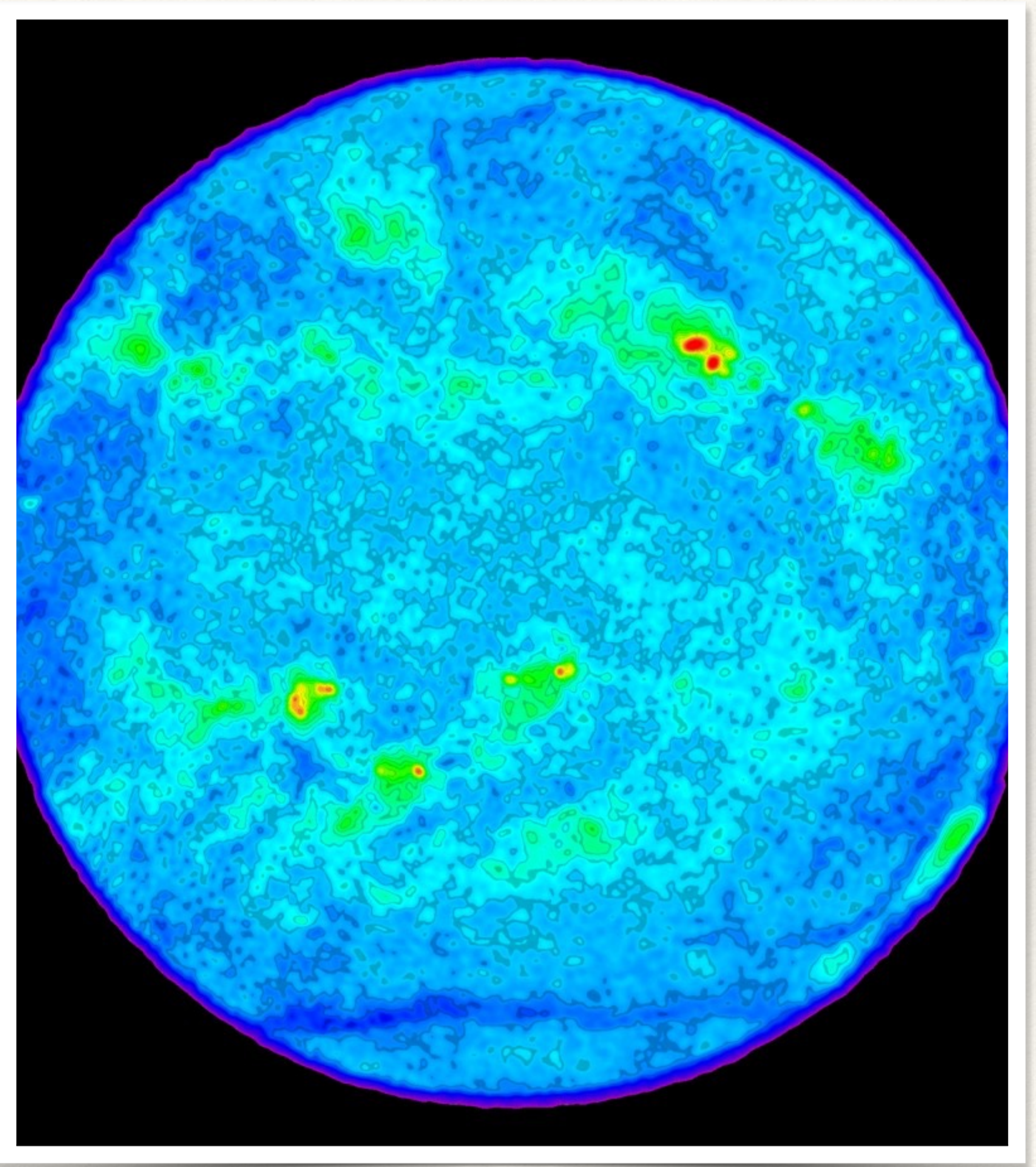
Cygnus A

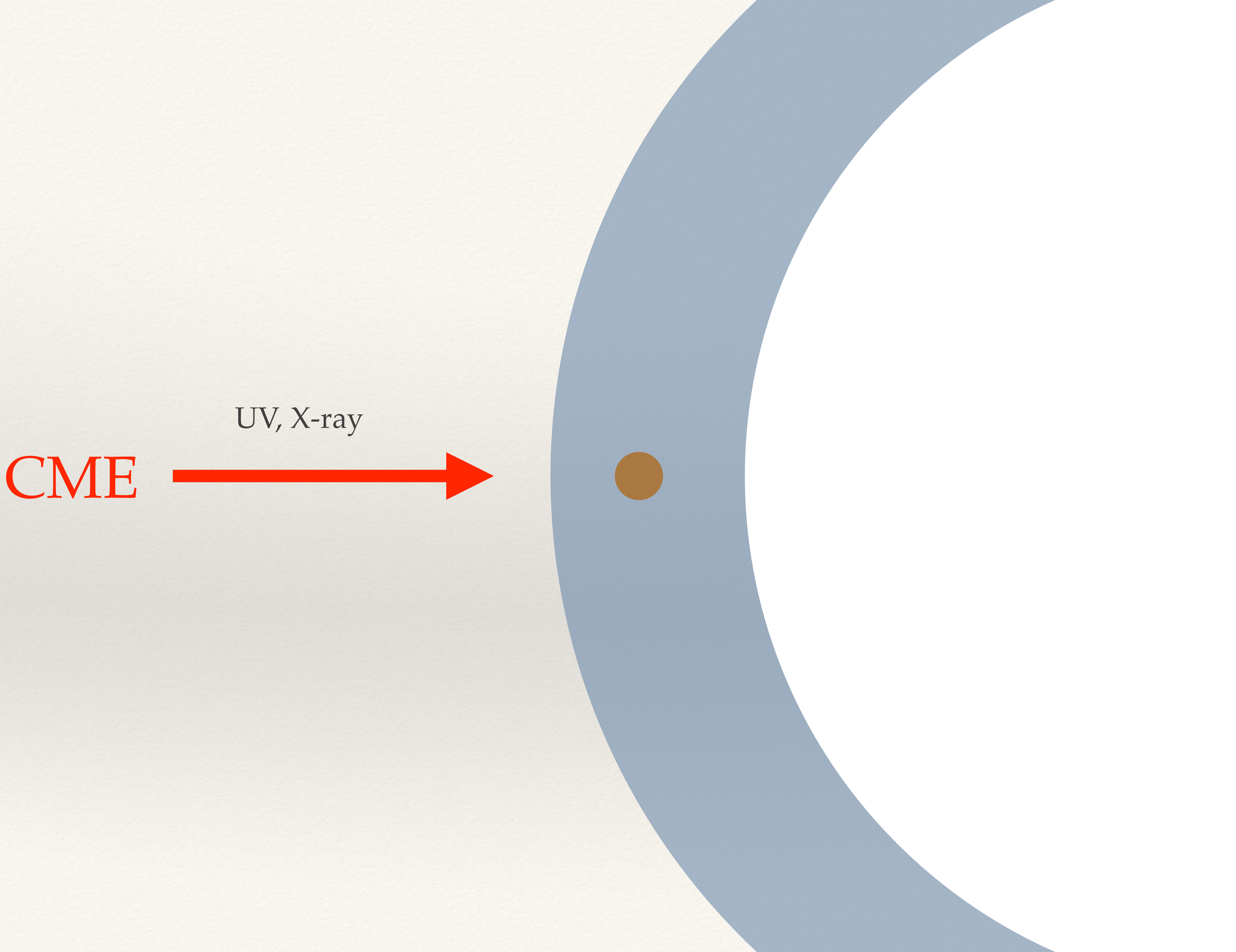


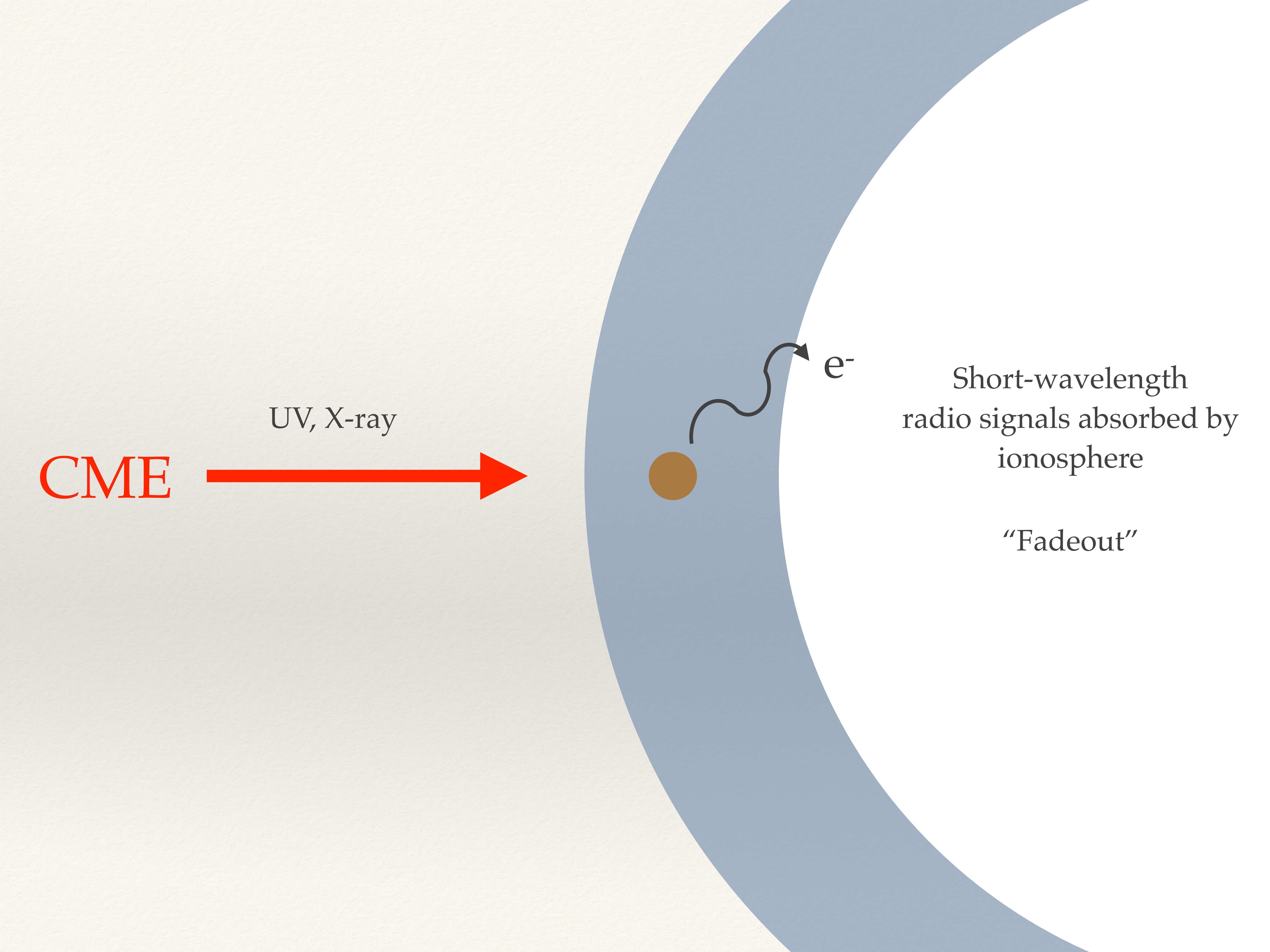
Cygnus A

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

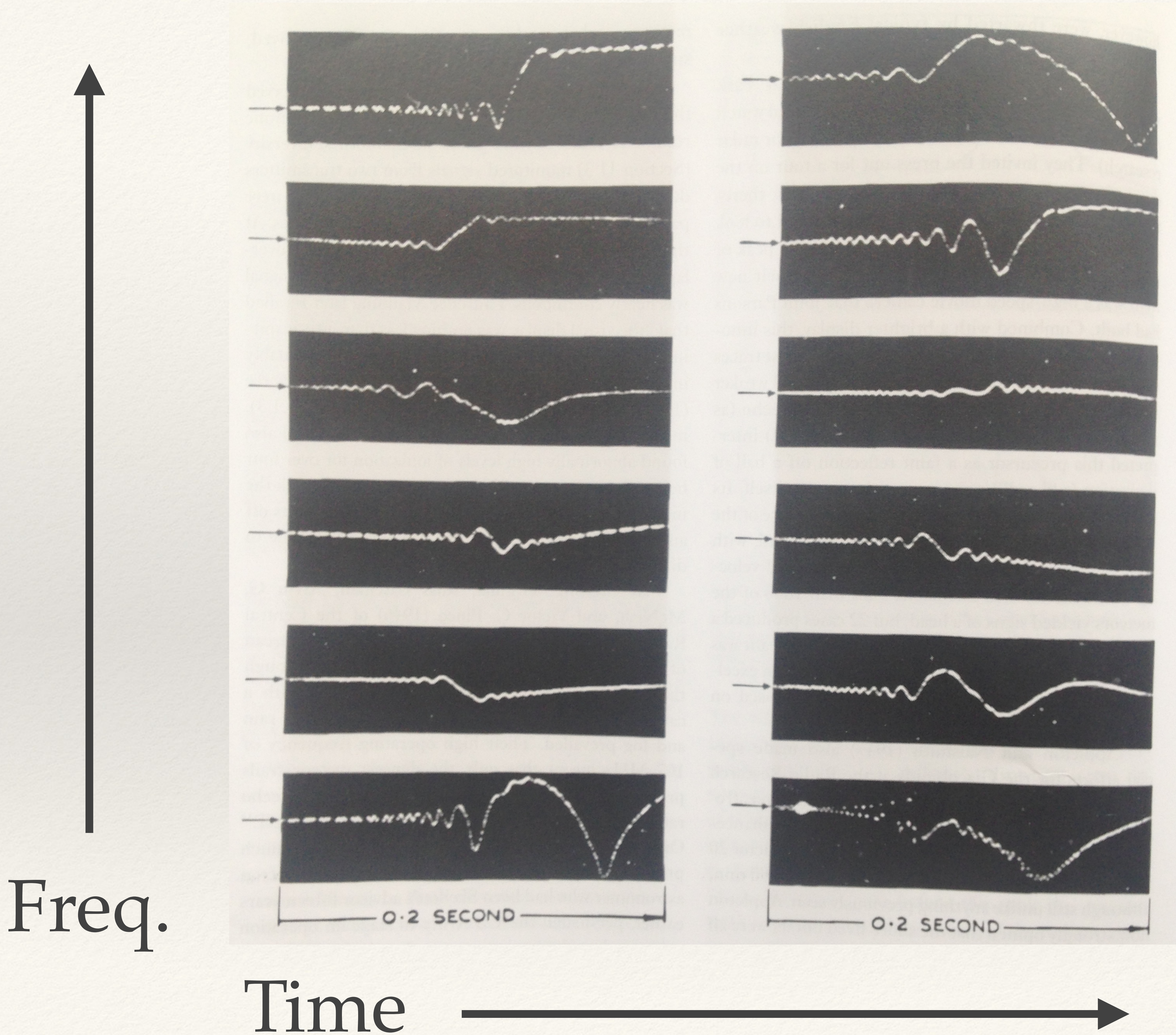


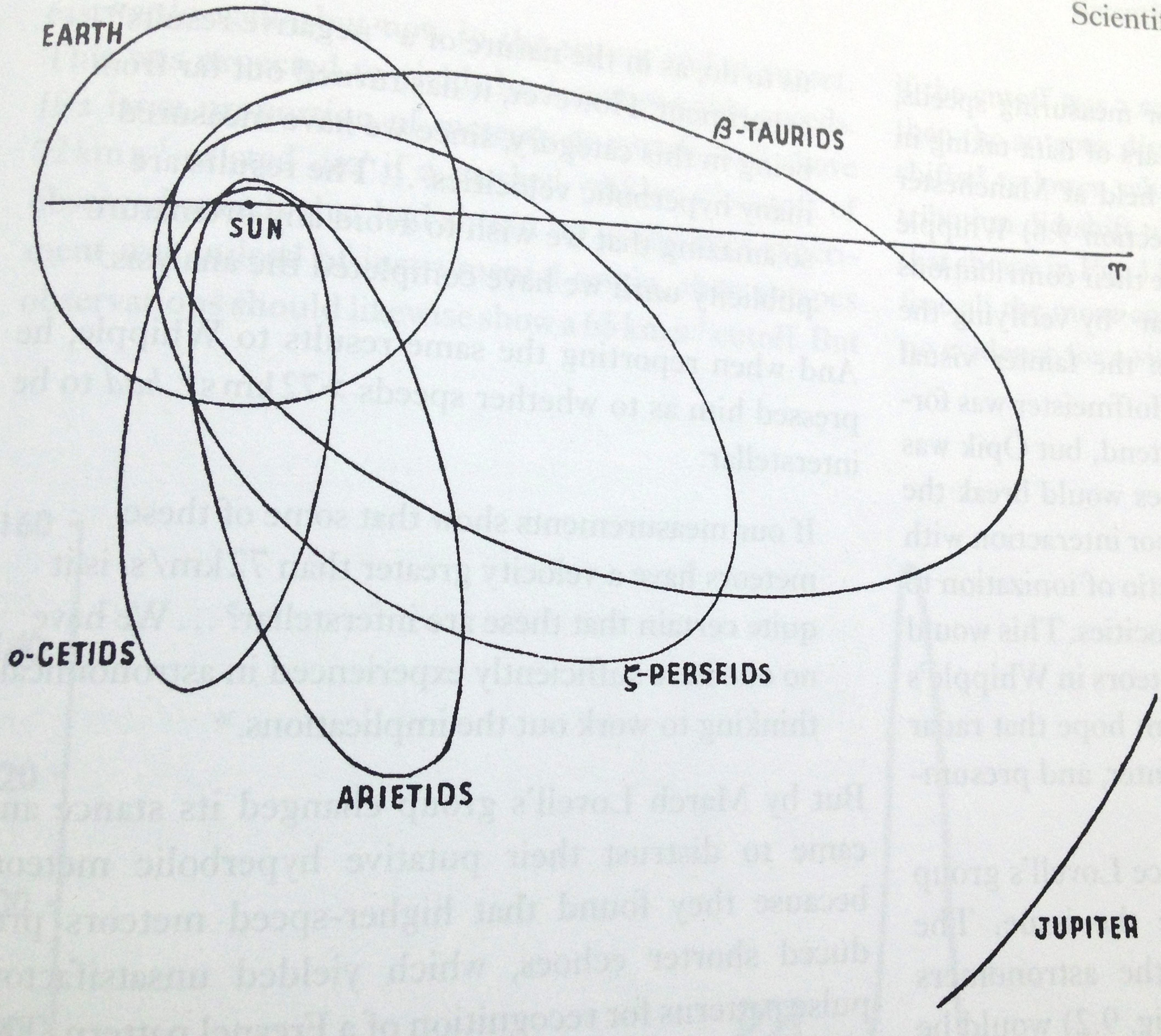

UV, X-ray
CME


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

Post-war: Meteor-radar astronomy

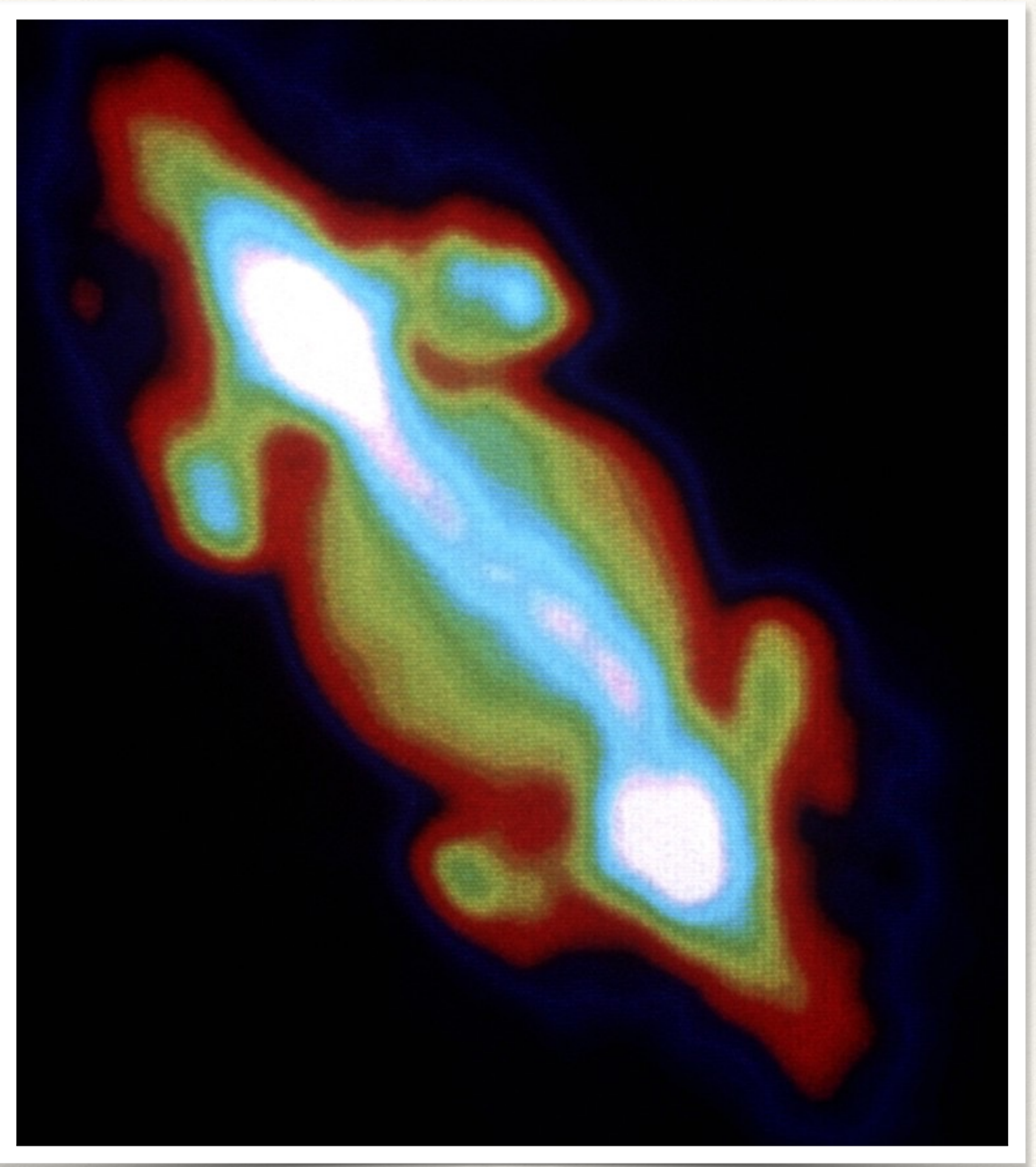
- Idea: bounce RADAR off the ionised tails of meteorites. Already knew atmospheric disturbance affects radio propagation
- Daytime meteor showers!


0·2 SECOND
0·2 SECOND
Freq.
Time


EARTH
β-TAURIDS
SUN
♈
o-CETIDS
ζ-PERSEIDS
ARIETIDS
JUPITER

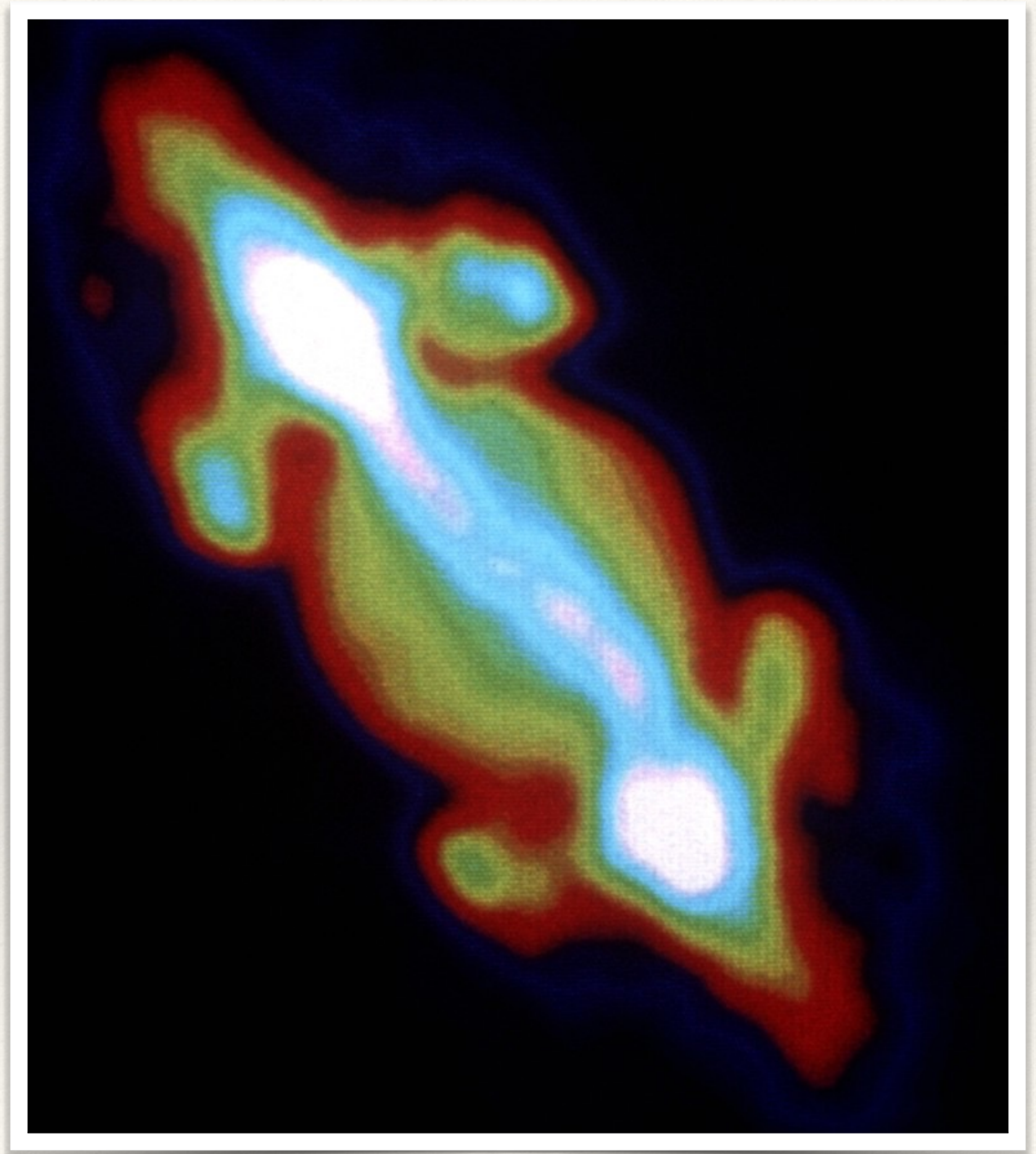
Farther afield…

- 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’

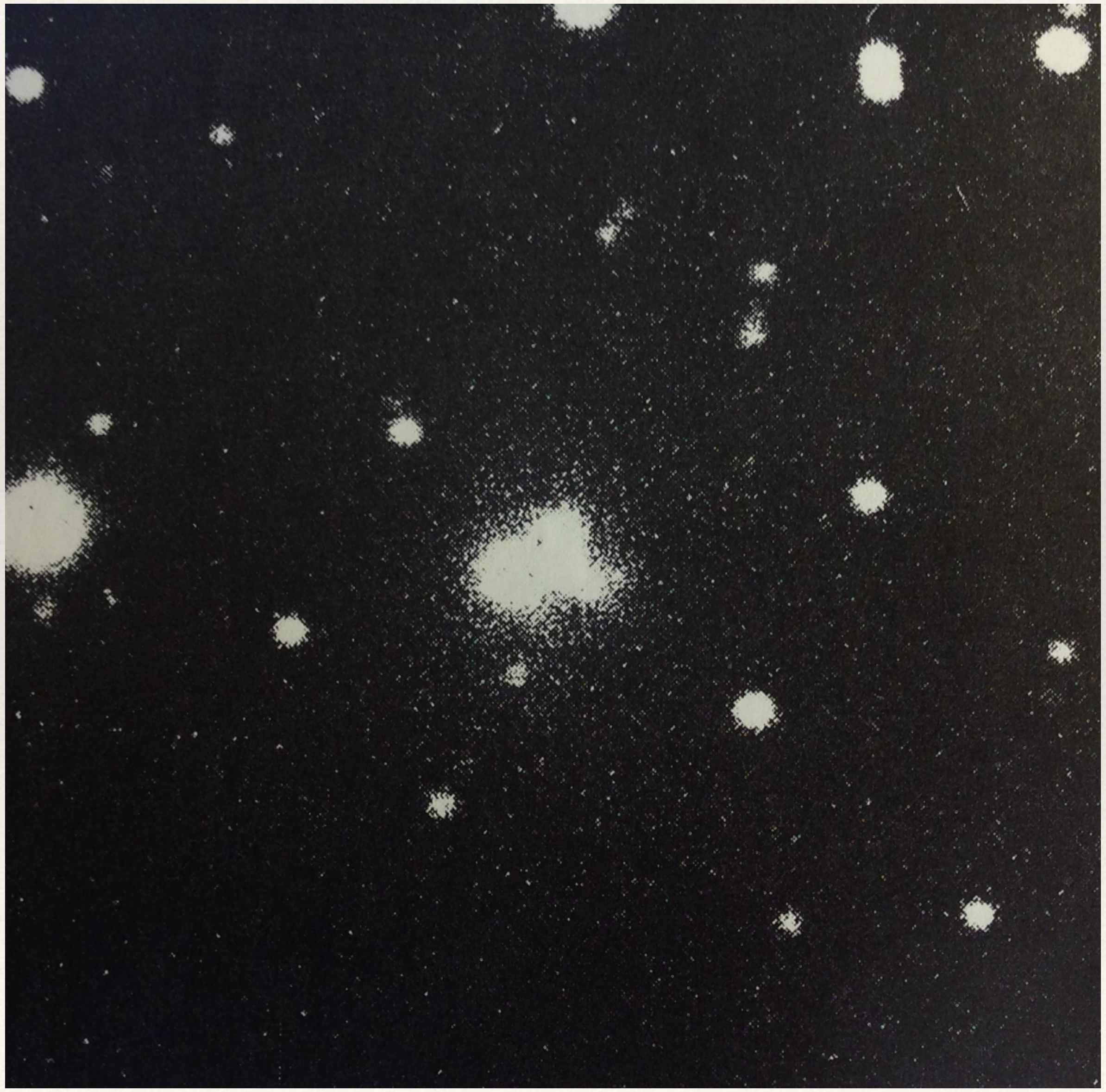
A few discrete radio sources were identified optically… the vast majority were, at first, totally mysterious

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

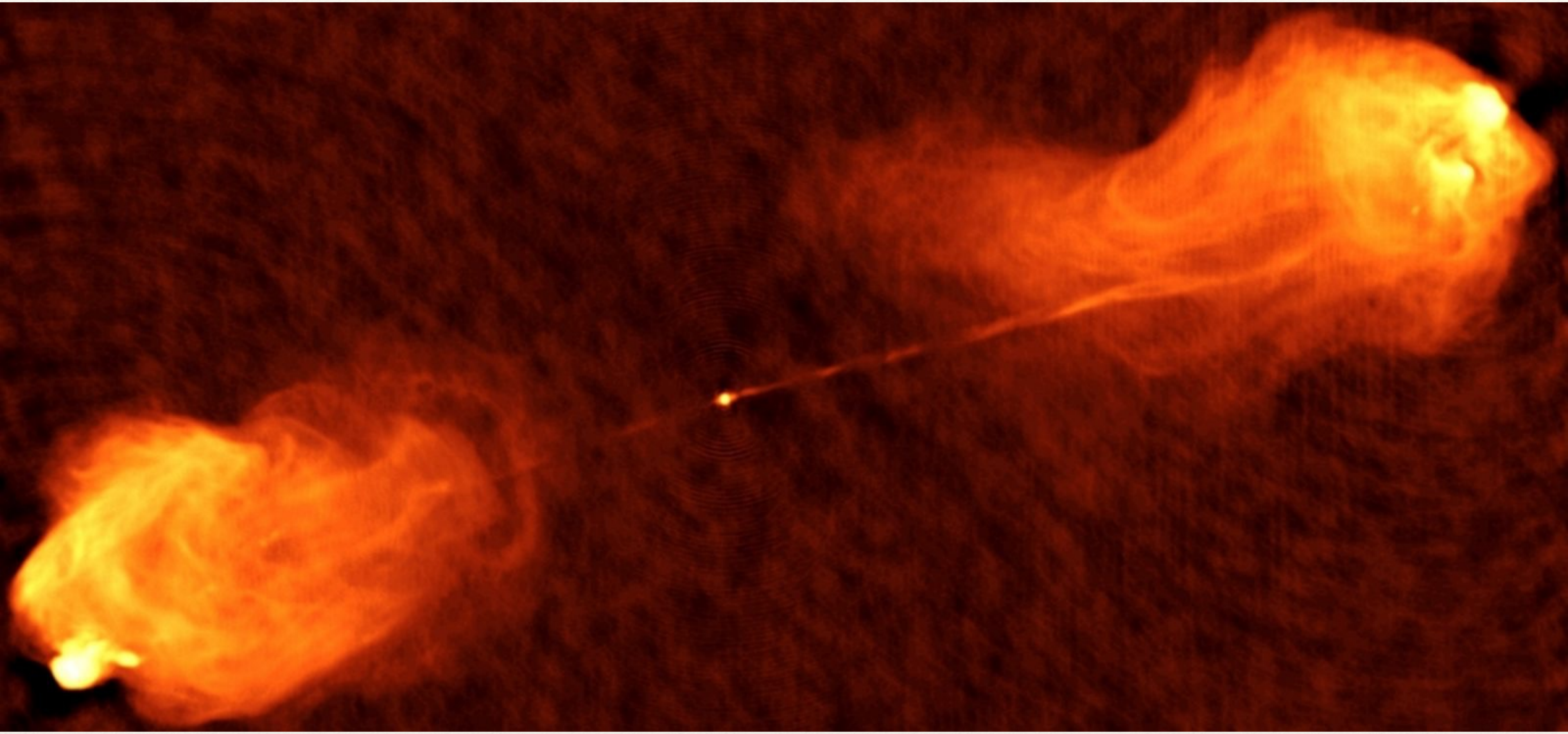
- Van de Hulst, 1951

‘Radio stars’

How to address issue? Optical followup!



Cyg A



Cygnus A

‘Radio stars’

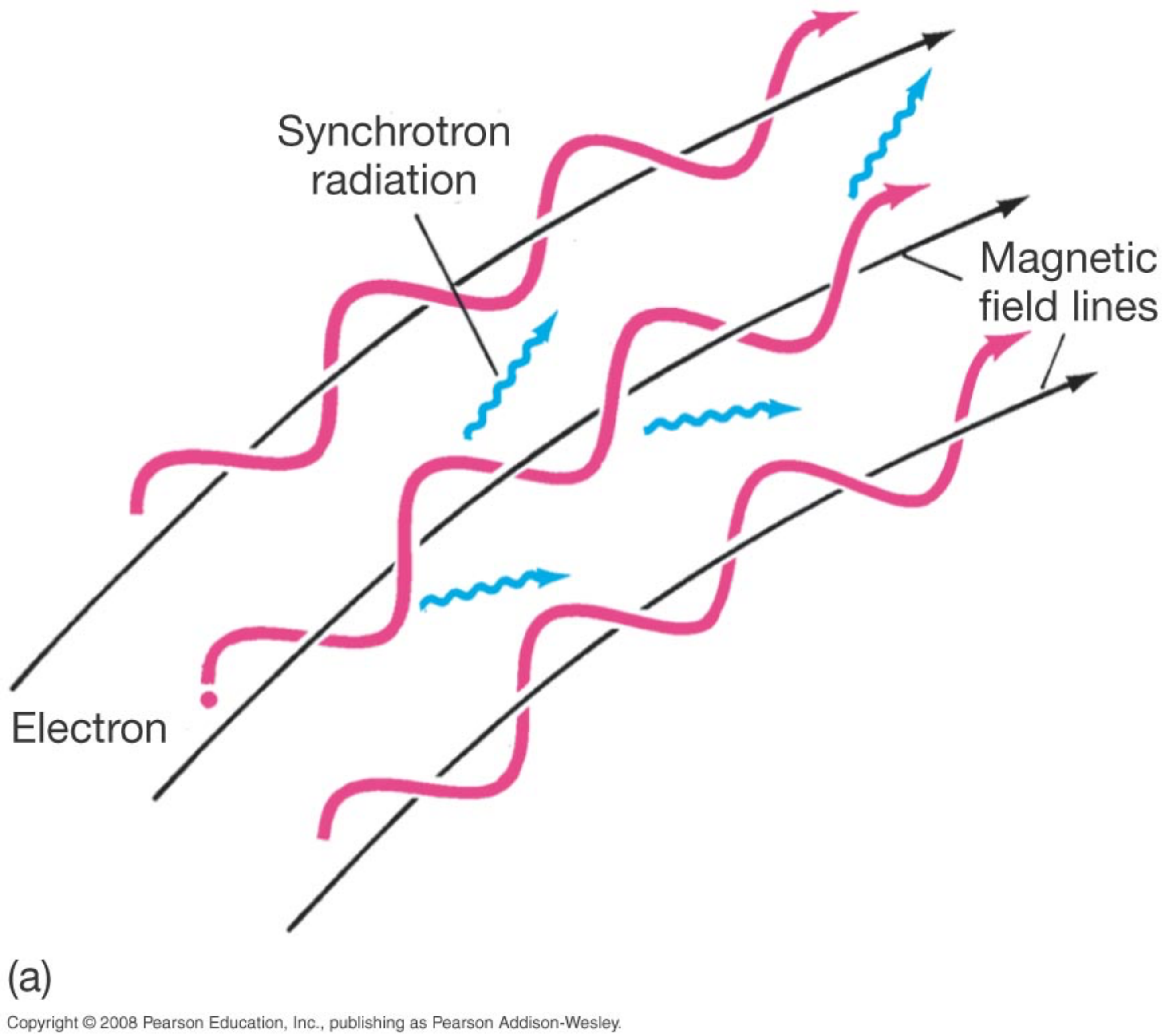
Velocity of radio stars showed that many were extragalactic (Cyg A has *cz*~15,000 km/s)

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

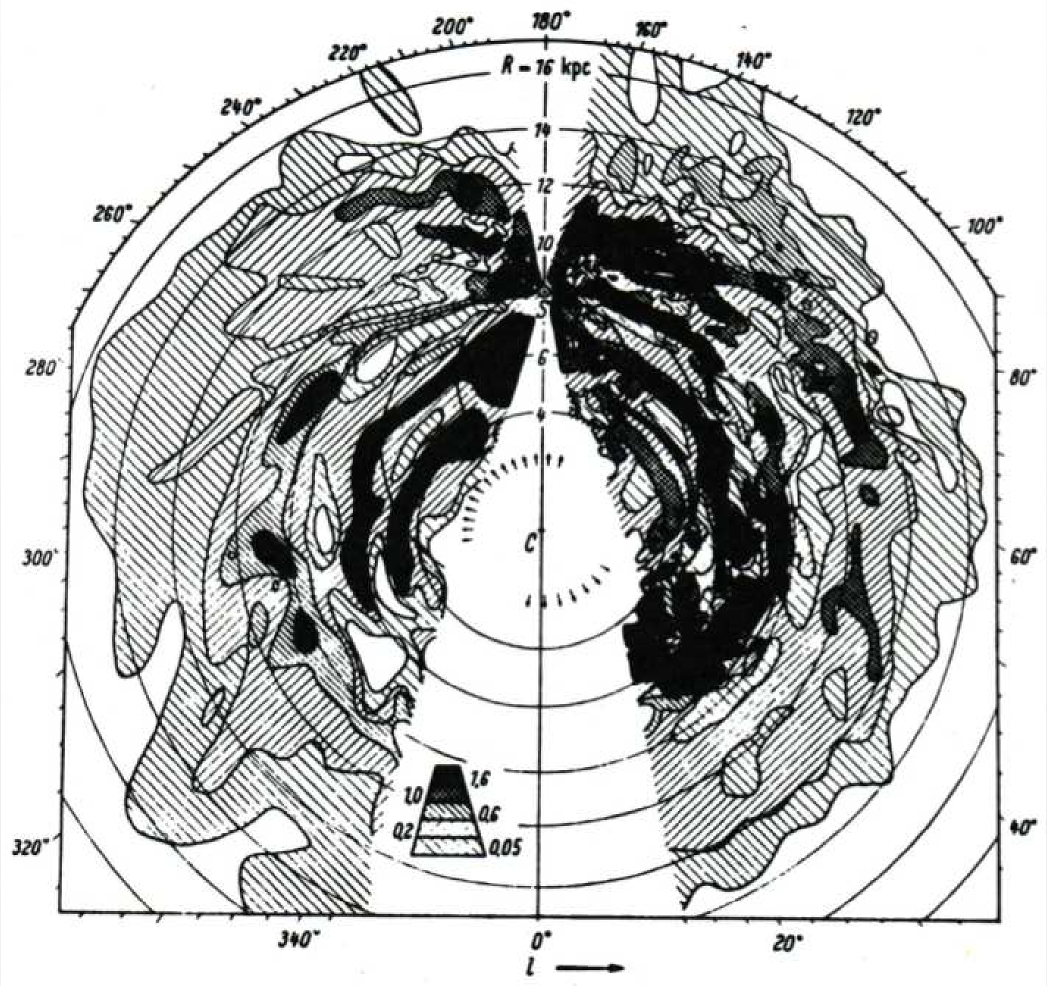
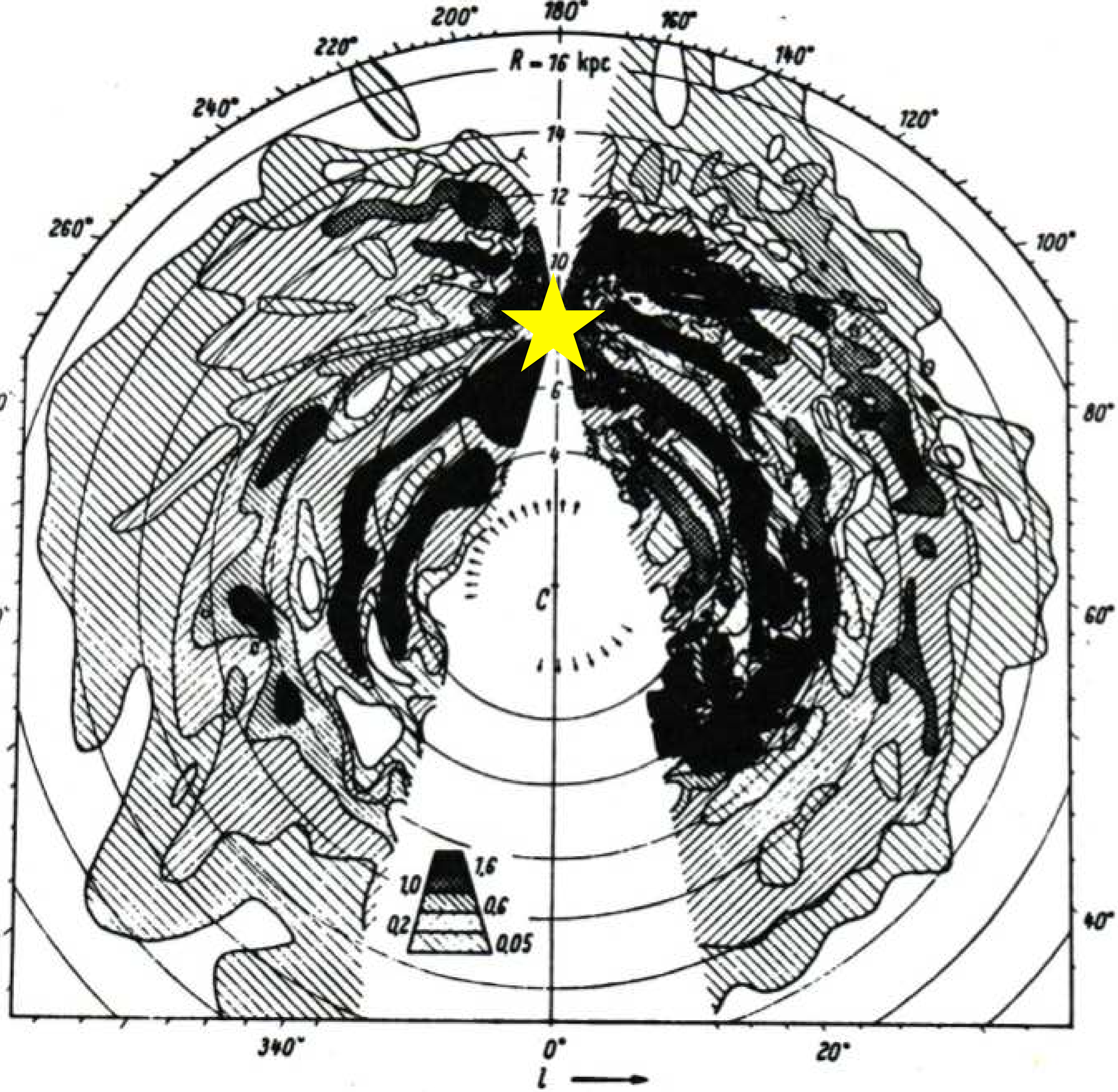


Fig. 1. Map of neutral atomic hydrogen (21-cm line) published by Oort (1959); figure taken from the text book Scheffler & Elsässer (1992). The Sun is in the upper part of the plot at 8 kpc.

1950s, early 1960s

Jan Oort maps atomic hydrogen

Discovers Milky Way spiral structure



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

Topics

- Background: the history of radio astronomy
- Single aperture radio dishes
- Interferometry

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 x 10^{-19} J)
- Radio photon, 1m wavelength…
- Energy = 0.000001 eV!

Why ‘antennas’?

- Radio photons are pretty wimpy
- I
- E
- E

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

- Radio photon, 1m wavelength…
- Energy = 0.000001 eV!

Two main classes of radio telescope

Dipoles

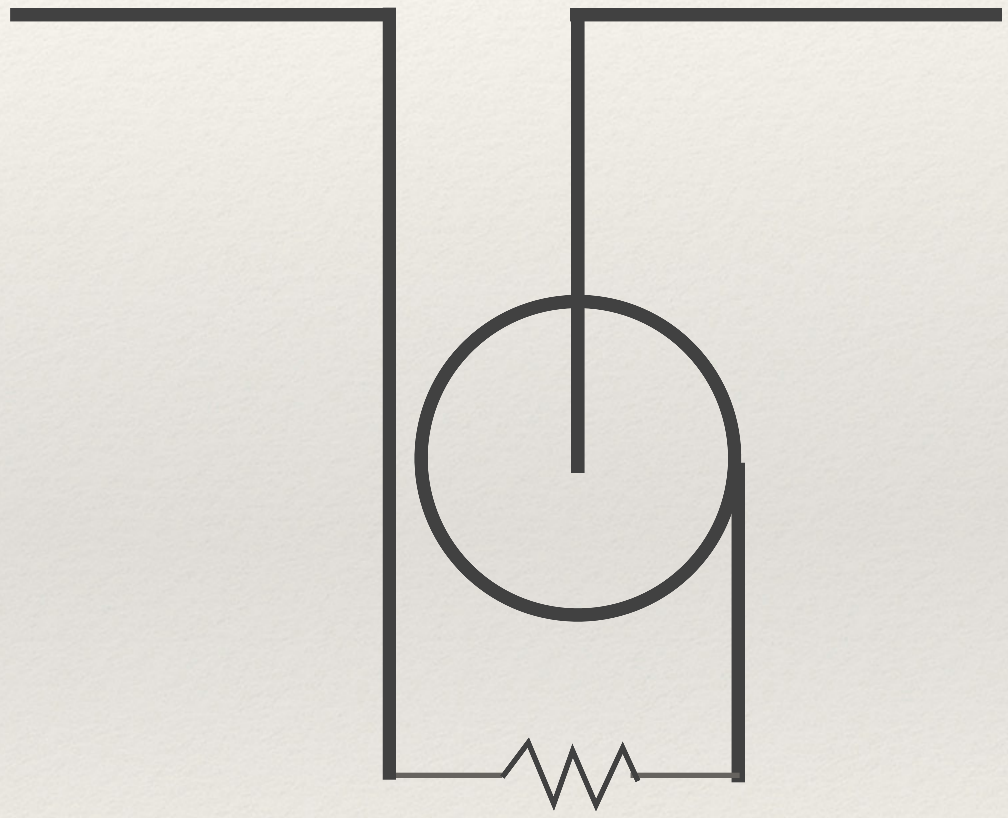
Dishes

Dipoles are (relatively) simple

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

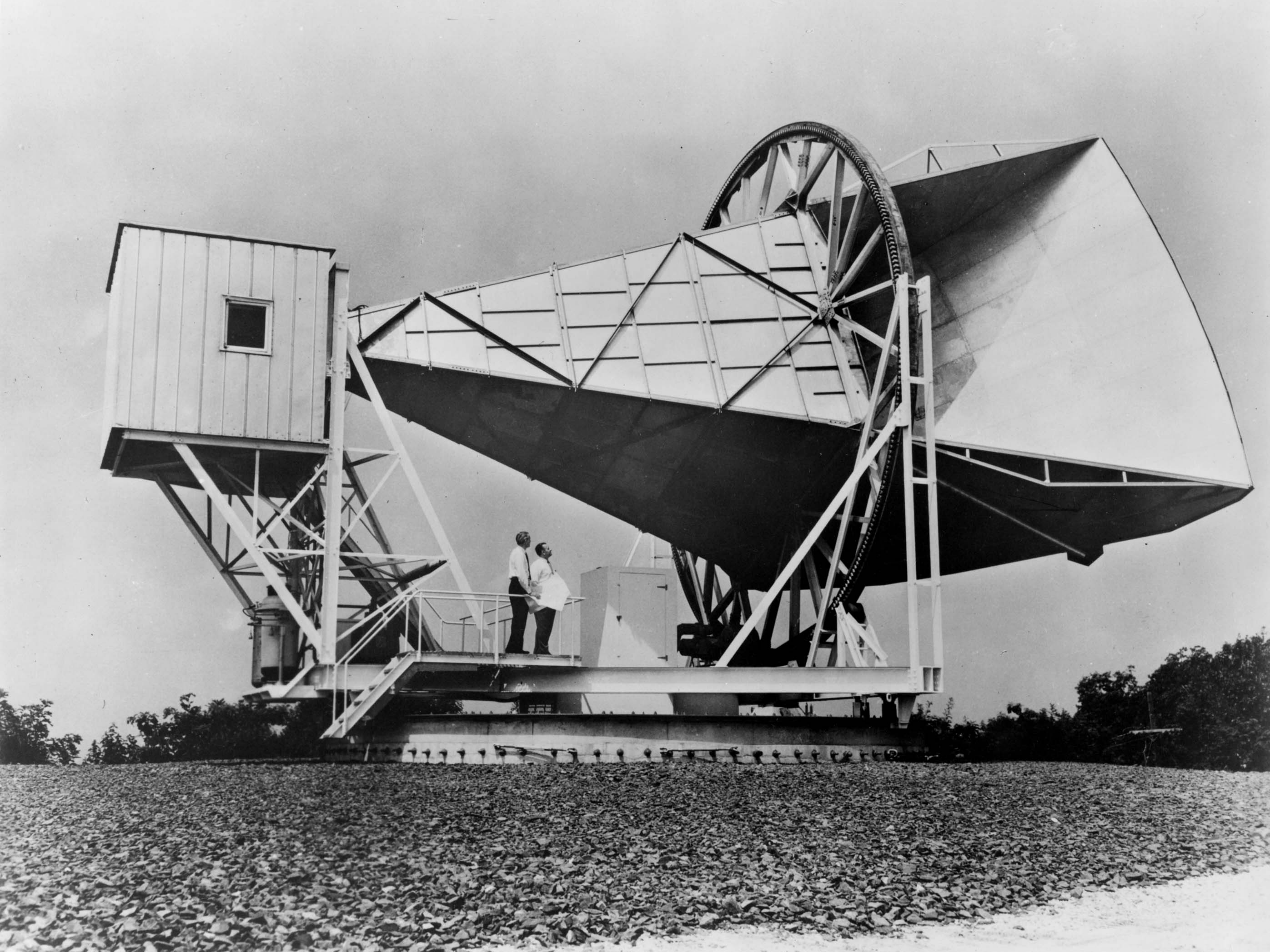
Dipole antennas

- E-field of incoming radiation sets up current in antenna
- Voltage measured across resistor
- Current induced by field parallel to antenna



Waveguide horns

- Towards higher frequencies, getting good sensitivity requires ‘directive aperture antennas’
- One example: waveguide horn



Waveguide horns

- Towards higher frequencies, getting good sensitivity requires 'directive aperture antennas'
- One example: waveguide horn
- Advantages: lack of structure means that there is little blocking the aperture. Can calculate absolute flux densities easily! Large dishes typically only measure relative flux densities, and require calibration sources

Two main classes of radio telescope

Dipoles

Dishes

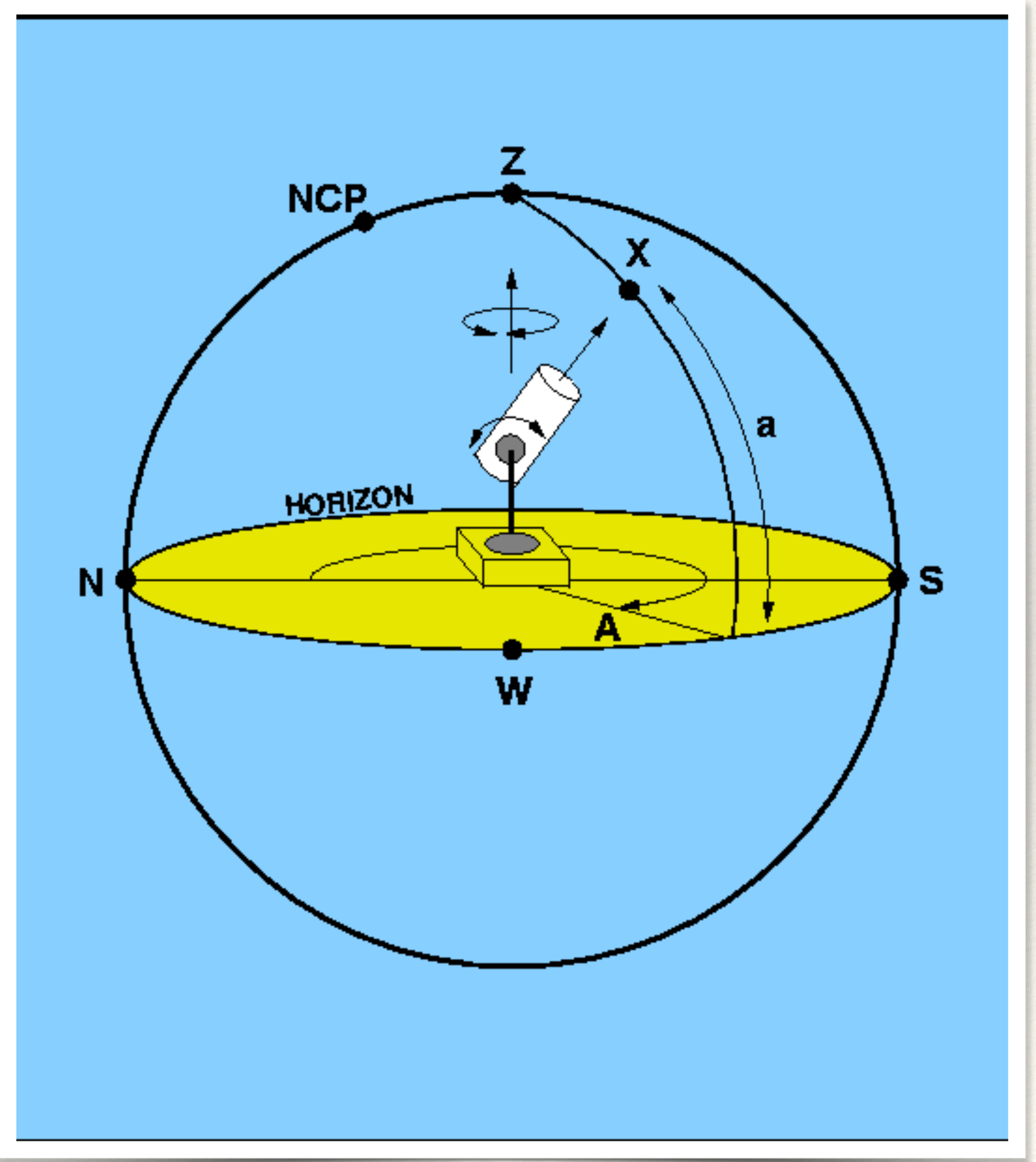
Dishes (AKA parabolic telescopes)
Used at high frequencies
Boundary between dish and dipole is ~300 MHz
This will shift to higher frequencies as technology improves

Cambridge
1 Mile Telescope

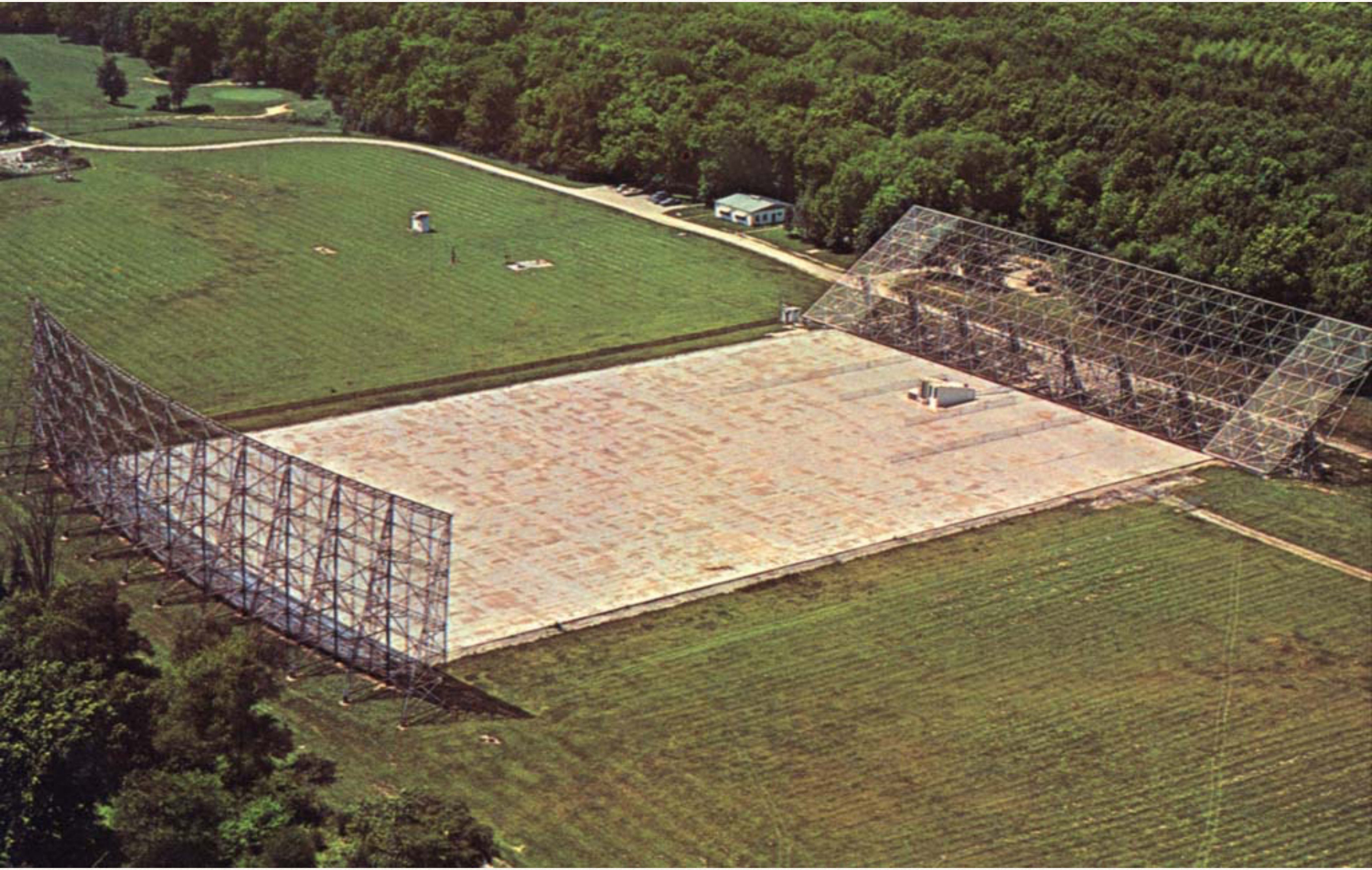
Manchester
Lovell Telescope

Alt-Az mount

- Most modern radio telescopes use an “Alt-Az mount” (rotate around 2 axes)



Other weird telescope designs…



Angular resolution of radio telescope

How to think about the sensitivity of a radio telescope?

Reciprocity theorem: any radio receiver can, equally, be thought of as a radio transmitter

(This is technically because Maxwell's equations are time-reversible)

Angular resolution of radio telescope

How to think about the sensitivity of a radio telescope?

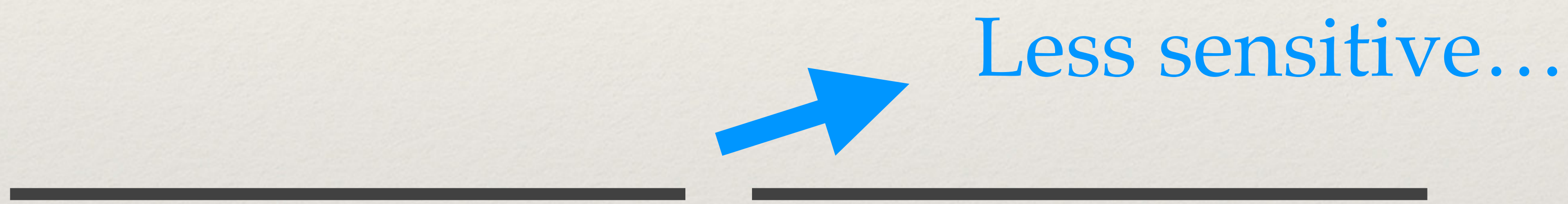
Reciprocity theorem: any radio receiver can, equally, be thought of as a radio transmitter

So, if we imagine what the properties of the telescope are as a transmitter, that tells us its properties as a receiver

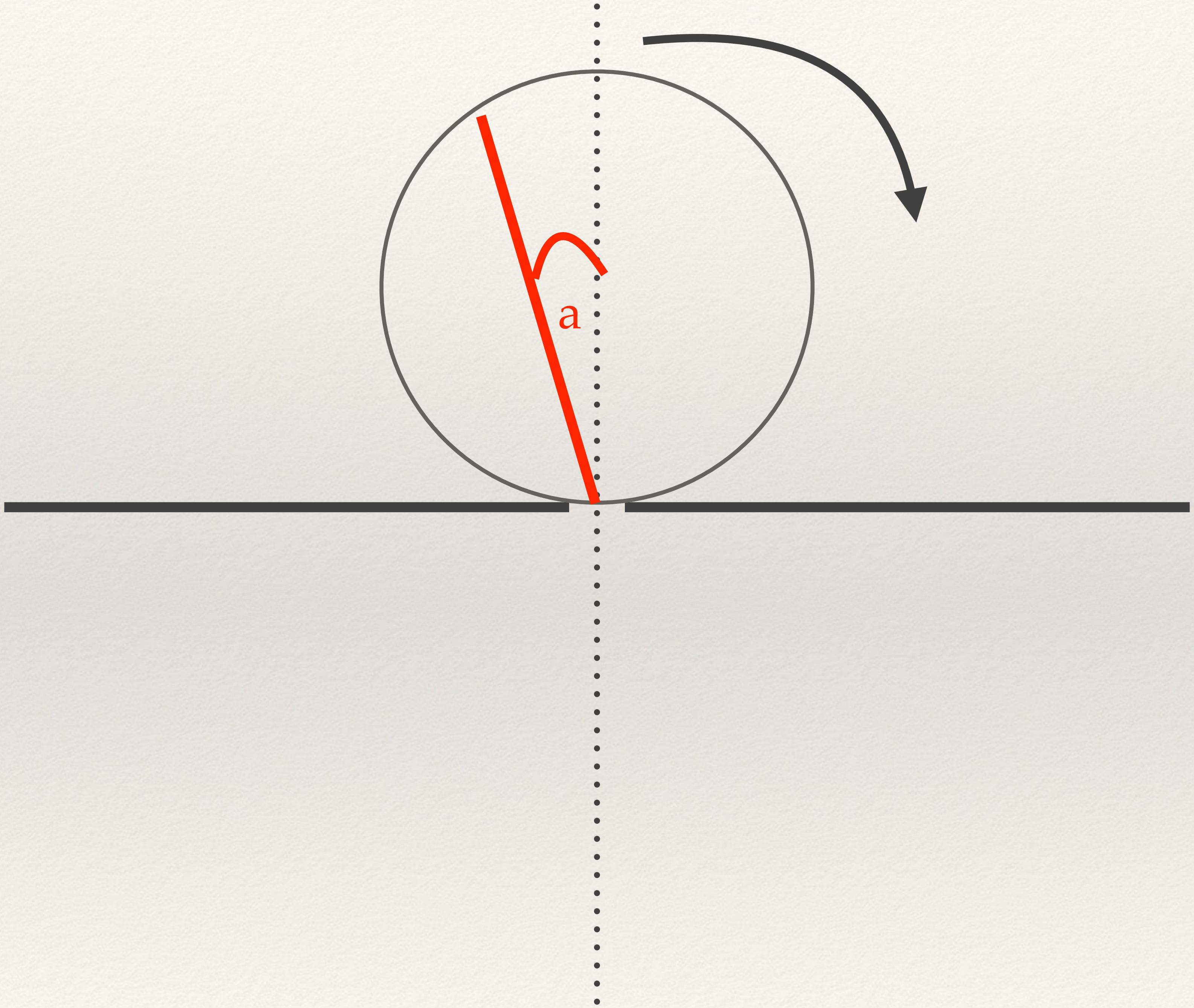
Angular resolution of radio telescope

Angular resolution of radio telescope

Angular resolution of radio telescope



Angular resolution of radio telescope



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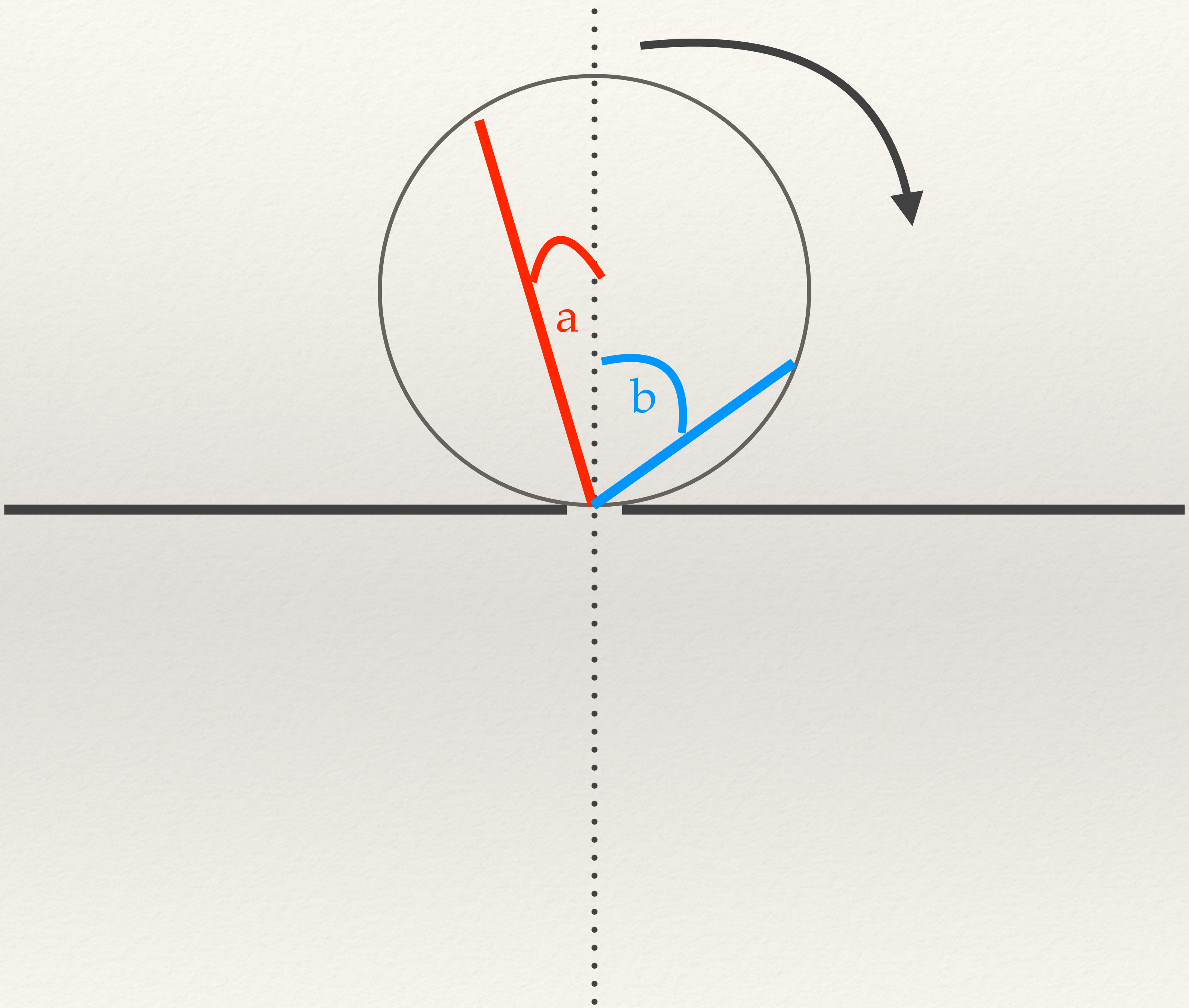

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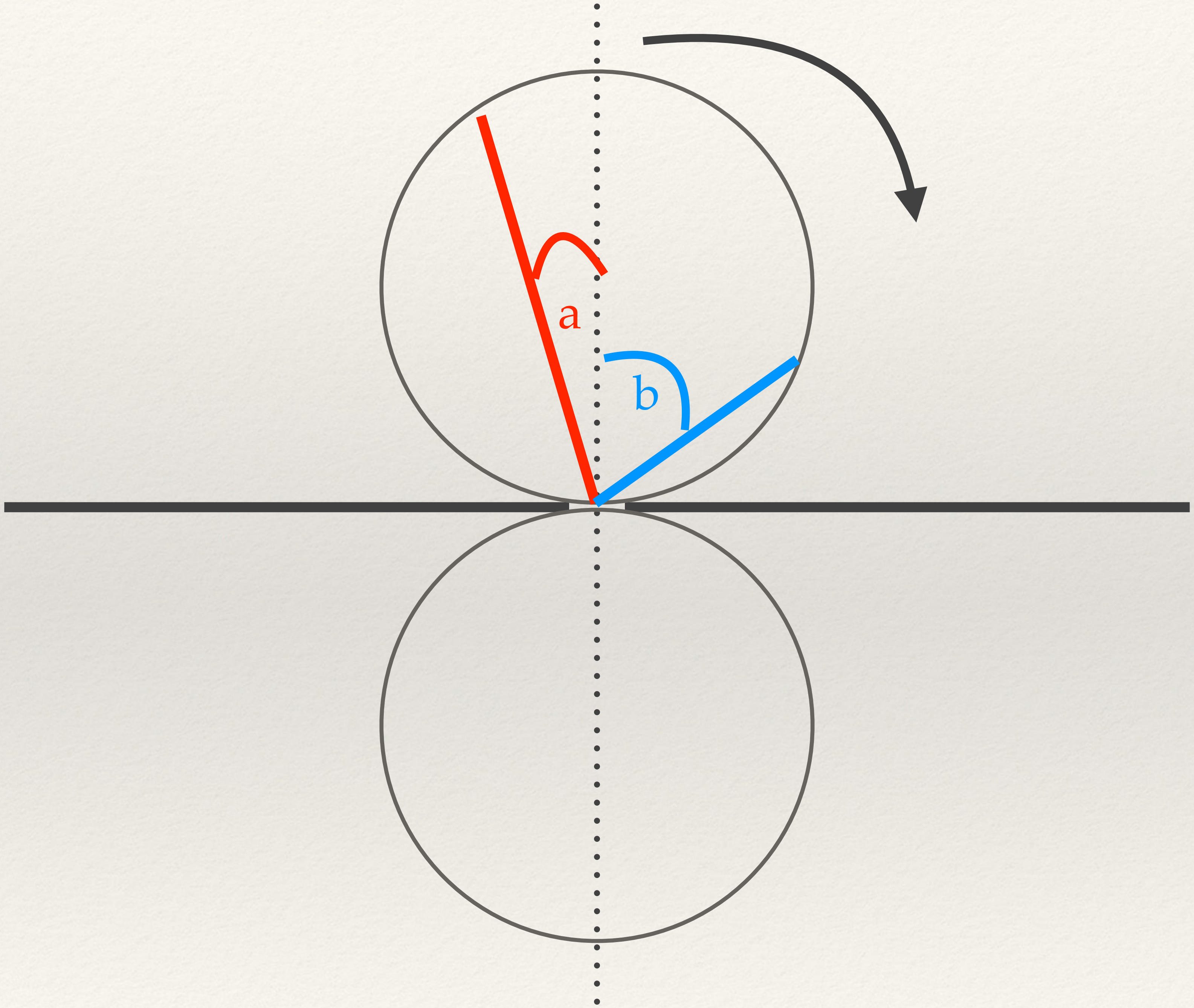

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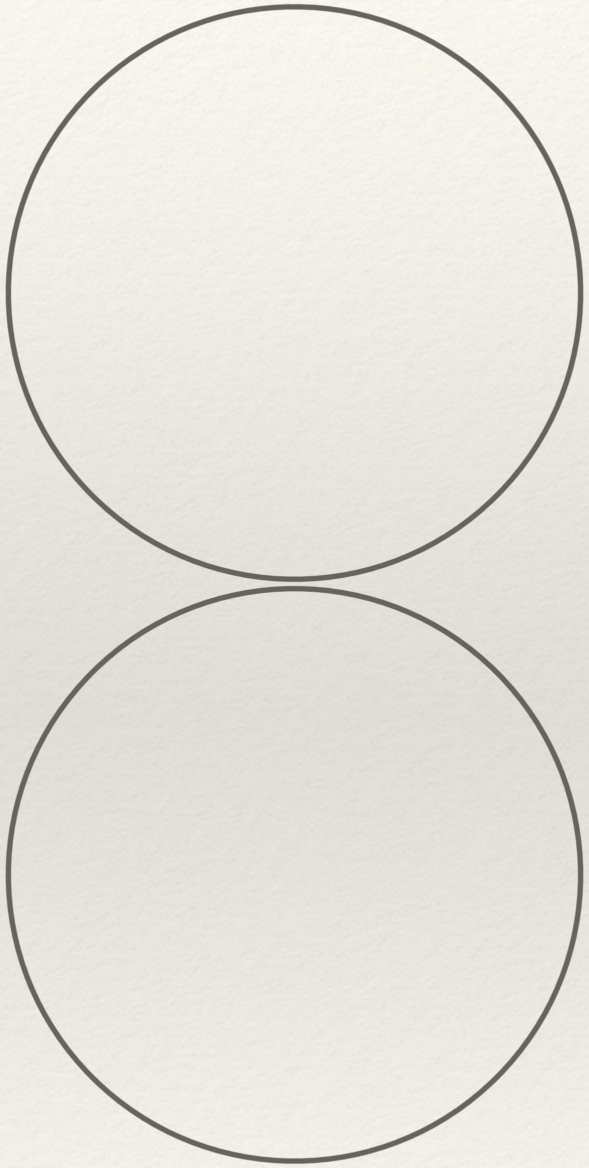
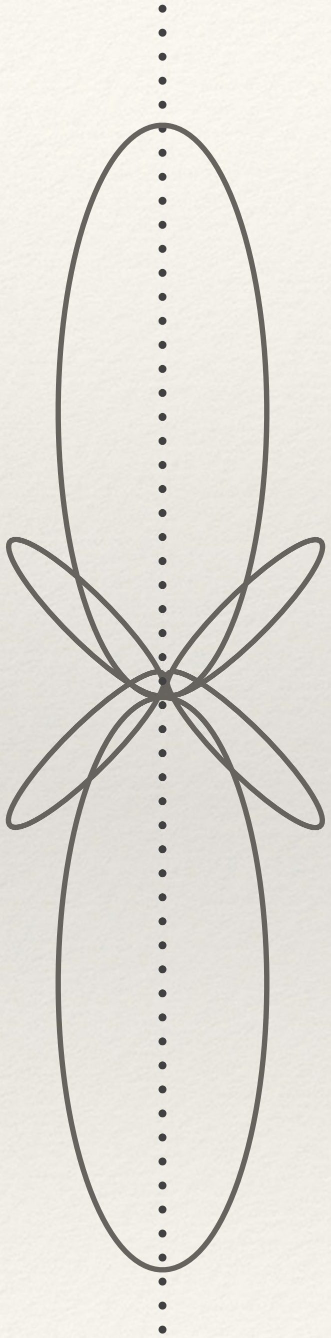


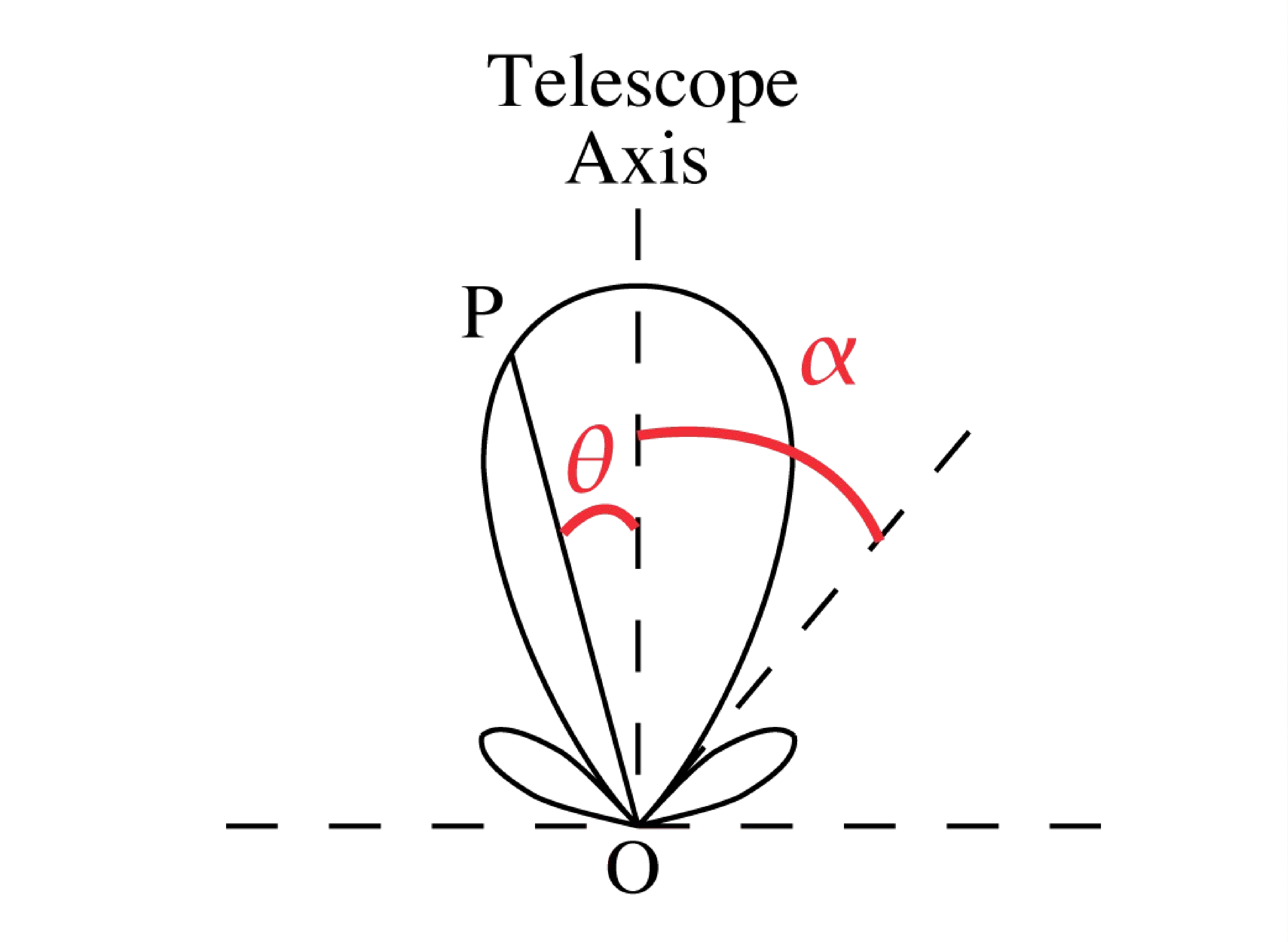
Polar diagram for most basic dipole

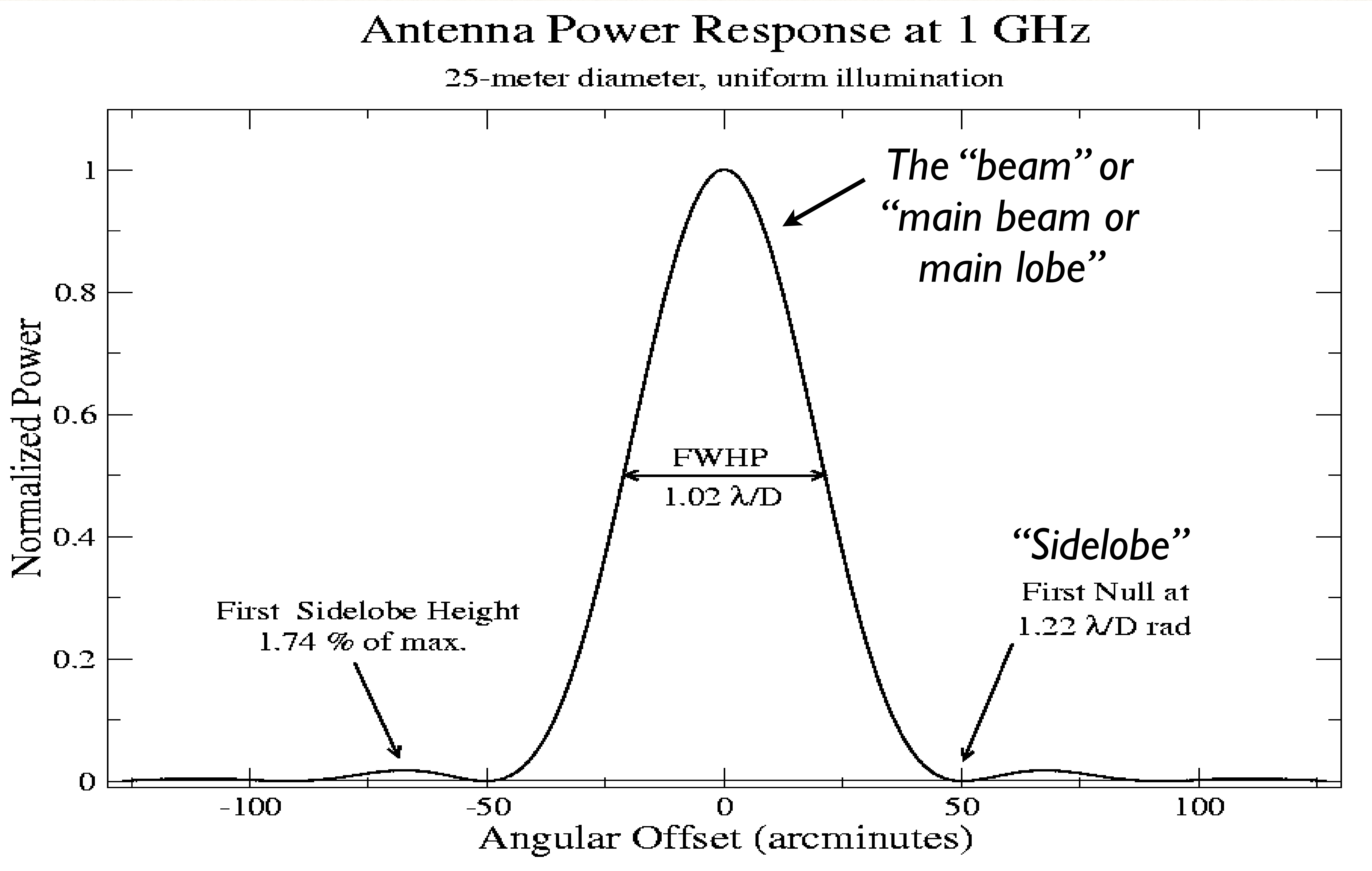
Angular resolution of radio telescope

Angular resolution of radio telescope



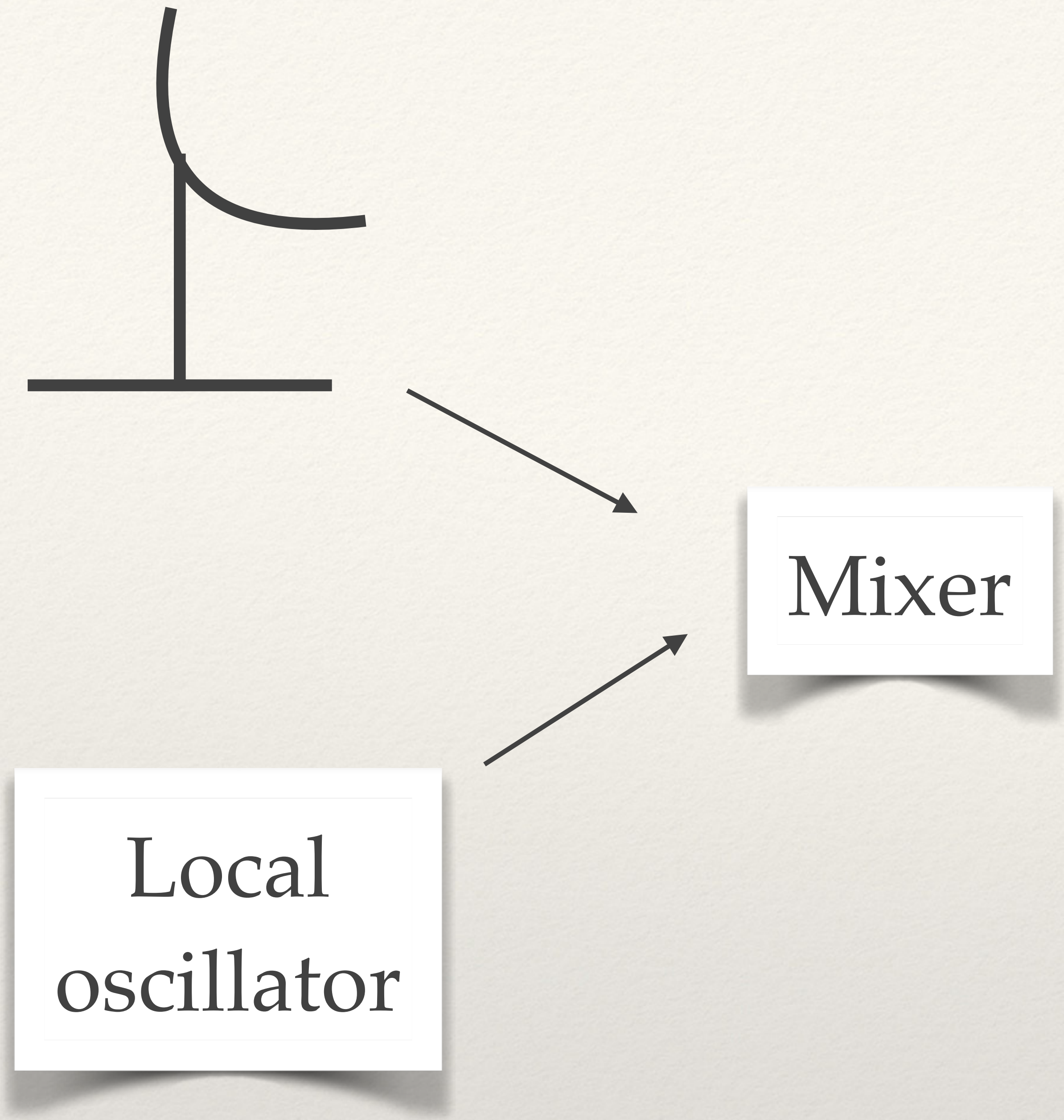
Angular resolution of radio telescope

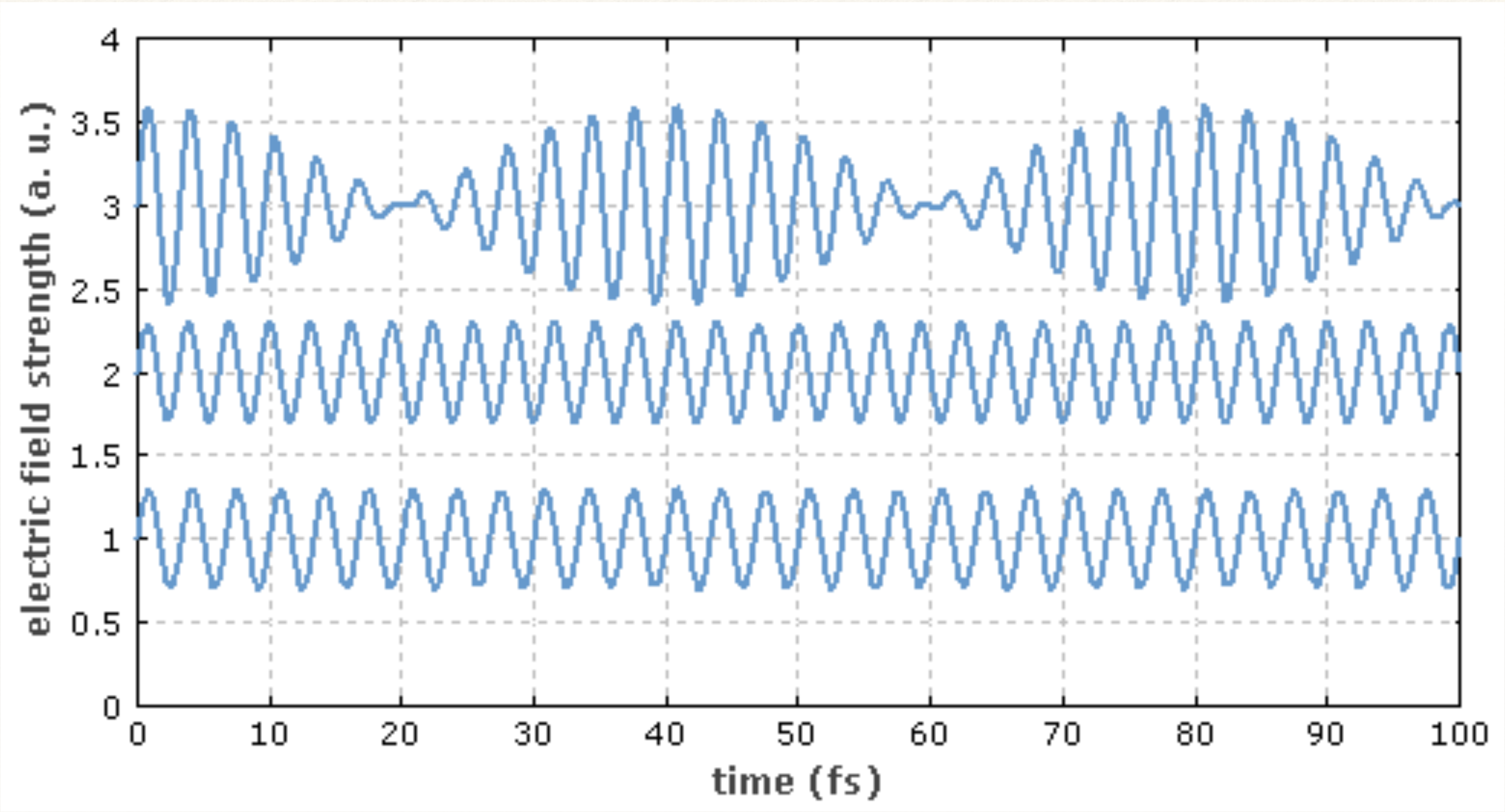



Antenna Power Response at 1 GHz
25-meter diameter, uniform illumination
Normalized Power
0
0.2
0.4
0.6
0.8
1
-100
-50
0
50
100
Angular Offset (arcminutes)
The "beam" or "main beam or main lobe"
FWHP
1.02 λ/D
"Sidelobe"
First Null at
1.22 λ/D rad
First Sidelobe Height
1.74 % of max.

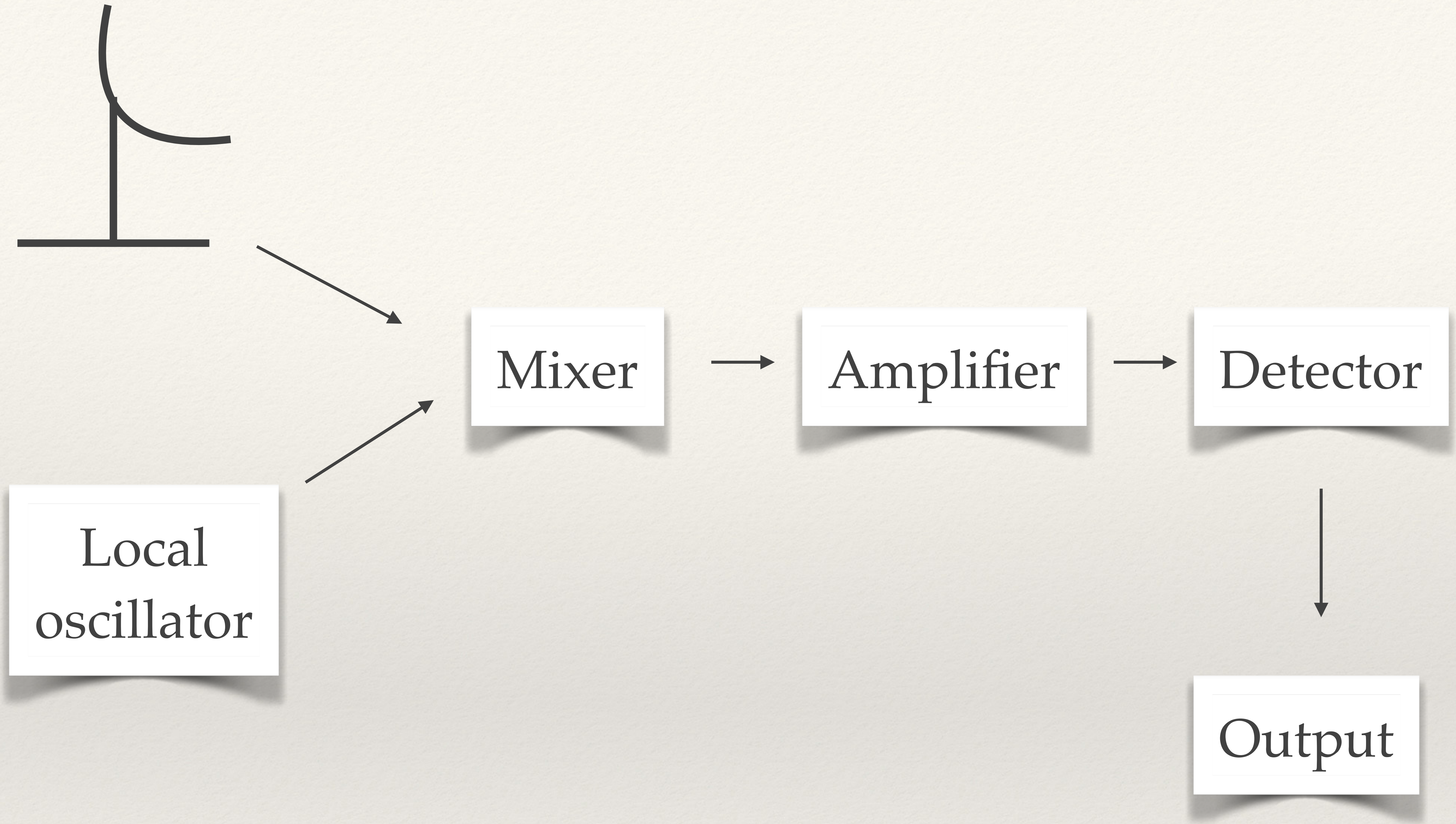
The Heterodyne receiver

- Sensitive to incoming electric field
- Frequency of incoming signal is down-converted by a reference signal (mixer), which is generated locally
- The resulting lower frequency signal is easier to sample and study
- (*Hetro* = different, *dyne* = frequency)


Mixer
Local oscillator



4
3.5
3
2.5
2
1.5
1
0.5
0
0
10
20
30
40
50
60
70
80
90
100
time (fs)
electric field strength (a. u.)



Mixer
Amplifier
Detector
Local oscillator
Output

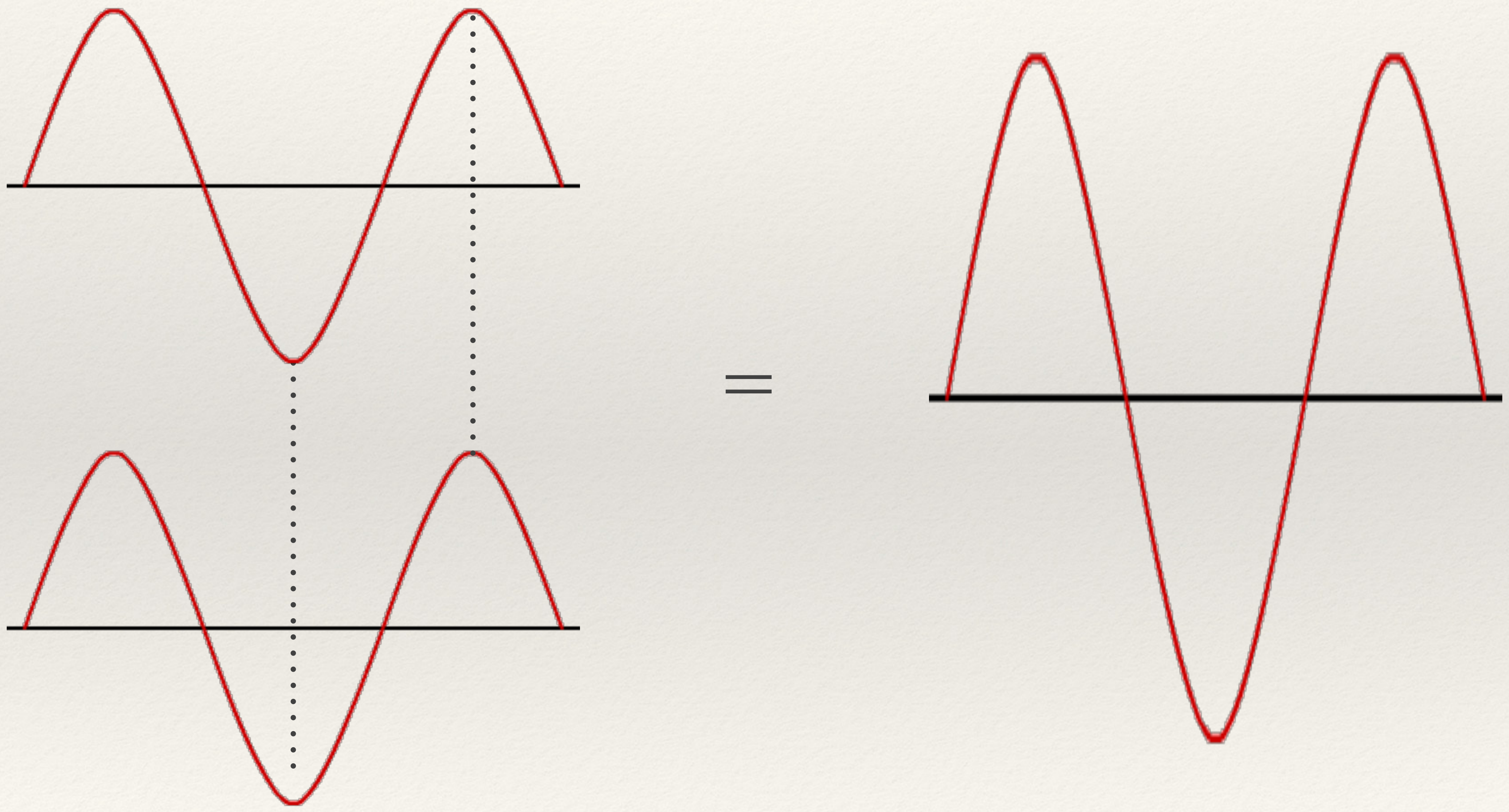
Lecture 3 topics

- Background: the history of radio astronomy
- Single aperture radio dishes
- Interferometry

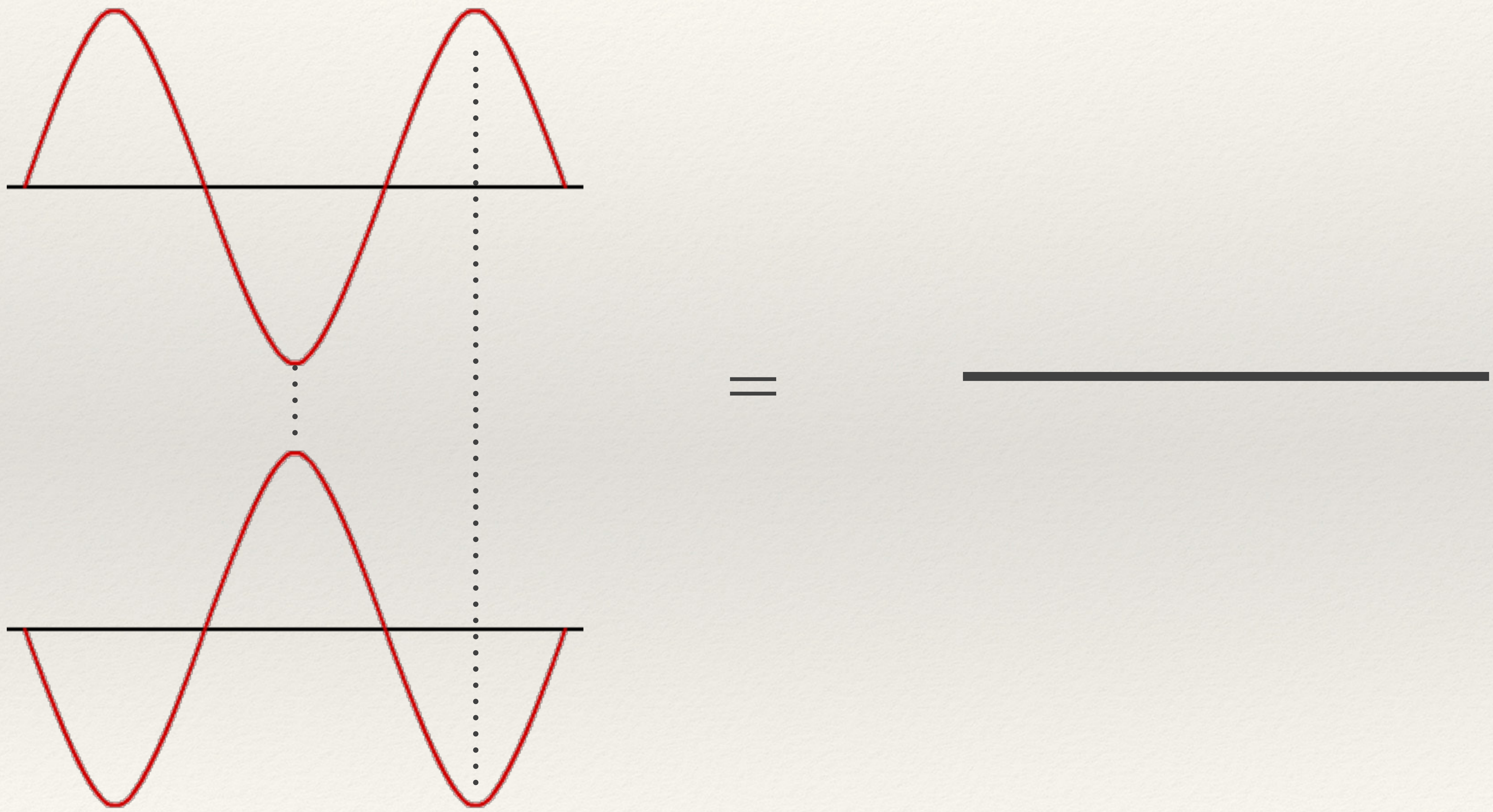
Introduction to Interferometry

- Rather than using single telescopes, it's possible to link up *networks* of telescopes, and use them as a single large instrument
- The angular resolution of the interferometer depends on the dish *separation*, not the diameter
- Critical thing: what is measured is not the signal, but the *phase difference* between each pair of receivers

Background: adding waves

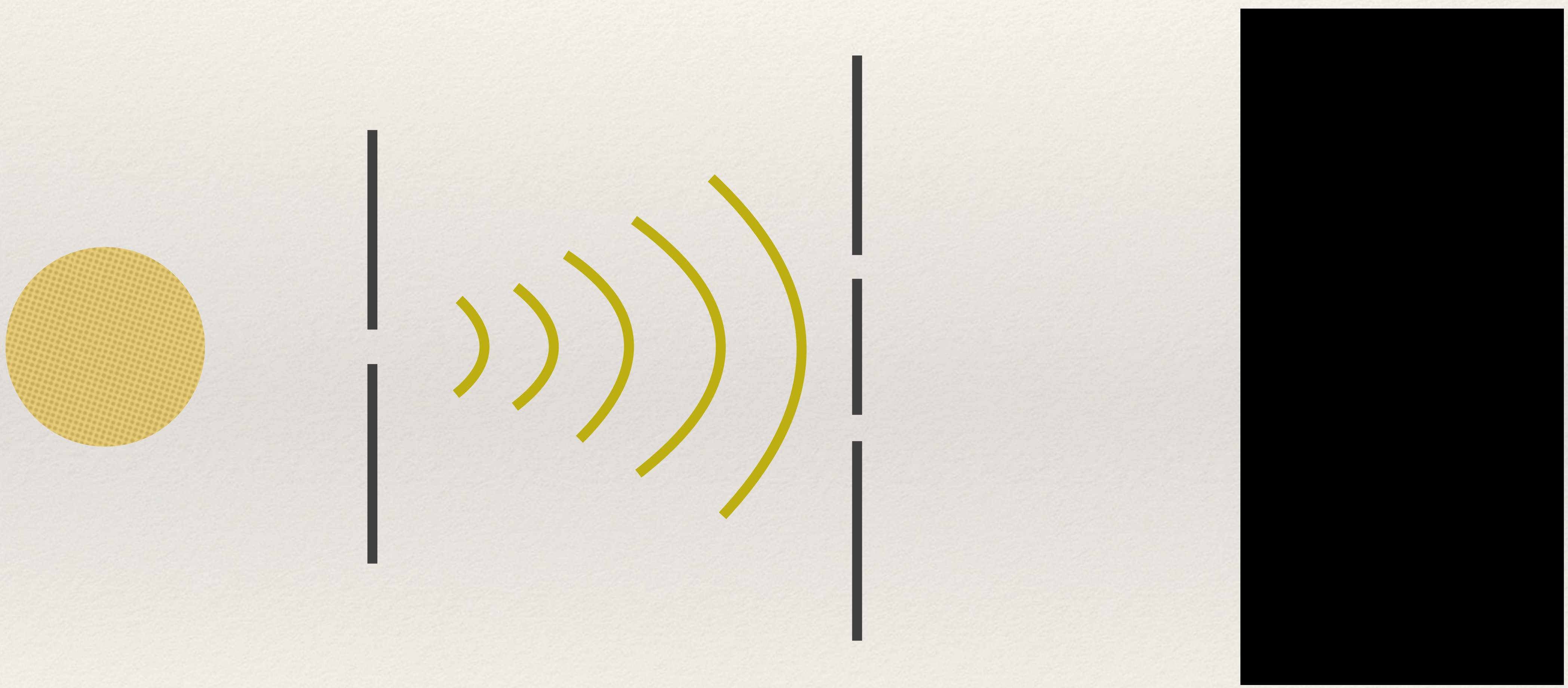


Background: adding waves



Background: adding waves

Young's "two slit experiment"



Background: adding waves

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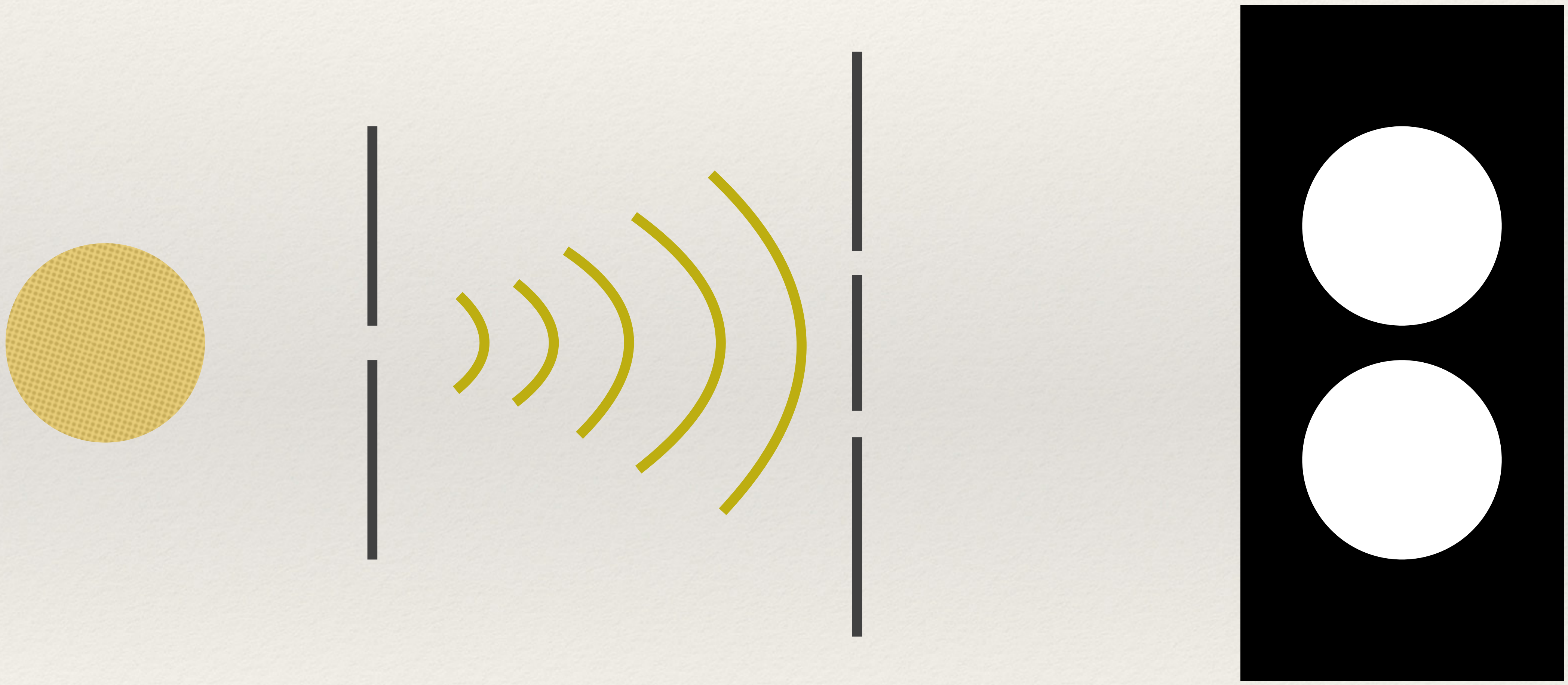

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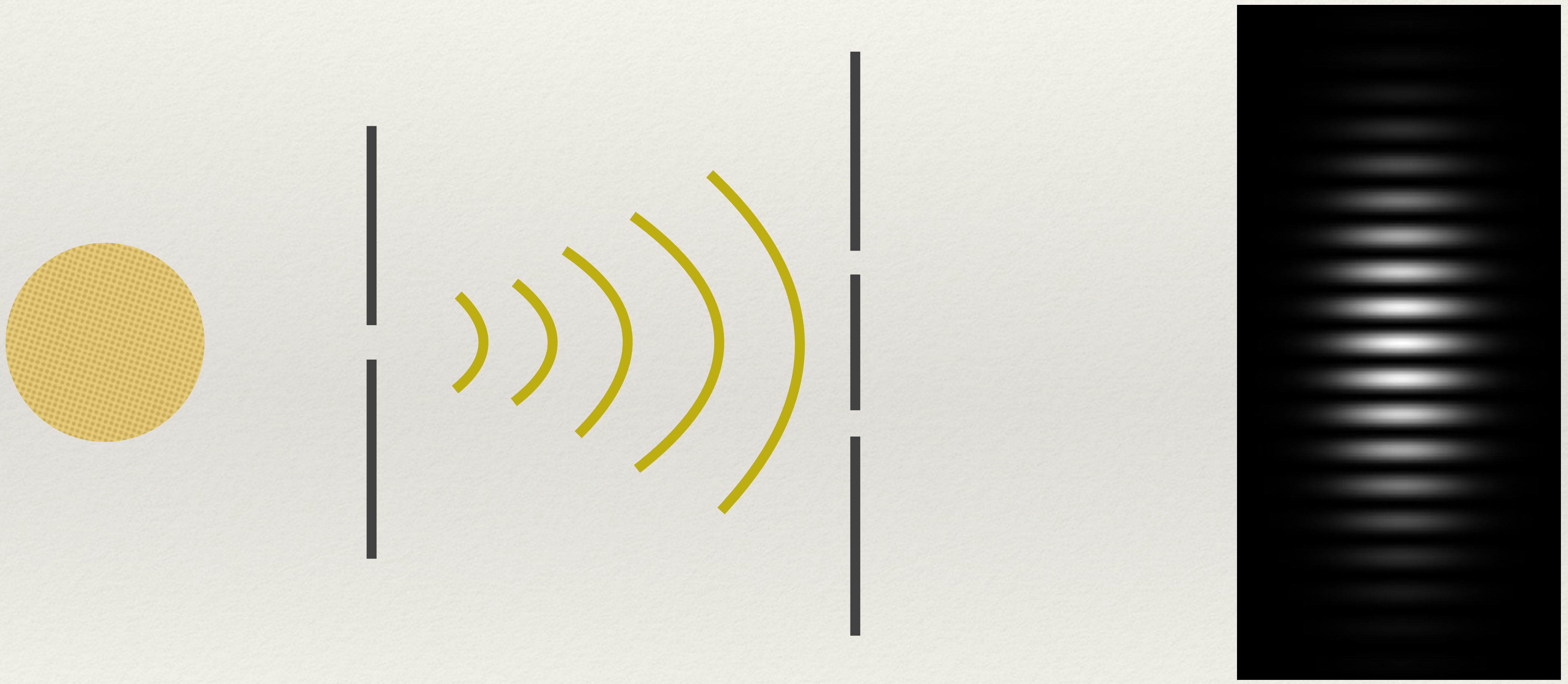
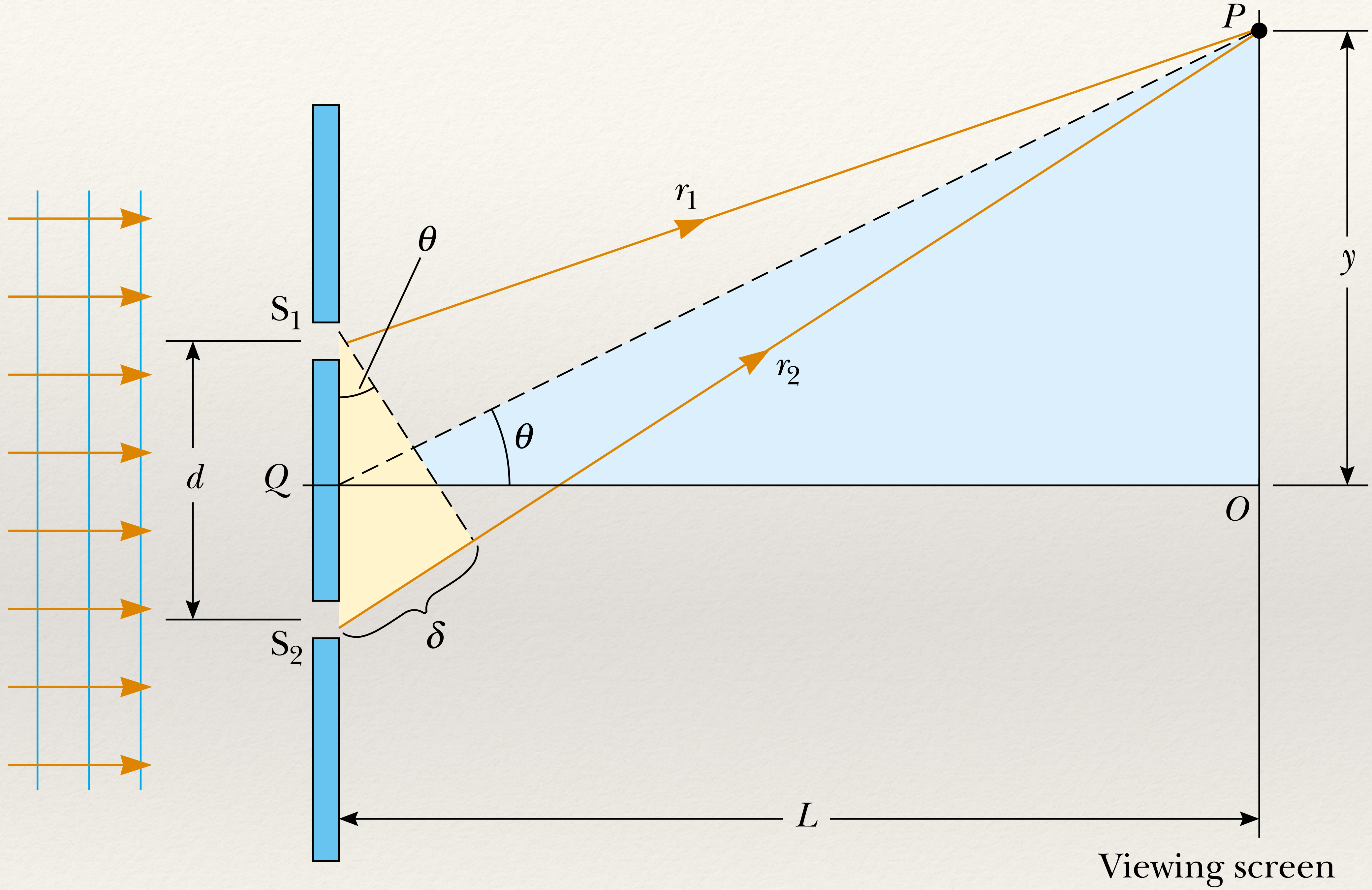
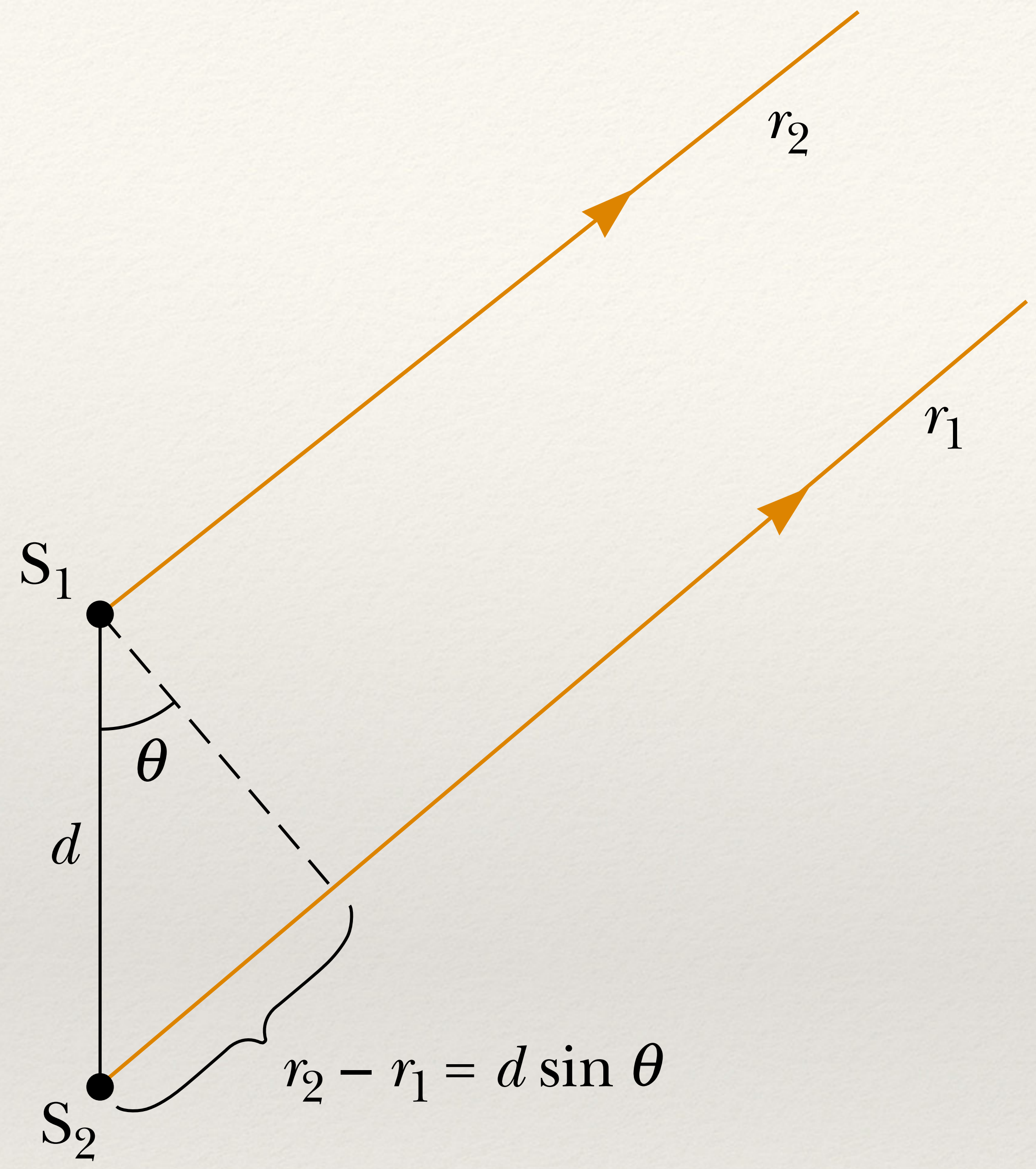




P
r_1
θ
S_1
r_2
θ
d
Q
O
y
δ
S_2
L
Viewing screen

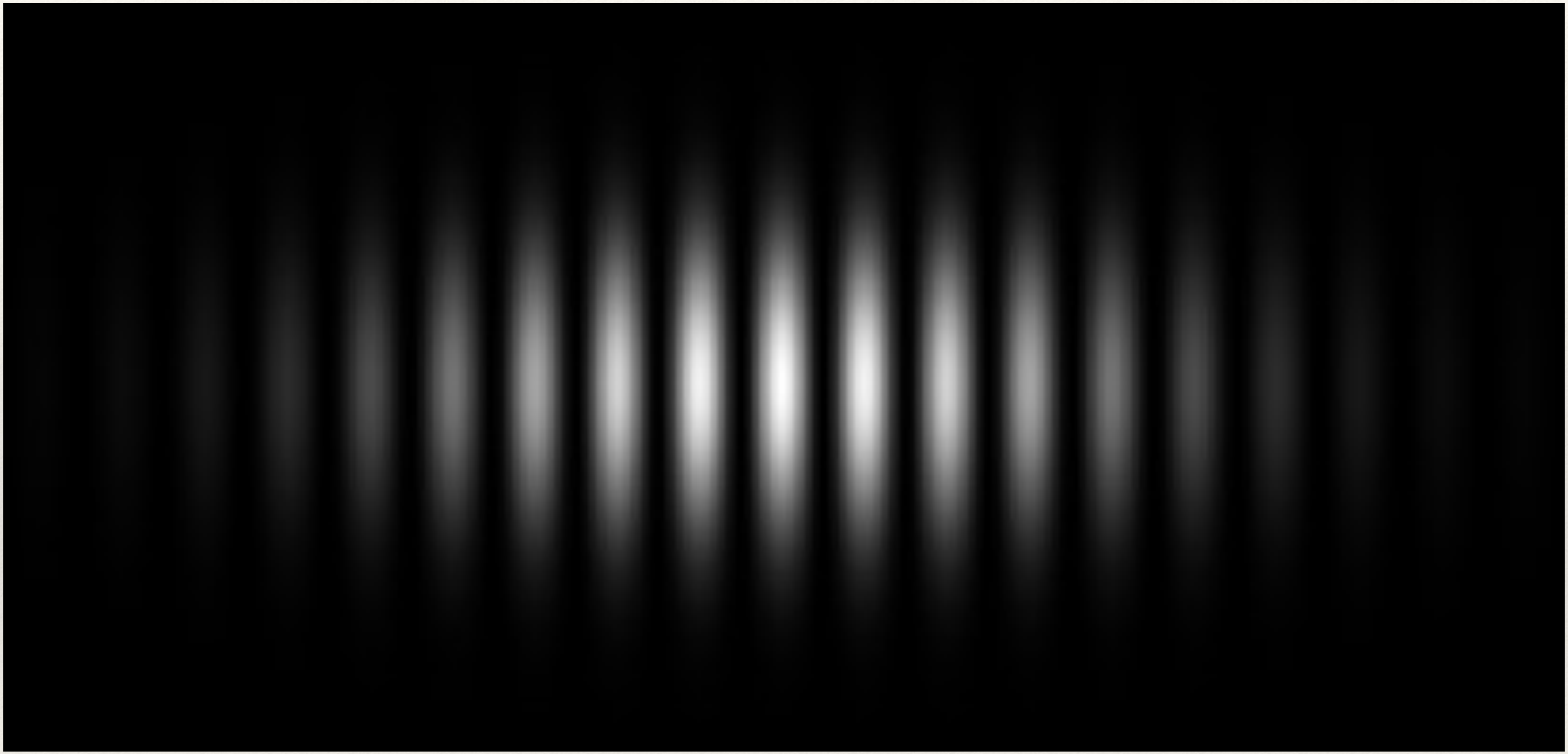


$$d\sin\theta = m\lambda$$

= constructive interference.
Bright patch

$$d\sin\theta = (m + 1/2)\lambda$$

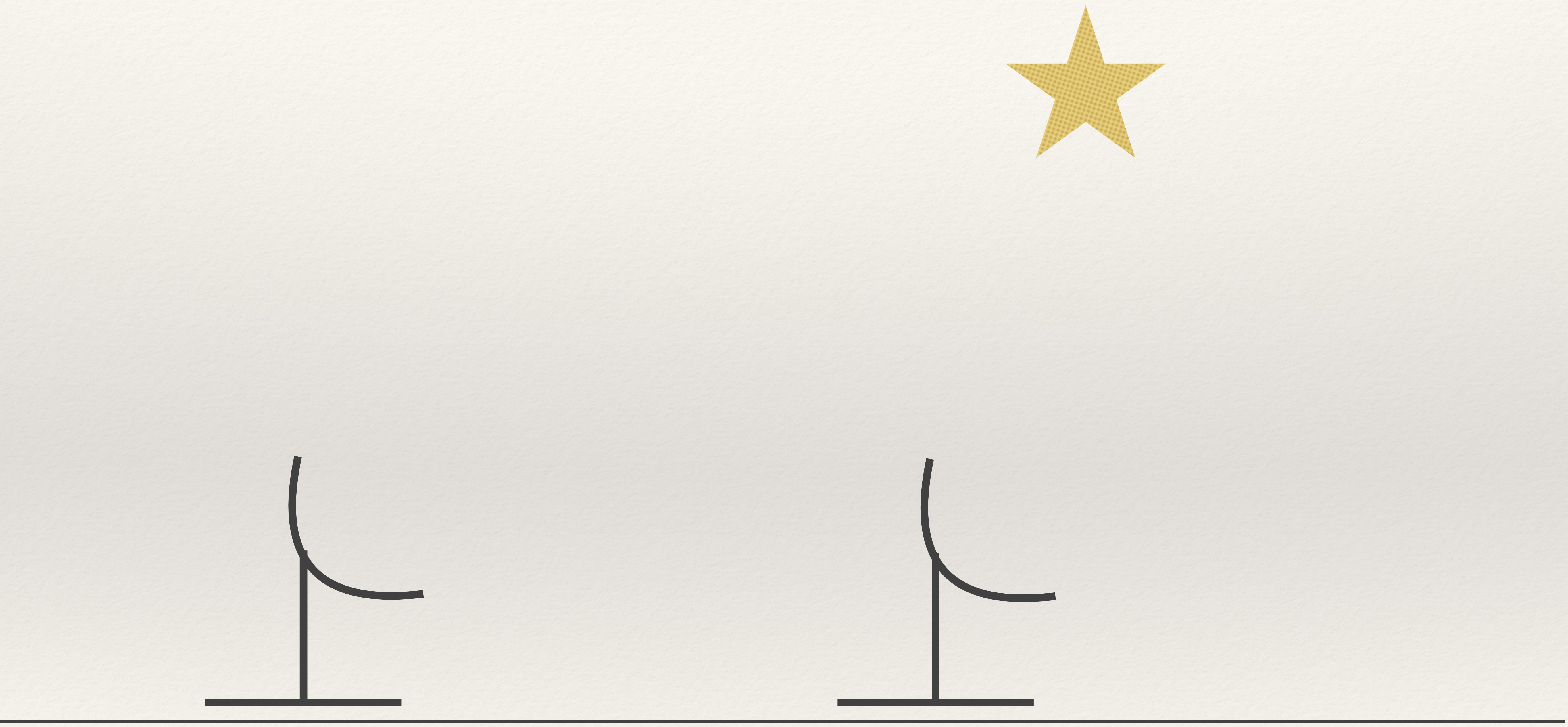
= destructive interference.
Dark patch



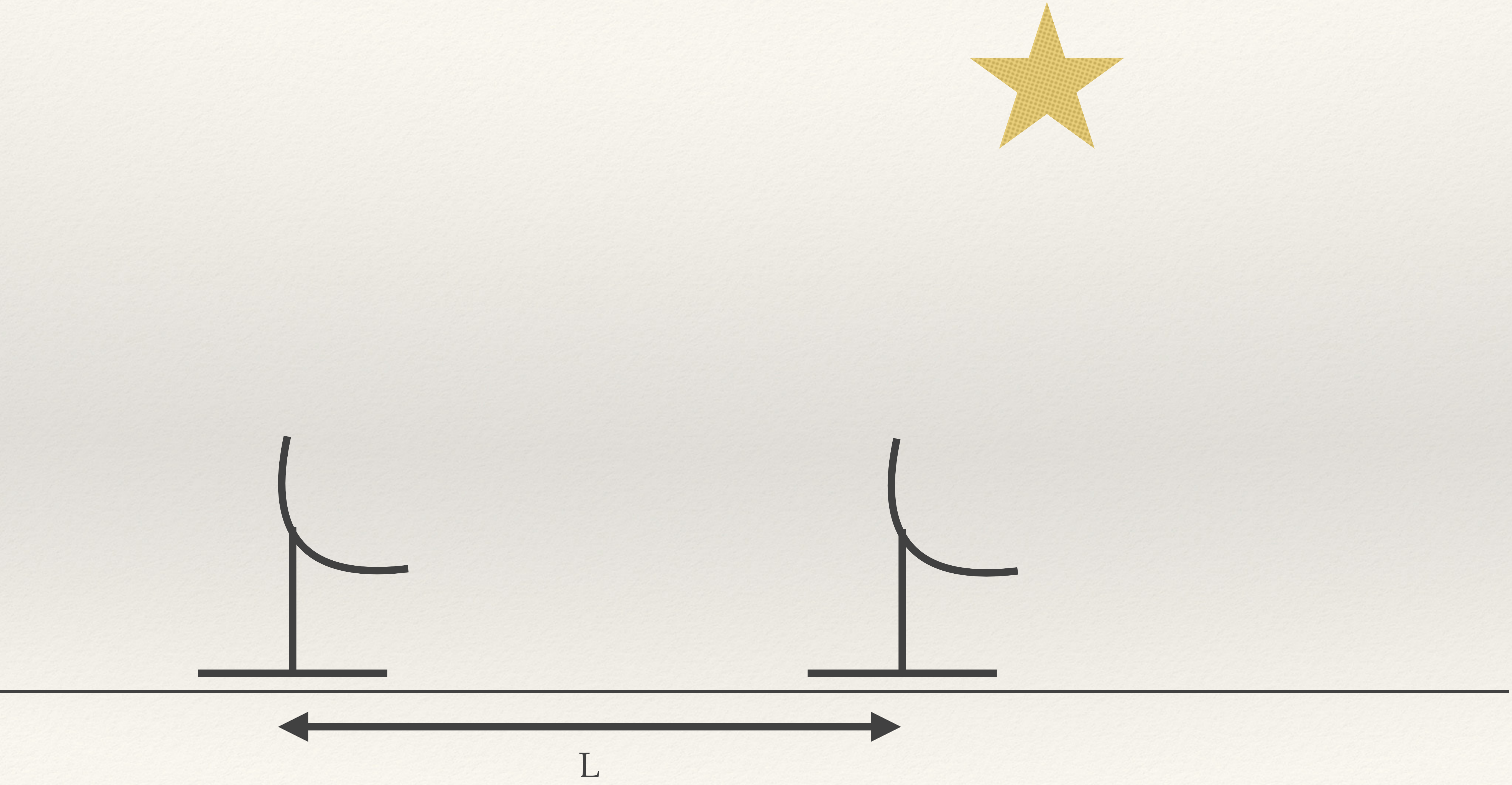
This is how interferometry works

- Combine signal from 2 (or more!) telescopes
- These produce an interference pattern caused by the phase differences
- Use interference pattern to reconstruct information about source
- Can obtain far higher resolutions than single dish instruments (can be >0.05 arcseconds)

Two-element interferometer



Two-element interferometer



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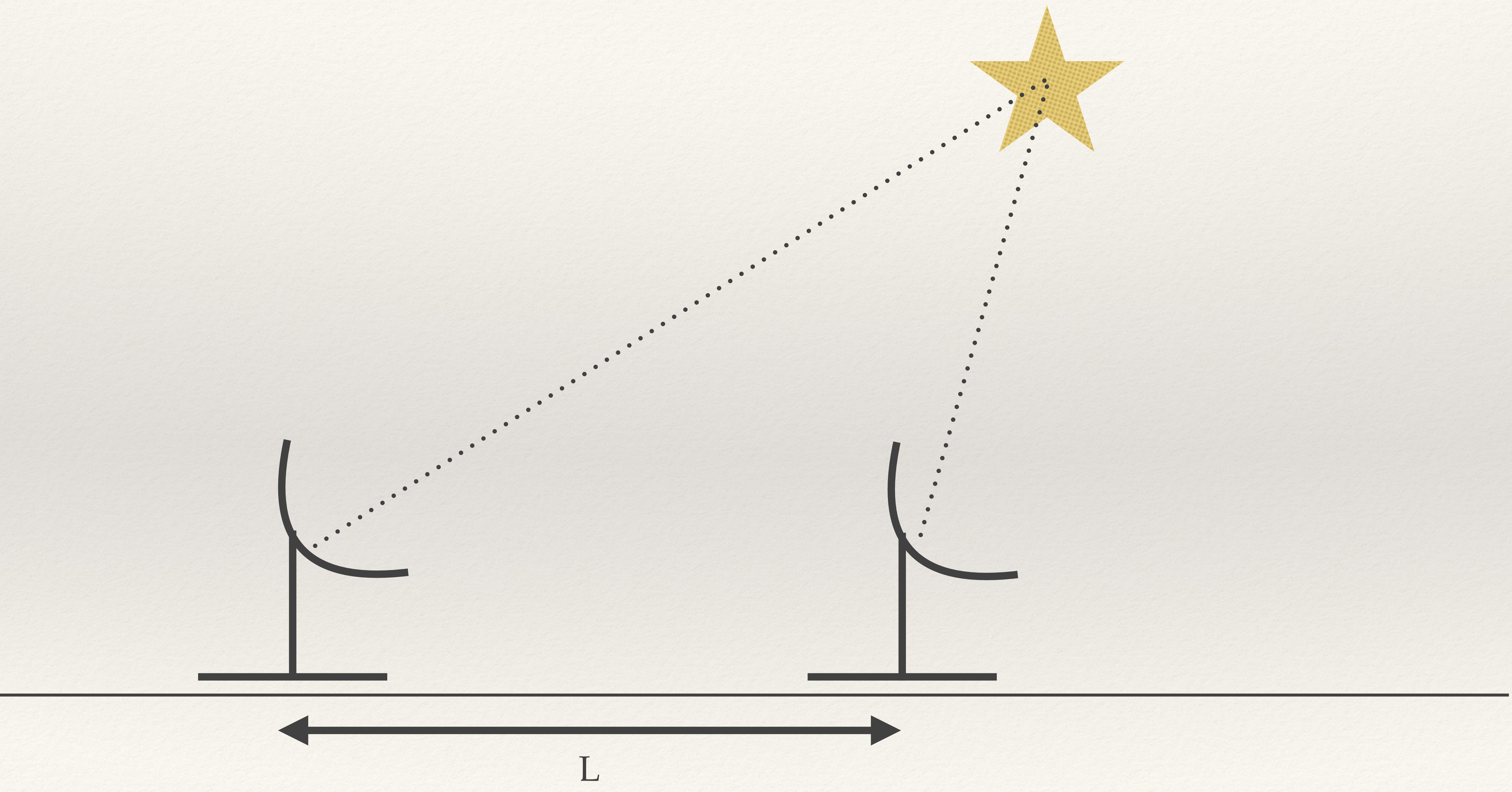

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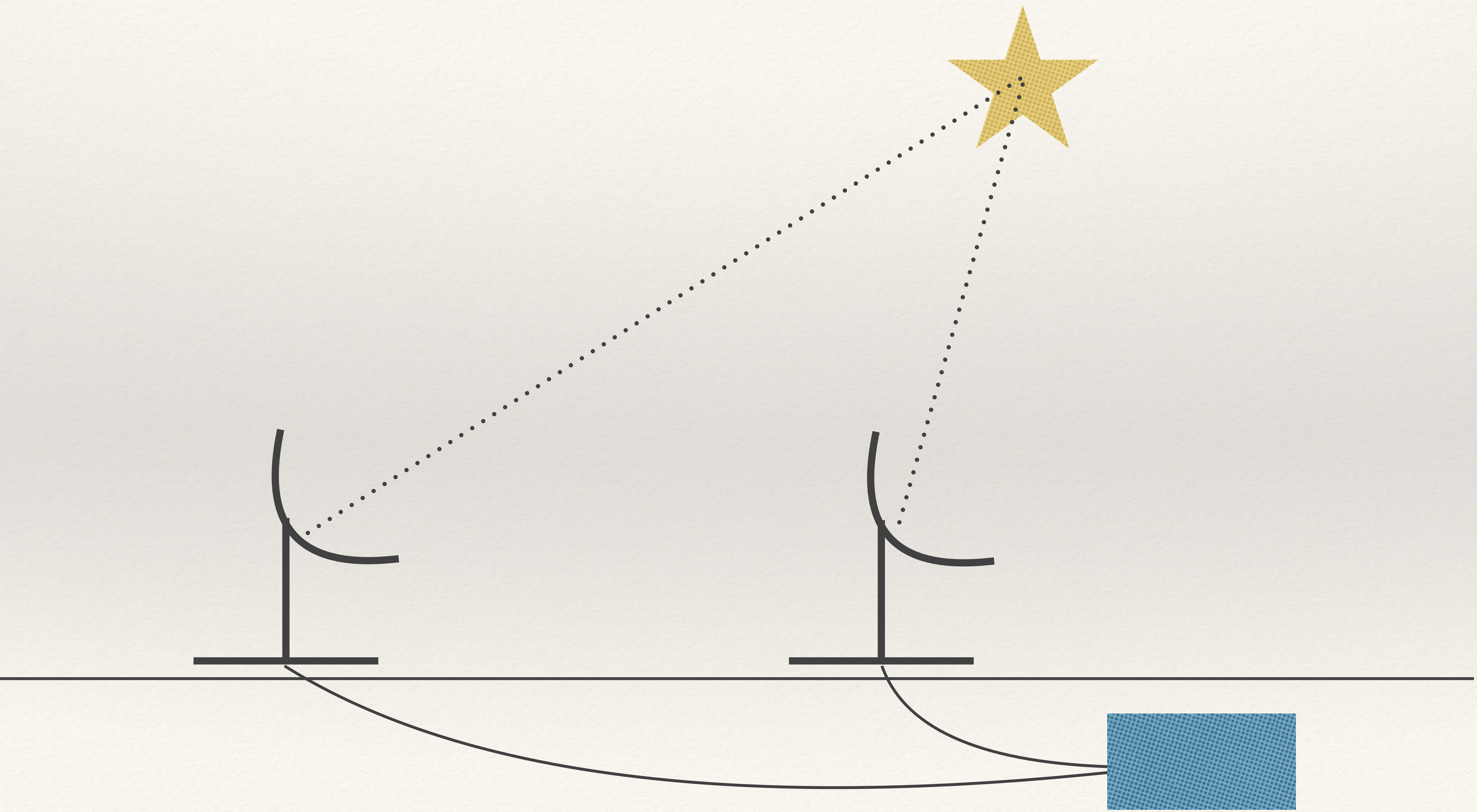

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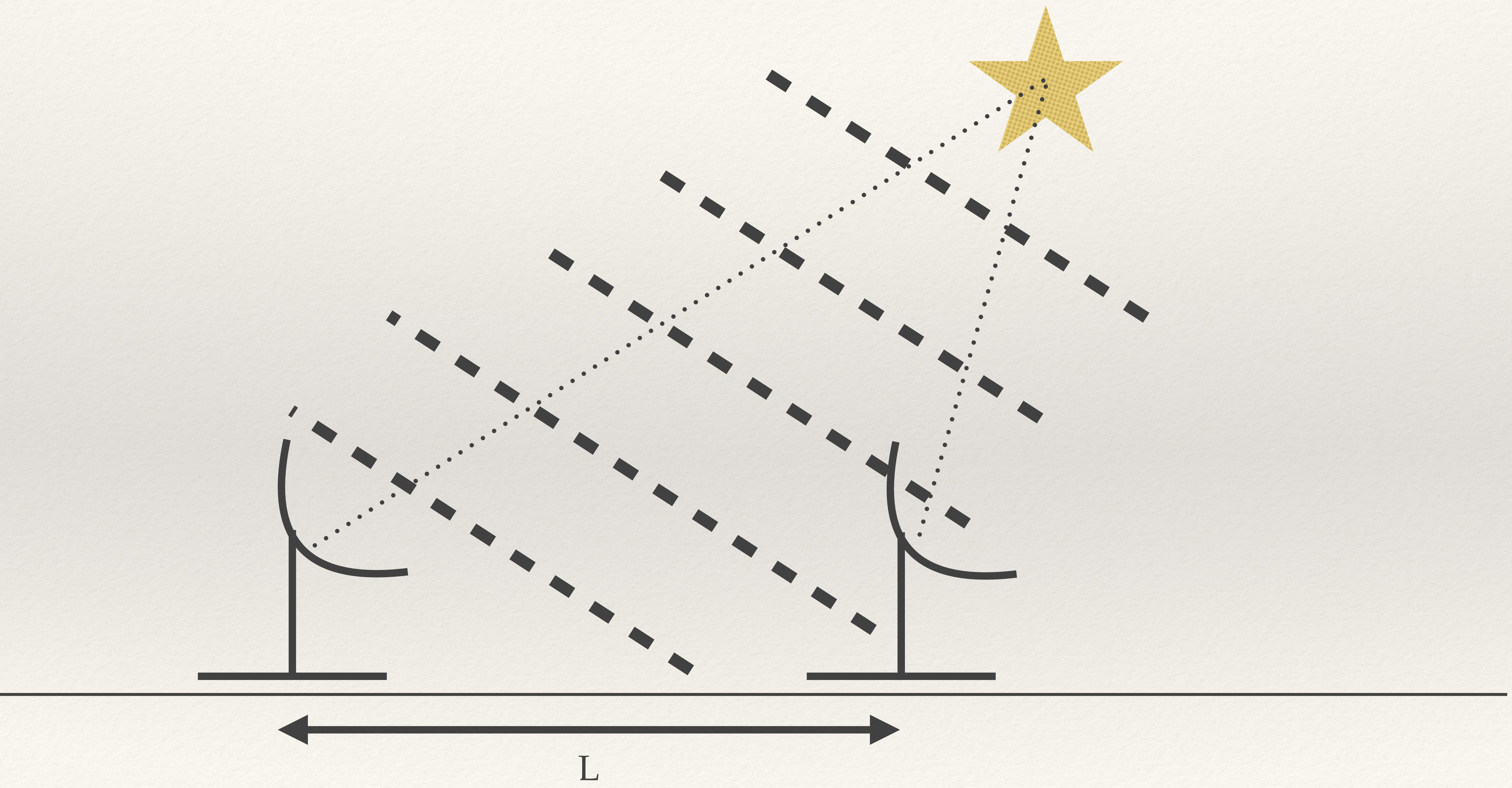
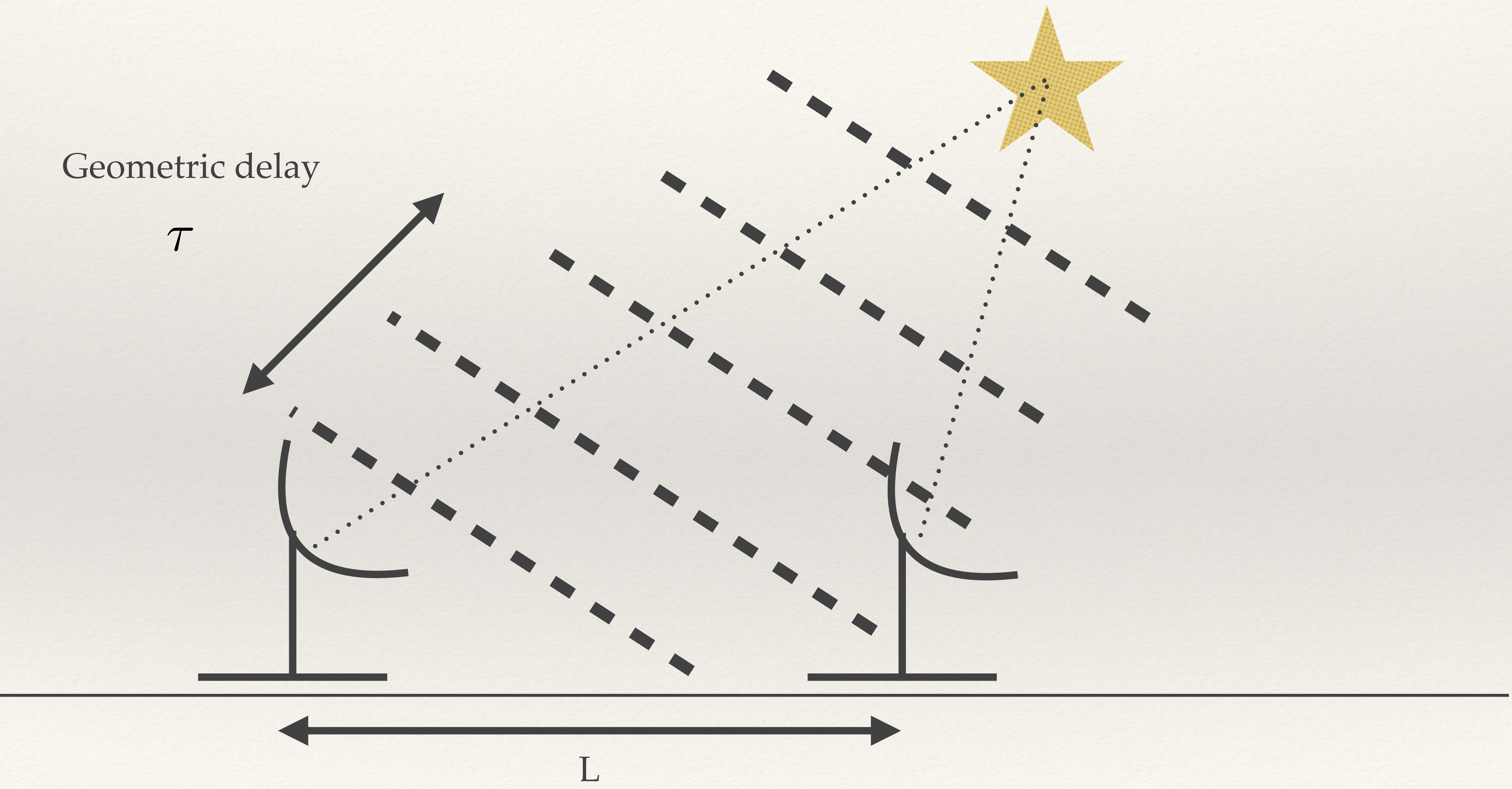


Two-element interferometer

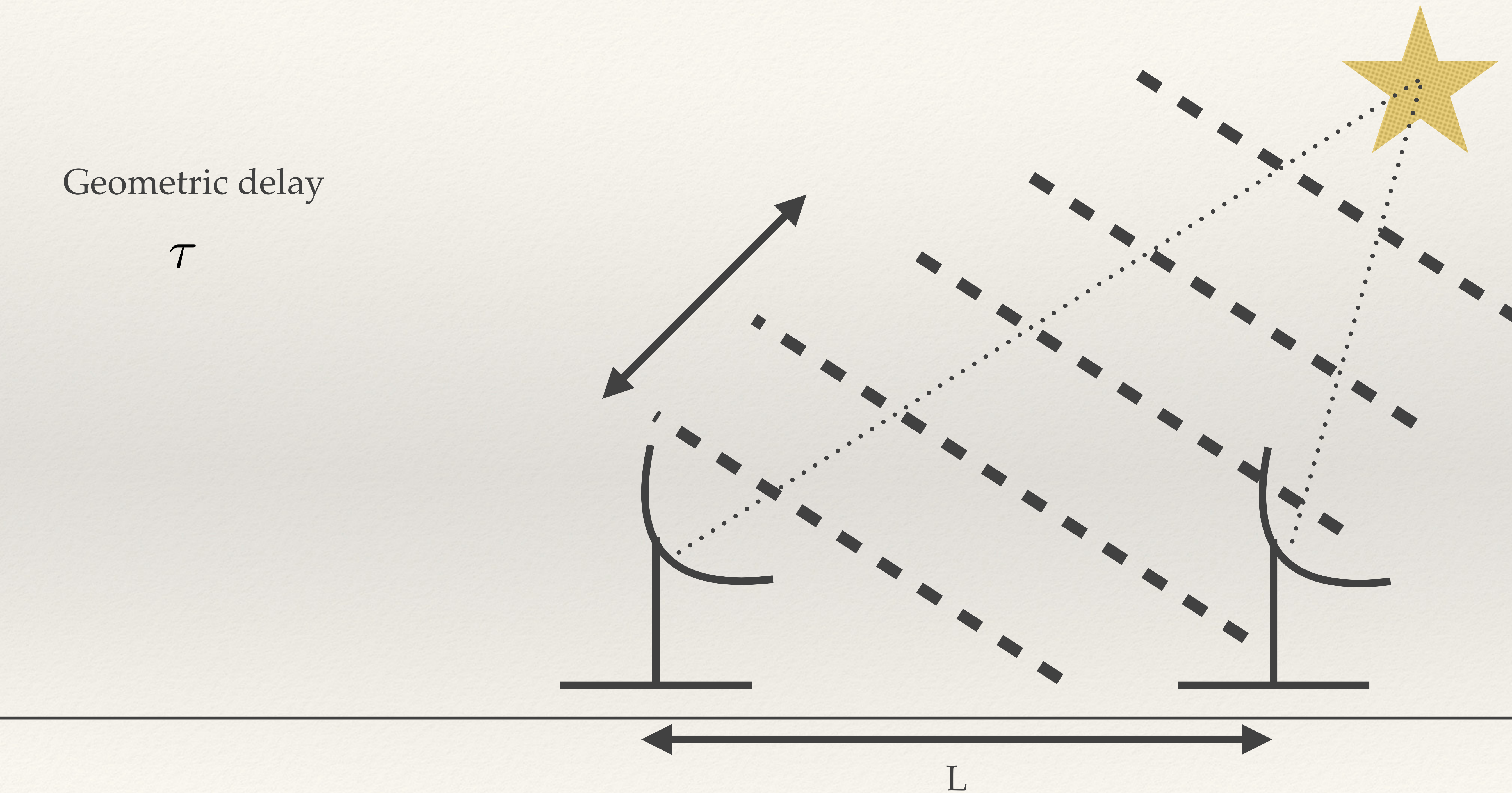
Geometric delay



Two-element interferometer

Geometric delay

τ



Two-element interferometer

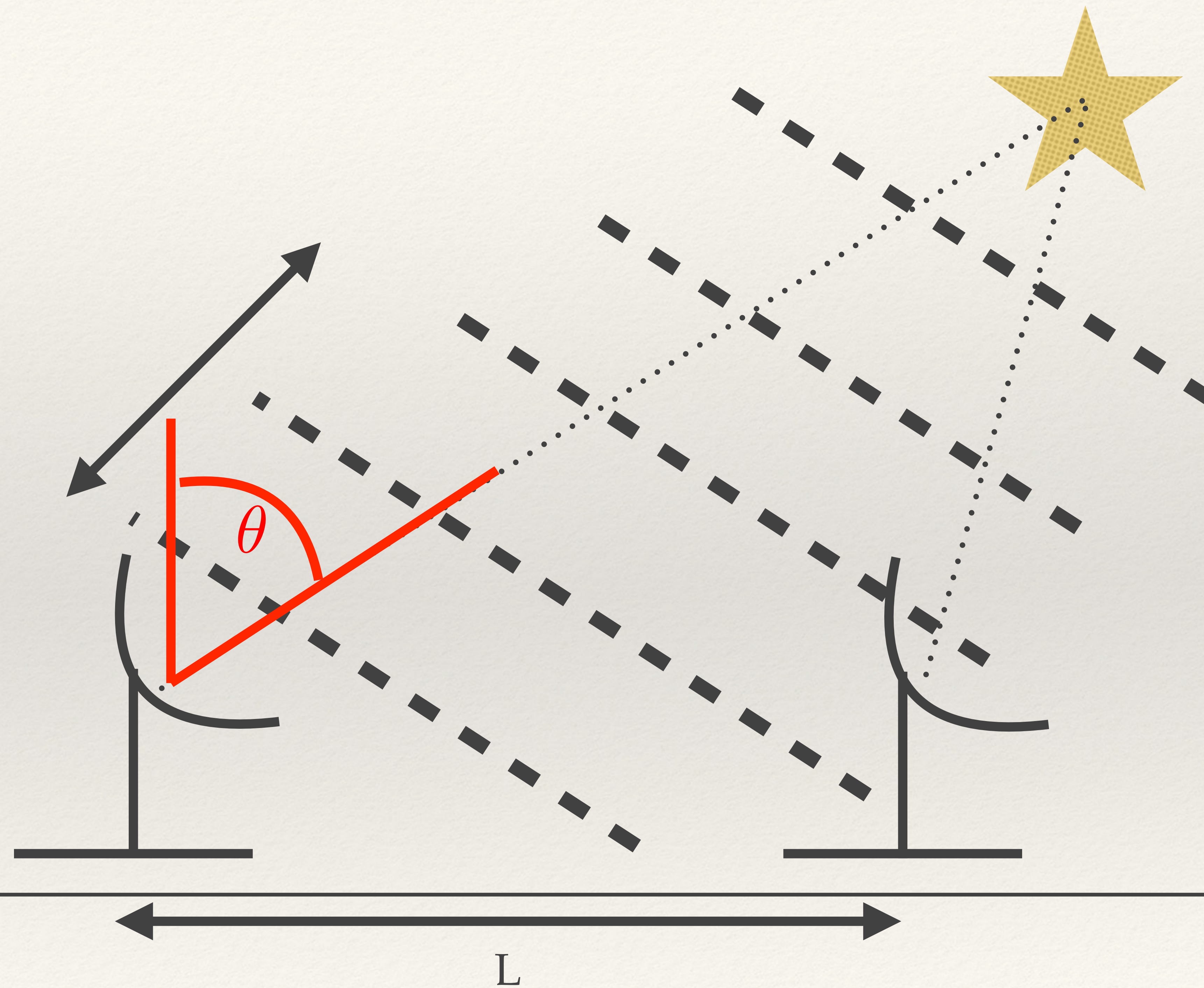
Geometric delay

$$\tau$$

$$= \mathrm{L}\sin\theta$$

Constructive interference:

$$= m\lambda$$



Two-element interferometer

As Earth rotates, angle varies. Produces constructive (m=1,2,3…) and destructive (m = 1/2, 3/2, 5/2…) interference fringes

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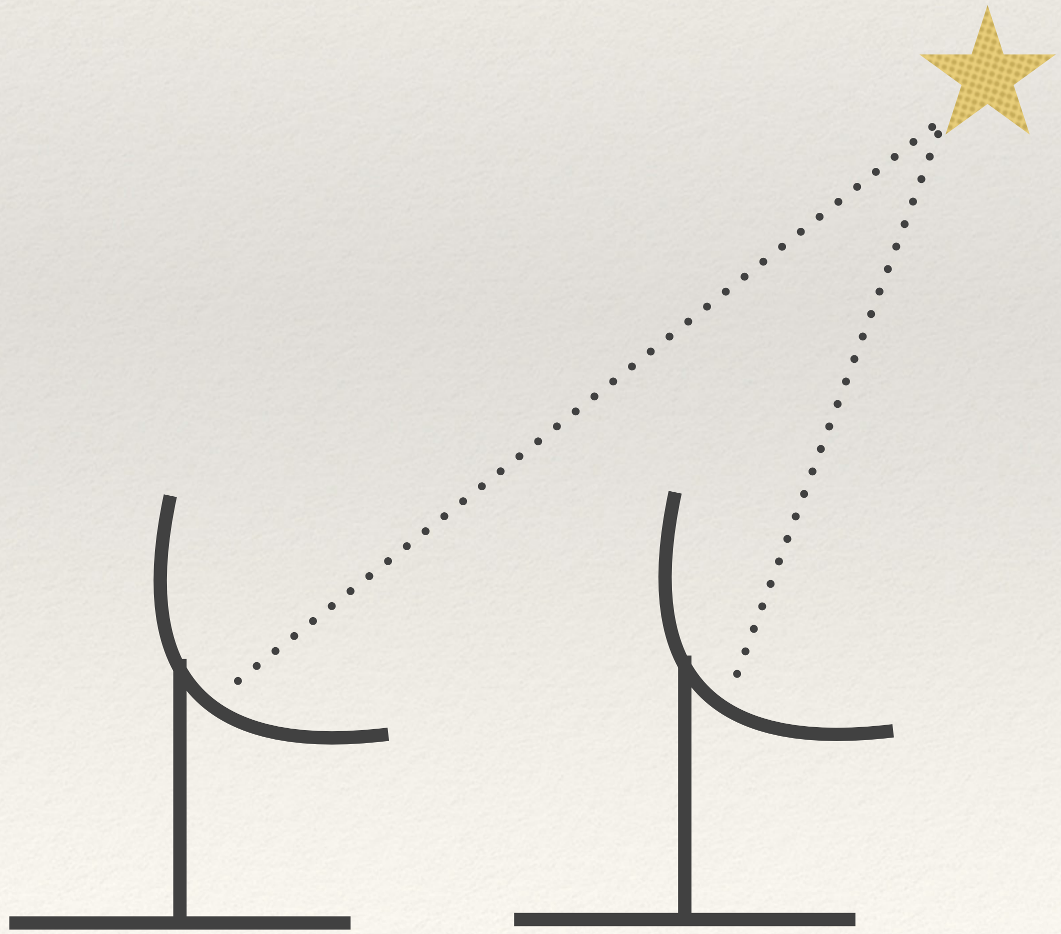

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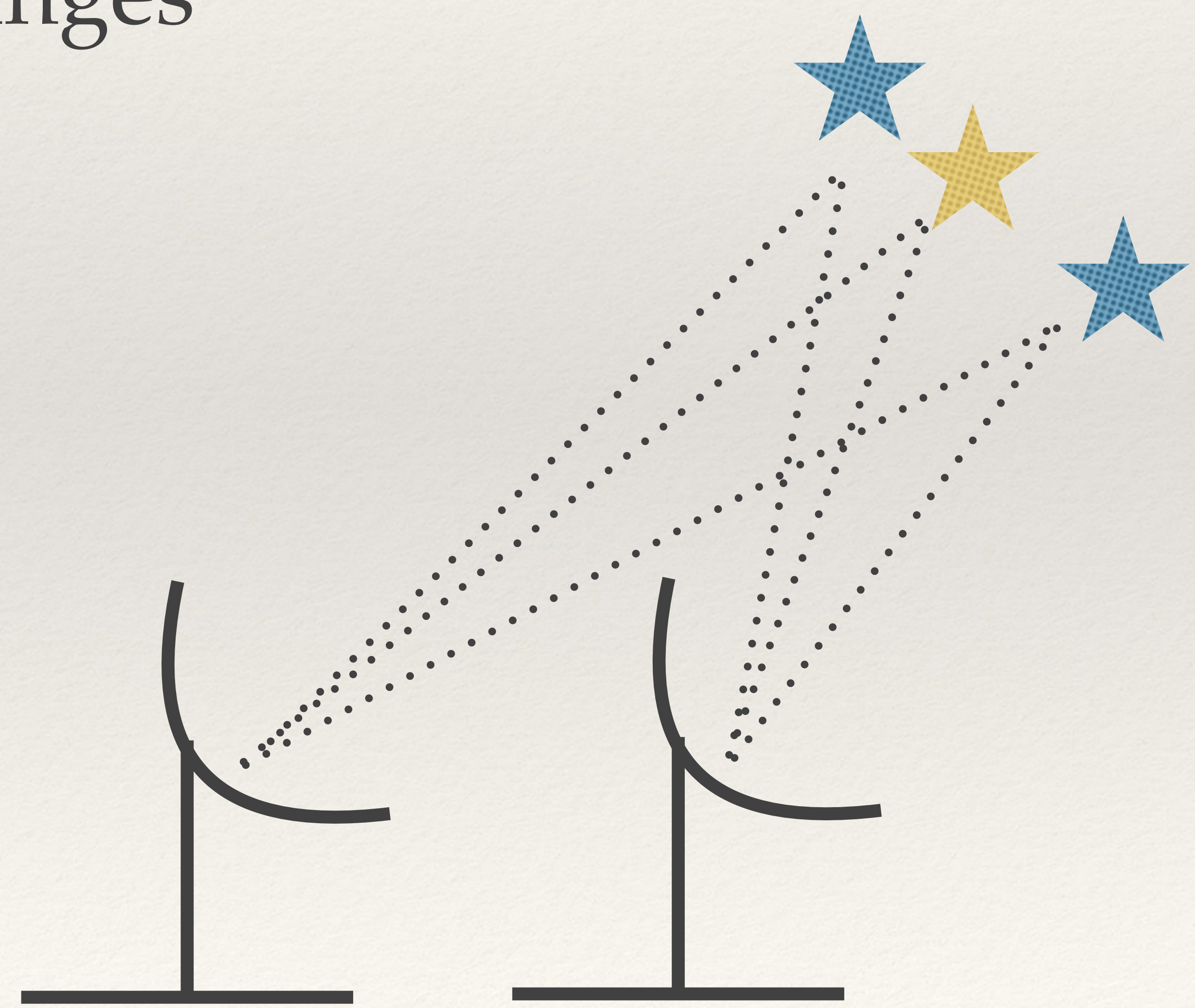

Two-element interferometer

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Maxima at $\mathrm{L}\sin\theta_1 = m\lambda$ $\mathrm{L}\sin\theta_2 = (m+1)\lambda$

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$$\sin\theta_2 - \sin\theta_1 = \frac{\lambda}{\mathrm{L}}$$

$$\sin\theta \sim \theta$$

(Small angle approx.)

Two-element interferometer

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$$\sin\theta_2 - \sin\theta_1 = \frac{\lambda}{\mathrm{L}}$$

$$\sin\theta \sim \theta$$ (Small angle approx.)

So, fringe separation $\theta_f = \theta_2 - \theta_1 \simeq \dfrac{\lambda}{\mathrm{L}}$

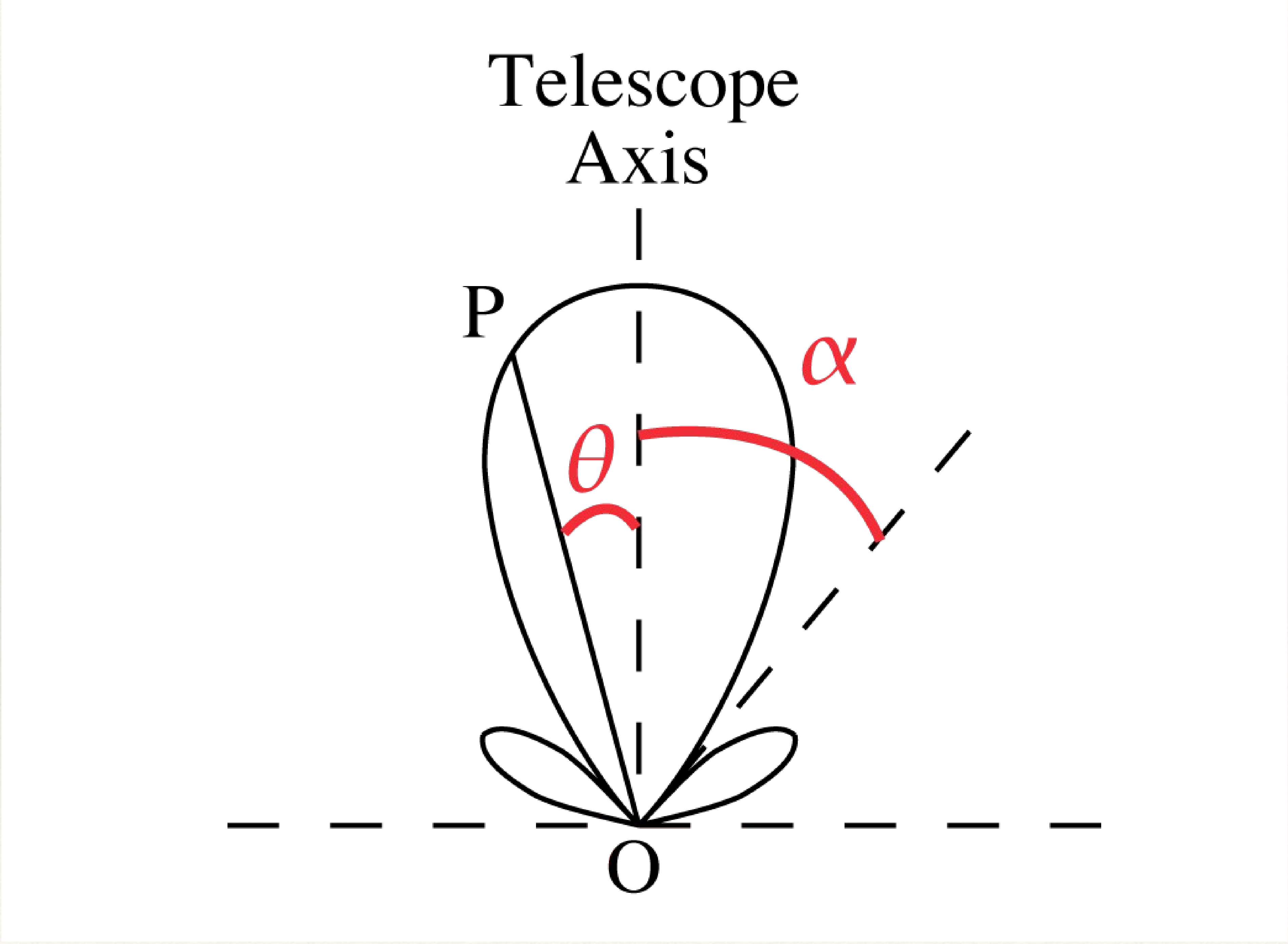
Two-element interferometer

So, fringe separation $$\theta_f = \theta_2 - \theta_1 \simeq \frac{\lambda}{\mathrm{L}}$$

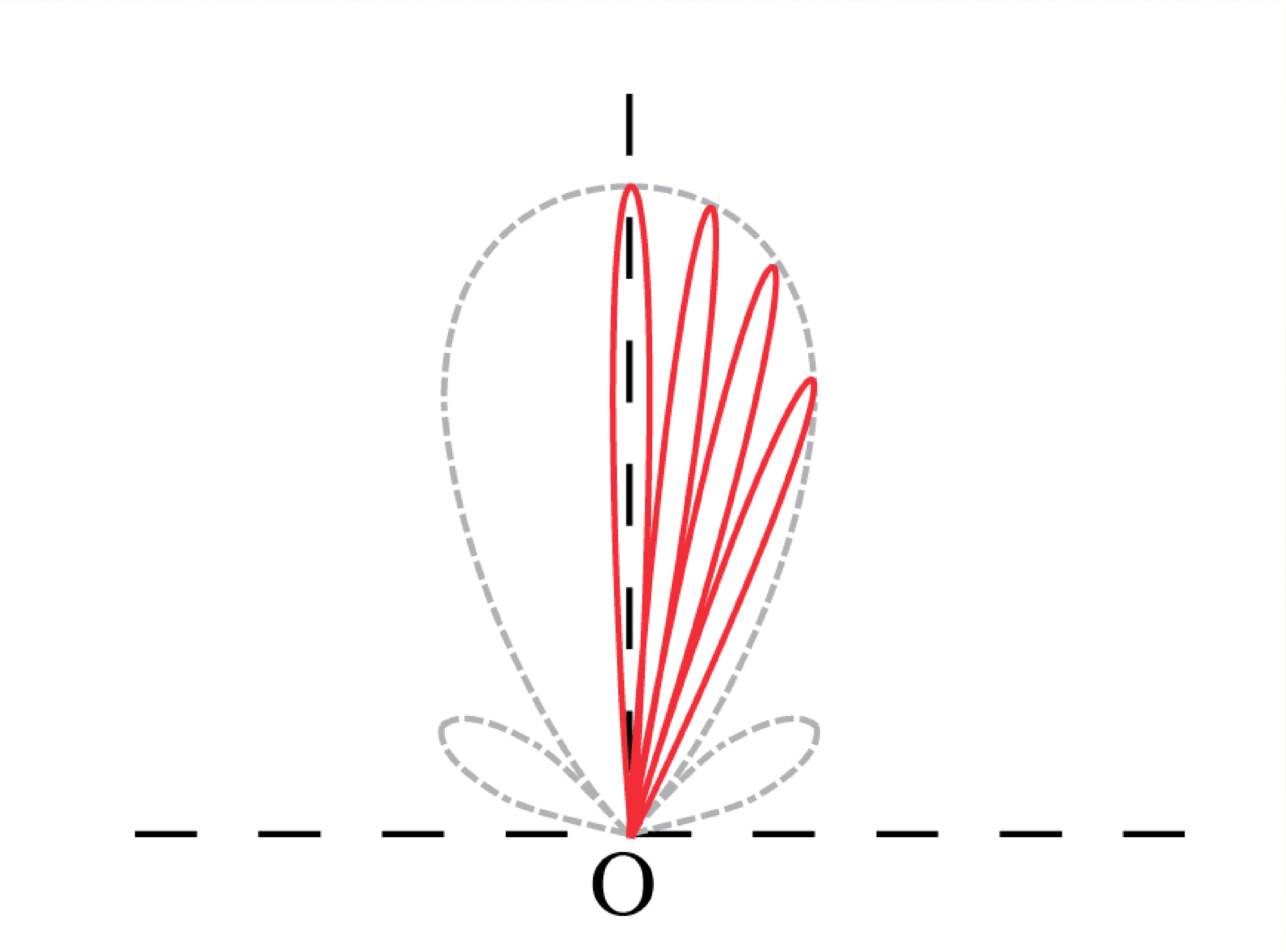
Resolution of interferometer!

Our simple, two-element interferometer acts like a single dish with diameter L

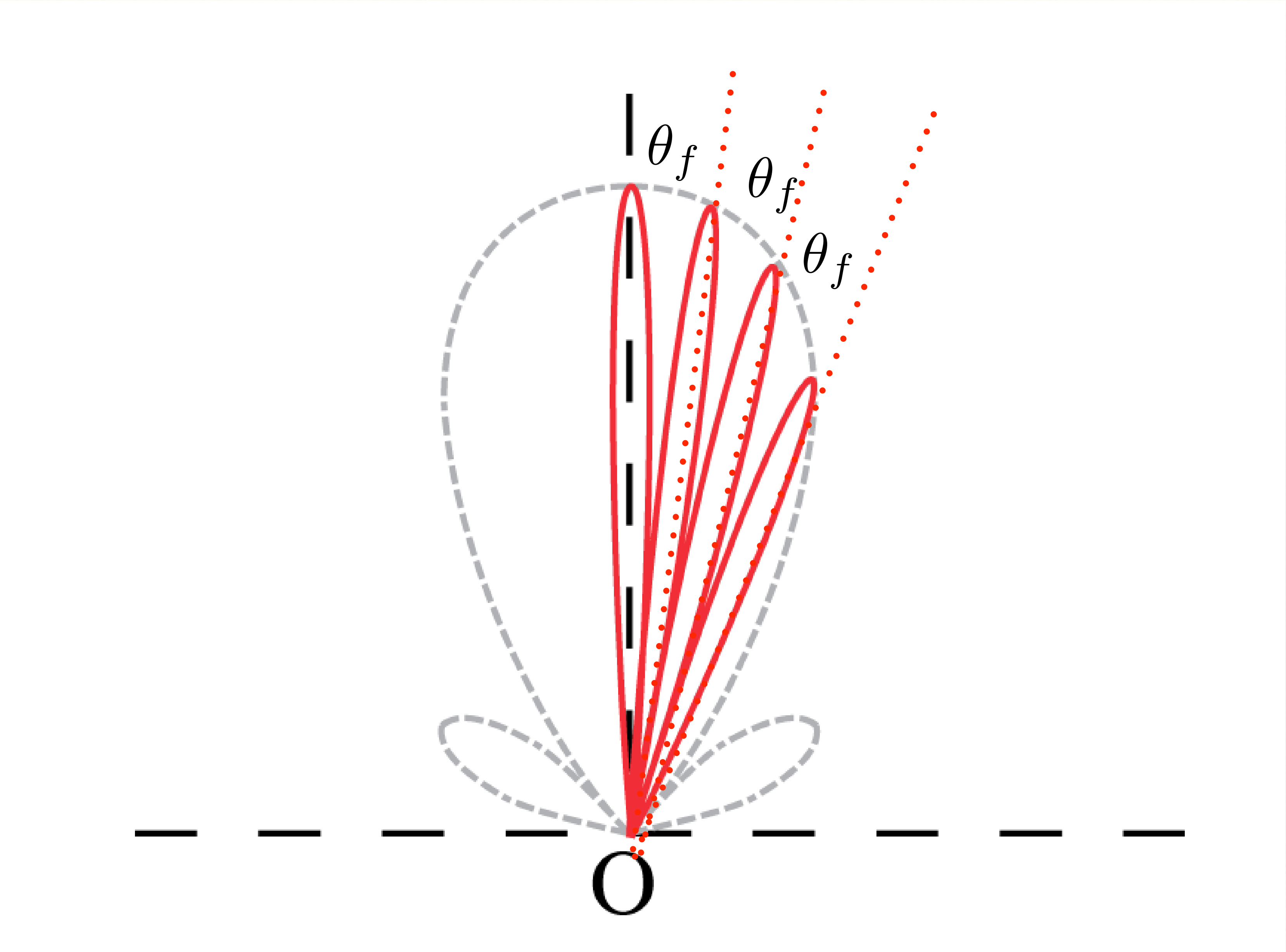
Two-element interferometer



Two-element interferometer

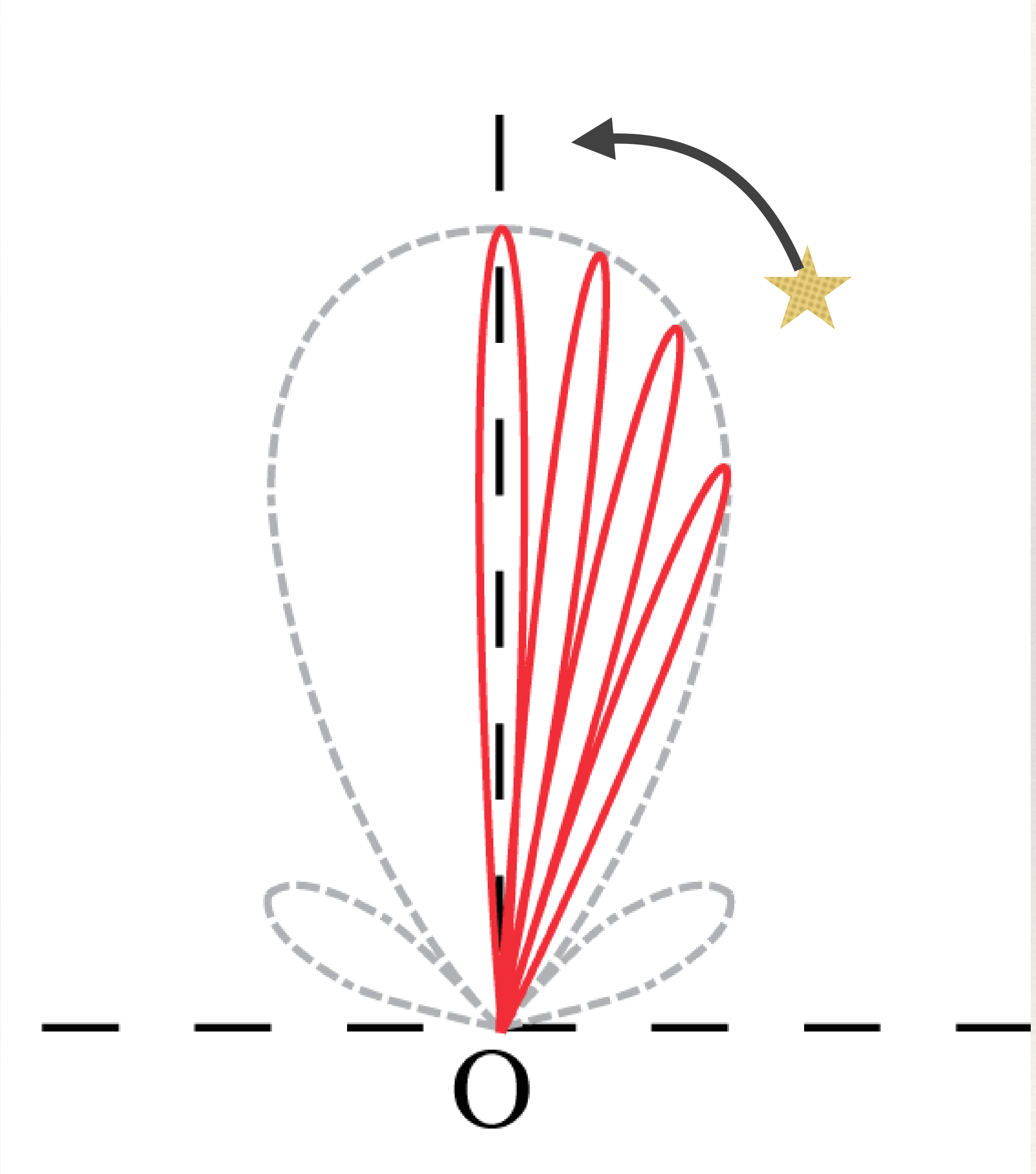


Two-element interferometer



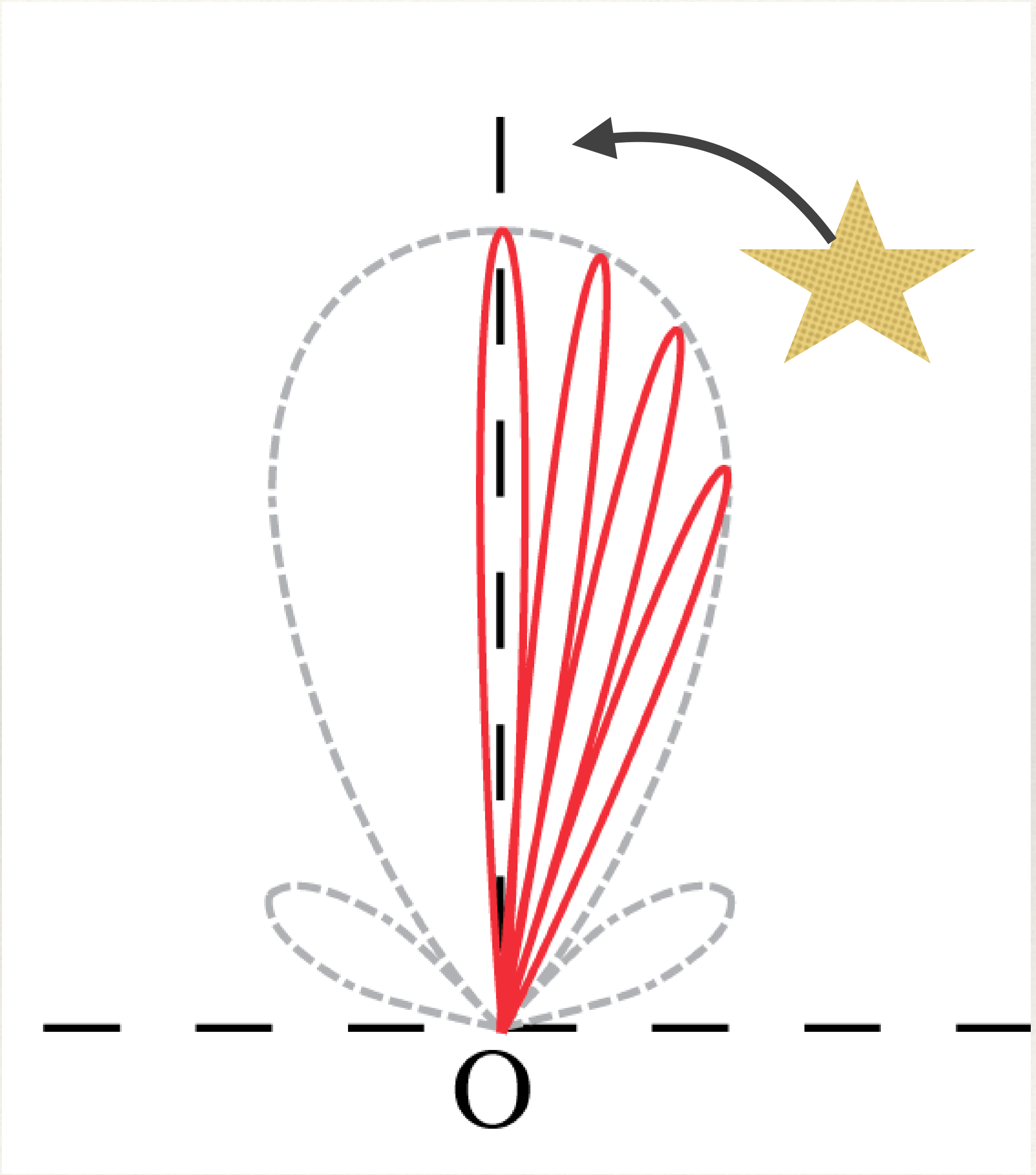
Two-element interferometer

- Small source: at fringe peak, all signal interferes constructively
- Full power of object measured
- Object unresolved by interferometer



Two-element interferometer

- Large source: some of source will always interfere destructively
- Full power of object not measured
- Object resolved by interferometer



Two-element interferometer

- Resolution depends on baseline — separation between antennas
- Interferometer is sensitive to particular angular scales — you adjust the baseline depending on your desired resolution
- If source is too large for the interferometer configuration, it begins to be 'resolved out', and you lose flux

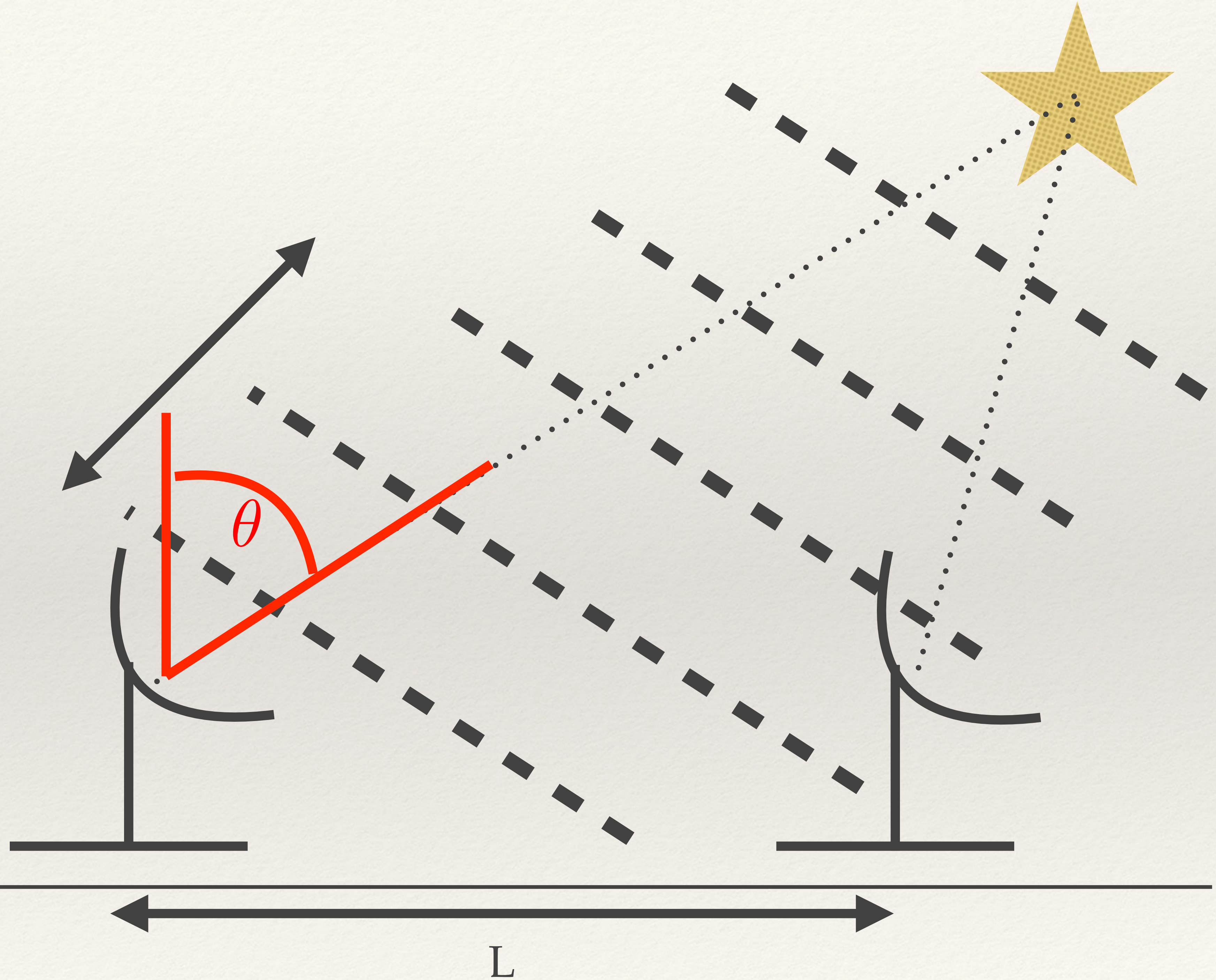
Two-element interferometer

Geometric delay τ

$$= \mathrm{L}\sin\theta$$

$$\phi = \frac{2\pi}{\lambda} L \sin\theta$$

We measure phase using interference: unmatched positional accuracy!



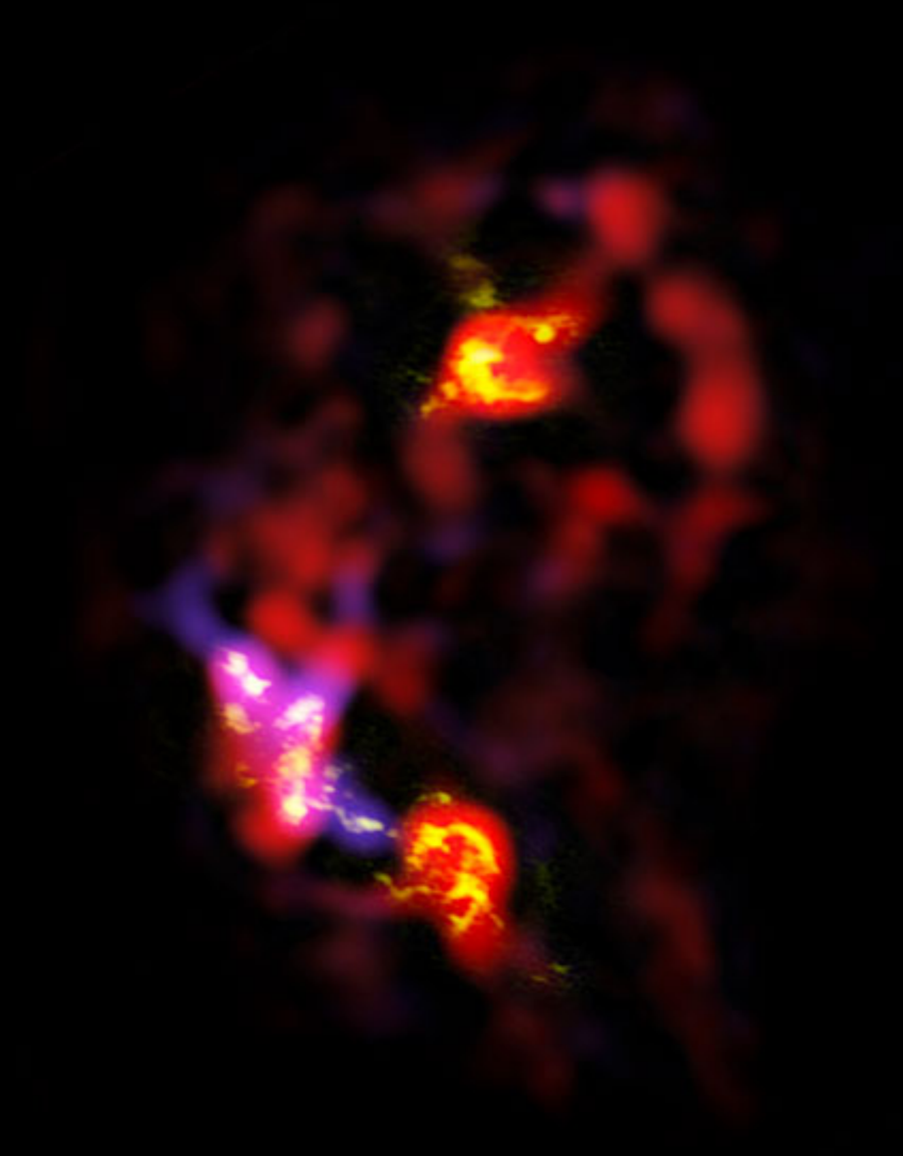
Interferometer arrays

- Real interferometers use more than two telescopes at a time
- Number of baselines increases with number of telescopes…

$$N = \frac{n^2 - n}{2}$$


Very Large Array (VLA)
27 dishes
351 baselines

ALMA image of antenna galaxies



Radio astronomy techniques: take home points

- Dipoles vs dishes
- Polar diagrams for dipoles, dipole arrays, dishes
- Angular resolution of radio telescope
- Interferometry!