The University of Manchester
Jodrell Bank
Observatory

MANCHESTER
1824

ANNA SCAIFE
JODRELL BANK CENTRE FOR ASTROPHYSICS
@RADASTRAT

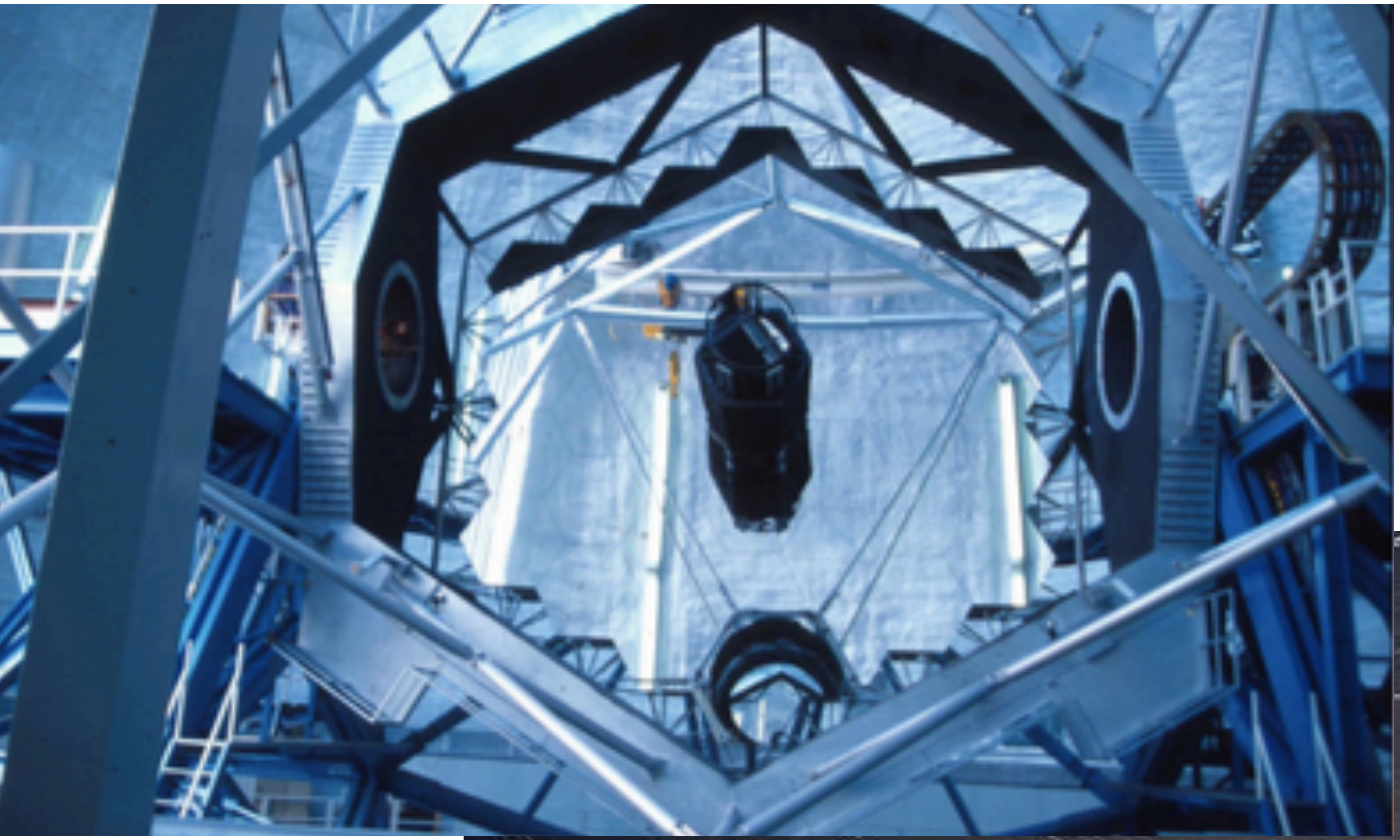
THE SQUARE KILOMETRE ARRAY

ANNA SCAIFE
JODRELL BANK CENTRE FOR ASTROPHYSICS
@RADASTRAT

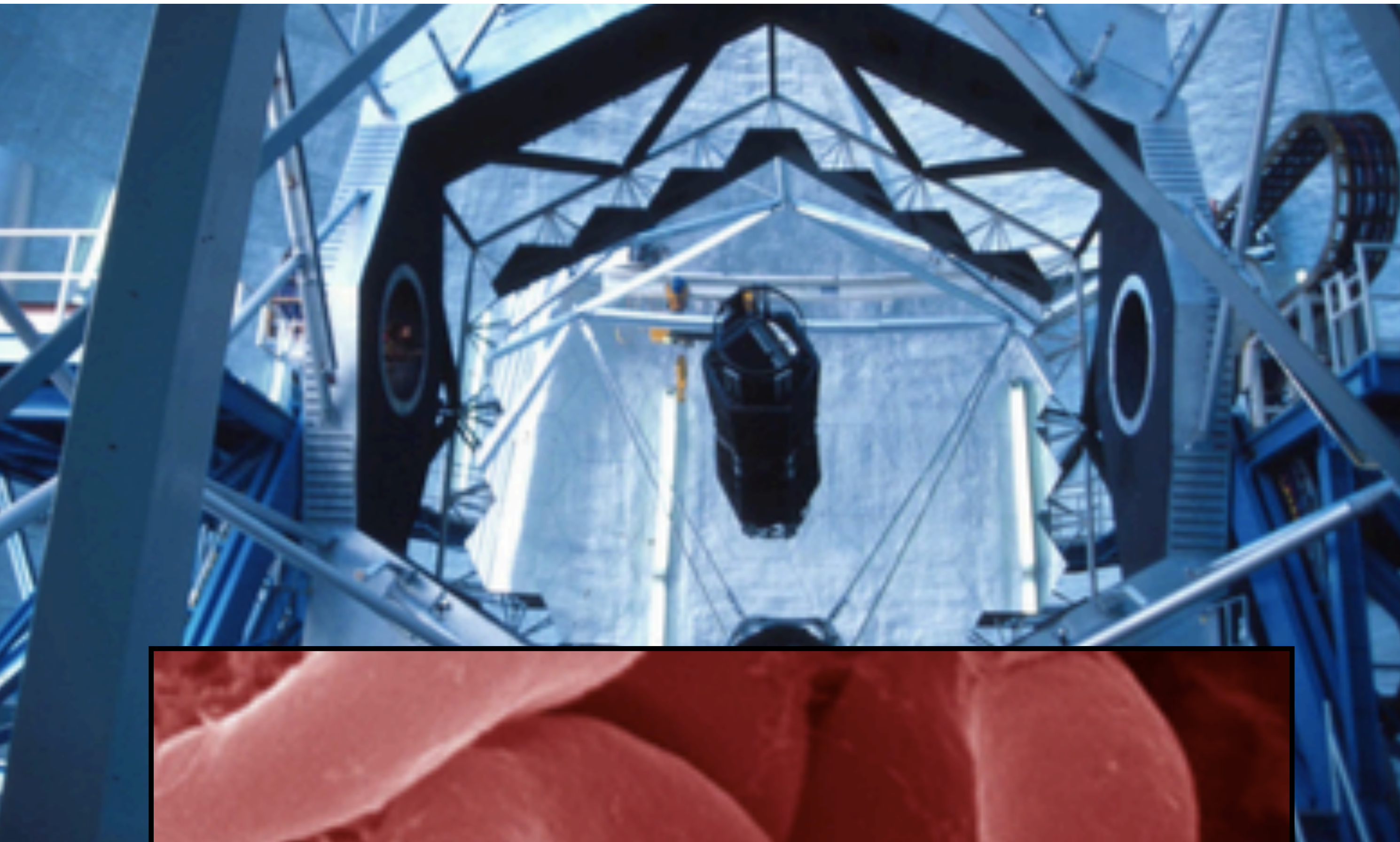
THE SQUARE KILOMETRE ARRAY

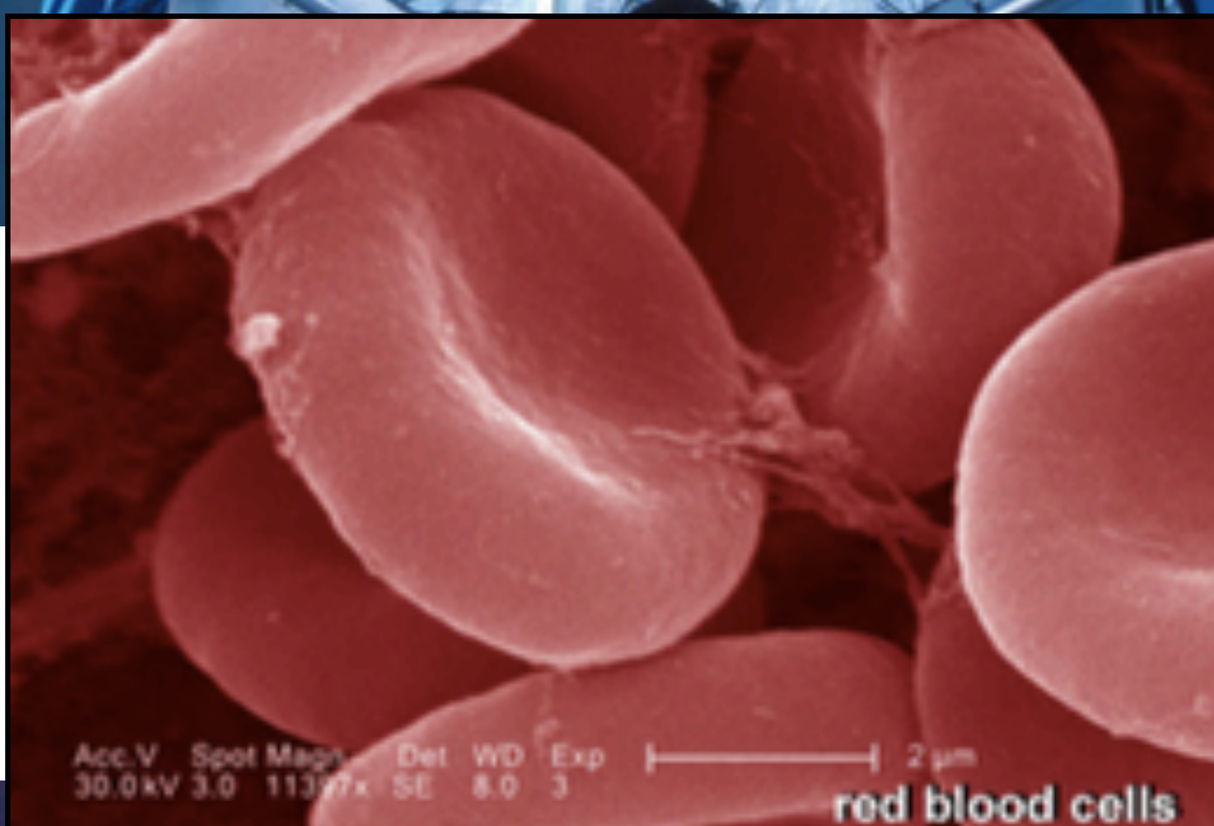
https://github.com/as595/NITheP

WHAT IS A TELESCOPE?

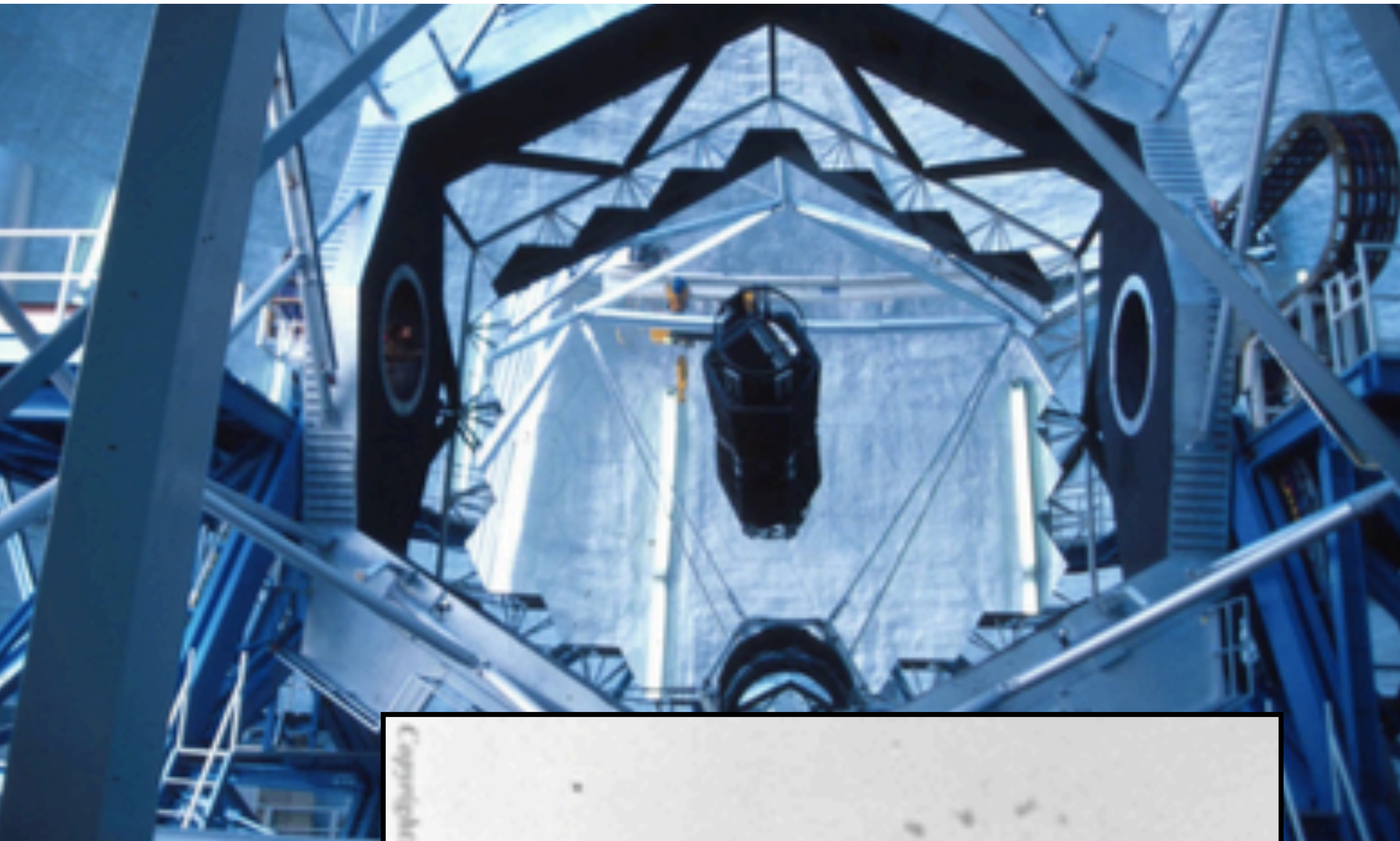


Optical: $\lambda = 350\text{-}750\text{nm}$



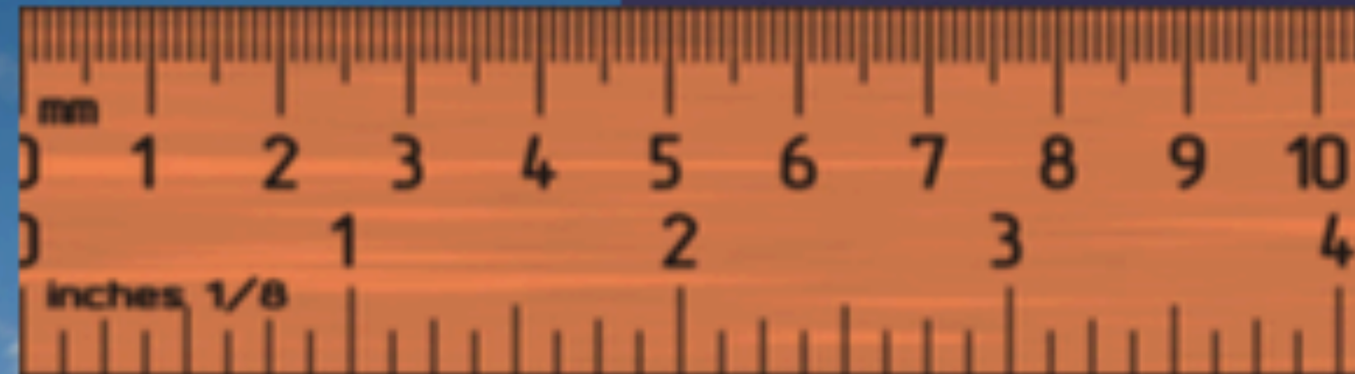


Optical: $\lambda = 350\text{-}750\text{nm}$

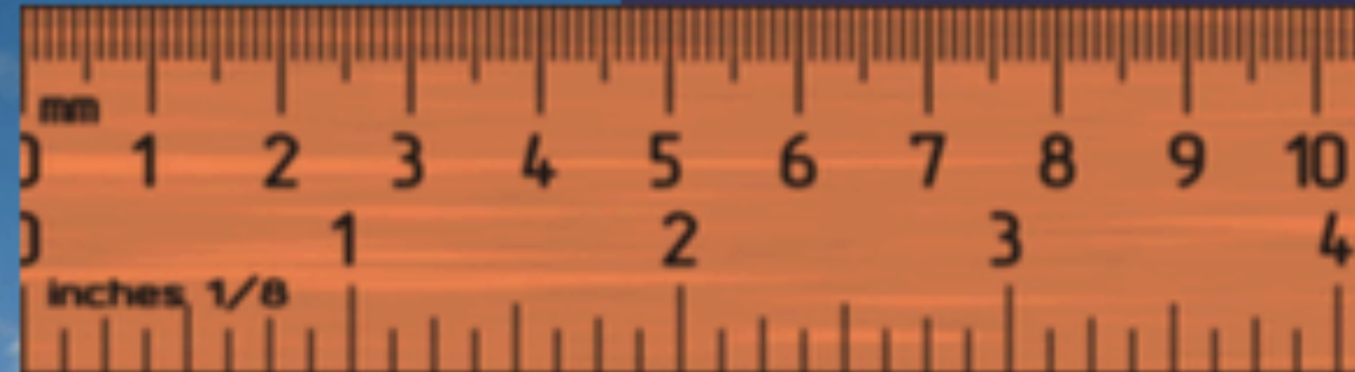


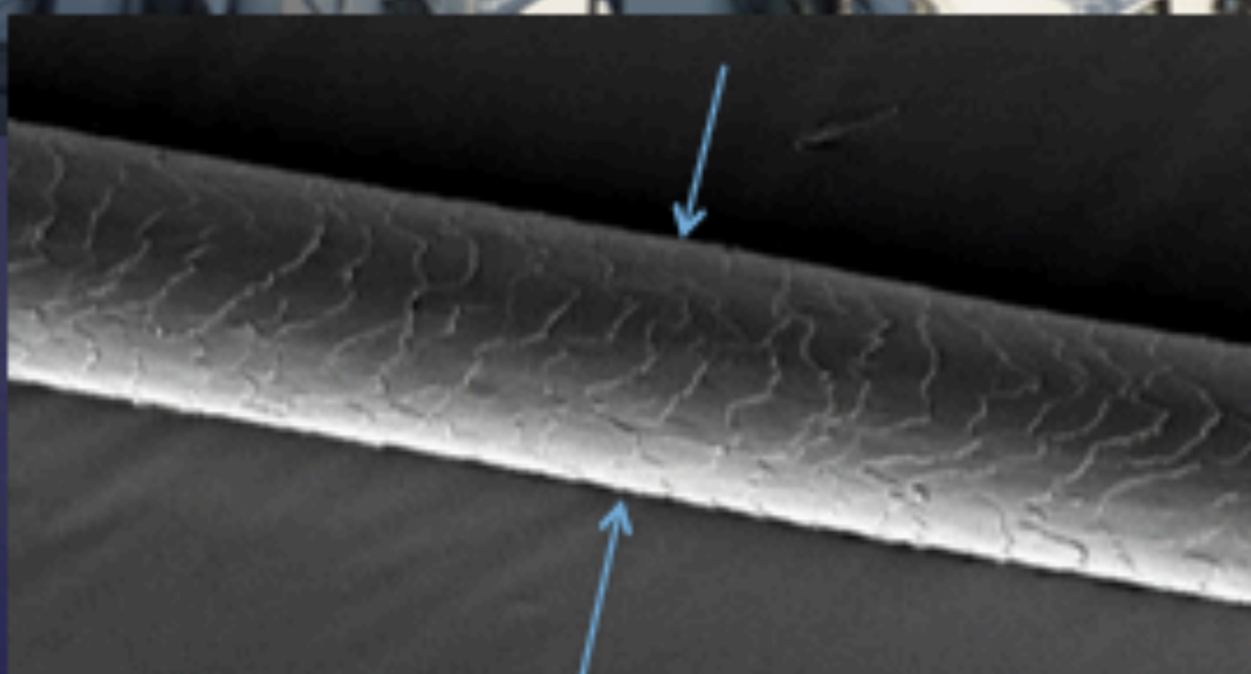
Optical: λ = 350-750nm

High Frequency Radio: $\lambda = 1 - 21$ cm



High Frequency Radio: $\lambda = 1 - 21$ cm

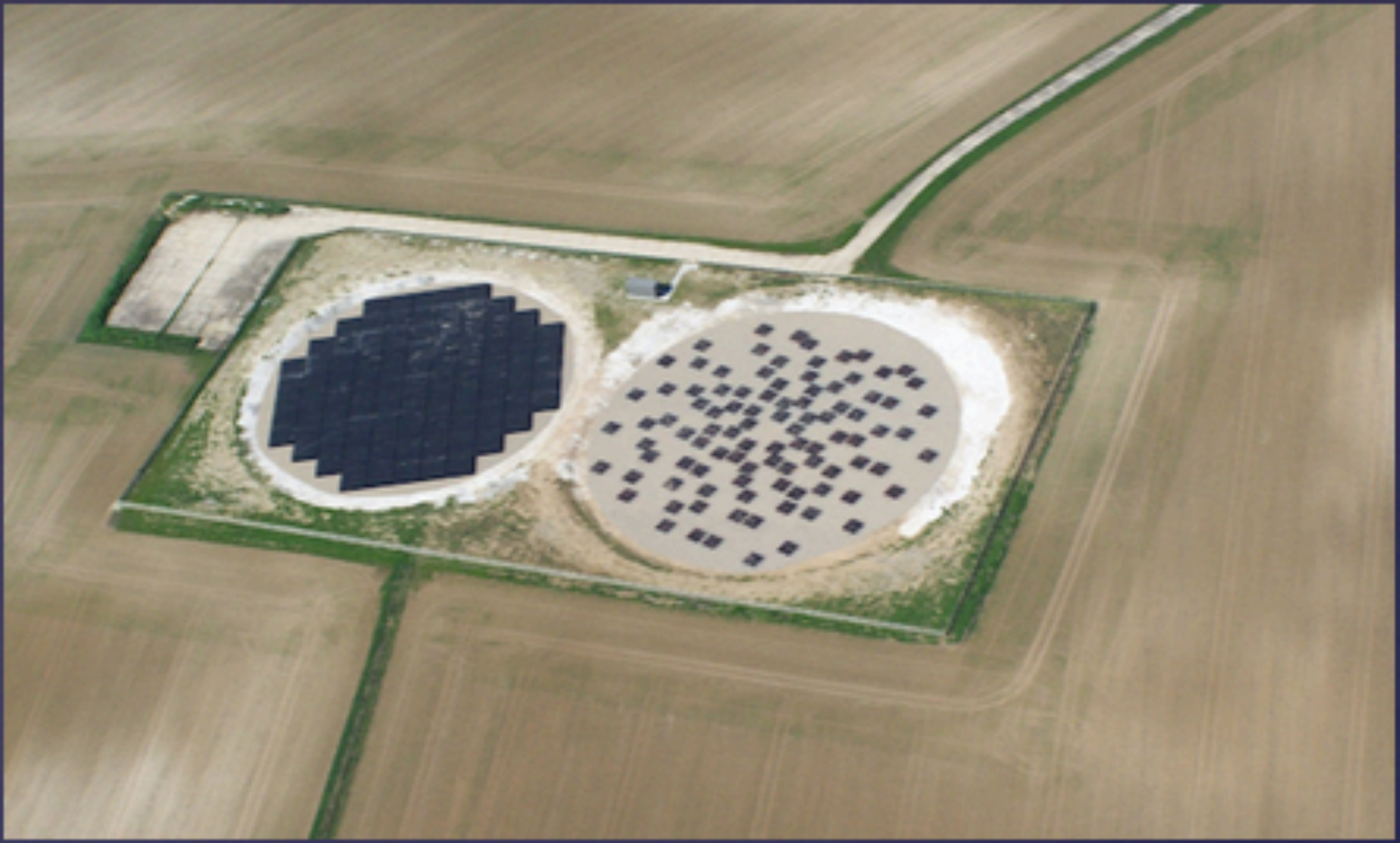




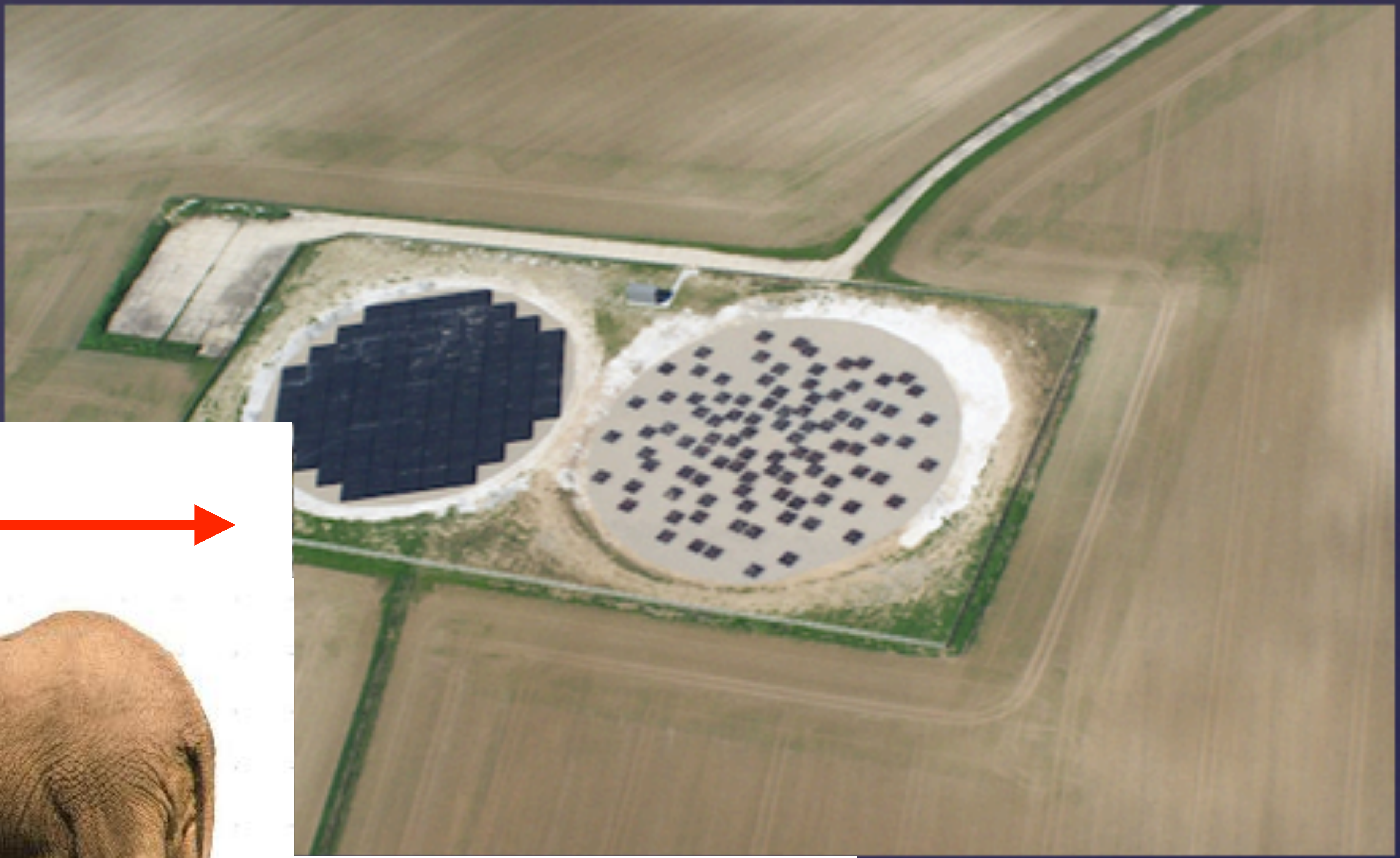
High Frequency Radio: $\lambda = 1 - 21$ cm

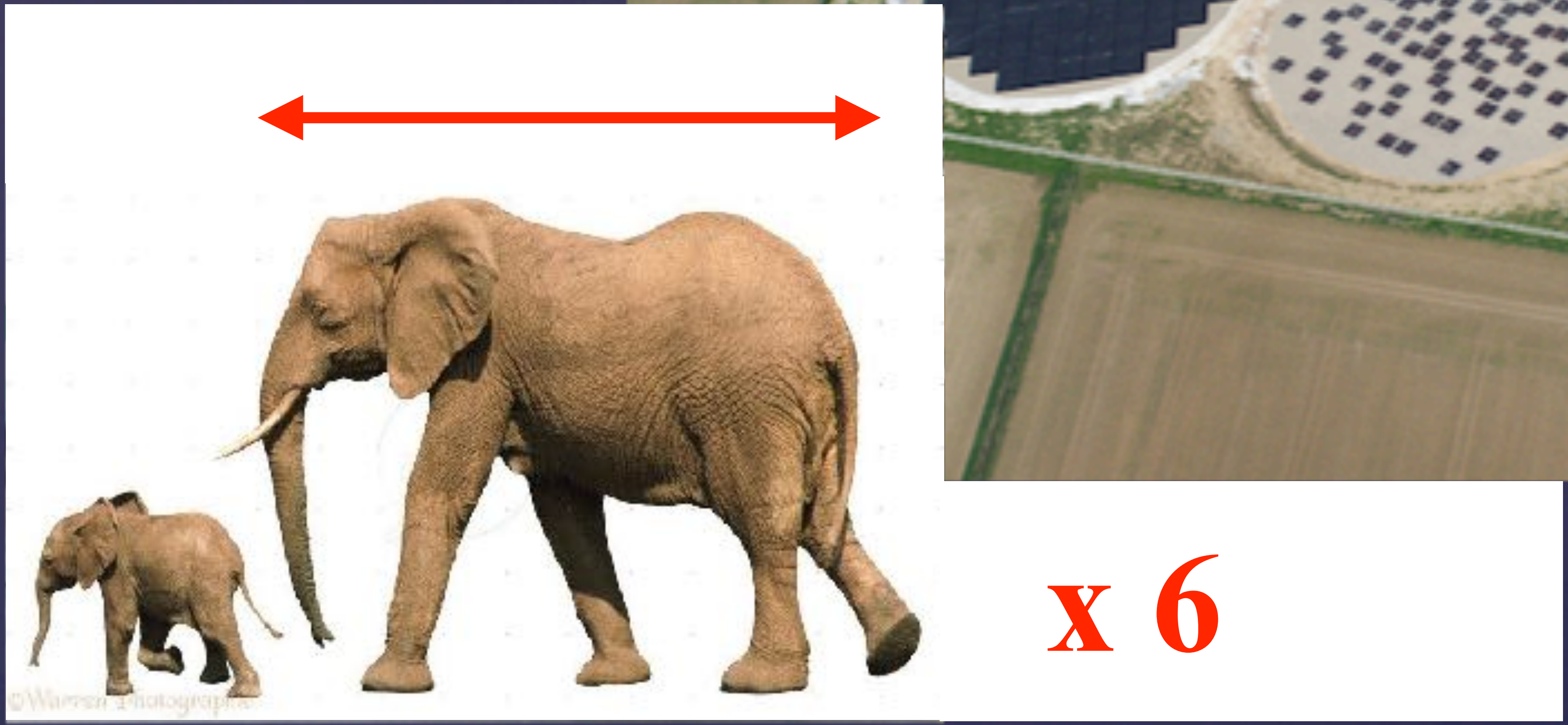
Lower Radio Frequency…

LOFAR-UK @
Chilbolton
Observatory



Low Radio Frequency!
$\lambda = 1\text{-}30\text{m}$





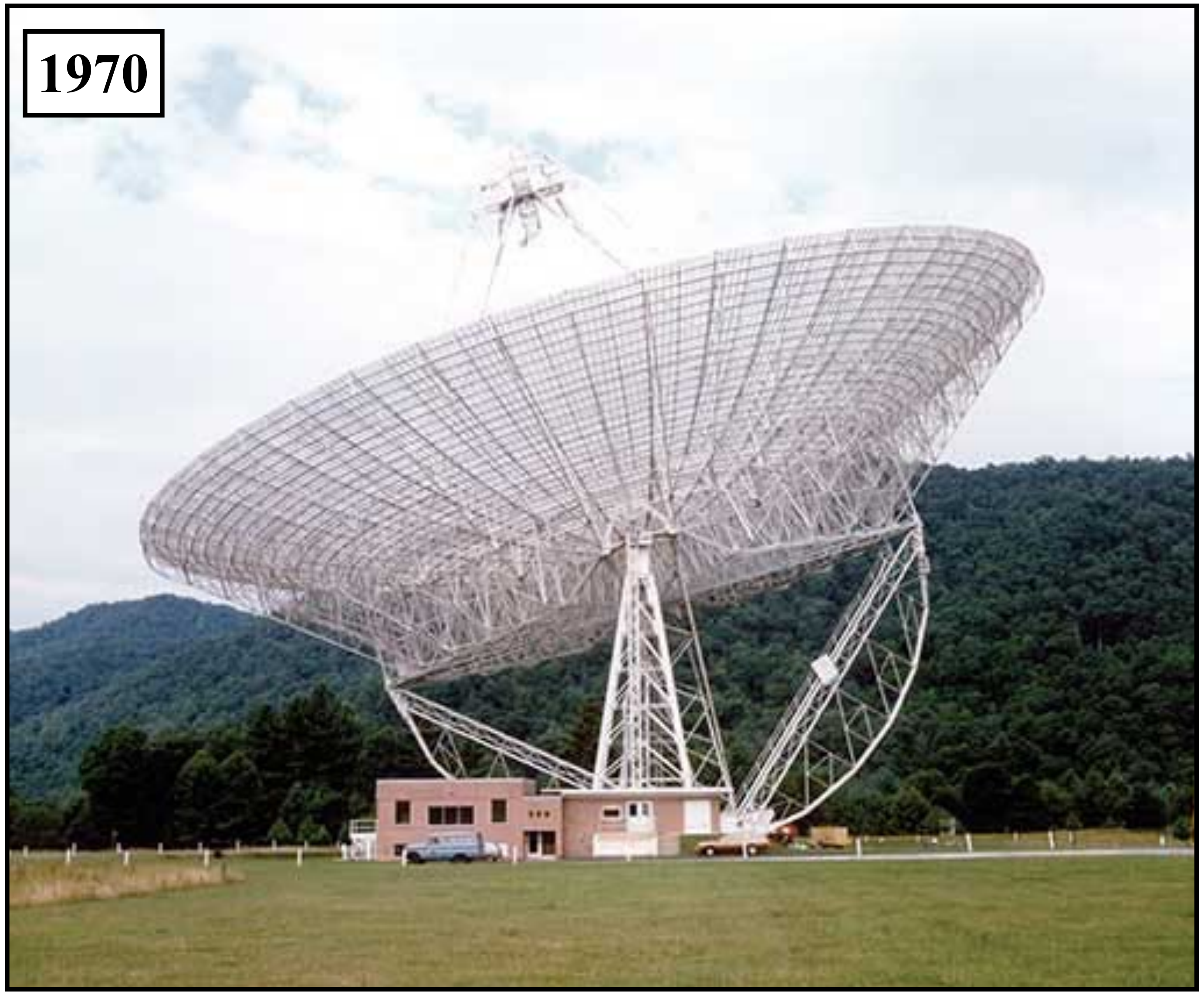
Low Radio Frequency!

$\lambda = 1\text{-}30\text{m}$

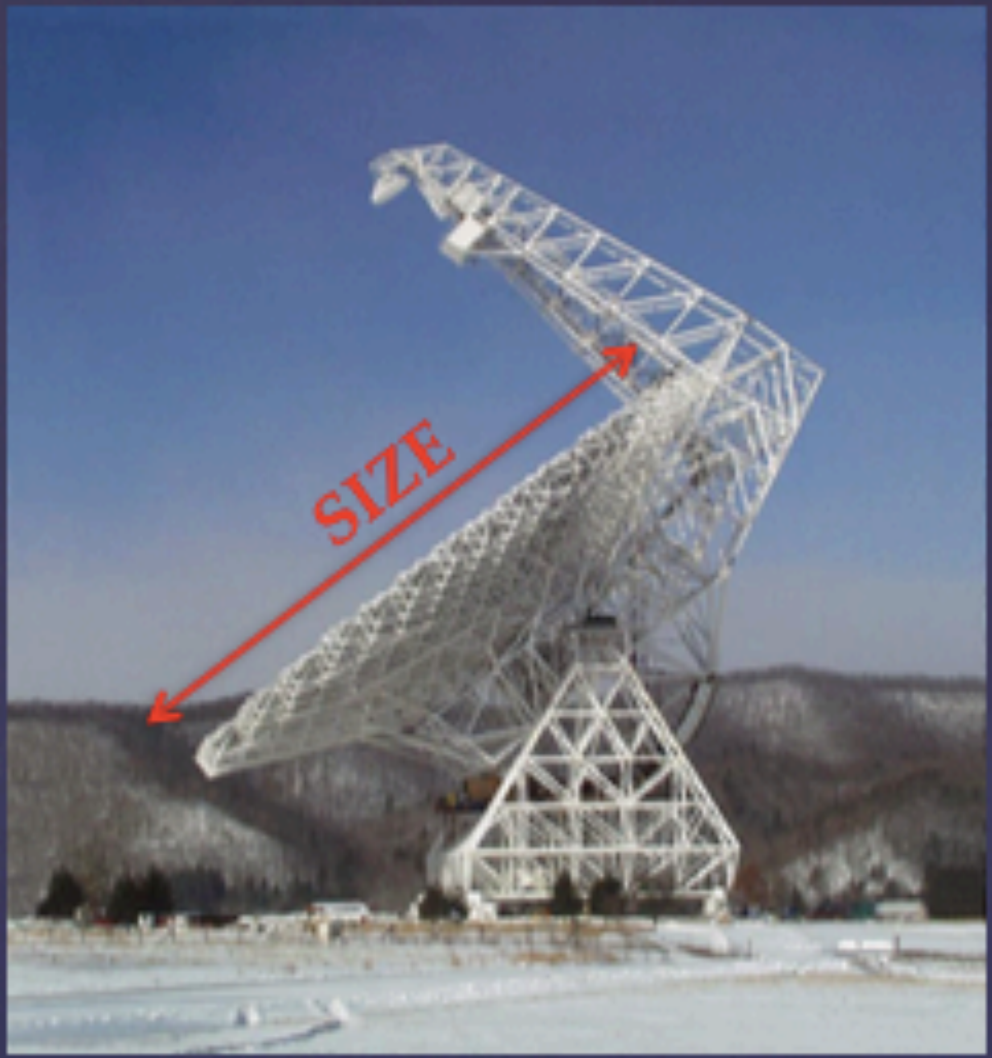
RESOLUTION:

$$\sim \frac{\lambda}{\mathrm{SIZE}}$$

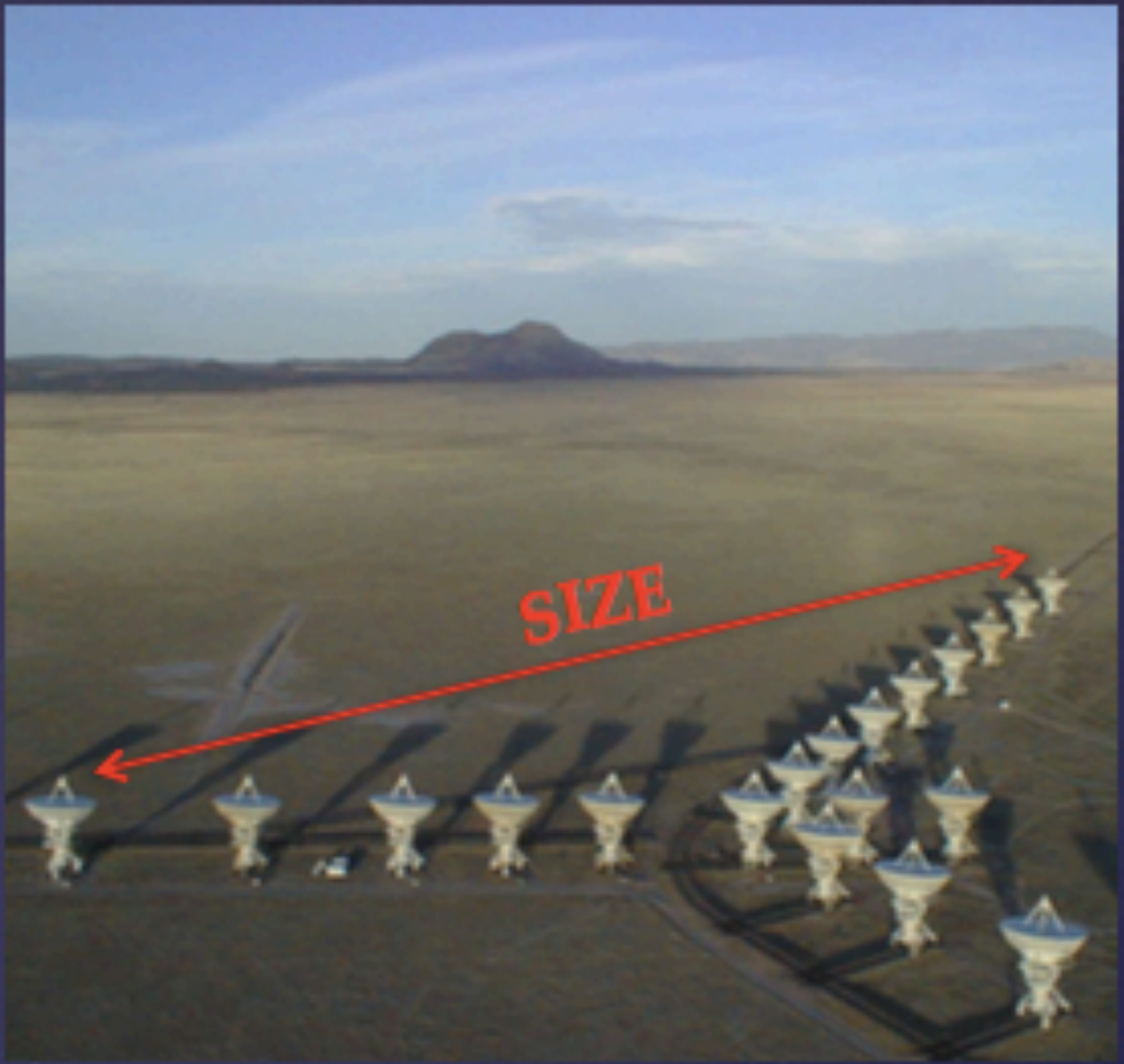
Greenbank 300ft Telescope



Greenbank 300ft Telescope



Green Bank Telescope, West Virgina, USA

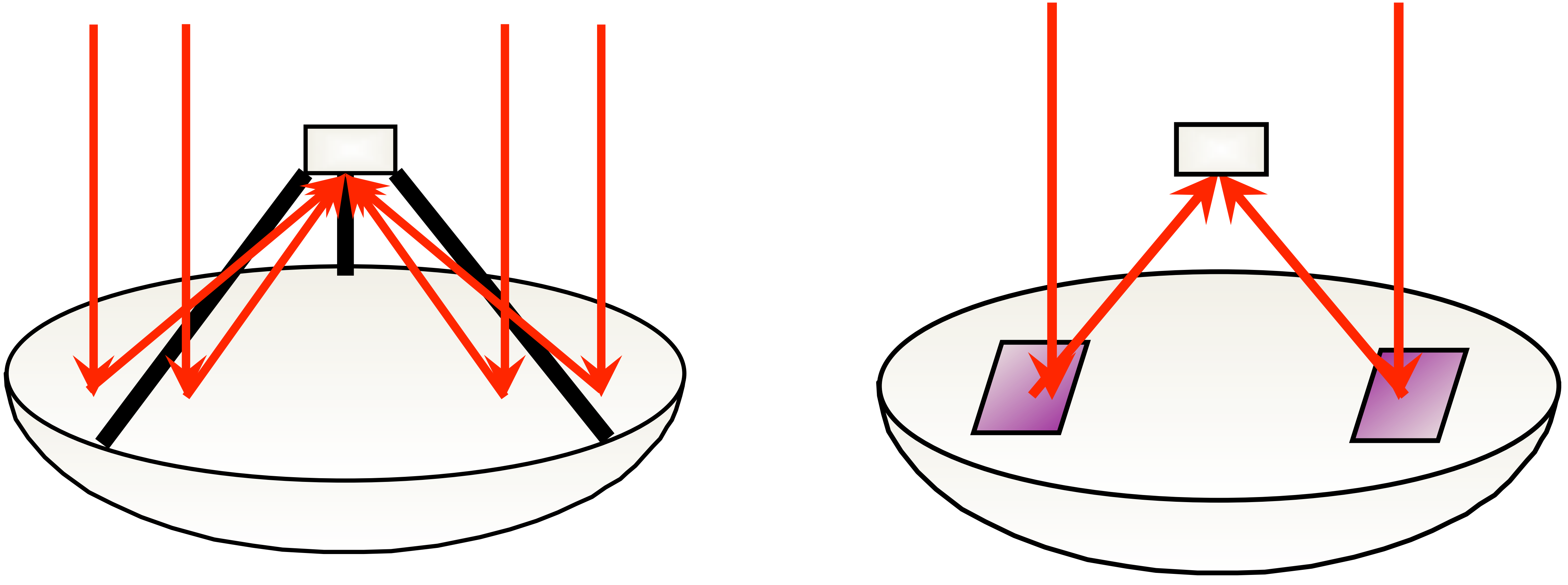


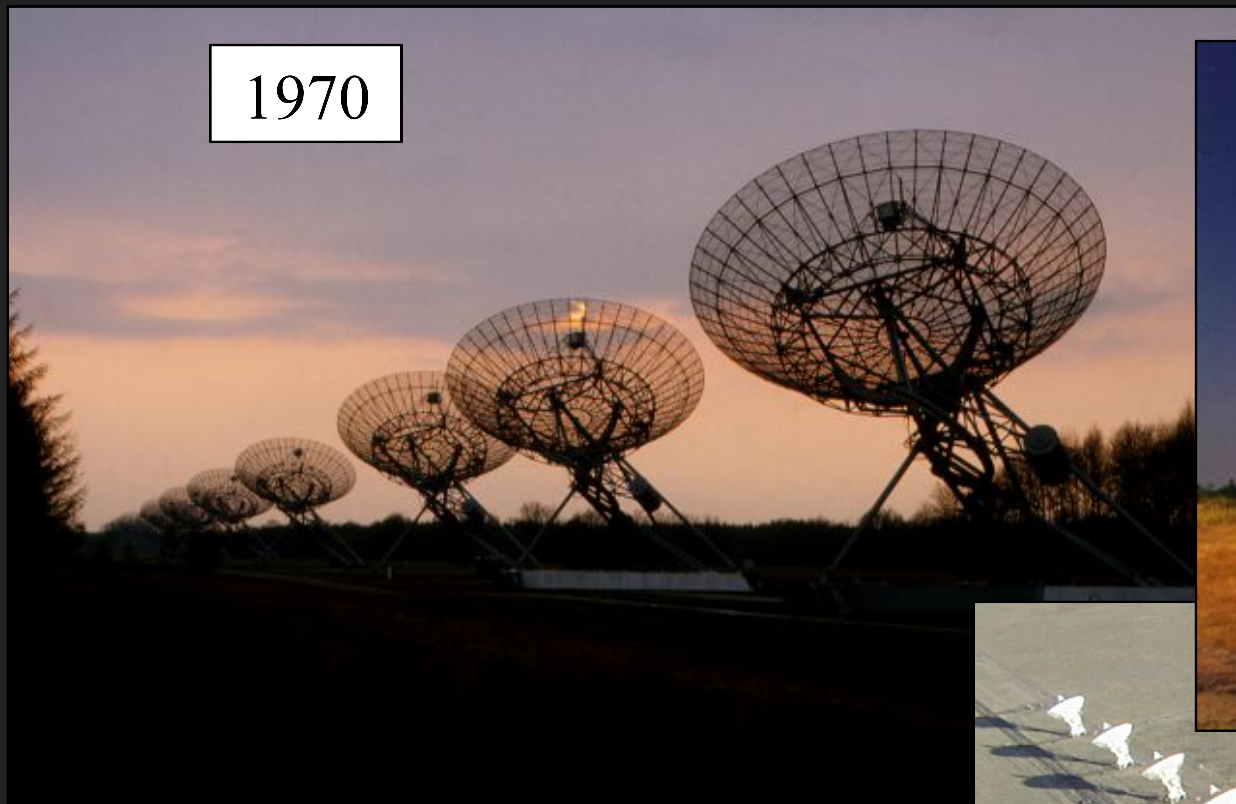
Very Large Array (VLA), New Mexico, USA

Single Dish

Array

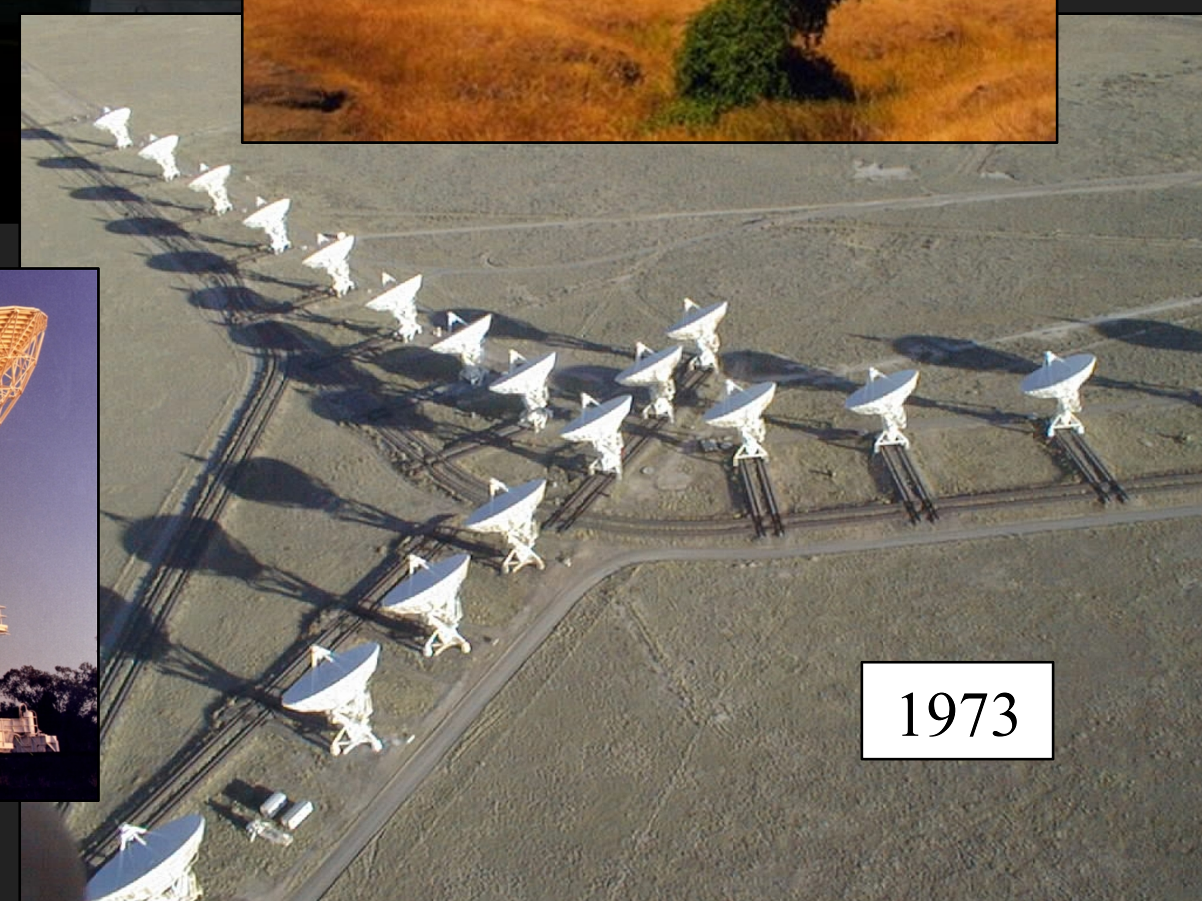
FILLED APERTURES

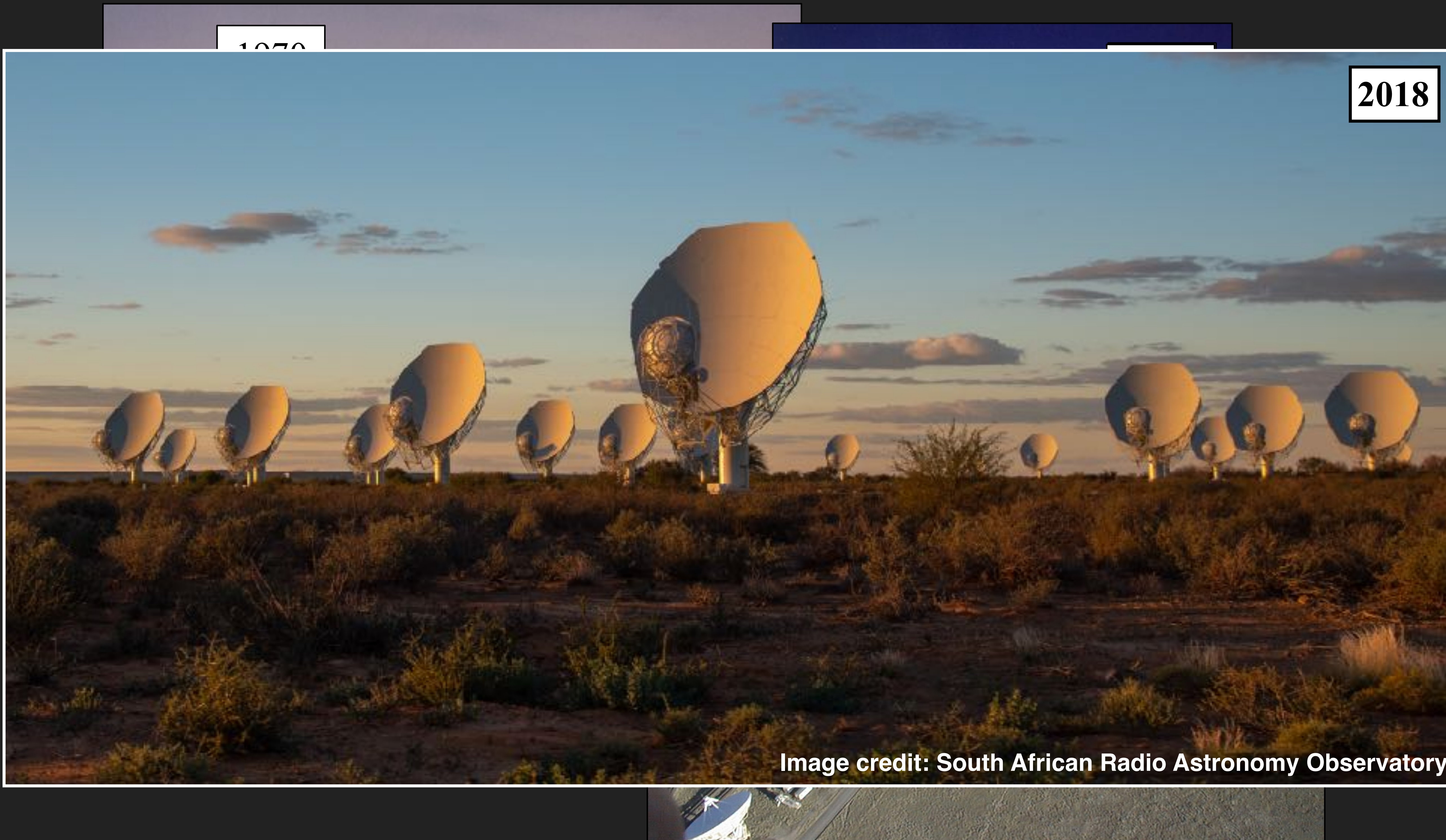



1970


1995

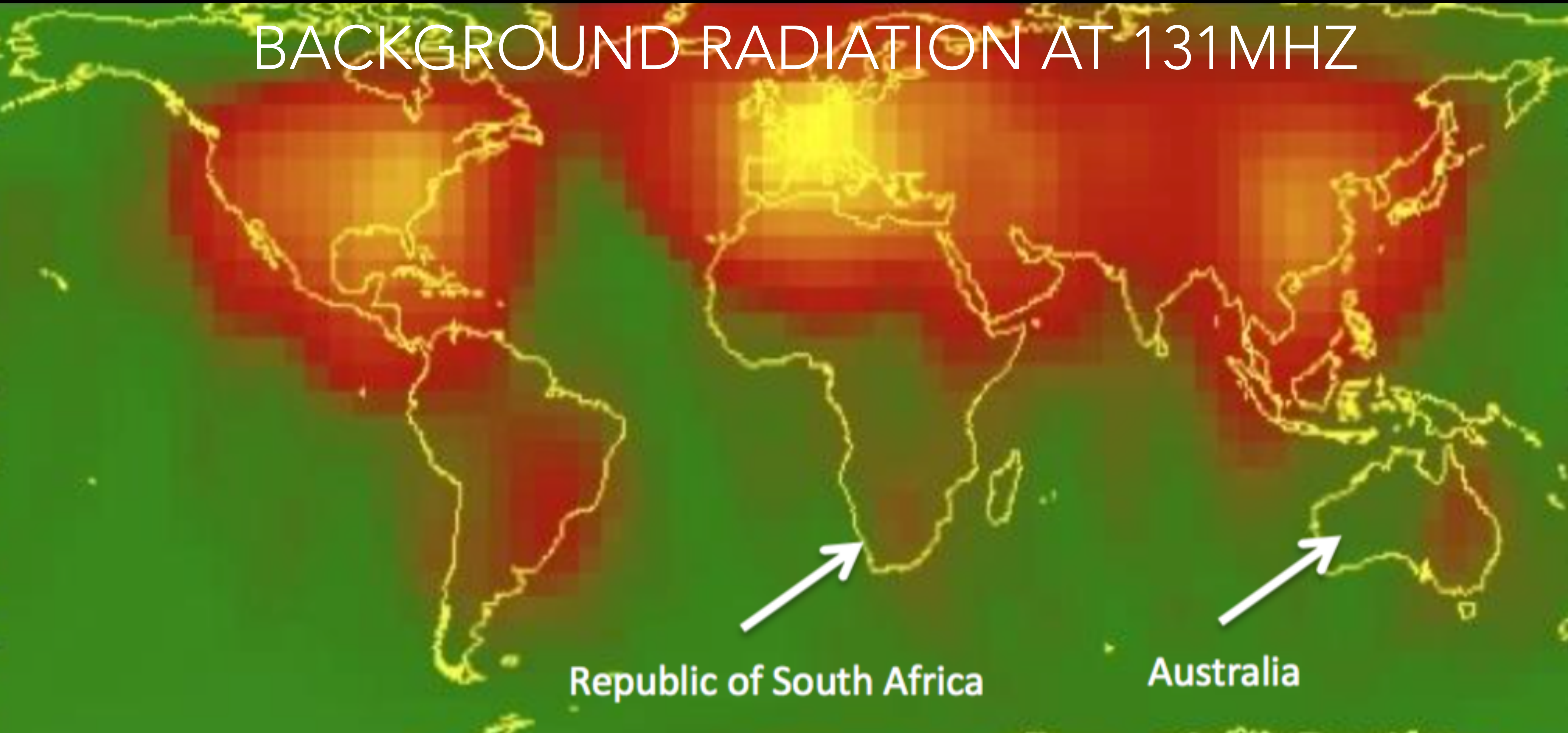

1988


1973


2018
Image credit: South African Radio Astronomy Observatory

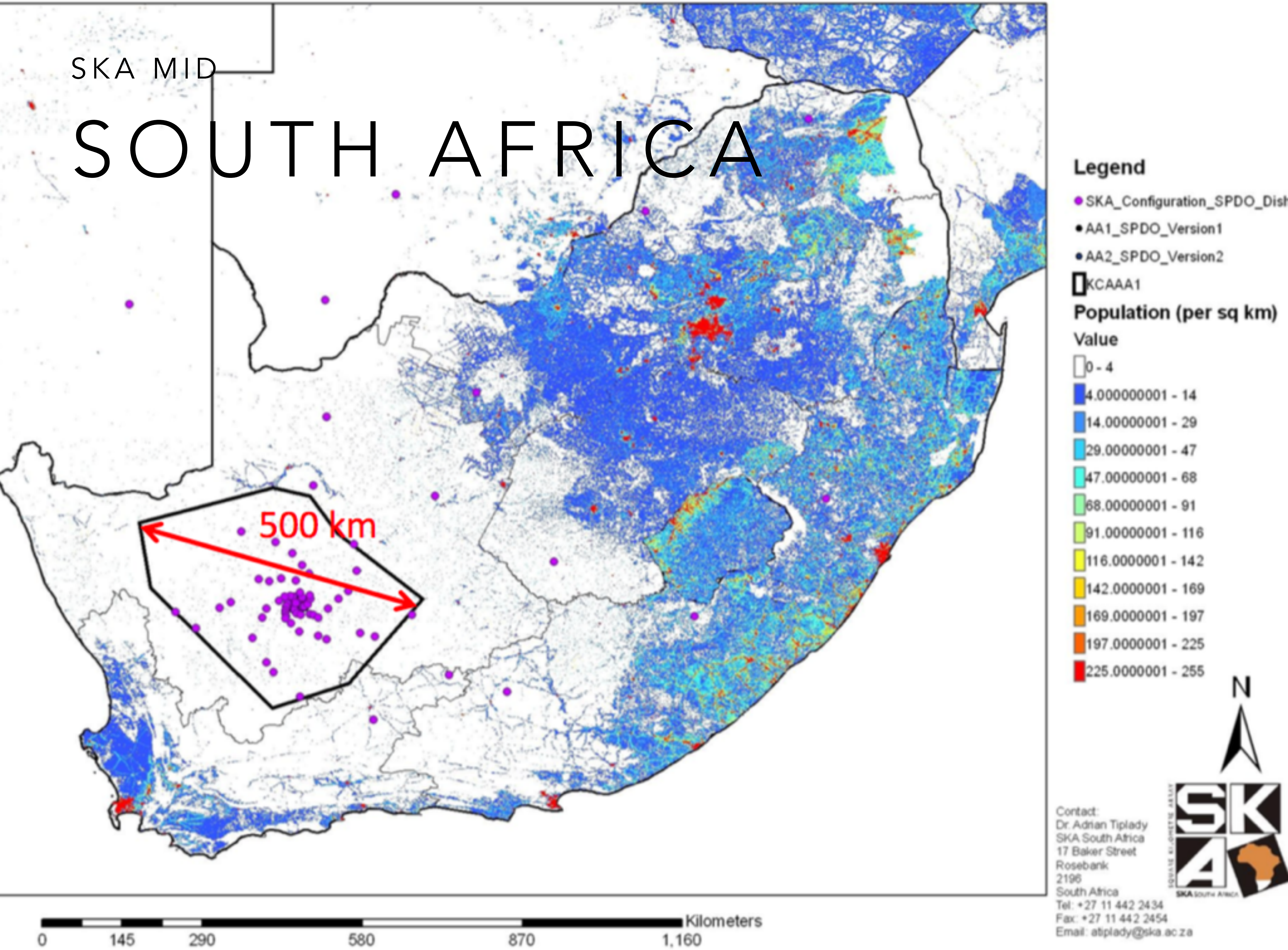
LOCATION

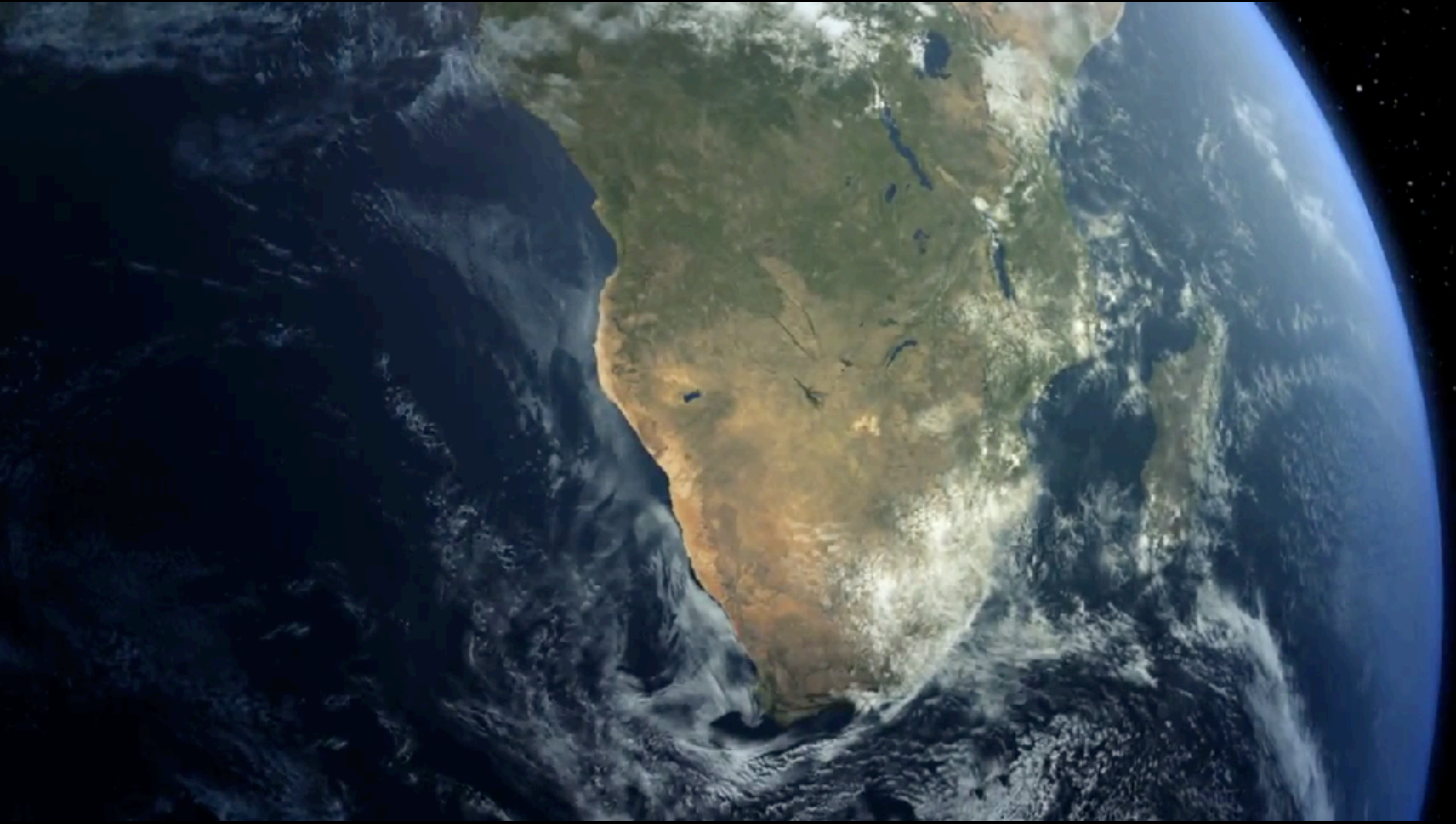
- THE TELESCOPE NEEDS TO BE SOMEWHERE “RADIO QUIET”

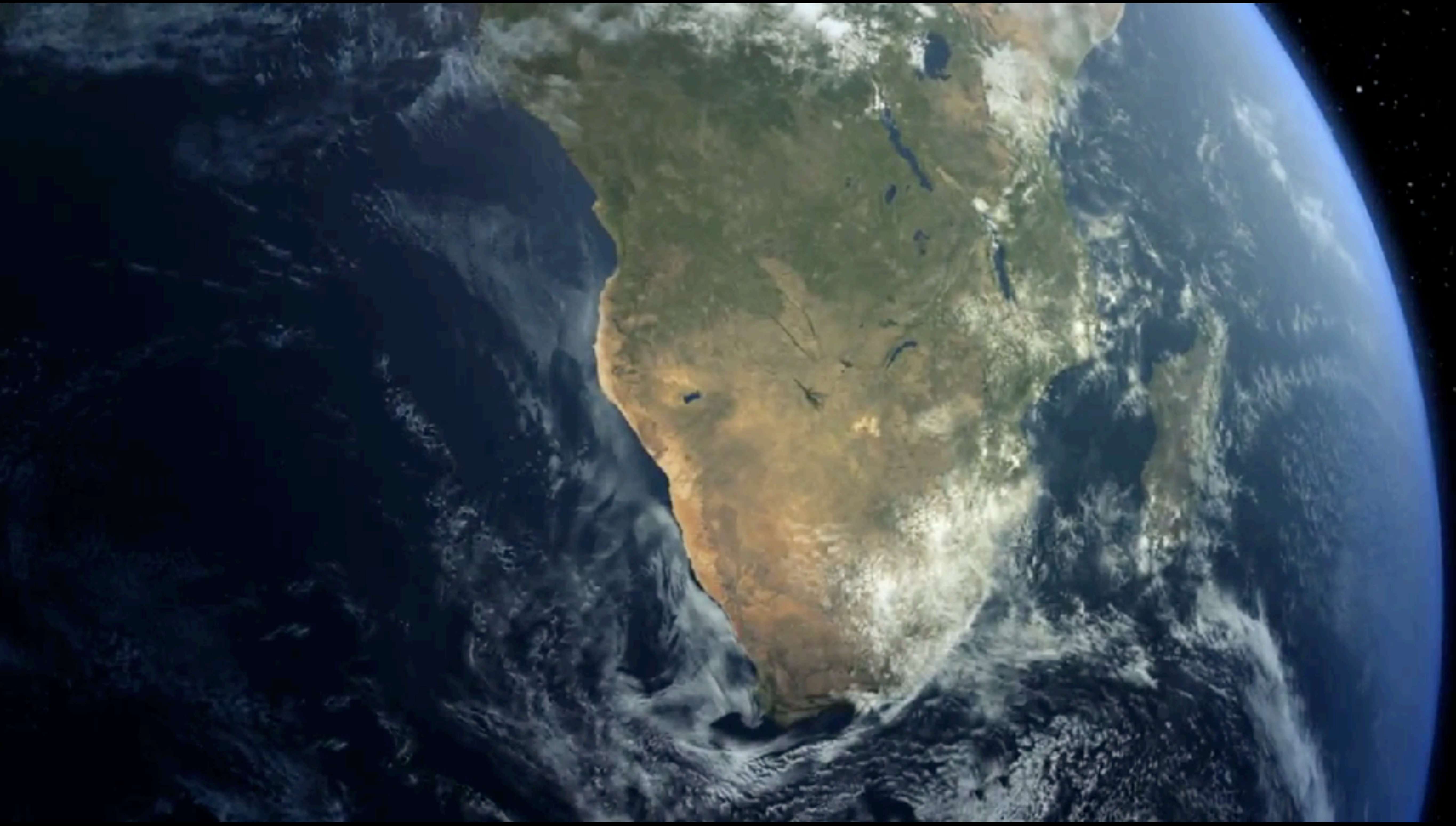


SKA MID

SOUTH AFRICA







SKA LOW
AUSTRALIA

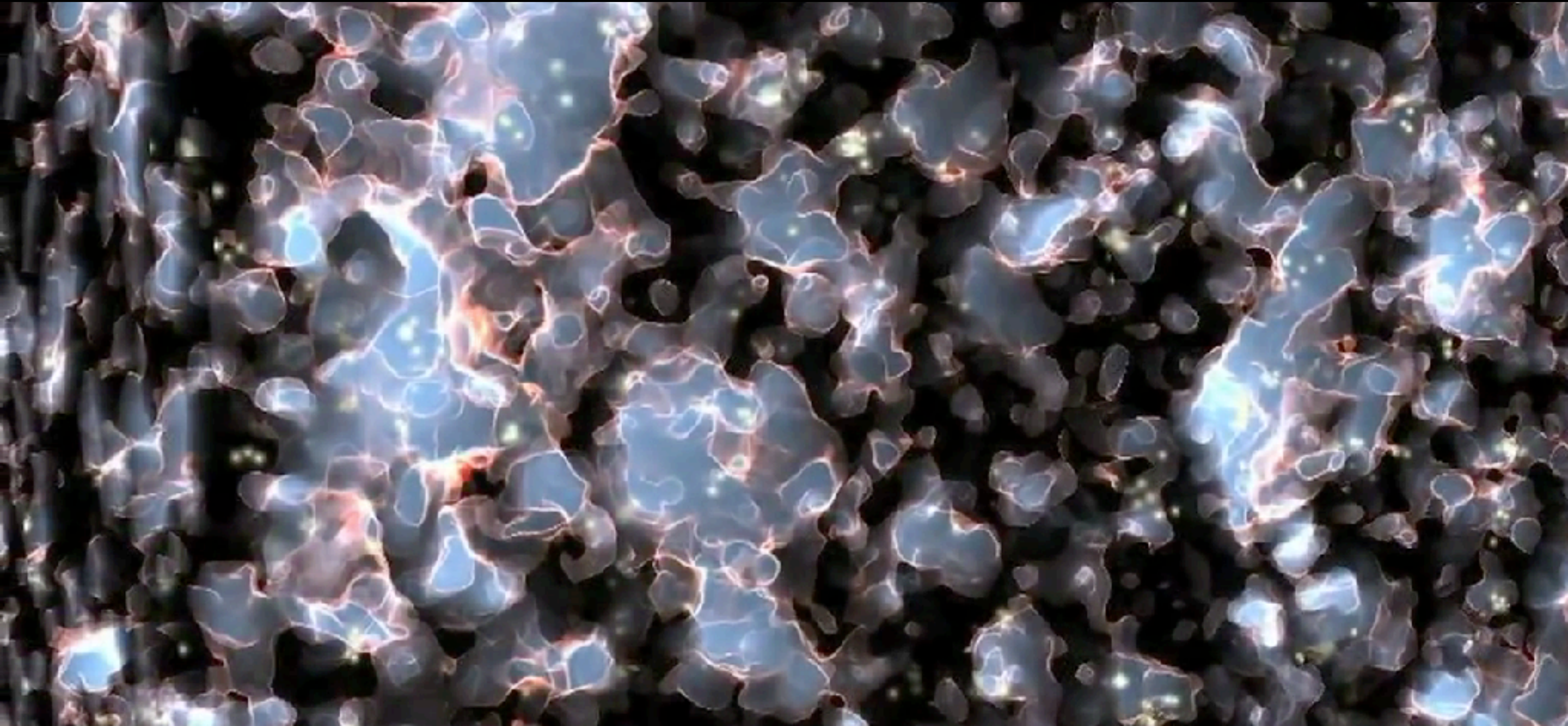
SHIRE OF MURCHISON:

- 50 000 KM^2
- 0 TOWNS
- 29 SHEEP/CATTLE STATIONS
- POP. **110** PEOPLE

  = 0.002 PPL / KM^2

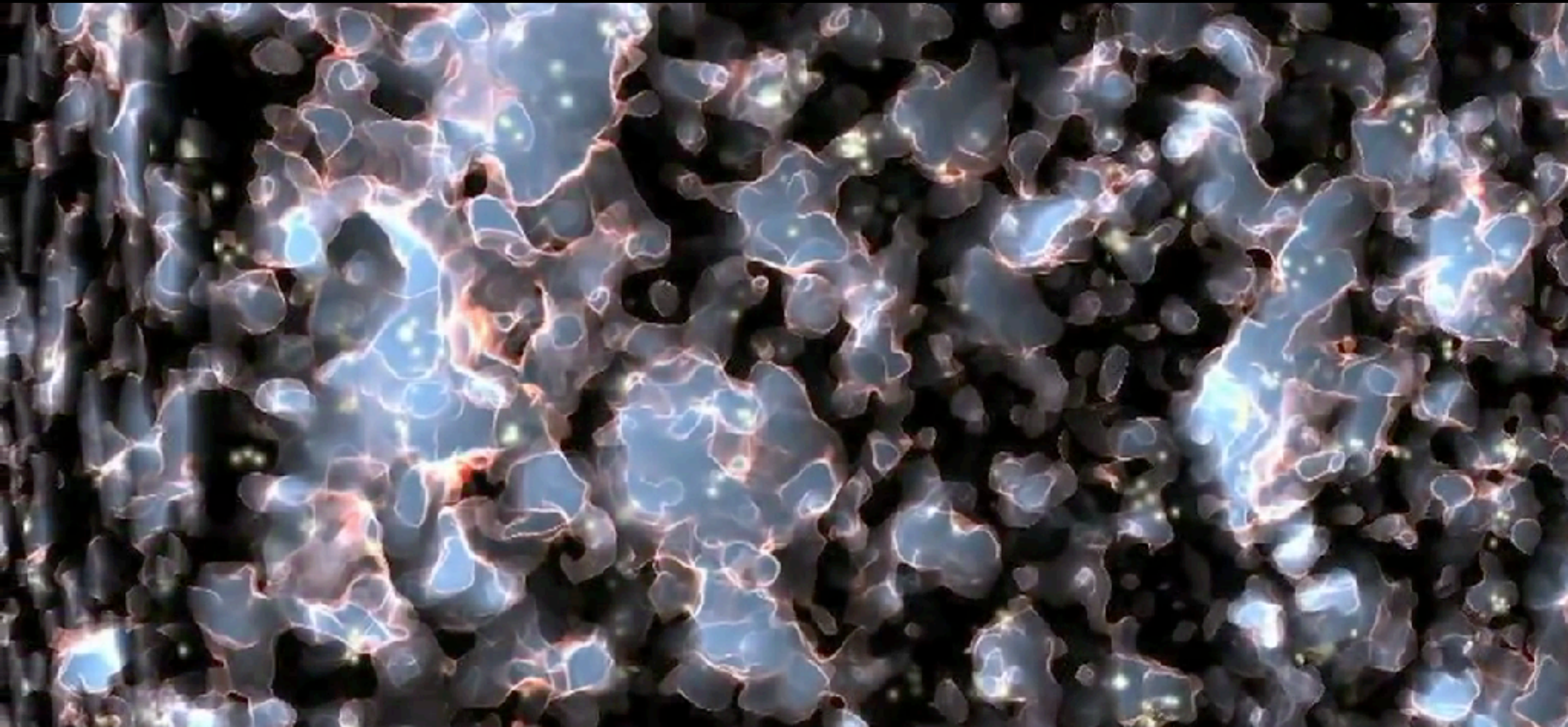
EPOCH OF REIONIZATION

- **HOW** THE FIRST STARS & GALAXIES FORMED
- **WHEN** THE FIRST STARS & GALAXIES FORMED
- REVEALED BY REDSHIFTED HYDROGEN



EPOCH OF REIONIZATION

- **HOW** THE FIRST STARS & GALAXIES FORMED
- **WHEN** THE FIRST STARS & GALAXIES FORMED
- REVEALED BY REDSHIFTED HYDROGEN



GRAVITATIONAL WAVES

- RIPPLES IN SPACE-TIME
- USE A NETWORK OF PULSARS TO DETECT THEM
- CAUSED BY INTER-ACTING SUPER-MASSIVE BLACK HOLES

GRAVITATIONAL WAVES

- RIPPLES IN SPACE-TIME
- USE A NETWORK OF PULSARS TO DETECT THEM
- CAUSED BY INTER-ACTING SUPER-MASSIVE BLACK HOLES

COSMIC MAGNETISM

- DETERMINE THE ORIGIN OF COSMIC MAGNETIC FIELDS.
- USE RADIATION FROM THE EARLY UNIVERSE THAT HAS PASSED THROUGH MAGNETIC FIELDS.
- LOOK FOR ROTATION OF THE PLANE OF POLARISATION.

COSMIC MAGNETISM

- DETERMINE THE ORIGIN OF COSMIC MAGNETIC FIELDS.
- USE RADIATION FROM THE EARLY UNIVERSE THAT HAS PASSED THROUGH MAGNETIC FIELDS.
- LOOK FOR ROTATION OF THE PLANE OF POLARISATION.

CRADLE OF LIFE

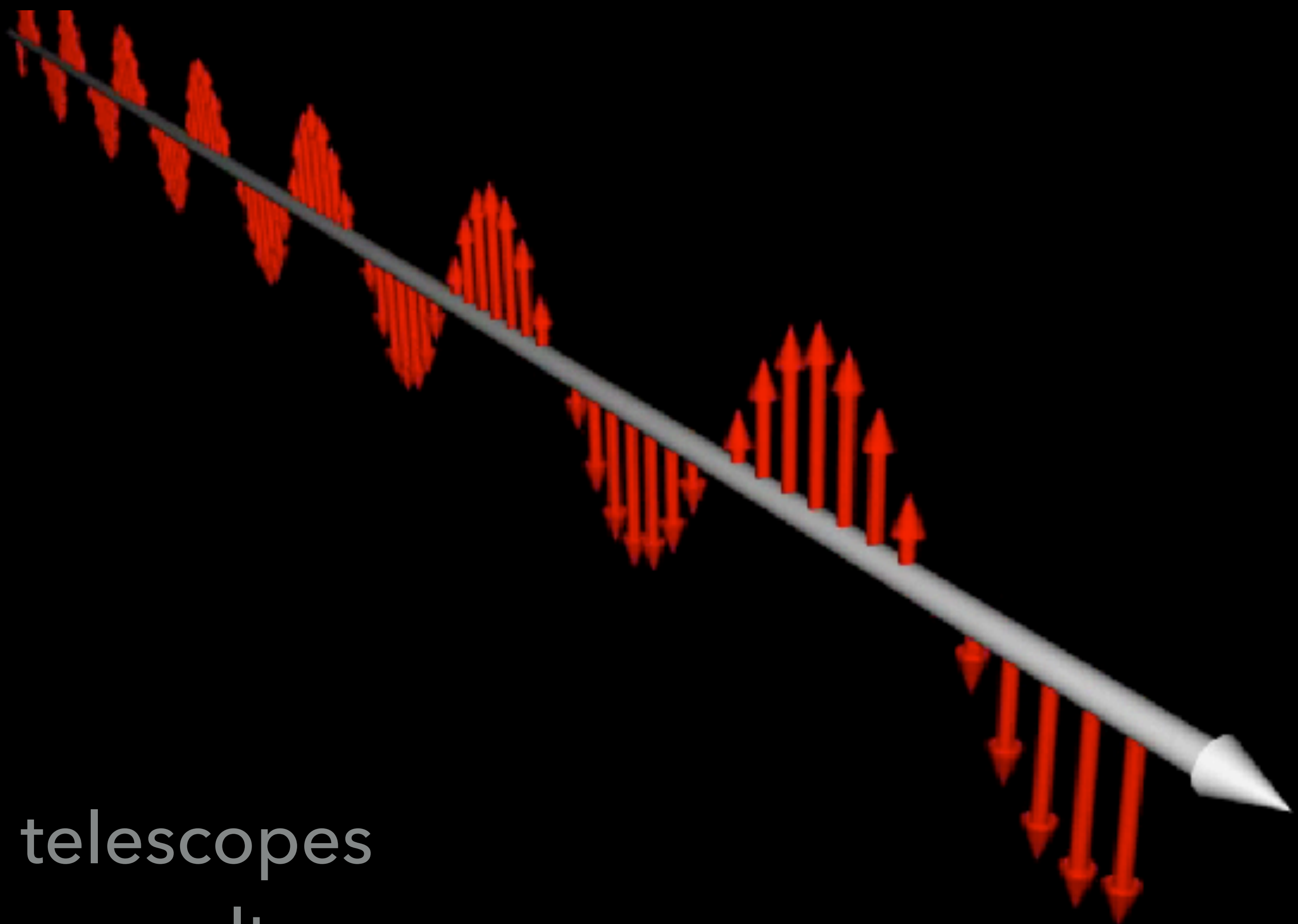
- LOOK FOR EMISSION FROM ORGANIC MOLECULES.
- IDENTIFY “EARTH-LIKE” PLANETS.
- ARE WE ALONE?

CRADLE OF LIFE

- LOOK FOR EMISSION FROM ORGANIC MOLECULES.
- IDENTIFY “EARTH-LIKE” PLANETS.
- ARE WE ALONE?

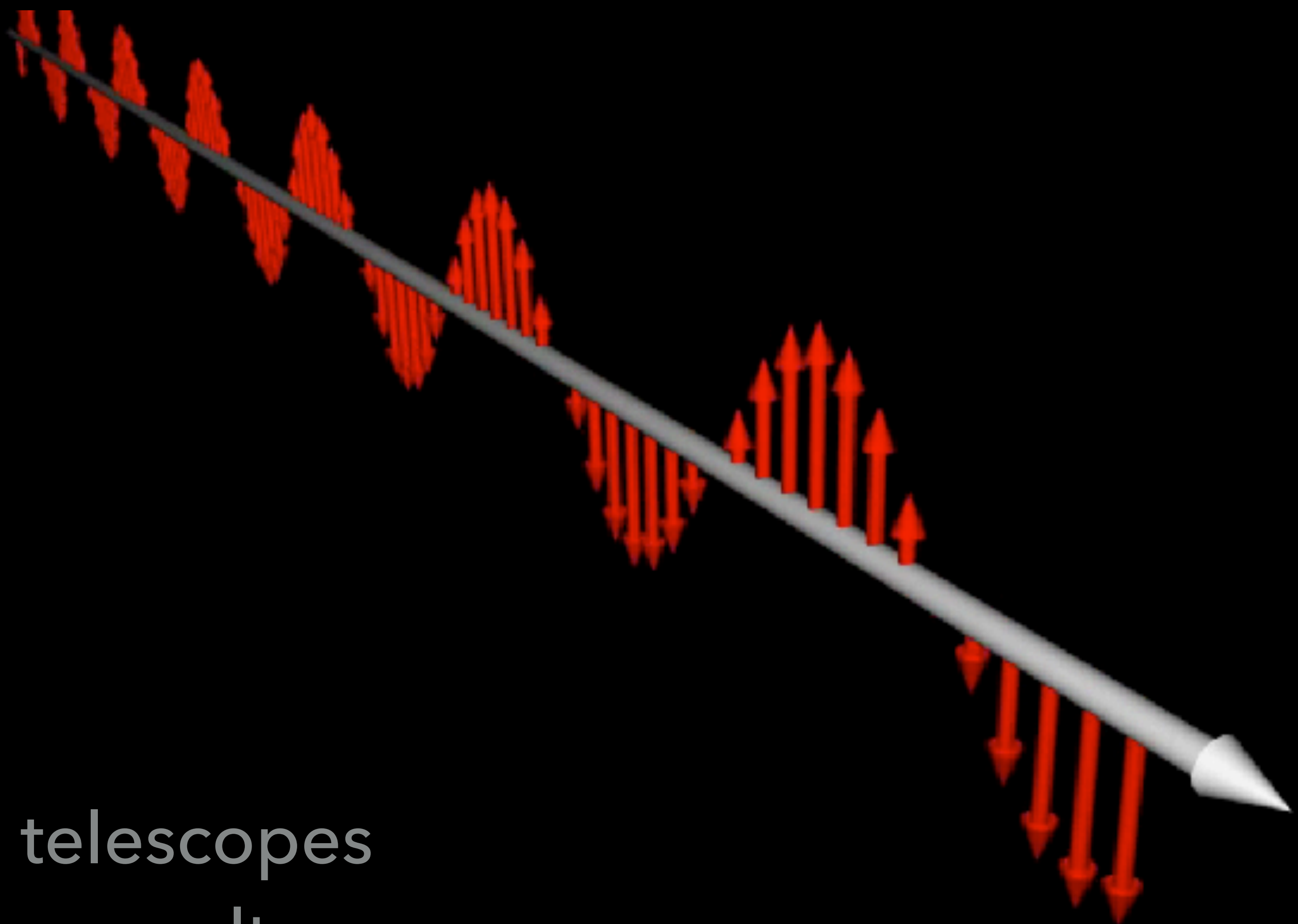
(GENTLE) INTRODUCTION TO INTERFEROMETRY

Animation by FilmSense



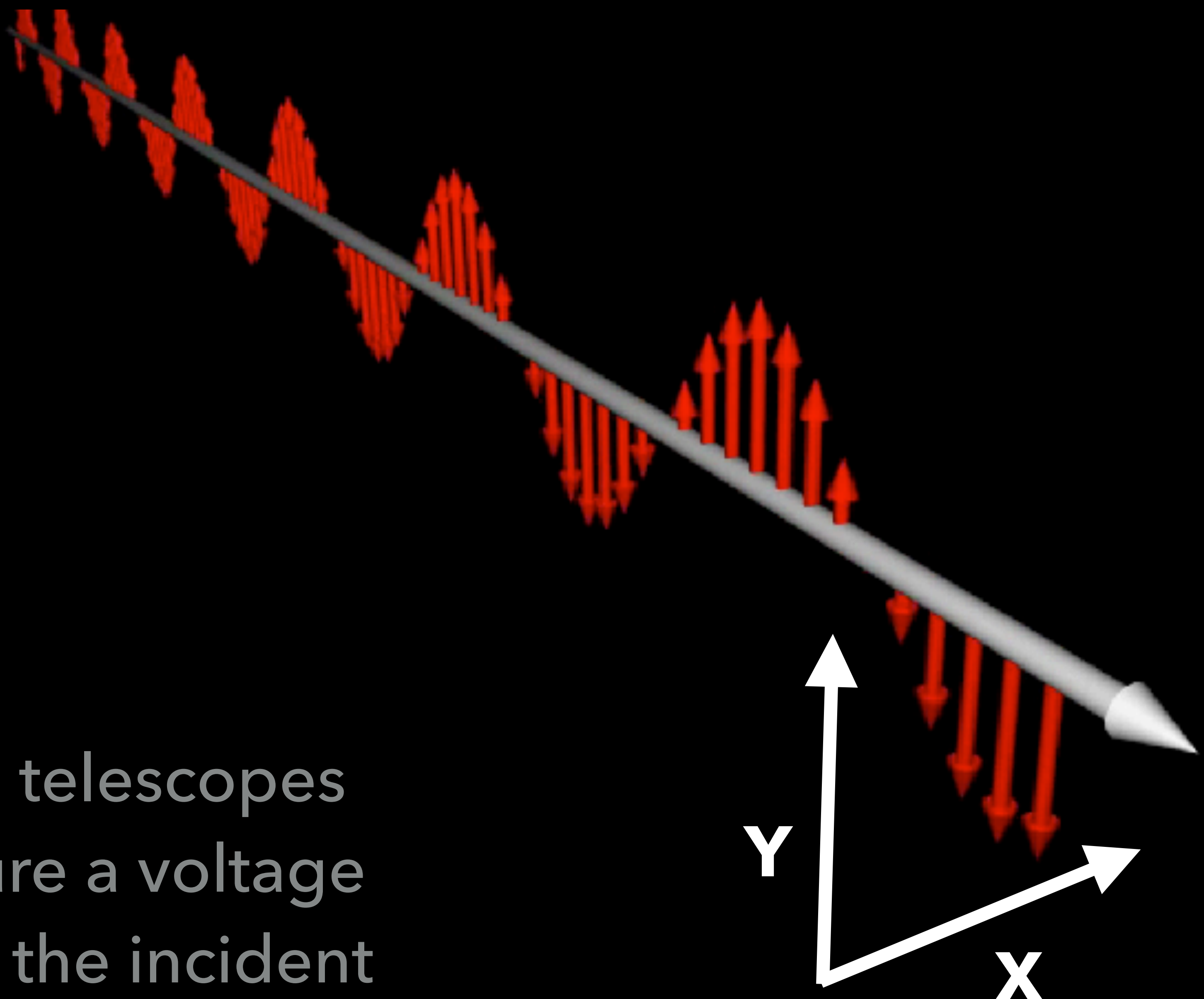
Radio telescopes measure a voltage due to the incident EM radiation

Animation by FilmSense



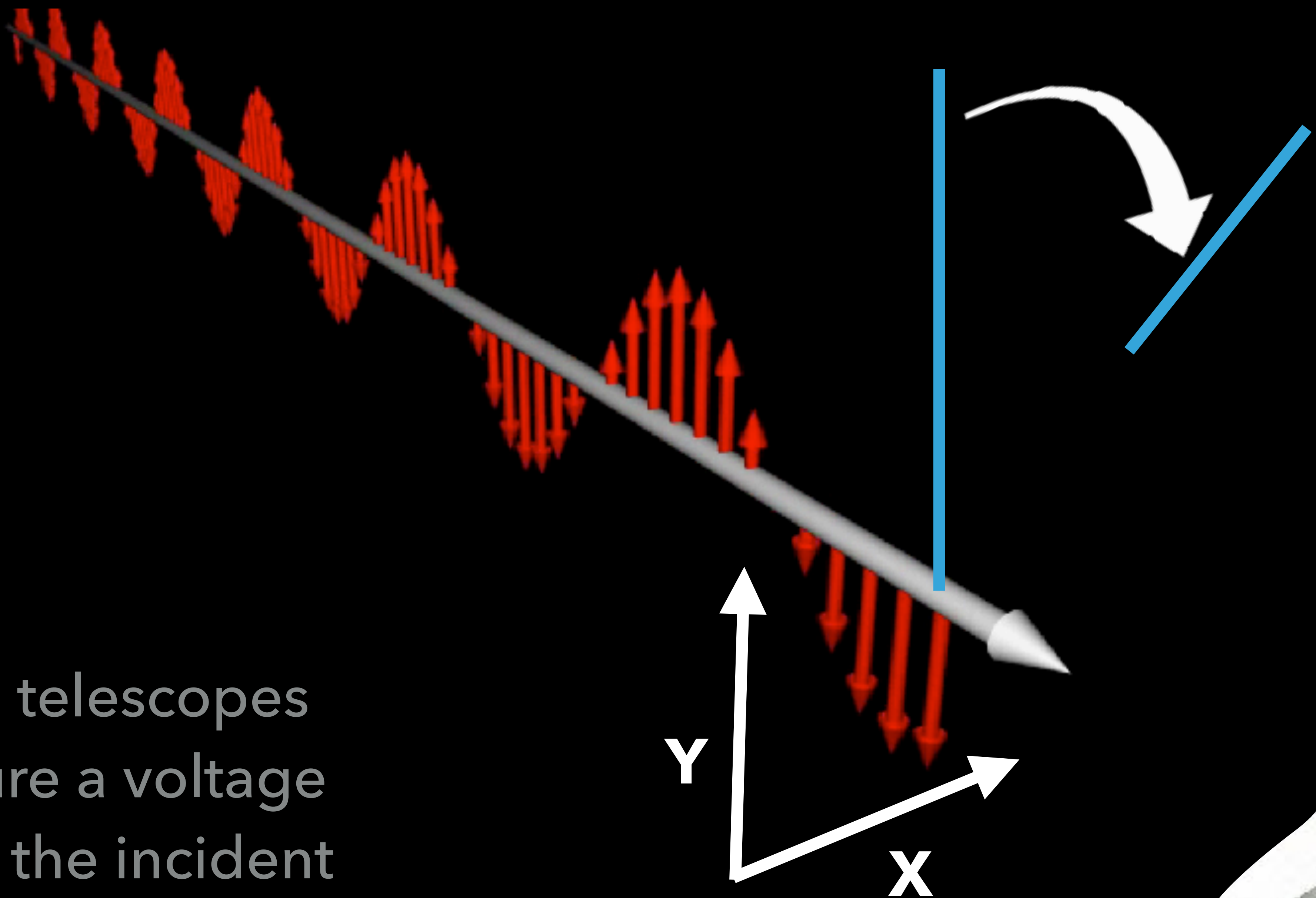
Radio telescopes measure a voltage due to the incident EM radiation

Animation by FilmSense

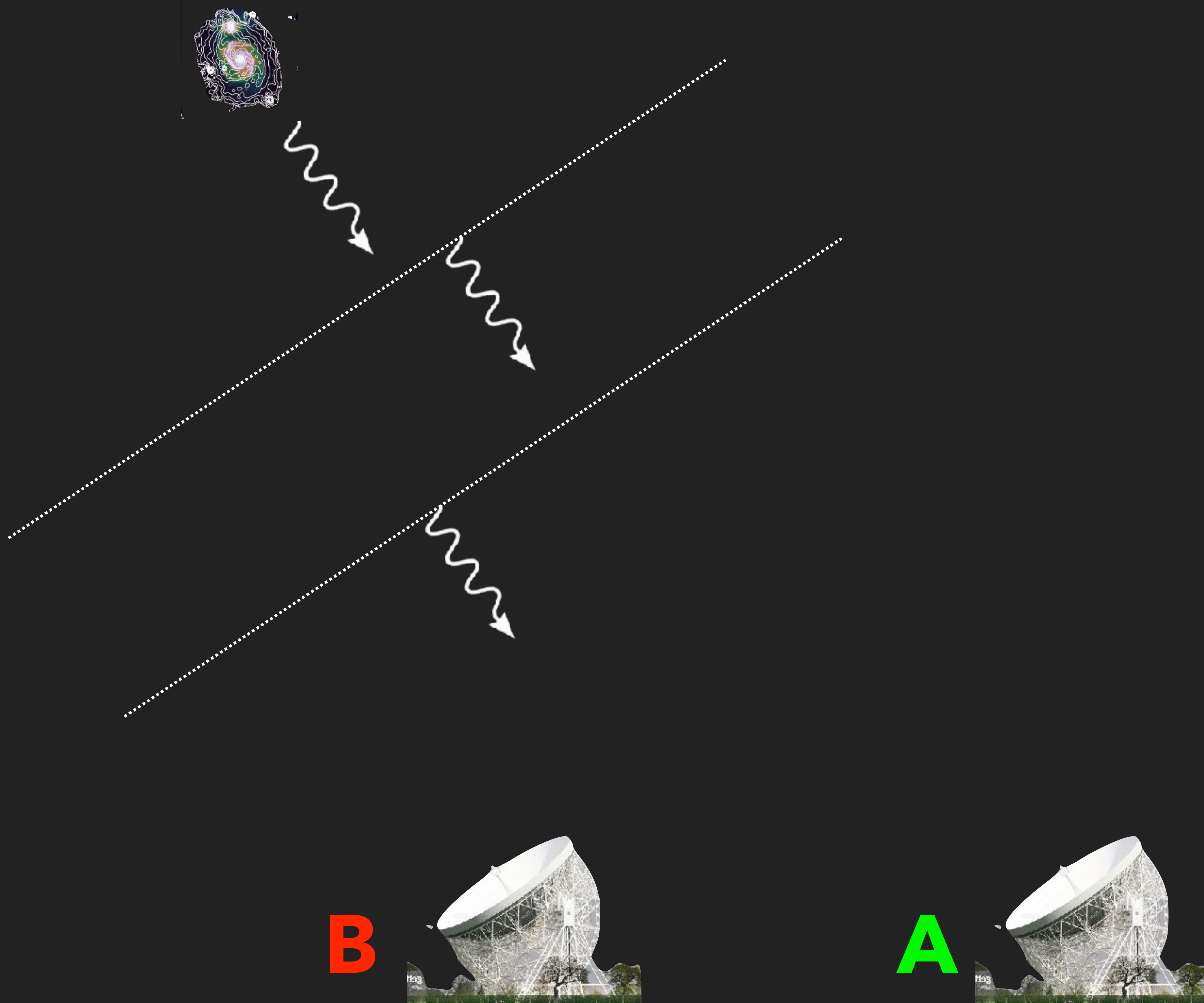


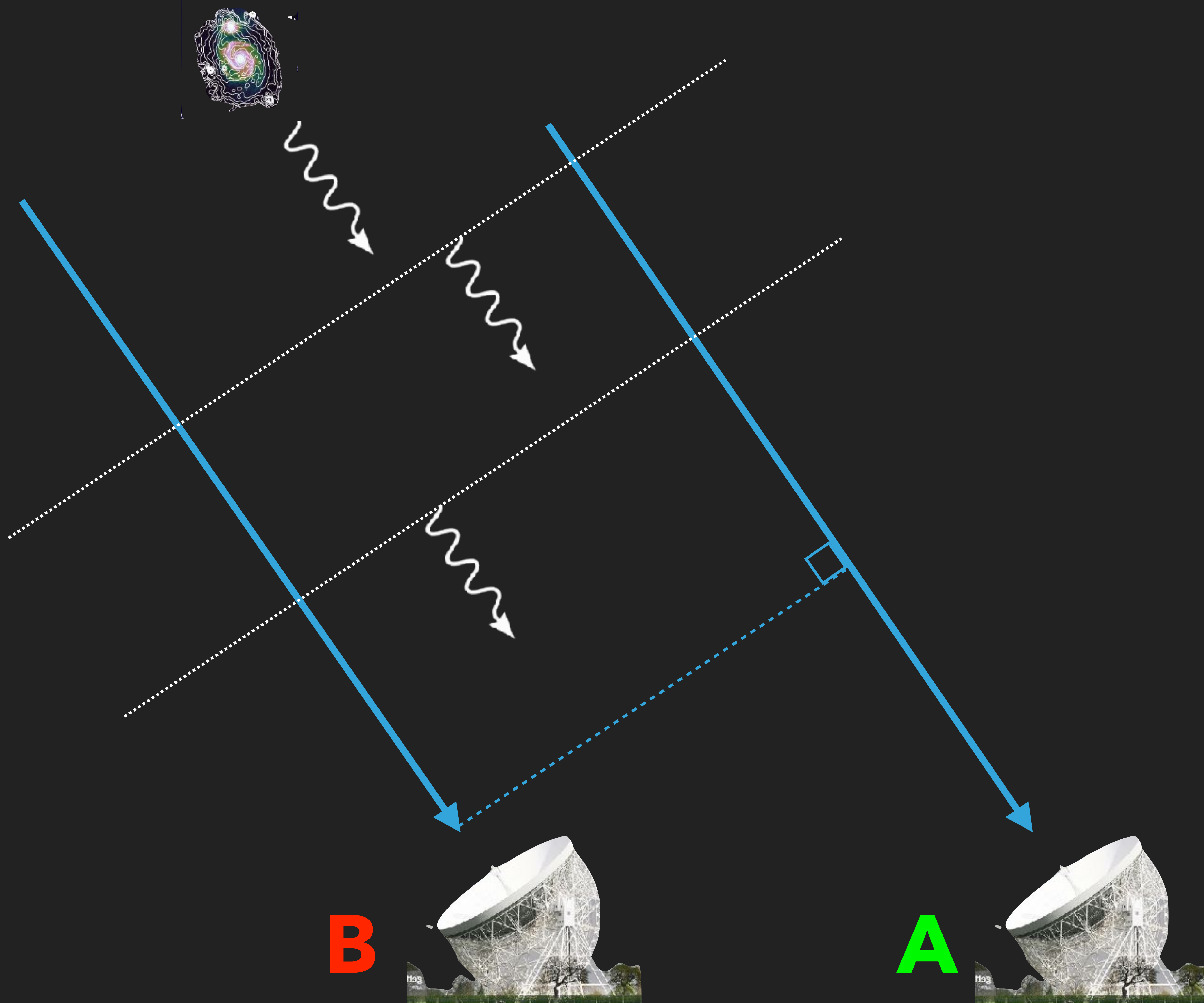
Radio telescopes measure a voltage due to the incident EM radiation

Animation by

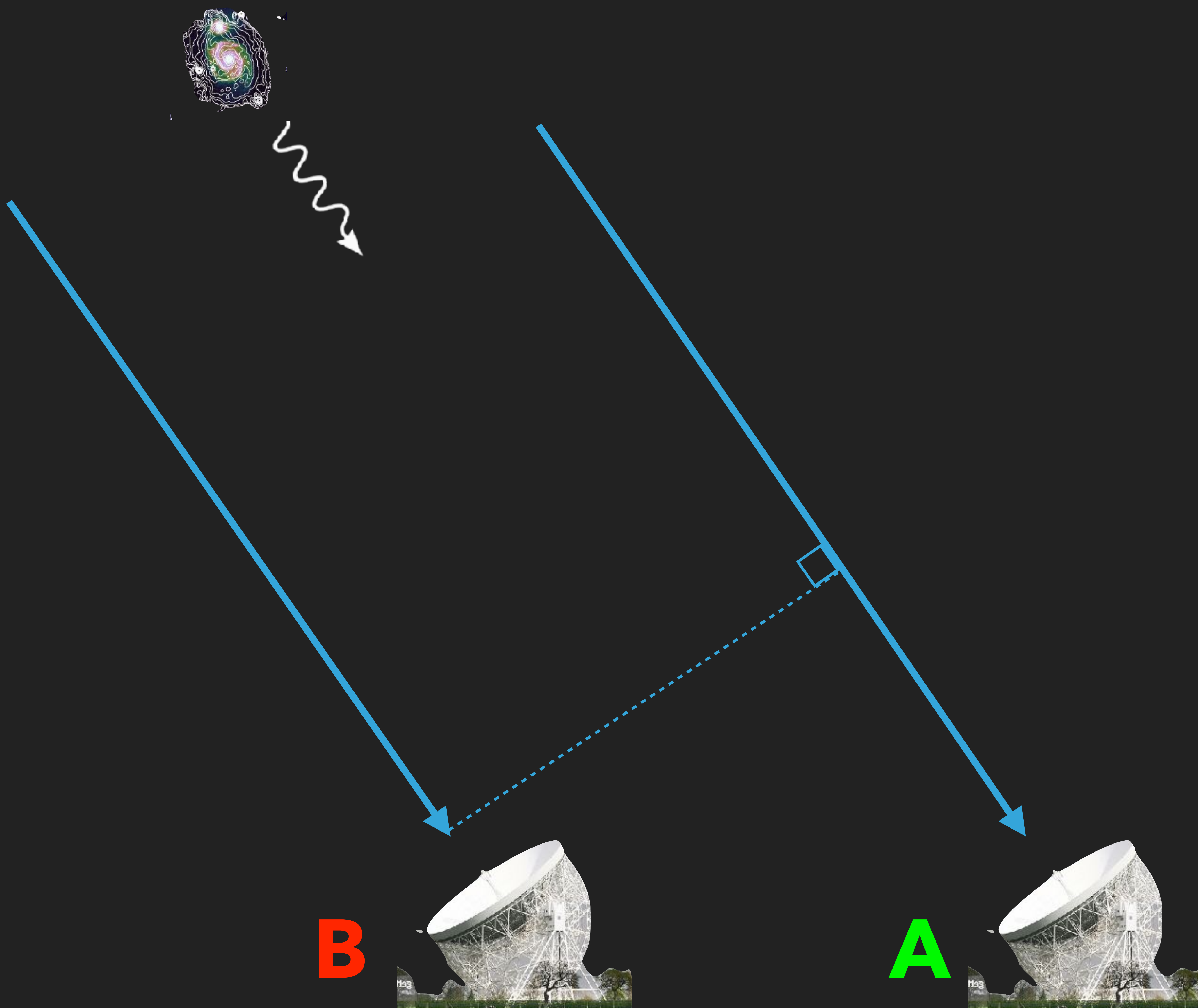


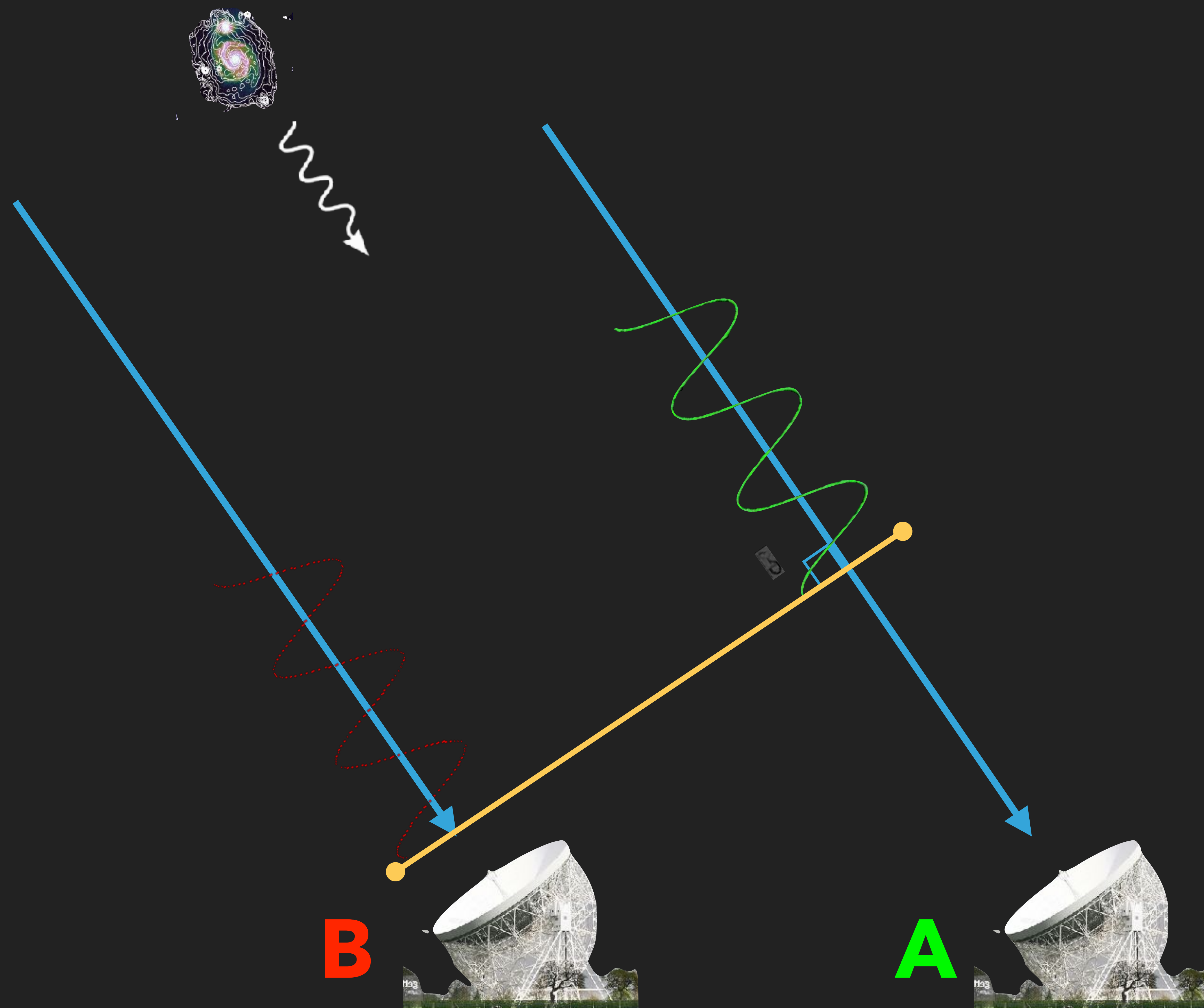
Radio telescopes measure a voltage due to the incident EM radiation

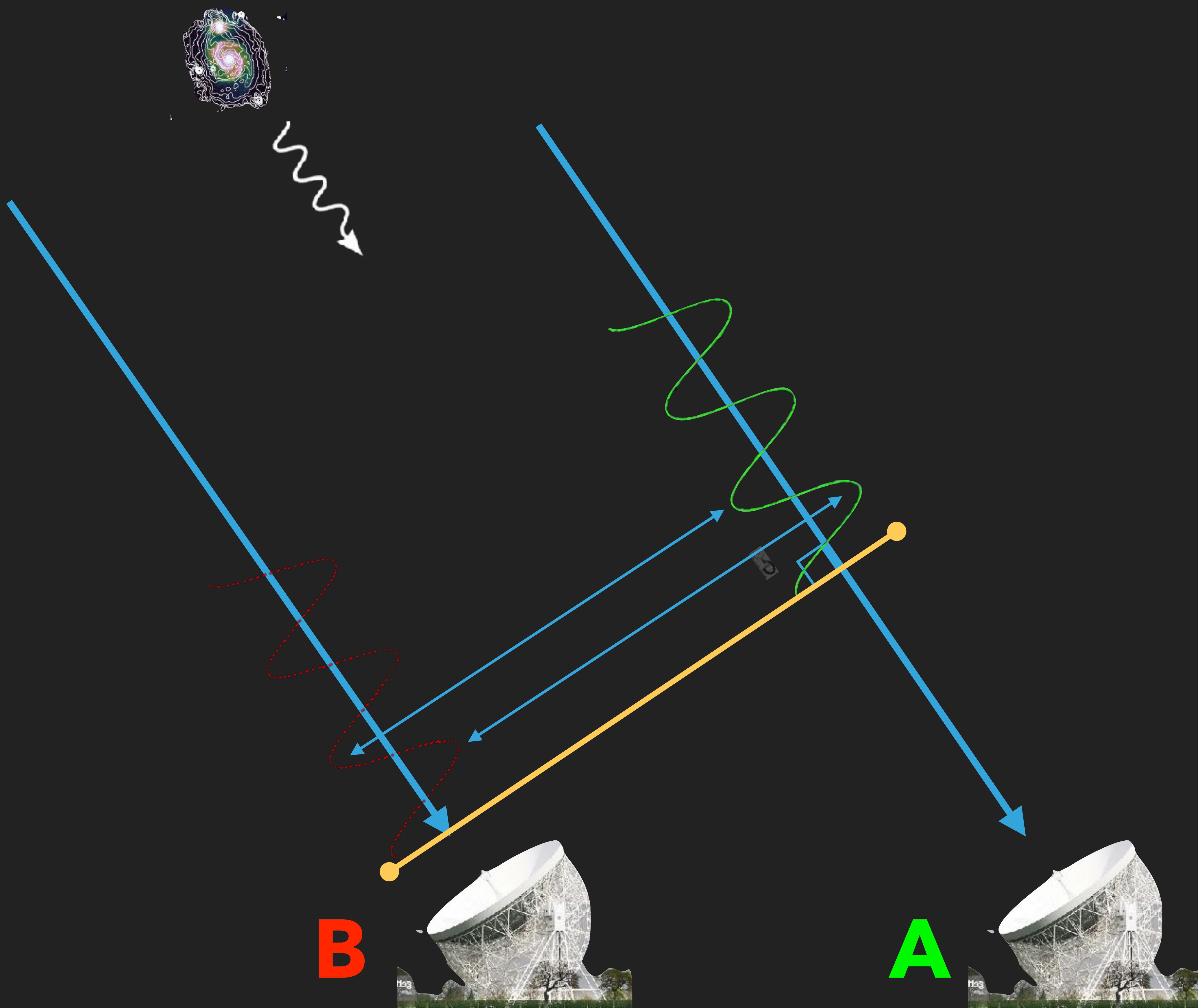

B
A

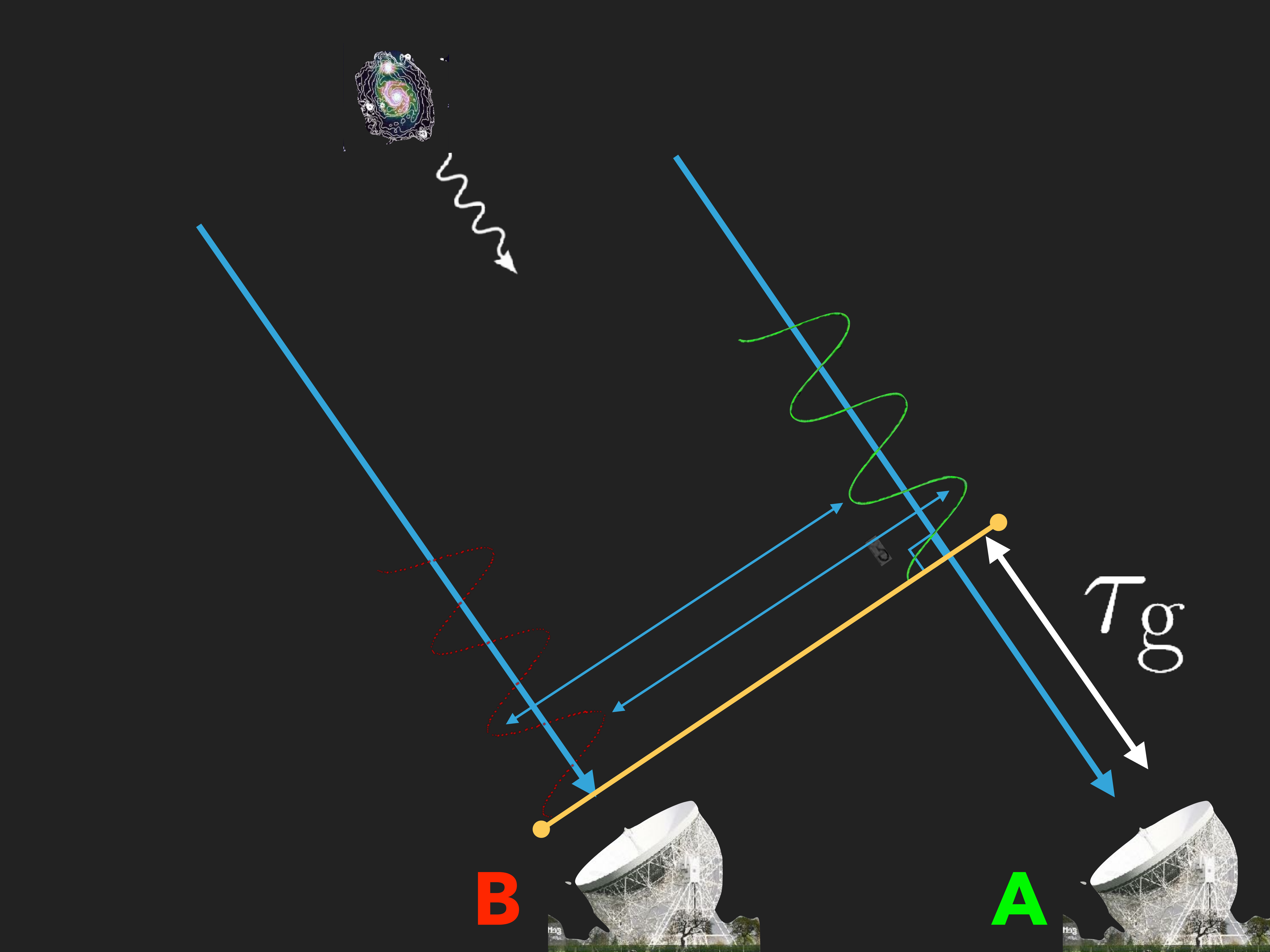


B
A


B
A

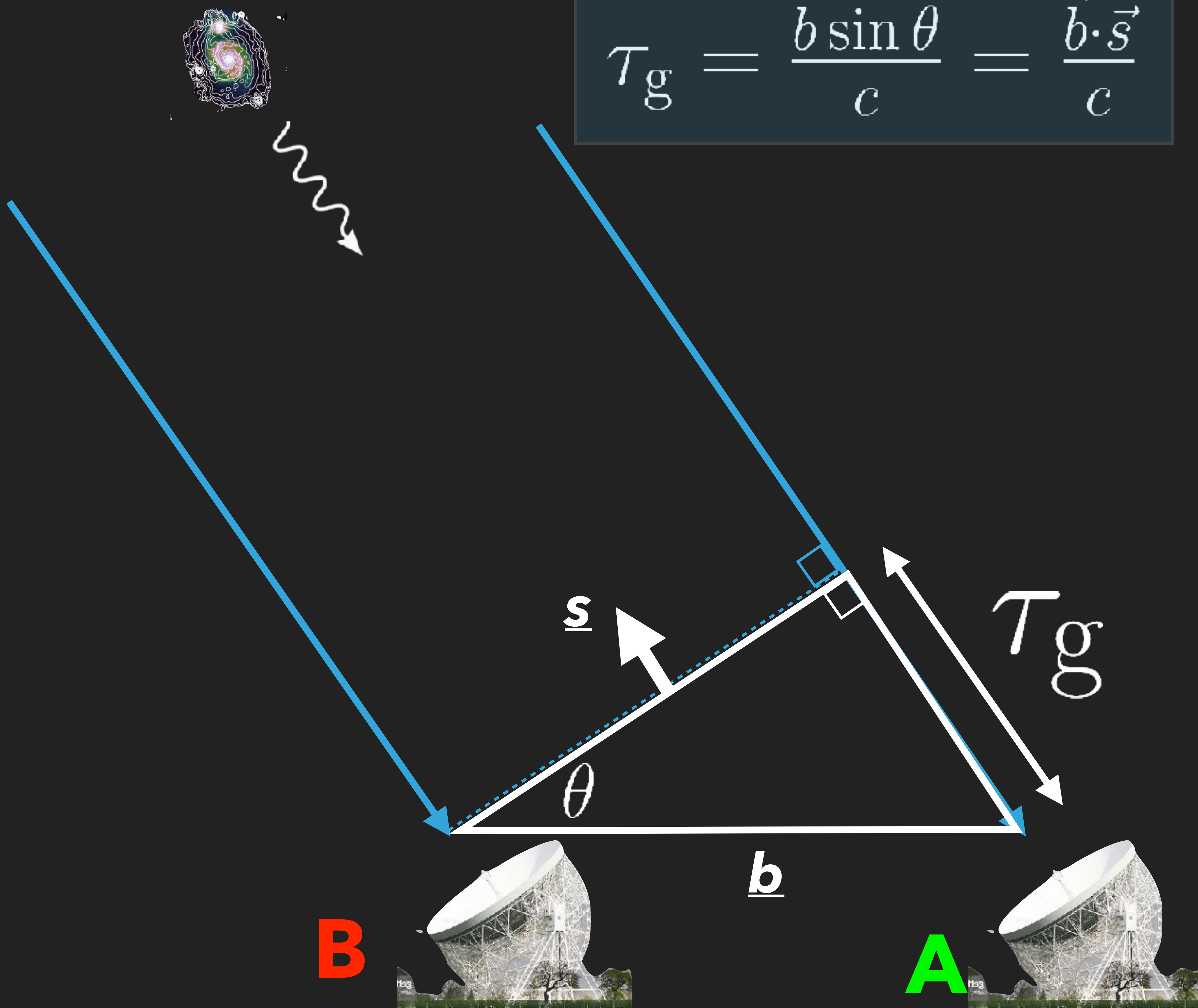

B
A

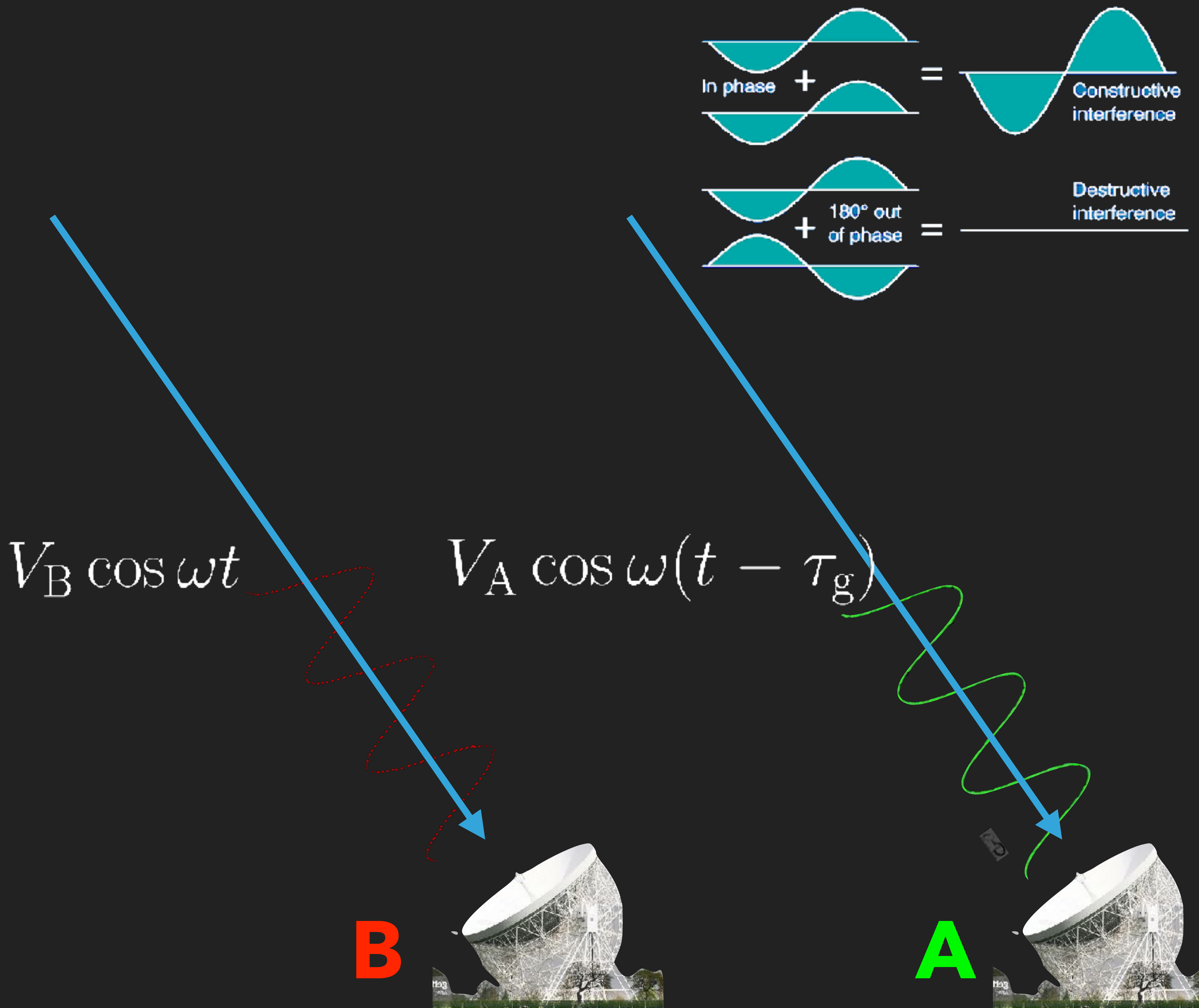

B
A

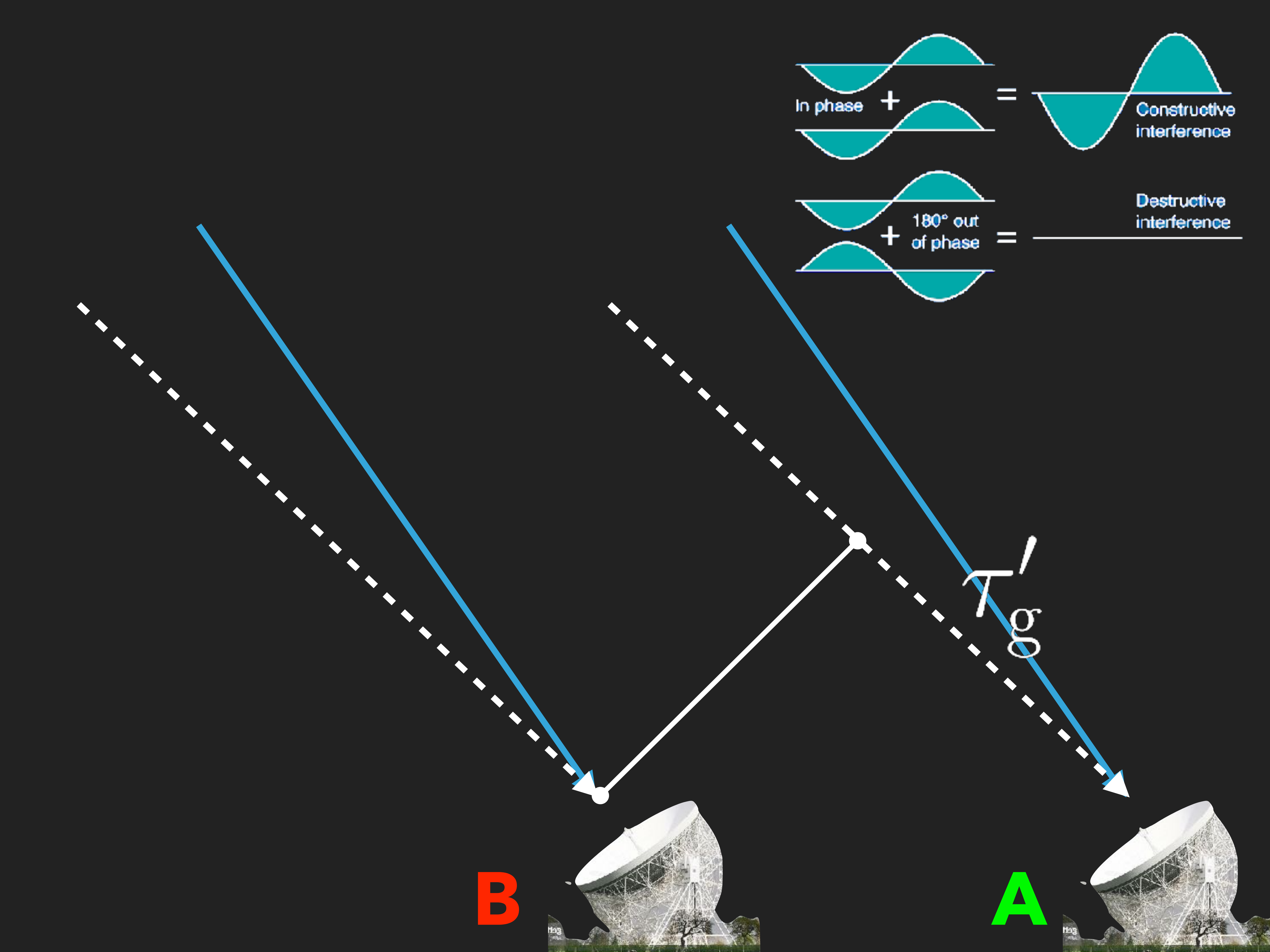


τ_g
B
A

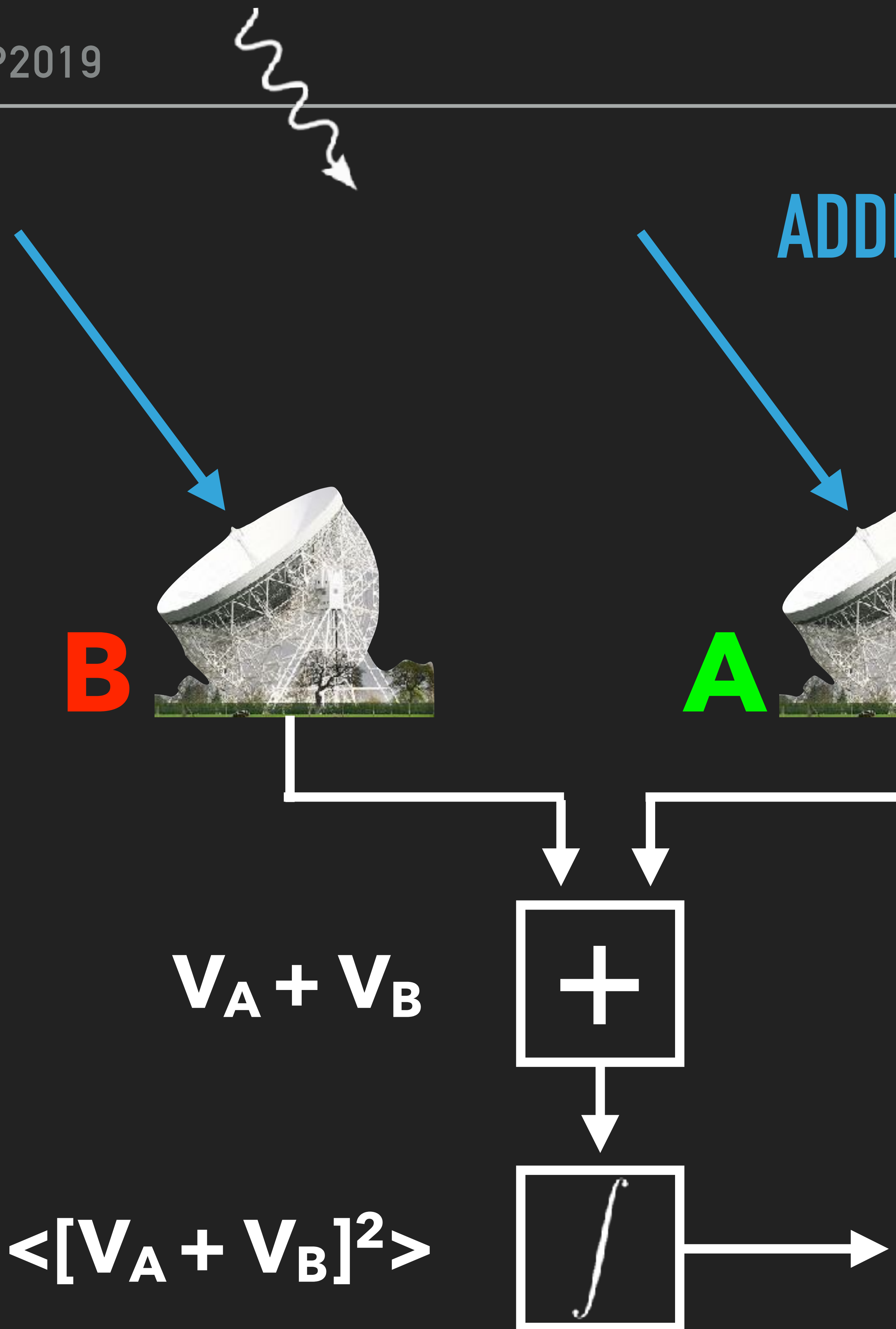
$$\tau_{\mathrm{g}} = \frac{b\sin\theta}{c} = \frac{\vec{b}\cdot\vec{s}}{c}$$




In phase
Constructive interference
180° out of phase
Destructive interference
$V_B \cos \omega t$
$V_A \cos \omega (t - \tau_g)$
B
A


In phase
Constructive interference
180° out of phase
Destructive interference
τ_g'
B
A

ADDING INTERFEROMETER



ADDING INTERFEROMETER

$$R \propto \langle [V_\mathrm{A} \cos \omega(t - \tau_\mathrm{g}) + V_\mathrm{B} \cos(\omega t) + V_\mathrm{rec,A} + V_\mathrm{rec,B}]^2 \rangle$$

$$R \propto \frac{1}{2} \langle [V_\mathrm{A}^2 + V_\mathrm{B}^2] + [V_\mathrm{rec,A}^2 + V_\mathrm{rec,B}^2] + [V_\mathrm{A} V_\mathrm{B} \cos(\omega \tau_\mathrm{g})] \rangle$$

1

Antenna noise powers
- usually small

2

Receiver noise powers -
usually dominate

3

Interference fringes vary with τ_g

s: <u>time dependent</u>

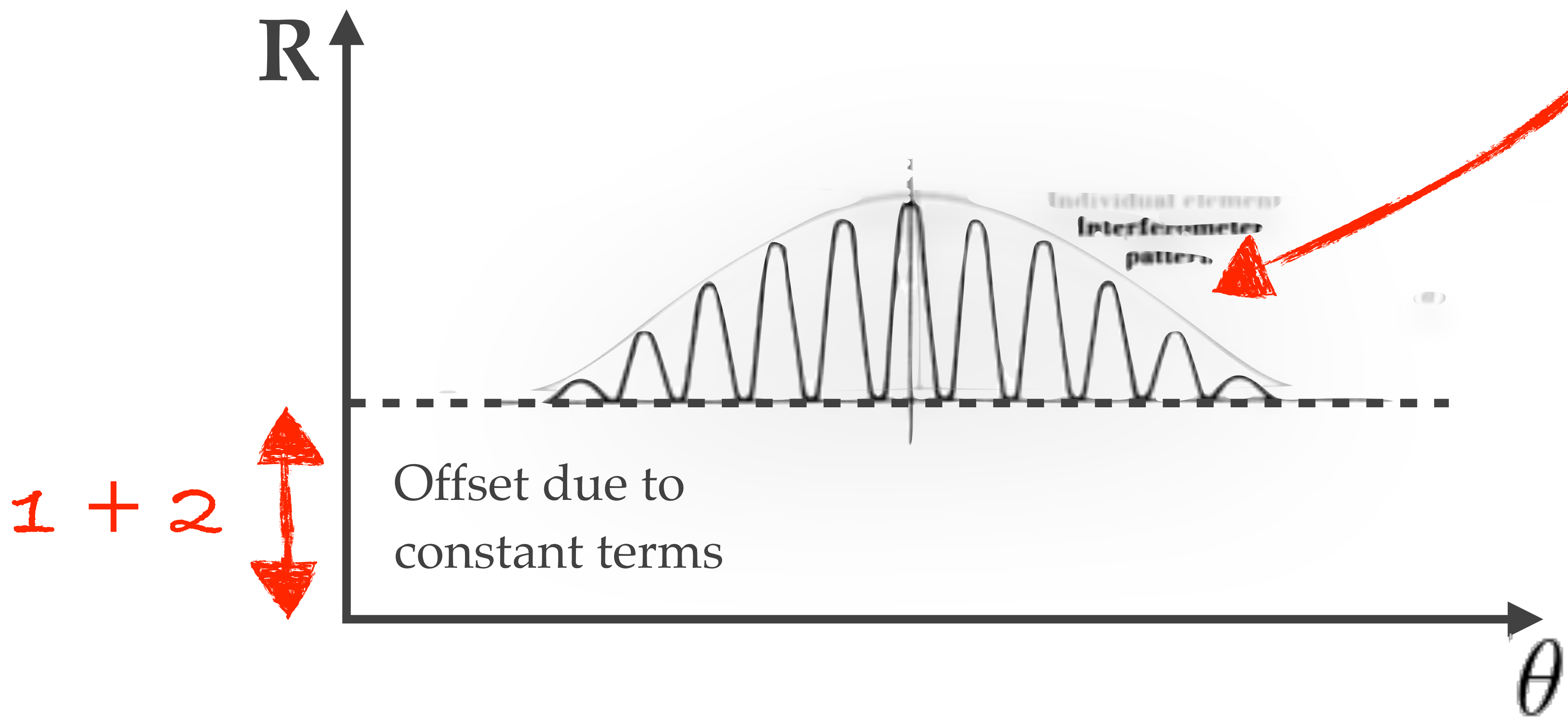
b: fixed geometric distance

$$\tau_{\mathrm{g}} = \frac{b\sin\theta}{c} = \frac{\vec{b}\cdot\vec{s}}{c}$$

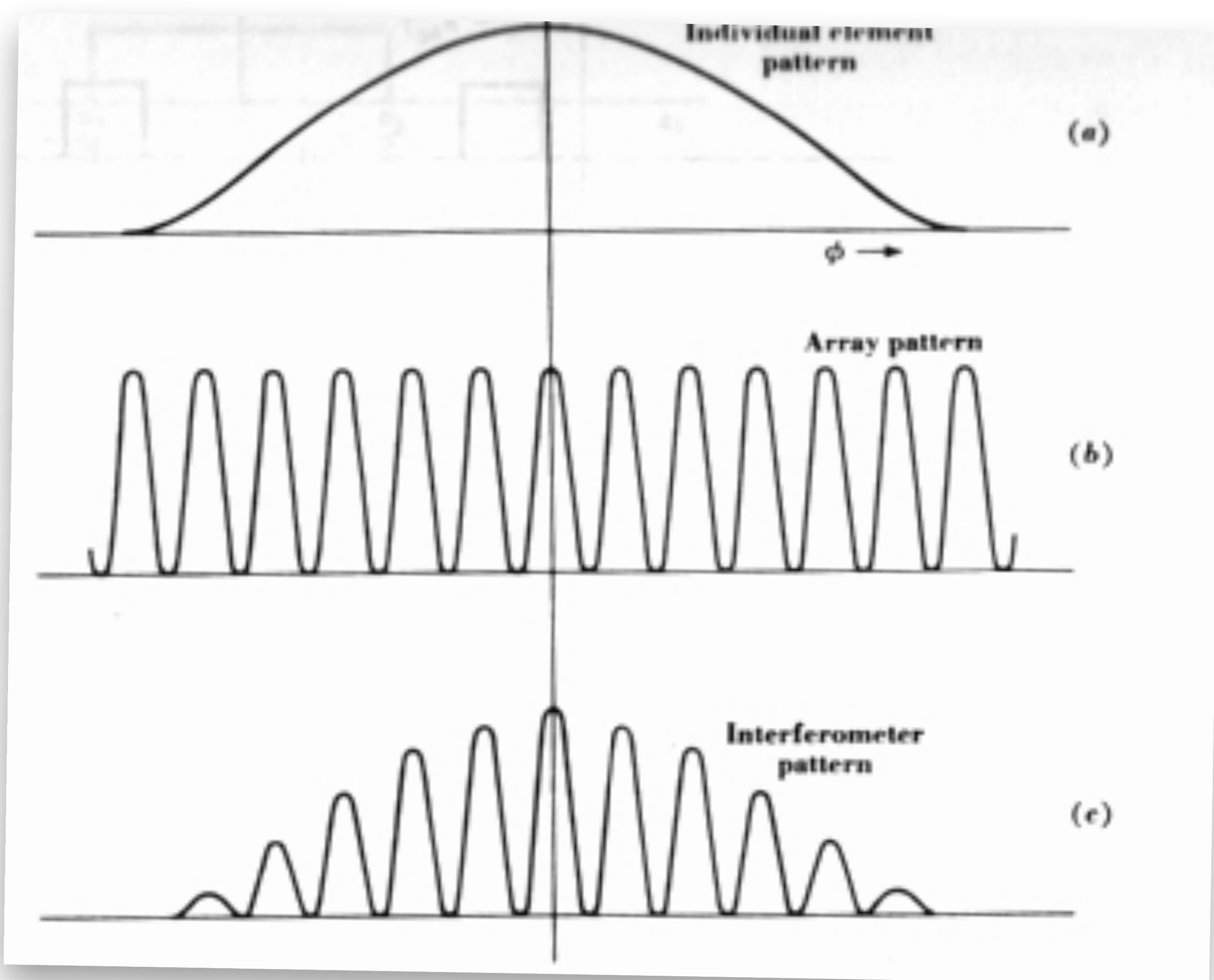
c: constant velocity

ADDING INTERFEROMETER

$$R \propto \frac{1}{2}\langle \underbrace{[V_{\mathrm{A}}^2 + V_{\mathrm{B}}^2]}_{1} + \underbrace{[V_{\mathrm{rec,A}}^2 + V_{\mathrm{rec,B}}^2]}_{2} + \underbrace{[V_{\mathrm{A}} V_{\mathrm{B}} \cos(\omega \tau_{\mathrm{g}})]}_{3} \rangle$$



ADDING INTERFEROMETER

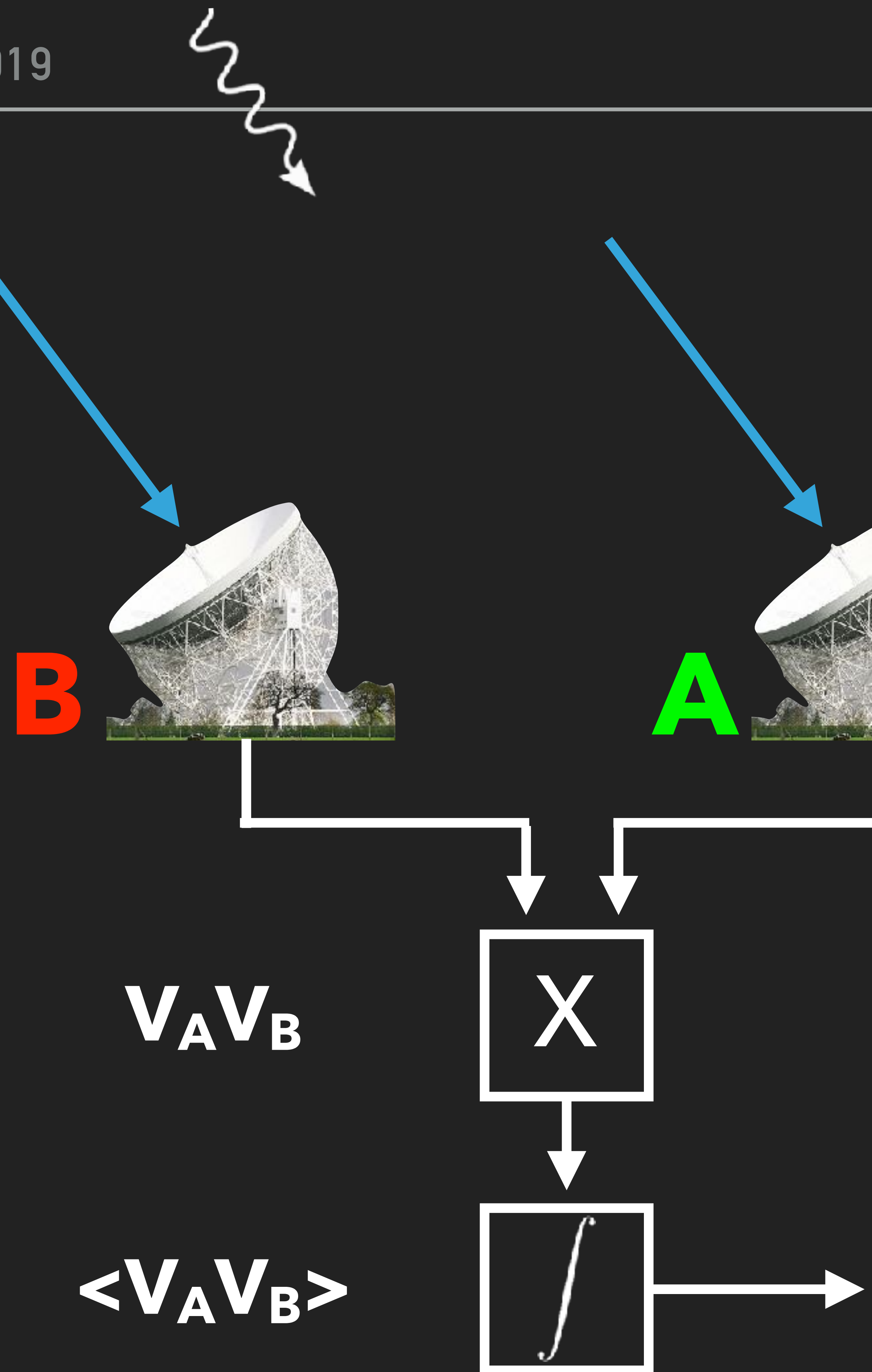


Envelope due to primary beam $\frac{\lambda}{D}$

Fringes due to interference pattern $\frac{\lambda}{b}$

Combination

MULTIPLYING INTERFEROMETER

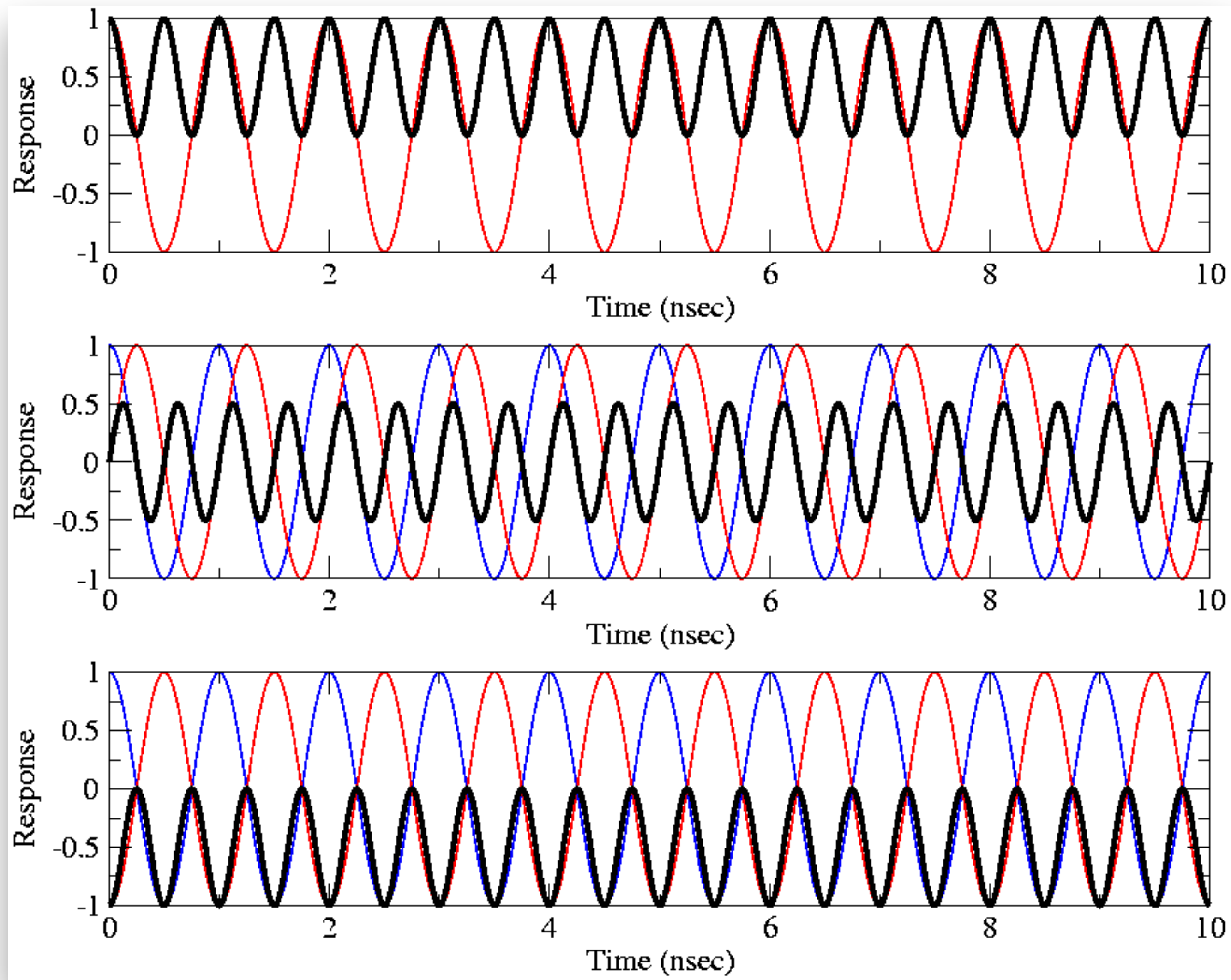


MULTIPYING INTERFEROMETER

IN PHASE

QUADRATURE PHASE

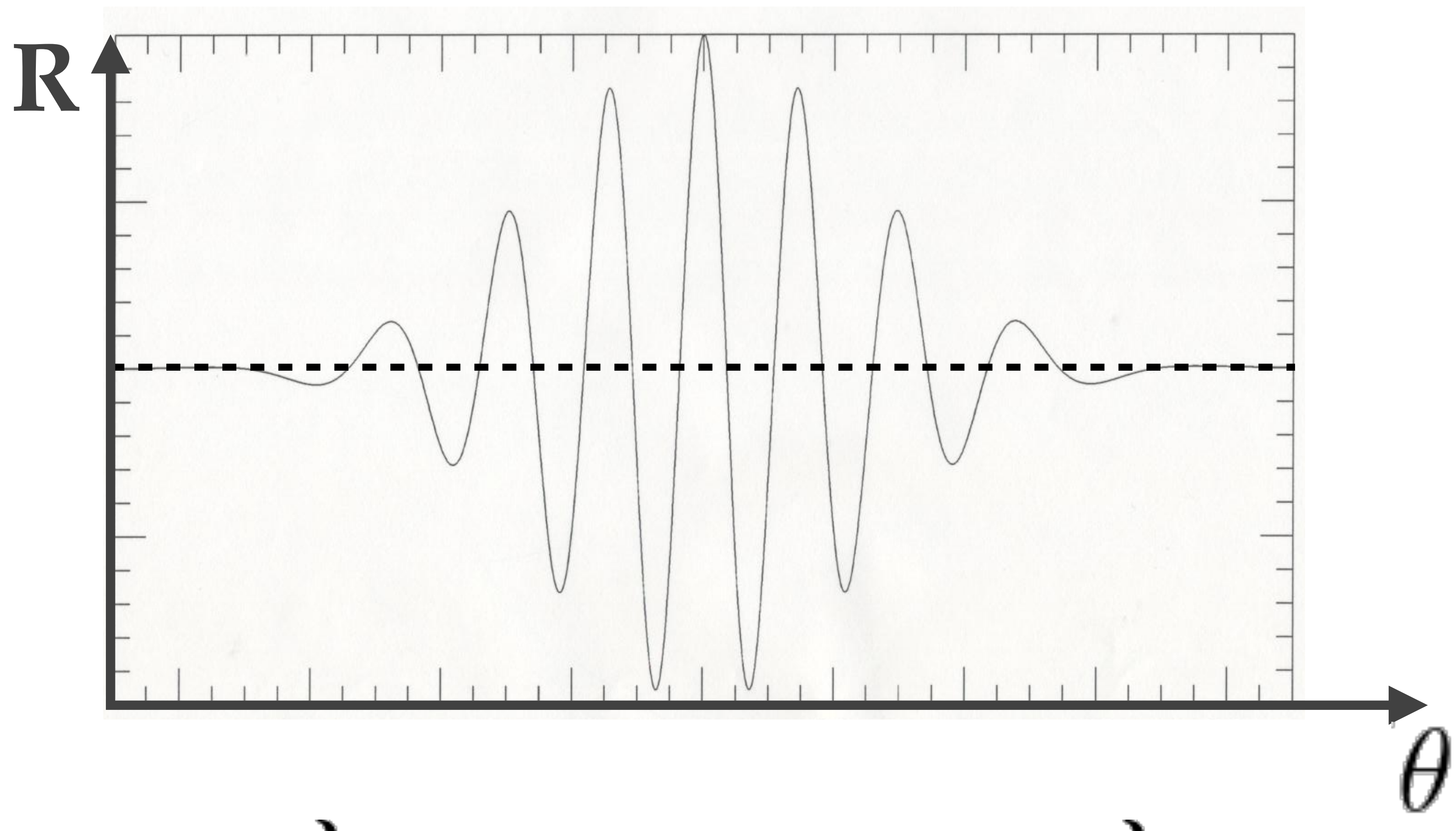
OUT OF PHASE



$$\tau_g = \frac{b \sin\theta}{c} = \frac{\vec{b}\cdot\vec{s}}{c}$$

MULTIPLYING INTERFEROMETER

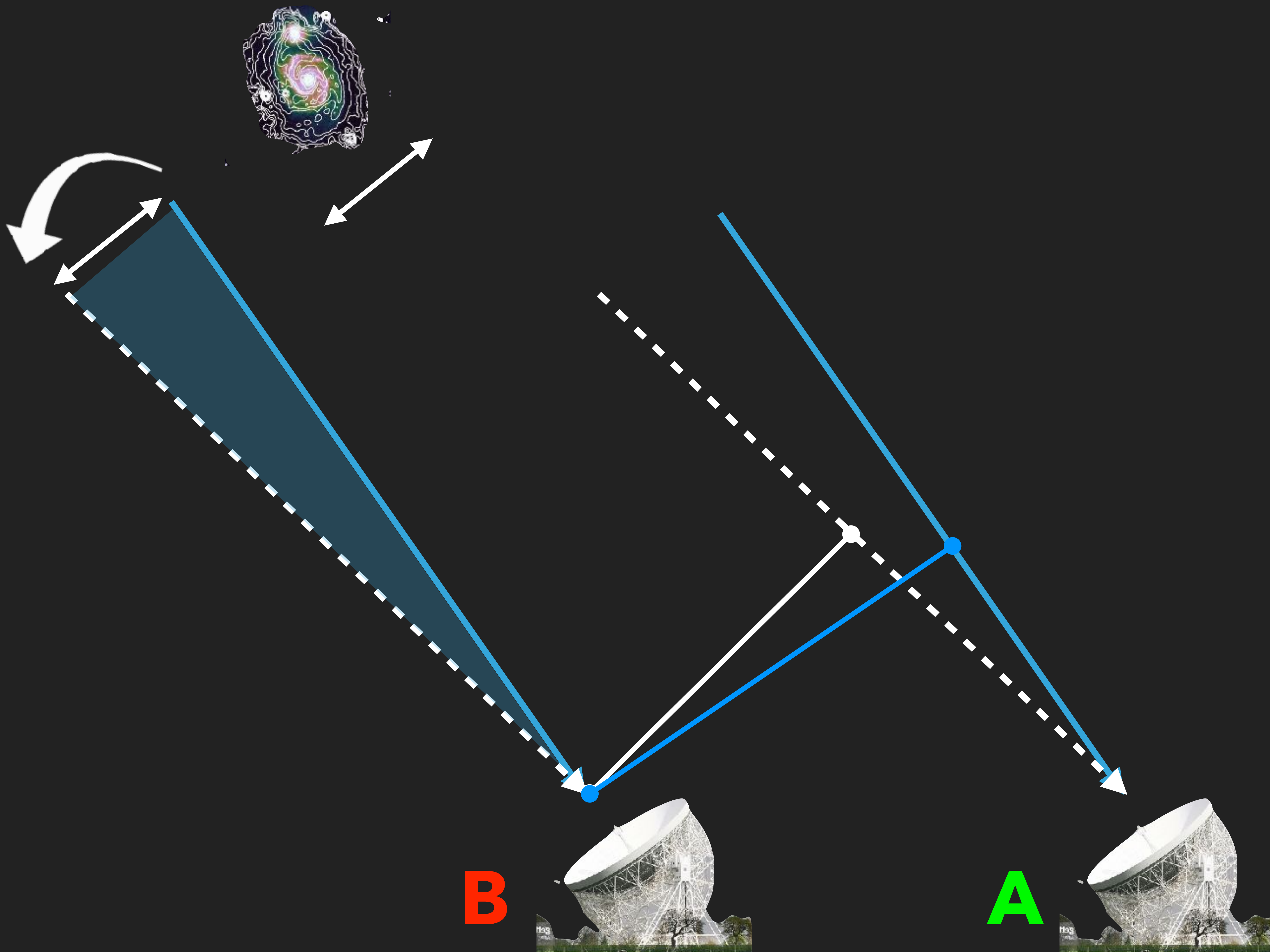
$$R \propto \langle V_A \cos\omega(t-\tau_g)\cdot V_B \cos\omega t\rangle = \tfrac{1}{2}V_A V_B \cos\tau_g$$



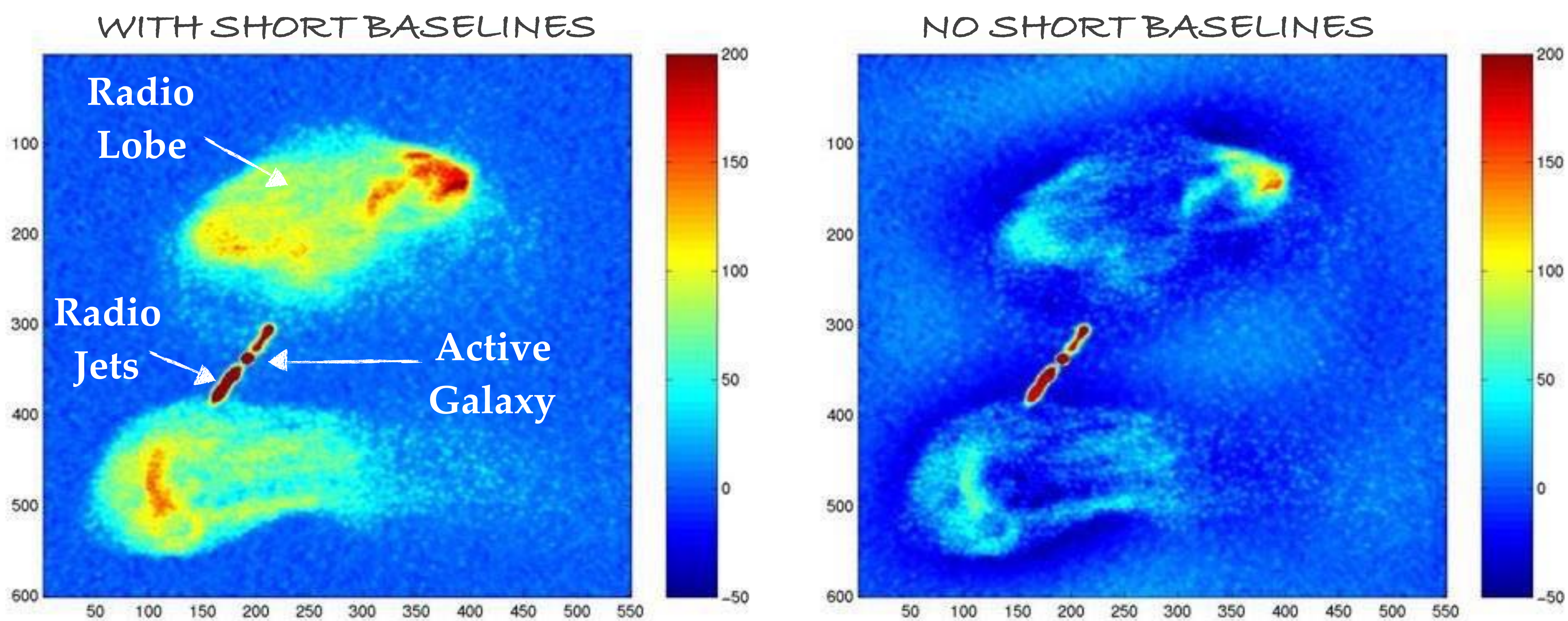
primary beam envelope: $\dfrac{\lambda}{D}$

fringe spacing: $\dfrac{\lambda}{b}$

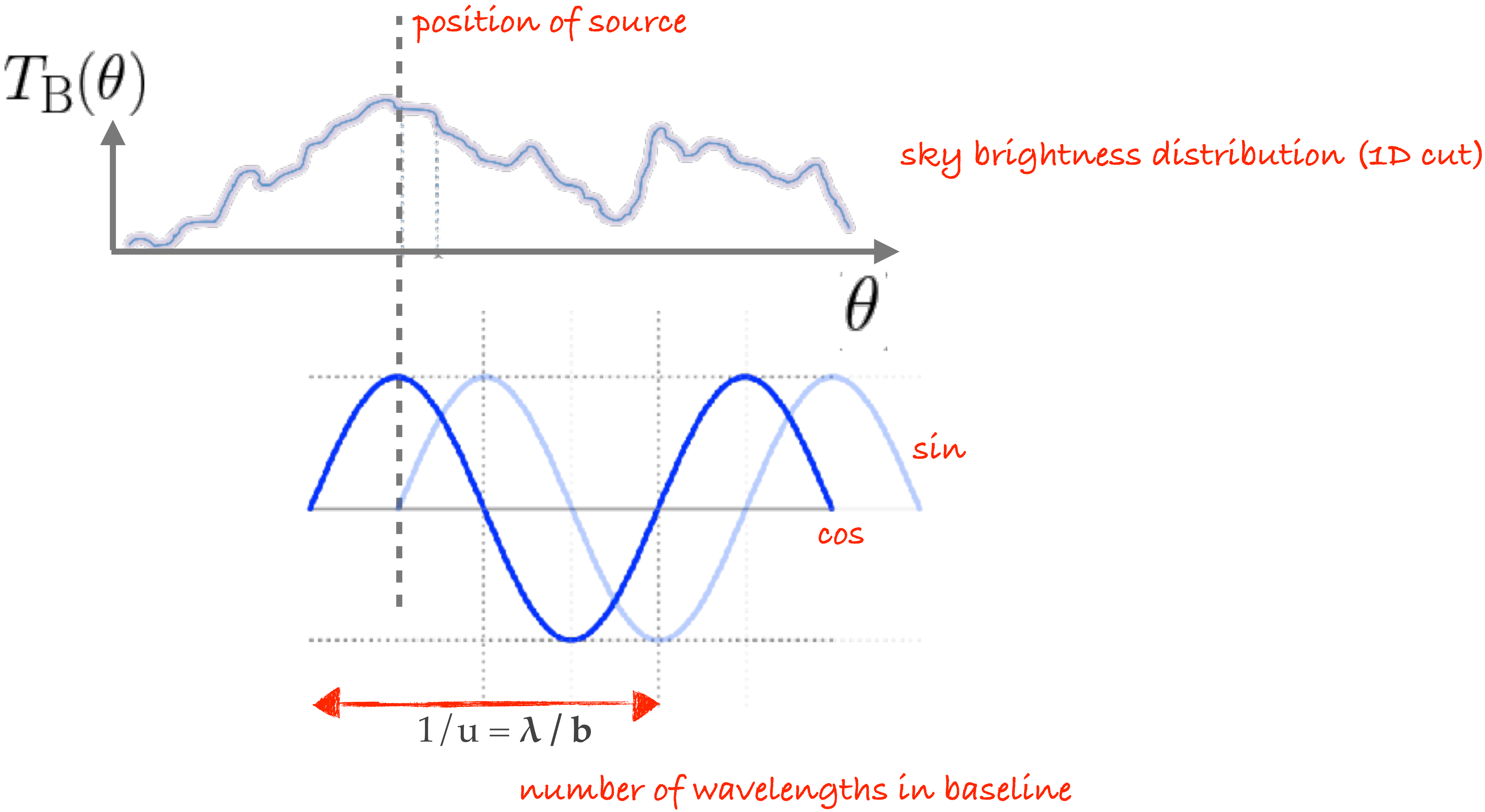
THE EFFECT OF BASELINE LENGTH


B
A

BASELINE LENGTH



Missing short baselines results in poor sensitivity to low brightness extended structure. Notice the negative "holes" (darker blue) underlying the bright structure.


position of source
$T_{\mathrm{B}}(\theta)$
sky brightness distribution (1D cut)
θ
sin
cos
$1/u = \lambda / b$
number of wavelengths in baseline

COMPLEX VISIBILITIES

In reality the response will be 2D, but in 1D for simplicity:

power out as a function of baseline

$$R_{\cos}(u) = \int_{\mathrm{src}} B(\theta) \cos(2\pi\, u\, \theta) \mathrm{d}\theta$$

$$R_{\sin}(u) = \int_{\mathrm{src}} B(\theta) \sin(2\pi\, u\, \theta) \mathrm{d}\theta$$

The sky brightness distribution is **not an even function**. If we want to reconstruct it from its Fourier components then we need **both the cos and sin terms**.

VAN CITTERT ZERNIKE FUNCTION

The (2-D) lateral coherence function of the radiation field in space is the Fourier Transform of the (2-D) brightness (or intensity) distribution of the source.

$$\langle V(x_1,t)V(x_2,t)\rangle = \int\int B(\theta,\phi)\mathrm{e}^{-2\pi i(u\theta+v\phi)}\mathrm{d}\theta\mathrm{d}\phi$$

$$u = \frac{(x_1 - x_2)}{\lambda} \qquad v = \frac{(y_1 - y_2)}{\lambda}$$

The Visibility Function is therefore another name for the spatial correlation function.

VISIBILITY

From these components we define the **complex fringe visibility** for a particular baseline:

$$Ae^{i\Psi}$$

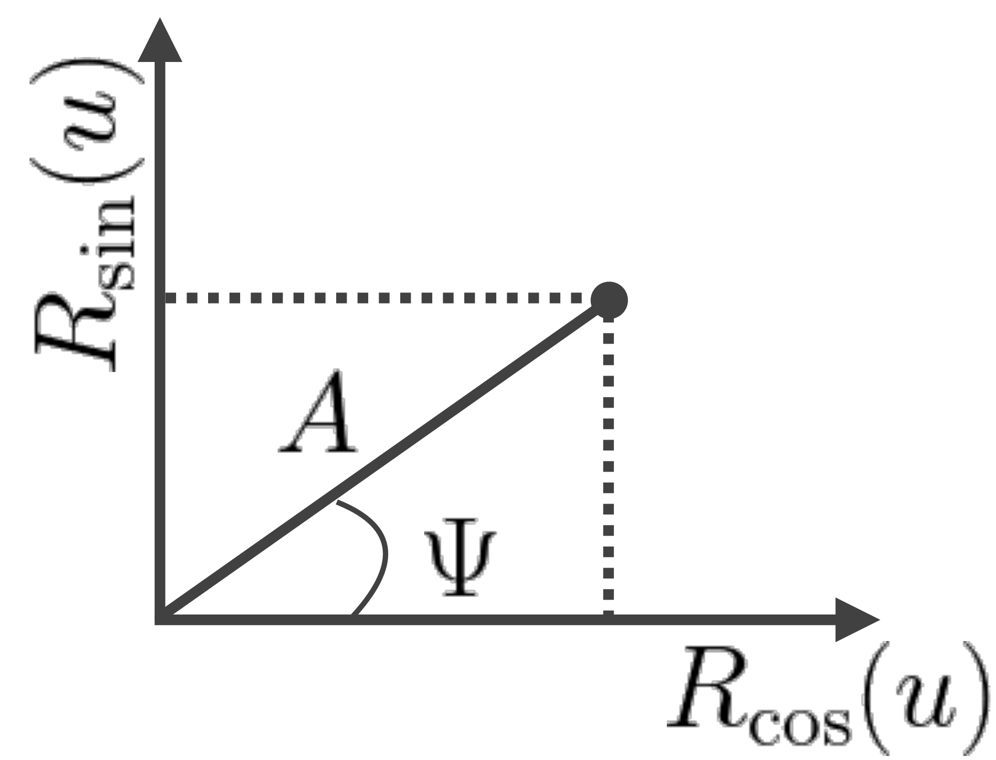
phase

$$\Psi = \tan^{-1}\left[\frac{R_{\sin}}{R_{\cos}}\right]$$

amplitude

$$A = \left[R_{\cos}^2 + R_{\sin}^2\right]^{1/2}$$

Ψ is the **shift** (in radians) of the Fourier component with respect to the reference position.



VISIBILITIES & IMAGES

$$I_{meas}(l,m) = \frac{1}{M}\sum_{i=1}^{M} V(u_i,v_i)e^{2\pi i(u_i l + v_i m)}$$

$$= \frac{1}{M}\sum_{i=1}^{M} V(u_i,v_i)\left[\cos[2\pi(u_i l + v_i m)] + i\sin[2\pi(u_i l + v_i m)]\right]$$

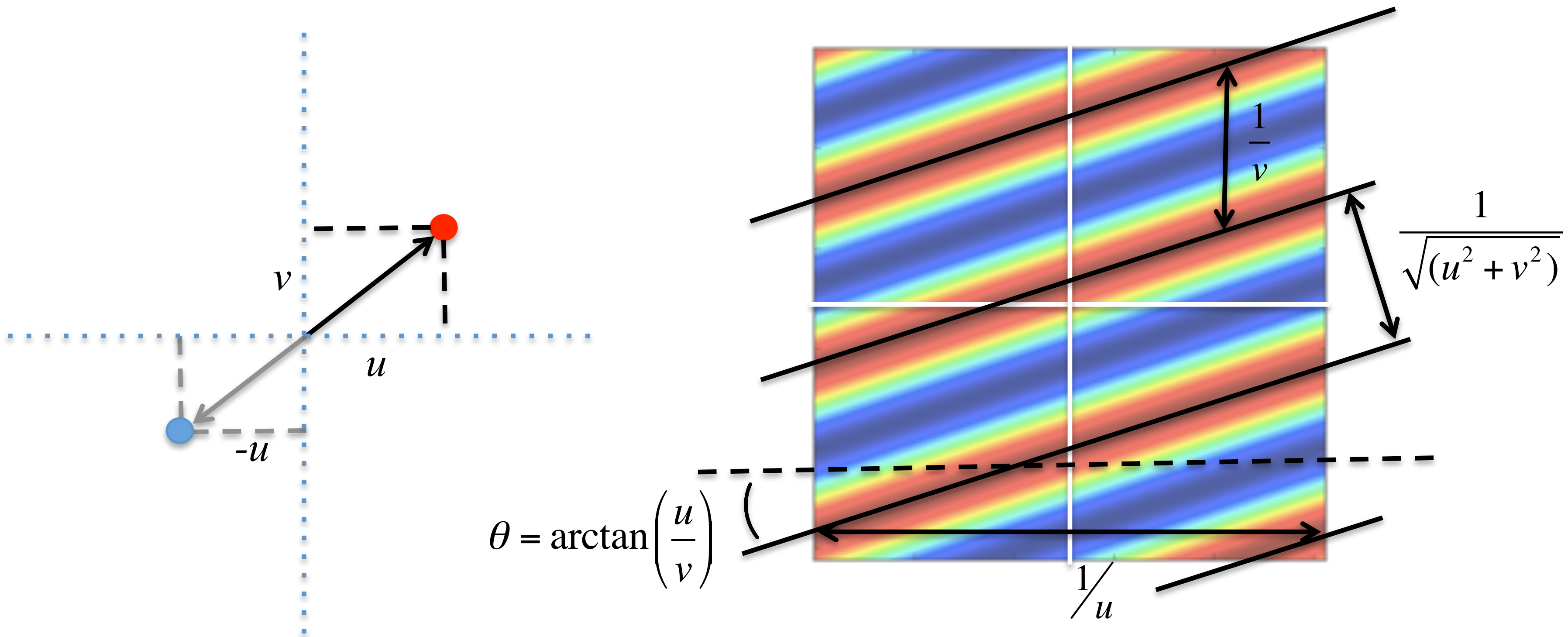
This is a **complex** quantity, but the sky intensity is **real**.

$$\boxed{V(-u,-v) = V^*(u,v)}$$

If we change our notation slightly, so that $V = Ae^{i\phi}$, we can write:

$$I_{meas}(l,m) = \frac{1}{M}\sum_{i=1}^{M} A(u_i,v_i)\cos[2\pi(u_i l + v_i m) + \phi_i]$$

FOURIER COMPONENTS



Writing the equation in this way allows us to visualise how our image is composed.

$$I_{meas}(l,m) = \frac{1}{M}\sum_{i=1}^{M} A(u_i,v_i)\cos[2\pi(u_i l + v_i m) + \phi_i]$$

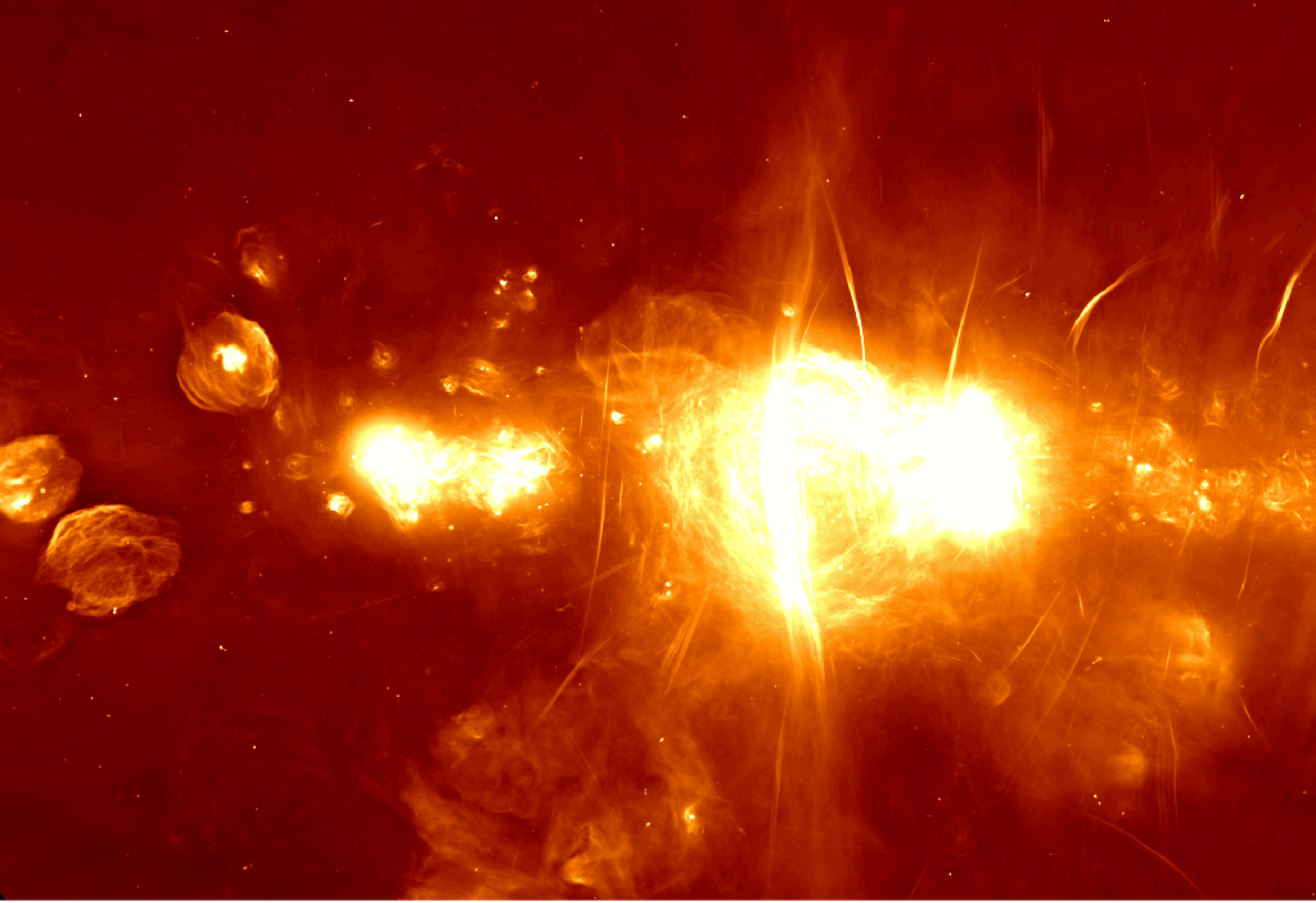


Image credit: South African Radio Astronomy Observatory

- The key to interferometry is the geometric delay;
- A 2-element adding interferometer is a direct analogue of Young's slits;
- The sky is not symmetric - we need both cosine & sine waves to make a picture of it;
- Interferometers measure complex visibilities, which are the Fourier components of the sky brightness.