

ANNA SCAIFE
JODRELL BANK CENTRE FOR ASTROPHYSICS
@RADASTRAT

THE SQUARE KILOMETRE ARRAY

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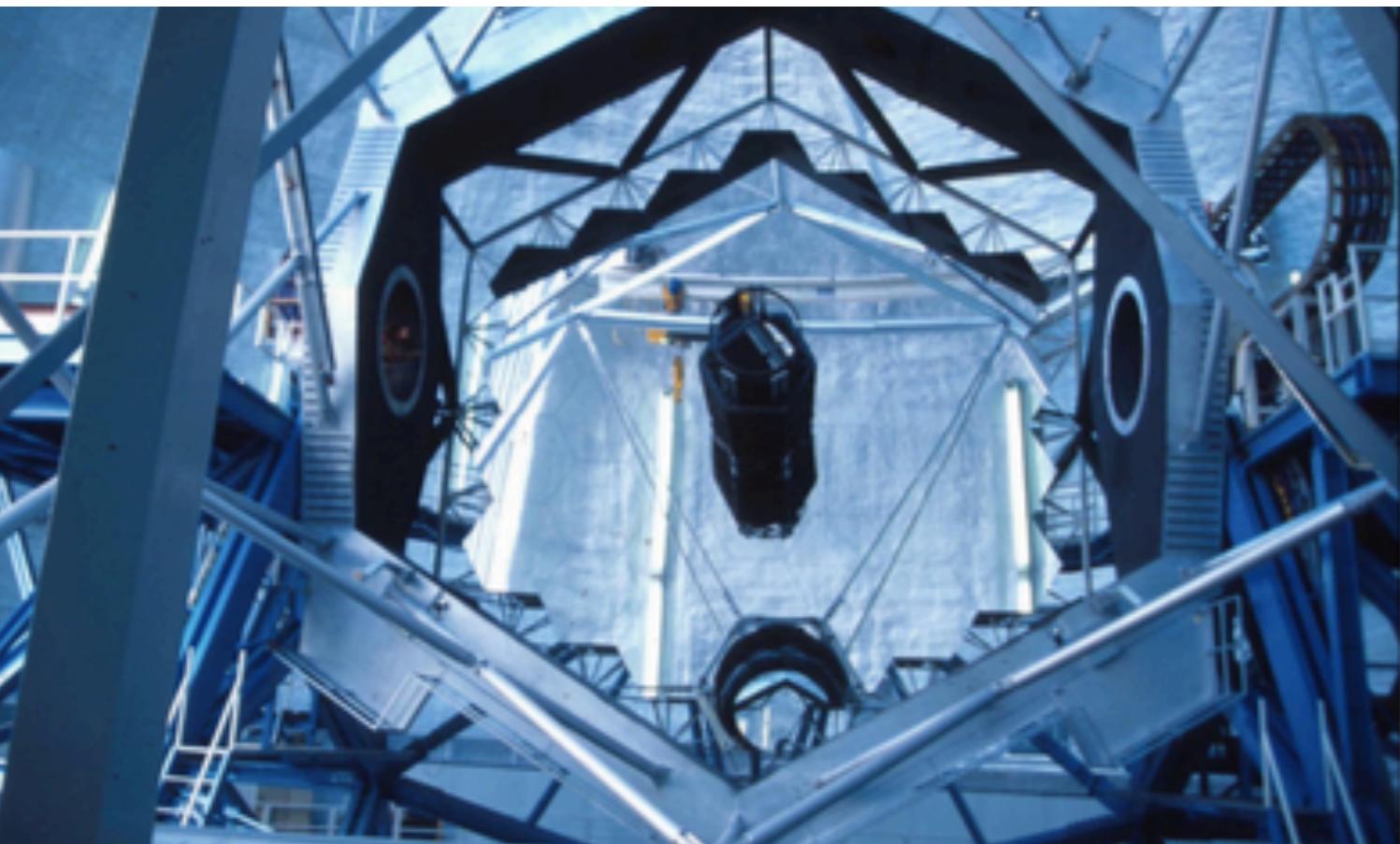
THE SQUARE KILOMETRE ARRAY



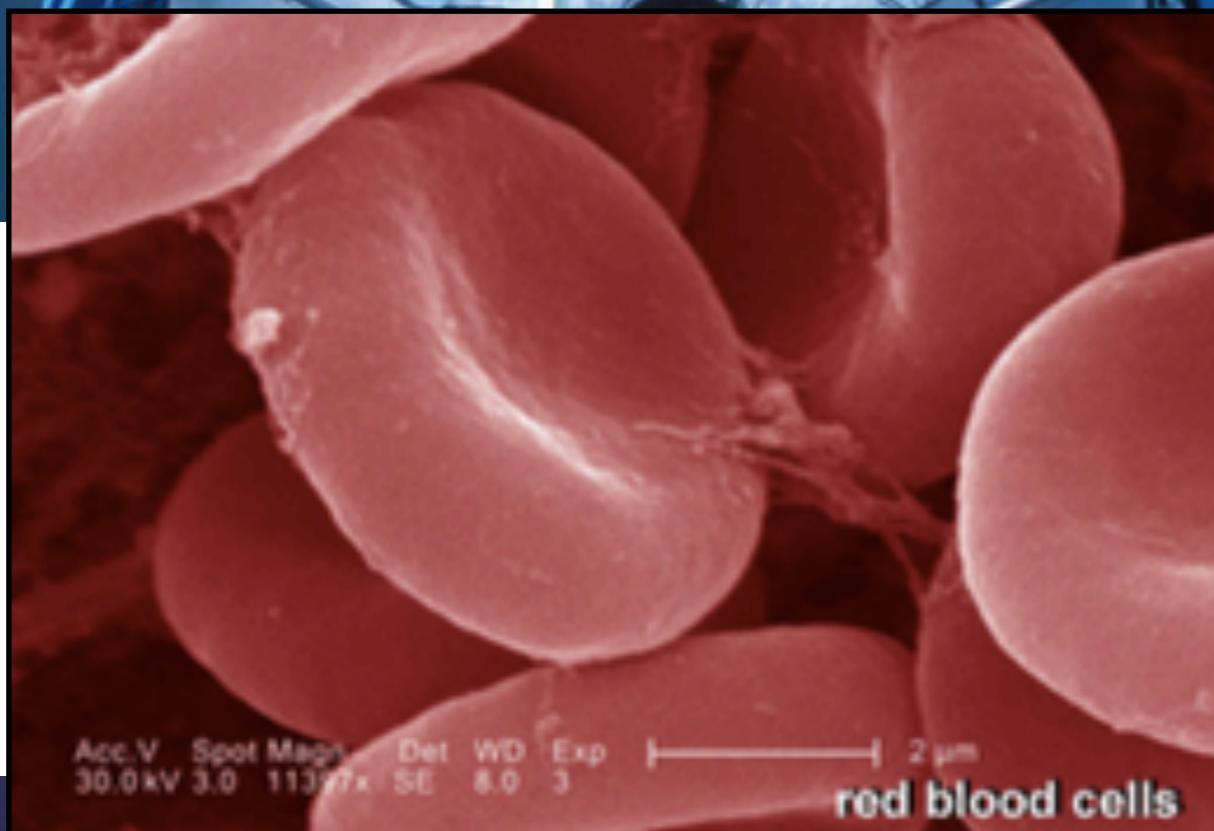
<https://github.com/as595/NITheP>

#CHPCNITHEP2019

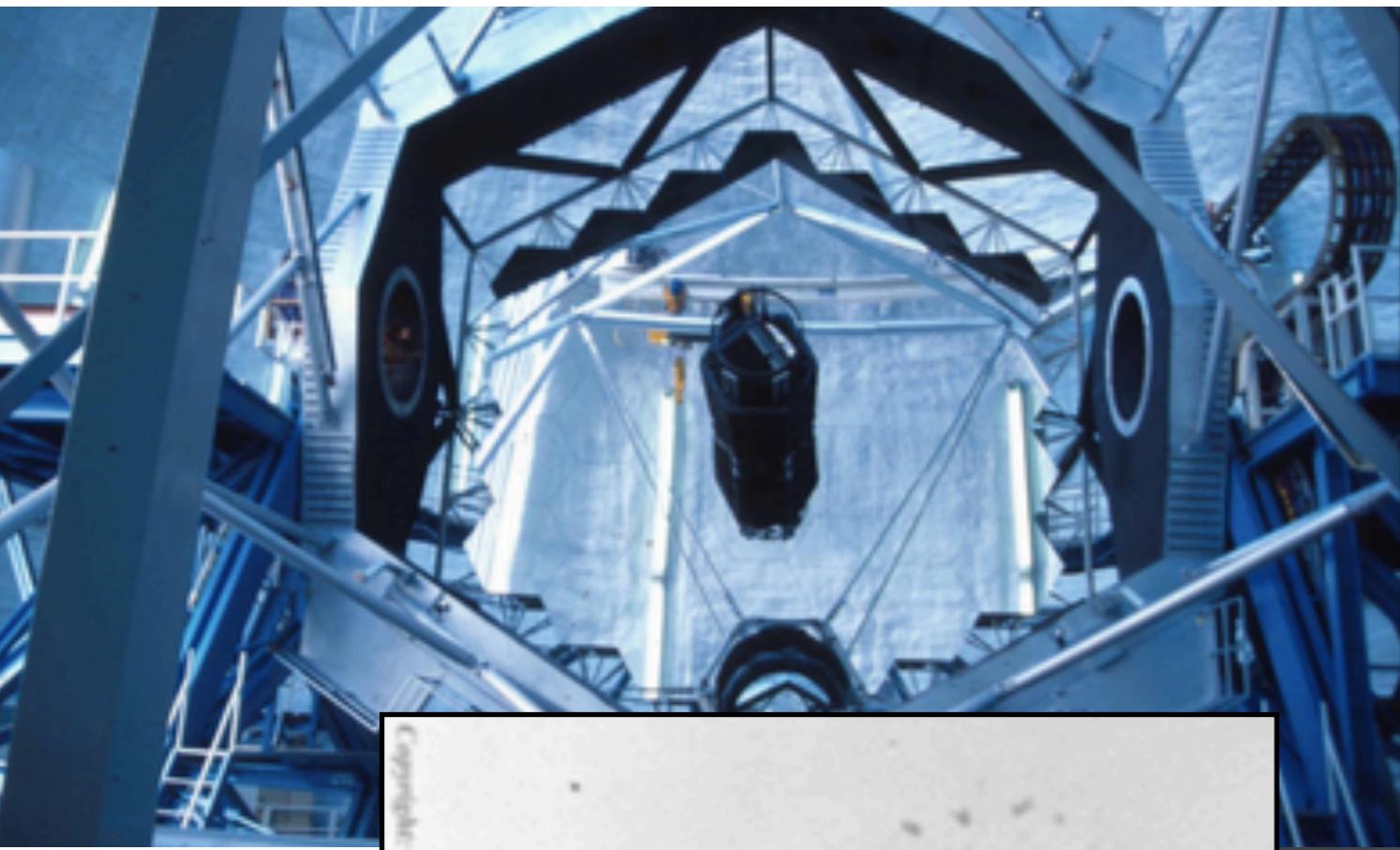
WHAT IS A TELESCOPE?



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



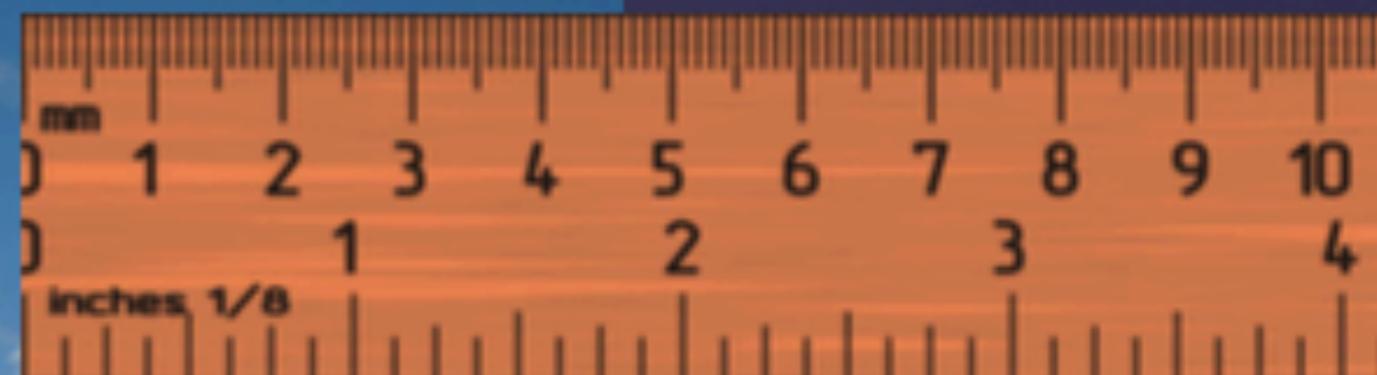
Optical: $\lambda = 350\text{-}750\text{nm}$



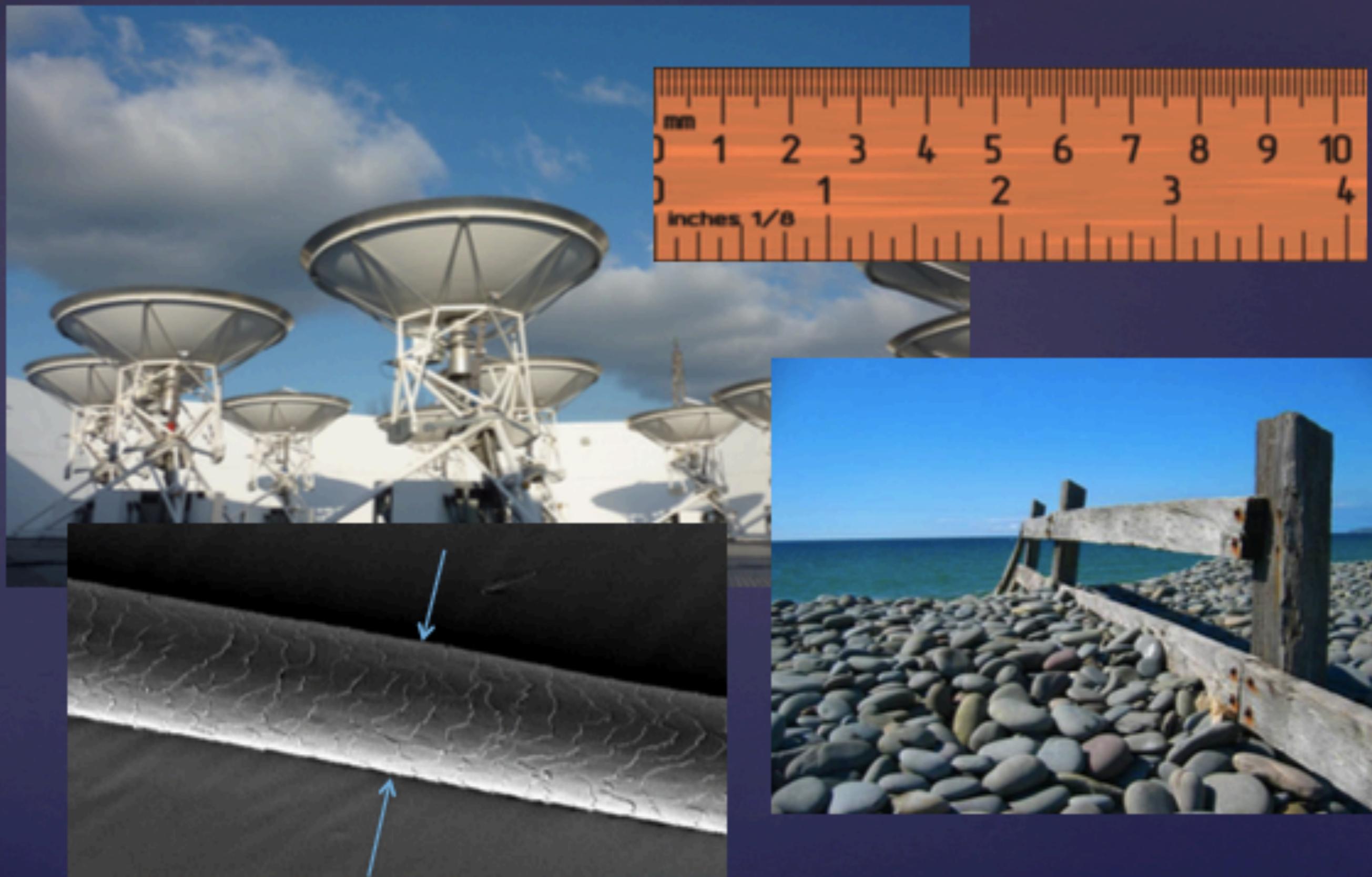
Optical: $\lambda = 350\text{-}750\text{nm}$



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



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

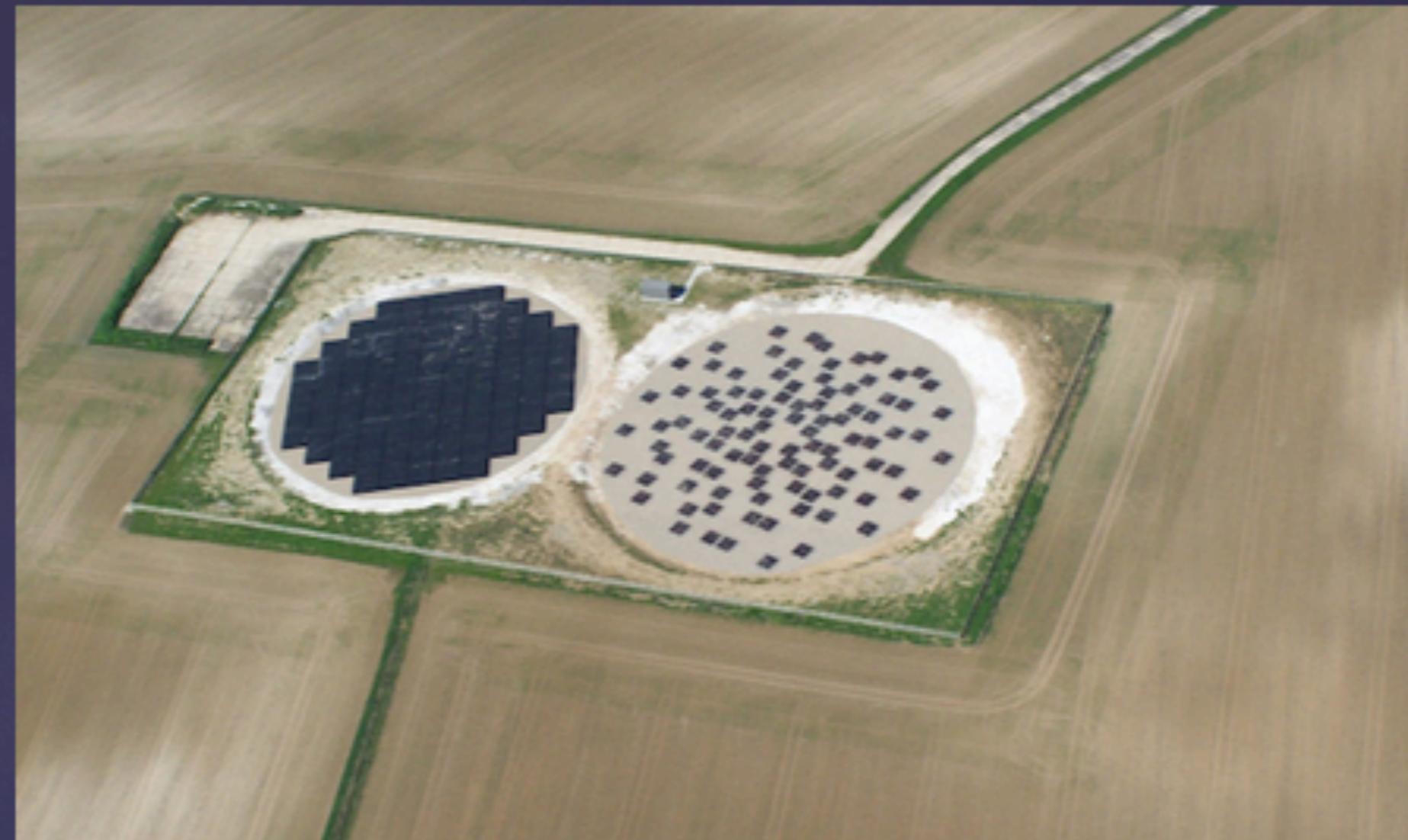


High Frequency Radio: $\lambda = 1 - 21$ cm

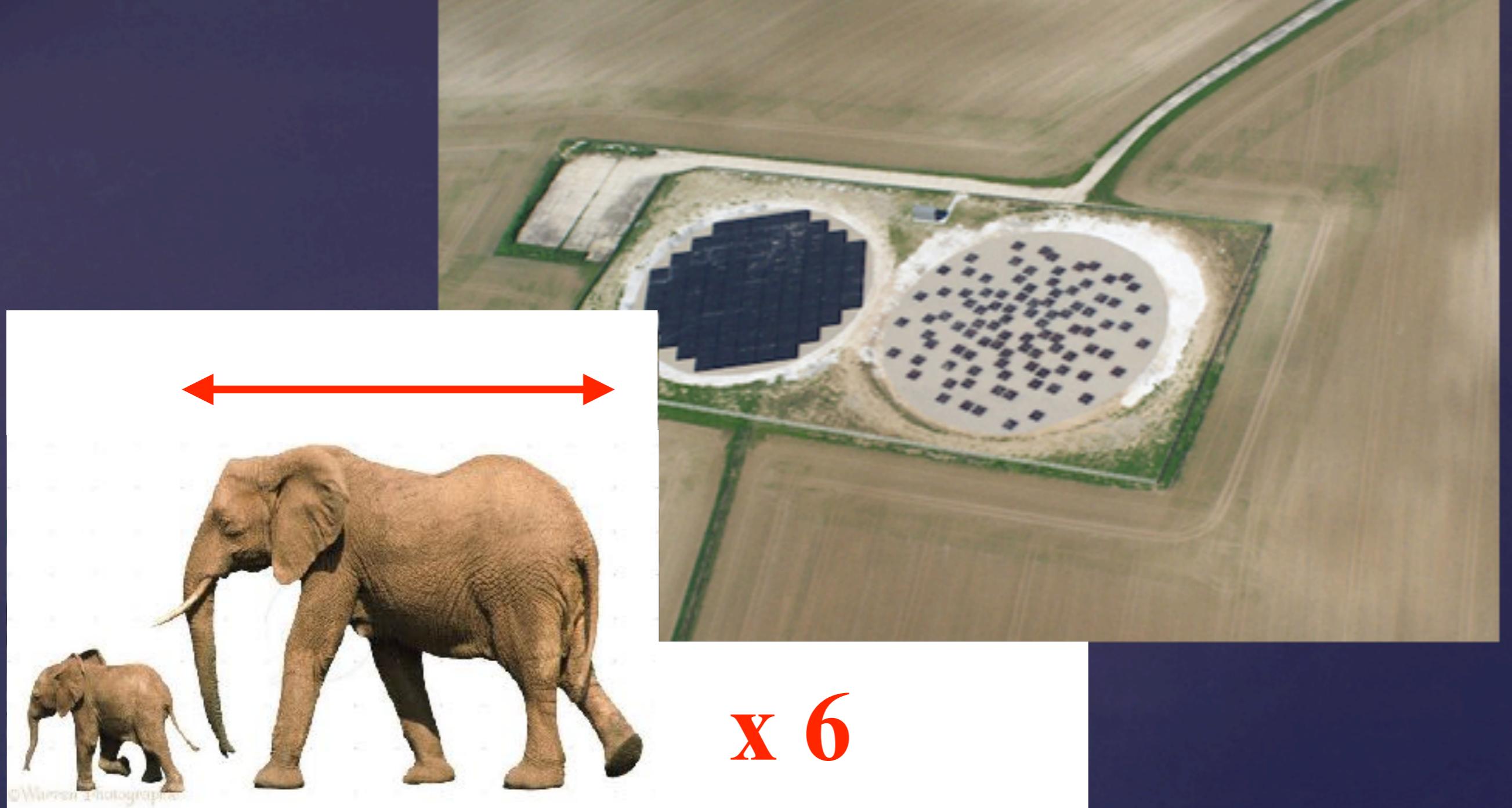


Lower Radio Frequency...

LOFAR-UK @
Chilbolton
Observatory



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



x 6

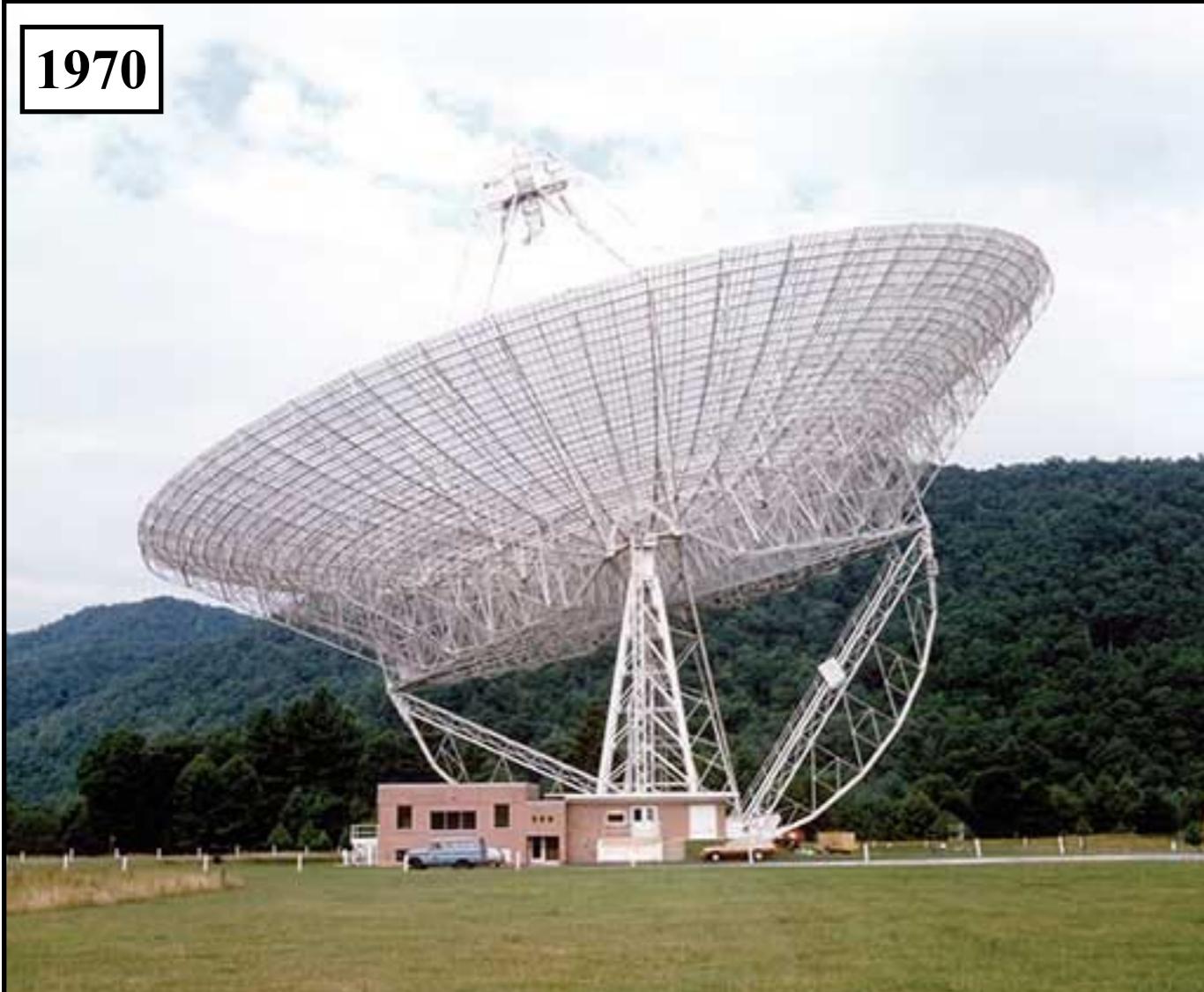
Low Radio Frequency!

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

RESOLUTION:

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

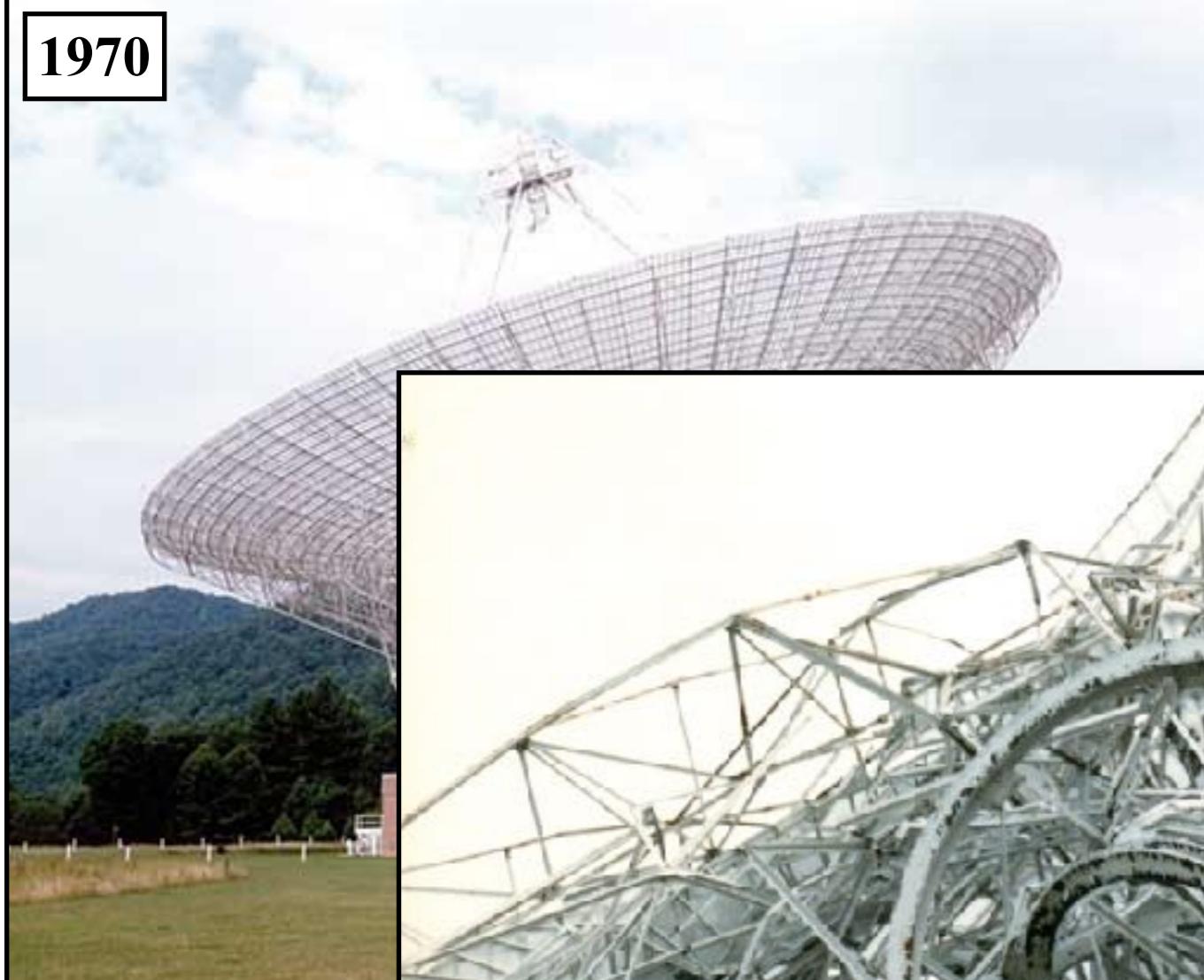
1970



Greenbank 300ft Telescope

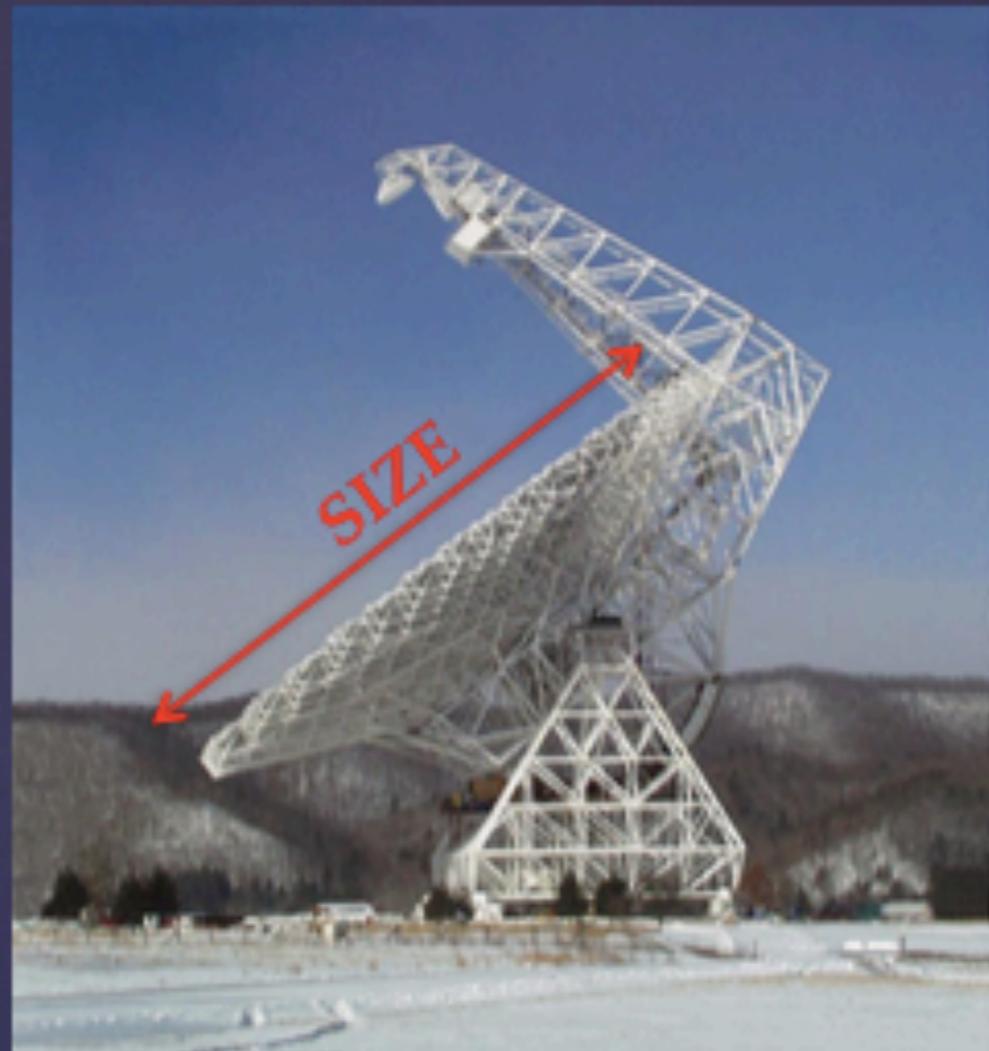
1970

Greenbank 300ft Telescope



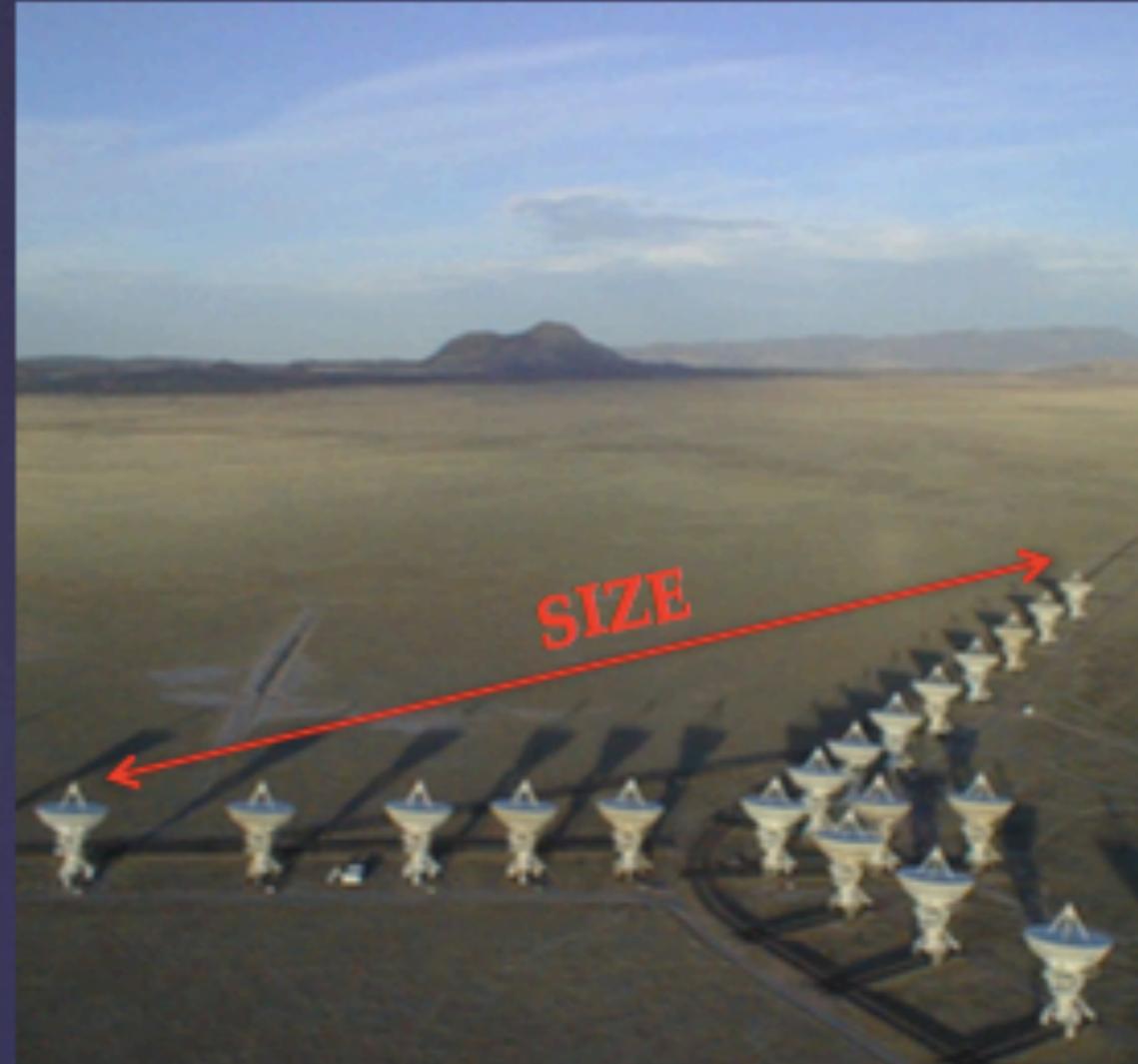
1988





Green Bank Telescope, West
Virginia, USA

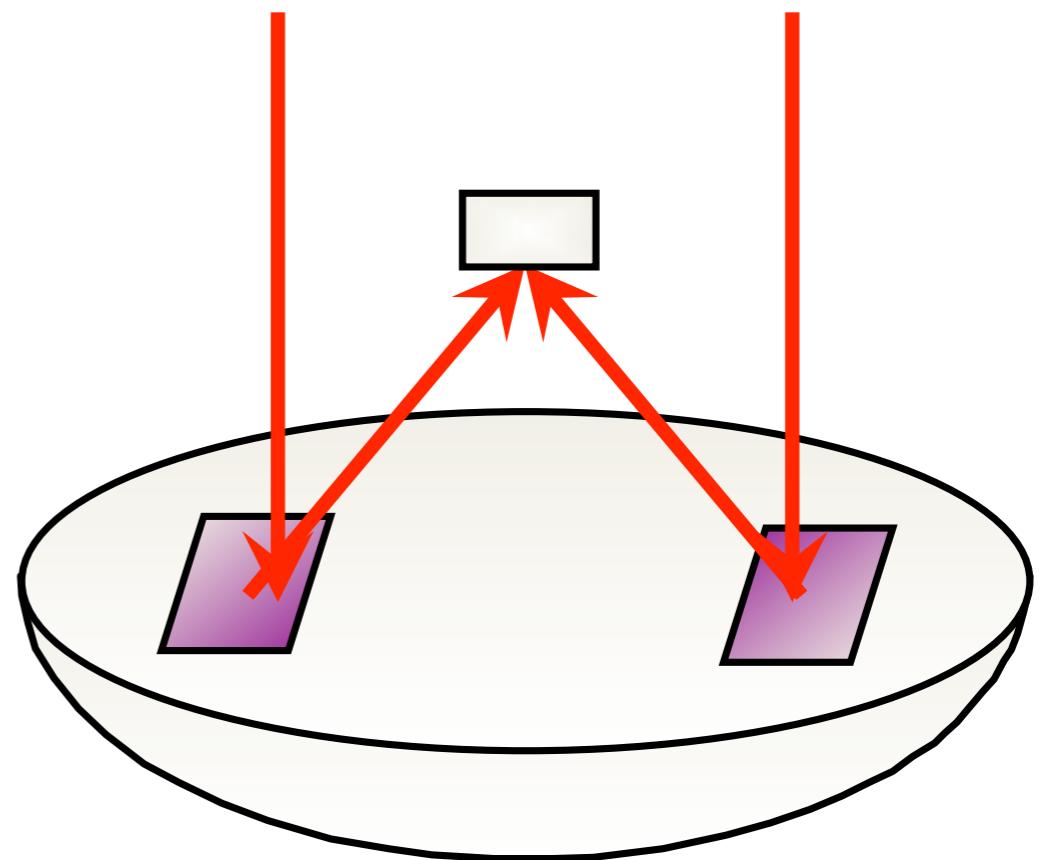
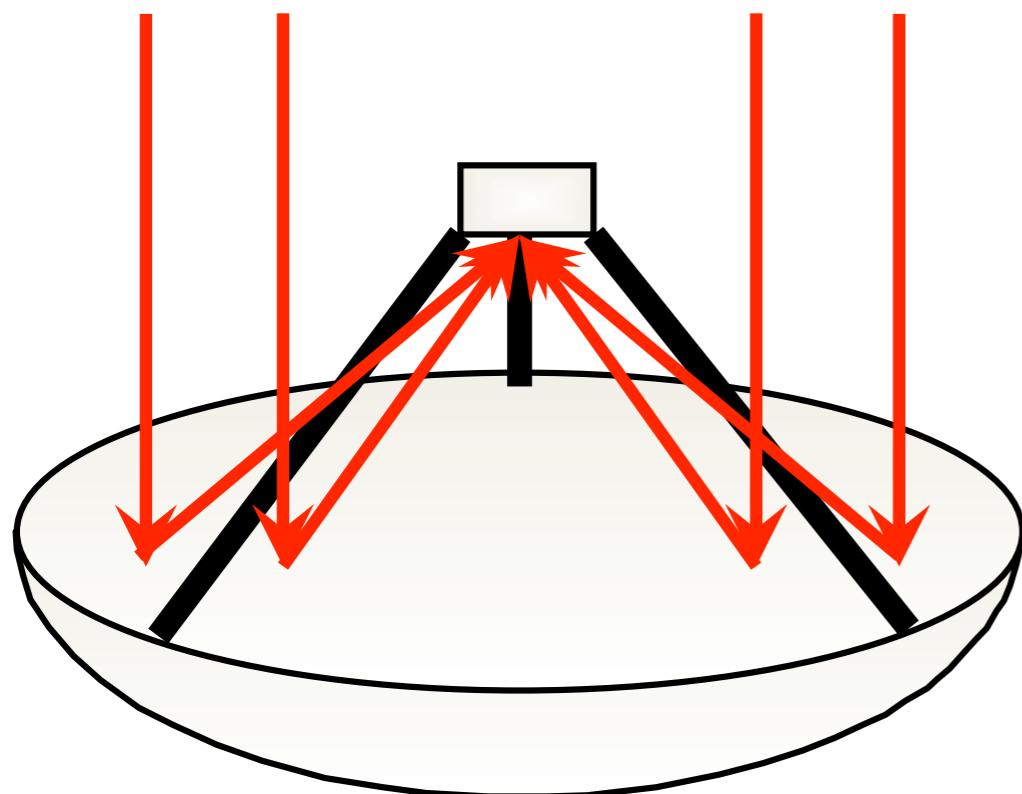
Single Dish



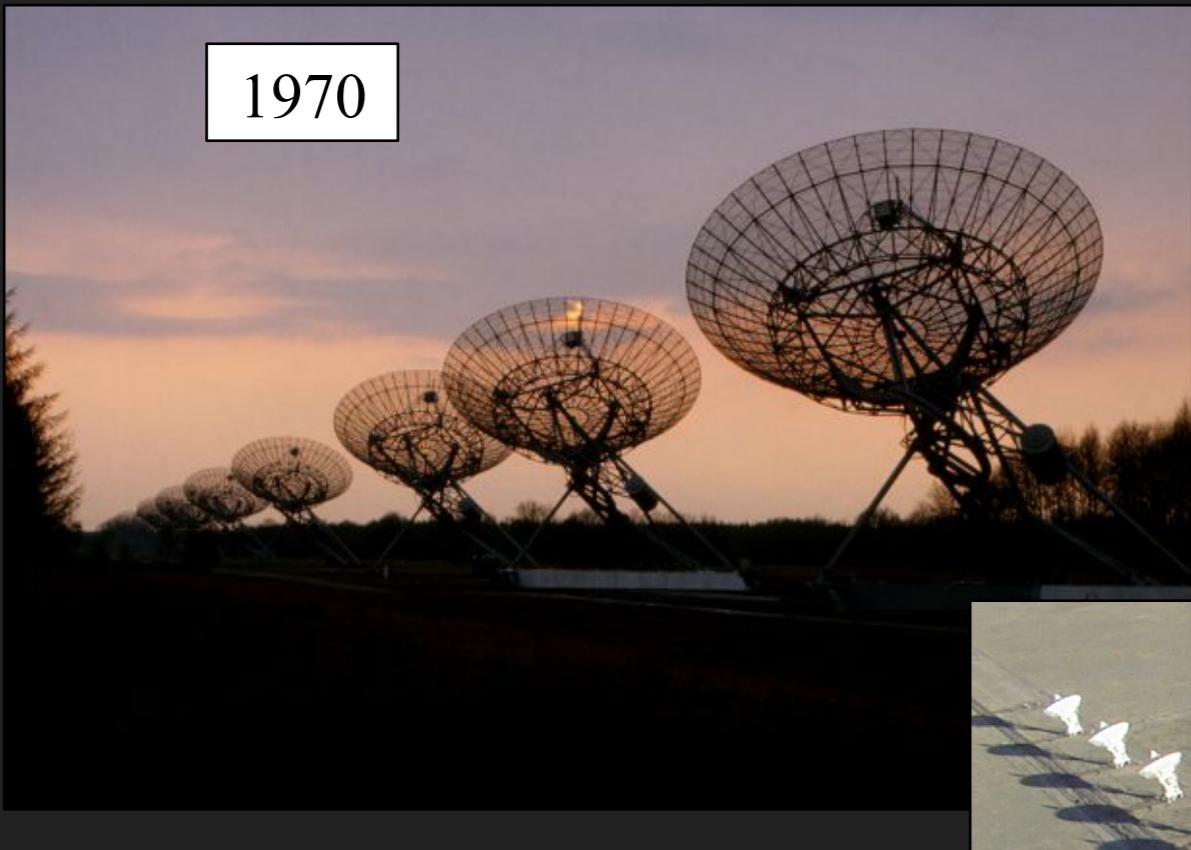
Very Large Array (VLA),
New Mexico, USA

Array

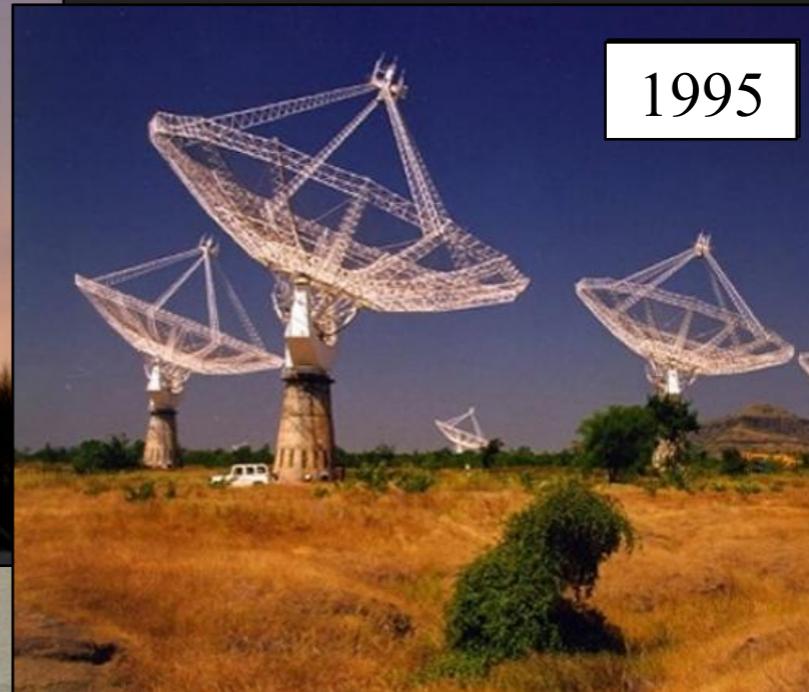
FILLED APERTURES



1970



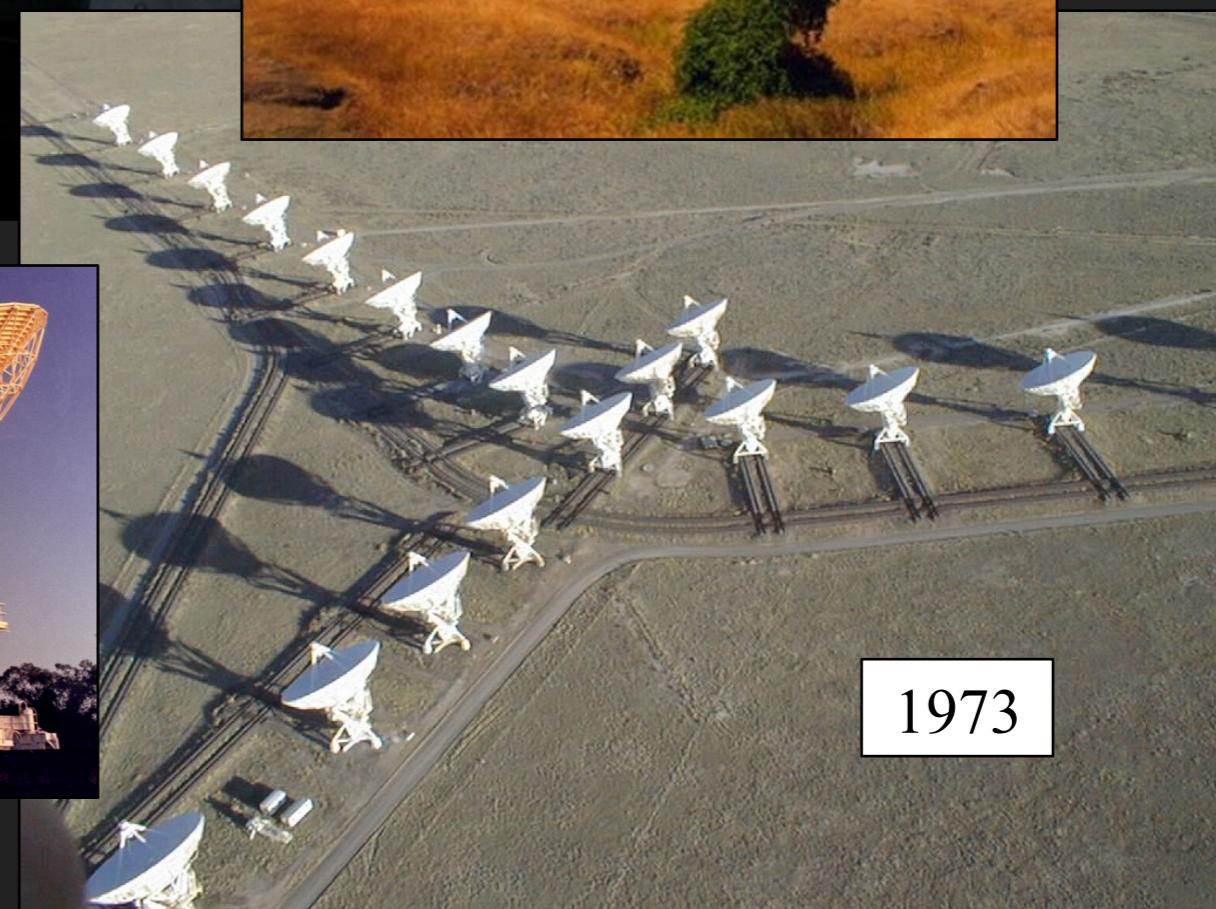
1995



1988



1973



1970

2018

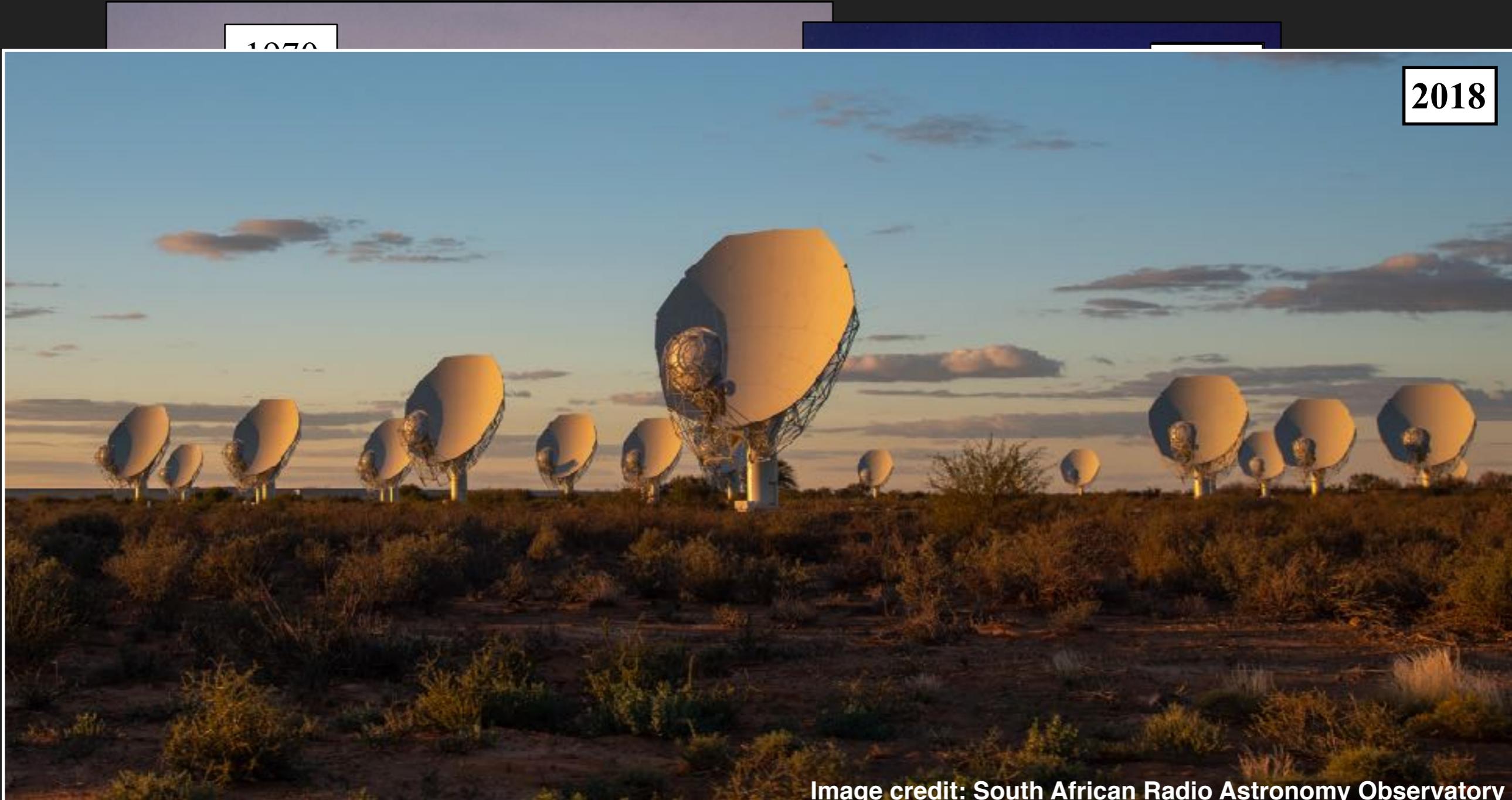


Image credit: South African Radio Astronomy Observatory

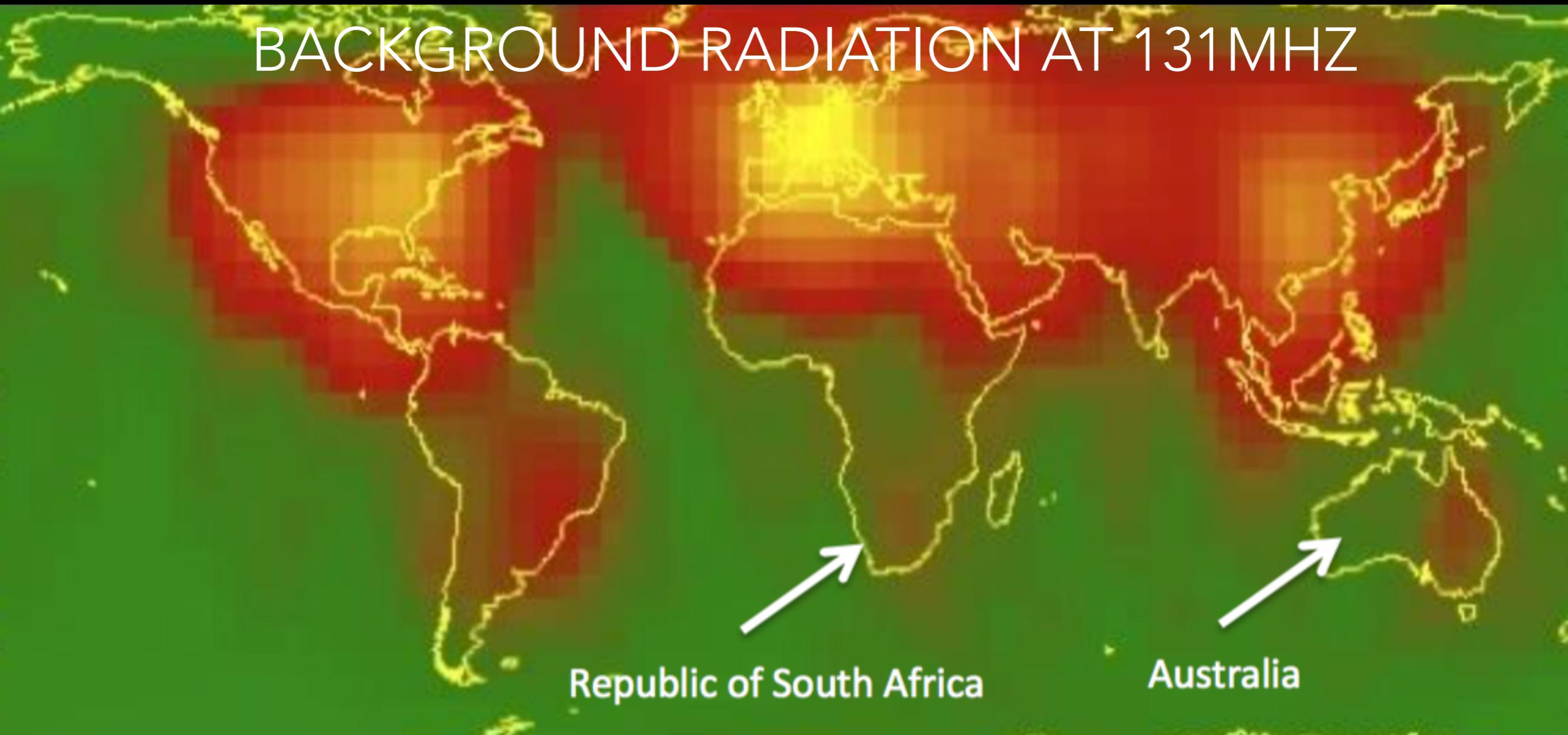






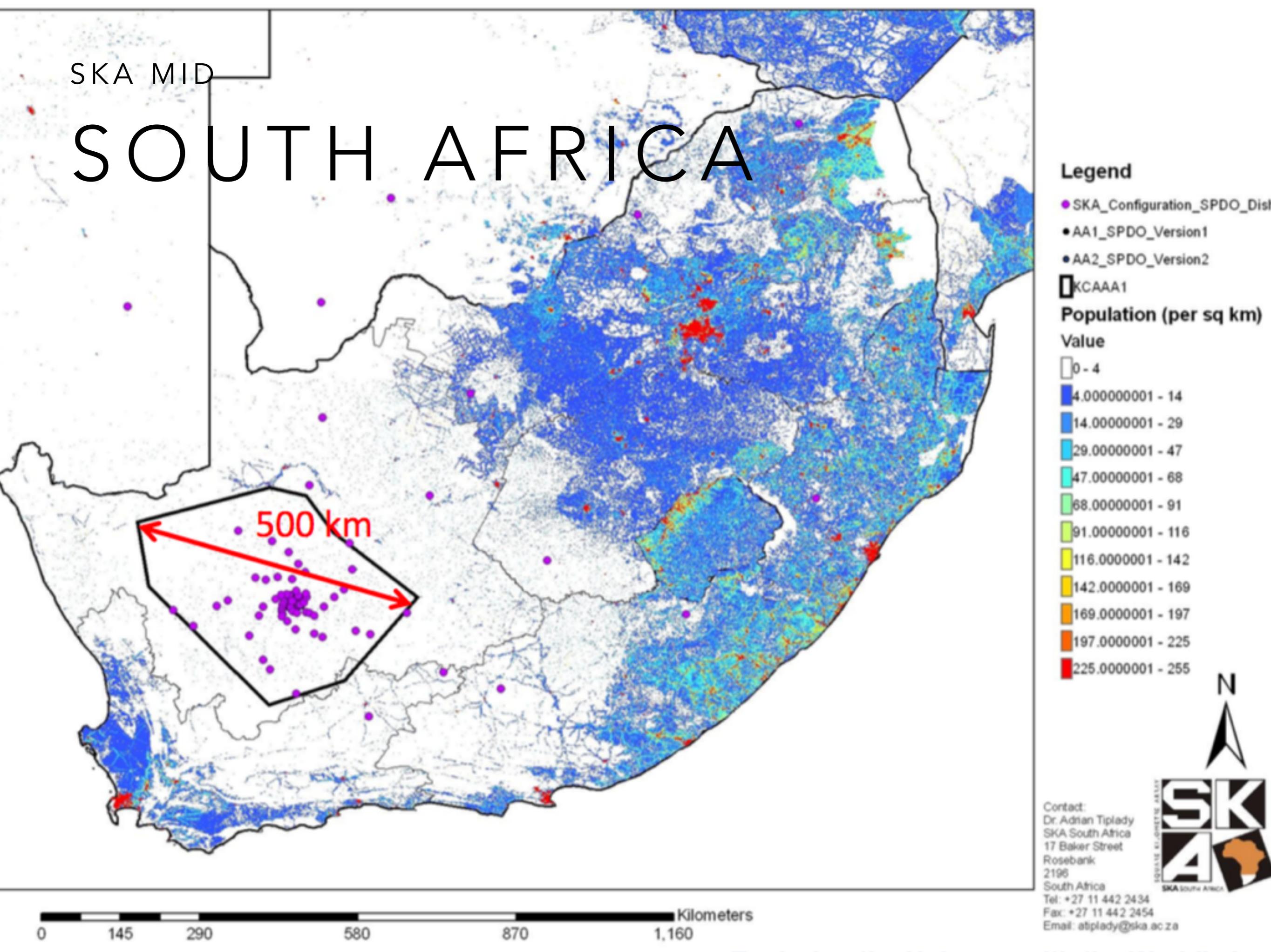
LOCATION

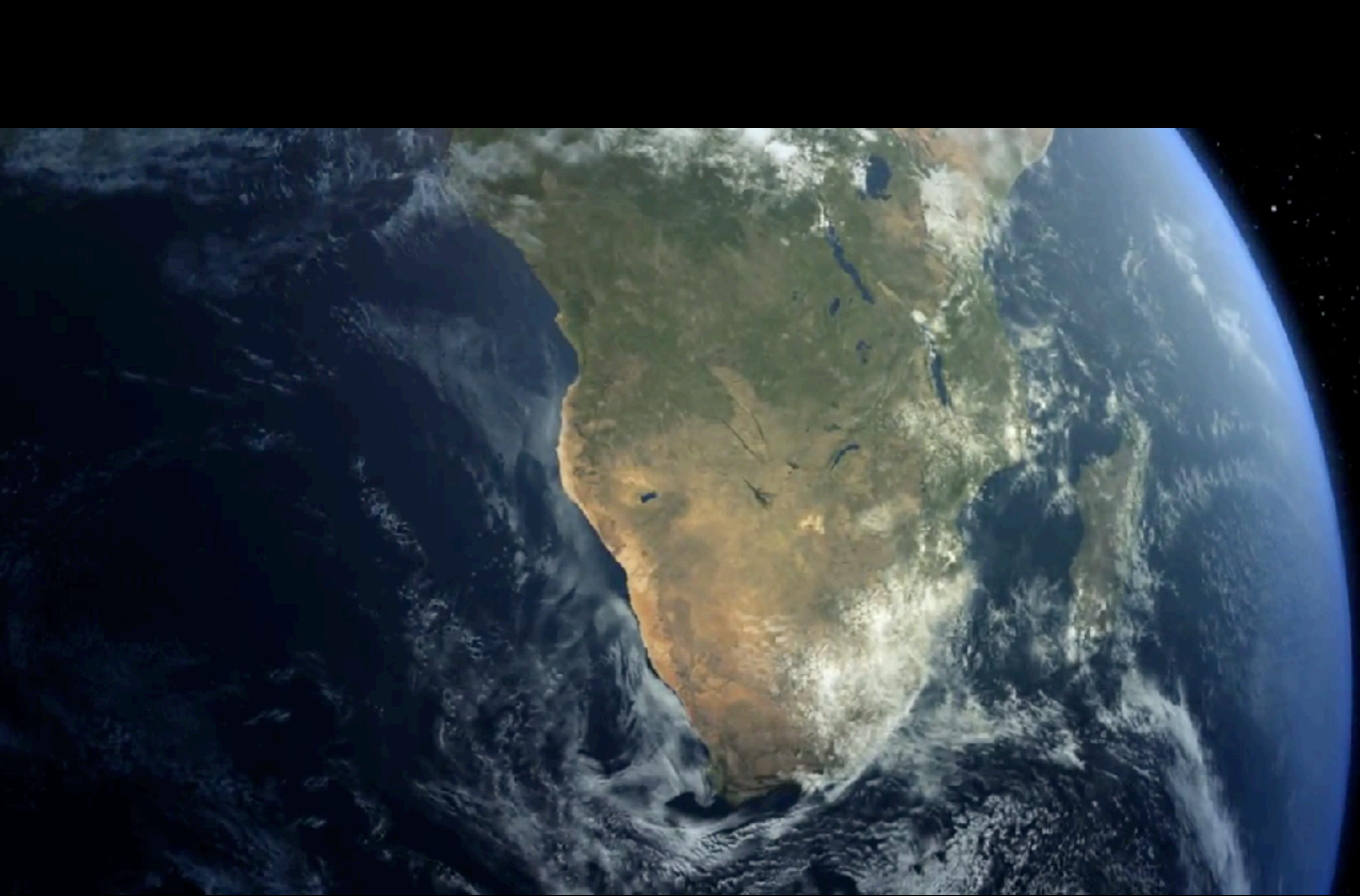
- THE TELESCOPE NEEDS TO BE SOMEWHERE “RADIO QUIET”

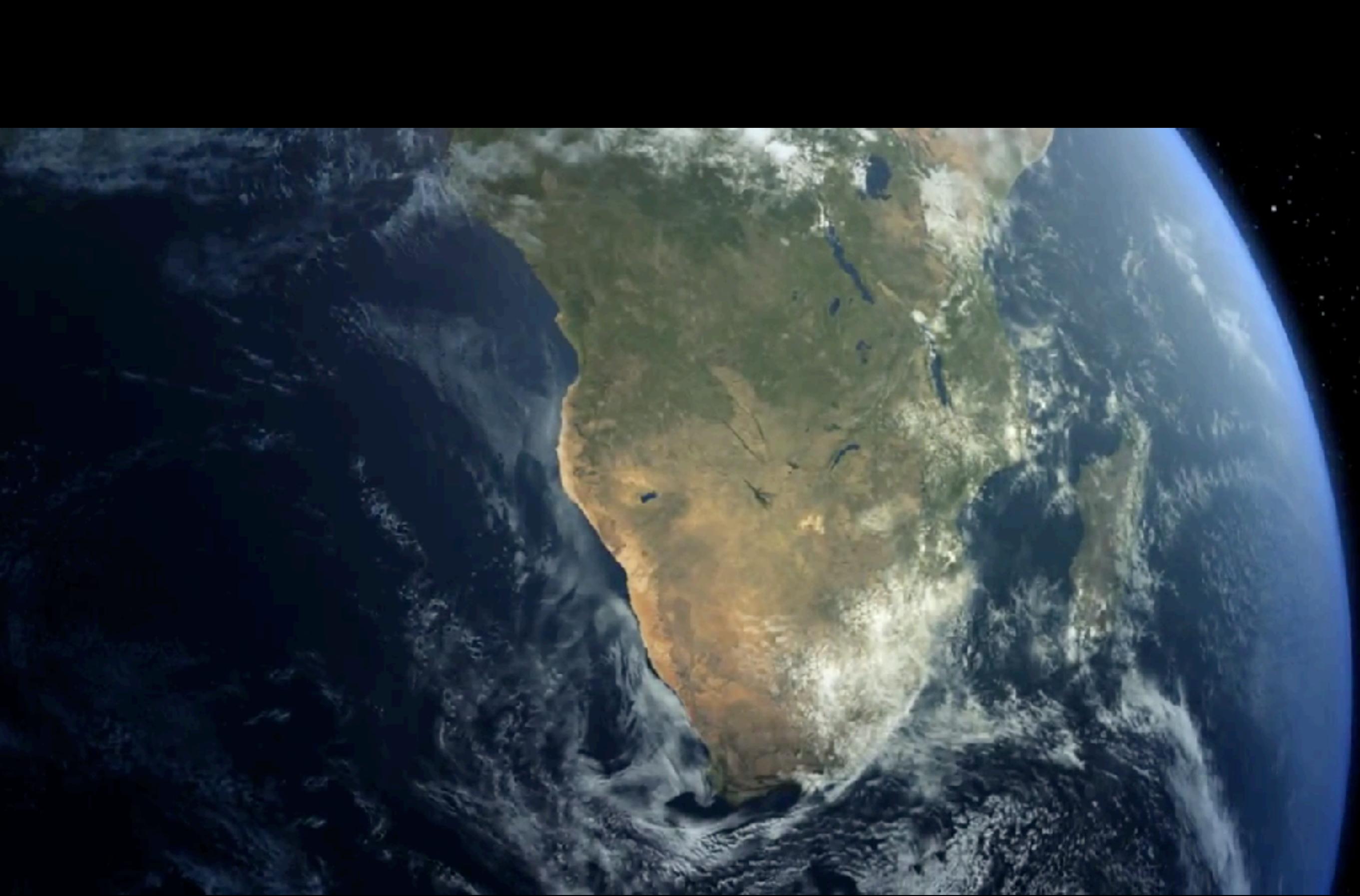


SKA MID

SOUTH AFRICA







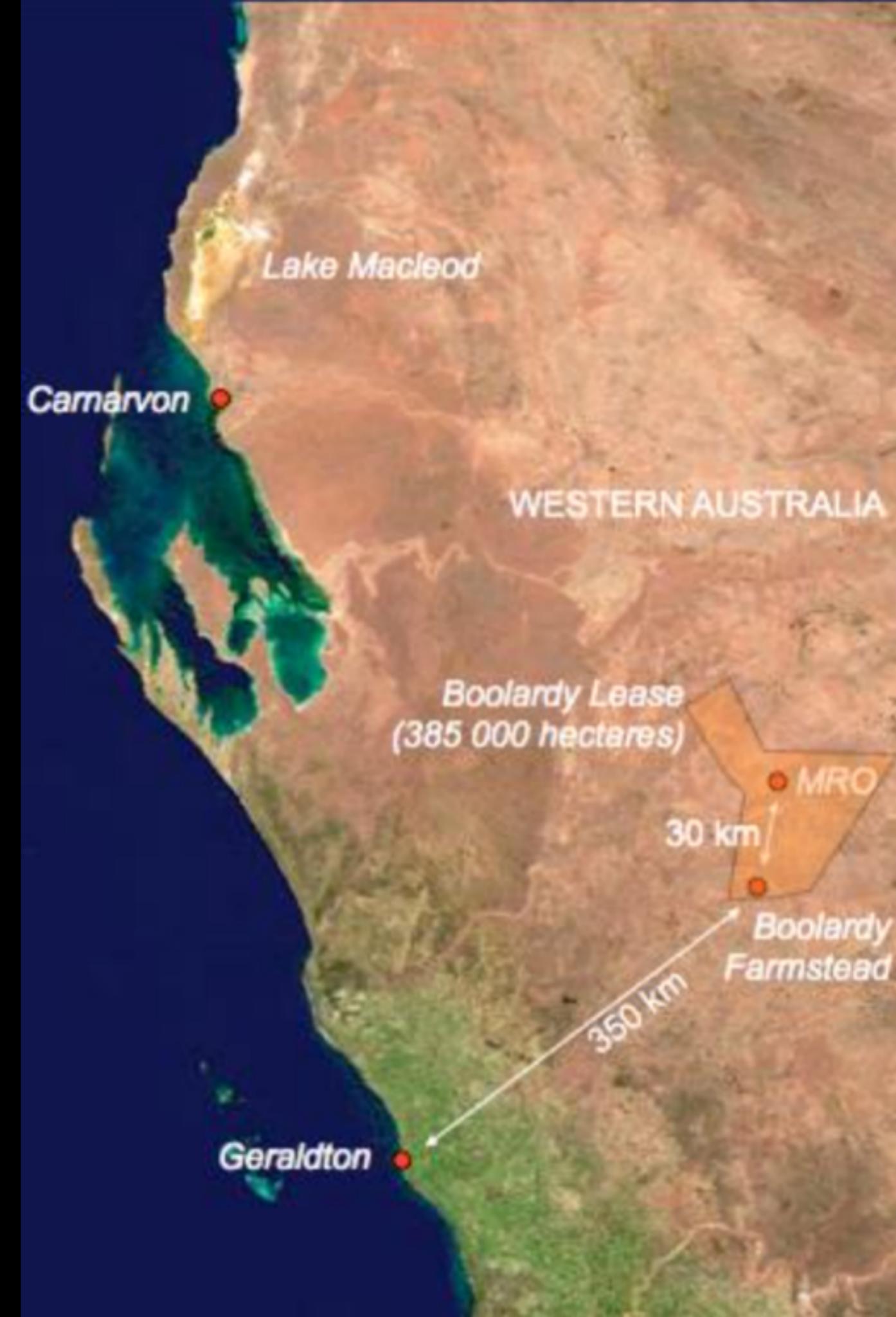




SKA LOW AUSTRALIA

SHIRE OF MURCHISON:

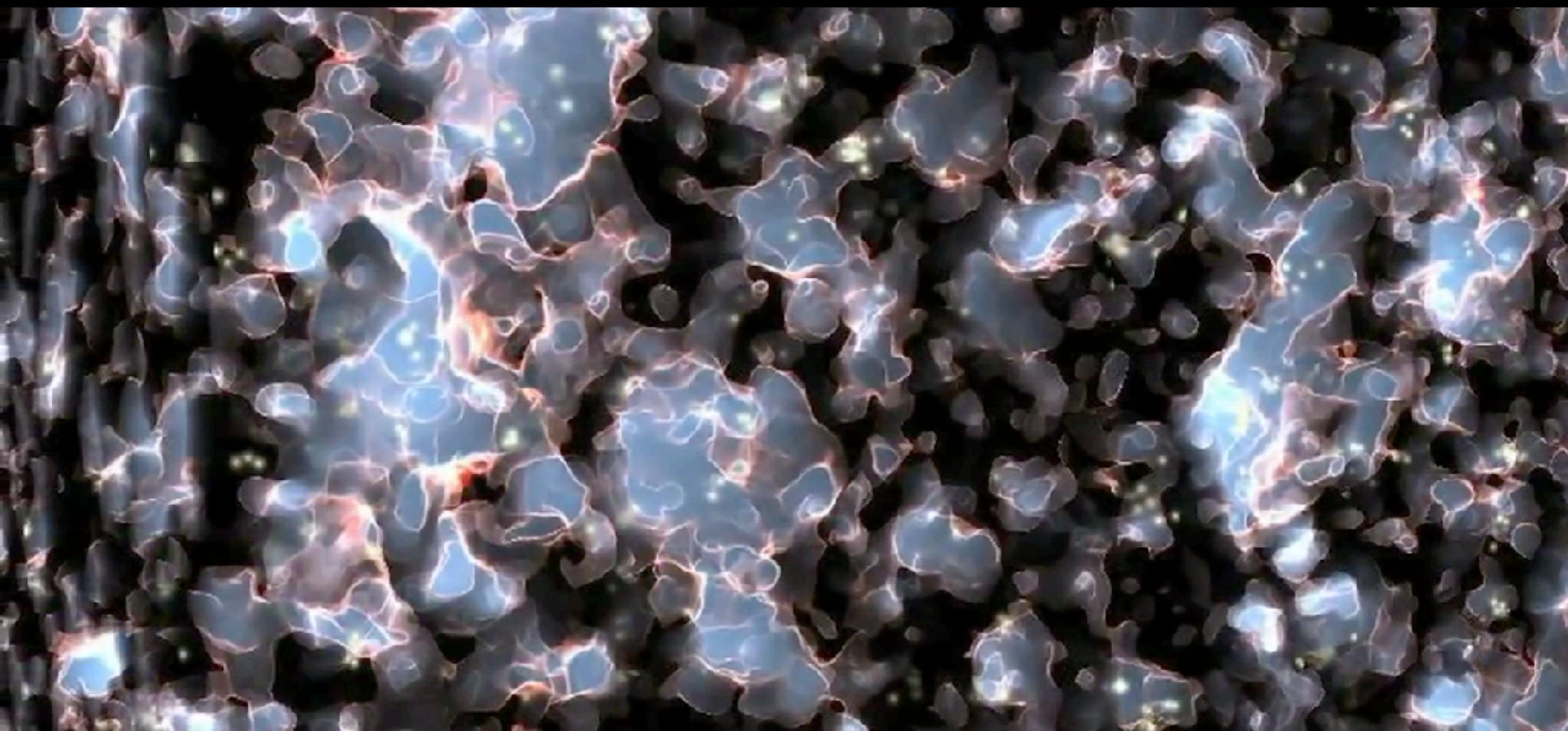
- 50 000 KM²
- 0 TOWNS
- 29 SHEEP/CATTLE STATIONS
- POP. **110** PEOPLE
 $= 0.002 \text{ PPL / KM}^2$





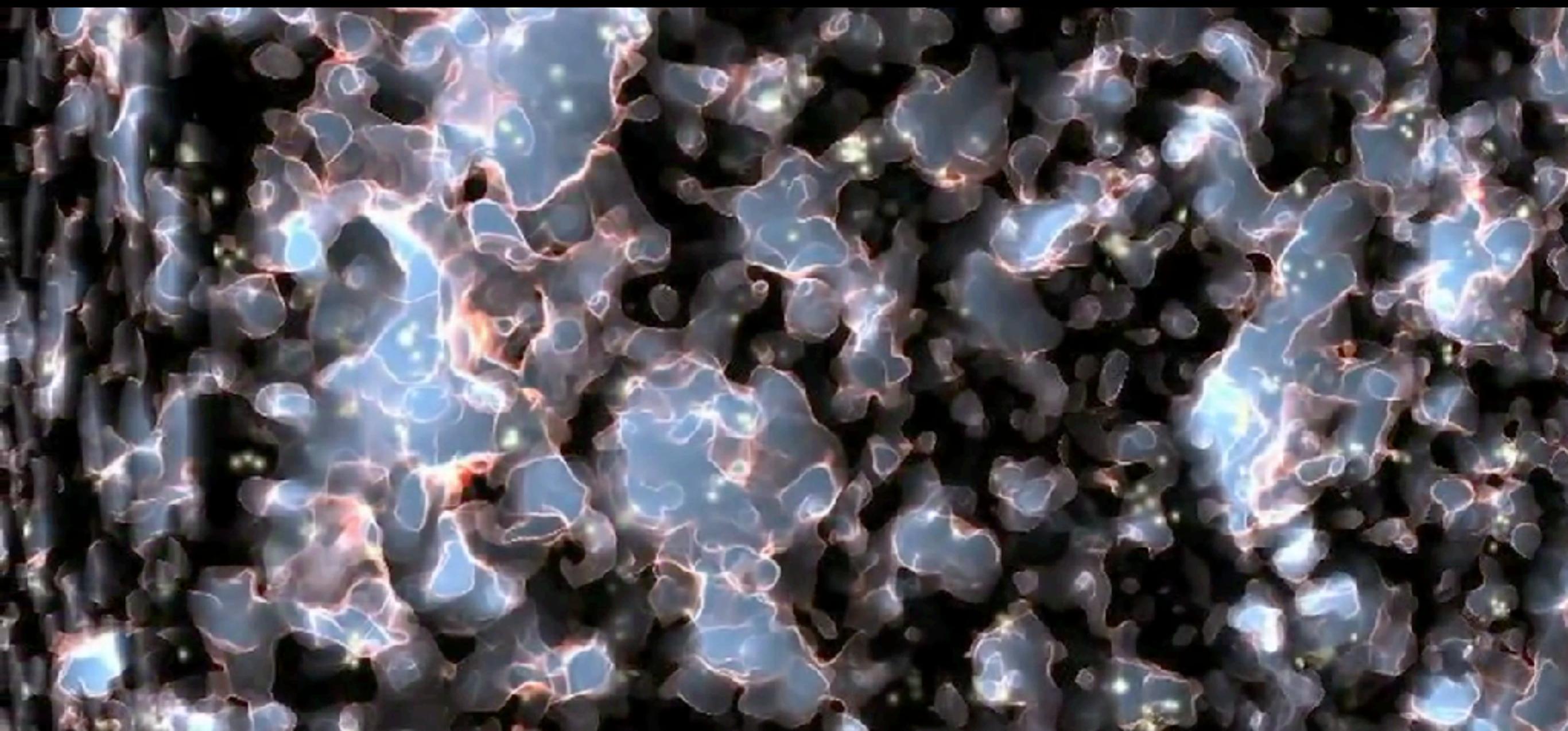
EPOCH OF REIONIZATION

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



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- **HOW** THE FIRST STARS & GALAXIES FORMED
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GRAVITATIONAL WAVES

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



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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.



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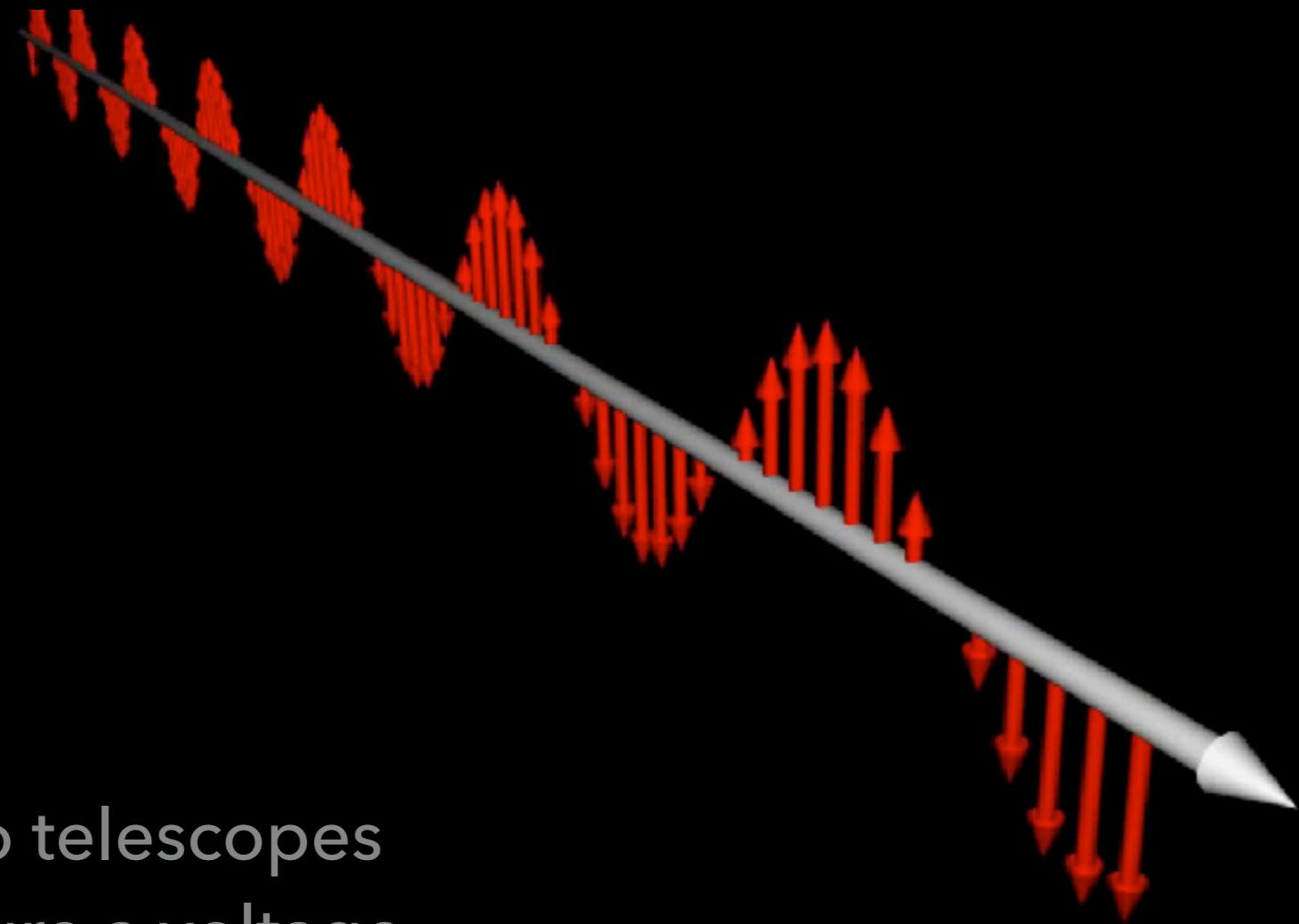
CRADLE OF LIFE

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

CRADLE OF LIFE

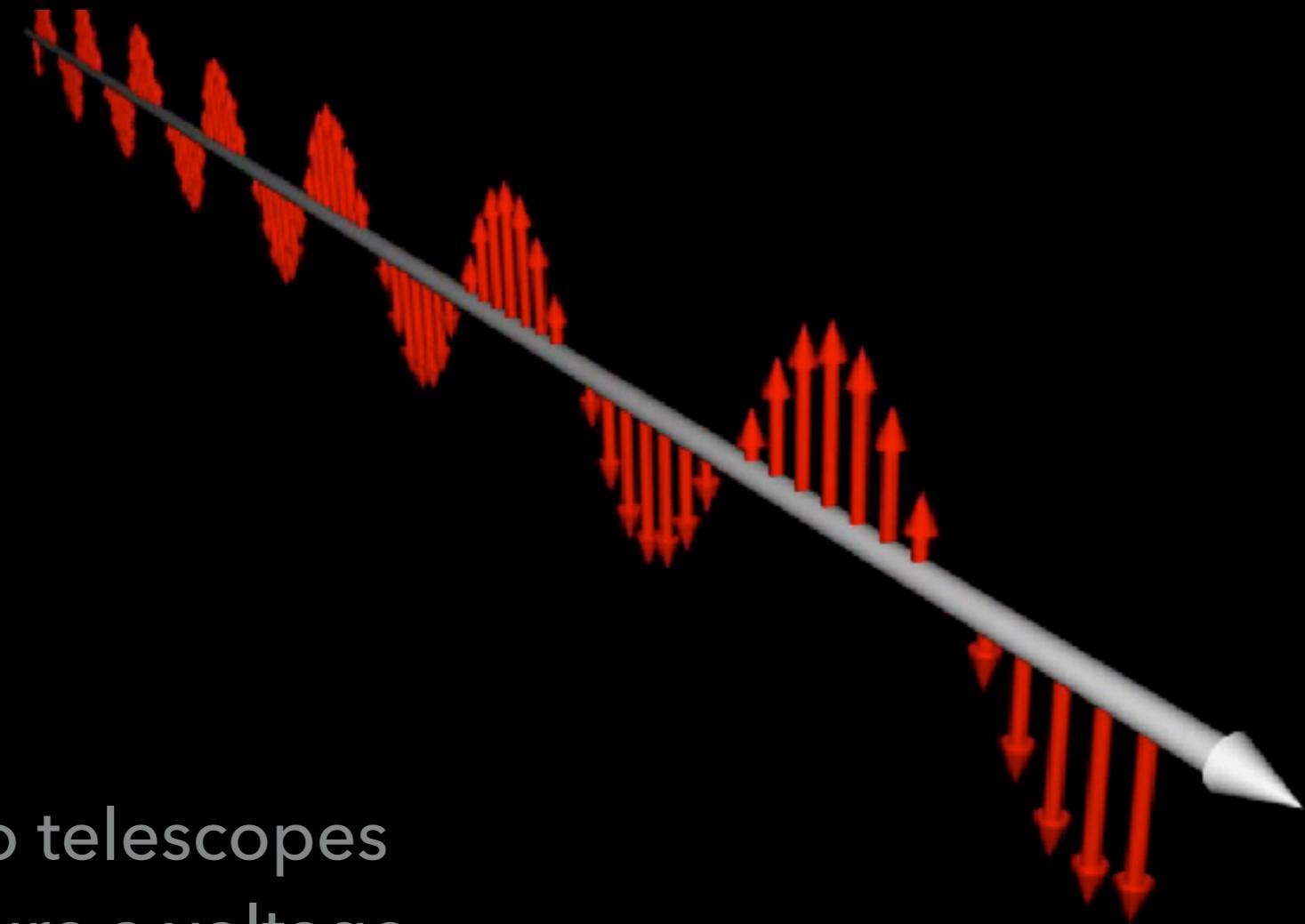
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- ARE WE ALONE?

(GENTLE) INTRODUCTION TO INTERFEROMETRY

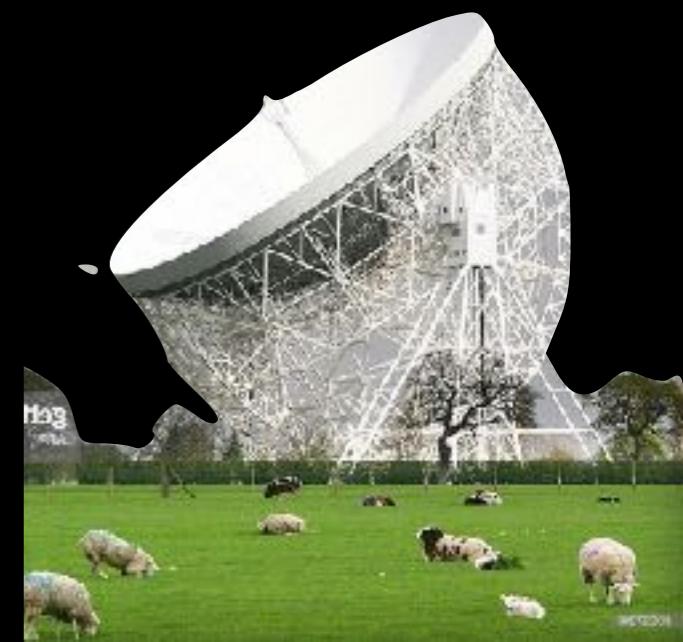


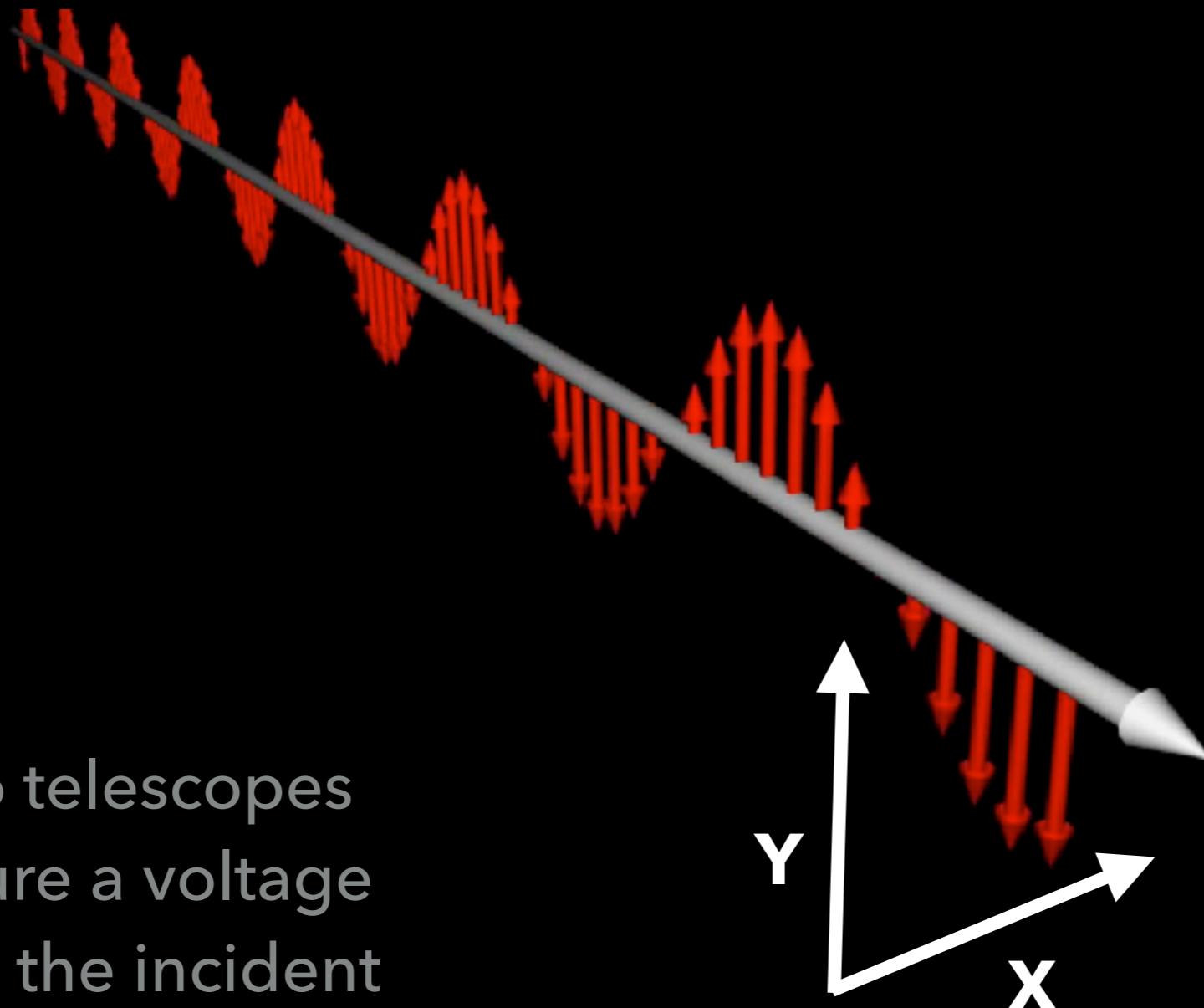
Radio telescopes
measure a voltage
due to the incident
EM radiation





Radio telescopes
measure a voltage
due to the incident
EM radiation





Radio telescopes
measure a voltage
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EM radiation

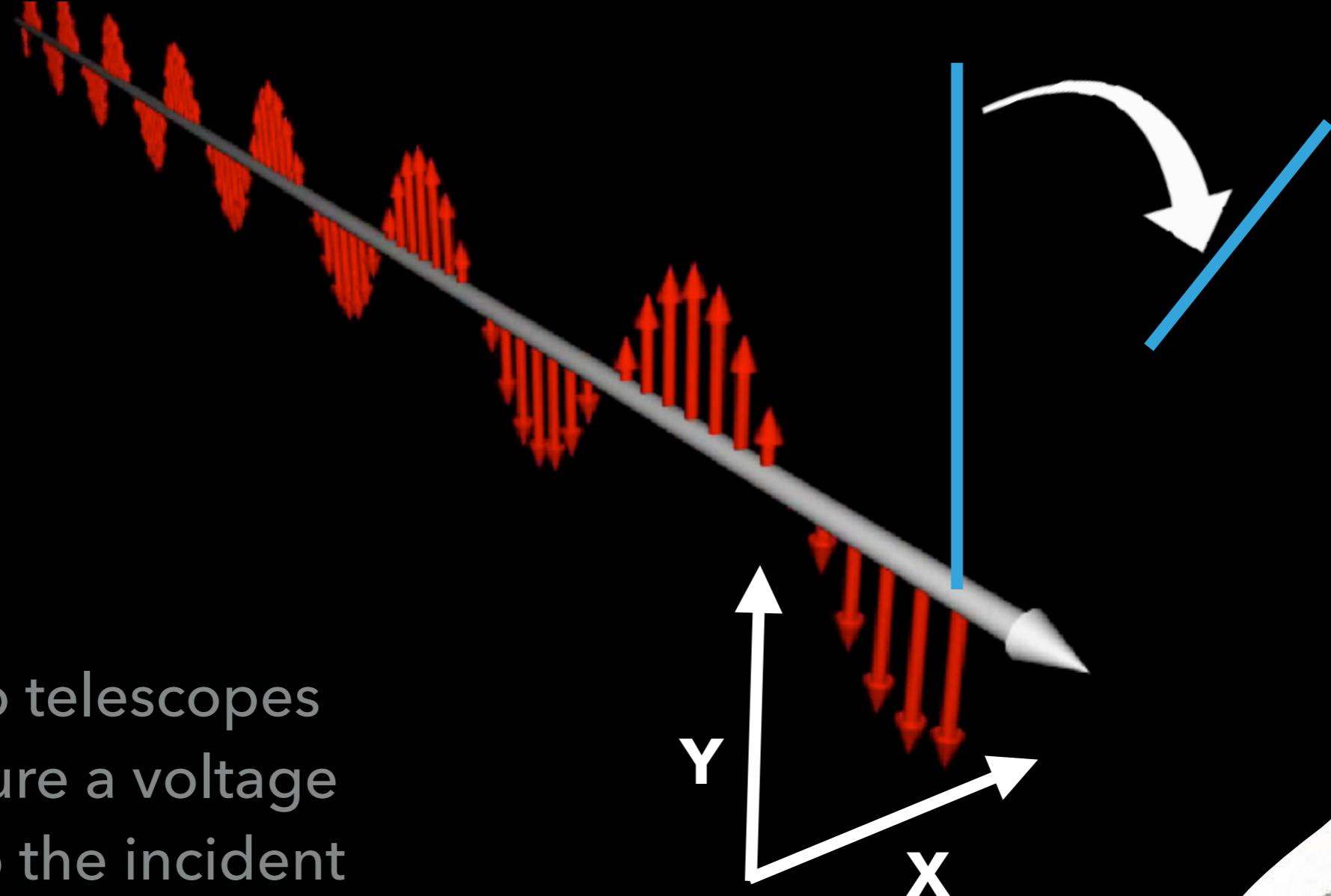


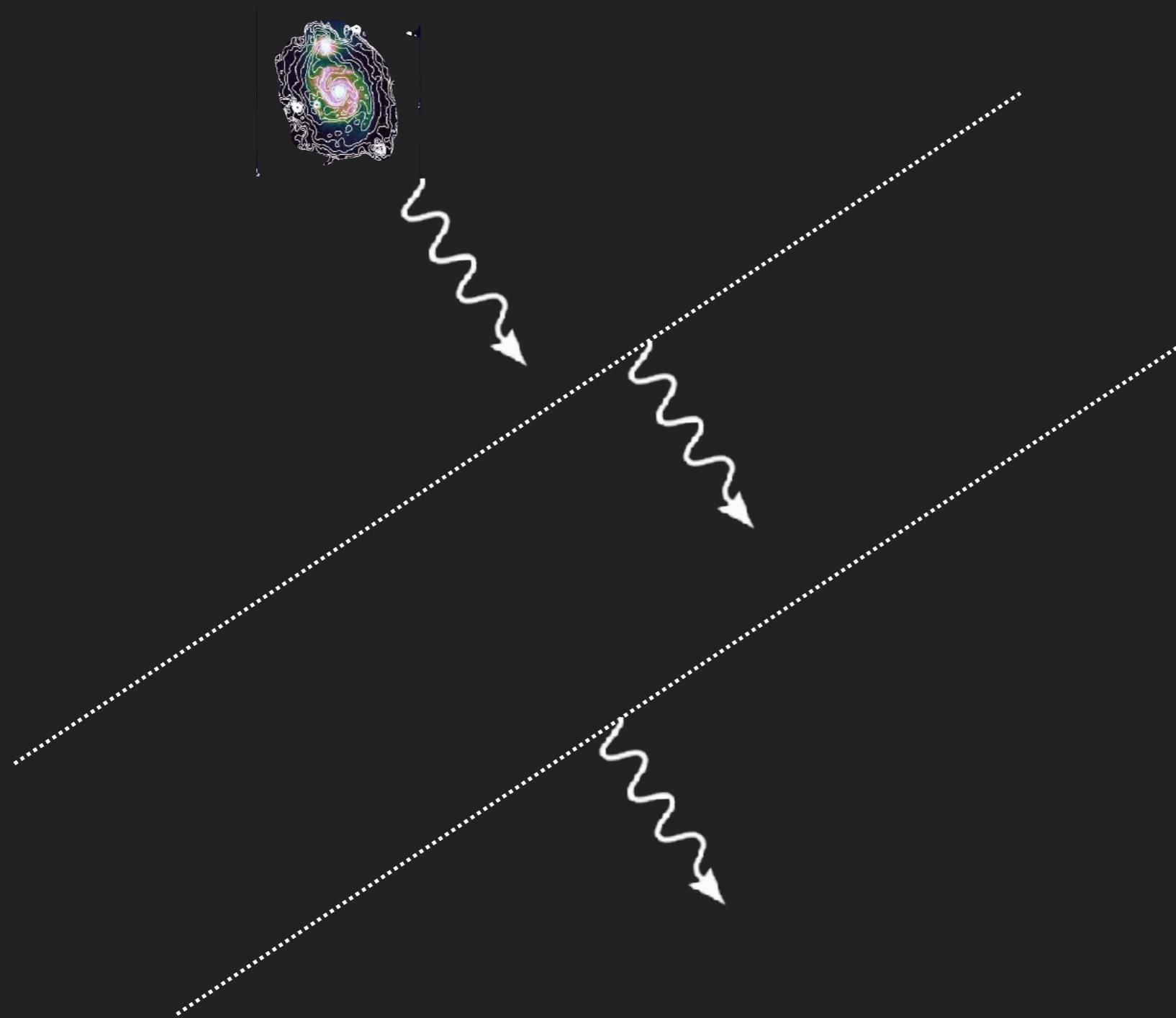


Animation by



Radio telescopes
measure a voltage
due to the incident
EM radiation



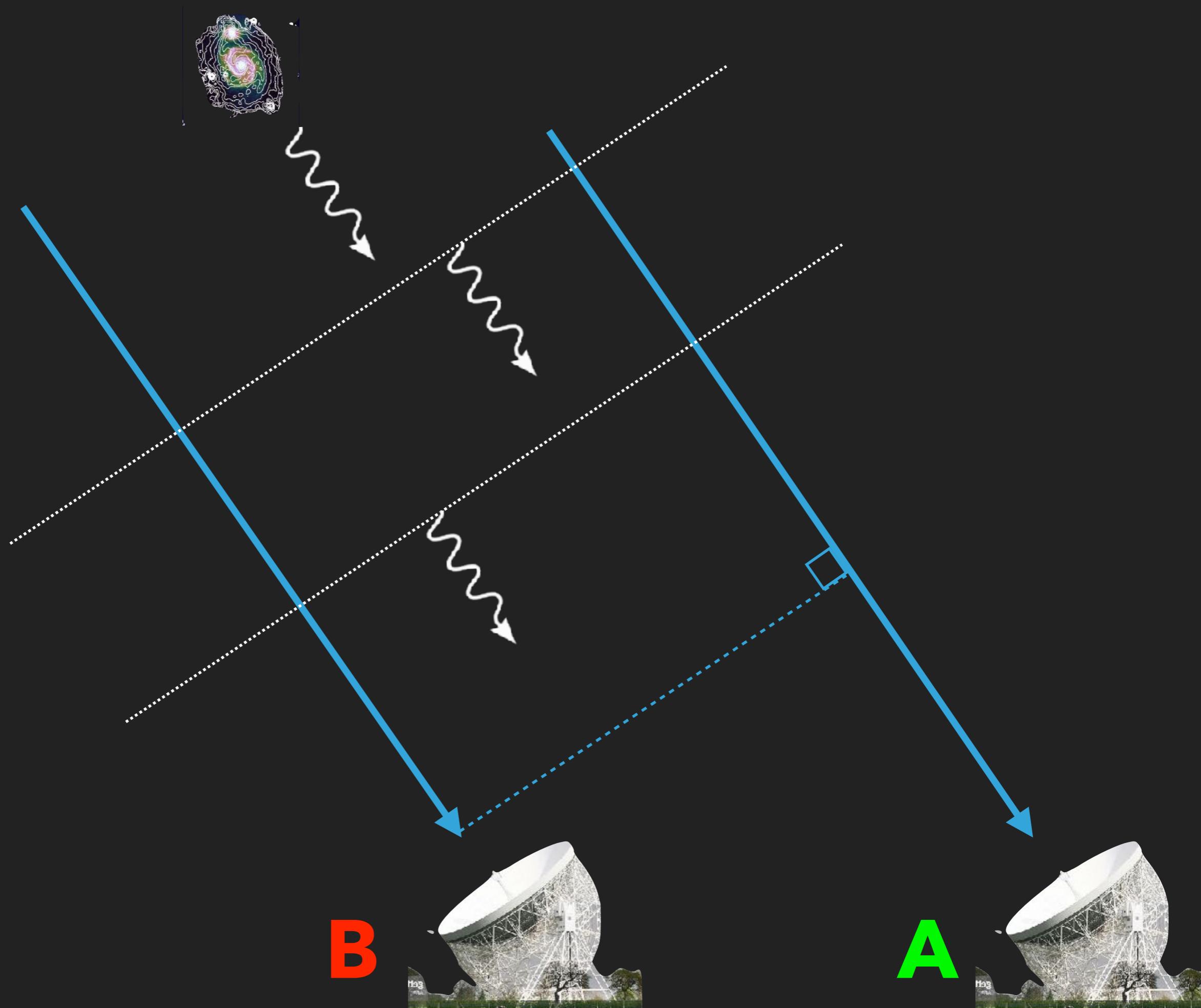


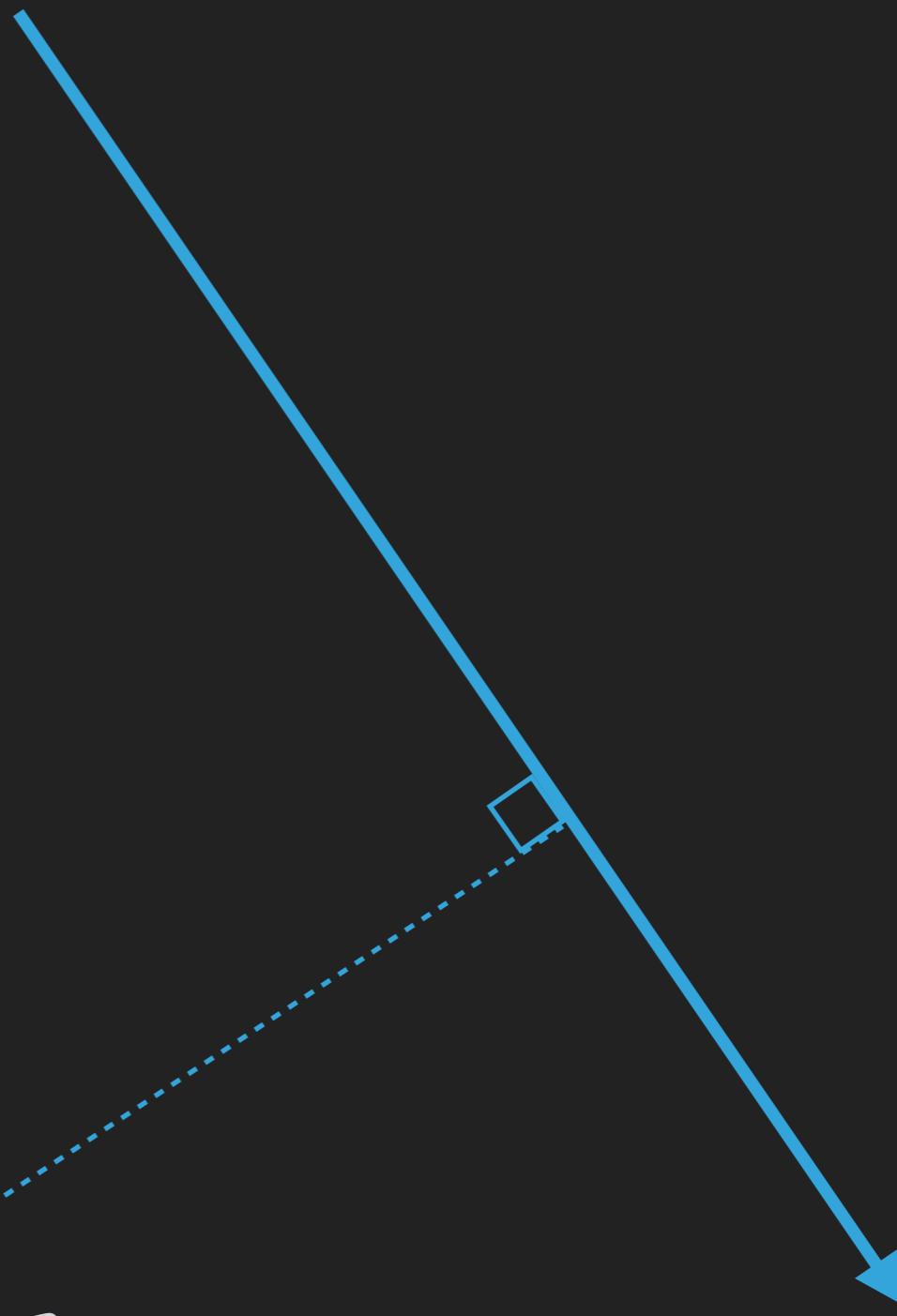
B



A





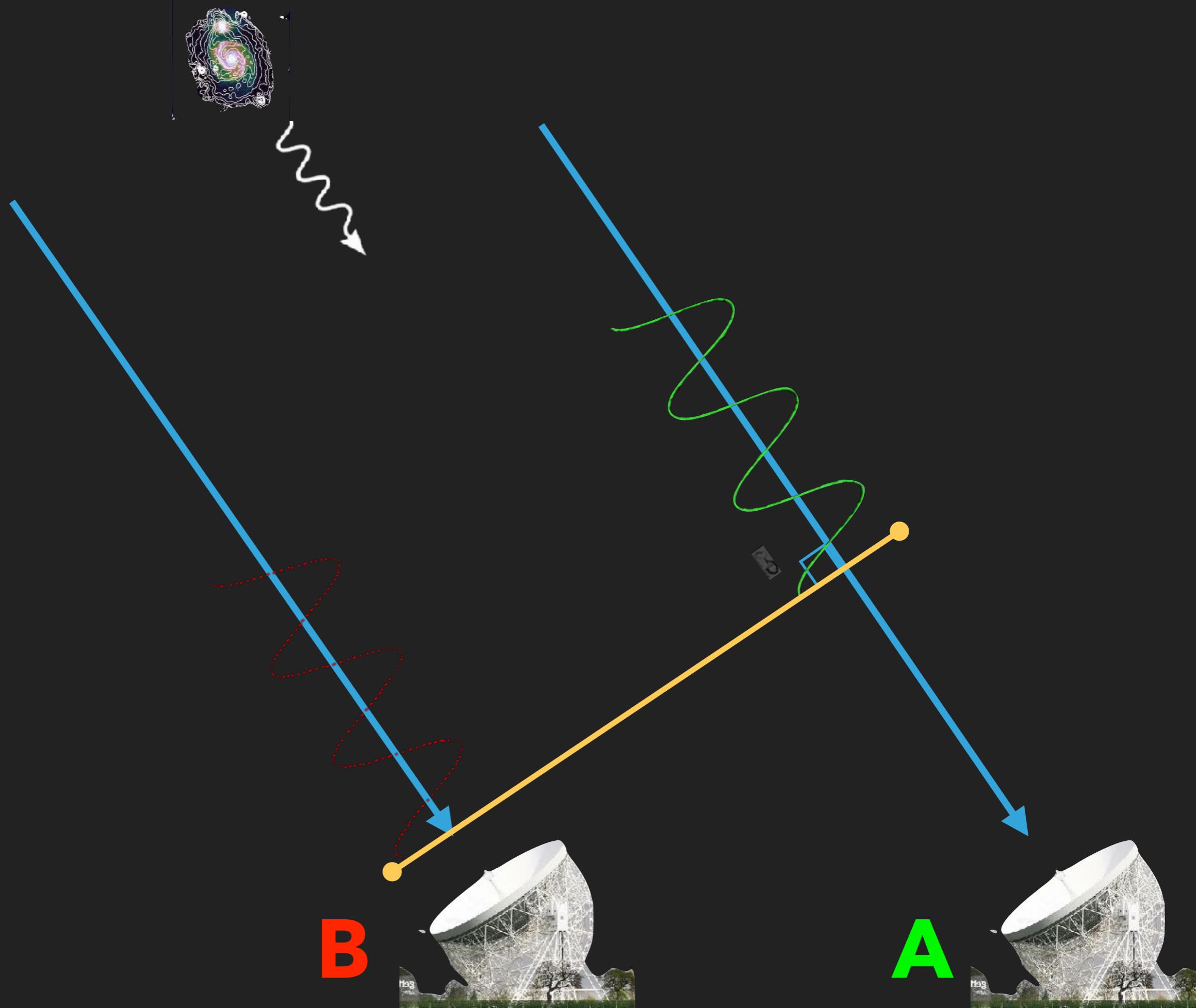


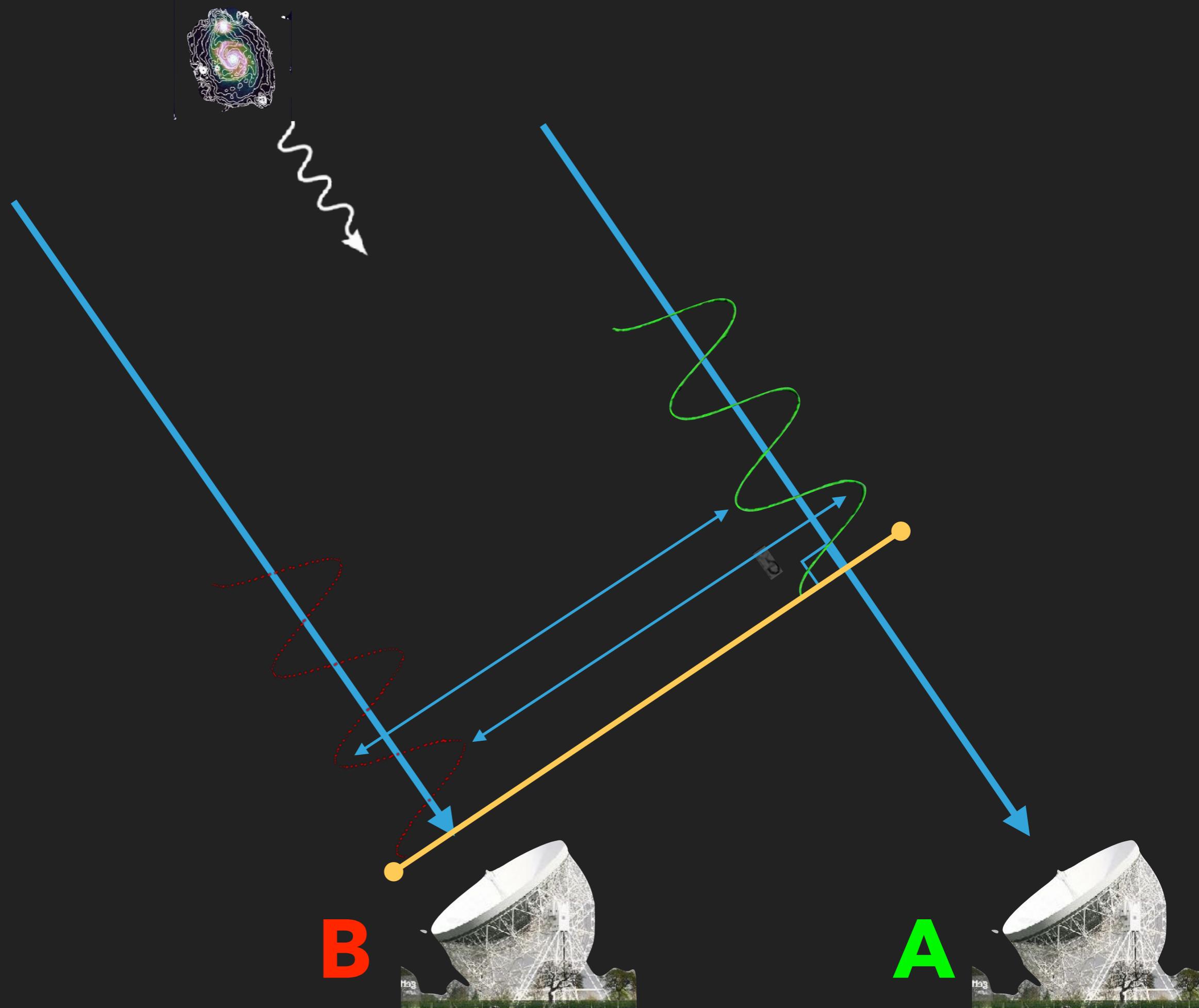
B

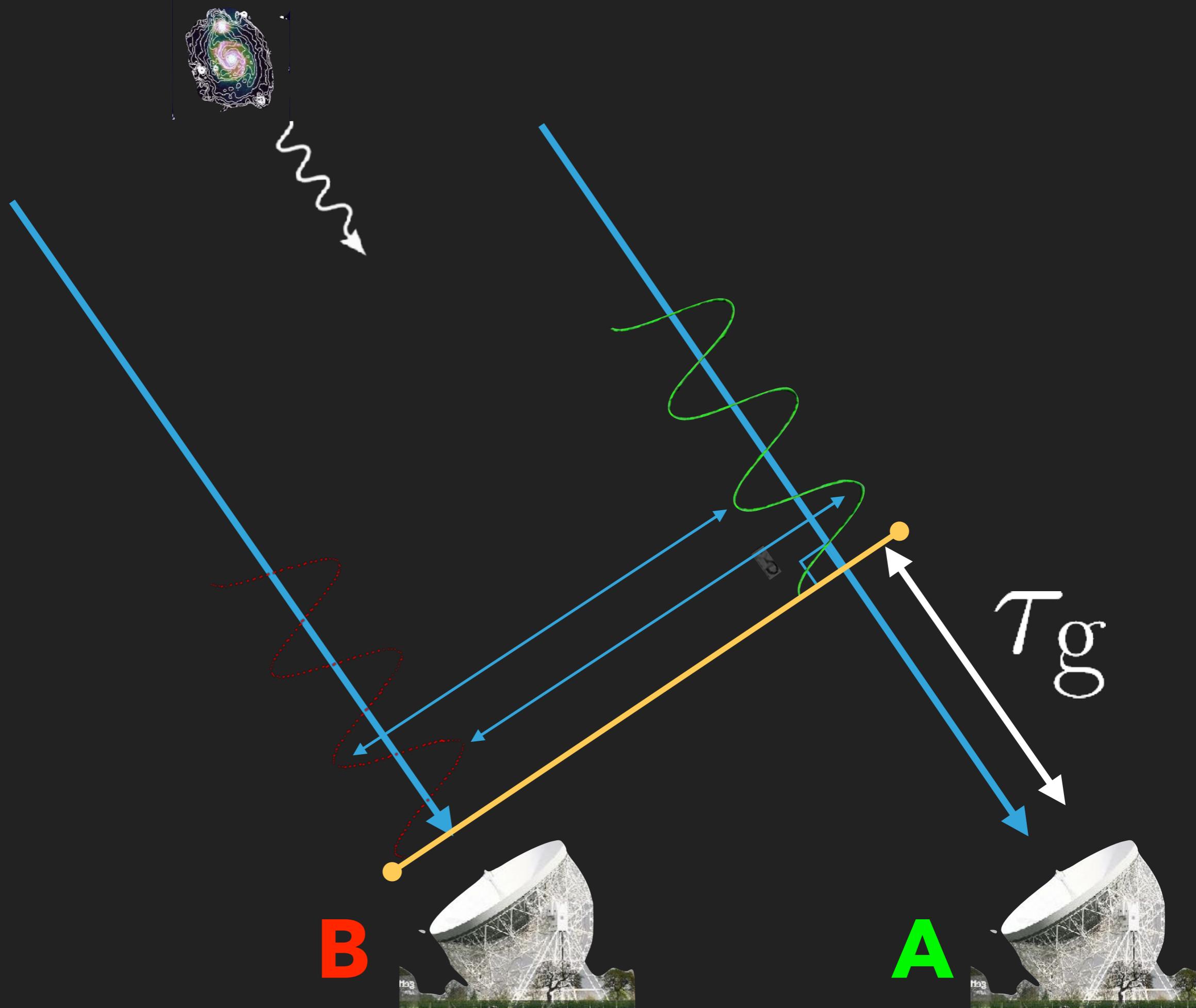


A



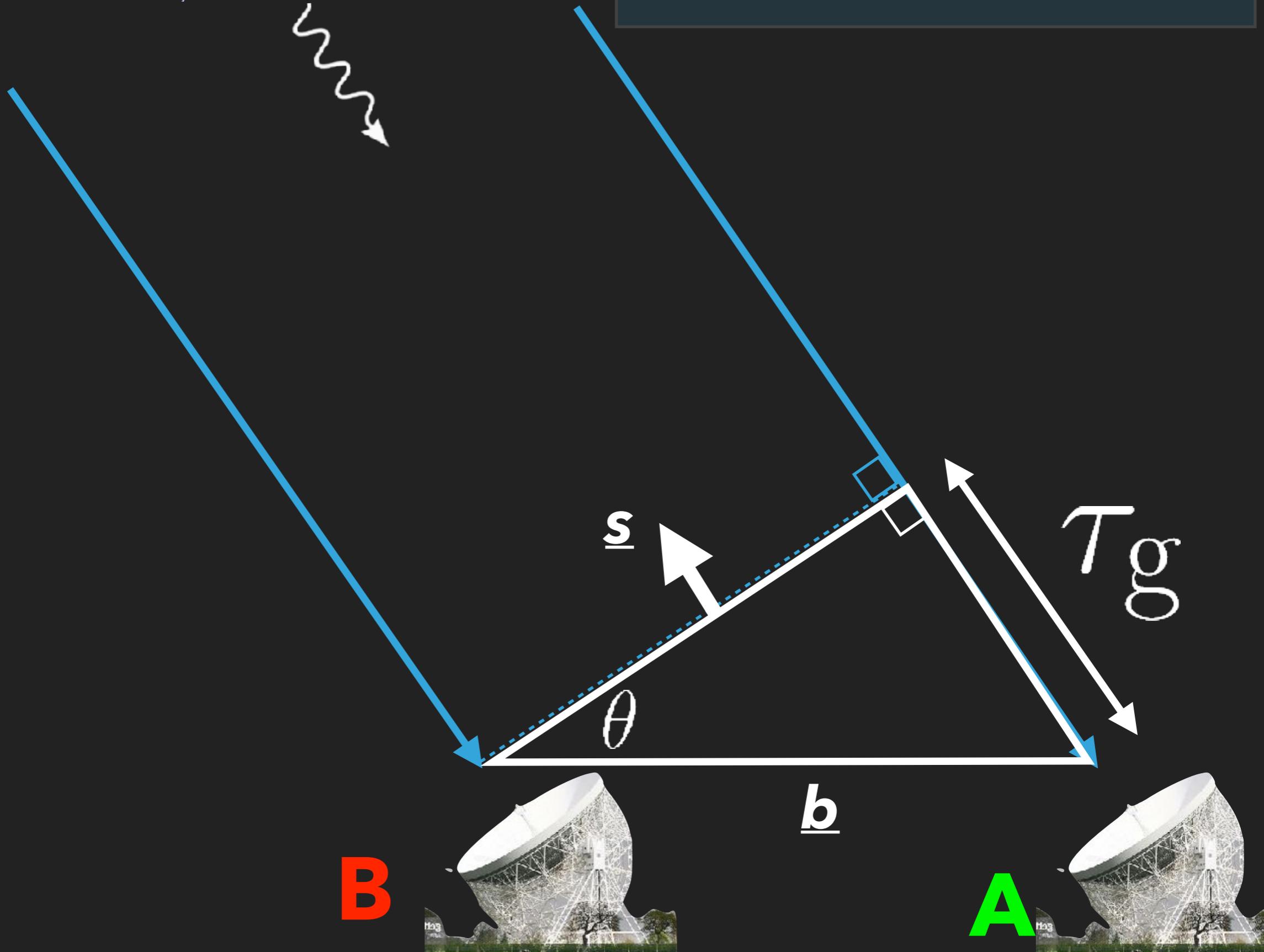


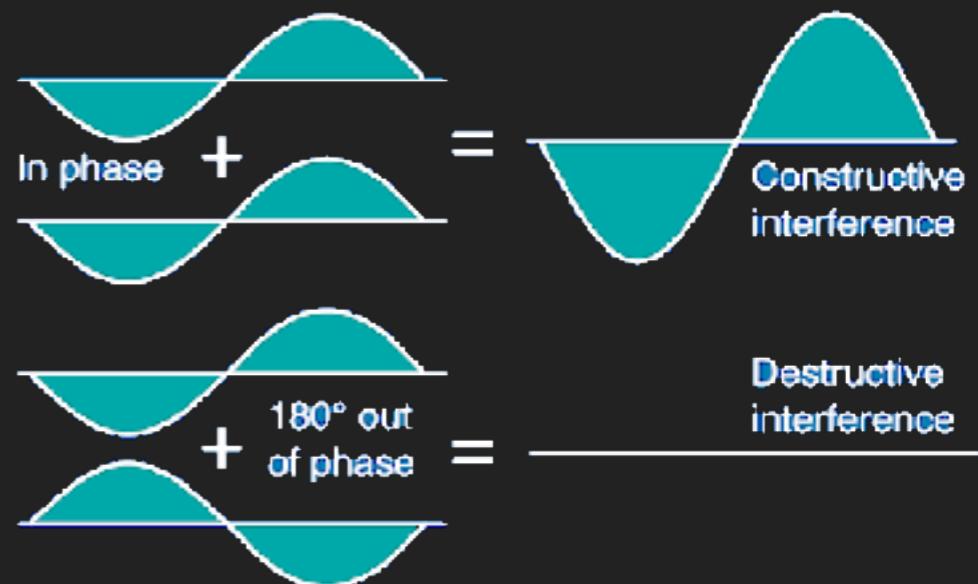






$$\tau_g = \frac{b \sin \theta}{c} = \frac{\vec{b} \cdot \vec{s}}{c}$$





$$V_B \cos \omega t$$

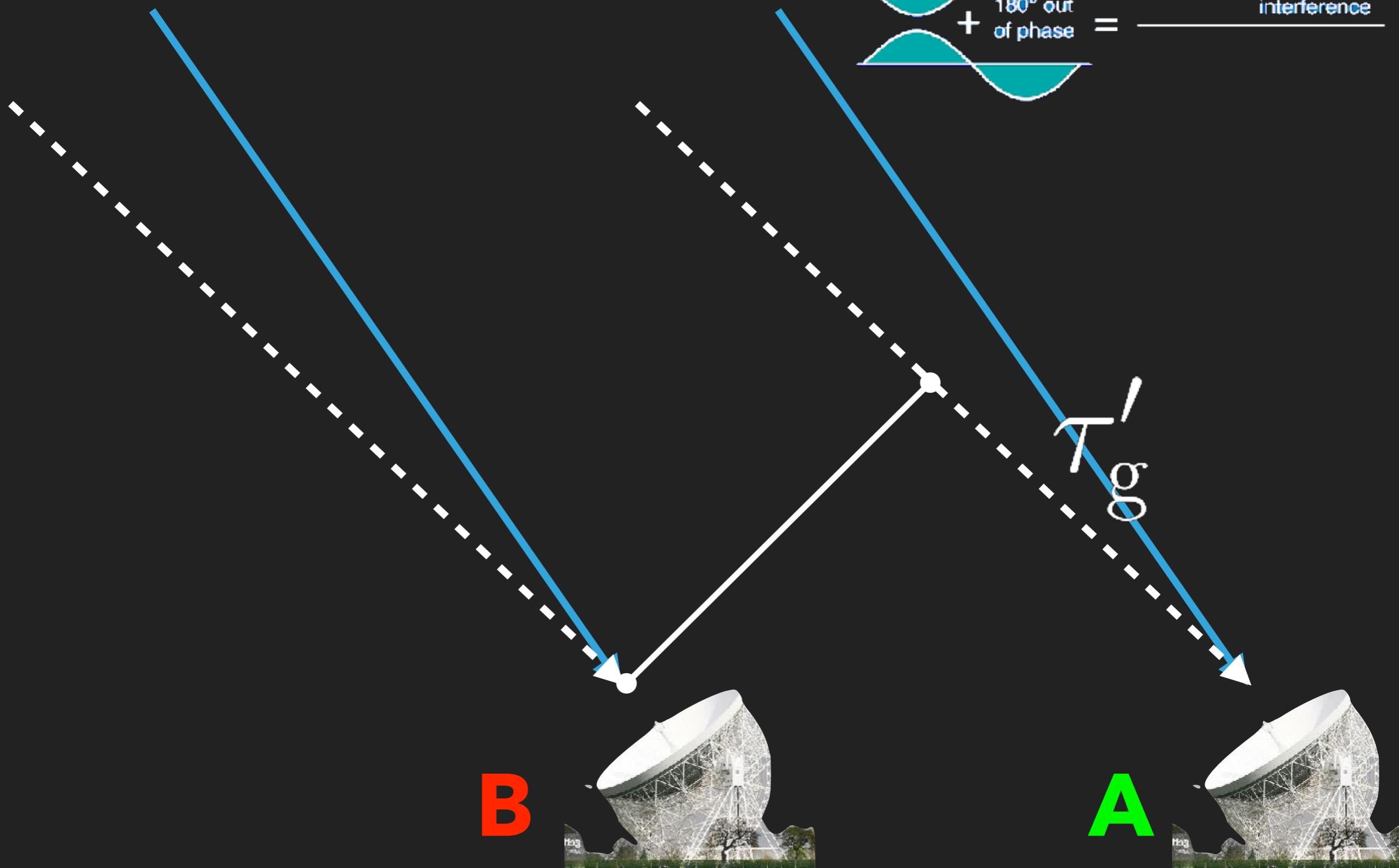
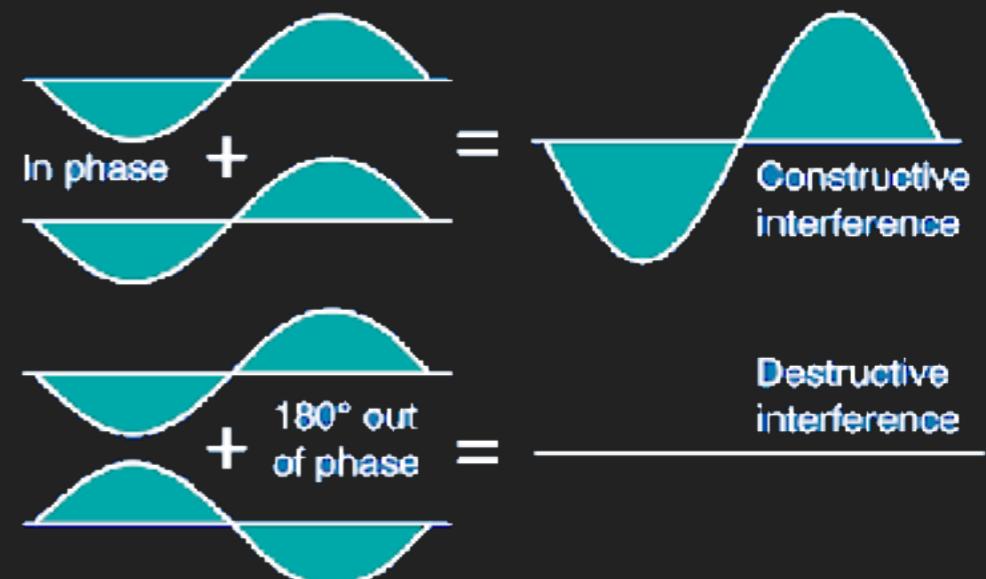
$$V_A \cos \omega(t - \tau_g)$$

B

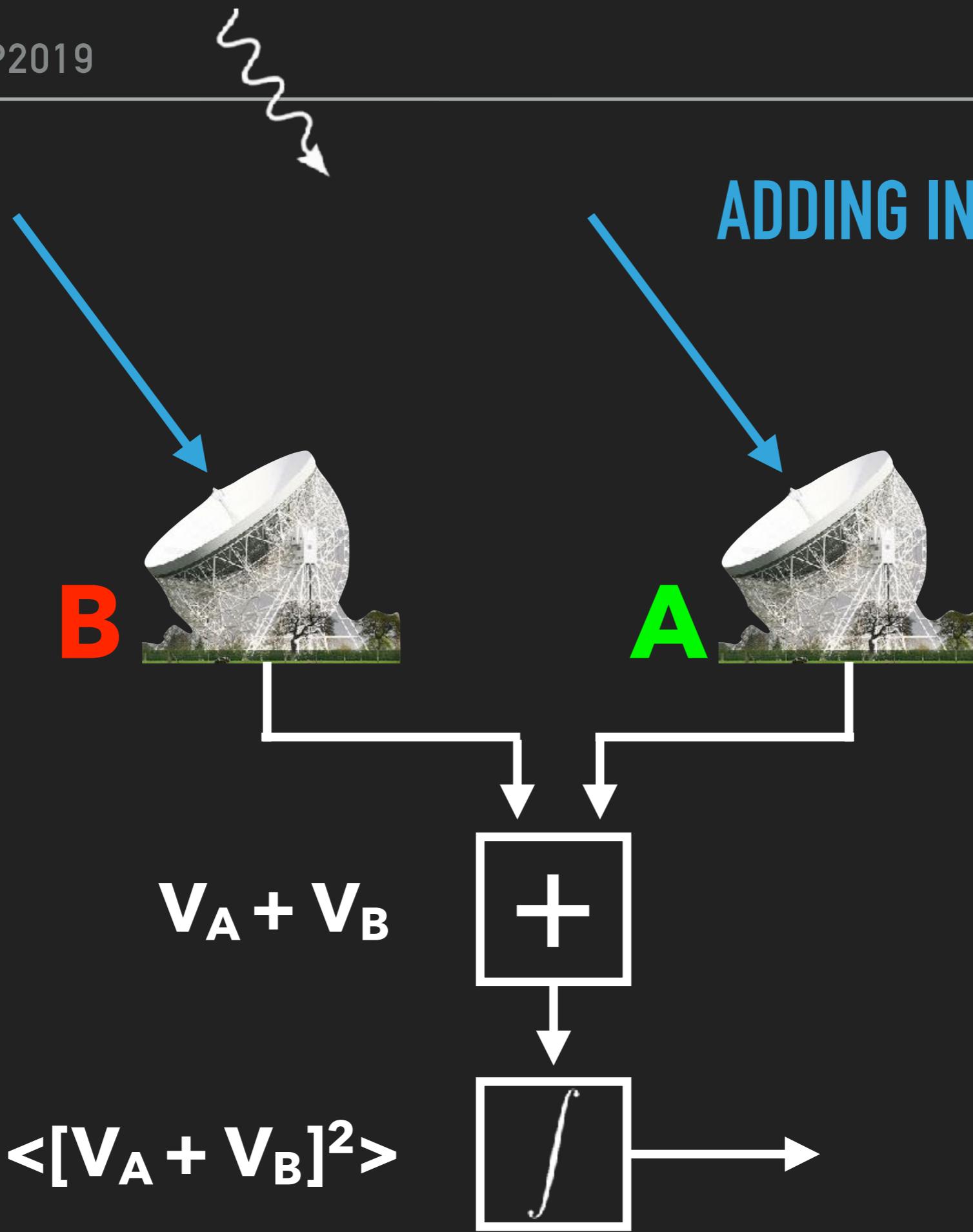


A





ADDING INTERFEROMETER



ADDING INTERFEROMETER

$$R \propto \langle [V_A \cos \omega(t - \tau_g) + V_B \cos(\omega t) + V_{\text{rec},A} + V_{\text{rec},B}]^2 \rangle$$

$$R \propto \frac{1}{2} \langle [V_A^2 + V_B^2] + [V_{\text{rec},A}^2 + V_{\text{rec},B}^2] + [V_A V_B \cos(\omega \tau_g)] \rangle$$



Antenna noise
powers
- usually small



Receiver noise
powers -
usually dominate

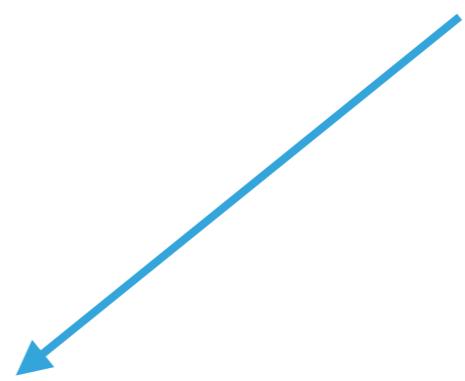


Interference fringes
vary with τ_g

s: time dependent

b: fixed geometric distance

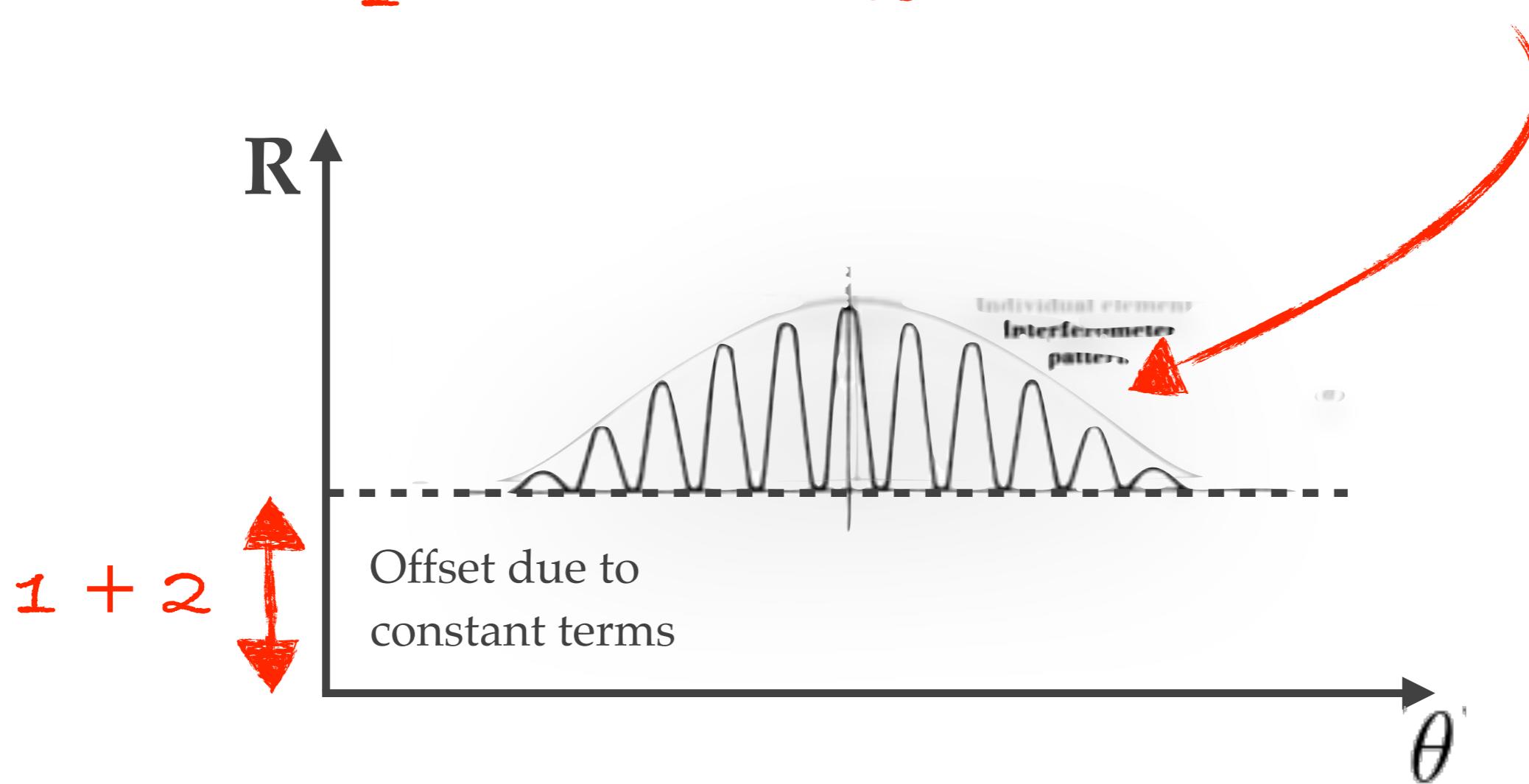
$$\tau_g = \frac{b \sin \theta}{c} = \frac{\vec{b} \cdot \vec{s}}{c}$$



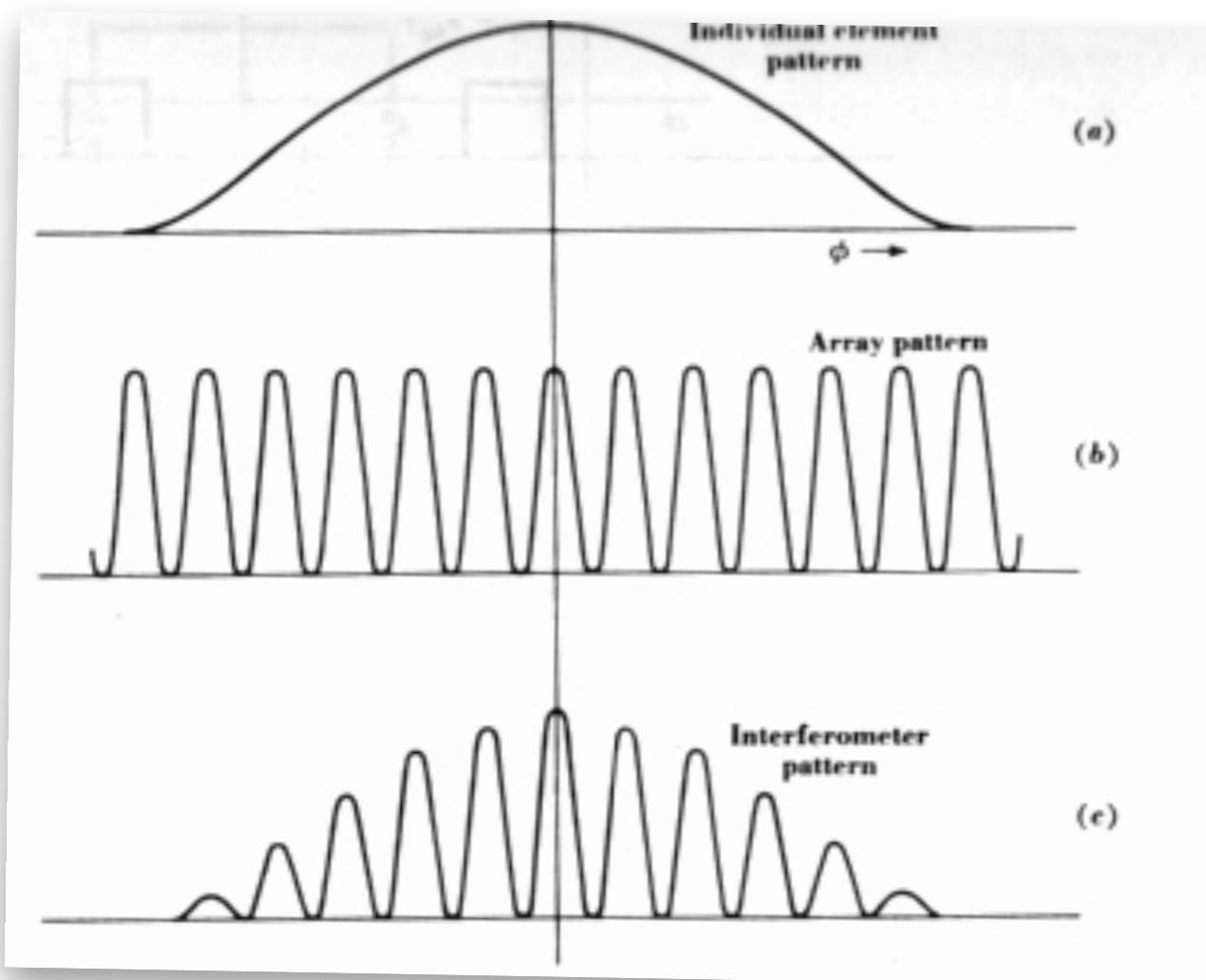
c: constant velocity

ADDING INTERFEROMETER

$$R \propto \frac{1}{2} \langle [V_A^2 + V_B^2] + [V_{\text{rec},A}^2 + V_{\text{rec},B}^2] + [V_A V_B \cos(\omega \tau_g)] \rangle$$



ADDING INTERFEROMETER



Envelope due to primary beam

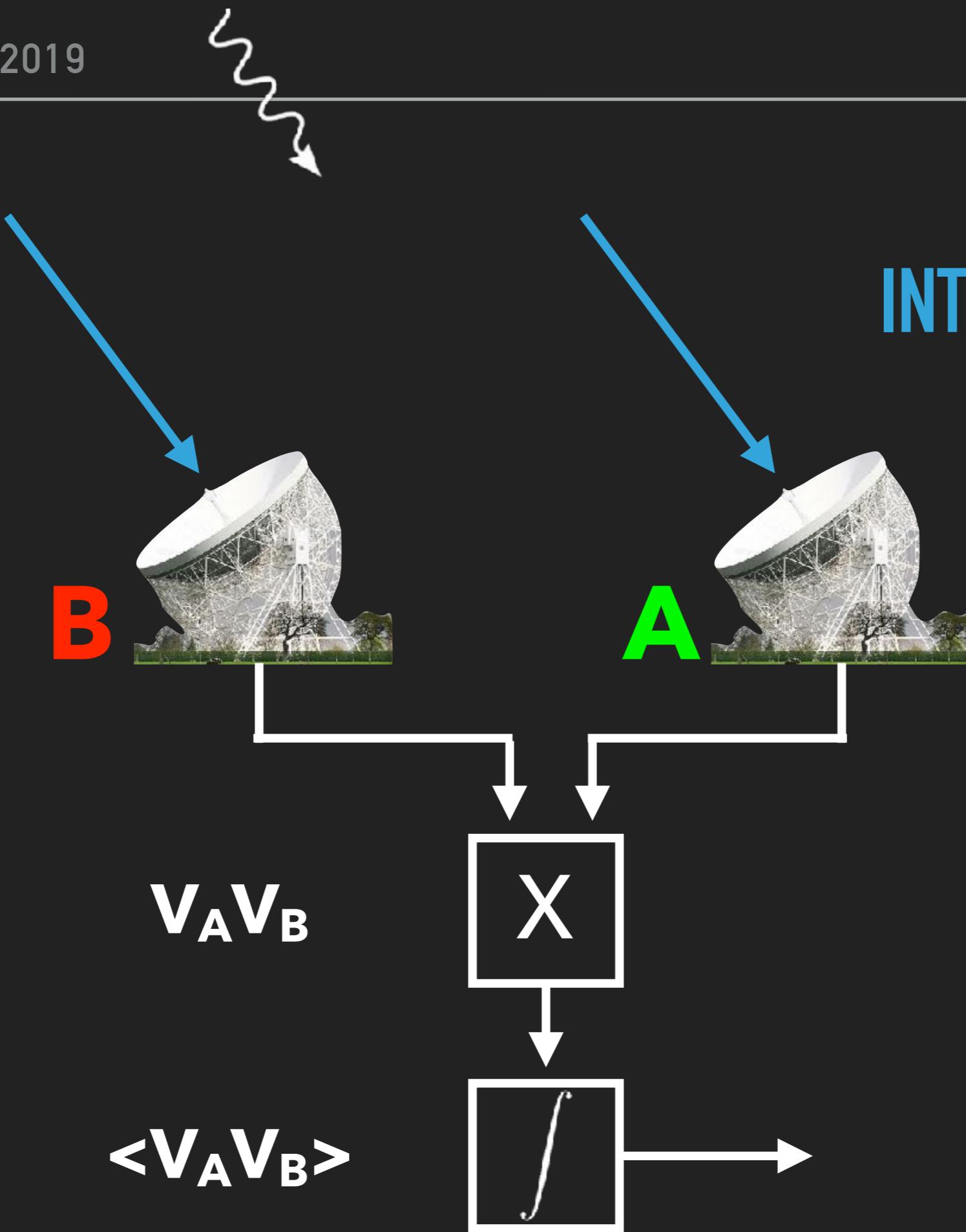
$$\frac{\lambda}{D}$$

Fringes due to interference pattern

$$\frac{\lambda}{b}$$

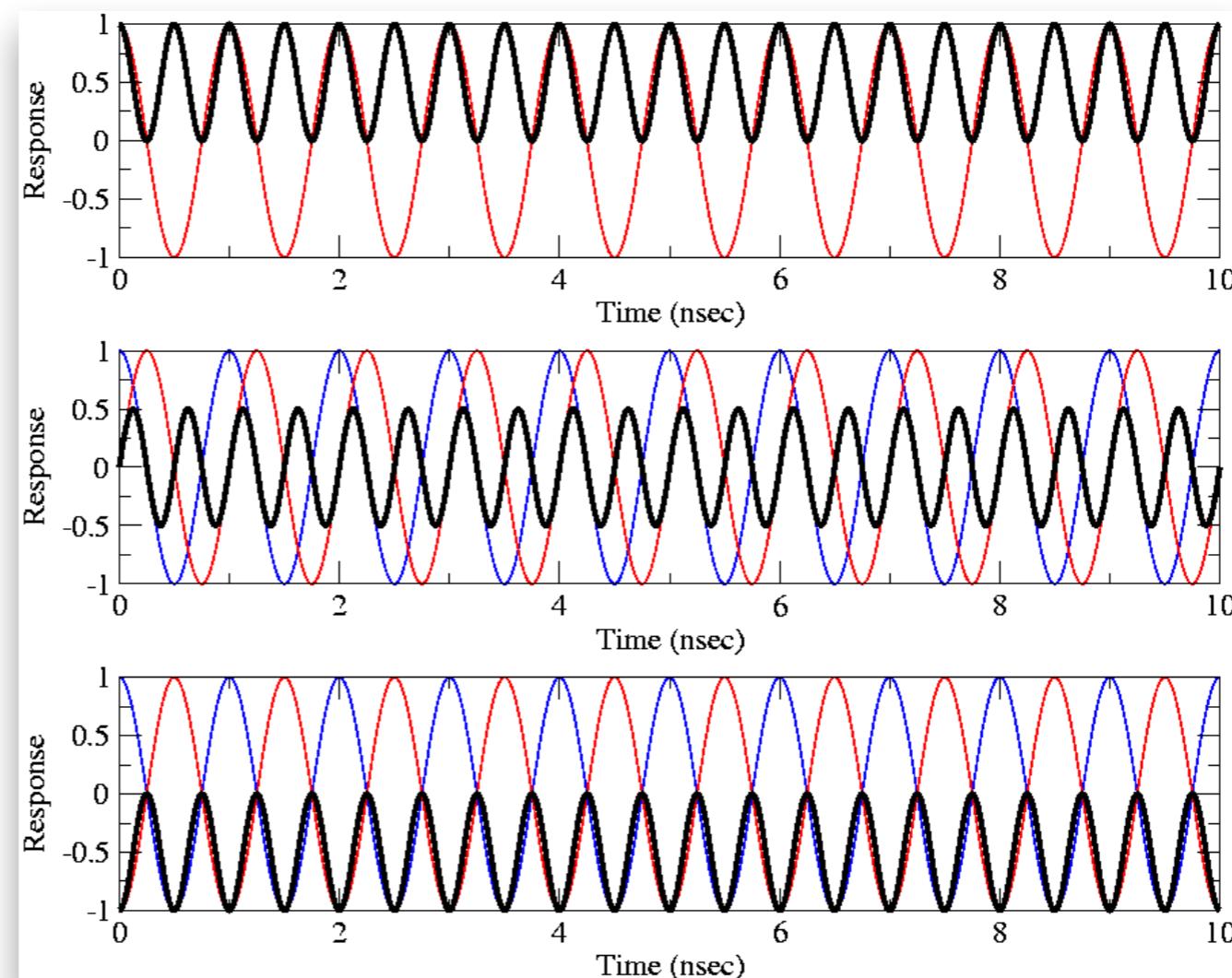
Combination

MULTIPLYING INTERFEROMETER



MULTIPLYING INTERFEROMETER

IN PHASE



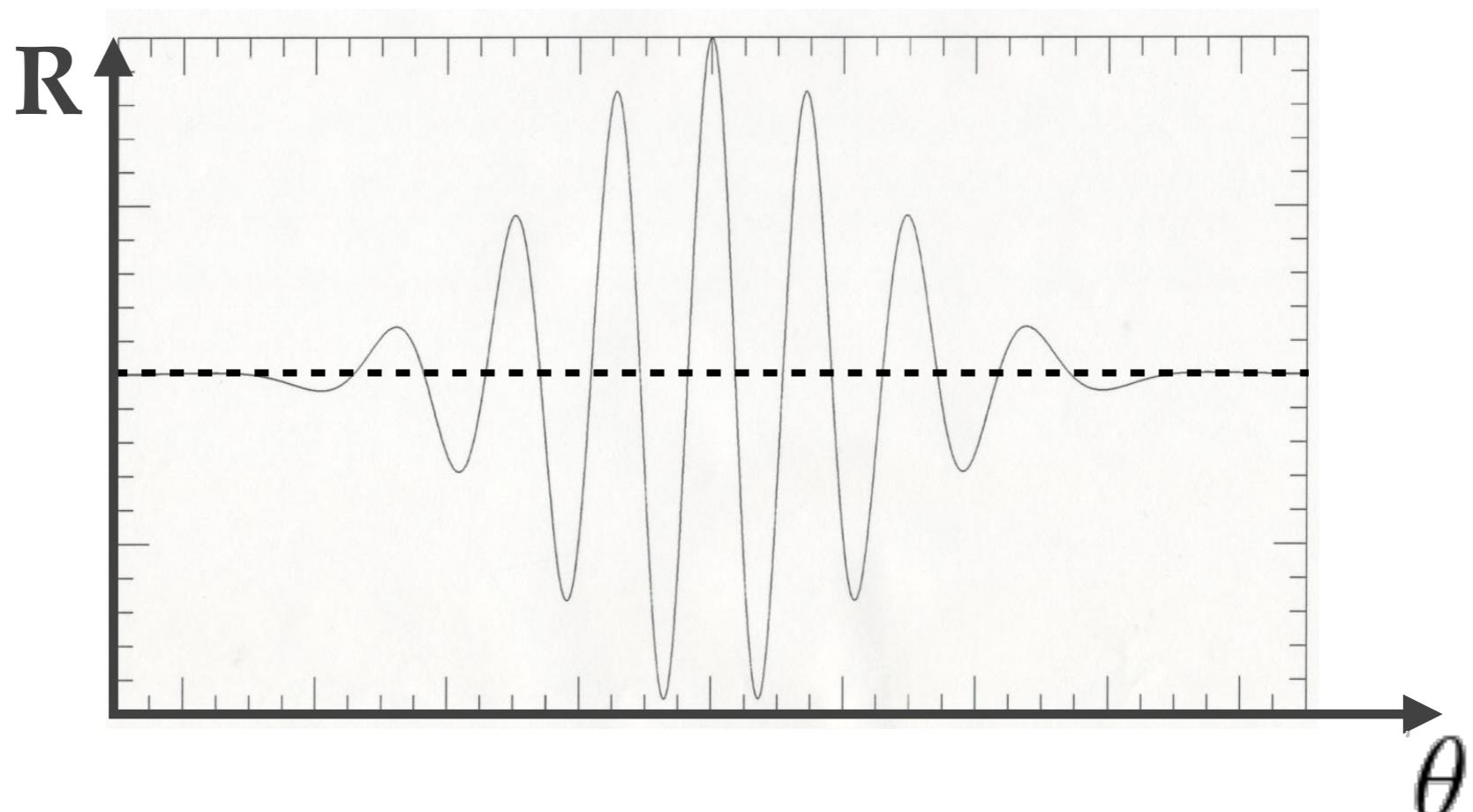
QUADRATURE PHASE

OUT OF PHASE

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

MULTIPLYING INTERFEROMETER

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



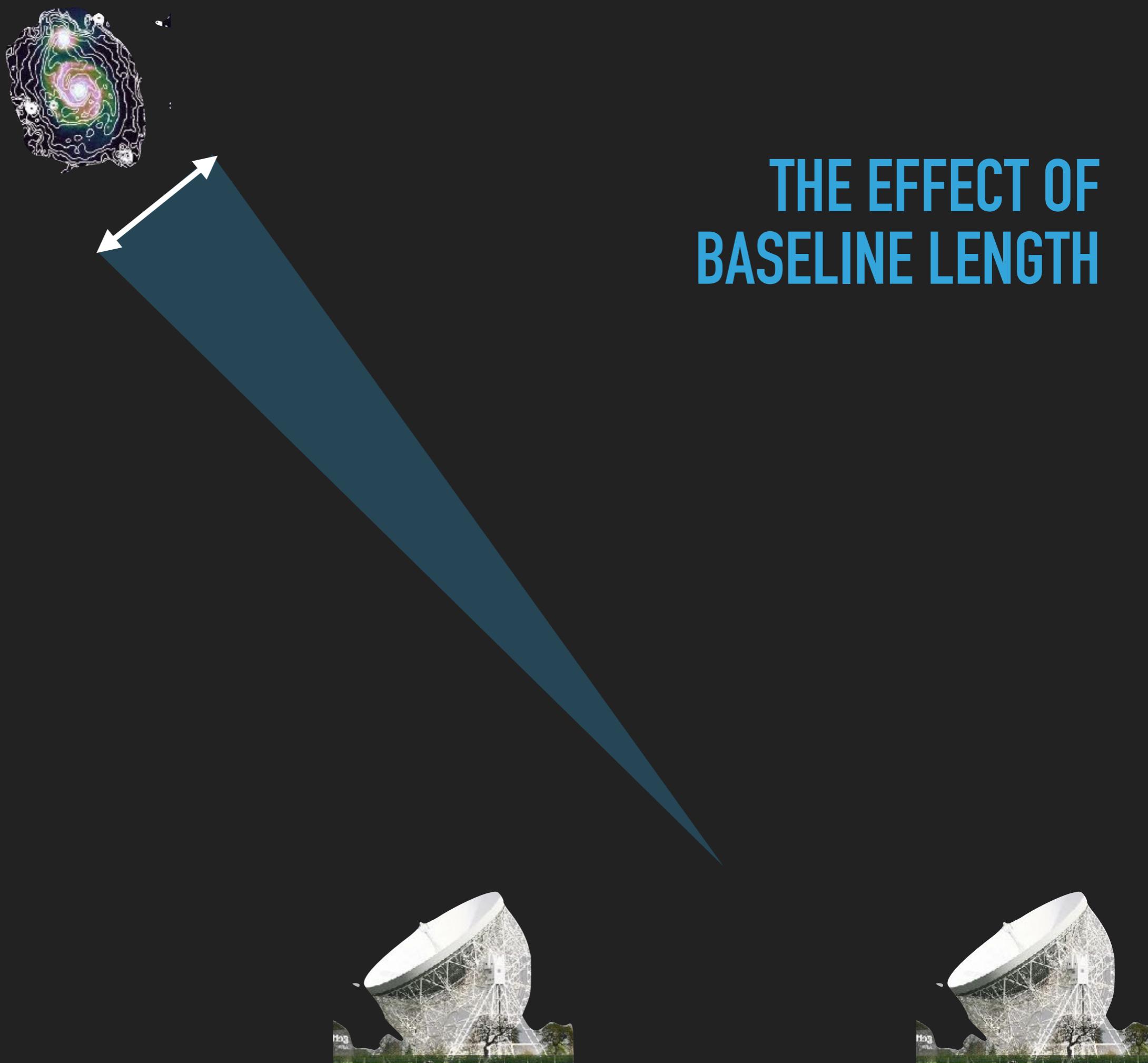
primary beam envelope:

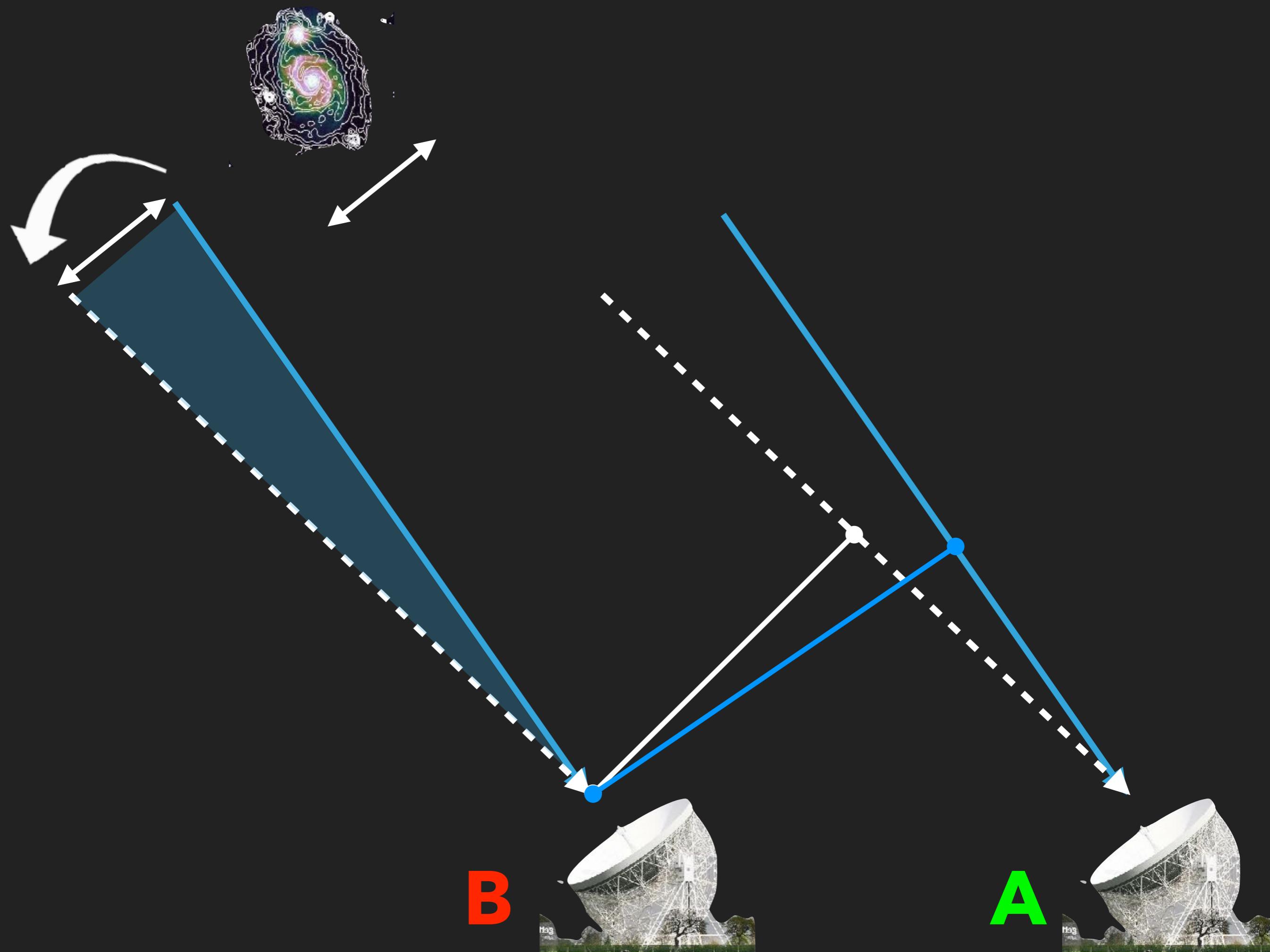
$$\frac{\lambda}{D}$$

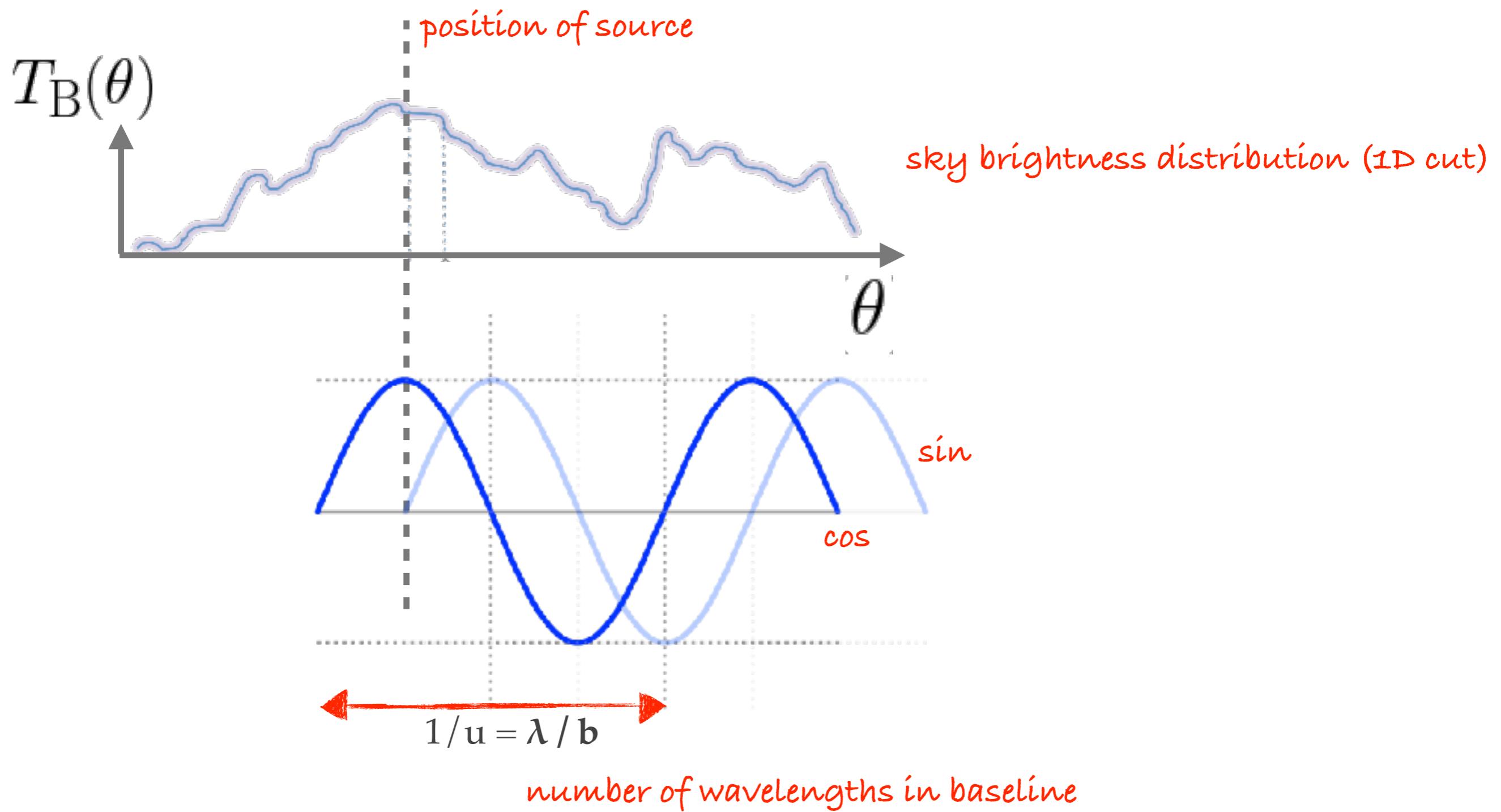
fringe spacing:

$$\frac{\lambda}{b}$$

THE EFFECT OF BASELINE LENGTH







COMPLEX VISIBILITIES

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

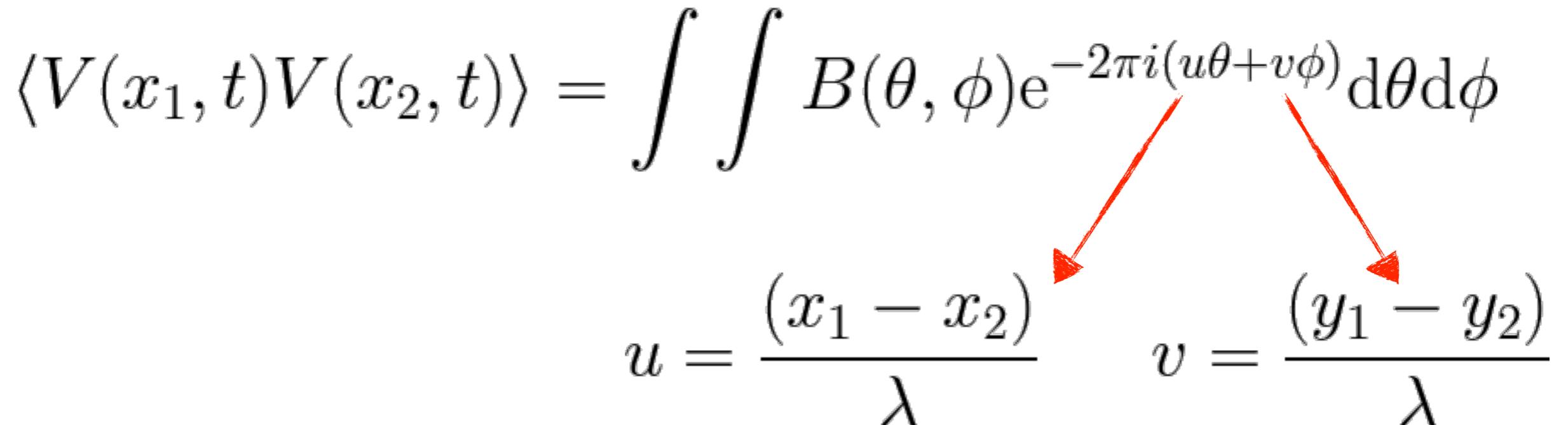
power out as a
function of
baseline

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

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

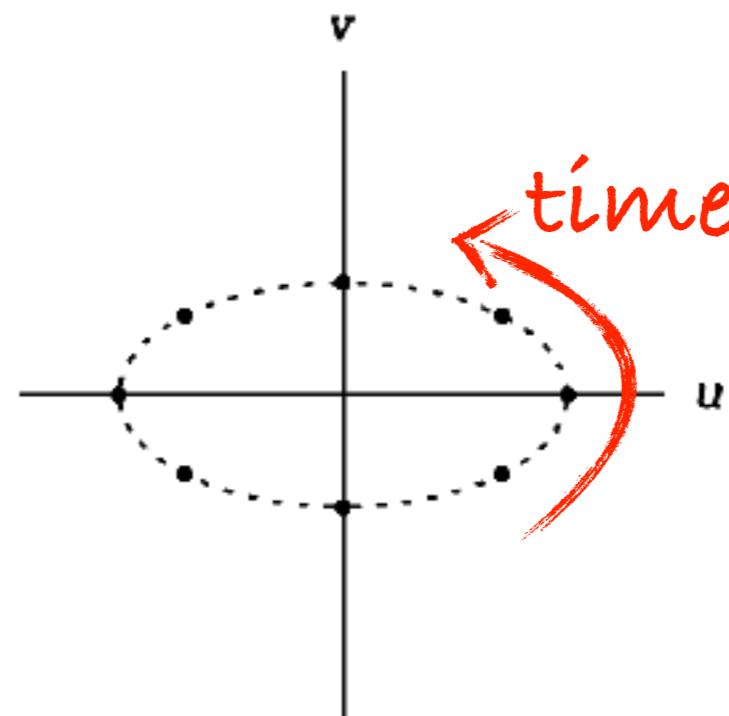
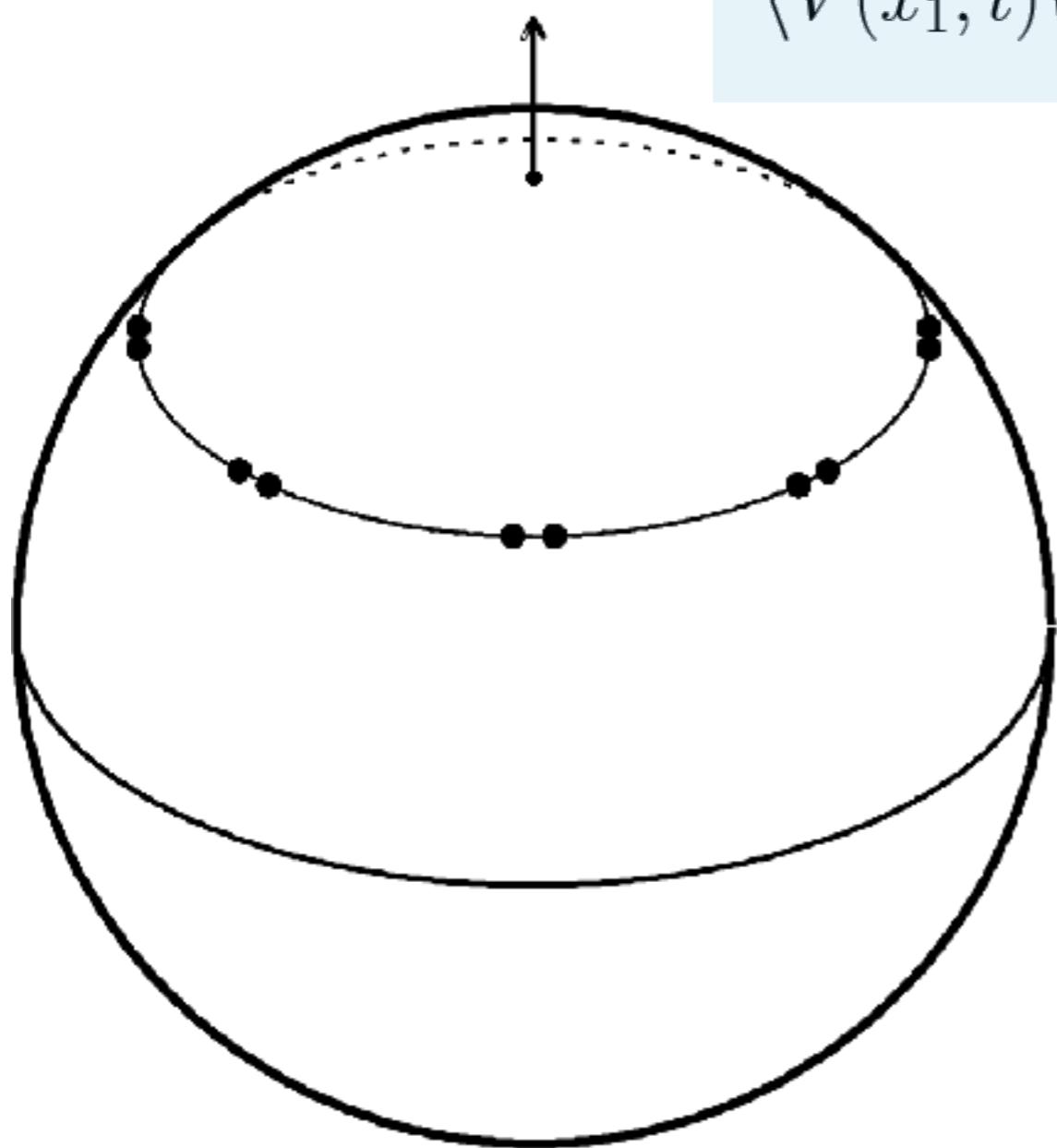
The (2-D) lateral coherence function of the radiation field in space is the Fourier Transform of the (2-D) brightness (or intensity) distribution of the source.

$$\langle V(x_1, t)V(x_2, t) \rangle = \iint B(\theta, \phi) e^{-2\pi i(u\theta + v\phi)} d\theta d\phi$$
$$u = \frac{(x_1 - x_2)}{\lambda} \quad v = \frac{(y_1 - y_2)}{\lambda}$$


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

EARTH ROTATION APERTURE SYNTHESIS

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



VISIBILITY

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

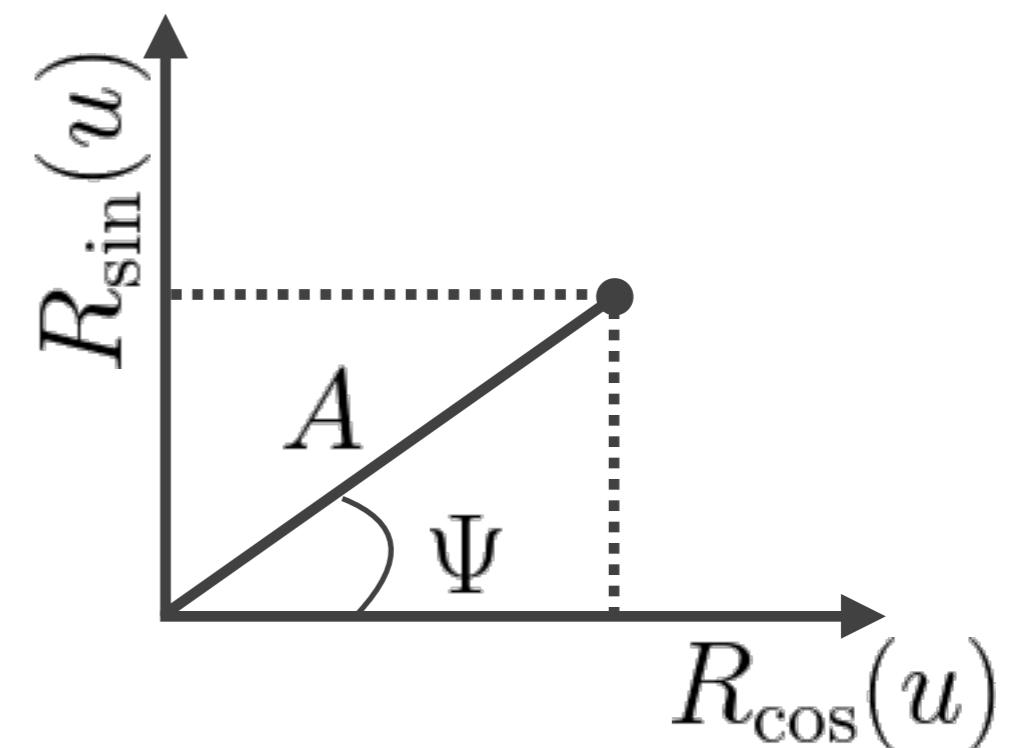
$$A e^{i\Psi}$$

amplitude phase

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

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

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



VISIBILITIES & IMAGES

$$\begin{aligned} I_{meas}(l,m) &= \frac{1}{M} \sum_{i=1}^M V(u_i, v_i) e^{2\pi i (u_i l + v_i m)} \\ &= \frac{1}{M} \sum_{i=1}^M V(u_i, v_i) [\cos[2\pi(u_i l + v_i m)] + i \sin[2\pi(u_i l + v_i m)]] \end{aligned}$$

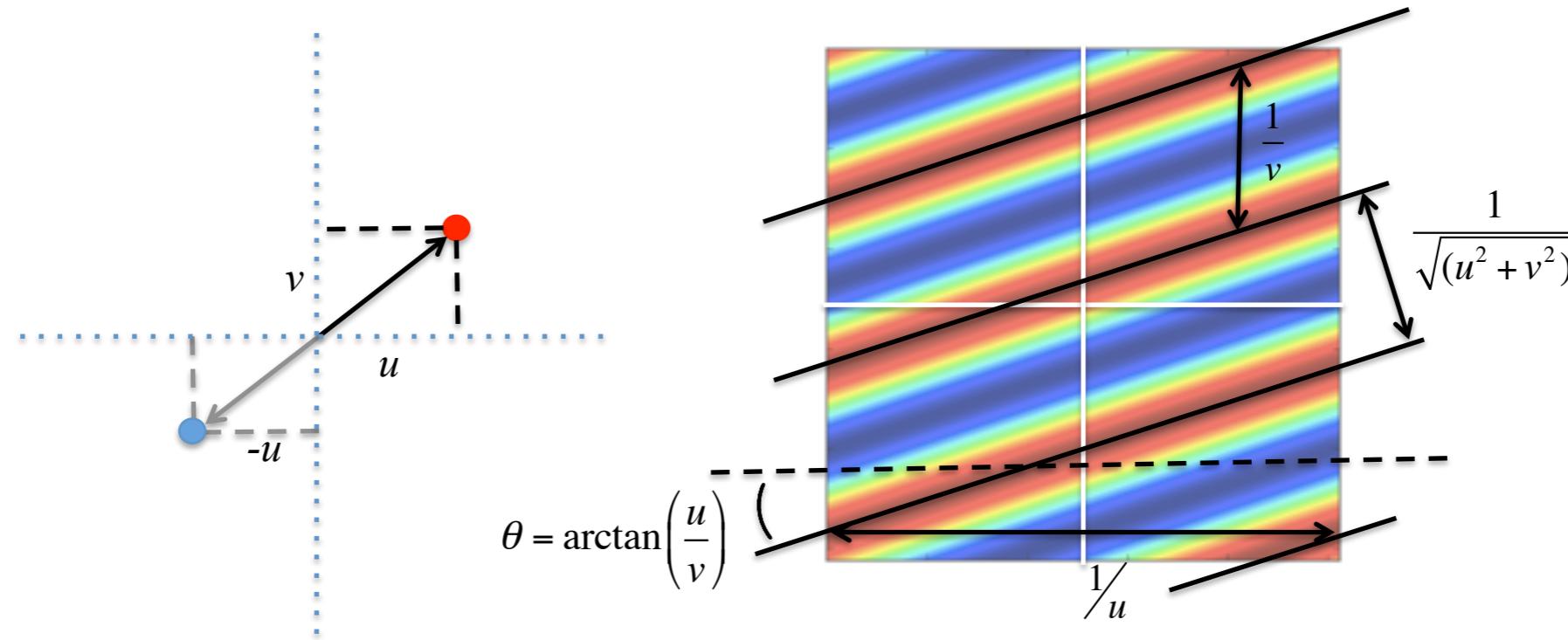
This is a **complex** quantity, but the sky intensity is **real**.

$$V(-u, -v) = V^*(u, v)$$

If we change our notation slightly, so that $V = A e^{i\phi}$, 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

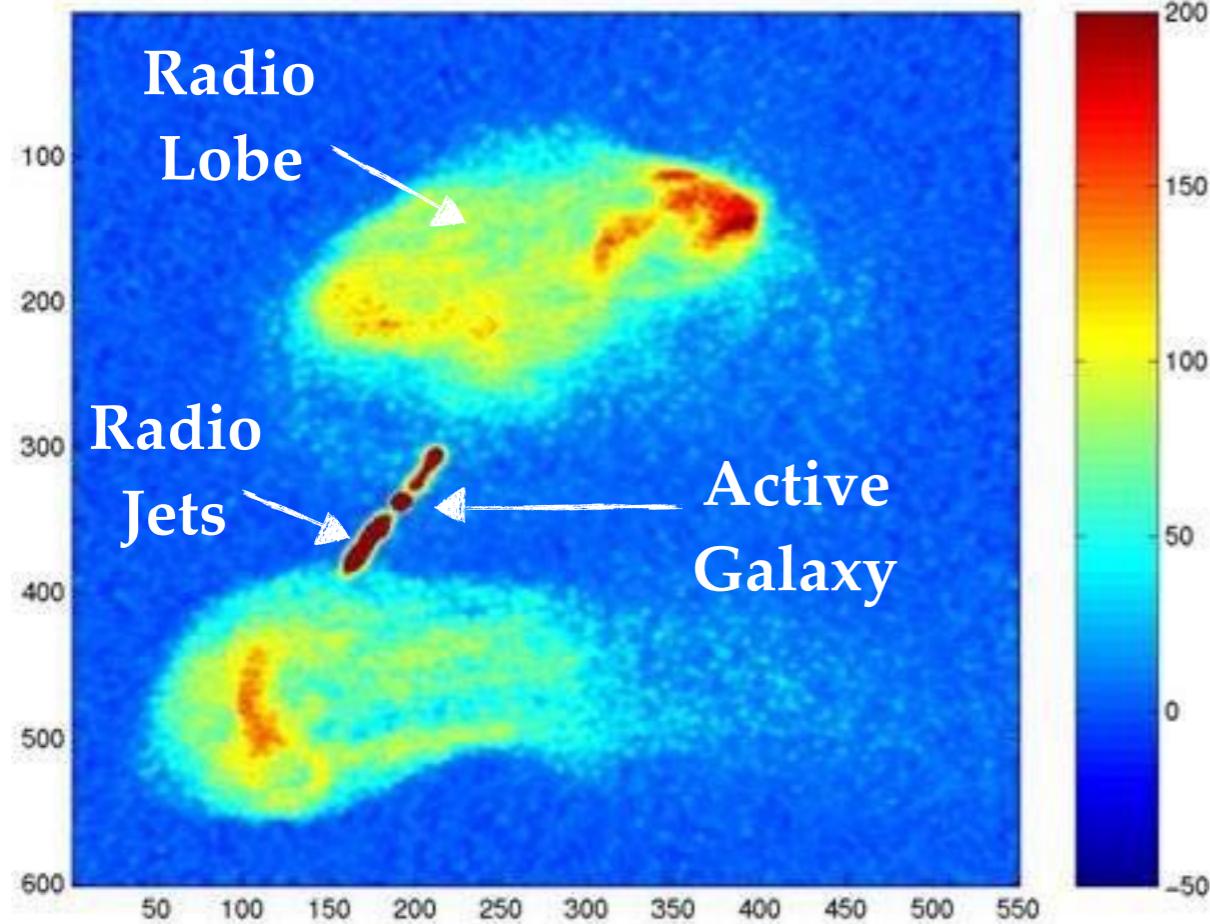


Writing the equation in this way allows us to visualise how our image is composed.

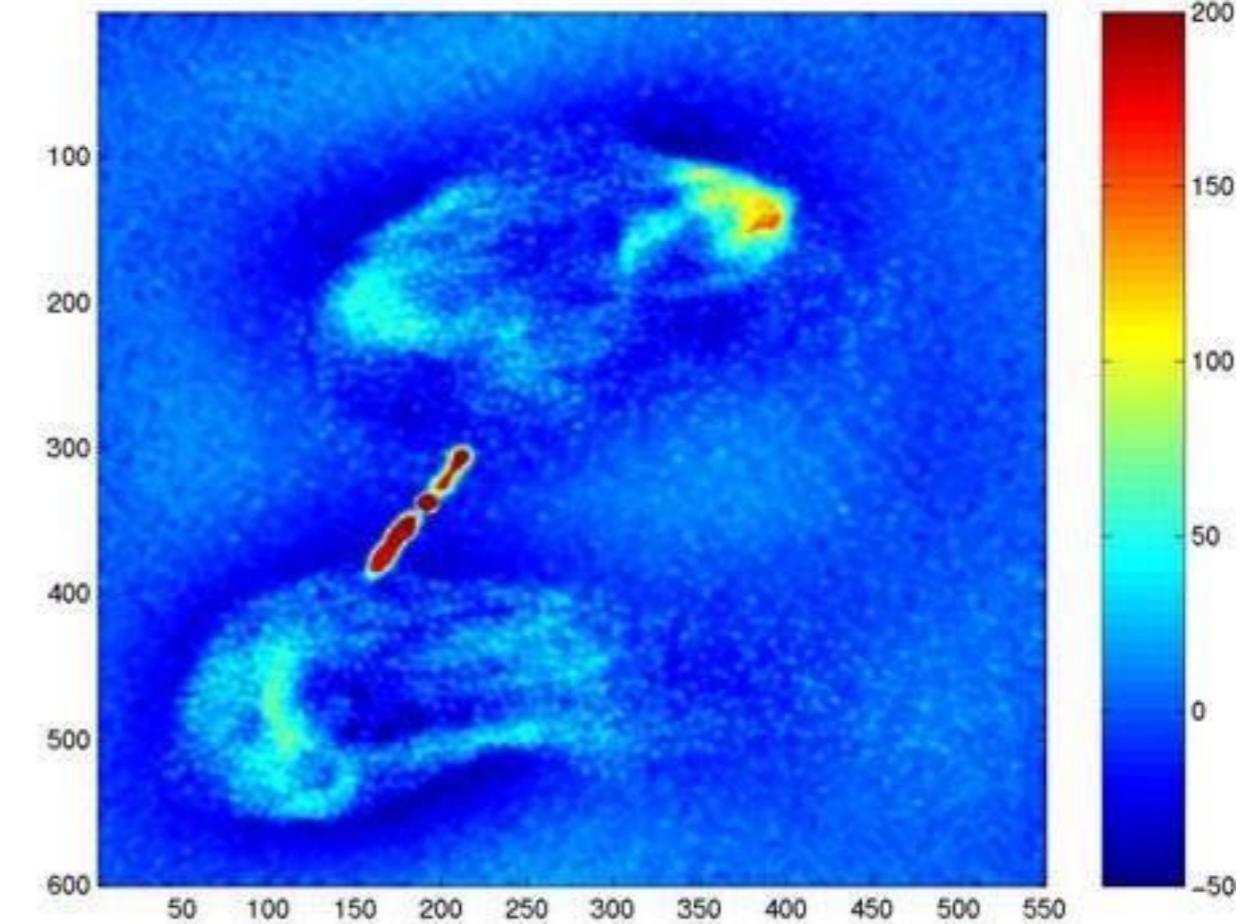
$$I_{meas}(l,m) = \frac{1}{M} \sum_{i=1}^M A(u_i, v_i) \cos[2\pi(u_i l + v_i m) + \phi_i]$$

BASELINE LENGTH

WITH SHORT BASELINES



NO SHORT BASELINES



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

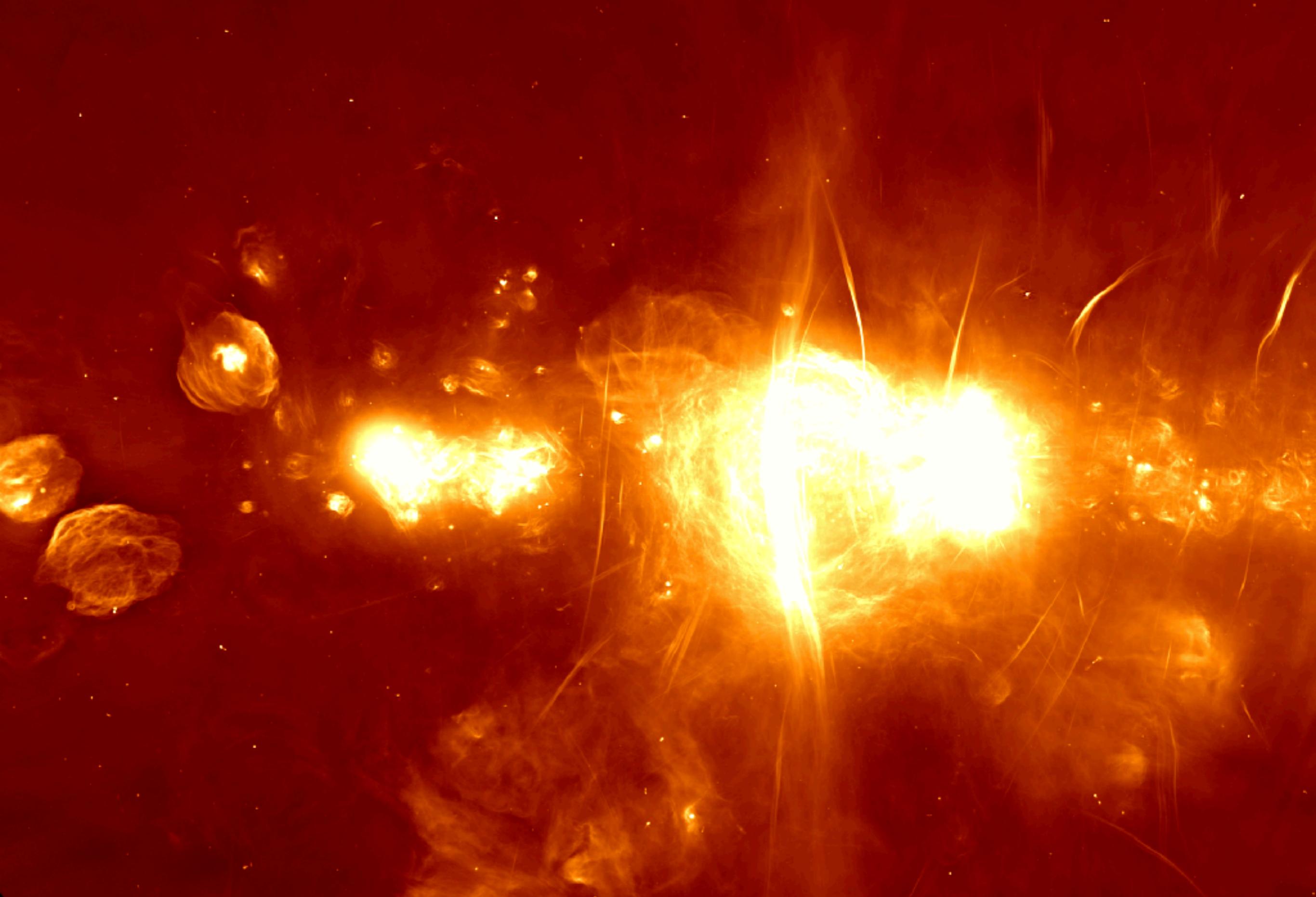


Image credit: South African Radio Astronomy Observatory

- ▶ 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.