Radio Astronomy (Lecture I)

Plan

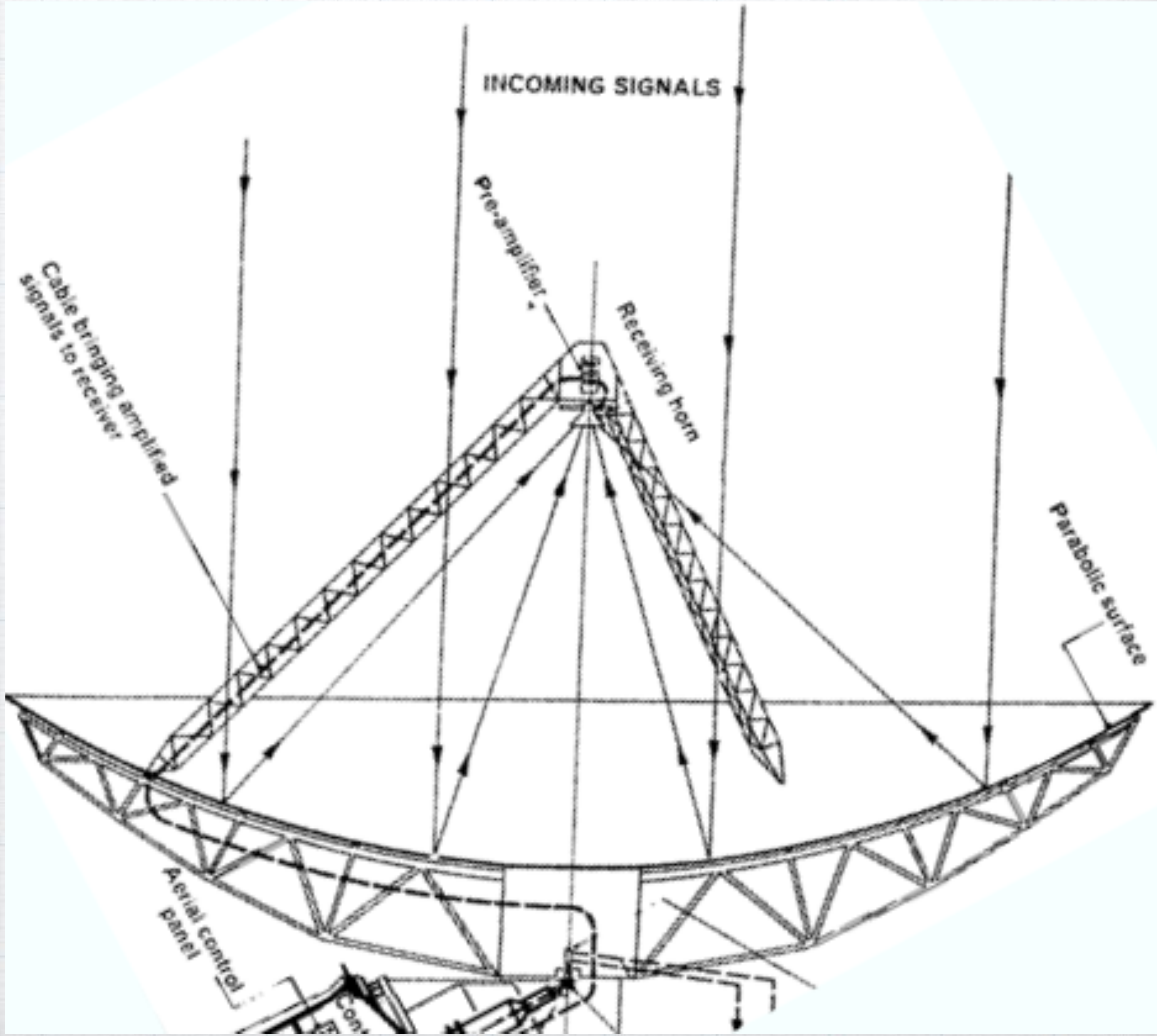
- **build a radio interferometer / GMRT**
    - Why?
- **Why radio astronomy**?
    - (assorted) examples
- **Aperture synthesis**
    - interferometer
    - (introducing) GMRT
- **Science at NCRA-TIFR**
    - What do radio astronomers do?
        - ... some **fun stuff**

Angular resolution: its importance

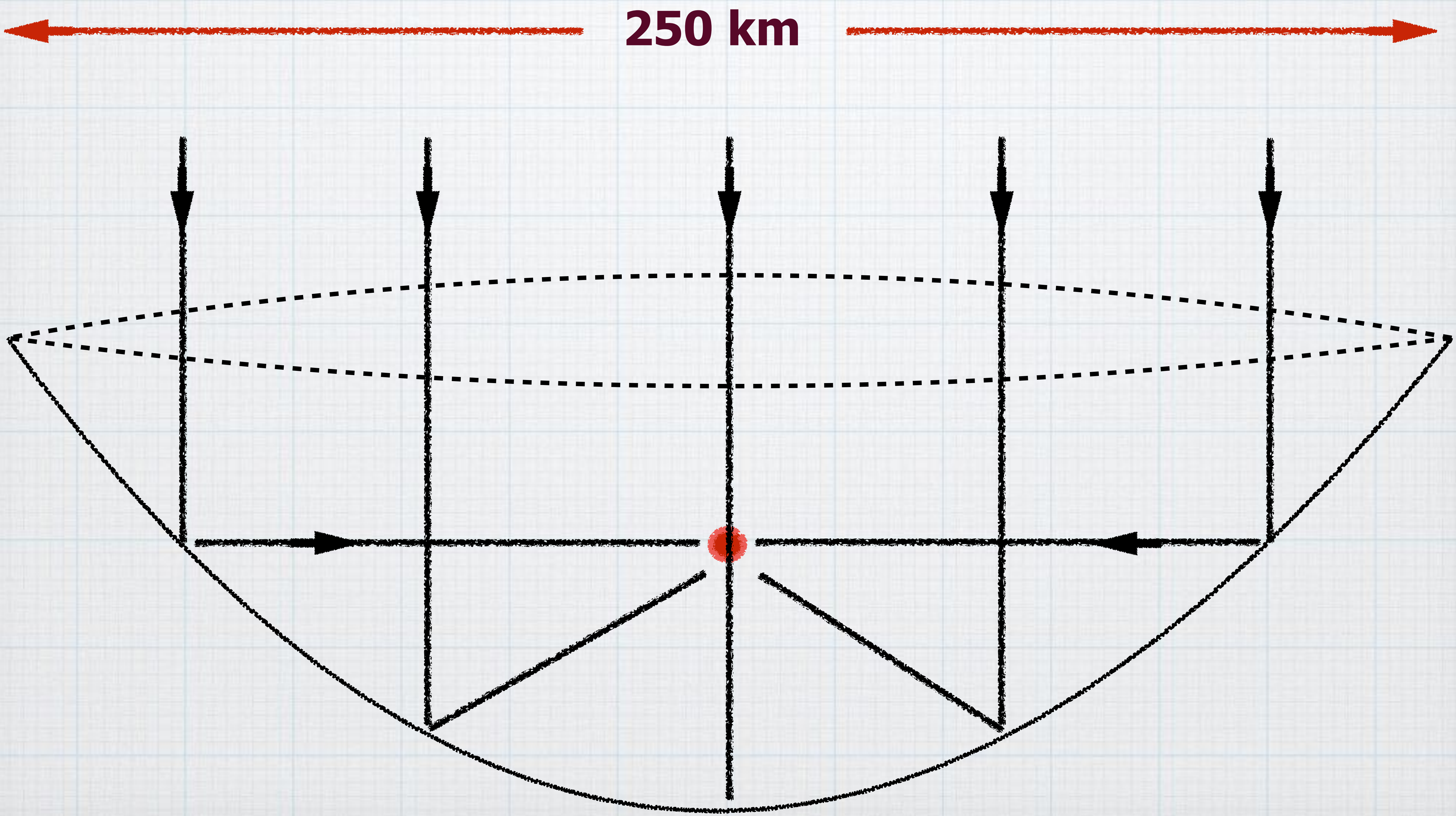
- Human eye pupil: 0.5 cm diameter
  - ~0.05 deg resolution at 600 nm (yellow-light)

- Radio telescope:
  - 10 m diameter, 1.4 deg resolution at 2 m
  - 2.8 km diameter for same resolution as human eye
  - 250 km diameter for same resolution as optical telescope

Angular resolution

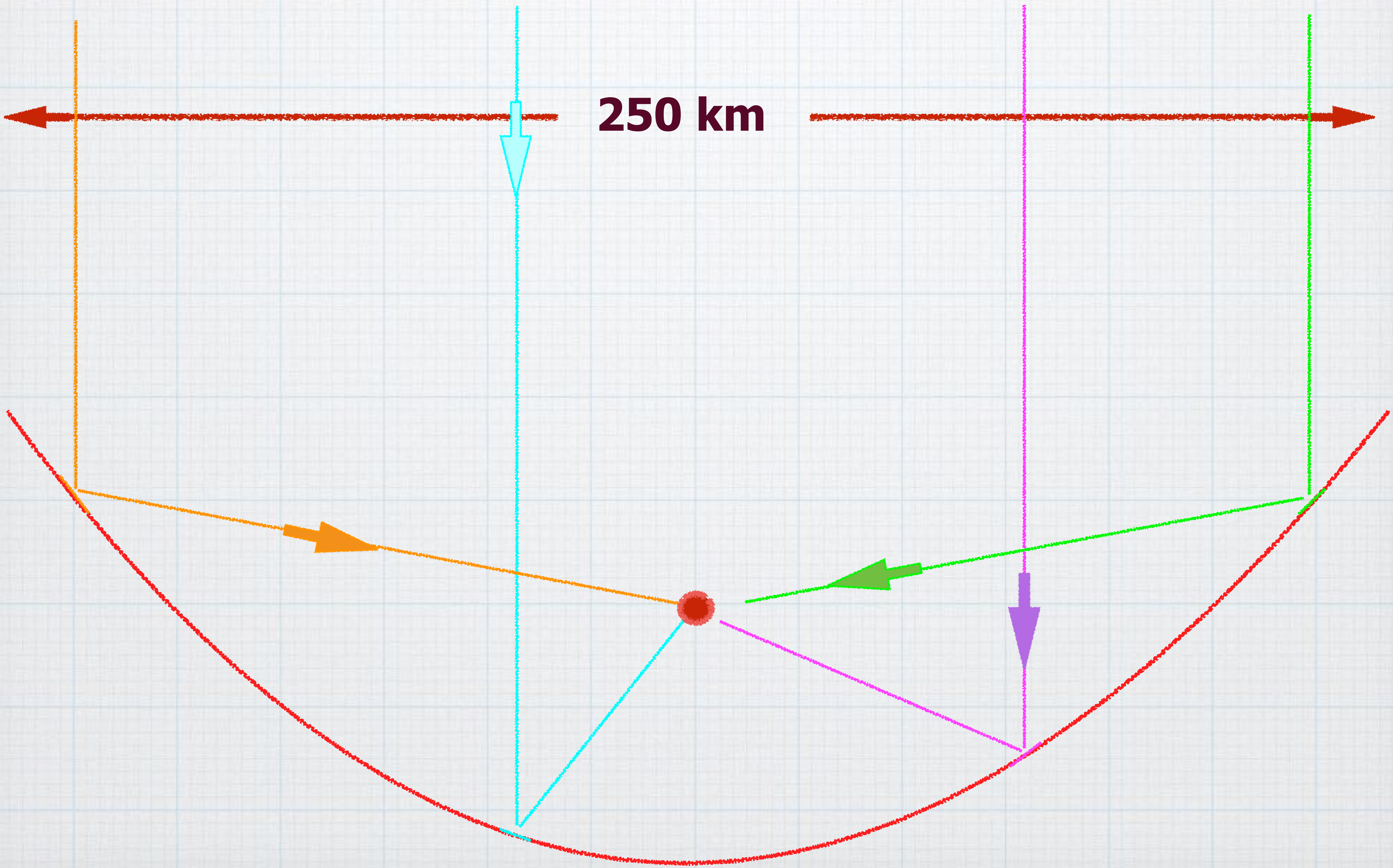


build an interferometer

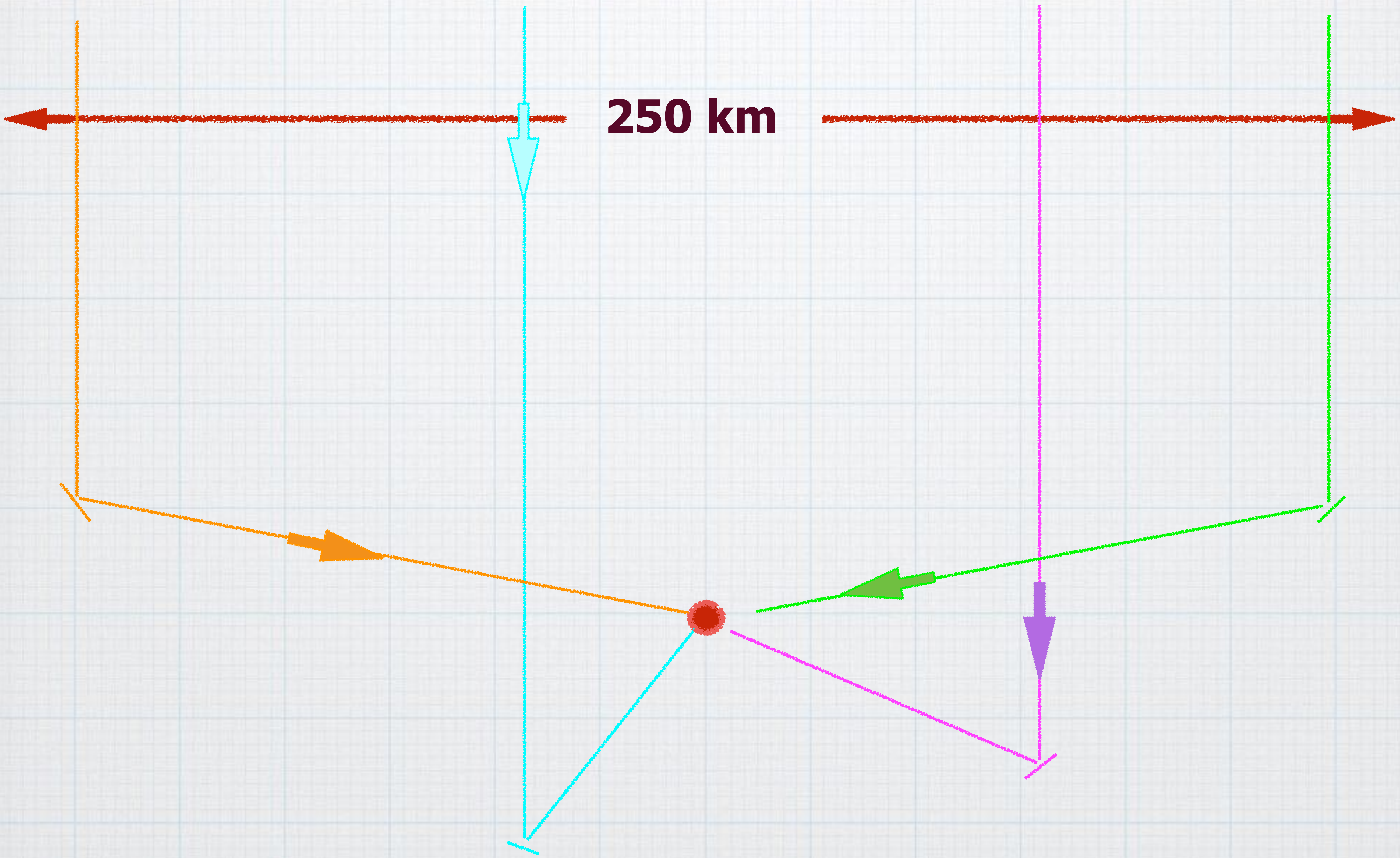


build GMRT

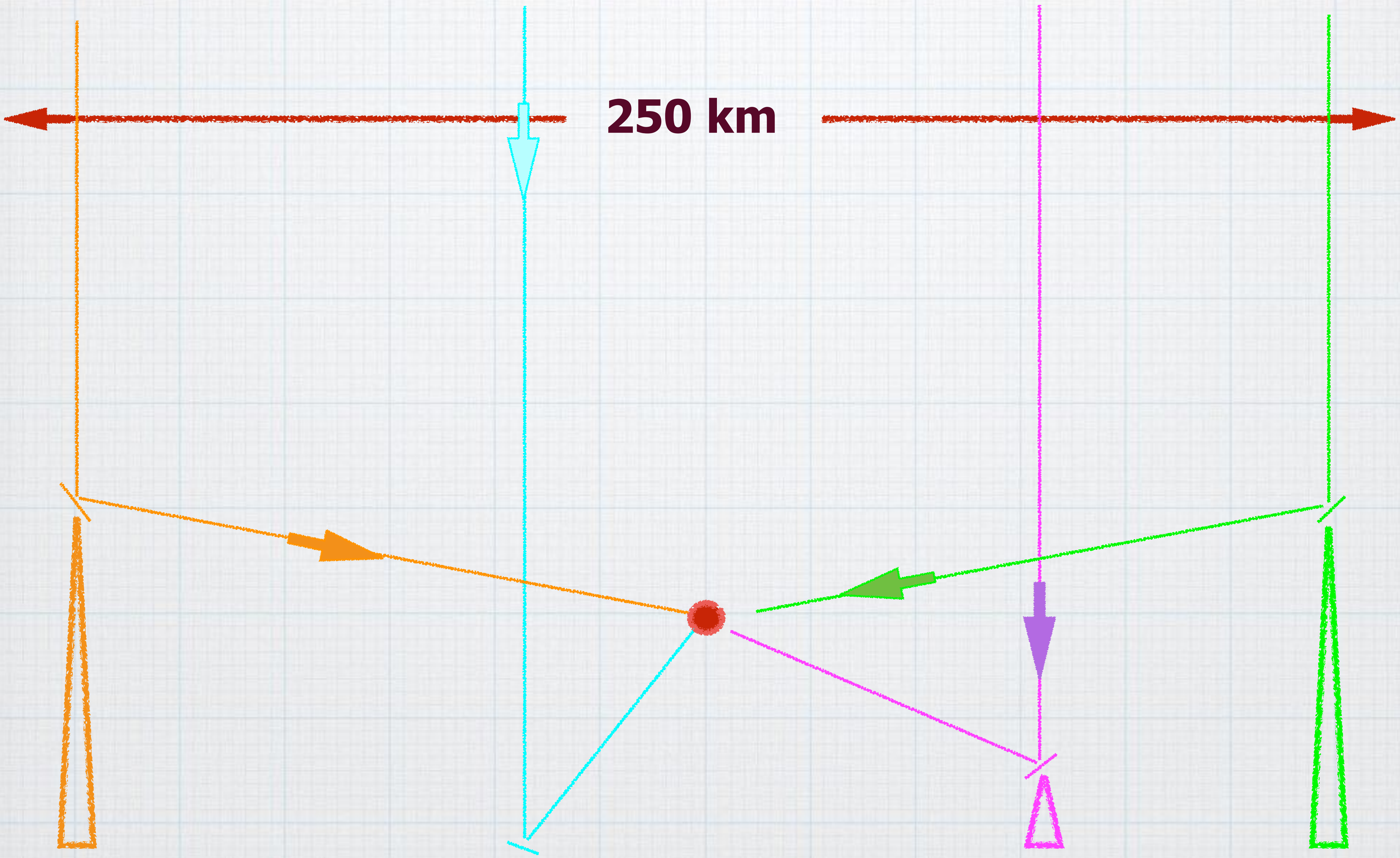
build GMRT



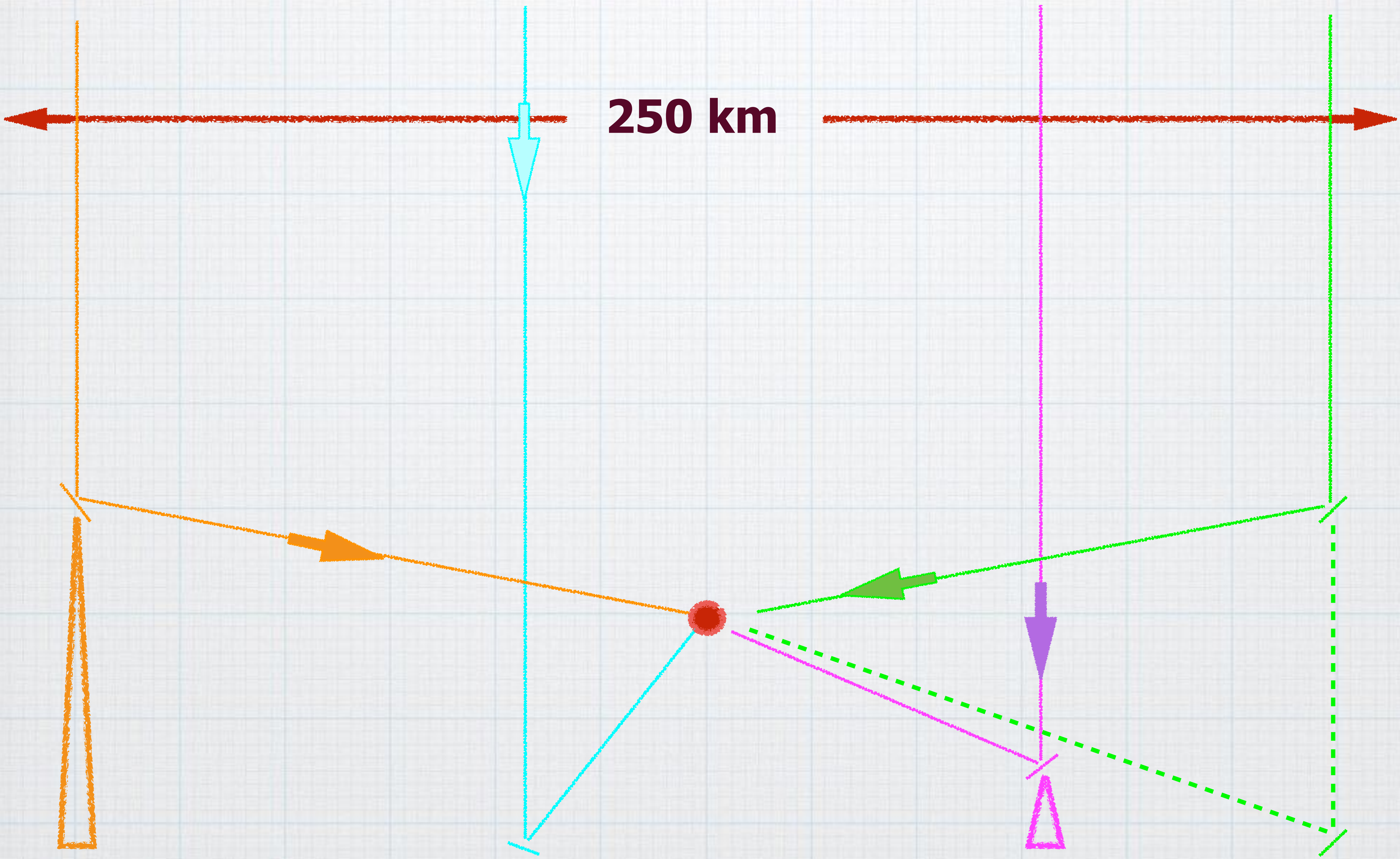
build GMRT



build GMRT



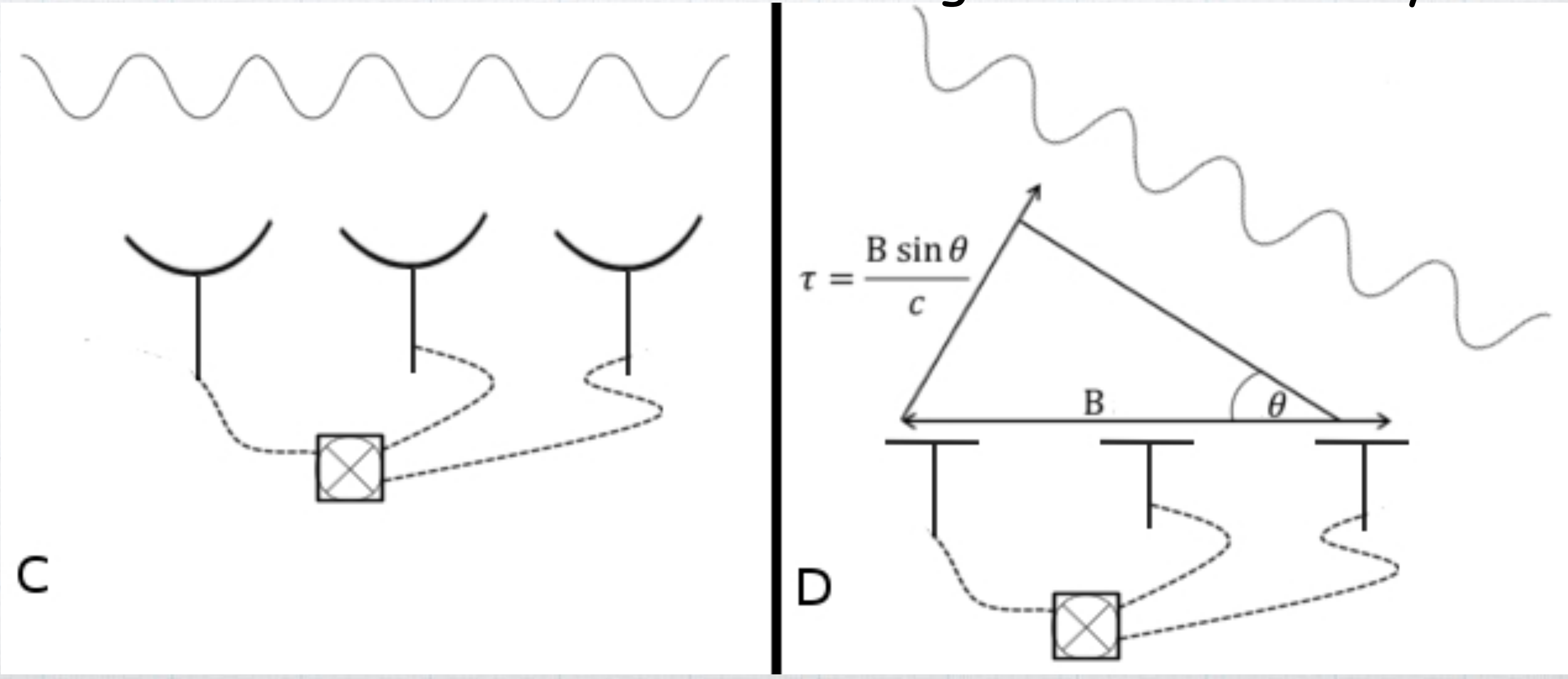
build GMRT



GMRT: A radio interferometer

Van Cittert-Zernicke Theorem

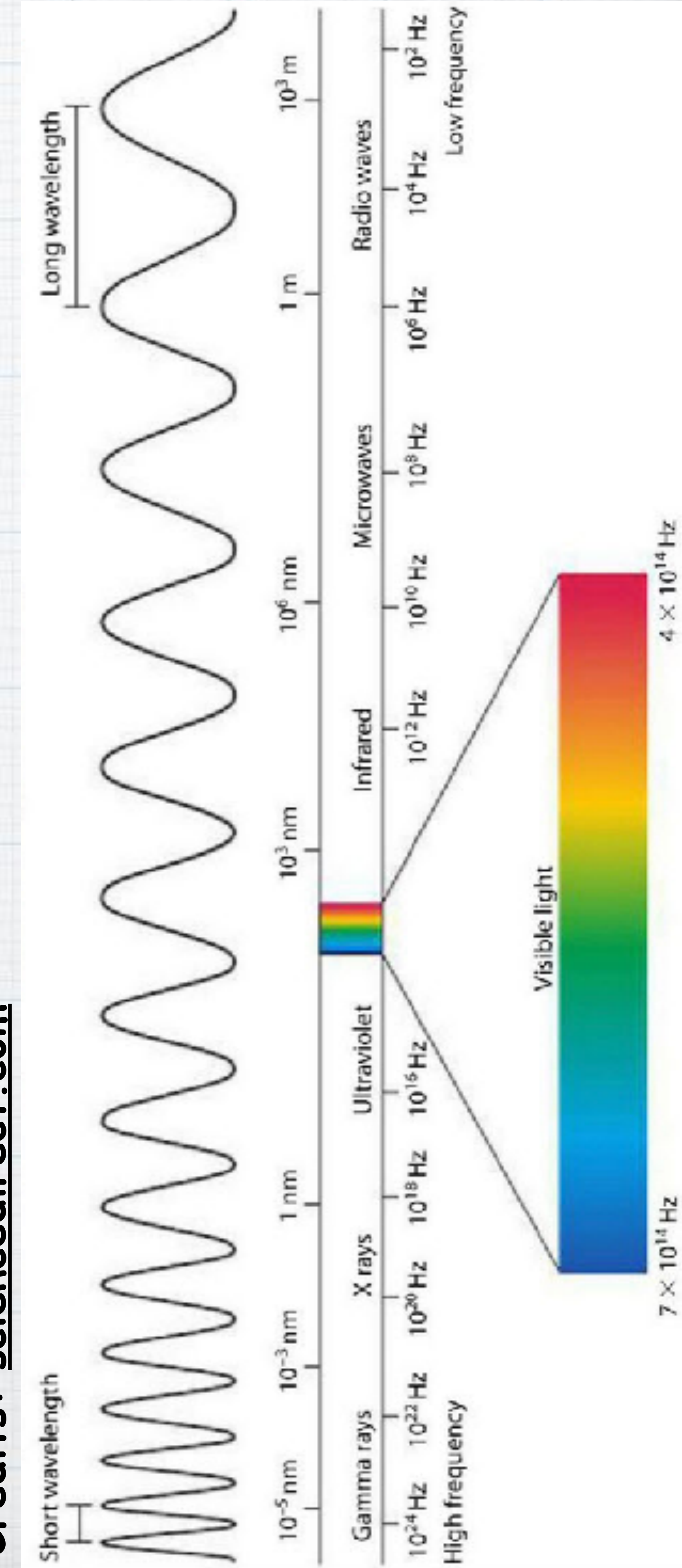
- An interferometer measures the interference pattern produced by pairs of apertures.
  - The interference pattern is directly related to the source brightness: (for small fields-of-view) the complex visibility is the 2D Fourier transform of the brightness on the sky.



Credits: ALMA science (ESO)

Why RA (part-I)?

large part of e.m. spectrum



Credits: sciencedirect.com

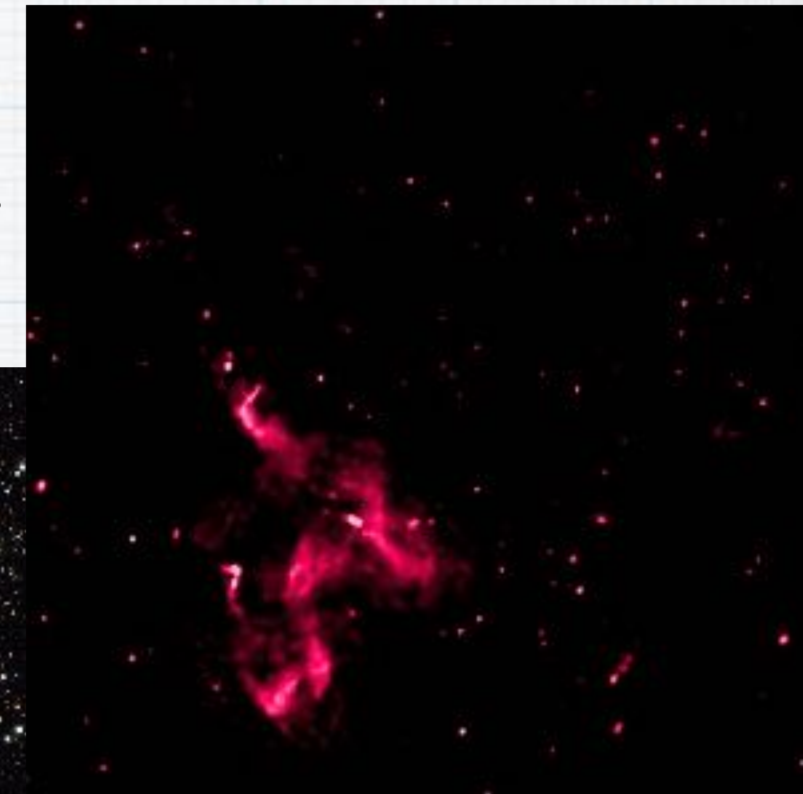
Why RA (part-II)?

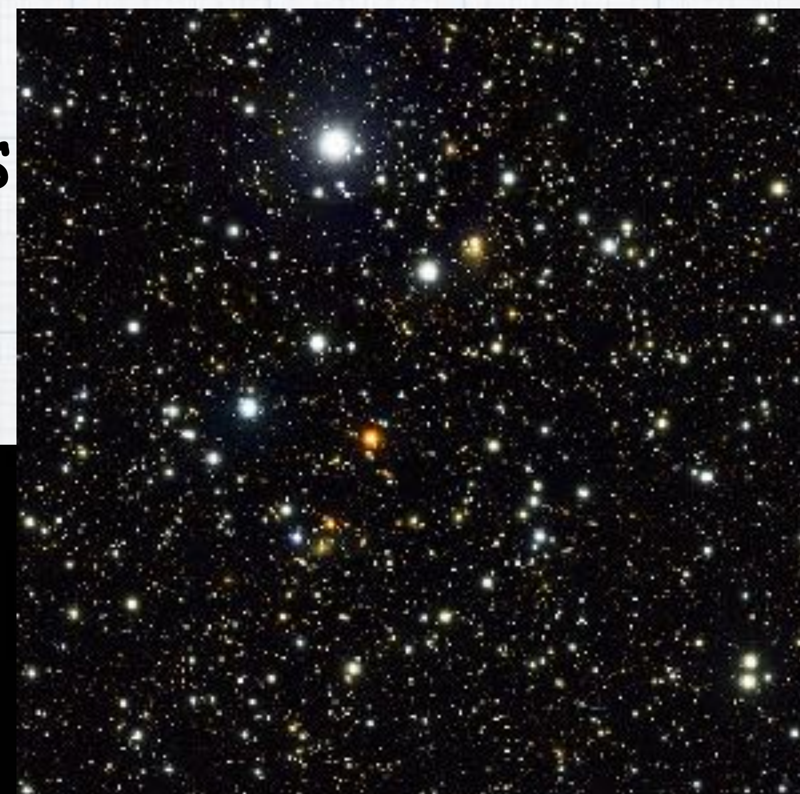
Access to the invisible (to eye) part of spectrum

Credits: NRAO (NSF)

Why RA (part-III)?

- **some stuff visible only in radio**
  - optical emission mainly comes from stars
  - Radio-wave comes mainly from gas or hot plasma
  - full (e.m.) observations
    - give a complete info

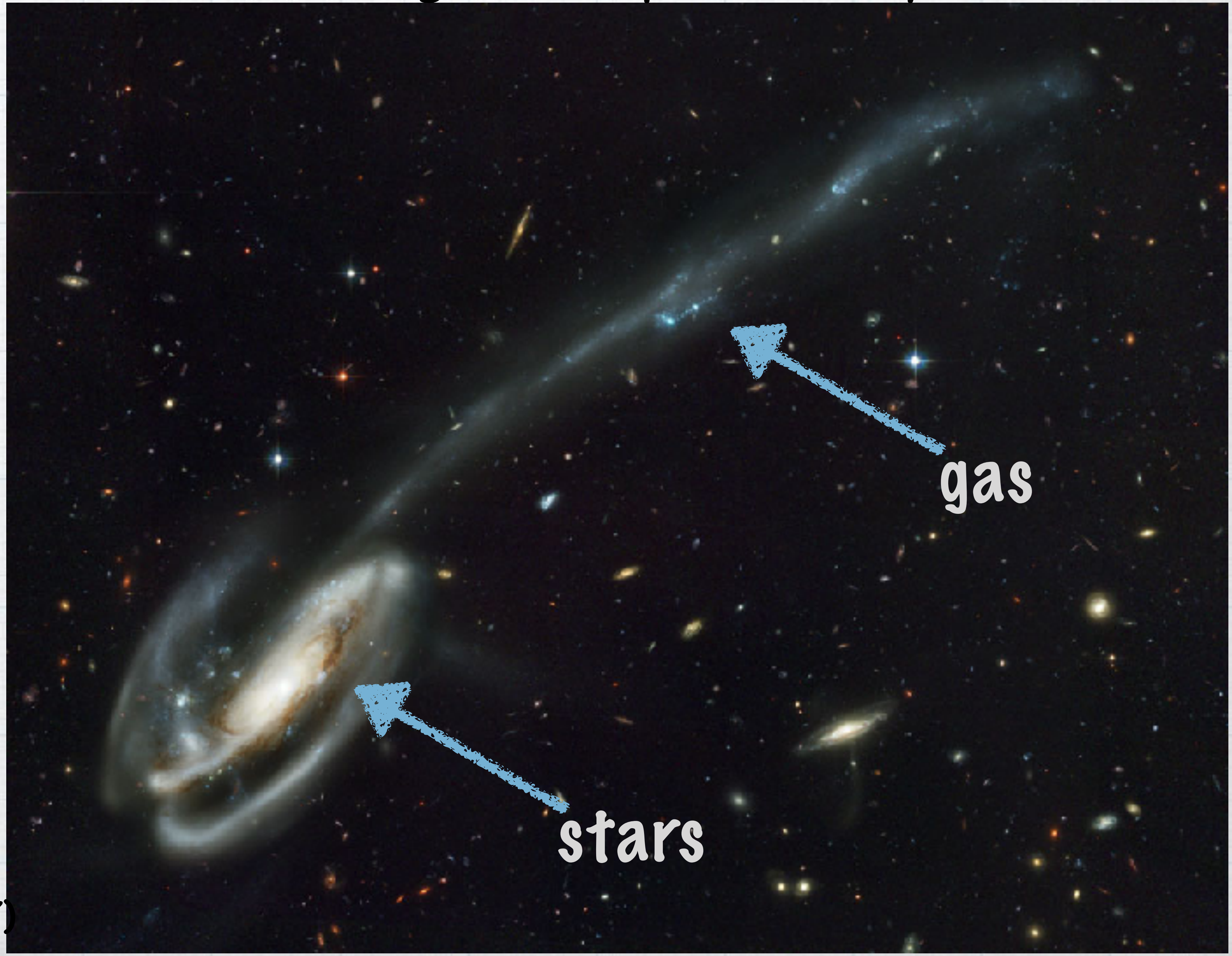




Credits: van Weeren+ 2017

Why RA (part-III)?

- **some stuff visible only in radio**
  - optical and radio observations give complementary information



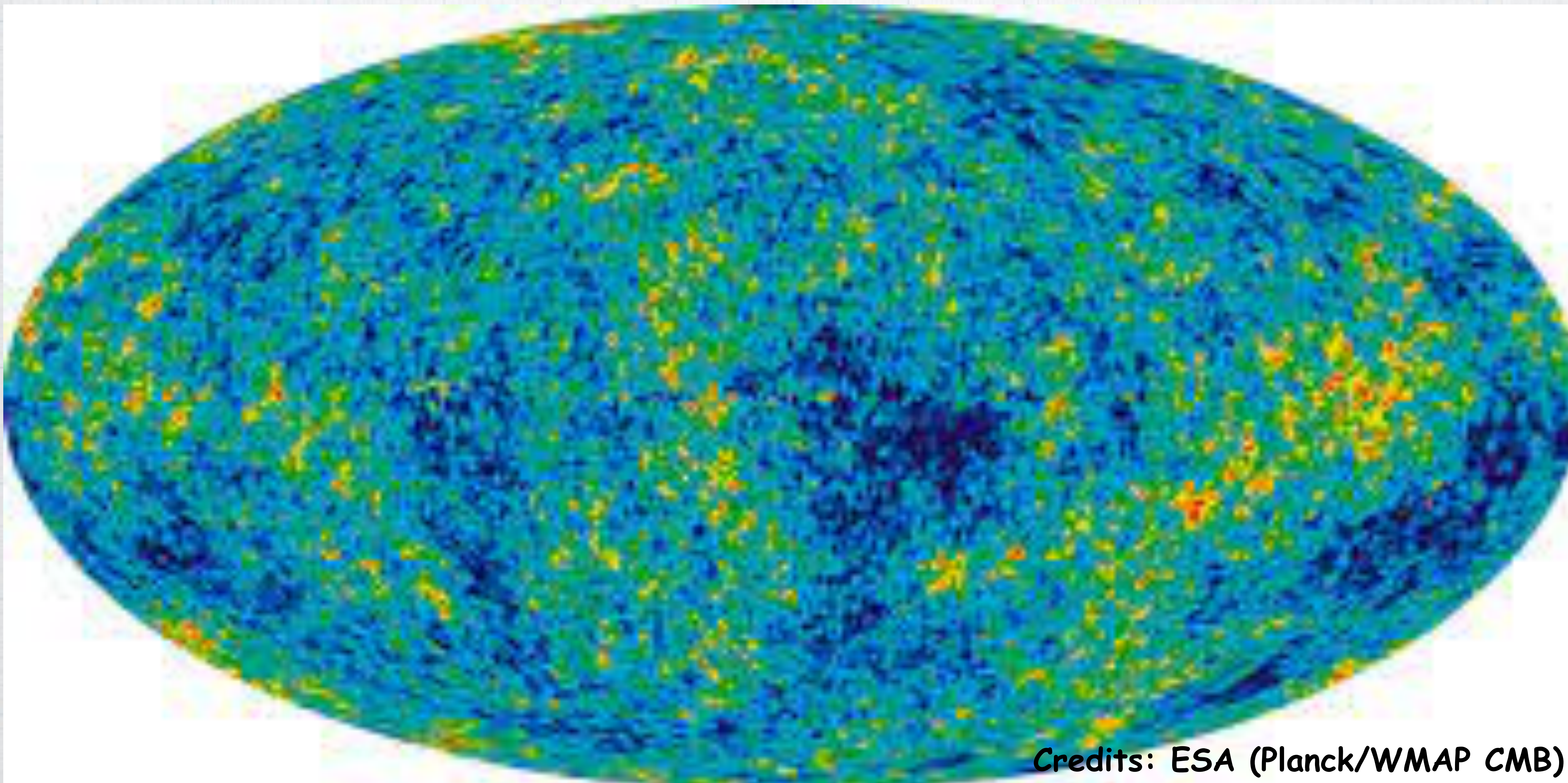
Credits: SpARCS (Noble+ 2017)

What's so special about RA?

CMB

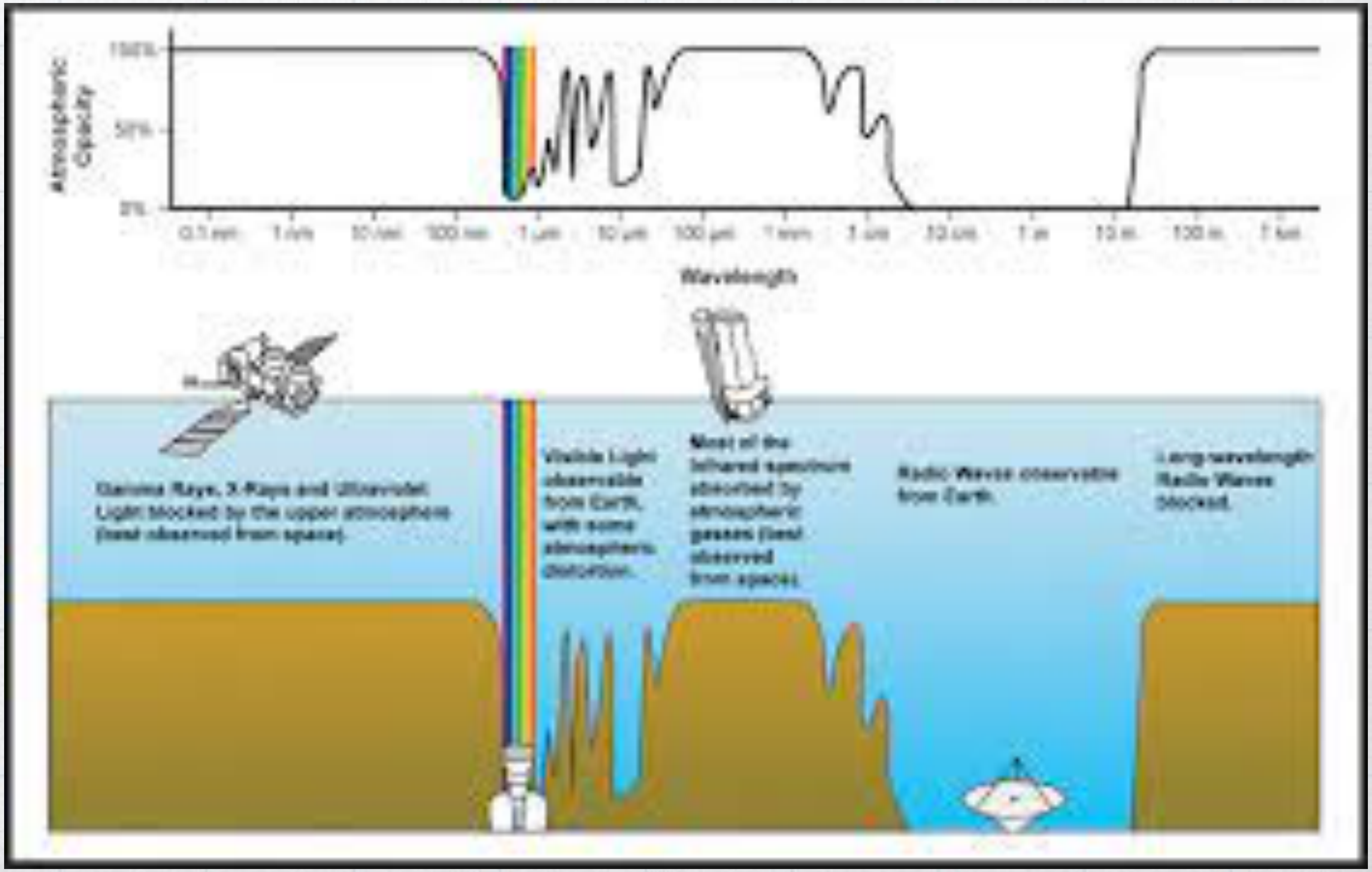
-or-

the (far) far-away Universe



What's so special about RA?

Ground-based (24x7) observing



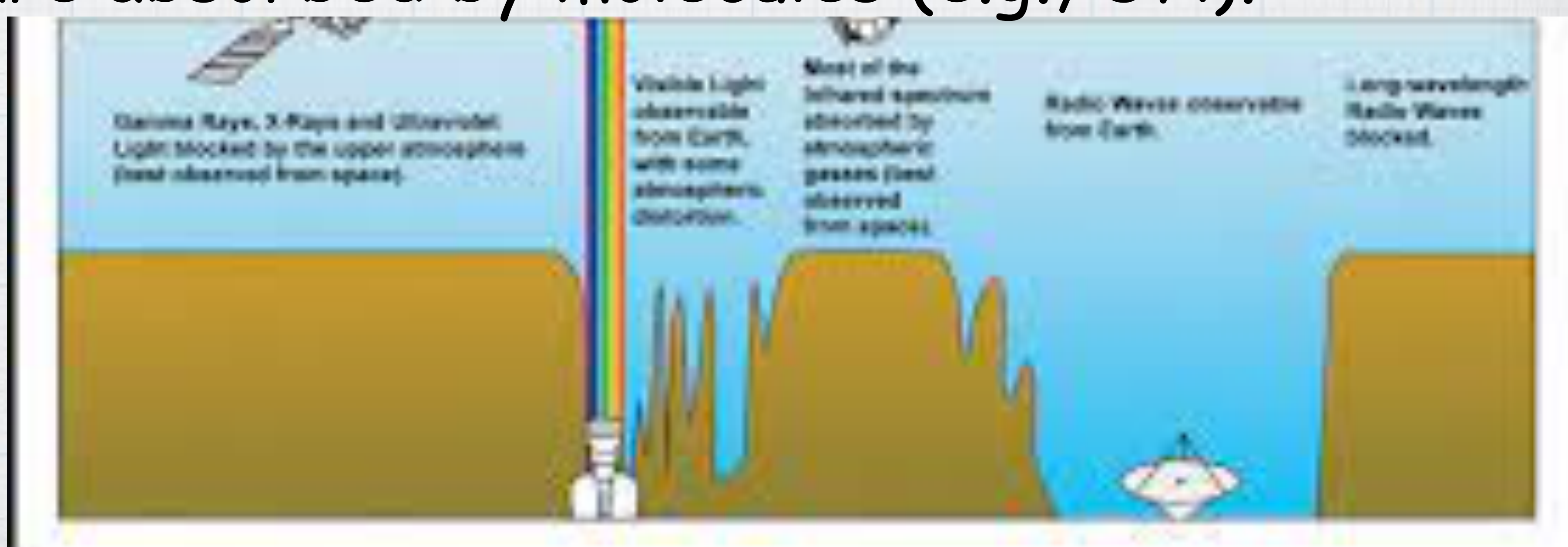
Credits: ESO

What’s so special about RA?

Ground-based (24x7) observing

- Only optical/IR and radio waves penetrate thr’u the atmosphere
- Ground-based, (i.e. “cheap”) telescopes can be used to observe celestial objects

- Radio window extends between 1mm and 10m
  - Long-waves are cut off due to absorption by plasma in the ionosphere
  - Short-waves are absorbed by molecules (e.g., OH).



Credits: ESO

What's so special about RA?

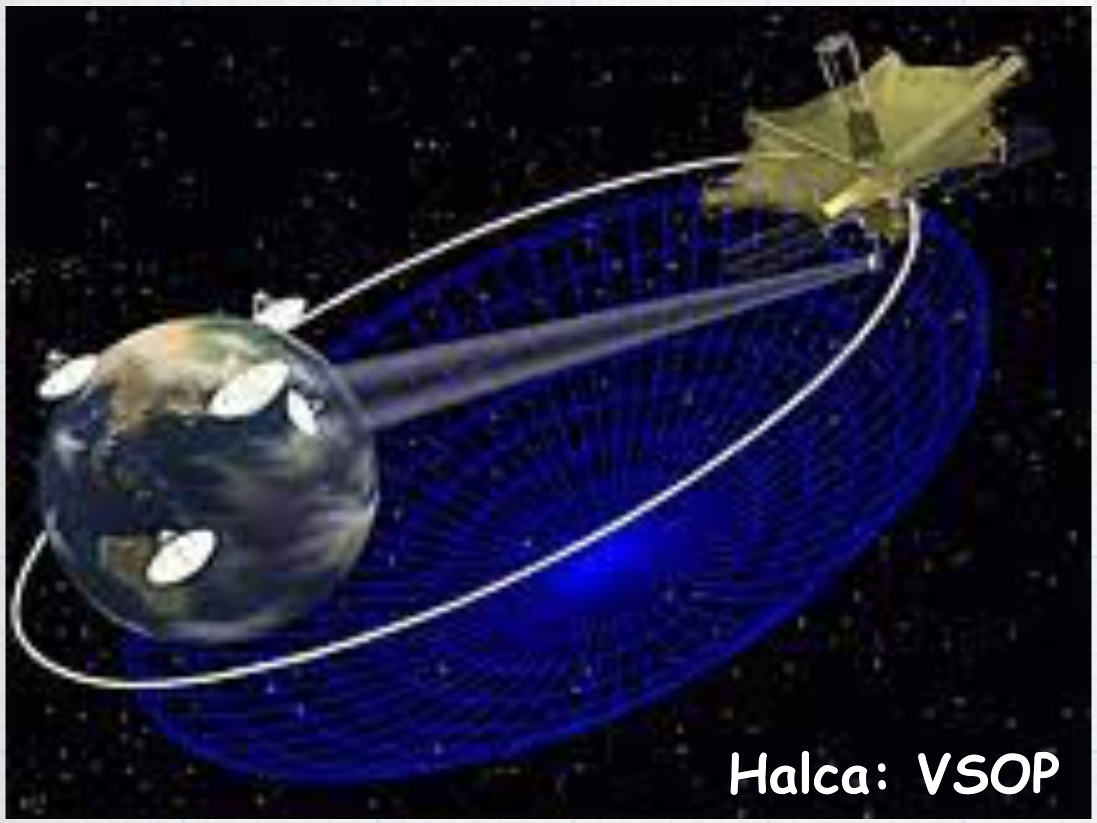
Ridiculously high angular resolution

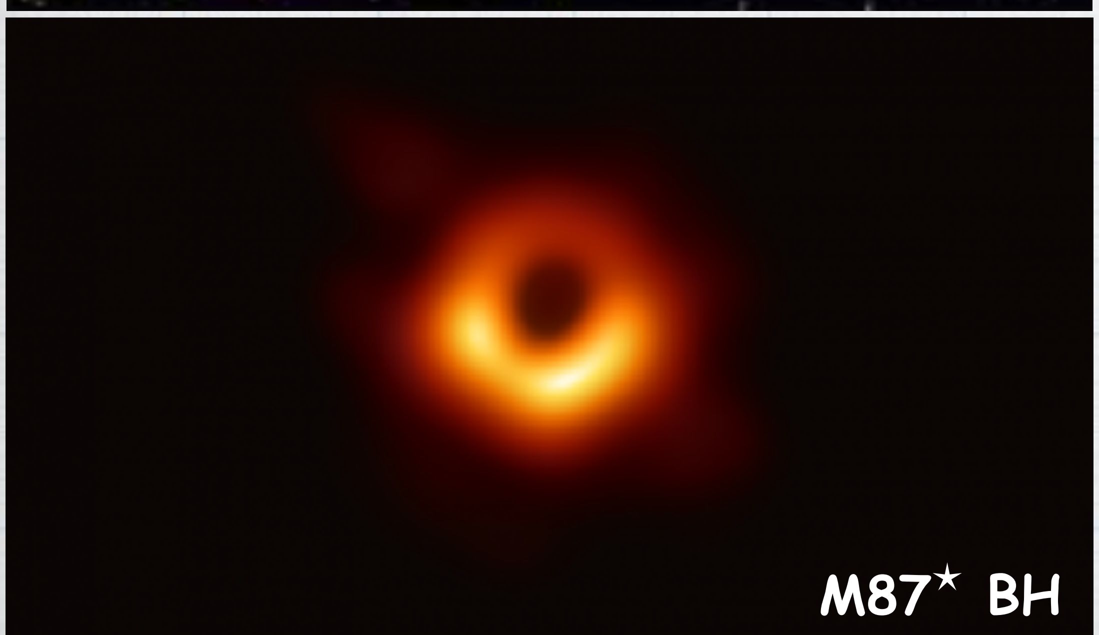
Credits: NRAO (NSF)

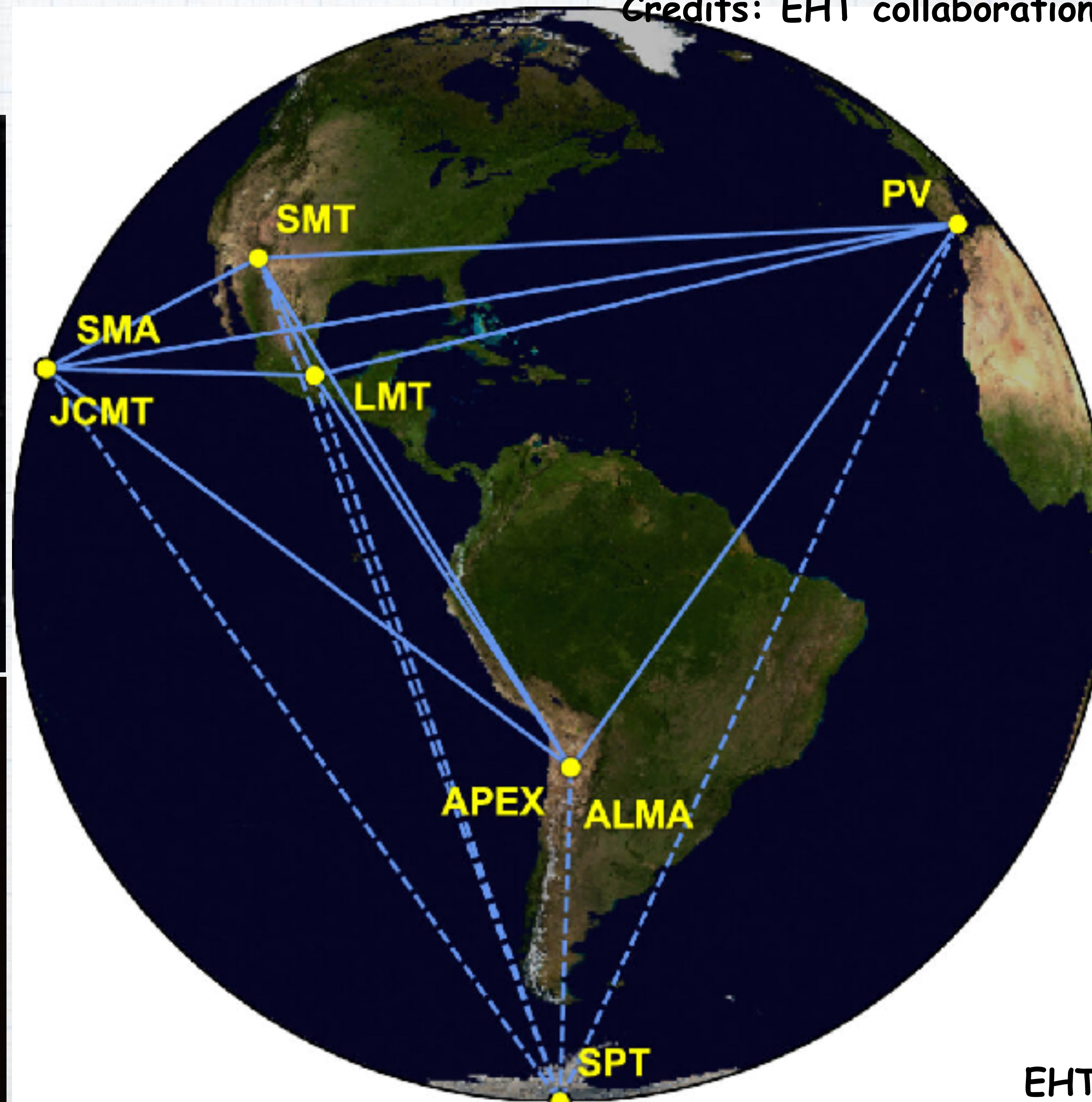
What's so special about RA?

Ridiculously (ridiculously) high angular resolution

Credits: EHT collaboration







Radio Astronomy (Lecture II)

Plan

- **build a radio interferometer / GMRT**
    - Why?
- **Why radio astronomy**?
    - (assorted) examples
- **Aperture synthesis**
    - interferometer
    - (introducing) GMRT
- **Science at NCRA-TIFR**
    - What do radio astronomers do?
        - ... some **fun stuff**

The radio telescope Zoo

- Optical window 3,000 Å - 10,000 Å
  - Only a factor of 3 in wavelength
  - All optical telescopes are broadly similar

- Radio window extends over a factor of 1000 in wavelength
  - Radio telescopes at long wavelength are radically different from those at short wavelength

JCMT

GMRT

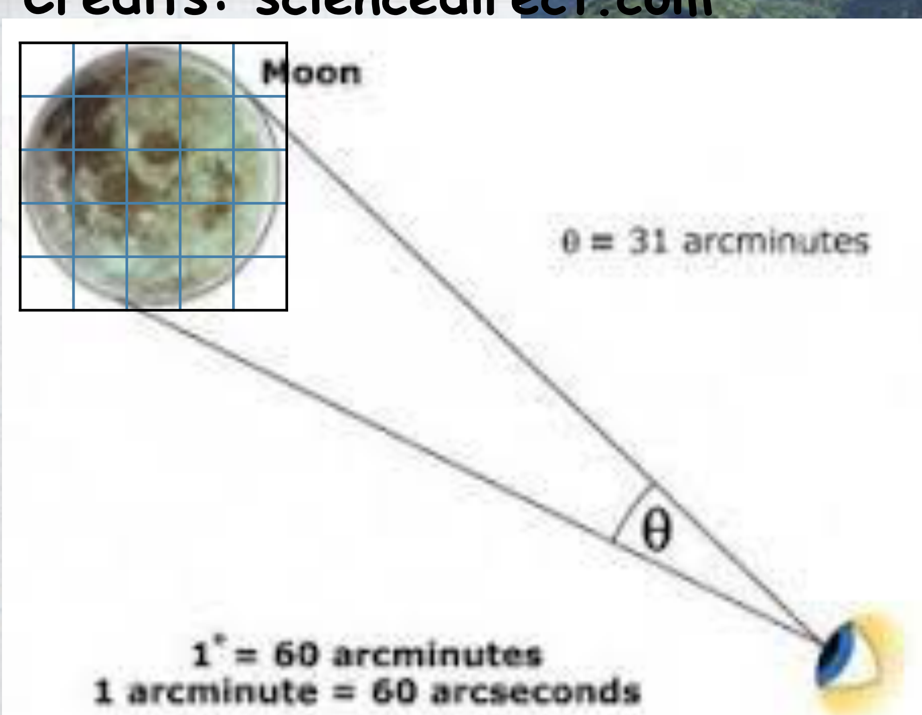
Lofar (+ Effelsberg)

Radio telescope fundamentals

- Telescopes are useful to
  - detect faint objects
    - (bigger telescopes collect more light)
  - see details in distant objects, "improve resolution"
    - (resolution = λ/D)

- World's largest radio telescope (500 m) has a resolution = 6 arcmin

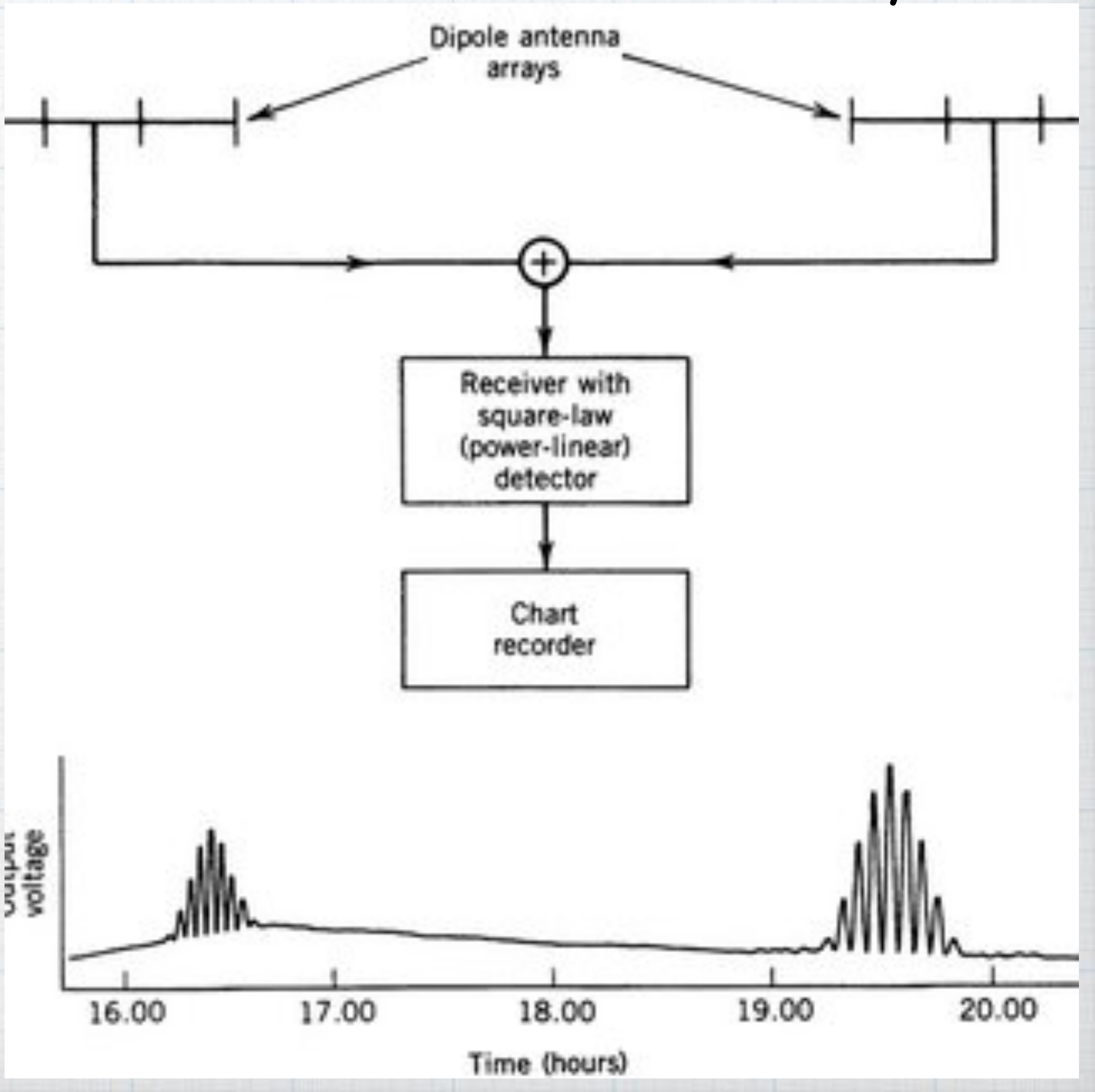
Credits: sciencedirect.com



Two antennas

- interferometry
  - High resolution can be obtained by adding the signals from two distant antennas
    - (no imaging capability though)

Ryle 1952

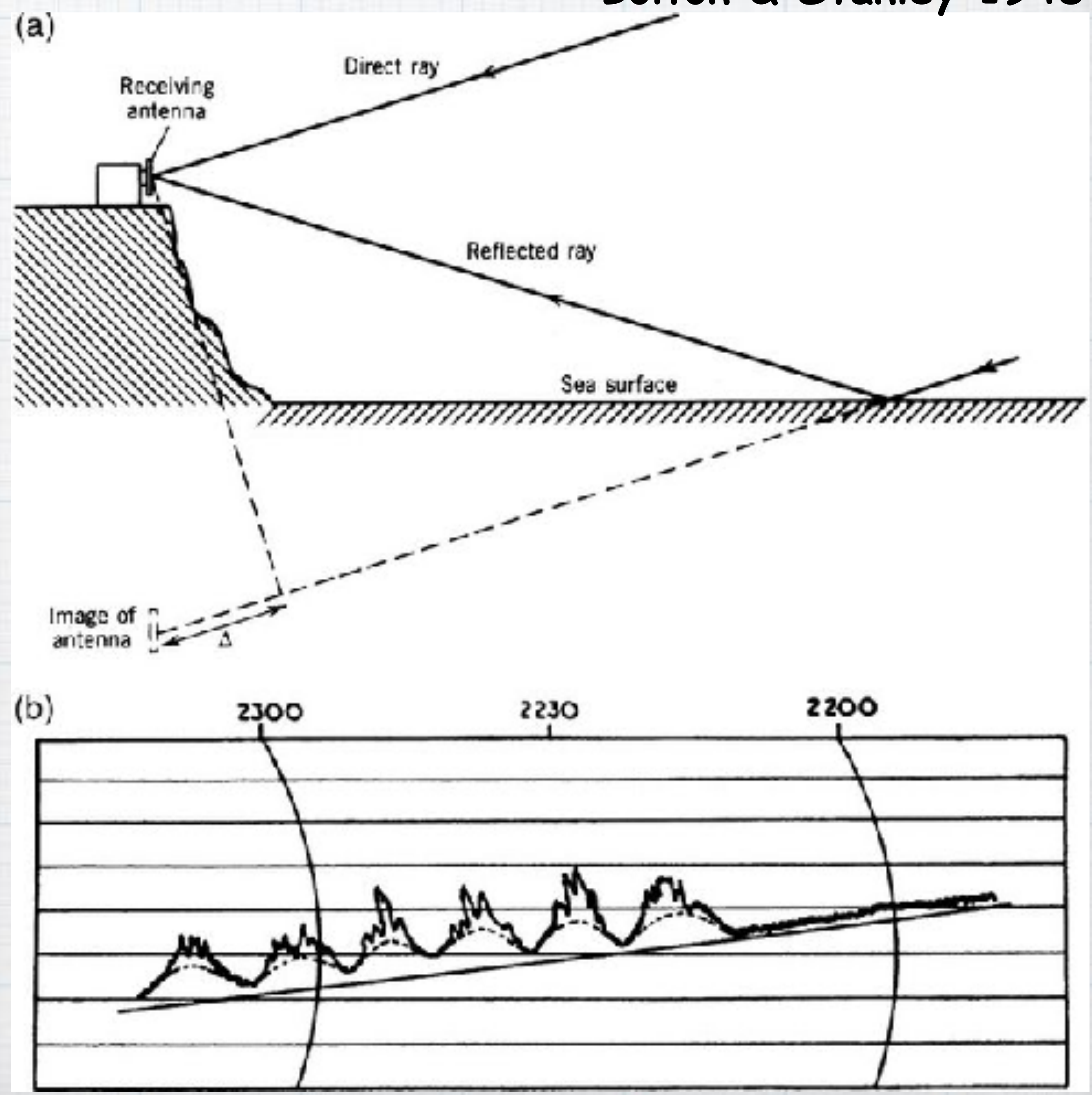


- Resolution scales with
  - Antenna separation
    - Addition for d = l
      - (i.e. θ = 0)
    - Cancellation for d = $\lambda/2$
      - (i.e. θ = $\lambda/2l$)
- And collecting area
  - Independent of l

One (instead of two) antennas

- interferometry
  - High resolution can be obtained by adding the signals from two distant antennas
    - (no imaging capability though)

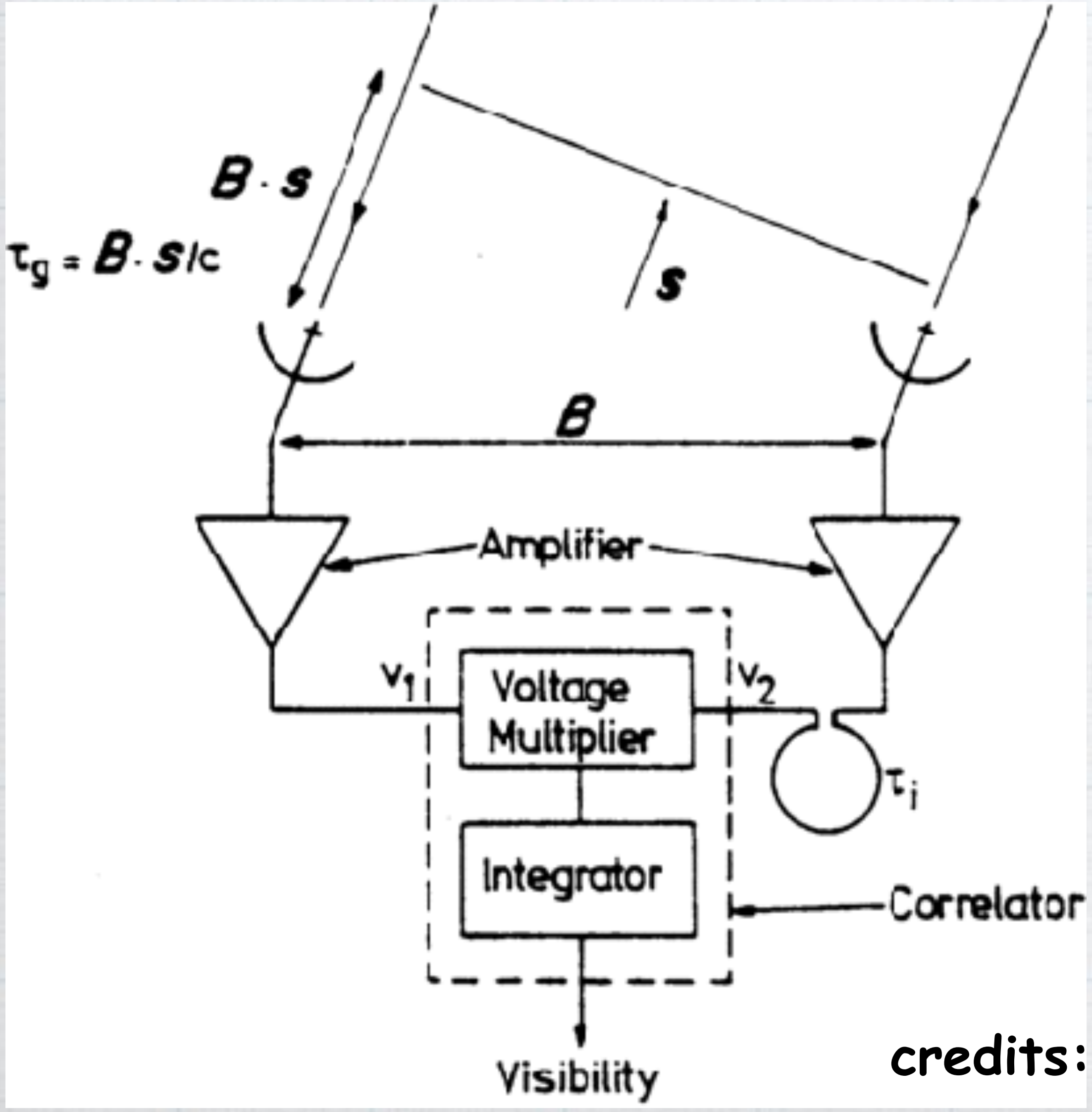
Bolton & Stanley 1948



Two antennas (imaging)

- **interferometry**
  - **Correlate the voltages instead of adding them**
  - **Correlation = multiplication + integration**

- An interferometer measures the interference pattern produced by pairs of apertures.



- The interference pattern is directly related to the source brightness: (for small fields-of-view) the complex visibility is the 2D Fourier transform of the brightness on the sky.

credits: 1996 NRAO Synthesis Imaging Summer School

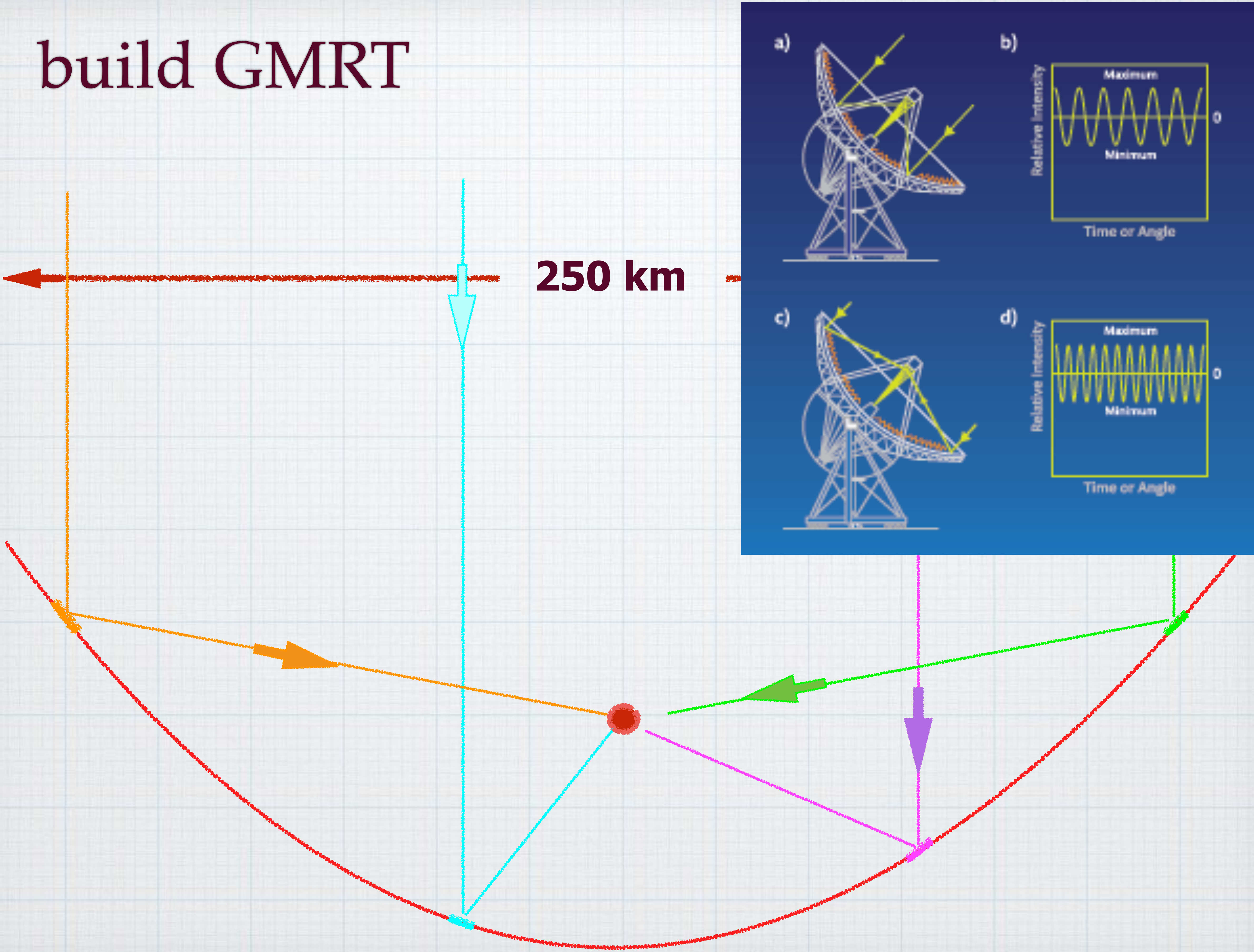
Imaging arrays

- Indirect image formation is possible if one correlated the signal instead of adding

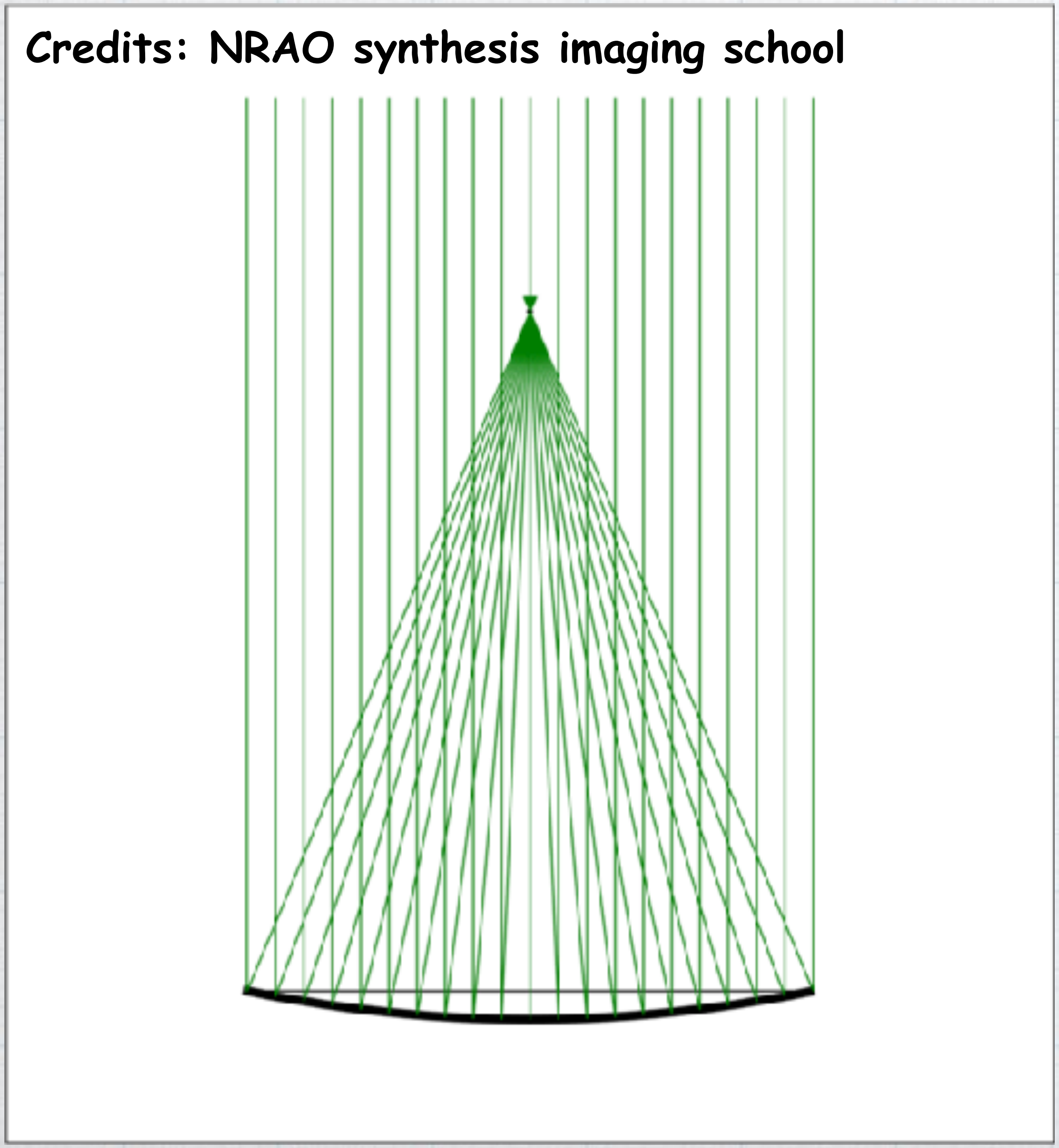
- Each correlation gives information at a specific angular scale
  - Under suitable approximations this information can be inserted to give the image
  - i.e., the antenna pair is like a filter, which picks out one spatial frequency component
  - Wide pairs pick out fine details and close pairs pick out large scale structure.

- For high fidelity inversion one needs good sampling of all scales,
  - i.e., need both distant and close antenna pairs.

build GMRT

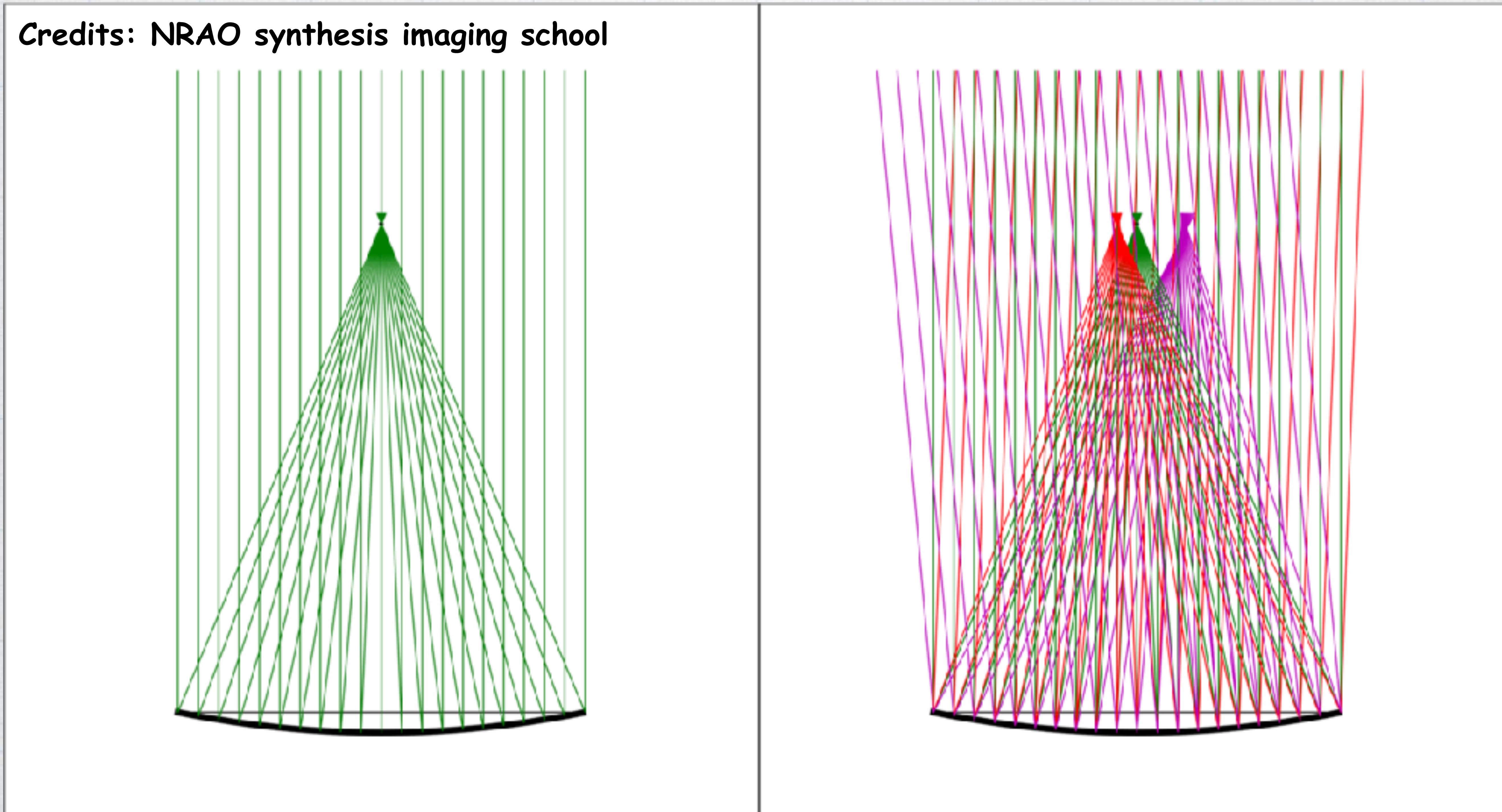

250 km
a)
b)
Maximum
0
Minimum
Relative Intensity
Time or Angle
c)
d)
Maximum
0
Minimum
Relative Intensity
Time or Angle

A filled aperture



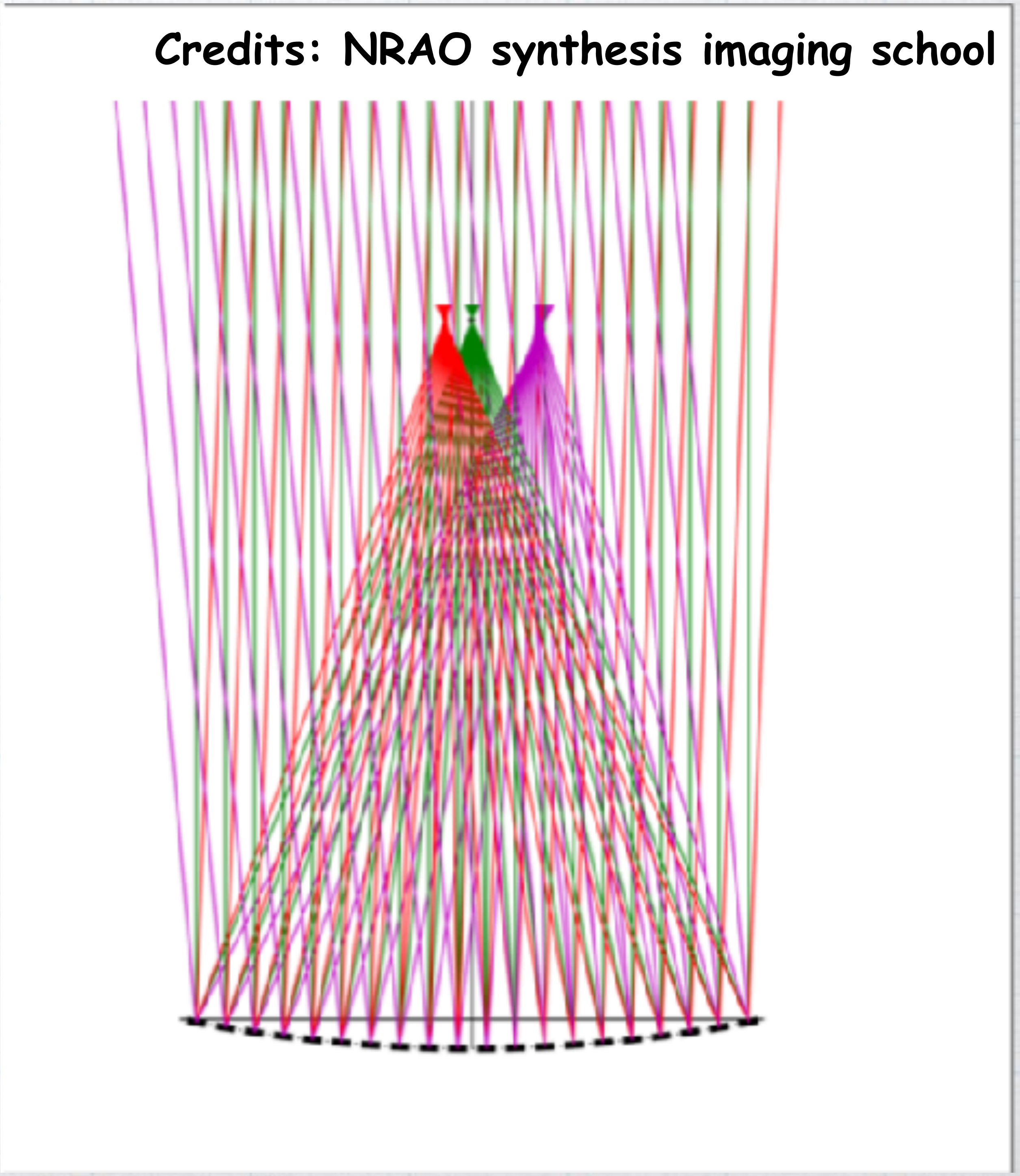
- Focusing instrument
  - Eye
  - Camera
  - Conventional telescope
- Properties
  - Collecting area
  - Resolution

A filled aperture



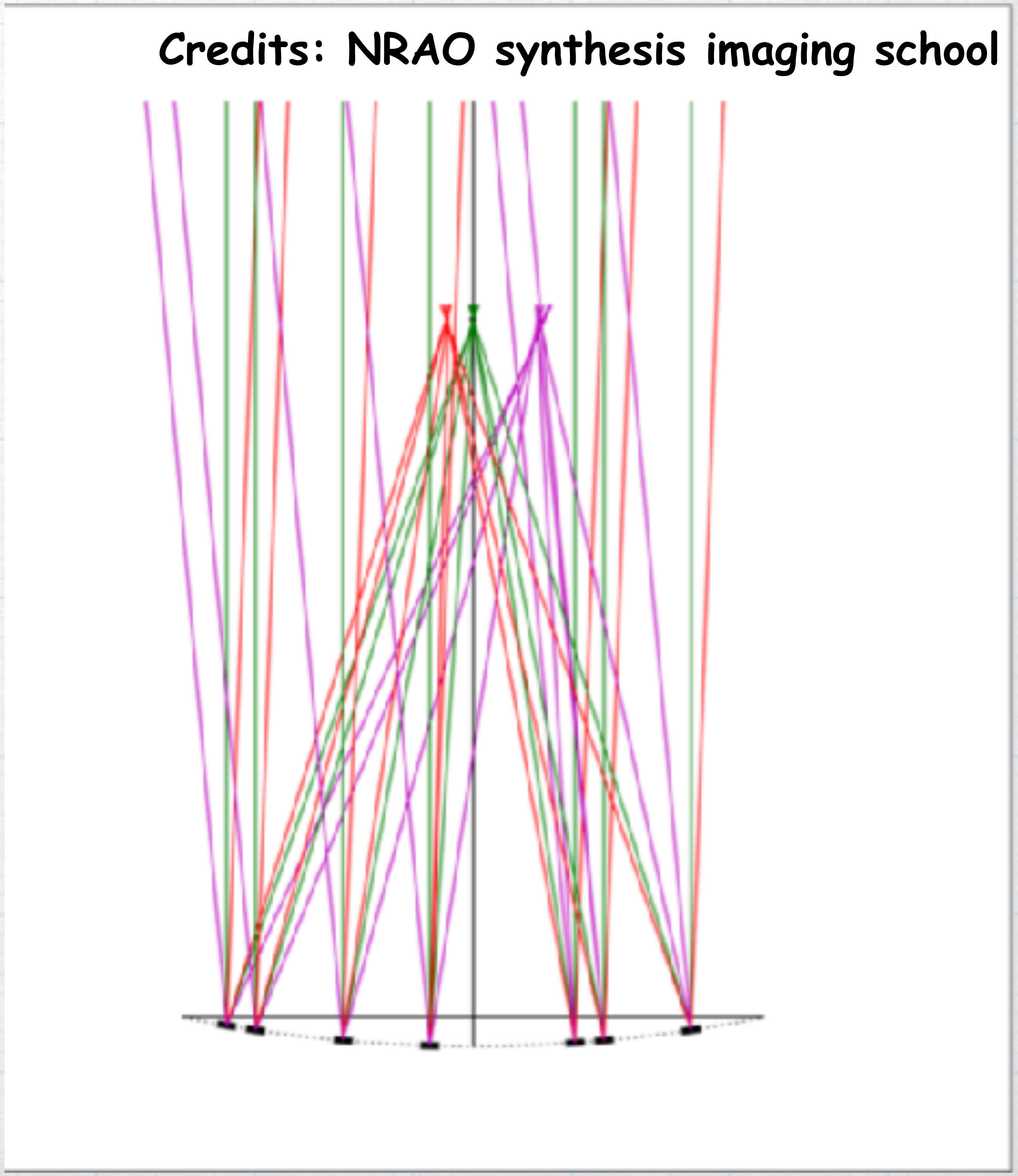
A (segmented) filled aperture

- Each segment gathers ‘em’ field
  - Parabolic figure redirects net information to the focal plane



An unfilled aperture

- Each segment gathers 'em' field
  - Parabolic figure redirects net information to the focal plane
- But fewer segments, and pairs thereof
  - Less collecting area
  - Uglier diffraction pattern

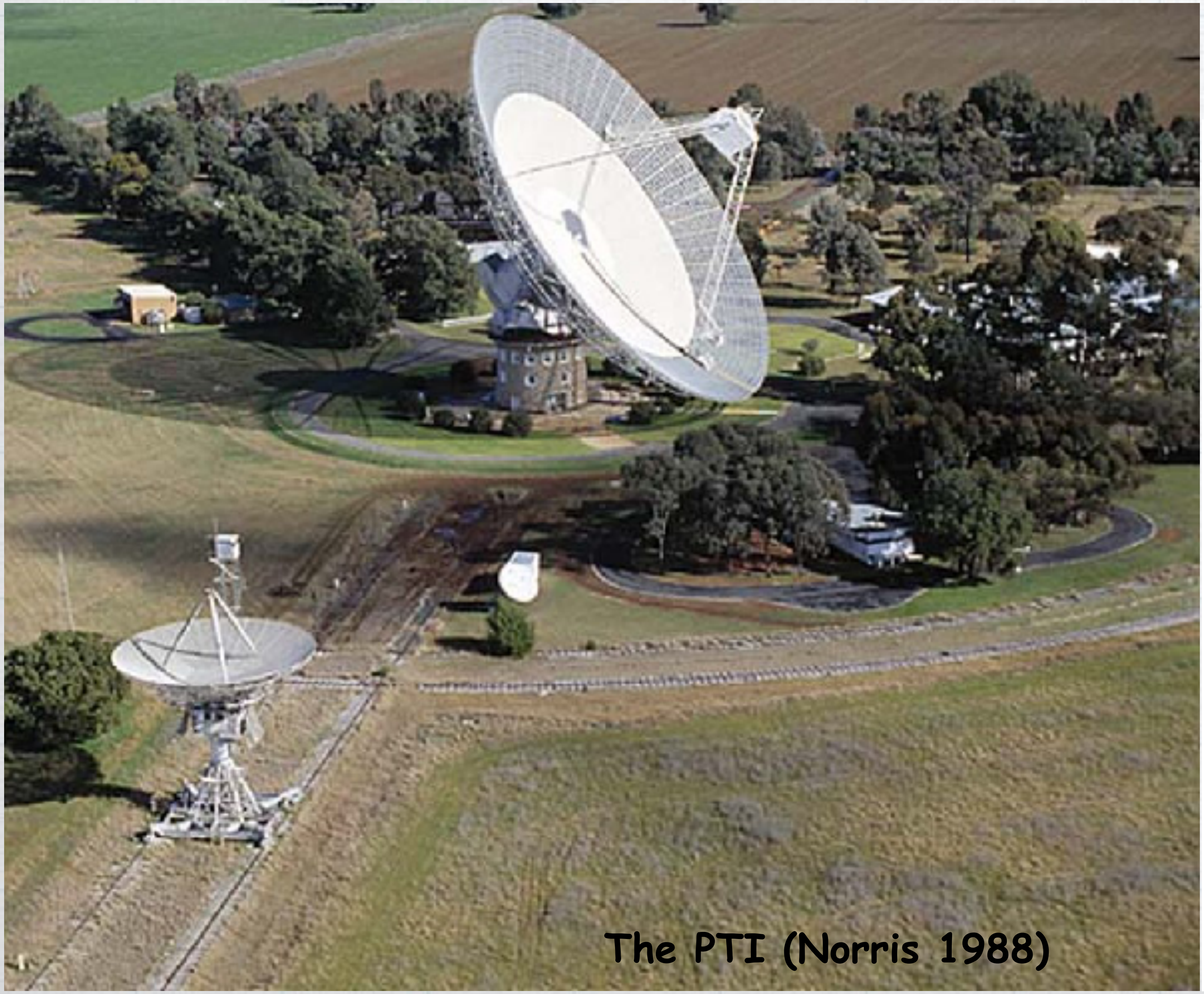


Imaging arrays (include tricks)

- Celestial sources do not vary on human timescales
  - i.e., their statistical parameters do not vary!
- Synthesize a large aperture using repeated observations with a few antennas whose spacings can be varied
  - e.g., by mounting the antennas on tracks
- -or- by tracking the source as it rises and sets
  - The Earth's rotation changes the projected separation between the antennas
  - Thus, one can get a good coverage of the Fourier (u,v) plane without moving the antennas

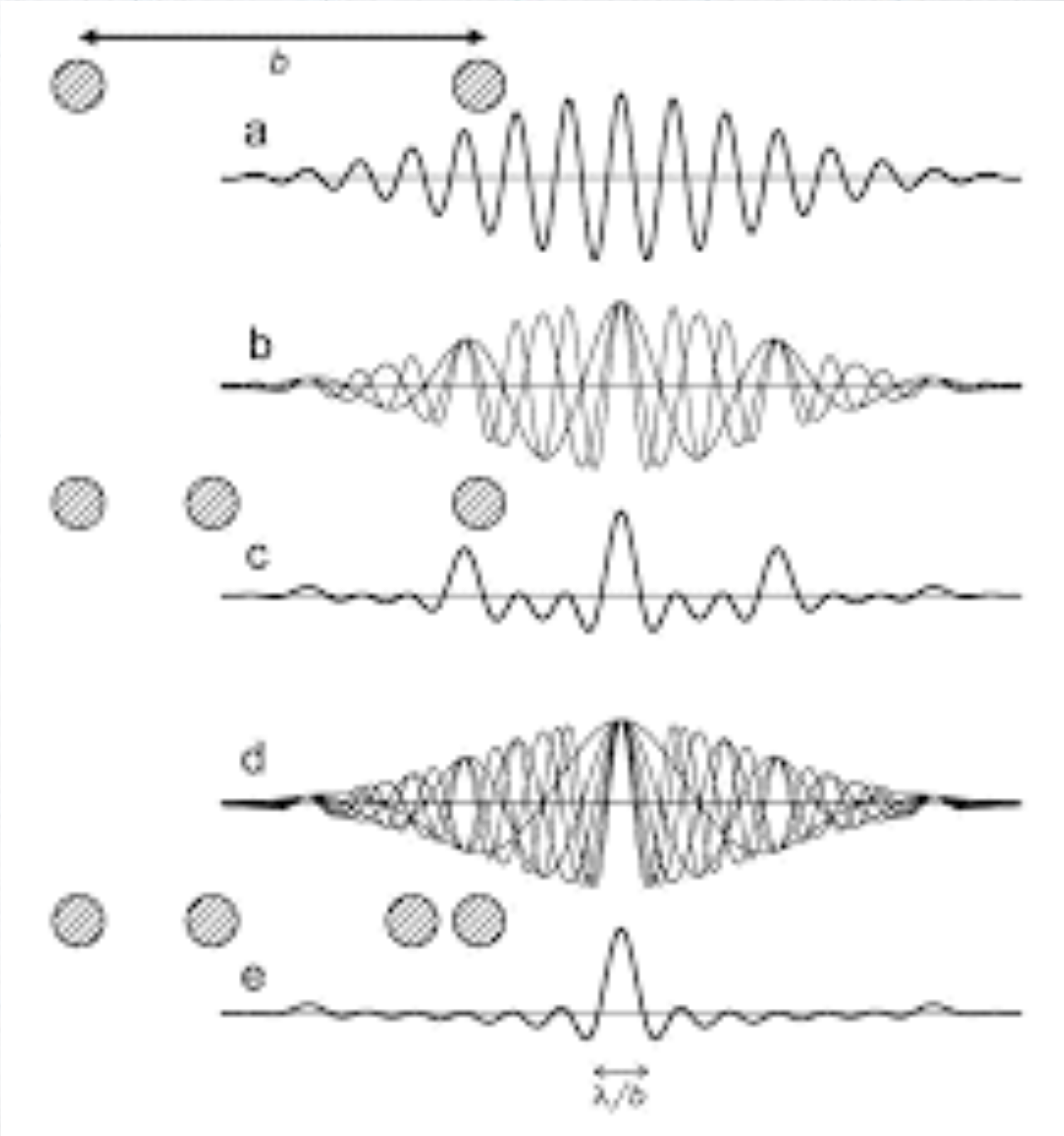
Two antennas

- interferometry
  - Correlate the voltages instead of adding them
  - Correlation = multiplication + integration



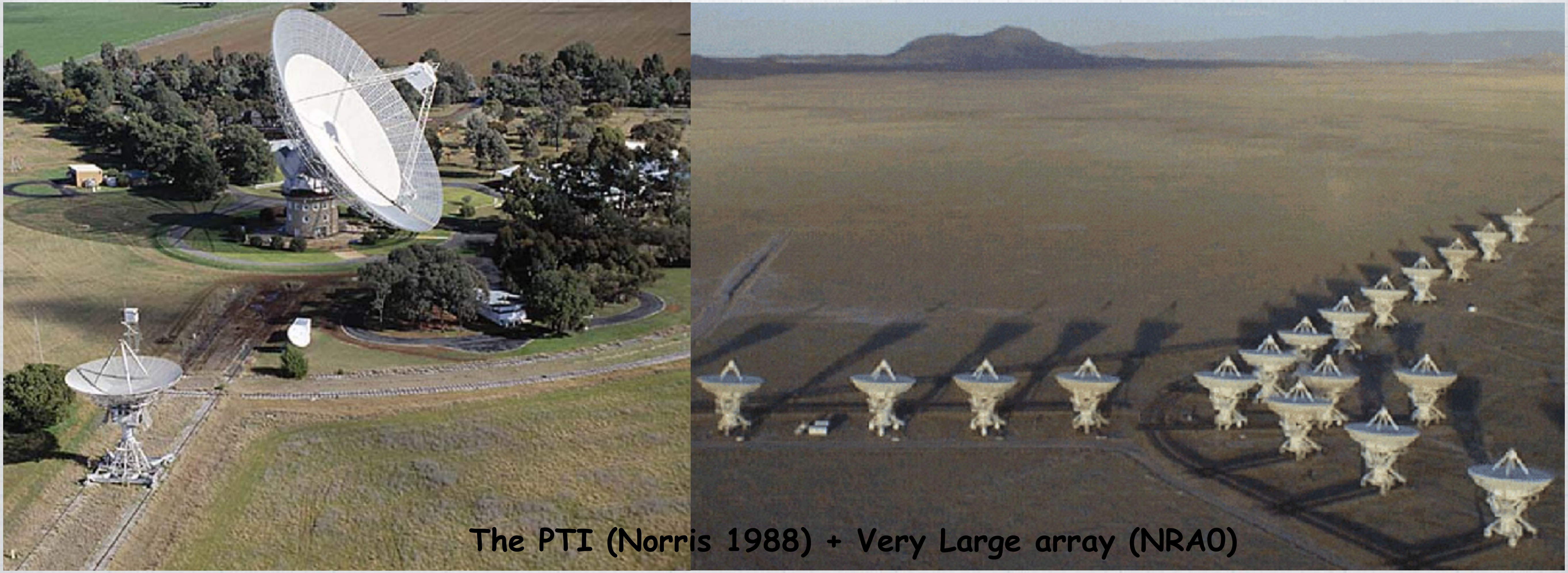
The PTI (Norris 1988)

Radio Astronomy (NJIT.edu)



Two dishes→several movable antennas

- One can picture this as making an image with a mirror ("aperture") with holes
  - The "aperture" being synthesises is in dimensions of λ/d
  - More densely packed the array the fewer the holes
  - A large instantaneous λ coverage would also give a denser coverage of "aperture"



The PTI (Norris 1988) + Very Large array (NRAO)

Aperture synthesis

- A correlation interferometer measures one component of the image Fourier transform
  - The component corresponding to the spatial frequency b/l
- Assuming that
  - The fov is small and/or
  - The measurements are all in a single plane
  - The observation bandwidth is small compared to central-frequency
  - Instrumental and propagation effects have been calibrated
- Given enough interferometers one can measure enough components of Fourier transform and do a Fourier inversion to get the image
- One can thus synthesise a telescope of size equal to the array size

Radio sources

1952: Structure of Radio sources

- Two-element interferometer at 2.4-m (wavelength) with baselines up to 5.4 km
- Showed Cygnus A to have a double or twin lobed structure

Dennison & Das Gupta (1953)

INTERFEROMETER SPACINGS N AND CORRESPONDING CORRELATION COEFFICIENT ρ^2 FROM THE EXTRA-TERRESTRIAL RADIO SOURCE CYGNUS 1

N at 113°	N projected into 90°	$\rho^2 \pm 0{\cdot}04$
610	560	0·460
650	598	0·500
900	830	0·200
1,450	1,340	0·045
1,558	1,440	0·065
1,655	1,520	0·120
1,952	1,800	0·245
2,100	1,930	0·280
2,230	2,050	0·290

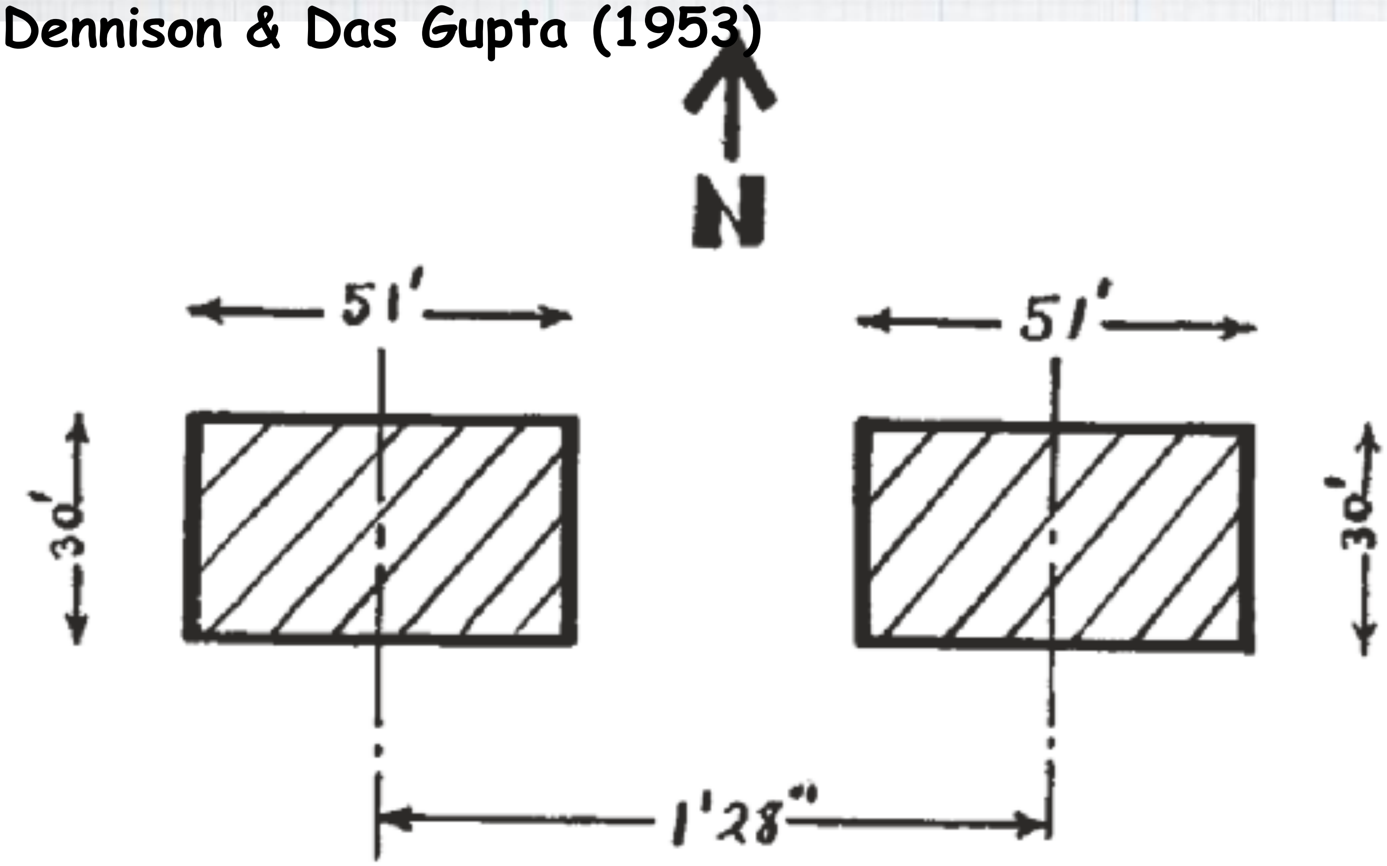
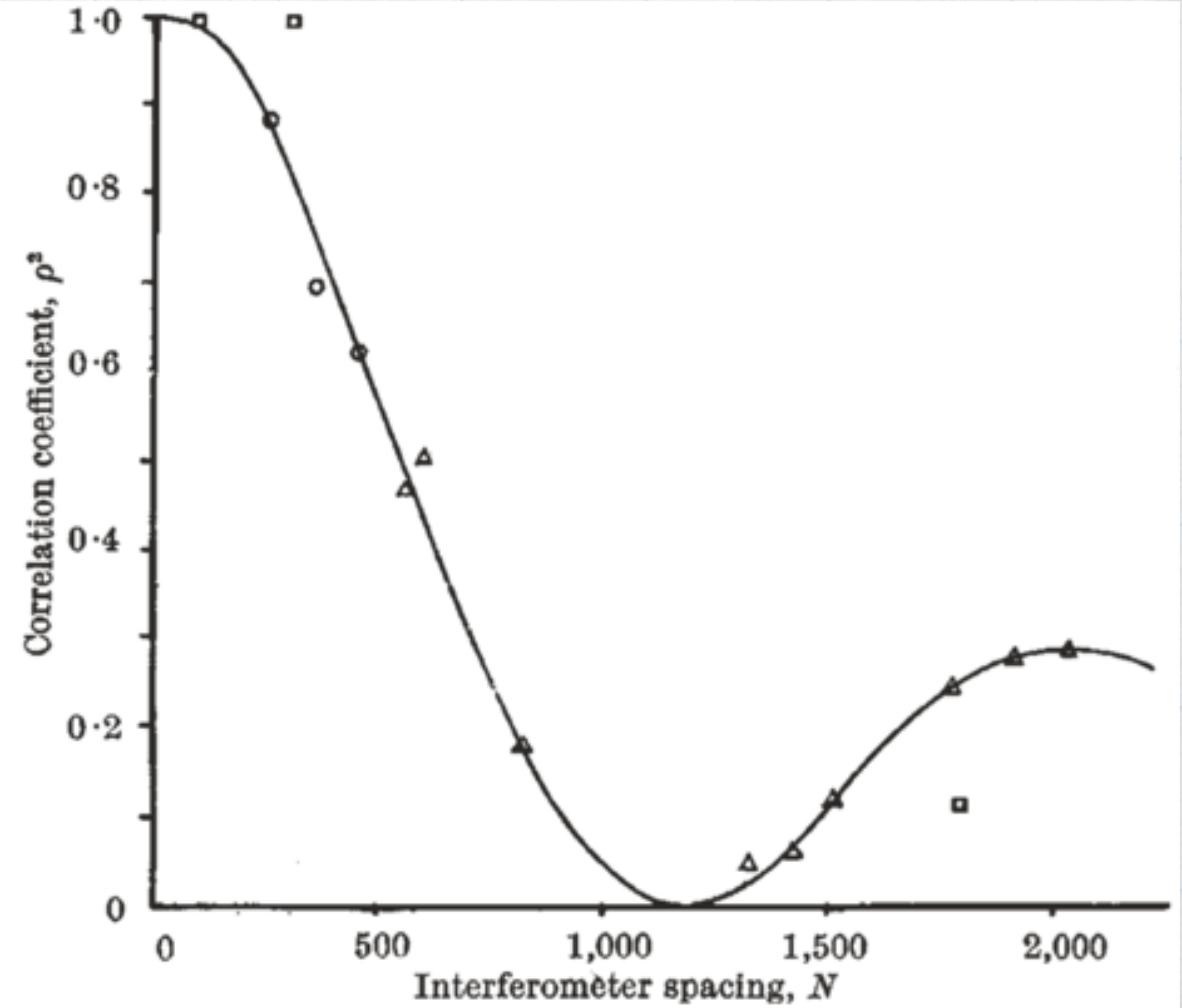


Fig. 2. Approximate intensity distribution of the extra-terrestrial radio source in Cygnus



Radio sources

1952: Structure of Radio sou

- Two-element interferometer at 2.4-m (wavelength) with baselines up to 5.4 km
- Showed Cygnus A to have a double or twin lobed structure

larger than the visual object described above. The two components of the radio source straddle the visual object with little overlap between the regions of optical and radio emission. If this identification of the radio source is correct, there would appear to be no direct correlation between the radio emission and the visible light from the colliding galaxies.

The simplest distribution which will yield the transform shown in Fig. 1 consists of two components of equal intensity, each of length 51″, separated by 1′ 28″. The additional information[1] supplied by the results obtained on bearings of 179° and 58° indicates that the source has a very small minor axis—less than 35″ in a position angle of approximately 180°—and it is apparent that the components forming the source must be distributed in a narrow strip as shown in Fig. 2.

Dennison & Das Gupta (1953)

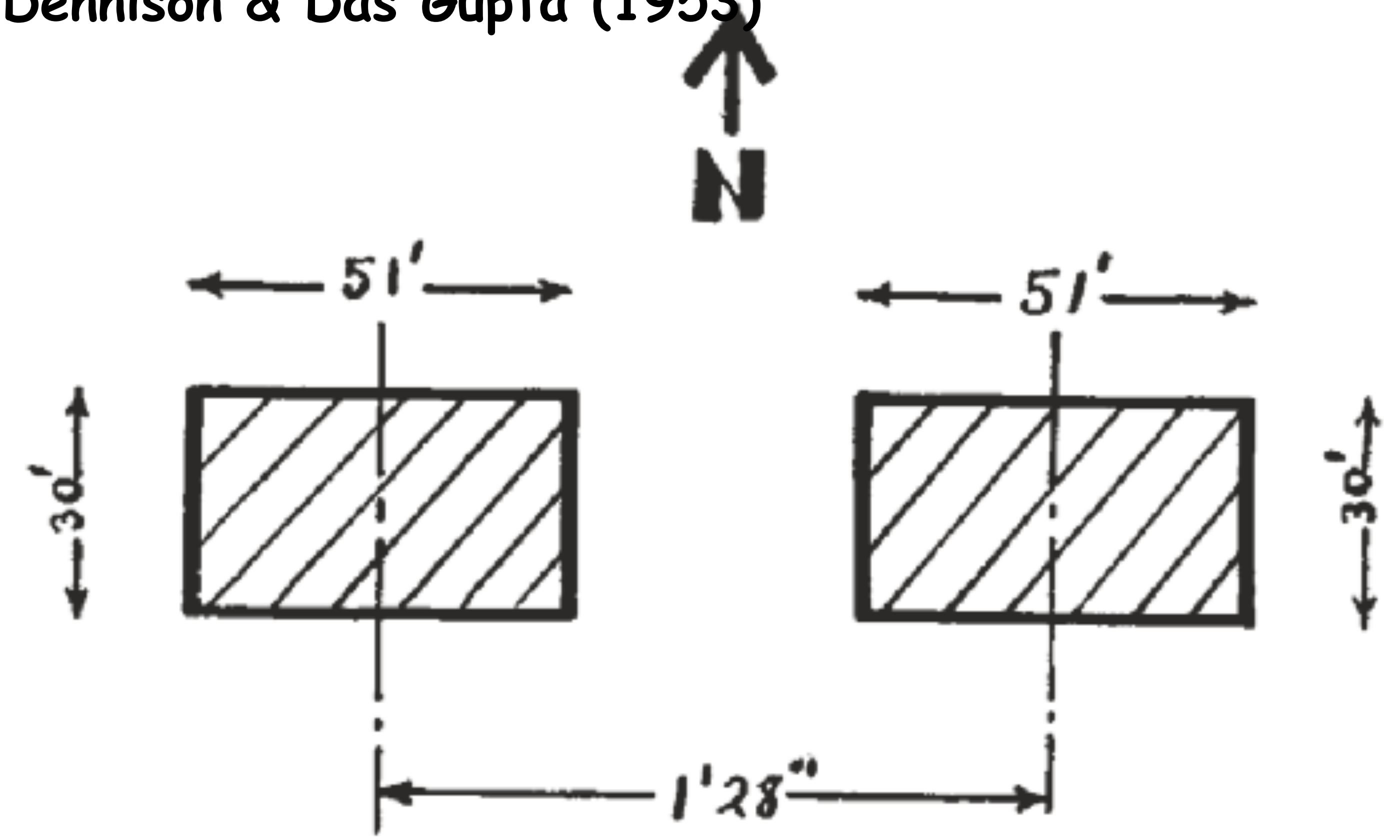


Fig. 2. Approximate intensity distribution of the extra-terrestrial radio source in Cygnus

Radio sources

1952 / 1974:

The Structure of Radio so

Hargrave & Ryle (1974)

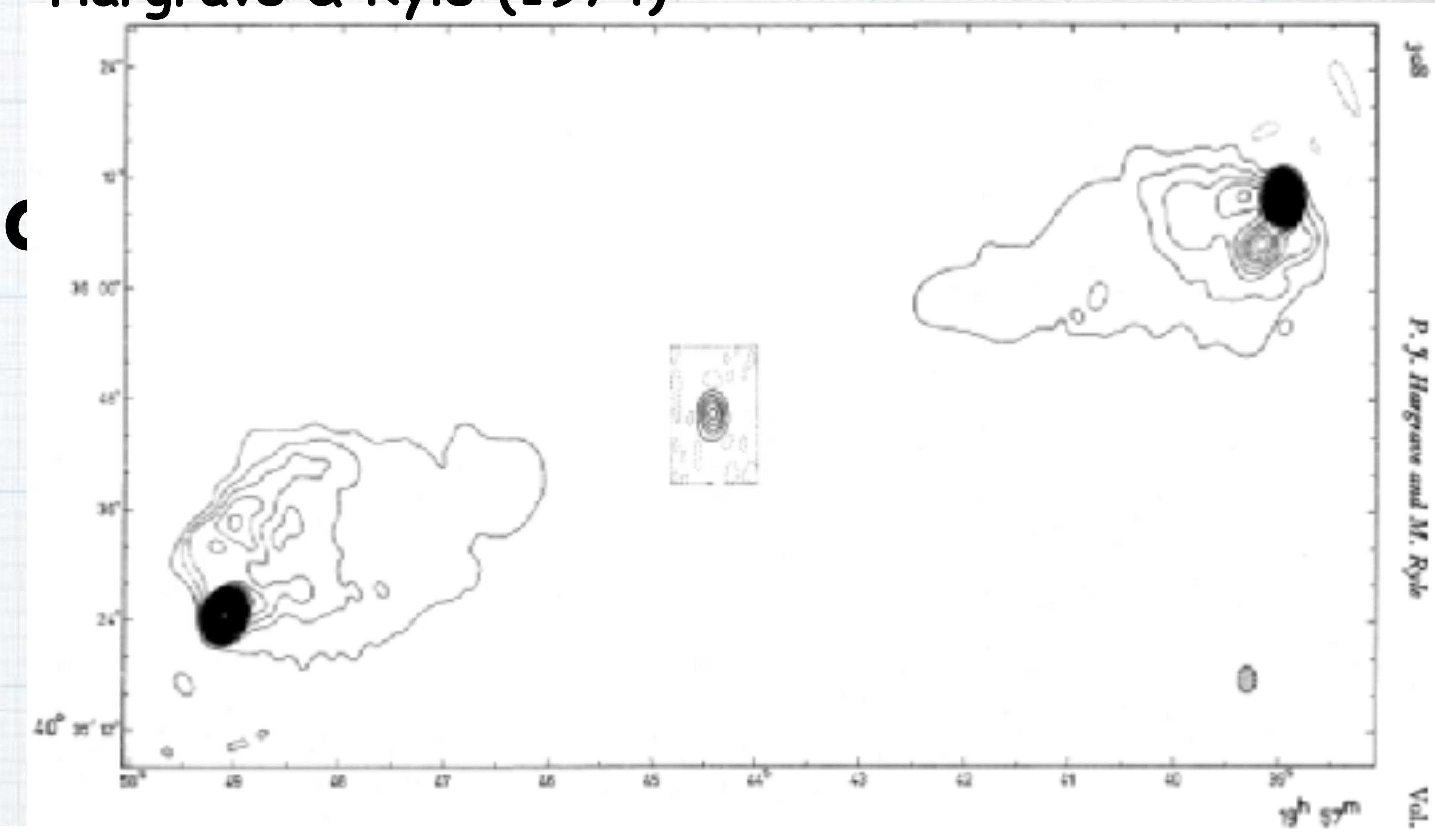


Fig. 1. The contours of brightness temperature in Cygnus A at 5 GHz. For the two main components the contour interval is 10^4 K and the outermost contour represents a brightness temperature of 0 ± 2500 K. The solid regions in the Np and Sf component reach 31 and 41 contours respectively. The area surrounding the central component is drawn with an interval of 2000 K. The half-power beamwidth is indicated by the shaded ellipse.

Dennison & Das Gupta (1953)

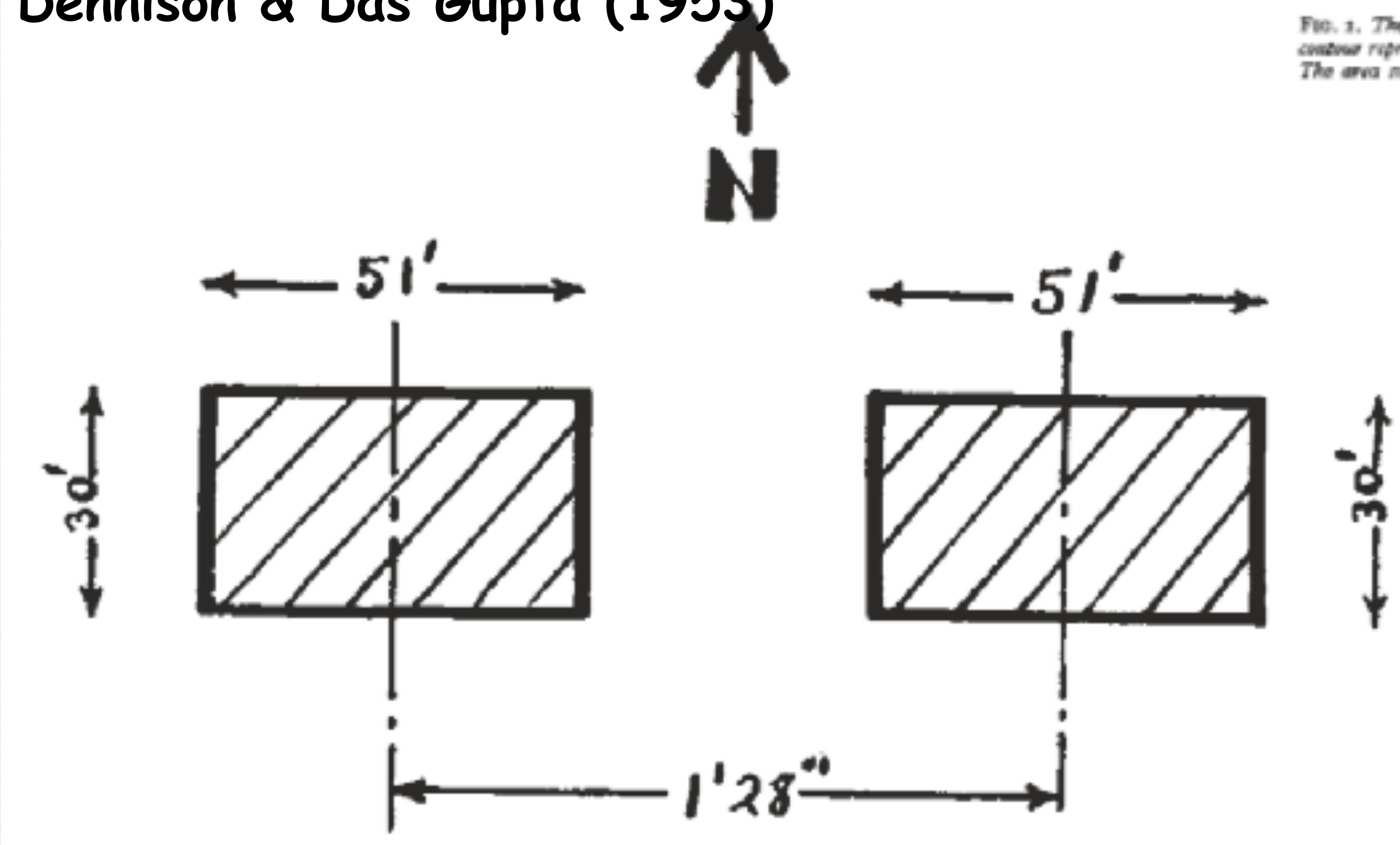
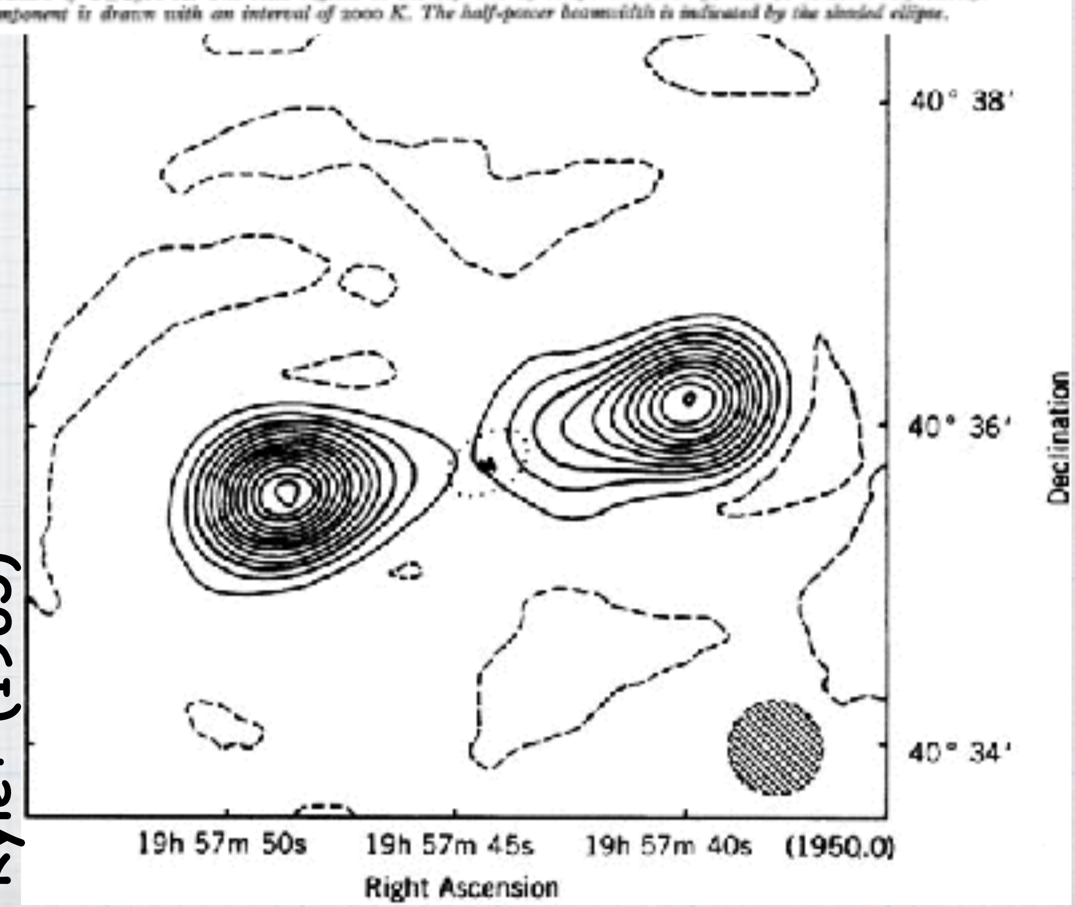


Fig. 2. Approximate intensity distribution of the extra-terrestrial radio source in Cygnus

Ryle+ (1965)



GMRT and its upgrade

- A **major upgrade** has been completed at the **GMRT**, with focus on
  - (nearly) seamless frequency coverage from
  - ~30 MHz to 1500 MHz,
  - design of completely new 'feeds' and 'receiver' system
- Improved G/T_{sys},
  - i.e., use of better tech. receivers and reduce T_{sys}
- Increased instantaneous bandwidth to 400 MHz
  - from present 32 MHz using new digital 'backend' receiver
- Revamp Servo-system for the antennas
- Modern and more versatile 'control and monitor' system
- Matching improvements in off-line computing facilities and other infrastructure