Introduction to Giant Metrewave Radio Telescope

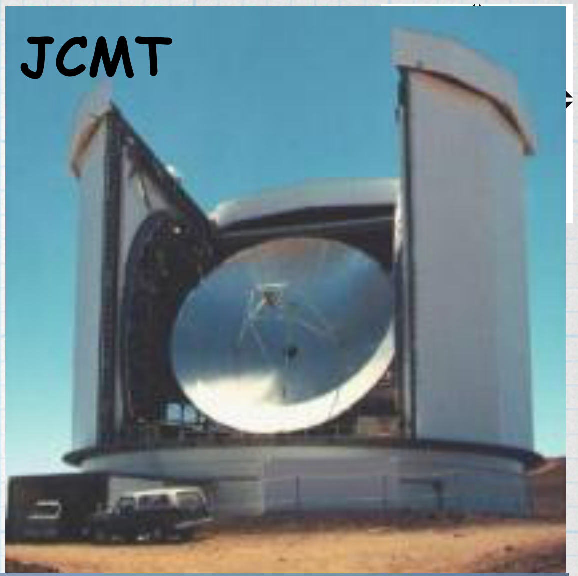
Plan

- **Introduce a radio telescope / interferometer (/ GMRT)**
  - Why?
  - Aperture synthesis
    - Interferometer
- **Why (GMRT /) radio astronomy**?
  - (assorted) examples
- **Giant Metrewave Radio Telescope**
  - (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

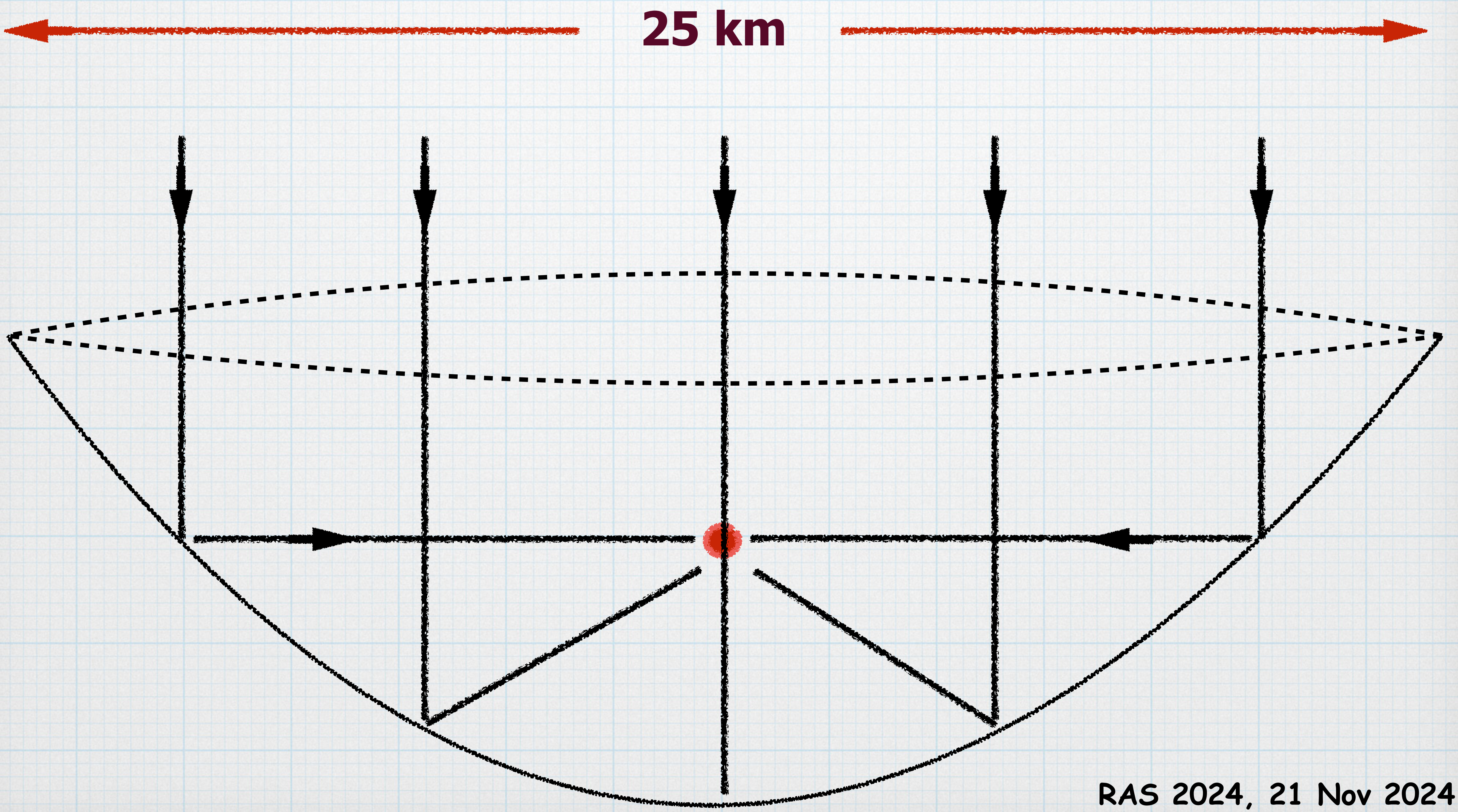
- Radio window extends over a factor of 1000 in wavelength
  - Radio telescopes at long wavelength are radically different from those at short wavelength



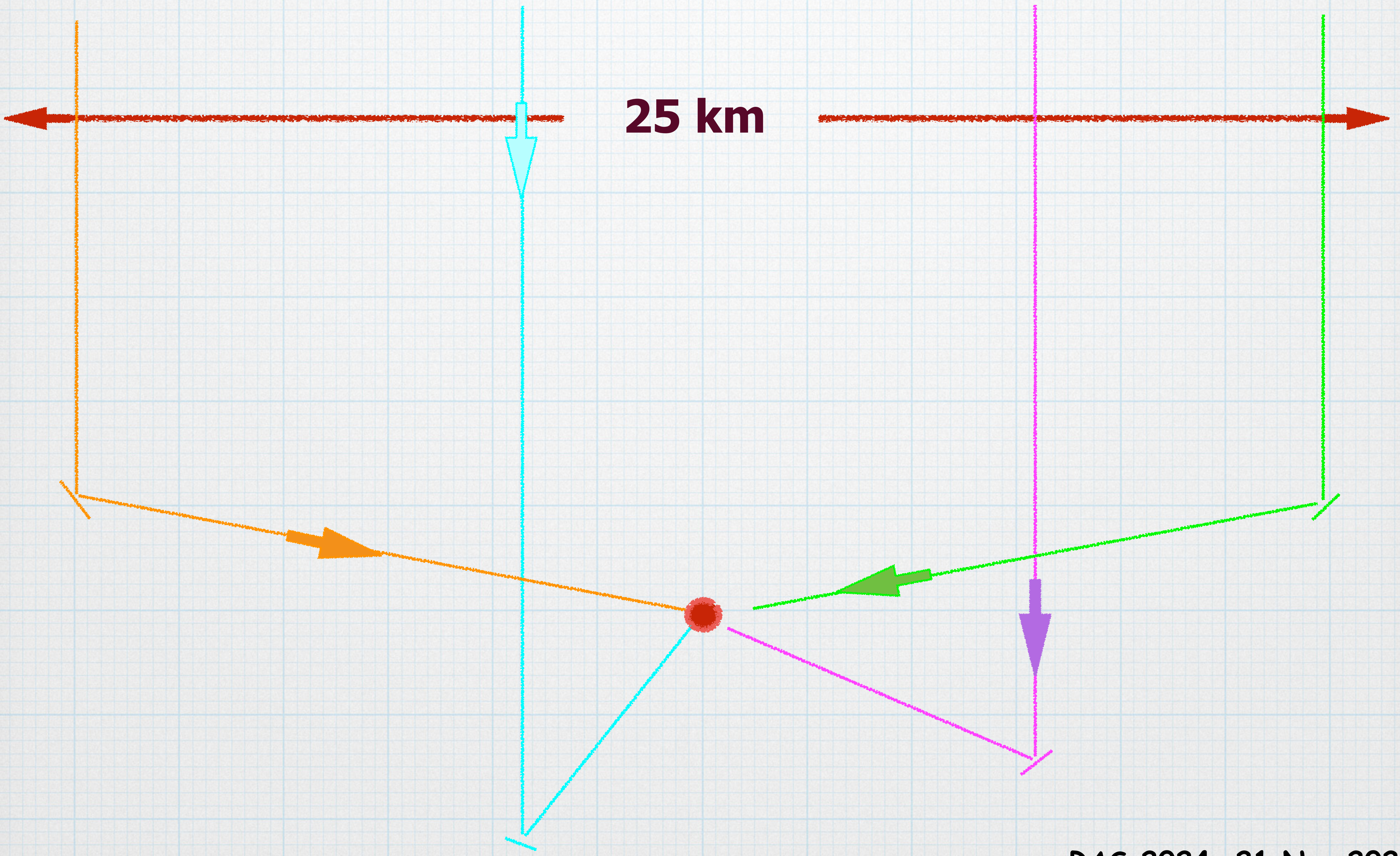
Angular resolution: its importance

$$\text{Resolution}\left(\approx\frac{\lambda}{D}\right)=\frac{6000\ \text{Å}}{0.5\ \text{cm}}=\frac{1\ \text{m}}{8.3\ \text{km}}$$

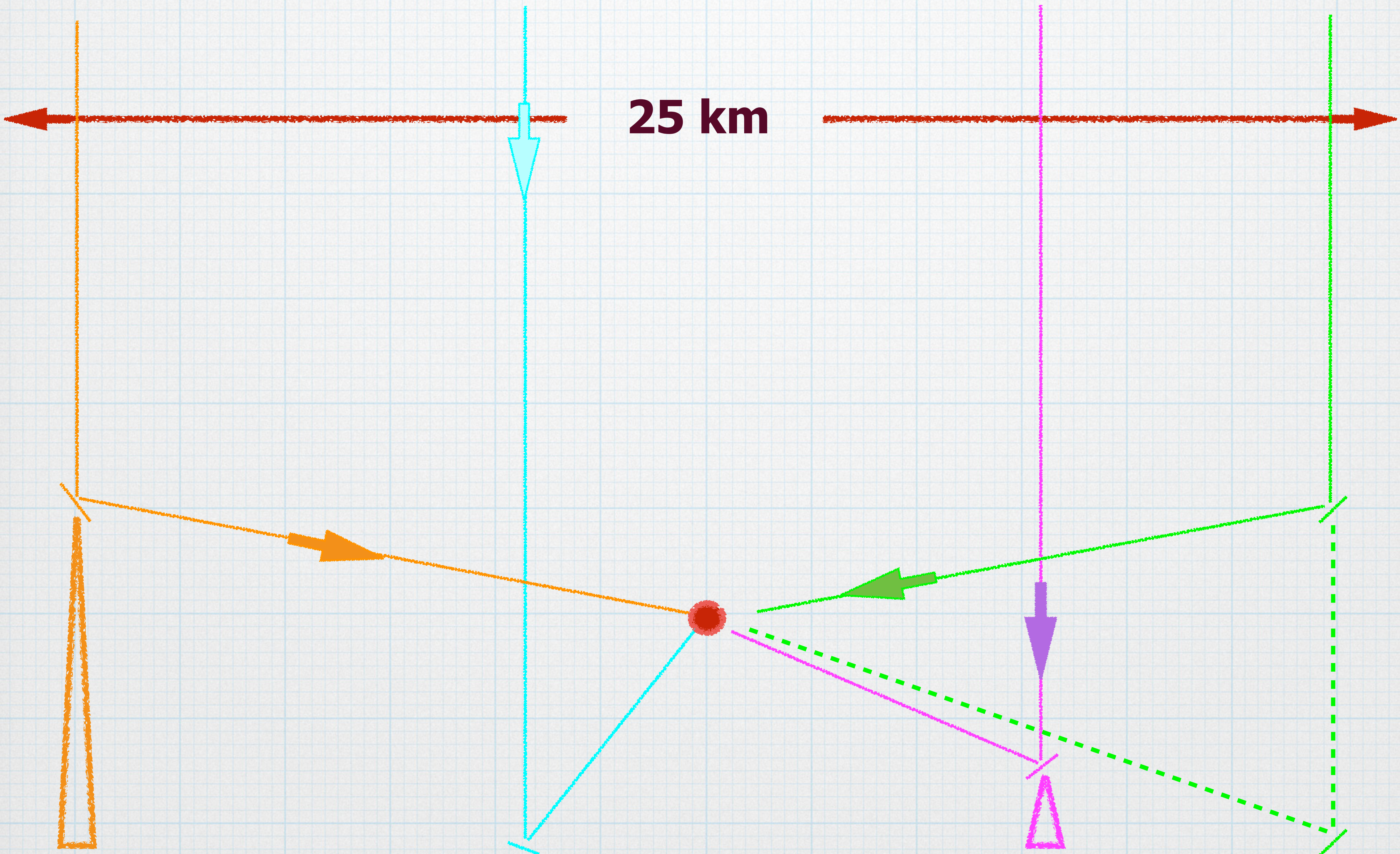
build an interferometer



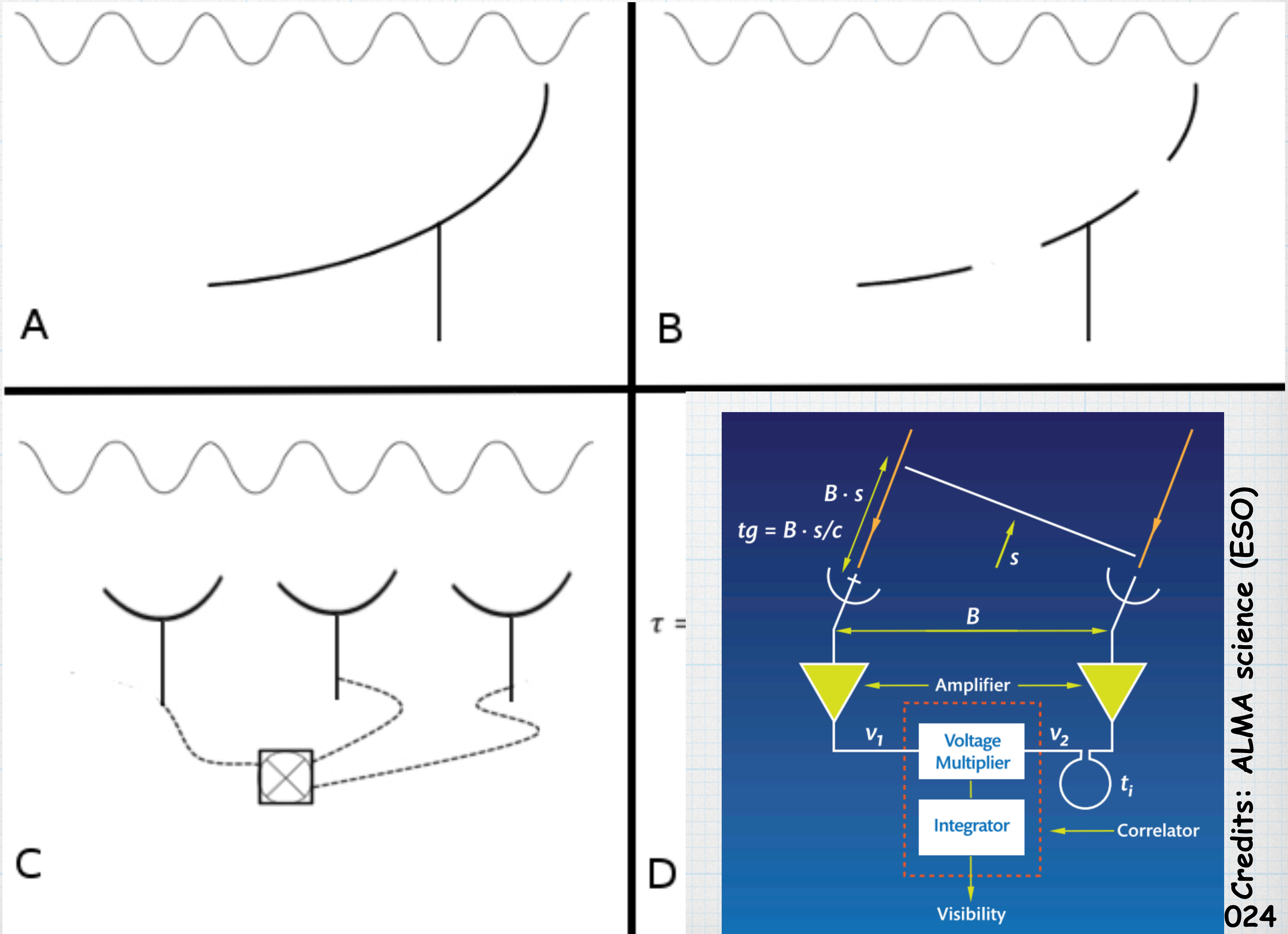
build GMRT



build GMRT



build GMRT



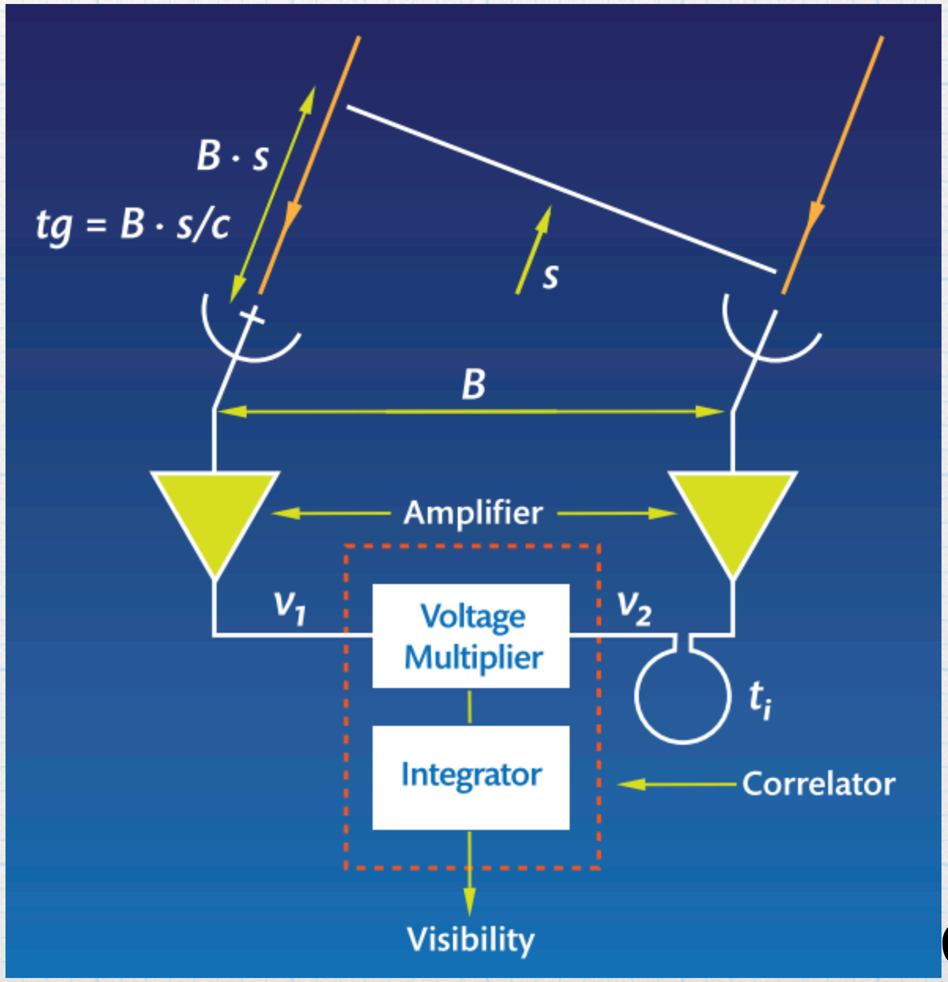
Credits: ALMA science (ESO)

024

GMRT: A radio interferometer

Van Cittert-Zernicke Theorem

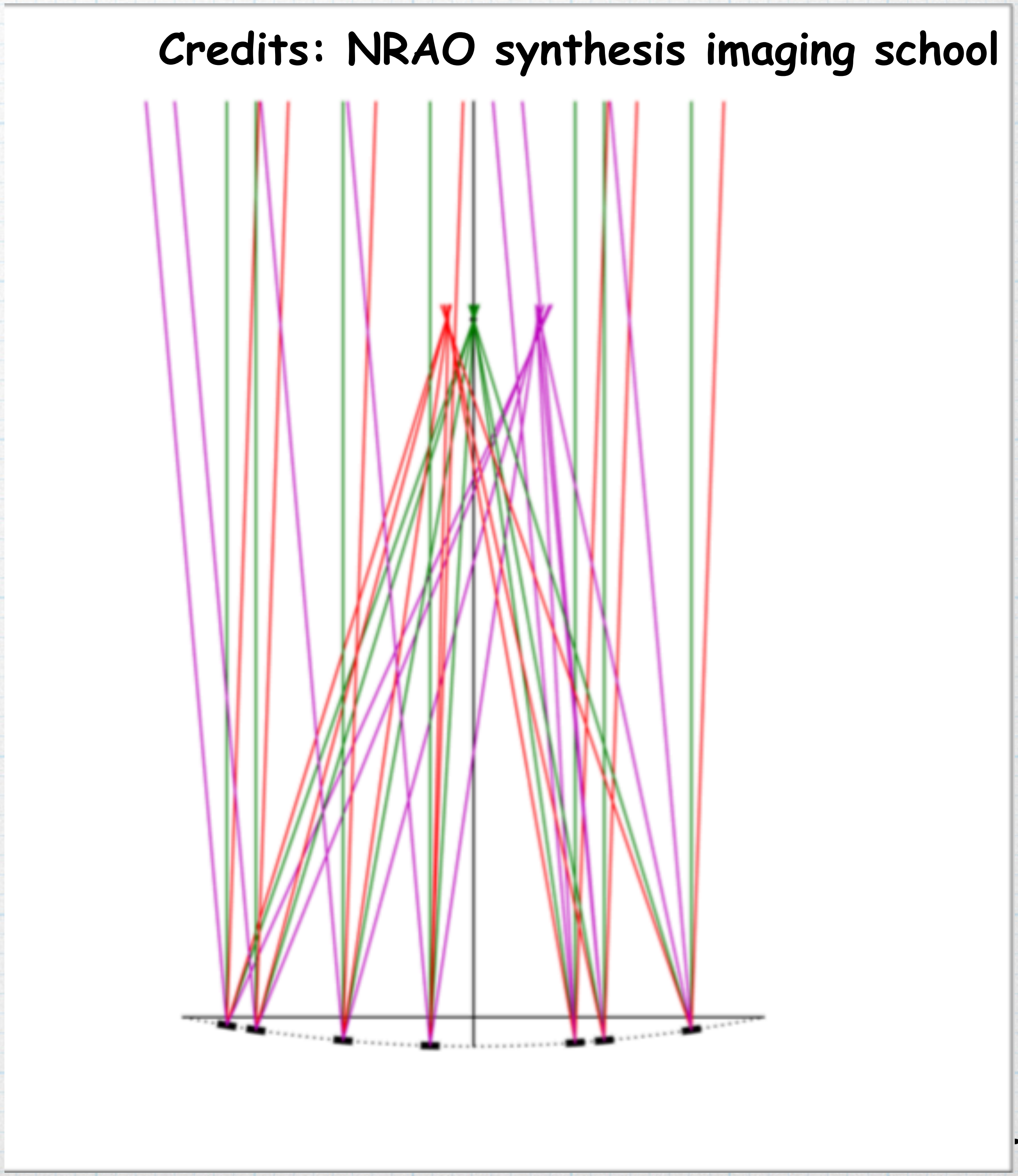
- An interferometer measures the interference pattern produced by pairs of apertures.
  - The interference pattern is directly related to the source brightness: (for small fields-of-view) the complex visibility is the 2D Fourier transform of the brightness on the sky.



Credits: ALMA science (ESO)

An unfilled aperture

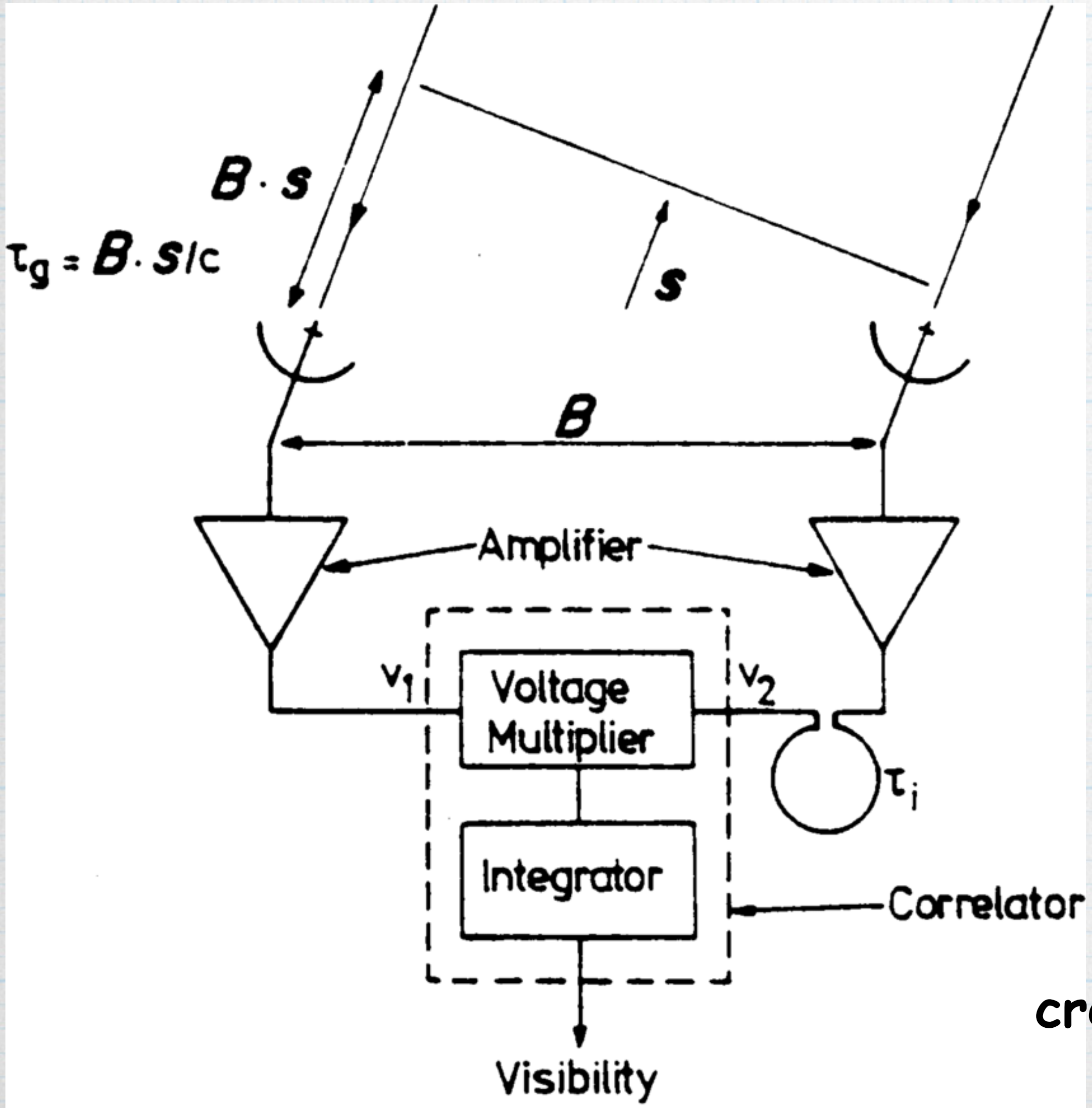
- Each segment gathers 'em' field
  - Parabolic figure redirects net information to the focal plane
- But fewer segments, and pairs thereof
  - Less collecting area
  - Uglier diffraction pattern



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 (include tricks)

- Celestial sources do not vary on human timescales
  - i.e., their statistical parameters do not vary!

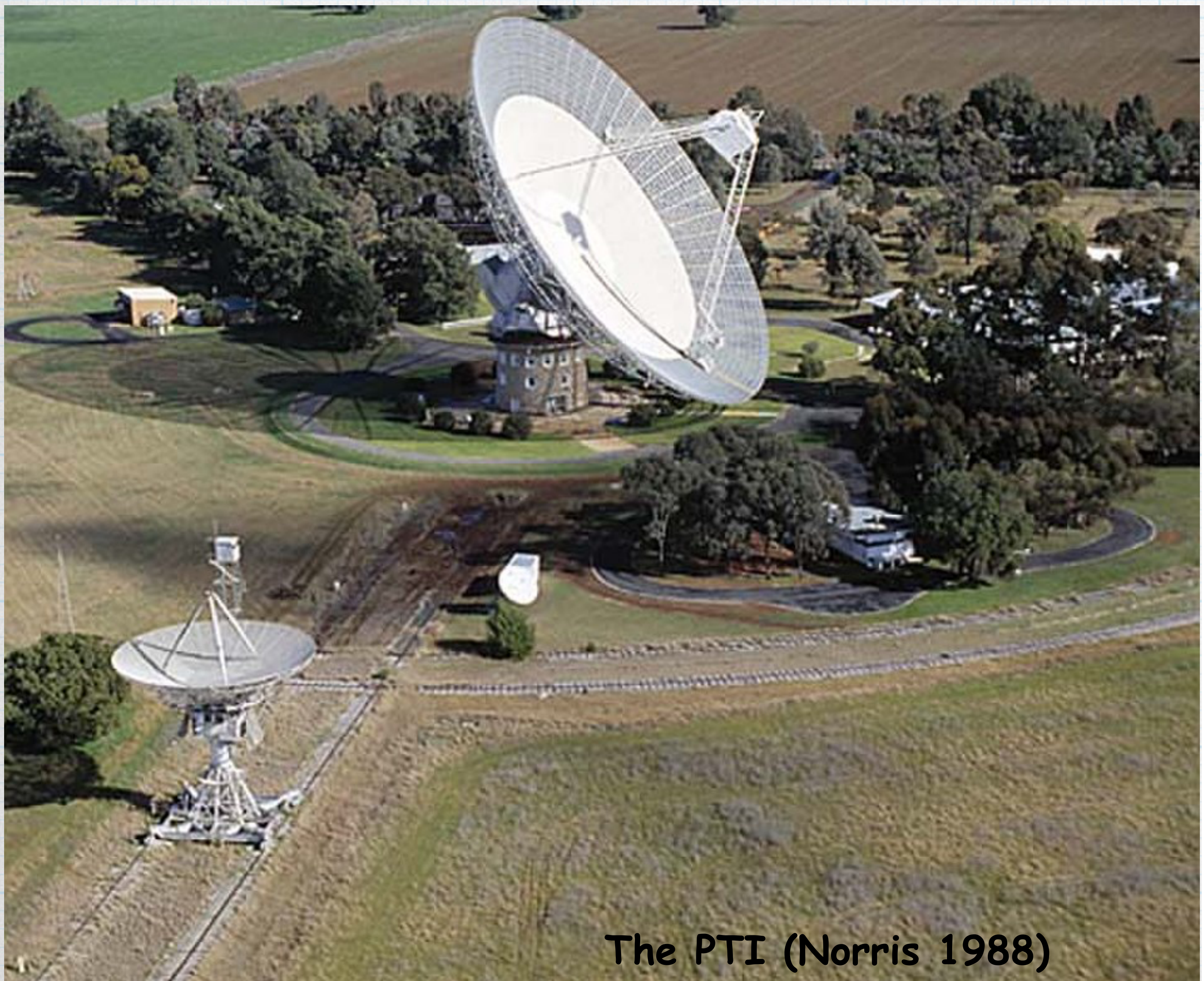
- Synthesize a large aperture using repeated observations with a few antennas whose spacings can be varied
  - e.g., by mounting the antennas on tracks

- -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

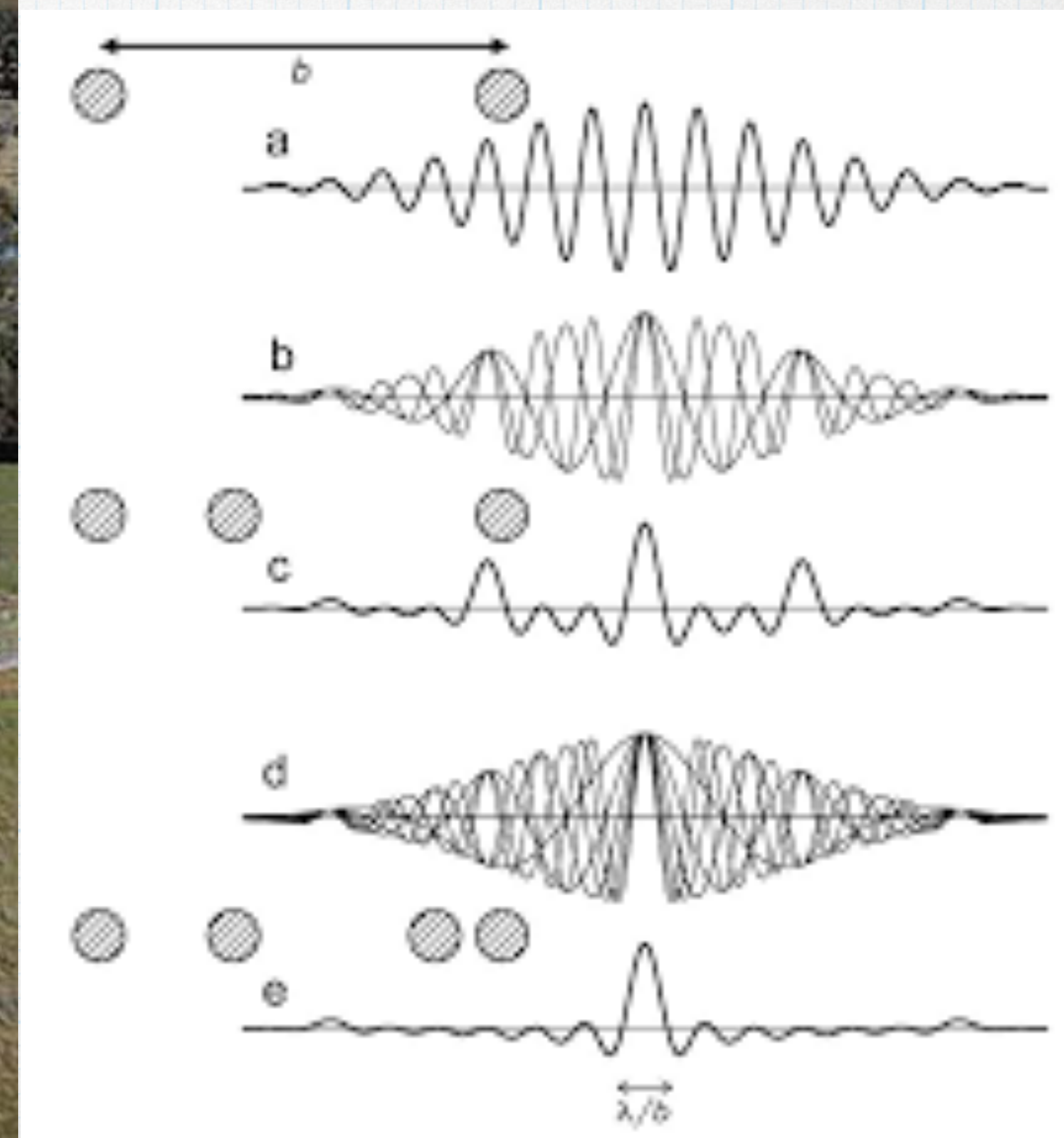
NCRA • TIFR

- interferometry
  - Correlate the signal
  - Correlation = multiplication + integration



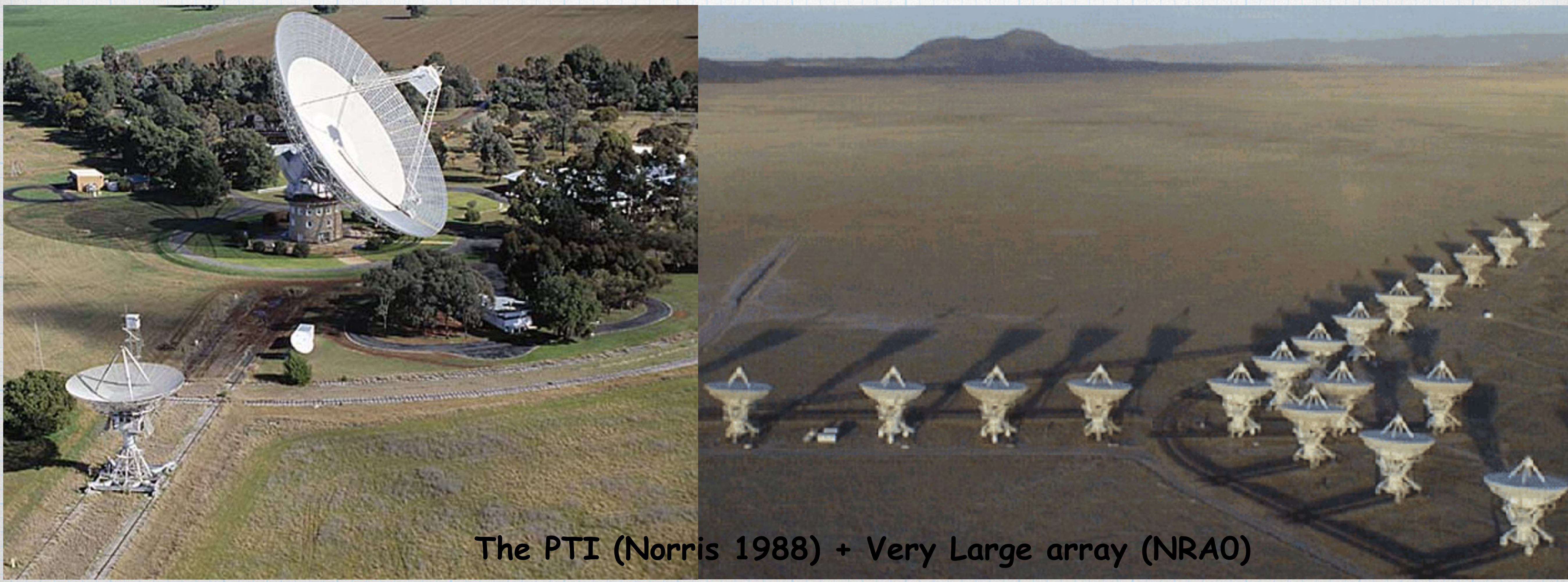
The PTI (Norris 1988)

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 synthesised 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

- One can picture this as making an image with a mirror ("aperture") with holes
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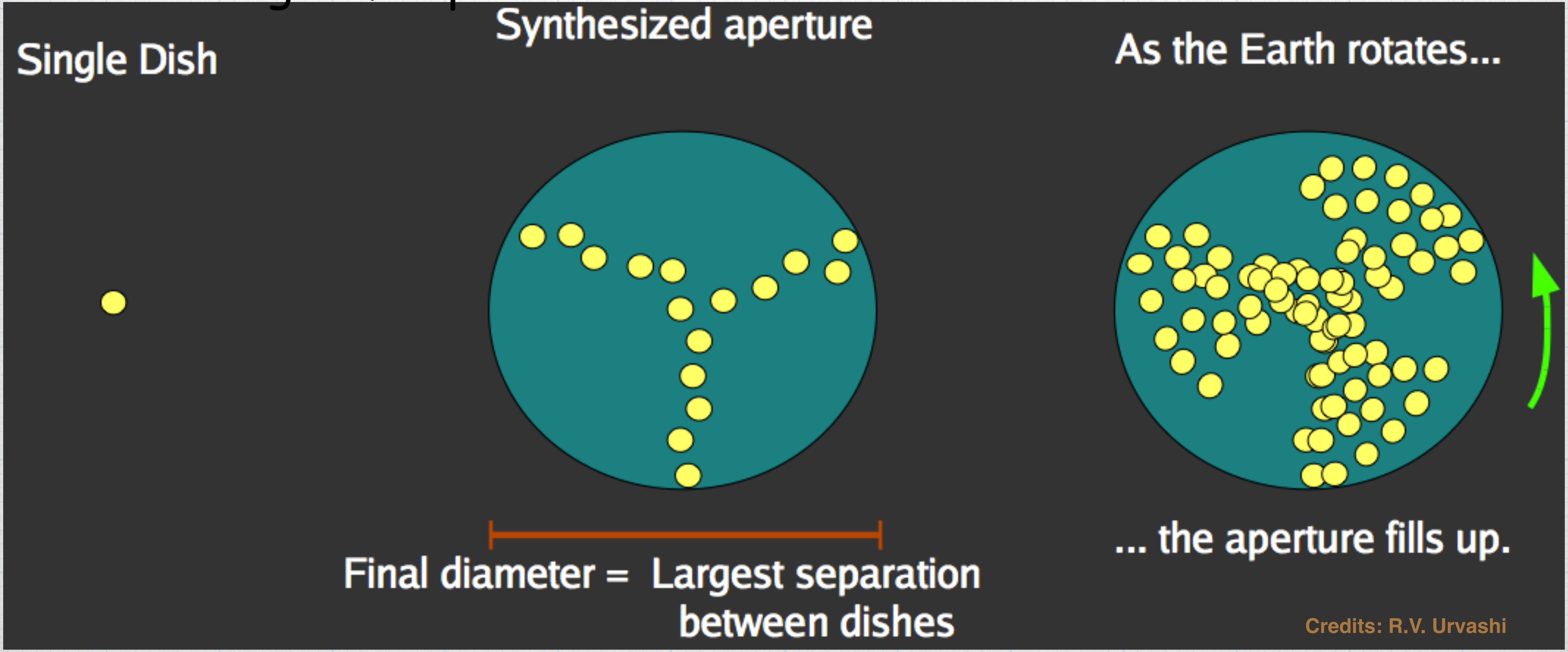


Aperture synthesis

- A correlation interferometer measures one component of the image Fourier transform
  - The component corresponding to the spatial frequency b/λ
- 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 source (Cygnus A)

- 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

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

Dennison & Das Gupta (1953)

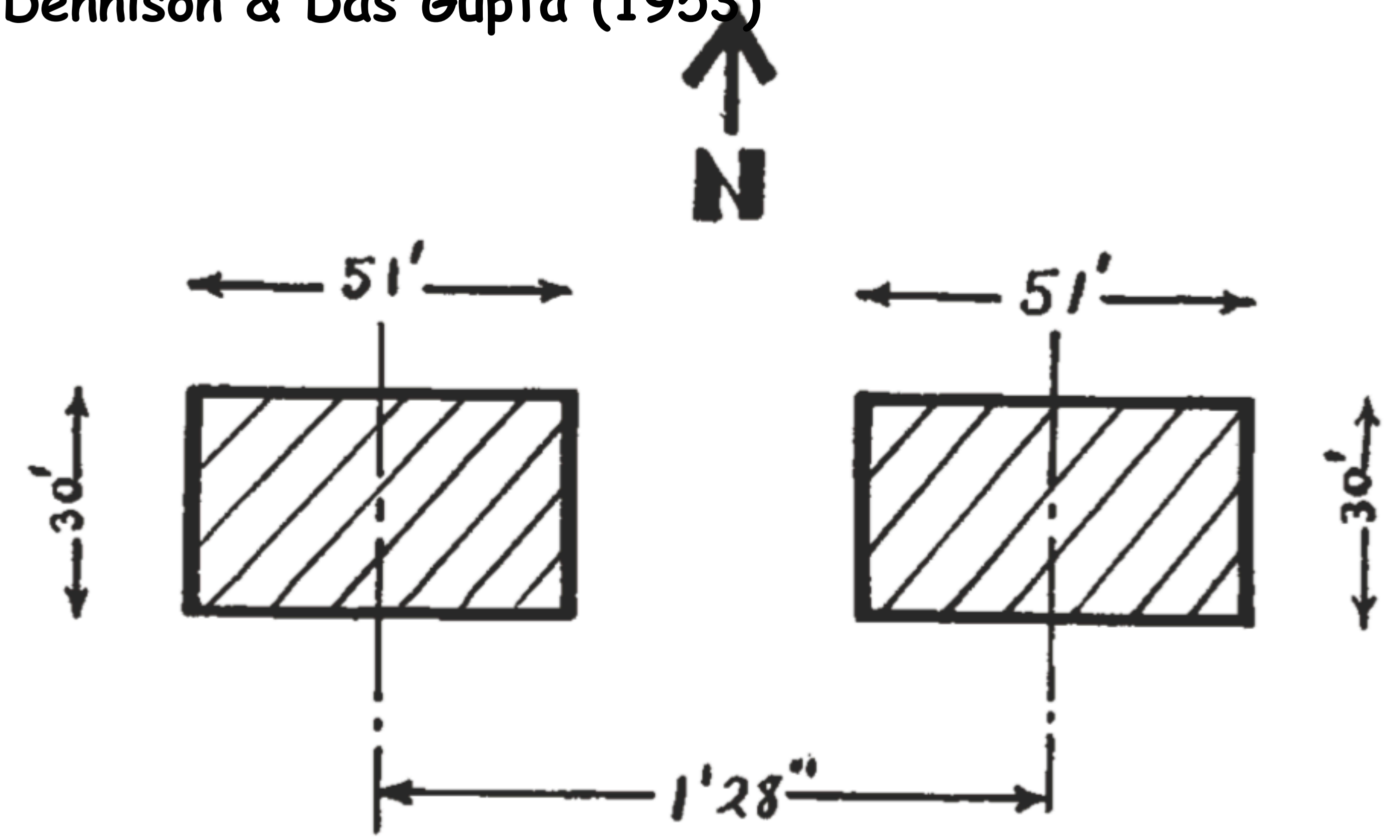
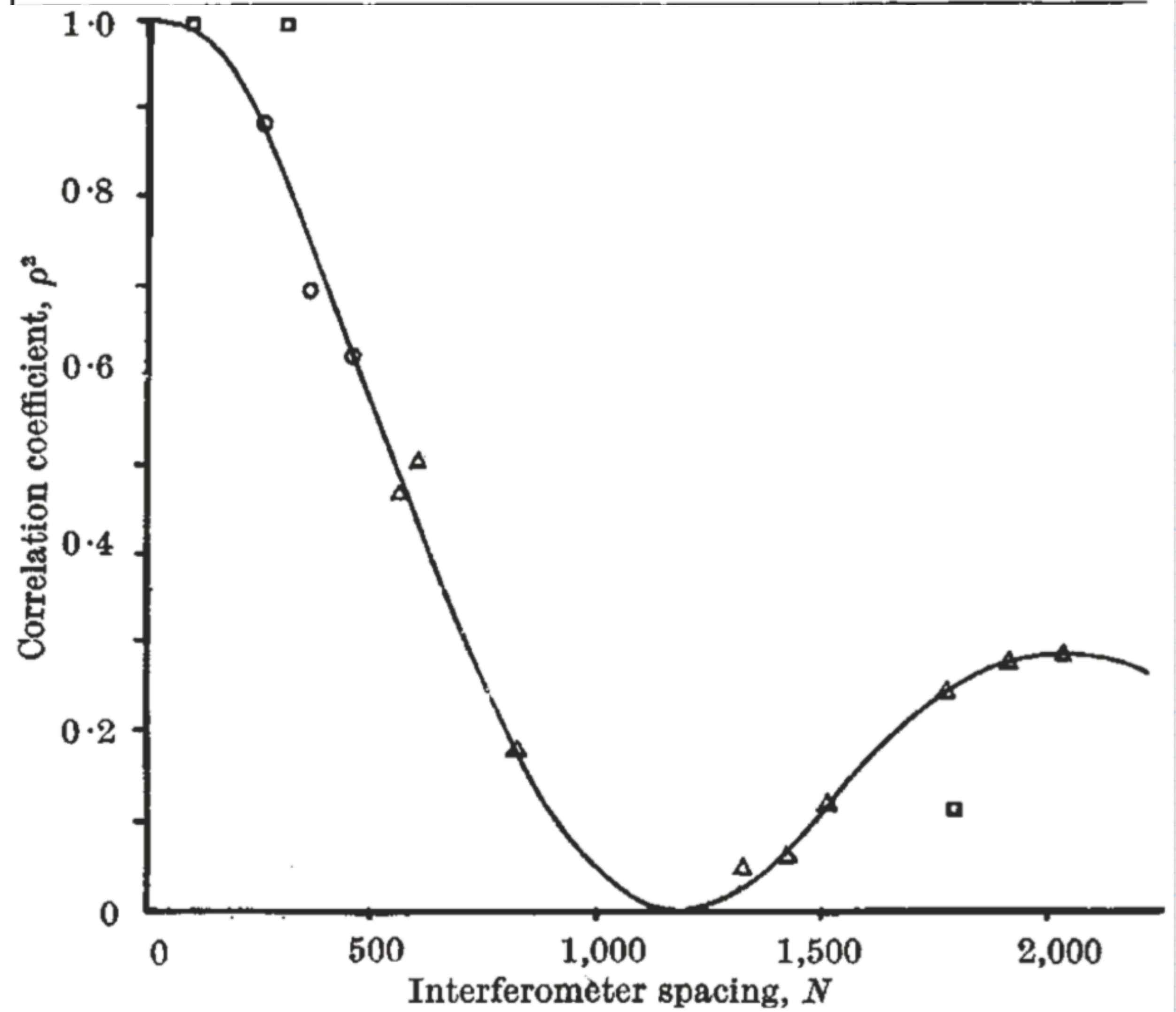


Fig. 2. Approximate intensity distribution of the extra-terrestrial radio source in Cygnus



Radio sources

1952 / 1974:

The Structure of Radio sc

Hargrave & Ryle (1974)

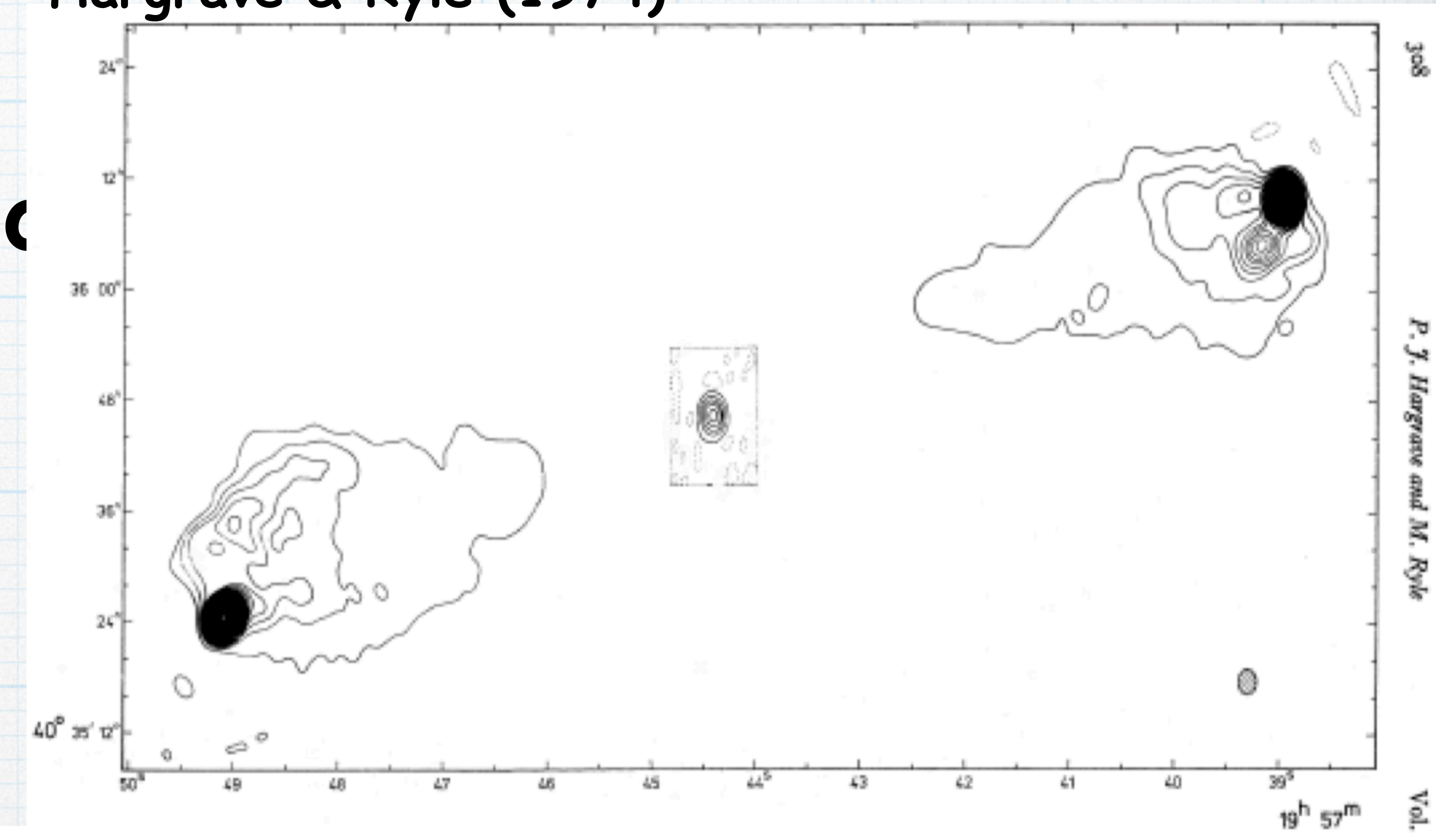


FIG. 2. The contours of brightness temperature in Cygnus A at 5 GHz. For the two main components the contour interval is 10^4 K and the outermost contour represents a brightness temperature of 0±2500 K. The solid regions in the Np and Sf component reach 31 and 41 contours respectively. The area surrounding 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)

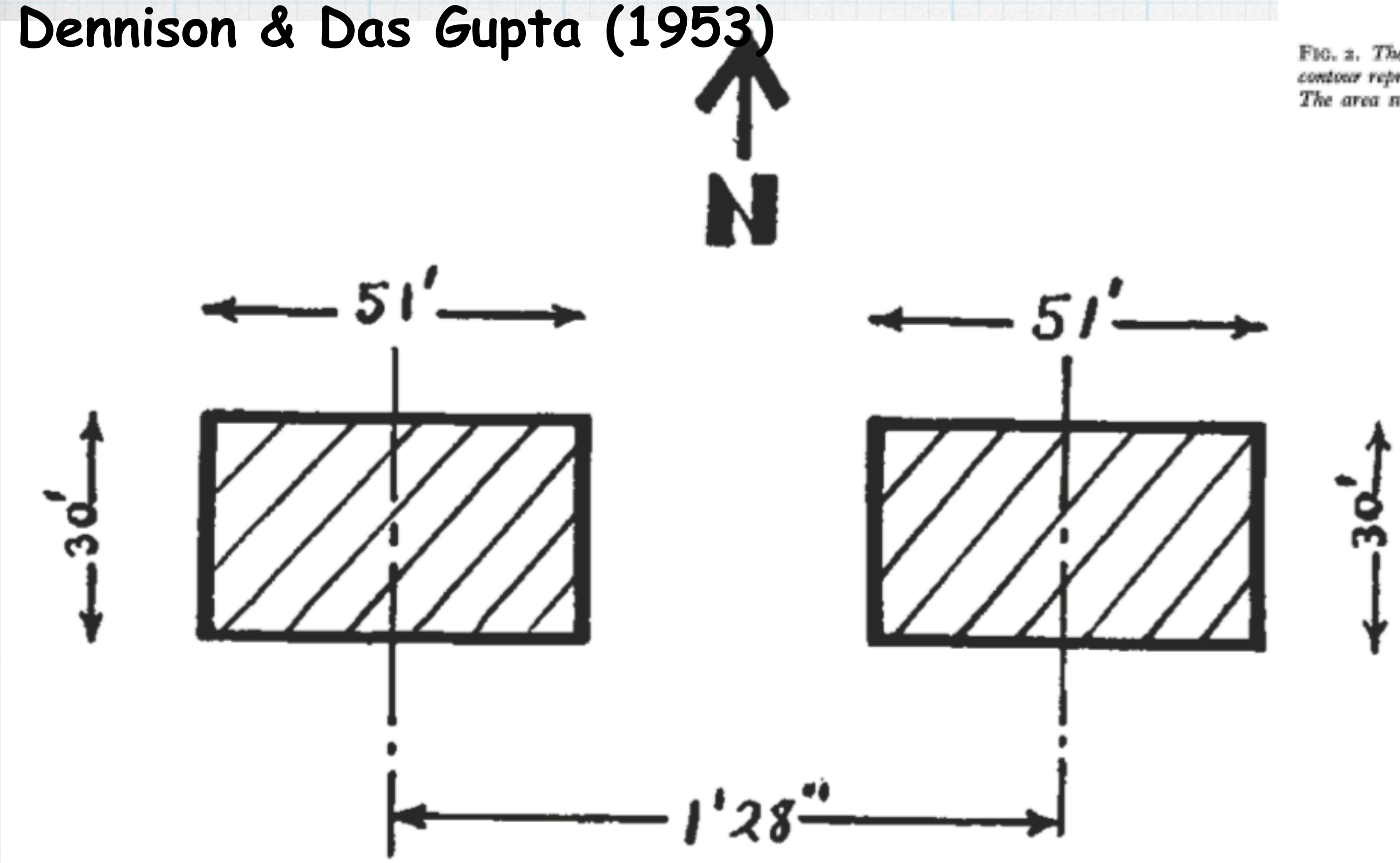
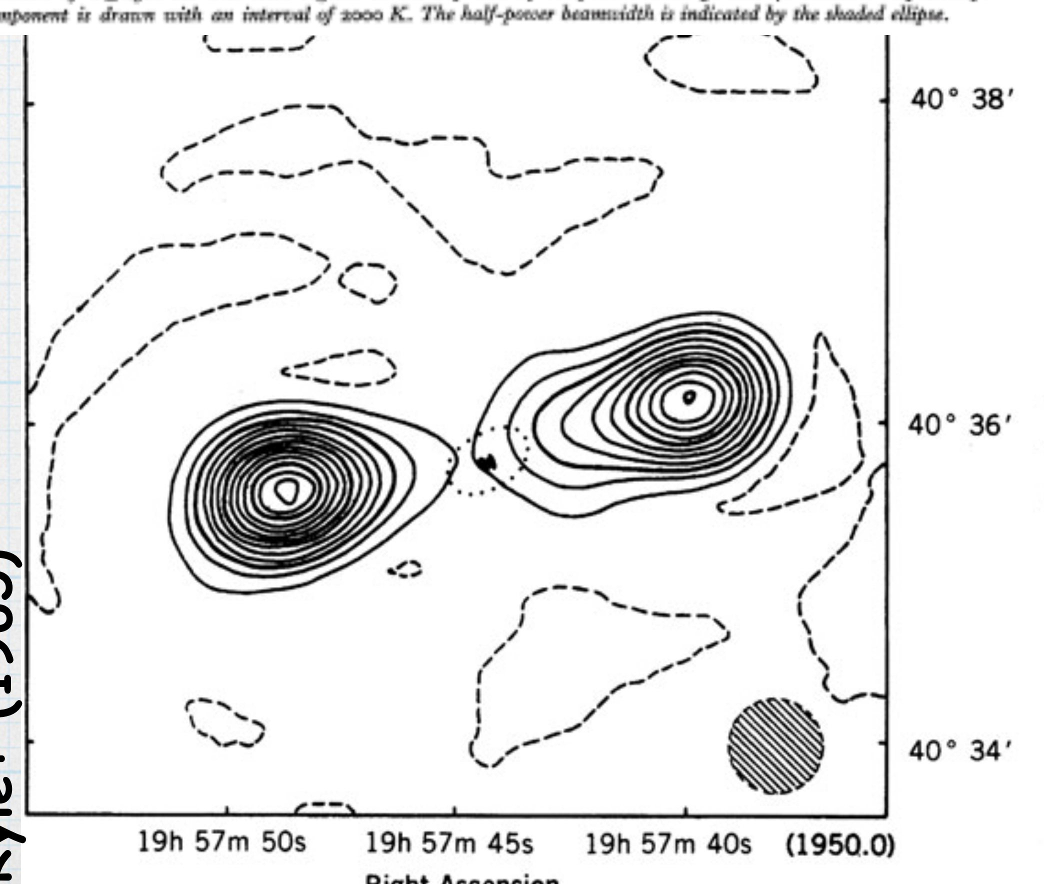


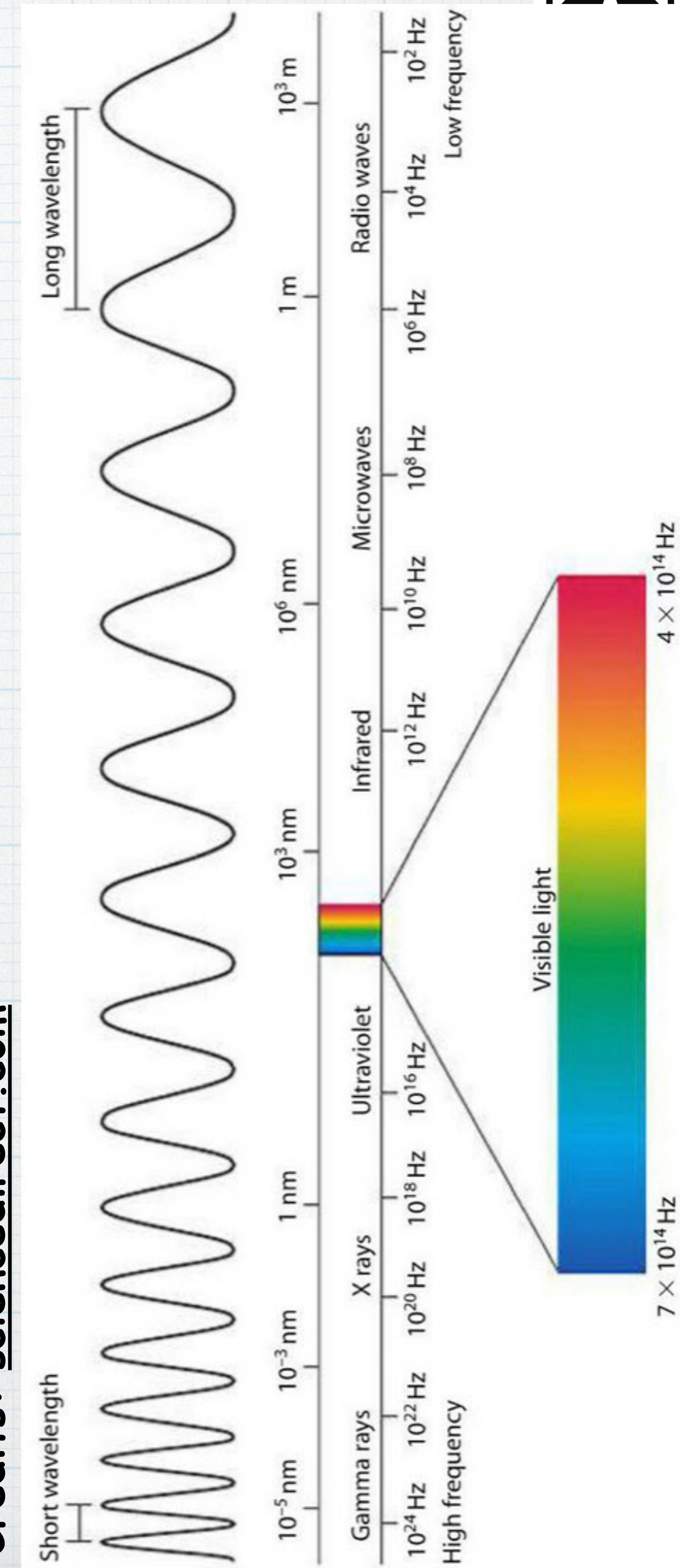
Fig. 2. Approximate intensity distribution of the extra-terrestrial radio source in Cygnus

Ryle+ (1965)



Why RA (part-I)?

large part of e.m. spectrum



Credits: sciencedirect.com

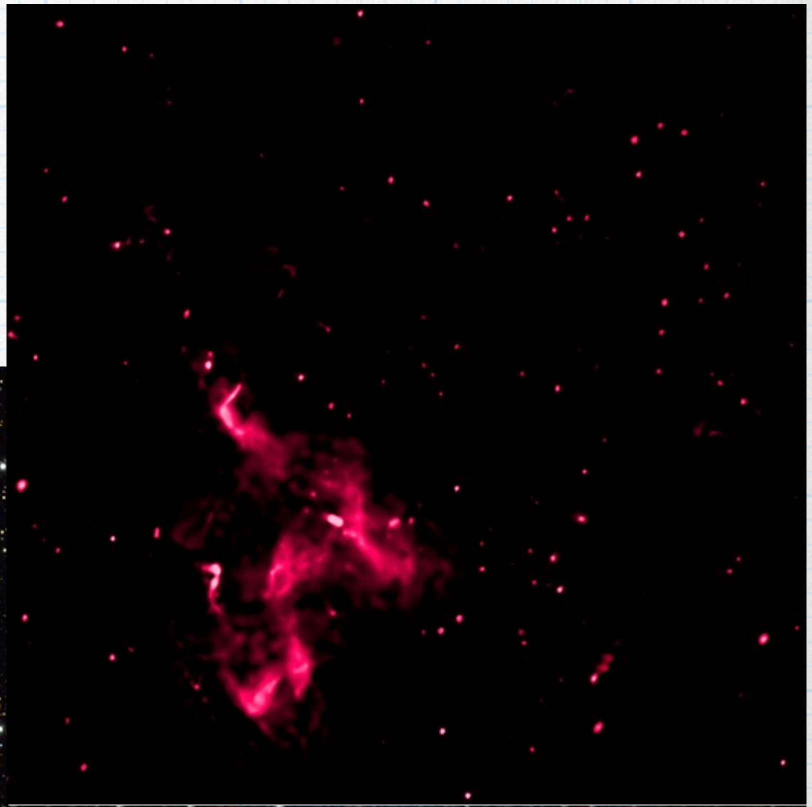
Why RA (part-II)?

Access to the invisible (to eye) part of spectrum

Credits: NRAO (NSF)

Why RA (part-III)?

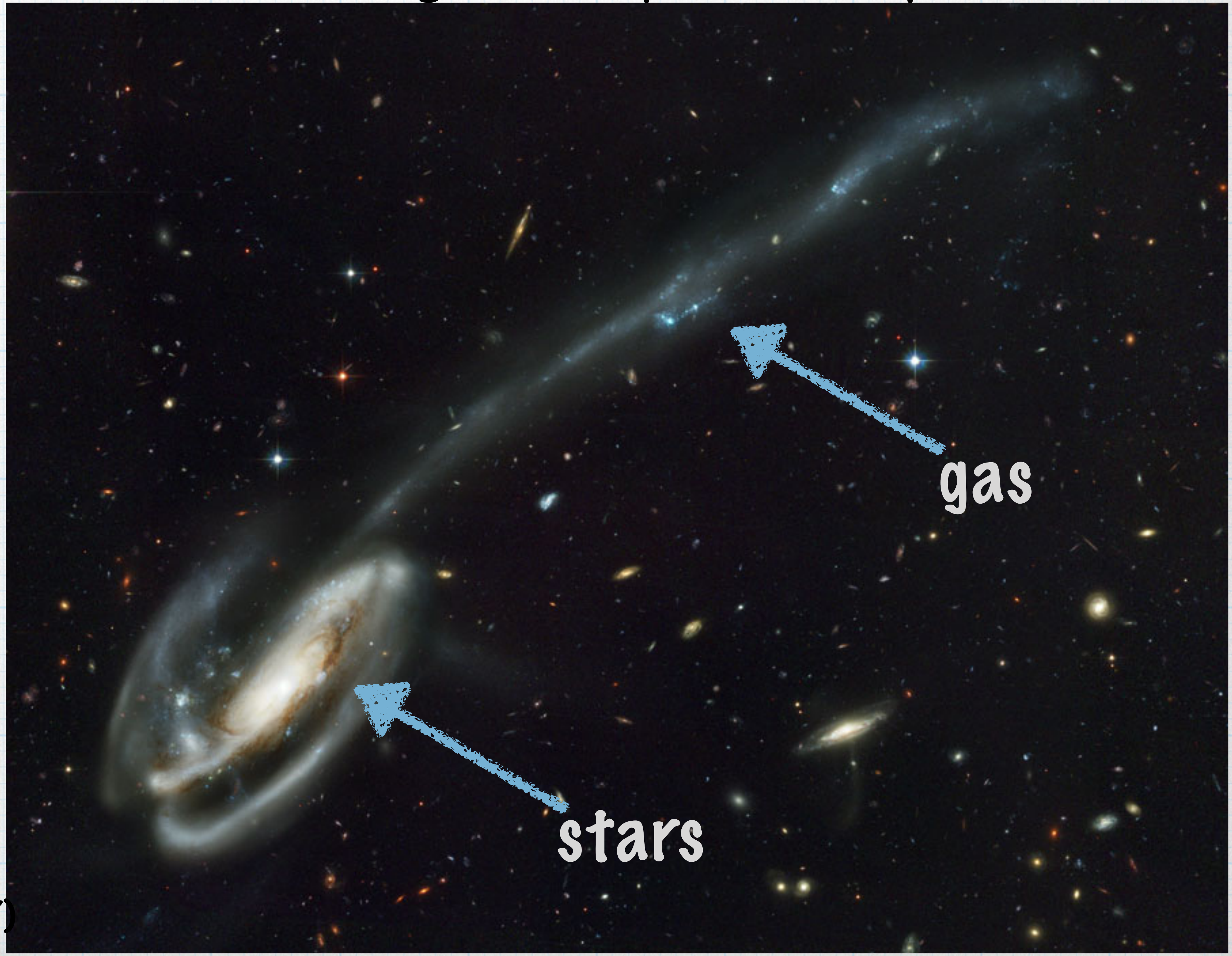
- **some stuff visible only in radio**
  - optical emission mainly comes from stars
  - Radio-wave comes mainly from gas or hot plasma
  - full (e.m.) observations
    - give a complete info



Credits: van Weeren+ 2017

Why RA (part-III)?

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



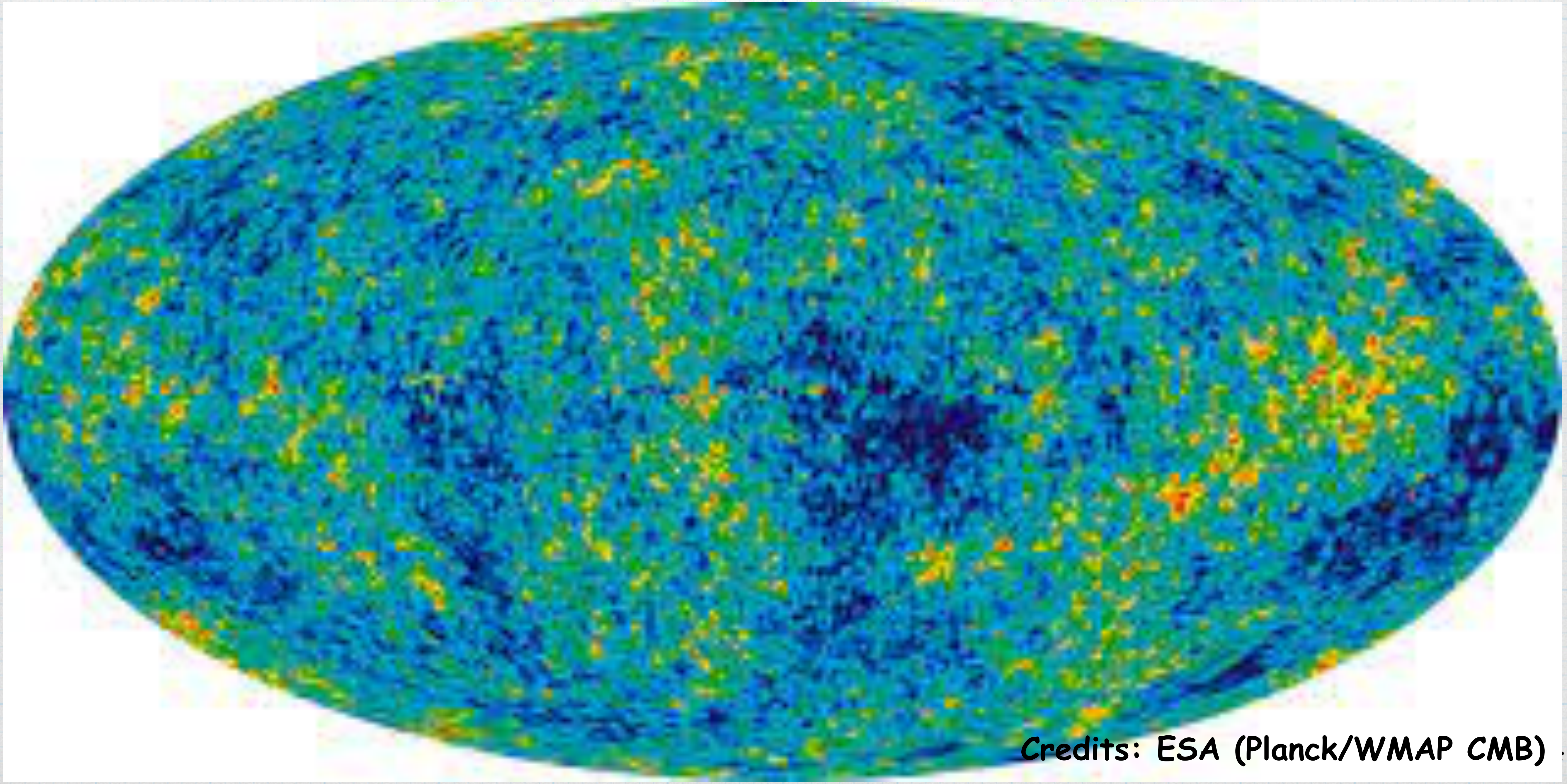
Credits: SpARCS (Noble+ 2017)

What's so special about RA?

CMB

-or-

the (far) far-away Universe

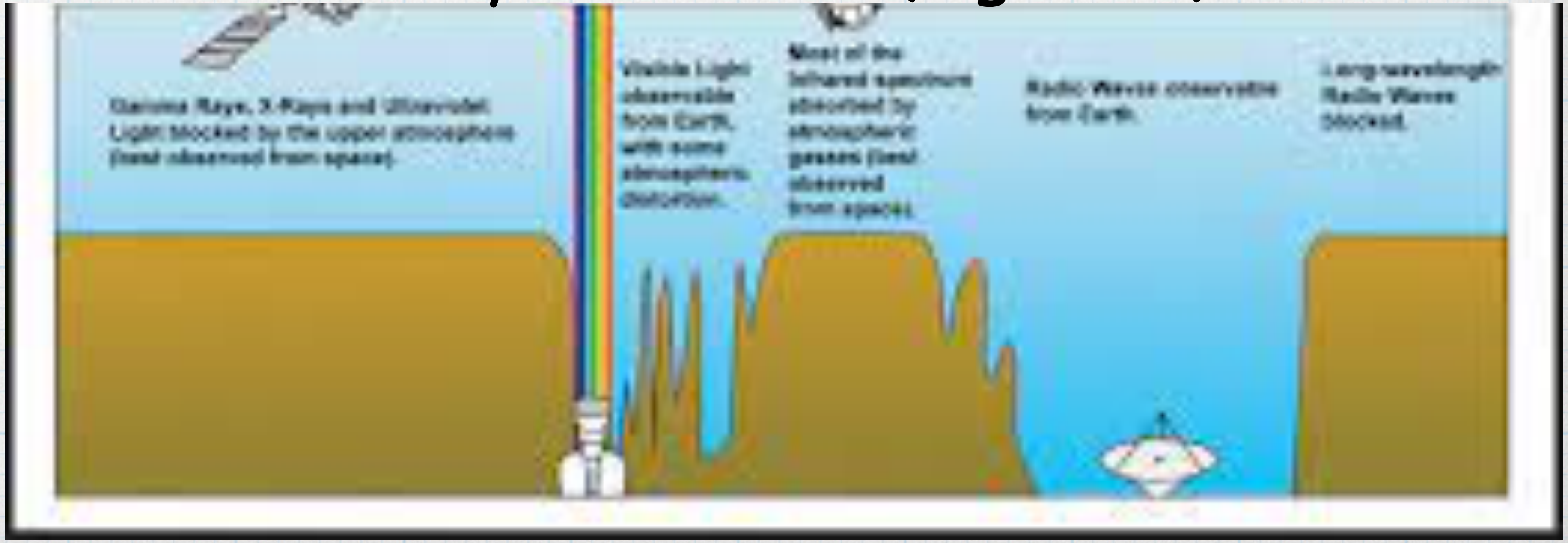


What's so special about RA?

Ground-based (24x7) observing

- 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).

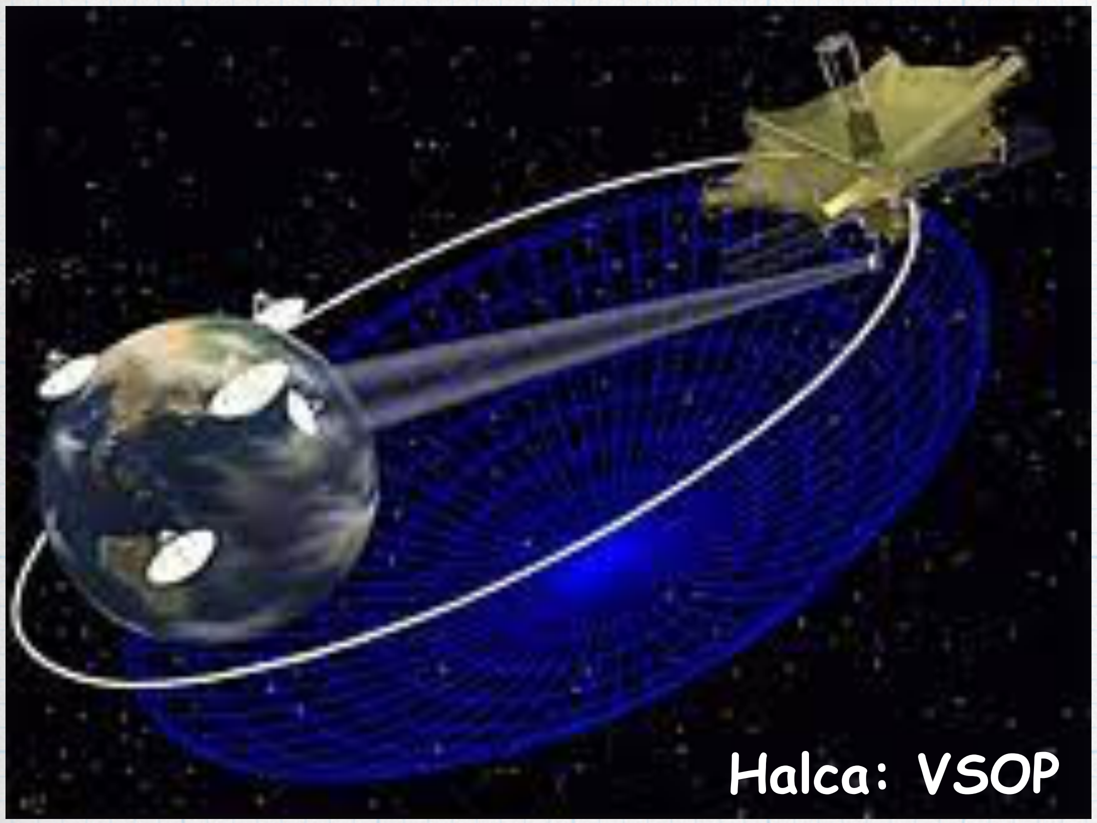


Credits: ESO

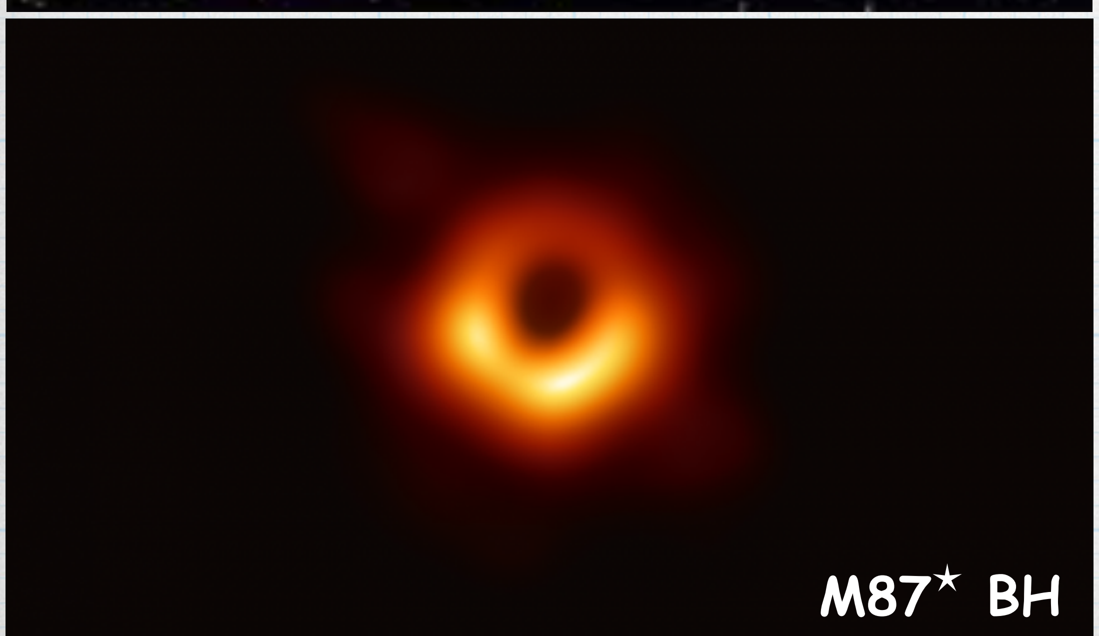
What's so special about RA?

Ridiculously (ridiculously) high angular resolution

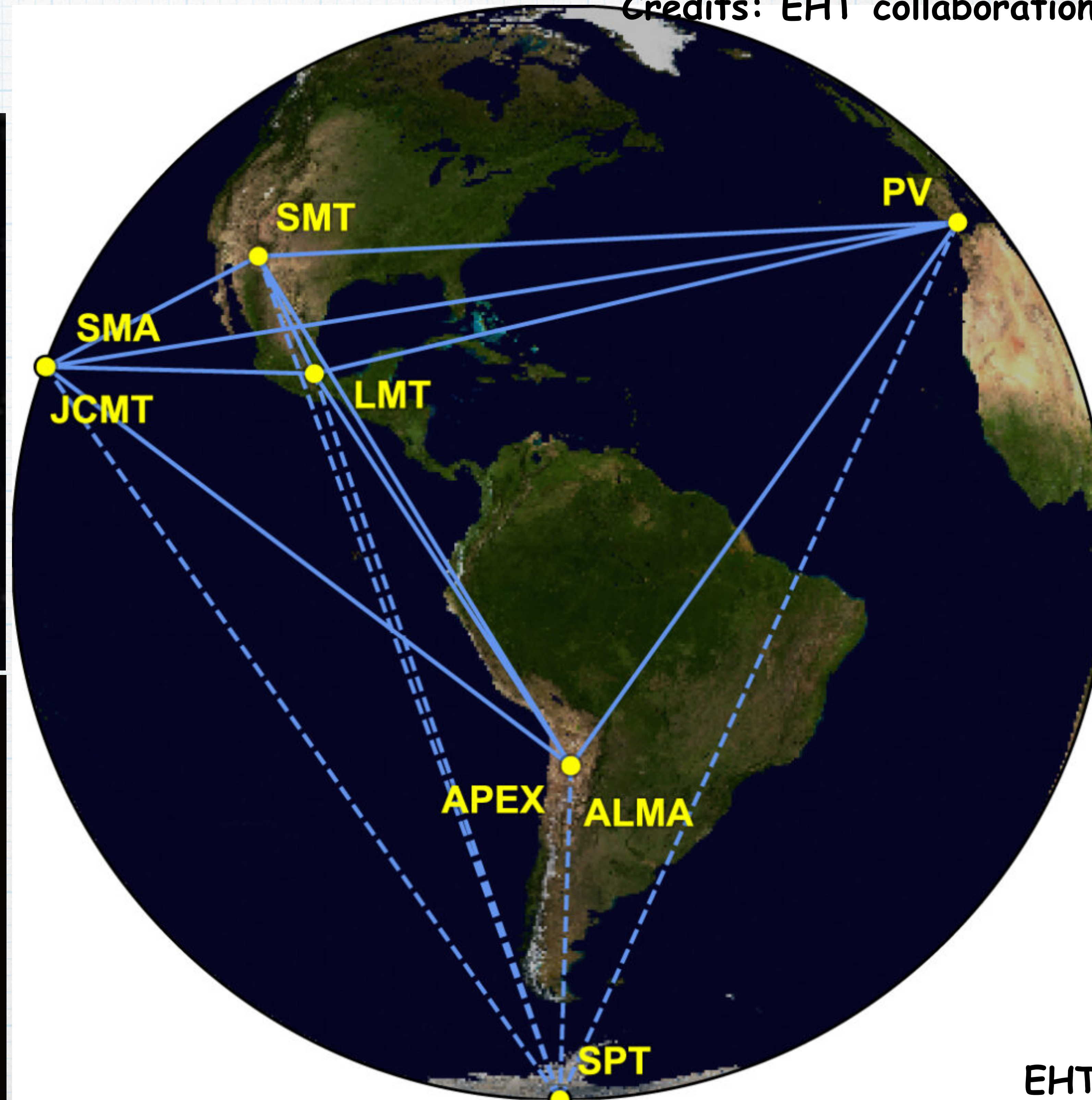
Credits: EHT collaboration



Halca: VSOP



M87* BH



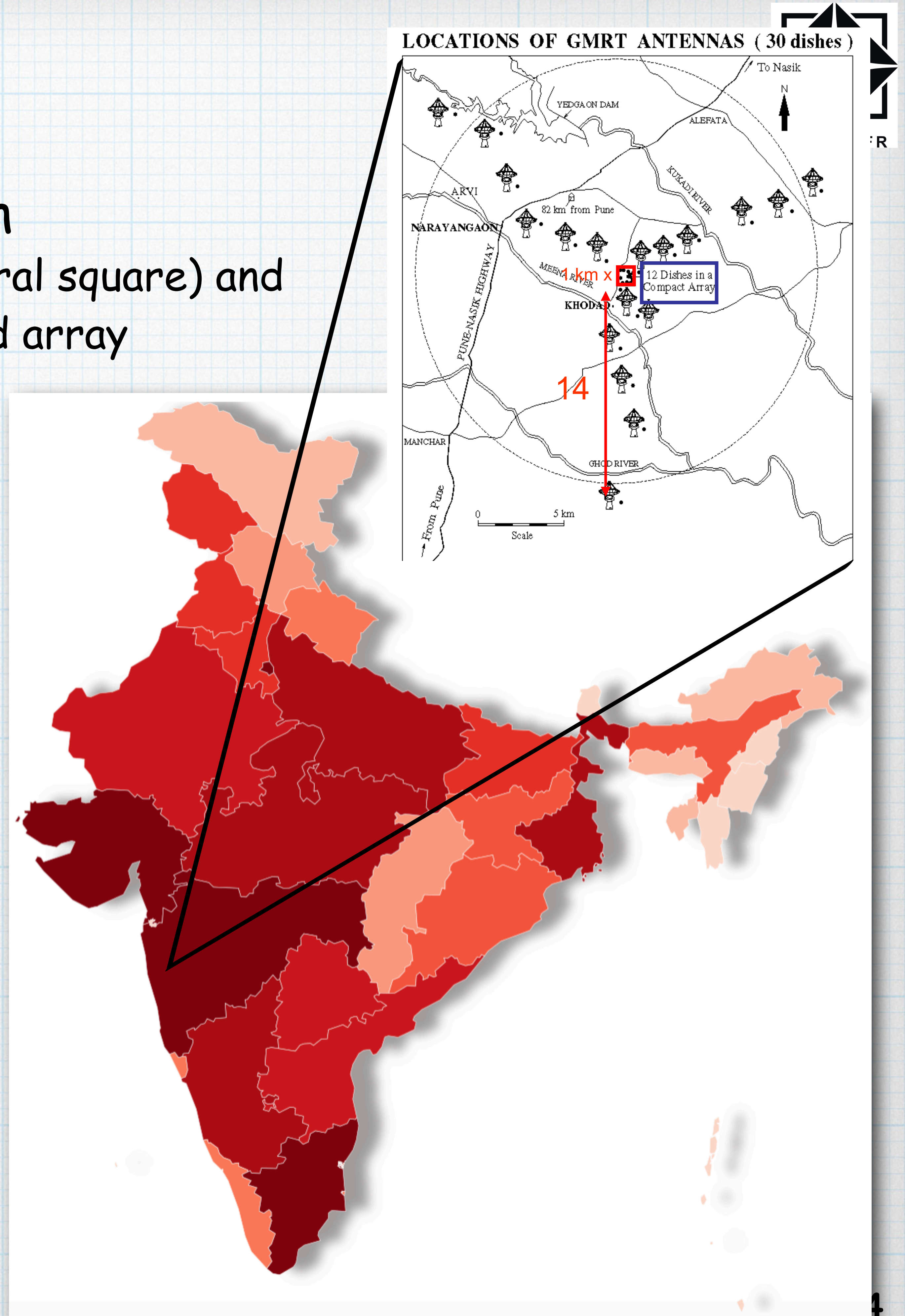
EHT

GMRT: dedication

- GMRT was built during the 1990s
- Dedication of the GMRT on 04 October 2001
- It was made available to the user community from early 2002

legacy GMRT

- 30 dishes, 45 m diameter each
  - 12 dishes in a inner 1 km^2 region (central square) and
    - remaining along 3 arms of Y-shaped array
  - baselines : ~200 m ~30 km
- Frequency range:
  - 130-170 MHz
  - 225-245 MHz
  - 300-360 MHz
  - 580-660 MHz
  - 1000-1450 MHz
    - max instant. BW = 32 MHz
- A_{eff} (2-3% of SKA):
  - 30,000 m^2 at lower frequencies
  - 20,000 m^2 at highest frequencies
- Supports 2 modes of operation:
  - Interferometry, aperture synthesis
  - Array mode (incoherent & coherent)



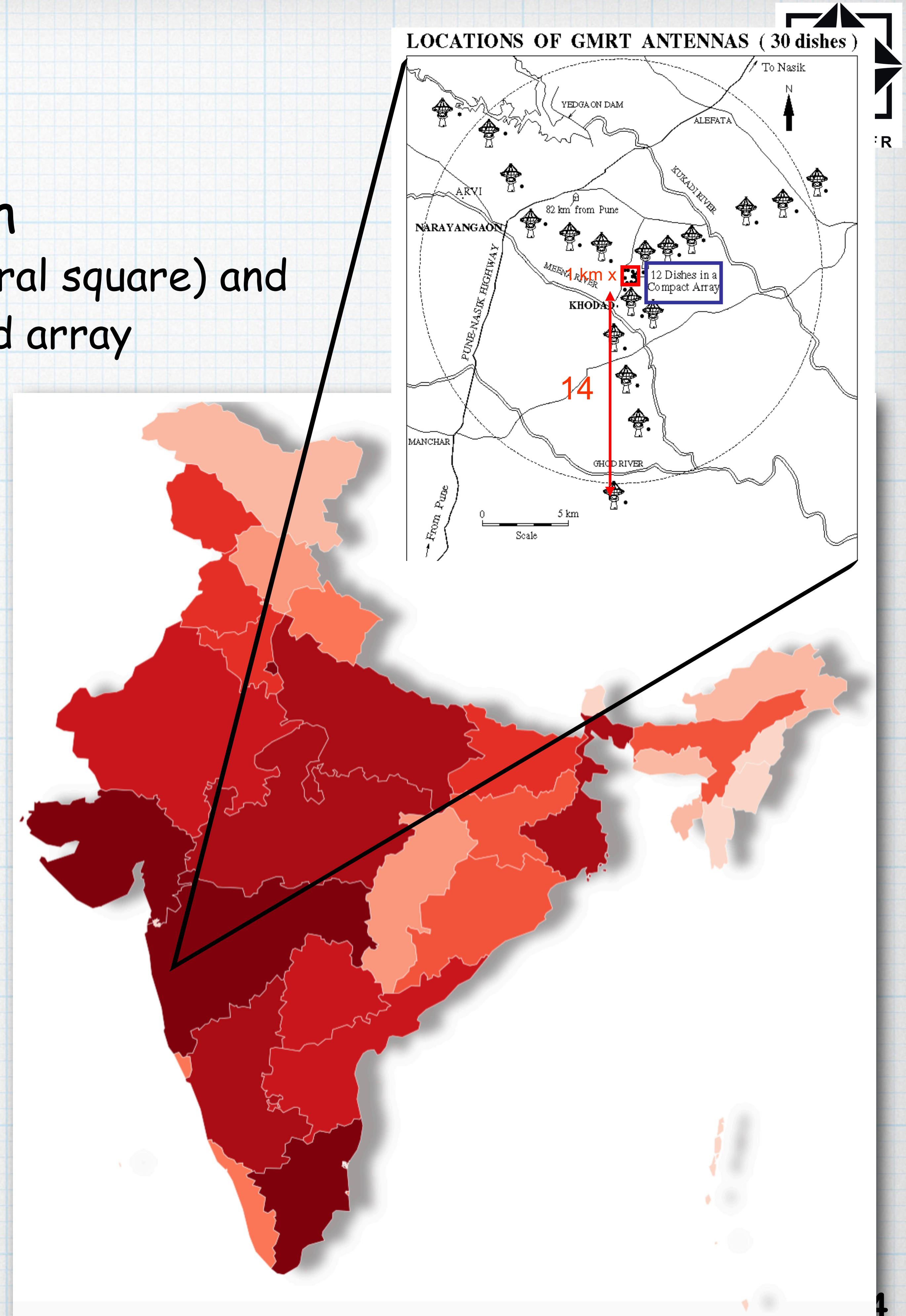
GMRT and its upgrade

- A **major upgrade** has been completed at the **GMRT**, with focus on
  - (nearly) seamless frequency coverage from
  - ~120 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

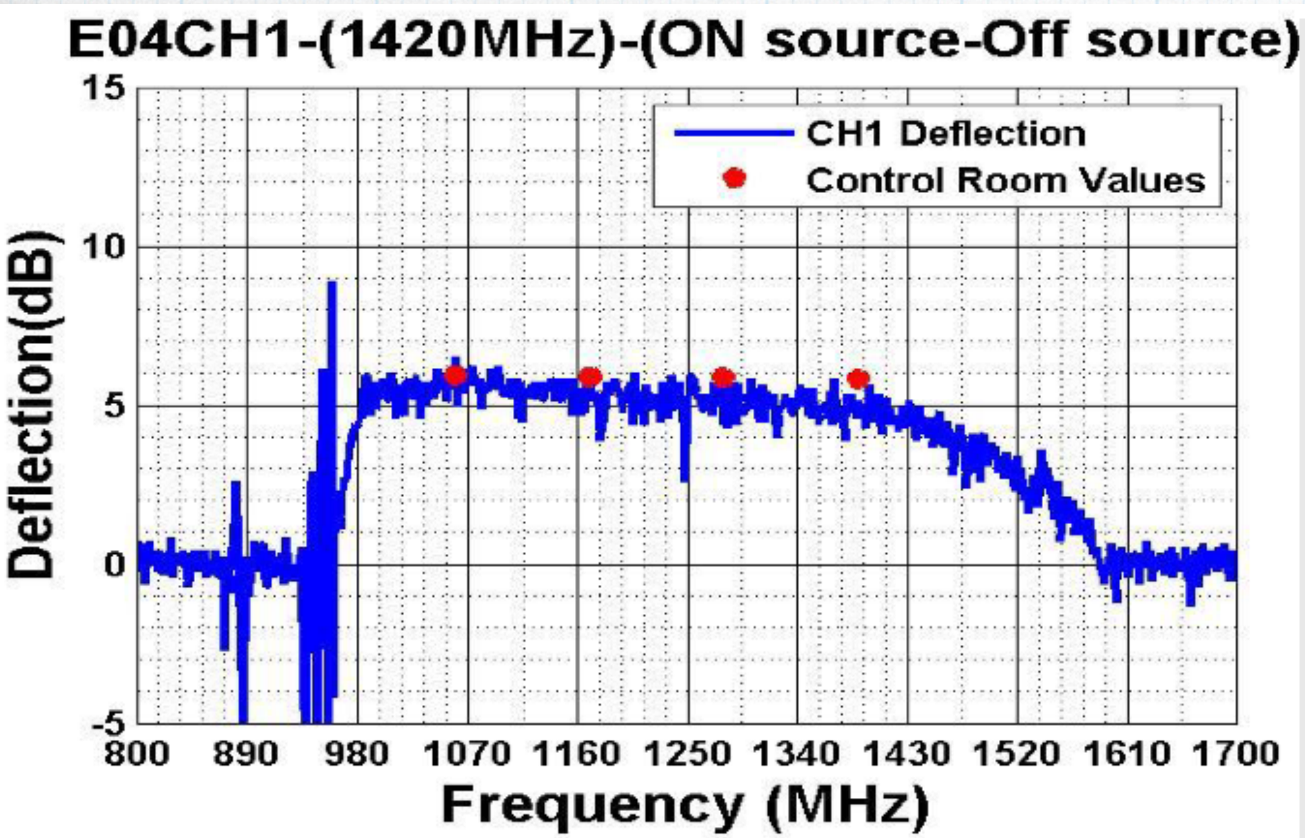
Without compromising availability of "existing GMRT" to users!

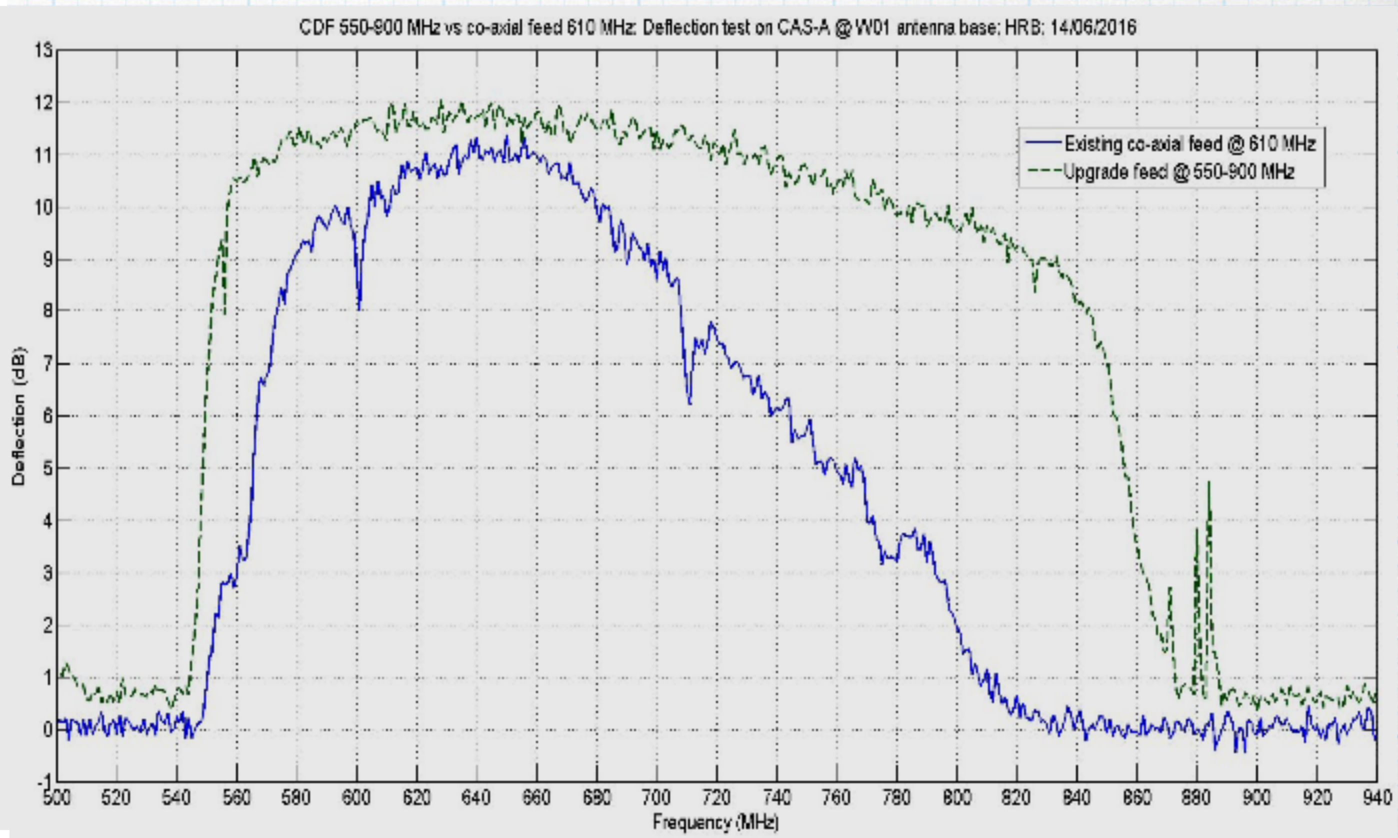
upgraded GMRT

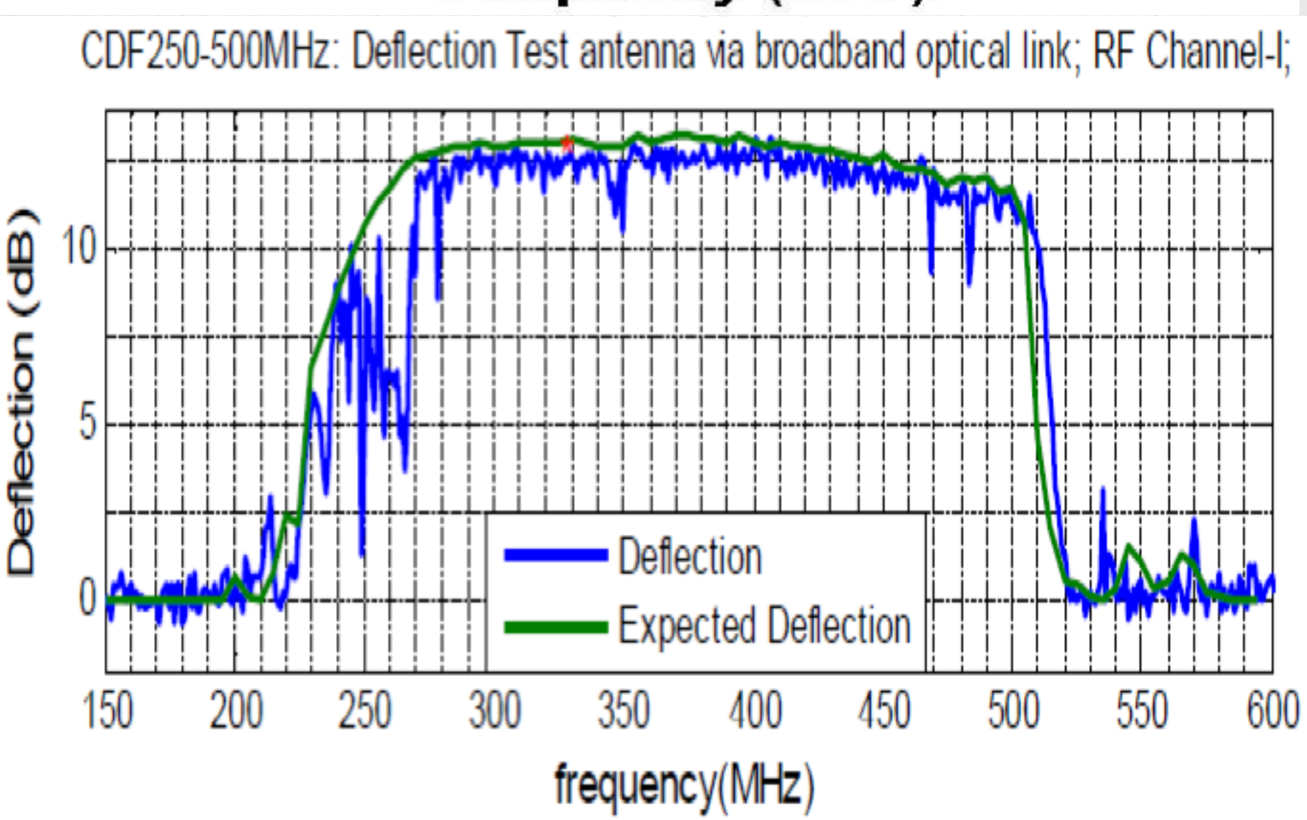
- 30 dishes, 45 m diameter each
  - 12 dishes in a inner 1 km^2 region (central square) and
    - remaining along 3 arms of Y-shaped array
  - baselines : ~200 m ~30 km
- Frequency range:
  - 125-250 MHz
  - 250-500 MHz
  - 550-850 MHz
  - 1050-1450 MHz
    - max instant. BW = 200/400 MHz
- A_{eff} (2-3% of SKA):
  - 30,000 m^2 at lower frequencies
  - 20,000 m^2 at highest frequencies
- Supports 2 modes of operation:
  - Interferometry, aperture synthesis
  - Array mode (incoherent & coherent)



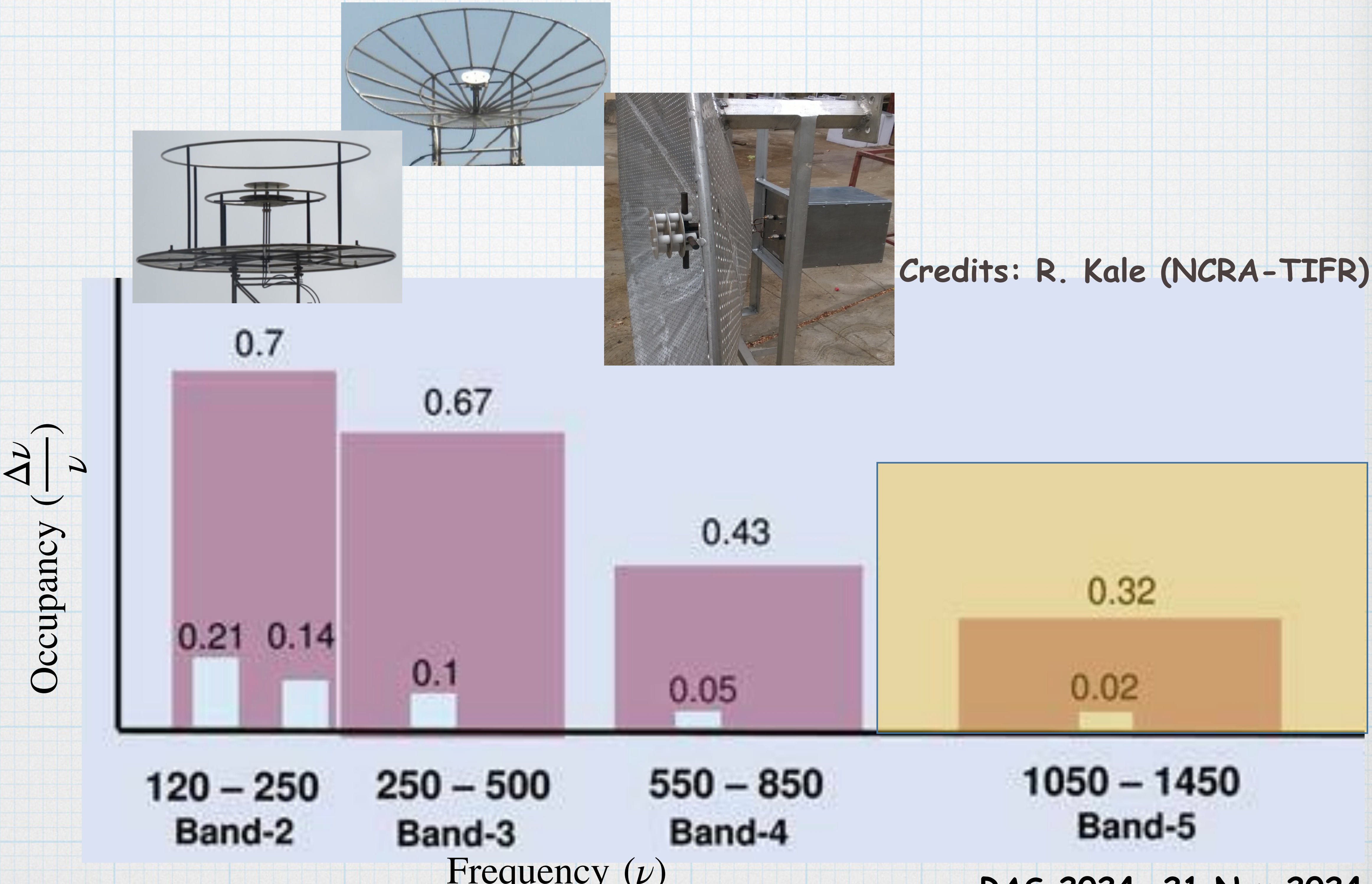
from legacy to upgraded GMRT







uGMRT: expected performance

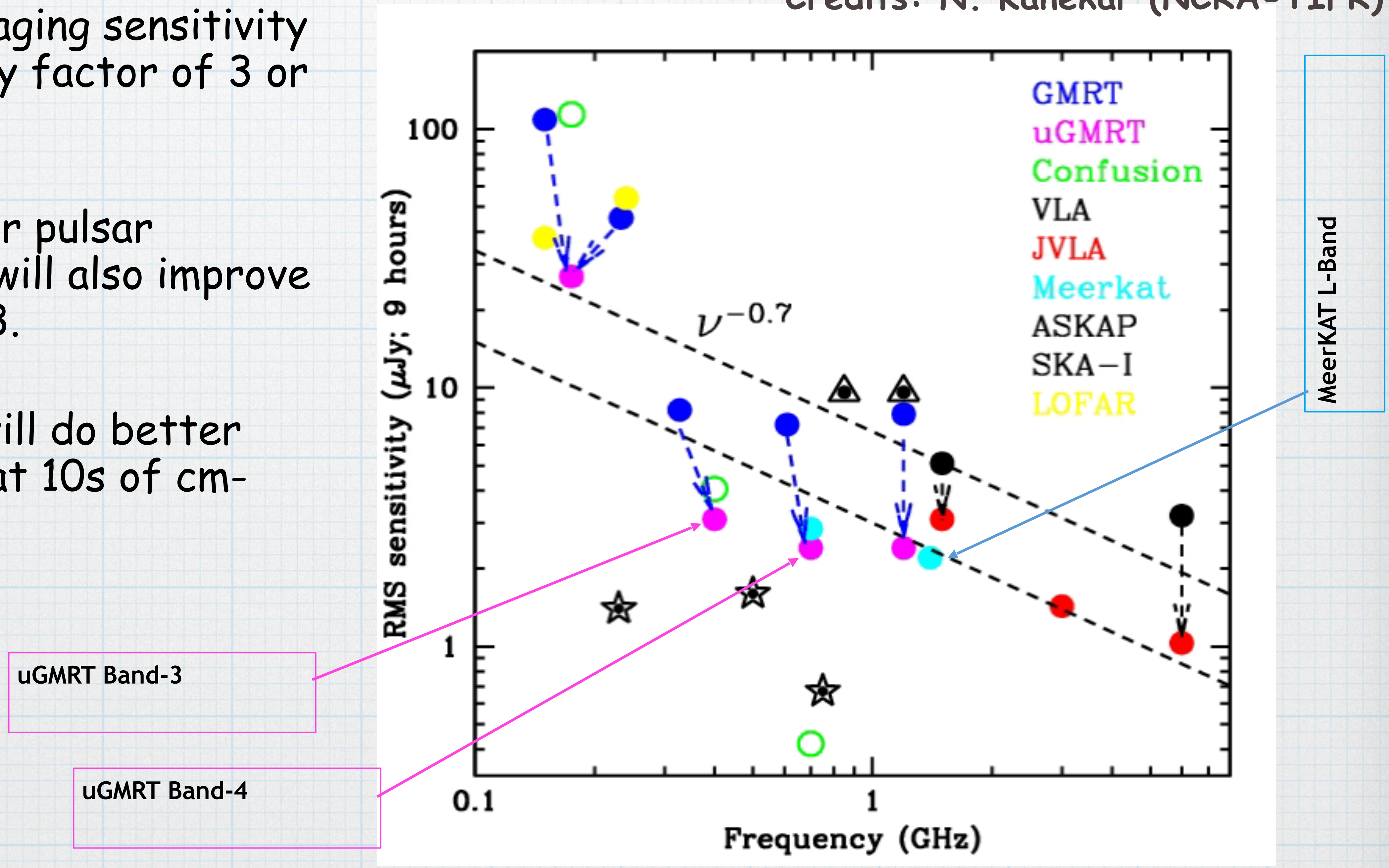


Credits: R. Kale (NCRA-TIFR)

uGMRT: expected performance

- 30 dishes, 45 m diameter each
  - Spectral lines : broadband coverage will give significant increase in the redshift space for HI lines + access to other lines
  - Continuum imaging sensitivity will improve by factor of 3 or so.
  - Sensitivity for pulsar observations will also improve by factor of 3.
  - Only SKA-I will do better then uGMRT at 10s of cm-wavelengths

Credits: N. Kanekar (NCRA-TIFR)



uGMRT: expected performance

30 dishes, 45 m diameter each

- Spectral lines : broadband coverage - significant increase in the redshift space for HI + access to other lines
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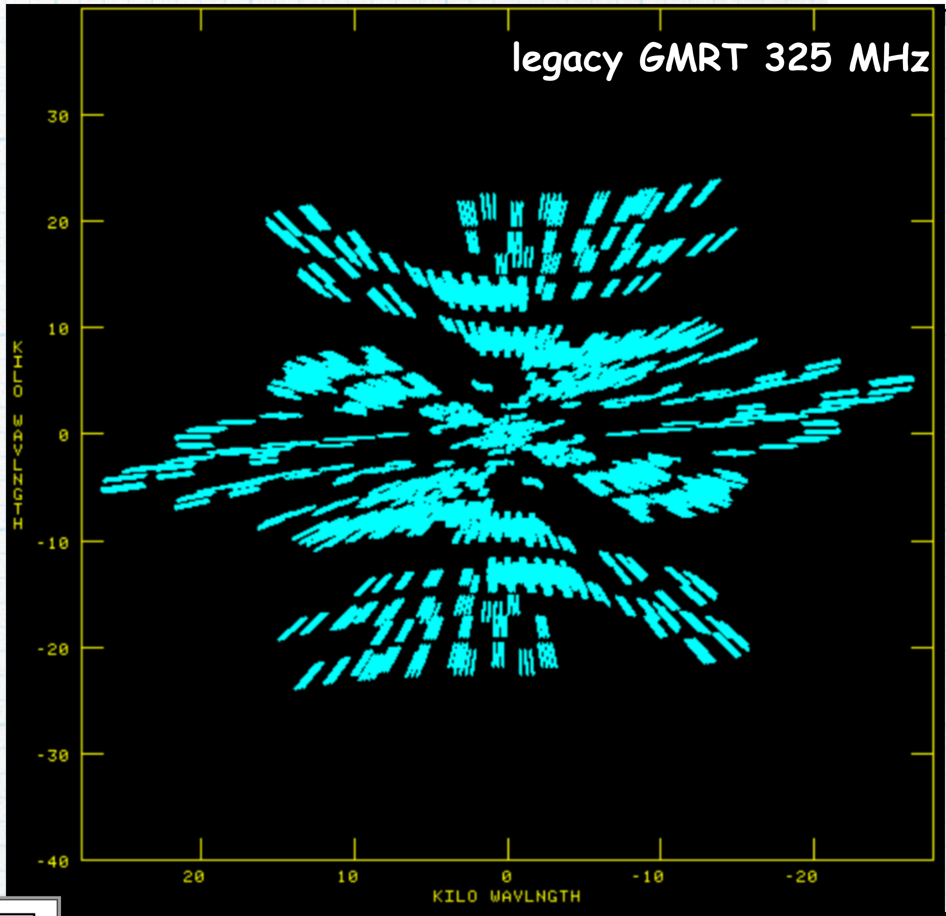
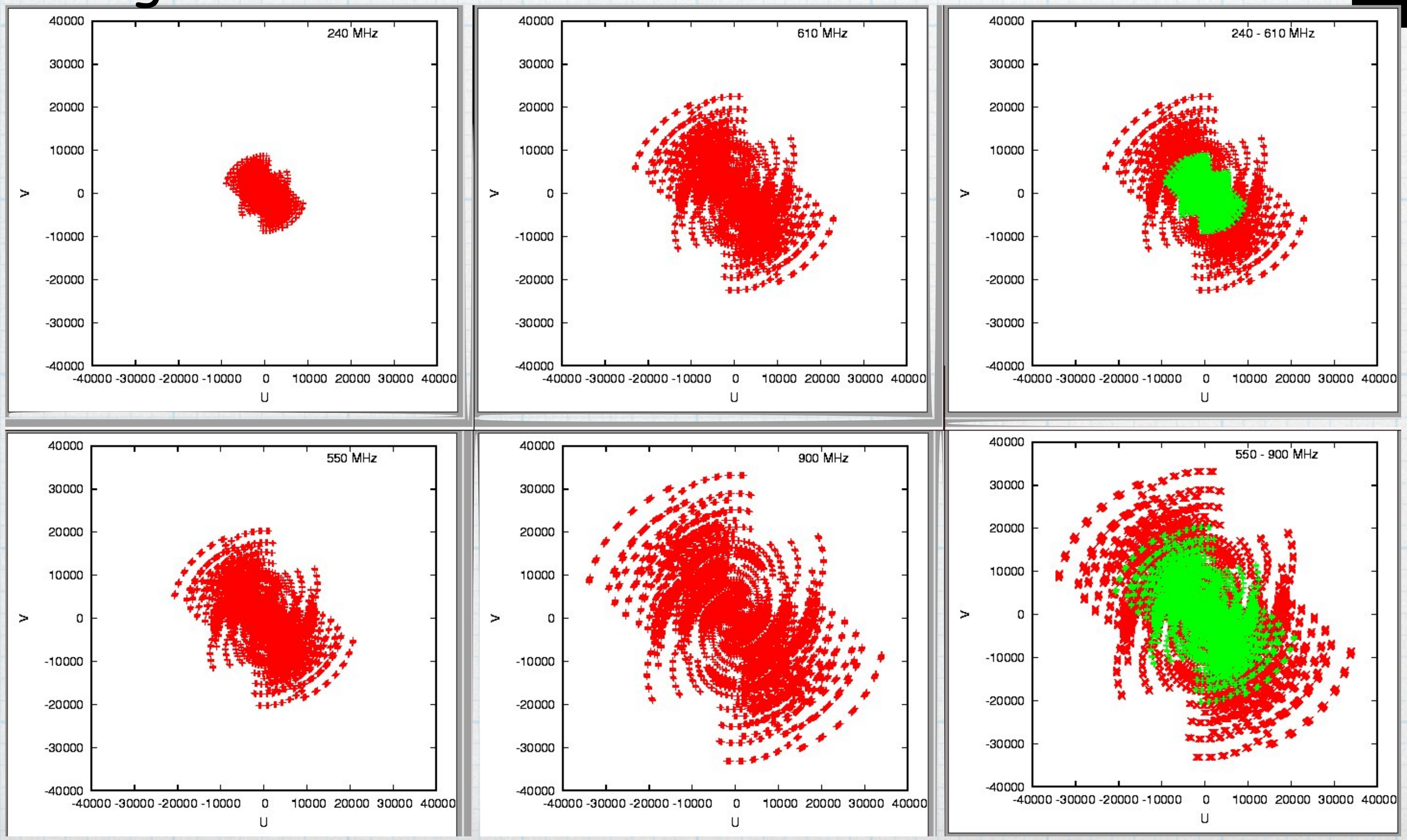
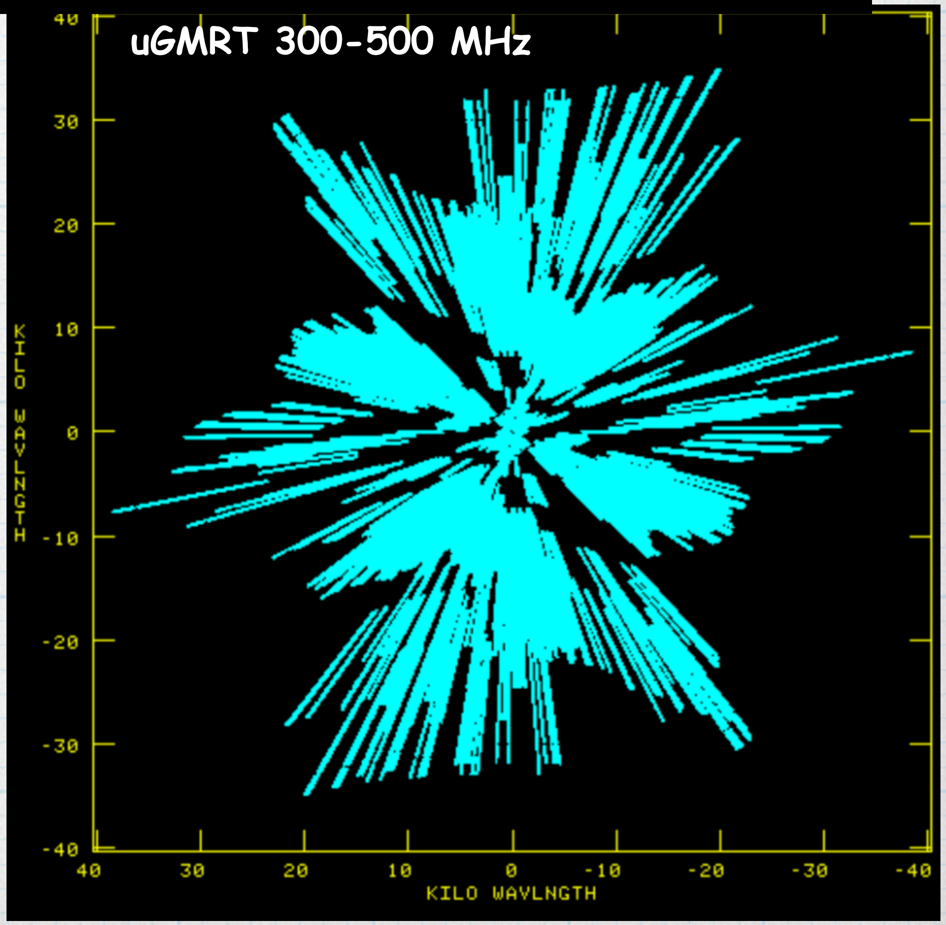


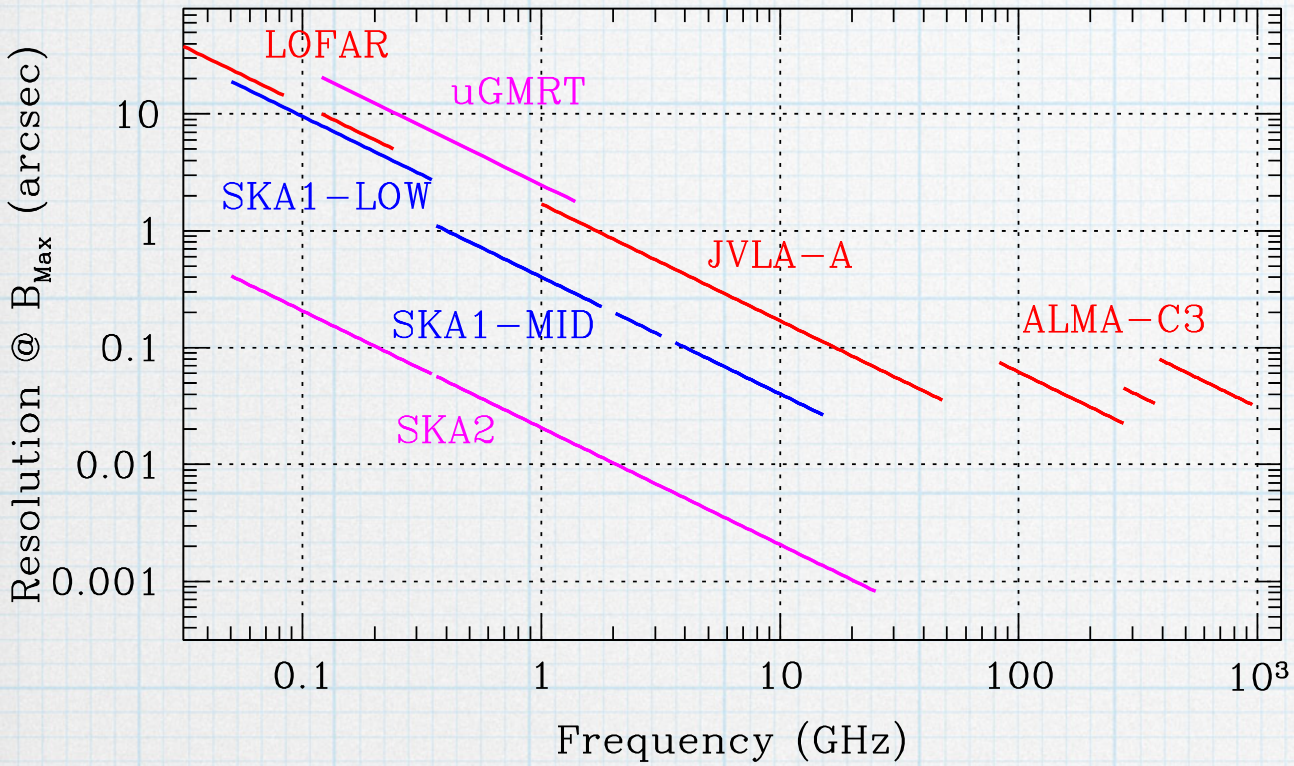
Credits: Biny Sebastian

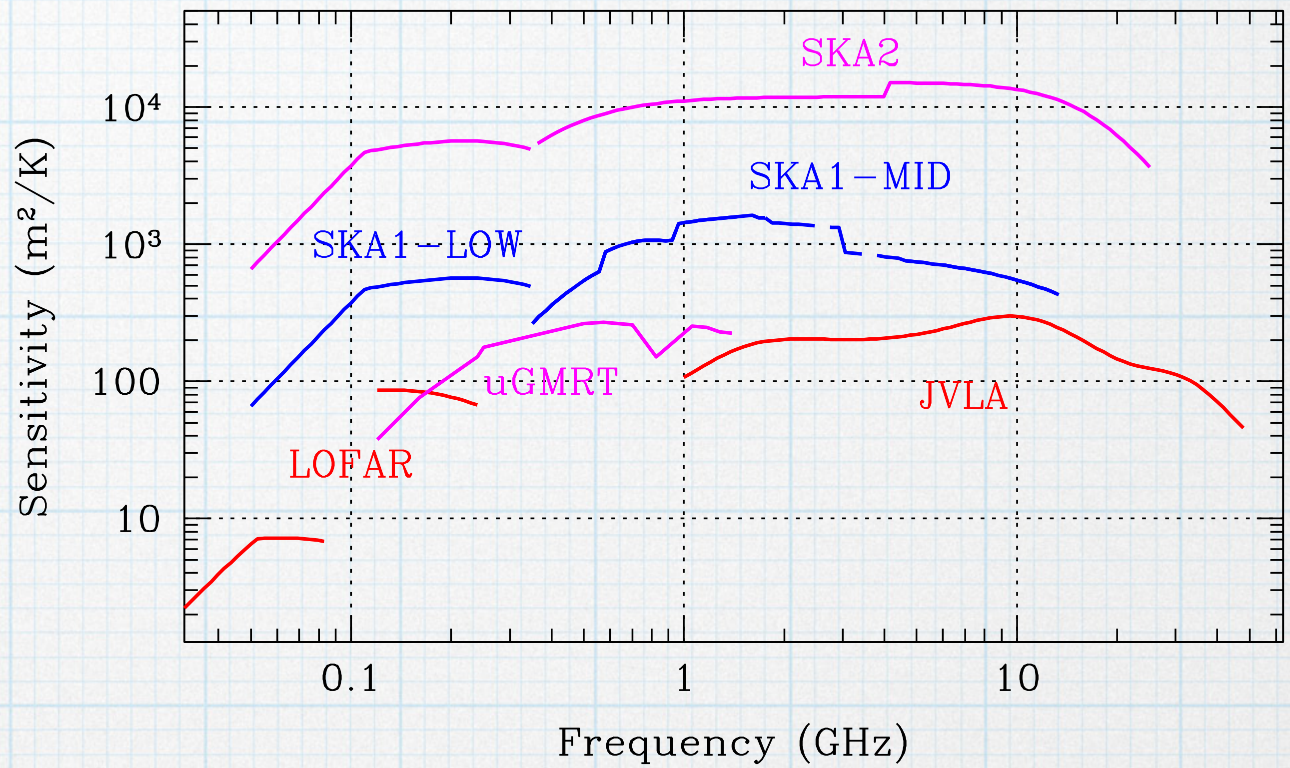


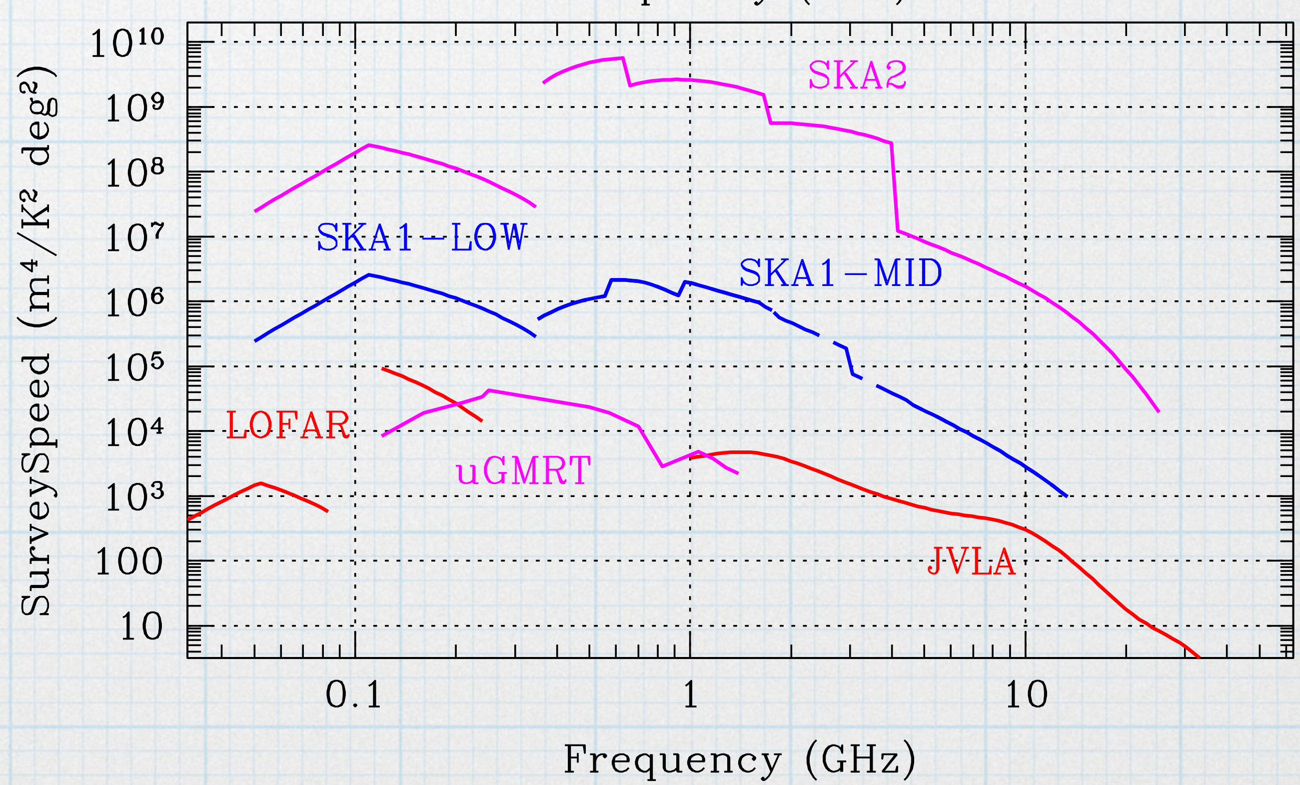


uGMRT: expected performance

Credits: R. Braun

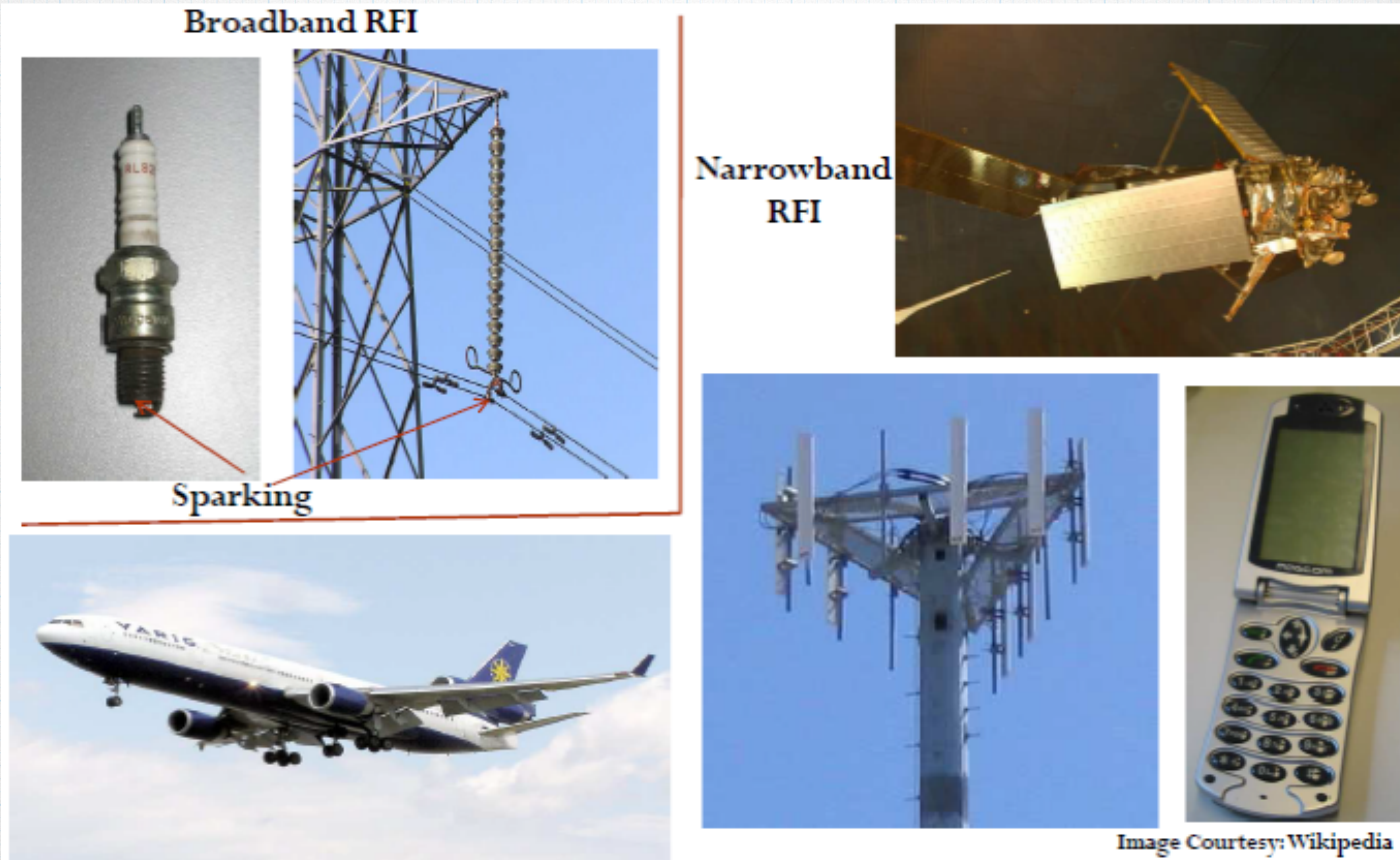






uGMRT: radio freq. interference

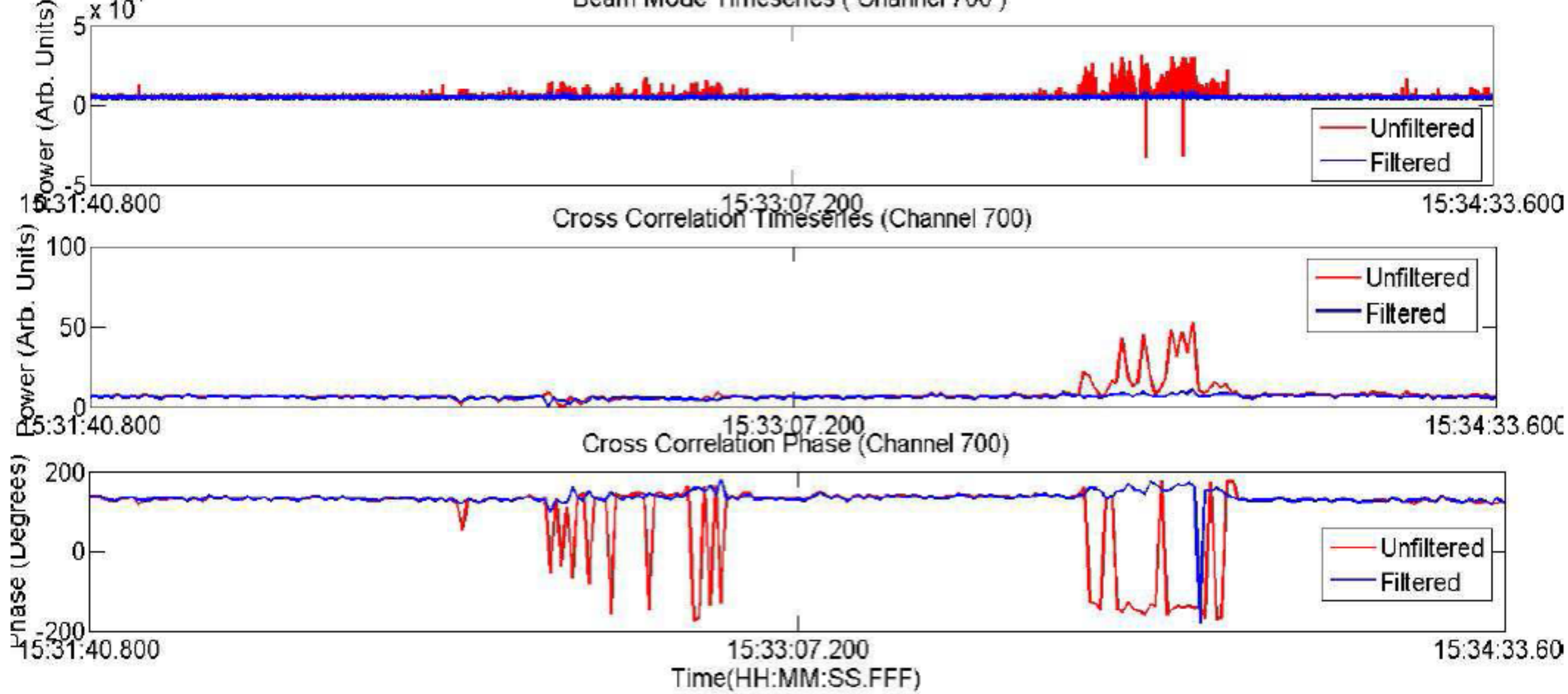
External sources of RFI



uGMRT: wideband / (u,v) coverage

- Real-time filter running on BB voltage data of each antenna
  - panels show effect of this filtering,
  - in beamformer time series (top) and
  - in visibility domain data (bottom-two!)

Credits: Kaushal Buch



uGMRT: avoiding satellite RFI

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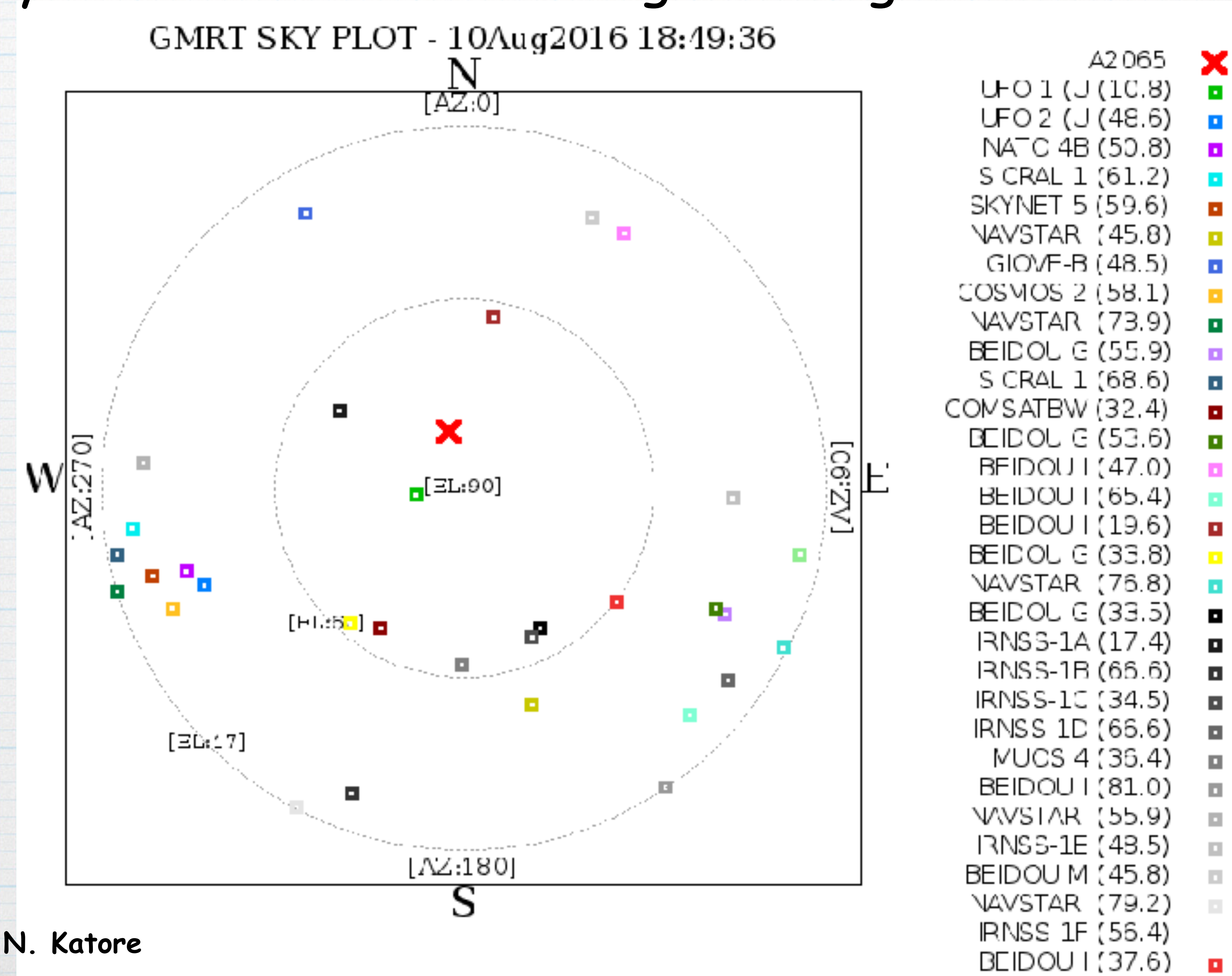
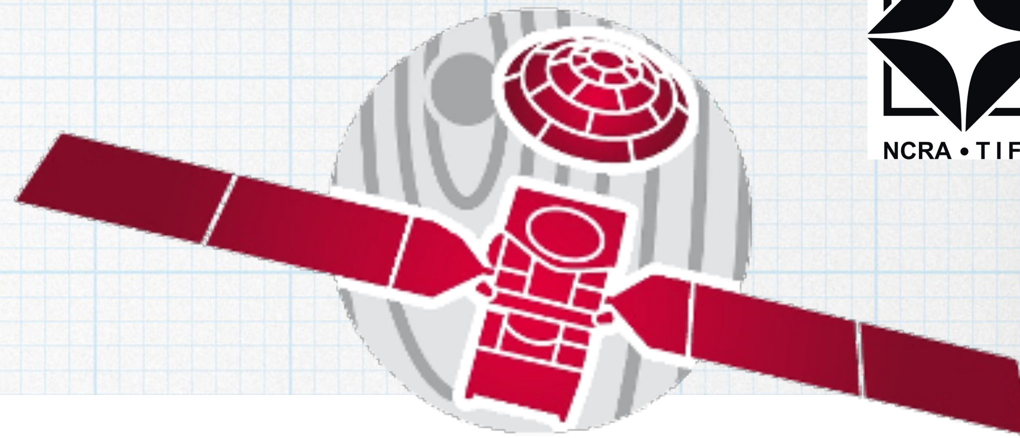
- Real-time prediction of positions of known satellites
  - both stationary and moving…
- Real-time warning when observing antenna beam comes within zone of avoidance (decided by beam-width and strength of signal from satellite)
- Predictive warning: can work on your submitted observing file
- Post-facto warning: can work on your recorded data file



Credits: Santaji N. Katore

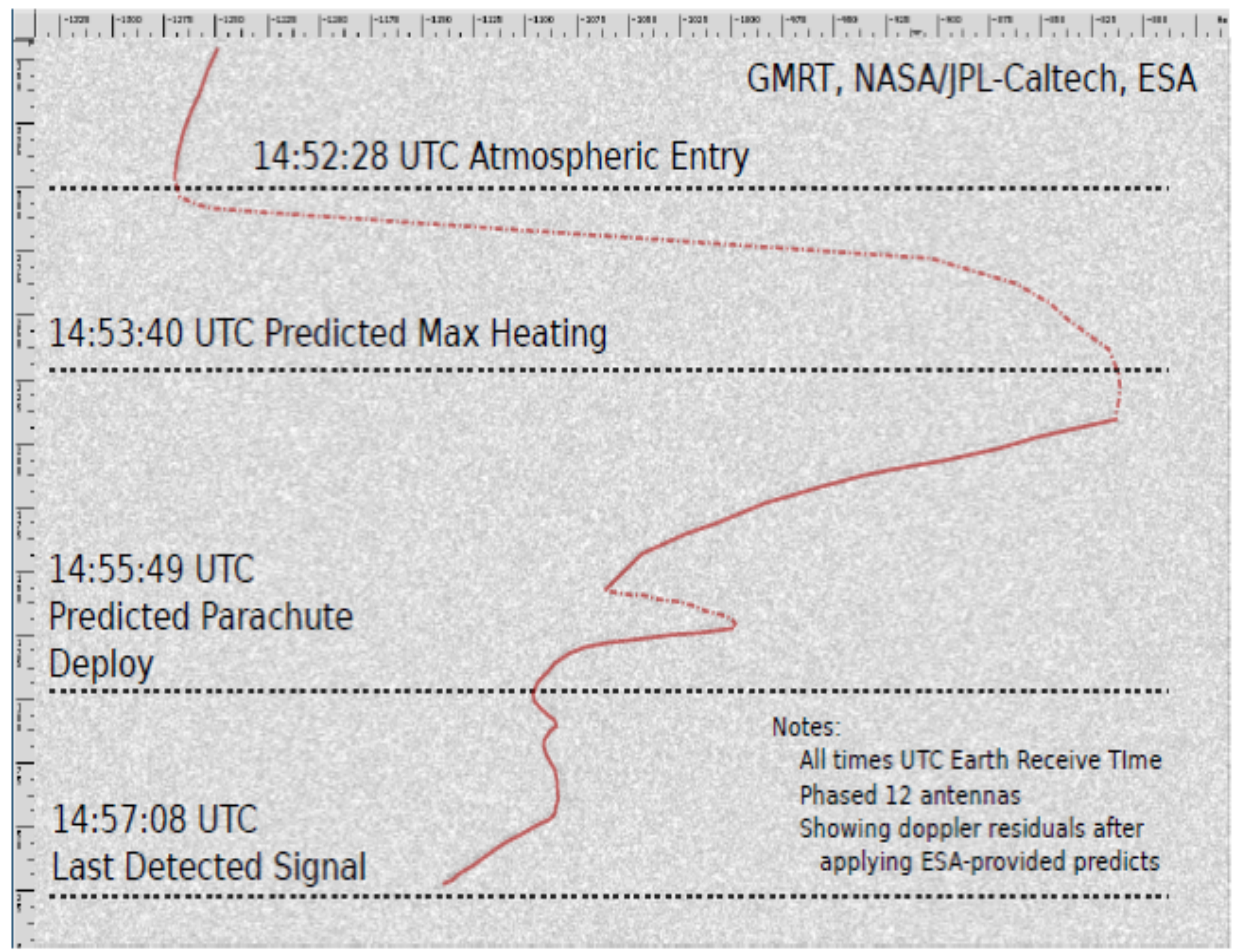
uGMRT: some fun stuff



Tracking space probe with the uGMRT

- Ground support for ExoMars mission of ESA
- GMRT + NASA collaboration
- Faithfully tracked ESA's Schiaparelli Lander module: ~ 3 W signal @401 MHz from Mars!
- ExoMars / Schiaparelli / EDM
  - Entry, Decent, Landing Detection at GMRT, India (2016/10/19)

Spectrogram Frequency (Hz) vs. Time (s)

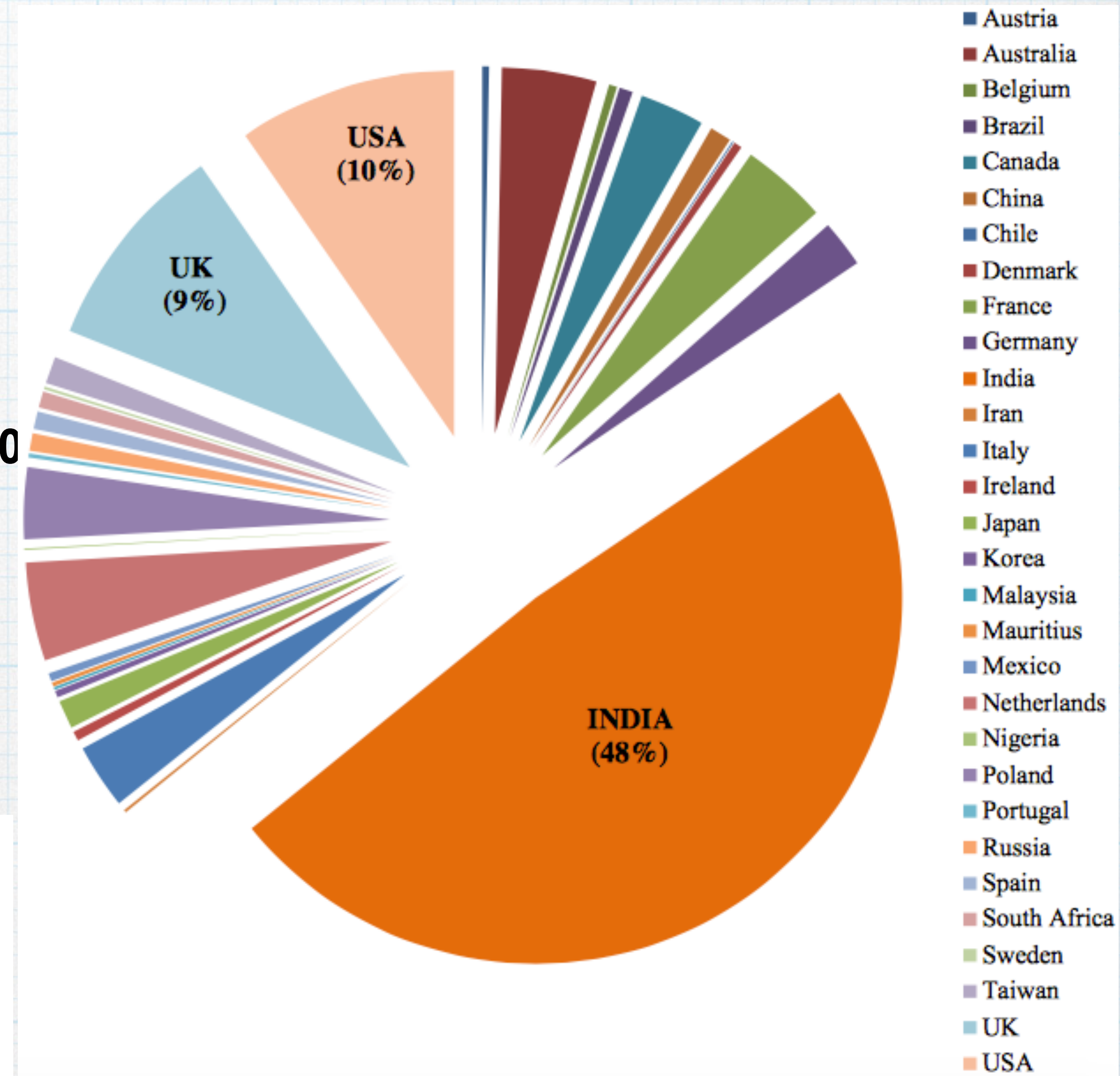


14:57:50 : Predicted Backshell & Parachute Jetison
(This exposes +6 dBiC antenna), Thrusters On
14:58:20 : Predicted Thursters Off & Touchdown

GMRT: usage statistics

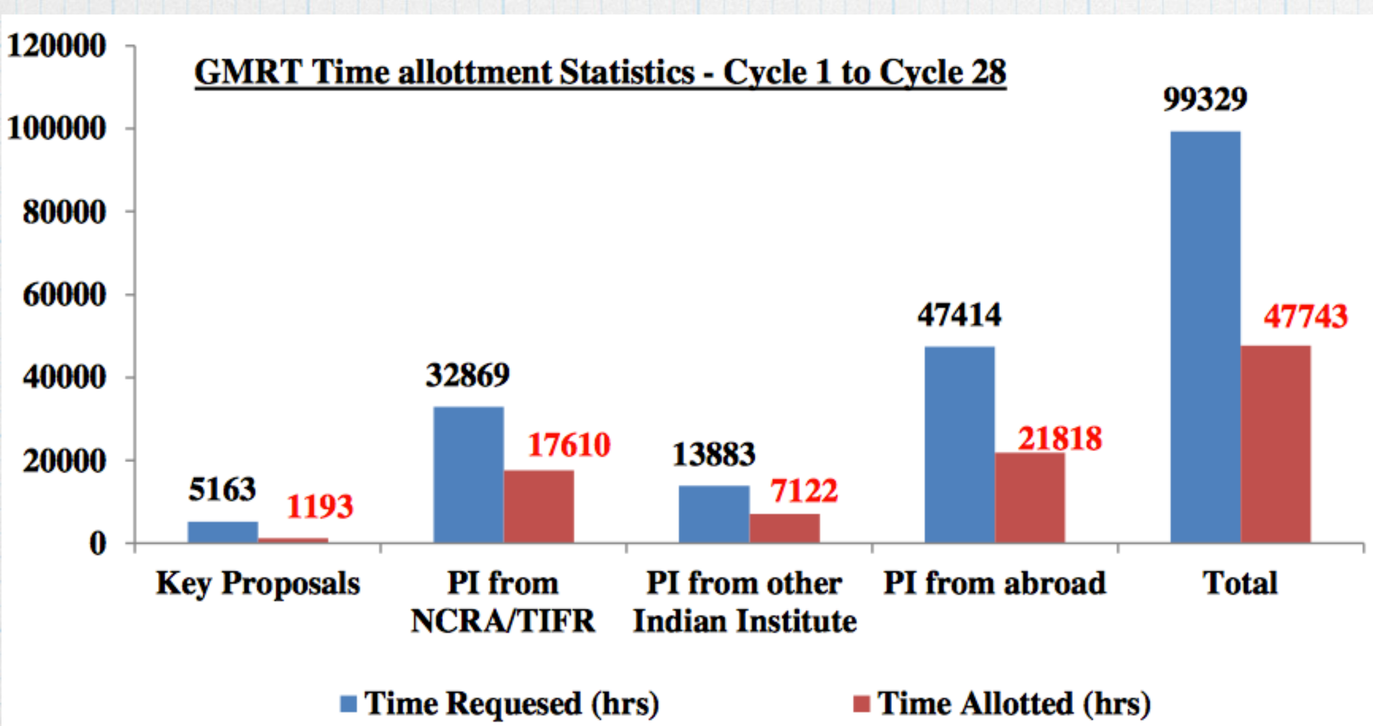
NCRA • TIFR

- Users/Community, since Oct 4, 2001
- Open sky policy
  - Two calls for observing proposals (15 Jan and 15 Jul) every years
- GMRT sees users from all over the world
  - (users) Indian:Foreign = 45:55
- The GMRT has been typically oversubscribed by a facto



Country	Nos	Country	Nos	Country	Nos	Country	Nos	Country	Nos
Argentina	13	China	19	Iran	2	Mauritius	3	Russia	13
Austria	5	Chile	1	Italy	49	Mexico	7	Spain	14
Australia	75	Denmark	6	Ireland	7	Netherlands	75	South Africa	16
Belgium	7	France	66	Japan	21	Nigeria	1	Sweden	2
Brazil	11	Germany	40	Korea	6	Poland	55	Taiwan	20
Canada	50	India	847	Malaysia	3	Portugal	3	UK	163
								USA	169
Total Proposals Received 1769									

Credits: Reena S. (GTAC)



What do radio astronomers do?

- The Sun
  - What heats up the Solar corona
  - How does mass ejected from the Sun travel and its effect on Earth
- Stellar evolution and end products (Supernovae, SNR, Pulsars)
  - Pulsar as probes of ISM and Fundamental Physics
- Spectral line emission from ionised, atomic and molecular gas
  - How does material cycle between gas and stars?
  - What is the total (dark) matter content of galaxies?
  - How does the gas content of galaxies and the IGM evolve?
- Diffuse plasma in between stars and galaxies
  - e.g., how does the Universe get magnetised?
- Active galactic nuclei
  - What role SMBHs play in evolution of the galaxies?
- Clusters of galaxies
  - Interplay between RGs and their hot gas environments!