Radio Astronomy Overview

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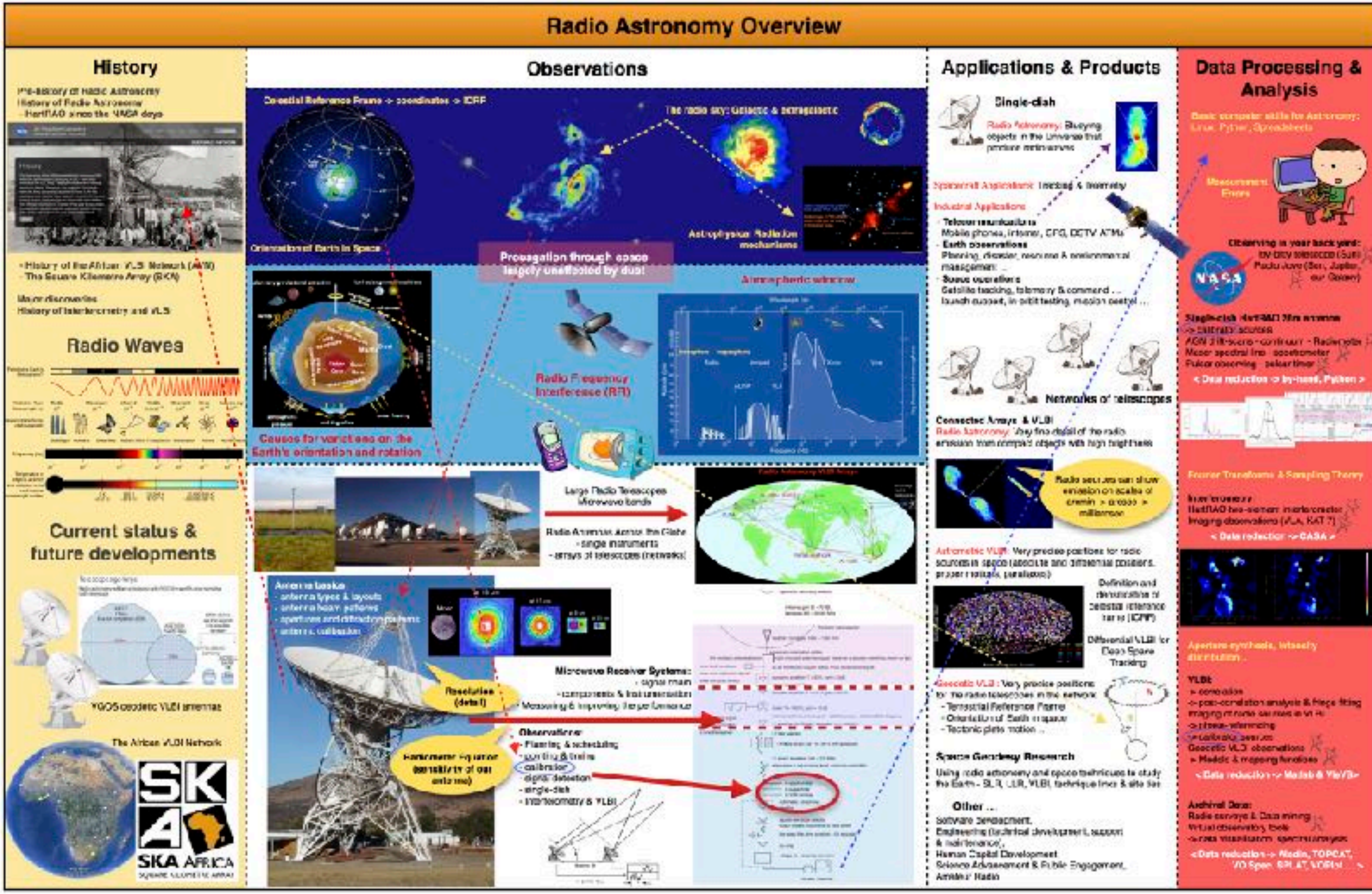
AVN/Newton-fund 2017
Observational & Technical Training HartRAO

NRF
National Research Foundation

HartRAO
Hartebeesthoek Radio Astronomy Observatory



Radio Astronomy Overview

NRF
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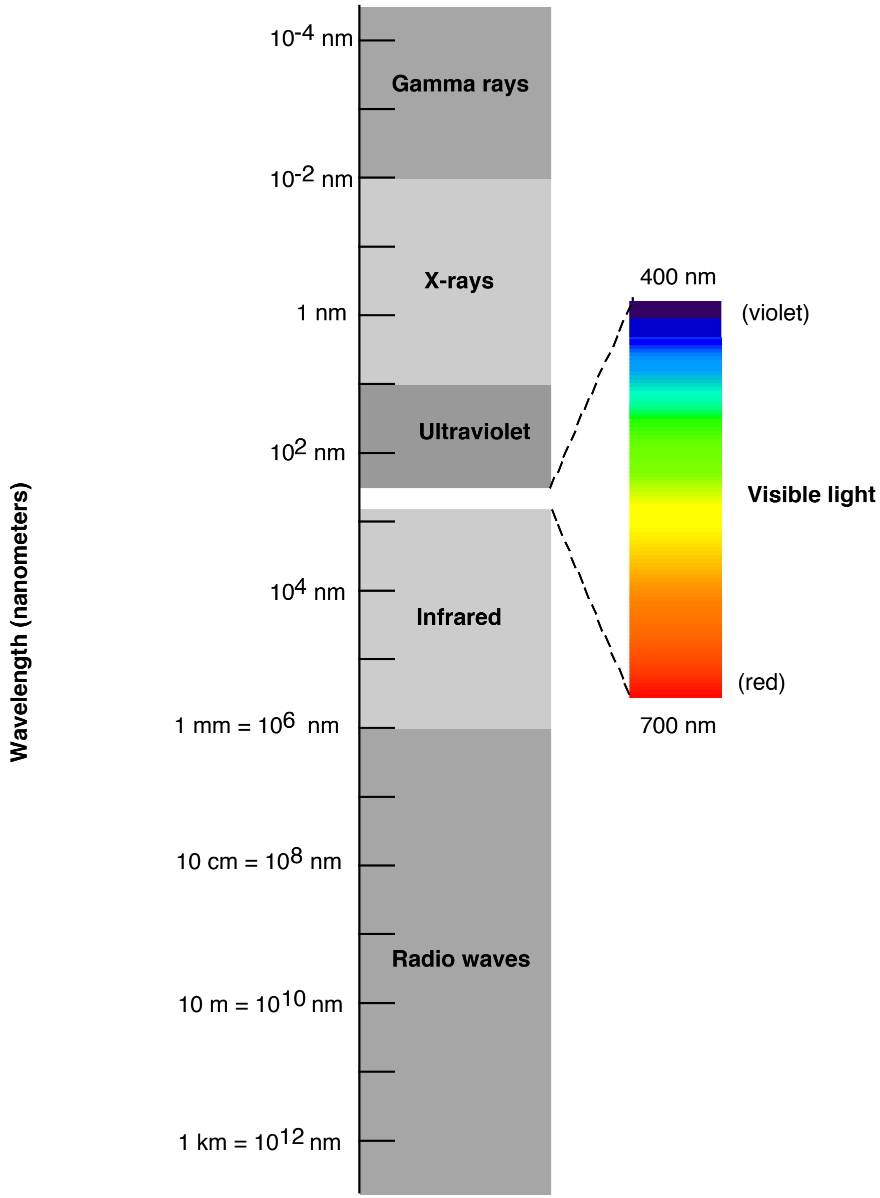
Radio Astronomy

- Radio Waves => electromagnetic waves with λ = 0.3mm - 100km
  (1 THz - 3 kHz)

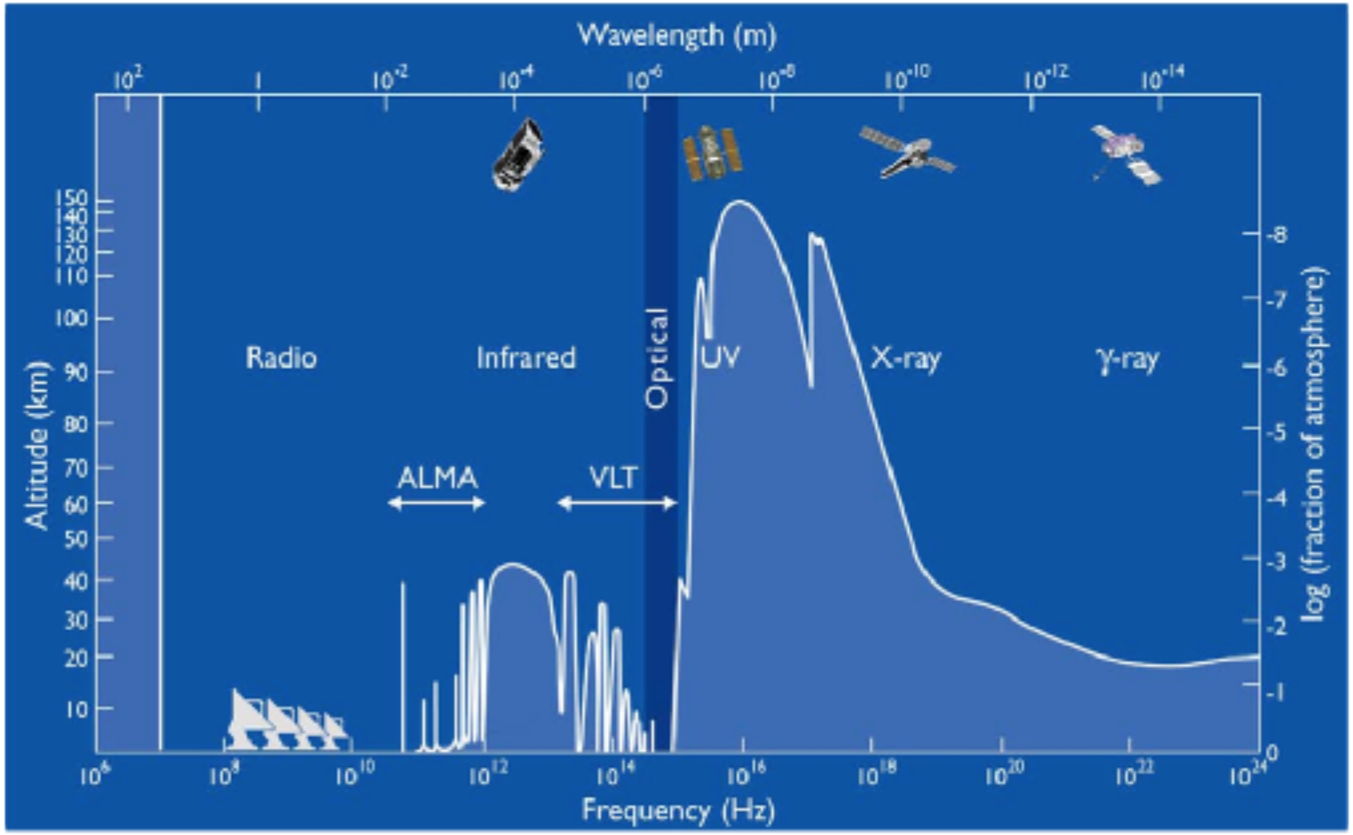
- Most radio telescopes and interferometers > 500 MHz (0.6 m)



- **Microwaves** (1 cm - 30 m)
  (30 GHz - 10 MHz)
- **Millimetre** (1 mm to 10 mm)
  (300 GHz - 30 GHz)
- **Sub-millimetre** (< 1 mm, up to 0.4 mm)
  (< 30 GHz)

Radio Astronomy

- Optical and radio astronomy can be done from the ground!



Special:
Radio waves largely unaffected by dust... !

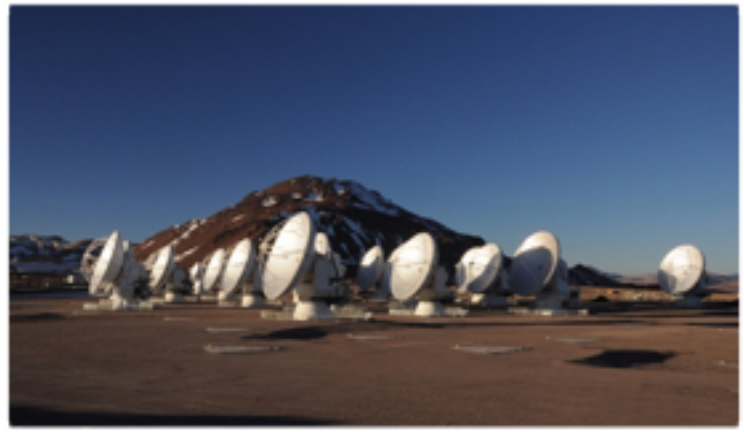
=> Can observe day and night!

=> can look inside collapsing clouds forming new stars or the centre of our Milky Way galaxy. Studies of the early obscured Universe are possible.

- Earth's atmosphere transparent to radio waves from mm to decametre wavelengths
- The Earth's ionosphere prevents ground-based observations at wavelengths > 30 m

Radio Astronomy

High Frequency (mm/sub-mm):
JCMT
λ ~ 2000 - 345 μm
ν ~ 150 - 870 GHz
ALMA
λ ~ 3mm - 400 μm
ν ~ 84 - 720 GHz (40 - 950 GHz)



Low Frequency:
LOFAR
λ ~ 1 - 20 m
ν ~ 10 - 240 MHz
(10-90, 110-240)

Large Radio Telescopes
ν > 500 MHz:
GBT (ν ~ 0.32 - 100 GHz)

L Band	18 cm	1.40 GHz
S Band	13 cm	2.3 GHz
C Band	6 cm	5.0 GHz
X Band	3.5 cm	8.4 GHz
U Band	2.5 cm	15 GHz
K Band	1.3 cm	22 GHz
Ka Band	0.9 cm	32 GHz
Q Band	0.7 cm	43 GHz

Radio Astronomy

- Commercial FM radio and TV stations => $\nu = 88 - 108$ MHz, $\lambda \sim 3$m

- Microwave ovens operate at => $\nu = 2.4$ GHz, $\lambda = 12$cm

- Cellphones => $\nu = 900$ MHz, $\lambda = 33$ cm

- DSTV satellites transmit at => $\nu = 12$ GHz, $\lambda = 2.5$cm

HartRAO 26m Telescope

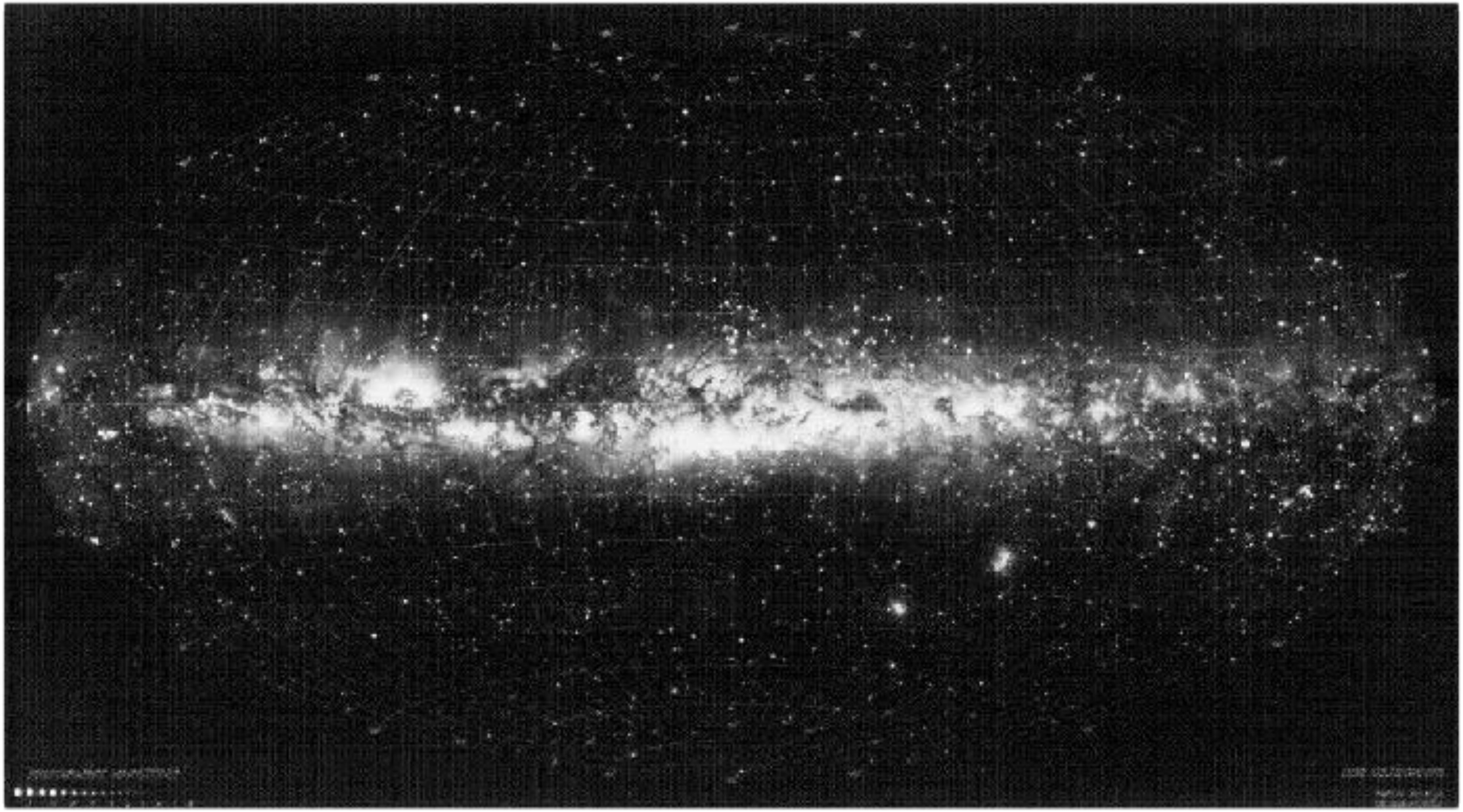
NRF HartRAO

HartRAO 26m Telescope

Band	<18 cm>	<13 cm>	<6 cm>	<4.5 cm>	<3.5 cm>	<2.5 cm>	<1.3 cm>
Feed horns	1 x circular	1 x circular	2 x diagonal[1]	1 x diagonal + parallel-plate polarizer [2]	2 x circular[1]	1 x circular	1 x circular
Polarization	LCP & RCP	LCP & RCP	LCP & RCP	LCP & RCP	LCP & RCP	LCP & RCP	LCP & RCP
Amplifier	cryogenic HEMT	cryogenic HEMT	cryogenic HEMT	cryogenic HEMT	cryogenic HEMT	uncooled PHEMT	cryogenic HEMT
Standard frequency (MHz)	1666[(2)]	2280	5000	6670	8580	12180	23000
Lower frequency limit (MHz)	1608	2210	4650	6008	8180	12048	22000
Upper frequency limit (MHz)	1727	2450	5200	6682	8980	12216	24000
Receiver bandwidth (MHz)[3]	120	240	400	660	800	168	2000
Beamwidth: full width at half max. (degrees)	0.494	0.332	0.160	0.113	0.092	0.059	0.033
Beamwidth: between first nulls (degrees)	1.19	0.80	0.36	0.32	0.23	0.16	0.073
Minimum system temperature at Zenith (K)	39[4]	36	55	57	50	100[7]	45[8]
Point Source Sensitivity per polarization (Jy/K/Pol)[5]	5.1[4]	4.8	6.0	5.1	6.1	5.8	10.5[8]
System Equivalent Flux Density SEFD (Jy)	430[6]	410[6]	650[7]	700[6]	630[7]	1175[7]	950[8]

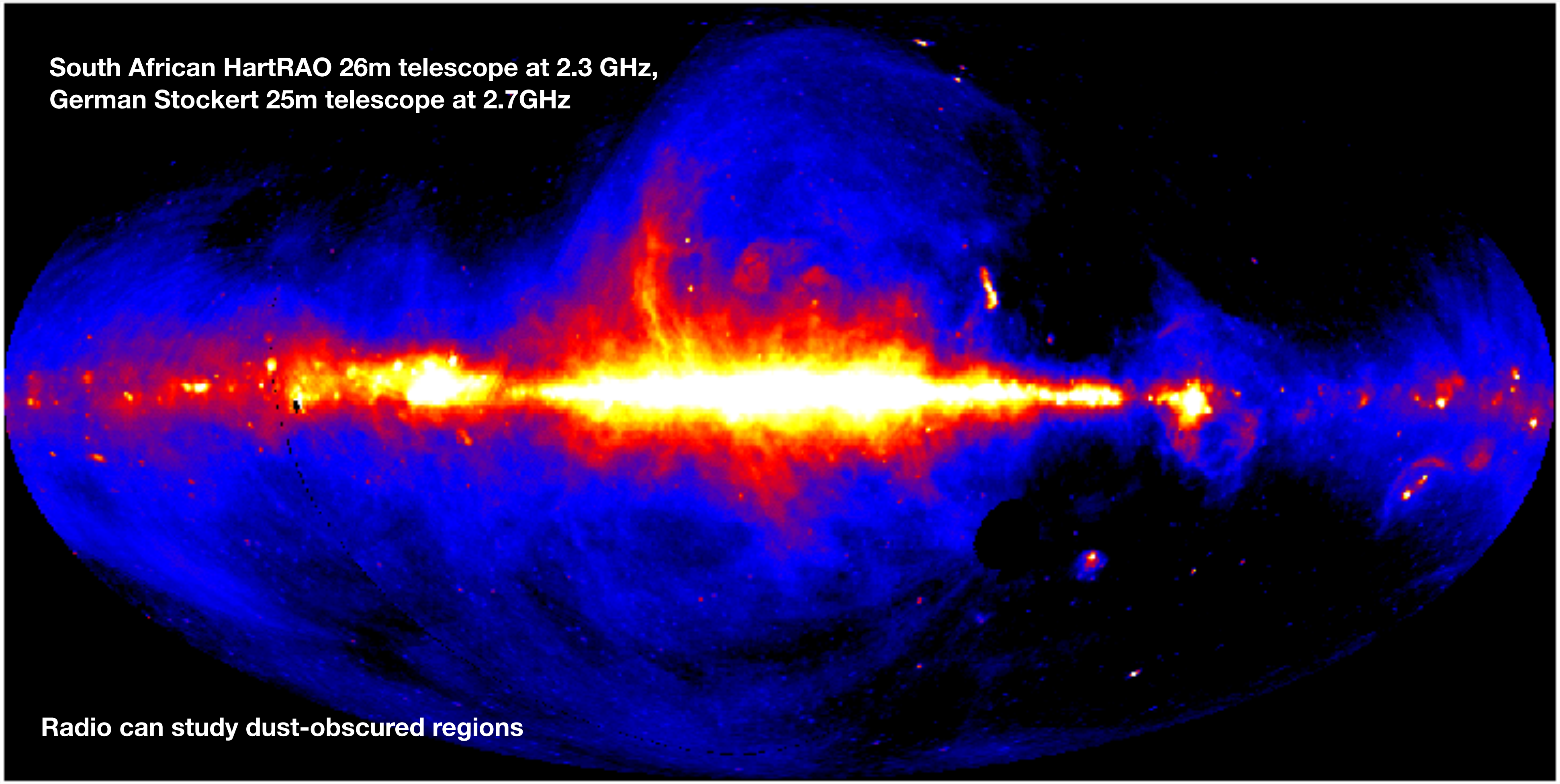
Technical details: www.hartrao.ac.za

Radio Astronomy



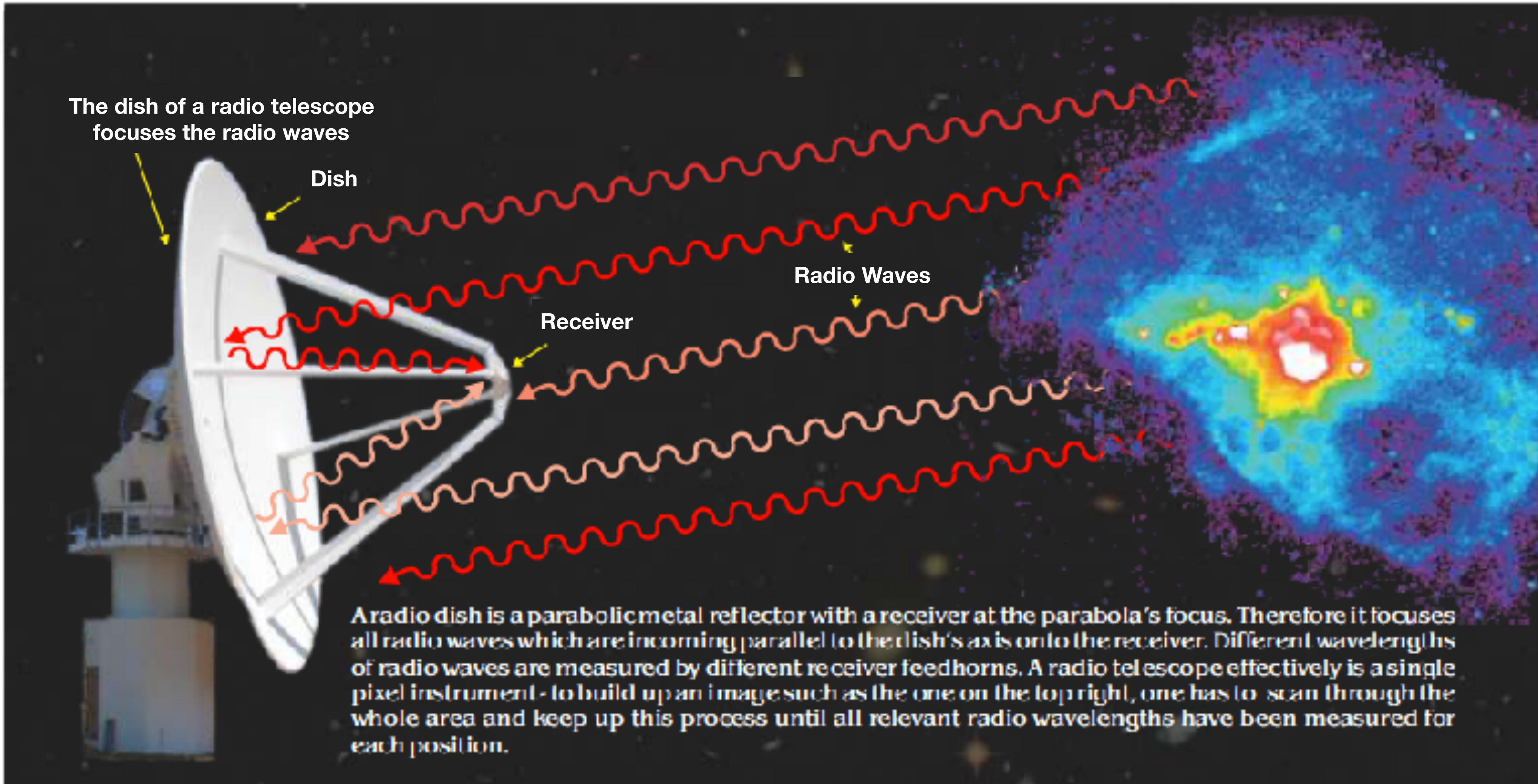
- Milky Way all-sky: Visual wavelengths

Radio Astronomy



- Radio Waves from the Milky Way: as seen by Radio Telescopes in SA and Germany

Radio Astronomy



Sensitivity: Ability to measure weak sources of radio emission

area and efficiency of dish, sensitivity of receiver used to amplify and detect signals, duration of observation, receiver bandwidth

Radio Astronomy

- Radio waves are long wavelength, low frequency forms of electromagnetic radiation. This means that a radio wavelength region photon carries very little energy (orders of magnitude less than its optical counterpart).

- Radio photons are too wimpy to do very much - we cannot usually detect individual photons.

- e.g. optical photons of 600 nanometre => 2 eV or 20000 Kelvin (hv/kT).
  e.g. radio photons of 1 metre => 0.000001 eV or 0.012 Kelvin.

- Photon counting in the radio is not usually an option, we must think classically in terms of measuring the source electric field
  => i.e. measure the voltage oscillations induced in a conductor (antenna) by the incoming EM-wave.

Radio Astronomy

- To work out the flux density of a source we would measure the power in watts, divide by the number of square metres and divide by the bandwidth (in Hz). This would be a tiny number for every known radio source in the sky!

$$1\ \mathrm{Jy} = 10^{-26}\ \mathrm{W\ m^{-2}\ Hz^{-1}}$$

- The power from a 1 Jy source collected in 1 GHz bandwidth by a 12 m antenna would take about 300 years to lift a 1 gm feather by 1mm.

Radio Emission Processes

- Electromagnetic emission can be divided into two types:

Continuum emission

=> emission over a very broad frequency range
usually due to the acceleration of charged particles moving with a wide-range of energy

Spectral line emission

=> emission over a very narrow frequency range
usually due to the discrete transitions in the internal energy states of atoms or molecules

Radio Emission Processes

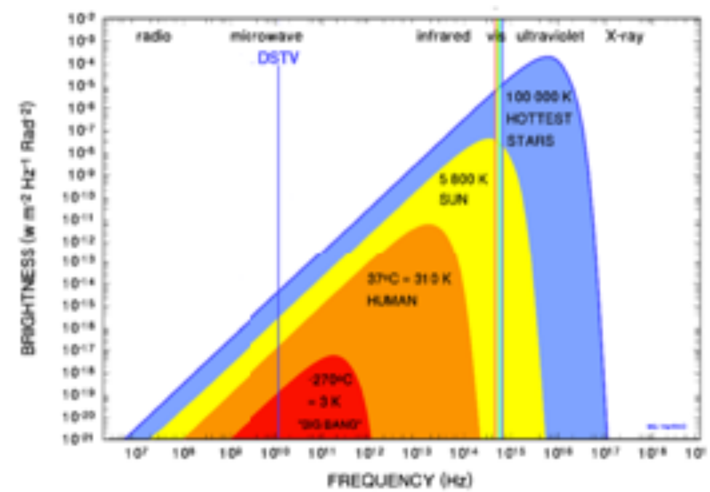
- Continuum emission

Thermal Emission

Radio astronomy is **cool** 😎

=> Black body radiation for objects with temperature T ~ 3-30 K (CMB radiation peaks at T = 2.7 K, 0.001metres, 300 GHz).

=> Bremsstrahlung (free-free) emission: deflection of a charged particle (electron) in the electric field of another charged particle (ion)



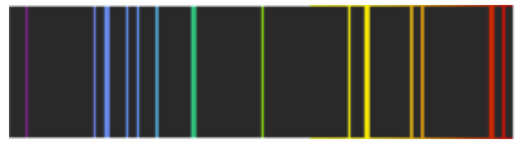
Non-thermal Emission

=> emission that does not depend on source temperature e.g. synchrotron emission (relativistic charged particles spiral around magnetic field lines).

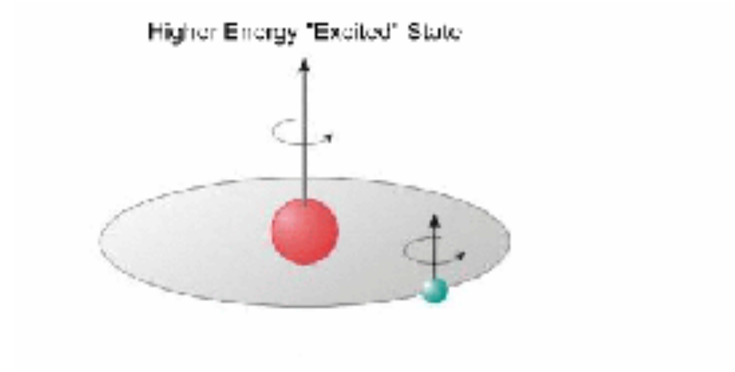
=> Since synchrotron radiation is strongest at low frequencies (long wavelength) it can be detected with **radio telescopes**.

Radio Emission Processes

- Spectral Line Emission

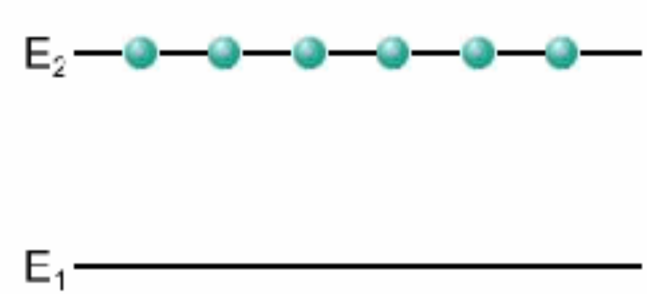


Neutral hydrogen HI (21 cm)
=> Most NB spectral line in the radio.
=> spin-flip transition between high-energy state and low-energy state of the H atom (aligned vs opposed spins for p+ and e-).
=> Although this transition is rare - there is just so much H in the ISM !



Molecular lines (CO, CS, CN,...)
=> Produced by changes in the vibrational or rotational states of their electrons (due to collisions or interactions)

Maser emission (OH, H20, SiO,…)
=> Amplification of incident radiation passing through clouds of gas



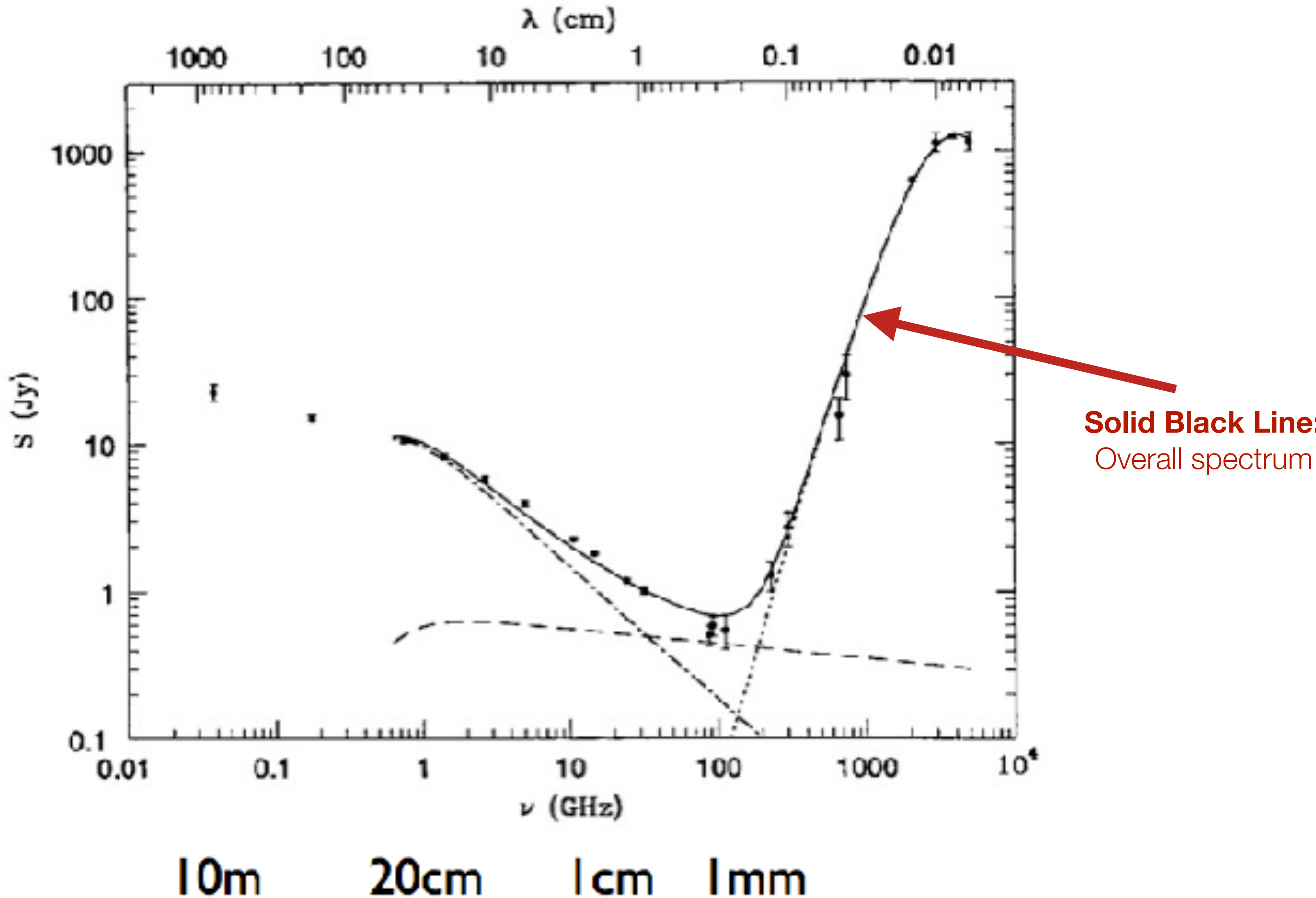
Radio Emission Processes

Wavelength	Spectral Line	Continuum
meter, cm, mm	Neutral Hydrogen (HI) 21 cm fine structure line - neutral gas Hydrogen recombination lines - ionised gas OH, H_2O, SiO Masers - dense warm molecular gas Molecular rotation lines - cold molecular gas	Thermal Bremsstrahlung (free-free emission) - HII regions Synchrotron Radiation - jets in radio galaxies, pulsars, shocks in supernovae, cosmic ray electrons in the magnetic fields of normal galaxies etc.., acceleration of electrons in stellar and planetary systems Thermal emission from dust - cold dense gas
sub-mm (and FIR)	Molecular rotation lines - warm, dense gas Solid state features (silicates) - dust Hydrogen recombination lines - ionised HII regions	Thermal emission - warm dust

Credit: Prof. Mike Garrett (ASTRON/Leiden/Swinburne)Radio Astronomy course notes

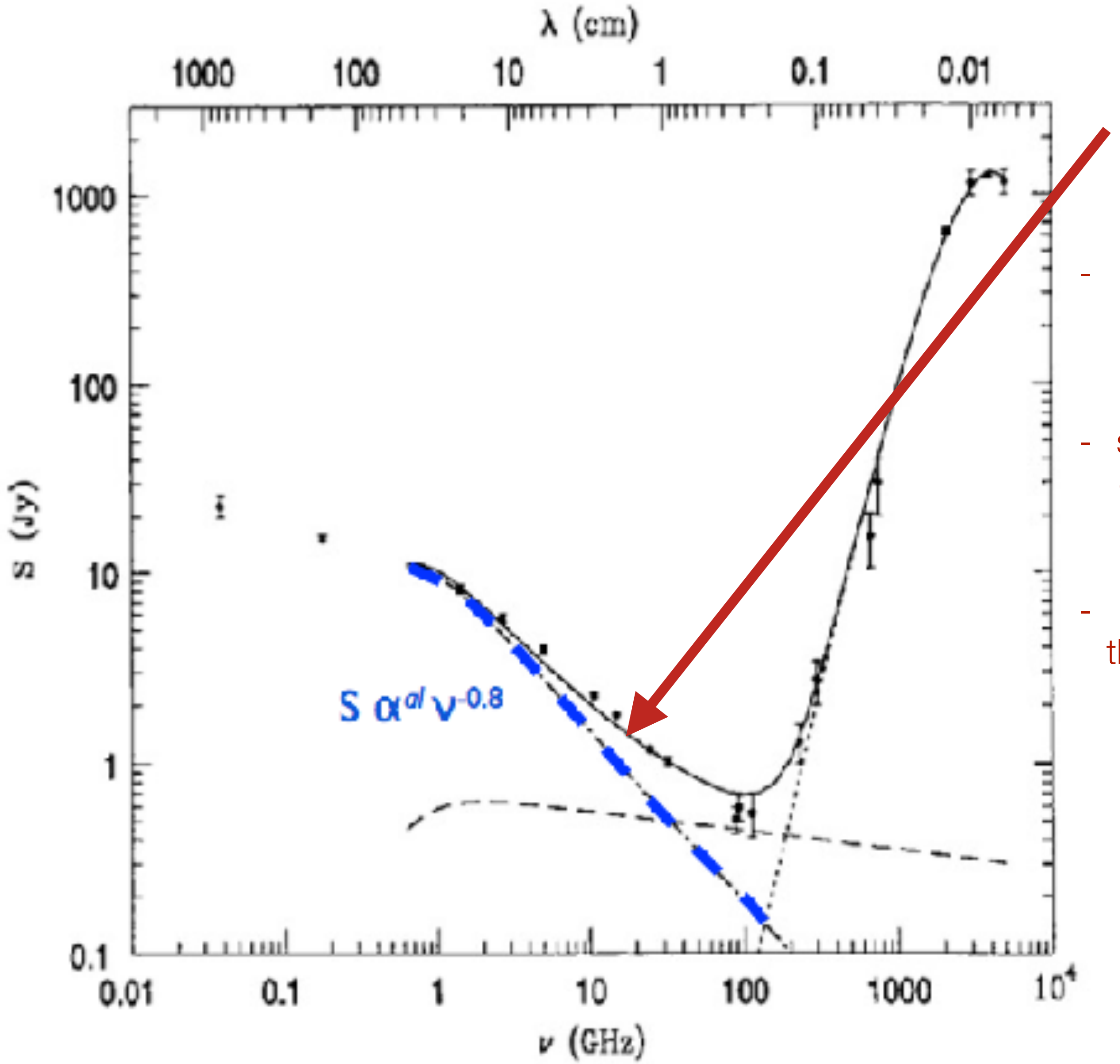
Radio Emission Processes

Example: the radio spectrum of a “normal” star forming galaxy like M82



Credit: Prof. Mike Garrett (ASTRON/Leiden/Swinburne)Radio Astronomy course notes

Radio Emission Processes

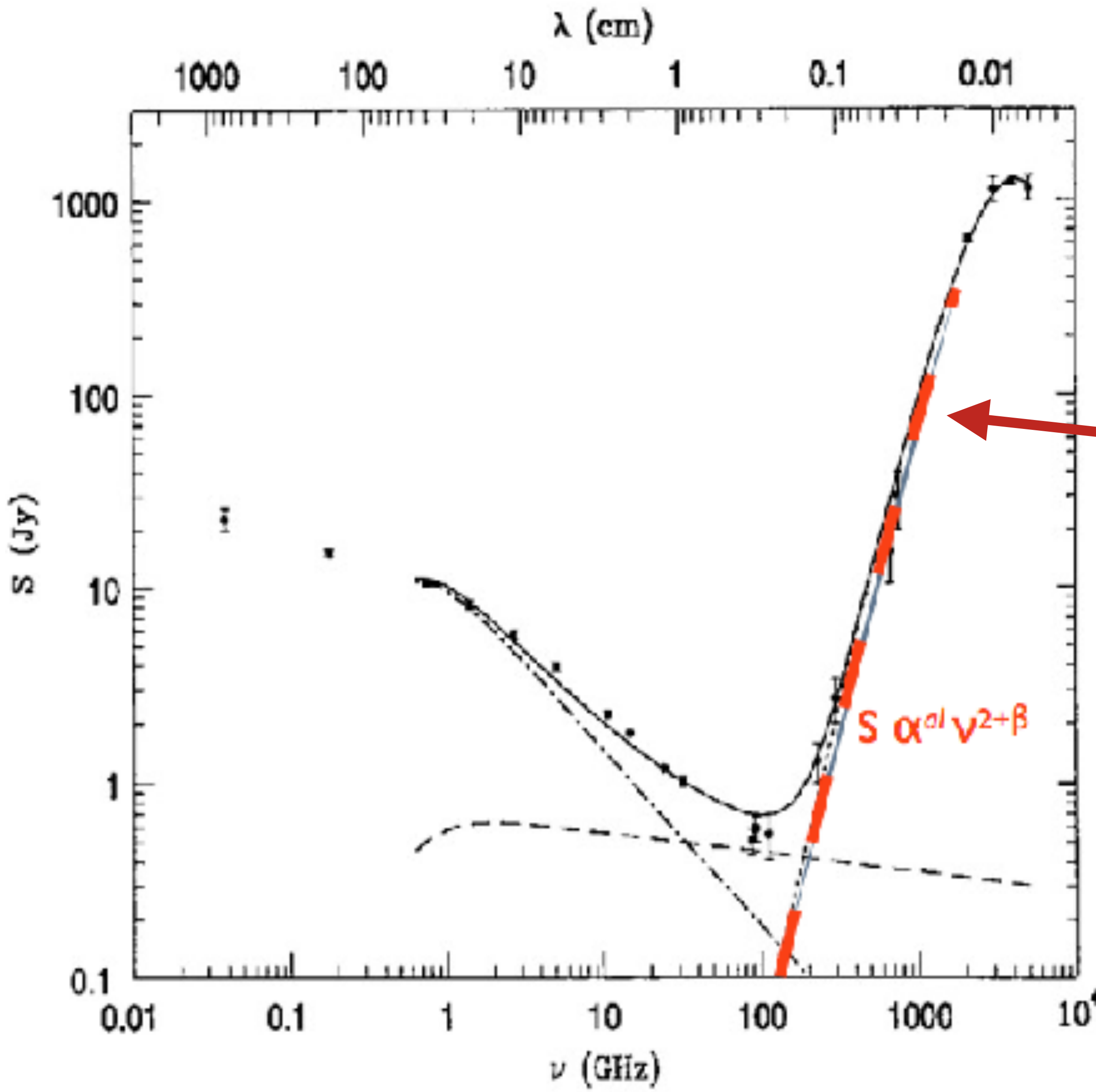


Blue Line is a steep spectrum.
synchrotron emission:

- cosmic ray electrons accelerated in M82's magnetic field.
- source of the cosmic ray electrons is shocks from supernovae
- supernovae events themselves produce short lived synchrotron emission

Credit: Prof. Mike Garrett (ASTRON/Leiden/Swinburne)Radio Astronomy course notes

Radio Emission Processes



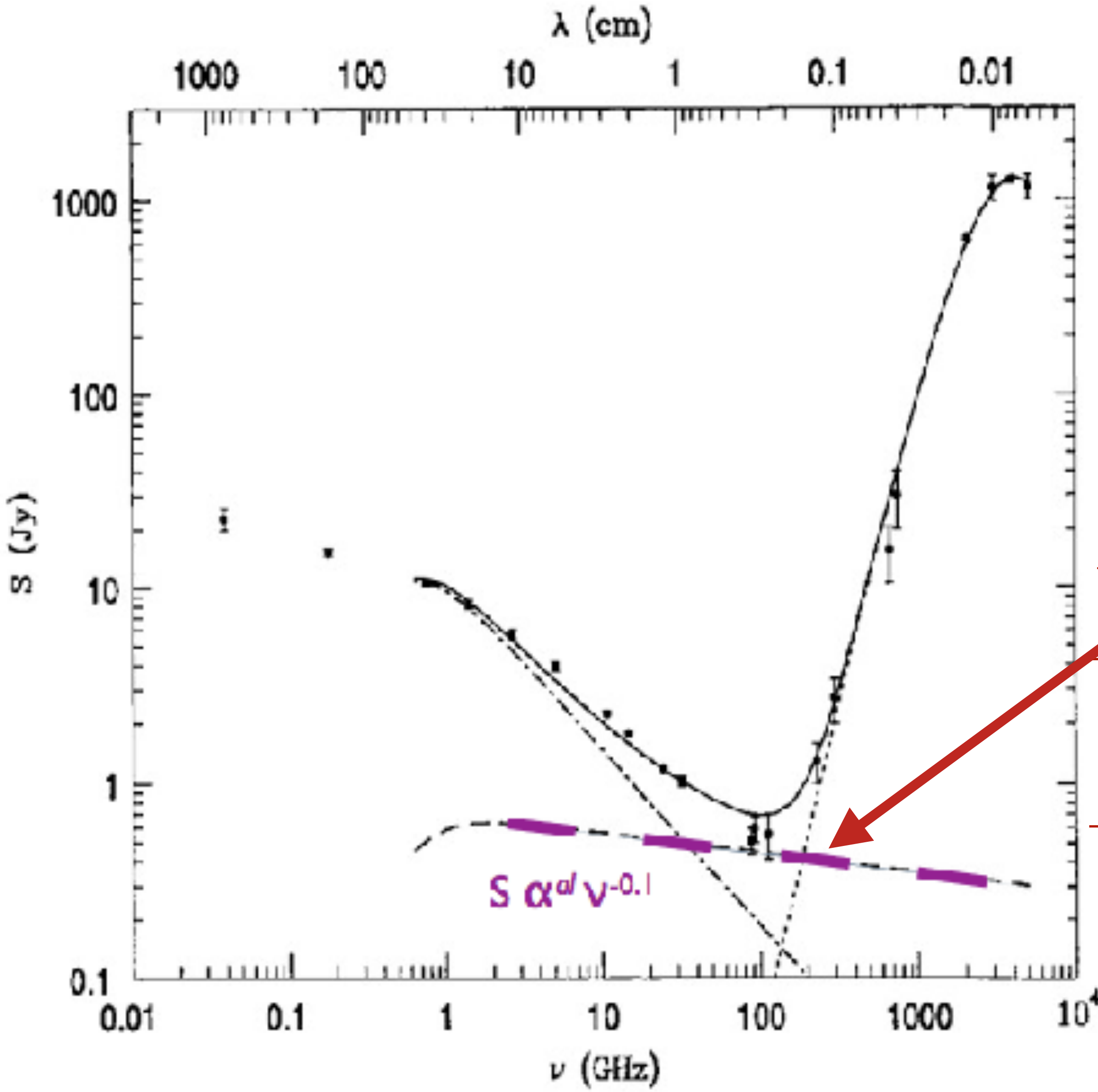
Red line.
thermal BB emission:

- dust heated up by the uv-photons from massive stars.

The same stars that produced the supernovae that fuel the radio emission.

Credit: Prof. Mike Garrett (ASTRON/Leiden/Swinburne)Radio Astronomy course notes

Radio Emission Processes



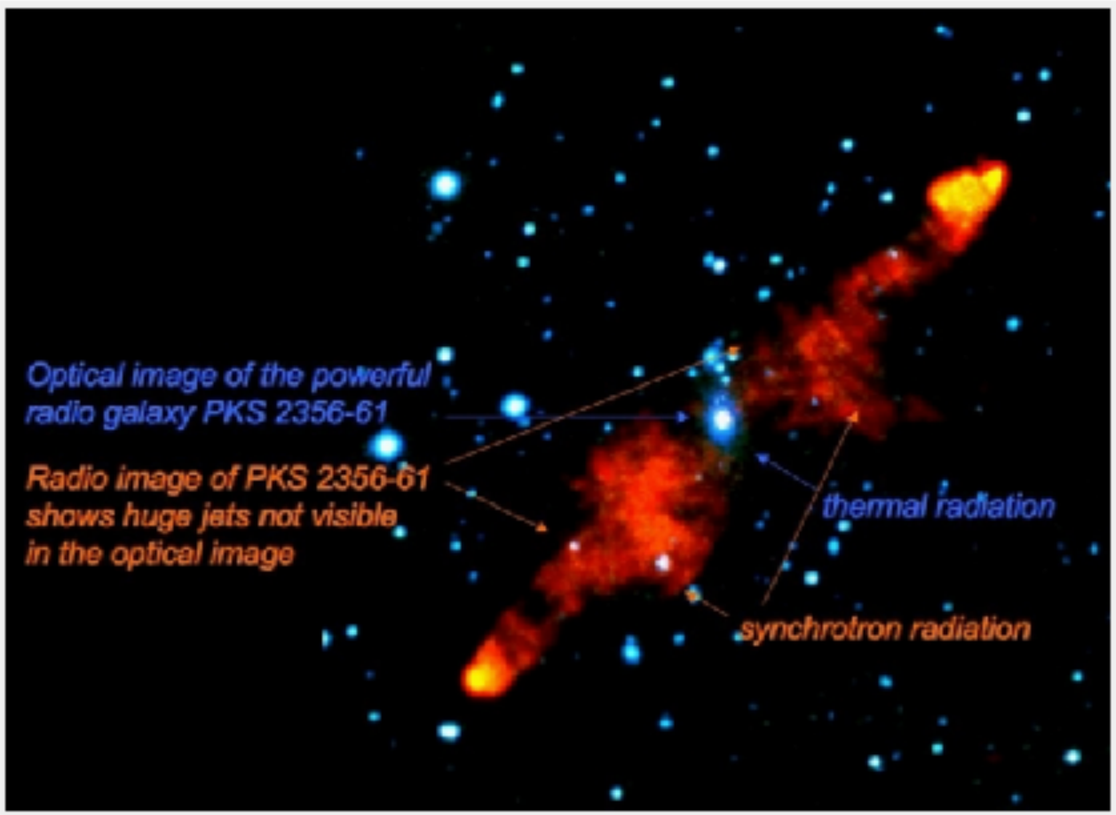
Purple Line.
thermal free-free emission:

- from HII regions that are common in star-forming regions that contain young massive stars.
- The same stars that produce the supernovae and that heat the dust.

Credit: Prof. Mike Garrett (ASTRON/Leiden/Swinburne)Radio Astronomy course notes

Radio Emission Processes

- The combined emission from a source, detected over a range of wavelengths, might result in a **composite** of all the processes we have looked at.

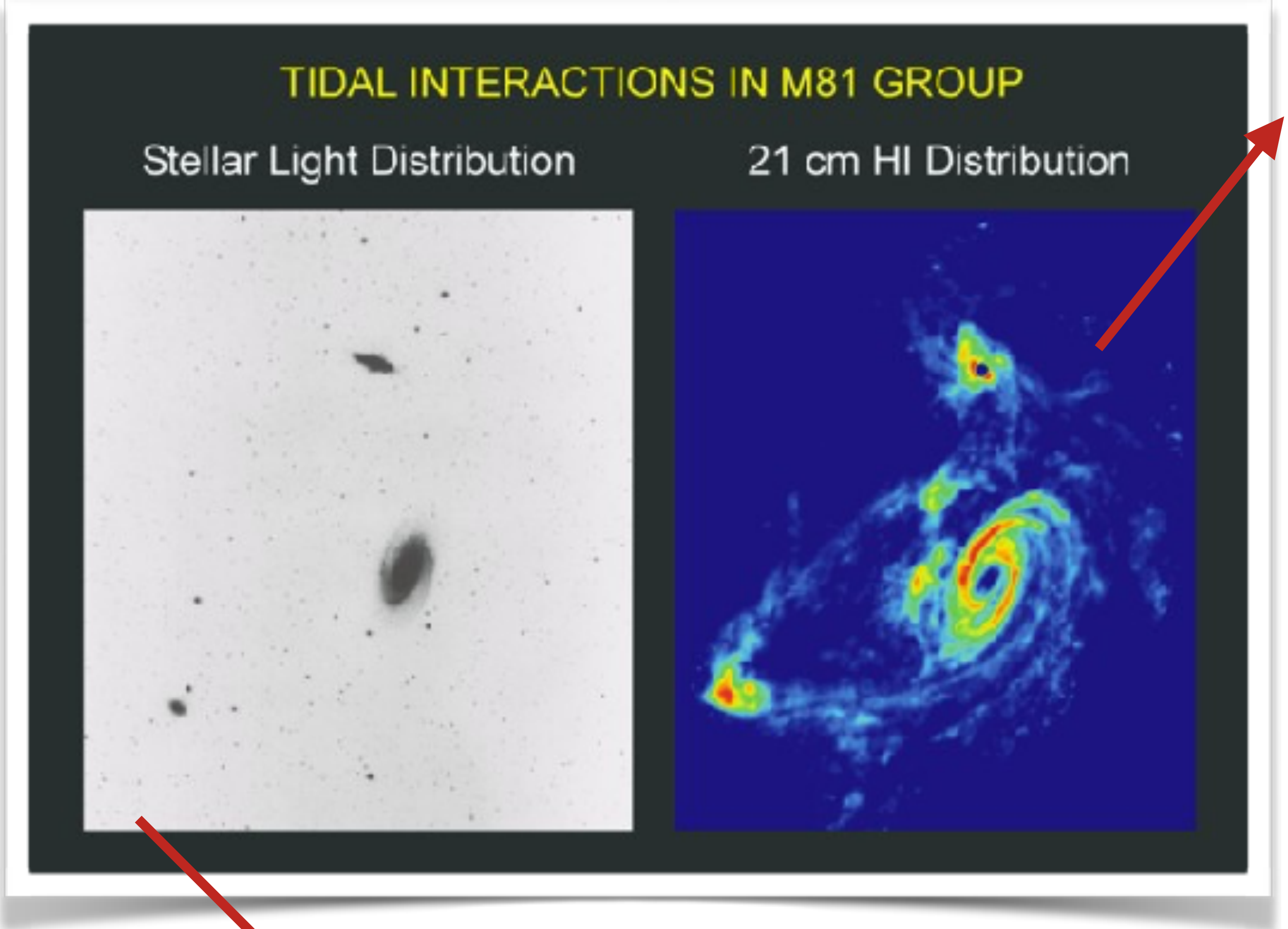


Optical/Radio composite image of the powerful radio galaxy PKS 2356-61

Credit: A. Koekemoer, R. Schilizzi, G. Bicknell and R. Ekers (ATCA)/ATNF

If we only observe the source in the visible, we would only get part of the picture

Radio Emission Processes



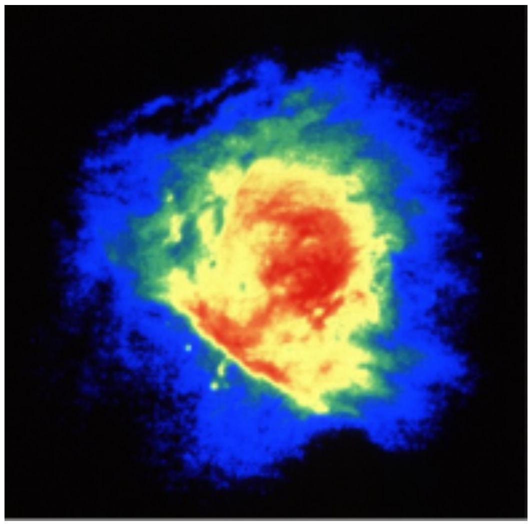
A radio image made with the VLA.
Shows hydrogen gas, including streamers of gas connecting the galaxies.
From the radio image it becomes apparent that this is an interacting group of galaxies

Visible light image shown in reverse grayscale.
Most of the light comes from stars in the galaxy

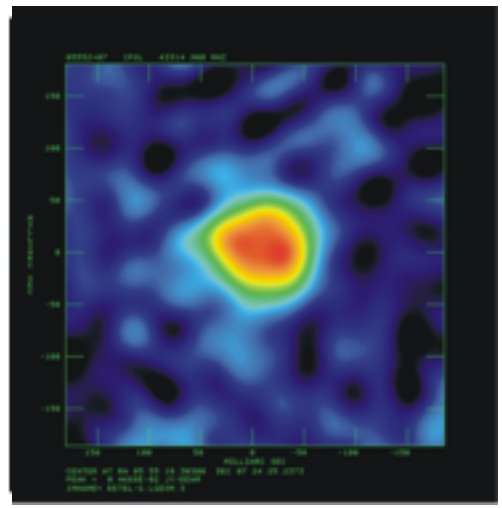
Images courtesy of NRAO/AUI

The Radio Sky: Galactic Objects

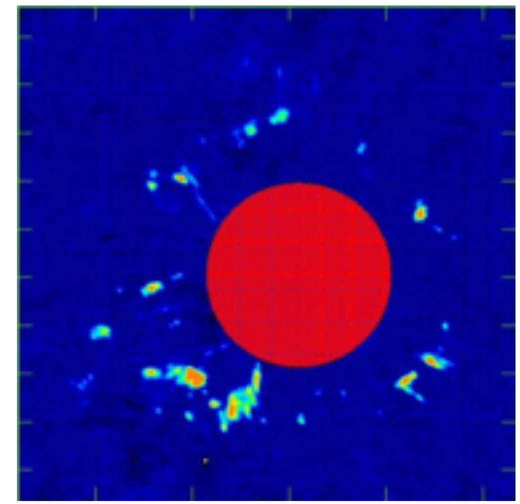
Ionized gas in the Orion nebula



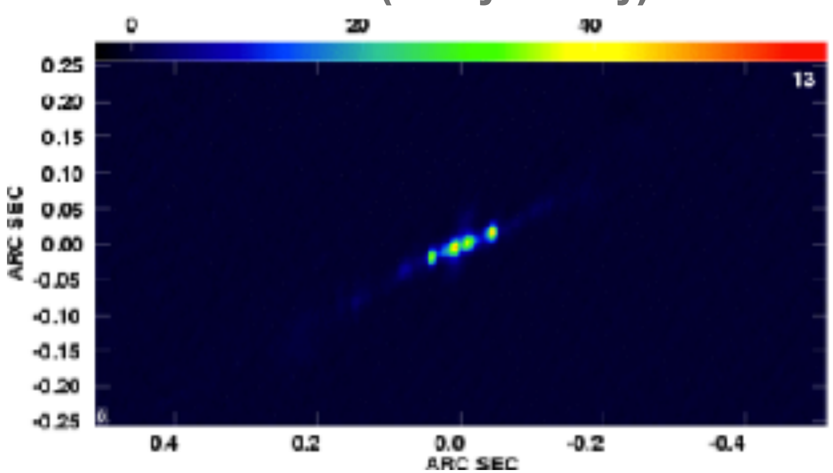
Betelgeuse



SiO Masers around the star TX Cam

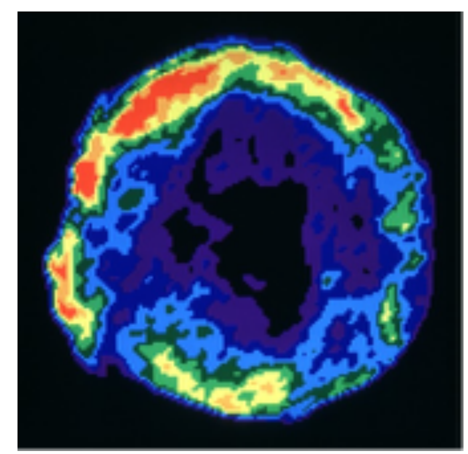


SS 433 (X-ray binary)



Pulsars

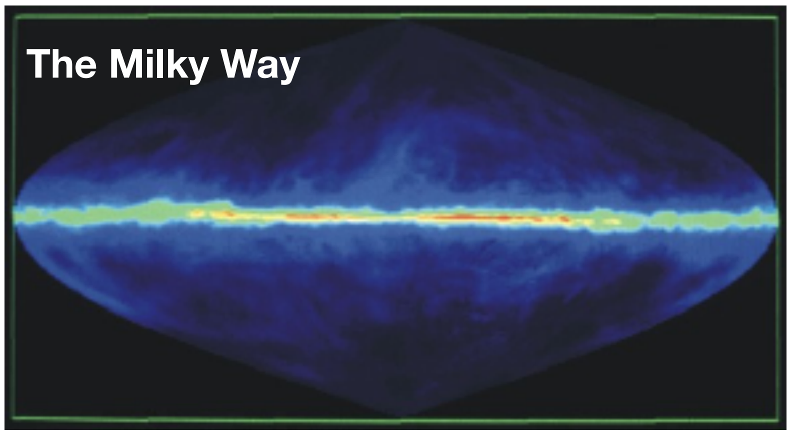
Tycho's SNR (3c10)

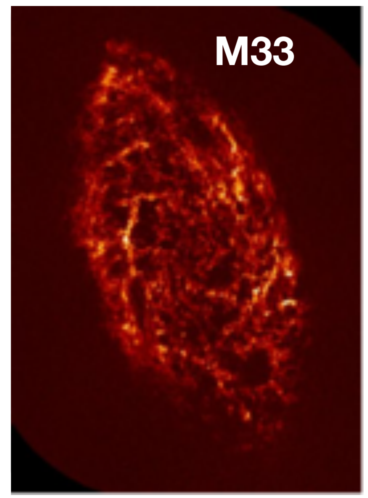


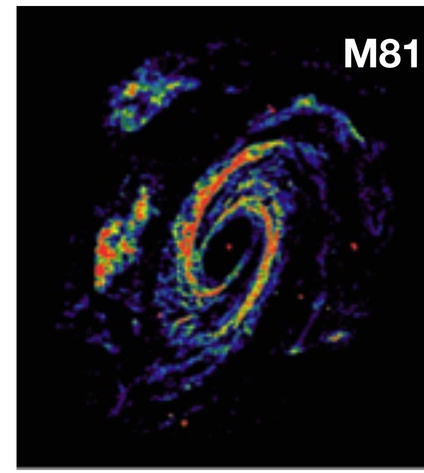
Images courtesy of NRAO/AUI

The Radio Sky: Galaxies and AGN

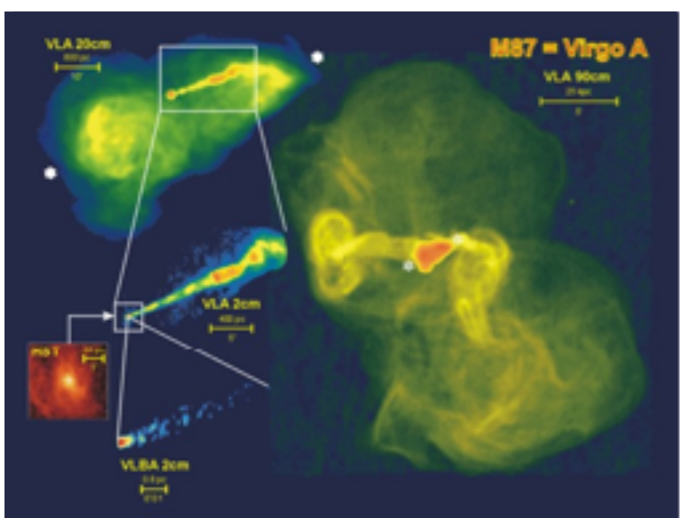
Atomic hydrogen emission

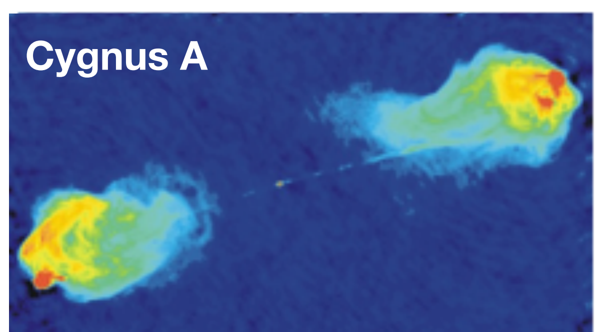


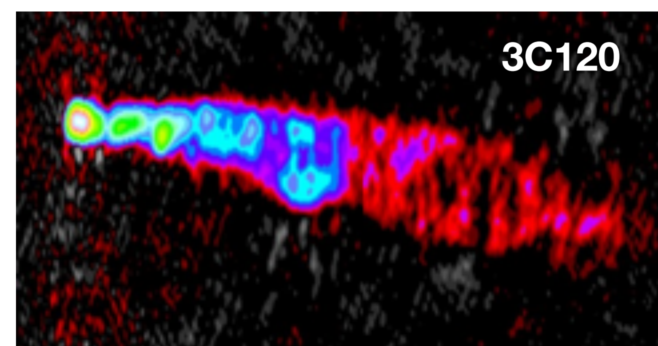




Continuum emission





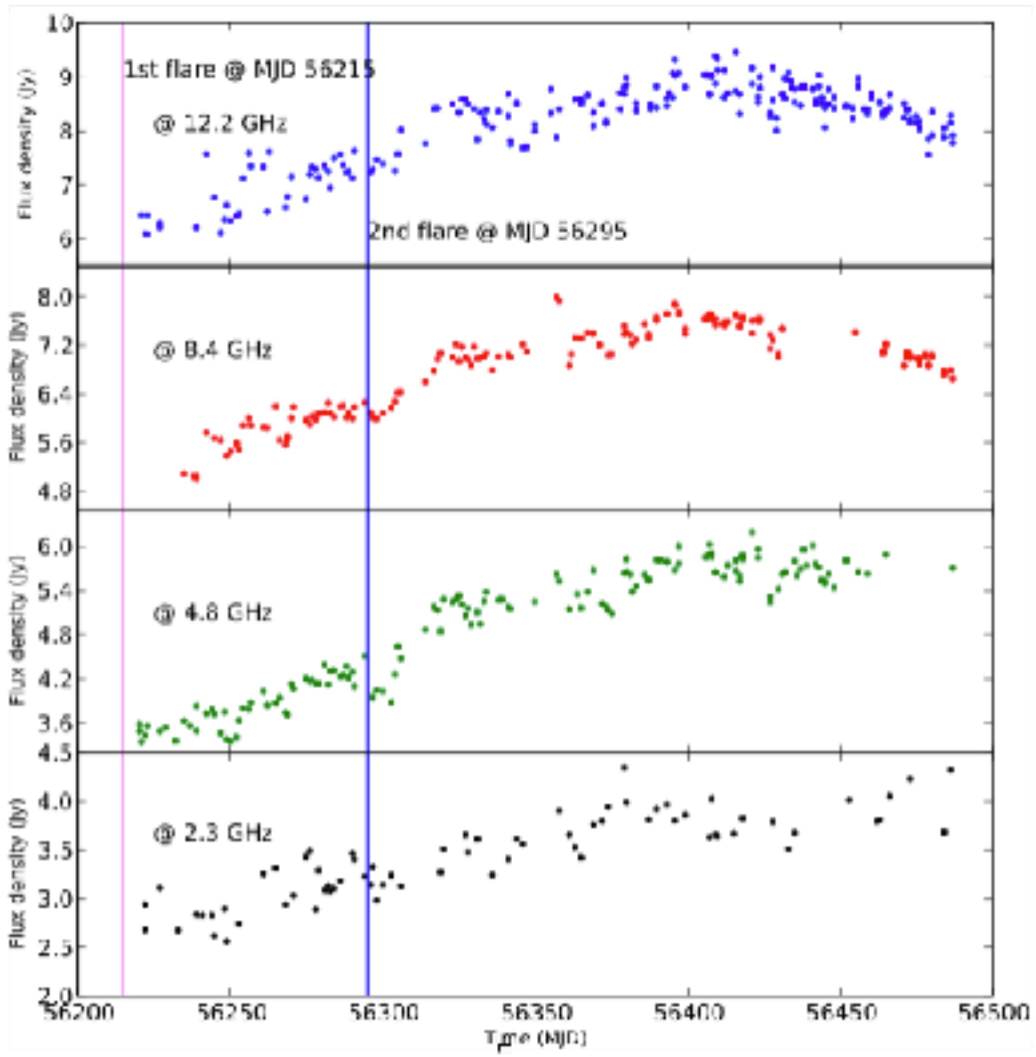


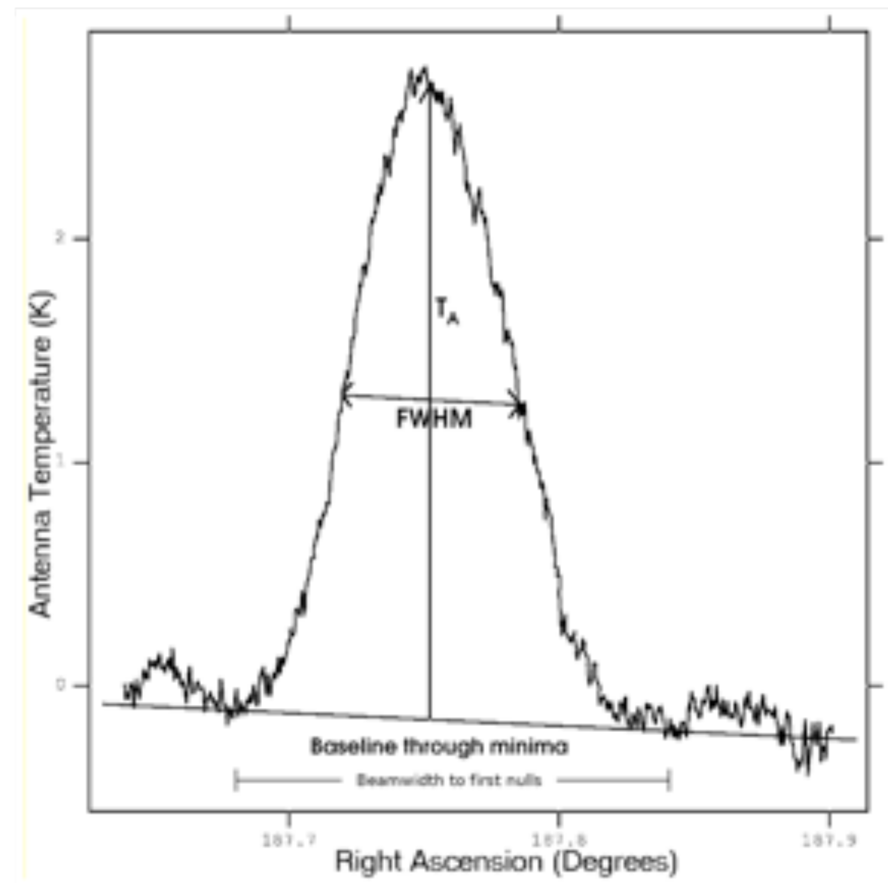
Images courtesy of NRAO/AUI

Single Telescopes

- **Radiometry –** measuring the strength of radio emission from objects in space in a specific frequency band
- **Spectroscopy –** measuring the strength of emission lines at specific frequencies emitted by atoms and molecules
- **Pulsar timing –** measuring the arrival time of radio pulses from the collapsed remnants of stars that have exploded

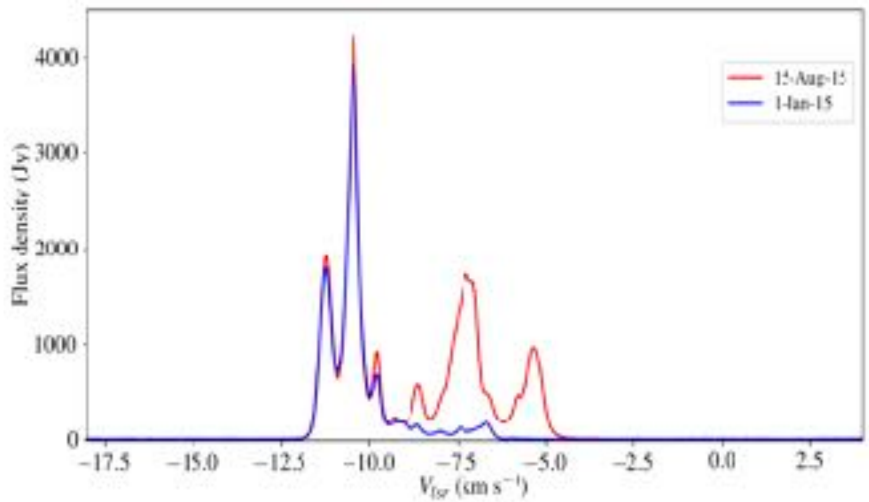
Single Telescopes



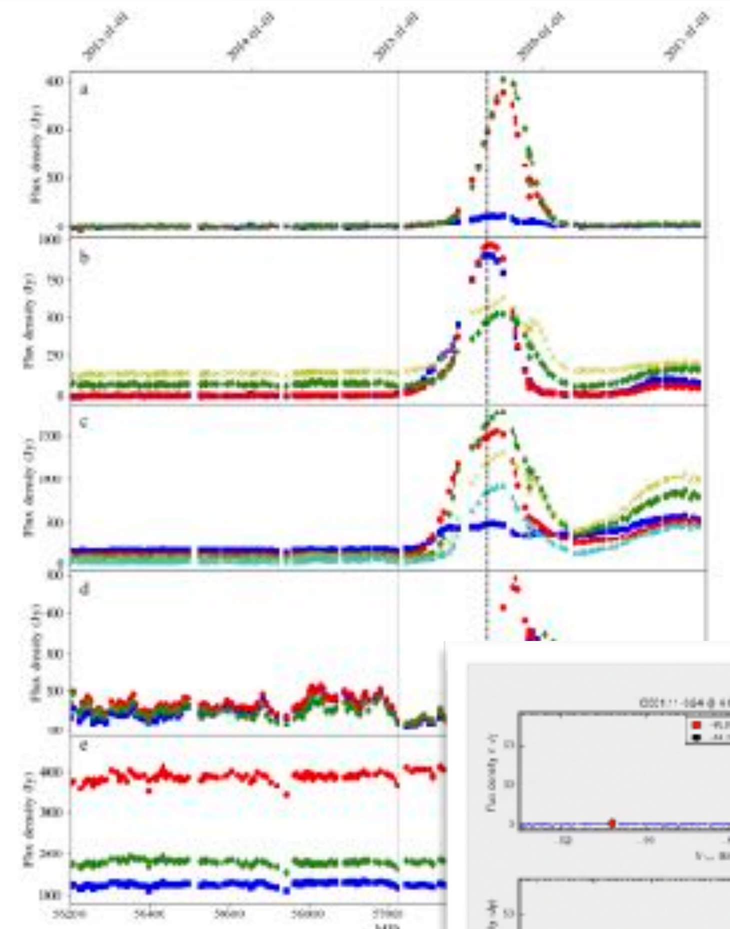


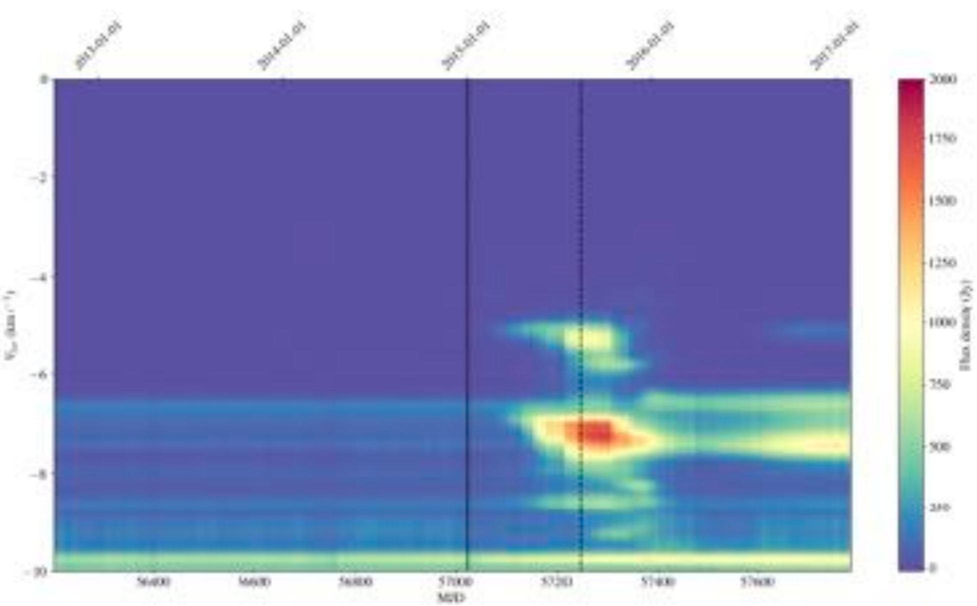
PKS 1424-41 / J1427-4206
Image Credit: Pfesesani Nemanashi, Mike Gaylard

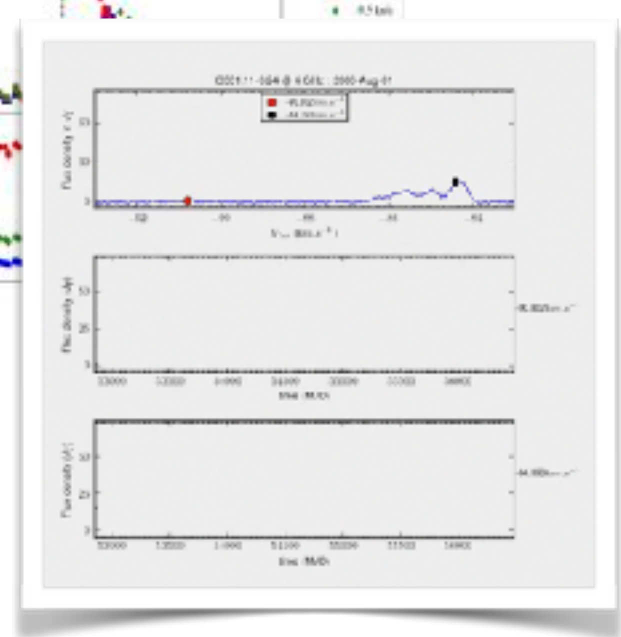
Single Telescopes



NGC6334F, 6.7 GHz (methanol) masers
Image Credit: Dr Gordon MacLeod

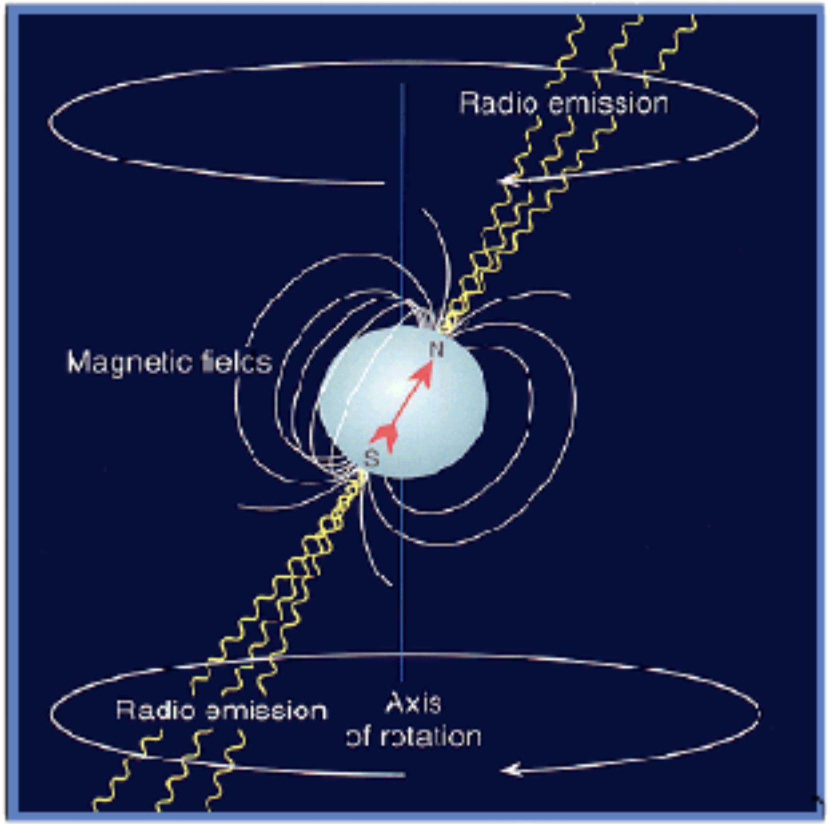


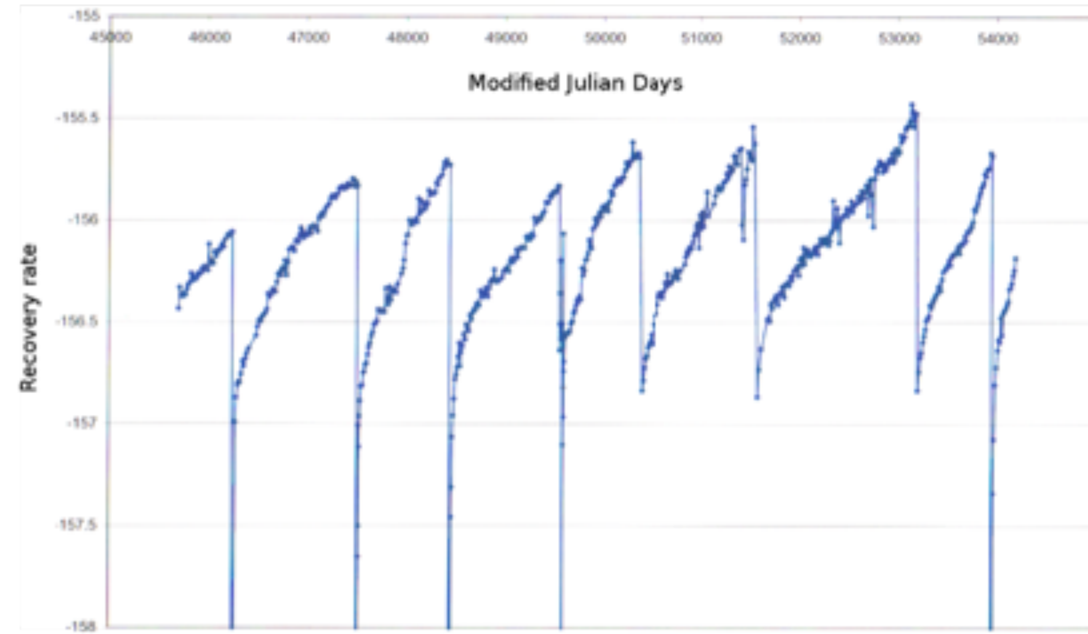




6.7 GHz (methanol) masers from massive star forming regions.
Image Credit: Jabulani Maswanganye

Single Telescopes

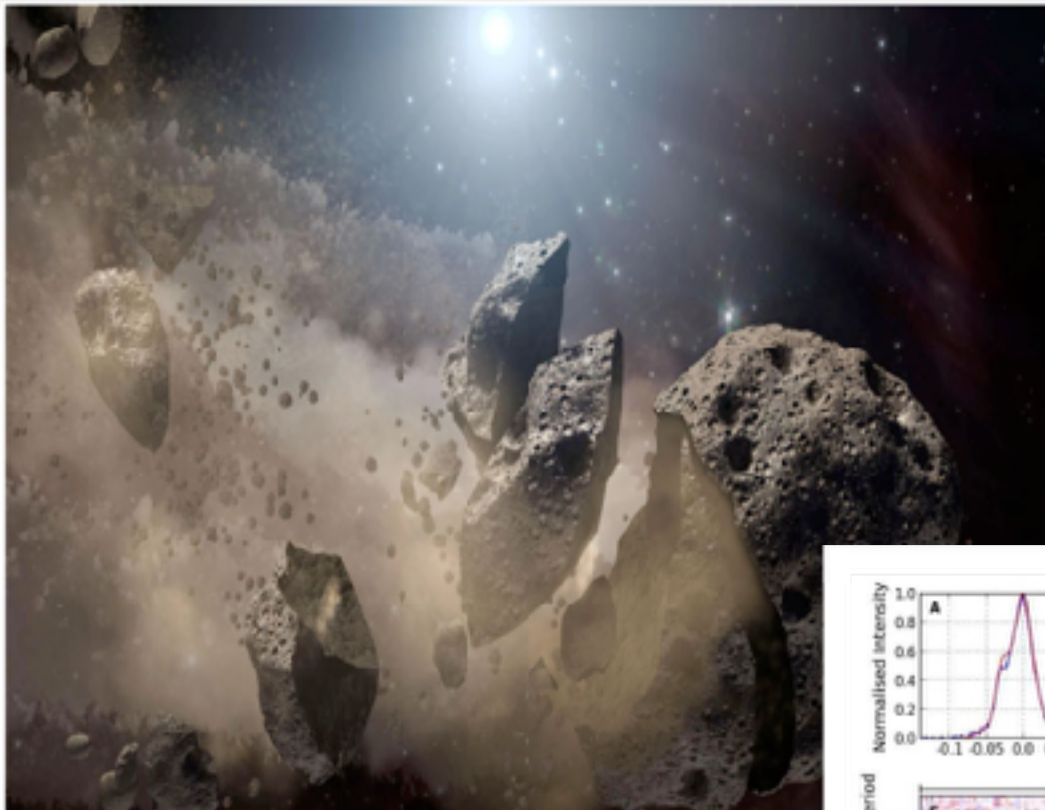




Pulsars are usually very stable clocks. But occasionally they suddenly speed up in an event known as a glitch.
By monitoring how the pulsar spin rate recovers from a glitch we can find out about the inside of the neutron star.
Image Credit: Sarah Buchner

A massive star ends its life in a supernova explosion. Left behind is a small dense, rapidly rotating neutron star. This emits radiation at its magnetic poles. These beams sweep across the sky like a lighthouse. Each time the beam passes the Earth we see a pulse.

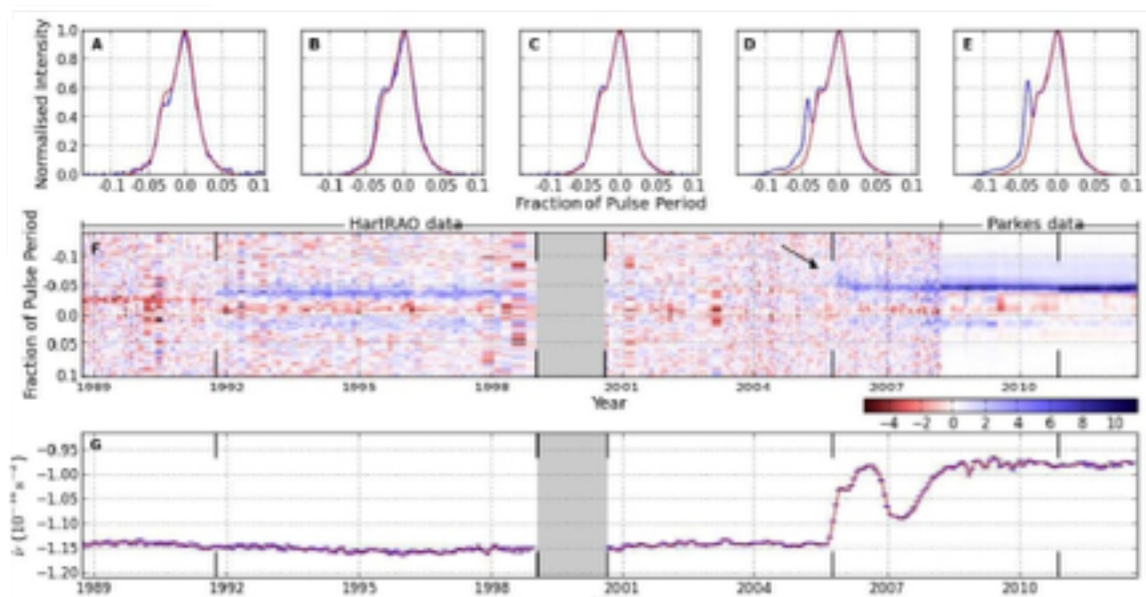
Single Telescopes



Artist's impression of an asteroid being vaporised (JPL-Caltech/ NASA)

PSR J0738-4042 in the constellation Puppis are regularly monitored by radio astronomer Sarah Buchner using the HartRAO 26 m antenna.

Analysis of the data show pulse profile changes occurring coincided with an abrupt, significant change in the rotation rate.



We expect that material ejected in a supernova explosion will form debris disks and asteroid belts around the newly formed pulsar. An infalling asteroid would interact with the pulsar magnetosphere to produce changes in the pulse shape and rotation rate.

Radio Interferometry

- Single element radio telescopes have limited **spatial resolution**
  $\theta = 1.22\ \lambda/D \sim \lambda/D$

- Resolution of the GBT 100m telescope at cm wavelengths is comparable to the human eye, and much worse than a small optical telescope.

Eye	D ~ 1mm	λ = 600nm	θ ~ 2’
GBT	D = 100m	λ = 6cm	θ ~ 2’
HST	D = 2.4m	λ = 500nm	θ ~ 50 mas

Radio Interferometry

- **Cost** and **constructional** limitations on size of a single dish telescope:

  - Steerable: GBT & Effelsberg 100m dishes
  - Non-steerable: 305m Arecibo dish.

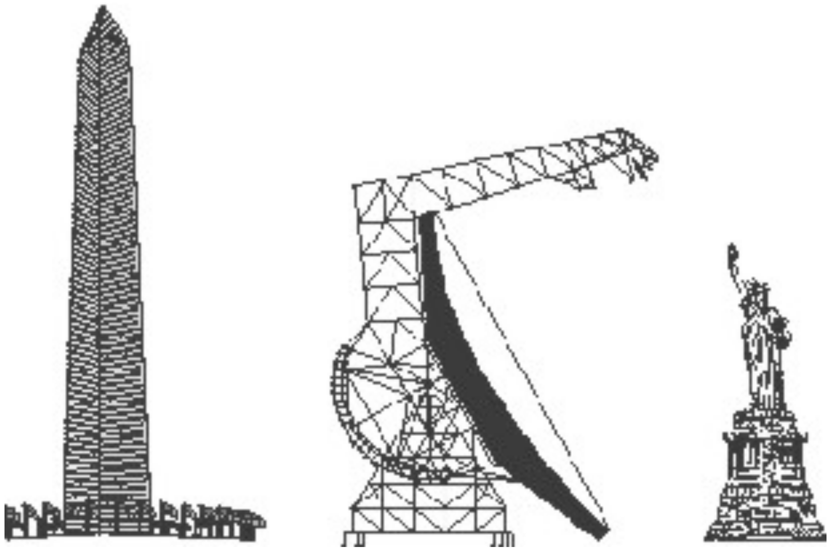
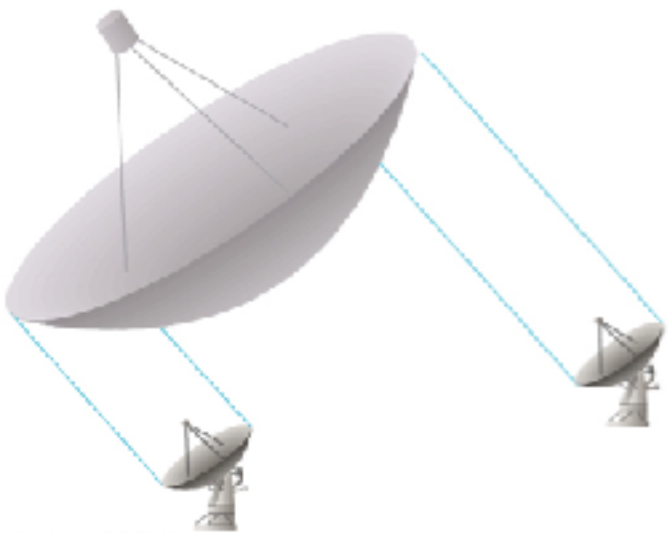


Image Credit: NRAO/AUI

- **Synthesize** a giant radio telescope by combining the signals of many small telescopes together - array.



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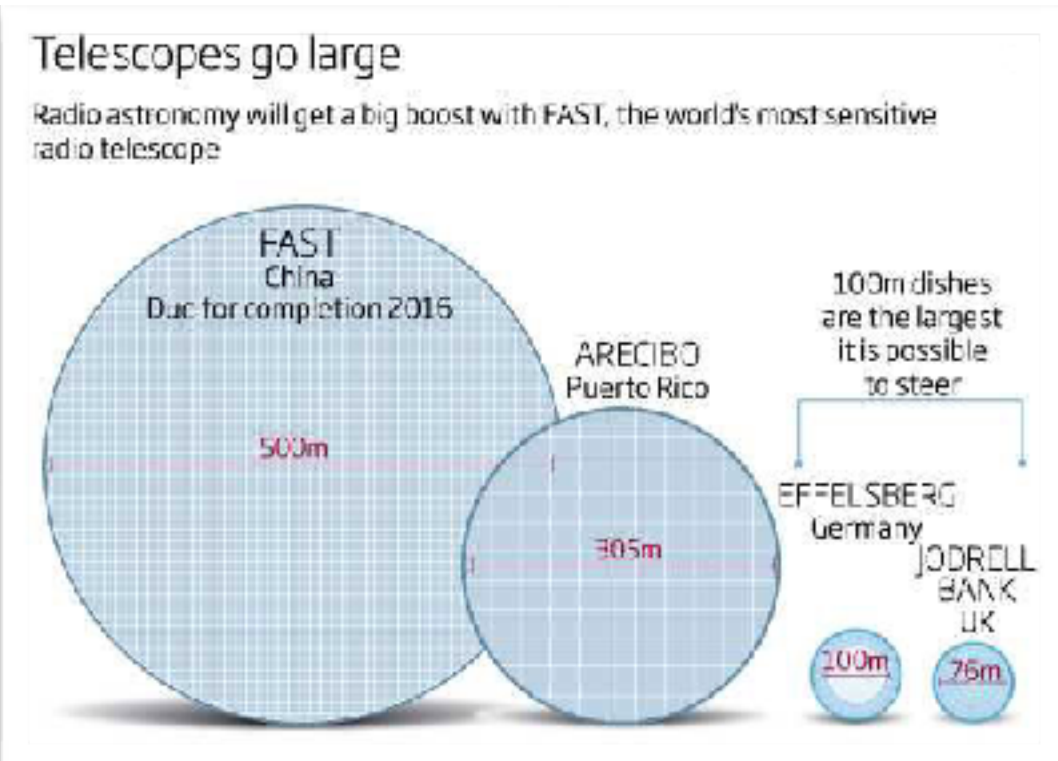
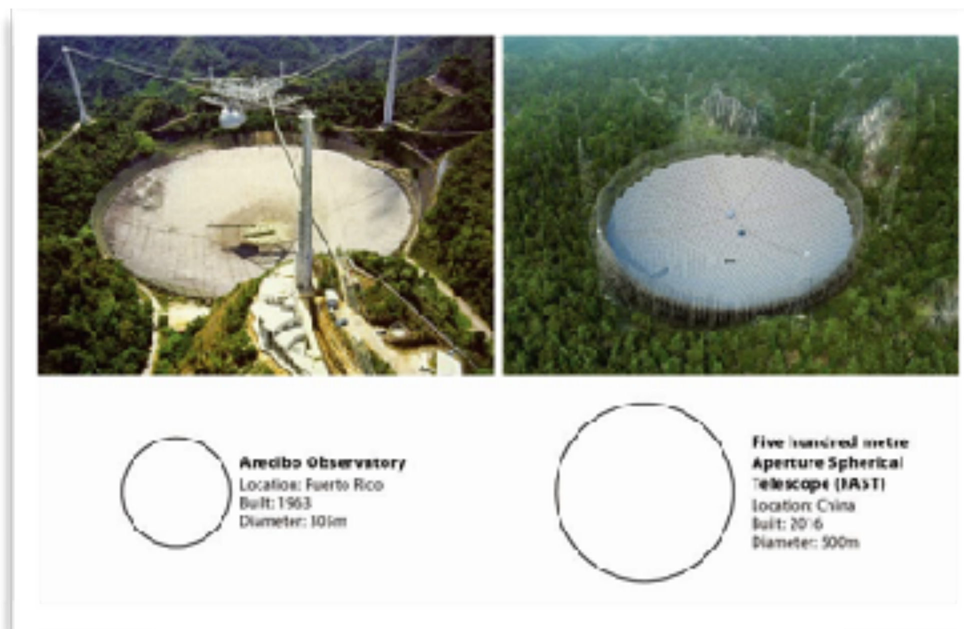
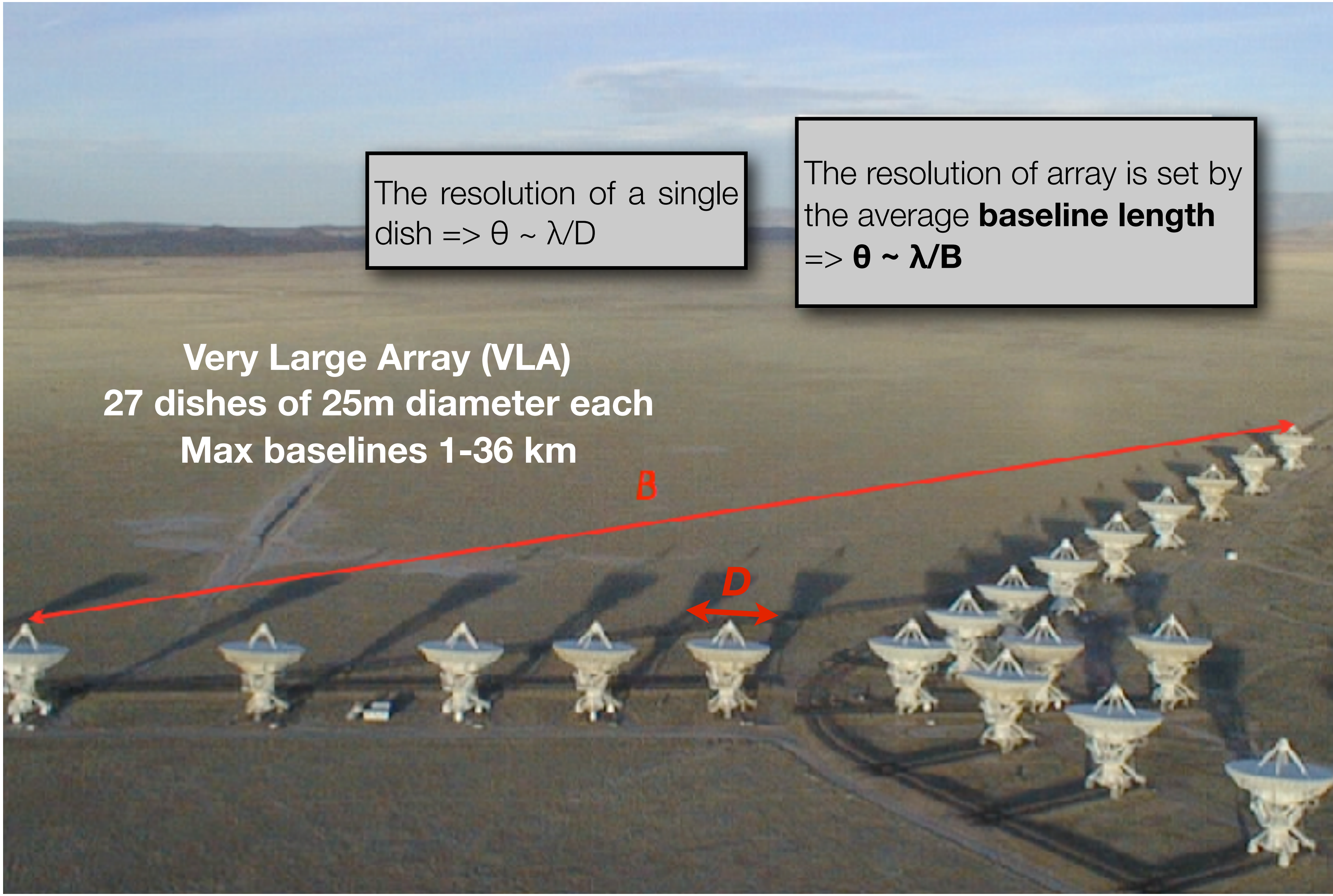
Radio Interferometry

- FAST, China - 500m







Radio Interferometry

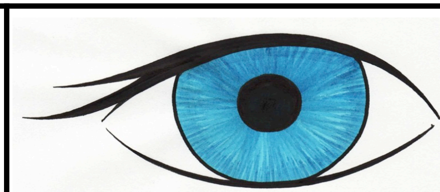
Interferometers, like the VLA are connected: antennas are physically linked (cables, optical fibers or radio link) - distance between antennas limited to several kilometers; signals are combined in real-time in a nearby correlator.

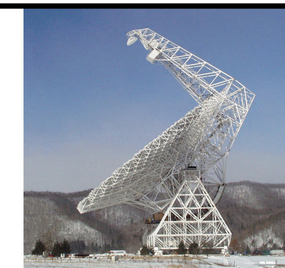
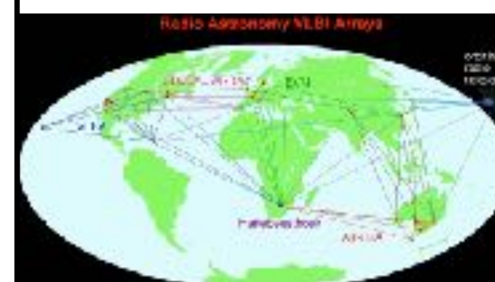
Very Long Baseline Interferometry (VLBI): independent antennas - The longest distance (baseline) corresponds to the diameter of the Earth (~12 000 km).

Resolution can reach **submilliarcsecond** level.
e.g. λ= 4 cm, B= 12 000 km, θ ~ 0.8 mas

Radio Interferometry

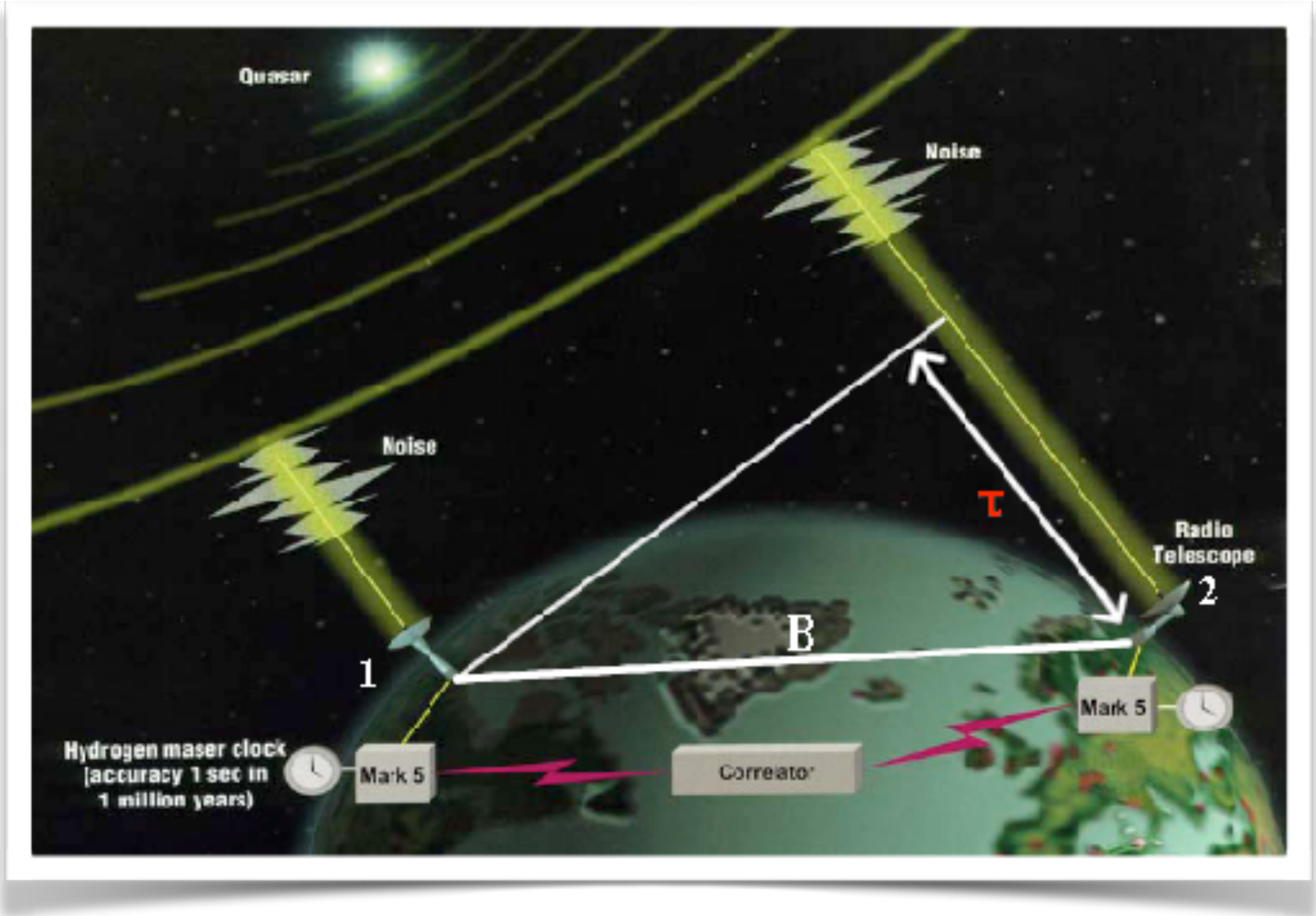
Optical and Radio Resolutions

Human eye λ/D ~60 arcsec = 1-2 arcmin (Sun diameter ~30 arcmin)	
Galileo's telescope λ/D ~ 4 arcsec (Jupiter diameter ~40 arcsec)	
10 cm optical telescope λ/D ~ 1 arcsec (~2 km on moon)	
10 m optical telescope λ/D ~ 0.01 arcsec (but limited to ~0.2 arcsec by atmosphere)	
Hubble telescope (2.4 m) λ/D ~ 0.05 arcsec (~100 m on moon)	

100m telescope at λ=1cm λ/D ~ 20 arcsec (Jupiter ~40 arcsec)	
VLA (~35 km) at λ=1 cm λ/D ~ 0.1 arcsec (~2 km on moon; ~2 m at 5000 km)	
10,000 km array, λ=1cm λ/D ~ 200 micro-arcsec (~40 cm on moon; ~5 mm at 5000 km)	
5,000 km array, λ=1 mm λ/D ~ 40 micro-arcsec (~8 cm on moon; ~0.1 mm at 1000 km; 35 Sun diameters at 25,000 ly)	

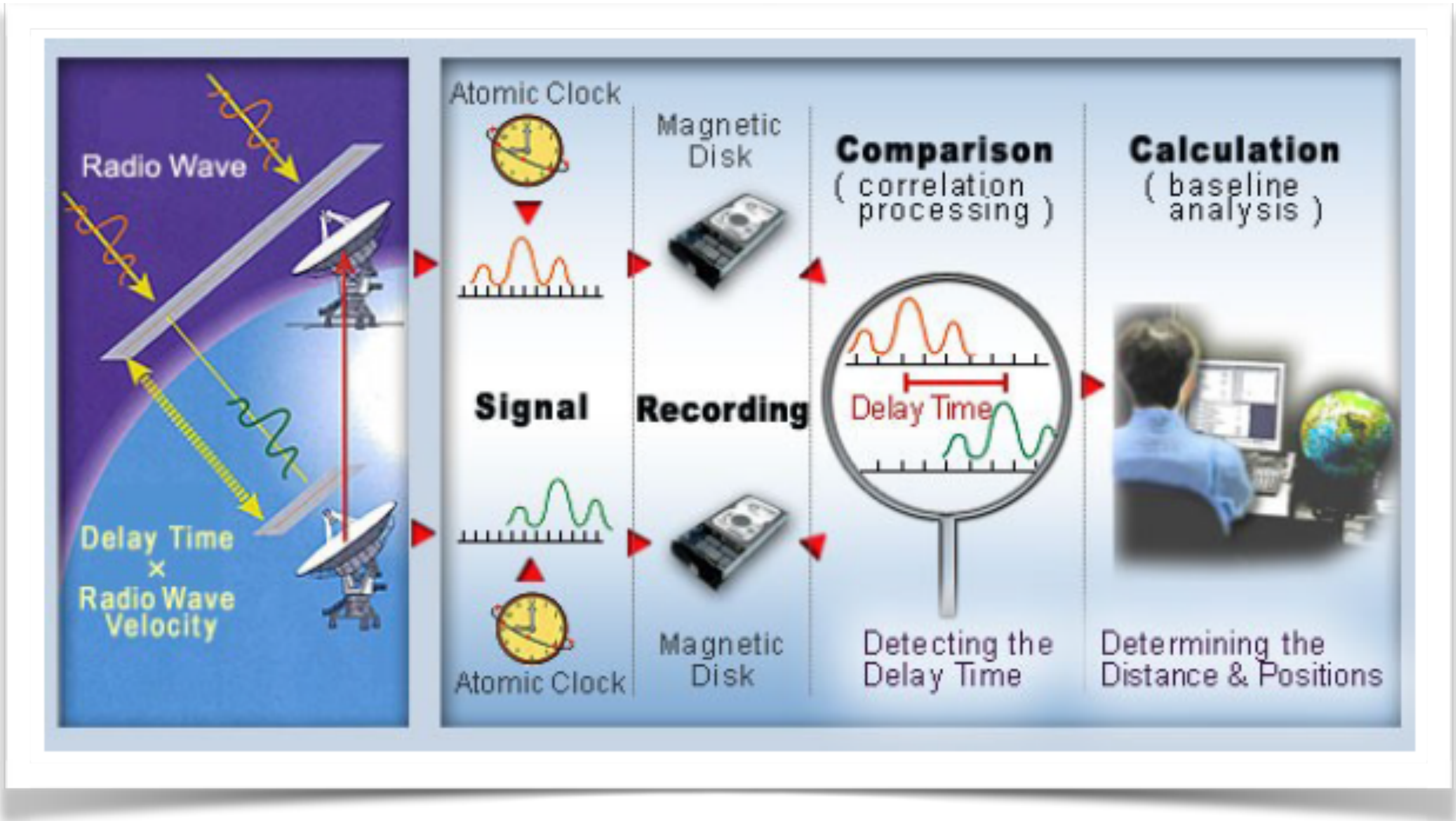
The VLBI Technique

- Two stations on Earth observe the same celestial object (e.g. quasar)
- Each station registers the radio signal on disk, along with the timing information, obtained thanks to a local hydrogen maser.

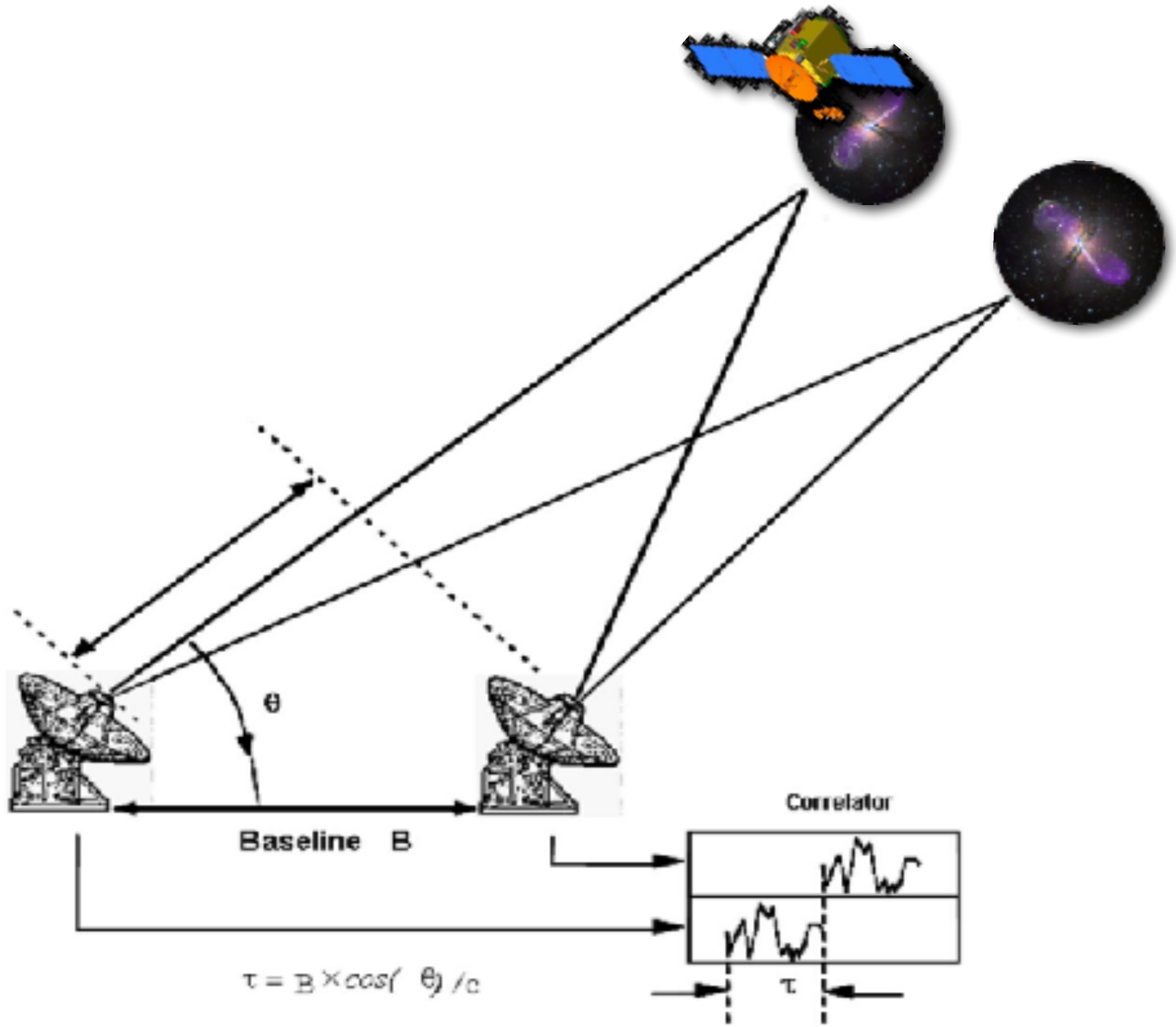


The VLBI Technique

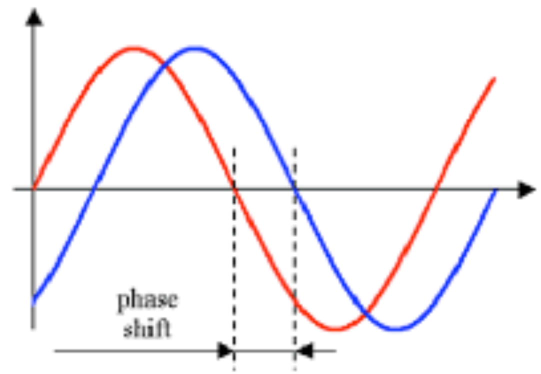
- The disks are sent to a remote **correlator**, where the two signals are played back and multiplied (correlated).
- Recently signals can be directly transferred from each station to the correlator through the Internet via optical fibre cables, and correlated in real-time: **e-VLBI**

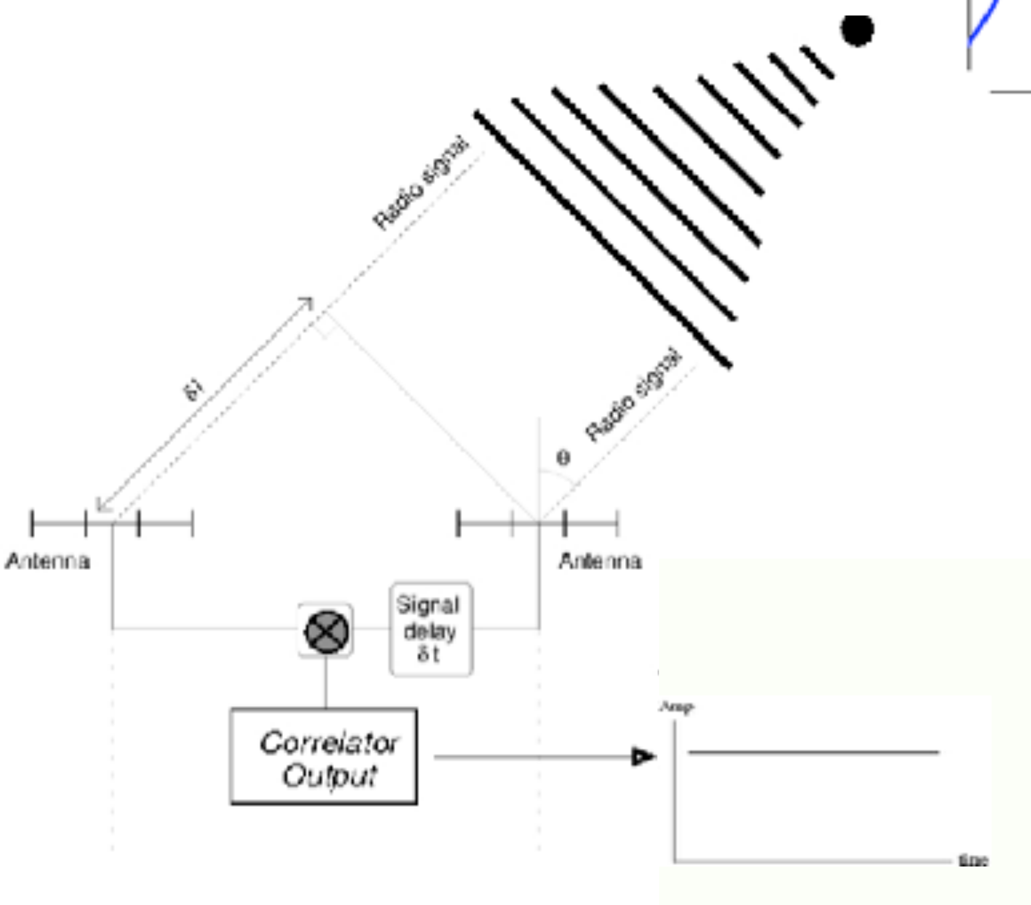


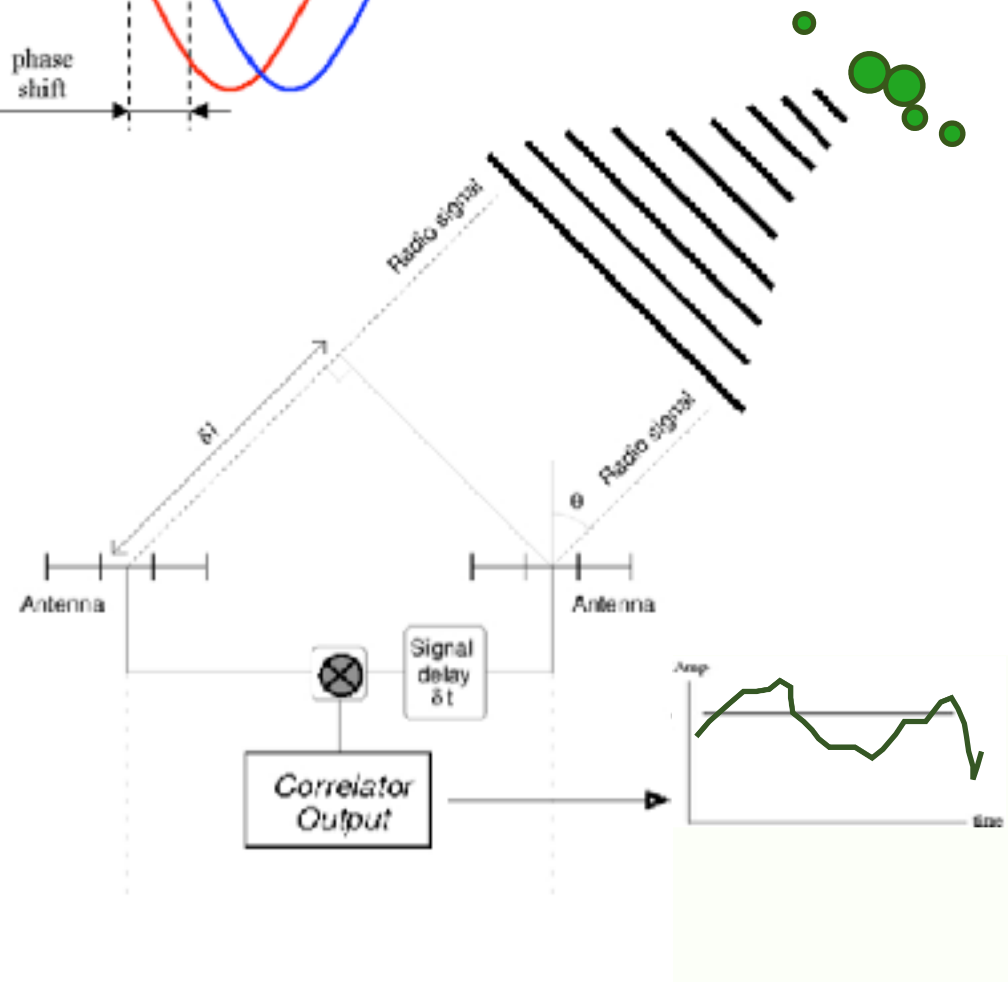
The VLBI Technique



The VLBI Technique







Very Long Baseline Interferometry (VLBI)

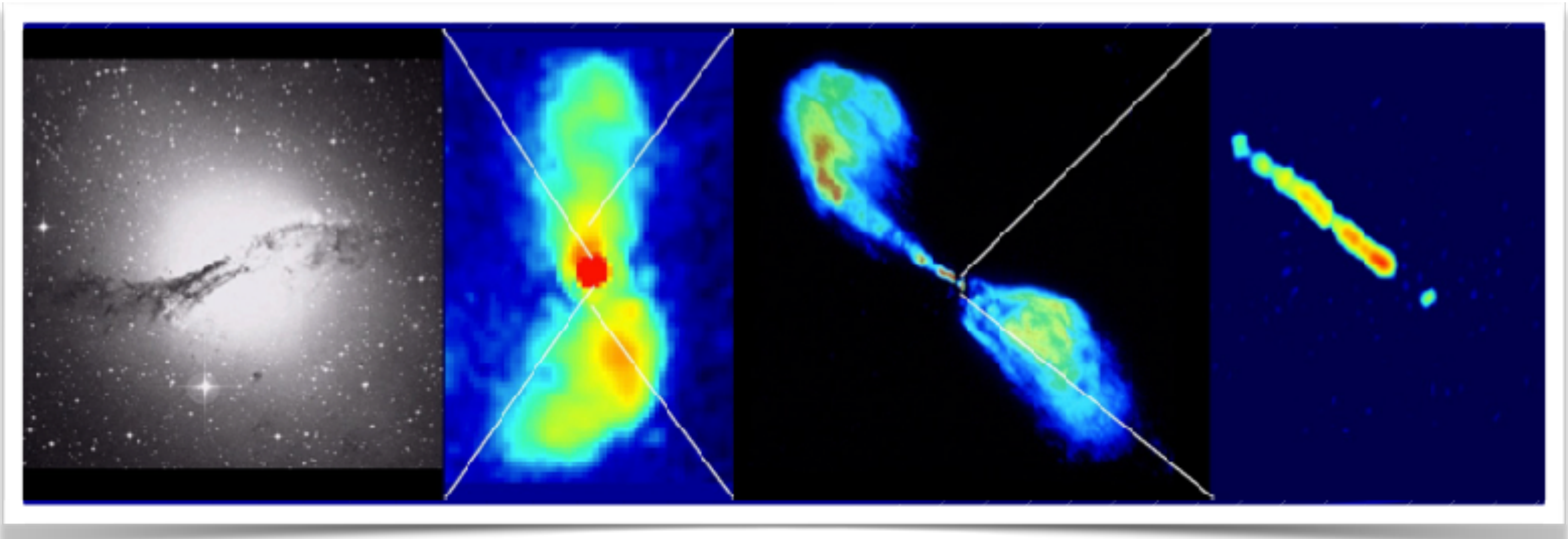
- **Astronomy** -
  Very fine detail of the radio emission from compact objects with high brightness temp e.g. active galactic nuclei (AGN's), interstellar masers (star-forming regions), Megamasers (extragalactic), radio stars, core collapse supernovae, pulsars

- **Astrometry** -
  Very precise positions for radio sources in space:
  - Sources absolute and differential positions, proper motions, parallaxes
  - definition and densification of the celestial reference frame (ICRF)
  - spacecraft tracking

- **Geodesy** -
  Very precise positions for the radio telescopes in the network:
  - Terrestrial reference frame
  - Earth orientation and rotation (the length of day)
  - Tectonic plate motion

VLBI: Astronomy

Optical image: angular extent on the sky of about **one quarter of a degree.**

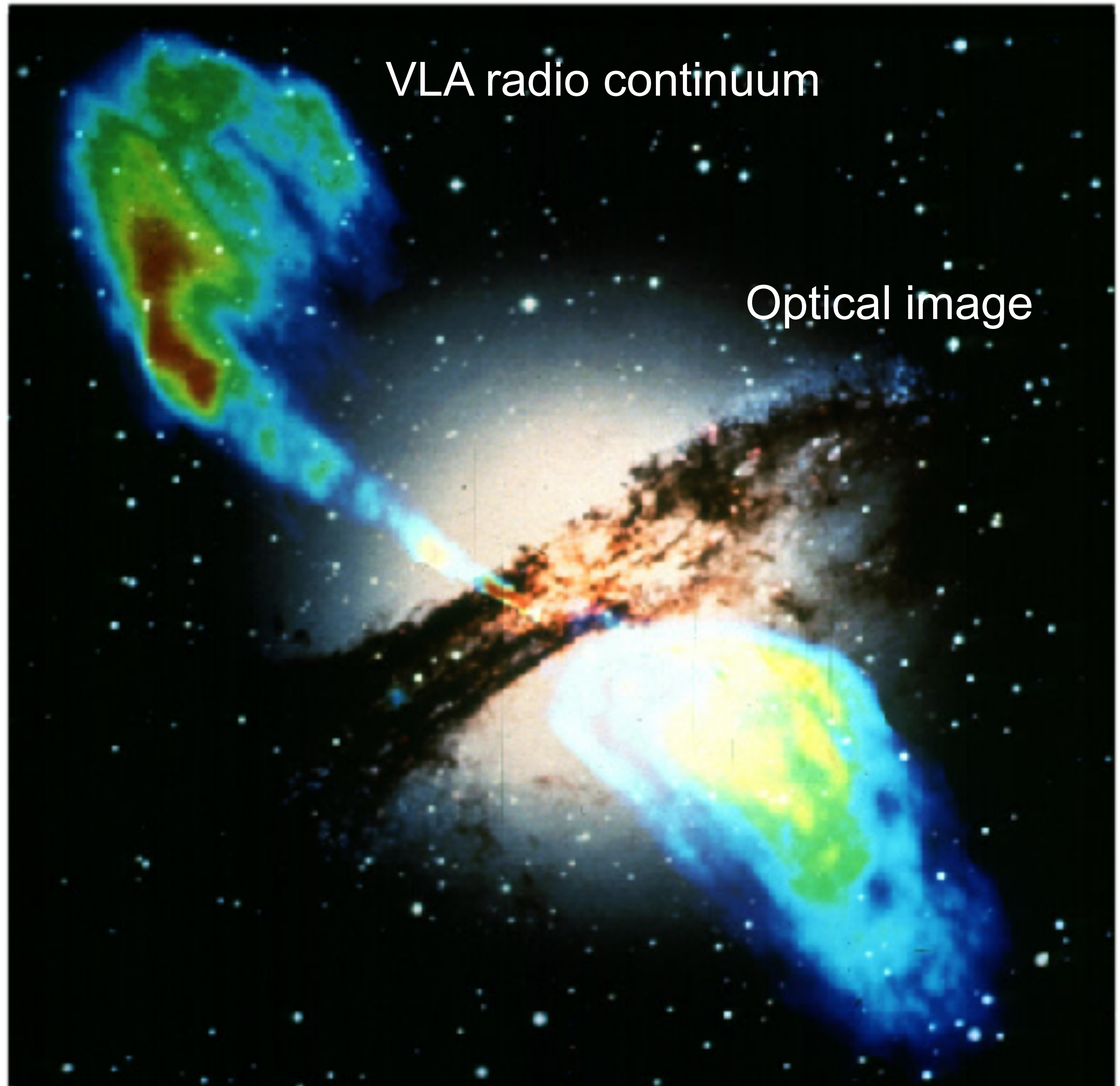


The full radio emission: HartRAO 26m at 13cm, **resolution of 1/3 of a degree.** Cover nearly **ten degrees on the sky.**

VLA radio continuum observations of the inner lobes at 20cm. **Field of view 11x11 arcmin** at a **resolution 30x10 arcsec.**

NGC5128 / Centaurus A

VLBI: Astronomy

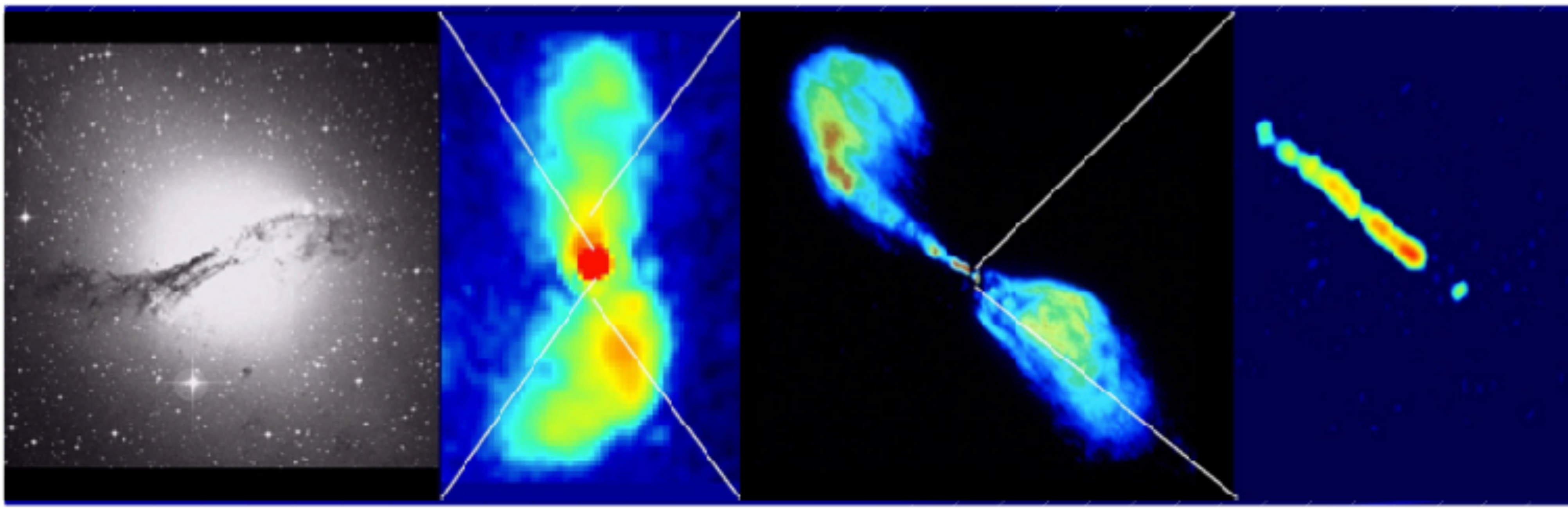


NGC5128 / Centaurus A

VLBI: Astronomy

Optical image: angular extent on the sky of about **one quarter of a degree.**

VLBI (LBA + HartRAO) image: fine details of upper jet as it leaves the area around the black hole (centre). This part of the jet is about **one hundred thousandth of a degree** long, and we see details smaller than **a millionth of a degree.**



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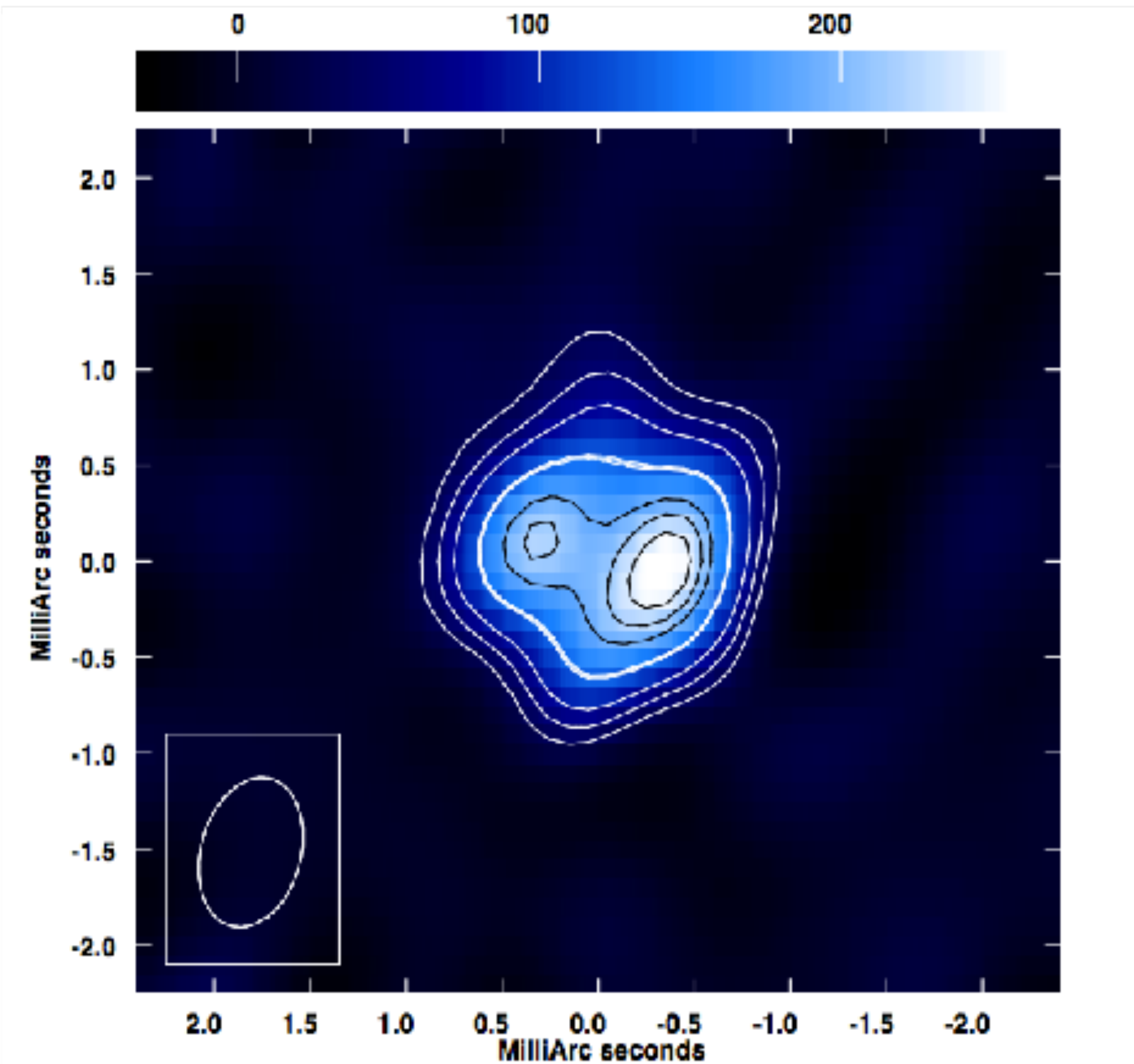
NGC5128 / Centaurus A

VLBI: Astronomy

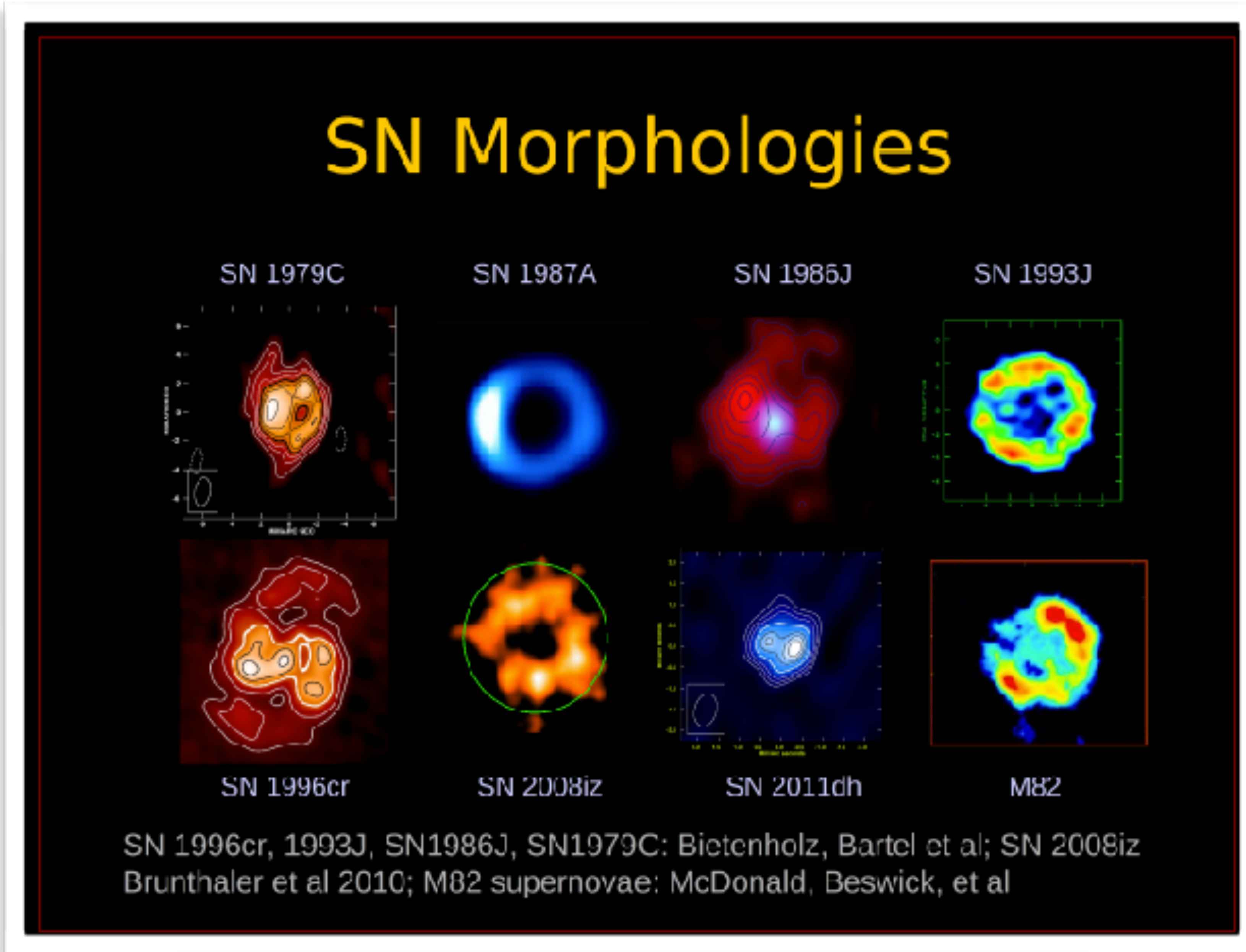


Only very few supernovae are close enough and radio bright enough that the expanding shell of ejecta can be clearly resolved by VLBI observations.

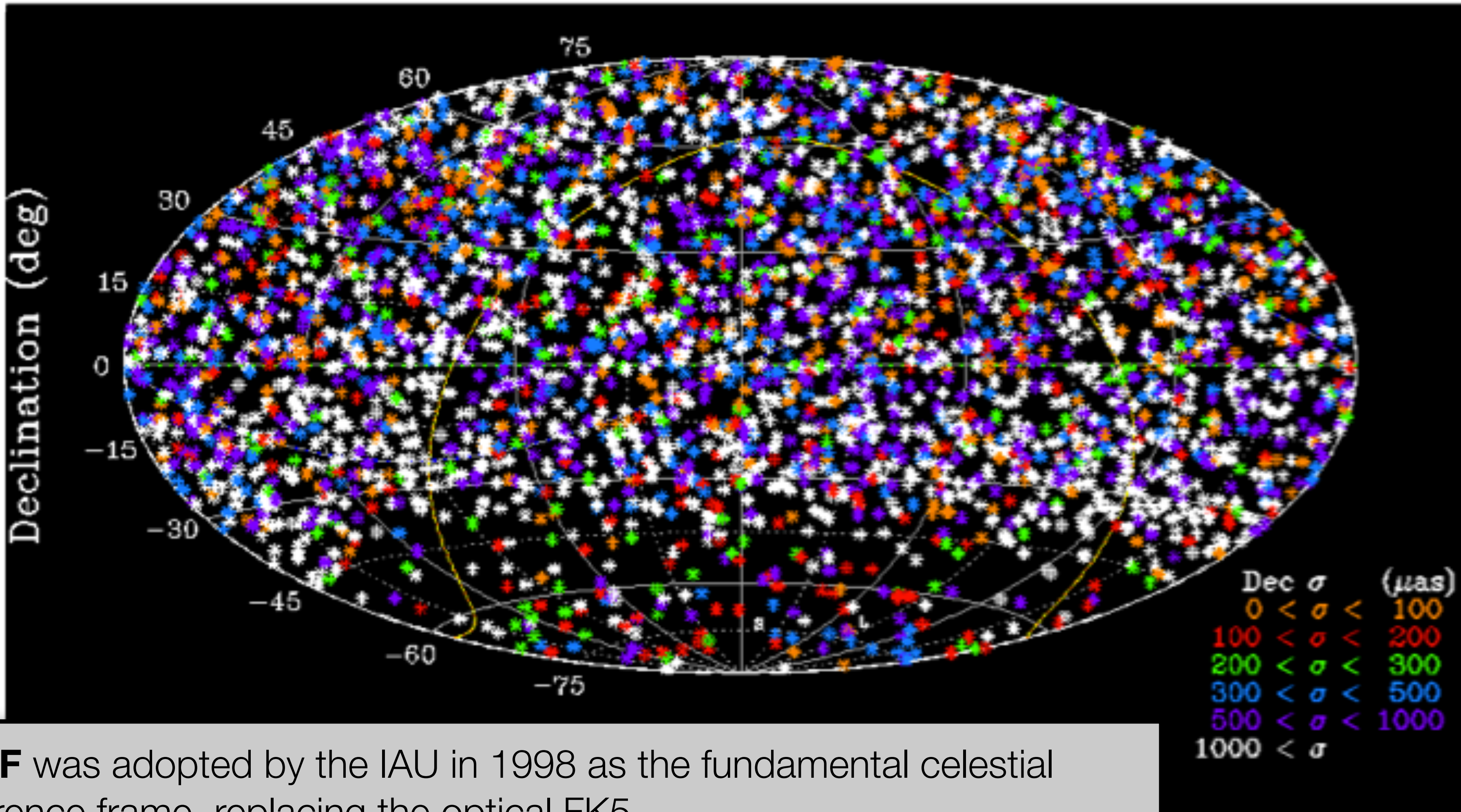
SN 2011dh is one of only a few supernovae for which the shell has been resolved.

SUPERNOVA 2011dh.
VLBA observations at 8.4 GHz.
A circular shell structure is visible, but there is a hot-spot to the west

VLBI: Astronomy



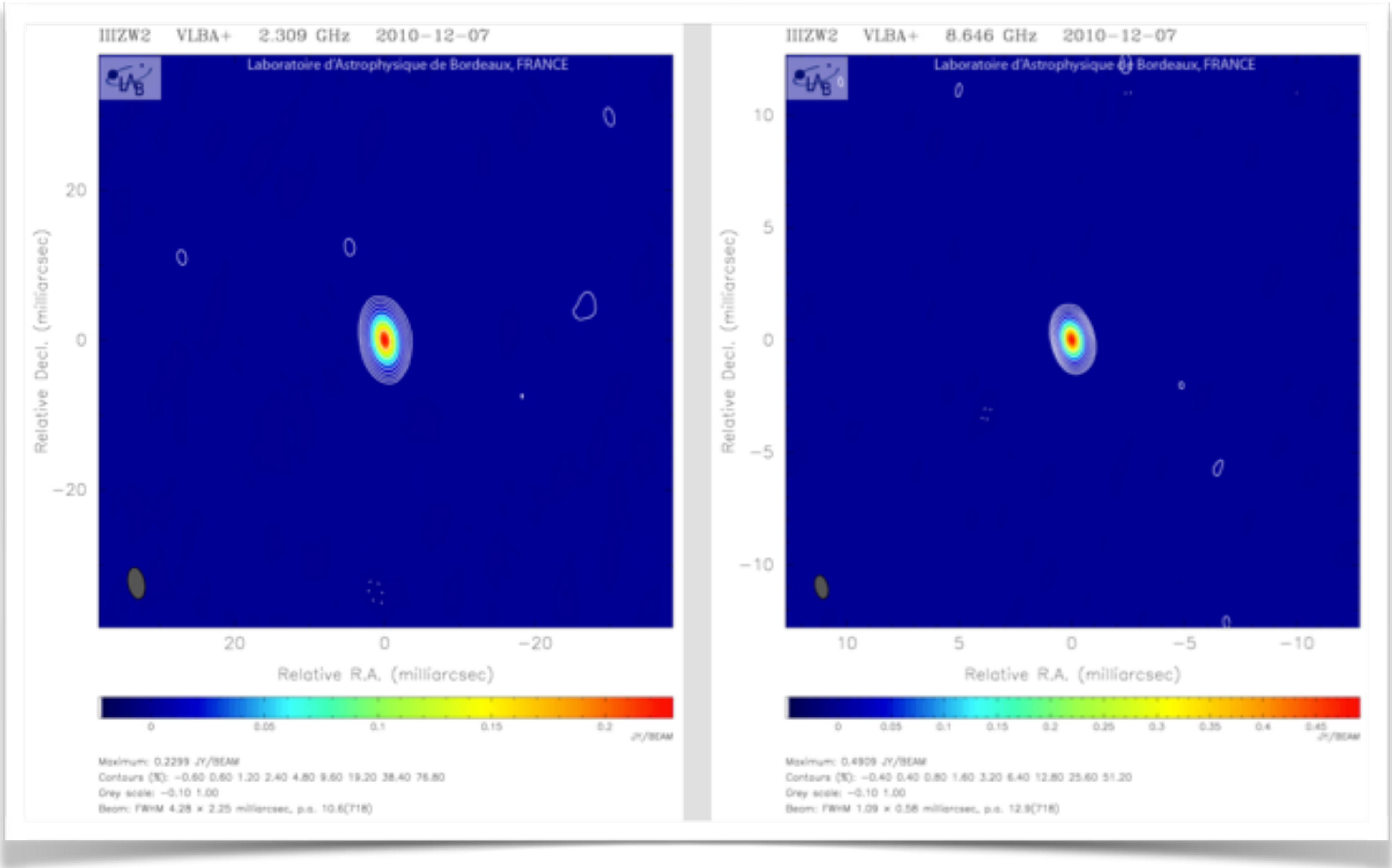
VLBI: Astrometry



- **ICRF** was adopted by the IAU in 1998 as the fundamental celestial reference frame, replacing the optical FK5.
- Since 1 January 2010 the IAU adopted the ICRF-2 including coordinates of 3414 extragalactic sources (AGN's), comprising 295 defining sources.
- ICRF-3 currently being built by a working group of the IAU.

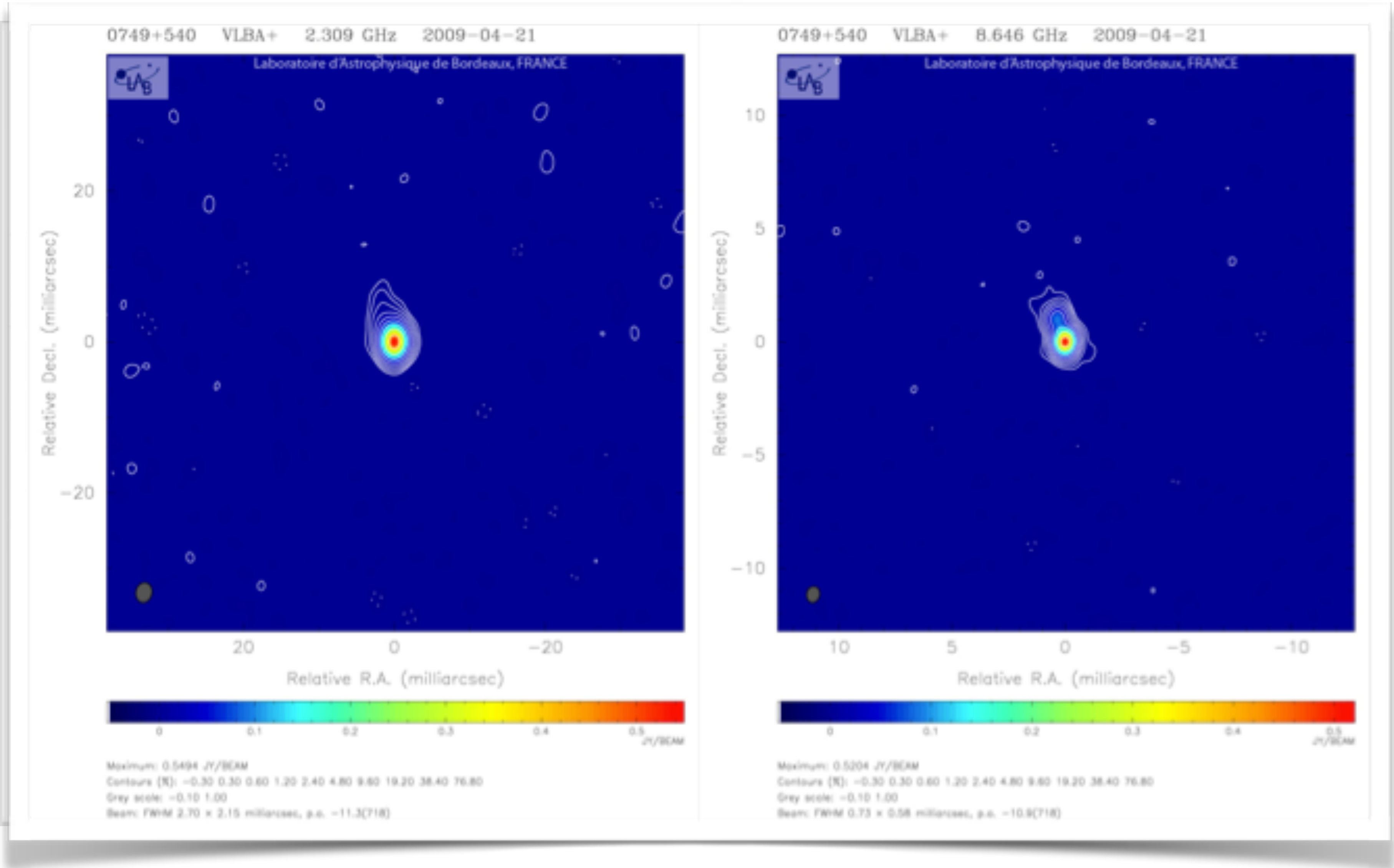
VLBI: Astrometry

- good source



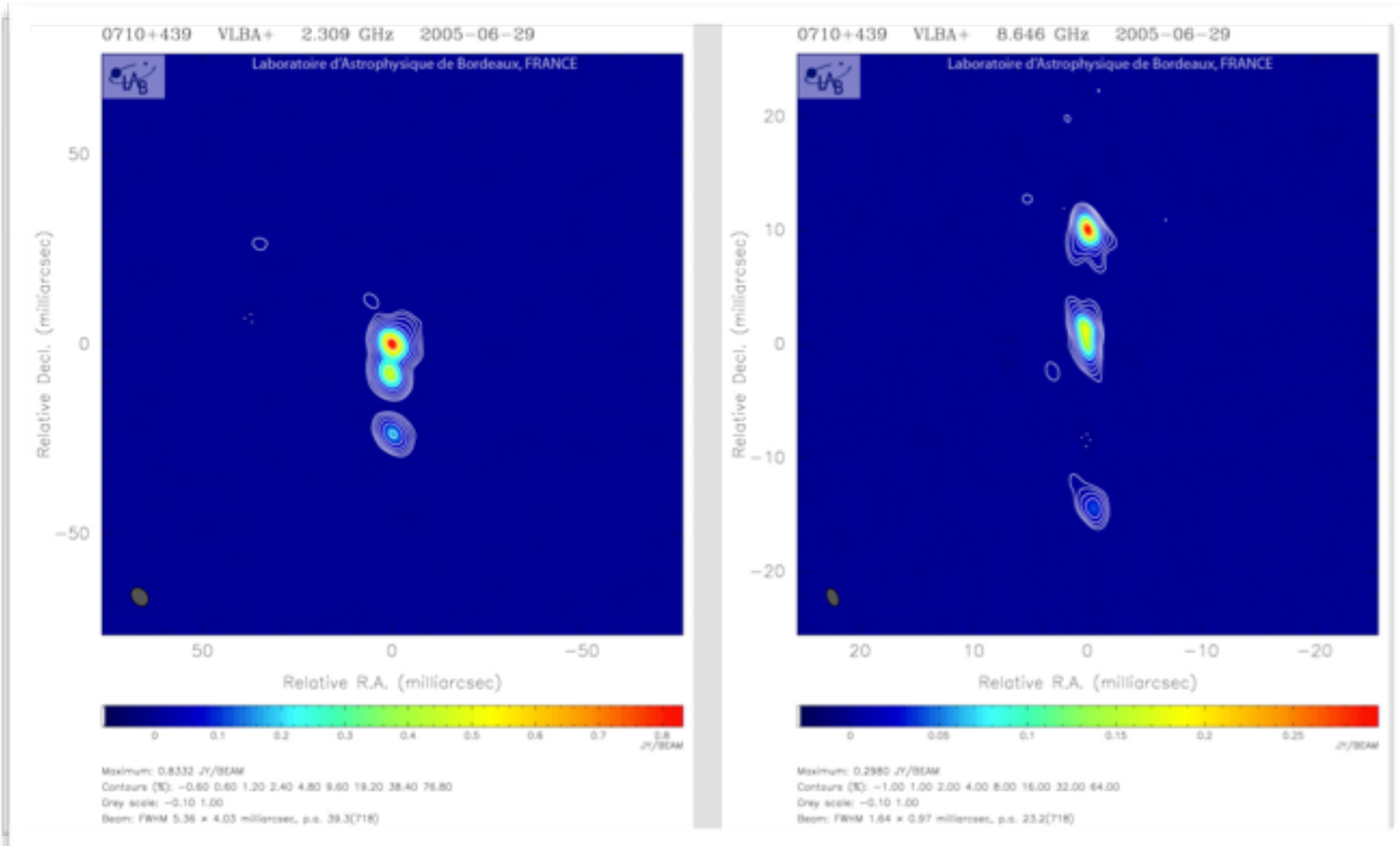
VLBI: Astrometry

- ok source

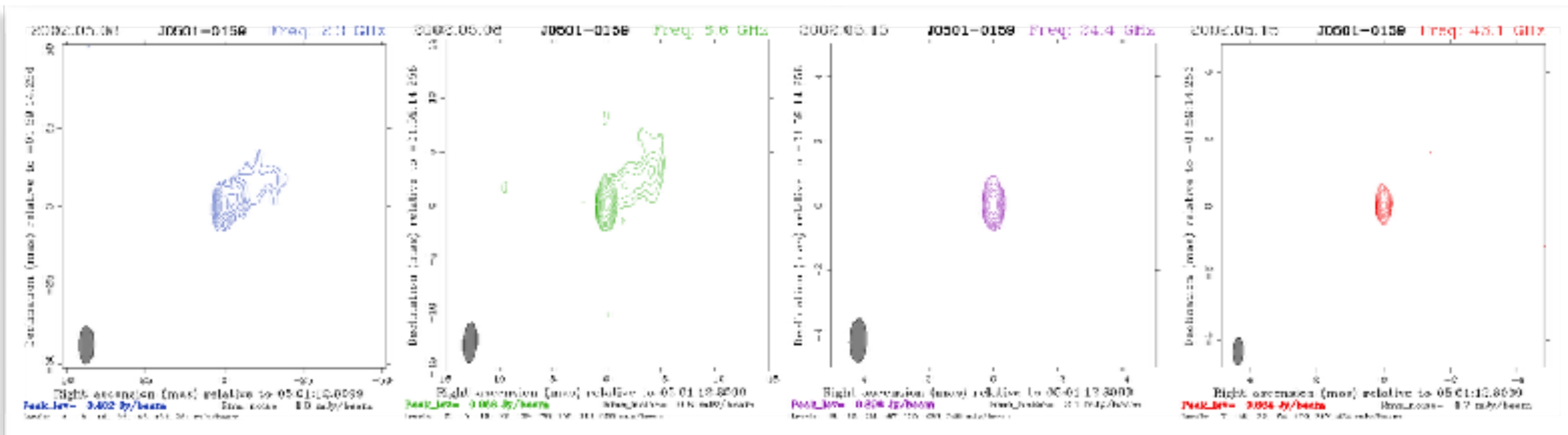


VLBI: Astrometry

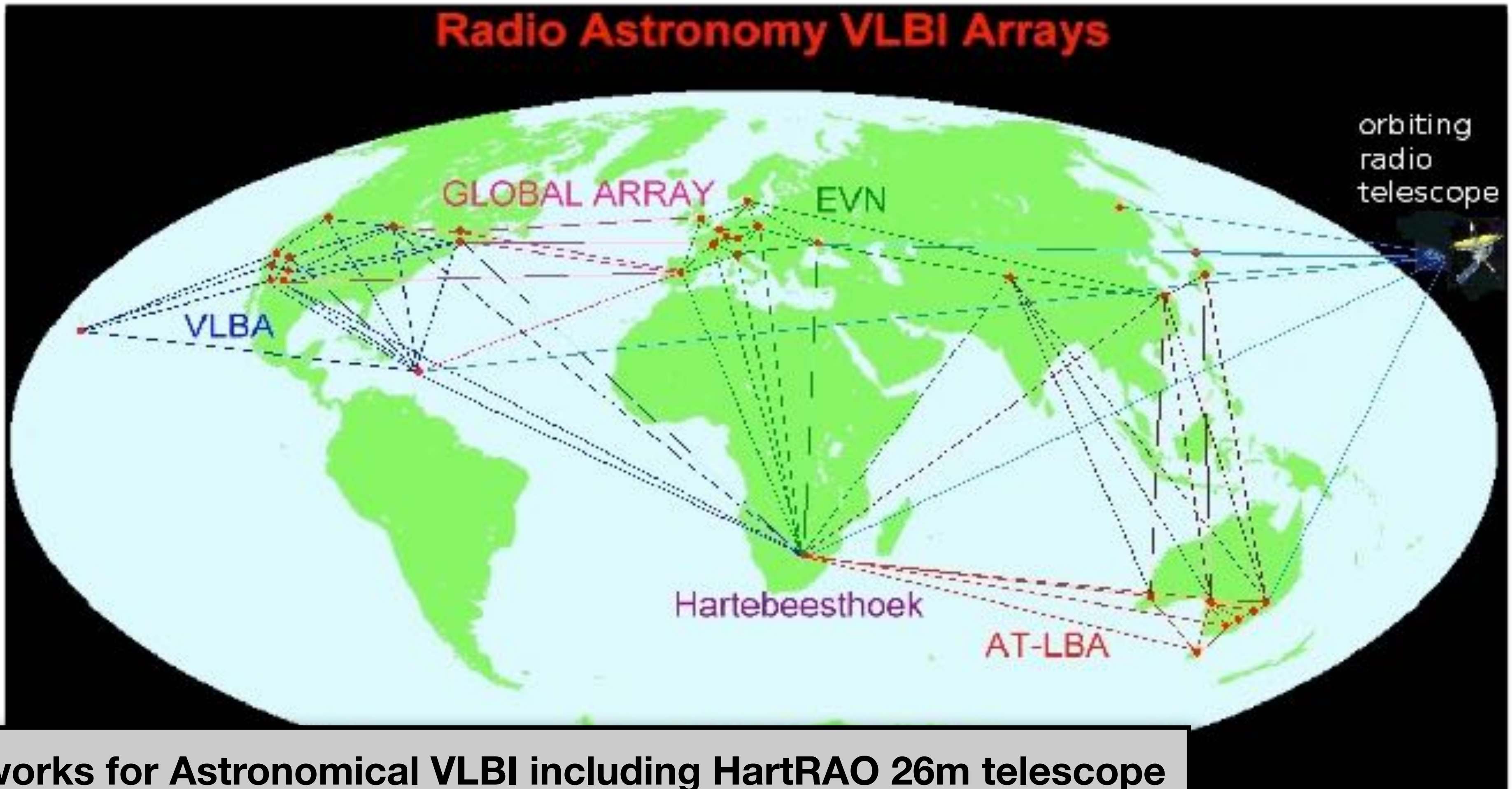
- bad source



VLBI: Astrometry



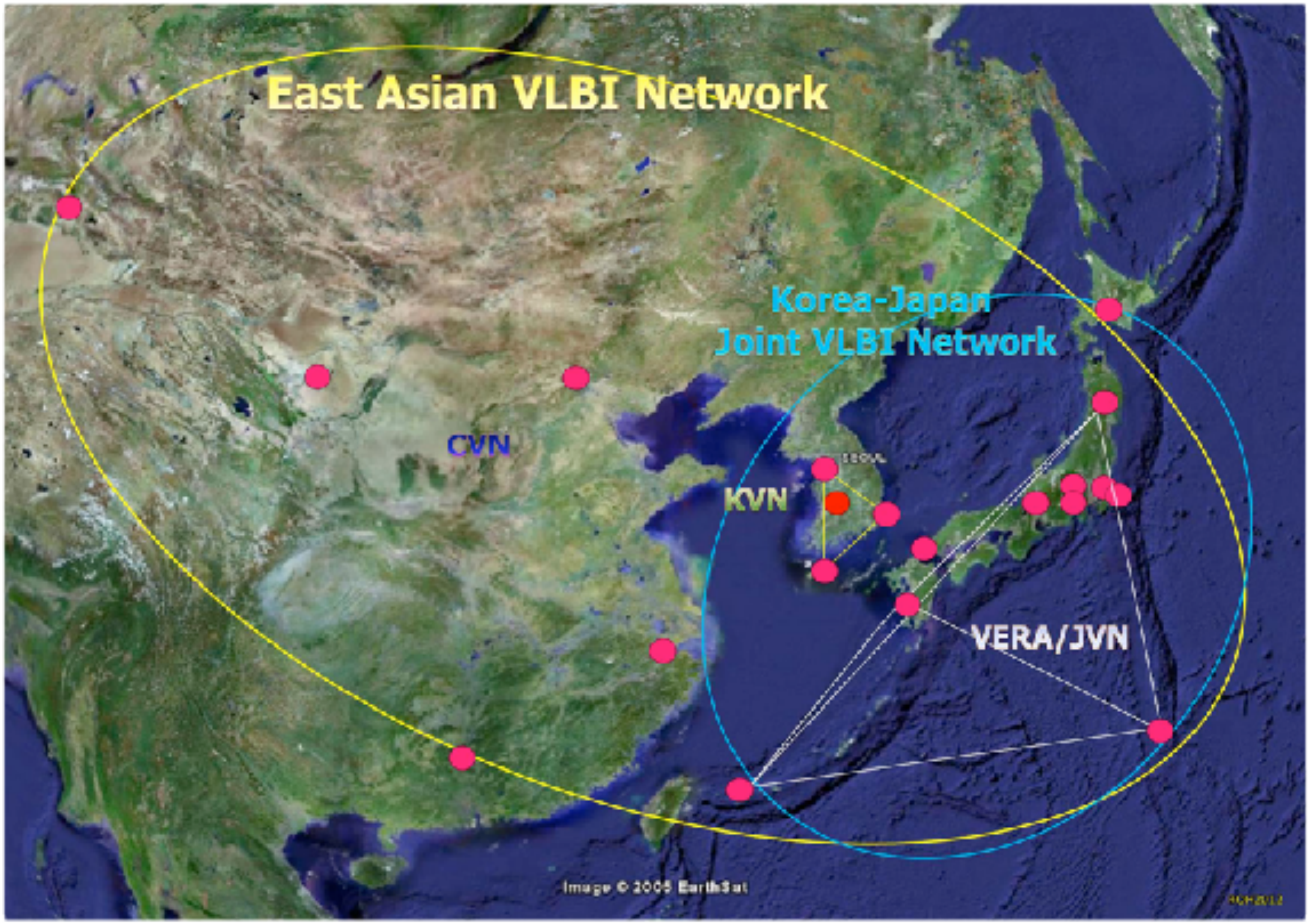
VLBI Networks



Networks for Astronomical VLBI including HartRAO 26m telescope

- EVN: European VLBI Network (eEVN)
- AT-LBA: The Australian Telescope Long Baseline Array
- Global Array: EVN + US VLBA + others
- Space VLBI: RadioAstron

VLBI Networks



EAVN: East Asia VLBI Network (CVN, JVN, KVN)

VLBI: Astrometry

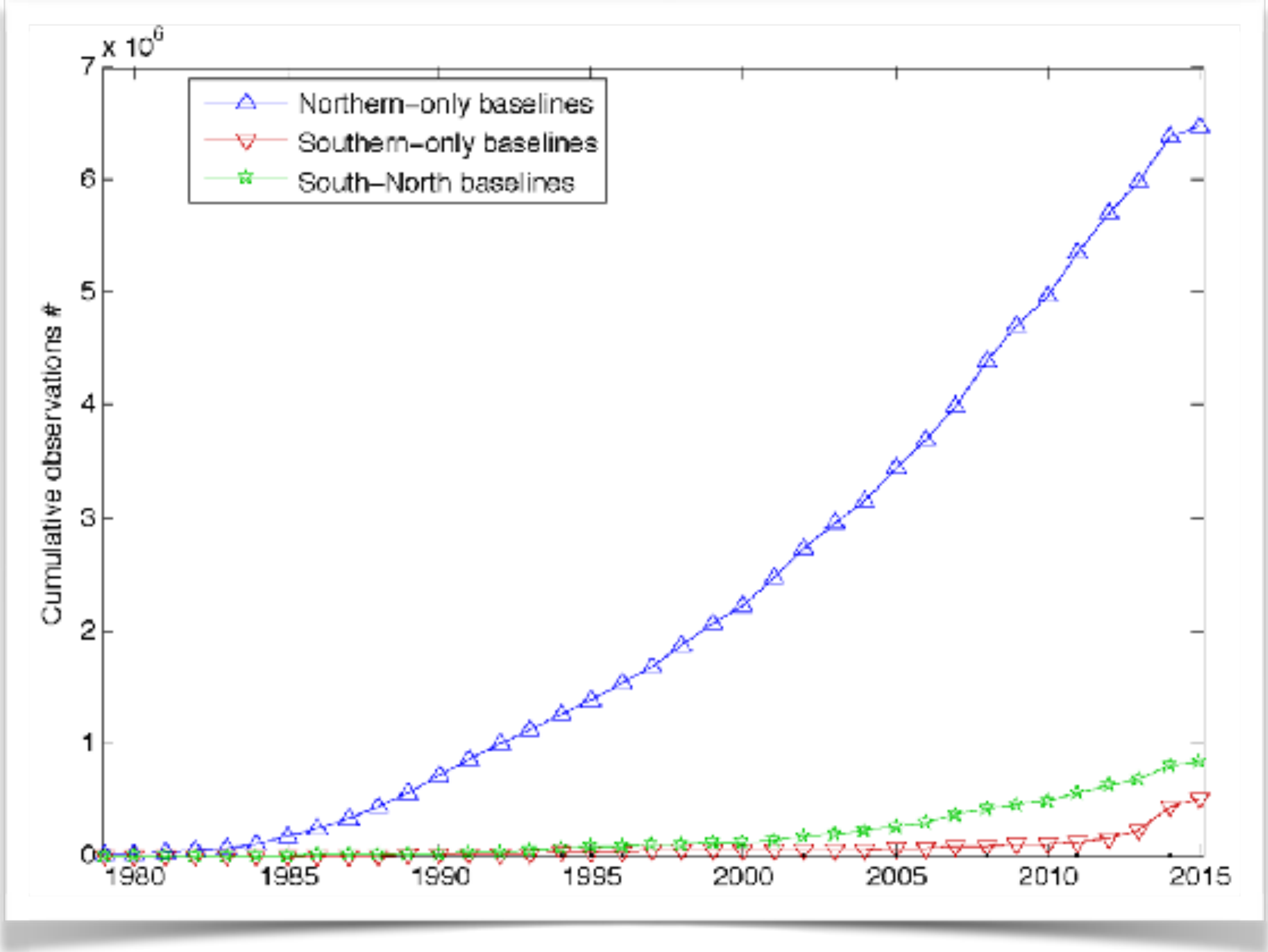


Image Credit: Chopo Ma, NASA/Goddard Space Flight Center

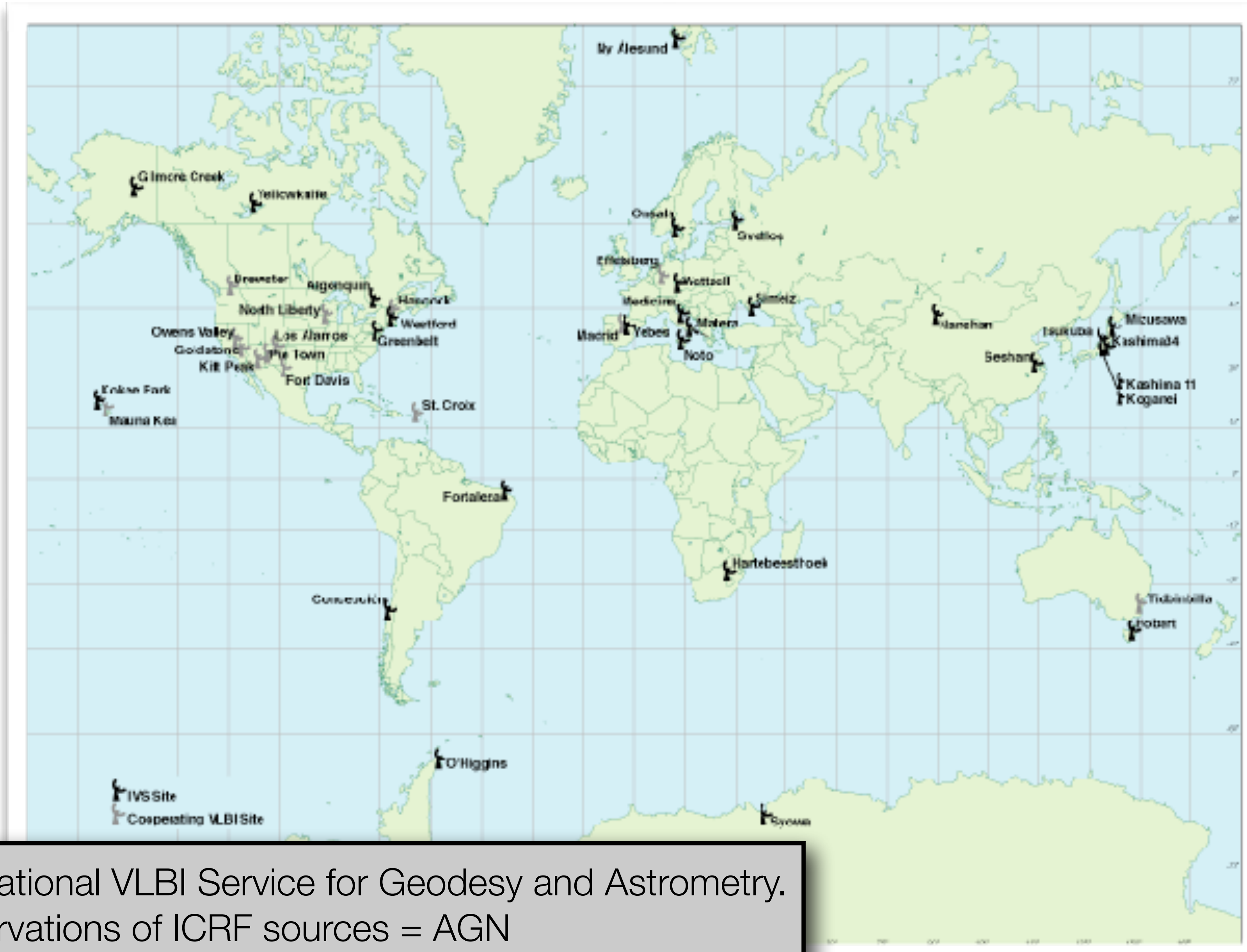
VLBI Networks

- AVN - African VLBI Network (HartRAO and SA SKA project)

1. Start with HartRAO/SA
2. Add countries with available large satellite antennas
3. Add countries with new antennas

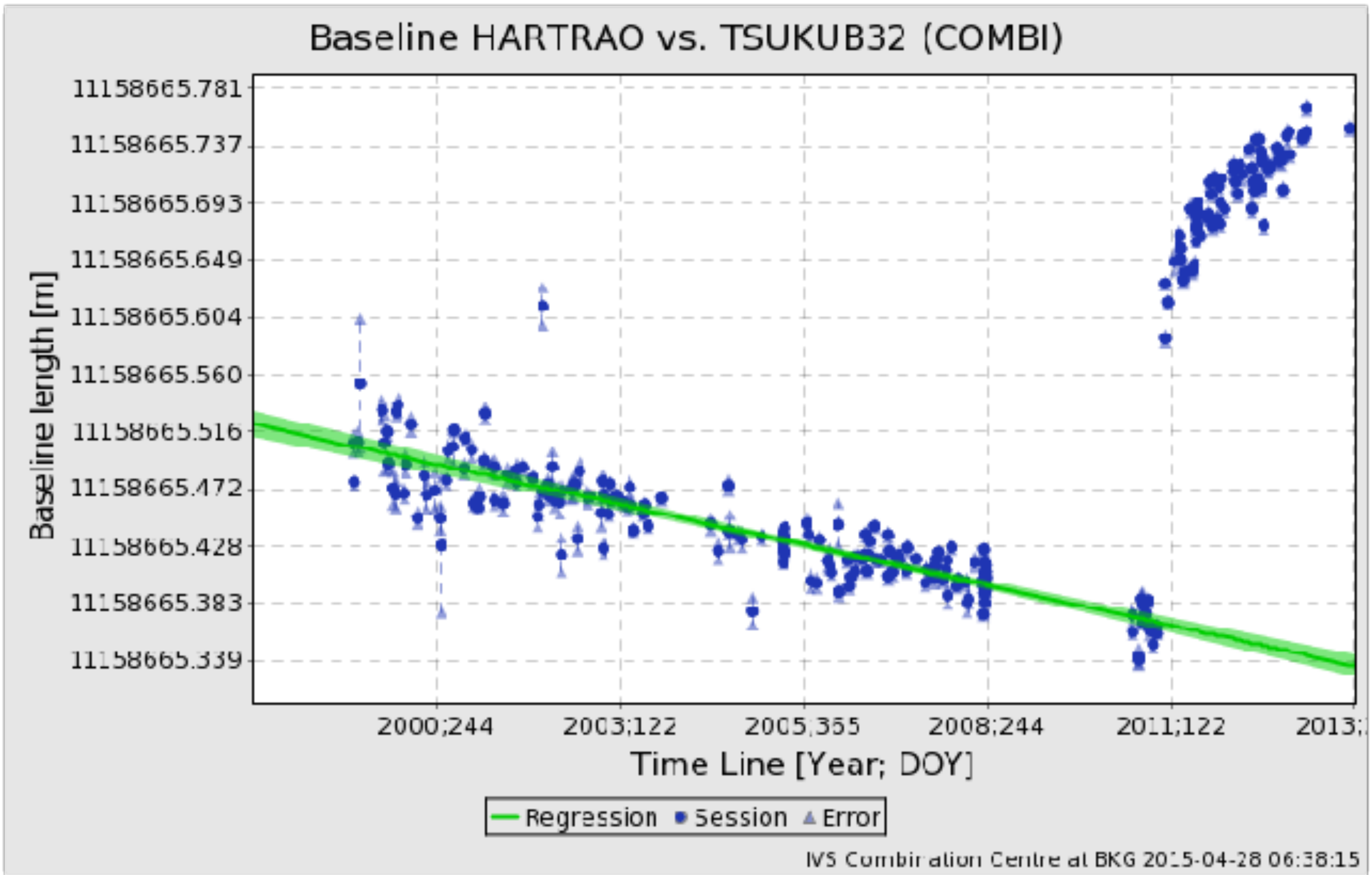
The 32m dish in Ghana shown on the right.

VLBI Networks



IVS: International VLBI Service for Geodesy and Astrometry.
VLBI observations of ICRF sources = AGN

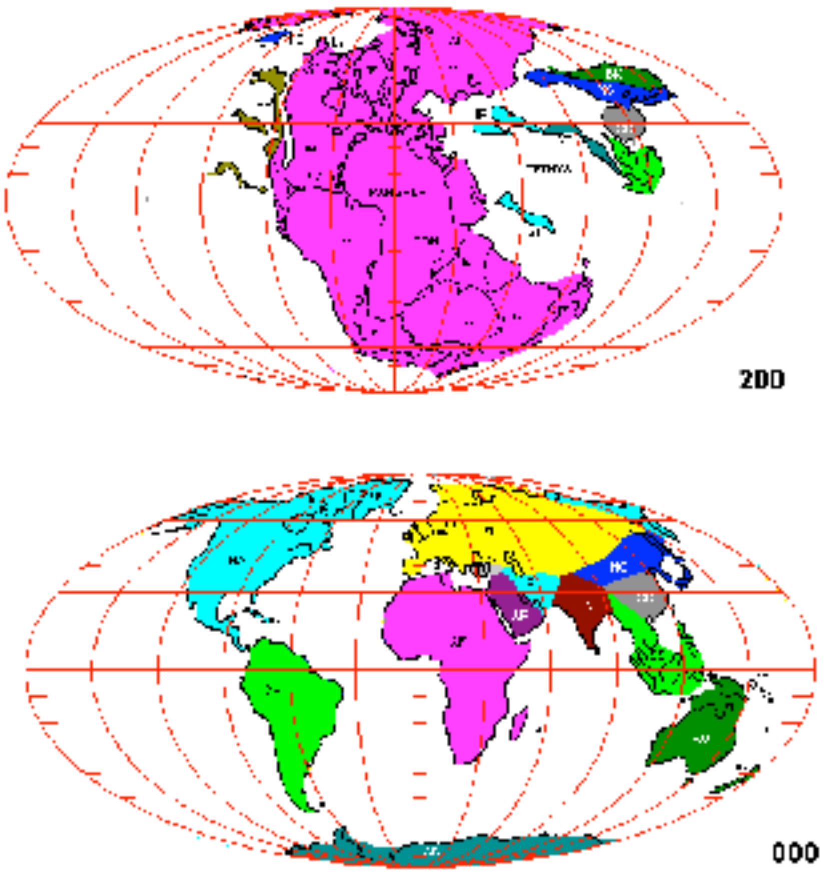
VLBI: Geodesy



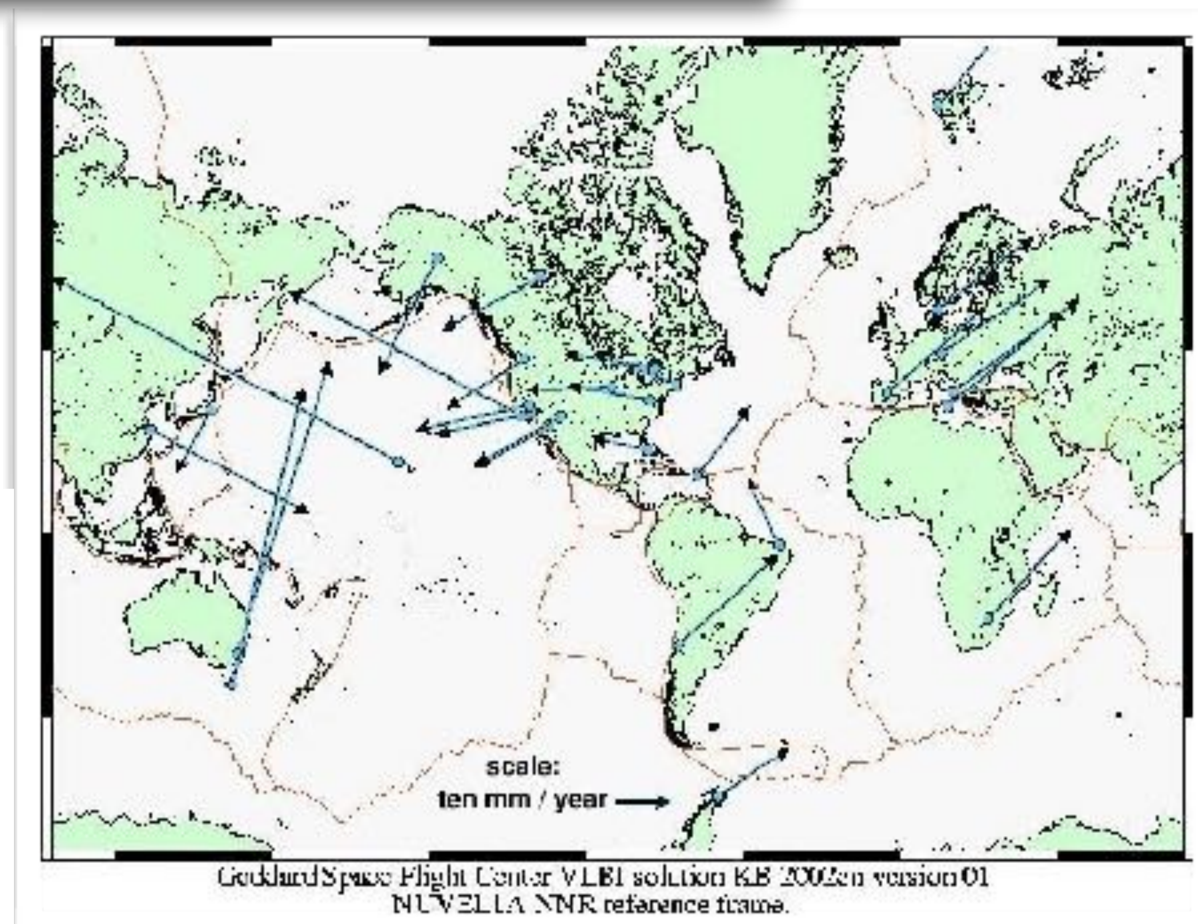
VLBI Measuring Radio Telescope Separations => South Africa – Japan (post-Earthquake)

VLBI: Geodesy

Geodetic VLBI measures continental and regional **plate tectonic motion**



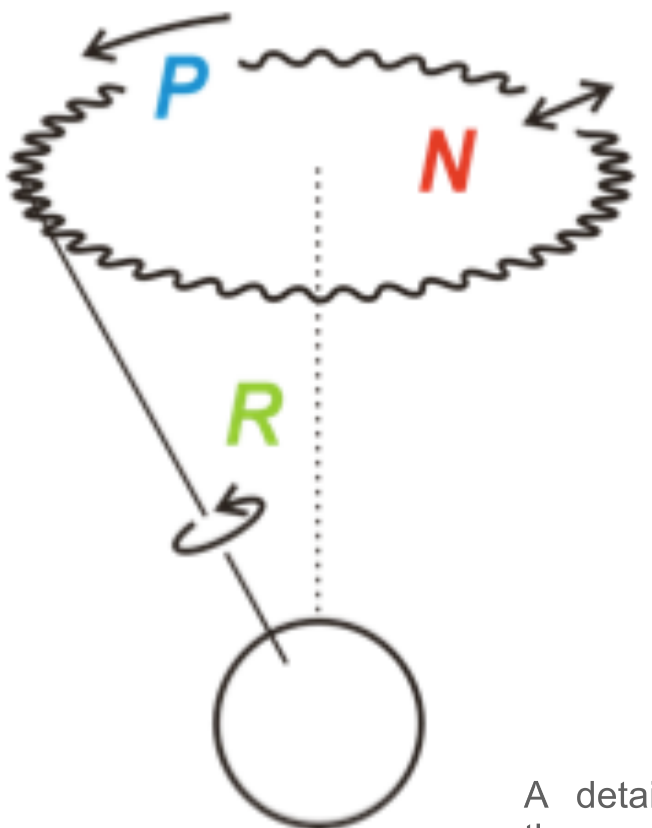
Animation of motion over last 200 Million years, reconstructed by geologists



Present day motion measured by radio telescopes in VLBI global networks. HartRAO is moving North-East at 25mm/ year

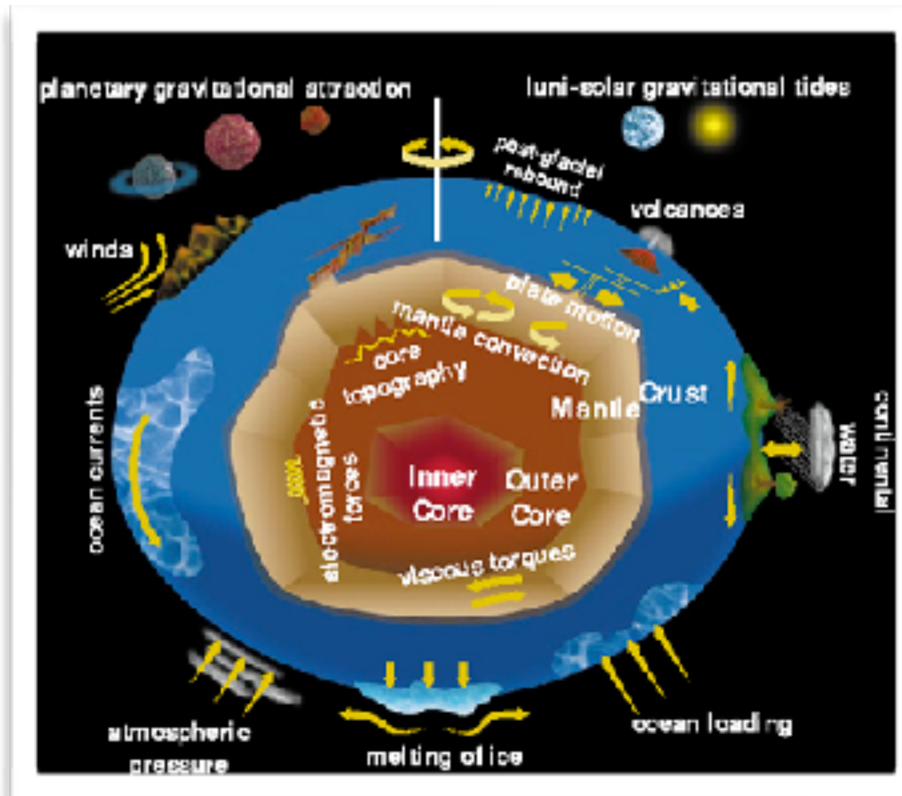
VLBI: Geodesy

Precise VLBI measurements also permit the **orientation of the Earth (EOP's)** to be determined.

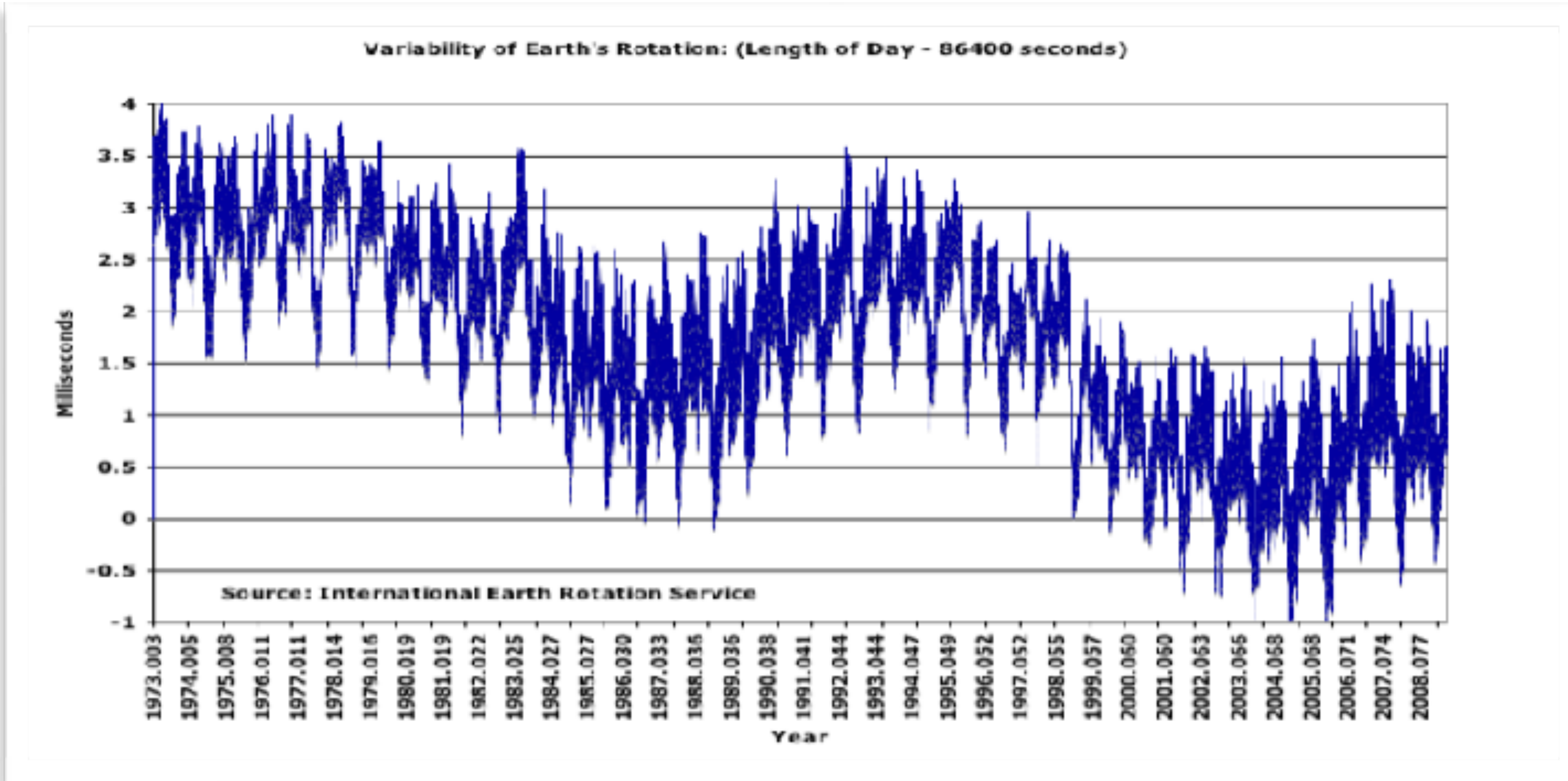


Nutation (N) and Precession (P) can be measured by VLBI as well as changes in the Earth's rotation rate (R) (length of the day also referred to as "UT1")

A detailed description of the causes for variations on the Earth's Orientation and rotation rate include:



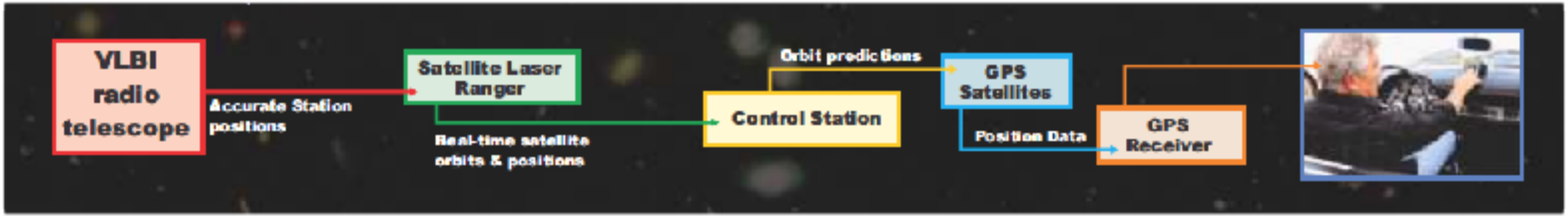
VLBI: Geodesy



VLBI measurements show that the Earth's rotation rate is slowing => the length of the day is increasing

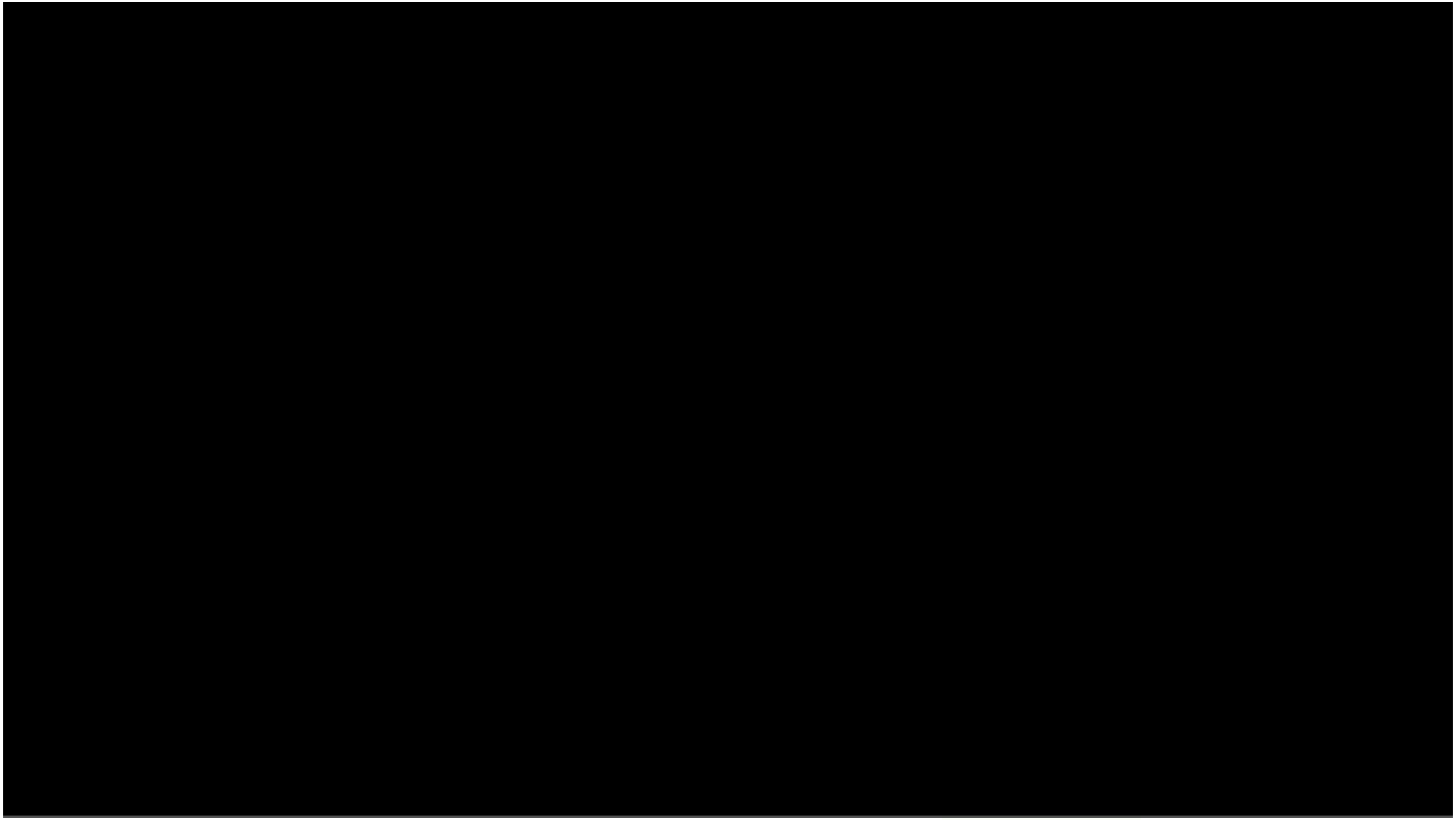
The length of an Earth day has distinct small-scale variations, changing by about one thousandth of a second over the course of a year. Roughly every 100 years, the day gets about 1.4 milliseconds longer.

VLBI: Geodesy



Knowledge of the Earth's rotation rate is also required for precision navigation (GPS).

VLBI: Geodesy

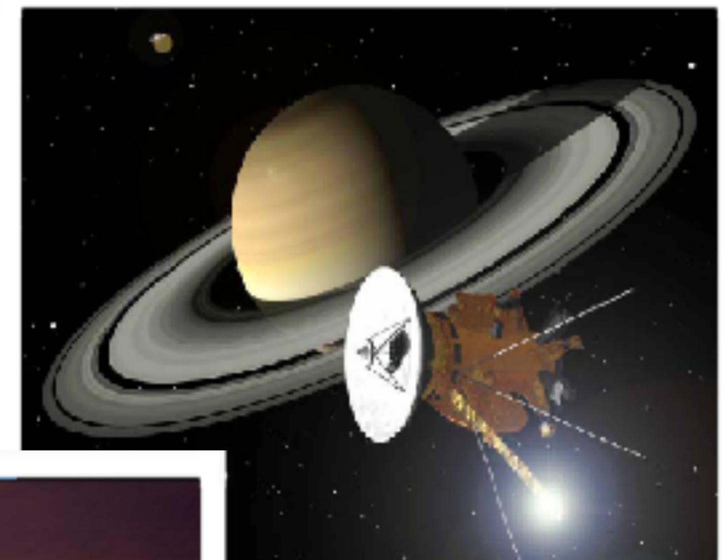


Differential VLBI for Deep Space Tracking

Track spacecraft in 2-dimensions on the sky by measuring difference position to nearby quasar

Abandoned by NASA in 1980's; reinstated after losing two spacecraft on Mars

Also saved the day for the Huygen's probe to Saturn's moon Titan



Cassini-Huygens probe to Saturn (14 January 2005)

Huygens probe parachuting to Titan

Geodesy

- **Satellite Laser Ranger (SLR)** for precise orbit determination (cm accuracy) as part of the International Laser Ranging Service **(ILRS).** The SLR measures the time it takes for a pulse of laser light to travel to a satellite and back again.

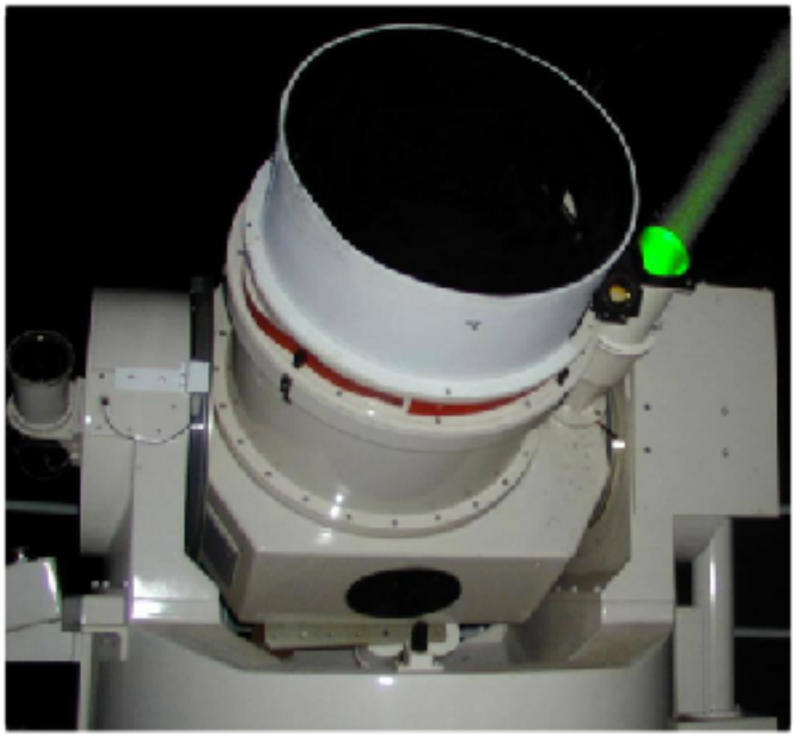
- **Lunar Laser Ranger (LLR)** measures the distance between the Earth and the Moon. Lasers on Earth are aimed at special mirrors placed on the moon during the Apollo and other programmes.

- **Seismometer** for measuring seismic events

- **Gravimeter** for measuring Earth's changing gravity field, ties in with precise position measuring systems

- **Global Navigation Satellite Systems (GNSS),** GNNS satellites like GPS transmit radio signals that let us measure the **positions of receivers** on the ground to within a few millimetres, and their change with time. Measure **atmospheric water vapour content** – provides corrections for radio astronomy data & data for weather predictions. Measure the **total electron content** of the ionosphere – ionospheric science, space weather, HF radio communication prediction.

Geodesy



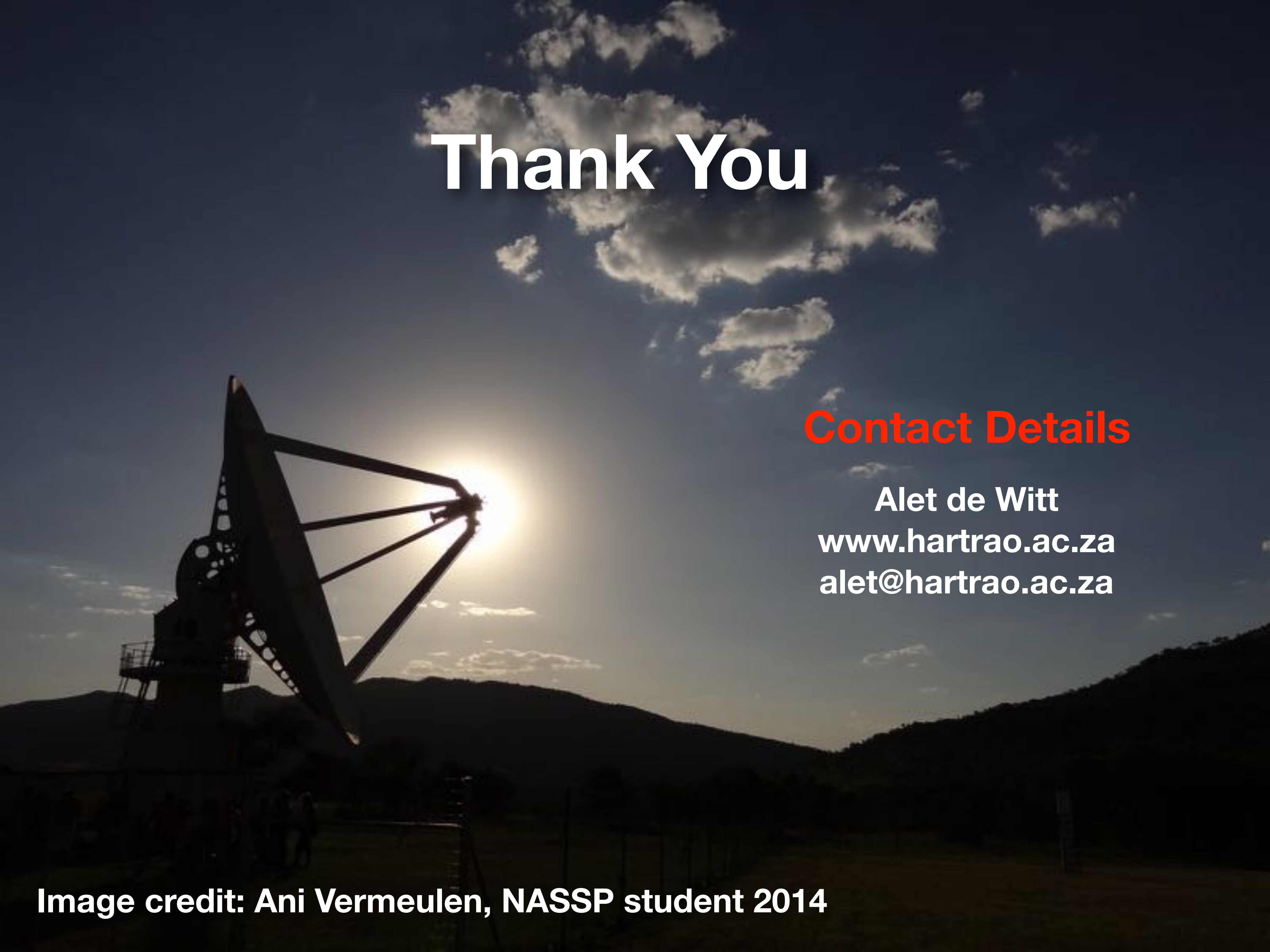
HartRAO/NASA **Satellite Laser Ranger**
New Russian SLR !

HartRAO
Lunar Laser Ranger

Global Navigation Satellite System (GNSS) receivers for GPS, GLONASS and Galileo, at HartRAO and at other locations, for geodesy

Gravimeter, Seismometer
Seismic network across SA, Gough and Marion island: 10 additional seismic stations.

Gough Island **Tide Gauge** installed.



Thank You

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Image credit: Ani Vermeulen, NASSP student 2014