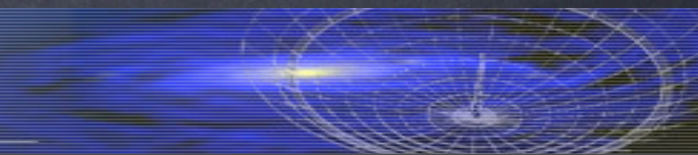


Introduction to Radio Interferometers

Mike Garrett (ASTRON/Swinburne)

Overview of Lecture

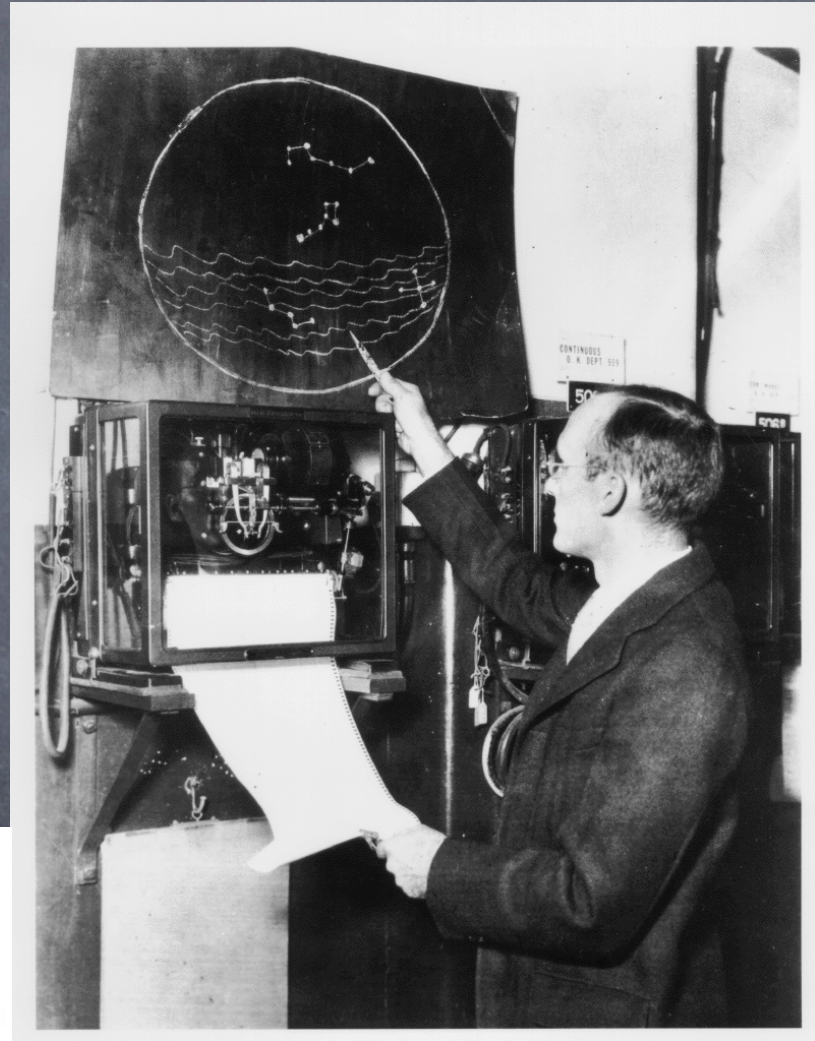
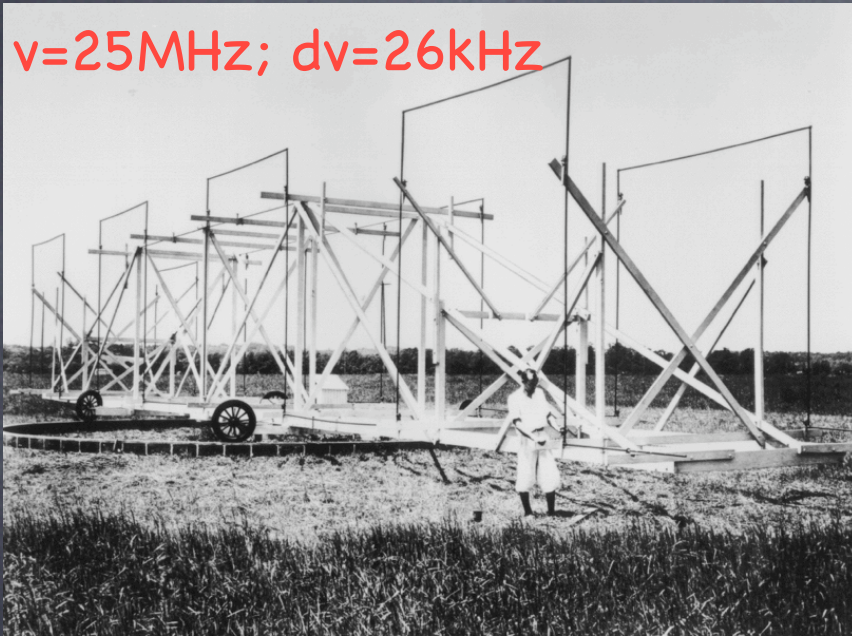
- Early radio astronomy
 - what makes radio astronomy "special"!
- Radio Interferometry
 - early days and motivation
- Interferometer arrays
 - metre, cm, mm and sub-mm wavelengths
- Types of object we can study - science
- The Future is VERY, VERY, VERY bright!



Early days of radio astronomy

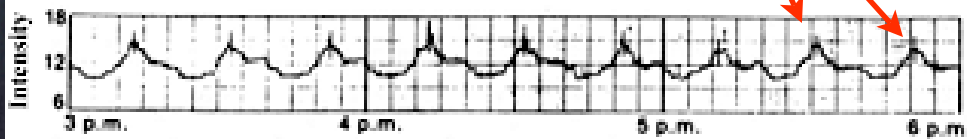
👁️ 1932 Discovery of cosmic radio waves (Karl Jansky)

$\nu = 25\text{MHz}$; $d\nu = 26\text{kHz}$



Galactic centre

20.5 MHz Recording 16 Sept 1932



The first radio astronomer (Grote Reber)

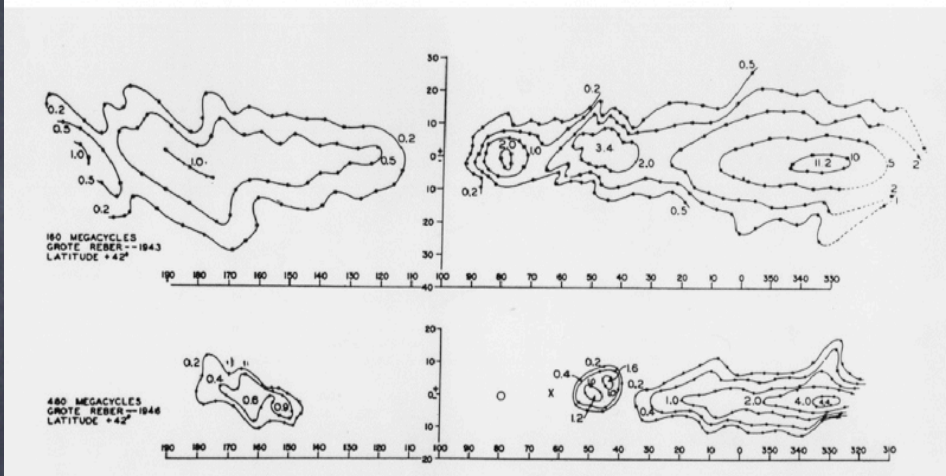
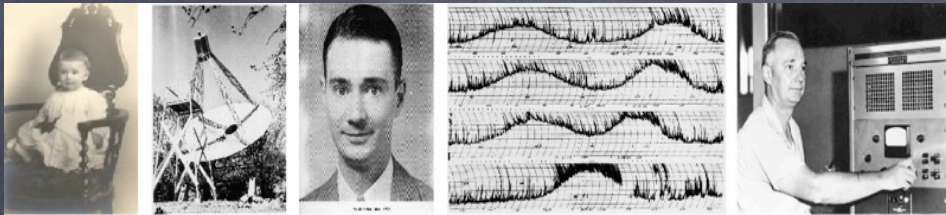
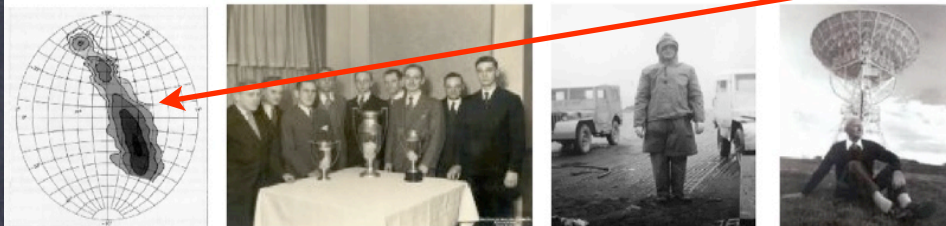
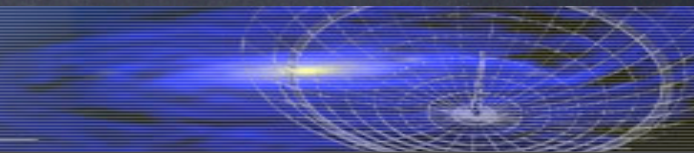


Fig. 7.—Contours of constant intensity at 160 MHz and 480 MHz, taken at Wheaton, Illinois.



- Built the first radio telescope
- "Good" angular resolution
- Good visibility of the sky
- Detected Milky Way, Sun, Cas-A, Cyg-A, Cyg-X @ 160 & 480 MHz (ca. 1939-1947).
- Published his results in ApJ
- Multi-frequency observations



The first radio astronomer (Grote Reber)

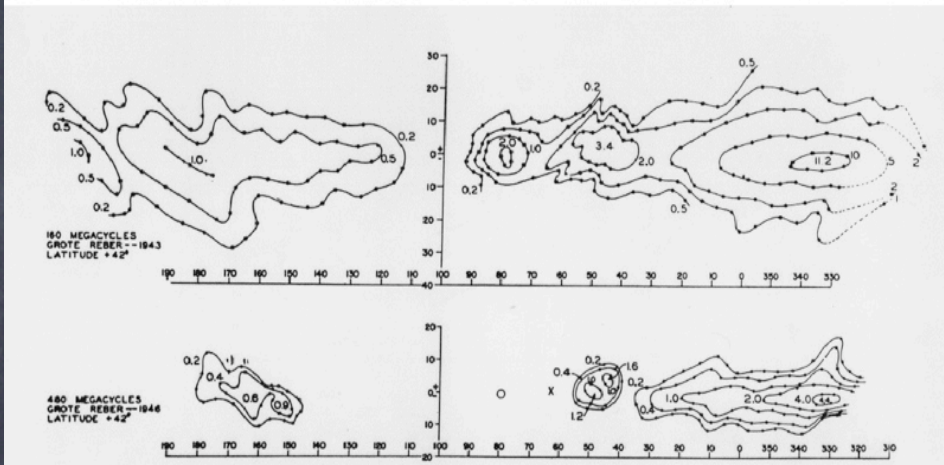
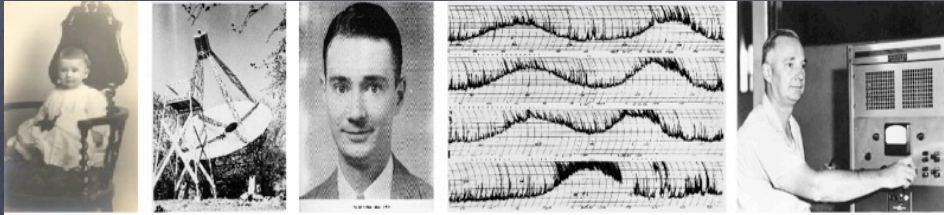
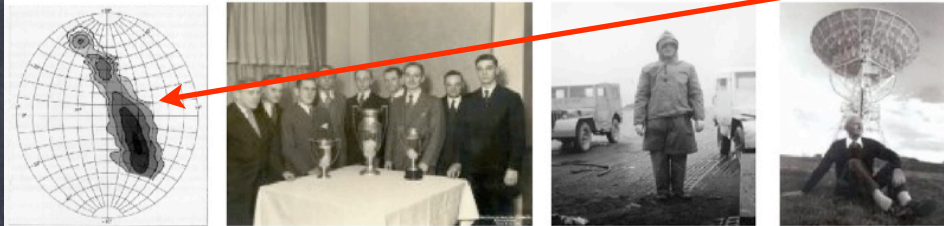
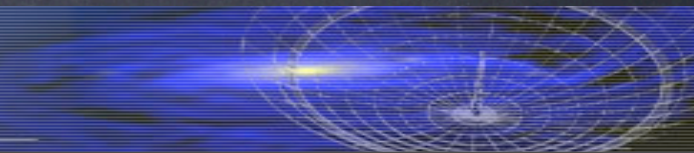


Fig. 7.—Contours of constant intensity at 160 MHz and 480 MHz, taken at Wheaton, Illinois.

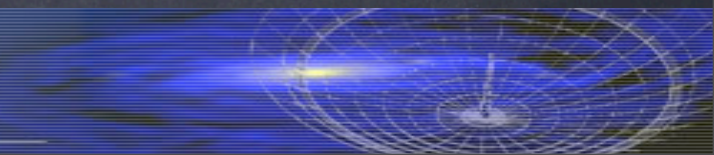
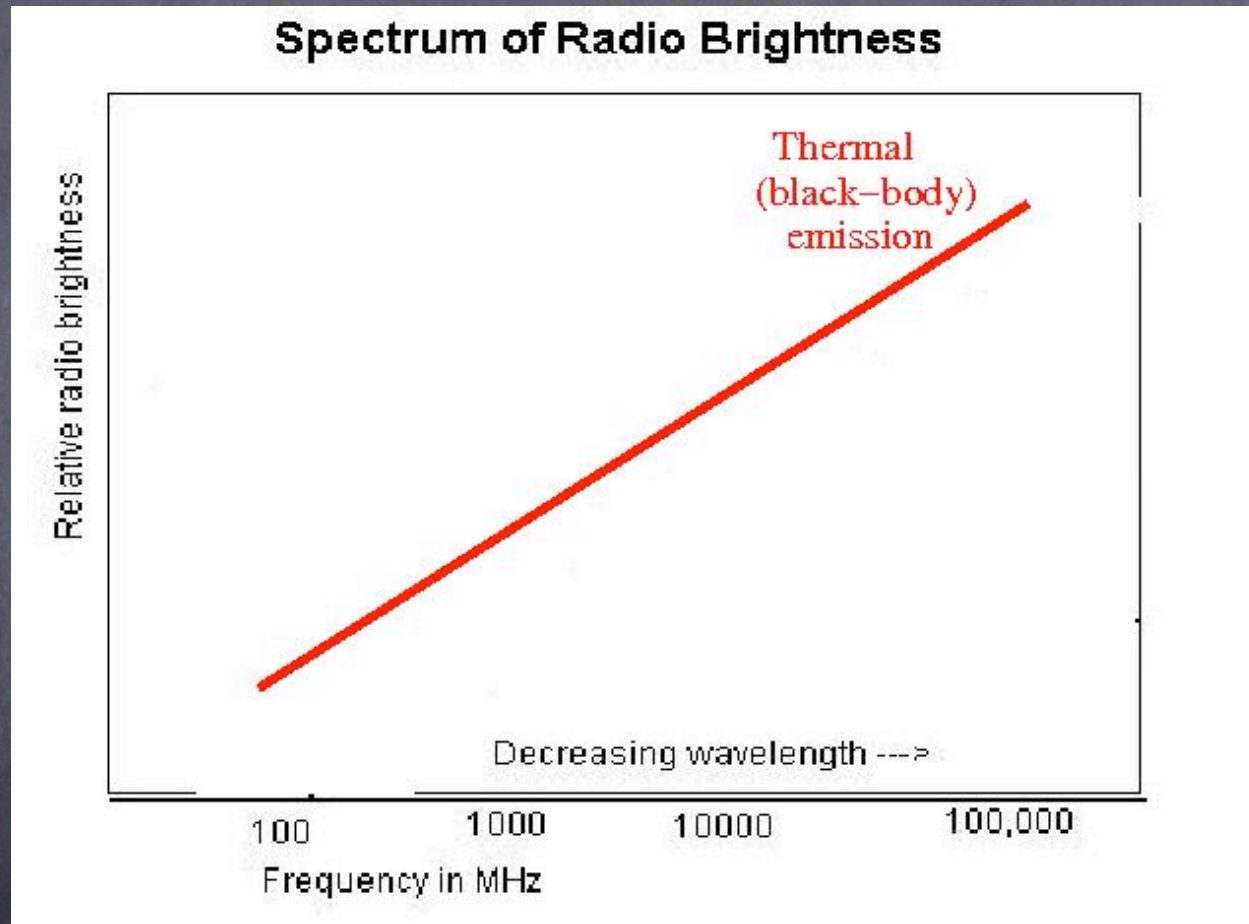


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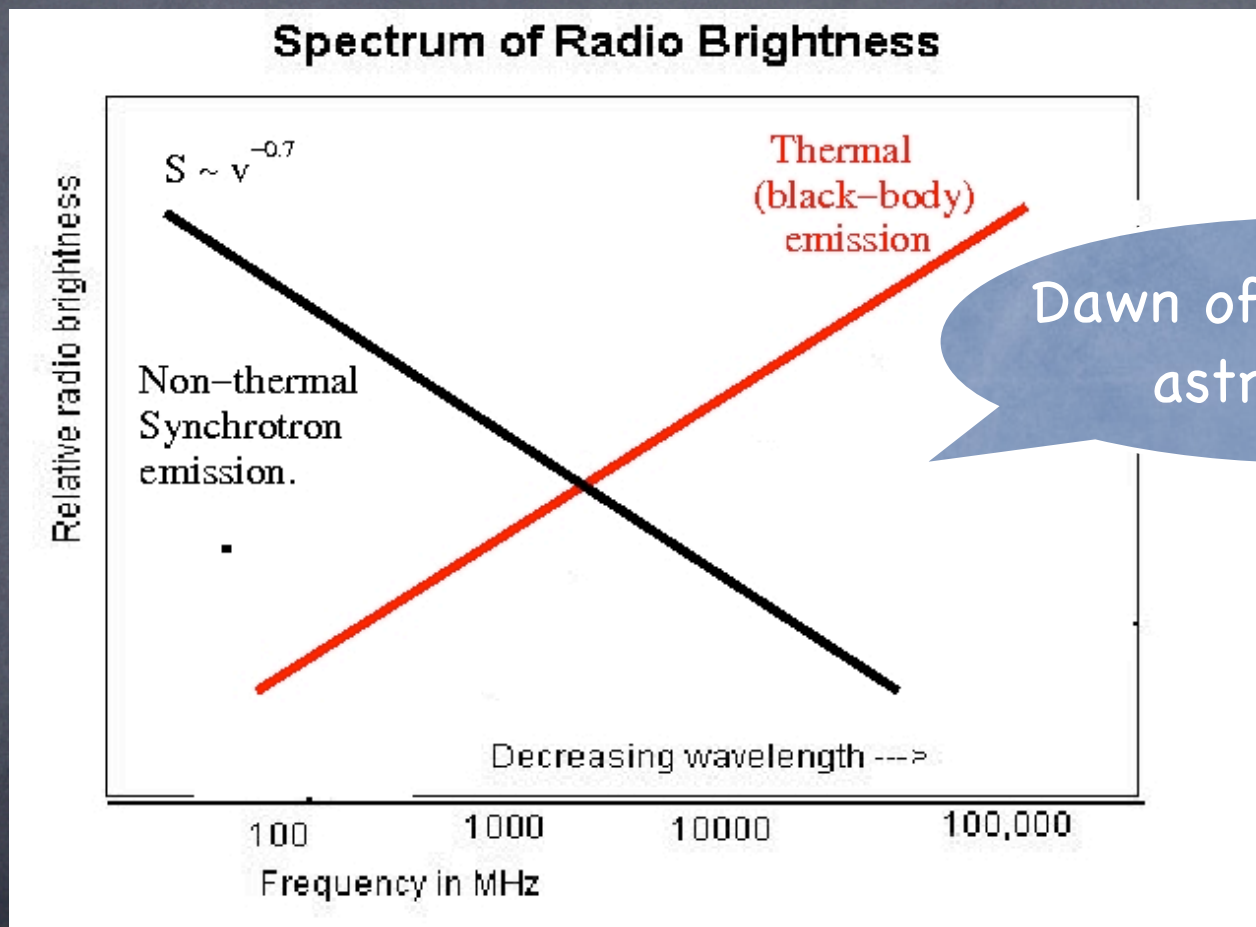
The things that make radio astronomy "special"

- Reber's multi-frequency observations revealed the non-thermal nature of radio emission (UNEXPECTED!)



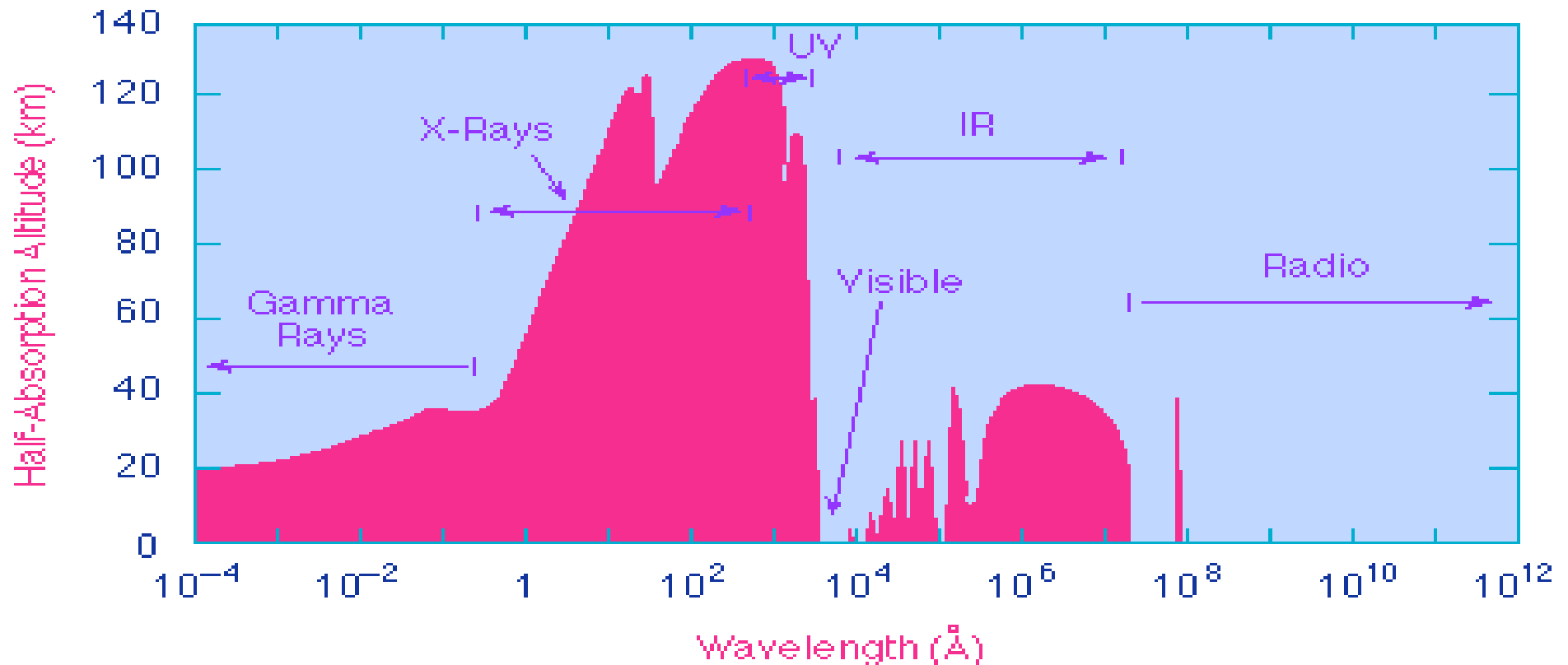
The things that make radio astronomy "SPECIAL"

- Rebers multi-frequency observations revealed the non-thermal nature of radio emission (UNEXPECTED!)



A new transparent window on the Universe

- Radio window covers 5 decades of freq/wavelength:

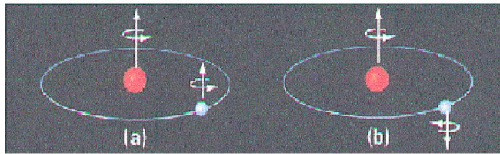


- SPECIAL:** Radio waves largely unaffected by dust...
 - > Can observe Day and Night!
 - > Studies of the Early Universe possible.

Radio Spectral-lines

- 1944: van der Hulst predicts discrete 1420 MHz (21 cm) emission from neutral Hydrogen (HI).

INTERSTELLAR HYDROGEN

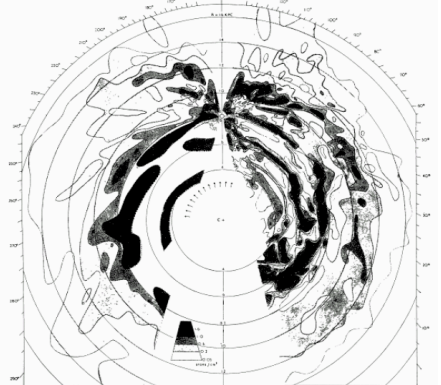


HYPERFINE STRUCTURE OF THE GROUND STATE

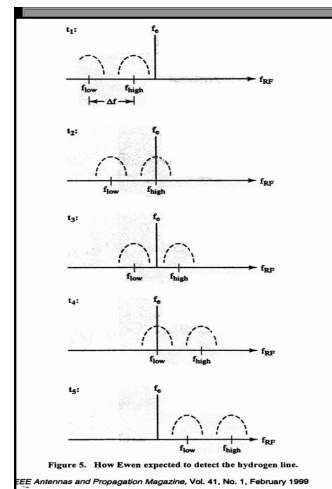
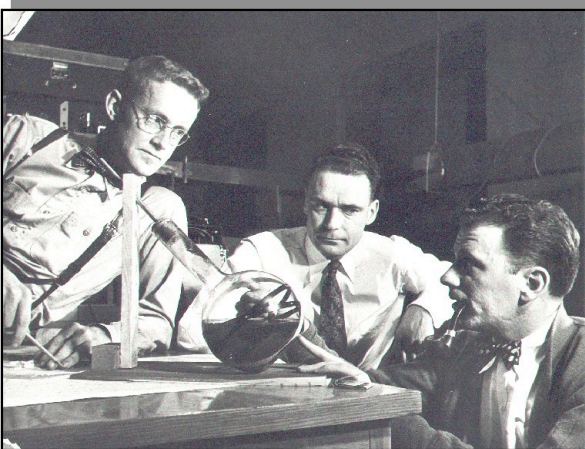
1951



Wurzburg "Riese" Radar Antenna, 7.5 m diameter



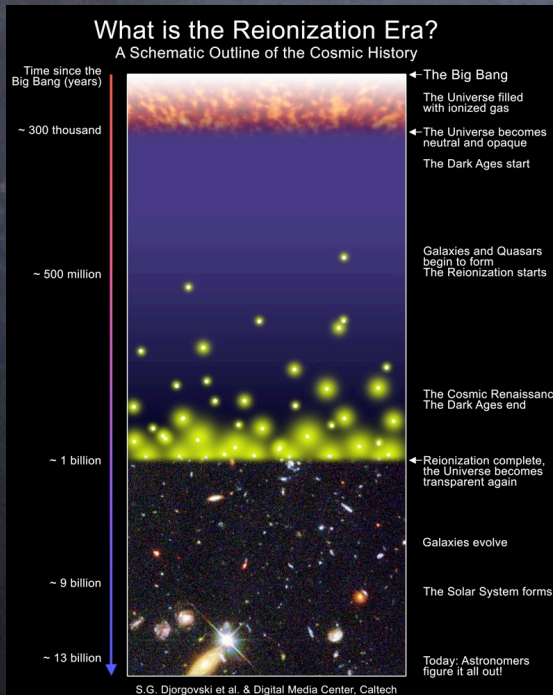
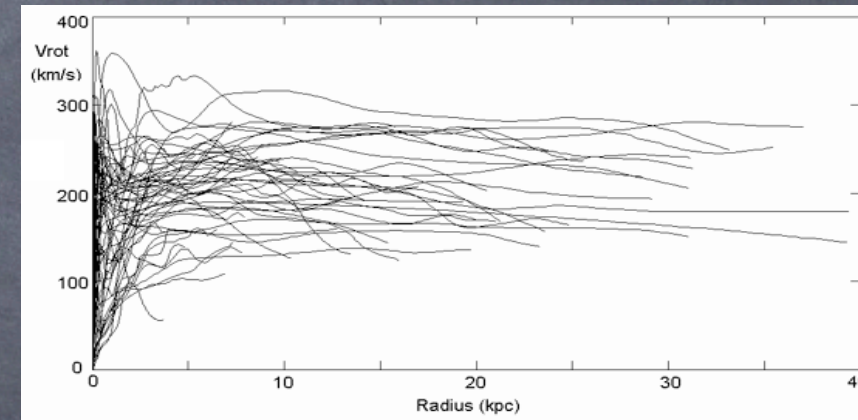
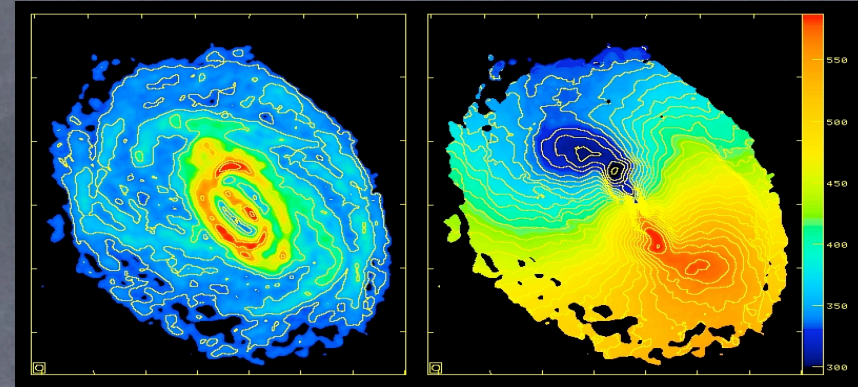
- Detected by Ewen & Purcell (1951):



SPECIAL - HI - most abundant element in the Universe!

Gas DYNAMICS:

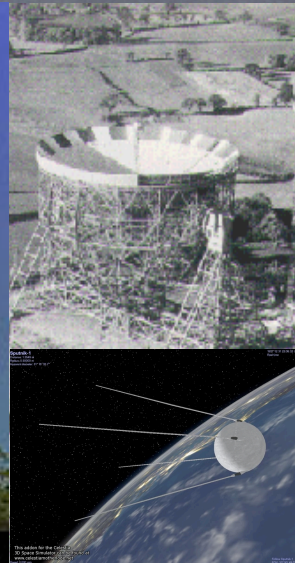
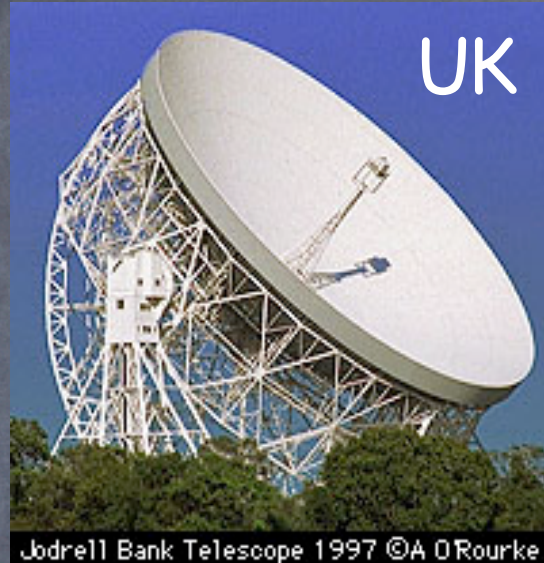
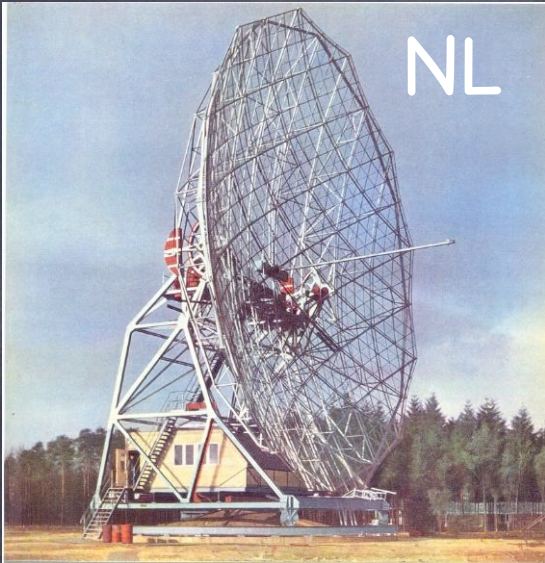
- Scale/Structure of the Milky Way
- Tracing Dark Matter in other galaxies



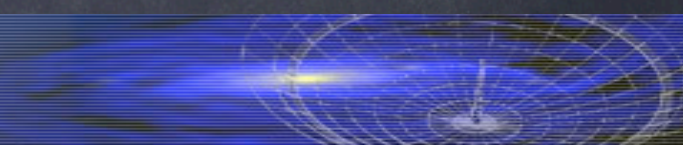
— The Dark Ages...

1950-60's: Construction of Large Telescopes

cm wavelengths:



(NETHERLANDS FOUNDATION FOR RESEARCH IN ASTRONOMY)



The need for better ANGULAR RESOLUTION

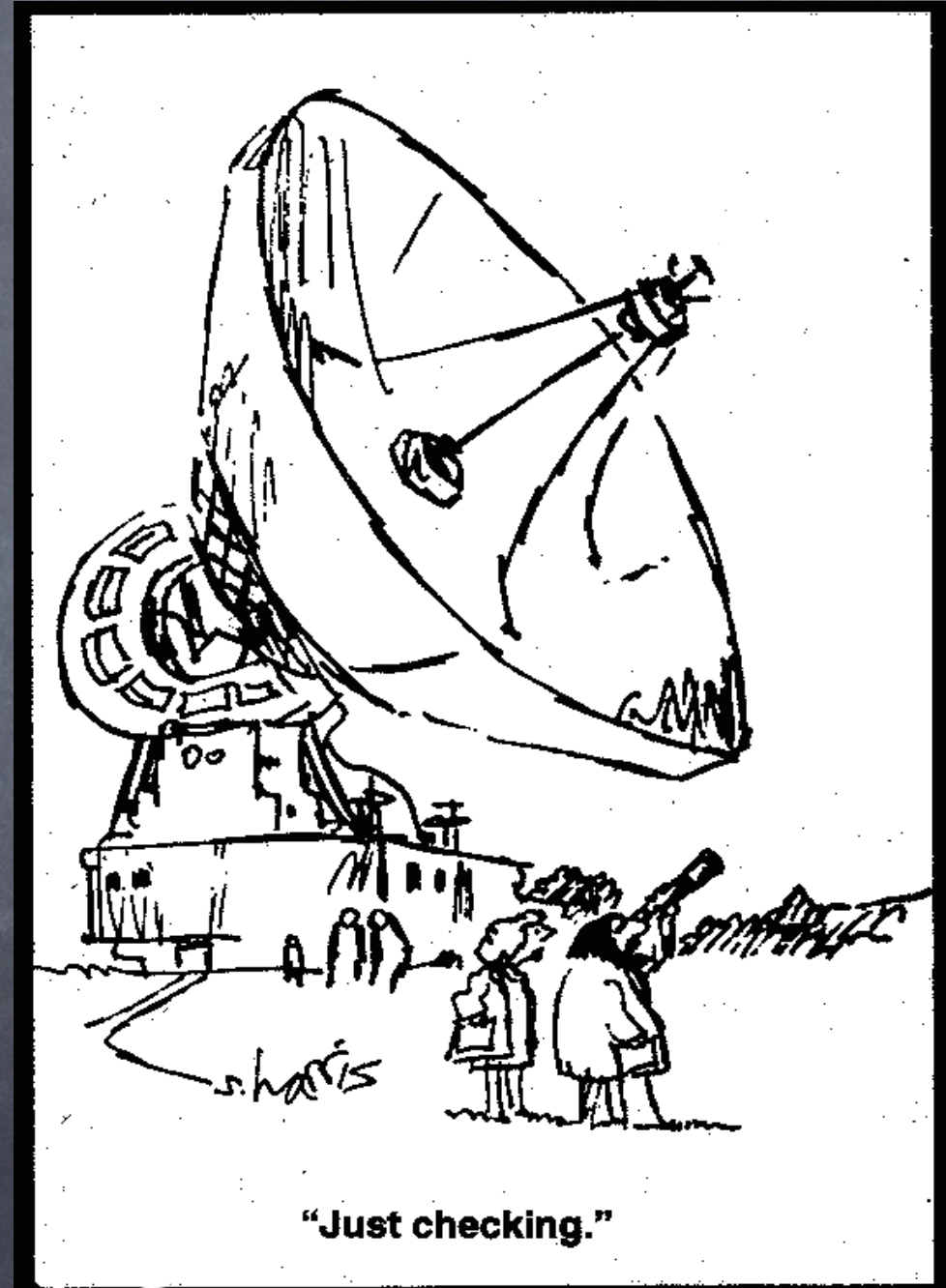
Ang. resolution:

$$\theta = \frac{1.22\lambda}{D}$$

$$\theta = \frac{2.1 \times 10^5 \lambda}{D}$$

arcseconds

- Human eye: 17 arcsecs
- Effelsberg 100-m @ 21cm: 440 arcsecs (8 arcmins)



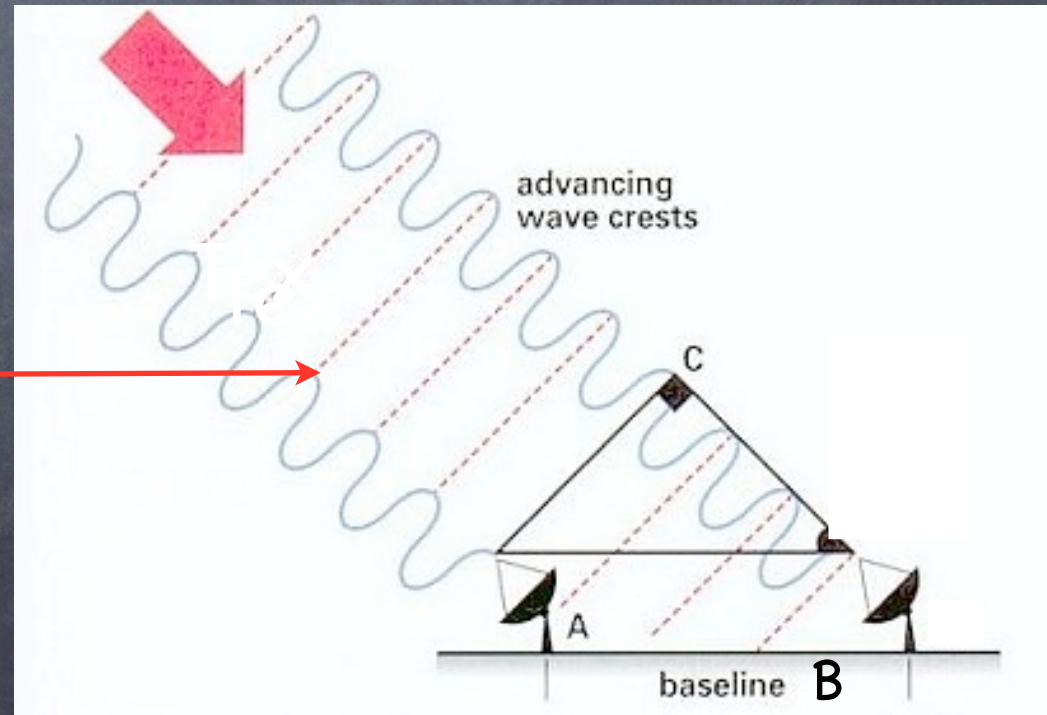
The answer RADIO INTERFEROMETRY

Ang. resolution: $\theta = \frac{1.22\lambda}{B}$ B = Baseline i.e. telescope separation

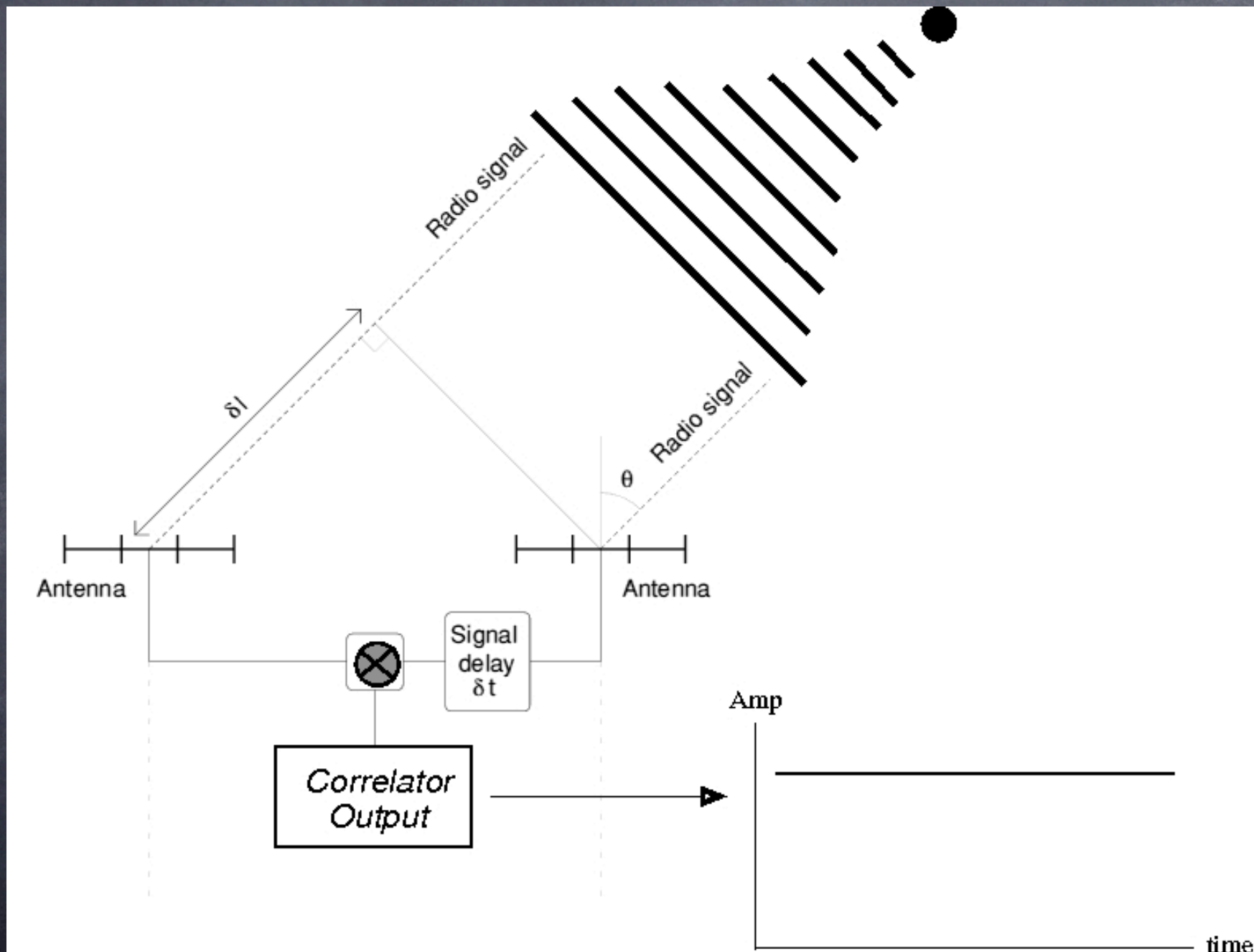
For 2 telescopes separated by 30 km

=> Ang. resolution: ~ 1 arcsecond - MUCH BETTER!

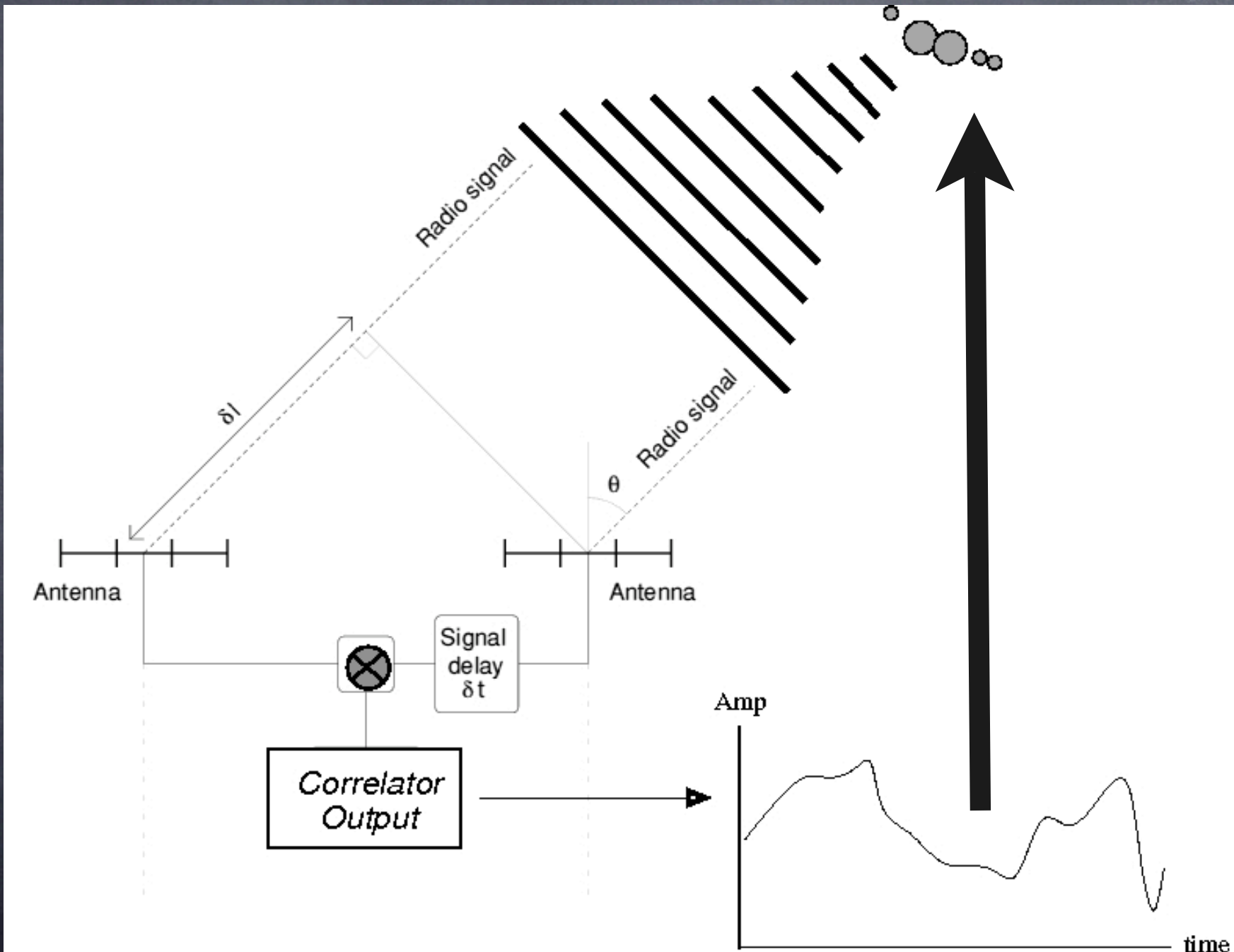
Wave-fronts from distant source perfectly in phase



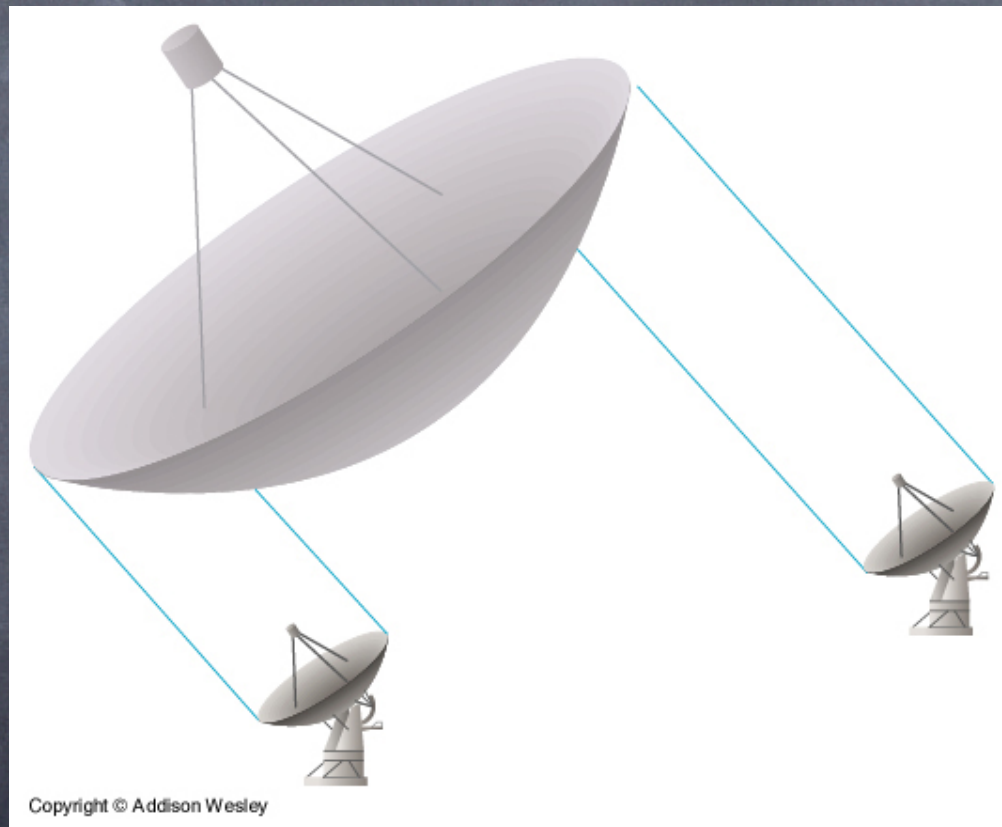
RADIO INTERFEROMETRY & Correlation

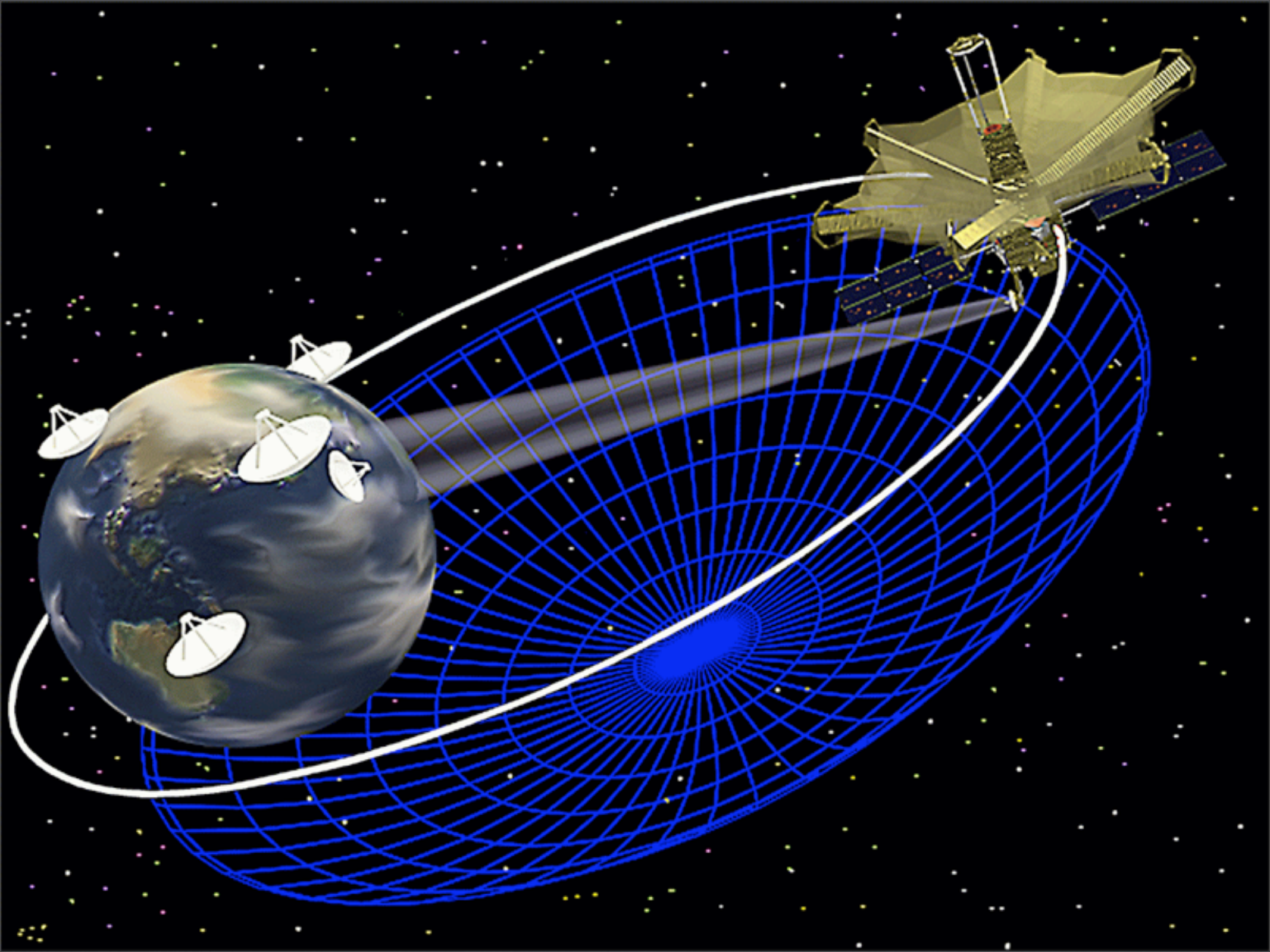


RADIO INTERFEROMETRY & Correlation

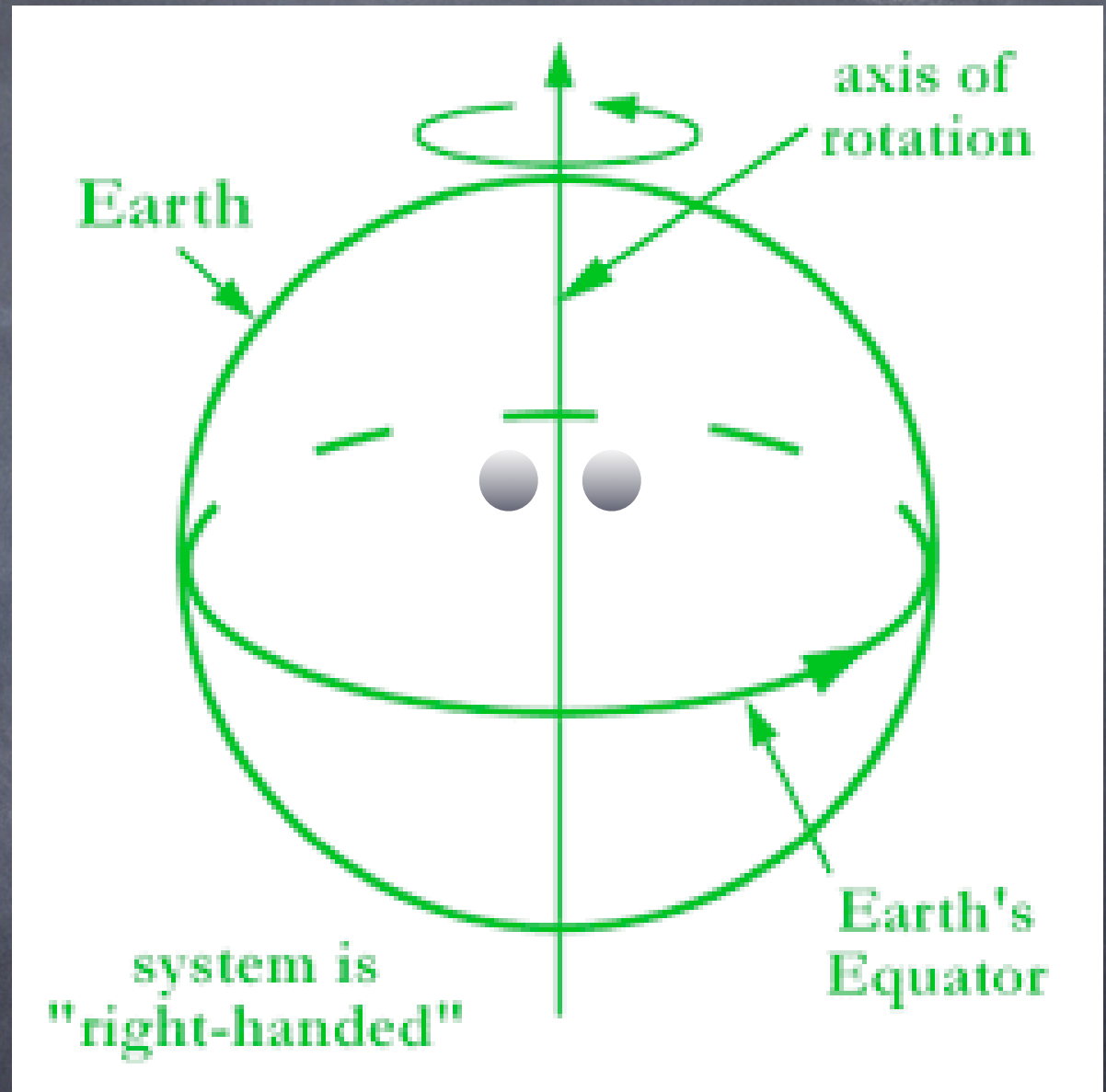
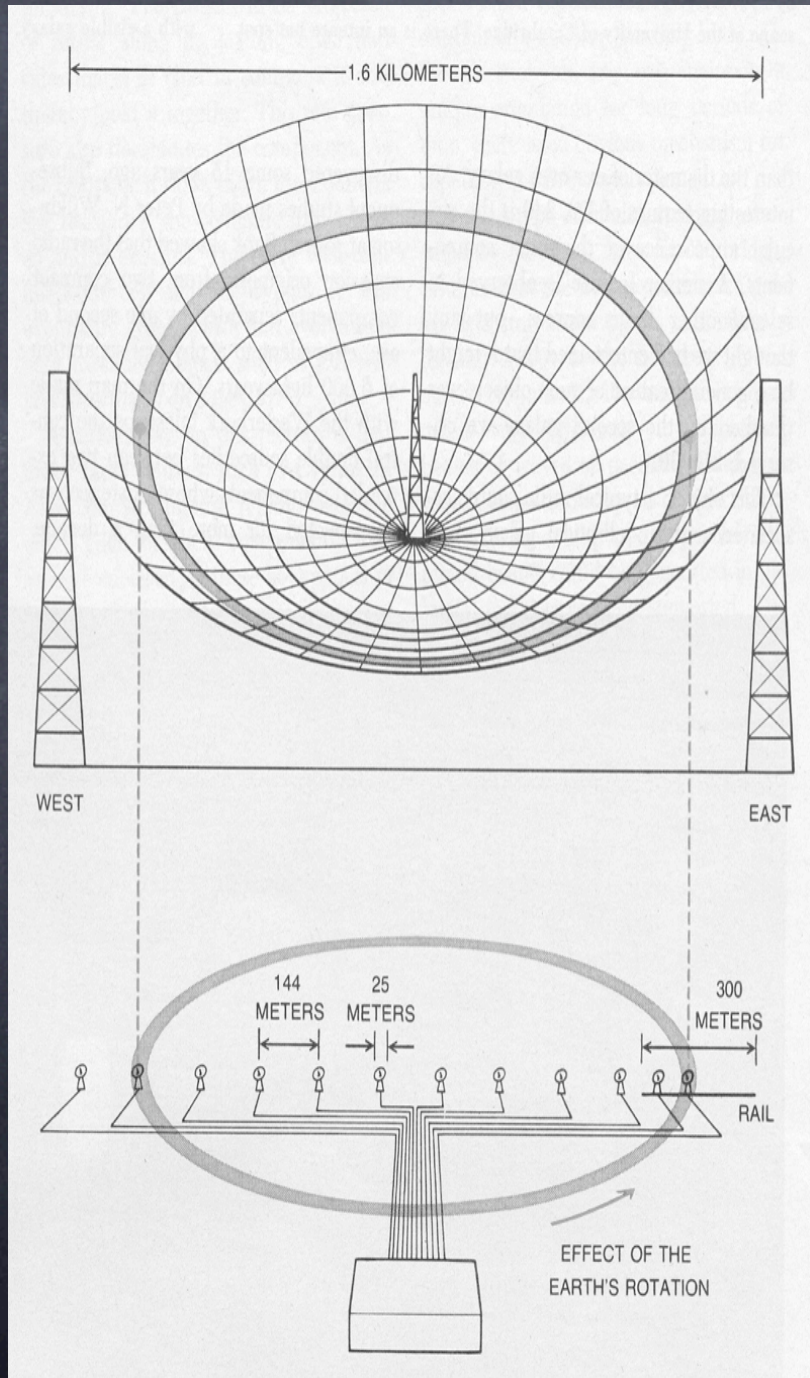


Interferometry tries to synthesise a GIANT telescope from lots of small ones:



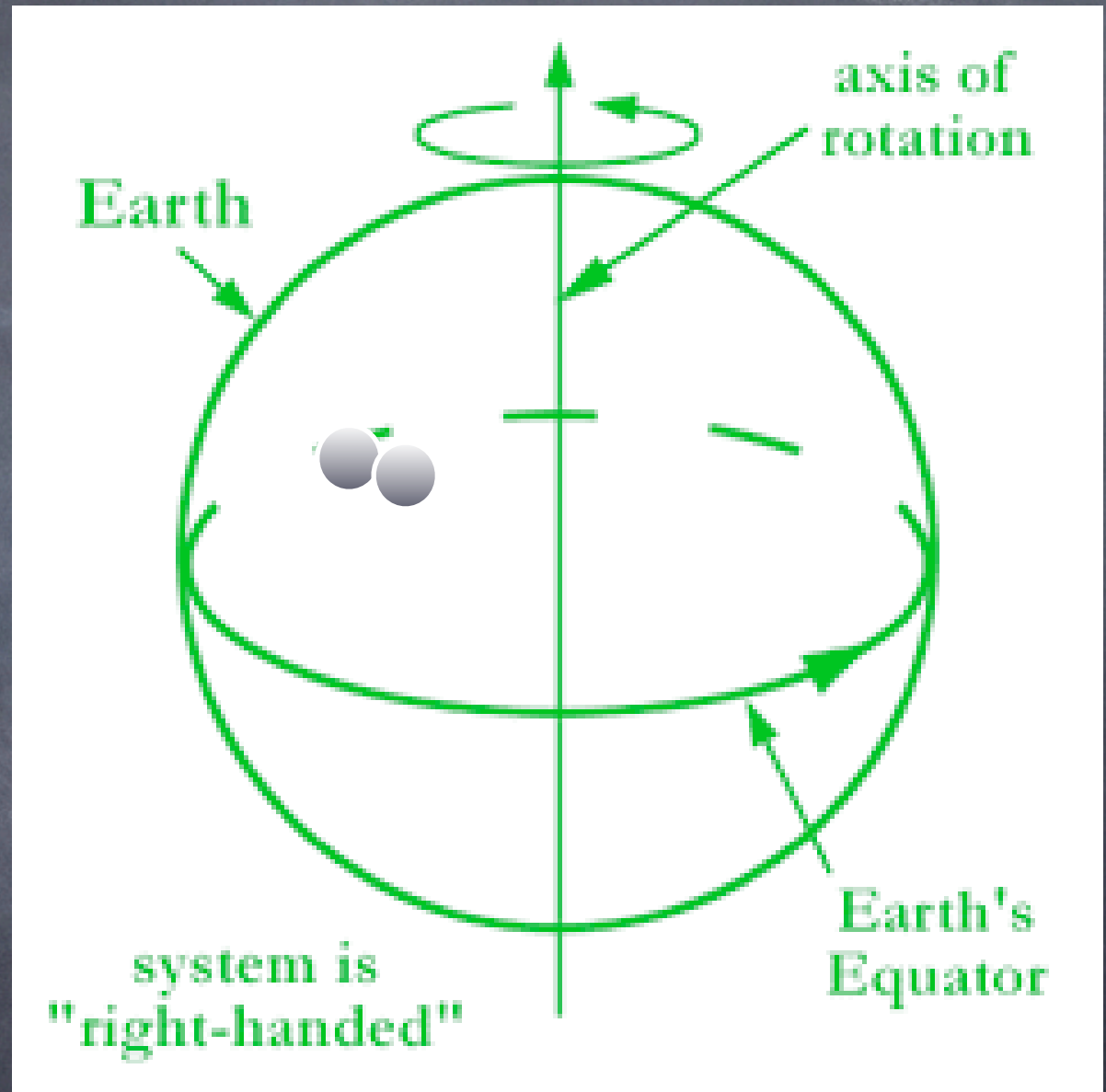
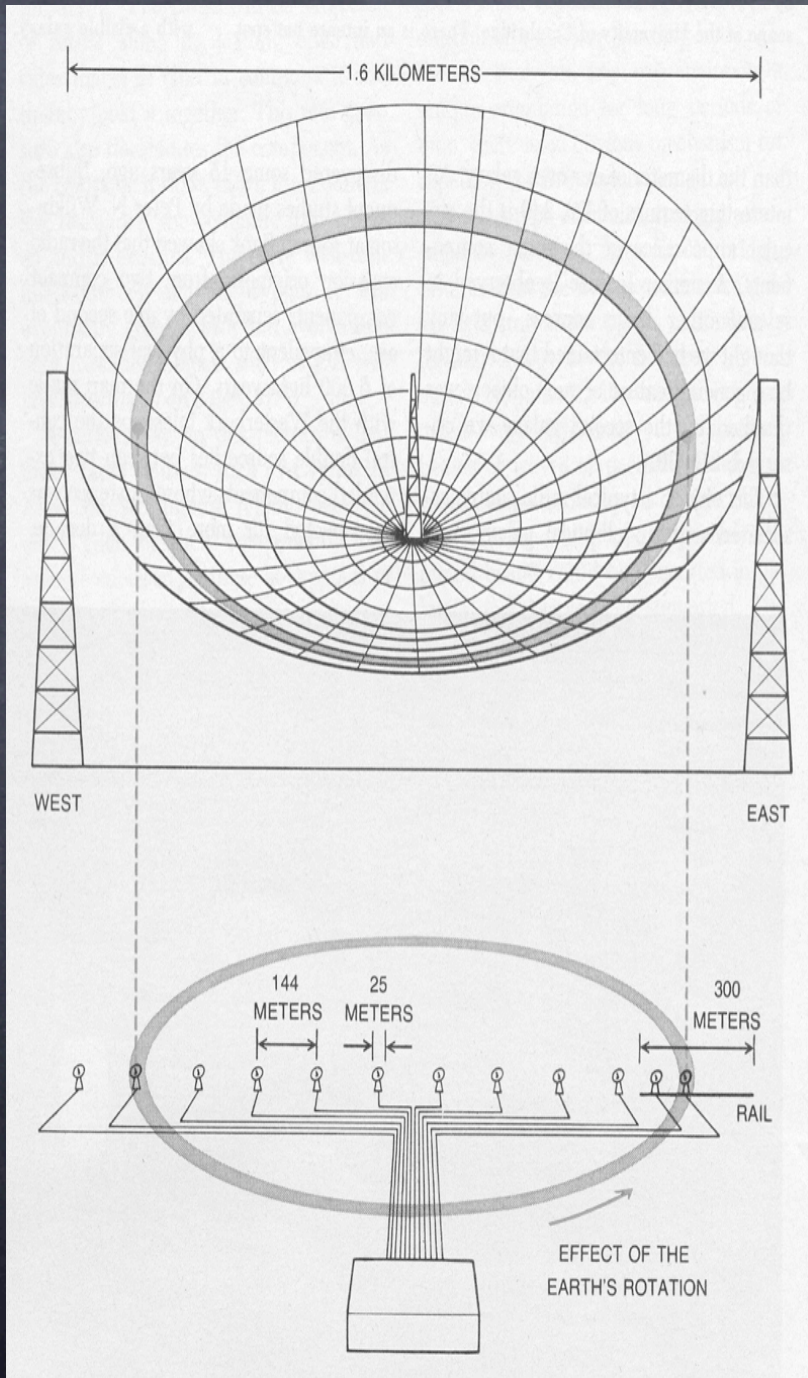


Earth rotation helps too (Ryle):



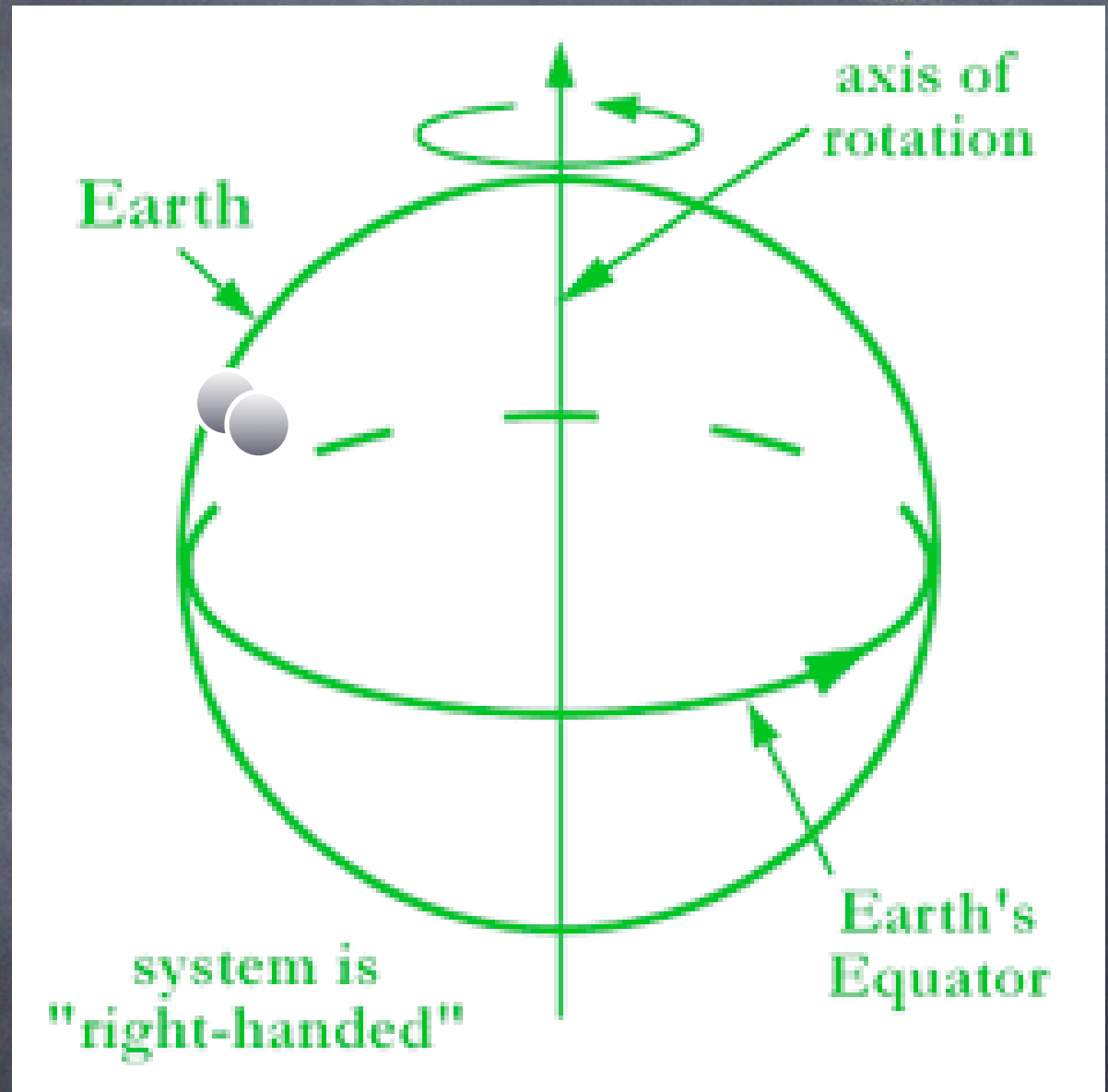
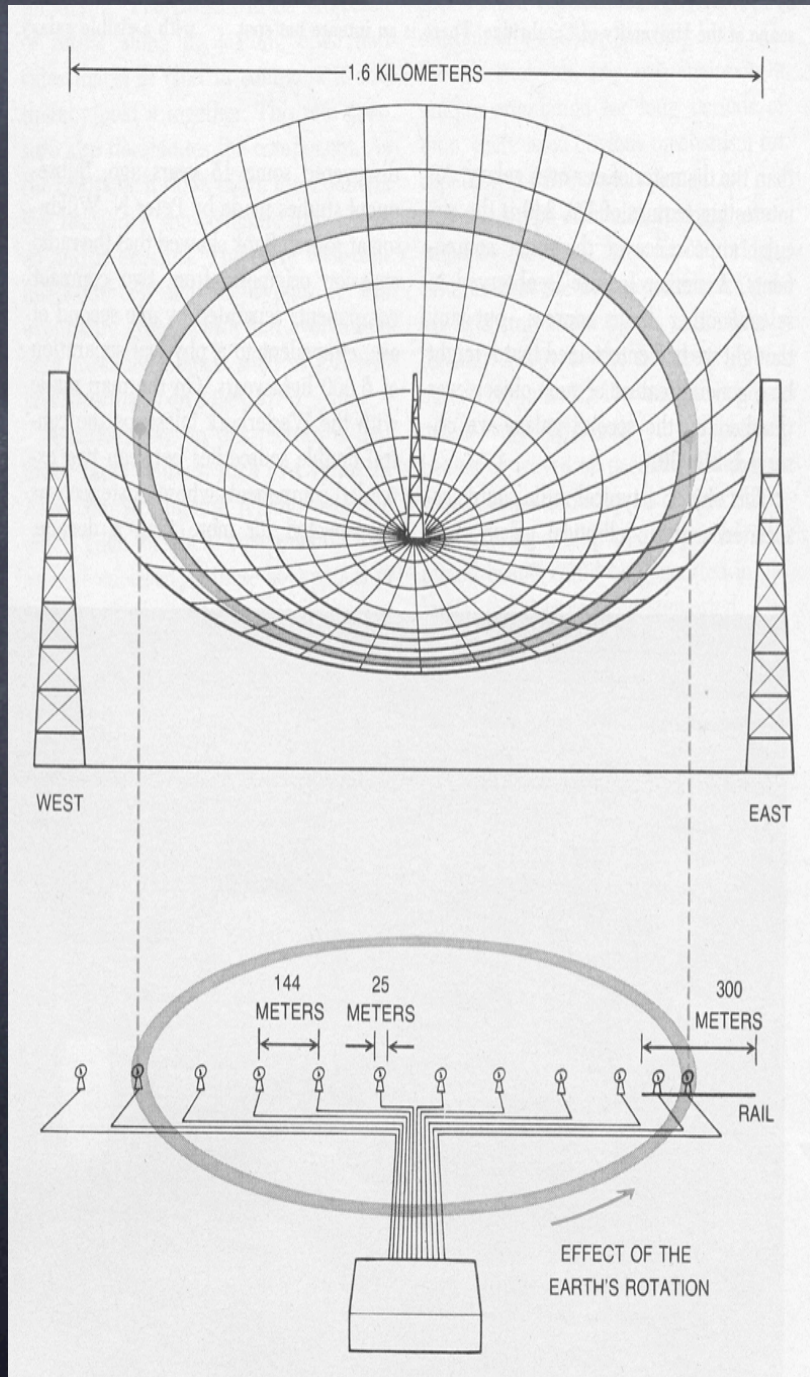
Projected Baseline changes
for source

Earth rotation helps too (Ryle):



Projected Baseline changes
for source

Earth rotation helps too (Ryle):



Projected Baseline changes
for source

The first radio interferometers

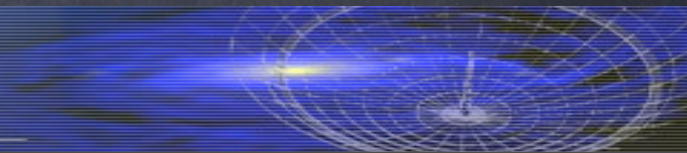
- Early interferometer arrays pioneered by UK and Australian astronomers:

1-mile telescope (1963)

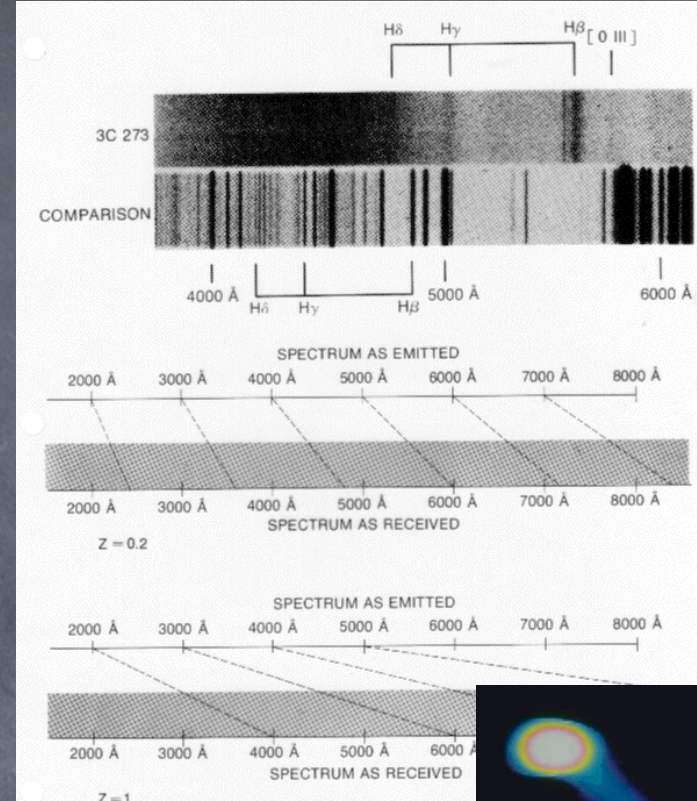


MILLS CROSS (CSIRO)

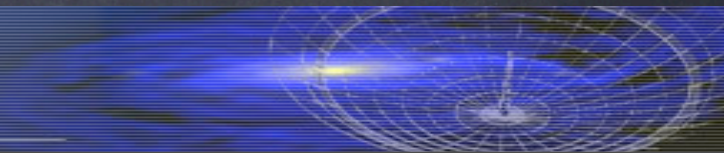
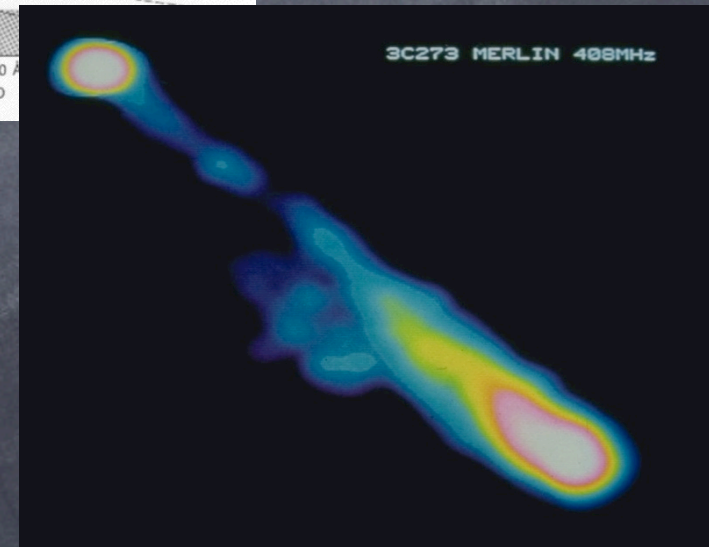
- Motivation was to identify radio sources with plausible optical counterparts...



3c273 - first AGN (Hazard, Schmidt et al) 1963



- > Stellar objects ????
- > Redshifted lines $z=0.2 \Rightarrow$ cosmological distance objects
- > 1000 x more luminous than Milky-Way

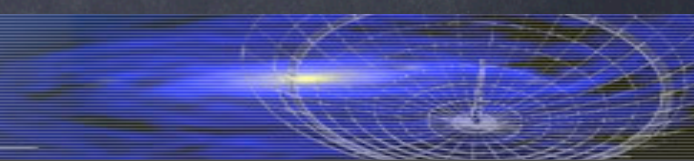
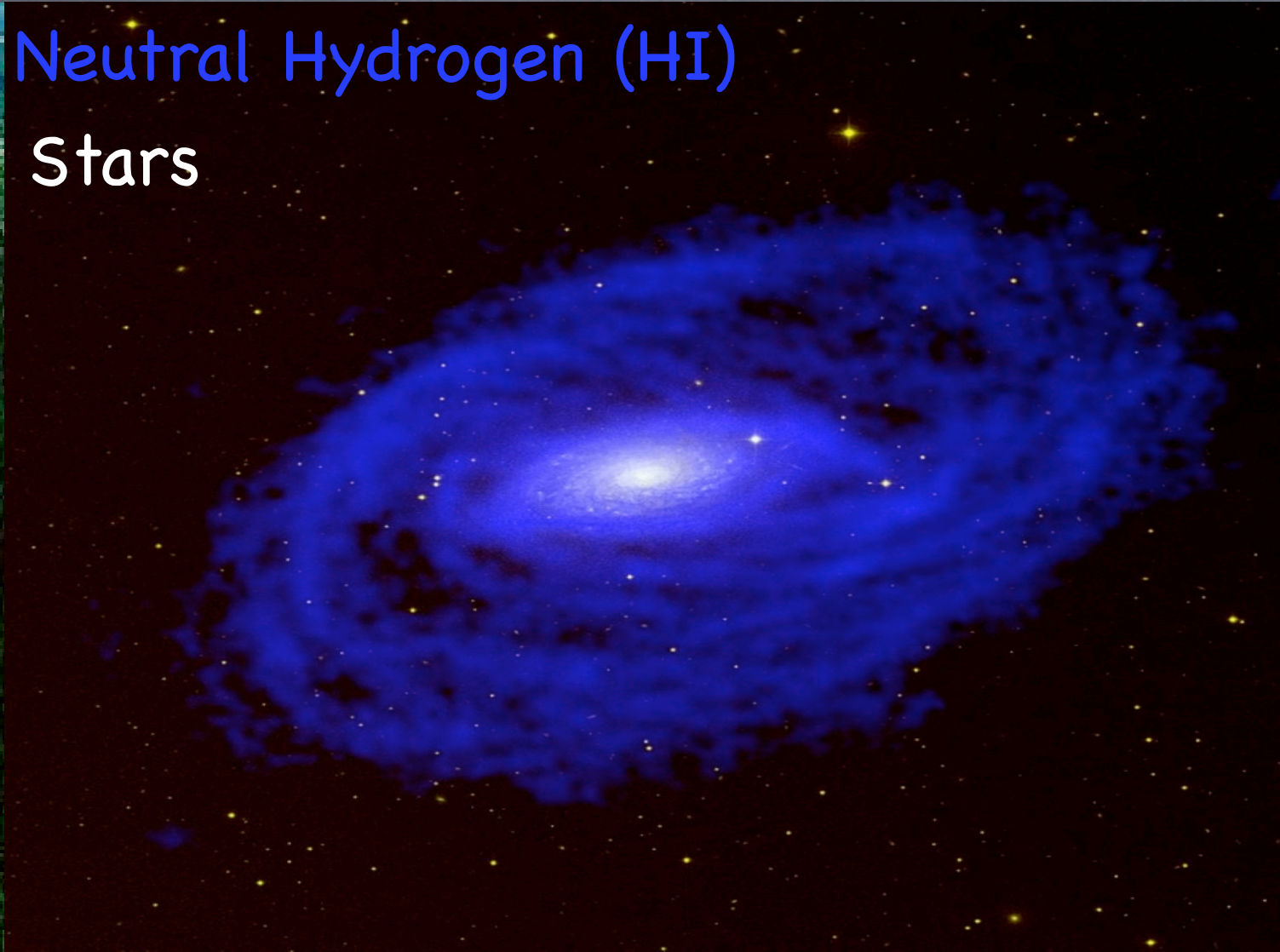


1970 - Westerbork Synthesis Radio Telescope

👁️ 14 x 25 metre telescopes, 91 baselines, 3km baseline.

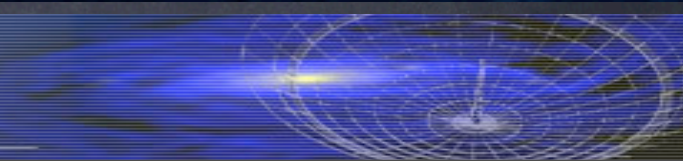


Neutral Hydrogen (HI)
Stars

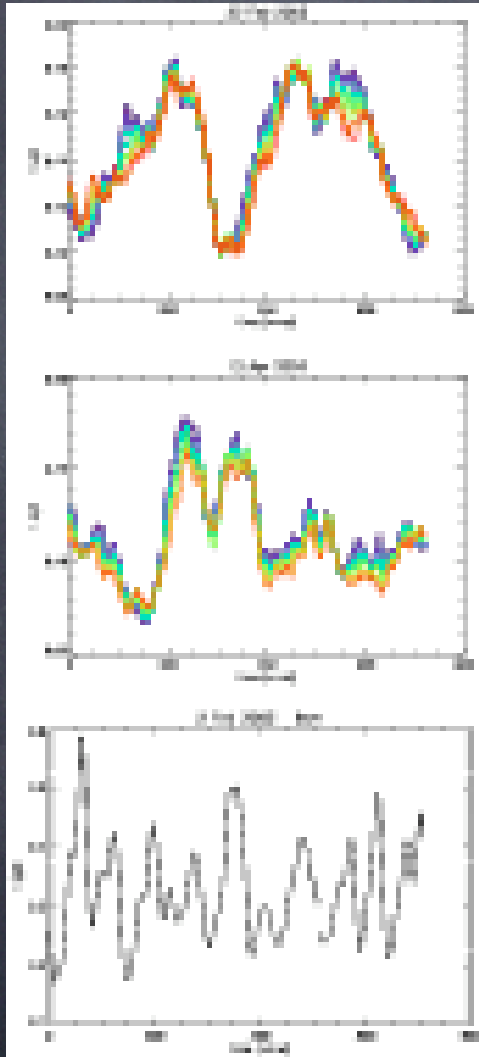


The SPECIAL nature of the radio sky

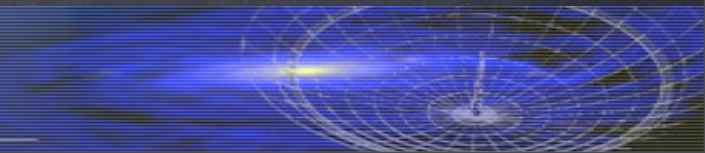
- Nearly all the bright radio sources are extra-galactic and EXOTIC - AGN (Quasars, radio galaxies etc.)
- Nearly all are located at cosmological distances ($z \sim 1$)
 - c.f. optical sky ($z=0$ for naked-eye objects!)
- Huge excess of faint sources: \Rightarrow first evidence of rapid cosmic evolution...!
- Non-thermal emission - synchrotron mechanism \Rightarrow violent Universe powered by gravitation rather than fusion.

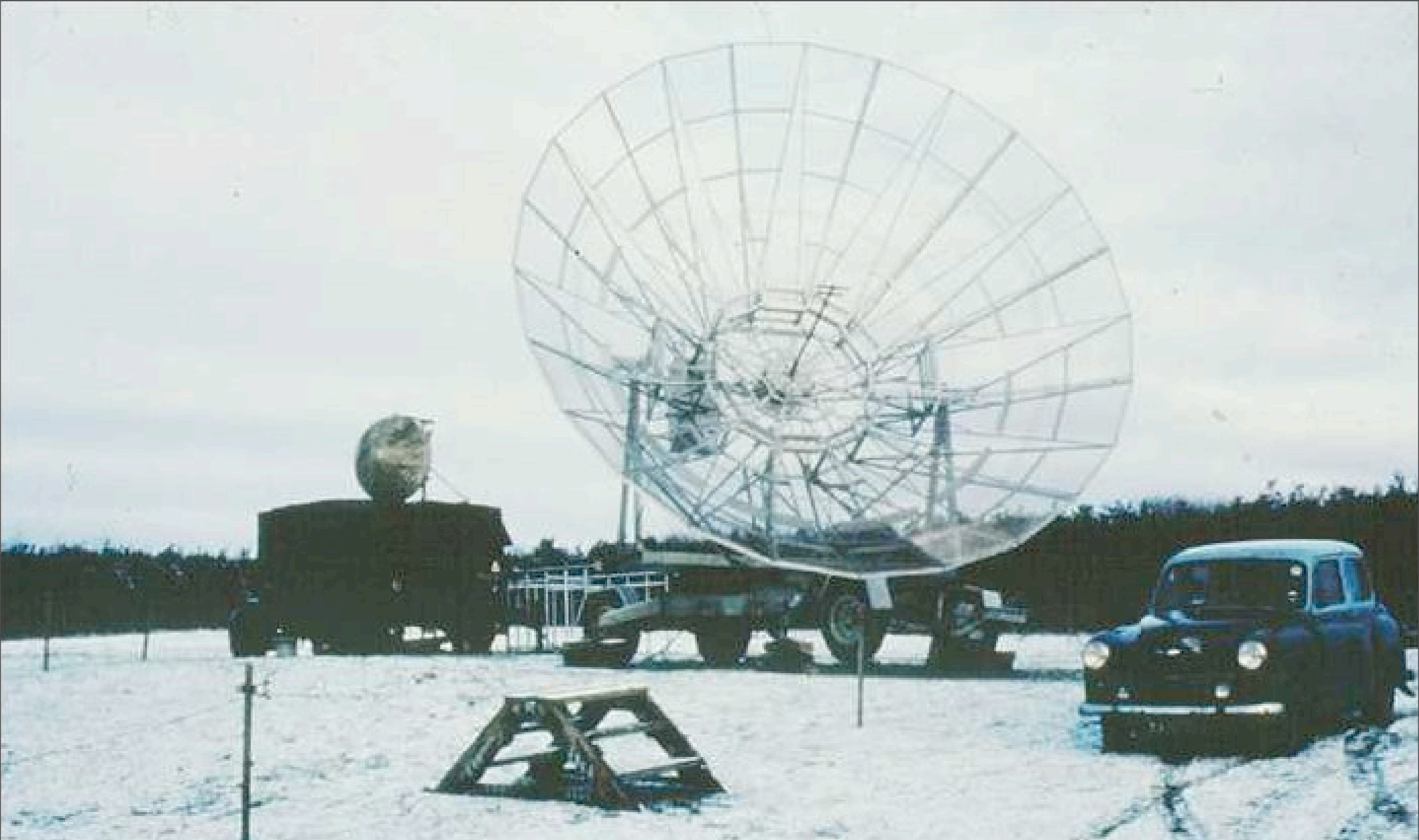


Radio sources also discovered to be highly variable on time scales of hours or less:

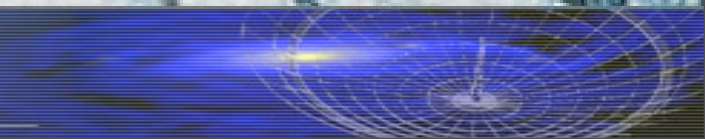


- > ==> very compact objects - scales \sim solar system.
- > At $z=1$, 1 arcsecond corresponds to ~ 10 kpc (30,000 lt years).
- > Need for much HIGHER RESOLUTION (baselines \sim Earth diameter, 12000 km)





☉ Pioneering long-baseline interferometry show many Radio sources unresolved on sub-arcsecond scales



1967: Very Long Baseline Interferometry

Quasar

Noise

Noise

1000x better
resolution than
Optical telescopes
- its so easy!

Radio
Telescope

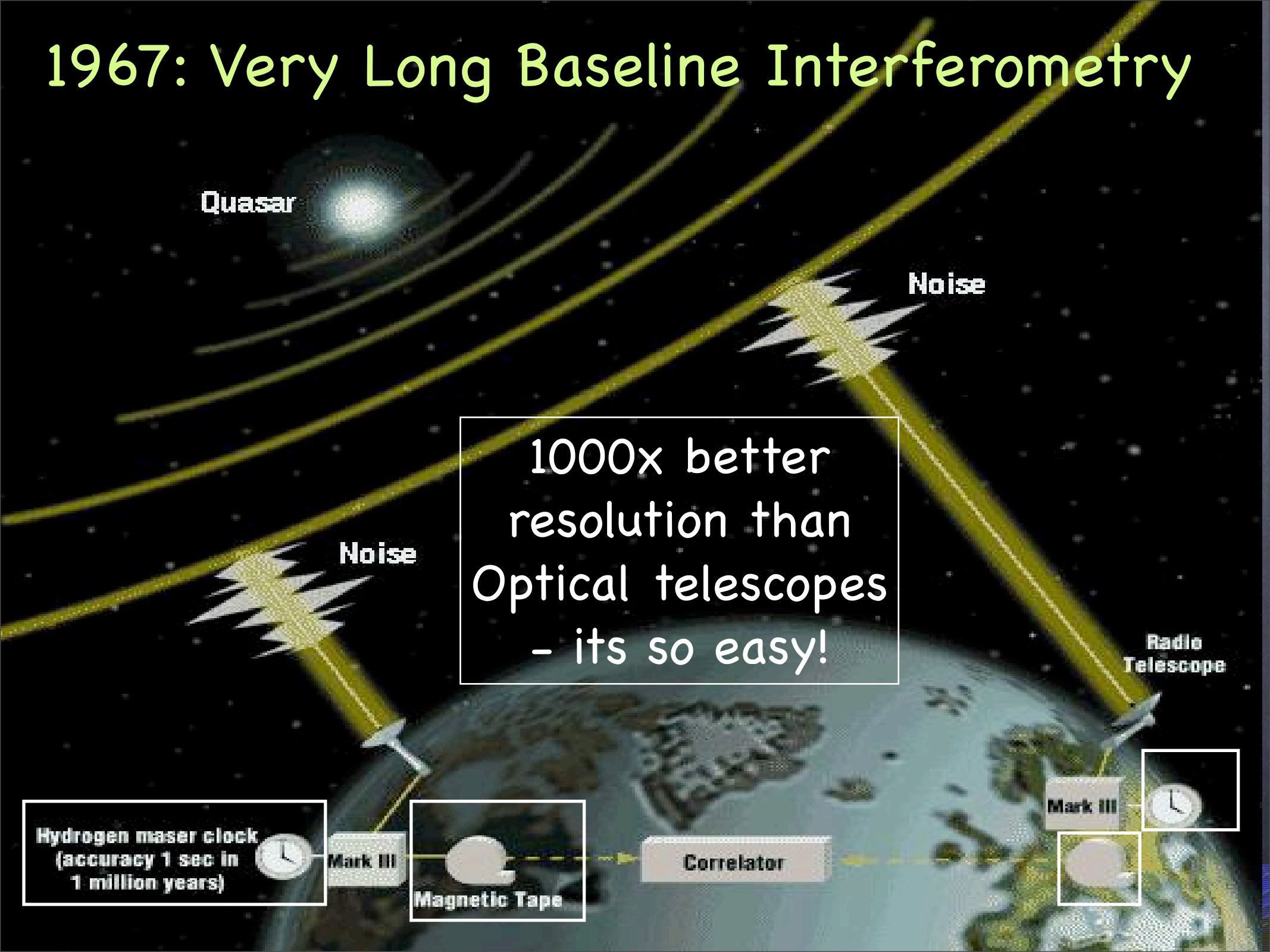
Hydrogen maser clock
(accuracy 1 sec in
1 million years)

Mark III

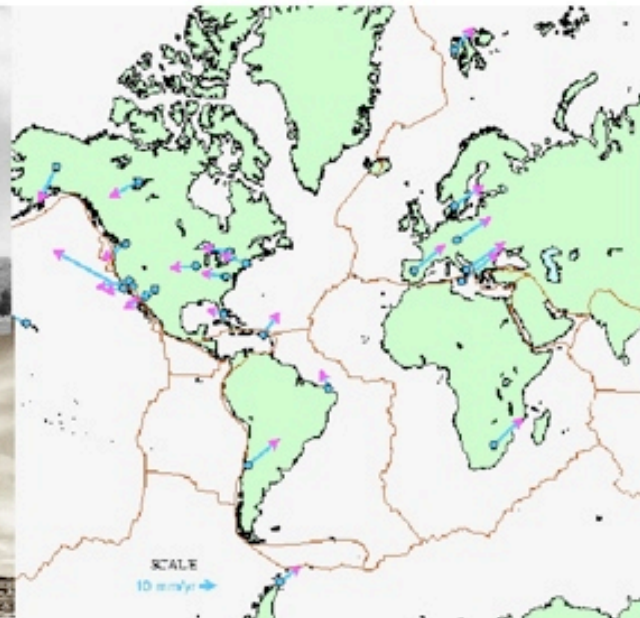
Magnetic Tape

Correlator

Mark III



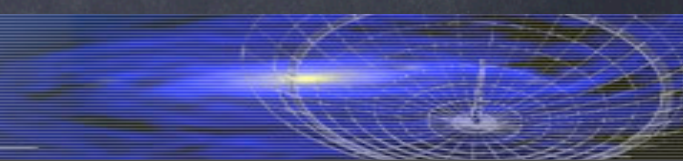
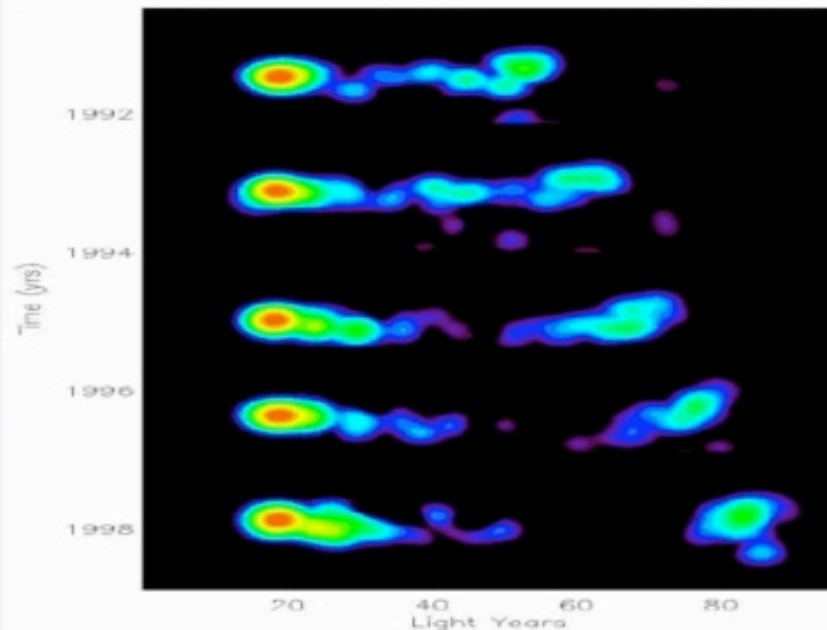
40 Years of Very Long Baseline Interferometry (VLBI)



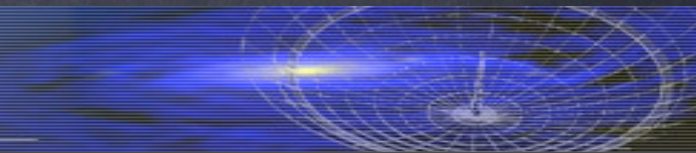
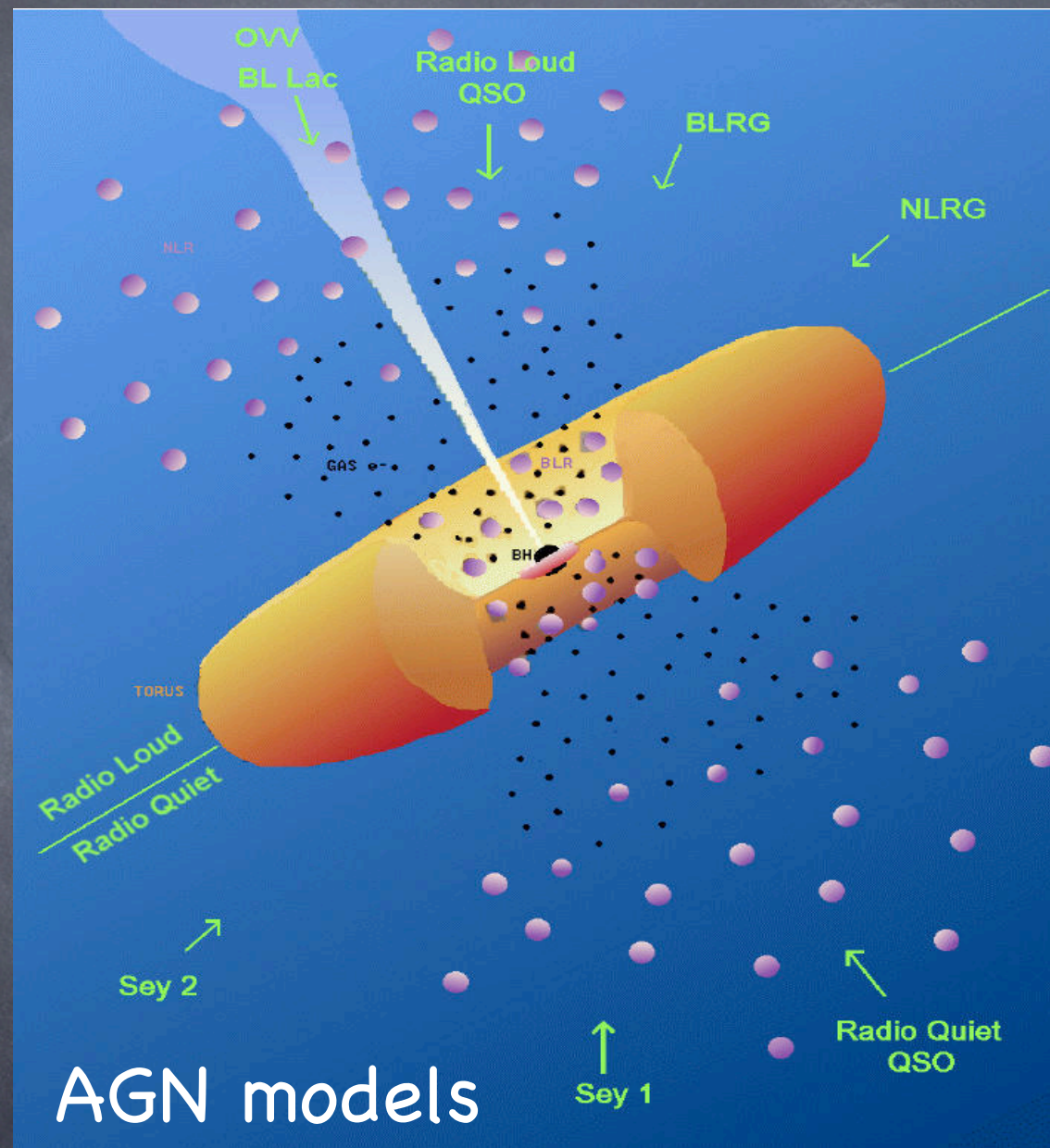
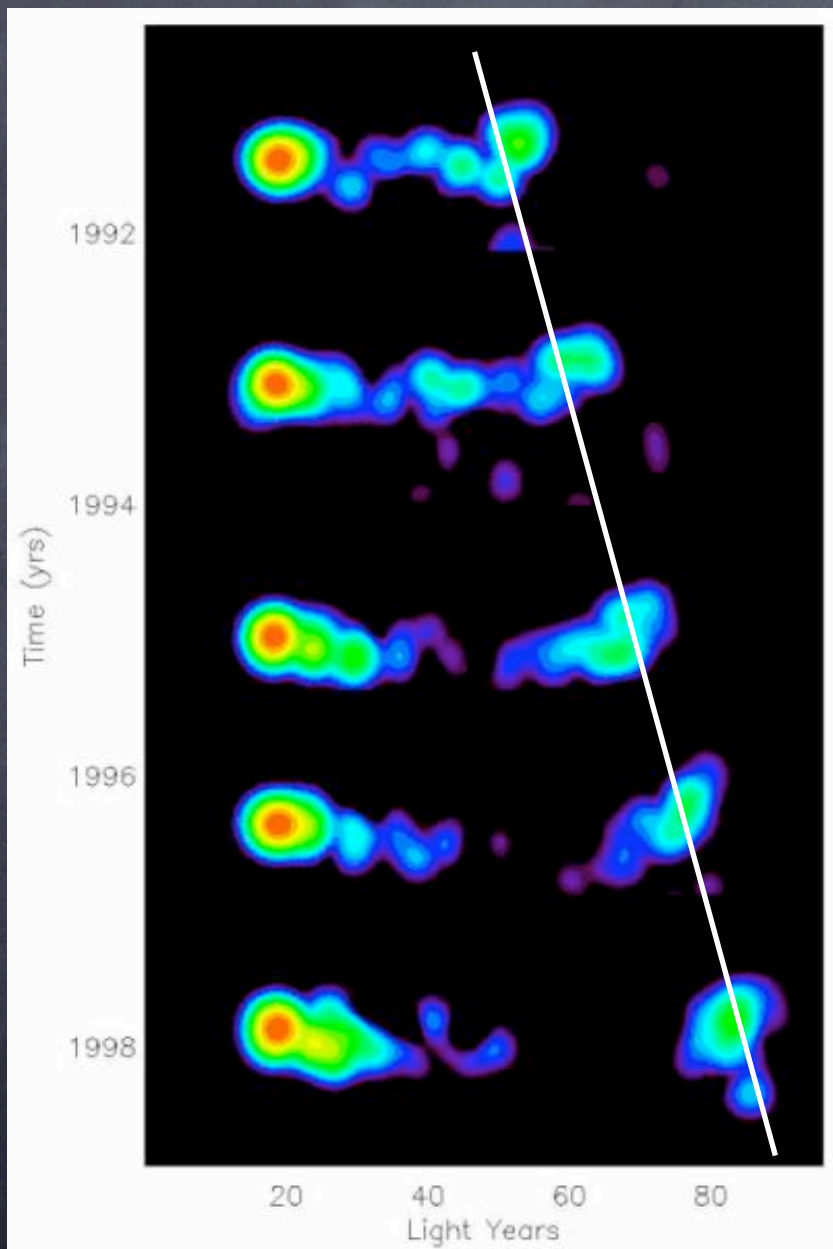
“FATHERS OF VLBI” AT IAU164, 1997



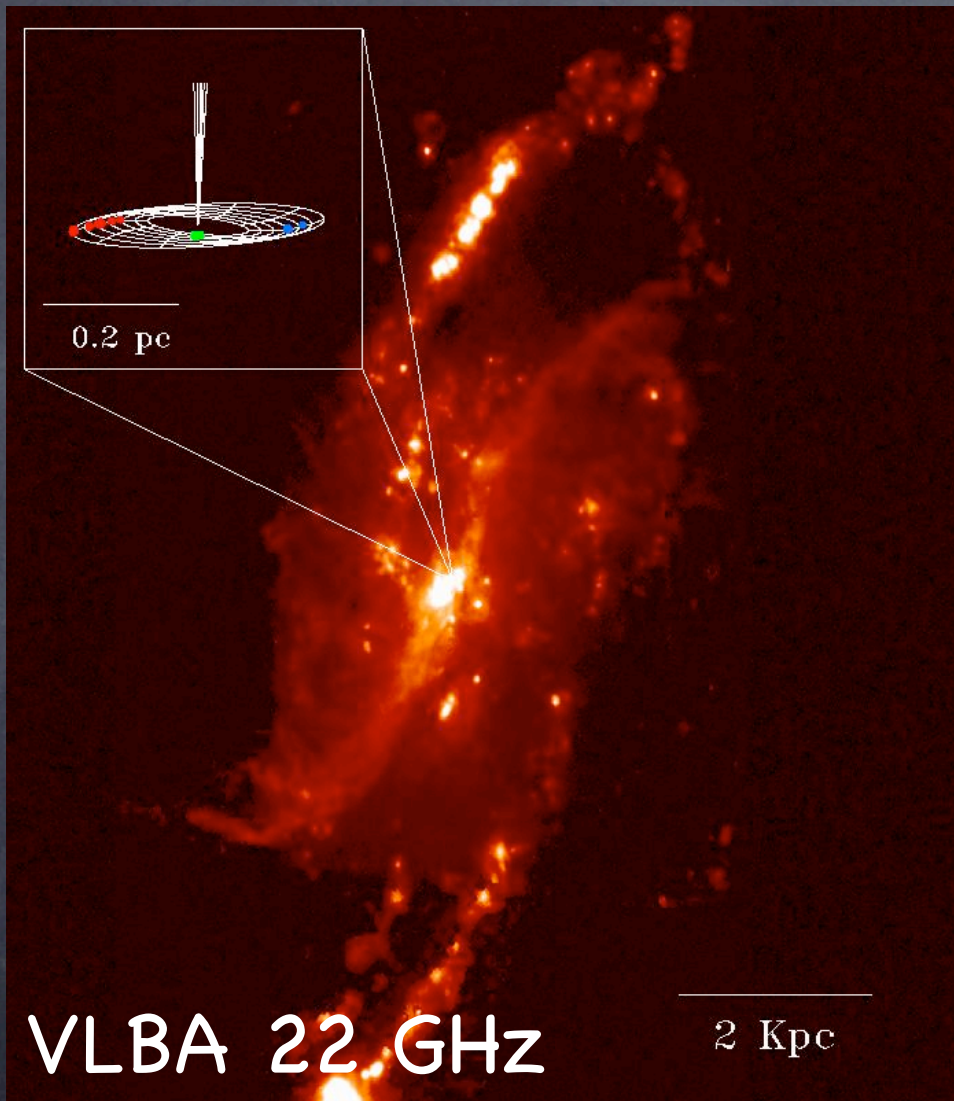
Jim Moran Marshall Cohen Bernard Burke
 Dave Jauncey Ken Kellermann Barry Clark



Superluminal motion discovered - Whitney et al. 1973.



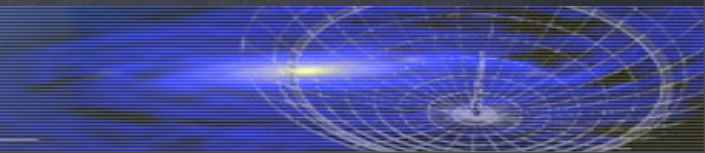
Weighing the black hole in NGC4258 – Myoshi et al. 1995.



> velocity and motion of water maser gas clouds permit:

– Mass of Black hole $\sim 10^7 M_{\text{sun}}$.

– DISTANCE of NGC 4258 $\Rightarrow H_0$



VLBI Brings the Universe to life...

***VLBA 22 GHz Observations
of
3C120***

José-Luis Gómez

IAA (Spain)

Alan P. Marscher

BU (USA)

Antonio Alberdi

IAA (Spain)

Svetlana Marchenko-Jorstad

BU (USA)

Cristina García-Miró

IAA (Spain)

A Decade of Expansion of SN1993J

J.M. Marcaide, A. Alberdi,
I. Martí-Vidal, E. Ros, et al.

© J.M. Marcaide, Universitat de València, 2004

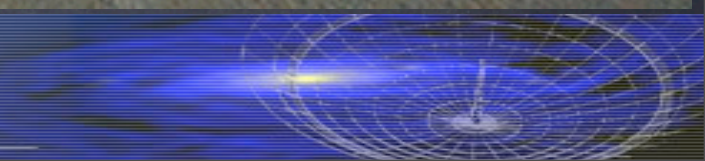
The Very Large Array (VLA)

Wide Frequency
range up to 50 GHz

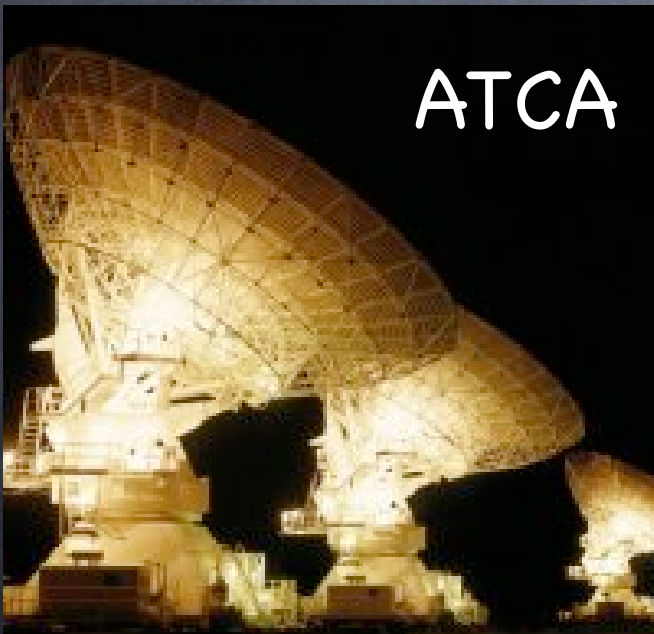
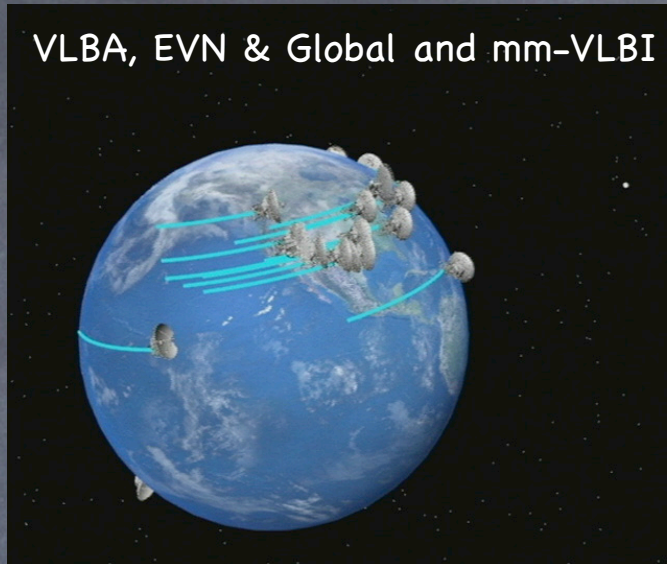
Good sensitivity $\sim 6\mu\text{Jy}$
in 12 hrs (8.4 GHz)

25-m diameter
antennas on rails -
Baseline 1 - 36 km

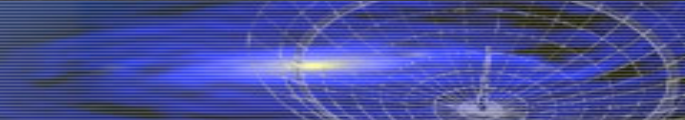
see www.nrao.edu



Other Interferometer Arrays



(NETHERLANDS FOUNDATION FOR RESEARCH IN ASTRONOMY)



European Radio Telescope Resources (incl. single dishes)



TRANSNATIONAL ACCESS



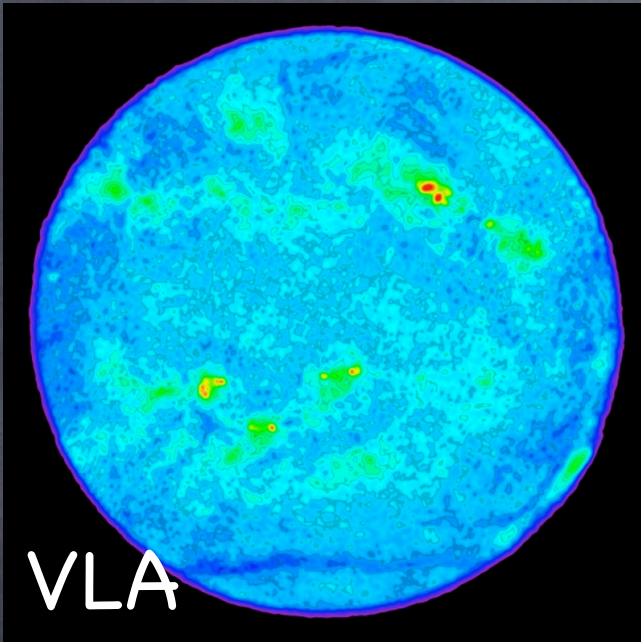
Pickmere (UK) Darnhall (UK) Metsähovi (FI) Westerbork (NL)



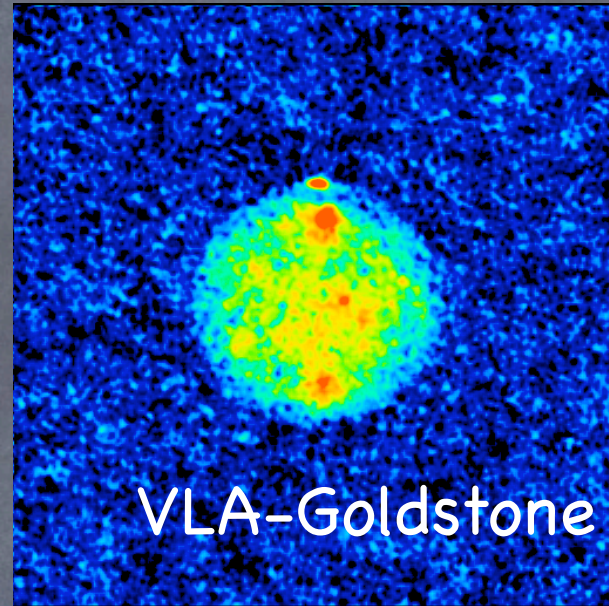
KEY

- EVN antennas
- EVN and/or MERLIN antennas
- MERLIN antennas
- EVN and/or stand alone
- stand alone antennas or arrays

Radio Sources in the Solar system



Thermal emission from the quiet sun

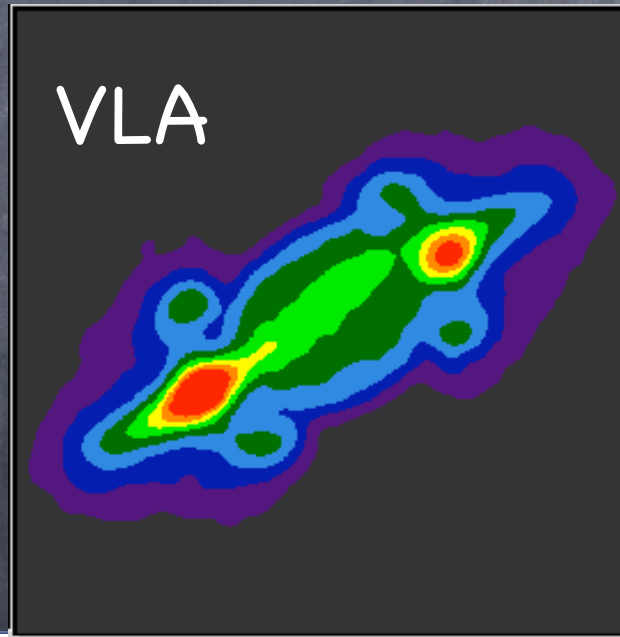


Bi-static radar image of Mercury

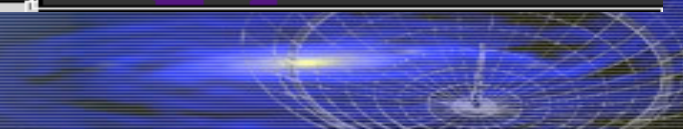
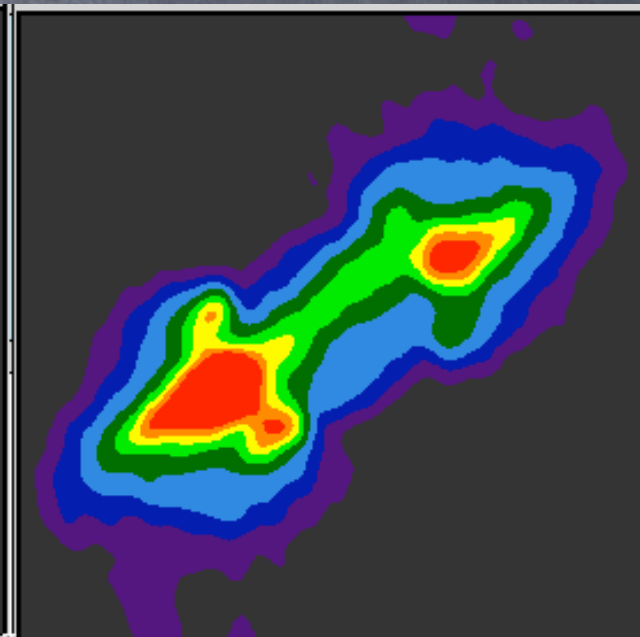
VLA

VLA-Goldstone

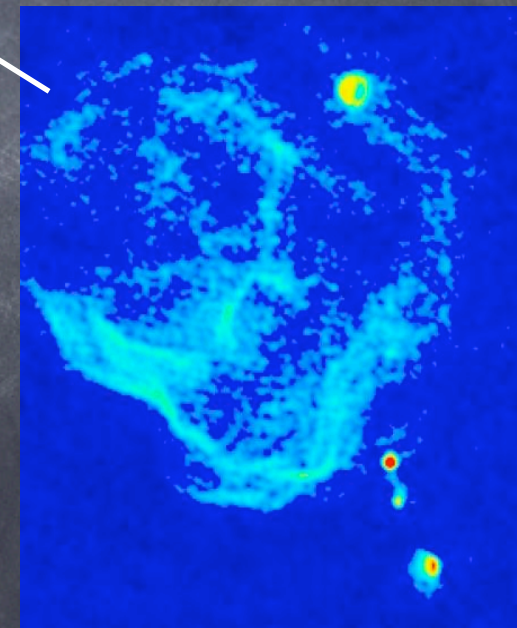
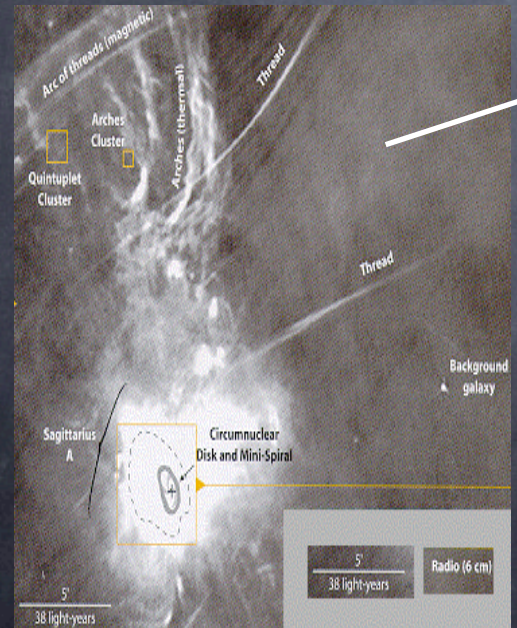
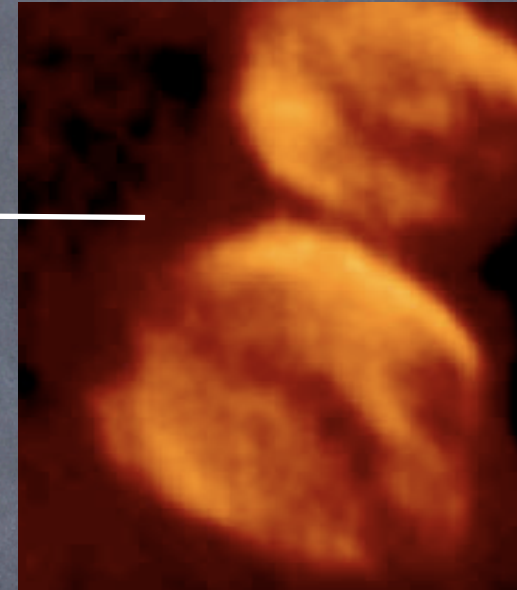
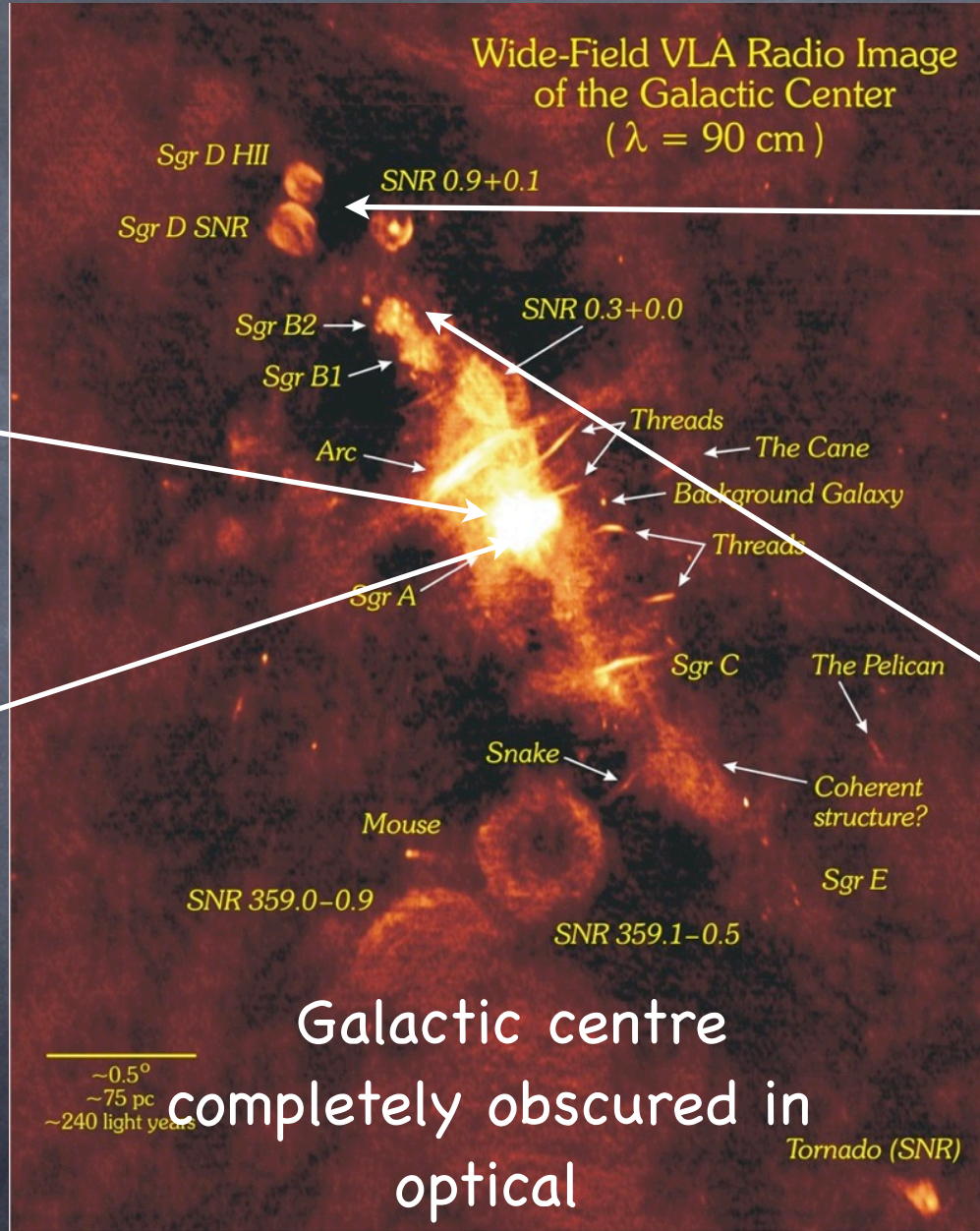
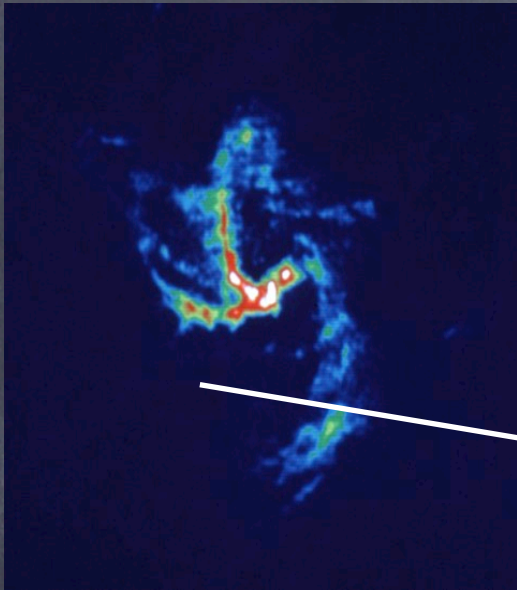
Synchrotron emission from Jupiter (before and after comet SL9 impact)



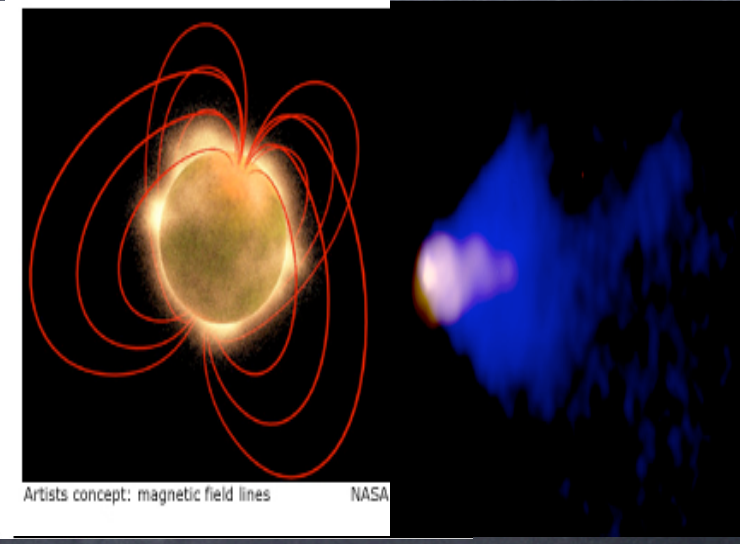
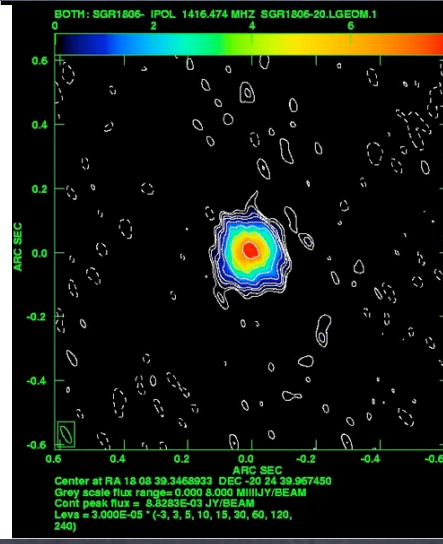
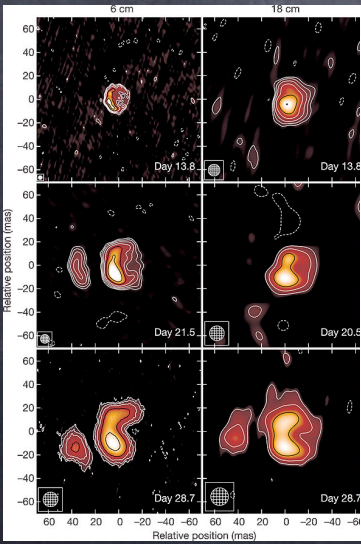
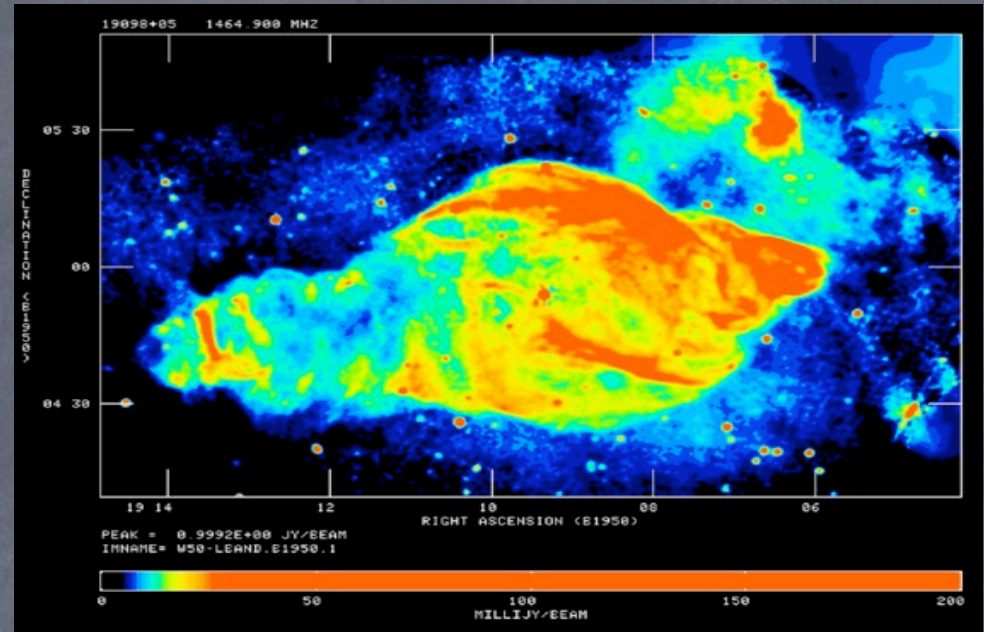
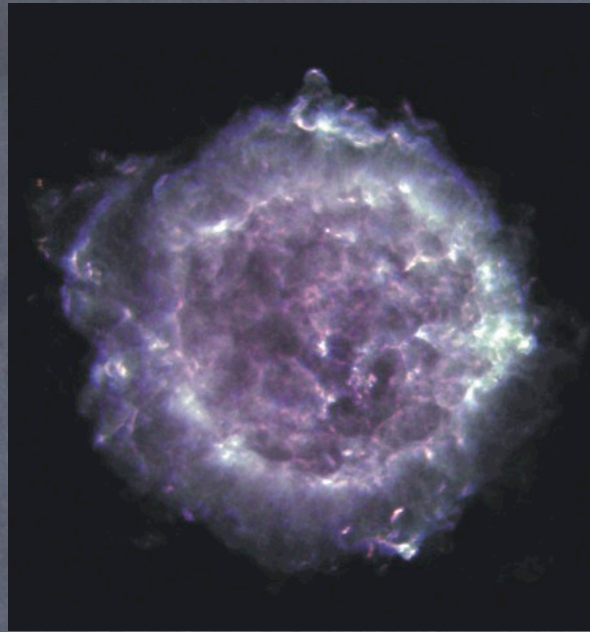
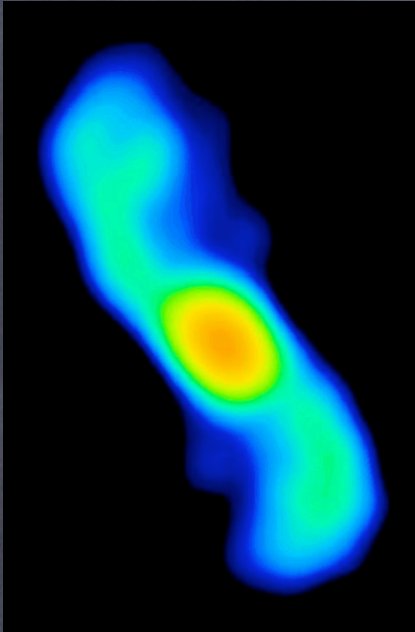
VLA



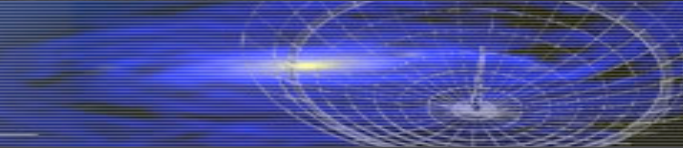
Galactic Centre



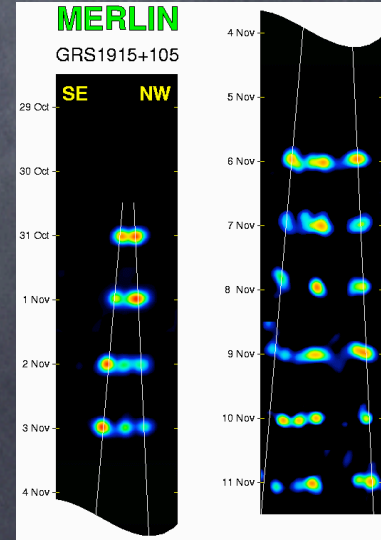
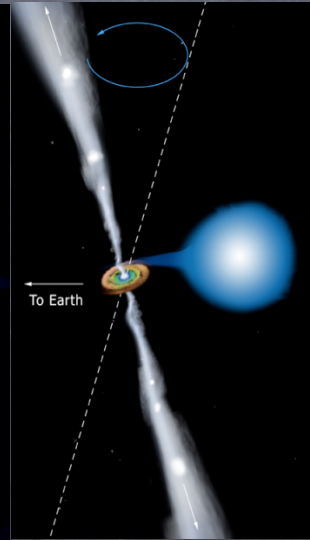
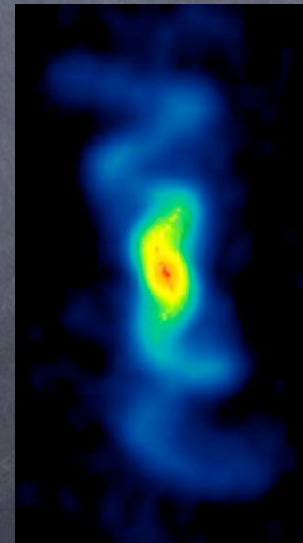
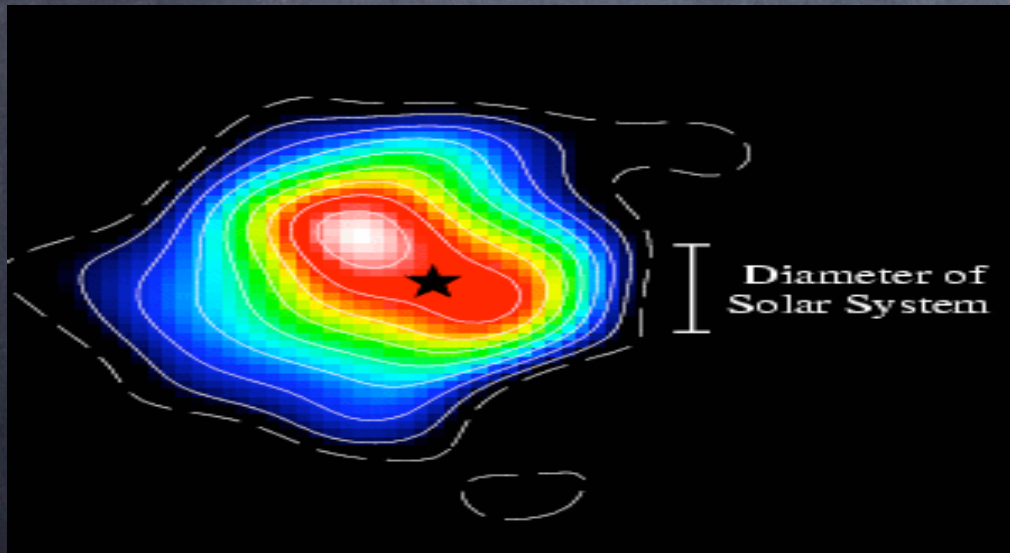
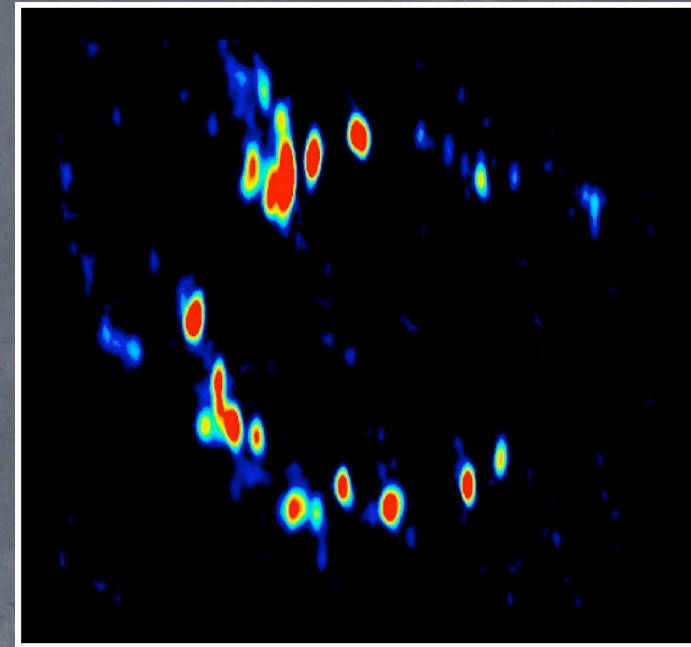
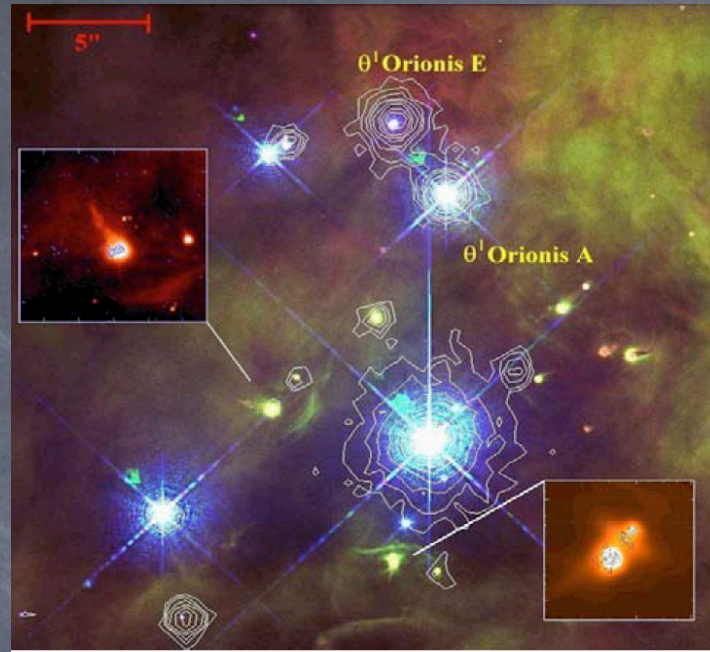
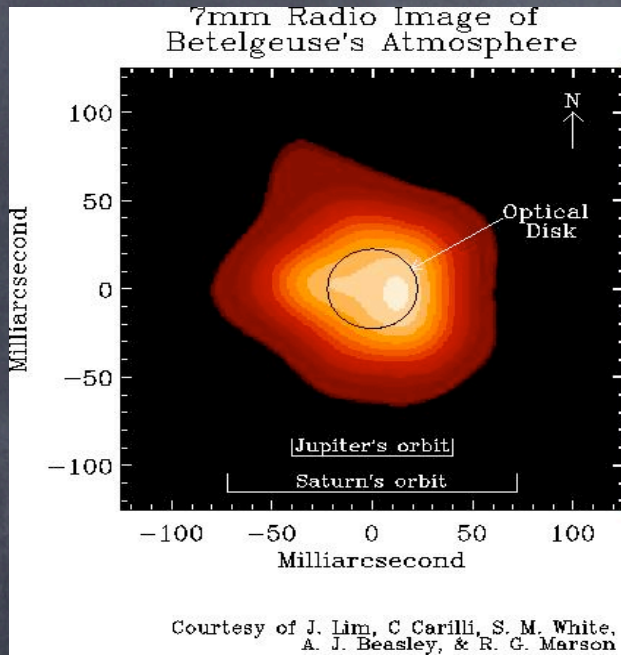
Galactic PNe, SNRs, Novas, PSRs



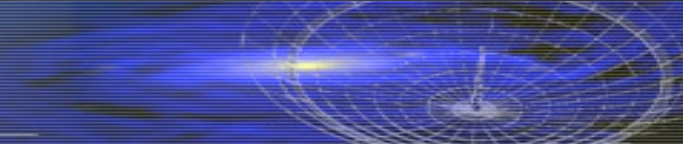
(NETHERLANDS FOUNDATION FOR RESEARCH IN ASTRONOMY)



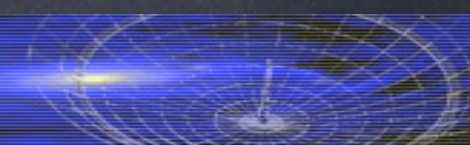
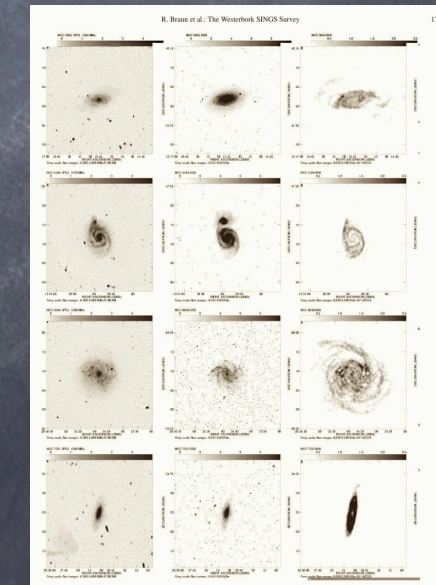
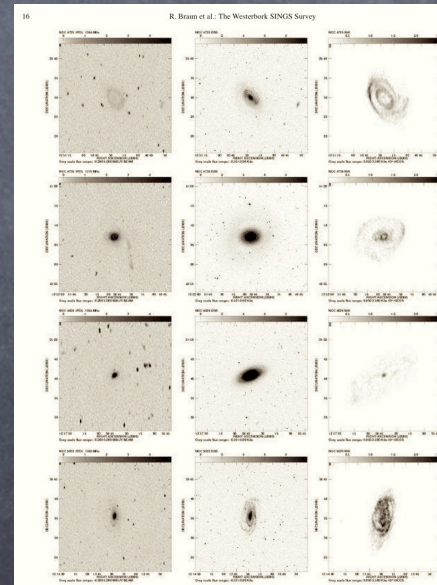
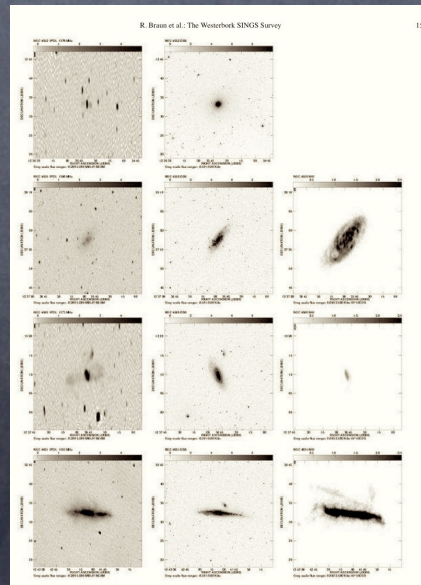
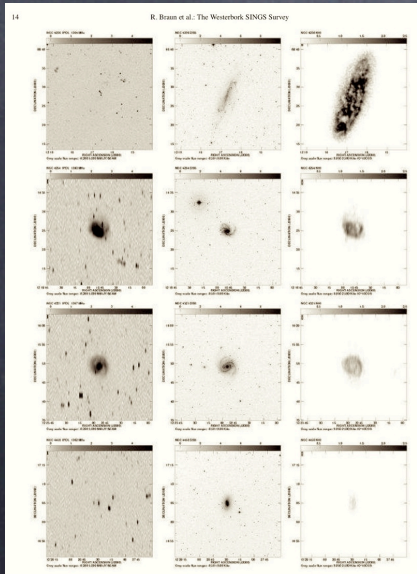
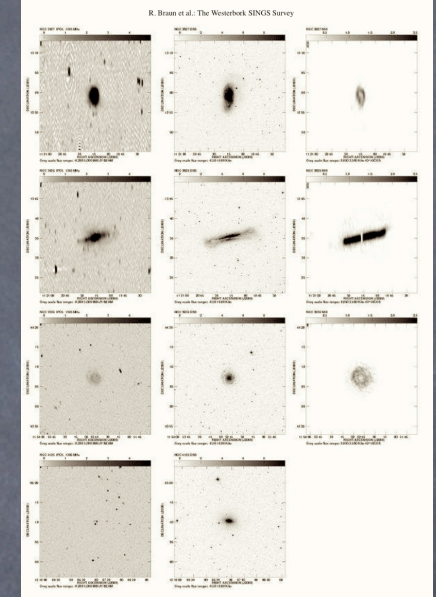
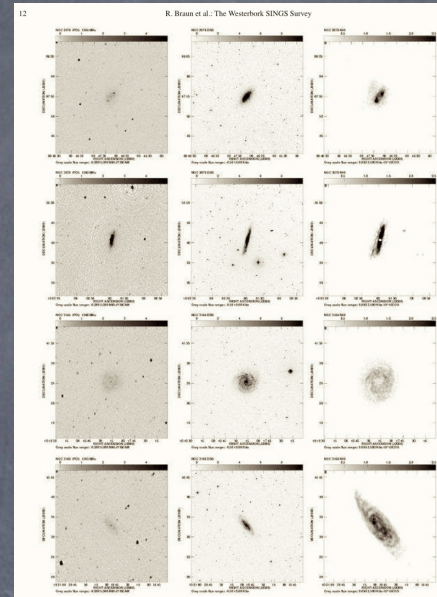
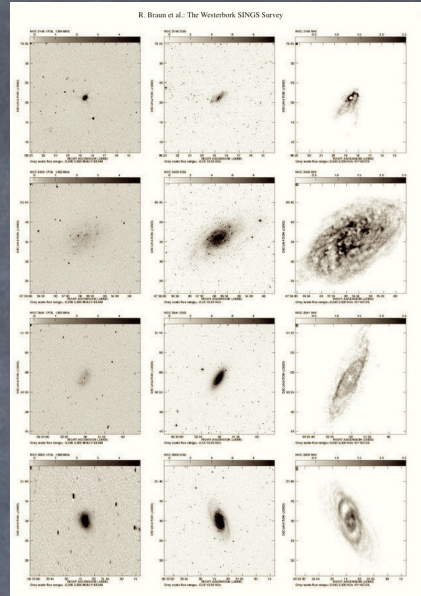
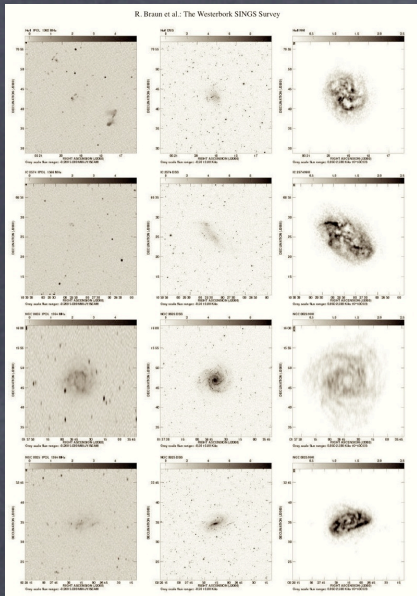
Other Galactic sources (stars, exo-solar systems, masers X-ray binaries)



(NETHERLANDS FOUNDATION FOR RESEARCH IN ASTRONOMY)

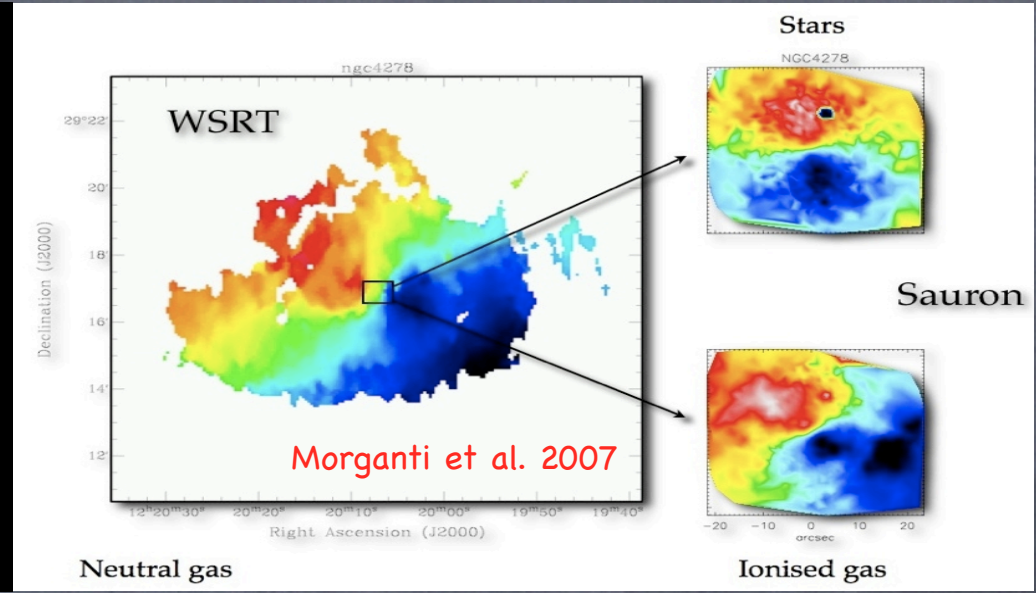
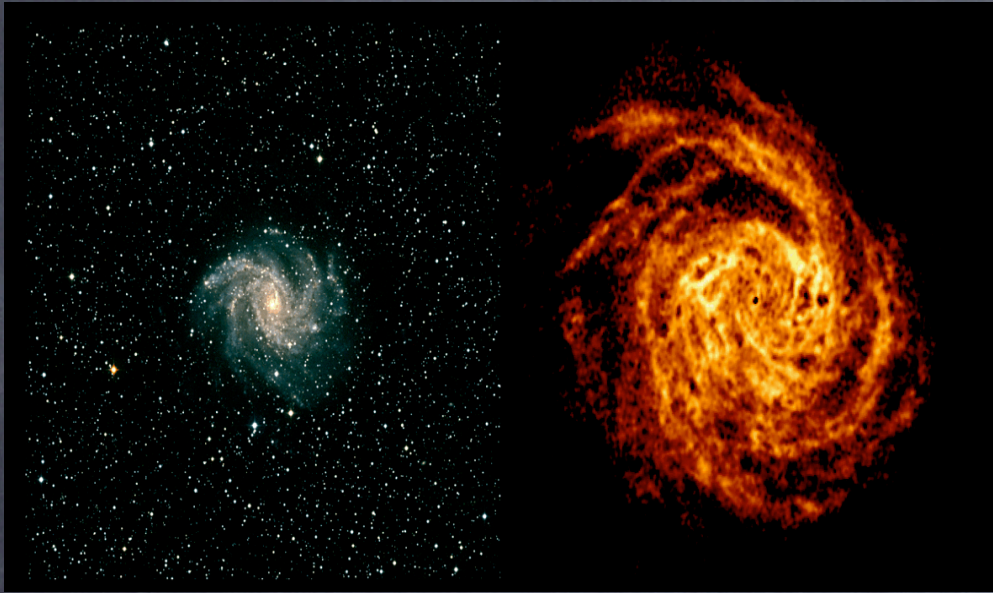


Nearby Galaxies (cont & HI) - WSRT - Braun et al.

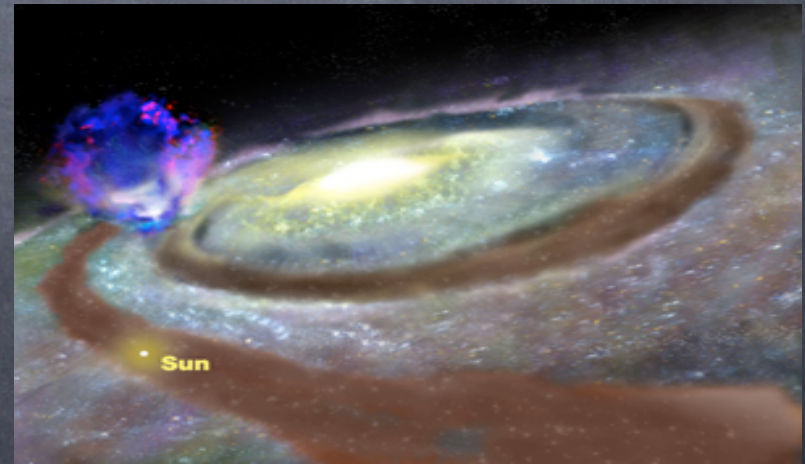
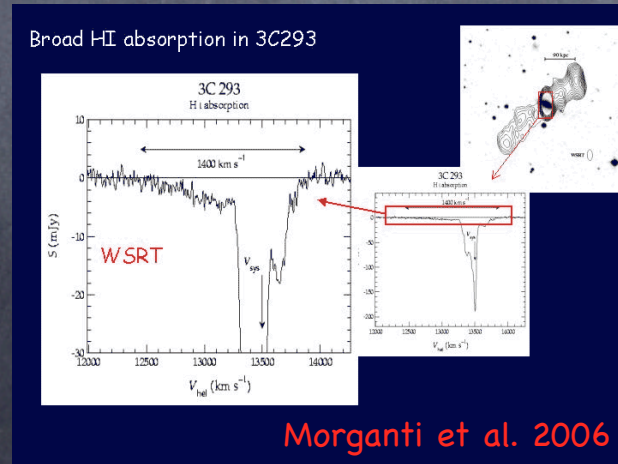


HI in Galaxies - emission & Absorption

Dynamics of stars, neutral gas (HI) and ionised gas:



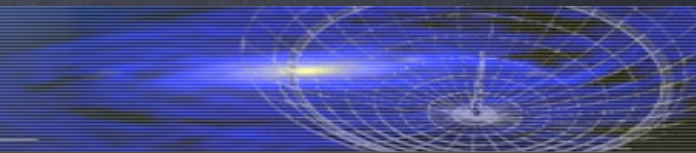
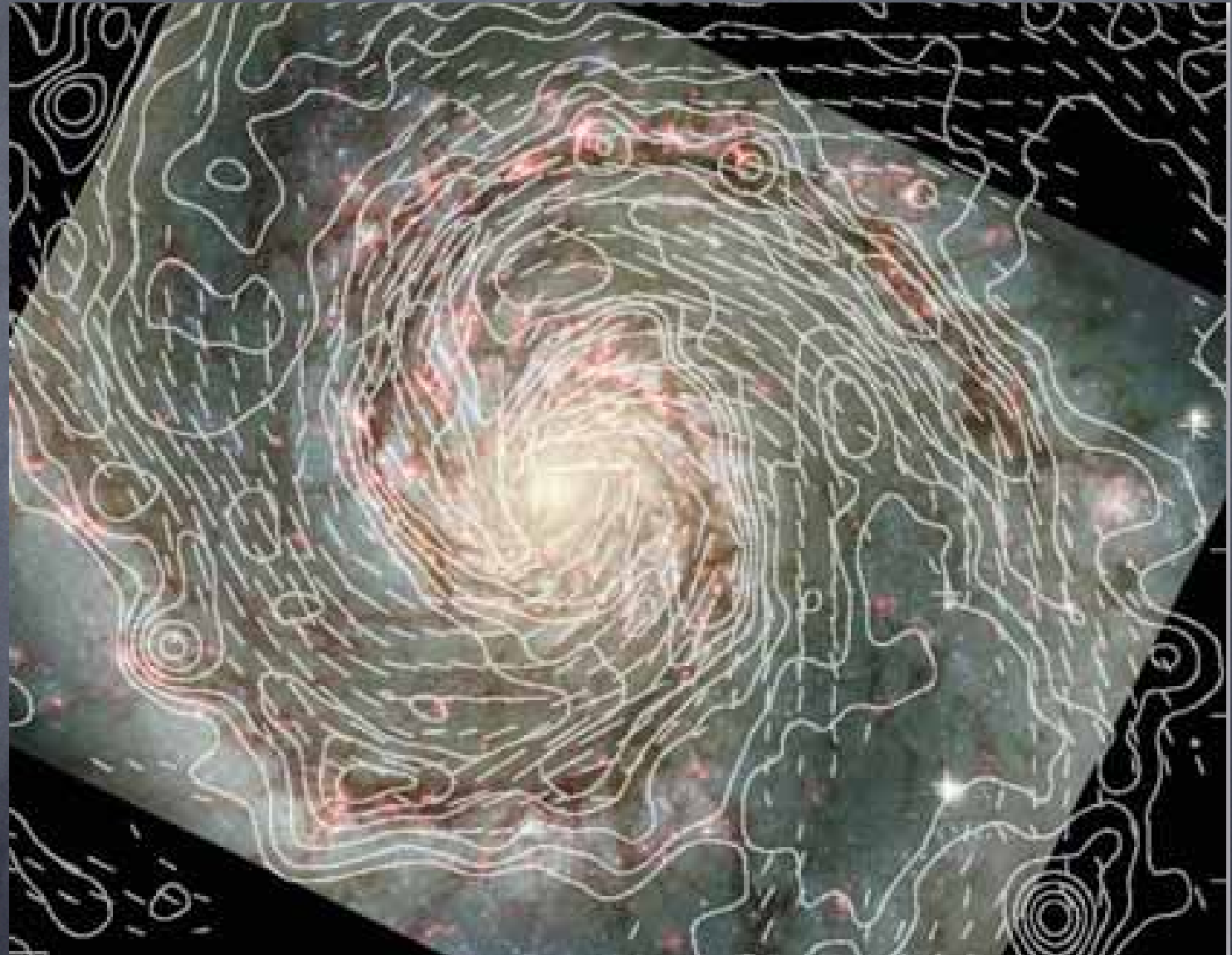
HI absorption against bright AGN reveals outflow and inflow of gas



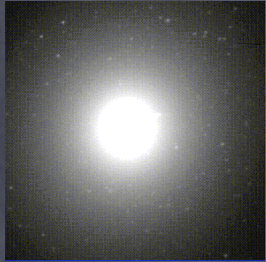
The magnetic Universe...

Polarised Radio
emission:

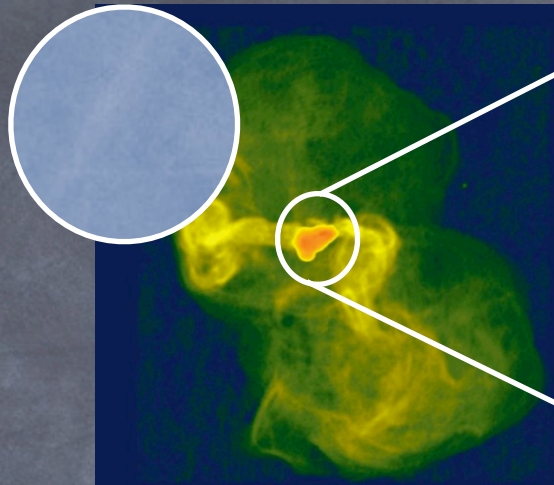
SPECIAL: Just
about the only
way to study
magnetic fields
in the ISM, in
galaxies, & AGN



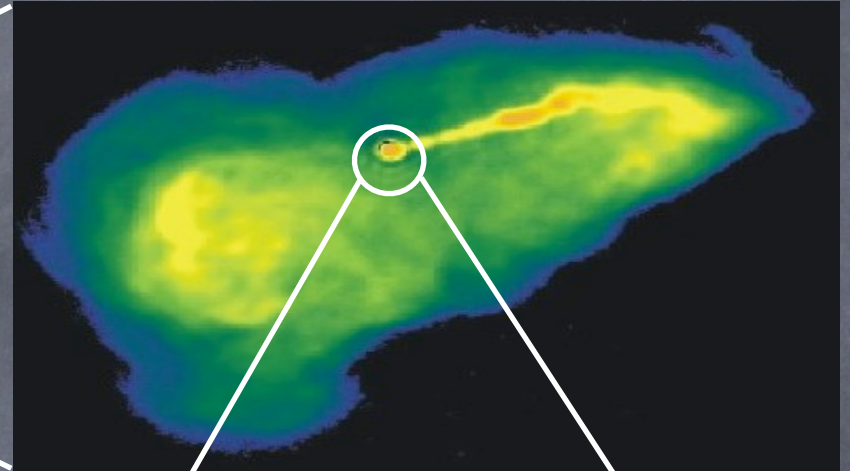
AGN - Imaging on all scales - M87 an example



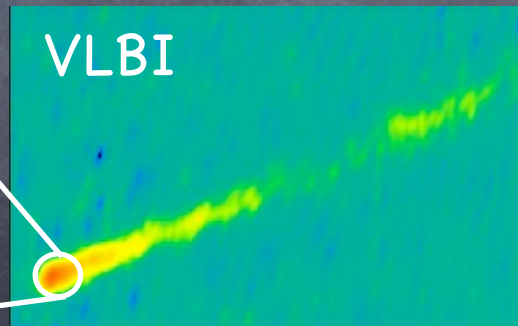
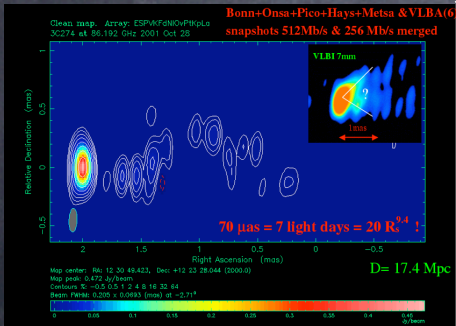
Kitt Peak 2-m optical



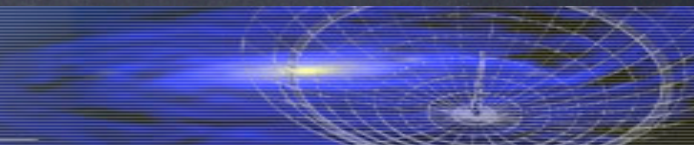
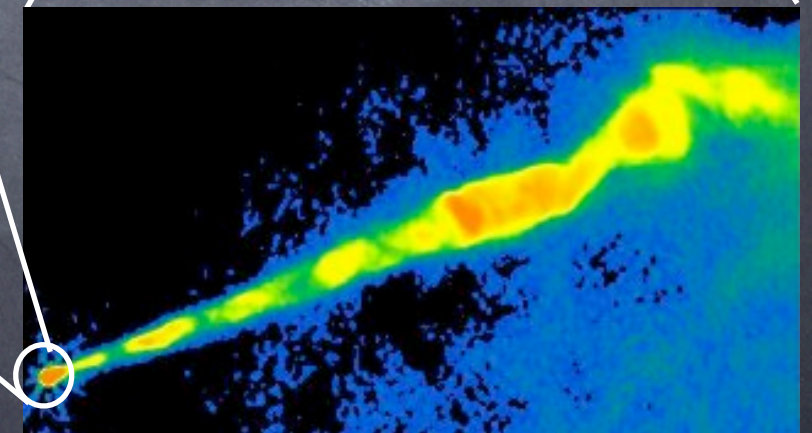
~ 80kpc



mm-VLBI

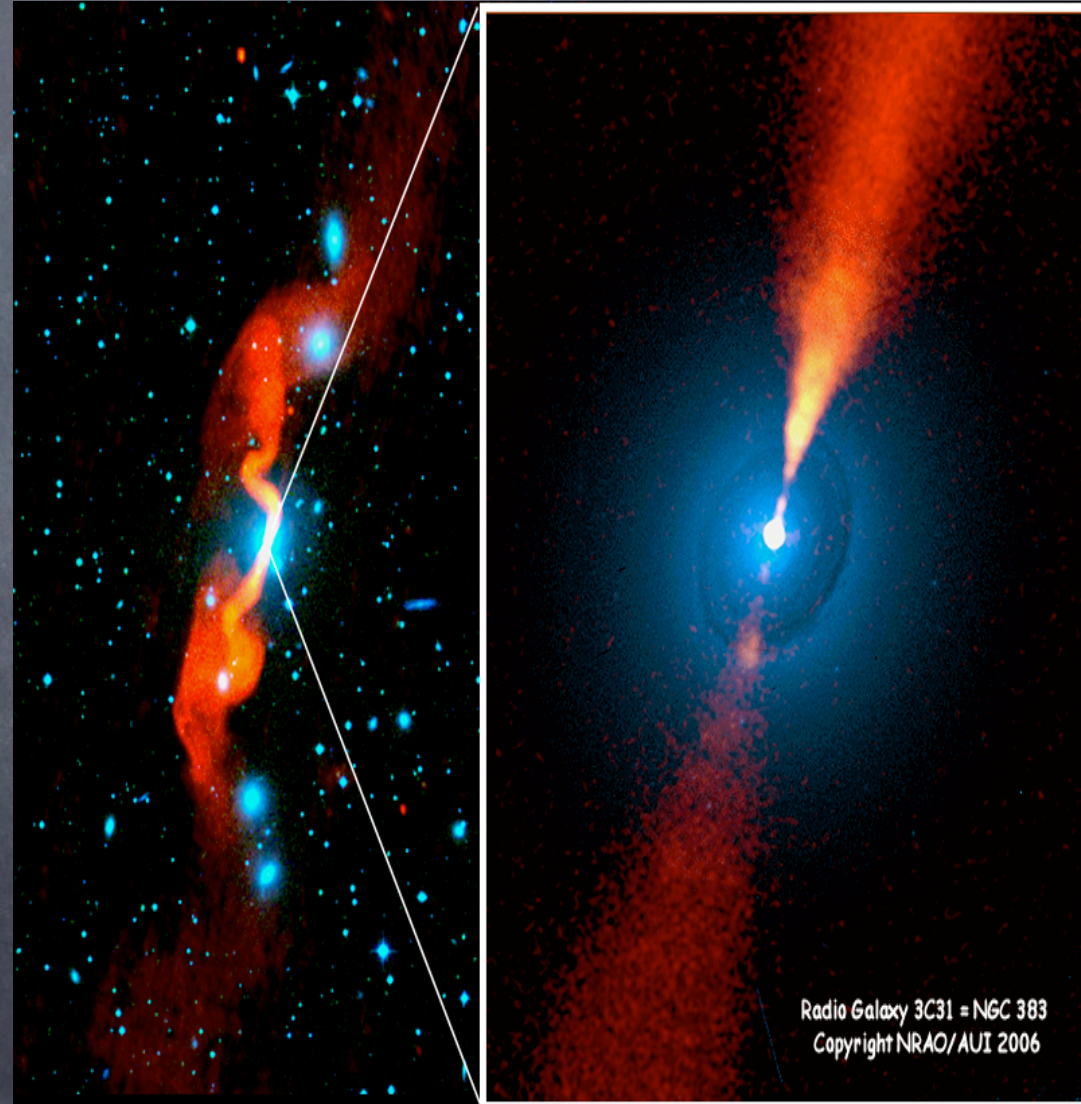
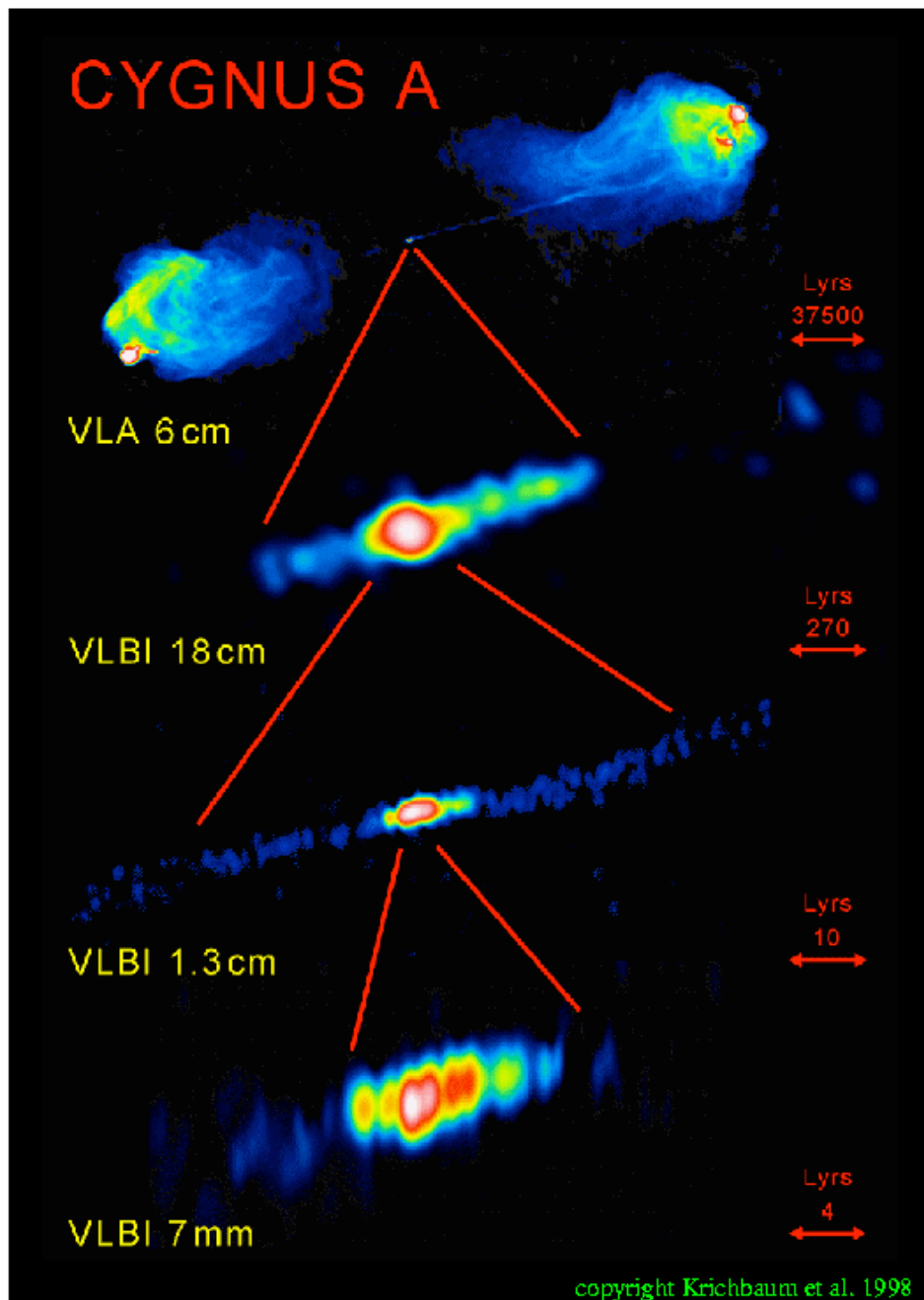


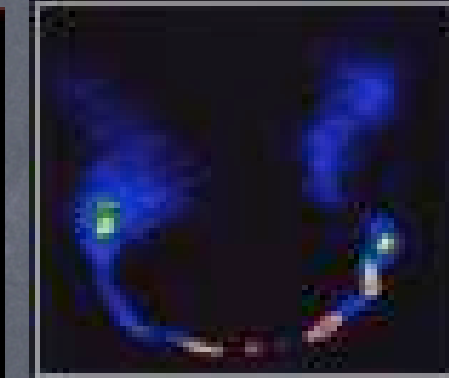
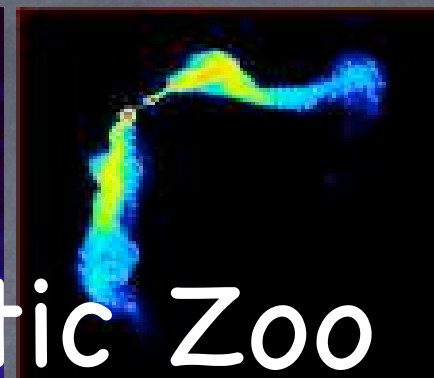
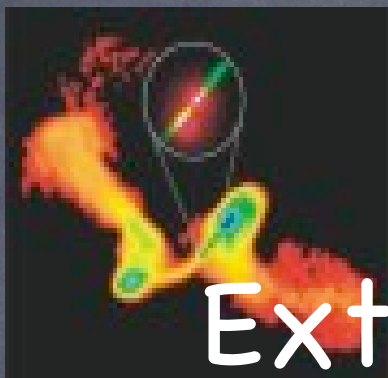
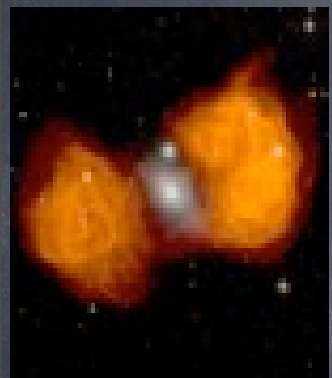
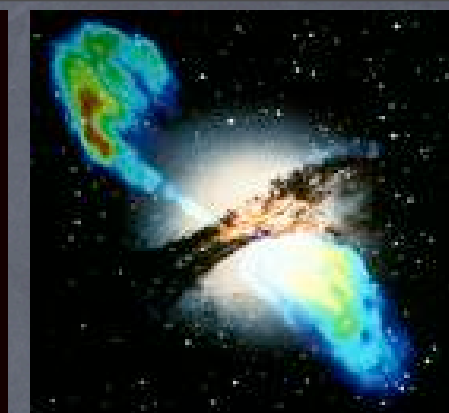
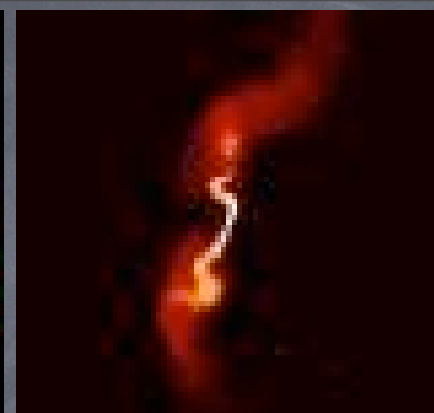
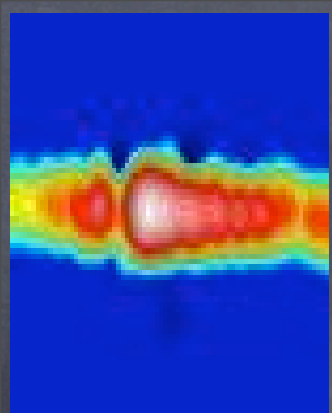
~ sub-pc



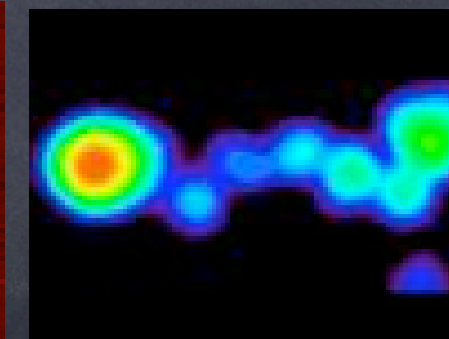
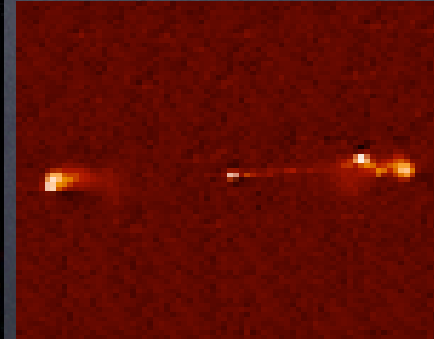
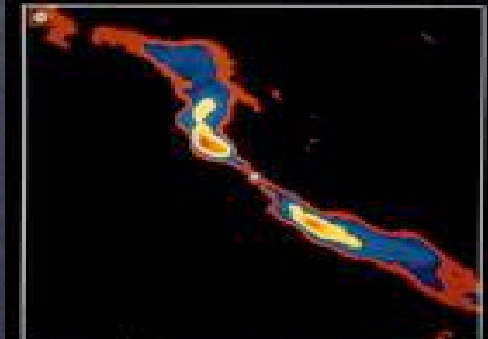
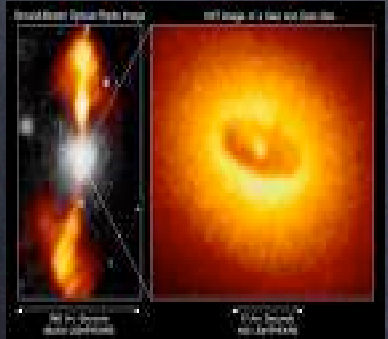
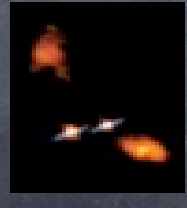
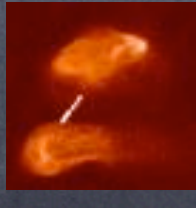
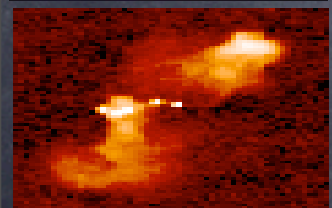
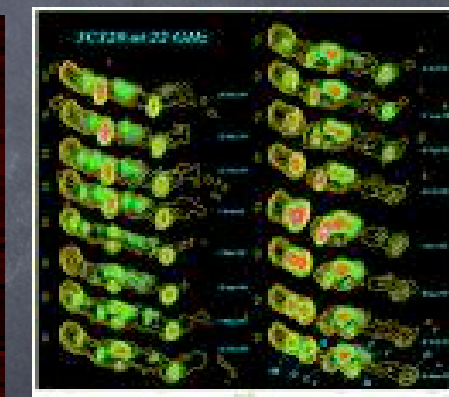
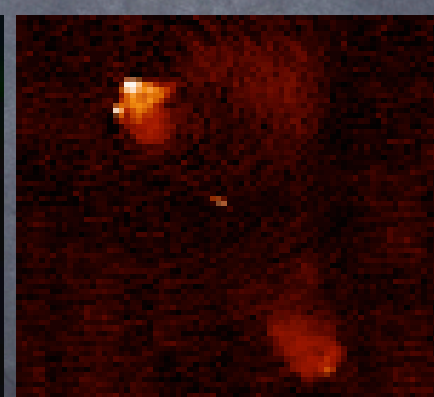
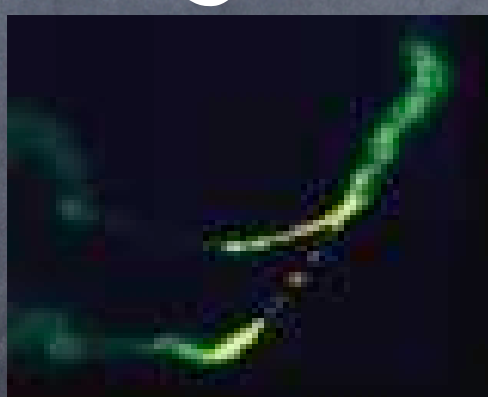
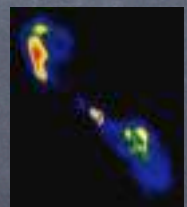
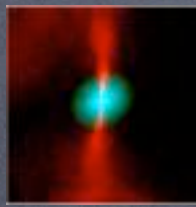
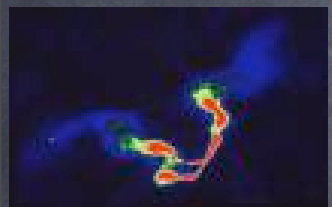
Many other examples of powerful radio galaxies

Powerful radio galaxies usually associated with Elliptical galaxies



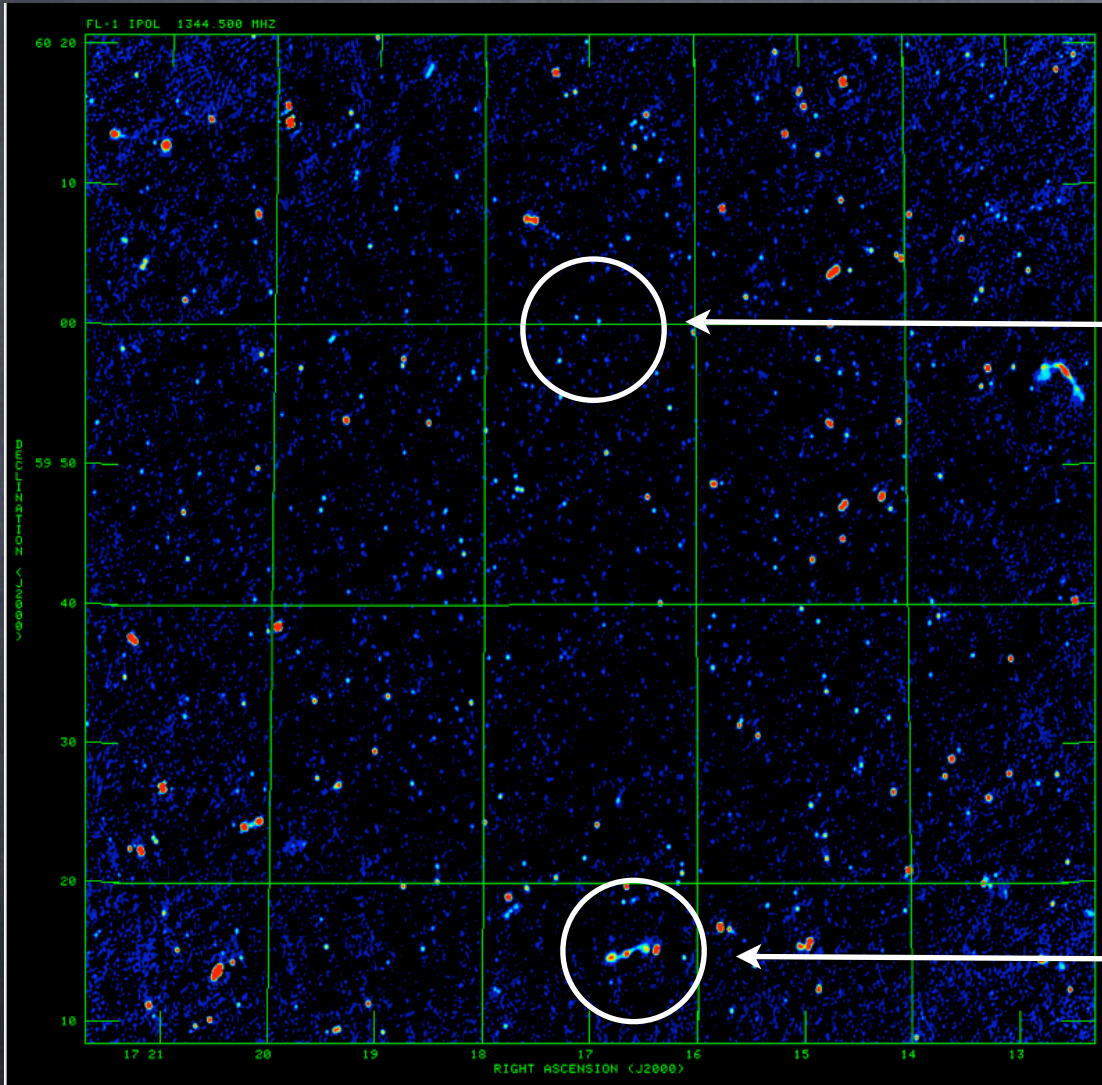


Extra-galactic Zoo

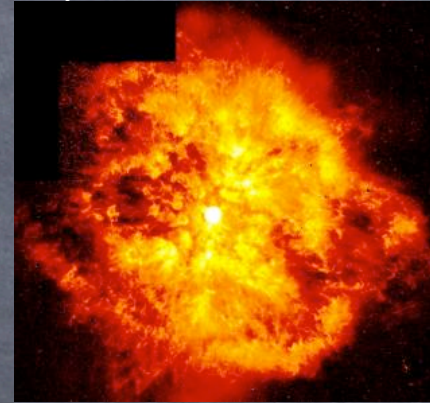


The silent majority - faint radio sources

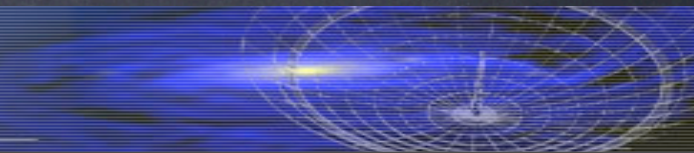
As you go deeper in the radio, the Universe comes towards you!



Mostly moderate redshift
star-forming galaxies
==> radio emission powered
by massive star formation.

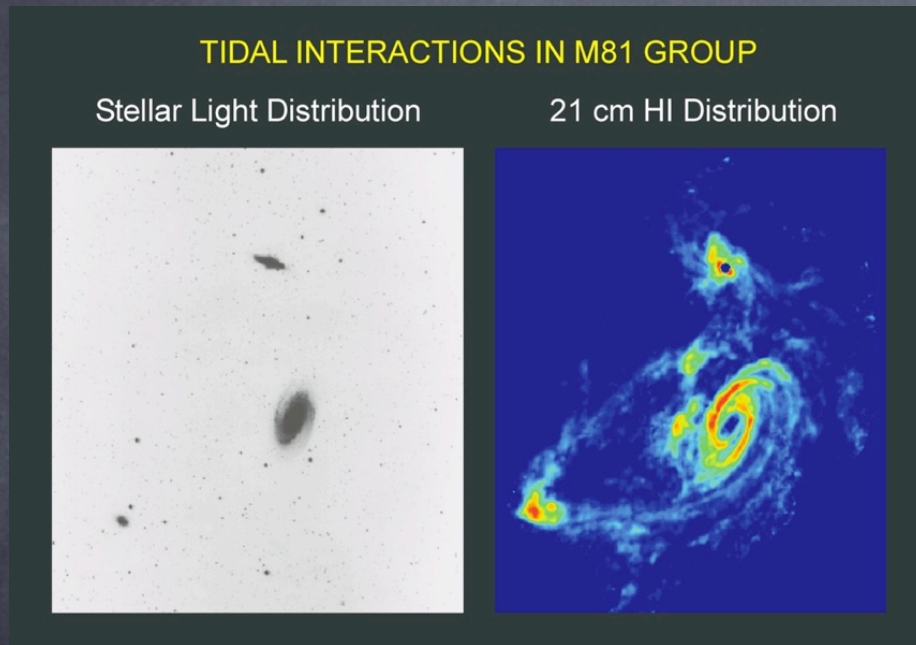


AGN monster



Resolution still important for these faint sources...

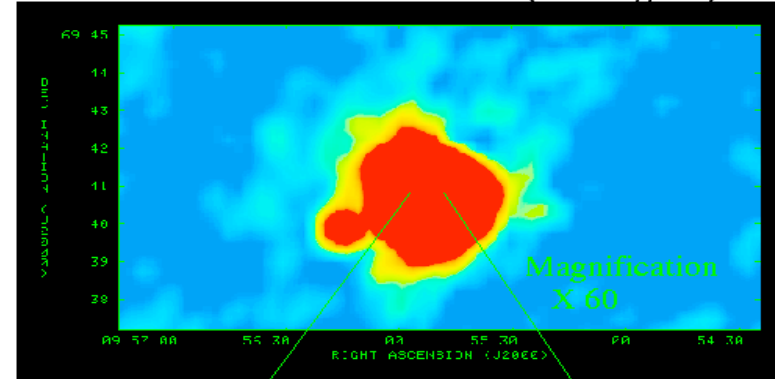
Star forming galaxies - radio emission on galactic/sub-galactic scale e.g. M82



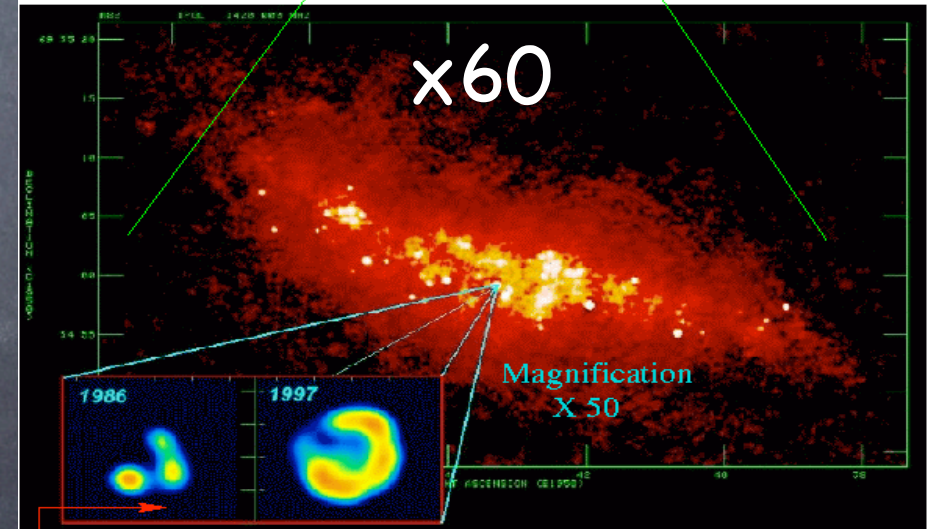
Extended emission on kpc scale
SNe and SNR on tens of pc.

M82 Starburst Galaxy - observed with increasing RESOLUTION

VLA 20cm Resolution = 45 arcsecs (0.01 degrees)

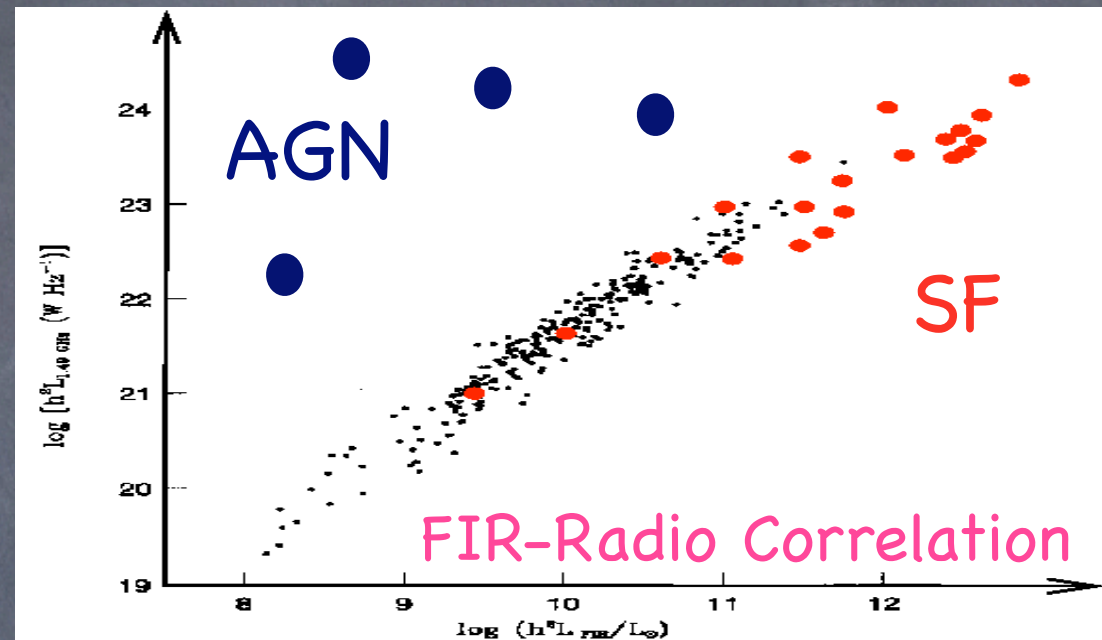
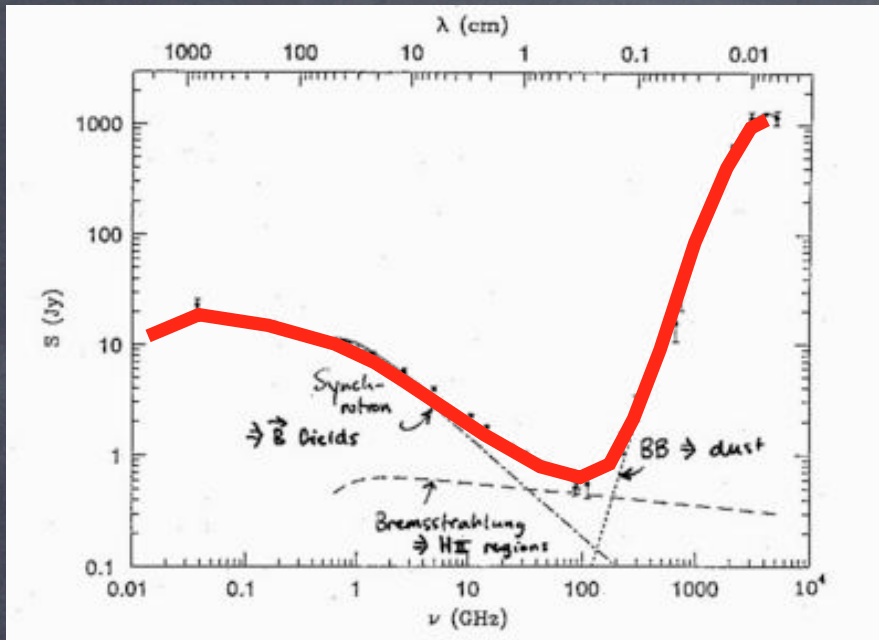


VLA/MERLIN 18cm Resolution = 0.75 arcsec



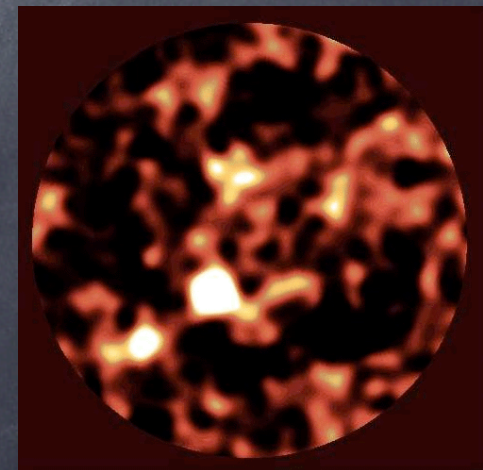
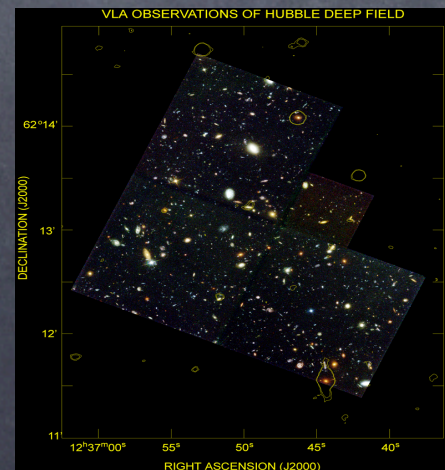
European VLBI Network 18cm Resolution = 0.015 arcsec

Radio-FIR Spectral Energy Distribution of "Normal" Galaxies (e.g. Milky Way, M82):



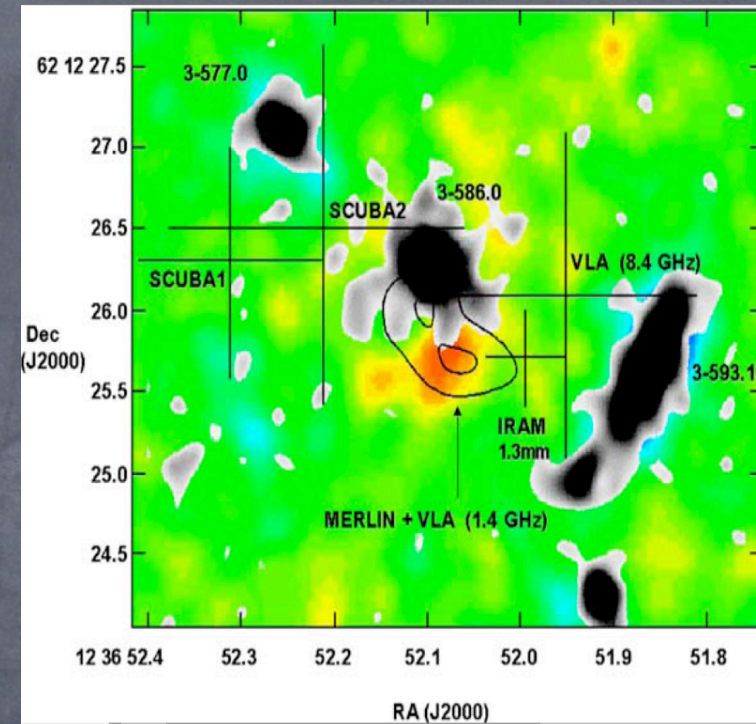
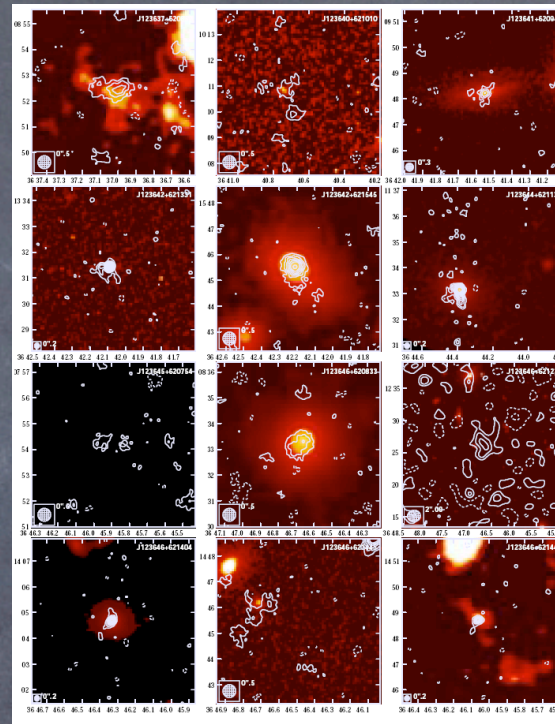
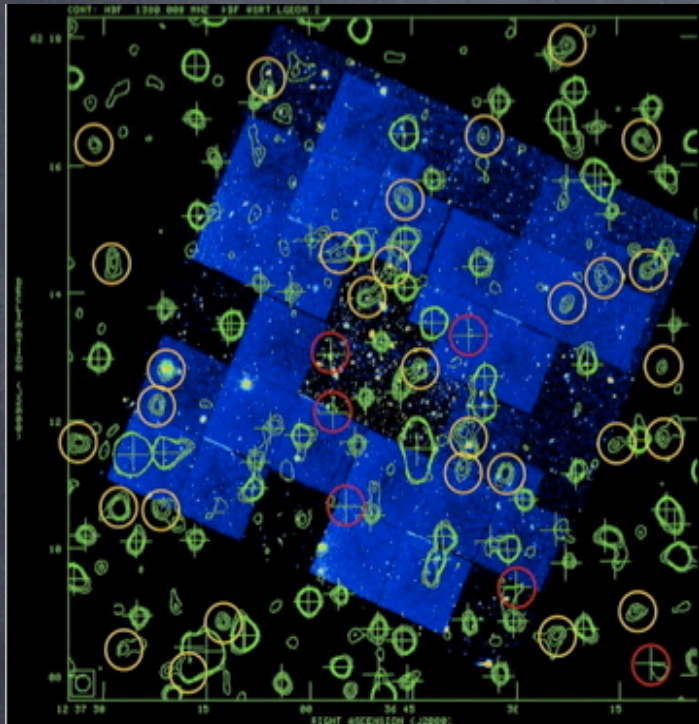
Both Radio and FIR (sub-mm at high redshift) are sensitive measures of MASSIVE Star formation in the local and distant galaxies.

Radio and sub-mm observations closely allied in the study of the DUSTY High-z Universe.



Going even deeper... microJy source population

A few areas of sky studied at μJy levels (e.g. HDF-N, Muxlow et al. 2005)

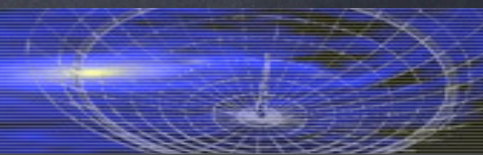


MicroJy sensitivity Universe begins to move away from us - high-z

The faintest radio sources dust obscured - no optical id - Sub-mm associations - Good ASTROMETRY - **SPECIAL**

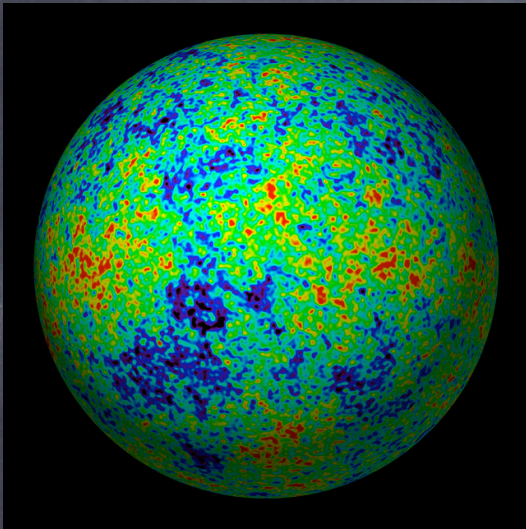


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Radio Interferometry & Cosmology

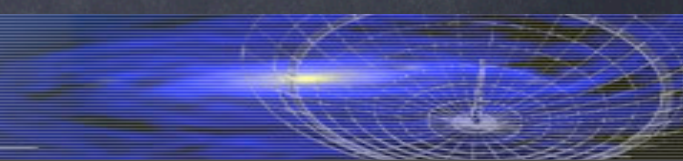
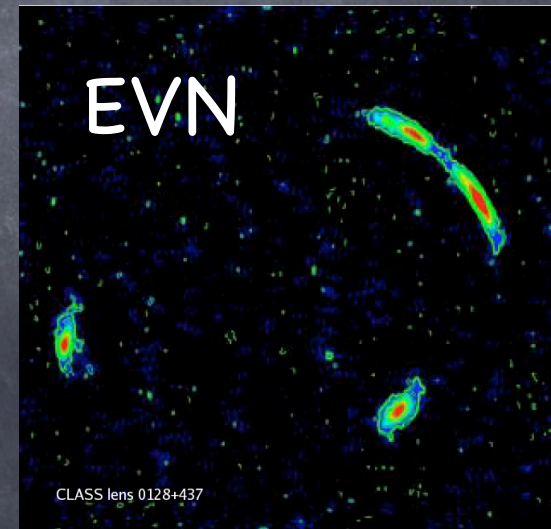
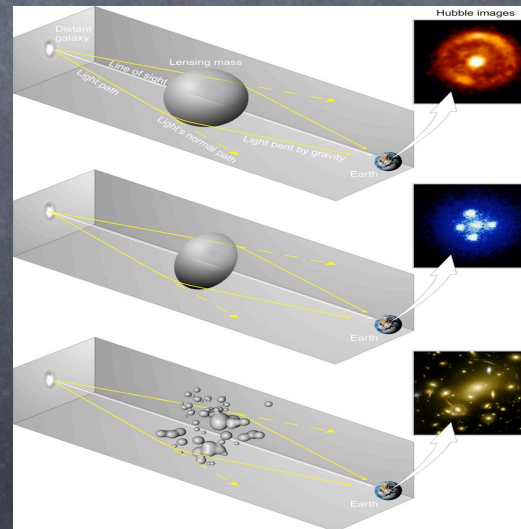
CMB experiments - interferometry offers many advantages...



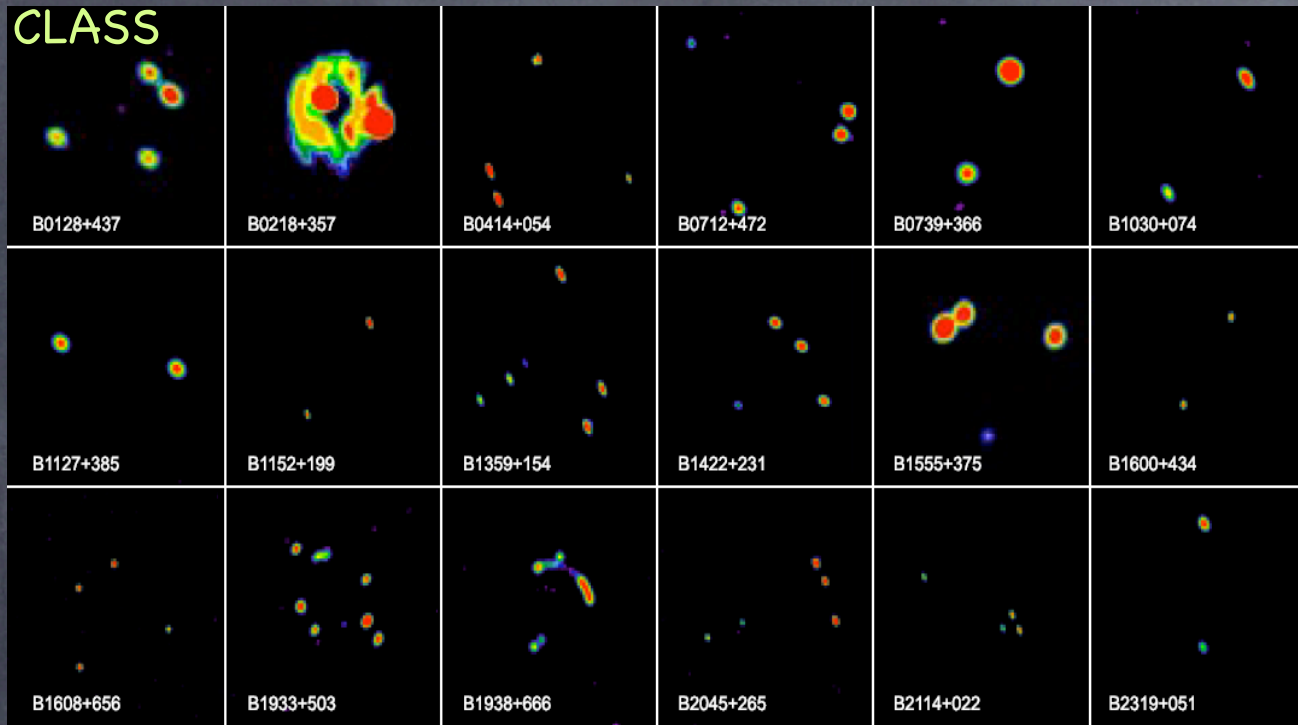
SPECIAL: Noise is independent for each antenna - disappears during correlation e.g. RFI -

Gravitational lensing - Ho

High resolution of radio interferometers makes them ideal for detecting and imaging resolved gravitational lens phenomena



Gravitational lens surveys



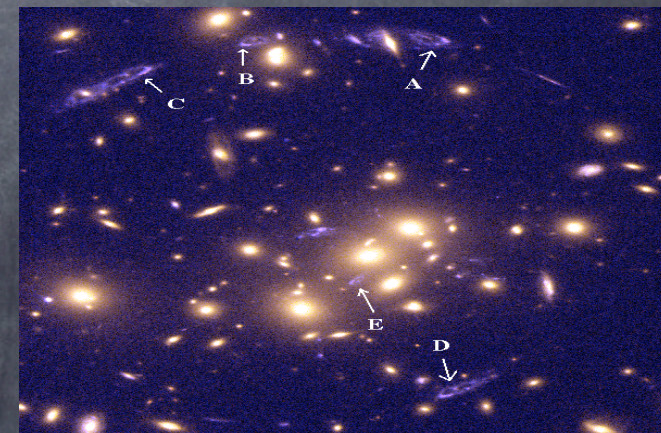
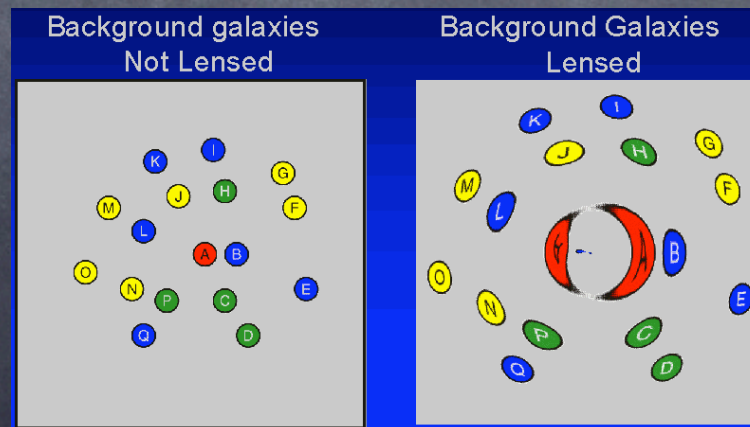
Radio surveys ideal for finding lenses...

Source population typically at high- z

Separation ~ 1 arcsec

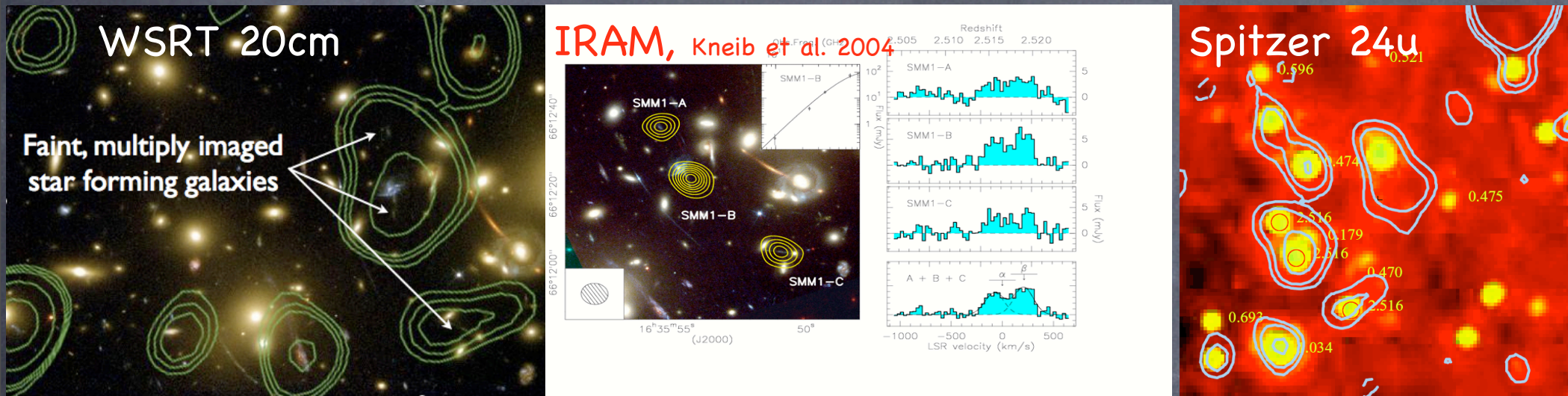
Flat spectrum radio sources rare.

Gravitational lensing - also **MAGNIFIES** sources



Lenses as giant cosmic magnifying glasses:

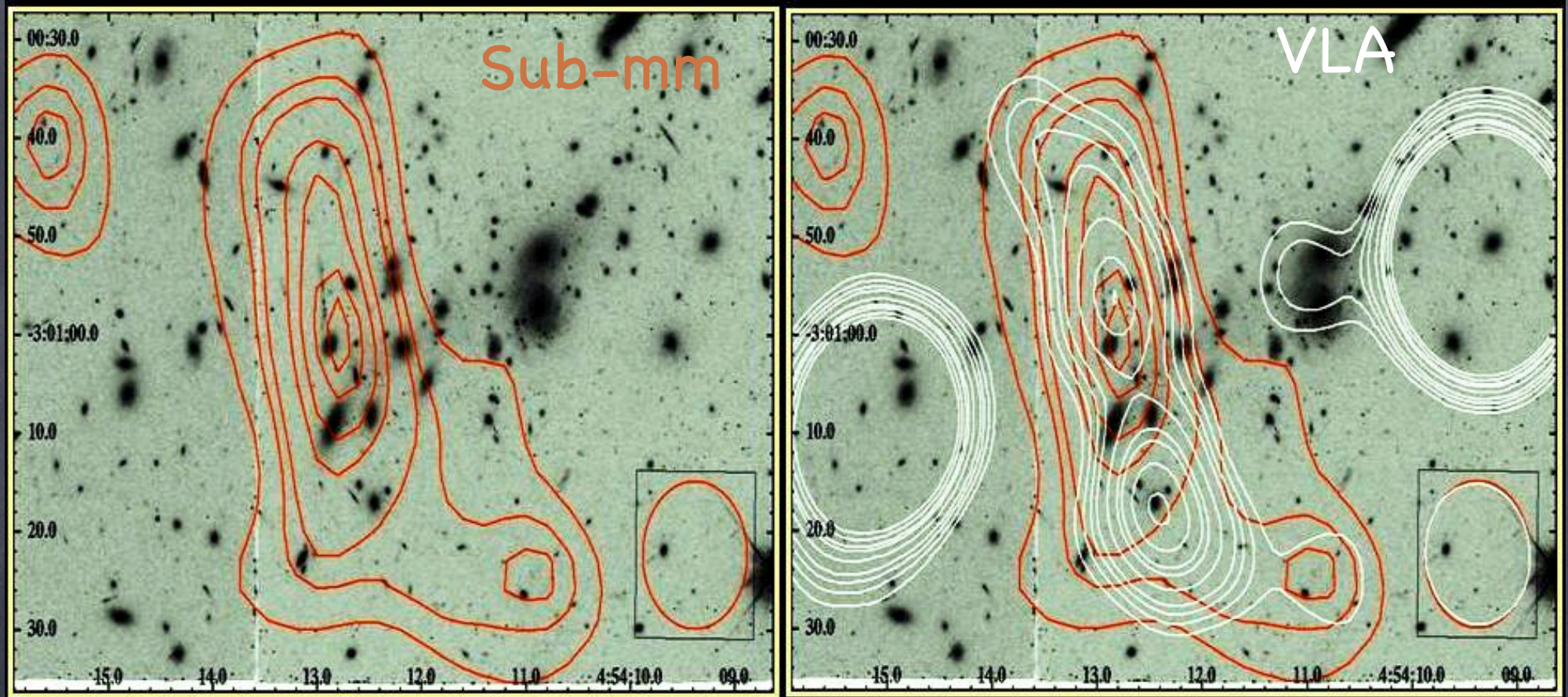
Magnification permits us to detect cosmologically distant star forming galaxies e.g. Garrett et al. 2005; Berciano Alba et al. (2007); Garrett et al. (in prep).



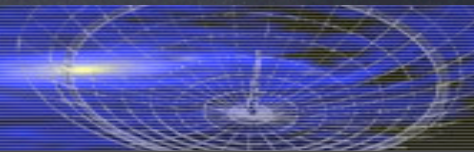
Total magnification of cluster is $\times 45$

Source is an intrinsically faint, $z=2.5$ SMG & μJy radio source - undetectable without the lens.

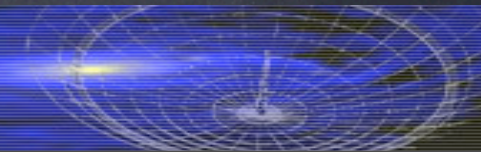
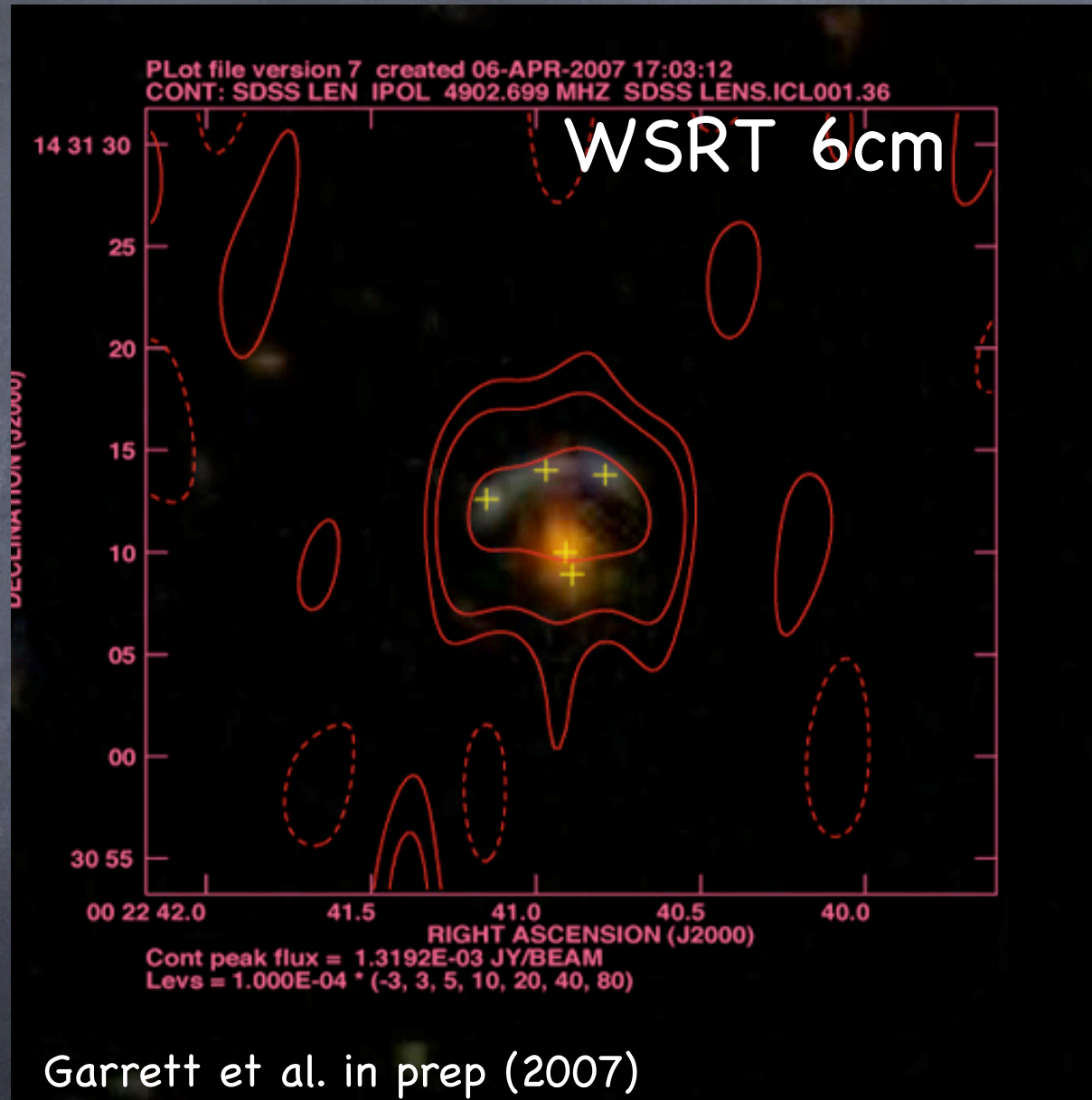
More [lensed] distant star-forming galaxies



Berciano alba et al. (2007)



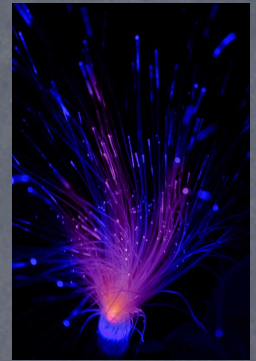
Most luminous Ly-break Galaxy (8 o'clock lens)



The Future...

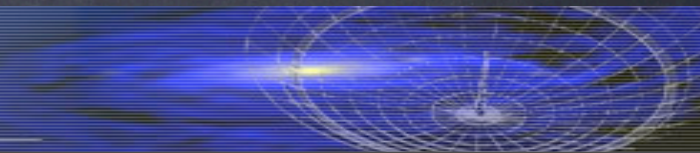
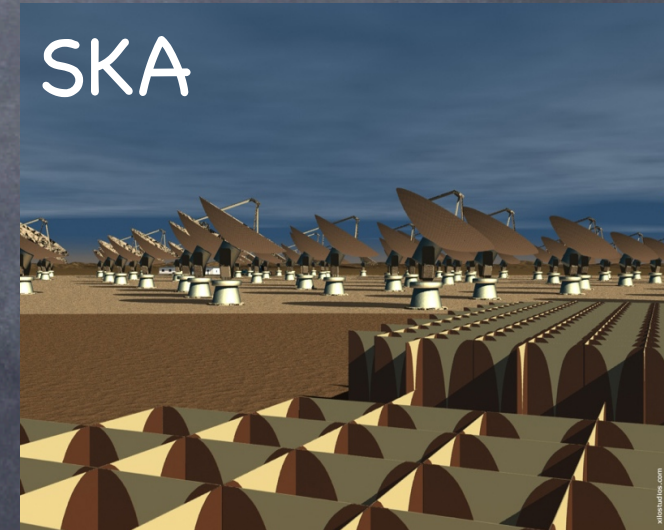
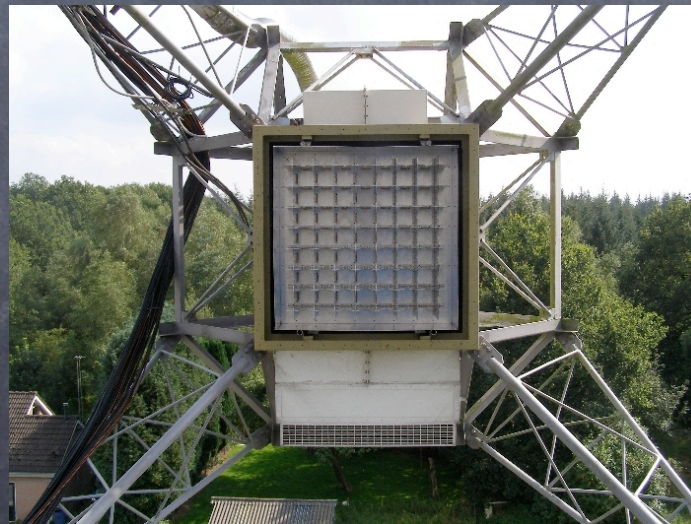
Activity is intense!

Many telescope upgrades in progress: EVLA, e-MERLIN, e-VLBI (2009)

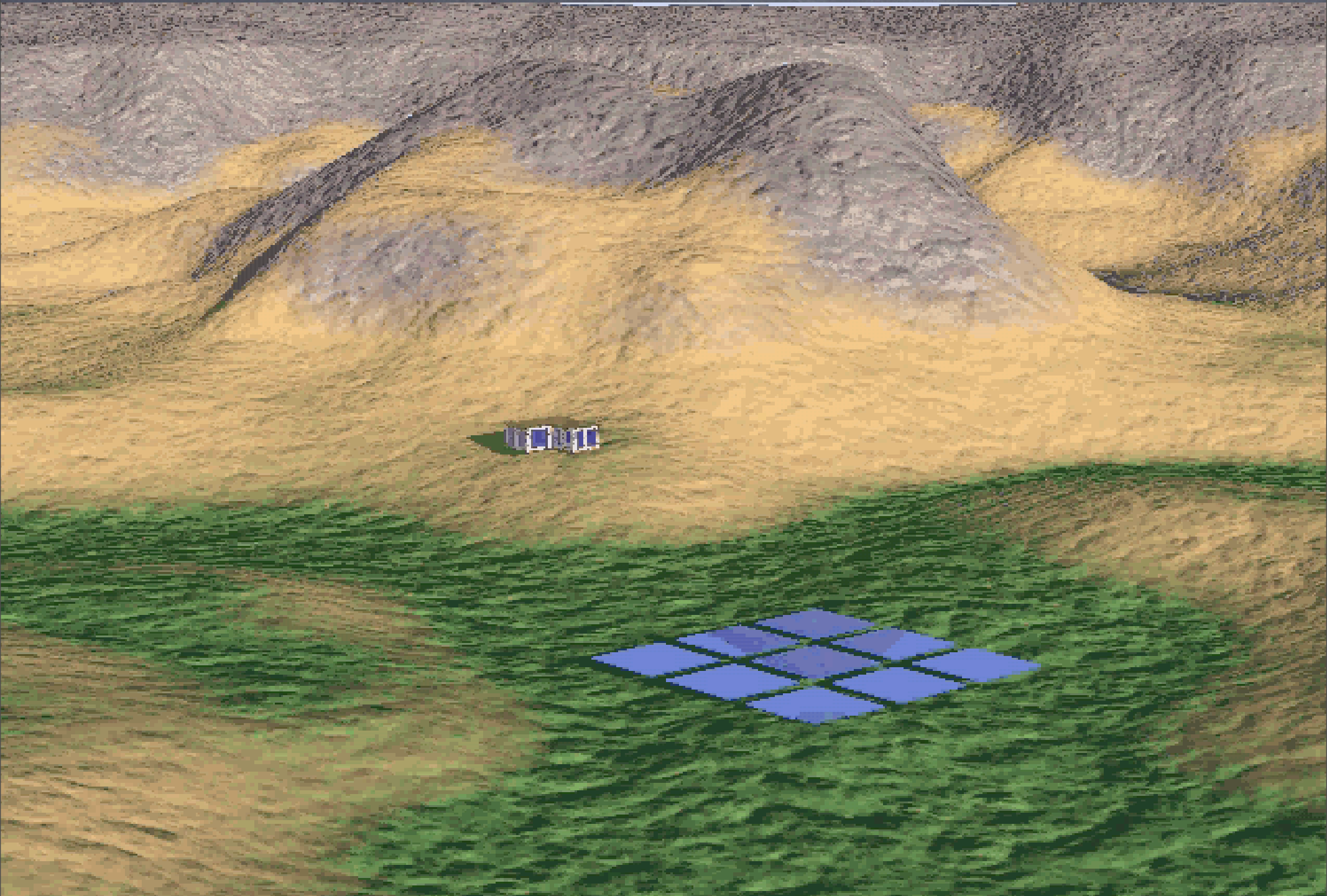


Many NEW telescope arrays under construction (pathfinders for the Square Km Array): ATA, LOFAR, MWA, ASKAP, MeerKAT.

Key issues are cost and field-of-view:



● Aperture Arrays - multiple, independent, simultaneous beams (LOFAR)



LOFAR (ASTRON)

E-LOFAR

**Expansion of LOFAR
into Europe...**



40 stations

Current status:

Germany ~12 stations

UK ~2-3 stations

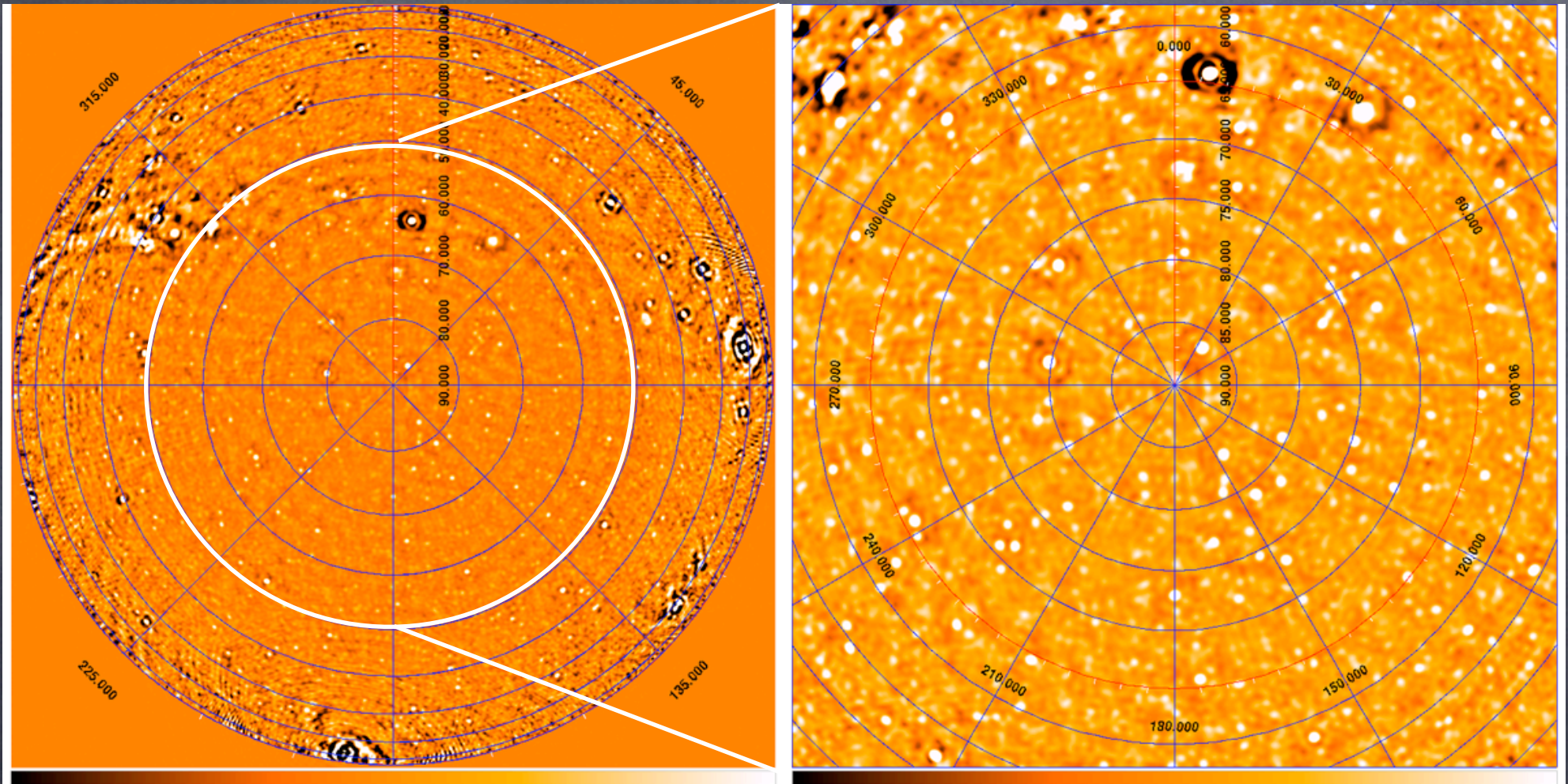
Italy ~2 stations

France ~1 station?

Other EVN sites...

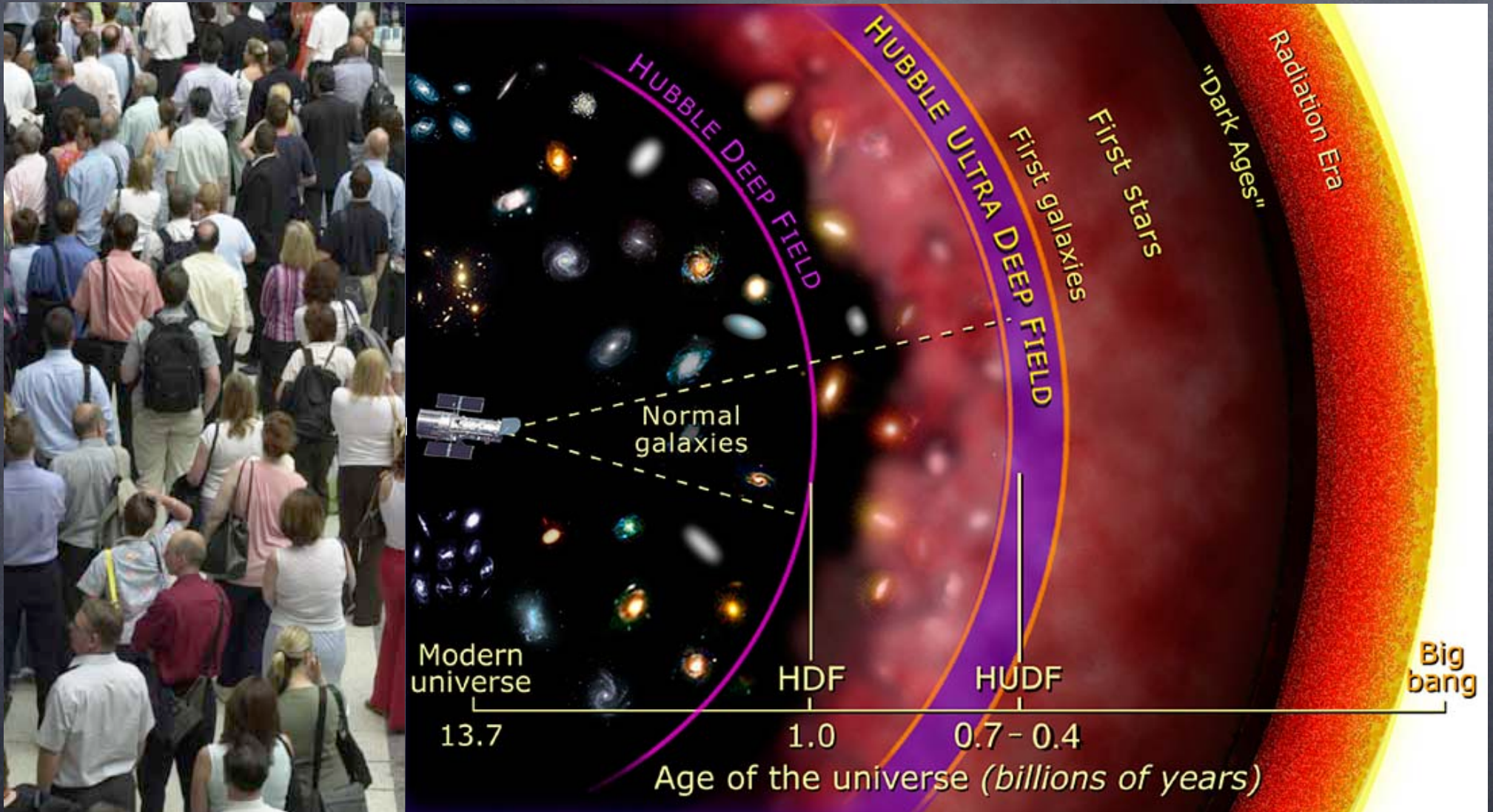


LOFAR first images (see Ger de Bruyn's lecture)

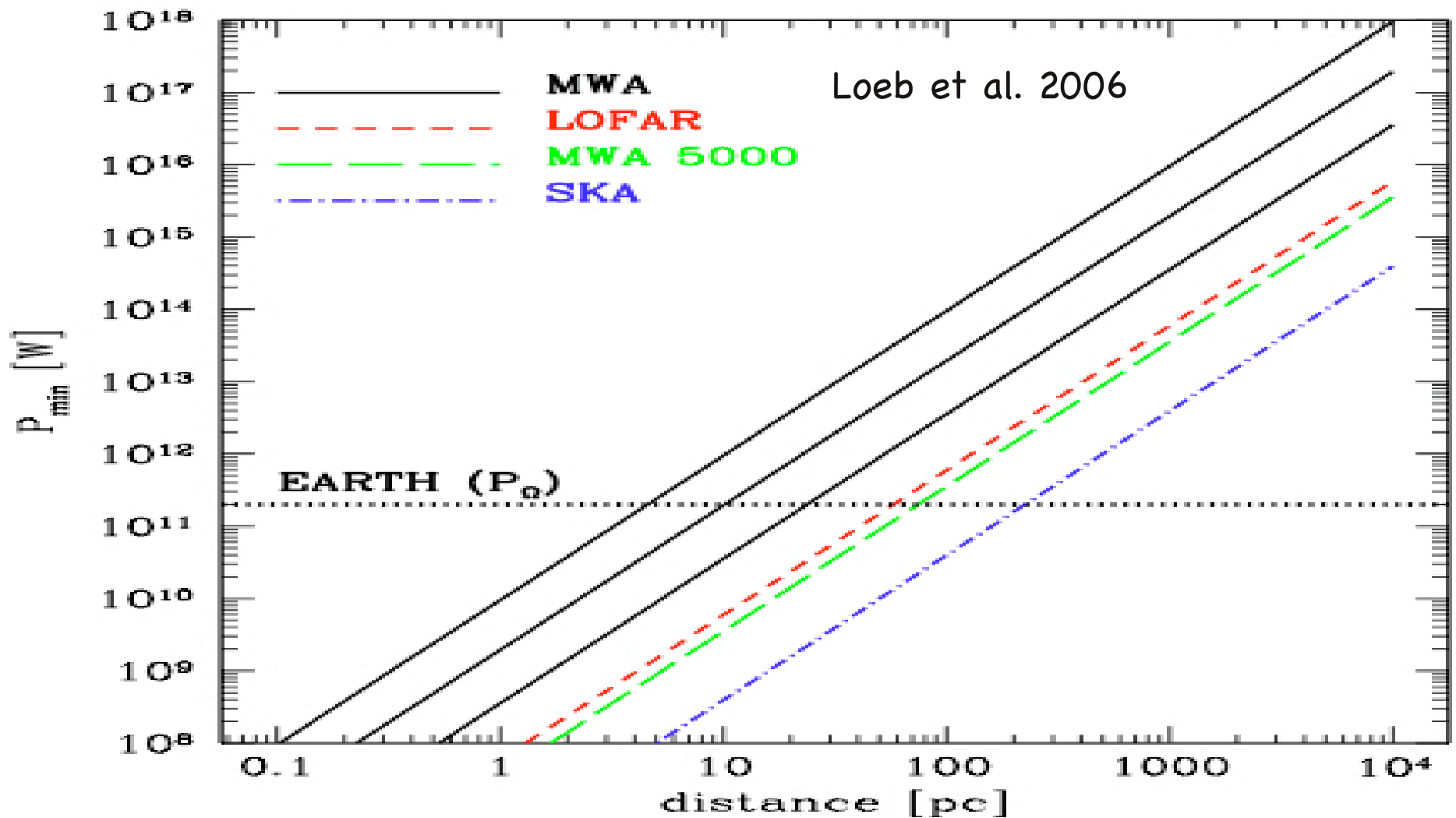


Amazing Field of view – superb survey instrument
– if we can calibrate it!

Understanding the Universe

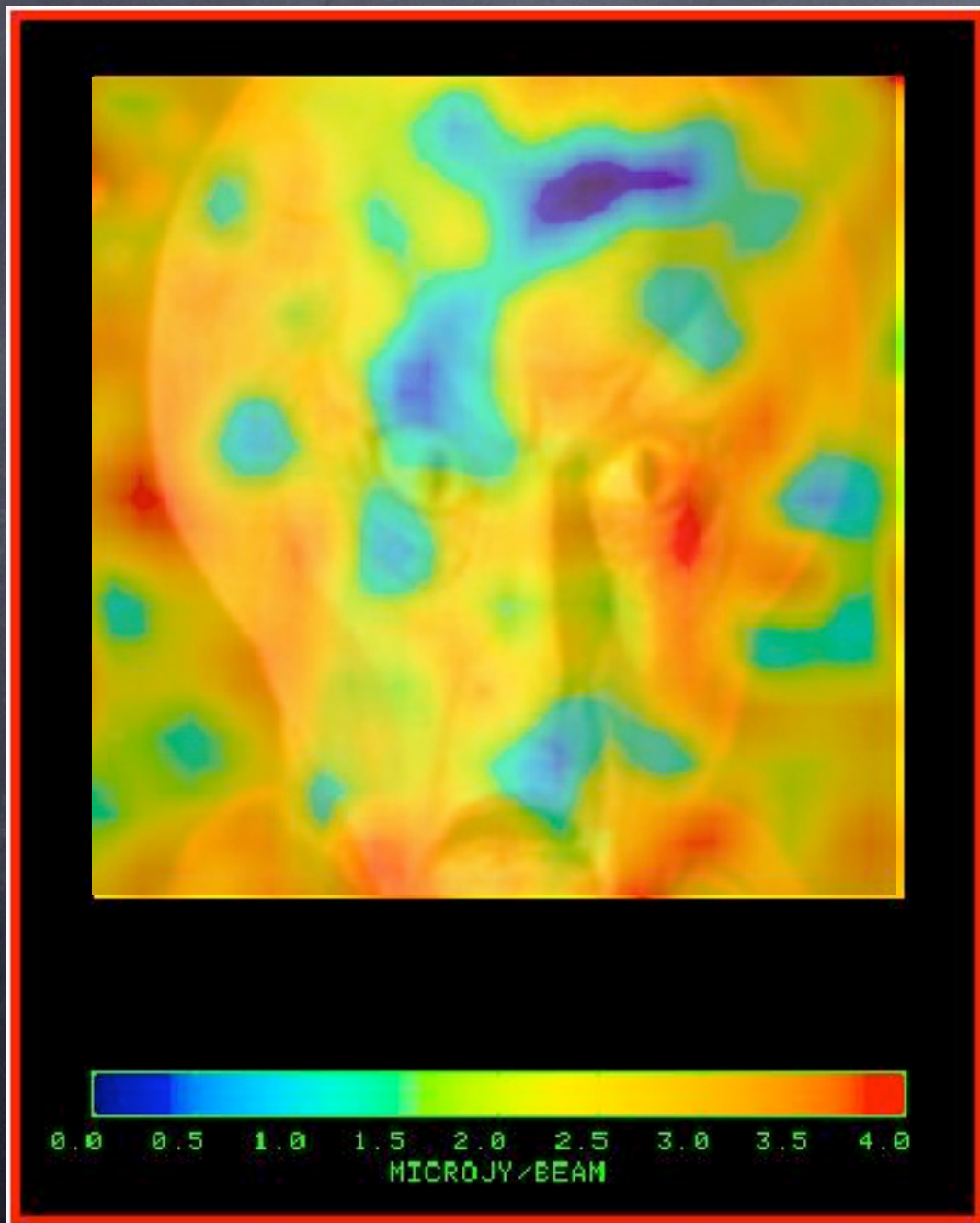


Amazing Field of view – superb survey instrument
– if we can calibrate it!



Maybe possible to detect leakage radiation from nearby Extra-terrestrial Civilisations...

Stacking 32000 G-type stars (NVSS)



3 μ Jy noise level
==> leakage from
planet >> G-type
stars

There has never been a better time to do...

RADIO ASTRONOMY!