NWO ASTRON LOFAR RadioNet EUROPEAN VLBI NETWORK SKADS SWINBURNE UNIVERSITY OF TECHNOLOGY

(NETHERLANDS FOUNDATION FOR RESEARCH IN ASTRONOMY)

Introduction to Radio Interferometers

Mike Garrett (ASTRON/Swinburne)

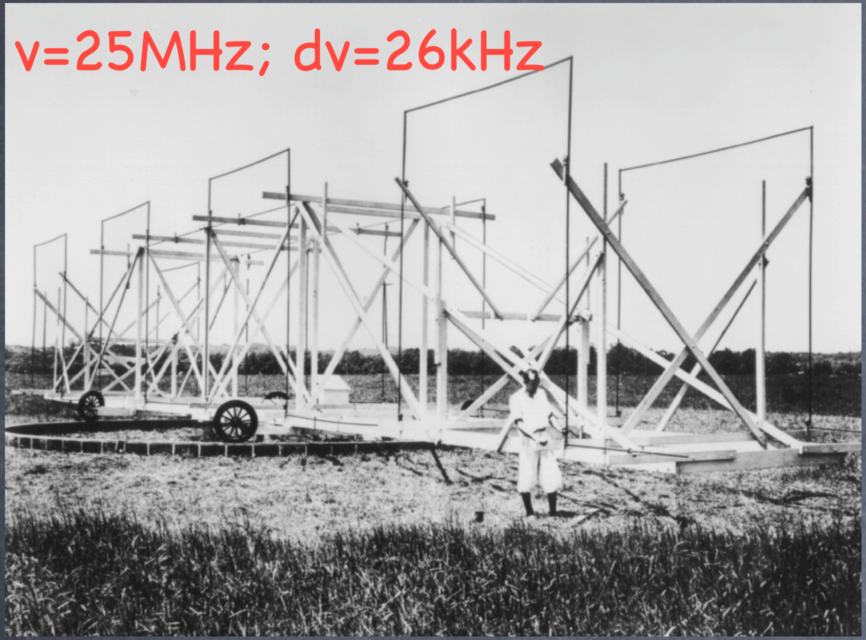
ERIS School - Bonn - Sep 11, 2007.

Overview of Lecture

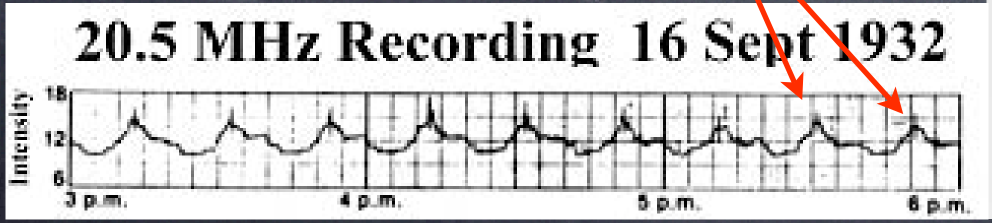
- Early radio astronomy
  – what makes radio astronomy "special"!
- Radio Interferometry
  – early days and motivation
- Interferometer arrays
  – metre, cm, mm and sub-mm wavelengths
- Types of object we can study - science
- The Future is VERY, VERY, VERY bright!

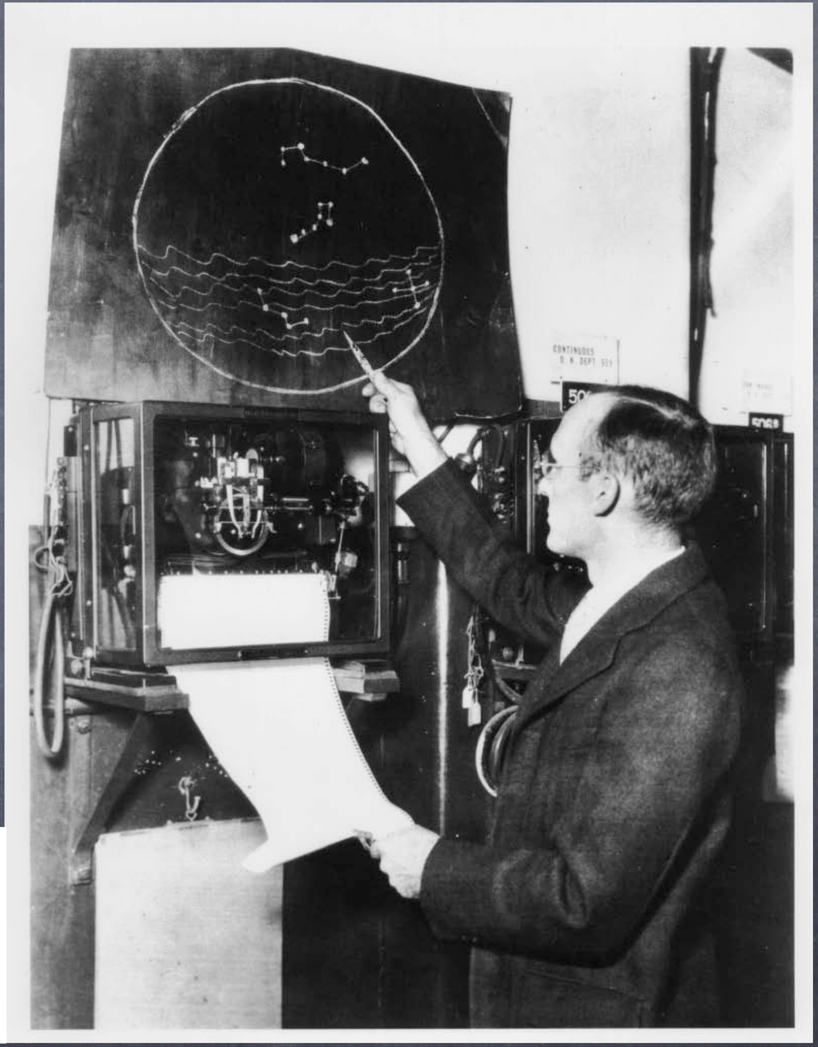
Early days of radio astronomy

- 1932 Discovery of cosmic radio waves (Karl Jansky)

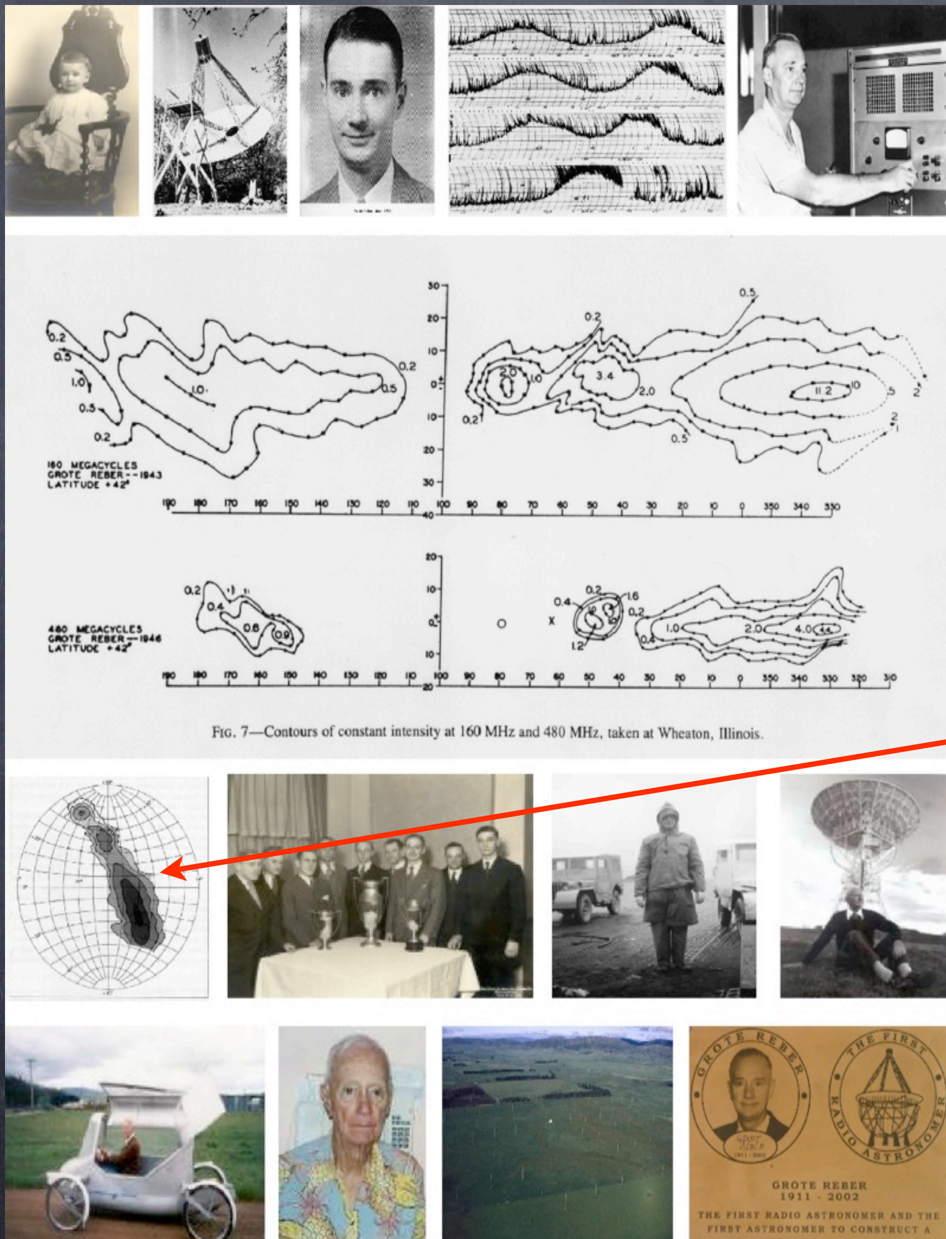


Galactic centre





The first radio astronomer (Grote Reber)



- 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

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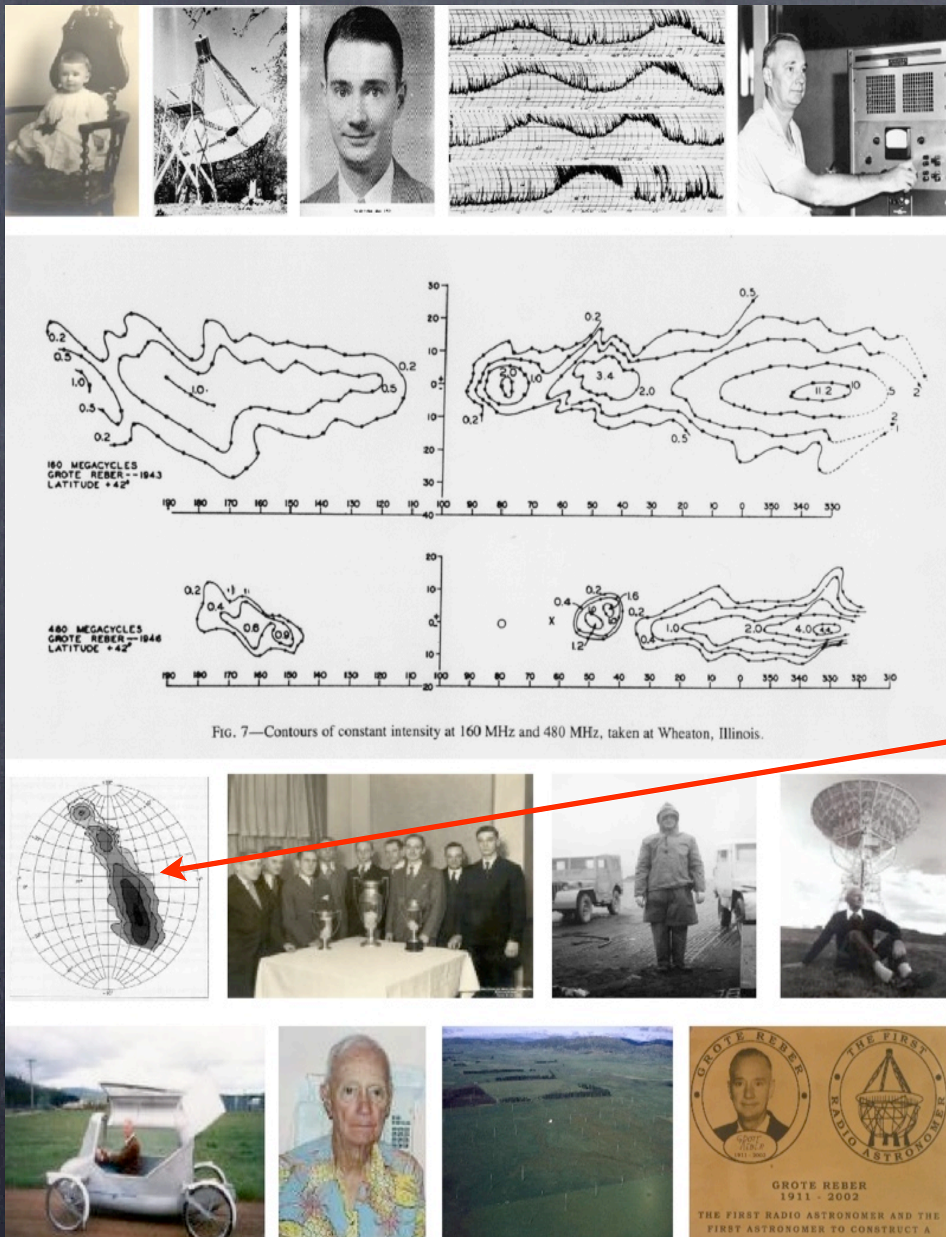

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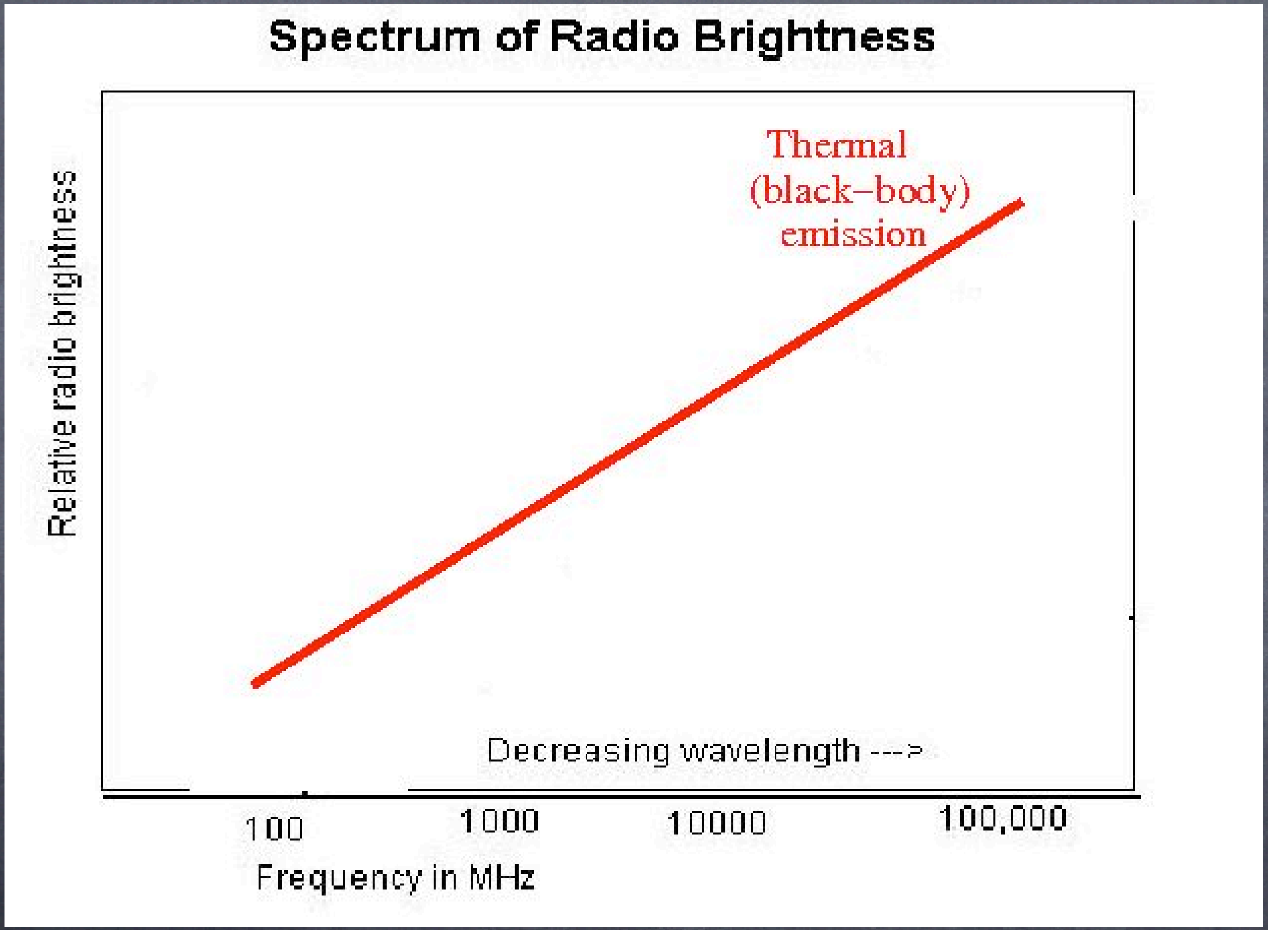
The things that make radio astronomy "special"

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



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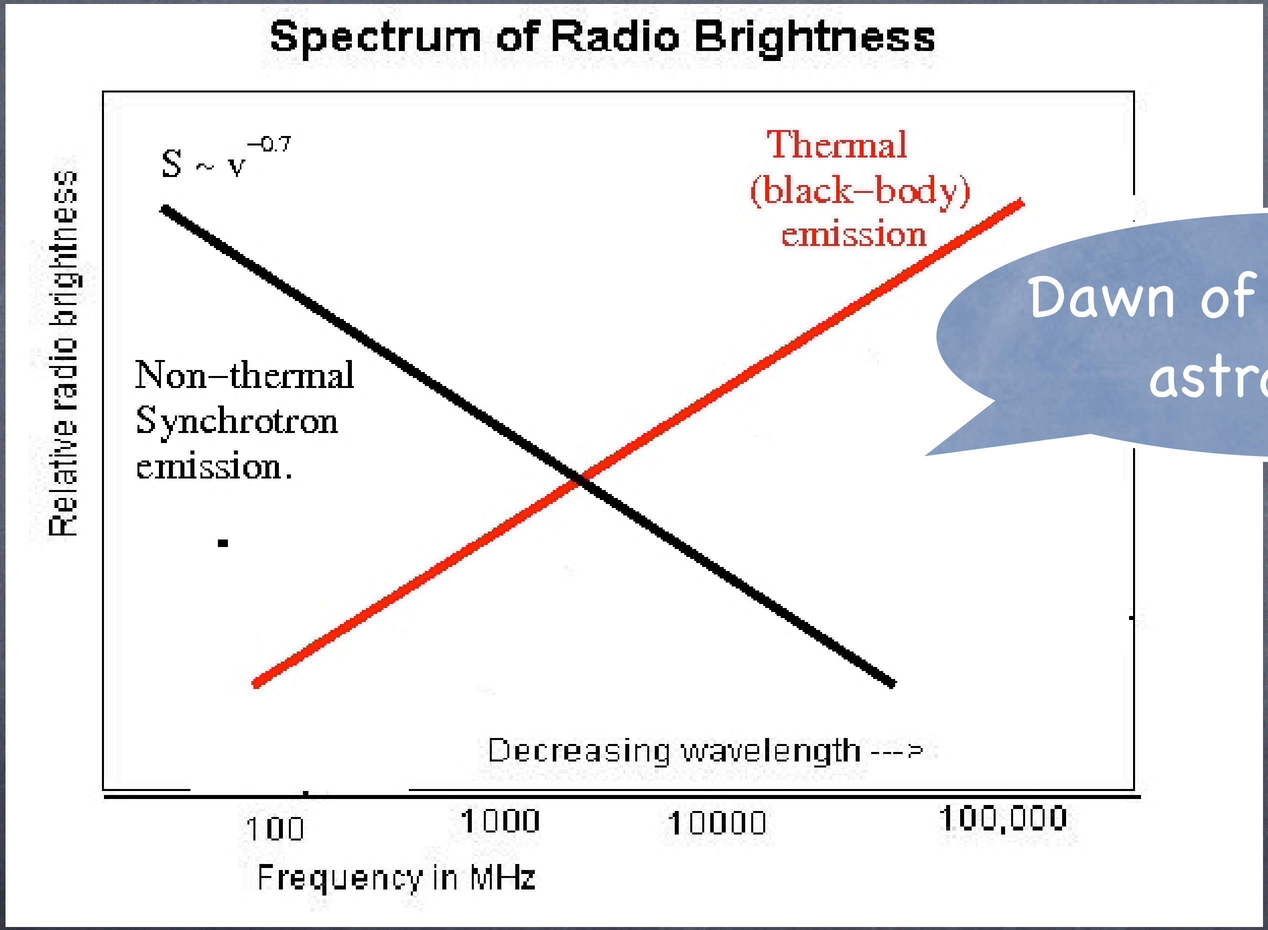
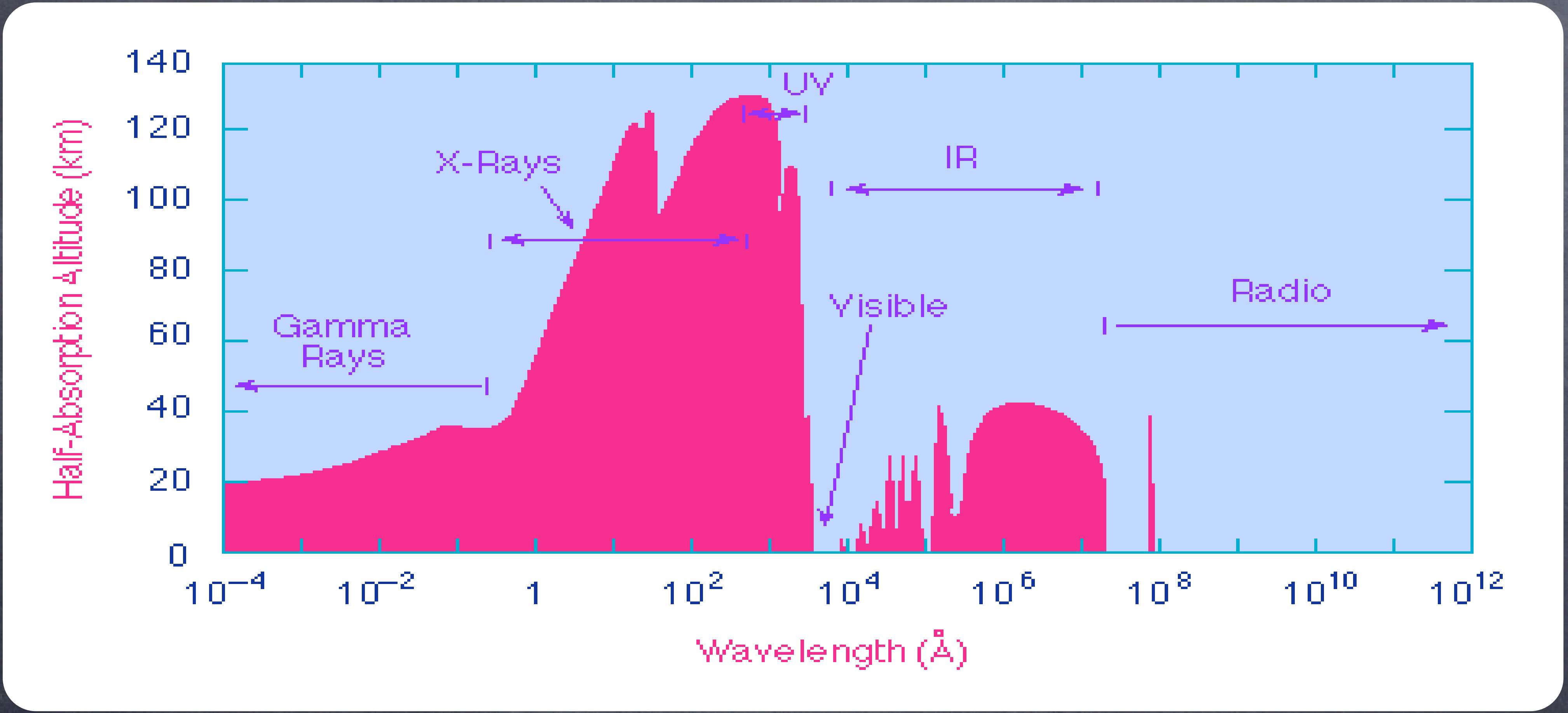


Dawn of High-energy astrophysics!

A new transparent window on the Universe

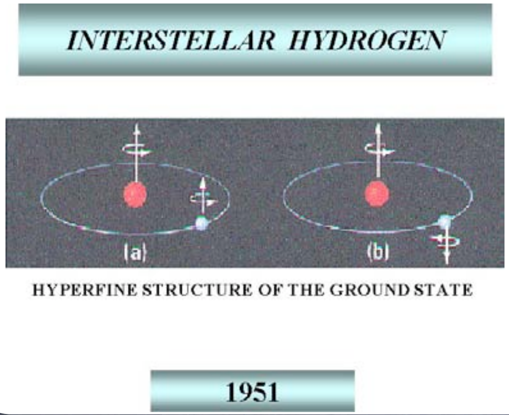
- Radio window covers 5 decades of freq/wavelength:



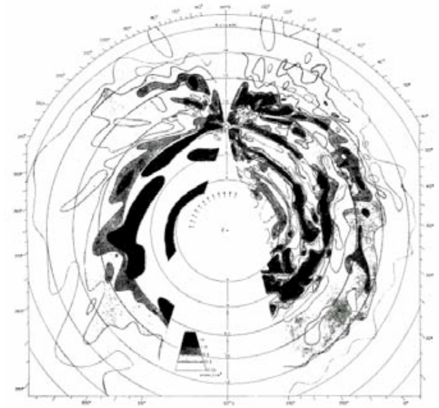
- SPECIAL: Radio waves largely unaffected by dust...
  - Can observe Day and Night!
  - Studies of the Early Universe possible.

Radio Spectral-lines

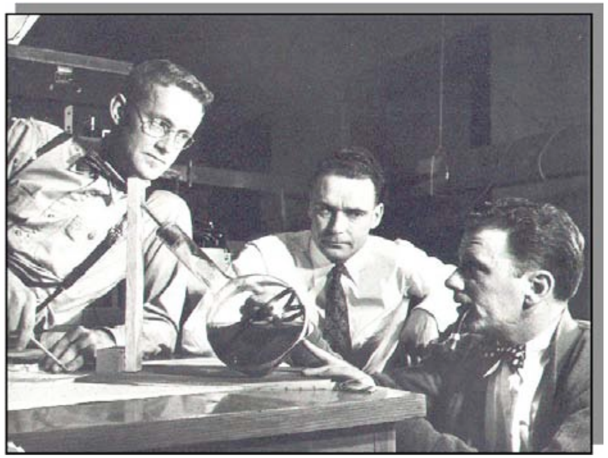
- 1944: van der Hulst predicts discrete 1420 MHz (21 cm) emission from neutral Hydrogen (HI).

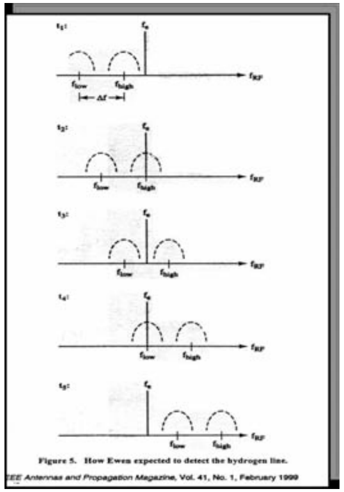


Wurzburg “Riese” Radar Antenna, 7.5 m diameter



- Detected by Ewen & Purcell (1951):

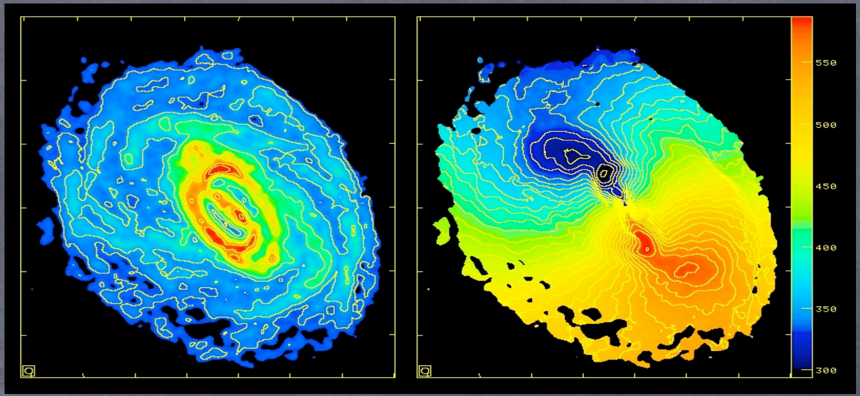


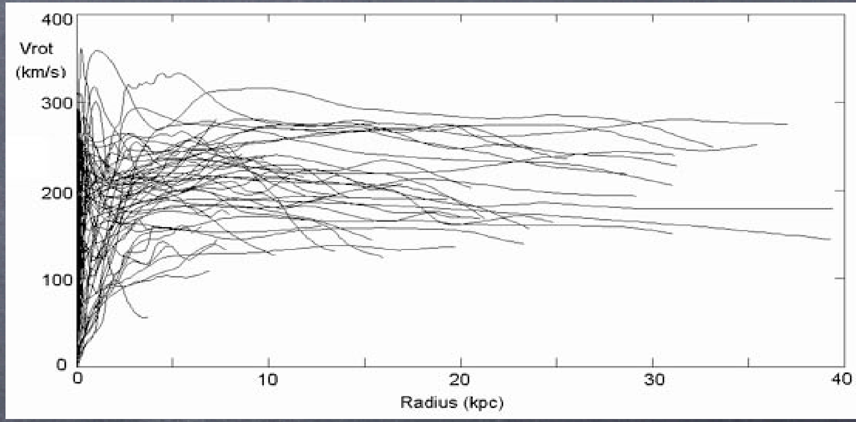


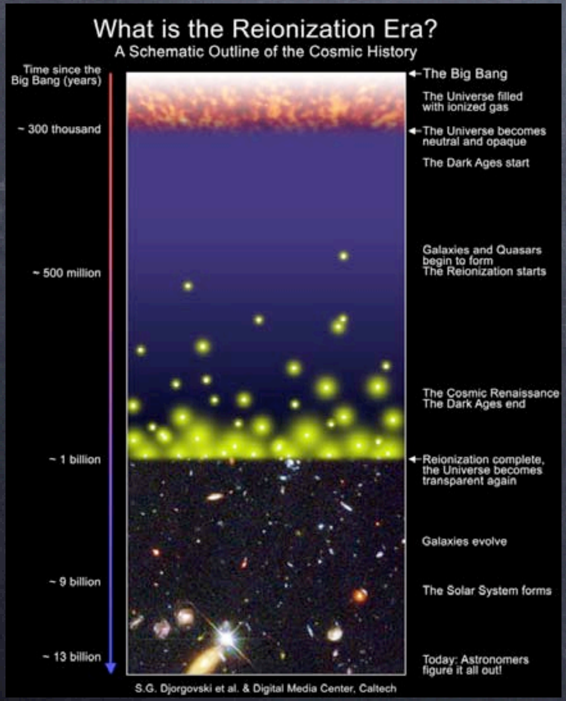
SPECIAL - HI - most abundant element in the Universe!

Gas DYNAMICS:

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



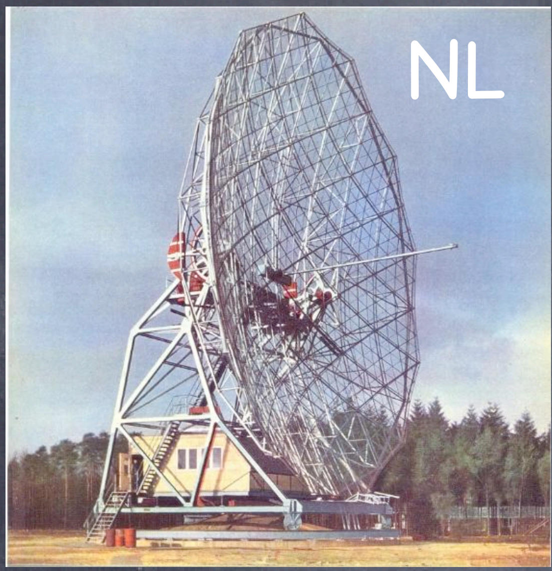


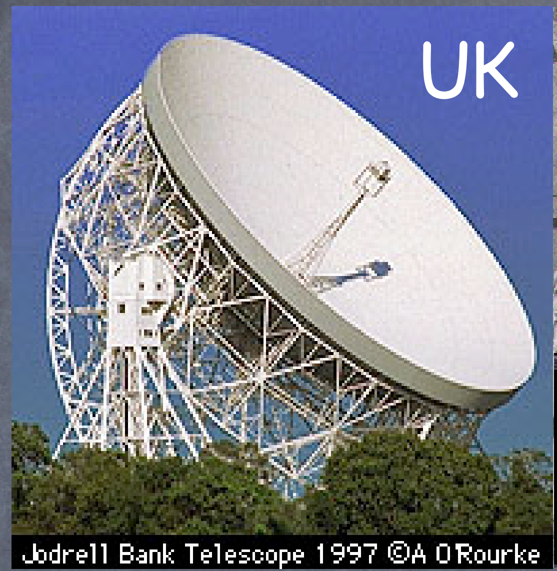


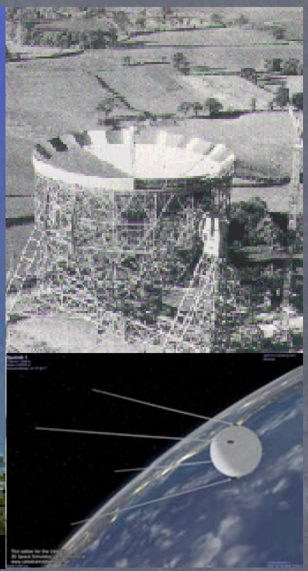
—The Dark Ages...

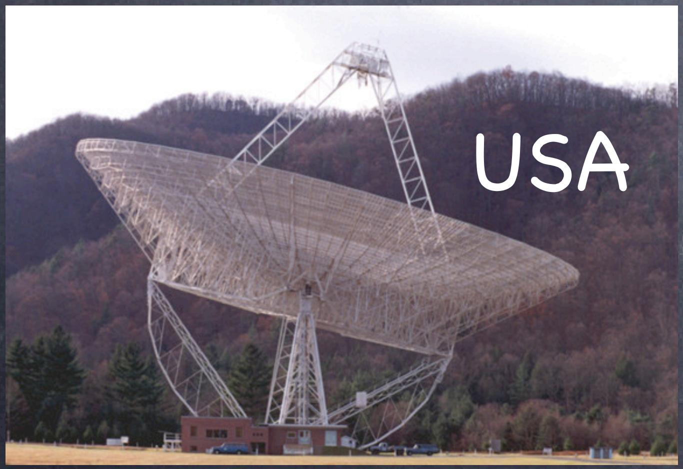
1950-60's: Construction of Large Telescopes

- cm wavelengths:







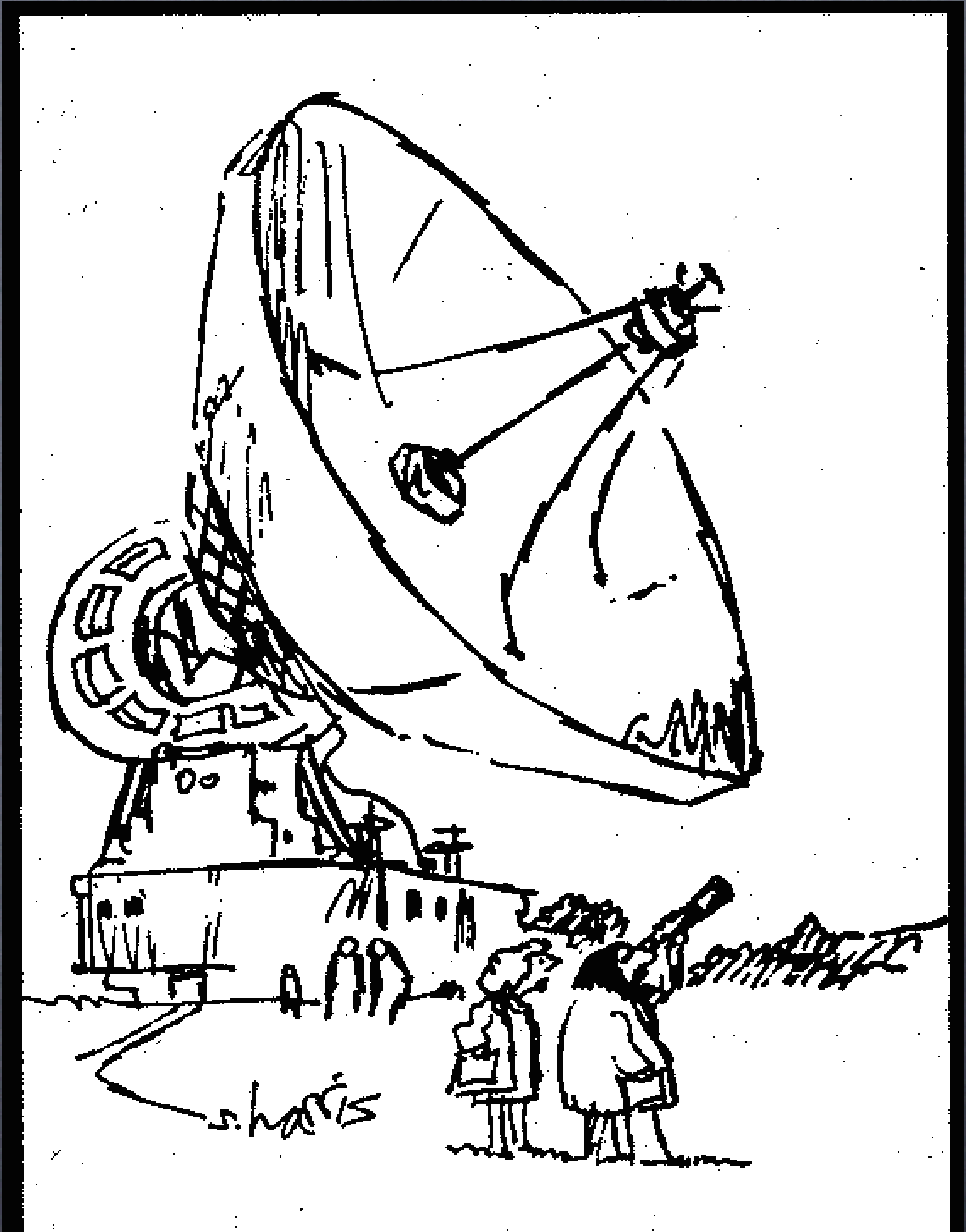


The need for better ANGULAR RESOLUTION

Ang. resolution: $$\theta = \frac{1.22\lambda}{D}$$

$$\theta = \frac{2.1\times10^5\lambda}{D}$$ arcseconds

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



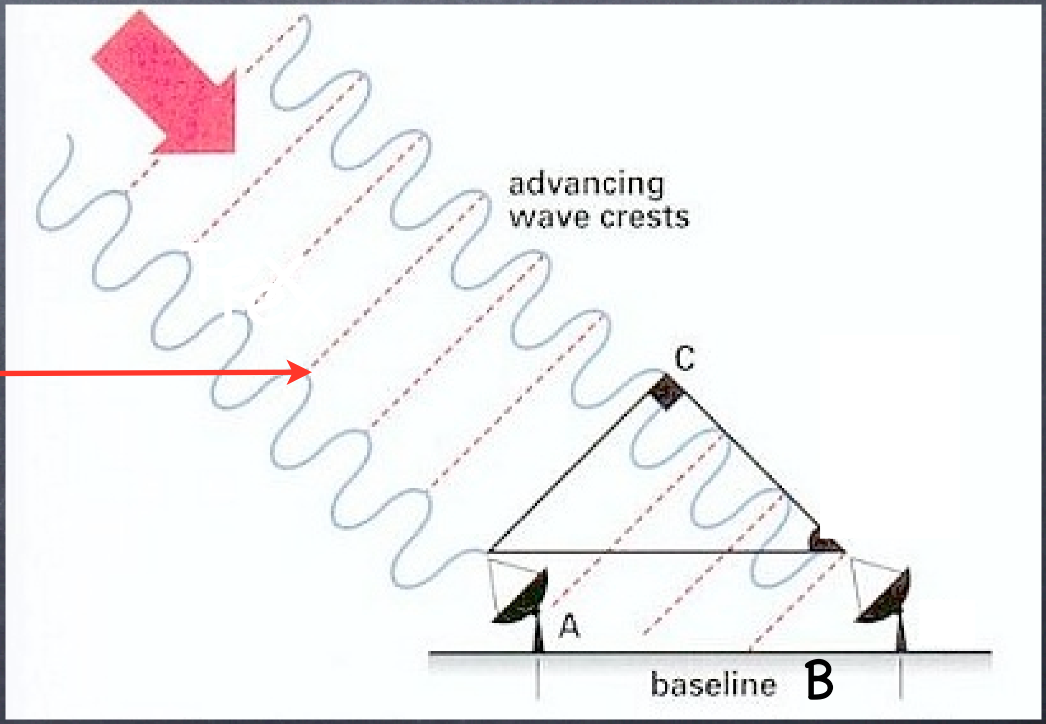
"Just checking."

The answer RADIO INTERFEROMETRY

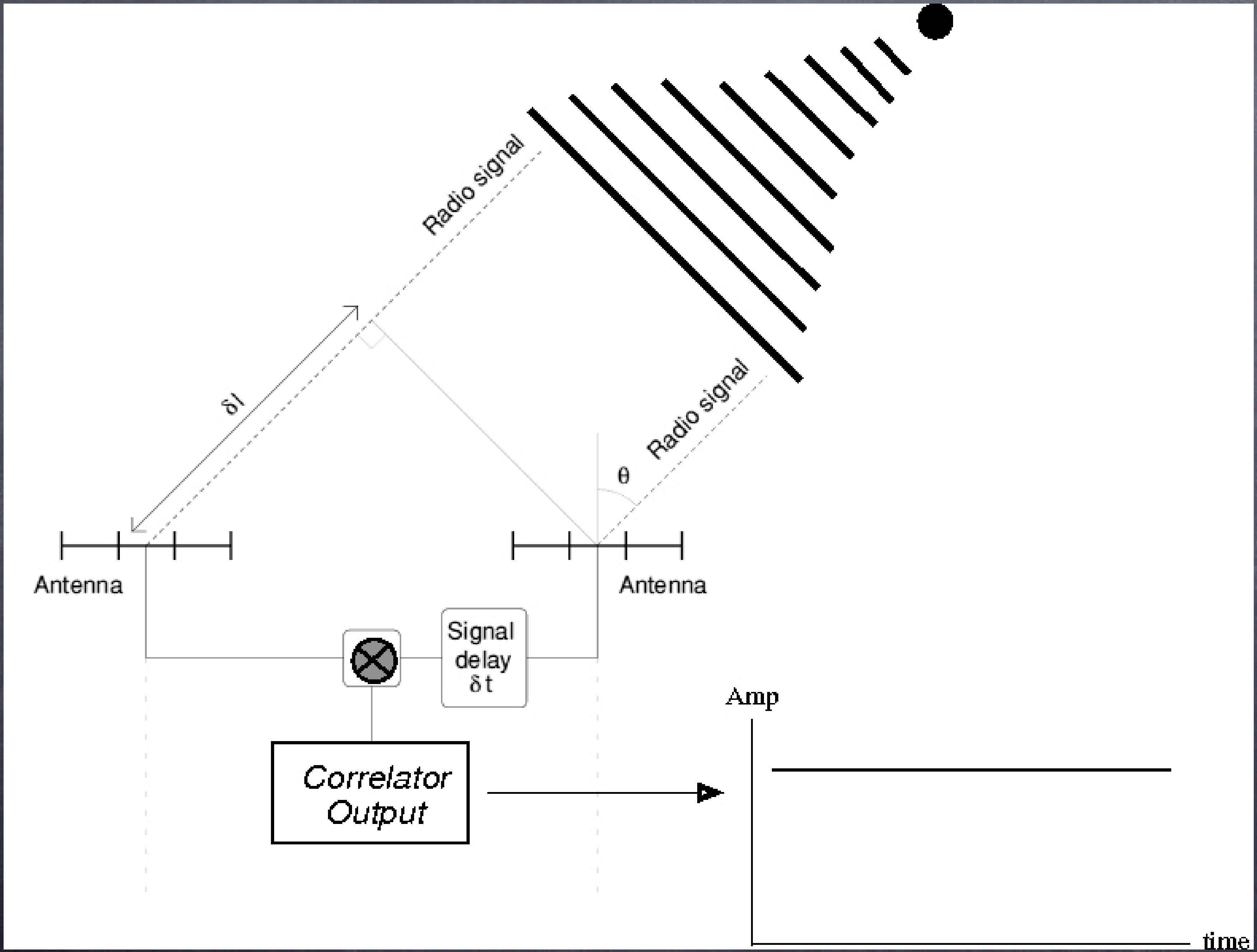
Ang. resolution: $\theta = \dfrac{1.22\lambda}{B}$ B = Baseline i.e. telescope separation

For 2 telescopes separated by 30 km
==> Ang. resolution: ~ 1 arcsecond - MUCH BETTER!

Wave-fronts from distant source perfectly in phase



RADIO INTERFEROMETRY & Correlation



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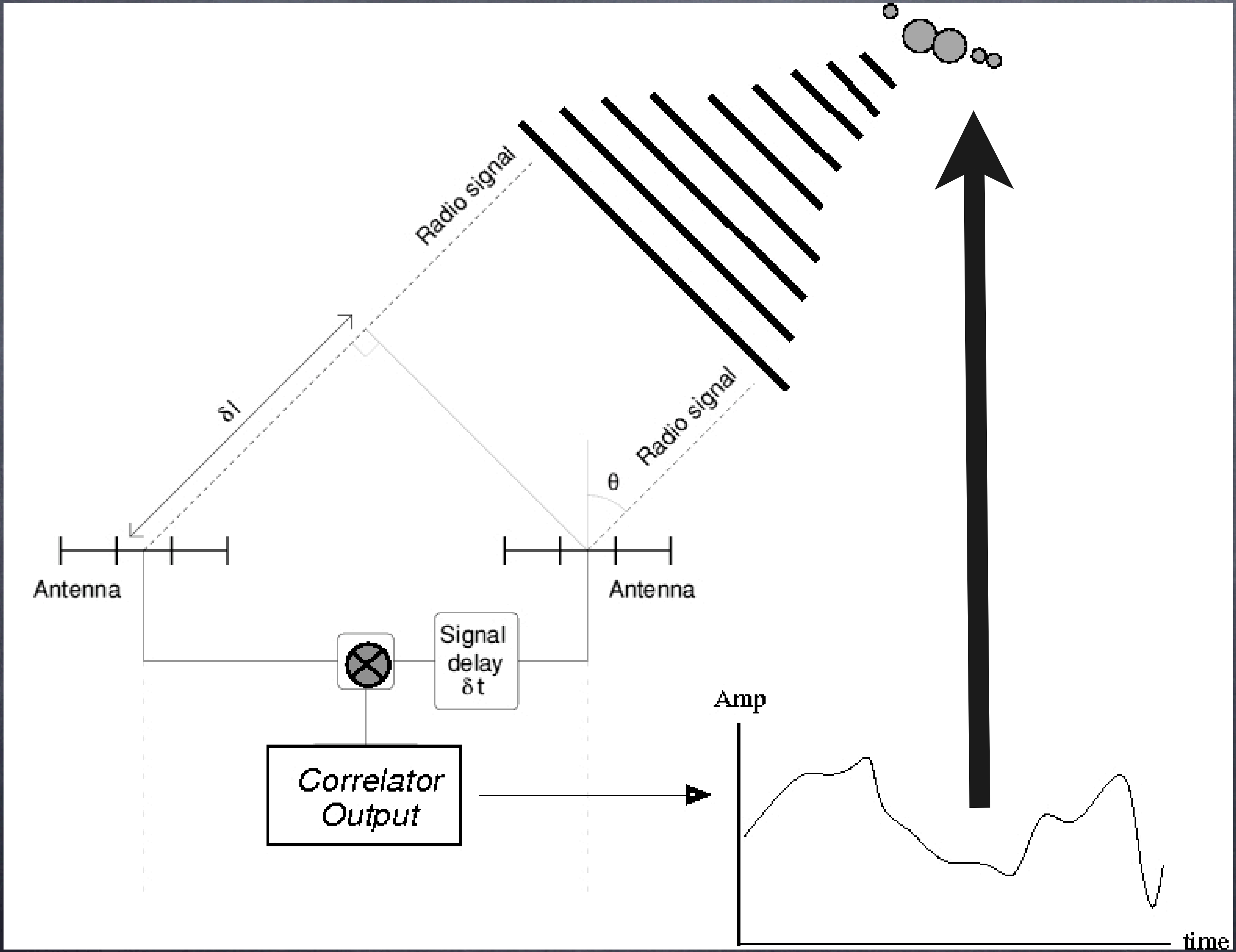
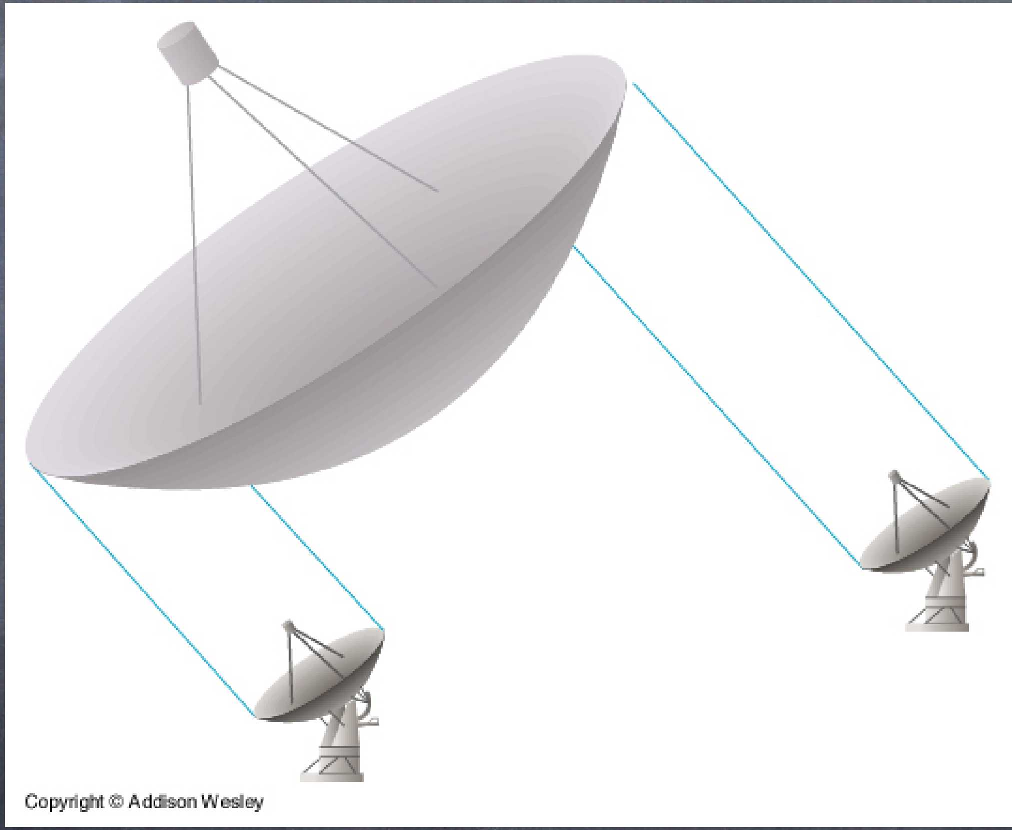
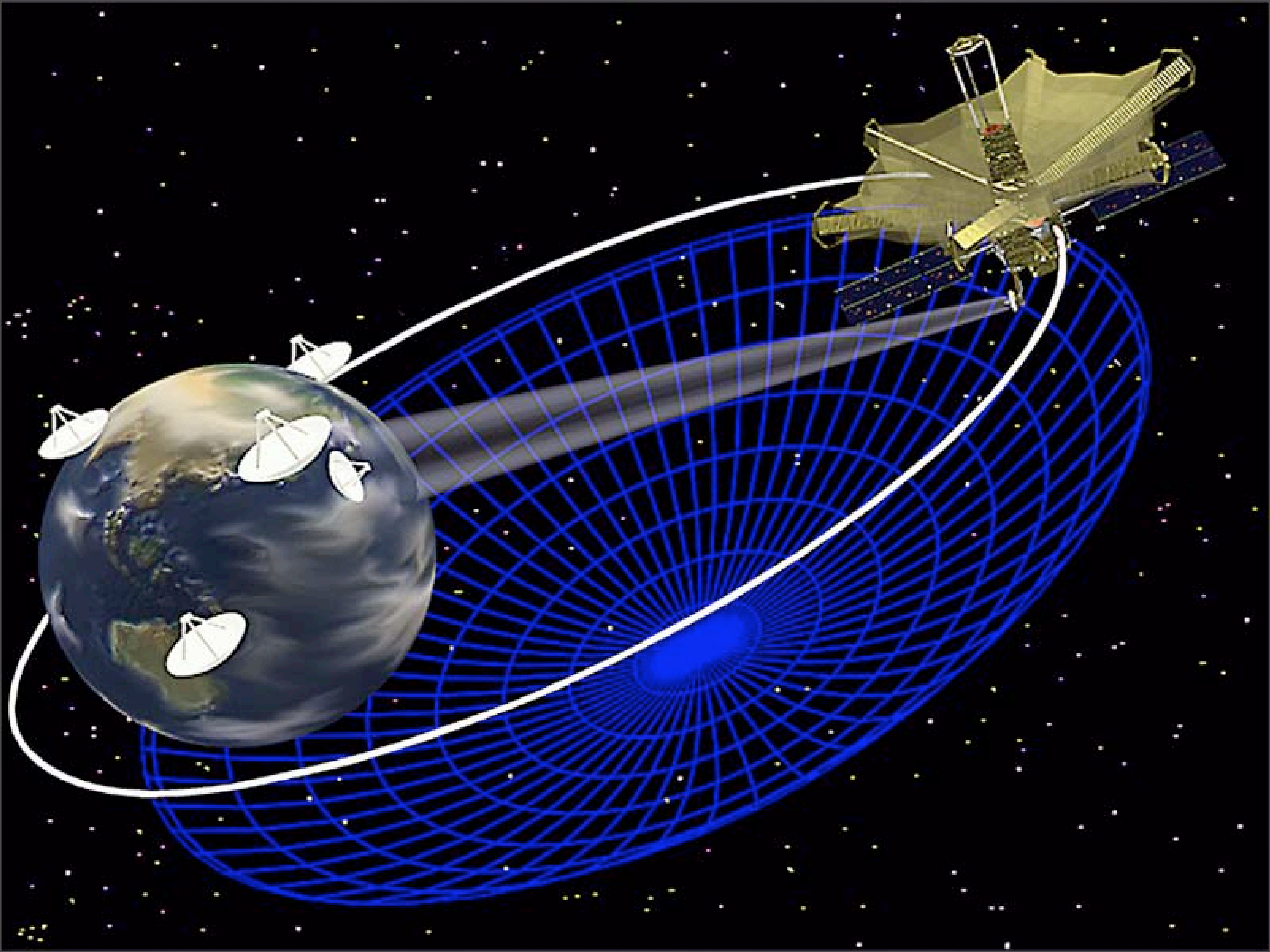
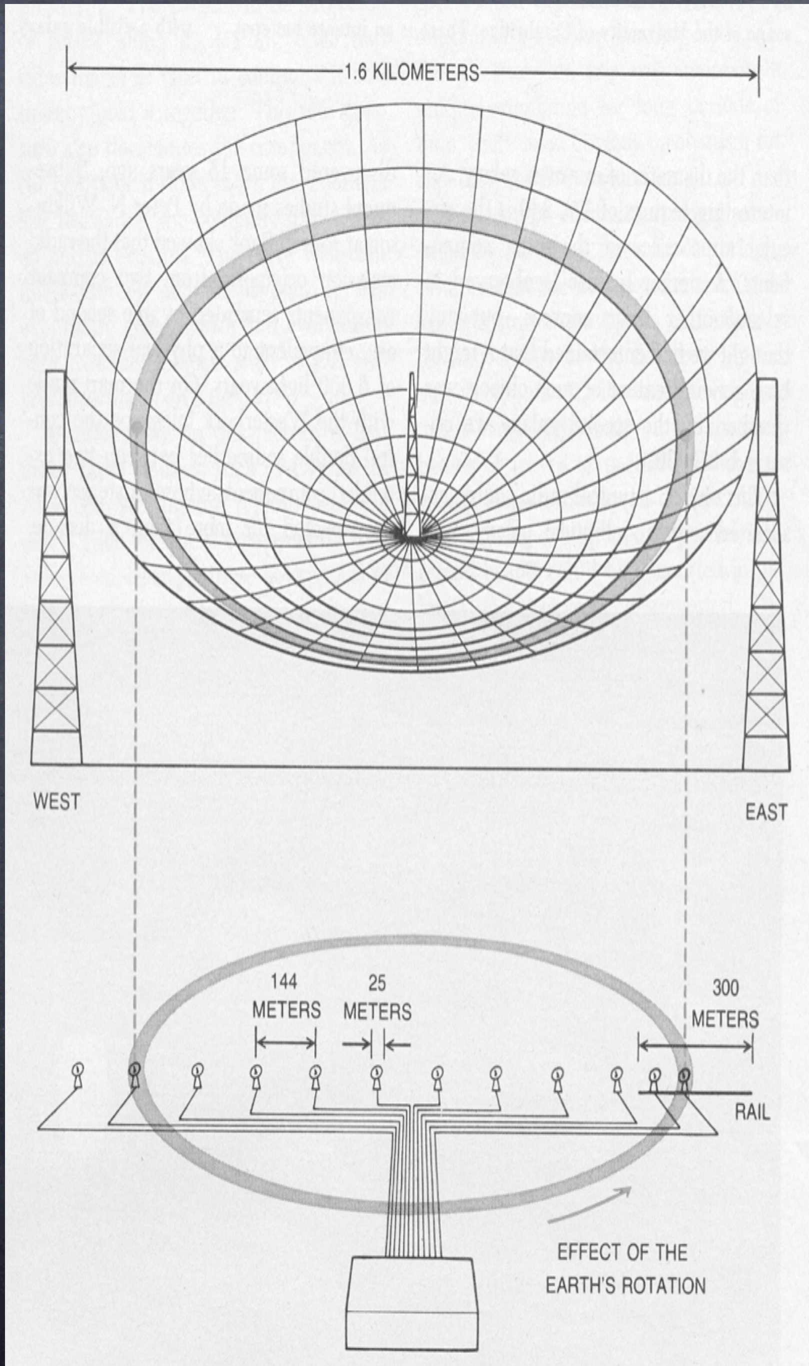


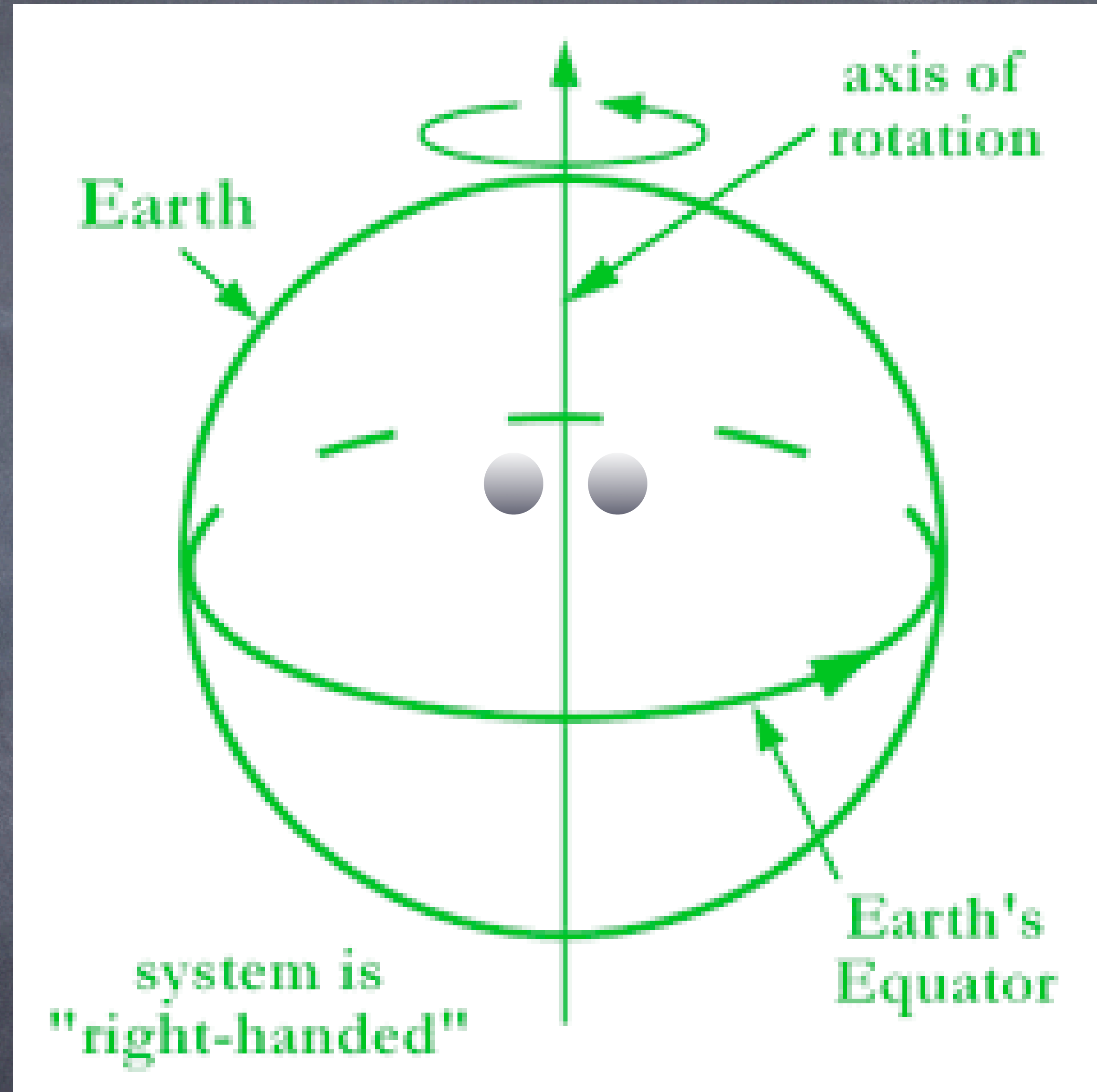
Interferometry tries to sythesise a GIANT telescope from lots of small ones:





Earth rotation helps too (Ryle):





Projected Baseline changes for source

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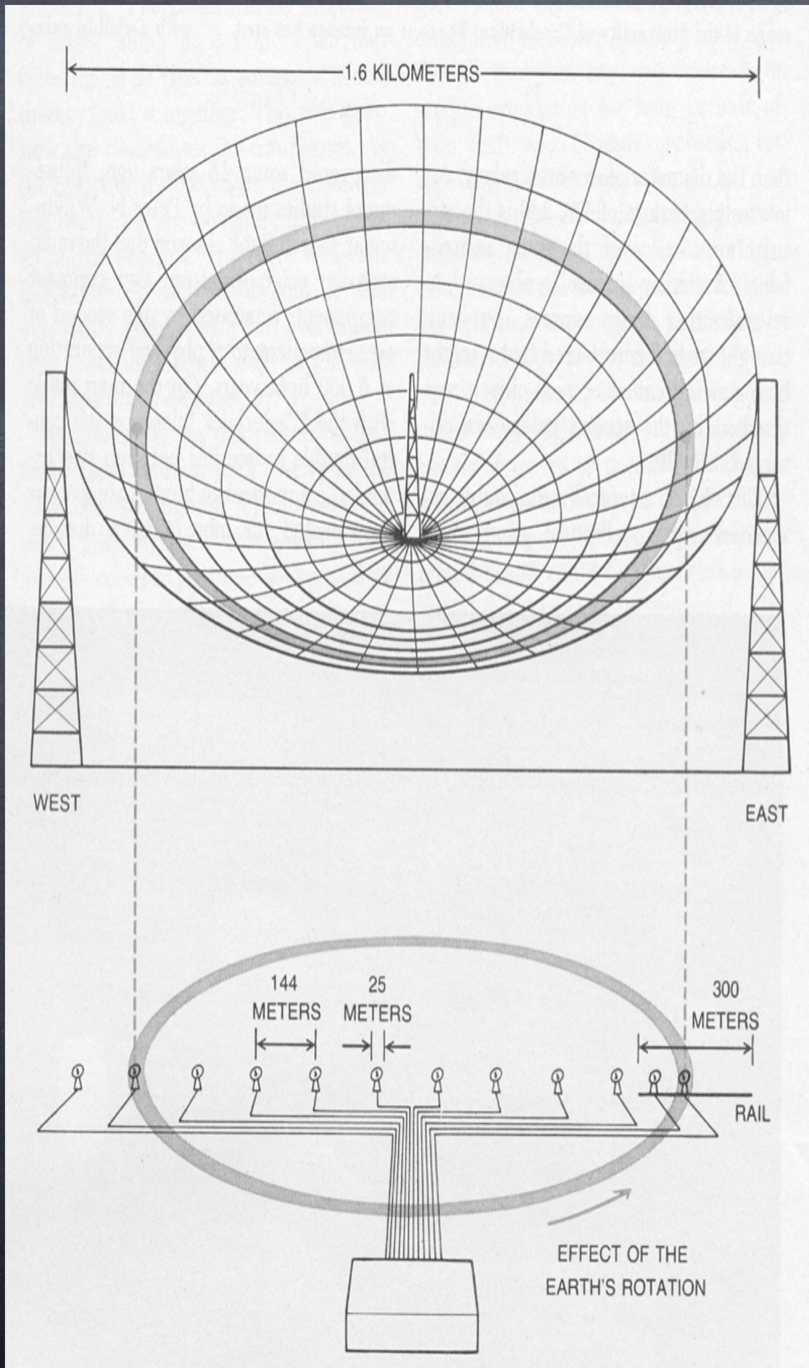

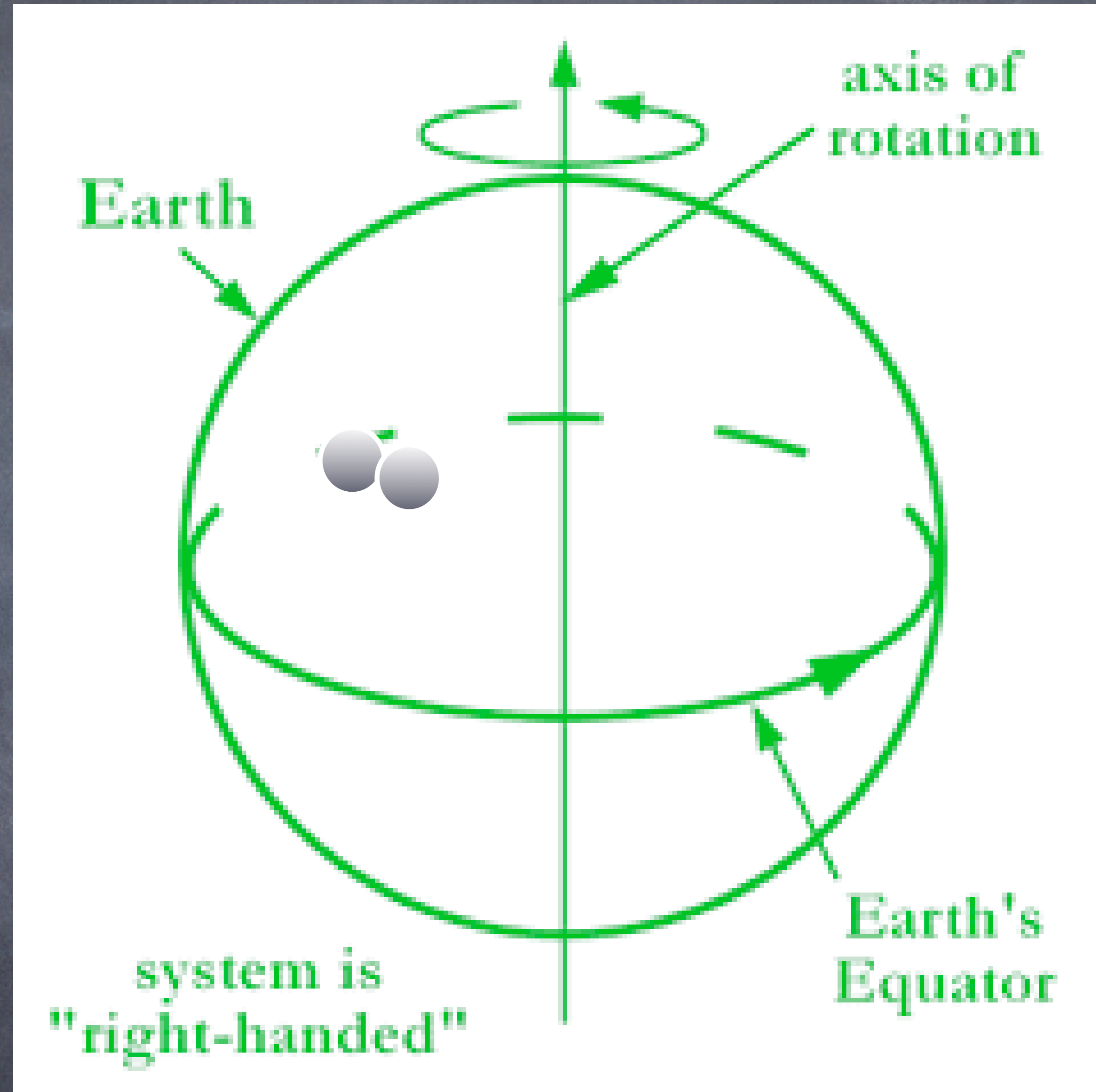

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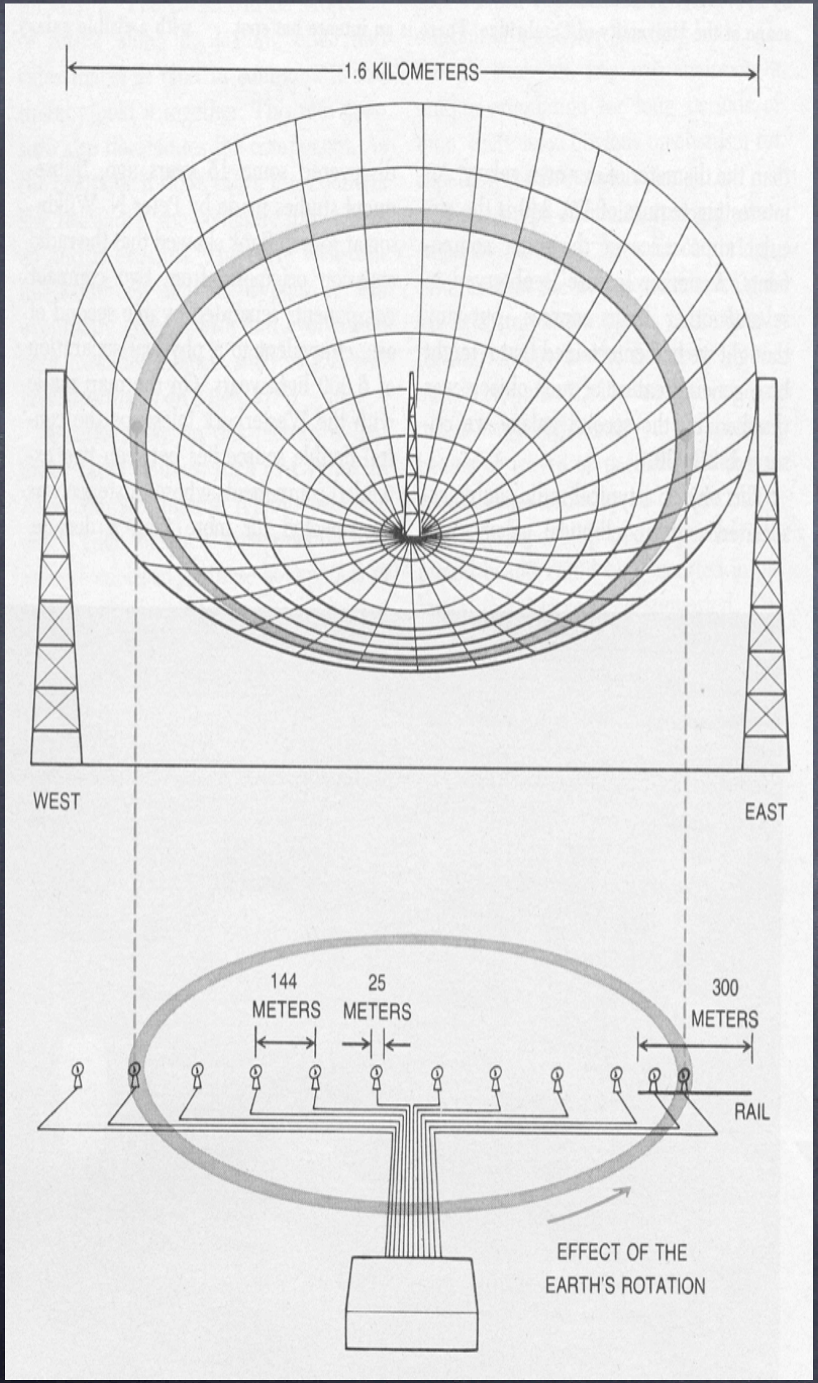
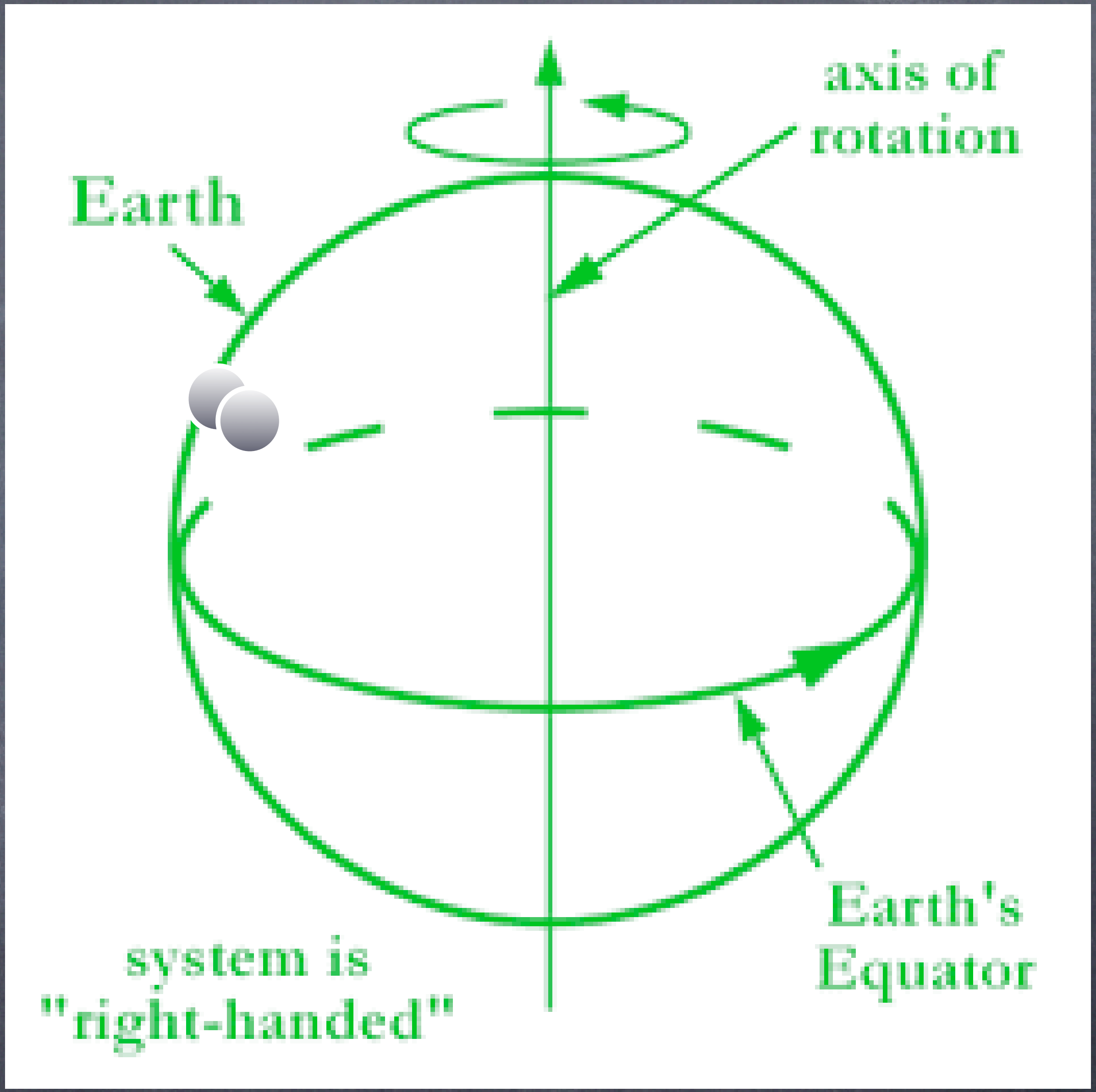
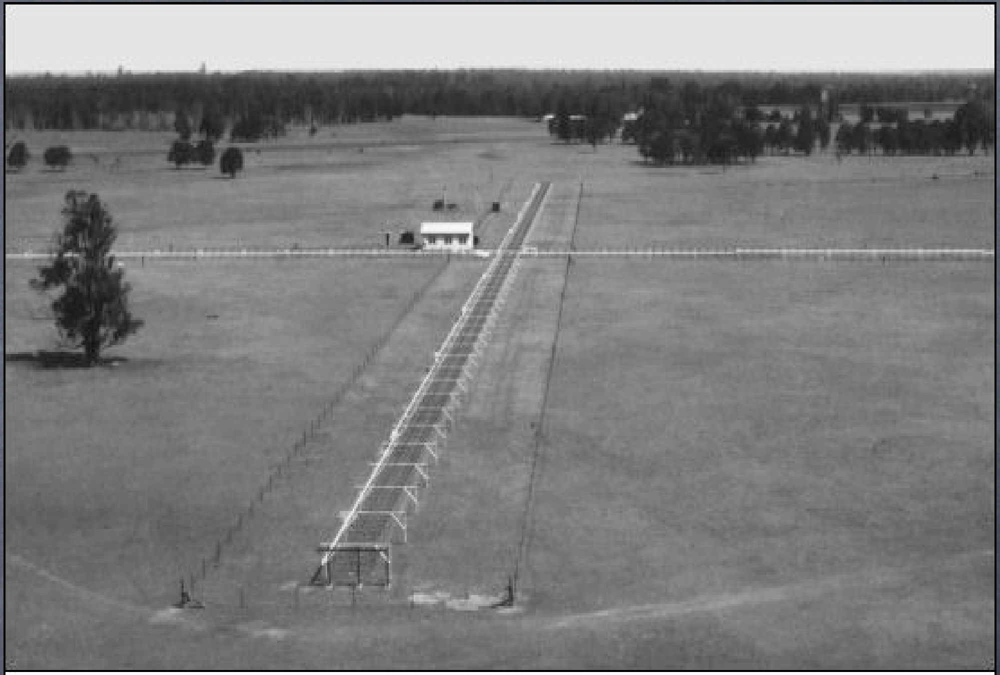




Projected Baseline changes
for source

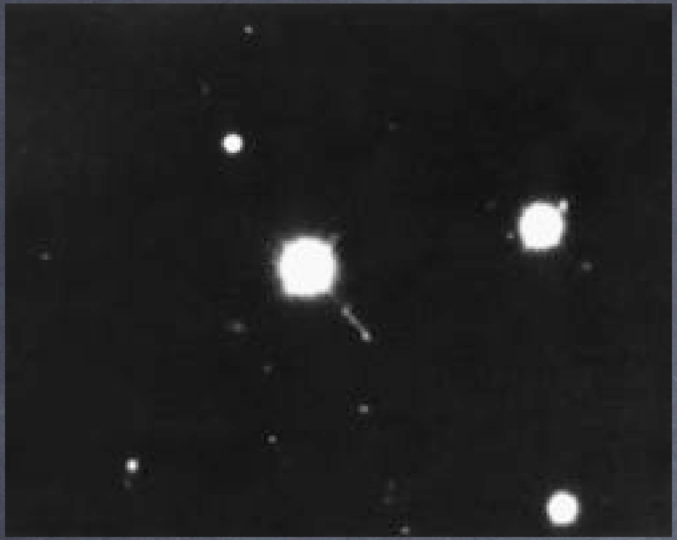
The first radio interferometers

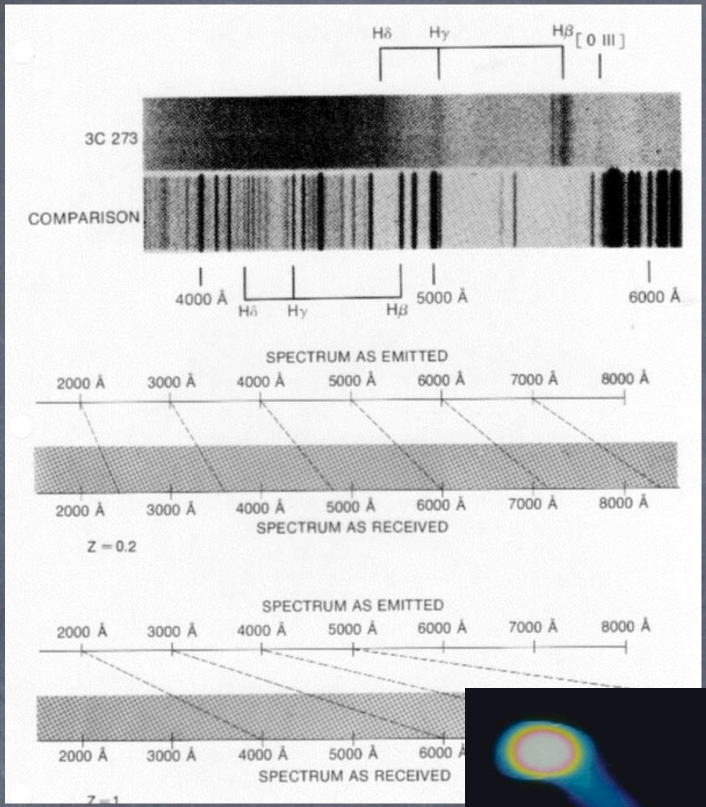
- Early interferometer arrays pioneered by UK and Australian astronomers:


MILLS CROSS (CSIRO)

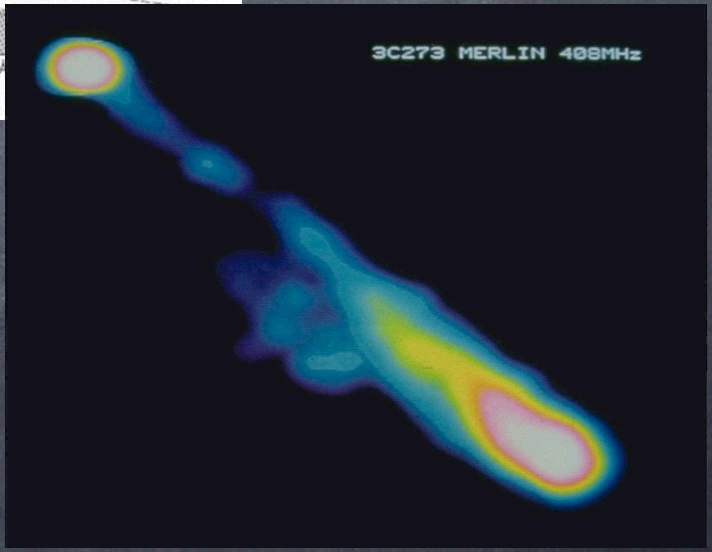
  - Motivation was to identify radio sources with plausible optical counterparts...

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



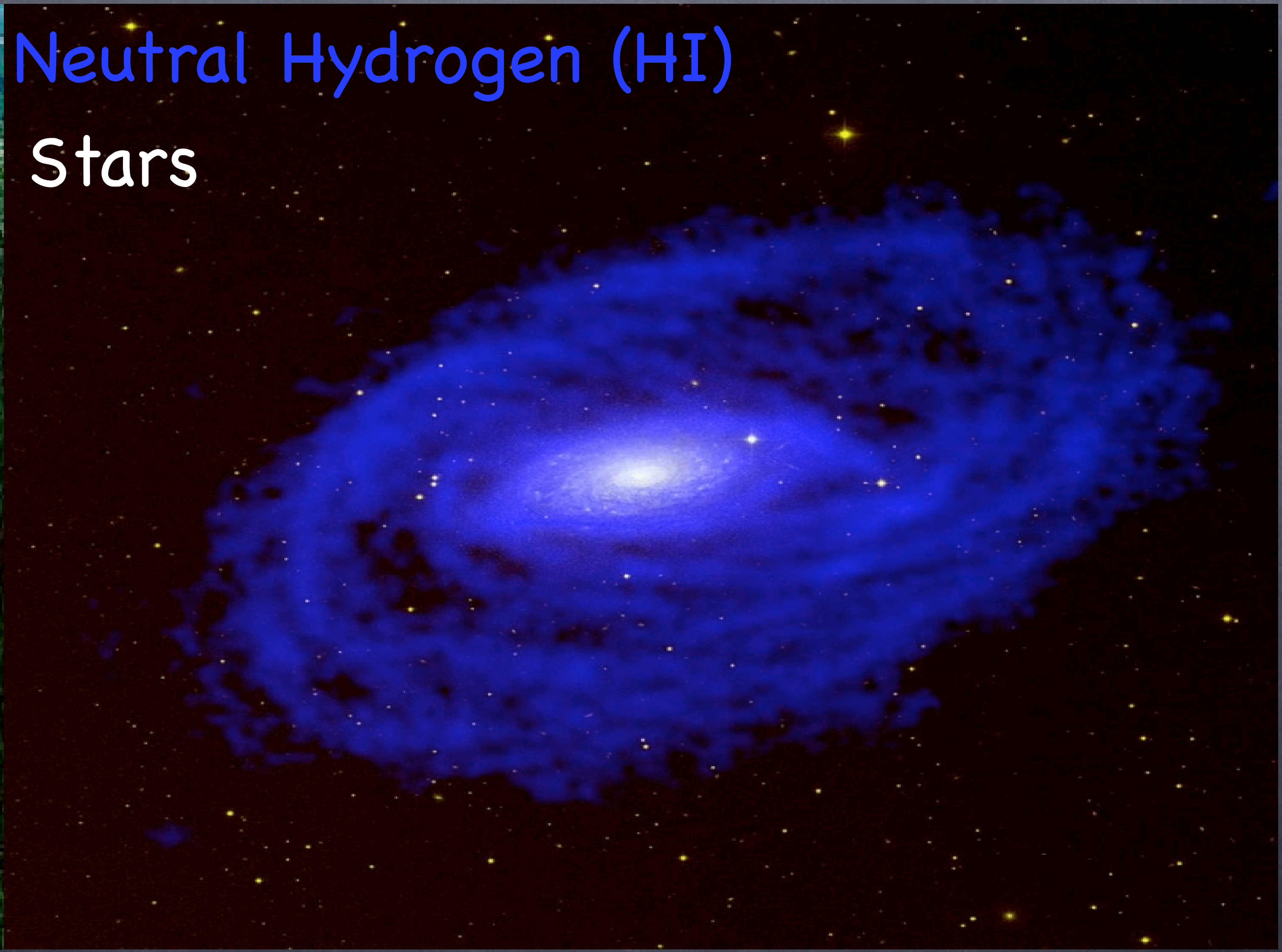


- Stellar objects ????
- Redshifted lines z=0.2 => cosmological distance objects
- 1000 x more luminous that Milky-Way



1970 - Westerbork Synthesis Radio Telescope

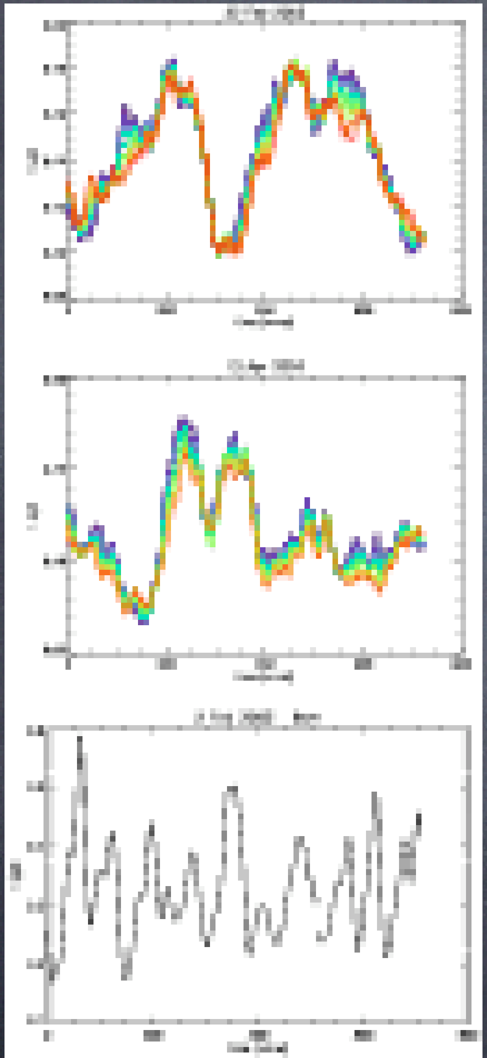
- 14 x 25 metre telescopes, 91 baselines, 3km baseline.



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 ~ 1)
  - c.f. optical sky (z=0 for naked-eye objects!)
- Huge excess of faint sources: ==> first evidence of rapid cosmic evolution...!
- Non-thermal emission - synchrotron mechanism ==> violent Universe powered by gravitation rather than fusion.

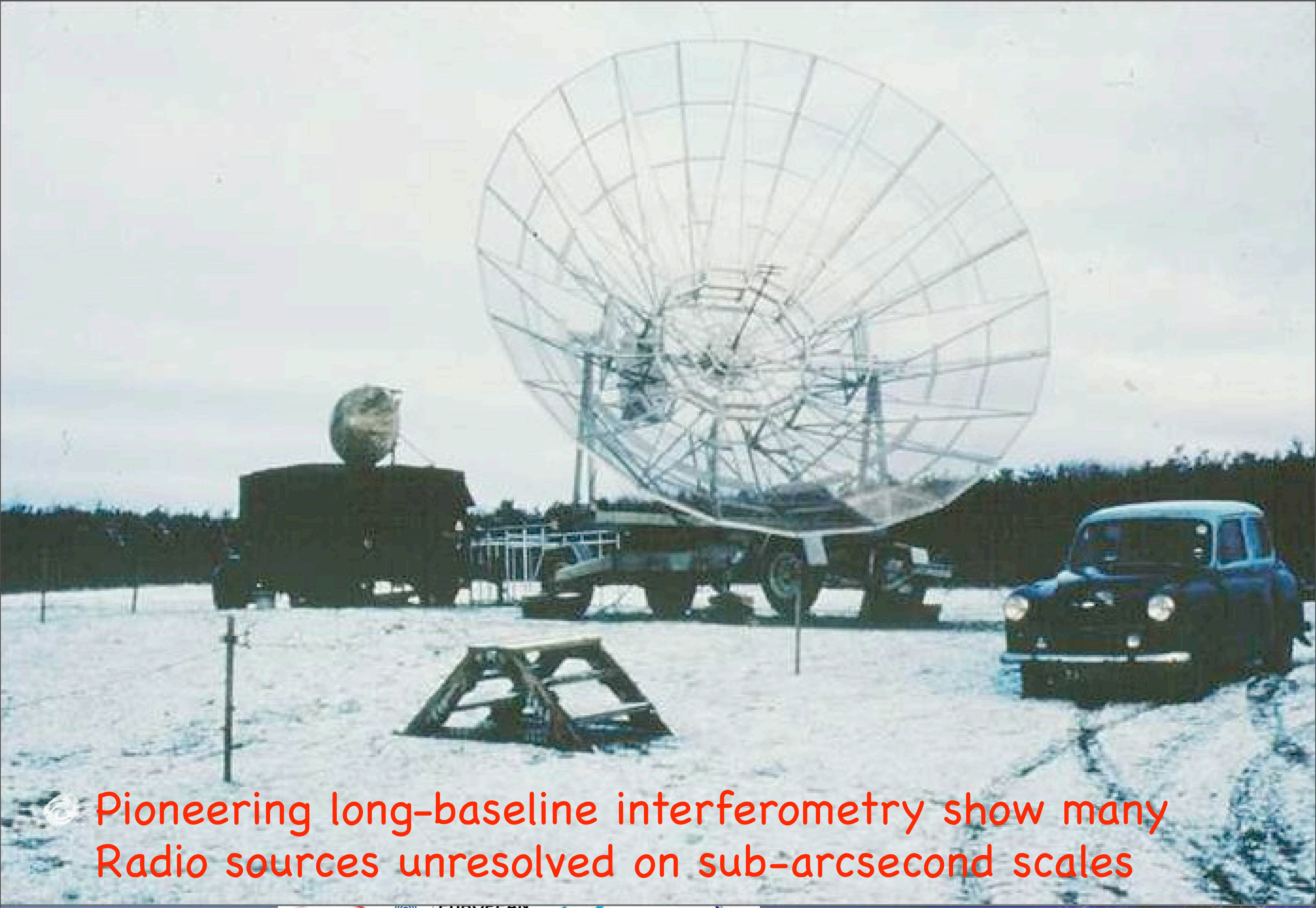
- Radio sources also discovered to be highly variable on time scales of hours or less:



> ==> very compact objects - scales ~ solar system.

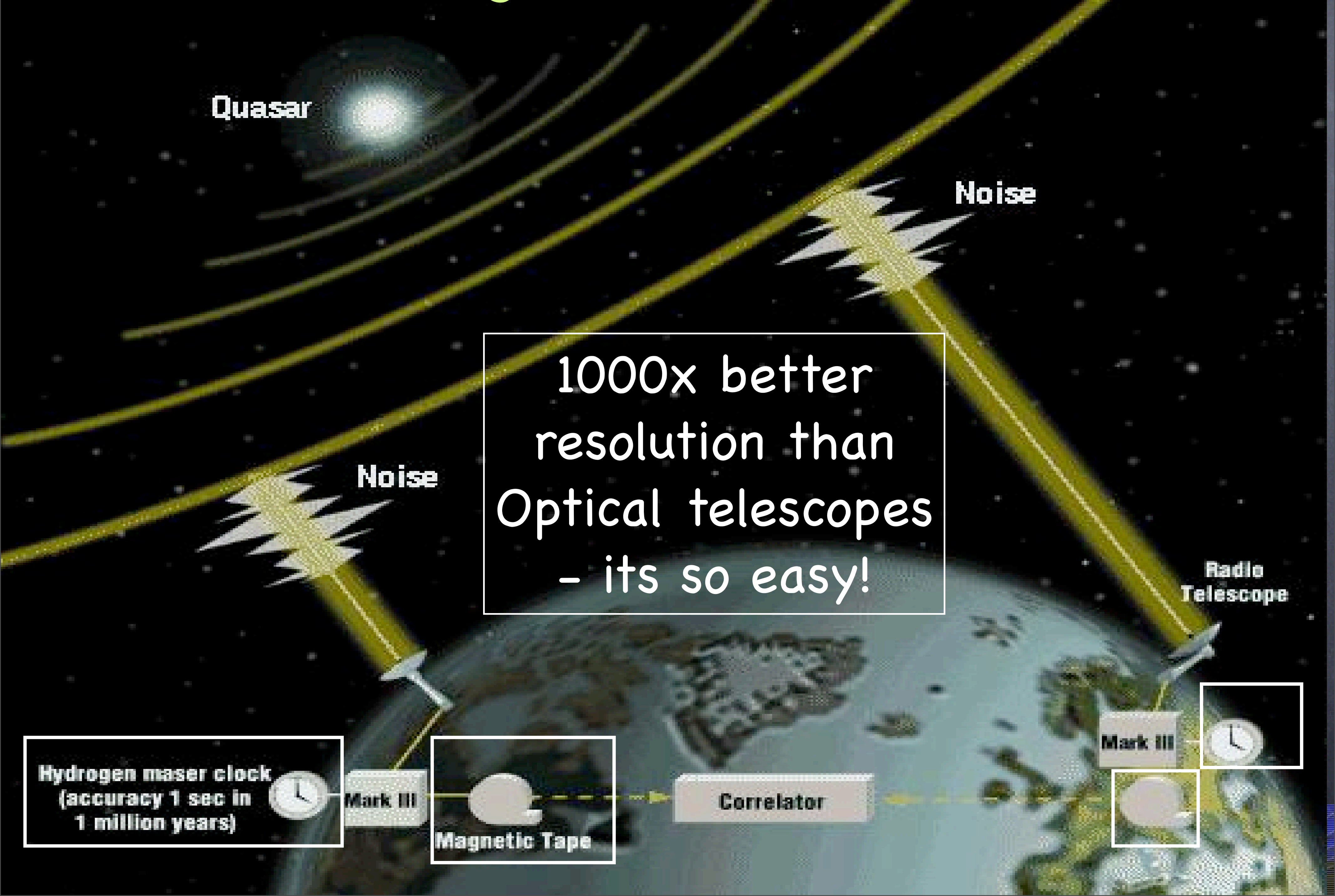
> At z=1, 1 arcsecond corresponds to ~ 10 kpc (30,000 lt years).

> Need for much HIGHER RESOLUTION (baselines ~ Earth diameter, 12000 km)



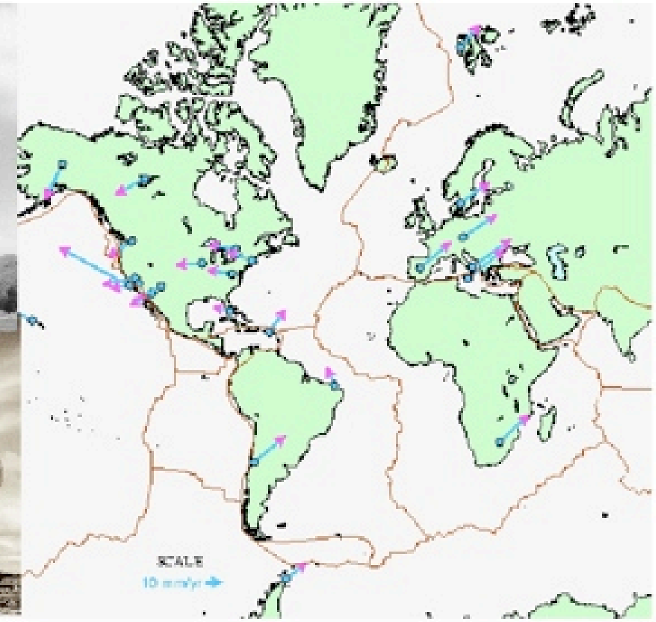
Pioneering long-baseline interferometry show many Radio sources unresolved on sub-arcsecond scales

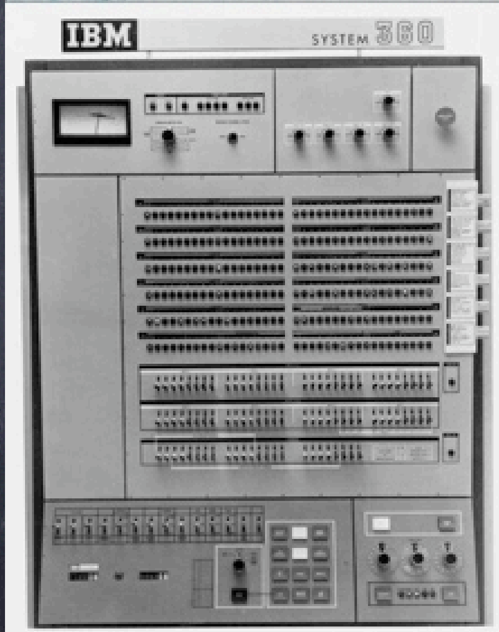
1967: Very Long Baseline Interferometry



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

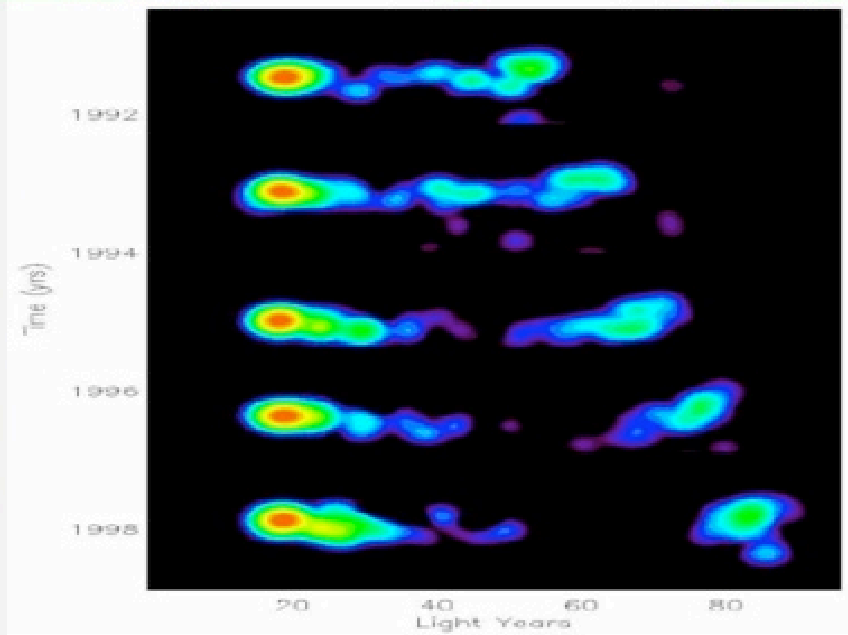
40 Years of Very Long Baseline Interferometry (VLBI)



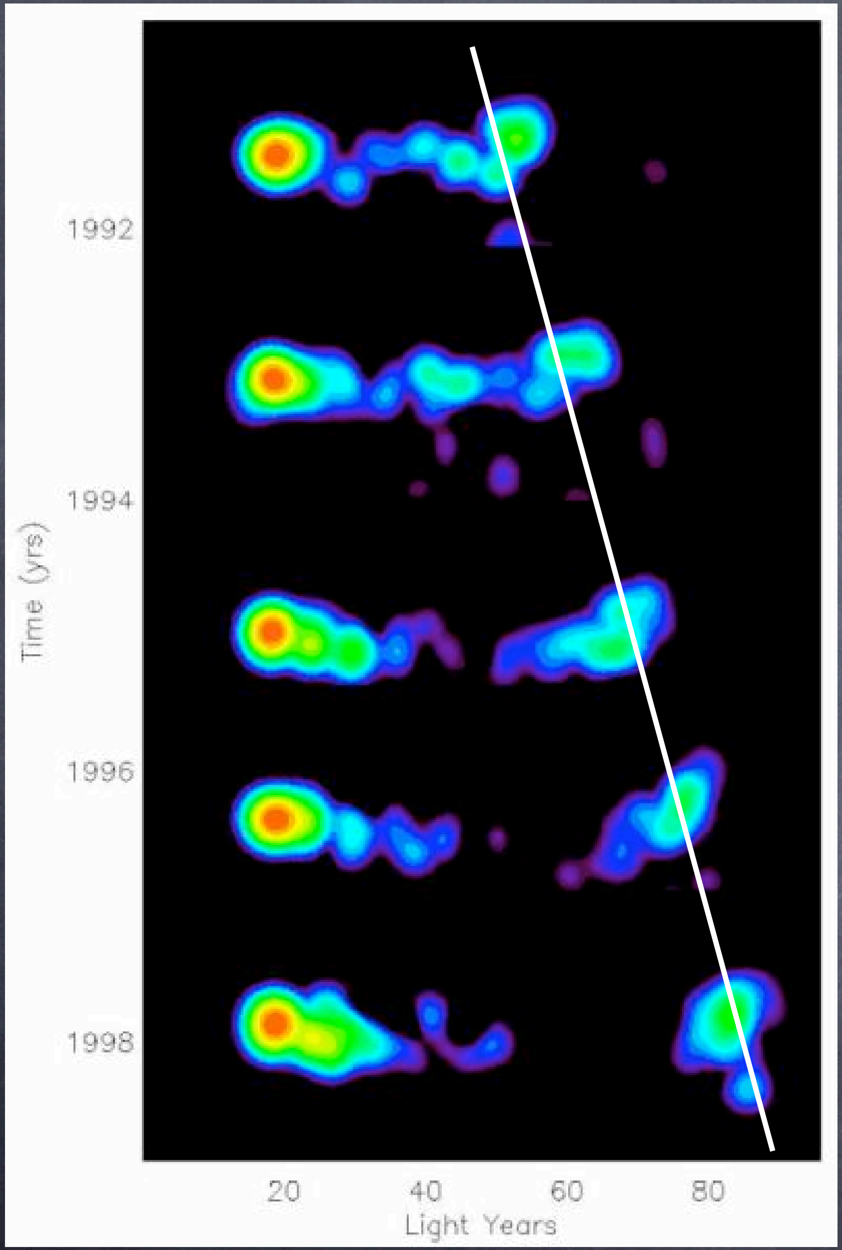


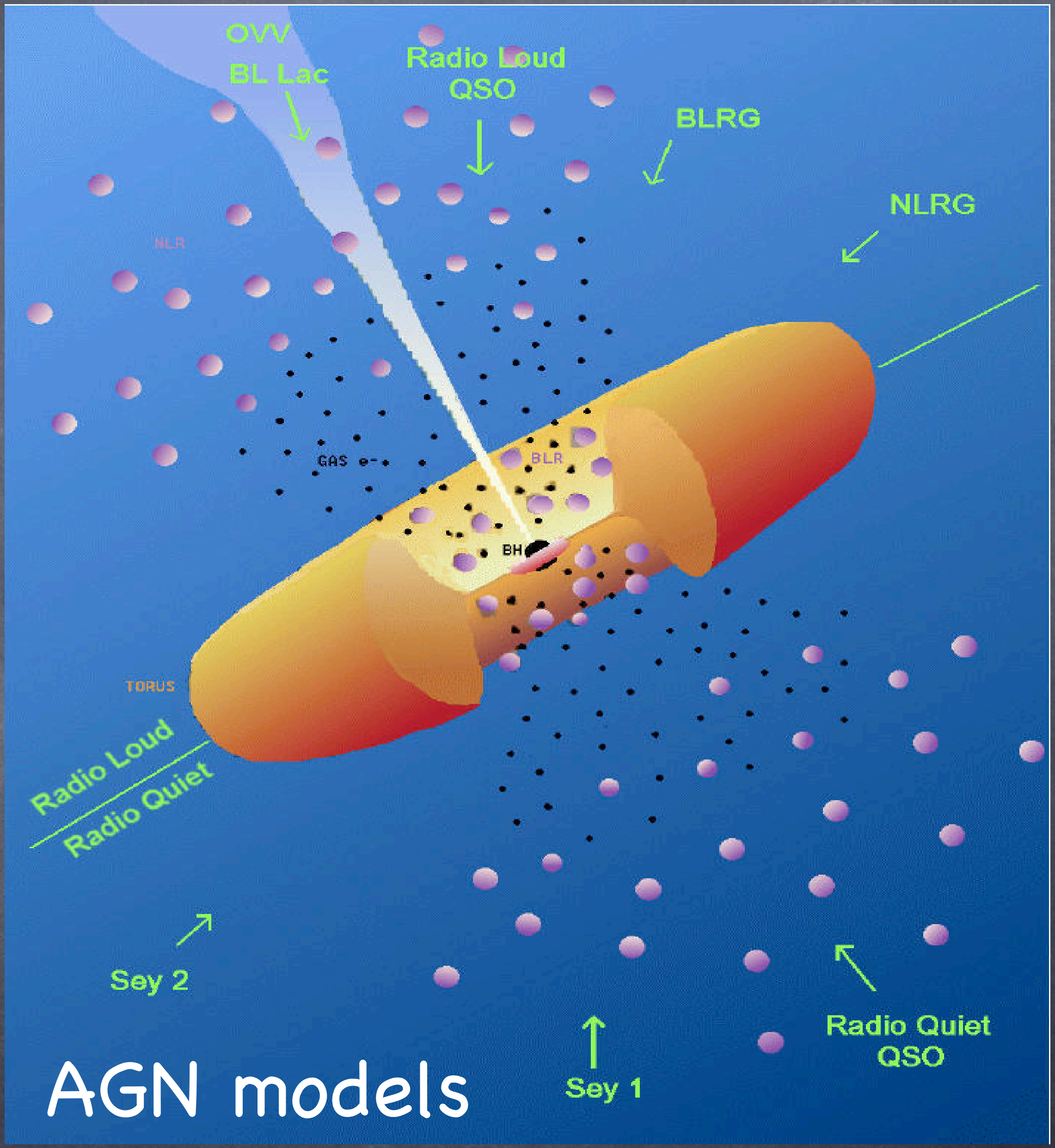
"FATHERS OF VLBI" AT IAU164, 1997

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

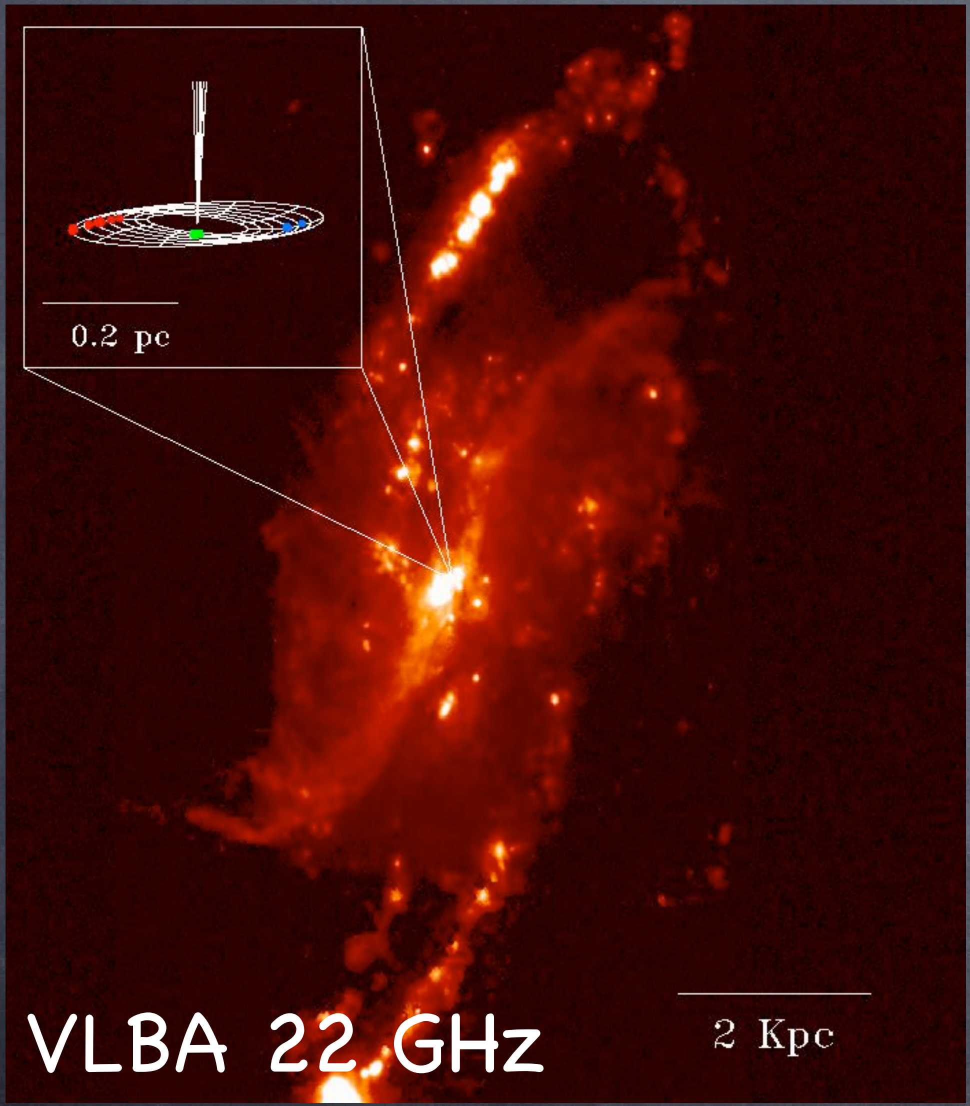


Superluminal motion discovered - Whitney et al. 1973.





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



> velocity and motion of water maser gas clouds permit:

- Mass of Black hole ~ 10^7 Msun.
- DISTANCE of NGC 4258 => Ho

VLBI Brings the Universe to life...

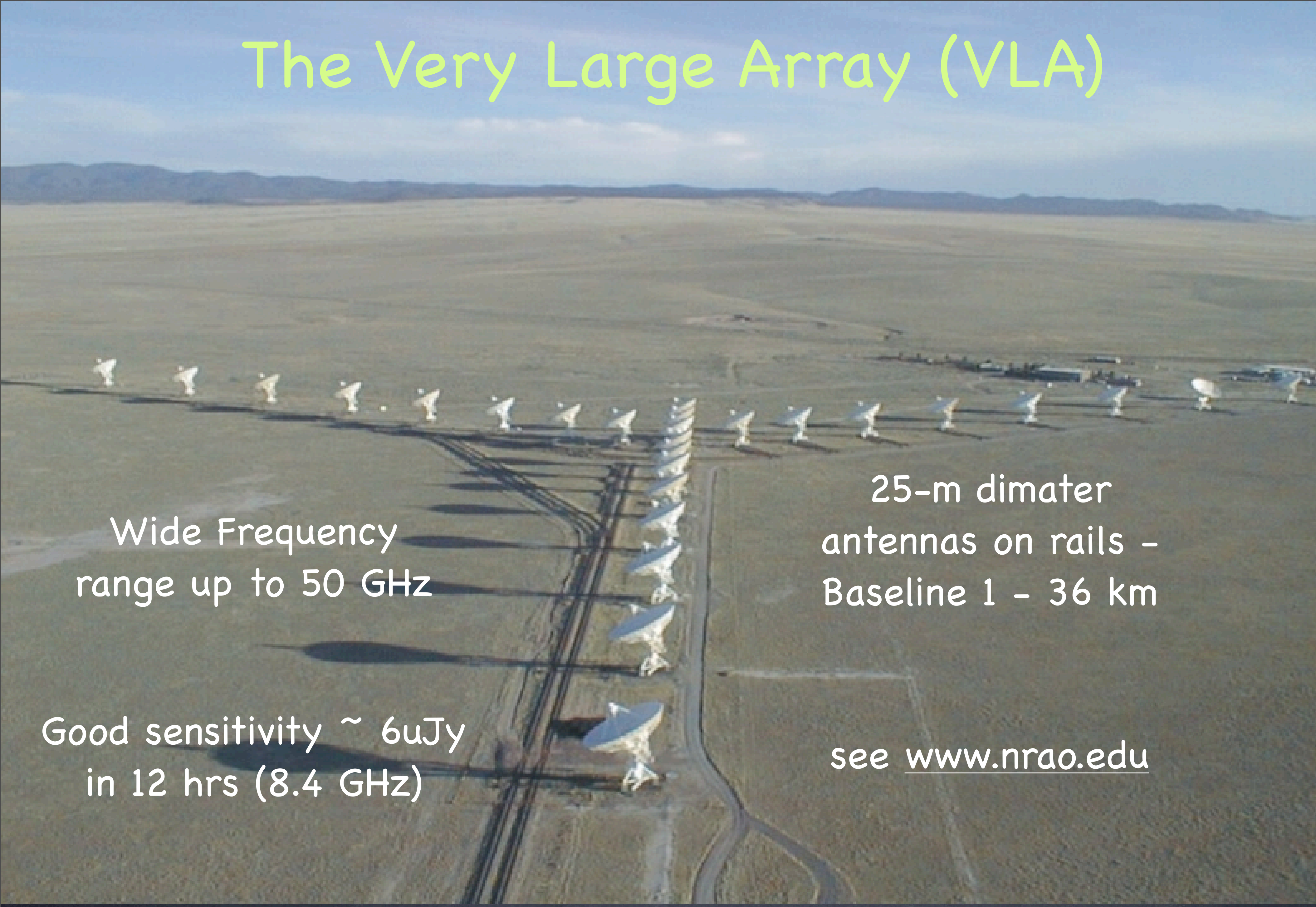
VLBA 22 GHz Observations of 3C120

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.

The Very Large Array (VLA)



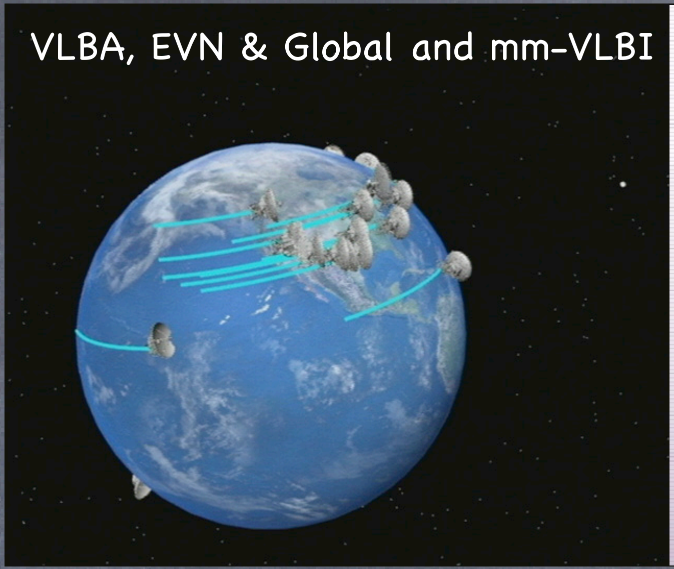
Wide Frequency range up to 50 GHz

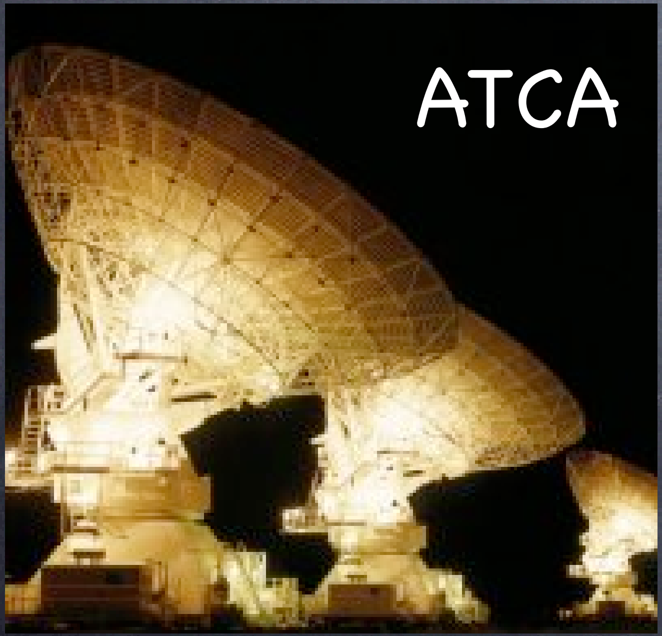
Good sensitivity ~ 6uJy in 12 hrs (8.4 GHz)

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

see www.nrao.edu

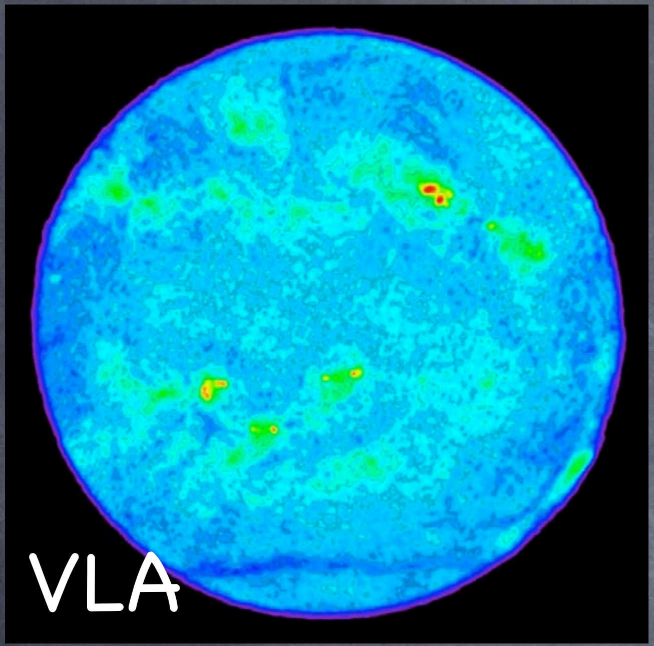
Other Interferometer Arrays



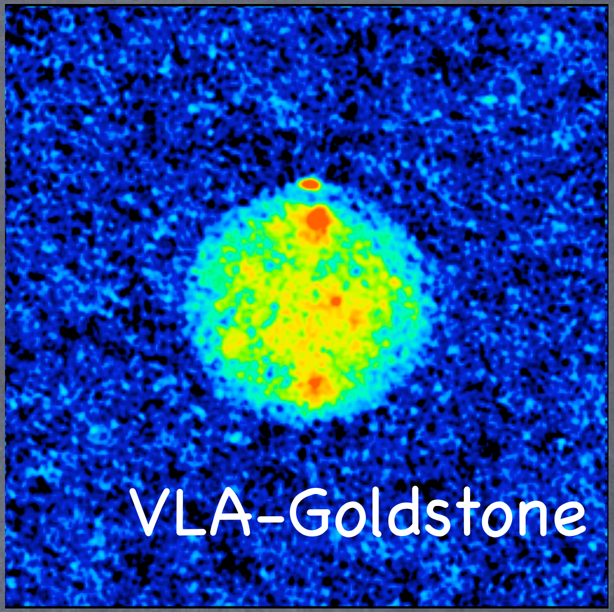


European Radio Telescope Resources (incl. single dishes)

Radio Sources in the Solar system

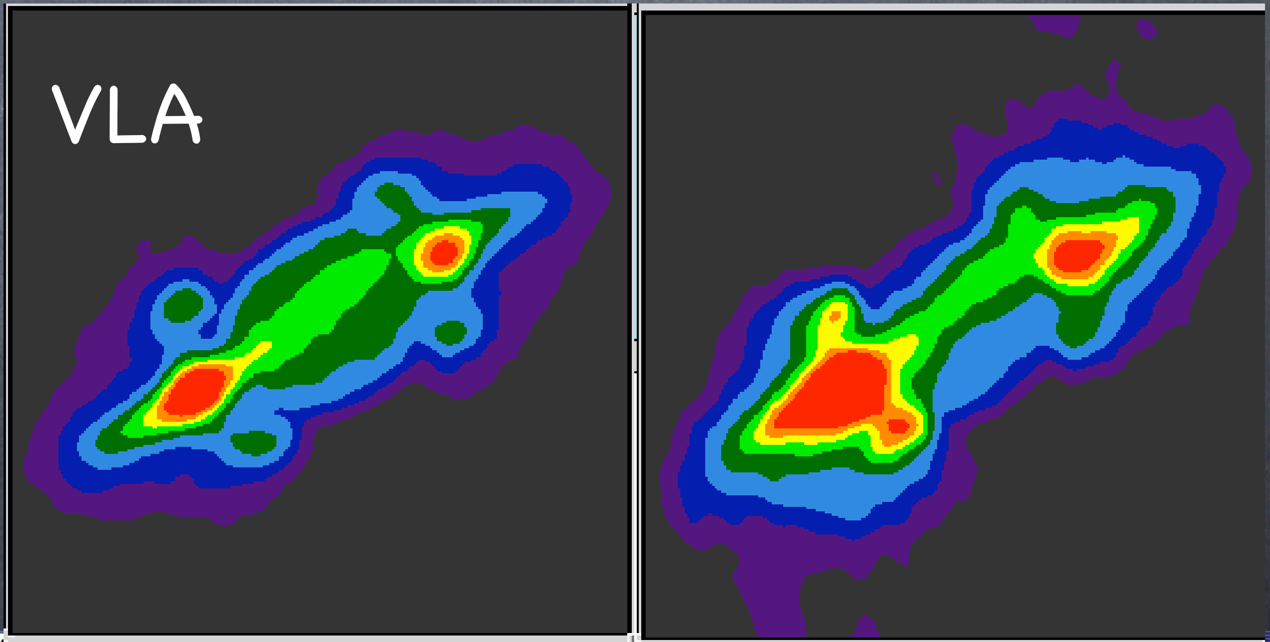


Thermal emission from the quiet sun

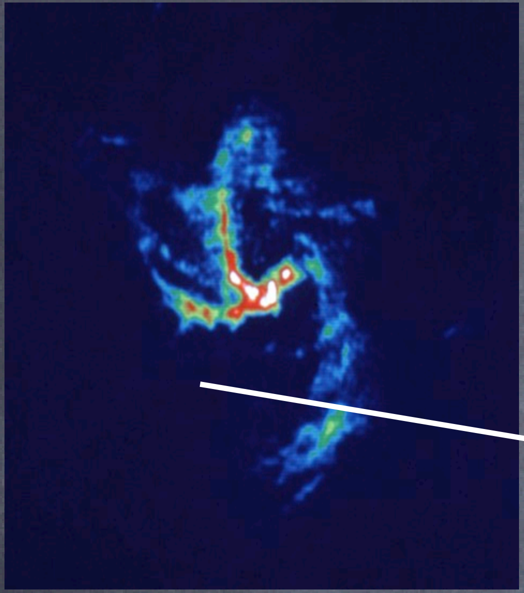


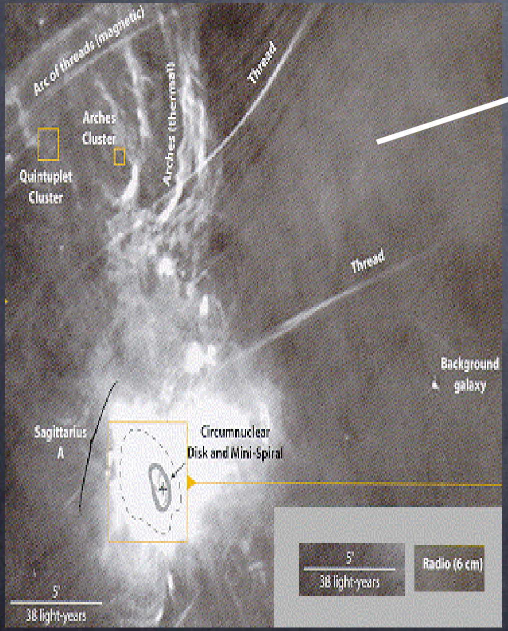
Bi-static radar image of Mercuty

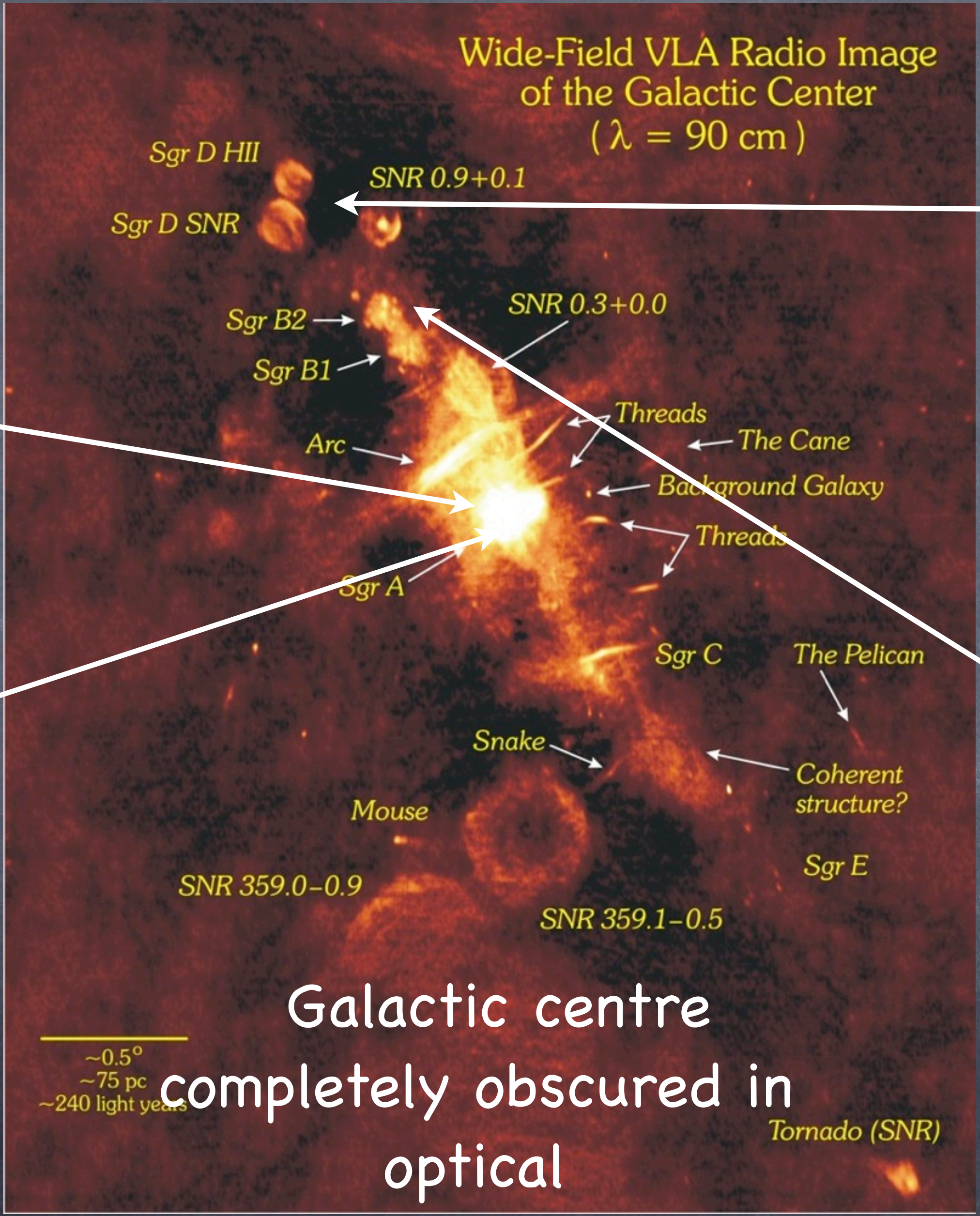
Synchrotron emission from Jupiter (before and after comet SL9 impact



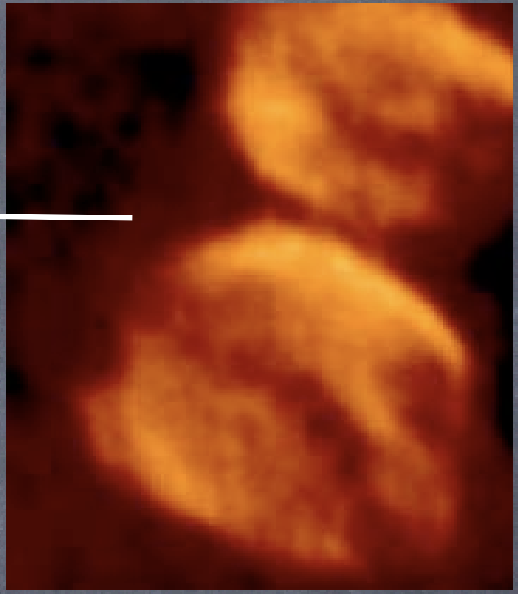
Galactic Centre

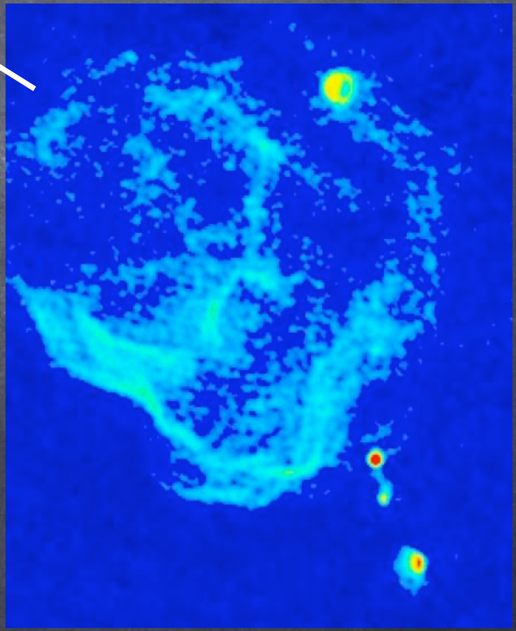




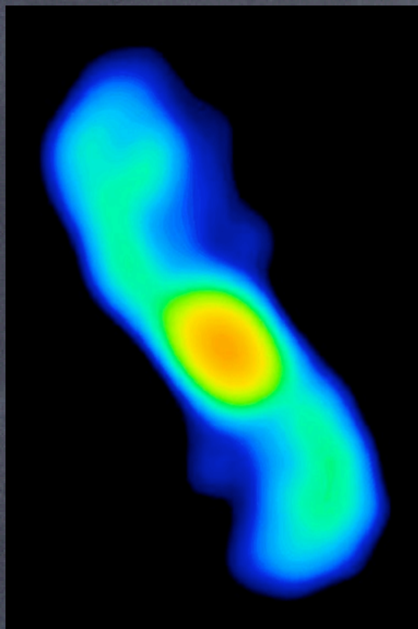


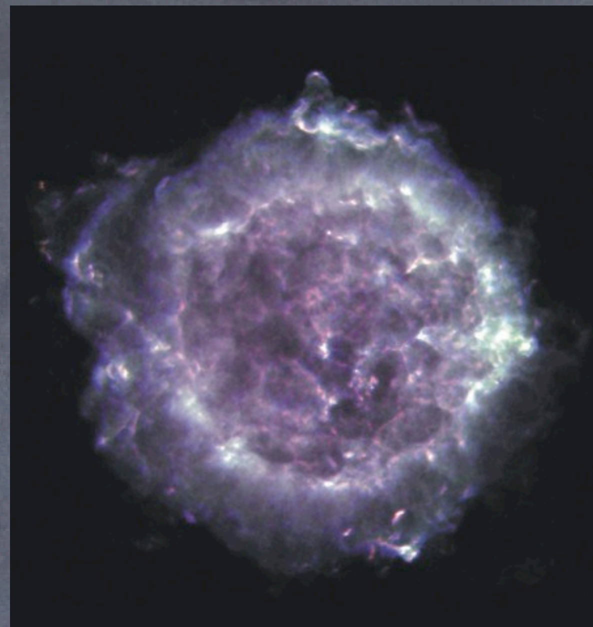
Galactic centre completely obscured in optical

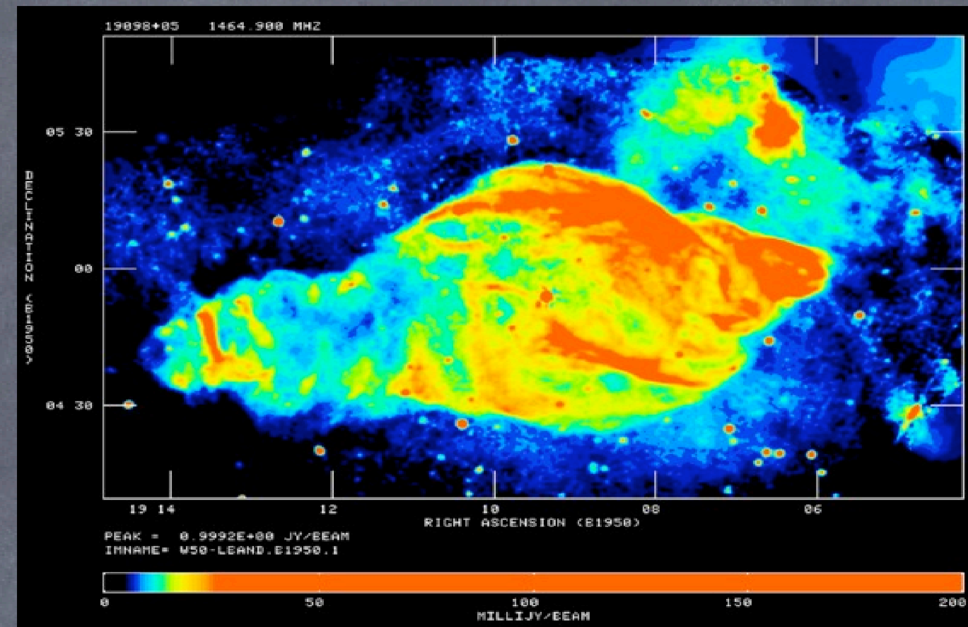


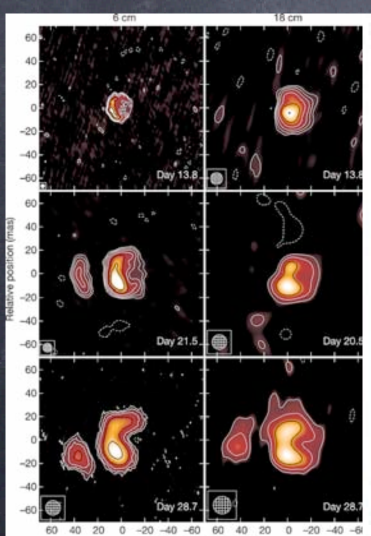


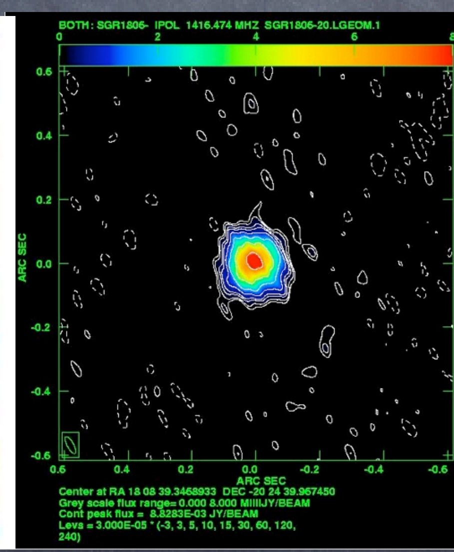
Galactic PNe, SNRs, Novas, PSRs

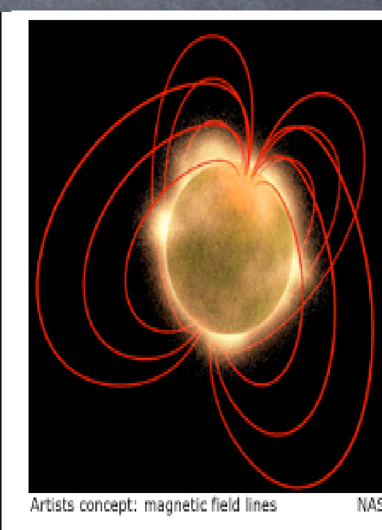


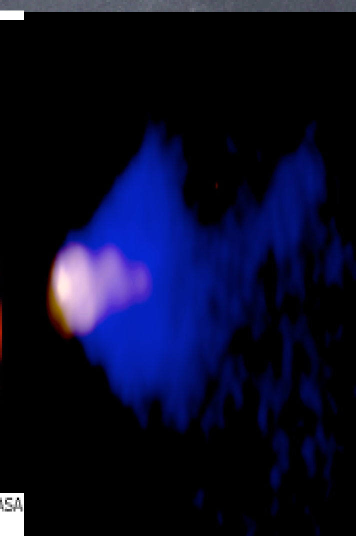




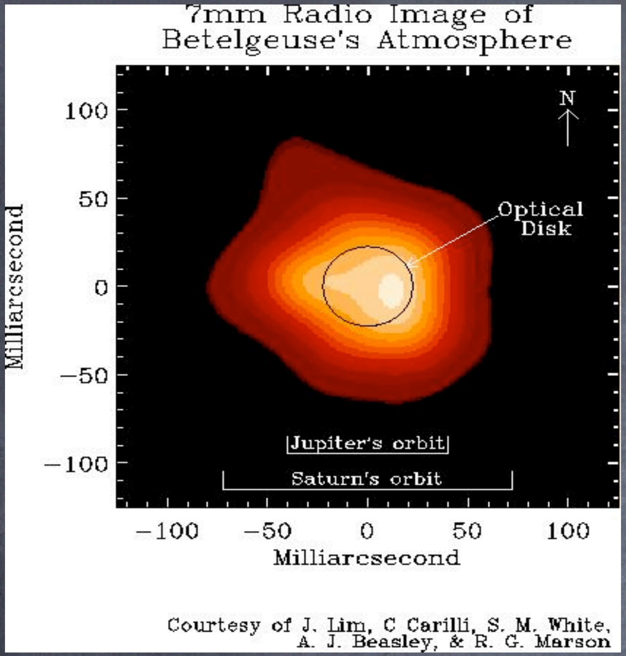


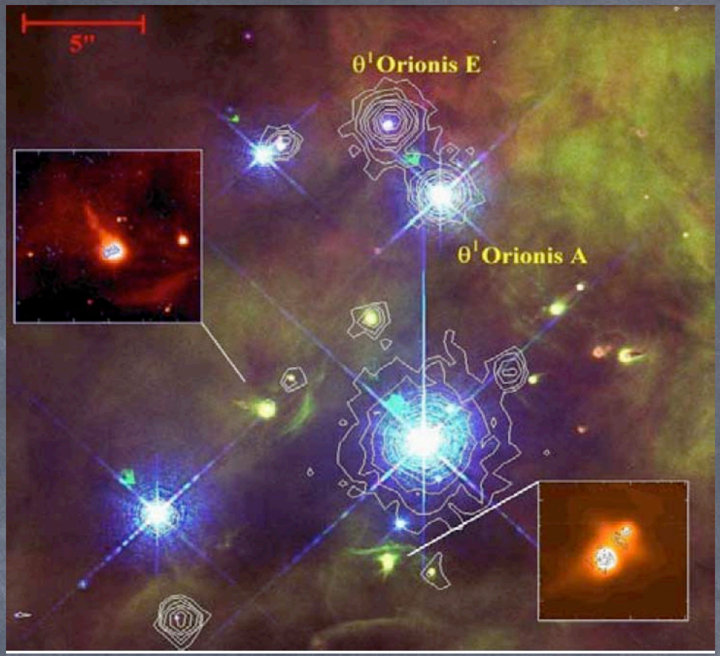


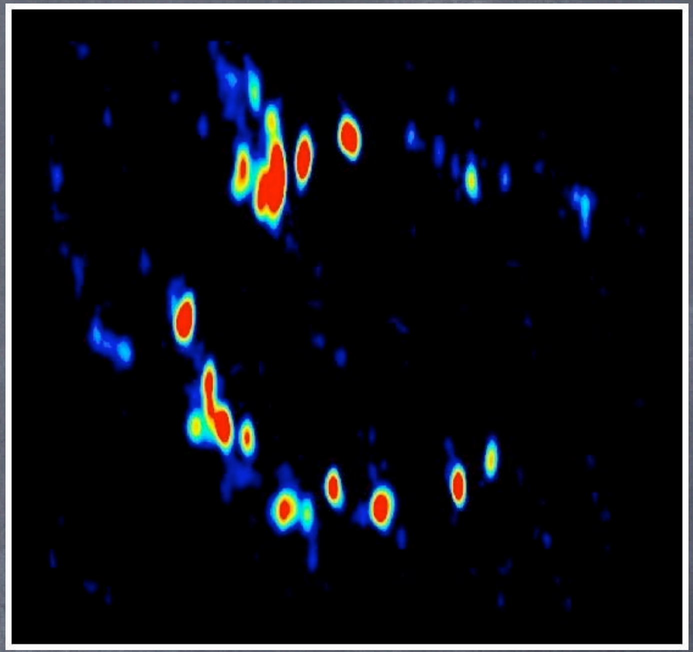


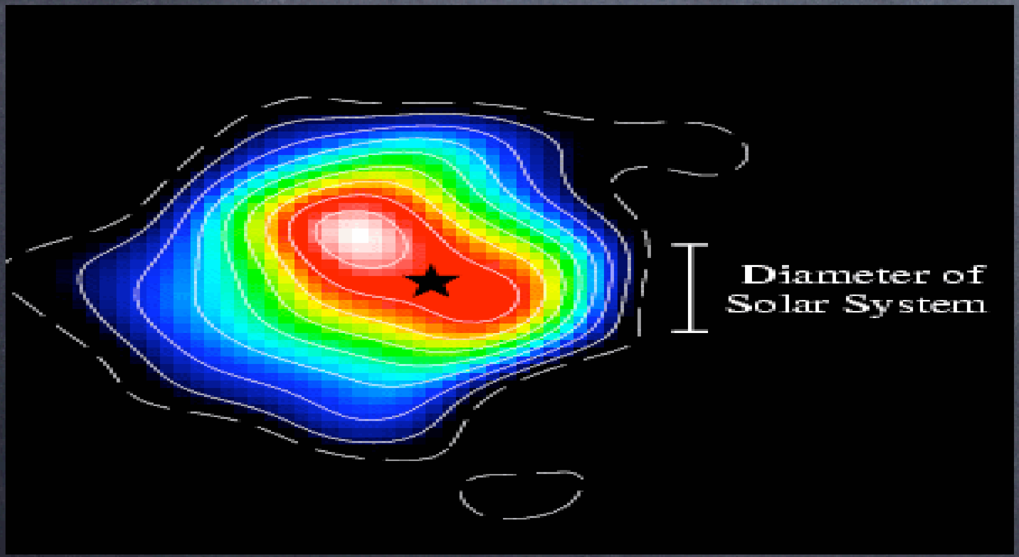


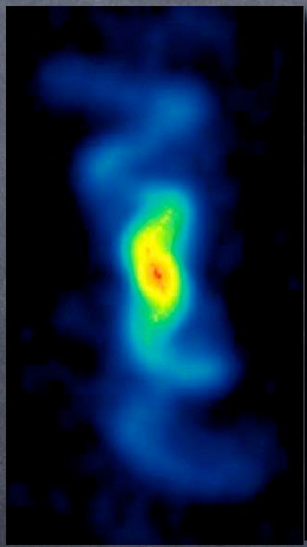
Other Galactic sources (stars, exo-solar systems, masers X-ray binaries)

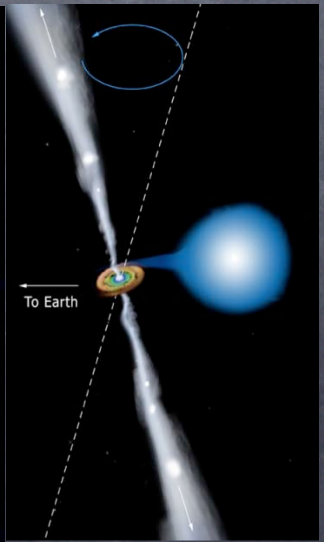


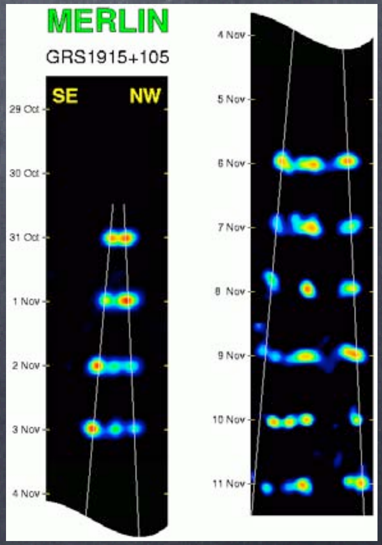




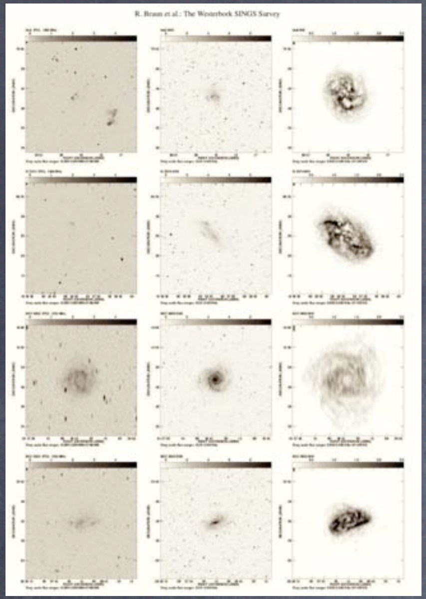


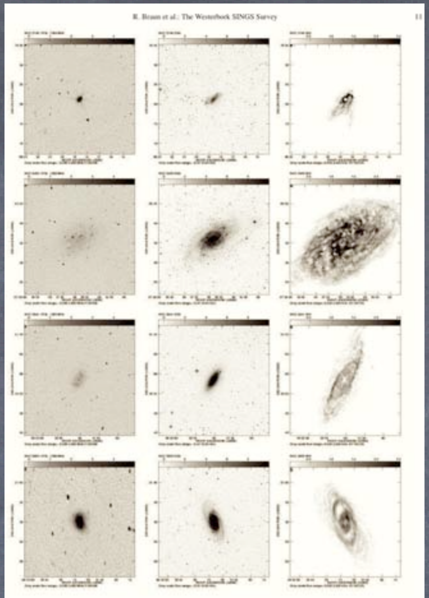


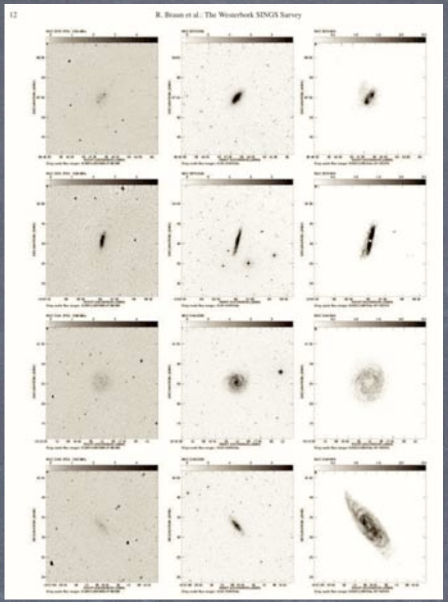


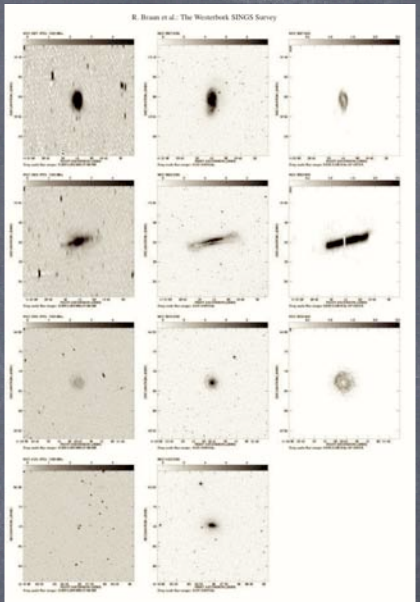


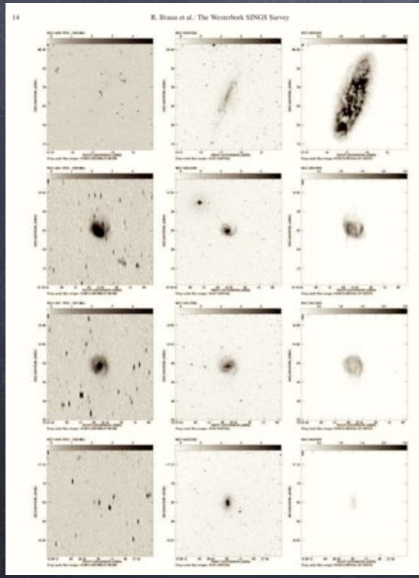
Nearby Galaxies (cont & HI) - WSRT - Braun et al.

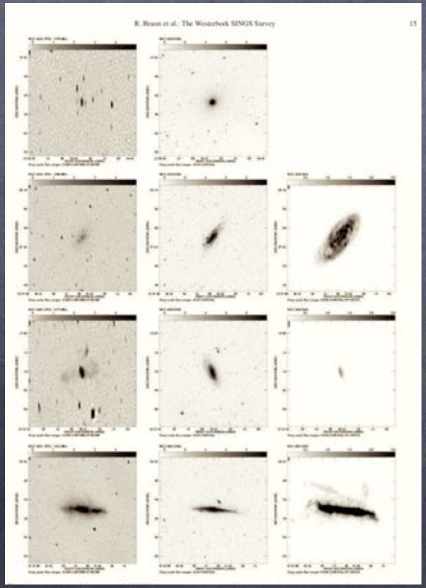


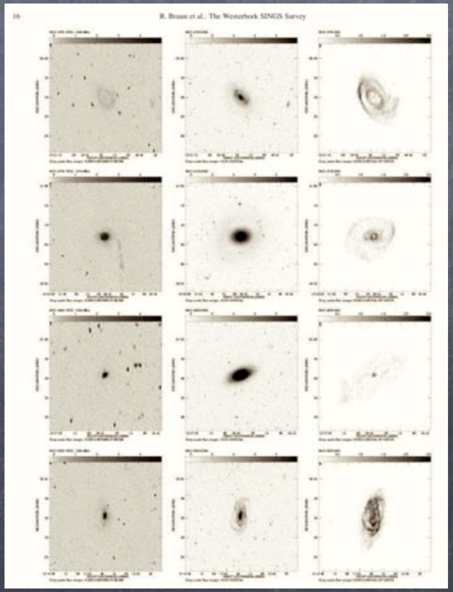


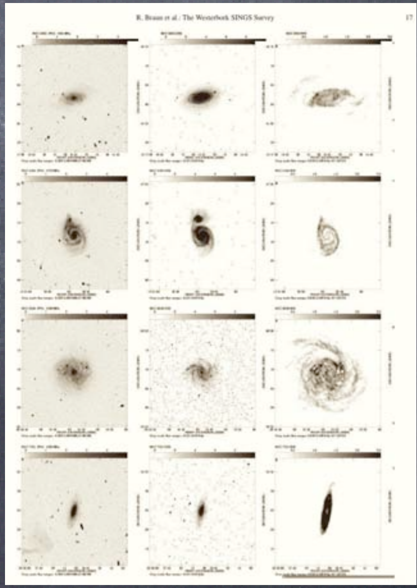






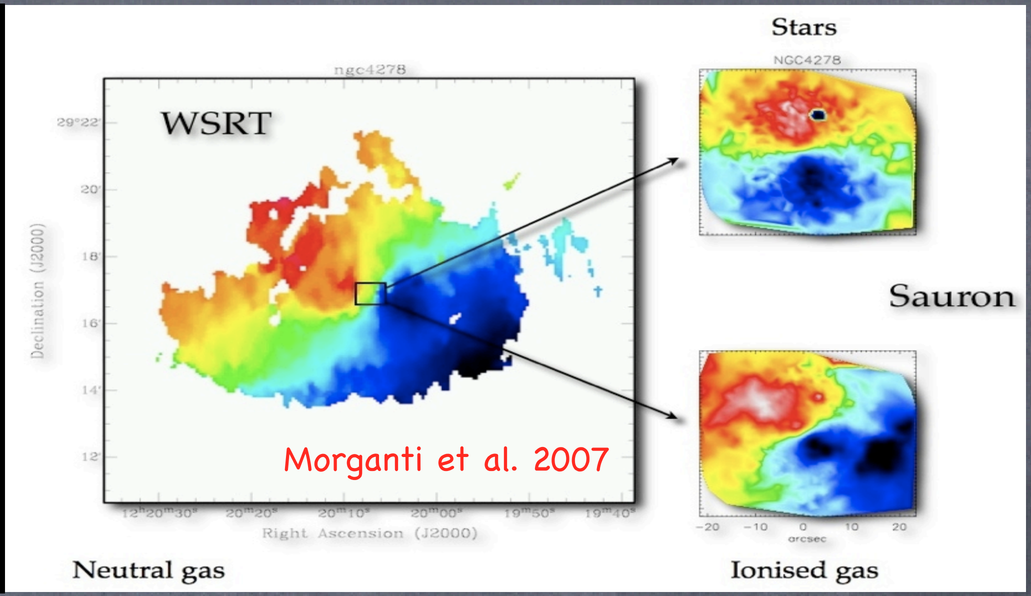




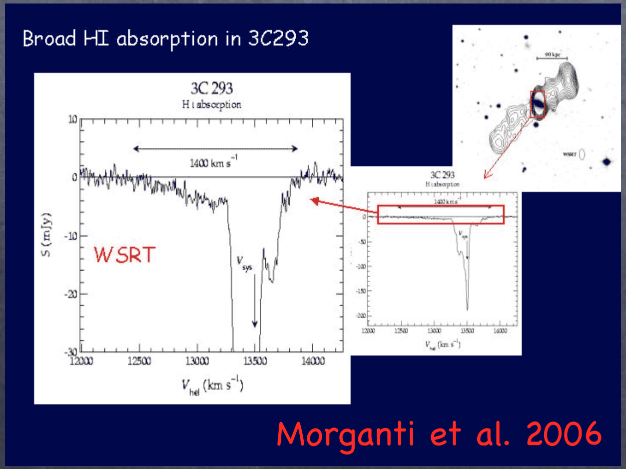


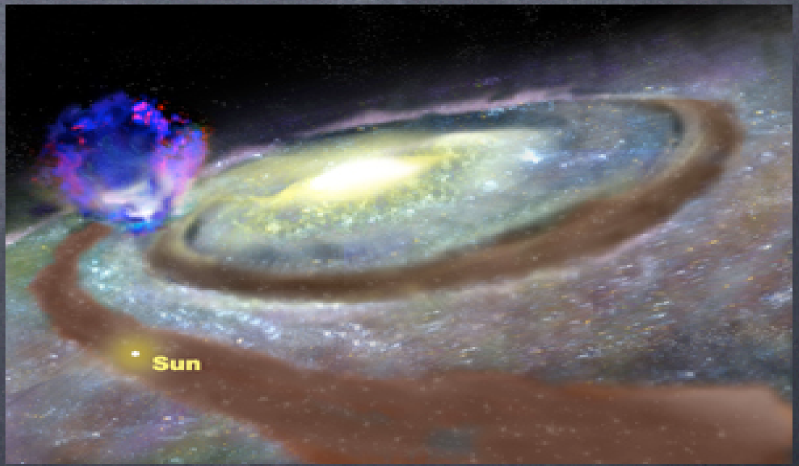
HI in Galaxies - emission & Absorption

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



HI absorption against bright AGN reveals outflow and inflow of gas

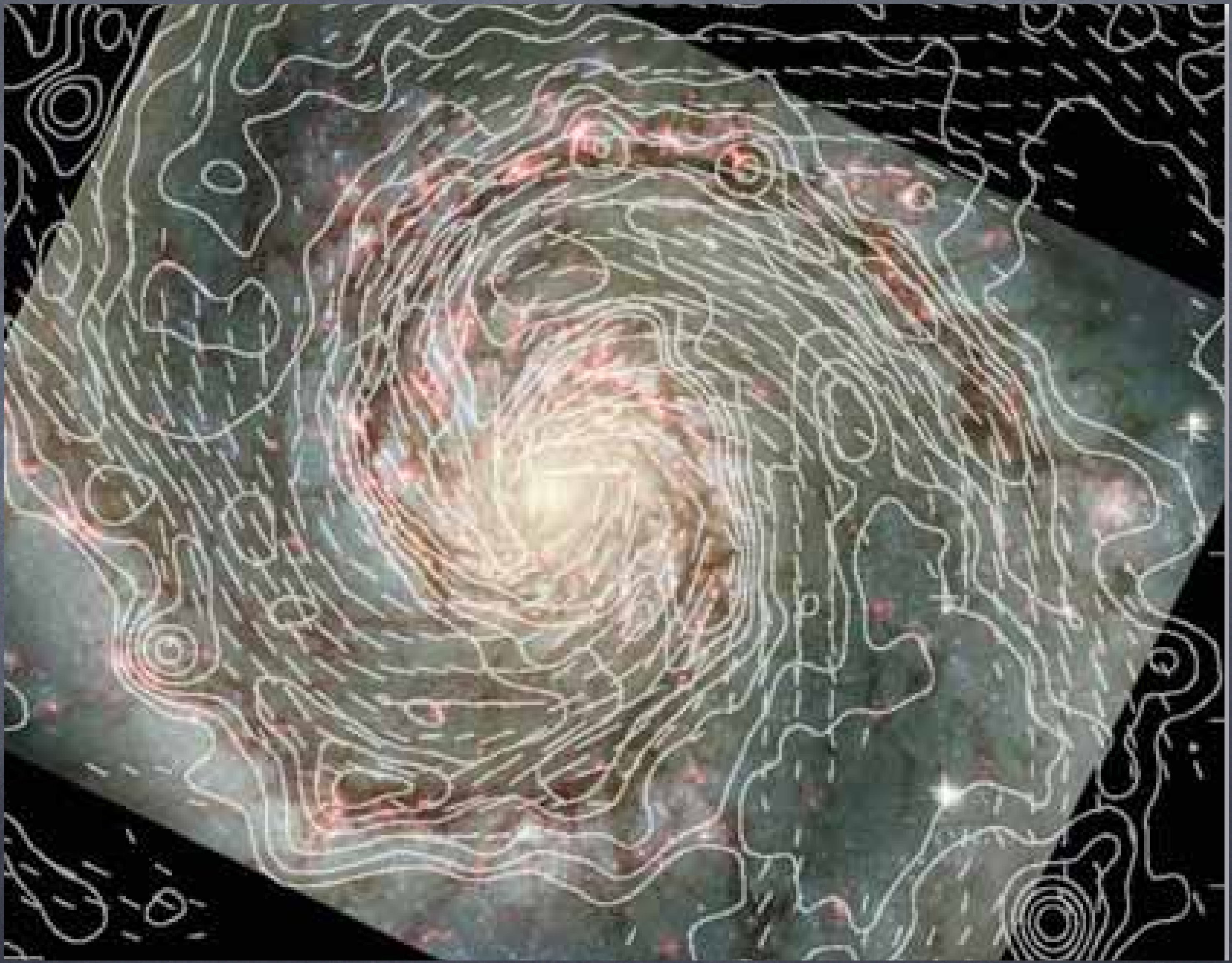




The magnetic Universe...

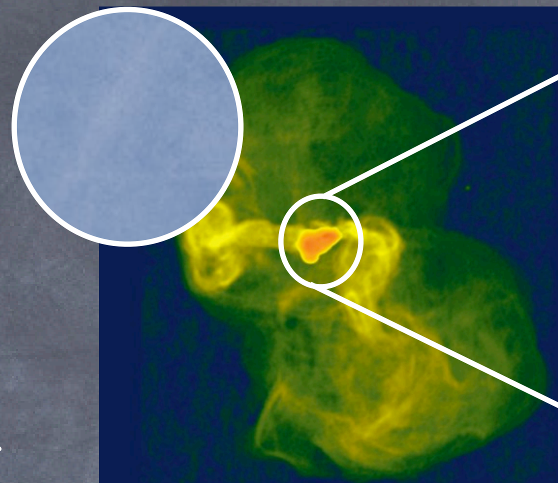
Polarised Radio emission:

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

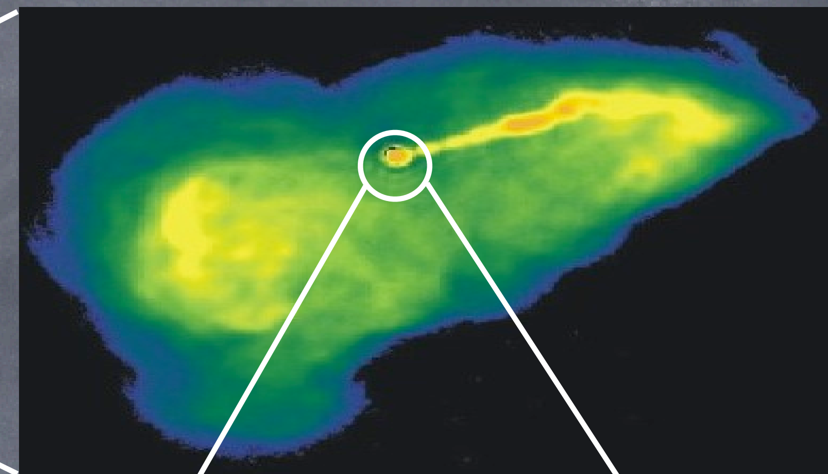


AGN - Imaging on all scales - M87 an example

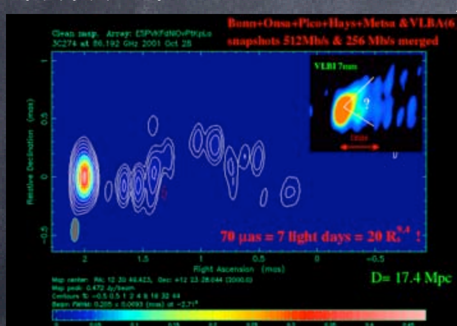
Kitt Peak 2-m optical



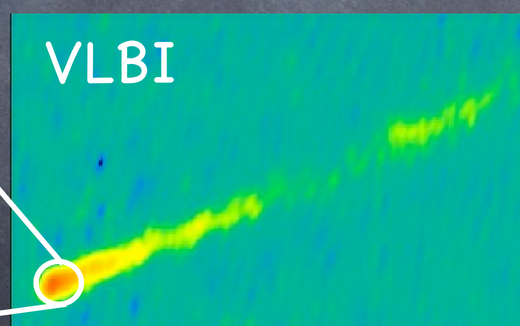
~ 80kpc

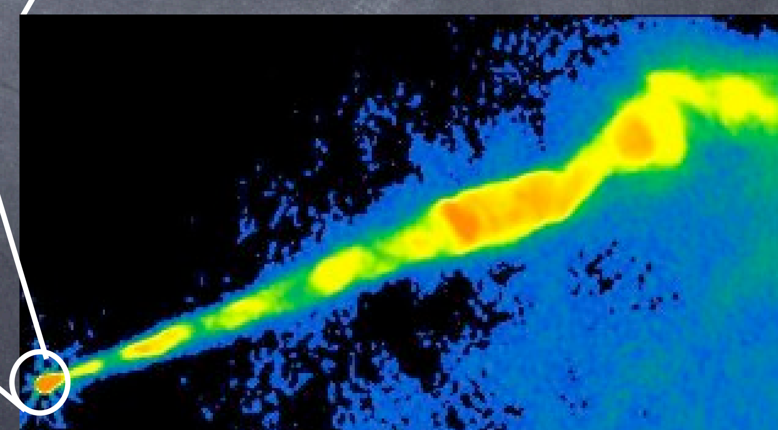


mm-VLBI

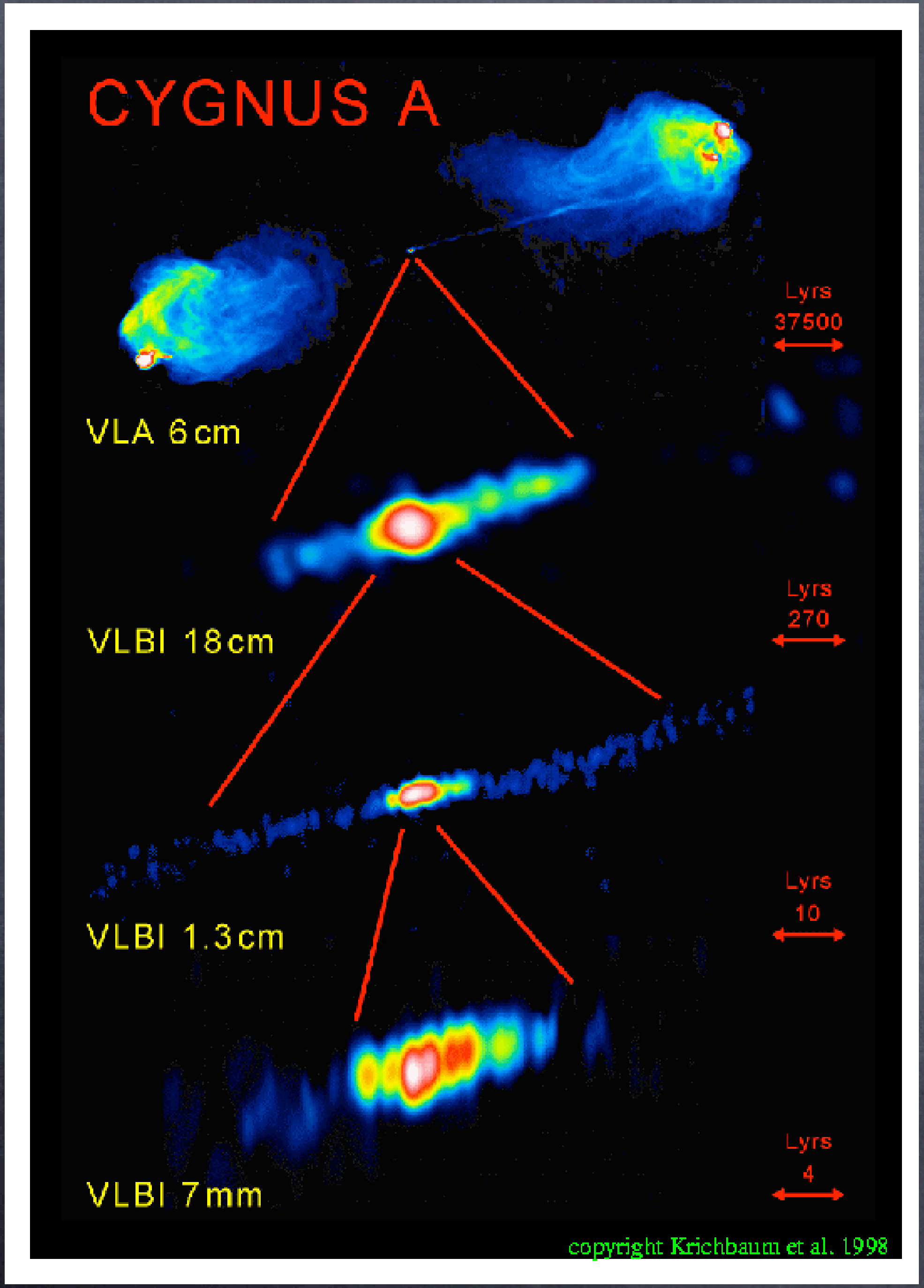


~ sub-pc

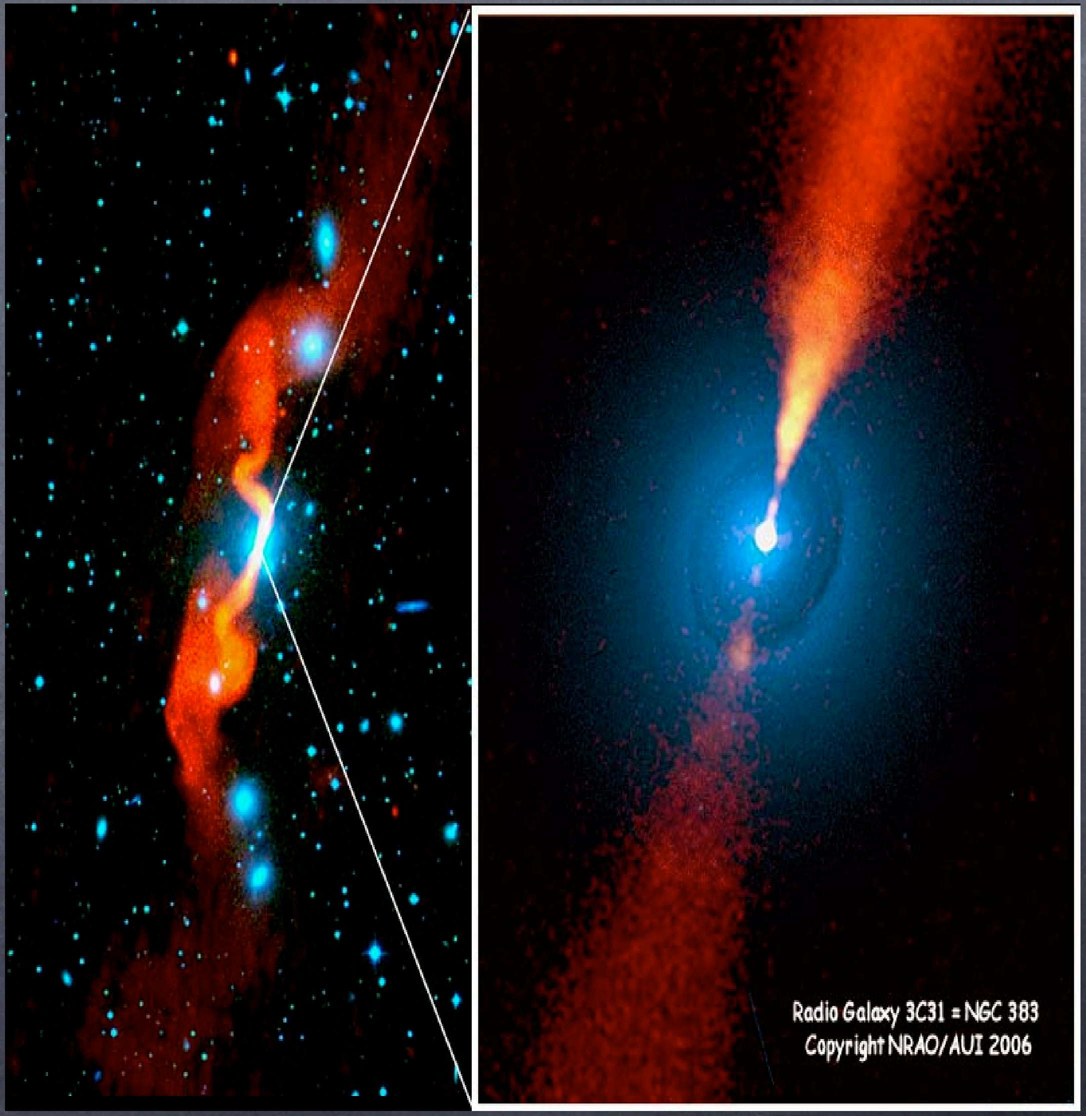




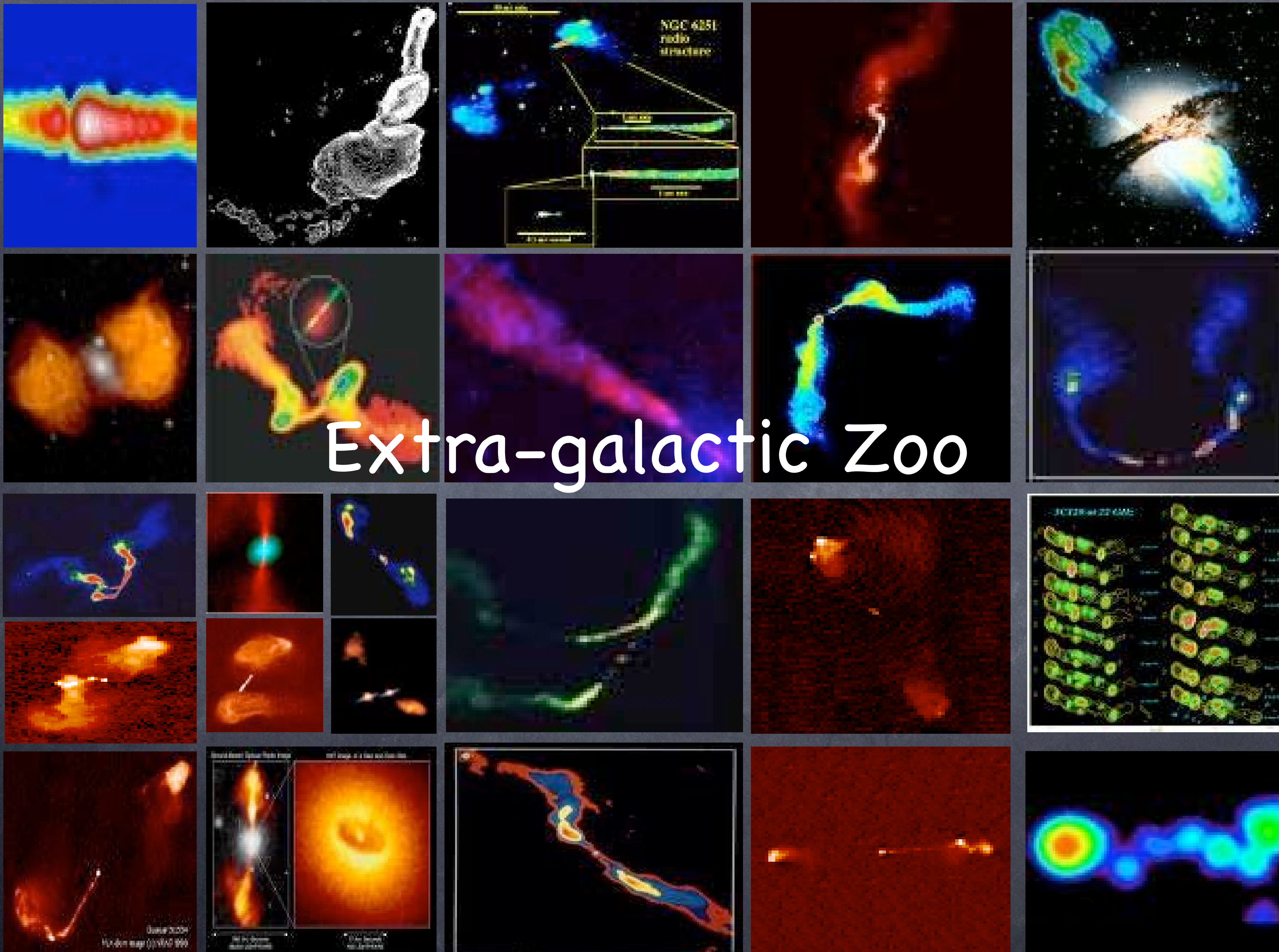
Many other examples of powerful radio galaxies



Powerful radio galaxies usually associated with Elliptical galaxies

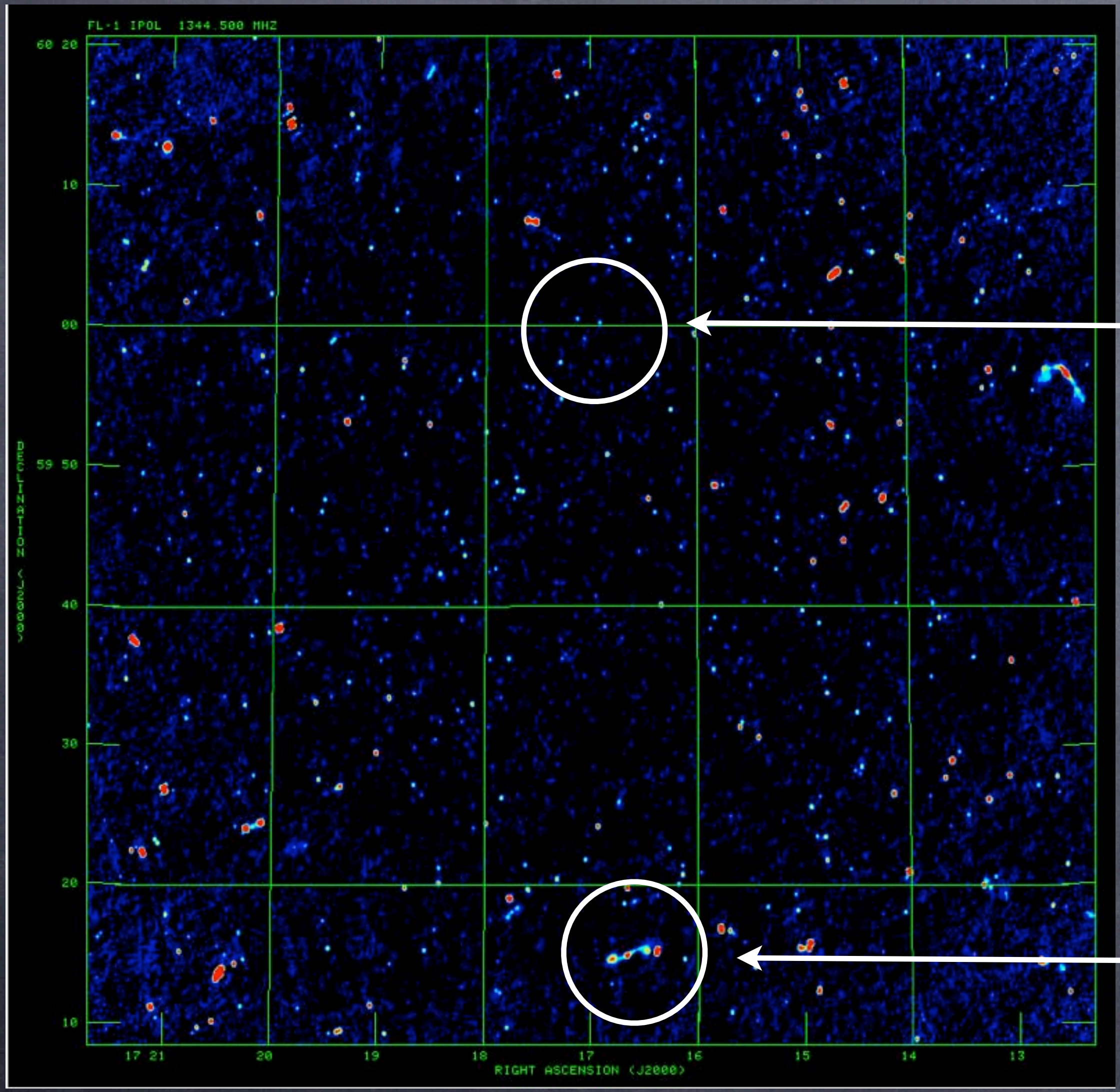


Extra-galactic Zoo

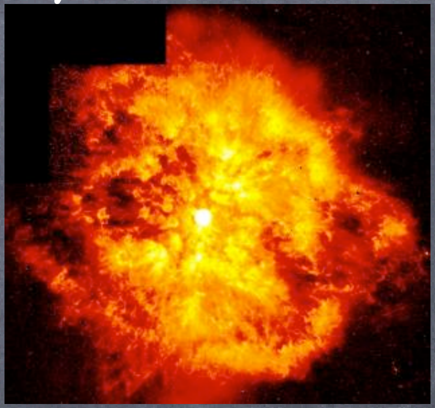


The silent majority - faint radio sources

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



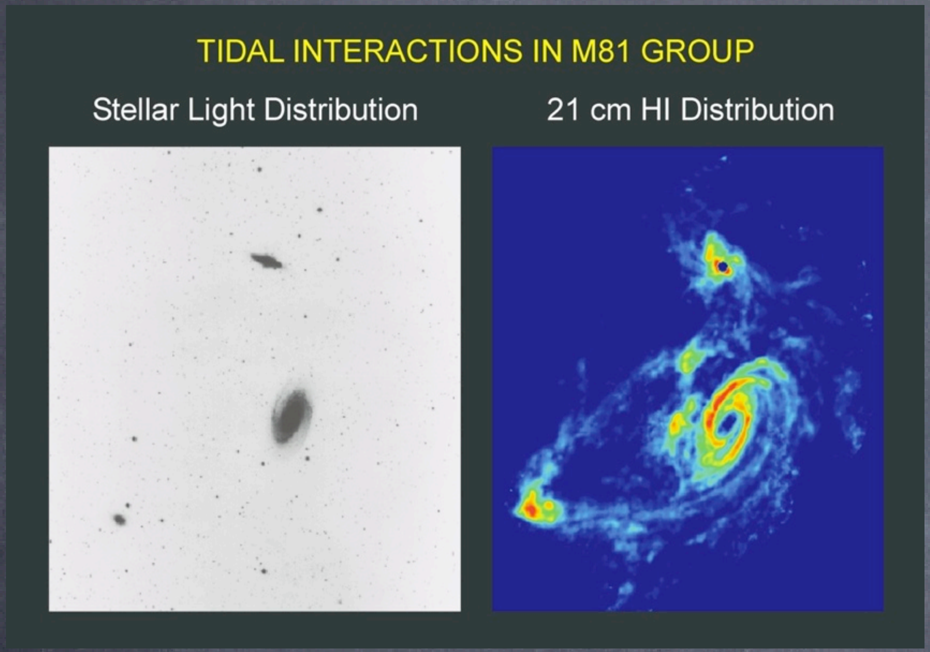
Mostly moderate redshift star-forming galaxies
==> radio emission powered by massive star formation.

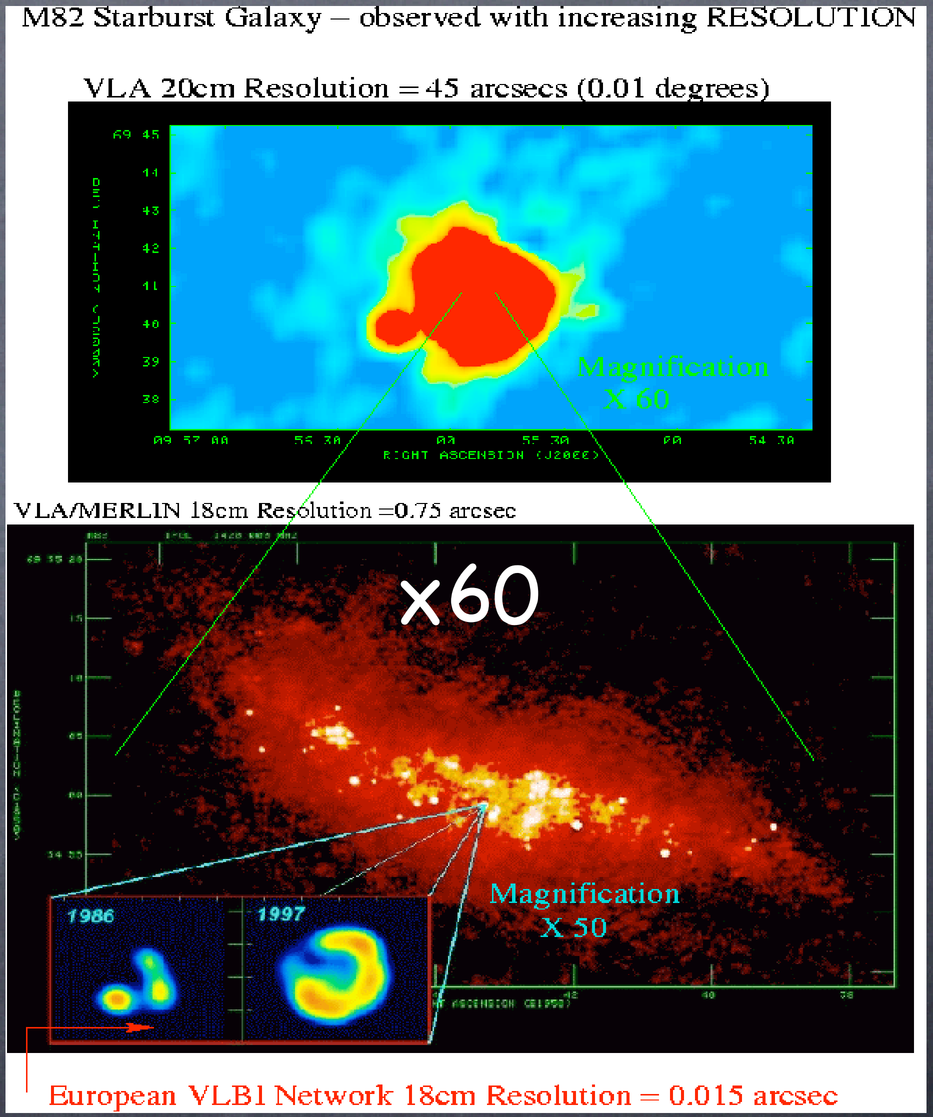


AGN monster

Resolution still important for these faint sources...

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

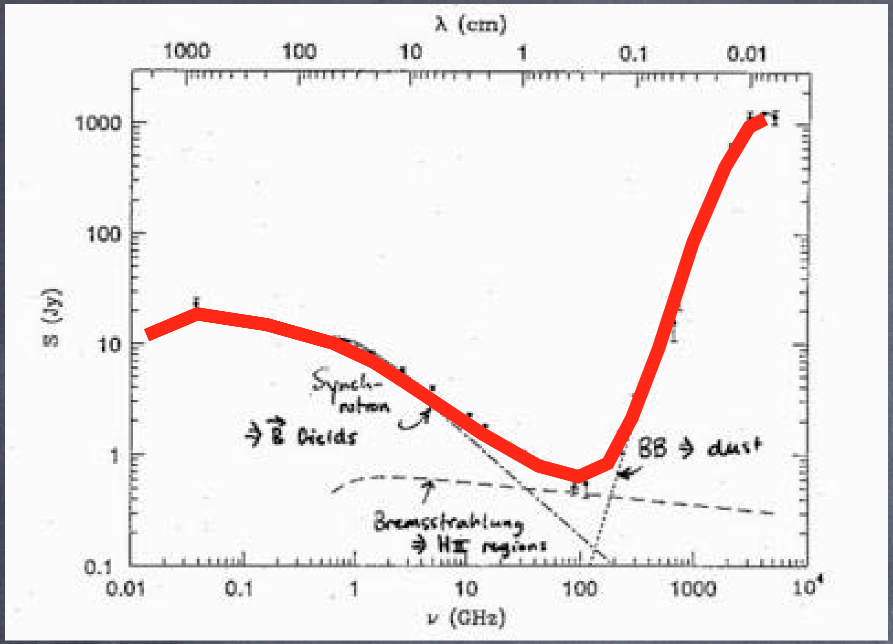


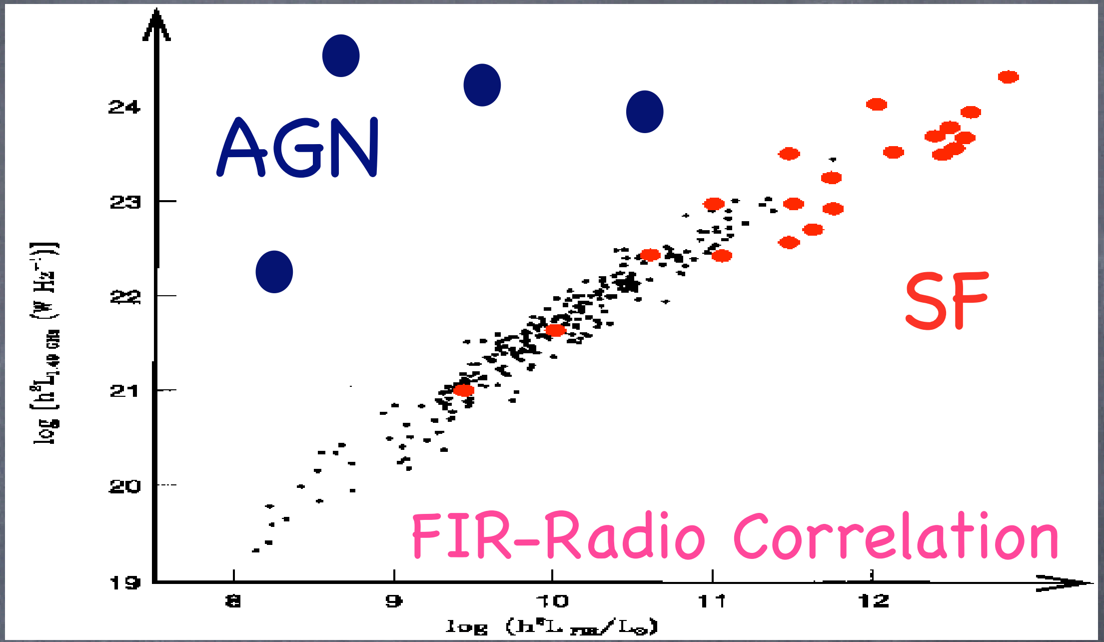


Extended emission on kpc scale

SNe and SNR on tens of pc.

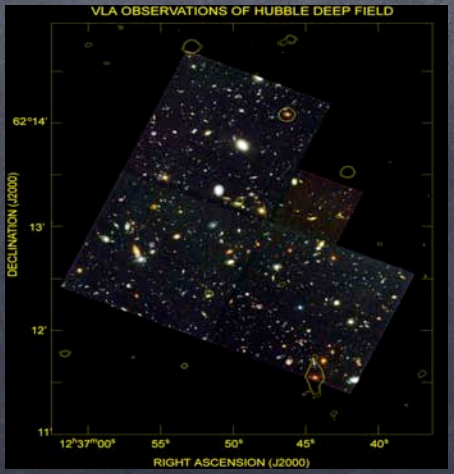
- Radio-FIR Spectral Energy Distribution of "Normal" Galaxies (e.g. Milky Way, M82):

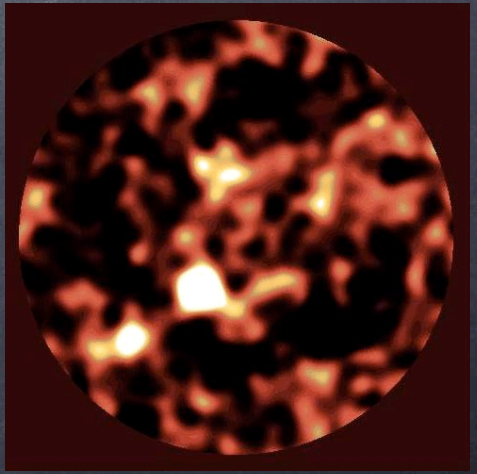




- Both Radio and FIR (sub-mm at high reshift) are sensitive measures sures of MASSIVE Star formation in the local and distant galaxies.

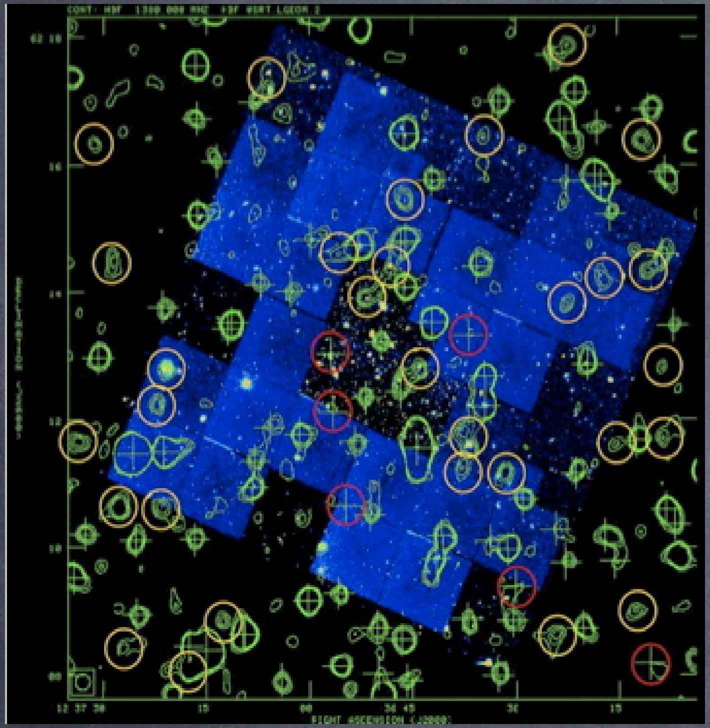
- Radio and sub-mm observations closely allied in the study of the DUSTY High-z Universe.

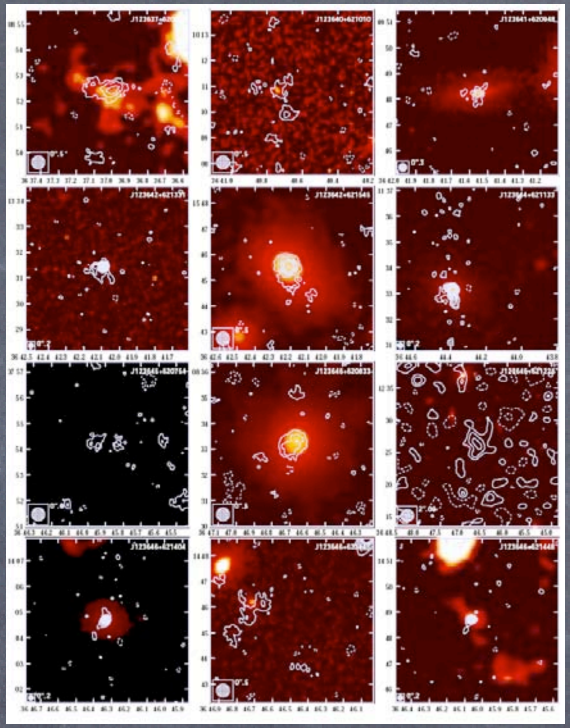


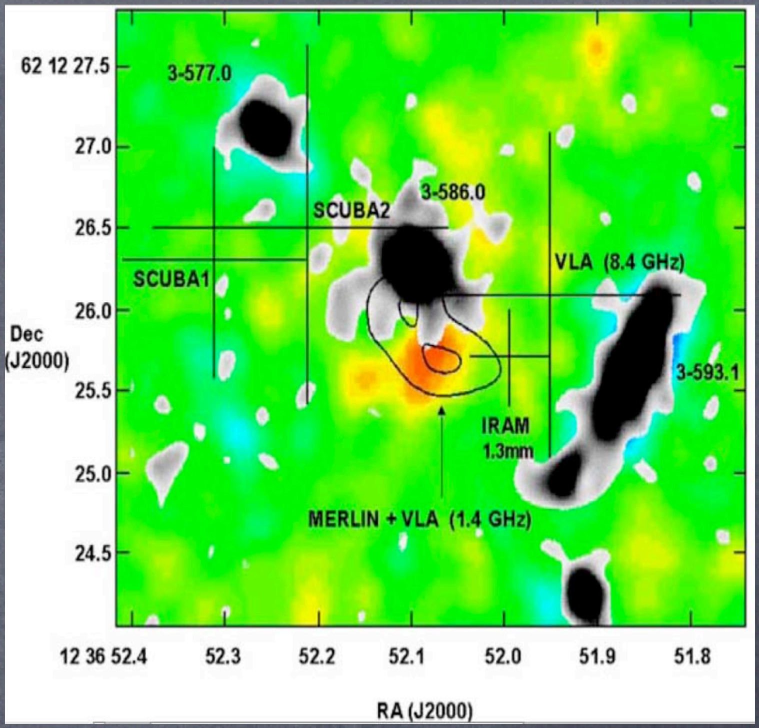


Going even deeper... microJy source population

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





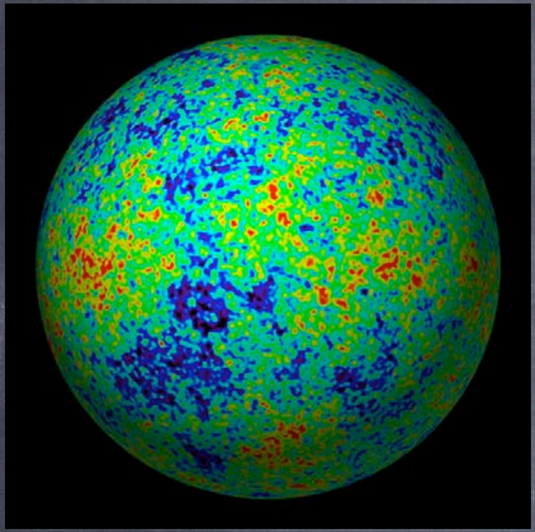


MicroJy sensitivity Universe begins to move away from us - high-z

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

Radio Interferometry & Cosmology

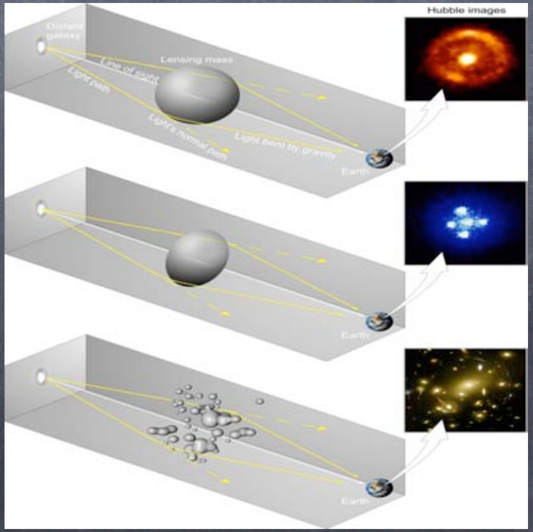
CMB experiments - interferometry offers many advantages...

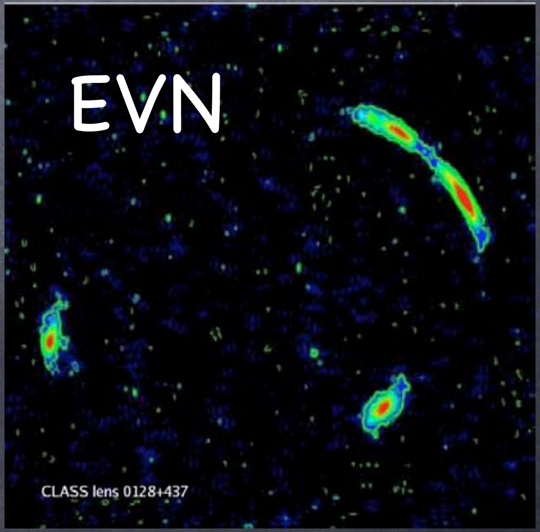


SPECIAL: Noise is independant for each antenna - disappears during correlation e.g. RFI -

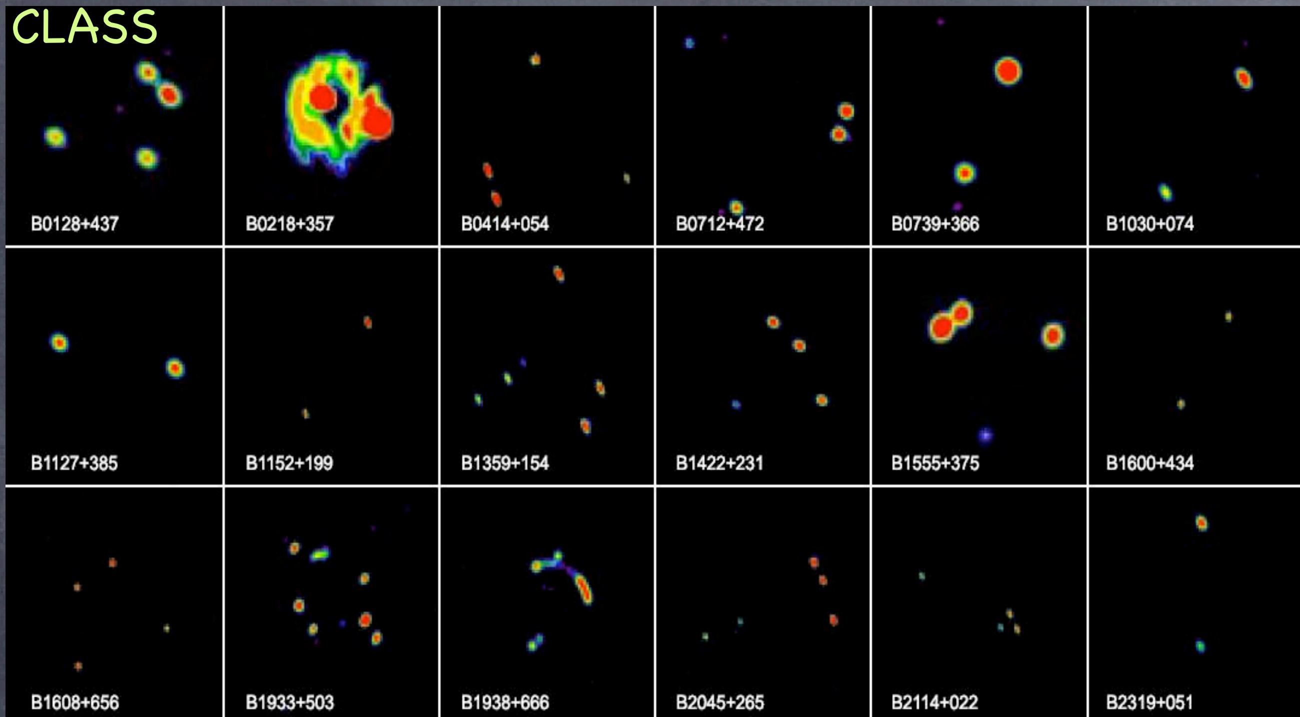
Gravitational lensing - Ho

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





Gravitational lens surveys



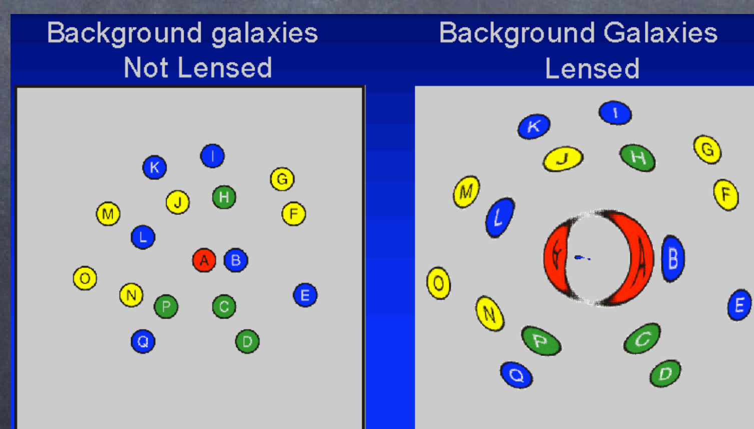
Radio surveys ideal for finding lenses...

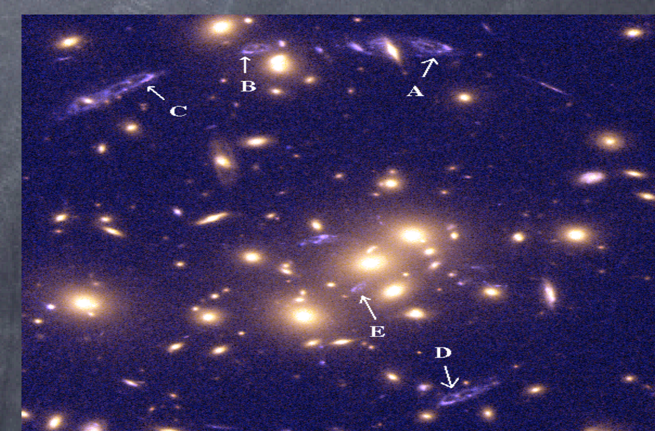
Source population typically at high-z

Seperation ~ 1 arcsec

Flat spectrum radio sources rare.

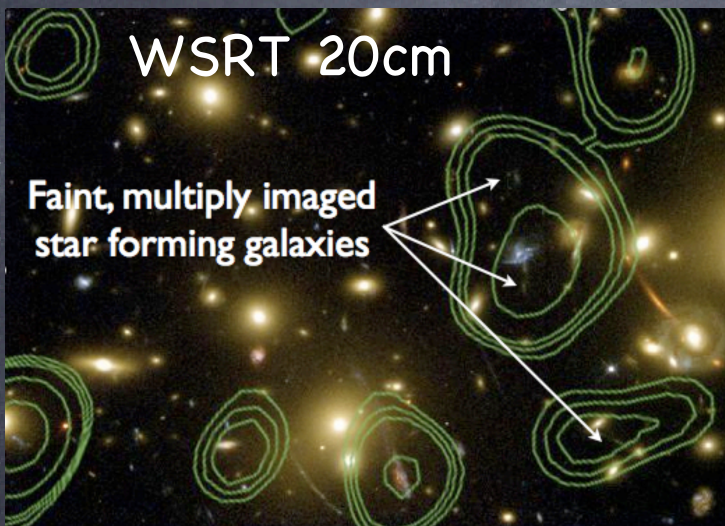
Gravitational lensing - also MAGNIFIES sources

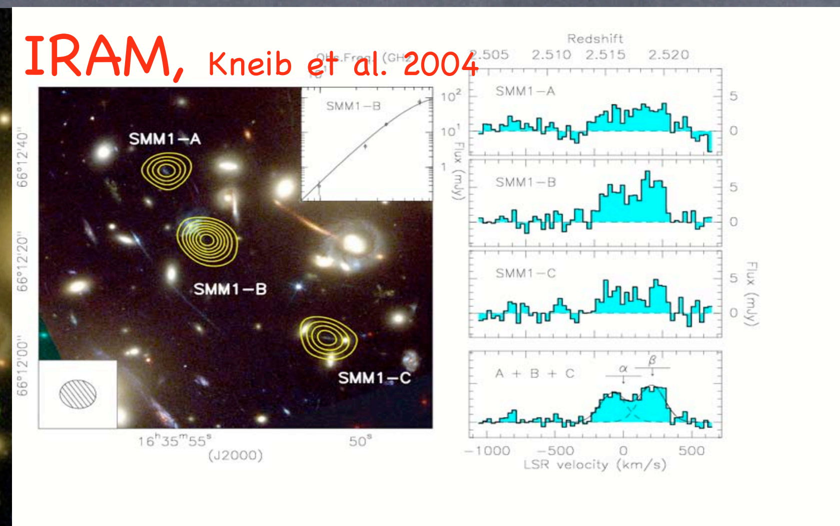


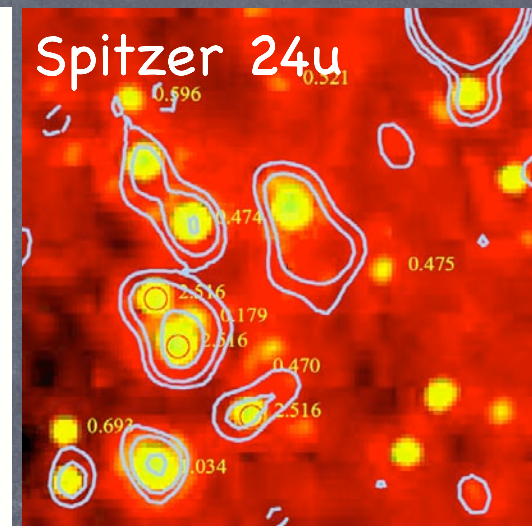


Lenses as giant cosmic magnifying glasses:

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



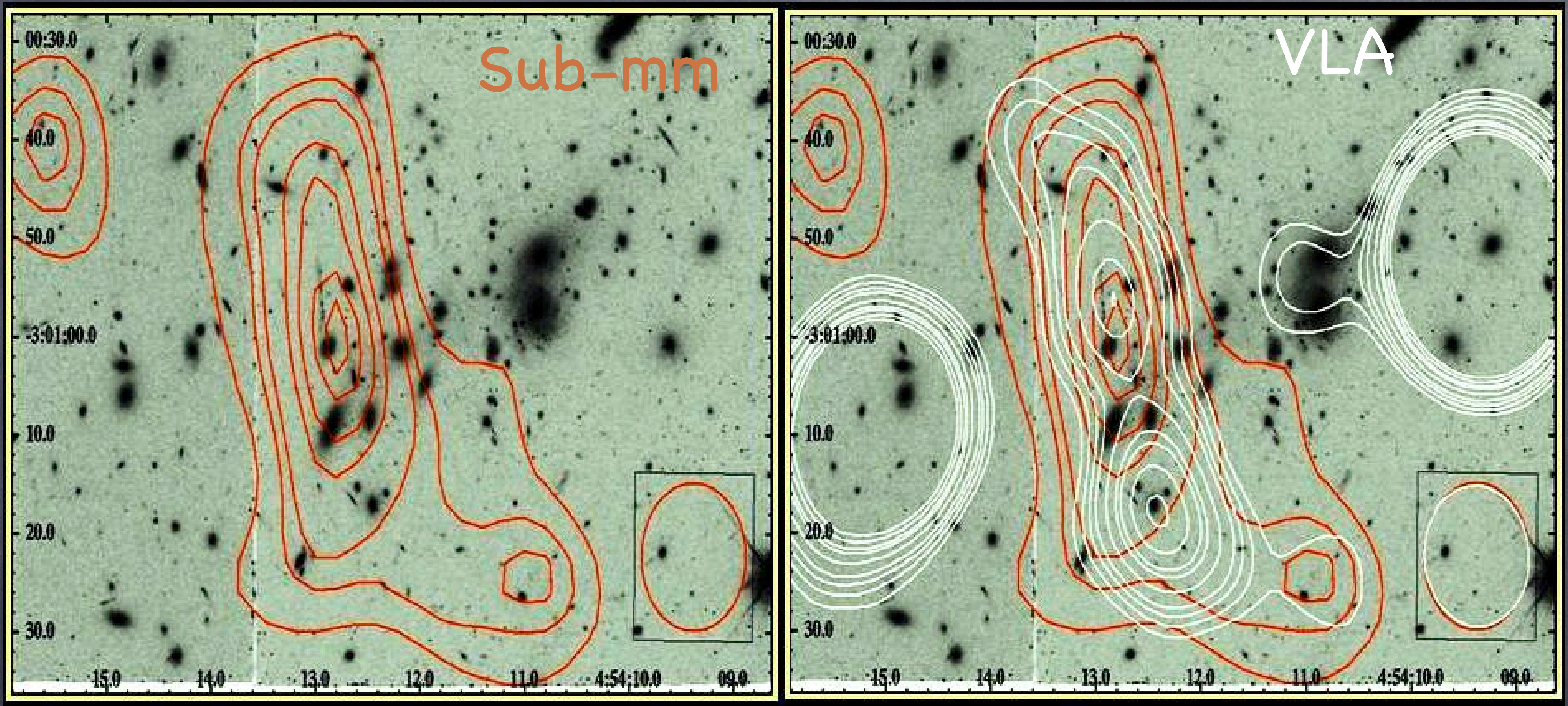




Total magnification of cluster is x45

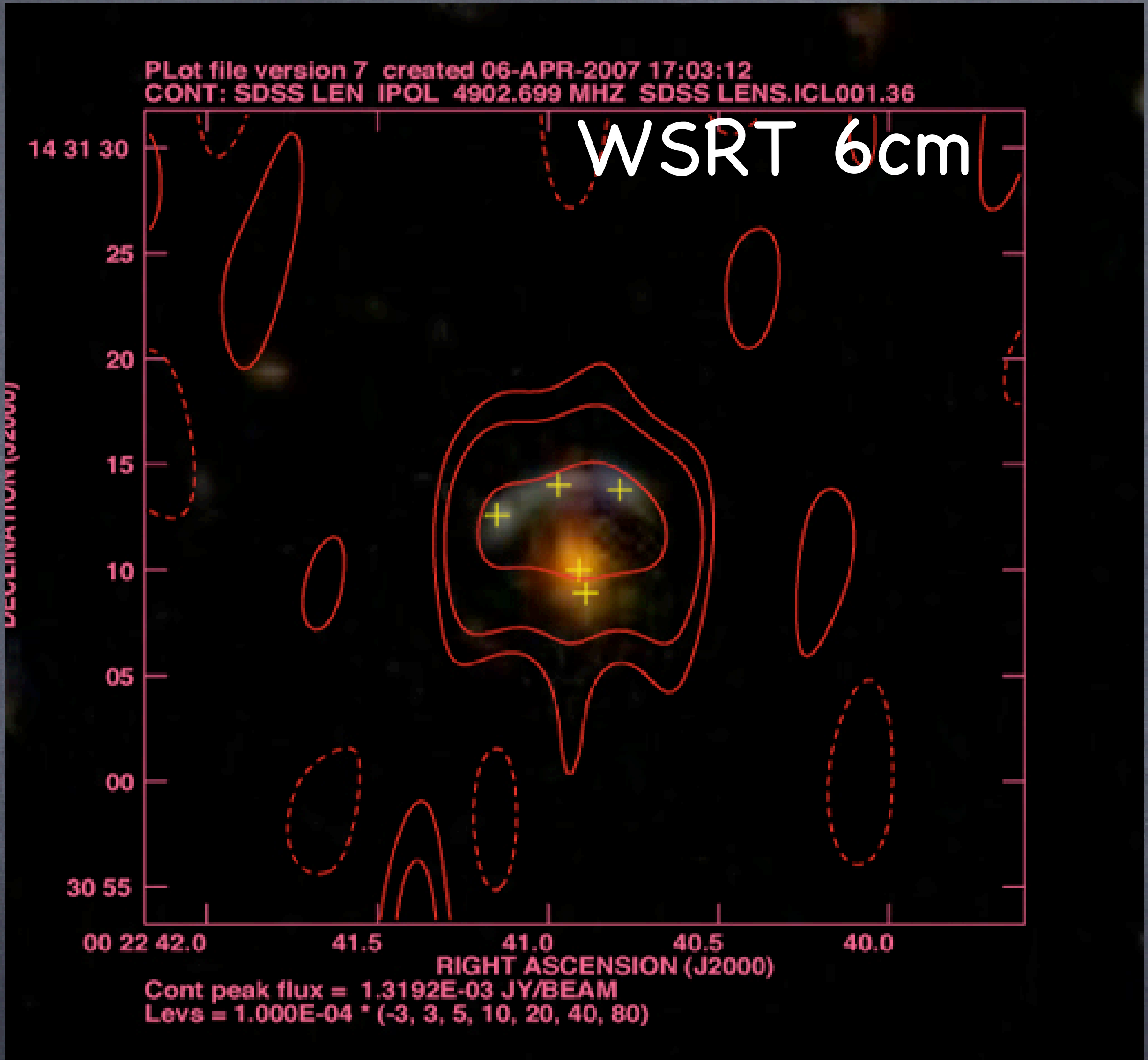
Source is a intrinsically faint, z=2.5 SMG & uJy radio source - undetectable without the lens..

More [lensed] distant star-forming galaxies



Berciano alba et al. (2007)

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



Garrett et al. in prep (2007)

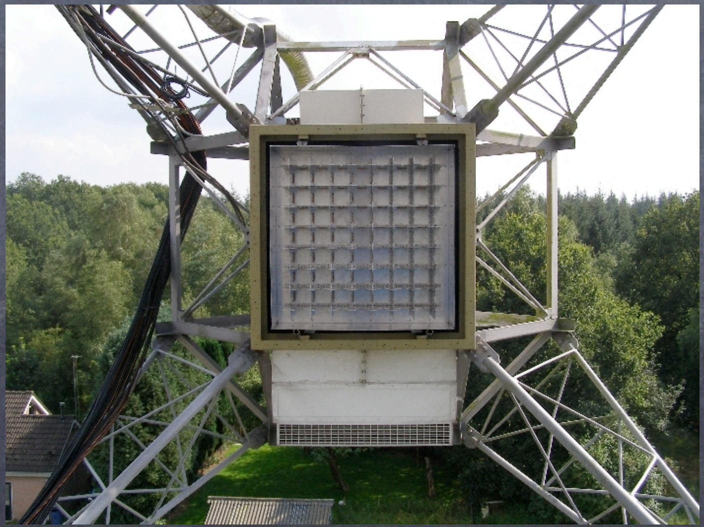
The Future...

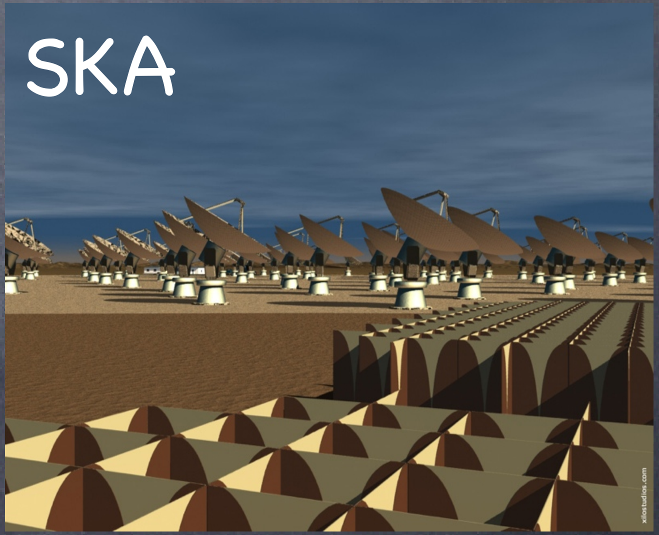
Activity is intense!

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

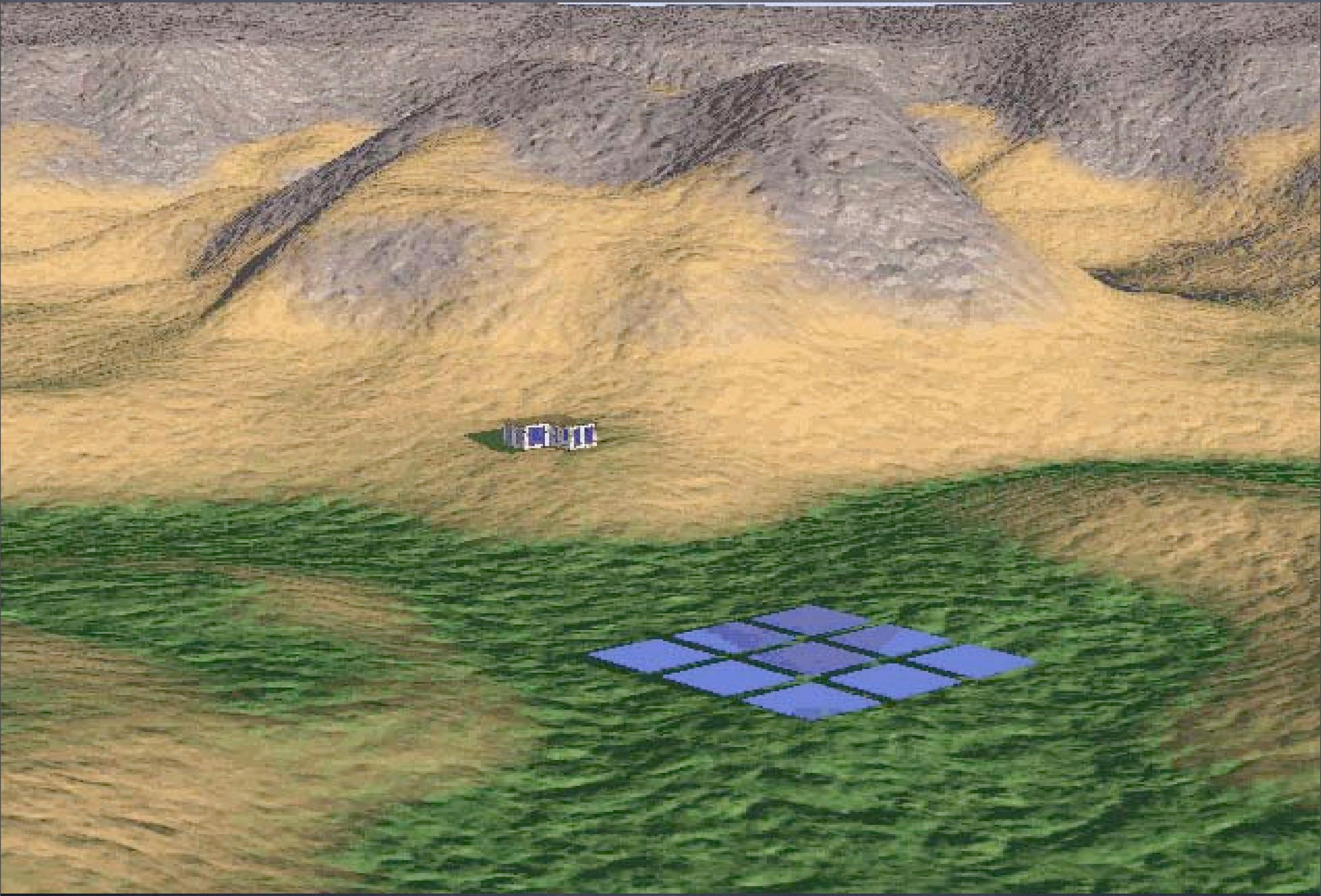
Many NEW telescope arrays under construction (pathfinders for the Square Km Array): ATA, LOFAR, MWA, ASKAP, MeerKAT.

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

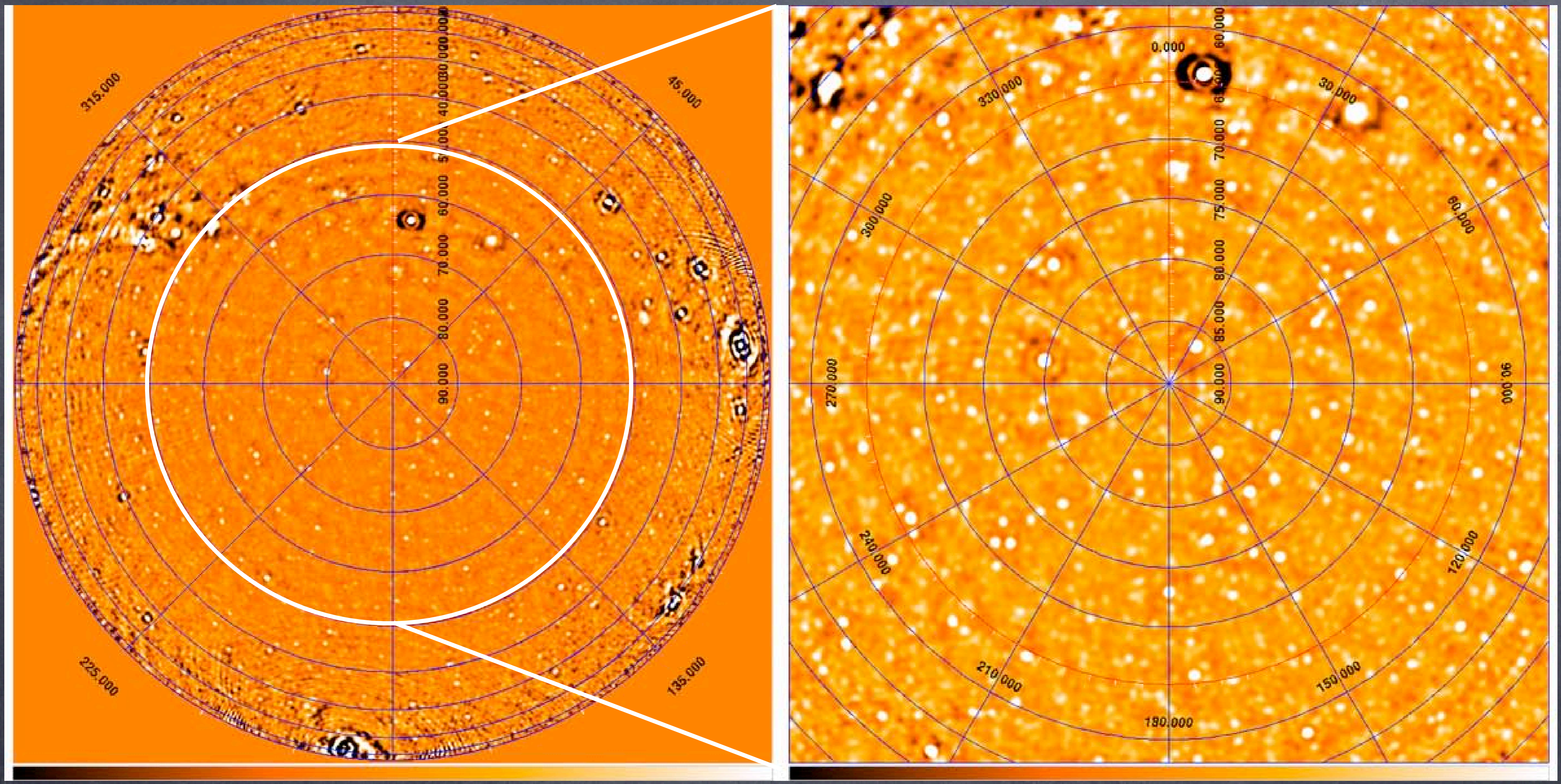
UK ~2-3 stations

Italy ~2 stations

France ~1 station?

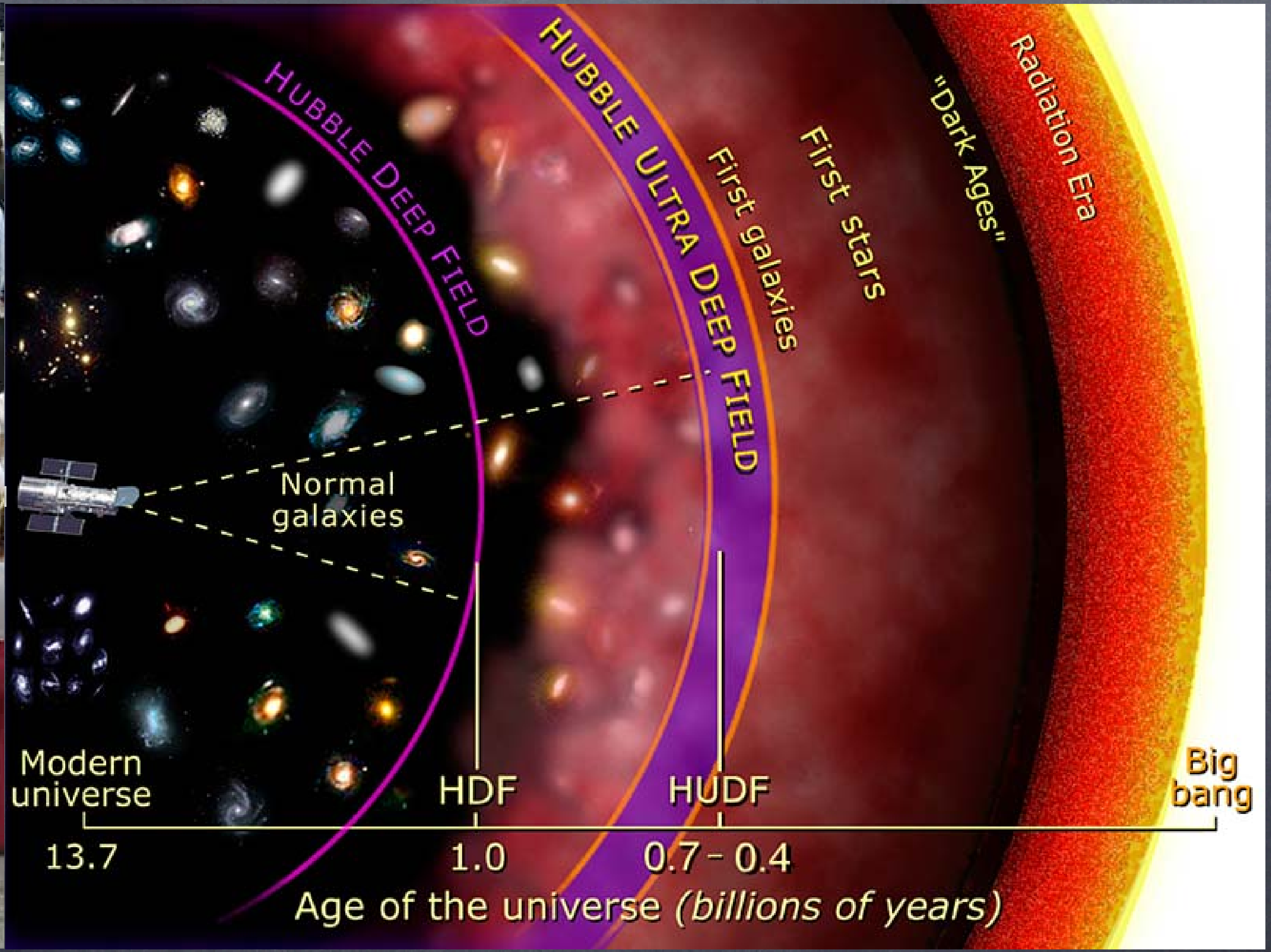
Other EVN sites...

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

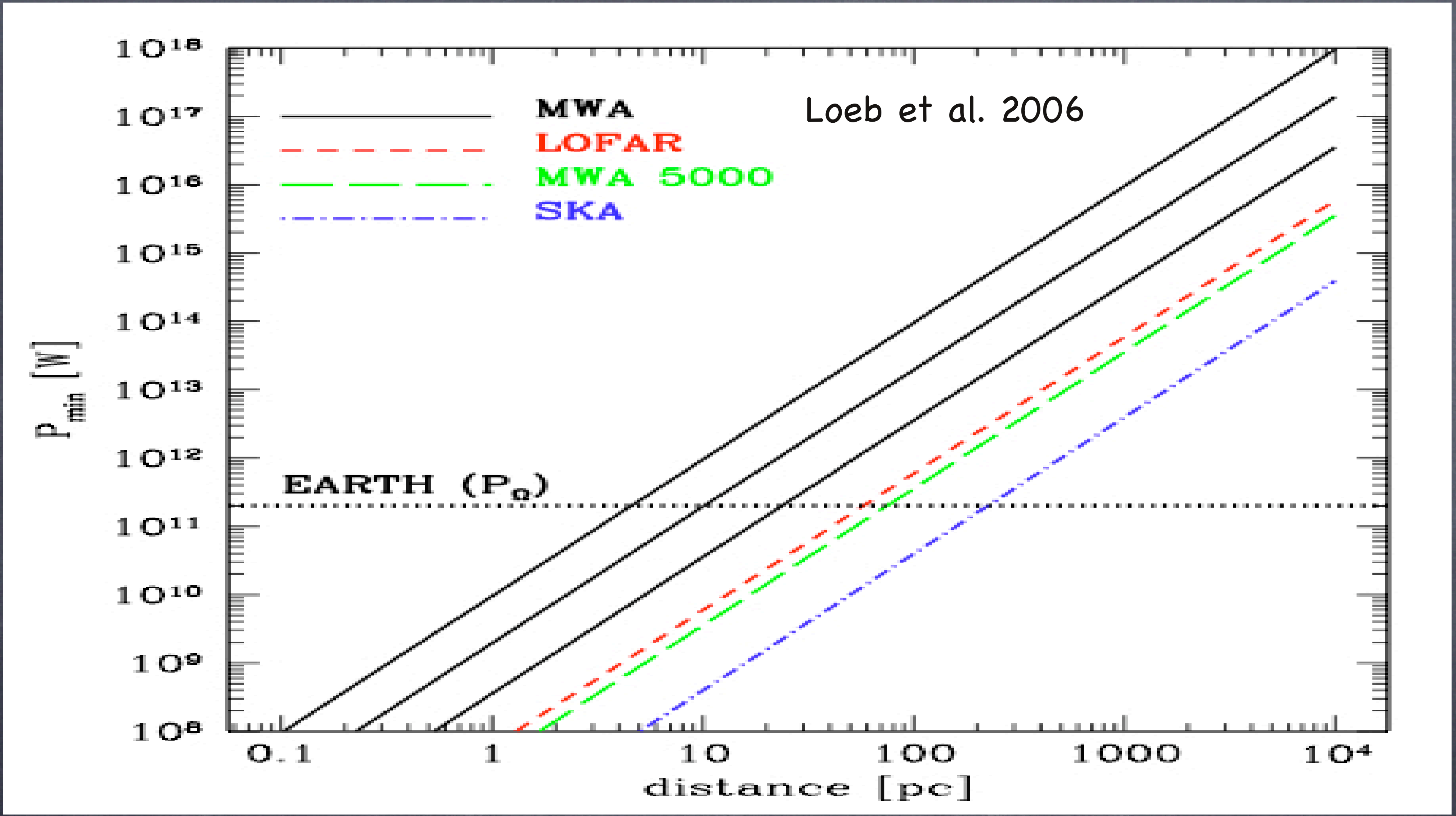


Amazing Field of view - superb survey instrument - if we can calibrate it!

Understanding the Universe

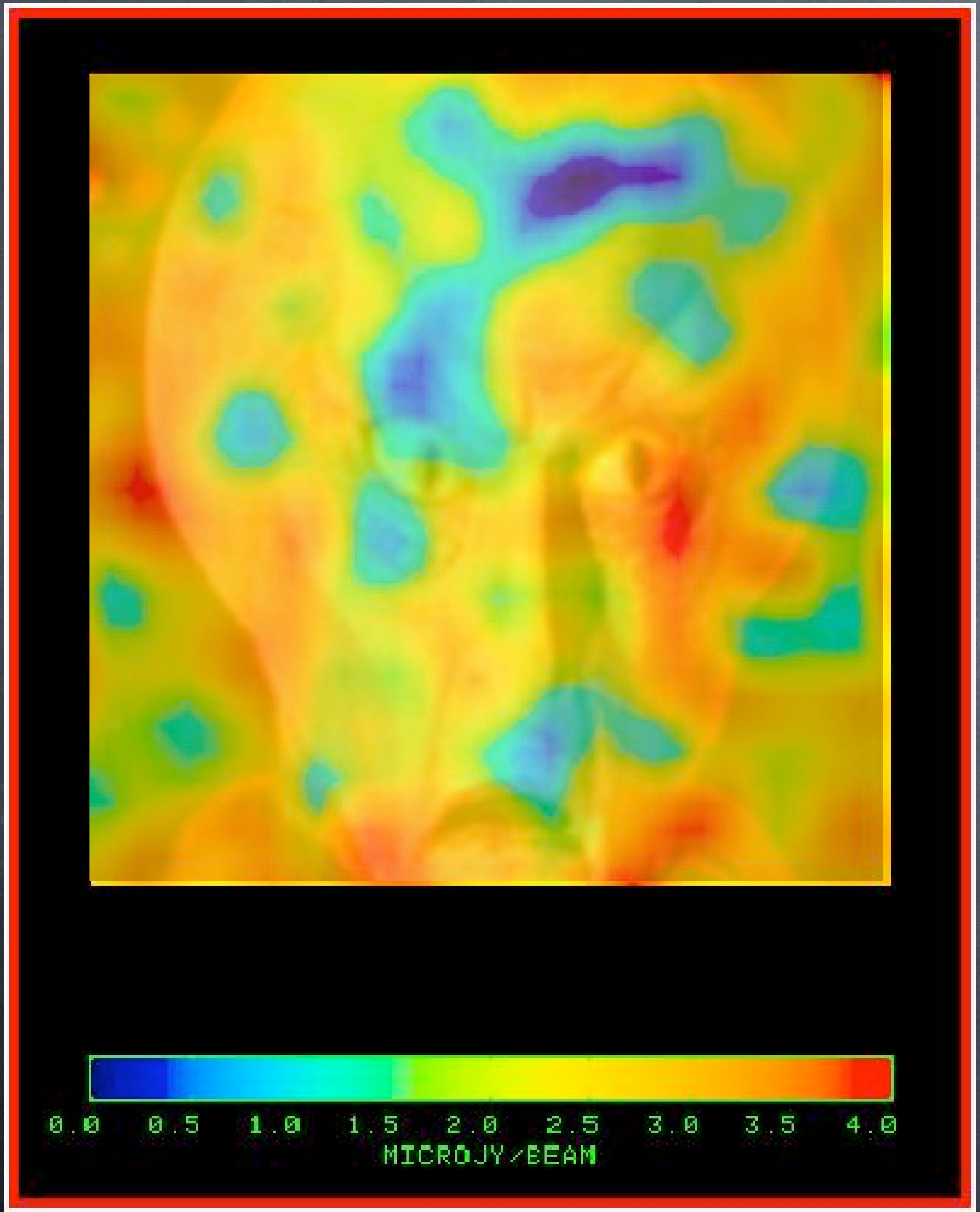


Amazing Field of view - superb survey instrument - if we can calibrate it!



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

Stacking 32000 G-type stars (NVSS)



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

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

RADIO ASTRONOMY!