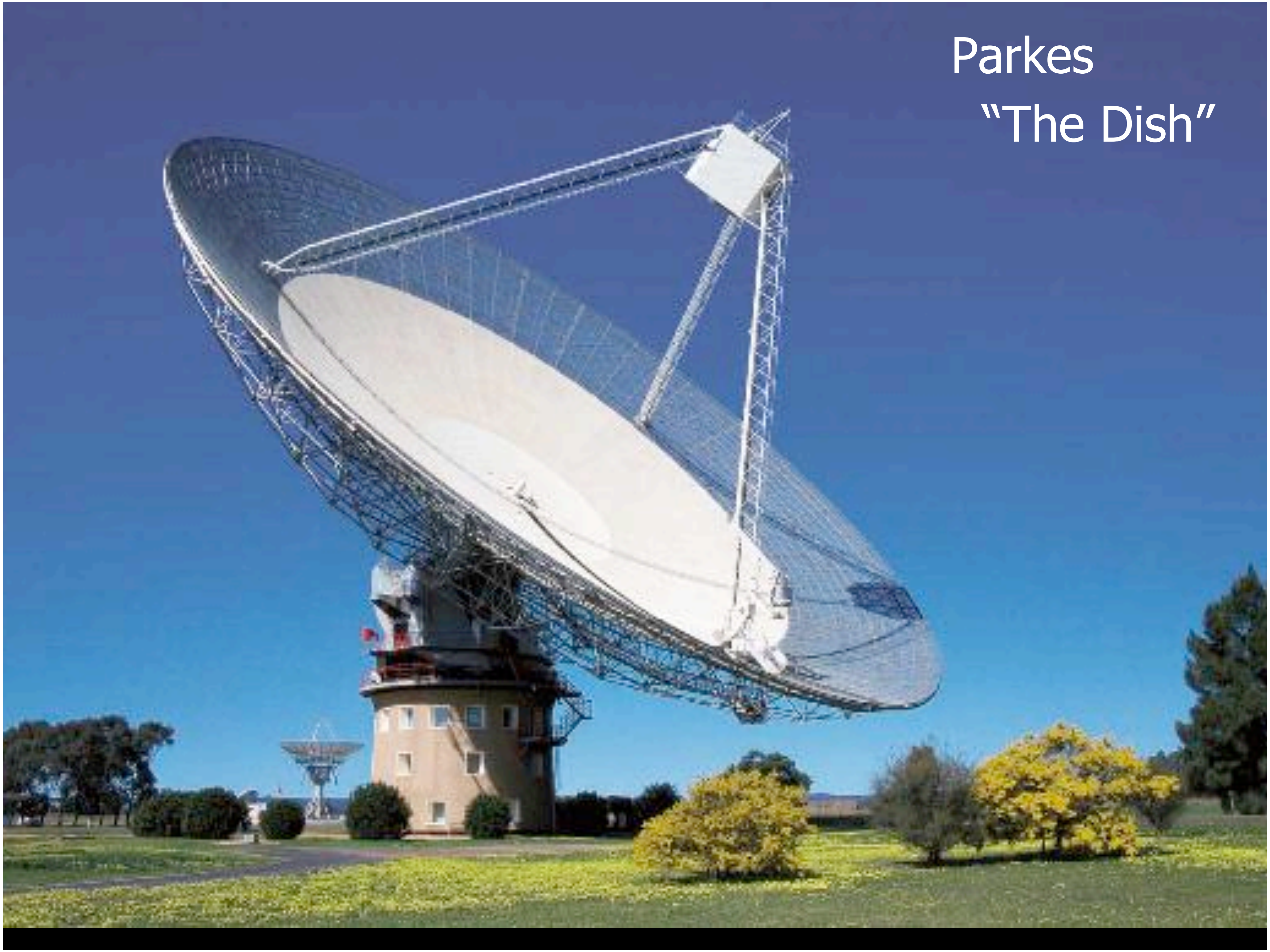
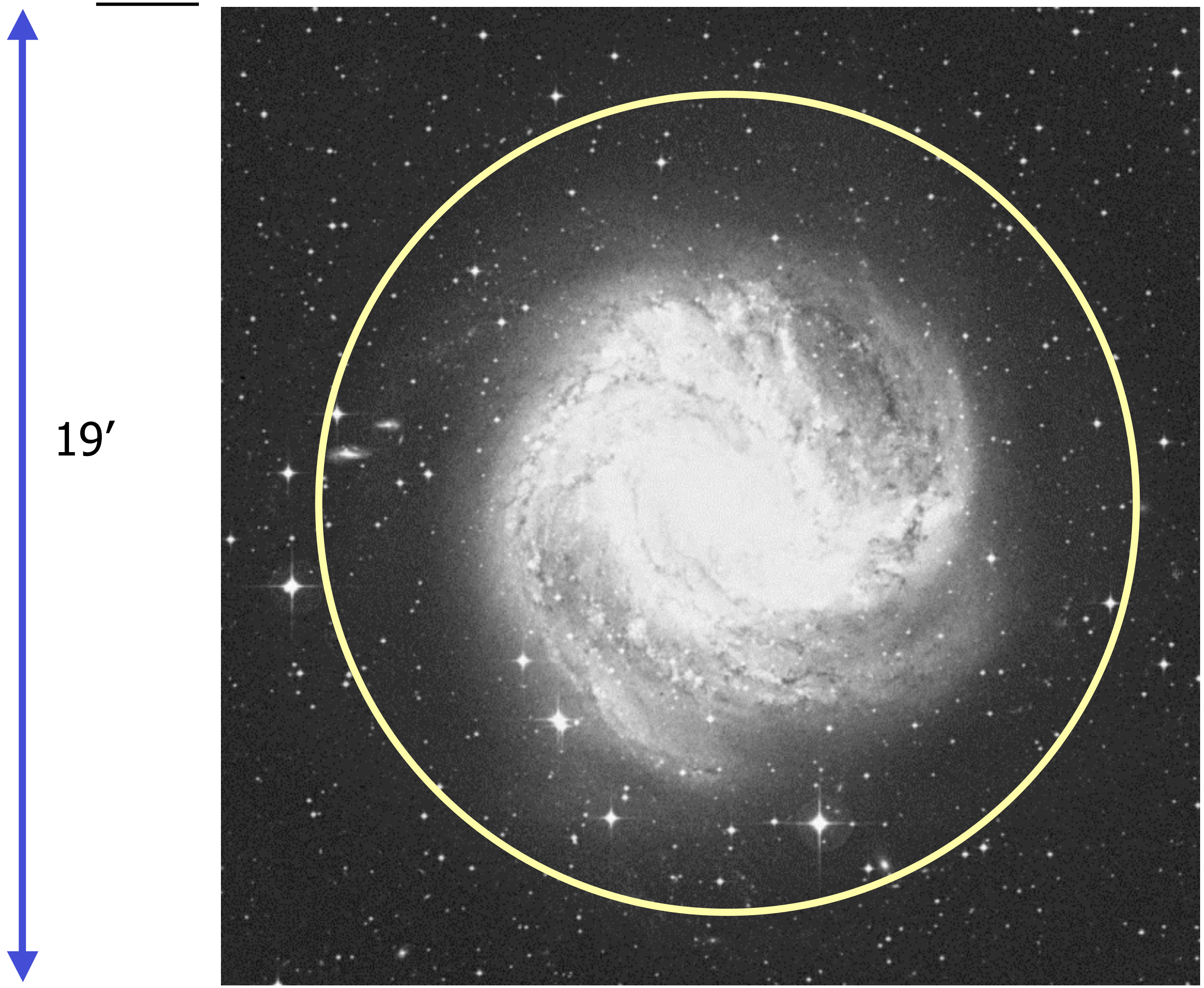
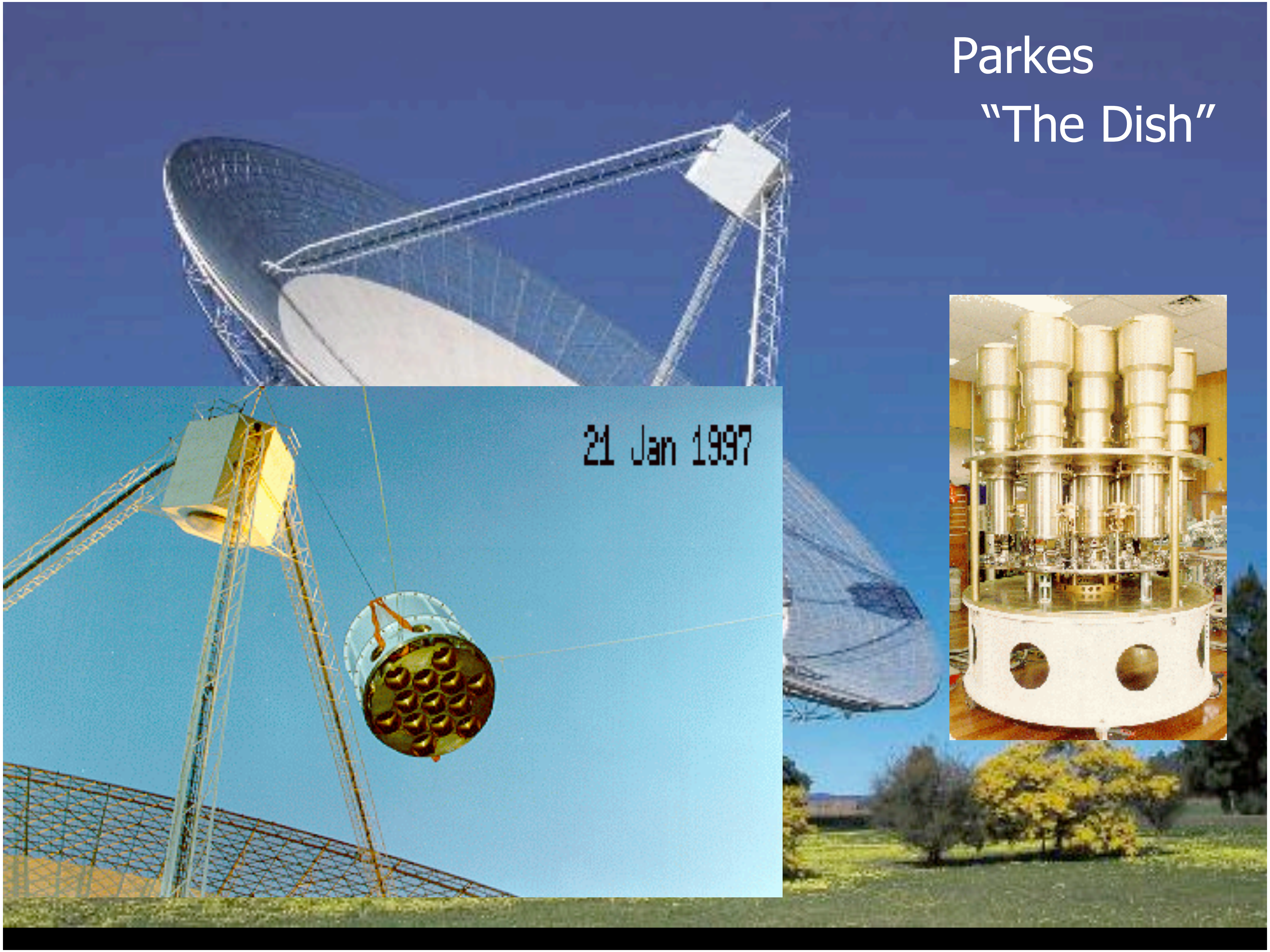

Parkes
“The Dish”

M83

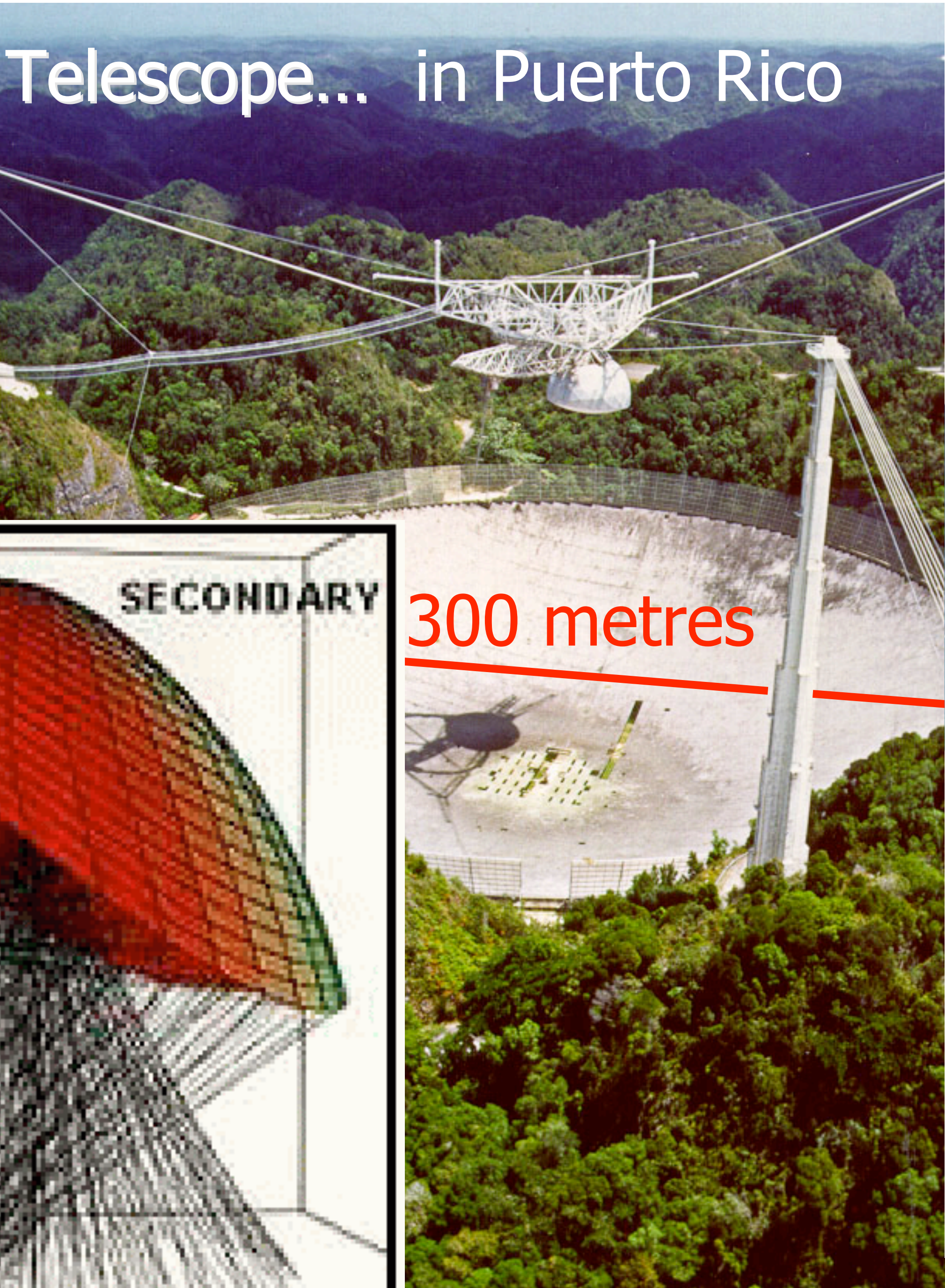


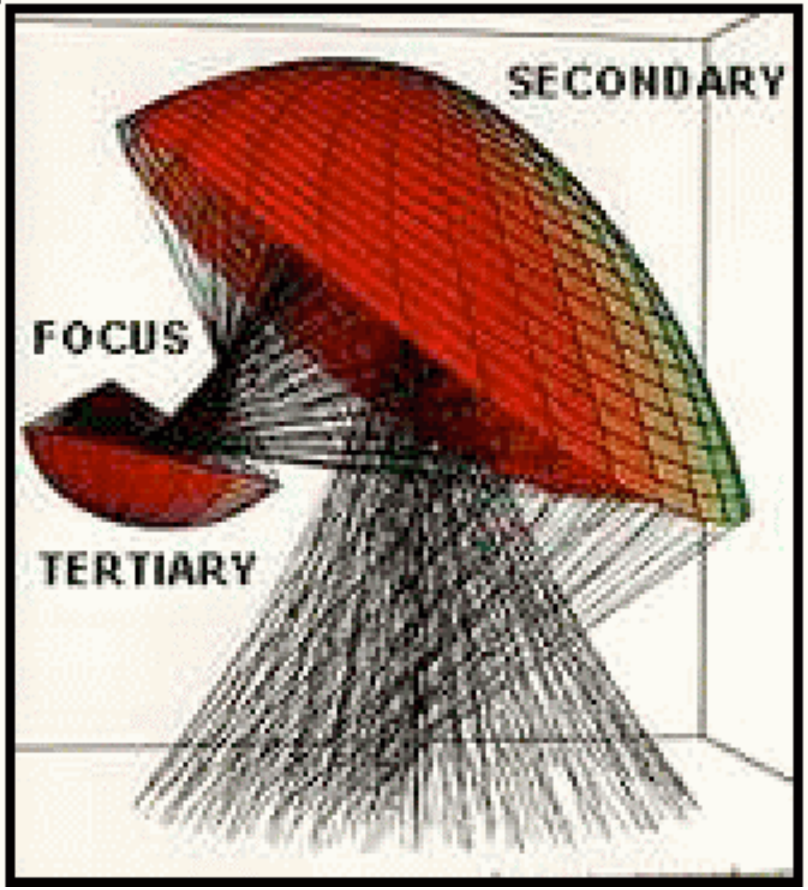
Parkes
“The Dish”




VLA, Very Large Array
New Mexico

Arecibo Telescope... in Puerto Rico



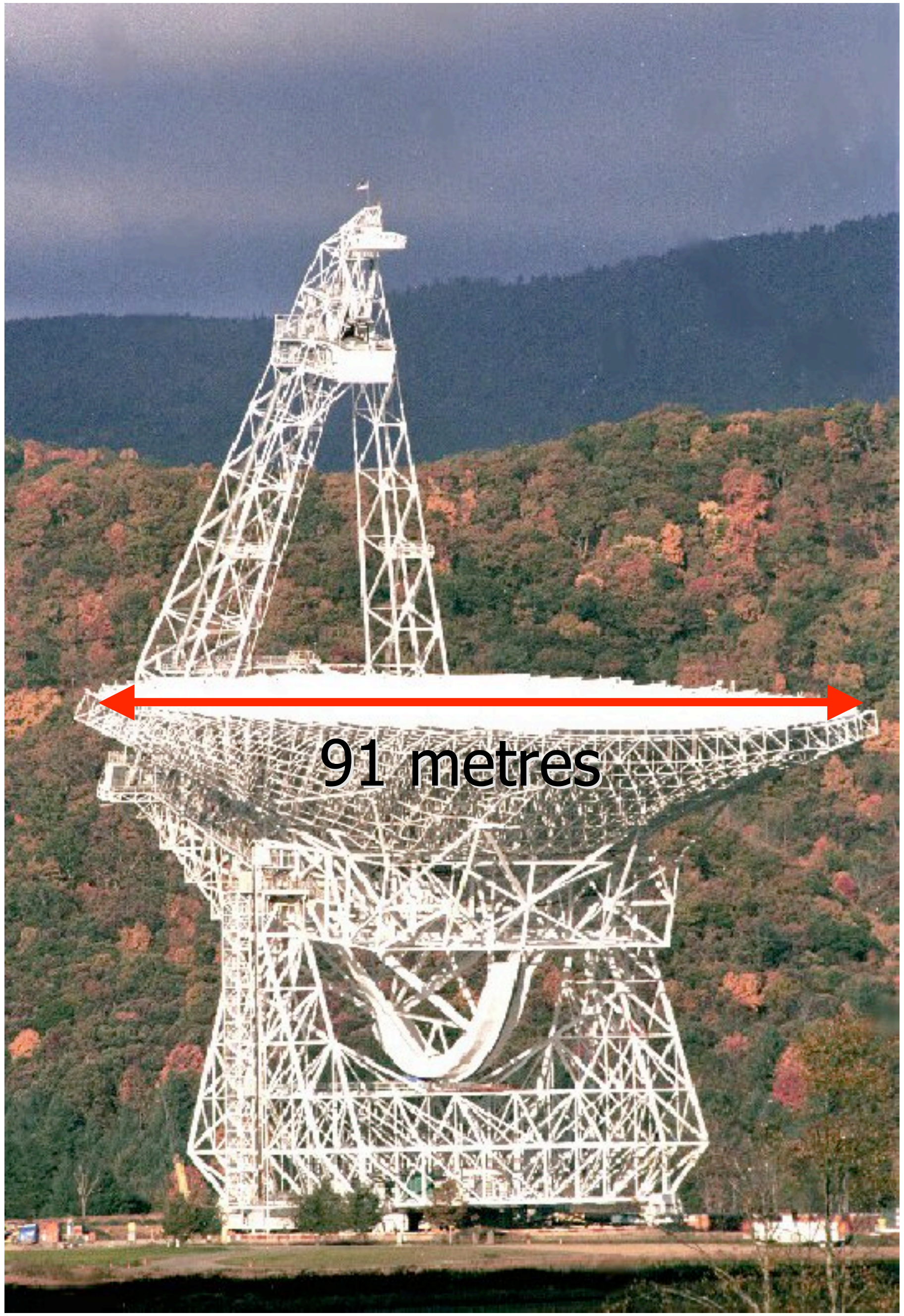


GBT

Green Bank
West Virginia

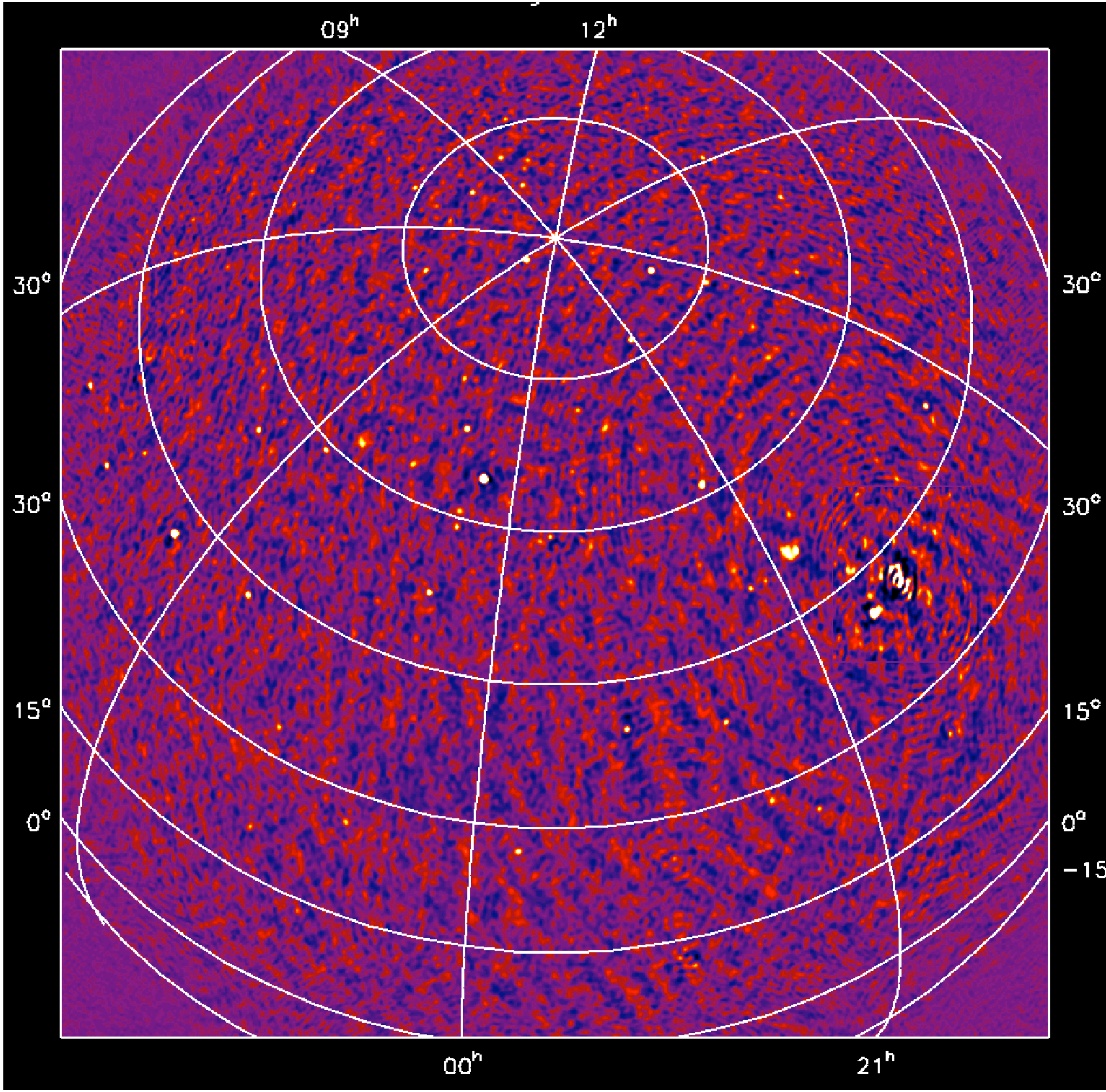
... the newest...
... and *last* (*perhaps*)...
... big dish

Unblocked
Aperture



LOFAR “elements”

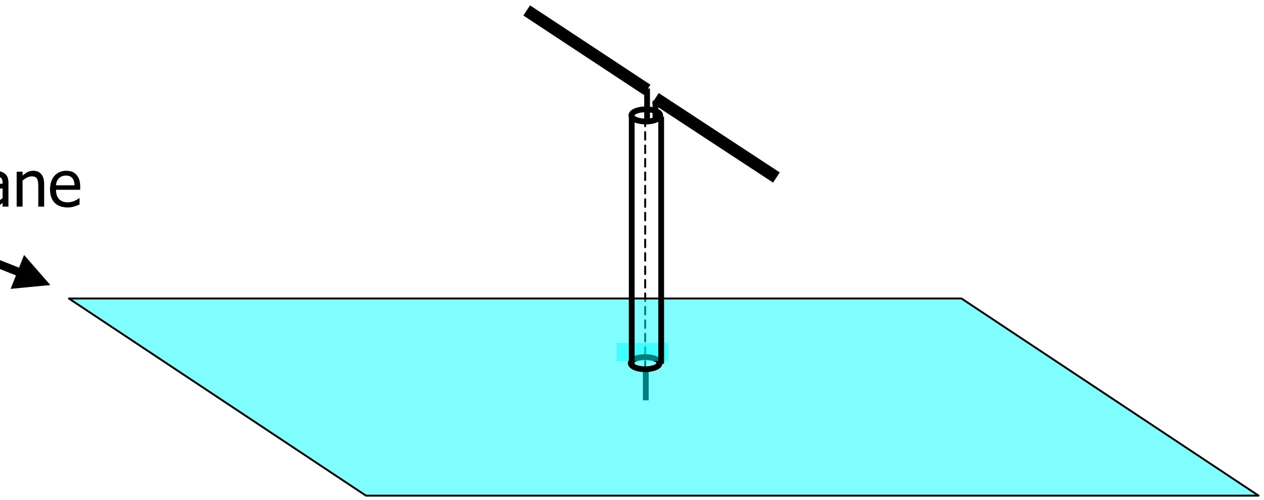

http://www.astron.nl/press/250407.htm



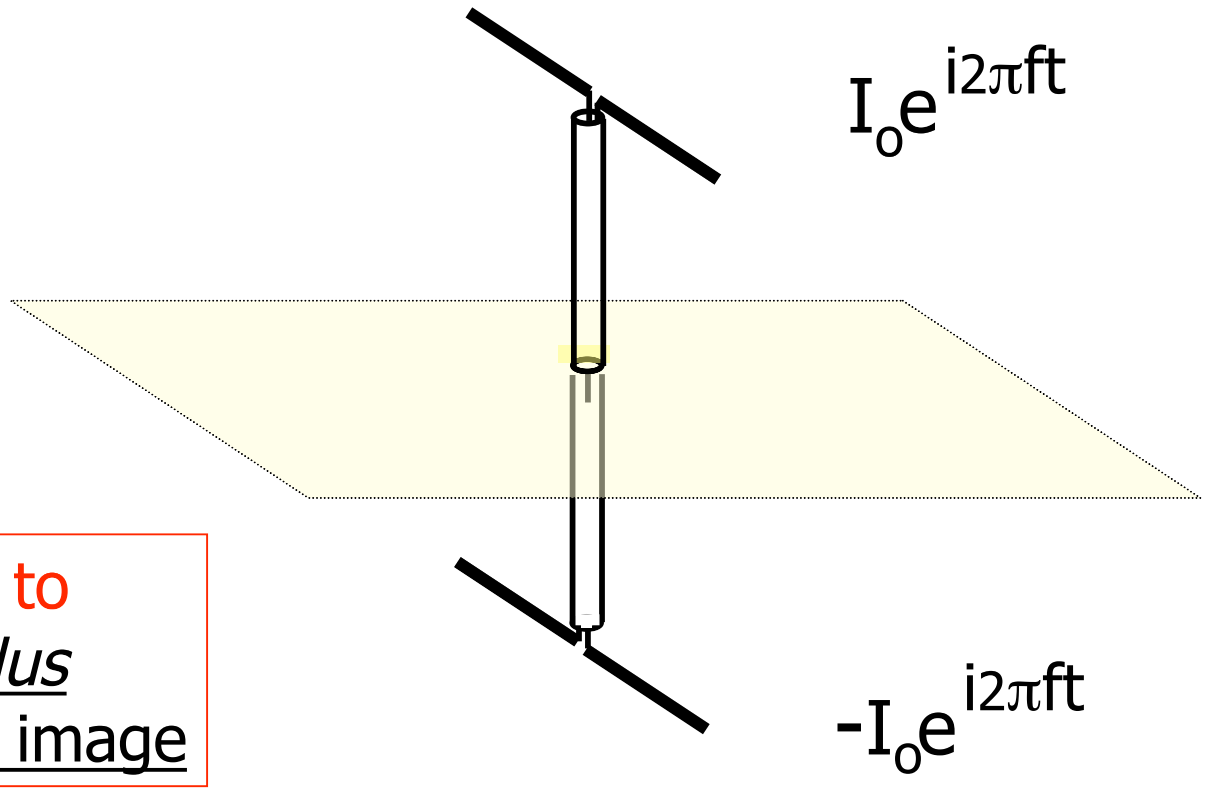
LOFAR
image at
~ 50MHz
(Feb 2007)

Dipole + ground plane: a model

conducting
ground plane



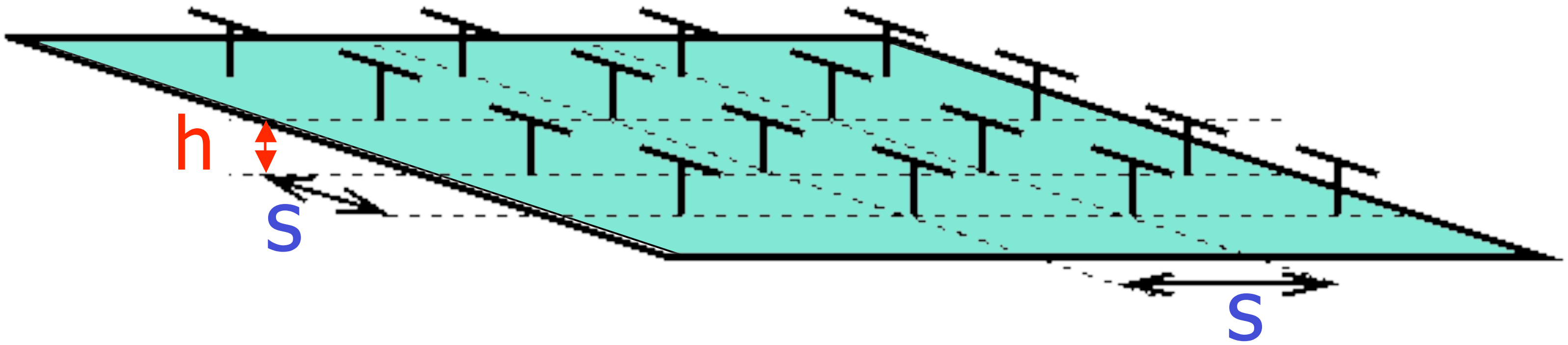
Dipole + ground plane



equivalent to
dipole *plus*
mirror image

4x4 array of dipoles on ground plane

- the 'LFD' element

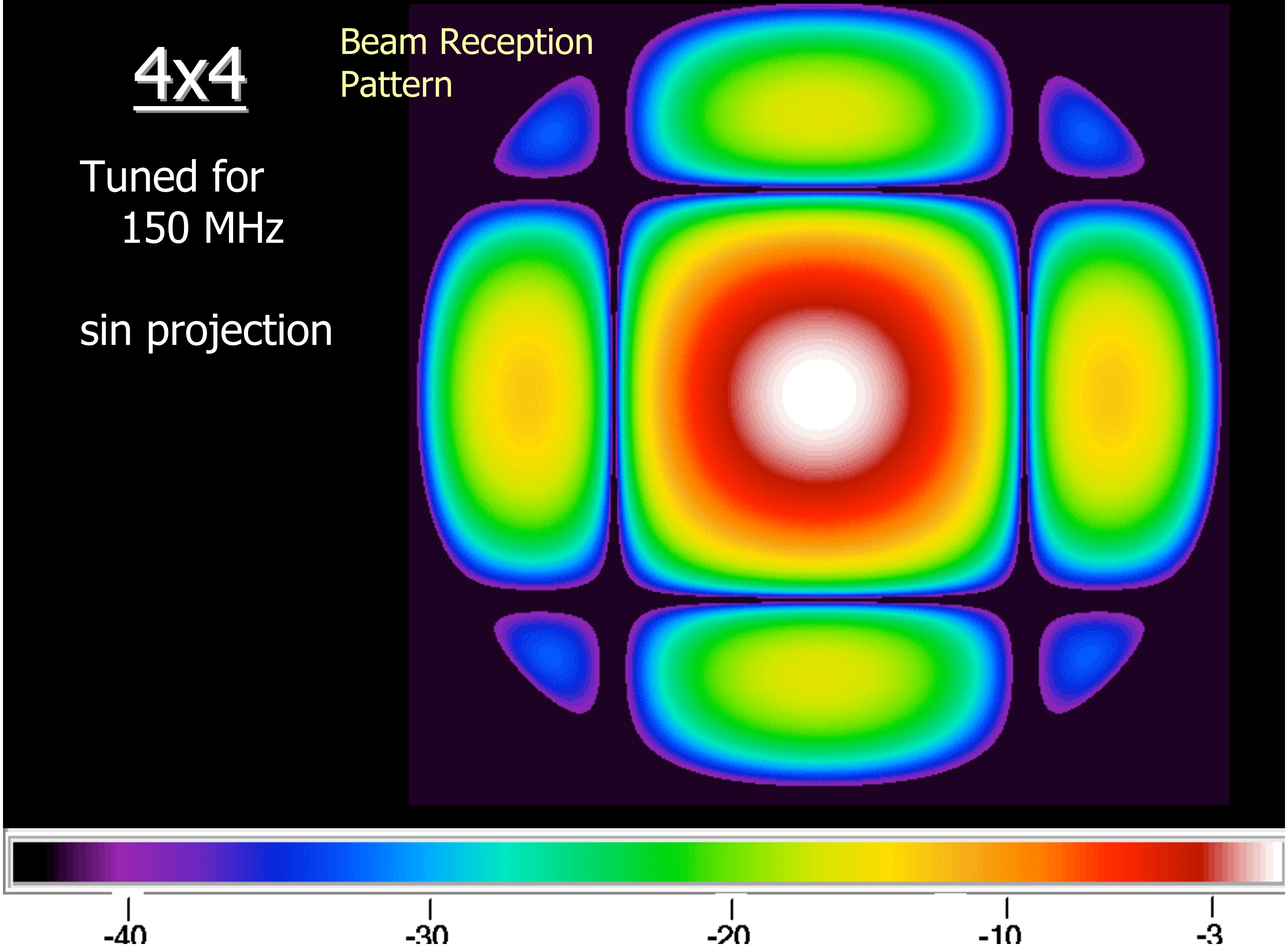


(many analogies to gratings for optical wavelengths)

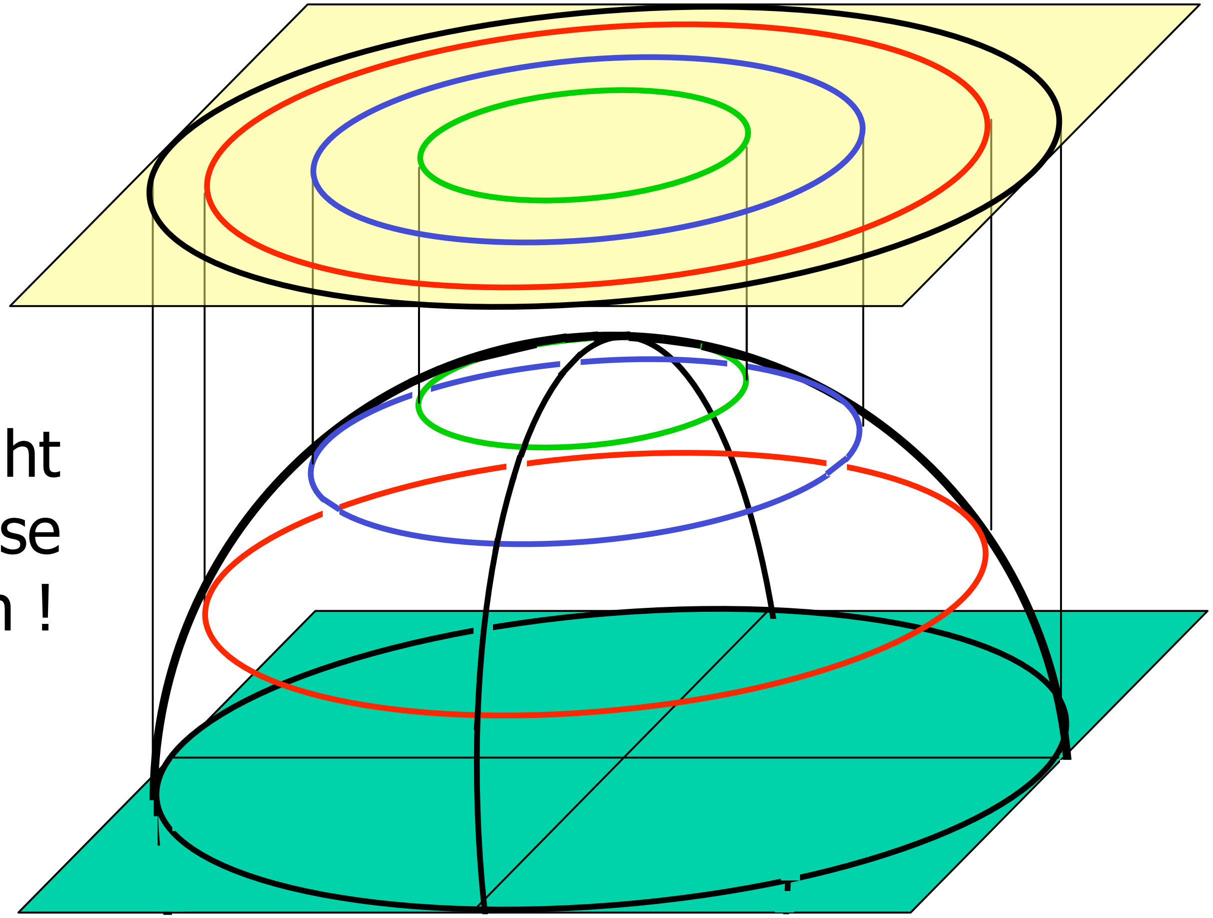
4x4

Tuned for
150 MHz

sin projection

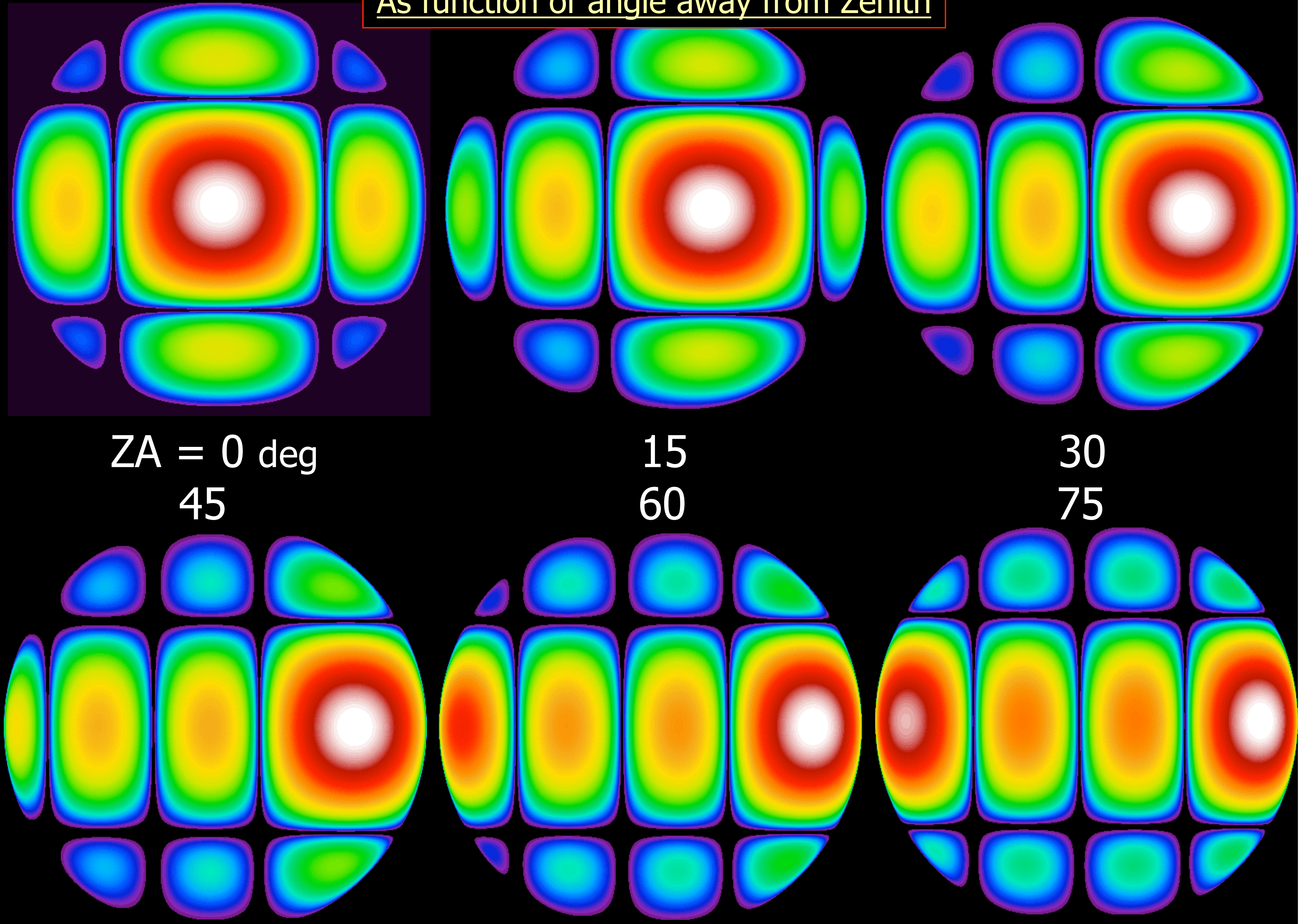


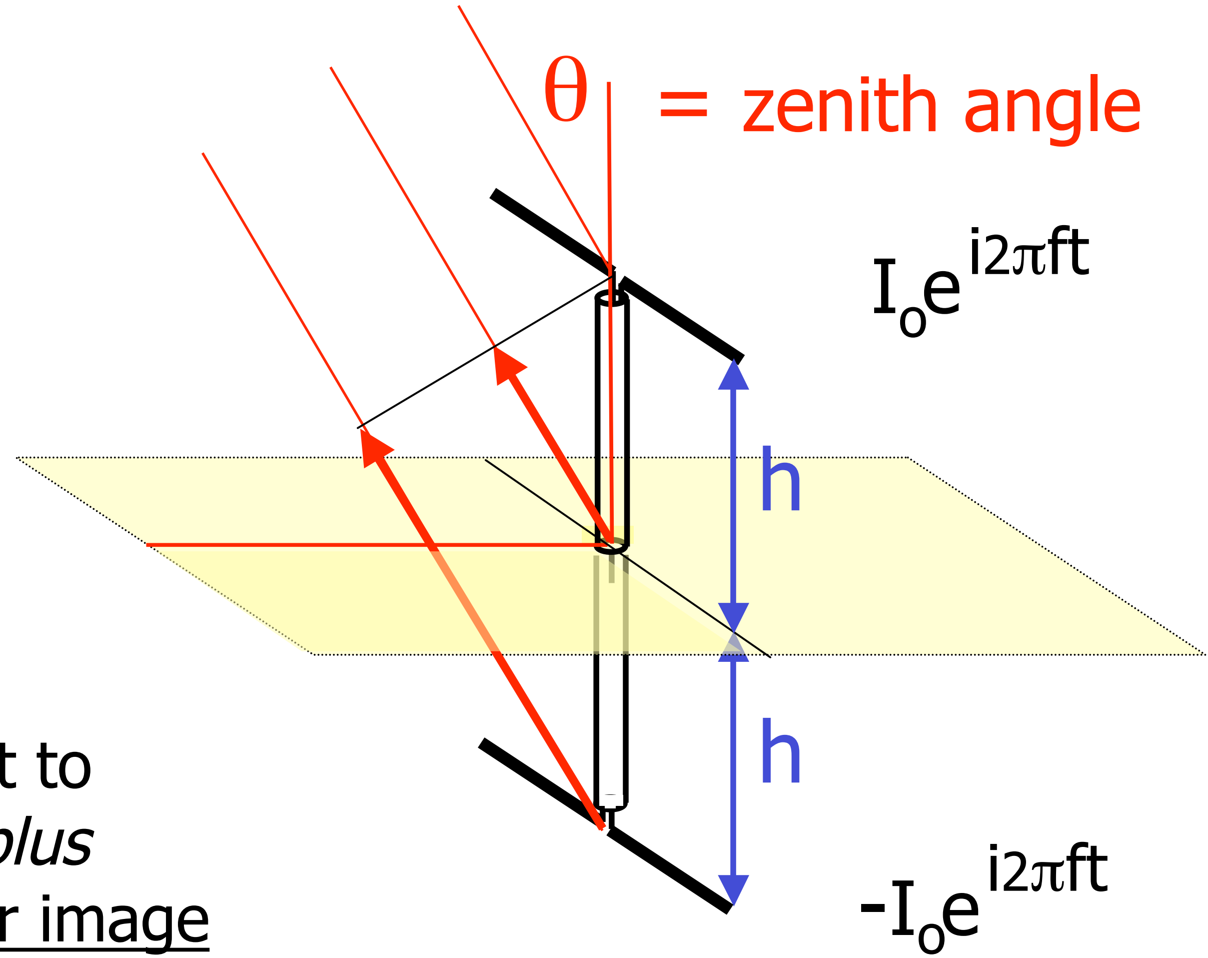
‘sin projection’



gives
little weight
to sky close
to horizon !

As function of angle away from Zenith





equivalent to
dipole *plus*
mirror image

$$P(\theta) \sim \sin^2[2\pi h \cos(\theta)/\lambda]$$

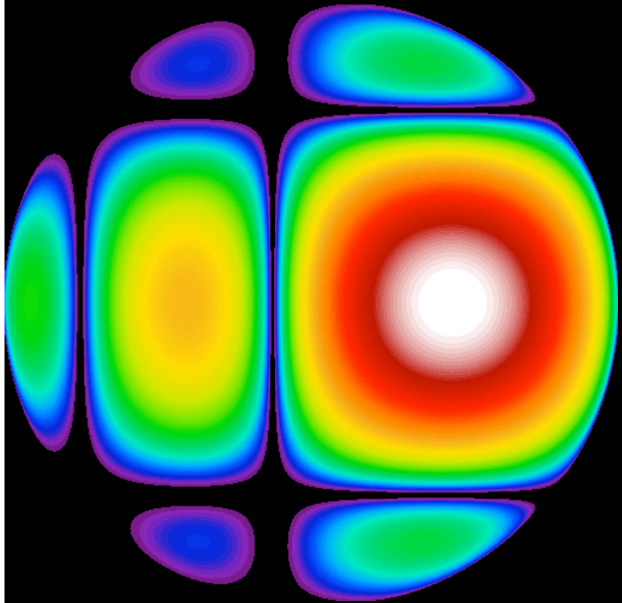
(maximize response at $\theta=0$ if $h=\lambda/4$)

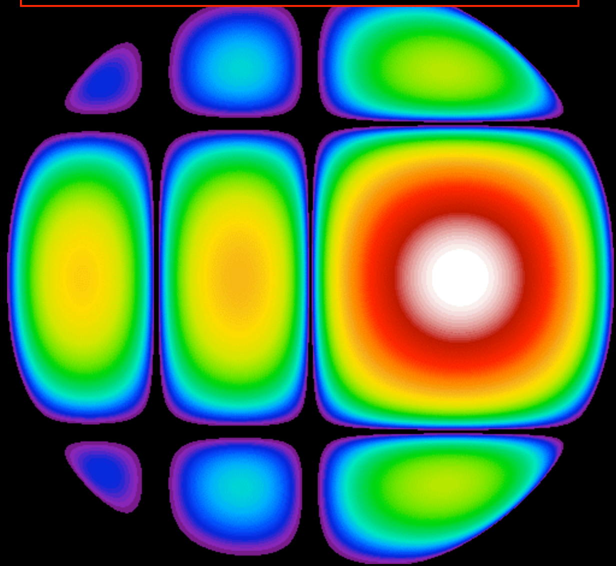
As function of frequency

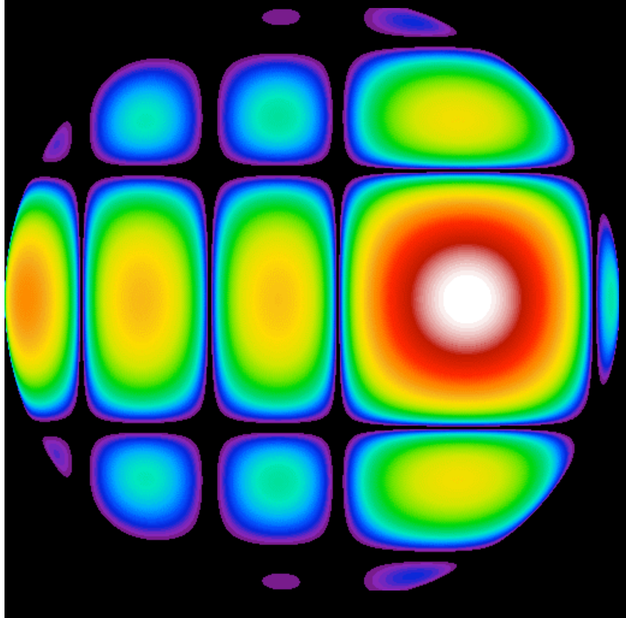
4x4 Patterns

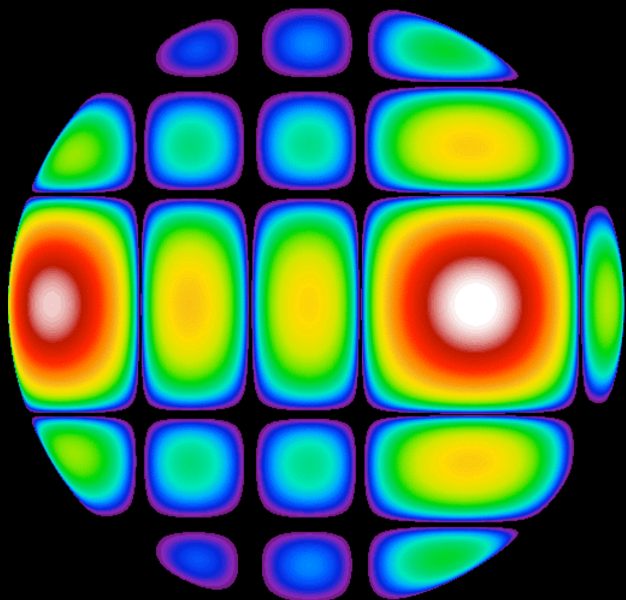
- ZA = 30 deg
- tuned for 150 MHz

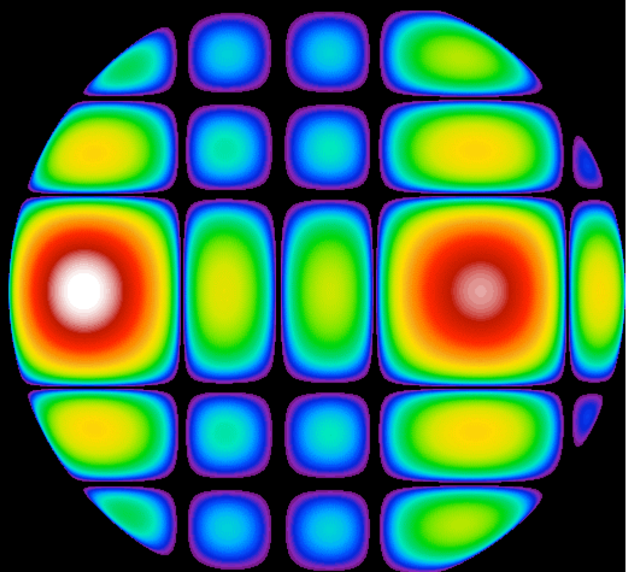
120	150	
180	210	240

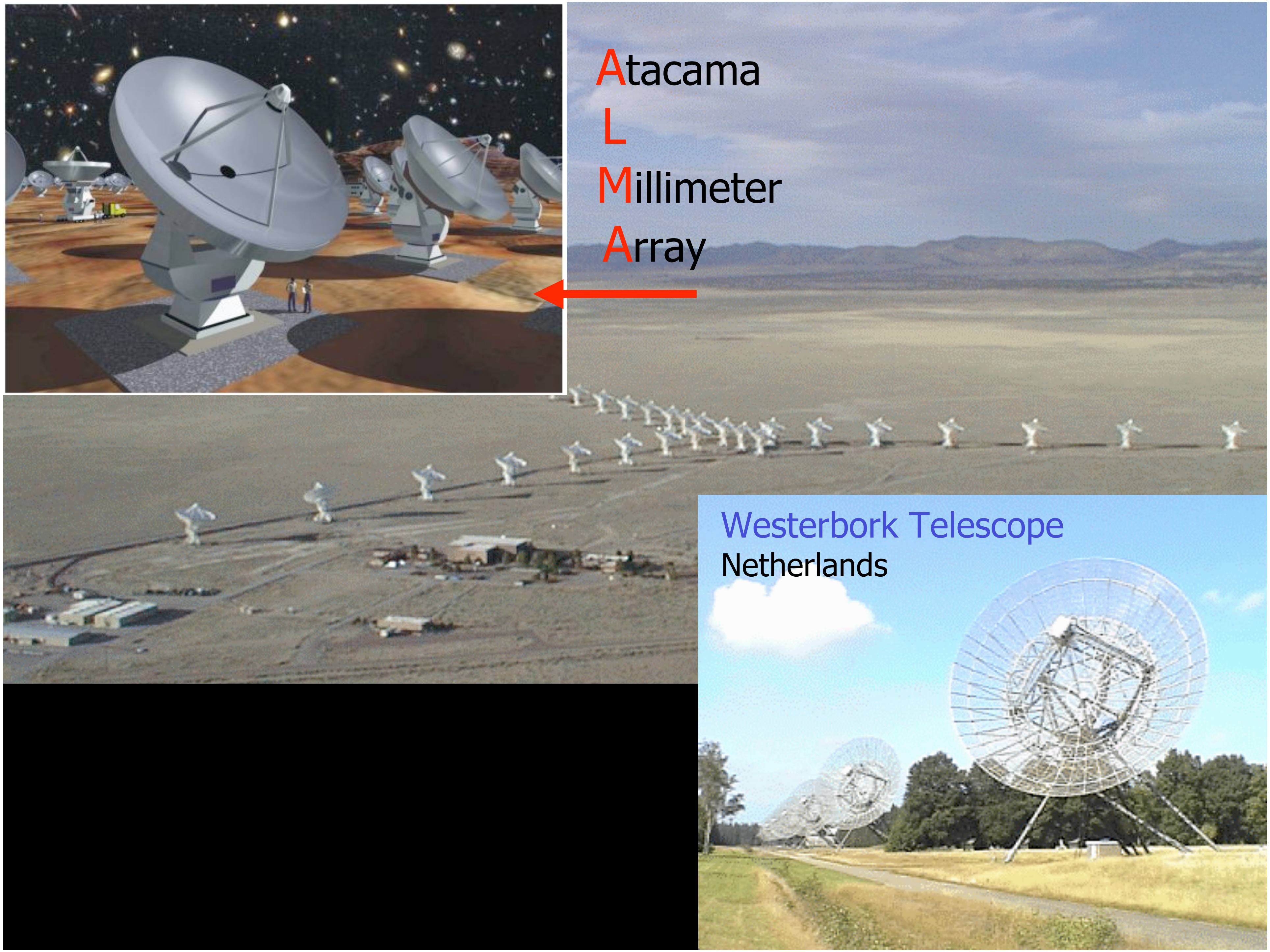











Atacama
L
Millimeter
Array
Westerbork Telescope
Netherlands

VLBA

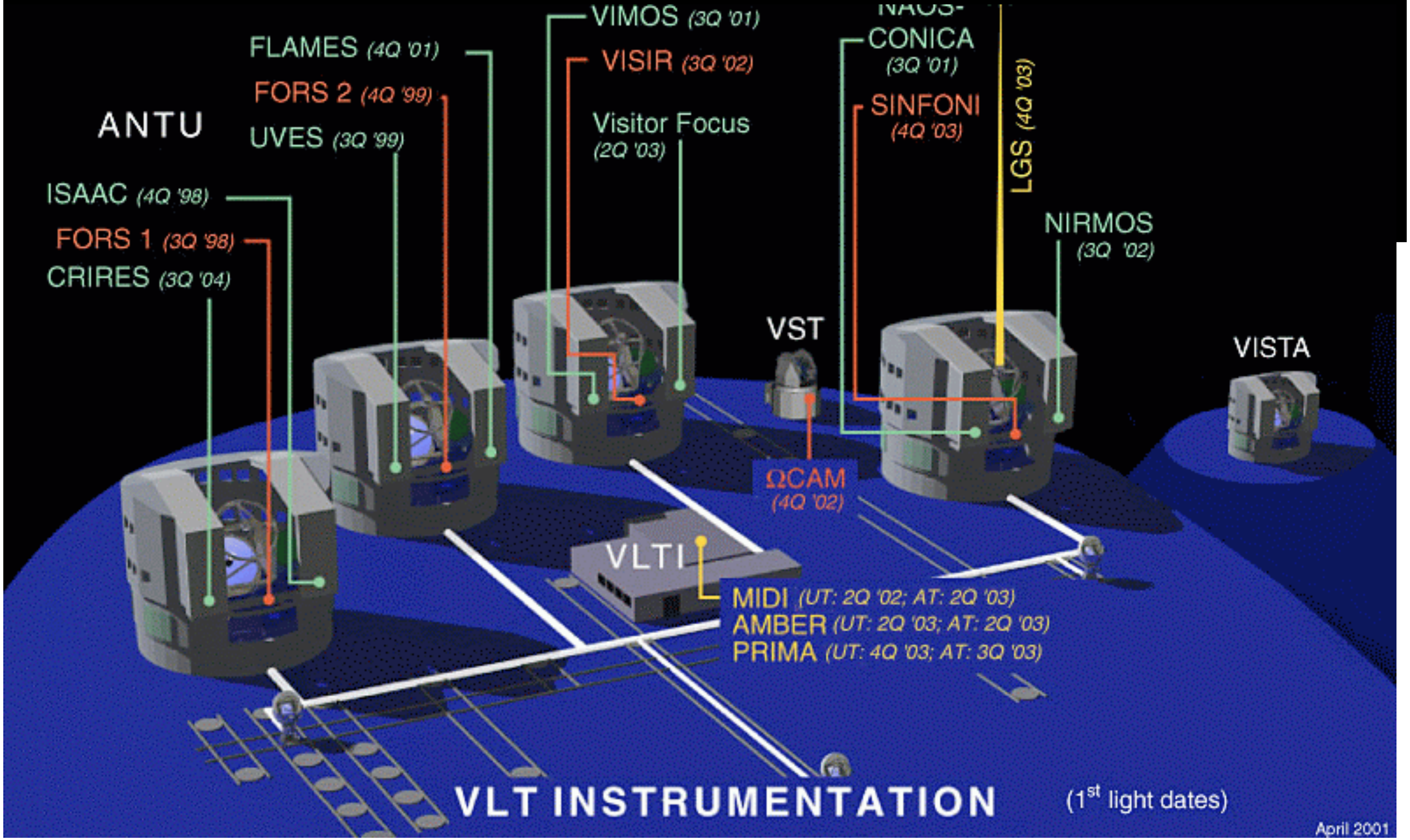
Very
Long
Baseline
Array

for:
Very
Long
Baseline
Interferometry

EVN: European VLBI Network (more and bigger dishes than VLBA)

LBA: Long Baseline Array in AU

ESO Paranal, Chile



Observational Techniques:
Radio Astronomy Techniques

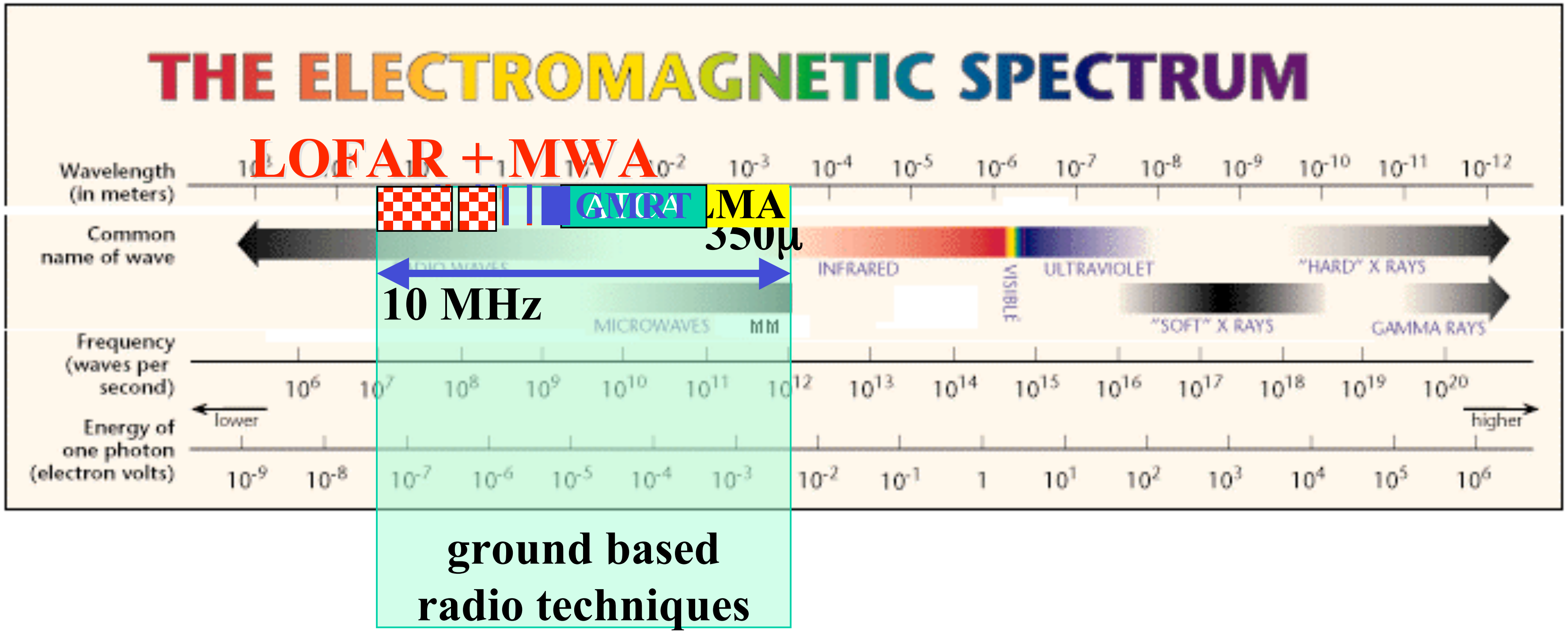
- Kraus, J. D. 1986, Radio Astronomy (QB476.5.K725 1986).
- * Rohlfs, K. 1986, Tools of Radio Astronomy (QB475.R63 1986).
- *** Thompson, A. R., Moran, J. M., & Swenson, G. W. 1986 Interferometry and Synthesis in Radio Astronomy (QB479.3.T47 1986). *(biblical status in field)*
- Brouw, W. N. 1975, Methods in Computational Physics, Vol. 14, 131 (QB475.M47 1975).
- Ball, J. A. 1975, Methods in Computational Physics, Vol. 14, 177 (QB475.M47 1975).
- Christiansen, W. N., & Högbom, J. A. 1985, Radio Telescopes (QB479.2.C5 1985).
- Kitchin, C. R. 1984, Astrophysical Techniques (QB461.K57 1984).

More references:

- Synthesis Imaging in Radio Astronomy, 1998, ASP Conf. Series, Vol 180, eds. Taylor, Carilli & Perley

- Single-Dish Radio Astronomy, 2002, ASP Conf. Series, Vol 278, eds. Stanimirovic, Altschuler, Goldsmith & Salter

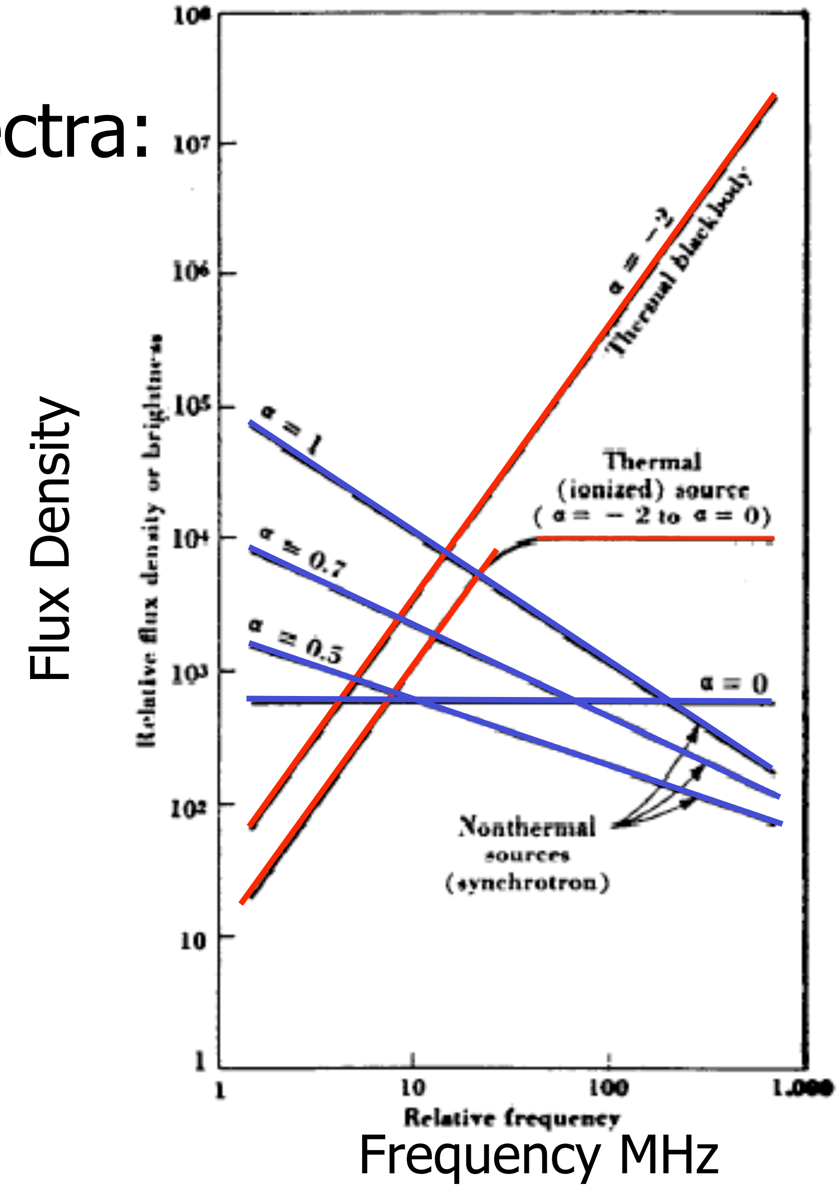
- AIPS Cookbook, http://www.aoc.nrao.edu/aips/


THE ELECTROMAGNETIC SPECTRUM
LOFAR + MWA
350µ
10 MHz
Wavelength (in meters)
10-2 10-3 10-4 10-5 10-6 10-7 10-8 10-9 10-10 10-11 10-12
Common name of wave
INFRARED
VISIBLE
ULTRAVIOLET
"HARD" X RAYS
MICROWAVES
MM
"SOFT" X RAYS
GAMMA RAYS
Frequency (waves per second)
10^6 10^7 10^8 10^9 10^10 10^11 10^12 10^13 10^14 10^15 10^16 10^17 10^18 10^19 10^20
lower
higher
Energy of one photon (electron volts)
10-9 10-8 10-7 10-6 10-5 10-4 10-3 10-2 10-1 1 10^1 10^2 10^3 10^4 10^5 10^6
ground based radio techniques

Radio "Sources"

1) Thermal
2) Non-Thermal

Spectra:



1) Thermal

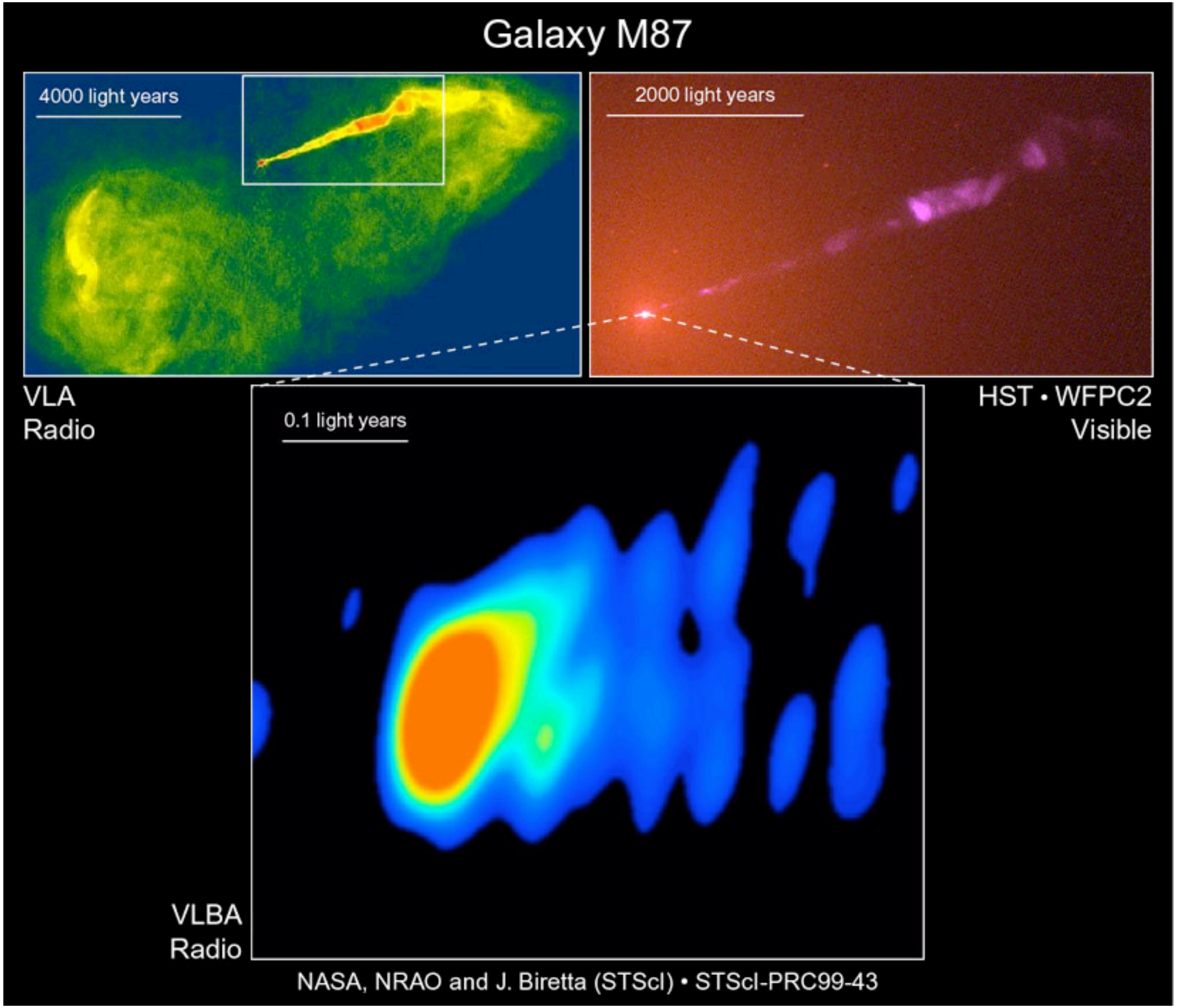
emission mechanism related to Planck BB… electrons have ~Maxwellian distribution

2) Non-Thermal

emission typically from relativistic electrons in magnetic field… electrons have ~power law energy distribution

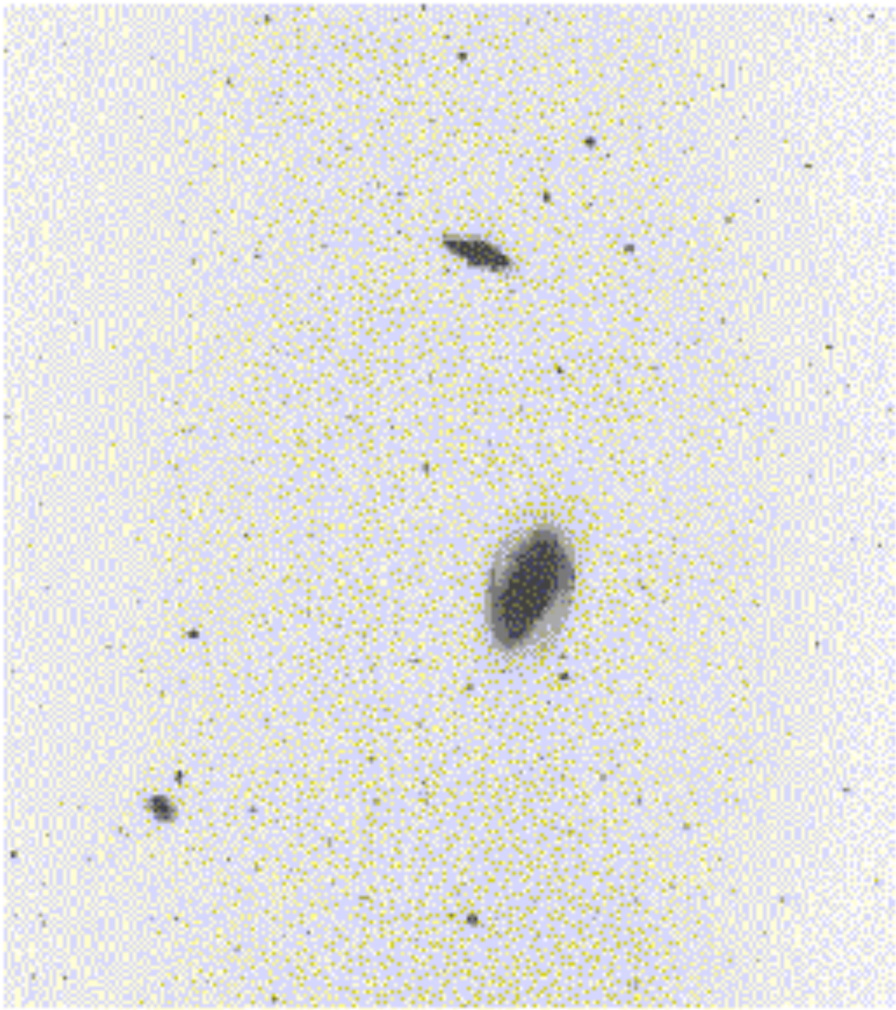
Distinctive Radio Spectra !

Nonthermal

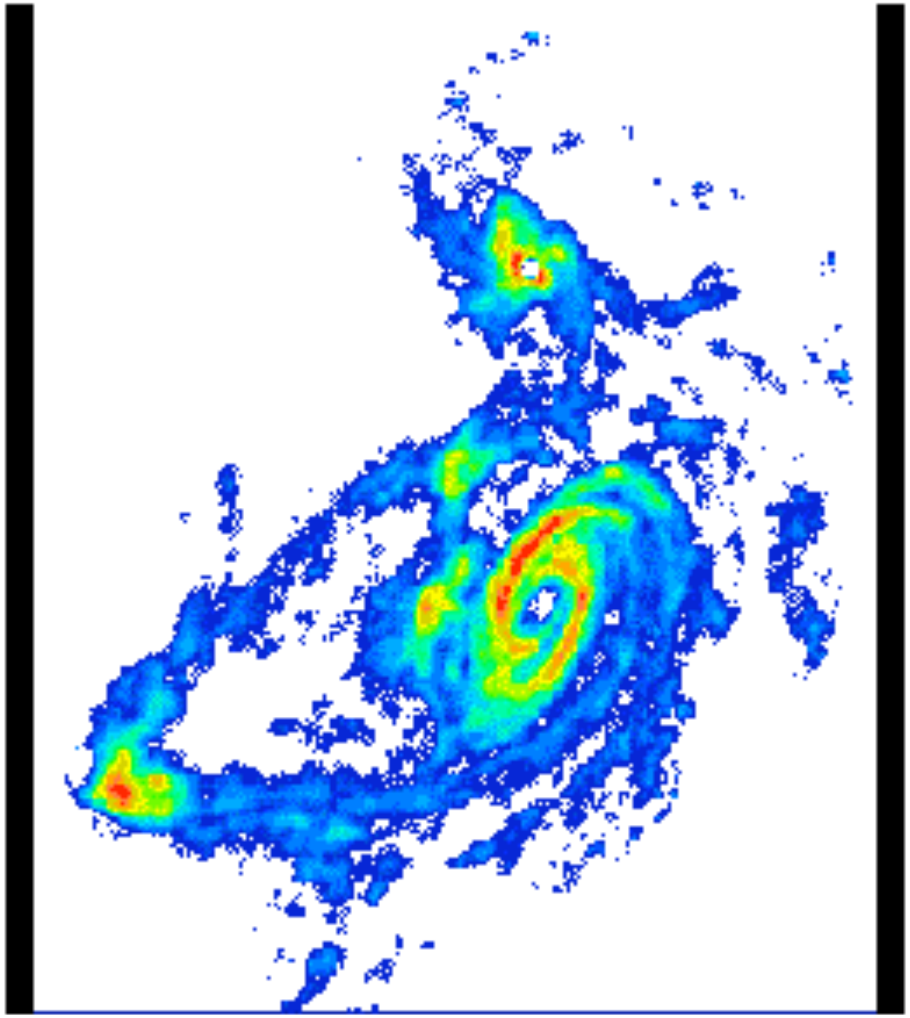

Galaxy M87
4000 light years
2000 light years
VLA
Radio
HST • WFPC2
Visible
0.1 light years
VLBA
Radio
NASA, NRAO and J. Biretta (STScI) • STScI-PRC99-43

M81 Group of Galaxies

Thermal



Visible Light



Radio map of
cold hydrogen gas

Basic Definitions (from P. McGregor notes)

- Solid angle of a cone is:

$$\Omega = \frac{A}{r^2}$$

  - Ω measured in units of steradians.
  - 4π sterad $\equiv$ whole sky.

- Basic parameter for specifying radiation energy is $I_\nu \equiv$ "brightness" or "specific intensity":
  - I_ν is energy per unit time per unit area per unit frequency per unit solid angle.
  - I_ν is measured in units of W m^{-2} Hz^{-1} sterad^{-1}.
  - 1 Watt $\equiv$ 1 Joule s^{-1} $\equiv 10^7$ erg s^{-1}.

- Flux density S_ν of a source of extent $\Delta\Omega$ and brightness distribution I_ν is:

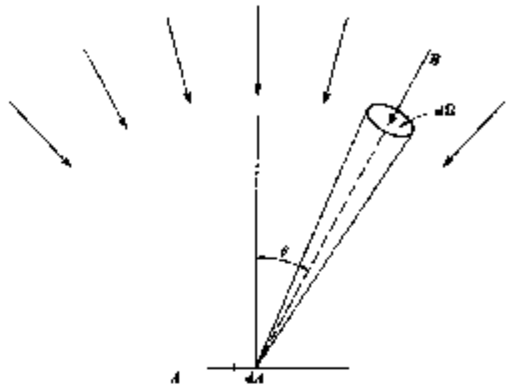
$$S_\nu = \int_{\Delta\Omega} I_\nu d\Omega$$

  - S_ν is measured in units of 1 Jansky $= 10^{-26}$ W m^{-2} Hz^{-1}.
  - S_ν is often erroneously called *flux*.

Basic Definition (cont'd)

- Define total brightness I to be the integral of I_ν over some frequency range $\Delta\nu$:

$$I = \int_{\Delta\nu} I_\nu d\nu$$



- The flux F in a given direction is the net radiant energy in the frequency range $\Delta\nu$ crossing unit area normal to that direction per unit time:

$$F = \int_{\Delta\Omega} I \cos\theta d\Omega$$

  - F is measured in units of W m^{-2}.

- The luminosity L of a source is the total radiant energy emitted per unit time:

$$L = \int_A F dA = \int_A \int_{\Delta\Omega} I \cos\theta d\Omega dA = A \int_{\Delta\Omega} I \cos\theta d\Omega$$

  - L is measured in units of Watts.

- The radio power W received over bandwidth $\Delta\nu$ from solid angle $\Delta\Omega$ is:

$$W = A \int_{\Delta\nu} \int_{\Delta\Omega} I_\nu \cos\theta d\Omega d\nu \equiv L$$

  - W, like L, is measured in units of Watts.

Basic Definitions (cont'd)

- κ_ν = absorption coefficient $\equiv$ opacity.
- ϵ_ν = emission coefficient $\equiv$ emissivity.
- Then equation of radiative transfer through a slab of thickness ds is:

$$\frac{dI_\nu}{ds} = -\kappa_\nu I_\nu + \epsilon_\nu$$

- Define the optical depth $d\tau_\nu$ by:

$$d\tau_\nu = -\kappa_\nu ds$$

- Then for an isothermal gas in thermodynamic equilibrium at temperature T:

$$I_\nu(s) = I_\nu(0)e^{-\tau\nu(0)} + B_\nu(T)(1 - e^{-\tau\nu(0)})$$

- $B_\nu(T)$ is the Planck function.

$$B_\nu(T) = \frac{2h\nu^3/c^2}{e^{h\nu/kT} - 1}$$

- Rayleigh-Jeans approximation applies at radio frequencies $(h\nu << kT)$:

$$B_\nu(T) \sim \frac{2\nu^2 kT}{c^2} = \frac{2kT}{\lambda^2}$$

- For $\tau_\nu(0) \to \infty$, $I_\nu(s) \to B_\nu(T)$.

Basic Definitions (cont'd)

- Brightness temperature T_B is used to measured radio power:
  - T_B is the temperature of an optically-thick blackbody filling the telescope beam and producing the same radio power.
  - From the Rayleigh-Jeans approximation:

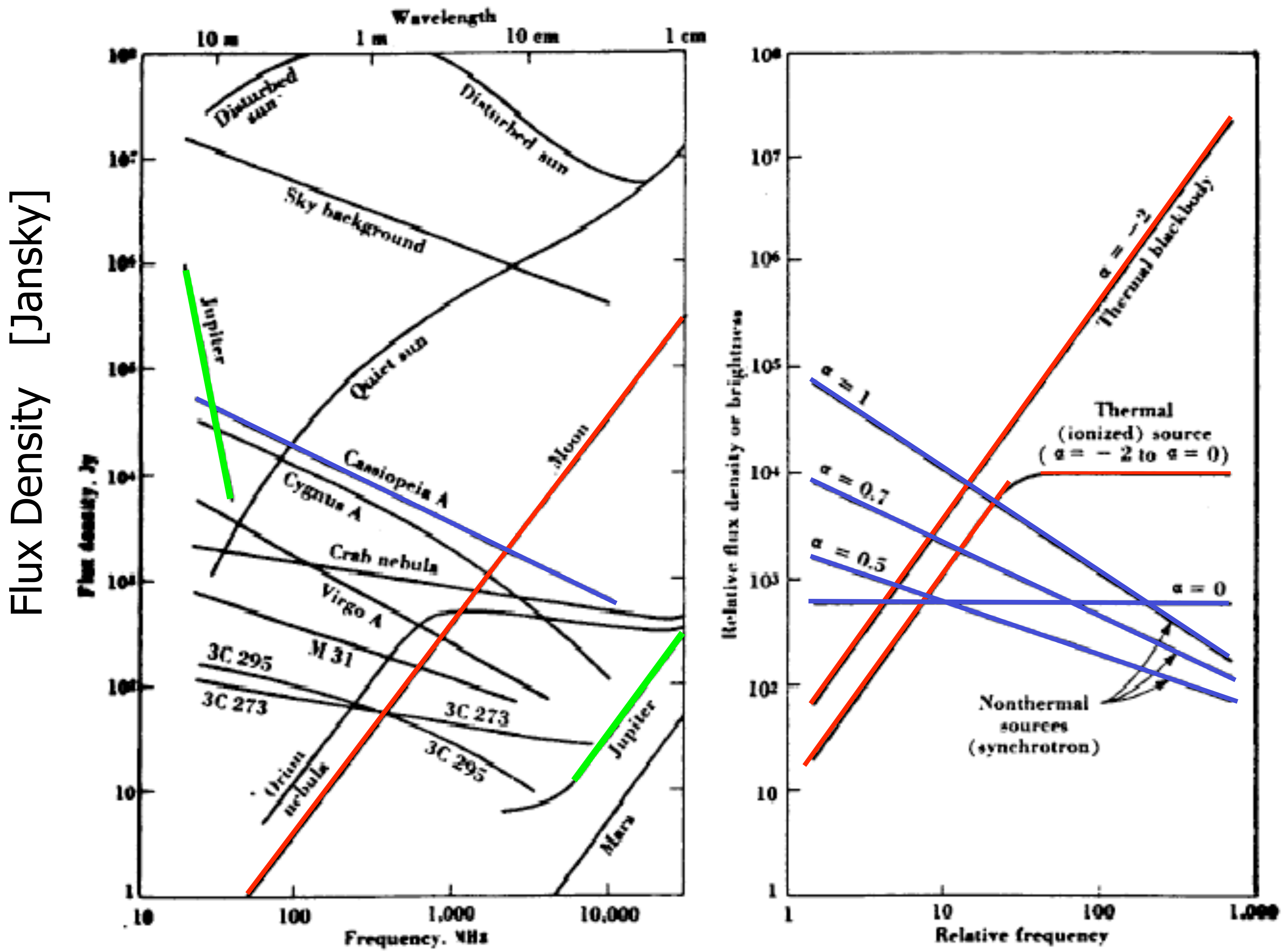
$$T_B = \frac{\lambda^2}{2k} I_\nu \quad \text{where} \quad I_\nu \sim S_\nu/\Omega$$

can assign "brightness temperature" to objects where "Temp" really has no meaning…

  - $T_B < T_{source}$ if $\tau_\nu < 1$ when $\Omega_{source} > \Omega_{beam}$.
  - $T_A < T_B$ when $\Omega_{source} < \Omega_{beam}$.
- Spectral index (α) is another measure of radio spectrum shape:
  - With $S_\nu \propto \nu^{-\alpha}$,

$$\alpha = -\frac{\log(S_1/S_2)}{\log(\nu_1/\nu_2)}$$

Brightest Sources in Sky



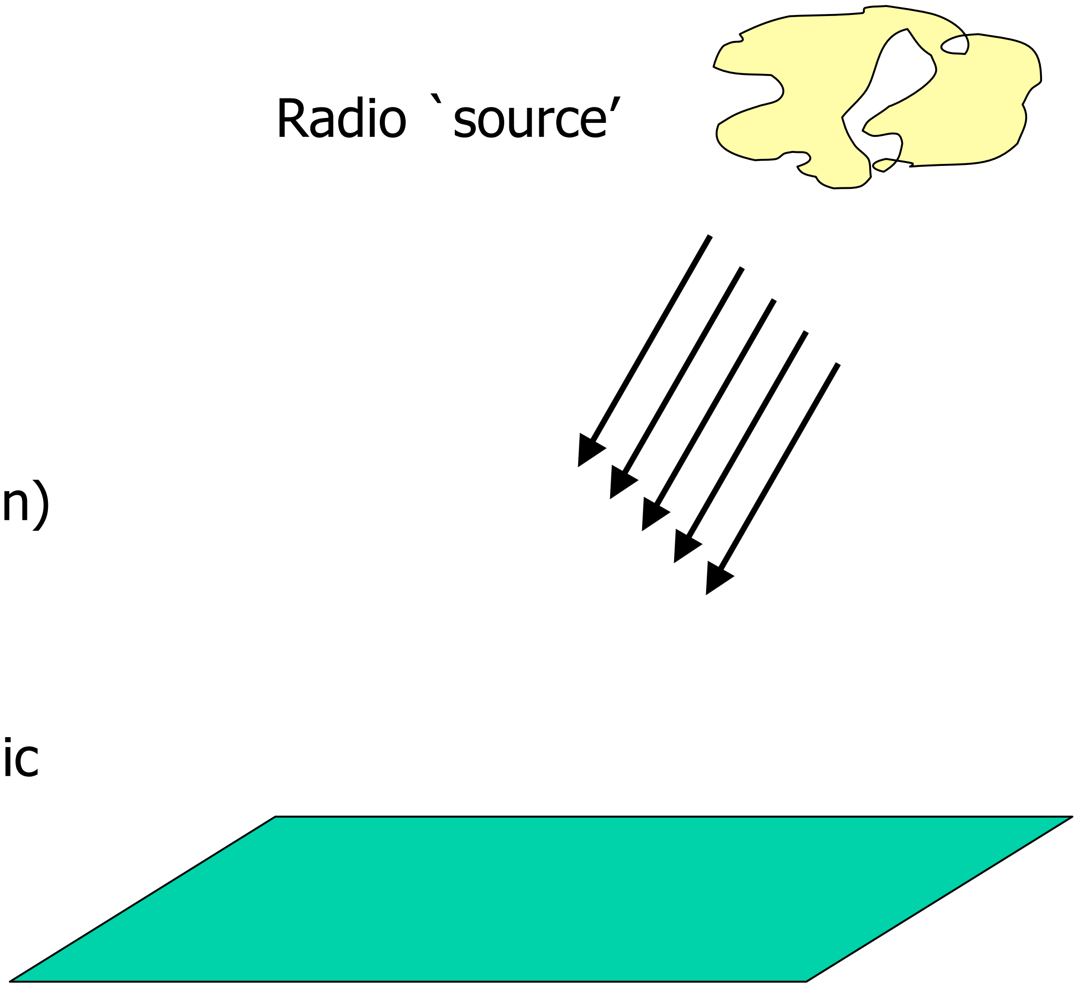
Frequency MHz

(from Kraus, Radio Astronomy)

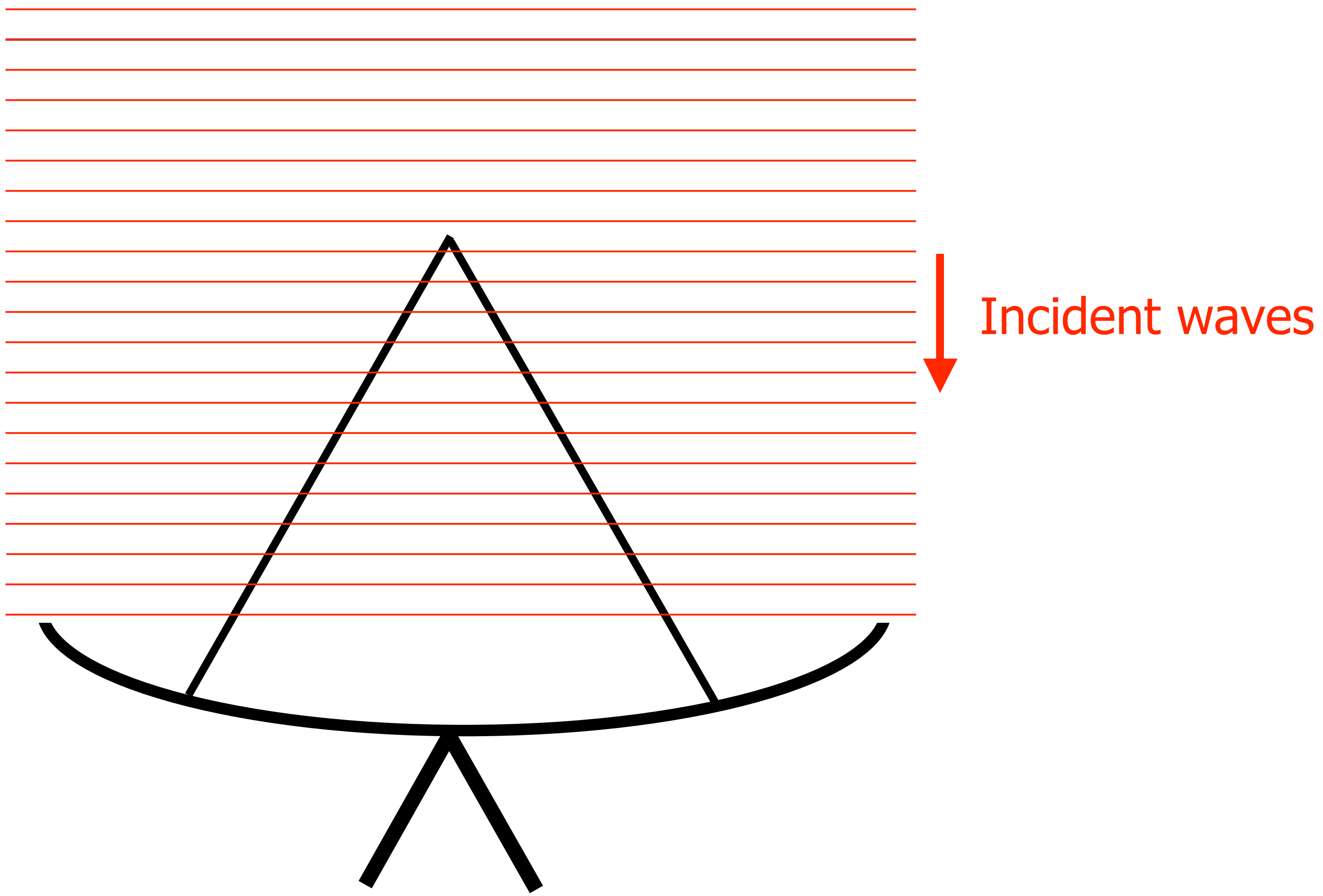
Goals of telescope:

- maximize collection of energy (sensitivity or gain)

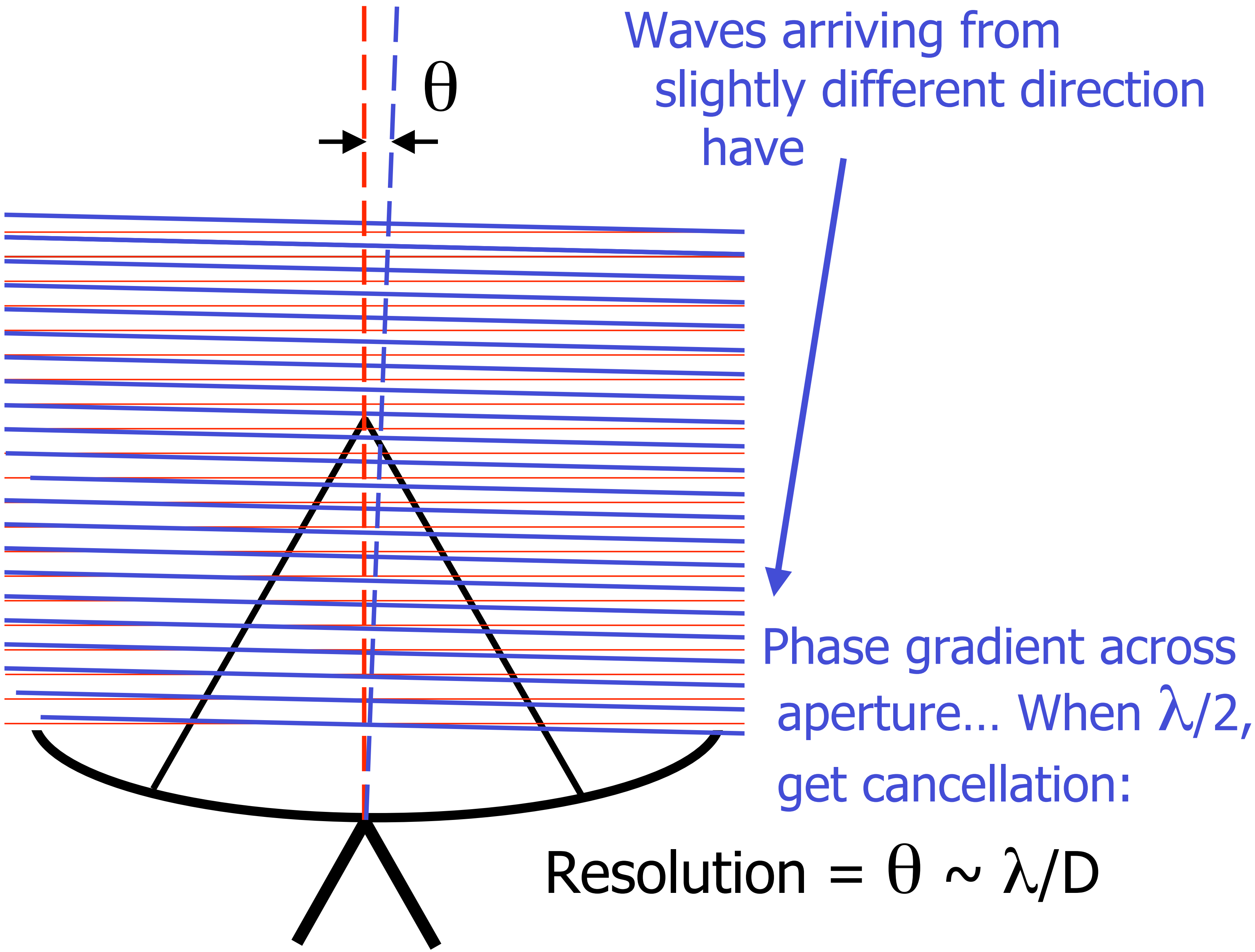
- isolate source emission from other sources… (directional gain… dynamic range)



Radio telescopes are ***Diffraction Limited***



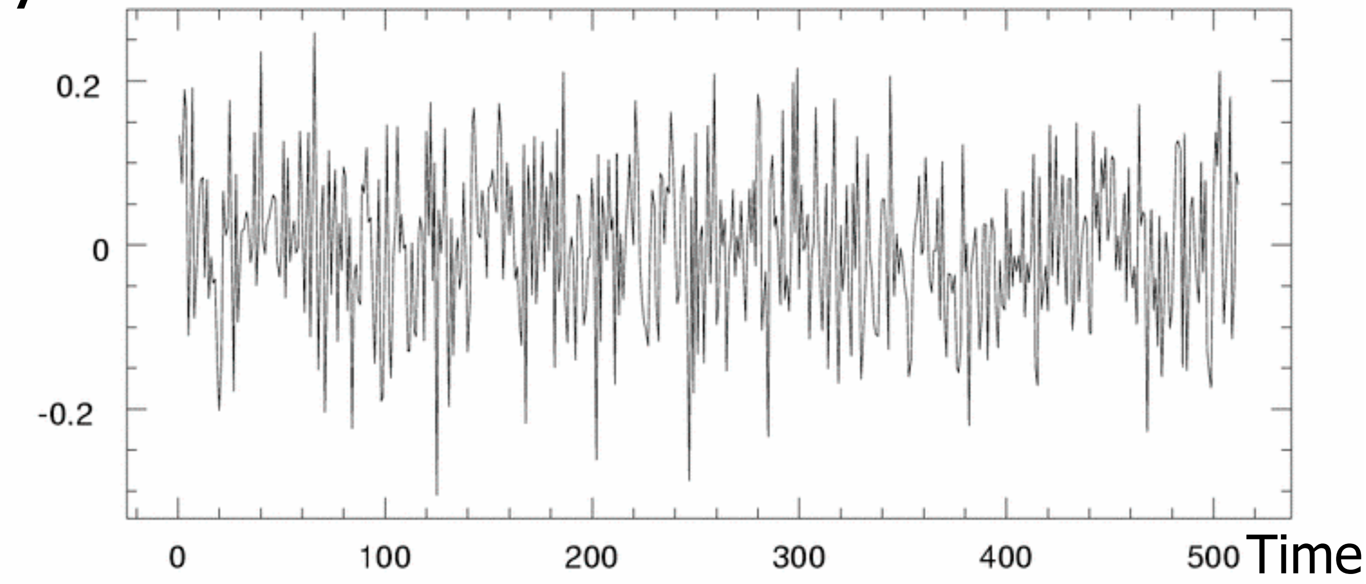
Radio telescopes are *Diffraction Limited*



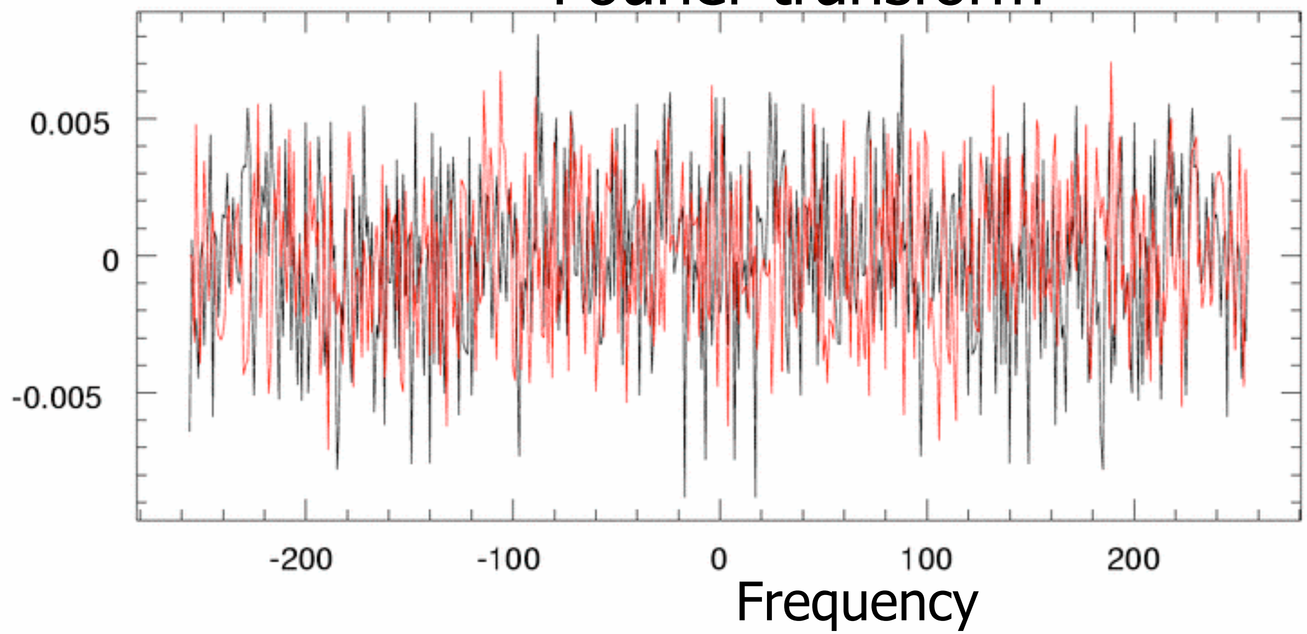
Resolution = $\theta \sim \lambda/D$

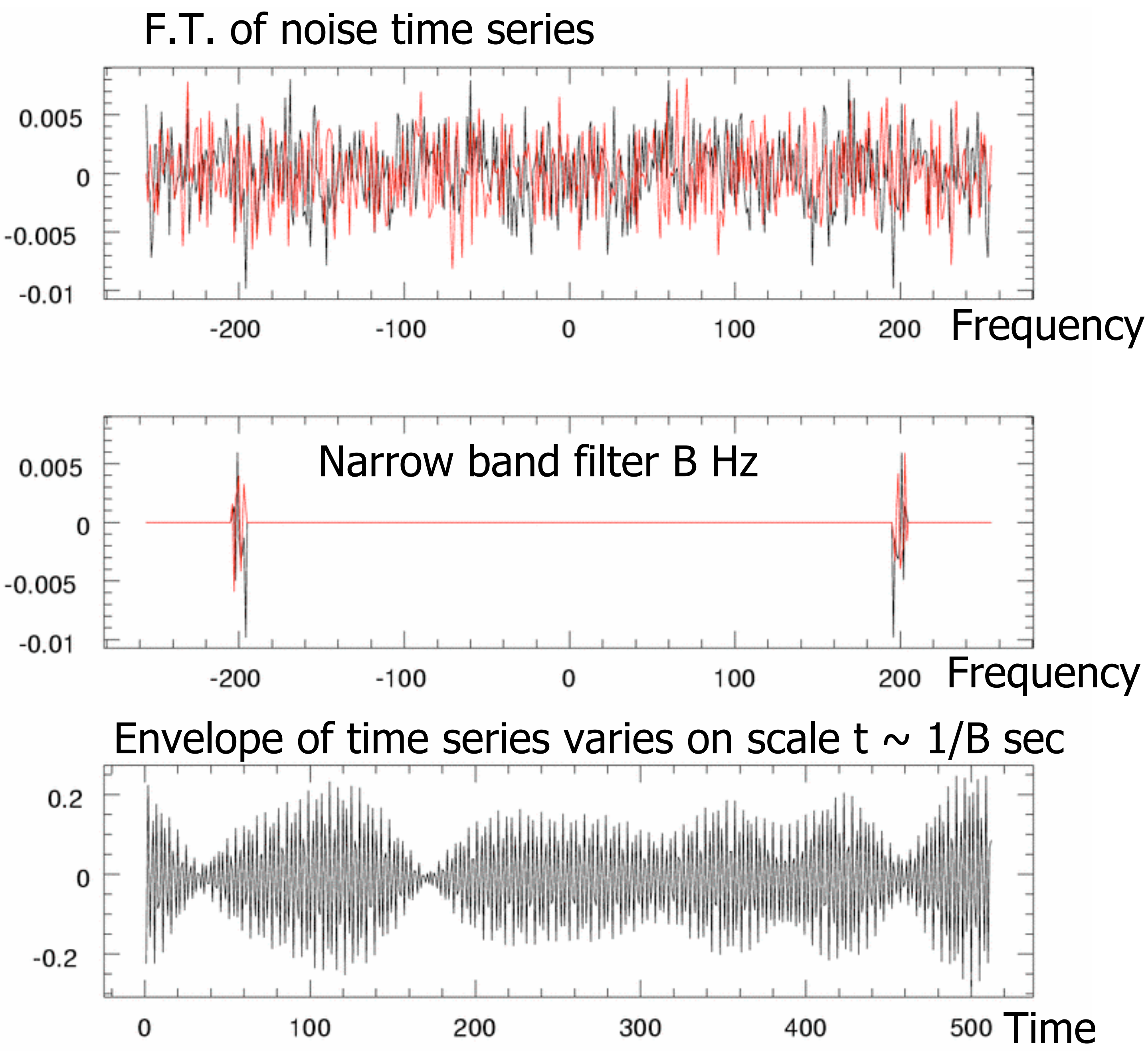
Celestial Radio Waves?

Actually....... Noise .... time series



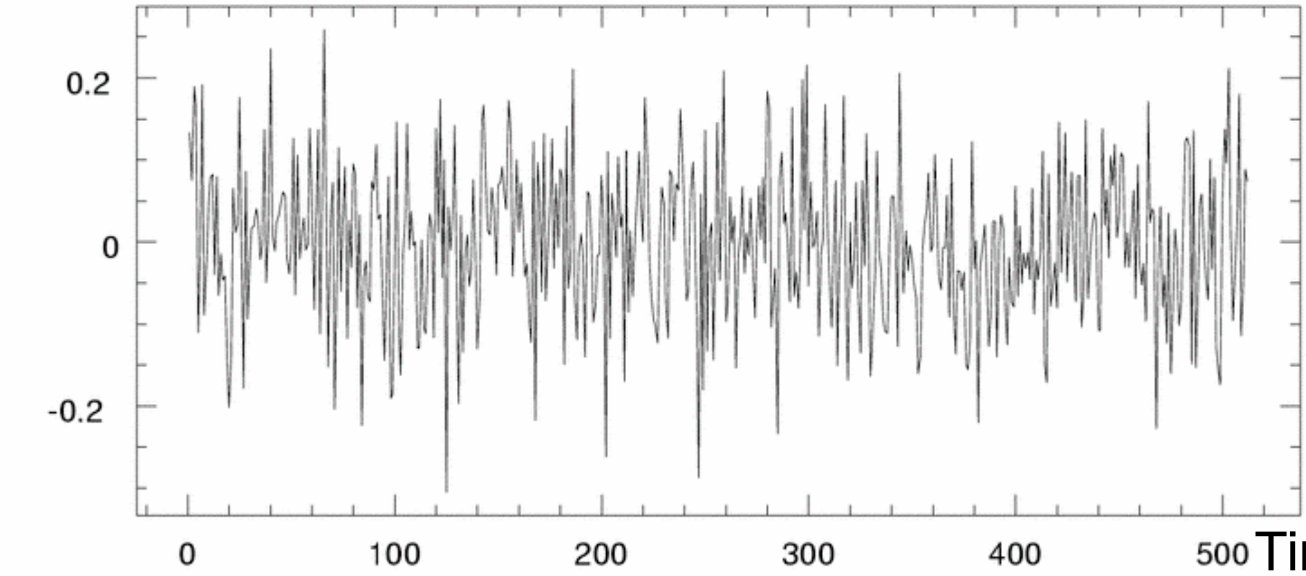
Fourier transform




F.T. of noise time series
0.005
0
-0.005
-0.01
-200
-100
0
100
200
Frequency
Narrow band filter B Hz
0.005
0
-0.005
-0.01
-200
-100
0
100
200
Frequency
Envelope of time series varies on scale t ~ 1/B sec
0.2
0
-0.2
0
100
200
300
400
500
Time

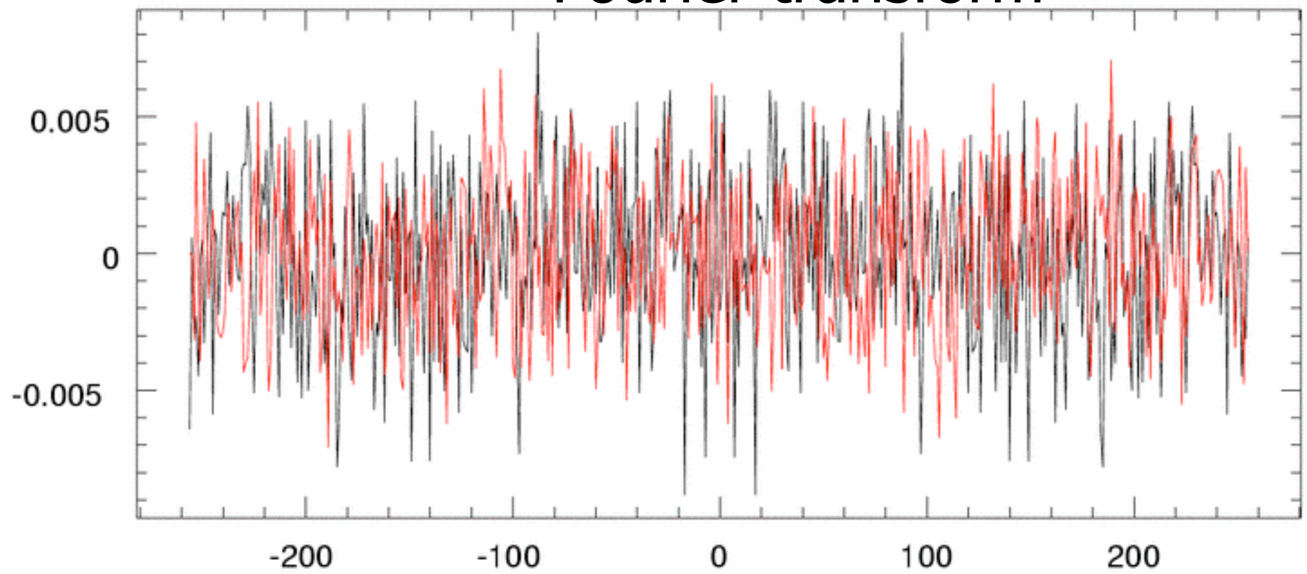
Observe “Noise” .... time series

V(t)



Time

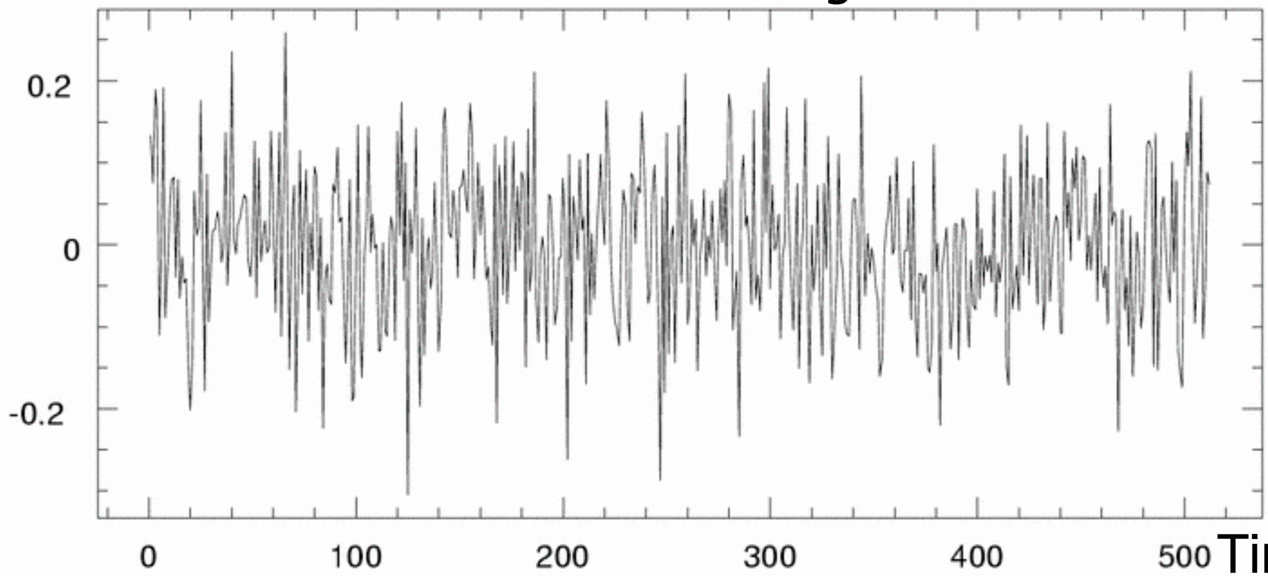
Fourier transform



Frequency

…want “Noise Power” … from voltage time series => $V(t)^2$

V(t)

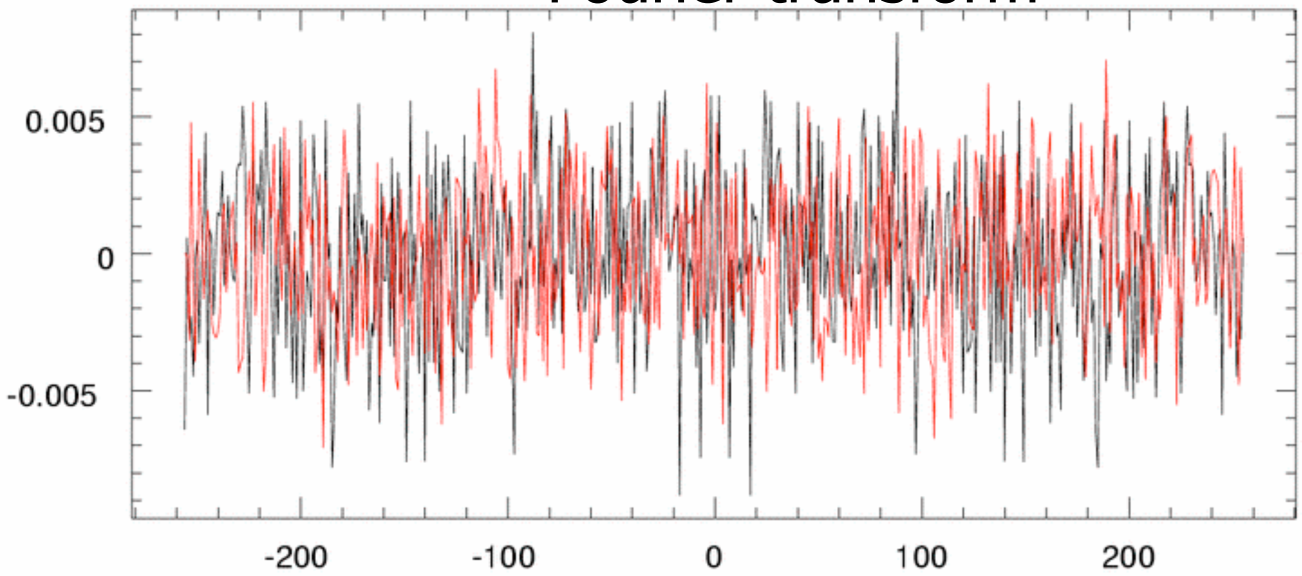


Time

then average power samples

“integration”

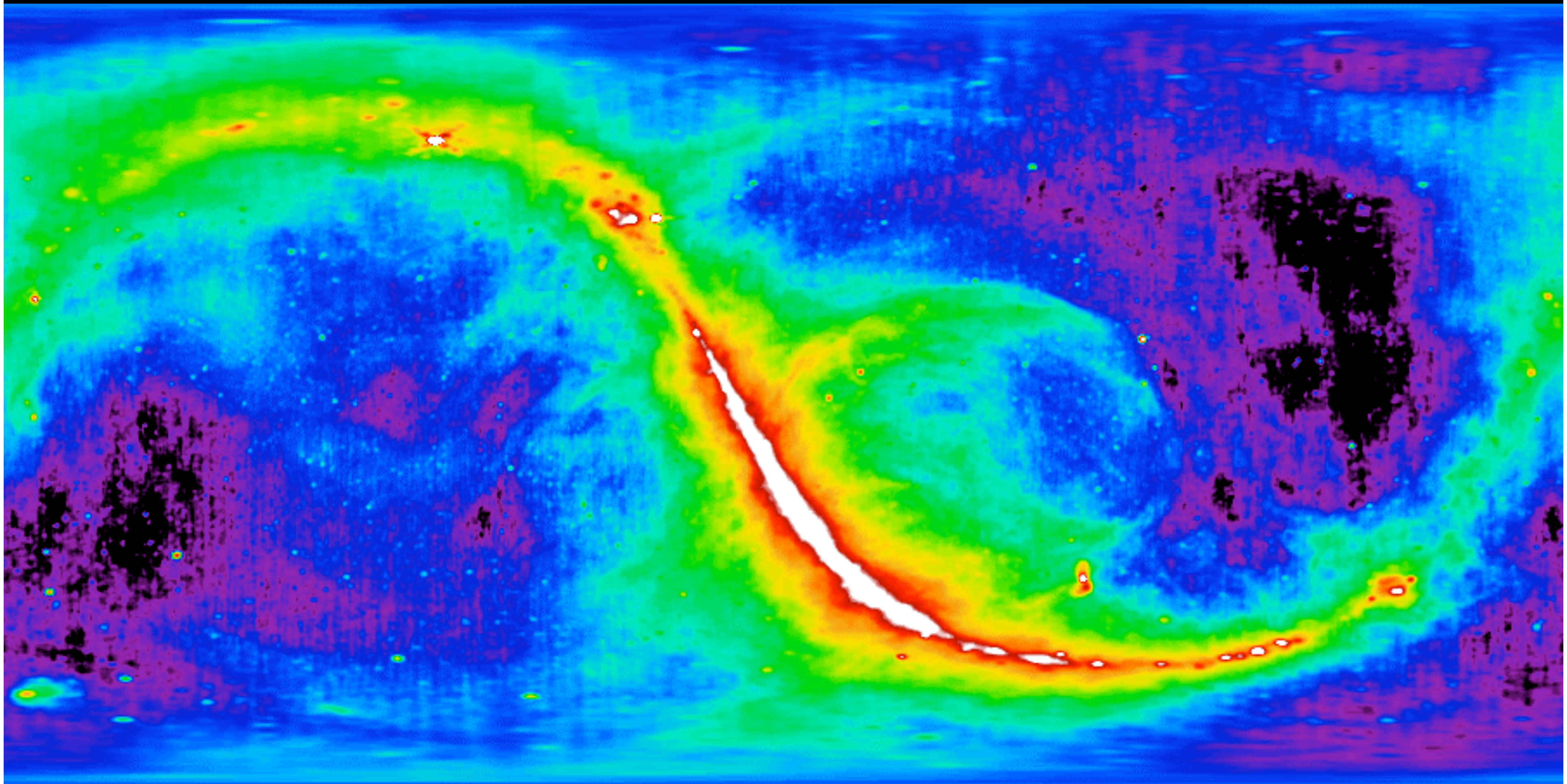
Fourier transform



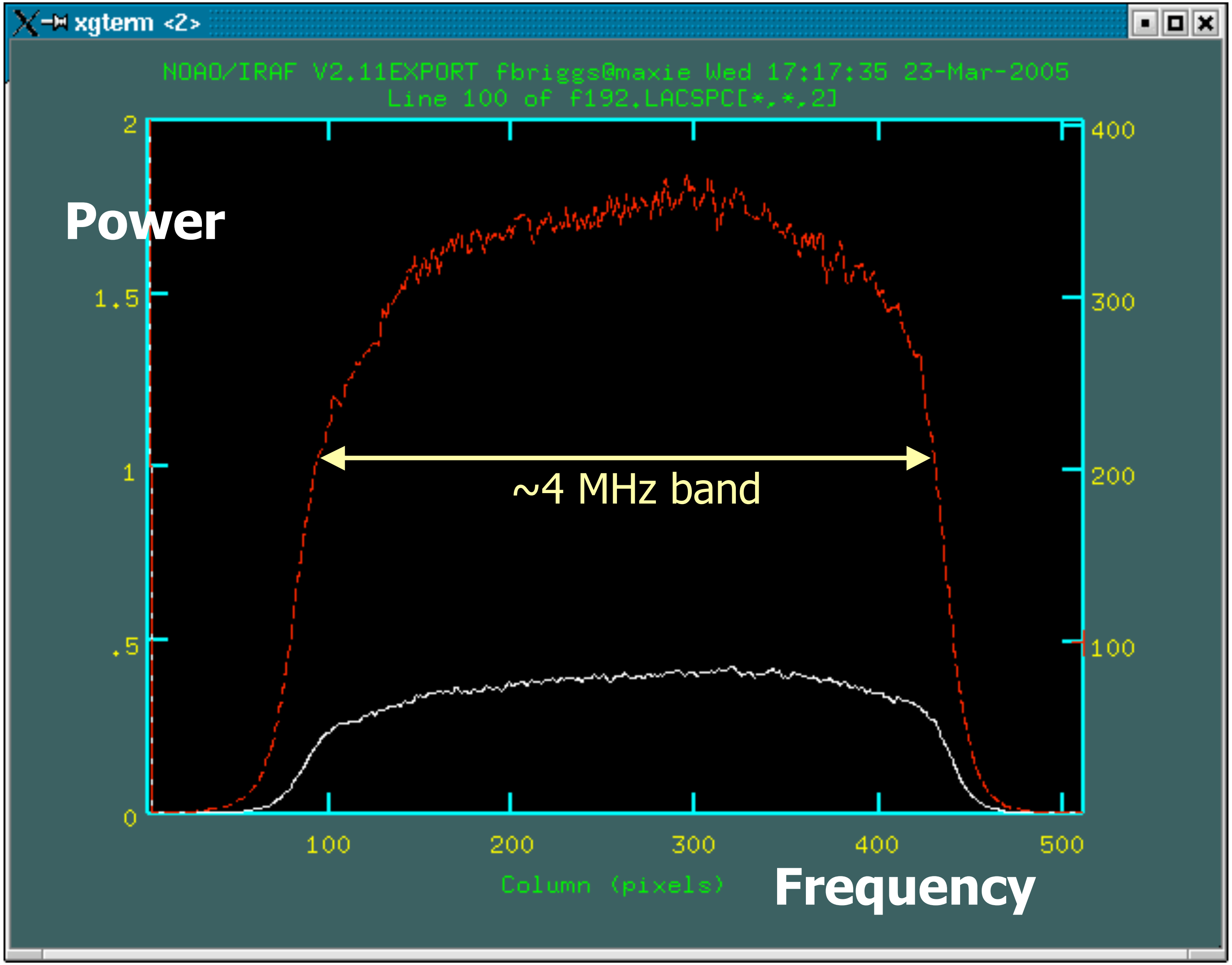
Frequency


1CHN 324

Radio sky in 408 MHz continuum (Haslam et al)

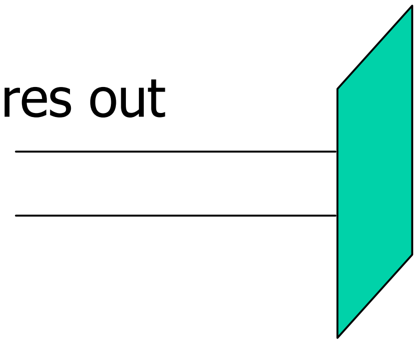


Difference between pointing at Galactic Center and Galactic South Pole at the LFD in Western Australia



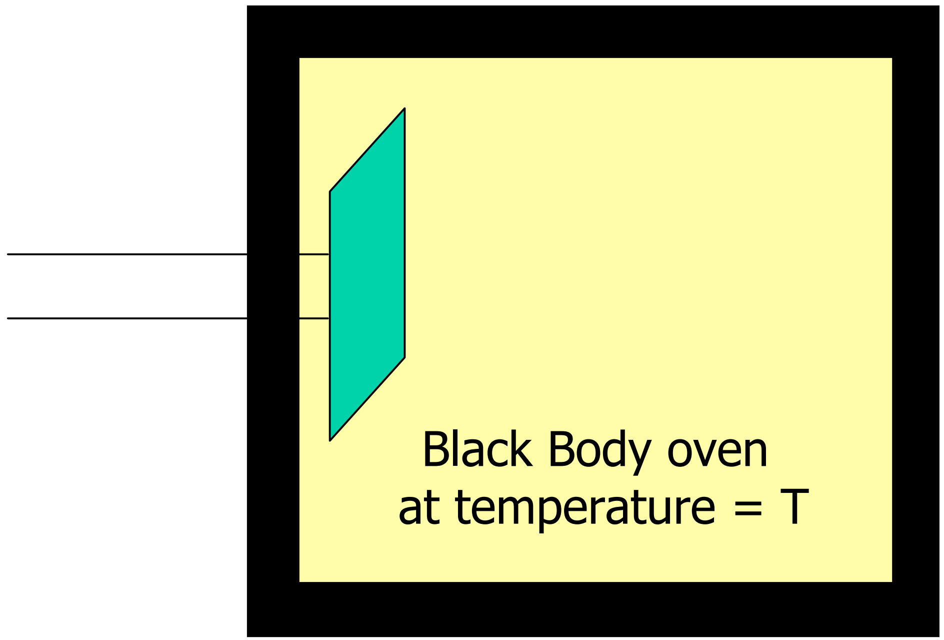
thought experiment…

Cartoon antenna

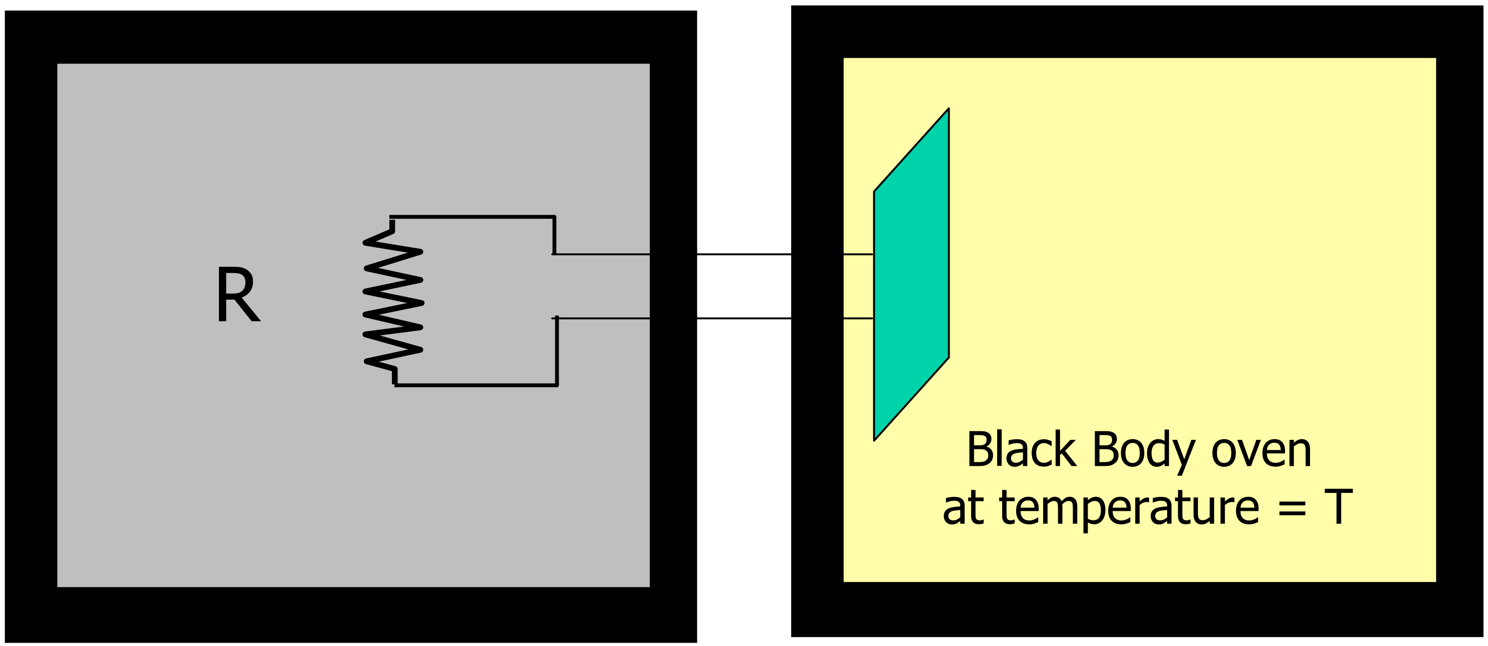


(antennas are "reciprocal" devices… can receive or broadcast)

thought experiment...

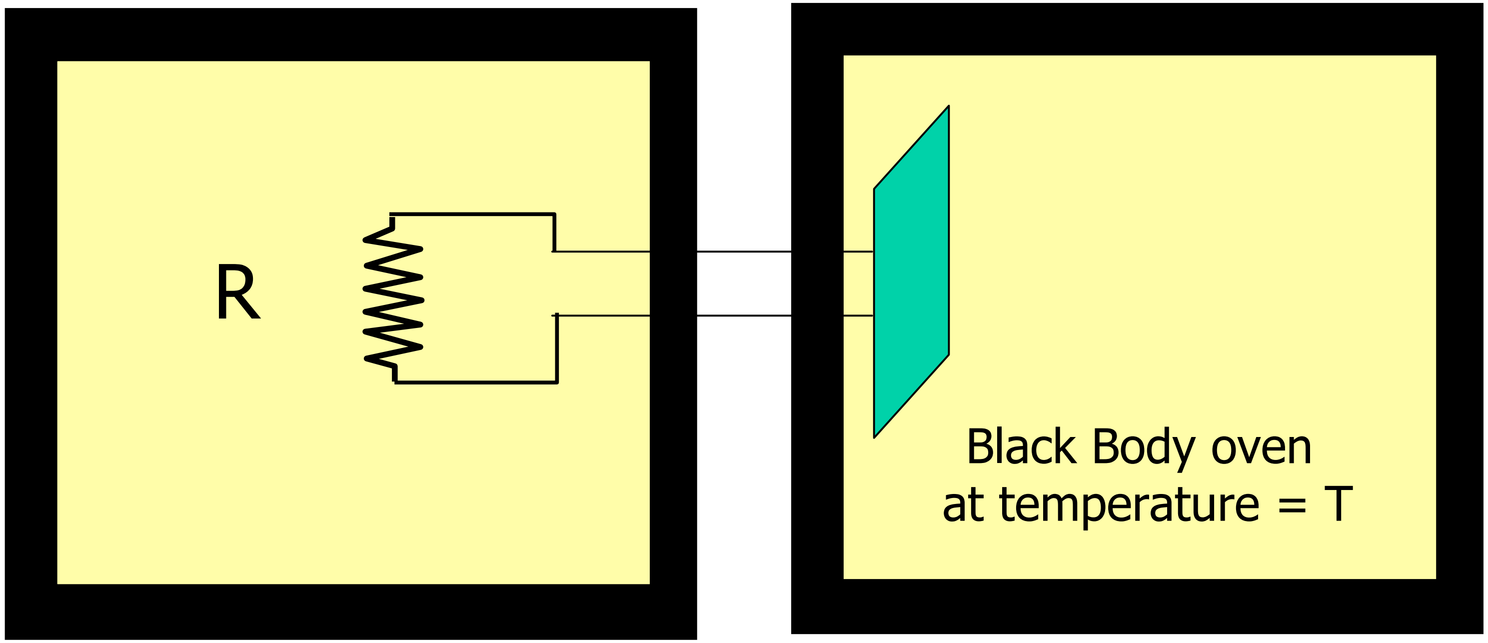


thought experiment...



thought experiment...

... wait a while... reach equilibrium... at T

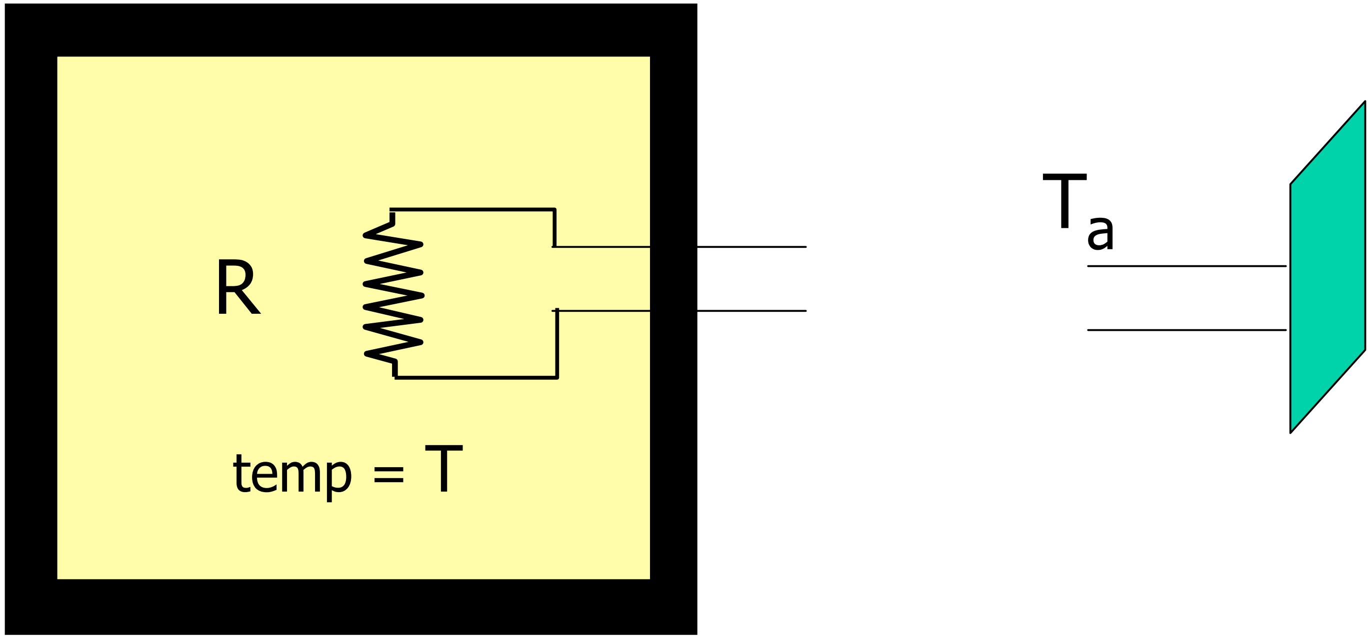


warm resistor delivers power P = kT B

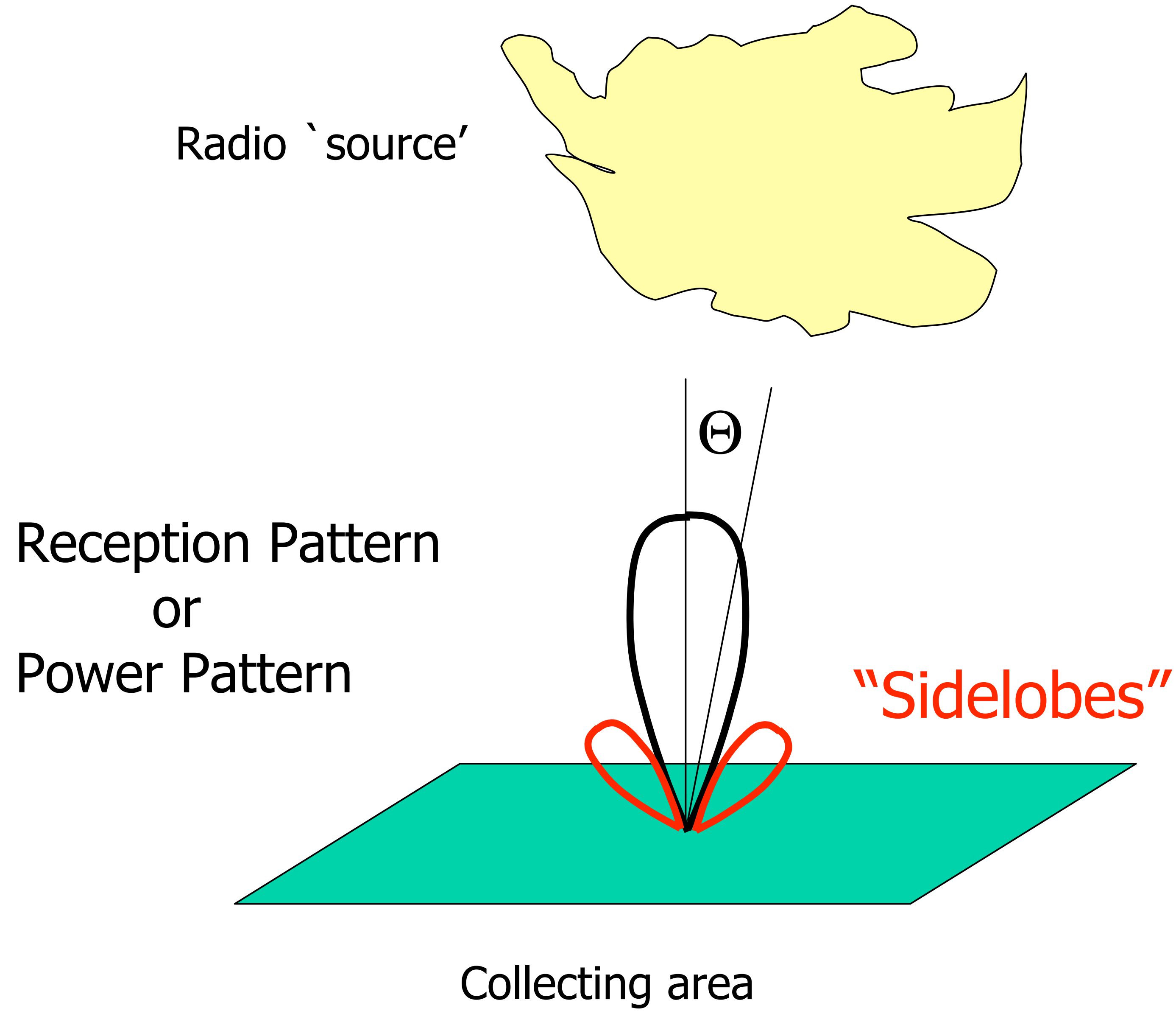
(B = frequency bandwidth; k = Boltzmann Const) real definition...

Measure Antenna output Power as "T_a"

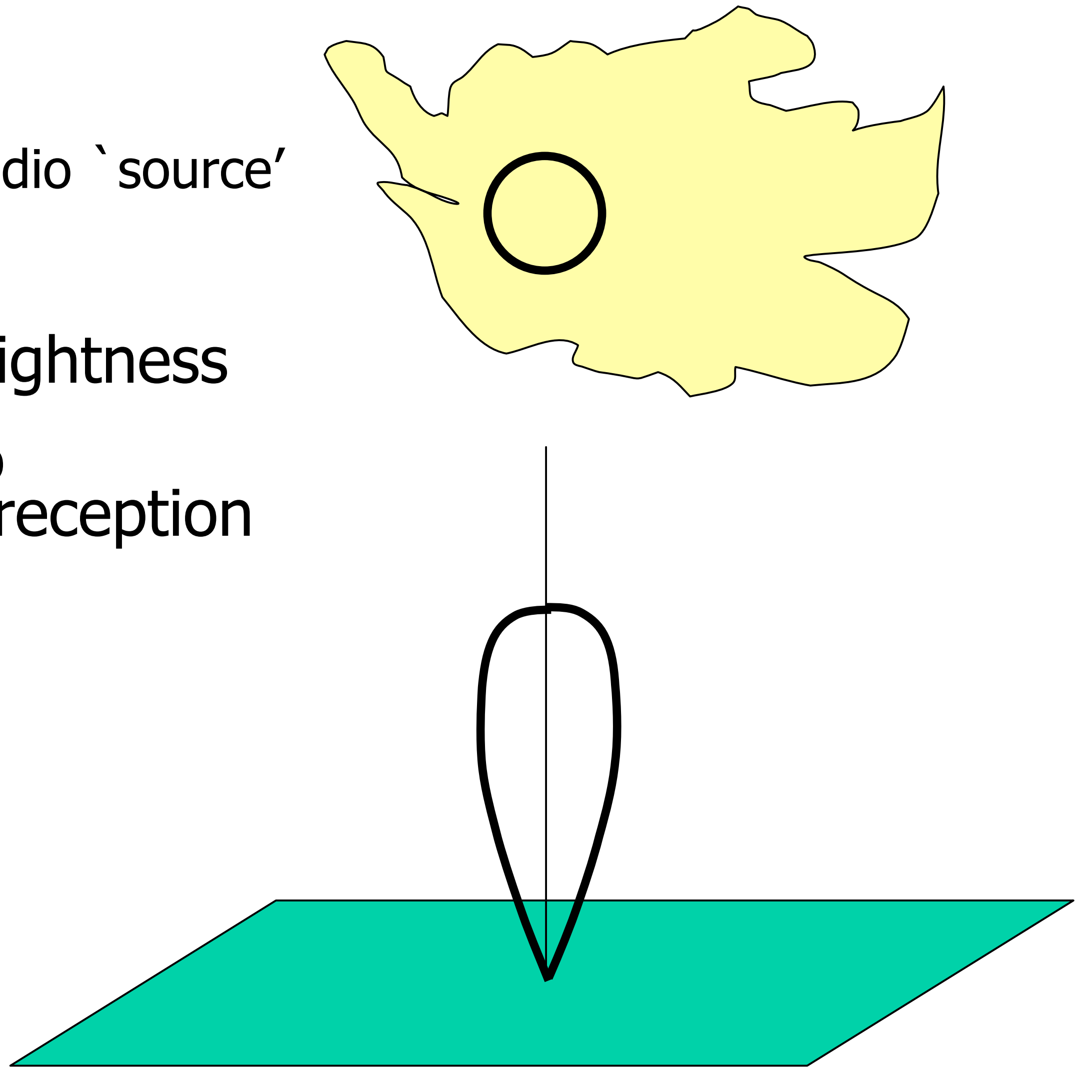
= ***antenna temperature***



warm resistor produces $P = kT\,B = P_a = kT_a\,B$


Radio `source’
Θ
Reception Pattern
or
Power Pattern
“Sidelobes”
Collecting area

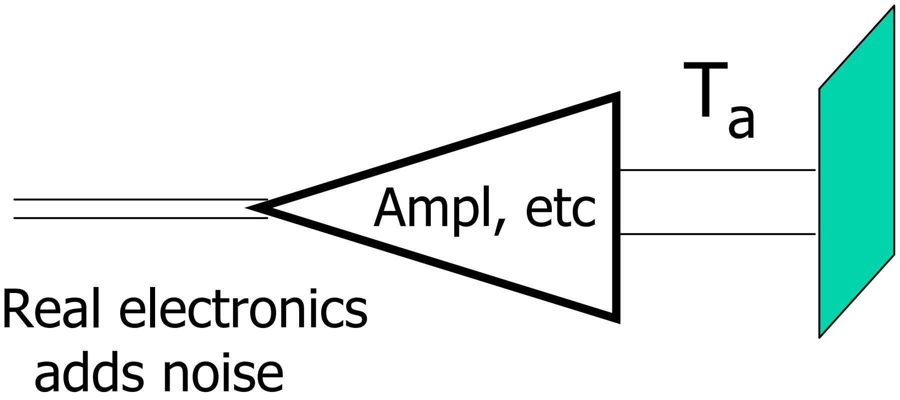
If source with brightness temperature T_b fills the beam (reception pattern), then $T_a = T_b$



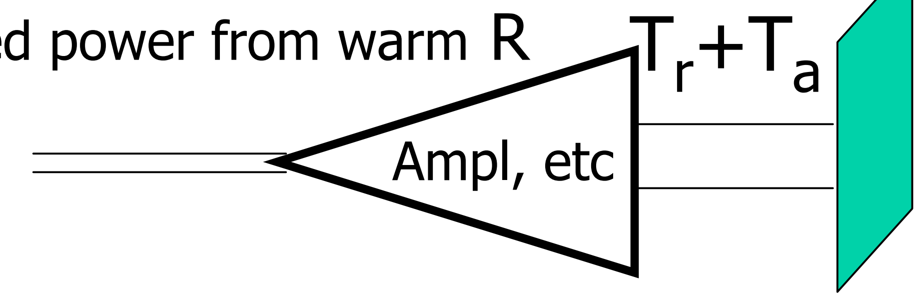
(!! No dependence on telescope if emission fills beam !!)

receiver "temperature"...

quantify Receiver internal noise Power as "T_r"
= "***receiver temperature***"



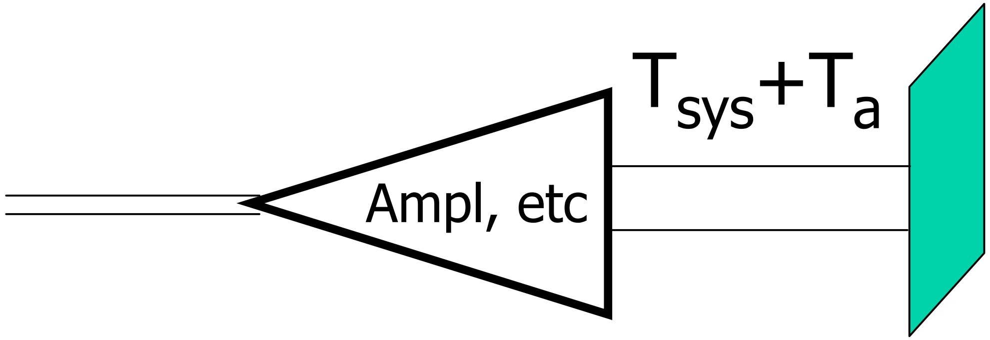
…treat as ideal, noise-free amp
with added power from warm R



"***system temperature***"...

quantify total receiver System noise power as "T_{sys}"

[include spillover, scattering, etc]



RMS fluctuations = ΔT

$$\Delta T = (fac)T_{sys}/(B\, t_{int})^{1/2}$$

Fac ~ 1 – 2

B = Bandwidth, Hz

t_{int} = integration time, seconds

Radio `point source’

Power collected = $S_\nu A_{eff} B/2$

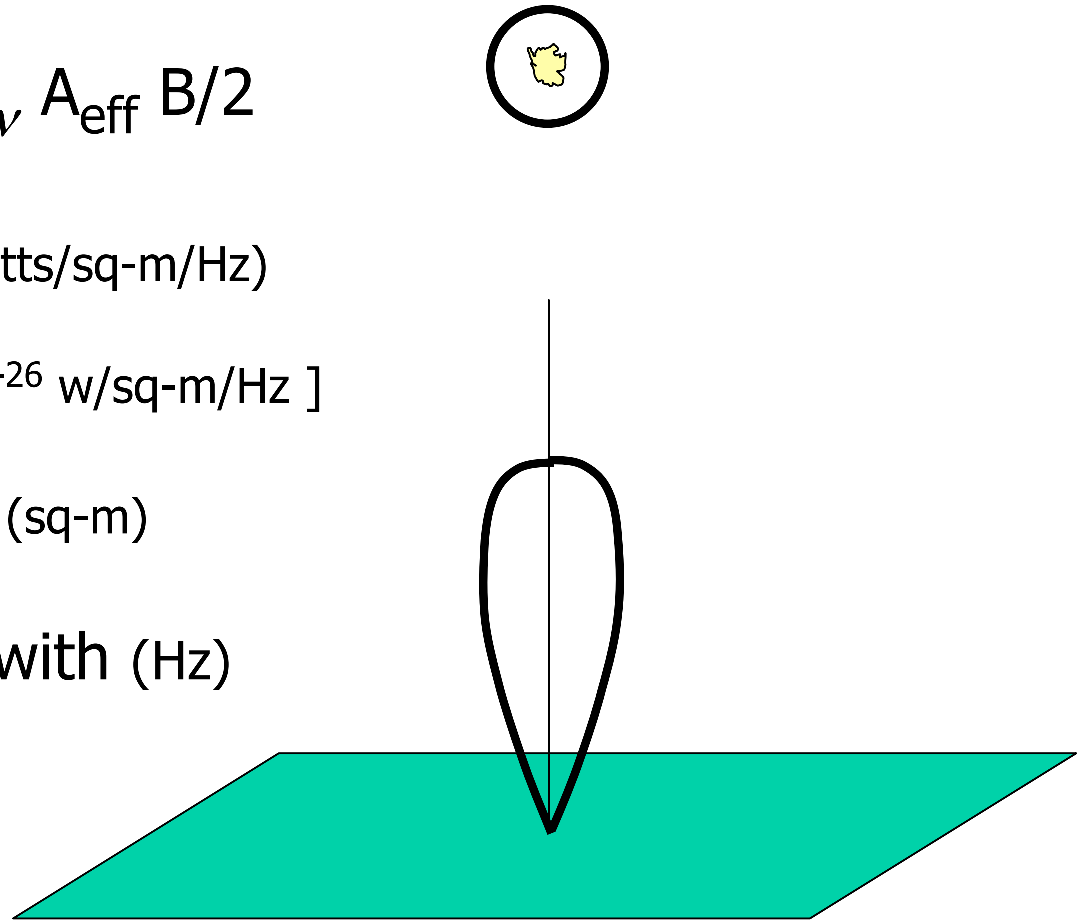
S_ν = flux density (watts/sq-m/Hz)

[1 Jansky = 1 Jy = 10^{-26} w/sq-m/Hz]

A_{eff} = effective area (sq-m)

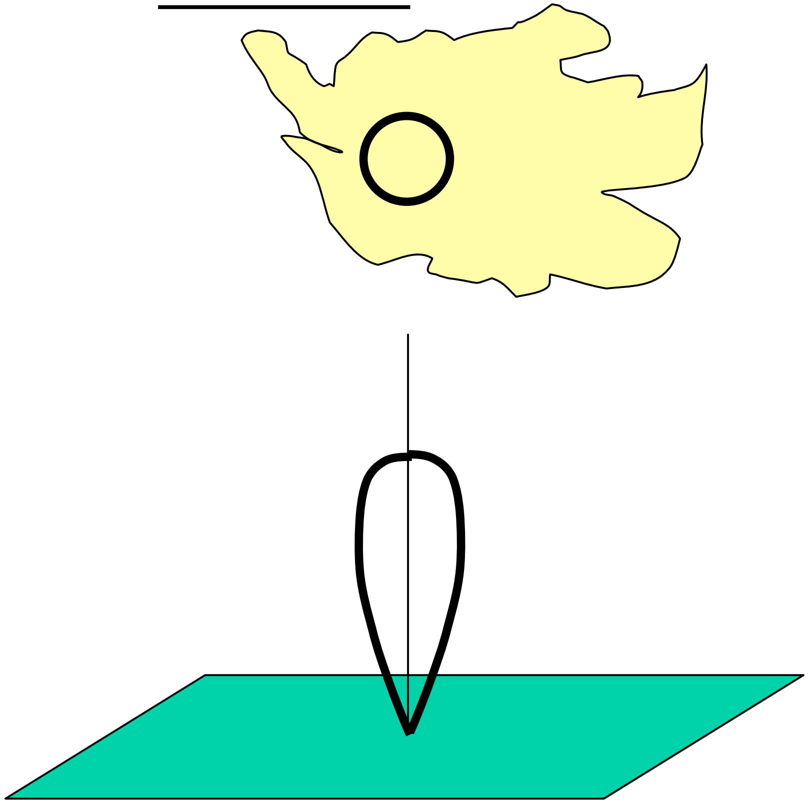
B = frequency bandwith (Hz)

$T_a = S_\nu A_{eff} /2k$



Collecting area

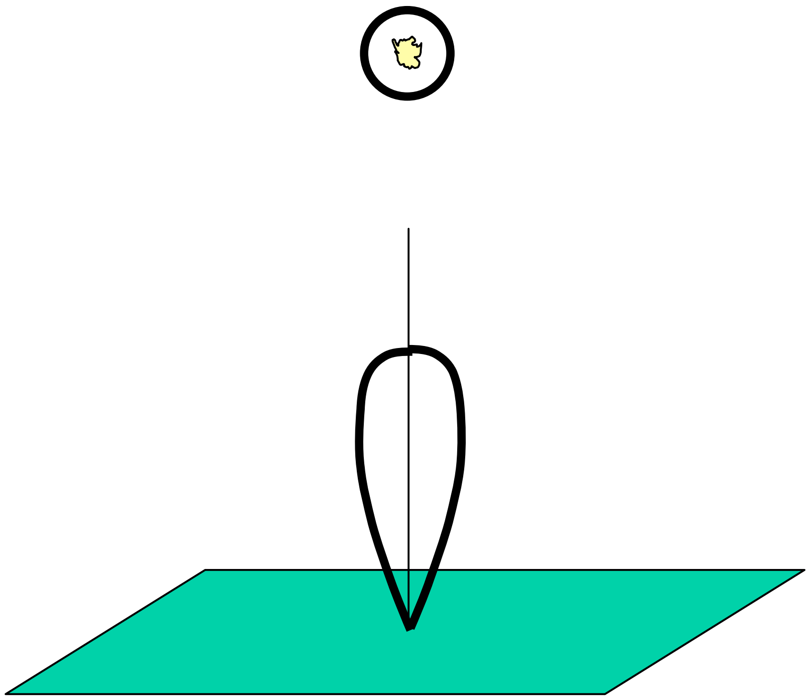
“Resolved”



If source fills the beam

$T_a = T_b$

“Unresolved”



S_ν = flux density

A_{eff} = effective area (sq-m)

$T_a = S_\nu A_{eff} / 2k$

$$RMS = \Delta T = (\mathrm{fac}) T_{sys} / (B\, t_{int})^{1/2}$$

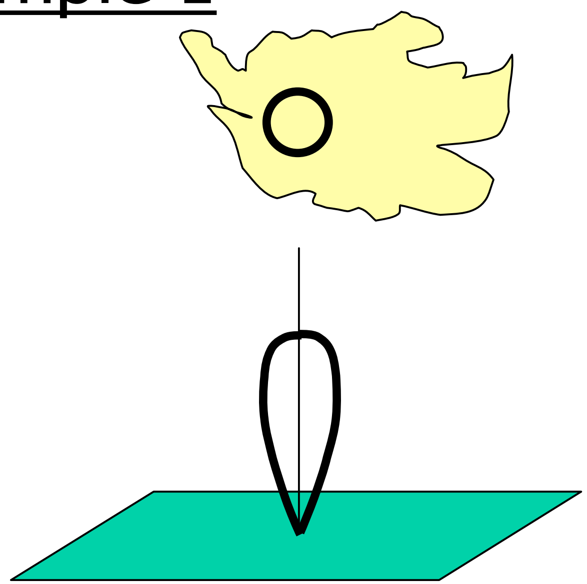
fac ~ 1 – 2

B = Bandwidth

t_{int} = integration time

Example 1

High Velocity HI Cloud:
$N_{HI} = 1 \times 10^{19}\ \ cm^{-2}$



$N_{HI} = 1.8 \times 10^{18}\, T_b\, \Delta V_{\ km/s}$
$\quad = 1.8 \times 10^{18}\, T_b\, (10)$
$T_b = 0.6\ K$

$B = (10/3x10^5)x1420x10^6$
$\quad = 50\ KHz$

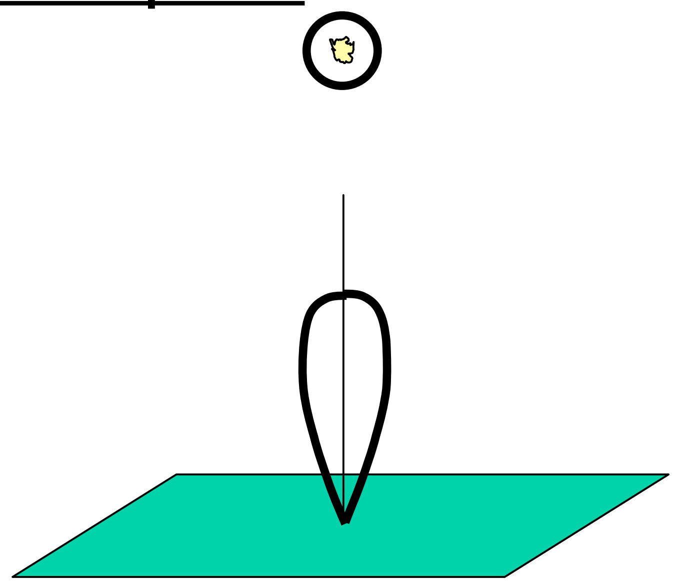
$5\ rms = 5\Delta T = T_b = 0.6\ K$

$rms = \Delta T = (fac)T_{sys}/(B\ t_{int})^{1/2}$
$\quad = (1)(30)/(B\ t_{int})^{1/2}$

$t_{int} = (30/0.12)^2/(50x10^3)$
$\quad =$ <u>1.2 seconds</u>

(To reach $N_{HI} = 1 \times 10^{17}\ \ cm^{-2}$ need 10,000 times longer ~ 3 hours)

<u>Example 2</u>



High redshift quasar with continuum flux density S_ν = 100 mJy

$$(T_a = S_\nu A_{eff} / 2k)$$

$$K_a = T_a / S_\nu = A_{eff} / 2k \quad [K/Jy]$$

= 0.7 K/Jy Parkes

= 10 K/Jy Arecibo

= 2.7 K/Jy VLA

= 300 K/Jy SKA

<u>Parkes</u>: 100 mJy yields T_a = 70 mK

64 MHz continuum bandwidth for receiver

5 *rms* = $5\Delta T = T_b$ = 0.07 K

rms = ΔT = $(fac)T_{sys}/(B\, t_{int})^{1/2}$

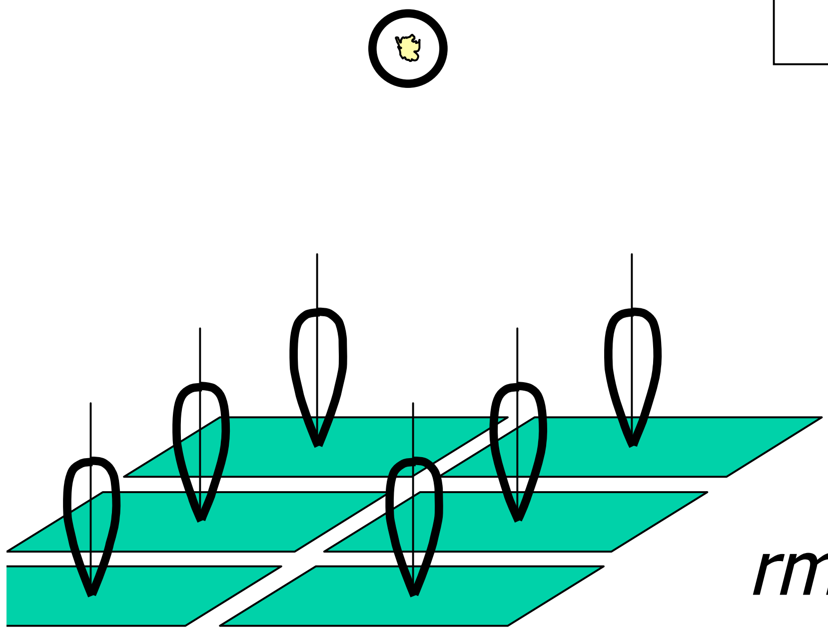
$= (1)(30)/(B\, t_{int})^{1/2}$

$t_{int} = (30/0.014)^2/(64\times10^6)$

~ <u>0.1 sec</u>

Example 3: Array

High redshift quasar with continuum flux density S_ν = 1 mJy



$(T_a = S_\nu A_{eff} / 2k)$

$K_a = T_a / S_\nu = A_{eff} / 2k$ [K/Jy]

= 0.7 K/Jy Parkes

= 6 x 0.1 = 0.6 K/Jy ACTA

$rms = \Delta S = (fac)(T_{sys} / K_a)/(B\, t_{int})^{1/2}$

ATCA (B=128 MHz): 1 mJy = 5 *rms* means ΔS = 0.2 mJy

$rms = \Delta S = (fac)(T_{sys} / K_a)/(B\, t_{int})^{1/2}$

$= (1.4)(30/0.6)/(B\, t_{int})^{1/2}$

$t_{int} = (70/0.0002)^2/(128 \times 10^6)$

$\sim$ 16 min