Introduction to Radio Astronomy & VLBI

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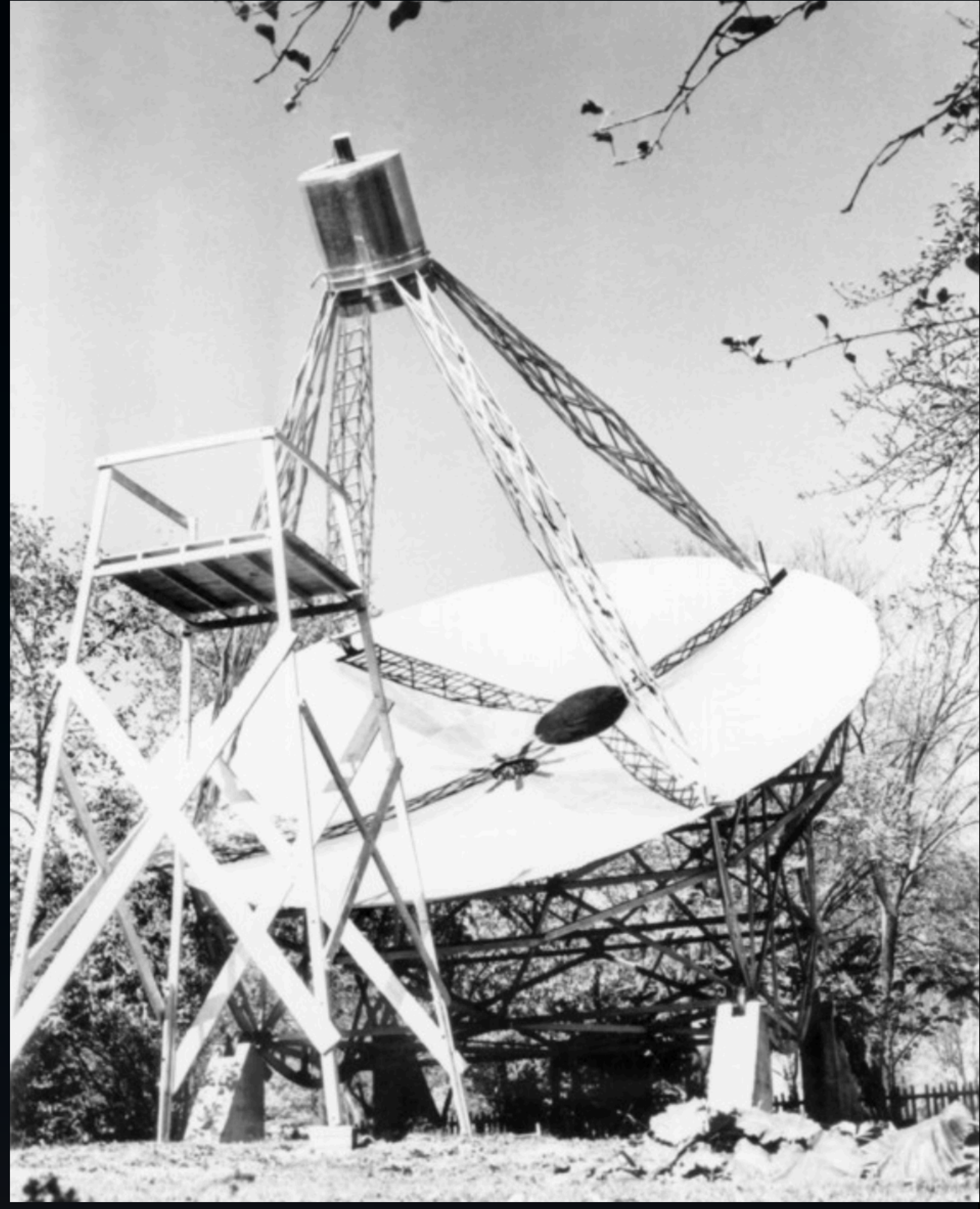
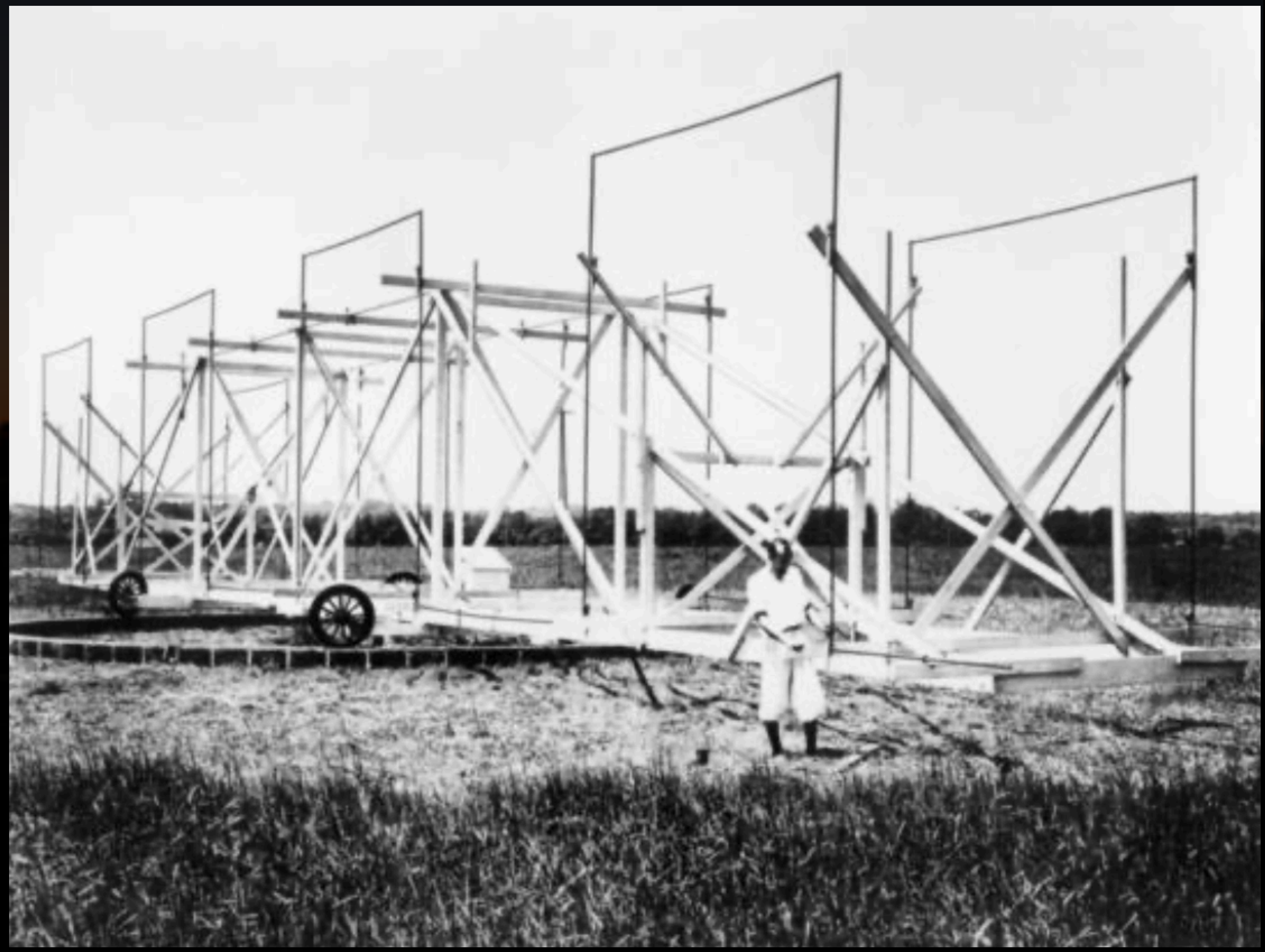
Overview

- RAD1 (Intro to radio astronomy and radio telescopes)
- RAD2 (Single-dish data processing)
- RAD3 (Single-dish data processing)
- RAD4 (Radio interferometry)
- RAD5 (Interferometric data processing)
- RAD6 (Interferometric data processing)

History of radio astronomy

- 1932 - Karl Jansky (Bell Telephone Labs) ~20 MHz detected Galactic emission
- 1938 - Grote Reber built a 10m parabolic telescope and mapped the Galaxy at 160 MHz
- 1950's - Discrete sources detected
- 1960's - High resolution interferometry
- 1970's/80's - Interferometric imaging array (e.g. VLA)
- 2000s - Development of software-based receivers
- 2020s - Start of SKA, conceived in 1991, first MoU in 2000





EM Spectrum

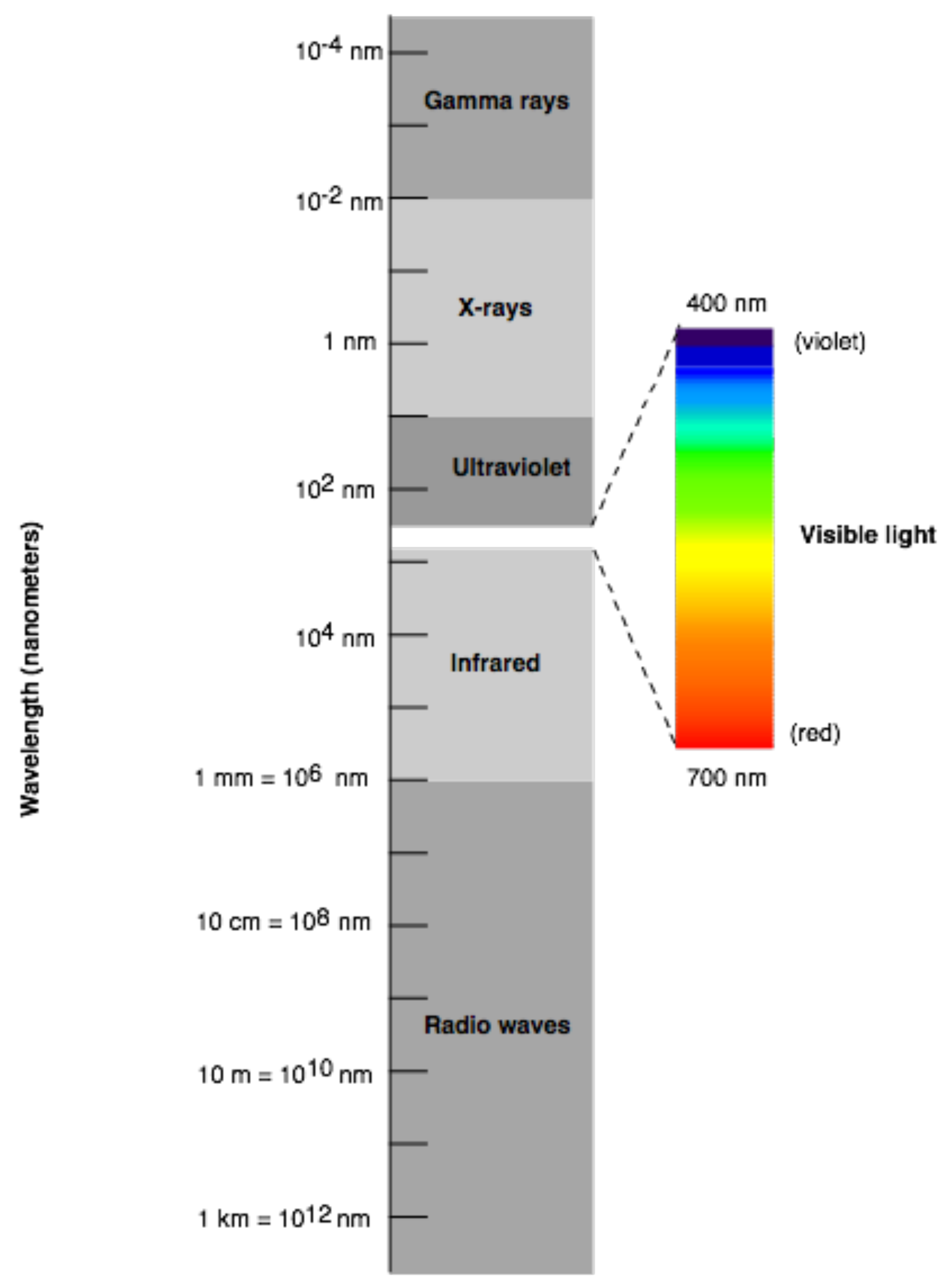
Radio Waves => electromagnetic waves with λ = 0.3mm - 100km
(1 THz - 3 kHz)

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

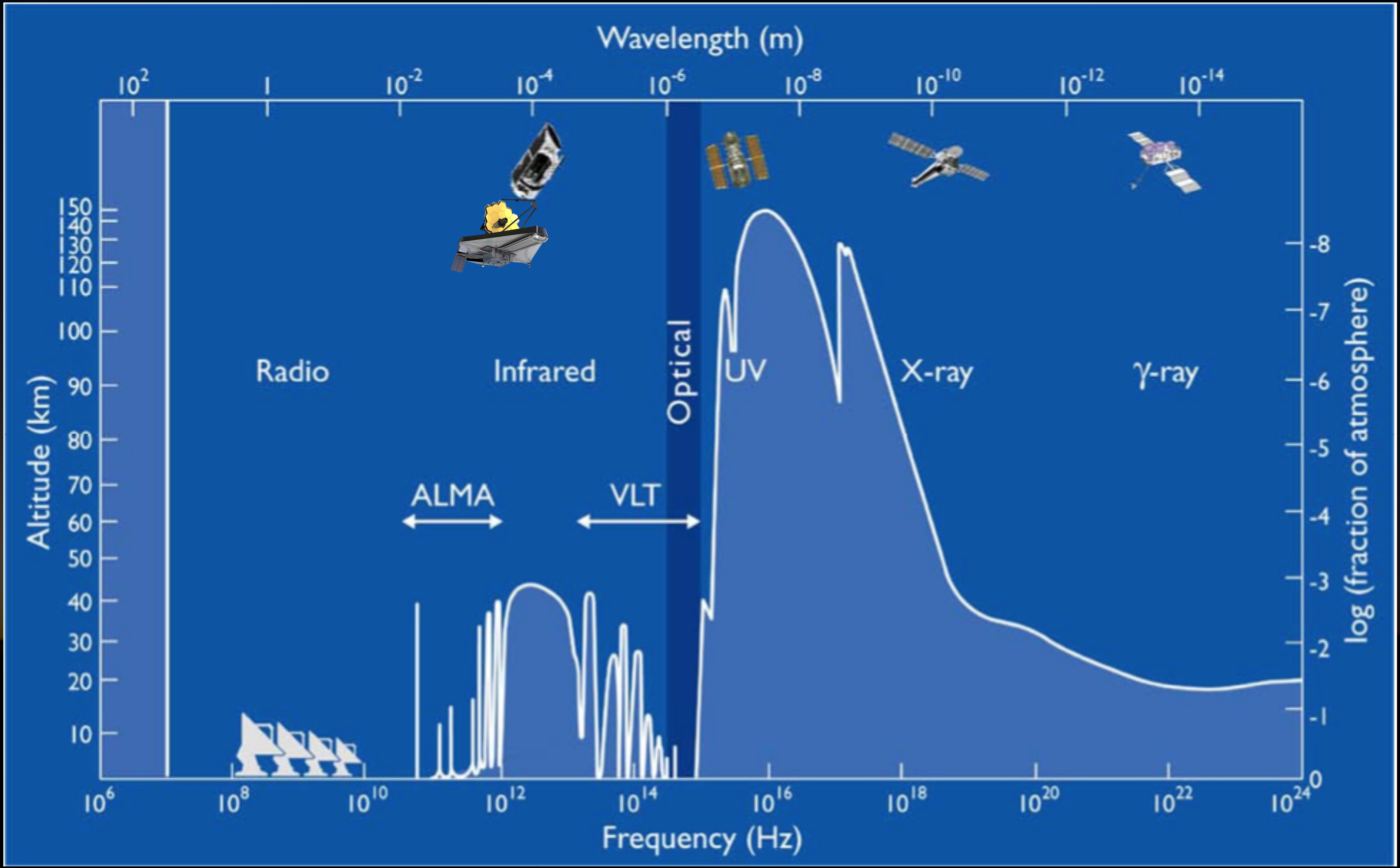
Microwaves (1 cm - 30 m)
(30 GHz - 10 MHz)

Millimetre (1 mm to 10 mm)
(300 GHz - 30 GHz)

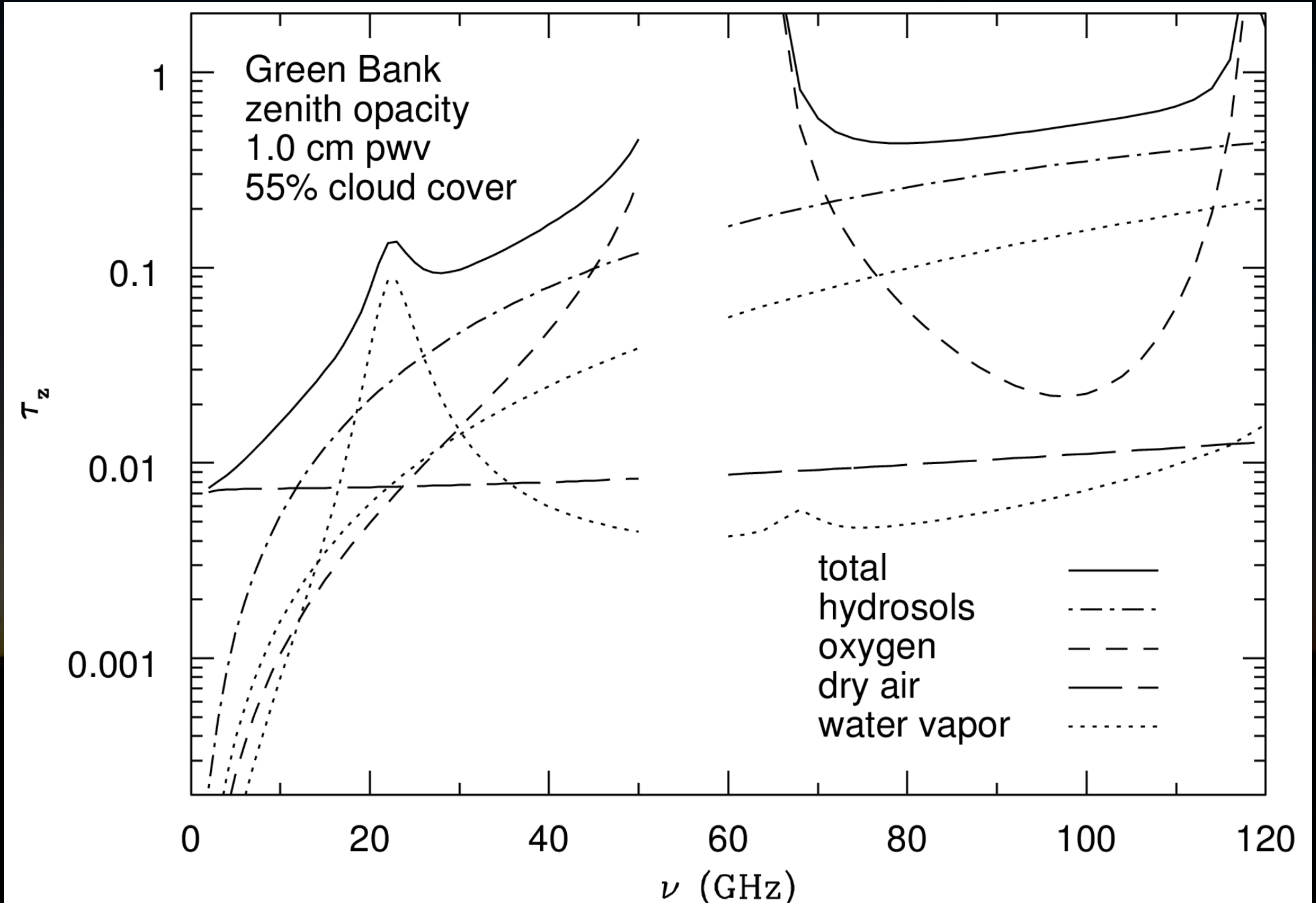
Sub-millimetre (< 1 mm, up to 0.4 mm)
(> 300 GHz)



Why should we care about the radio band?



Opacity in radio bands



Bands and naming conventions

High Frequency (mm/sub-mm):

JCMT

λ ~ 2000 - 345 μm

ν ~ 150 - 870 GHz

ALMA

λ ~ 3mm - 400 μm

ν ~ 84 - 720 GHz (40 - 950 GHz)

Low Frequency:

LOFAR

λ ~ 1 - 20 m

ν ~ 10 - 240 MHz

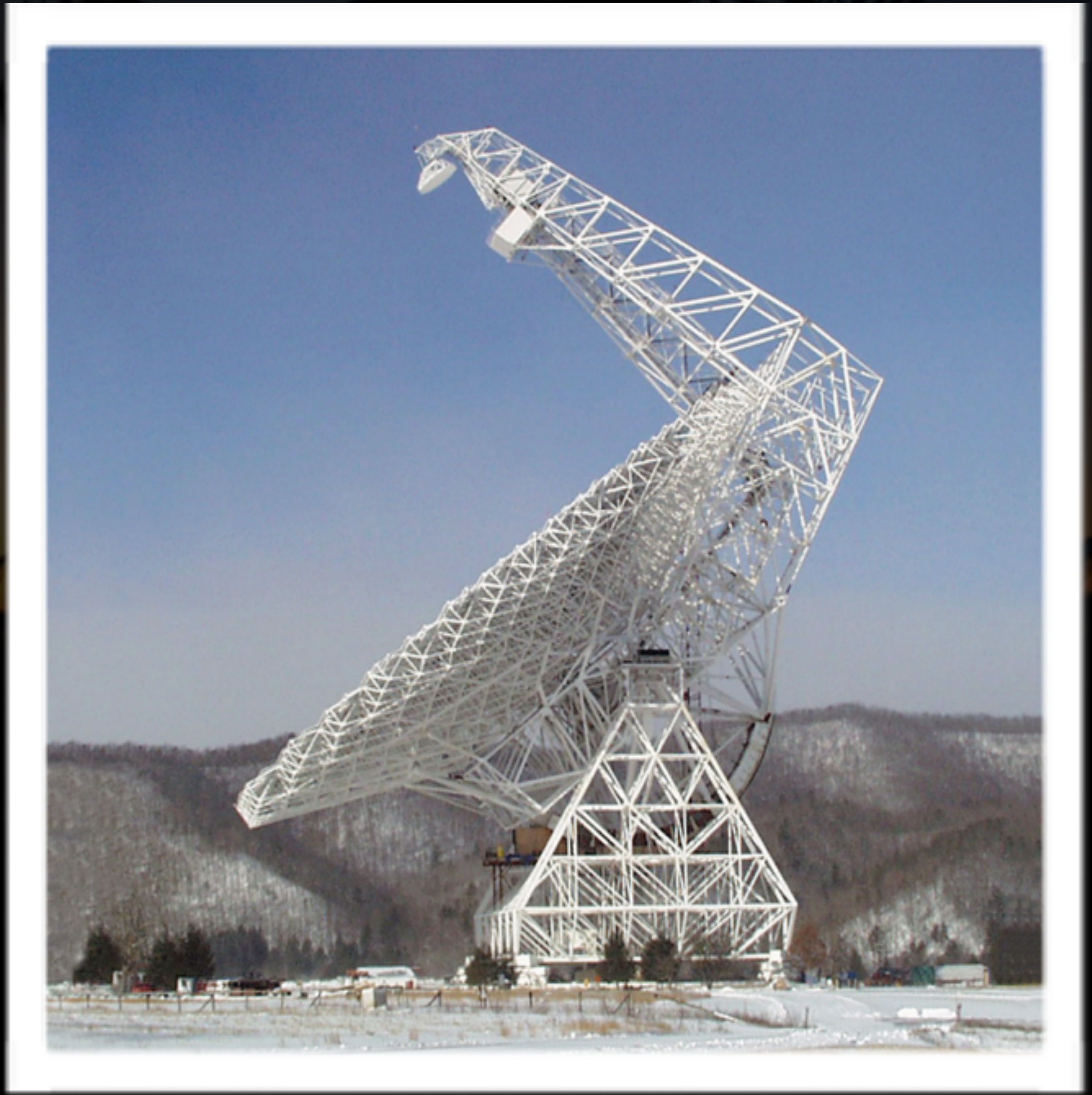
(10-90, 110-240)

Large Radio Telescopes

ν > 500 MHz:

GBT (ν ~ 0.32 - 100 GHz)

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



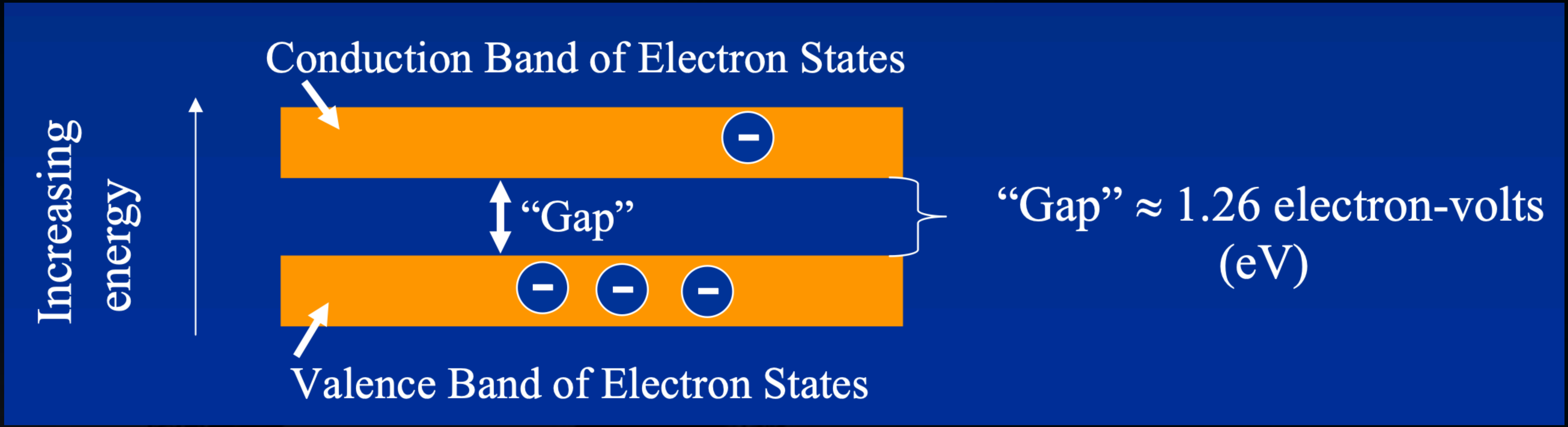
How much energy does a radio photon carry?

Energies

	λ	E	T ($= h\nu/k$)
Optical photons	600nm	$\sim 2eV$	20,000 K
Radio photons	1m	$\sim 10^{-6} eV$	0.012 K

$\Rightarrow$ photon-counting is not an option in radio ast.

CCD



E = 1.26 electron Volts

- 1 eV = 1.602×10^{-12} erg = 1.602×10^{-12} Joule

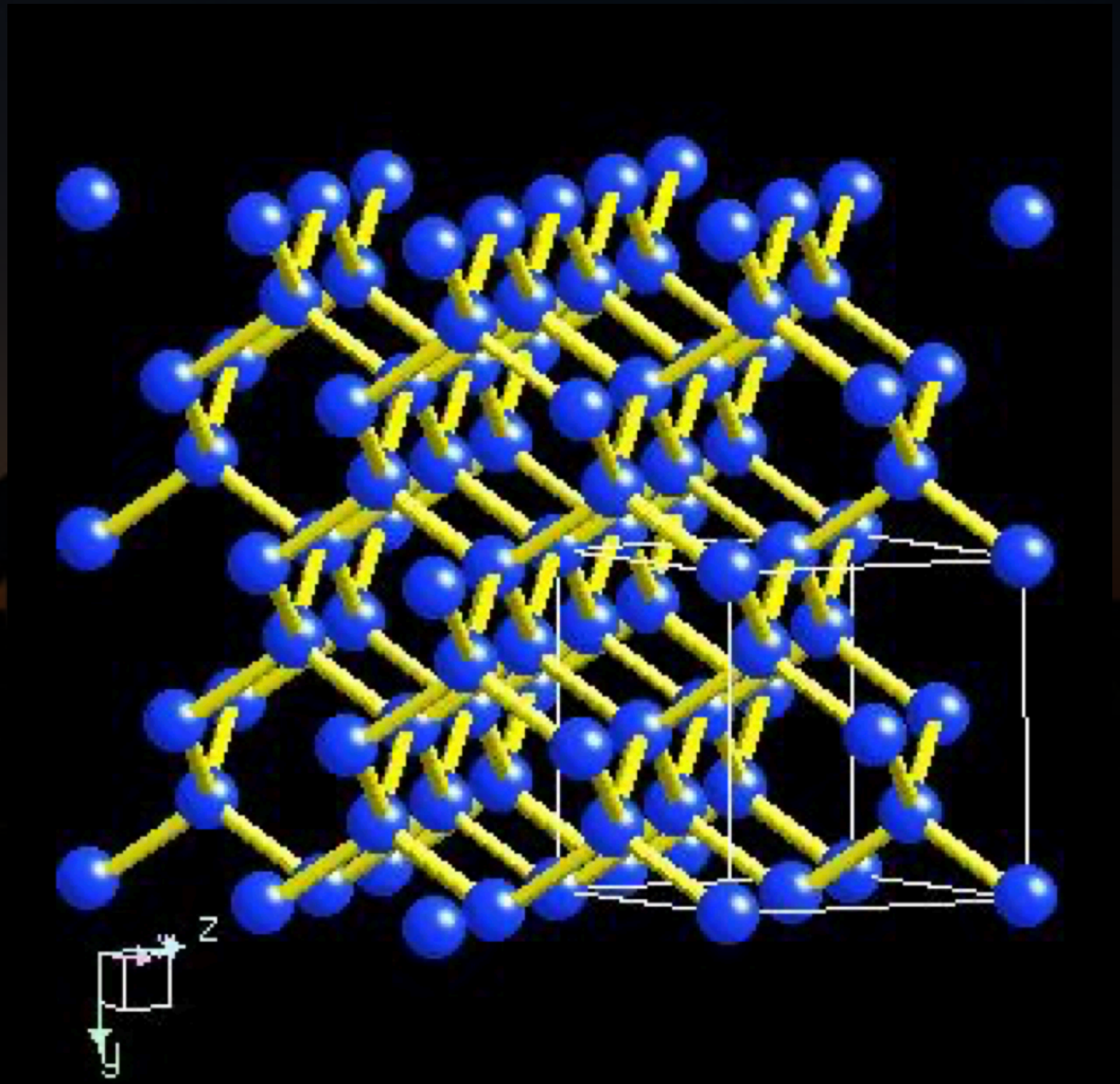
$$\lambda = \frac{hc}{E} = \frac{\left(6.624\times10^{-27}\, erg-\sec\right)\cdot\left(3\times10^{8}\,\frac{m}{\sec}\right)}{1.26eV\times\left(1.602\times10^{-12}\,\frac{erg}{eV}\right)}$$

$$= 9.84\times10^{-7}\, m = 984\, nm$$

$\Rightarrow$ To Energize Electron in Si Lattice Requires

$\lambda < 984$ nm $\cong 1$ μm

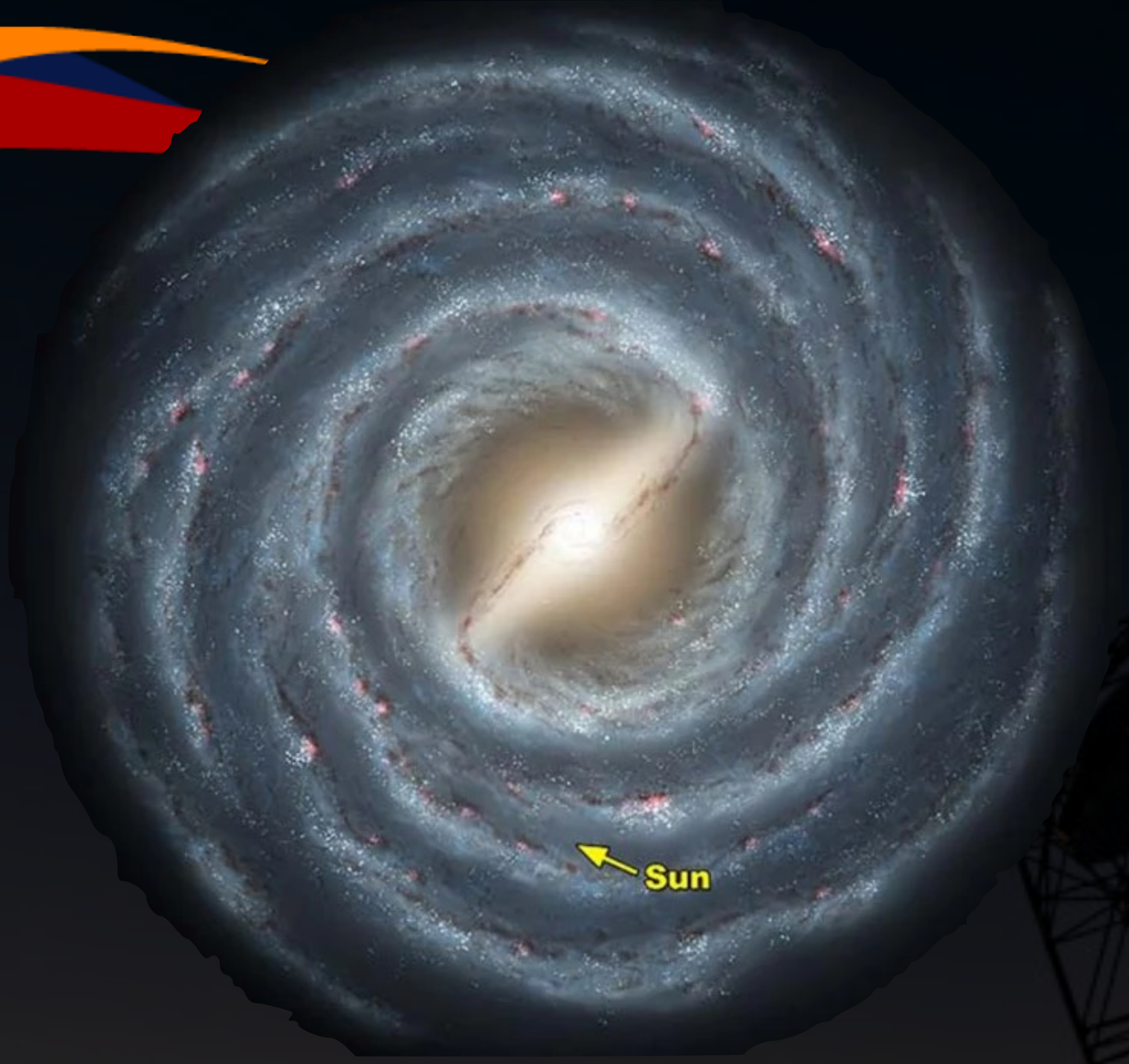
Silicon

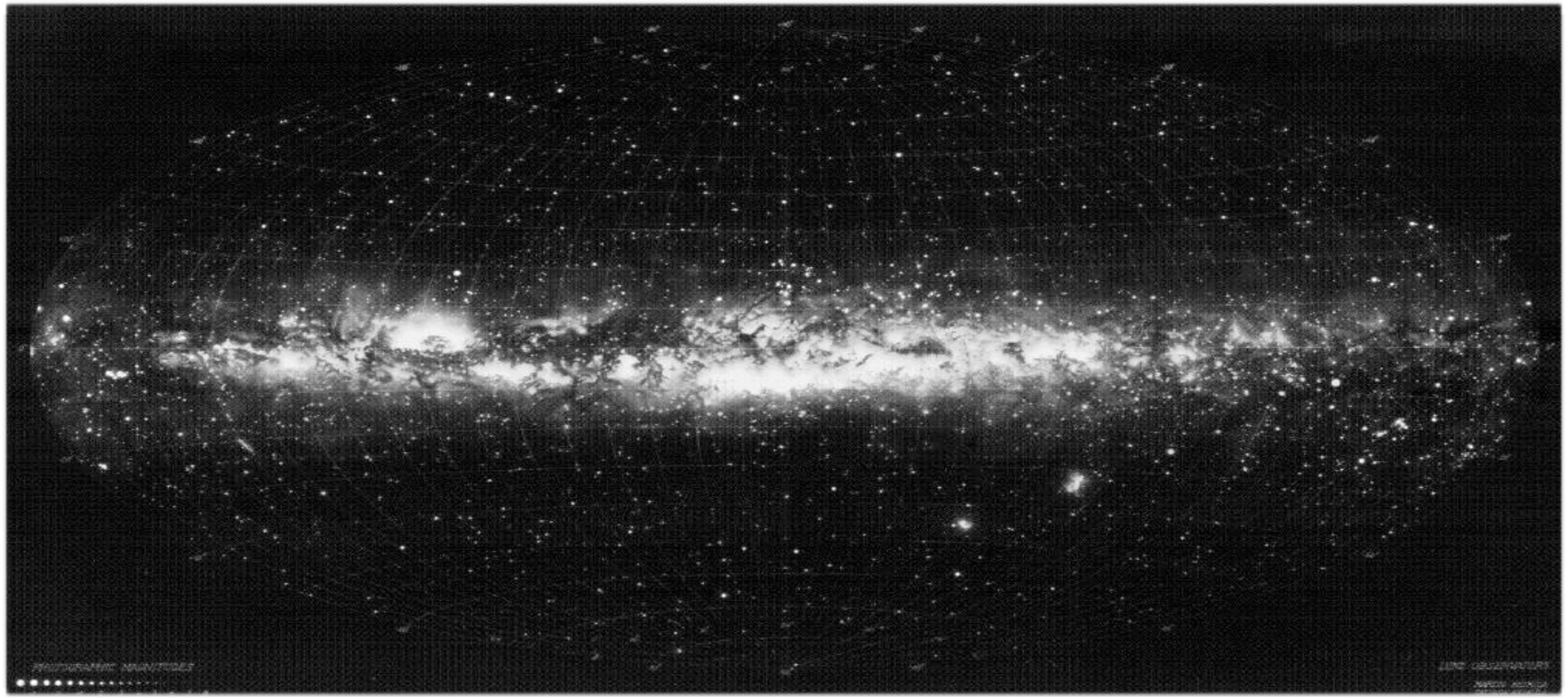


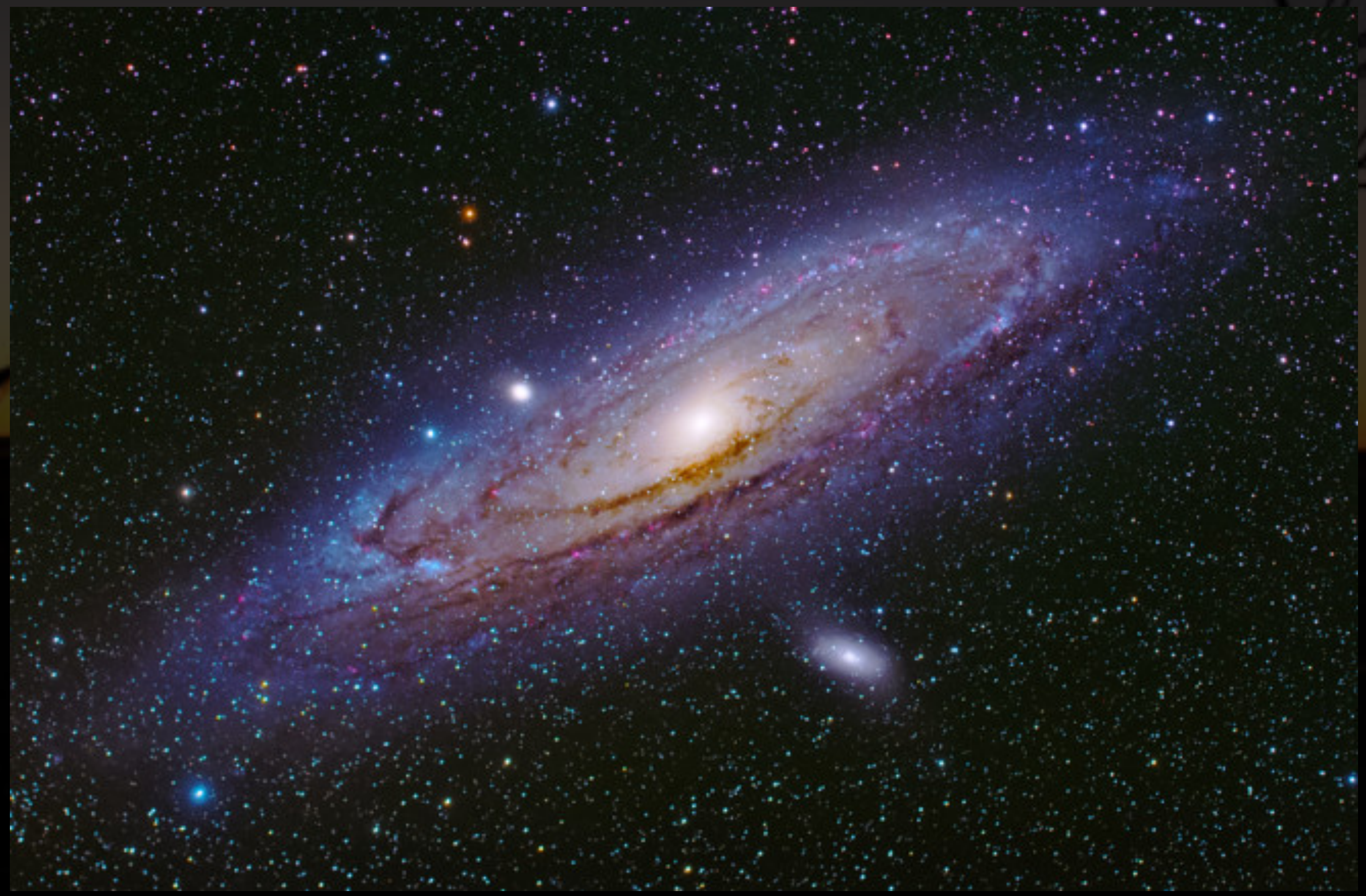
What do we measure in radio observations?

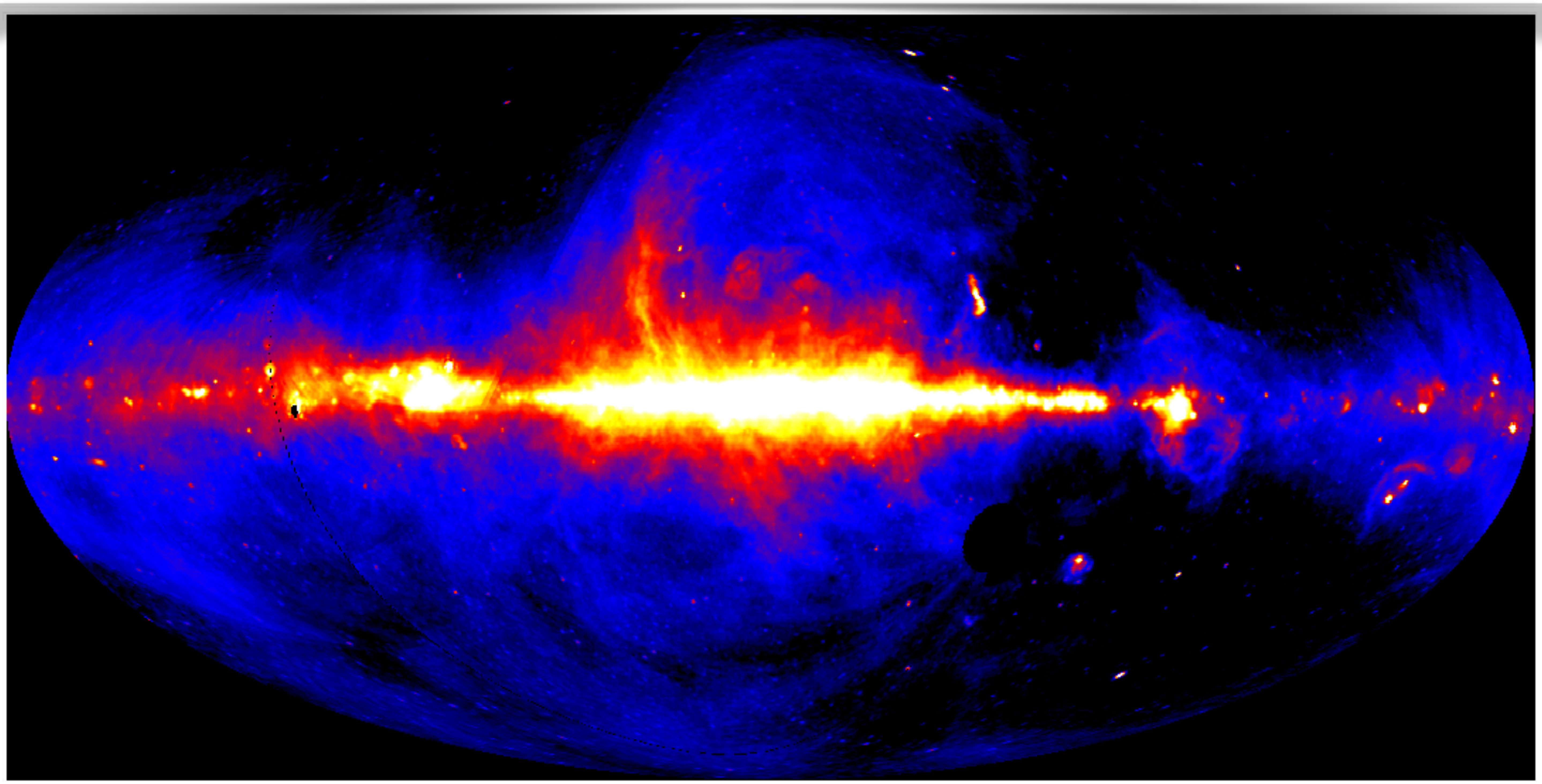
Photon counting in the radio is not usually an option, we must think classically in terms of measuring the source electric field

=> i.e. measure the voltage oscillations induced in a conductor (antenna) by the incoming EM-wave.

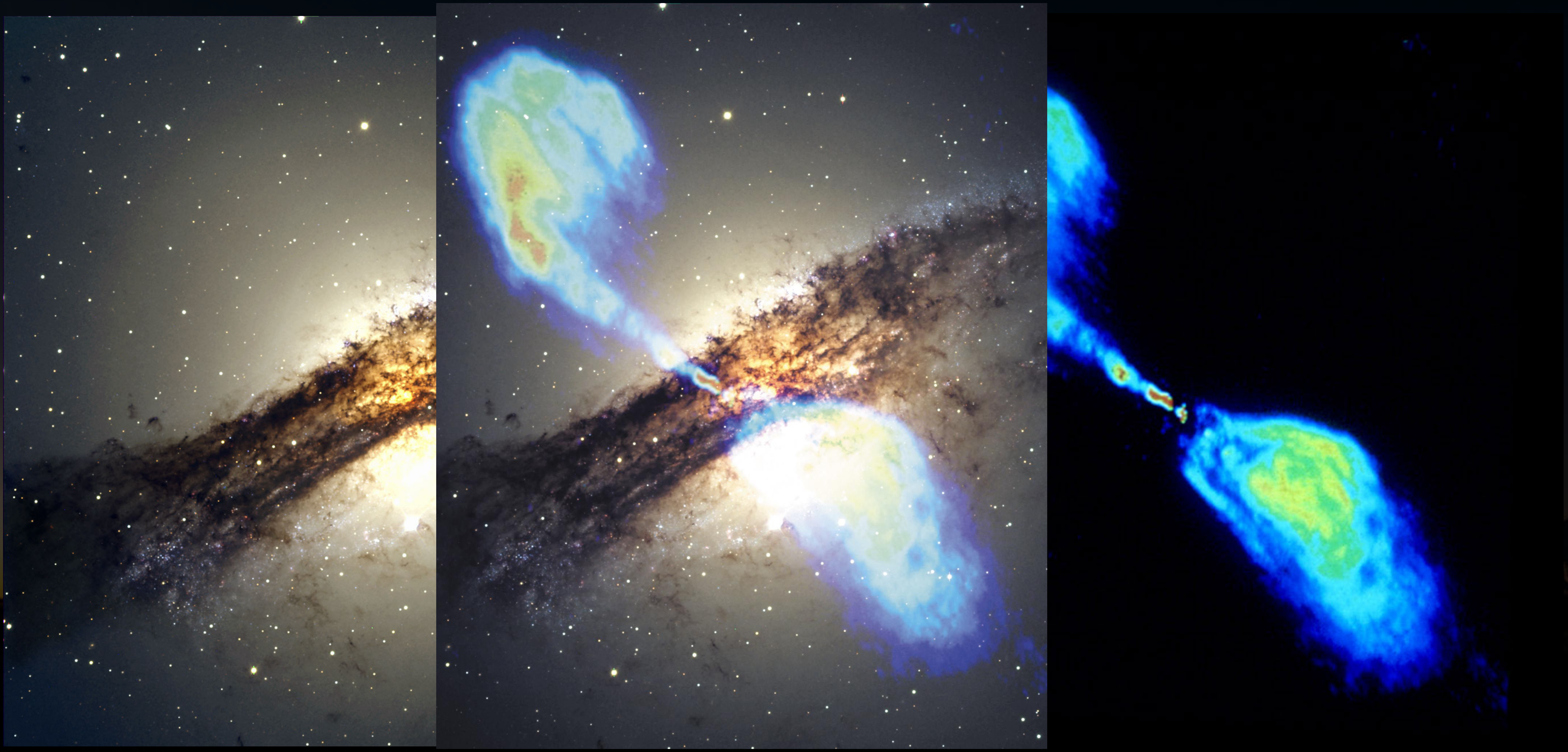

Sun





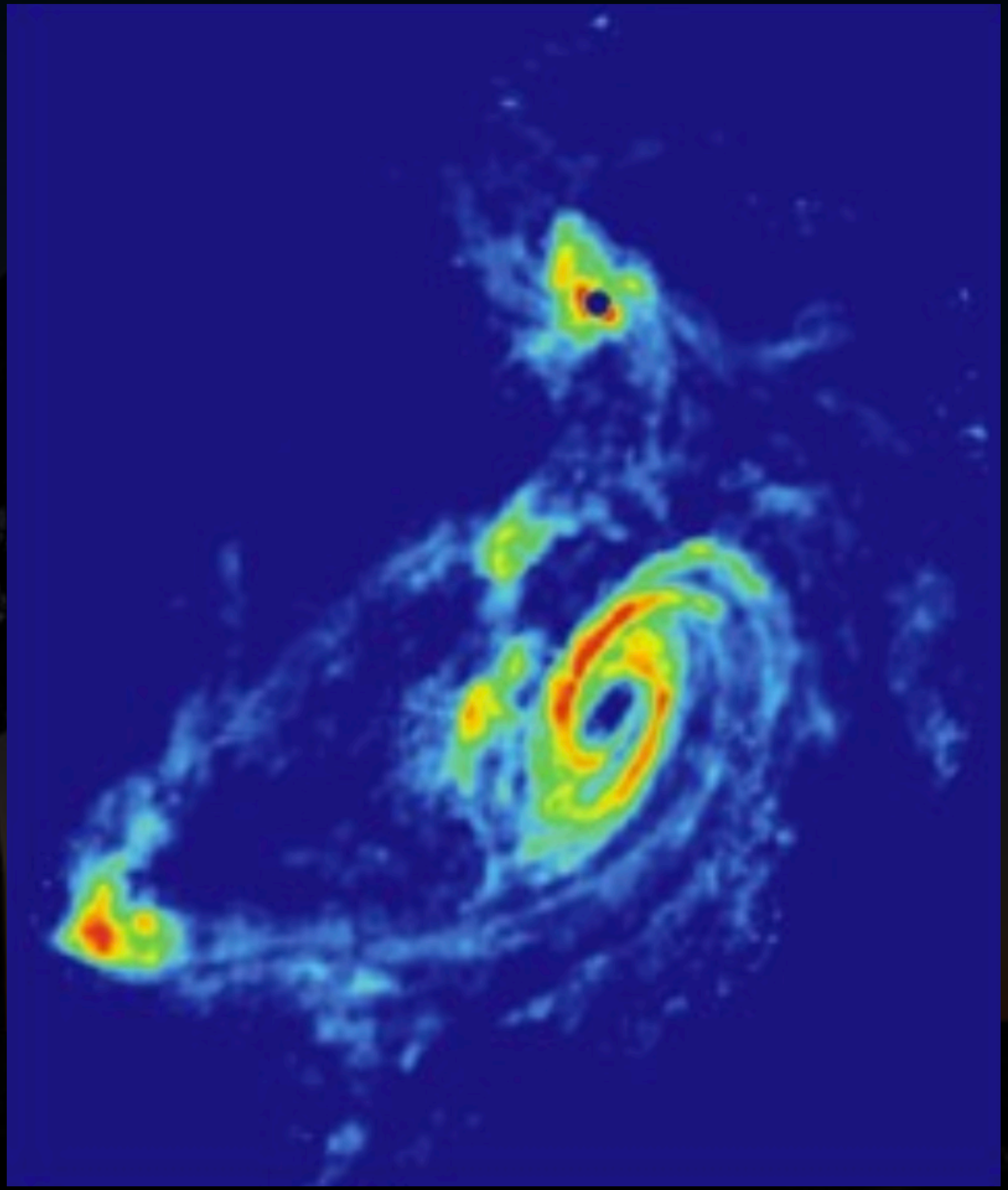


Incomplete picture without radio data….



Centaurus A galaxy

What do you see in the optical image?



How are radio emissions from astronomical objects produced?

Radio Emission Processes

- Electromagnetic emission can be divided into two types:

Continuum emission

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

Spectral line emission

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

$$B_\nu = \frac{2kT\nu^2}{c^2} = \frac{2kT}{\lambda^2} \qquad (h\nu \ll kT)$$

Radio Emission Processes

Radio astronomy is **cool** 😎

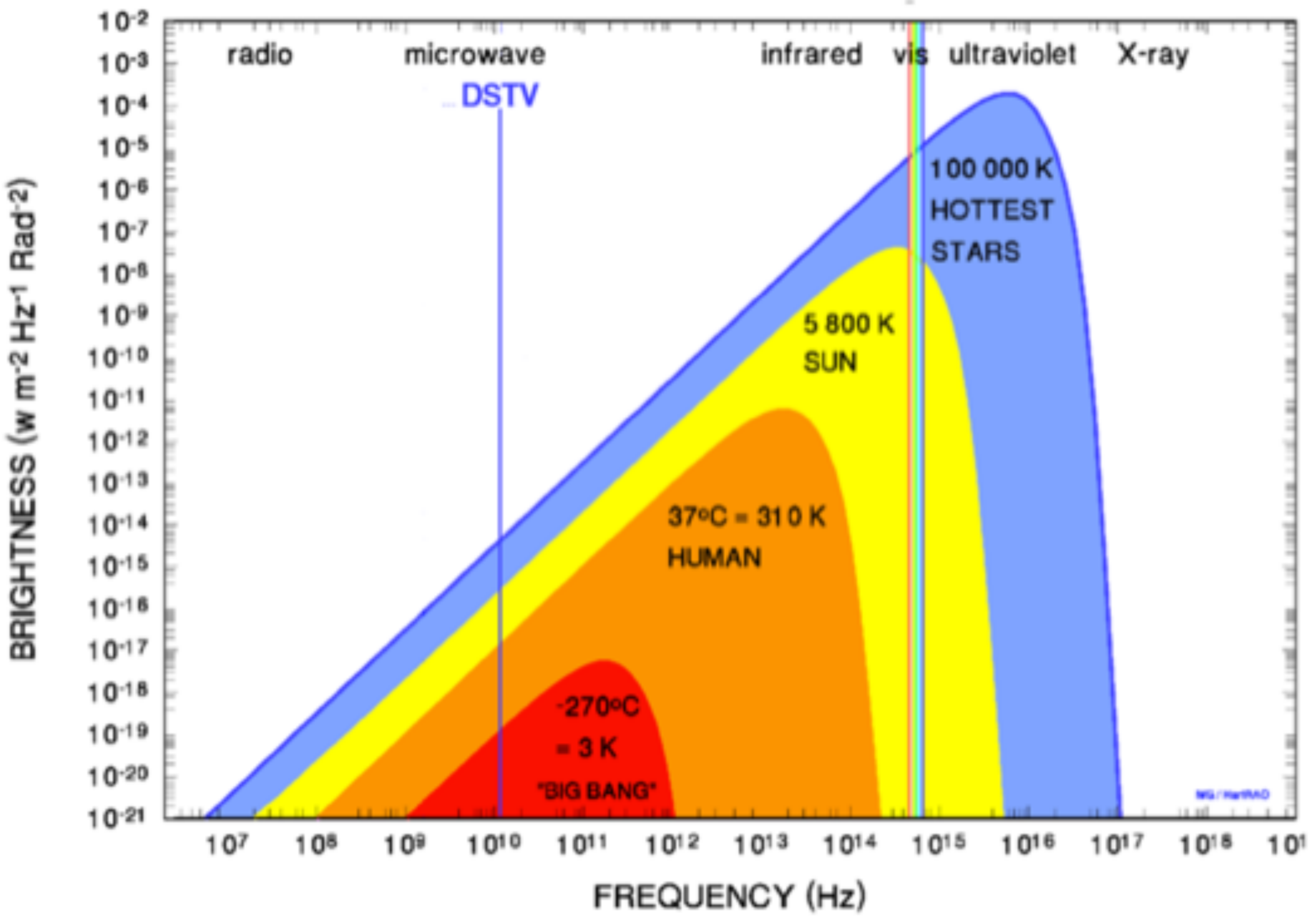
- Continuum emission

Thermal Emission

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

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

$$B_\lambda(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda k_B T}} - 1}.$$



Radio Emission Processes

- Continuum emission

Radio astronomy is **cool** 😎

Thermal Emission

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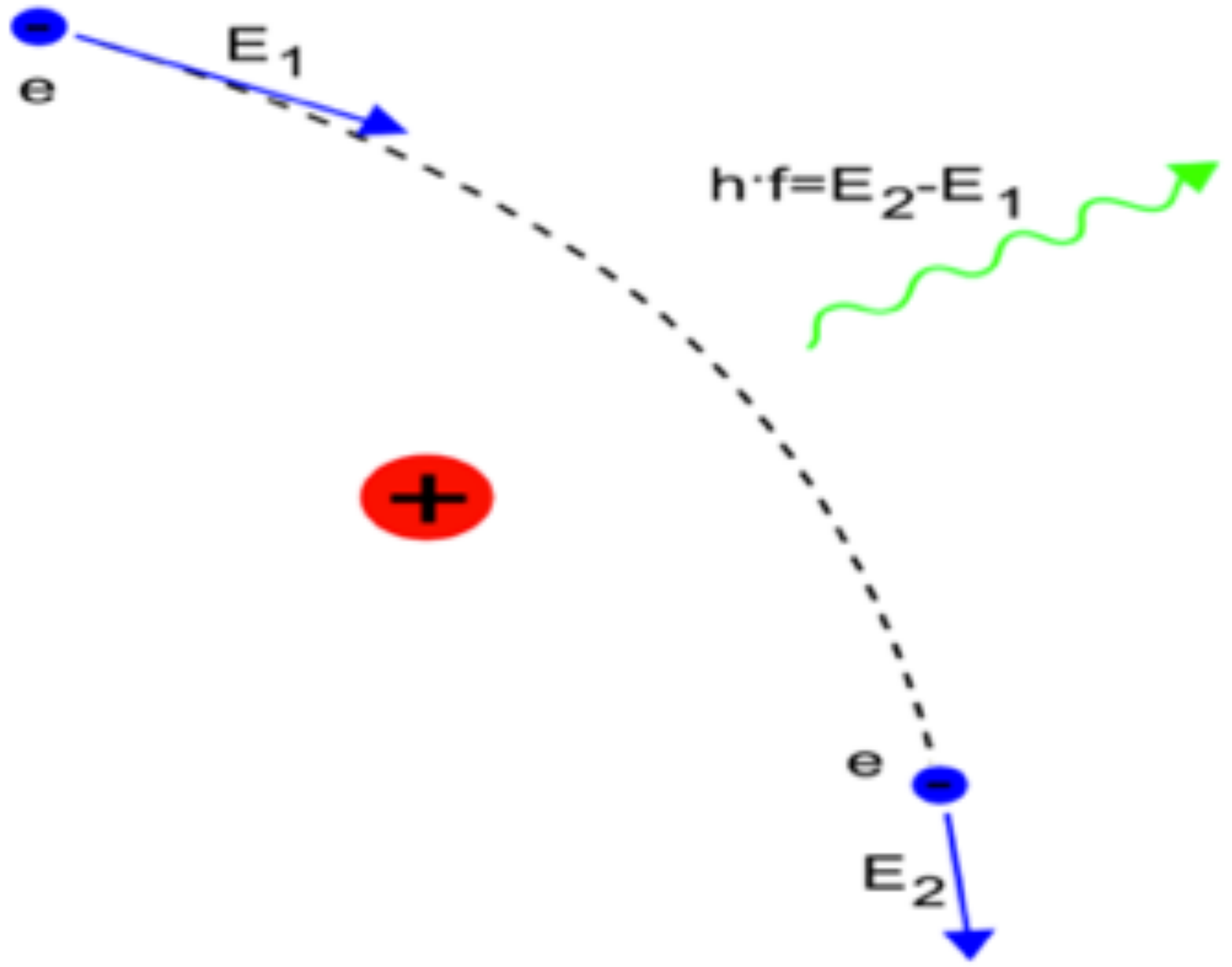
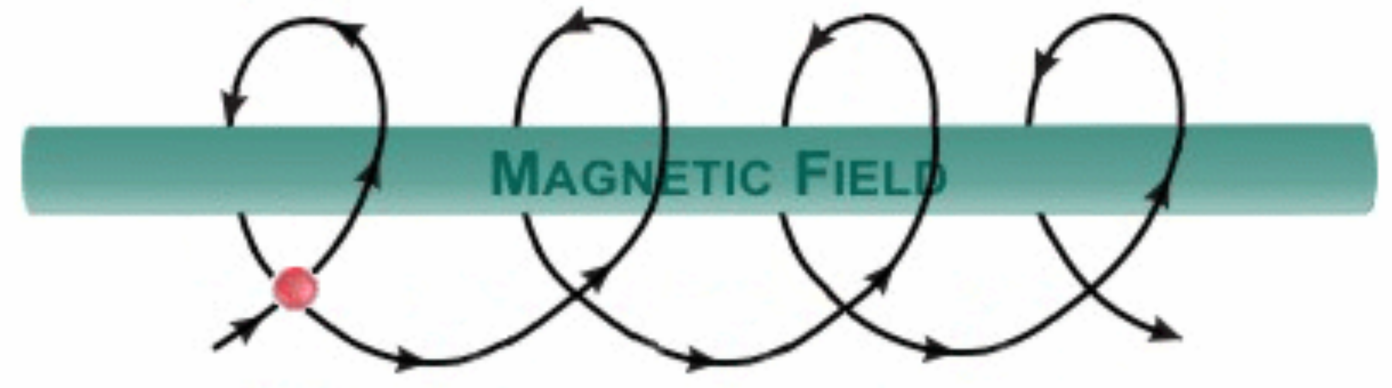


Radio Emission Processes

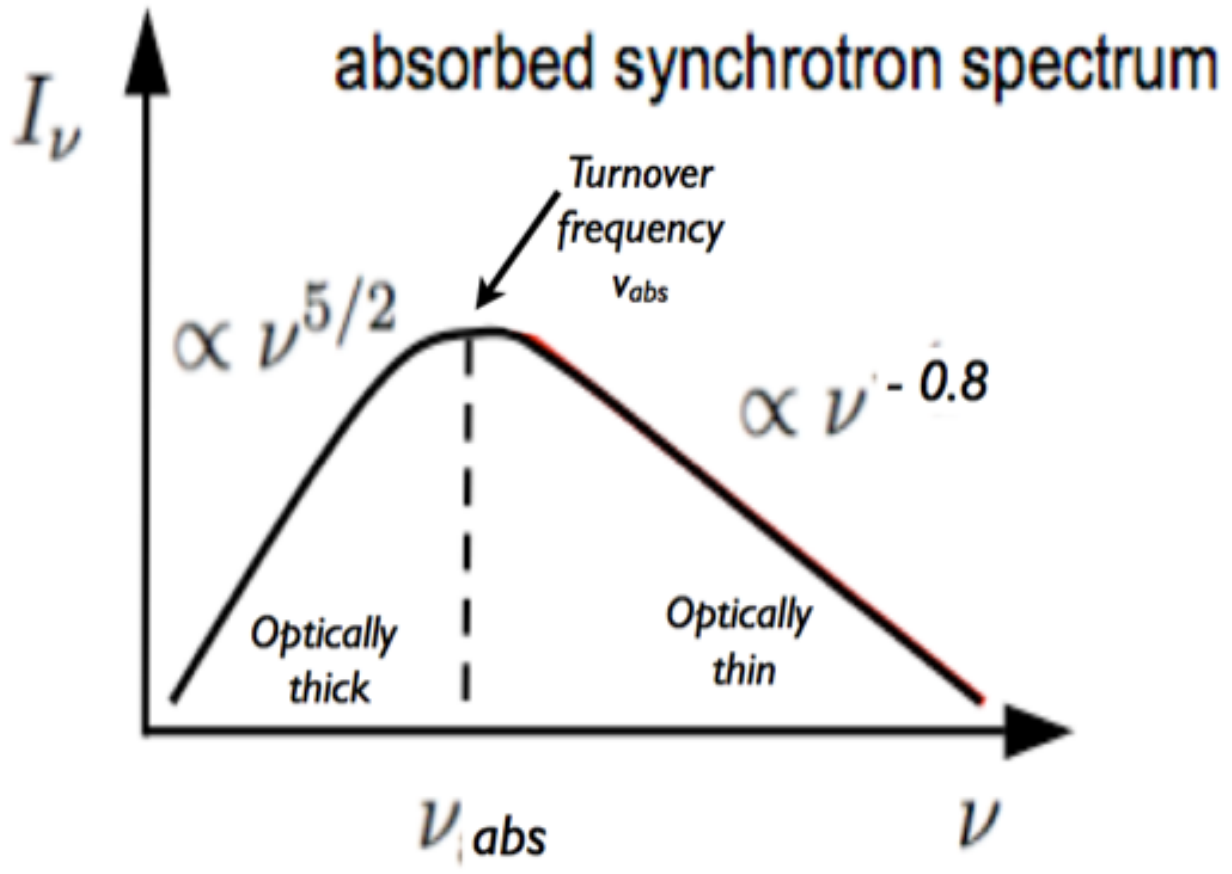
- Continuum emission



Non-thermal Emission

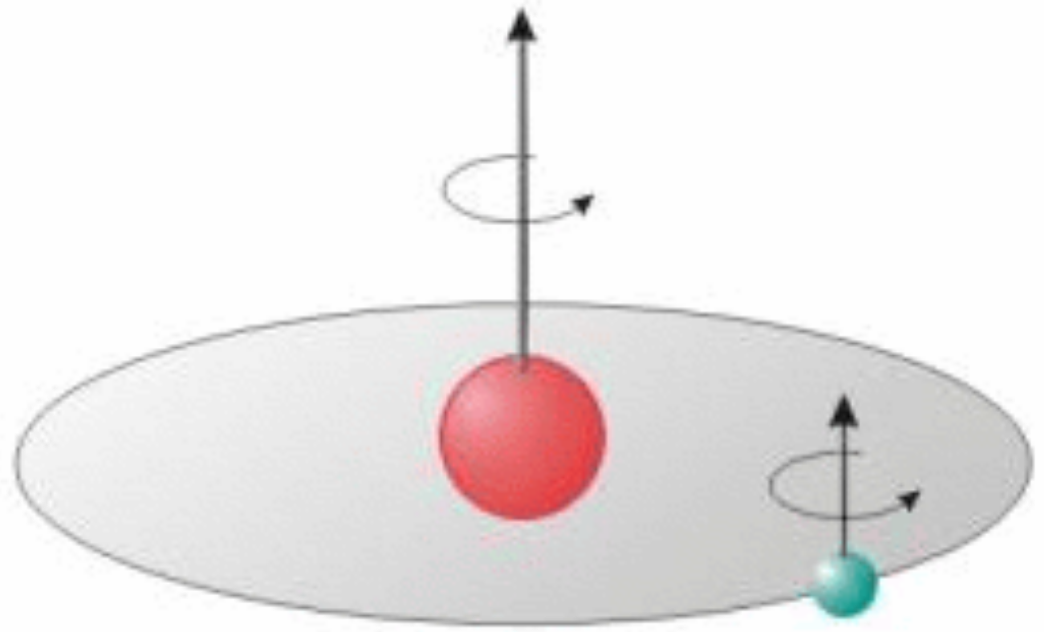
=> Synchrotron radiation: relativistic electrons spiraling around weak magnetic field lines.

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

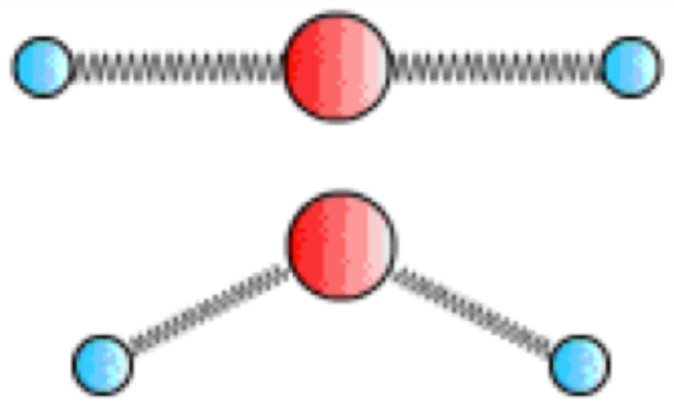


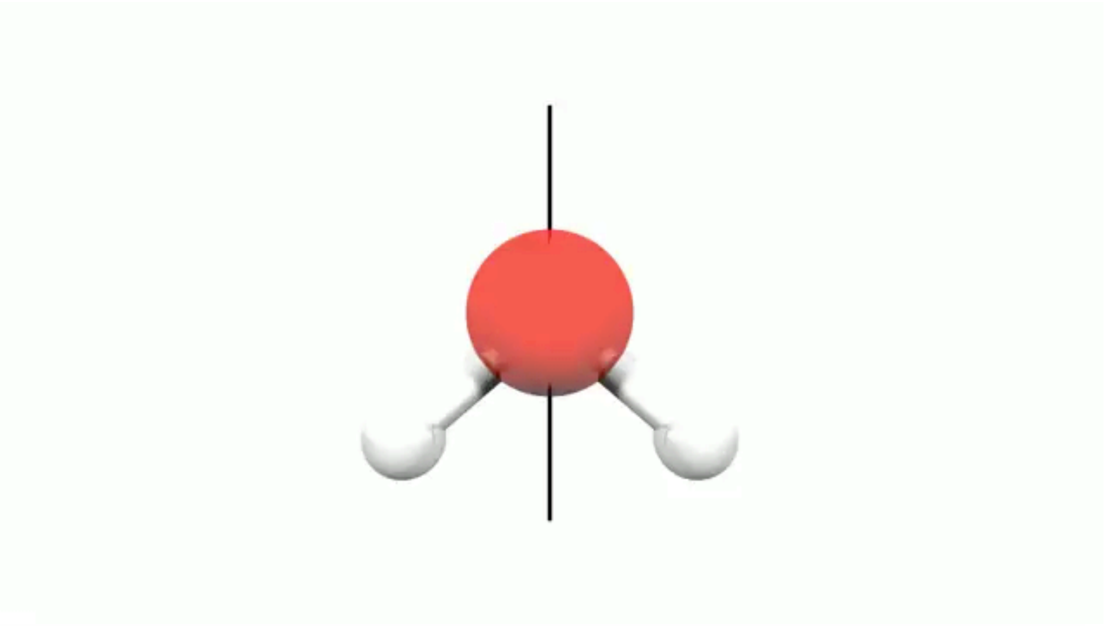
Radio Emission Processes

- Spectral Line Emission



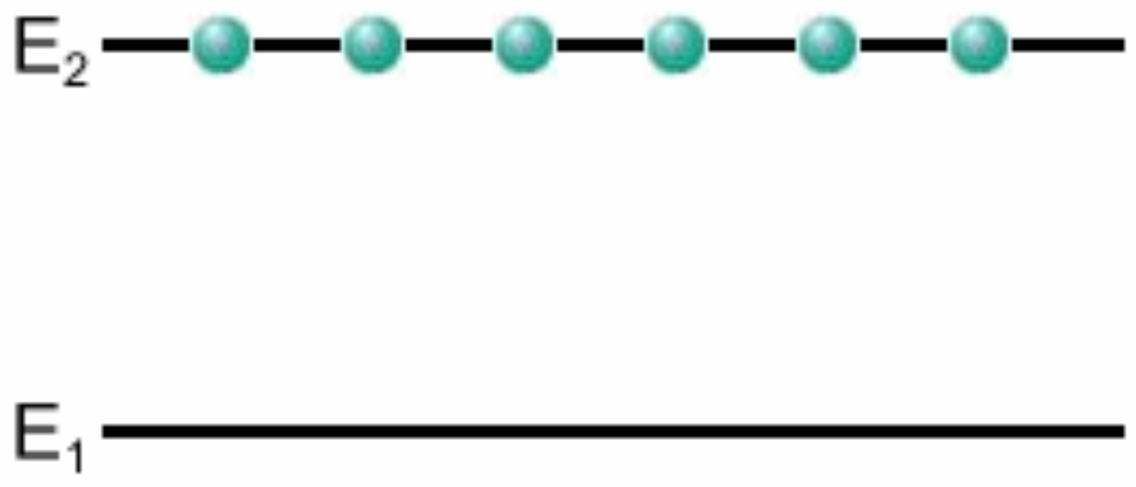
Neutral hydrogen HI (21 cm)
=> Most NB spectral line in the radio.
=> spin-flip transition between high-energy state and low-energy state of the H atom (aligned vs opposed spins for p+ and e-).
=> Although this transition is rare - there is just so much H in the ISM !

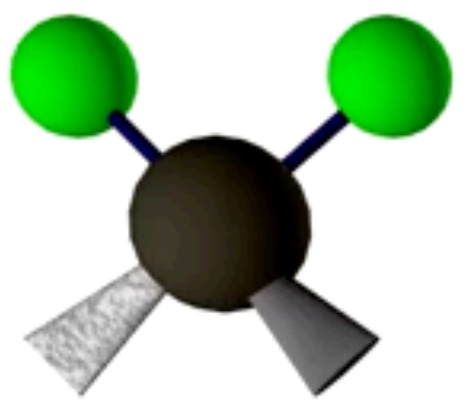




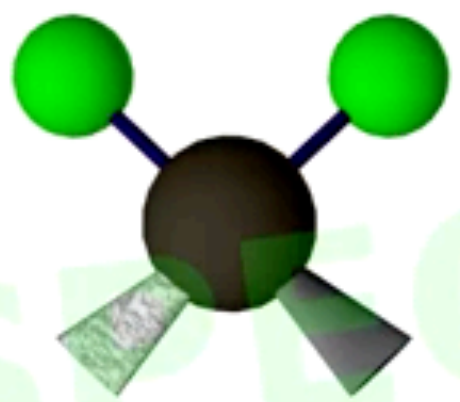
Molecular lines (CO, CS, CN,...)
=> Produced by changes in the vibrational or rotational states of their electrons (due to collisions or interactions)

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

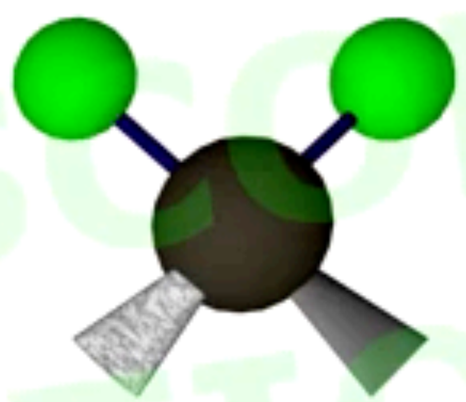




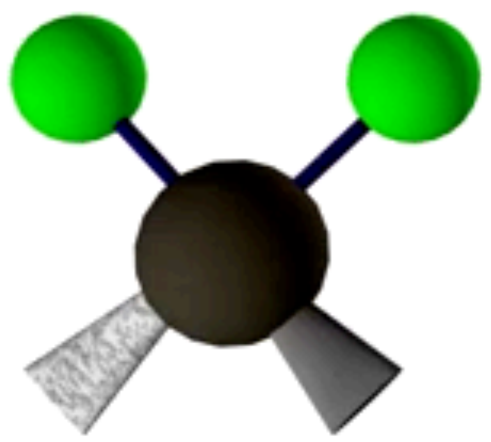
SYMMETRIC STRECHING



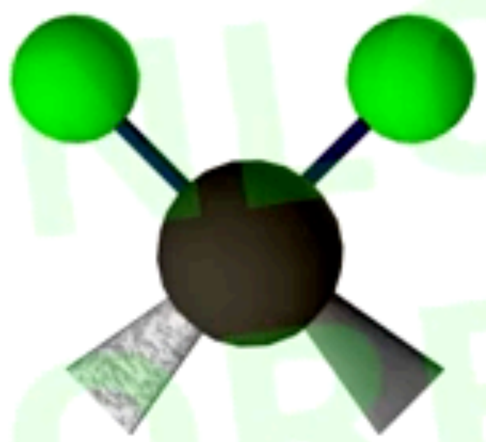
ANTISYMMETRIC STRECHING



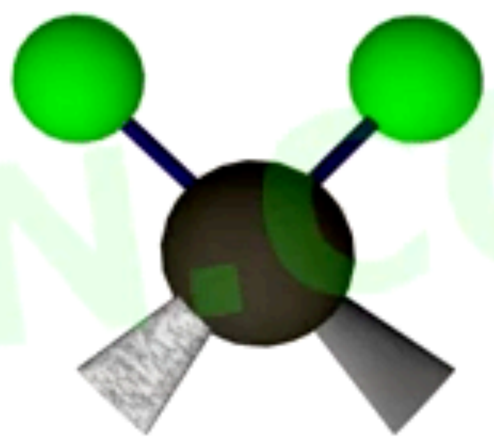
ROCKING



WAGGING



TWISTING



SCISSORING

INFRARED SPECTROSCOPY VIBRATIONS ANIMATION
DOWNLOAD AT CAPTAINCORROSION.COM

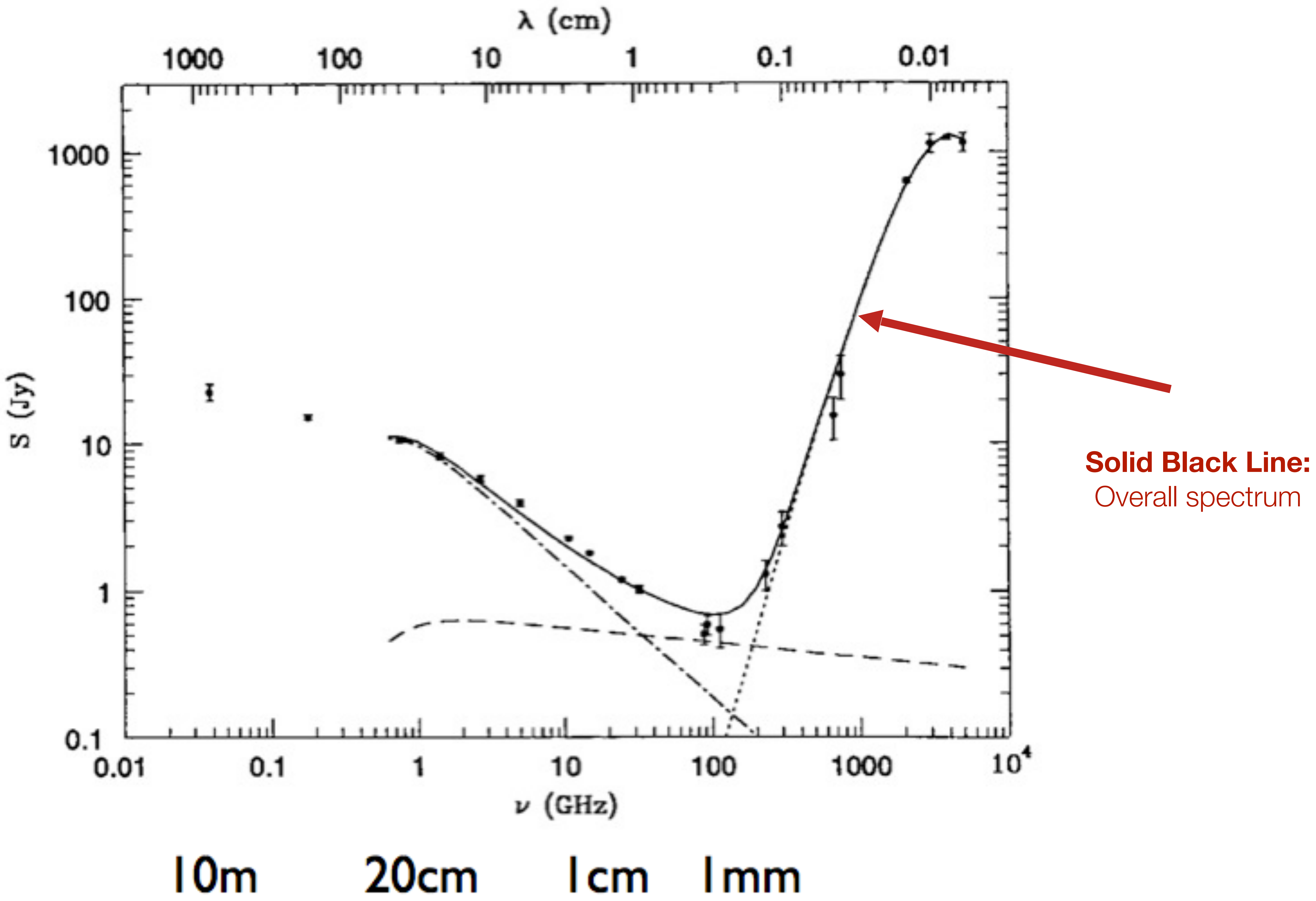
Radio Emission Processes

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

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

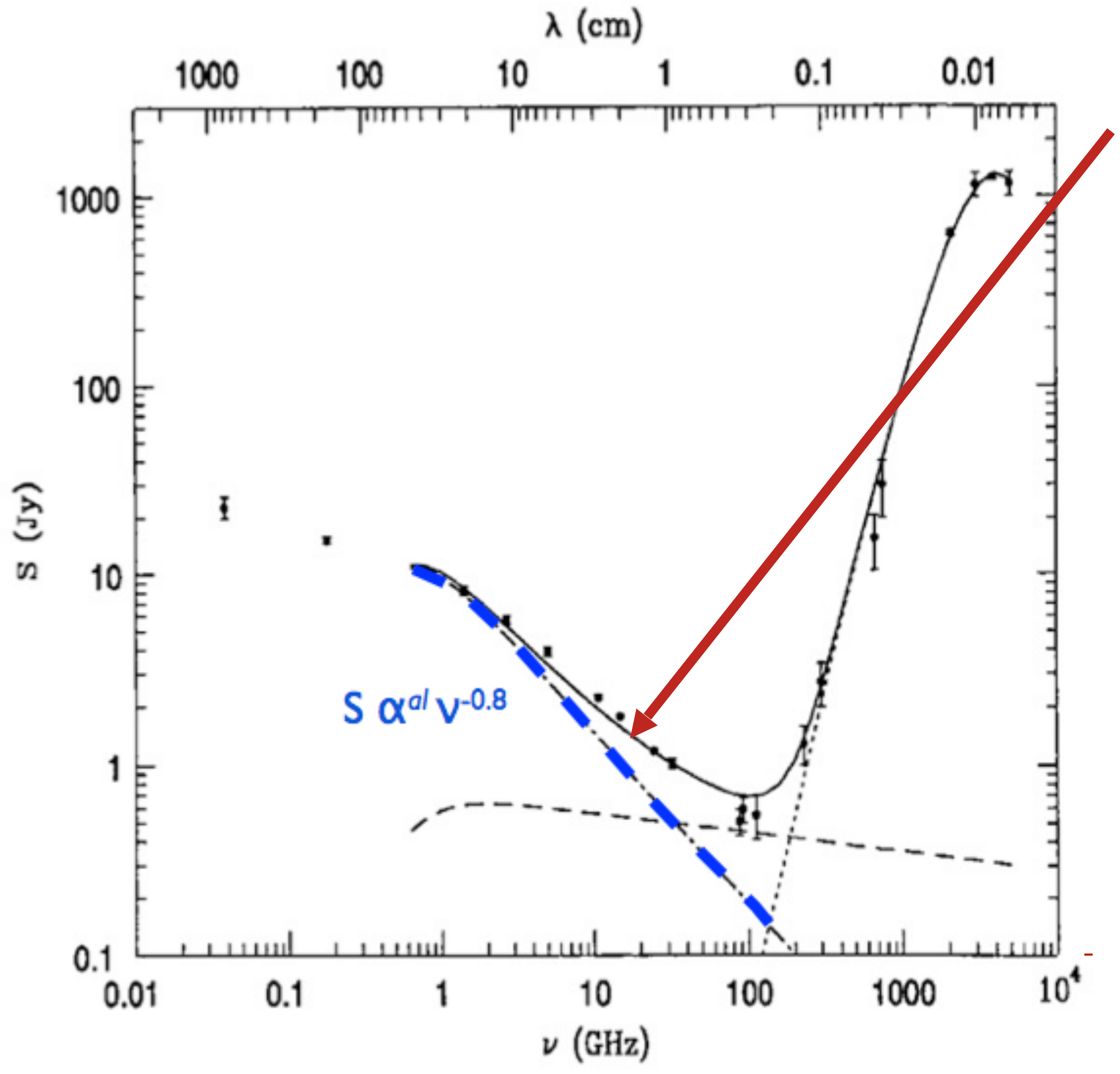
Radio Emission Processes

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



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

Radio Emission Processes

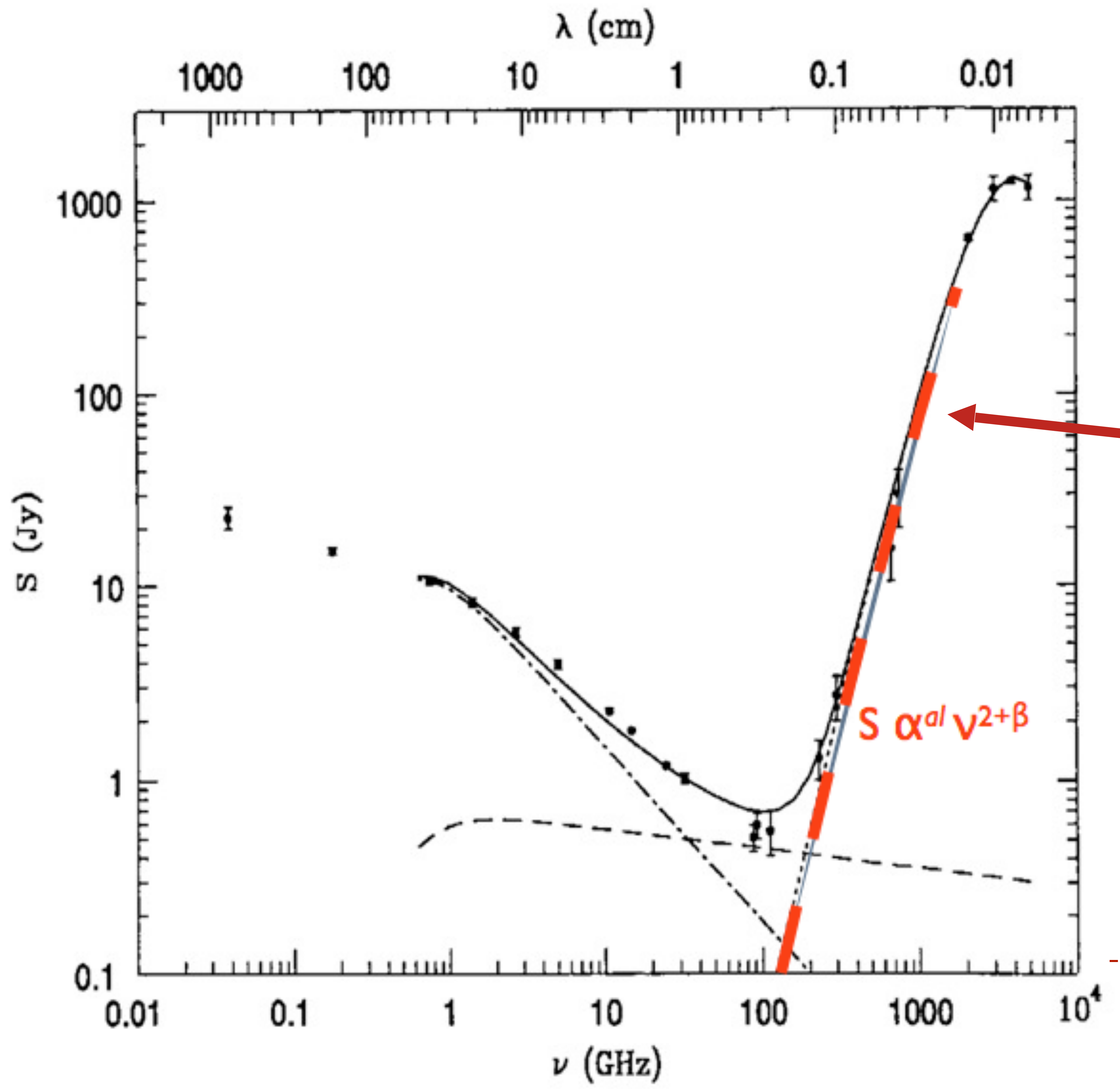


Blue Line is a steep spectrum.
synchrotron emission:

- cosmic ray electrons accelerated in M82's magnetic field.
- source of the cosmic ray

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

Radio Emission Processes

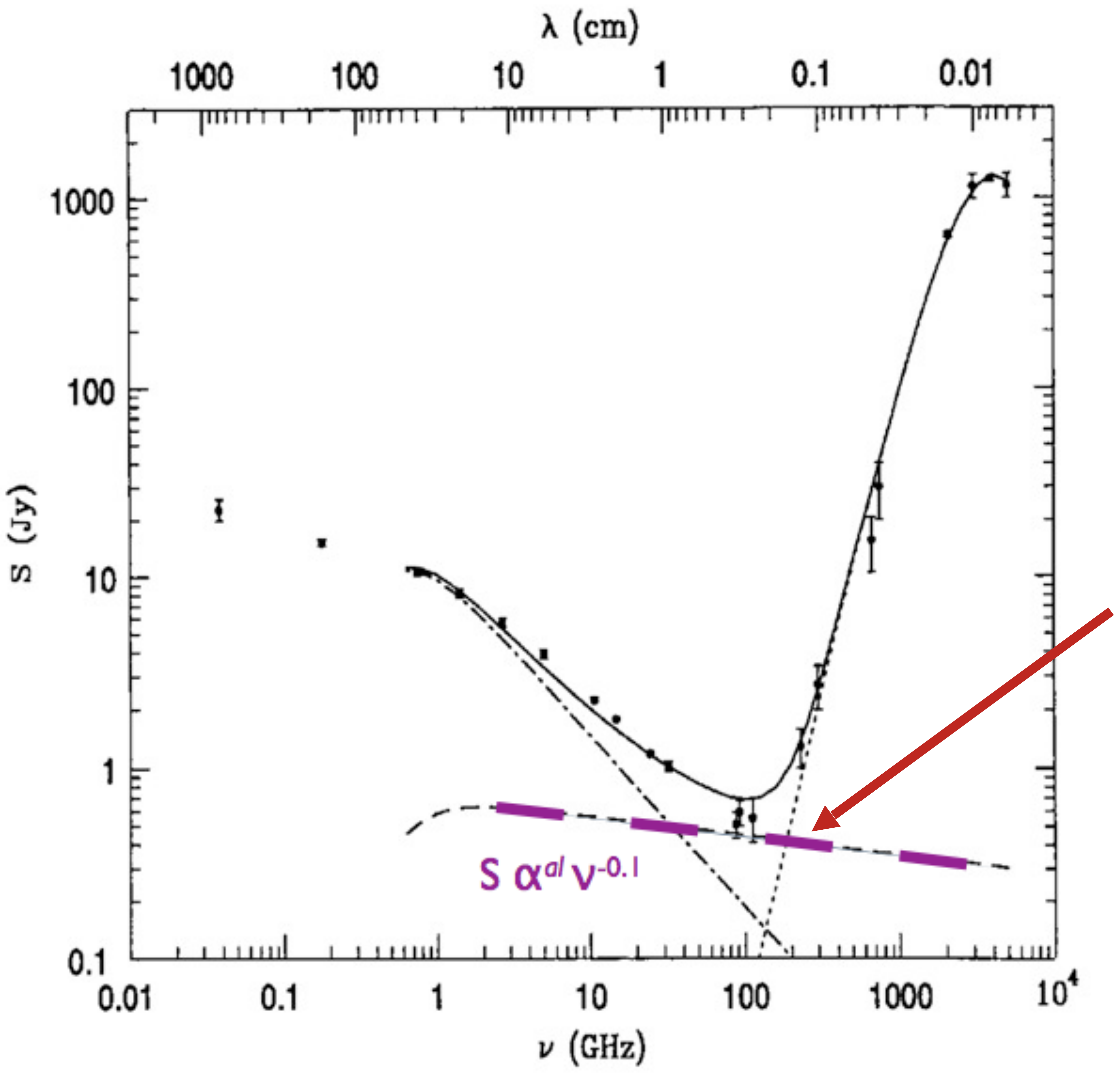


Credit: Prof. Mike Garrett (ASTRON/Leiden/Swinburne)Radio Astronomy course notes

Red line.
thermal BB emission:

- dust heated up by the uv-photons from massive stars.
The same stars that produced the supernovae

Radio Emission Processes



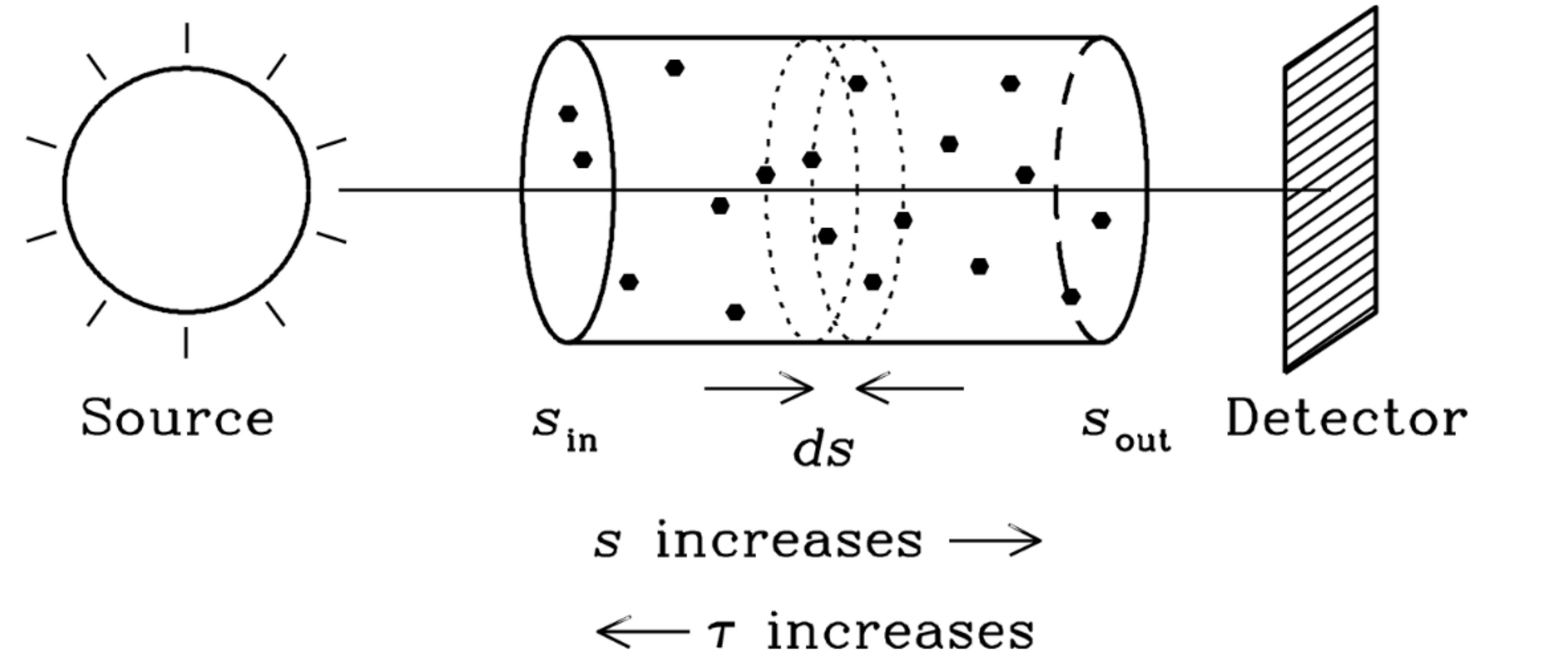
Credit: Prof. Mike Garrett (ASTRON/Leiden/Swinburne)Radio Astronomy course notes

Purple Line.
thermal free-free emission:

Propagation of radio waves

Radiative transfer

- Absorption coefficient
- Emission coefficient



Absorption coefficient:

$$\kappa \equiv \frac{dP}{ds} \qquad \frac{dI_\nu}{I_\nu} = -\kappa\, ds$$

$$\frac{I_\nu(s_{\text{out}})}{I_\nu(s_{\text{in}})} = \exp\left[-\int_{s_{\text{in}}}^{s_{\text{out}}} \kappa(s')\, ds'\right]$$

$$\tau \equiv -\int_{s_{\text{out}}}^{s_{\text{in}}} \kappa(s')\, ds' \quad \text{so} \quad \frac{I_\nu(s_{\text{out}})}{I_\nu(s_{\text{in}})} = \exp(-\tau)$$

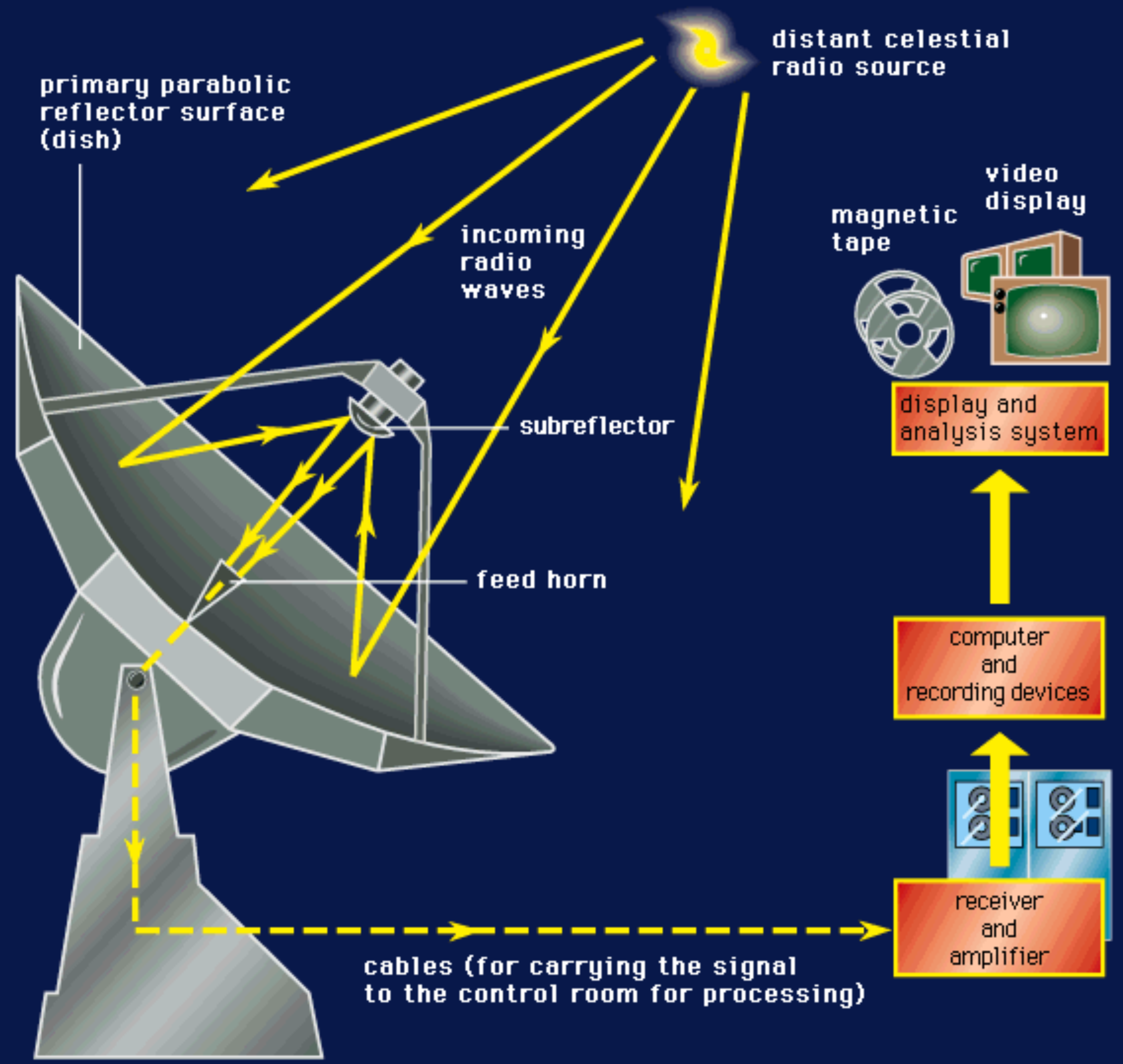
Emission coefficient

$$j_\nu \equiv \frac{dI_\nu}{ds}$$

Radiative transfer equation

$$\frac{d\,I_\nu}{ds} = -\kappa I_\nu + j_\nu$$

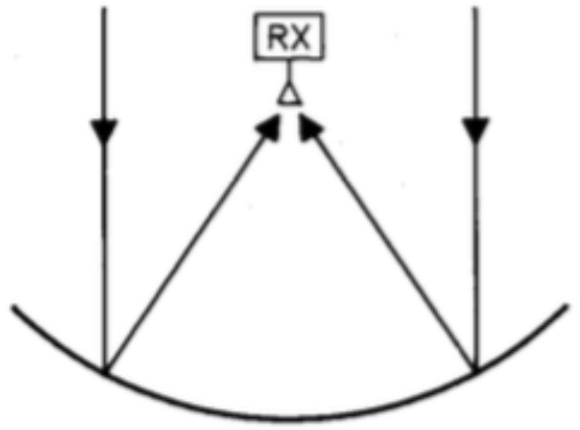
How radio telescopes work?



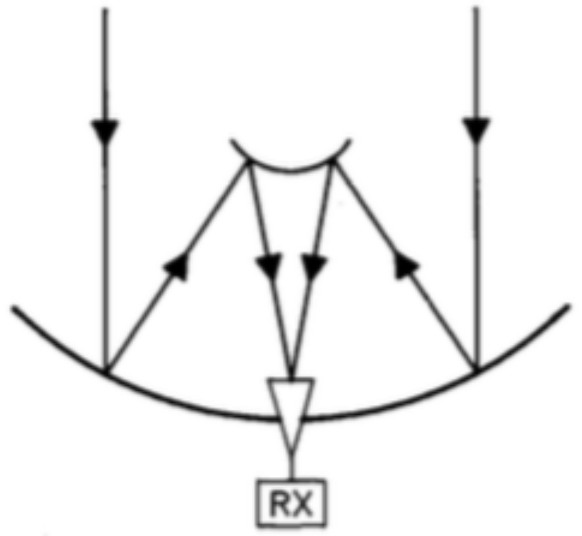
Reflector antennas

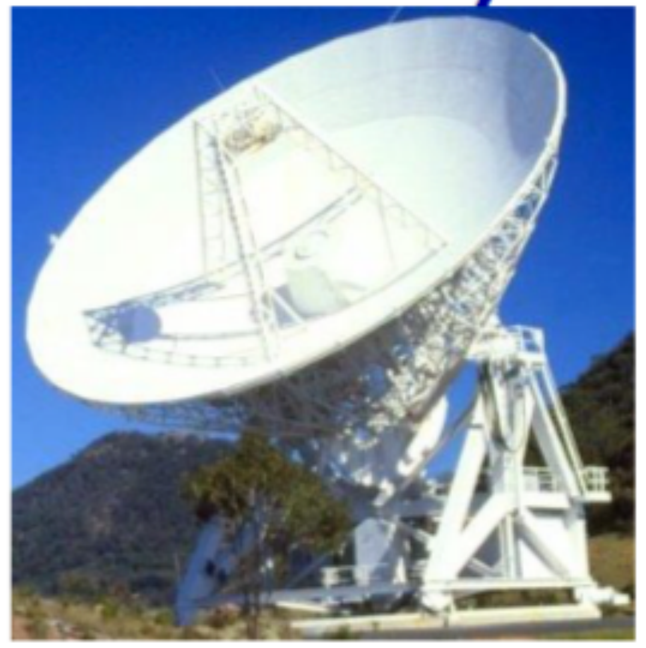
GMRT

Prime Focus



On-axis Cassegrain (best for array receivers)

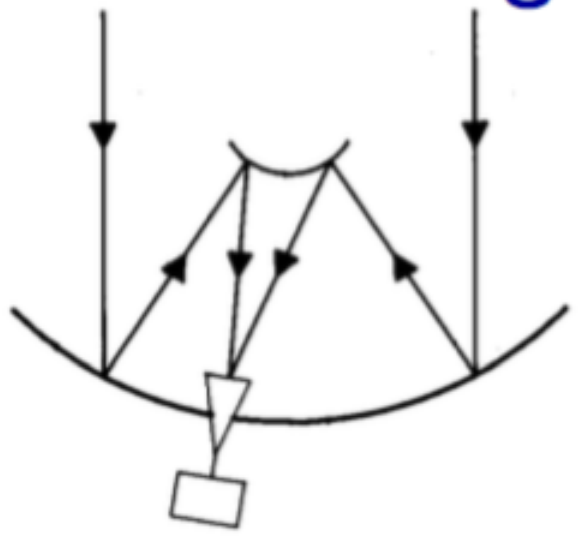




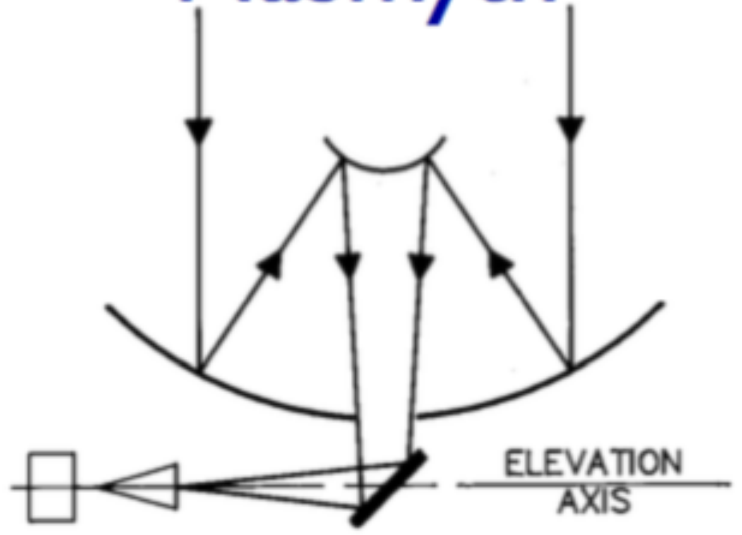
ATCA, Mopra

VLA, ALMA

Offset Cassegrain



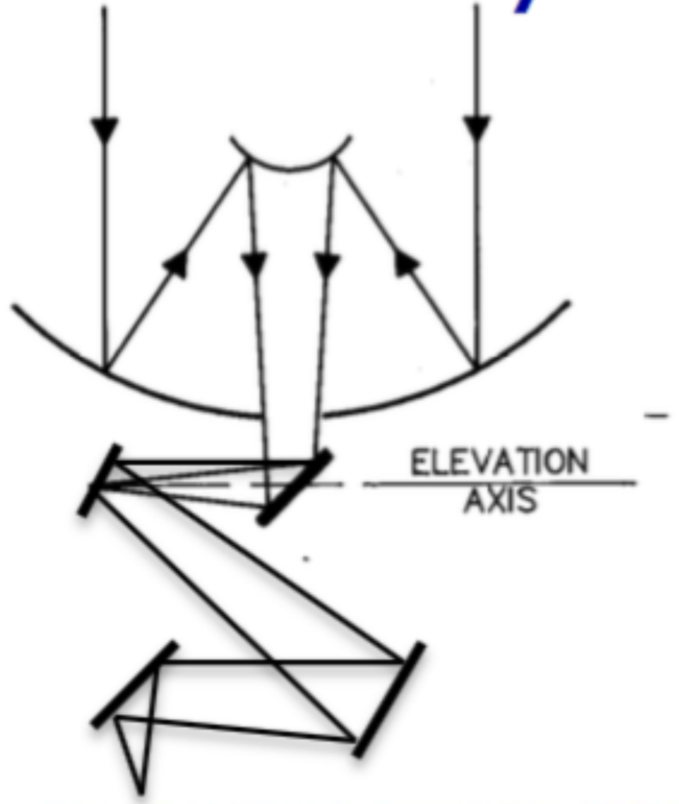
Nasmyth



CARMA, CSO

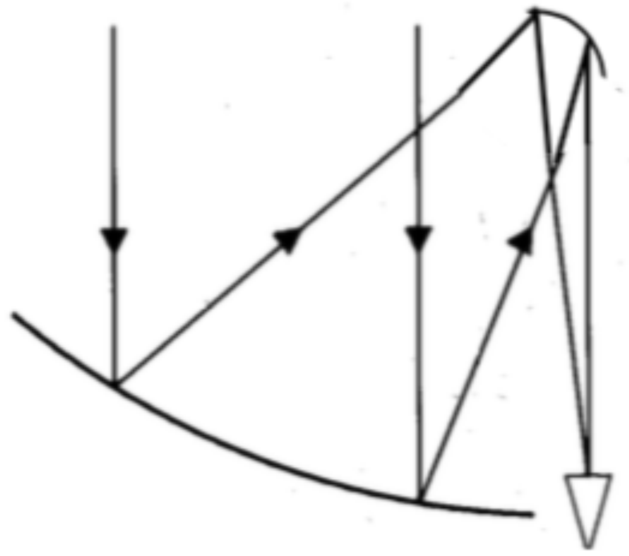
SMA

Bent Nasmyth



Receivers do not tilt in elev.

Dual offset Gregorian

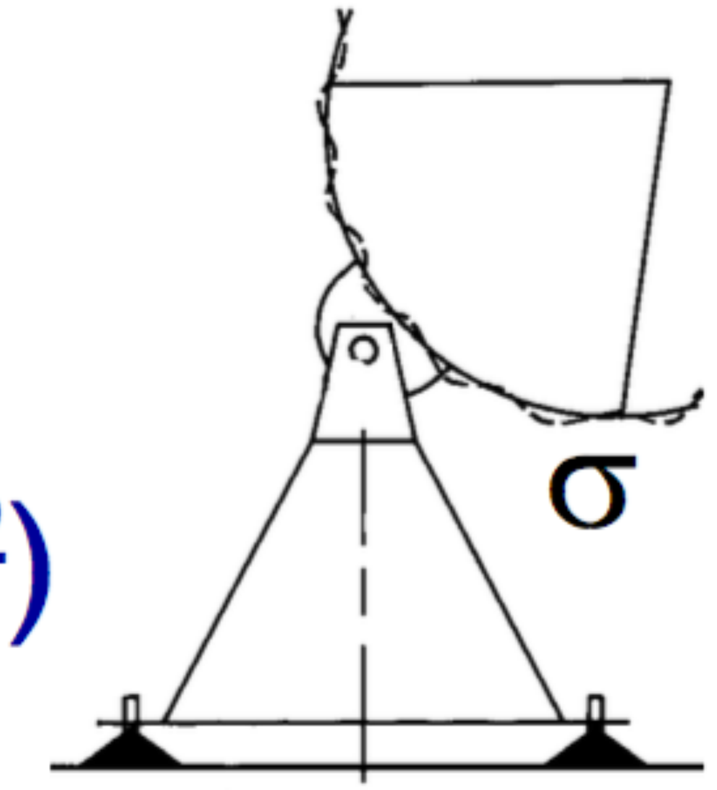


GBT

Cleanest beam, minimizes standing waves, polarization asymmetry compensated -- Mizugutch et al. (1976)

NRAO

Reflector antenna efficiencies



Response pattern (primary beam): $\boldsymbol{A}(\nu,\theta,\phi) = A(\nu,\theta,\phi)/A_0$

Effective area (on-axis): $A_0=\eta A=$(aperture efficiency)(πR^2)

where $\eta = \eta_{surface}\eta_{blockage}\eta_{spillover}\eta_{taper}\eta_{radiation}\eta_{misc}$

$\eta_{surface} = \exp(-(4\pi\sigma/\lambda)^2)$ σ = rms surface error (Ruze 1966)

= 0.44 for $\sigma = \lambda/14$ (VLA at 43 GHz) σ_{VLA}~500μm

= 0.79 for $\sigma = \lambda/26$ (VLA at 22 GHz) σ_{ALMA}~25μm

$\eta_{blockage}$ = blockage efficiency (feed legs and subreflector)

$\eta_{spillover}$ = feed spillover efficiency

η_{taper} = feed taper efficiency

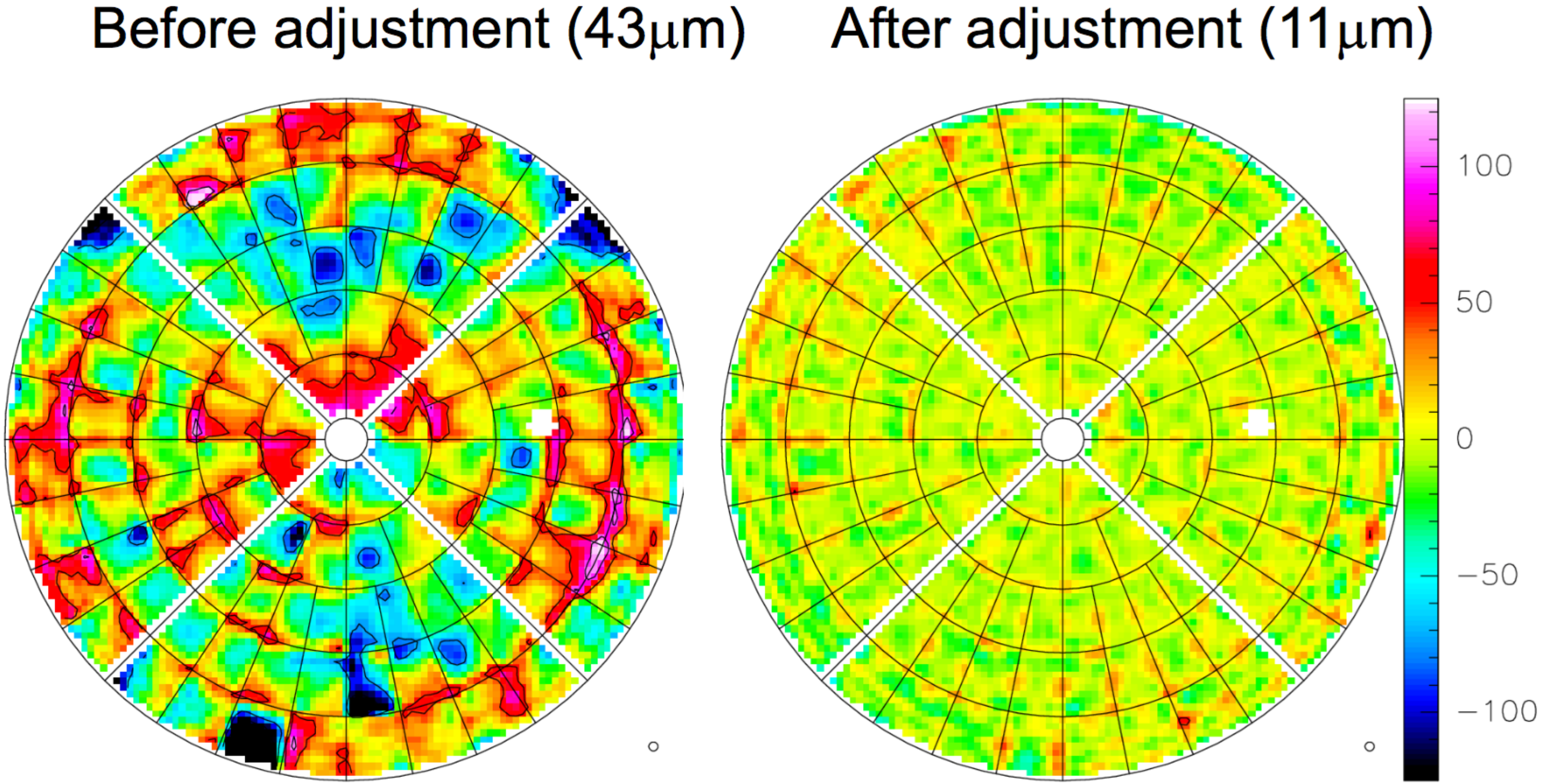
} $\eta_{illumination}$=0.8 for -10dB taper

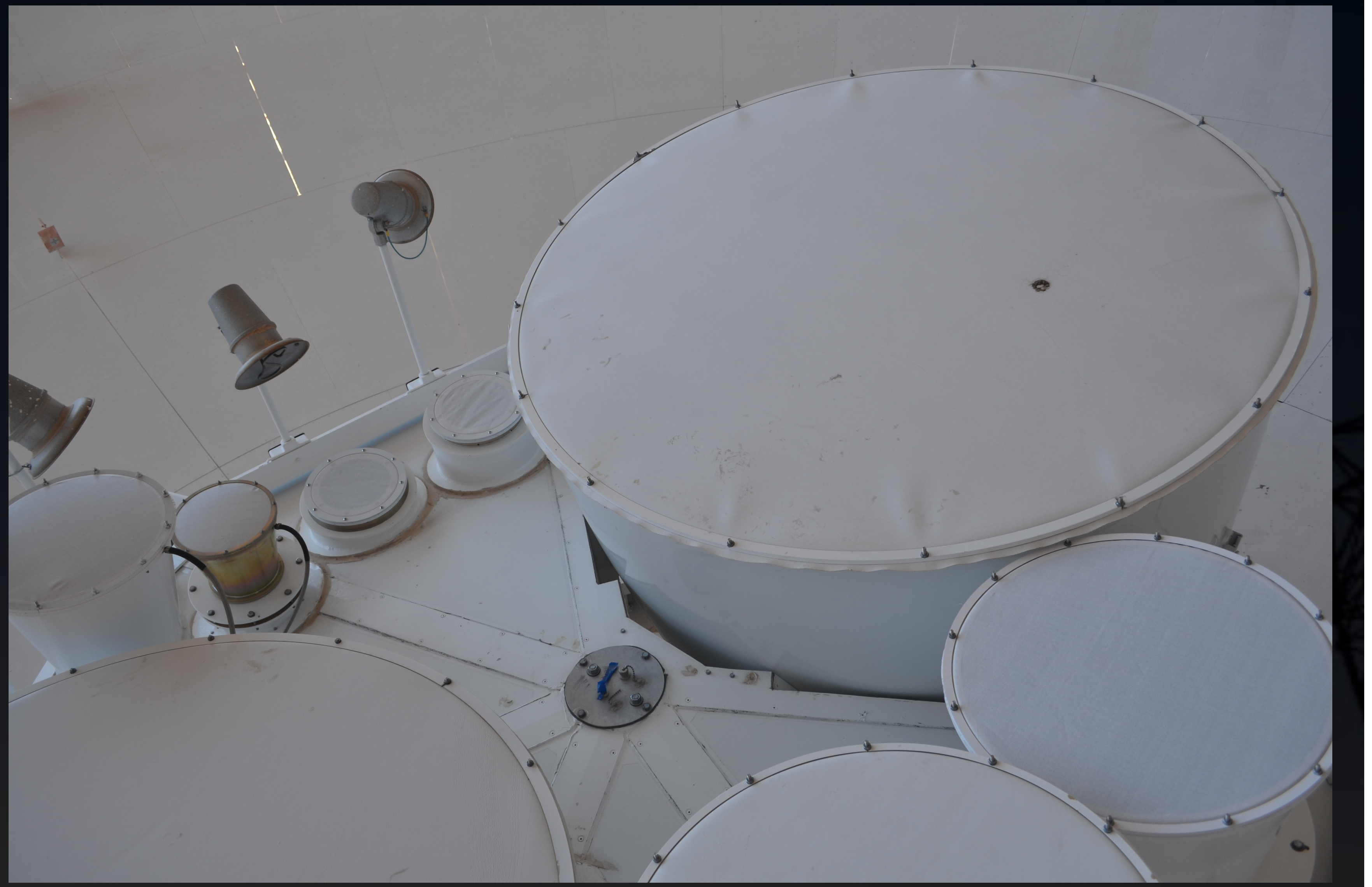
$\eta_{radiation}$ = metal reflection efficiency (~0.99 per Al mirror)

η_{misc}= diffraction, phase, focus error, polarization efficiencies

Holography: ALMA surface panel adjustment

Phase map converted to path length error from ideal paraboloid

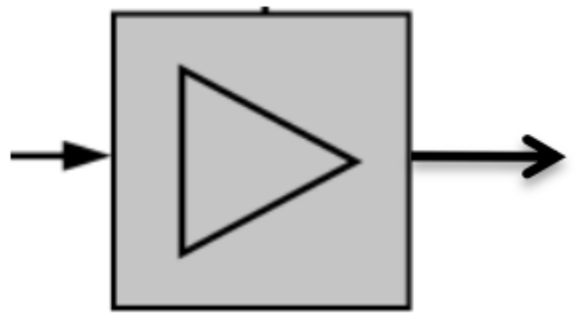




Amplifiers and mixers

Let's compare an amplifier and a mixer:

1. Amplifiers are <u>2-port</u> devices: one input and one output

IN  OUT (10-30dB stronger, same frequency)

Example: NRAO Cryogenic Low Noise Amplifiers (LNAs) using Heterostructure Field Effect Transistors (HFETs) used on the VLA, VLBA, GBT:

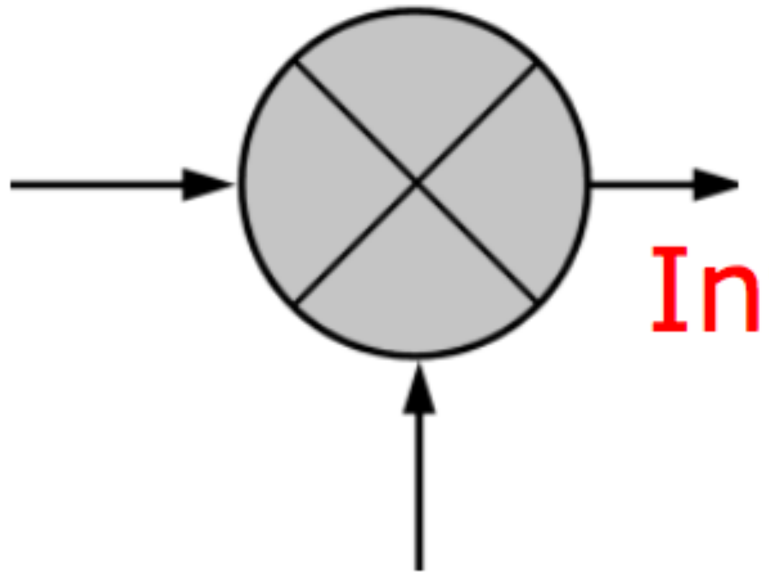
- Operate at ~15 K
- Tnoise ~ 5 hf/k
  (i.e. 5 x quantum limit)
- M. Pospieszalski (2012) (MIKON conference)

What is a mixer?

Mixers are 3-port devices: LO and RF inputs, and IF output.

- Invented around WWI for radio direction finding (see IEEE Microwave Magazine Sept. 2013 special issue).
- They multiply the LO & RF signals and transfer the phase from the RF to the IF by "heterodyning". Typically the IF contains signals from two sidebands.
- They are key components for interferometers!!

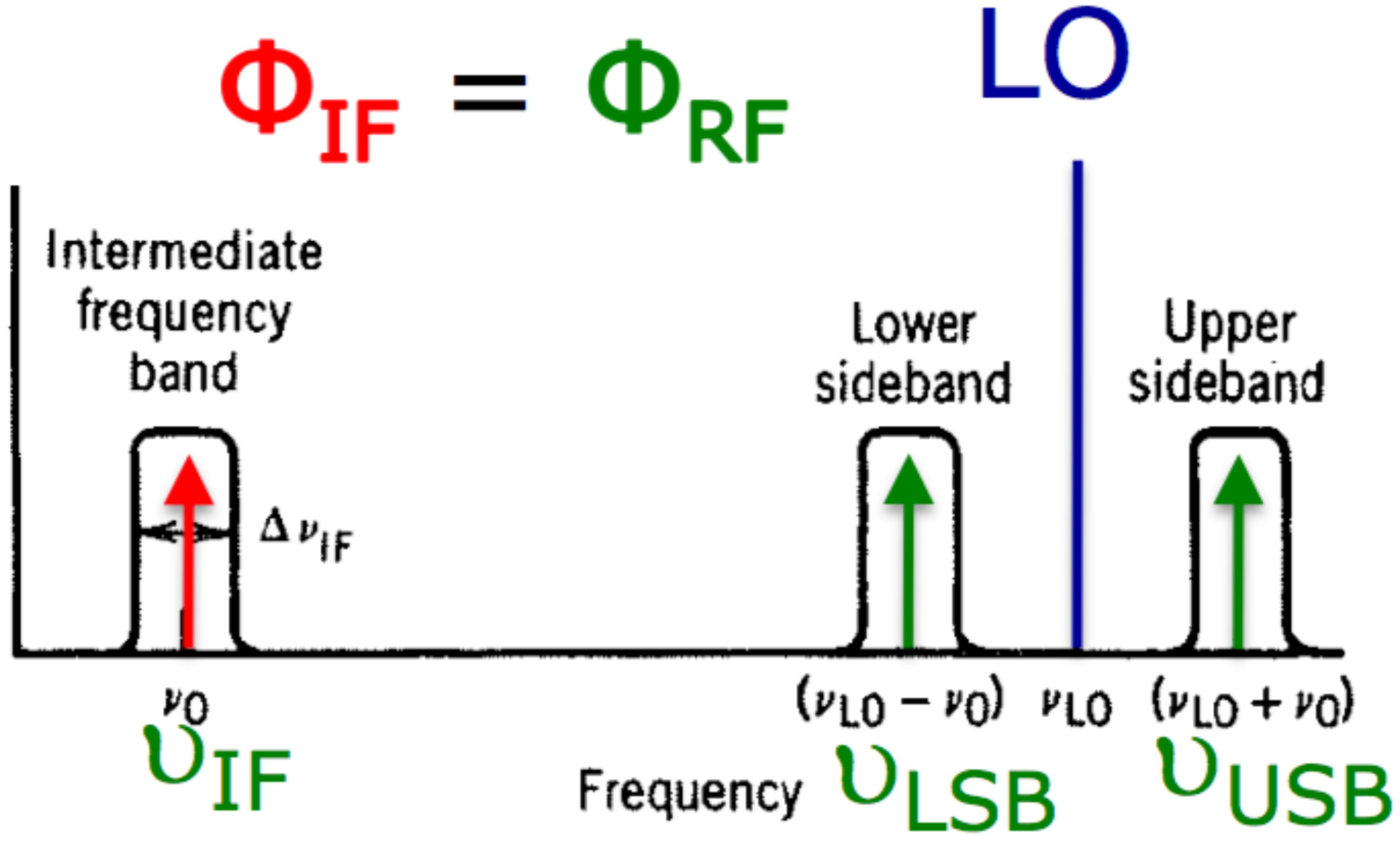
RF input = "Radio" Frequency



IF output = Intermediate Freq.

LO = Local Oscillator

$\Phi_{IF} = \Phi_{RF}$



$$\sin(2\pi f_1 t)\sin(2\pi f_2 t) = \frac{1}{2}\cos[2\pi(f_1 - f_2)t] - \frac{1}{2}\cos[2\pi(f_1 + f_2)t]$$

Calibrating single-dish telescope data

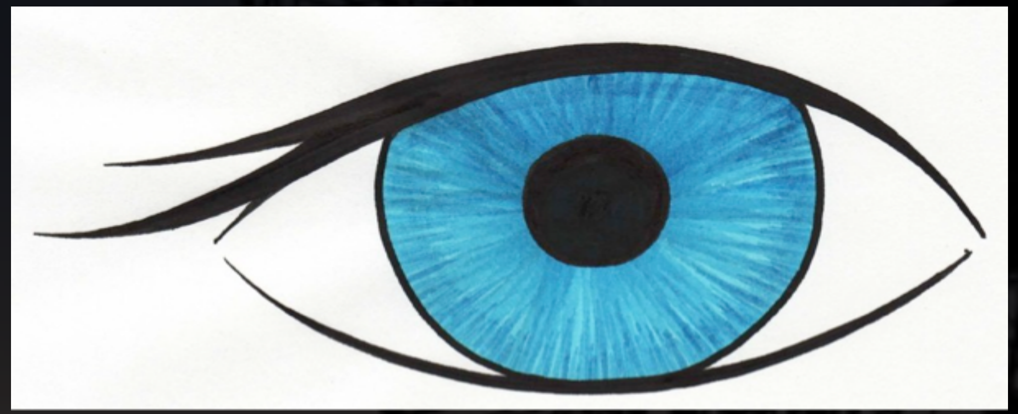
- Convert from power densities to antenna temperatures
- Correct bandpass and pointing errors
- Derive Kelvin to Jansky conversion factor
- Apply to target

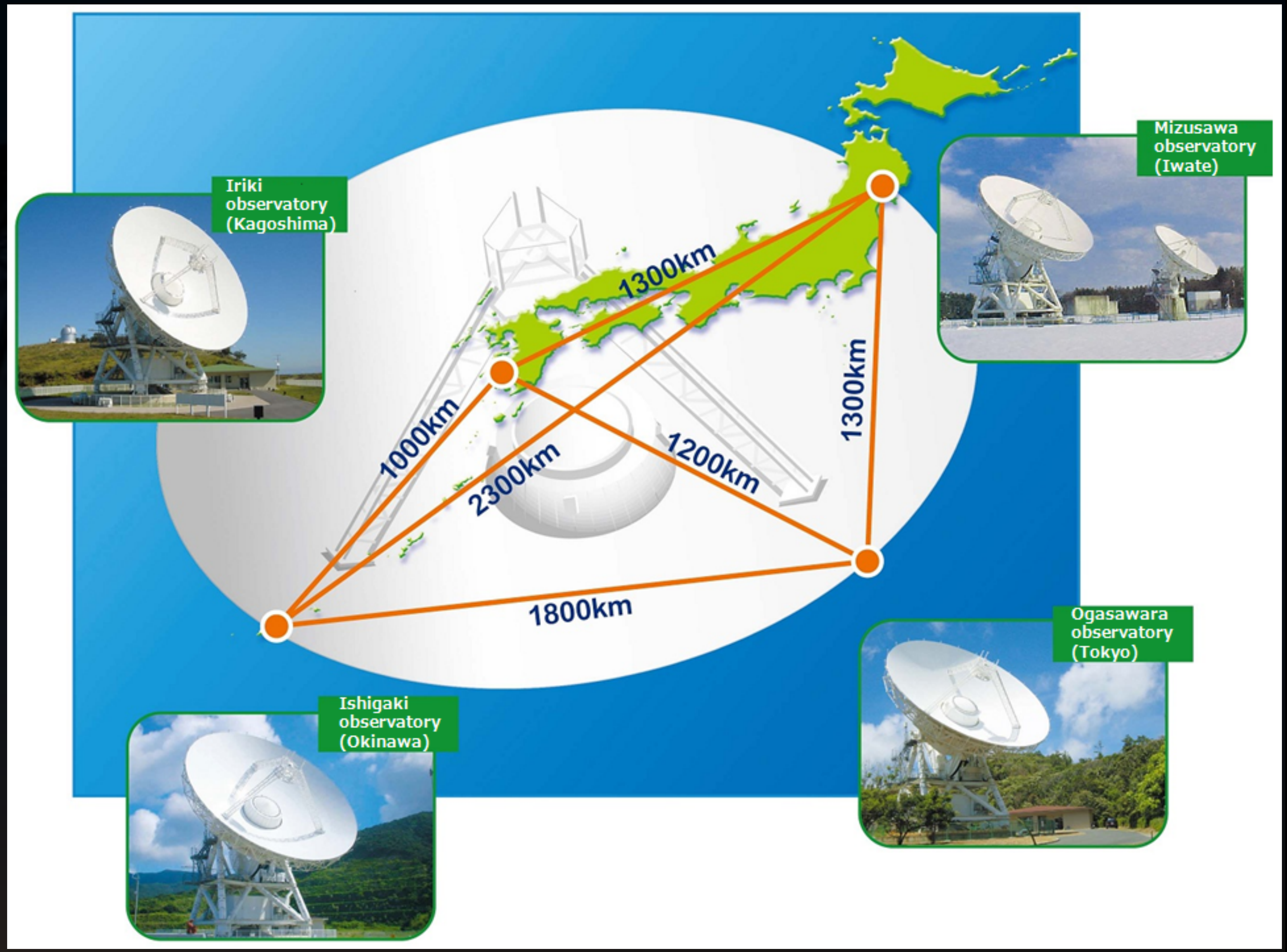
$$T_{\rm s} = T_{\rm cmb} + T_{\rm rsb} + \Delta T_{\rm source} + [1 - \exp(-\tau_{\rm A})]T_{\rm atm} + T_{\rm spill} + T_{\rm r} + \cdots$$

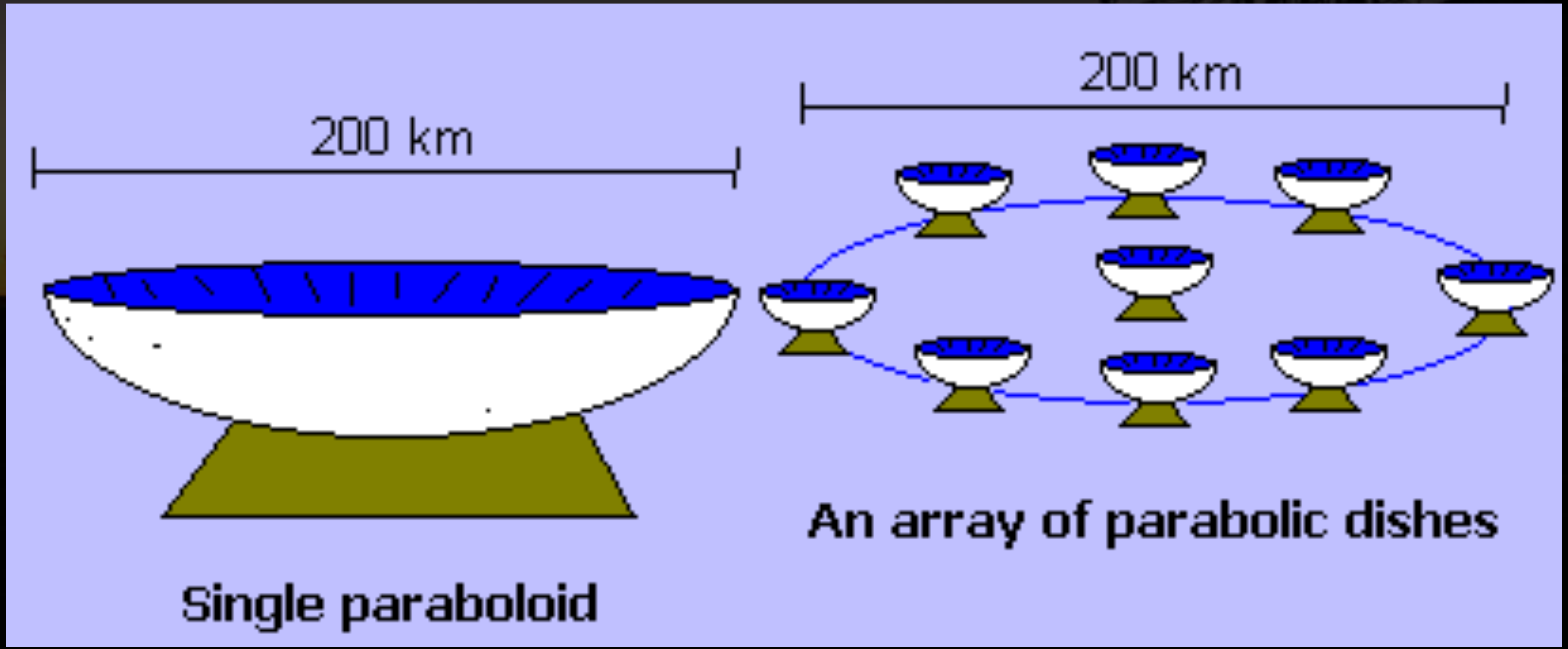
Radio interferometry

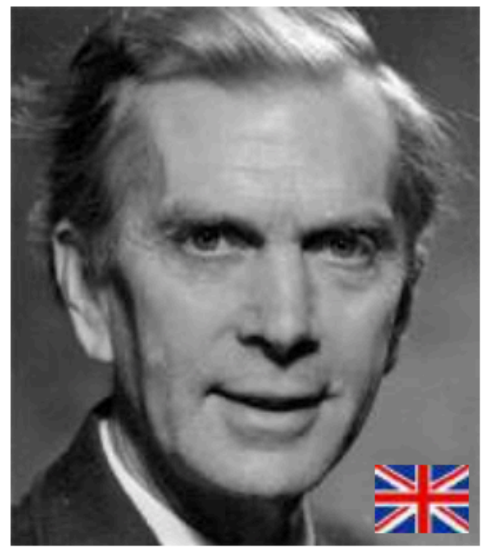
$\theta \sim \lambda/D \sim \lambda/B$

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









Sir Martin Ryle
1918-1984

1974 Nobel
Prize in Physics