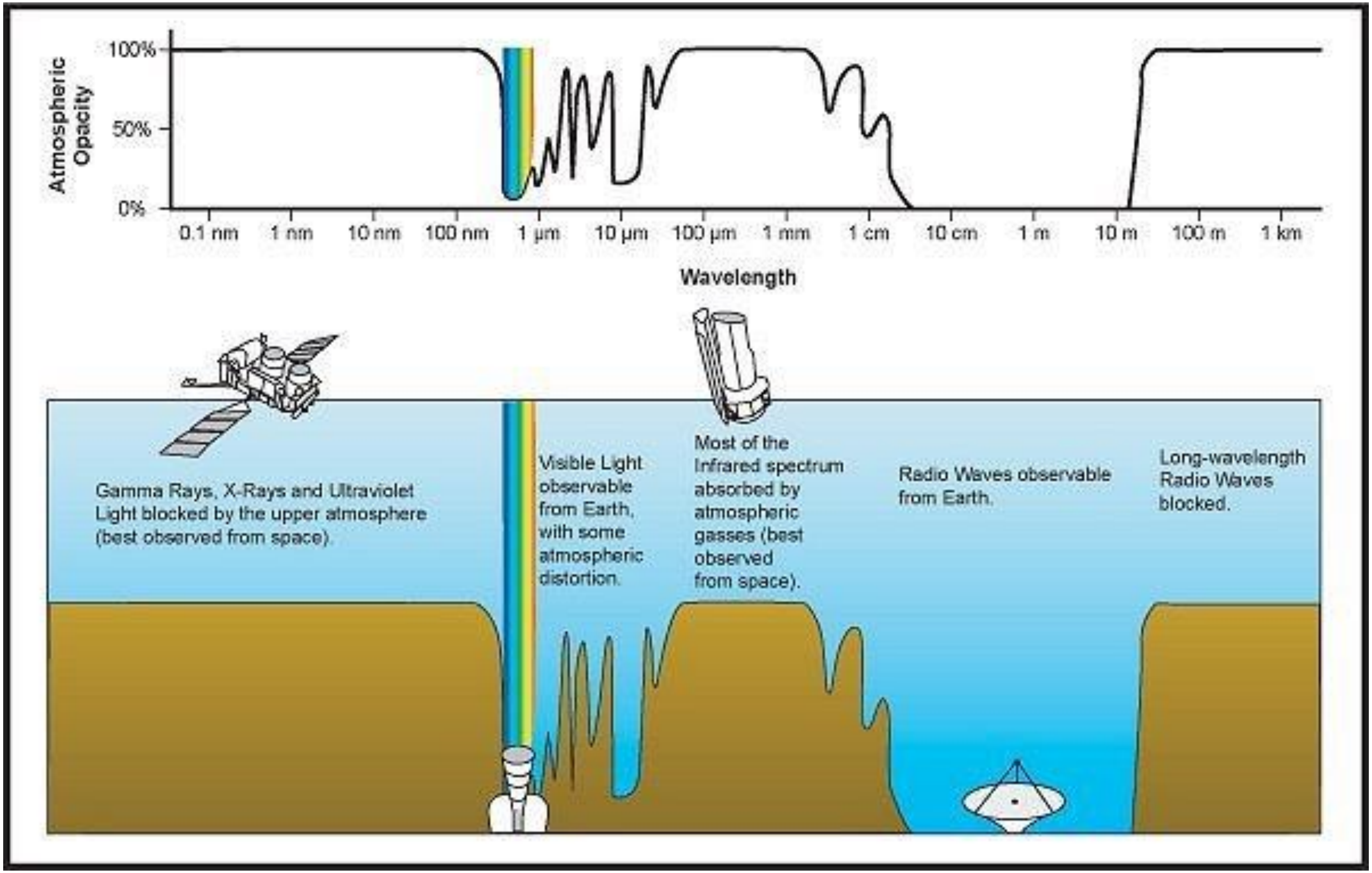
Astronomical Observing Techniques 2019

Lecture 6: Your Favourite Radio Station

Huub Rottgering
rottgering@strw.leidenuniv.nl

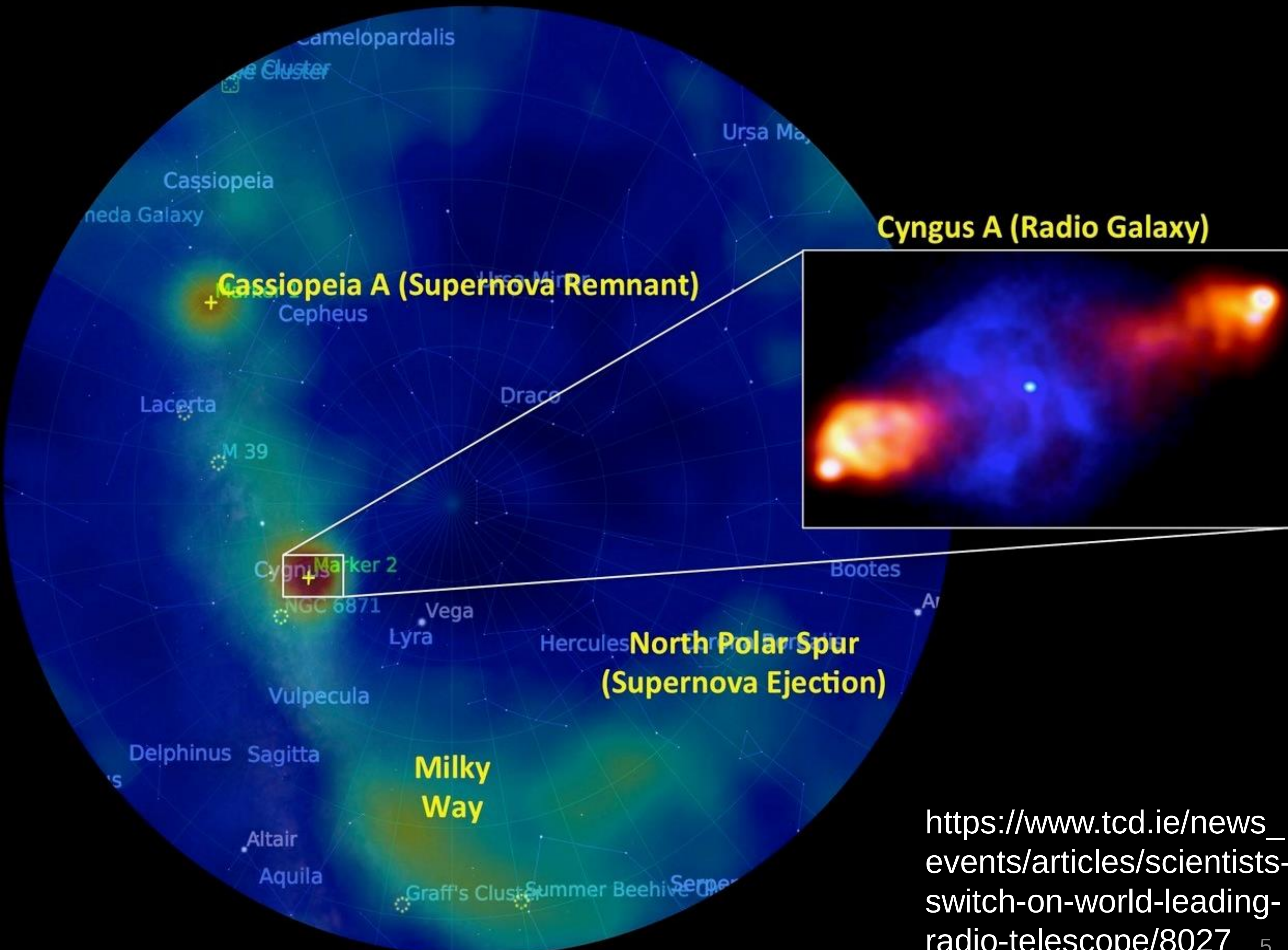
Content

1. Brief history of Radio Astronomy
2. Emission mechanisms
3. Antennas
4. Telescopes
5. Beams
6. Frequency down conversion
7. Backends



- Radio window from ~10 MHz (30m) to 1 THz (0.3mm)
- Low-frequency limit given by (reflecting) ionosphere
- High frequency limit given by molecular transitions of atmospheric H_2O and N_2

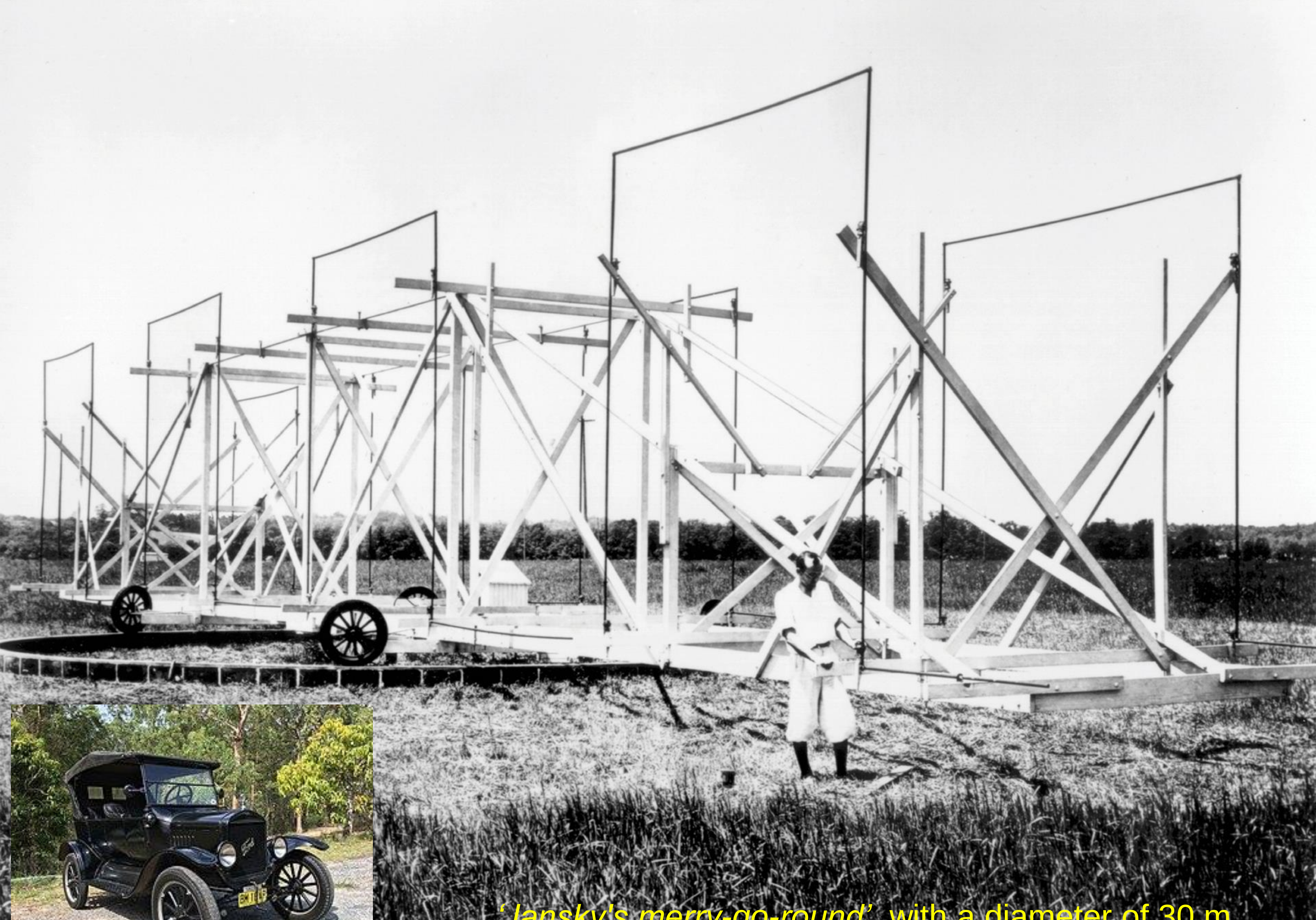
Irish LOFAR station



https://www.tcd.ie/news_events/articles/scientists-switch-on-world-leading-radio-telescope/8027

Karl G. Jansky (1905-1950)

- built an antenna system to determine source of radio noise at Bell Telephone Laboratories
- At 20.5 MHz (λ~14.6m), first detection of astronomical radio waves (from galactic center) in 1933
- Jansky as a unit: 1 Jy = 10^{-26} W m^{-2} Hz^{-1}



‘Jansky's merry-go-round’, with a diameter of 30 m, mounted on a turntable with wheels four Ford Model-T.

His assignment from his bosses at Bell Laboratories in 1931 was simple: Build a 100-foot-long rotating antenna to find out what was causing the noise that interfered with trans-Atlantic telephone calls. After recording signals from all directions for several months, Jansky eventually categorized them into three types of signal: nearby thunderstorms, distant thunderstorms, and *a faint steady hiss of unknown origin*. He spent over a year investigating the source of the third type of static. The location of maximum intensity rose and fell once a day, leading Jansky to initially surmise that he was detecting radiation from the Sun.

After a few months of following the signal, however, the brightest point moved away from the position of the Sun. Jansky also determined that the signal repeated on a cycle of 23 hours and 56 minutes, the period of the Earth's rotation relative to the stars (sidereal day), instead of relative to the sun (solar day). By comparing his observations with optical astronomical maps, Jansky concluded that the radiation was coming from the Milky Way and was strongest in the direction of the center of the galaxy, in the constellation of Sagittarius. His discovery was widely publicized, appearing in the *New York Times* of May 5, 1933.

https://en.wikipedia.org/wiki/Karl_Guthe_Jansky

NEW RADIO WAVES TRACED TO CENTRE OF THE MILKY WAY

Mysterious Static, Reported by K. G. Jansky, Held to Differ From Cosmic Ray.

DIRECTION IS UNCHANGING

Recorded and Tested for More Than Year to Identify It as From Earth's Galaxy.

ITS INTENSITY IS LOW

Only Delicate Receiver Is Able to Register—No Evidence of Interstellar Signaling.

Discovery of mysterious radio waves which appear to come from the centre of the Milky Way galaxy was announced yesterday by the Bell Telephone Laboratories. The discovery was made during research studies on static by Karl G. Jansky of the radio research department at Holmdel, N. J., and was described by him in a paper delivered before the International Scientific Radio Union in Washington.

The galactic radio waves, Mr. Jansky said, differ from the cosmic rays and also from the phenomenon of cosmic radiation, described last week before the American Philosophical Society at Philadelphia by Dr. Vesto M. Slipher, director of the Lowell Observatory at Flagstaff, Ariz.

Unlike the cosmic ray, which comes from all directions in space, does not vary with either the time of day or the time of the year, and may be either a photon or an electron, the galactic waves, Mr. Jansky pointed out, seem to come from a definite source in space, vary in intensity with the time of day and time of the year, and are distinctly electro-magnetic waves that can be picked up by a radio set.

New Waves Have High Frequency.

The cosmic radiation discovered by Dr. Slipher is a mysterious form of light apparently radiated independently of starlight, originating, Dr. Slipher concluded, at some distance above the earth's surface, and possibly produced by the earth's atmosphere.

The galactic radio waves, the announcement says, are short waves, 14.6 meters, at a frequency of about 20,000,000 cycles a second. The intensity of these waves is very low, so that a delicate apparatus is required for their detection.

Unlike most forms of radio disturbances, the report says, these newly found waves do not appear to be due to any terrestrial phenomena, but rather to come from some point far off in space—probably far beyond our solar system.

If these waves came from a terrestrial origin, it was reasoned, then they should have the same intensity all the year around. But their intensity varies regularly with the time of day and with the seasons, and they get much weaker when the earth, moving in its orbit, interposes itself between the radio receiver and the source.

A preliminary report, published in the Proceedings of the Institute of Radio Engineers last December, described studies which showed the presence of three separate groups of static: Static from local thunderstorms, static from distant thunderstorms, and a "steady hiss type static of unknown origin." Further studies this year determine the unknown origin of this third type to be from the direction of the centre of the Milky Way, the earth's own home galaxy.

Direction of Arrival Fixed.

The direction from which these waves arrive, the announcement asserts, has been determined by investigations carried on over a considerable period. Measurements of the horizontal component of the waves were taken on several days of each month for an entire year, and by an analysis of these readings at the end of the year their direction of arrival was disclosed.

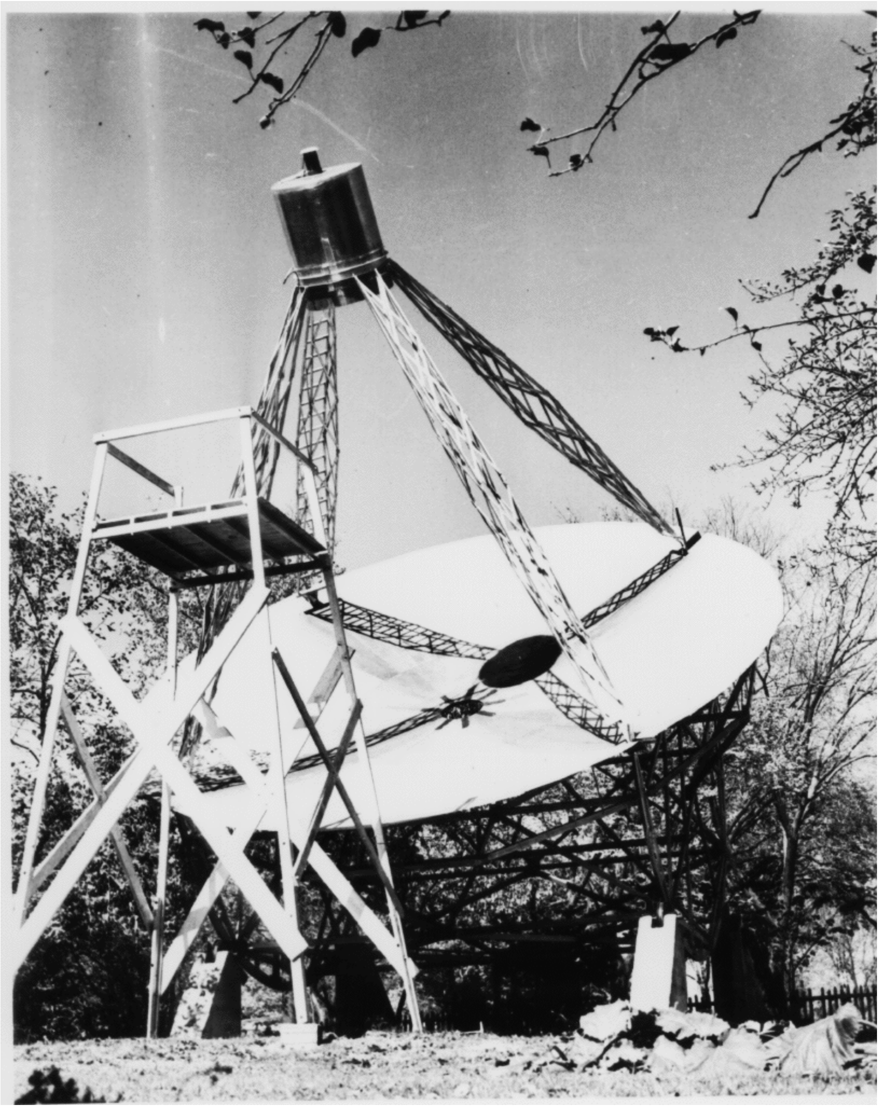
"The position indicated," it was explained, "is very near to the point where the plane in which the earth revolves around the sun crosses the centre of the Milky Way, and also to that point toward which the solar system is moving with respect to the other stars.

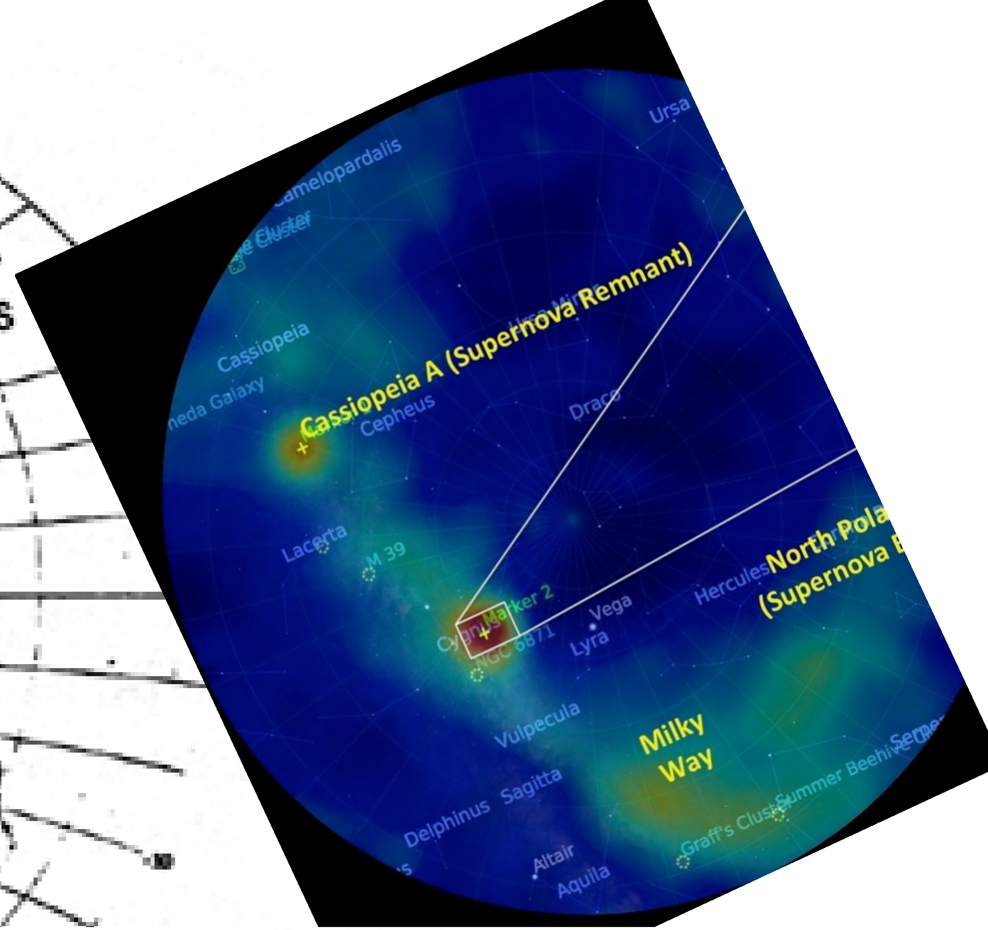
"Further verification of this direction is required, but the discovery, like that of the cosmic rays and of cosmic radiation, raises many cosmological questions of extreme interest."

There is no indication of any kind, Mr. Jansky replied to a question, that these galactic radio waves constitute some kind of interstellar signalling, or that they are the result of some form of intelligence striving for intra-galactic communication.

Grote Reber (1911-2002)

- extended Jansky's work, conducted first radio sky survey
- built 9-m diameter dish in backyard, detected sources
- was the world's only radio astronomer for nearly a decade





Grote Reber's map of the radio sky showing radiation concentrated along the plane of the Milky Way with a large maximum (11 units) in Sagittarius (the center of our galaxy) and smaller maxima in Cygnus (3 units) and Cassiopeia (2 units). The map was made in 1944 at a wavelength of 1.9 meters.

Reber graduated from Armour Institute of Technology (now Illinois Institute of Technology) in 1933 with a degree in electrical engineering.

When he learned of Karl Jansky's work in 1933, he decided this was the field he wanted to work in, and applied to Bell Labs, where Jansky was working. However, this was during the height of the Great Depression and there were no jobs available.

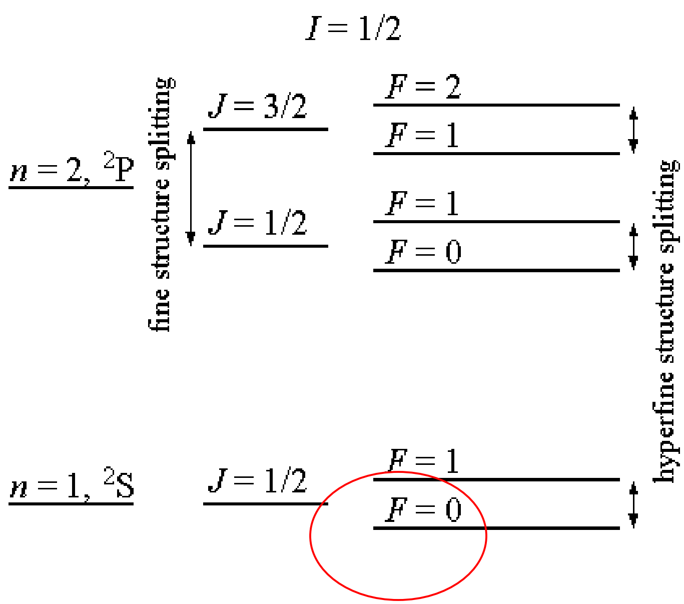
In the summer of 1937, Reber decided to build his own radio telescope in his back yard in Wheaton. Reber's radio telescope was considerably more advanced than Jansky's, and consisted of a parabolic sheet metal dish 9 meters in diameter, focusing to a radio receiver 8 meters above the dish. The entire assembly was mounted on a tilting stand, allowing it to be pointed in various directions, though not turned. The telescope was completed in September 1937.

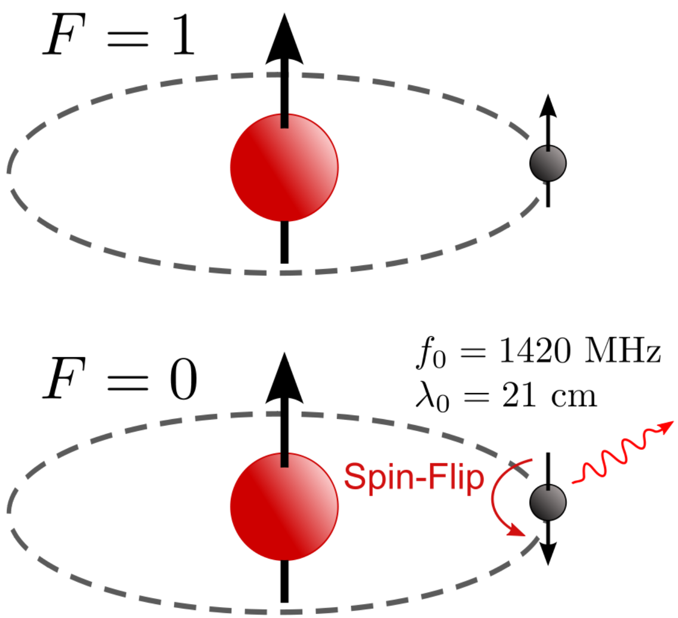
Reber's first receiver operated at 3300 MHz and failed to detect signals from outer space, as did his second, operating at 900 MHz. Finally, his third attempt, at 160 MHz, was successful in 1938, confirming Jansky's discovery. He turned his attention to making a radiofrequency sky map, which he completed in 1941 and extended in 1943. He published a considerable body of work during this era, and was the initiator of the "explosion" of radio astronomy in the immediate post-Second World War era. His data, published as contour maps showing the brightness of the sky in radio wavelengths, revealed the existence of radio sources such as Cygnus A and Cassiopeia A for the first time. For nearly a decade from 1937 on he was the world's only radio astronomer, a field that only expanded after World War Two when scientists, who had gained a great deal of knowledge during the wartime expansion of RADAR, entered the field.

https://en.wikipedia.org/wiki/Grote_Reber

The HI 21cm (1420.4 MHz) Line

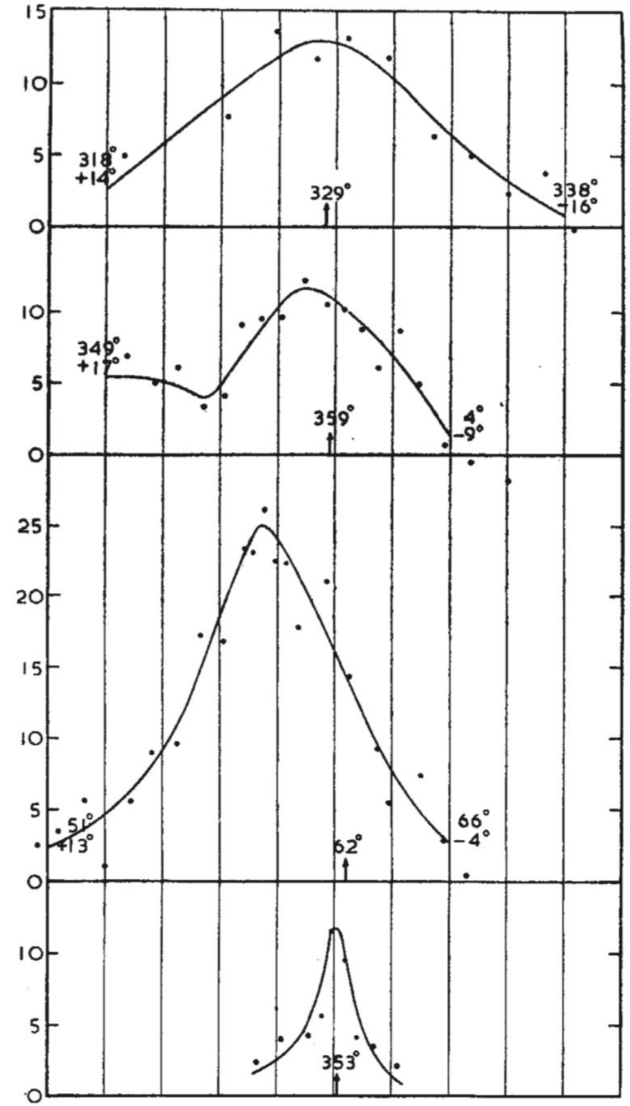
Hendrik van de Hulst (1918-2000) predicted in 1944 that neutral hydrogen could produce radiation at ν = 1420.4 MHz due to two closely spaced energy levels in the ground state of the hydrogen atom.





Early Observations of the HI 21cm Line

- First observed in 1951 by Ewen and Purcell at Harvard University
- Confirmed by Dutch astronomers Muller and Oort also in 1951
- After 1952: first maps of neutral hydrogen in Galaxy, revealed spiral structure of the Milky Way



Muller & Oort 1951

Figure 3: The Würzburg at Kootwijk used for observing the 21 cm HI line between 1951 and 1955.

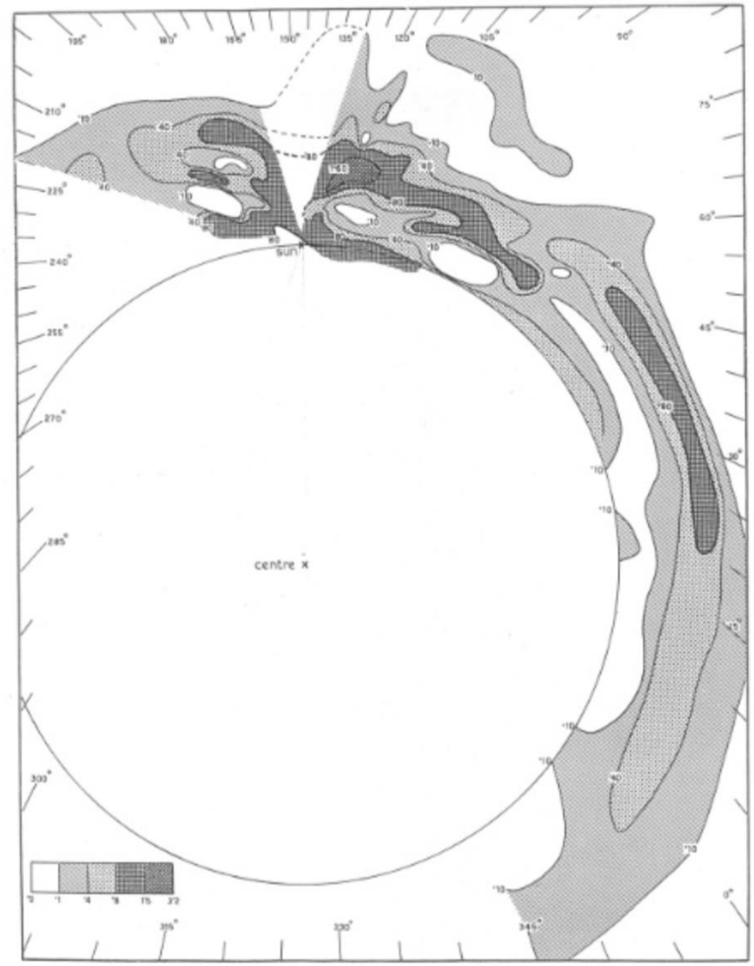


Figure 9: The first HI map of the Galaxy outside of the solar circle, showing spiral structure, with contour shading to indicate "points of equal density" (after Van de Hulst et al., 1954: 146).

https://www.astron.nl/~leeuwen/video/dloo/JAHH9p3.pdf

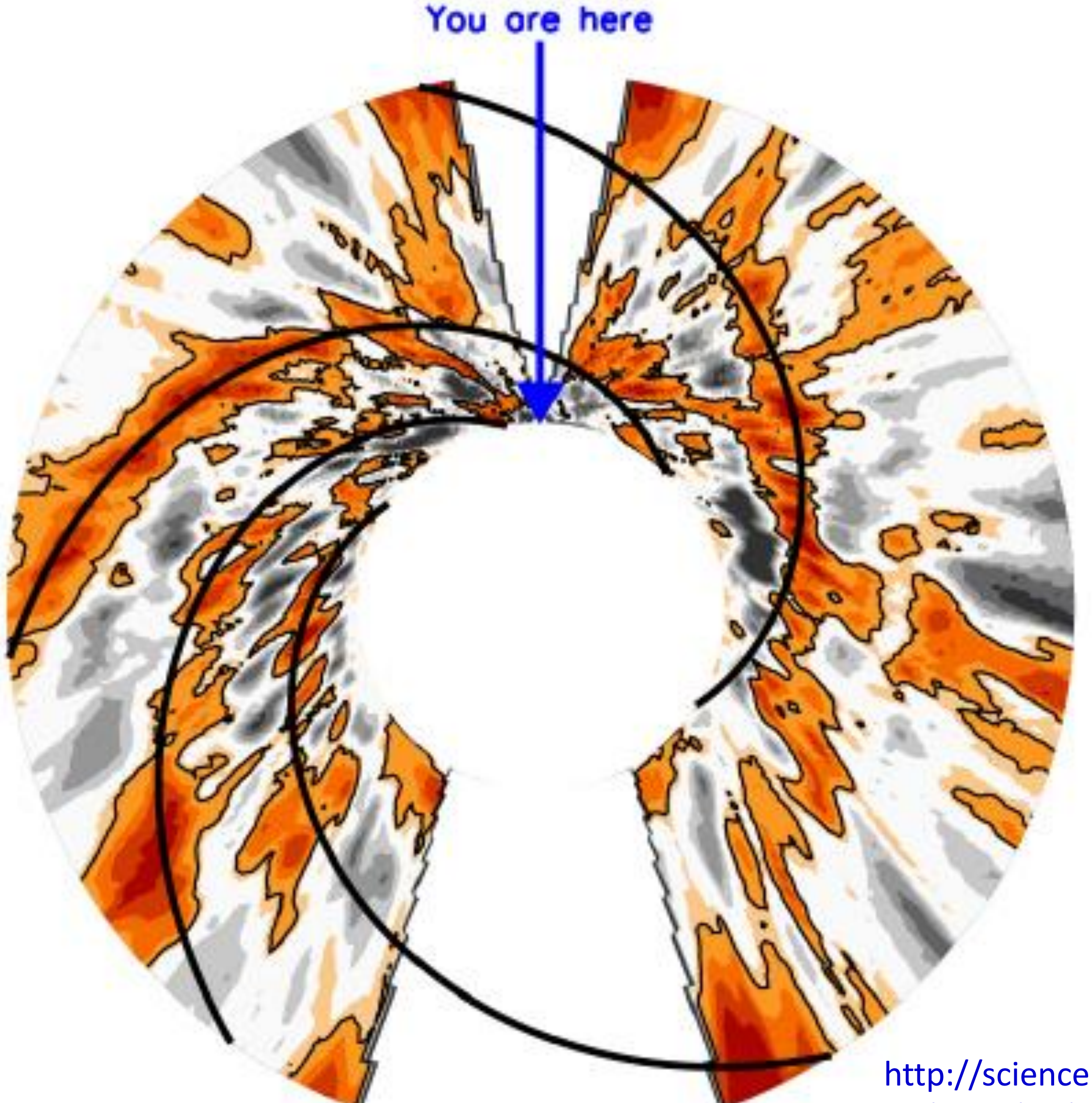
Dwingeloo radio telescope

The **Dwingeloo Radio Observatory** is a single-dish radio telescope near the village of Dwingeloo in the northeastern Netherlands. Construction started in 1954, and the telescope was completed in 1956. The radio telescope has a diameter of 25 m.[1] At the time of completion it was the largest radio telescope in the world, but it was overtaken in 1957 by the 76-m Lovell Telescope.

https://nl.wikipedia.org/wiki/Dwingeloo_Radiotelescoop

https://nl.wikipedia.org/wiki/Dwingeloo_Radiotelescoop

Location of hydrogen emission in our Milky Way from line-of-sight Doppler shift due to galactic rotation



http://science.sciencemag.org/content/sci/early/2006/06/01/science.1128455.full.pdf

The **Fourth Cambridge Survey** (**4C**) is an astronomical catalogue of celestial radio sources as measured at 178 MHz using the 4C Array. It was published in two parts, in 1965 (for declinations +20 to +40) and 1967 (declinations -7 to + 20 and +40 to +80), by the Radio Astronomy Group of the University of Cambridge. References to entries in this catalogue use the prefix **4C** followed by the declination in degrees, followed by a period, and then followed by the source number on that declination strip, e.g. 4C-06.23.

The 4C Array, which used the technique of aperture synthesis, could reliably position sources with flux densities of around 2 Jy, to within about 0.35 arcmin in Right ascension and 2.5 arcmin in declination.

20°

Number 4C20.	Position (1950.0) R.A. h	m	s	Dec. °	'	Flux Density 10^{-26} MKS
1	00	11	16.9	20	31.4	5.3
2	00	25	51.9		57.9	4.8
3	00	33	50.0		40.5	2.2
4	00	43	53.0		14.0	2.4
5	00	50	58.5		36.1	2.3

https://en.wikipedia.org/wiki/Fourth_Cambridge_Survey

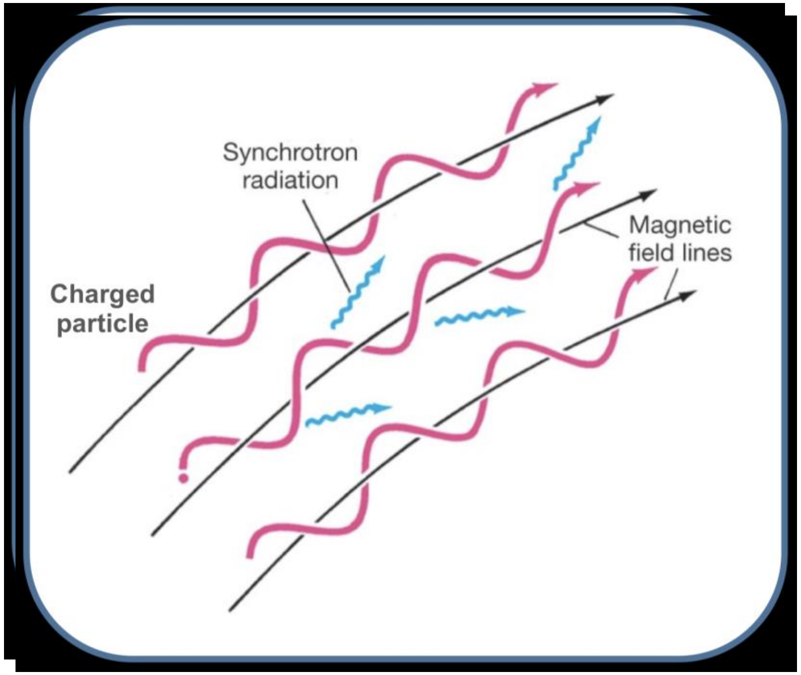
Radio Astronomy Discoveries

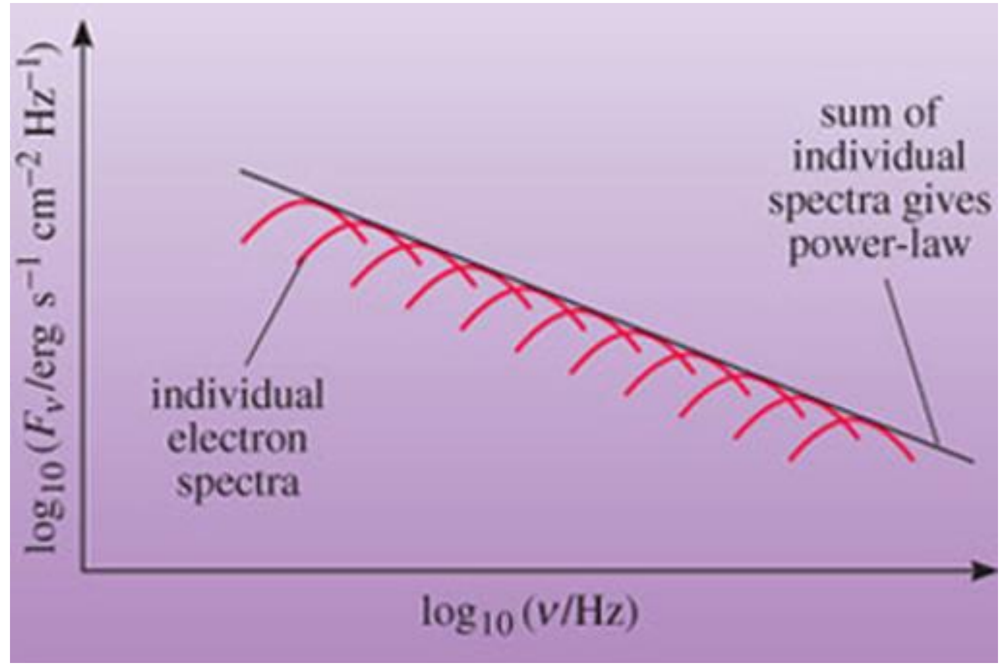
- 1933: Radio synchrotron emission of Milky Way
- 1948: First discrete cosmic radio sources: supernova remnants and radio galaxies
- 1951: 21-cm line of atomic hydrogen
- 1963: Quasi Stellar Objects (Quasars)
- 1965: Cosmic Microwave Background
- 1968: Interstellar molecules ⇔ star formation
- 1968: Pulsars
- 1974: Binary pulsar
- 1979: Gravitational lenses
- 1983: Millisecond pulsars
- 1983: The Sunyaev-Zeldovich effect
- 2005: Molecules in high-redshift galaxies

Radio Emission Mechanisms

1. Synchrotron emission: electrons spiraling in magnetic fields
2. Free-free emission (thermal Bremsstrahlung): electrons scattering off ions
3. Thermal emission: blackbody radiation from gas and dust grains
4. Spectral lines: electrons bound to atom changing energy states

Synchrotron Emission





- Caused by highly relativistic electrons spiraling around magnetic field lines
- Polarized because of relation with magnetic field direction
- Continuous spectrum due to power law-like distribution of energies of emitting elections

Synchrotron Radiation

- Angular velocity ω given by balance of magnetic and centripetal forces, independent of particle velocity $v \ll c$:

$$\omega = \frac{qB}{mc}$$

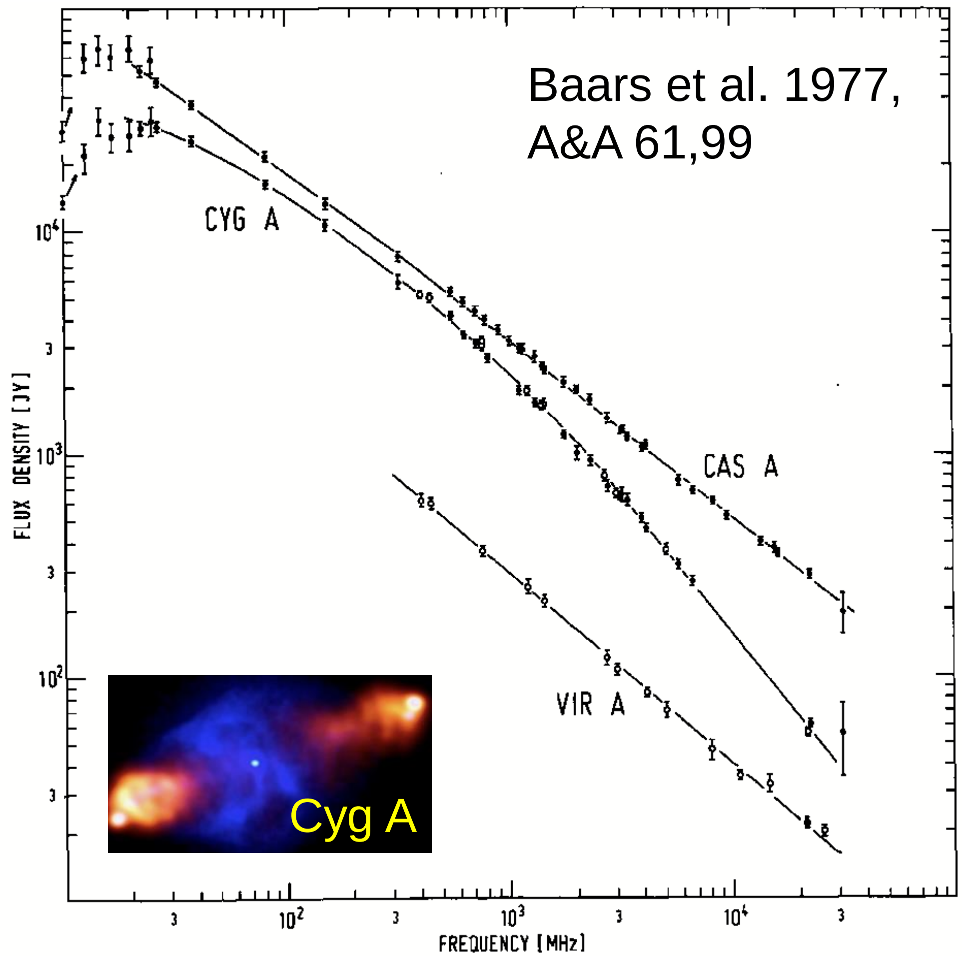
  - q: particle charge
  - B: magnetic field strength
  - m: particle mass
  - c: speed of light

- spectral index

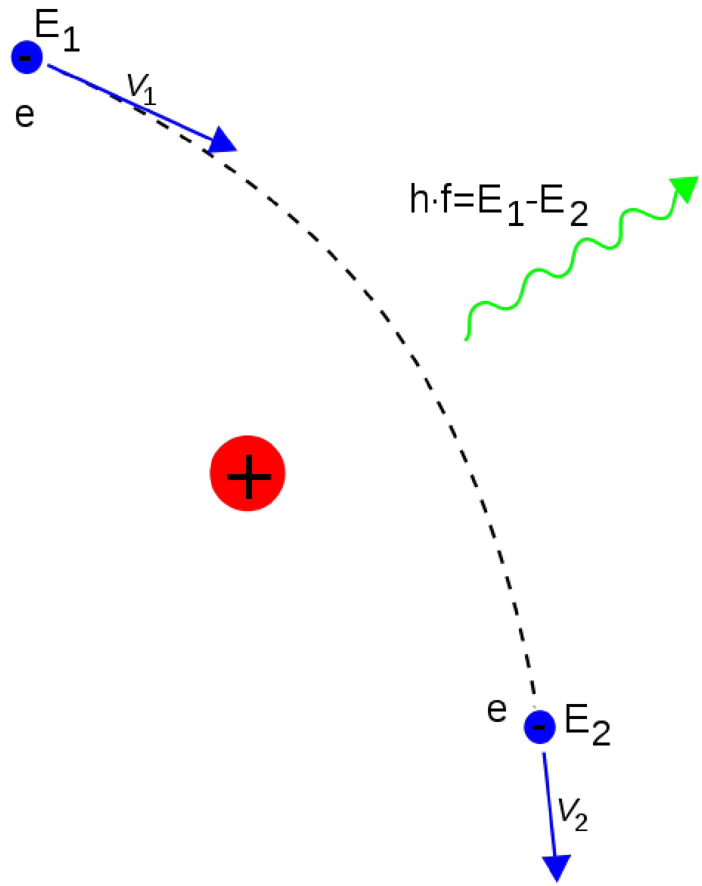
$$P_\nu \sim \nu^\alpha$$

- (or in the uk:

$$P_\nu \sim \nu^{-\alpha}$$)



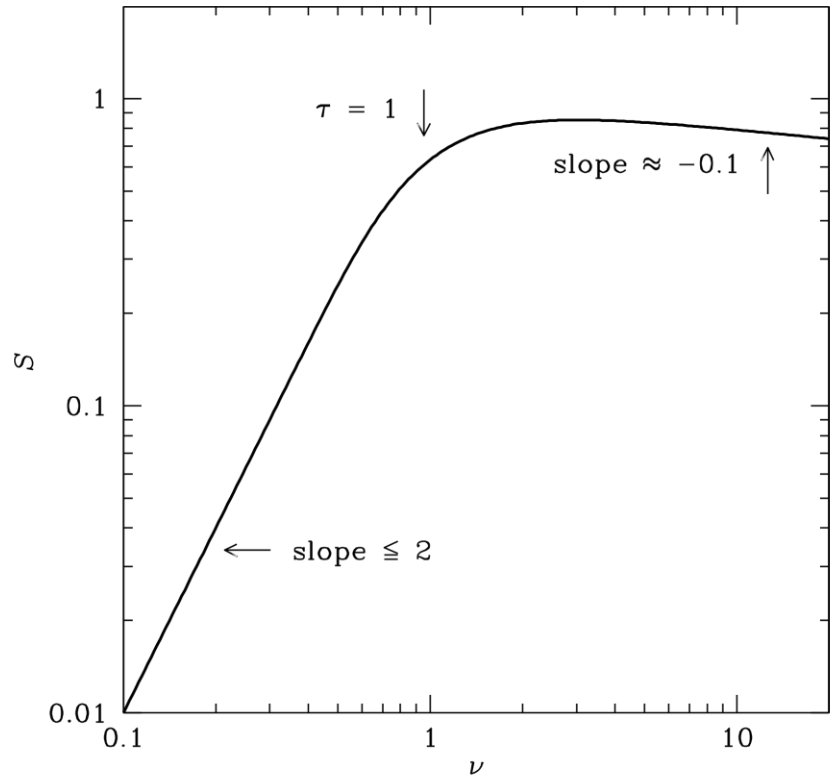
Free-Free Emission



Free electrons scattering off ions (e.g. in HII regions) without being captured

Free-Free Radiation

- only electrons scattering off ions produce significant radiation
- no electron capturing → continuous spectrum
- spectral index close to 0 for higher frequencies in an HII region



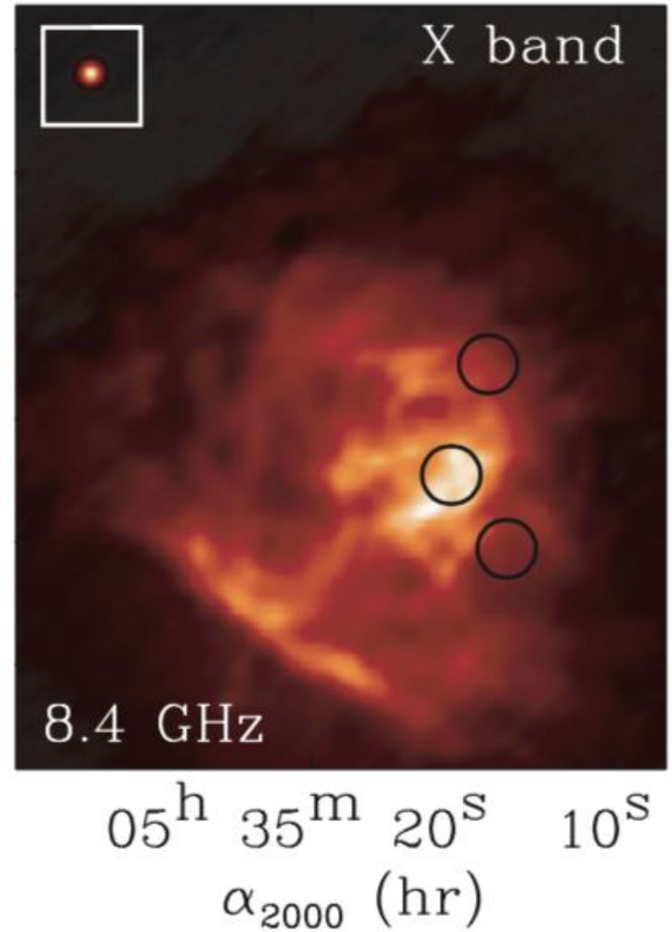
www.cv.nrao.edu/~sransom/web/Ch4.html

An **H II region** is a region of interstellar atomic hydrogen that is ionized. It is typically a cloud of partially ionized gas in which star formation has recently taken place, with a size ranging from one to hundreds of light years, and density from a few to about a million particles per cubic cm. The Orion Nebula, now known to be an H II region, was observed in 1610 by Nicolas-Claude Fabri de Peiresc by telescope, the first such object discovered.

H II regions may be of any shape, because the distribution of the stars and gas inside them is irregular. The short-lived blue stars created in these regions emit copious amounts of ultraviolet light that ionize the surrounding gas. H II regions are often associated with giant molecular clouds. They often appear clumpy and filamentary, sometimes showing intricate shapes such as the Horsehead Nebula. H II regions may give birth to thousands of stars over a period of several million years. In the end, supernova explosions and strong stellar winds from the most massive stars in the resulting star cluster will disperse the gases of the H II region, leaving behind a cluster of stars which have formed, such as the Pleiades.

https://en.wikipedia.org/wiki/H_II_region

The entire Orion Nebula in a composite image of visible light and infrared; taken by [Hubble Space Telescope](https://en.wikipedia.org/wiki/Hubble_Space_Telescope)



Free-free emission
http://adsabs.harvard.edu/abs/2009ApJ...705..226D

https://en.wikipedia.org/wiki/Orion_Nebula

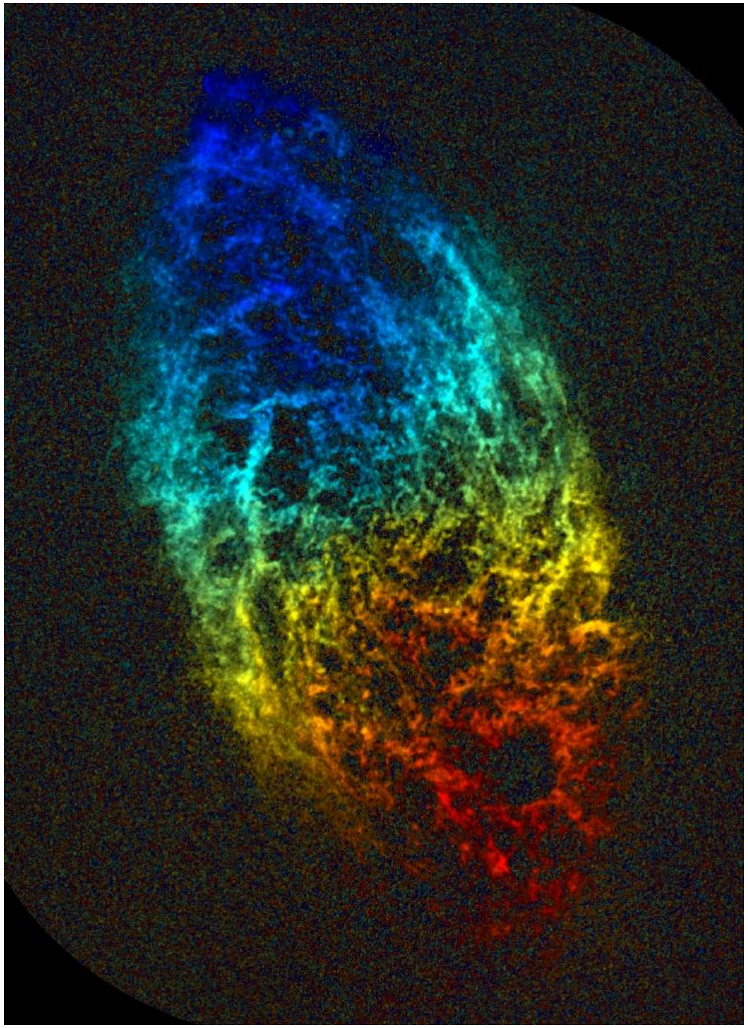
Spectral Lines

- Hydrogen 21-cm line
- Radio recombination lines: highly excited electrons transitioning between states with large orbital angular momentum states *n*
- Spectral lines due to molecules rotating and vibrating
- Masers

Astronomical Relevance of HI 21cm Line

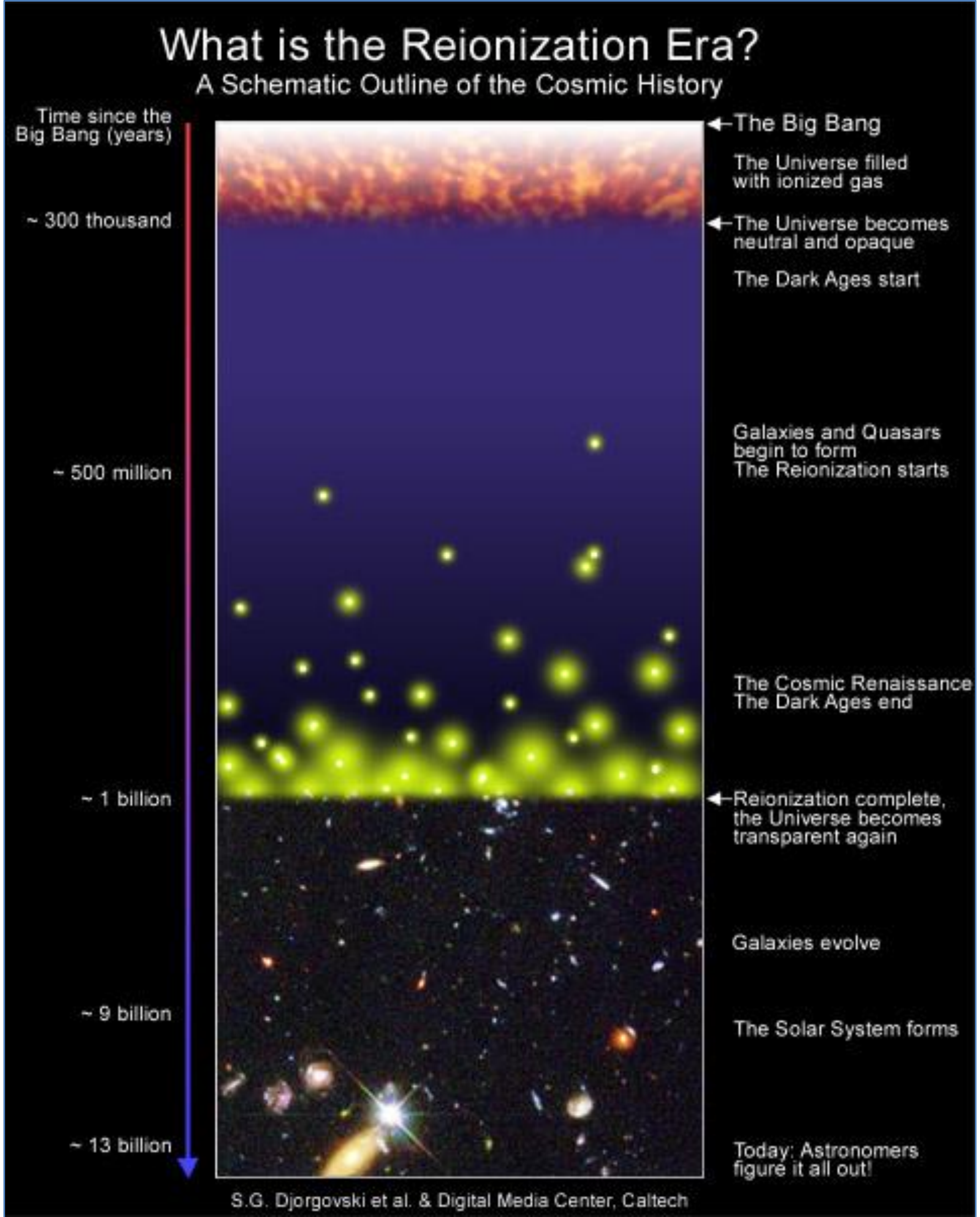
Main applications:

1. Distribution of HI in galaxies
2. Big Bang cosmology: redshifted HI line could be observed around 100 MHz to provide info on how the Universe was reionized (HI which has been ionized by stars or quasars will appear as holes)



HI radial velocity field of M33 in color coding (Thilker, Braun & Walterbos 1998)

Composite optical image, showing stars and dust absorption



21 cm emission/absorption

Carbon radio recombination absorption lines as observed towards CasA with LOFAR

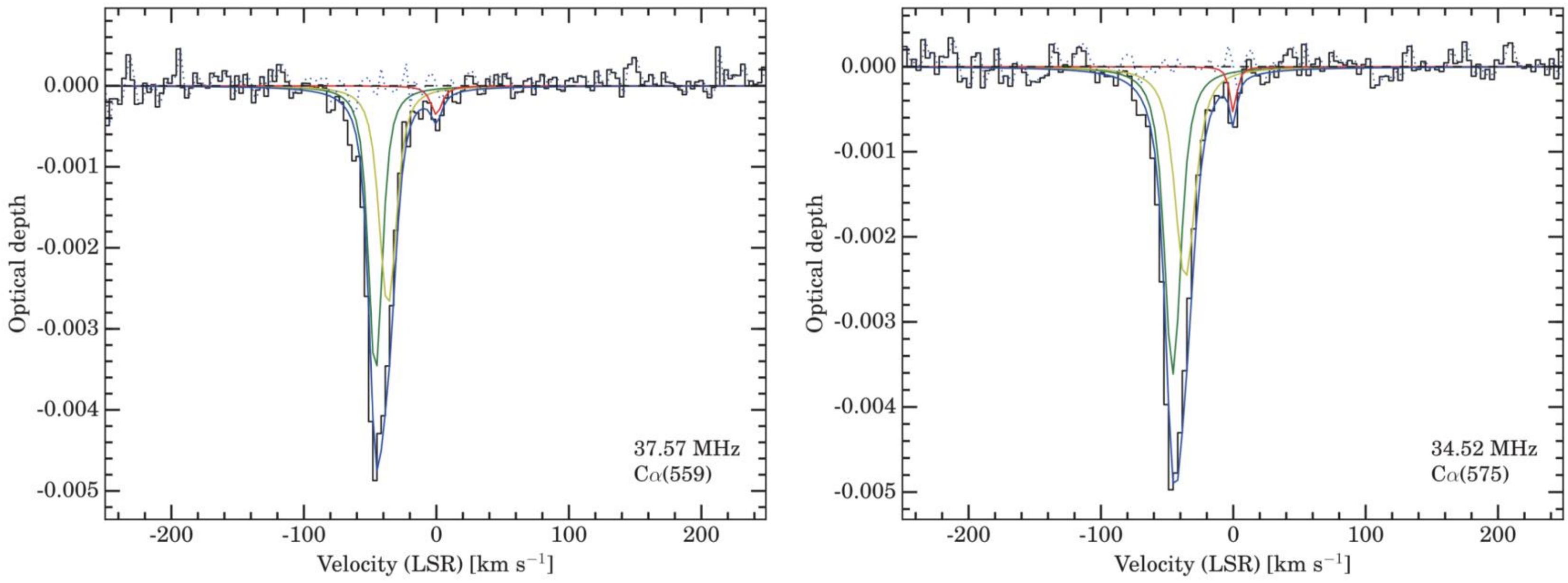


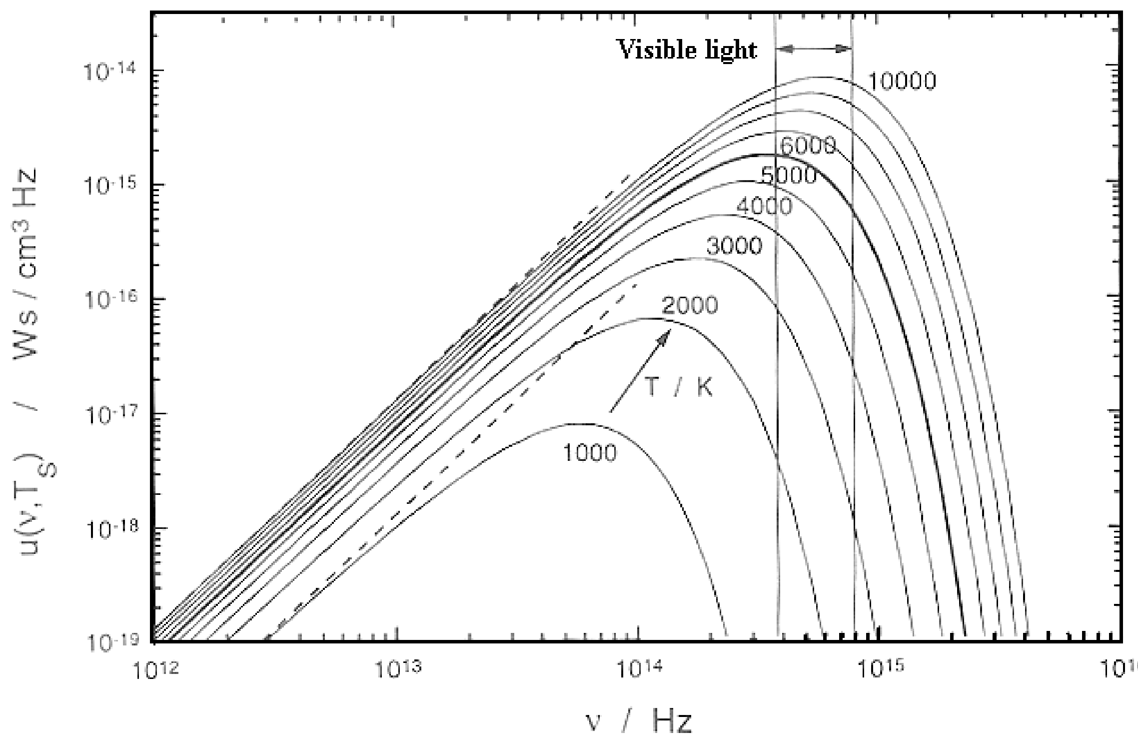
Figure 5. LOFAR LBA 56–33 MHz: stacked CRRL spectra. The green, yellow and red lines show the decomposition into the −47, −38 and 0 km s^{-1} components. The blue dotted line shows the residuals after subtracting the fitted line profiles.

http://adsabs.harvard.edu/abs/2017MNRAS.465.1066O

Thermal Emission

Rayleigh-Jeans tail of thermal emission from e.g. dust grains produces radio emission with spectral index $\alpha \approx 2$

$$I_\nu(T) \approx \frac{2\nu^2}{c^2} kT = \frac{2kT}{\lambda^2}$$



“True” Brightness Temperature

- Brightness and effective temperature are strictly proportional
- Use brightness temperature to describe source intensity:

$$T_B = \frac{c^2}{2k\nu^2} B_{RJ} = \frac{\lambda^2}{2k} B_{RJ}$$

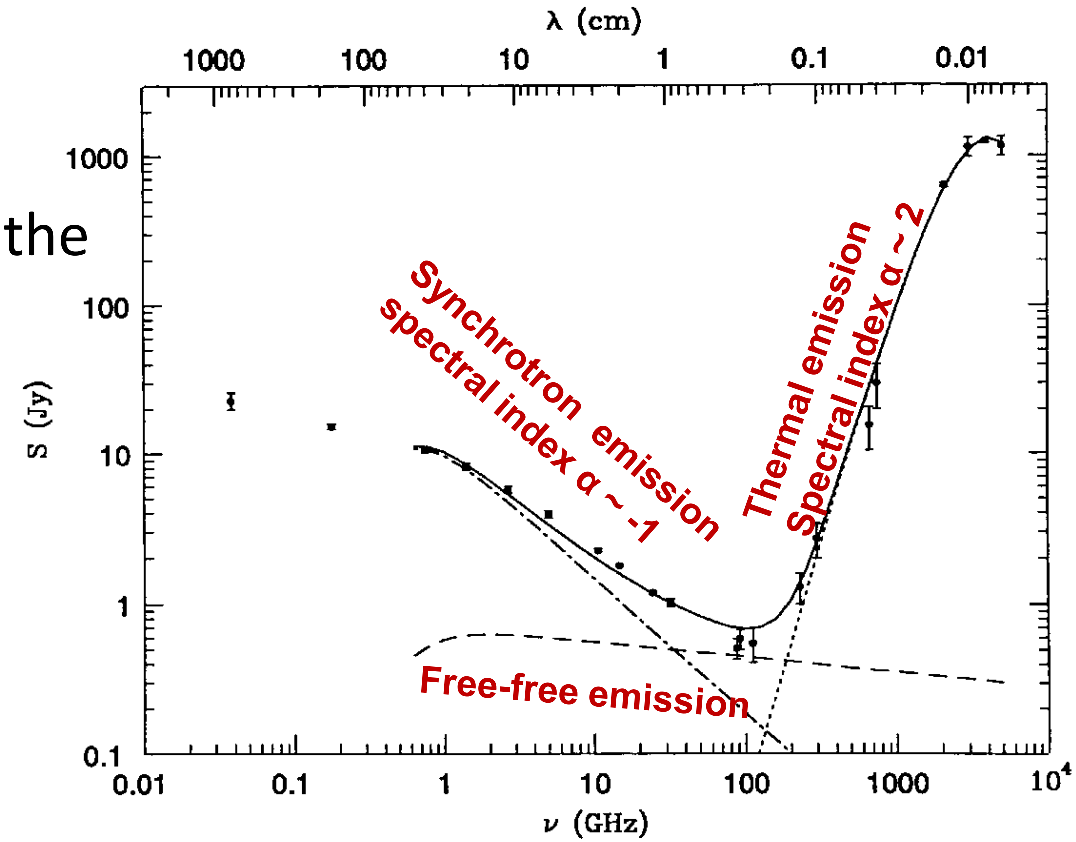
- For real blackbody sources and *hν* << kT, T_B is independent of *ν*
- If the emission is non-BB (e.g., synchrotron, free-free, …) T_B will depend on *ν* but the brightness temperature is still being used

Summary of Radio Emission Mechanisms

1. Synchrotron emission
2. Free-free emission (thermal Bremsstrahlung)
3. Thermal (blackbody) emission (also from dust grains)
4. Spectral lines

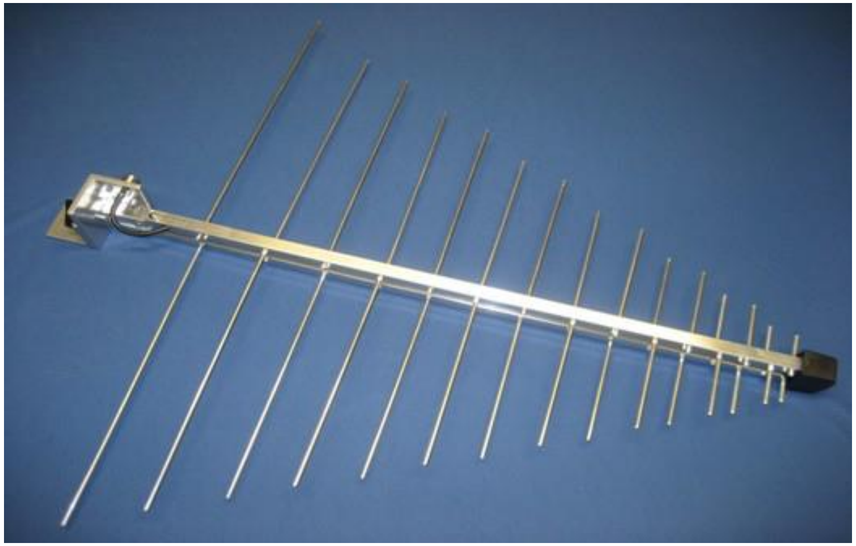
Comparison of three emission components (for the starburst galaxy M82)

- Synchrotron radiation dominates at low frequencies
- Thermal dust emission dominates at high frequencies



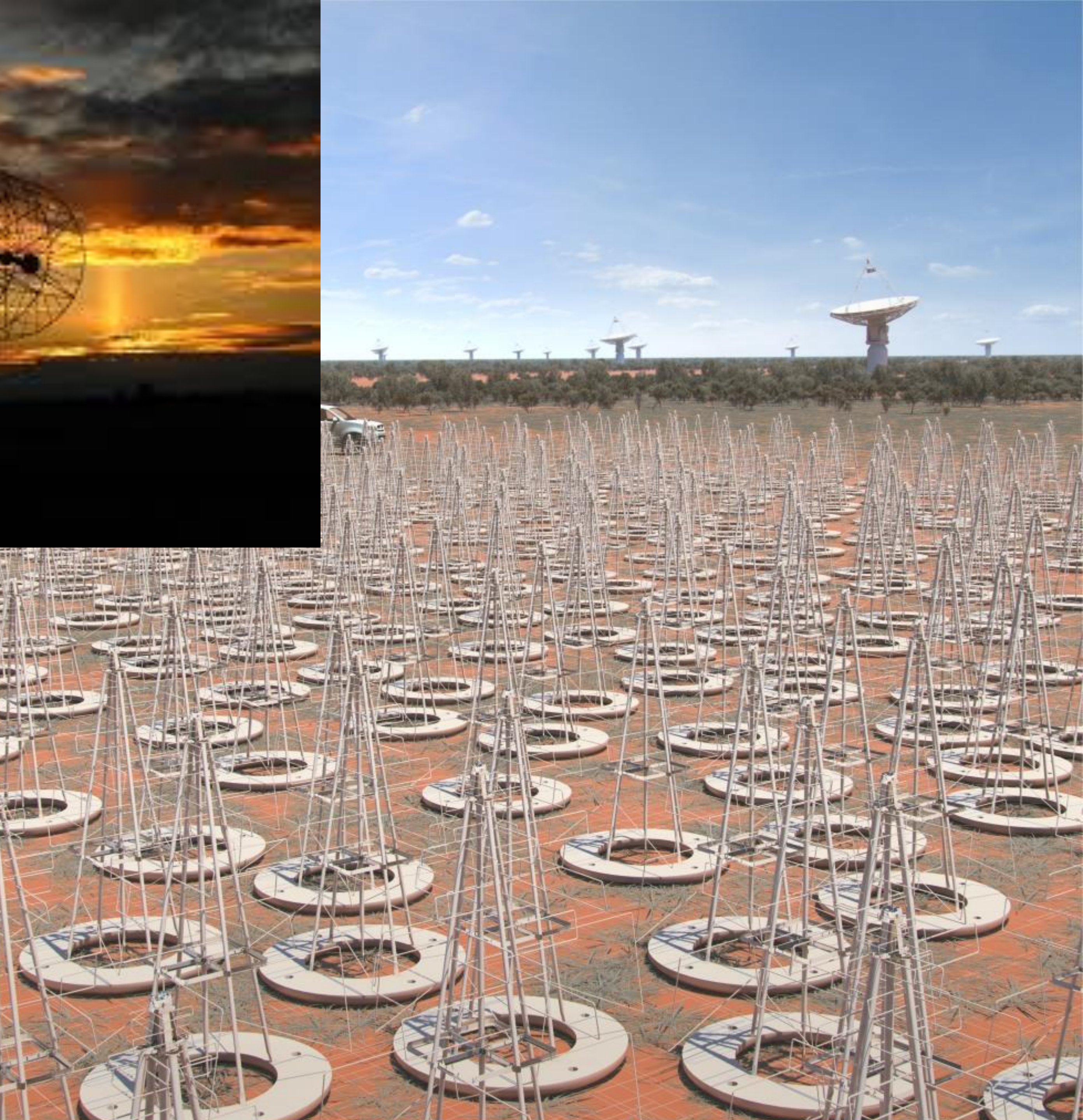
Receiving radiation using antennas

helical



Log-periodic

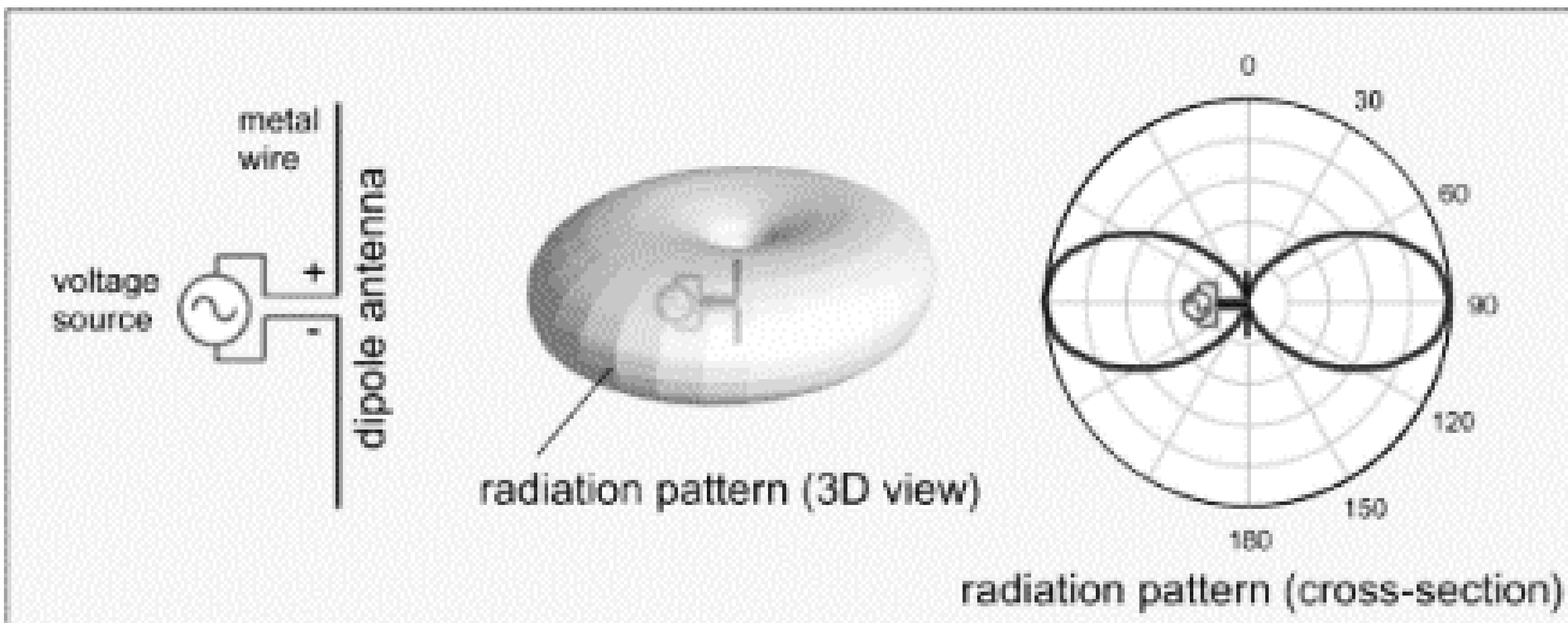
URT2 – Ukraine



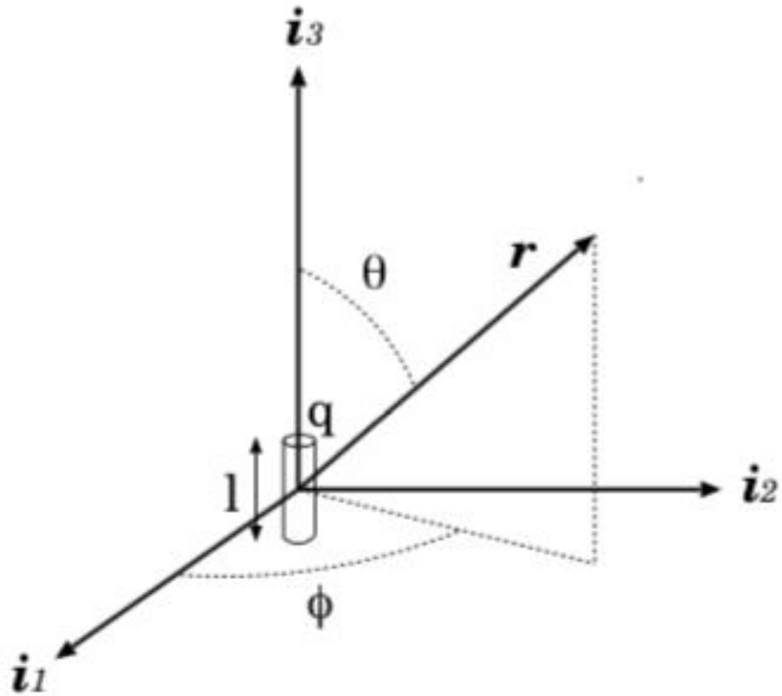
Concept SKA-low

Radiation from Hertz Dipole

- Radiation is linearly polarized
- Electric field lines along direction of dipole
- Radiation pattern has donut shape, defined by zone where phases match sufficiently well to combine constructively
- Along the direction of the dipole, the field is zero
- Best efficiency: size of dipole = 1/2 λ



Hertz Dipole



Let us consider an infinitesimally small cylinder with infinitesimal cross section q and infinitesimal length l, which is located at the origin of a rectangular coordinate system and directed towards 3–rd axis (Figure 29).

Let us assume a homogeneous electric current I, which is flowing within the cylinder and harmonically oscillating in time proportionally to $e^{-i\omega t}$.

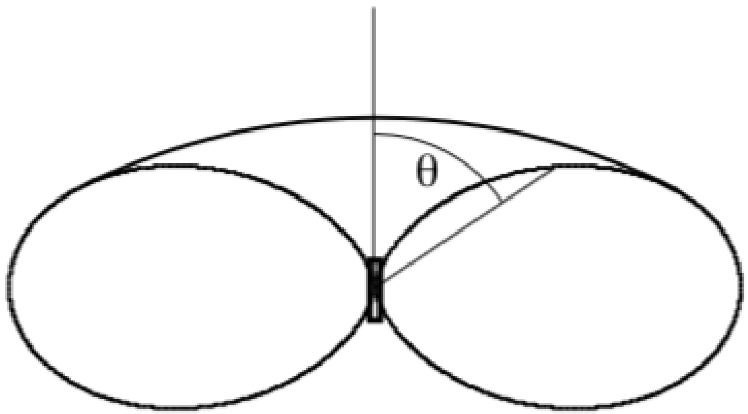
http://iaaras.ru/media/library/kchap2.pdf

Now we consider power flux density $\mathcal{S}$ of the radio wave generated from the Hertz dipole. For this purpose, following the definition of the IEEE (1977), we calculate time average $\overline{\boldsymbol{S}}$ of Poynting vector $\boldsymbol{S}$, which is given by $\boldsymbol{S} = \boldsymbol{E}_r \times \boldsymbol{H}_r = E_{r_\theta} H_{r_\phi} \boldsymbol{n}$ in this case. Taking absolute value, we have

$$\mathcal{S} = |\, \overline{\boldsymbol{S}} \,| = \overline{E_{r\theta} H_{r\phi}} = Z \left(\frac{Il}{2\lambda} \right)^2 \frac{\sin^2\theta}{r^2} \overline{\sin^2(kr - \omega t)} = \frac{Z}{2} \left(\frac{Il}{2\lambda} \right)^2 \frac{\sin^2\theta}{r^2}, \tag{106}$$

since, in general,

$$\overline{\sin^2(kr - \omega t)} = \frac{1}{2}.$$



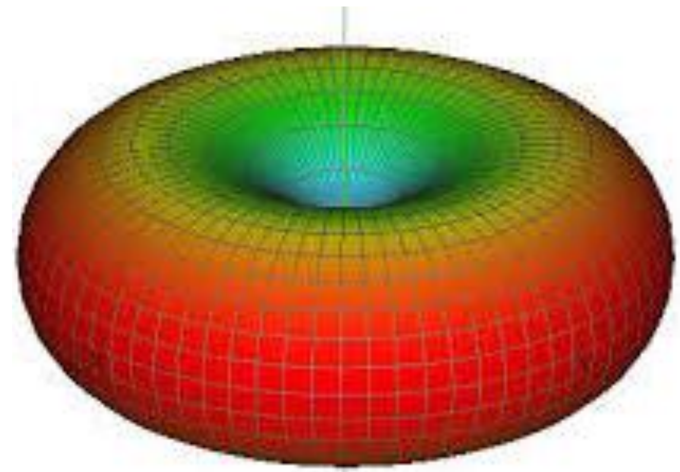
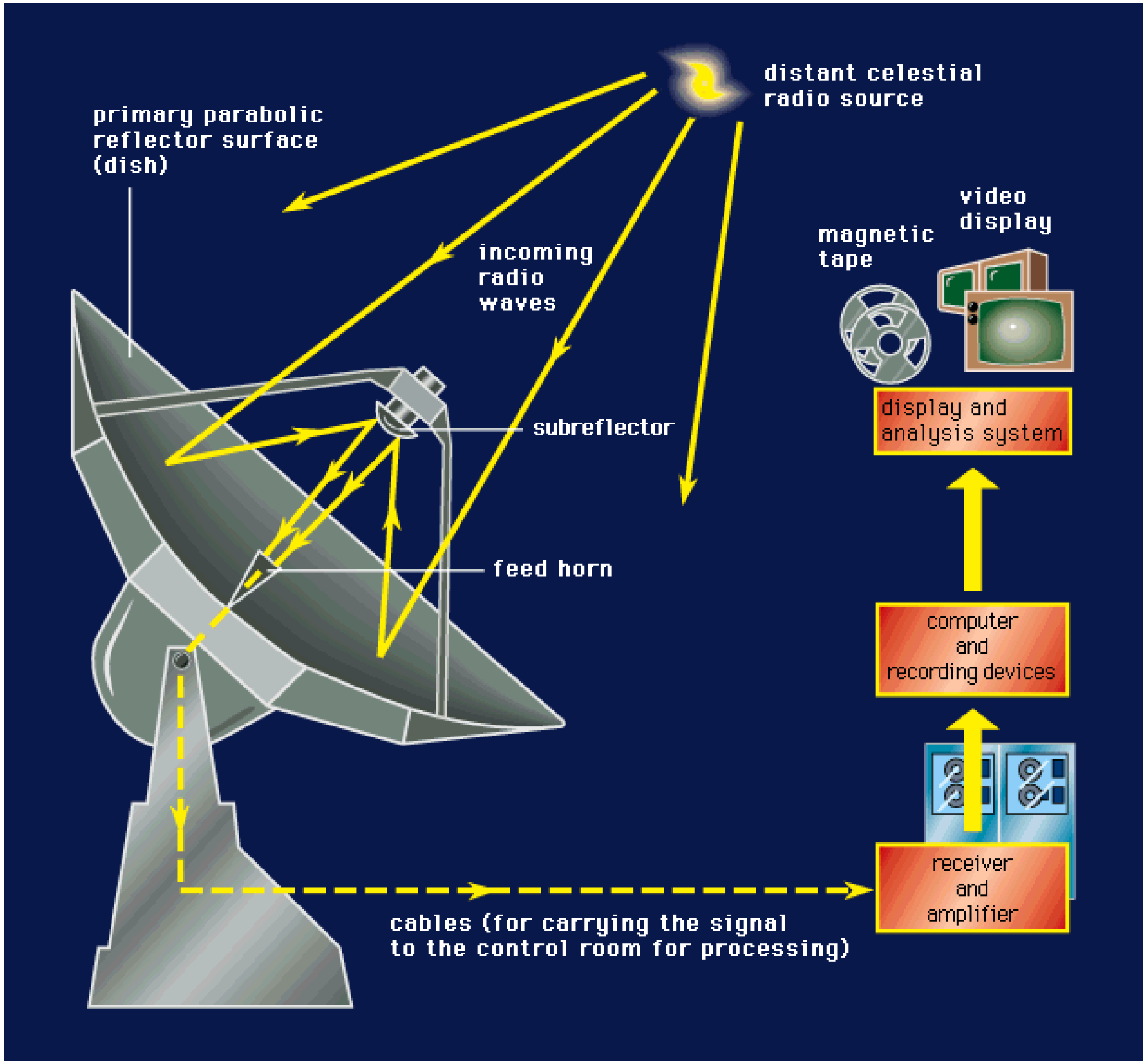


Figure 31: Power pattern of Hertz dipole.

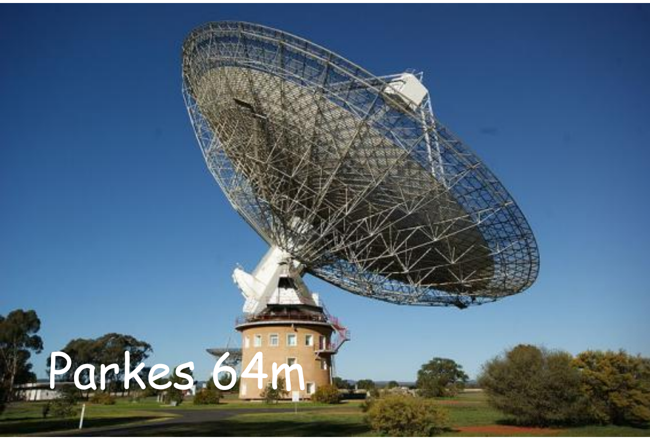
The $\sin^2\theta$ dependence shows effectiveness of transmission of the power of the electromagnetic wave to a certain direction, which is called the **“power pattern”** (Figure 31).

Radio dishes



- Directly measure electric fields of electro-magnetic waves
- Electric fields excite currents in antenna
- Currents can be amplified and split electrically

Famous Radio Telescopes (Single Dish)


Parkes 64m


Jodrell Bank 76m


Arecibo, Puerto Rico, 305m


Effelsberg, 100m


Dwingeloo, 25m


Greenbank, USA – after structural collapse

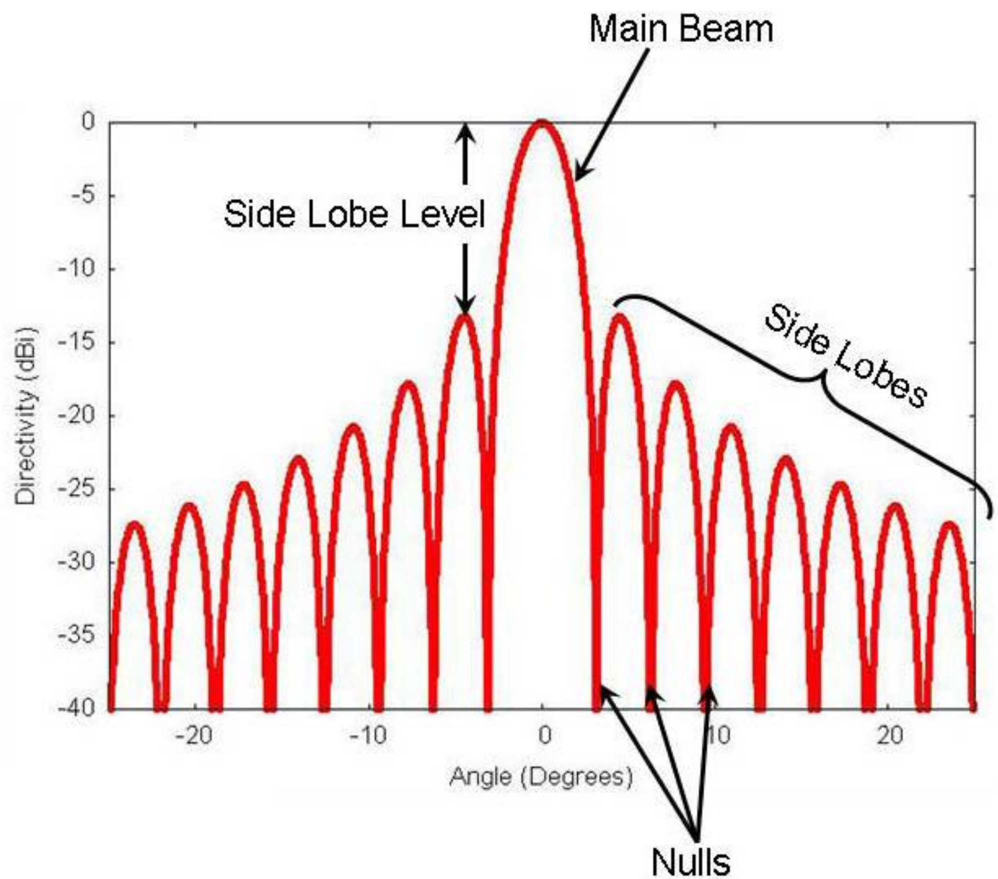
500-meter Aperture Spherical Telescope (FAST)

Radio Beams

Similar to optical telescopes, angular resolution given by

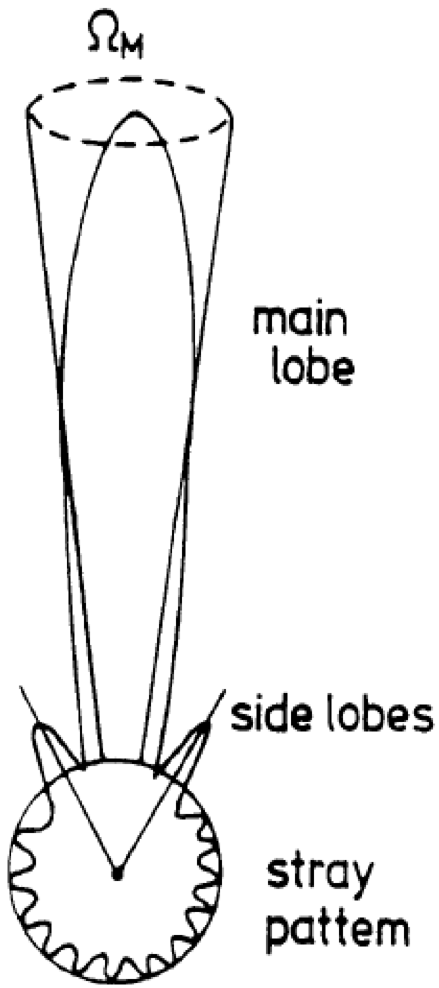
$$\theta = k\frac{\lambda}{D} \qquad \text{where } k \sim 1$$

- Radio beams also show Airy pattern
- lobes at various angles, directions where the radiated signal strength reaches a maximum
- nulls at angles where radiated signal strength falls to zero

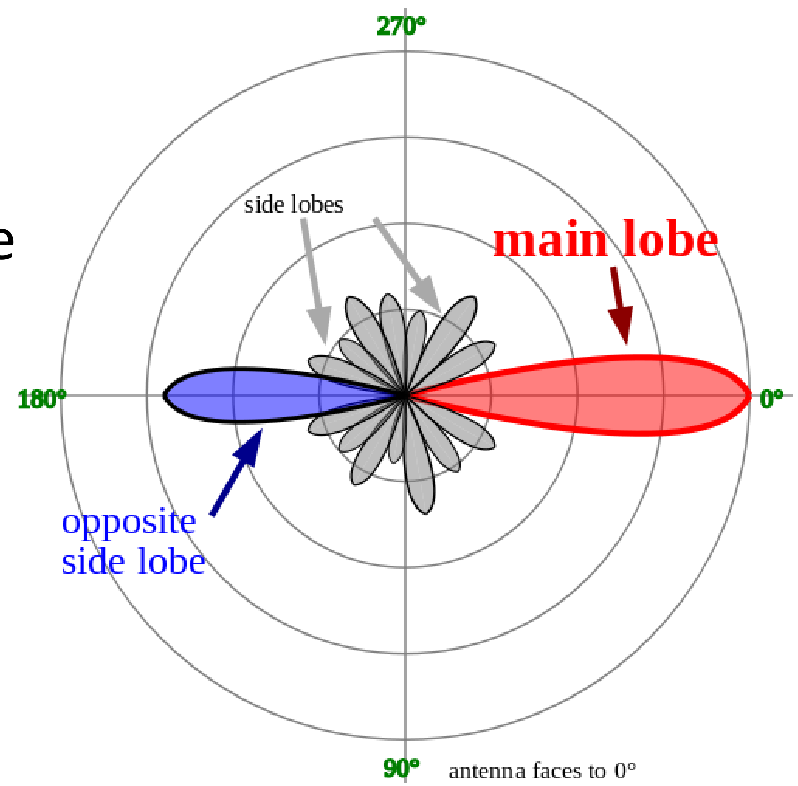


Main Beam and Sidelobes

Highest field strength in “main lobe”, other lobes are called “sidelobes” (unwanted radiation in undesired directions)



Side lobes may pick up interfering signals, and increase the noise level in the receiver.
The side lobe in the opposite direction (180°) from the main lobe is called the “back lobe”.



Main Beam Efficiency

The beam solid angle Ω_A in steradians of an antenna is given by:

$$\Omega_A = \iint_{4\pi} P_n(\vartheta,\varphi)\,d\Omega = \int_0^{2\pi}\int_0^{\pi} P_n(\vartheta,\varphi)\sin\vartheta\, d\vartheta\, d\varphi$$

With the normalized power pattern $$P_n(\vartheta,\varphi) = \frac{1}{P_{\max}} P(\vartheta,\varphi)$$

Main beam solid angle Ω_{MB} is:

$$\Omega_{MB} = \iint_{\text{main lobe}} P_n(\vartheta,\varphi)\,d\Omega$$

Main beam efficiency η_B, the fraction of the power concentrated in the main beam is $$\eta_B = \frac{\Omega_{MB}}{\Omega_A}$$

Main Beam Brightness Temperature

Relation between flux density S_ν and intensity I_ν:

$$S_\nu = \int_{\Omega_B} I_\nu(\theta,\varphi)\cos\theta \, \mathrm{d}\Omega$$

Definition of T_B:

$$T_B = \frac{c^2}{2k\nu^2} B_{RJ} = \frac{\lambda^2}{2k} B_{RJ}$$

For discrete sources, the source extent $\Delta\Omega$ is important. With $I_\nu = B_{RJ}$

$$S_\nu = \frac{2k\nu^2}{c^2} T_B \cdot \Delta\Omega$$

... or simplified for a source with a Gaussian shape:

$$\left[\frac{S_\nu}{\mathrm{Jy}}\right] = 0.0736 T_B \left[\frac{\theta}{\mathrm{arcsec}}\right]^2 \left[\frac{\lambda}{\mathrm{mm}}\right]^{-2}$$

Generally, for an antenna beam size $\vartheta_{\mathrm{beam}}$ the observed source size (for a Gaussian source) is:

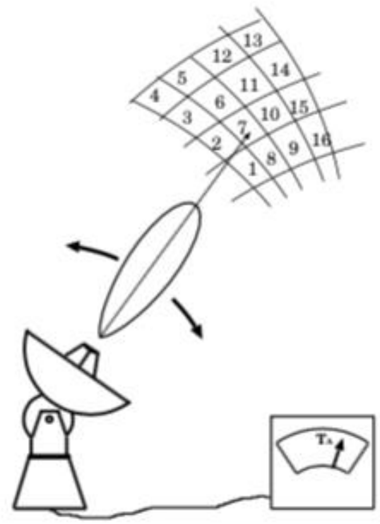
$$\theta_{observed}^2 = \theta_{source}^2 + \theta_{beam}^2$$

...which relates the true brightness temperature with the main beam brightness temperature:

$$T_{MB}\left(\theta_{source}^2 + \theta_{beam}^2\right) = T_B \, \theta_{source}^2$$

Radio cameras

- Traditionally, radio telescope are like single-pixel cameras in focus of diffraction-limited telescope

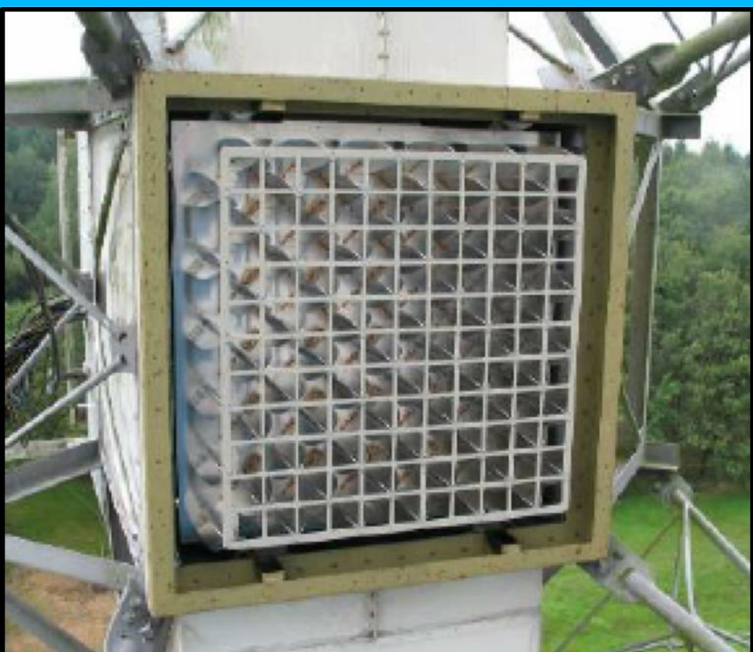
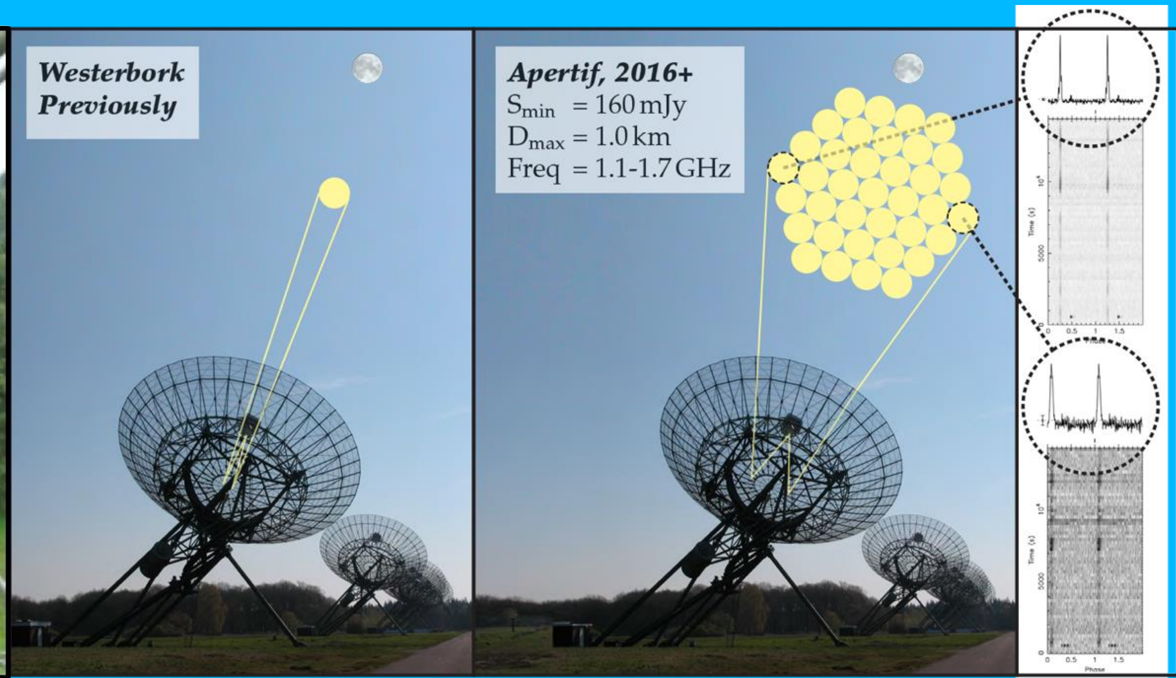


- Recent developments are focal plane arrays, i.e. APERTIF on Westerbork

Westerbork Synthesis Radio Telescope
-- APERTIF --

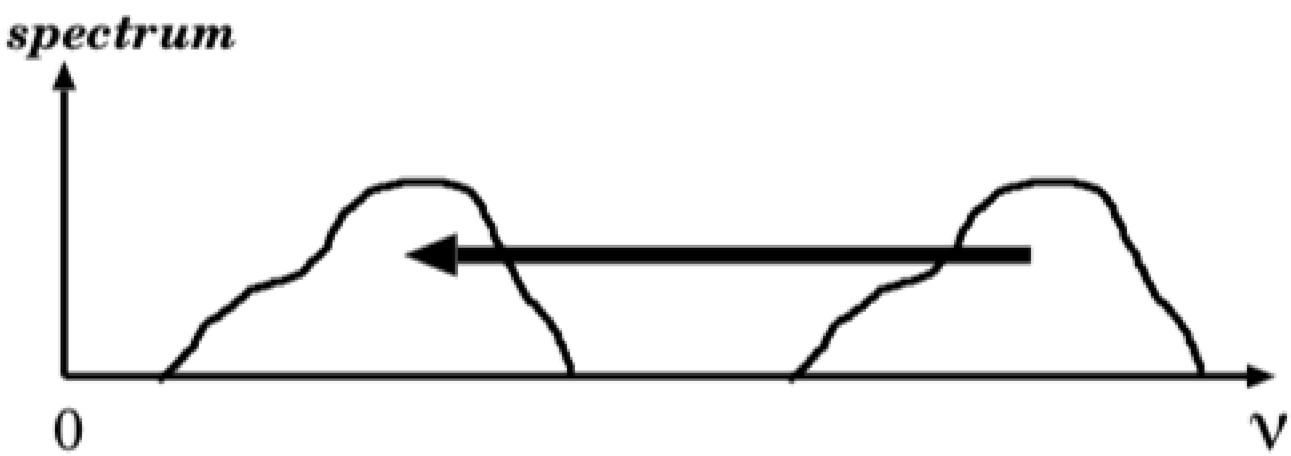
APERTIF
APERture Tile In Focus
ASTRON

- APERture Tile In Focus:
  APERTIF replaces the ***single*** pixel detectors with an array of ***121 detectors*** forming up to ***40 beams***

Frequency down conversion

If a radio signal is band limited, that means it has zero spectral power outside a certain frequency range. We can shift the central frequency of such a signal (usually to the lower side) without losing any spectral information.



Need for frequency down conversion

- Problems with detecting and amplifying signals (without adding to much noise) at high frequencies
- I.e. higher frequencies have frequencies too high to sample for standard electronics / detectors

$\lambda = 1\ \mu m$	$\Leftrightarrow$	$\nu = 300$ THz	$\Leftrightarrow$	$\Delta t = 3.3 \cdot 10^{-15}$ s	
$\lambda = 100\ \mu m$	$\Leftrightarrow$	$\nu = 3$ THz	$\Leftrightarrow$	$\Delta t = 3.3 \cdot 10^{-13}$ s	
$\lambda = 1$ cm	$\Leftrightarrow$	$\nu = 30$ GHz	$\Leftrightarrow$	$\Delta t = 33$ ps	
$\lambda = 10$ cm	$\Leftrightarrow$	$\nu = 3$ GHz	$\Leftrightarrow$	$\Delta t = 3$ ps	
$\lambda = 1$m	$\Leftrightarrow$	$\nu = 300$ MHz	$\Leftrightarrow$	$\Delta t = 0.3$ ps	LOFAR uses standard electronics
$\lambda = 10$m	$\Leftrightarrow$	$\nu = 30$ MHz	$\Leftrightarrow$	$\Delta t = 30$ ns	

In 1 ns travels light 30 cm

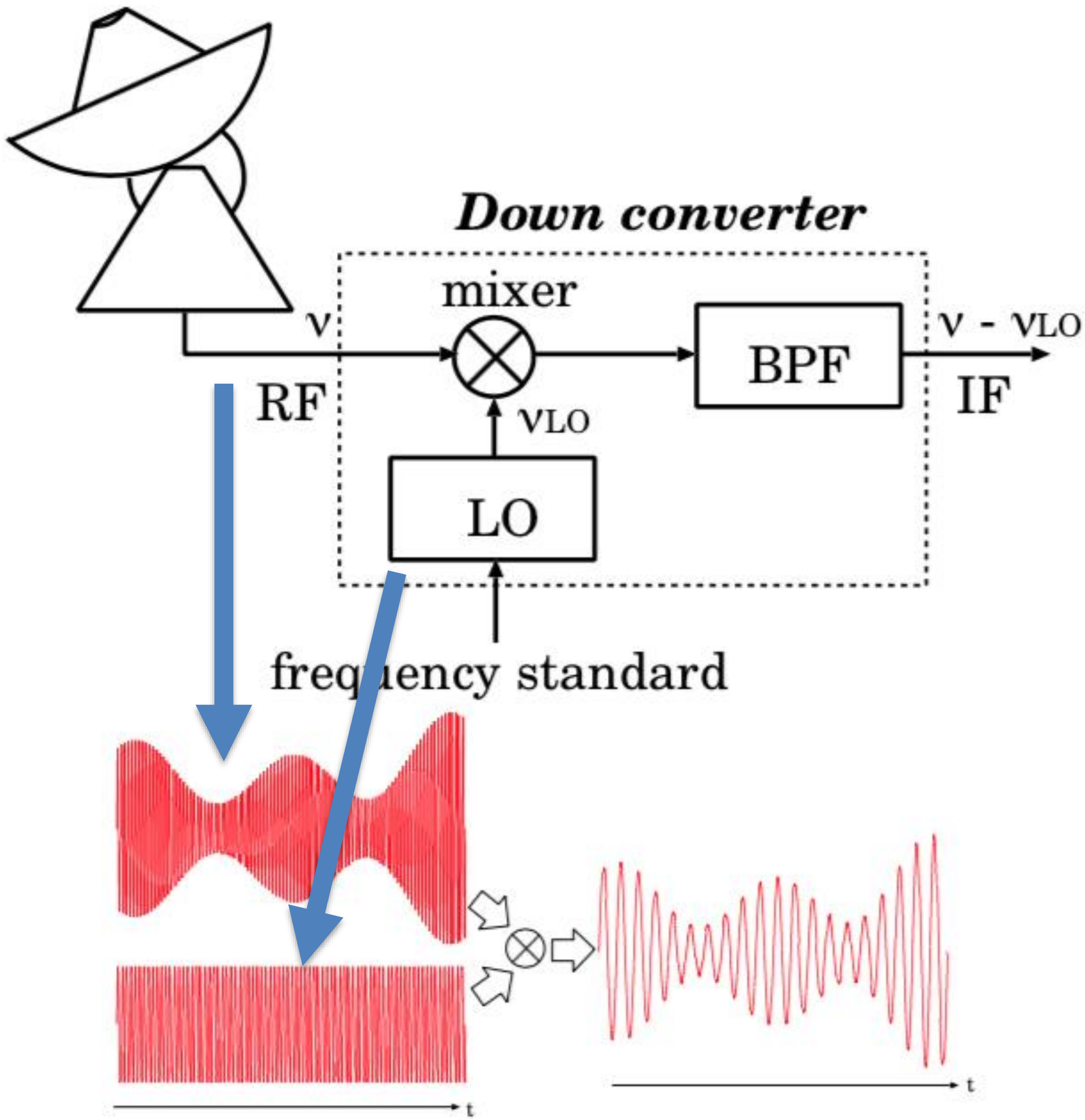


Figure 108: Elements and technical terms used in the frequency conversion.

- **radio frequency (RF)**: the high frequency involved in the band which is directly received by an antenna, sometimes called also as "sky frequency",
- **intermediate frequency (IF)**: the low frequency obtained by the frequency conversion,
- **local oscillator (LO)**: an oscillator which provides a sinusoidal reference signal with a specified frequency,
- **mixer**: a nonlinear device which multiplies the reference signal to the received signal,
- **bandpass filter (BPF)**: a filter which passes only necessary band of the intermediate frequency and cuts off all other frequency components in the output from the mixer,
- **down converter**: a unit composed of the LO, mixer and BPF which converts RF ν to IF $\nu - \nu_{LO}$, where ν_{LO} is the frequency of the reference signal provided by the LO which is often called "LO frequency",
- **superheterodyne receiver**: a receiver based on the frequency conversion technique.

Figure 108 shows elements of the frequency conversion. For example, in a typical Mark III–type geodetic VLBI observation at 8 GHz, we can choose 8180 MHz $\sim$ 8600 MHz as the RF band and 8080 MHz as the LO frequency ν_{LO} to get 100 MHz $\sim$ 520 MHz as the IF band.

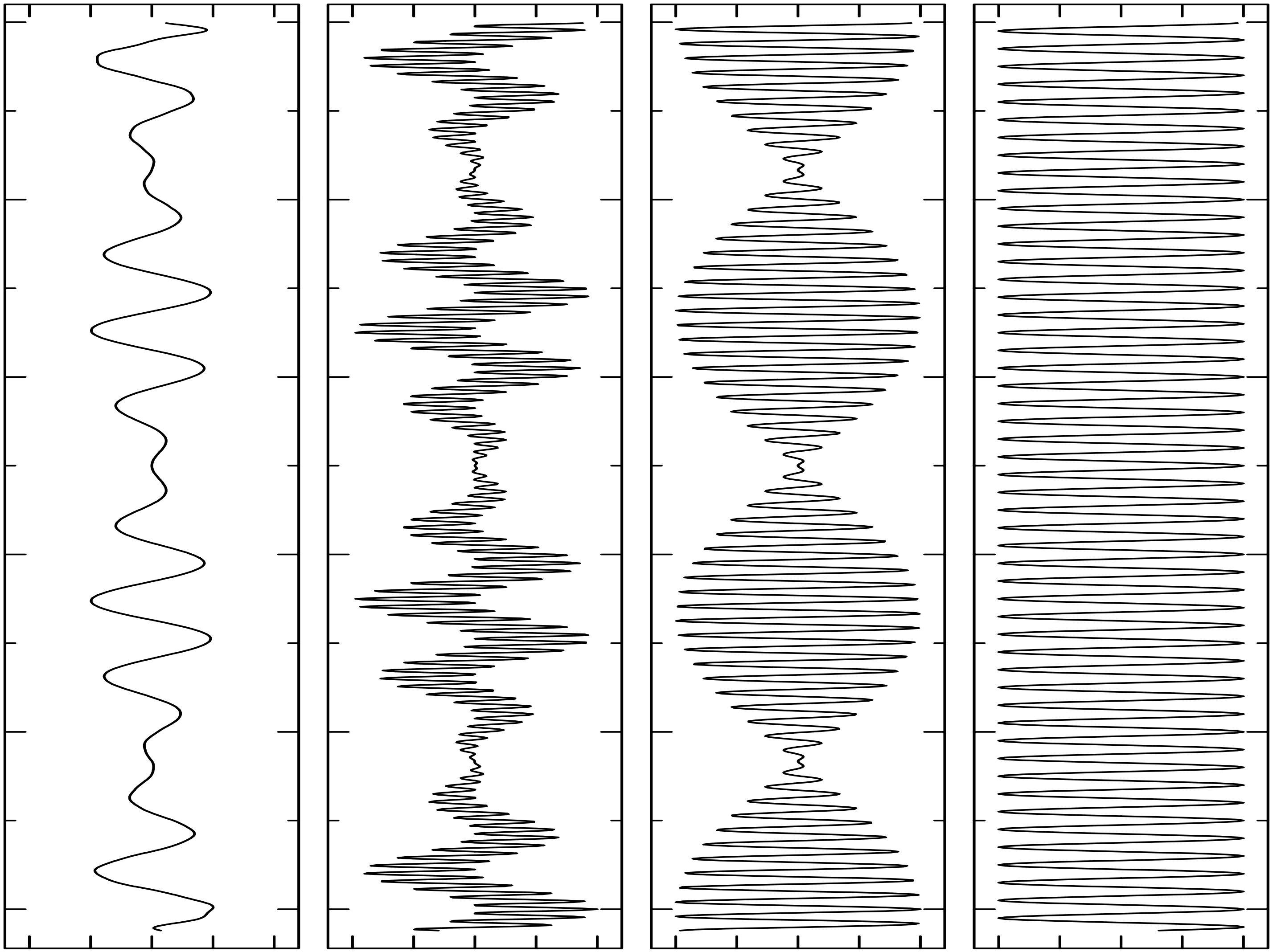
Principle of Frequency Mixing

- Multiply (mix) radio-frequency signal ($A \sin \omega_S t$) with fixed-frequency signal (ω_{LO}, local oscillator) in middle of desired frequency band

$$A \sin \omega_S t \cdot \sin \omega_{LO} t$$
$$= \frac{A}{2}\{\cos[(\omega_{LO} - \omega_S)t] - \cos[(\omega_{LO} + \omega_S)t]\}$$

- Generates sum and difference frequency signals
- Frequency difference much smaller than radio-frequency signal for $(\omega_{LO} - \omega_S)/\omega_S \ll 1$
- Also called heterodyning, resulting signal also called intermediate frequency (IF) signal

Mixing Example

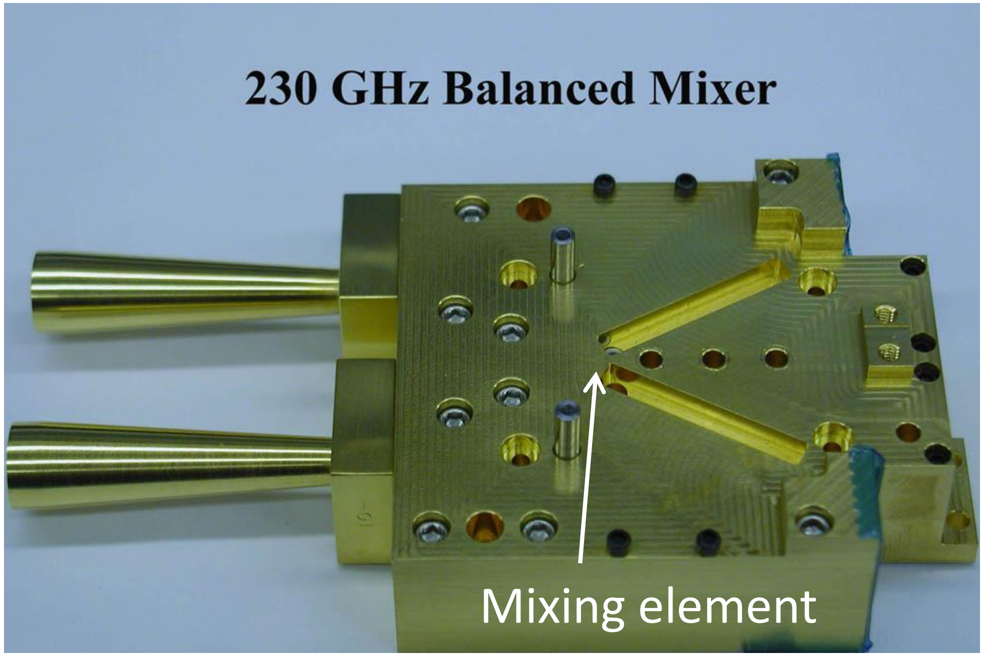


Mixer Technology

Example of a mixer:

Source signal →

Local oscillator signal →



Problem: good & fast "traditional" photo-conductors only exist for low frequencies

➔
- Schottky diodes
- SIS junctions
- Hot electron bolometers

The term “Back End” is used to specify the devices following the IF amplifiers. Many different back ends have been designed for specialized purposes such as continuum, spectral or polarization measurements.

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Further Information

- Essential Radio Astronomy: science.nrao.edu/opportunities/courses/era/
- http://iaaras.ru/media/library/kchap2.pdf
- MSc course on Radio Astronomy