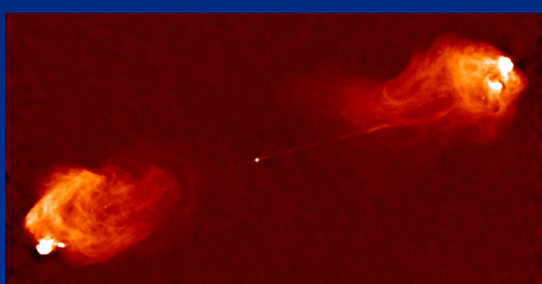
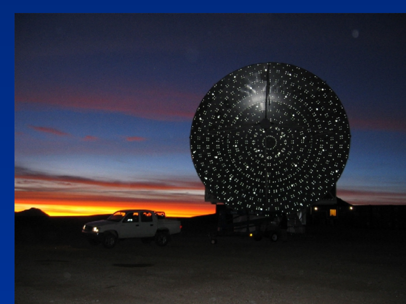
Radio Astronomy

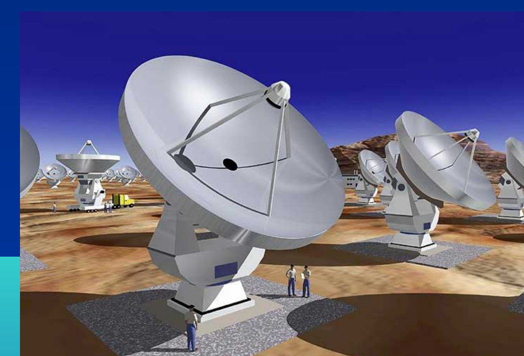
PD Dr. Henrik Beuther and Dr. Hendrik Linz

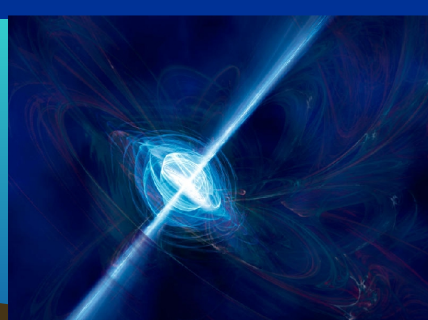
MPIA Heidelberg

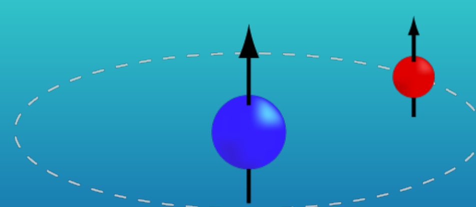
An elective lecture course for the winter term 2012/13 at the Ruperto Carola University Heidelberg











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23.10. Emission mechanisms, physics of radiation (HB)
30.10. Telescopes – single-dish (HL)
06.11. Telescopes – interferometers (HB)
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11.12. Radiation transfer (HL)
18.12. Buffer ...
08.01. Molecules and chemistry (HL)
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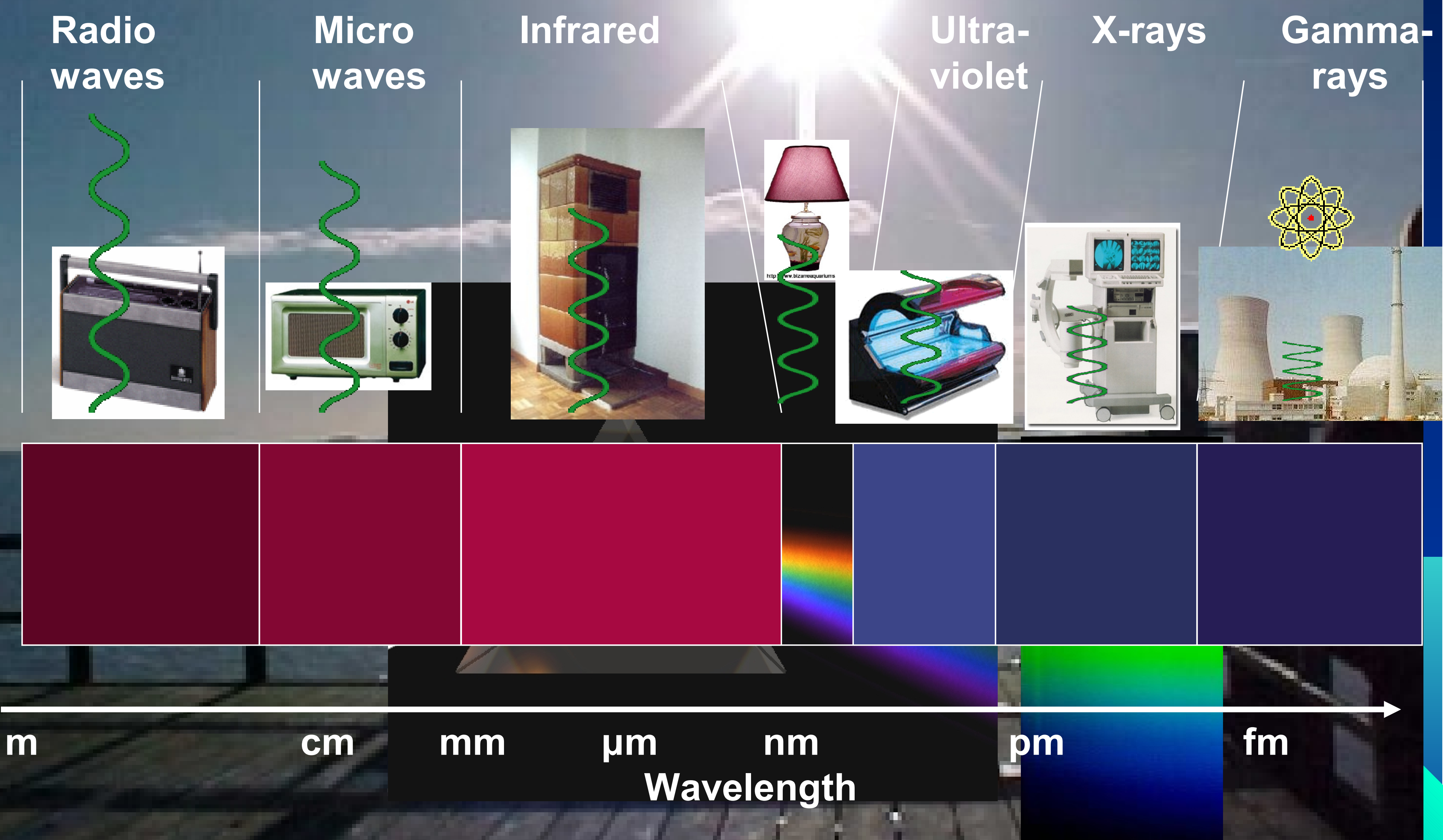
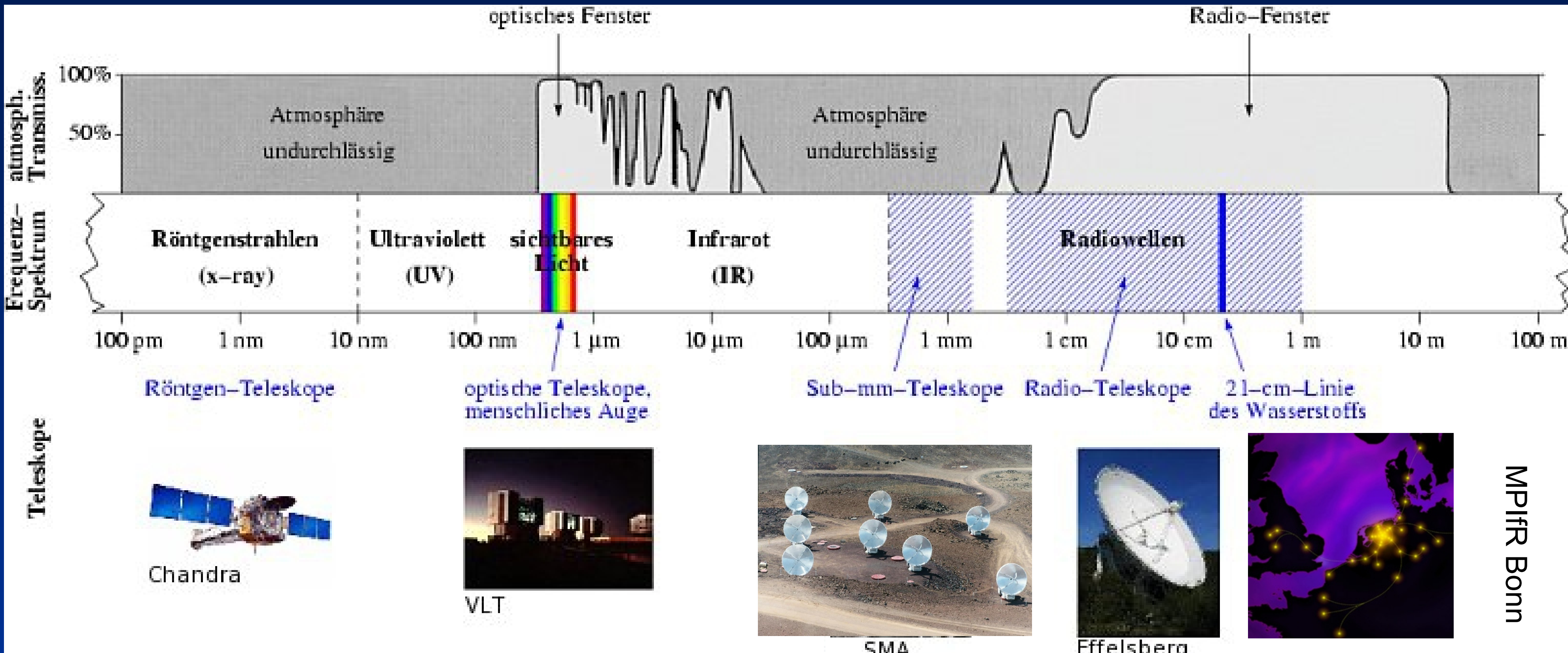
22.01. Applications (HL)
29.01. Applications (HB)
05.02. Exam week

The electromagnetic spectrum



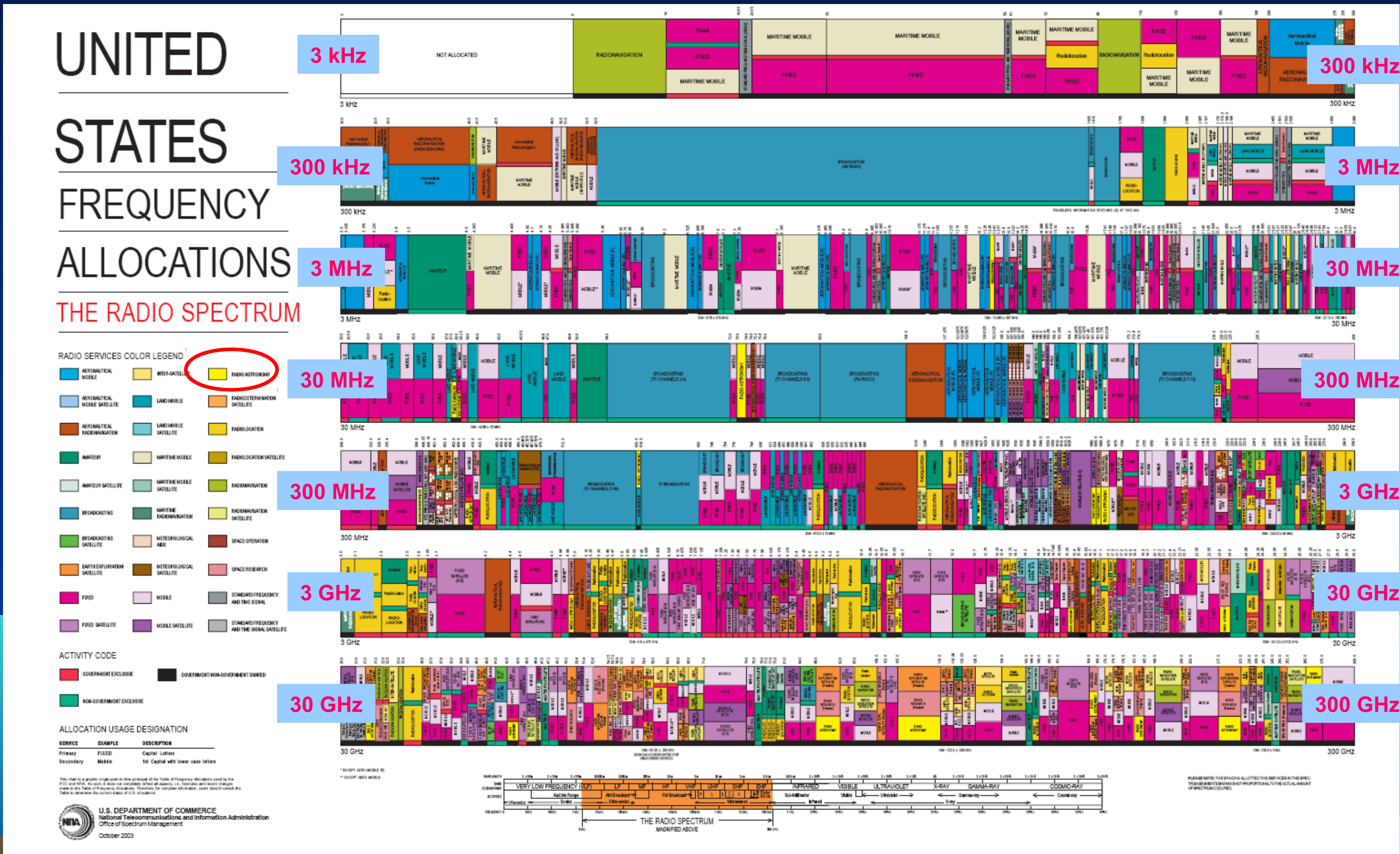
Radio signals and the Earth atmosphere



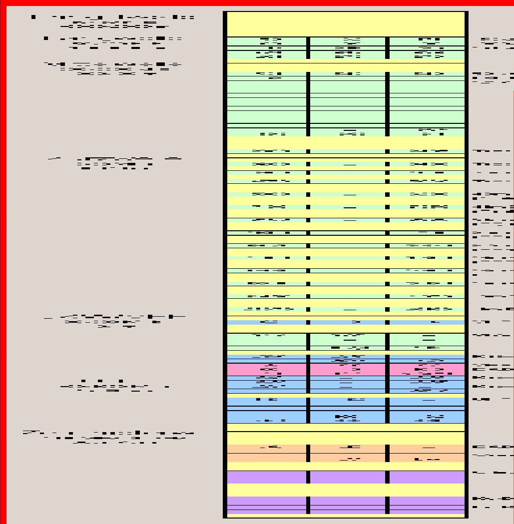
Remember: speed of light = wavelength x frequency

$$c = \lambda \times \nu$$

Terrestrial Frequency Mess-up . . .



Actual radio and television . . .



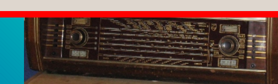
Kurzwelle
3-30 MHz
100-10 m

3200	...	3400	Tropenband (3200-3400 kHz) / 41 Kanäle
3900	...	4000	75m Band (3900-4000 kHz) / 21 Kanäle
4750	...	5060	Tropenband (4750-5060 kHz) / 63 Kanäle
5900	...	6200	49m Band (5950-6200 kHz) / 51 Kanäle (*) (*) ab 2007 5900-6200 kHz / 61 Kanäle
7100	...	7350	41m Band (7100-7300 kHz) / 41 Kanäle (**) (**) ab 2007 7100-7350 kHz / 51 Kanäle
9400	...	9990	31m (***
11600	...	12100	25m (****
13570	...	13870	22m (****
15100	...	15800	19m (****
17480	...	17900	16m (****
18900	...	19020	15m
21450	...	21850	13m
25670	...	26100	11m

UKW/VHF
30-300 MHz
10-1 m

UHF
300-1000 MHz
1m-30cm

K2	K3	K4	VHF Band I (TV) (48-68 MHz) / 3 TV-Kanäle
87,5	87,6	...	UKW (87.5-108 MHz) / 69 Kanäle / 205 Frequenzen
...	...	...	
...	...	...	
...	107,9	108	
S04	S05	..	Kabel Sonderkanäle (TV) (125-170 MHz) / 12 TV-Kanäle
..	S09	S10	
K5	K6	K7	VHF Band III (TV) (175-230 MHz) / 8 TV-Kanäle
K8	K9	K10	DAB Band III (175-235 MHz) / 38 DAB Kanäle
K11	K12	K13/S11	
S12	...	S20	Kabel Sonderkanäle S12-S25 (TV) (235-335 MHz) / 14 TV-Kanäle
S21	...	S25	
S26	...	...	Kabel Hyperband S26-S38 (TV) (340-440 MHz) / 13 TV-Kanäle
...	...	S38	
K21	K22	...	UHF Band III (TV) (470-850 MHz) / 45 TV-Kanäle
...	...		
...	K61	K62	
K63	K64	K65	



. . . Some more human-made radio sources …

Garage door openers:	*~ 40 MHz*
cordless phones:	*40 – 50 MHz*
Remote-controlled miniature cars and planes:	*72 - 75 MHz*
Sender for tracing wildlife:	*215 – 220 MHz*
Some mobile phones:	*824 – 849 MHz*
GPS System:	*1227 + 1575 MHz*
Galileo System:	*1176 + 1279 + 1575 MHz*
Microwave ovens:	*2.7 GHz*
ASTRA Satellite:	*11.7 GHz*

Radio Astronomy … what's covered?

***Classical radio range*: centimeter and meter waves,**
MHz and GHz frequencies (< 30 GHz),
ionosphere reflects signals below 10 MHz

***Millimeter range*: mm waves, i.e. 10 … 1 mm**
(30 - 300 GHz),
atmospheric windows at 7, 3 and 1.3 mm

***Sub-millimeter range*: ~ 300 – 1000 µm**
(1000 … 300 GHz), atmospheric windows at 350, 450 and 850 µm (only at good sites useful !)

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Radio Astronomy … what we will cover:

All wavelength ranges where the electromagnetic field can be directly accessed by the measurement equipment:

> ***I.e., field amplitudes and field phases accessible, not only the intensities!***

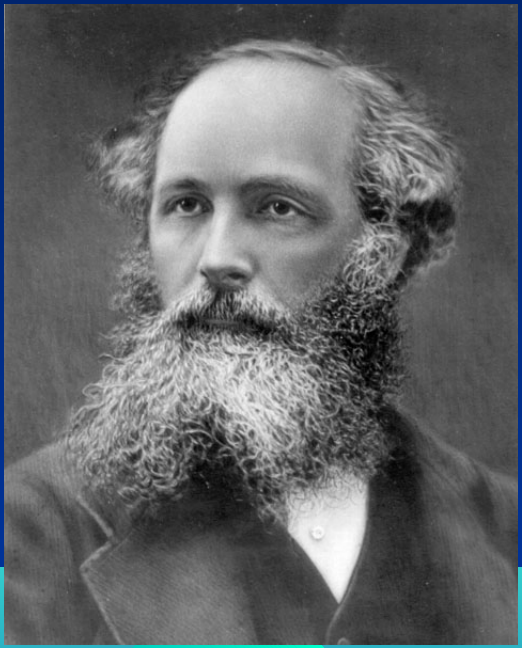
<u>Heterodyne technique</u> can be used in this case,
a differential measurement technique with very high spectral resolution (> 10^6)

The GREAT heterodyne instrument onboard the SOFIA stratospheric observatory operates up to 5 THz!
(This is 60 μm = 0.06 mm wavelength)

Before it began . . .

The physical foundations: J.C. Maxwell and Heinrich Hertz

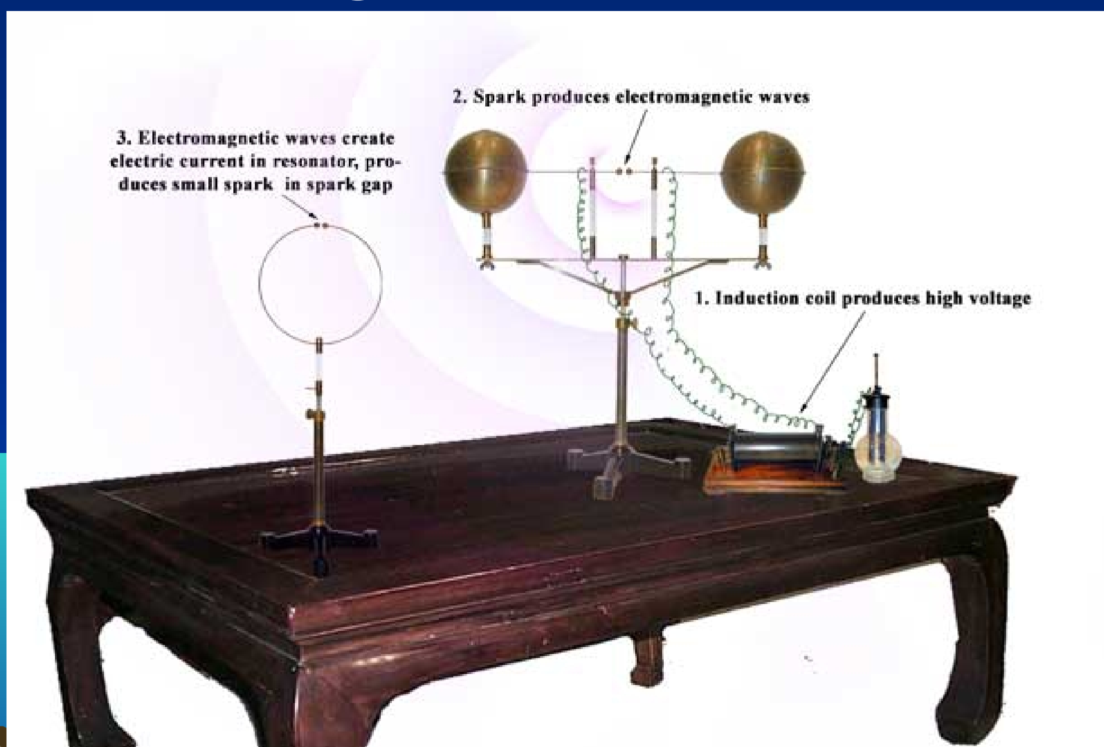
- **1864 James Clerk Maxwell: recognises the relevance of d/dt D (displacement current)**
- **d/dt D as last missing link to have the complete set "Maxwell equations"**
- **Wave equations for E and B result: prediction of electro-magnetic waves**

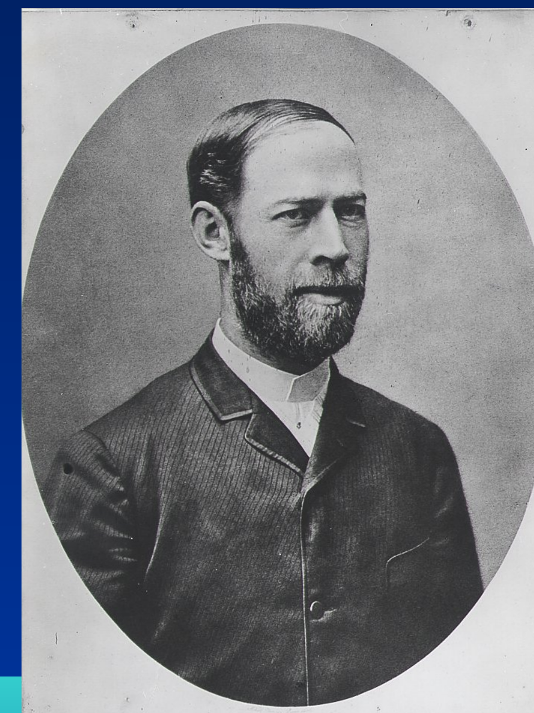


Before it began . . .

The physical foundations: J.C. Maxwell and Heinrich Hertz

- **1888 Heinrich Hertz: first experimental emission and detection of electro-magnetic radio waves**
-





How it all began . . .

The pioneers of radio astronomy: Jansky and Reber

- **1932 Karl Jansky finds radio emission of cosmic origin at 15 m wavelength (20.5 MHz), spatial resolution ~ 30°**
- **1937 Grote Reber uses his self-made 9.4-m parabola antenna in his backyard,**
  first mapping of galactic radio emission at 1.9 m (160 MHz), spatial resolution 12°, published in 1940
- **World War II: radio astronomy stalled, but radar technology booms**

How it all began . . .

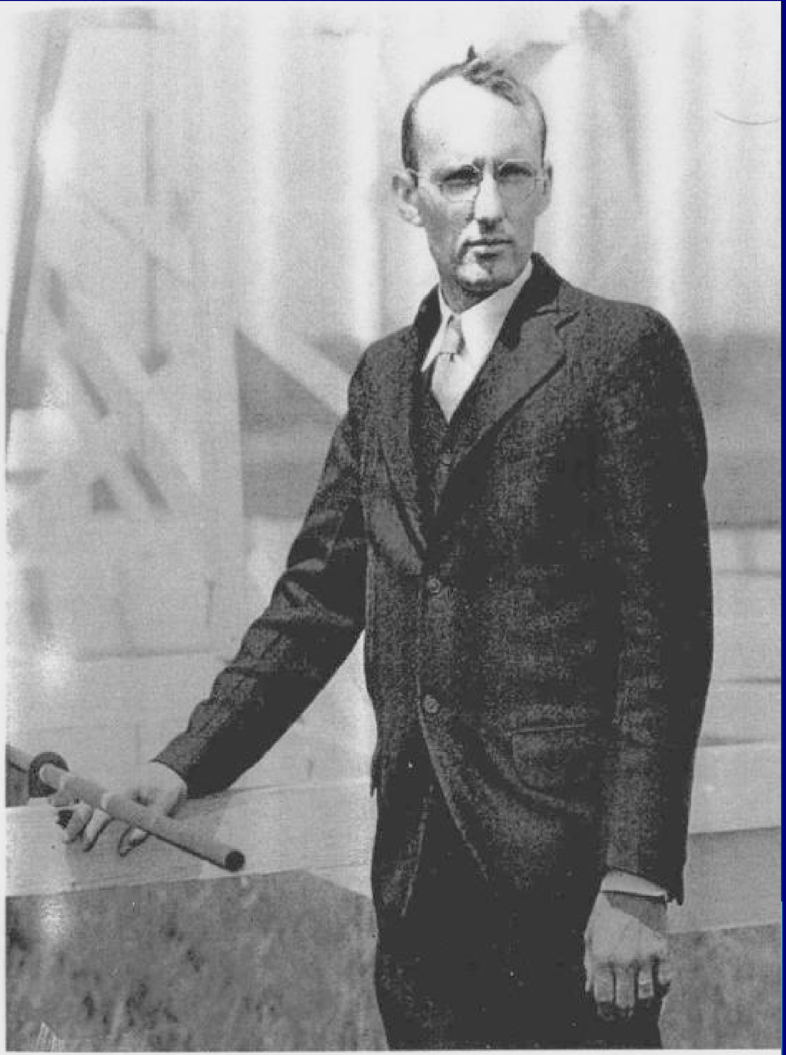
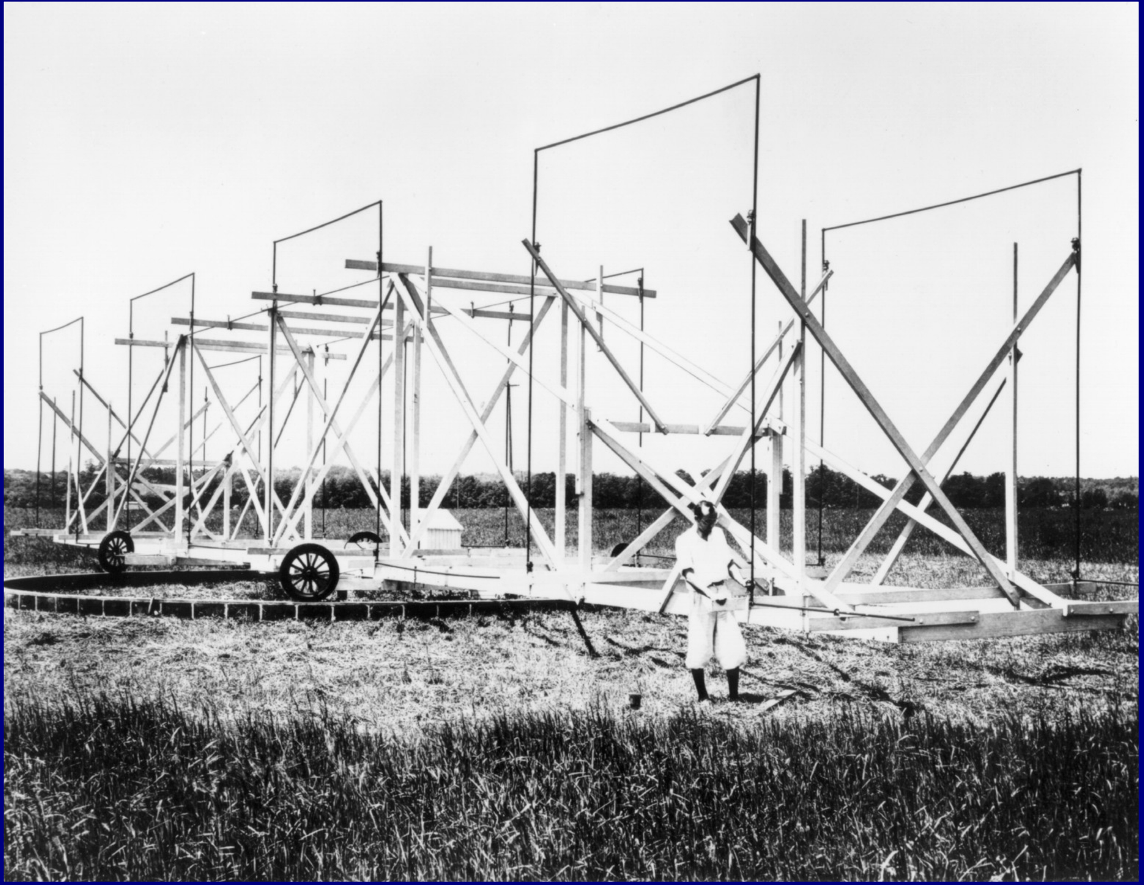


Fig. 1—Karl Guthe Jansky, about 1933.



Jansky with his 30-m dipole antenna

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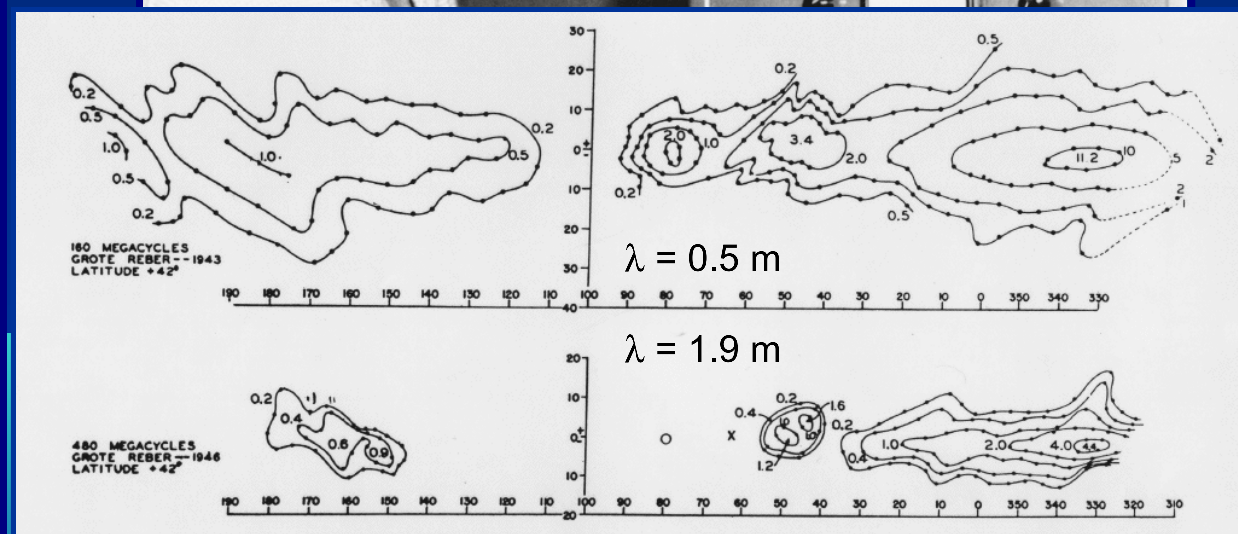

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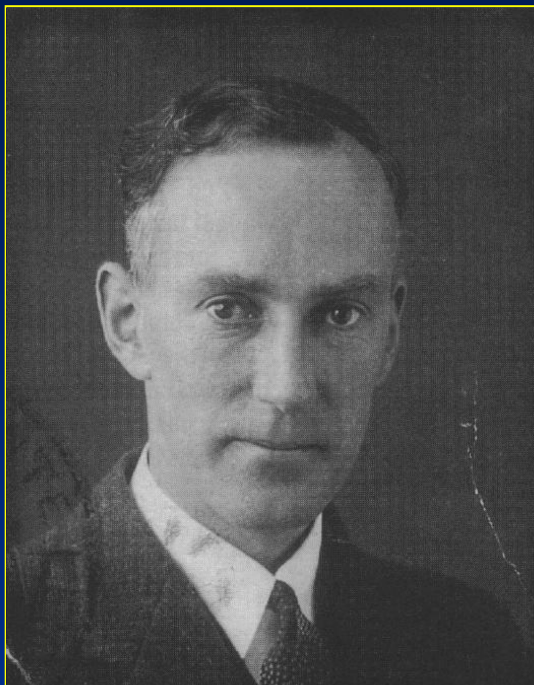
Opening a new door of research: Search for neutral hydrogen



Jan H. Oort (1900-1992)

Hendrik van de Hulst (1918-2000)

1944:

Theoretical search for astrophysical mechanisms for radio spectral lines

$\Rightarrow$ hyper fine structure transition

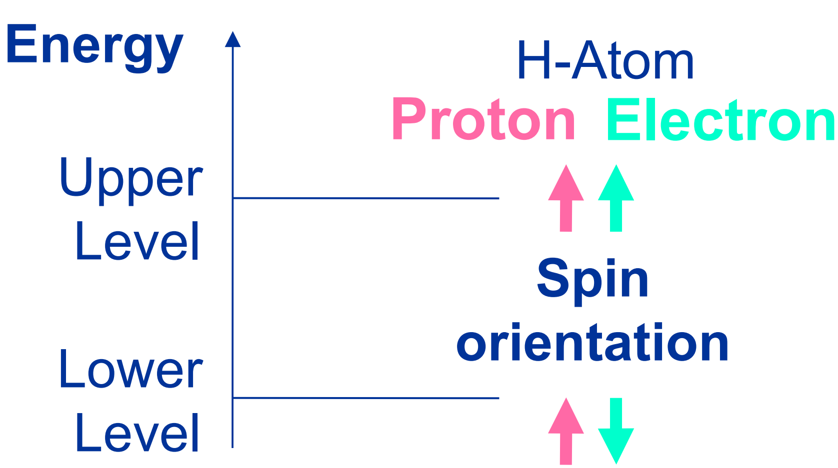
H $\quad$ $F = 1 \rightarrow 0$

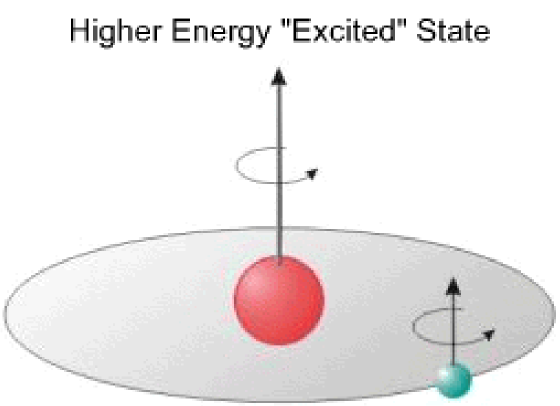
Line predicted at λ = 21.1cm

ν =1420 MHz

Prediction by van de Hulst (NL) and independently by Shklovsky (USSR)

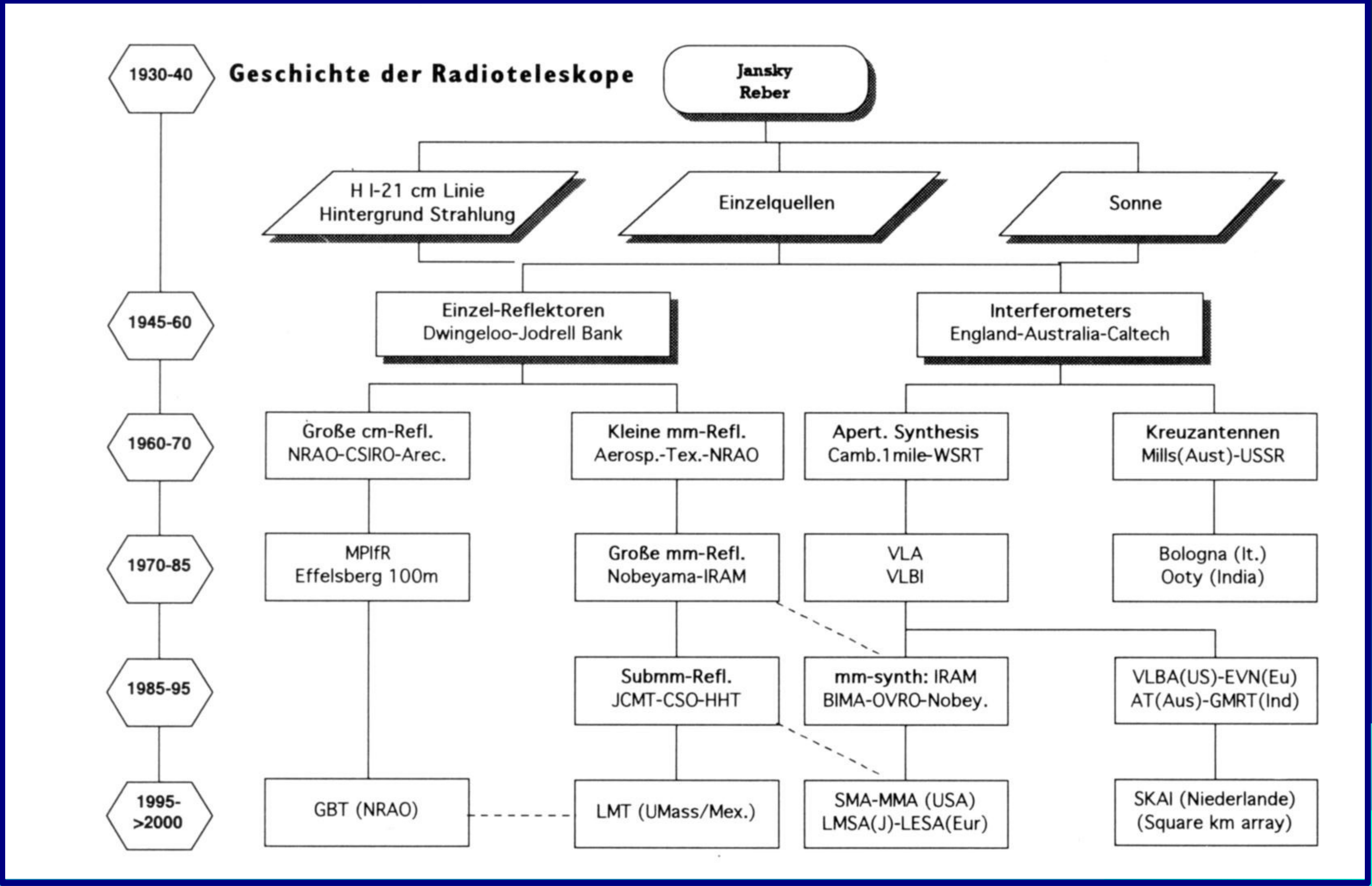
1951: final detection in interstellar space by 3 independent groups



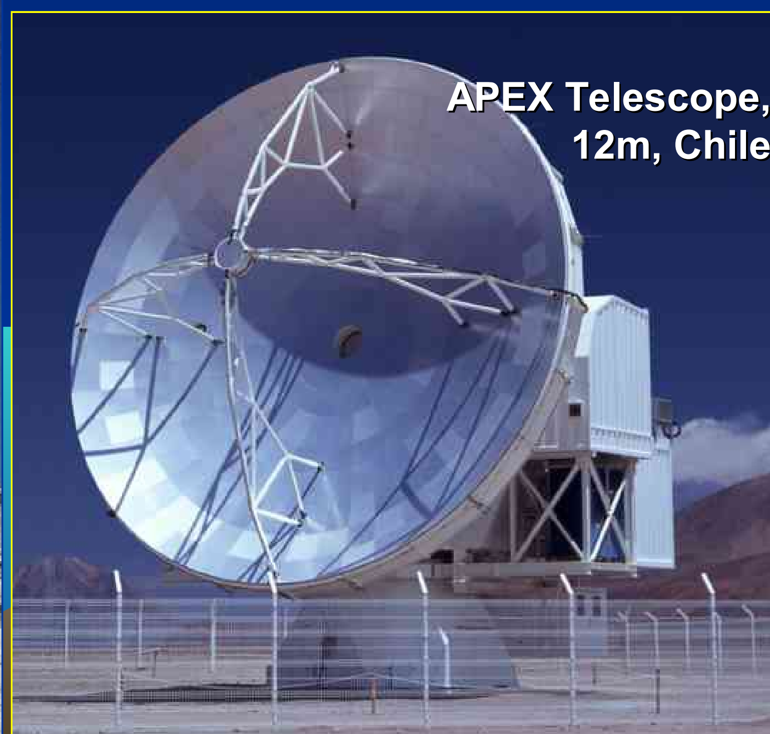


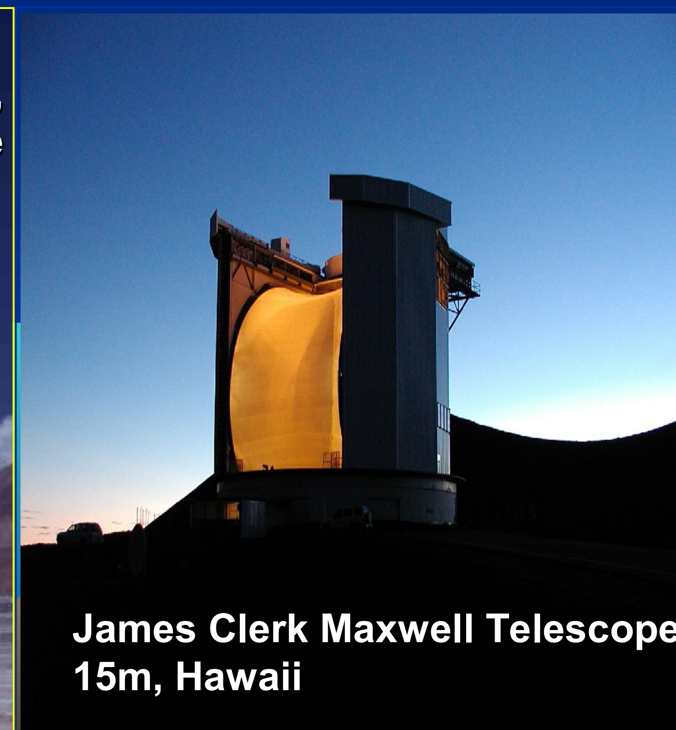
1s $^1S_{1/2}$

History – Flow chart

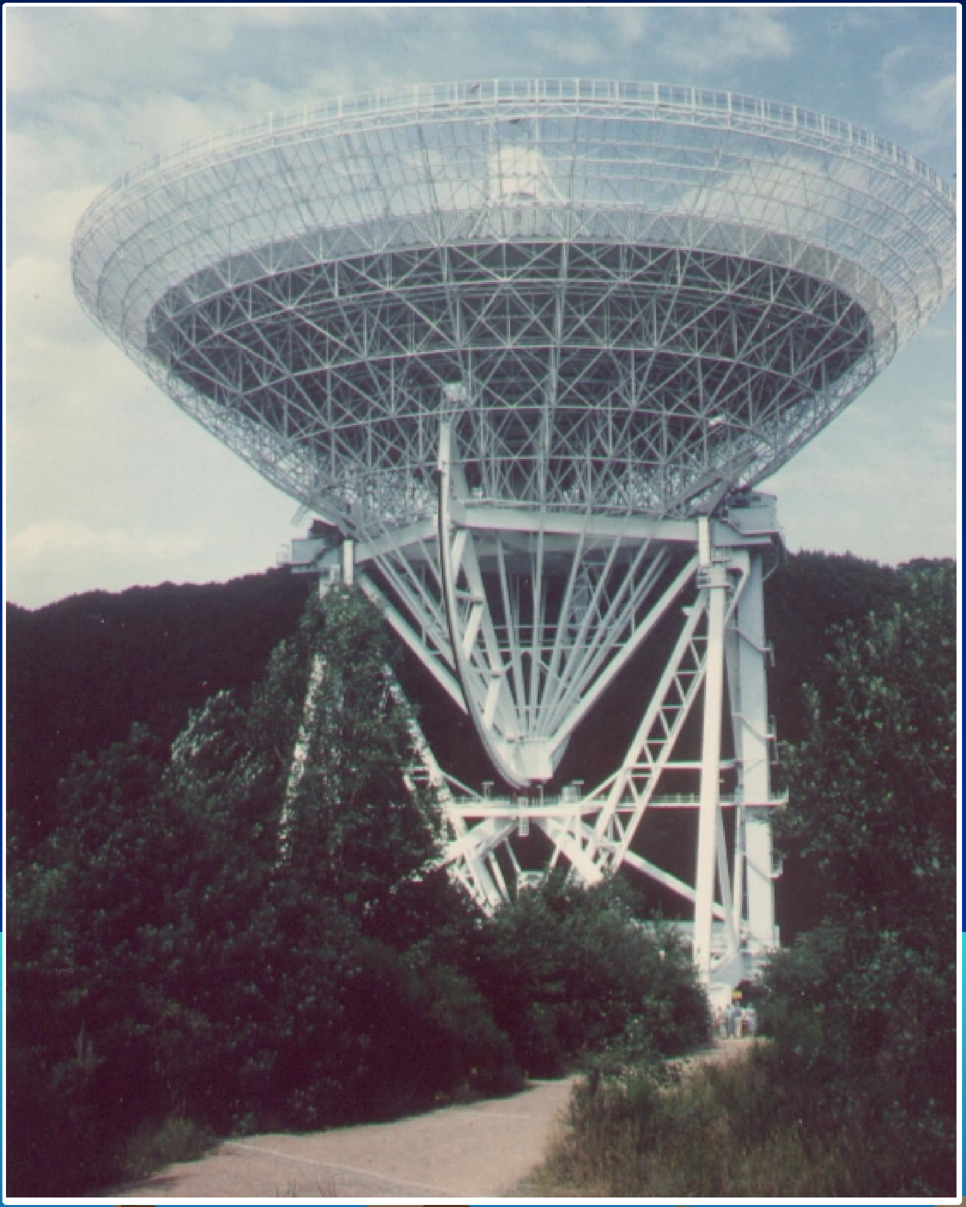


Single-dish radio telescopes in operation





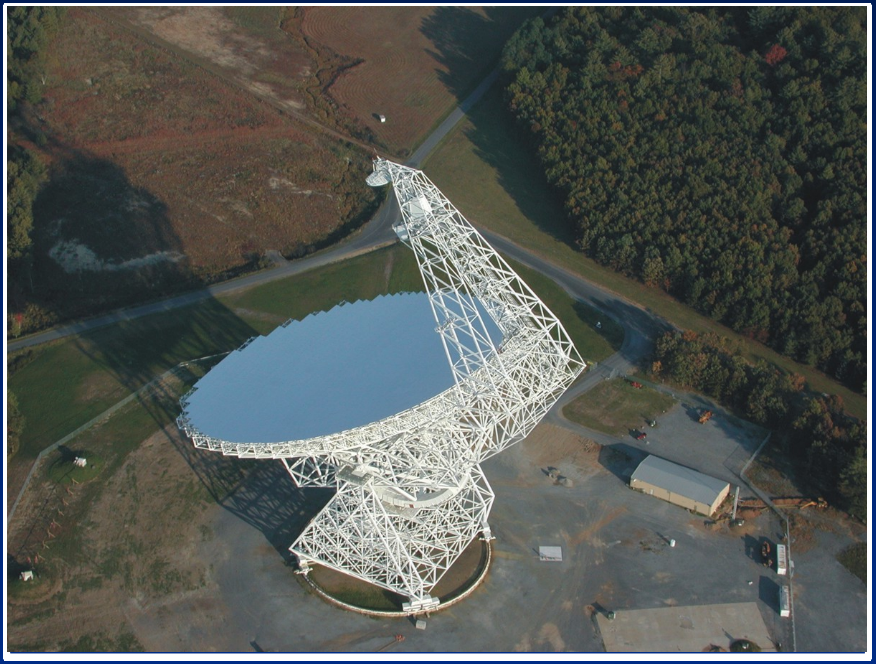
Larger and larger Antennas (I)

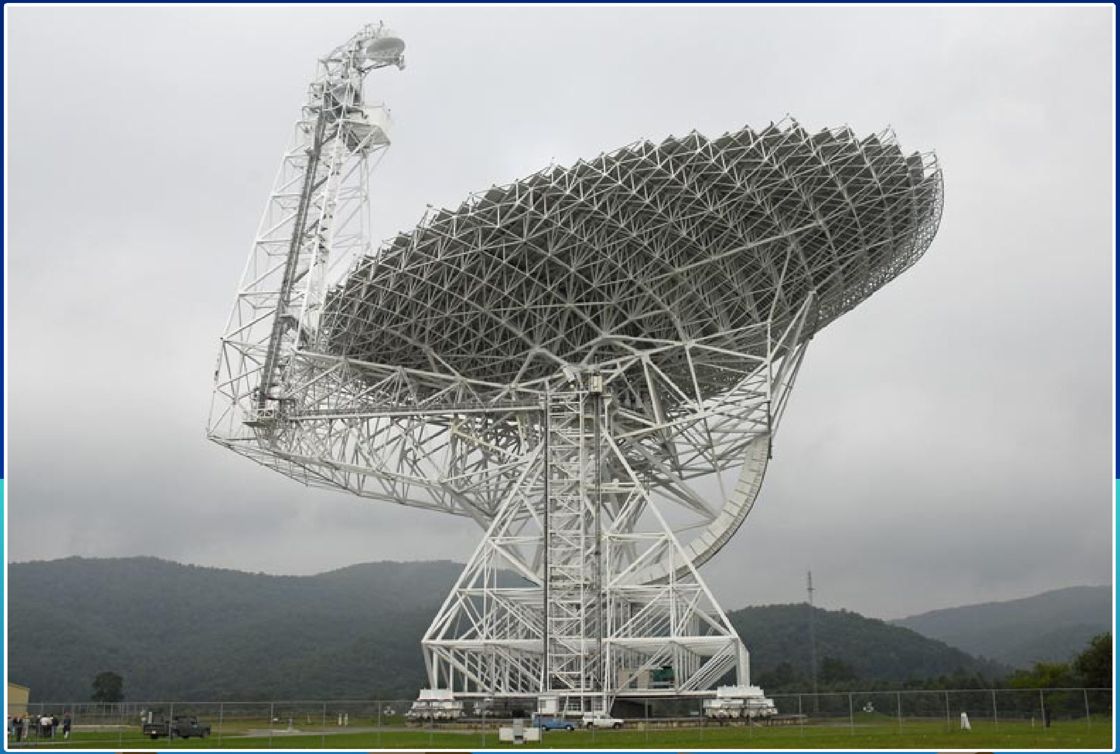


100-m Effelsberg Telescope in the Eifel (Germany)
"domestic telescope" of the Max-Planck-Institute for Radio Astronomy (MPIfR) in Bonn, wavelengths as short as 7 mm are possible

Larger and larger Antennas (II)

110-m Green-Bank Telescope (GBT) in West Virginia (USA)



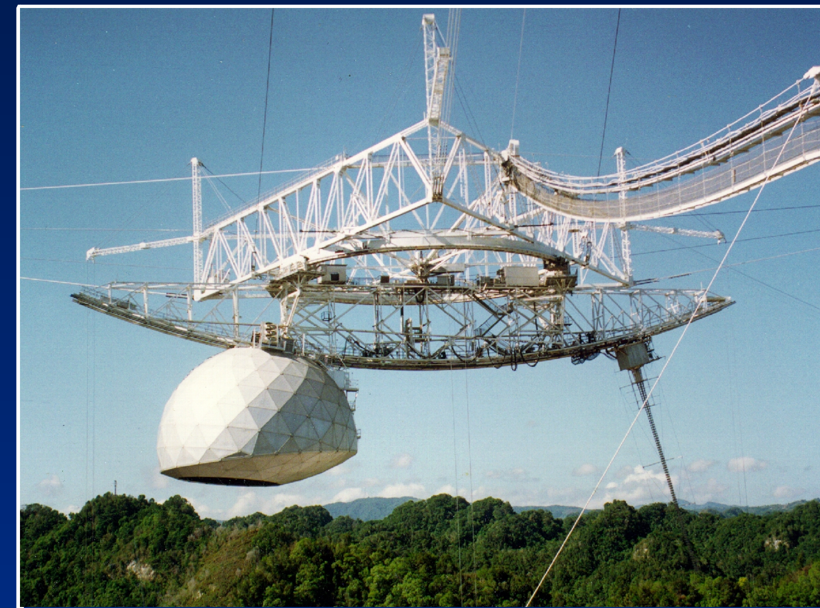


Special design with off-axis secondary mirror,

Wavelengths as short as 3 mm can be handled ...

Larger and larger Antennas (III)

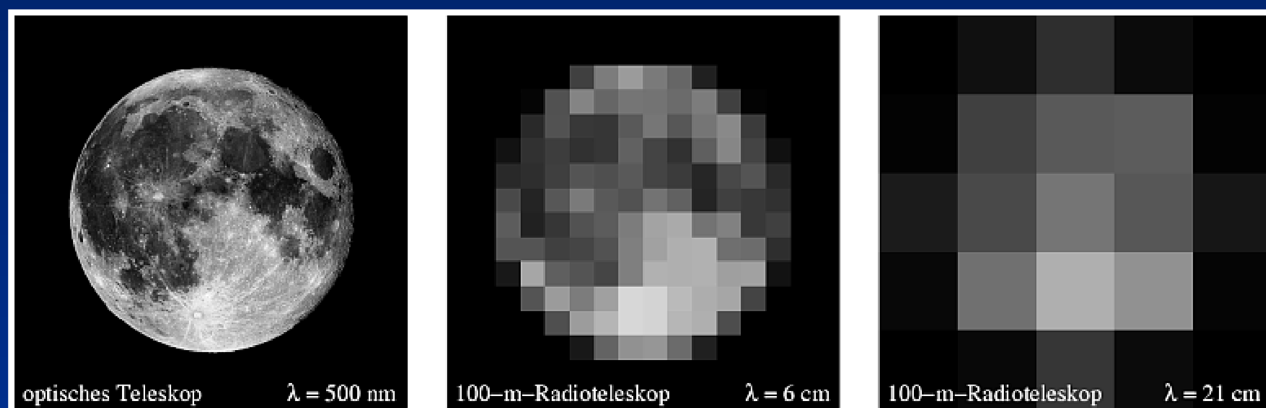
305-m Arecibo Telescope in Puerto Rico (USA)



Main dish not steerable, celestial objects tracked by moving the secondary mirror,
Wavelengths as short as 3 cm are possible

Modest spatial resolution for single-dish radio telescopes

The full moon (angular diameter ~ 30 arcminutes):
Observations in the optical and (via simulations) with the 100-m Effelsberg Telescope.



MPIfR Bonn

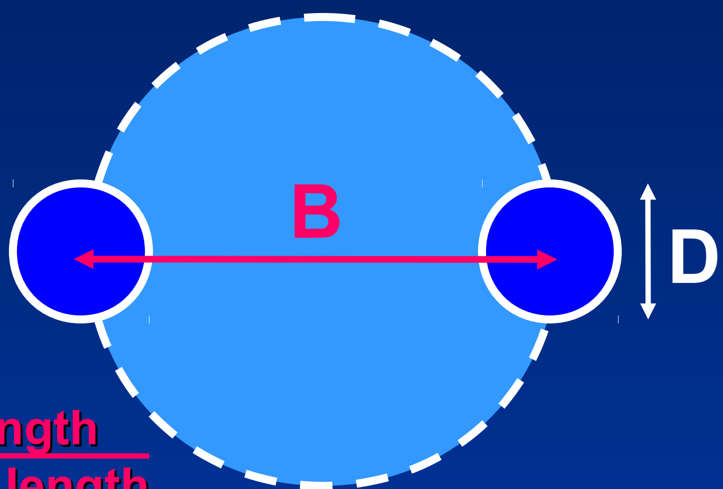
$\lambda = 0.00005$ cm $\lambda = 6$ cm $\lambda = 21$ cm

Keep in mind: angular resolution ~ $\dfrac{\text{wavelength}}{\text{telescope diameter}}$

The solution: Interferometry

Combining several telescopes by utilising the interference properties of electro-magnetic waves: e.g., in form of a Michelson-Interferometer

Achievable resolution is now depending on the baseline length B:

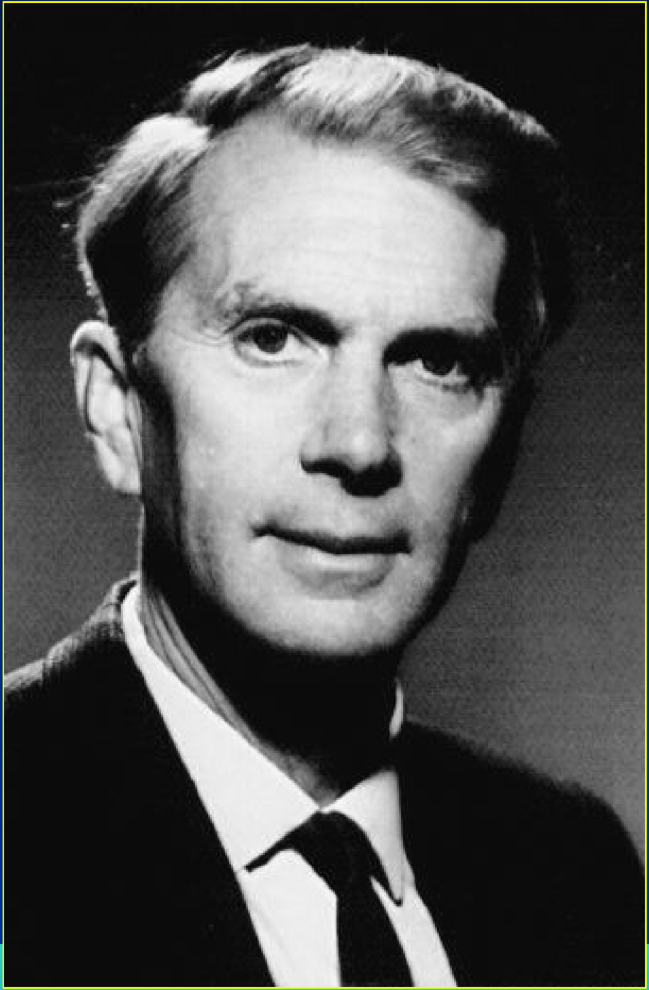


Angular resolution ~ Wavelength / Baseline length

But: The virtual large telescope is not "filled"! No direct images right away …

→ Take many telescopes and employ the earth rotation in order to change the projected baseline lengths and position angles!

The interferometric principle applied ... The 1950s ...



Sir Martin Ryle (1918-1984)

Ryle Telescope Array, University Cambridge

Radio interferometry + Aperture synthesis = high-fidelity maps !

⇒ **Nobel Price (1974)**

A few interferometer examples from the previous decade

ATCA Interferometer (Australia)
6 x 22 m

Plateau de Bure-Interferometer (France)
6 x 15 m

CARMA Interferometer (USA): 6 x 10 m + 9 x 6 m

The Very Large Array (VLA): 1980-2010

- In New Mexico, USA;
  27 Antennas with 25 m diameter, characteristic Y-shape
- Up to 351 base lines, very flexible, good instantaneous uv-coverage
- Receivers for λ = 4m–7mm (sub-divided in bands)
- 4 main configurations possible (16-months cycle),
  max. base lines 1 – 36 km,
  resolution @ 7mm: 1.5" – 0.05"

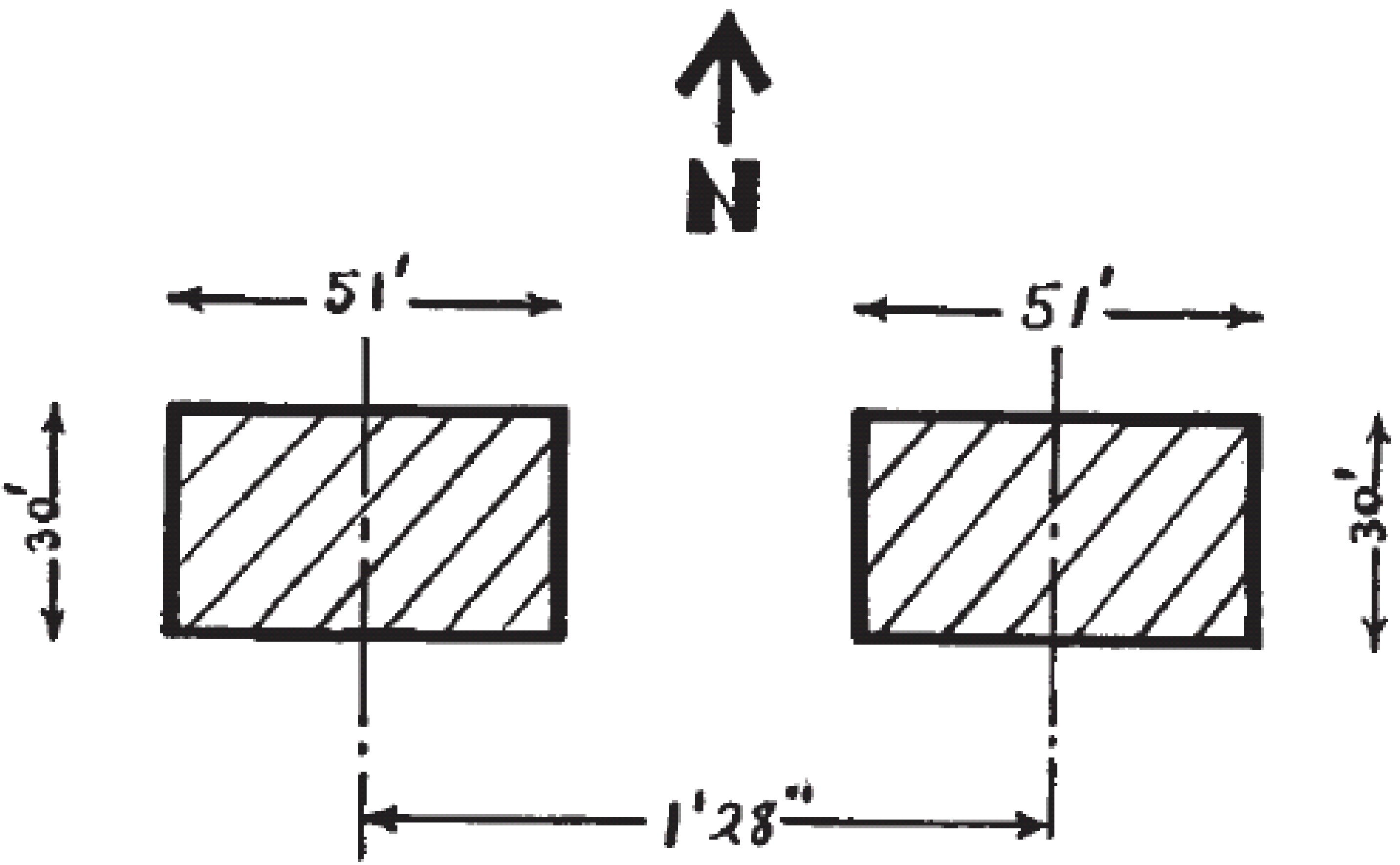
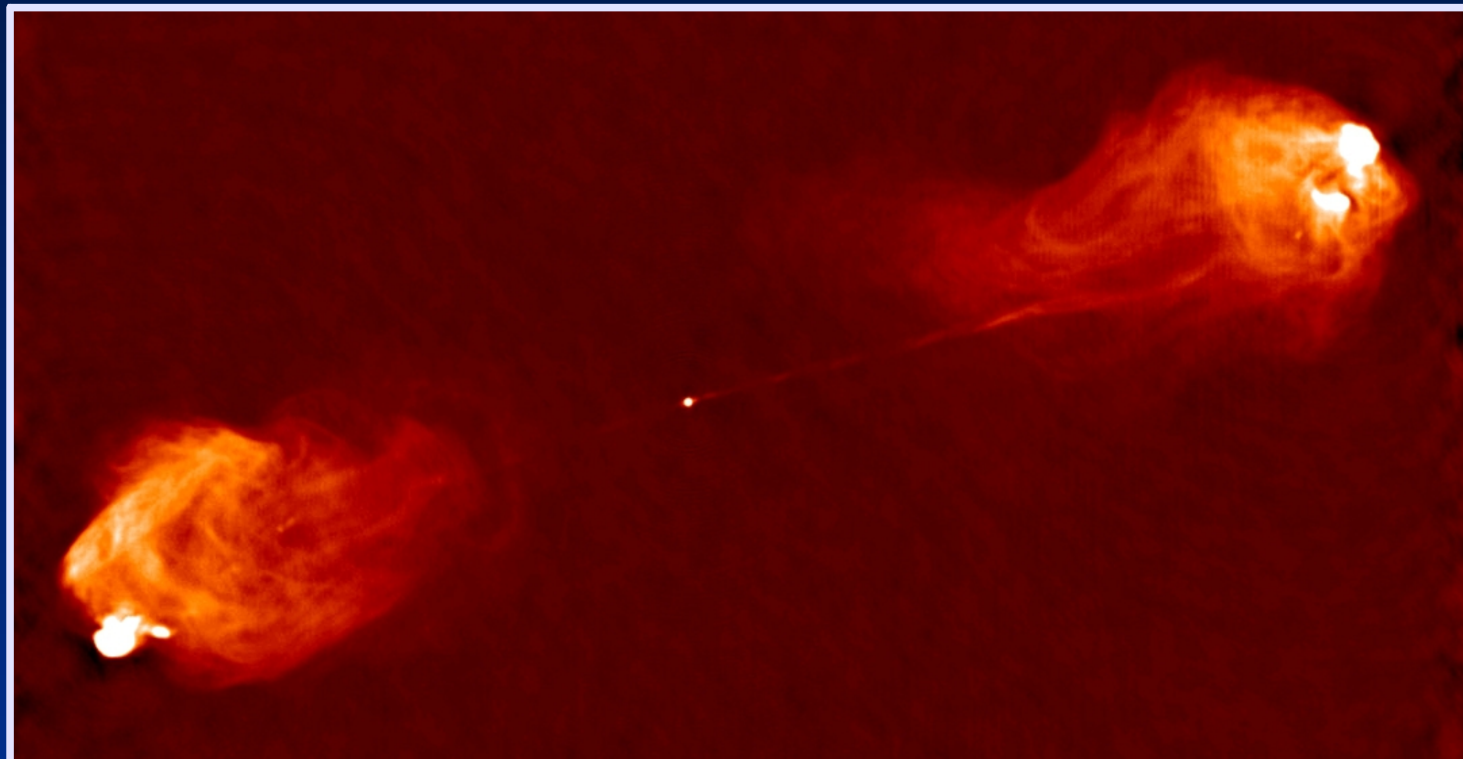


Fig. 2. Approximate intensity distribution of the extra-terrestrial radio source in Cygnus

Jennison & Das Gupta 1953, Nature 172, 996: interferometric observations at ν = 125 MHz. First indication that one of the two discrete "compact" sources in the Reber (1940) all-sky map – Cygnus A - has a double-lobed structure.

The Very Large Array (VLA)



Radio-Galaxy "Cygnus A" with the VLA at ~ 6 cm (4.8 GHz), spatial resolution ~ 0.4 arcseconds

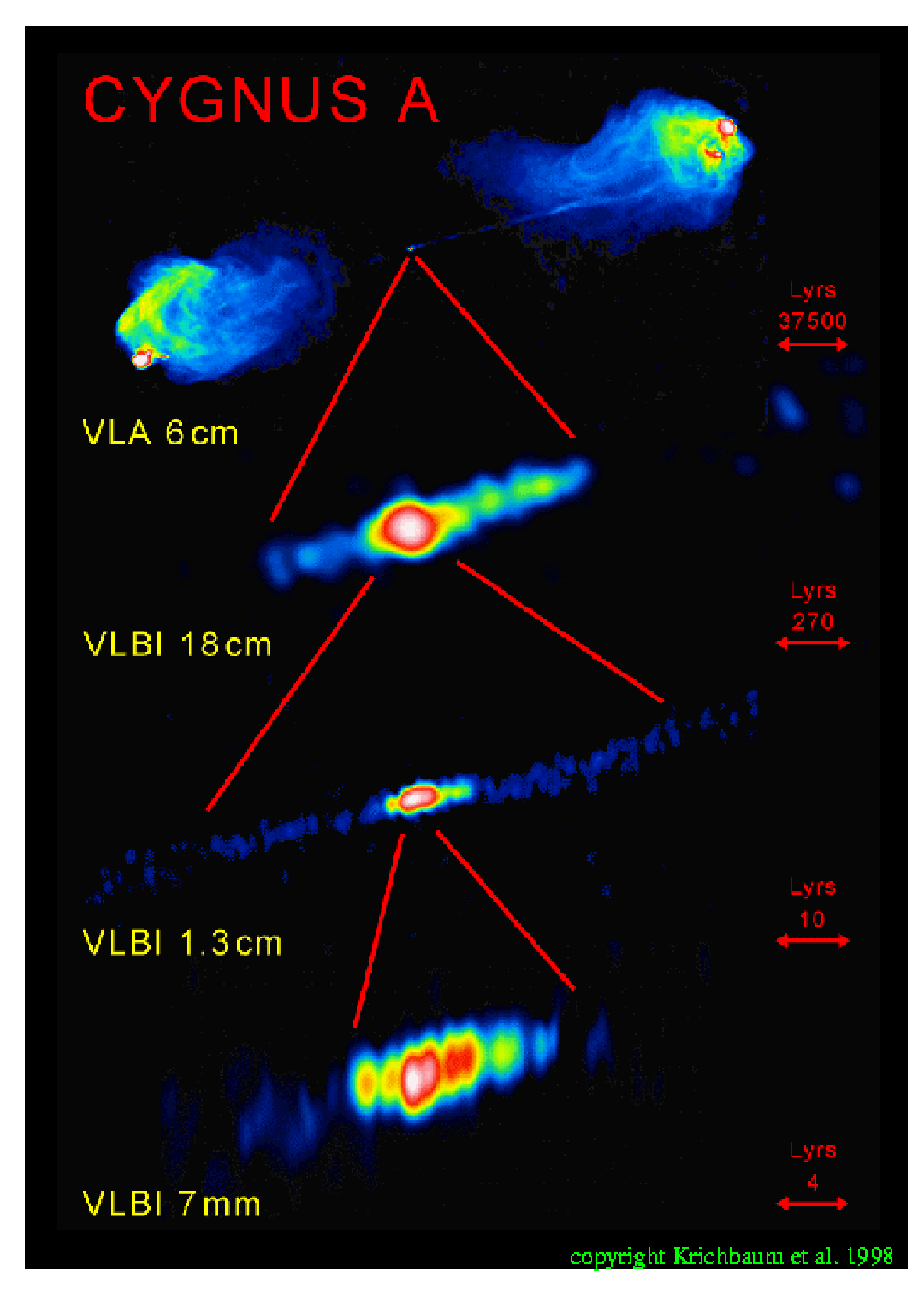
published in: Perley, Dreher & Cowan 1984, ApJ 285, L35

strongly improved contrast thanks to "Self-calibration method"

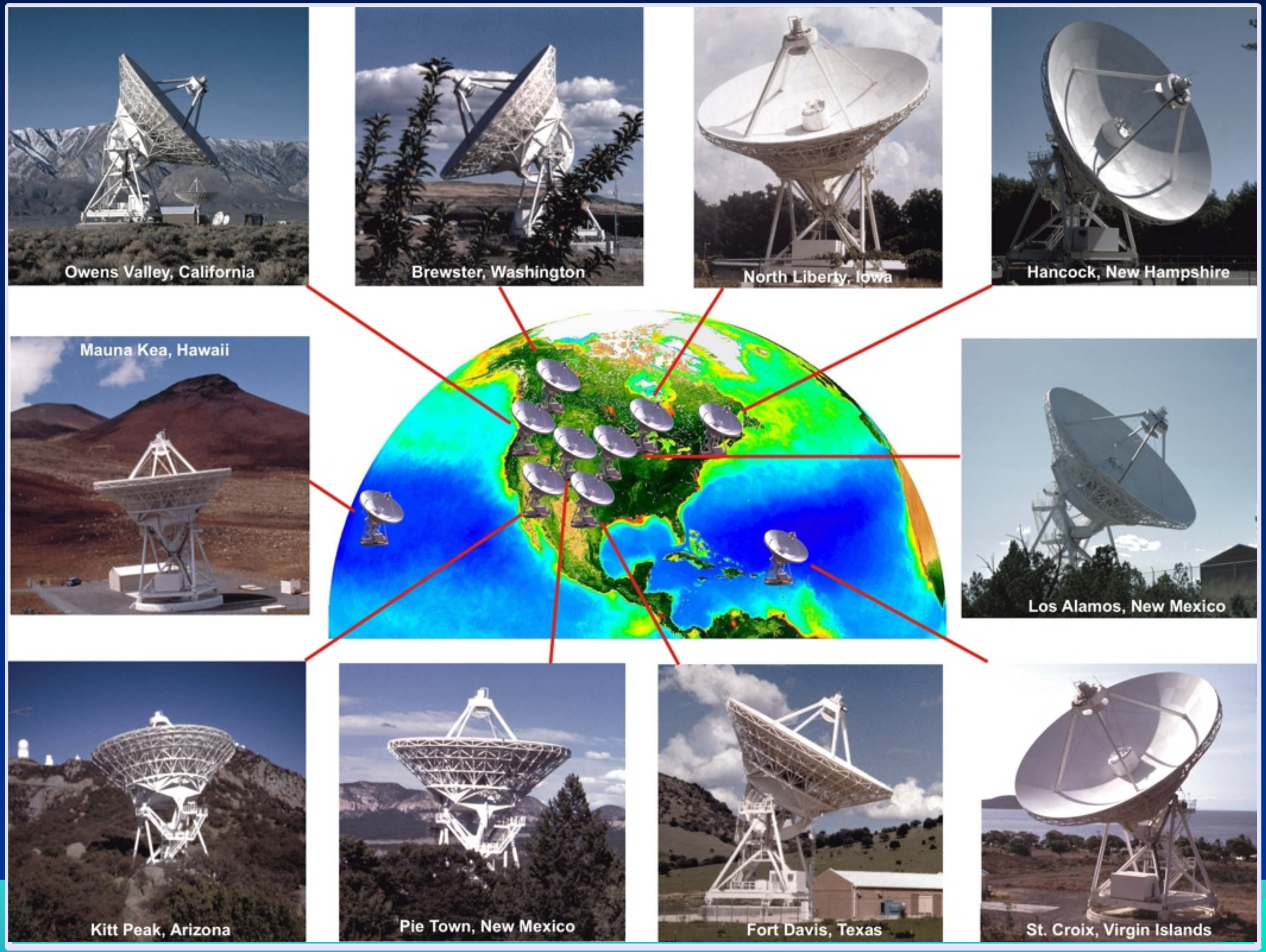
Very Long Baseline Interferometry (VLBI)

Radio-Galaxy “Cygnus A”:
The quest continues …
Towards higher and higher spatial resolution:
VLBI (Very Long Baseline Interferometry)

↳ from arcseconds to milli-arcseconds in spatial resolution!

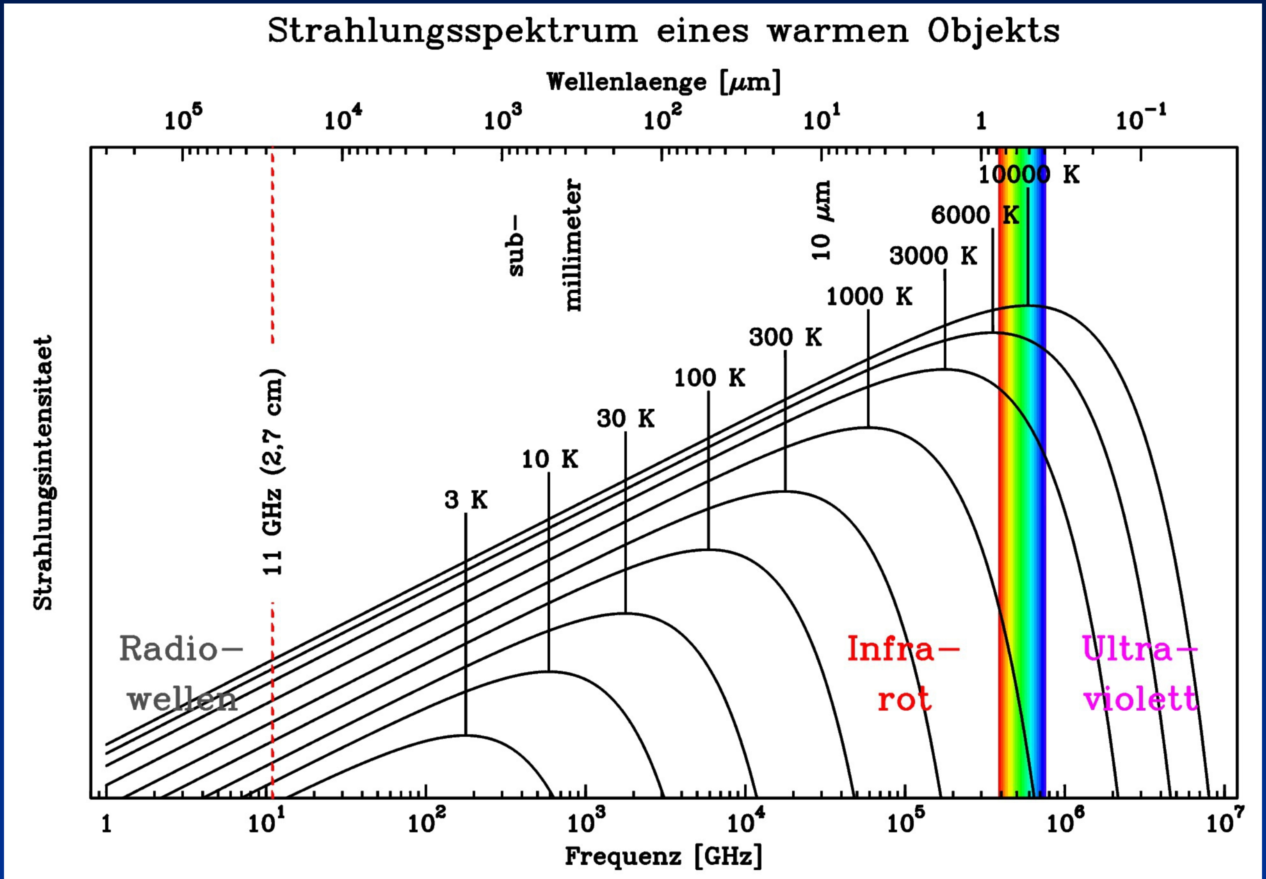


The Very Large Baseline Array (VLBA)



10 antennas à 25 m diameter, distributed over North America (from Hawaii to the Virgin Islands), Maximum baselines 8611 km!

The Planck Function

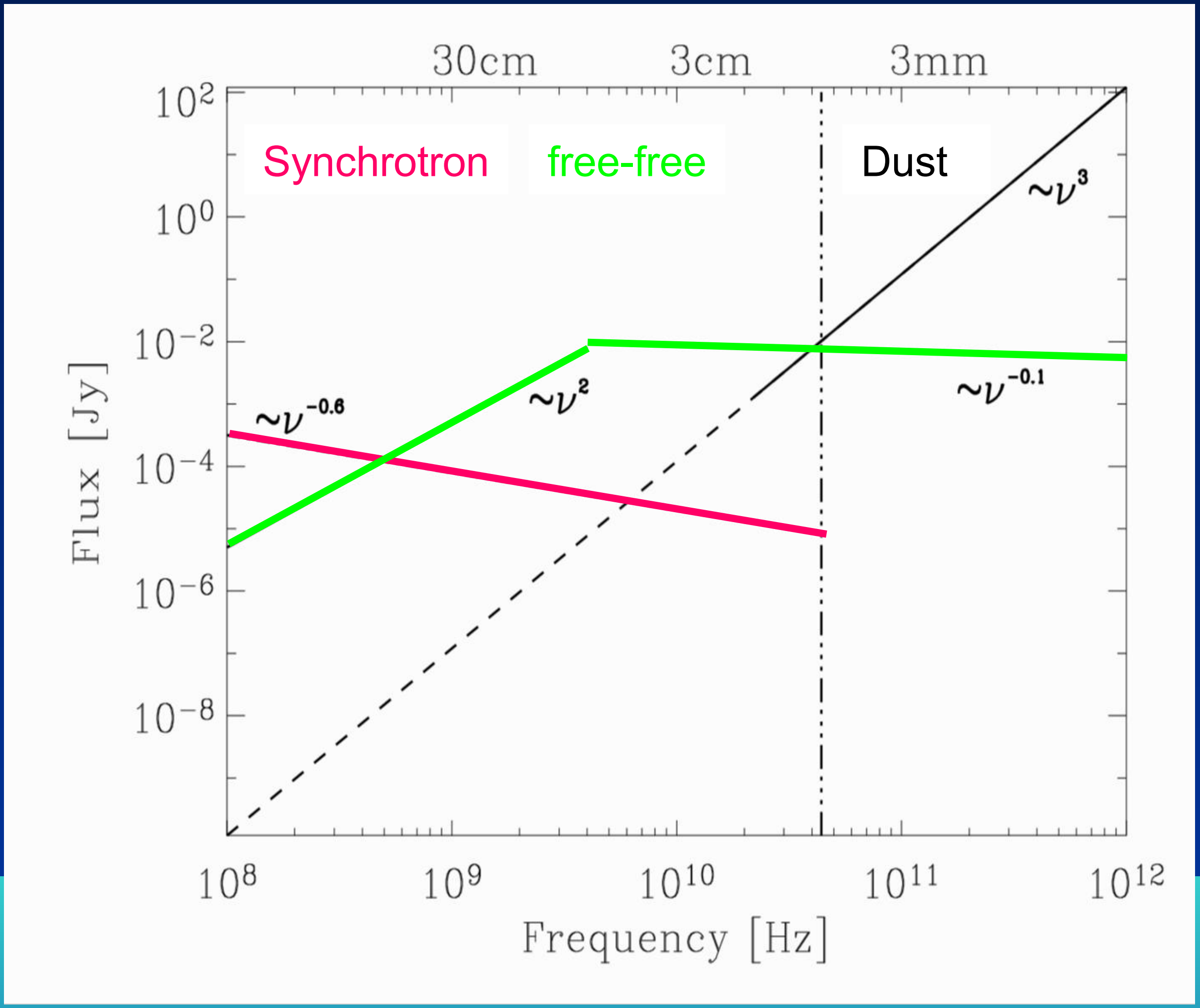


Stellar photospheres and hot dust have their maximum emission at < 10 μm.

Cold dust (10 – 20 K) has the maximum at 100 – 200 μm.

The cosmic microwave background (CMB) peaks at around 1.8 mm!

Mechanisms of astronomical radio emission



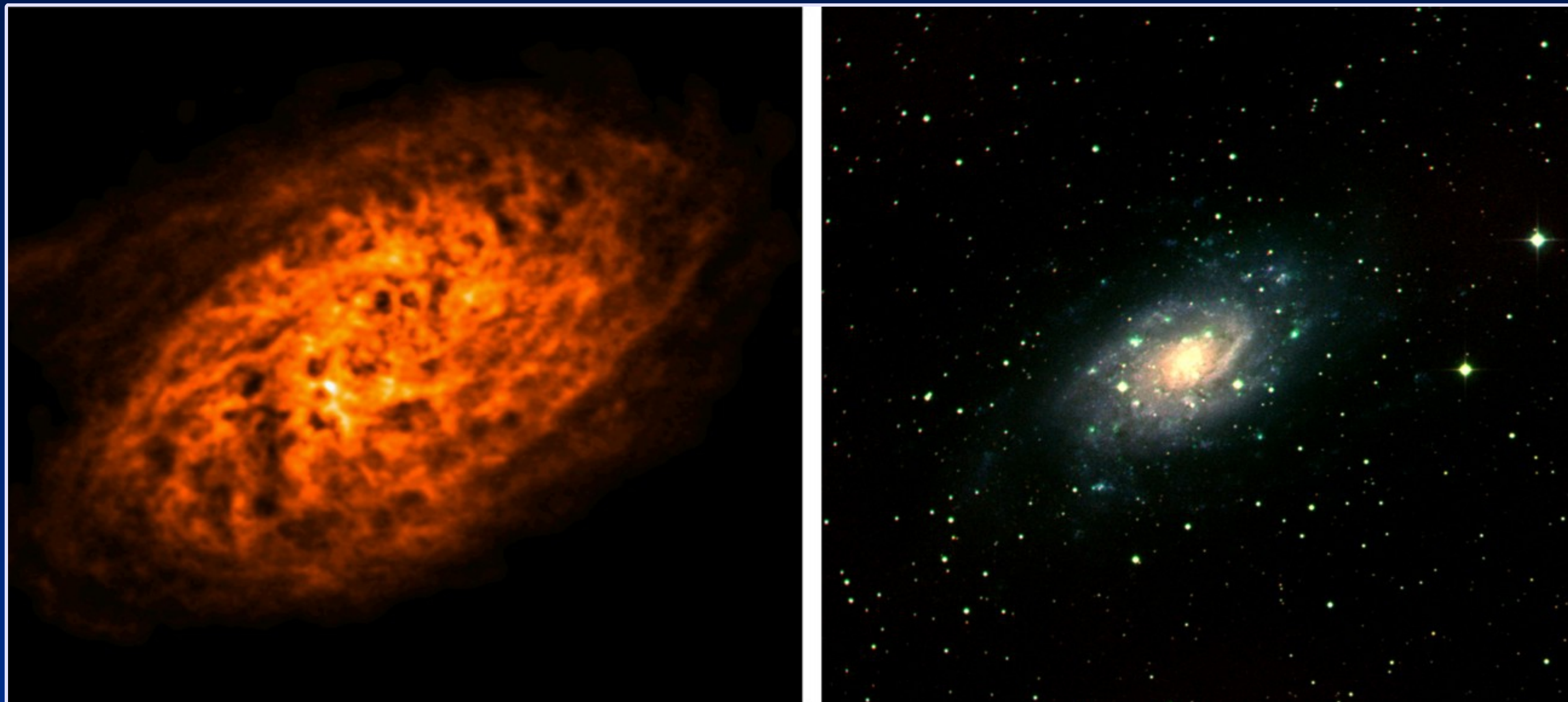
Thermal dust emission:
Micrometer- to millimeter-sized dust grains with temperatures 10 … 100 K

Synchrotron radiation:
Fast charged particles in a magnetic field

Free-Free emission:
In a plasma: free electrons have close encounters with ions

Furthermore: line radiation from atoms and molecules!

Radio data and a complementary view



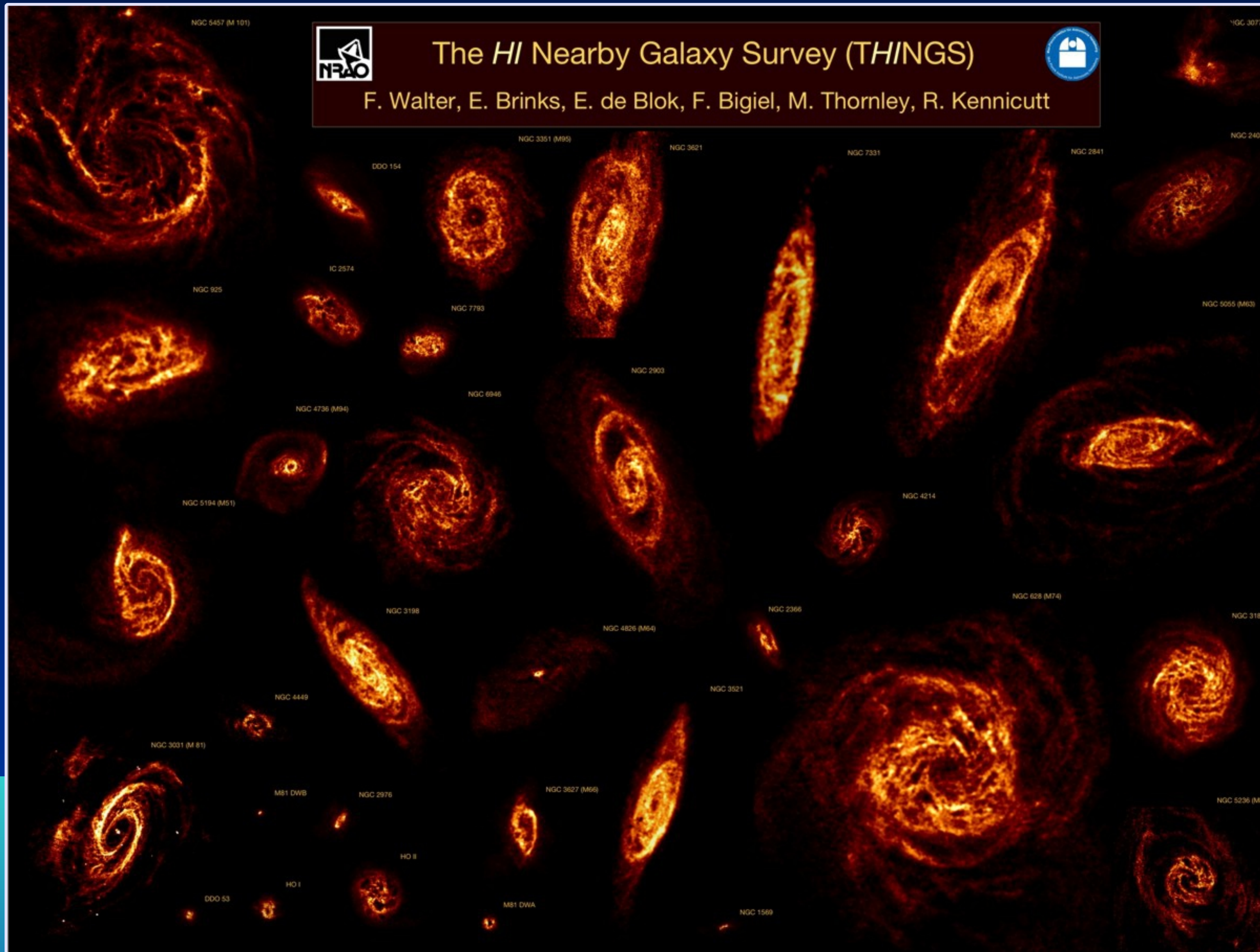
Tom Osterloo (Astron, The Netherlands)

Galaxy “NGC 2403”

with the VLA at 21 cm (1.4 GHz) in the line of neutral Hydrogen

In the Optical with identical size scaling

A large HI survey of Galaxies with the VLA



Fabian Walter (MPIA) & Frank Bigiel (ITA Heidelberg)

A good time to get interested in radio astronomy …

Established facilities are in the process to get major upgrades …

IRAM / Europe:

NOEMA as 6-antenna extension to the existing Plateau de Bure millimeter interferometer (France),

From 15 to 66 baselines …

Two stages: 2016 – 2018

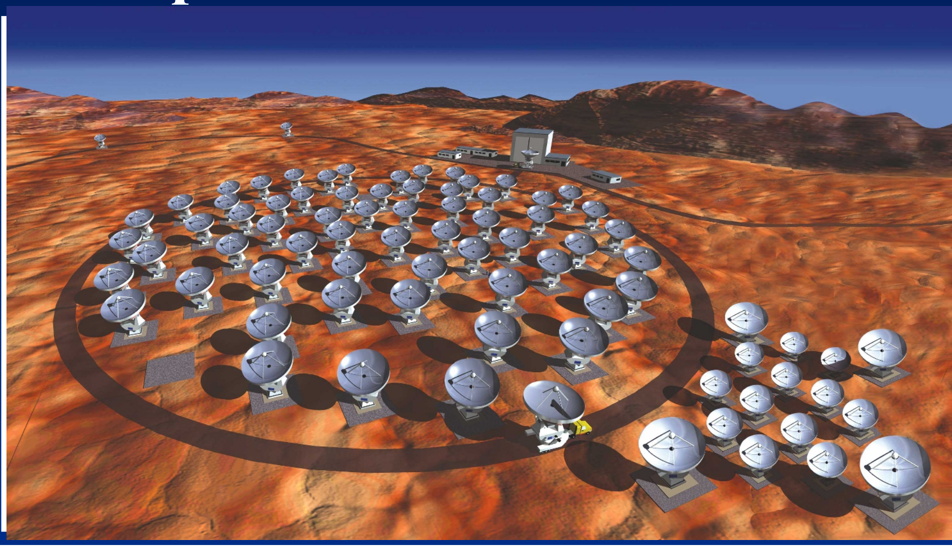
NRAO / U.S.A.:

Name changes over the years:
VLA → EVLA → Karl G. Jansky VLA
New versatile correlator, new receivers,
Seamless frequency coverage from 1 – 50 GHz,

Finished by end of 2013

A good time to get interested in radio astronomy …

New powerful observatories are on the horizon or nearing completion …



ALMA (Atacama Large Millimeter Array):

50 + 12 + 4 antennas for the millimeter and sub-millimeter wavelength range,

Chajnantor plateau, 5100 m altitude (Chile), completion ~ 2014

SKA (Square Kilometer Array):

Low frequency array for the range 30 MHz – 30 GHz with a collection area of around 1 square kilometer (13.7 x Arecibo),

to be put in radio-quiet regions in Australia and South Africa, completion > 2020

Radio Astronomy

PD Dr. Henrik Beuther and Dr. Hendrik Linz
MPIA Heidelberg

http://www.mpia.de/homes/beuther/lecture_ws1213.html

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Radio Astronomy

Some of the used nomeclature and abbrevations:

Frequency measured in Hertz:

1 Hertz = 1 Hz = 1 vibration/s … 1 MHz = 10^6 Hz

1 GHz = 10^9 Hz

1 THz = 10^12 Hz

Spectral energy flux density measured in Jansky:

1 Jansky = 1 Jy = 10^-26 Watt / (m^2 * Hz)

NRAO: National Radio Astronomy Observatory (conglomeration of radio astronomy institutions in the USA)

IRAM: Institut de Radioastronomie Millimétrique (international organisation funded by French, Spanish and German science institutions)

VLBI: Very Long Baseline Interferometry – antennas can be thousands of kilometers apart, for instance in case of the VLBA facility (Very Long Baseline Array)