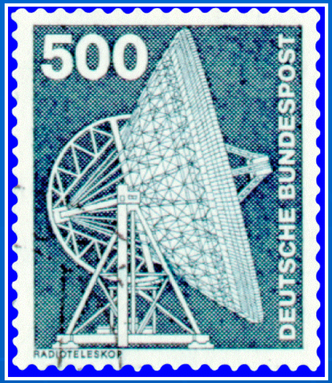
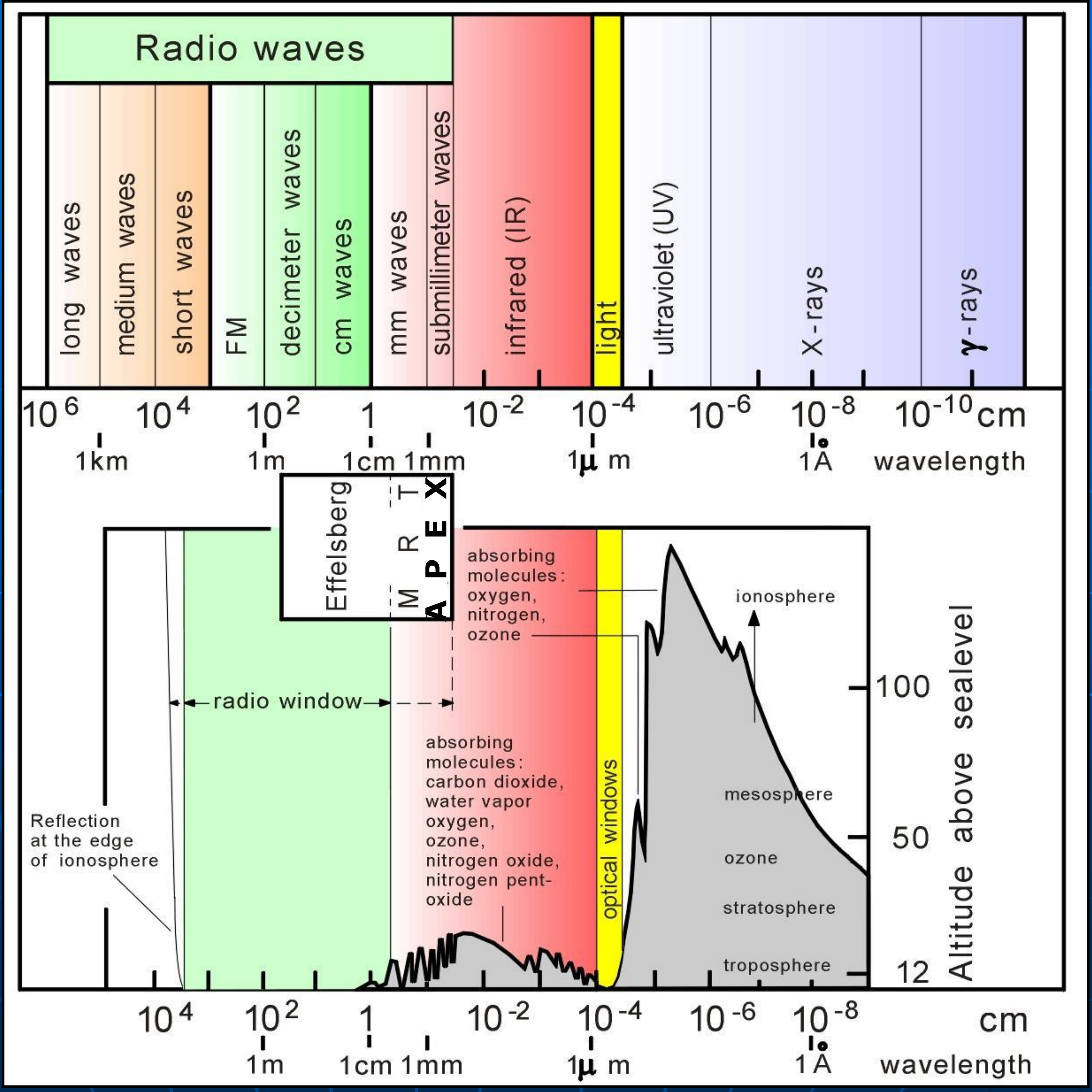


Lecture 2:

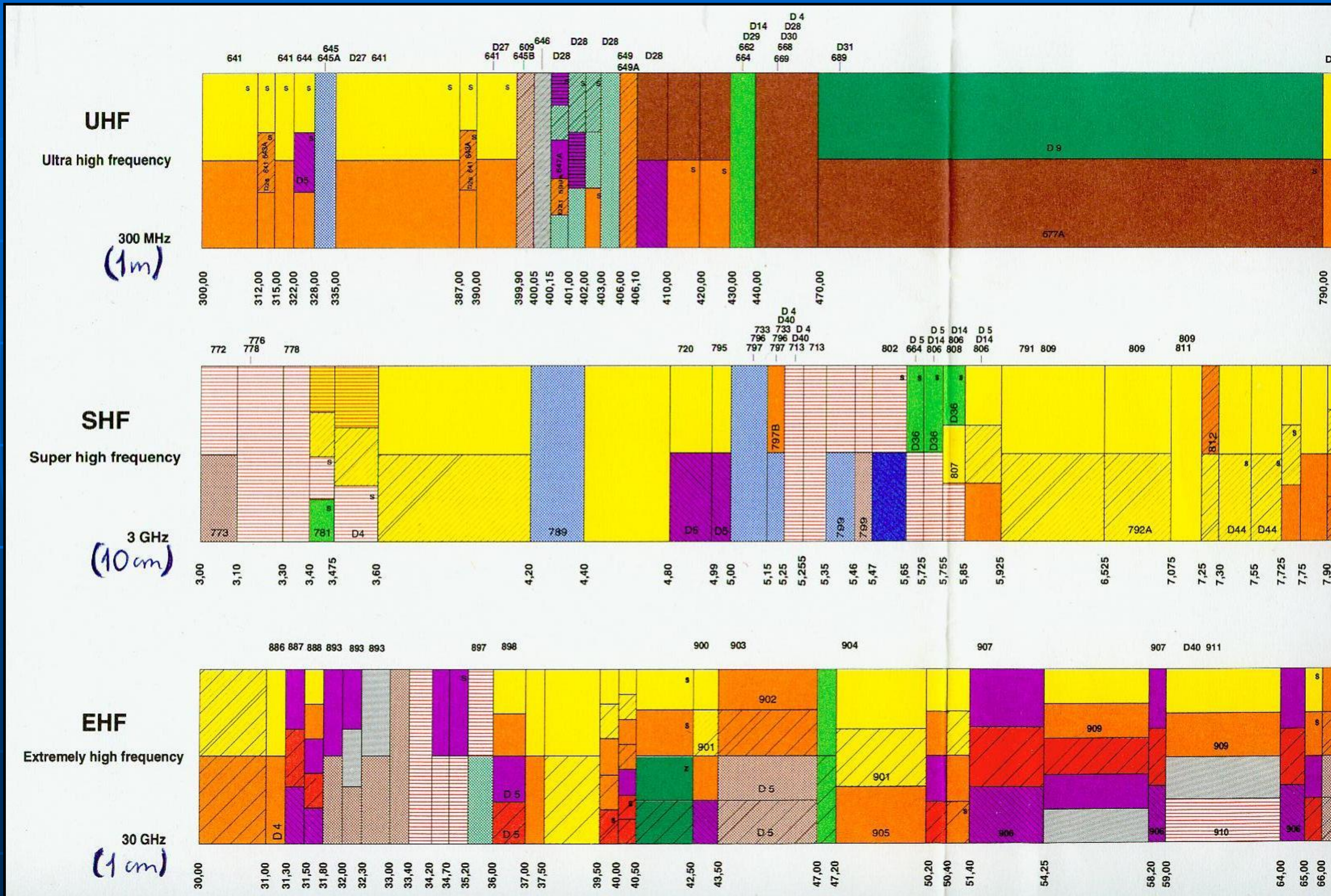
Basics of Radio Astronomy

Dr. Rainer Beck, MPIfR Bonn



W. Fußhöller,
MPIfR Bonn

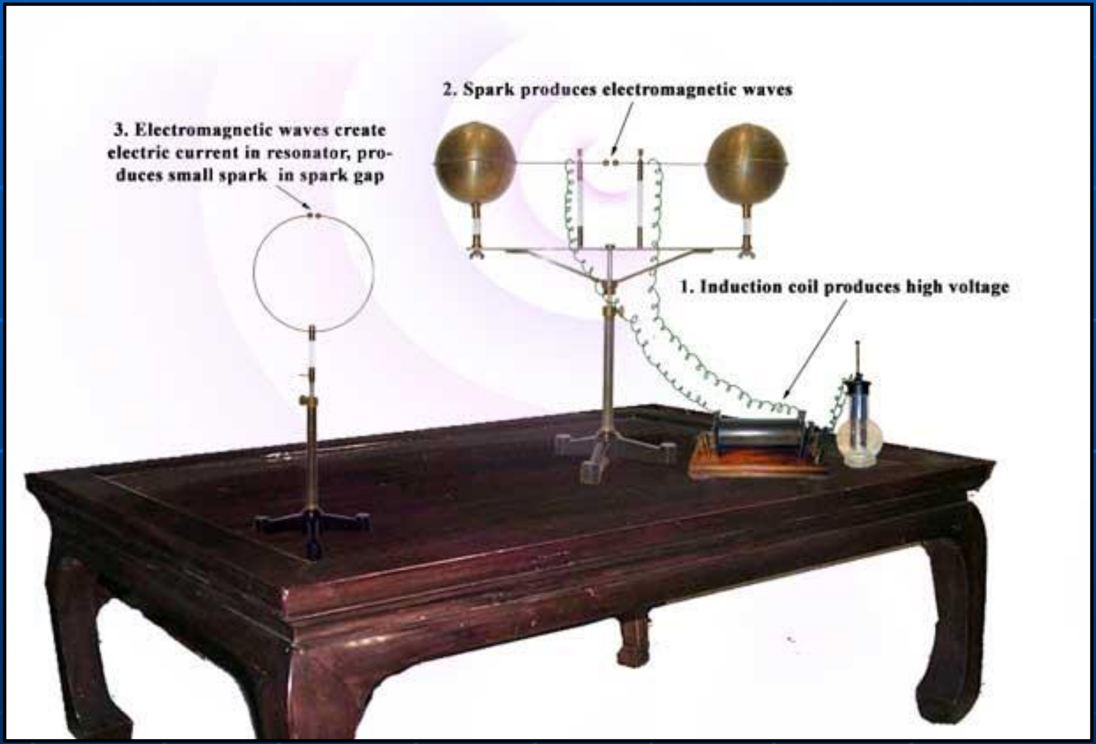
Allocation of radio frequency bands



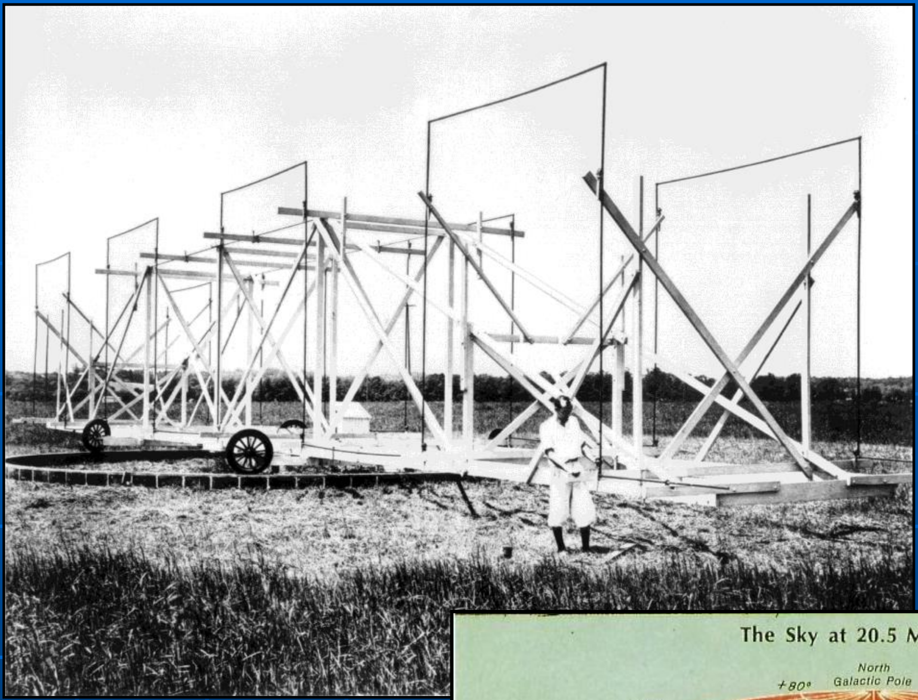
Discovery of radio waves: 1887

Heinrich Hertz (Germany)

(1857-1894)



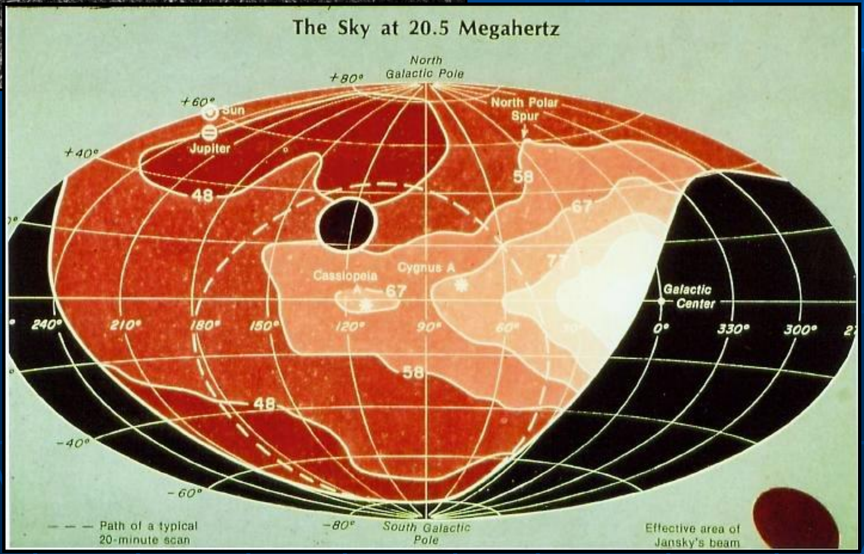
Discovery of cosmic radio waves: 1933

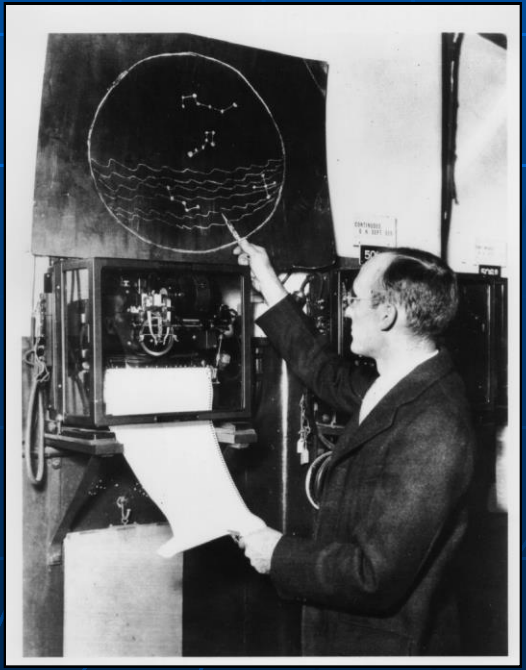


Karl Guthe Jansky

(USA)

20 MHz (15m wavelength)





The first radio dish telescope: 1937

Grote Reber

(USA)

160 MHz (1.9m)

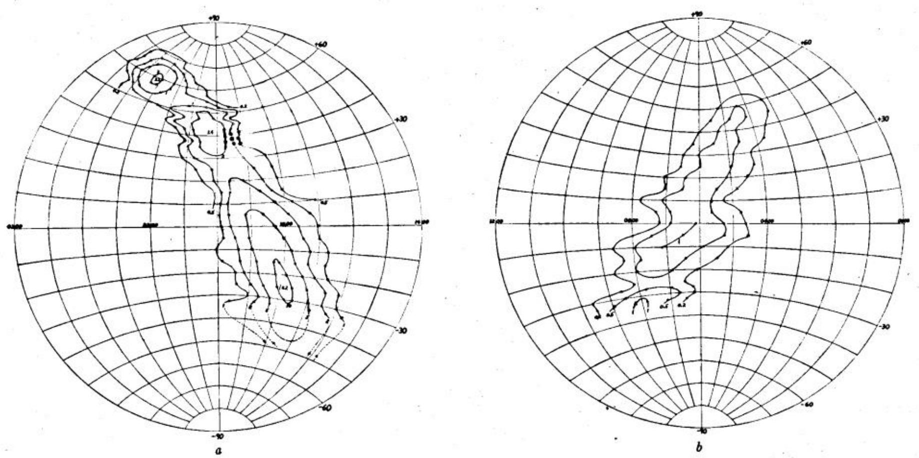
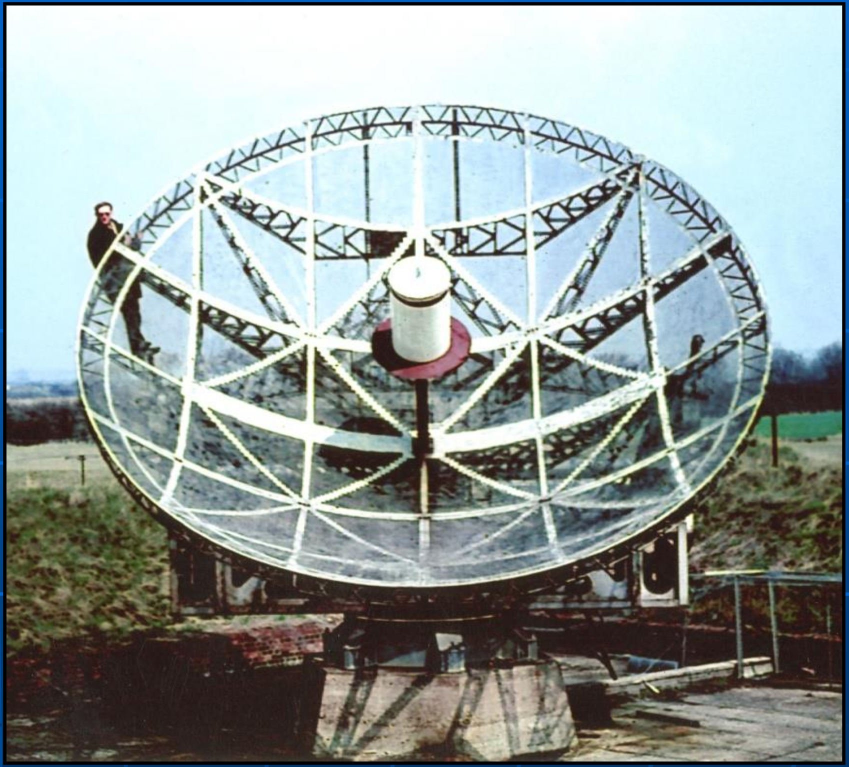


FIG. 4.—Constant intensity lines in terms of 10^{-22} watt/sq. cm./cir. deg./M.C. band

German WW2 relics: “Würzburg Riese”

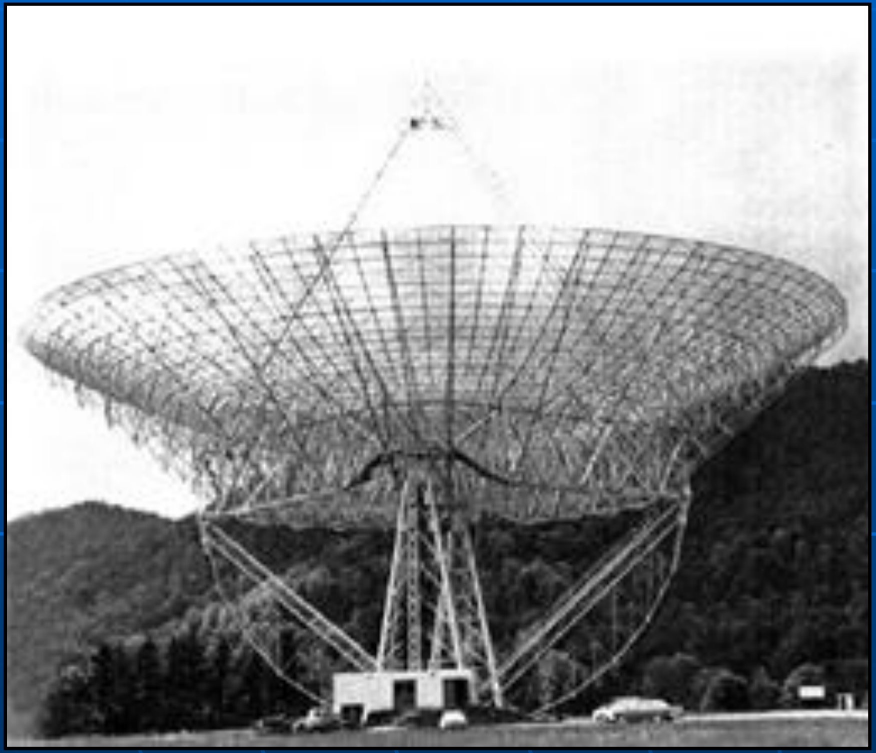
Denmark



Cambridge/England

First large radio telescope in England: 1957
(Jodrell Bank, 76 m diameter)

First large radio telescope in the USA: 1957
(Green Bank, 90 m diameter)

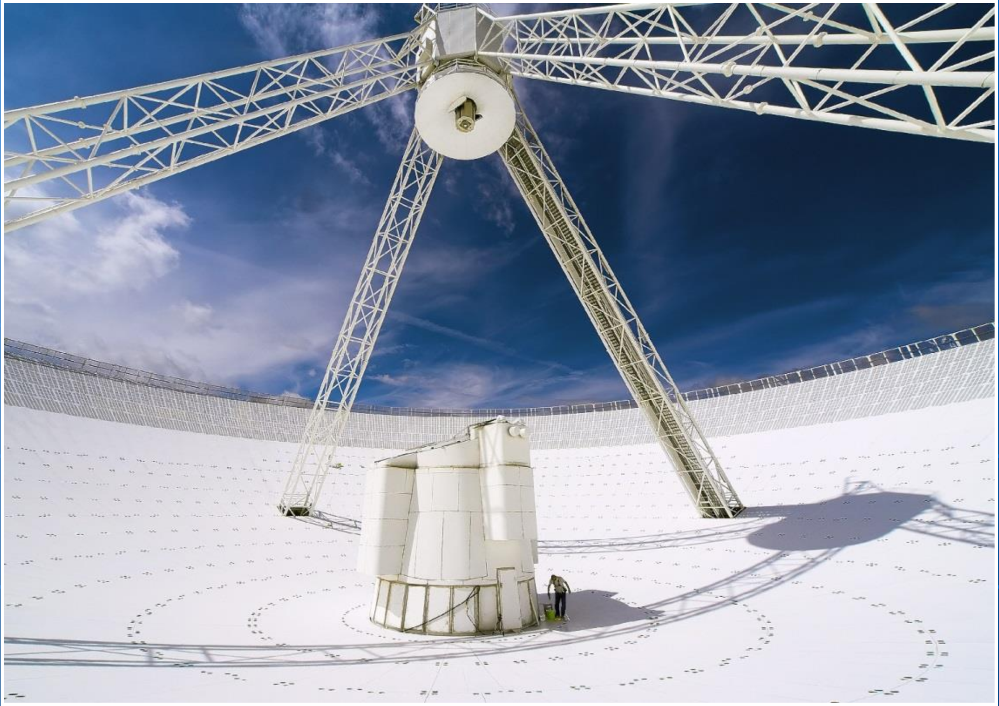


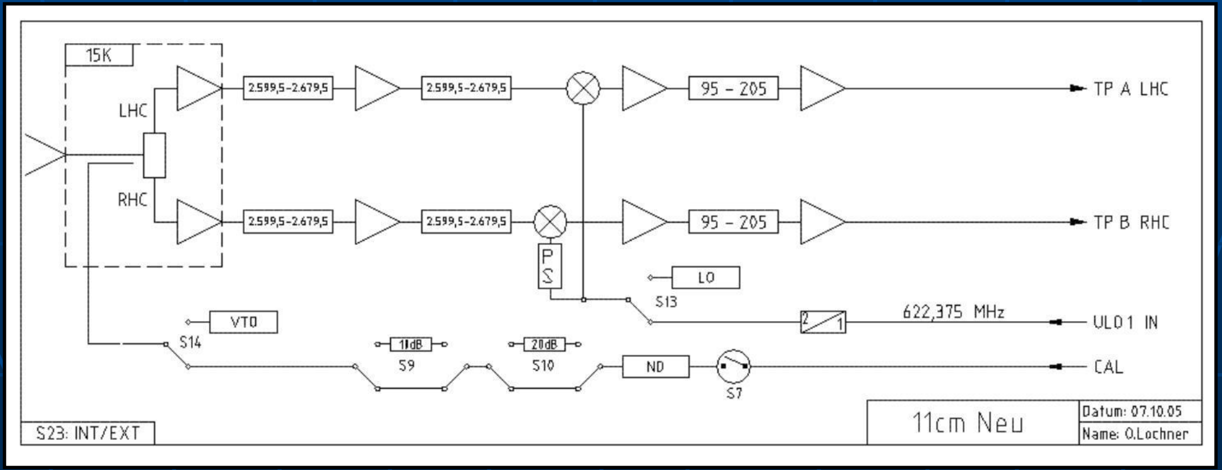
1962

1988

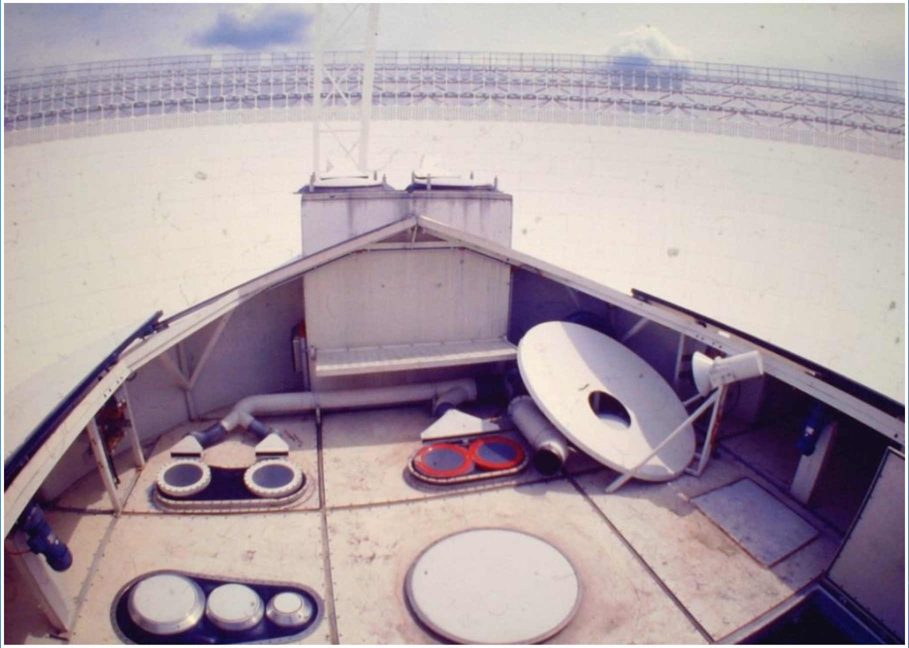

1971:
Effelsberg 100 m
0.7 - 95 GHz
(43 cm - 3 mm)

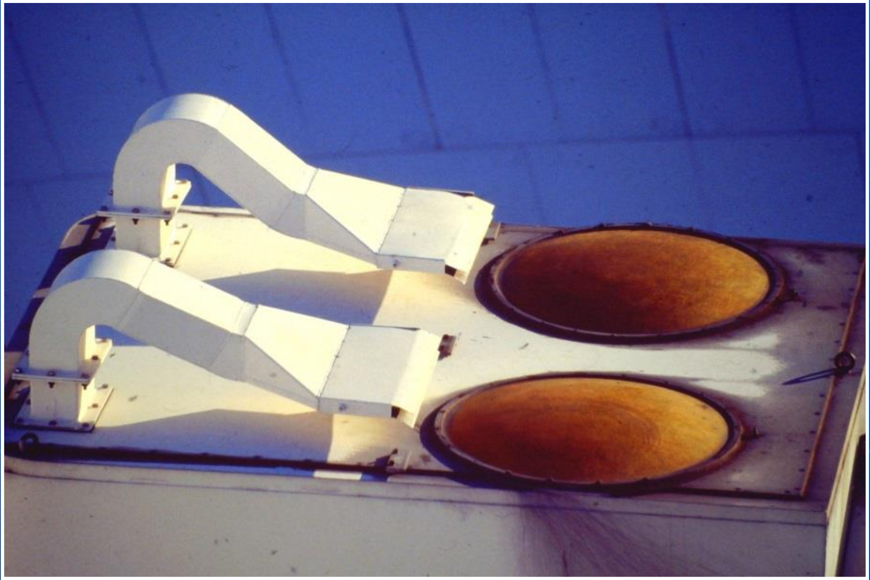
Effelsberg: 11 cm single-horn receiver

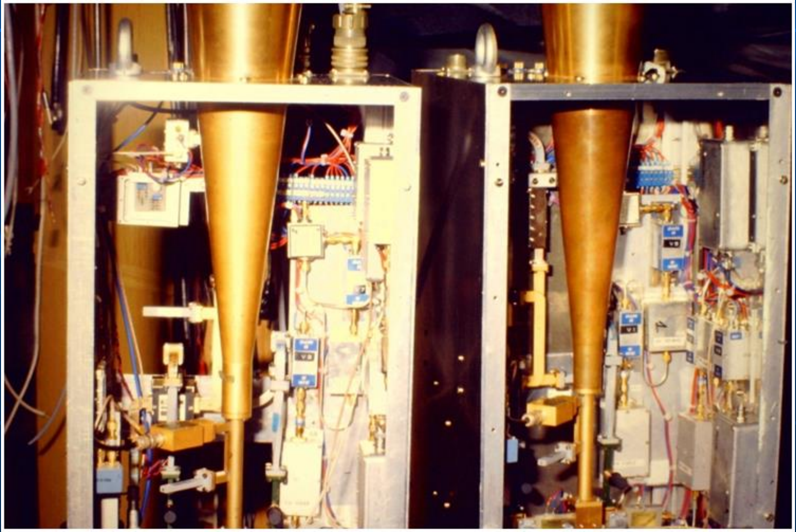




Effelsberg: Multi-horn receivers



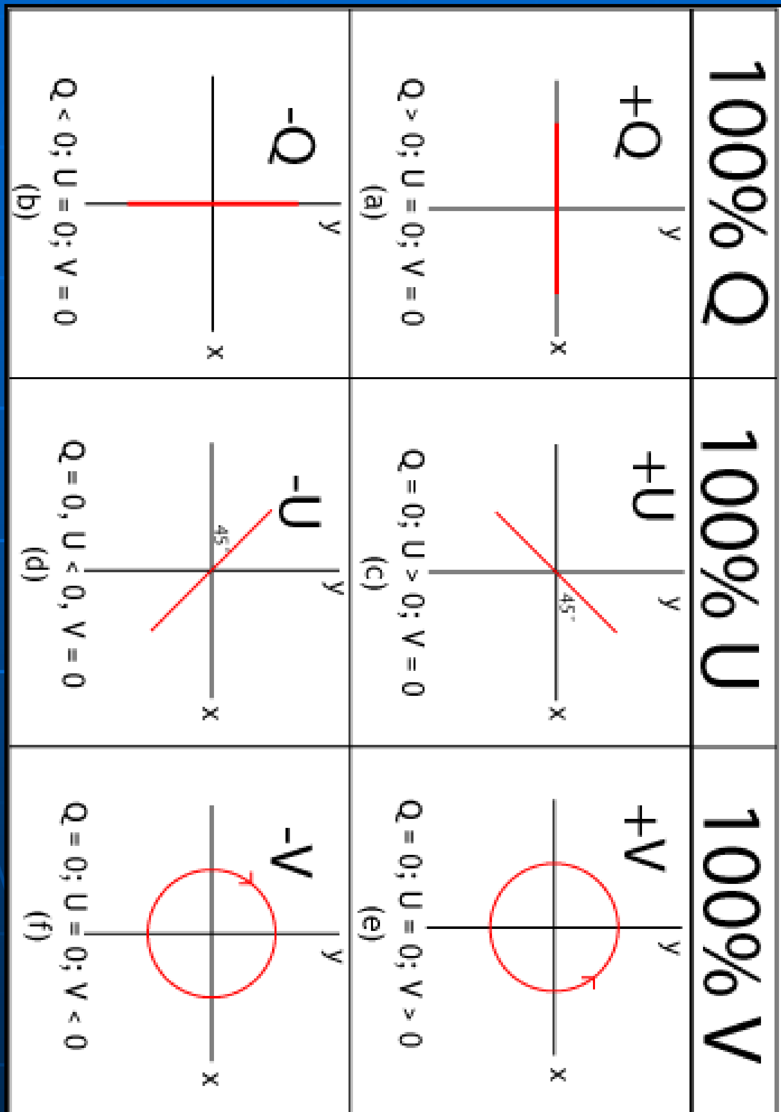




Continuum & polarization mapping with the Effelsberg dish

- Single-horn receivers in primary focus (1.4 GHz) or in secondary focus (2.6 and 8.4 GHz)
- Multi-horn receivers in secondary focus (4.8, 10.4, 32 GHz):
- These receivers detect circularly polarized & unpolarized signals (Channels in Stokes parameters R and L)
- A digital correlator generates signals of linear polarization in Stokes parameters U and Q

Stokes parameters



Linear polarization angle:

ψ = 0.5 arctan (U/Q)

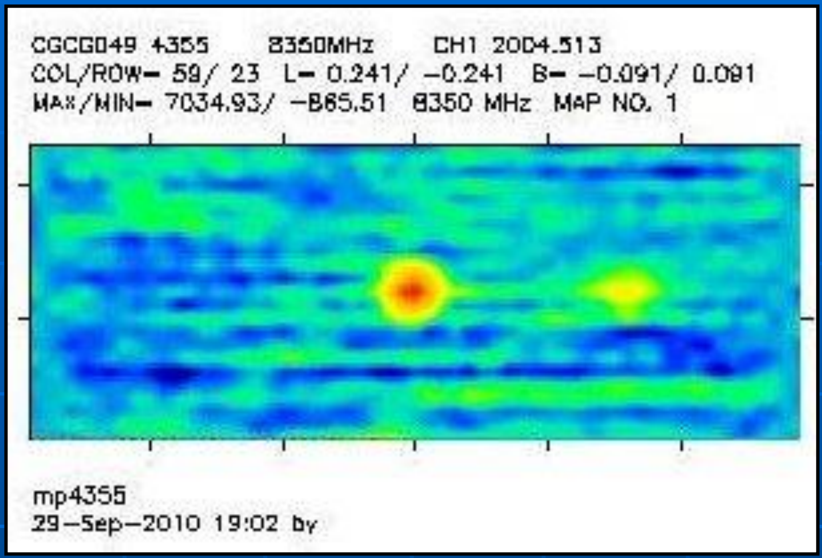
counted counterclockwise from the north

Synchrotron emission:

Linear polarization "vector" is oriented ⊥ to the magnetic field, B-"vector" is aligned with the magnetic field

Raw Stokes maps (8.4 GHz)

I



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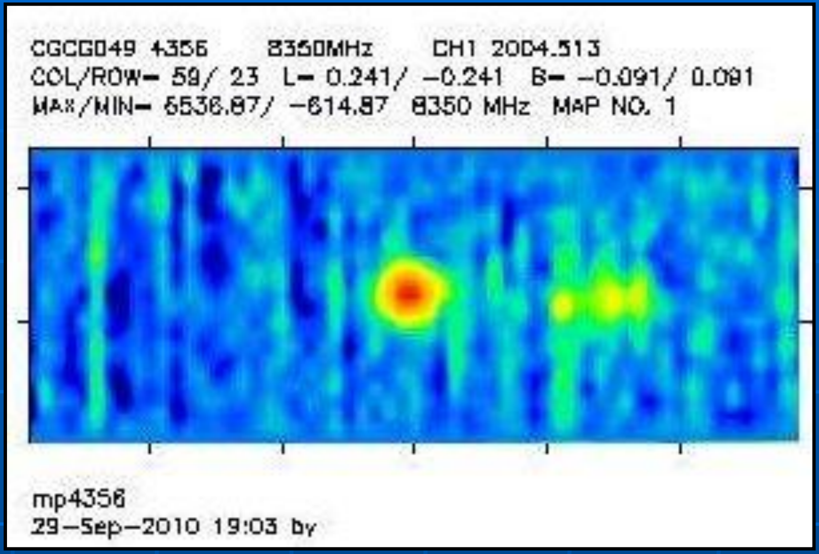
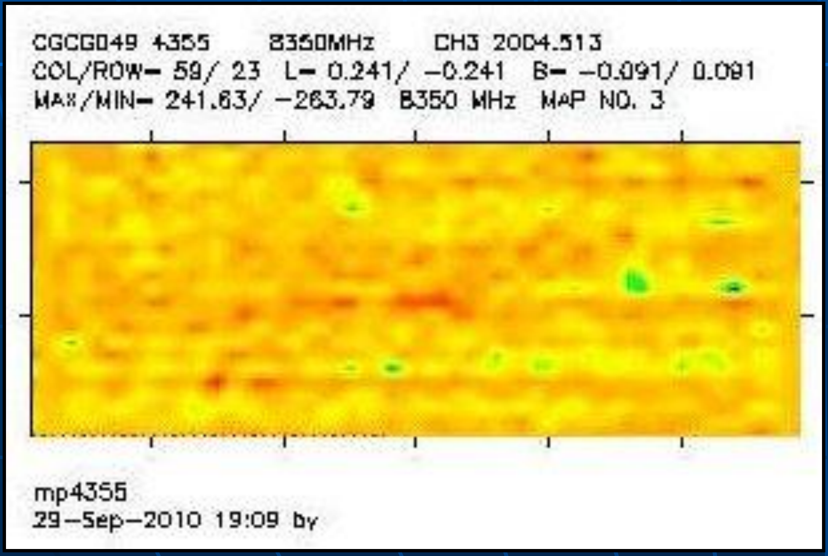
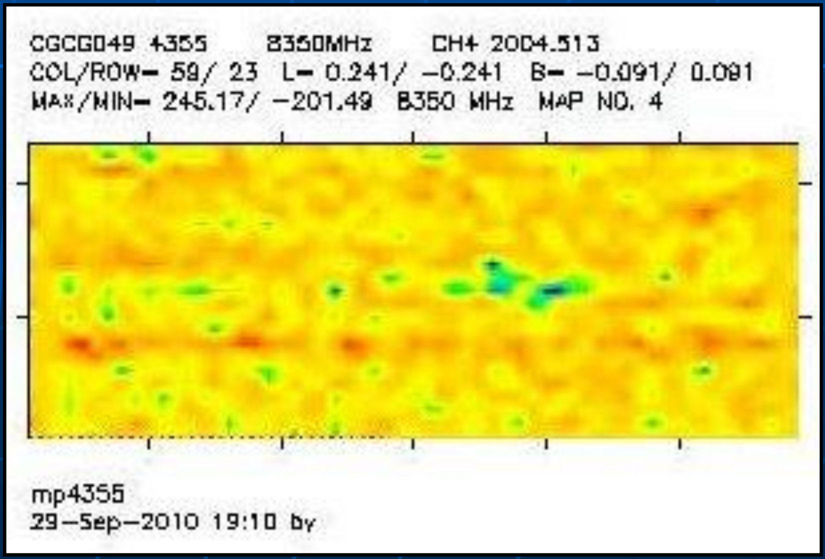


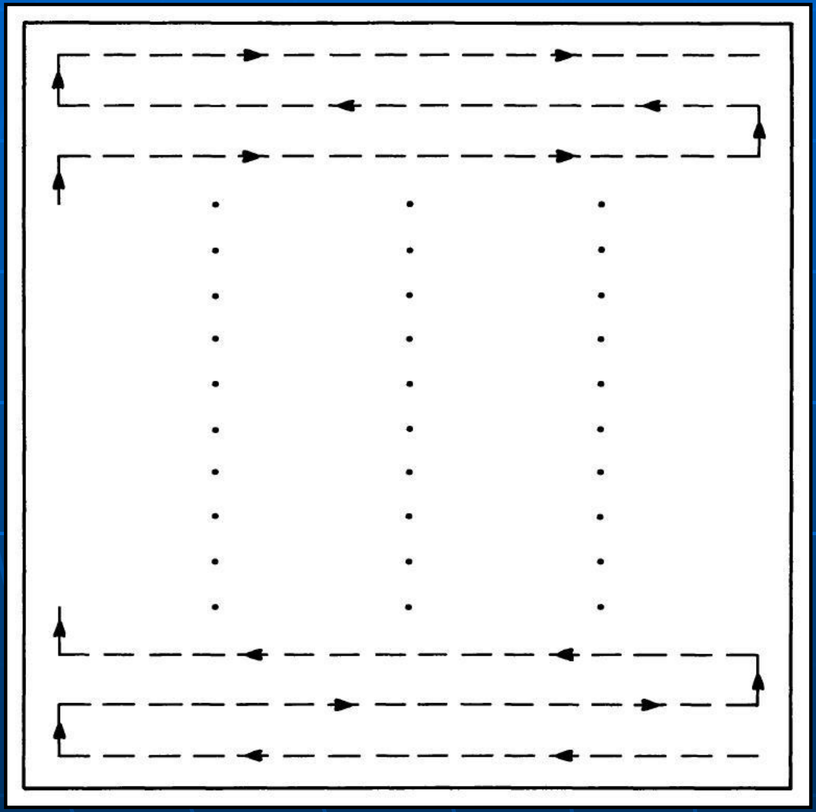
U

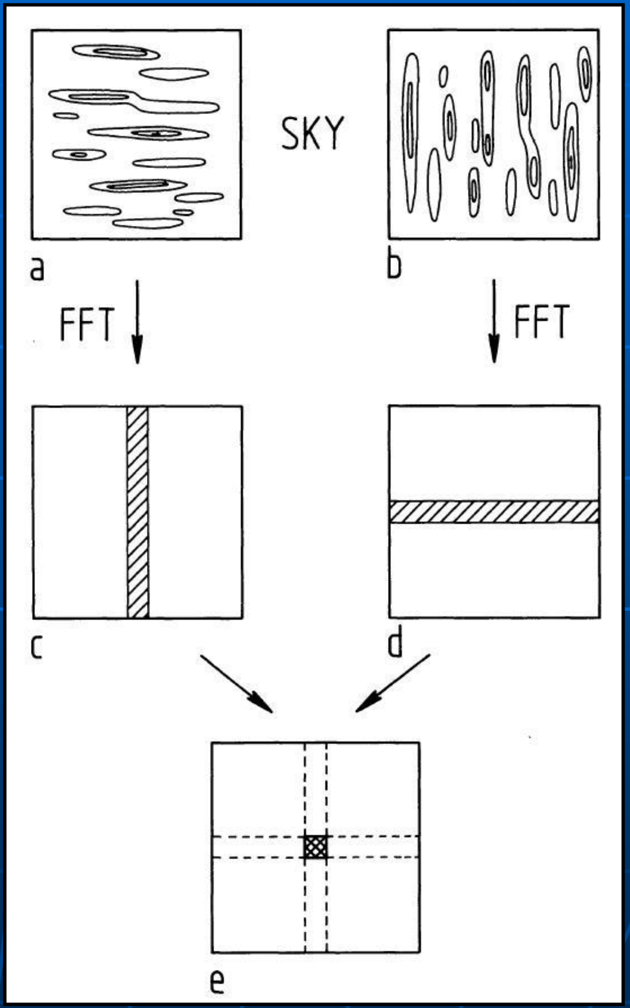


Q



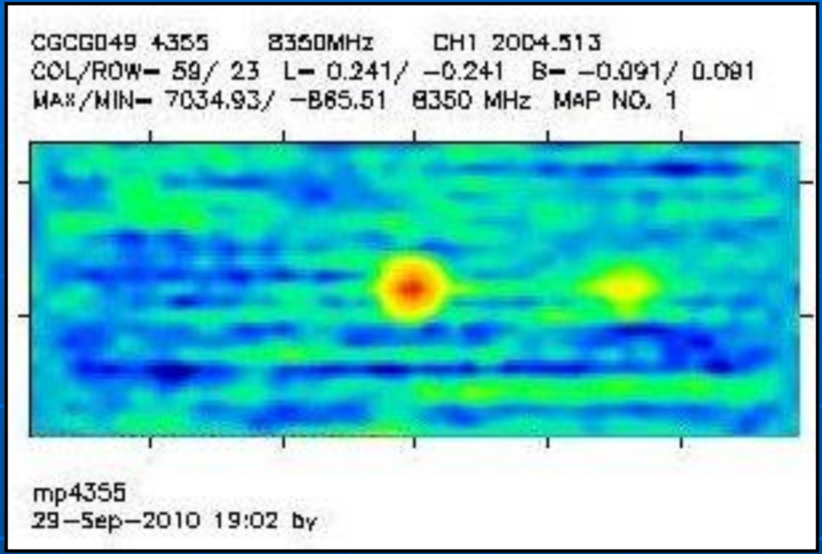
Suppressing scanning noise: Scanning in different directions

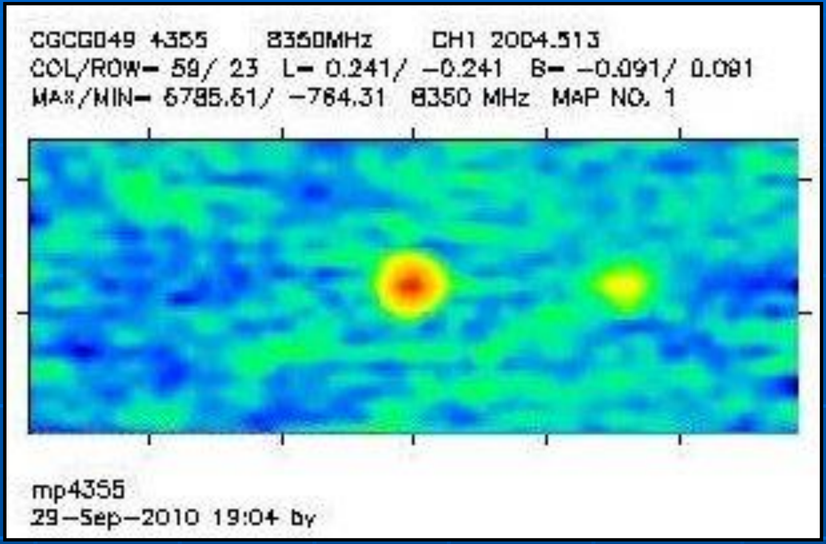




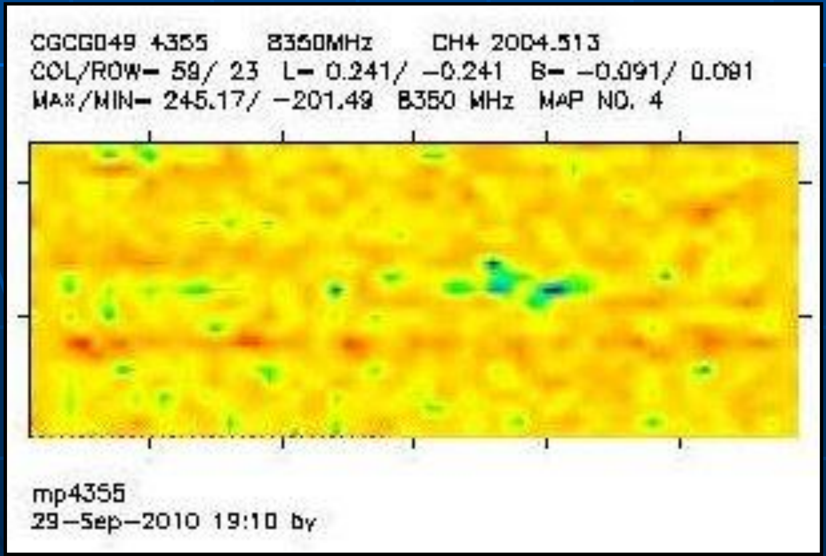
Suppressing scanning noise (8.4 GHz)

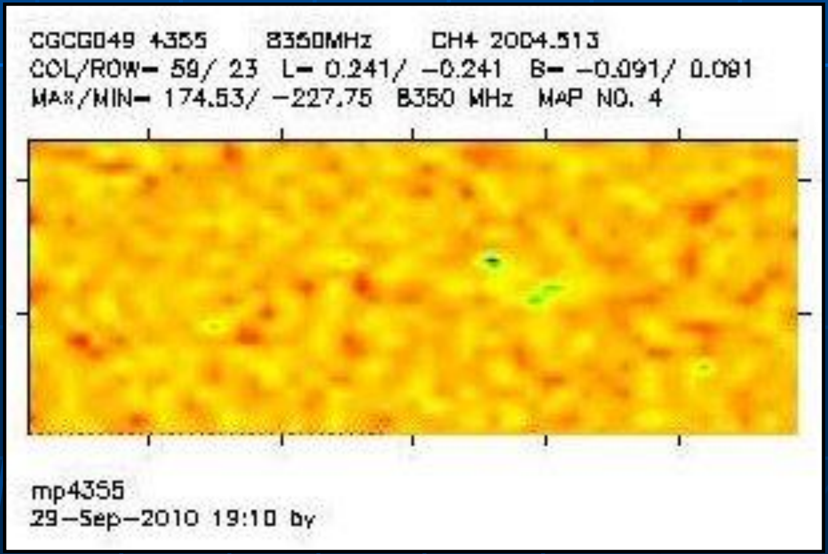
I



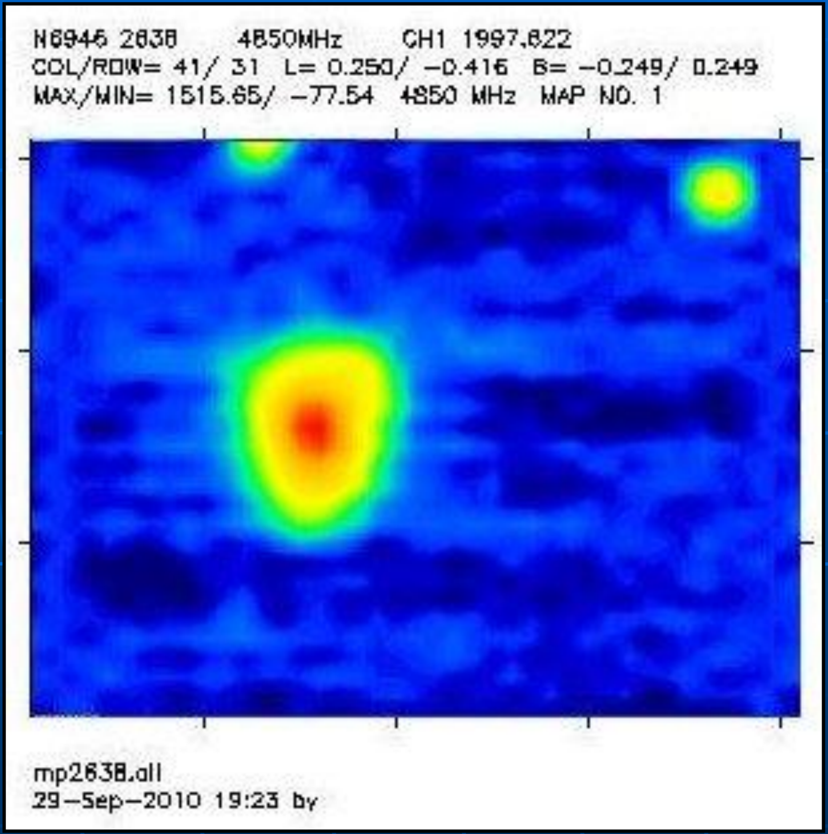


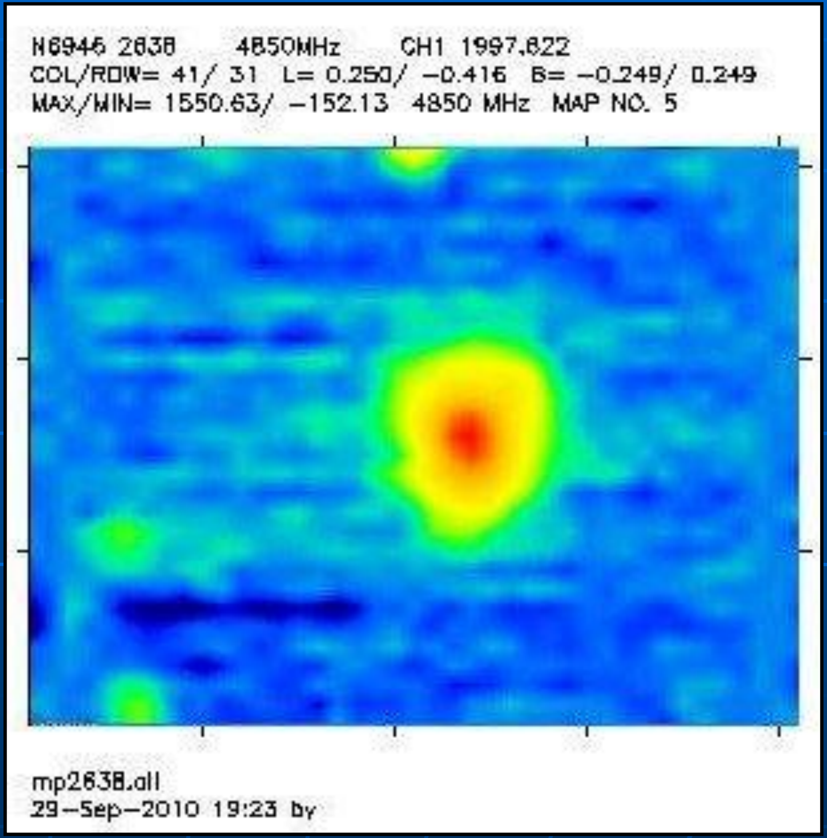
Q





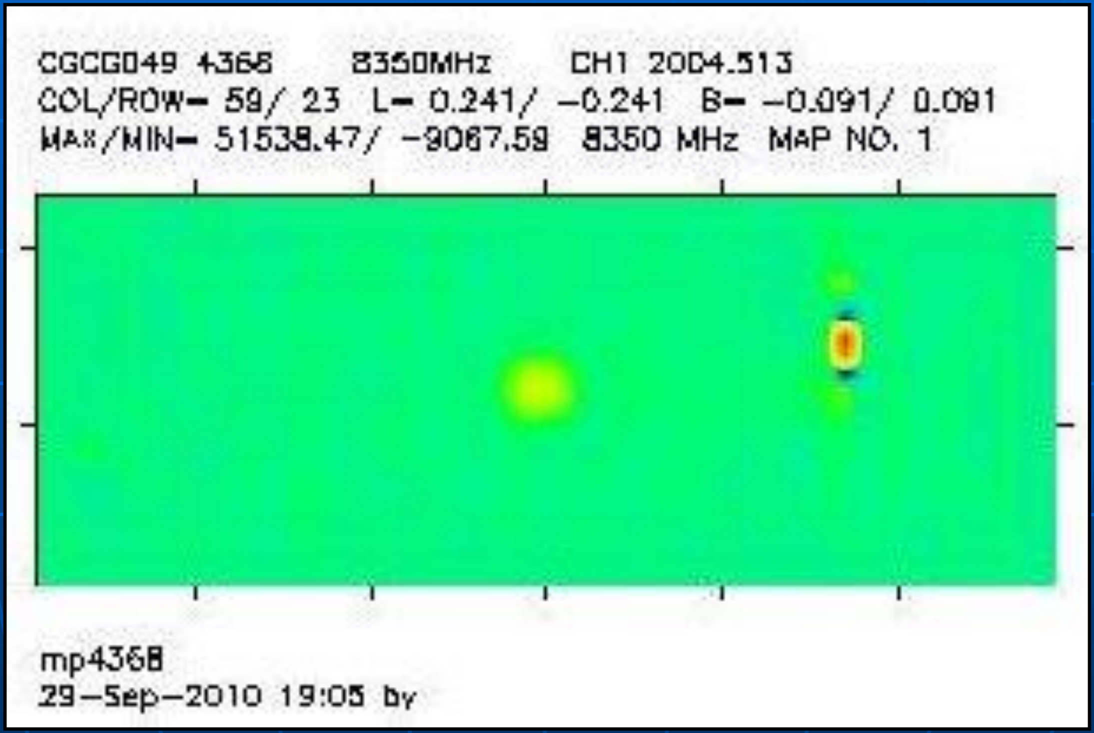
Suppressing scanning noise: Dual-horn observations (4.8 GHz)





I

Severe problem:
Radio Frequency Interference (RFI)



Largest fully steerable dish:

GBT 102 m

(Green Bank/USA)

0.3 – 115 GHz

(1 m – 3 mm)

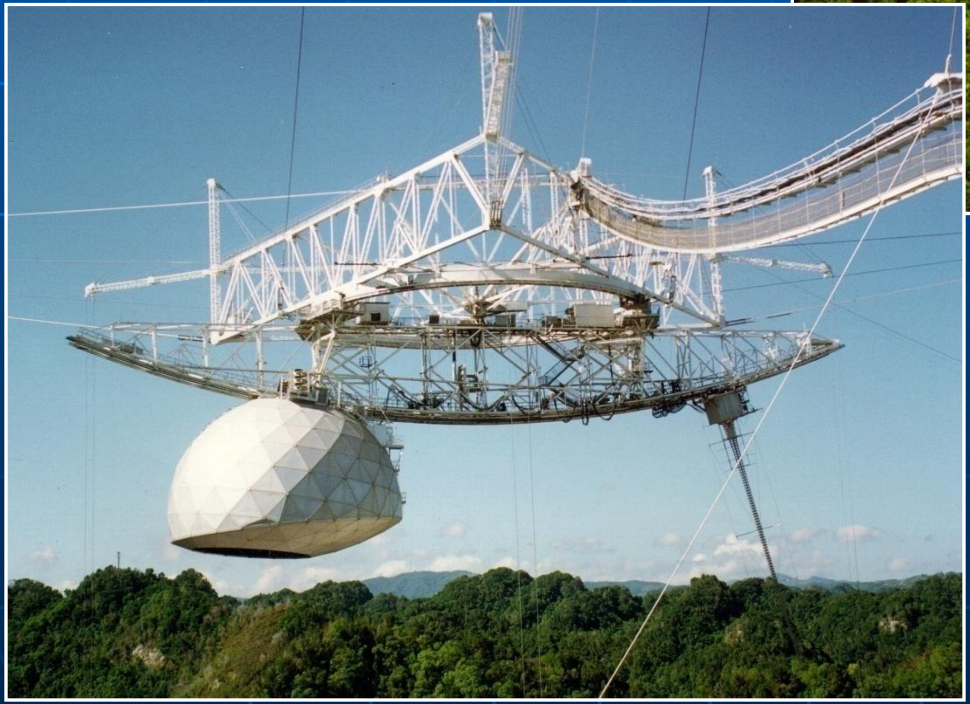
Largest radio dish:

Arecibo 305 m

(Puerto Rico/USA)

0.3 – 10 GHz

(1 m – 3 cm)



Largest radio telescope:

RATAN600

576 m

(Selentschukskaja/
Russia)

0.6 – 2 GHz

(2 - 50 cm)

Largest millimeter telescope:

IRAM 30 m

(Pico Veleta/Spain)
80 - 280 GHz
(4 - 1 mm)

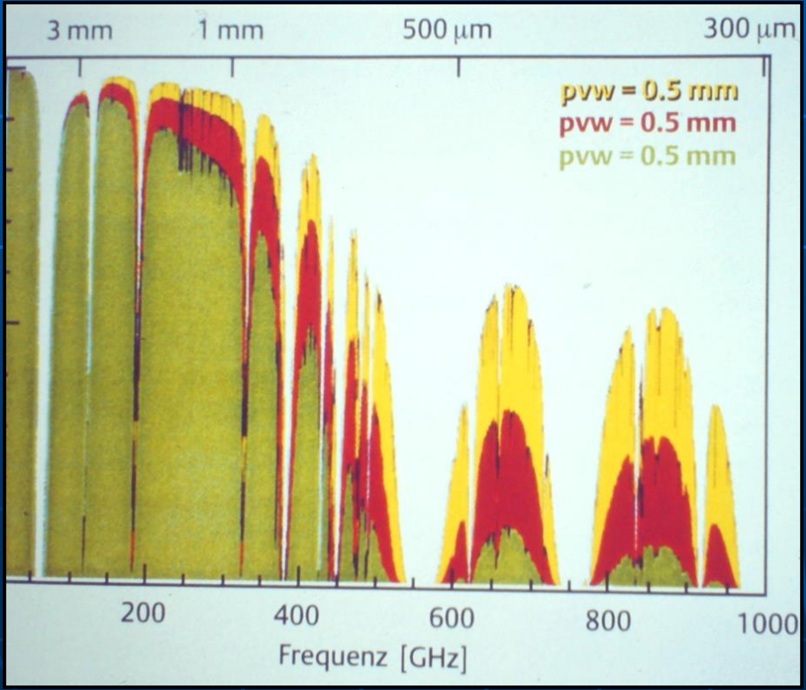
Largest submillimeter telescope:

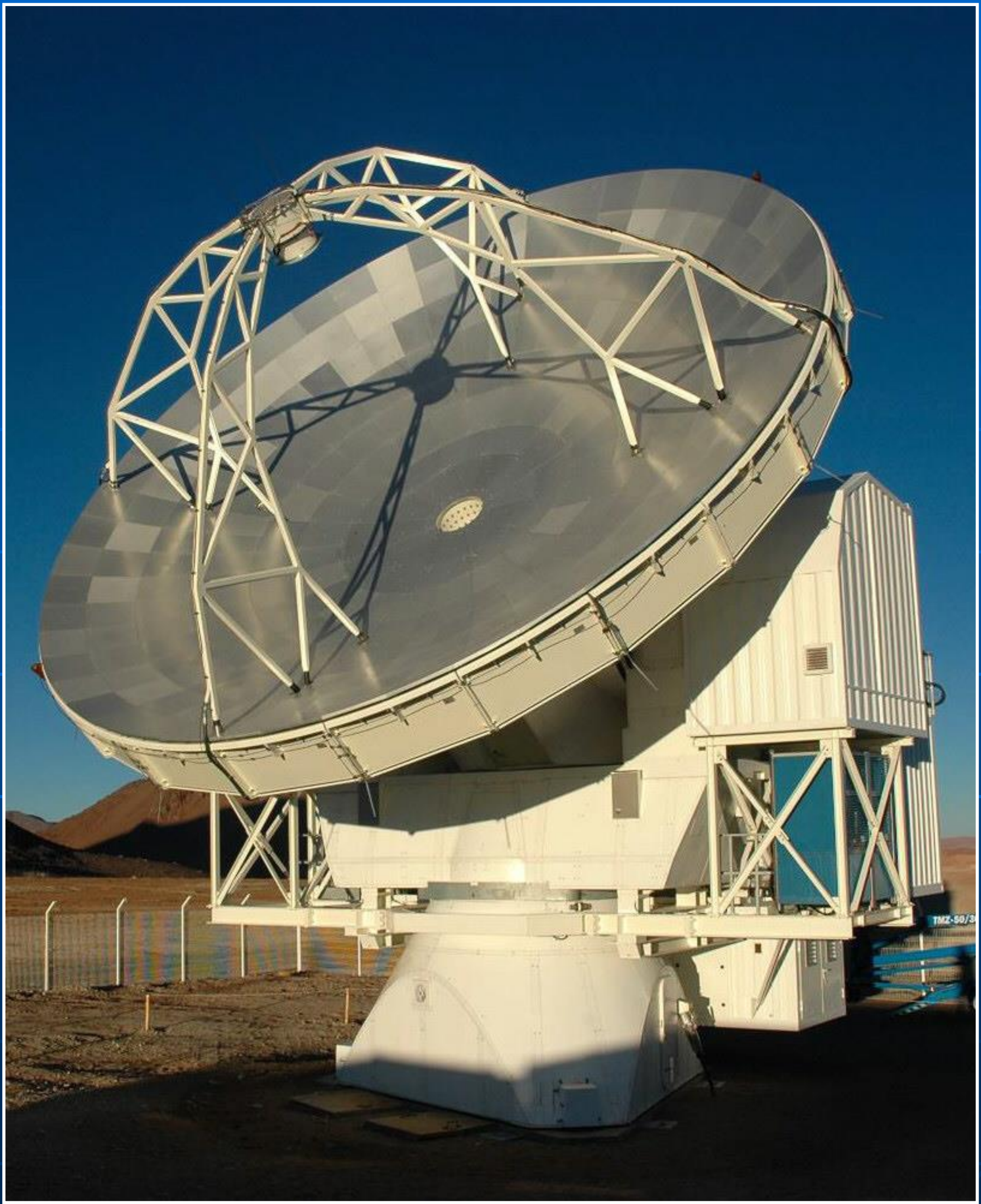
APEX 15 m

(Atacama/Chile)

210 - 1500 GHz

(1.4 – 0.2 mm)





Interferometer:
Westerbork (Netherlands)
Baselines ≤ 6 km

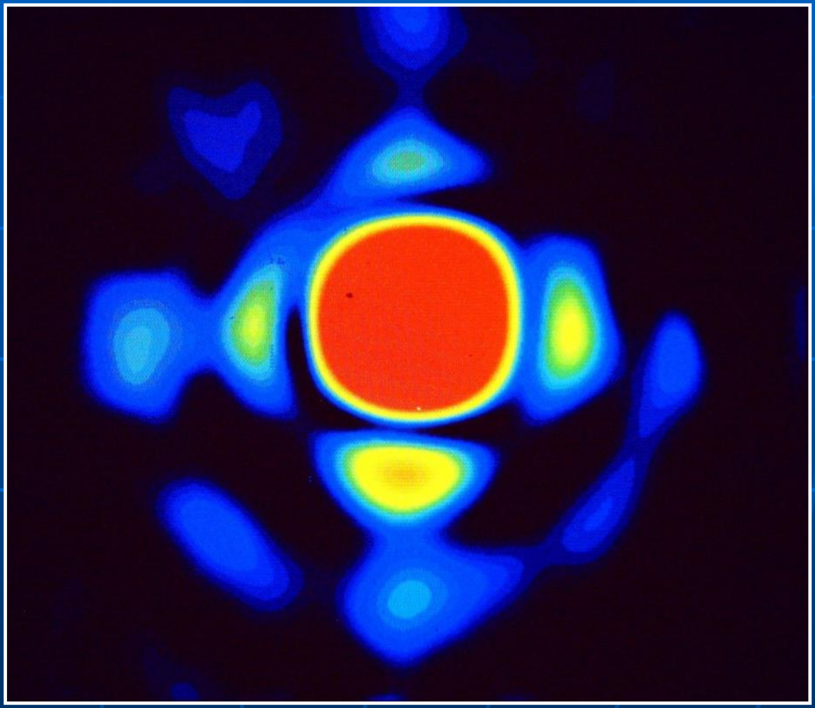
Interferometer:

Very Large Array (Socorro/USA)

Baselines ≤ 25 km

Angular resolution of radio telescopes

$\theta \approx 65^{o} \lambda / D$



Effelsberg: D = 100 m

λ = 3 cm: $\theta \approx 1.2'$

VLA: D = 25 km

λ = 3 cm: $\theta \approx 0.3''$

VLA: configuration DnC

DnC configuration

Last updated on 09/20/2010

NOTES:

1. All antennas are now EVLA

2. Preferred Y27 VLB antenna: **N/A (N/A)**

3. Preferred Y1 VLB antenna: **N/A (N/A)**

4. Antenna replaced by Pietown: **N/A (N/A)**

5. Antenna out of service: **26**

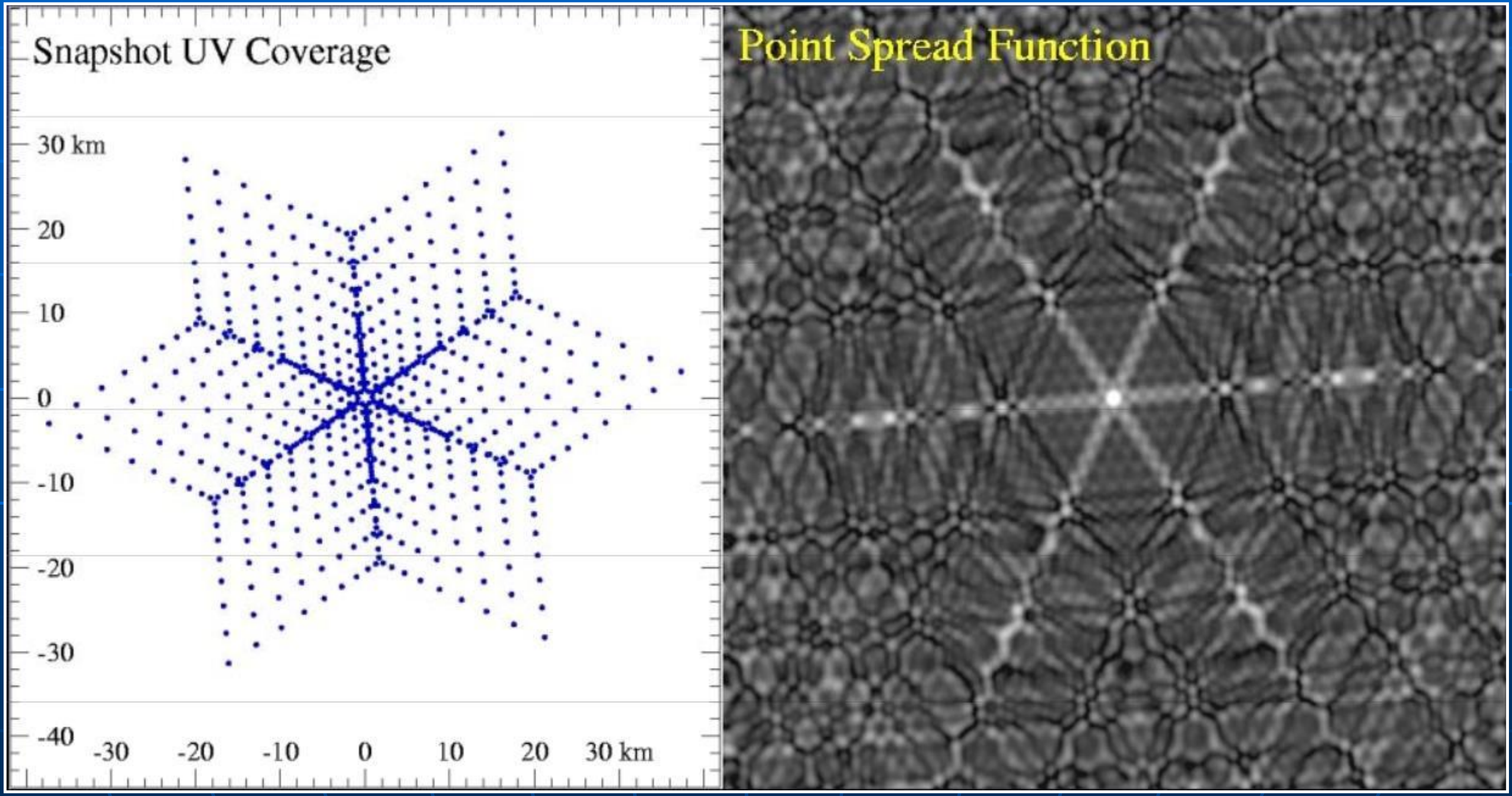
6. WEB: http://www.vla.nrao.edu/operators/CurrentPos.ps
http://www.vla.nrao.edu/operators/CurrentPos.pdf
http://www.vla.nrao.edu/operators/CurrentPos.xls
http://www.vla.nrao.edu/operators/CurrentPos.jpg

Arm	ID	Station	Distance
North:	**25**	CN1 / N2	54.9
	22	CN2 / N4	134.9
	6	CN3 / N6	266.4
	28	CN4 / N8	436.4
	8	CN5 / N10	640.0
	13	CN6 / N12	875.1
	10	CN7 / N14	1140.1
	18	CN8 / N16	1433.7
	20	CN9 / N18	1754.8
East:	**21**	DE1 / E1	39.0
	2	DE2 / E2	44.8
	27	DE3 / E3	89.9
	11	DE4 / E4	147.3
	7	DE5 / E5	216.0
	9	DE6 / E6	295.4
	23	DE7 / E7	384.9
	12	DE8 / E8	484.0
	3	DE9 / E9	592.4
West:	**4**	DW1 / W1	39.0
	16	DW2 / W2	44.9
	N/A	DW3 / W3	89.9
	19	DW4 / W4	147.4
	24	DW5 / W5	216.1
	15	DW6 / W6	295.5
	17	DW7 / W7	384.9
	5	DW8 / W8	484.0
	1	DW9 / W9	592.4
Master Pad:	**14**	MAS / MAS	N/A
Pie Town:	**29**	VPT / VPT	174635.3
AAB:	**26**	AAB / AAB	N/A
Recommissioned:	**N/A**	N/A / N/A	N/A

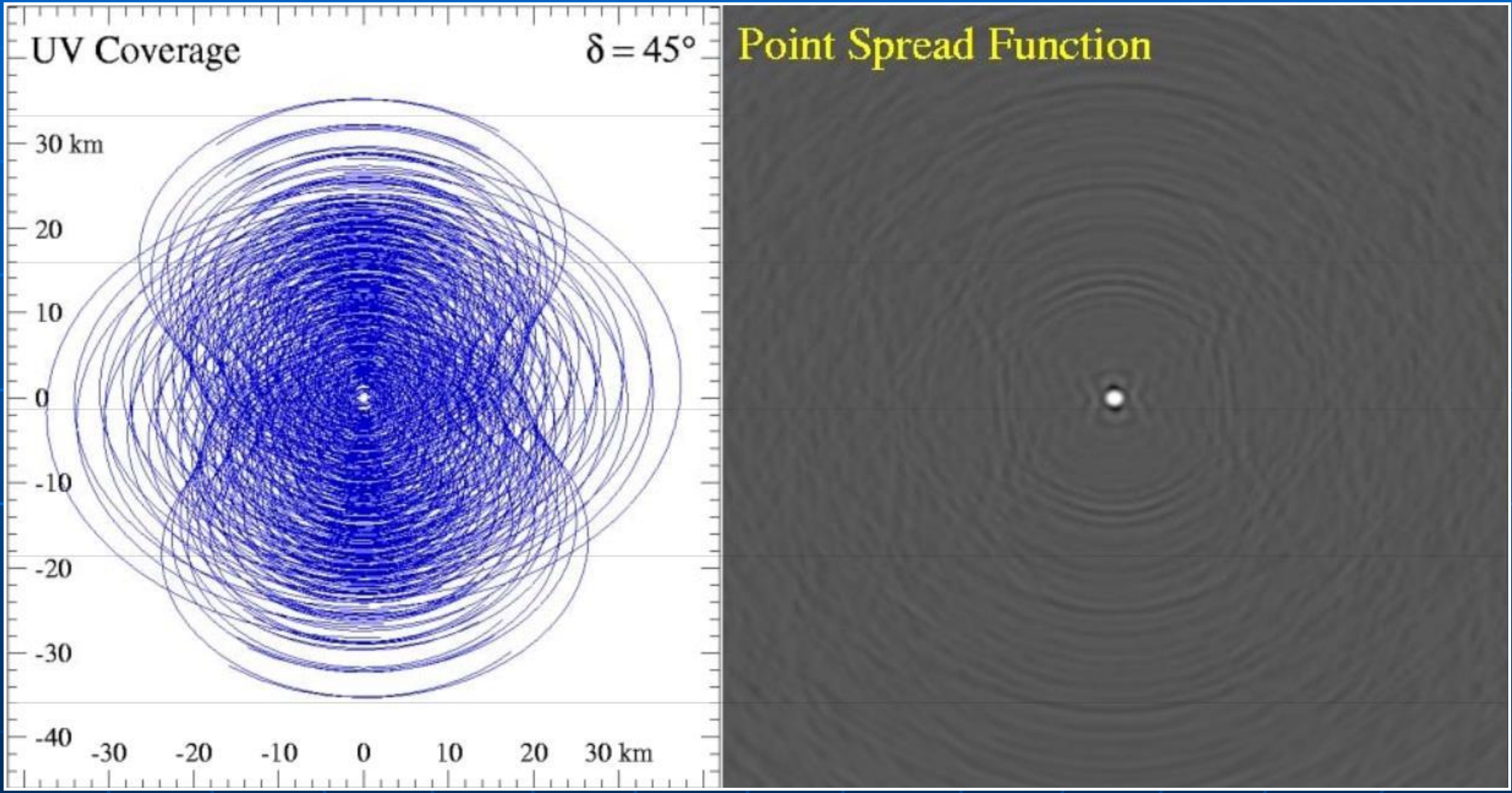
CN9 (20)
CN8 (18)
CN7 (10)
CN6 (13)
CN5 (8)
CN4 (28)
CN3 (6)
CN2 (22)
CN1 (25)
DW1 (4) DE1 (21)
DW2 (16) DE2 (2)
DW3 (N/A) DE3 (27)
DW4 (19) DE4 (11)
DW5 (24) DE5 (7)
DW6 (15) DE6 (9)
DW7 (17) DE7 (23)
DW8 (5) DE8 (12)
DW9 (1) DE9 (3)

IAT-UTC:	34 seconds
Antennas with Q-band:	All
Hybrid L-band:	All except 6, 7, 9, 14, 17, 20, 22, 24

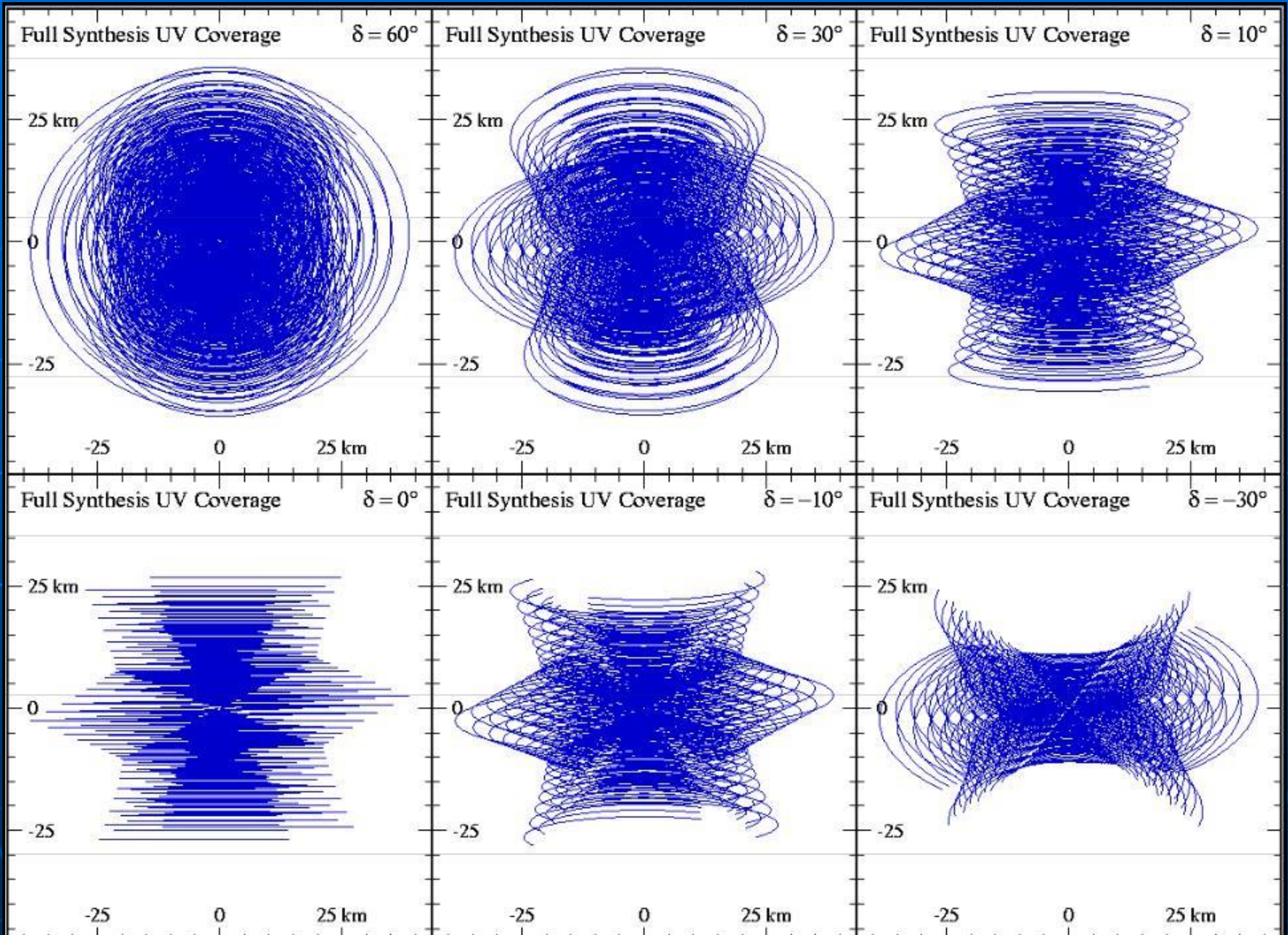
VLA: UV coverage for snapshot observations



VLA: UV coverage for full 12h observations

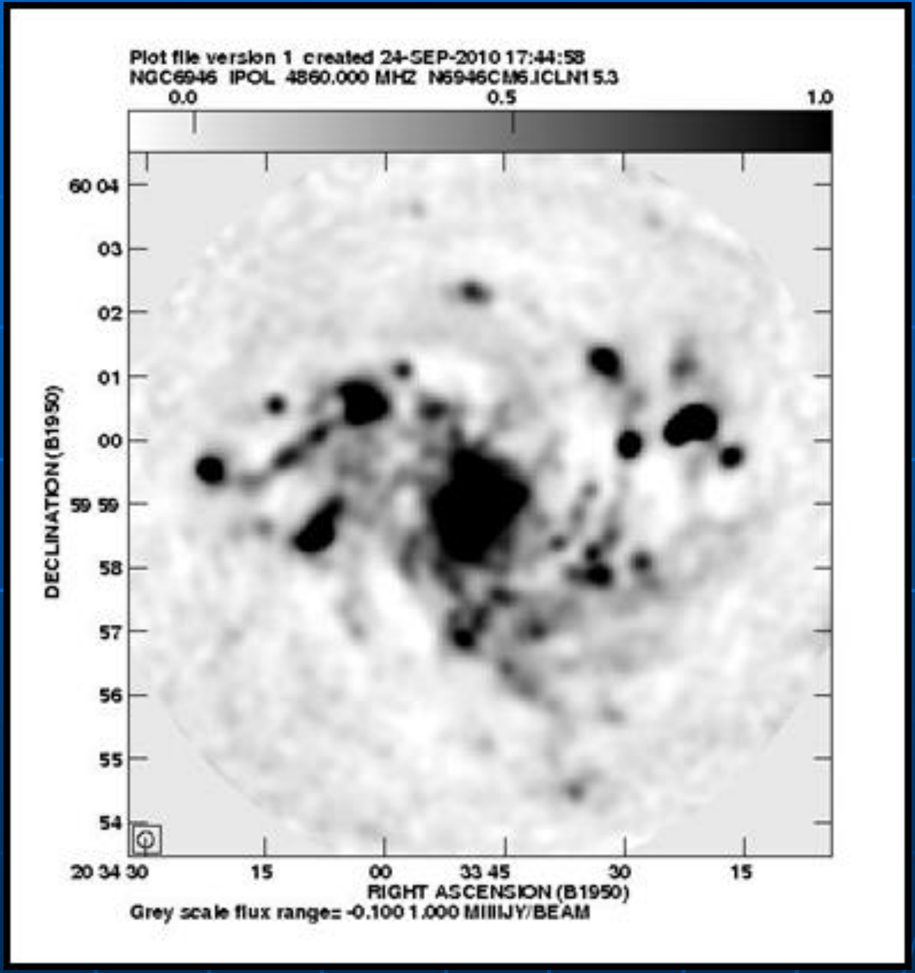


VLA: UV coverage for different declinations



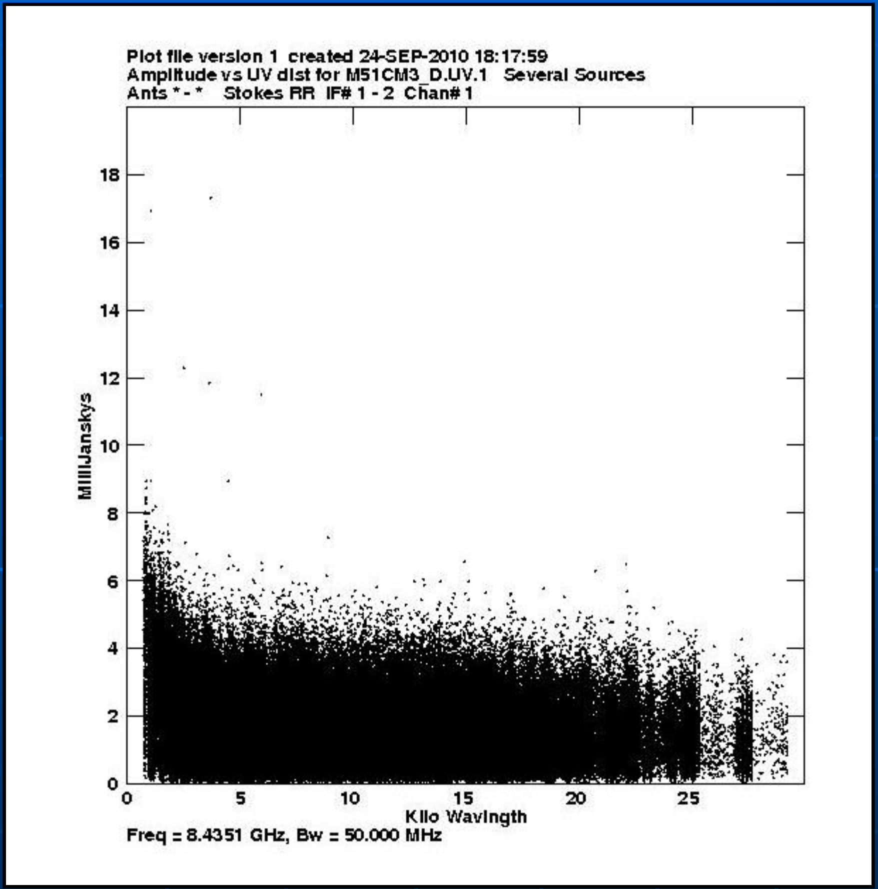
Tracks: elevation > 10 degrees

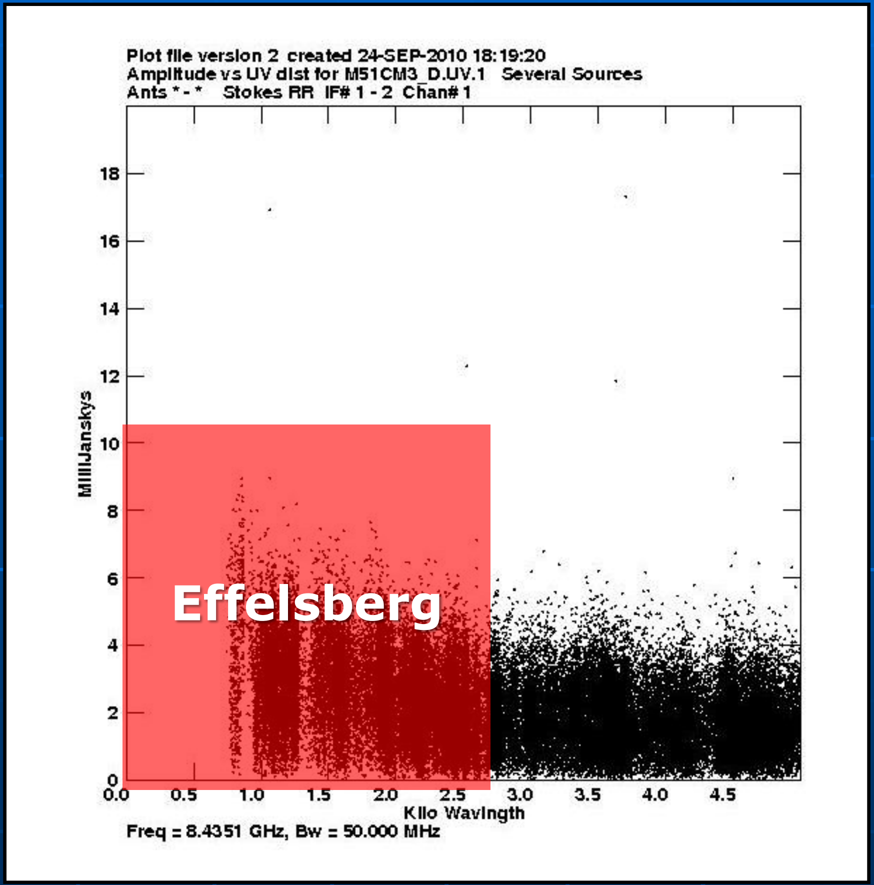
VLA: the effect of missing spacings



Combination of interferometer and single-dish data

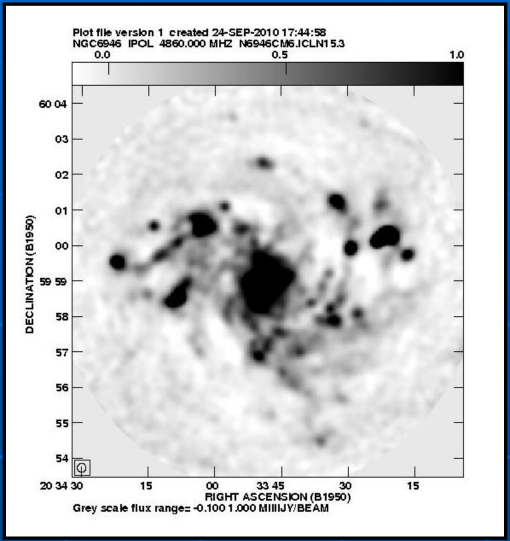
UV coverage of VLA data
(3 cm D array)

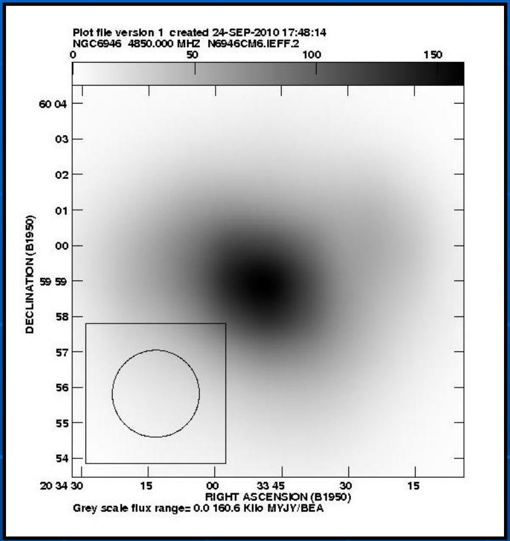


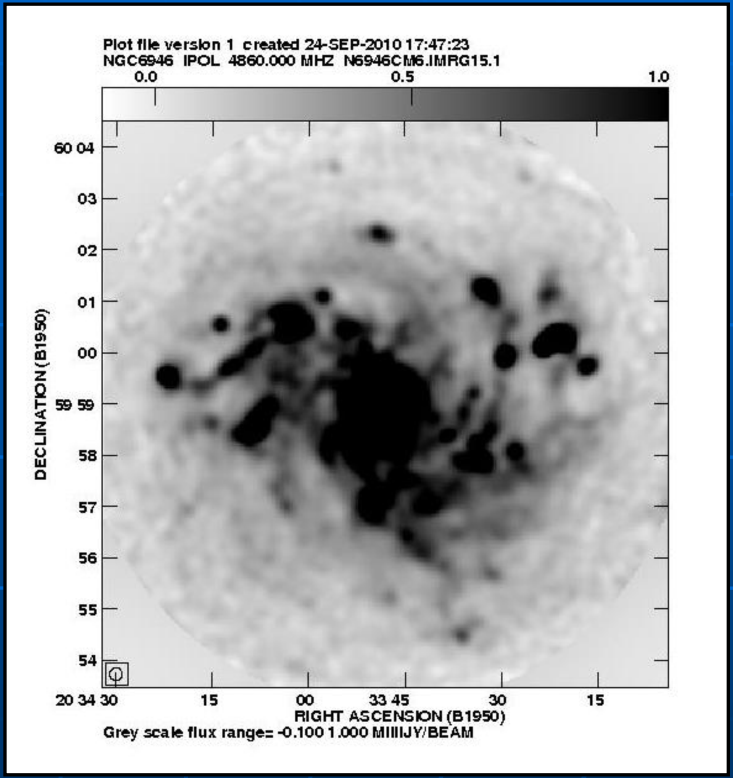


Minimum baseline: 25 m ≈ 700 kλ

Combination of VLA and Effelsberg data
(NGC 6946 6 cm Stokes I)







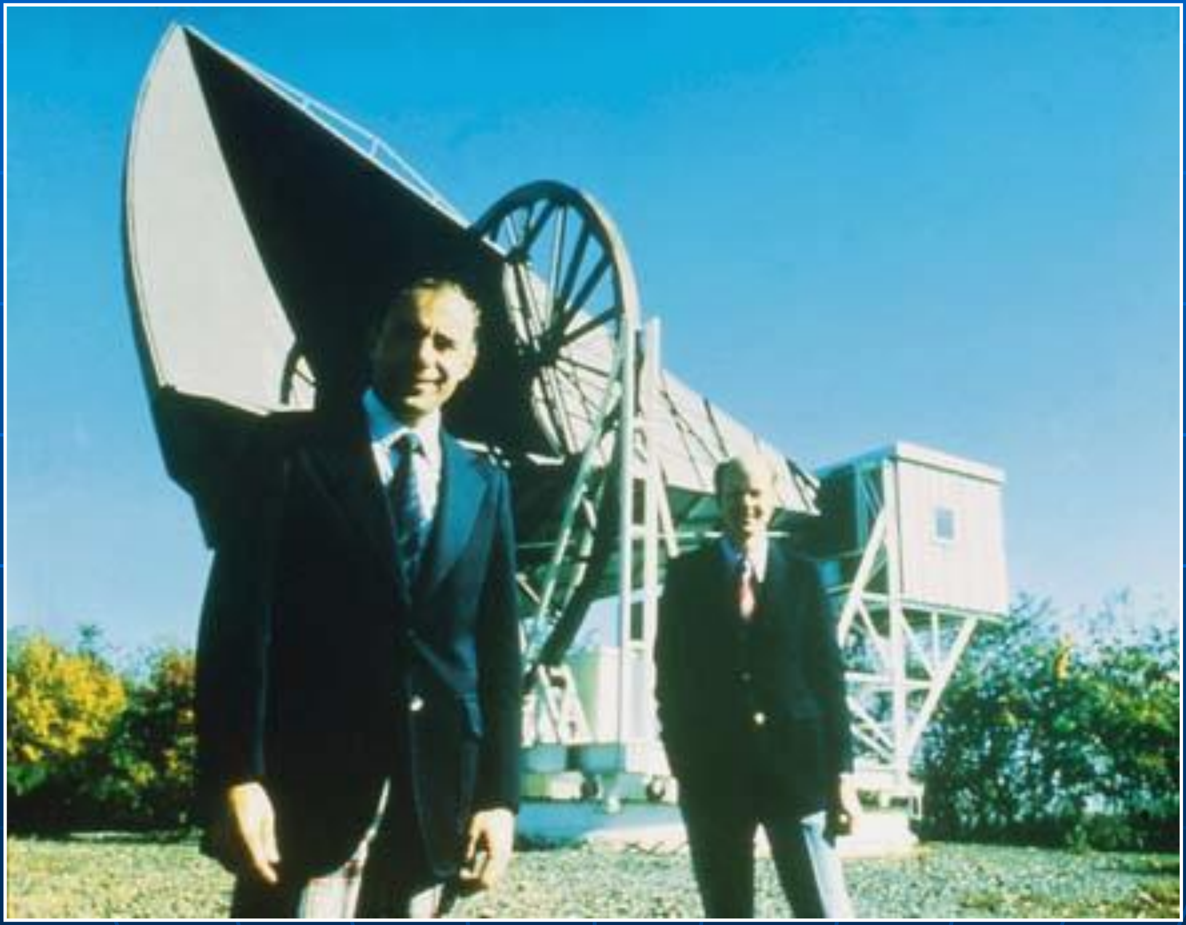
VLA alone:
≈ 50% total flux

Single dish observations
are crucial
for any interferometer telescope
to fill the “missing spacings”

Results & discoveries

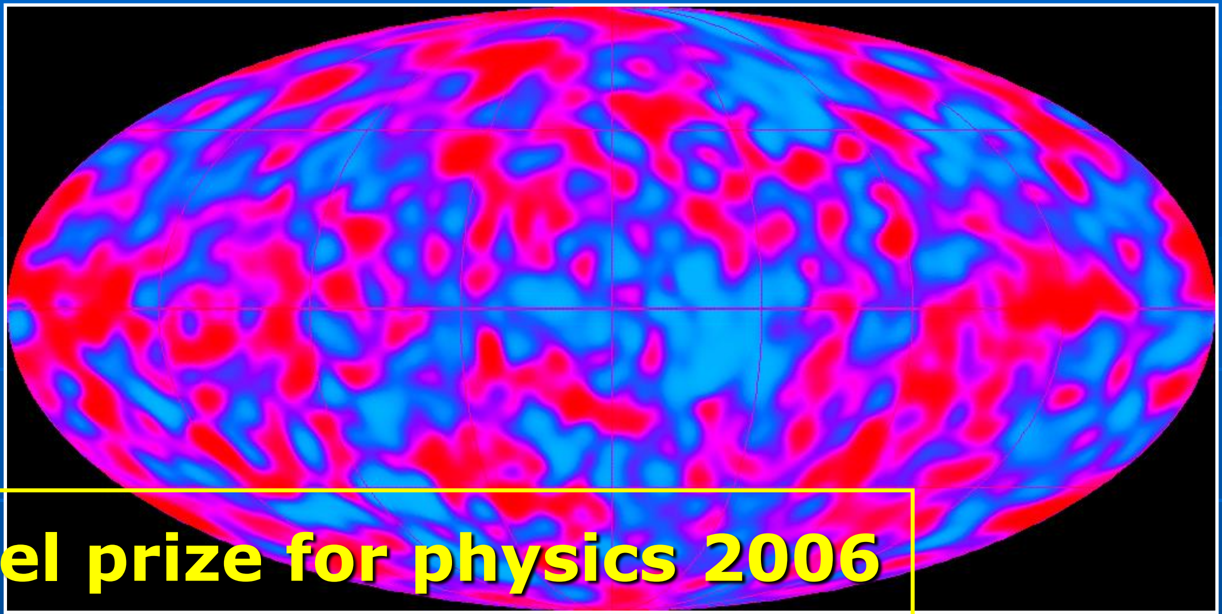
Discovery of the Cosmic Microwave Background

Penzias & Wilson (1960)

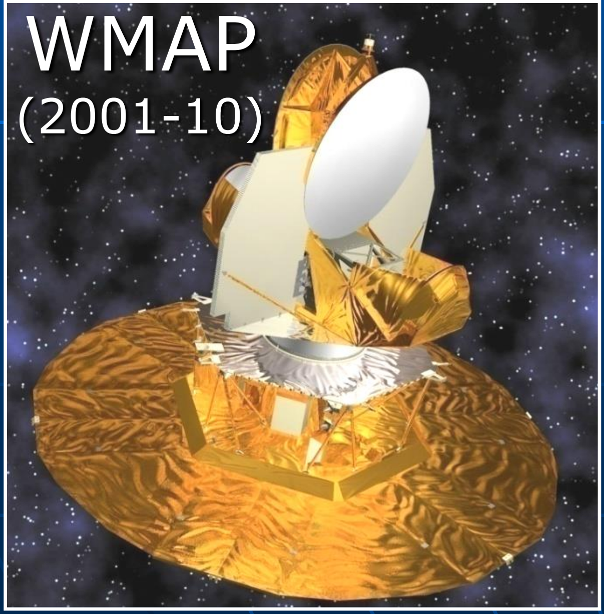


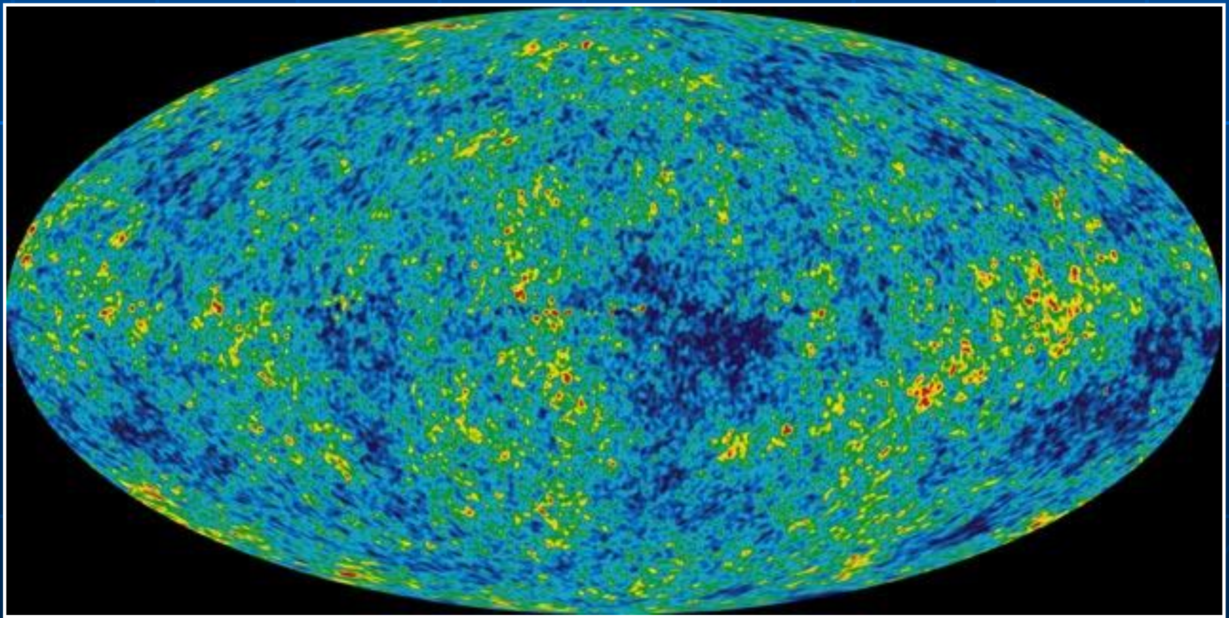
Nobel prize for physics 1978

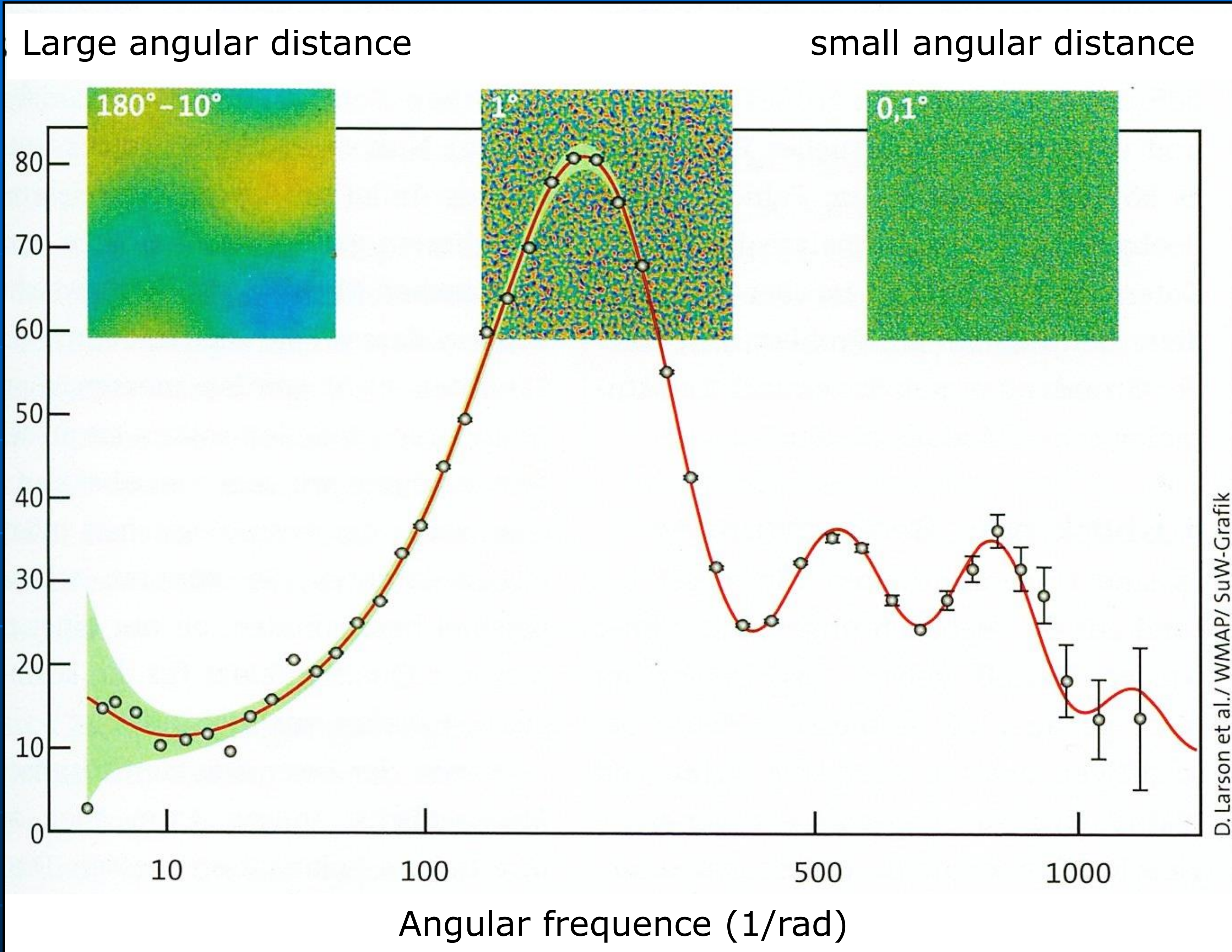
Cosmic Microwave Background (CMB)



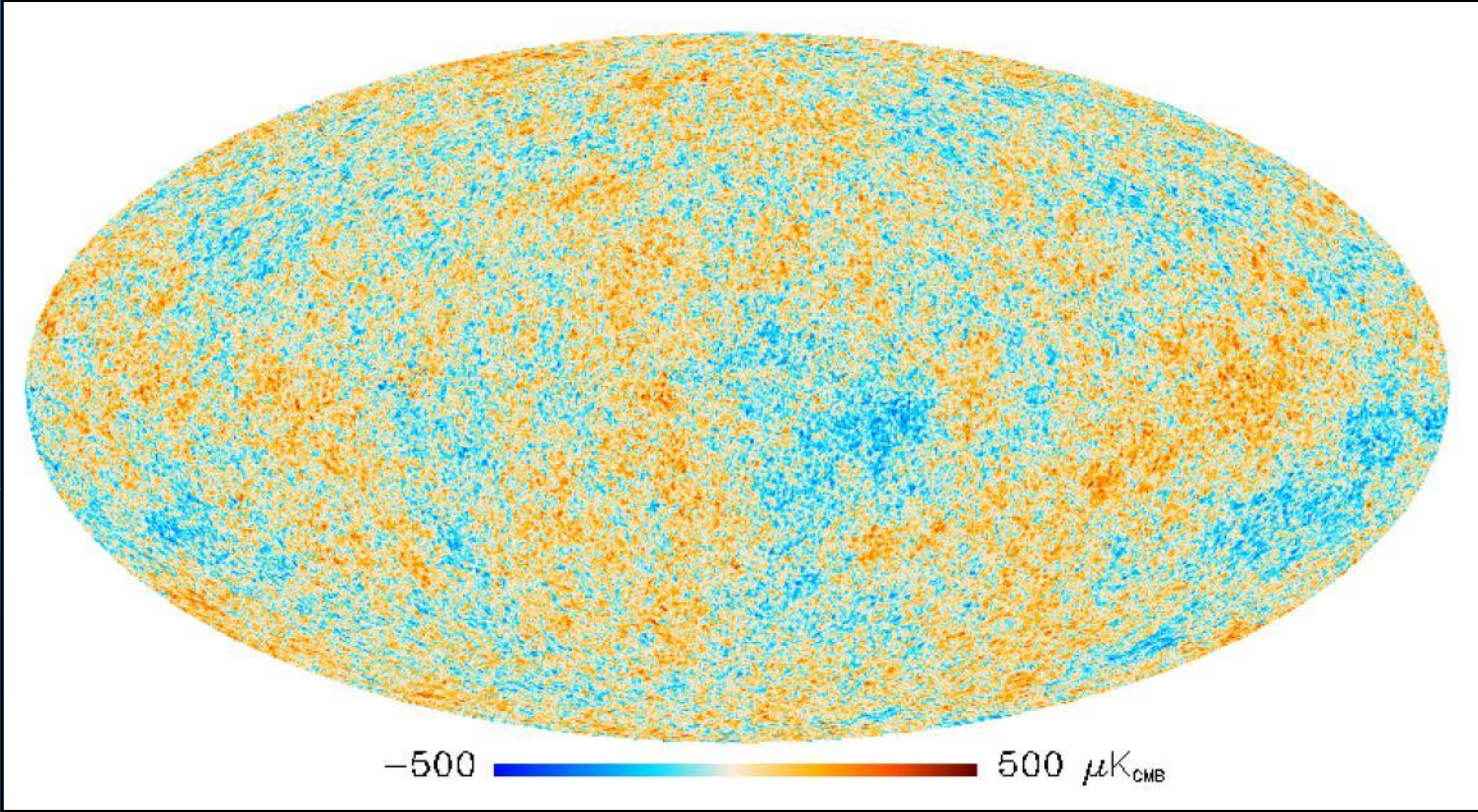
Nobel prize for physics 2006



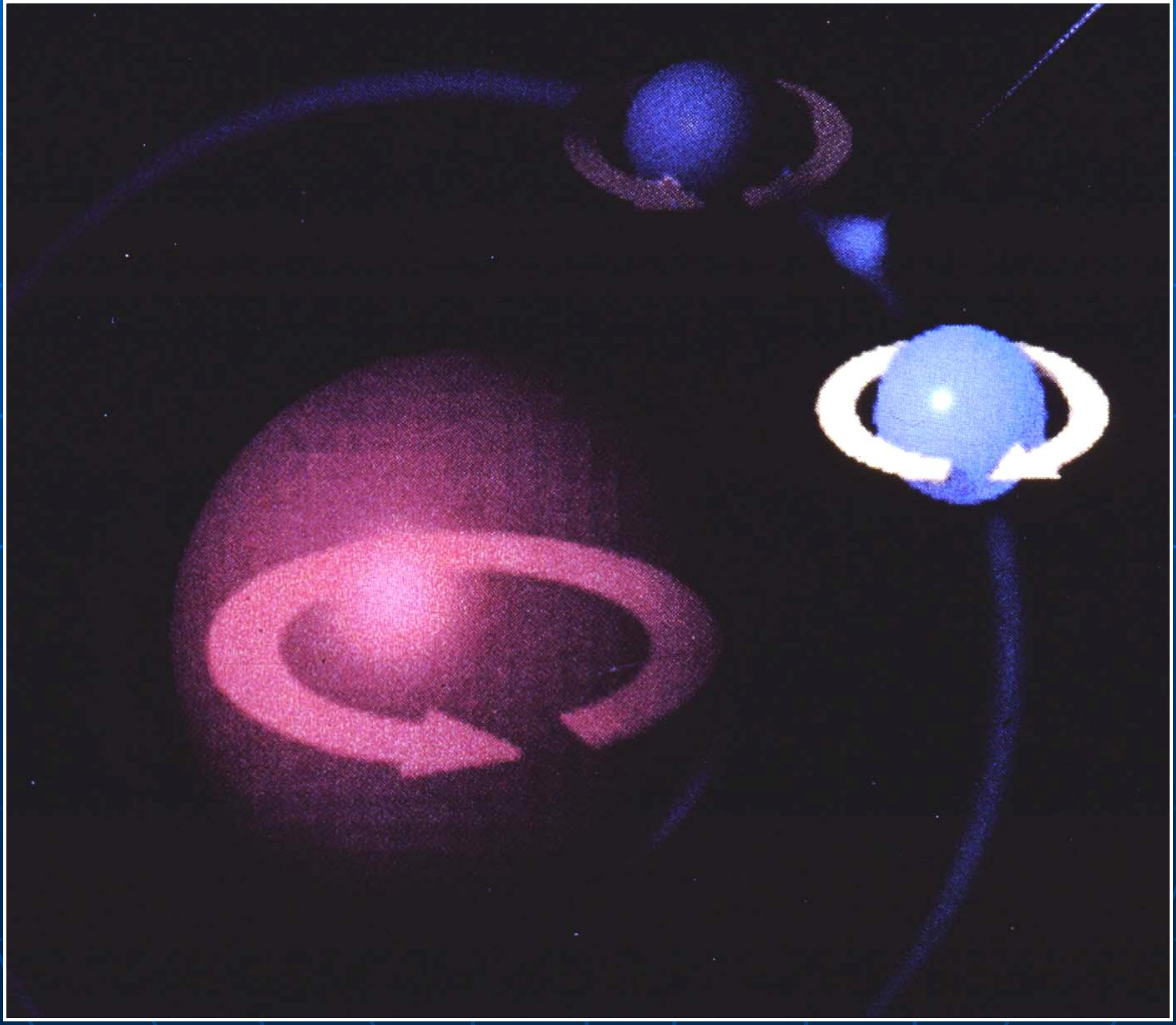



Large angular distance
small angular distance
180° - 10°
1°
0,1°
80
70
60
50
40
30
20
10
0
10
100
500
1000
D. Larson et al./ WMAP/ SuW-Grafik
Angular frequence (1/rad)

PLANCK (2010 - ?)



Line emission of cold neutral hydrogen (HI) at 21.1 cm

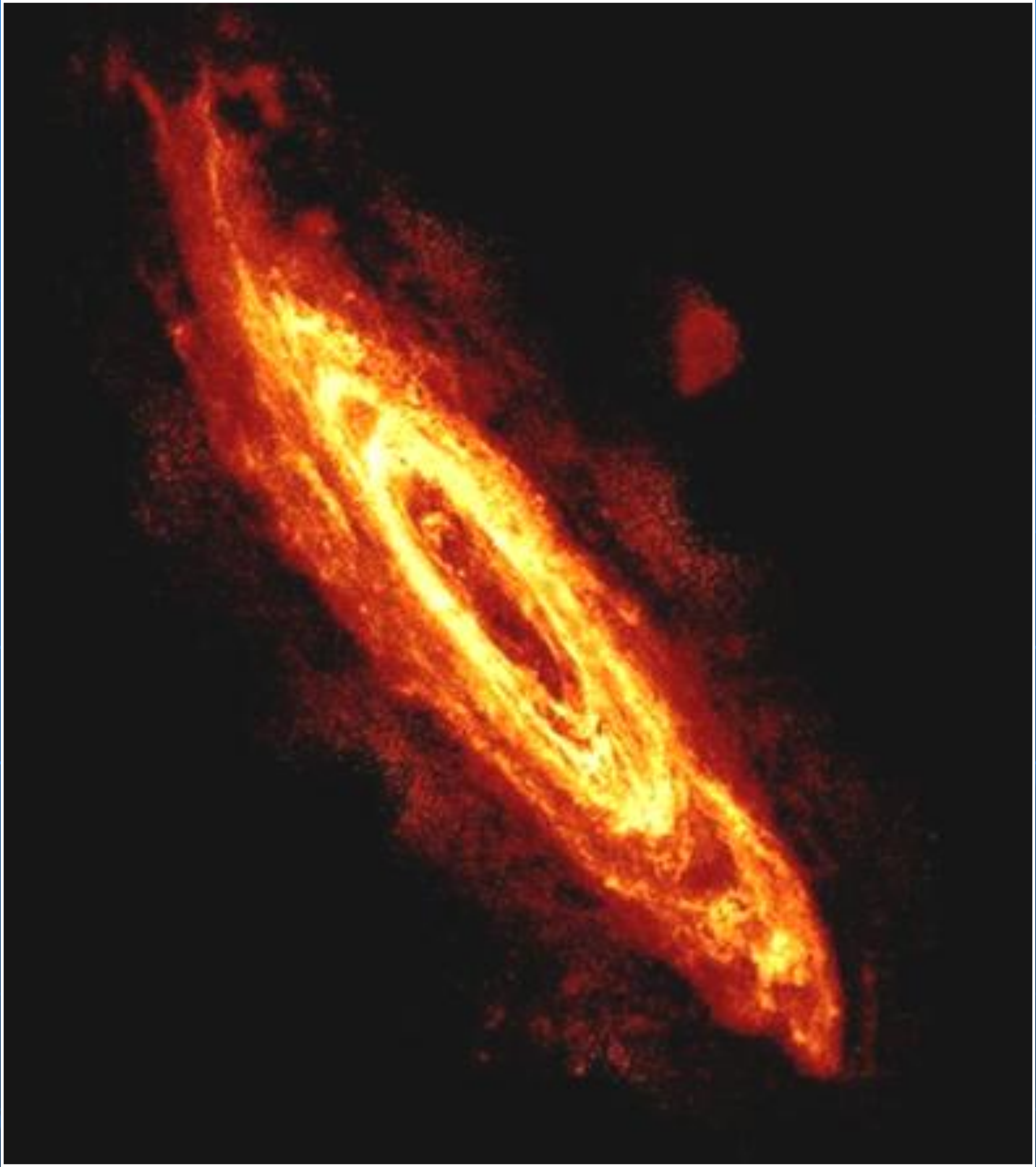


M 31

HI line emission

Westerbork

(Braun et al. 2005)

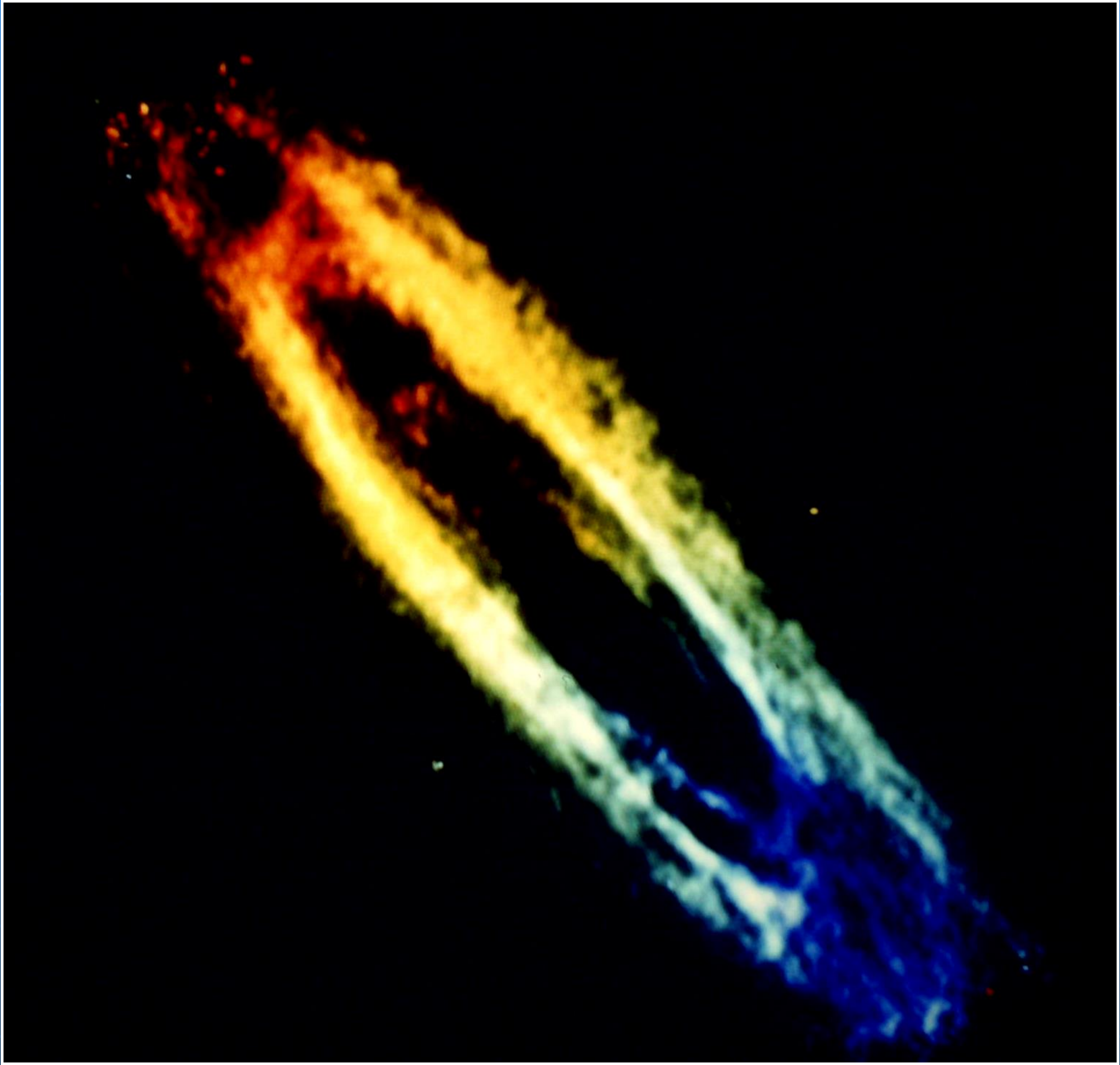


M 31

HI line velocities

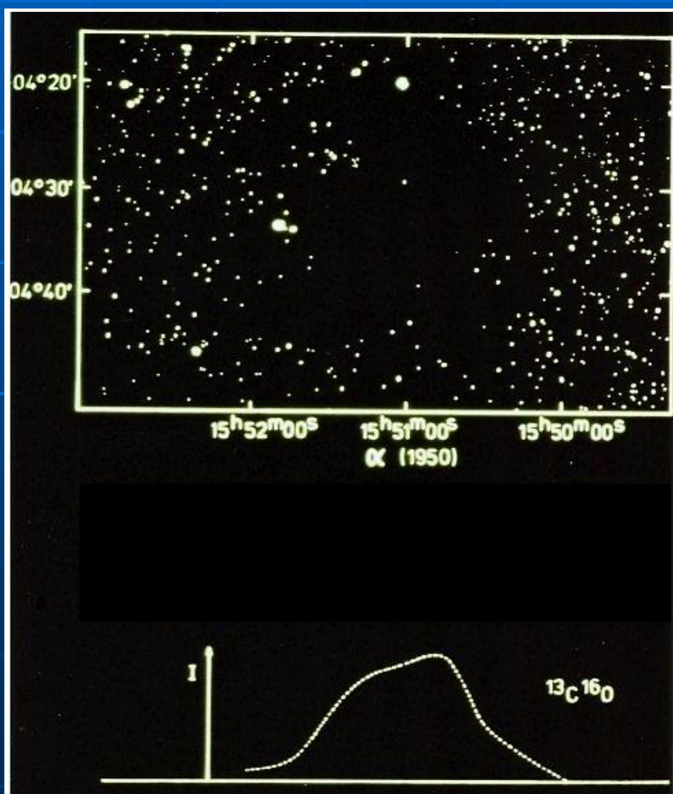
Red: -100 km/s

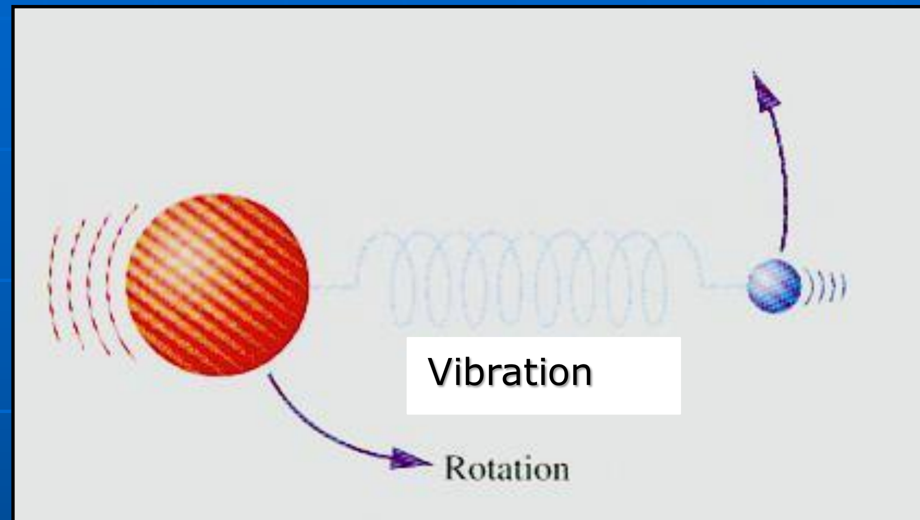
Blue: -600 km/s



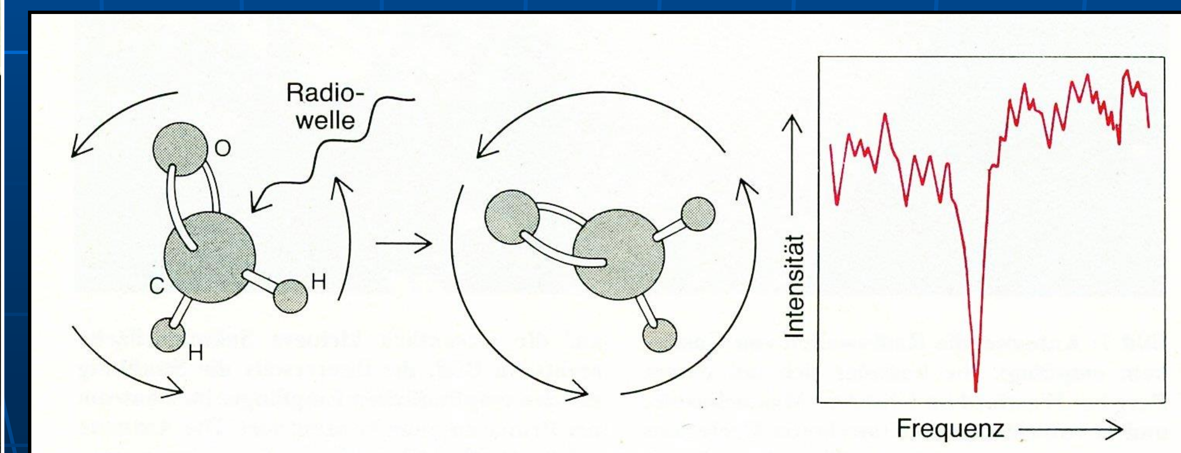
Radio emission of cold molecular clouds

Radio-bright,
not dark !





CO (carbon monoxide) 2.6 mm



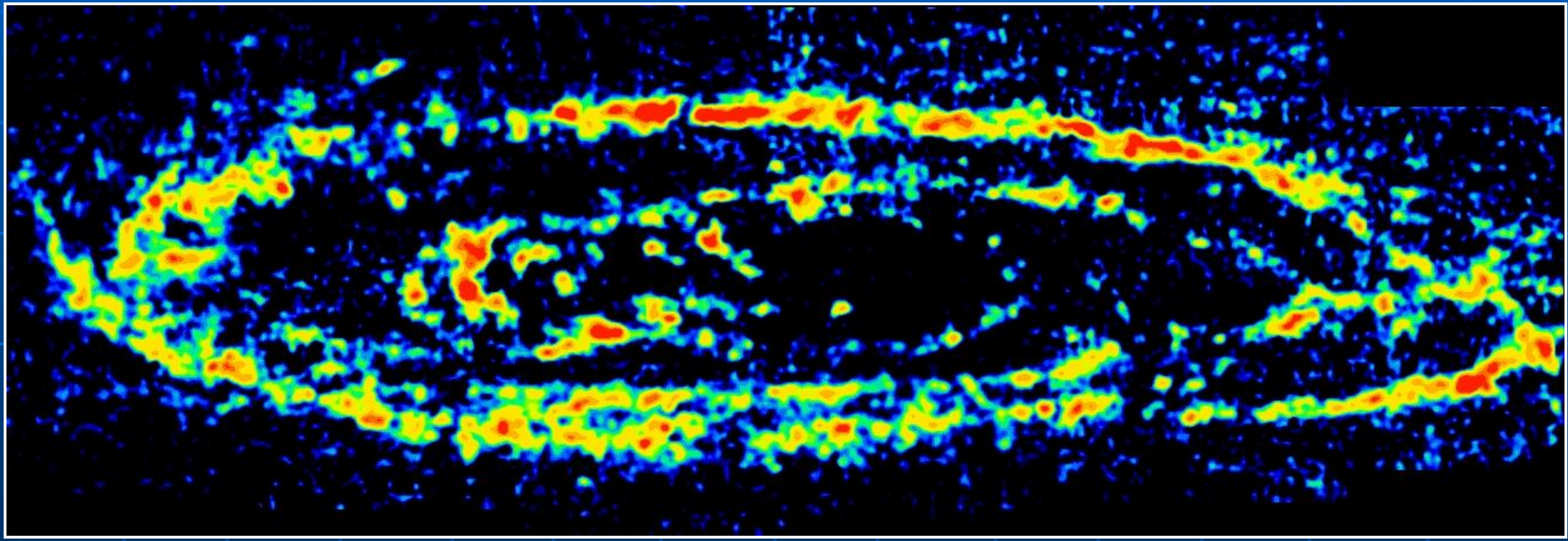
H_2CO (formaldehyde) 6.2 cm

M 31: carbon monoxide (CO)

2.6 mm line emission

IRAM (Pico Veleta/Spain)

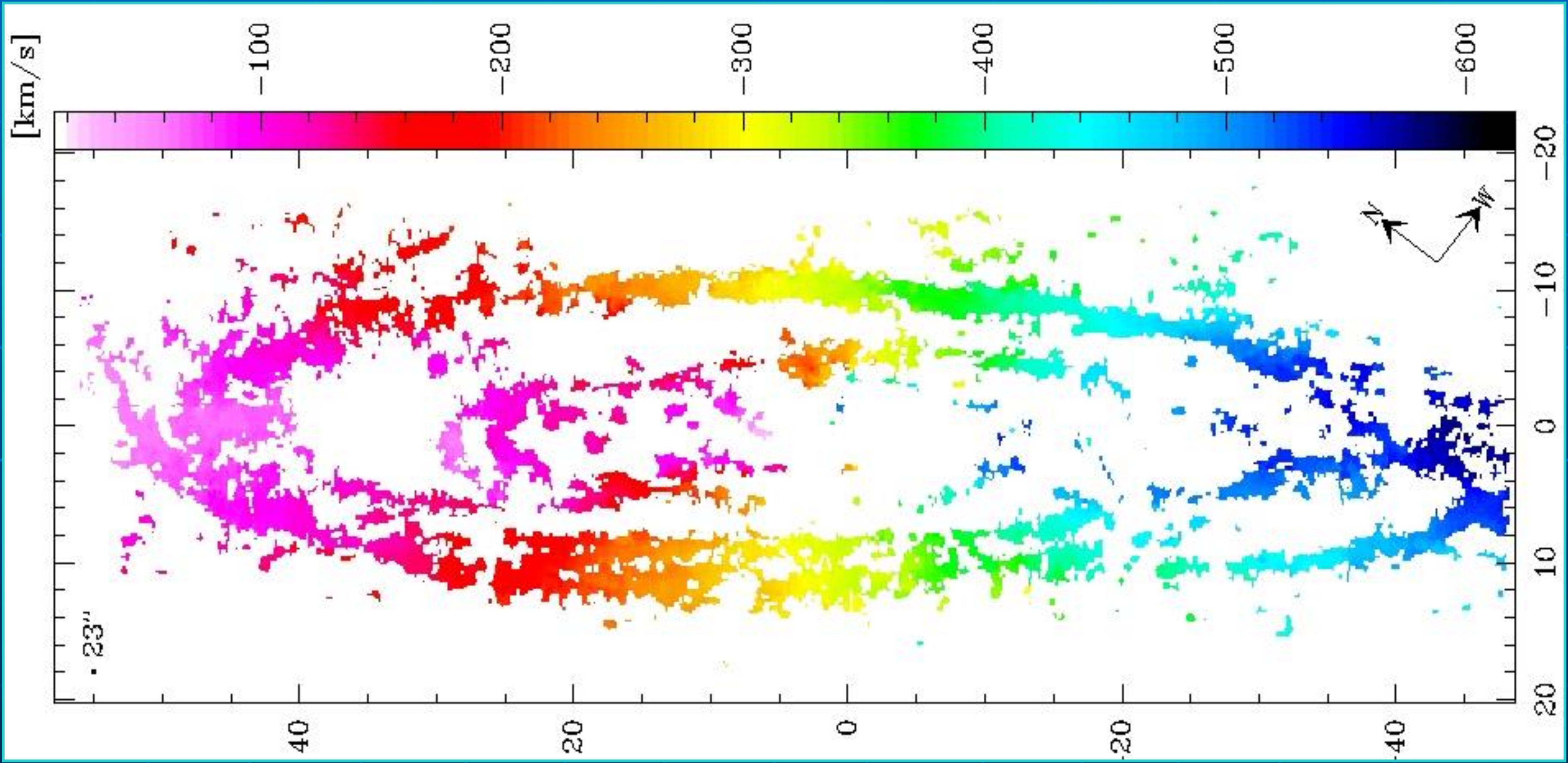
(Nieten et al. 1999)



M 31: CO line velocities

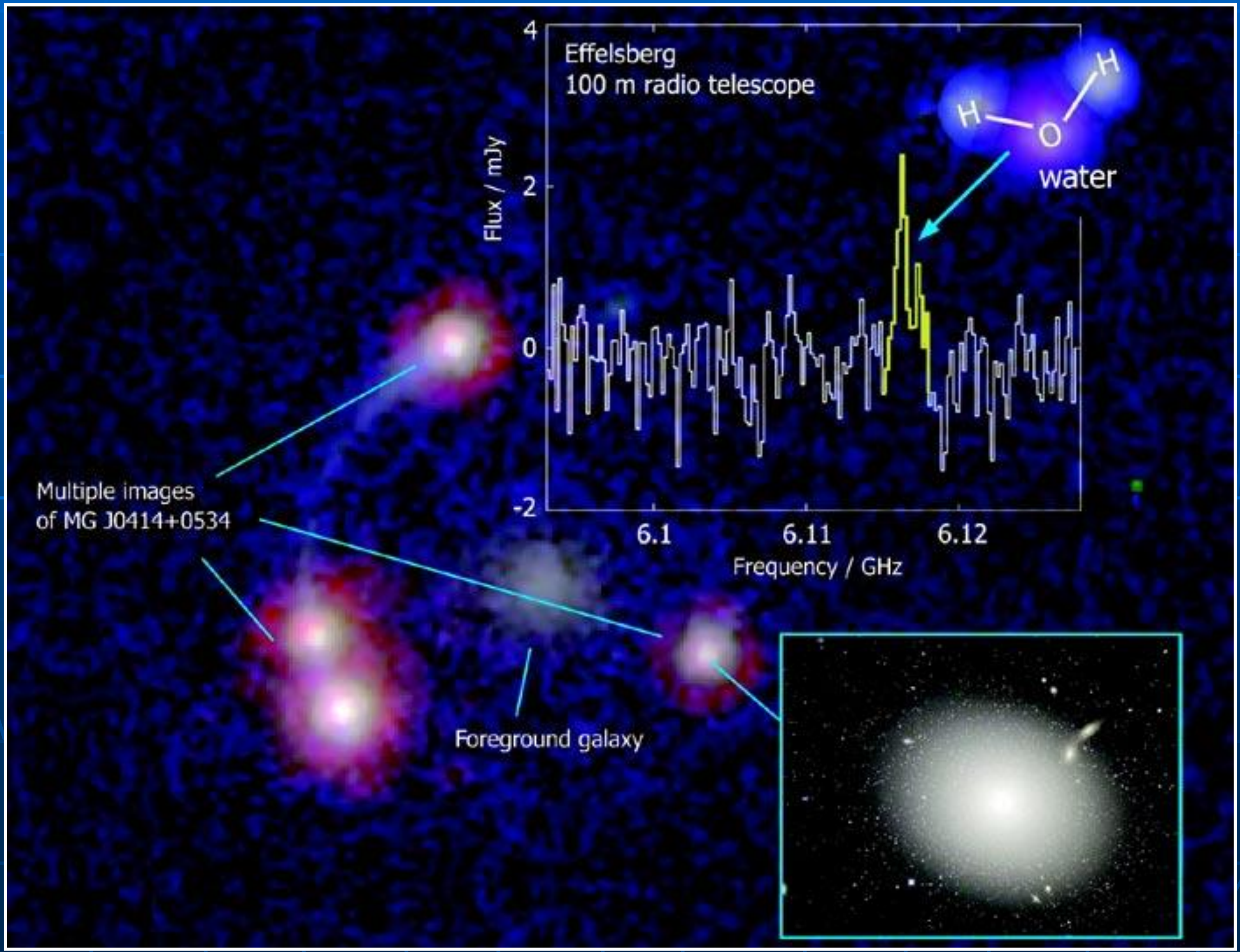
IRAM (Pico Veleta)

(Nieten et al. 1999)

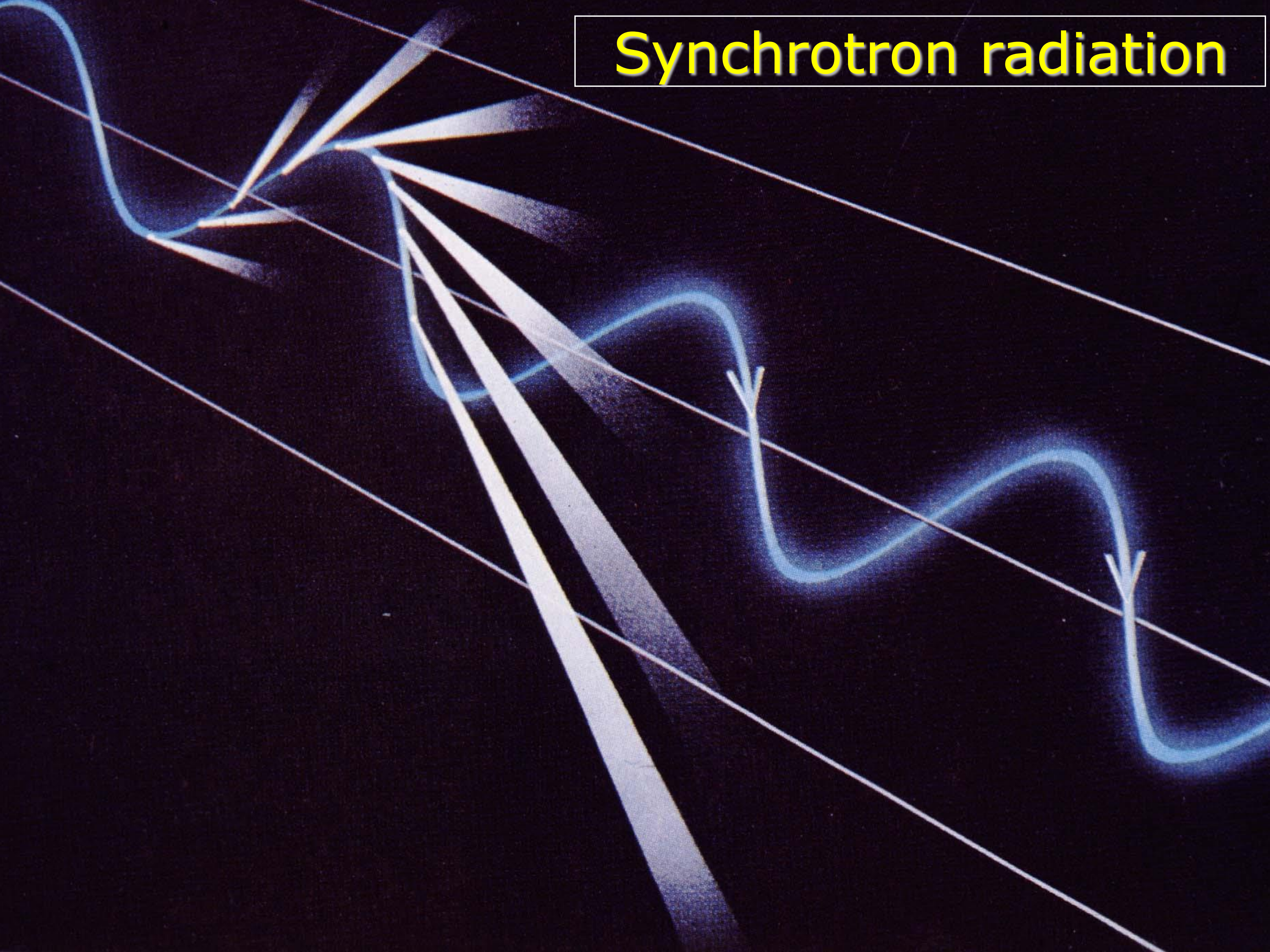


Radio line of water vapour
in a galaxy core at 11 billion light years distance
(Effelsberg 6.1 GHz)

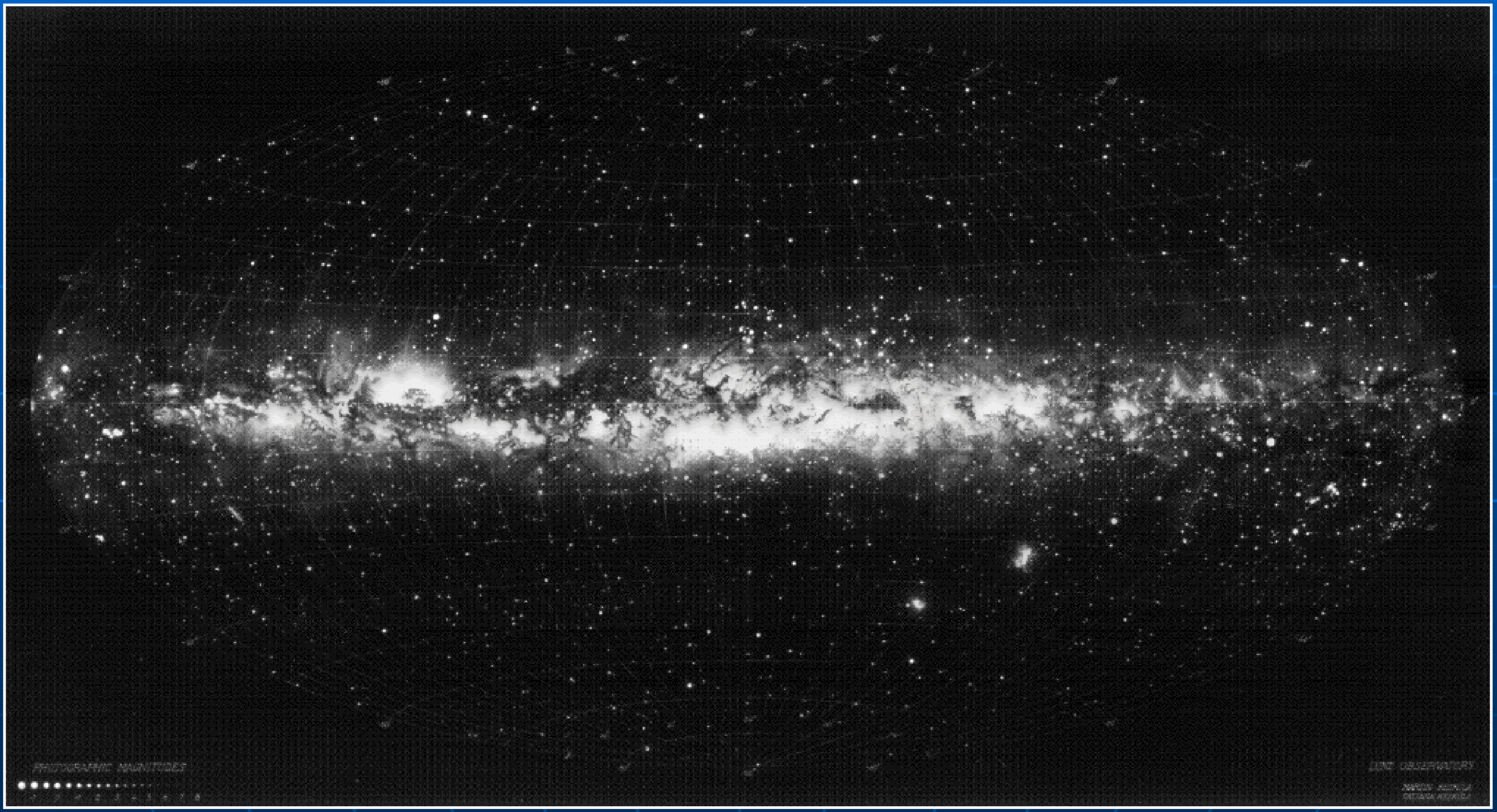
(Impellizzeri et al. 2008)



Synchrotron radiation

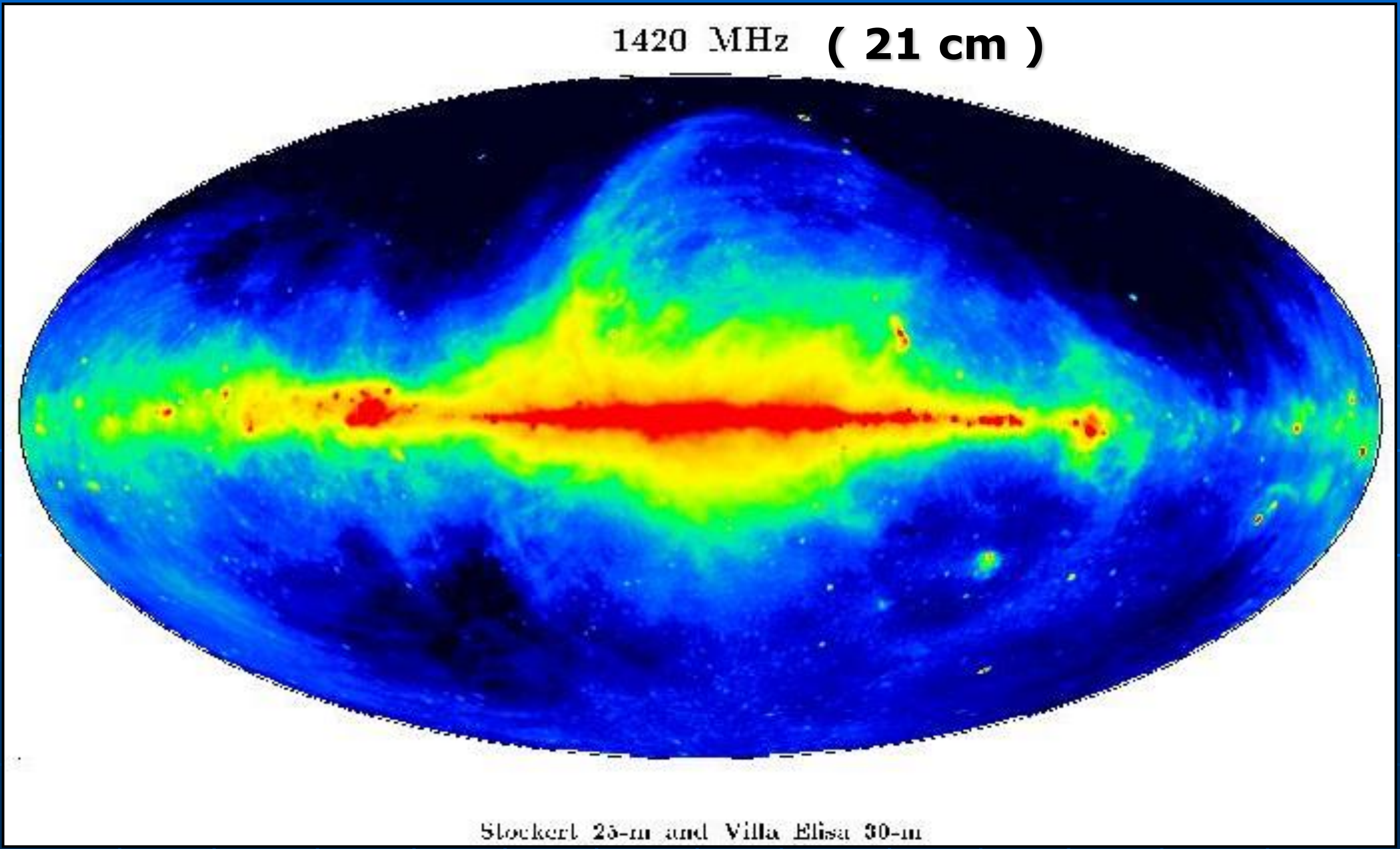


The Milky Way in optical light



Lund Observatory

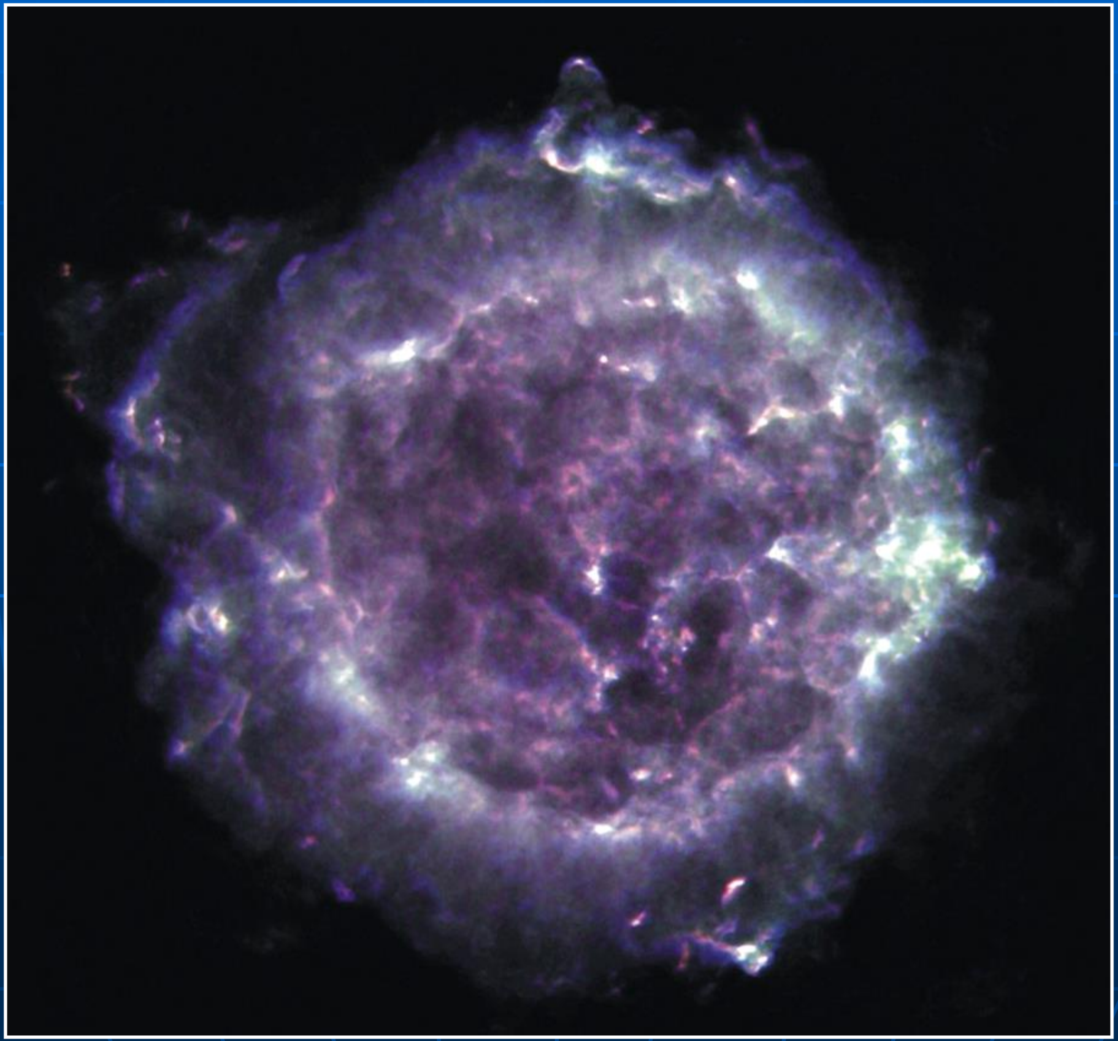
The Milky Way in synchrotron light



Reich & Reich 1986

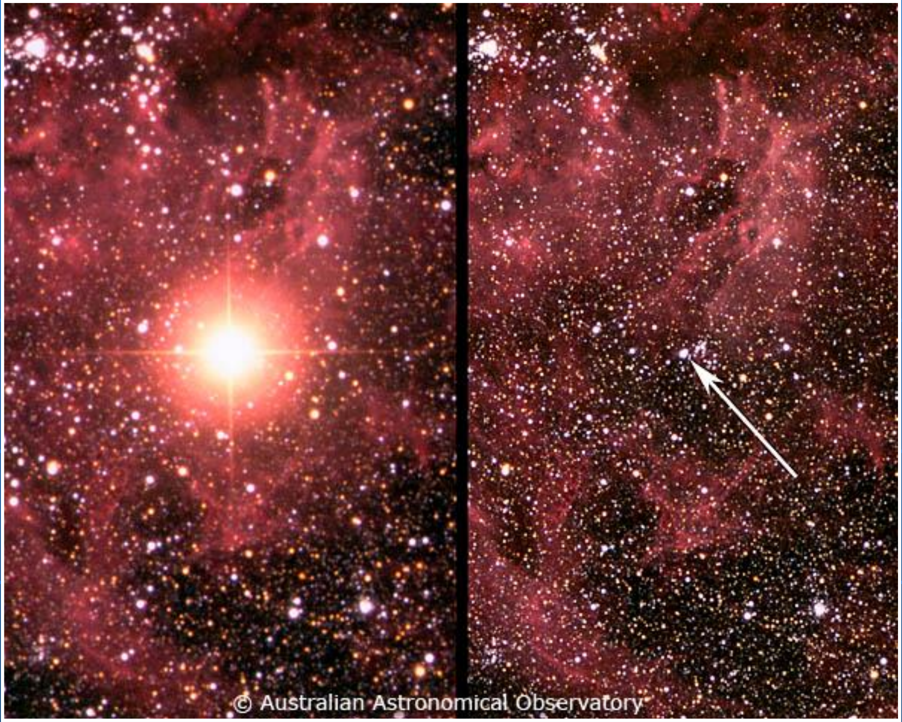
Supernova ~1667, remnant: Cas A

Radio: VLA 3+6+20 cm

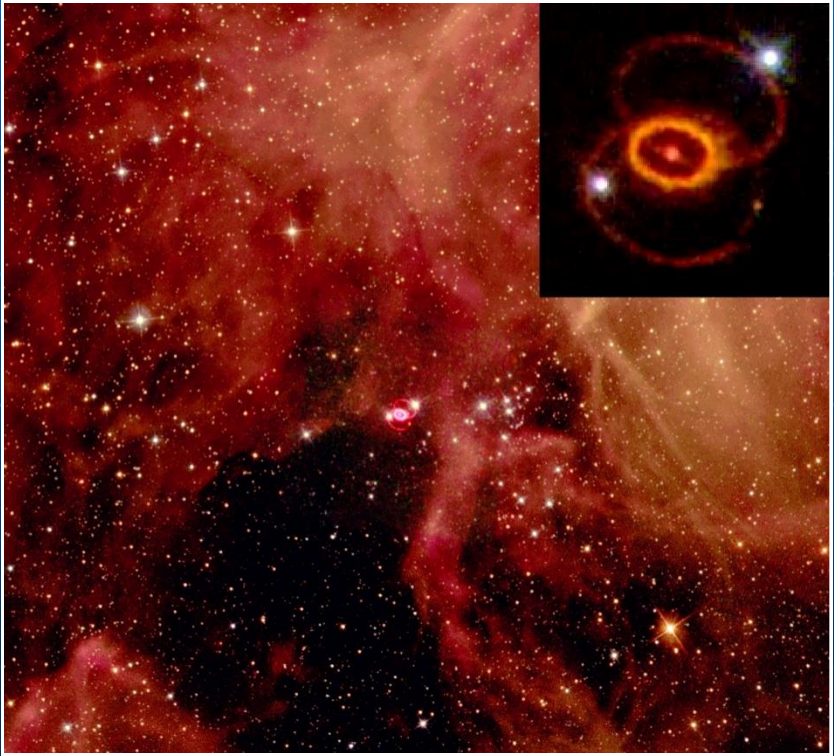


L. Rudnick, NRAO

Supernova 1987A in the LMC
(optical)



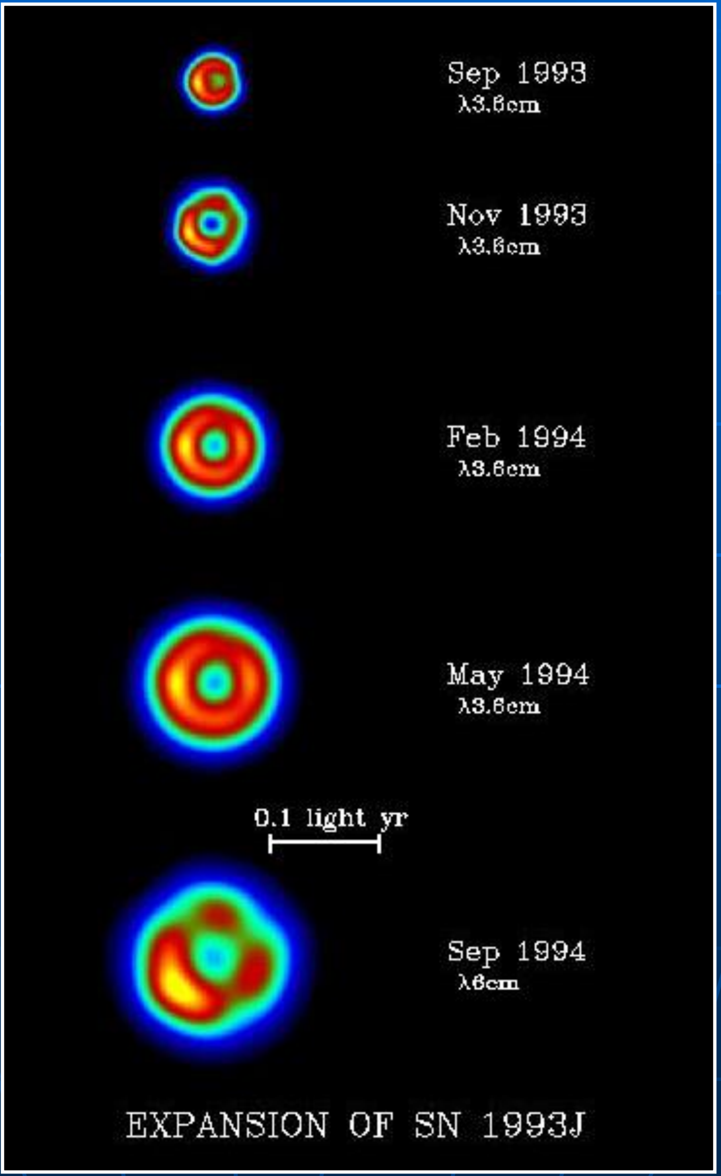
AAO



Hubble Space Telescope

Supernova 1993J in M 81 (VLBI)

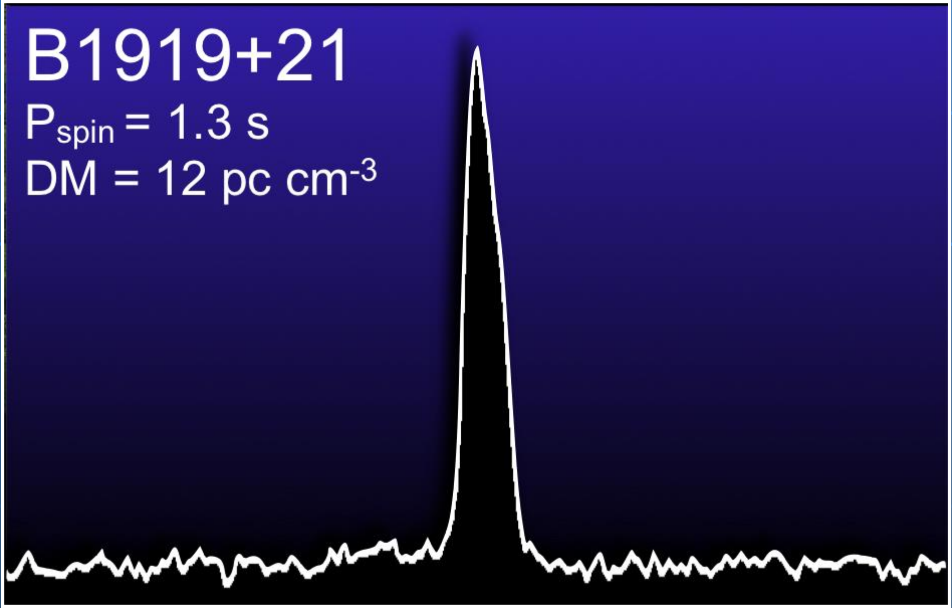
Diameter:
1-3 milli-arcsec
(0.05-0.15
light years)



Marcaide et al. 1995

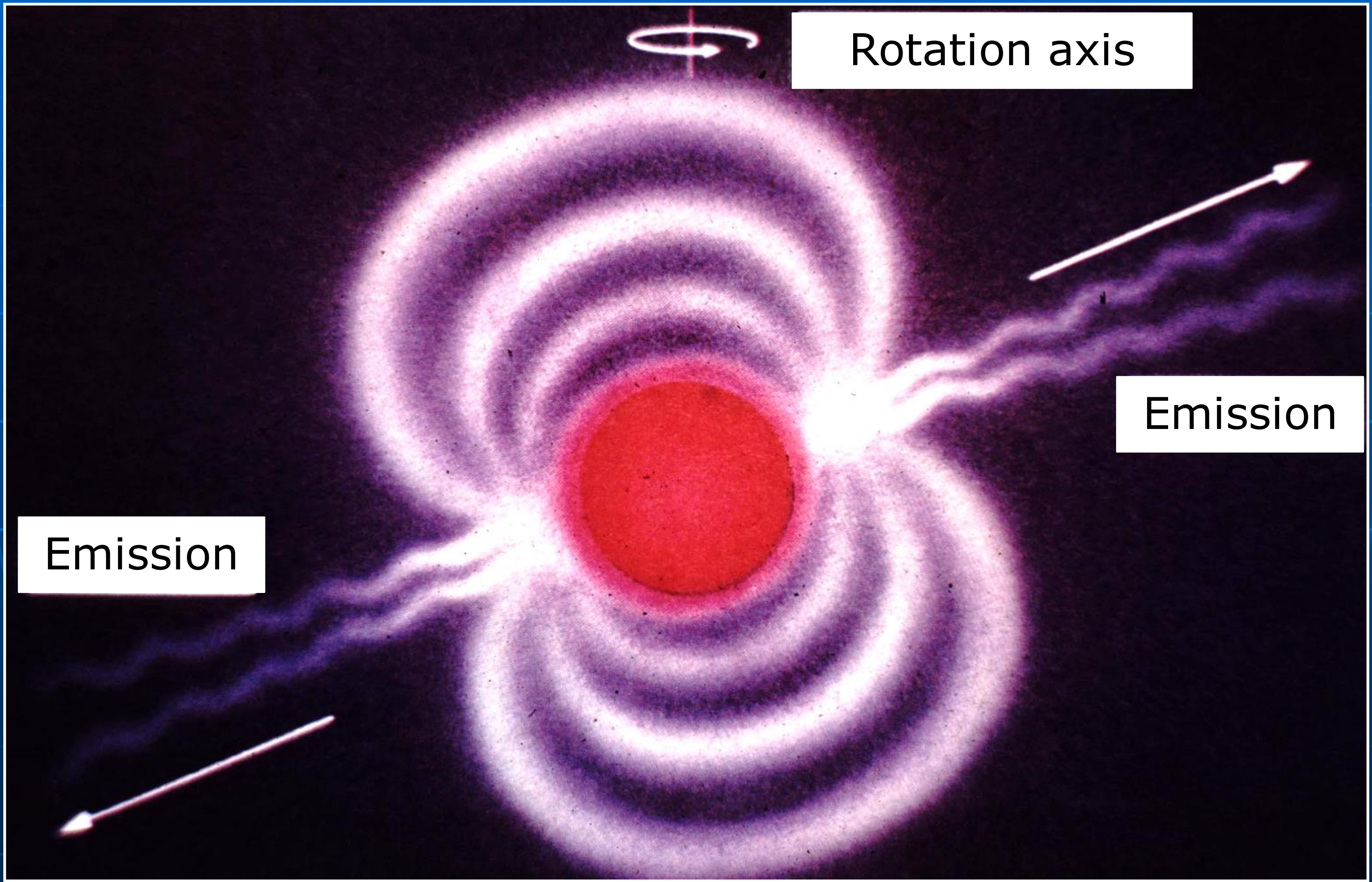
Discovery of pulsars: 1968

Jocelyn Bell Burnell
& Antony Hewish
(Cambridge/UK)
80 MHz (3.7m)



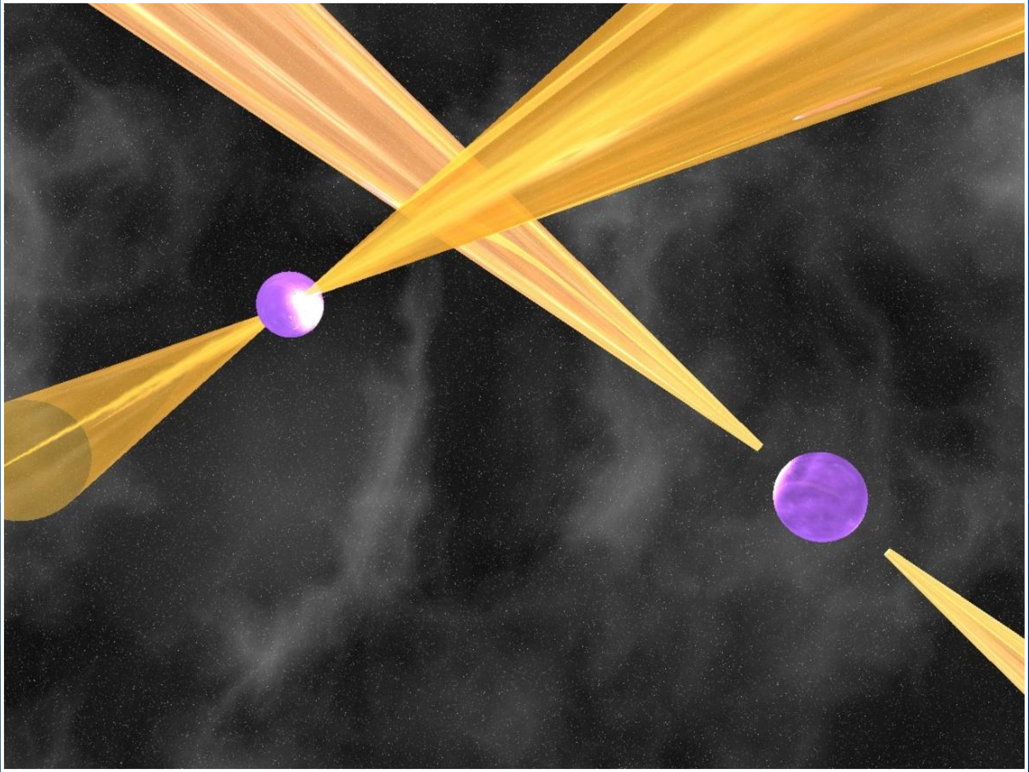
Nobel prize for physics 1974

Pulsars: Magnetic lighthouses



Discovery of gravitational waves

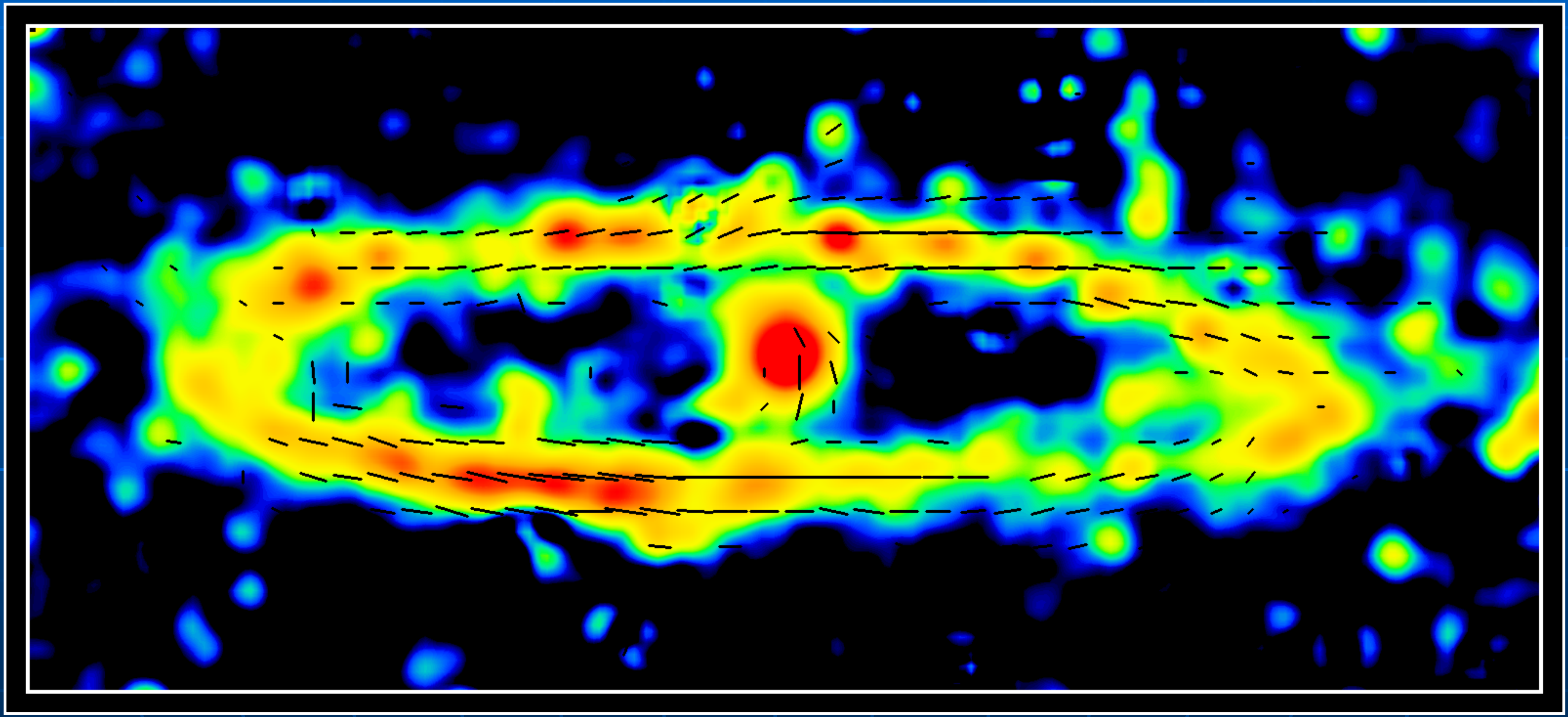
with the double pulsar B1913+16 (1974)



Russell Hulse
& Joseph Taylor
(Princeton/USA)

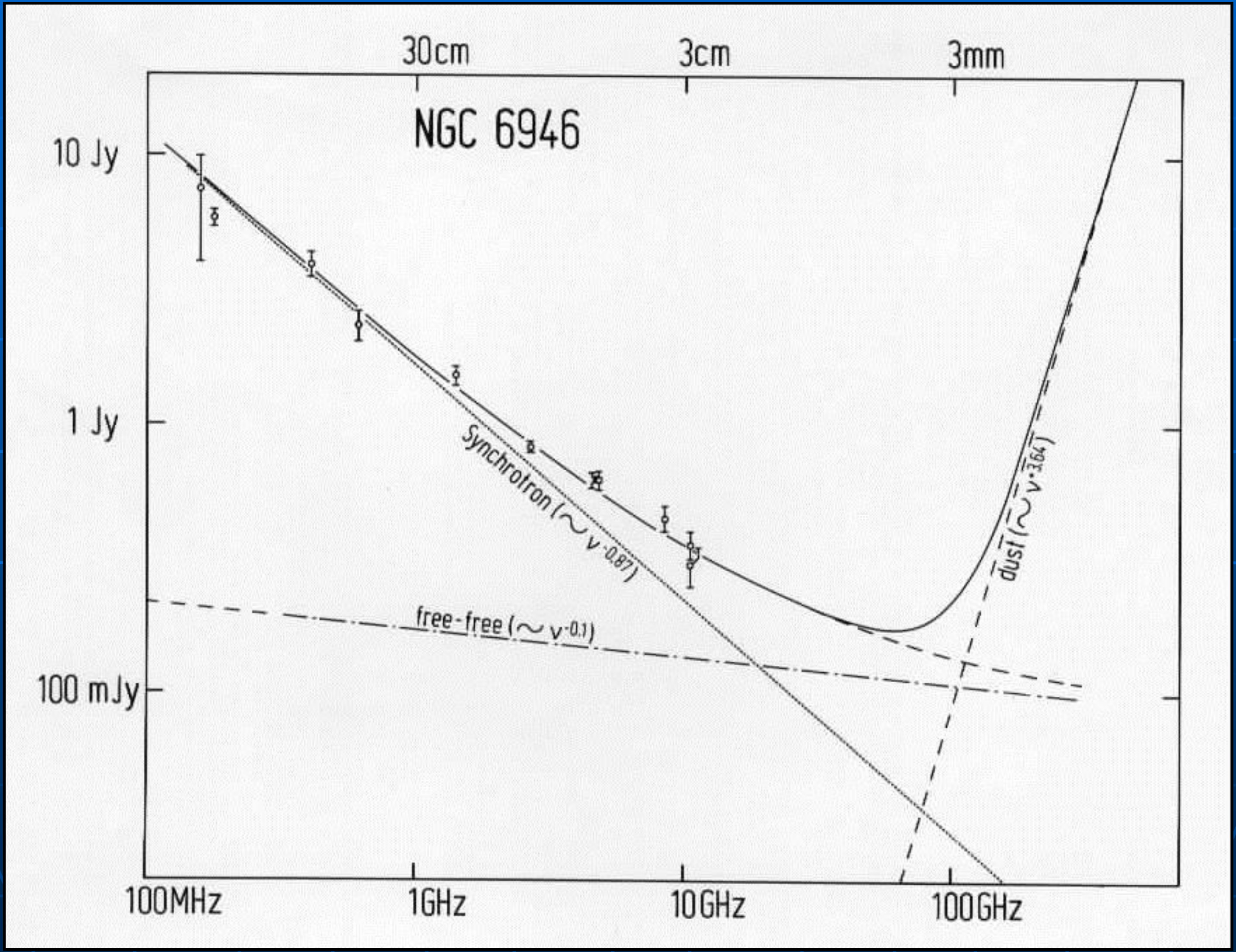
Nobel prize for physics 1993

Synchrotron emission of M 31 (Effelsberg 6 cm)



R. Beck

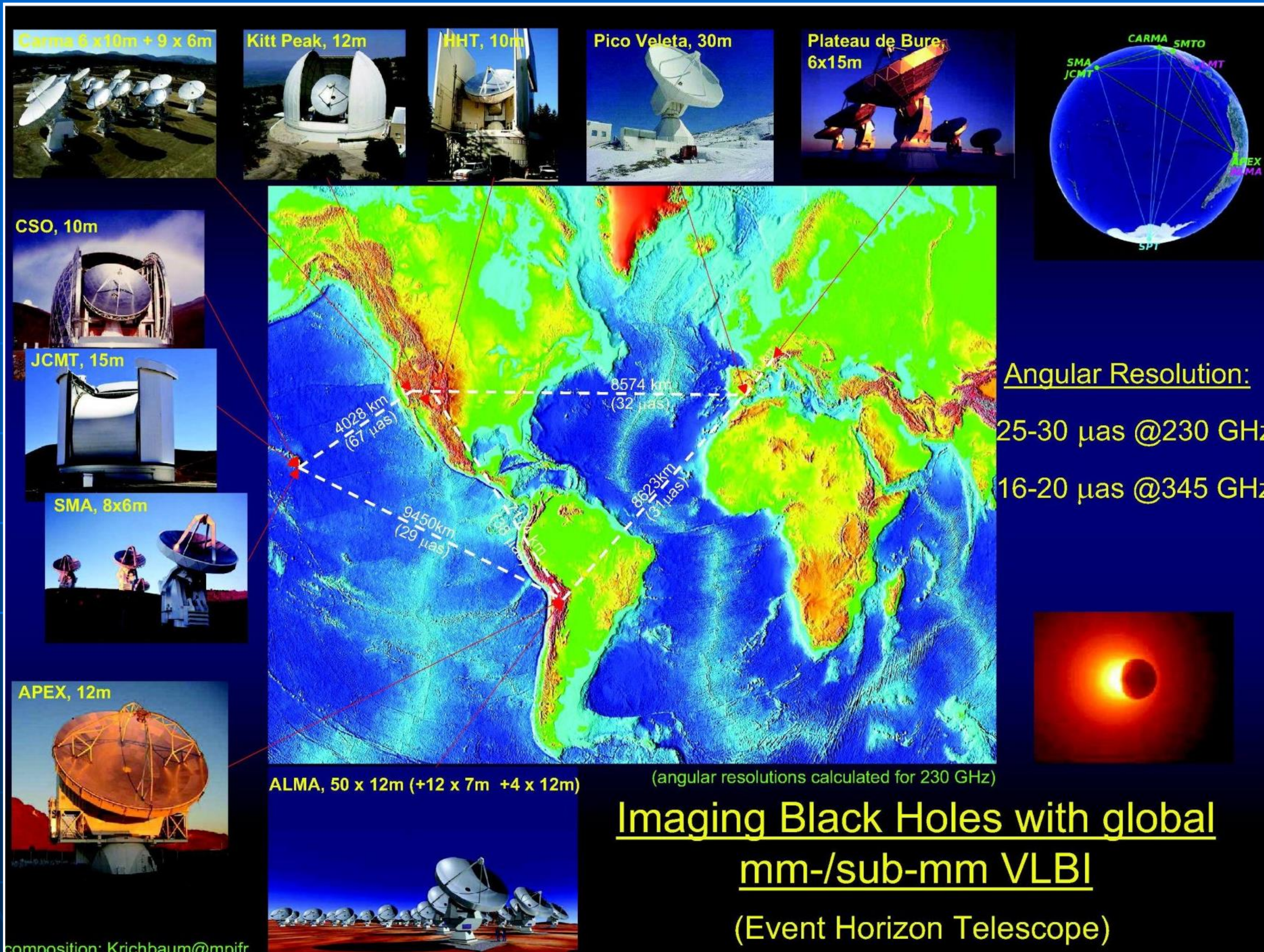
Typical radio spectrum of a galaxy



New radio telescopes

- Higher sensitivity
- Higher resolution

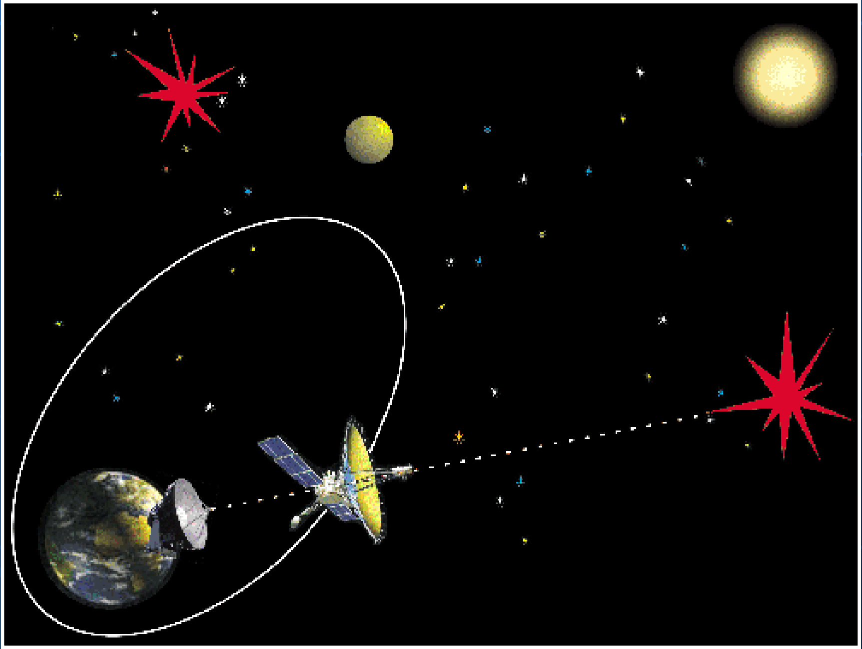
As the universe expands more and more, we need a larger telescope …


Carma 6 x10m + 9 x 6m
Kitt Peak, 12m
HHT, 10m
Pico Veleta, 30m
Plateau de Bure, 6x15m
CARMA
SMTO
SMA
JCMT
LMT
APEX
ALMA
SPT
CSO, 10m
JCMT, 15m
SMA, 8x6m
APEX, 12m
ALMA, 50 x 12m (+12 x 7m +4 x 12m)
4028 km (67 µas)
8574 km (32 µas)
9450km (29 µas)
8623km (31 µas)
Angular Resolution:
25-30 µas @230 GHz
16-20 µas @345 GHz
(angular resolutions calculated for 230 GHz)
Imaging Black Holes with global mm-/sub-mm VLBI
(Event Horizon Telescope)
composition: Krichbaum@mpifr

Space VLBI: Spektr-R (RadioAstron)
(Start: July 2011)

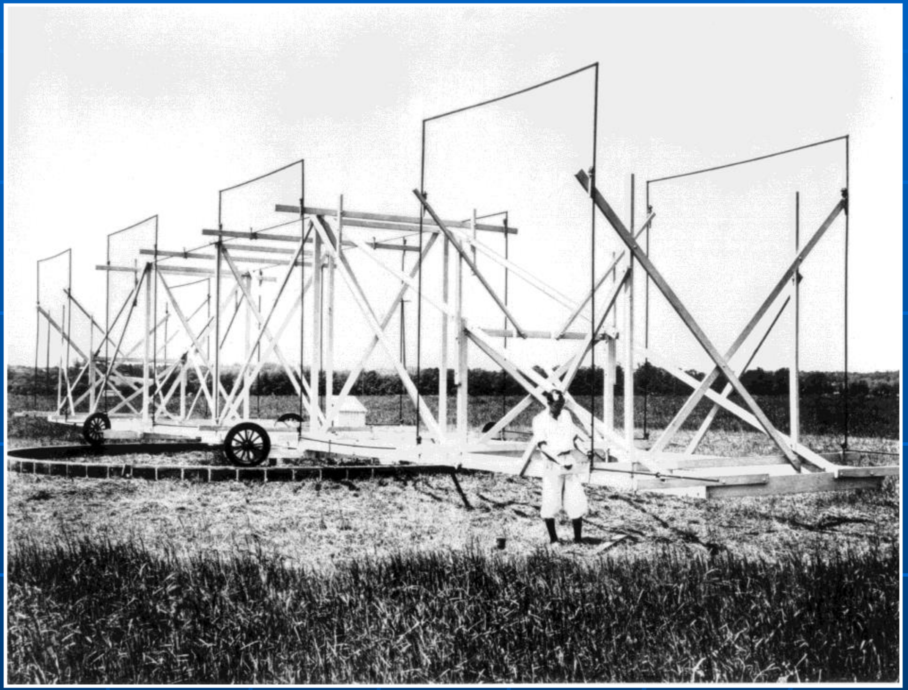
Quasar 0212+735:

baseline ≤ 350 000 km,
angular resolution
10-40 micro-arcseconds

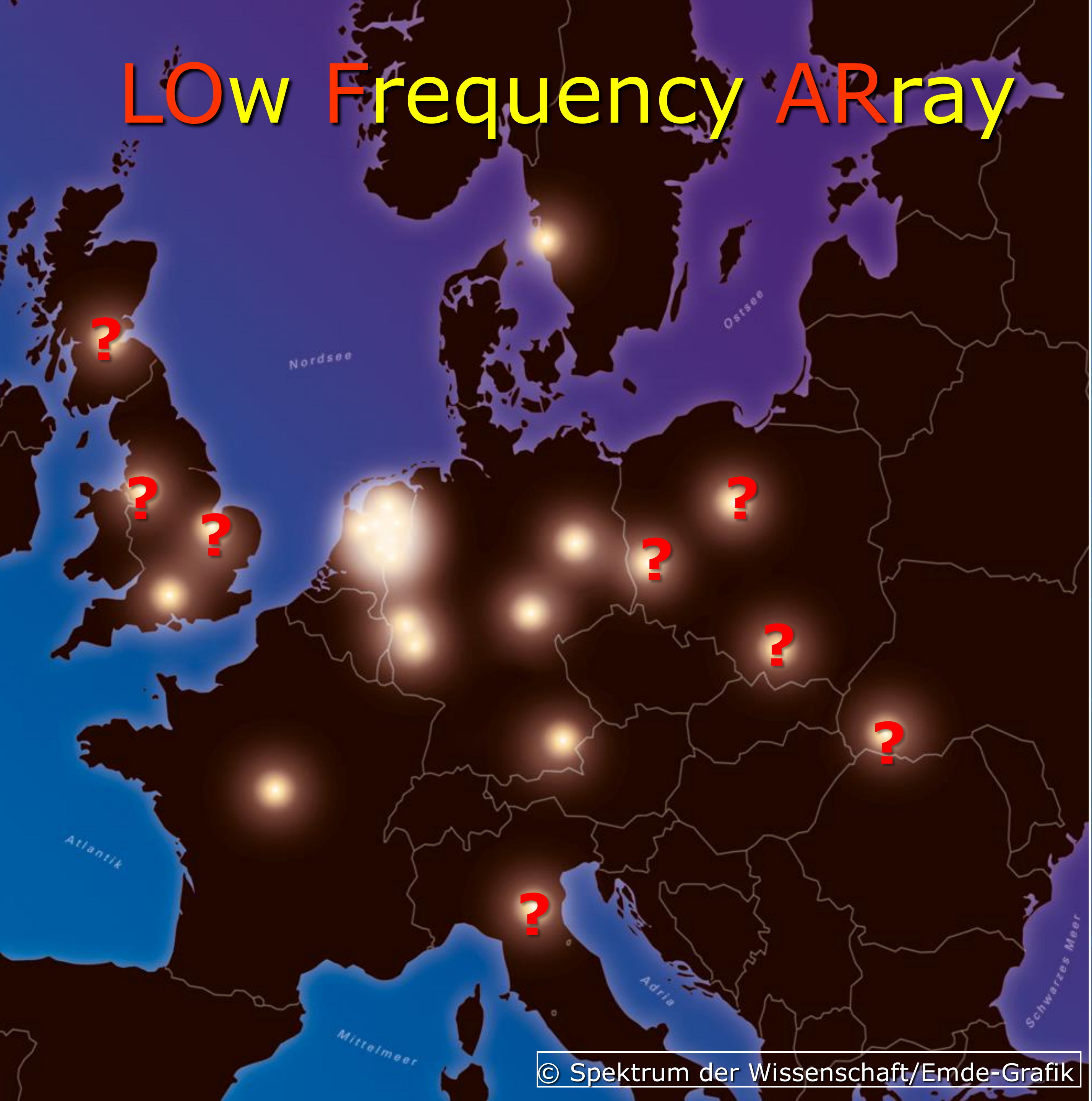


New radio telescopes at low frequencies:

"Back to the roots"



LOw Frequency ARray



LOFAR

10-80 MHz
110-240 MHz

36+8 stations

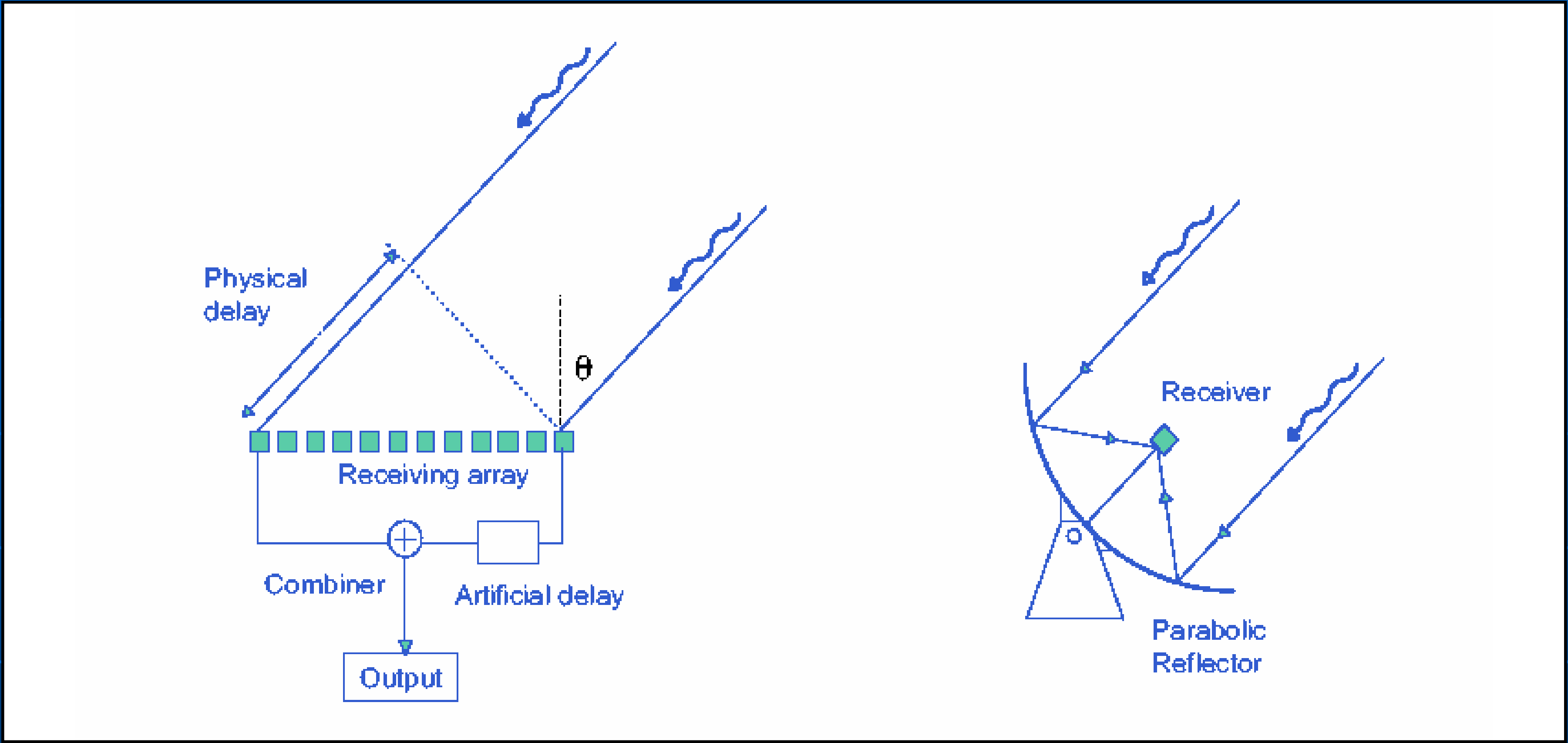
www.lofar.org

www.lofar.de

LOFAR

A revolution in radio telescope design:

- Pure software telescope: no moving parts, no mirrors, simultaneous multi-beaming, low costs
- Technological challenge in computing power, data transfer and data storage



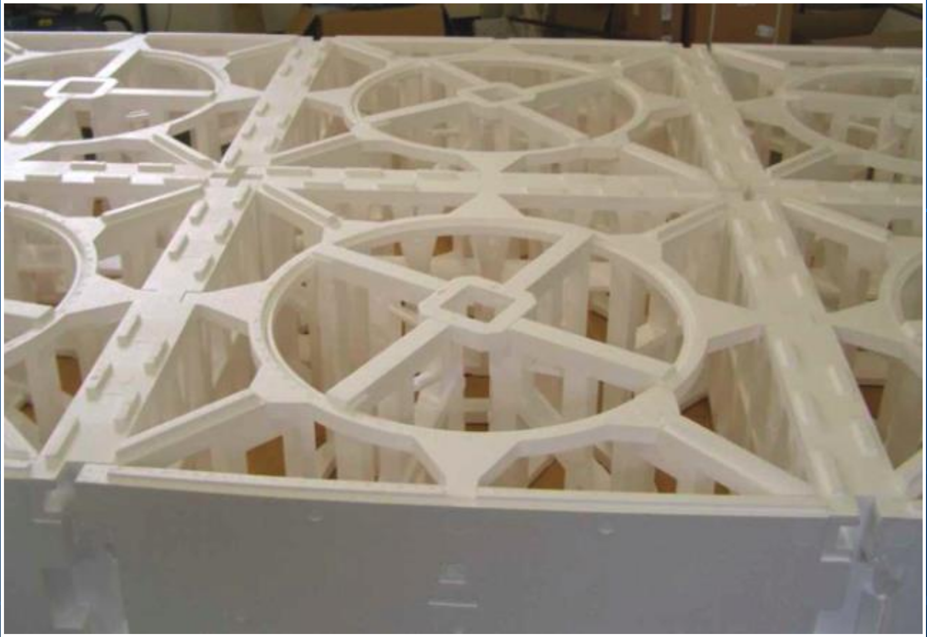
Software telescope:
direction chosen
by phase delays

Classical radio telescope:
direction by moving
the dish

Design of the LOFAR antennas

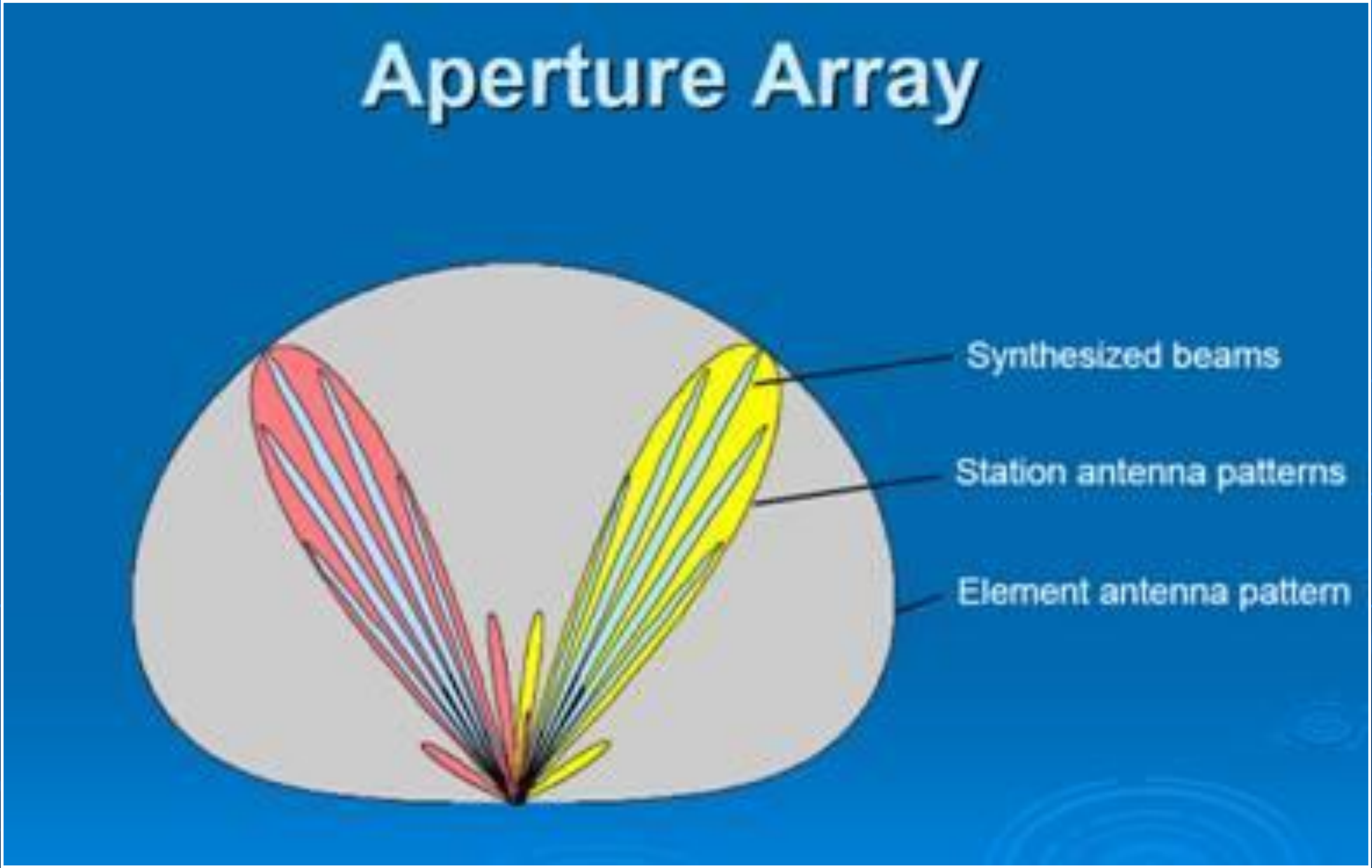
Lowband:
10 – 80 MHz (30m – 4m),
96 antennas per station
(image: MPIfR)

Highband:
110 – 240 MHz (3m – 1.2m),
48 or 96 elements per station
(image: ASTRON)



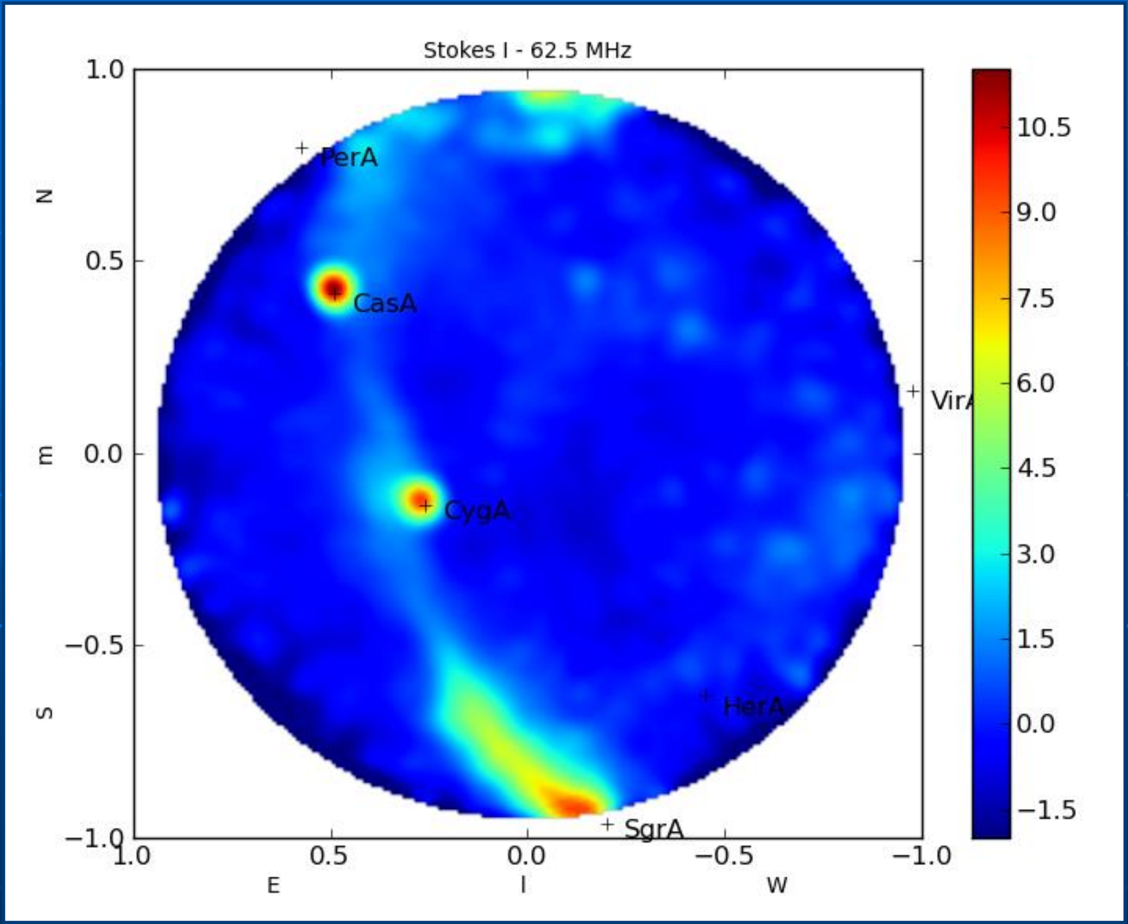
LOFAR core stations (Netherlands)

First international station Effelsberg


Aperture Array
Synthesized beams
Station antenna patterns
Element antenna pattern

All-sky image with the Effelsberg LOFAR station

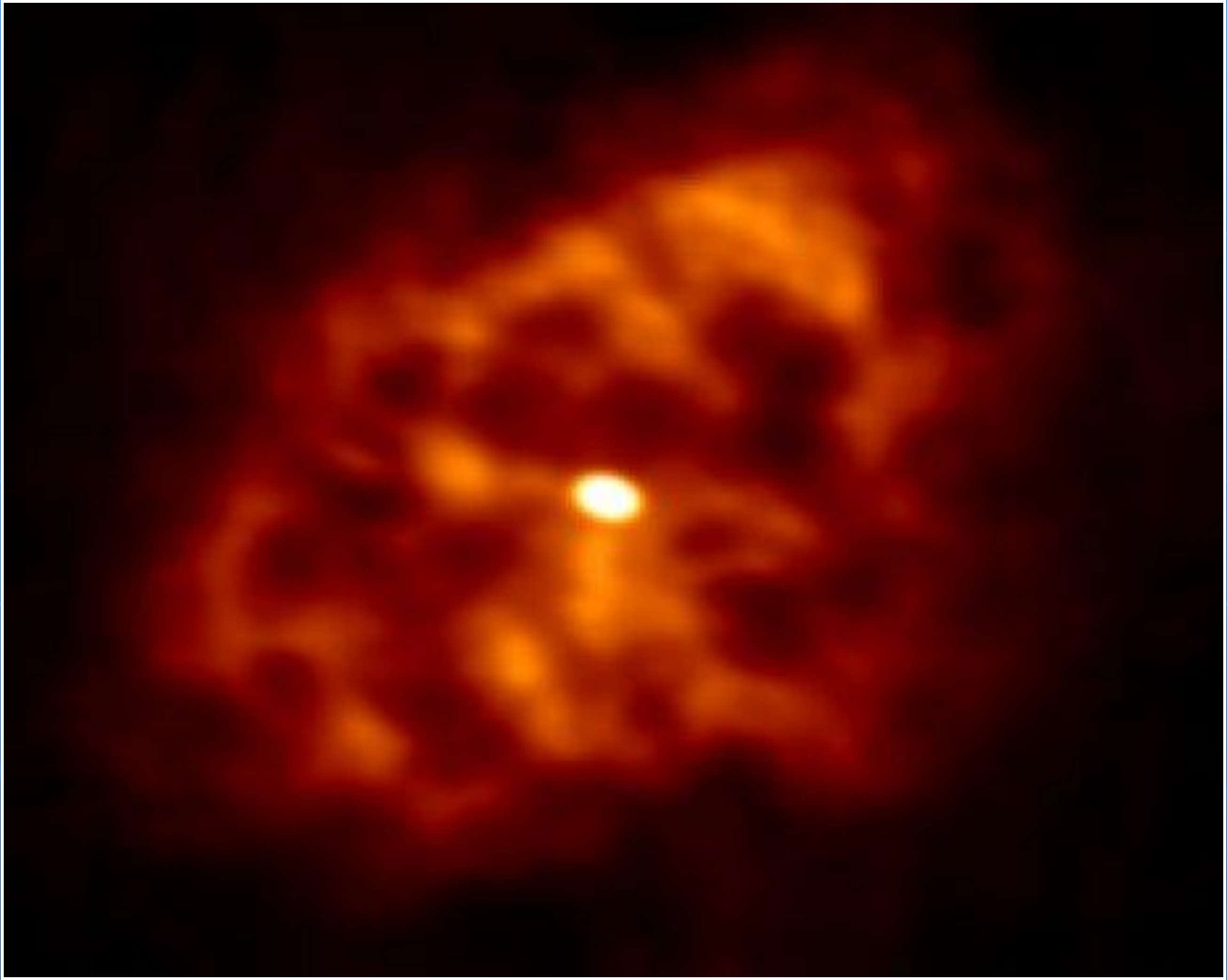
(J. Köhler & J. Anderson, MPIfR)



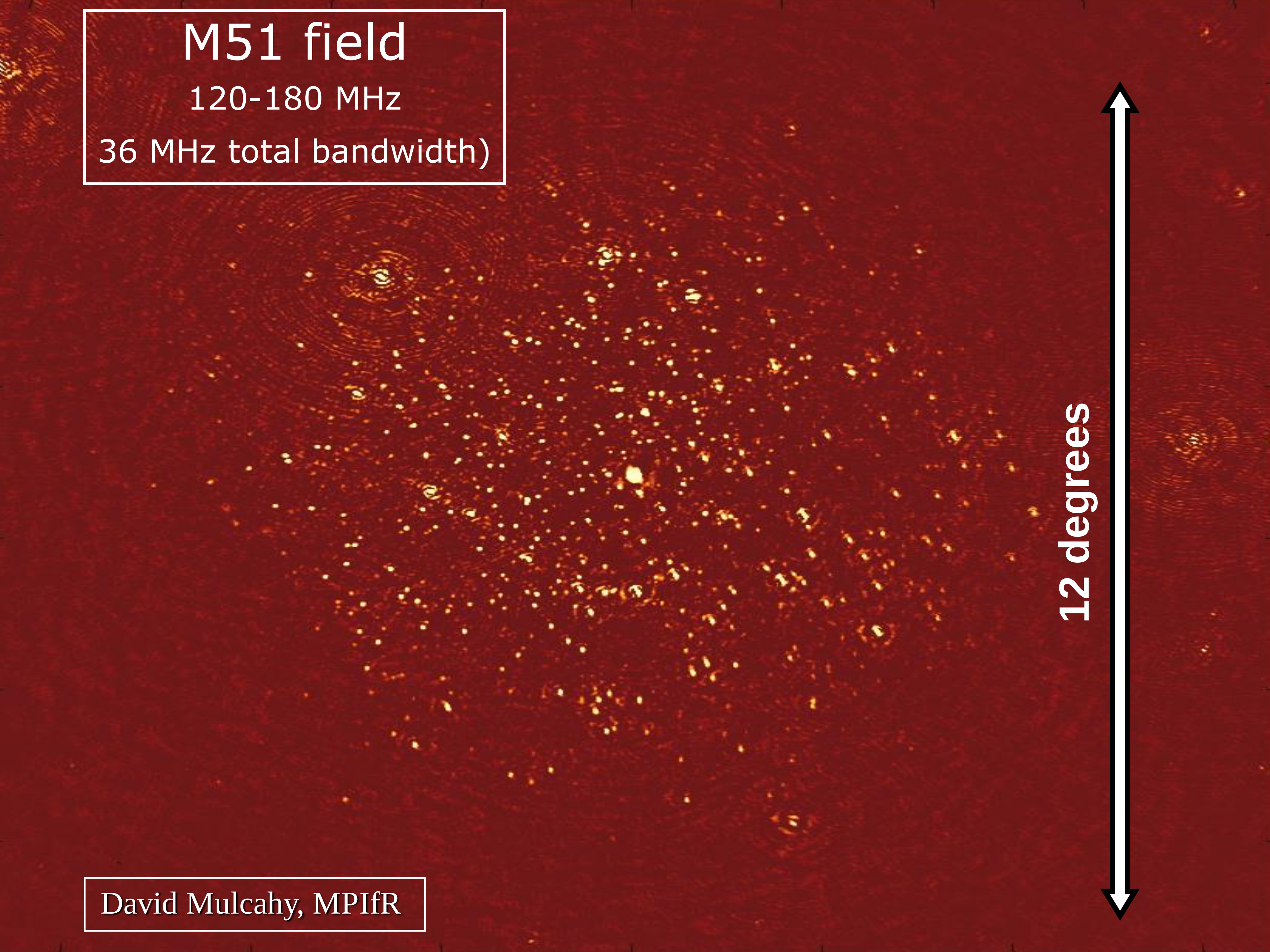
- Single channel at 62.5 MHz with 200 kHz bandwidth
- **1.3 sec integration time**

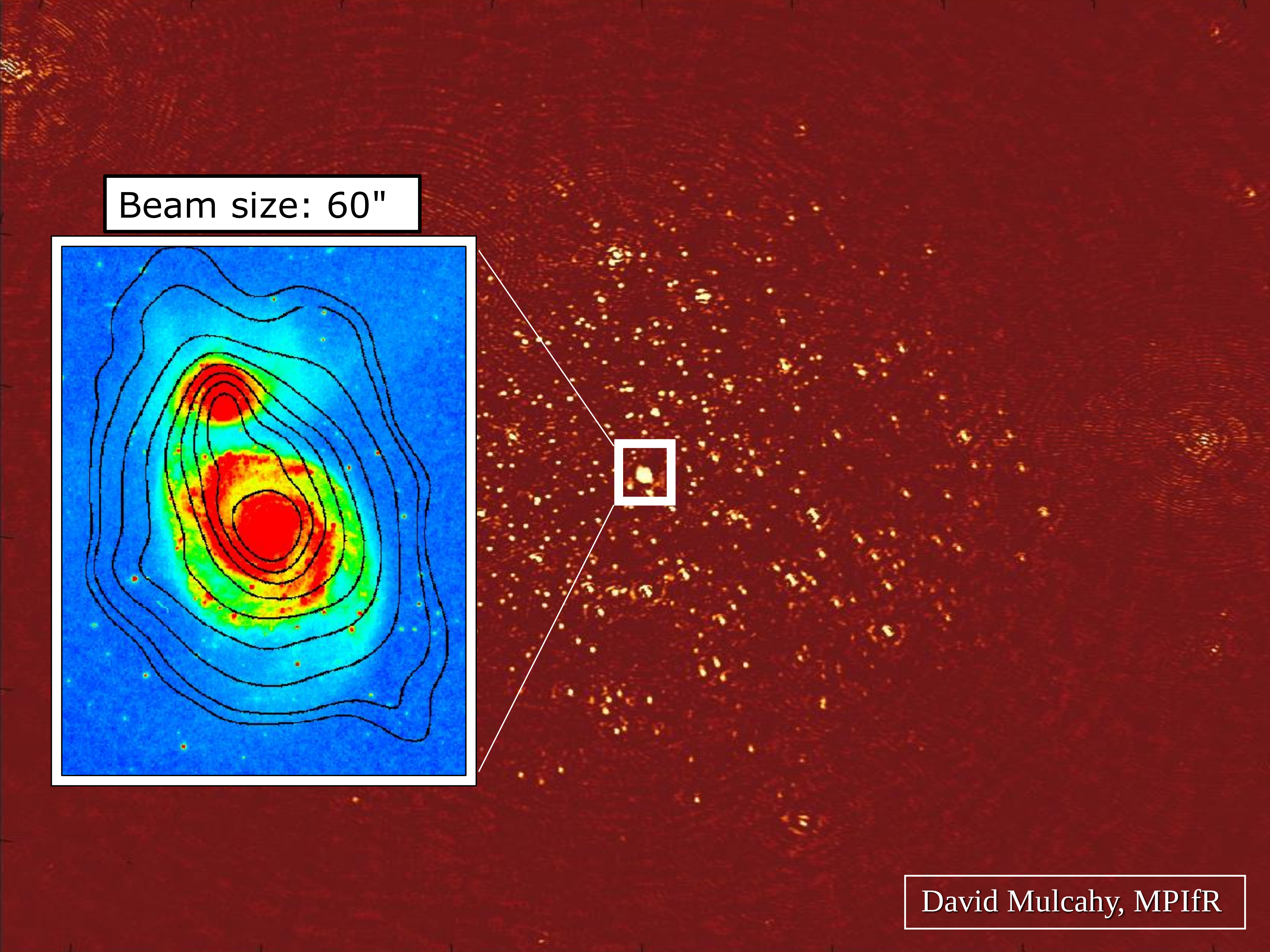
Crab Nebula (supernova of 1054)

LOFAR HBA 115-150 MHz, international stations, resolution 9"x14"

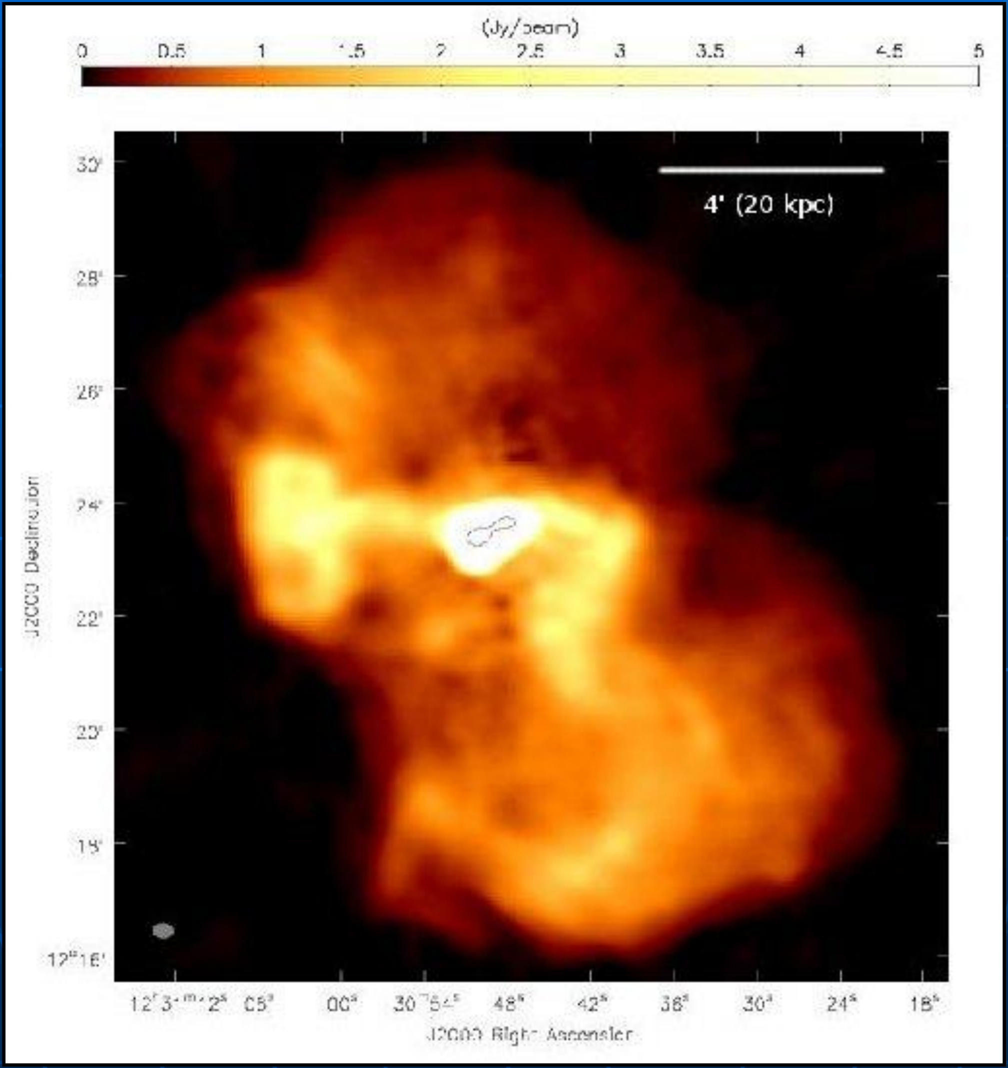


Olaf Wucknitz, MPIfR


M51 field
120-180 MHz
36 MHz total bandwidth)
12 degrees
David Mulcahy, MPIfR

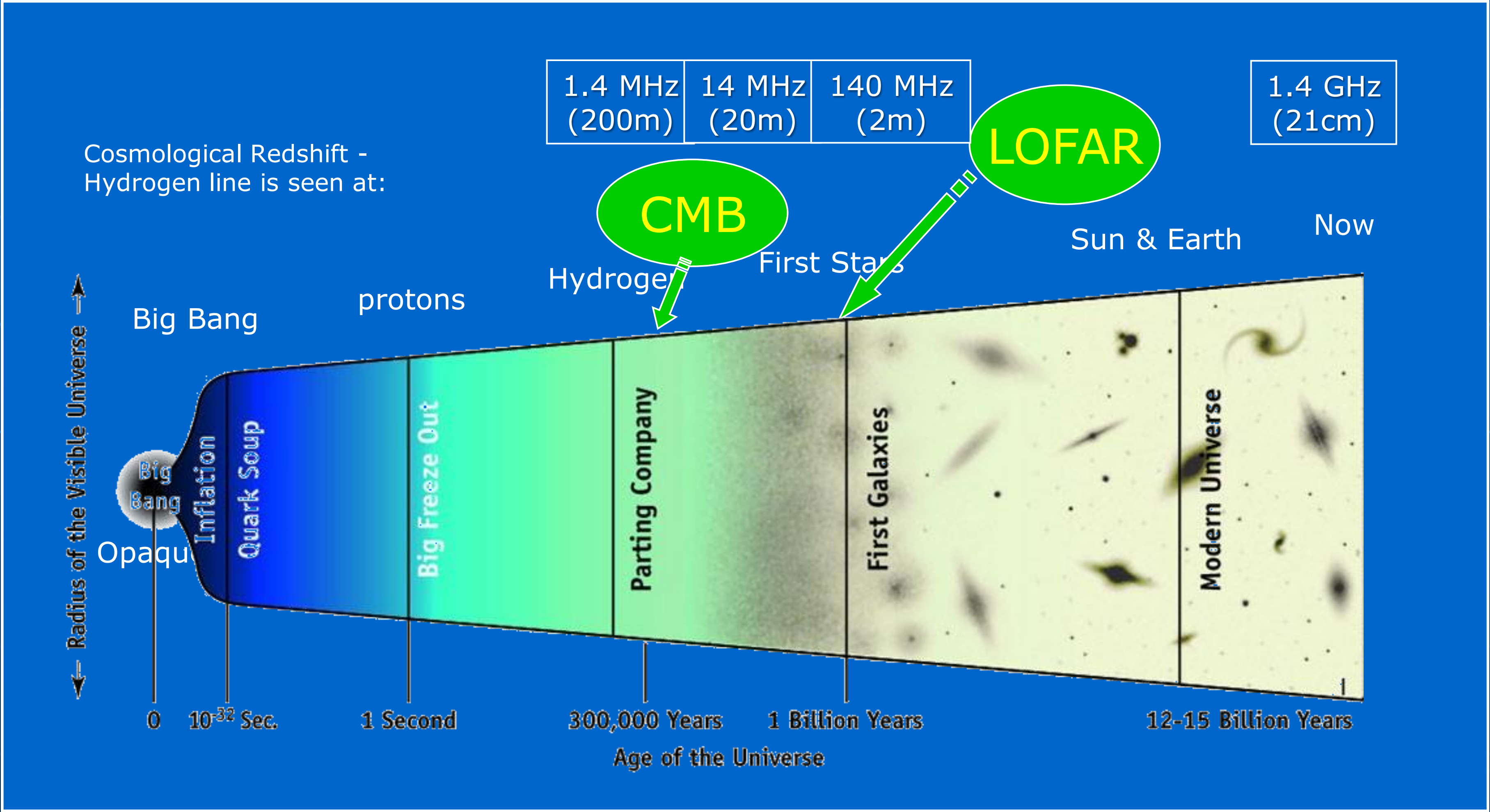

Beam size: 60"
David Mulcahy, MPIfR

Radio galaxy M 87 / Virgo A
LOFAR HBA 115-162 MHz



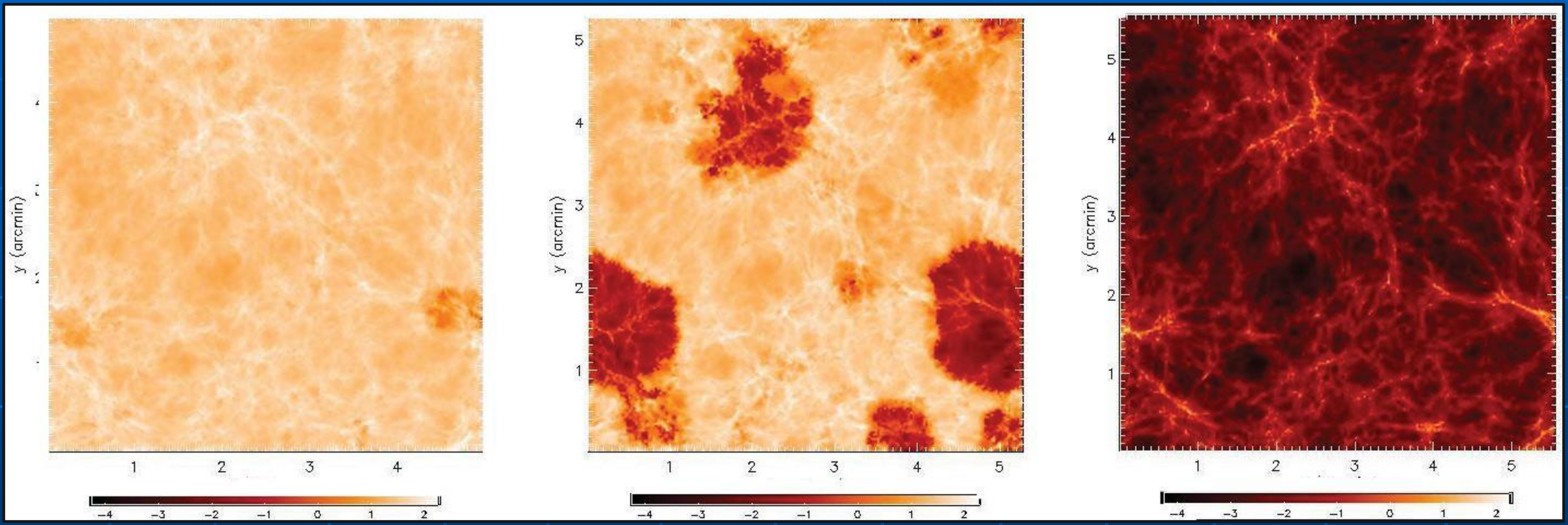
Francesco de Gasperin, Hamburg

Primary target of LOFAR: Epoch of re-ionization (EoR)



The Epoch of Re-ionisation (EoR)
300 - 700 million years after the Big Bang

Possibly observable with the strongly redshifted HI line



z=12
(109 MHz)

z=9
(141 MHz)

z=7
(178 MHz)

S. Furlanetto

Redshift z:
Observation frequency = 1412 MHz / (z+1)

The next big step :

Square Kilometre Array

SKA

SQUARE KILOMETRE ARRAY

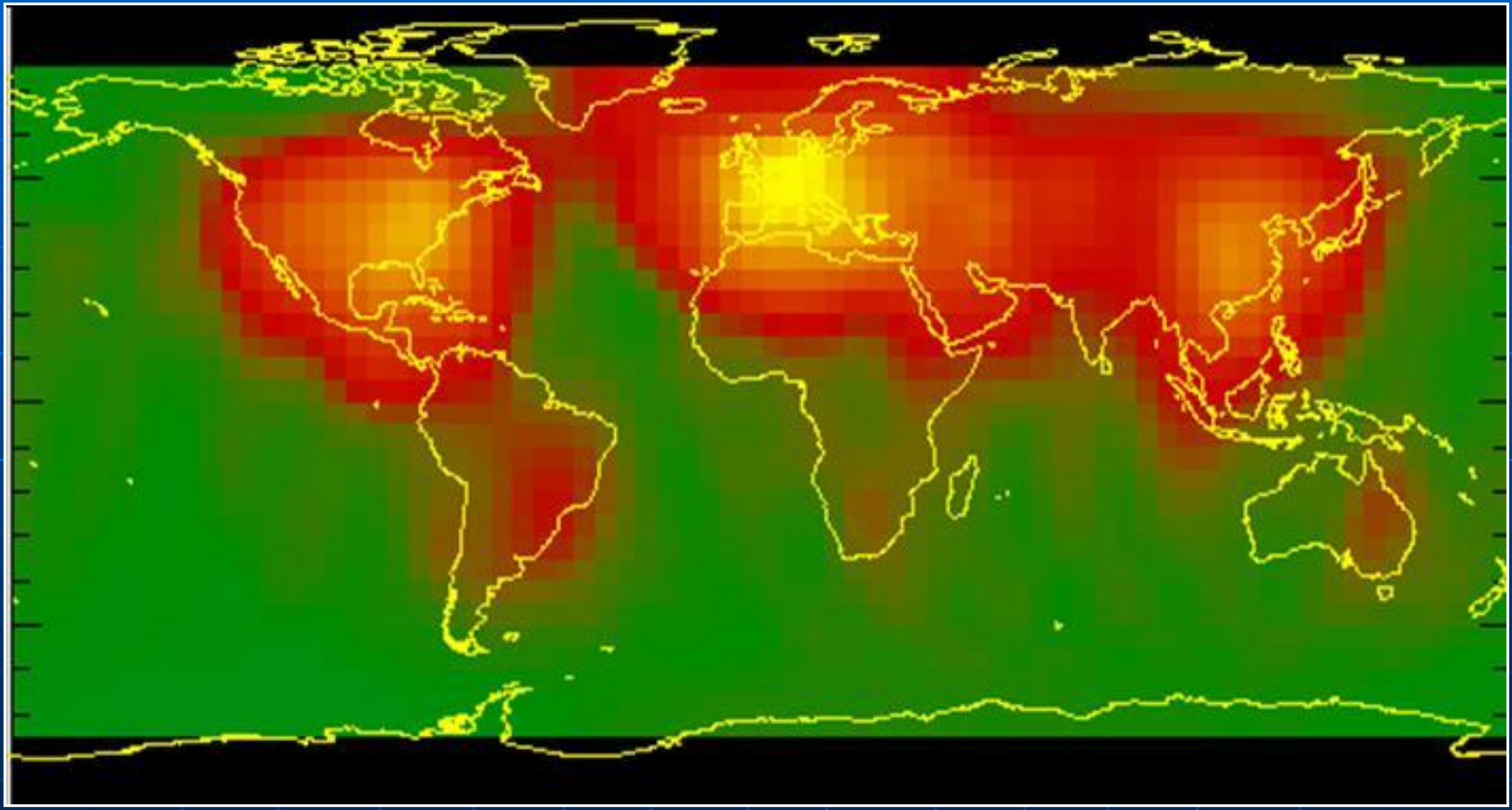
www.skatelescope.org

Square Kilometre Array (SKA)

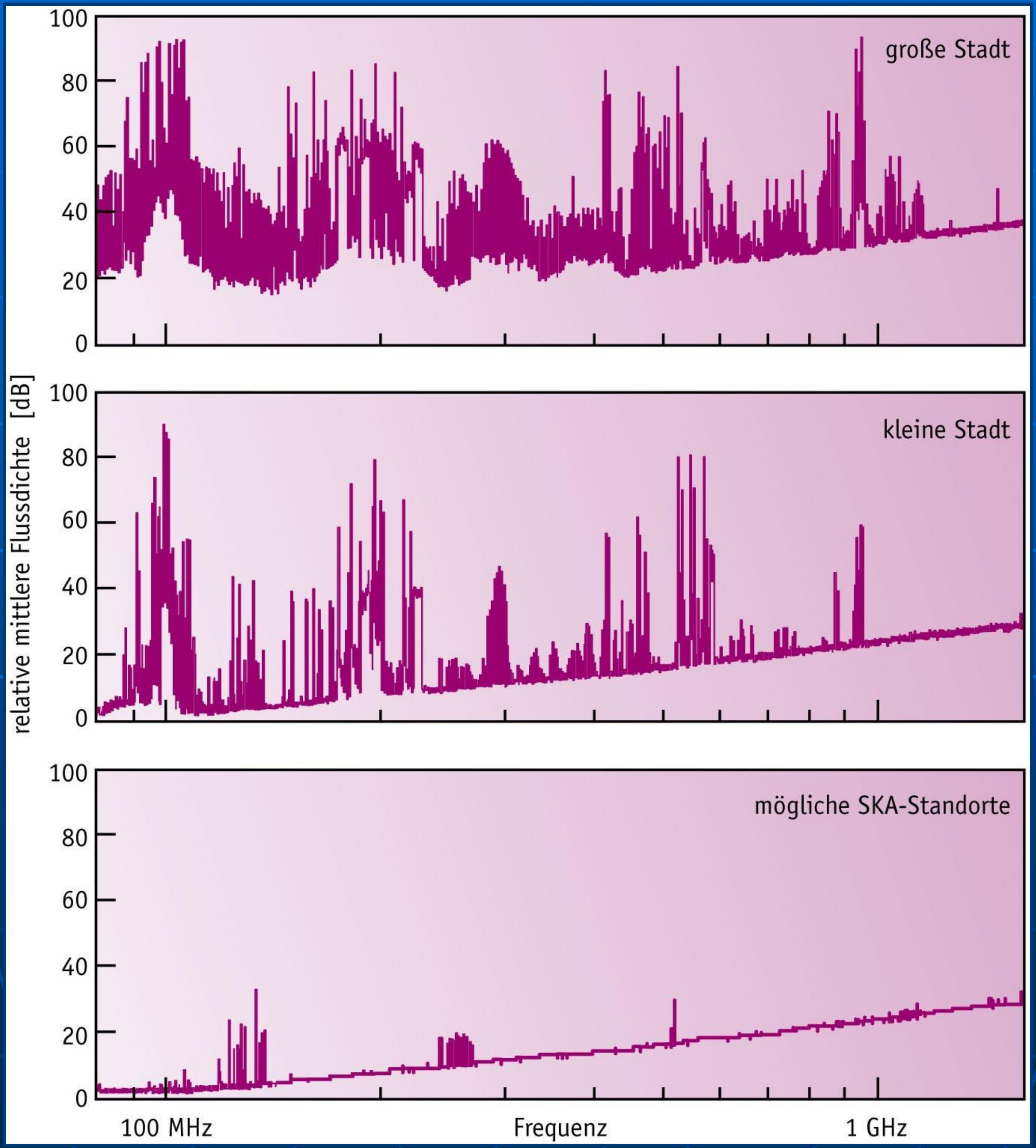
Three array concepts:

- Low (50 - 300 MHz)
- Mid (1000 - 2000 MHz)
- High (350 - 14000 MHz)

Man-made interference
(satellite FORS, 131 MHz)



Man-made interference

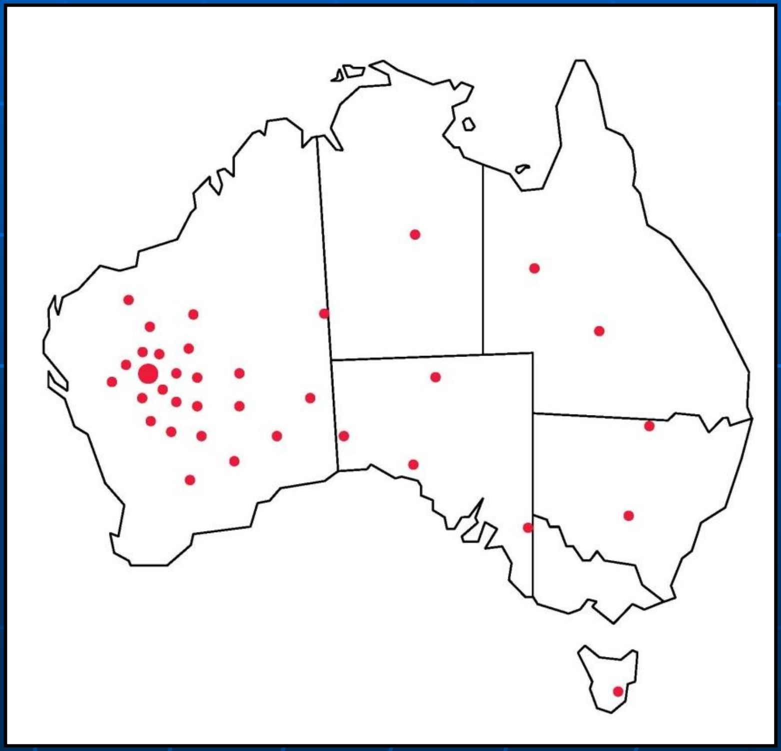


Large city

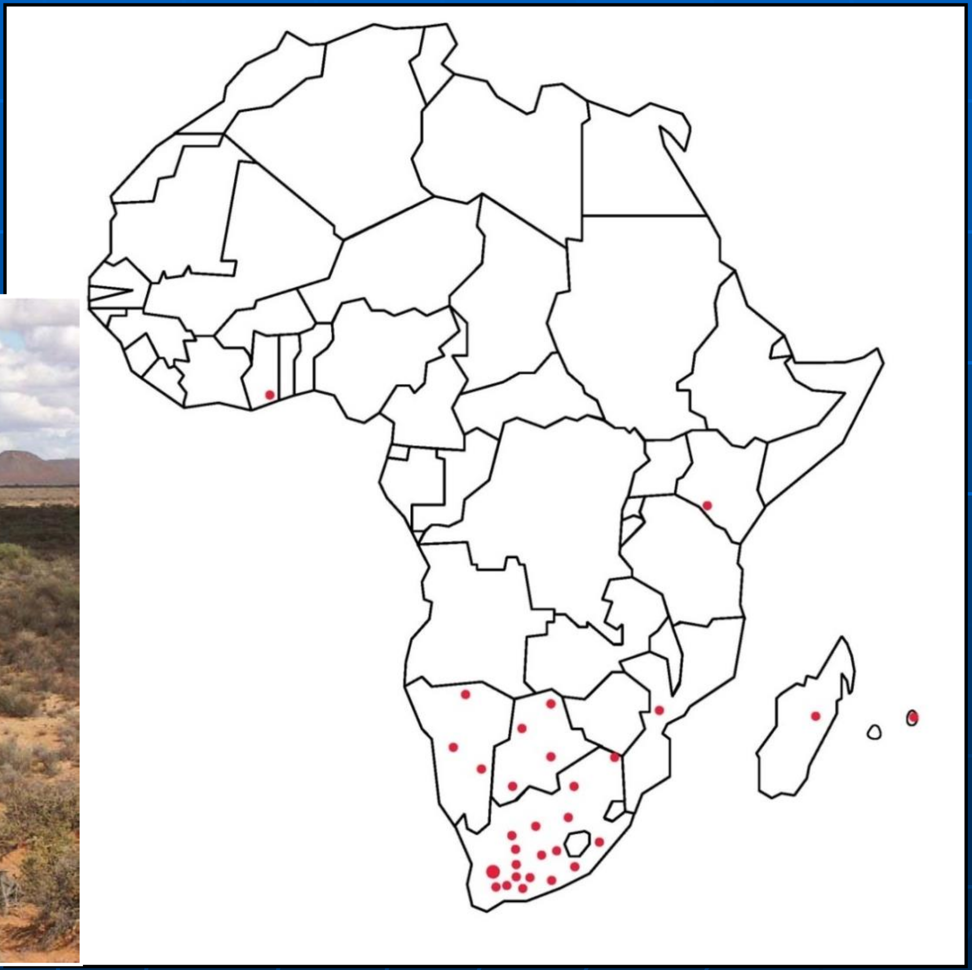
Small city

SKA site

Australian site:
low + high frequencies



South African site:
medium + high frequencies



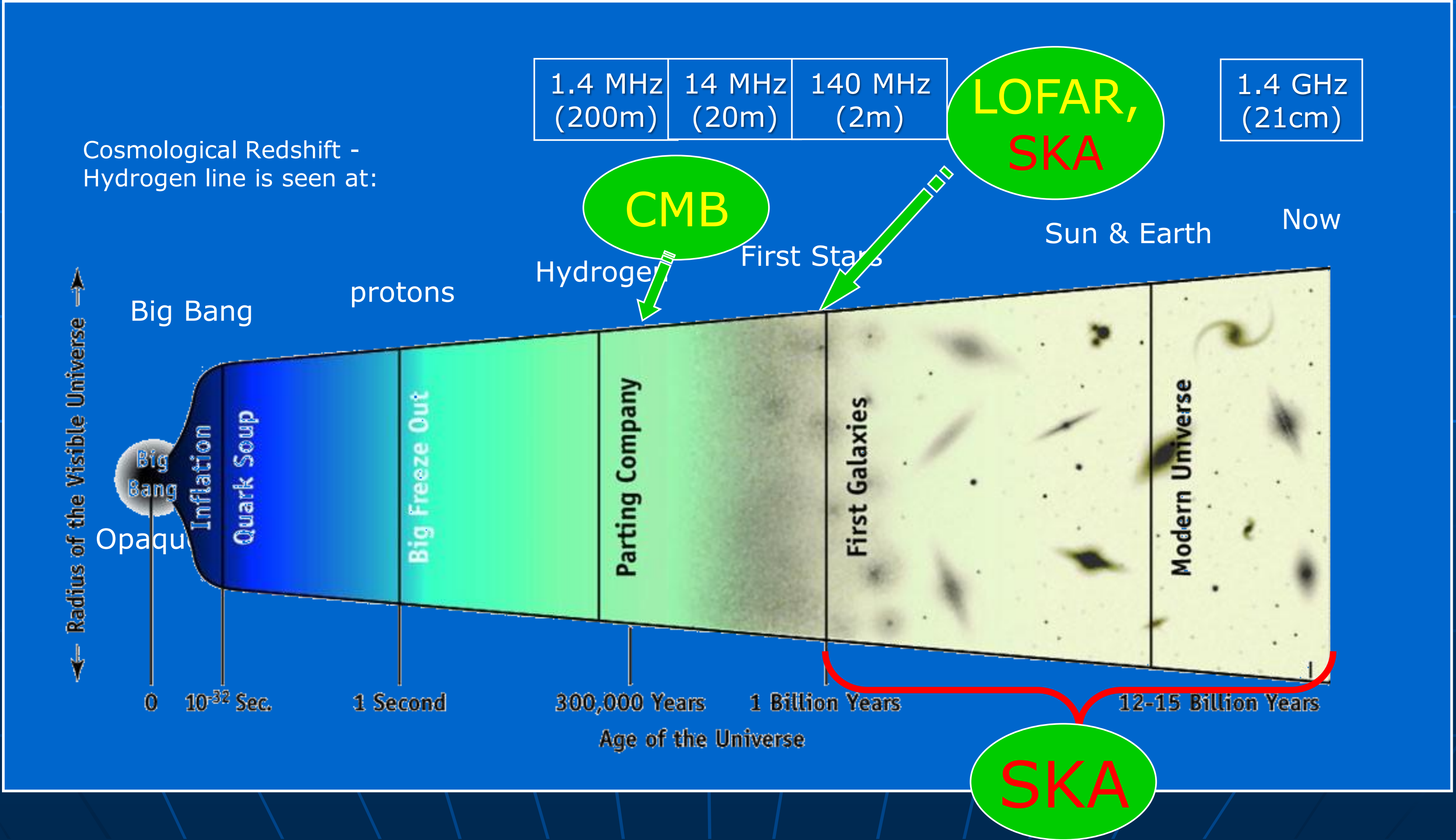
SKA Timeline

- Start of Phase 1 construction (10% area): 2018
- Start of early observations: ≈2020
- Start of Phase 2 construction (100% area): ≈2022

6 SKA Key Science Projects

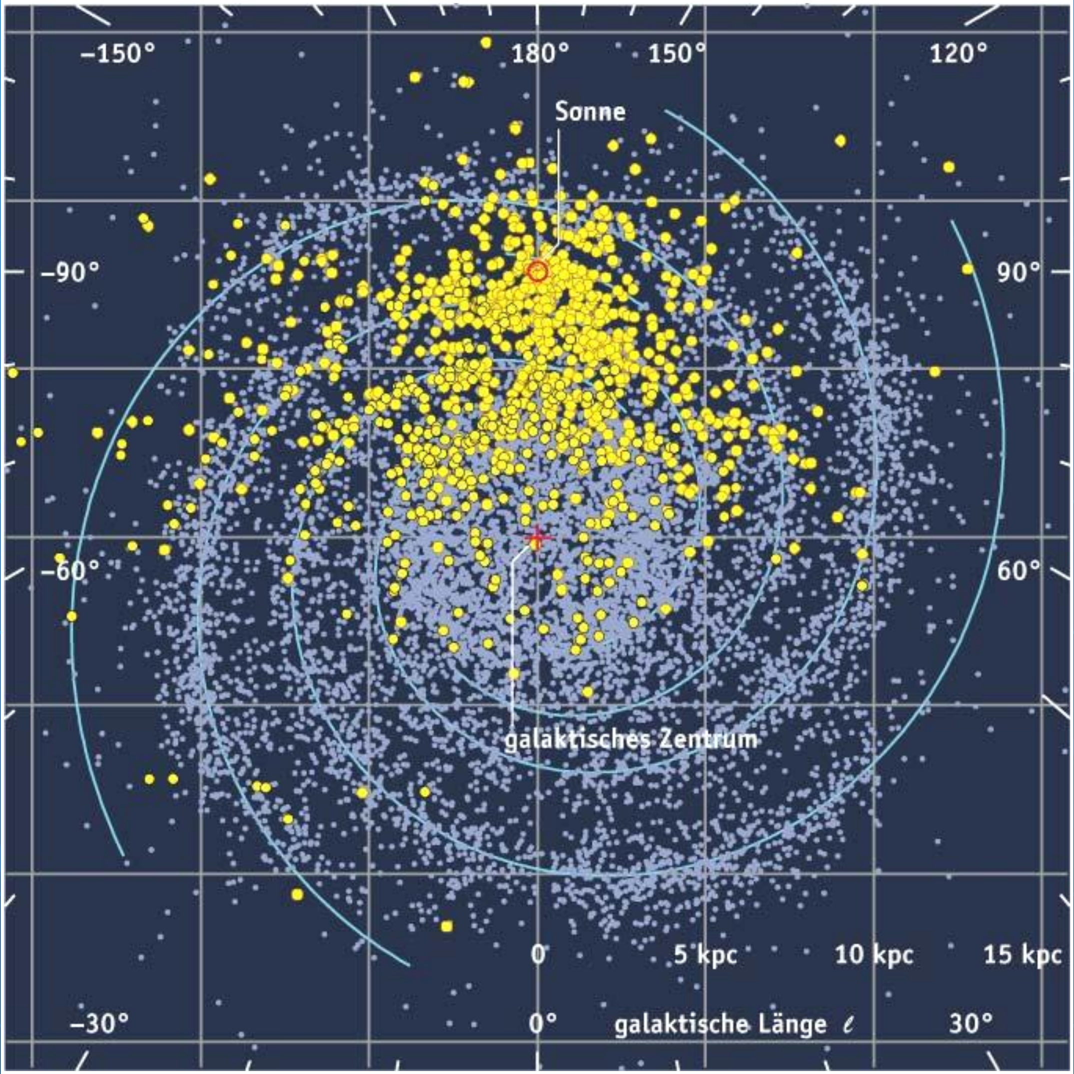
- The Dark Ages & Dark Energy
- Galaxy evolution & large-scale structures
- Testing theories of gravitation
- Cosmic magnetism
- The Cradle of Life
- Exploration of the Unknown

SKA: Measuring 100 million galaxies in HI line emission



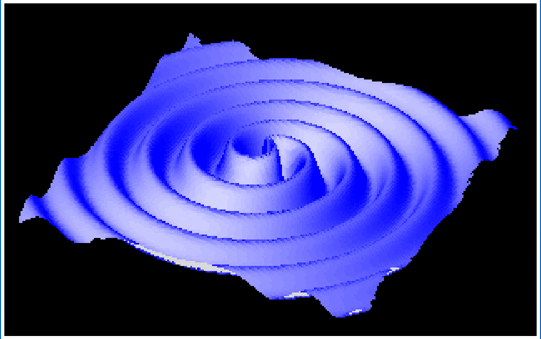
To be discovered:
about 30000 pulsars in the Milky Way

Yellow:
Pulsars known today

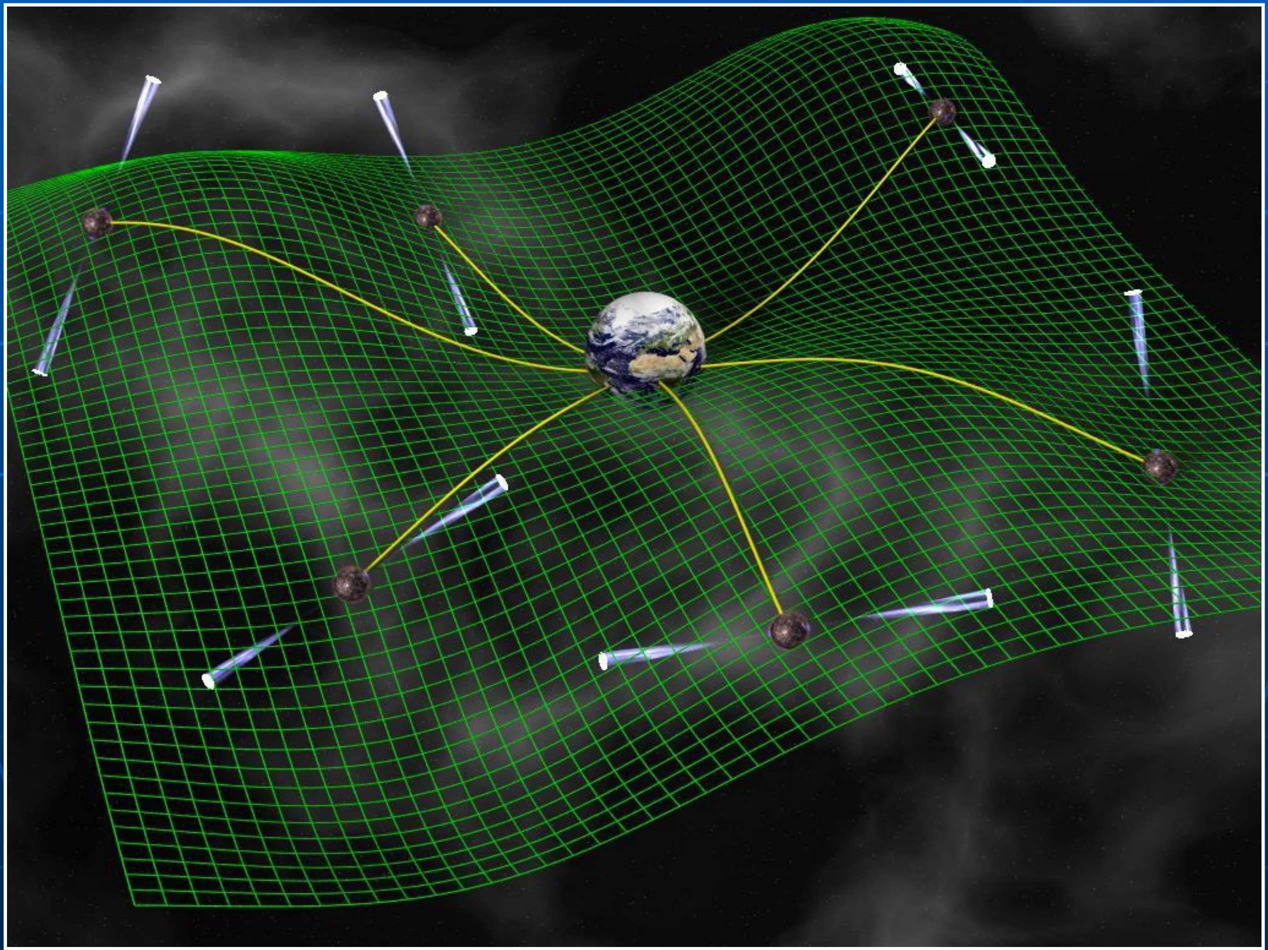


Cordes 2001

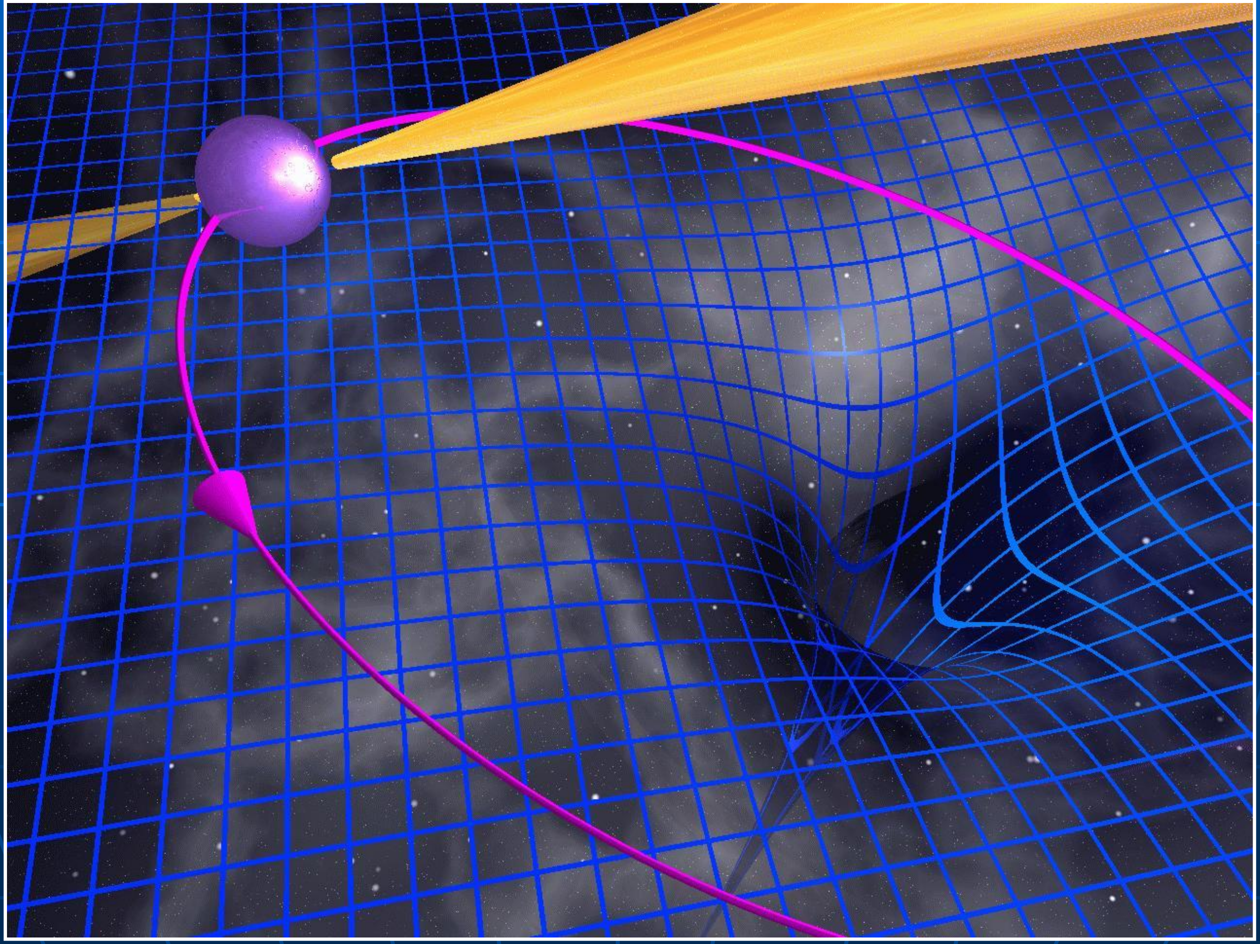
Search for gravitational waves



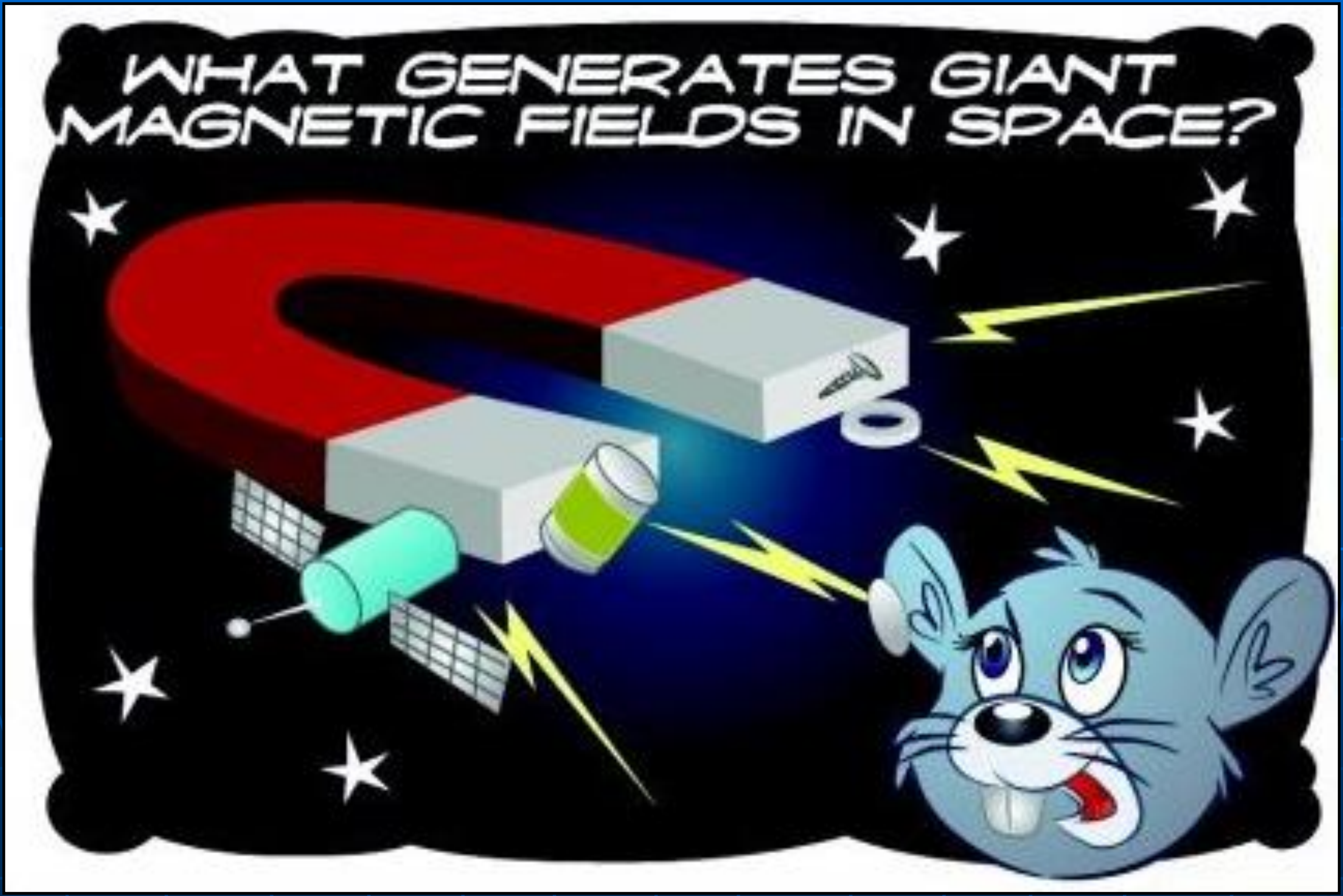
Millisecond pulsars serve as a giant detector



Pulsars orbiting black holes:
Testing General Relativity under extreme conditions

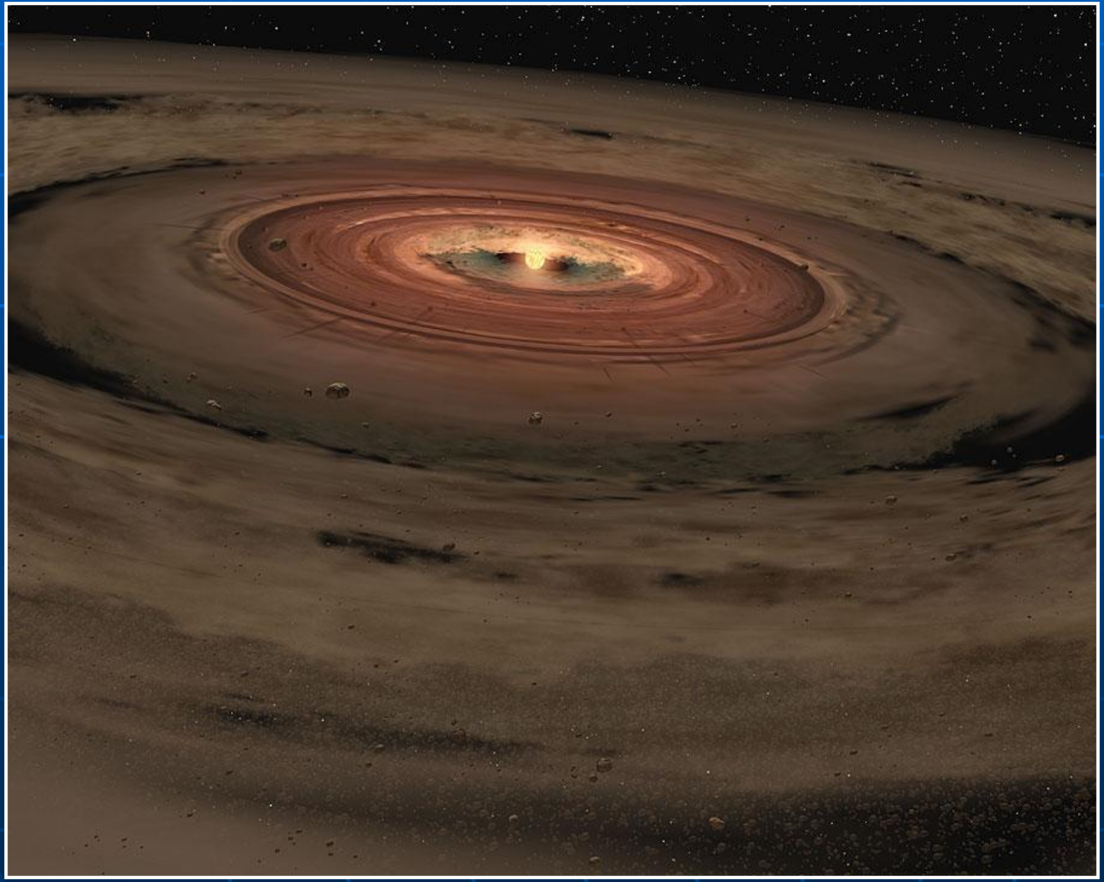


Origin of cosmic magnetism

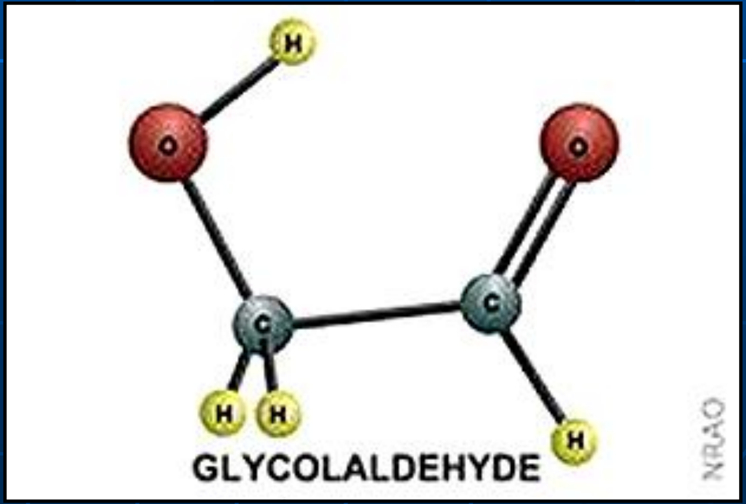


The Cradles of Life

SKA: finding hundreds of protoplanetary disks,
Resolution: 0.15 AU in 500 LJ distances



Biomolecules



SETI: Are we alone ?

SKA will detect :

- Mobile phones out to 0.003 LJ
- TV stations out to 2 LJ
- Airport radar out to 30 LJ
- Ionosphere radar out to 1500 LJ
- Arecibo-type planet radar out to 15000 LJ

Wanted:
10^9 € - and excellent people !