Radio Telescopes and Fundamentals of observations

I. Basic properties of radio telescopes

Alex Kraus

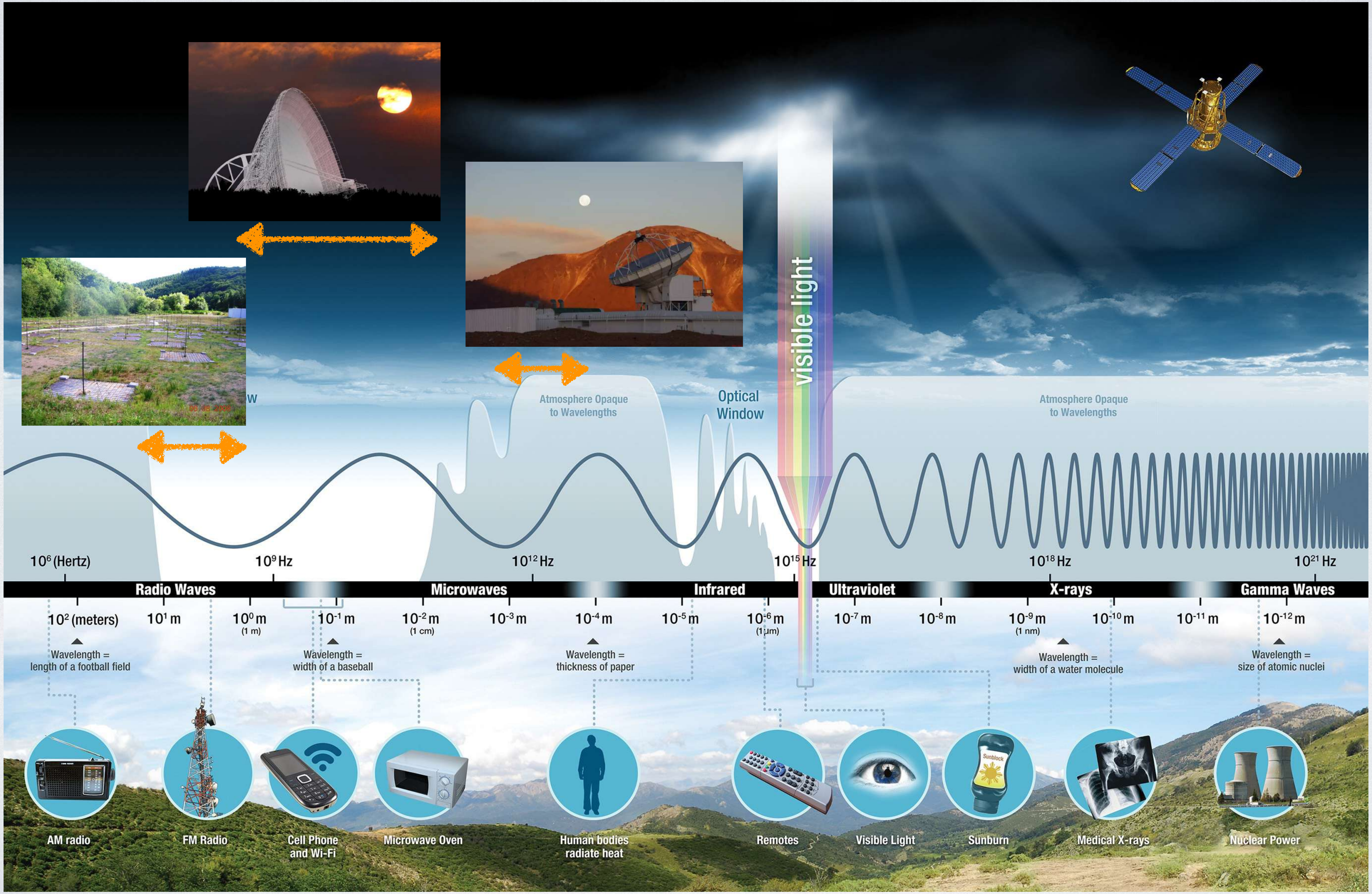
September 2025

XIX IAG/USP Advanced School on Astrophysics

TOPICS

- The role of Radioastronomy
- Basic design of Radio Telescopes
- Observational quantities
- Telescope beams
- Sensitivities, efficiencies
- Additional topics

THE ELECTROMAGNETIC SPECTRUM



NASA

WHY DO WE DO RADIOASTRONOMY?

Max-Planck-Institut für Radioastronomie

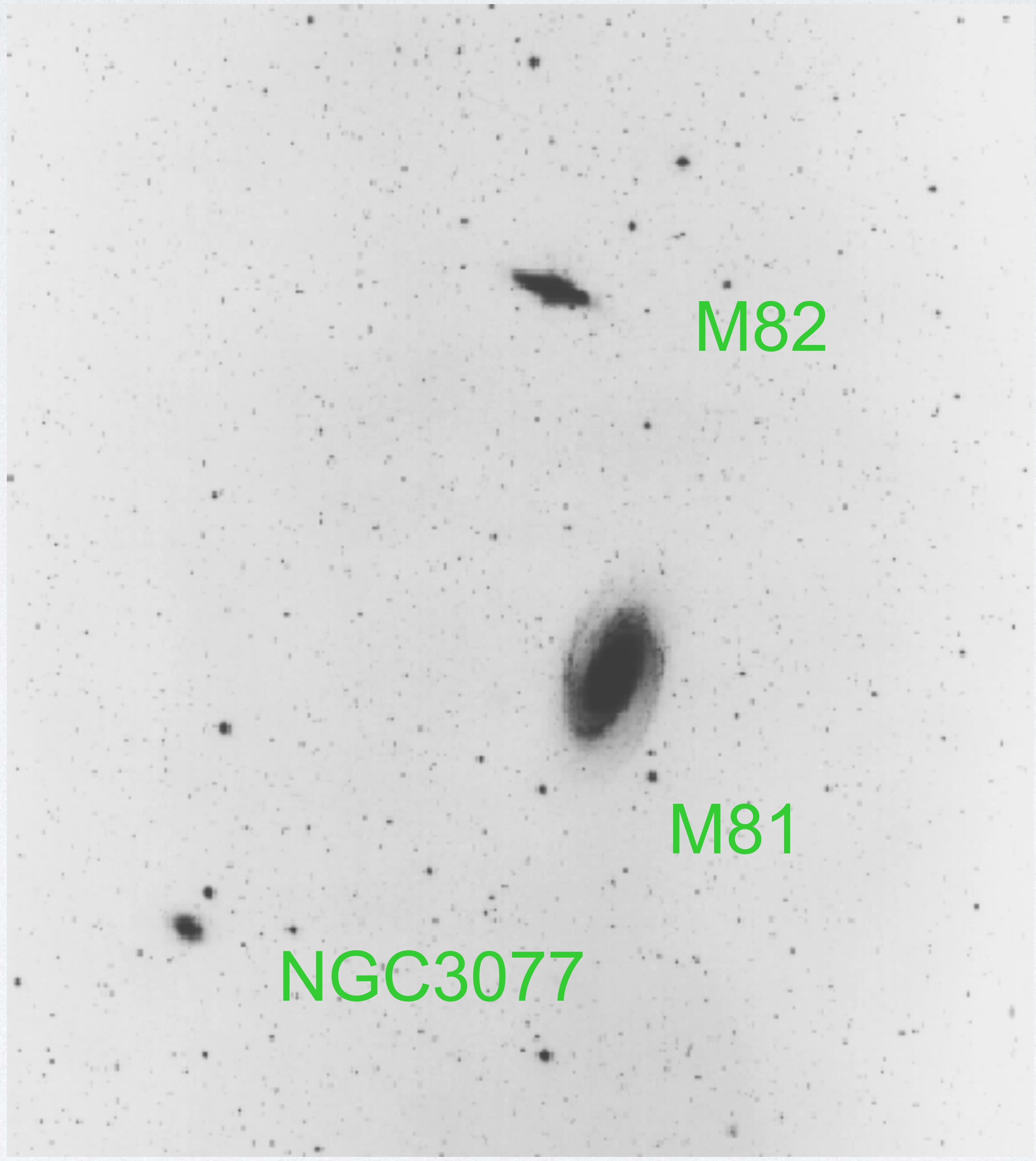
→ different physical processes emit electromagnetic waves in different frequency regimes.

optical astronomy: hot objects (e.g., stars), blackbody emission

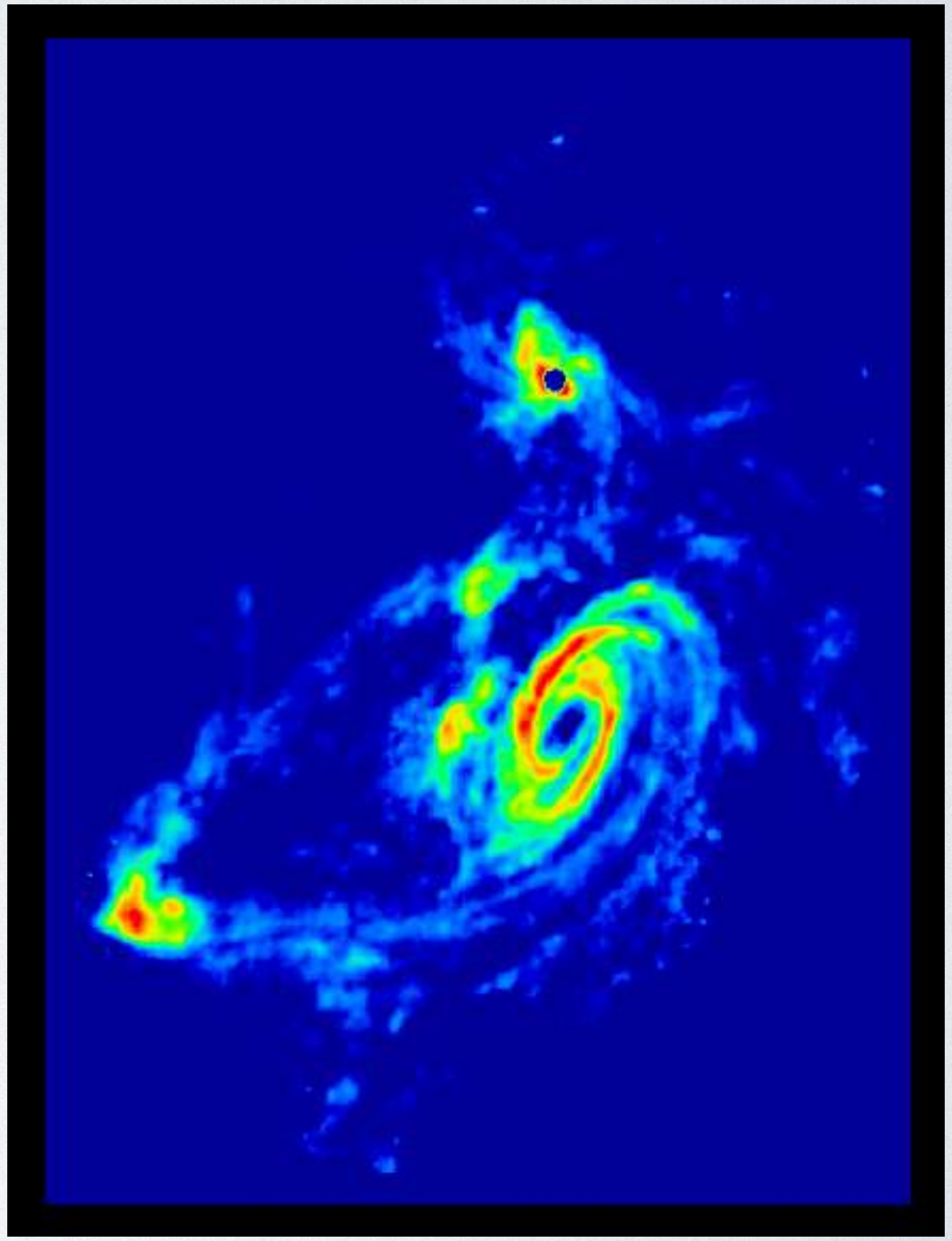
radio astronomy:

- neutral hydrogen and other atoms / molecules
- maser emission of molecules
- synchrotron radiation, magnetic fields (relativistic electrons)
- pulsars: cosmic „clocks“

optical

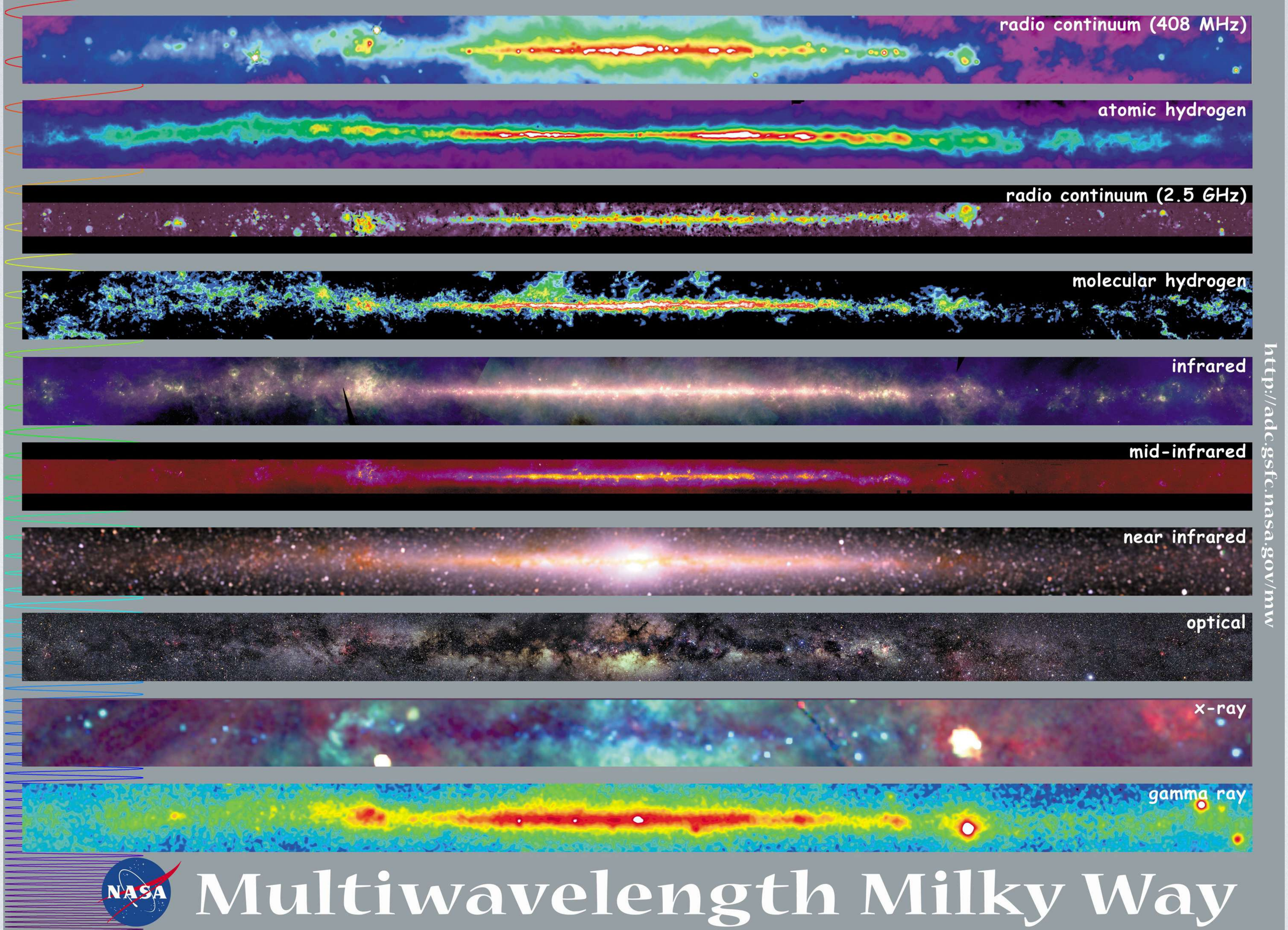


Radio (HI)

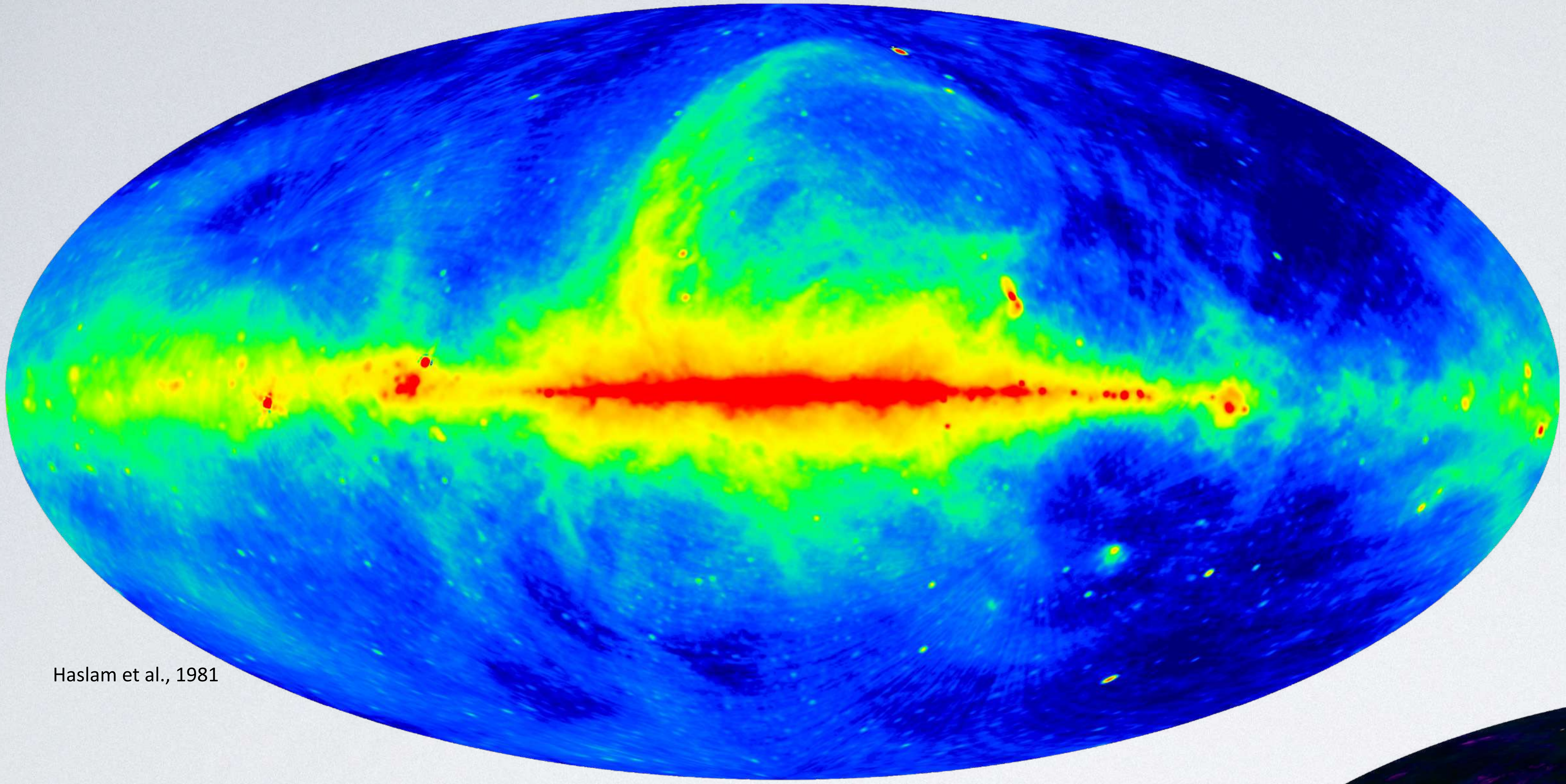


Yun et al., Nature 1994

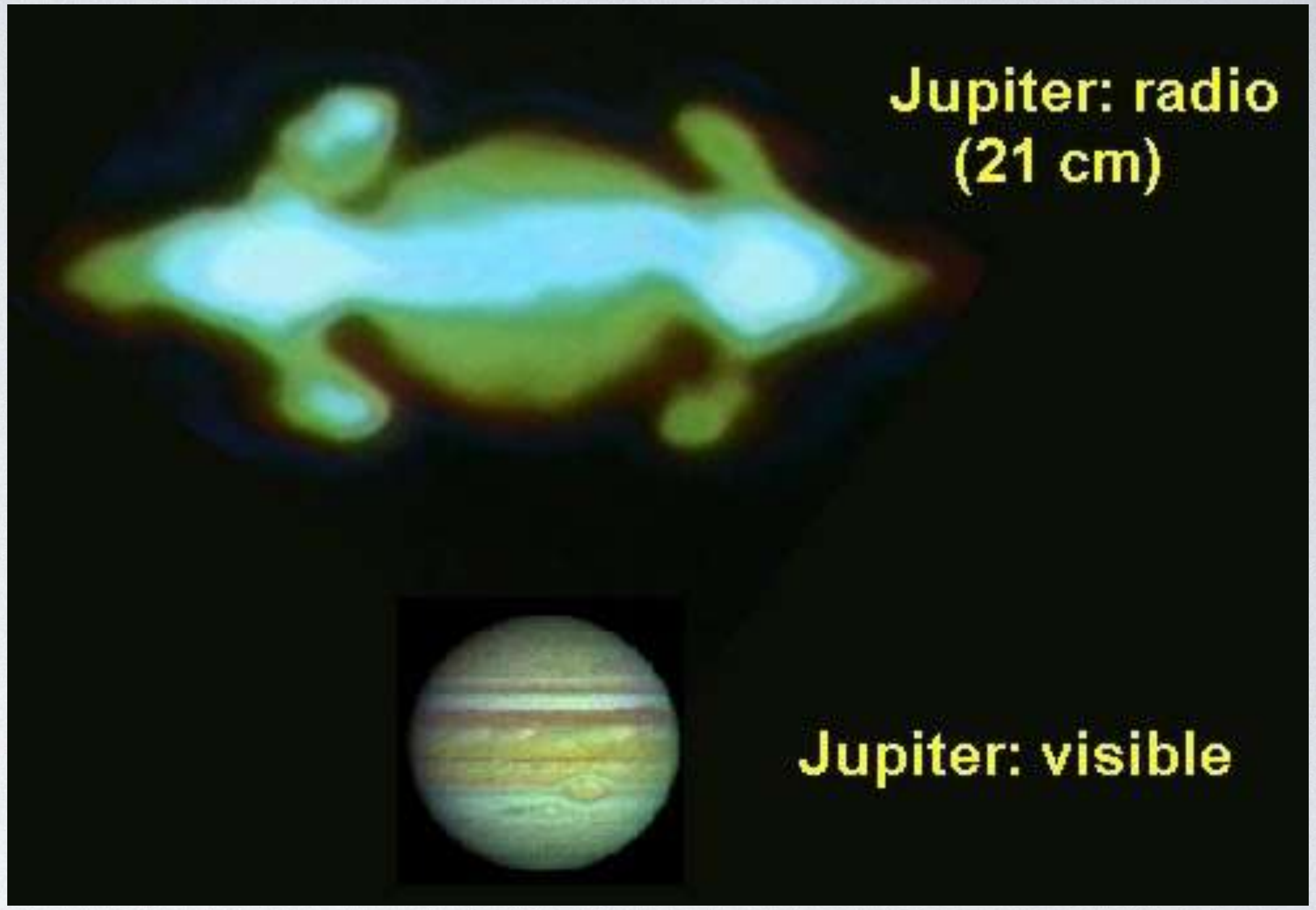
Galaxies M81 and M82 (and NGC3077)


radio continuum (408 MHz)
atomic hydrogen
radio continuum (2.5 GHz)
molecular hydrogen
infrared
mid-infrared
near infrared
optical
x-ray
gamma ray
http://adc.gsfc.nasa.gov/mw
NASA
Multiwavelength Milky Way

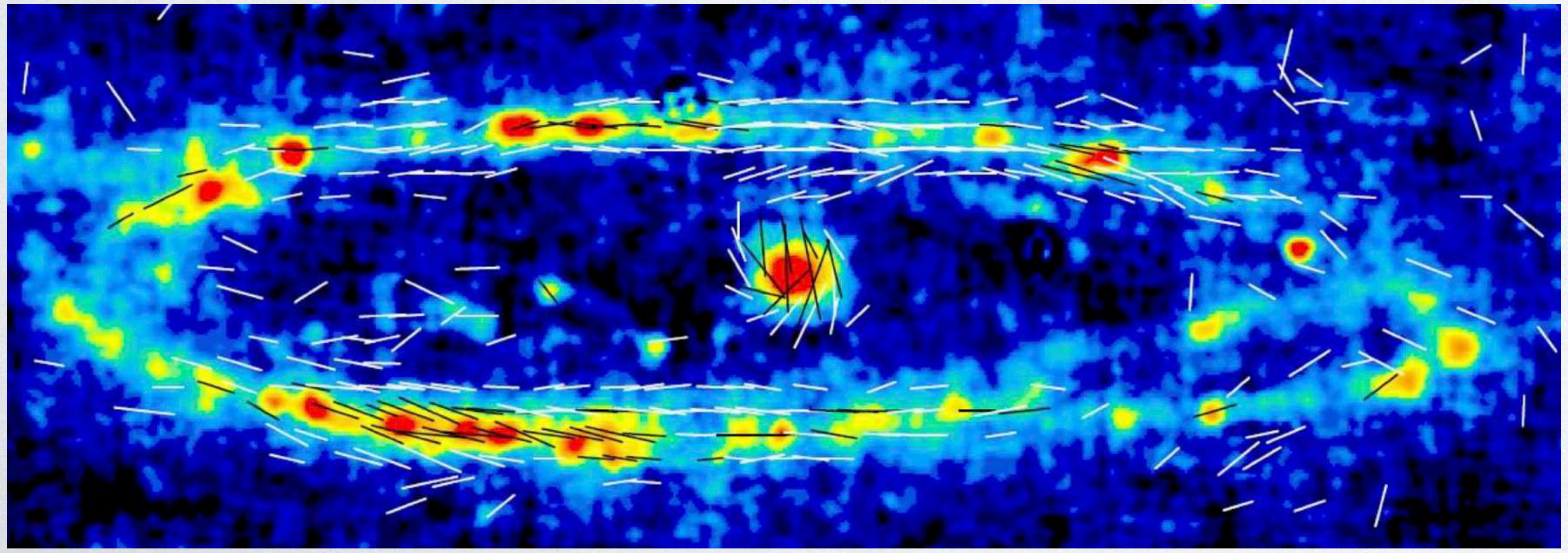
NASA GSFC



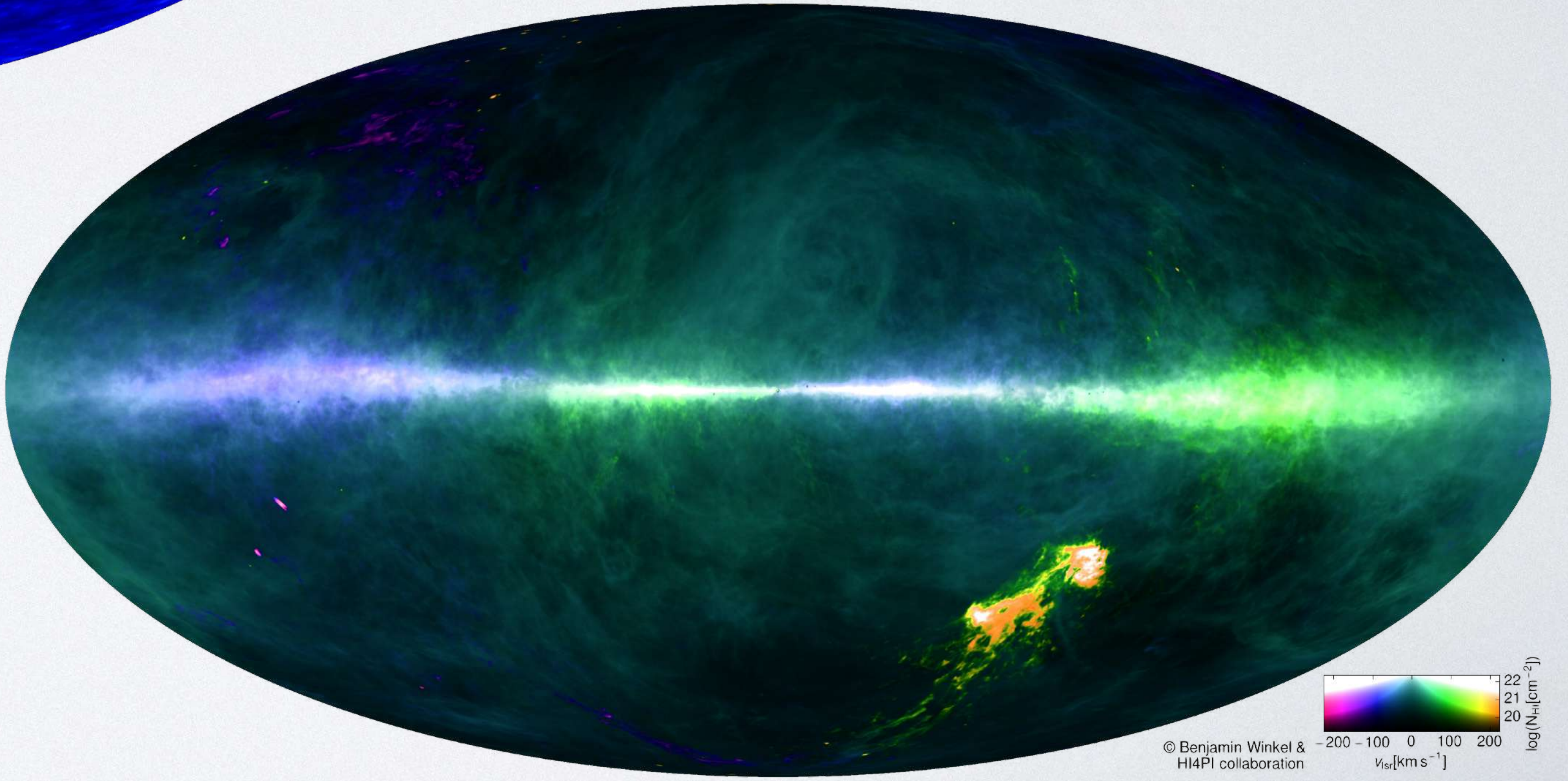
Haslam et al., 1981



https://taylorsciencegeeks.weebly.com/blog/electromagnetic-spectrum-radio-waves



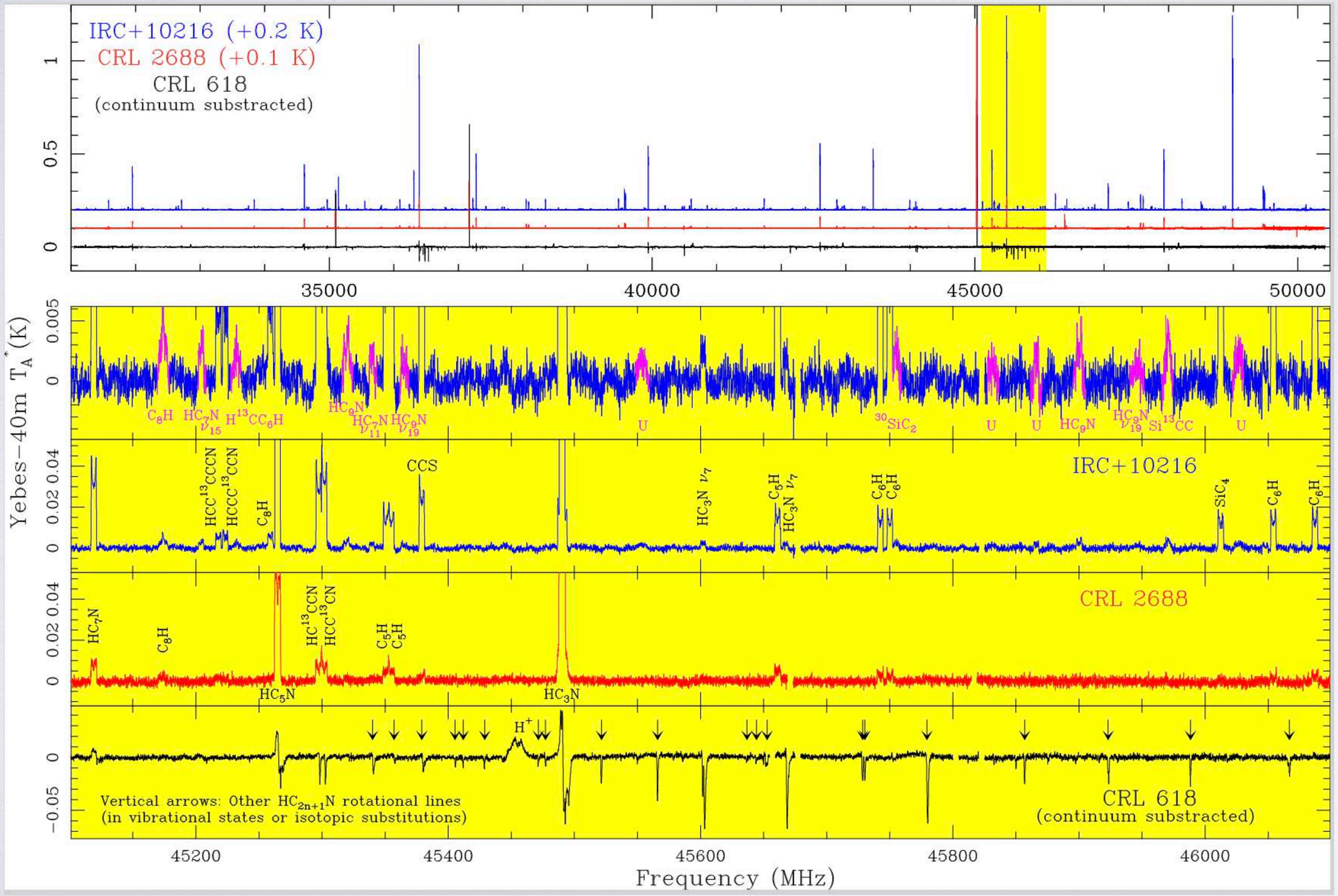
(Beck et al., 2020)



The 1.28 GHz MeerKAT Galactic Center Mosaic

Max-Planck-Institut für Radioastronomie

SPECTROSCOPY



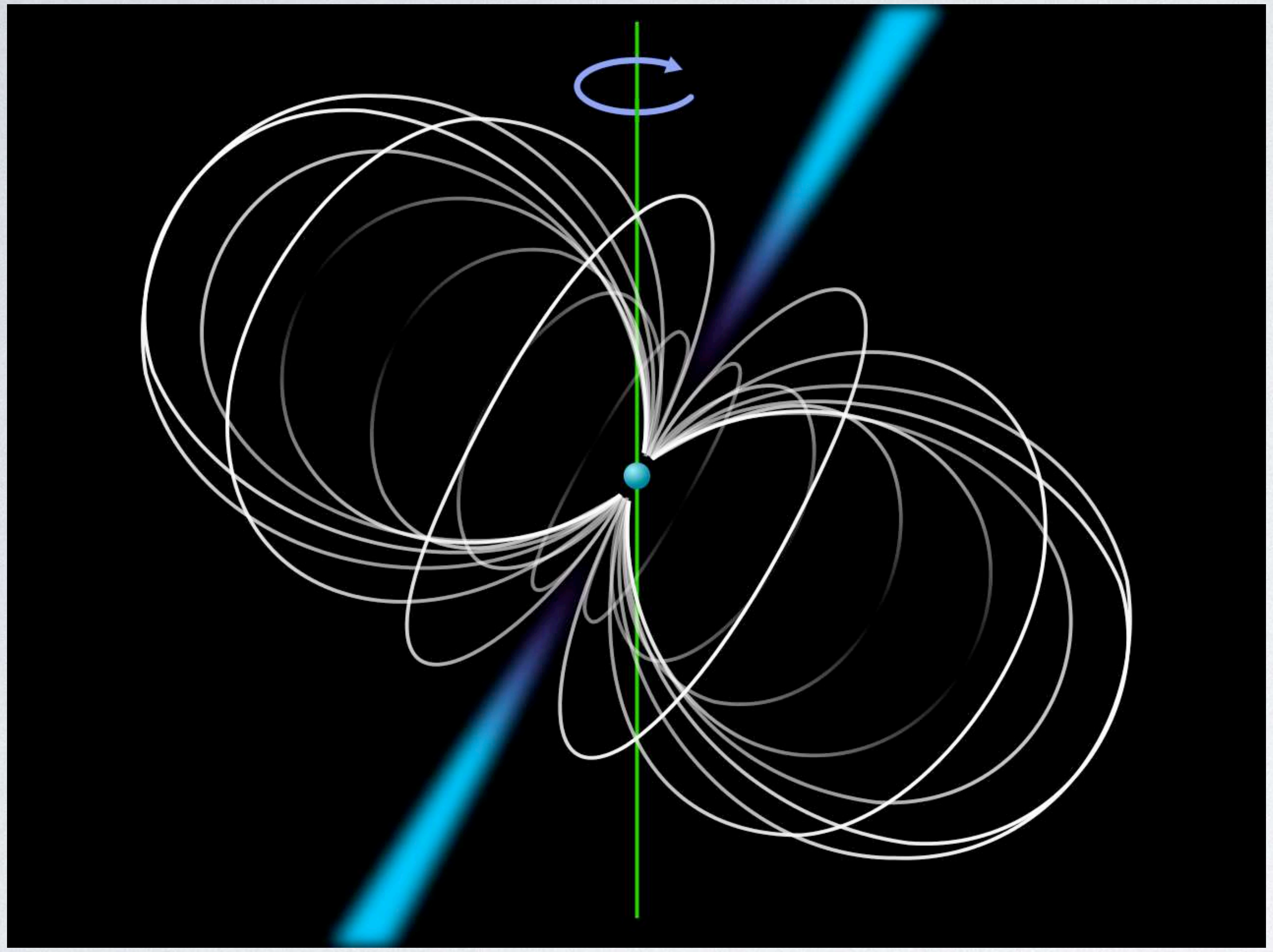
Yebes observatory

Yebes 40-m telescope

Tercero et al., 2021

Max-Planck-Institut
für Radioastronomie

PULSARS

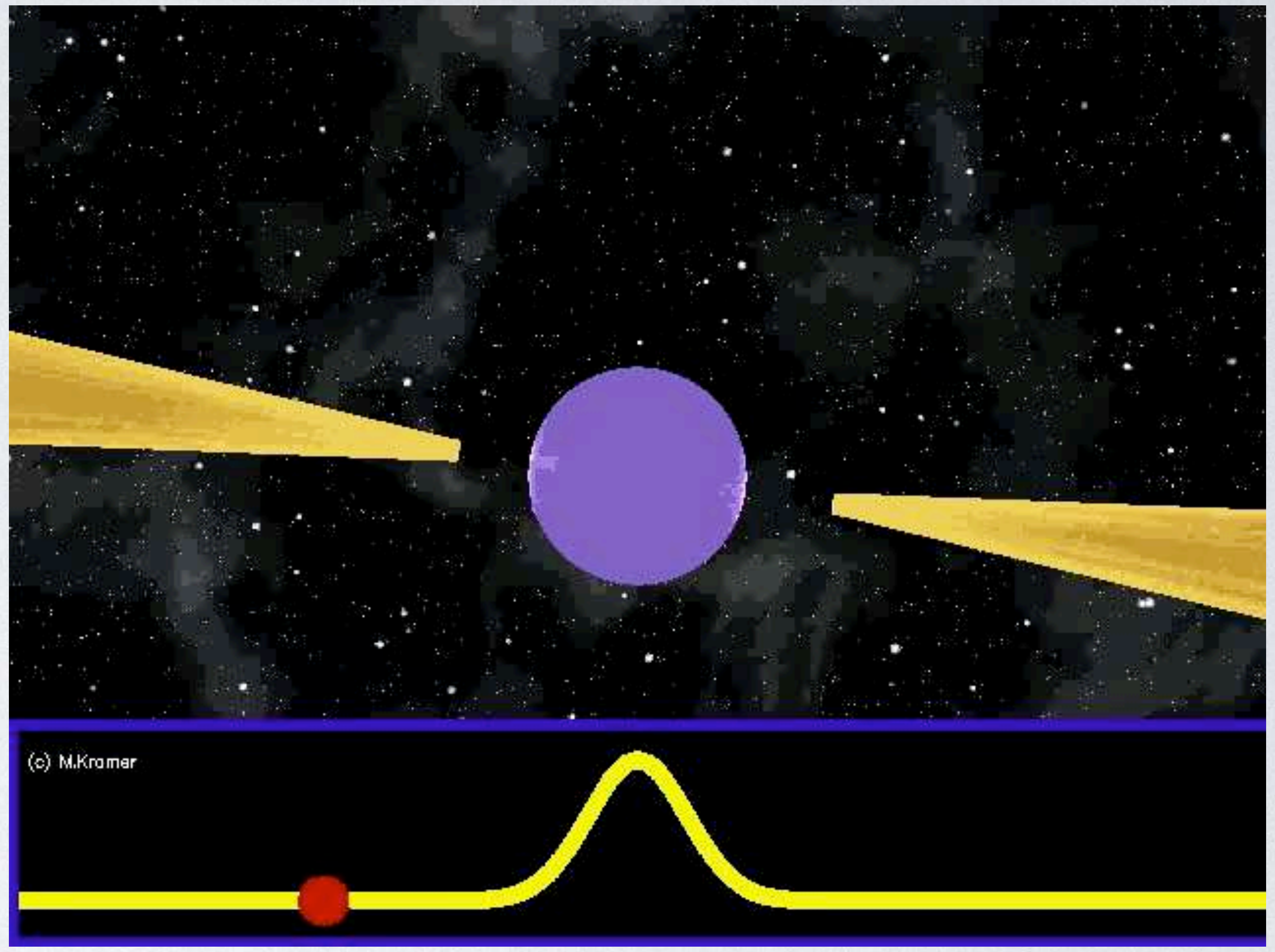


Wikipedia - Mysid

Neutron Stars with extrem stable rotation (e.g., PSR J1012+5307):

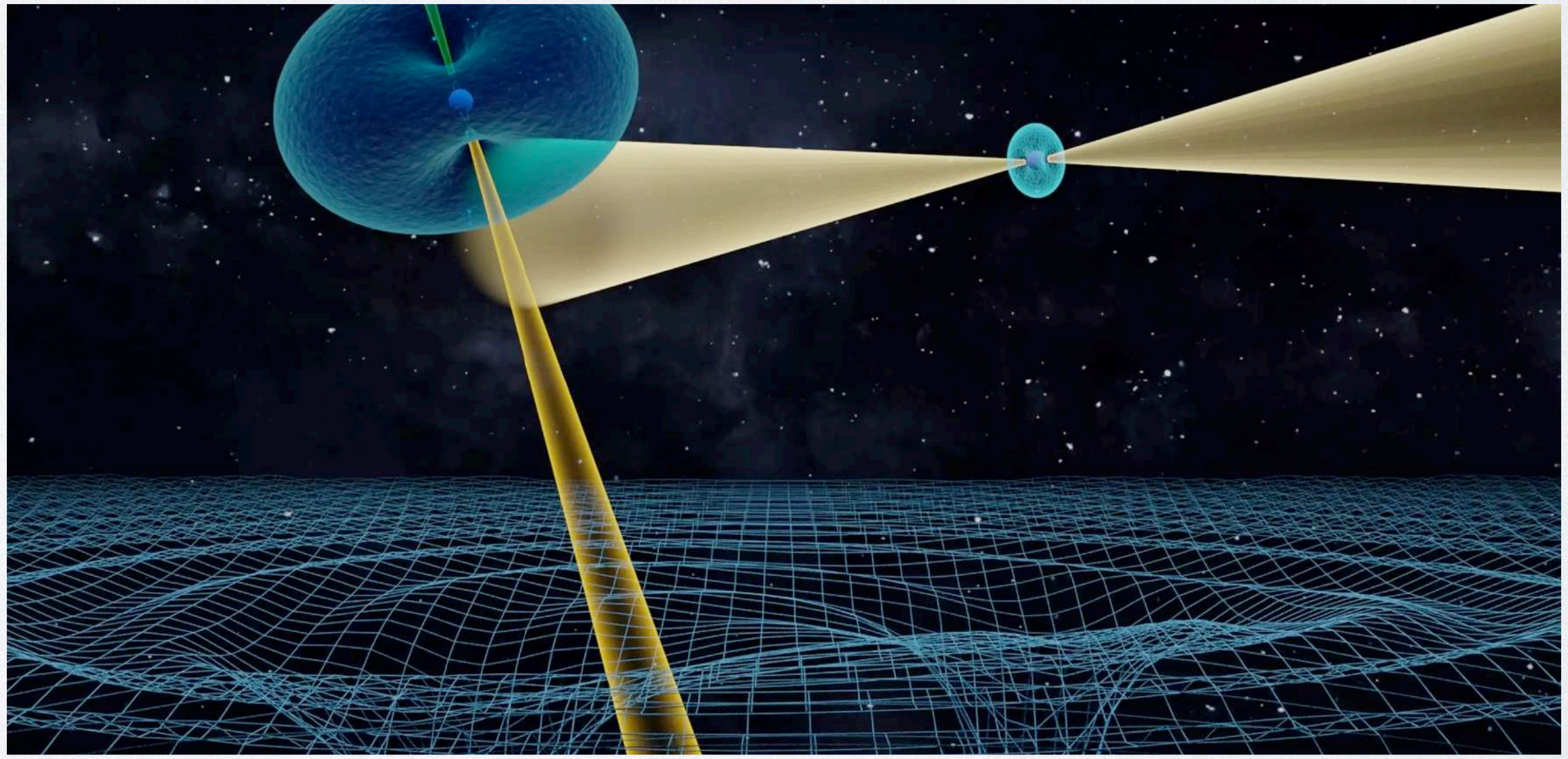
P = 5.25575 ± 0.000000000000015 ms
Uncertainty ~ 10^{-15}

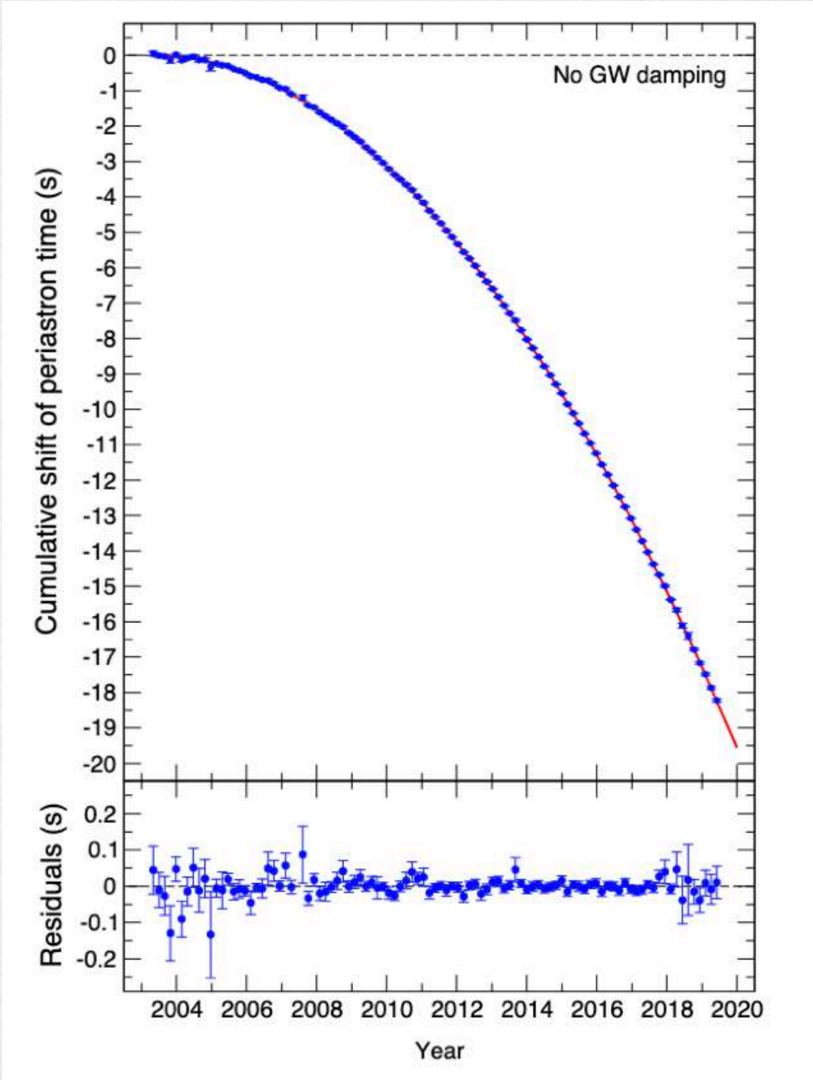
(Lazaridis et al., 2009)



Goals:

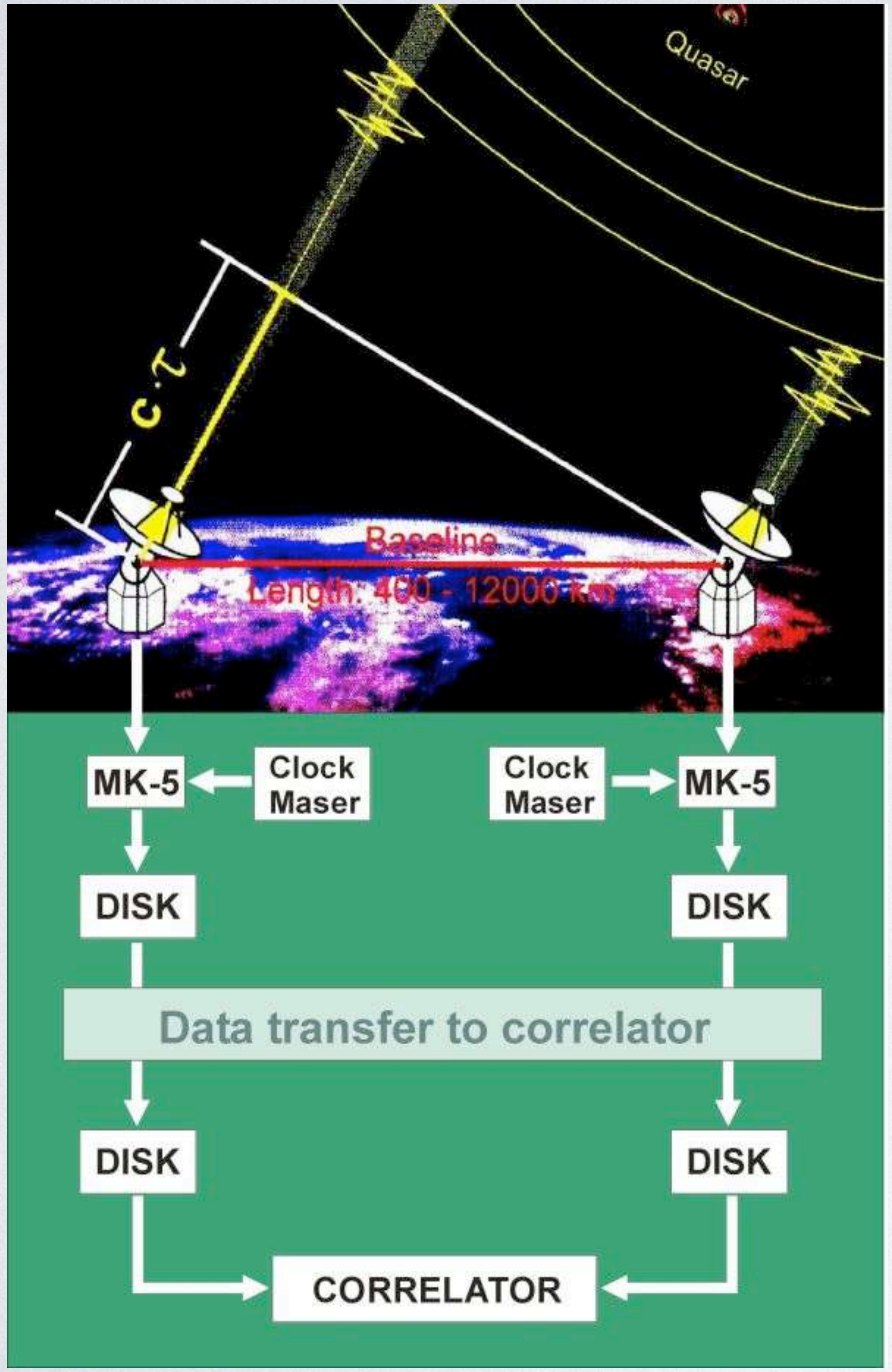
* Unterstand the formation and structure of NS
* Test General Relativity and other theories
* Detect gravitational waves



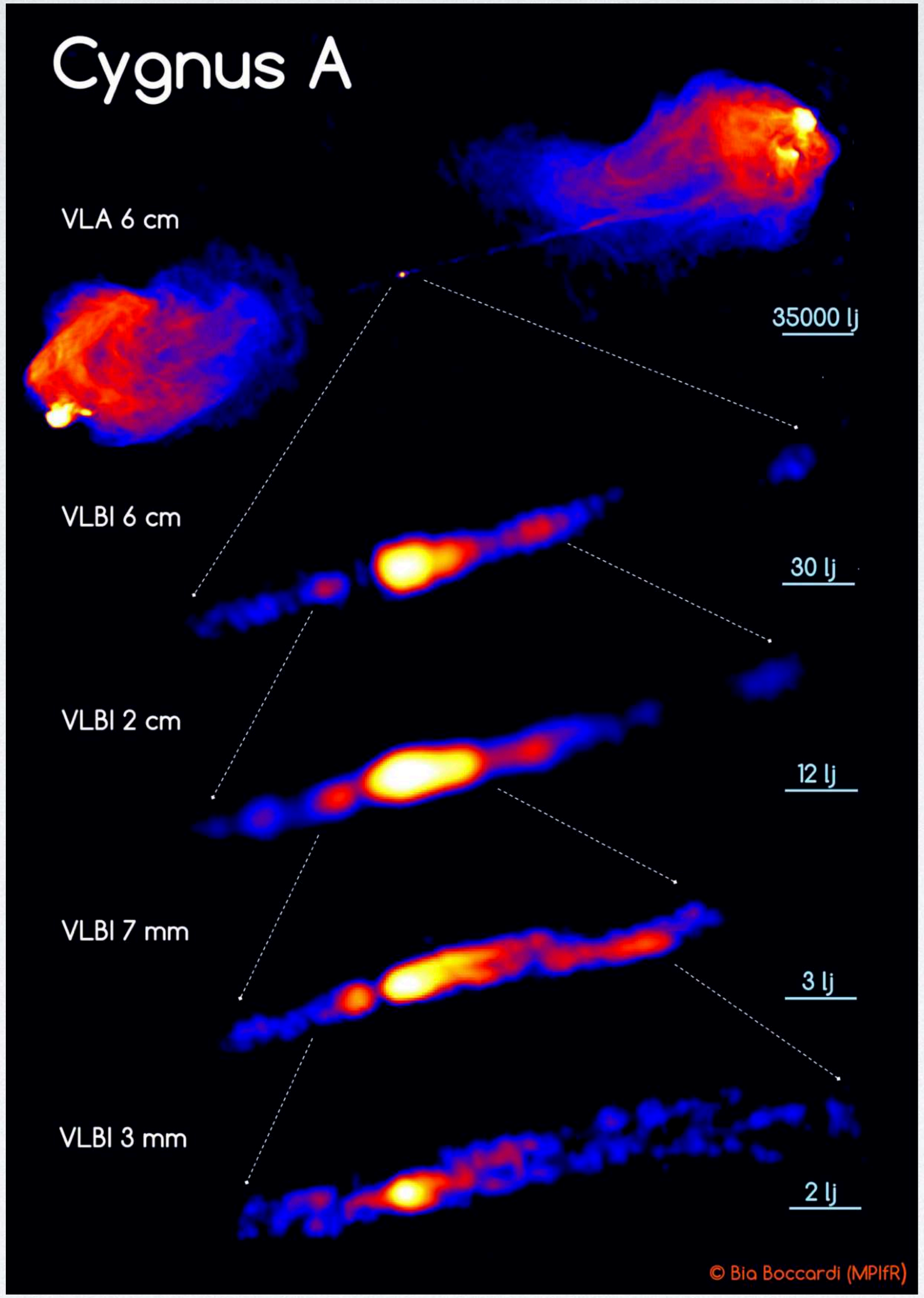


Kramer et al., 2021

VLBI



Bundesamt für Kartographie und Geodäsie



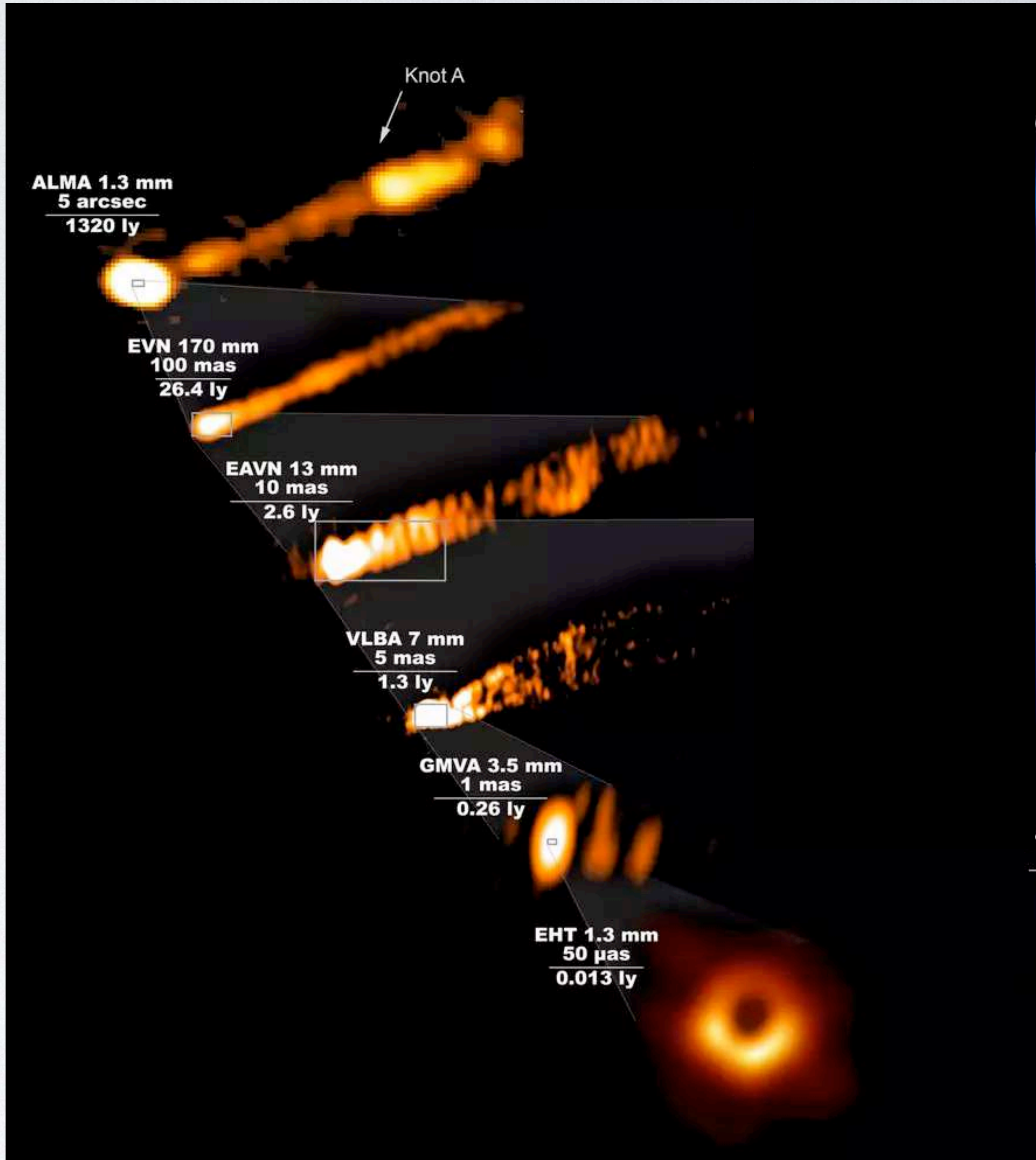
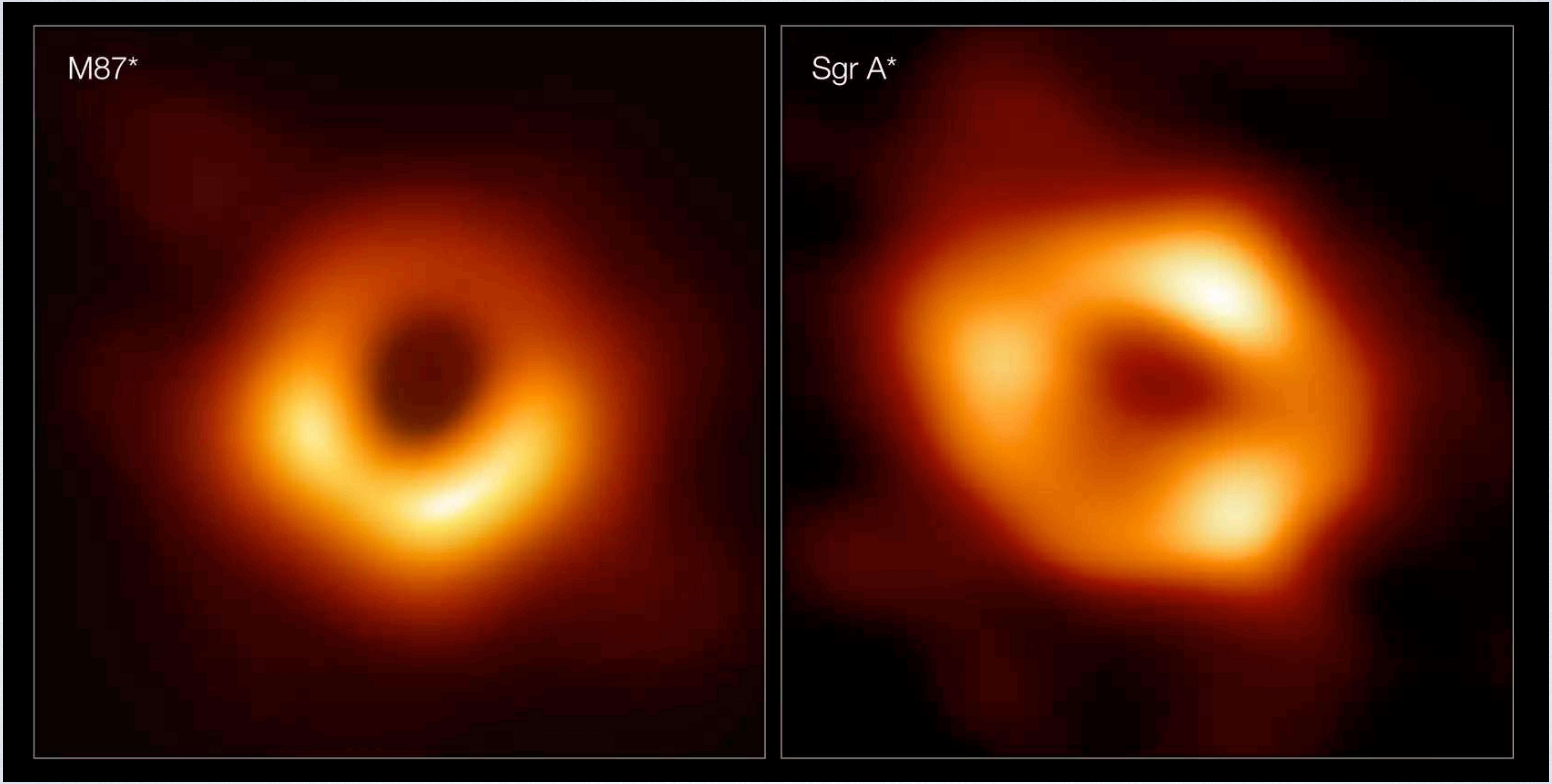


Image Credit: The EHT Multi-wavelength Science Working Group; the EHT Collaboration; ALMA (ESO/NAOJ/NRAO); the EVN; the
the Chandra X-ray Observatory; the Nuclear Spectroscopic Telescope Array; the Fermi-LAT Collaboration; the H.E.S.S collaboration

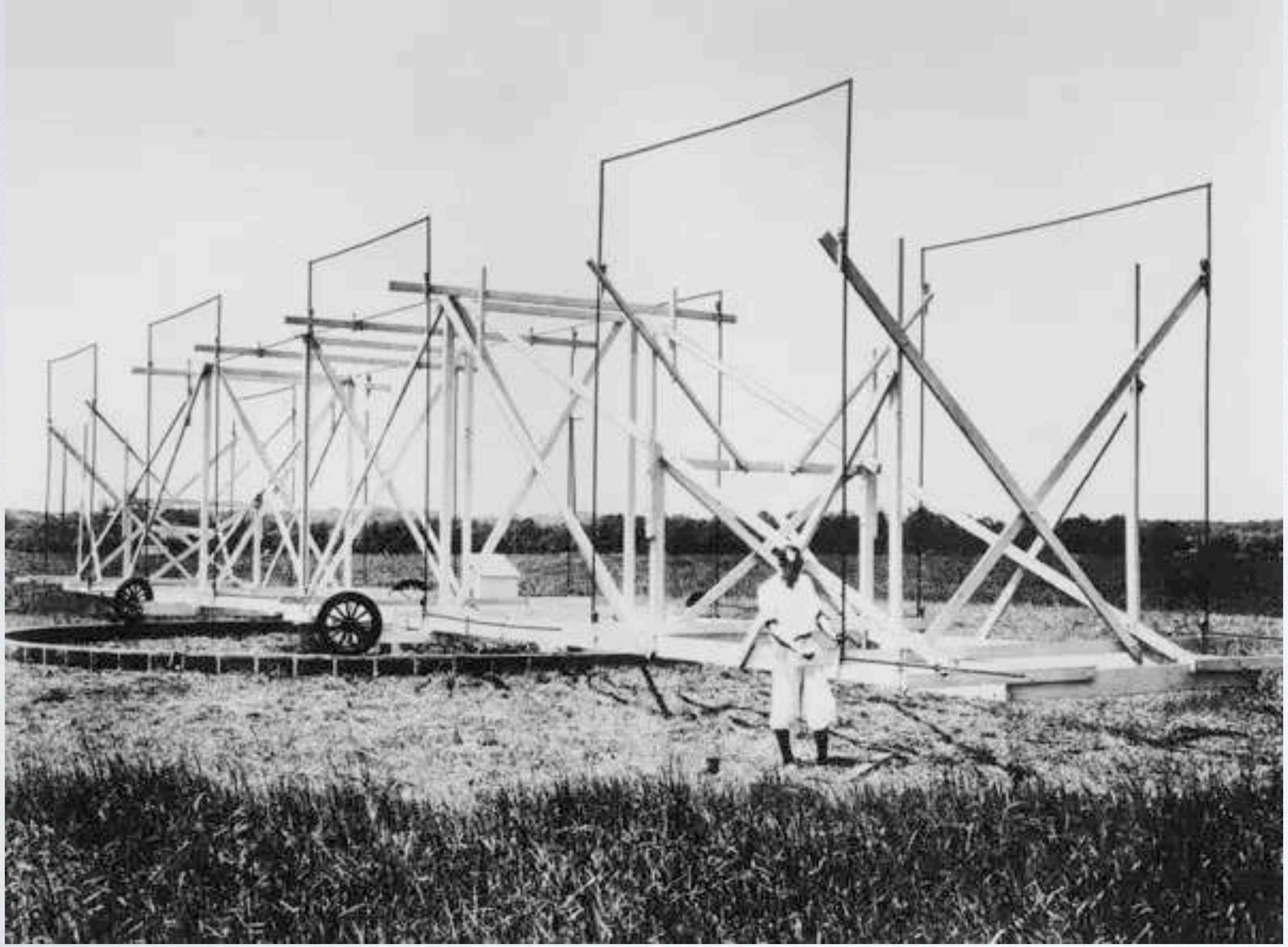
EHT

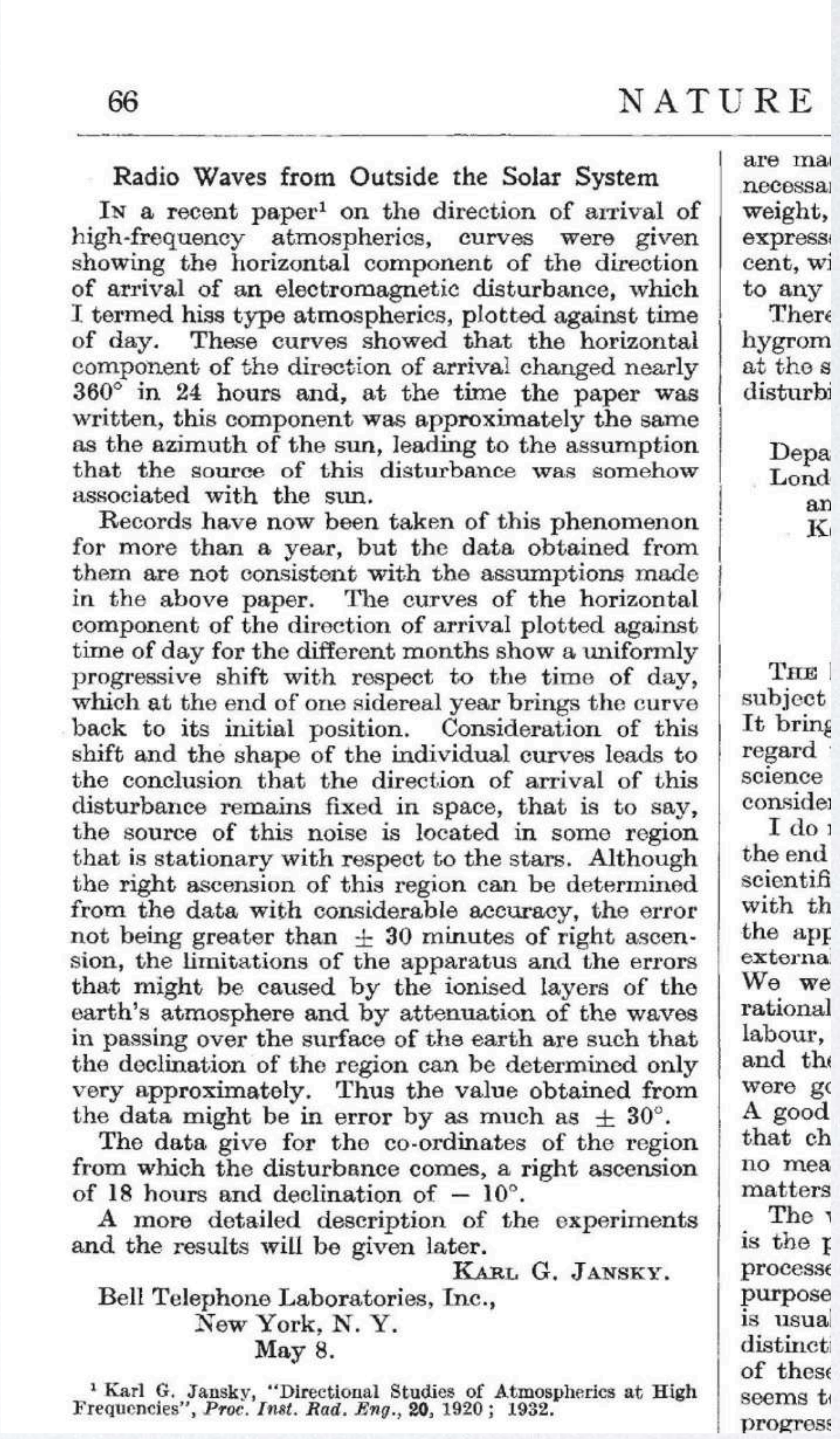


Event Horizon Telescope Collaboration

BIRTH OF RADIOASTRONOMY

Karl G. Jansky was looking for disturbances in short-wave transmissions at $\lambda = 14.6$ m
„steady hiss type static of unknown origin.“





66 NATURE

Radio Waves from Outside the Solar System

In a recent paper[1] on the direction of arrival of high-frequency atmospherics, curves were given showing the horizontal component of the direction of arrival of an electromagnetic disturbance, which I termed hiss type atmospherics, plotted against time of day. These curves showed that the horizontal component of the direction of arrival changed nearly 360° in 24 hours and, at the time the paper was written, this component was approximately the same as the azimuth of the sun, leading to the assumption that the source of this disturbance was somehow associated with the sun.

Records have now been taken of this phenomenon for more than a year, but the data obtained from them are not consistent with the assumptions made in the above paper. The curves of the horizontal component of the direction of arrival plotted against time of day for the different months show a uniformly progressive shift with respect to the time of day, which at the end of one sidereal year brings the curve back to its initial position. Consideration of this shift and the shape of the individual curves leads to the conclusion that the direction of arrival of this disturbance remains fixed in space, that is to say, the source of this noise is located in some region that is stationary with respect to the stars. Although the right ascension of this region can be determined from the data with considerable accuracy, the error not being greater than ± 30 minutes of right ascension, the limitations of the apparatus and the errors that might be caused by the ionised layers of the earth's atmosphere and by attenuation of the waves in passing over the surface of the earth are such that the declination of the region can be determined only very approximately. Thus the value obtained from the data might be in error by as much as ± 30°.

The data give for the co-ordinates of the region from which the disturbance comes, a right ascension of 18 hours and declination of − 10°.

A more detailed description of the experiments and the results will be given later.

Karl G. Jansky.

Bell Telephone Laboratories, Inc.,
New York, N. Y.
May 8.

[1] Karl G. Jansky, "Directional Studies of Atmospherics at High Frequencies", *Proc. Inst. Rad. Eng.*, **20**, 1920; 1932.

Images courtesy of NRAO/AUI.

Nature Publishing Group, 1933

$$1\,\text{Jansky} = 10^{-26}\frac{\text{W}}{\text{m}^2\,\text{Hz}}$$

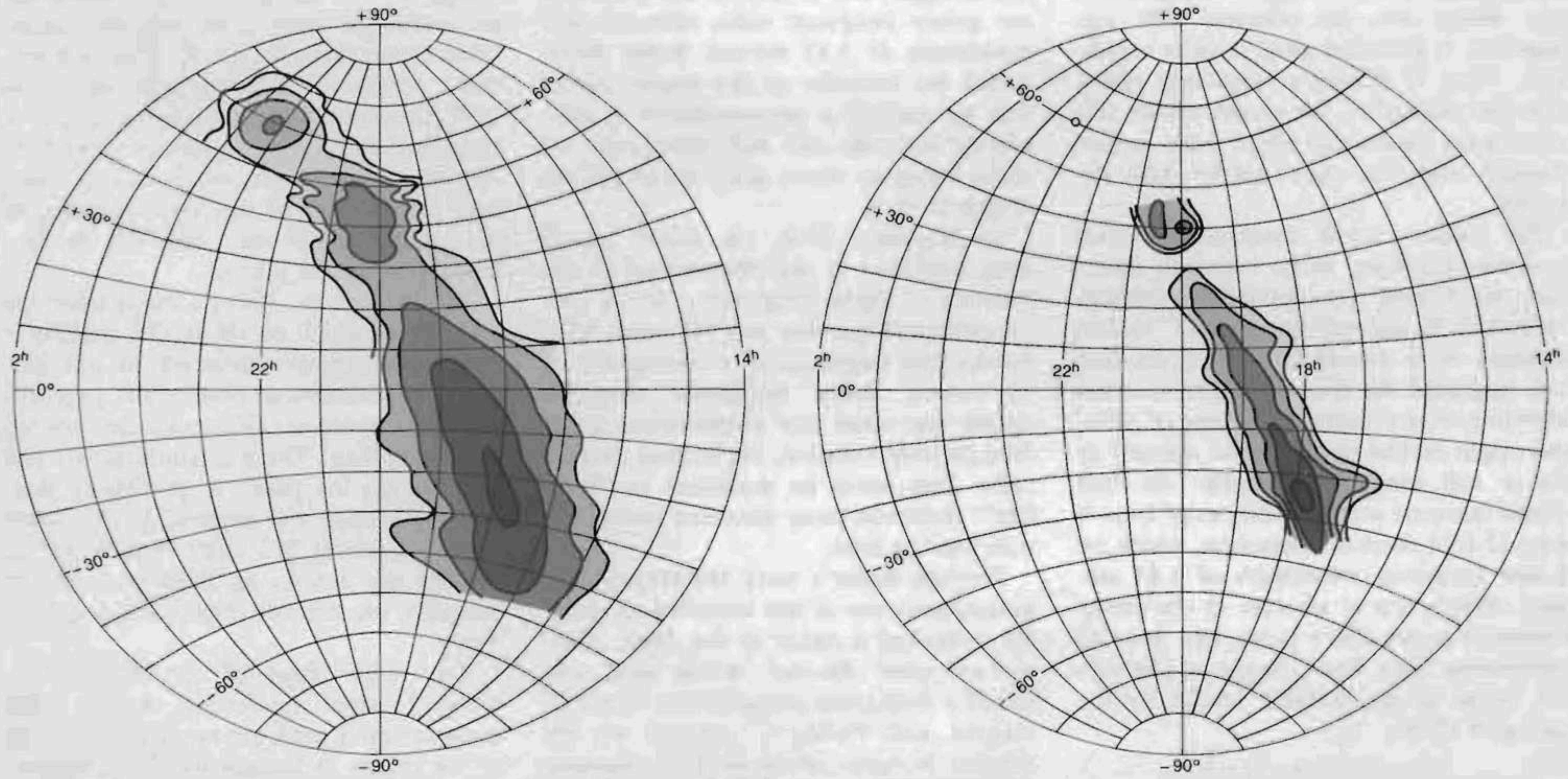
GROTE REBER

Max-Planck-Institut für Radioastronomie

Jarek Tuszyński

NRAO Archives

First radio map of the Galaxy - at $\lambda = 1.87$ m



Left: **The first radio map of the Milky Way resulted from some 200 traces made at a wavelength of 1.87 meters with an effective beamwidth of about 12°. Contours of equal intensity reveal the center of our galaxy at declination –25°, as well as peaks in Cygnus (+40°) and Cassiopeia (+60°). Adapted from Reber's November, 1944, article in the *Astrophysical Journal*. *Right:* This radio map has greater resolution because it was made at a wavelength of only 62.5 centimeters, resulting in a beamwidth of about 4°. Note that two peaks are now resolved in Cygnus at declination +40°. The small circle in Cassiopeia (+60°) is a supernova remnant. Adapted from an article by Reber in the October, 1948, *Proceedings* of the Institute of Radio Engineers.**

30 Sky & Telescope, *July, 1988*


FAST, China
Xinhua News Agency


Green Bank Telescope, USA
NRAO/AUI/NSF


Effelsberg, Germany
N. Tacken, MPIfR

MM / SUB-MM TELESCOPES

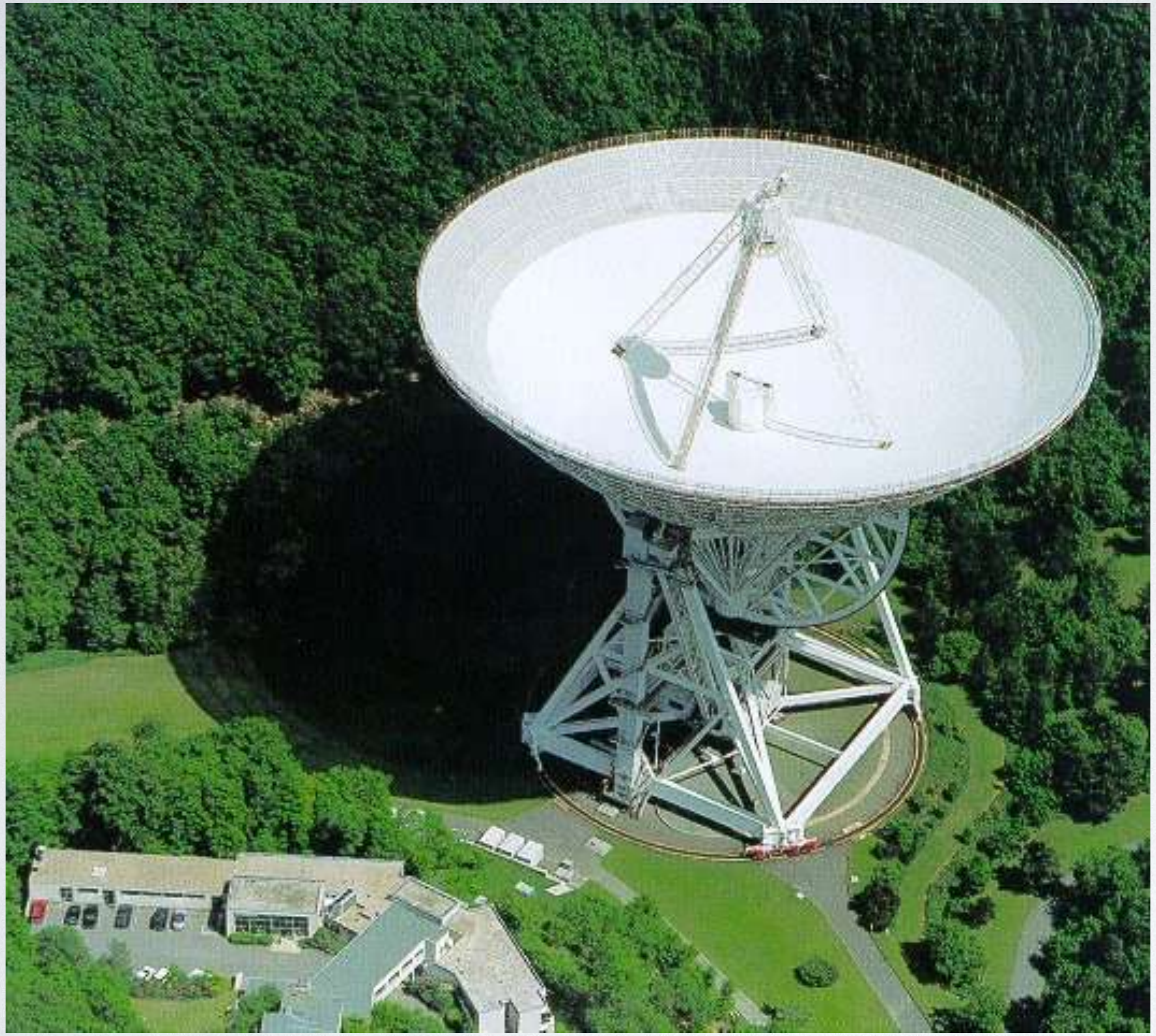

Very Large Array, USA
Wikipedia, NRAO


MeerKat / SKA, Südafrika
SARAO


Atacama Large mm-Array, Chile
ESO / Stéphane Guisard

Max-Planck-Institut für Radioastronomie

WHY ARE RADIOTELESCOPES SO BIG?



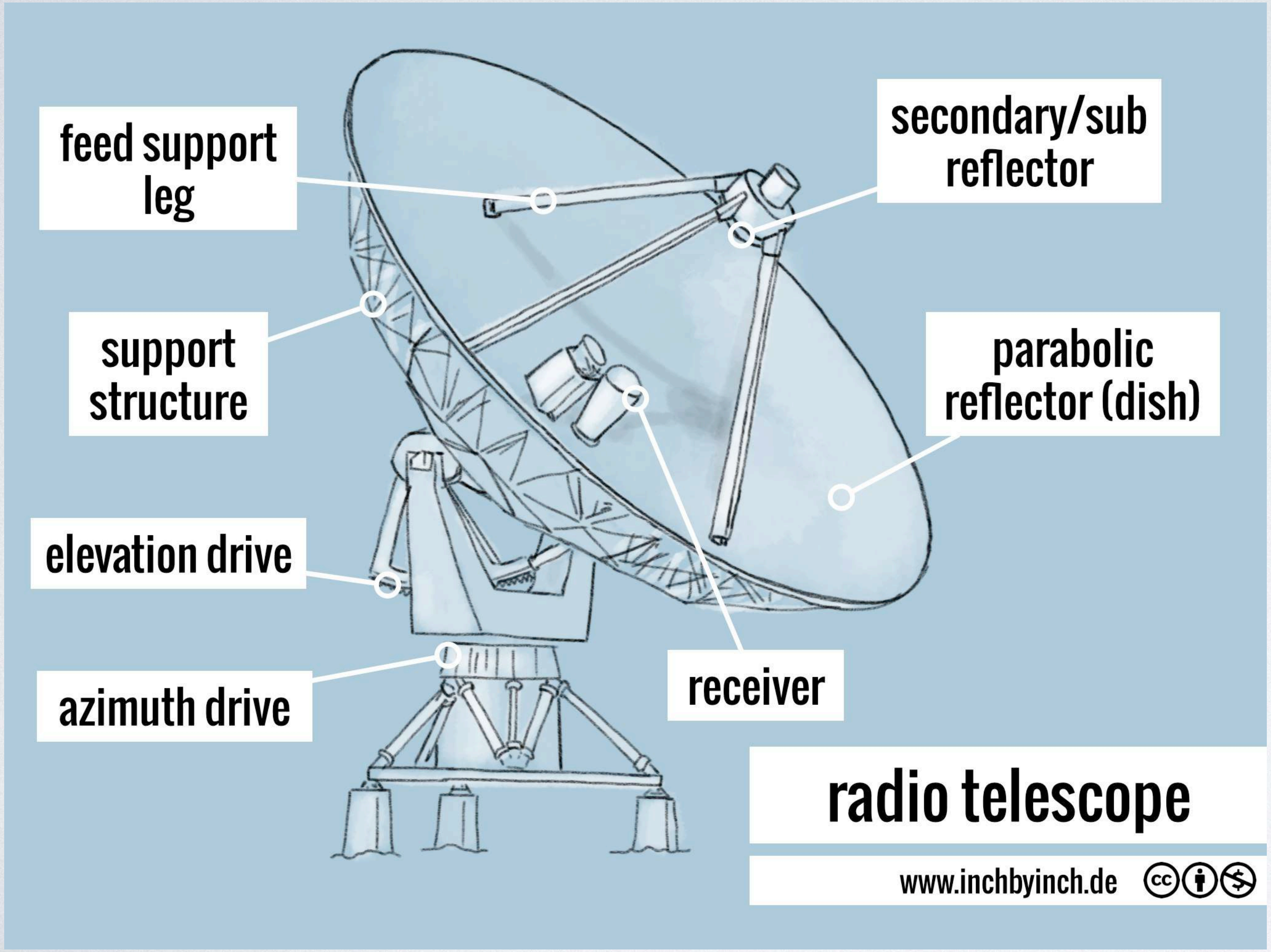
$$\text{sensitivity} \simeq \text{diameter}^2$$

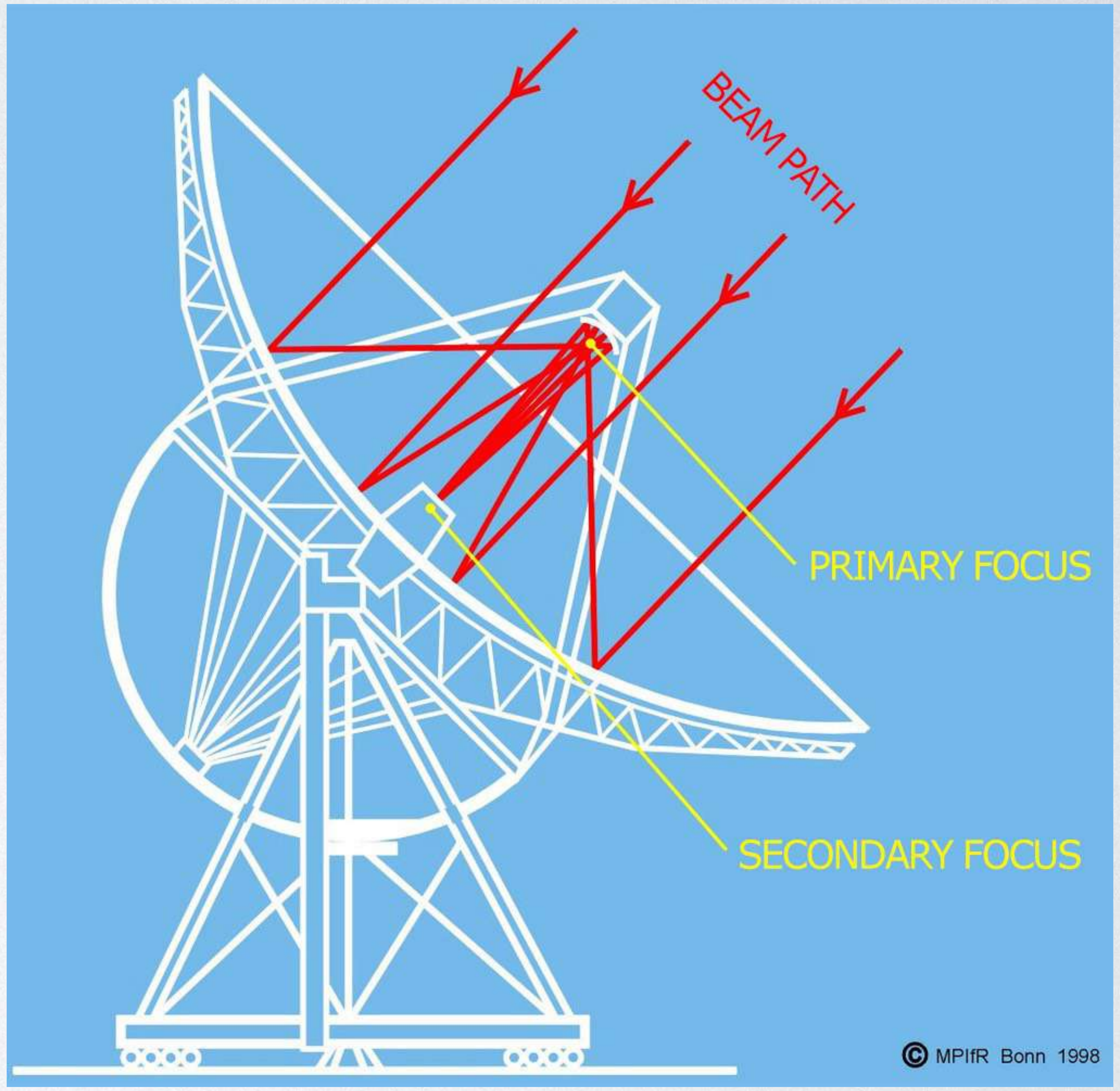
(Amplification: 60-85 dB = 1.000.000 – 300.000.000)

$$\text{resolution} \simeq \frac{\text{wavelength}}{\text{diameter}}$$

Resolution of the naked human eye: ~ 1 minute of arc (~1/60 degrees)
100-m telescope at 6cm wavelength: ~ 2.5 minutes of arc
Intercontinental Interferometry: ~ milli-arcsec to µarcsec

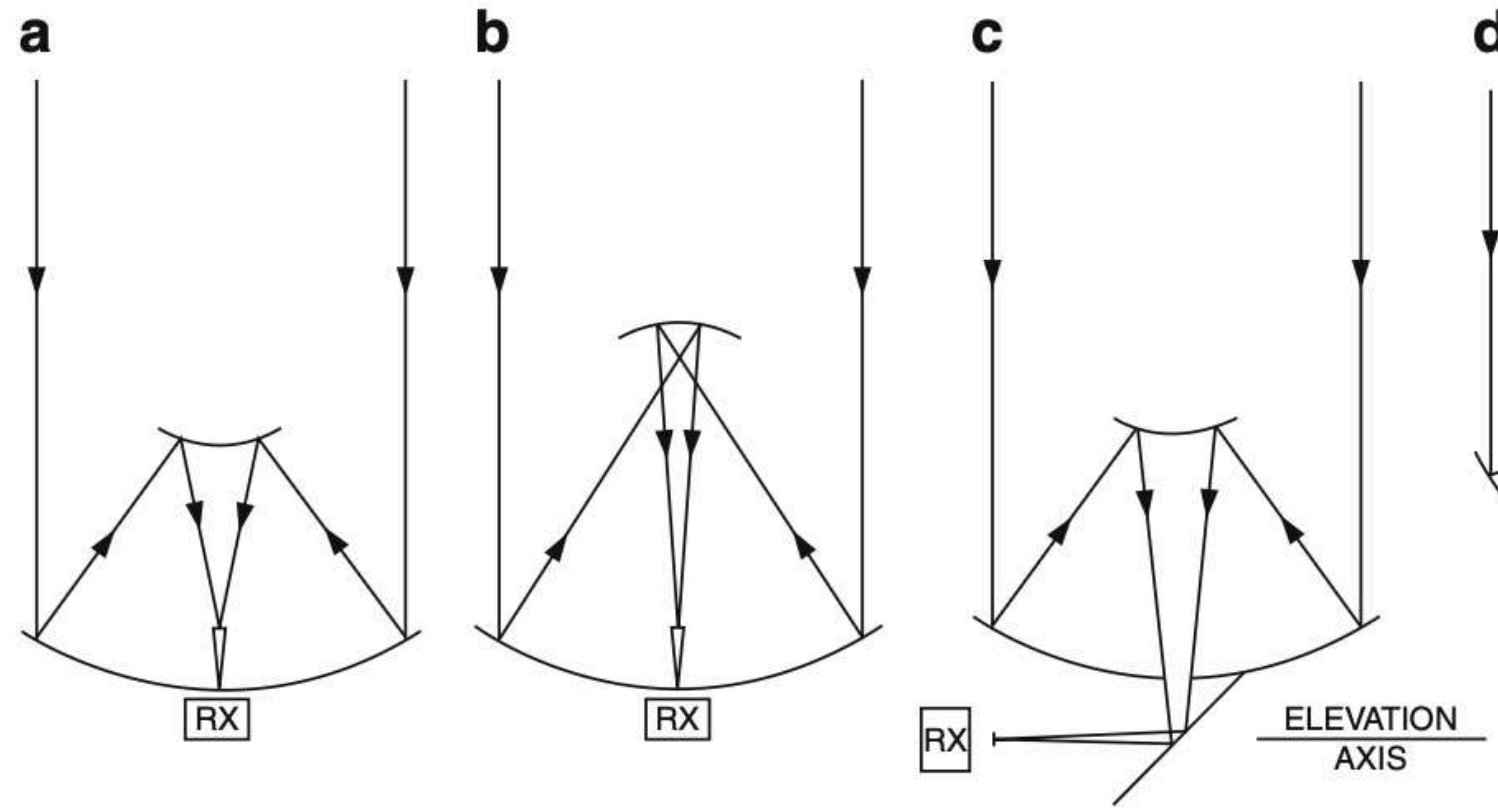
COMPONENTS OF A RADIO TELESCOPE





Max-Planck-Institut für Radioastronomie

OPTICS



Wilson, Rohlfs, Hüttemeister, 2013

Cassegrain Gregory Nasmyth Offset-Cassegrain

INTENSITY / FLUX DENSITY

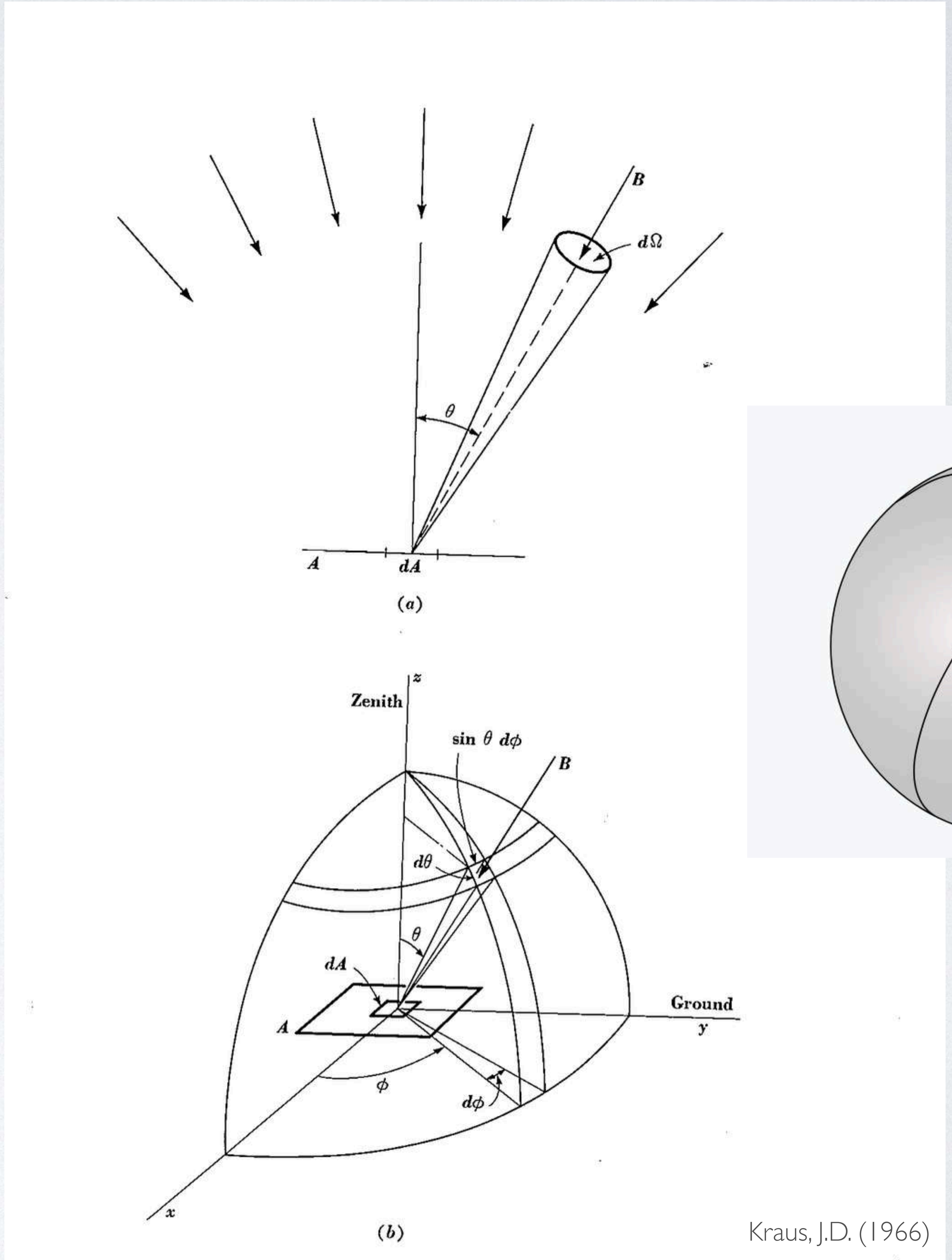
Max-Planck-Institut für Radioastronomie

The power of an EM wave received by an area dA from a source with solid angle dΩ within a bandwidth dν is

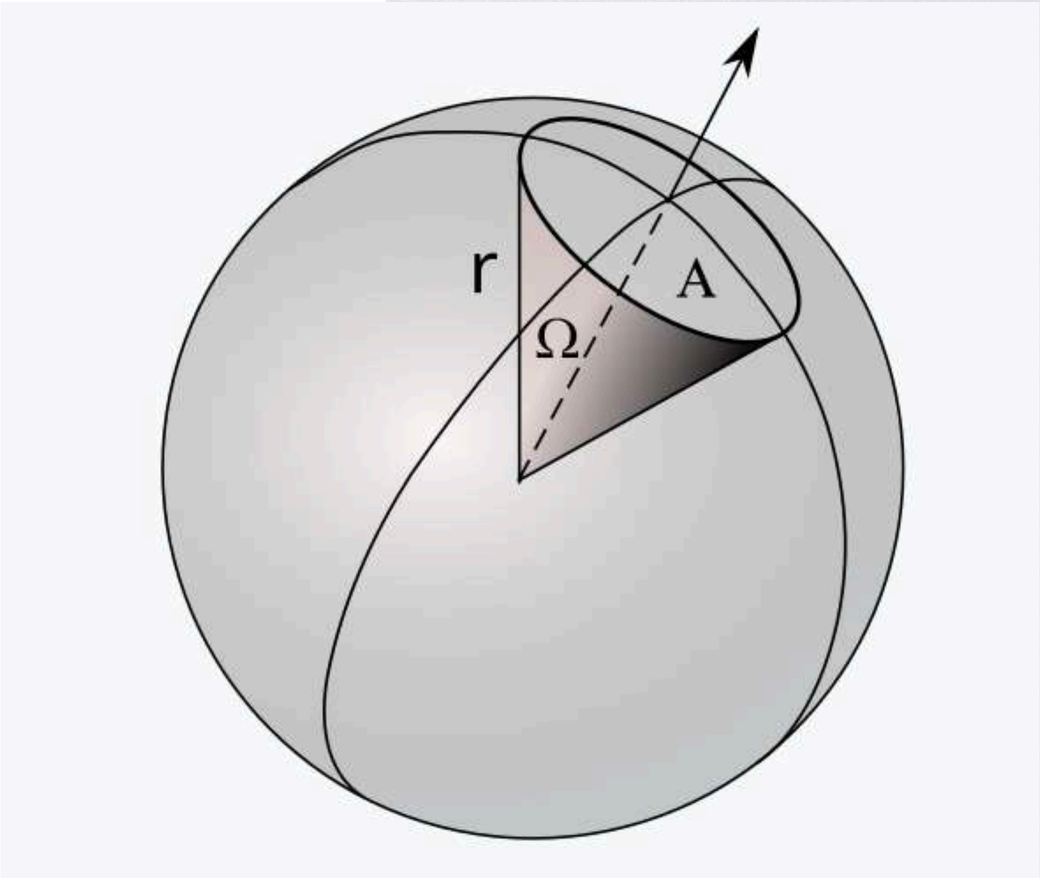
$$dP = I_\nu \cos\theta \, d\Omega \, dA \, d\nu$$

I_ν is the specific intensity (sometimes surface brightness) of the source, measured in

$$[I_\nu] = \frac{\mathrm{W}}{\mathrm{m^2\,Hz\,sr}}$$



Kraus, J.D. (1966)



Wikipedia CC

FLUX DENSITY

With the intensity and the solid angle of the source, one can define its spectral flux density:

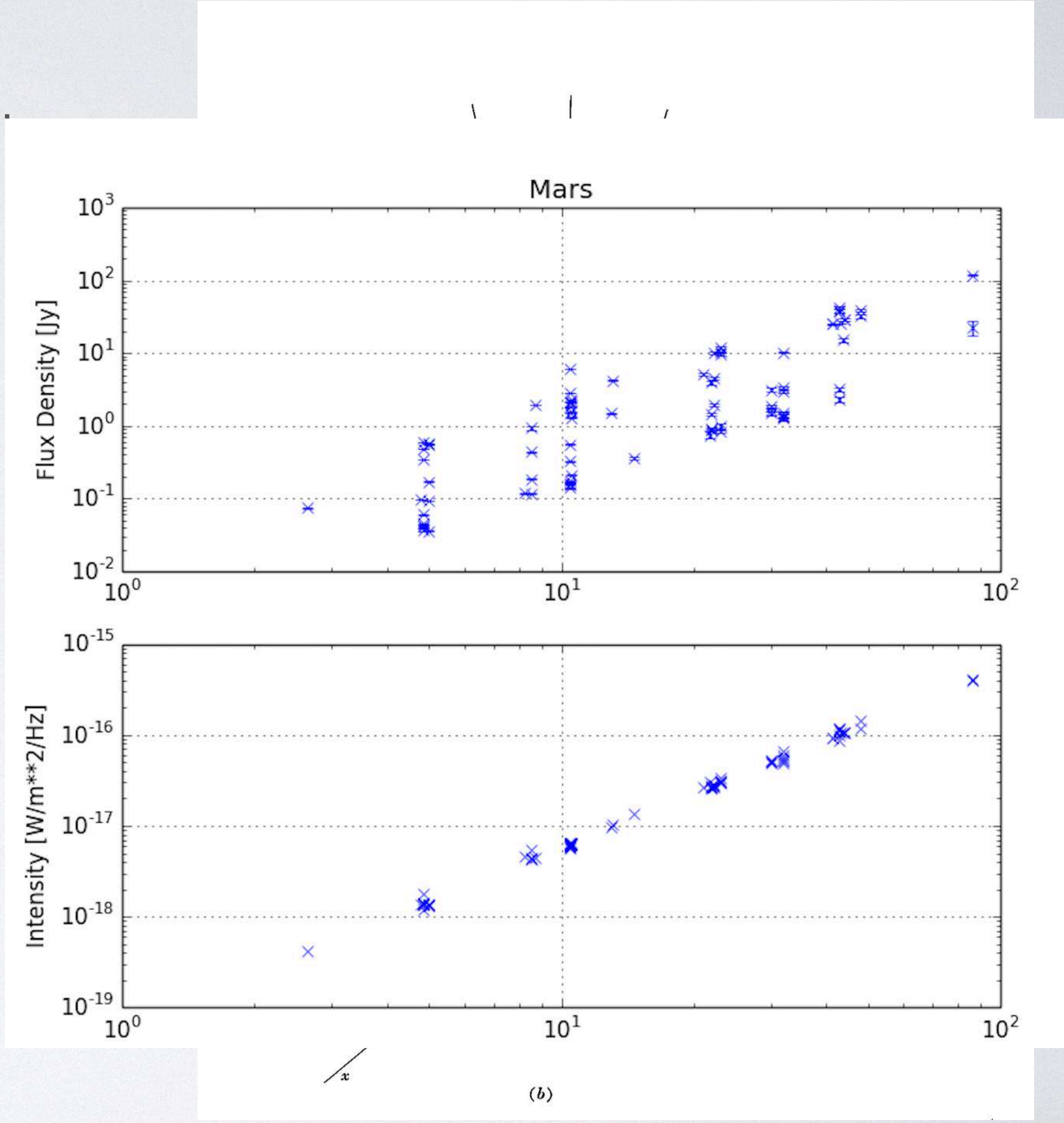
Integral of brightness over source solid angle

$$S_\nu = \int_{\Omega_{src}} I_\nu(\theta, \phi)\, d\Omega$$

$$1\,\text{Jy} = 10^{-26}\frac{\text{W}}{\text{m}^2\,\text{Hz}} = 10^{-23}\frac{\text{ergs}}{\text{cm}^2\,\text{Hz}}$$

Note, the dependence on distance:

$$S_\nu = L_\nu/4\pi d^2 \qquad \Omega \propto 1/d^2$$



Kraus, J.D. (1966)

BLACKBODY RADIATION

Max-Planck-Institut für Radioastronomie

$$I_\nu = B_\nu(T) = \frac{2\mathrm{h}\nu^3}{\mathrm{c}^3}\frac{1}{\exp\left(\frac{\mathrm{h}\nu}{\mathrm{kT_B}}\right) - 1}$$

„Planck's law"

For Radioastronomy, $\mathrm{h}\nu \ll \mathrm{kT_B}$, and the Rayleigh-Jeans approximation can be used:

$$I_\nu = \frac{2\mathrm{k}\nu^2}{\mathrm{c}^2} \cdot T_B$$

In terms of flux density:

$$S_\nu = \int_{\Omega_{\mathrm{src}}} I_\nu(\theta, \phi)\, d\Omega = \frac{2\mathrm{k}\nu^2}{\mathrm{c}^2}\int_{\Omega_{\mathrm{src}}} T_B(\theta, \phi)\, d\Omega$$

Note: Most astrophysical sources are not blackbodies! Still, radio astronomers like to give the brightness in $\mathrm{KT_B}$. Consequently, these are not „real" temperatures!

NON-THERMAL BRIGHTNESS TEMPERATURES

The Astrophysical Journal Letters, 820:L9 (6pp), 2016 March 20
doi:10.3847/2041-8205/820/1/L9

RADIOASTRON OBSERVATIONS OF THE QUASAR 3C273: A CHALLENGE TO THE BRIGHTNESS TEMPERATURE LIMIT

Y. Y. Kovalev[1,2], N. S. Kardashev[1], K. I. Kellermann[3], A. P. Lobanov[2,4], M. D. Johnson[5], L. I. Gurvits[6,7], P. A. Voitsik[1], J. A. Zensus[2], J. M. Anderson[2,8], U. Bach[2], D. L. Jauncey[9,10], F. Ghigo[11], T. Ghosh[12], A. Kraus[2], Yu. A. Kovalev[1], M. M. Lisakov[1], L. Yu. Petrov[13], J. D. Romney[14], C. J. Salter[12], and K. V. Sokolovsky[1,15]

Table 1
RadioAstron Ground-to-space Radio Interferometer Measurements of the Quasar 3C 273

λ (cm) (1)	Epoch (2)	GRT (3)	r_{uv} (10^3 km; Gλ) (4)	P.A. (deg) (5)	S/N (6)	S_t (Jy) (7)	S_c (mJy) (8)	θ (μas) (9)	T_b (10^{12} K) (10)	$T_{b,min}$ (10^{12} K) (11)	$T_{b,char}$ (10^{12} K) (12)
1.3	2013 Feb 02	Gb, Y27	103; 7.6	−7	9.8	3.4	125 ± 22	26	14	5.3	12
6.2	2012 Dec 30	Ar, Ef	90; 1.45	10	18.6	4.3	125 ± 17	142	13	4.5	18
6.2	2013 Feb 02	Ar	103; 1.69	−8	11.6	4.3	123 ± 19	122	17	5.2	15
18	2013 Jan 08	Gb	157; 0.87	−32	8.9	5.0	42 ± 7	275	34	4.0	10
18	2013 Jan 25	Ar, Gb	171; 0.95	−38	12.0	5.0	52 ± 9	246	42	6.3	18

WHAT DOES A RADIO TELESCOPE MEASURE?

Max-Planck-Institut
für Radioastronomie

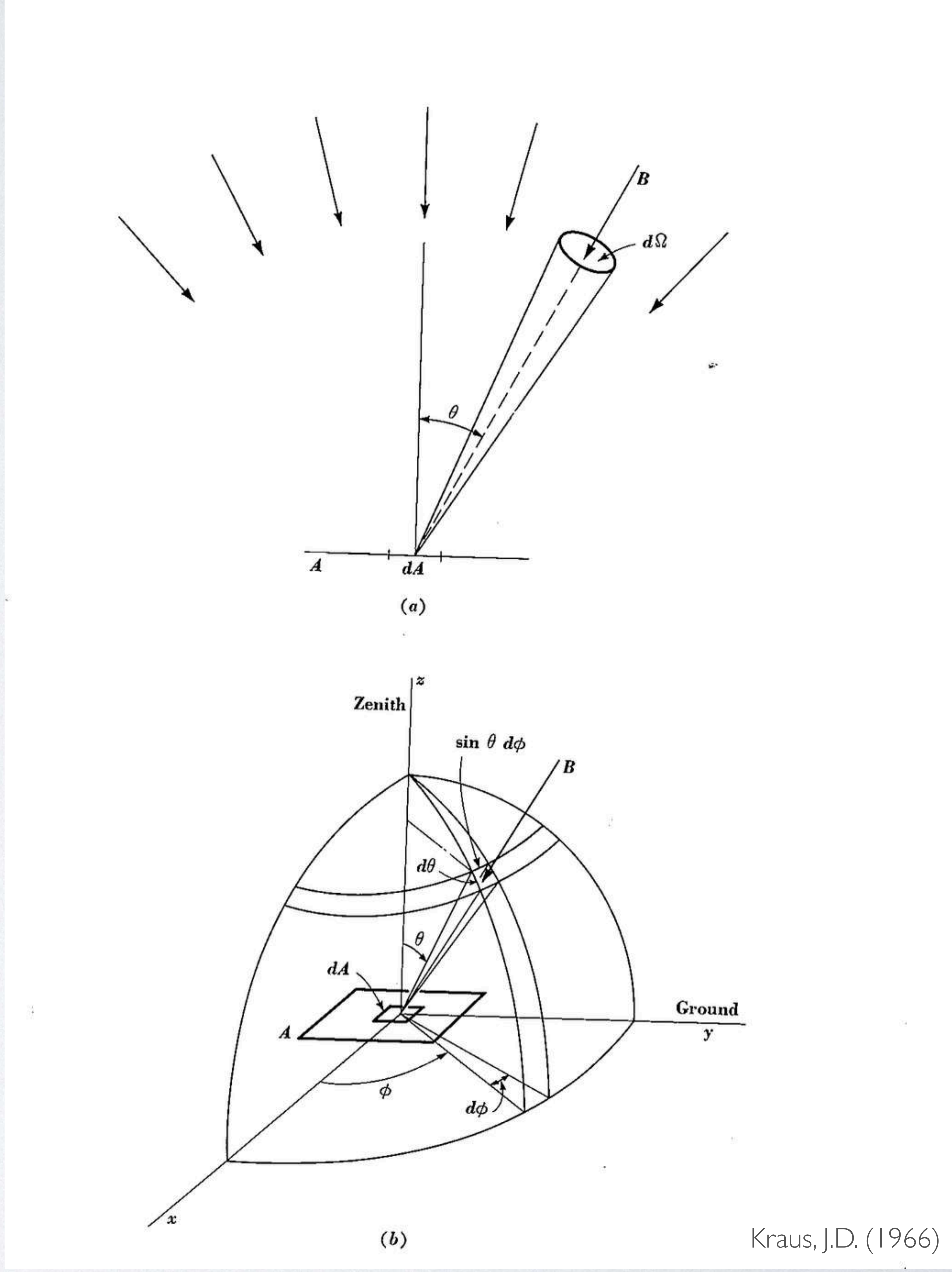
The power of an EM wave received by an area dA from a source with solid angle dΩ within a bandwidth dν is

$$dP = I_\nu \cos\theta \, d\Omega \, dA \, d\nu$$

Assume θ is small, then the power detected by the telescope is:

$$P_{\rm rec} = \frac{1}{2} \cdot A_{\rm eff} \cdot d\nu \int_{4\pi} I_\nu(\theta, \phi) P_n(\theta - \theta', \phi - \phi') \, d\Omega$$

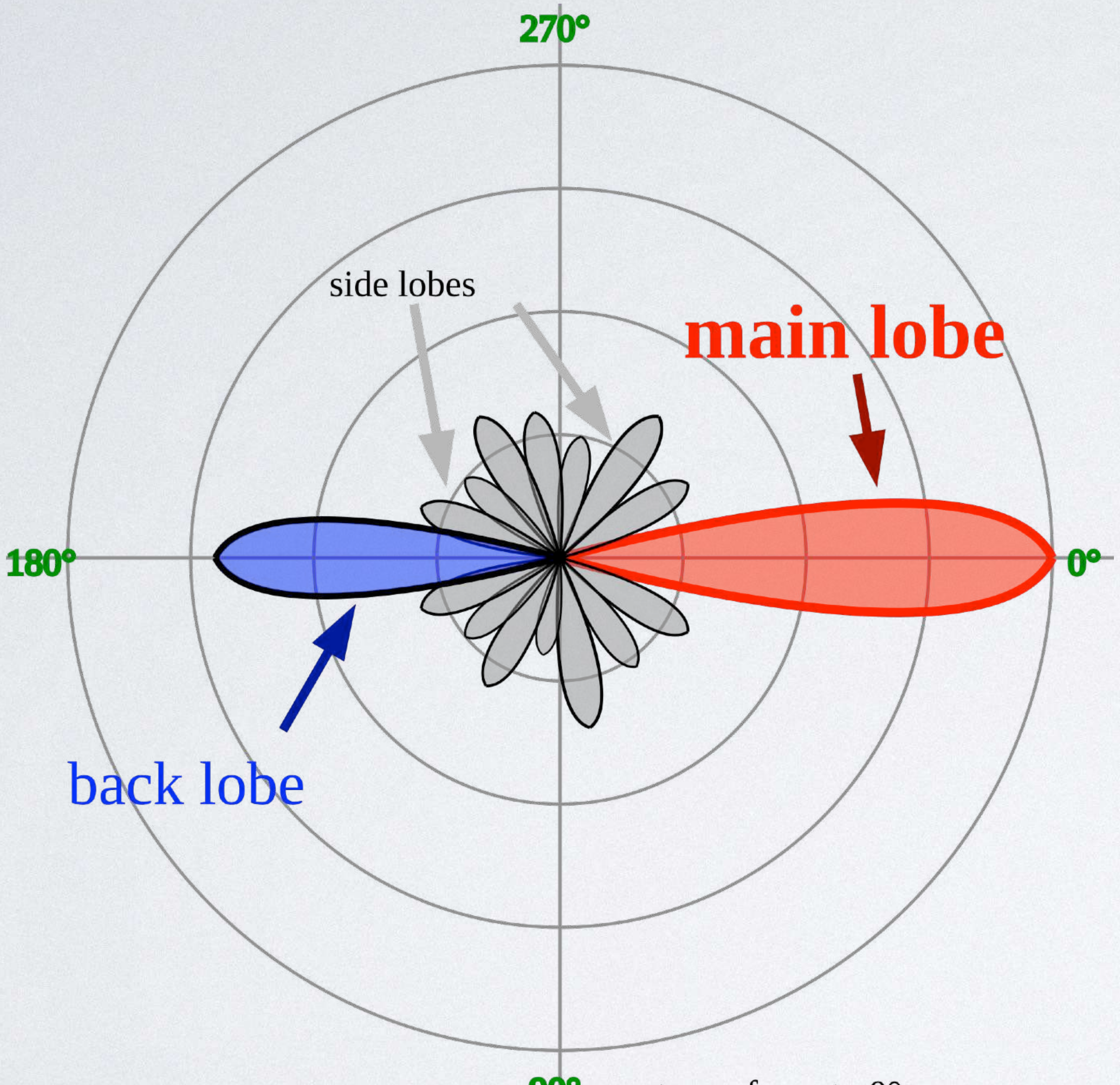
only one polarization — losses in the antenna — diffraction pattern

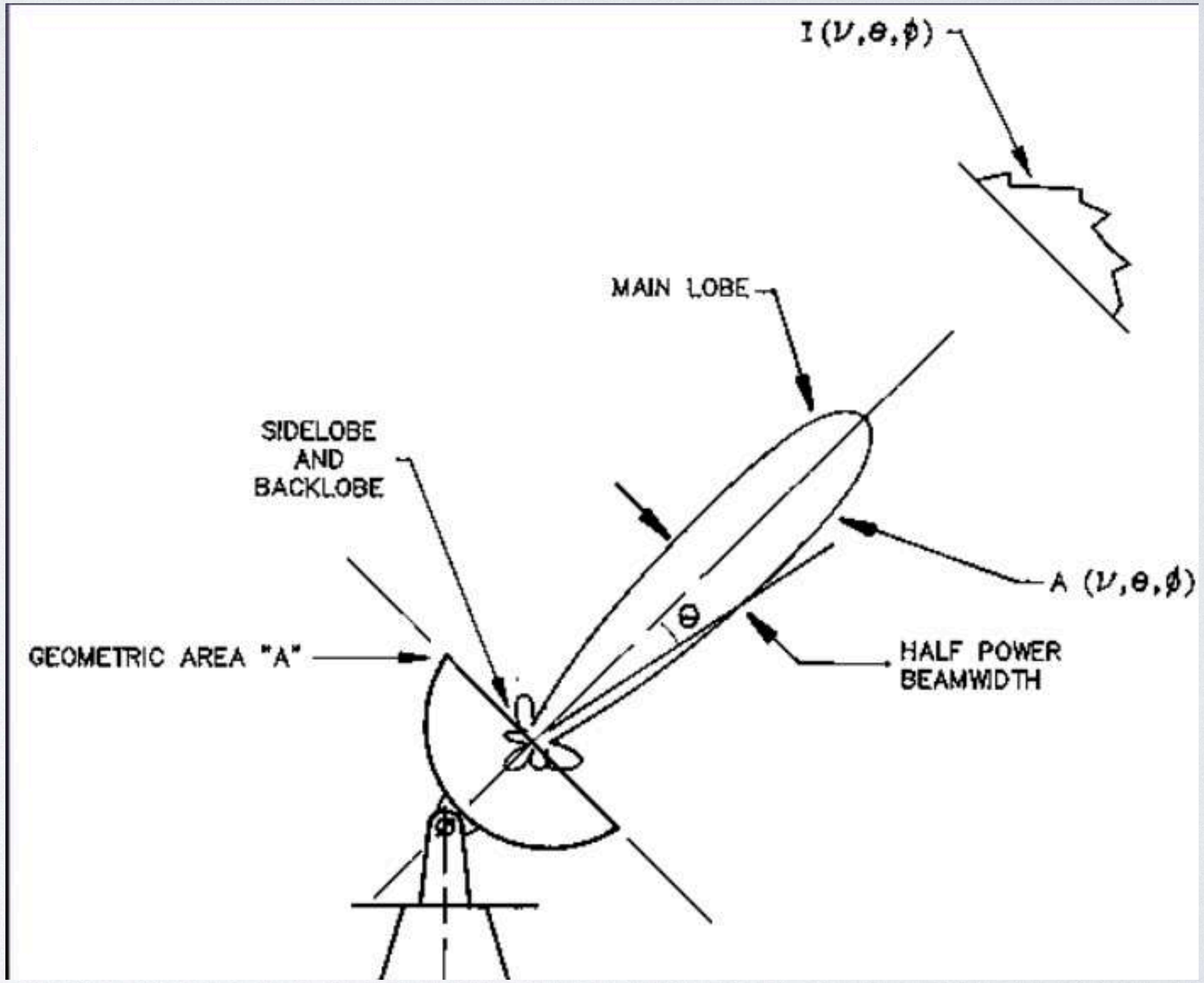


Kraus, J.D. (1966)

DIFFRACTION PATTERN

How does the diffraction pattern of the antenna look?





NRAO

ANTENNA PATTERN - CALCULATION

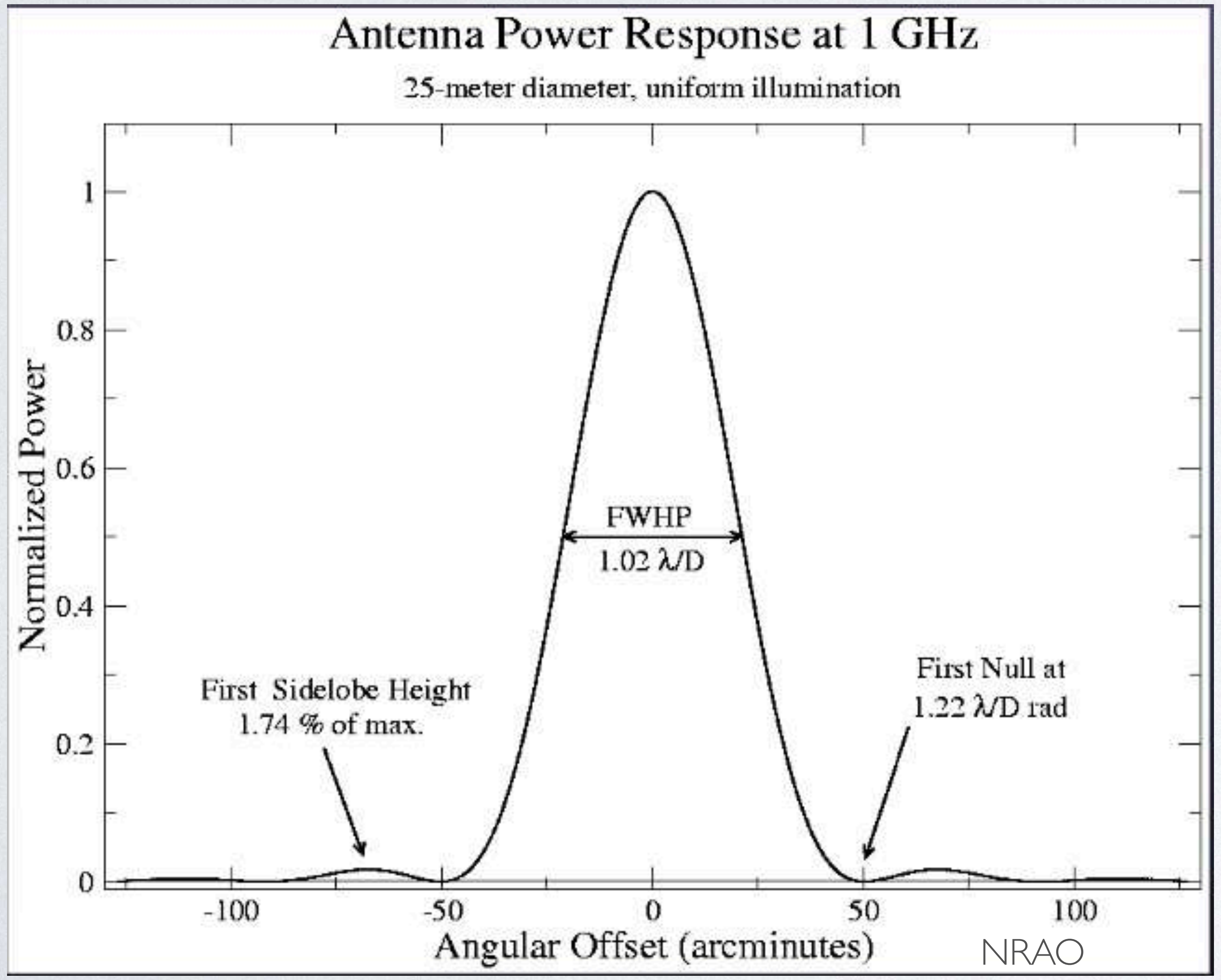
—> Hankel transformation of the illumination function g(r).

$$P_n(u) = \left(\frac{\int_0^\infty g(r) J_0(2\pi u r) r dr}{\int_0^\infty g(r) r dr} \right)^2$$

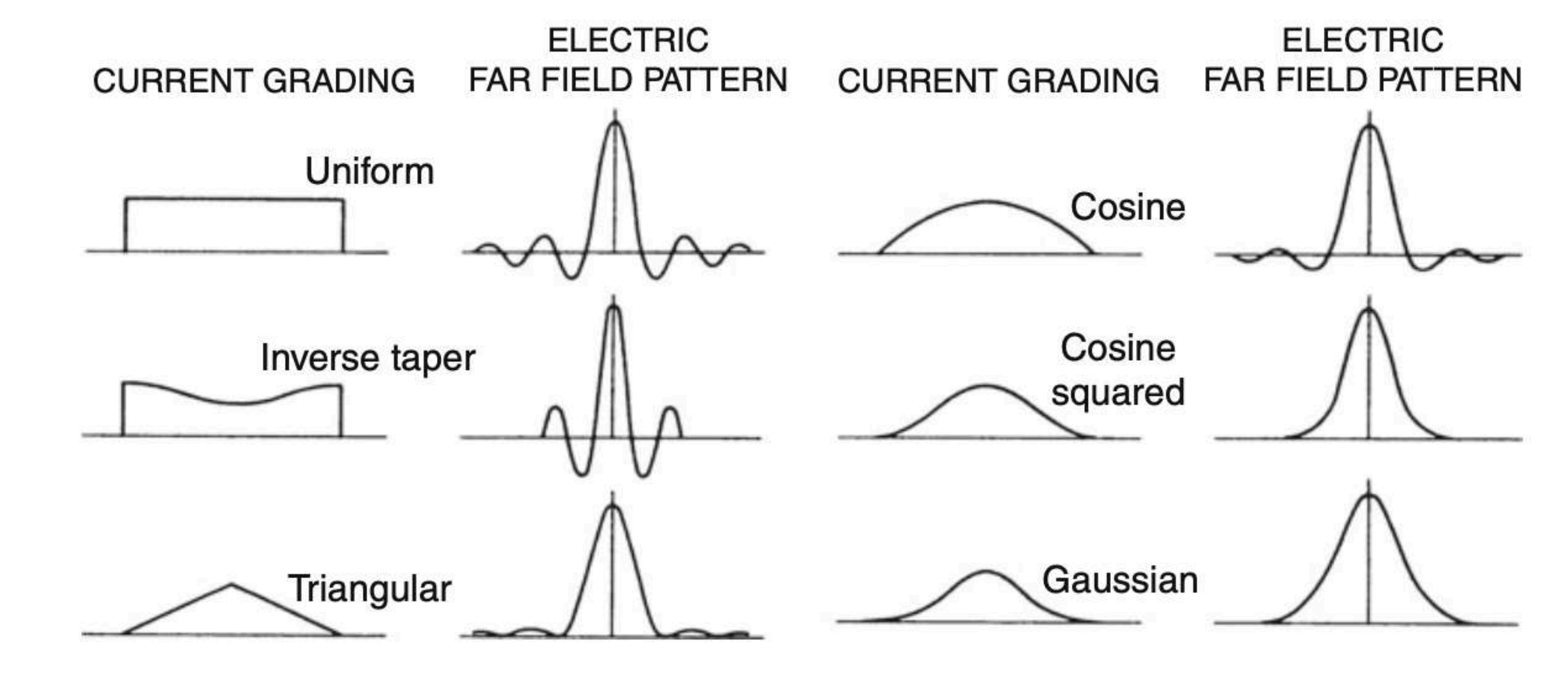
normalized power pattern

Note: Only in the far-field!

Far-field distance: $\frac{2D^2}{\lambda}$



NRAO



Wilson, Rohlfs, Hüttemeister, 2013

MORE COMPLEX CASES

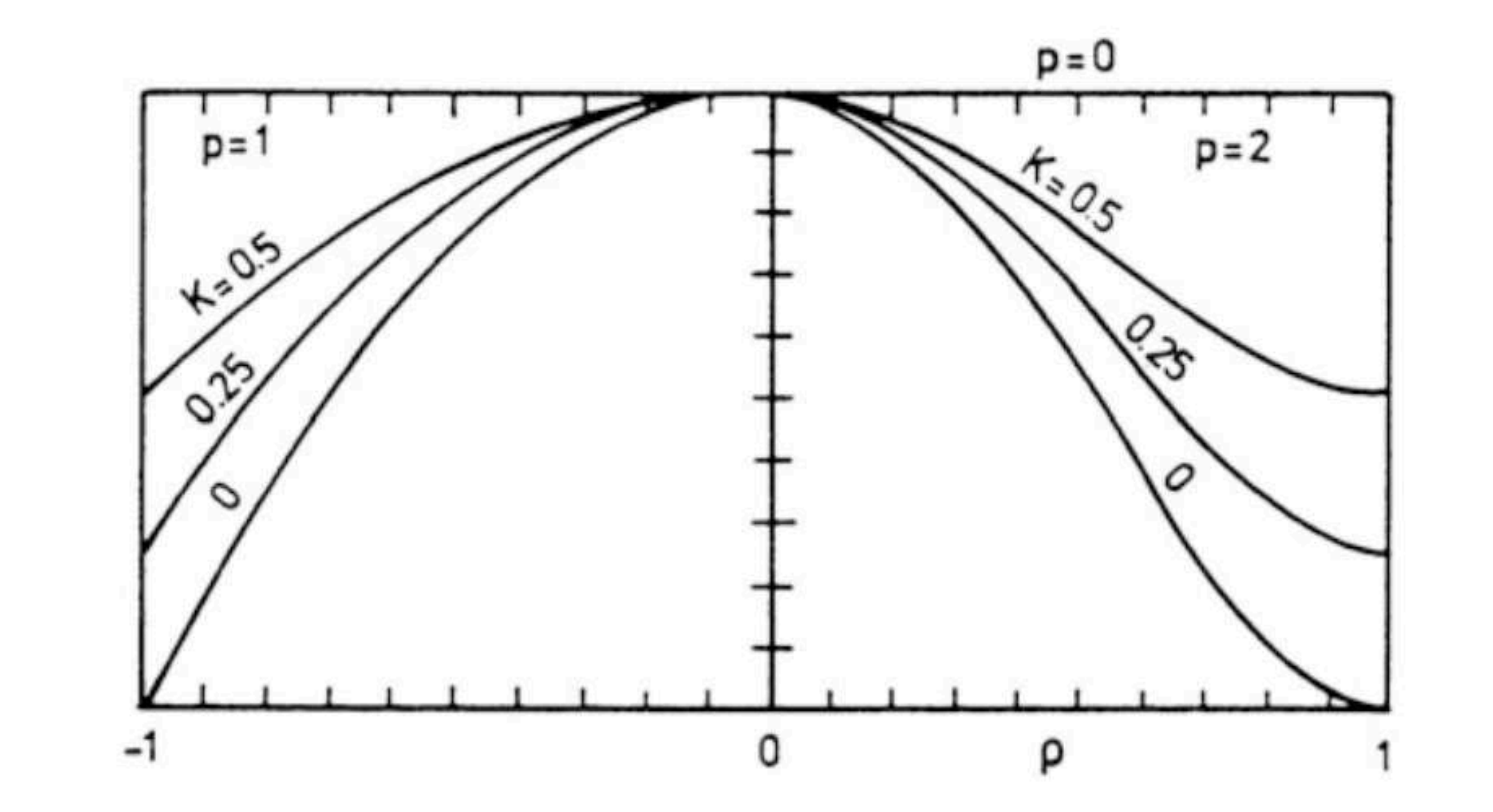
Tapered illumination:

$$g(r) = \left(1 - r^2\right)^2 + K$$

$$P_n(u) = \left(\frac{2^{p+1} p! J_{p+1}(\pi u D/\lambda)}{(\pi u D/\lambda)^{p+1}} \right)^2$$

Stronger taper —> broader beam, weaker sidelobes

More complicated with blocked apertures, support legs, etc.



p	K	FWHP (rad)	BWFN (rad)	Relative gain	First side lobe (dB)
0		1.02	2.44	1.00	−17.6
1		1.27	3.26	0.75	−24.6
2		1.47	4.06	0.56	−30.6
1	0.25	1.17	2.98	0.87	−23.7
2	0.25	1.23	3.36	0.81	−32.3
1	0.50	1.13	2.66	0.92	−22.0
2	0.50	1.16	3.02	0.88	−26.5

Wilson, Rohlfs, Hüttemeister, 2013

BEAM PATTERN

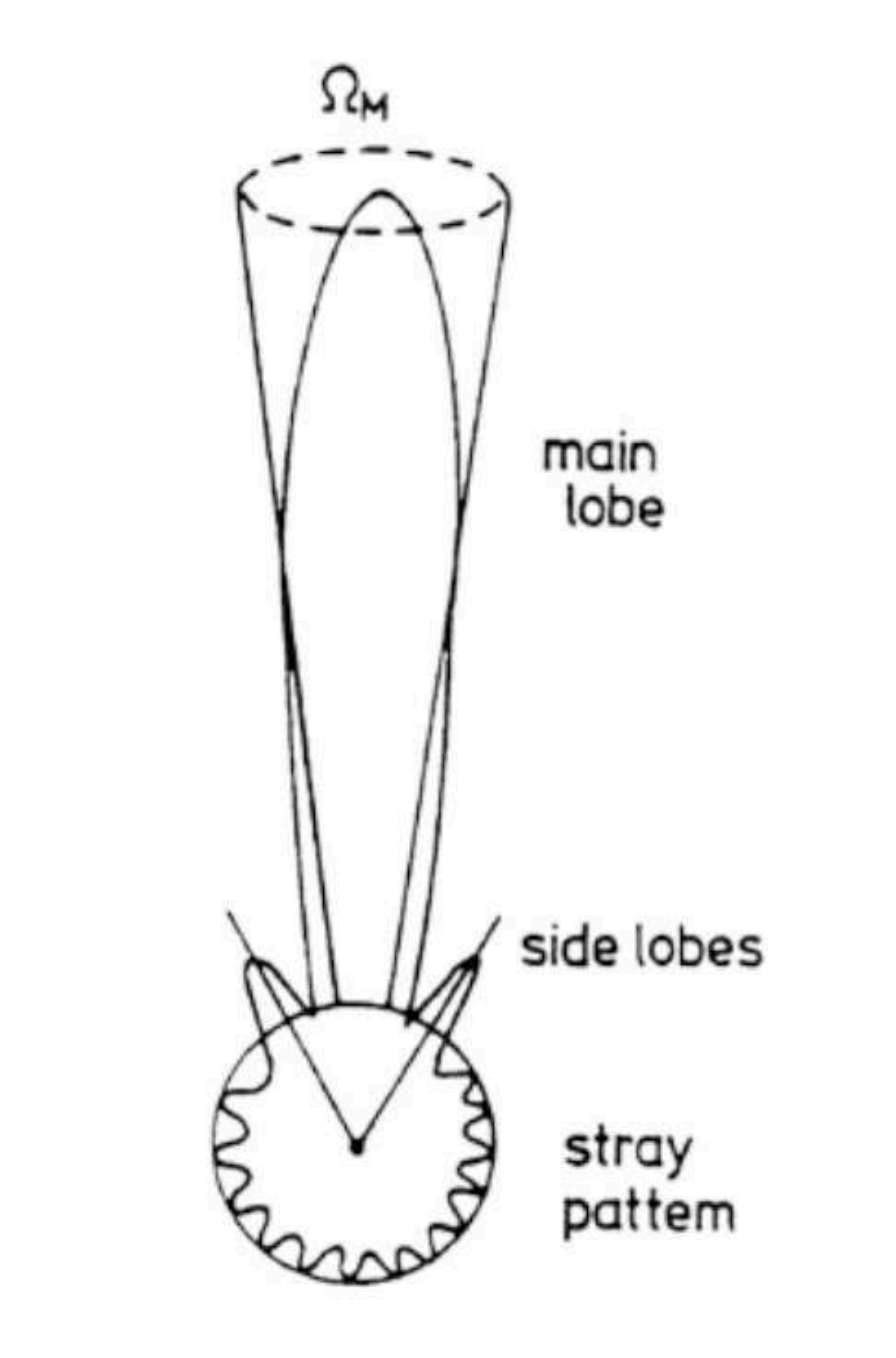
Definitions:

(Full) beam solid angle: $$\Omega_A = \iint_{4\pi} P_n(\theta, \phi) d\Omega$$

$$= \int_0^{2\pi} \int_0^{\pi} P_n(\theta, \phi) \sin\theta d\theta d\phi$$

Main beam solid angle: $$\Omega_{\rm MB} = \iint_{\rm MB} P_n(\theta, \phi) d\Omega$$

Main beam efficiency: $$\eta_{\rm MB} = \frac{\Omega_{\rm MB}}{\Omega_{\rm A}}$$



Wilson, Rohlfs, Hüttemeister, 2013

OBSERVED PATTERN

$$P_{\text{rec}} = \frac{1}{2} \cdot A_{\text{eff}} \cdot d\nu \int_{4\pi} I_\nu(\theta, \phi) P_n(\theta - \theta', \phi - \phi')\, d\Omega$$

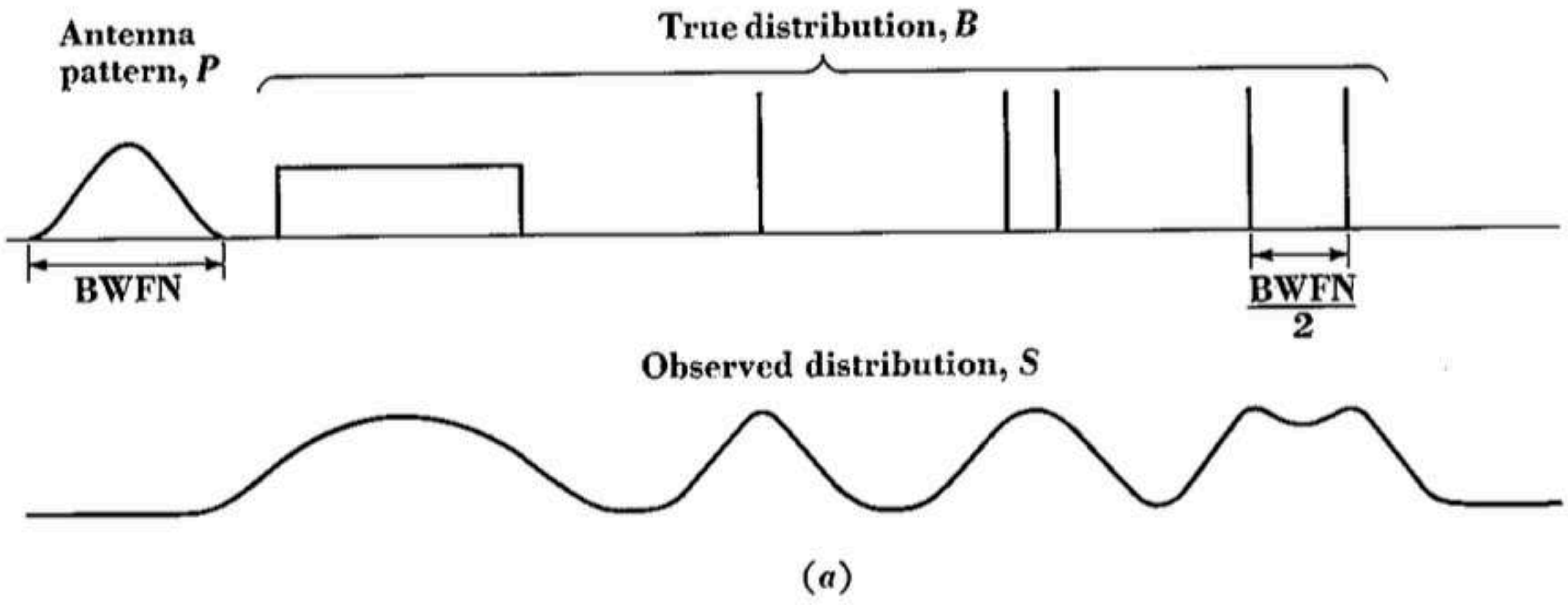
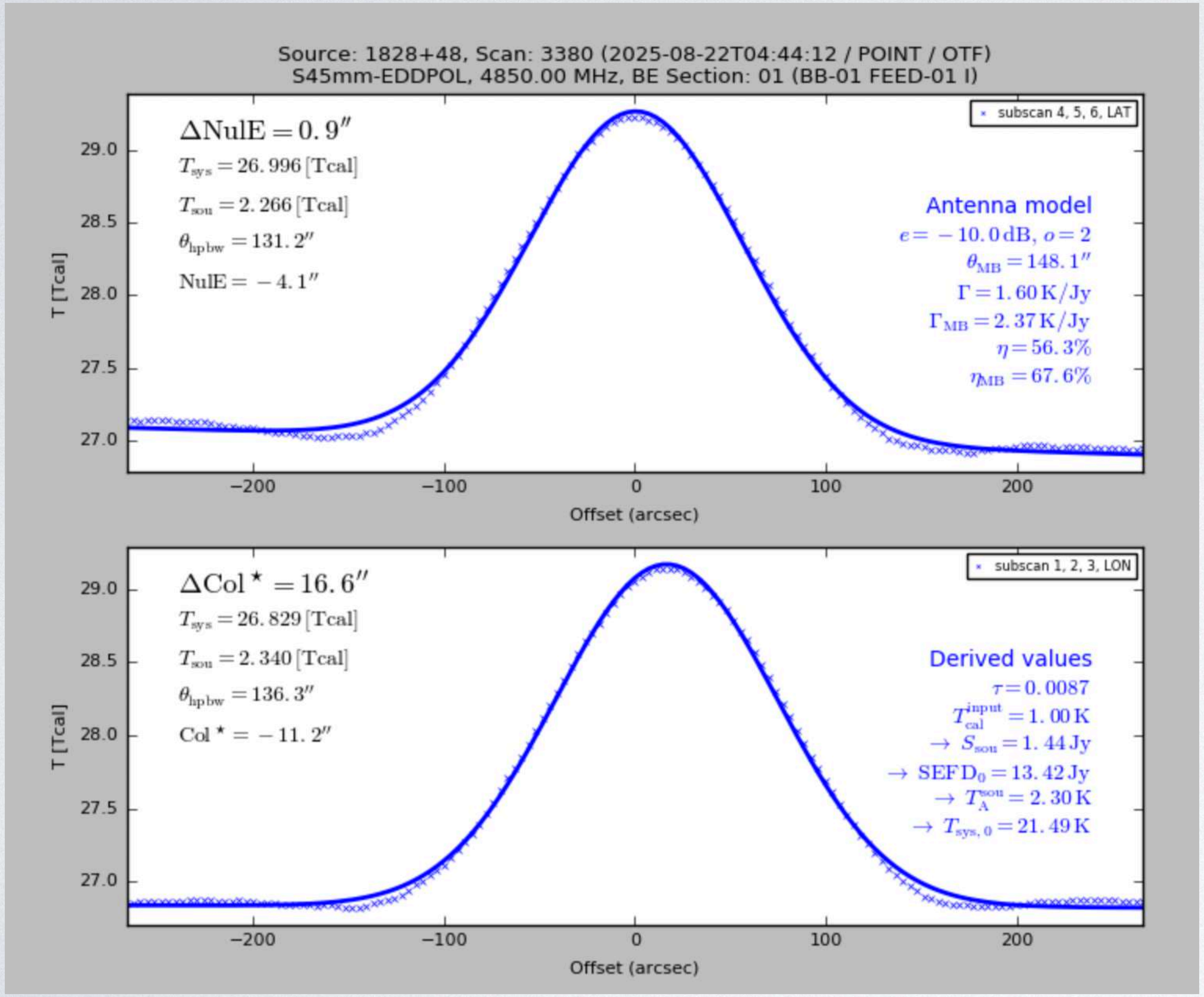
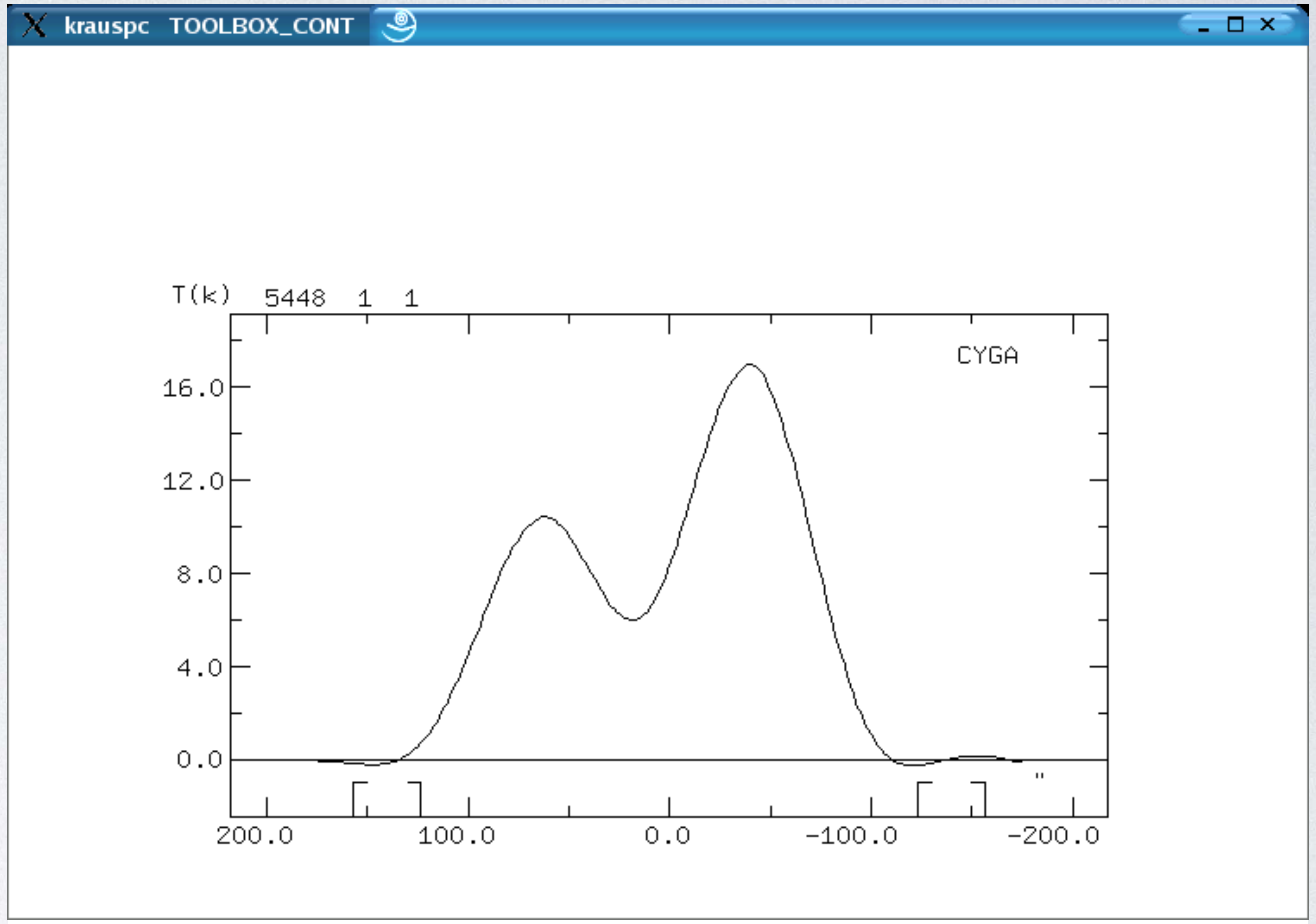


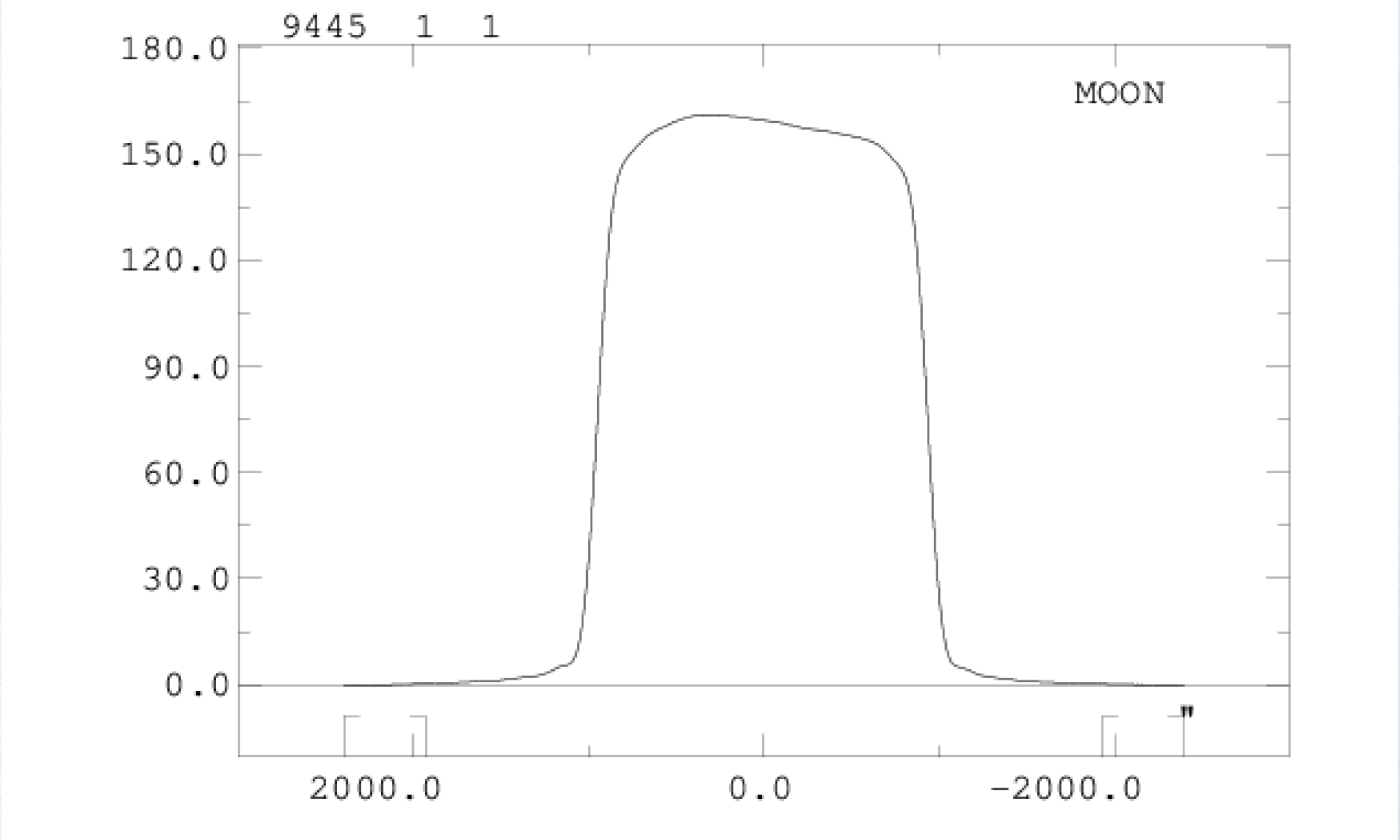
Fig. 6-11a. Smoothed distribution S observed with antenna pattern P.

Kraus, J.D., 1966

POINT-LIKE AND EXTENDED SOURCES







CONCEPT OF ANTENNA TEMPERATURE

For convenience, radio astronomers often consider the ,,noise temperature“ which corresponds to the power received:

$$\mathrm{P = k\,T\,\Delta}\nu \qquad \text{Johnson-Nyquist theorem (1928)}$$

$$P_{\mathrm{rec}} = \frac{1}{2} \cdot A_{\mathrm{eff}} \cdot d\nu \int_{4\pi} I_\nu(\theta, \phi) P_n(\theta - \theta', \phi - \phi')\, d\Omega$$

and therefore, we have

$$T_{\mathrm{A}} = \frac{A_{\mathrm{eff}}}{2k} \int_{4\pi} I_\nu(\theta, \phi) P_n(\theta - \theta', \phi - \phi')\, d\Omega$$

Max-Planck-Institut für Radioastronomie

EFFECTIVE APERTURE

$$A_{\rm eff} = \eta_A \cdot A_{\rm geom}$$

$$A_{\rm geom} = \frac{\pi}{4} D^2$$

η_A : aperture efficieny

Spectral power (i.e. per bandwidth) received by an antenna:

$$P_\nu = \frac{1}{2} A_{\rm eff} \cdot S_\nu = k \cdot T_A$$

Therefore, we have (outside the atmosphere):

$$\frac{T'_A}{S} = \frac{A_{\rm eff}}{2k} = \eta_A \frac{A_{\rm geom}}{2k} = \eta_A \frac{\pi D^2}{8k} =: \Gamma$$

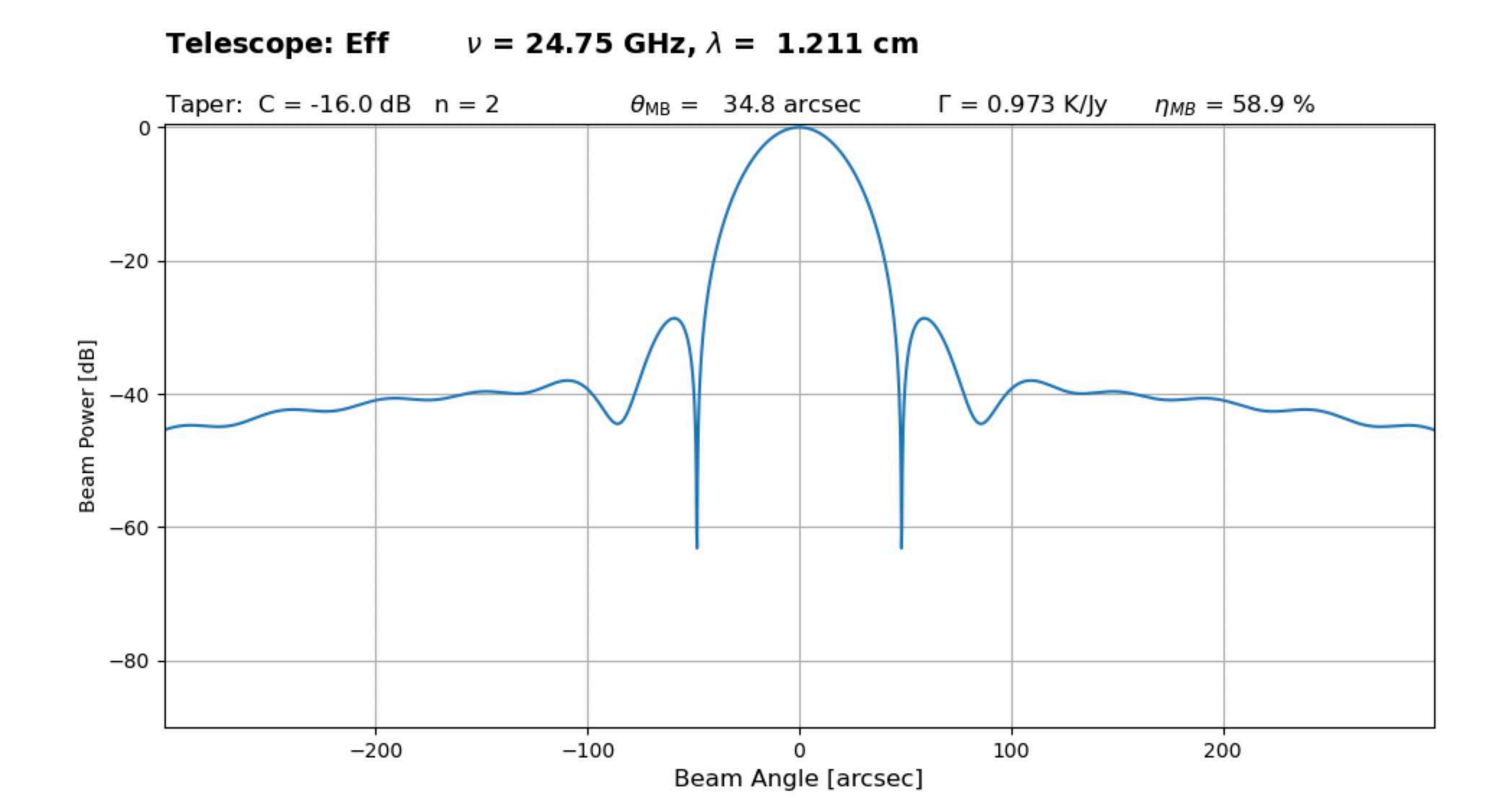
sensitivity of the antenna (in K/Jy)

The sensitivity describes how efficient the antenna „process" the incoming radiation.

ANTENNA EFFICIENCY

The aperture efficiency is a product of various efficiencies describing different losses:

$$\Gamma = \frac{\pi D^2}{8k} \cdot \eta_A = \frac{\pi D^2}{8k} \cdot \eta_{\text{surface}} \cdot \eta_{\text{block}} \cdot \eta_{\text{taper}} \cdot \eta_{\text{spill}} \cdots$$



Calibration means to determine the aperture efficiency.

Example:
Effelsberg @ 24.75 GHz

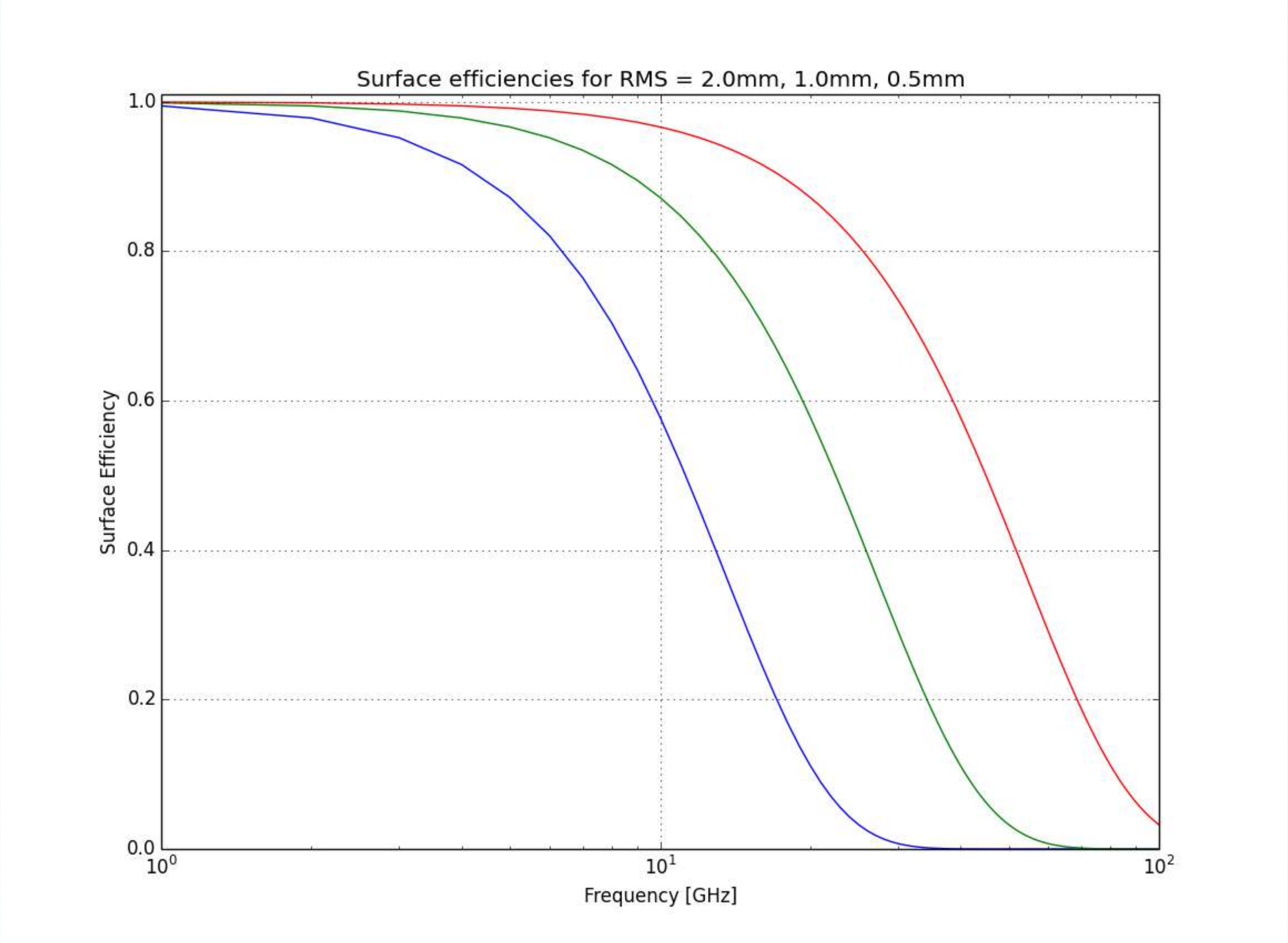
```
Efficiencies:
Tapering efficiency   = 59.20 %
Blocking efficiency   = 69.57 %
Surface efficiency    = 84.07 %
Spillover efficiency  = 99.26 %
Radiation efficiency  = 99.50 %
-----
Total efficiency      = 34.19 %
-----
Sensitivity = 34.19 % * 2.8442 K/Jy
            = 0.9725 K/Jy
-----
effective Aperture    = 2685.5 m^2
Antenna Gain          = 83.6 dB
```

EFFICIENCIES

Surface efficiency with surface RMS σ:

$$\eta_{\text{surface}} = \exp\left(-\left(\frac{4\pi\sigma}{\lambda}\right)^2\right)$$ Ruze 1966

$\sigma \simeq \lambda/16$ —> $\eta_{\text{surface}} \simeq 0.54$

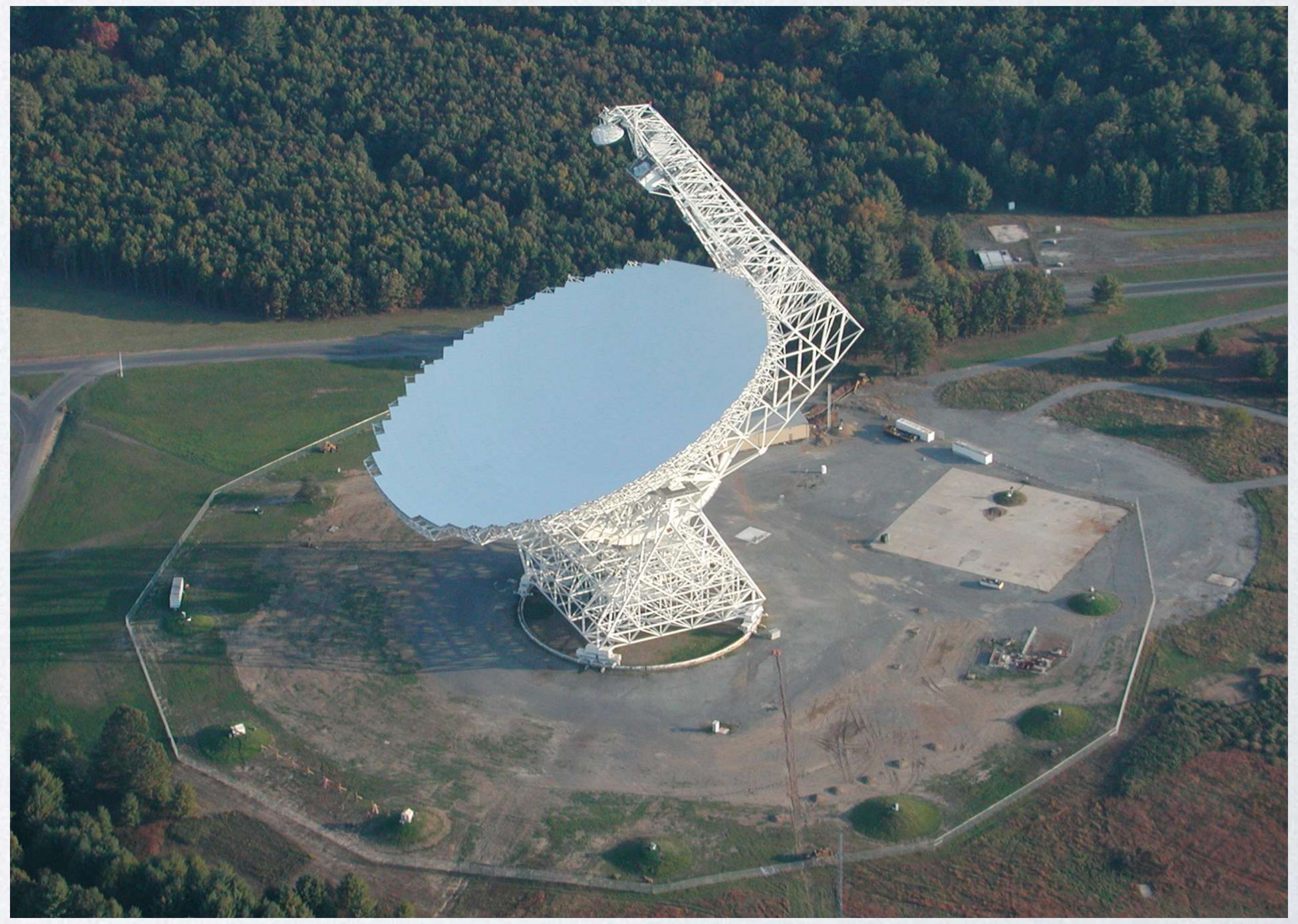


Blocking efficiency:

$\eta_{\text{bl}} = (1 - A_{\text{bl}}/A_{\text{tot}})^2$

Effelsberg 100m: $\eta_{\text{bl}} \sim 0.7$

GBT 100m: $\eta_{\text{bl}} \sim 1.0$



NOISE

Each observation has to deal with various noise components,
which increase the total system noise (aka „system temperature")

$$T_{\rm sys} = T_{\rm CMB} + T_{\rm gal} + T_{\rm atm} + T_{\rm spill} + T_{\rm rec} + T_{\rm cal} + \ldots$$

atmospheric noise:

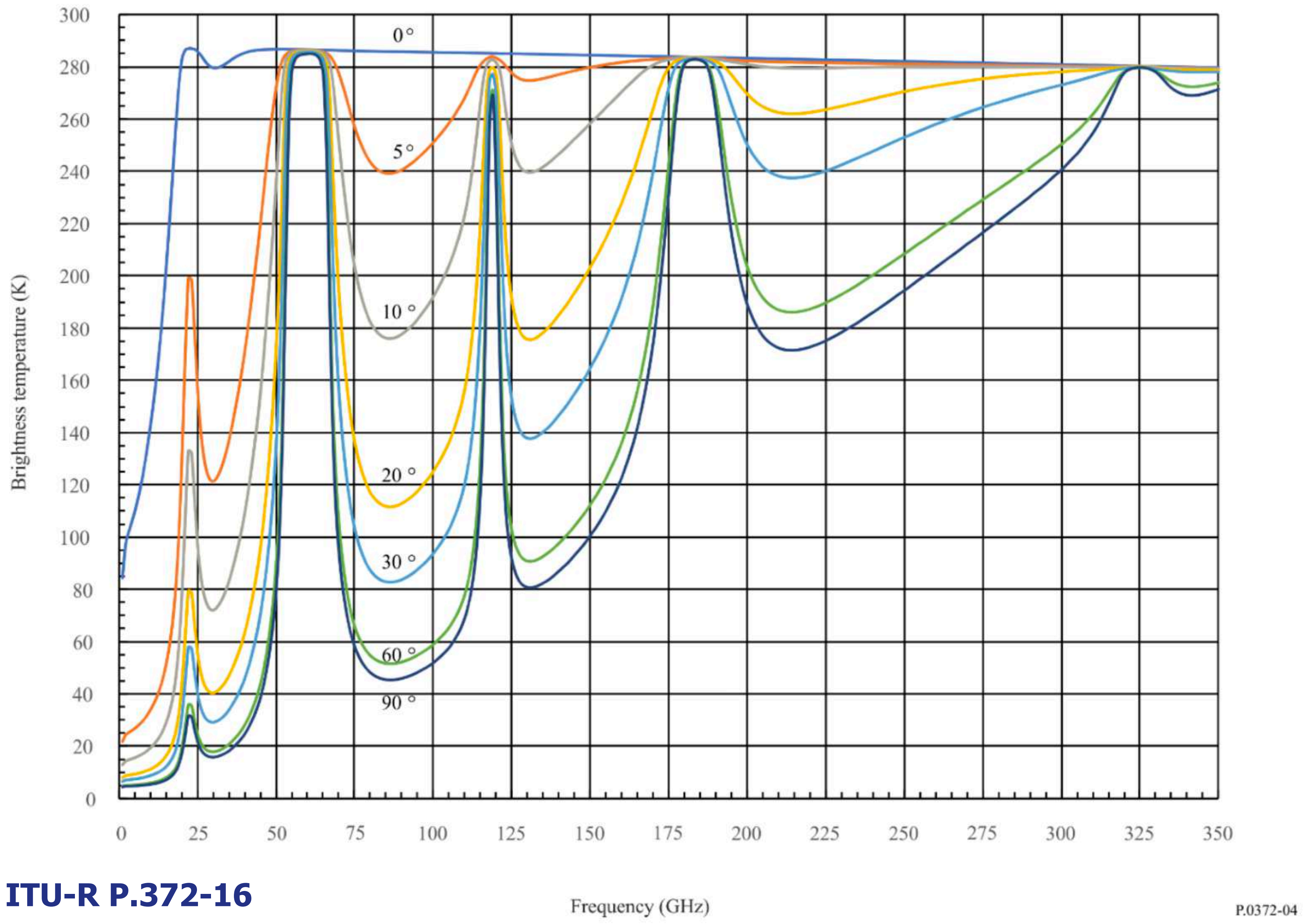
$$T_{\rm sky}(\nu) = T_{\rm Atm}(\nu) \cdot \left(1 - e^{\tau(\nu)/\sin({\rm elv})}\right)$$

$$\simeq T_{\rm Atm}\tau/\sin({\rm elv}) = T_{\rm Atm}\tau \,{\rm Airmass}$$

depends e.g. on the water vapor concentration,
i.e. weather, height above sea level, …

FIGURE 4

Brightness temperature (clear air) for 7.5 g/m³ water vapour concentration (surface temperature and pressure equal to 15°C and 1 023 mb); θ is the elevation angle



ITU-R P.372-16

RADIOMETER EQUATION

Gives the minimal reachable noise!

Gaussian Noise: error of N samples is $1/\sqrt{N}$, hence $T_{\text{sys}}/\sqrt{N}$

For bandwidth $\Delta\nu$, the number of samples is $\Delta\nu \cdot \tau$ with the integration time τ

Therefore: $$\Delta T = \frac{T_{\text{sys}}}{\sqrt{\Delta\nu\tau}}$$

Example: $T_{\text{sys}} = 20\,\text{K}, \Delta\nu = 100\,\text{MHz}, \tau = 1\,\text{s}$ => $\Delta T = 2 \cdot 10^{-3}\,\text{K}$

In reality, that value is higher, due to
receiver instabilities (gain variations), weather instabilities, etc.

EXAMPLE

Max-Planck-Institut für Radioastronomie

Assume we observe Mars ($T_B = 200\,K$)
with a 100-m telescope (Effelsberg) and a 5-m dish

$\phi = 4.1$ arcsec (currently) $\rightarrow \Omega = 3.1 \cdot 10^{-10} sr$ $\qquad \Omega \simeq \frac{\pi}{4}\phi^2$

Let's go for $\nu = 4.85\,\mathrm{GHz}$ —> $I = 1.44 \cdot 10^{-18} \frac{\mathrm{W}}{\mathrm{m^2 Hz sr}}$ $\qquad I_\nu = \frac{2\mathrm{k}\nu^2}{\mathrm{c}^2} \cdot T_B$

Therefore, $S = 0.045\,\mathrm{Jy}$

EB: $A_{\mathrm{eff}} = 0.6 \cdot 7854\,\mathrm{m}^2 = 4712\,\mathrm{m}^2$ $\qquad$ 5m-dish: $A_{\mathrm{eff}} = 0.8 \cdot 19.6\,\mathrm{m}^2 = 15.7\,\mathrm{m}^2$

With $T_A = \frac{A_{\mathrm{eff}}}{2k} \cdot S$, we get $T_A^{100\mathrm{m}} = 0.077\,\mathrm{K}$, $\quad T_A^{5\mathrm{m}} = 2.55 \cdot 10^{-4}\,\mathrm{K}$

—> Size matters!

EXAMPLE

How much observing time do we need?

We have $T_A^{100\mathrm{m}} = 0.077\,\mathrm{K}, \quad T_A^{5\mathrm{m}} = 2.55 \cdot 10^{-4}\,\mathrm{K}$

From the radiometer equation, we get $\tau = \frac{1}{\Delta\nu}\left(\frac{T_{\mathrm{sys}}}{\Delta T}\right)^2$

Assume $T_{\mathrm{sys}} = 20\,\mathrm{K}$, $\Delta\nu = 100\,\mathrm{MHz}$, $\Delta T = T_A/3$ (3-sigma detection):

$$\Rightarrow \tau^{100\mathrm{m}} = 0.006\,s, \quad \tau^{5\mathrm{m}} = 554\,s$$

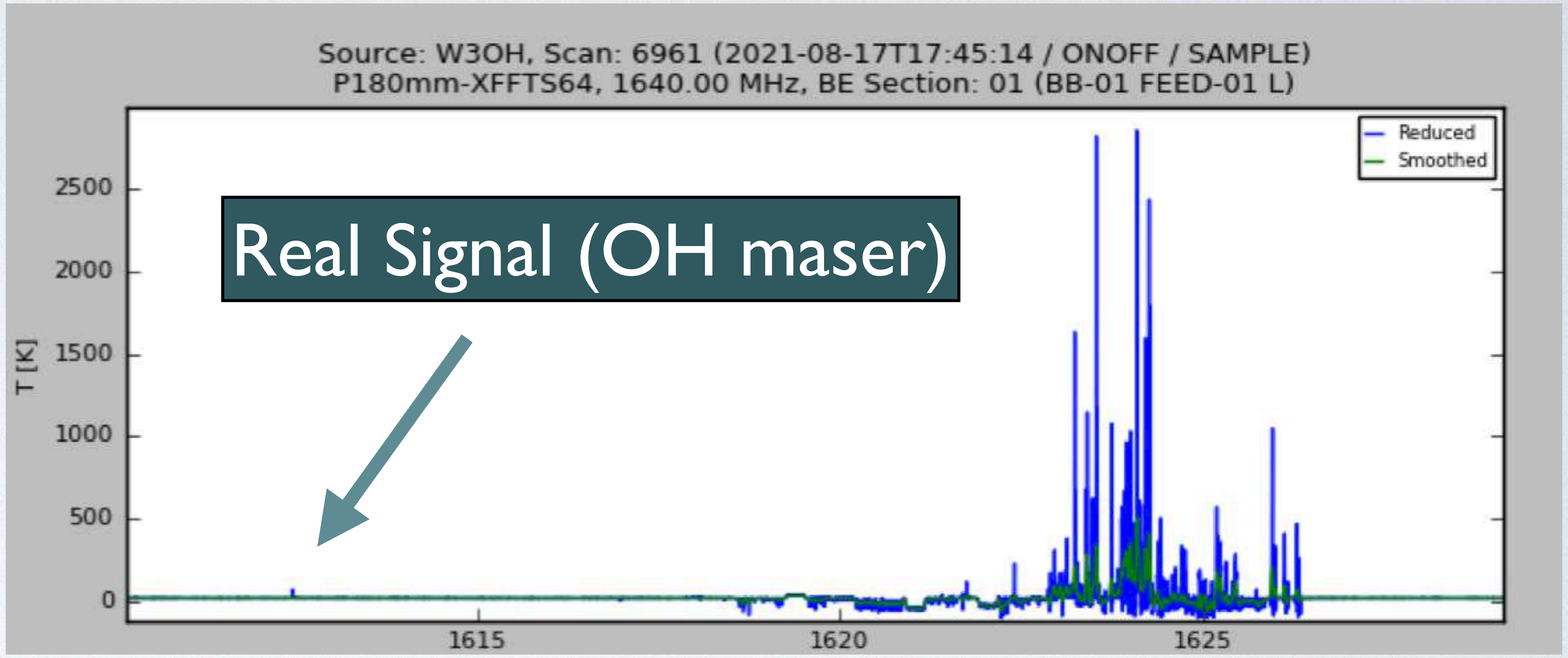
INTERFERENCE

Problem: Radio astronomy is a passive service that must receive and process extremely weak signals!
Man-made radio waves are many times more powerful than natural ones!

Typical strength of a radio astronomical signal:

1 Jy = 10^{-26} W m^{-2} Hz^{-1}

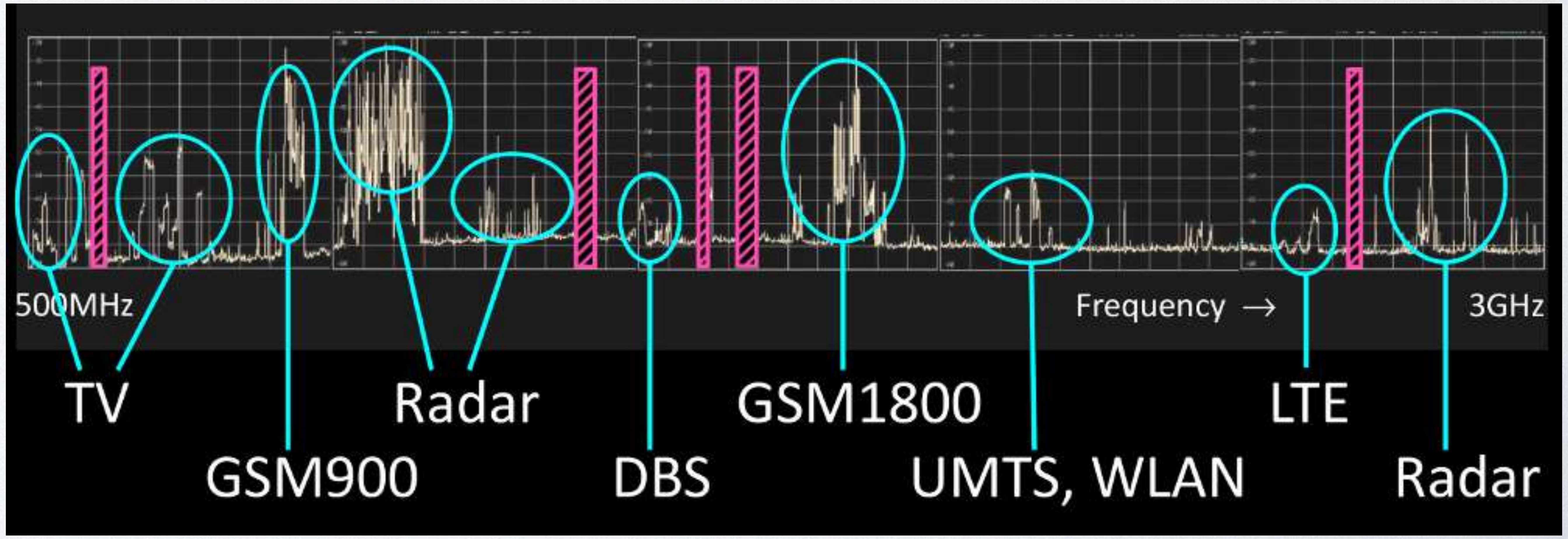
— corresponds to a 1 W transmitter at a distance of approximately 9 million km.



Less than 2% of the total spectrum
(below 50 GHz) is protected for radio astronomy.

Countermeasures:

* Mitigation
* Regulation / Coordination
* Avoid / suppress own sources of interference



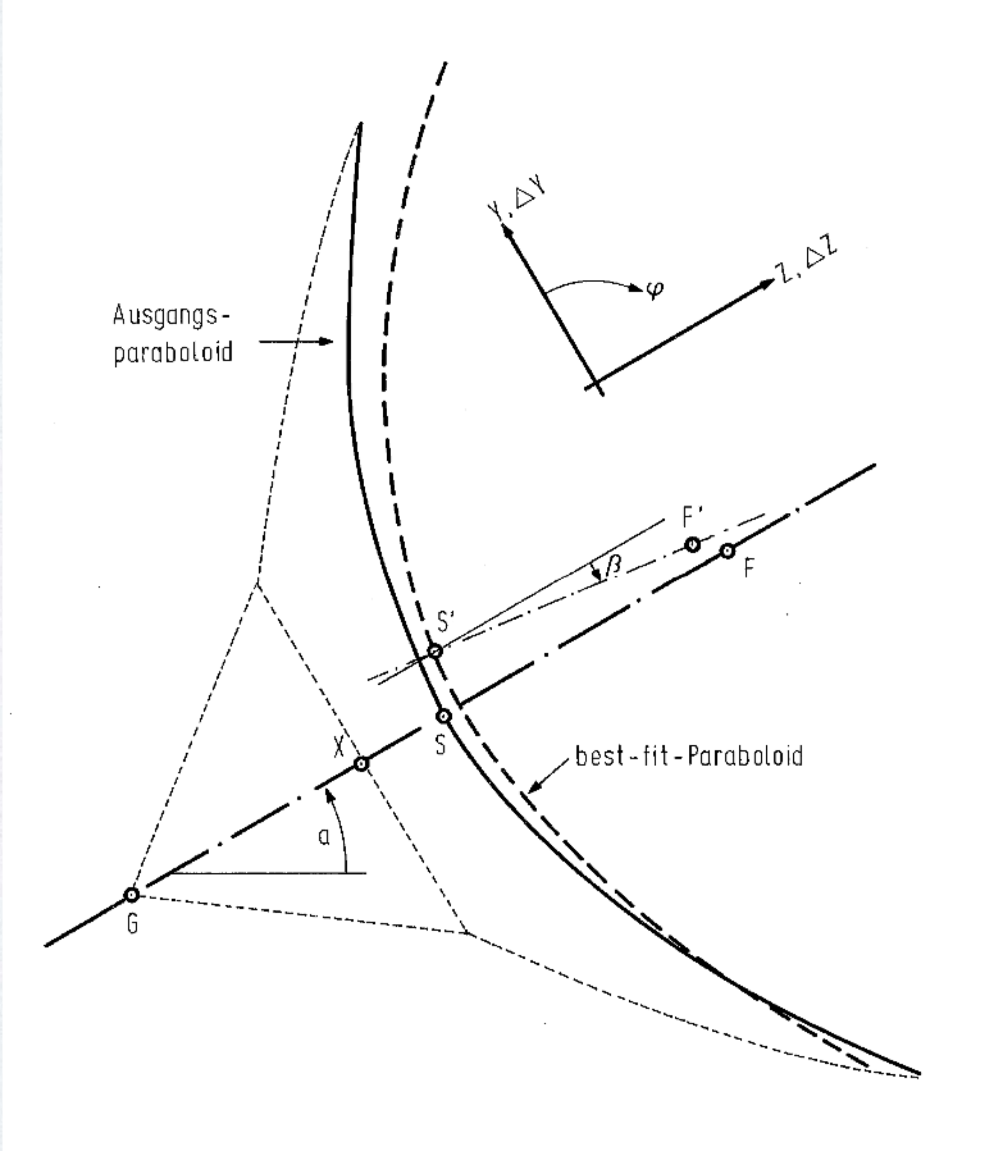
ADDITIONAL CONSIDERATIONS

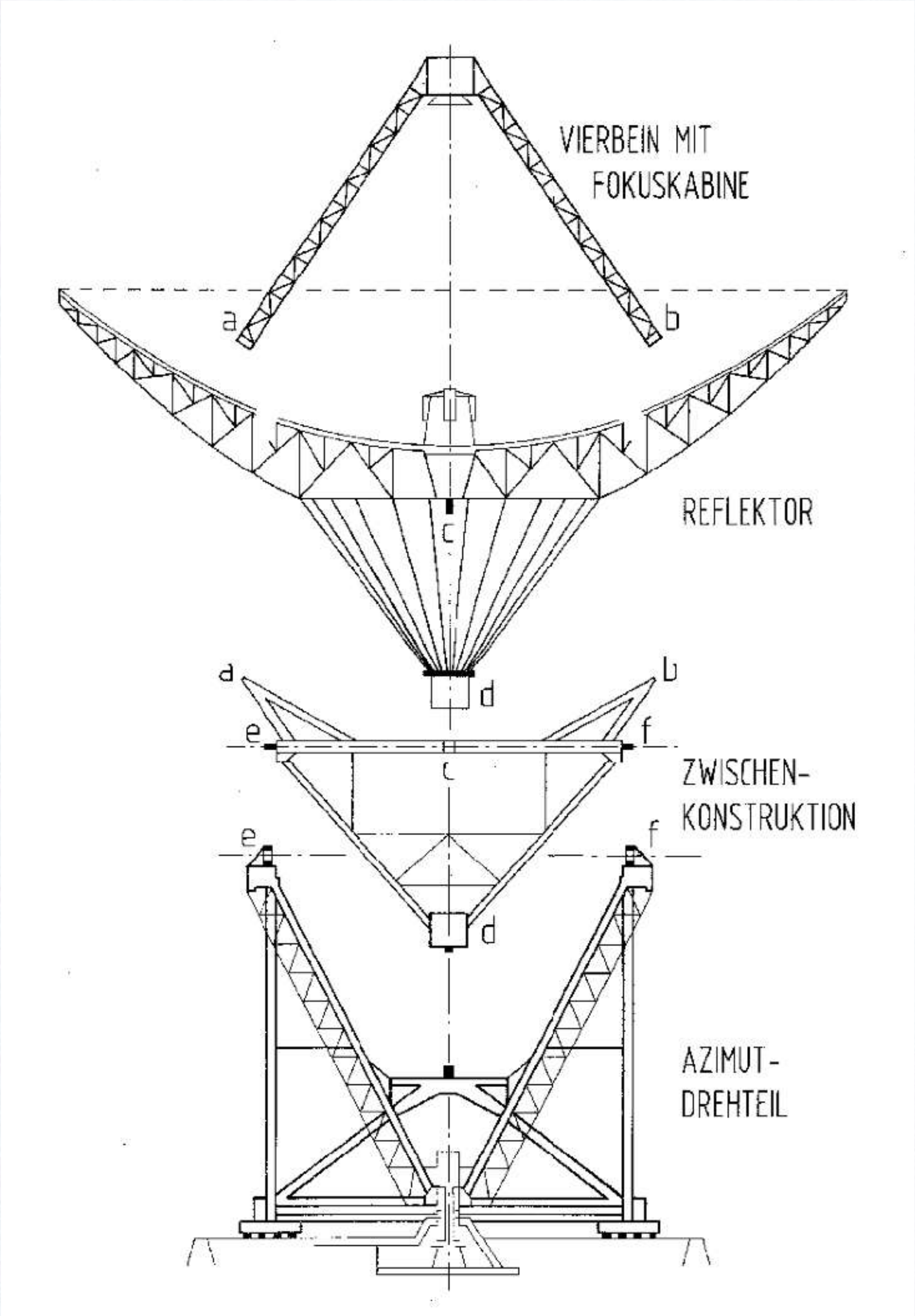
Max-Planck-Institut für Radioastronomie

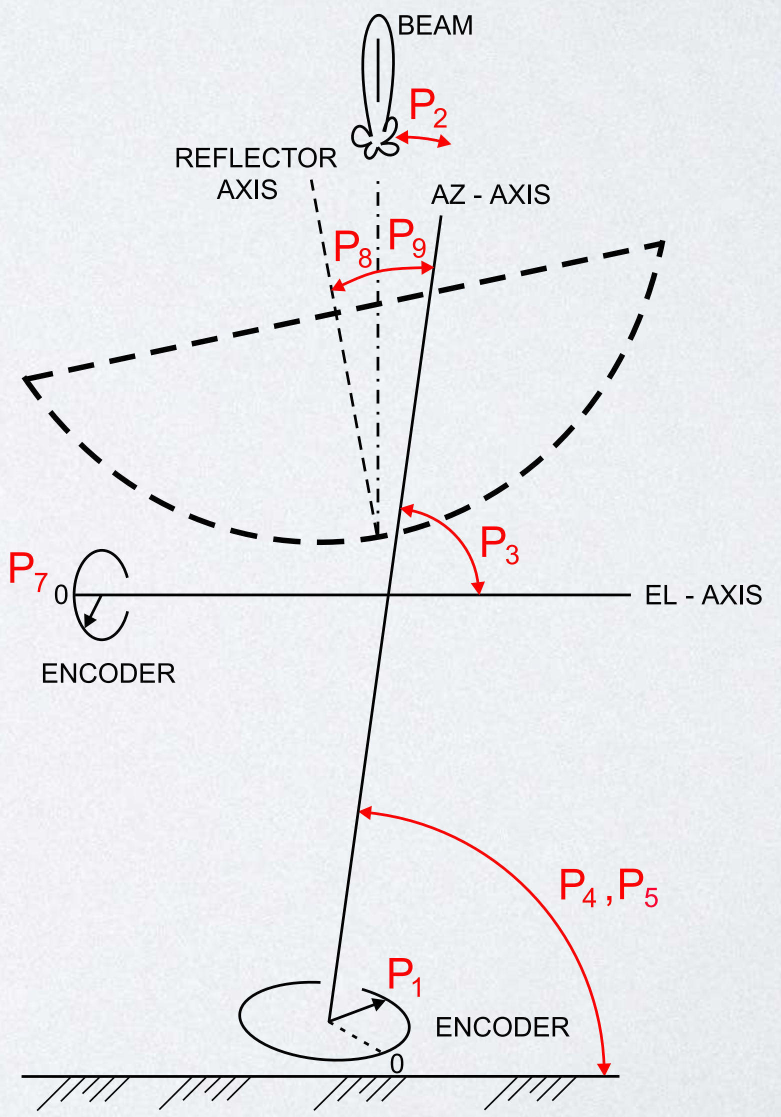
* Telescope site: RFI Situation, Horizon
* Surface accuracy: Homology, active surface
* Telescope drives: positioning accuracy
* Pointing and focus
* Costs?

The Pointing Model used at the 100m Telescope

$\Delta Az \cdot \cos El$	$= (P_1 + NULA) \cos El$	Encoder offset / Zero-shift
	$+ (HYSA \cdot \epsilon) \cos El$	Hysteresis – ϵ: sign of velocity
	$+ ((230° - Az) \cdot 10''/360°) \cos El$	influence of cable twist
	$+ (P_2 + COL * + RXAZ)$	Collimation (electrical axis vs. elevation axis)
	$+ P_3 \cdot \sin El$	Collimation of axes (vertical vs. horizontal)
	$+ P_4 \cdot \cos Az \cdot \sin El$	Inclination 1: towards west
	$+ P_5 \cdot \sin Az \cdot \sin El$	Inclination 2: towards north
	$+ P_6 \cdot \sin Az$	Errors in position
ΔEl	$= (P_7 + NULE + RXEL)$	Encoder offset / Zero-shift
	$+ (FC_1 \cdot BDF \cdot 6''.875)$	Focus 1 („Radiale“) – $6''.875 = 1\,\mathrm{mm}/30\,\mathrm{m}$
	$+ (HYSE \cdot \epsilon)$	Hysteresis – ϵ: sign of velocity
	$+ (FC_3 \cdot 0.005833)$	Focus 3 („Kippung“) – only for SF
	$+ (El - \arcsin(\cos RXAZ \cdot \sin El))$	high elevation correction – only for SF
	$- P_4 \cdot \sin Az$	Inclination 1: towards west
	$+ P_5 \cdot \cos Az$	Inclination 2: towards north
	$+ P_6 \cdot \cos Az \cdot \sin El$	Errors in position
	$+ P_8 \cdot \cos El$	Bending
	$+ P_9 \cdot \sin El$	Sinusoidal correction in Elv ("BHG-term")
	$+ R \cdot \cot El$	Refraction correction
	$+ R_3 \cdot \cot^3 El$	third order term in refraction





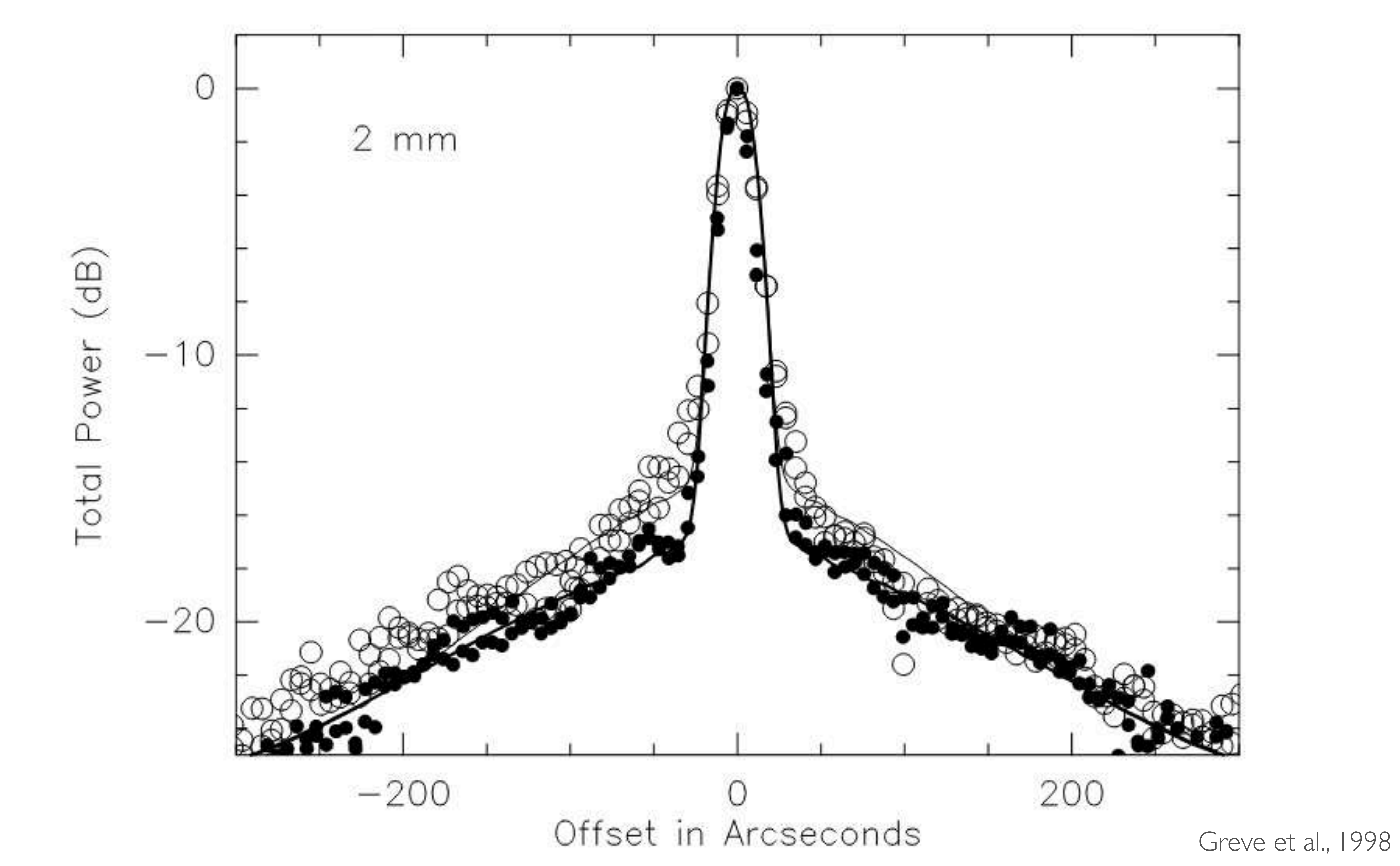


ALT - AZIMUTH TELESCOPE

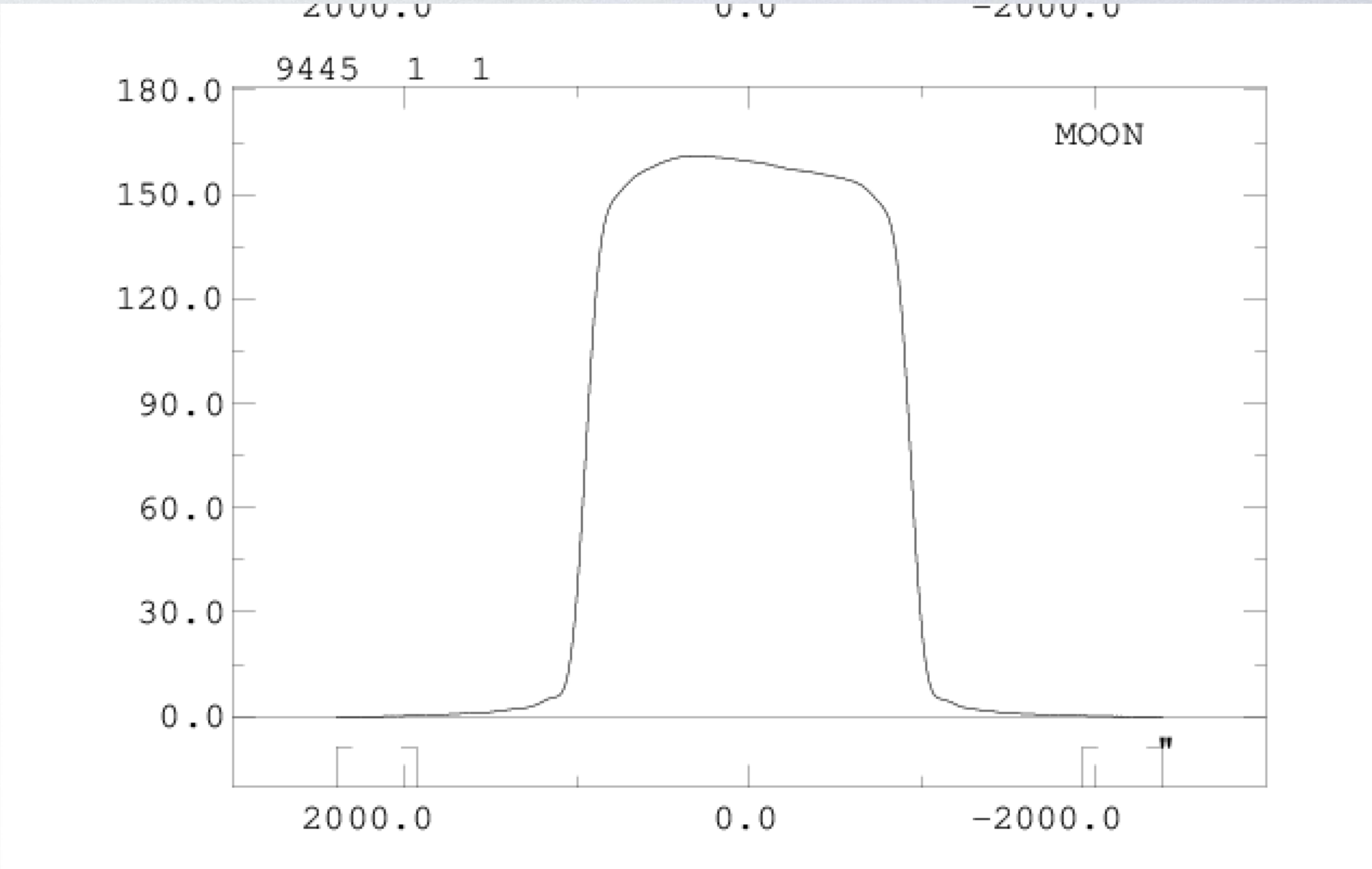
MOON OBSERVATION

Max-Planck-Institut
für Radioastronomie

Observing the moon allows the determination of the beam pattern (main and „error“ beam)



Greve et al., 1998



* Observe the moon with a cross-scan
* Result is the convolution of the diffraction pattern with the moon brightness distribution (a box profile).
* Differentiate the observed pattern to get the beam —> Why?

Max-Planck-Institut
für Radioastronomie

LITERATURE

- Kraus, John D. - Radio Astronomy
- Wilson, Rohlfs, Hüttermeister - Tools of Radio Astronomy
- Burke & Graham-Smith - An Introduction to Radio Astronomy
- Thompson, Moran, Swenson - Interferometry and Synthesis in Radio Astronomy
- Essential Radio Astronomy (NRAO online course) https://science.nrao.edu/opportunities/courses/era

Just a selection - not complete!!