Radio Astronomy
An Introduction

Felix James "Jay" Lockman
NRAO
Green Bank, WV

References

Thompson, Moran & Swenson
Kraus (1966)
Christiansen & Hogbom (1969)
Condon & Ransom (nrao.edu)
Single Dish School Proceedings (2002) ADS
GOLDSMITH
CAMPBELL
LISZT ★★★★

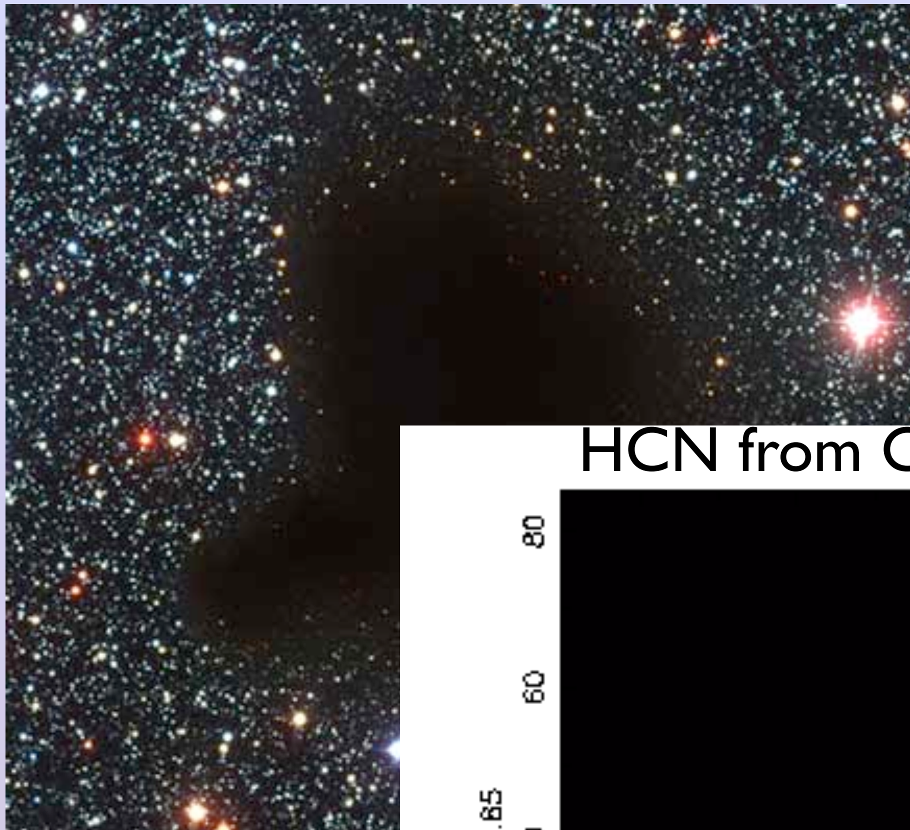
NRAO


Radio telescope

Astronomy at Radio Wavelengths

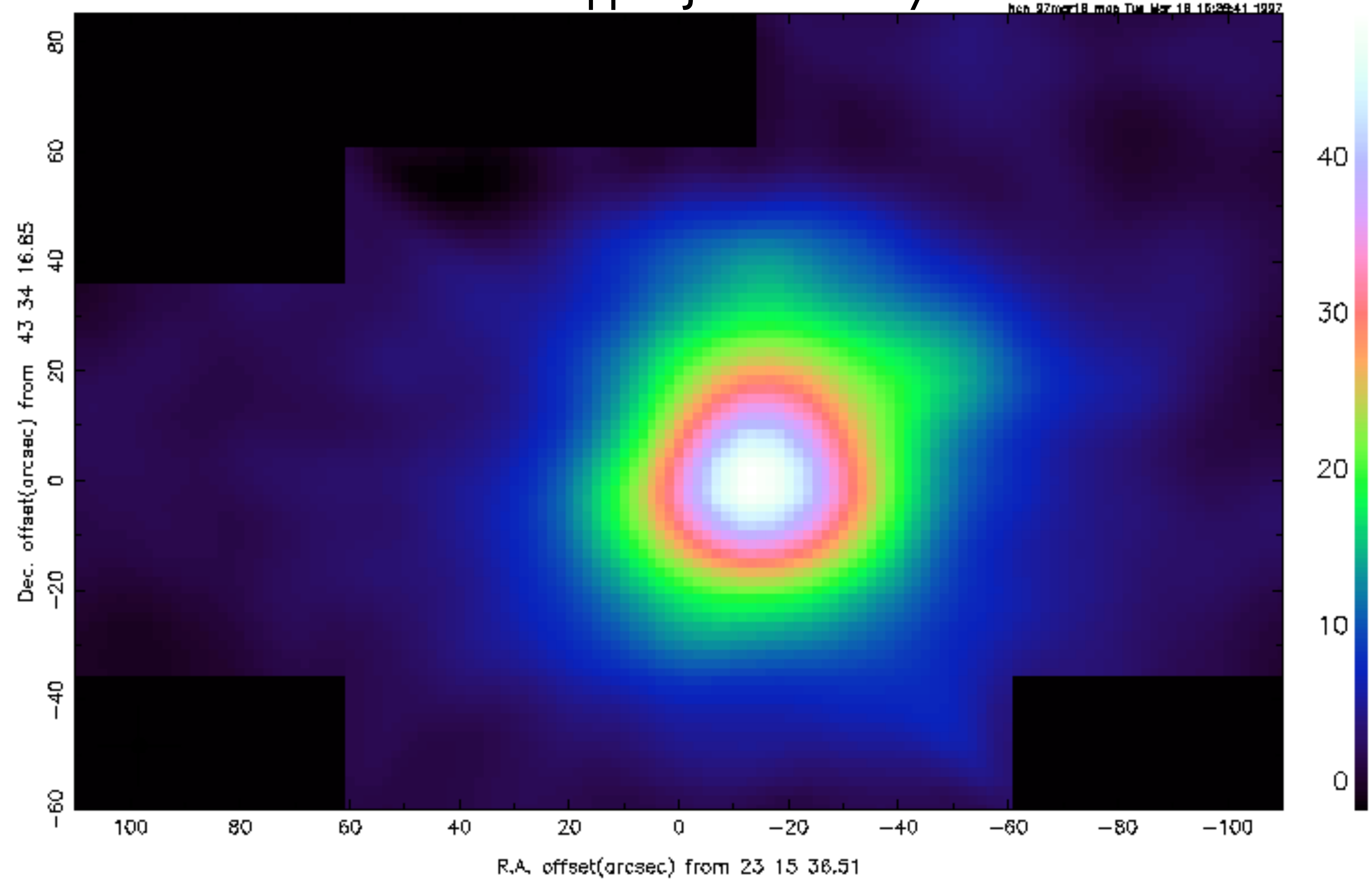
More than 130 interstellar molecules

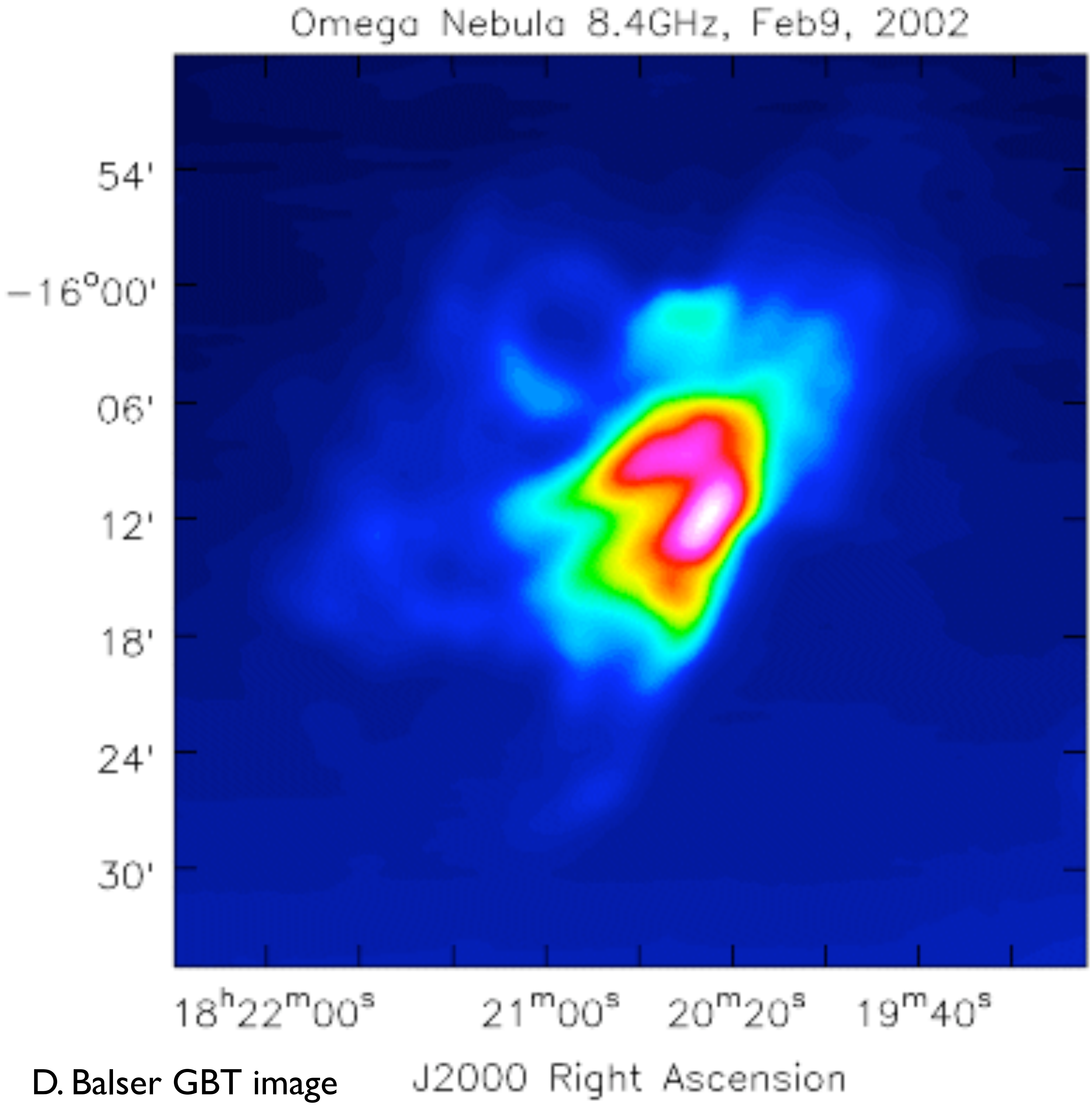
Astronomy at Radio Wavelengths



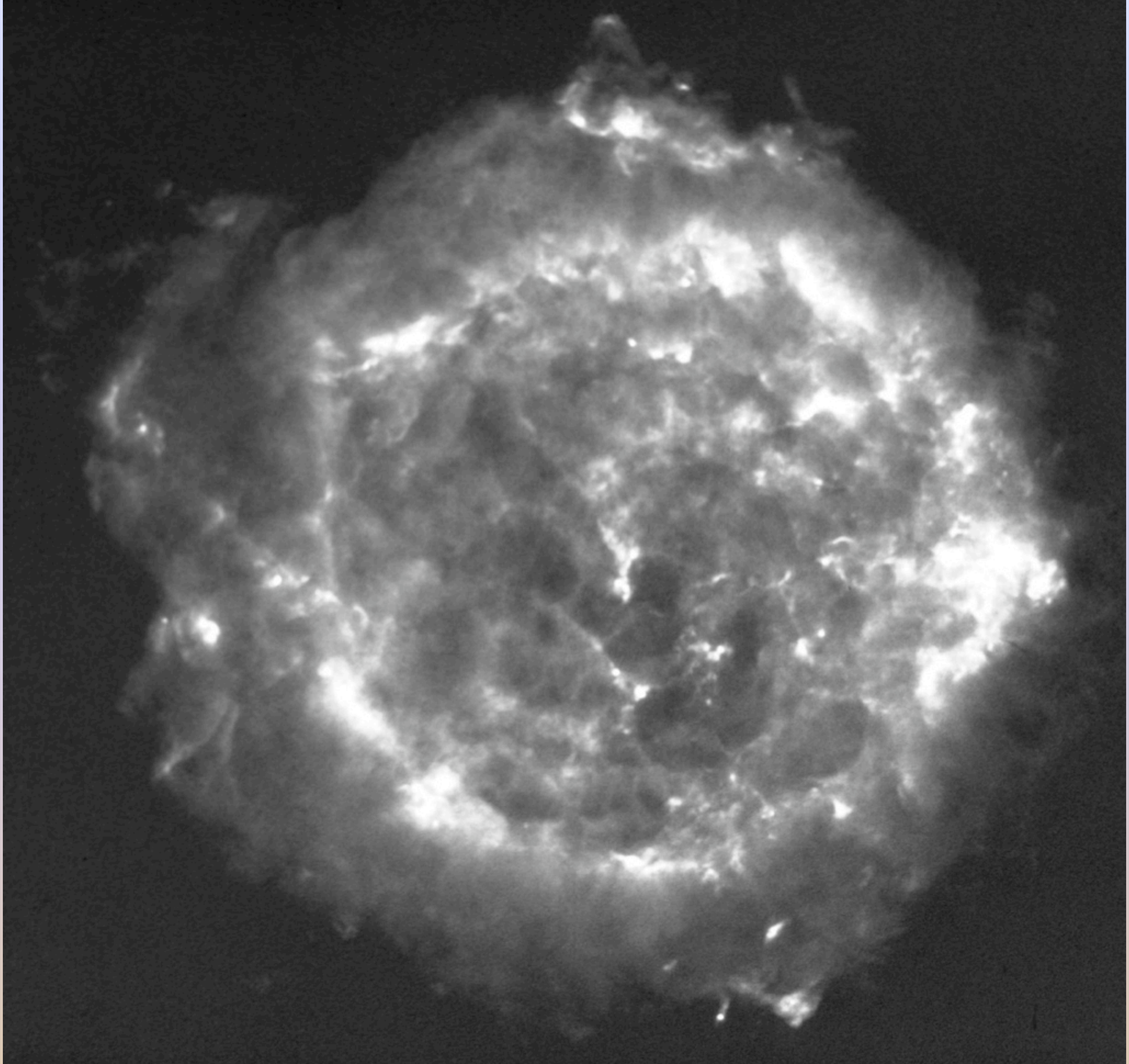
More than 130 interstellar molecules

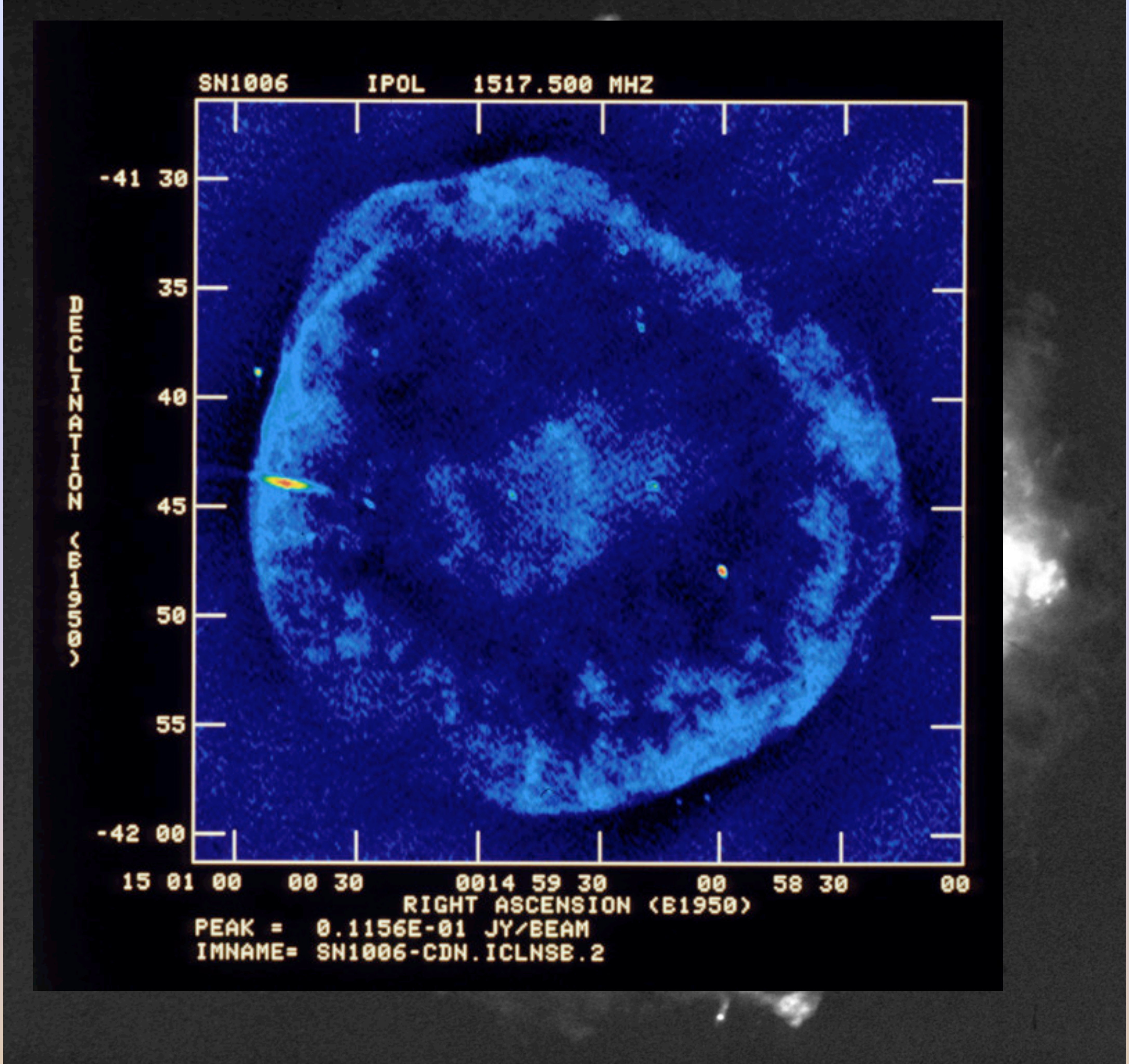
HCN from Comet Hale-Bopp -- Jewit & Saney





D. Balser GBT image




SN1006 IPOL 1517.500 MHZ
DECLINATION (B1950)
-41 30
35
40
45
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-42 00
15 01 00
00 30
0014 59 30
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58 30
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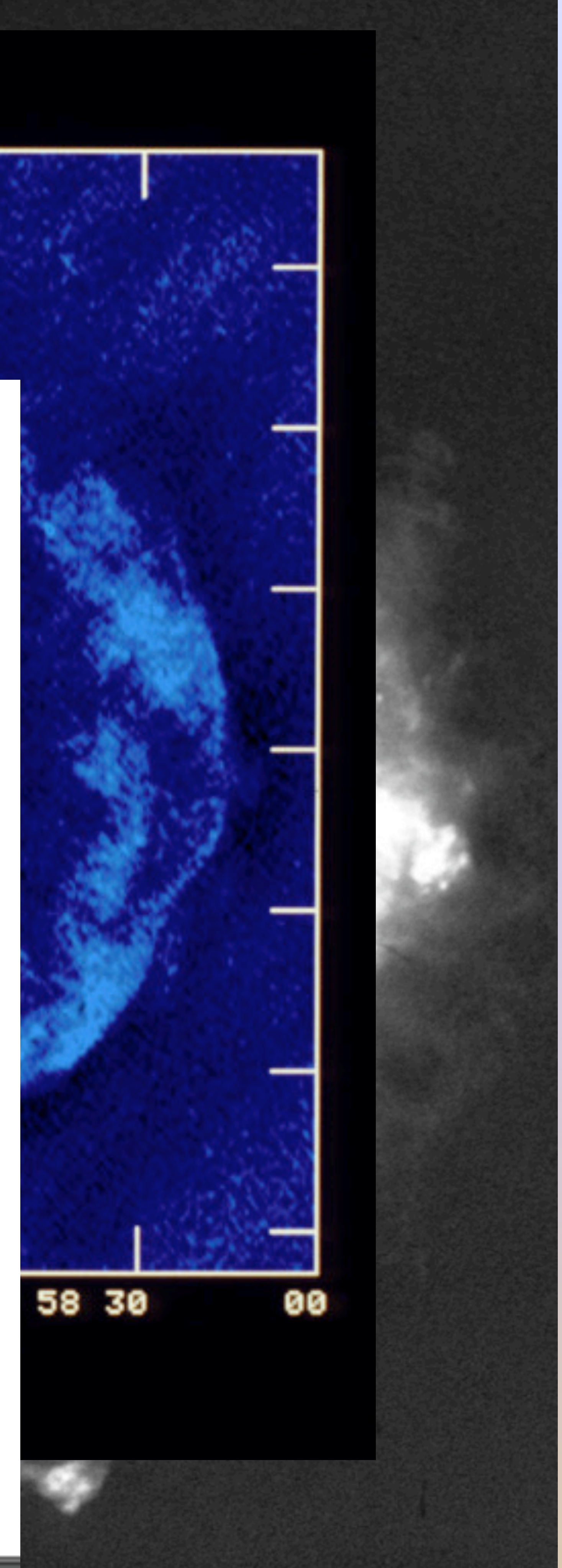
RIGHT ASCENSION (B1950)
PEAK = 0.1156E-01 JY/BEAM
IMNAME= SN1006-CDN.ICLNSB.2



Breton et al (2008)

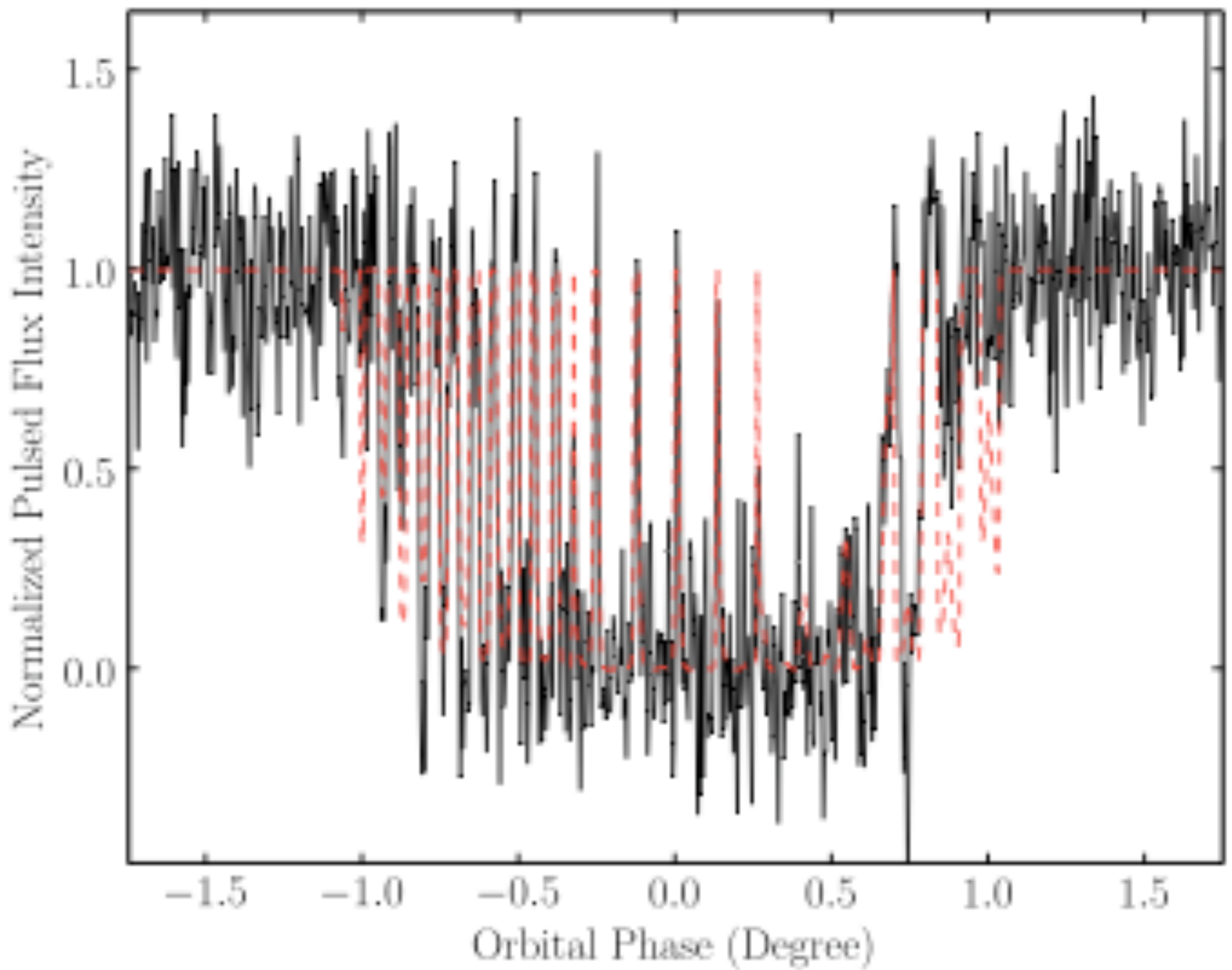
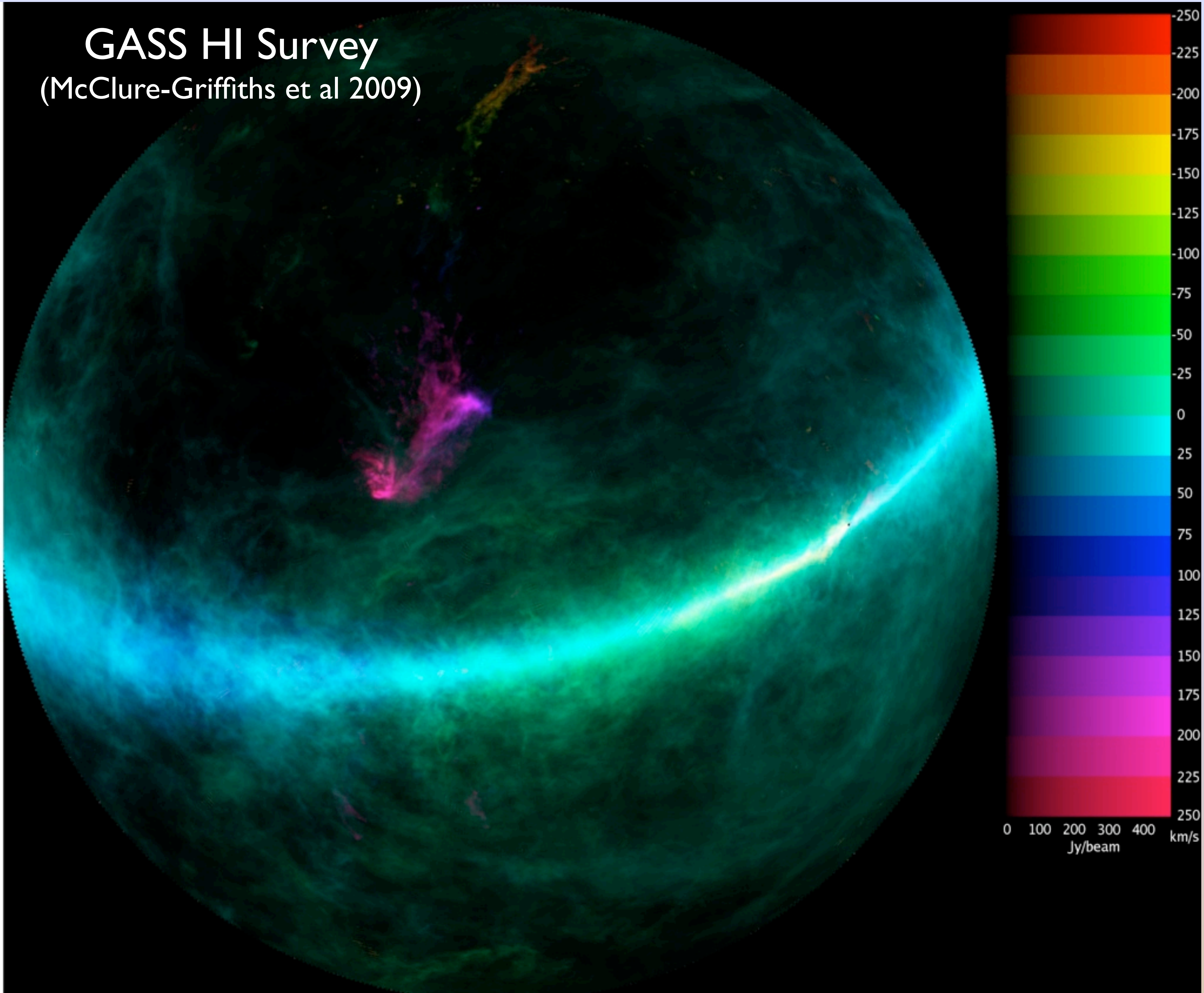


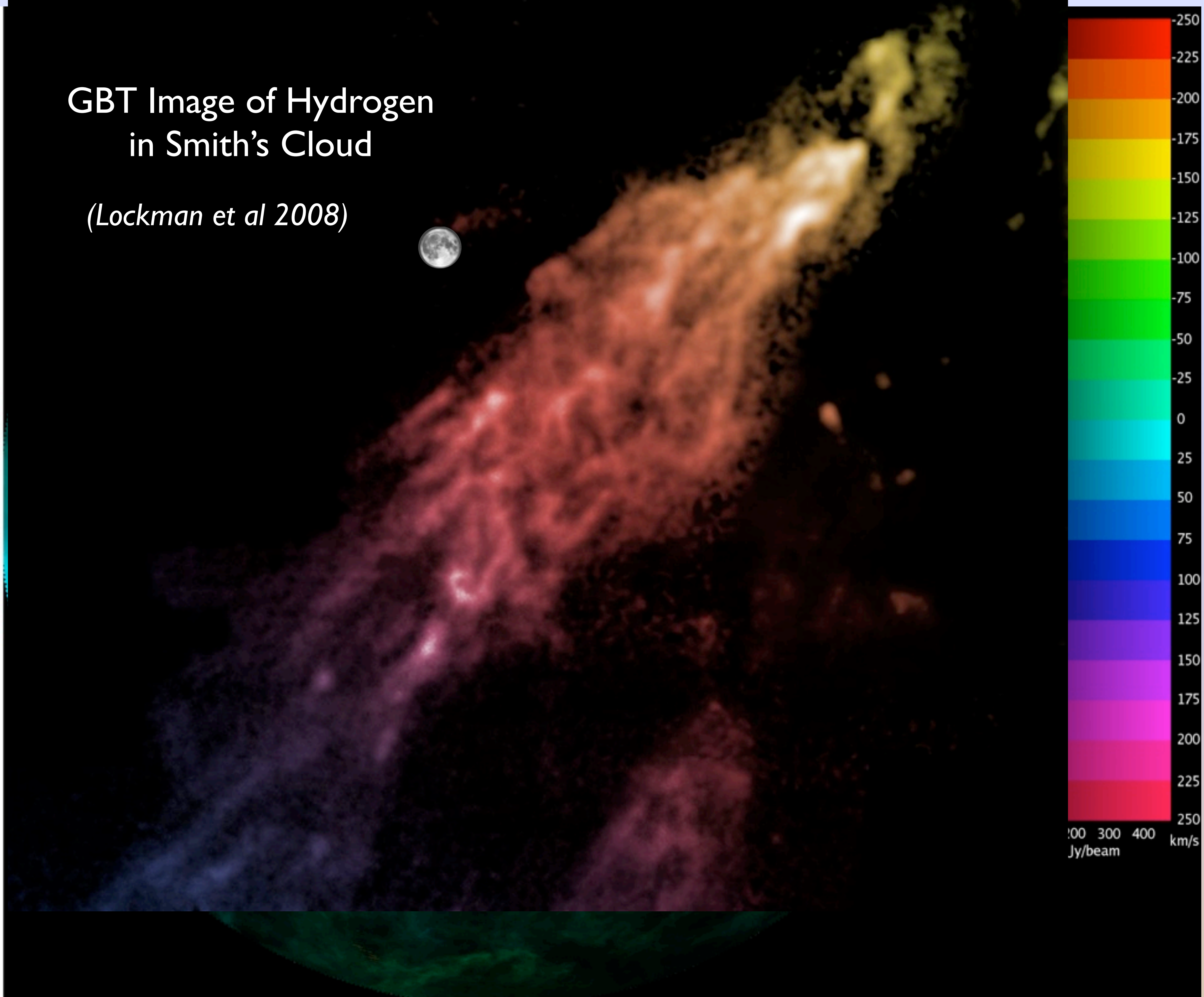
Figure 3: Average eclipse profile of pulsar A consisting of eight eclipses observed at 820 MHz over a five-day period around April 11, 2007 (black line) along with a model eclipse profile (red dashed line). The relative pulsed flux density of pulsar A is normalized so the average level outside the eclipse region is unity. The resolution of each data point is ~91 ms while 1° in orbital phase corresponds to 24.5 s. Note that near orbital phase 0.0 the spikes are separated by the spin period of pulsar B.

GASS HI Survey
(McClure-Griffiths et al 2009)



GBT Image of Hydrogen in Smith's Cloud

(Lockman et al 2008)



Astronomy at Radio Wavelengths -- Why is it Different?

Atmosphere
Low Energy Photons
Diffraction
Coherent Signal Processing
Noise

What does every radio telescope shown so far have in common?

Astronomy at Radio Wavelengths -- Why is it Different?

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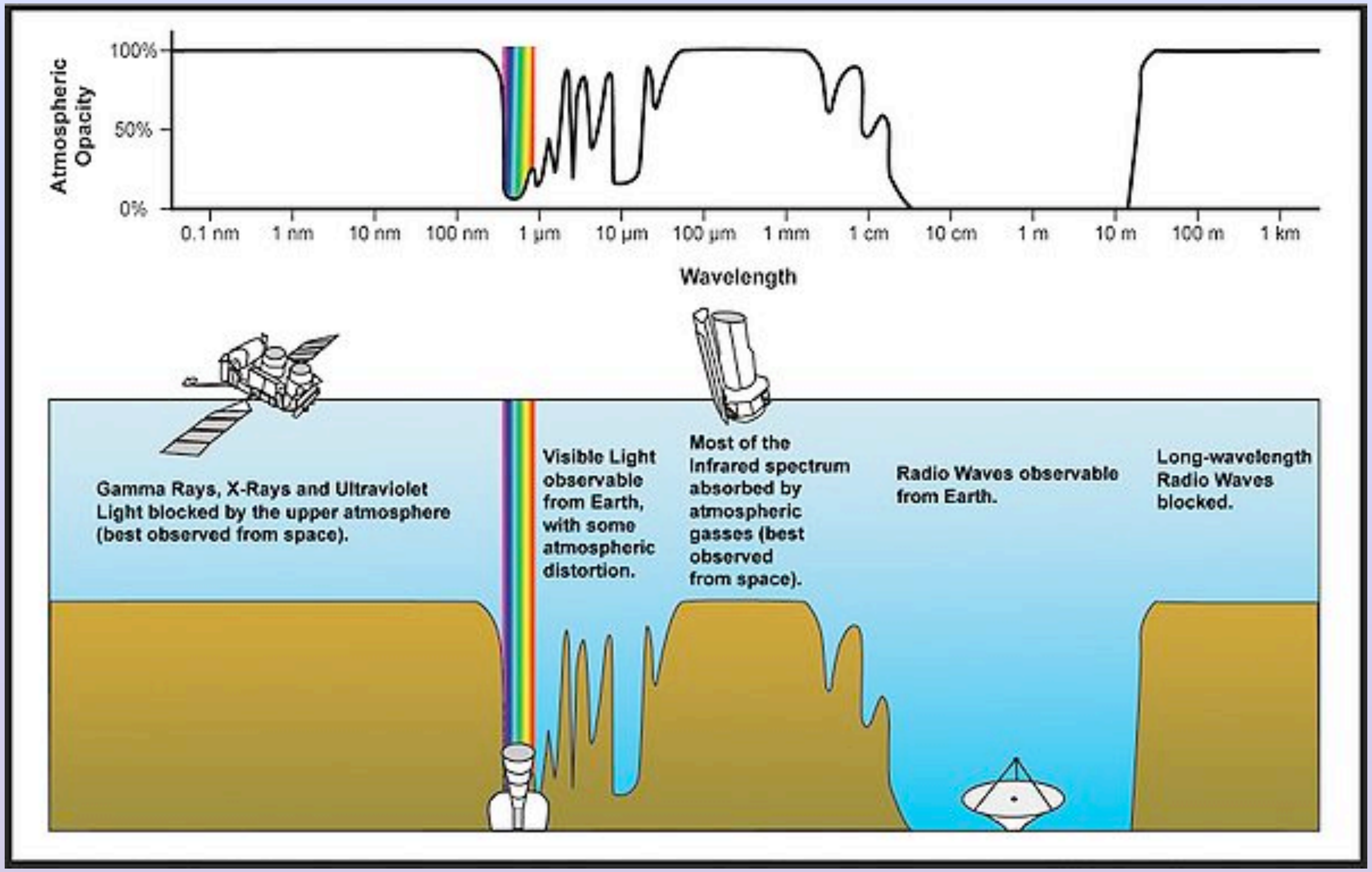
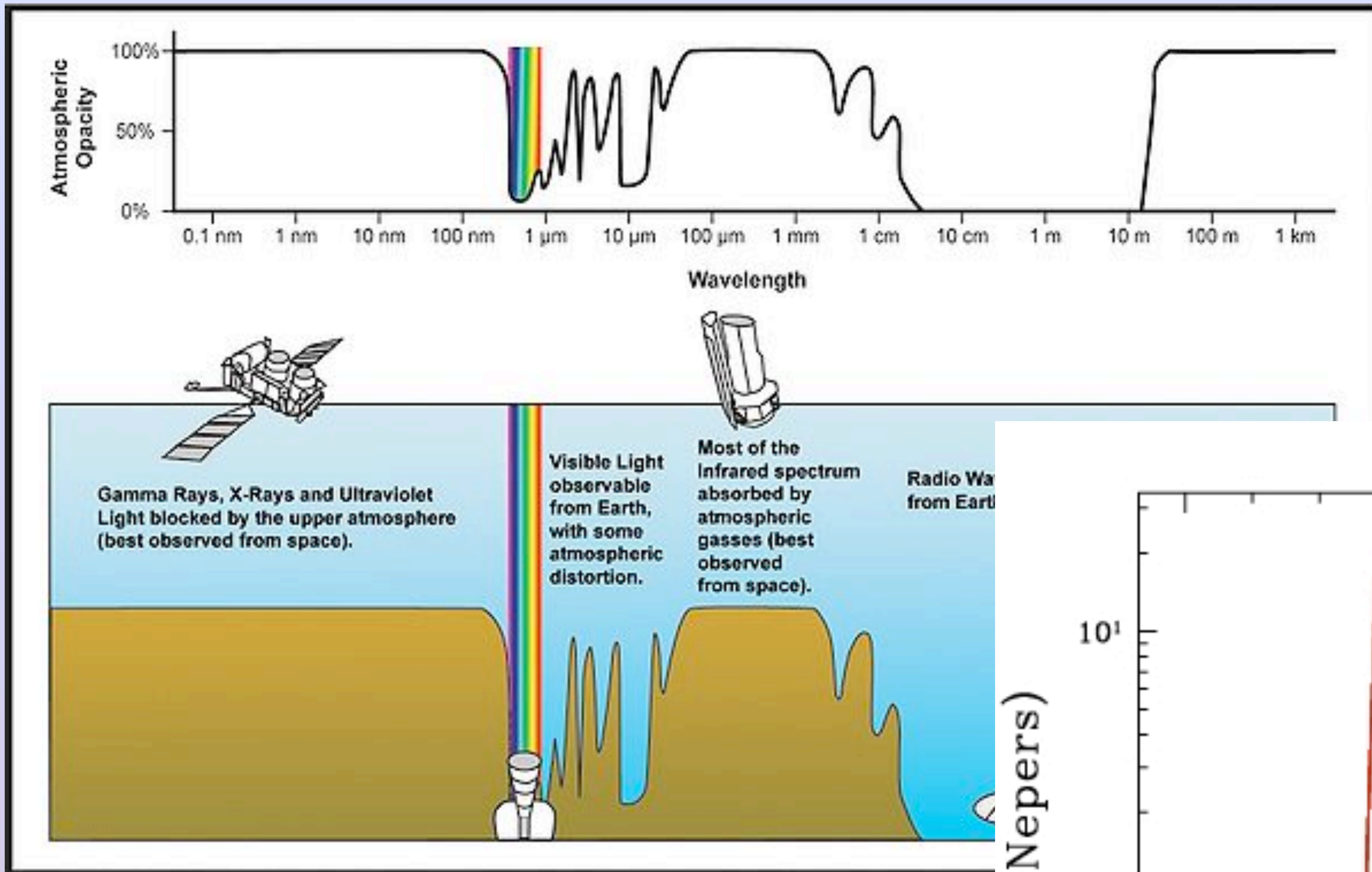


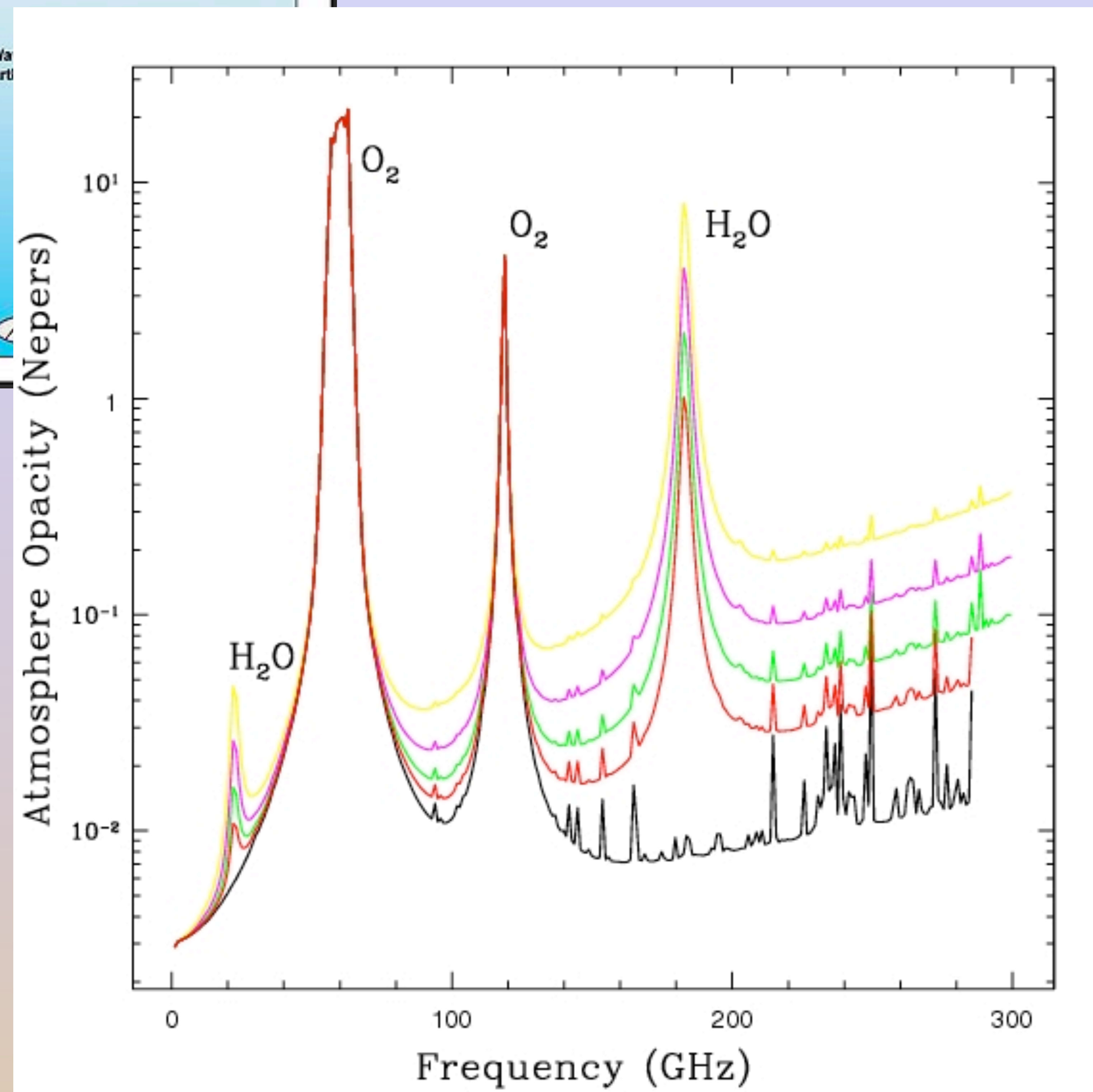
The Radio Window

0.01 GHz - 1000 GHz

The Radio Window

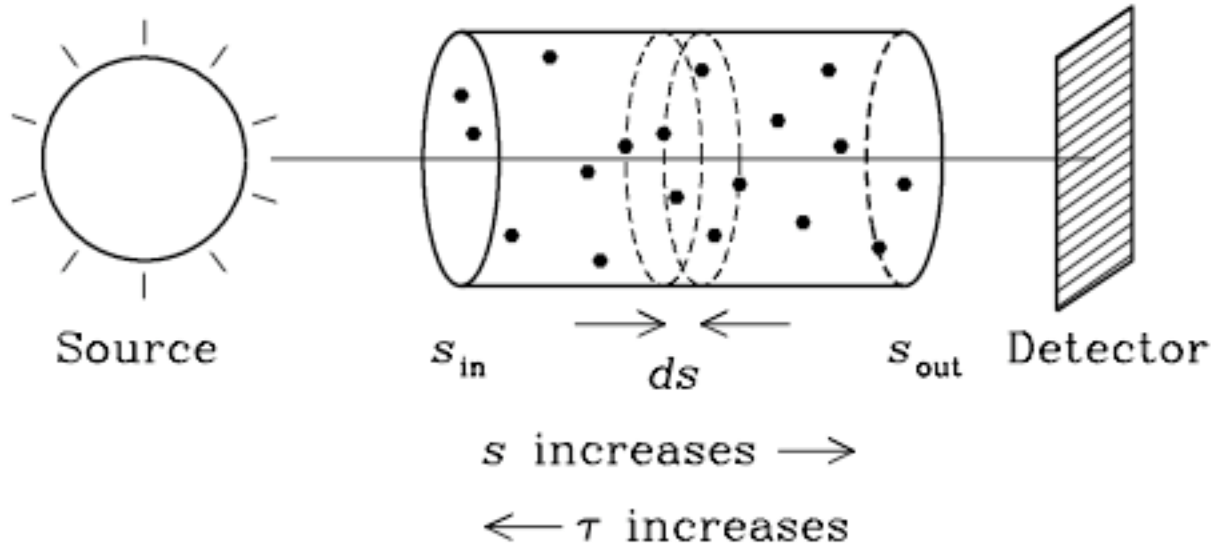
0.01 GHz - 1000 GHz





Transparency of the Atmosphere depends on altitude and H_2O

Radiative Transfer -- Specific Intensity



Linear Absorption Coefficient + emissivity

$$\frac{dI_\nu}{ds} = -I_\nu \kappa_\nu + j_\nu$$

Optical Depth

$$\tau = \int \kappa ds$$

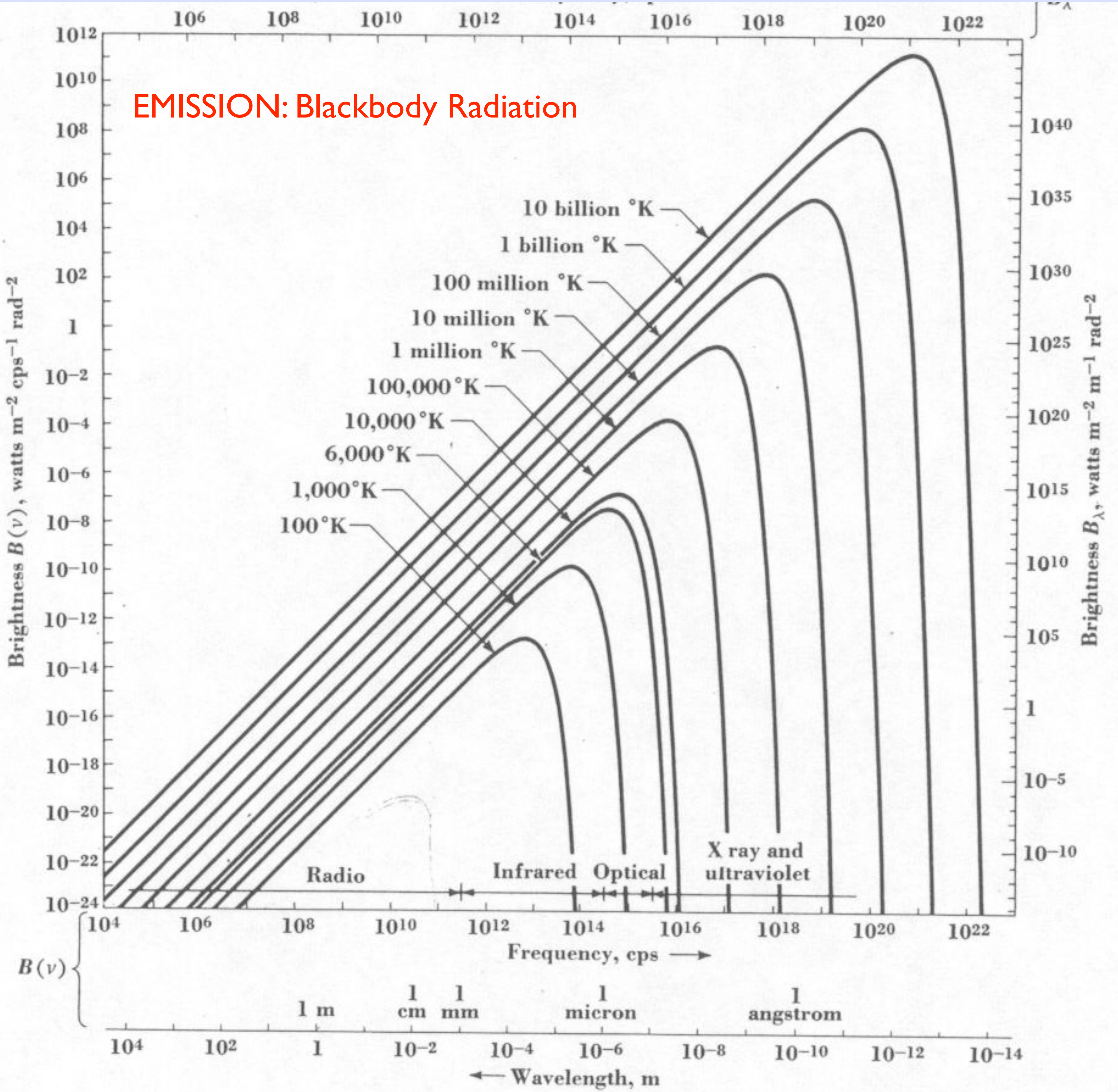
Relations through black-body radiation

$$j_\nu = \kappa_\nu B_\nu(\mathrm{T_{ex}})$$

Absorption + emission

$$I_\nu = I_\nu(0)e^{-\tau_\nu} + B_\nu(\mathrm{T_{ex}})(1 - \mathrm{e}^{\tau_\nu})$$

EMISSION: Blackbody Radiation



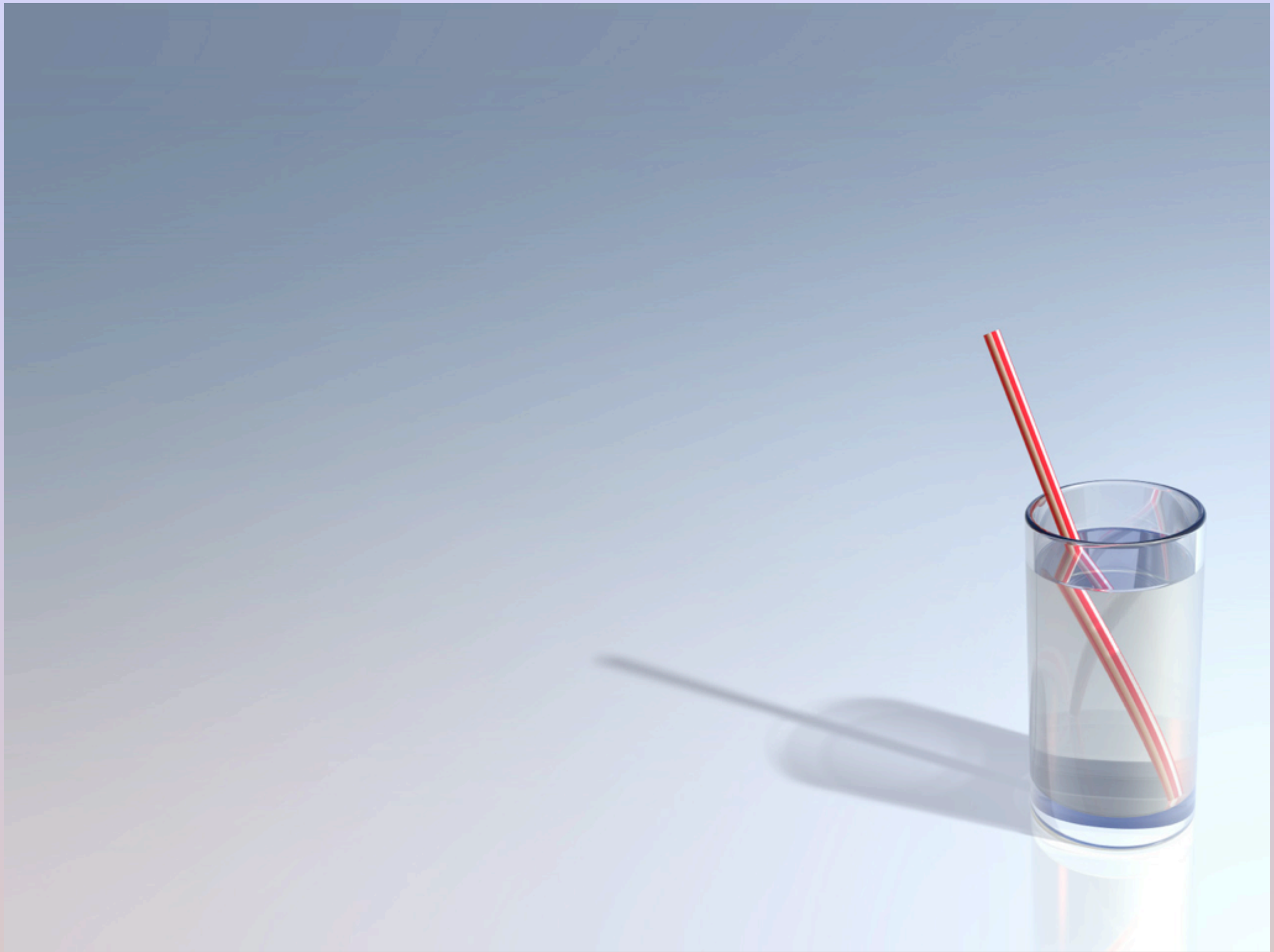
Blackbody radiation

$$I_\nu(thermal) = \frac{2h\nu^3}{c^2}\frac{1}{exp(h\nu/kT) - 1}$$

$$\nu_{max}\ (\mathrm{GHz}) = 59\ T\ (\mathrm{K})$$

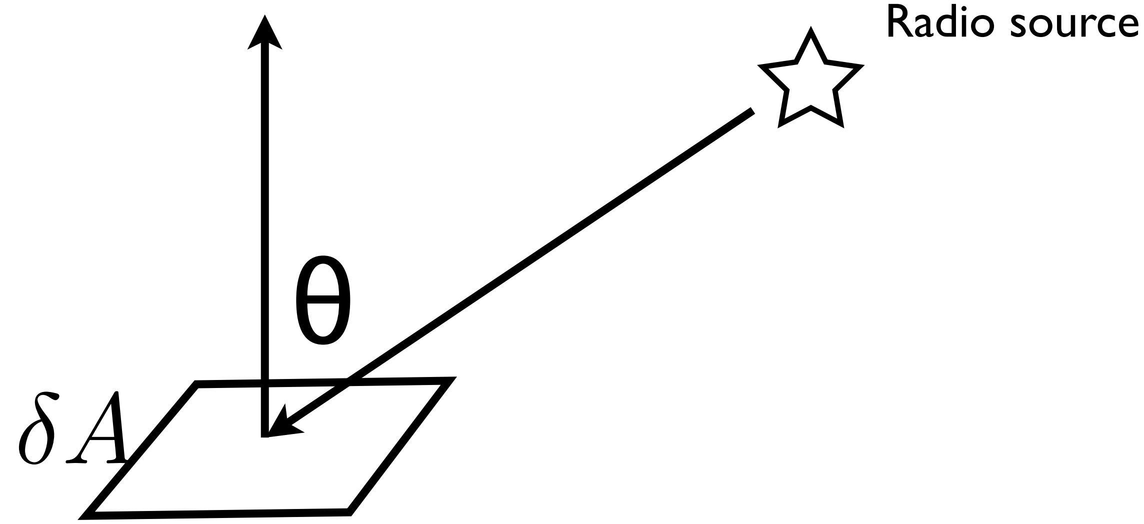
$$I_\nu(th) = \frac{2kT}{\lambda^2}$$

$$\nu(\mathrm{GHz}) << 22\ \mathrm{T(K)}$$



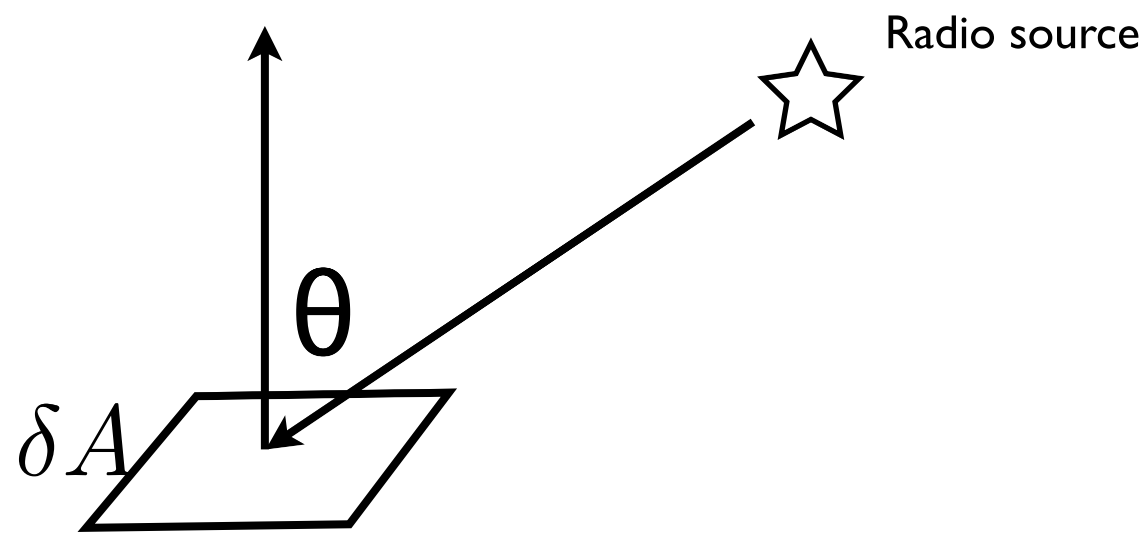
$$I_\nu = I_0 e^{-\tau_\nu}$$

An "aperture" in the abstract



$$\delta \mathrm{E} = I_\nu \; cos(\theta) \; \delta A \; \delta\Omega \; \delta\nu \; \delta t$$

An "aperture" in the abstract



$$\delta \mathrm{E} = I_\nu \; \underline{cos(\theta) \; \delta A} \; \delta\Omega \; \delta\nu \; \delta t$$

Power Received

$$\mathrm{W_m} = \frac{A_e}{2} \int_{4\pi} I_\nu(\theta, \phi) \; P_\nu(\theta, \phi) \; d\Omega \quad \mathrm{Watts\ Hz^{-1}}$$

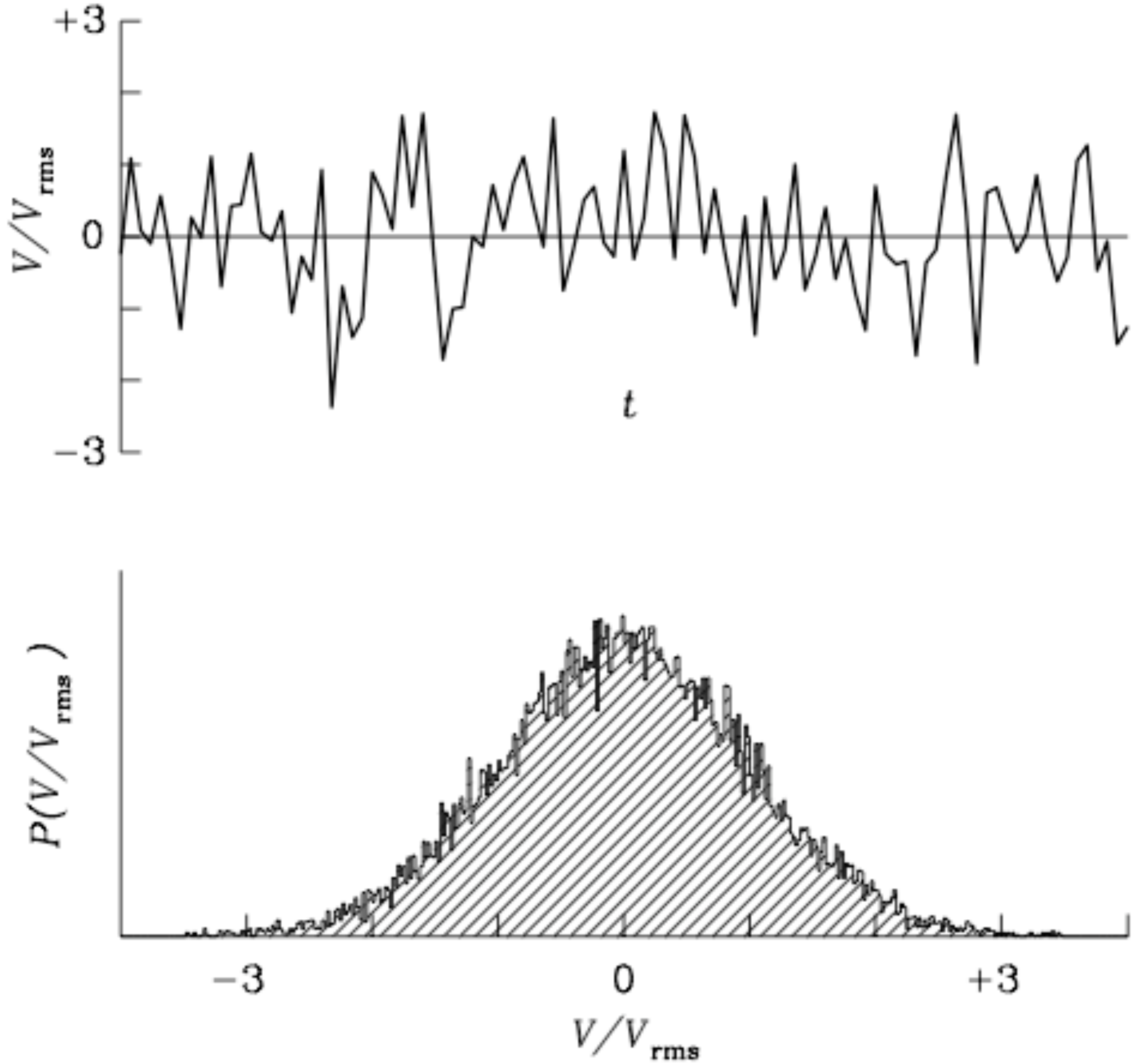
Power Pattern

$$P(0,0) = 1$$

When ν << 22 T

$$I_\nu(th) = \frac{2kT}{\lambda^2}$$

$$\mathrm{W_m} = \frac{kA_e}{\lambda^2}\int_{4\pi} T_{b\nu}(\theta,\phi)\ P_\nu(\theta,\phi)\ d\Omega \quad \mathrm{Watts\ Hz}^{-1}$$



The output voltage V of a radio telescope varies rapidly on short time scales, as indicated by the upper plot showing 100 independent samples of band-limited noise drawn from a Gaussian probability distribution $P(V/V_{\mathrm{rms}})$ (lower plot) having zero mean and fixed rms

From Condon & Ransom http://www.cv.nrao.edu/course/astr534

When ν << 22 T

$$I_\nu(th) = \frac{2kT}{\lambda^2}$$

$$\mathrm{W_m} = \frac{kA_e}{\lambda^2} \int_{4\pi} T_{b\nu}(\theta,\phi)\ P_\nu(\theta,\phi)\ d\Omega \quad \mathrm{Watts\ Hz^{-1}}$$

Power from a resistor

$$\mathrm{W} = kT \quad (\mathrm{watts\ Hz^{-1}})$$

Antenna Temperature

$$\mathrm{T_a} = \frac{A_e}{\lambda^2} \int_{4\pi} T_{b\nu}(\theta,\phi)\ P_\nu(\theta,\phi)\ d\Omega \quad (\mathrm{K\ Hz^{-1}})$$

$$\mathrm{T_a} = \frac{A_e}{\lambda^2} \int_{4\pi} T_{b\nu}(\theta,\phi)\ P_\nu(\theta,\phi)\ d\Omega \quad (\mathrm{K\ Hz^{-1}})$$

Enclose the antenna in a blackbody of temperature Tb

$$T_a = \frac{T_b A_e}{\lambda^2} \int_{4\pi} P_\nu(\theta,\phi)\ d\Omega$$

defining

$$\Omega_a = \int_{4\pi} P_\nu(\theta,\phi)\ d\Omega$$

$$\Omega_a\ A_e = \lambda^2$$

$$\mathrm{T_a} = \frac{A_e}{\lambda^2} \int_{4\pi} T_{b\nu}(\theta, \phi)\ P_\nu(\theta, \phi)\ d\Omega \quad (\mathrm{K\ Hz^{-1}})$$

But we are looking through the atmosphere!

$$\mathrm{T_a} = \frac{A_e}{\lambda^2} \int_{4\pi} T_{b\nu}(\theta, \phi)\ e^{-\tau(\theta,\phi)}\ P_\nu(\theta, \phi)\ d\Omega \quad (\mathrm{K})$$

Specific Intensity (Brightness)

$$I_\nu(\theta, \phi) \quad (\mathrm{Watts\ m^{-2}\ Hz^{-1}\ str^{-1}})$$

Flux Density

$$S_\nu = \int_{\Omega_s} I_\nu(\theta, \phi)\ d\Omega \ \ (\mathrm{Watts\ m^{-2}\ Hz^{-1}})$$

A flux density per unit area is actually a brightness!

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What determines P?

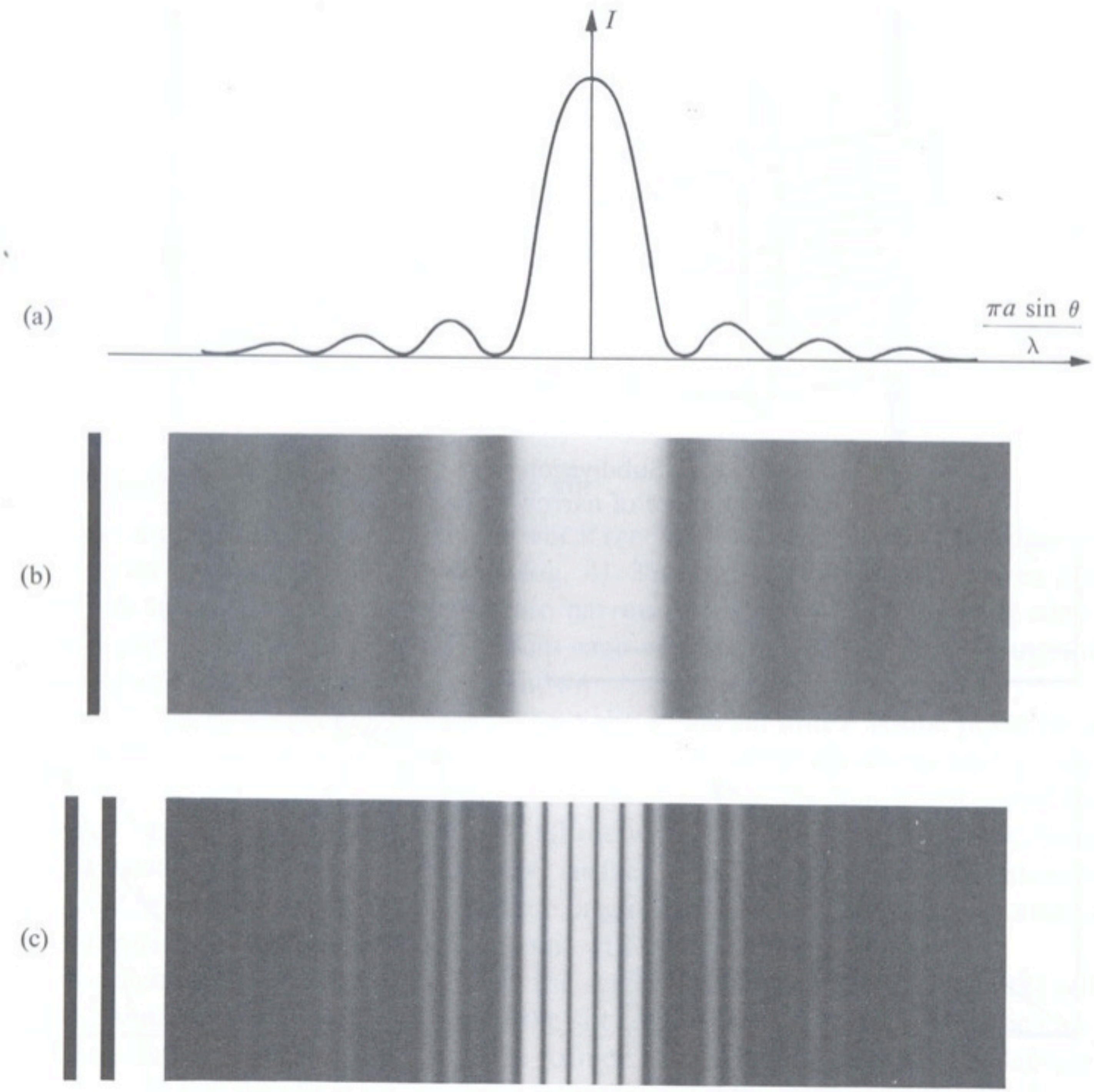
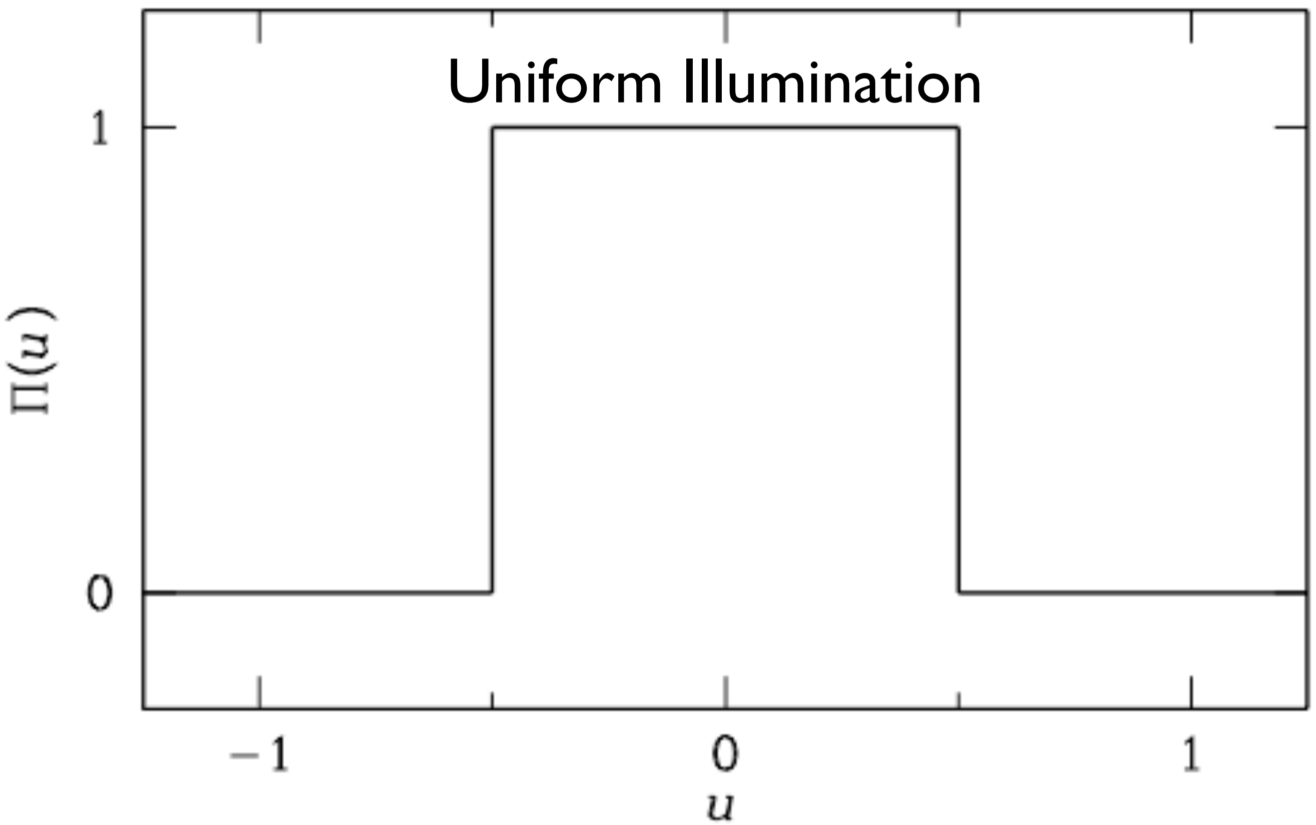
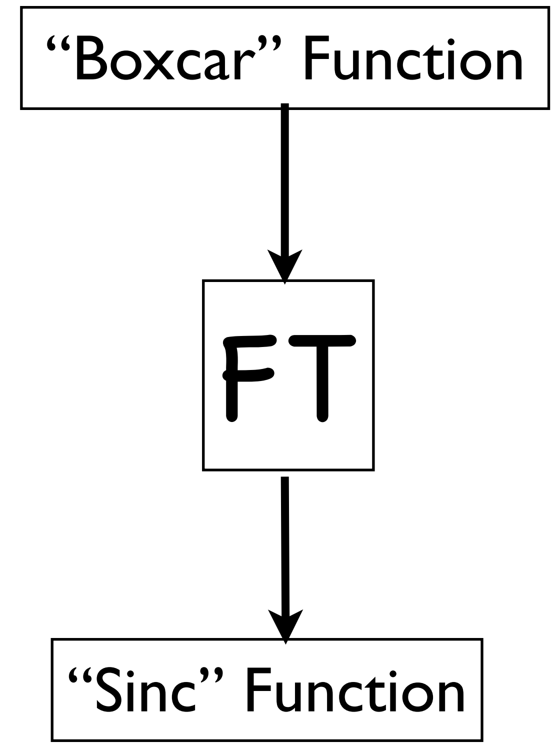
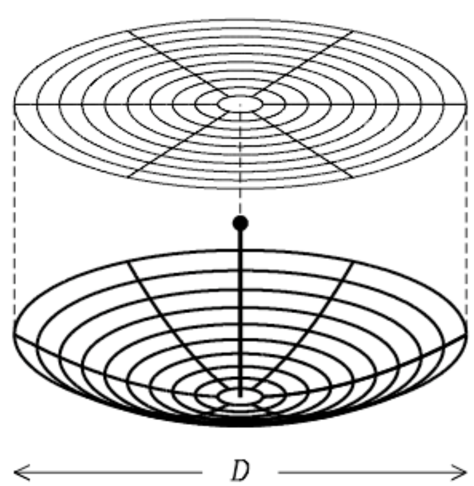


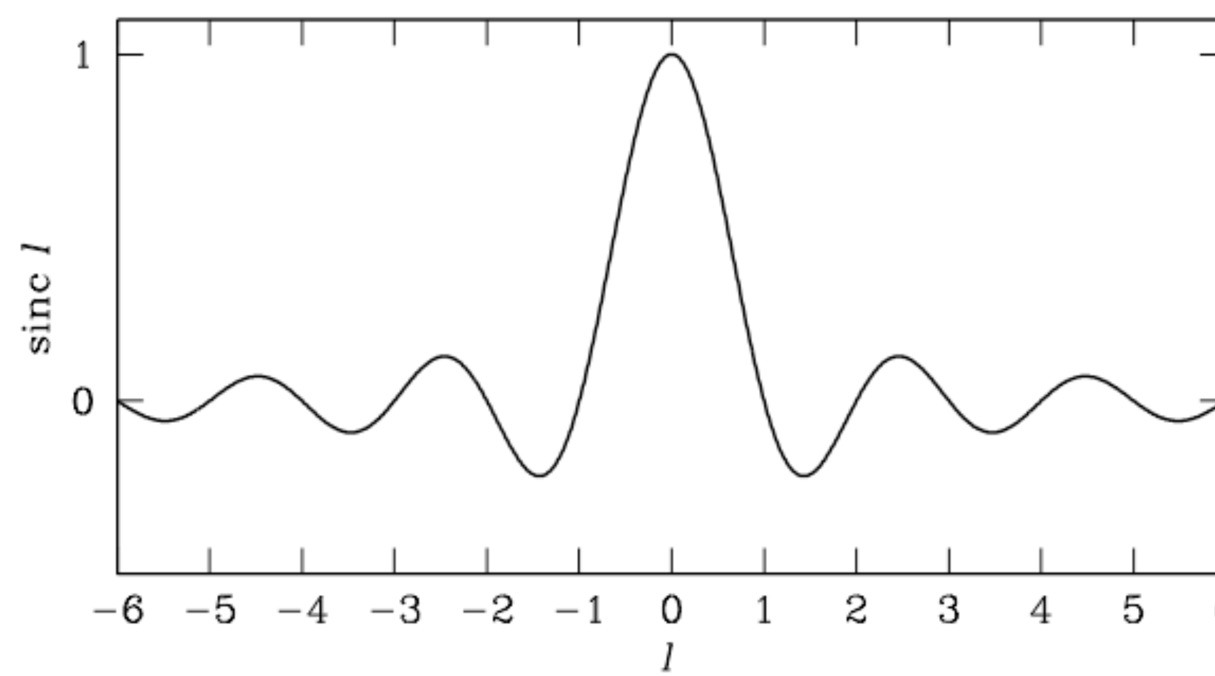
Fig. 41–28. (a) Intensity distribution. (b) Photograph of the Fraunhofer diffraction pattern of a single slit. (c) Fraunhofer diffraction pattern of a double slit.





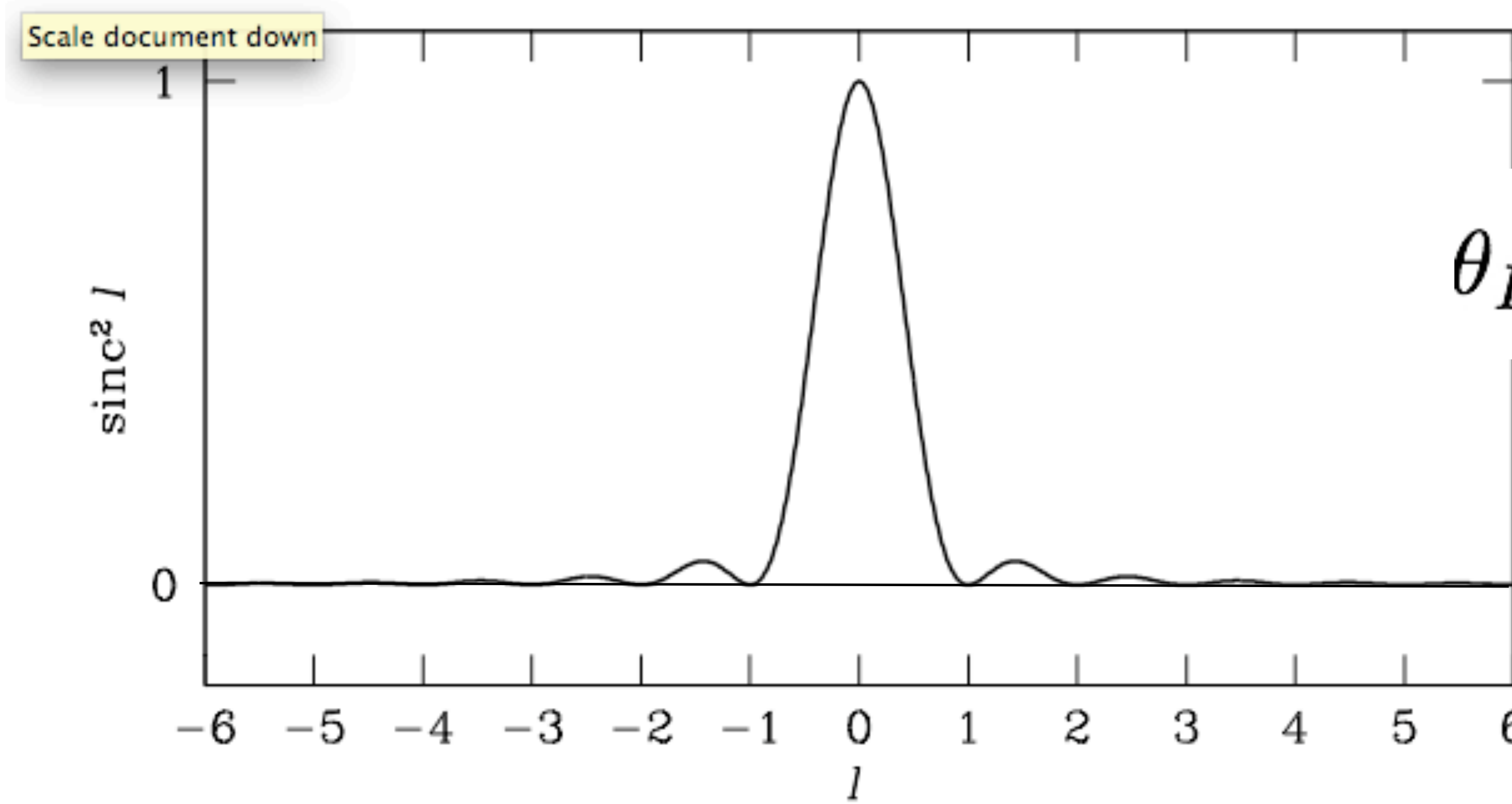
Aperture Plane





The function $\mathrm{sinc}(l) \equiv \sin(\pi l)/(\pi l)$ *is the Fourier transform*

For Uniform Illumination $$P(\theta) \propto sinc^2(\theta D/\lambda)$$



$$\theta_{HPBW} \approx \frac{\lambda}{D}$$

The power pattern of a uniformly illuminated unit ($D/\lambda = 1$) aperture. For large ($D \gg \lambda$) apertures, the zeros at $l = \pm 1, \pm 2, \ldots$ appear at the angles $\theta = \pm\lambda/D, \pm 2\lambda/D, \ldots$.

Airy rings

Main Beam and Sidelobes

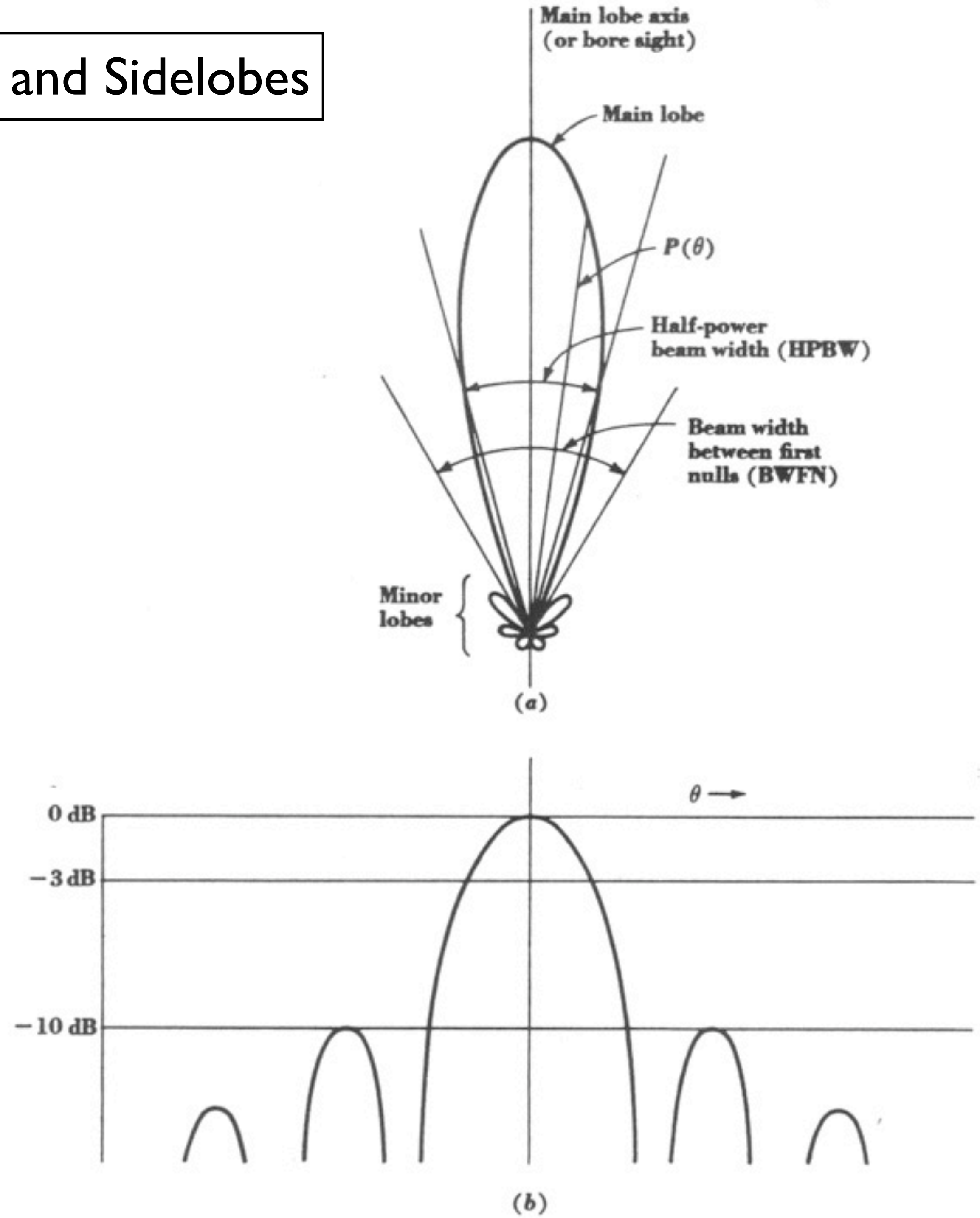


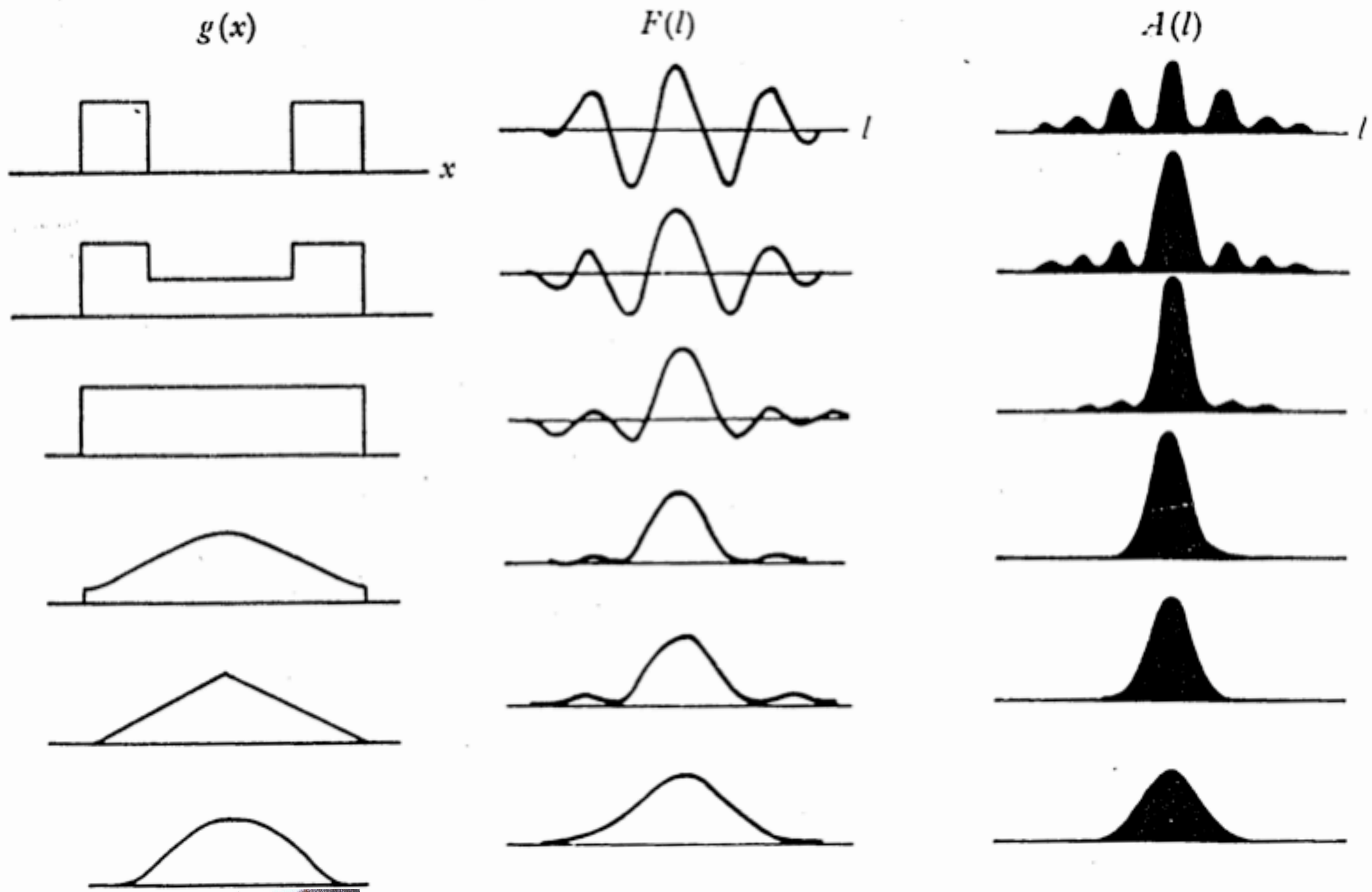
Fig. 6-1. (a) Antenna pattern in polar coordinates and linear power scale; (b) antenna pattern in rectangular coordinates and decibel power scale.

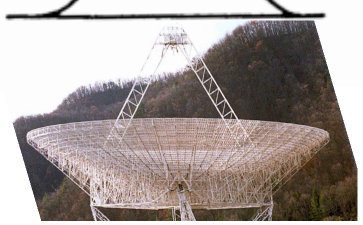
(from Kraus 1966)

$$\eta_{mb} = \frac{\Omega_{mb}}{\Omega_a}$$

Main Beam Efficiency

Fig. 2.7. A selection of gradings $g(x)$ for a line antenna, the field patterns $F(l)$ and effective areas $A(l)$.





- In the far field, the electric-field pattern, f, of an aperture antenna is the Fourier transform of the electric field illuminating the aperture. And the power pattern, P, is the square of the modulus of f.

$$\mathrm{W_m} = \frac{A_e}{2} \int_{4\pi} I_\nu(\theta, \phi)\; P_\nu(\theta, \phi)\; d\Omega \quad \text{Watts Hz}^{-1}$$

for a point source $W_m = kT_a = \frac{1}{2} A_e S_\nu$

$$T_a / S_\nu = \frac{A_e}{2k}\; 10^{-26}\; (\mathrm{K\ Jy}^{-1})$$

(an $\mathrm{A_e}$ of 2760 $\mathrm{m^2}$ gives 1.0 K/Jy)

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What is A_e?

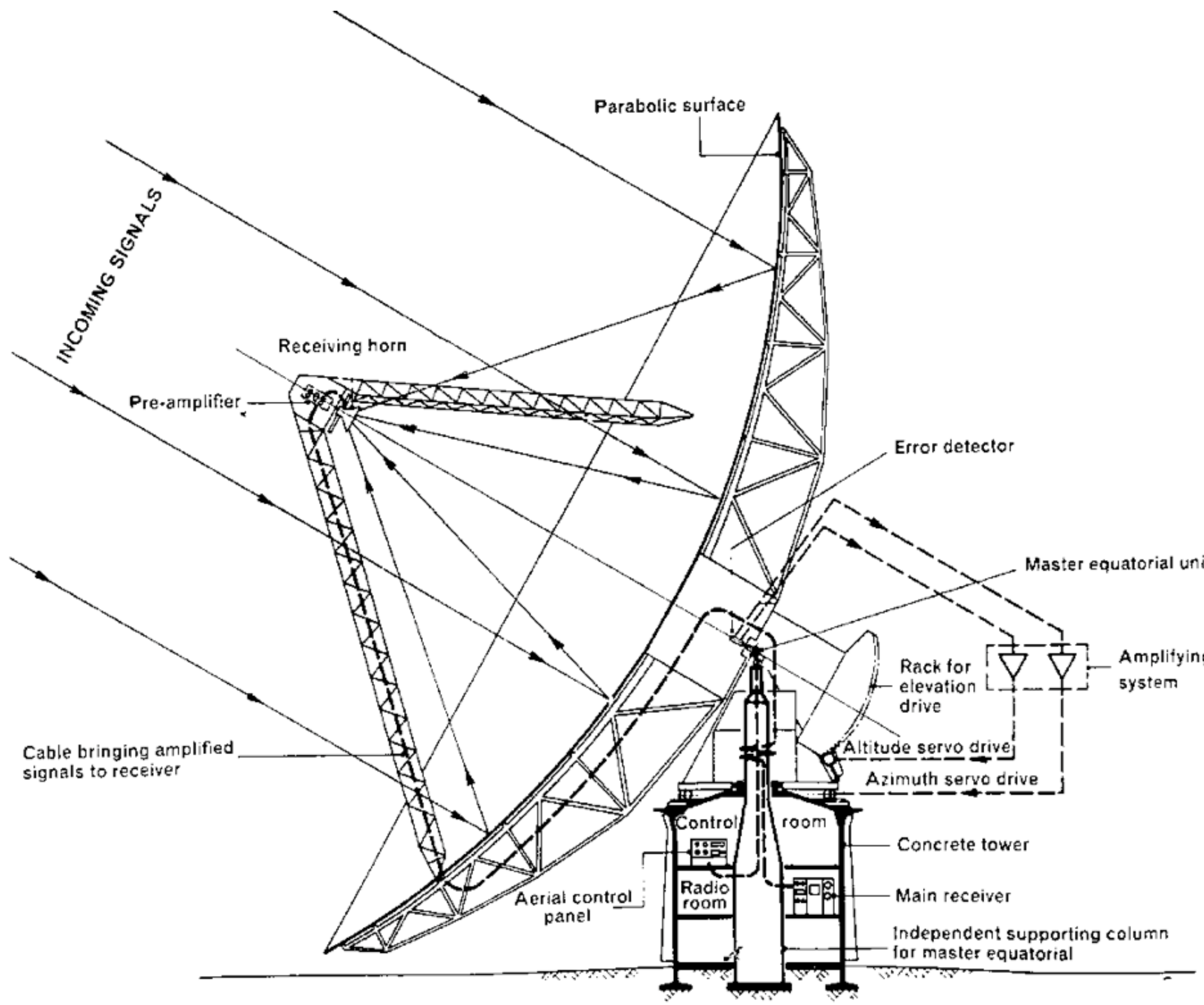
Geometric Area

$$A_g = \pi \ r^2 \ (\mathrm{m}^2)$$

Effective Area

$$A_e = \eta_a \ A_g \ (\mathrm{m}^2)$$

$$\eta_a < 1.0$$



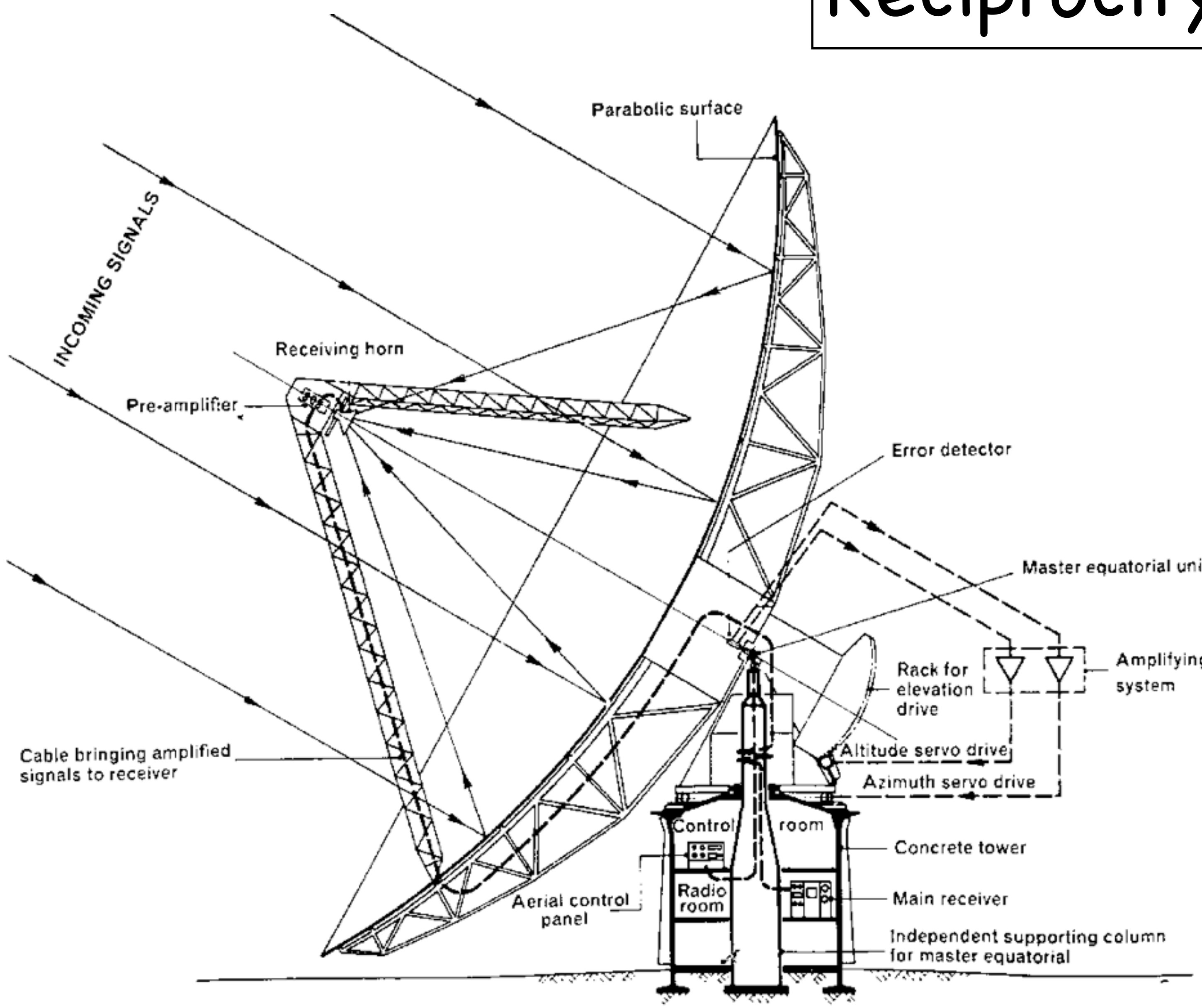
Geometric Area

$$A_g = \pi \; r^2 \; (\mathrm{m}^2)$$

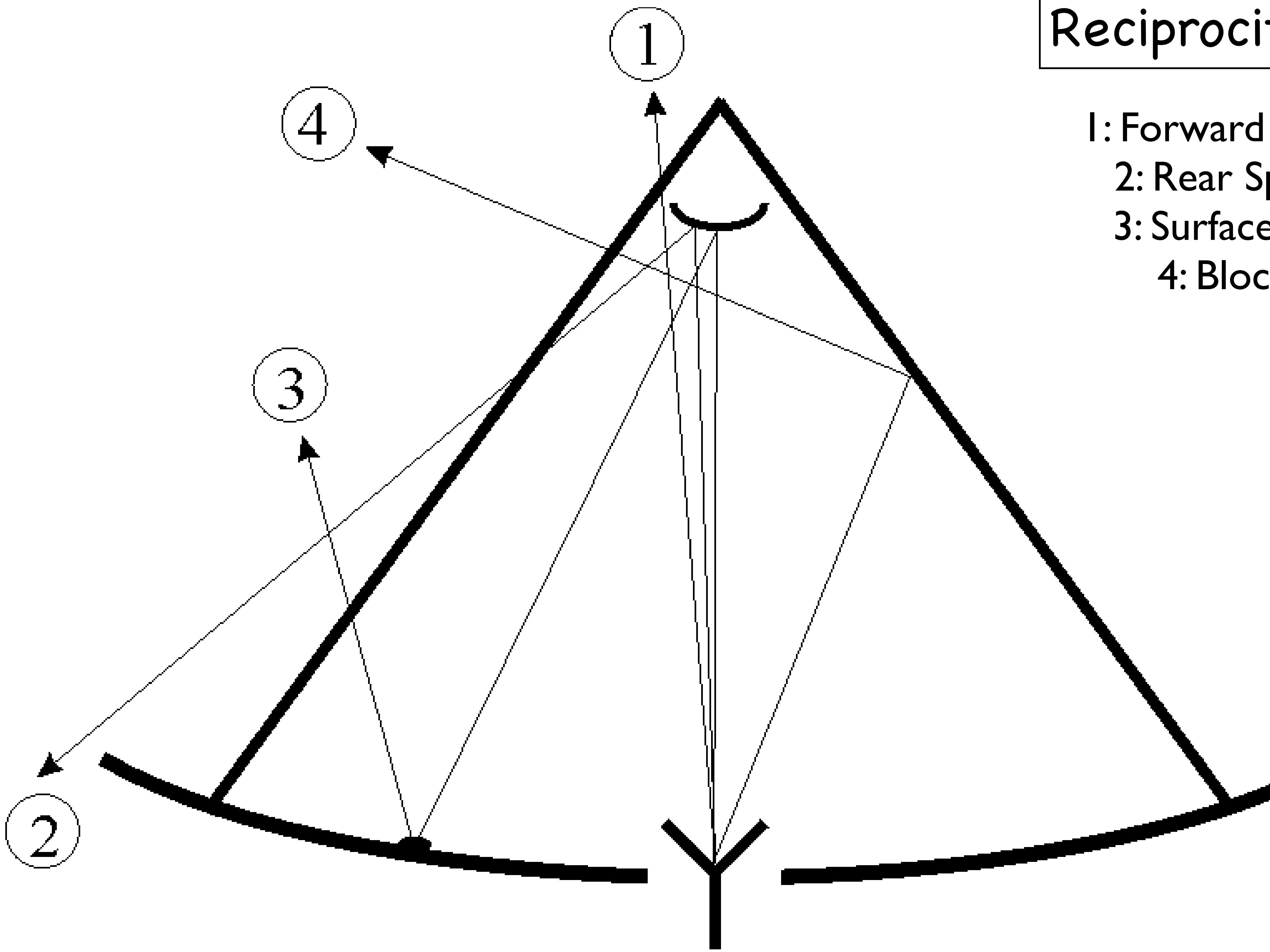
Effective Area

$$A_e = \eta_a \; A_g \; (\mathrm{m}^2) \qquad \eta_a < 1.0$$

Reciprocity: f(t) = f(-t)

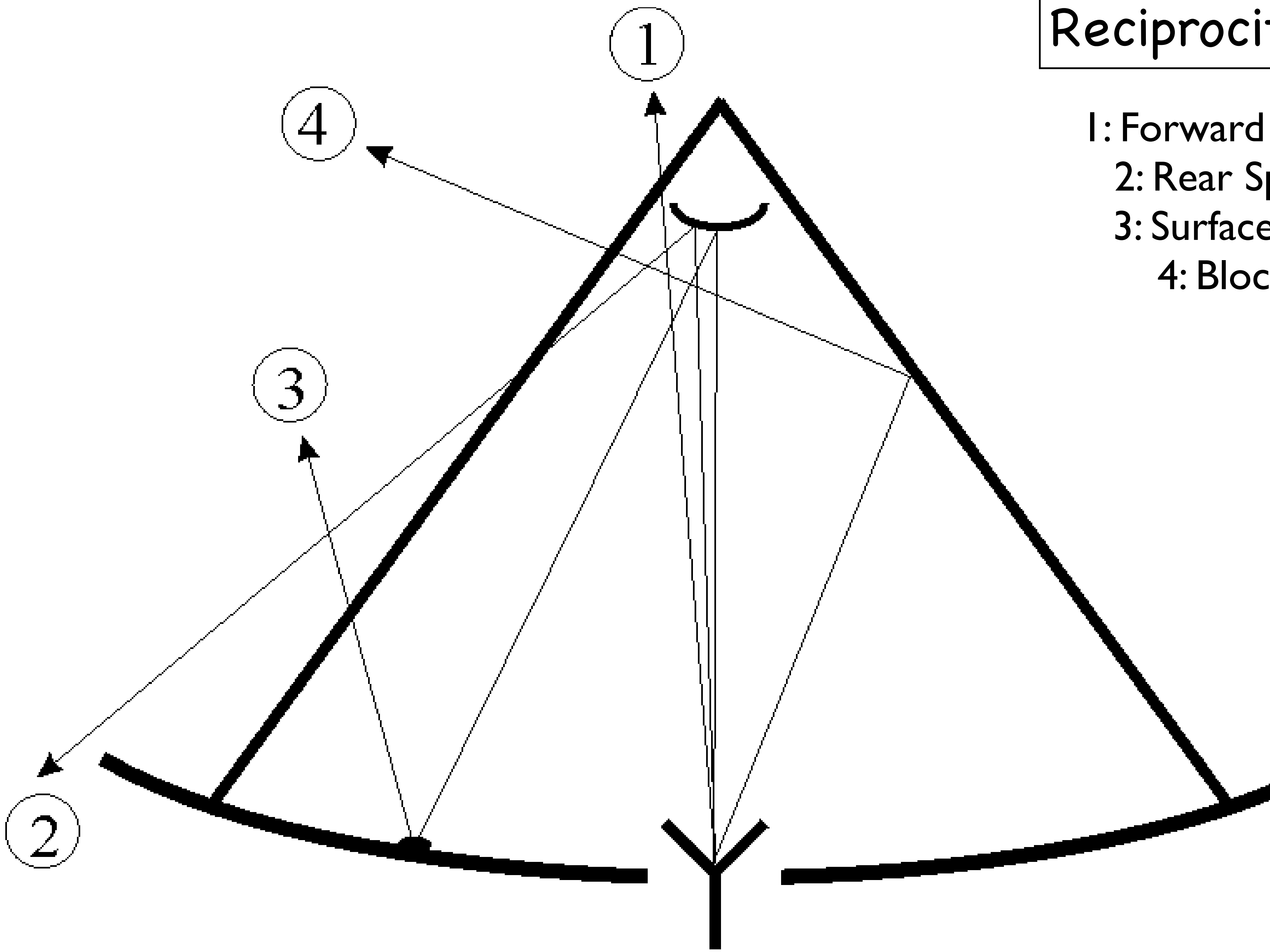


Reciprocity in action



1: Forward Spillover
2: Rear Spillover
3: Surface defect
4: Blockage

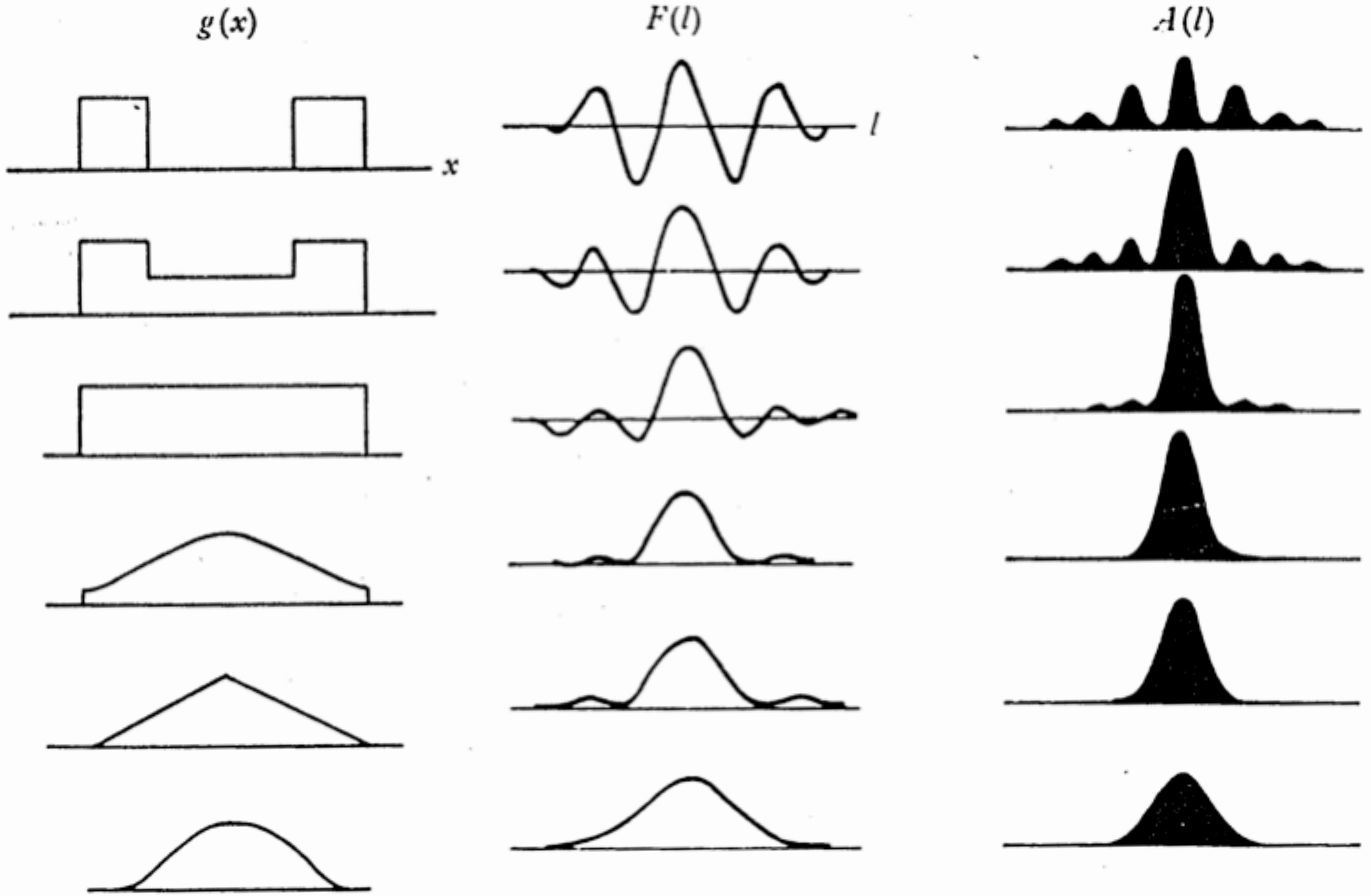
Reciprocity in action



1: Forward Spillover
2: Rear Spillover
3: Surface defect
4: Blockage

Diffractive Optics:
4m at 5000Å = $8 \times 10^6\ \lambda$
100m at 21cm = 475 λ

Fig. 2.7. A selection of gradings $g(x)$ for a line antenna, the field patterns $F(l)$ and effective areas $A(l)$.



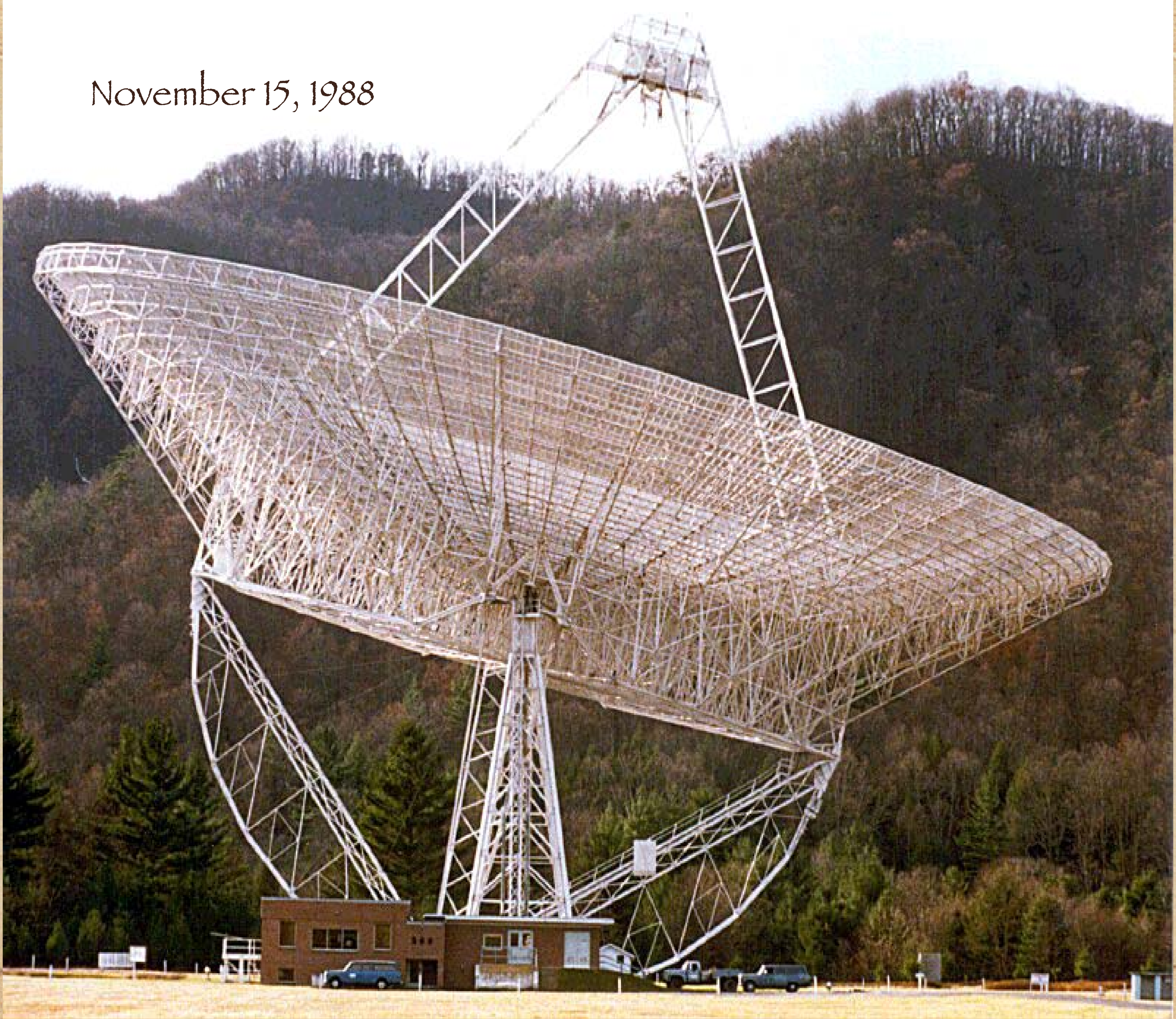
Spillover wastes power and can increase the noise, so taper the illumination

Table 2. Effects of Feed Taper for the GBT at 5 GHz

Edge Taper (dB)	Aperture Efficiency %	T_{spill} forward K	T_{spill} rear K
−12	70.0	0.4	2.6
−13	69.9	0.4	2.2
−14	69.3	0.4	1.9
−15	68.4	0.3	1.6
−16	67.3	0.2	1.4
−17	66.1	0.2	1.2

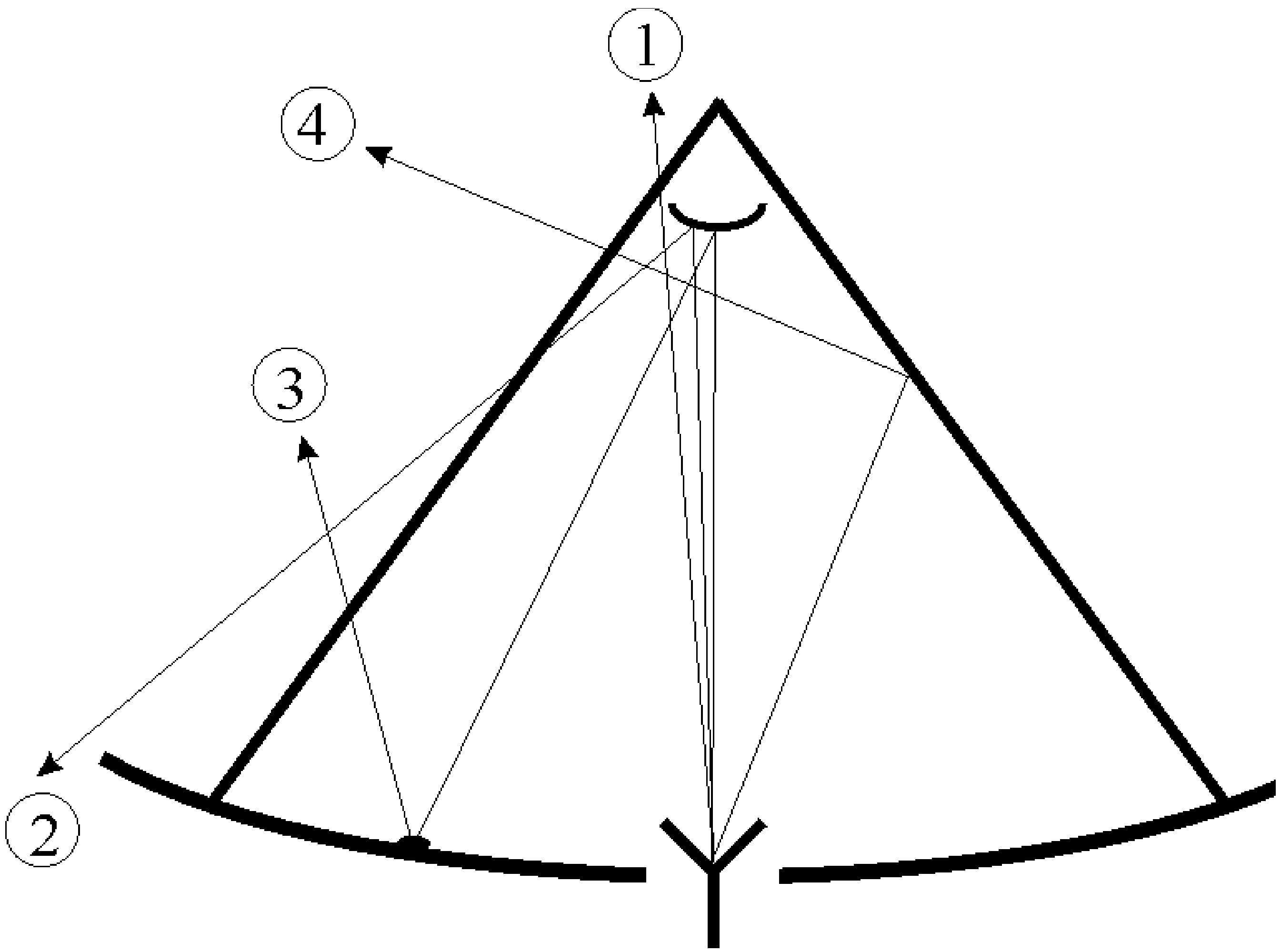
from S. Srikanth (1992)


9-28-66


November 15, 1988

November 16, 1988

Effects of surface errors -- phase errors



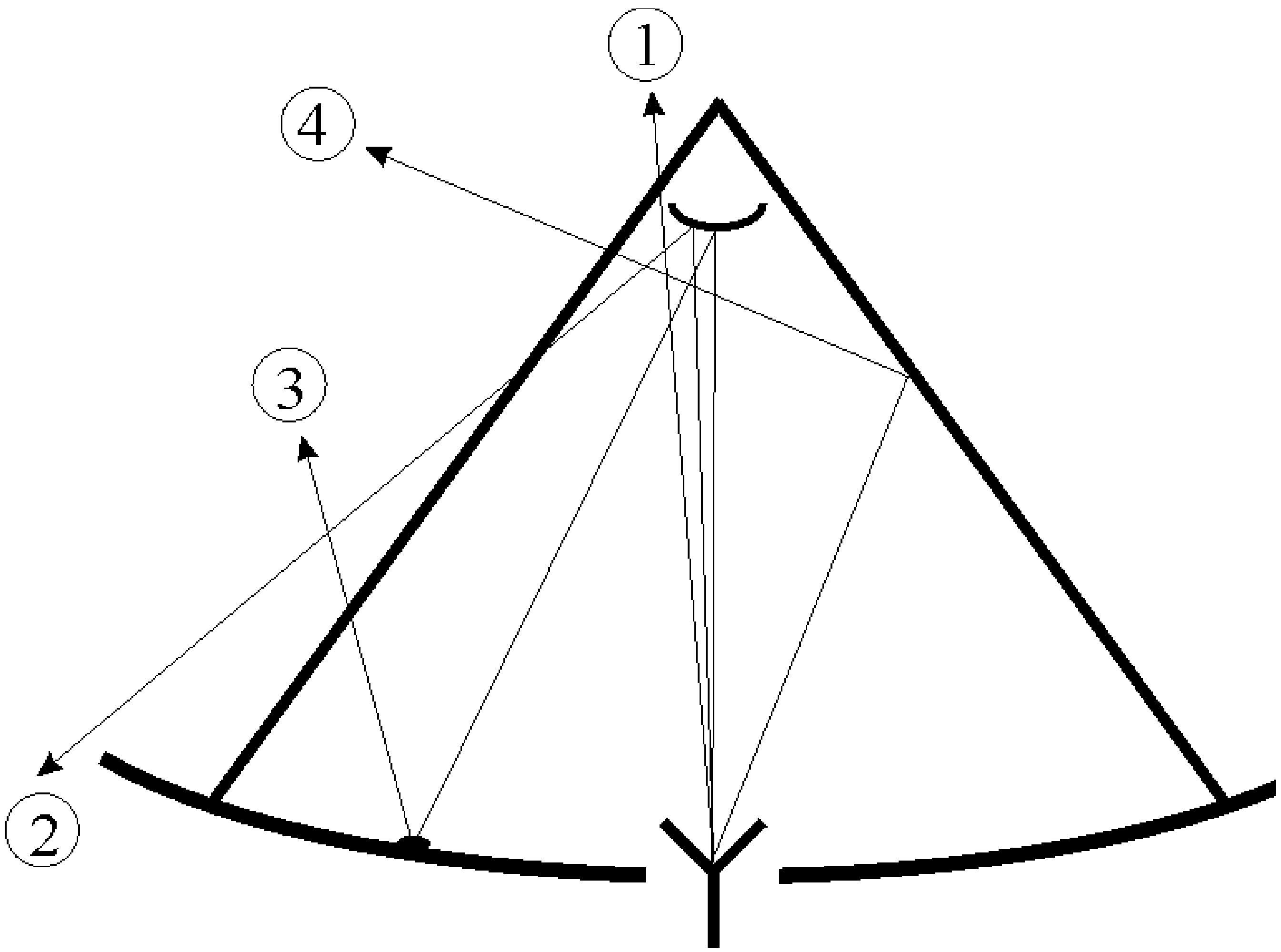
Scatter power out of main beam
Create a sidelobe
Reduce Ae

$\boxed{\text{Ruze equation for rms error } \sigma}$

$$\epsilon = e^{-(4\pi\sigma/\lambda)^2}$$

A_e reduced by factor of 2 for $\sigma=\lambda/16$

Effects of surface errors -- phase errors



Scatter power out of main beam
Create a sidelobe
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Ruze equation for rms error σ

$$\epsilon = e^{-(4\pi\sigma/\lambda)^2}$$

A_e reduced by factor of 2 for $\sigma=\lambda/16$

Where does it go?

Atm phase errors

Radio Astronomical Signals must be distinguished from a background of naturally occurring "noise"

$$T_{sys} = T_{receiver} + T_{atm} + T_{spill} + \ldots$$

Sources of Noise

$$T_{atm} \approx 300(1 - e^{-\tau_{atm}})$$

$$\tau_{atm} \approx \frac{\tau_{zen}}{cos(za)}$$

$$T_{cmb} = 2.7 \text{ K}$$

$$T_{spill} = 300\ \eta_{spill}\ \text{K}$$

$$T_{receiver} = 10 - 100 \text{ K}$$

Measurement error arising from noise

$$\sigma_{rms} = [\frac{1}{n}\Sigma(y_i)^2]^{\frac{1}{2}}$$

$$\sigma_{rms} = \frac{aT_{sys}}{(\Delta\nu\ \Delta t\ n_{pol})^{\frac{1}{2}}}$$

Example: detect the HI line from a cloud with NH=2×10^{18} and FWHM=20 km/s.

Expected T_L = 0.05 K

$$\sigma = \frac{20}{(5 \times 10^3\ (\mathrm{Hz})\ \Delta t\ 2)^{\frac{1}{2}}}$$

$$\Delta t = (0.2/\sigma)^2\ (\mathrm{s})$$

Blockage

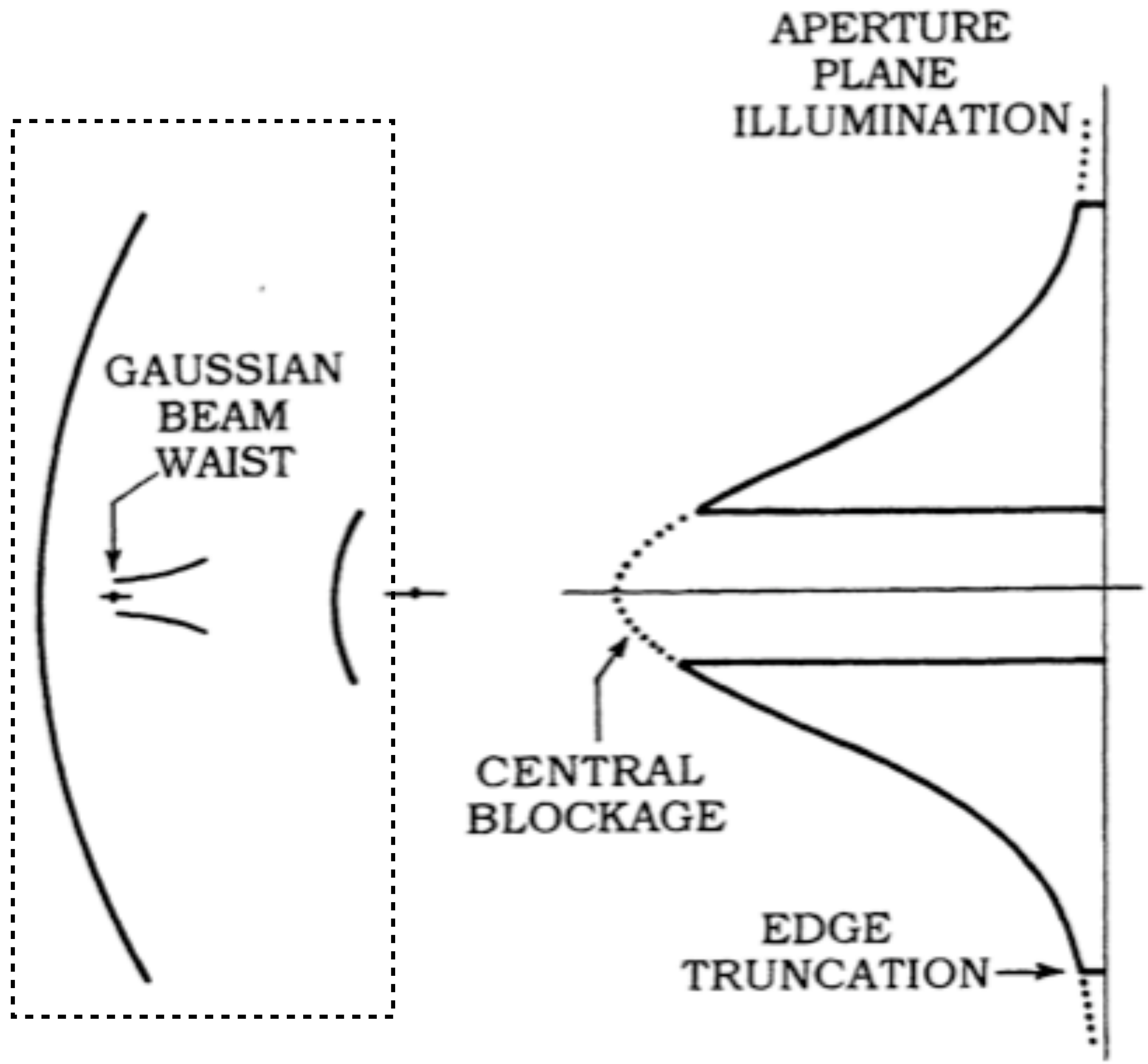
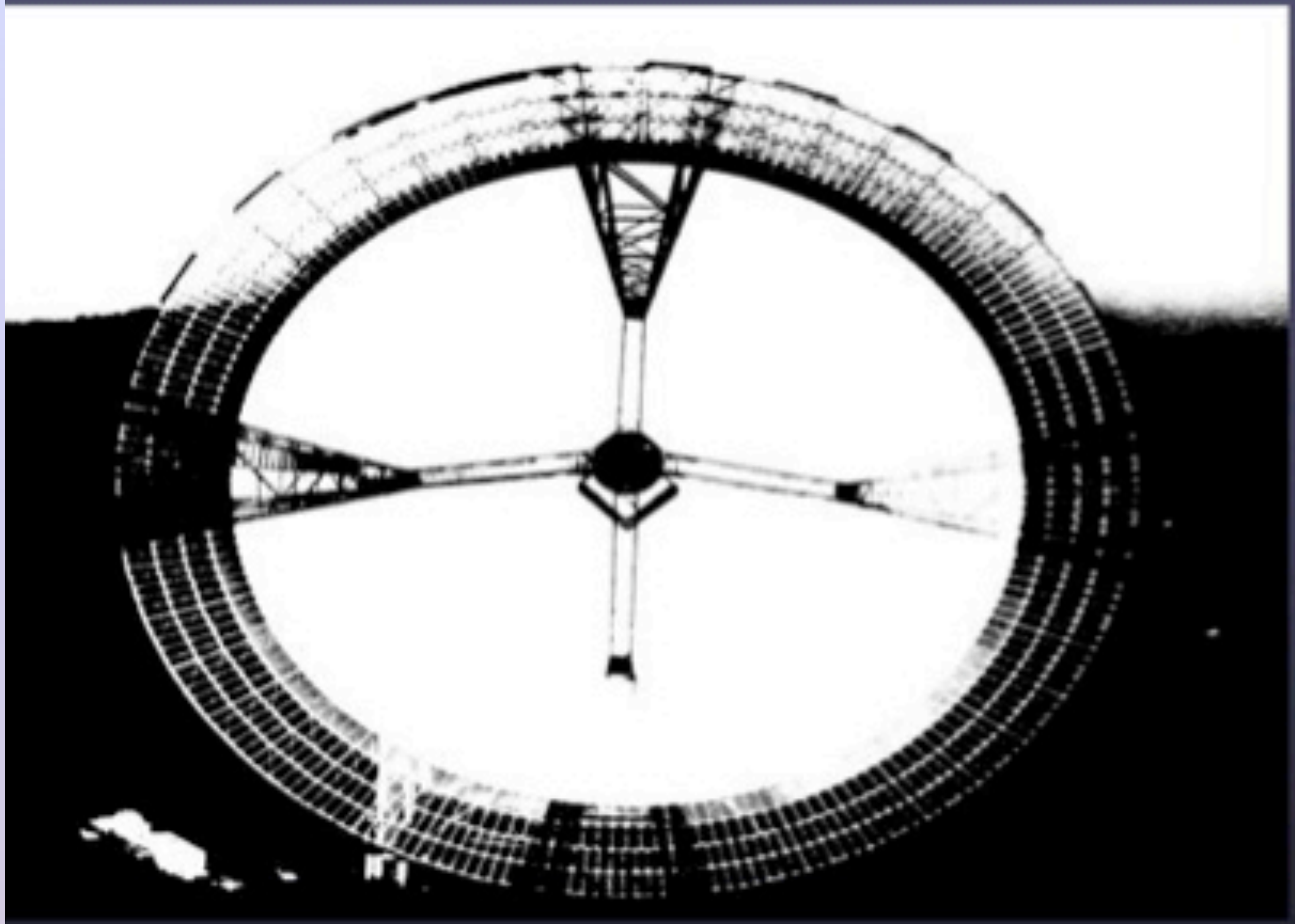


Figure 2. Schematic of the aperture plane with a Cassegrain reflector system.

(from Goldsmith 2002)

Effects of blockage on dynamic range

Effects of blockage on dynamic range



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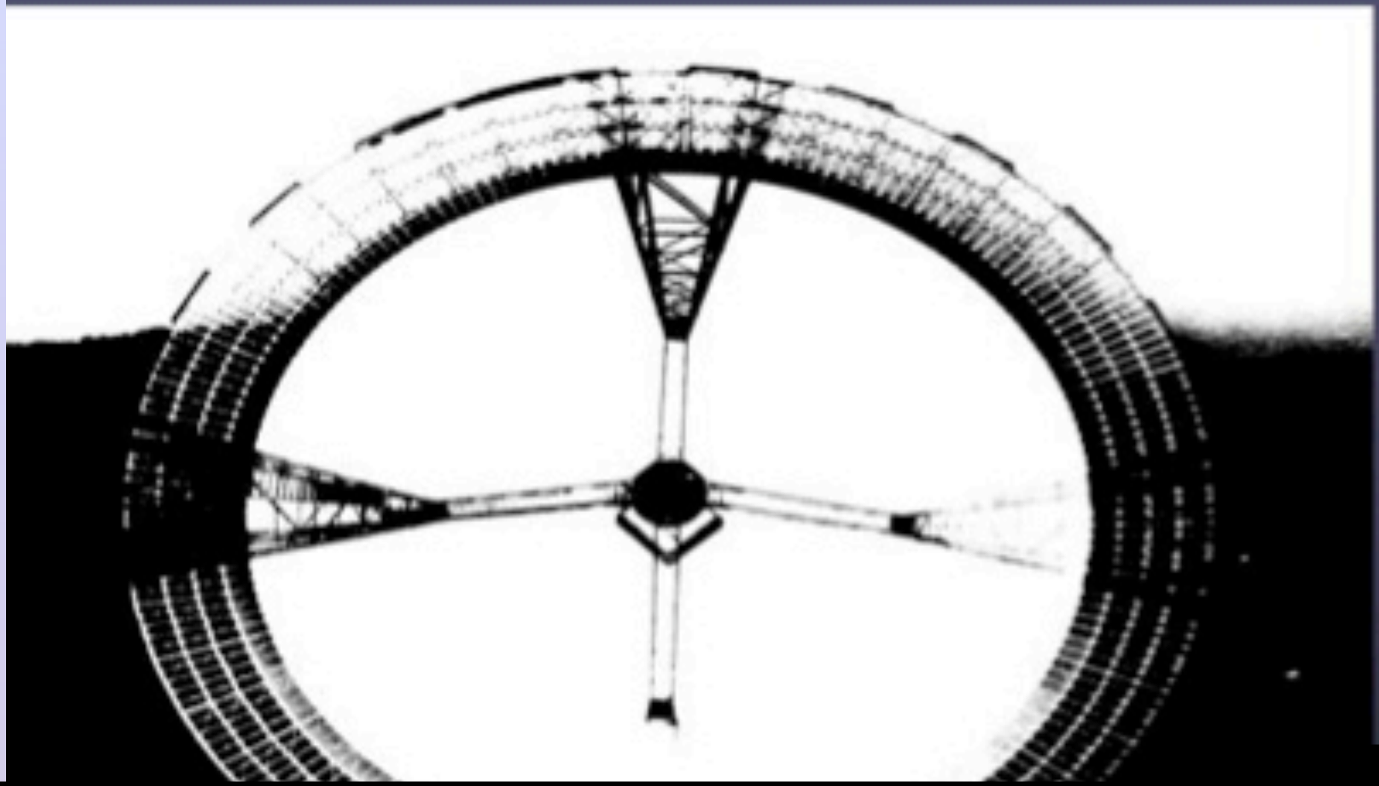
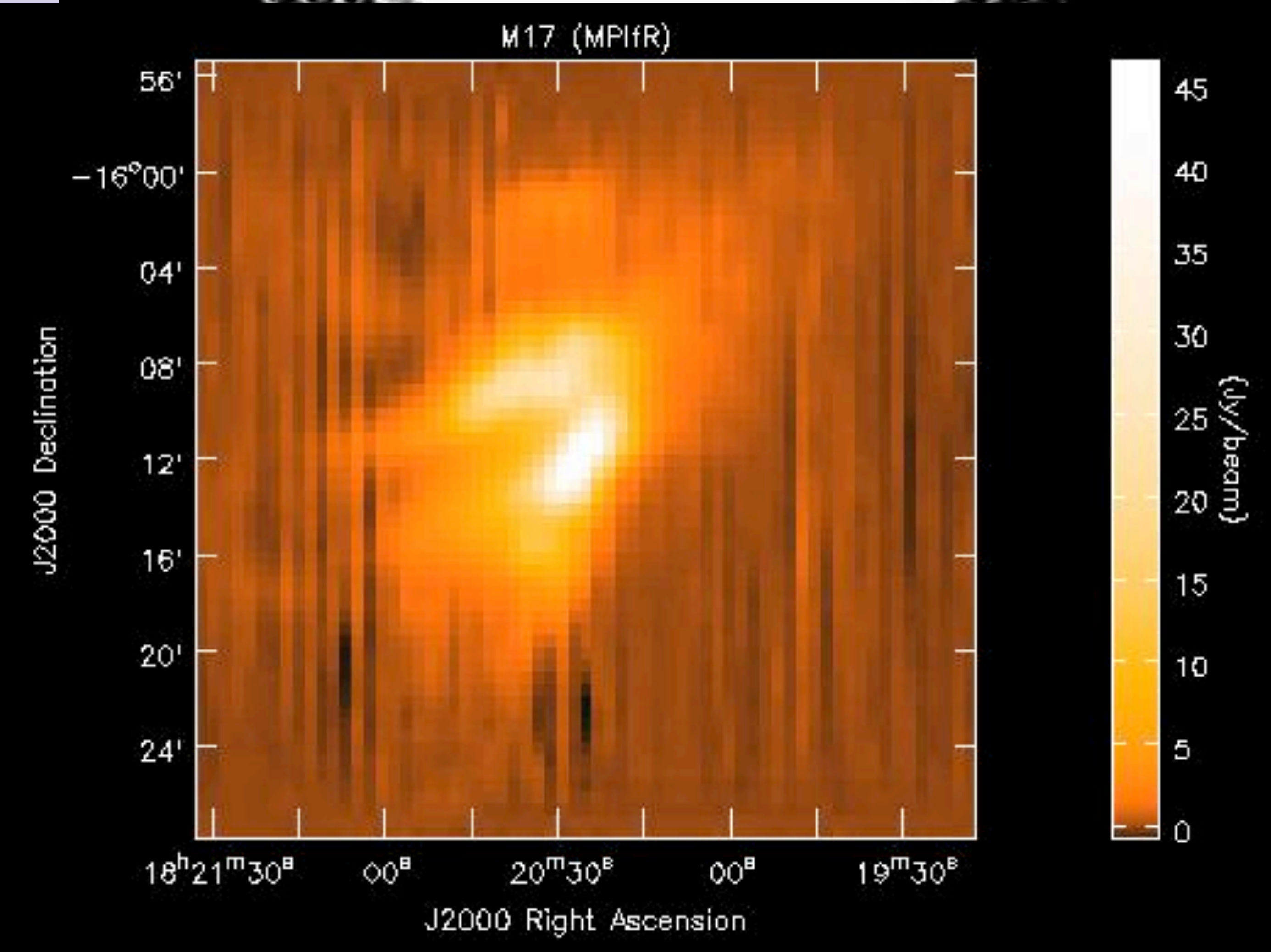
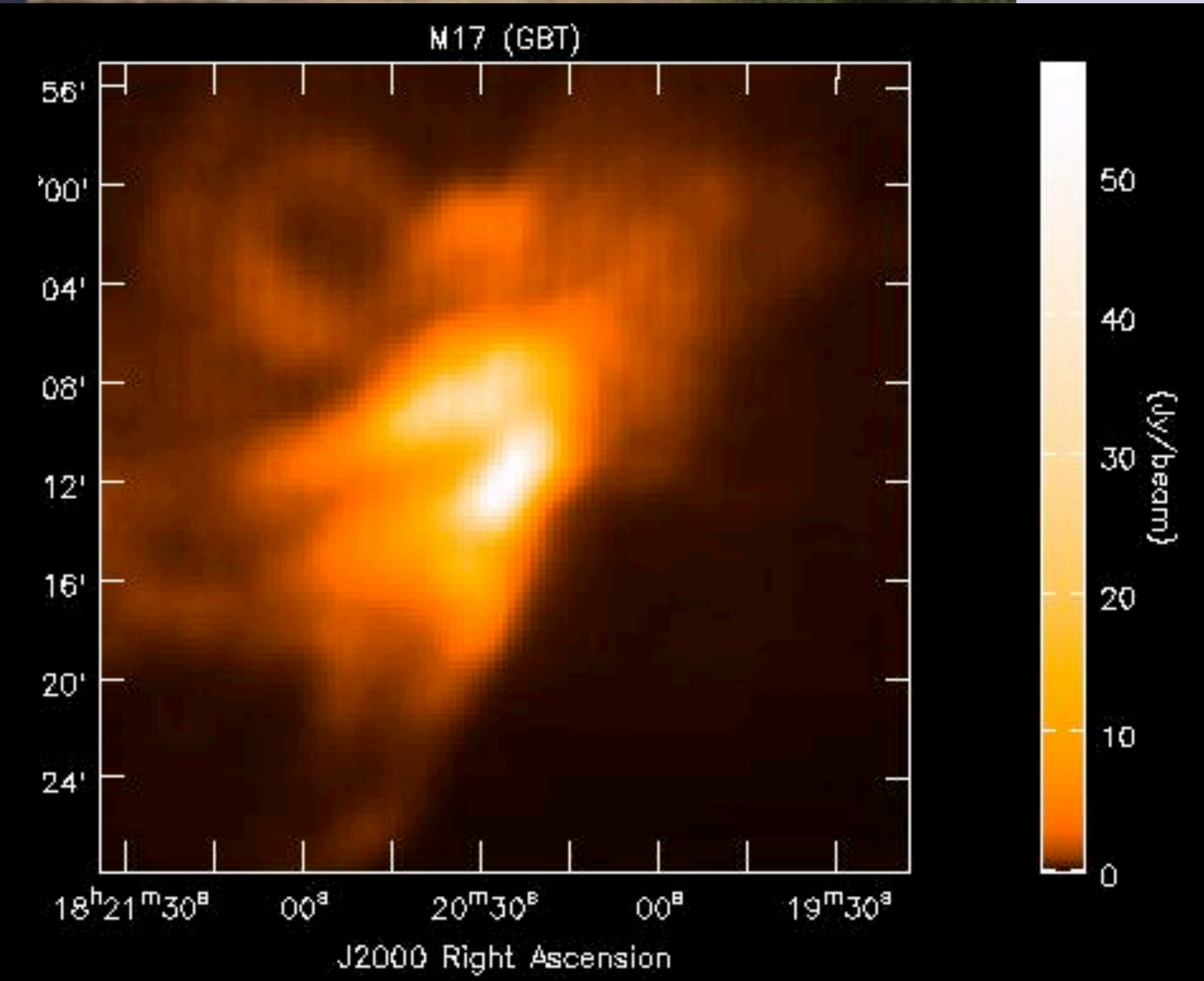
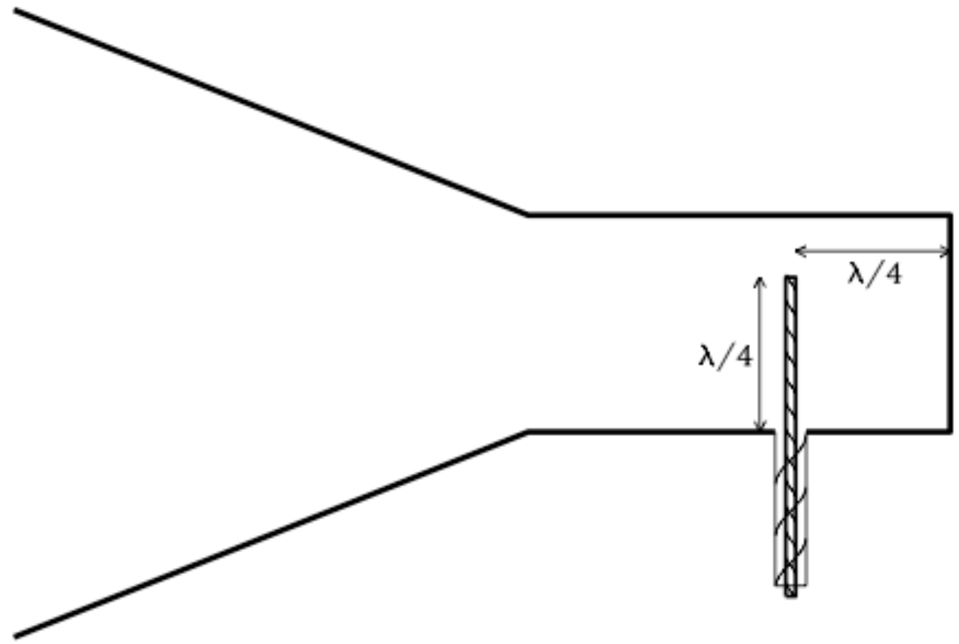






The marvelous radio receivers/detectors

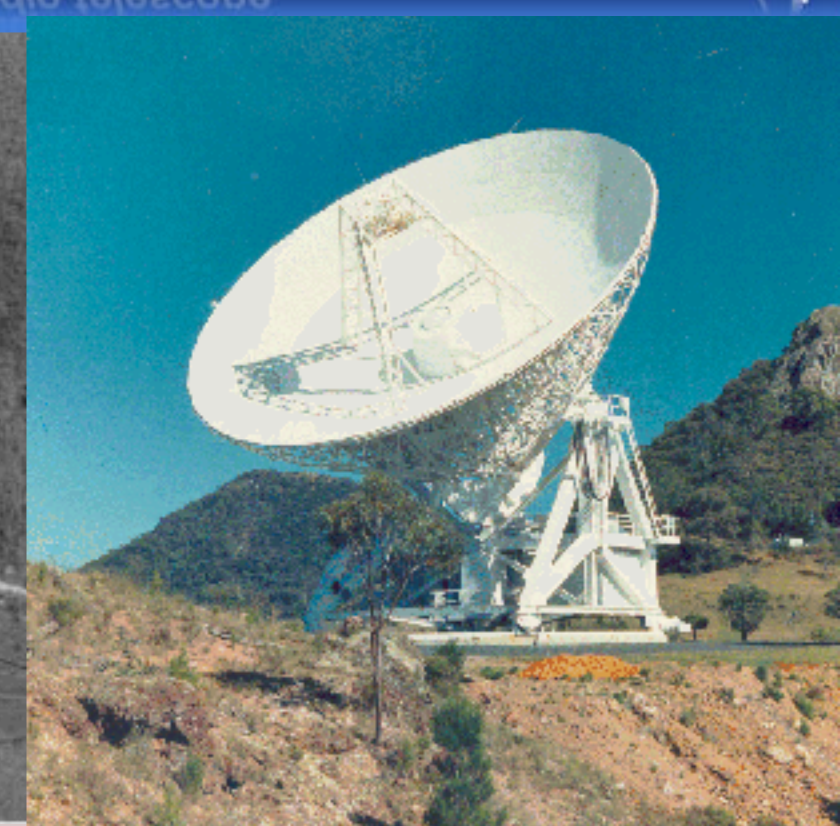


Most high-frequency feeds are quarter-wave ground-plane verticals inside waveguide horns. The only true antenna in this figure is the $\lambda/4$ ground-plane vertical, which converts electromagnetic waves in the waveguide to currents in the coaxial cable extending down from the waveguide.

From Condon & Ransom http://www.cv.nrao.edu/course/astr534







Talkin' about telescopes

Talkin' about telescopes

A radio telescope must:

Survive
Focus
Point
Track

So it has a

Mount
Surface
Optics
Receiver

Parkes 210-ft


Radio telescope