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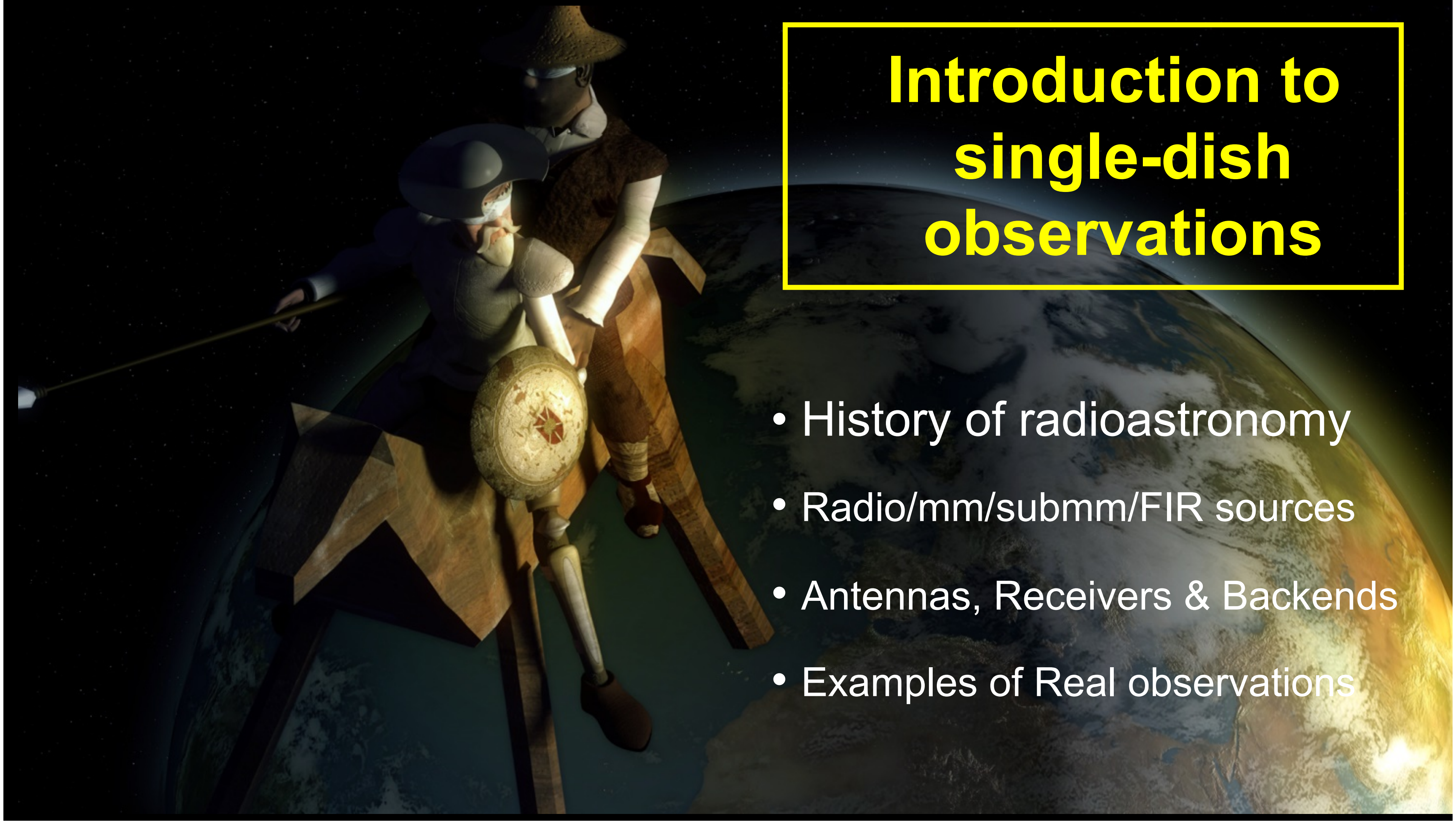
Mar/6, 2018

Consejo Superior de Investigaciones Científicas - Spain

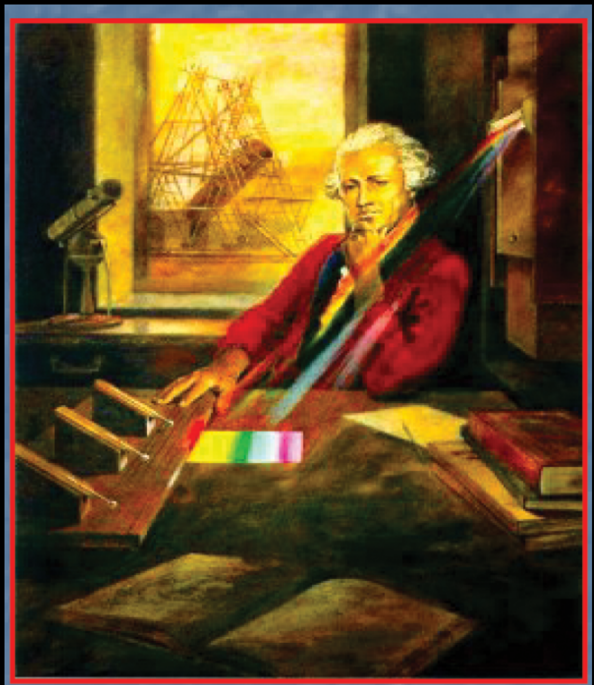
Introduction to single-dish observations



- History of radioastronomy
- Radio/mm/submm/FIR sources
- Antennas, Receivers & Backends
- Examples of Real observations

PART I: A quick walk though history…

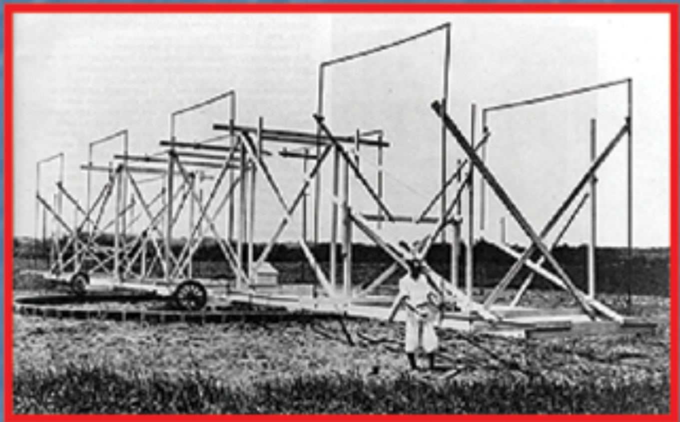
1800: First evidence of non-visible light

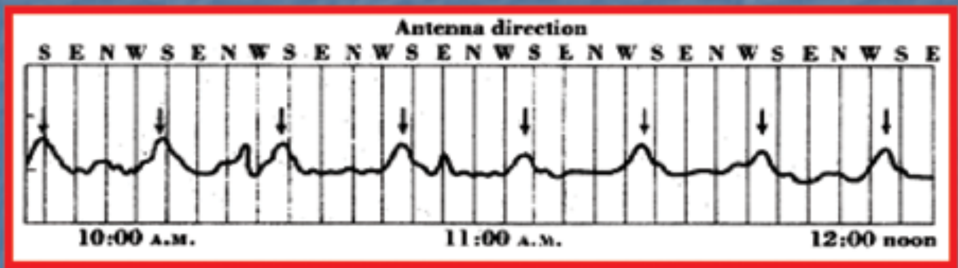


William Herschel noticed that the highest temperature was measured in a portion of the spectrum beyond the red where no sunlight was visible

INFRARED RADIATION

1931-32: The beginning of Radioastronomy





Bell Labs asks K. Jansky to investigate perturbations of radio voice transmission between USA and Europe. He builts an antenna of 30x4 m that rotates every 20 minutes. He discovers a “steady hiss static of unknown origin”.

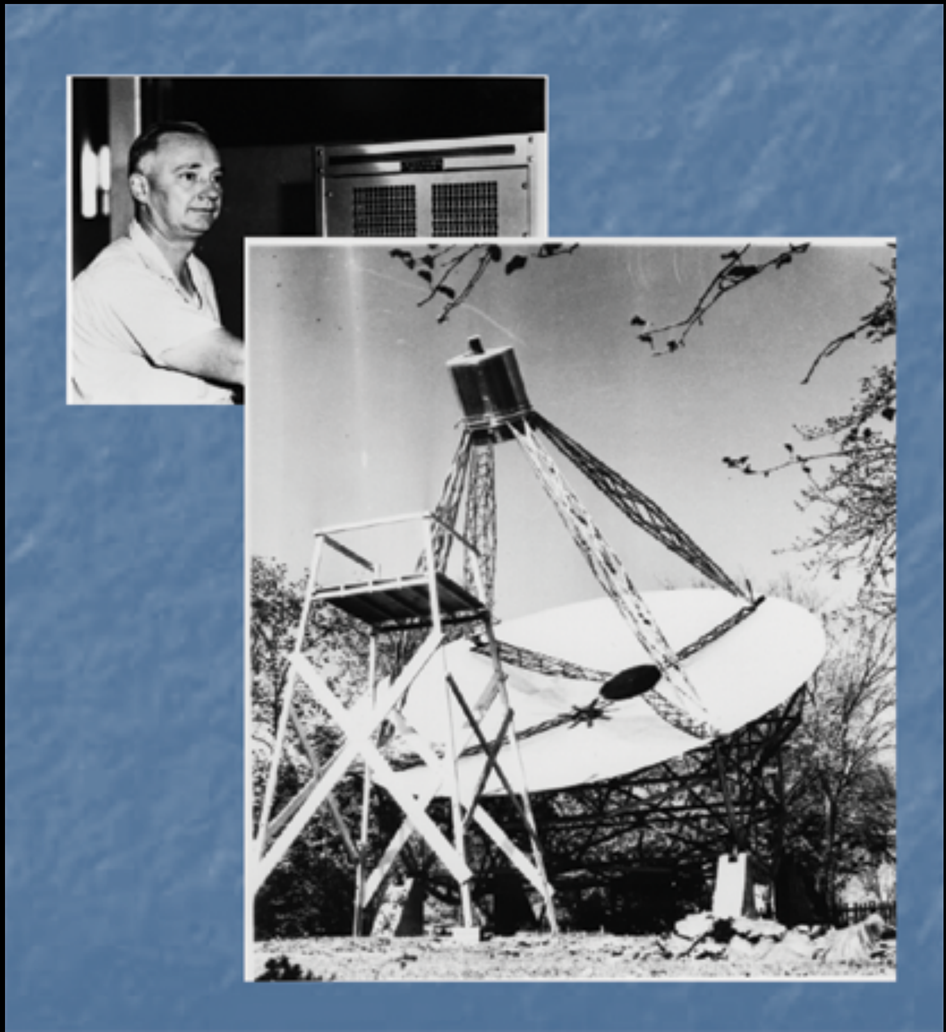
1933-35 Jansky solves mystery

The source of the radiation is established to be in a fixed direction of the sky with the following approximate coordinates:

RA: 18h dec: -10 deg

(The Galactic Center)

The followers: Reber

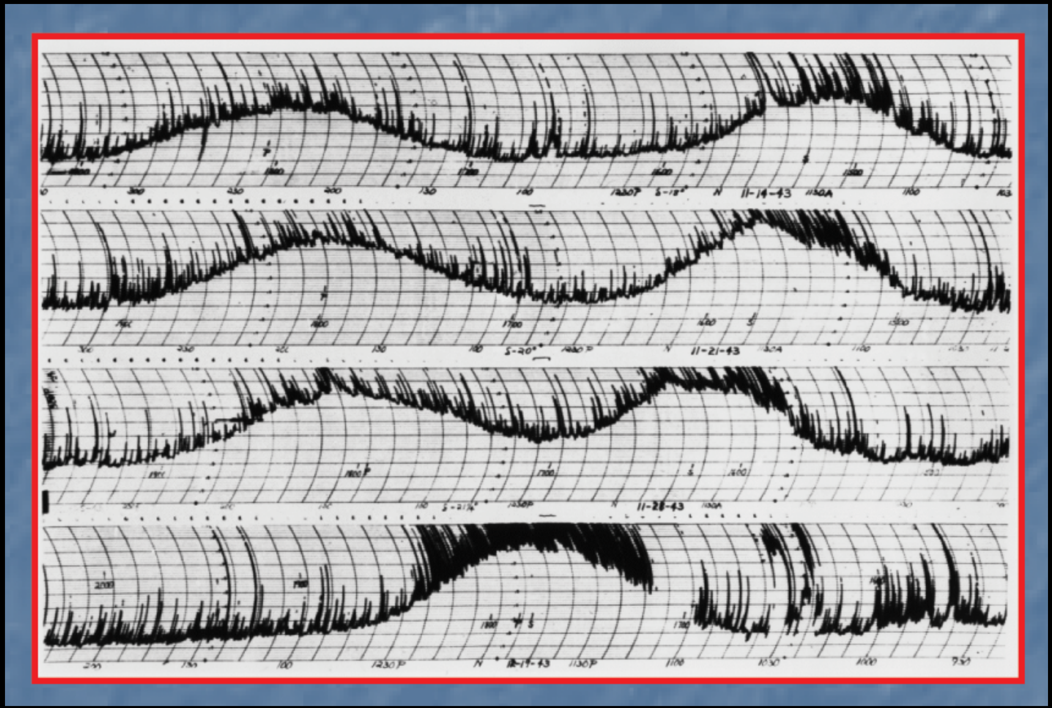


G. Reber was interested in investigating the nature of the signals revealed by Jansky's experiment. He could not get a job to do this due to great depression so he built this radiotelescope in his back yard.

Aprox. 10 m diameter, amplification of several million on the receiver placed within the cylinder at the focus. Signals recorded on a chart.

The parabolic design concentrates waves of all wavelengths to the same focus.

The first radio map of the Galaxy



First two receivers (3300 and 900 MHz failed to detect signals from outer space.

Finally, a third receiver at 160 MHz (1.9 meter wavelength made detection of the radio emission from the Milky Way and the Sun (broad features on the chart readings). Narrow peaks are due to interference with automobile engine sparks.

The first radio map of the Galaxy (II)

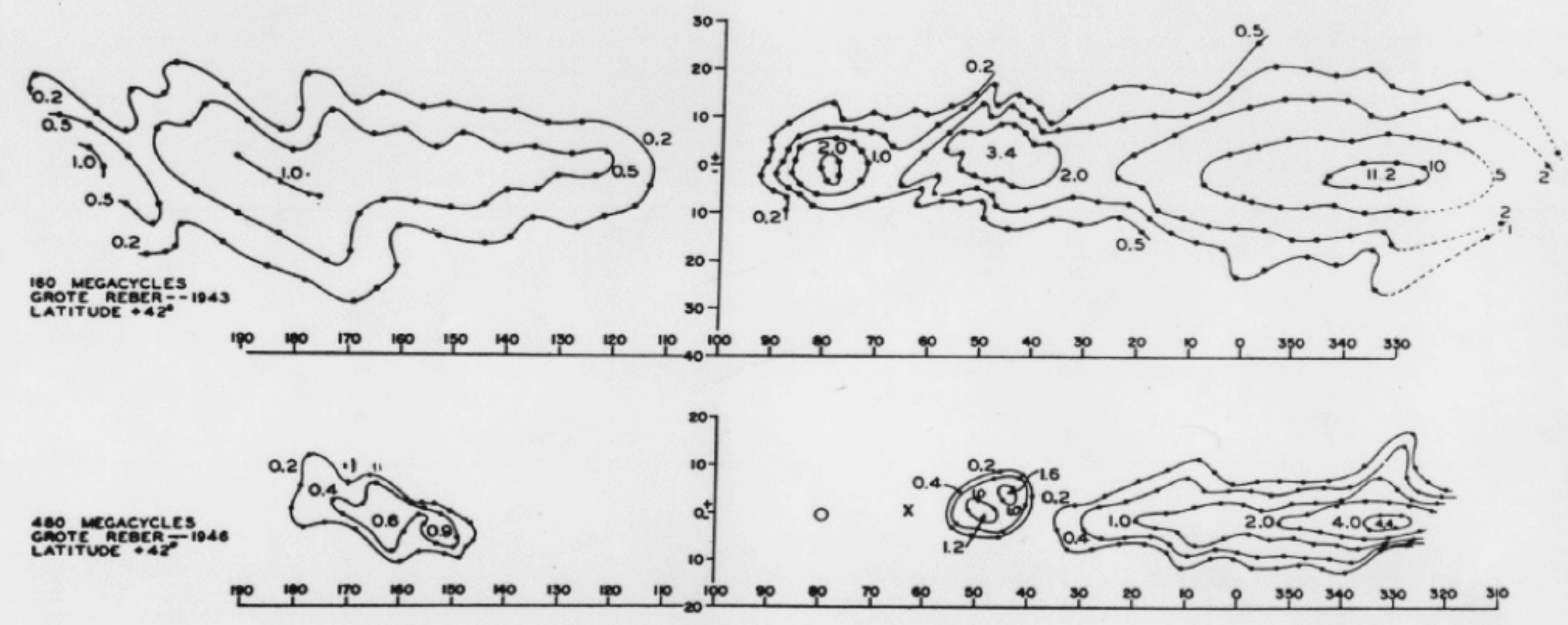


FIG. 7—Contours of constant intensity at 160 MHz and 480 MHz, taken at Wheaton, Illinois.

Reber presented his results in the form of contour diagrams showing that the brightest areas correspond to the Milky Way, specially towards its center. Other bright radio sources such as Cygnus and Cassiopeia were also discovered for the first time.

MOLECULAR SPECTRA

and

MOLECULAR STRUCTURE

I. SPECTRA OF DIATOMIC MOLECULES

BY

GERHARD HERZBERG, F.R.S.
National Research Council of Canada

With the co-operation, in the first edition, of
J. W. T. SPINKS, F.R.S.C.

SECOND EDITION

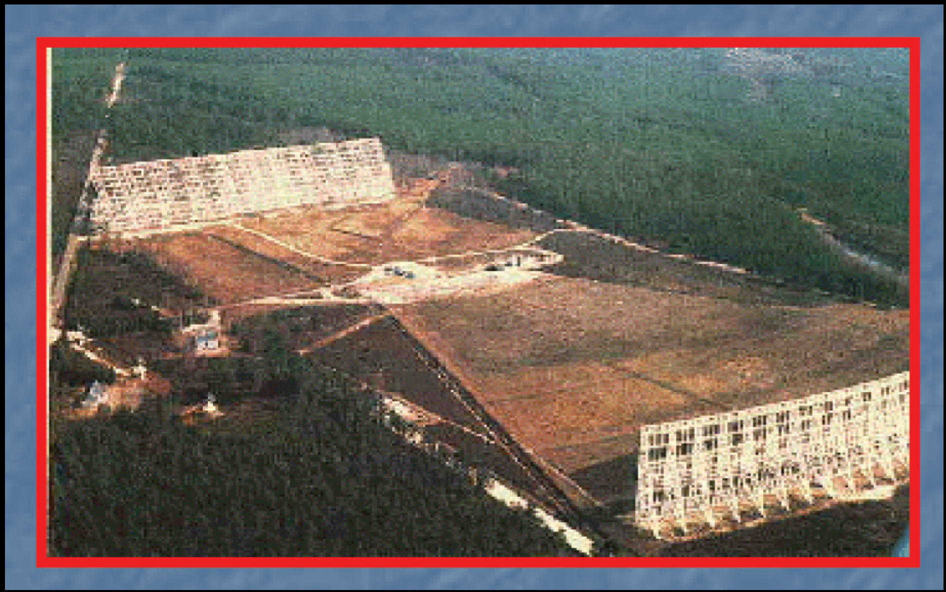
Molecular spectroscopy can lead to fundamental knowledge of the Universe

1950

The observation that in interstellar space only the very lowest rotational levels of CH, CH^+, and CN are populated is readily explained by the depopulation of the higher levels by emission of the far infrared rotation spectrum (see p. 4[illegible]) and by the lack of excitation to these levels by collisions or radiation. The intensity of the rotation spectrum of CN is much smaller than that of CH or CH^+ on account of the smaller dipole moment as well as the smaller frequency [due to the factor ν^4 in (I, 48)]. That is why lines from the second lowest level ($K = 1$) have been observed for CN. From the intensity ratio of the lines with $K = 0$ and $K = 1$ a rotational temperature of 2.3° K follows, which has of course only a very restricted meaning.

After World War II until the 70's

…essentially centimeter wavelengths

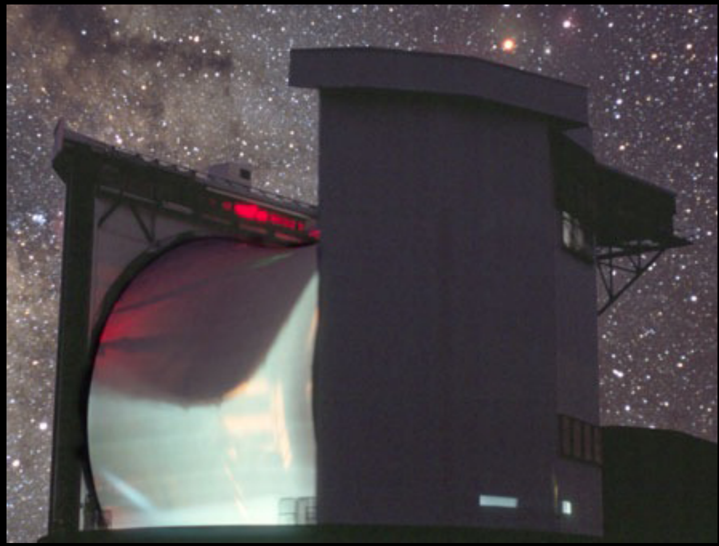


Nançay

Effelsberg

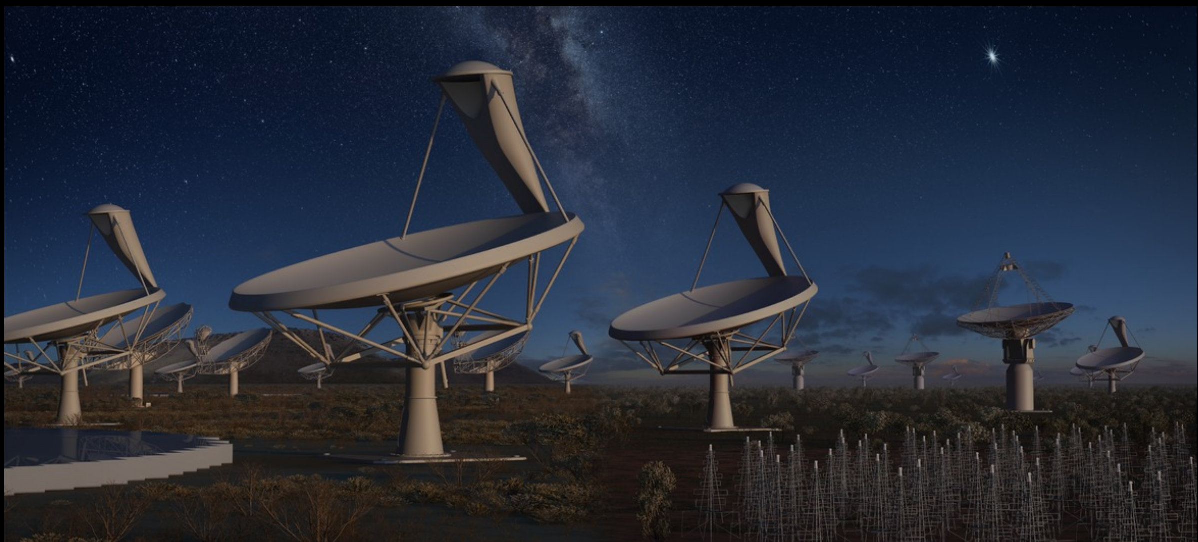
Present day falicilities:

millimeter and submillimeter single antenna



Present day falicilities:

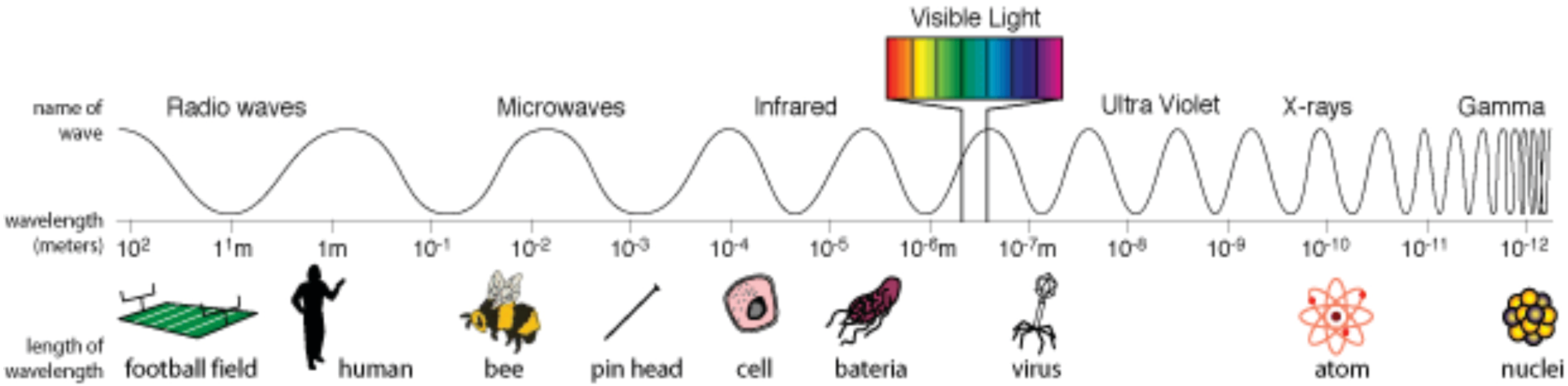
mm/submm interferometry and IR space telescopes



PART II: Sources of radio/mm/submm/FIR emission

Sources of Radio Emission

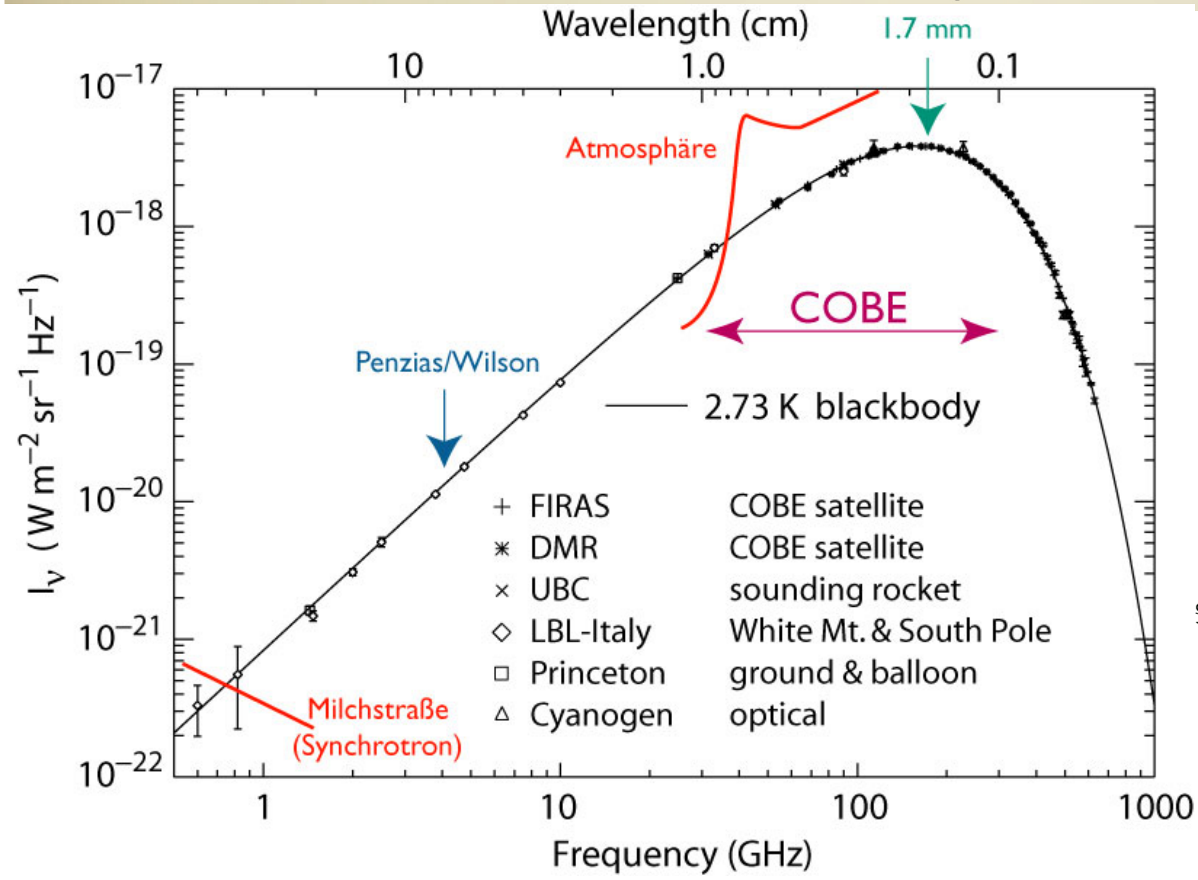
- Blackbody (thermal)
- Continuum sources (non-thermal)
- Spectral line sources

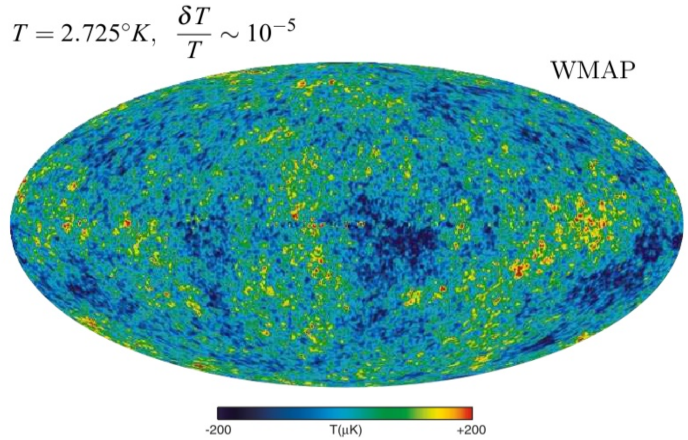


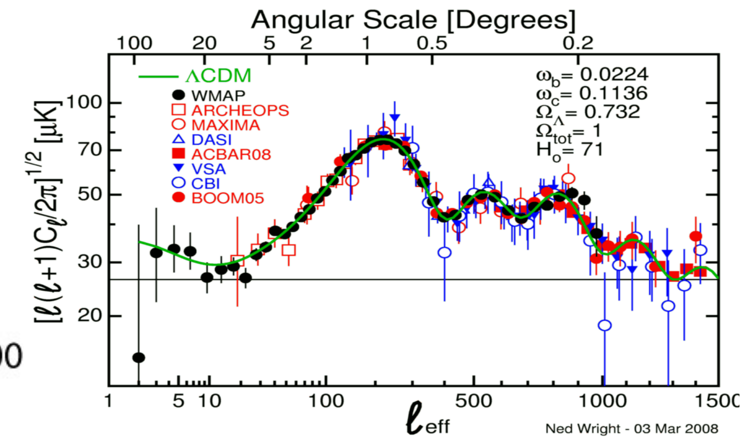
Blackbody Sources:

The cosmic microwave background, the planets

- Obs in cm requires low temperature: $\lambda_m T = 0.2898$ cm K
- Flux = const × ν^{α} × T
- For thermal sources α is ~2 (flatter for less opaque sources)





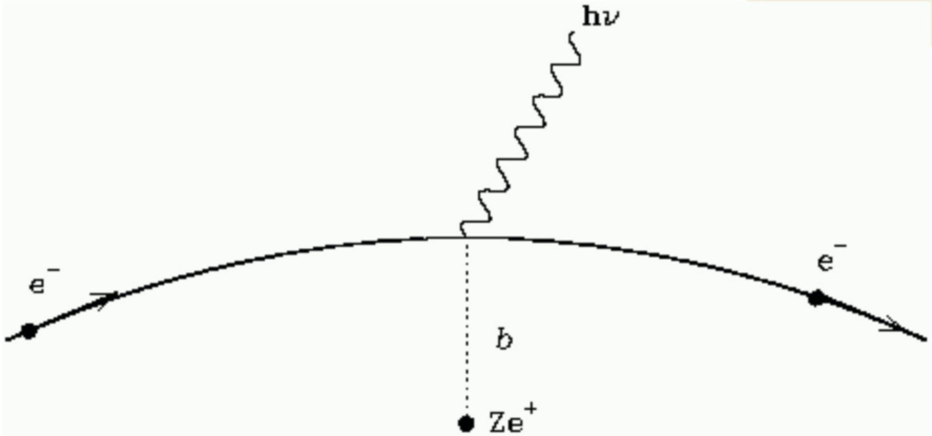


Continuum (non-thermal) Emission:

Emission at all radio wavelengths

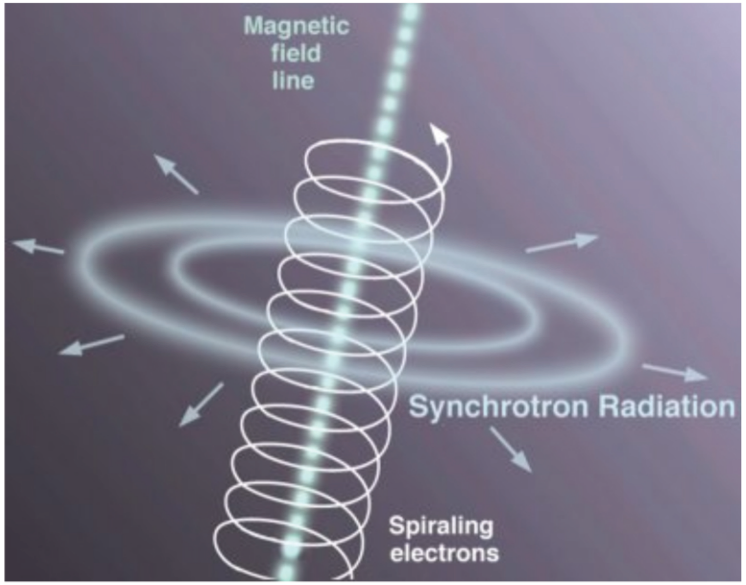
Bremsstralung (free-free):

Electron is accelerated as it passes a charged particle thereby emitting a photon



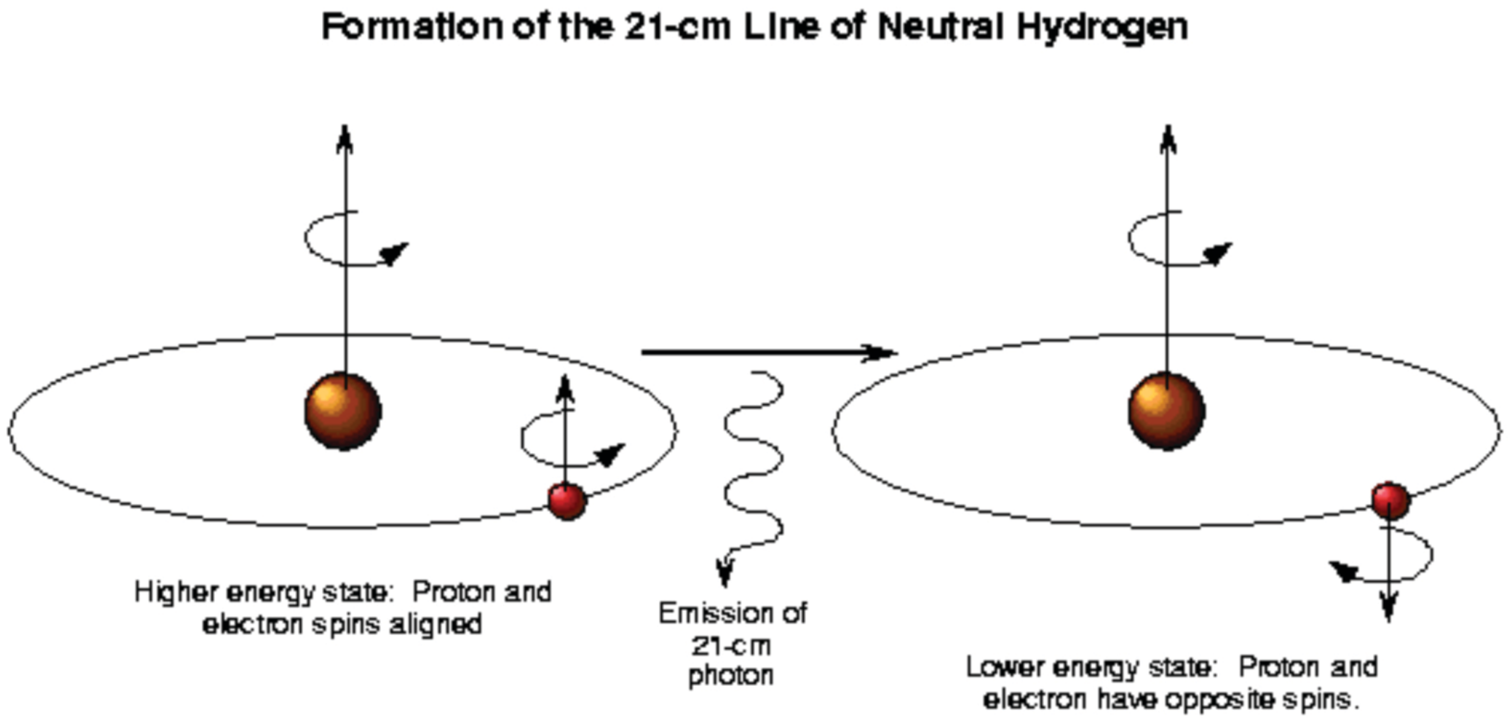
Synchrotron:

A charged particle moving in a magnetic field experiences acceleration and emits a photon



Radio Emission Lines

- Neutral hydrogen (HI) spin-flip transition
- Recombination lines (between high-lying atomic states)
- Molecular lines (CO, OH, etc.)



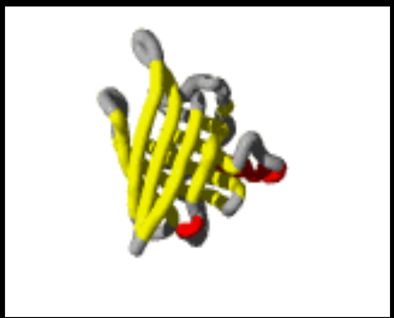
Spectroscopic lines

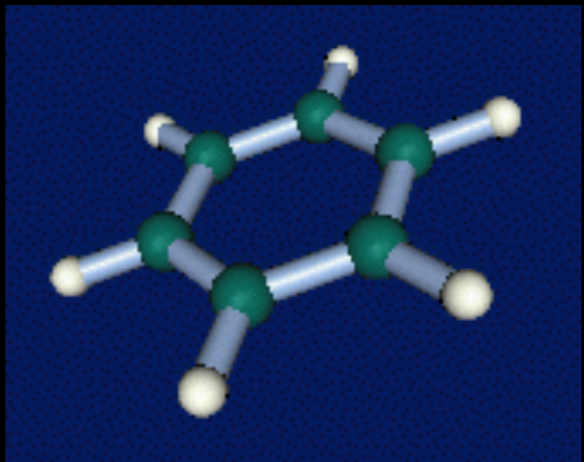
Energy, Frequency ($E=h\nu$)

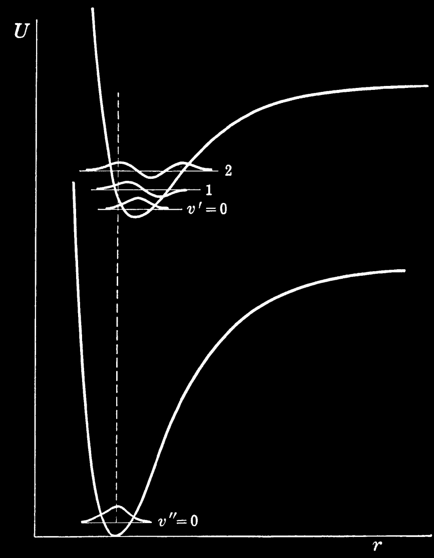
wavelength ($\lambda=c/\nu$)

3 Basic types of transitions

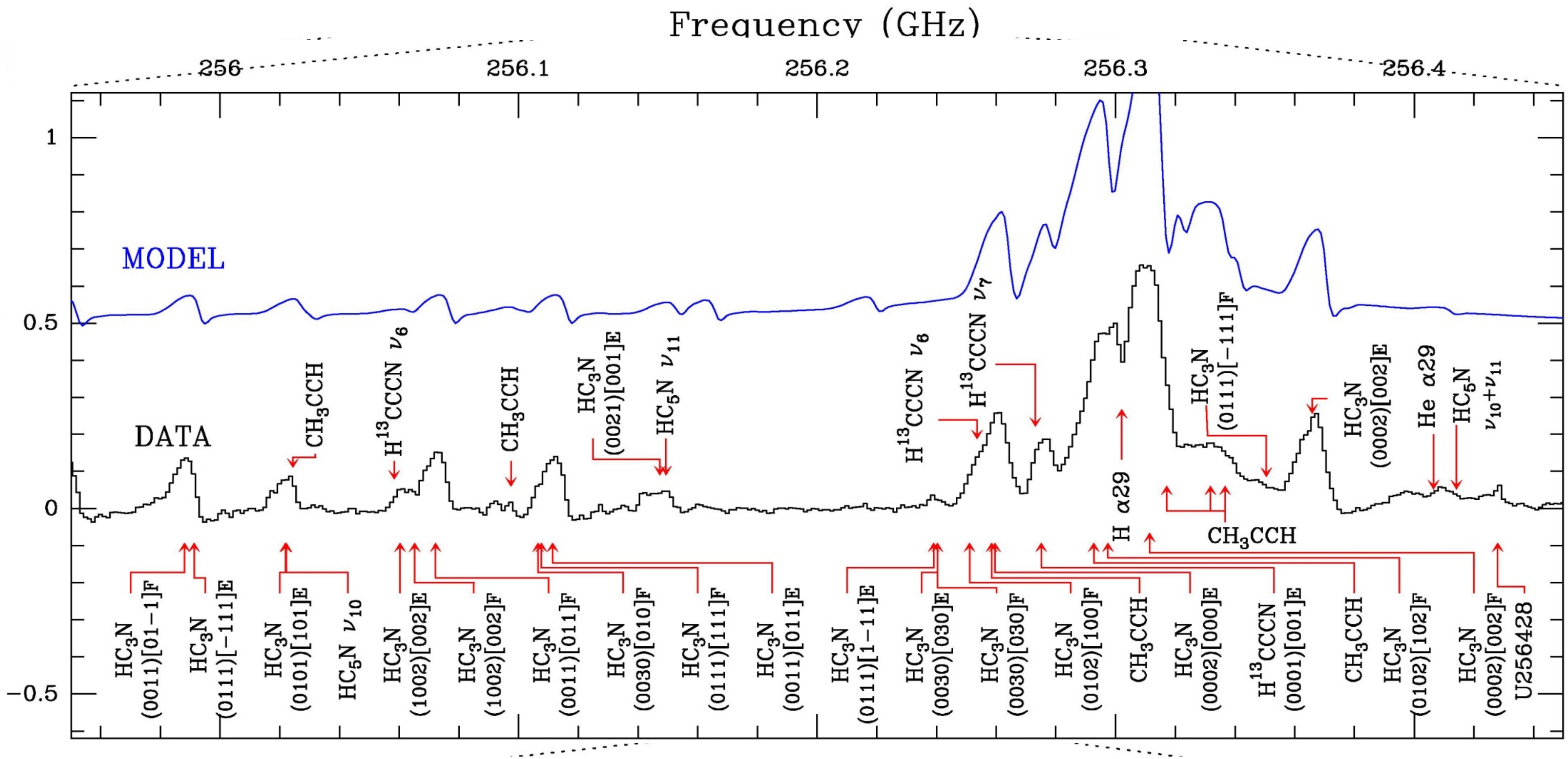
Rotational **Vibrational** **Electronic**







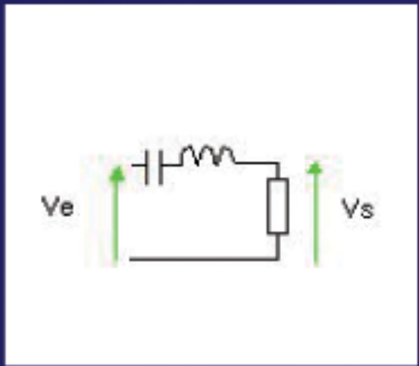
Rotational and ro-vibrational lines



PART III: Antennas, receivers and backends

Antennas: A simple model

An antenna is a RLC (resistance-inductance-condensator) circuit to which a voltage is applied to trasmit a signal.



R : Ohmic Losses

L : Self-indectance

C : charge accumulation

Free Regime :

$$\frac{d^2U}{dt^2} + \frac{R}{L}\frac{dU}{dt} + \frac{U}{LC} = 0$$

Analysis in harmonic modes: $U = U_0 e^{j\omega t}$

$$-\omega^2 + j\omega R/L + 1/LC = 0$$

Condition of signal propagation :

$$\frac{R^2}{L^2} - \frac{4}{LC} < 0$$

Cutoff frequency

$$\boxed{\omega^2 = \frac{1}{LC} - \frac{R^2}{4L^2}}$$

R=0 (no energy dissipation)

$R > 2(L/C)^{1/2}$ (no wave propagation)

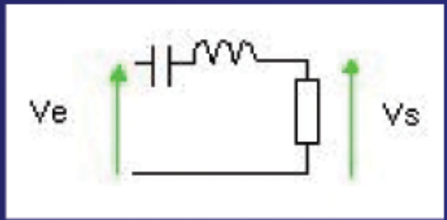
The Reciprocity Theorem

From Maxwell equations it is easy to demonstrate that if we have two antennas (1 and 2), if I1 and I2 are the total currents in antennas 1 and 2 respectively and U2 is the total voltage induced by antenna 2 in antenna 1 and U1 the total voltage induced by antenna 1 in antenna 2, then:

$$U_2 I_1 = U_1 I_2$$

From this it follows that it is always possible to formulate the properties of an antenna either as an emitter or as a receiver, without distinguishing between the two.

Noise: It is related to the power dissipated in a device due to the thermal agitation at temperature T



$\langle i \rangle = 0$

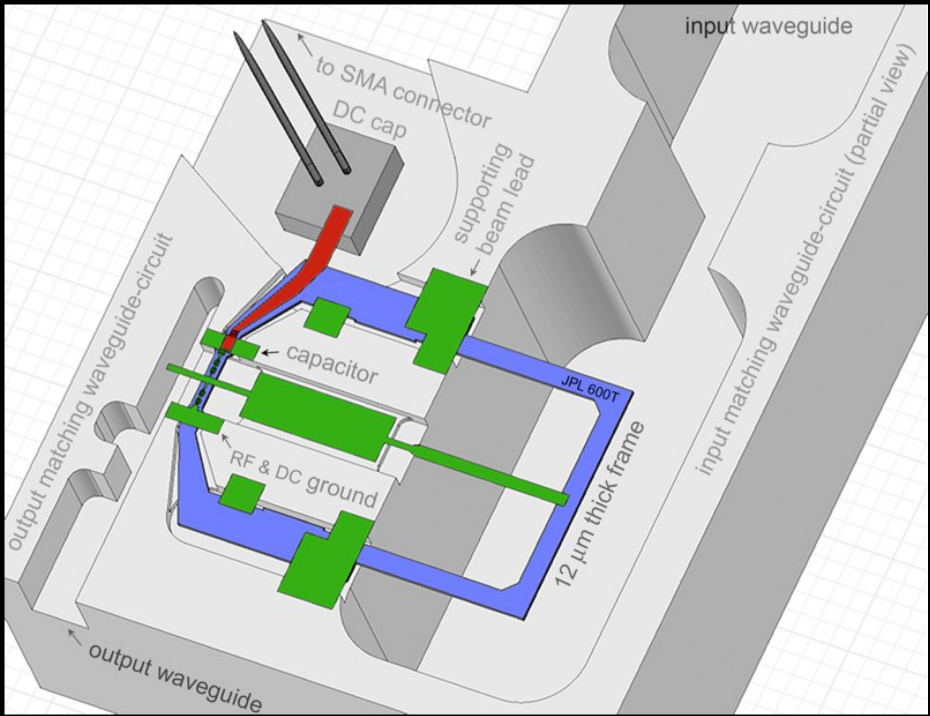
$\langle i^2 \rangle \neq 0$ **(e- thermal motion)**

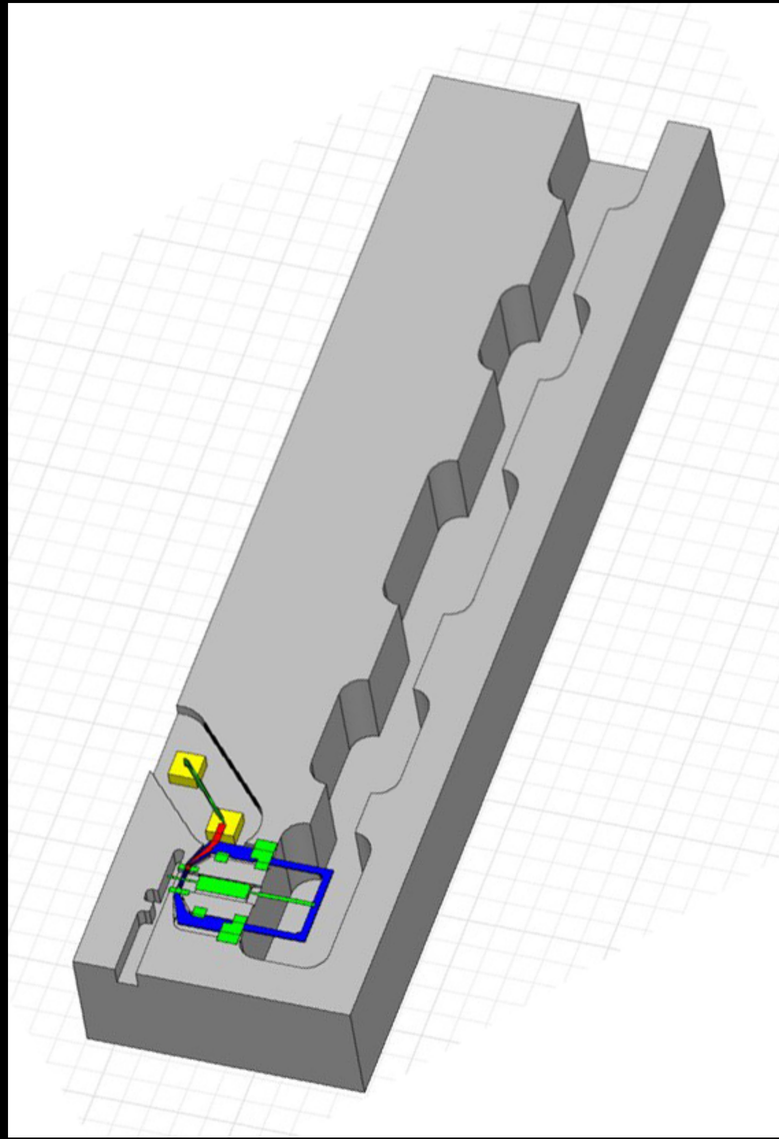
The power available in the resistance for dissipation is ½ kT. The larger the frequency range In which the dissipation takes place, the smaller the noise per unit frequency.

Nyquist (sampling theorem): Noise can be cancelled out if samples are taken and added frequently.

Antennas in practice

A radio telescope works as a collector. The radiation is focused into a feed horn in the focal plane. Inside there is a small device that is the real antenna. This element receives the guided wave and generates an output voltage.





Antennas in practice (II)

The reflector provides directivity and efficiency. These properties are mathematically contained in the beam pattern (the response of the antenna as a function of direction). By the reciprocity theorem, it is the same as a emitter or as a receiver.

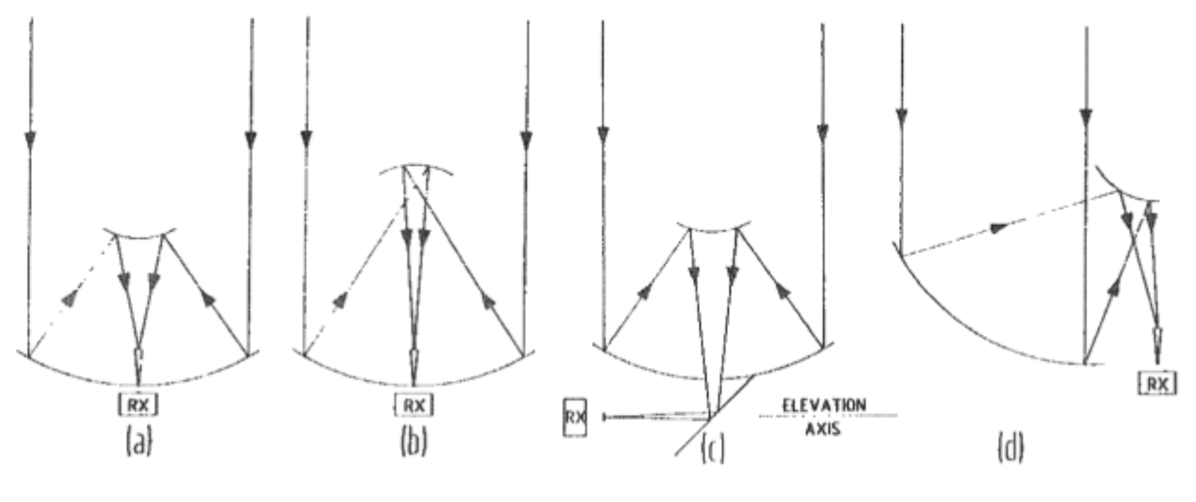
Types of reflectors

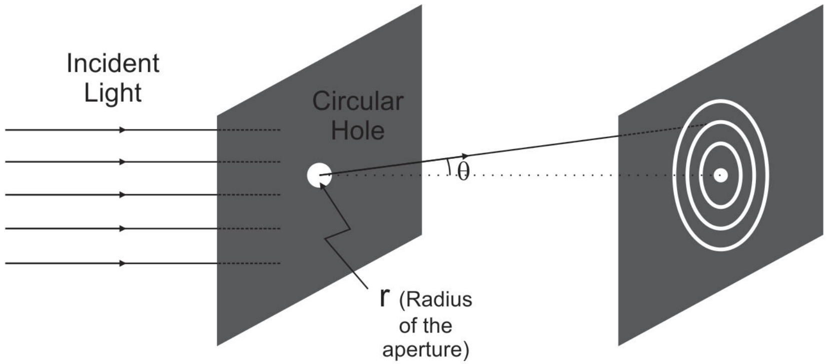
(a) Cassegrain

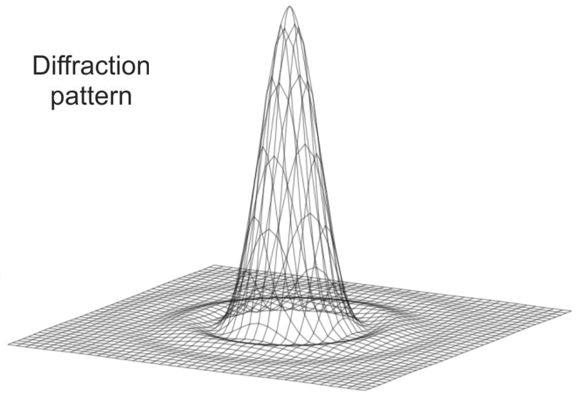
(b) Gregory

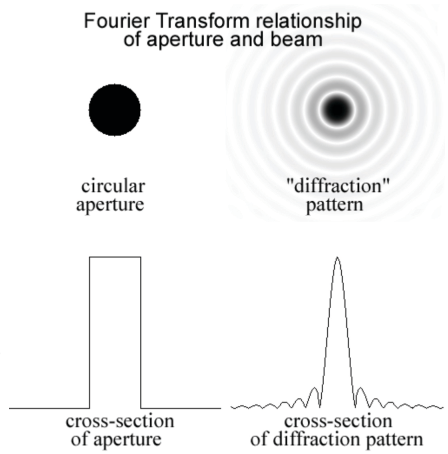
(c) Nasmith

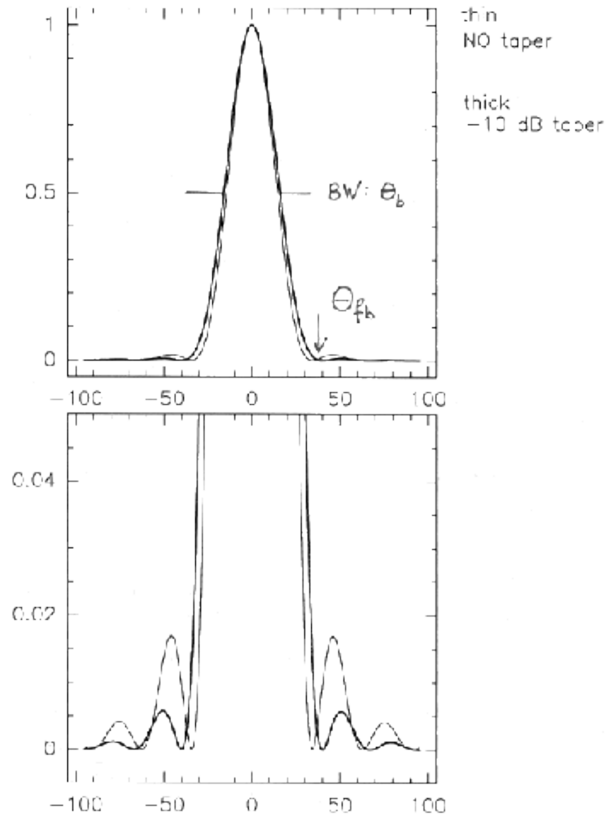
(d) Offset Cassegrain




Incident
Light
Circular
Hole
θ
r (Radius
of the
aperture)


Diffraction
pattern


Fourier Transform relationship
of aperture and beam
circular
aperture
"diffraction"
pattern
cross-section
of aperture
cross-section
of diffraction pattern

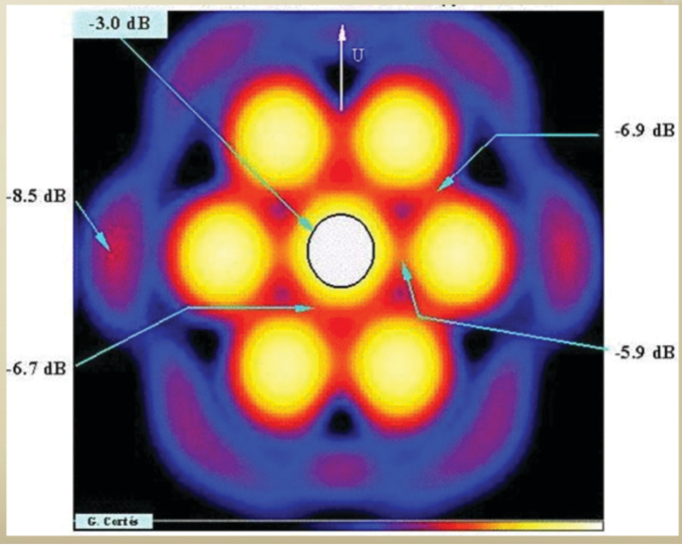

thin
NO taper
thick
−10 dB taper
BW: θ_b
1
0.5
0
0.04
0.02
−100
−50
50
100

Radio Telescope Characteristics
beam and sidelobes

- Diffraction pattern of telescope

  $\sin\theta = 1.22\ (\lambda/D)$

- Diffraction pattern indicates sensitivity to sources on the sky
- Uniformly illuminated circular aperture: central beam & sidelobe rings
- FWHM of central beam is called the *beamwidth*
- Note that you are sensitive to sources away from beam center



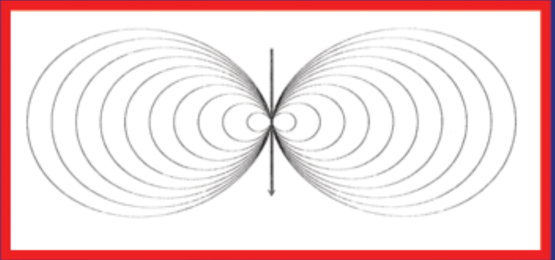
The Beam Pattern

- The case of the Hertz dipole:

at a distance r from the dipole, the radiated flux is (in the far-field)

$$|\langle \boldsymbol{S} \rangle| = |\mathrm{Re}(\boldsymbol{E} \times \boldsymbol{H}^*)| = \sqrt{\frac{\mu_0}{\varepsilon_0}} \left(\frac{I\,\Delta l}{2\,\lambda}\right)^2 \frac{\sin^2 \vartheta}{r^2}$$

The **power pattern** can be written as : $P(\Theta,\varphi) = P_0 \sin^2 \Theta$

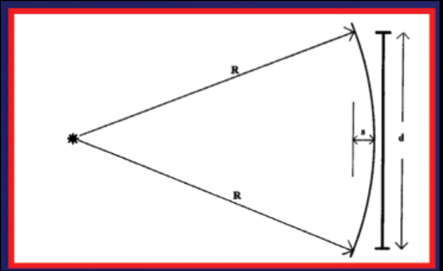


obviously anisotropic and axisymmetric !

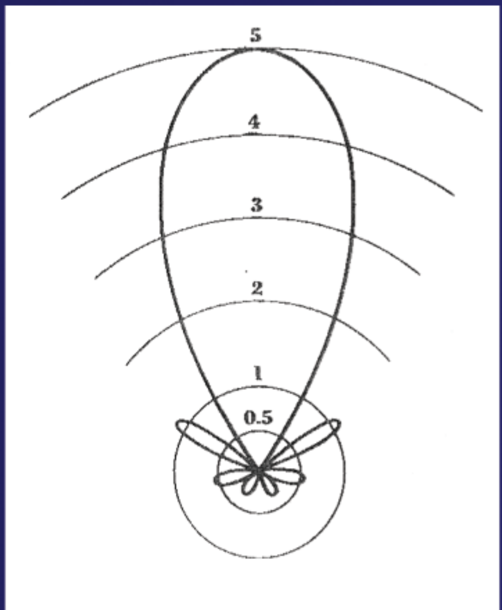
Normalized Power Pattern: $P_n(\Theta,\varphi) = P(\Theta,\varphi) / P_{max}$

- In real antennas the beam pattern has to be measured:

For that task in cm and mm wavelengths we use a radiosource of small diameter. An artificial source can also be used but it must be the far-field limit. For this the phase difference between the vertex and the edge of the reflector must be much less than π: This implies $\boxed{R >> D^2/4\lambda}$



Typical Astronomical Antenna Beam Pattern



Axisymmetrical pattern

Main lobe (largest maximum)

smaller (minor) **lobes : back and front**

Gain and Efficiency

- **Instead of dealing with Power distribution, one introduces the Gain distribution $G(\Theta,\varphi)$**

$$P(\Theta,\varphi) = P.\ G(\Theta,\varphi)$$

$$\int P(\Theta,\varphi)\, d\Omega = 4\pi\ P$$

Hertz Dipole :

$P(\Theta,\varphi) = P_0 \sin^2\Theta$ and $Pn(\Theta,\varphi) = \sin^2\Theta$ $\rightarrow G(\Theta) = 3/2 \sin^2\Theta$

Antenna Beam Solid Angle

$$\Omega_A = \int_{4\pi} P_n(\Theta,\varphi)\, d\Omega = \int_0^{\pi}\int_{-\pi/2}^{\pi/2} P_n(\Theta,\varphi)\ \sin\Theta\, d\Theta\ d\varphi$$

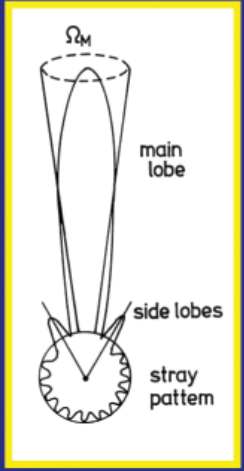
Solid angle of antenna with $P_n = 1$ inside Ω_A

=0 elsewhere

Main-beam solid angle

The main region is the region where $P_n(\Omega) > 0.5$

$$\Omega_{mb} = \int_{\text{Main Beam}} P_n(\Theta,\varphi)\, d\Omega$$

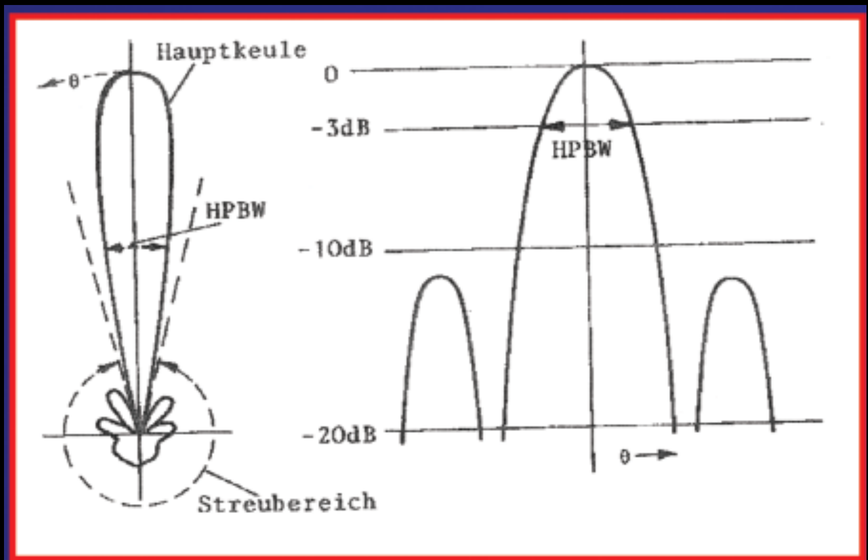


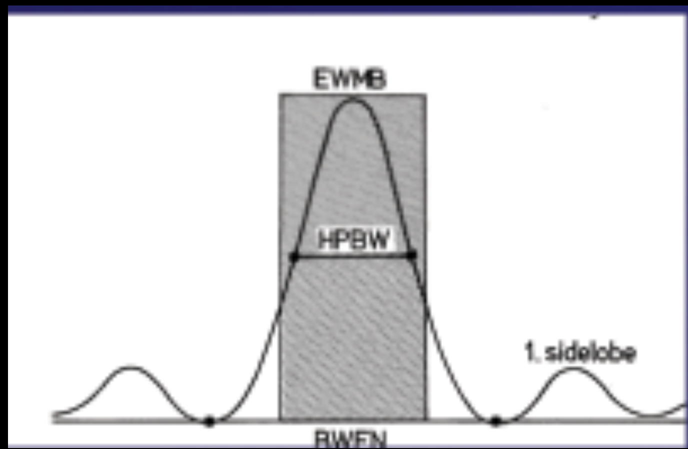
Gain and Efficiency (II)

Main Beam Efficiency $B_{eff} = \frac{\Omega_{MB}}{\Omega_A}$

It is desirable that the beam pattern is concentrated on the main beam as much as possible. The closer B_{eff} to 1, the better.

Half power beam width





Aperture efficiency

P_c = amount of power collected by an antenna illuminated by a plane wave with power density $|\mathbf{S}|$.

Effective aperture A_e: equivalent surface detecting P_c

In pratice, $A_e \neq$ geometrical surface of the antenna = $A_g = \pi D^2/4$

Aperture Efficiency

$$\eta_A = \frac{A_e}{A_g}$$

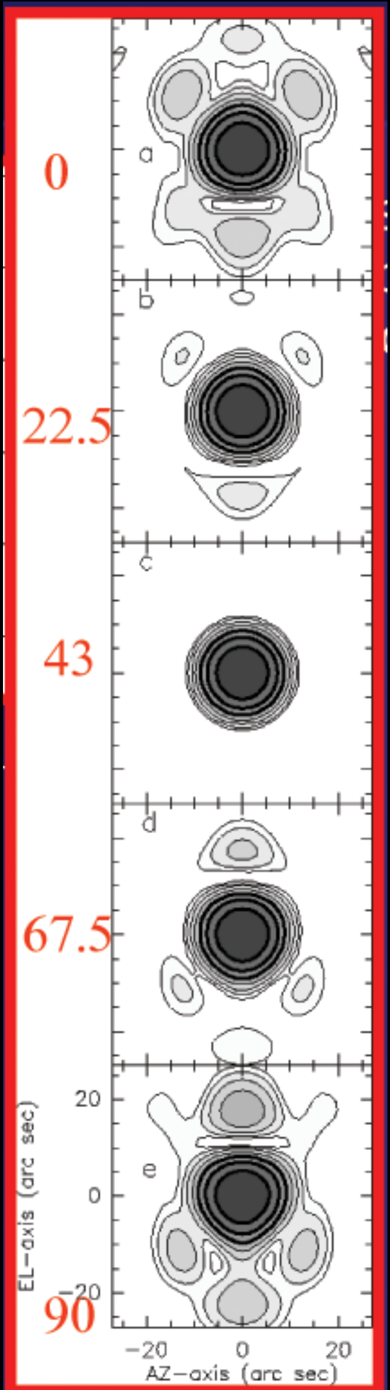
The effective aperture efficiency usually depends on the relative orientation of the antenna and the illuminating radiation. The effective aperture efficiency and the antenna beam solid angle are related via :

$$A_e \cdot \Omega_A = \lambda^2$$

ANTENNA TEMPERATURE: Is a measure of the power absorbed by the antenna:

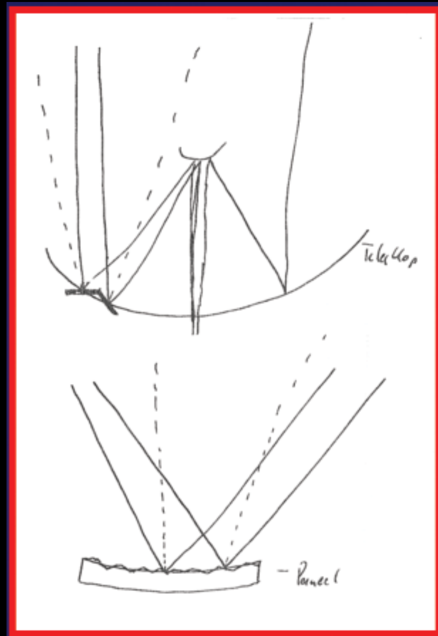
$$T_A = \frac{\eta_R}{\Omega_A} \iint \frac{\lambda^2}{2k} B(\Theta,\varphi).\ P_n(\Theta_0-\Theta,\varphi_0-\varphi)\, d\Omega$$

In an ideal, loss-free radio telescope, the antenna temperature is equal to the brightness temperature if the intensity of the received radiation is constant within the lobe.Temperatures are used in radioastronomy to express power because of the validity of the Rayleigh-Jeans approximation.

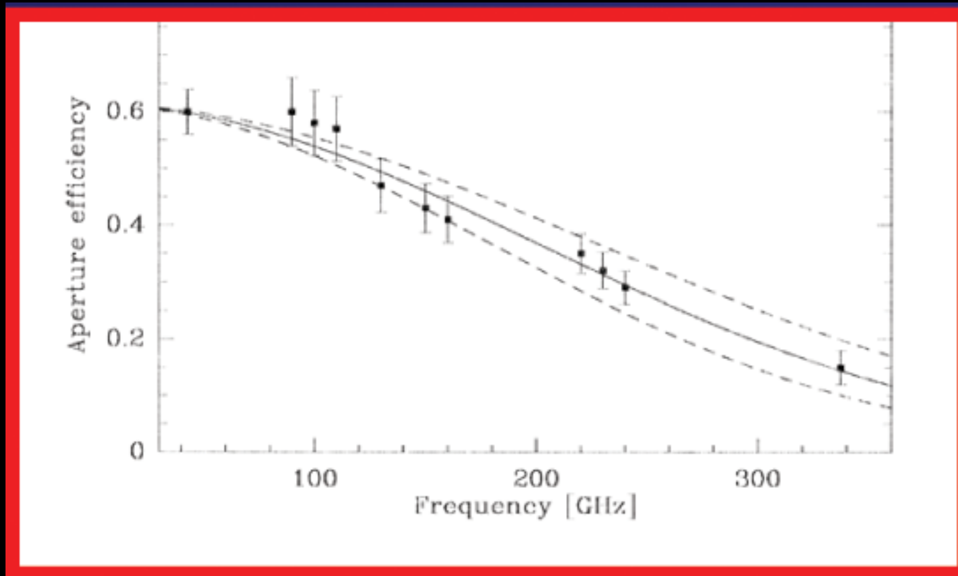


Telescope deformations and beam pattern

Surface imperfections



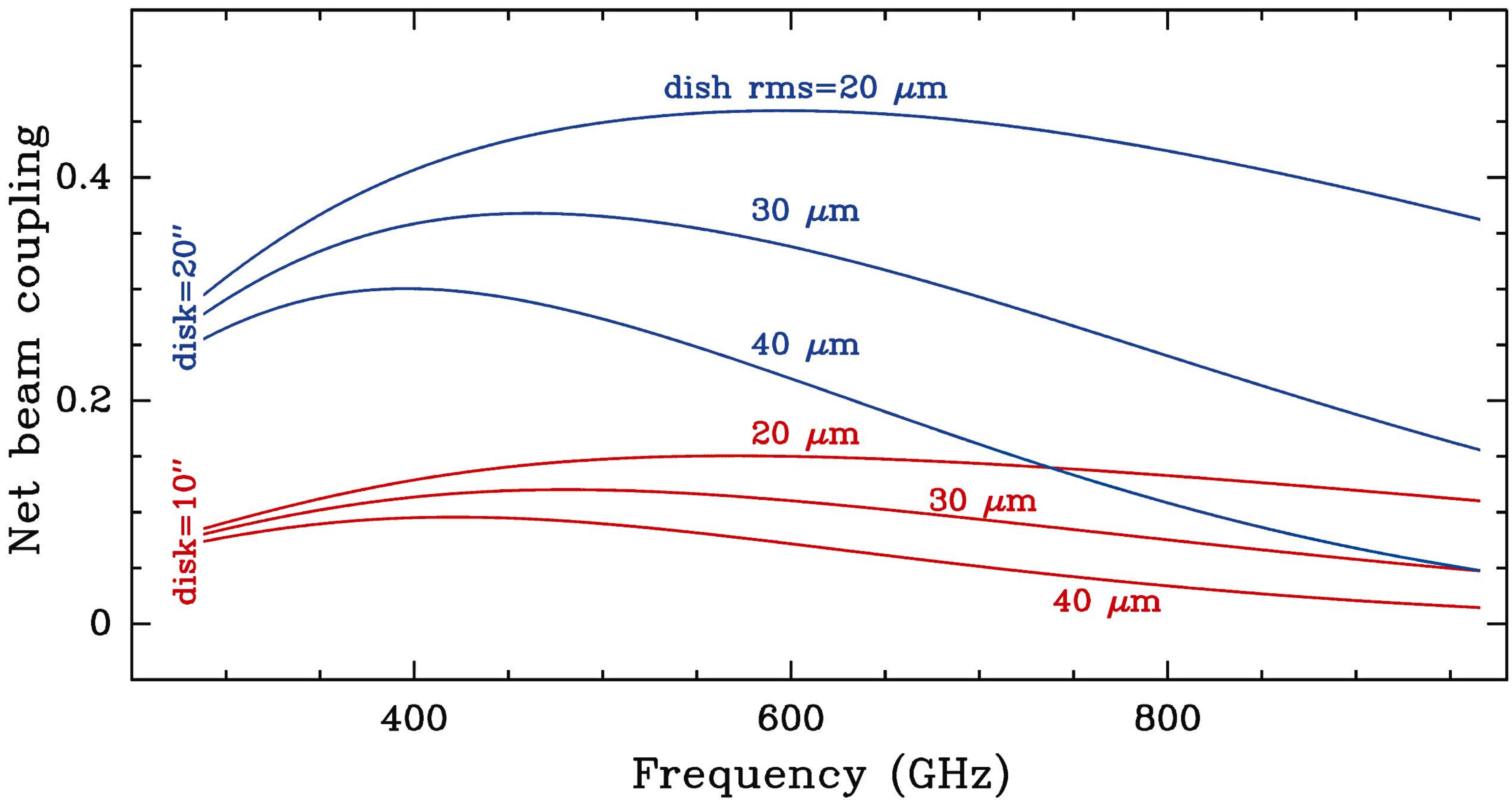
(Error beam)



Aperture efficiency varies as:

$\eta_A = \eta_{A0}.\exp((4\pi\varepsilon/\lambda^2)^2)$

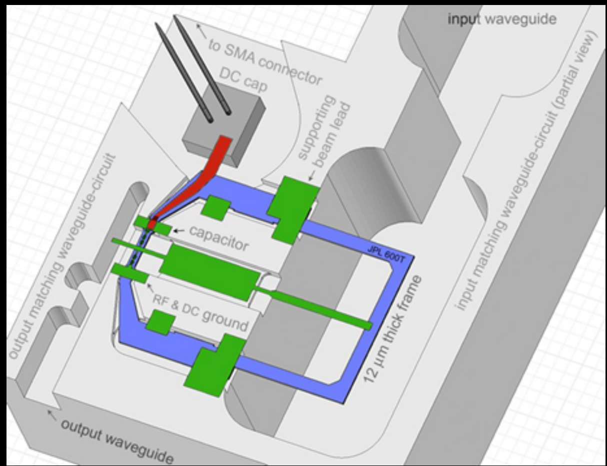
Coupling + loses net effect

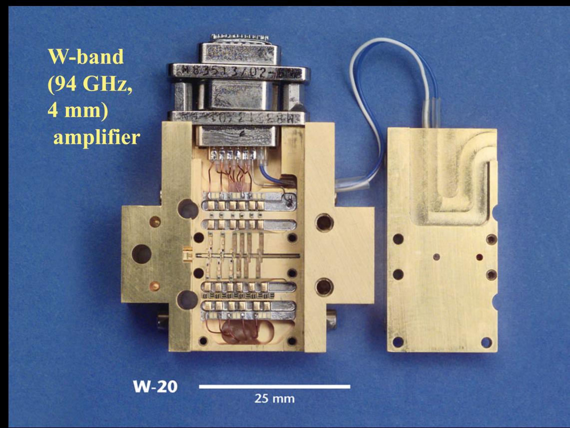


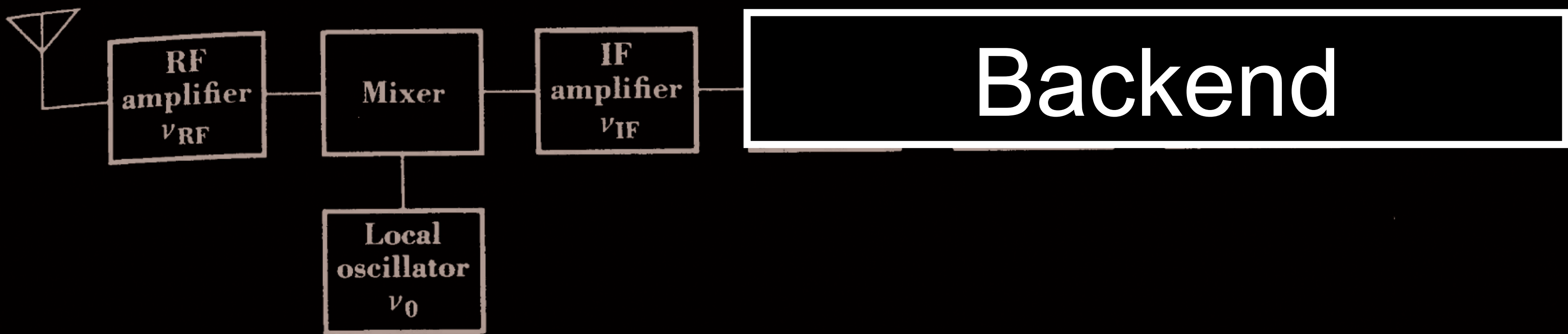
Antenna: Transition region between the free-space propagating wave and the guided wave

What is a Radiotelescope?

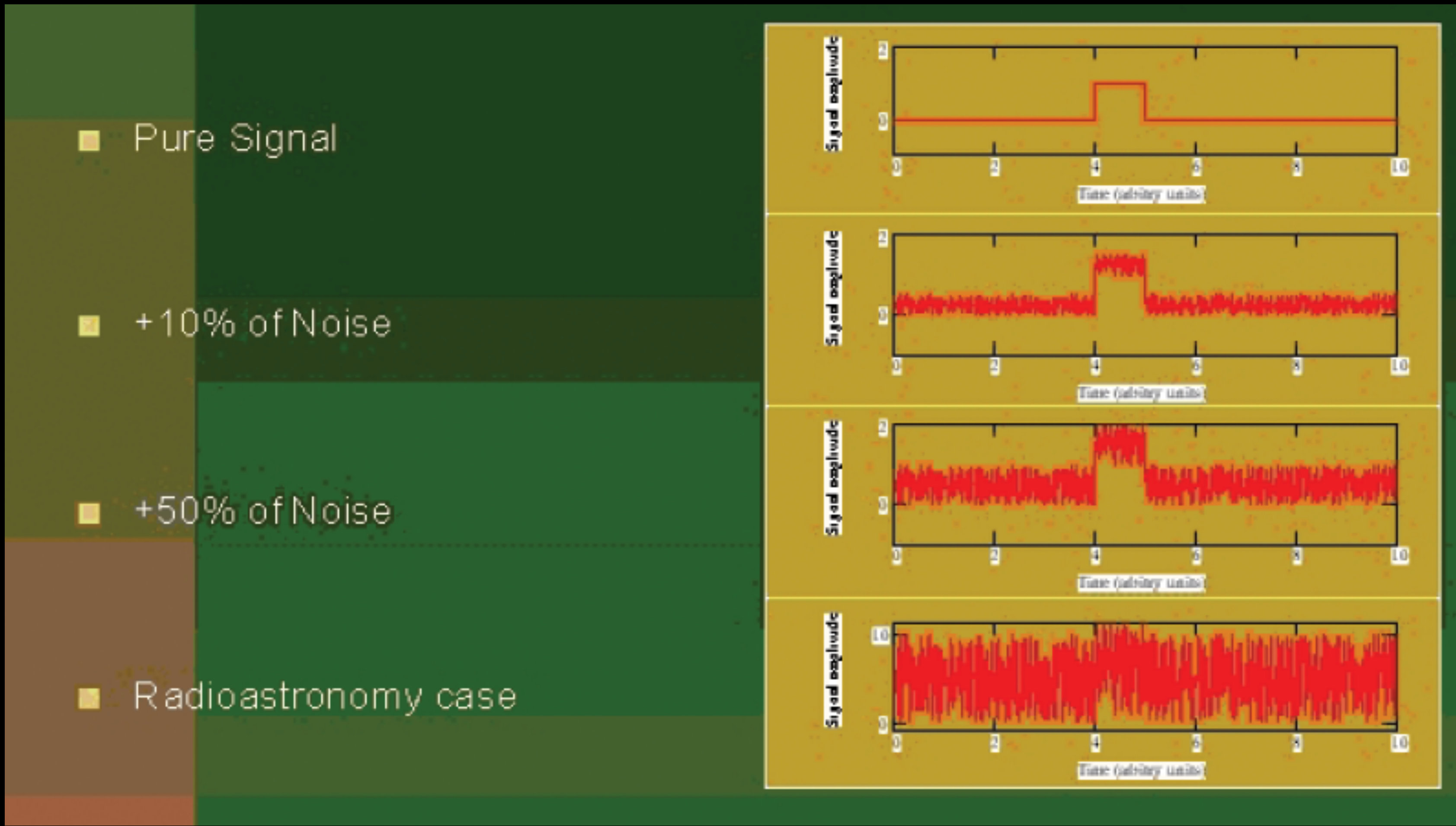
…a watt meter (amplification to be achieved ~ 10^{10} (signals are extremely week)



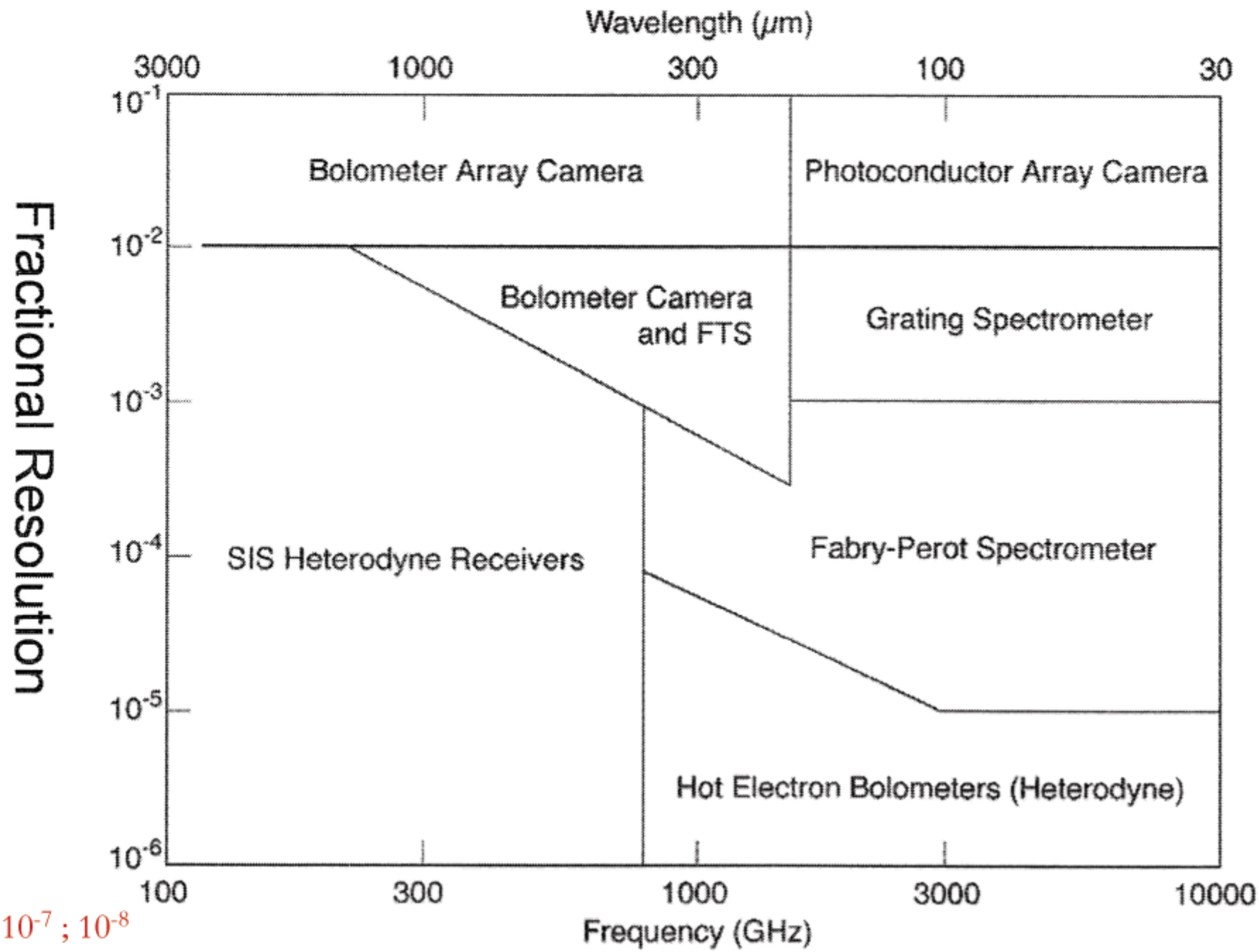




The peculiar case of radioastronomy



High sensitivity (amplifications od the order of 10^{10}) and high spectral resolution ($R \sim 10^{-7}$) required.


Wavelength (μm)
3000
1000
300
100
30
10-1
10-2
10-3
10-4
10-5
10-6
Fractional Resolution
Bolometer Array Camera
Photoconductor Array Camera
Bolometer Camera and FTS
Grating Spectrometer
SIS Heterodyne Receivers
Fabry-Perot Spectrometer
Hot Electron Bolometers (Heterodyne)
100
300
1000
3000
10000
Frequency (GHz)

10^{-7} ; 10^{-8}

Receiver noise and detectability limit

The detection limit is given by the thermal power fluctuations of the system. That includes hardware elements like the receiver itself but also the atmospheric fluctuations. The resulting noise is of gaussian type.

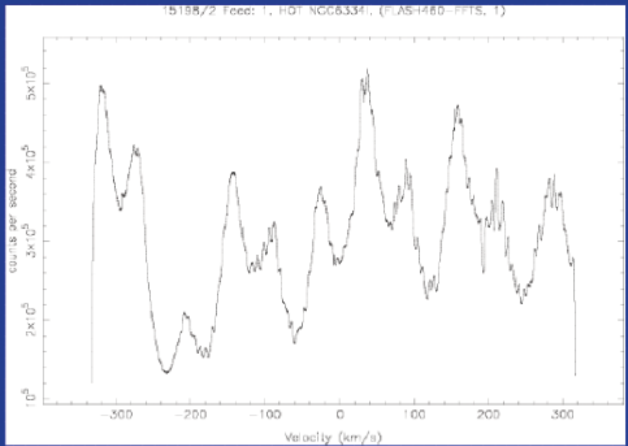
$$\Delta T_{rms} = \frac{T_{sys}}{(\Delta\nu \,.\tau)^{1/2}}$$

However the receiver suffers from gain fluctuations that are not gaussian. These fluctuations must be calibrated out by taken frequent reference scans on a referent load.

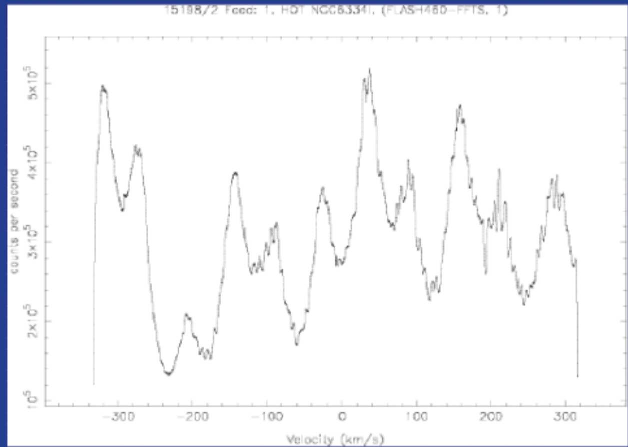
PART IV: Real Observations

Example of a calibration scan

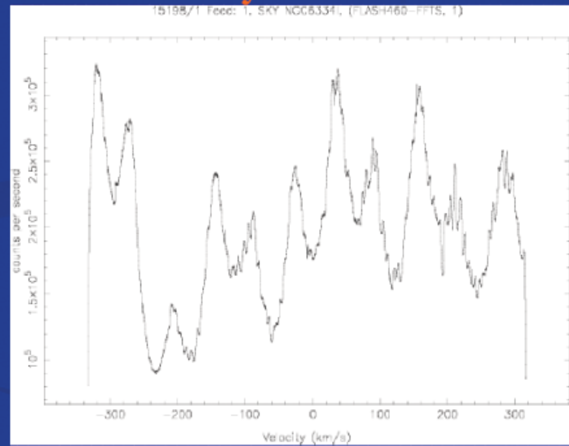
Cold Load



Hot Load

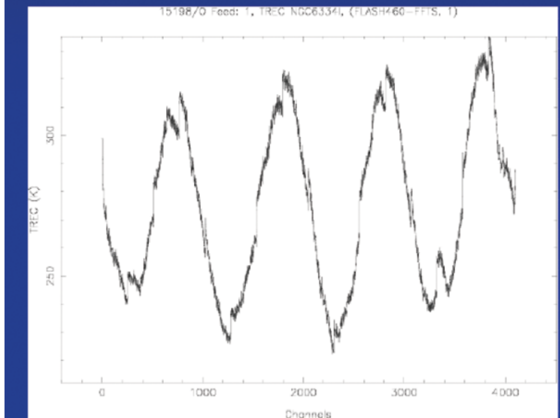


Sky

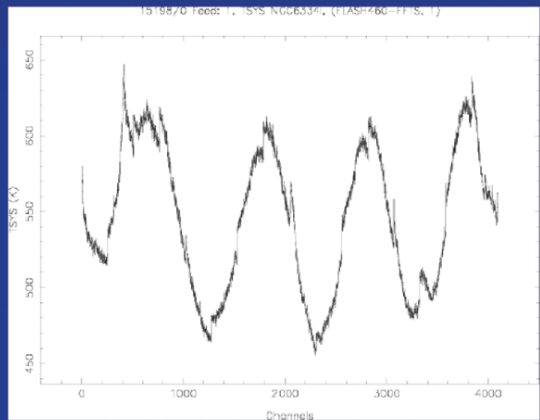


Emission dominated by the Receiver Bandpass…

Receiver Temperature



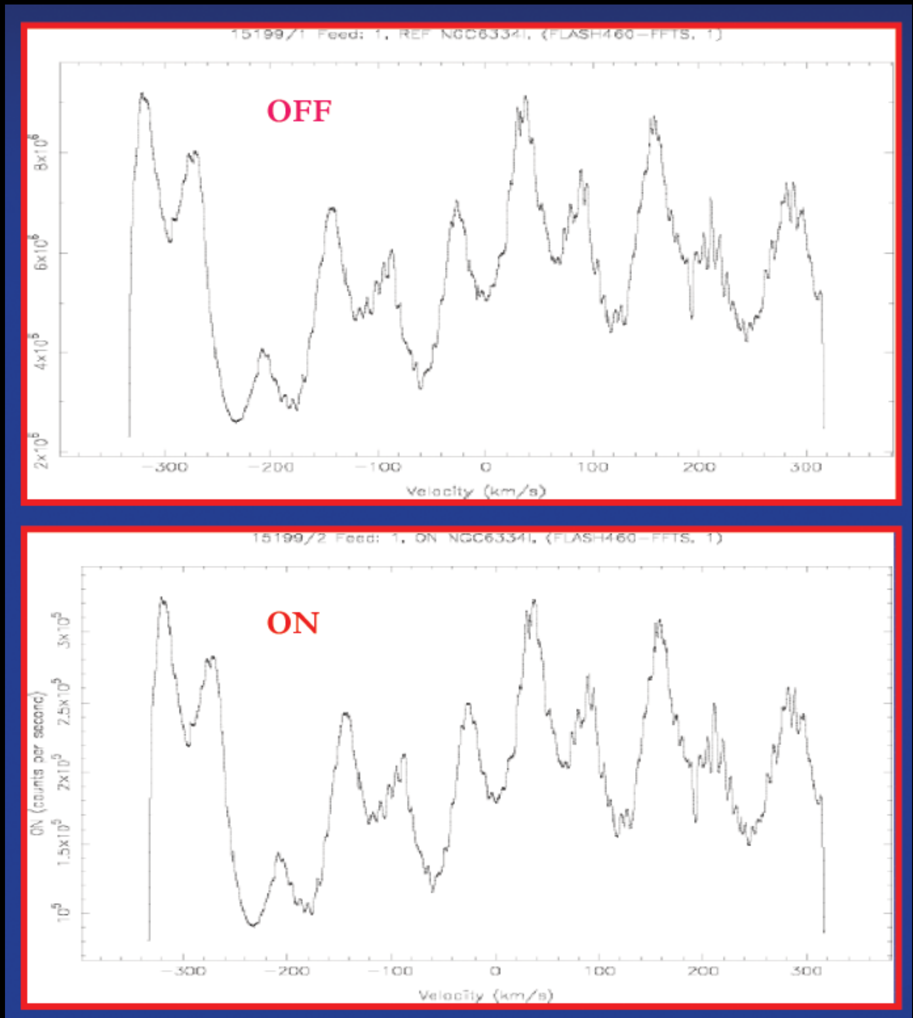
System Temperature

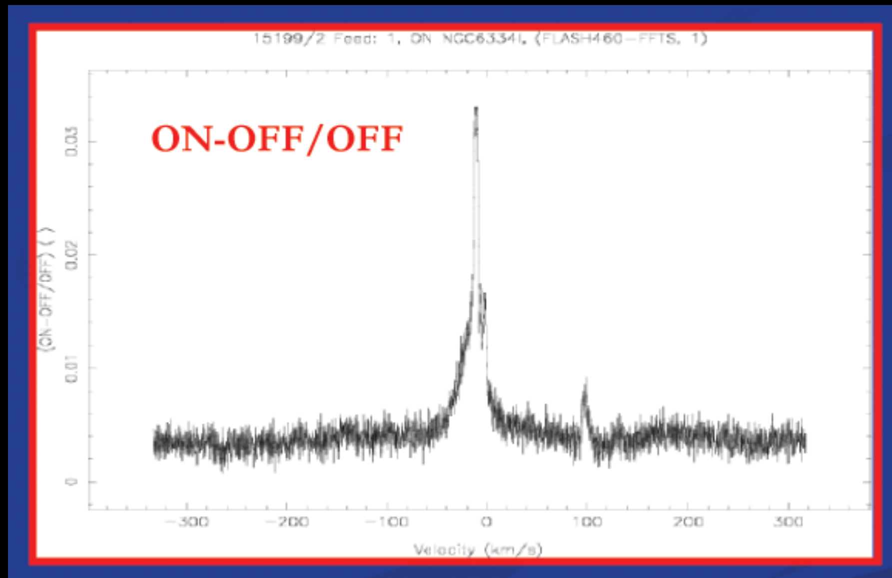


Standing waves… + an atmospheric feature

…you get a temperature scale by which to scale the received power (output actually is a voltage). Now for an astronomical observation you have to cancel out the atmosphere…

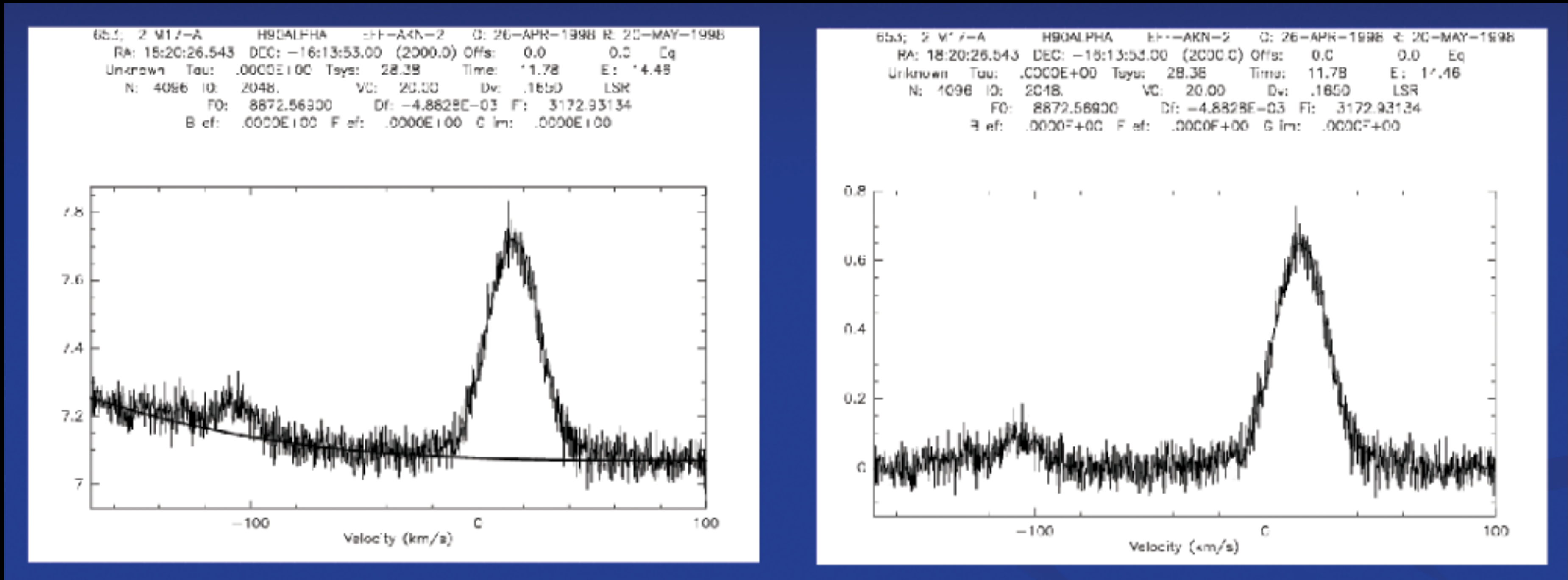
Example 1: calibration of an astronomical line observed with a heterodyne receiver



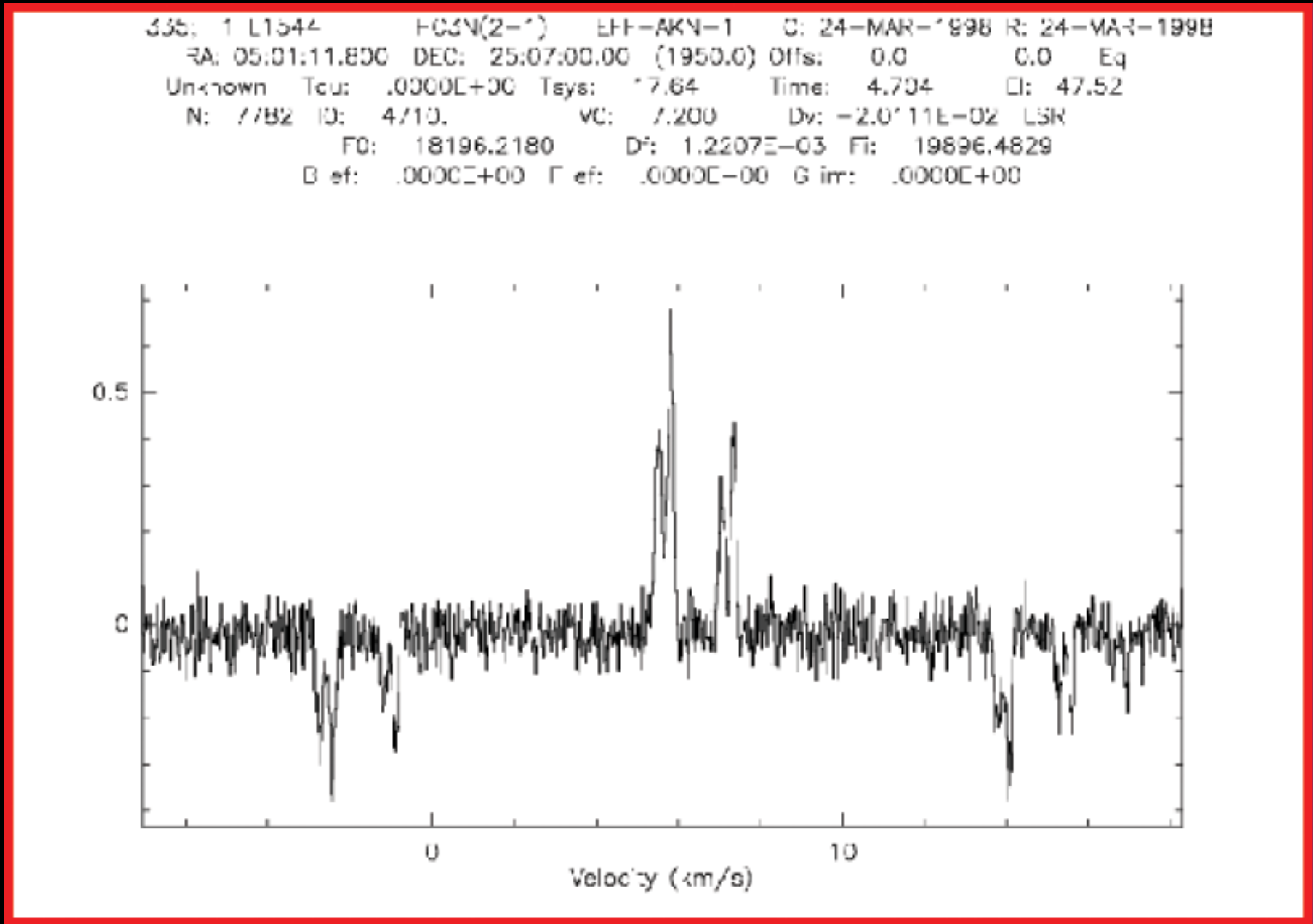


The scale remains to be calibrated using the CAL factor

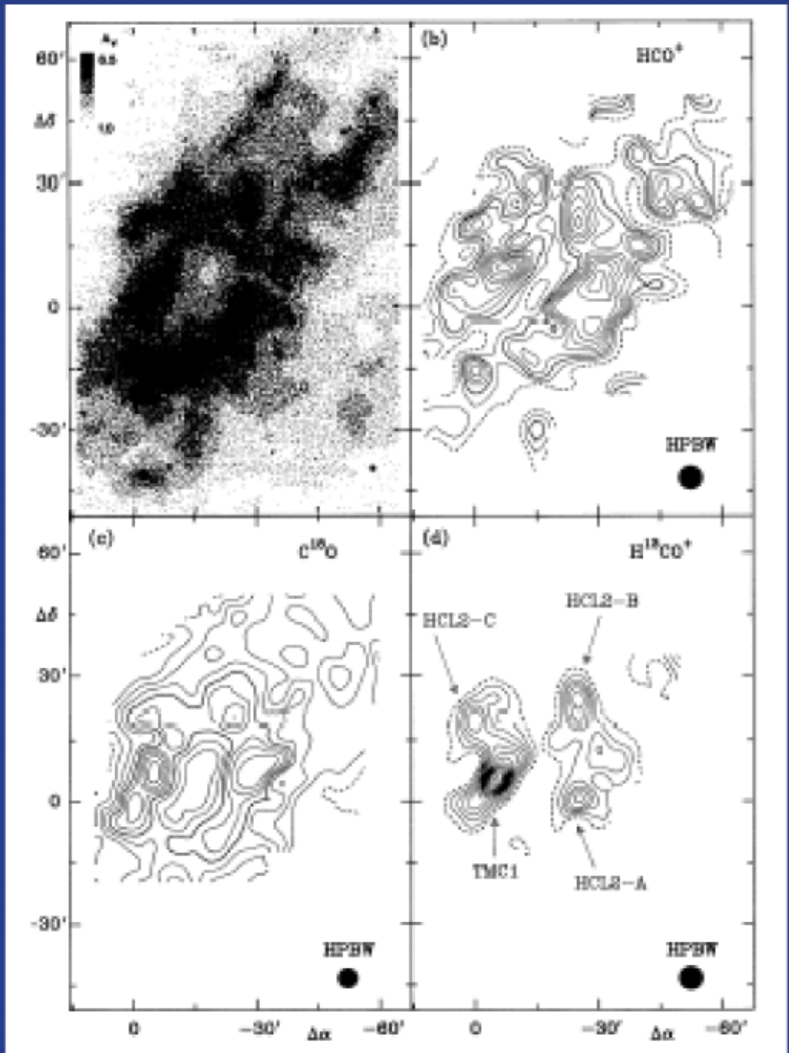
DATA ACQUISITION: POSITION SWITCHING

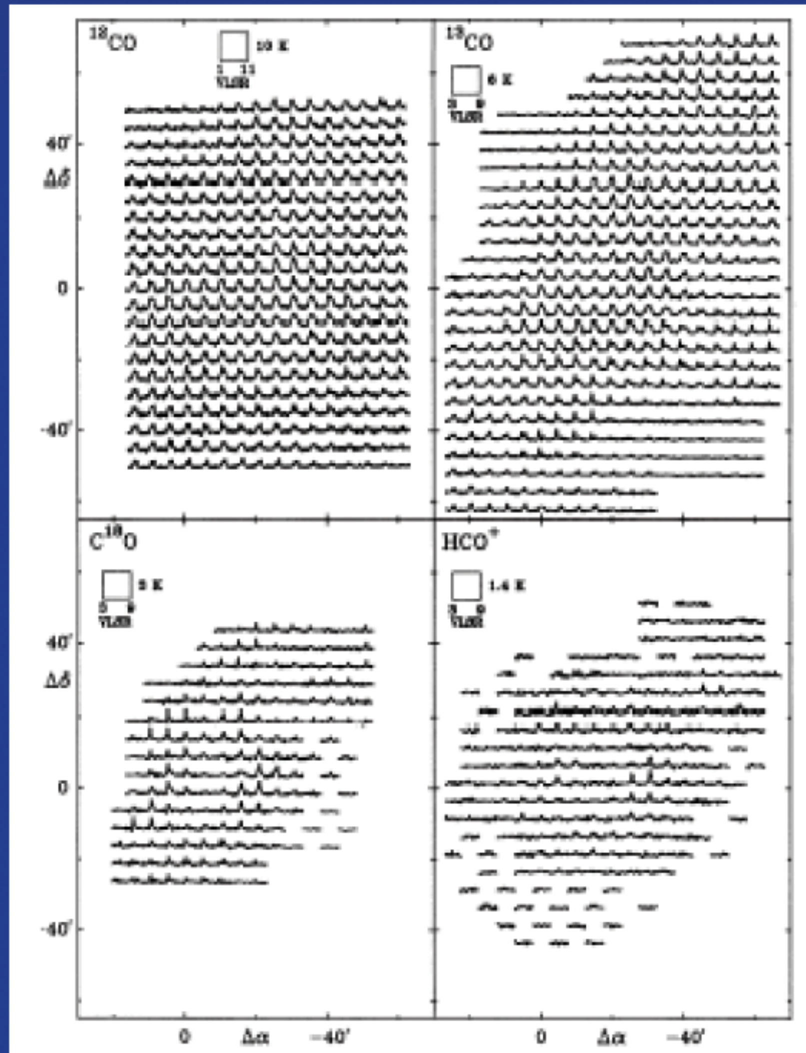


DATA ACQUISITION: FREQUENCY SWITCHING

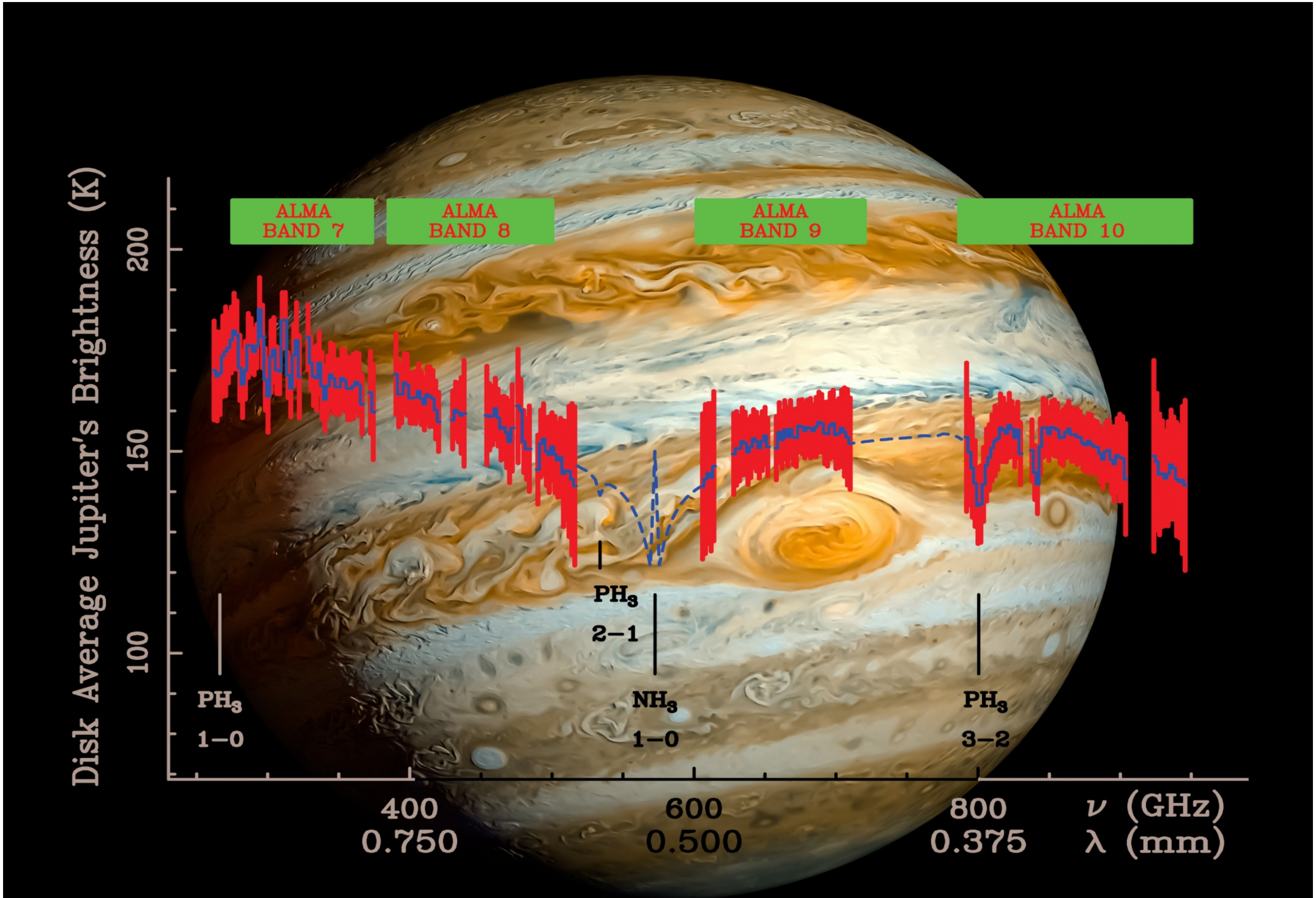


DATA ACQUISITION: MAPS





PART V: Example of a real and tricky observation

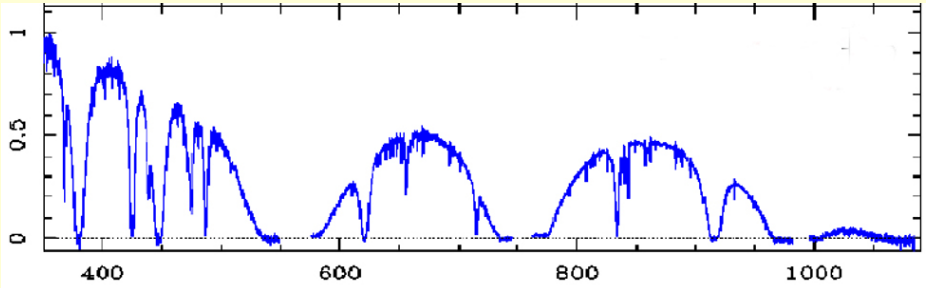


Pardo et al., Icarus 290, 150-155 (2017)

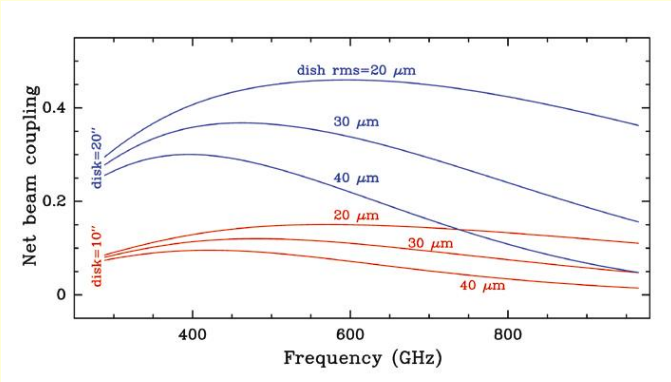
Even more complex calibration: Broadband measurements of the spectrum of planets

We have to deal with two problems:

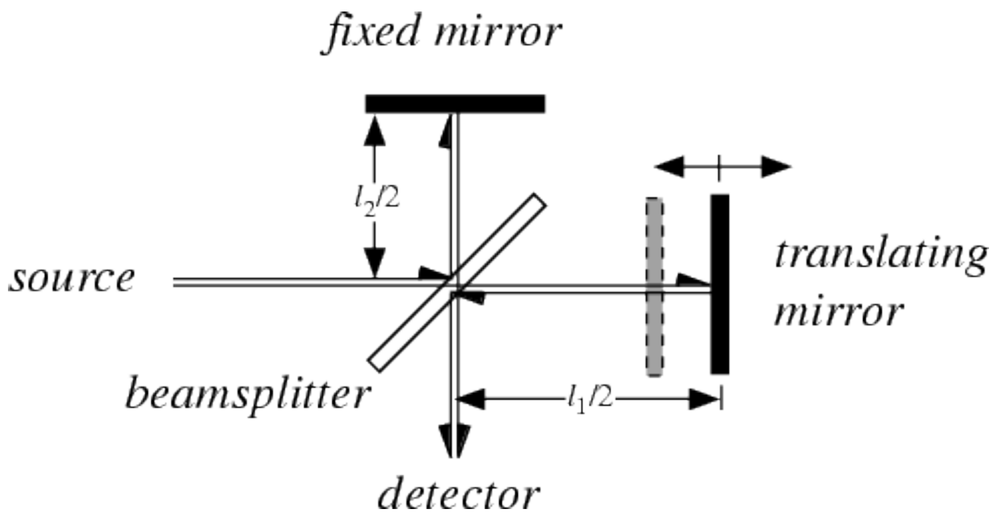
- The atmosphere



- The coupling and efficiency terms.

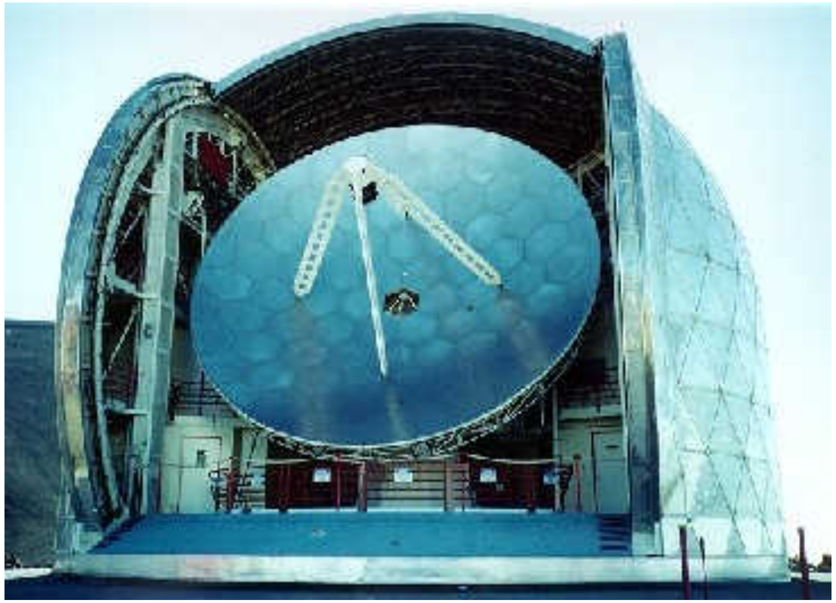


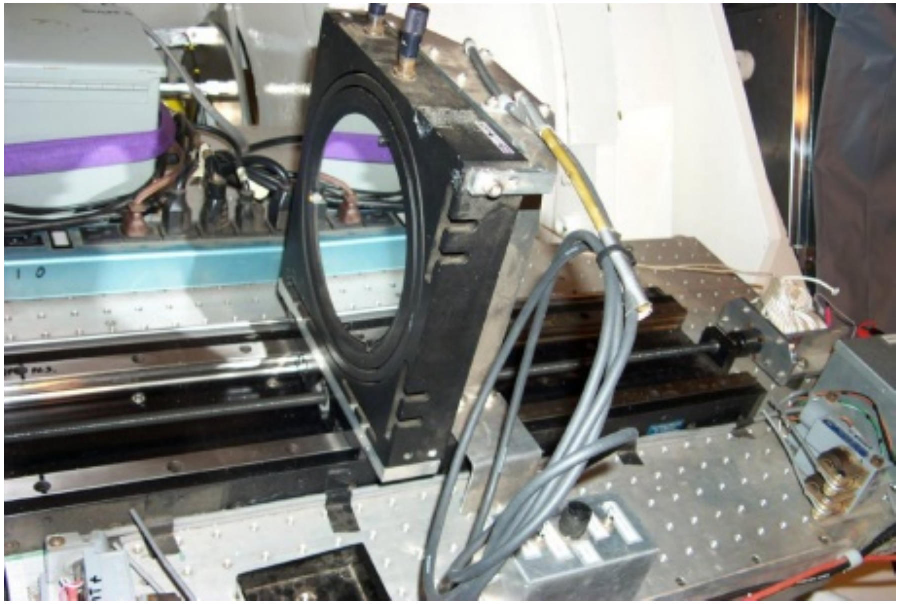
FTS detector at the CSO on Mauna Kea



Characteristics of CSO-FTS

- Mounted on Cassegrain focus of telescope for dedicated obs. runs.
- Detector: ^{3}He cooled Bolometer
- Moving arm: 50 cm ~ 200 MHz resolution
- Filters: 7 different (165 to 1600 GHz)

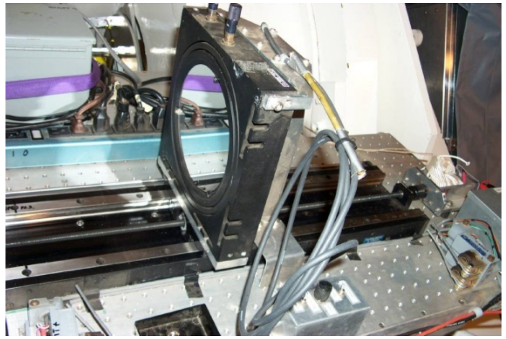


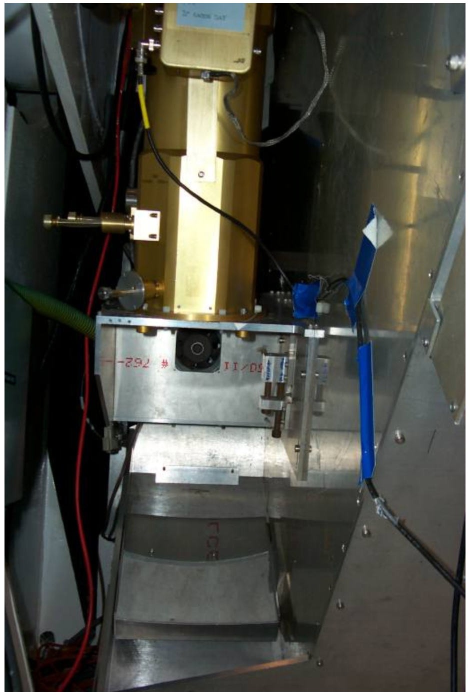



Mauna Kea (4200 m, -5 ºC), Hawai'i
Hapuna Beach (0 m, 25 ºC, Hawai'i)

The CSO-FTS experiment. Set-up.

- Detector: ^3He cooled Bolometer
- Moving arm: 50 cm → ~ 200 MHz resolution
- Filters: 7 different (165 to 1600 GHz)

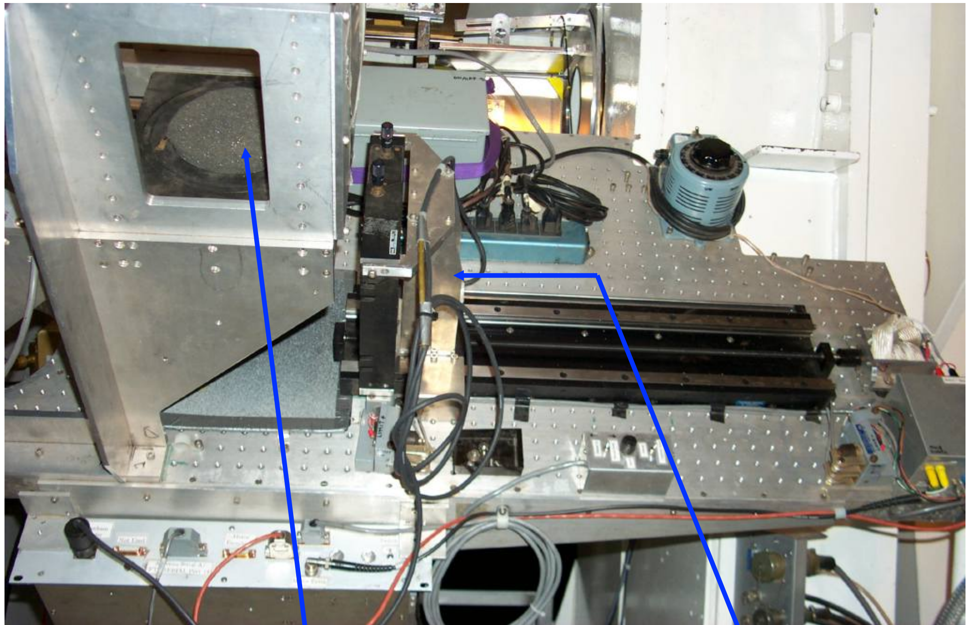




- **CO: Double Fabry-Pérot with maximum transmission at CO frequencies.**
- **550 GHz (low pass): to explore low frequencies.**
- **650 GHz: To explore the 450 μm window.**
- **850 GHz: To explore the 350 μm window.**
- **750 GHz: To simultaneously explore both.**
- **1.1 THz (low pass): To explore 300-1100 GHz.**
- **1.6 THz (low pass): To explore 300-1600 GHz.**

Caltech Submillimeter Observatory - Fourier Transform Spectrometer (CSO-FTS)

Last mirror and bolometer (cooled to liq. ^3He)



Measurement: $$m(\nu) = \frac{V_{sou} - V_{sky}}{V_{ground} - V_{sky}}$$

Where:

- $V_{sou} = G(\nu)\left[\eta_{sou}(\nu)P_{sou}(\nu) + (1-\eta_{sou}(\nu))P_{bgr}(\nu)\right]e^{-\tau_t(\nu)} + \\ + G(\nu)\left[\eta_{sky}(\nu)P_{sky}(\nu) + (1-\eta_{sky})P_{hot}\right]$
- $V_{sky} = G(\nu)\left\{\eta_{sky}(\nu)\left[P_{sky}(\nu) + P_{bgr}(\nu)e^{-\tau_t(\nu)}\right] + (1-\eta_{sky})P_{hot}\right\}$
- $V_{ground} = G(\nu)\eta_{hot}(\nu)P_{hot}(\nu)$; η_{hot}=1.0.

P: Spectra emitted by the different sources, η: Couplings to these sources, G: Optical-electrical gain factor

$$m(\nu) = \frac{\left[\eta_{sou}(\nu)P_{sou}(\nu) + (1-\eta_{sou}(\nu) - \eta_{sky}(\nu))P_{bgr}(\nu)\right]e^{-\tau_t(\nu)}}{\eta_{sky}\left[P_{hot}(\nu) - P_{sky}(\nu) + P_{bgr}(\nu)e^{-\tau_t(\nu)}\right]}$$

We want to extract: $\boxed{T_{EBB,sou}(\nu)}$

...after rearranging the equation

$$m(\nu) = \frac{\eta_{sou}(\nu)}{\eta_{sky}(\nu)} \frac{\frac{e^{-\tau_t}}{exp(h\nu/KT_{EBB,sou})-1}}{\frac{1}{exp(h\nu/KT_{hot})-1} - \frac{1-e^{-\tau_t}}{exp(h\nu/KT_e)-1}}$$

Two possibilities:

• $T_e(\tau_t,\nu) = T_{hot}$ (standard CSO T_A^* calibration)

$$T^*_{RJ,A}=m(\nu)T_{hot}(\eta_{sou}/\eta_{sky})T_{RJ,sou}$$

$$T^*_{PL,A}=m(\nu)(h\nu/k)[exp(h\nu/kT_{hot})-1]^{-1}=$$

$$(\eta_{sou}/\eta_{sky})\ (h\nu/k)[exp(h\nu/kT_{hot})-1]^{-1}$$

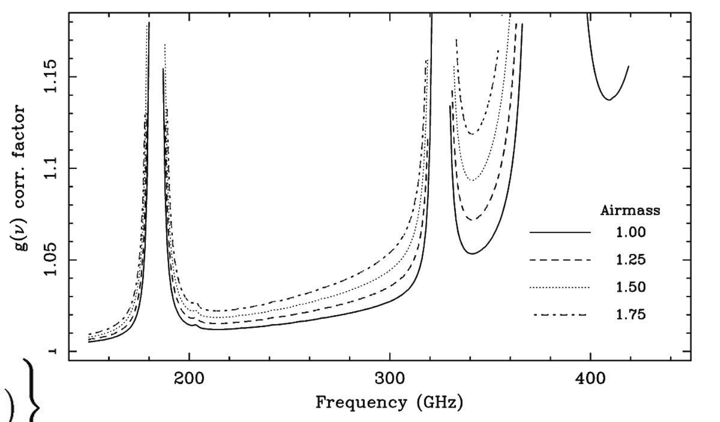
•$T_e(\tau_t,\nu) = T_{hot} - LHf(\tau_t)$

Mauna Kea

L: Tropospheric lapse rate 5.6 K(km)

H: Water vapor scale height 2.0 km

$g(\tau_t,\nu)$



$$g(\tau_t,\nu)=\left\{1+\frac{LHf(\tau_t)}{T_{hot}}\left(\frac{h\nu/KT_{hot}}{1-exp(-h\nu/KT_{hot})}\right)(e^{\tau_t}-1)\right\}$$

$$\boxed{T^{**}_{PL,A} = T^*_{PL,A}\ g(\nu) = (\eta_{sou}/\eta_{sky})\ (h\nu/k)[exp(h\nu/kT_{hot})-1]^{-1}}$$

PRIMARY CALIBRATION OBJECT: THE MOON

• Coupling and loses are not an issue on the Moon.

Requirement:

• Full Moon.

Problem:

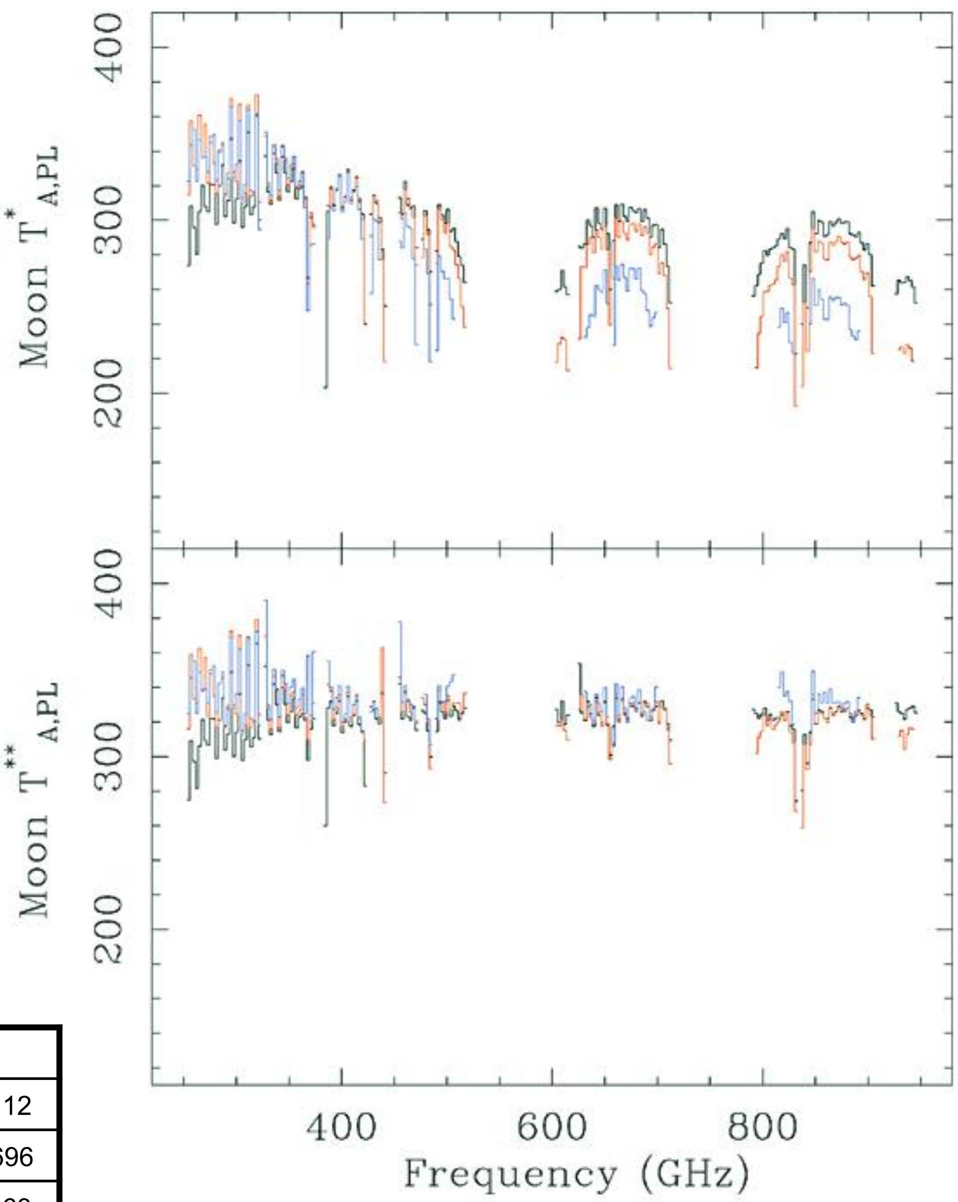
• Standard calibration scheme not accurate for high τ due to vertical temperature gradient.

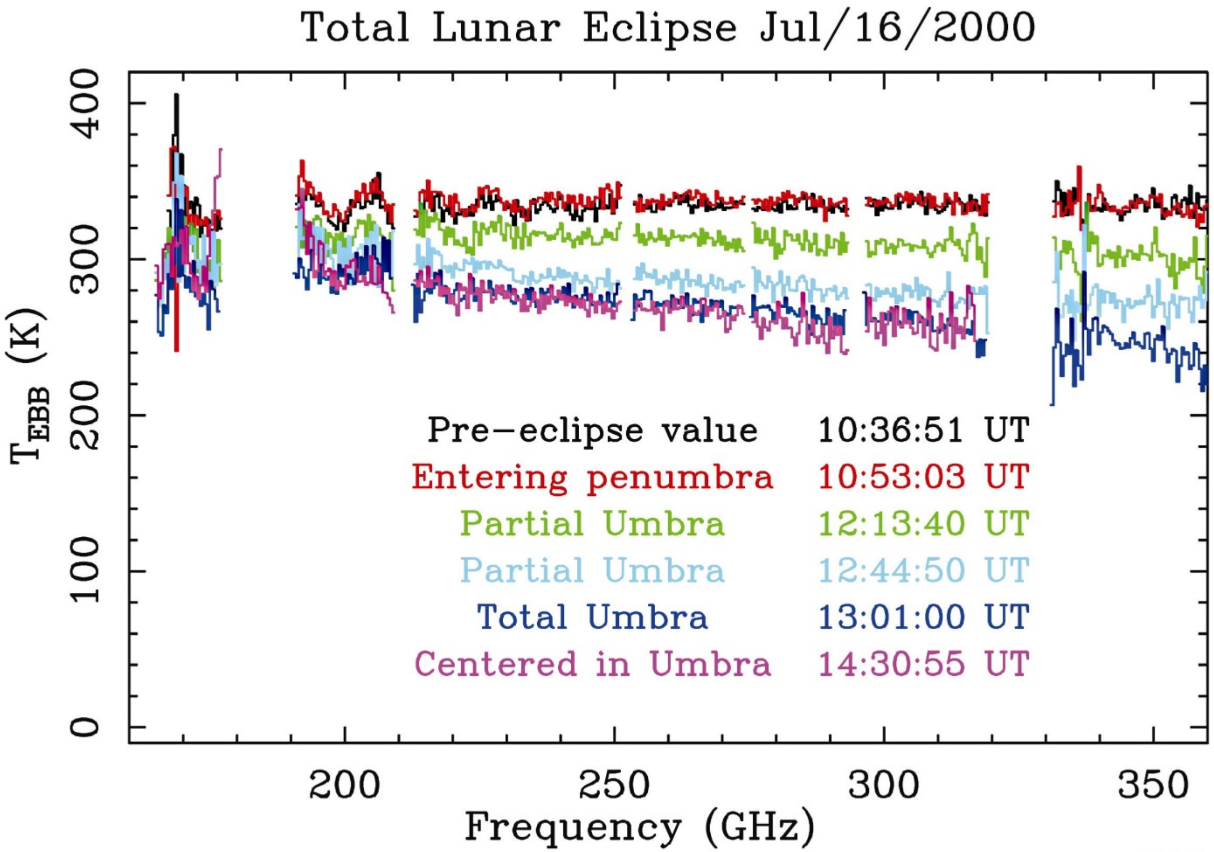
We need:

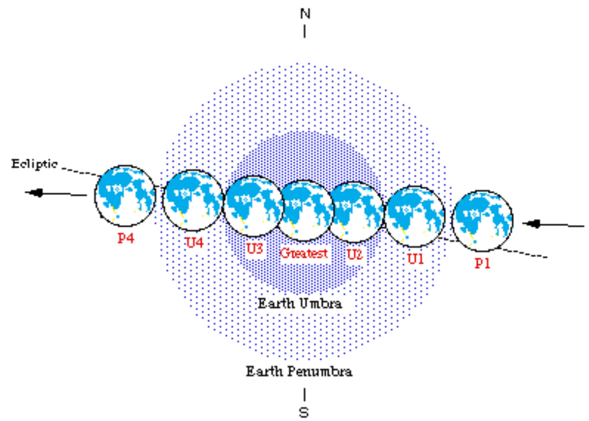
• τ-dependent correction scheme (it can be derived)

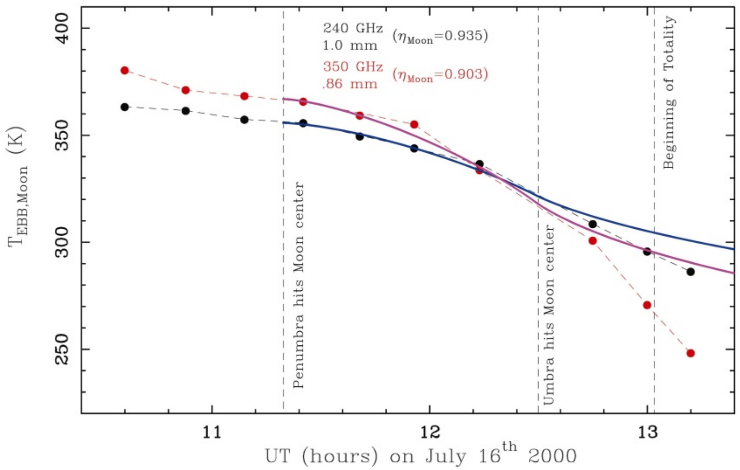
Elv=45º 0.5 mm H2O 1.0 mm H2O

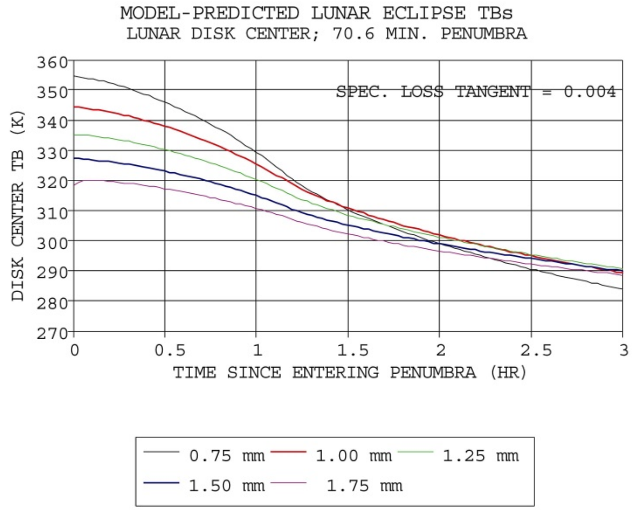
ν(GHz)	τatm	f(τ)	g(ν)	τatm	f(τ)	g(ν)
345	0.1396	0.9653	1.0061	0.2492	0.9385	1.0112
460	0.6300	0.8485	1.0318	1.1741	0.7295	1.0696
650	0.8760	0.7932	1.0483	1.6486	0.6381	1.1163
850	1.0065	0.7649	1.0586	1.8223	0.6069	1.1390




Total Lunar Eclipse Jul/16/2000
T_EBB (K)
Frequency (GHz)
Pre-eclipse value 10:36:51 UT
Entering penumbra 10:53:03 UT
Partial Umbra 12:13:40 UT
Partial Umbra 12:44:50 UT
Total Umbra 13:01:00 UT
Centered in Umbra 14:30:55 UT
0
100
200
300
400
200
250
300
350

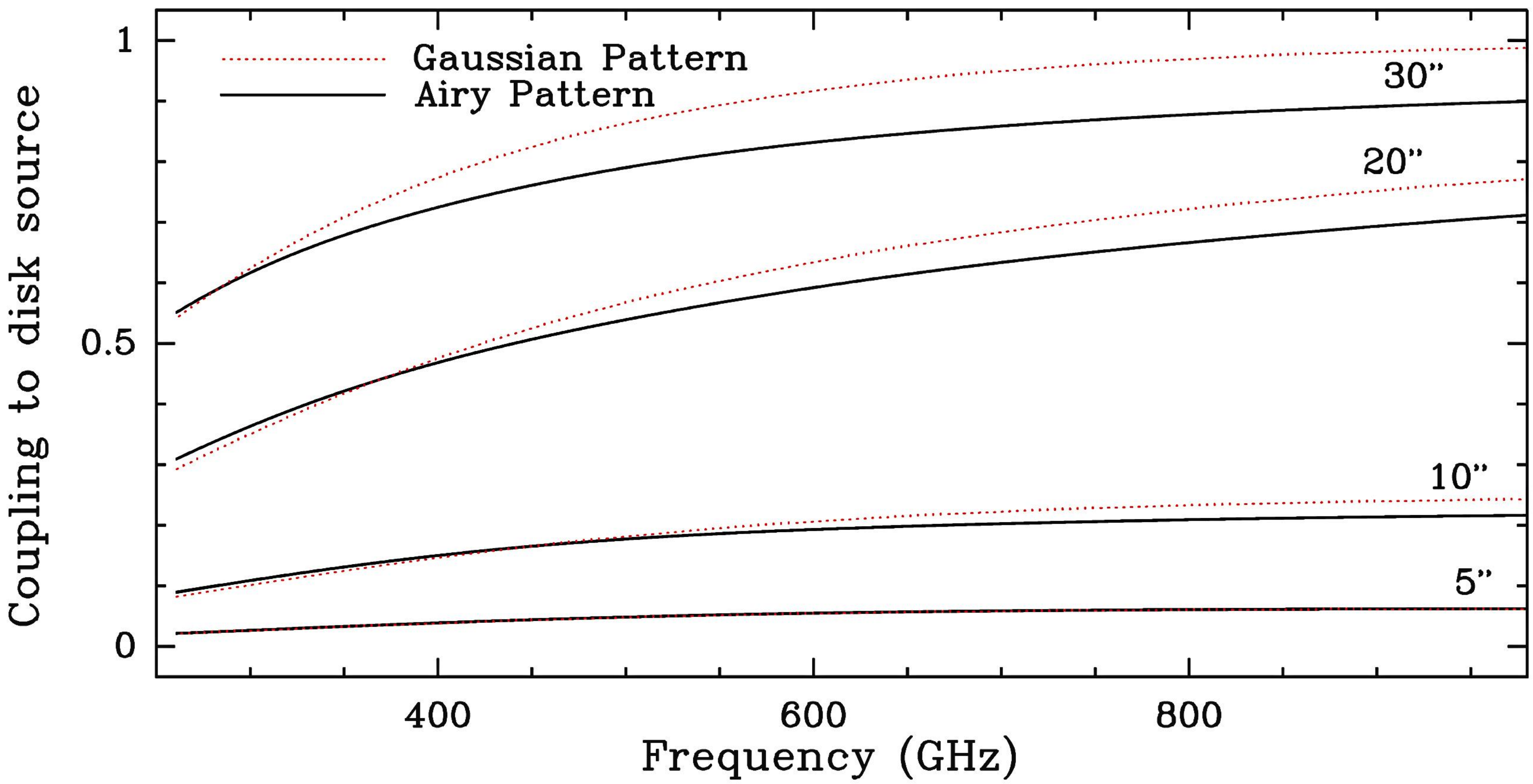

N
S
Ecliptic
P4
U4
U3
Greatest
U2
U1
P1
Earth Umbra
Earth Penumbra


240 GHz
1.0 mm
(η_Moon=0.935)
350 GHz
.86 mm
(η_Moon=0.903)
Penumbra hits Moon center
Umbra hits Moon center
Beginning of Totality
T_EBB,Moon (K)
UT (hours) on July 16th 2000
250
300
350
400
11
12
13


MODEL-PREDICTED LUNAR ECLIPSE TBs
LUNAR DISK CENTER; 70.6 MIN. PENUMBRA
SPEC. LOSS TANGENT = 0.004
DISK CENTER TB (K)
TIME SINCE ENTERING PENUMBRA (HR)
270
280
290
300
310
320
330
340
350
360
0
0.5
1
1.5
2
2.5
3
0.75 mm
1.00 mm
1.25 mm
1.50 mm
1.75 mm

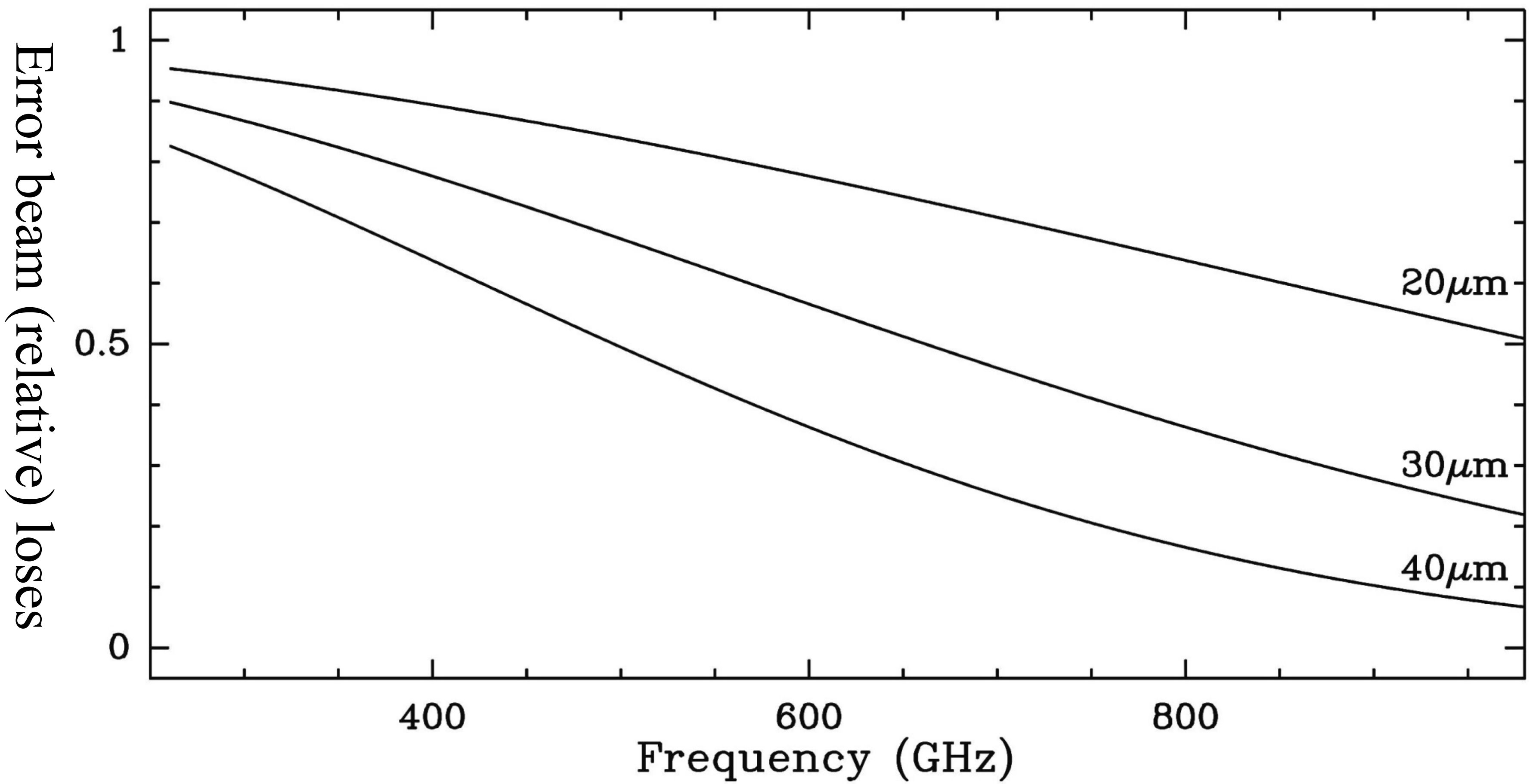
Coupling models to a disk source

Since we deal with a frequency range of ~ 700 GHz, the antenna HPBW changes from about 30" to 8".

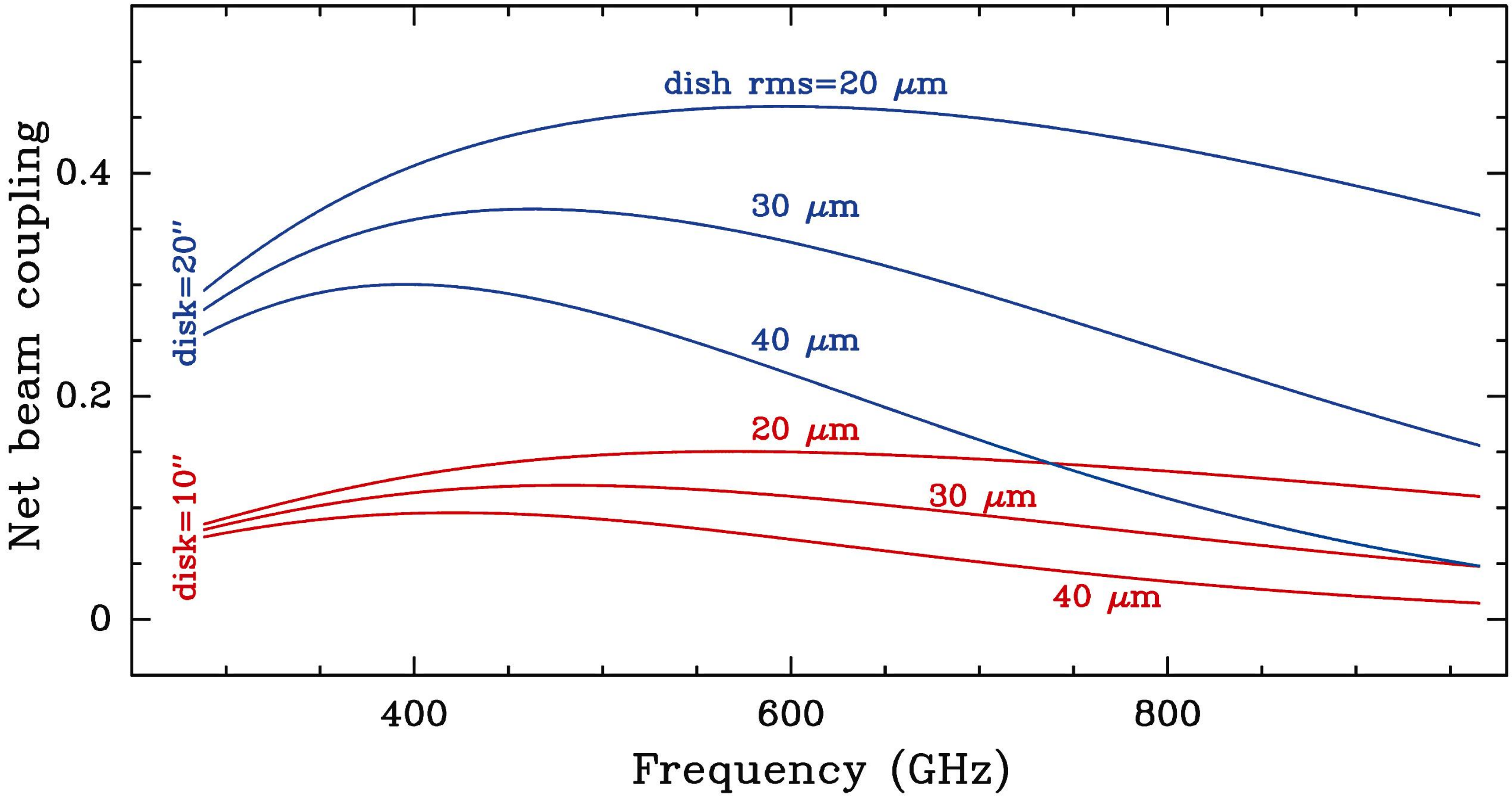


Loses due to the error beam

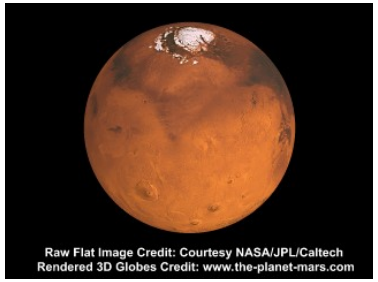
The error beam, realted to the dish rms is responsible for an efficiency drop as ν increases.

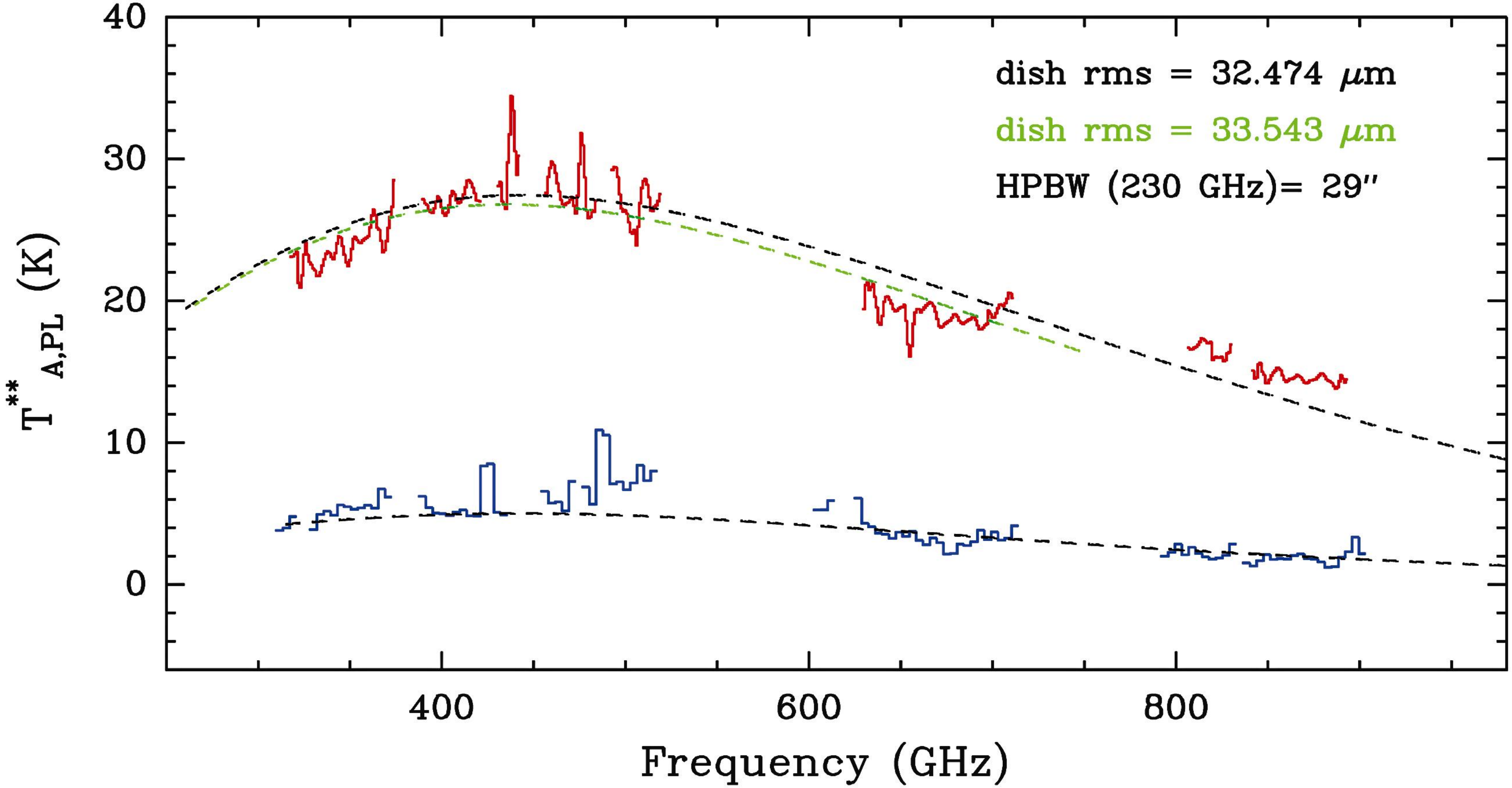


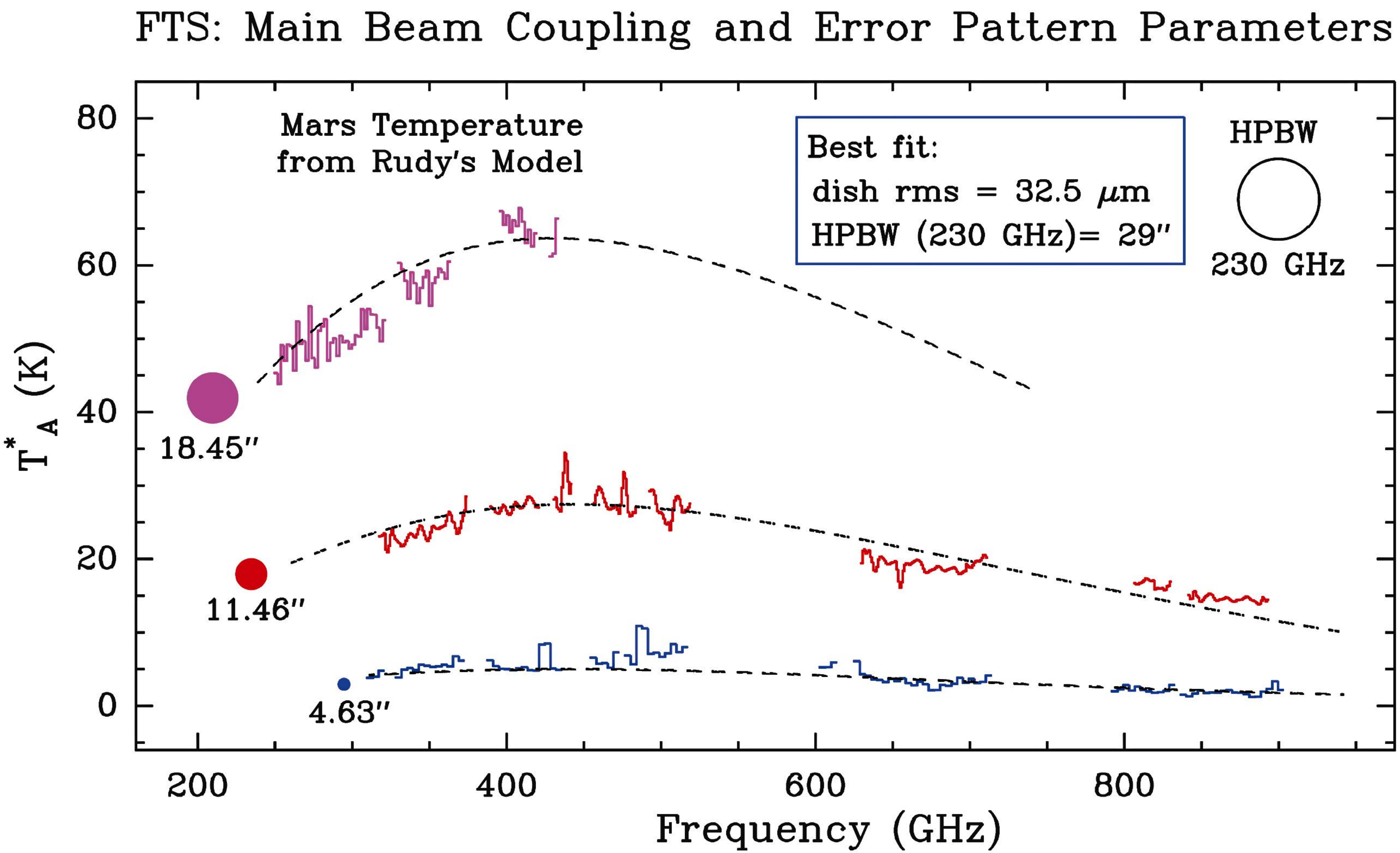
Coupling + loses net effect



Effect checked on Mars

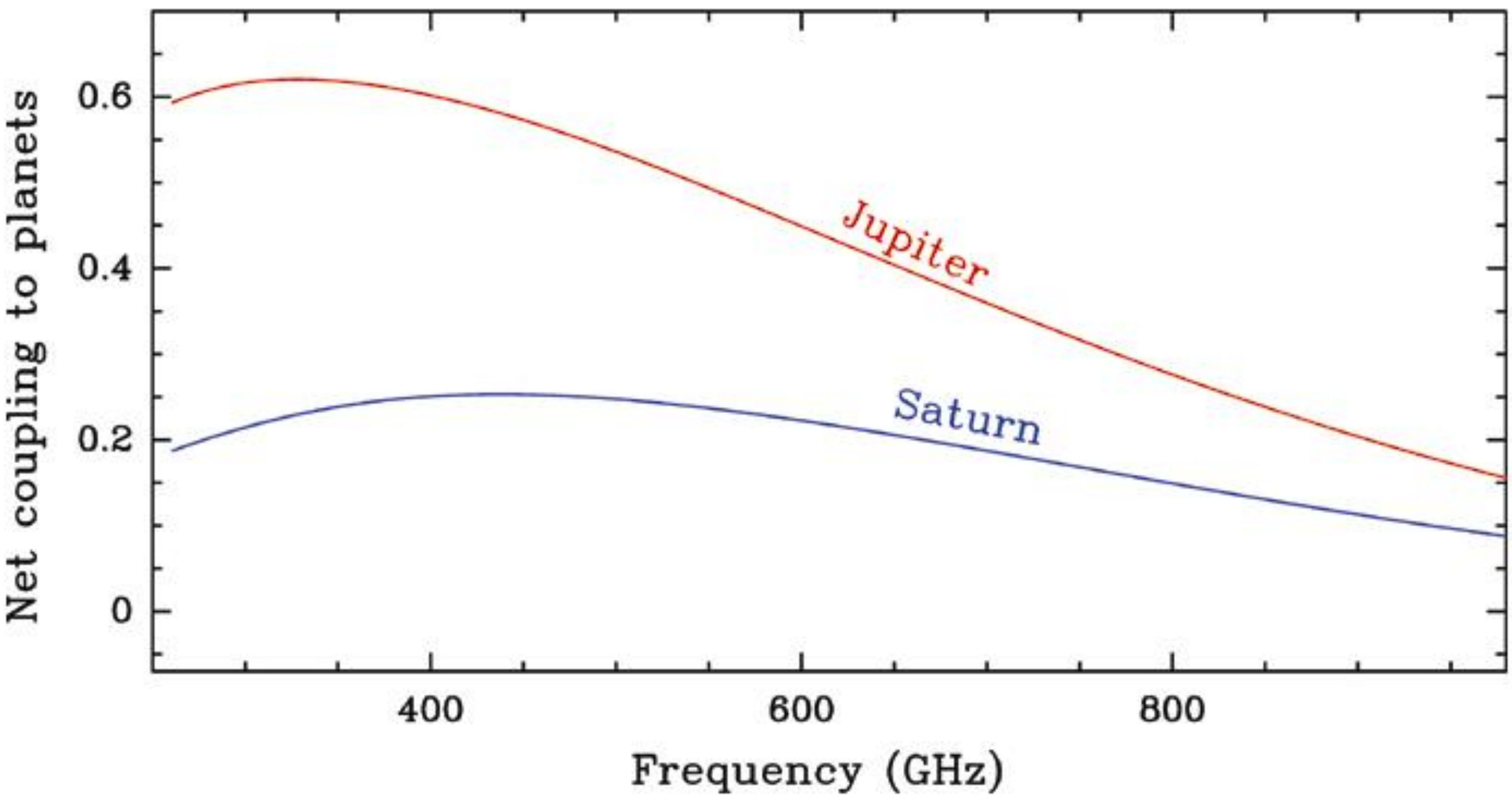


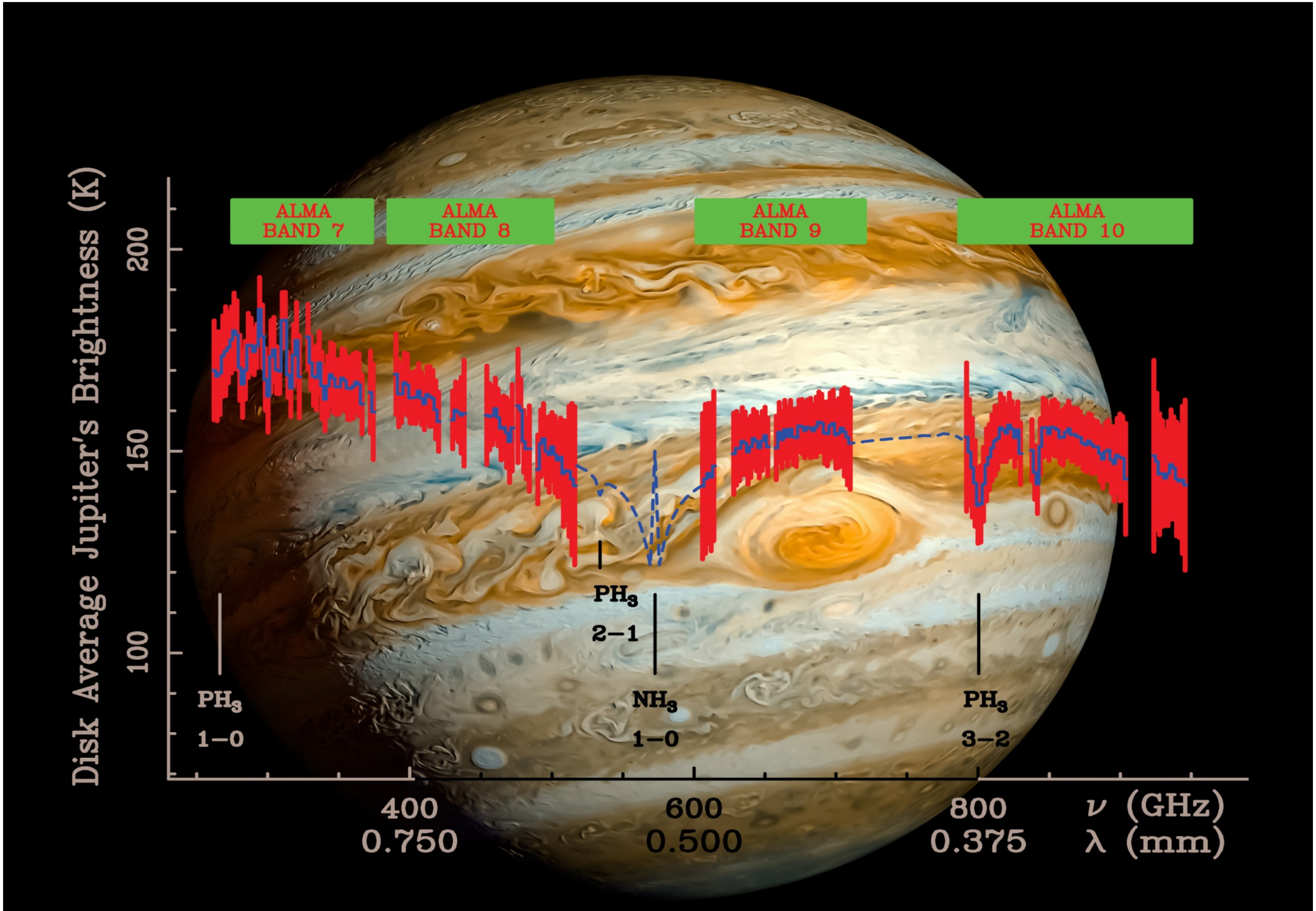




FTS: Main Beam Coupling and Error Pattern Parameters
Mars Temperature
from Rudy's Model
Best fit:
dish rms = 32.5 μm
HPBW (230 GHz)= 29''
HPBW
230 GHz
18.45''
11.46''
4.63''
T*A (K)
Frequency (GHz)
0
20
40
60
80
200
400
600
800

Predictions for Jupiter and Saturn on March 01



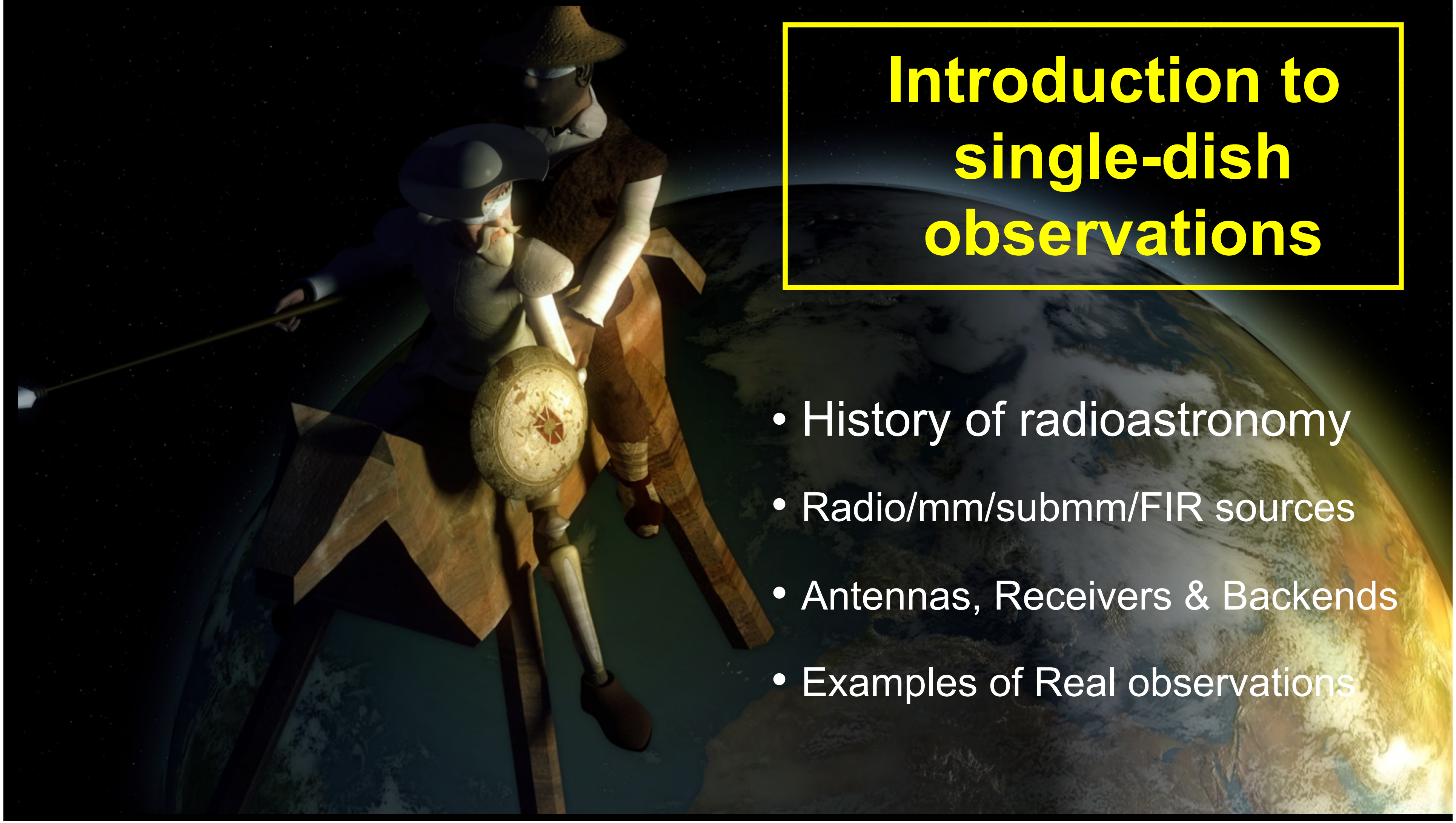


Pardo et al., Icarus 290, 150-155 (2017)

COSPAR Workshop, Quito
Mar/6, 2018

Juan Ramón Pardo Carrión

Consejo Superior de Investigaciones Científicas - Spain



Introduction to single-dish observations

- History of radioastronomy
- Radio/mm/submm/FIR sources
- Antennas, Receivers & Backends
- Examples of Real observations