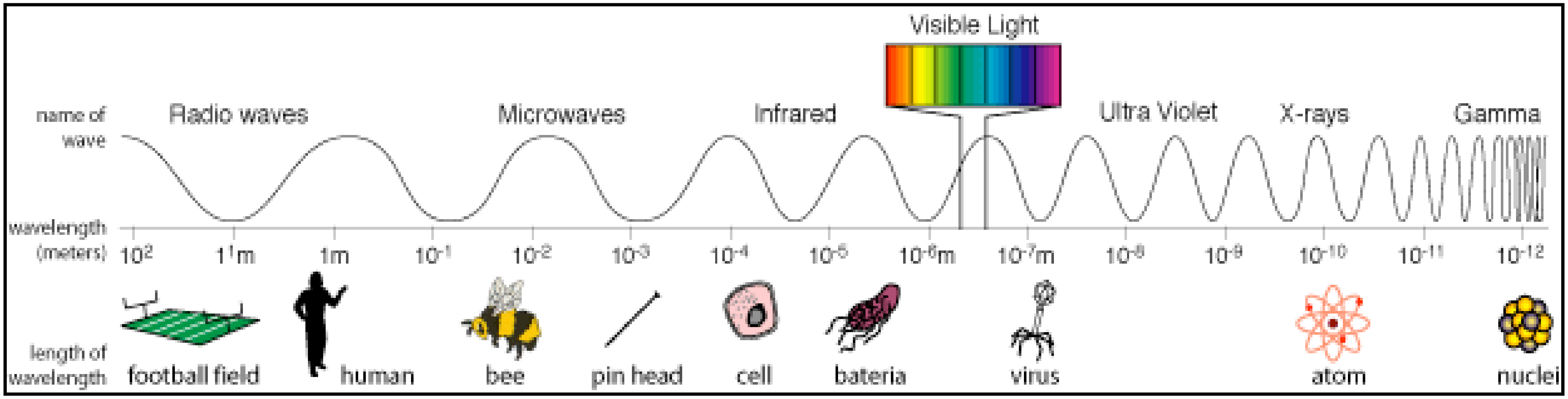
Introduction to Radio Astronomy

- Sources of radio emission
- Why radio astronomy is different from optical astronomy
- Radio telescopes - collecting the radiation
- Processing the radio signal
- Radio telescope characteristics
- Radio spectra characteristics
- Observing radio sources

Sources of Radio Emission

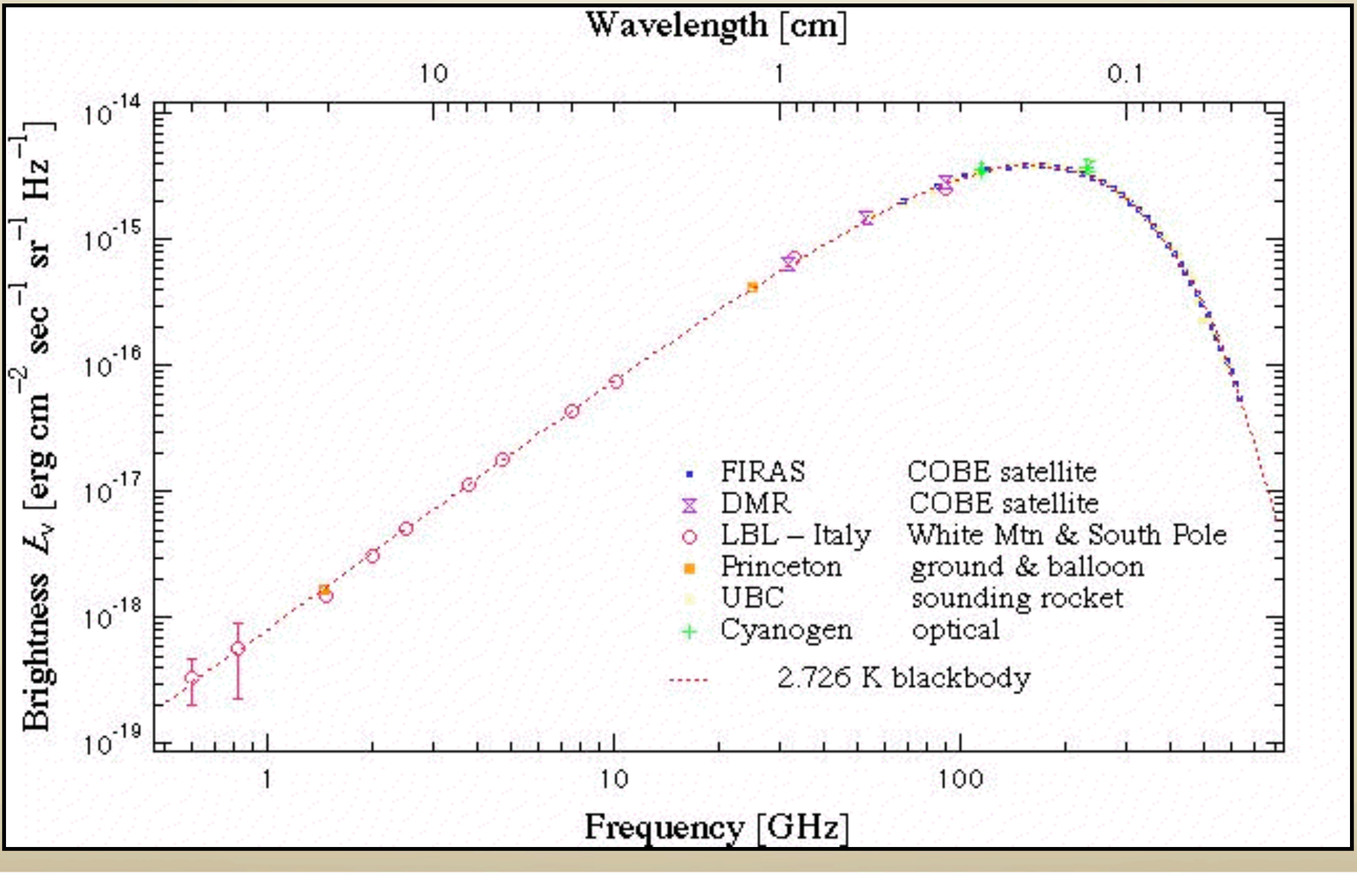
- Blackbody (thermal)
- Continuum sources (non-thermal)
- Spectral line sources



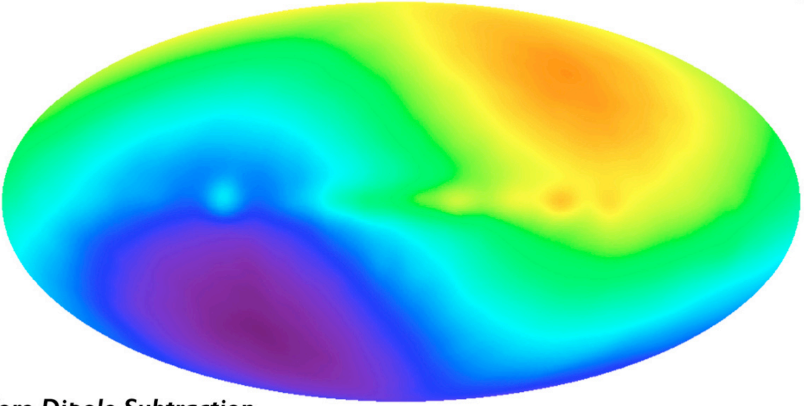
Blackbody Sources:

The cosmic microwave background, the planets

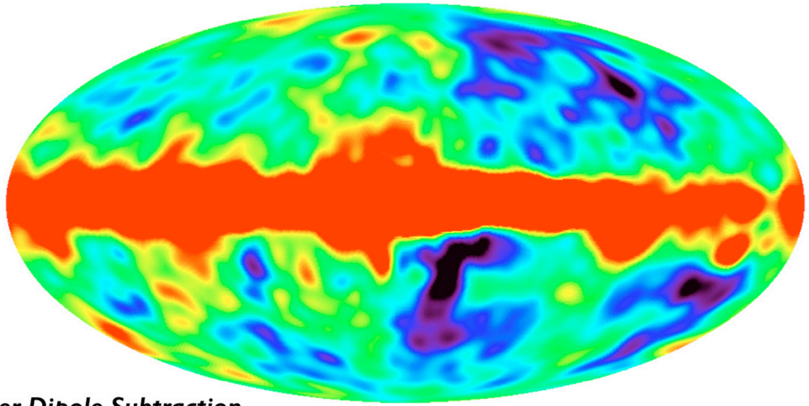
- Obs in cm requires low temperature: $\lambda_m T = 0.2898$ cm K
- Flux = const × ν^α × T
- For thermal sources α is ~2 (flatter for less opaque sources)



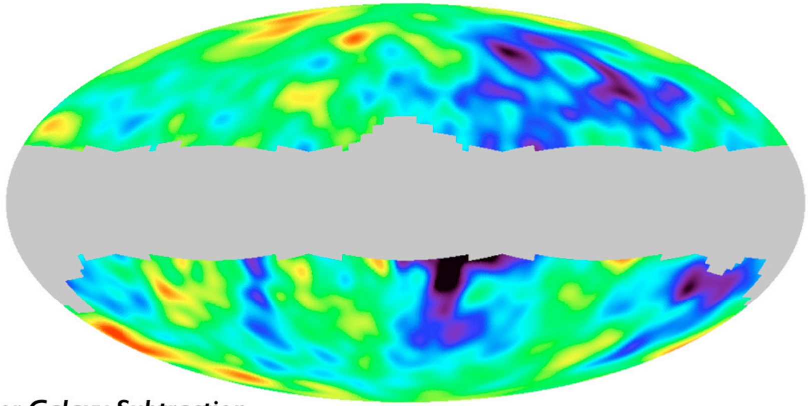
DMR 53 GHz Maps



Before Dipole Subtraction



After Dipole Subtraction



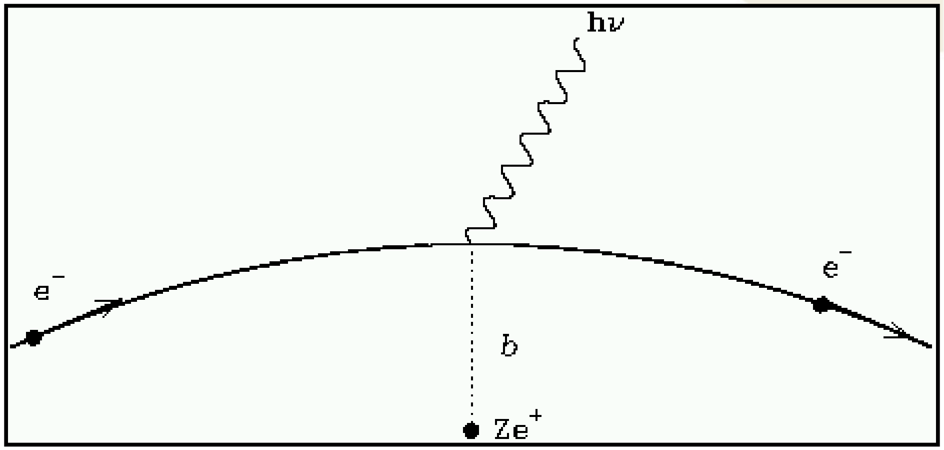
After Galaxy Subtraction

Continuum (non-thermal) Emission:

Emission at all radio wavelengths

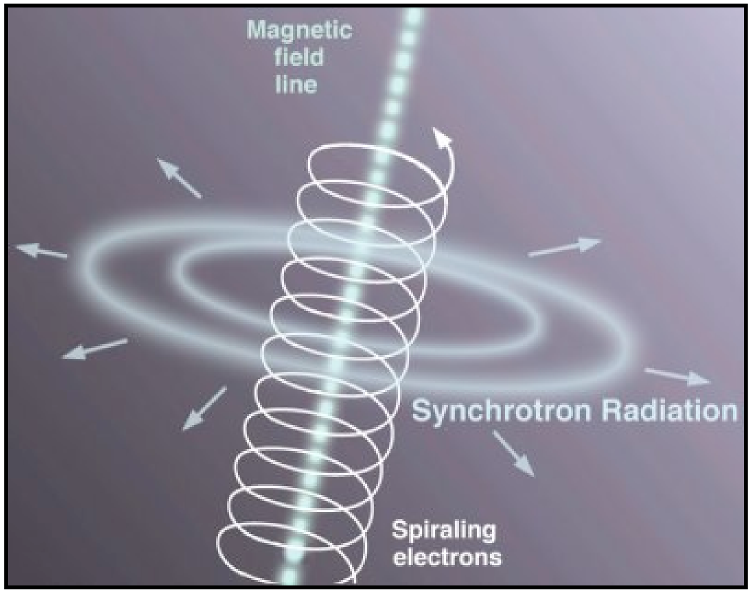
Bremsstralung (free-free):

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

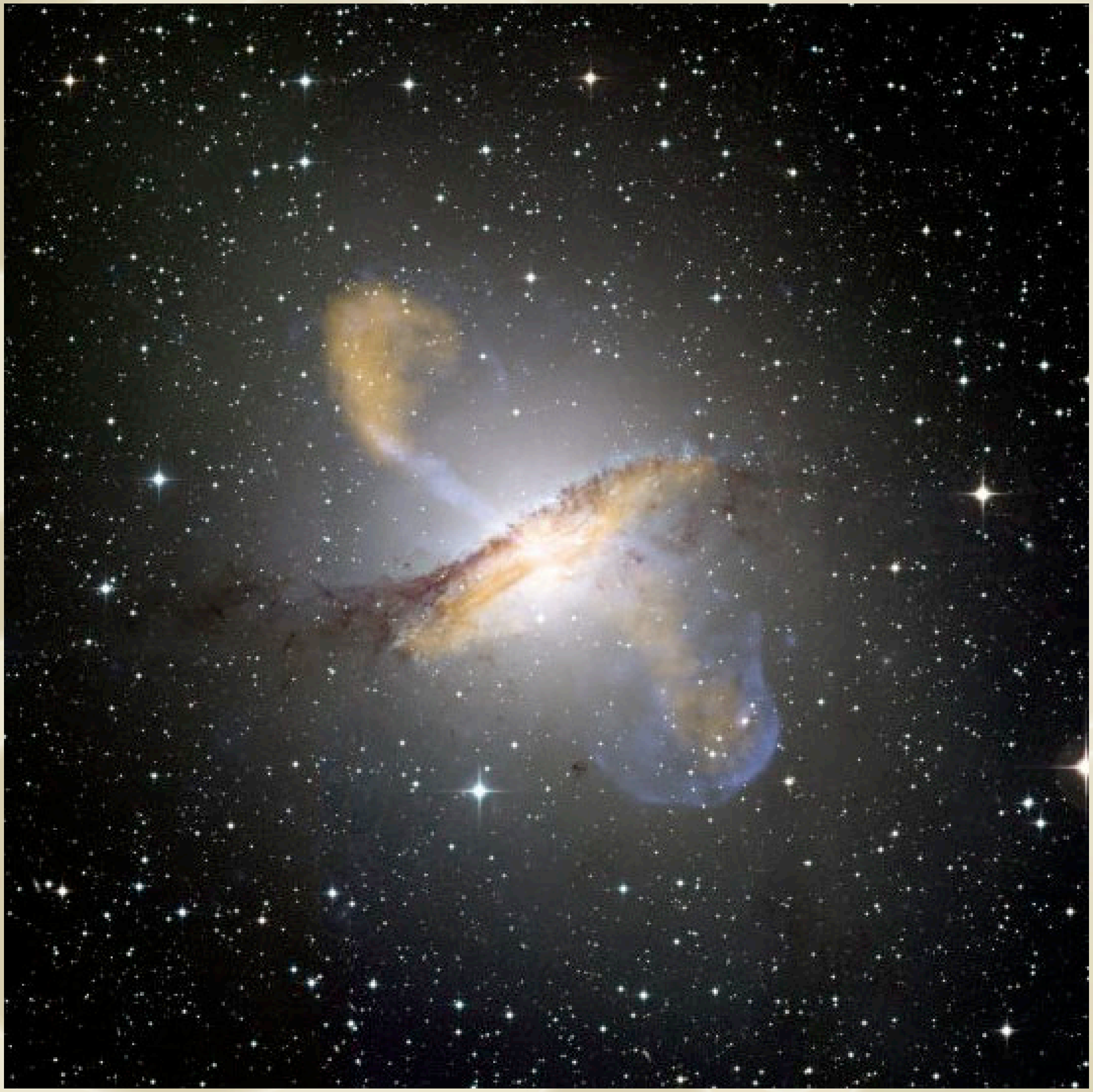


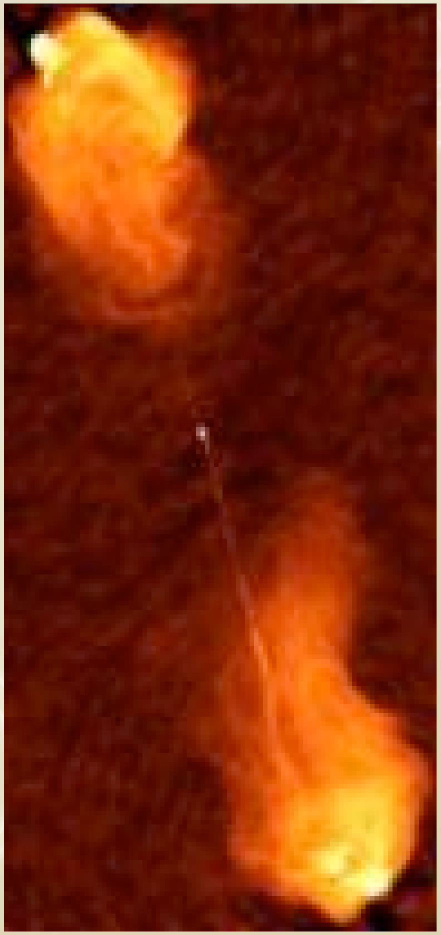
Synchrotron:

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



Sources of Continuum Emission

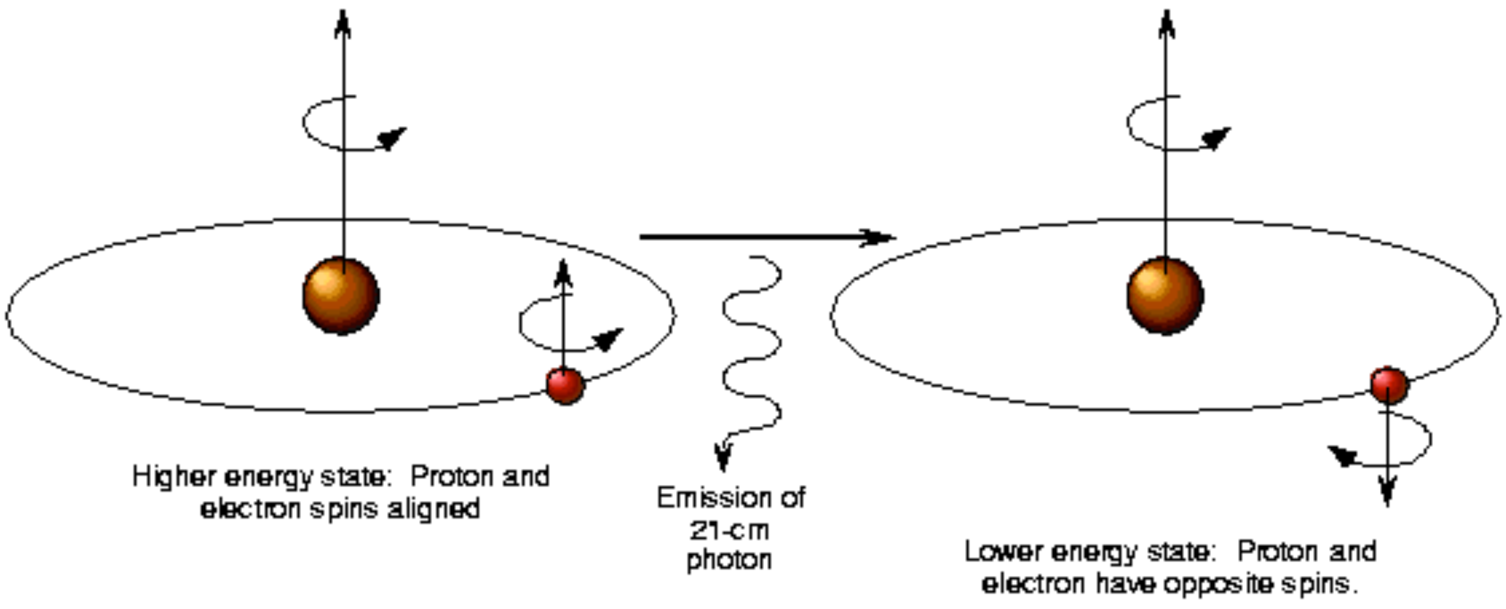




Radio Emission Lines

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

Formation of the 21-cm Line of Neutral Hydrogen

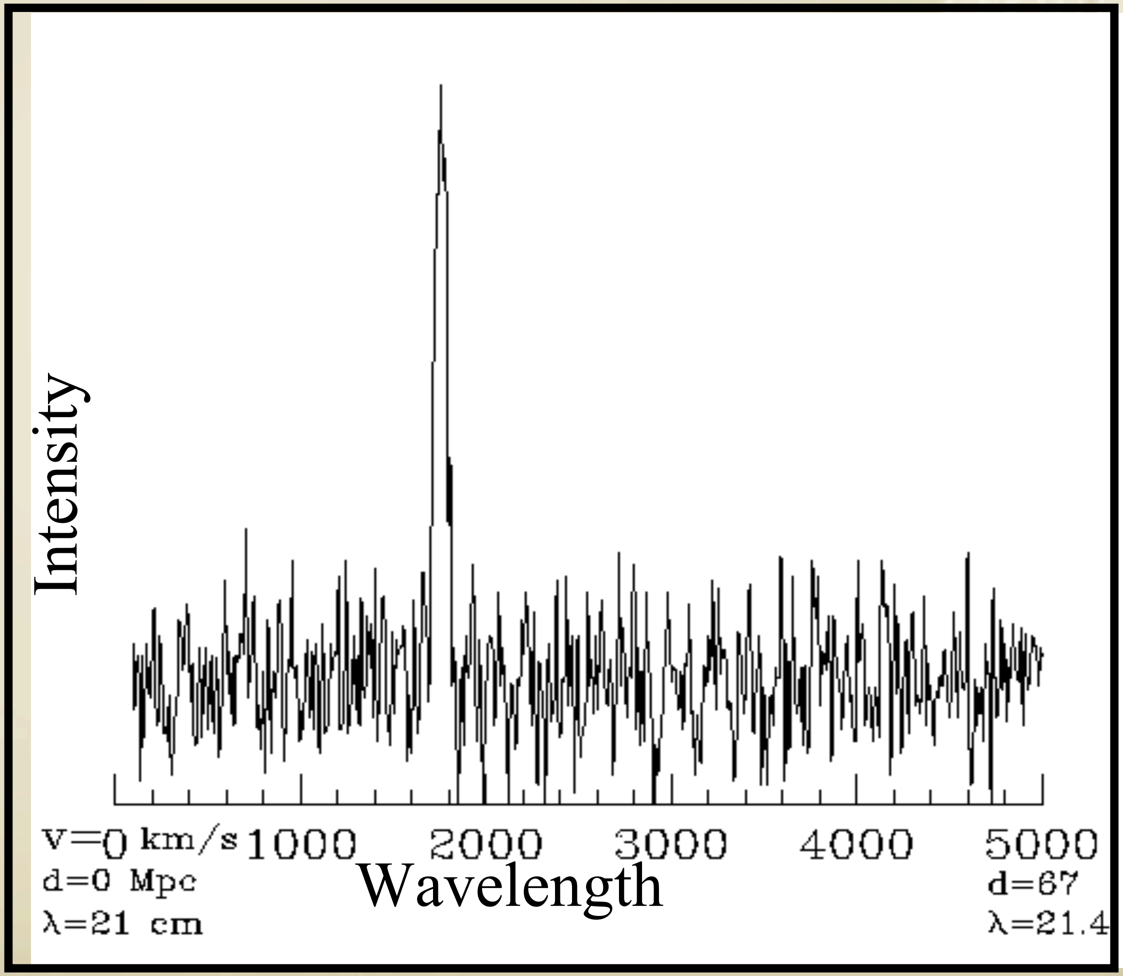


21cm Line of Neutral Hydrogen

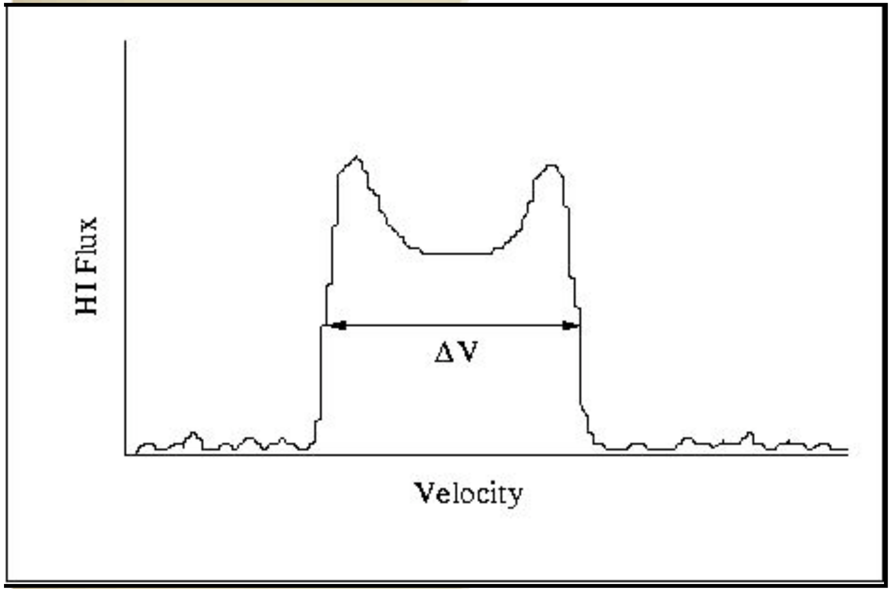
Not only are λ, ν, and E equivalent, but for the most part velocity and distance are as well.

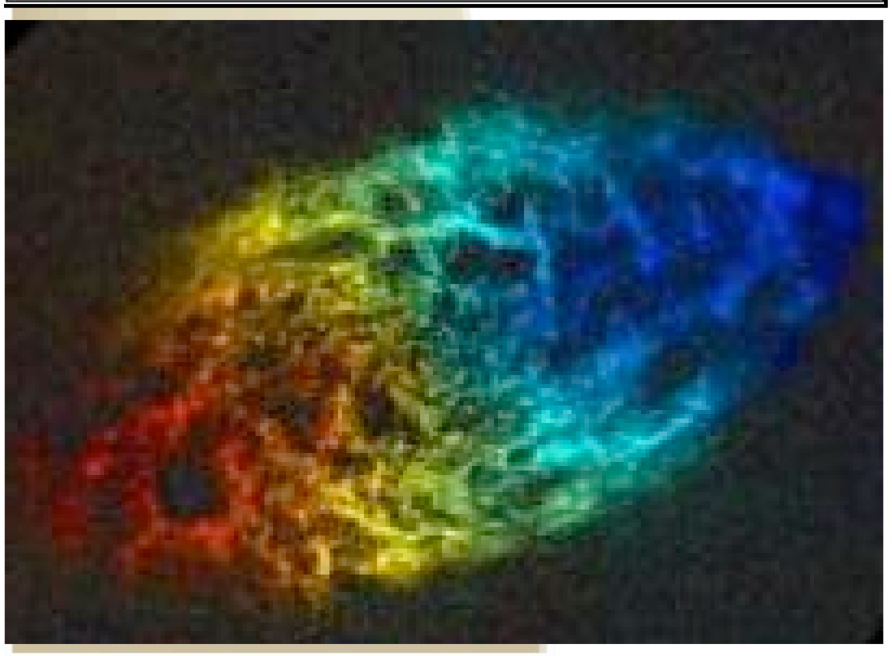
$$z = \frac{\lambda - \lambda_0}{\lambda_0} = \frac{\Delta v}{c}$$

$$d = v / H_0$$



21cm Line of Neutral Hydrogen, cont.

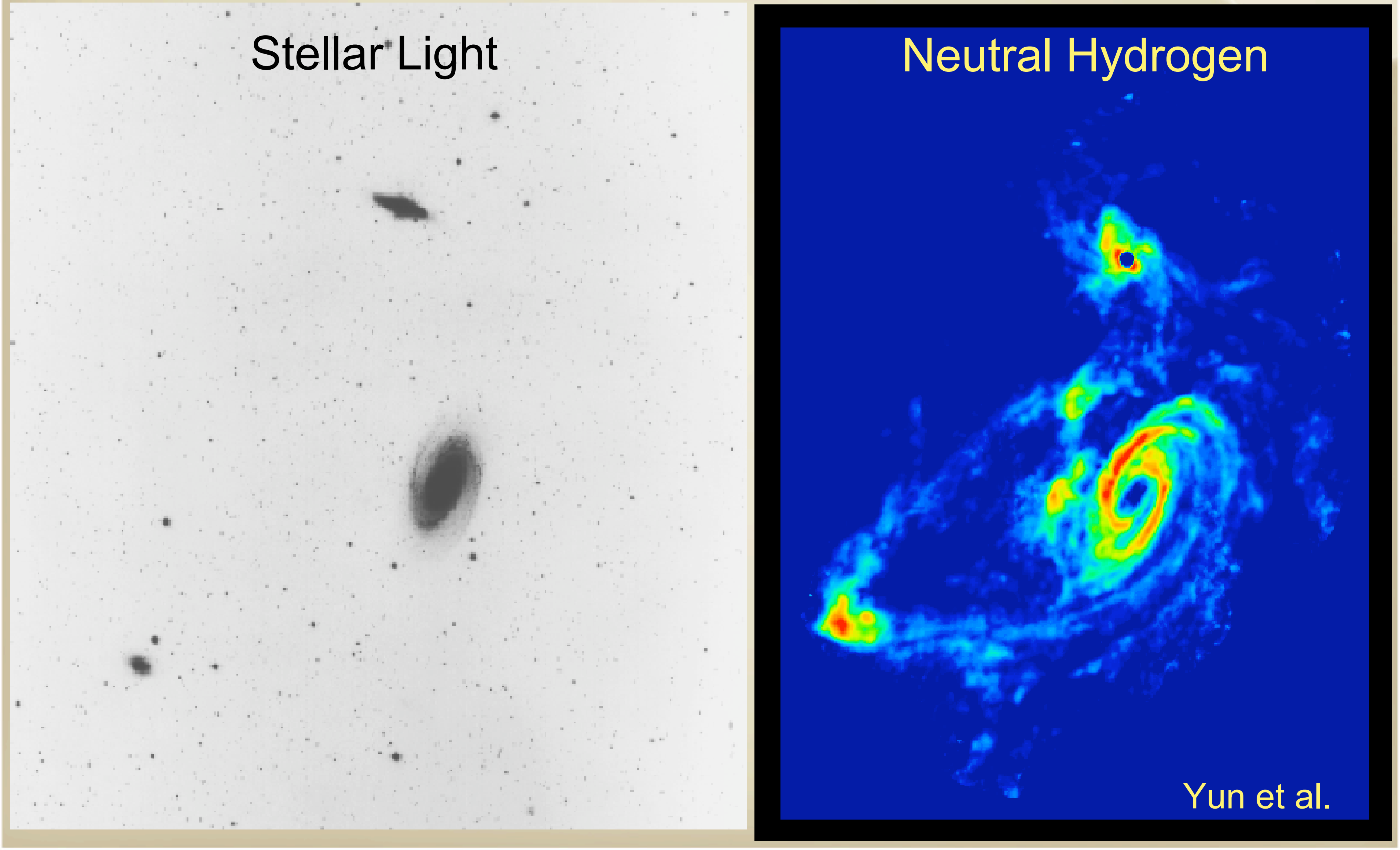




- HI spectral line from galaxy
- Shifted by expansion of universe (“recession velocity”)
- Broadened by rotation

21 cm Line Emission:

The M81 Group



Radio vs Optical Astronomy

- Primary difference is, well, wavelength

$$\lambda_{radio}/\lambda_{optical} \sim 10^5\text{-}10^6$$

$$\lambda_{21cm}/\lambda_{5500Å} = 3.8x10^5$$

- This ratio of wavelengths also effects the resolution. The 305m Arecibo telescope is equivalent to a .8mm optical telescope!:

$$\vartheta = \lambda/D$$

$$D_{21cm}/ D_{5500\,Å} = \lambda_{21cm}/\lambda_{5500Å}$$

Radio vs Optical Astronomy

- This difference in resolution means radio telescopes are diffraction limited
- The resolution is a function of aperture (telescope size) not seeing
- Resolution given by:

$$\vartheta=1.22(\lambda/D)$$

$$\vartheta_{\text{21 cm, Arecibo}}\sim 2.9'$$

- Radio telescope arrays allow for high res. observations not possible with a single dish

Radio Signal Detection

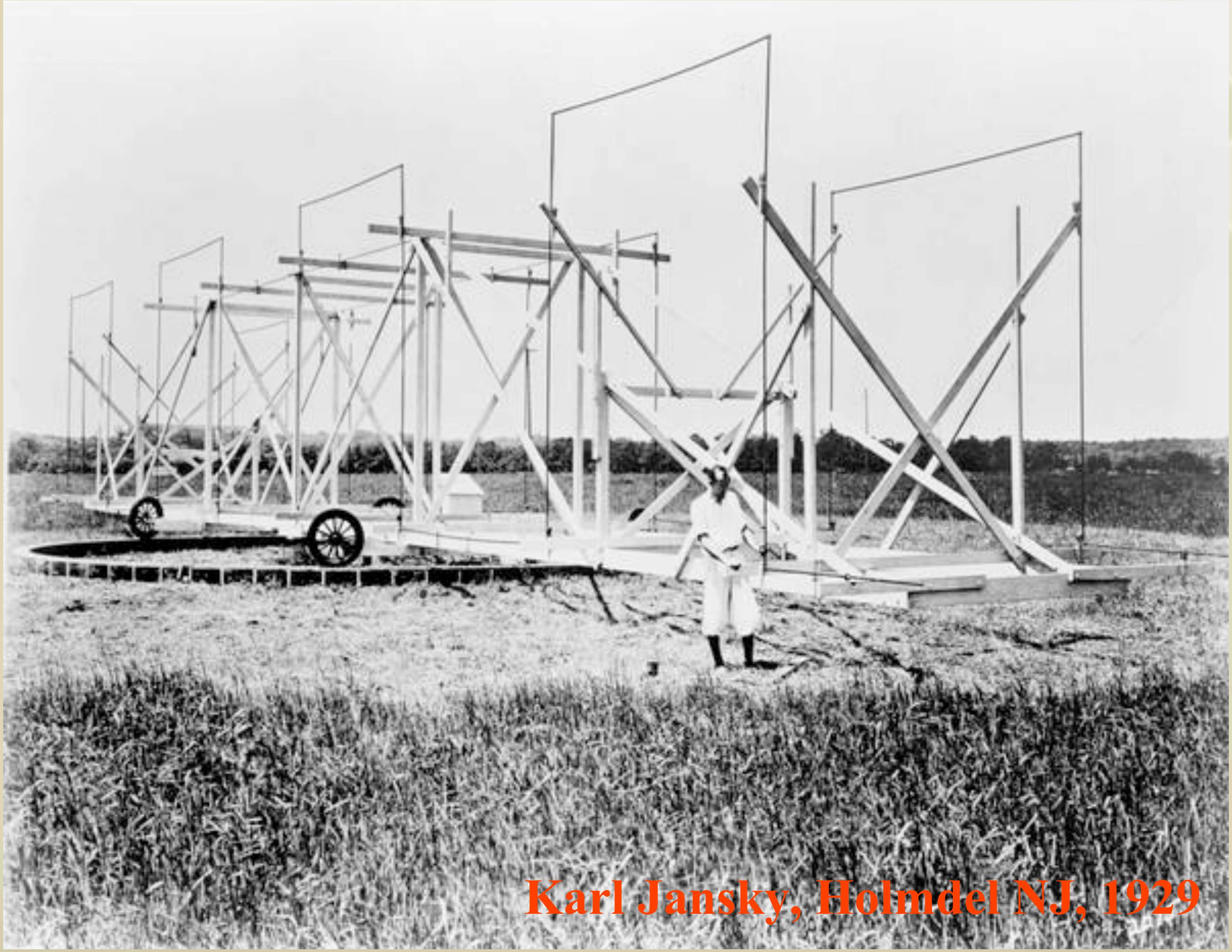
- Signal detected as a wave rather than a photon in contrast with optical
  - The receivers (detectors) are on order the size of incoming waves
- Wave detection preserves phase information:

$$V=V_0\sin(\omega t-\phi)$$

V_0 is amplitude, ϕ is the phase

- Phase info. makes interferometry easy

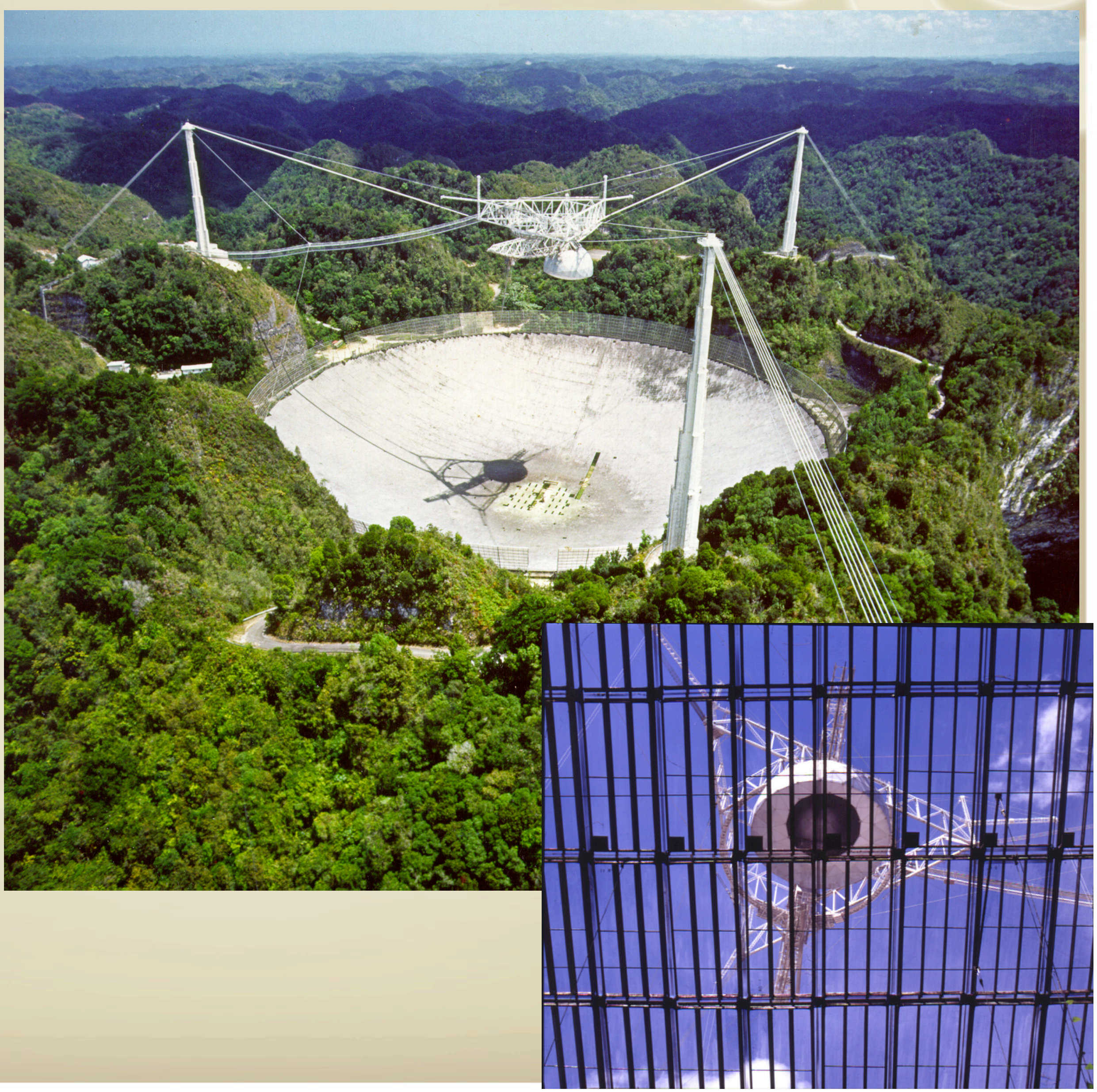
Radio Telescopes



Karl Jansky, Holmdel NJ, 1929

Radio Telescope Components

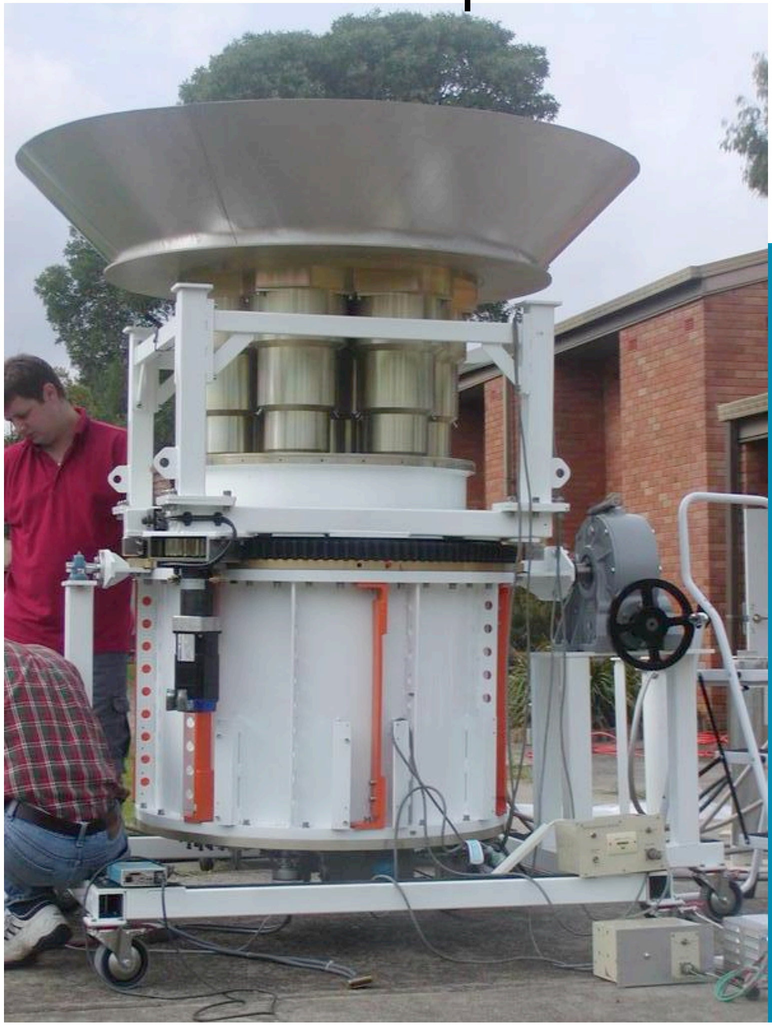
- Reflector(s)
- Feed horn(s)
- Low-noise amplifier
- Filter
- Downconverter
- IF Amplifier
- Spectrometer



Feedhorn

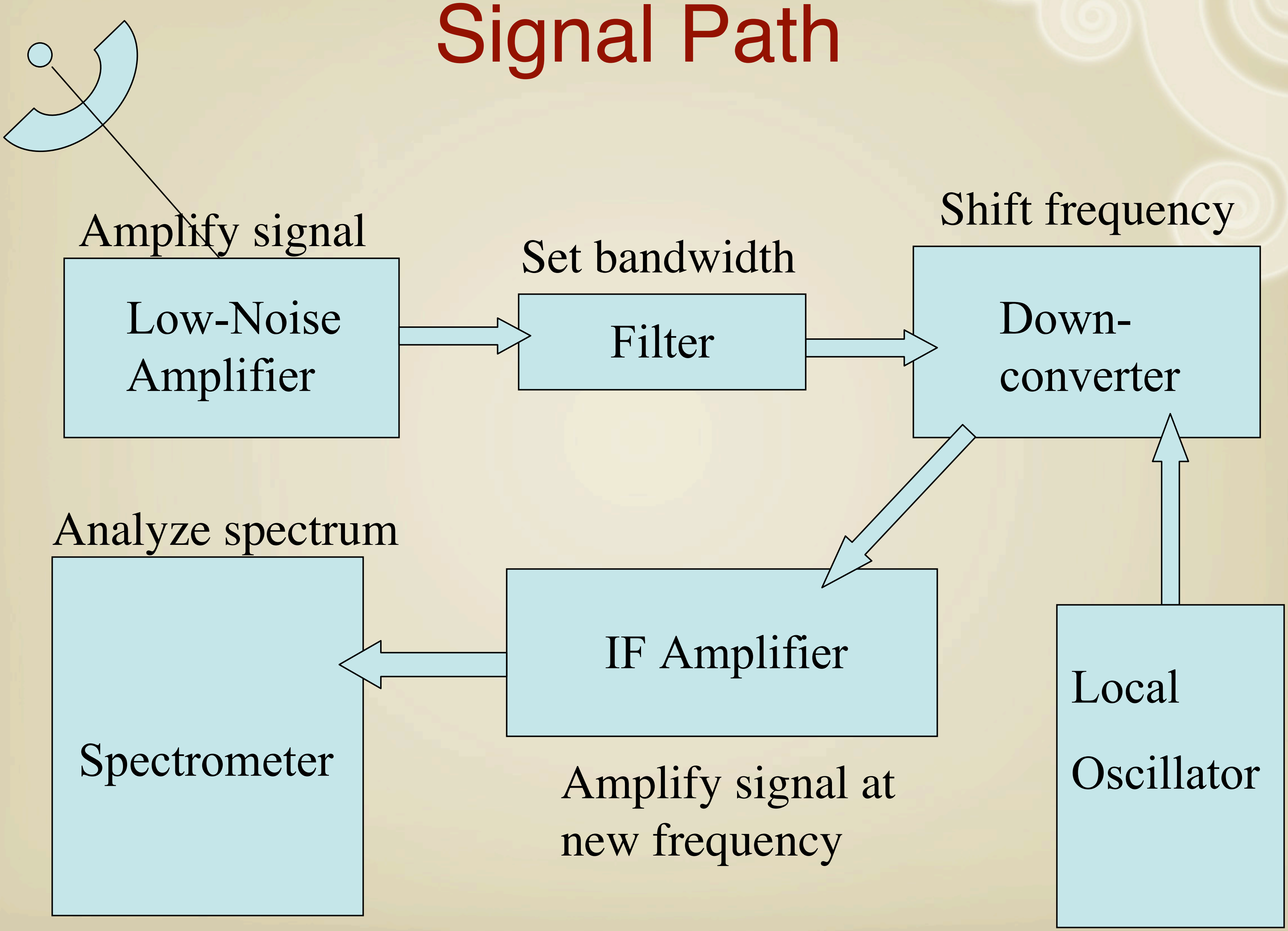
Hardware that takes the signal from the antenna to the electronics

Array of 7 feedhorns on the Arecibo telescope - ALFA



Typical cm-wave feedhorn

Signal Path



Amplify signal

Low-Noise Amplifier

Set bandwidth

Filter

Shift frequency

Down-converter

Local Oscillator

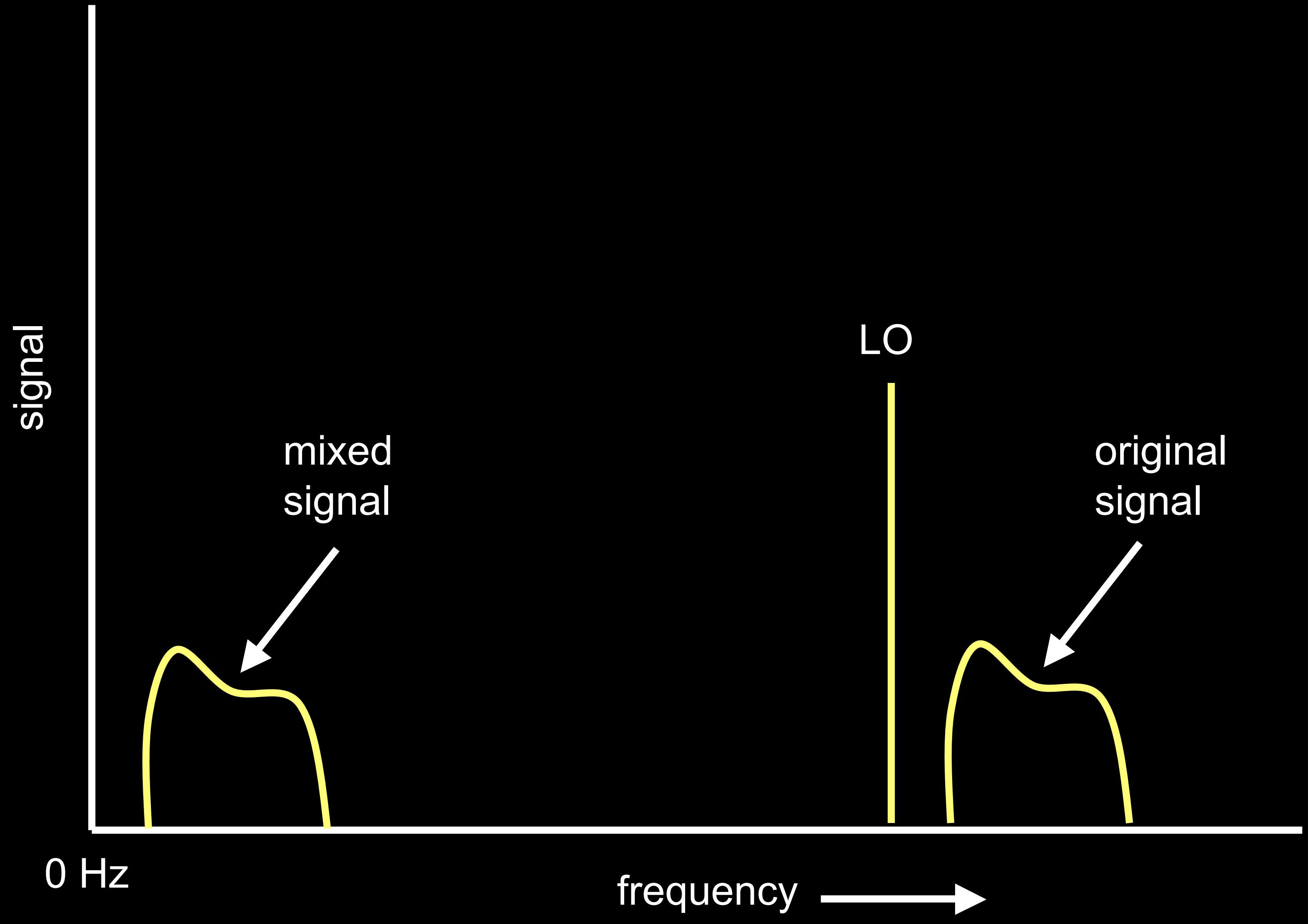
IF Amplifier

Amplify signal at new frequency

Analyze spectrum

Spectrometer

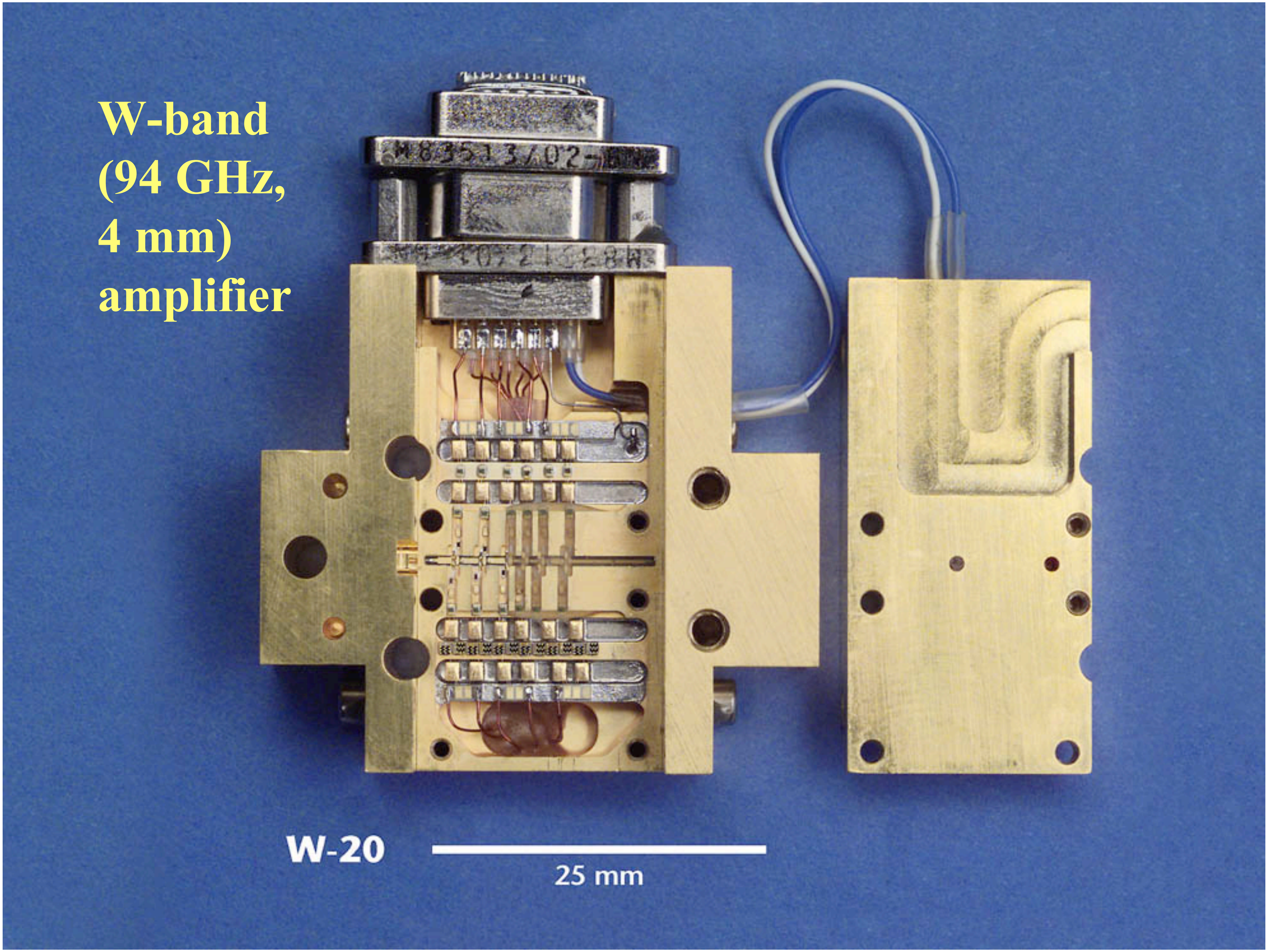
Mixers



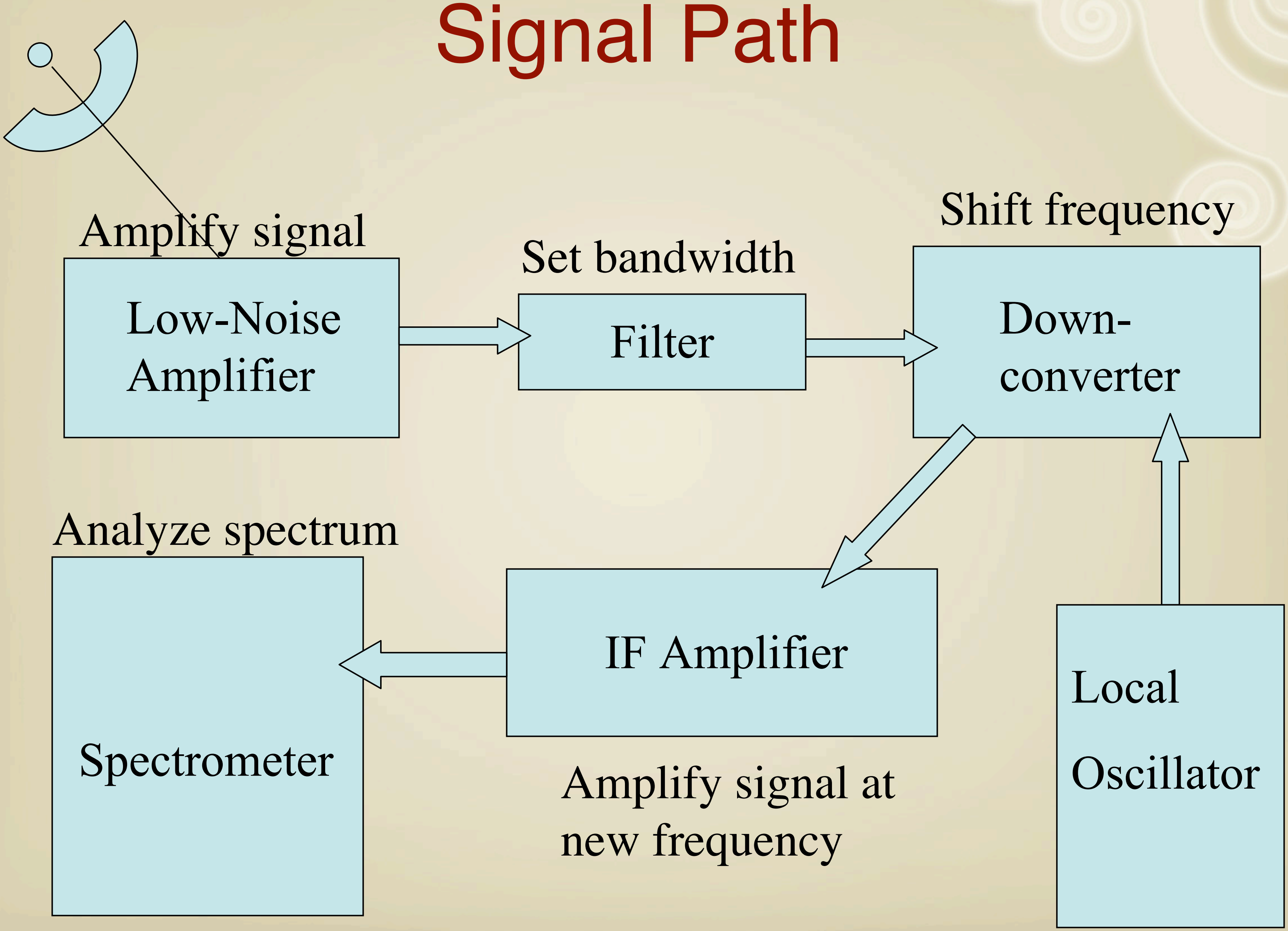
The Signal Path

- Strong amplification and stable receivers are required since the signal is much smaller than the thermal receiver noise.
- Switching techniques are often employed to monitor and correct for variations in amplifier gain
  - switching between sky and a reference source
  - between object and ostensibly empty sky
  - in frequency between a frequency of interest and a neighboring passband.
- Downconversion of the signal is necessary because smaller frequencies are much more convenient for the electronics

W-band
(94 GHz,
4 mm)
amplifier



Signal Path



Amplify signal

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IF Amplifier

Amplify signal at new frequency

Analyze spectrum

Spectrometer

Autocorrelation Spectrometer

Or how we actually make sense out of the signal

- Measures the fourier transform of the power spectrum
- Special-purpose hardware computes the correlation of the signal with itself:

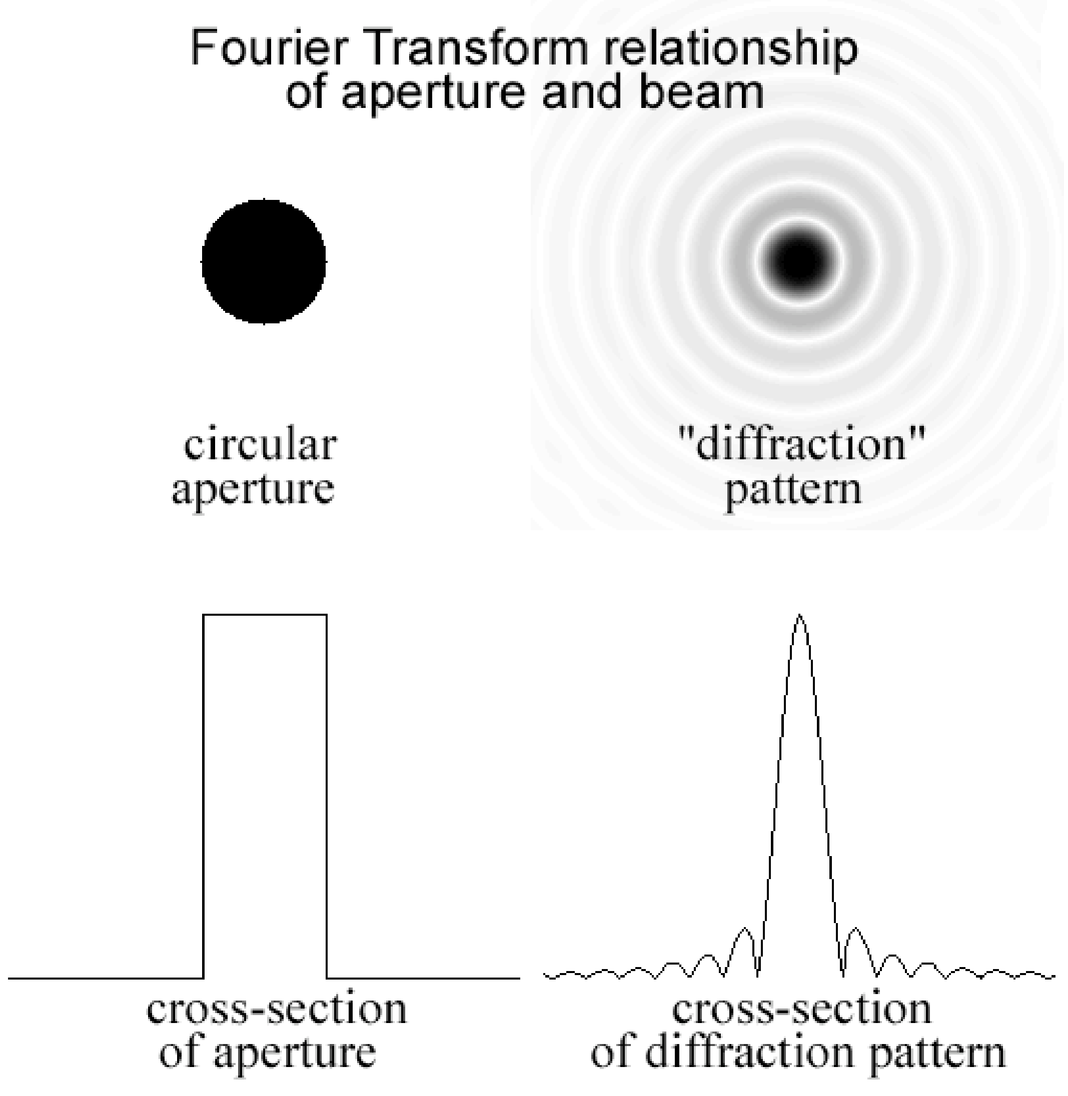
  $$R_n = N^{-1} \Sigma_1^N [\upsilon(t_j)\upsilon(t_j+n\delta t)]$$

  where δt is *lag* and υ is signal voltage; integer n ranges from 0 to $(\delta t\ \delta f)^{-1}$ if frequency channels of width δf are required
- Power spectrum is discrete Fourier transform (FFT) of R_n

Spectral Resolution

- The spectral resolution in a radio telescope can be limited by several issues:
  - integration time (signal-to-noise)
  - filter bank resolution (if you're using a filter bank to generate a power spectrum in hardware)

Fourier Transforms and Beam Patterns



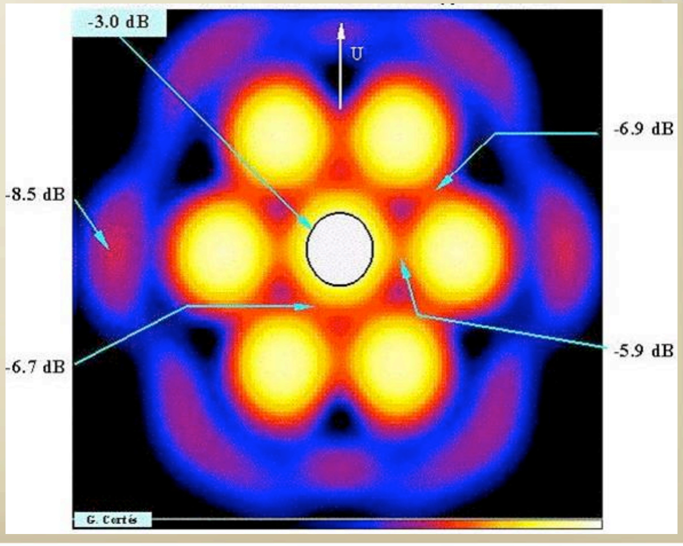
Radio Telescope Characteristics

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



Radio Telescope Characteristics

power and gain

- The power collected by an antenna is approximately:

$$P = S \times A \times \Delta\nu$$

S = flux at Earth, A = antenna area, $\Delta\nu$ = frequency interval or bandwidth of measured radiation

- The gain of an antenna is given by:

$$G = 4\pi A/\lambda^2$$

- Aperture efficiency is the ratio of the effective collecting area to the actual collecting area

Radio Telescope Characteristics

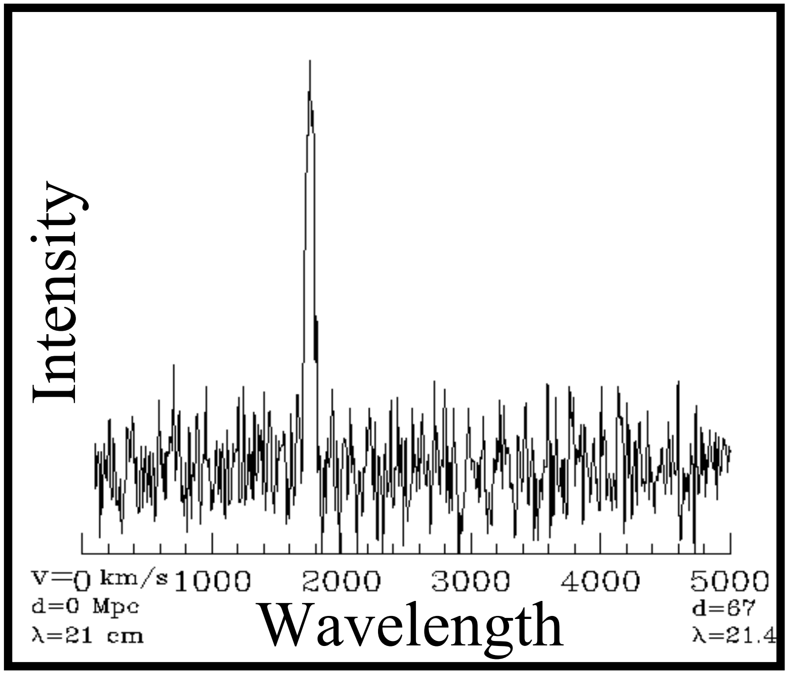
sensitivity

- **Sensitivity is a measure of the relationship between the signal and the noise**
- **Signal:** the power detected by the telescope
- **Noise:** mostly thermal from electronics but also ground radiation entering feedhorn and the cosmic microwave background. Poisson noise is ALWAYS important. Interference is also a HUGE problem (radar, GPS, etc.)

Radiometer Equation

$$T_{rms} = \alpha T_{sys} / \sqrt{\Delta \nu t}$$

- T_{rms} = rms noise in observation
- $\alpha \sim (2)^{1/2}$ because half of the time is spent off the source
    - off-source = position switch
    - off-frequency = frequency switch
- T_{sys} = System temperature
- $\Delta\nu$ = bandwidth, i.e., frequency range observed
- t = integration time



Radio Telescope Characteristics

semantics

- **Preferred unit of flux density:** (requires calibration) is Jansky:

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

- **Brightness:** Flux density per unit solid angle. Brightness of sources are often given in temperature units

Radio Telescope Characteristics

Temperatures

In radio astronomy power is often measured in temperature - the equivalent temperature of a blackbody producing the same power

- **System temperature**: temperature of blackbody producing same power as telescope + instrumentation without a source
- **Brightness temperature:** Flux density per unit solid angle of a source measured in units of equivalent blackbody temperature
- **Antenna temperature:** The flux density transferred to the receiver by the antenna. Some of the incoming power is lost, represented by the aperture efficiency

Radio Telescope Characteristics

polarization

- H I sources are un-polarized
- Synchrotron sources are often polarized – ***E***-field in plane of electron's acceleration
- Noise sources (man-made interference) are often polarized
- Each receiver can respond to one polarization – one component of linear or one handedness of circular polarization
- Usually there are multiple receivers to observe both polarization components simultaneously

Parameterization of Polarization

- Linear E_x and E_y with phase difference ϕ
- Stokes' parameters:
  $I = E_x^2 + E_y^2$
  $Q = E_x^2 - E_y^2$
  $U = 2E_xE_y\cos\phi$
  $V = 2E_xE_y\sin\phi$
- Unpolarized source: $E_x = E_y$ and $\phi = 0$
- Un-polarized $Q = 0$, $V = 0$, and $I = U$;
- Stokes' I = total flux (sum of x and y polarizations)

Baselines and Observing Schemes

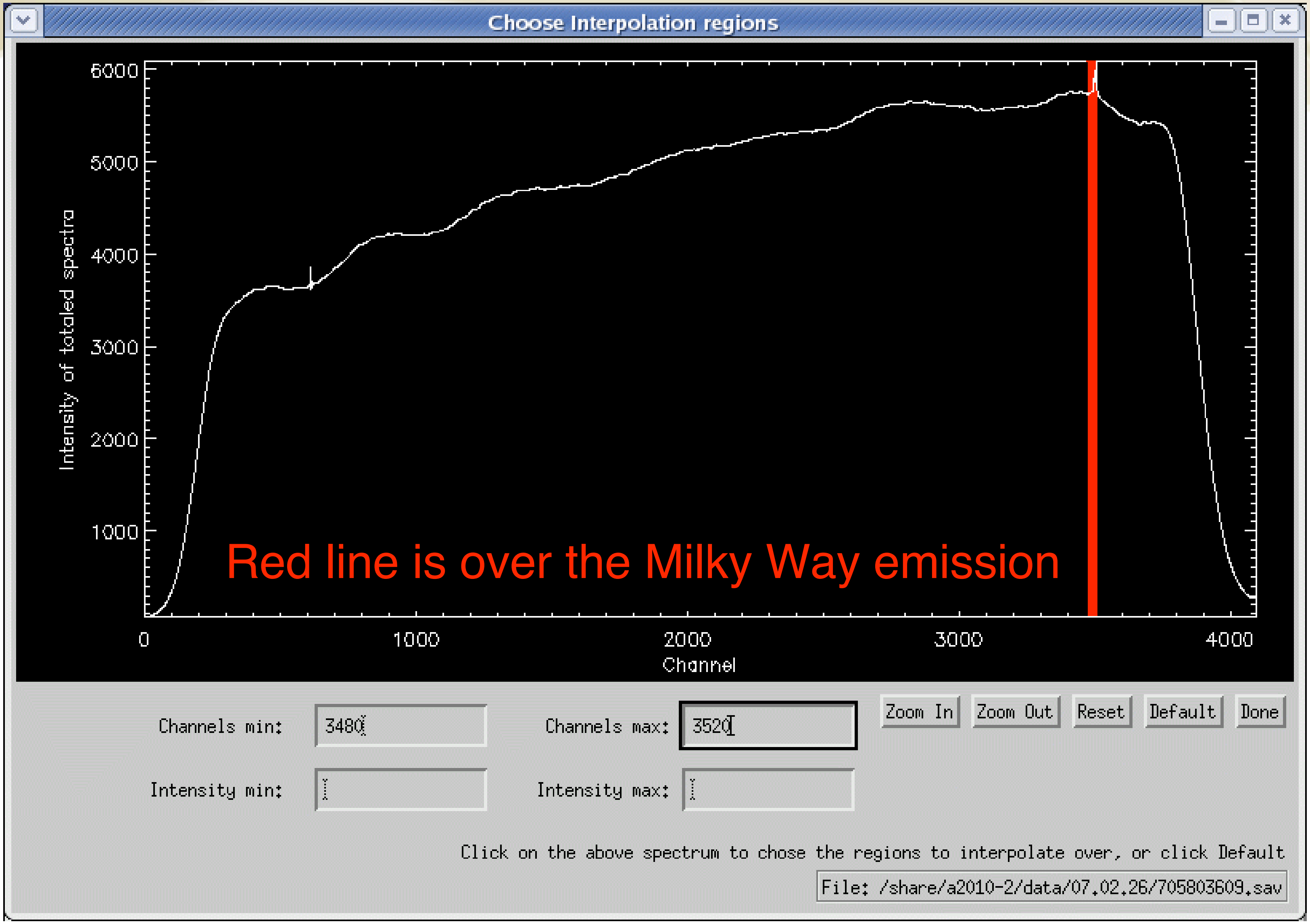
- Instrumental effects cause variations in the baseline that are often much larger than the signal that we want to measure

- We need to find a way to observe with and without the source but without changing the instrumental effects

- We usually accomplish the above with either beam (position) switching or frequency switching

Baselines

Raw baseline shape for a 21 cm observation with Arecibo



Red line is over the Milky Way emission

Channels min: 3480

Channels max: 3520

Intensity min:

Intensity max:

Click on the above spectrum to chose the regions to interpolate over, or click Default

File: /share/a2010-2/data/07.02.26/705803609.sav

Baselines and Observing Schemes

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ALFALFA Observing Technique:

HI 21 cm Observing in Action

- **Drift scan:** telescope is fixed, the position change is driven by the rotation of the Earth
- Baseline shape is removed using spectra that are adjacent in time and space
- Because the telescope does not move, the systematic noise does not change making the data easier to correct