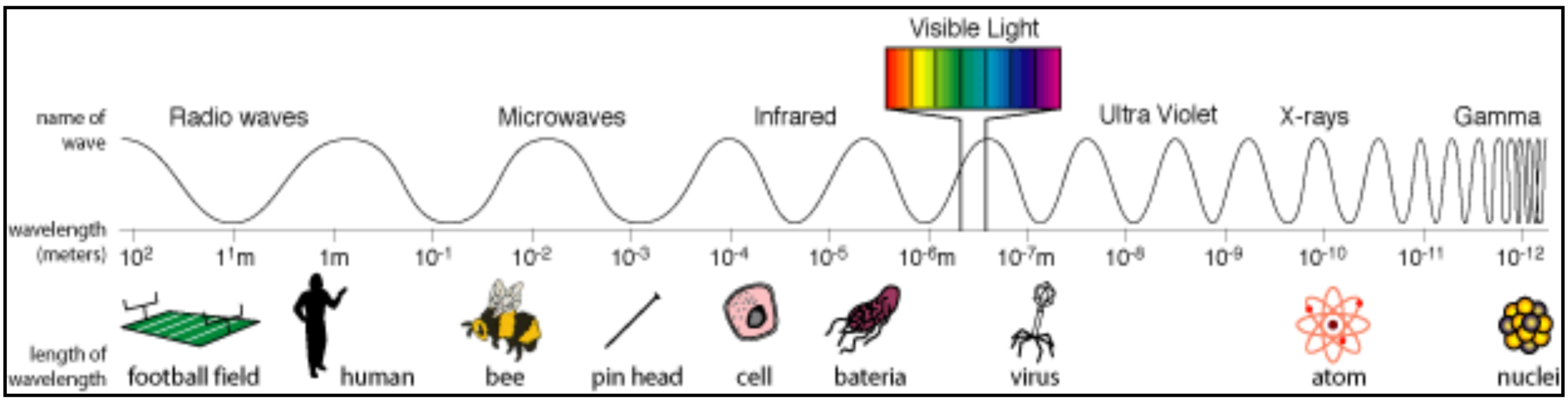
Introduction to Radio Astronomy

- Sources of radio emission
- Radio telescopes - collecting the radiation
- Processing the radio signal
- Radio telescope characteristics
- Observing radio sources

Sources of Radio Emission

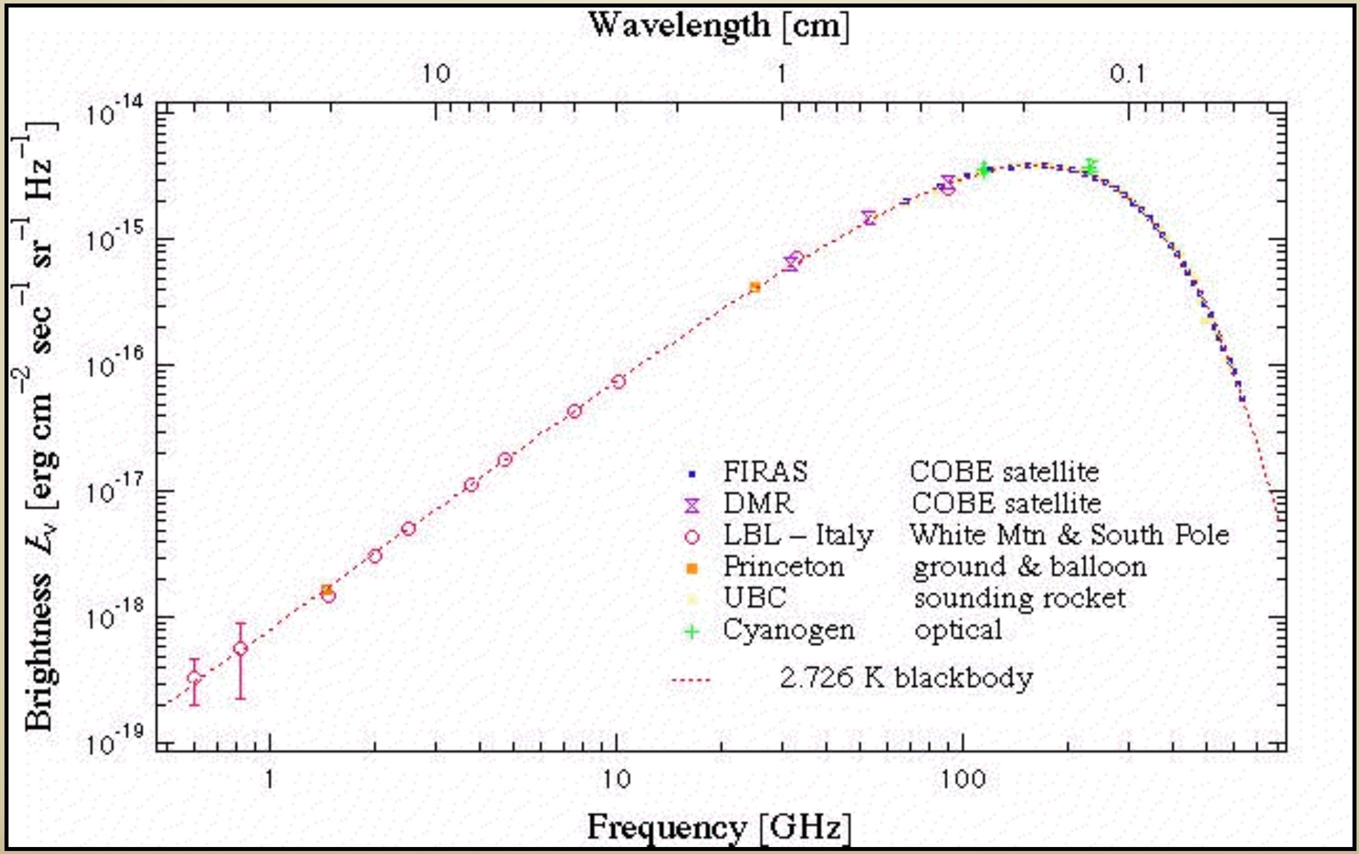
- Blackbody (thermal)
- Continuum sources (non-thermal)
- Spectral line sources



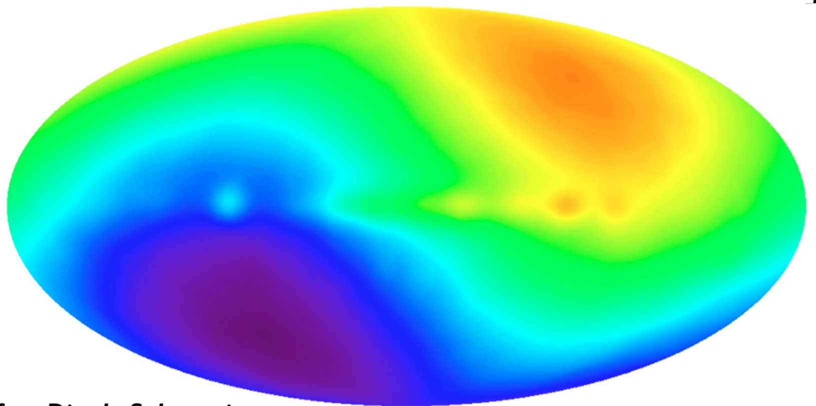
Blackbody Sources:

The cosmic microwave background, the planets

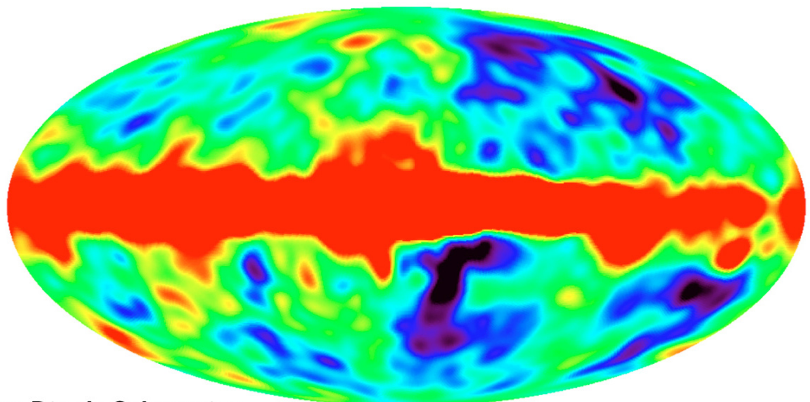
- Obs in cm requires low temperature: $\lambda_m T = 0.2898$ cm K
- Flux = const $\times \nu^{\alpha} \times$ T
- For thermal sources α is ~2 (flatter for less opaque sources)



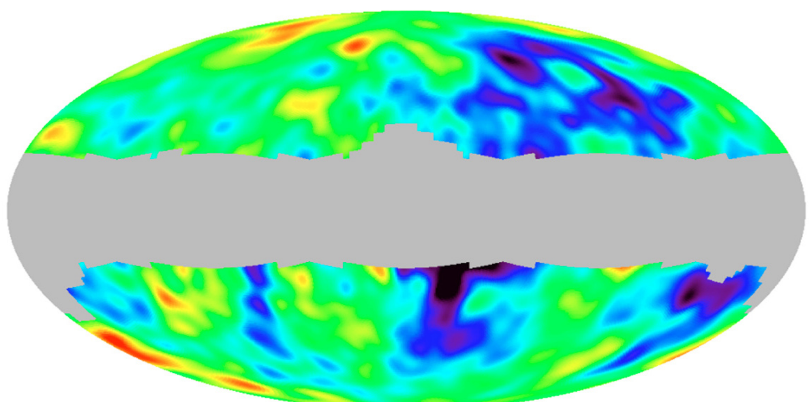
DMR 53 GHz Maps



Before Dipole Subtraction



After Dipole Subtraction



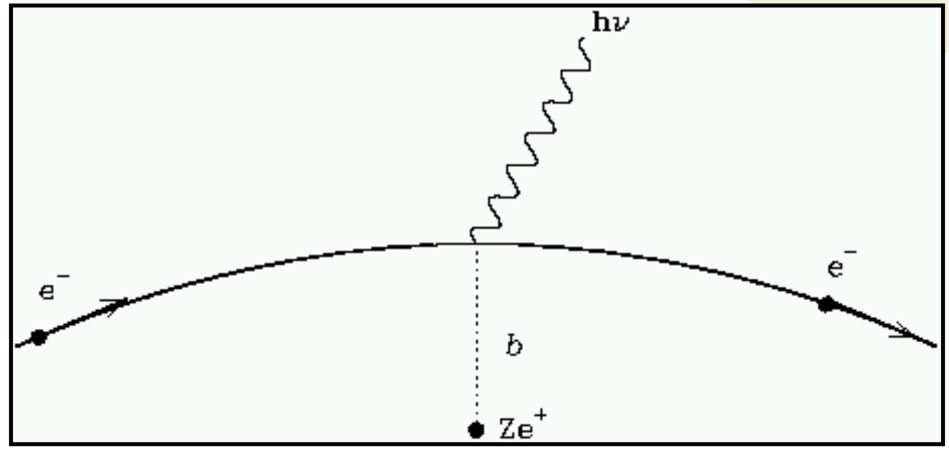
After Galaxy Subtraction

Continuum (non-thermal) Emission:

Emission at all radio wavelengths

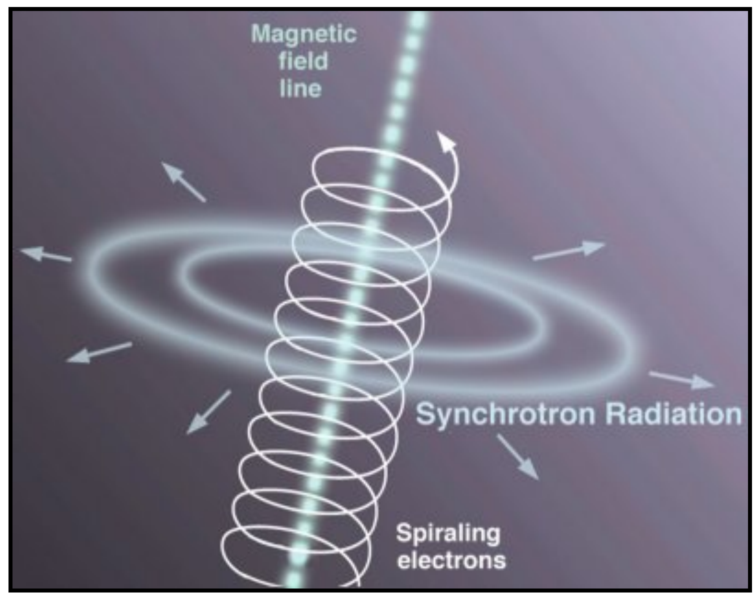
Bremsstralung (free-free):

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

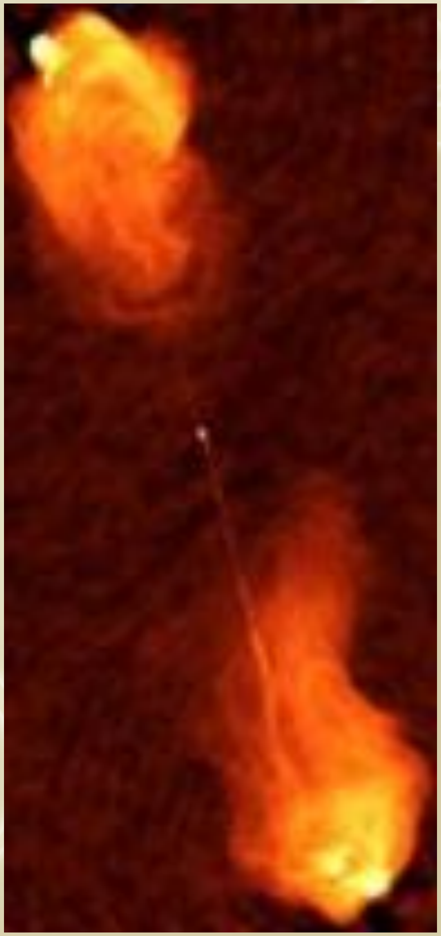


Synchrotron:

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

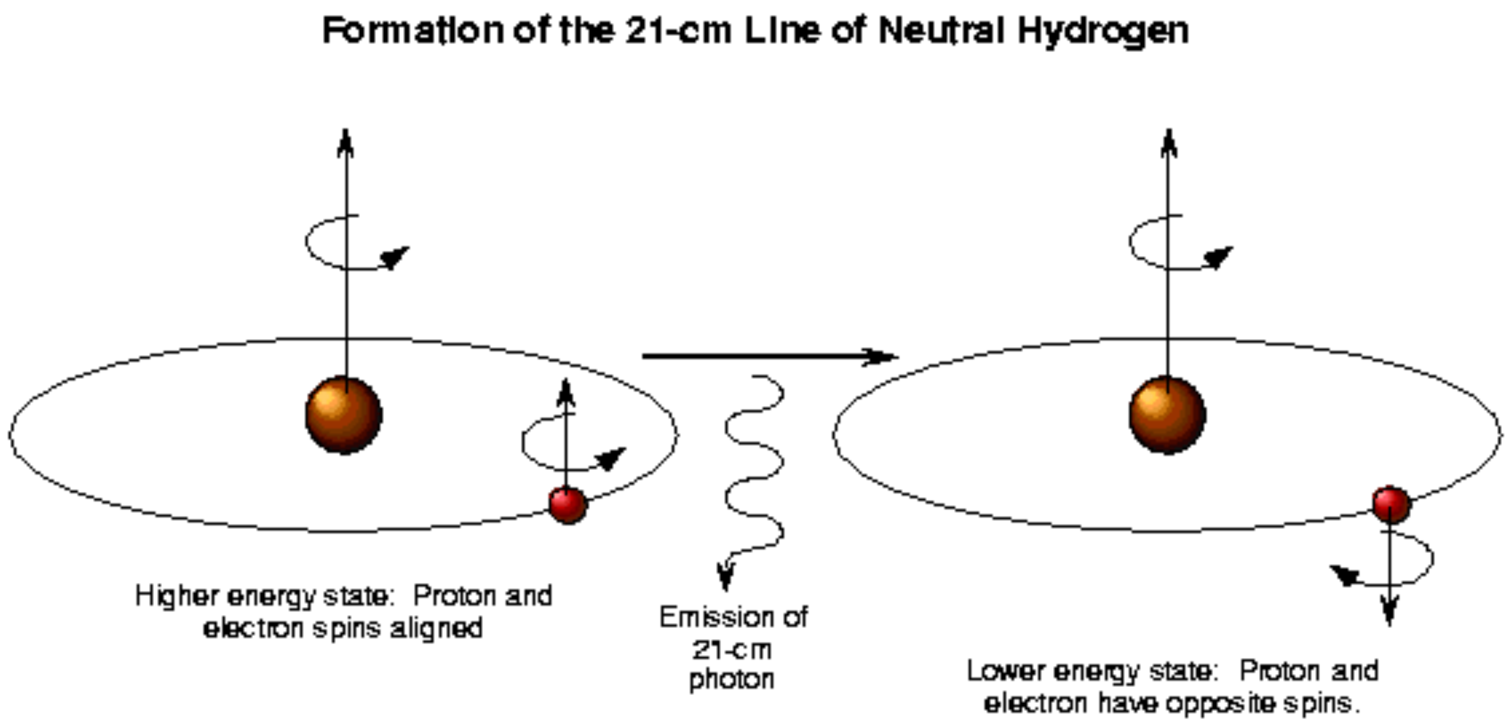


Sources of Continuum Emission



Radio Emission Lines

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

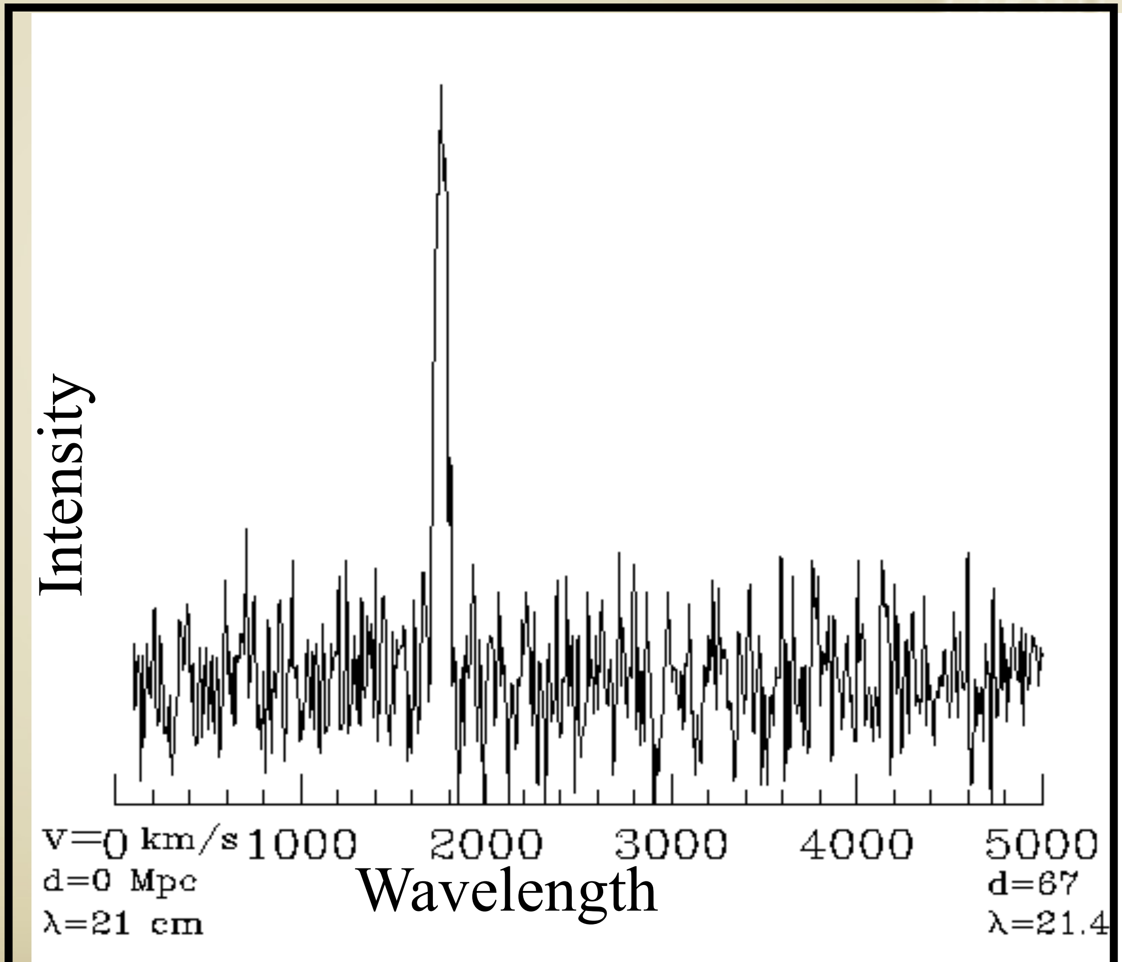


21cm Line of Neutral Hydrogen

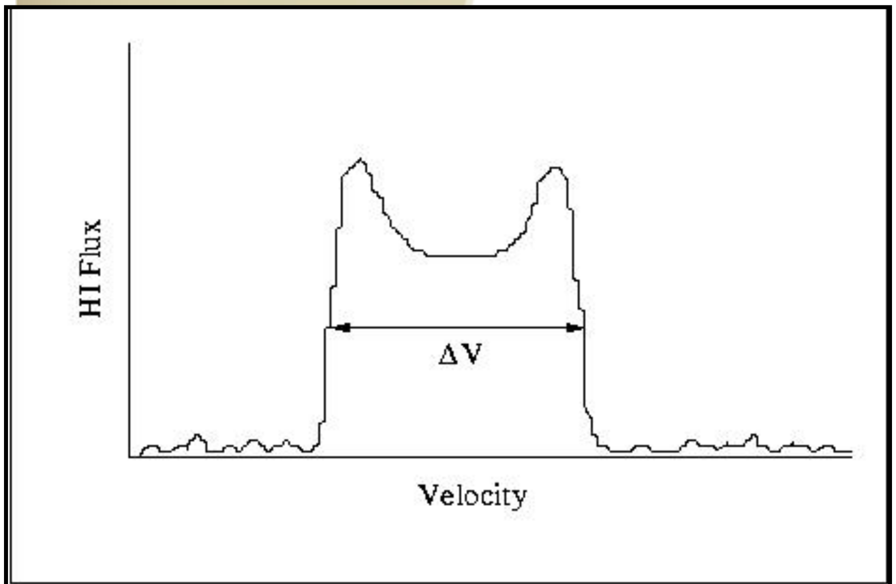
Not only are λ, ν, and E equivalent, but for the most part velocity and distance are as well.

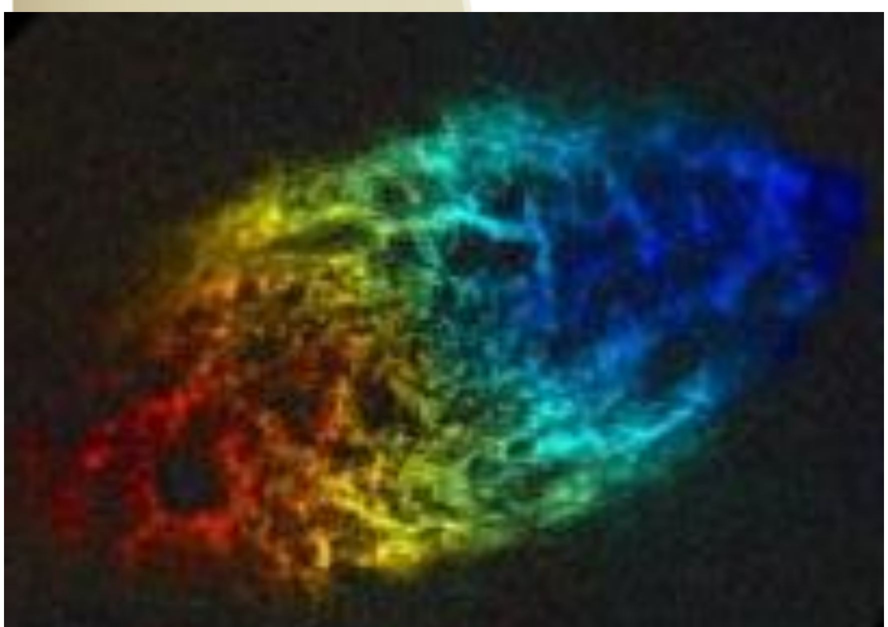
$$z = \frac{\lambda - \lambda_0}{\lambda_0} = \frac{\Delta v}{c}$$

$$d = v / H_0$$



21cm Line of Neutral Hydrogen, cont.

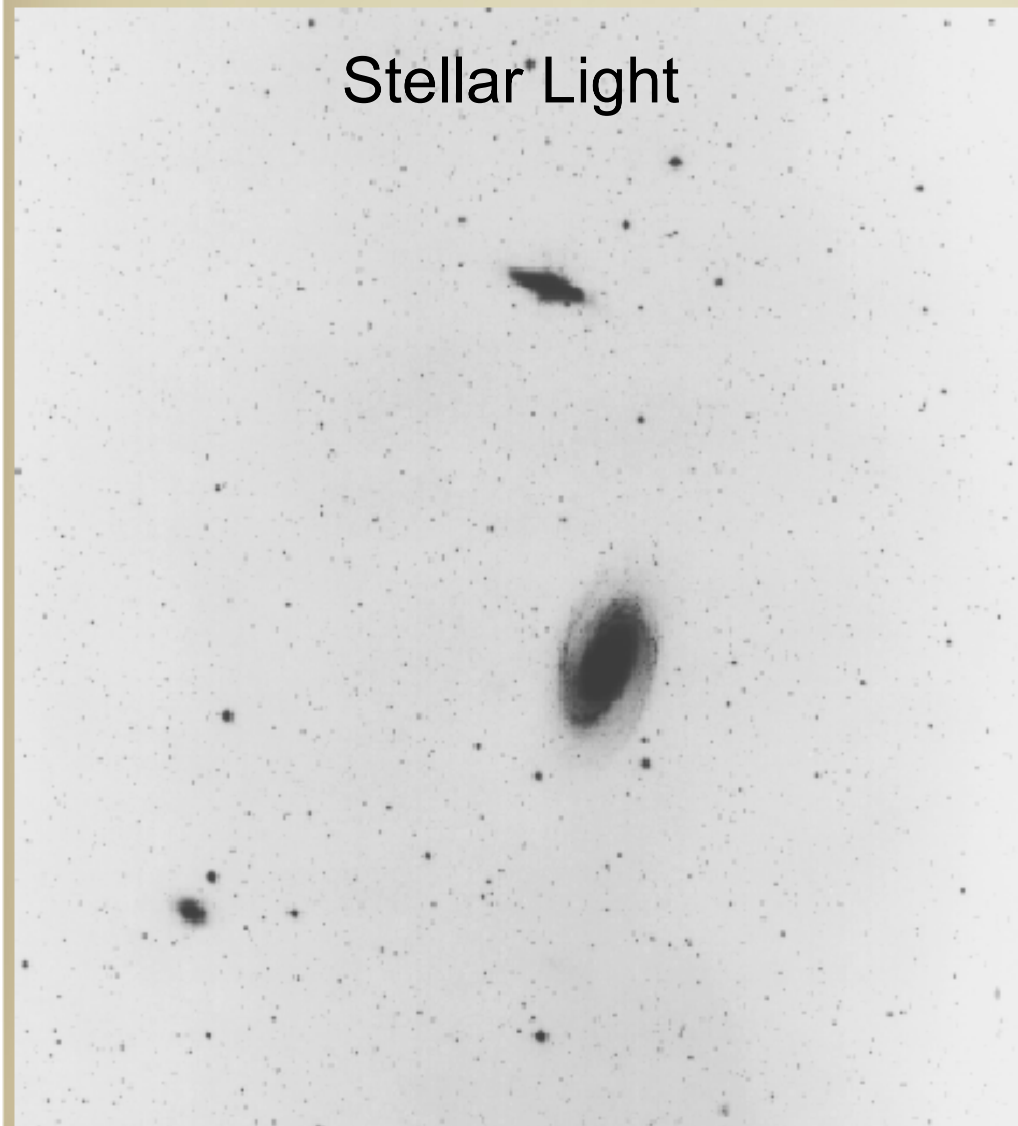


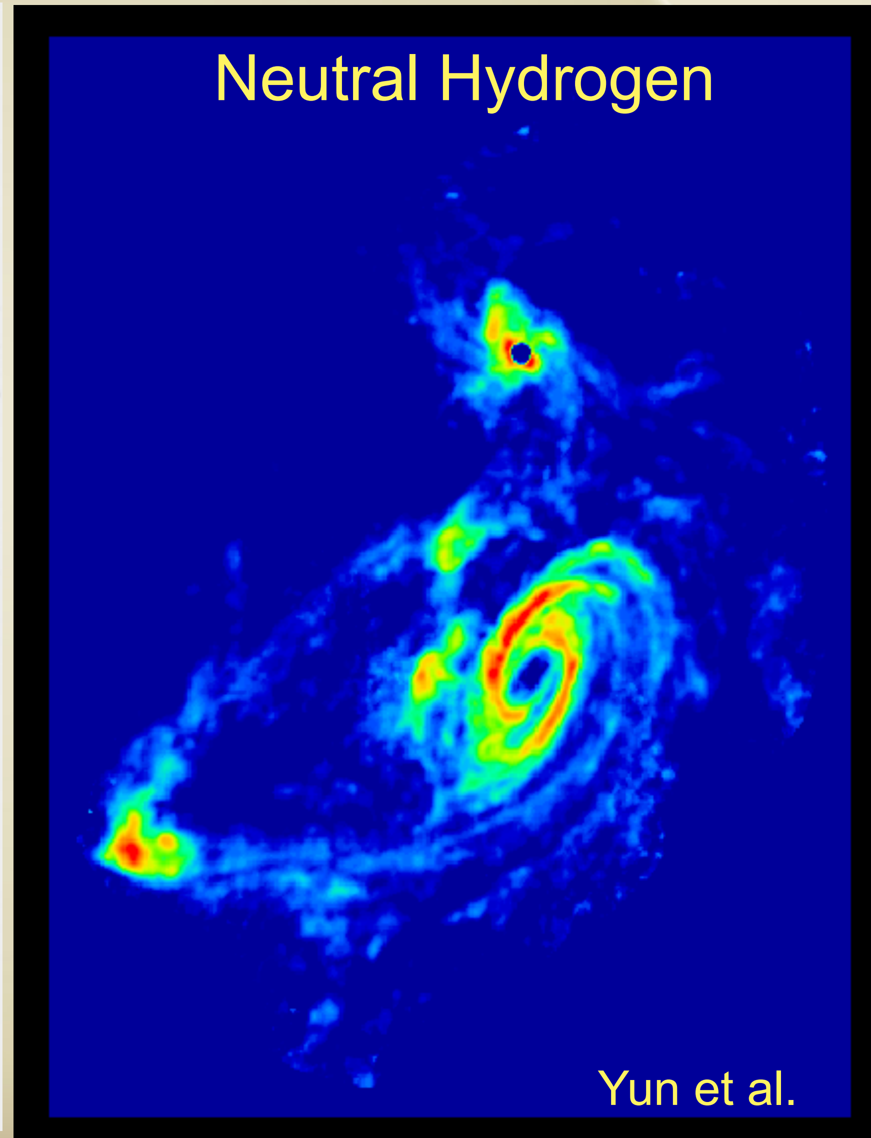


- HI spectral line from galaxy
- Shifted by expansion of universe (“recession velocity”)
- Broadened by rotation

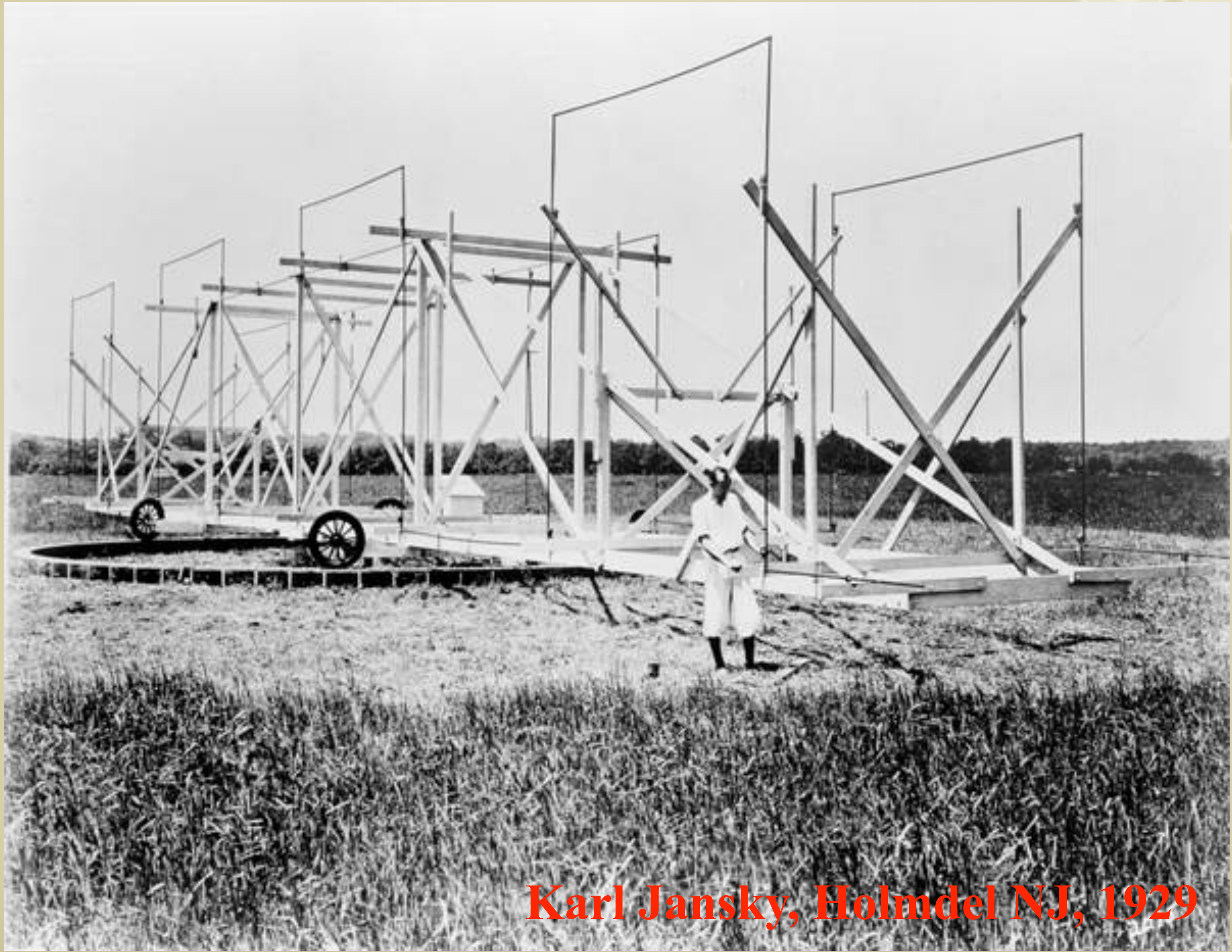
21 cm Line Emission:

The M81 Group



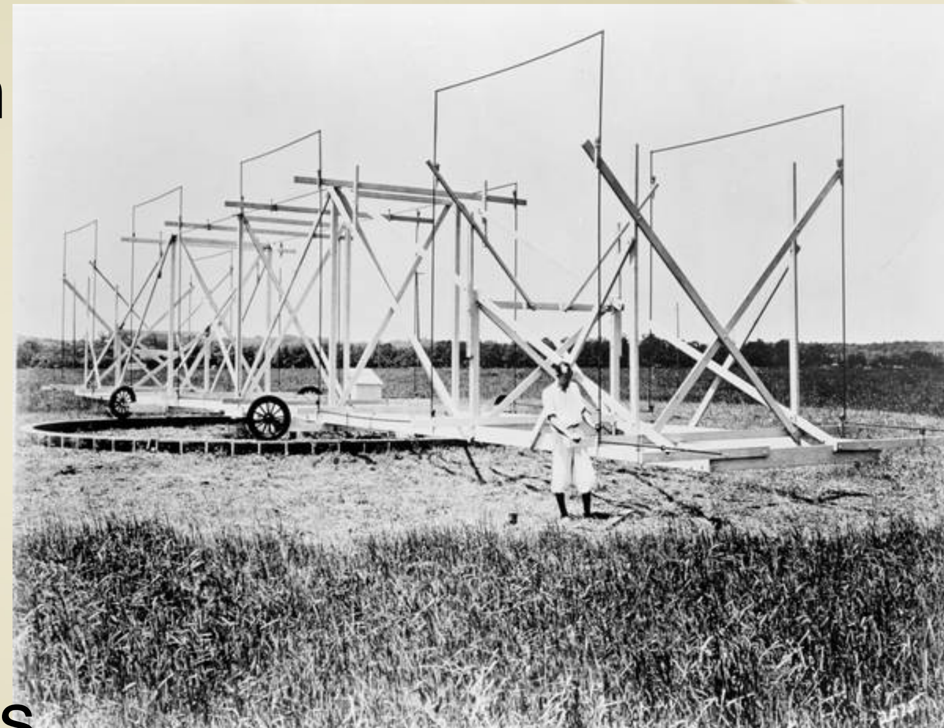


Radio Telescopes



Antennas

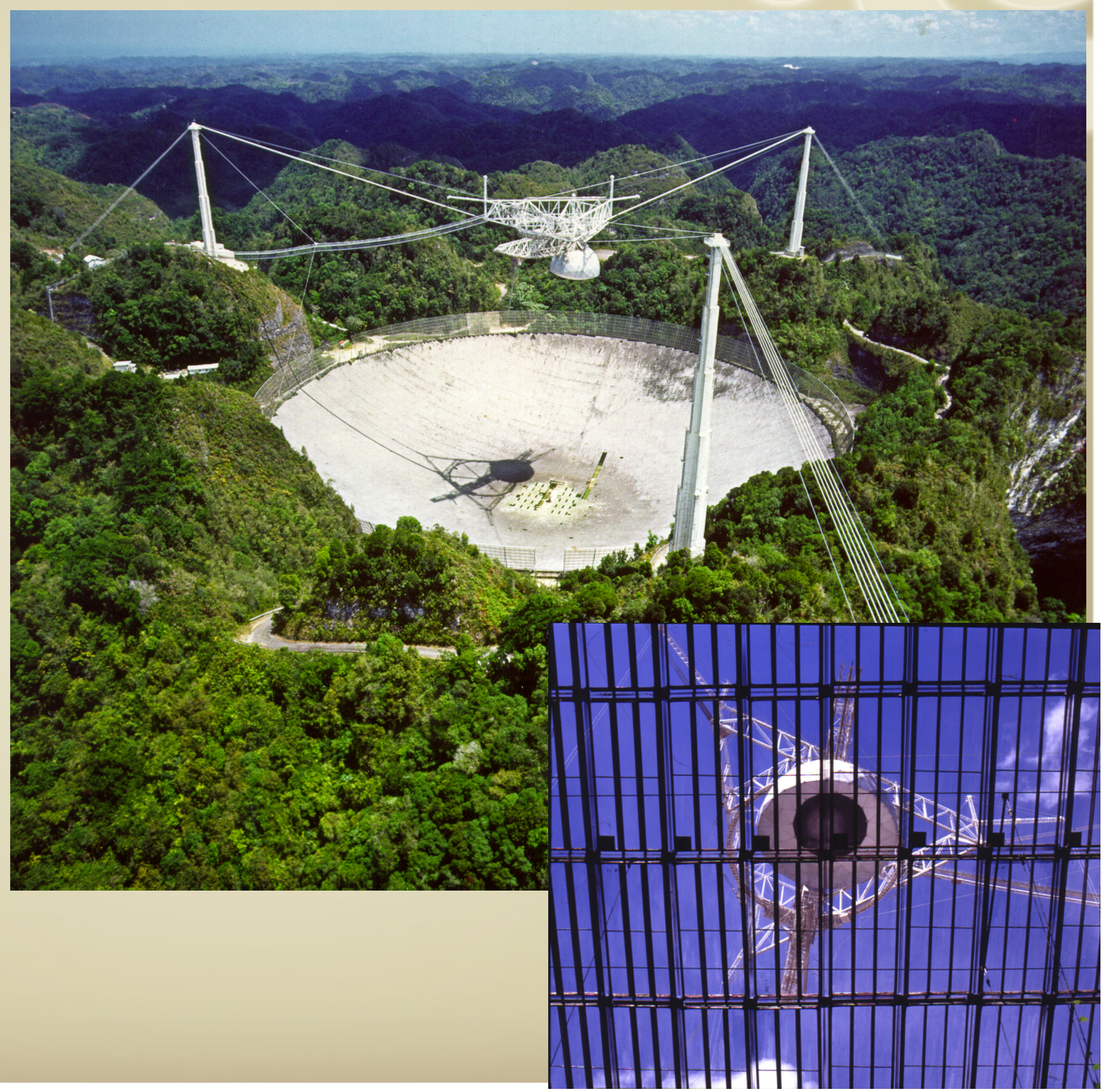
- Device for converting electromagnetic radiation into electrical currents or vice-versa.
- Often done with dipoles or feedhorns.
- The most basic "telescopes" are antennas + electronics



Karl Jansky, Holmdel NJ, 1929

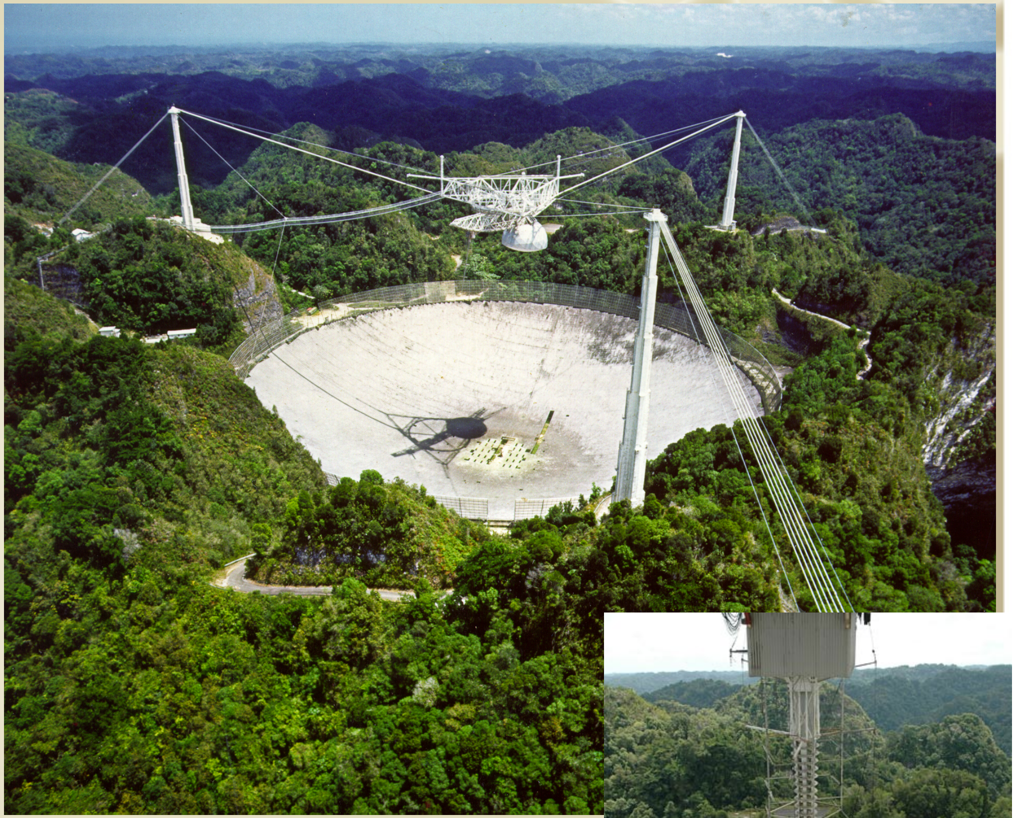
Radio Telescope Components

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



Reflector

- Increases the collecting area
- Increases sensitivity
- Increases resolution
- Must keep all parts of on-axis plane wavefront in phase at focus
- Spherical surface focuses to a line

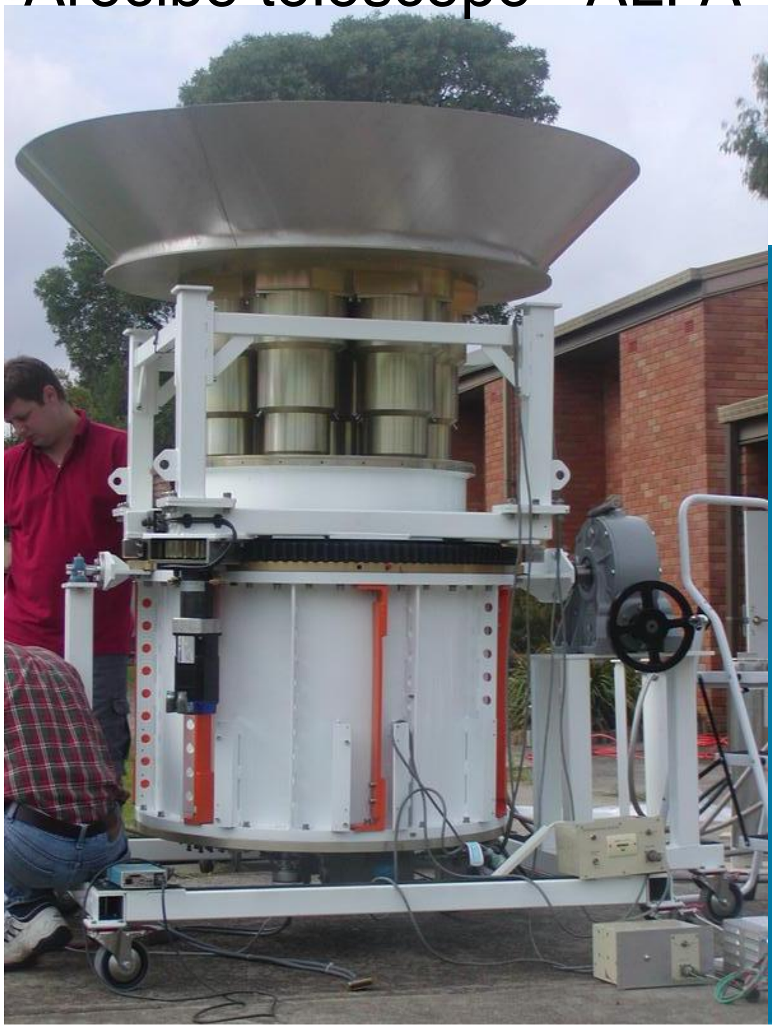


430 MHz
line feed

Antenna/Feedhorn

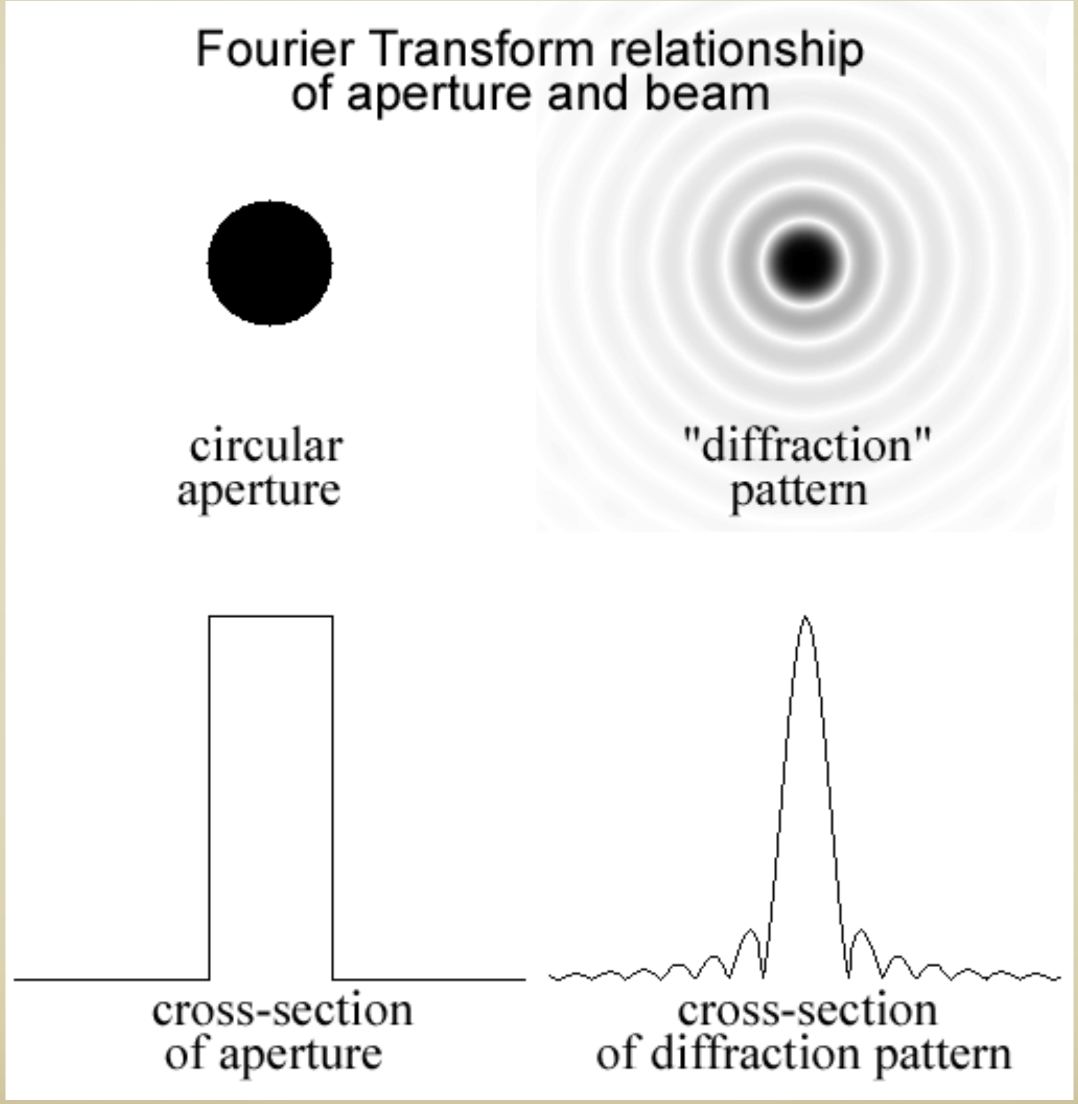
Hardware that takes the signal from the antenna to the electronics

Array of 7 feedhorns on the Arecibo telescope - ALFA



Typical cm-wave feedhorn

Fourier Transforms and Beam Patterns

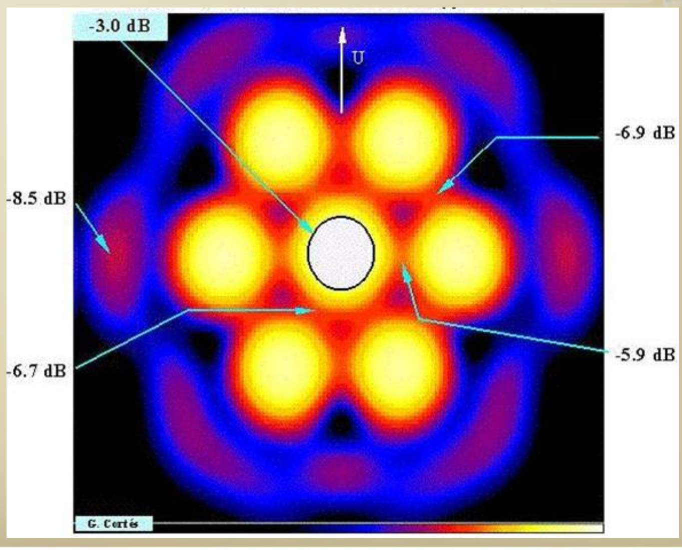


Radio Telescope Characteristics
beam and sidelobes

- 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:

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

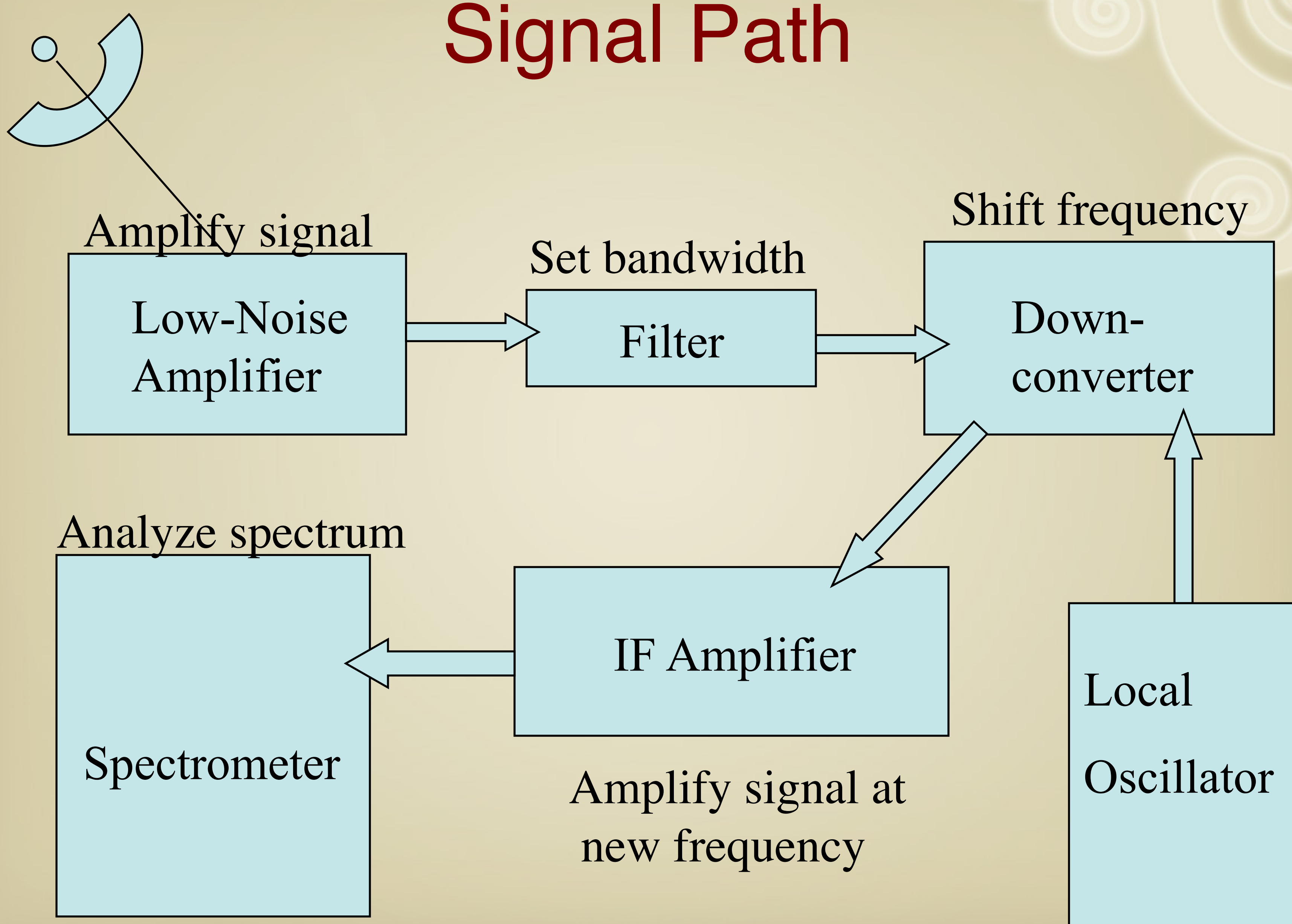
S = flux at Earth, A = antenna area, $\Delta\nu$ = frequency interval or bandwidth of measured radiation

- The gain of an antenna is given by:

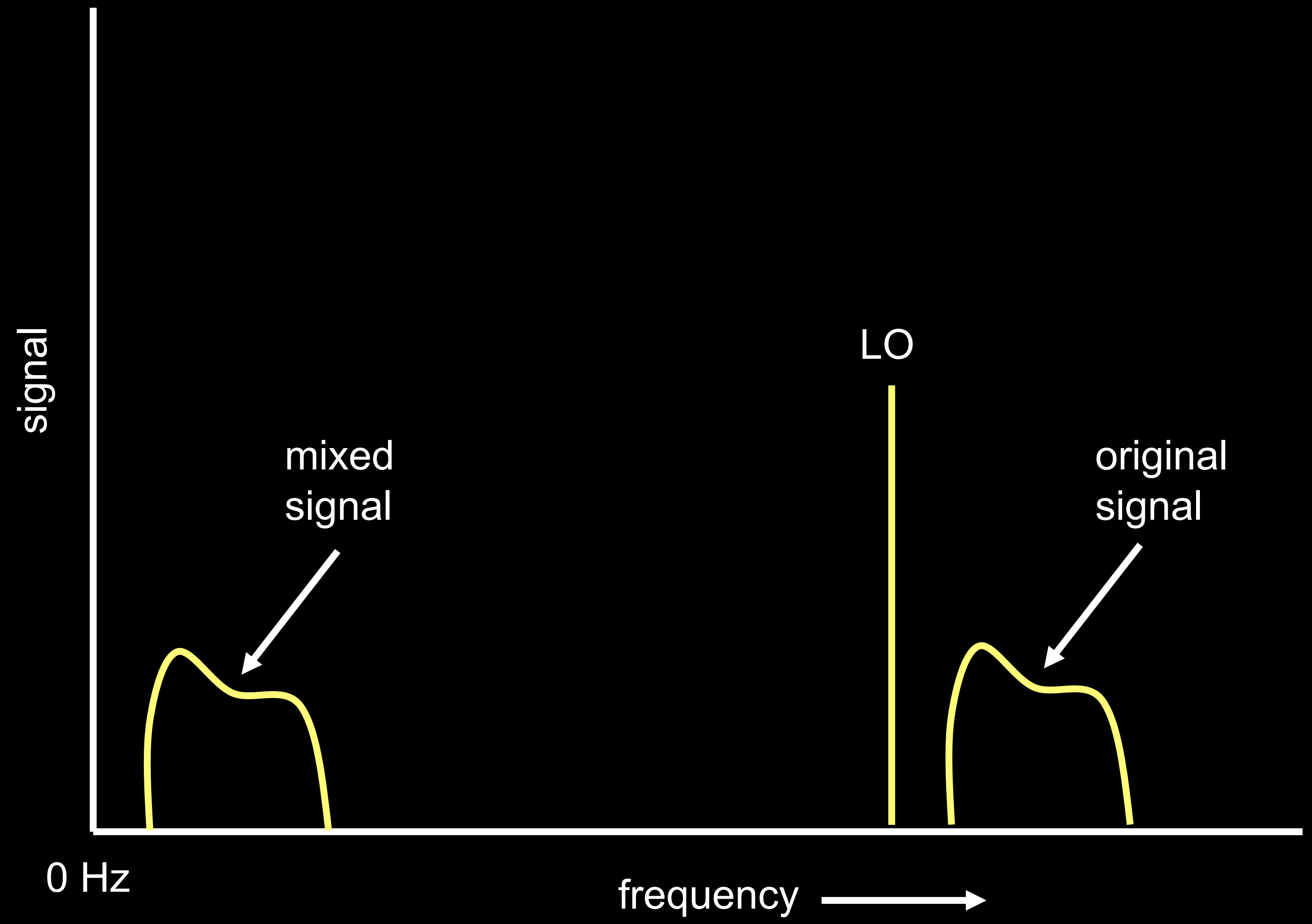
$$G = 4\pi A/\lambda^2$$

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

Signal Path

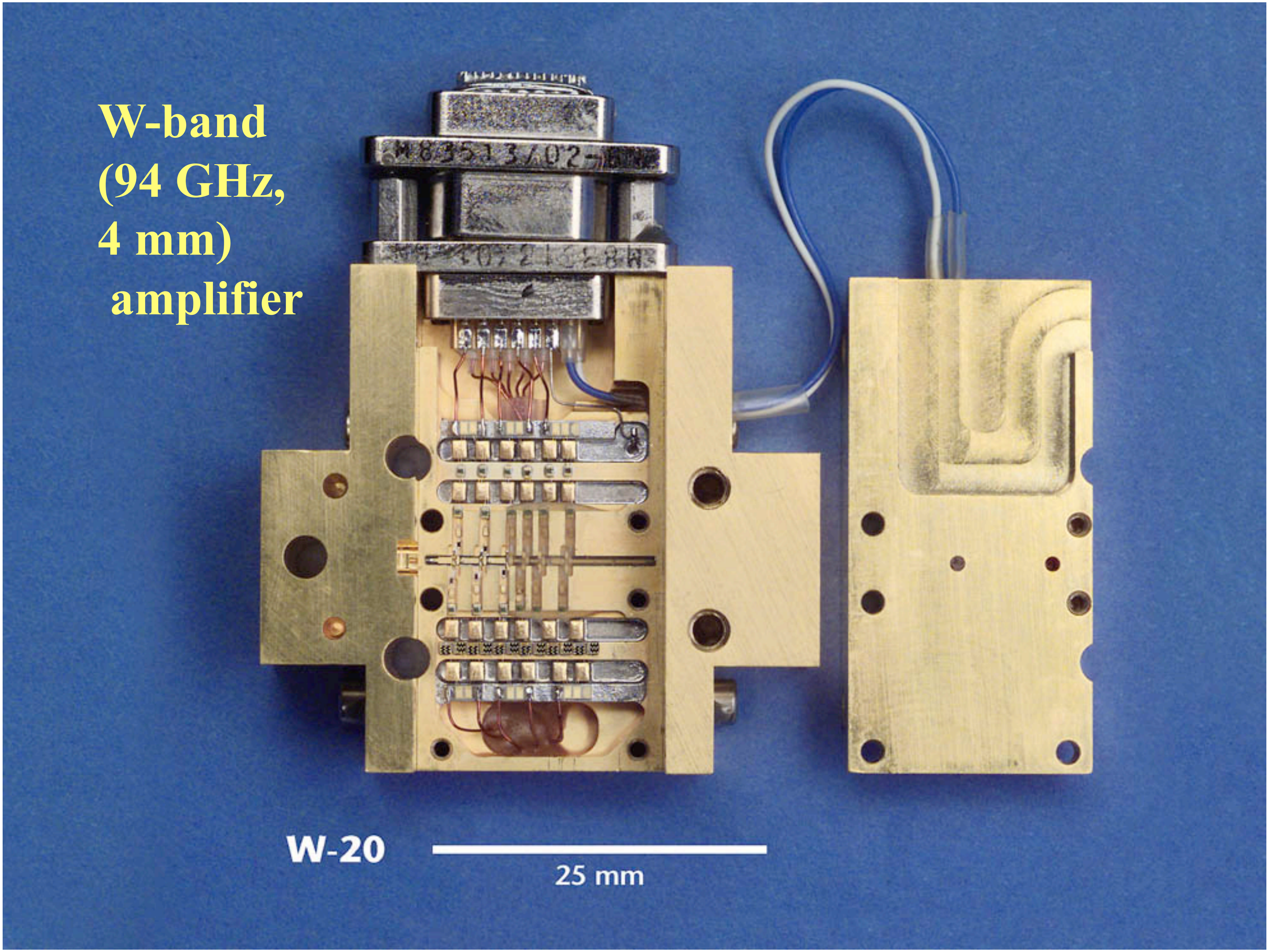

Amplify signal
Low-Noise
Amplifier
Set bandwidth
Filter
Shift frequency
Down-
converter
Analyze spectrum
Spectrometer
IF Amplifier
Amplify signal at
new frequency
Local
Oscillator

Mixers

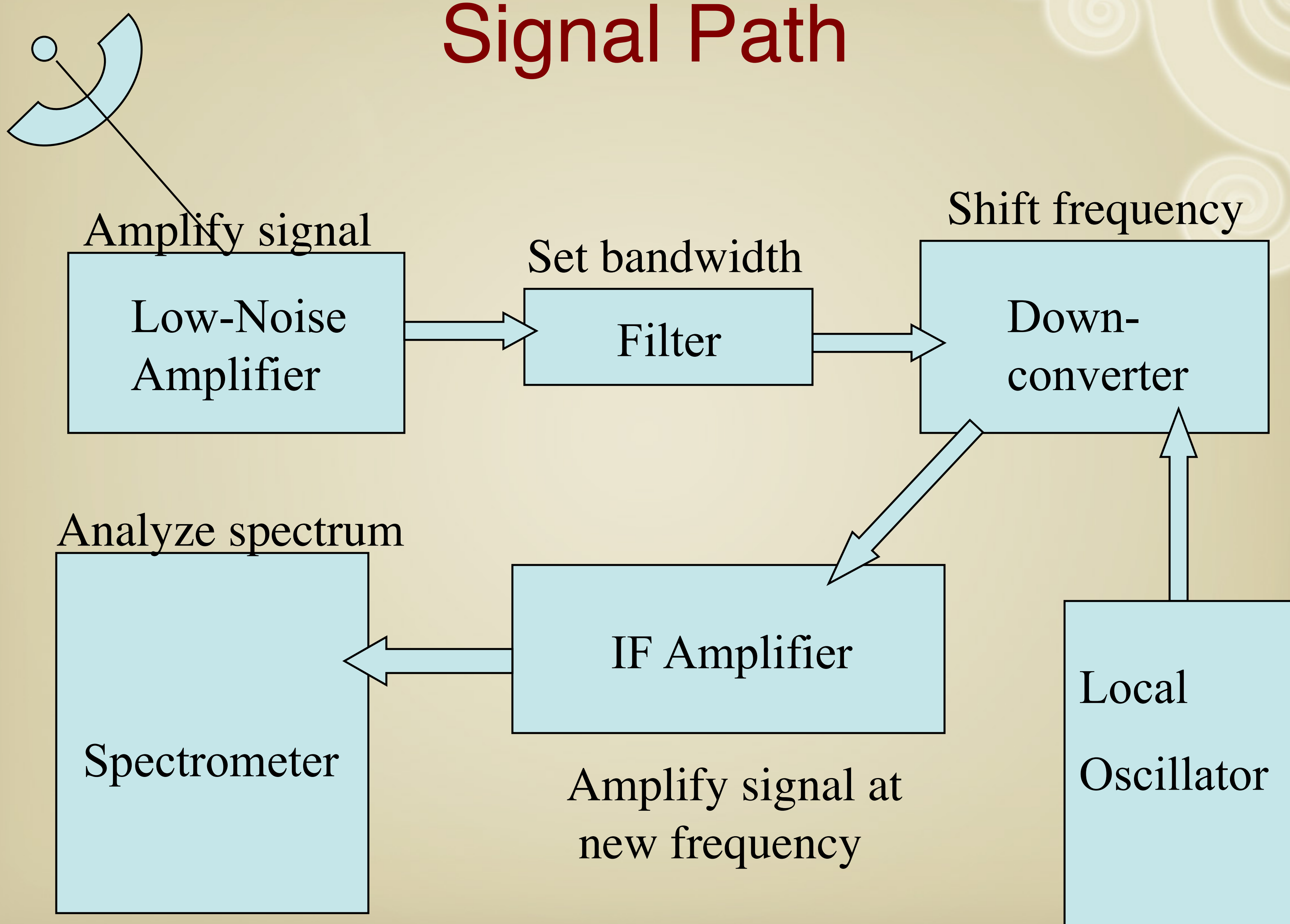


The Signal Path

- Signal MUCH small than thermal noise so strong amplification and stable receivers are required
- Variations in amplifier gain monitored and corrected using switching techniques:
  - between sky and reference source
  - between object and ostensibly empty sky
  - between frequency of interest and neighboring passband.
- Smaller frequencies are much more convenient for the electronics so signal is "downconverted"


W-band
(94 GHz,
4 mm)
amplifier
W-20
25 mm

Signal Path


Amplify signal
Low-Noise Amplifier
Set bandwidth
Filter
Shift frequency
Down-converter
Analyze spectrum
Spectrometer
IF Amplifier
Amplify signal at new frequency
Local Oscillator

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)

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

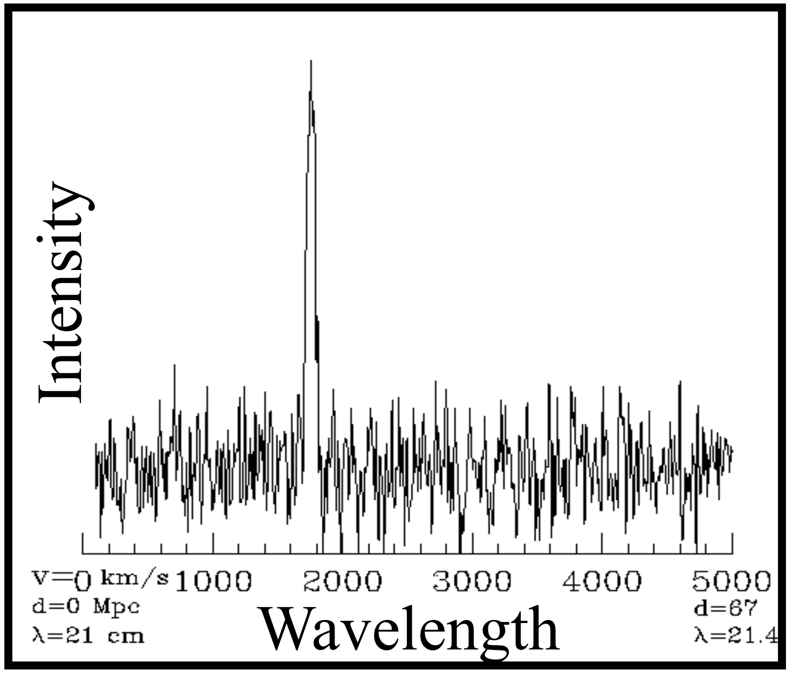
$$T_{rms} = \alpha T_{sys} / \sqrt{\Delta \nu t}$$

- 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)

Observing Schemes

- Total scan time [per] target will be 7 minutes using the LBW
- On-source/off-source data collection technique
  - LBW receiver will track source as it moves across the sky.
  - In order to flat field the image, data is taken over a period of blank sky (the off source) over the same altitude and azimuth path traveled by the target (the on source).
  - 3 min. on source, 1 min. to move back, 3 min. off source.
- The differences in the two passes provides corrections for local environmental noise as well as background sky noise using bandpass subtraction.
- The spectra will be analyzed with an interim 50 MHz correlator.
- LBW samples two orthogonal polarization states which can be treated independently in this stage of analysis.

Observing Schemes

- Position switching helps remove systematics in data

Reduced spectrum = (ON-OFF)/OFF

  - ON: Target source observation
  - OFF: blank sky observed over the same altitude and azimuth path traveled by target (on source).
  - corrections for local environmental noise as well as background sky noise

- Two polarizations can be compared to identify RFI or averaged to improve signal for an unpolarized source

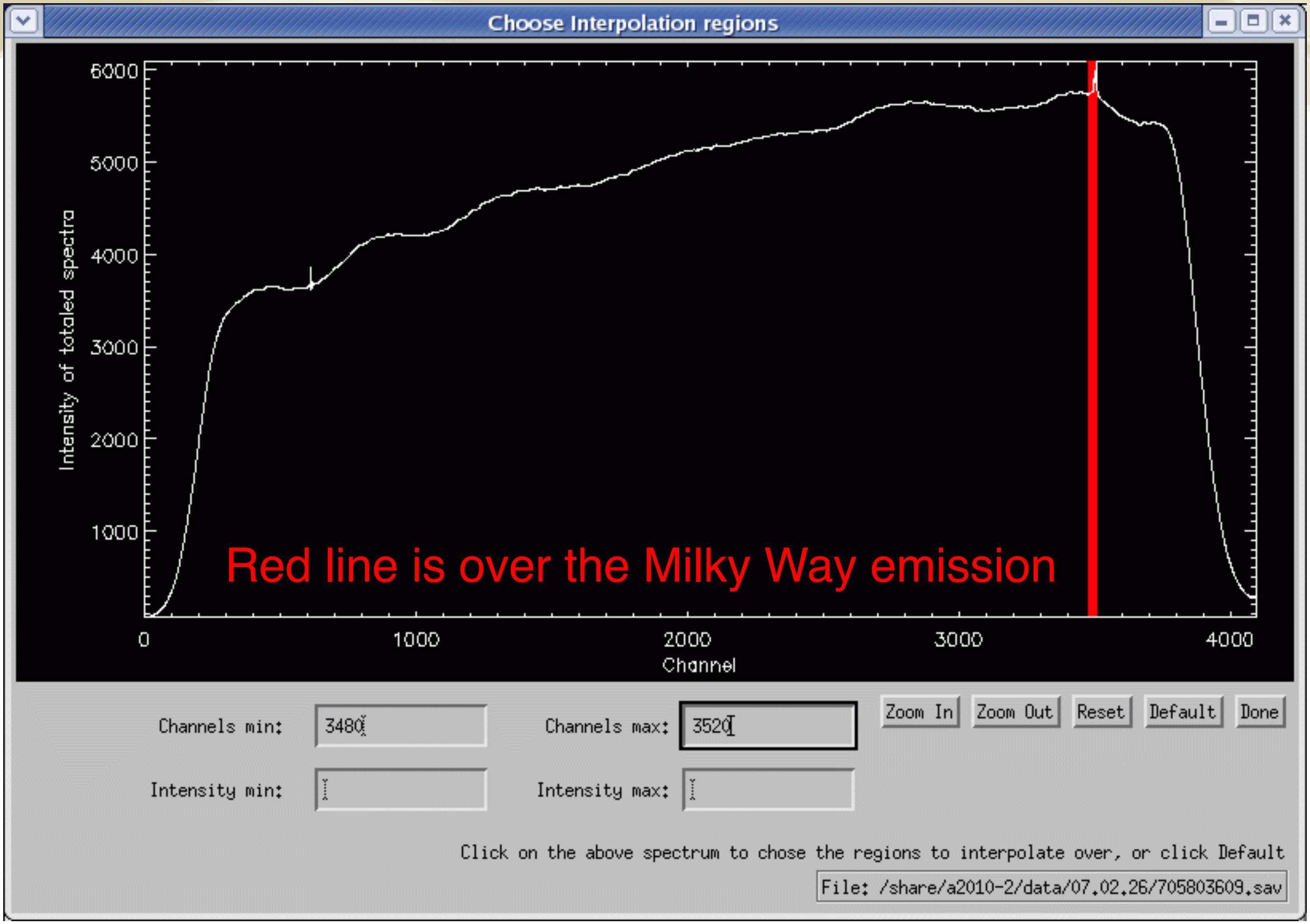
Happy Observing!!!

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



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