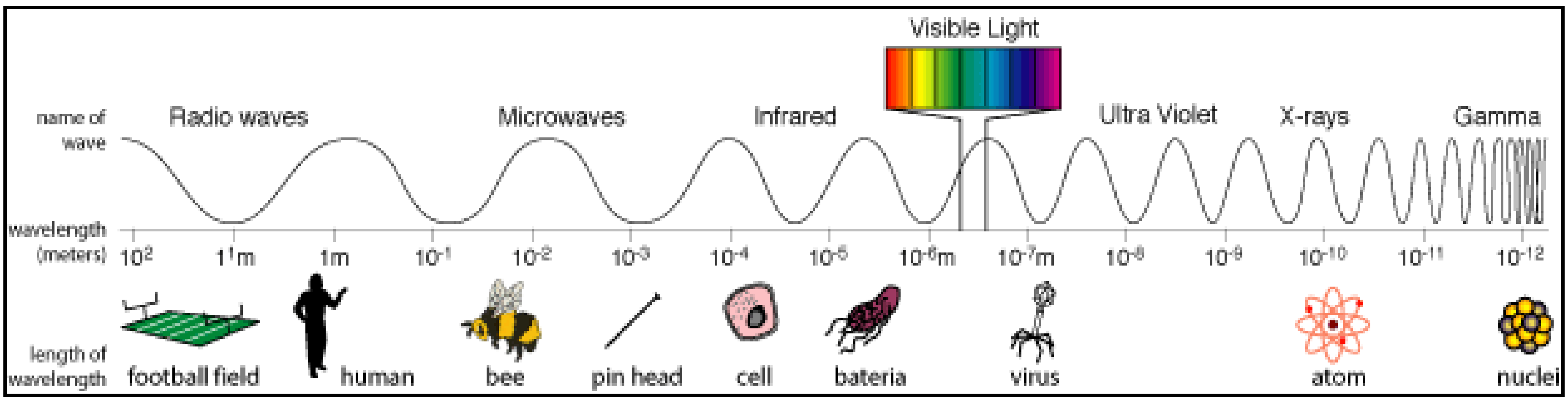
Introduction to Radio Astronomy

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

Sources of Radio Emission

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



Sources of Radio Emission

- What astronomical objects produce radio emission?
  - Planets (continuum, thermal)
  - Jets (continuum, synchrotron)
  - Cosmic microwave background (continuum, thermal)
  - Hydrogen gas, molecular gas (spectral lines)

- What is the peak wavelength for a 3°K blackbody?

$\lambda_m T = 0.2898$ cm K

  - 0.1 cm

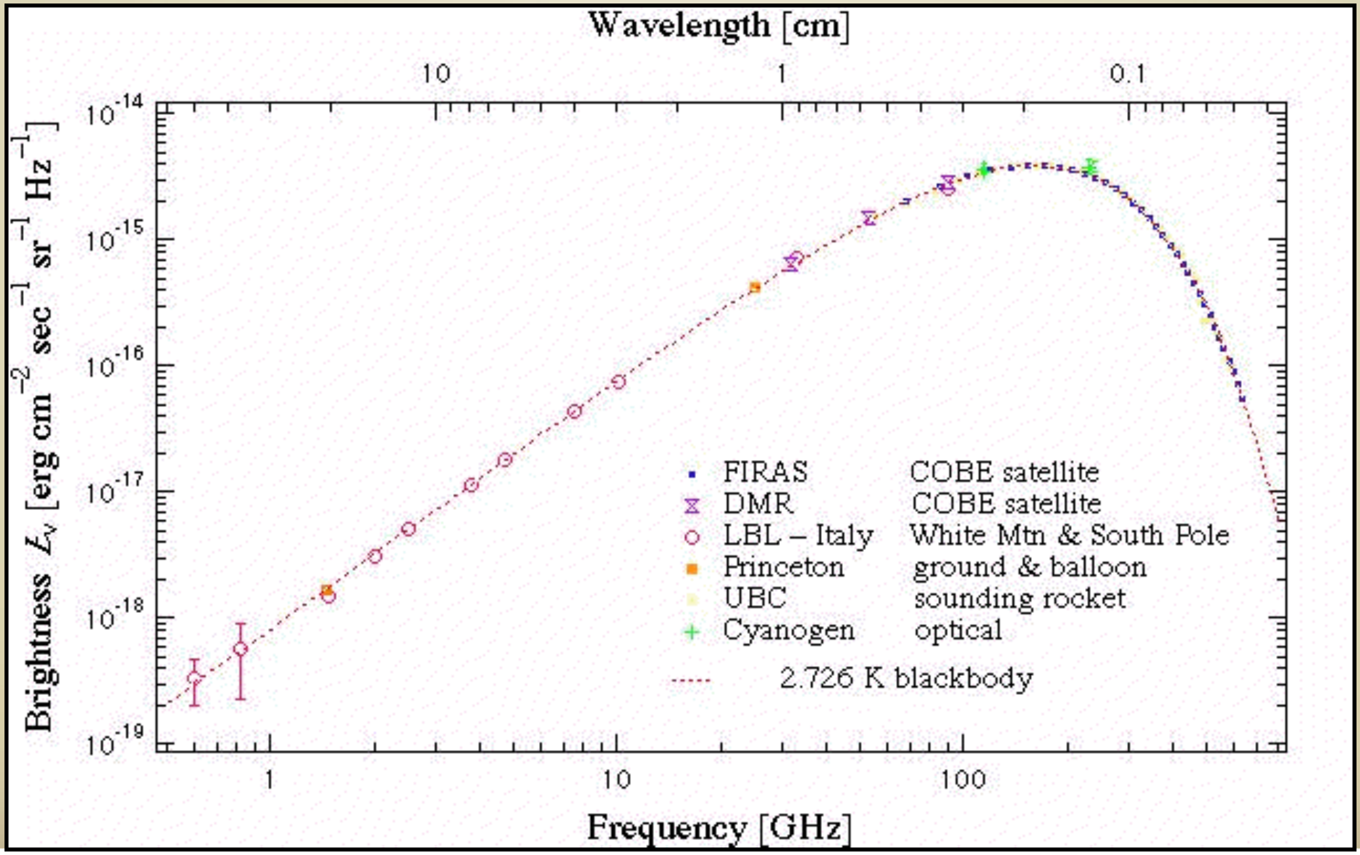
Blackbody Sources:

The cosmic microwave background, the planets

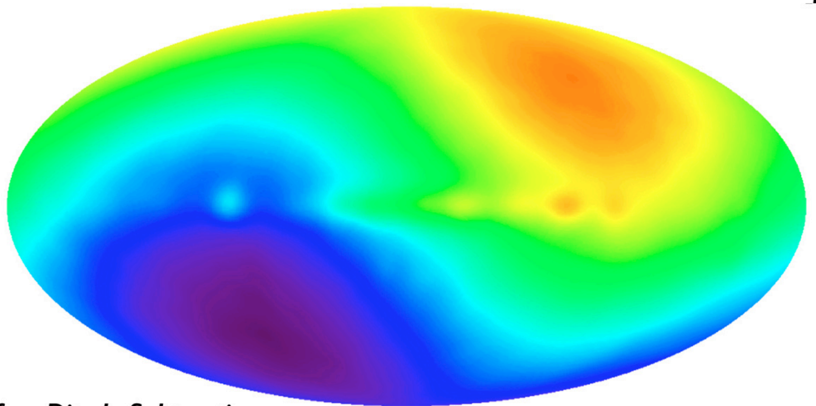
Observations at cm wavelengths requires low temperature

$\lambda_m T = 0.2898$ cm K

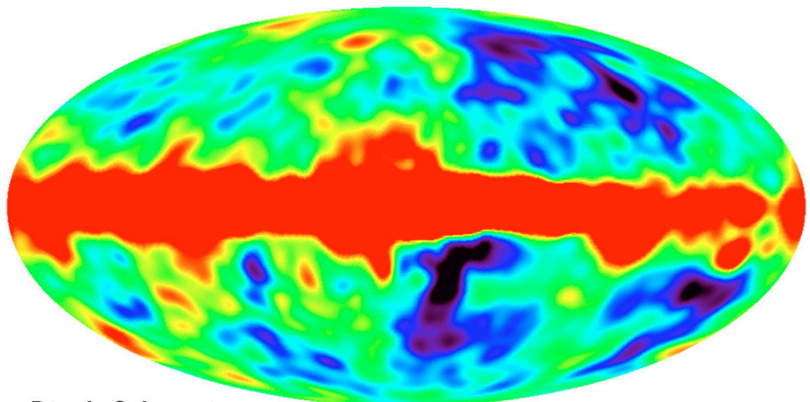
3°K peaks at 0.1 cm



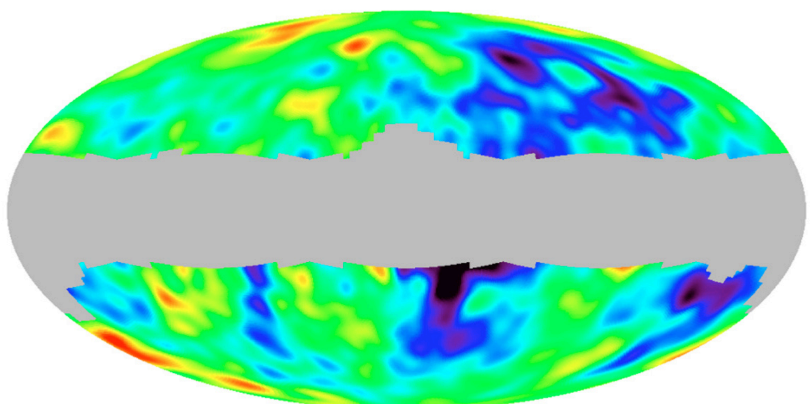
DMR 53 GHz Maps



Before Dipole Subtraction



After Dipole Subtraction



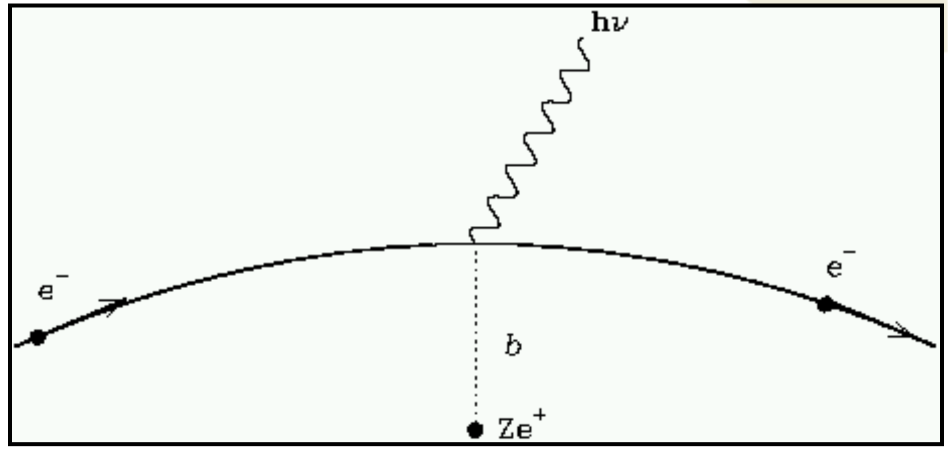
After Galaxy Subtraction

Continuum (non-thermal) Emission:

Emission at all radio wavelengths

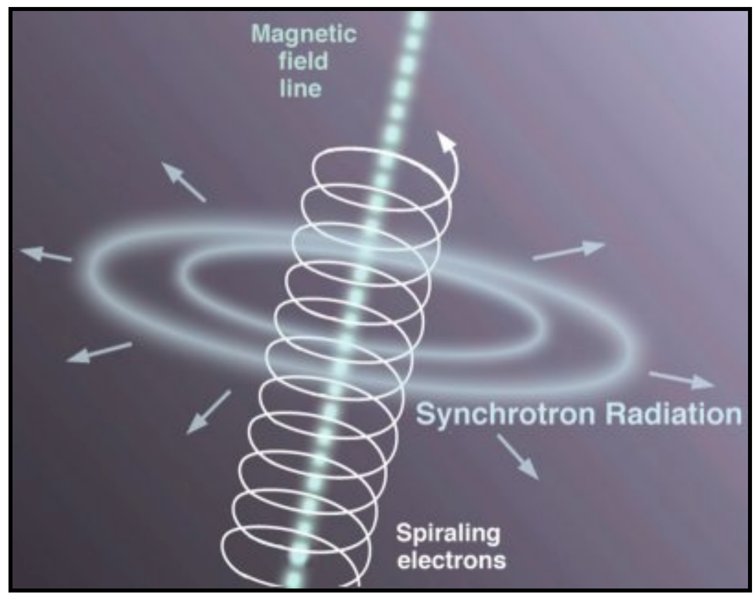
Bremsstralung (free-free):

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

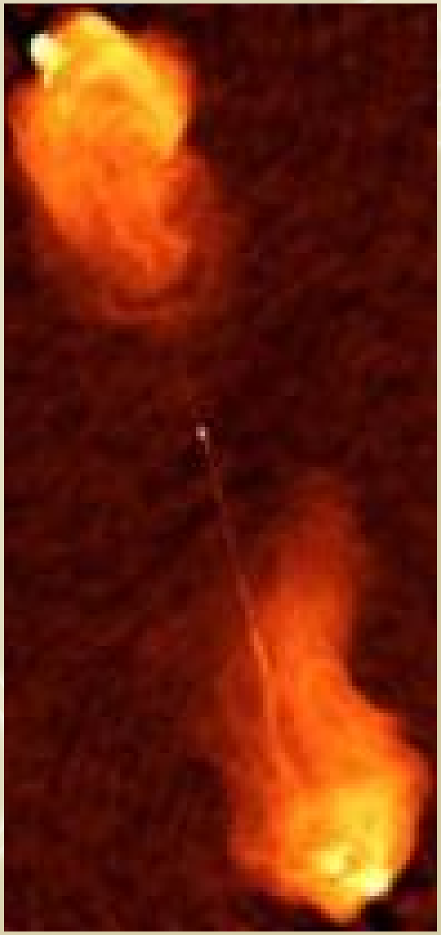


Synchrotron:

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

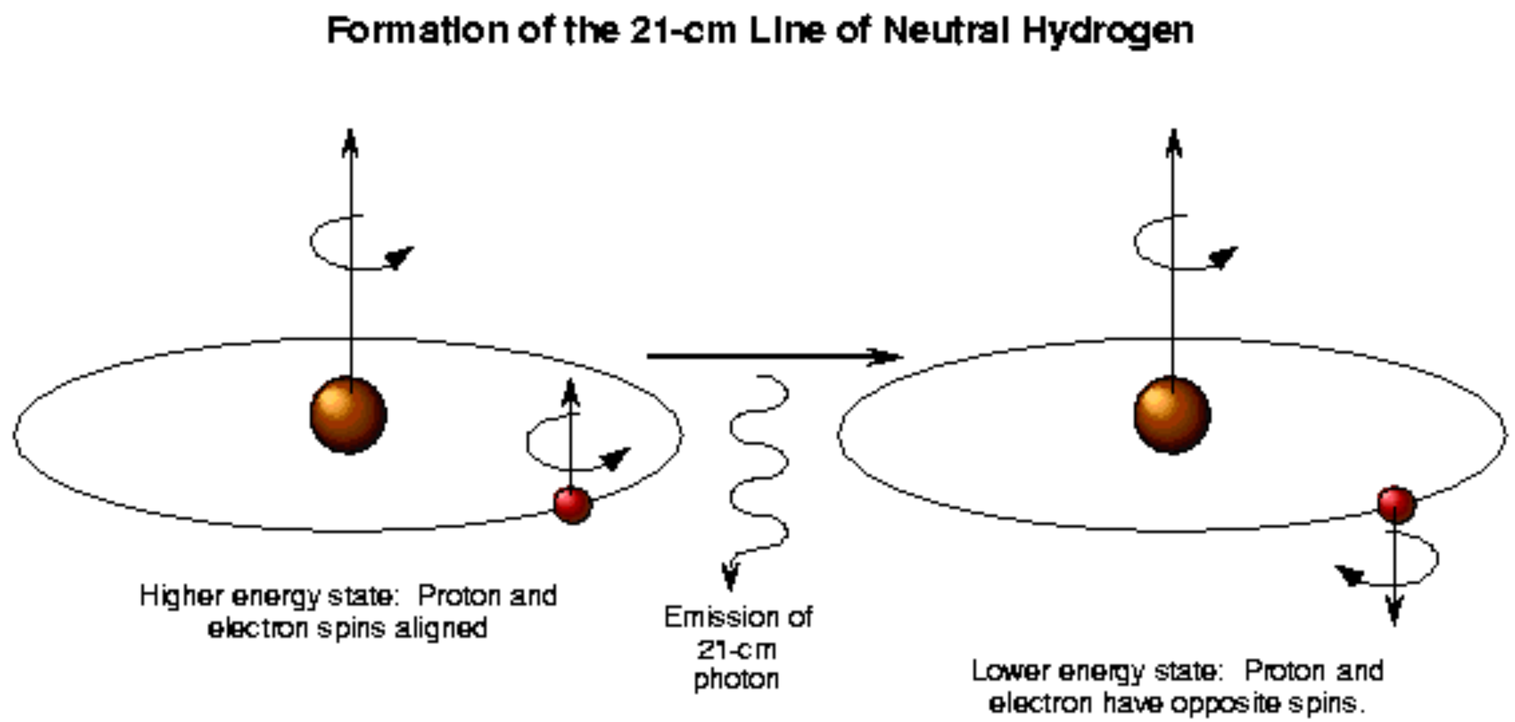


Sources of Continuum Emission



Radio Emission Lines

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

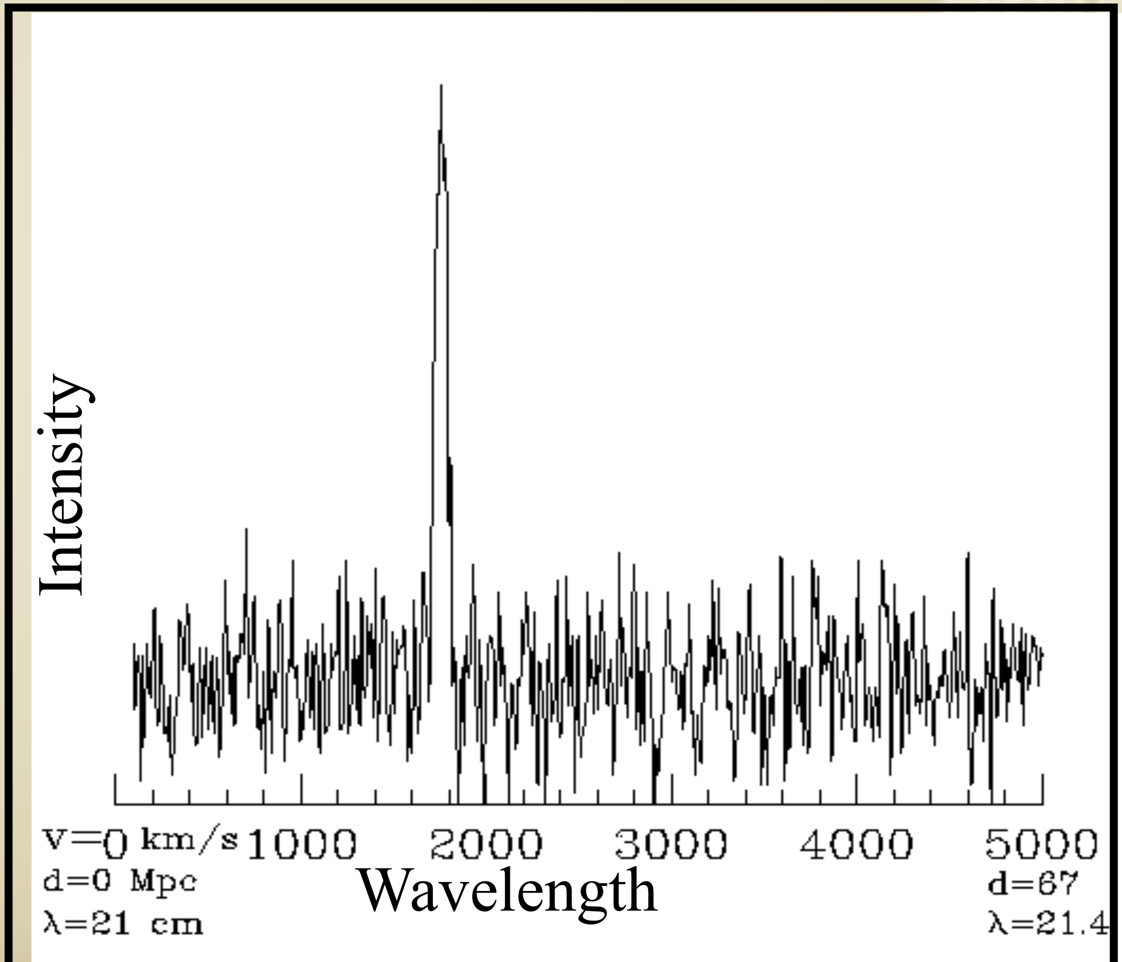


21cm Line of Neutral Hydrogen

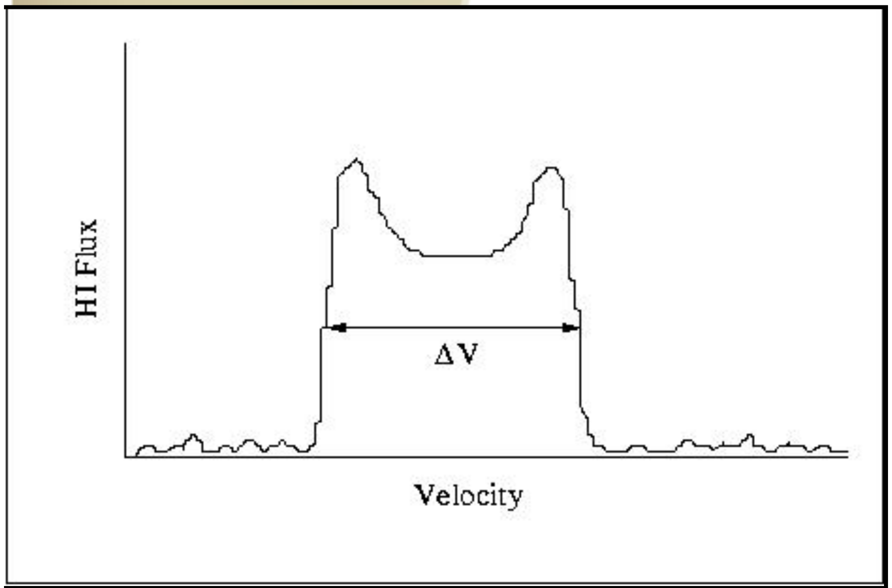
Not only are λ, ν, and E equivalent, but for the most part velocity and distance are as well.

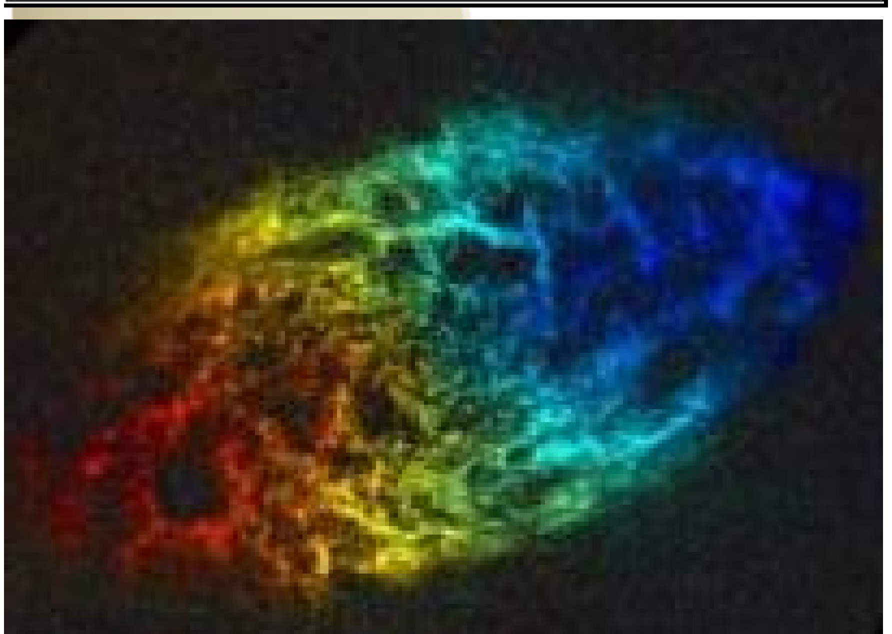
$$z = \frac{\lambda - \lambda_0}{\lambda_0} = \frac{\Delta v}{c}$$

$$d = v / H_0$$



21cm Line of Neutral Hydrogen, cont.

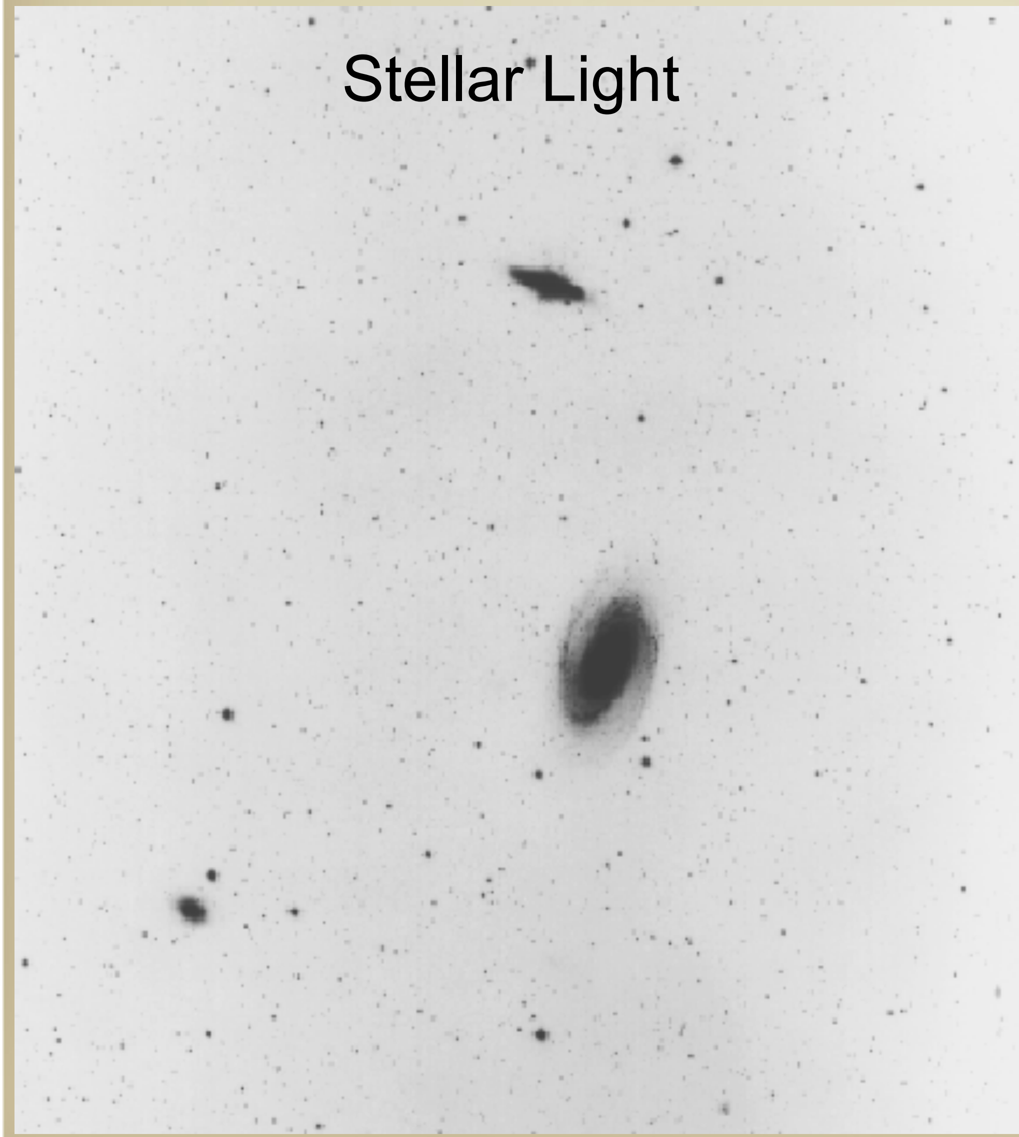


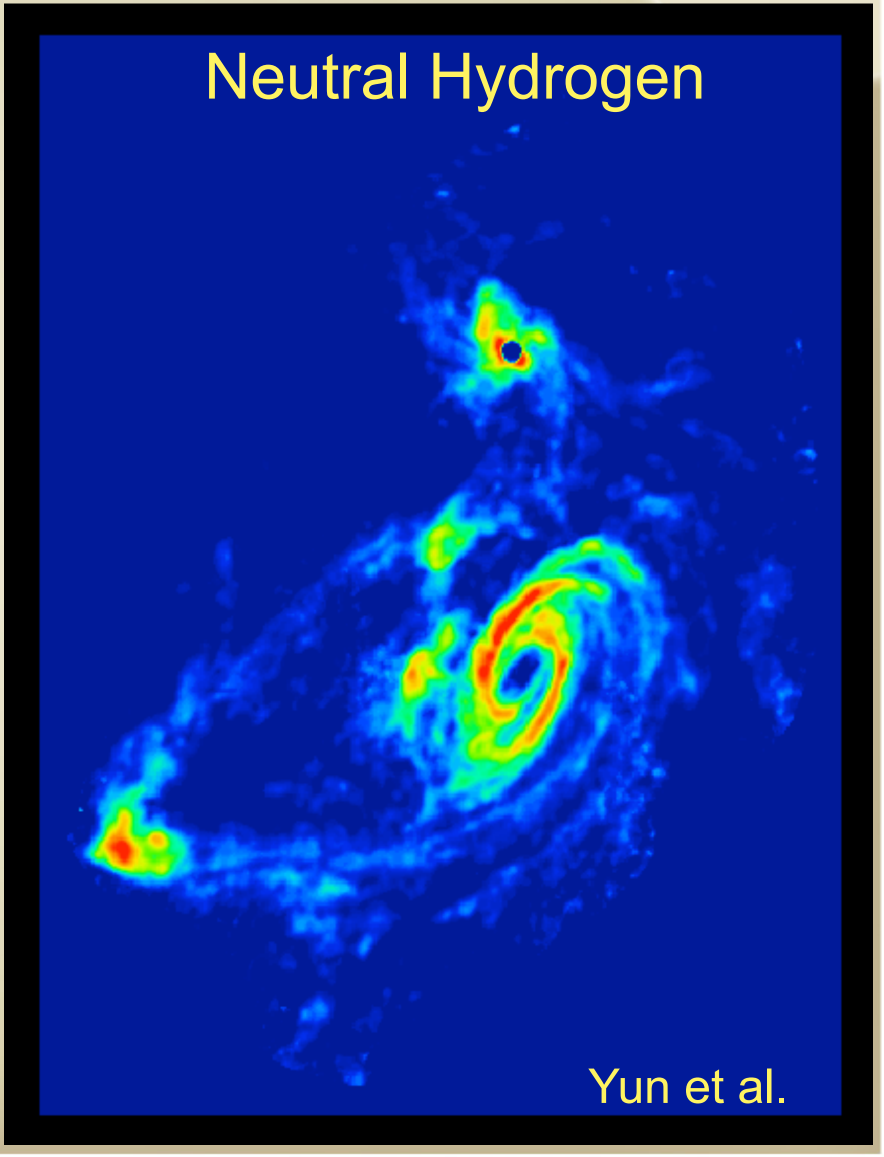


- HI spectral line from galaxy
- Shifted by expansion of universe ("recession velocity")
- Broadened by rotation

21 cm Line Emission:

The M81 Group





Radio Telescope Characteristics

semantics

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

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

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

Radio Telescope Characteristics
Temperatures

Power is often measured in as the temperature of a blackbody that produces the same amount of power

System temperature: telescope + instrumentation without a source

Brightness temperature: Flux density per unit solid angle of a source

Antenna temperature: The flux that reaches the receiver – some of the incoming power is lost before it gets there, represented by the aperture efficiency

Radio vs Optical Astronomy:
Radio Astronomy is Hard

- Huge difference in wavelength

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

$$\lambda_{21cm}/\lambda_{5500Å} = 3.8 \times 10^5$$

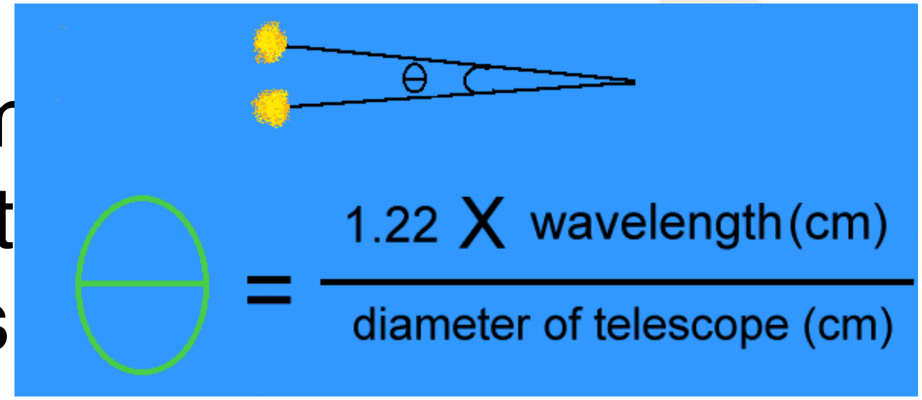
- Difference in wavelength effects resolution. The 305m Arecibo telescope is equivalent to a .8mm optical telescope!

$$\vartheta = \lambda/D$$

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

Radio vs Optical Astronomy

- Seeing is not a problem
  resolution is based on t
  atmospheric conditions



- Resolution given by:

Scavenger Hunt 0:

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

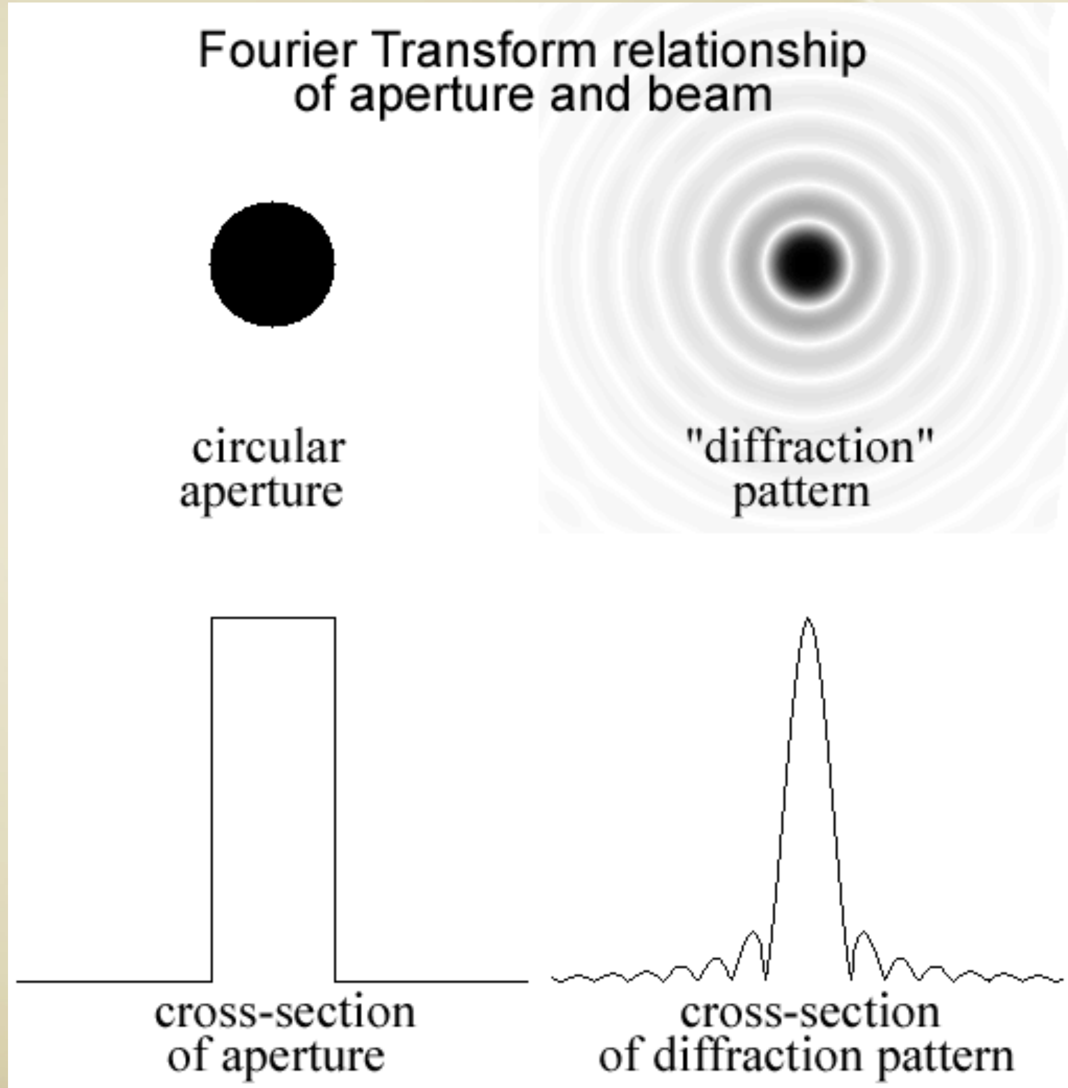
$$\vartheta_{21\text{ cm, Arecibo}} \sim 2.9'$$

The diffraction limit of a telescope can be described by the cartoon to the right. What is the diffraction limit of a 305 meter diameter telescope at 21 cm?

- Radio telescope arrays allow for higher resolution than possible with a single dish

Fourier Transforms and Beam Patterns

- Shining a uniform light on a circular (telescope) opening creates a diffraction pattern
- Pattern describes how light from a source will appear to be distributed on the sky



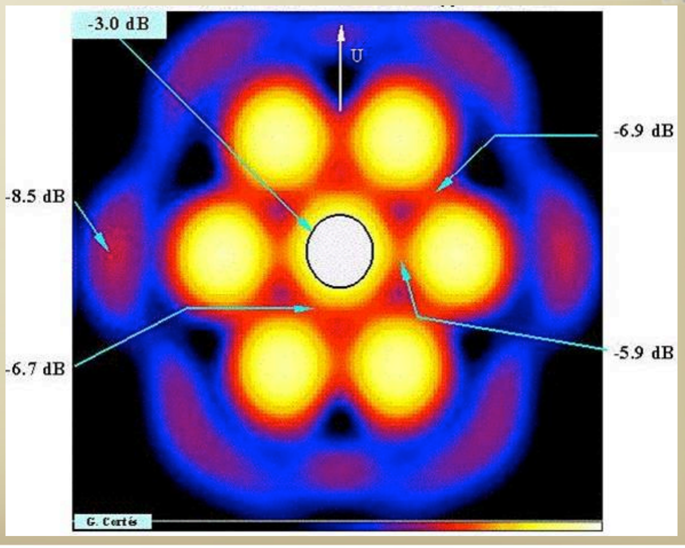
Radio Telescope Characteristics

beam and sidelobes

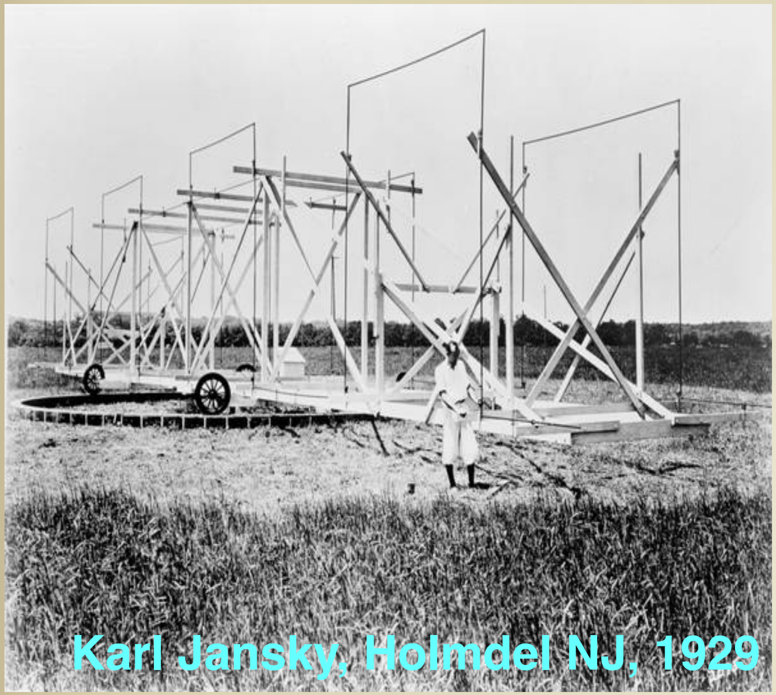
- Diffraction pattern of telescope

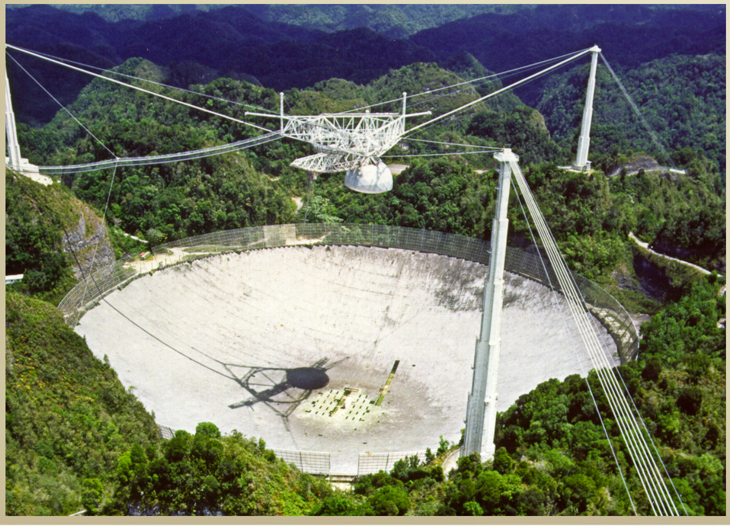
  $\sin\theta = 1.22\ (\lambda/D)$

- Diffraction pattern indicates sensitivity to sources on the sky
- FWHM of central beam is called the *beamwidth*
- Sidelobes are where you see the source beyond the central region
- Note that you are sensitive to sources away from beam center



Radio Telescopes





Optical Telescopes

Radio Telescopes Look Different

- 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:

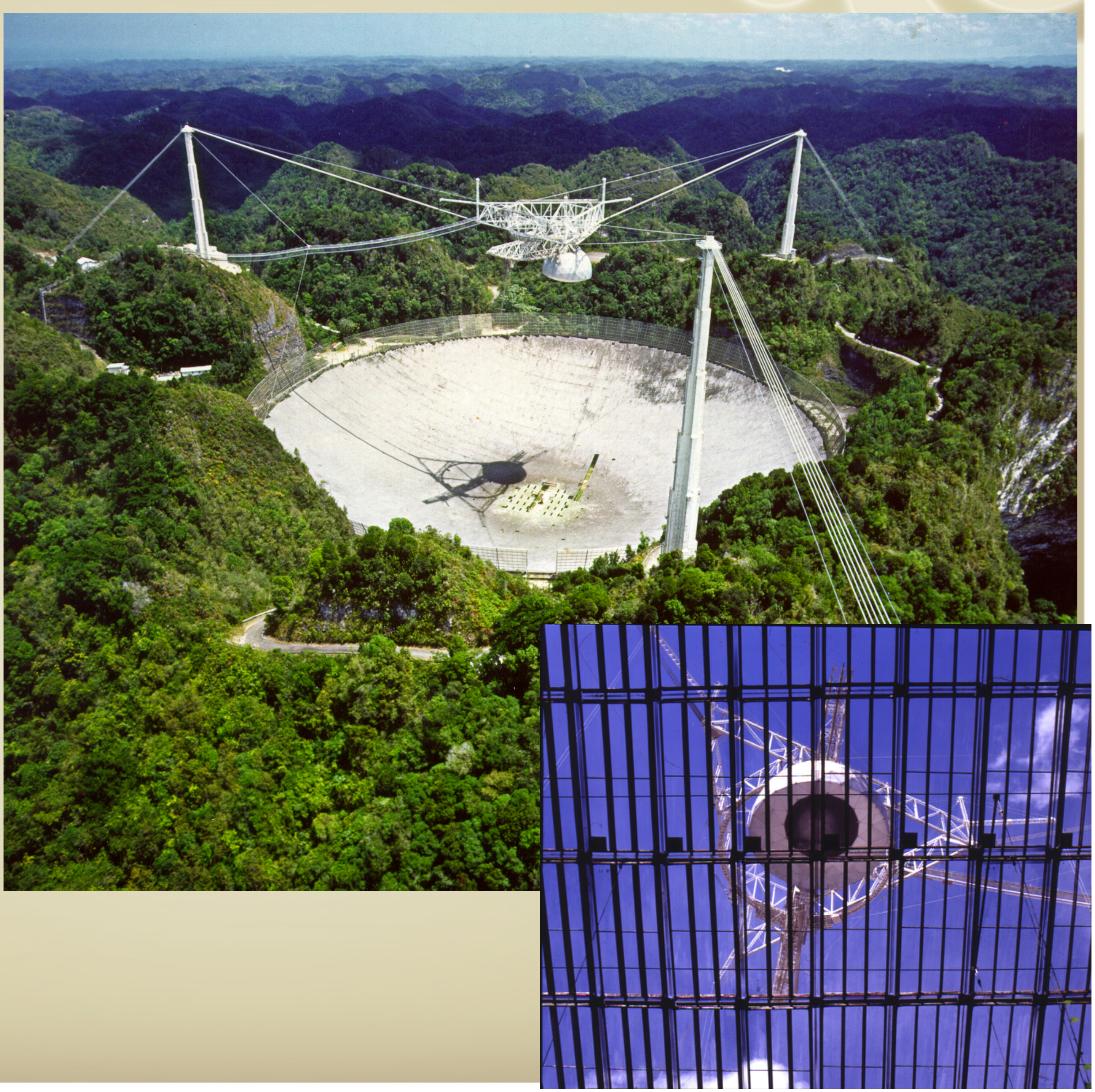
$$V=V_0\sin(\omega t-\phi)$$

V_0 is amplitude, ϕ is the phase

- Phase info. makes interferometry easy

Radio Telescope Components

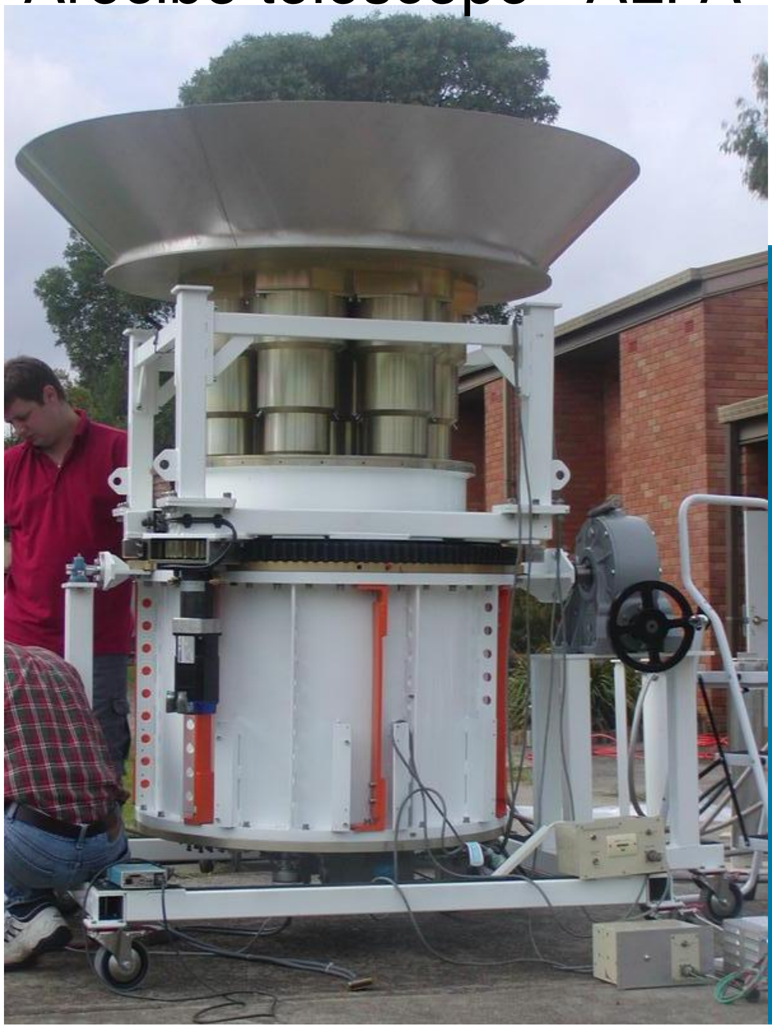
- Reflector(s)
- Feed horn(s)
- Low-noise amplifier
- Filter
- Downconverter
- IF Amplifier
- Spectrometer



Feedhorn

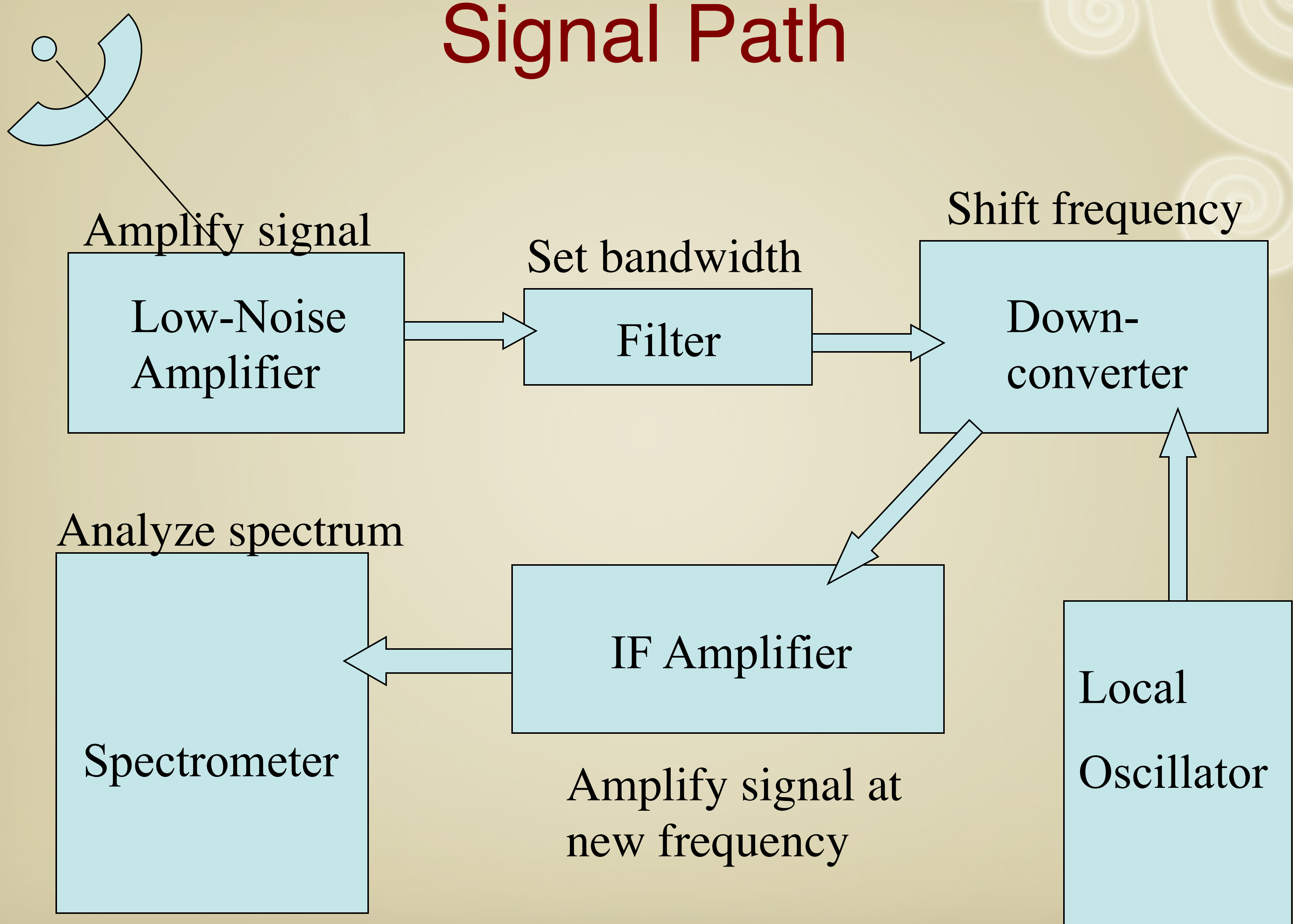
Hardware that takes the signal from the antenna to the electronics

Array of 7 feedhorns on the Arecibo telescope - ALFA



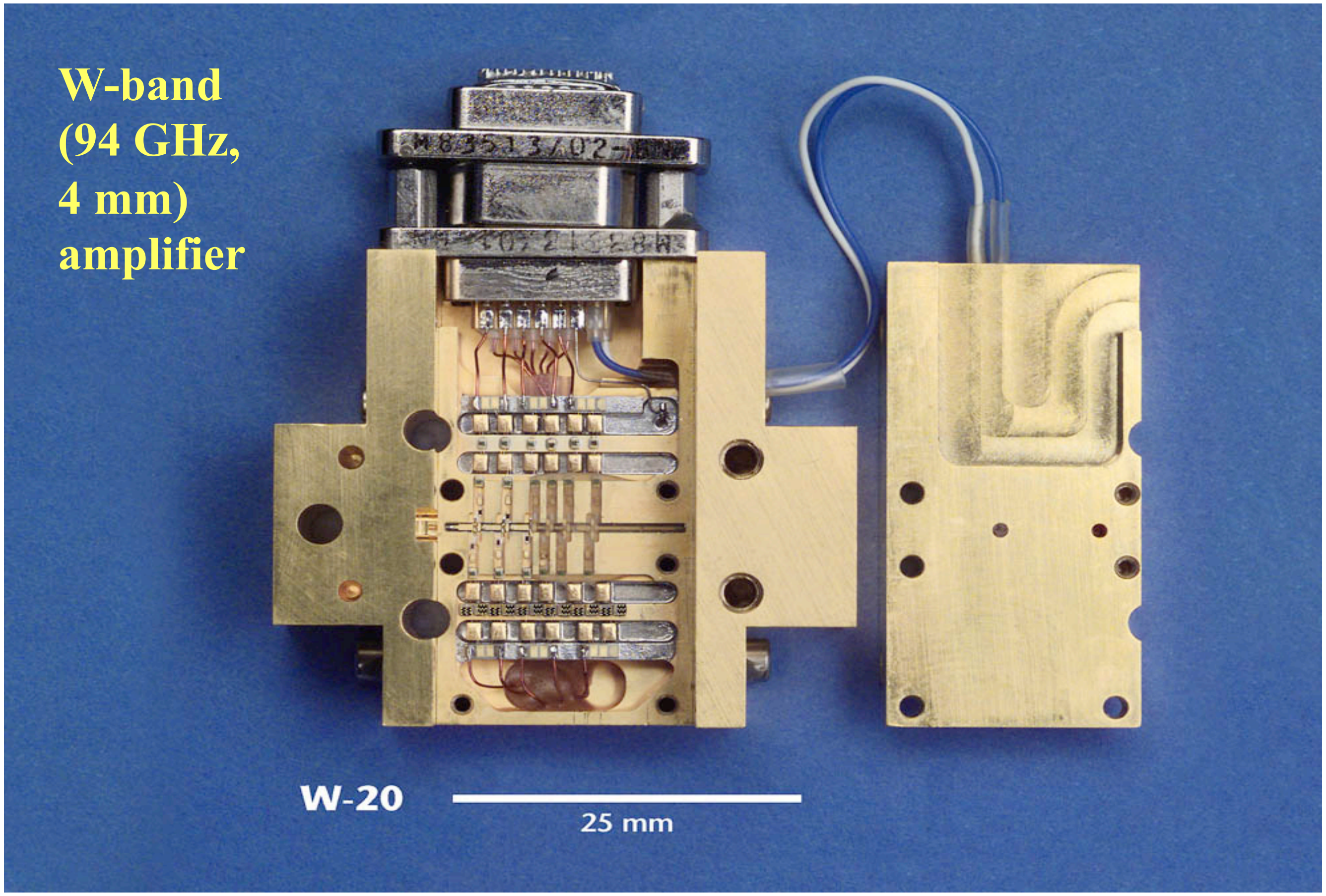
Typical cm-wave feedhorn

Signal Path

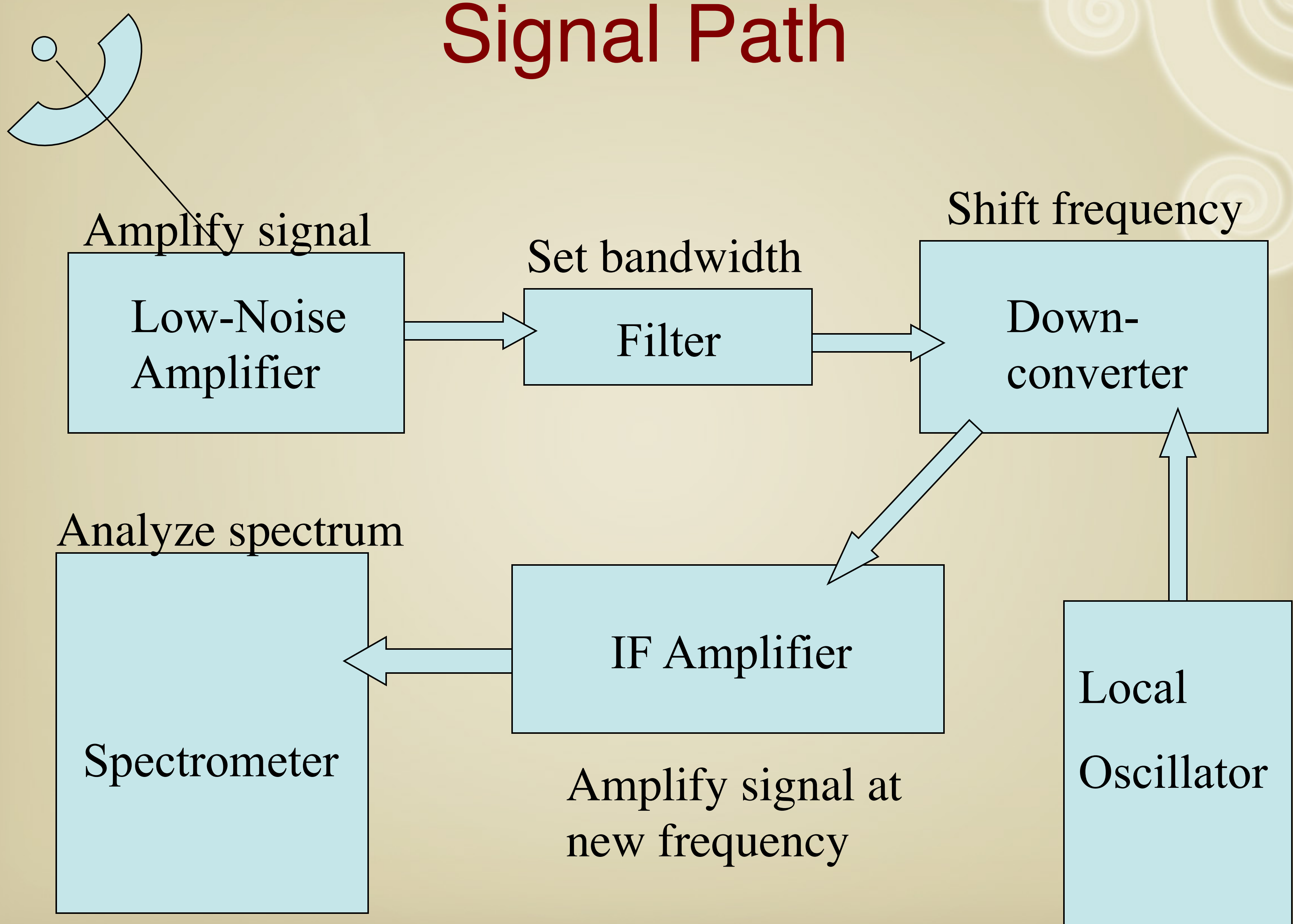

Amplify signal
Low-Noise Amplifier
Set bandwidth
Filter
Shift frequency
Down-converter
Analyze spectrum
Spectrometer
IF Amplifier
Amplify signal at new frequency
Local Oscillator

Why amplify the signal?

- Signal is very weak relative to the thermal receiver noise



Signal Path



Amplify signal
Low-Noise Amplifier
Set bandwidth
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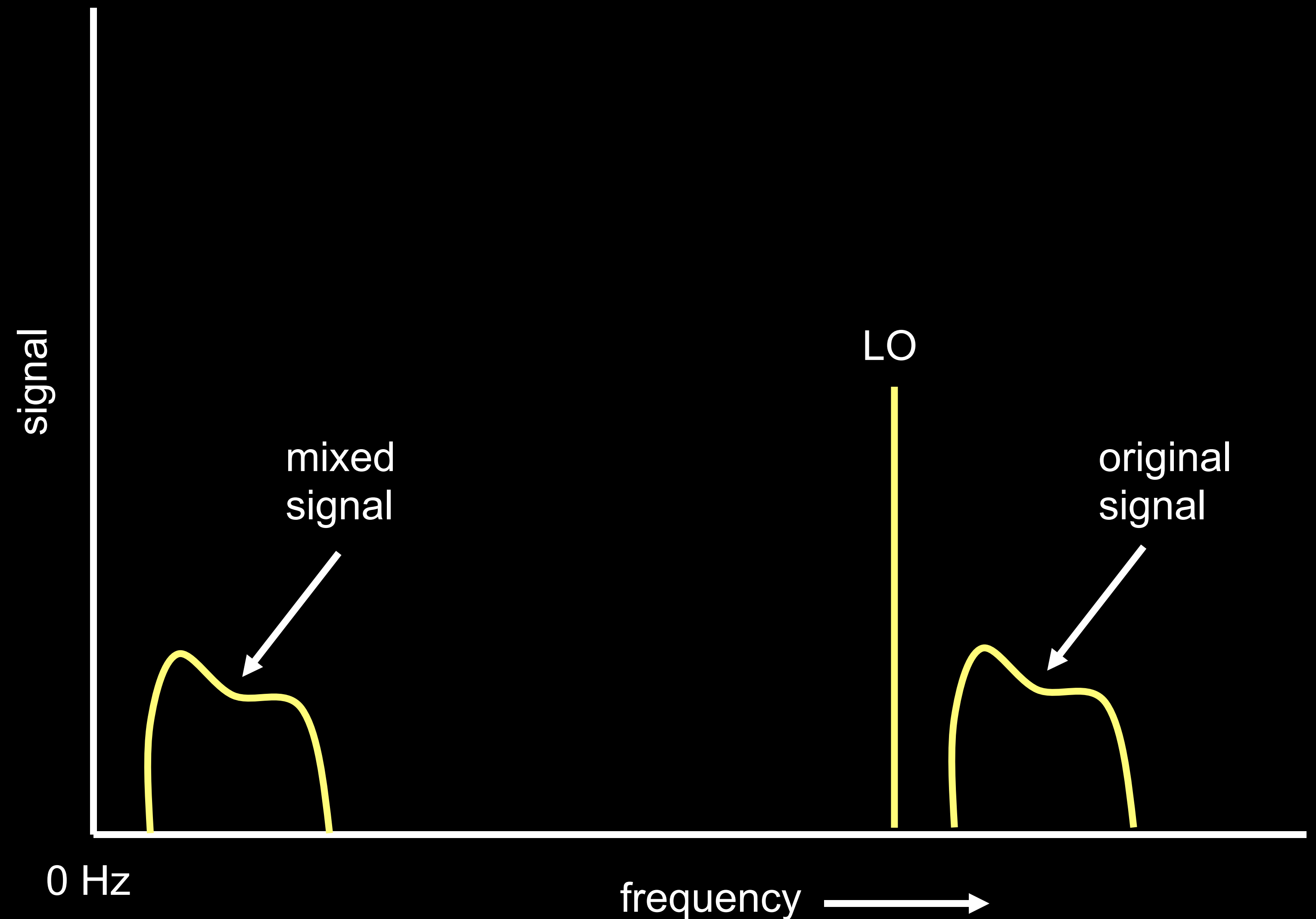
Amplify signal at new frequency
Local Oscillator

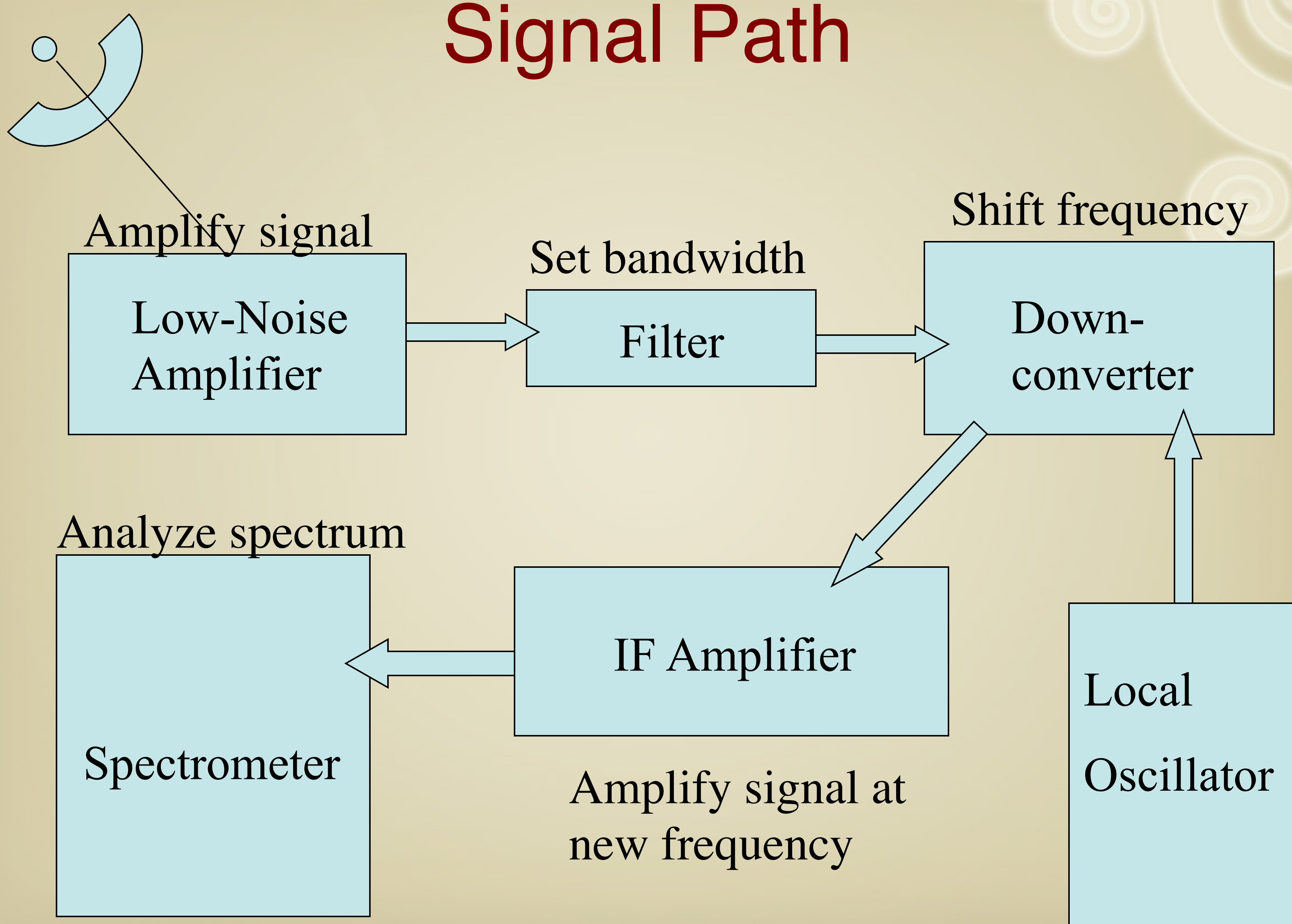
Why Shift Observed Frequency to a Lower One?

- Electronics don't operate well at these frequencies so we shift the signal to a more convenient band (downconversion)

Mixers/ Local Oscillators



Signal Path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Autocorrelation Spectrometer

Or how we actually make “sense” out of the signal

- Measures the fourier transform of the power spectrum
- Spectrometer combines the signal (υ) with itself (autocorrelation) slightly offset in time (lag, δt):

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

  integer n ranges from 0 to $(\delta t\ \delta f)^{-1}$ for frequency channels of width δf
- Power spectrum is discrete Fourier transform (FFT) of R_n – looks at how much signal there is as a function of the lag or frequency

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
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: the fraction of the incoming flux that makes it to the receiver

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.)

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)

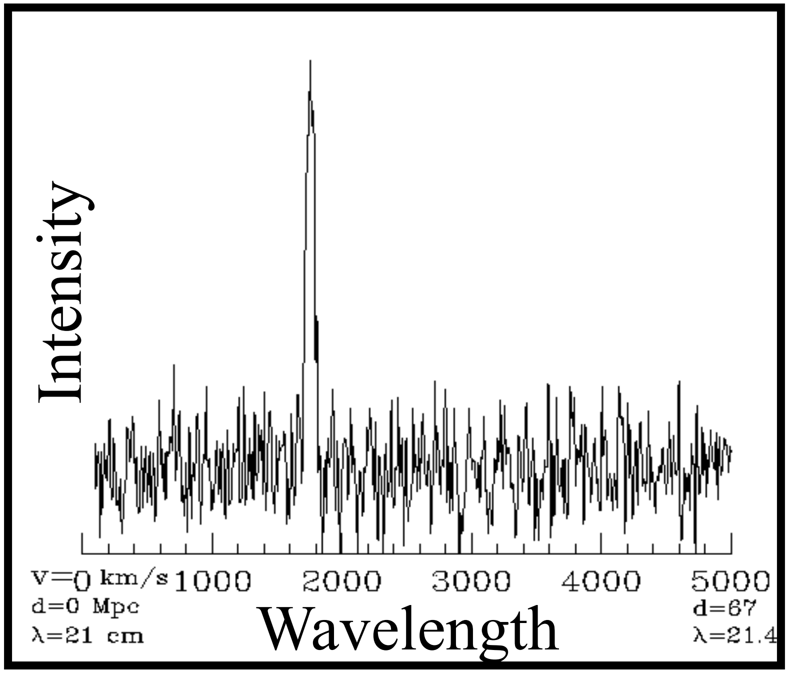
Radiometer Equation

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

- 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

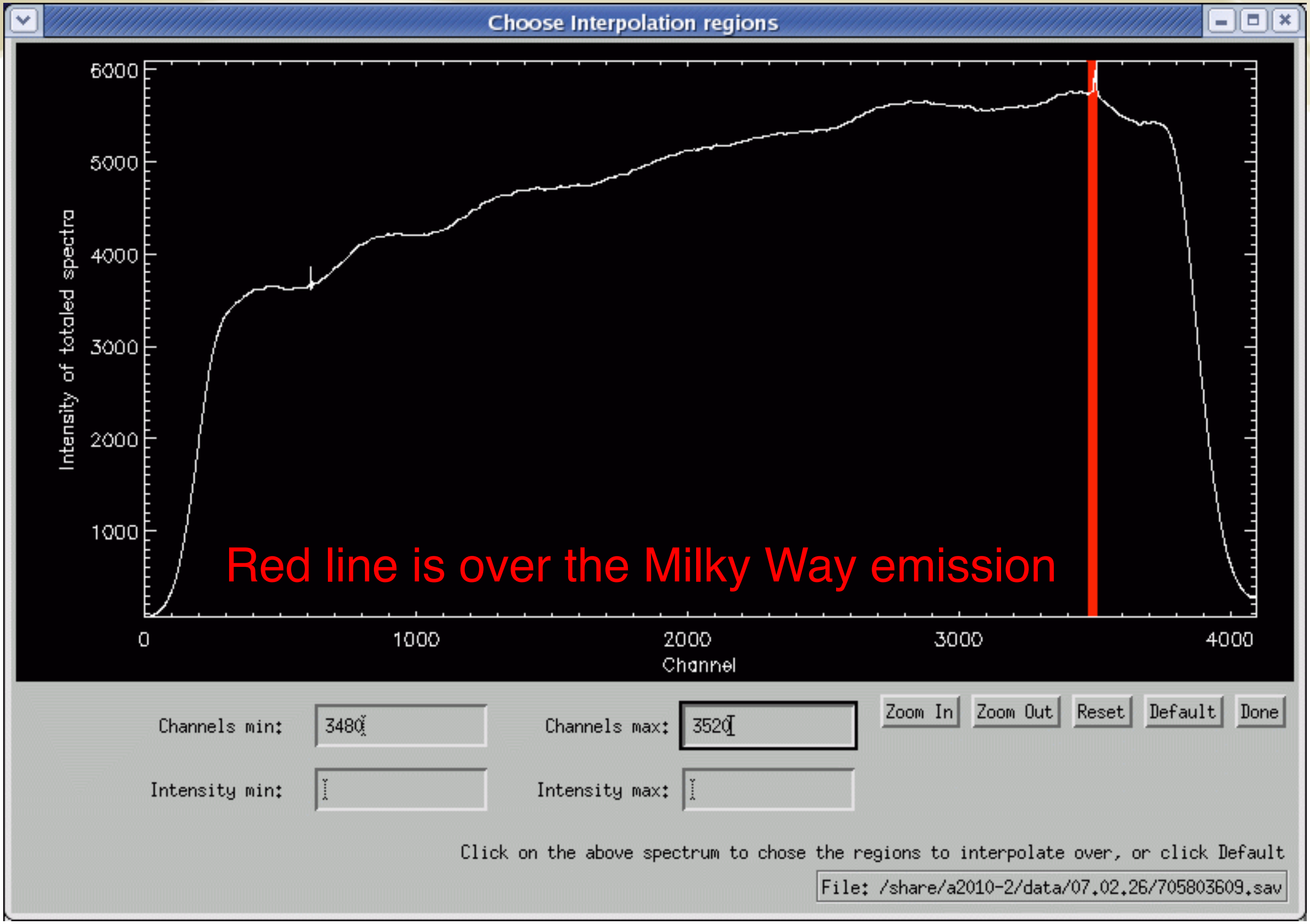


Baselines and Observing Schemes

- 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



ALFALFA Observing Techniques:

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

ALFALFA Observing Techniques:

HI 21 cm Observing in Action

Position switching: telescope observes a source then moves back to the starting position and observes the sky for the same amount of time

• Baseline shape is removed using spectra that are adjacent in time

• Telescope returns to the same position relative to the Earth (altitude and azimuth) to remove systematic noise – source has moved so should be blank sky in its wake

Radio Telescopes are Cool!