Introduction to Radio Astronomy

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2016 UAT Workshop @ Green Bank

Outline

Sources of Radio Emission

Continuum Sources versus Spectral Lines

The HI Line

Details of the HI Line

What is our data like?

What can we learn from each source?

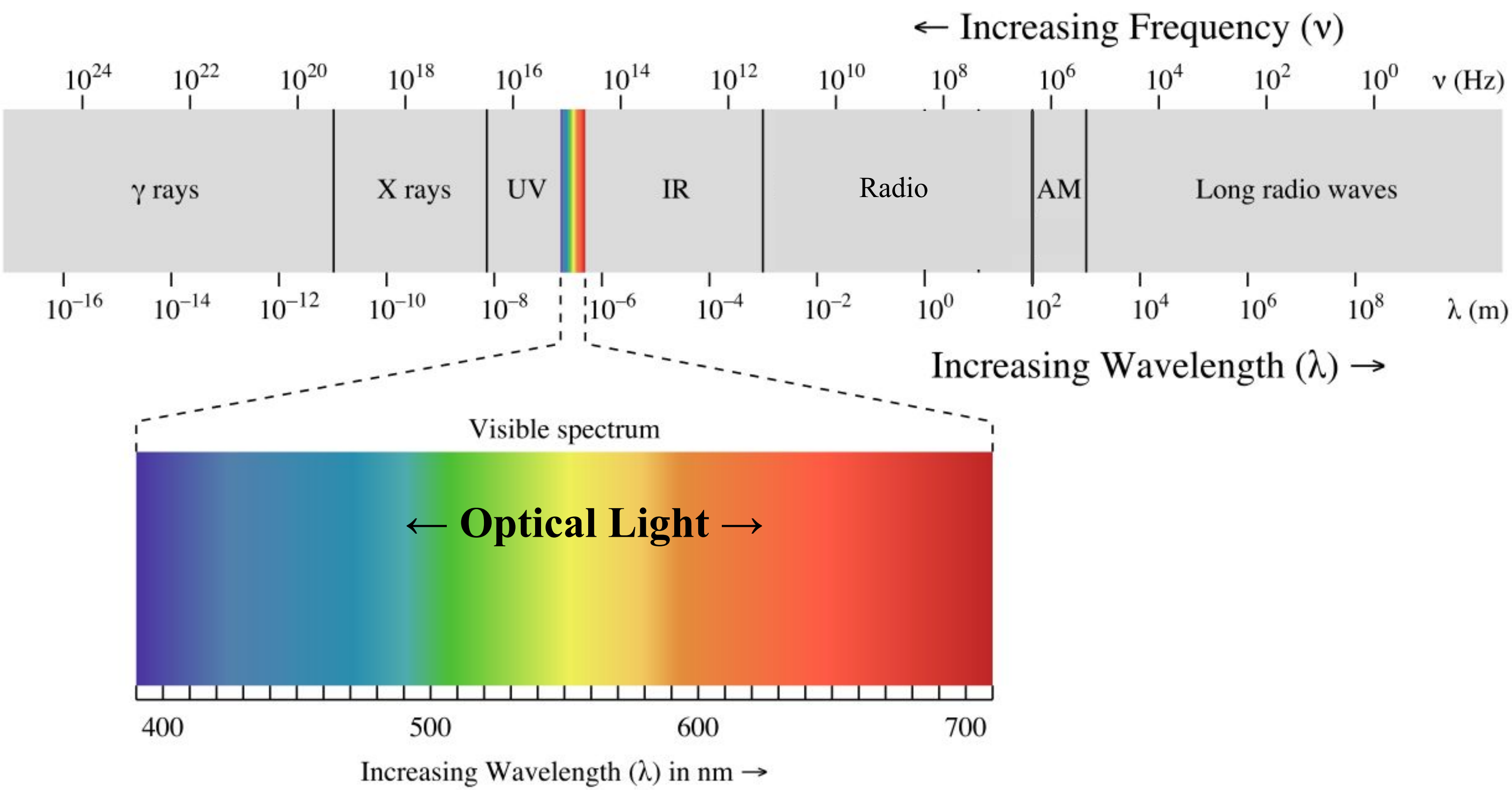
The Radio Telescope

How do we actually detect this stuff?

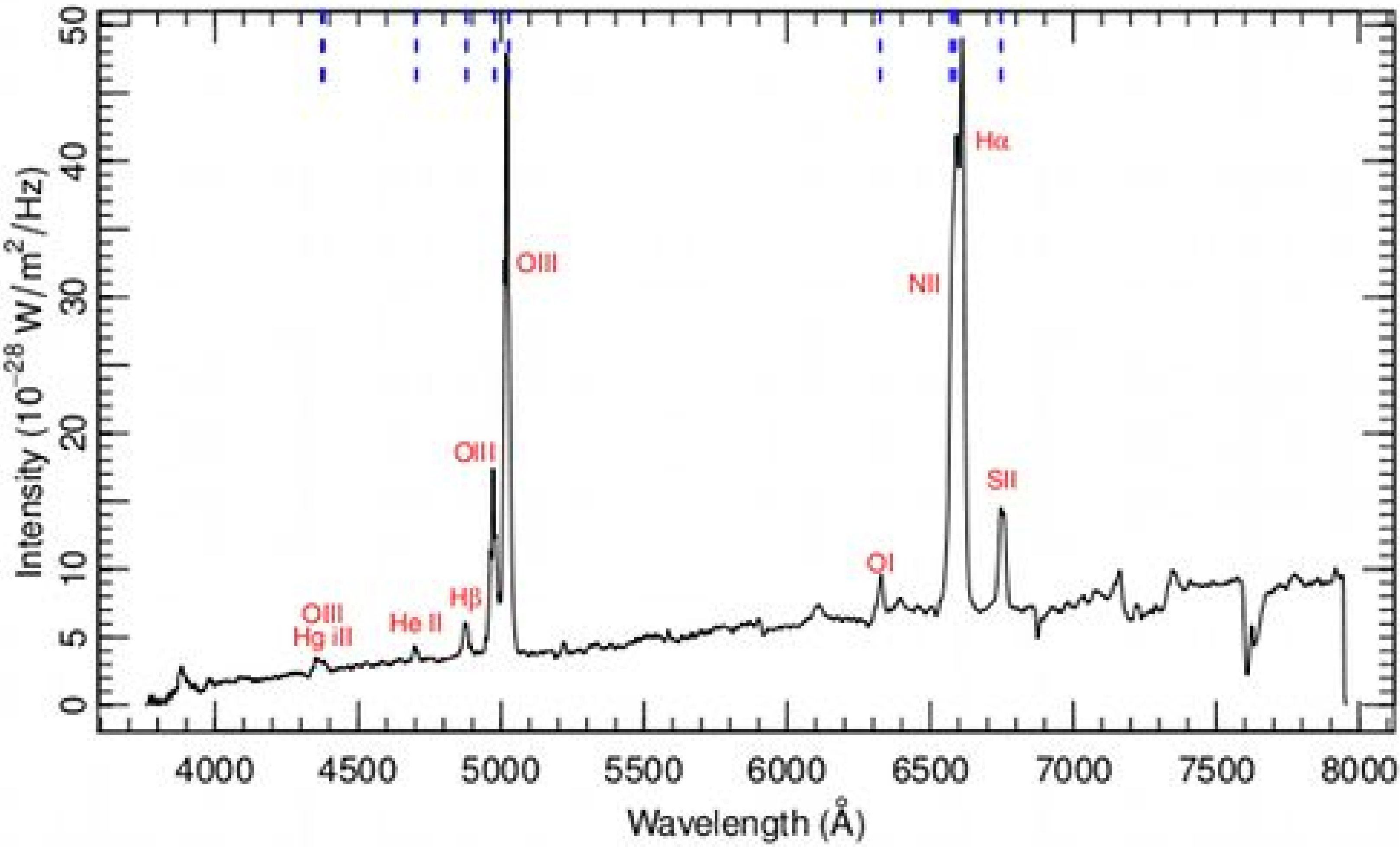
How do we get from the sky to the data?

I. Radio Emission Sources

The Electromagnetic Spectrum



A Galaxy Spectrum (Apologies to the radio astronomers)



Categories of Emission

Continuum Emission — “The Background”

Radiation at a wide range of wavelengths

- **Thermal Emission**
- **Synchrotron**
- Bremsstrahlung (aka free-free)
- Inverse Compton Scattering

Spectral Lines — “The Spikes”

Radiation at specific wavelengths

- **The HI Line**
- Pretty much any element or molecule has lines.

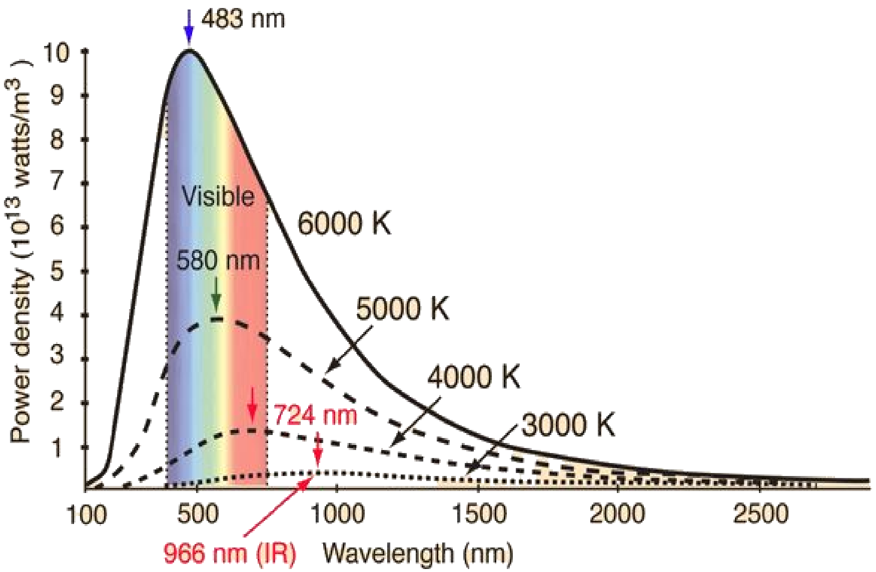
Thermal Emission

Hot Things Glow

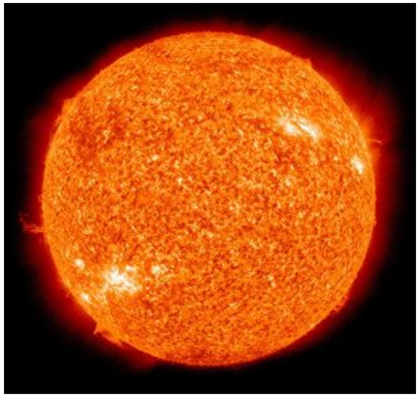
Emit radiation at *all* wavelengths

The peak of emission depends on T

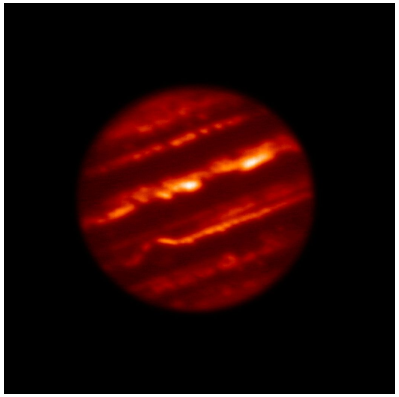
Higher T → shorter wavelength



Regulus (12,000 K)
Peak is 250 nm



The Sun (6,000 K)
Peak is 500 nm



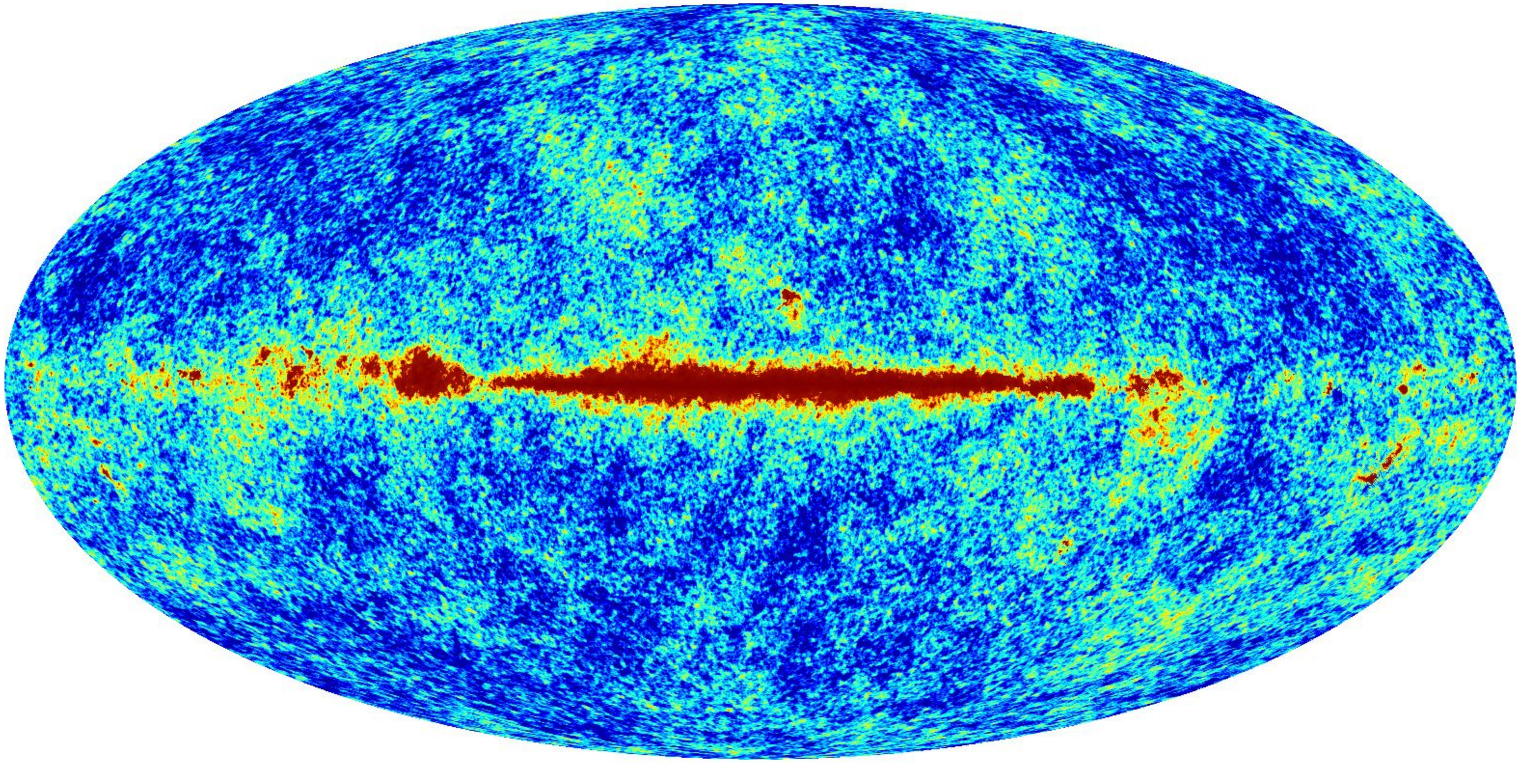
Jupiter (100 K)
Peak is 30 μm

Thermal Emission

How cold corresponds to a radio peak?

A 3 K source has peak at 1 mm.

Not getting any colder than that.

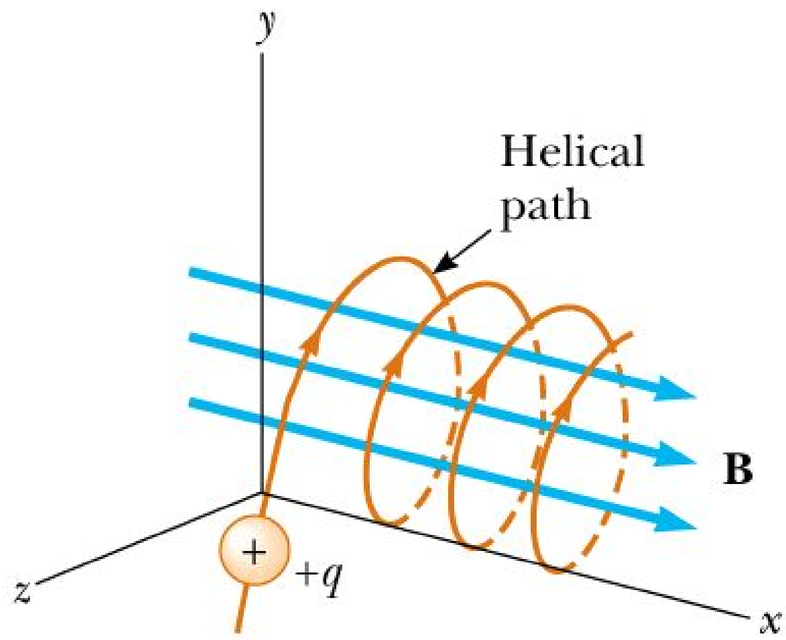


Synchrotron Radiation

Magnetic Fields

Make charged particles move in circles.

Accelerating charges radiate.



Synchrotron Ingredients

Strong magnetic fields

High energies, ionized particles.

Found in jets:

- ❖ Active galactic nuclei
- ❖ Quasars
- ❖ Protoplanetary disks

Synchrotron Radiation

Jets from a Protostar

At right: an optical image.

Half of jet is obscured by dust cloud

But radio can go right through dust...

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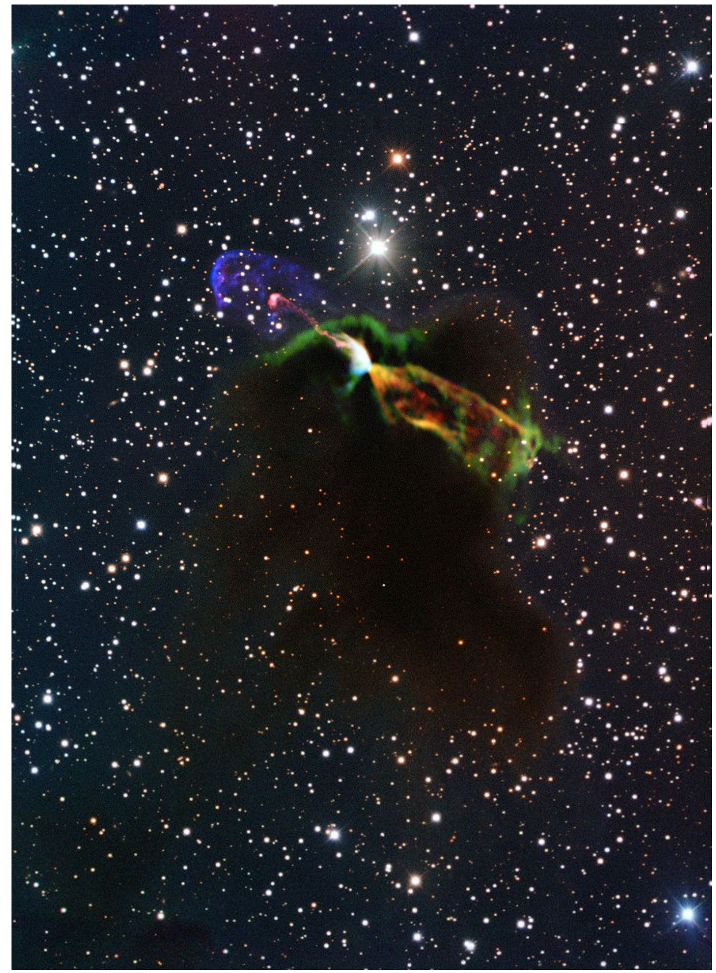
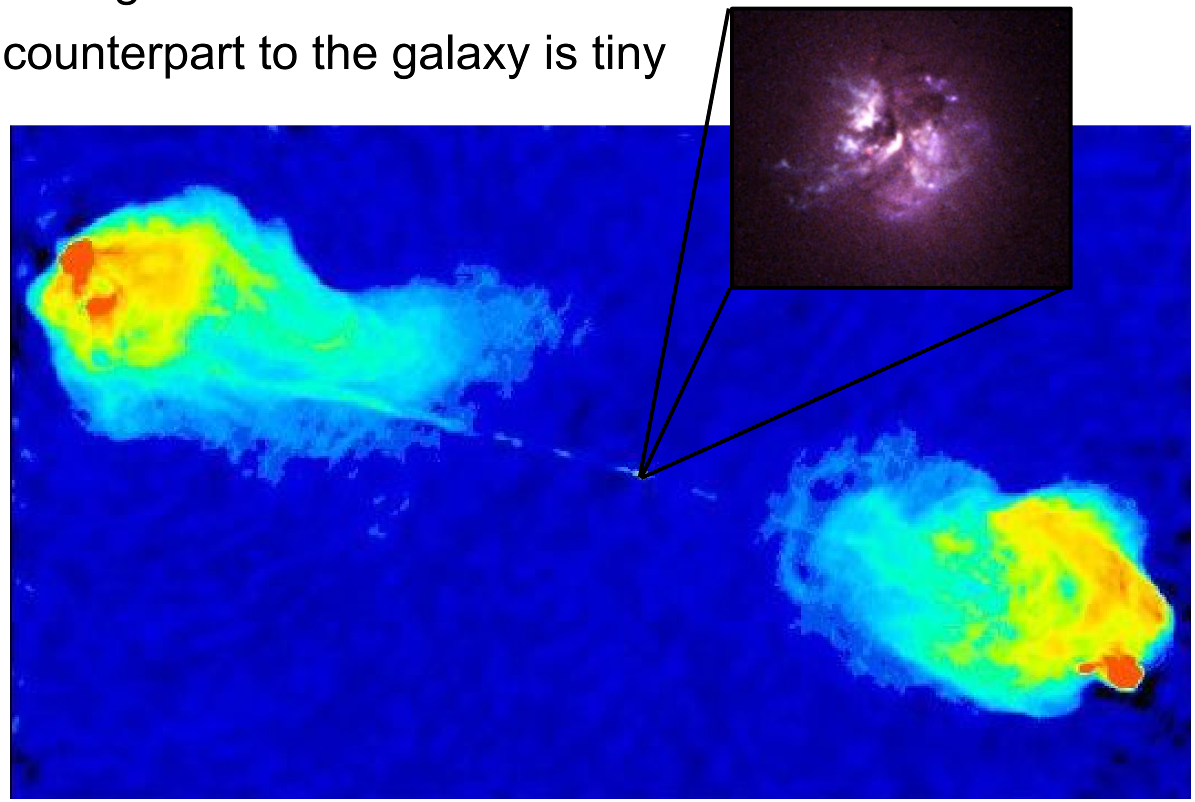


Synchrotron Radiation

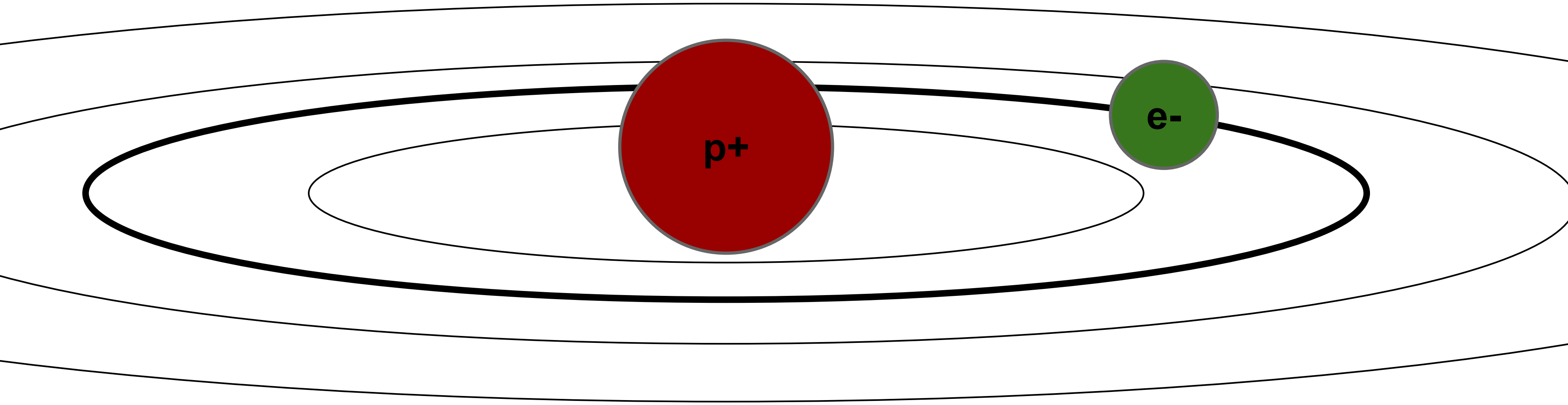
Jets from Cygnus A

At right: VLA image

The optical counterpart to the galaxy is tiny



The Hydrogen Atom

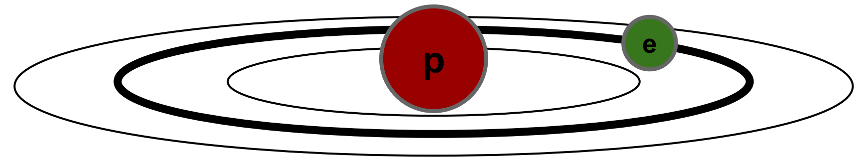


For Archaic Reasons:

H I Atomic "Neutral" Hydrogen

H II Ionized H^+

The Hydrogen Atom



n = 4; E = -0.9 eV

n = 3; E = -1.5 eV

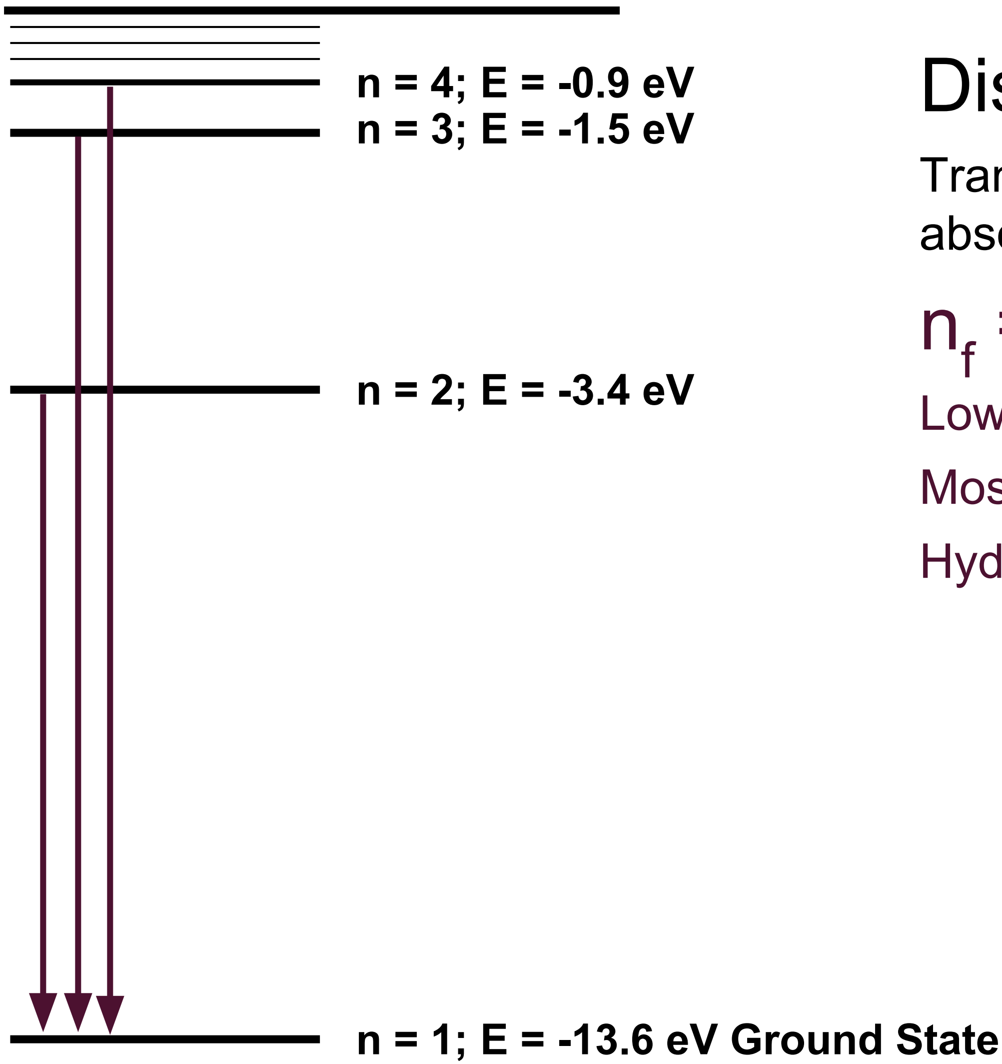
Discrete Energy Levels

Transitions due either to emission or absorption of photons.

n = 2; E = -3.4 eV

n = 1; E = -13.6 eV Ground State

The Hydrogen Atom



Discrete Energy Levels

Transitions due either to emission or absorption of photons.

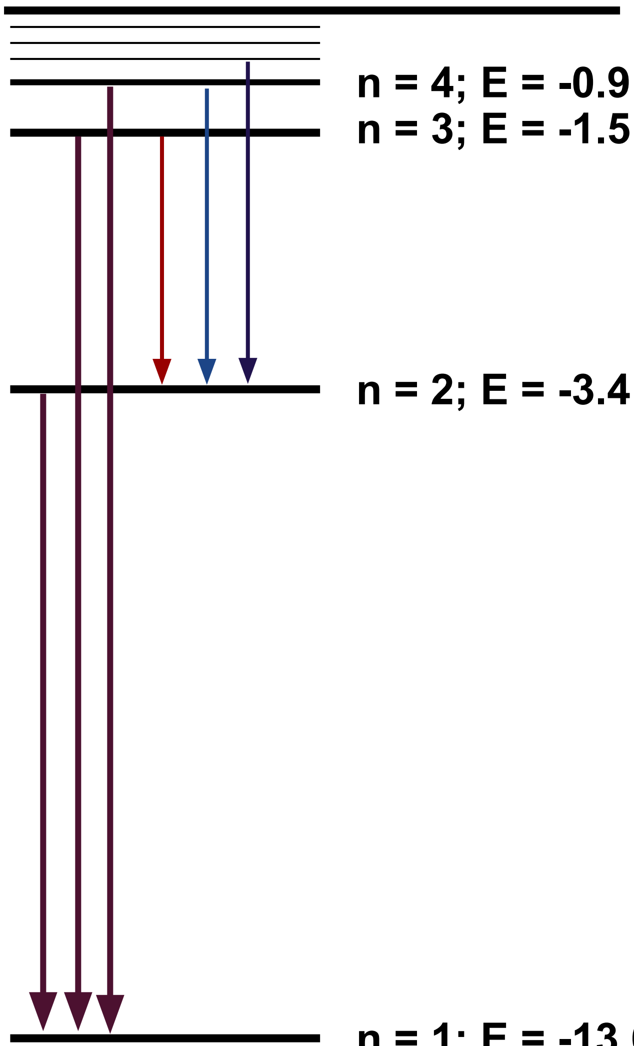
n_f = 1: Ultraviolet Light

Lowest Energy: 10.2 eV (121 nm)

Most Hydrogen sits at n = 1!

Hydrogen doesn’t emit much light.

The Hydrogen Atom



Discrete Energy Levels

Transitions due either to emission or absorption of photons.

n_f = 1: Ultraviolet Light

Lowest Energy: 10.2 eV (121 nm)

Most Hydrogen sits at n = 1!

Hydrogen doesn't emit much light.

n_f = 2: Visible Light

Red (656 nm; Hα),

Blue (486 nm; Hβ),

Violet (434 nm; Hγ),

and so on for $n_i \geq 4$

(the rest are all UV)

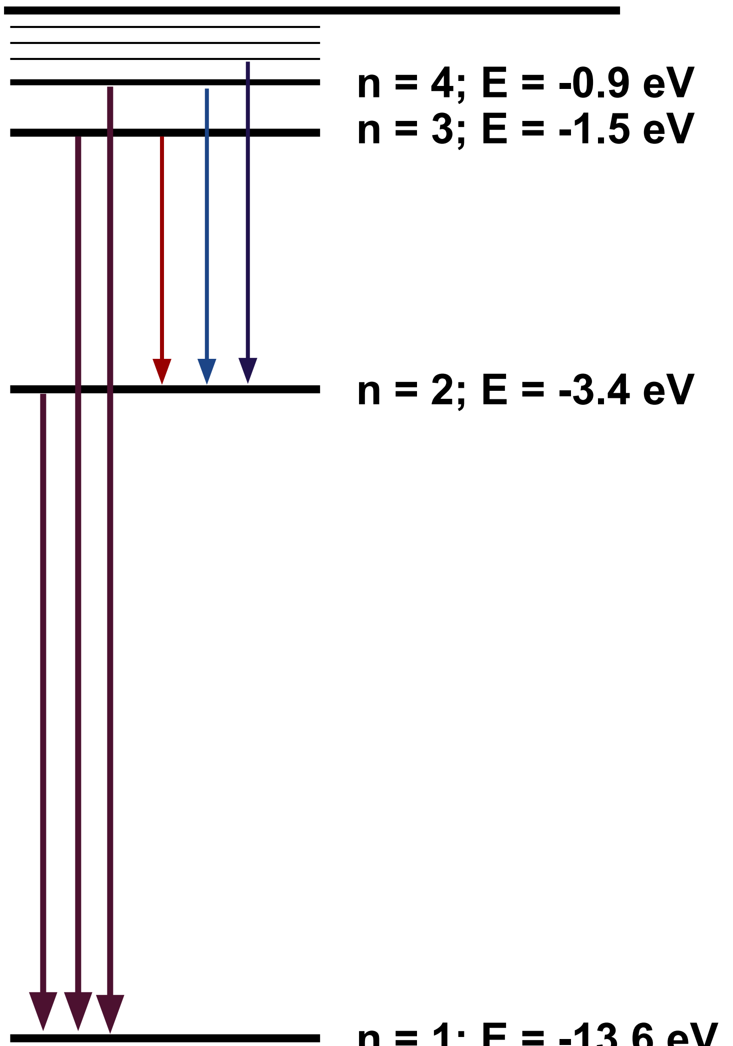
The HI Radio Line

Used to Observe HI

Frequency: 1420 MHz

Wavelength: 21 cm

Energy: $6{\times}10^{-6}$ eV



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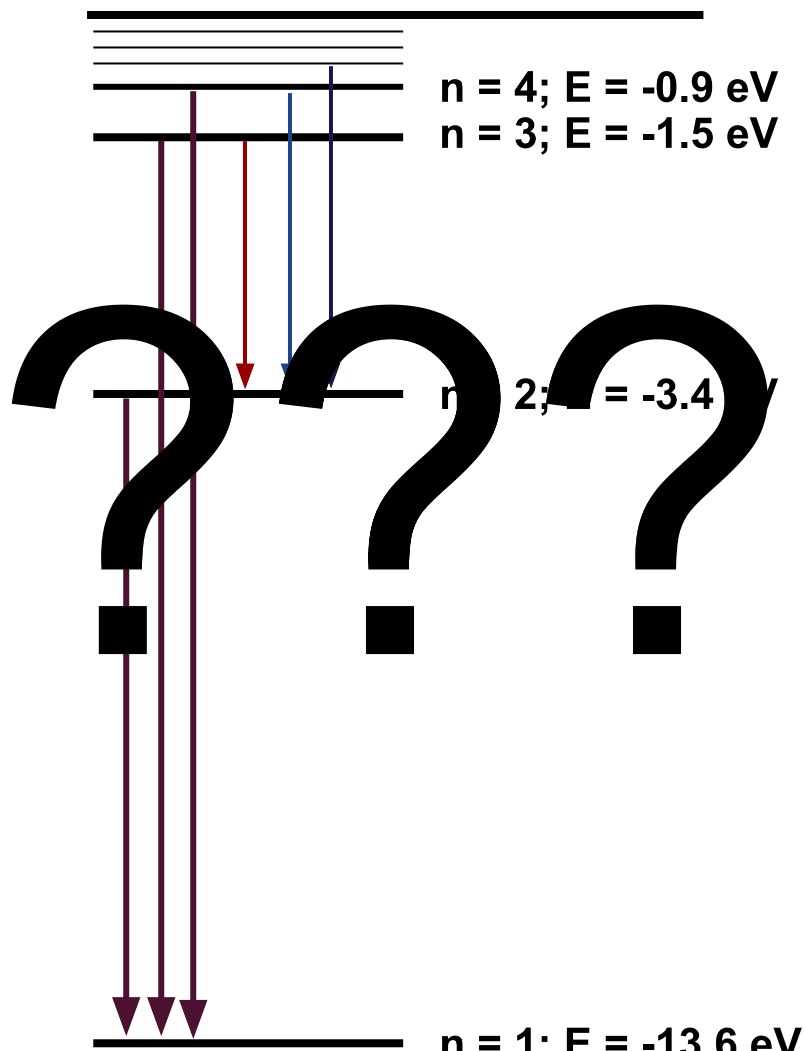
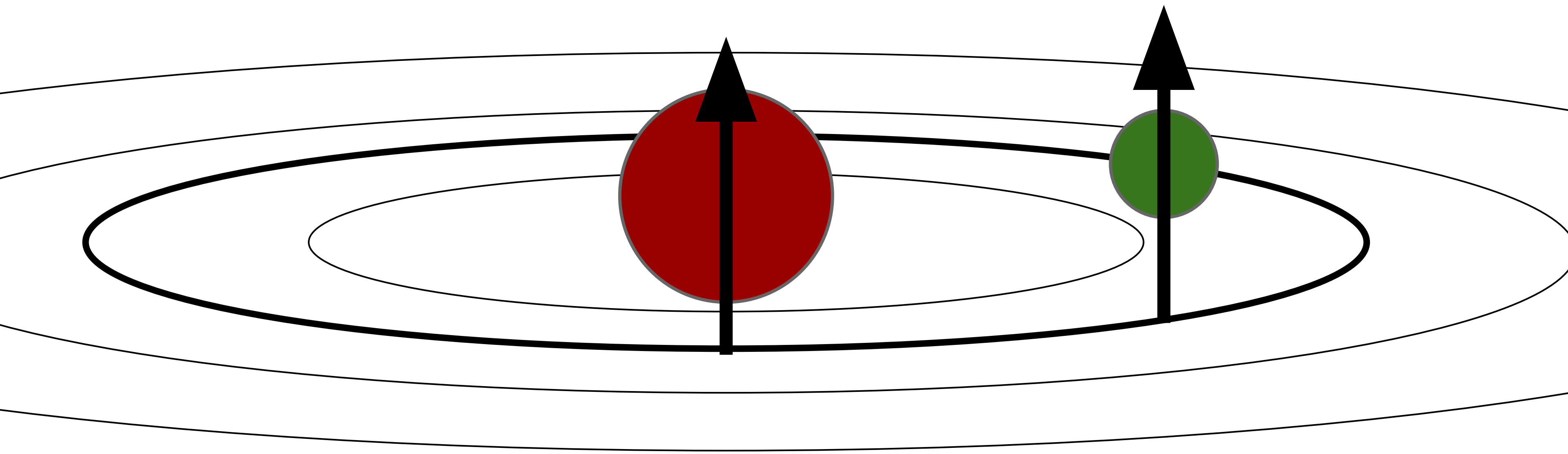


The Hydrogen Atom, Revisited

Proton and Electron Carry Angular Momentum



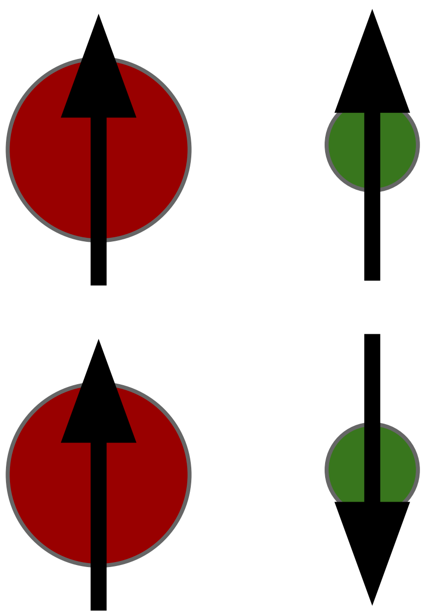
Specifically, Spin Angular Momentum

As if they were rapidly rotating objects.

(but electrons are likely of zero radius, so not quite)

The Hydrogen Atom, Revisited

Different Energies Depending on Alignment:



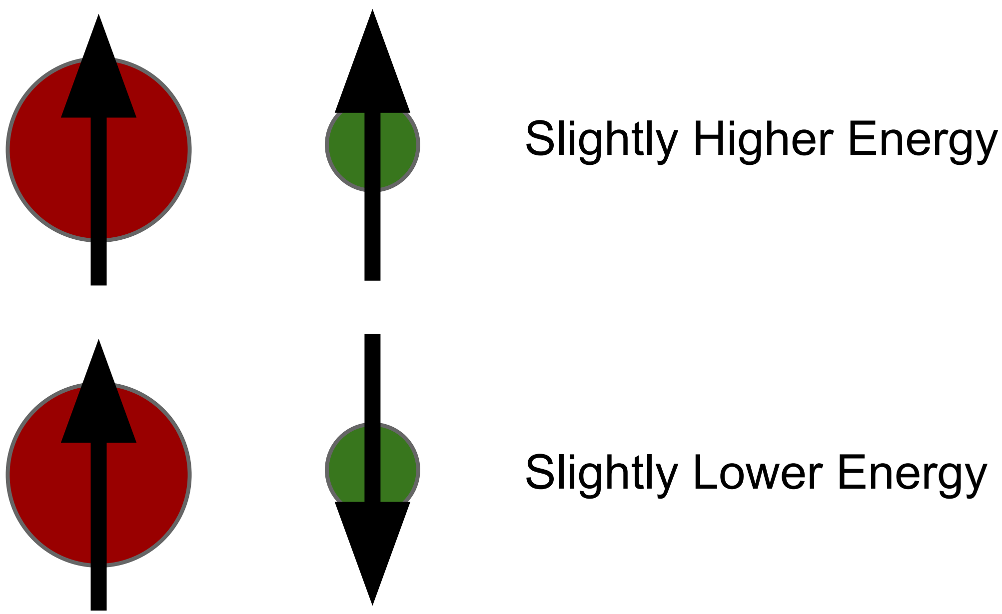
Slightly Higher Energy

Slightly Lower Energy

The Energy Difference is 6×10^{-6} eV (or λ = 21 cm).

Shenanigans

Why Are the Spin States Different Energies?



Spin + Charge = Magnetic Moment

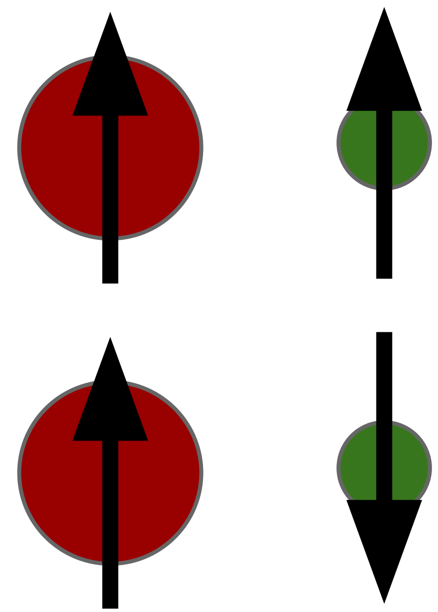
Different energies come from the alignment or misalignment of the magnets.

Properties of the HI Line

Excitation Temperature is 0.07 K ($T = E/k_B$)

So the actual temperature of the H doesn't matter.

i.e. hydrogen is always* excited



State Lifetime is 10^7 yrs.

Need a ton** of Hydrogen to observe it.

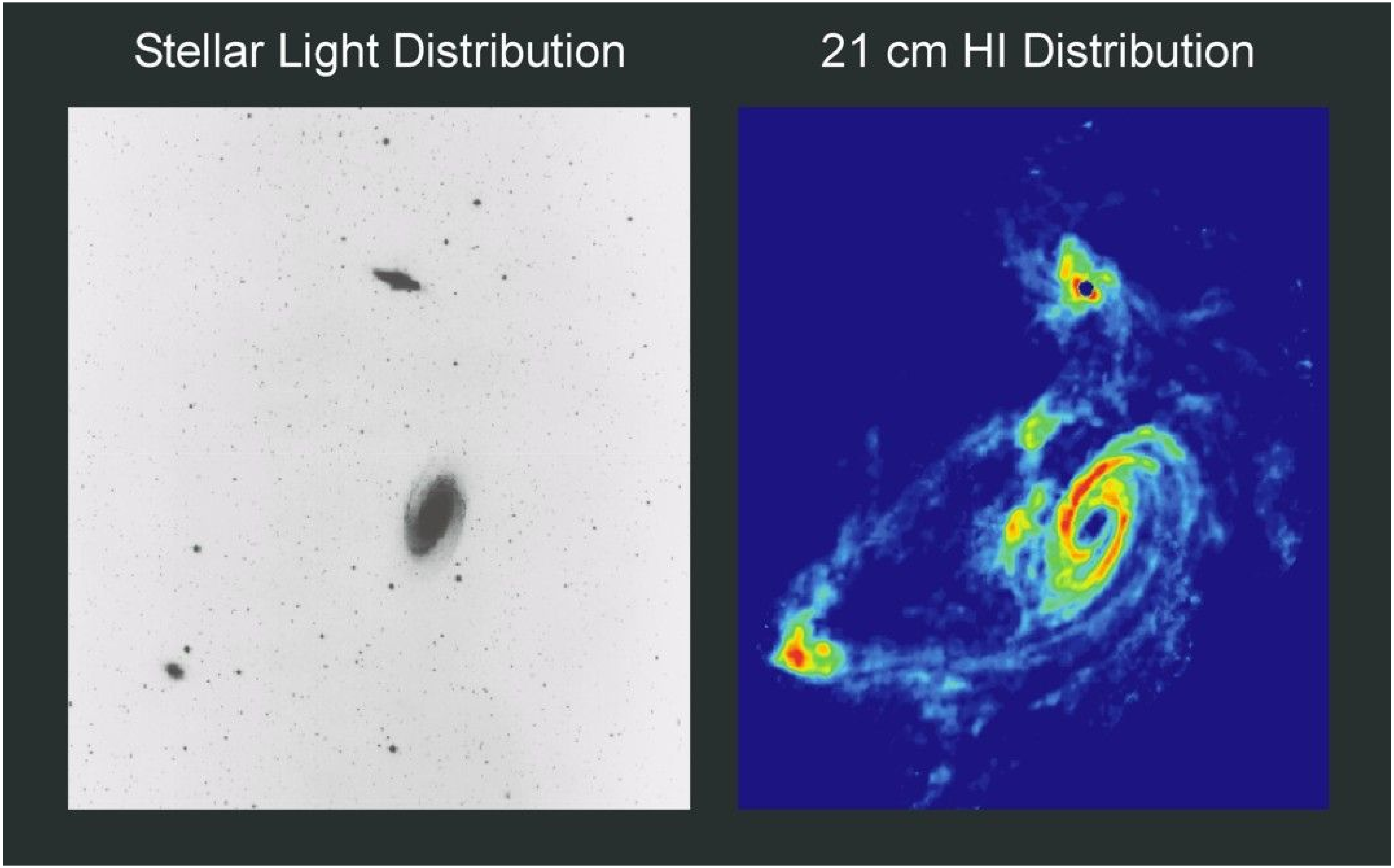
Unlikely to be Absorbed En Route

Total Energy from line directly proportional to mass.

*okay fine, *half* of it is always excited.

**well, a few solar masses.

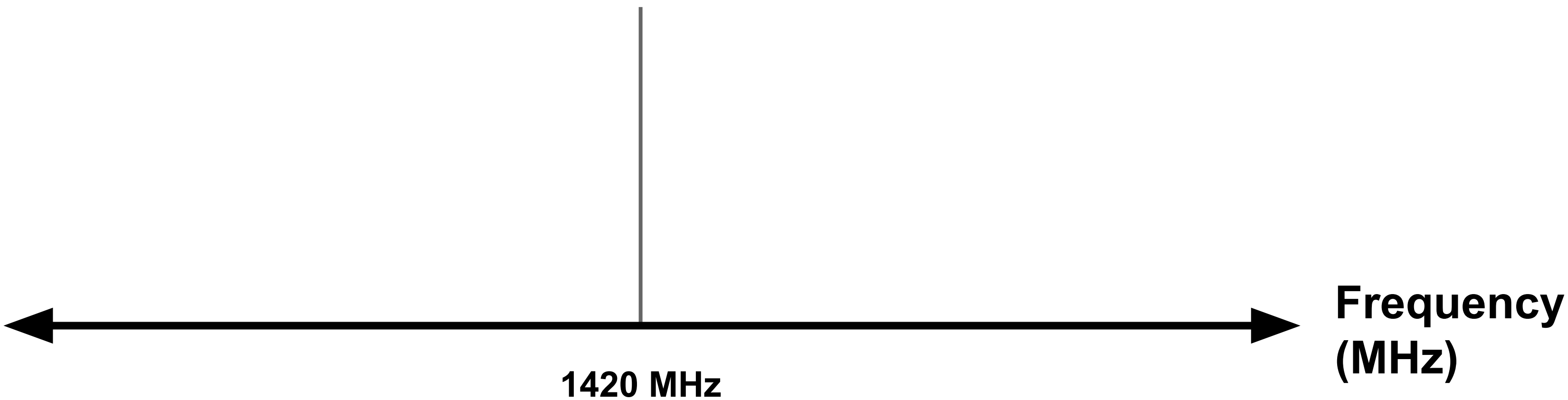
The HI Line



II. Details of the HI Line

The HI Line

When Observed, the Line Looks Like This:



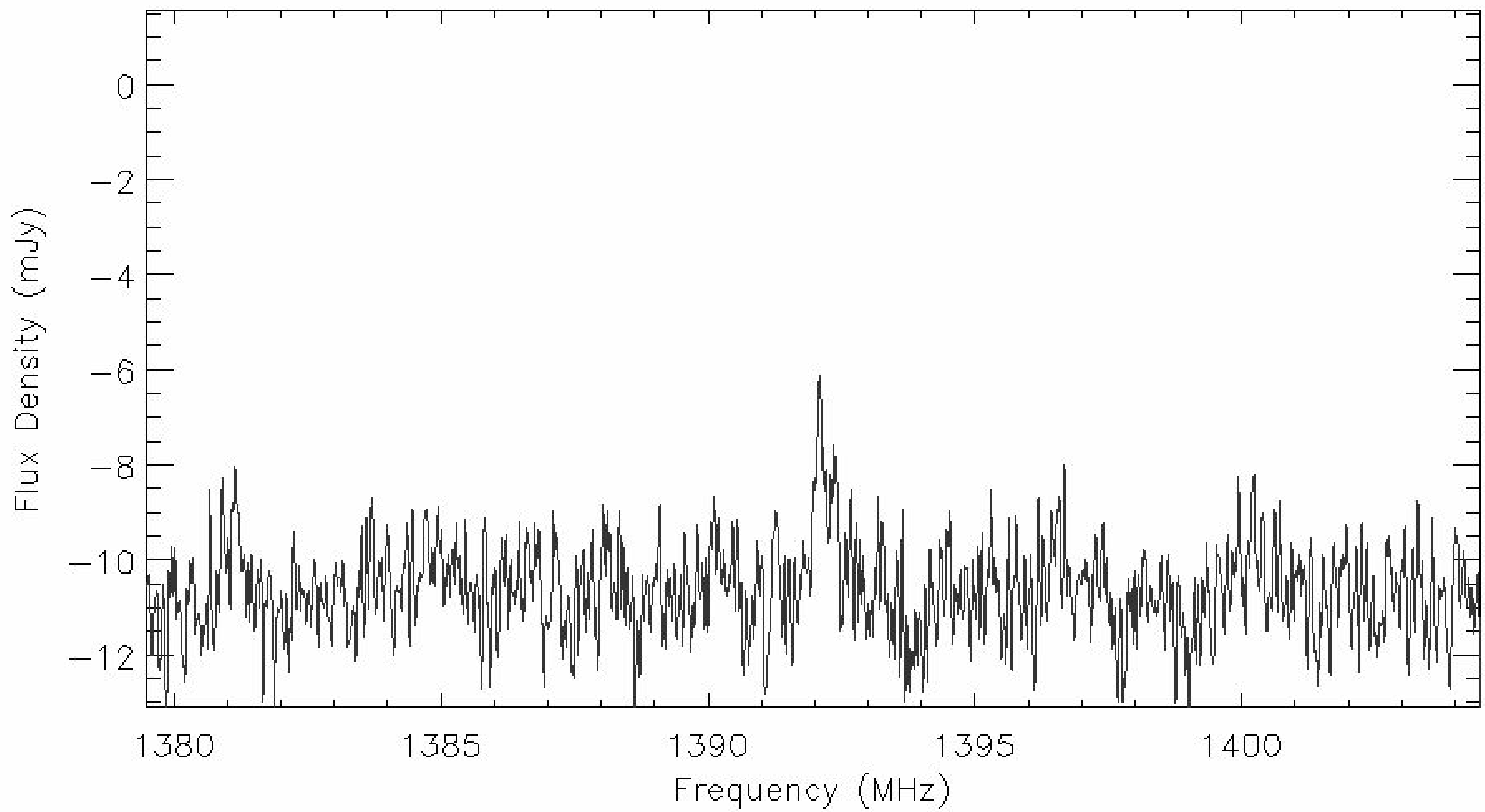
Features:

Centered at 1420 MHz

All Emission is at Single Feature

Line Has No Interesting Features; Nice Sharp Spike.

The HI Line



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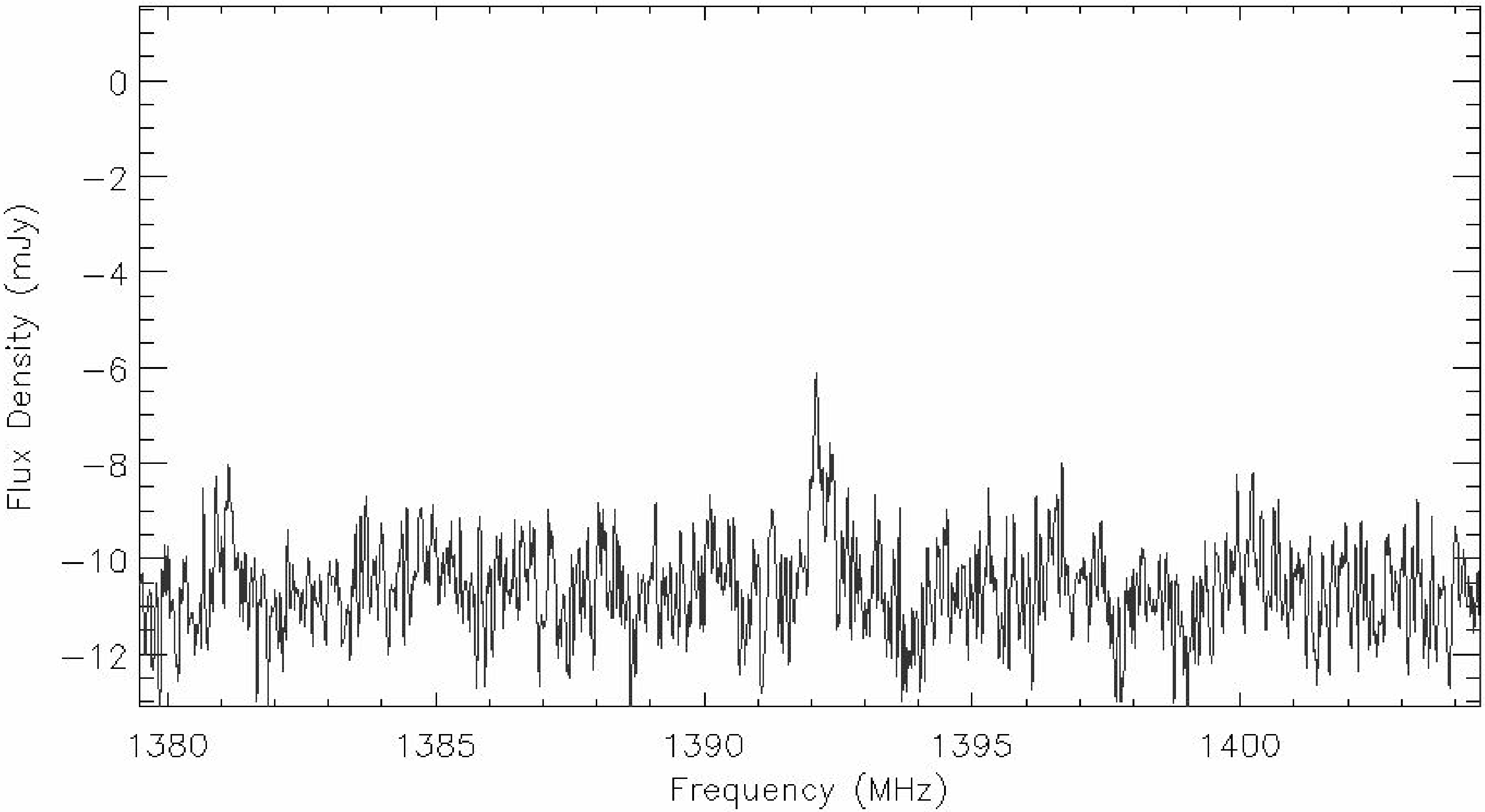


~~Centered at 1420 MHz~~

~~All Emission is at Single Feature~~

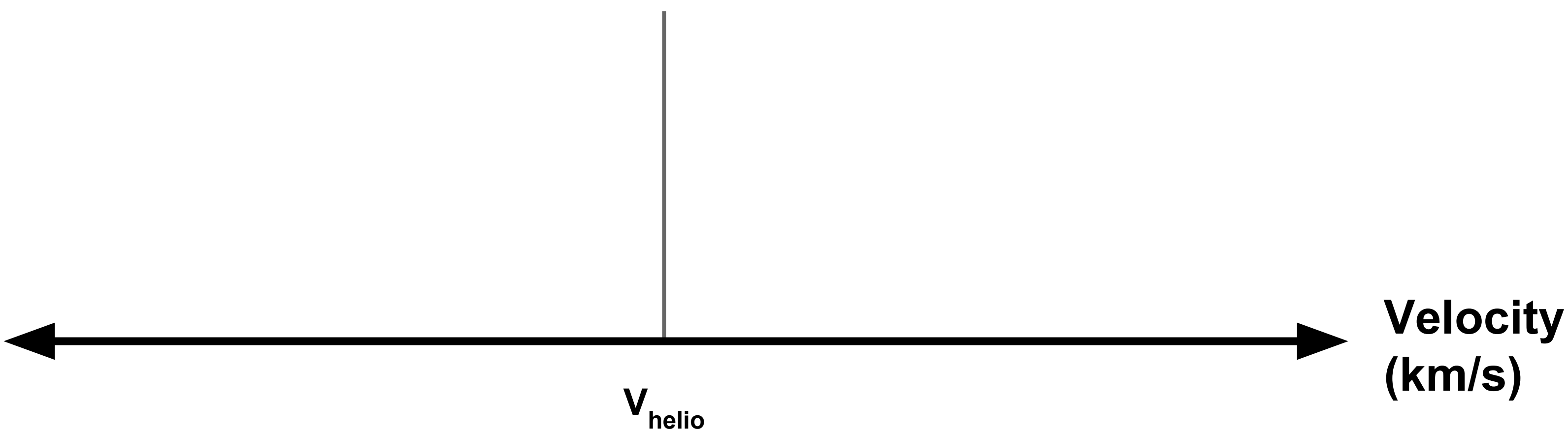
~~Line Has No Interesting Features; Nice Sharp Spike.~~

Doppler Shift

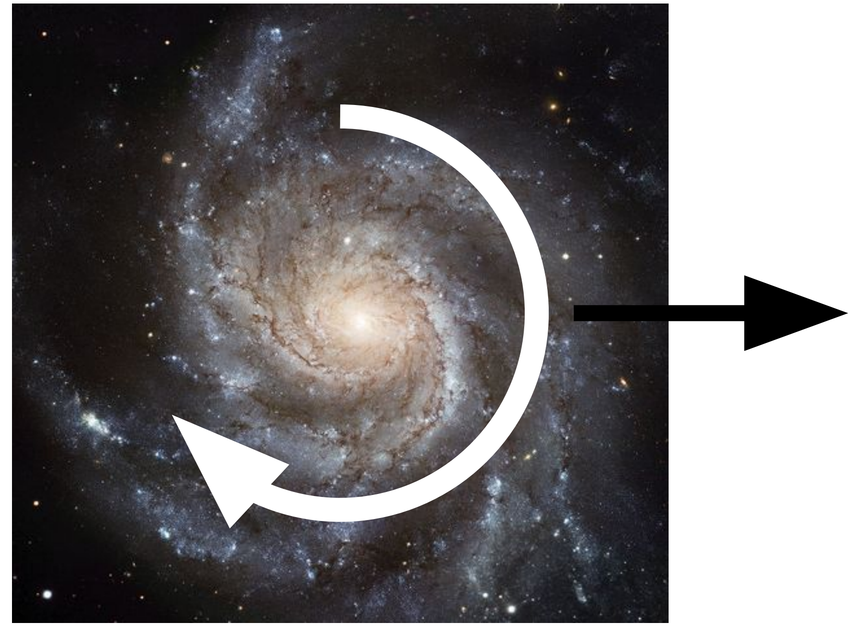
Galaxies are (usually) move away from us.

All of lines are *redshifted*

Know Rest frequency (1420 MHz), Can Find Velocity



Galaxy Rotation

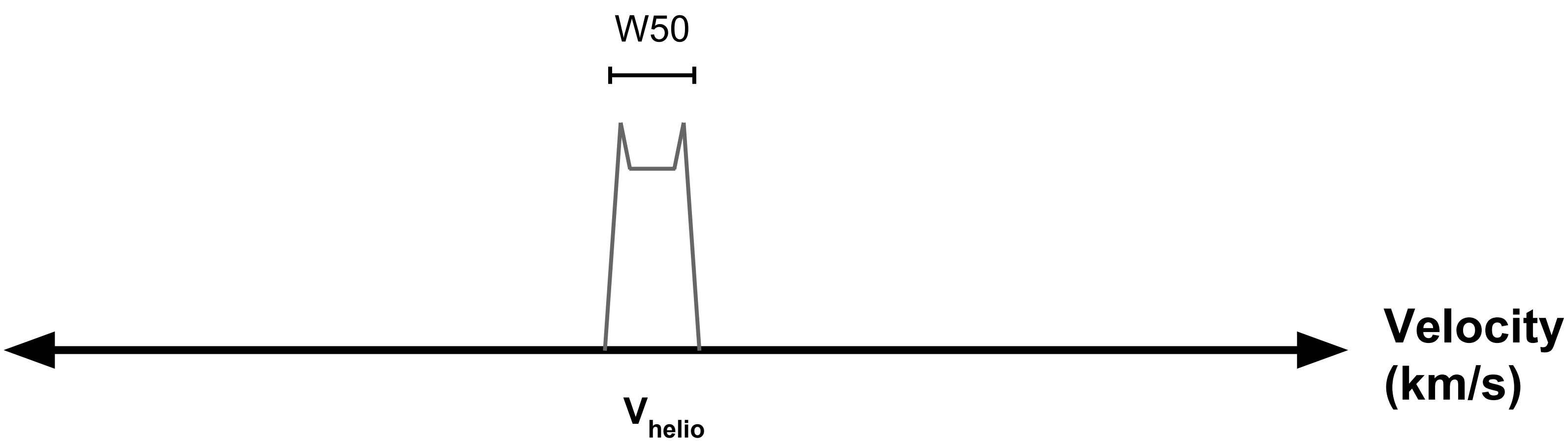


Galaxies Rotate:

- Half of galaxy is approaching us.
- Half of galaxy is moving away from us.
- (Relative to overall motion away)

Doppler Shift *within* galaxy broadens line.

Rotation nearly constant across galaxy → “horns”

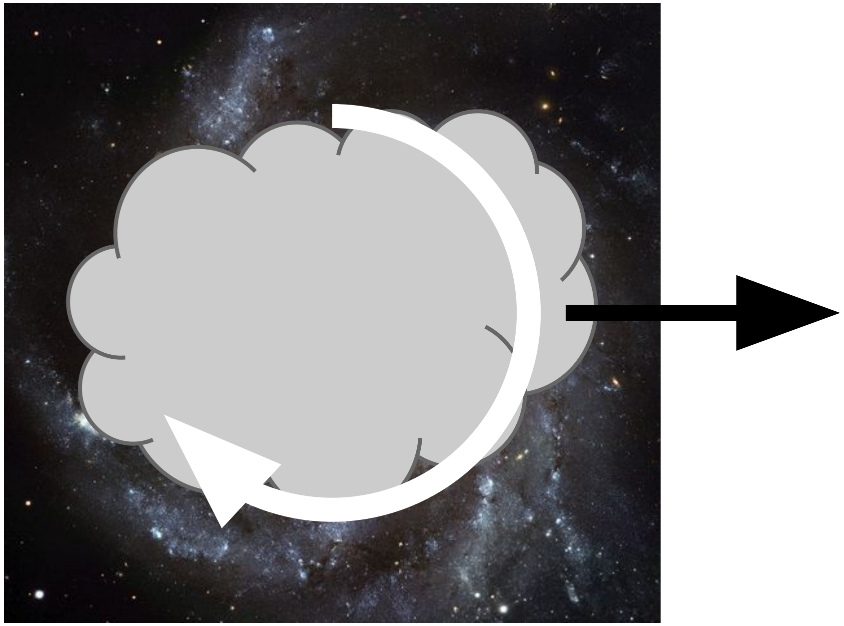


Hydrogen Mass

Galaxies Have Different Masses of HI

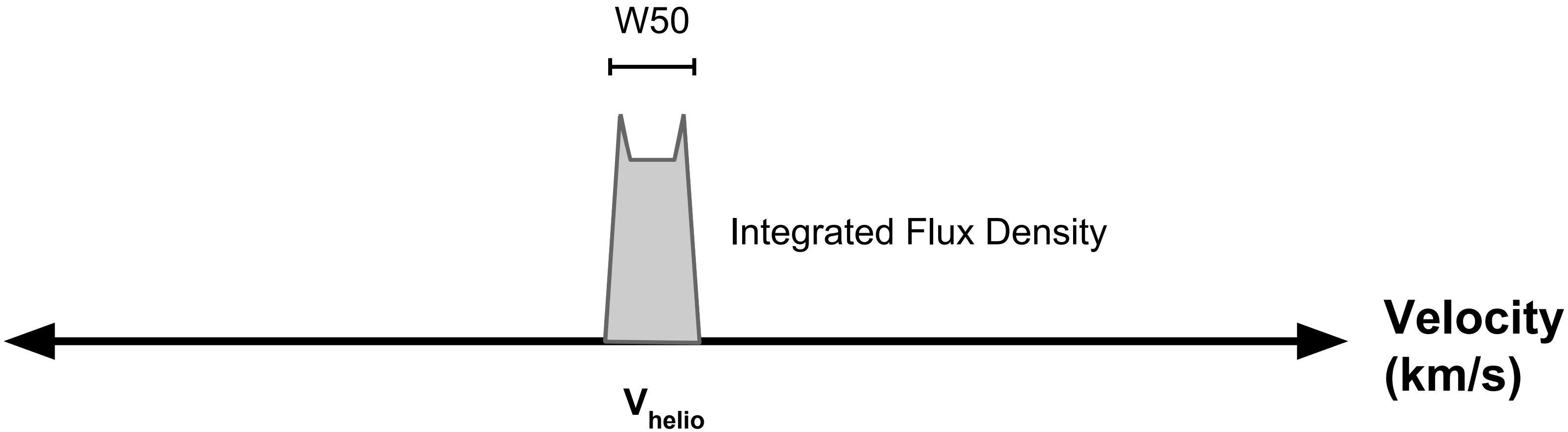
More HI, Stronger HI Line

(for a given distance from Earth)



Convert Area to Mass:

$$M_{\mathrm{H\,I}}/M_{\odot} = 2.356 \times 10^5 D_{\mathrm{Mpc}}^2 \int S(V)\,dV,$$



Recap: Features of HI Line

V_{helio} (Position of Line)

How Fast is the Galaxy Moving?

How Far is it from Earth?

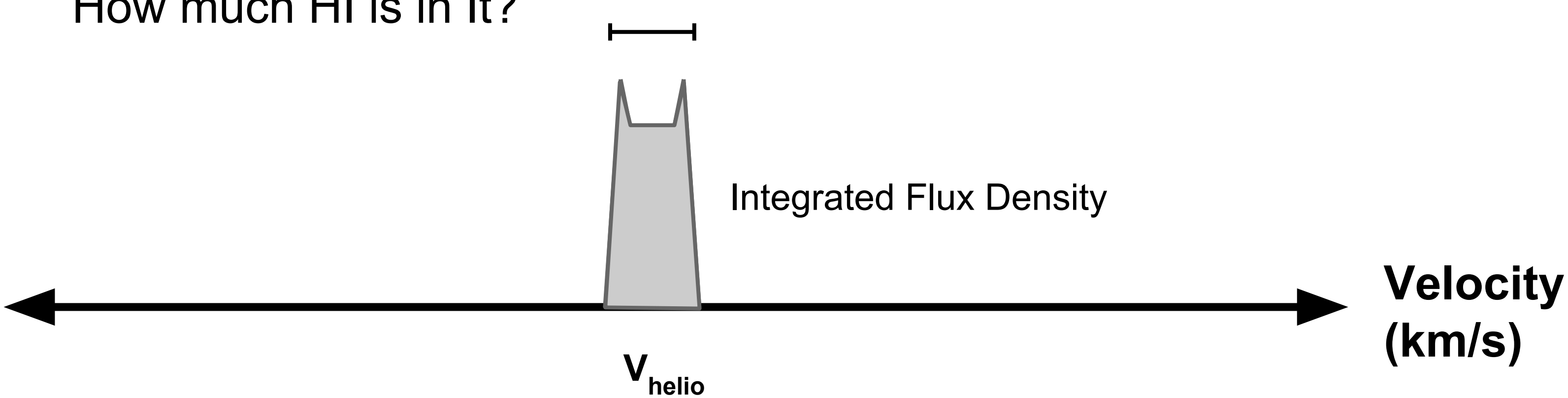
W50 (Line Width)

How Fast is it Rotating?

What are its Internal Kinematics Like?

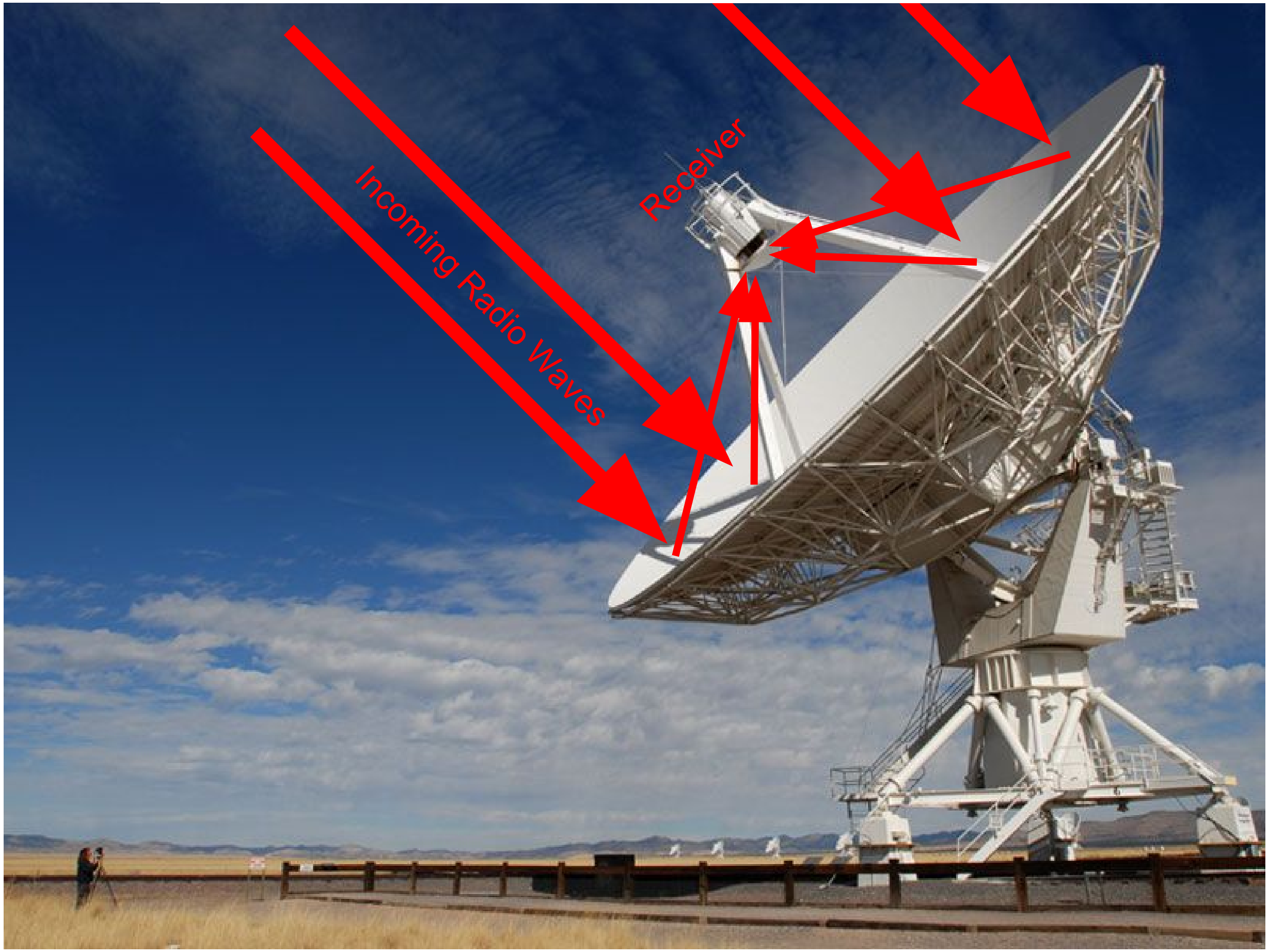
Integrated Flux (Area Under Curve)

How much HI is in It?



III. The Radio Telescope

Basic Principles

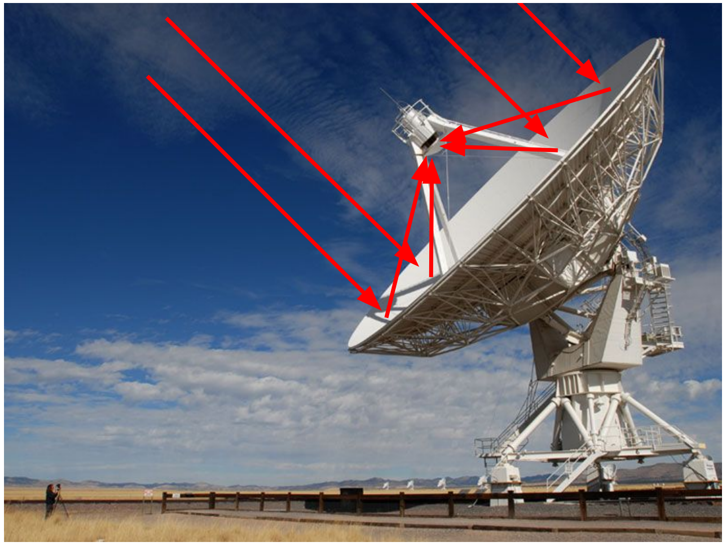


Schematic

The Dish

Collects incoming light, focuses at receiver.

Light then converted to electronic signals



Effects of Dish Size

Larger area → More sensitive

Larger diameter → better resolution

(Unlike optical telescopes)

Dish Size and Resolution

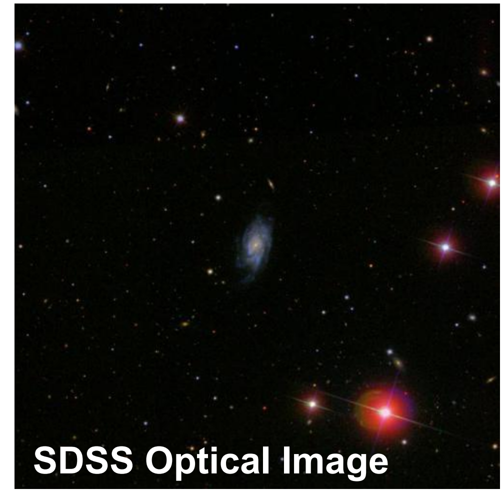
The telescope for the SDSS is 2.5 m ($\lambda \approx 500$ nm)

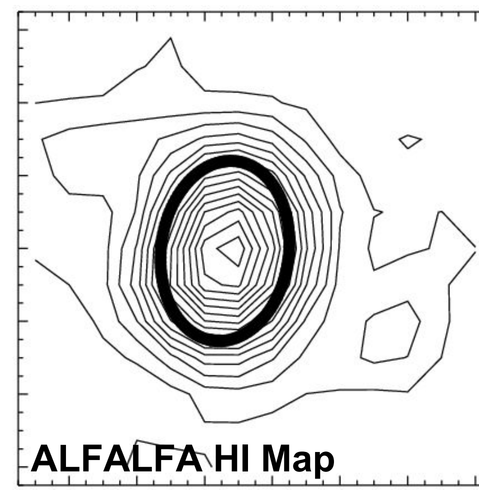
Arecibo is 300 m ($\lambda \approx 21$ cm)

$$\Delta\theta = 1.22\frac{\lambda}{D}$$

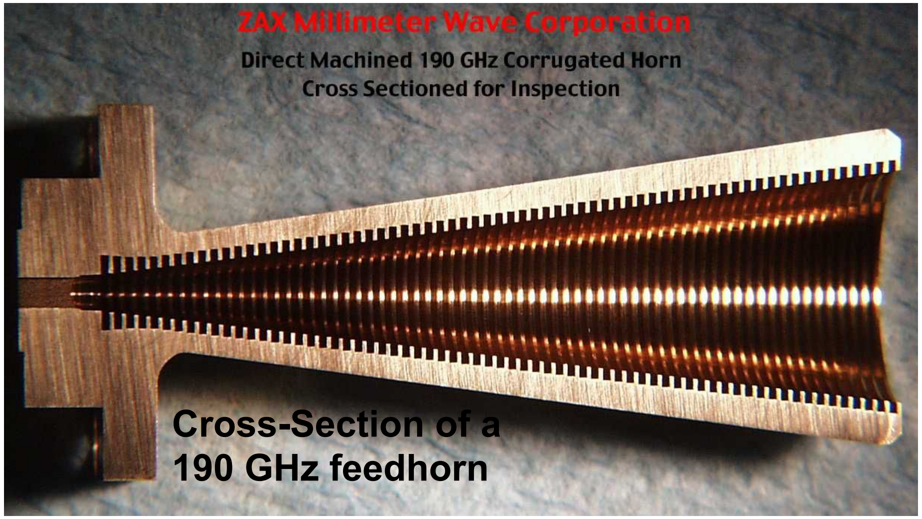
$\Delta\theta$	Telescope Resolution
λ	Wavelength
D	Telescope Diameter

→ SDSS Resolution is 3500× better!





Signal Path: From Receiver to You



Receiver

Convert radio wave to electric signal

Amplifier

Radio signals are extremely weak.

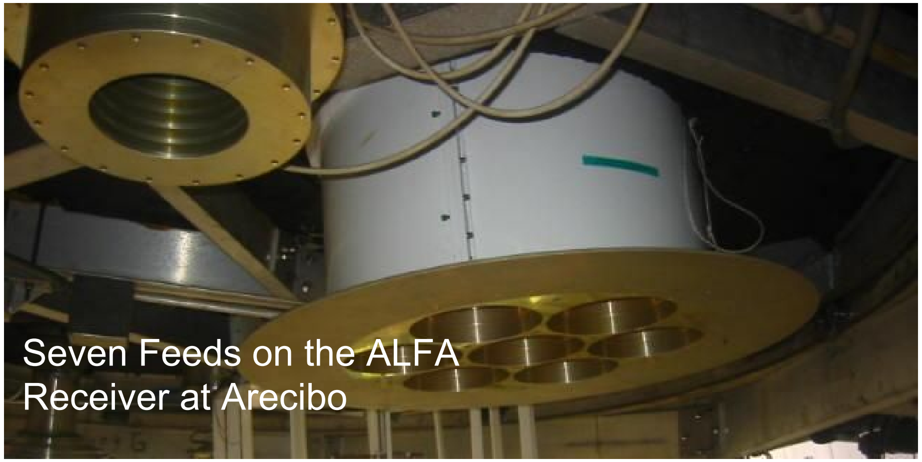
Downconverter

Converts signal to a lower frequency.

Another Amplifier

Spectrometer

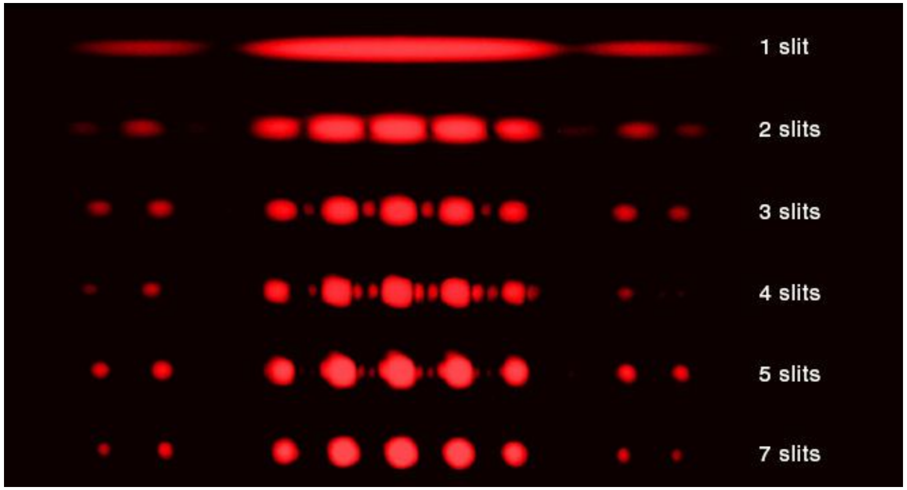
Turns signal into a spectrum.



What Does the Receiver See?

Interference

If λ ~ hole size, waves taking different paths “interfere” leaving pattern on far screen.



Effect on Telescope

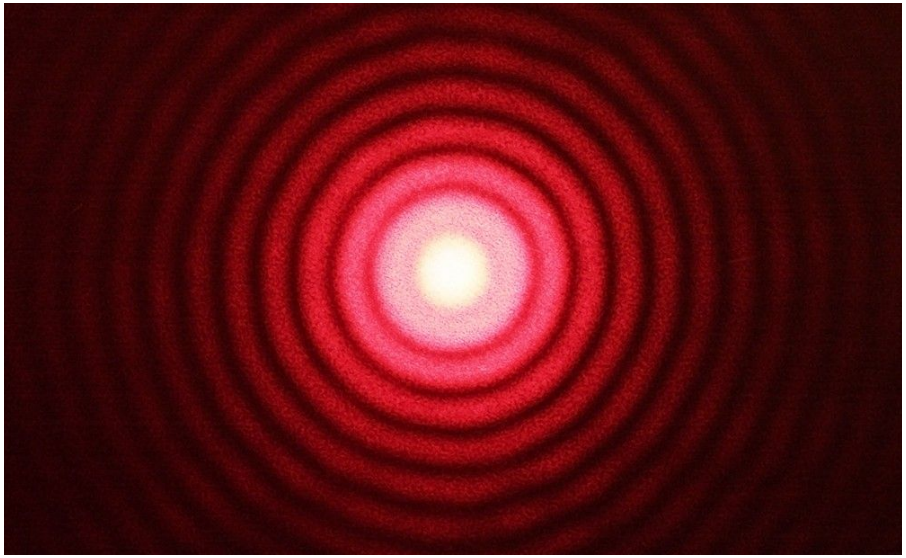
For radio, λ ~ 10 cm

Close to sizes of aperture.

Bright spot on sky is not a “spot”.

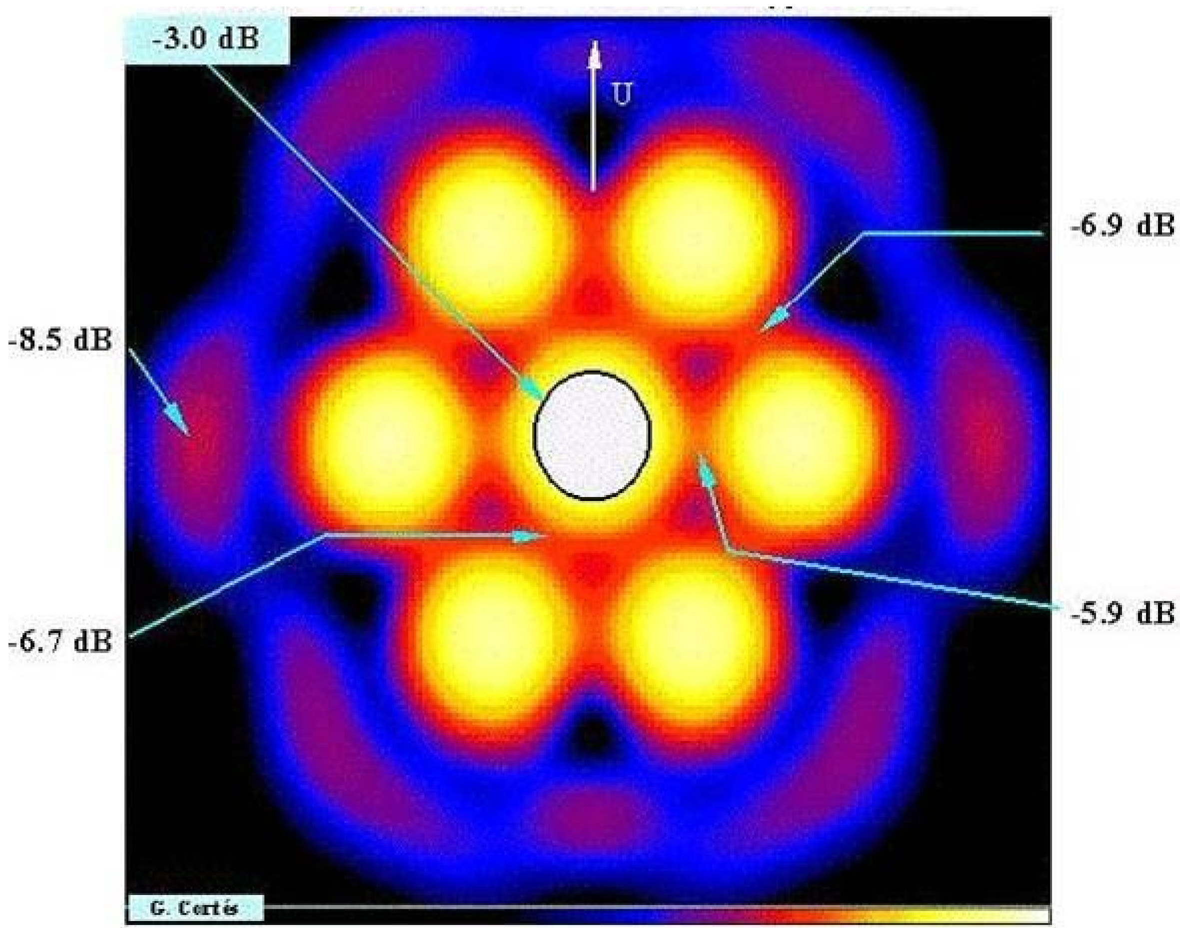
Additional “ripples” = side lobes

(No problem for optical λ ~ 500 nm telescopes)



What Does the Receiver See?

Arecibo's ALFA has seven beams packed close together.



The Downconverter

Optical Telescopes

Range in λ from 500 nm - 1000 nm (factor of ×2)
Use same receiver, electronics, etc.

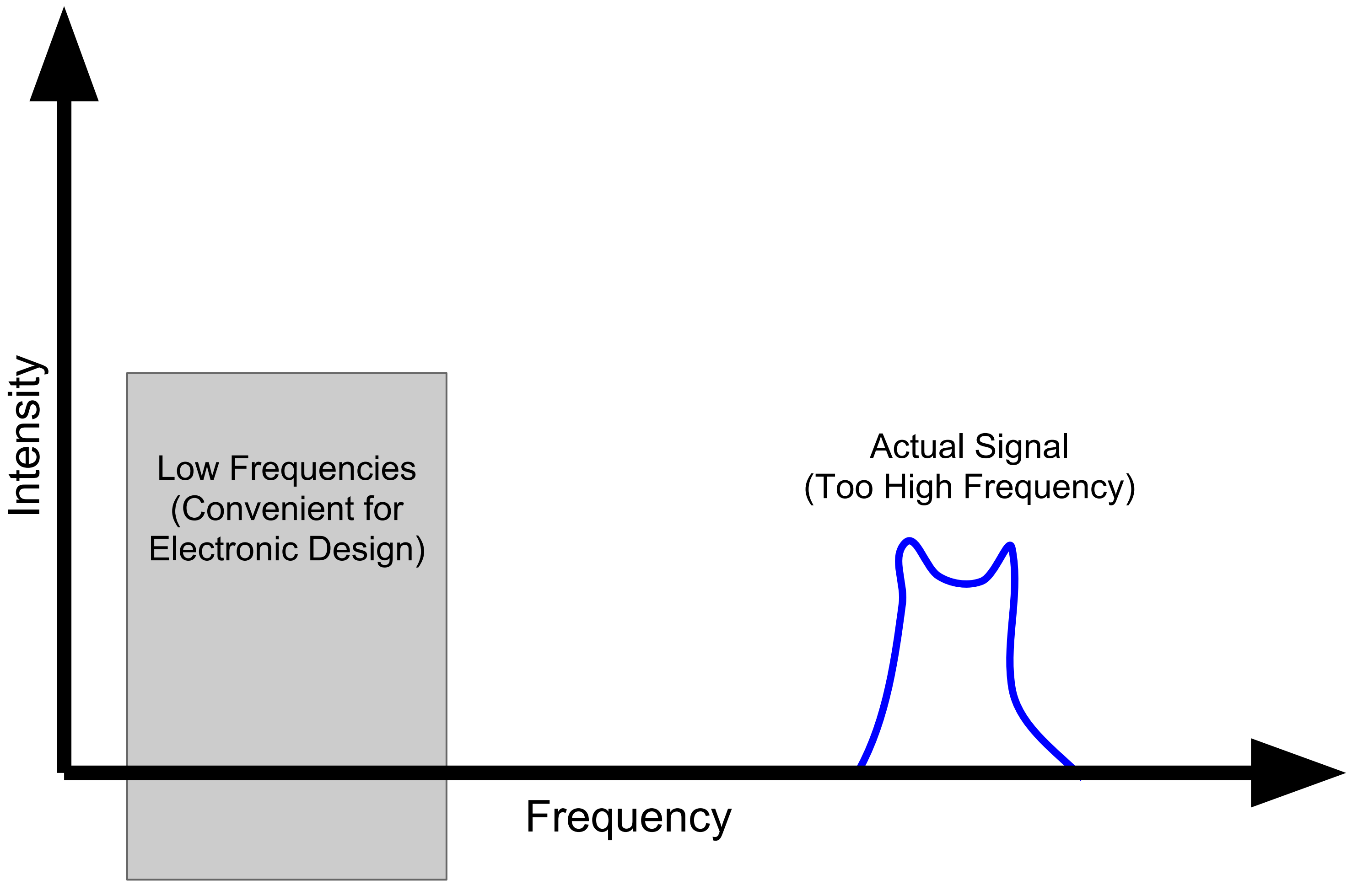
Radio Telescope

Range in λ from 1 cm - 1 m (factor of ×100)
Different wavelengths need different receivers.

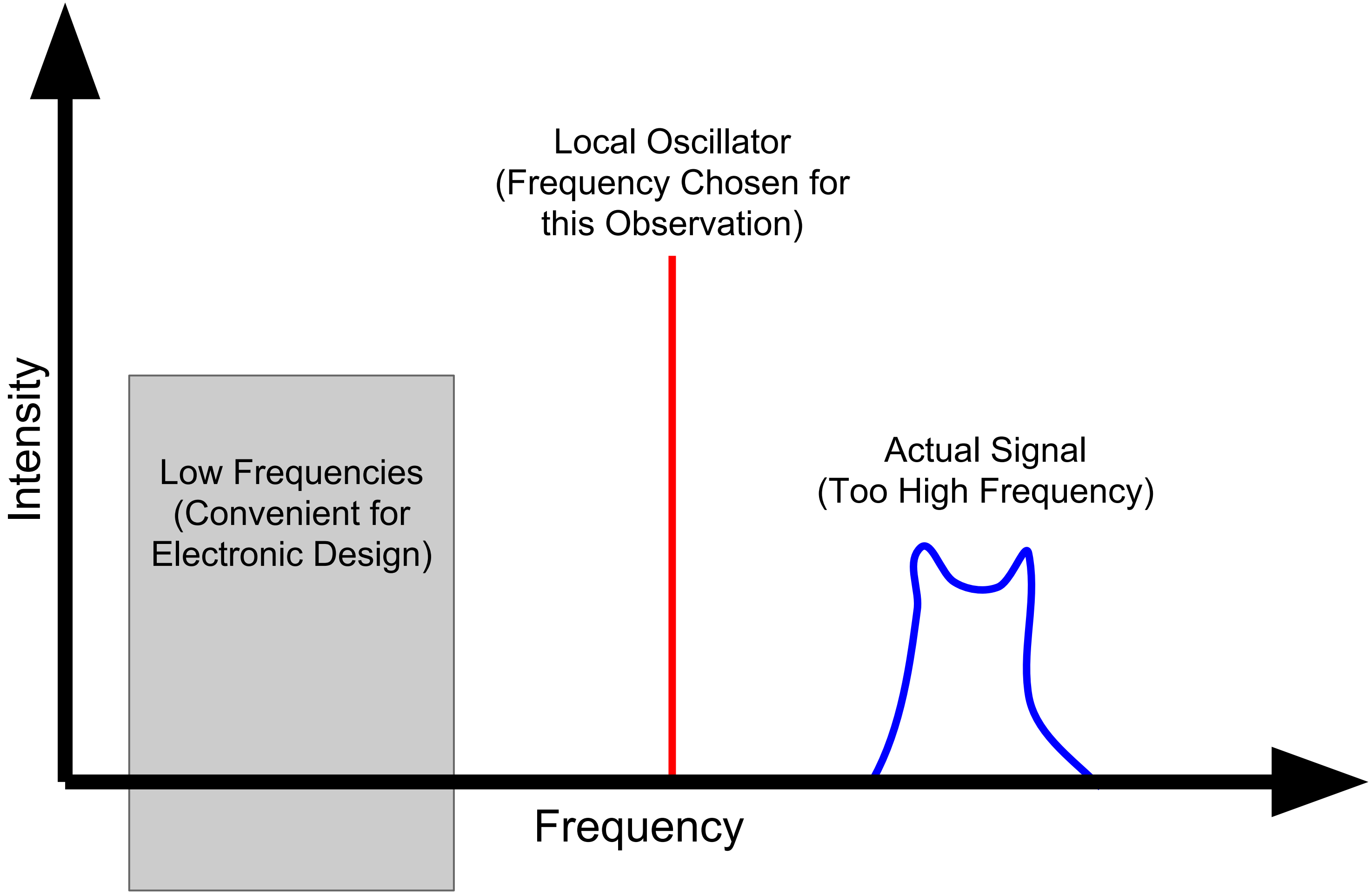
- ❖ *Need a smart way to reuse electronics*.
- ❖ *Electronics to at MHz frequencies more convenient than GHz-THz*.

Solution:
Mix signal with a fixed frequency, the **local oscillator.**

The Downconverter



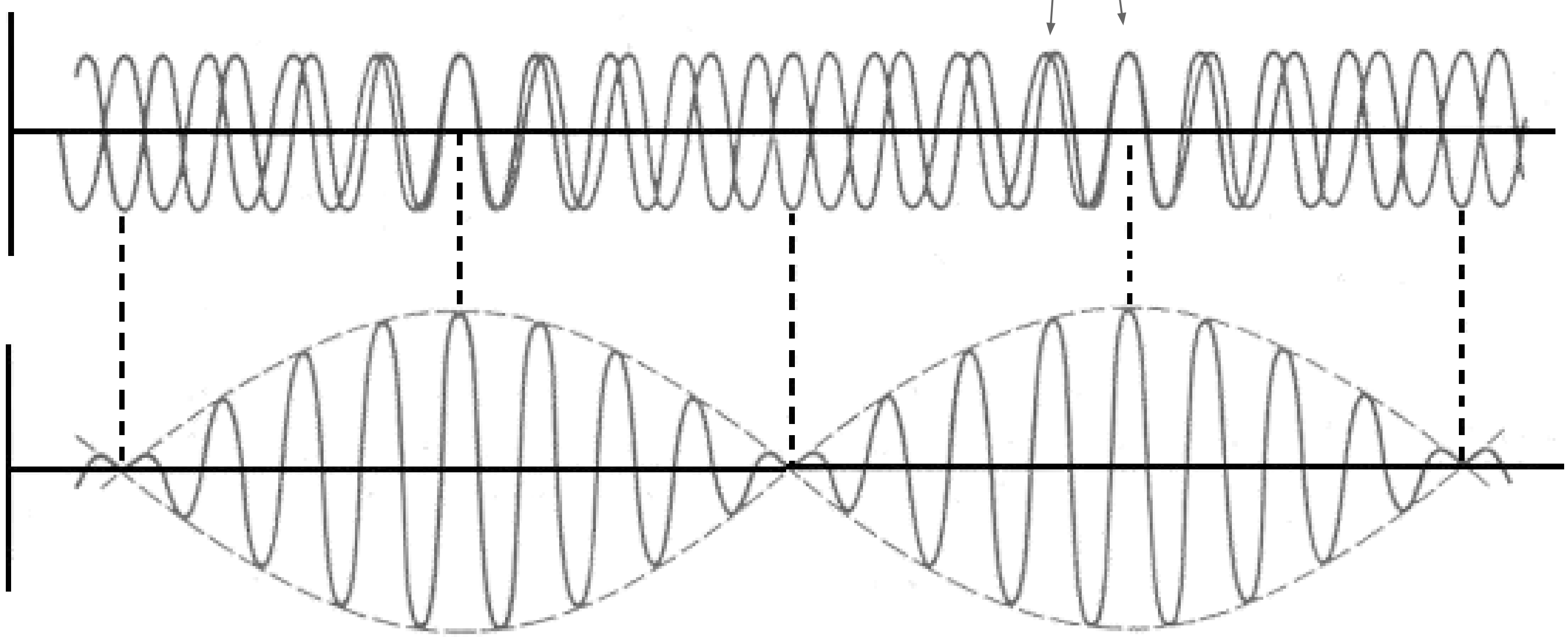
The Downconverter



The Downconverter

Signal and LO have almost same frequency

We add together the signal and the LO:

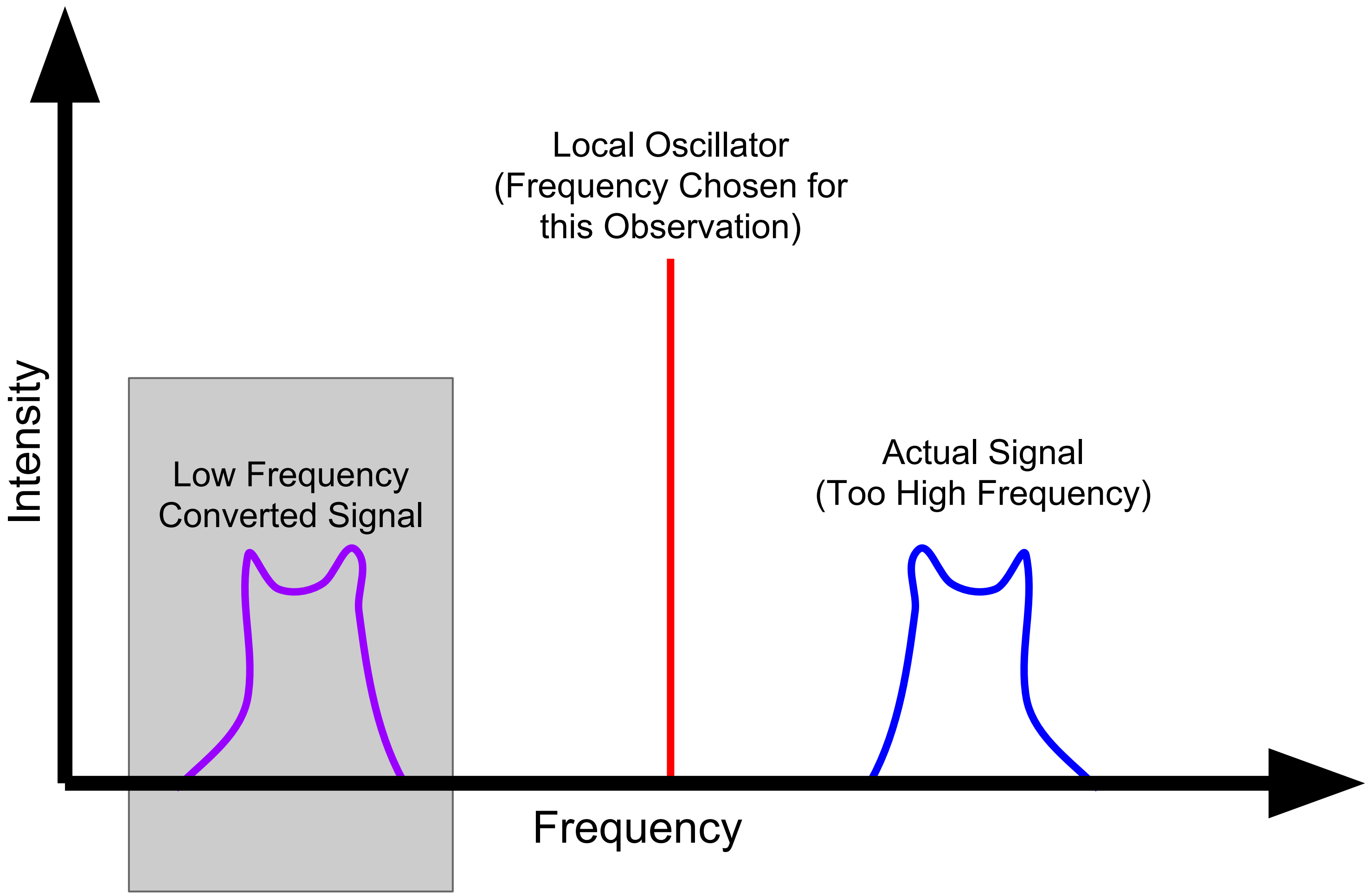


Trig Identity: $\cos(f_{sig}) + \cos(f_{lo}) = 2 \times \cos(f_{sig} + f_{lo}) \times \cos(f_{sig} - f_{lo})$

Rapidly varying signal (ignore)

Slowly varying signal (keep)

The Downconverter



The Spectrometer

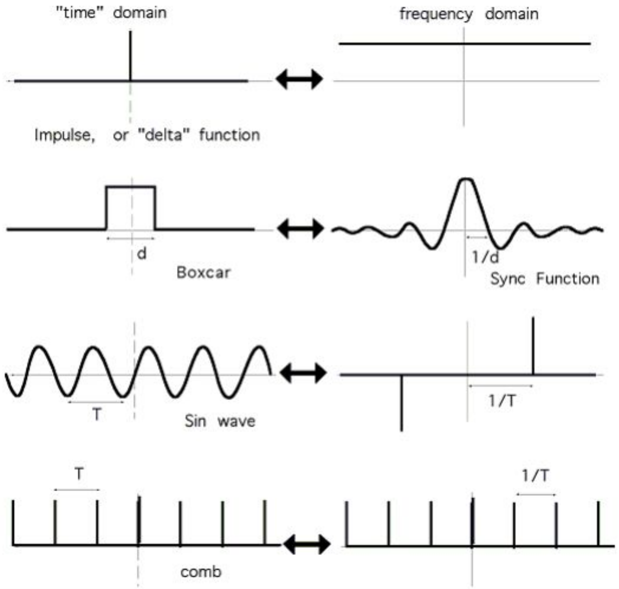
Convert signal in “time space” to spectrum in “frequency space”

Optical Equivalent

Use a prism, grism, or album cover of dark side of the Moon.

Radio Astronomy

Spectrometer performs Fourier Transform of electronic signal.



Signal is then saved to disk.

End of Talk.

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