Introduction to Radio Astronomy

Dominic Ludovici | 21st Synthesis Imaging Summer School| May 27, 2026

Learning Objectives

By the end of this talk, participants should be to:

- Define the unit of Jansky [Jy]
- Summarize common emission mechanisms in Radio Astronomy
- Recall the basics of an interferometer (for future lectures)
- Discuss the difference between six types of temperature typically encountered in Radio Astronomy

Past Synthesis Imaging Students!

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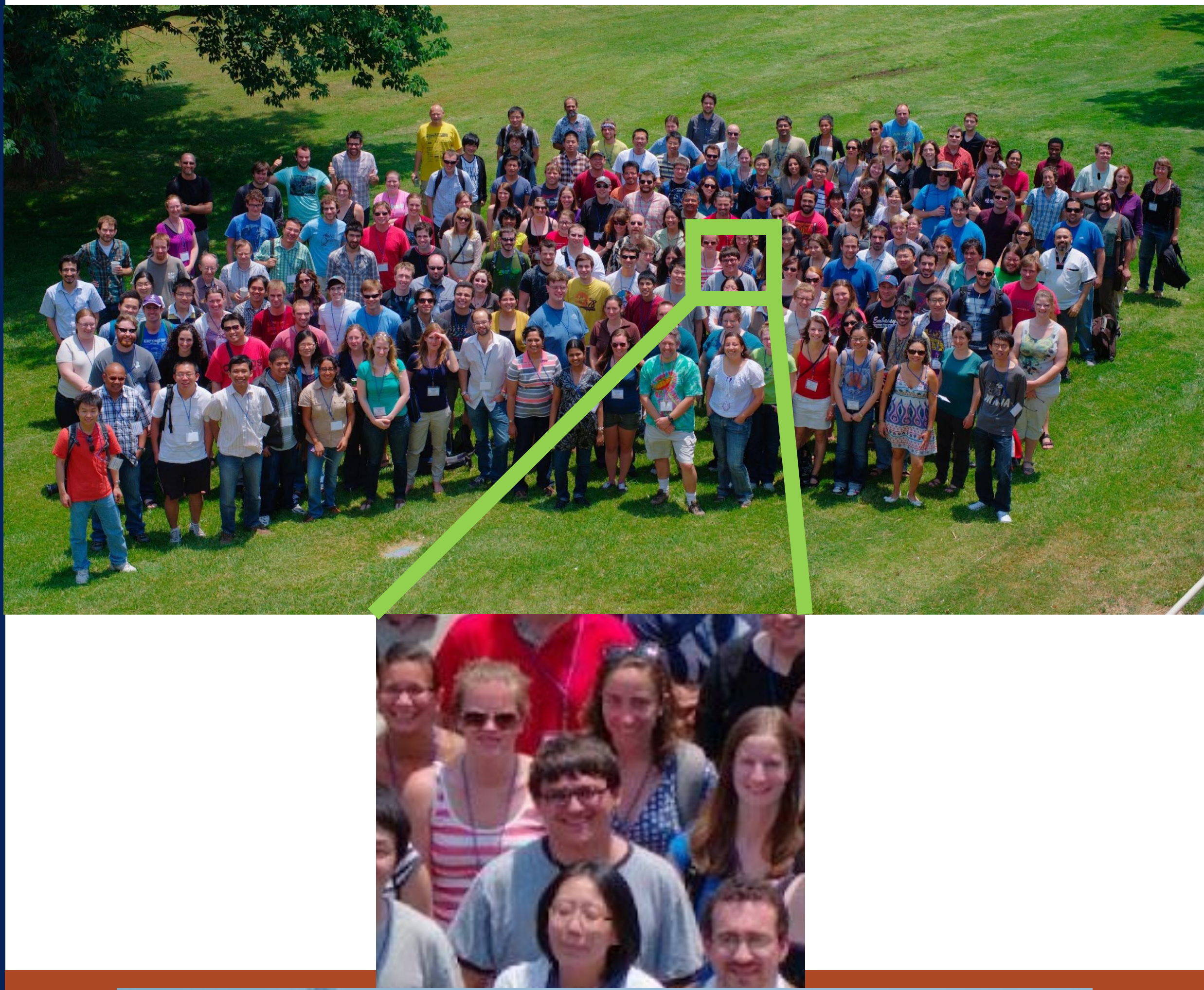
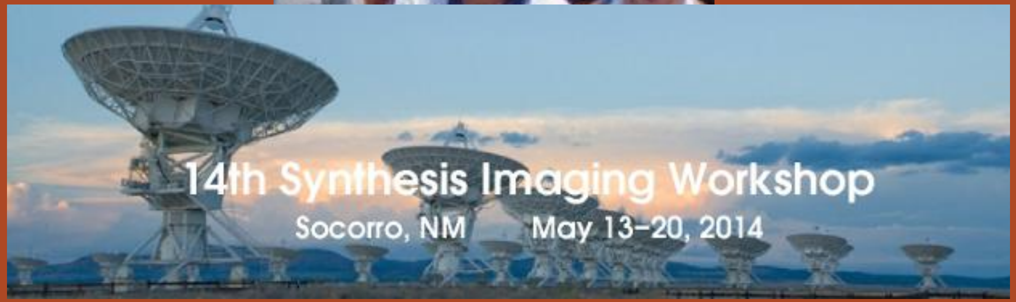


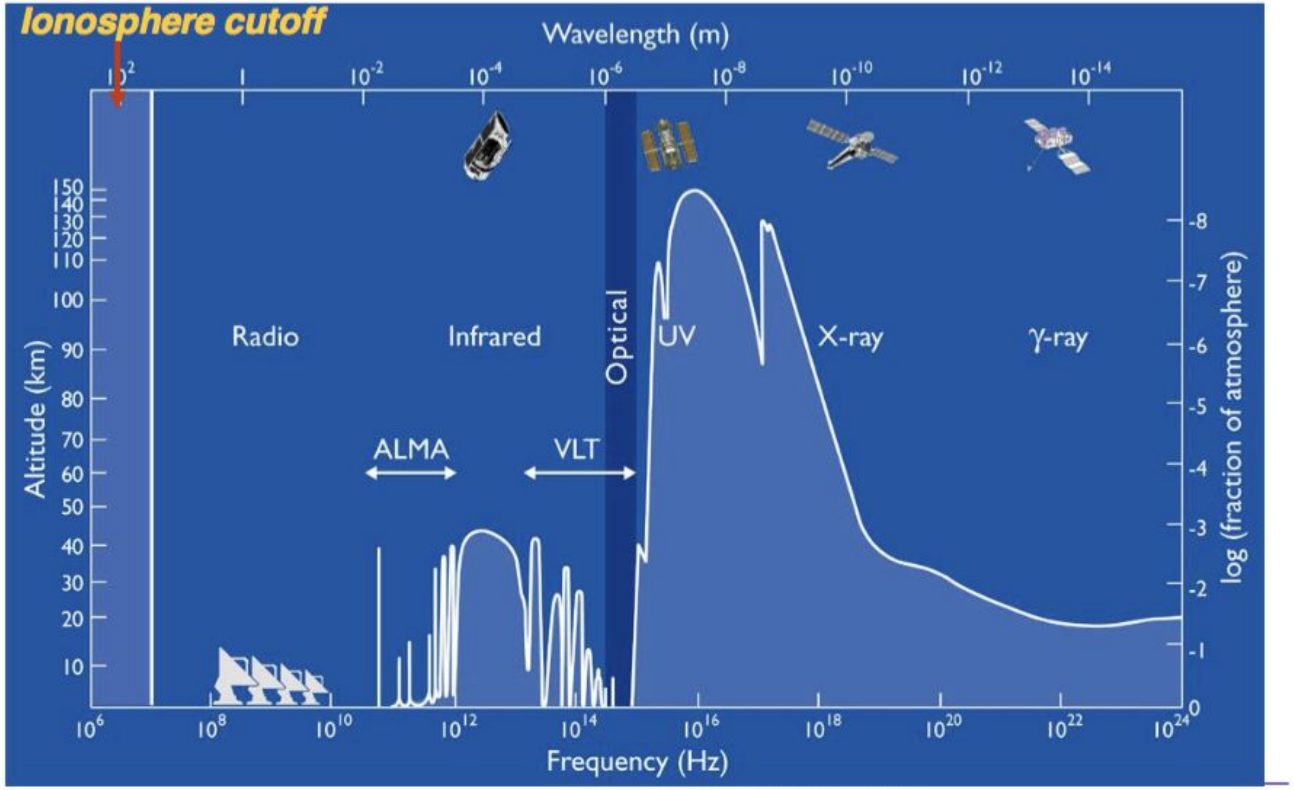


The Radio Window

Other than optical / near IR, radio offers the only opportunity for ground based astronomy.

The atmosphere still matters for some observing

Opacity of the Atmosphere (solid line is altitude at which transmission is reduced by factor of 2)



mm and sub-mm range

NRAO Synthesis Workshop 2014

Units

- Jansky
- $1\text{Jy} = 10^{-26}\ \text{W m}^{-2}\ \text{Hz}^{-1}$
- $1\text{Jy} = 10^{-23}\text{erg s}^{-1}\text{cm}^{-2}\text{Hz}^{-1}$

- Common unit of Radio Astronomy
- Fundamental unit of flux density
- Specific Intensity vs. Flux density vs. Flux

- <u>Tricky Units Note!</u>

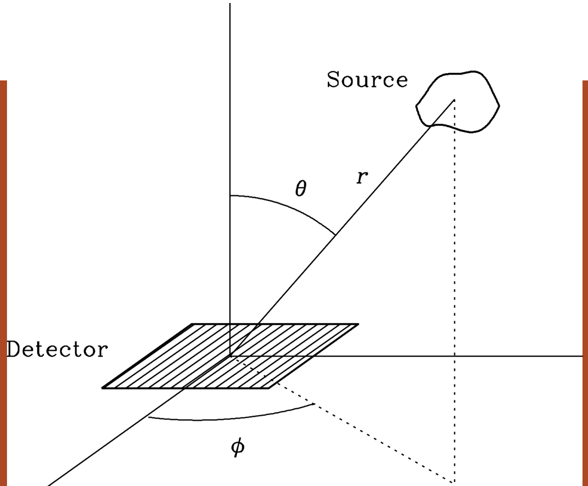
Specific intensity =

$$I_\nu = \left[\frac{\text{Jy}}{\text{beam}}\right] \text{or} \left[\frac{\text{Jy}}{\text{sr}}\right]$$

Flux density =

$$S_\nu = \int I_\nu d\Omega = [Jy]$$

- Flux = $S = \int S_\nu d\nu = \left[\frac{W}{m^2}\right]$



Emission Mechanisms

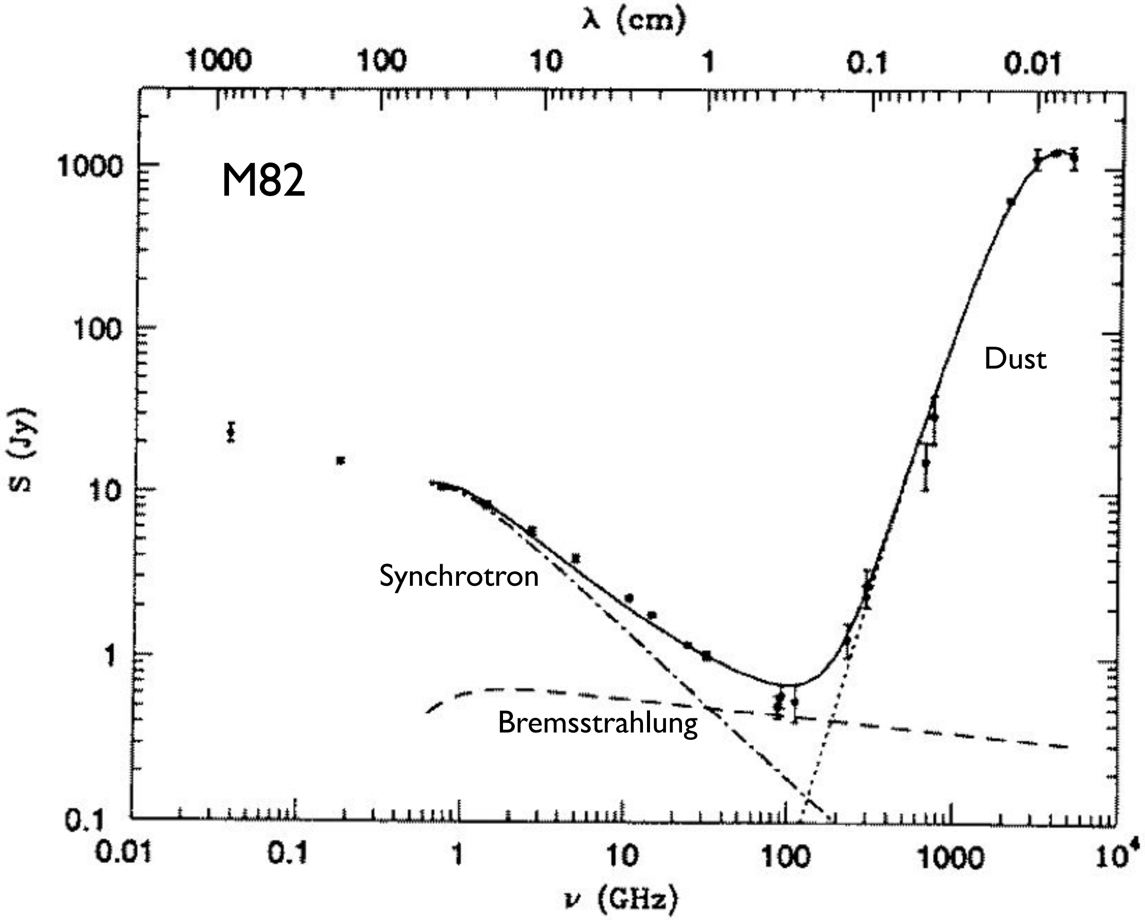
Bremsstrahlung

Thermal Dust

Synchrotron

Spectral Lines

Emission at Radio Wavelengths



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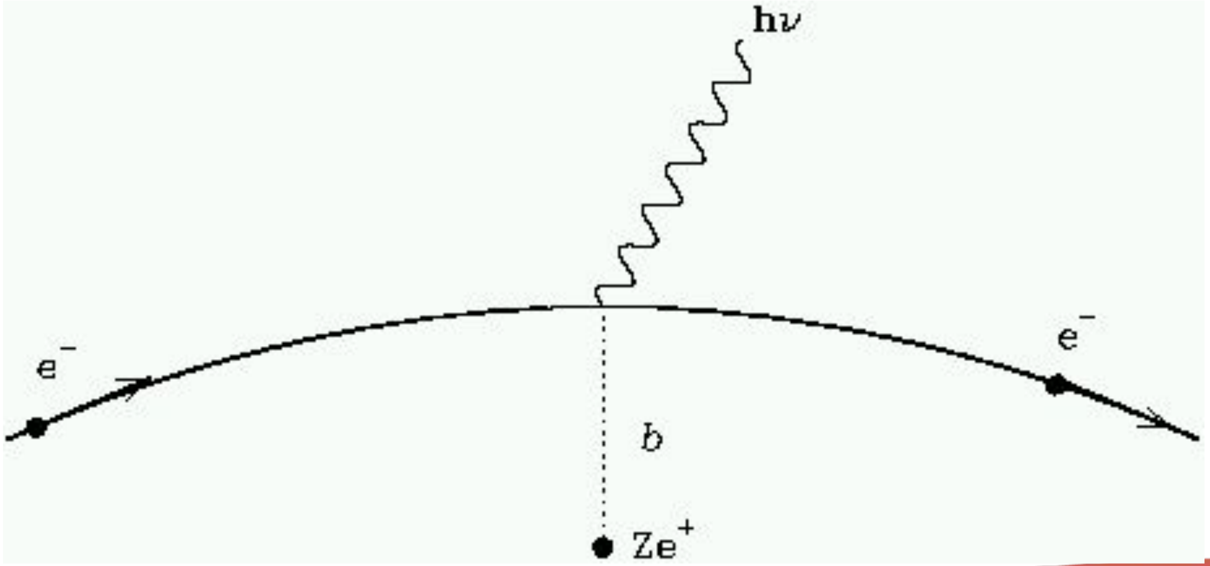
Emission at Radio Wavelengths

- Free-free emission (both particles are free)
- Braking emission
  - acceleration of the electron
- Thermal emission from ionized gas (e.g., HII regions)
- Optically thin
- Good for estimating density and temperature of ionized gas



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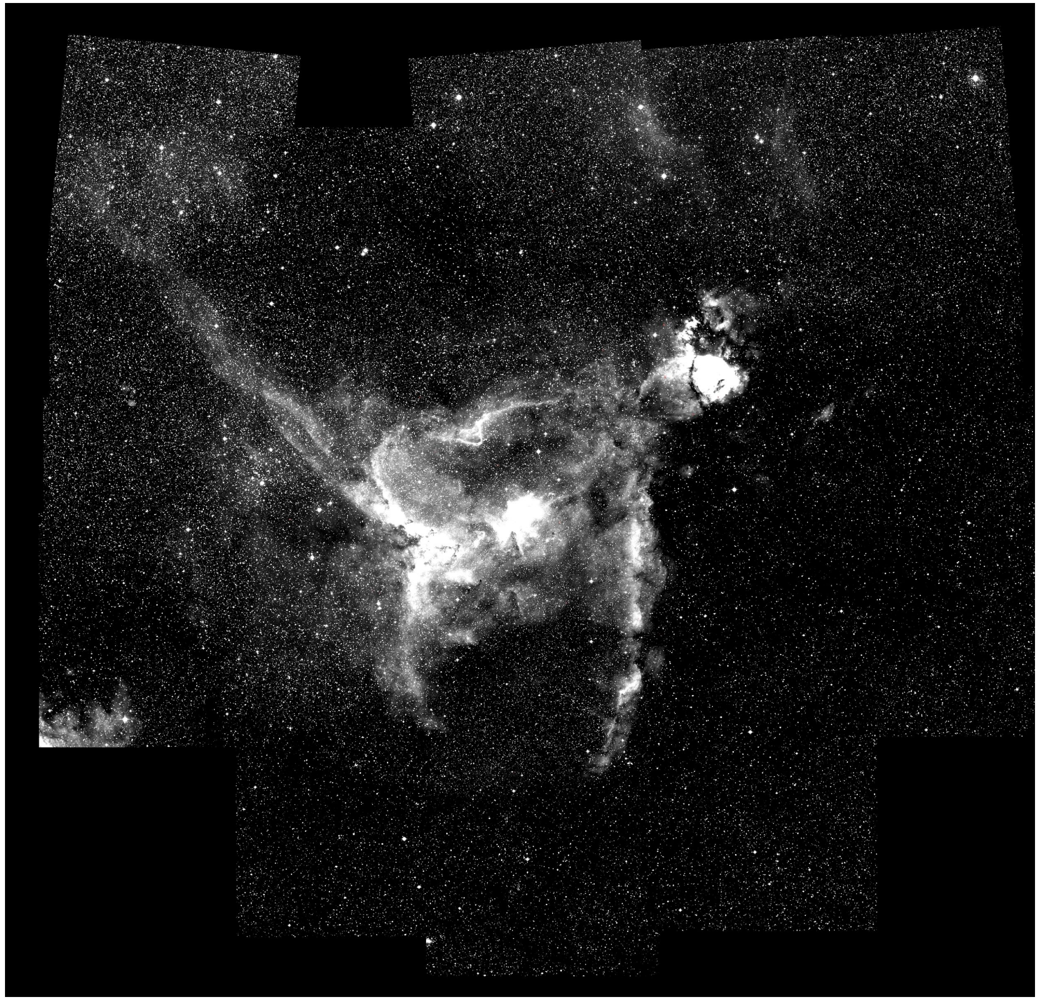

Canadian Galactic Plane Survey image of the Heart Nebula at 1.42 GHz

National Radio Astronomy Observatory

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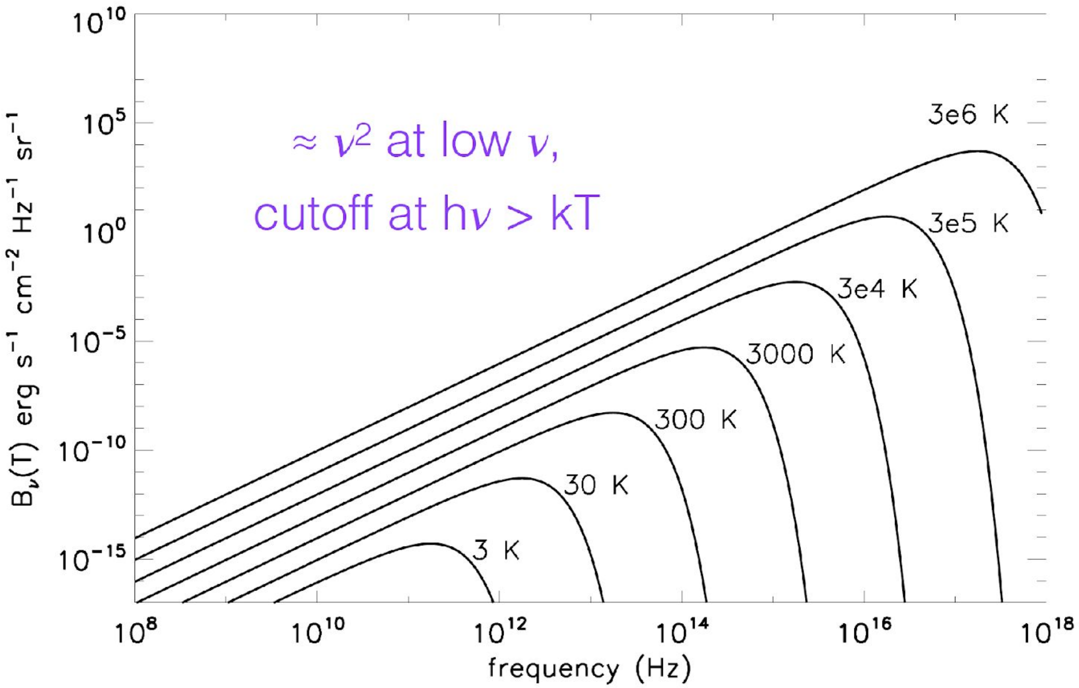
Emission at Radio Wavelengths

- Thermal radiation
  - Follows a blackbody spectrum
  - In the Rayleigh-Jeans Limit in Radio

$$B(\nu, T) = B_\nu(T) = \frac{2h\nu^3}{c^2} \frac{1}{e^{h\nu/k_B T} - 1}$$



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Emission Mechanisms

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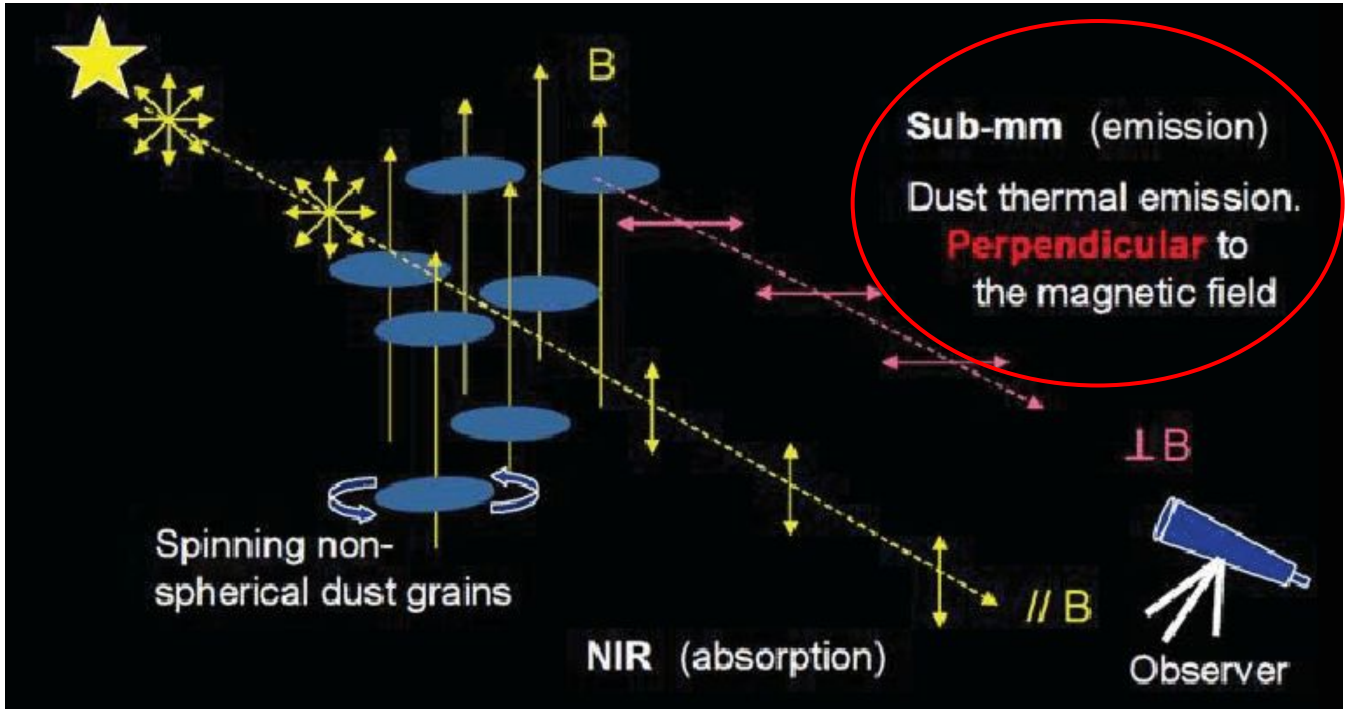
Spectral Lines

Emission at Radio Wavelengths

- Thermal radiation
  - Follows a blackbody spectrum
  - In the Rayleigh-Jeans Limit in Radio
  - Dust Polarization due to grain alignment



Emission at Radio Wavelengths

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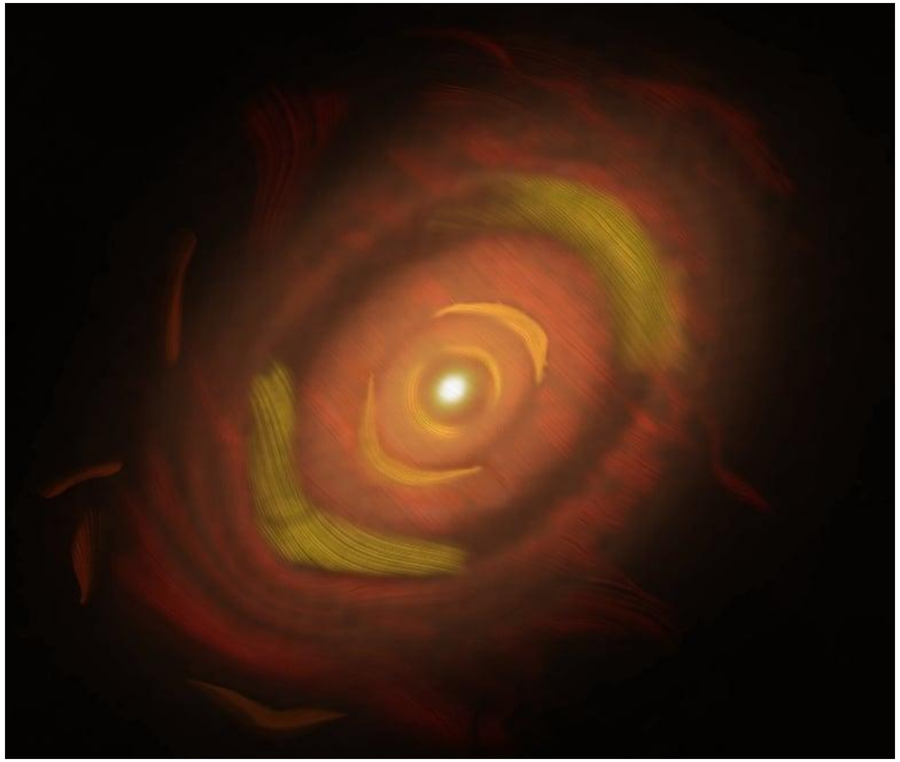
- Thermal radiation



The protoplanetary disk around the young star, HL Tauri, as photographed by ALMA. The gaps in the disk indicate the presence of new planets. Once enough heavy elements are present, some of these planets can be rocky. This system is already hundreds of millions of years old, and the planets there are likely nearing their final stages and orbits. ALMA (ESO/NAOJ/NRAO)

Emission Mechanisms

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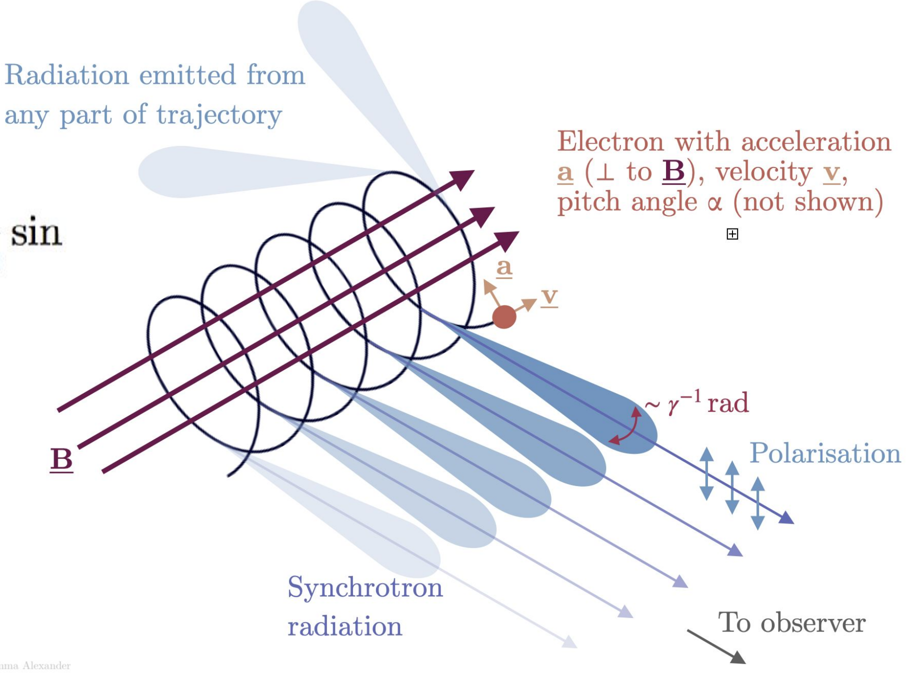
Spectral Lines

- Relativistic electrons spiraling around a magnetic field
- Polarized Emission / Relativistic Beaming
- Non-thermal emission
- Sources: Active Galactic Nuclei, Pulsars, Supernova Remnants

$$\nu_c = \frac{3}{4\pi}\gamma^2 \frac{eB}{mc} \sin$$



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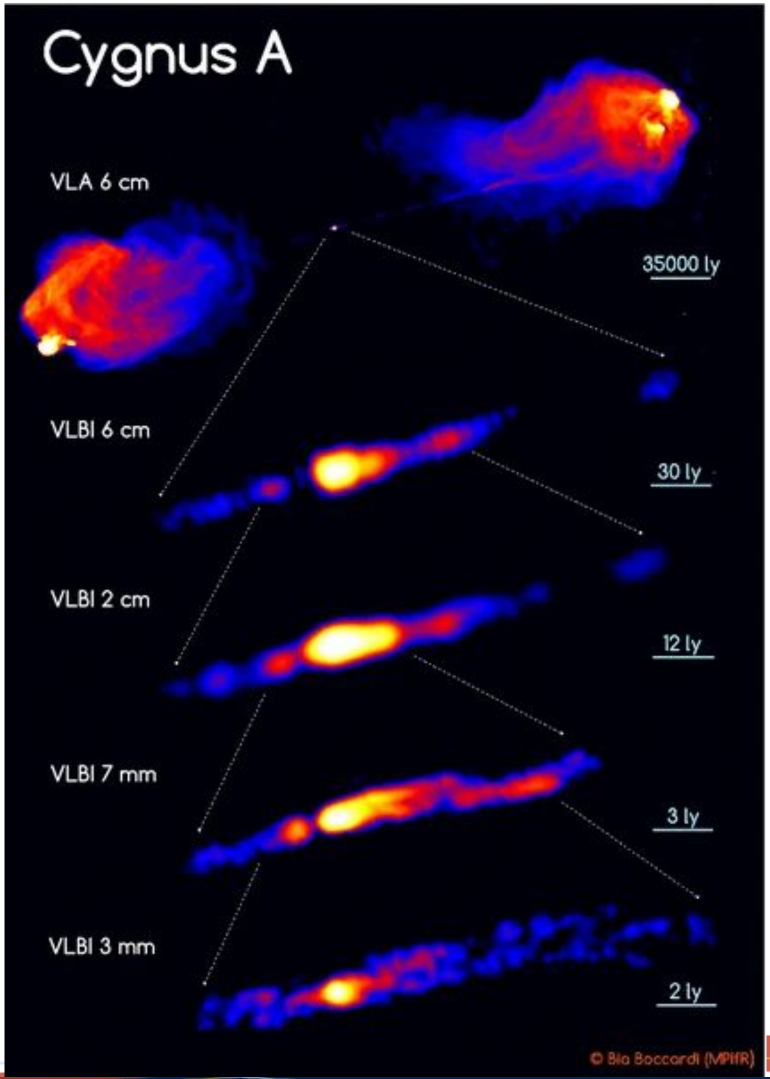
Emission at Radio Wavelengths

The radio galaxy Cygnus A on scales from hundreds of kilo-parsecs imaged with the Very Large Array (Perley et al. 1984) to the sub-parsec probed with mm-VLBI (Boccardi et al. 2016a, b). The VLBI images are created after stacking several epochs. Data at 2 cm are from the MOJAVE survey (Lister et al. 2009)



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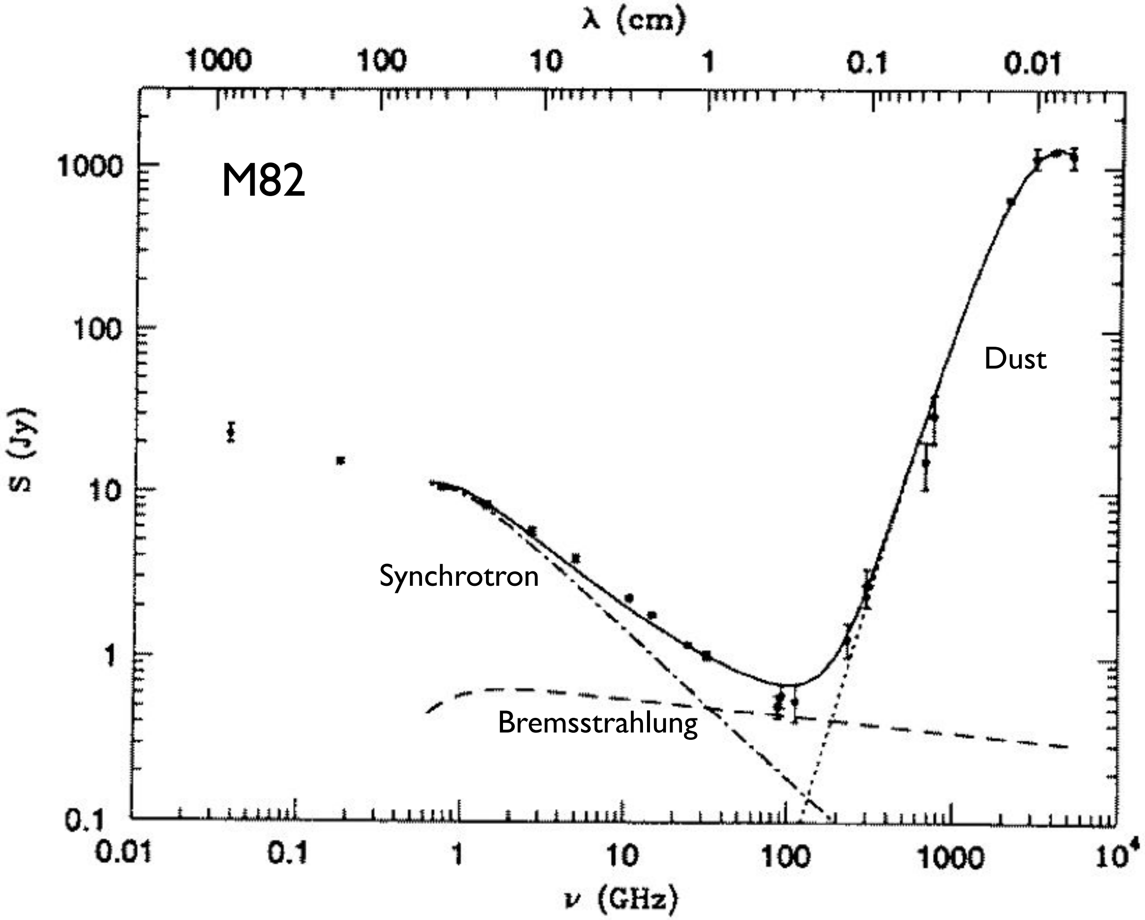
Identifying Emission at Radio Wavelengths



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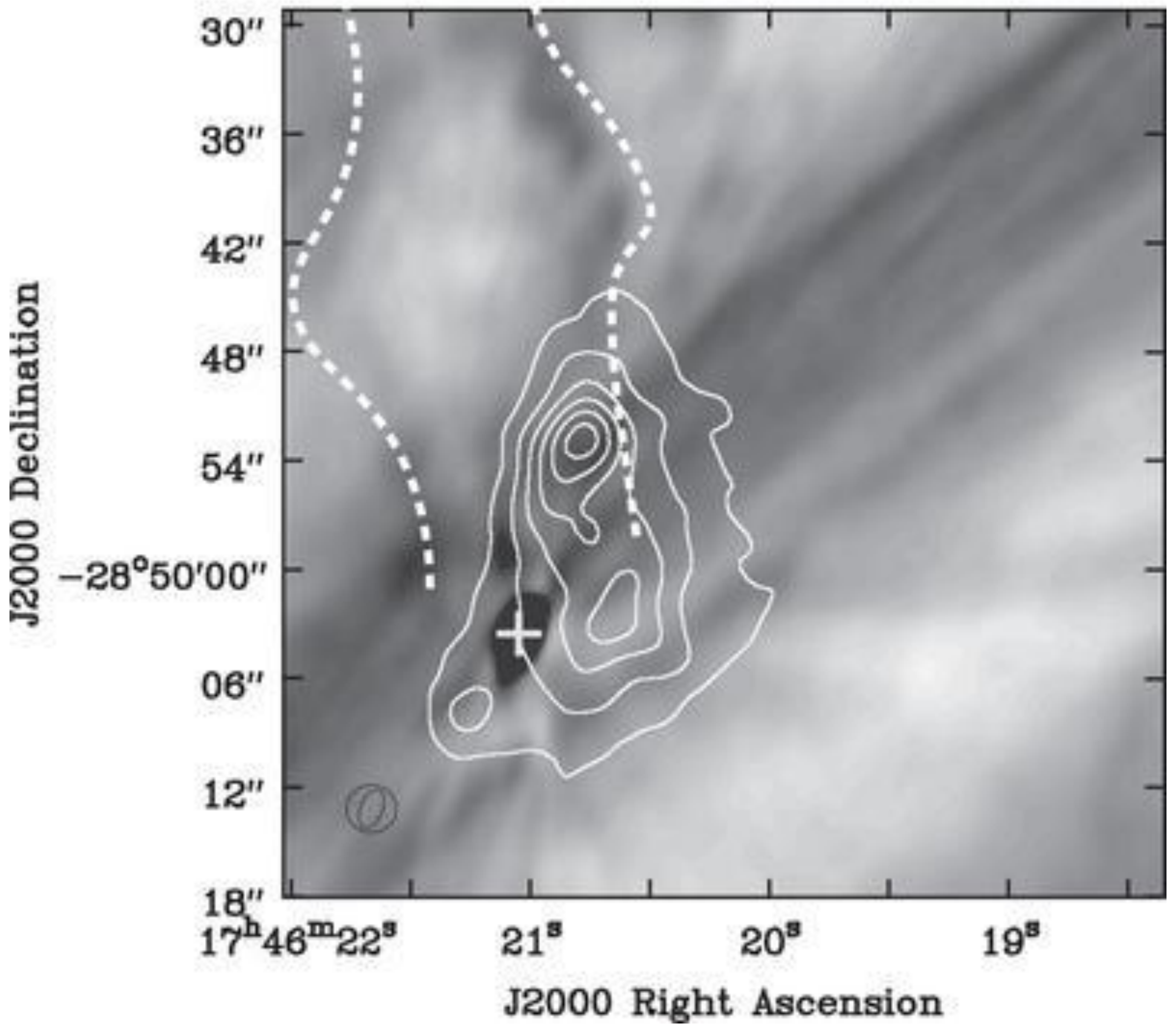

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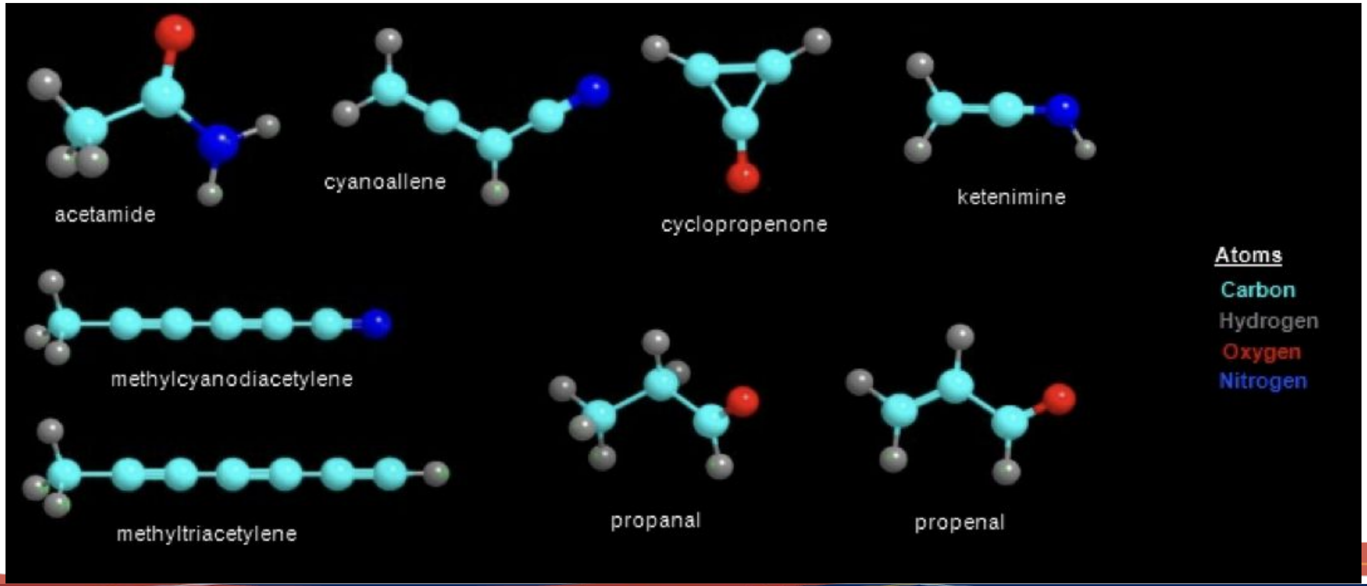
Emission at Radio Wavelengths

- **Molecular Gas**
- 2+ atom molecules (CO, HCN, NH3, etc)
- Rotational states in radio
- Molecules can form on the surfaces of dust grains or in the gas phase

https://splatalogue.online/



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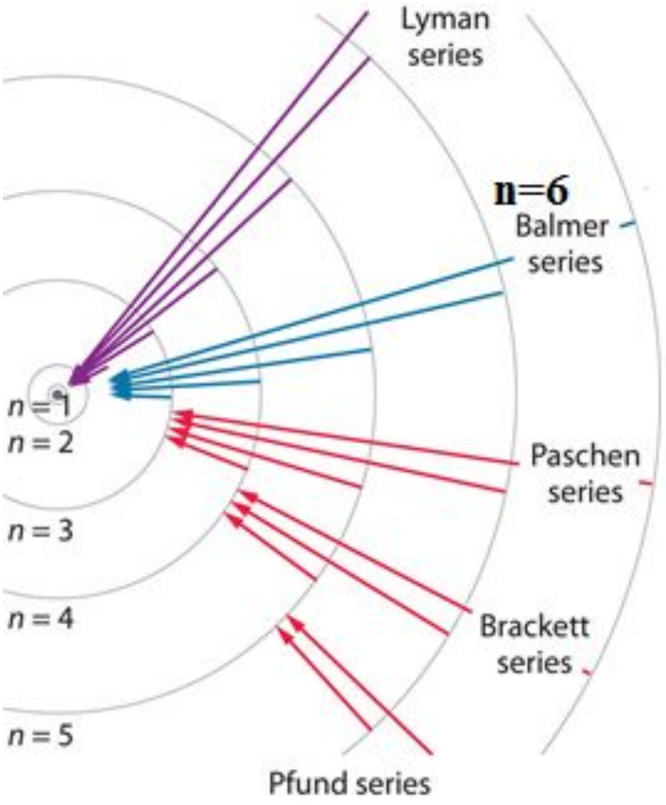
Spectral Lines

Ionized Gas

- Radio recombination lines
  - Like Balmer and Lyman series
  - Higher 'n' transitions (~20+)
- Cascade of the electron down to the ground state
- Can use multiple transitions together to boost SNR
  - E.g., H64a+H63a



Emission Mechanisms

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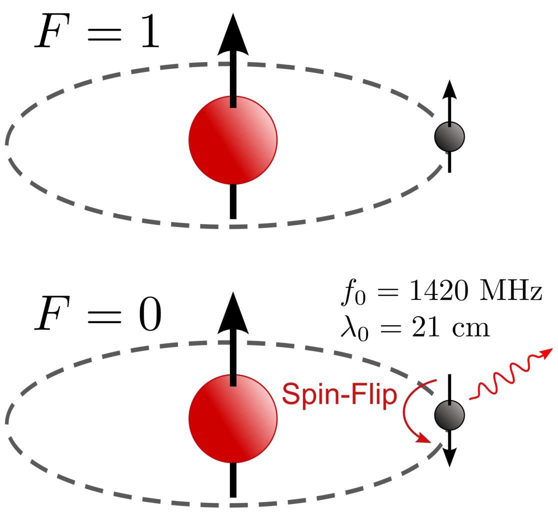
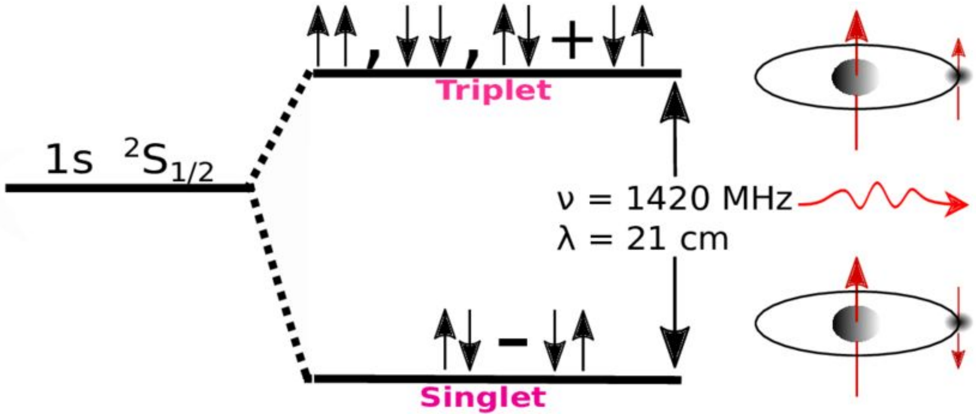
Spectral Lines

Neutral Hydrogen (HI)

- 21 cm spin flip of the electron
- Rest frequency is 1420 MHz
  - L band; observable with the VLA and GBT
- Detected in both emission and absorption
- Commonly observed in galactic and extragalactic studies





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Temperatures

Physical Temperature $(\boldsymbol{T})$

Excitation Temperature (T_E)

Brightness Temperature (T_B)

An object's physical temperature causes it to emit Black Body Radiation according to Plank's Law

$$B_\nu(T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/k_BT} - 1}$$

Often times in the Radio, we can use the Rayleigh-Jeans approximation, the low frequency limit of Plank's Law.

$$B_\nu(T) = \frac{2\nu^2 k_B T}{c^2}$$

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Temperatures

Physical Temperature (T)

Excitation Temperature (T_E)

Brightness Temperature (T_B)

Excitation temperature describes the relative populations of two energy levels in a collection of atoms/molecules/ions

$$\frac{n_2}{n_1} = \left(\frac{g_2}{g_1}\right) e^{-h\nu_0/KT_{ex}}$$

T_{ex} may or may not be equal to T depending on if the gas is in local thermodynamic equilibrium.

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Physical Temperature (T)

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Brightness Temperature $(\boldsymbol{T_B})$

$$B_\nu(T) \simeq \frac{2\nu^2}{c^2} k_B T$$

When $h\nu \ll k_B T$ (Rayleigh Jean's Approximation)

We define T_B as a scaled version of the specific intensity (Jy/beam)

$$I_\nu = 2\frac{\nu^2}{c^2} k_B T_B$$

In thermal regime for low optical depth, $T_B < T$
For non-thermal, there is no connection to T.

Types of Radio Telescopes

Single Dish

Interferometers

- Single Dish telescopes consist of a single antenna
- Examples: GBT, ALMA (Total Power), Parks, APEX
- Beam size dependent on dish size.
- $\theta \approx 1.2 \frac{\lambda}{D}$

GBO Single Dish School Also Offered

Types of Radio Telescopes

Single Dish

Interferometers

- Multiple Antennas work together to increase resolution of the telescope
- VLA, ALMA, NOEMA, ATCA, VLBA

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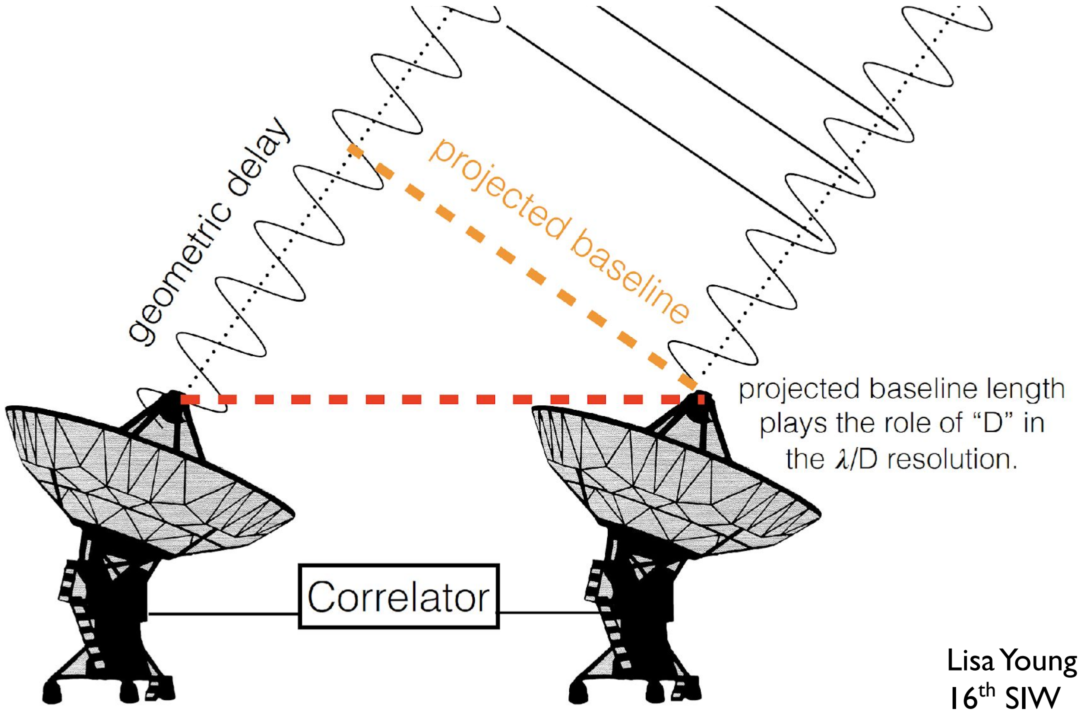

Lisa Young
16th SIW

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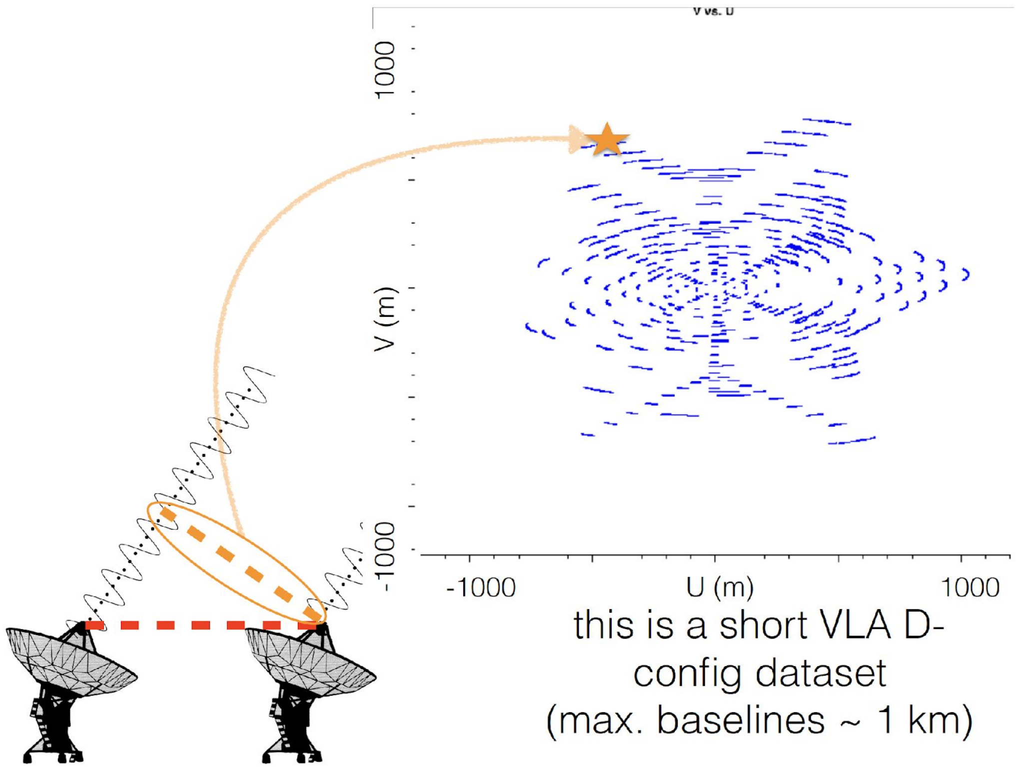

this is a short VLA D-config dataset (max. baselines ~ 1 km)

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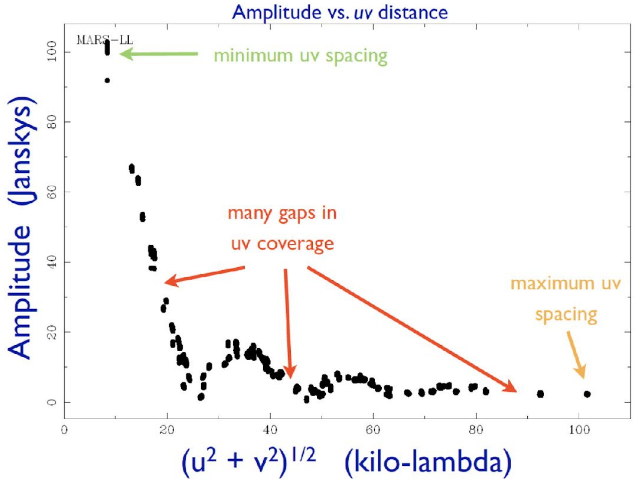

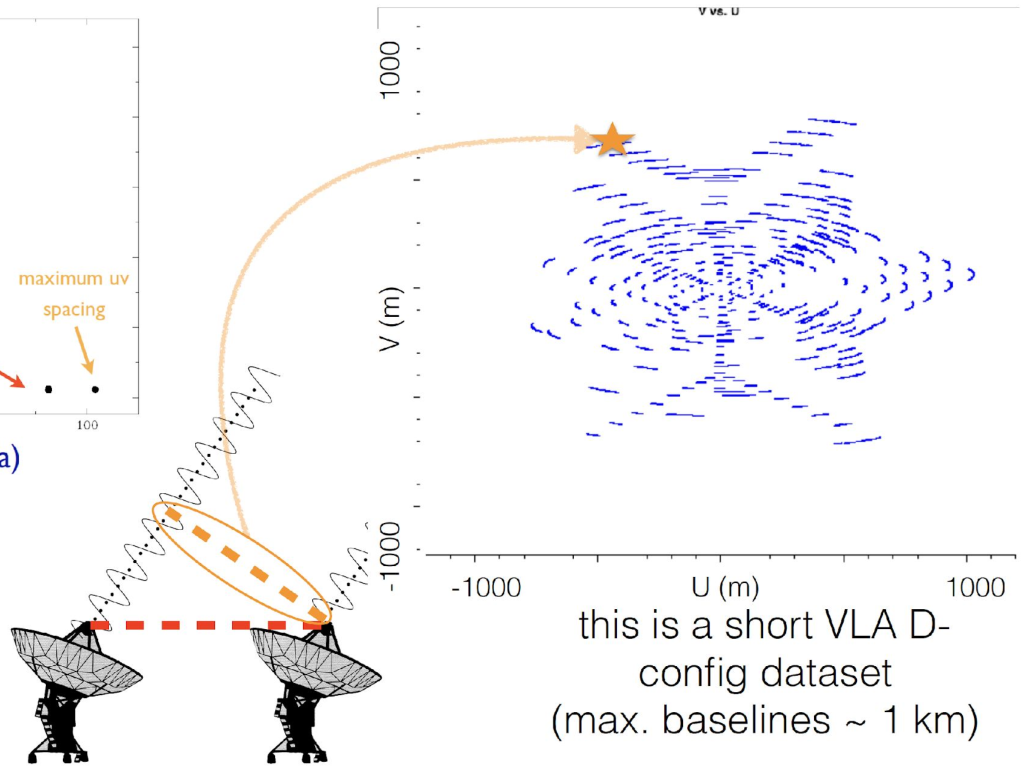

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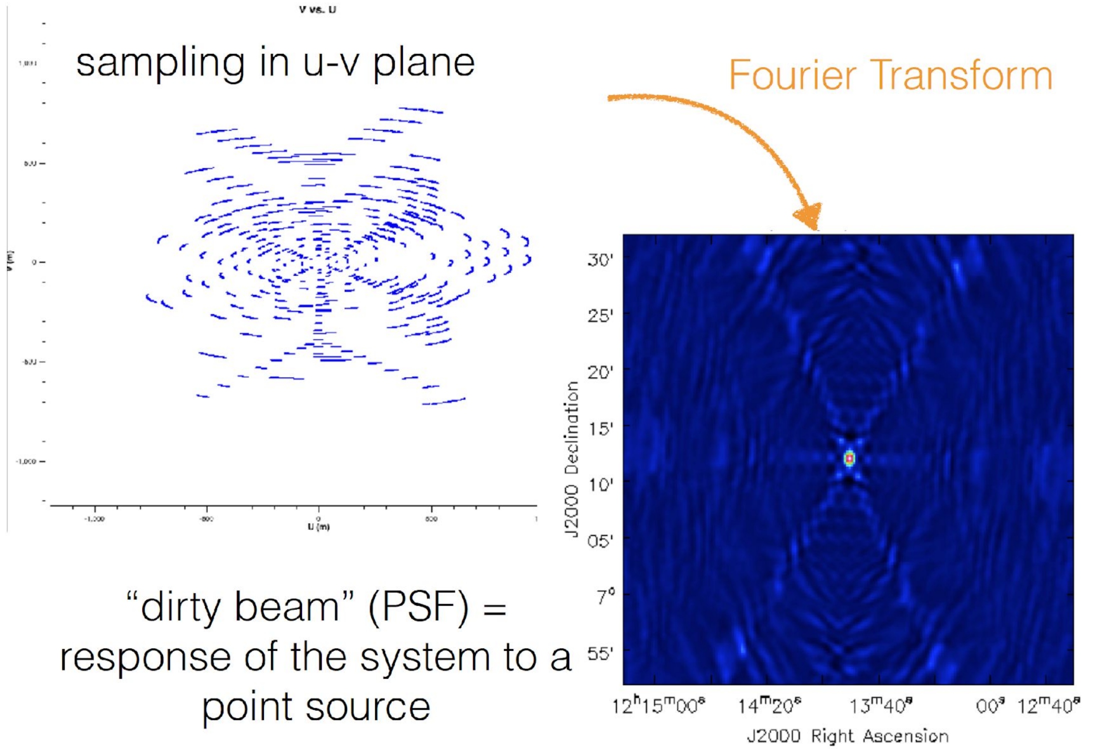

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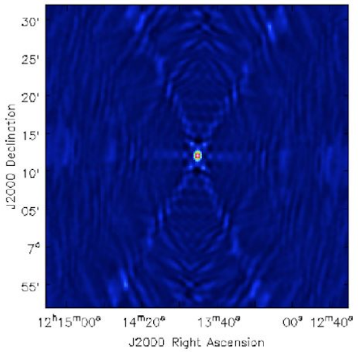
Types of Radio Telescopes

Single Dish

Interferometers



recall this is what point sources look like

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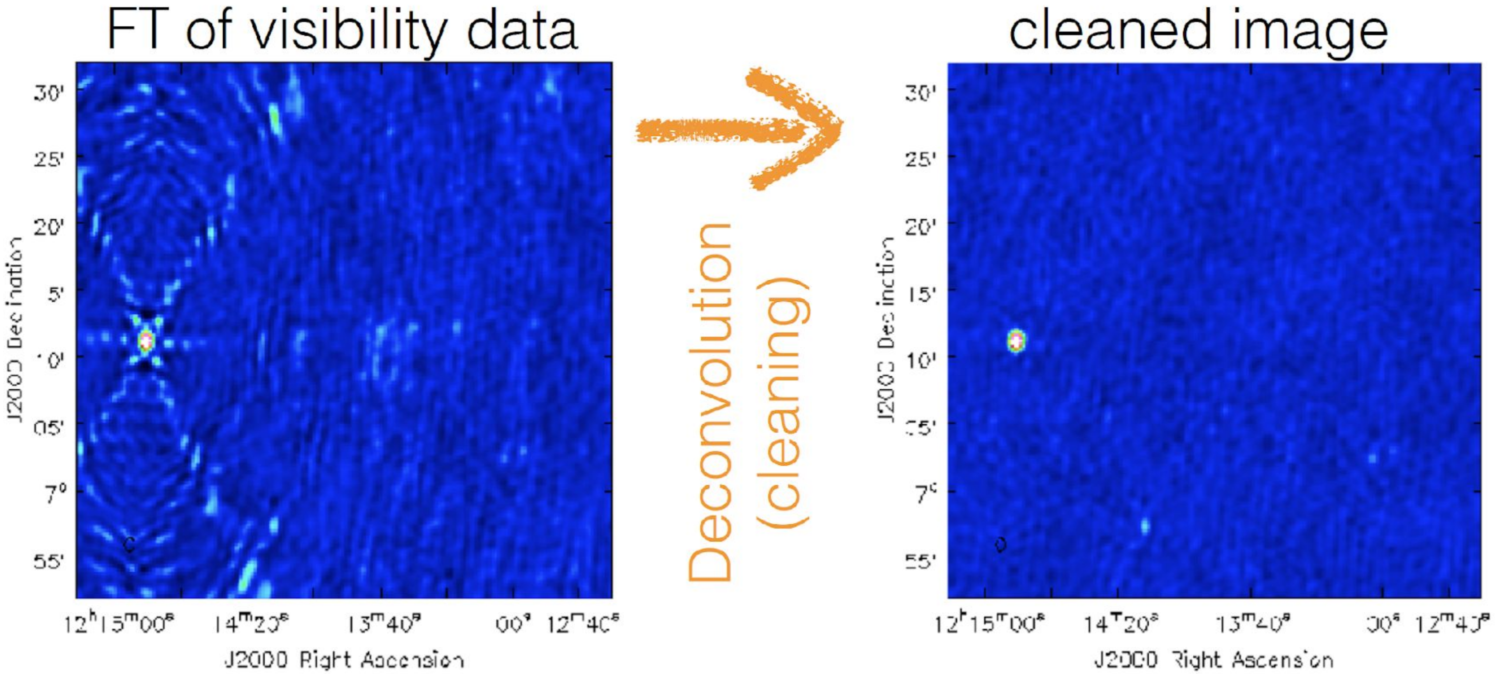

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Don’t worry, you will be going into a lot more depth on these topics throughout the rest of the workshop!

More Temperatures

- In addition to the temperatures that are related to the source, there are also instrumental temperatures.

VLBA Antenna

Temperatures

Physical Temperature (T)

Excitation Temperature (T_E)

Brightness Temperature (T_B)

Antenna Temperature $(\boldsymbol{T_A})$

Receiver Temperature (T_R)

System Temperature (T_{sys})

T_A is the power delivered by an equivalent thermal resistor at the input of the receiver. This is how single dish telescopes often report their sensitivities.

So T_A is a measure of how bright your source is & how it couples to your telescope beam. $T_A < T_B$ because of the telescope efficiency

Antenna Temperature can be converted to a point source flux density using

$$T_A = \frac{A_e S_\nu}{2k_B} = \frac{\Omega_S}{\Omega_A} T_B$$

Where Ω_s is the solid angle of the source and Ω_A is the beam solid angle

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Even without any signal, a receiver will generate noise which can again be modeled as a resistor of temperature T_R which is connected to a noiseless receiver. To make T_R as low as possible, receivers are often cryogenically cooled.

However, radiometers are not just matched resistors, so Tr may be either lower or higher than the physical temperature of the radiometer itself.

Temperatures

Physical Temperature (T)

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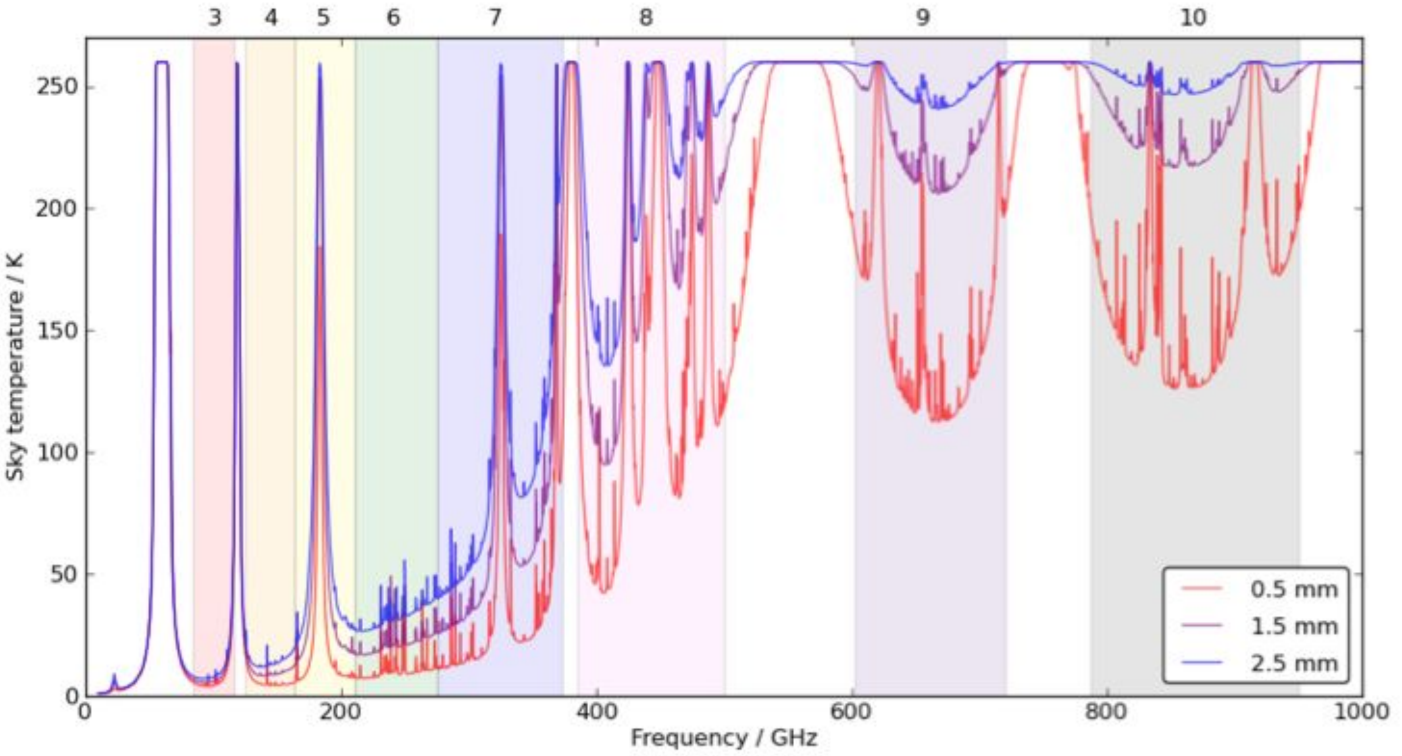
Antenna Temperature (T_A)

Receiver Temperature (T_R)

System Temperature (T_{sys})

T_{sys} quantifies the noise that will be contributed to your measurement by emission from the receiver, dish, atmosphere, etc.

At high frequencies T_{sys} is strongly weather-dependent



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System Temperature (T_{sys})

System temperature is particularly important because:

$$\Delta T_{rms} = \frac{T_{sys}}{\sqrt{\Delta \nu \ \tau}}$$

The rms of your measurement scales with T_{sys}. Increasing the bandwidth ($\Delta\nu$) and integration time (τ) helps lower the rms.

Practical Telescope Considerations

- Dynamic Range:
  - Is your faint feature next to a bright feature?
- Tuning:
  - Can you get all those spectral lines in one tuning?
- FOV:
  - FOV depends on frequency.
  - Sensitivity changes over the FOV.

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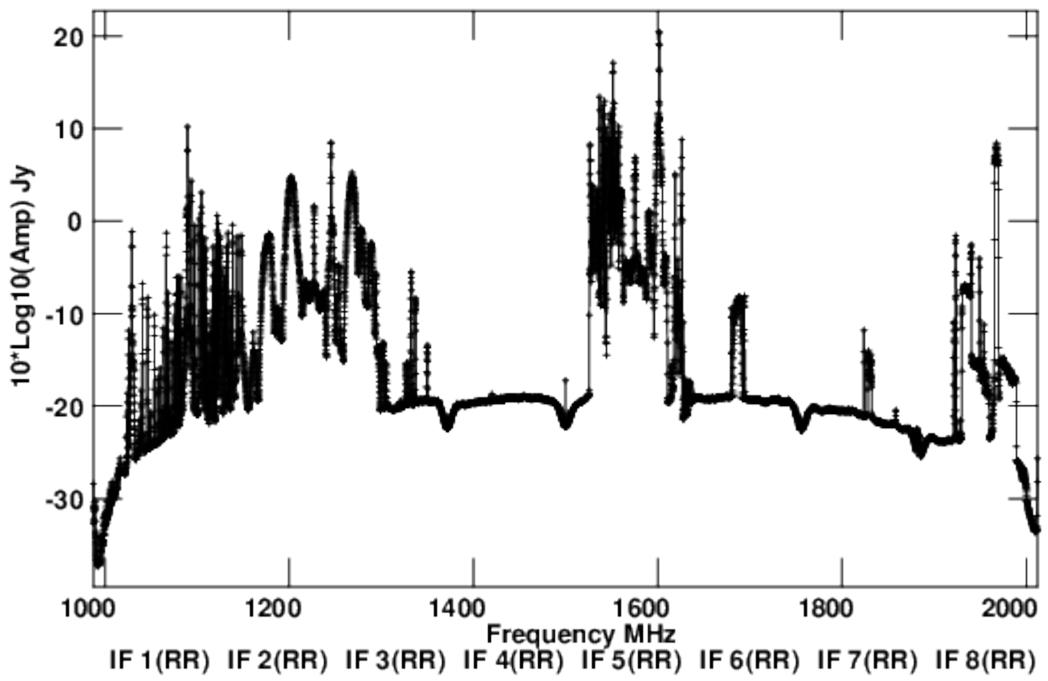
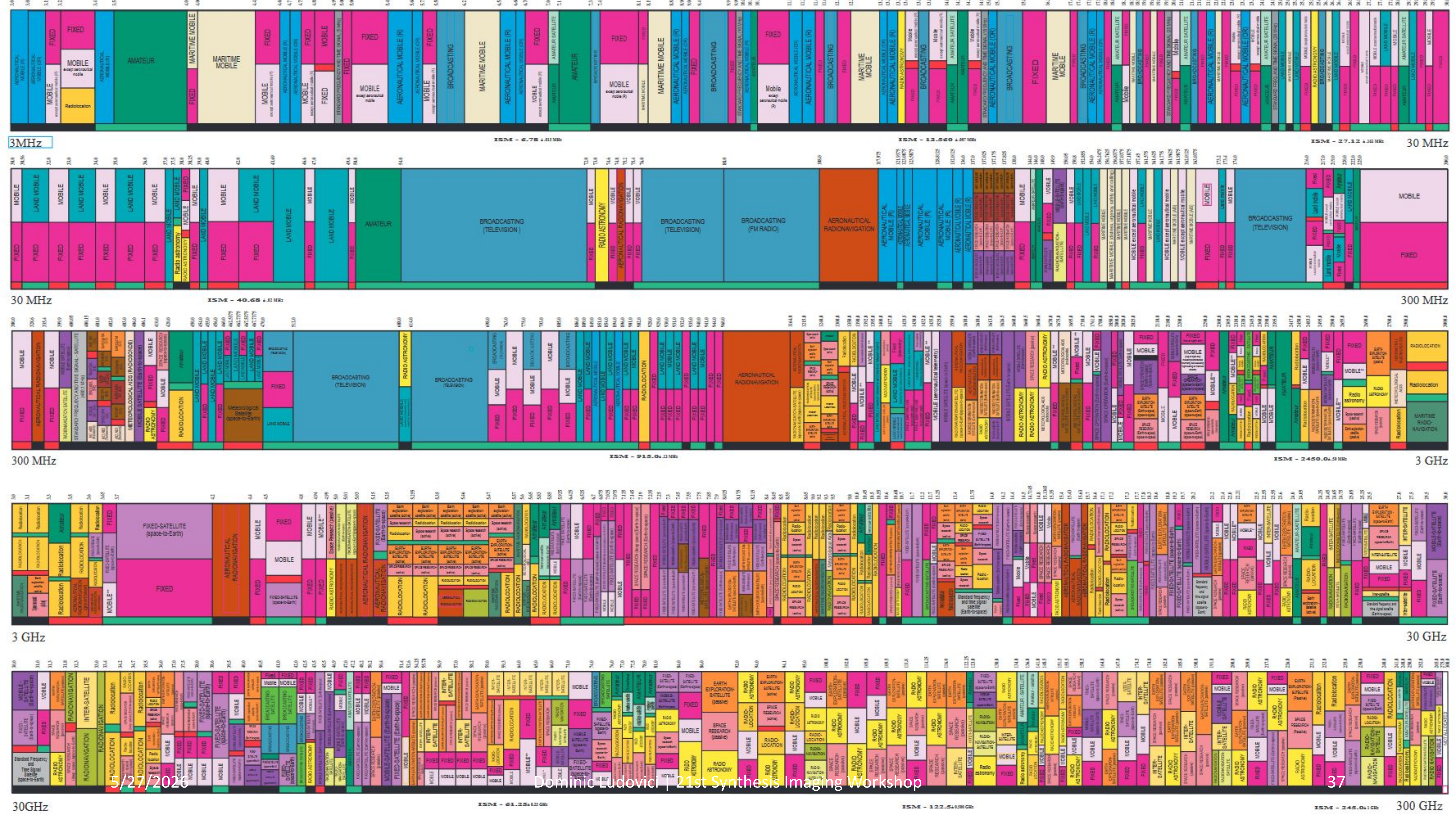
Radio Frequency Interference

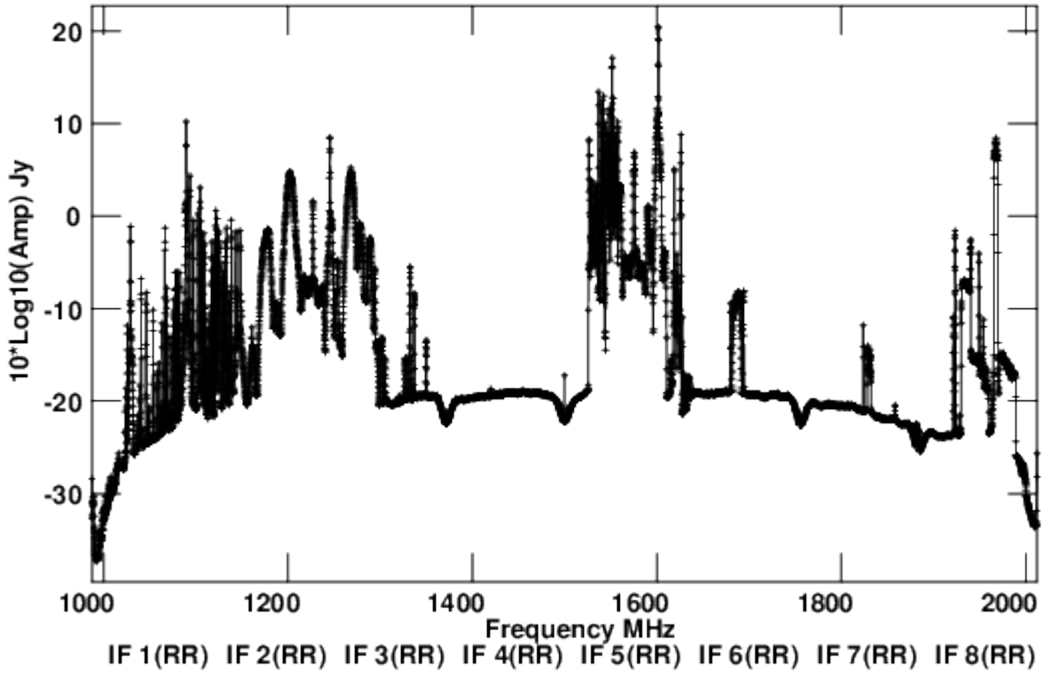
- Interference in radio astronomy observations due to terrestrial sources (e.g., short-wave radio, telecommunications, radar, thunderstorms, et. cetera)
- We have to share the spectrum.

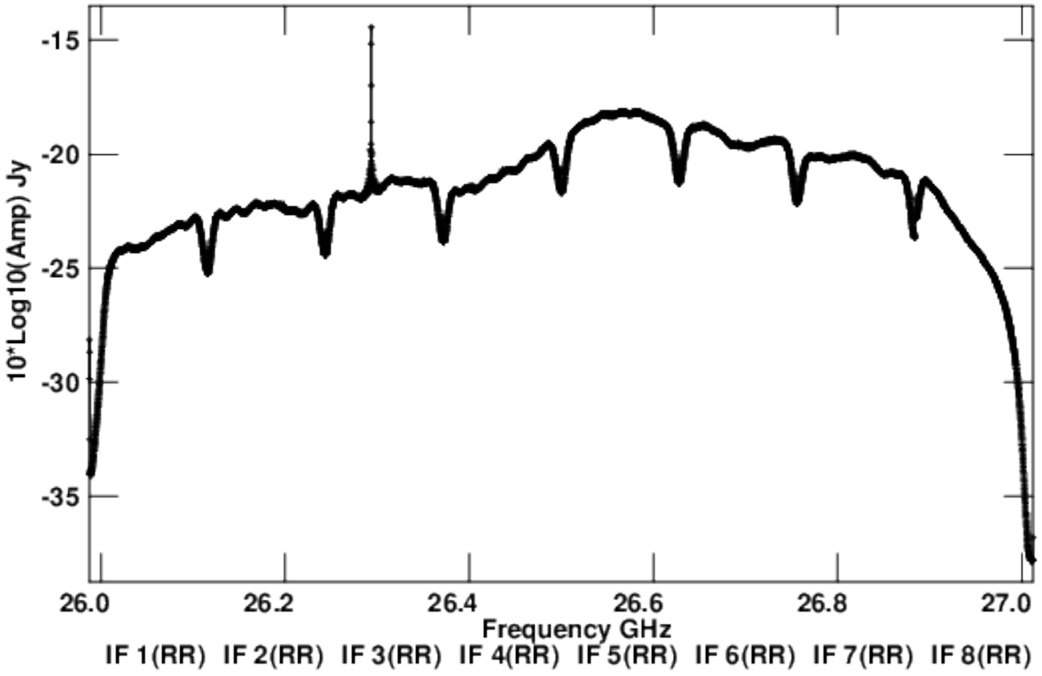


November 2023 RFI sweep at the VLA
L Band (1-2 GHz)


3MHz
30 MHz
ISM – 6.78
ISM – 13.560
ISM – 27.12
30 MHz
300 MHz
ISM – 40.68
300 MHz
3 GHz
ISM – 915.0
ISM – 2450.0
3 GHz
30 GHz
30GHz
300 GHz
ISM – 61.25
ISM – 122.5
ISM – 245.0
AMATEUR
MARITIME MOBILE
BROADCASTING
FIXED
BROADCASTING (TELEVISION)
BROADCASTING (FM RADIO)
AERONAUTICAL RADIONAVIGATION
FIXED-SATELLITE (space-to-Earth)
RADIO ASTRONOMY

L Band compared to Ka band.





Additional Resources

Helpful books:

- Radiative Processes in Astrophysics
  - Rybicki & Lightman
- Essential Radio Astronomy
  - Condon & Ransom

Online version of the Essential Radio Astronomy textbook can be found here:

https://science.nrao.edu/opportunities/courses/era/

SIW slides and recordings!

- Available online after the workshop