Basics of Radio Astronomy

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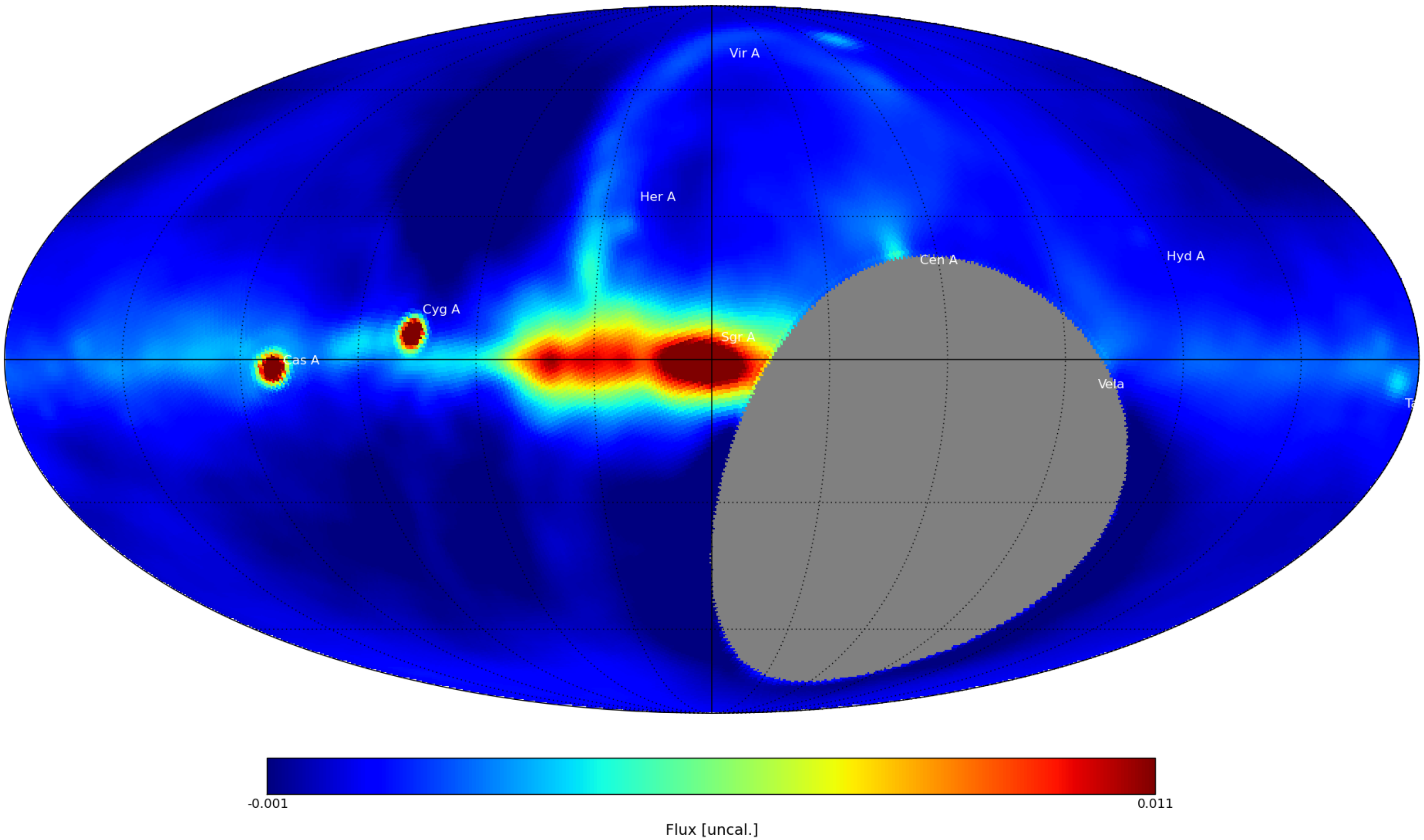
History Outline (a mix of science and technical)

- Lodge, Edison: nothing; Jansky (1932) first measurements
- Post-Jansky: Reber (built own parabolic reflector), Southworth & Hey (active Sun), Bolton (discrete sources), Pawsey (Sun), Ryle (Imaging), Hewish (Pulsars), Penzias & Wilson (CMB), Townes (molecules), NRAO, VLA, VLBA, GBT, ALMA
- Types of sources
- Temperatures; Black Body Radiation
  - Rayleigh-Jeans Limit
- Angular Resolution
- Receivers (***details in T. Hunter's talk***), Earth's Atmosphere
- Radiative Transfer in 1 dimension
- Relation of measurements and physical quantities

LWA all sky at 38 MHz made with the Long Wavelength Array



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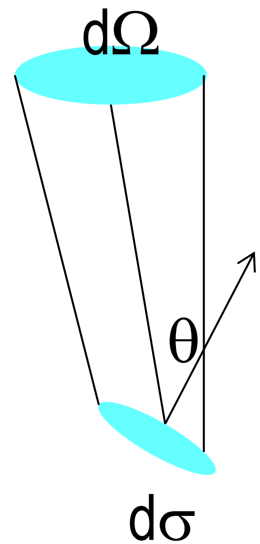
The Boring Basics

- Will consider radiation, then Black Body
- Antennas (***T. Hunter's talk)***
- Calibration, temperature scales (*G. Moellenbrock talk*)
  - A simple example of power from a source
  - Noise
- Angular Resolution
- The earth's atmosphere
- Radiative transfer in 1 dimension
- Spectral Lines



Power flows from $d\Omega$ to $d\sigma$

$$dP = I_\nu \cos\theta \, d\sigma \, d\nu$$

Assume source is small and

θ is small

The units are ***Watts*** $\boldsymbol{m^{-2}}$ ***Hz***$\boldsymbol{^{-1}}$ ***radians***$\boldsymbol{^{-2}}$

Integrating over angles: ***Watts*** $\boldsymbol{m^{-2}}$ ***Hz***$\boldsymbol{^{-1}}$ ***. A "Jansky" is*** $\boldsymbol{10^{-26}}$ ***Watts*** $\boldsymbol{m^{-2}}$ ***Hz***$\boldsymbol{^{-1}}$

Theory: Rayleigh-Jeans assumed that there was an energy kT per mode and derived $2kT/\lambda^{2}$ *for Intensity. Planck got the complete theory.* For a Black Body all incident radiation is absorbed, I_ν becomes $B_\nu(T)$.

$$B_\nu(T) = \frac{2\,h\nu_0^3}{c^3}\frac{1}{\exp\left(\frac{h\nu}{k\,T}\right)-1} = \frac{2k\nu^2}{c^2}T$$

Rayleigh-Jeans Approximation, where "T" is Brightness Temperature

Units are Watts m^{-2} Hz^{-1} radian^{-2}

$$S_\nu = \int B_\nu \, \mathrm{d}\Omega$$

$$S_\nu = 2.65\ T_B\ \theta^2/\lambda^2$$

Jy, arc minutes and cm are the units.

If the telescope system has a noise uncertainty ΔS_ν

There is a limit on T_B or ΔT_B

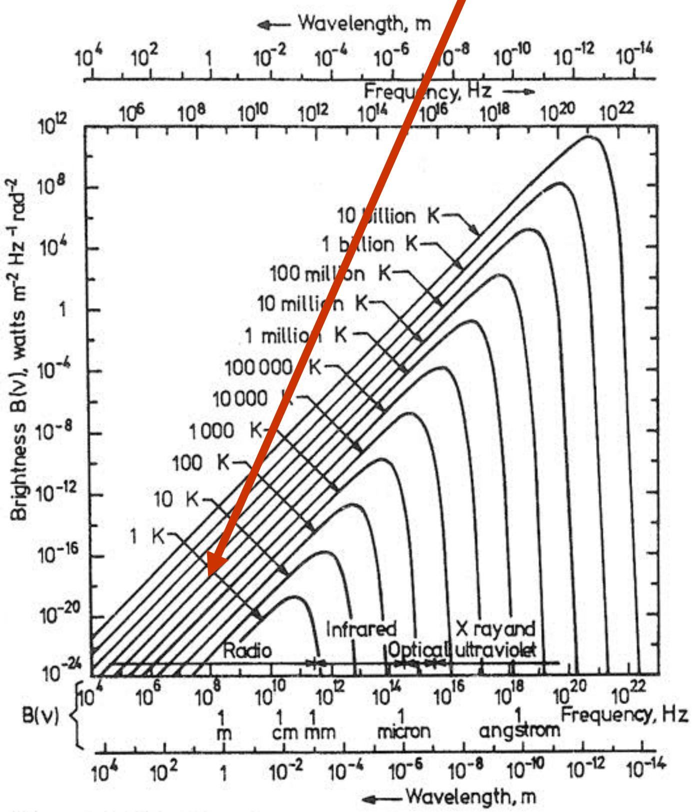


Fig. 1.6. The Planck spectrum for black bodies of different temperatures

Antennas-diffraction theory (*see T. Hunter's talk*)

$$\theta = \frac{\lambda}{D}\,\mathrm{rad} = 200''\,\frac{\lambda}{D}$$ (For FWHP; on right, λ in mm and D in meters)

So for D=100 meters, λ = 3 mm, get θ = 6". This is worse than optical, so radio telescopes need something extra to get higher angular resolution. This is interferometry (*see the **R. Perley and following** lectures*). For a filled aperture, if the power, P_ν, from a source with Flux Density S_ν , contained in the antenna beam:

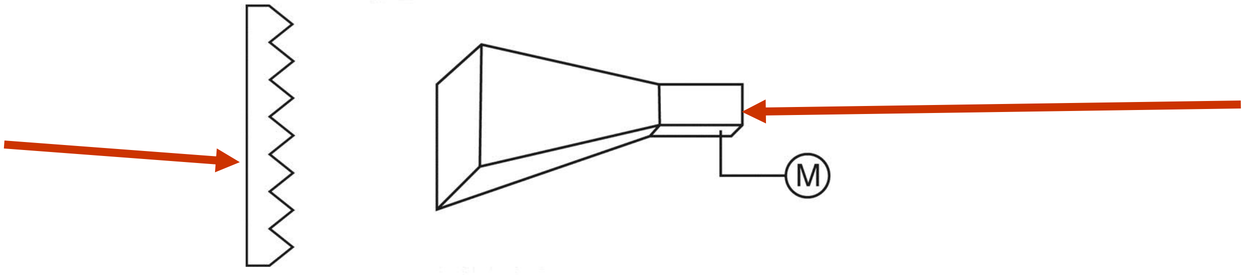
$$P_\nu = \frac{1}{2}\,S_\nu\,A_e\,\Delta\nu$$

Where the effective area of the dish, A_e , is related to the geometric, A_g , by the ***antenna efficiency***, η_A . The value of η_A is usually of order 0.5 to 0.7

For filled apertures, θ and A_e are related. This is ***not*** so for interferometers. Also the value of "D" can be more than 10,000 km (but noise may be a limit).

Performance of Receivers is Determined by Hot-cold load measurements

absorbers at known temperatures



Input to receiver

Need two temperature inputs for receiver calibration

Often T_L=77 K and T_H=273 K

This allows a determination of T_{rx}

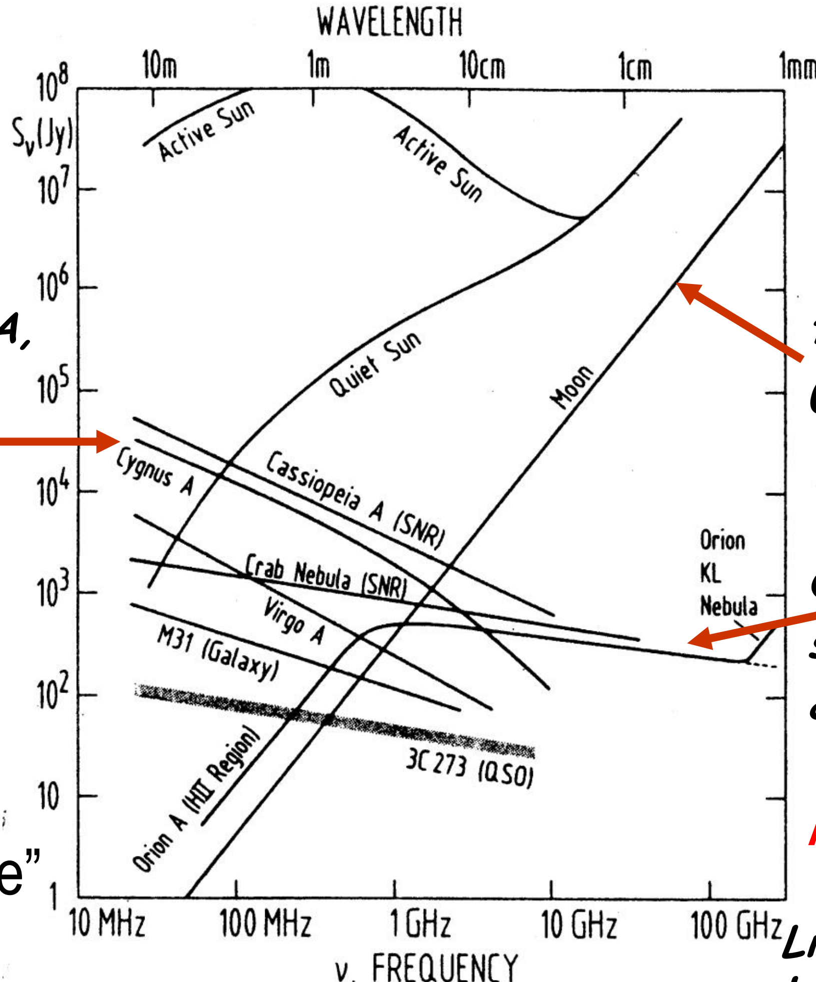
Simplified Receiver

- The output power is a factor of G (the “gain”) larger than the input power.
- There may be a constant offset in the output power
  - P_{out}=G (P_{in} + P_{rx})
  - A possible zero offset can be eliminated
  - Then need 2 measurements to determine “G” and “P_{rx}”
  - **Where Power=kT $\Delta\nu$**
    - These may be frequency dependent
- Heterodyning allows a shift in frequency without affecting phase or amplitude

Continuum Sources

Non-Thermal Sources
Cassiopeia A, Cygnus A,
Crab Nebula

"non-thermal" means "not characterized by a single Temperature"



True Black Bodies:
the Moon (and CMB)
(That is, a unique value of T)

Quasi Thermal: HII Regions
such as Orion A (size 2.5')
& dust emission

Also: Spectral Line Sources
HI, Atomic, Molecular Lines and Recombination Lines

S_ν in Jy is 10^{-26} W m^{-2} Hz^{-1} (intensity integrated over the source)

Measurement Process 1

Measure power, convert to Intensity, I_ν , in Watts m^{-2} Hz^{-1} steradian^{-1} or Temperature with $I_\nu = 2kT/\lambda^2$

If source size or beam size is known, this can be put in terms of Flux Density,

$$S = 2.65 T_{\mathbf{B}} \theta^2/\lambda^2$$

(with S in Jy (=$10^{\mathbf{-26}}$ W $m^{\mathbf{-2}}$ $Hz^{\mathbf{-1}}$, θ in arc min, λ in cm), and "$T_{\mathbf{B}}$" is a brightness temperature. The relation of T_A and T_B is η_B where is less then unity. η_B is less than η_A

Or express this as Flux Density per beam, which is actually a temperature.

Measurement Process 2

- Temperatures are an issue. “Brightness Temperature”, T_B is obtained from Flux Density, λ and θ. “Antenna Temperature”, T_A is the power delivered by a heated absorber at the input of the receiver. $T_A < T_B$ ***always!***
- Usually the measurements are based on comparisons with nearby sources or with internal thermal sources, that is, “cold loads”
- Absolute measurements are rare (but *are* done)

Noise (see T. Hunter talk)

- Is a random process which follows Gaussian Probability
- The Root Mean Square noise in a random process is

$$\boxed{\Delta P_{\mathrm{RMS}} = \frac{P}{\sqrt{N}} = \frac{P}{\sqrt{\Delta\nu\,\tau}}}$$

- The power per Hertz, P_ν, is given by $P_\nu = kT$, we have

$$\boxed{\Delta T_{\mathrm{RMS}} = \frac{T_{\mathrm{sys}}}{\sqrt{\Delta\nu\,\tau}}}$$

where:

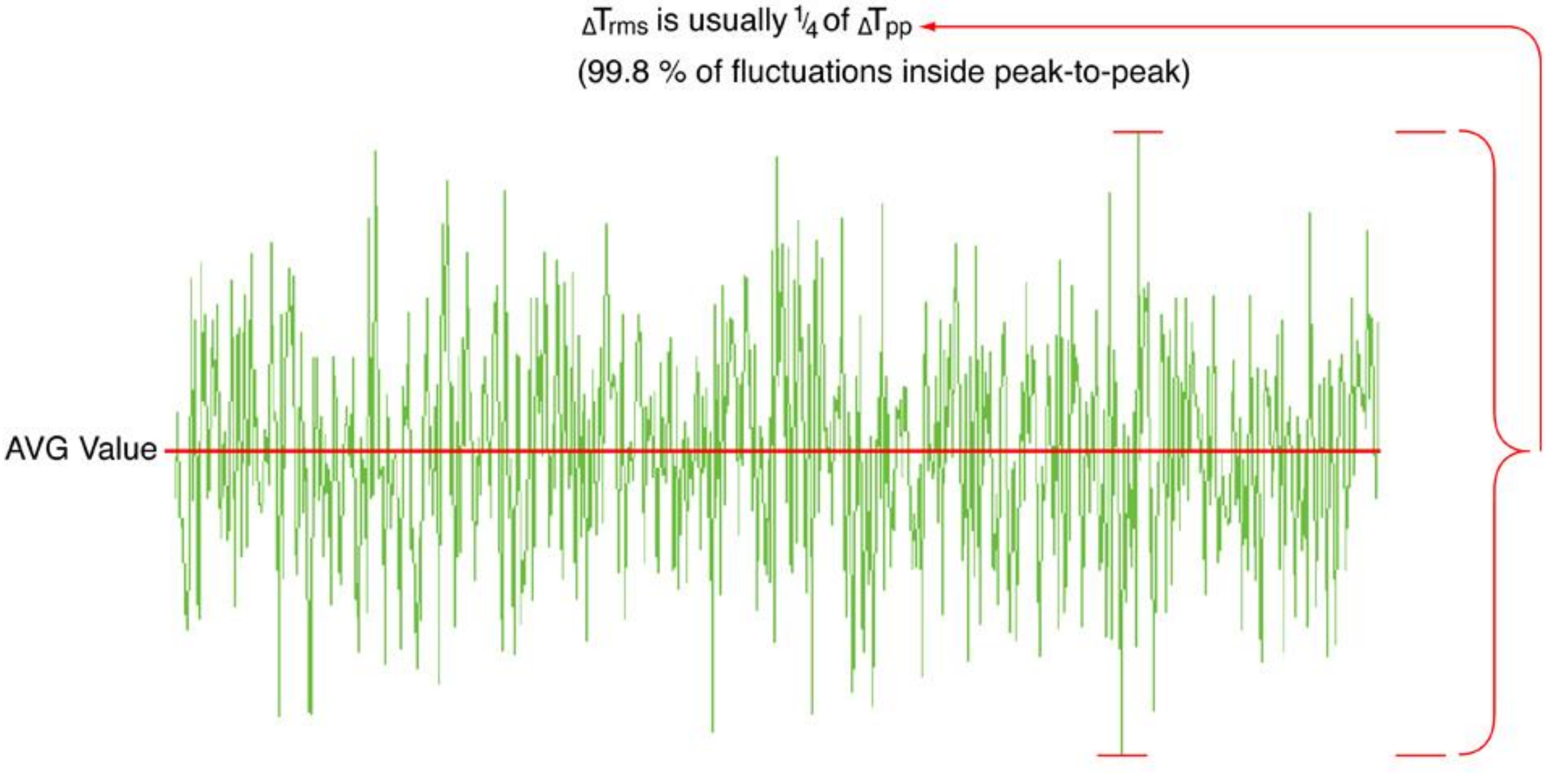
$$T_{\mathrm{sys}} = T_{\mathrm{rx}} + T_{\mathrm{input}}$$

And $\Delta\nu$ is bandwidth (continuum, as large as possible)

next determine the $T_{\mathbf{input}}$

Noise

With 1000 data points have 2 outside the 4 σ limits



Power, Flux Density and Signal-to-Noise

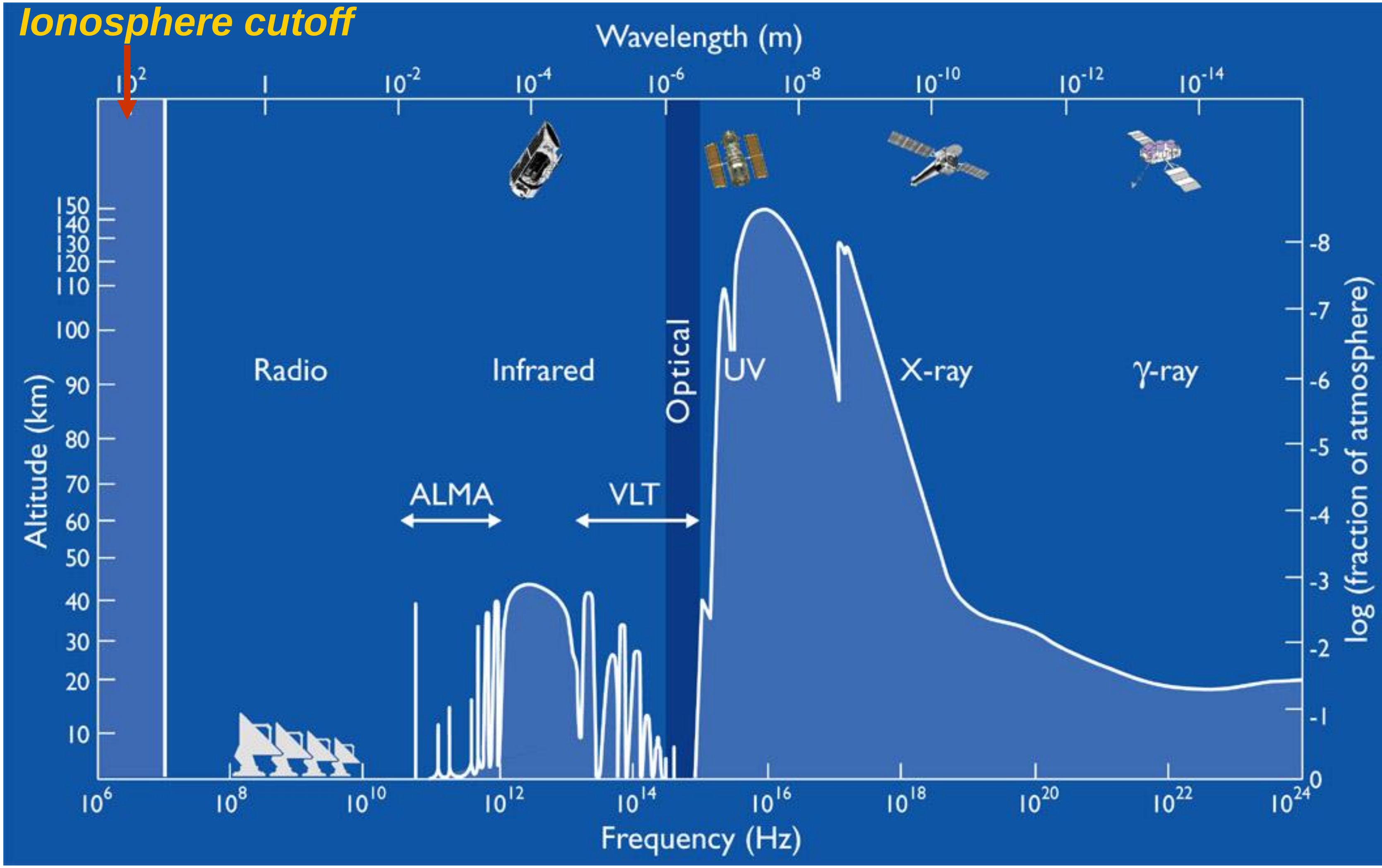
- Example: Orion A at 23 GHz (=1.3 cm) has a size of 2.5’, a flux density of 400 Jy. The peak continuum temperature from the Rayleigh-Jeans relation is 40K. The antenna temperature is about 25K.
- The receiver noise temperature is 20K + 25K. So the Noise for a bandwidth $\Delta\nu$=1 GHz in 1 second is 0.0014K.
- The Signal-to-RMS-Noise is 3 10^4

A 1 milli Watt Transmitter at Geo

- Distance=40,000 km
- Transmit a power of 1 mW as a 1 Hz wide signal in all directions
  - On earth, this gives a Flux Density of 5 10^{6} Jy
  - What is the effective temperature? ($P_{\nu}=kT\,\Delta\nu$)

  - Such beacons are often used for Holographic measurements of radio telescope surface accuracies (see T. Hunter talk).
  - Also used at the VLA for phase monitoring.

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



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mm and sub-mm range

Radiative transfer equation:

absorption *emission*

$$\boxed{\frac{\mathrm{d}I_\nu}{\mathrm{d}s} = -\kappa_\nu I_\nu + \varepsilon_\nu} \quad .$$

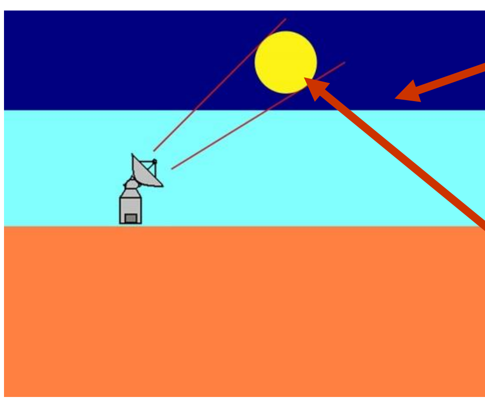
Solve for 1 dimension, and uniform medium. Then:

Absorption of Source

Emission from Atmosphere

$$\boxed{I_\nu(s) = I_\nu(0)\,\mathrm{e}^{-\tau_\nu(s)} + B_\nu(T)\,(1 - \mathrm{e}^{-\tau_\nu(s)})} \quad .$$

$$\tau_\nu = \kappa_\nu\, s$$



atmosphere

Source

(e.g. MOON)

Receiver sees noise from Moon, plus noise from the atmosphere. The source intensity is reduced because of loss in the atmosphere and there is noise from the atmosphere. Need calibration to relate receiver output to temperature.

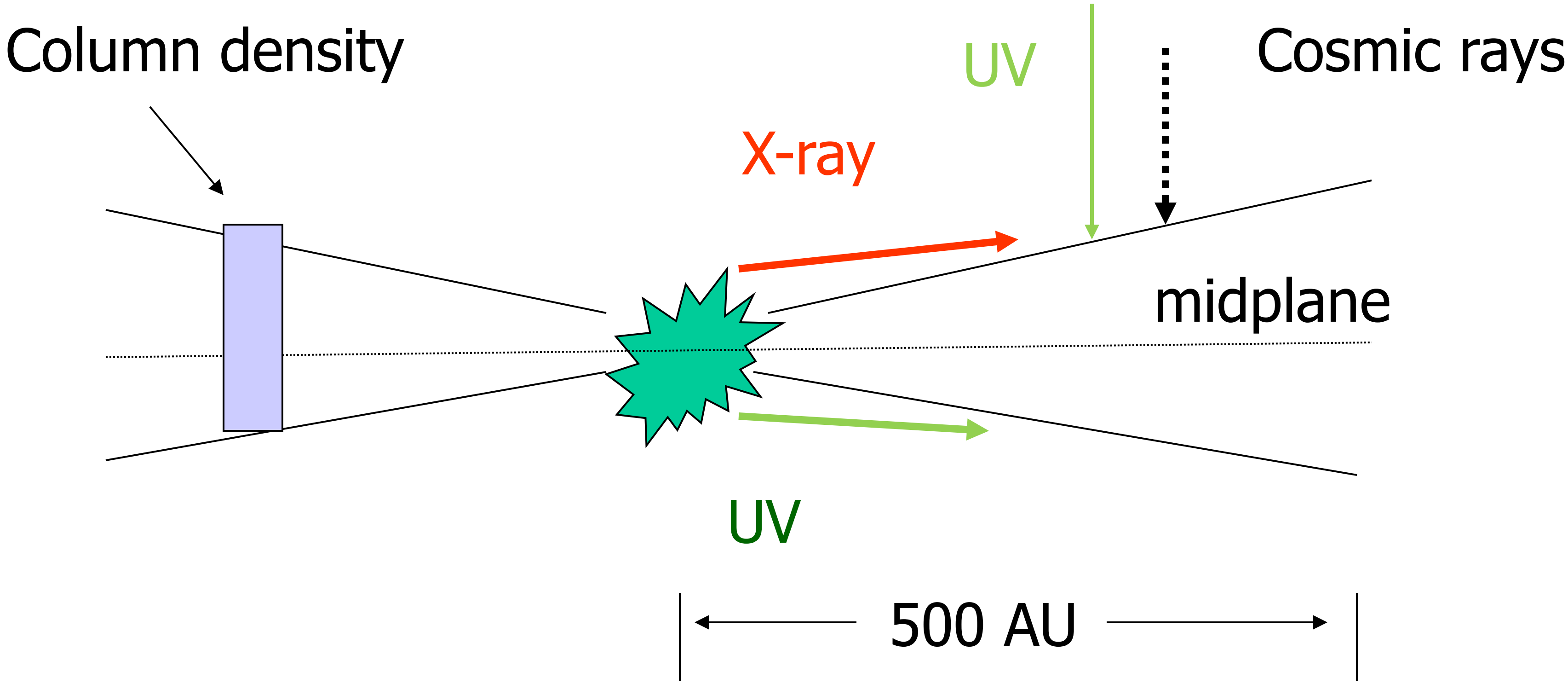
Spectral Lines

- Purely quantum phenomena
  - These arise from a transition between two stationary states
  - The first spectral line found in the radio range was the 21 cm line (1951).
    - This is a hyperfine transition ("spin flip")
    - Need finer frequency resolution to measure these. This led to spectrometers ***(A. Deller*** talk)
  - Next was the Λ doublet line of OH (1963; at 18 cm)
    - Some sources show maser emission; later H_2O masers, distances…
  - Radio recombination lines (principal quantum number ~60 or so)
  - Then lots of molecular lines (1968 onward; now about 160 species); stars form in molecular clouds; isotopes; chemistry…

Relating Intensities to Abundances

- We measure a T_{MB} but want an abundance. Need the properties of the species to be investigated. This is gotten from laboratory data.
  - For allowed rotational transitions, need permanent electric dipole moments. Such dipole moments can be obtained from semi-classical arguments
  - Measurements give the population in the two levels
  - Usually quote the population of a lower of the levels
  - This is a column density in cm^{-2}
  - Need to determine the total population
  - Usually, the assumption is that the excitation is close to Local Thermodynamic Equilibrium (LTE)
  - Assumption that chemistry is understood

Protoplanetary Disk



T Tauri star – 10^6 yr old

0.01-0.1 M_0

Keplerian rotation

Extragalactic Science

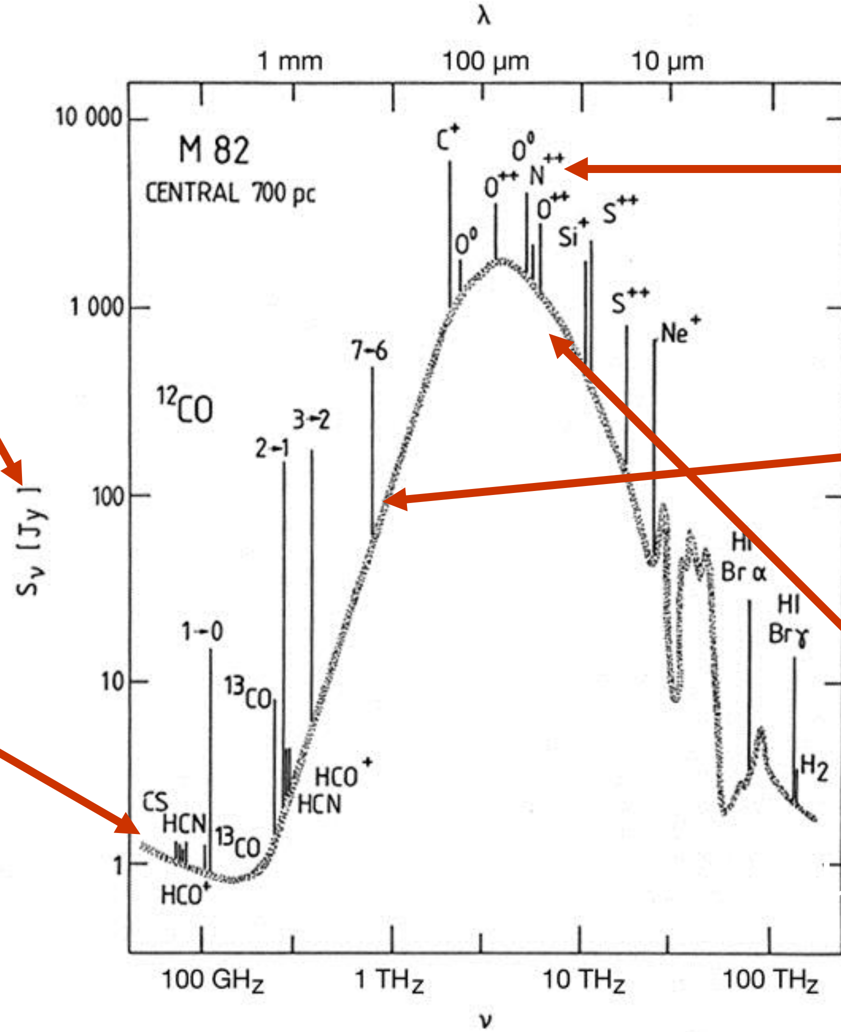
- We live in the Milky Way, so difficult to understand detailed structure
- Other galaxies allow comparisons, but like comparing Paris with NYC

Sources: M82 (starburst) in the radio, mm, sub-mm and FIR ranges

Flux density

Non-thermal emission

Broadband continuum
And spectral lines



Atomic Lines,

Molecular Lines

Broadband dust emission

This is a schematic

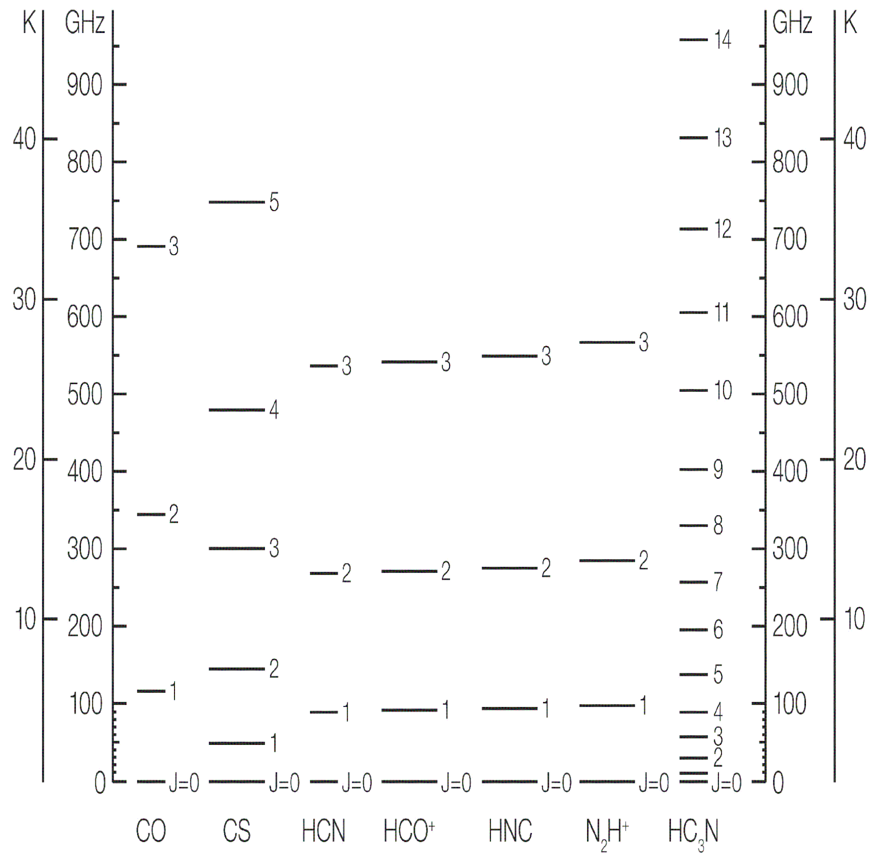
Concluding Remarks

- Ground based radio astronomy now extends from 30 meters to 0.3 mm; from satellites to shorter wavelengths
- The interpretation of the data are subject to a large number of subtle effects that can be extremely important. For molecules:
  - Excitation
  - Chemistry
  - Interpretations are the applications of rather complex theories

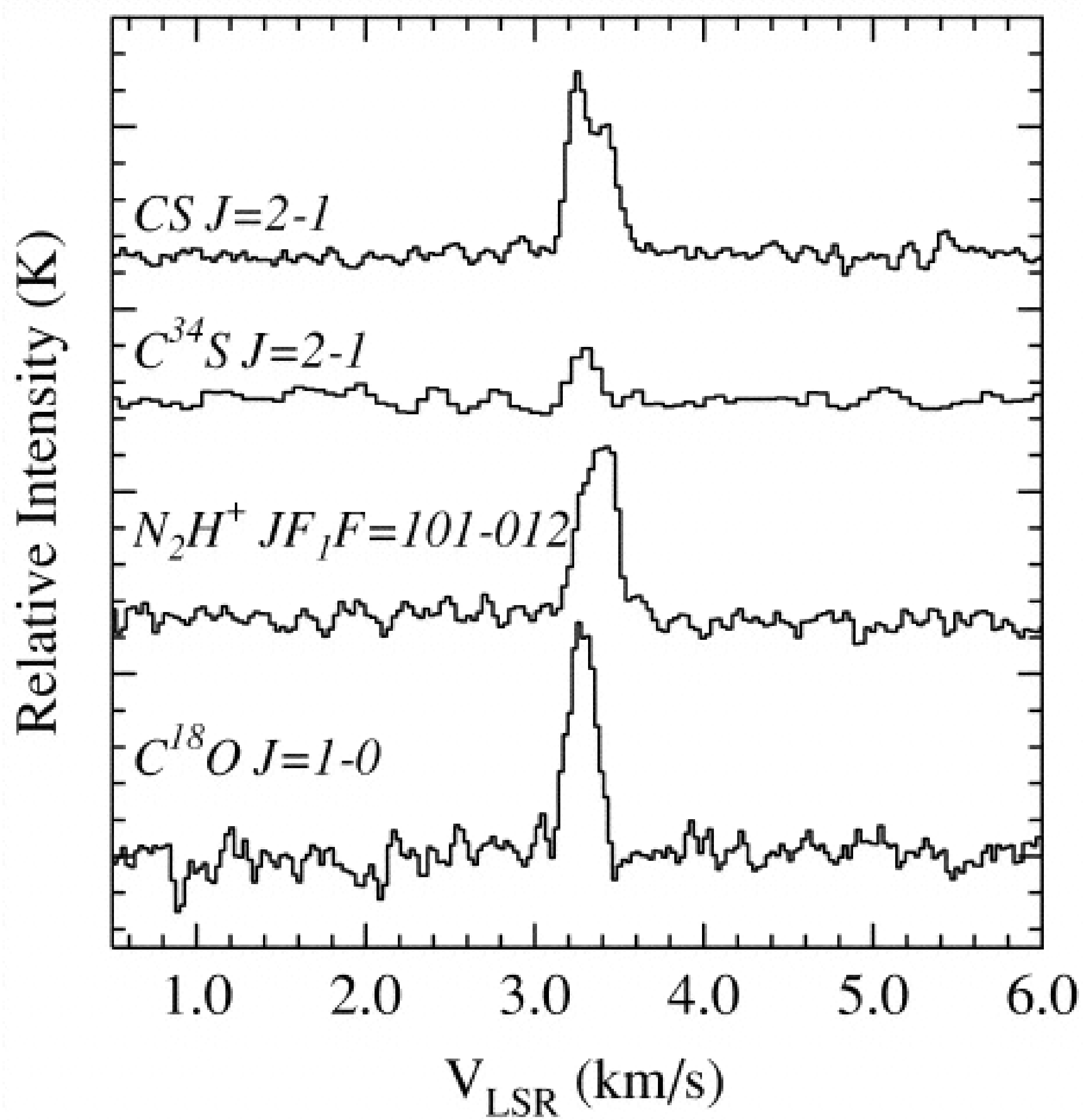
For continuum, dust properties. For non-thermal radiation, these include magnetic field strength, Lorentz factor, lifetimes, reacceleration, etc.


THE END

Some of the Simpler Interstellar Molecules



►CO has 0.1 Debye for an electric dipole moment



CS J=2-1
C34S J=2-1
N2H+ JF1F=101-012
C18O J=1-0
Relative Intensity (K)
1.0
2.0
3.0
4.0
5.0
6.0
VLSR (km/s)

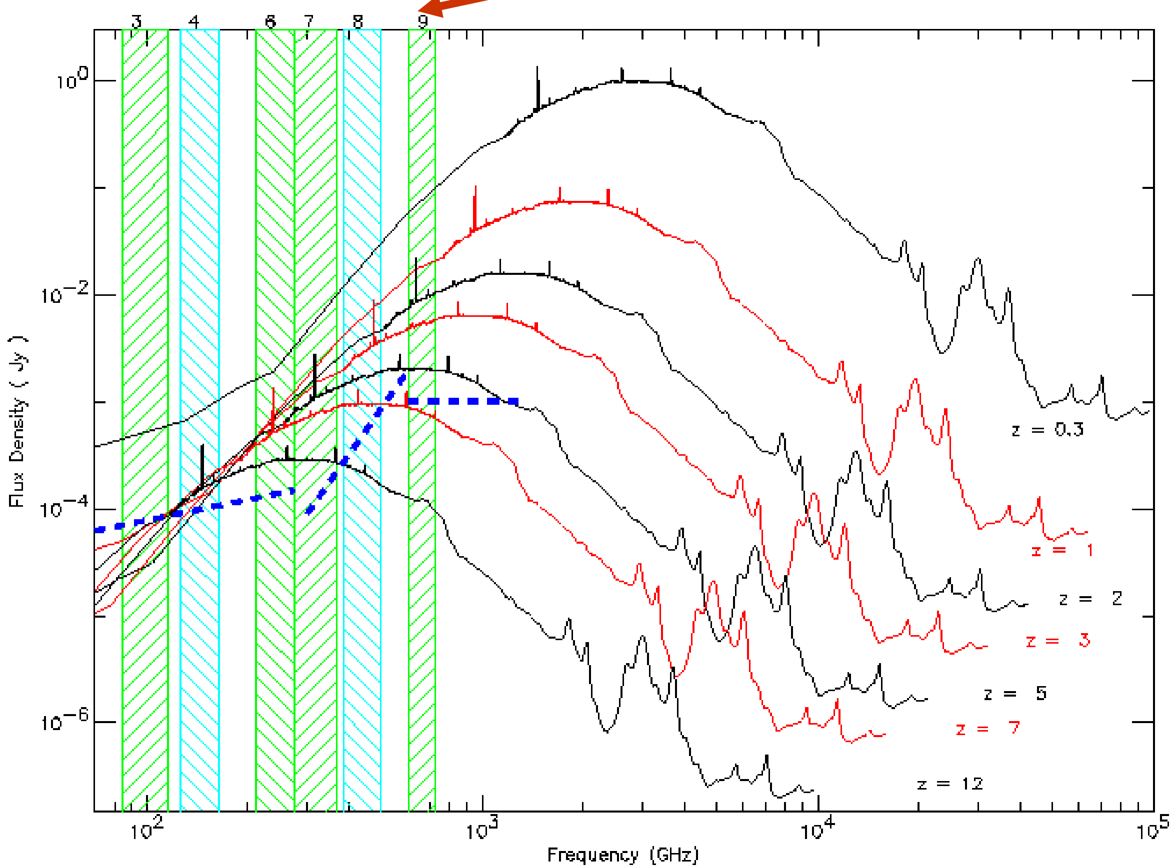
Infrared Luminous Galaxies

ALMA Receiver Bands

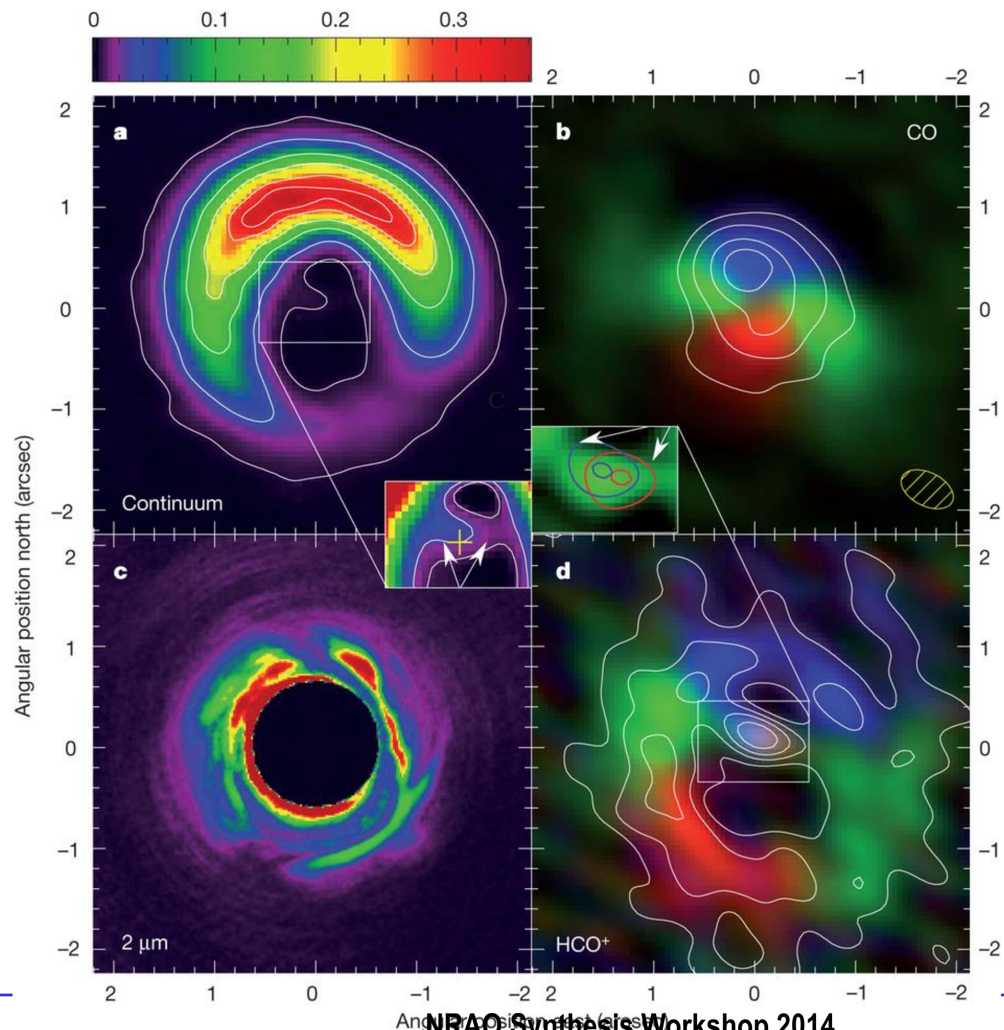
- As galaxies are redshifted, dimming due to distance, this is offset by the brighter part of the spectrum being shifted down. Hence, galaxies remain at relatively similar brightness out to high distances.

M82 from ISO

ALMA receiver bands



HD 142527


0
0.1
0.2
0.3
a
b
CO
c
d
Continuum
2 µm
HCO+
Angular position north (arcsec)