Estimating Molecular Cloud Mass Using Carbon Monoxide Emission Lines

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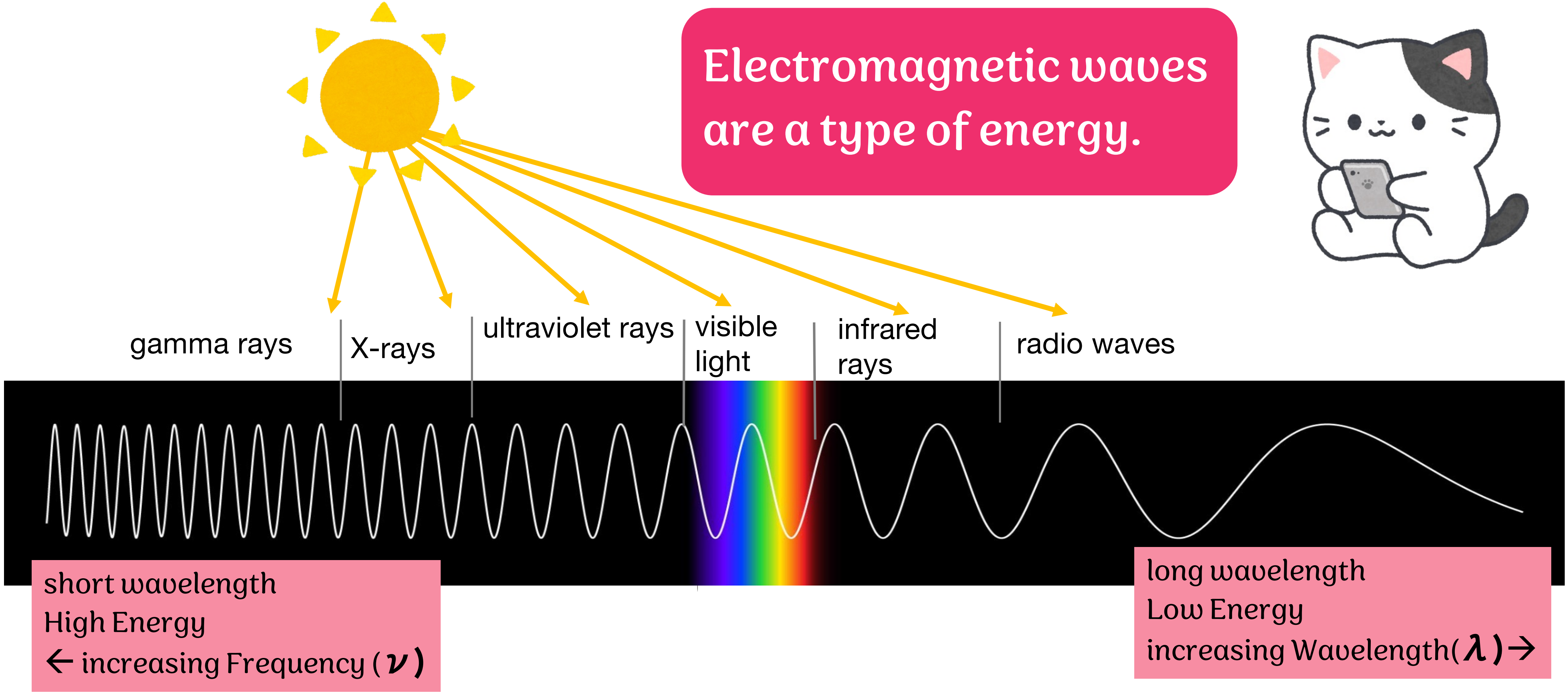
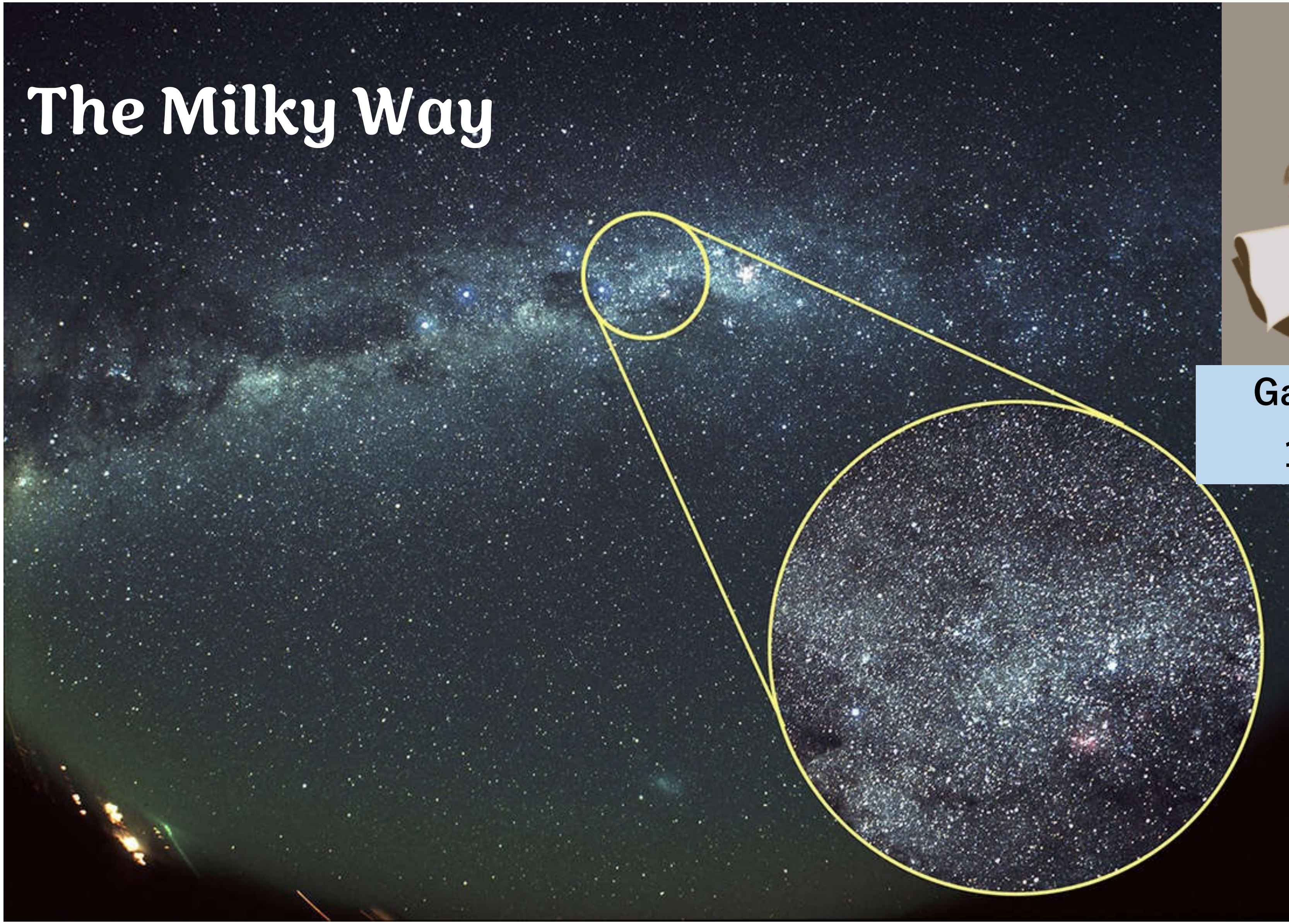
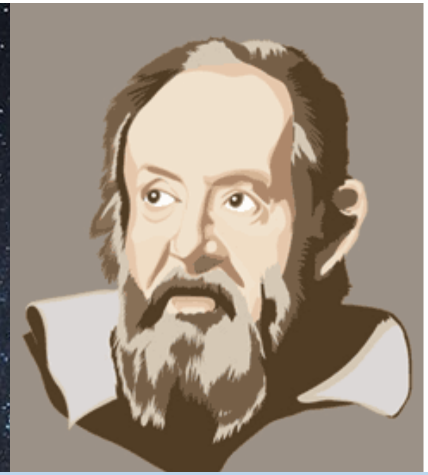
Objects in the universe send out an enormous range of electromagnetic radiation.

Electromagnetic waves are a type of energy.

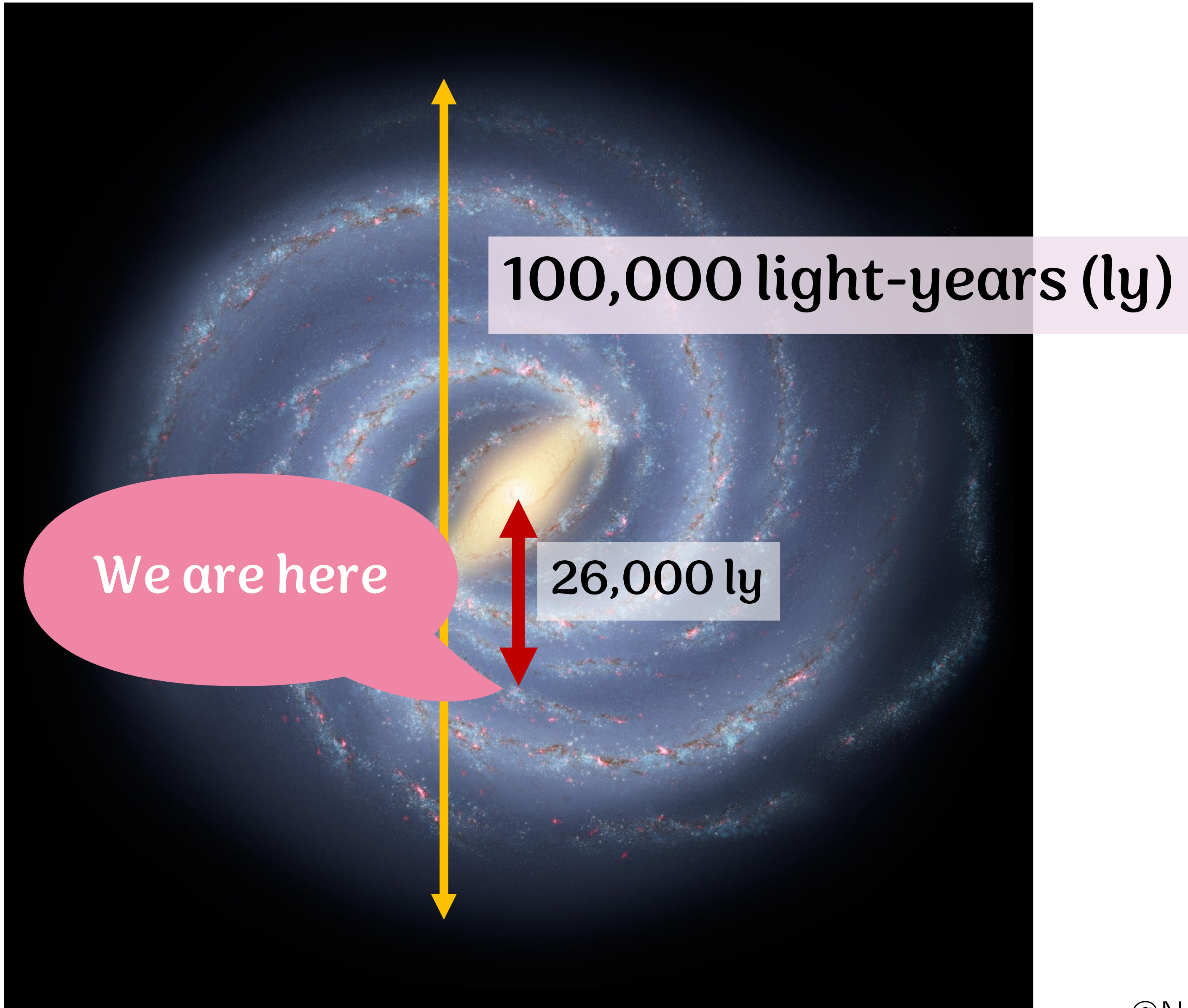






Galileo Galilei

1564- 1642



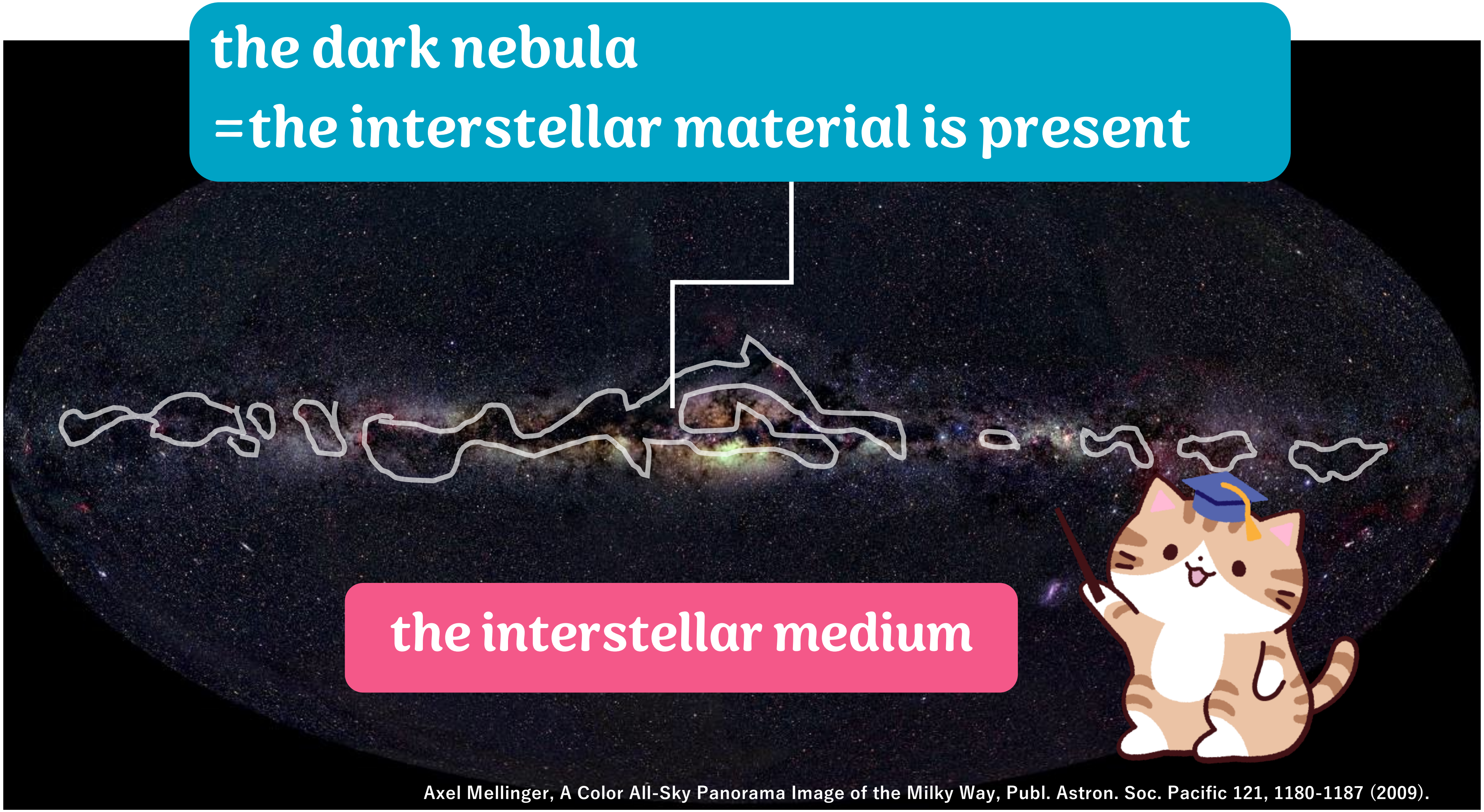
@NASA

How far is a light-year?

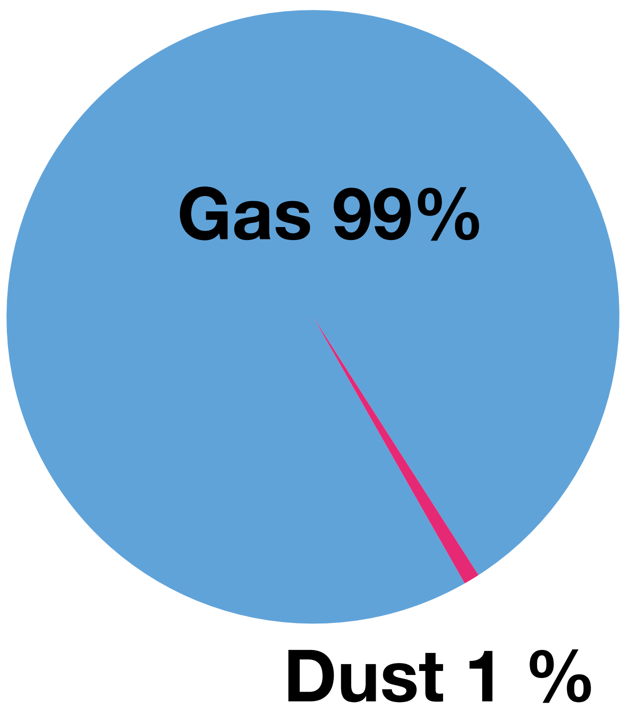
- A light-year is the distance that light travels in one year.
- One light-year is approximately 9.46 trillion kilometers.

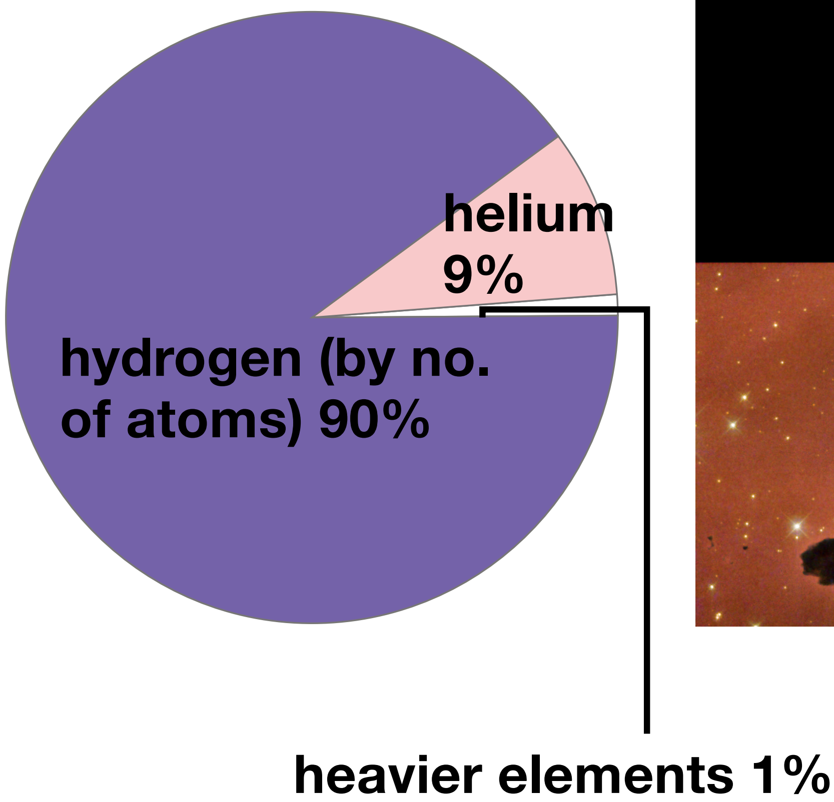
9.46×10^{12} km

https://www.youtube.com/watch?v=MX3PIkbTQwQ

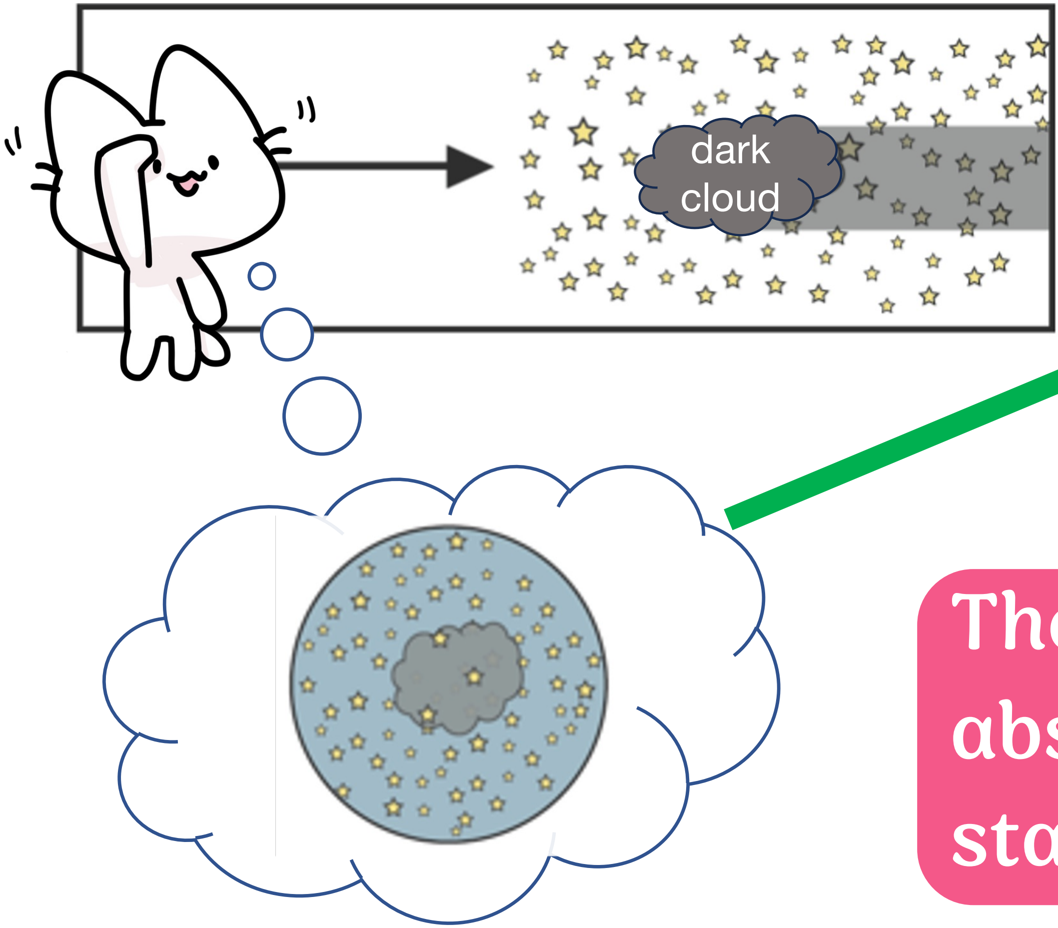

the dark nebula
=the interstellar material is present
the interstellar medium
Axel Mellinger, A Color All-Sky Panorama Image of the Milky Way, Publ. Astron. Soc. Pacific 121, 1180-1187 (2009).

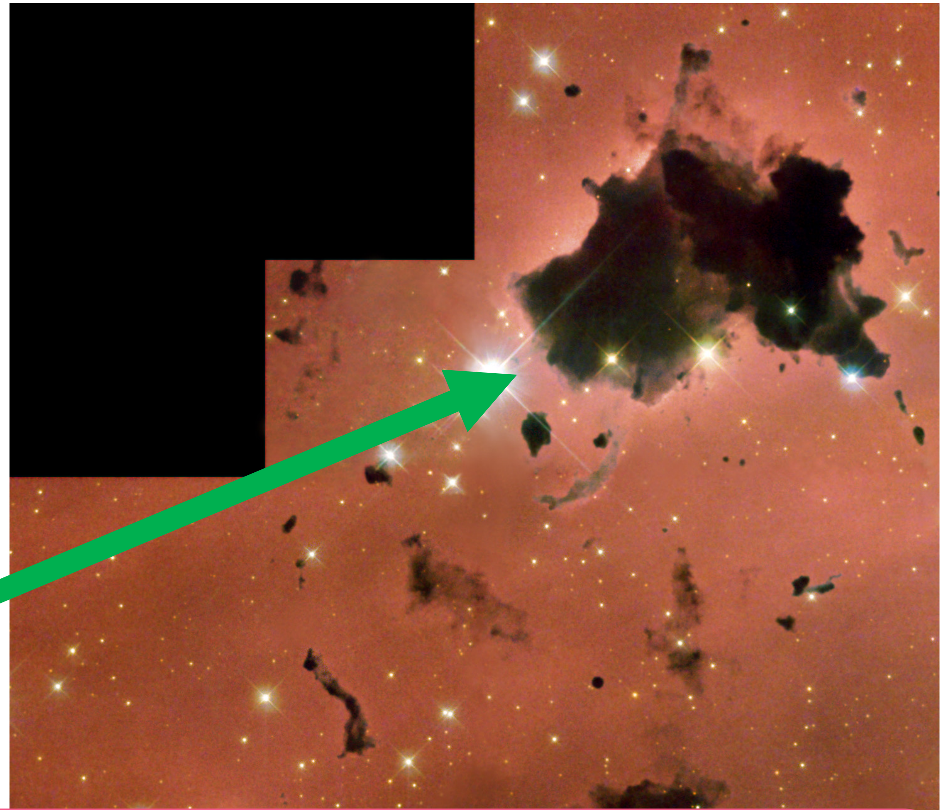
What is the Interstellar Medium?





Why does it look dark?





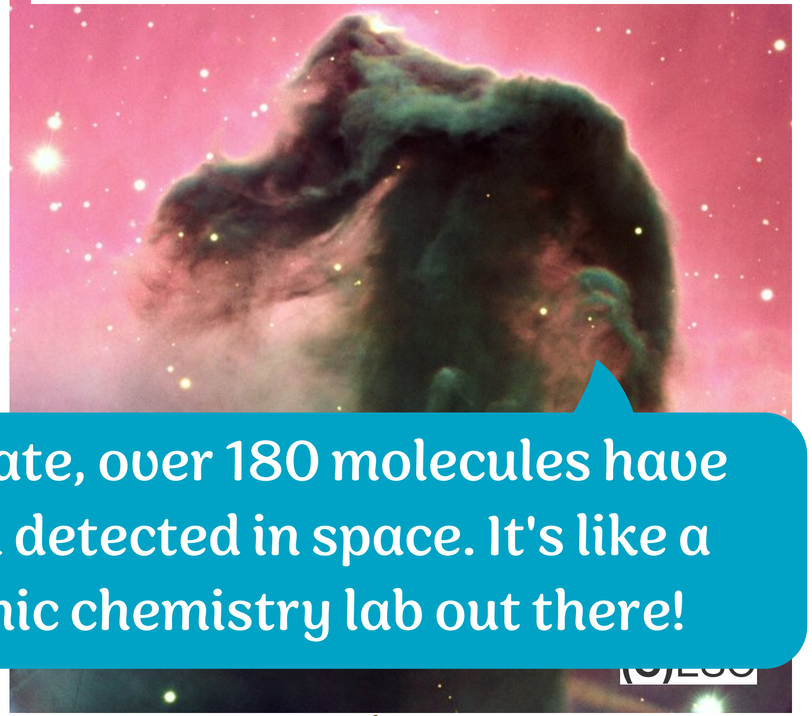
The dust in the dark cloud absorbs the light from the stars behind it!

Molecular Cloud

very cold!

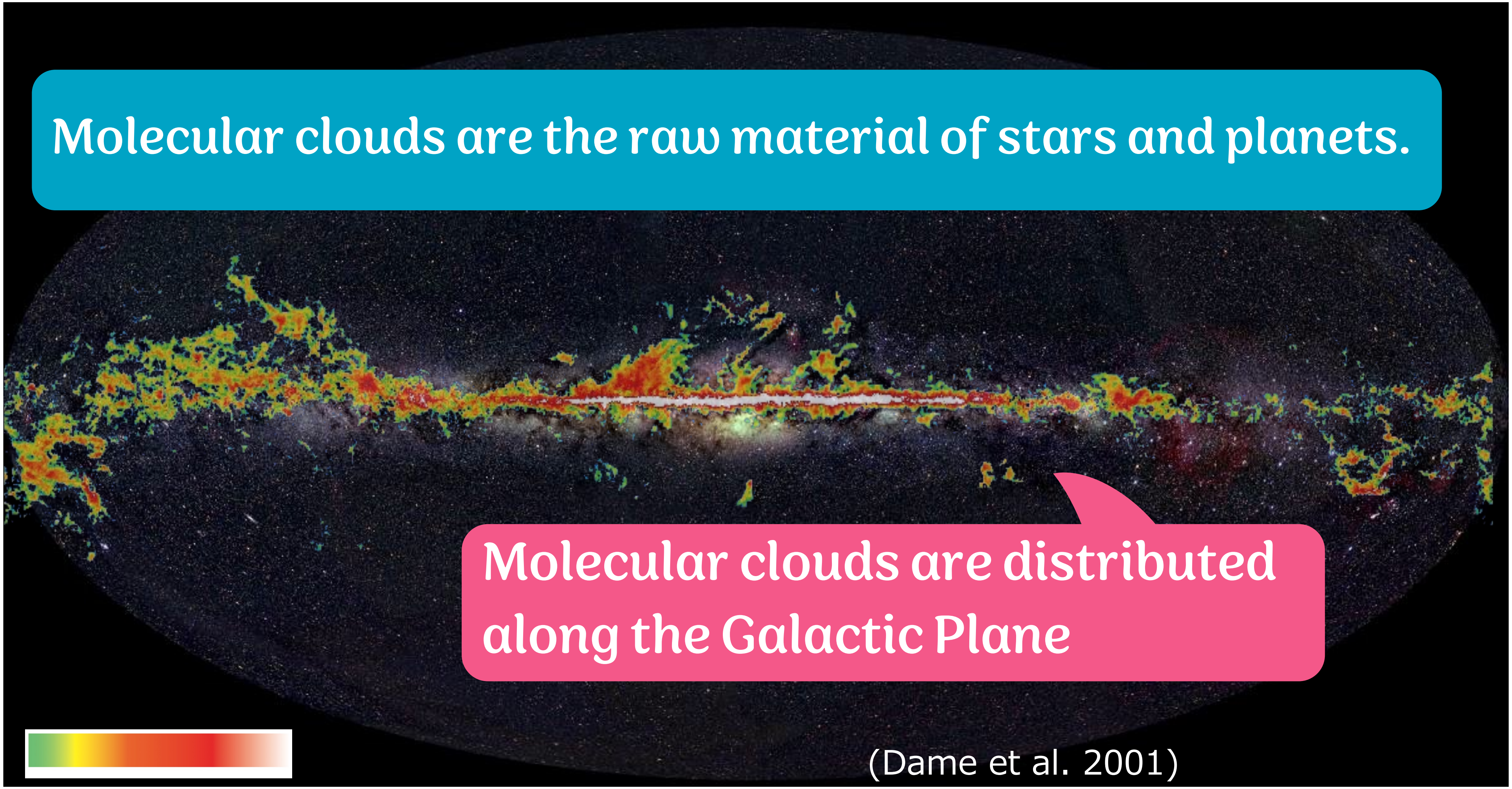
- Temperatures:
  10 K (-263°C)
- Principal components: H_2, He and other molecules
- Densities: $n > 10^{2\text{-}3}$ cm^{-3}
- Size: ~30 ly

A dense mass of gas and dust



To date, over 180 molecules have been detected in space. It's like a cosmic chemistry lab out there!

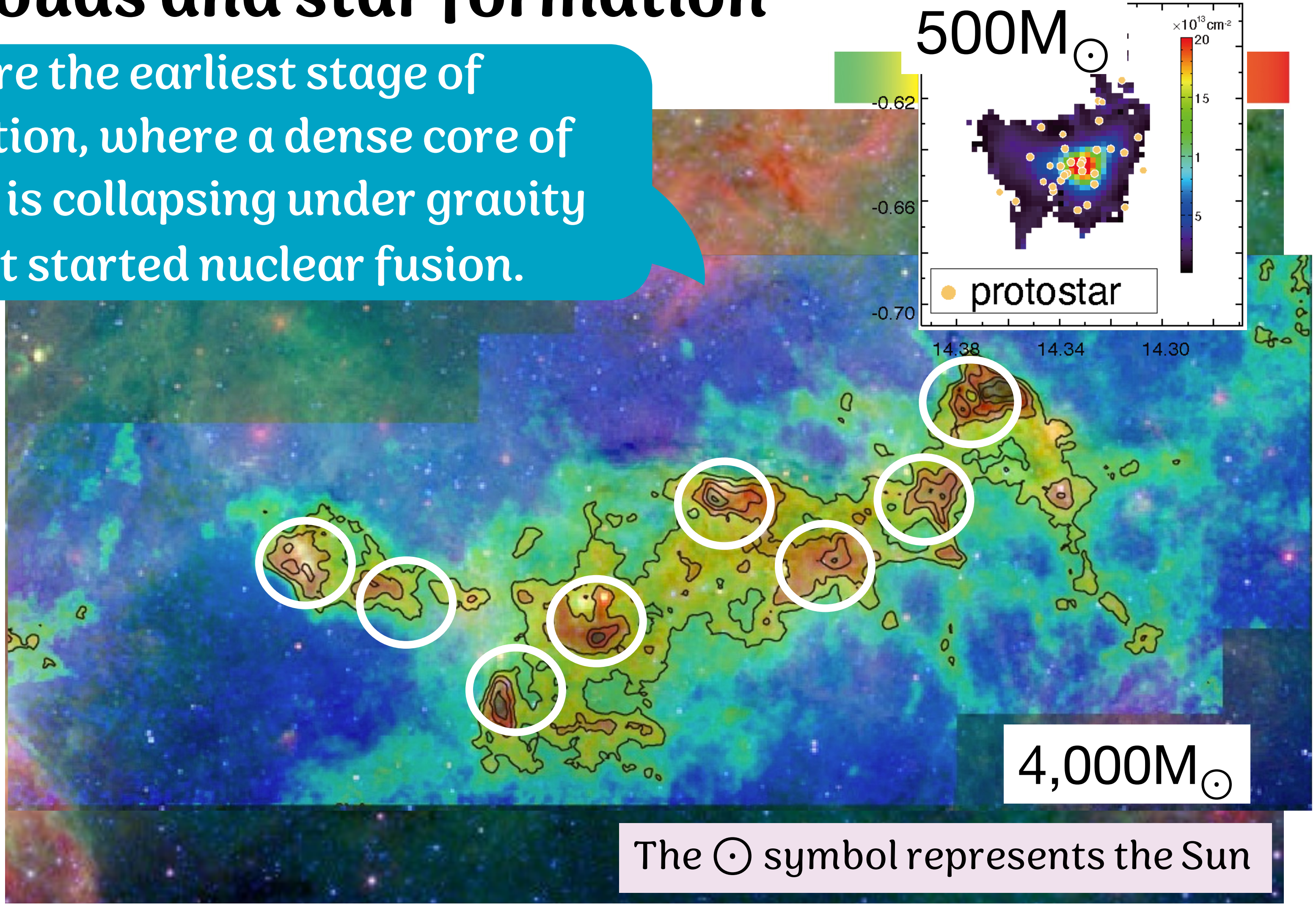
The gas is in the molecular state, hence the term 'molecular cloud'



The redder the color, the stronger the radio intensity.

Molecular clouds and star formation

Protostars are the earliest stage of stellar evolution, where a dense core of gas and dust is collapsing under gravity but hasn't yet started nuclear fusion.



The $\odot$ symbol represents the Sun

Fundamentals of Radio Astronomy

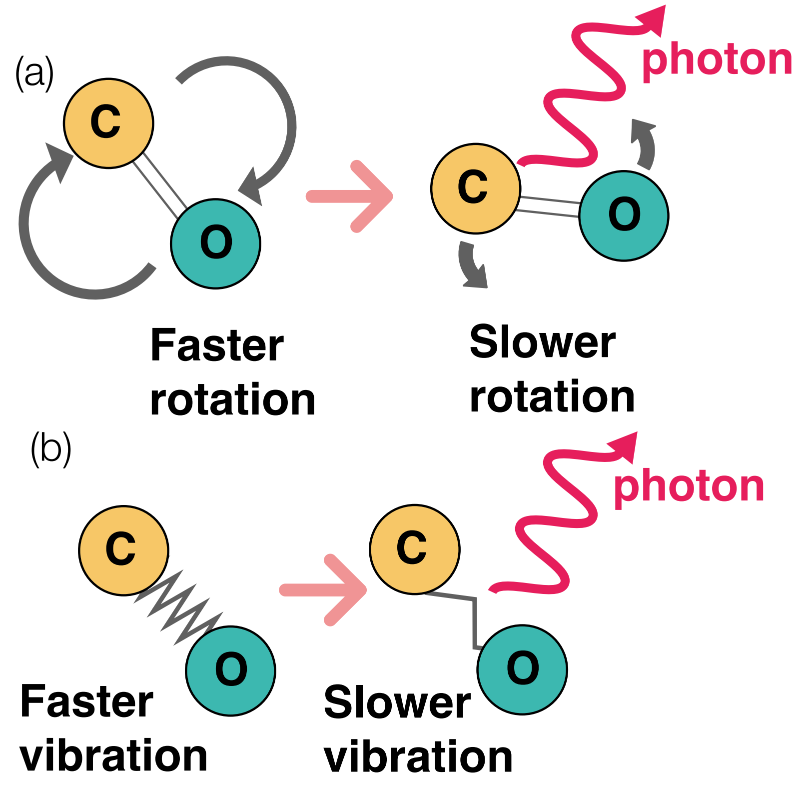
Molecular radiation

It's all about energy states.

✓Molecules can emit radiation by changing either their rotational or vibrational states.

✓The wavelength of the signals indicates from which molecule it comes.

Changes in molecular rotational and vibrational states produce spectral lines in various parts of the electromagnetic spectrum, including the radio and microwave regions.



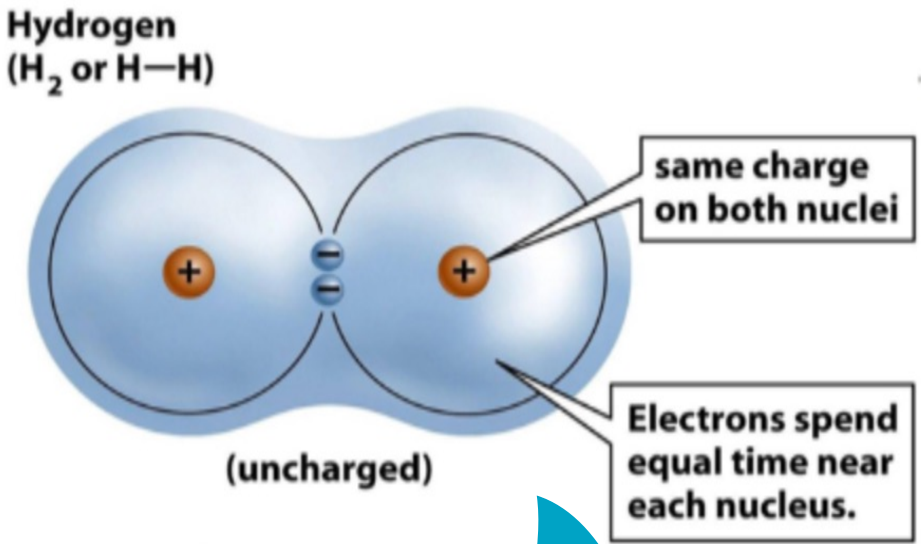
The emission of photons by a change in (a) the rotational state, and (b) the vibrational state of a carbon monoxide molecule.

Hydrogen is the most abundant molecule in molecular clouds.

H_2 is extremely hard to observe directly!

- **Molecular structure:**
  - Uncharged (electrically neutral)
  - Symmetrical molecule
  - Uniform charge distribution
- **No dipole moment** due to even charge distribution
- **Consequence:** Doesn't respond to electromagnetic radiation through rotation

Like a perfectly balanced spinning top
Spins without detectable wobble



A dipole moment occurs when there's an uneven distribution of charge in a molecule, which isn't the case for H_2.

https://www.chemtopper.com/myblog/wp-content/uploads/2019/07/1-2.png

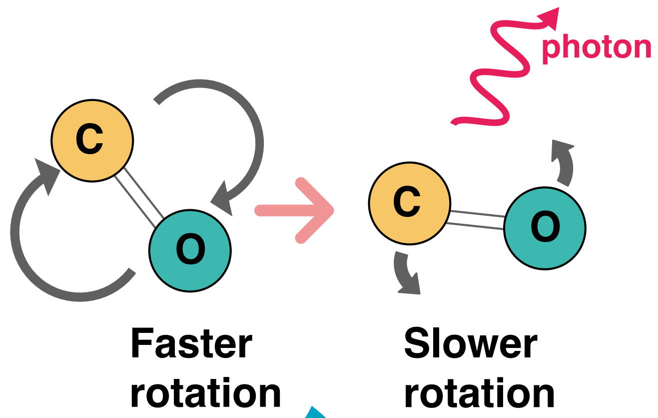
Carbon monoxide Molecule

CO is the second-most abundant molecule in molecular clouds after H_2.

✓CO tends to be present wherever H_2 is found and is often used to trace molecular hydrogen.

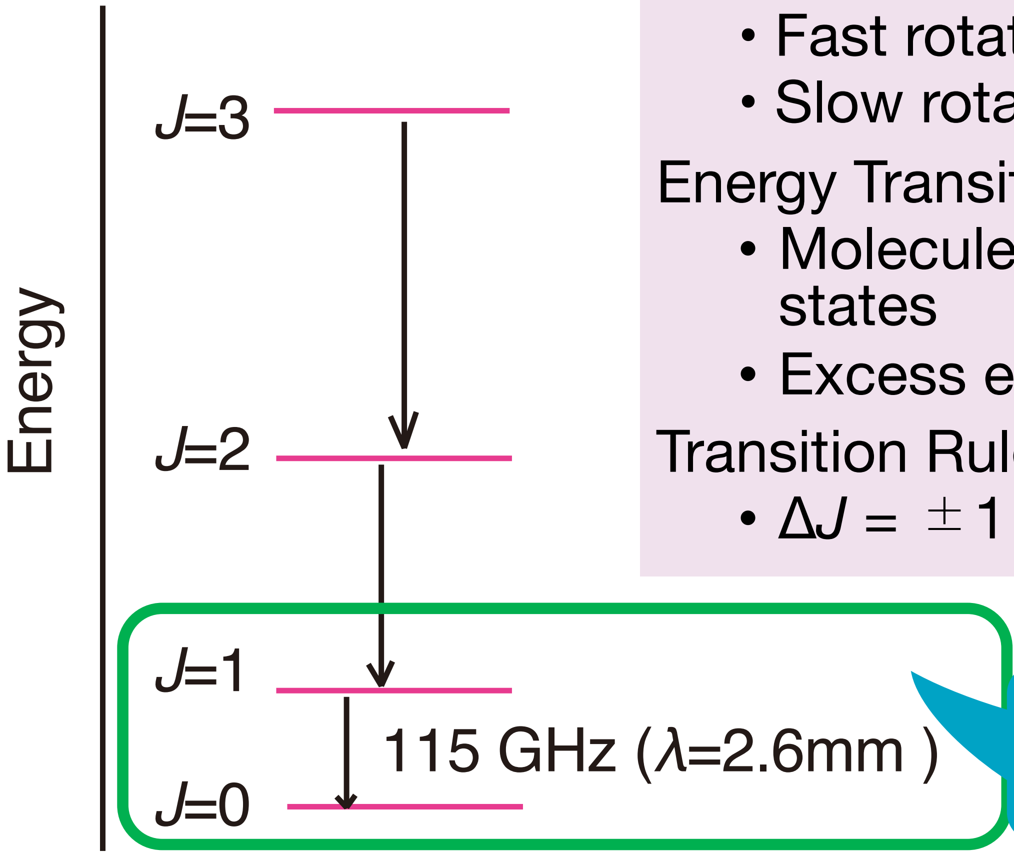
Carbon monoxide Molecule

- ✓CO has a permanent dipole moment, which allows for dipole transitions.
- ✓CO gets excited really easily
- ✓CO is a tough little molecule



CO molecules emit photons at millimeter wavelengths when they change rotational states.

CO Molecules: Energy States and Transitions



Rotation States:

- Fast rotation = High-energy state
- Slow rotation = Low-energy state

Energy Transition:

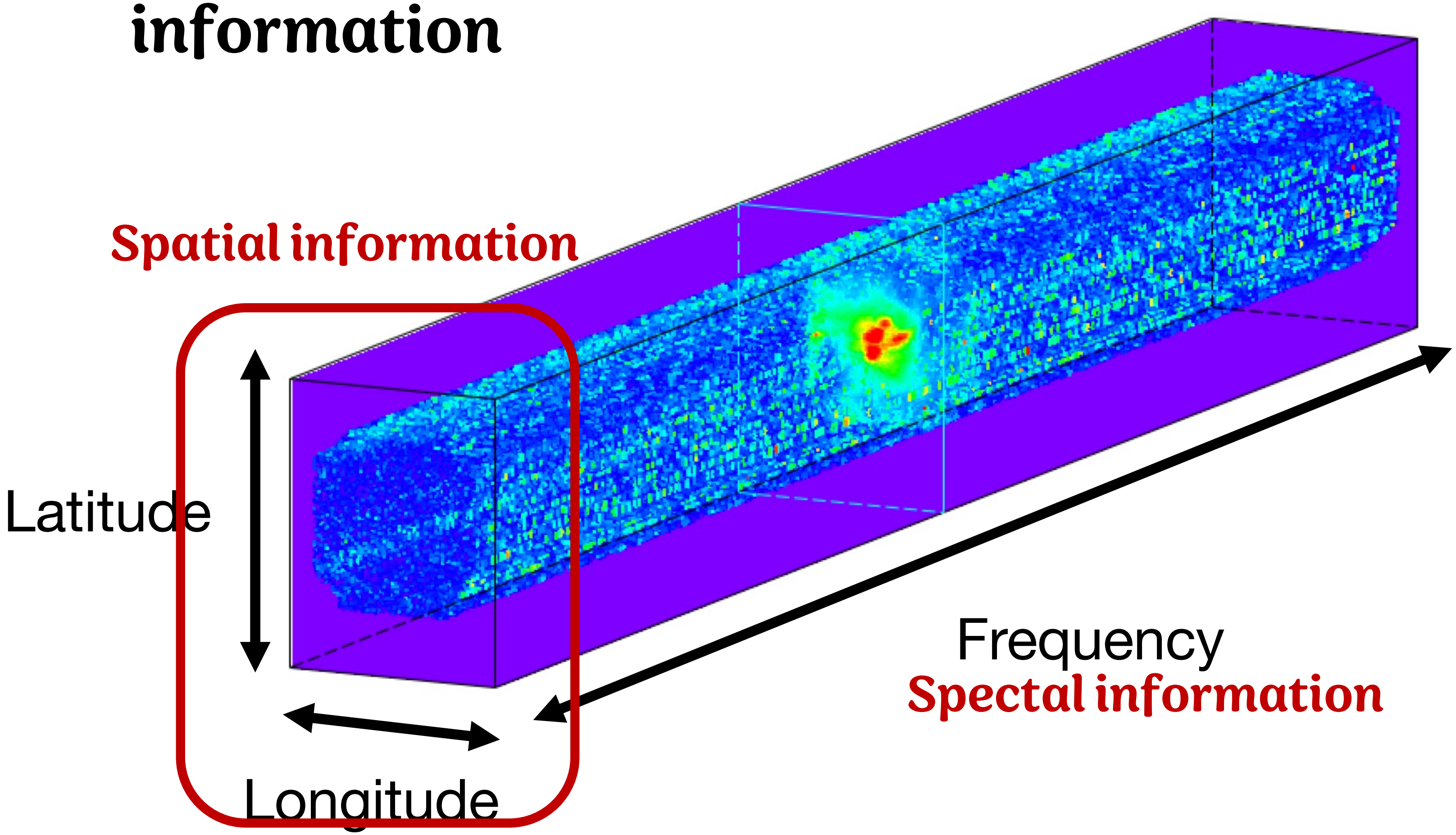
- Molecules transition from high to low energy states
- Excess energy released as radio waves

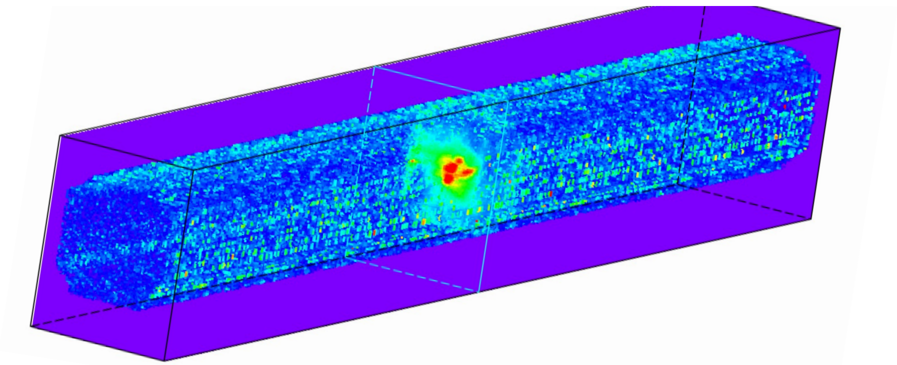
Transition Rule:

- $\Delta J = \pm 1$ (J: rotational quantum number)

Going from J=1 to J=0 releases energy

Radio observations allow us to obtain three-dimensional data due to a combination of spatial and spectral information

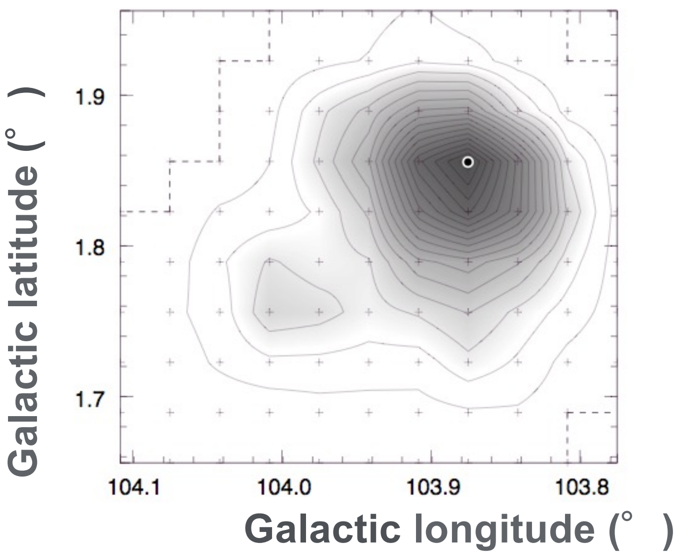


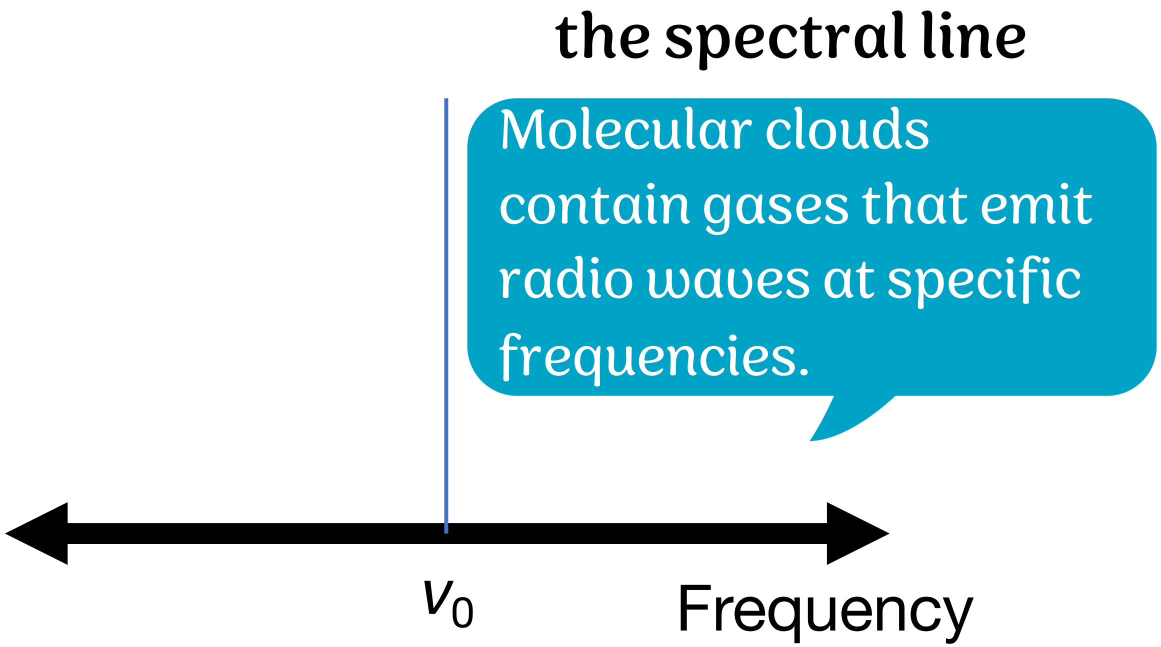


Two spatial dimensions

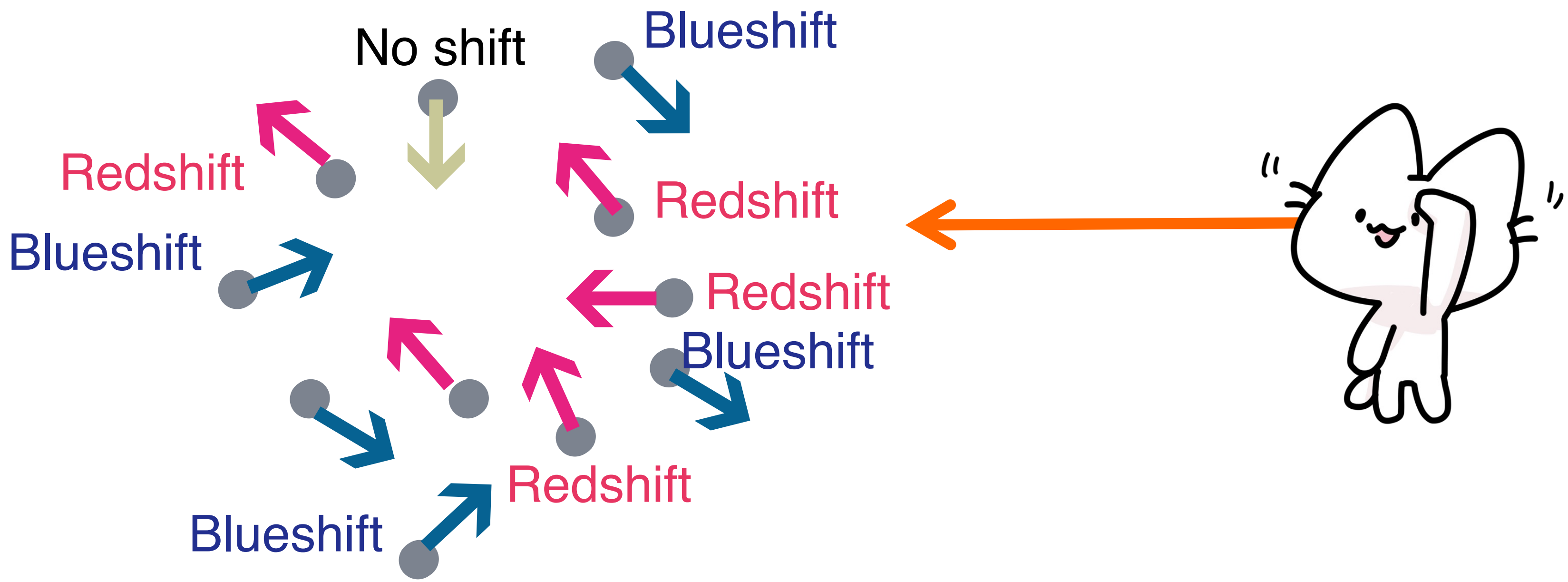
The third dimension

- Frequency or velocity





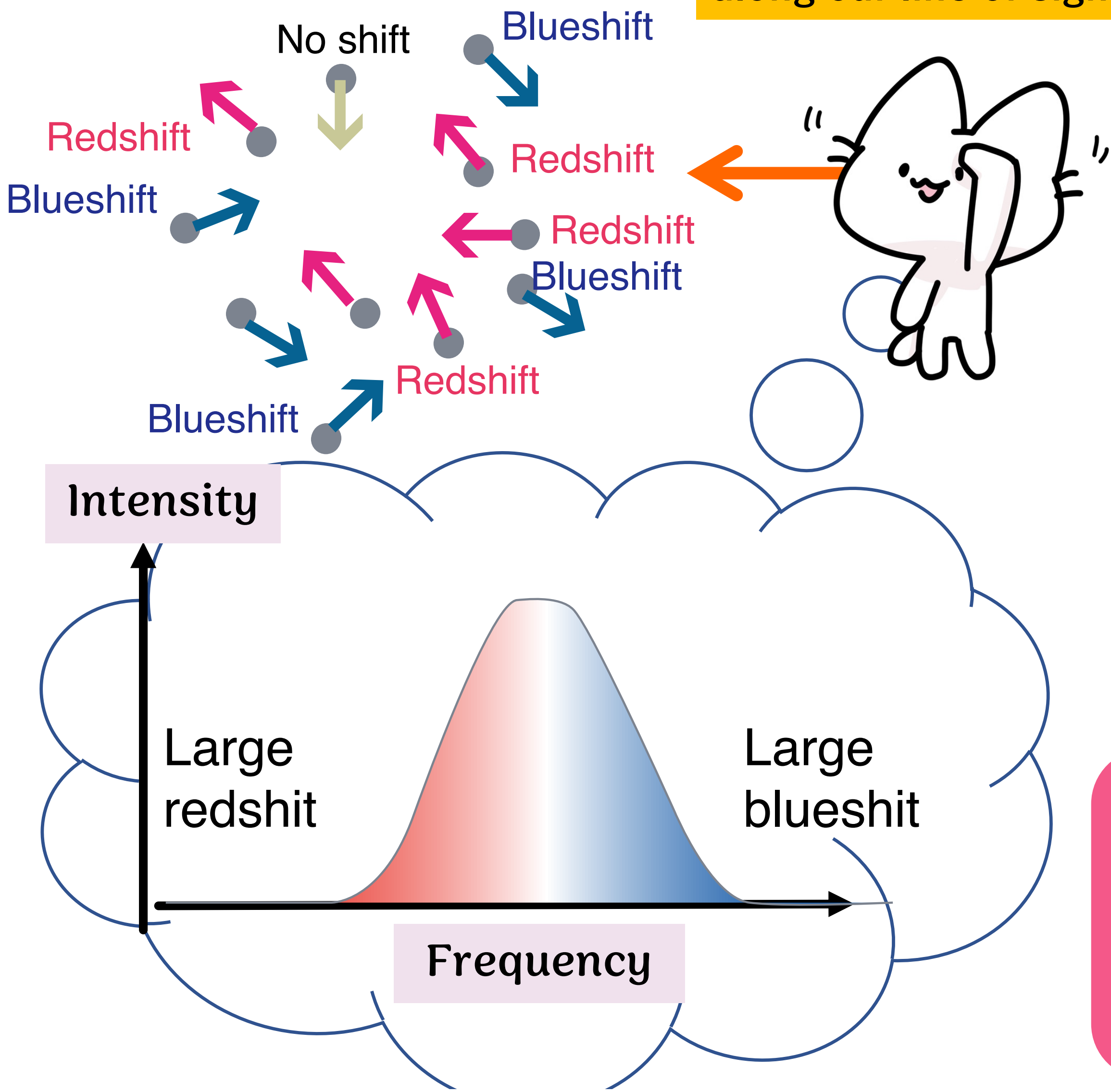
Observing Spectral Lines: What We Actually See



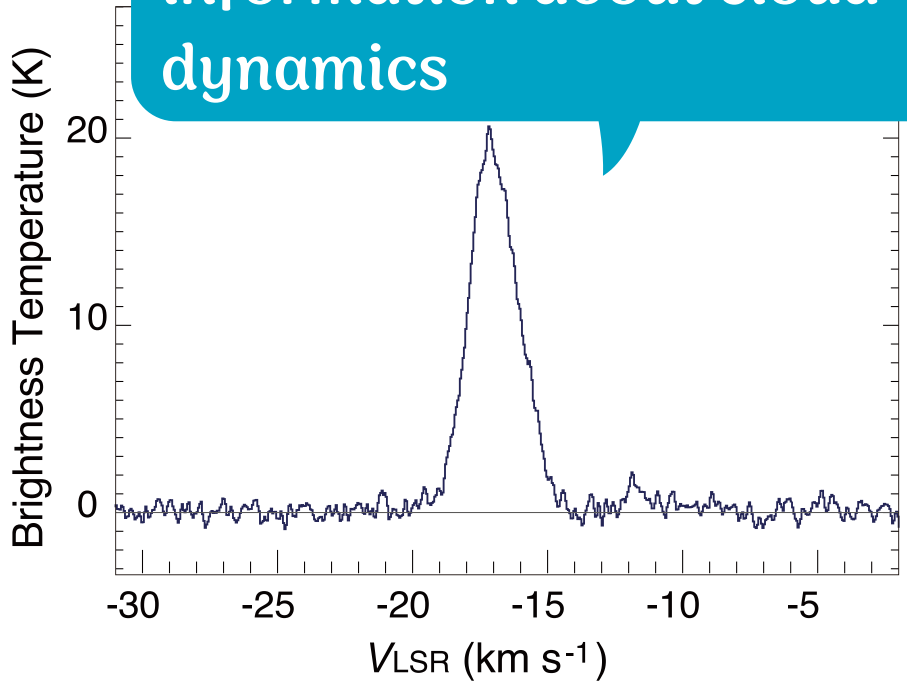
- **Blue Shift** = Molecule moving towards us Like an approaching ambulance
    - Light waves are compressed
    - We detect a higher frequency (bluer light)

- **Red Shift** = Molecule moving away from us Like a receding ambulance
    - Light waves are stretched out
    - We detect a lower frequency (redder light)

along our line of sight



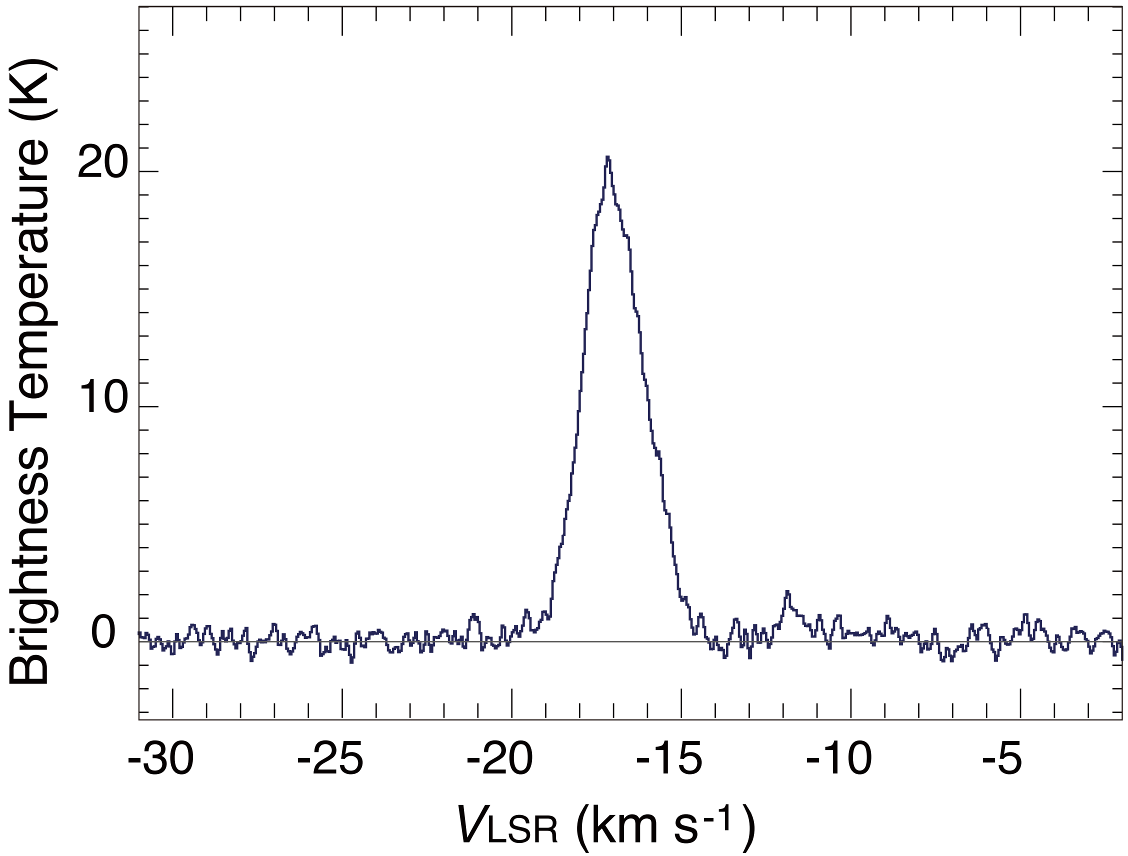
Shape and width provide information about cloud dynamics



molecules moving randomly produce broadened spectral lines as their individual redshifted and blueshifted emission lines merge in our detector.

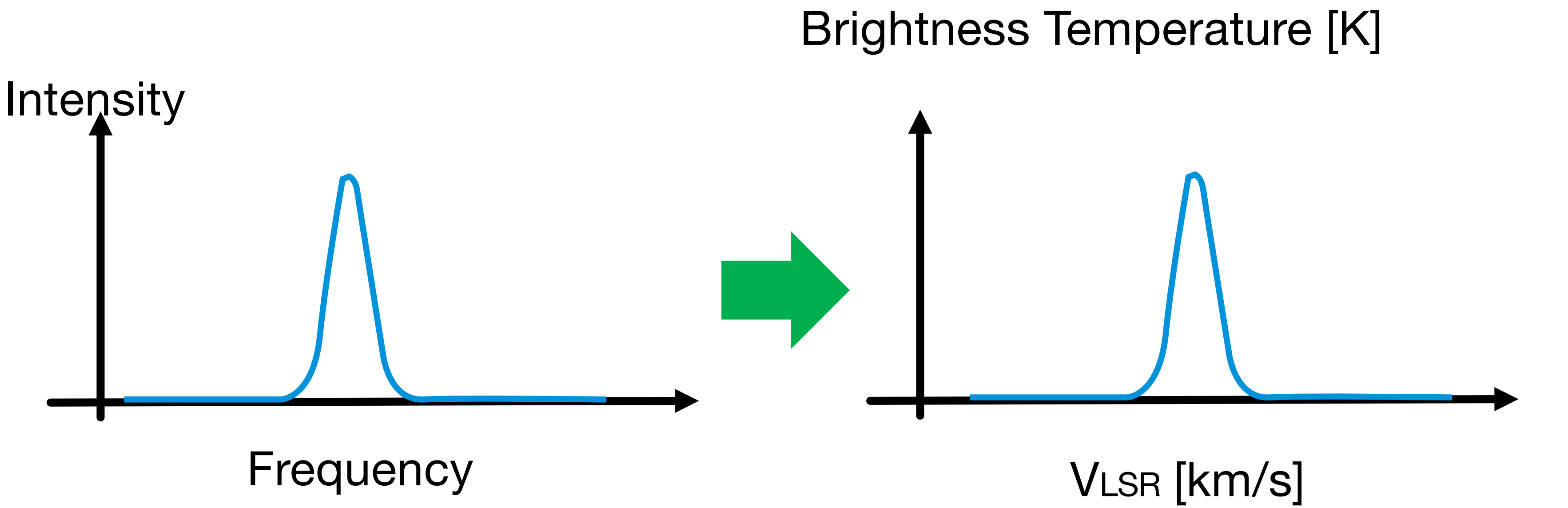
The radio intensity is proportional to the temperature of the gas in the molecular cloud.

the Rayleigh-Jeans law



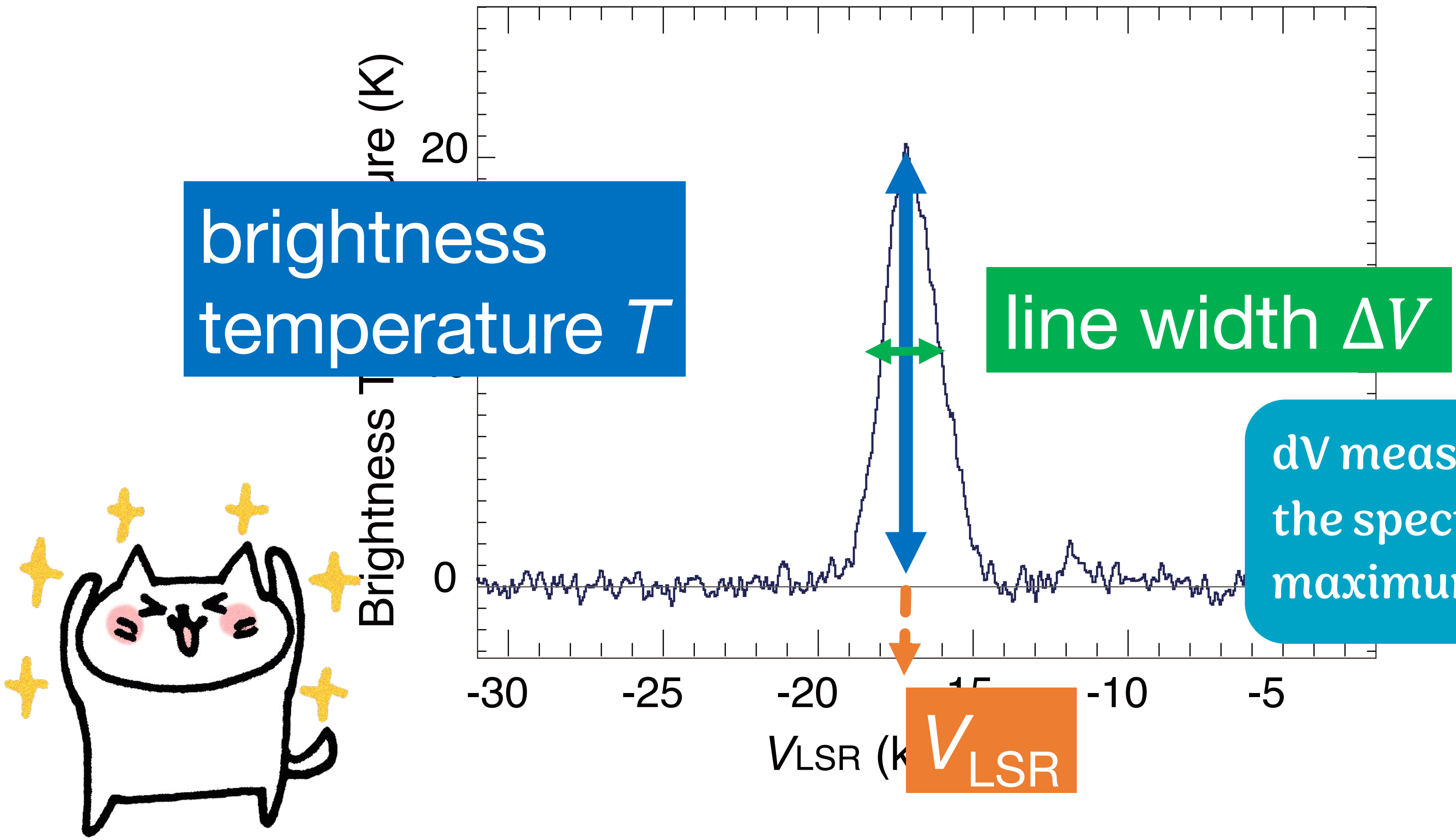
Doppler effect

The **Local Standard of Rest (LSR)** velocity is the velocity of an object relative to the average motion of nearby stars in our galaxy.



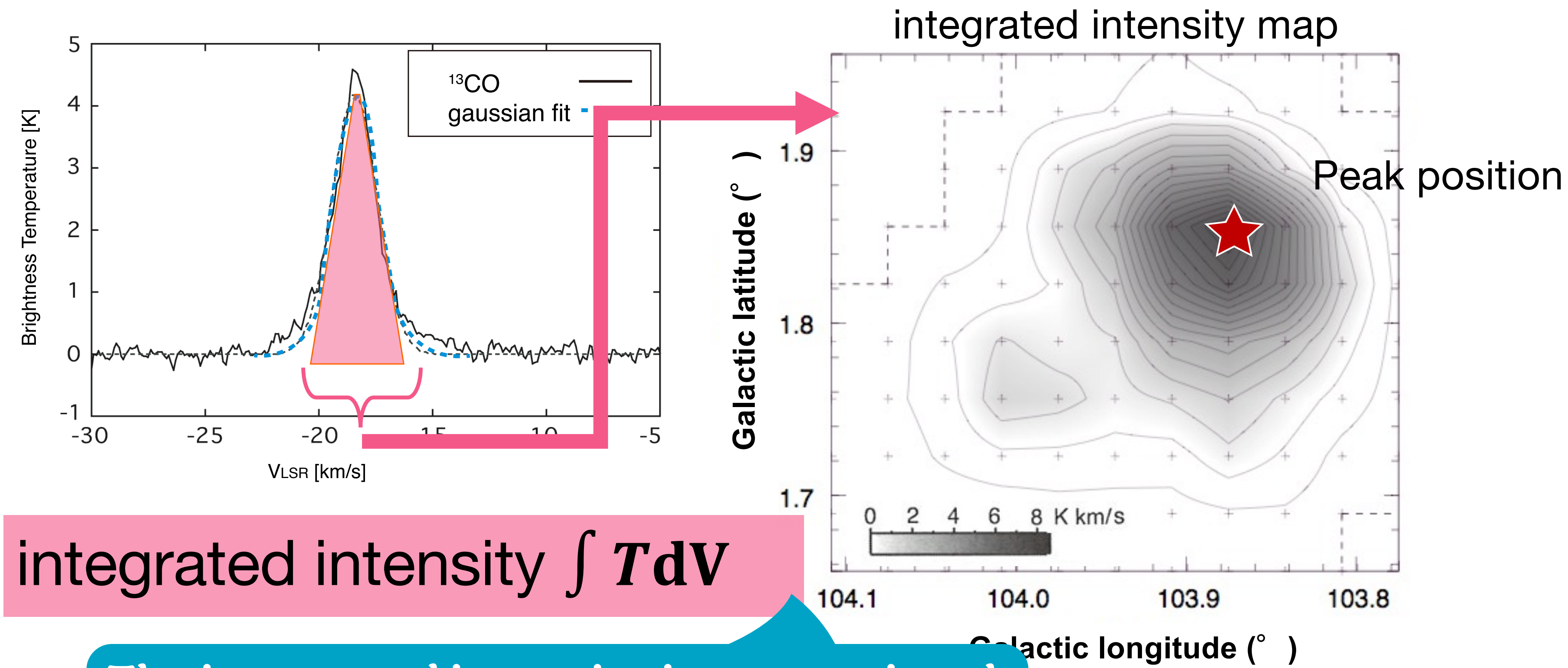
This transformation allows us to interpret the spectrum in terms of the physical properties and motion of the molecular cloud.

Reveals dynamics through Doppler shifts of lines



dV measures the width of the spectral line at half its maximum intensity.

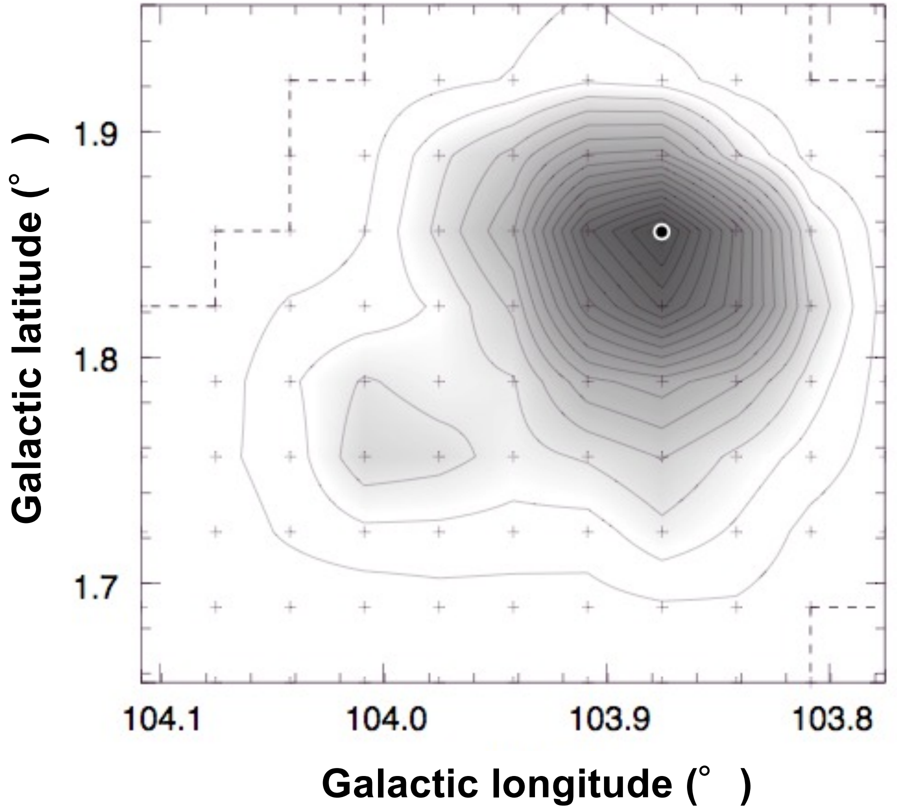
Integrated intensity map



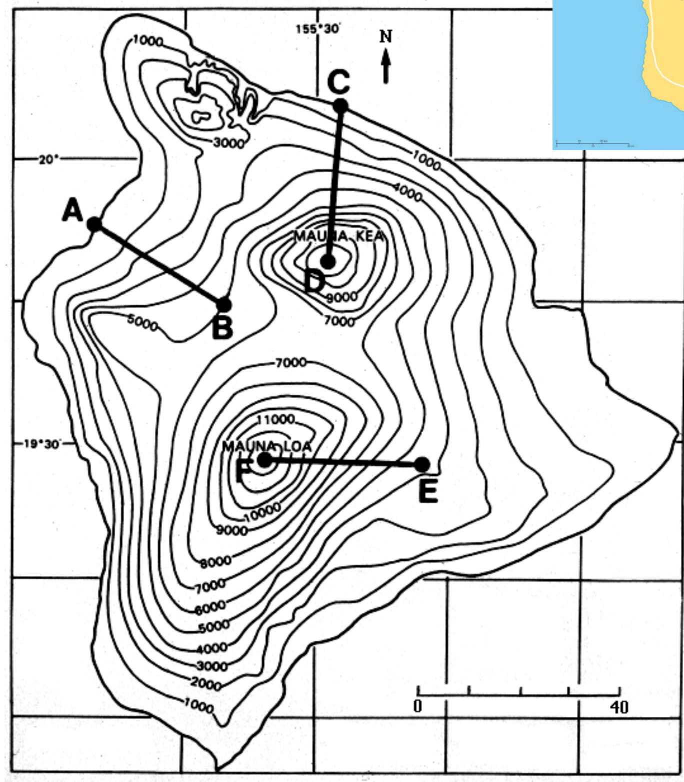
integrated intensity $\int T dV$

The integrated intensity is proportional to the number of molecules.

Integrated intensity map



the integrated intensity map of S134



the topographic map of Hawaii Island

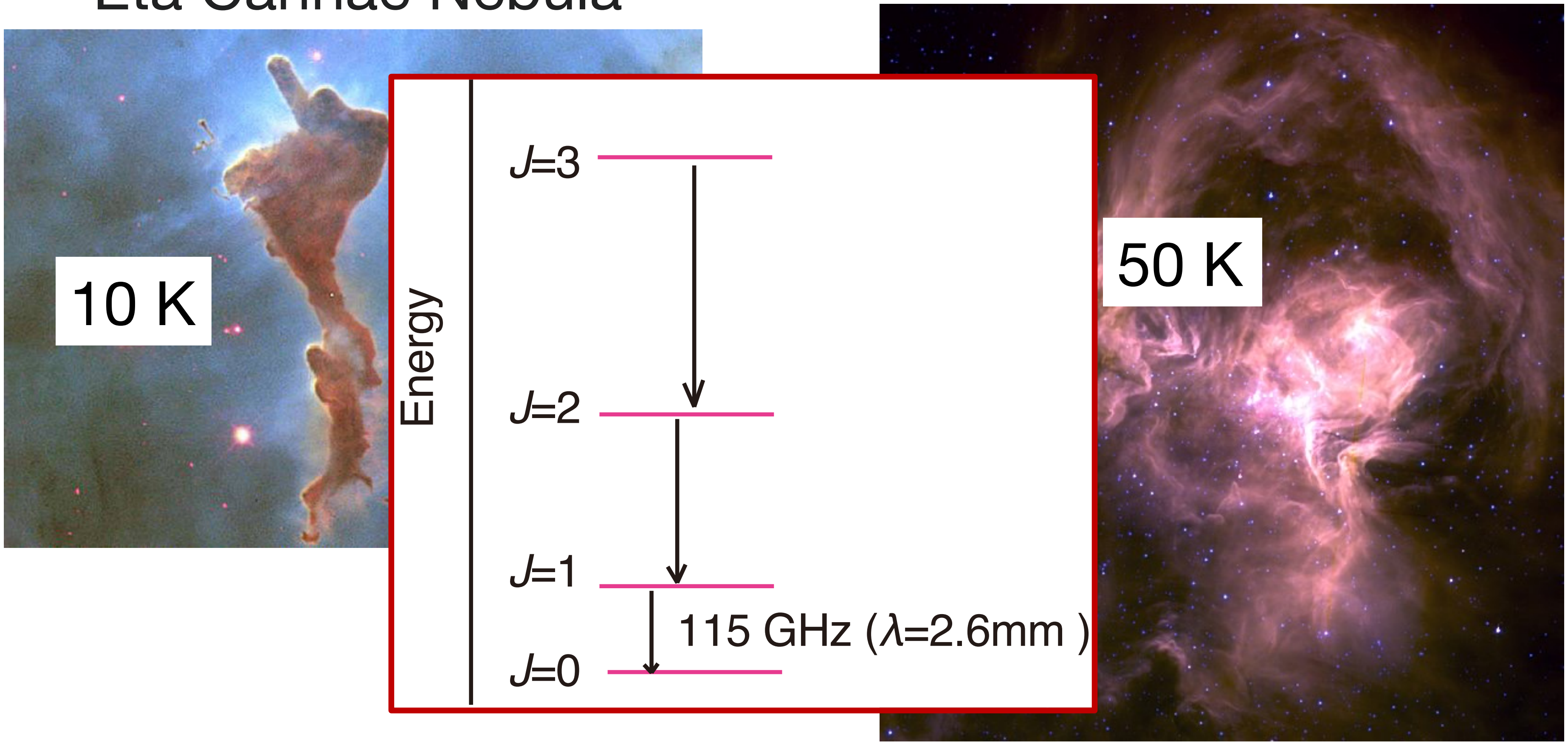
Key Concepts in Molecular Cloud Analysis

1. Excitation Temperature
2. Optical Depth
3. Column Density

1. Excitation Temperature

Eta Carinae Nebula

W40



2. Optical Depth τ

Optical depth measures how opaque or transparent a medium is to radiation.

- The fog represents the medium that radiation is passing through
- The car's headlights are our radiation source
- The slight dimming we see is the effect of optical depth

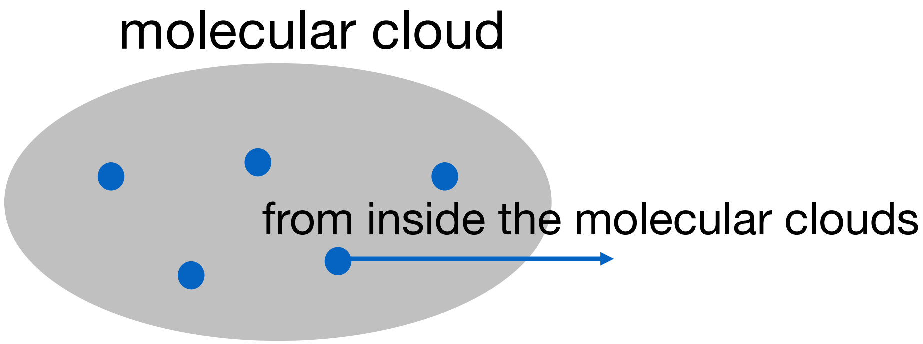
Optical depth is a convenient way to refer to the 'thickness' of a cloud in terms of its transparency to radiation.

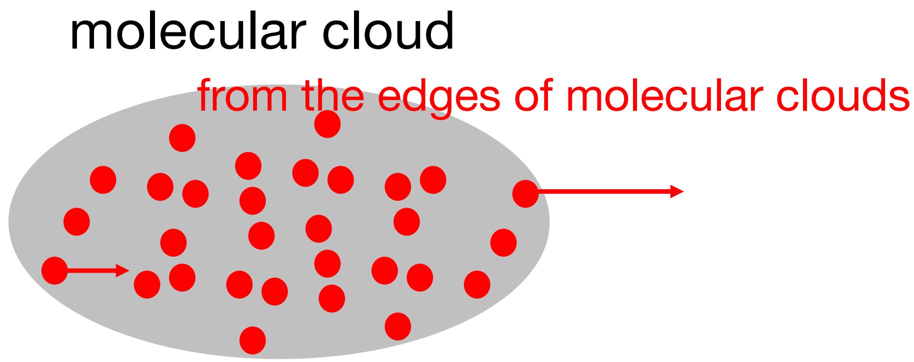
✓$\tau < 1$: Optically thin

most radiation passes through

✓$\tau > 1$: Optically thick

most radiation is absorbed or scattered





^{12}CO and ^{13}CO

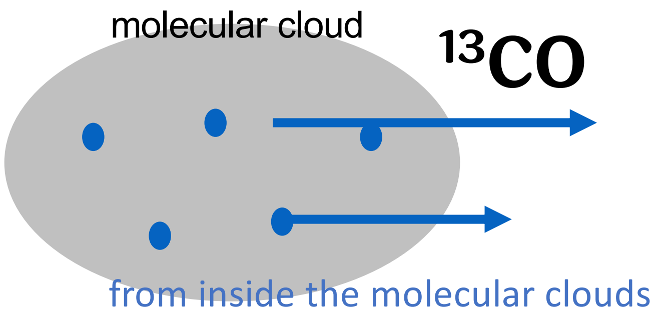
- ✓CO is one of the most abundant molecules in molecular clouds
- ✓CO's J=1-0 transition occurs at low energy and is easily excited
- ✓High CO abundance increases optical depth

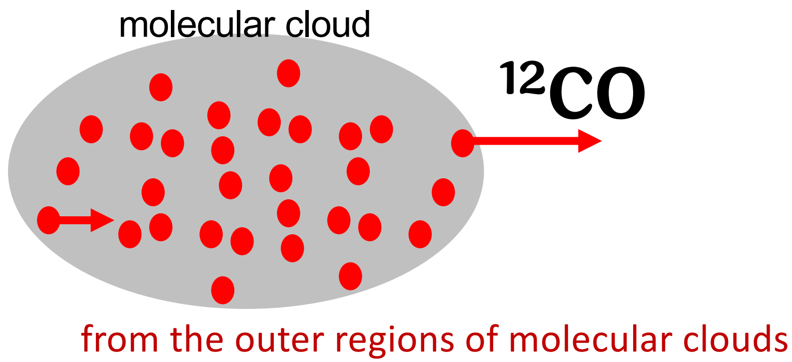
Abundance:
This ratio means that for every 91 carbon atoms in a typical molecular cloud, about 90 will be ^{12}C and only 1 will be ^{13}C.

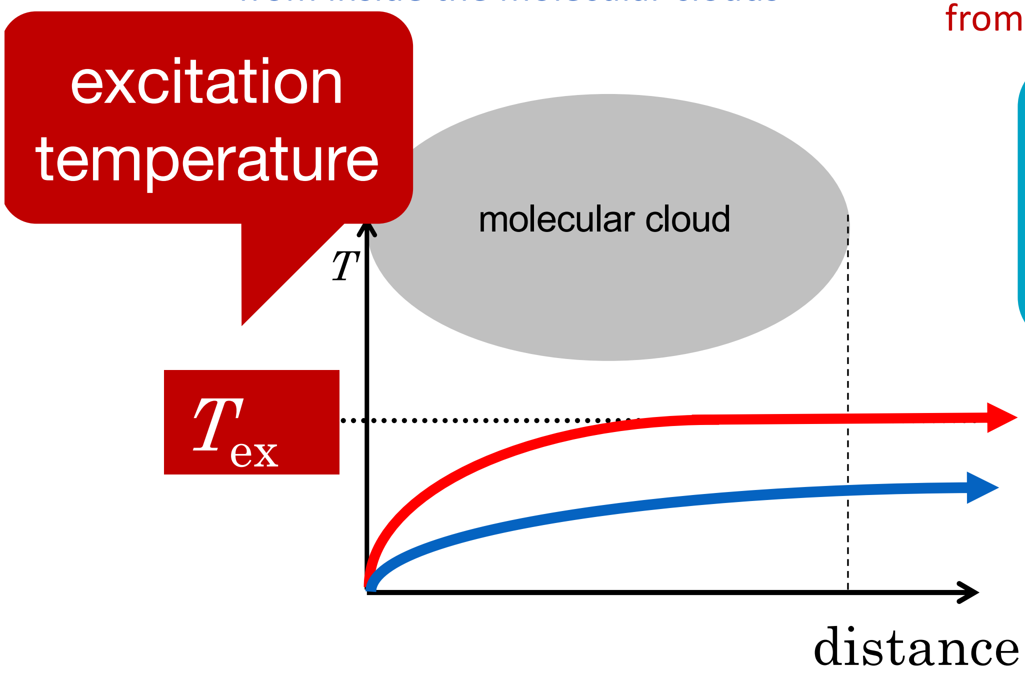
- ✓$^{13}C/^{12}C$ ratio is 1:90

^{12}C and ^{13}C are isotopes of carbon

^{12}CO is typically optically thick, ^{13}CO is optically thin







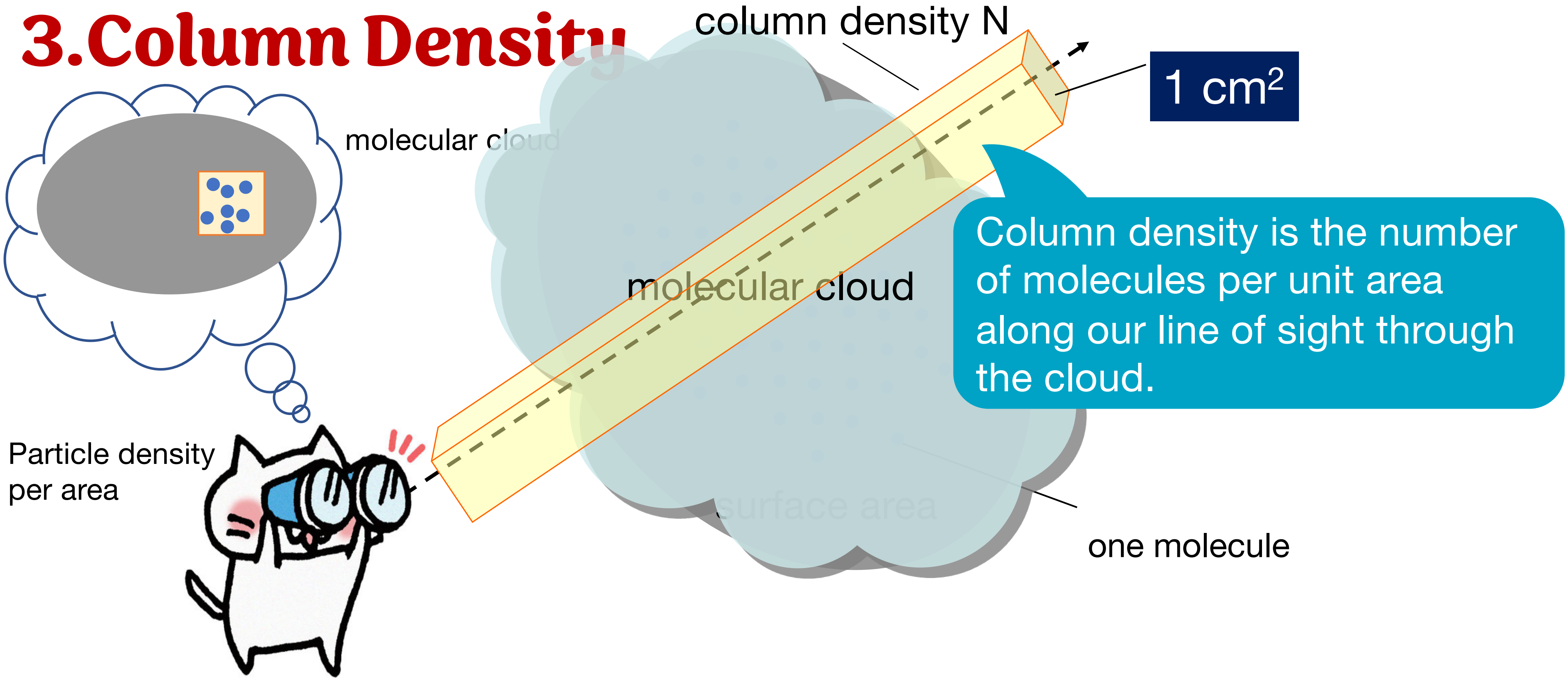
Excitation temperature is a measure that helps us understand how energetic the molecules are, rather than their physical temperature.

^{12}CO (Optically thick) ⇒ T_{ex}

^{13}CO (Optically thin) ⇒ τ

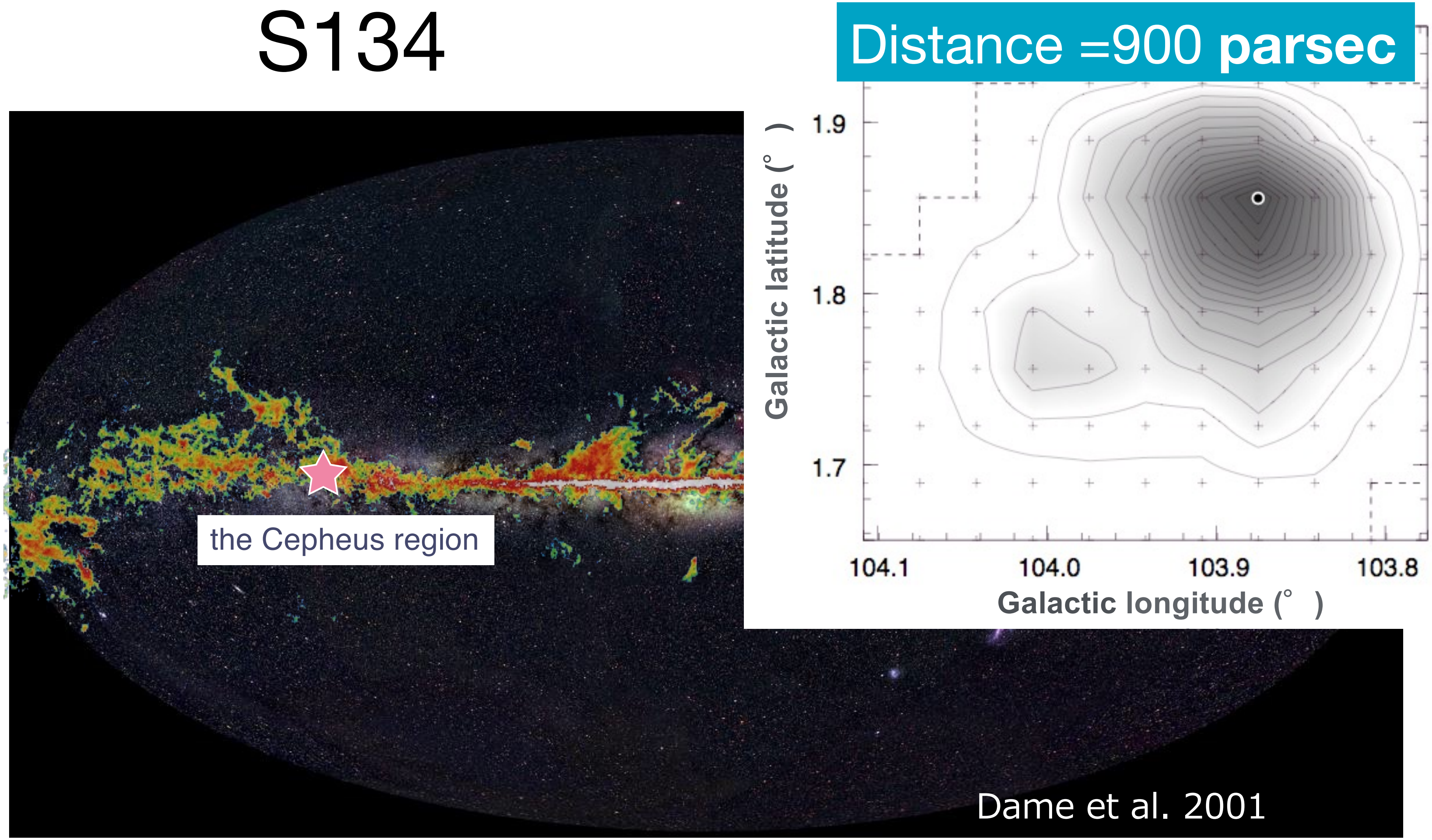
※ τ is a dimensionless quantity.

3.Column Density



Exercise

S134

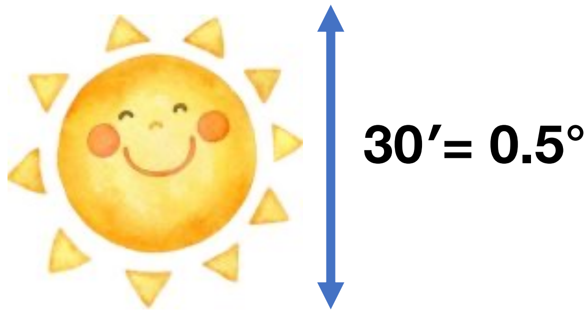

Distance =900 parsec
the Cepheus region
Galactic latitude (°)
1.9
1.8
1.7
104.1
104.0
103.9
103.8
Galactic longitude (°)
Dame et al. 2001

Angular and Distance Units in Astronomy

◇ **Angular Units**

1°＝ 60′

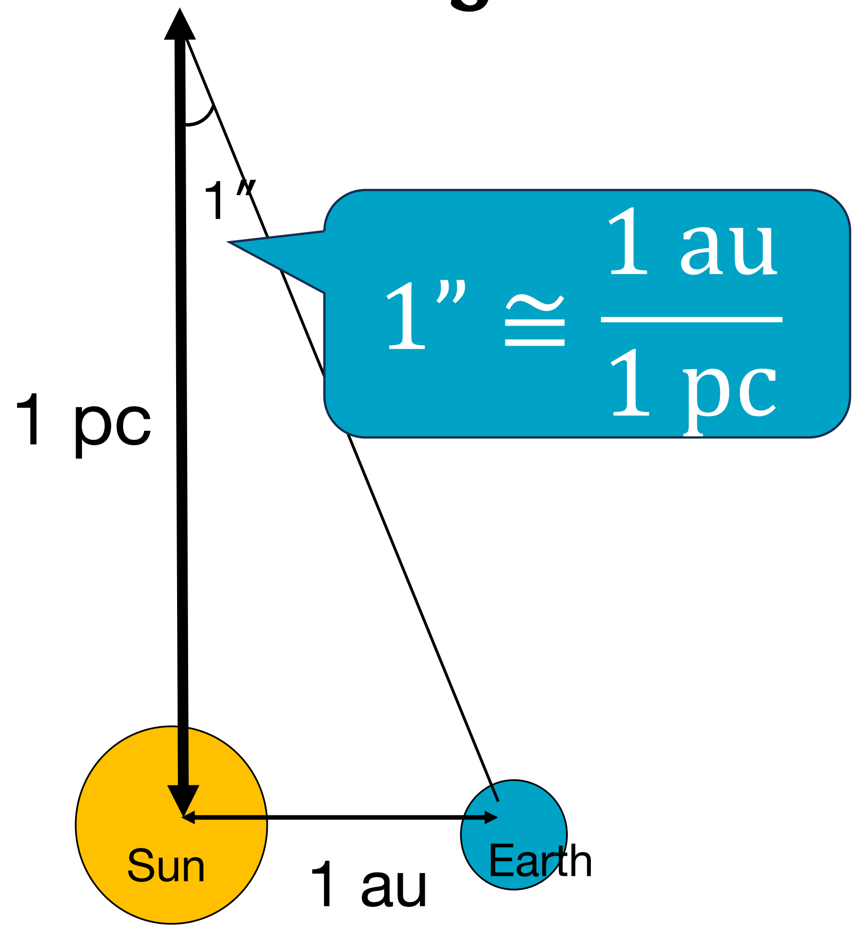
1′＝ 60″ ※**1°＝π/180 [rad]**



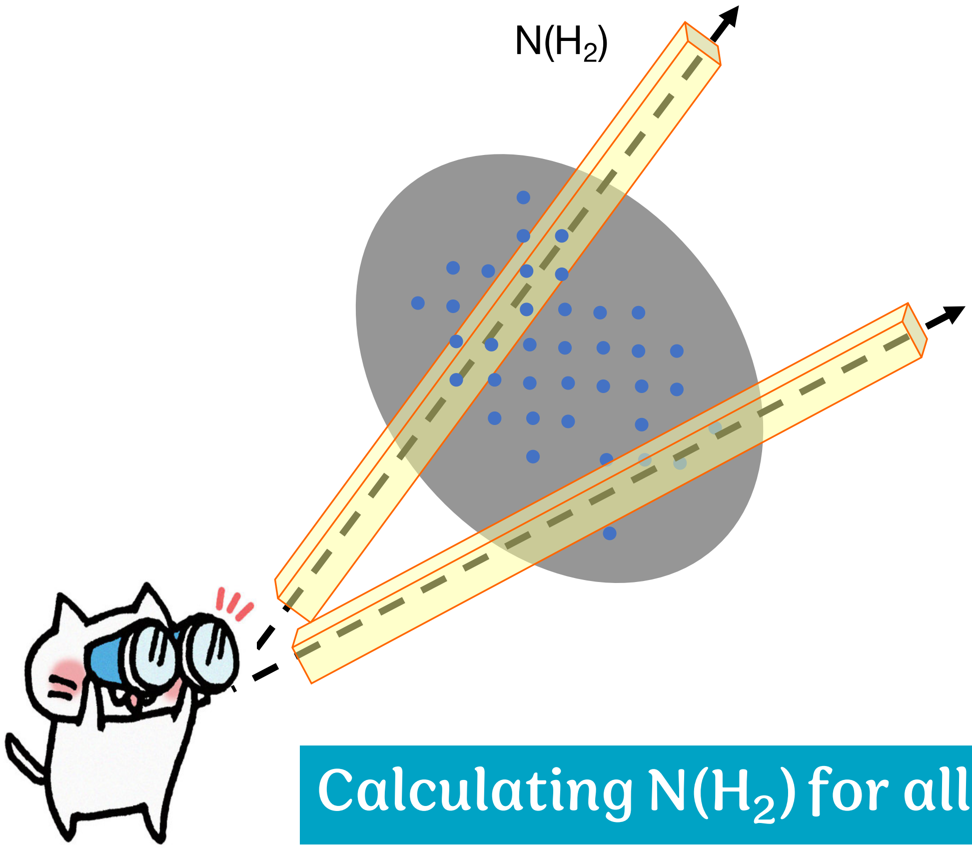
◇ **Distance Units**

★An **astronomical unit (=au)** is defined as the average distance between the Earth and the Sun. **1 au ～ 1.496×10^{13} [cm]**

★ A **parsec (=pc)** is defined as the distance at which 1 au subtends an angle of 1“. **1 pc ～ 3.08×10^{18} [cm]**



6 The Area of the Molecular Cloud and the Distribution of $N(H_2)$

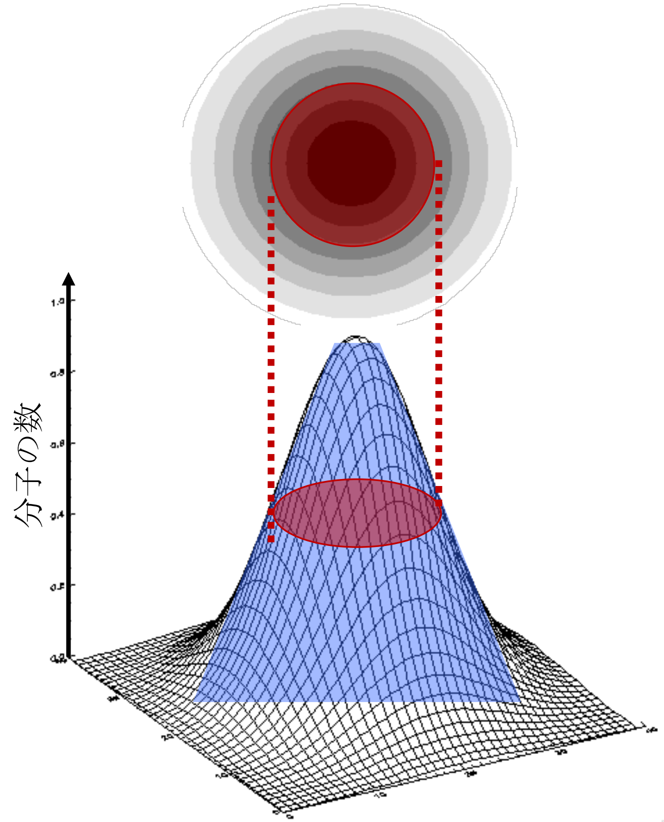


Real molecular clouds are not uniform:

- Density varies throughout the cloud
- Column density changes depending on observation direction

Calculating $N(H_2)$ for all directions would be a complex task.

we'll use a simplified approach:



✓Assumption:

- ✓More **^{13}CO** indicates more material overall
- ✓^{13}CO serves as our density tracer Analyze

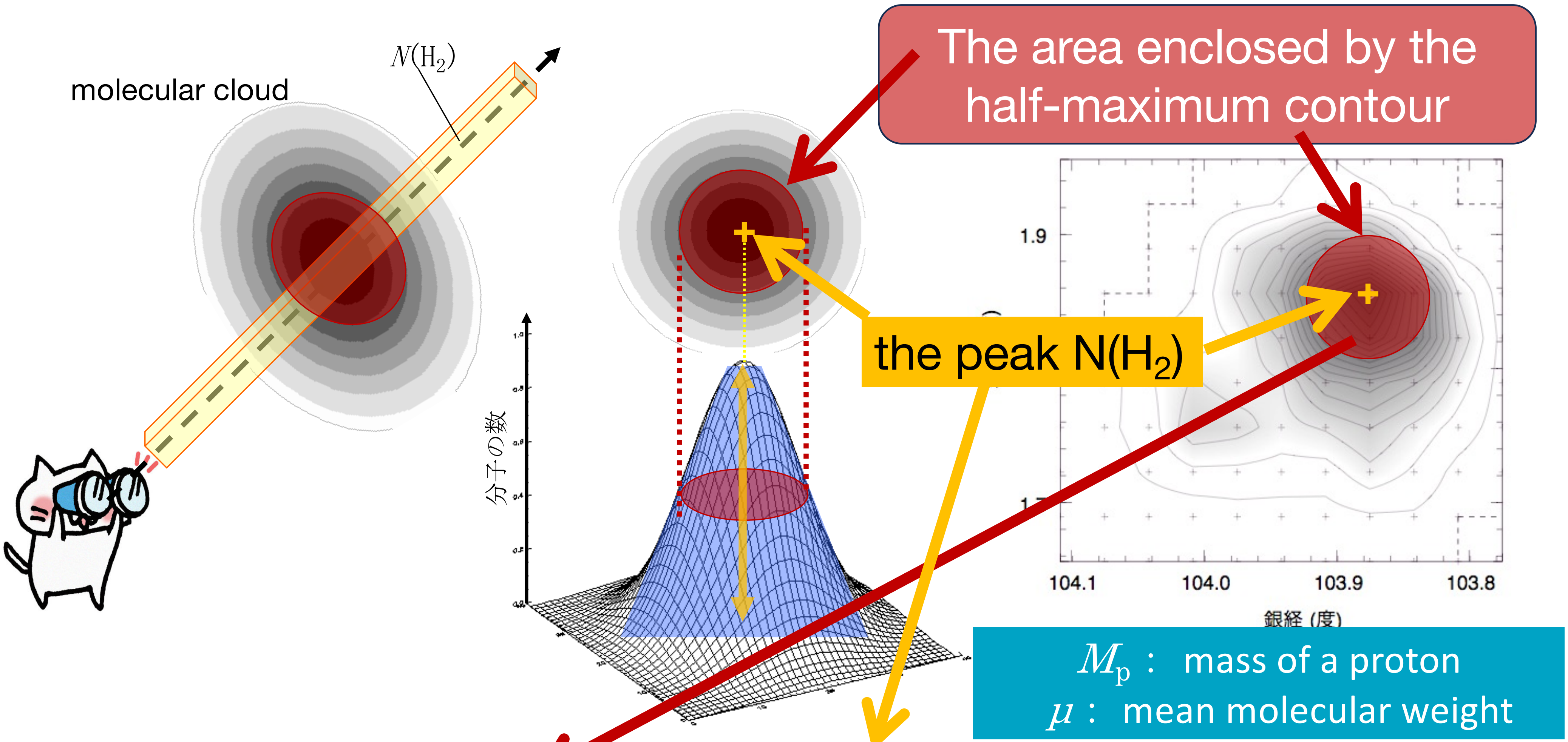
✓**^{13}CO map**: Find brightest spot - our **ground zero** (reference point)

✓Define cloud area (**S**):

- ✓Use line where brightness drops to **half** its maximum
- ✓ For 2D Gaussian, this area contains ~50% of total cloud mass

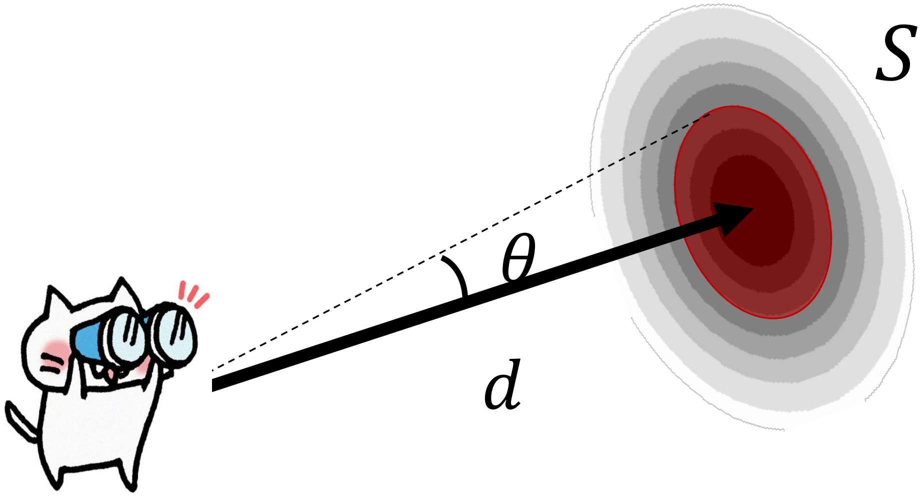
✓Adjust mass calculation:

- ✓Multiply previous formula by $1/\ln(2) \approx 1.44$
- ✓Accounts for Gaussian distribution of material

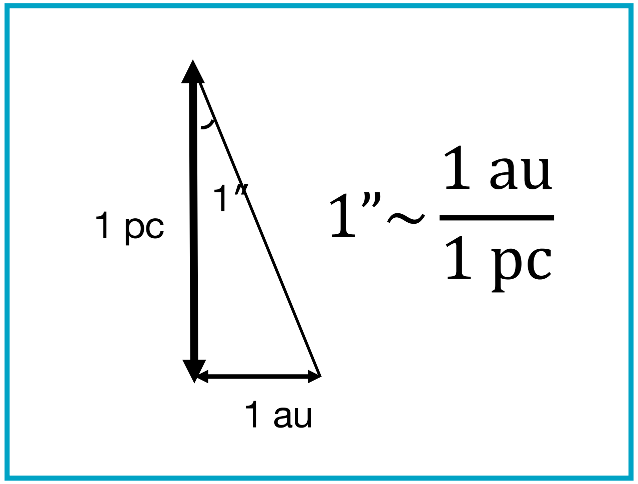


Mass of a molecular cloud = (The area X the peak column density X the mass of a single molecule ($\mu\, m_p$)) (1/ln2)

S can be calculated from its angular size and distance.

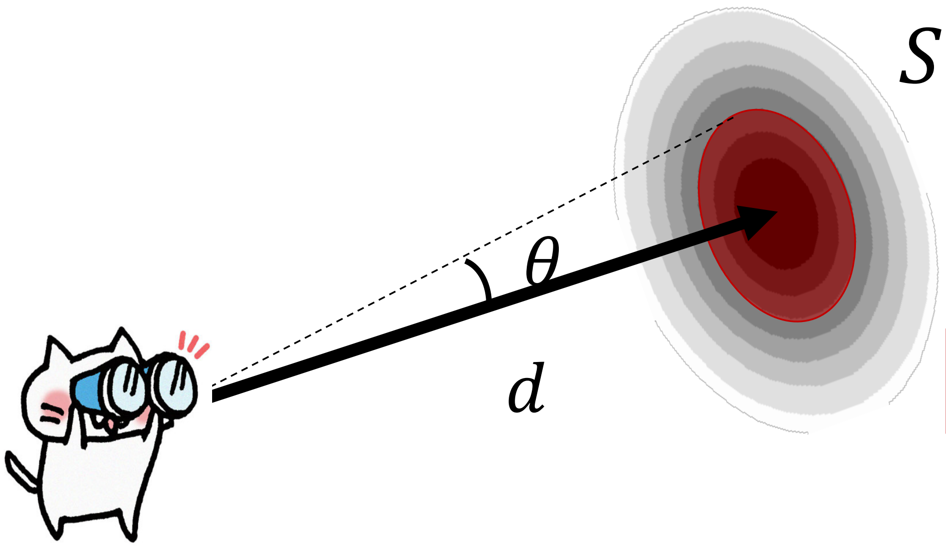


1. How big the cloud looks in the sky - we call this its angular size, θ
2. How far away it is - we measure this in parsecs, and we know the distance to S134, d=900 pc



- ✓ S [cm²]: The area or extent of the molecular cloud
- ✓ θ ["]: The angular size of the molecular cloud in arcseconds
- ✓ d [pc]: The distance to the molecular cloud in parsecs

S can be calculated from its angular size and distance.



When the angular size is very small, the value of the angle in radians is so small that the following relationship can be used.

$$1'' \sim \frac{1\ \mathrm{au}}{1\ \mathrm{pc}}$$

$$\boxed{r = \text{apparent size}(\theta) \times \text{distance(d)}}$$

Example: $\theta = 10'', \mathrm{d} = 200\ \mathrm{pc}$

$$r = 10'' \times (1\ \mathrm{au}/1\ \mathrm{pc}) \times 200\ \mathrm{pc}$$

$$\boxed{S \sim \pi(\theta \times d \times \{1\ \mathrm{au}\})^2}$$

- For a two-dimensional Gaussian function, the total mass is proportional to the product of the maximum $N(H_2)$ value and the area of the Full Width at Half Maximum (FWHM).
- The proportionality constant for this relationship is 1/ln2.
- S as the area enclosed by the contour line where the integrated intensity is half of its maximum value.
- S can be calculated from its angular size and distance.

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