# Spectral Line Science

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DARA - Zambia 2016
Based on ERIS 2015 talk by Anita Richards

# Spectral line science

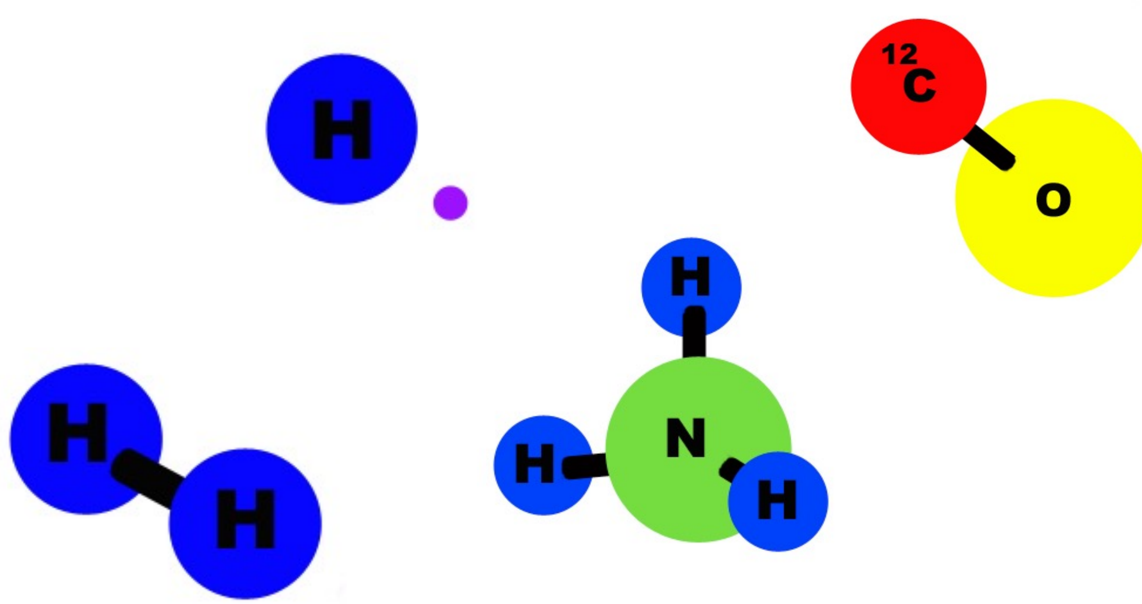
- Kinematics
    - Doppler velocities + proper motions = 3D dynamics
- Conditions
    - Temperature, pressure number density, radiation
- Chemistry
    - Composition, evolution
- Fundamental physics
    - Magnetic fields, maser physics …

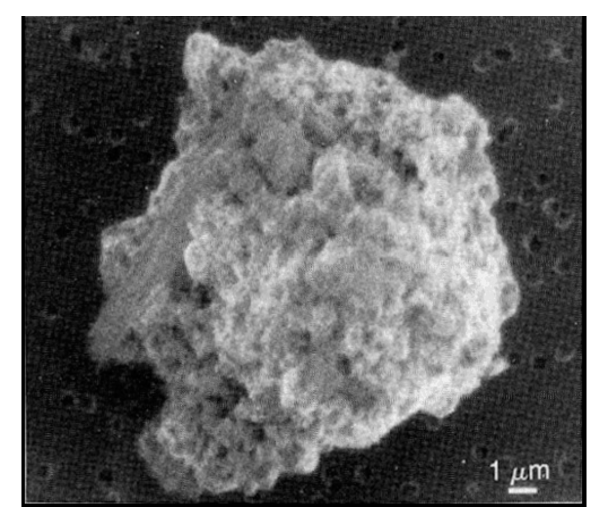
# Atoms and Molecules in Space

- There is a lot of “stuff” between the stars
  - > 200 molecular species have been identified
  - Gas and dust is concentrated in molecular clouds
    - molecular clouds are where star formation takes place
  - A wide range of densities and temperatures
- Atoms and molecules in space produce spectral lines which act like fingerprints that we can use to identify them
- Chemistry in space
- Spectral lines are powerful diagnostics of the physical and chemical conditions in astronomical objects

# Molecular cloud composition

- Molecular clouds are composed of mostly hydrogen **$H_2$(~75%)**, helium **He** (~25%), **dust** (1%), Carbon Monoxide **CO** ($10^{-4}$ by number) with >200 other molecules with low abundance

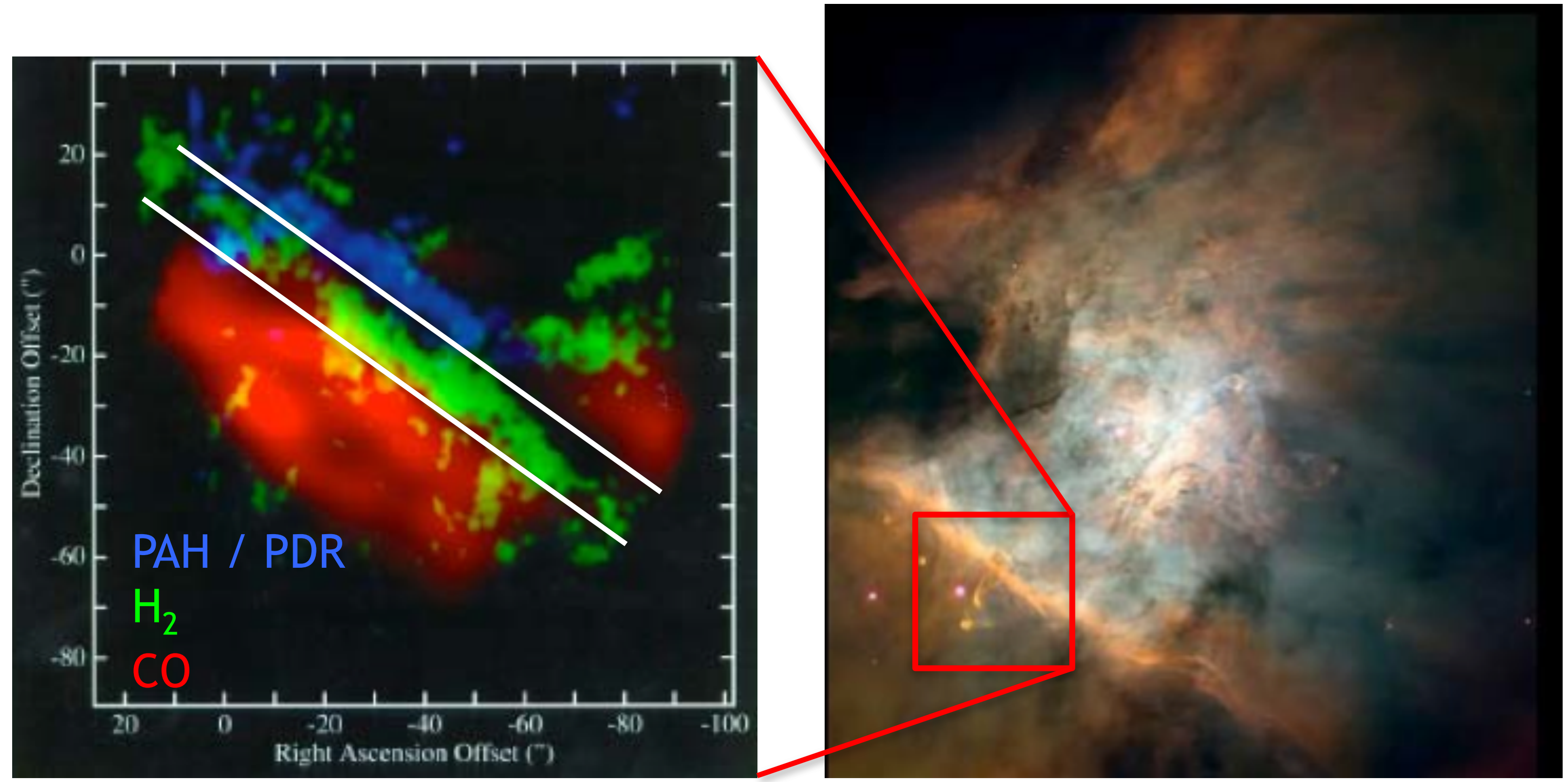


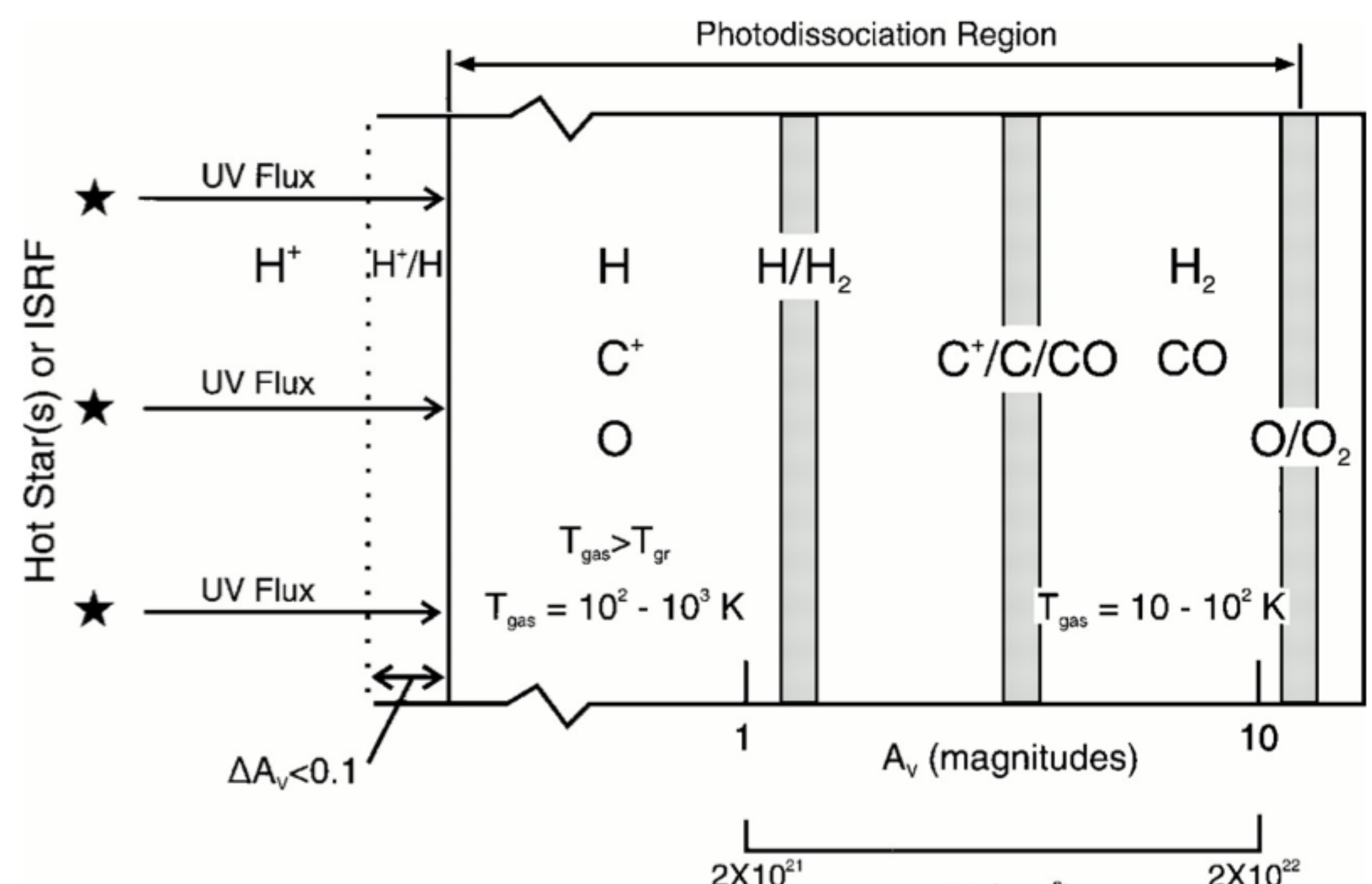

http://www.cv.nrao.edu/php/splat/http://physics.nist.gov/cgi-bin/micro/table5/start.pl

# Molecular cloud composition

- Temperature variations in the ISM lead to transition zones called **photodissociation regions** or **PDRs.**
- These exist between the hot (ionised) and cold (neutral) ISM.
- The physical and chemical properties of a PDR change with distance as the photons are absorbed
- When the density of dust and molecules is high enough it shields the interior from UV radiation
- This leads to a rich variety of atoms and molecules

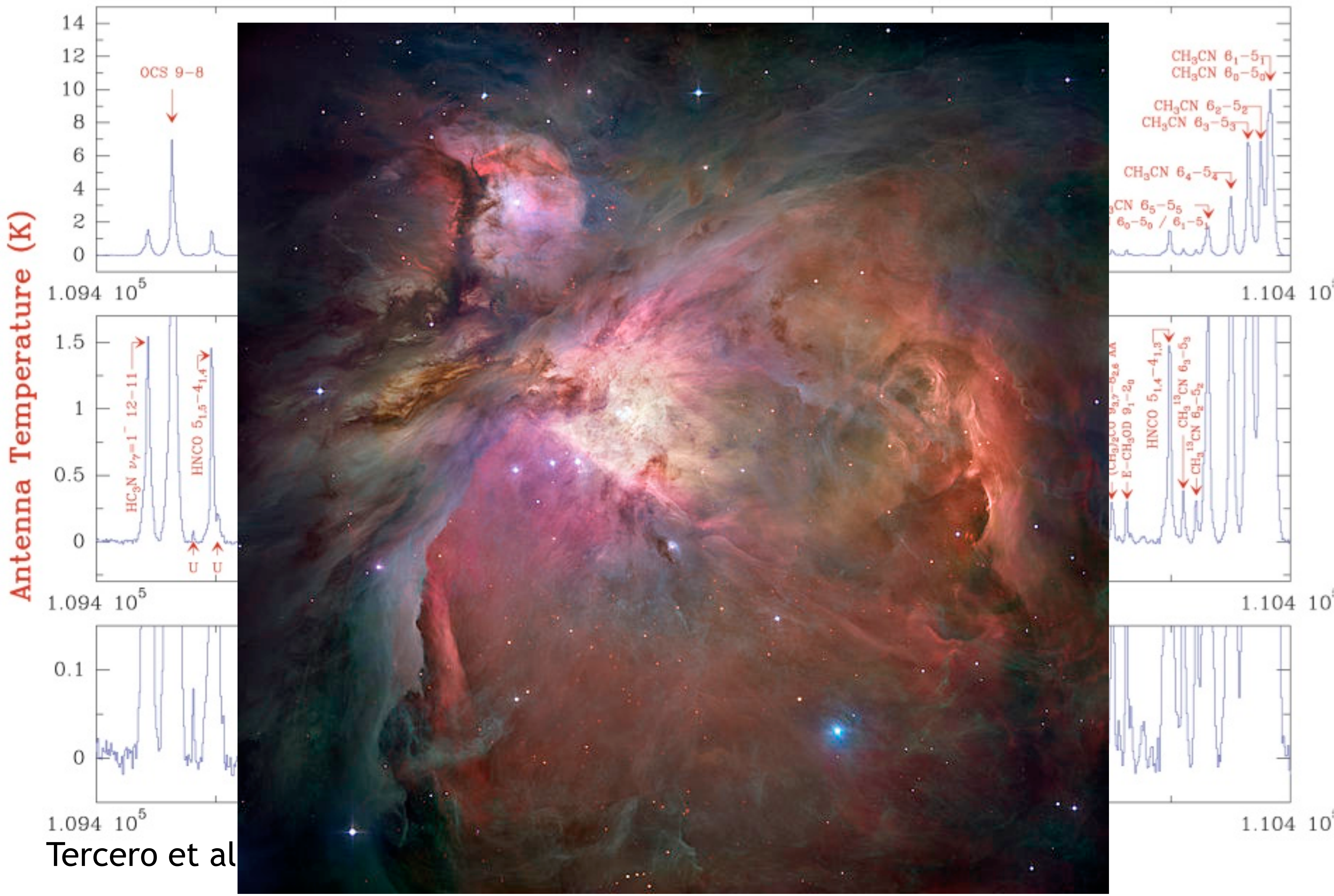



Tielens et al. 1993



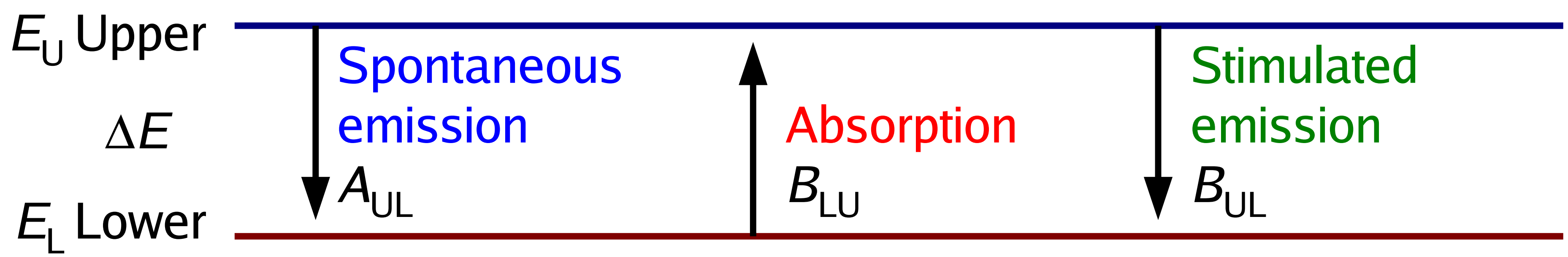

D. J. Hollenbach & A. G. G. M. Tielens ARAA 35, 179

# Orion KL survey at 3mm (100 GHz)




Tercero et al

# Origins of spectral lines



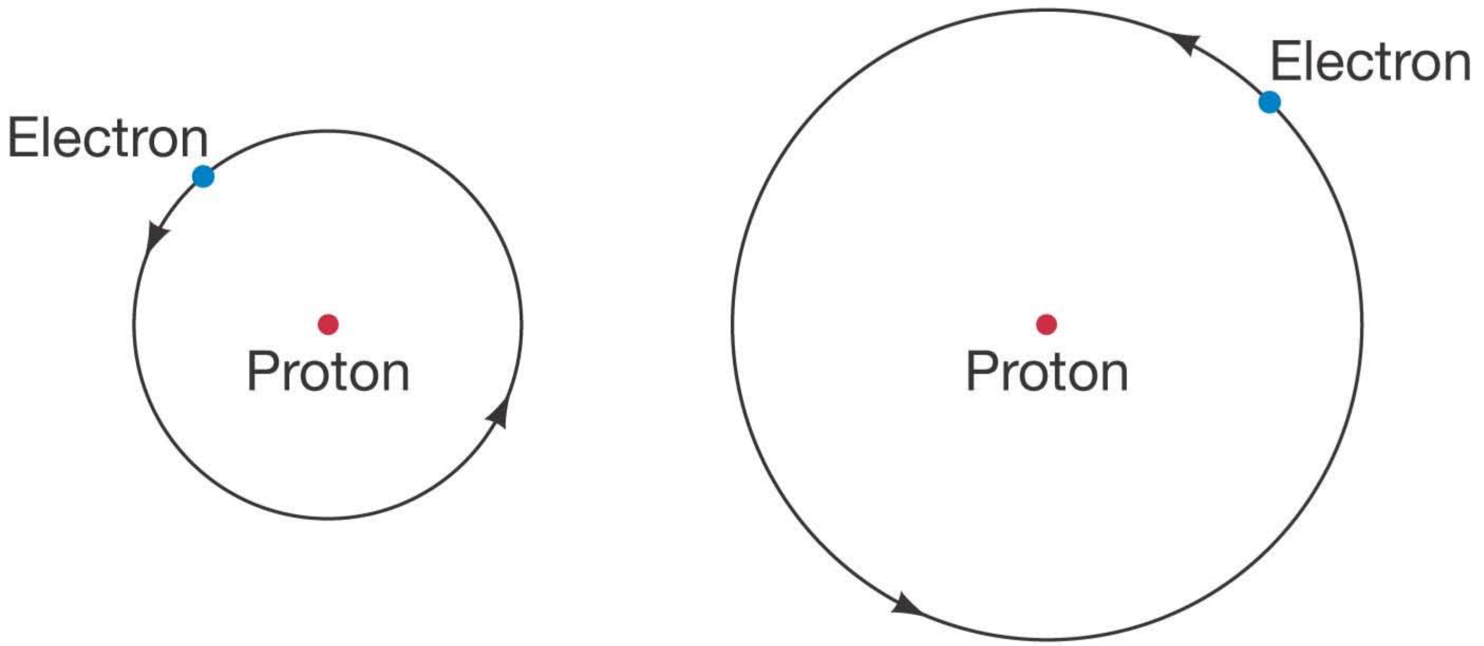

- Spontaneous emission rate depends on temperature
  - i.e Boltzmann distribution of molecular energies
- Absorption rate also depends on the energy field
  - Energy density $U_\nu$
- Stimulated emission
- The Einstein coefficients describe the probability of emission and absorption

# Origin of spectral lines

- Spectral lines form due to electronic transitions in atoms and molecules
    - Electron transitions between orbits
    - Vibrational and rotational states in molecules (requires a dipole moment)
    - Spin-flip transitions (i.e. HI)

# Electron transitions

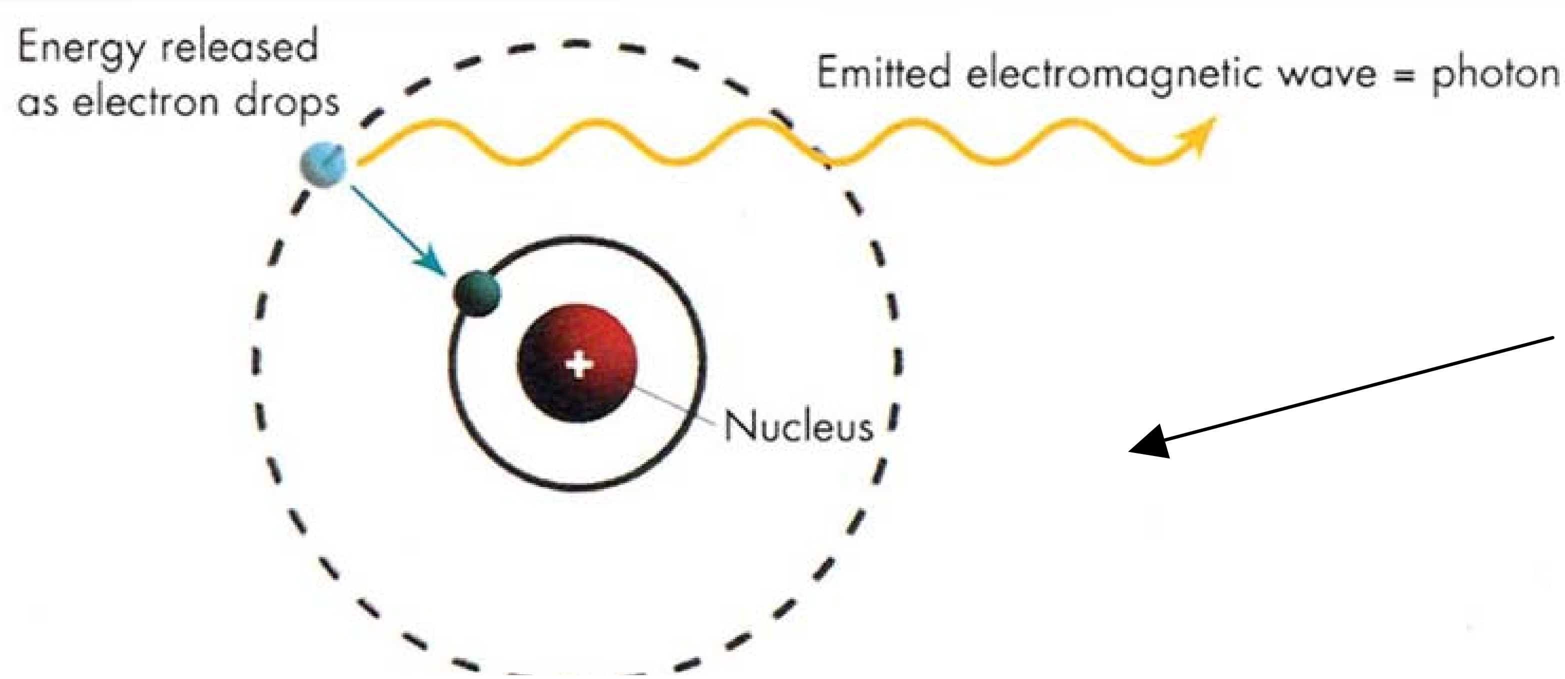
- **Emission energies** correspond to the energy differences between quantised electron orbits
- **Absorption** occurs when atoms / molecules absorb photons of the correct energy

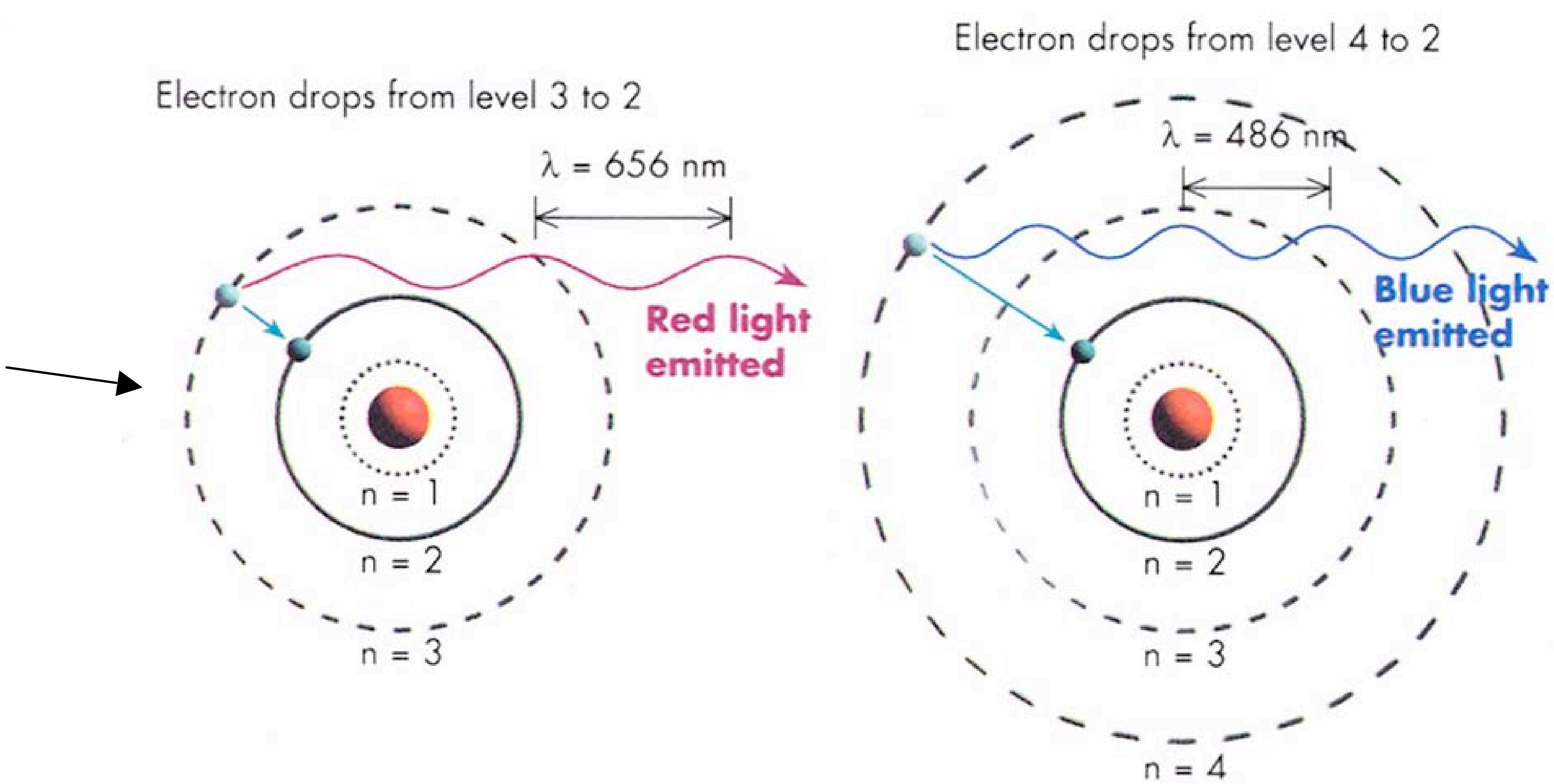

(a) Ground state

(b) Excited state

# Electron transitions




Energy is released when an electron drops from an upper to a lower orbit, causing the atom to emit EM radiation.

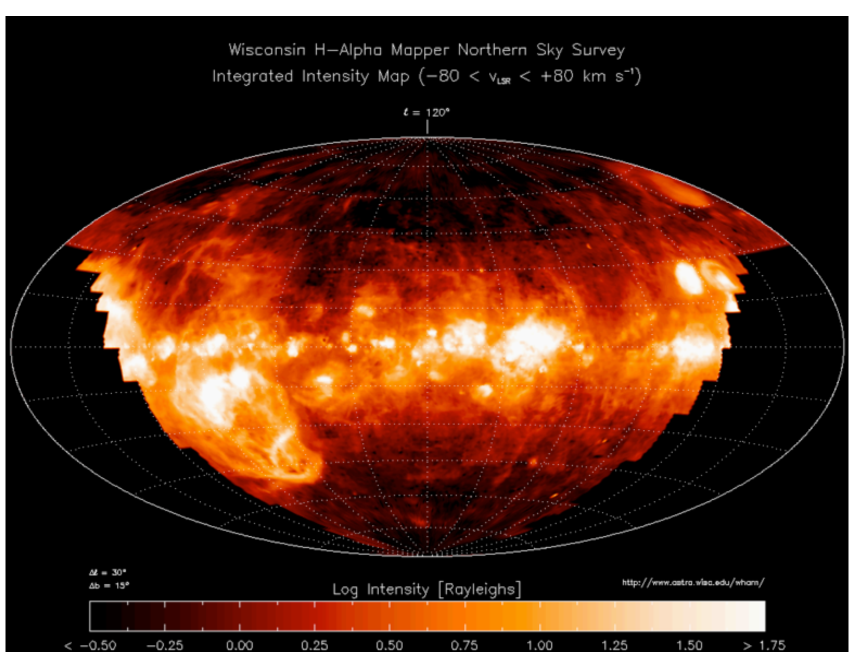


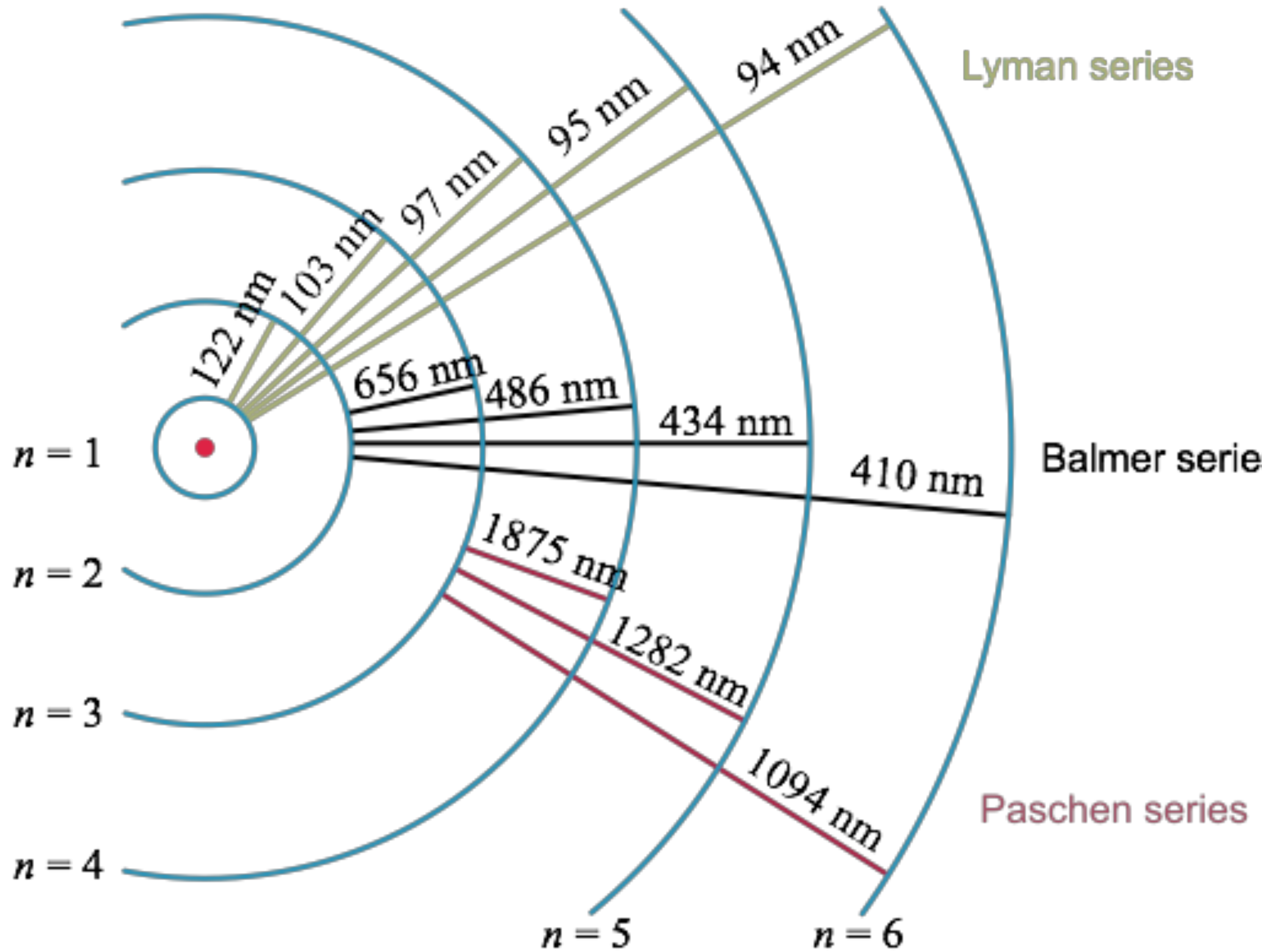

The light emitted has a wavelength corresponding to the energy difference between the two electron energy levels $\lambda = \Delta E/hc$

# Electron transitions

Transition between energy levels results in emission at discreet wavelengths

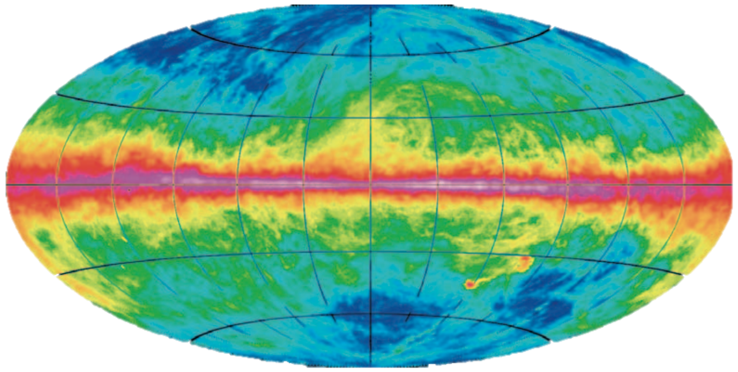
- These are called Lyman, Balmer, Paschen
- Due to the higher energy the emission is at much shorter wavelengths / higher frequency
- http://astro.unl.edu/naap/hydrogen/hydrogen.html
- Hα emission is generated when an electron in hydrogen moves from n=3 to n=2
- This is most likely to happen when the hydrogen captures and electron
- It is a good indicator of ionised gas
- Ionisation on large scales requires the presence of a massive star

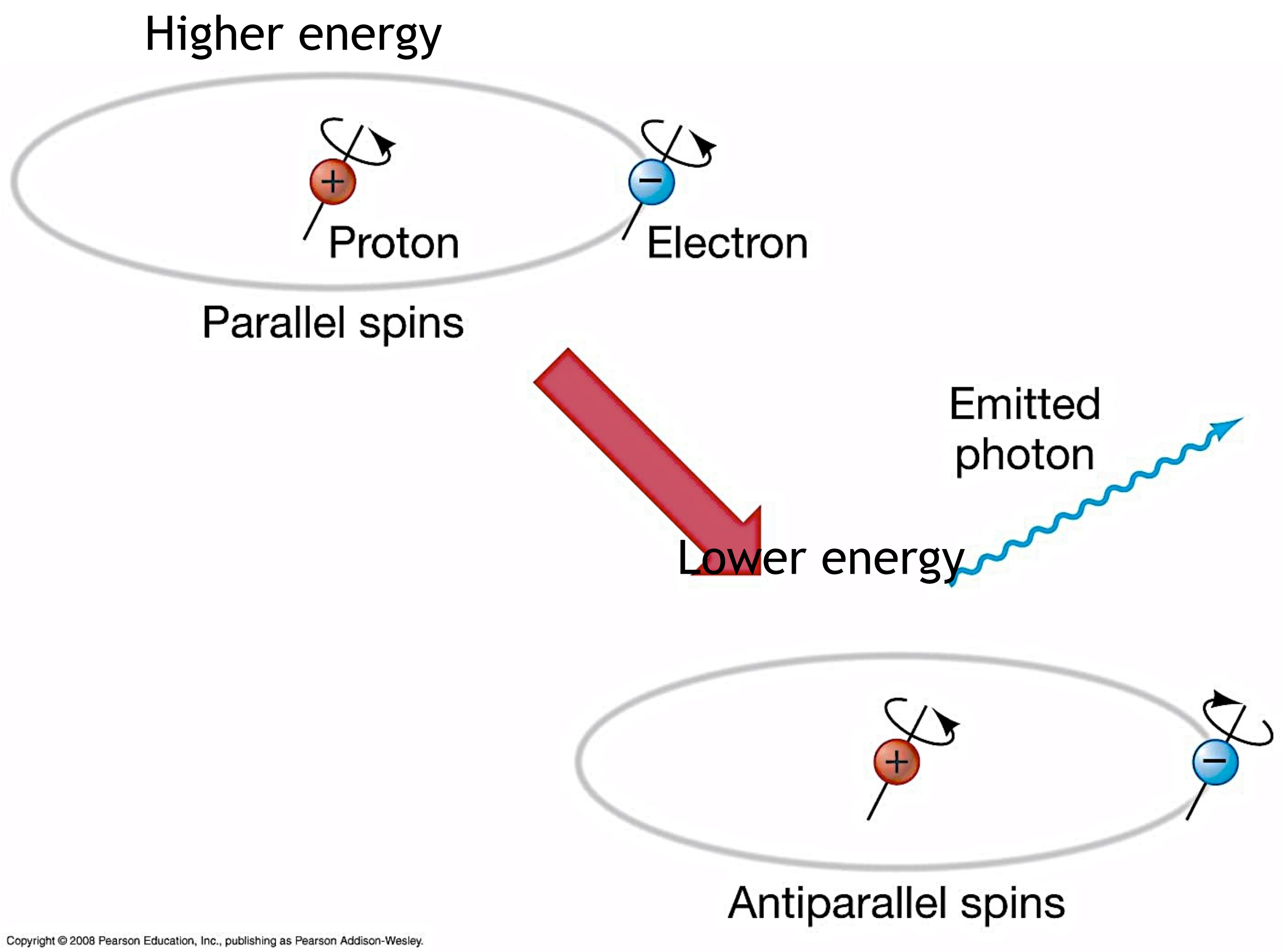



http://astro.unl.edu/naap/hydrogen/hydrogen.html

# 21-cm line



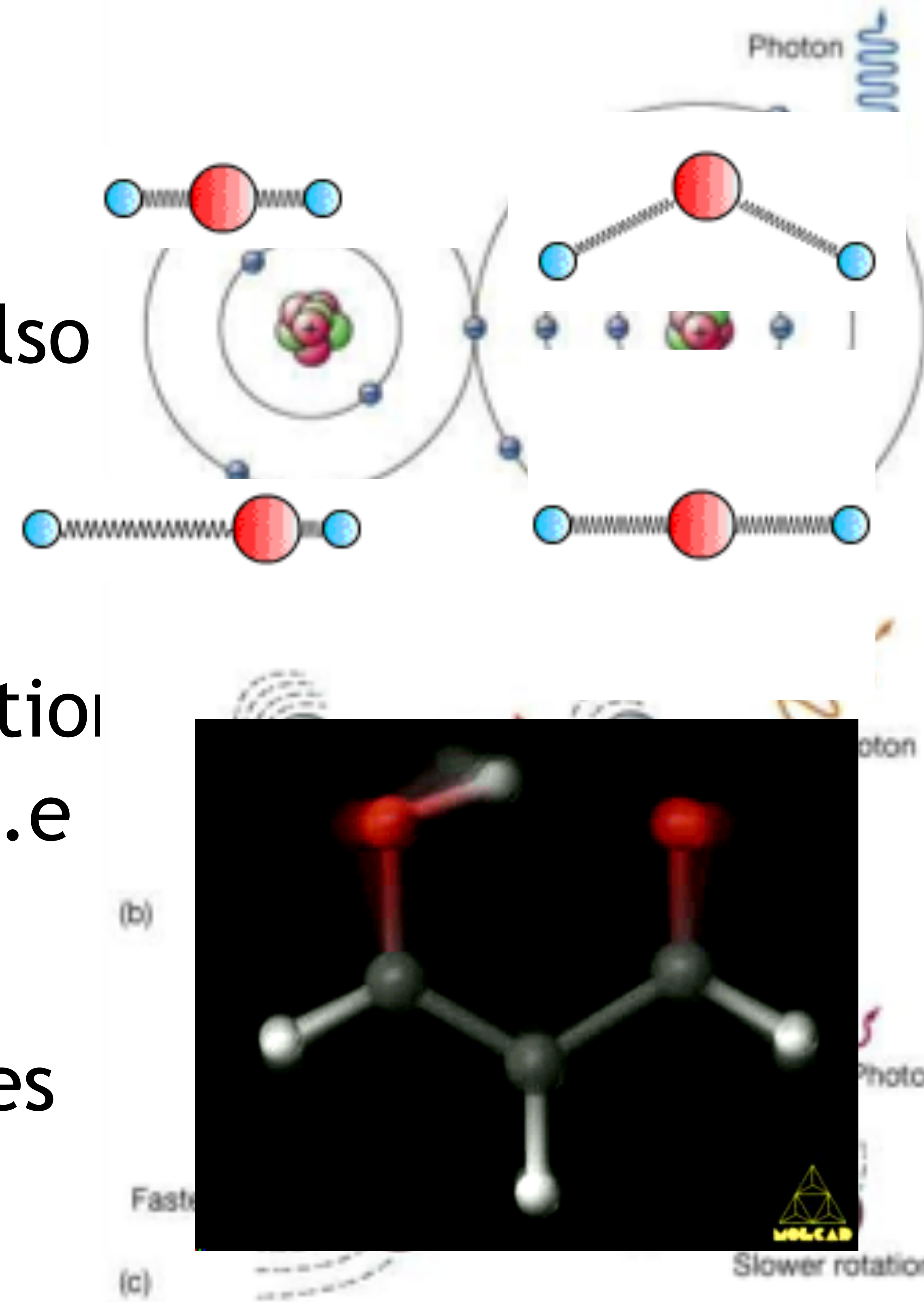



- Observations of the 21 cm line in 1951 marked the birth of spectral line radio astronomy
- Electrons and protons have a quantum property called **spin** which can be in two orientations relative to the proton
  - Parallel
  - Anti-Parallel
- **Parallel levels have higher energy than Anti-Parallel**
- Flipping between these is the same as the electron being accelerated
- This is a **low energy transition** leading to 21 cm radio waves
- The probability of this occurring is small **$2.9 \times 10^{-15}$ $s^{-1}$**
- 10 million years for a single hydrogen atom
- Despite this we still see 21-cm emission so there must be a lot of hydrogen about!

# Radiation Generation in Molecules

We have shown two ways in which atomic hydrogen emits radiation. Complex molecules also emit radiation:

- **Electronic**, **vibrational**, **rotational** transitions
- Collisional or radiative excitatio
- Energy levels are quantised (i.e discreet)
- Only certain transitions are allowed between energy states

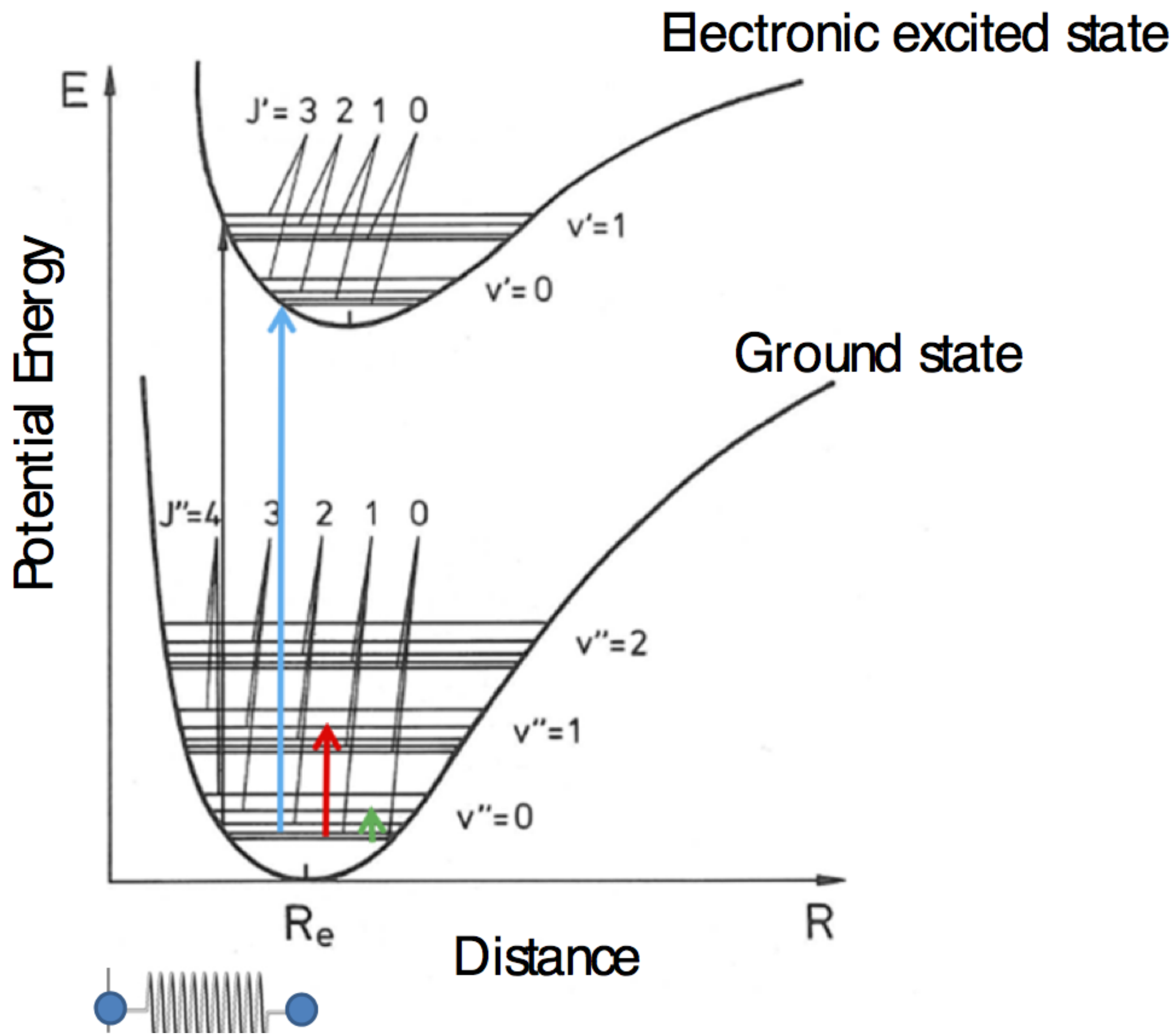


# Energy levels of molecules

Electronic Transitions:
ΔE = 1-15 eV
Visible-UV

Vibrational Transitions:
ΔE = 0.1-1 eV
Infrared

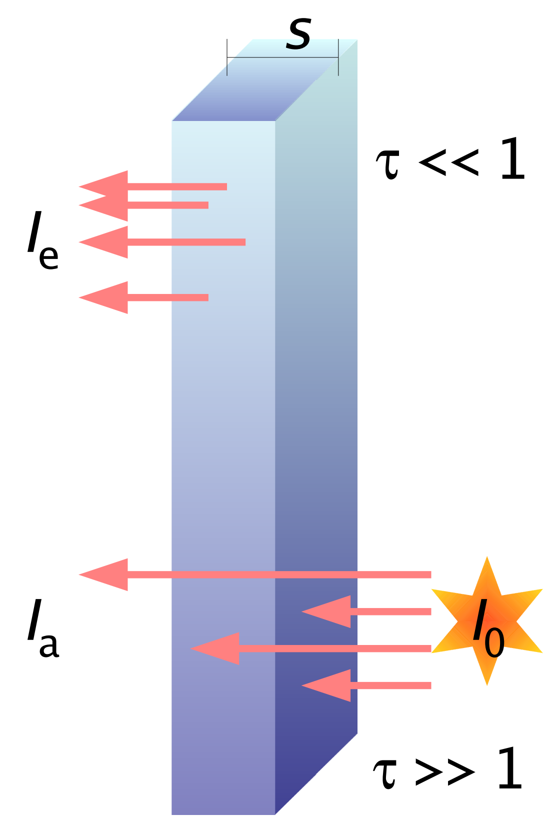
Rotational Transitions:
ΔE = 0.01-0.1 eV
(sub)-Millimeter



# Optical Depth

$$\tau_\nu = \int \kappa_\nu \, \mathrm{ds}$$

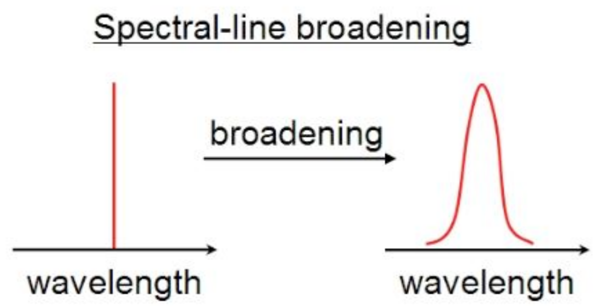
- Describes the fraction of radiation that passes through a medium
    - absorption and scattering
- Integrated absorptivity times path length at a given frequency through a medium of depth S




$$I_\mathrm{e} = S(1{-}e^{-\tau}) \sim S\tau \;(\text{for } 0 < \tau << 1)$$

$$I_\mathrm{a} = I_0 e^{-\tau}$$

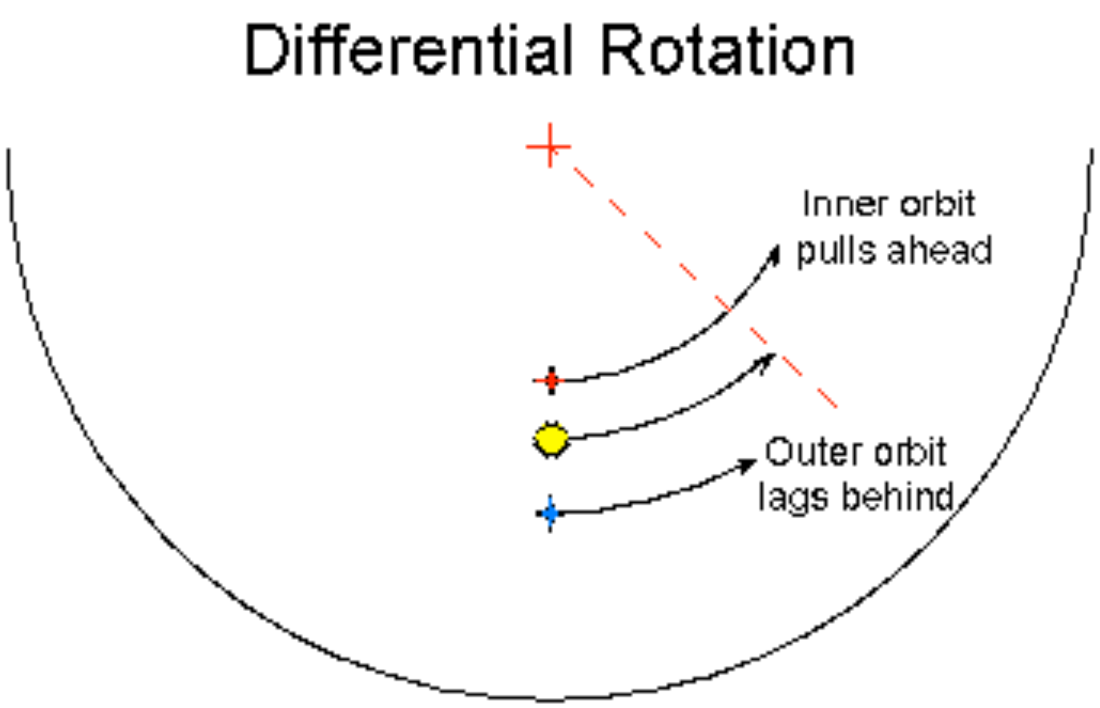
# Line Profiles

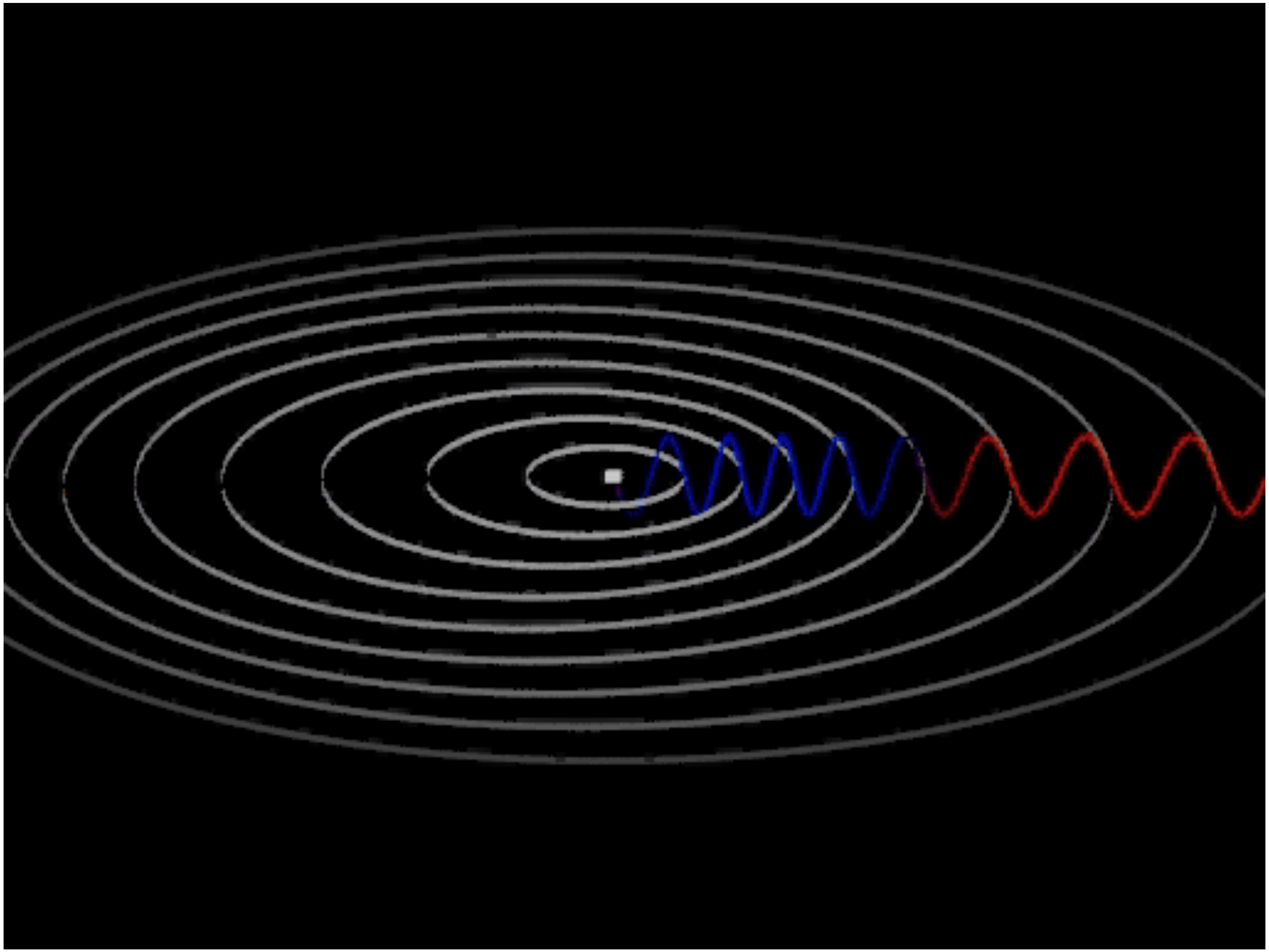



- The quantised transition would produce a line that is infinitely sharp, however:
  - Line broadening:
    - Natural broadening due to the Uncertainty Principle $\Delta E \Delta t = \hbar$
    - Thermal Doppler broadening: Thermal Boltzmann distribution of atoms / molecules
    - Collisional broadening: The collision of other particles interrupts the emission process and shortens the time leading to an increase in the uncertainty of the energy emitted
    - Zeeman splitting: Magnetic fields cause the spectral line emission to split into several features

# Kinematics - Doppler Effect

- Movement of an emitting source towards or away from the observer produces a shift in the frequency
    - Analogous to the sound of a passing siren being distorted
- For observations in the Milky Way the differential rotation leads to a shift in the frequency
    - Approaching sources are blue higher frequency / shorter wavelength
    - Receding sources are red lower frequency / longer wavelength



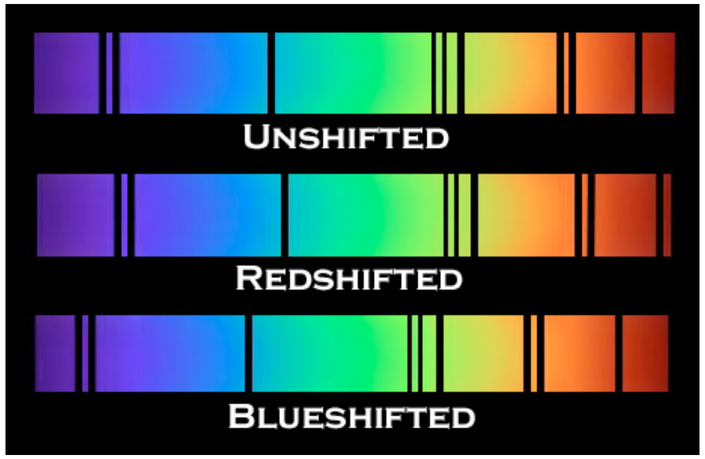


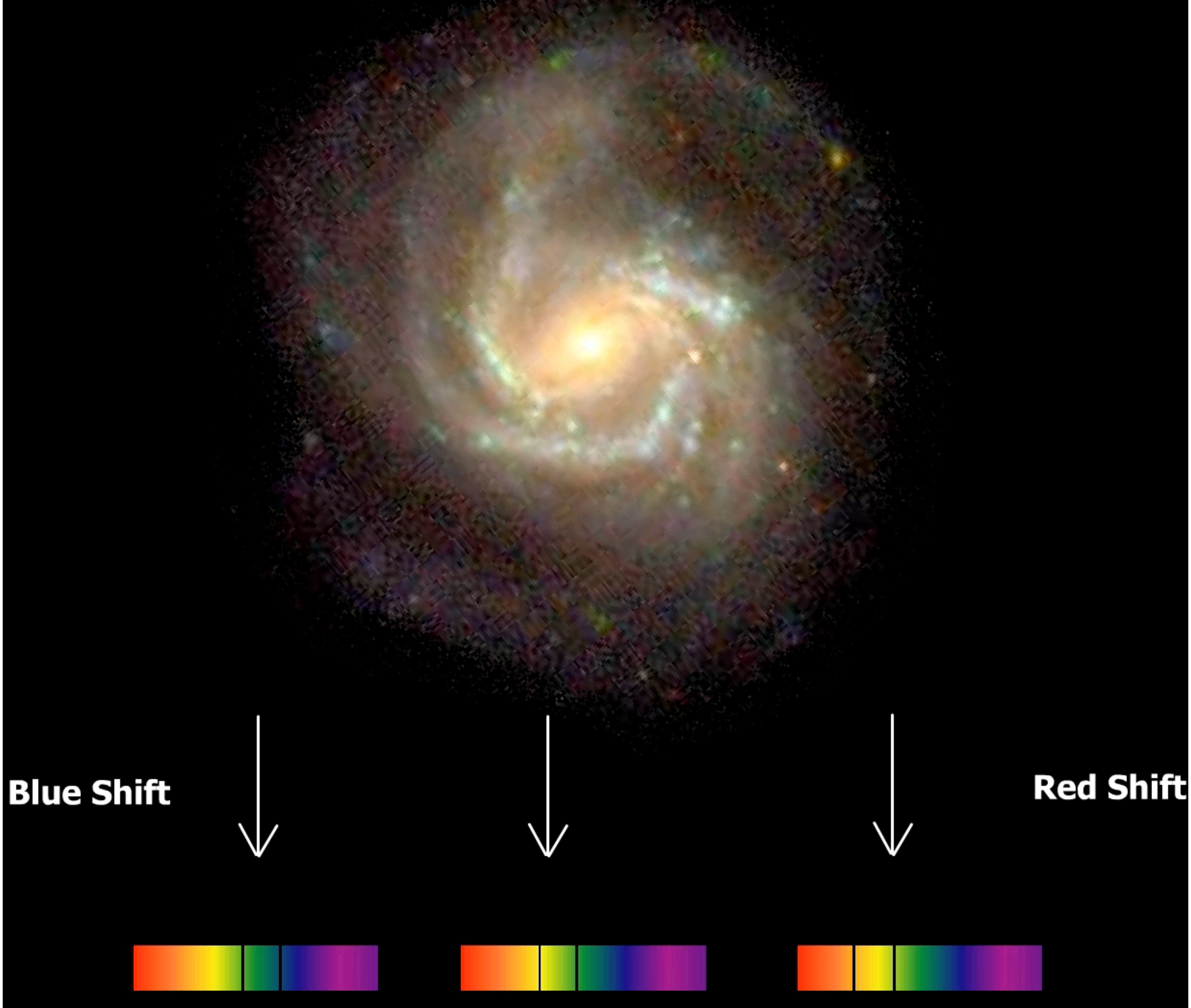
# Doppler Effect

- The Doppler effect allows us to determine the velocity that an object is moving towards or away from us known as the **radial velocity**
- If you can measure the shift in the wavelength of a spectral line you can determine the radial velocity via:

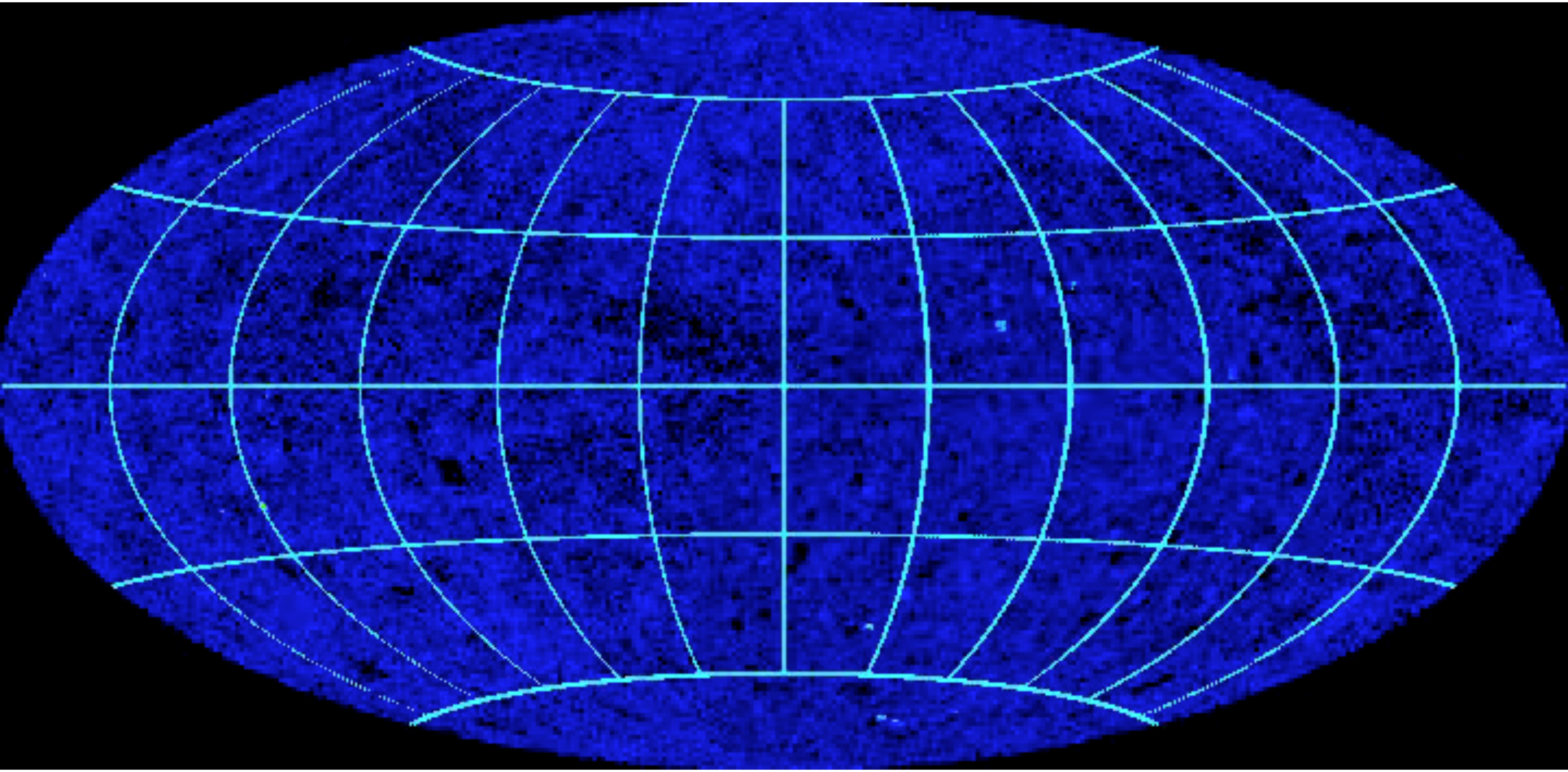
$$\frac{\lambda_{\text{obs}}}{\lambda_{\text{true}}} \approx 1 + \frac{v}{c}$$

- Where *v* is the relative radial velocity taken as positive for sources moving away from the observer and negative for sources moving towards the observer
- Knowing this we can map the distribution of gas in the galaxy




Blue Shift
Red Shift

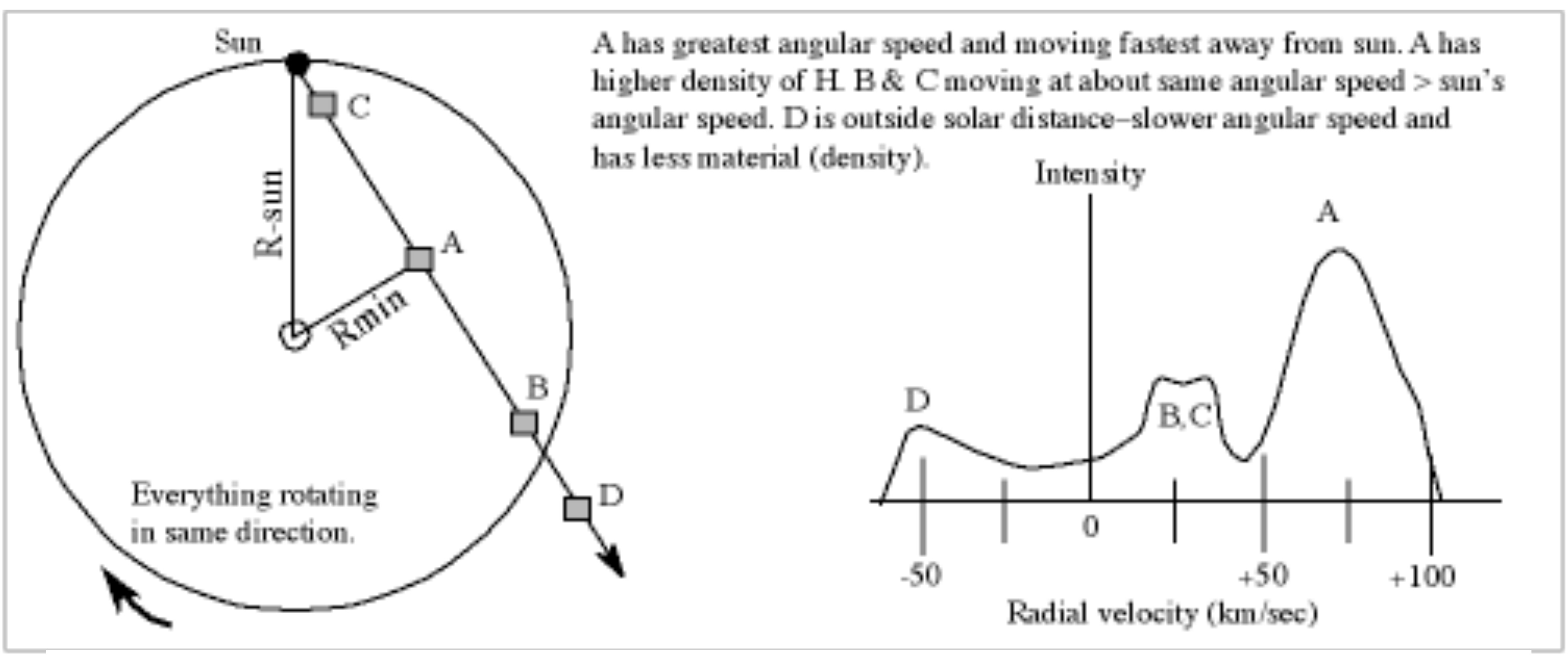
# Doppler Effect in HI (21 cm) Emission



HI emission integrated over the velocity range -400 < v < +400 km/s in the LAB dataset, shown in Aitoff projection. The Galactic centre is in the middle. The integrated emission (0 < NH < 2·1022 cm^(-2), logarithmic scale) yields column densities under the assumption of optical transparency; this assumption may be violated at latitudes within about 10° of the Galactic equator. (Kalberla et al. 2005)

# Kinematic distance ambiguity

- The velocity can be used to determine the distance to a source assuming some model of how the Galaxy rotates
- This is called the **kinematic distance**
- Unfortunately the geometry gives rise to a degeneracy where a source may be located at either a **near** or **far** kinematic distance

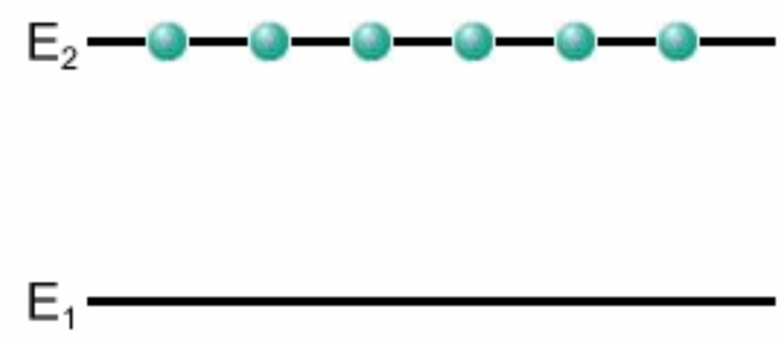


# Other Emission Mechanisms

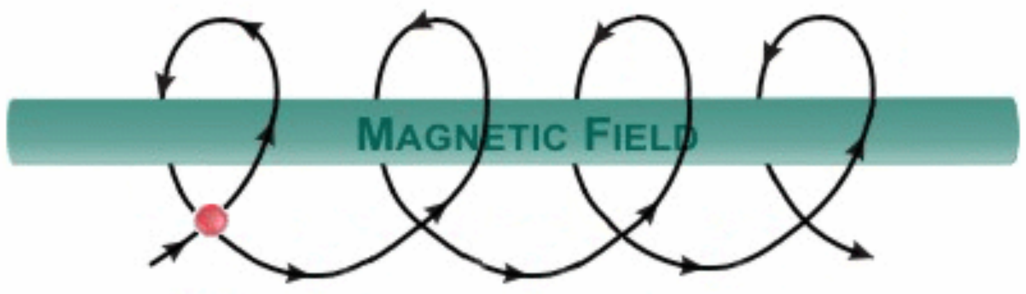
We have only looked at how atoms and molecules emit spectral line radiation and heated objects emit blackbody emission but their exists many other emission mechanisms such as:

- **Maser emission**
  - Stimulated emission of an inverted population
- **Synchrotron emission**
  - Electrons spiralling around magnetic fields
- **Thermal Bremsstrahlung** (free-free) emission
  - Electrostatic interactions in ionised (HII) regions

**Maser emission**
A group of molecules are pumped into an excited state. When photons with an energy equal to the energy separation between E1 and E2 pass it stimulates a cascade. Leads to discrete emission.




**Synchrotron emission**
As a charged particle (normally electrons) spirals around a magnetic field it will release photons. The frequency is directly related to the speed of the particle, very fast (relativistic) electrons are required. The particle looses energy as it emits photons and slows thus releasing energy at longer wavelengths.




**Free-Free emission**
Unlike the previous two this is a thermal emission mechanism (depends on temperature). In an ionised gas (plasma) charged particles undergo interactions. Electrons can be accelerated by charged particles. A wide range of frequencies are generated based on the speed.

# HI absorption

- Radio continuum grey scale
- HI absorption contours
- Gallimore+99

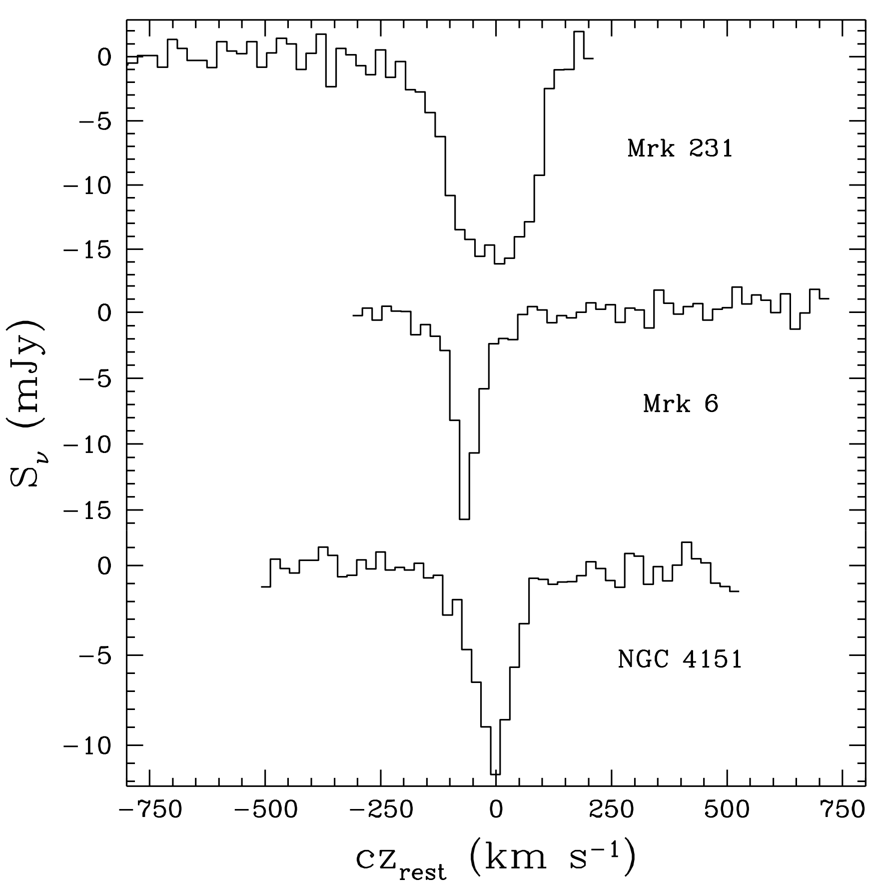
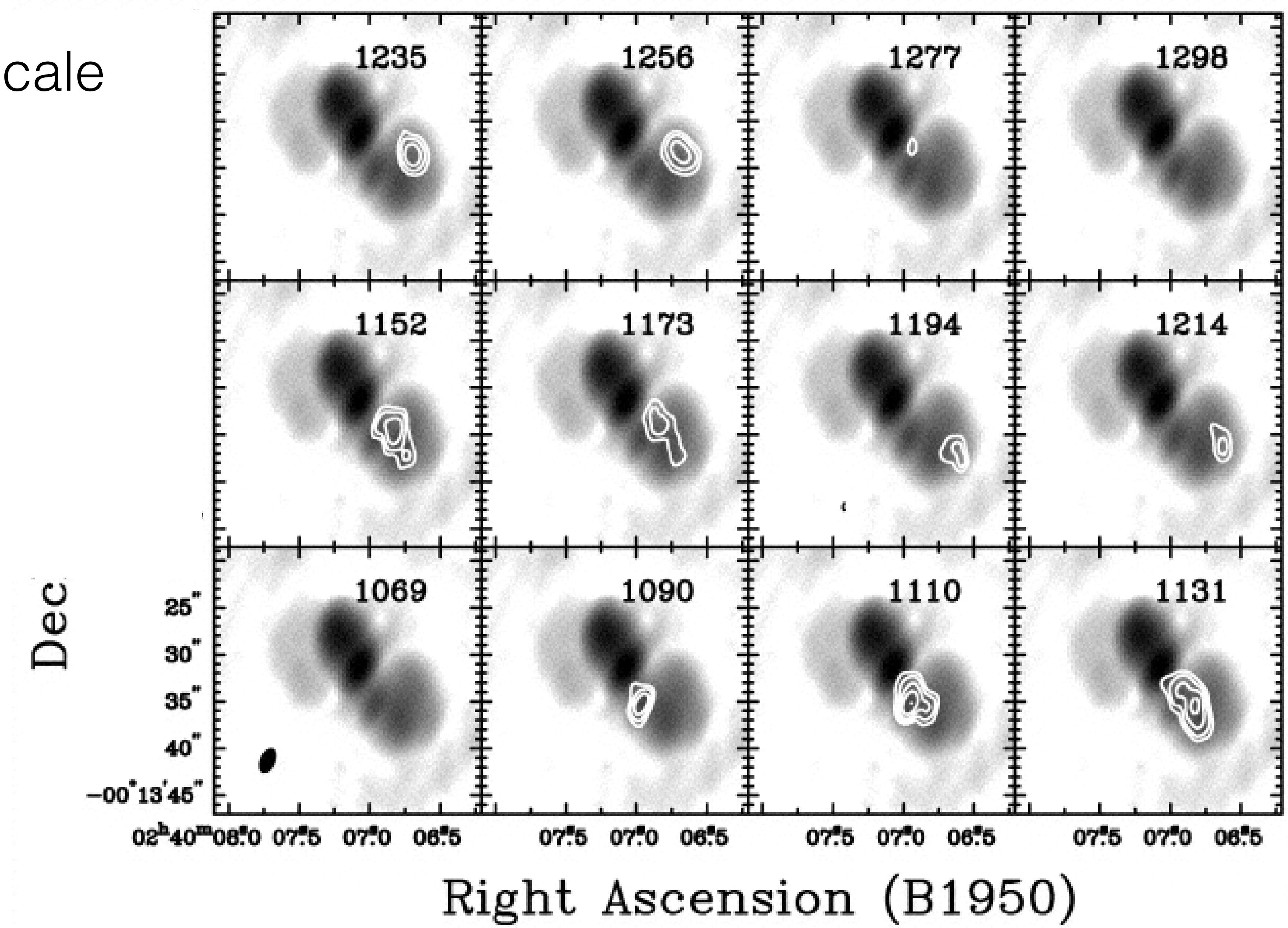
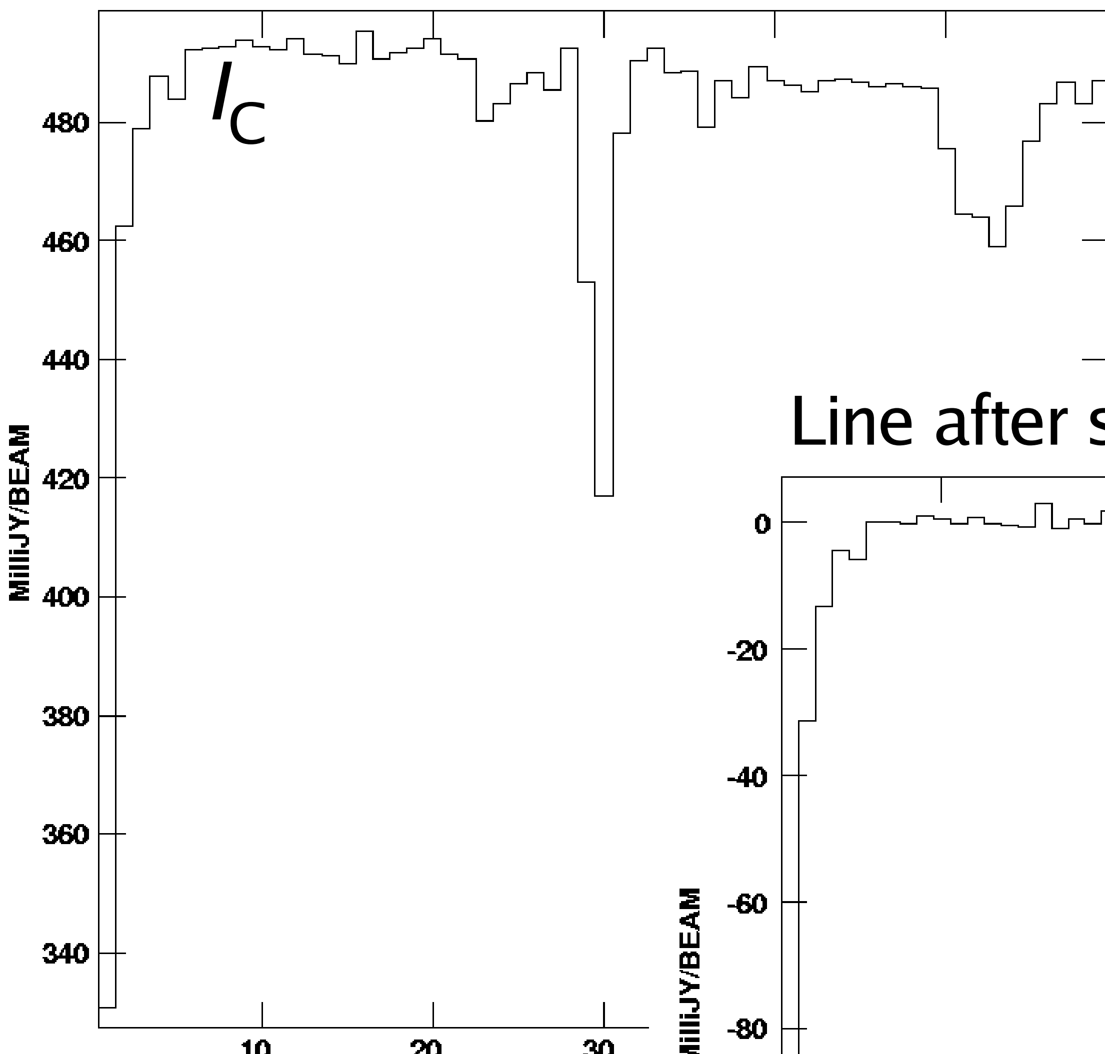



Fig. 1.—Global (spatially integrated) H I absorption spectra of Seyfert 1 nuclei. The spectra are continuum subtracted and corrected back to zero rest velocity based on the observed recessional velocities in Table 2. The only nondetection among the Seyfert 1 nuclei was Mrk 668.



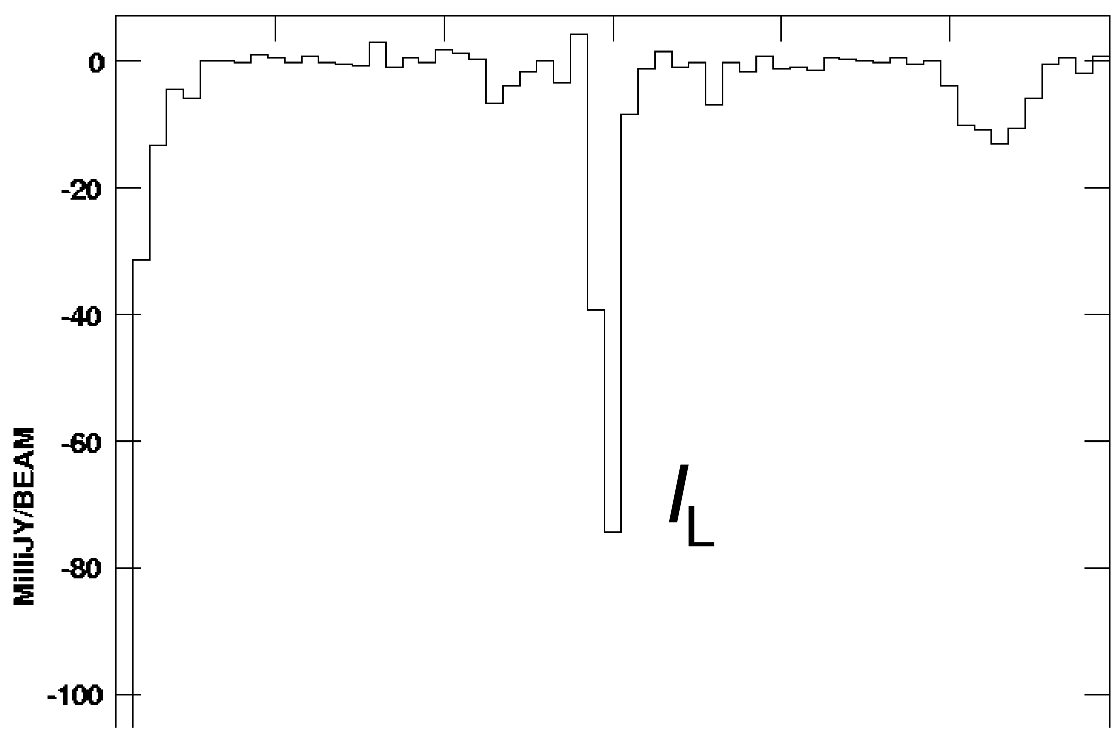
# Absorption measurements

Continuum + line




Velocity $v$ km $s^{-1}$

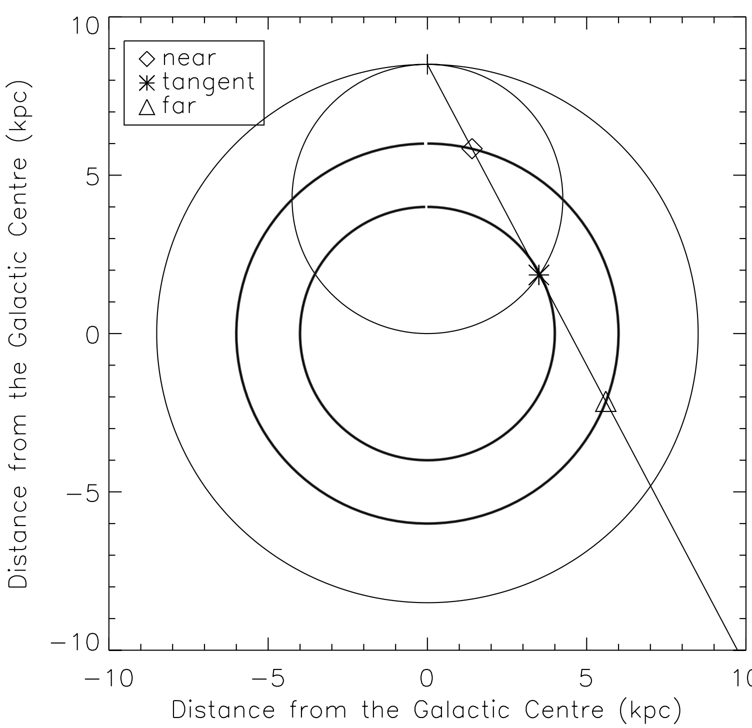
Line after subtraction




- $\tau = -\ln[(I_C - I_L)/I_C)$
  - HI column density $N_{HI}$
    $= 1.83\ 10^{22}\ T_s \int \tau(v)\, dv\ m^{-3}$
- See *Gallimore et al. (1999)* for more details

# Absorption measurements

- Can be used to resolve the kinematic distance ambiguity (Urquhart et al. 2012)



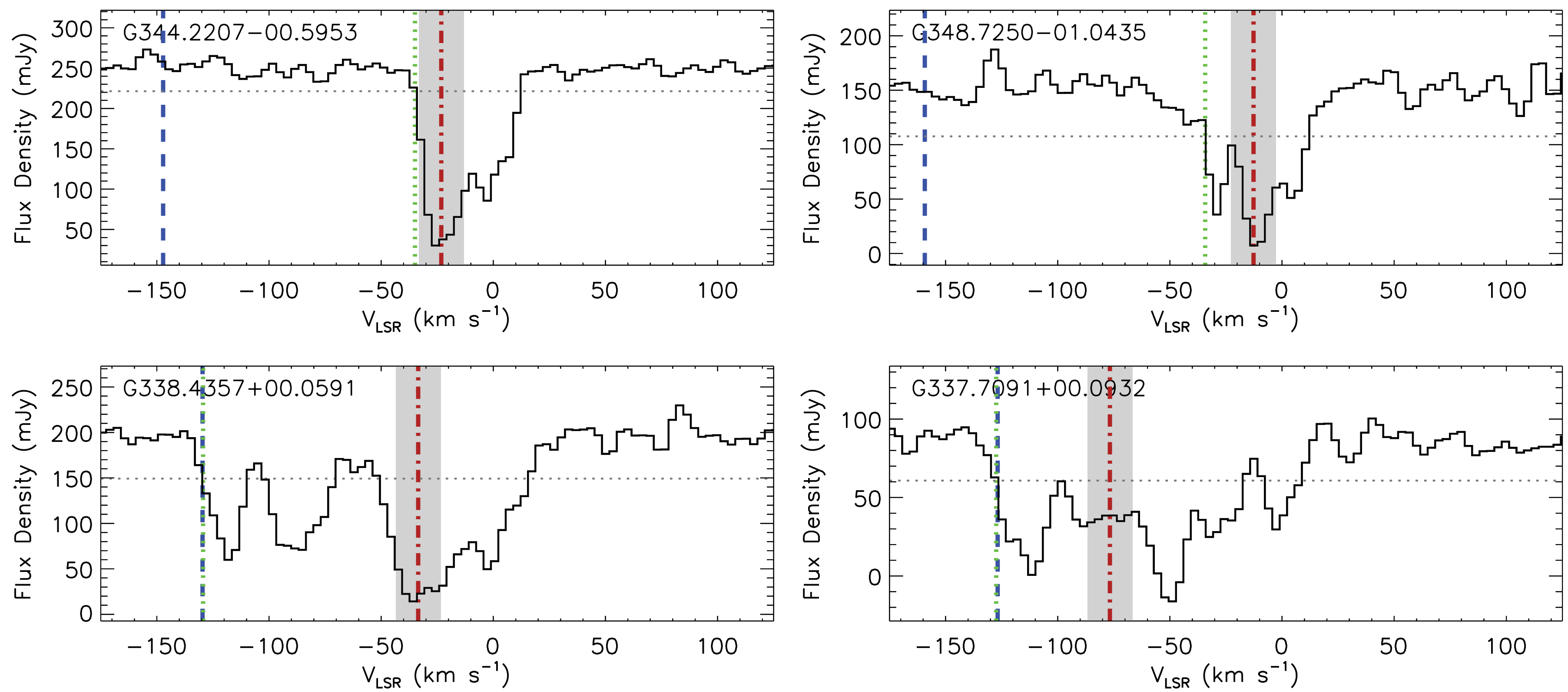
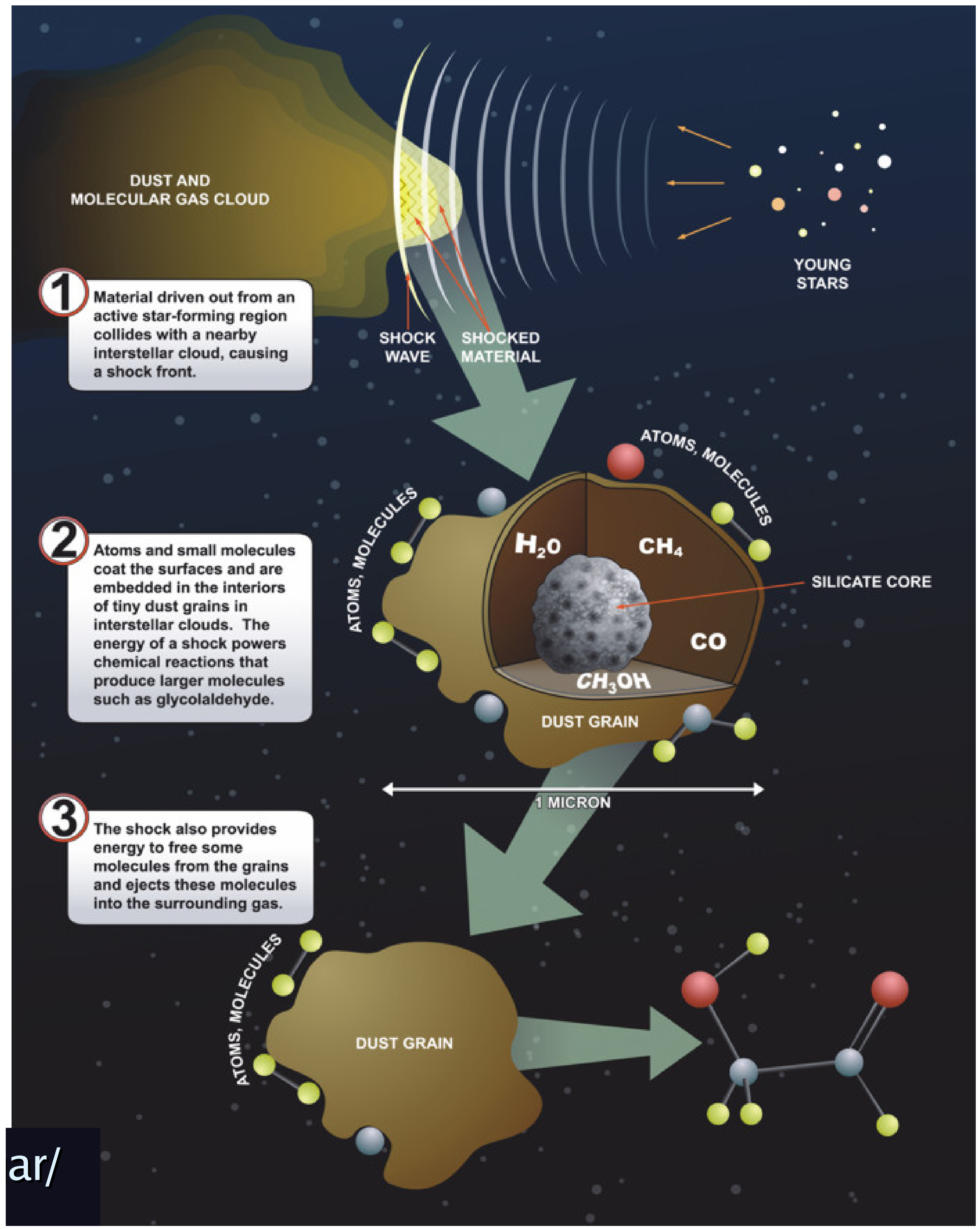




**Figure 3.** Source-averaged, high-resolution continuum-included H I spectra towards the H II regions observed with ATCA. The source velocity ($v_S$), the velocity of the tangent point ($v_T$) and the position of the first absorption minimum ($v_A$) are shown by the red, blue and green vertical lines, respectively. The grey vertical band covers the velocity region 10 km s$^{-1}$ either side of the source velocity and is provided to give an indication of the uncertainty associated with it due to streaming motions. The dotted horizontal line shows the $4\sigma_{rms}$ noise level determined from absorption-free parts of the spectra (see Section 2.3 for details). In the top and bottom panels, we provide examples of sources placed at the near and far distances, respectively. The full version of this figure is available in the online version of the journal – see Supporting Information.

# RNA precursor?

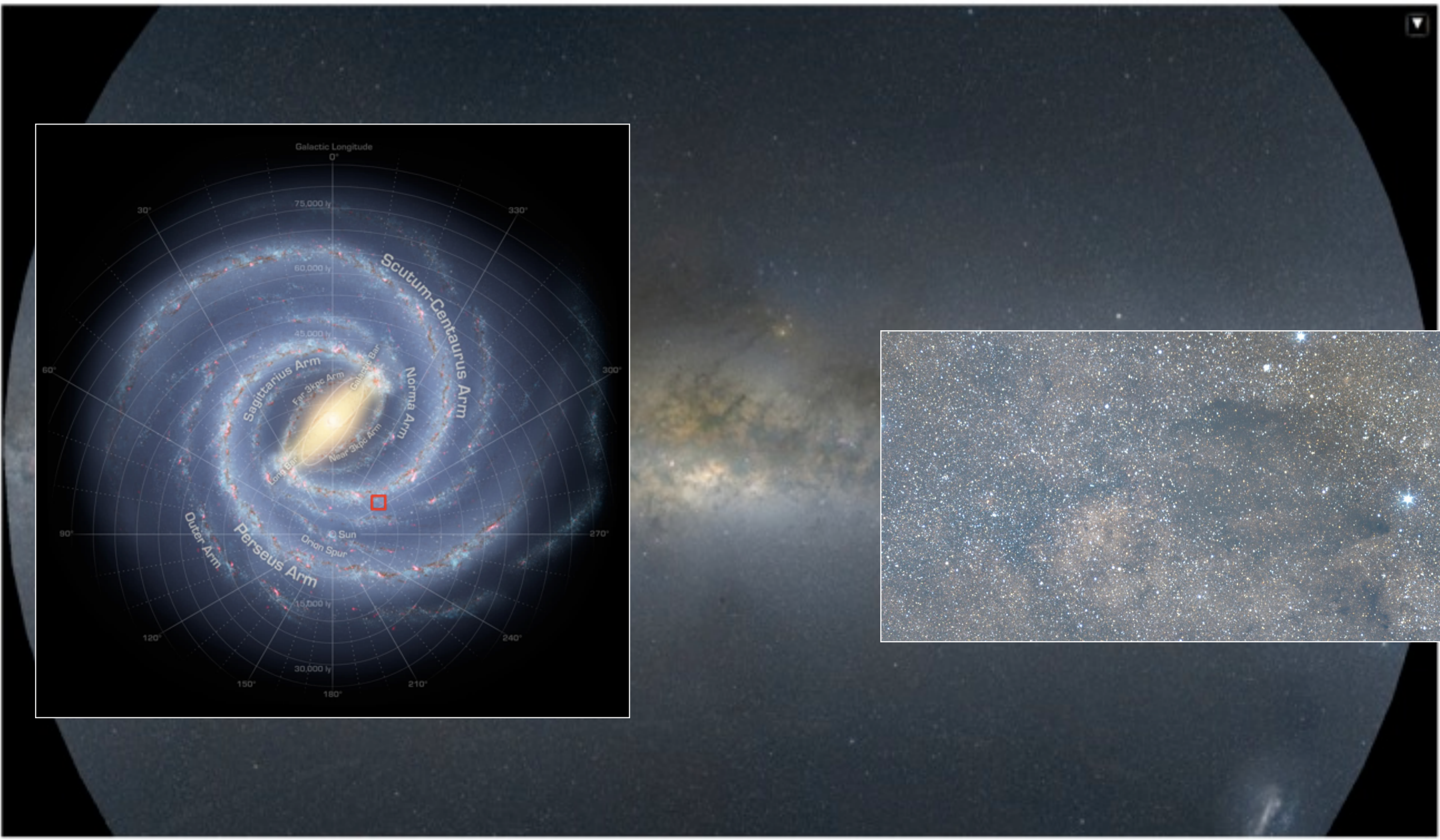
- Glycoaldehyde
  - 2nd isomer
- GBT detection in Sgr B2
  - *Hollis+ 2004*
  - Sugar in space!
    - Acetic acid is the 3rd isomer
  - Beer in space?
  -



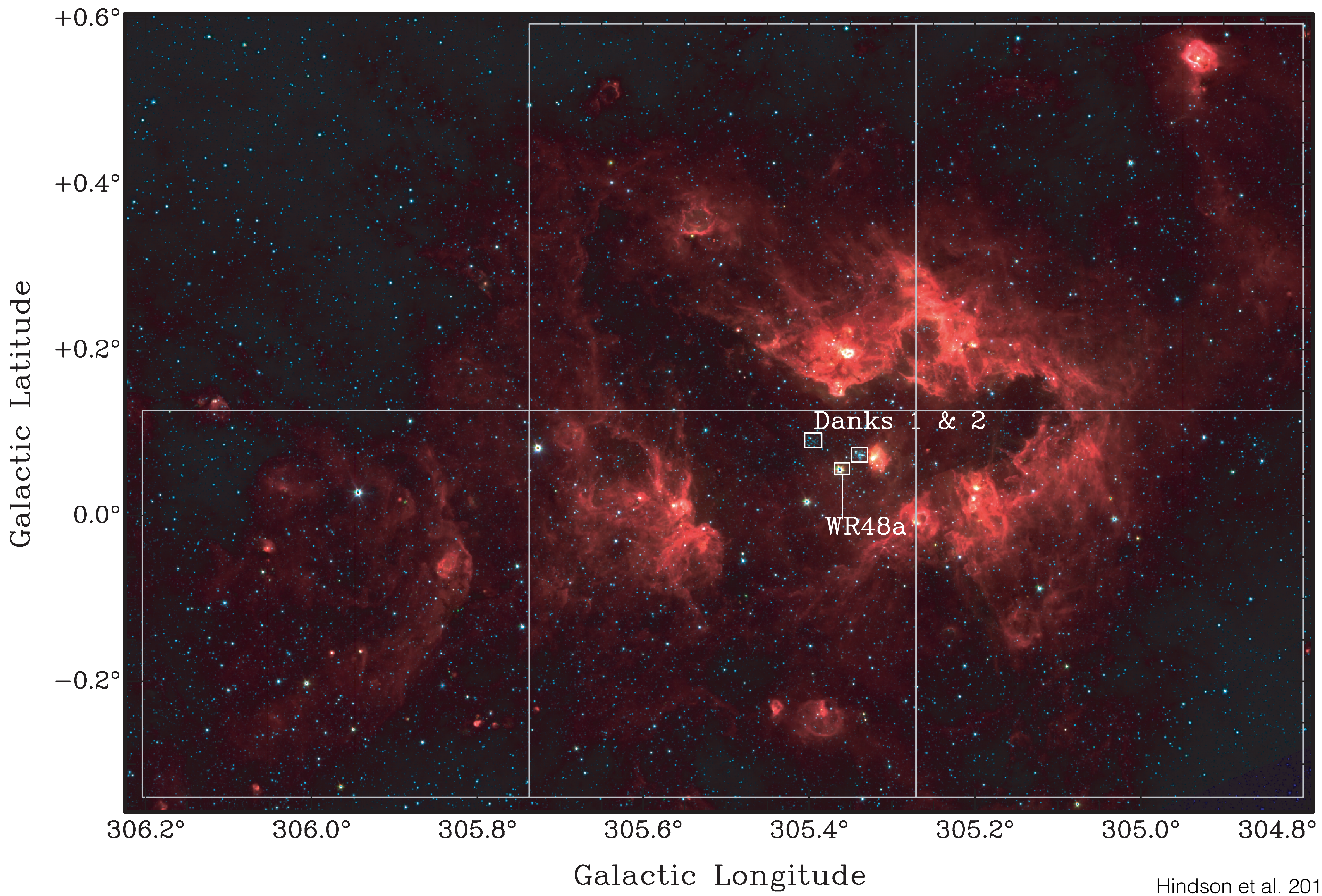

ar/

http://www.nrao.edu/pr/2004/coldsugar/

# The G305 Example



# The G305 Example



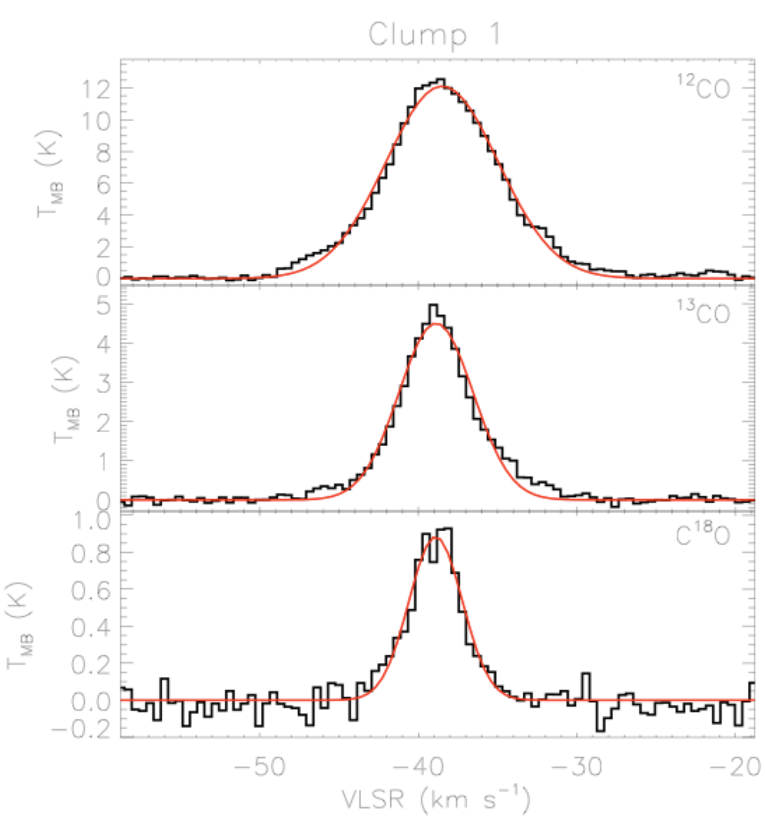

Hindson et al. 2010

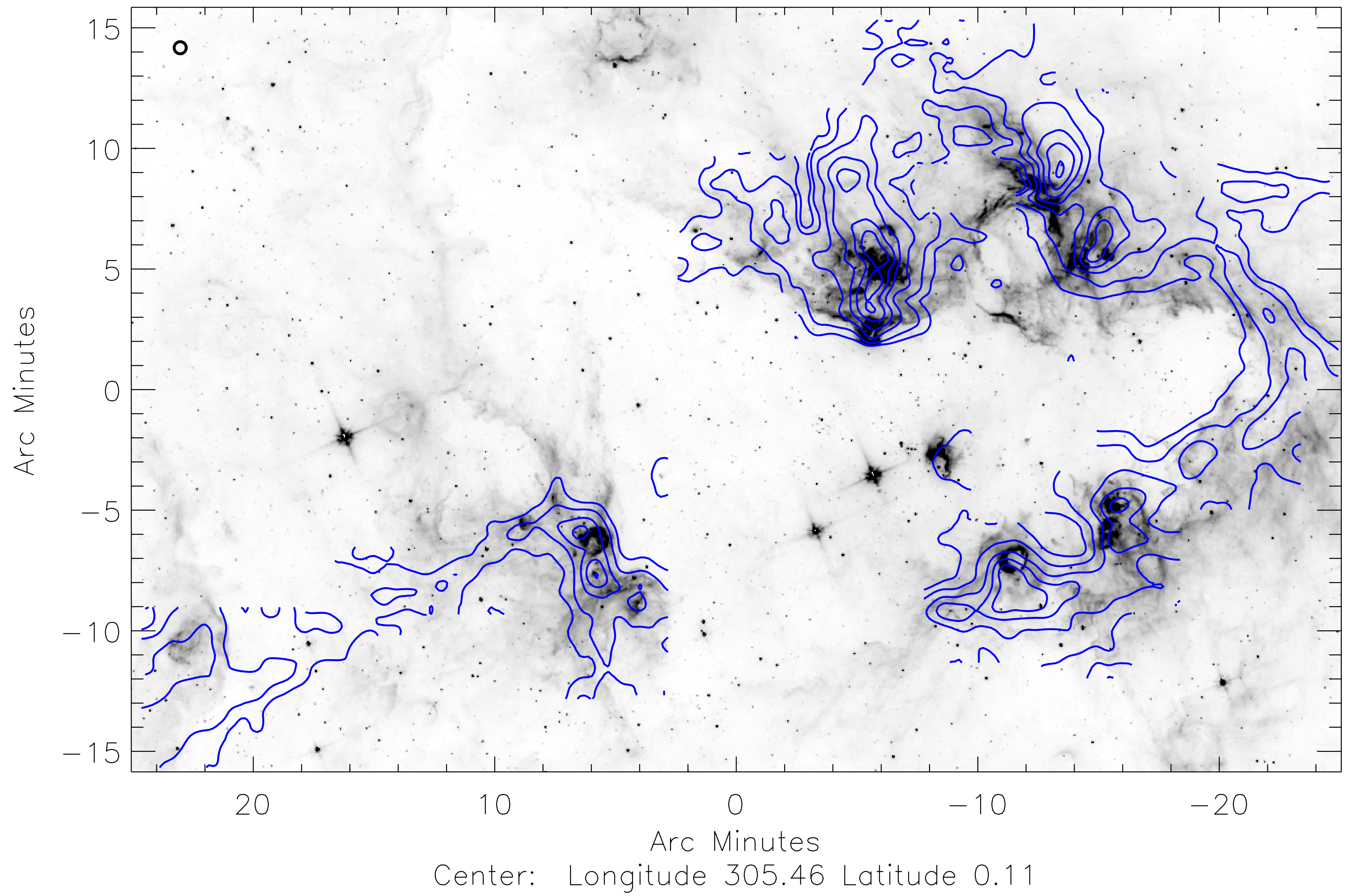
# CO observations

- The most abundant molecule after $H_2$
    - Critical density of $\sim 10^2$ $cm^{-3}$ traces the lower density global gas content
- Rotational mode leads to emission at ~110 GHz
- Observations of multiple CO lines allows physical properties to be determined
    - $^{12}CO$, $^{13}CO$, $C^{18}O$
- The following data can be obtained at:
    - wget ftp://star-ftp.herts.ac.uk/pub/Hindson/SpectraLine_Examples.tar.gz --no-passive-ftp

# CO results

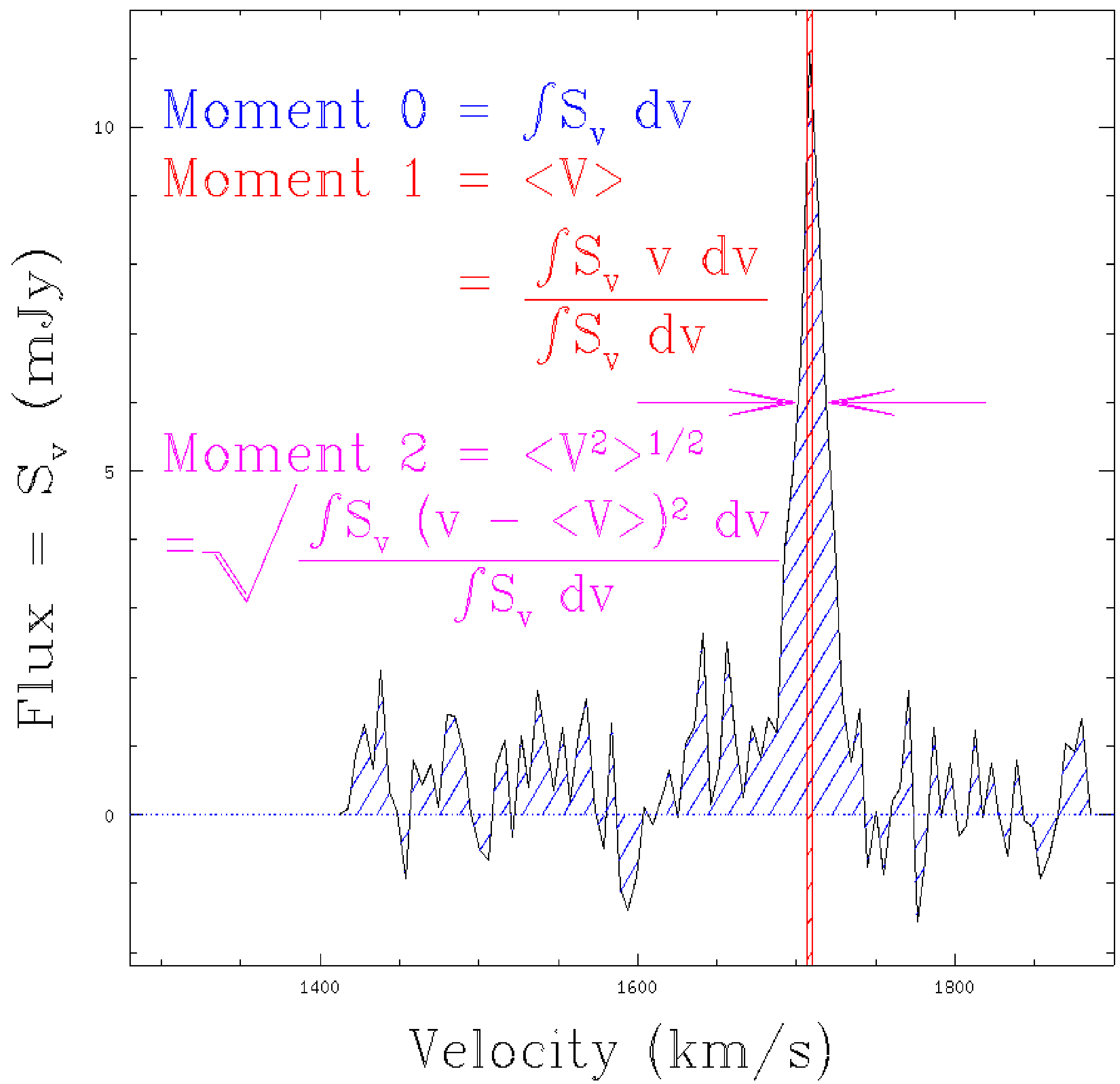
- Identified 57 clumps
- $T_{kin}$: ~12–21 K
- Sizes: 0.6 – 2.8 pc
- Mass: 100 – $1.6 \times 10^4$ $M_\odot$
- Total mass: ~$3 \times 10^5$ $M_\odot$
- Hindson et al. (2013)

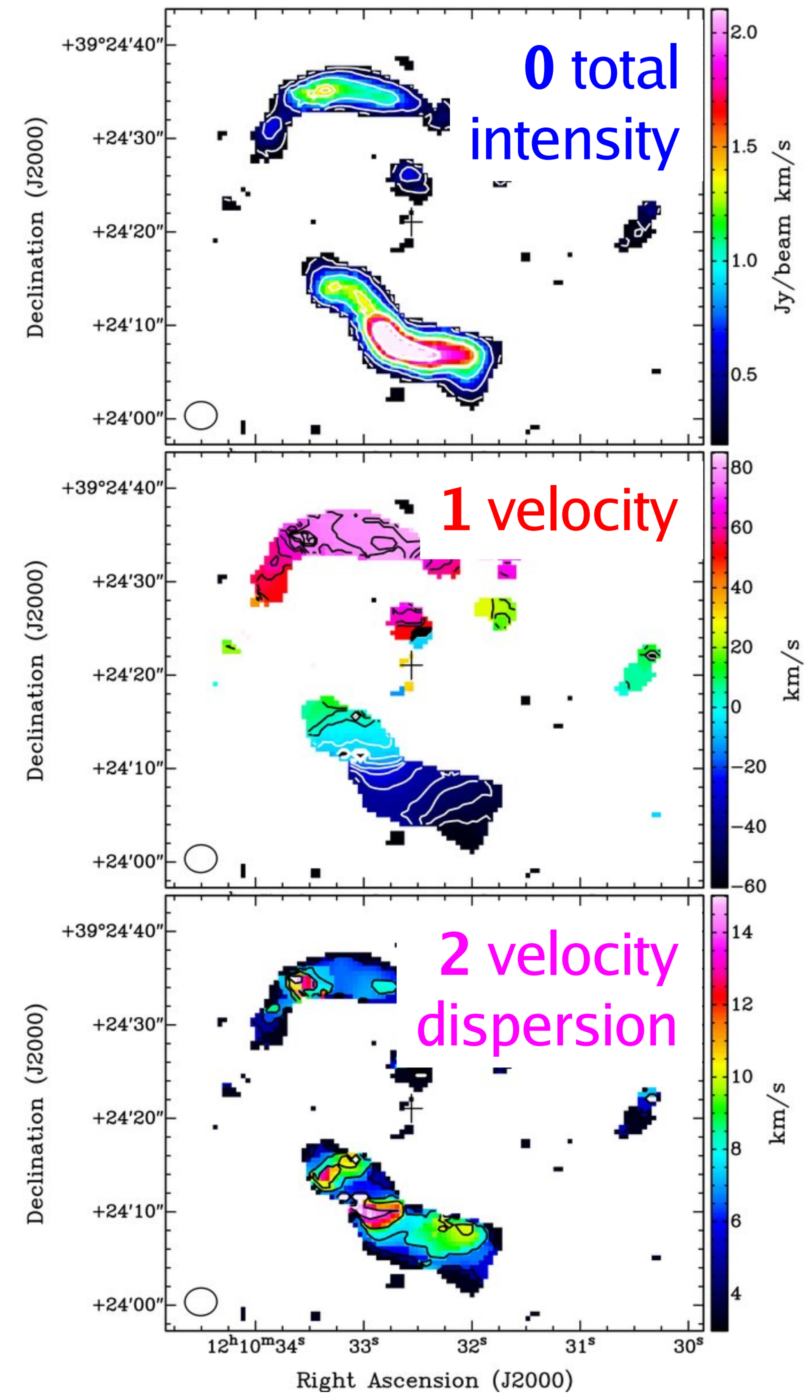



$^{12}$CO contours indicate the presence of molecular gas in G305 surrounding the central cavity

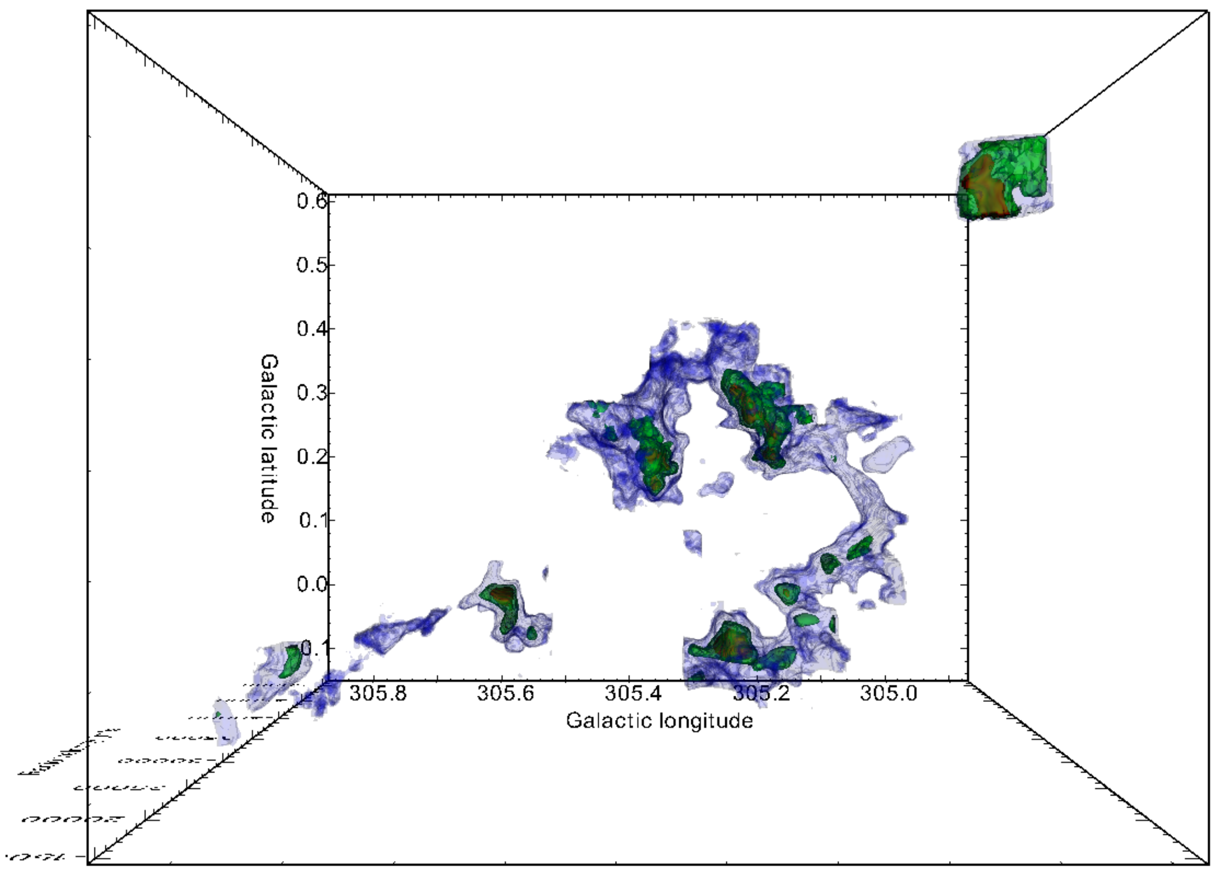
# Moment Maps

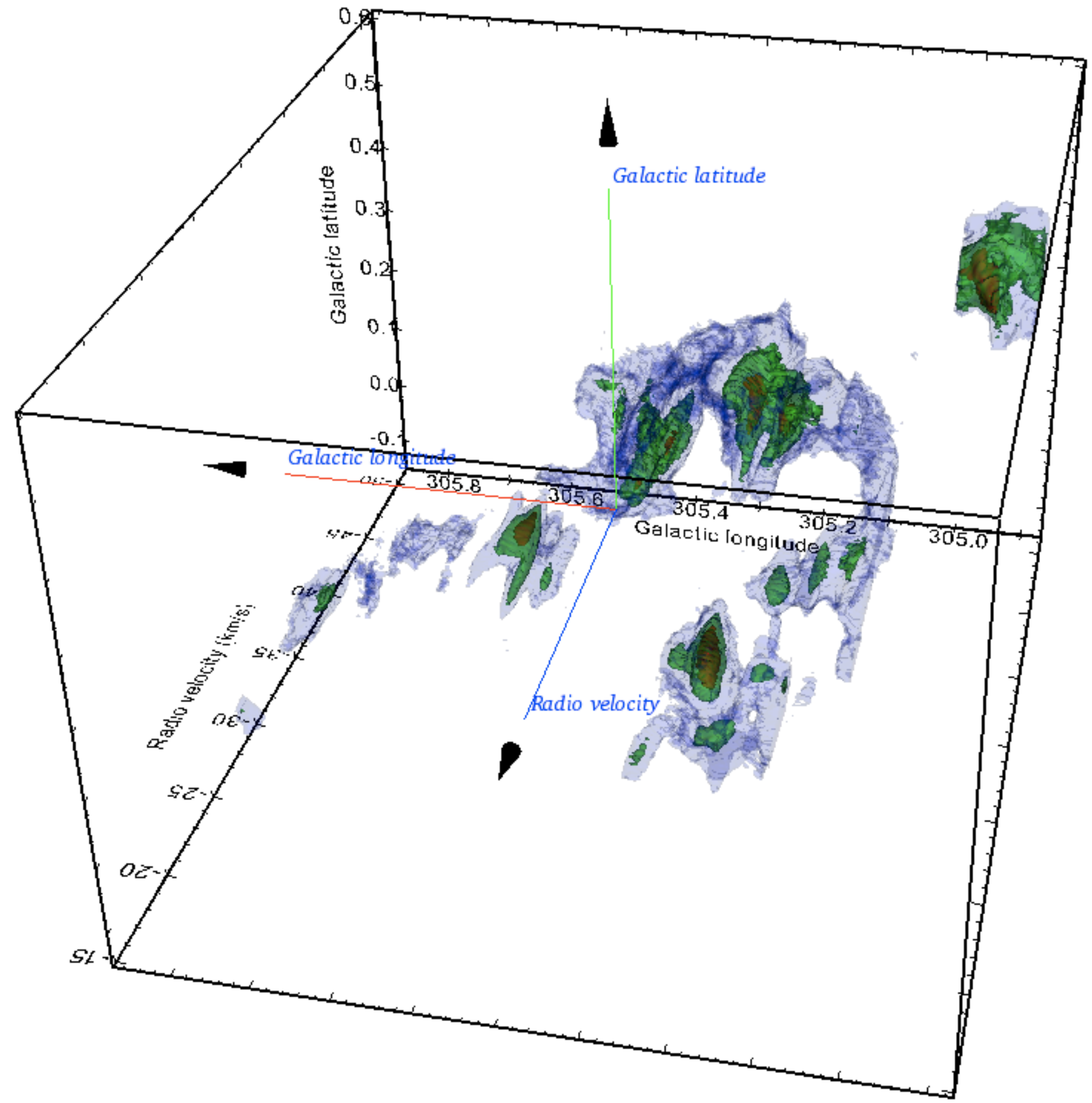



*Dumas+2010*

# 3-D visualisation

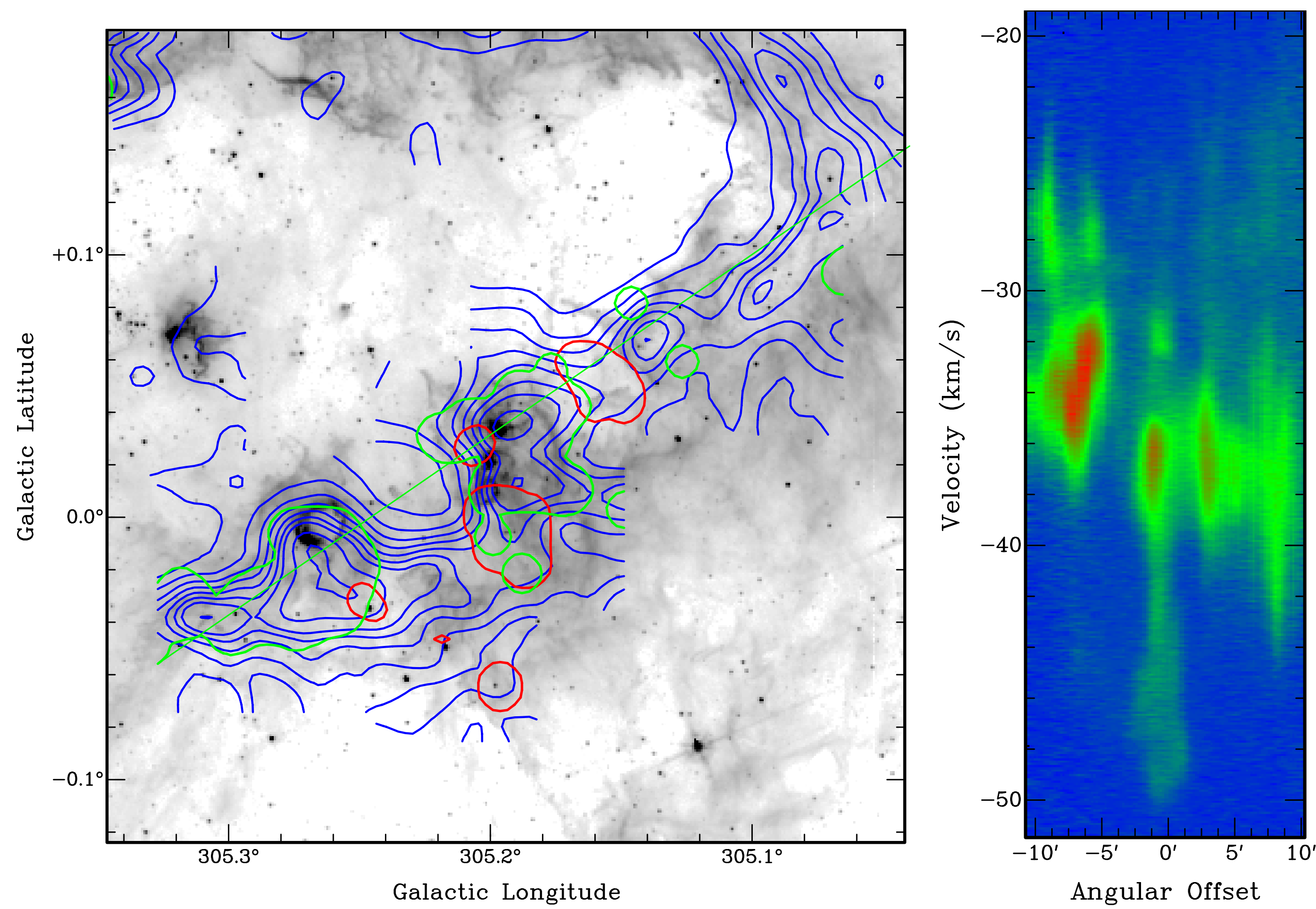



3-D viewers such as **Gaia** provide a way to search for velocity structures in a cube

# Outflow candidates

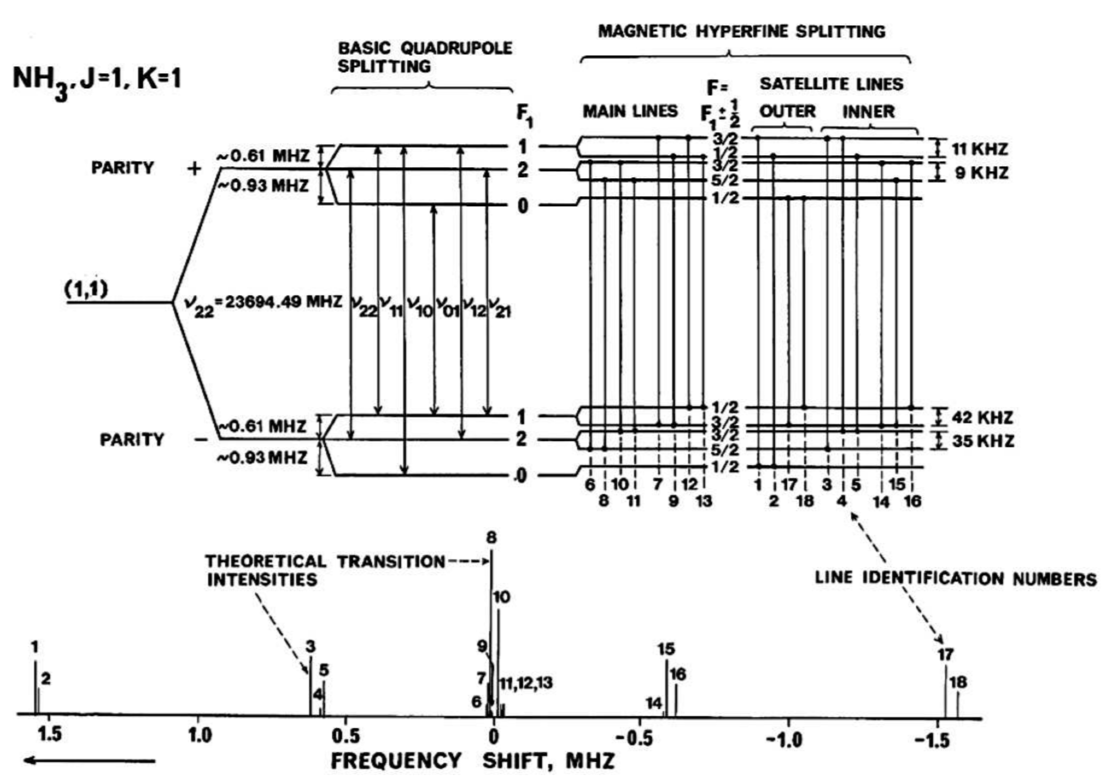
- Star formation leads to outflows of material
- This can be seen if it is orientated along the lone of sight
- **Position Velocity** (PV) diagrams can be used to explore the velocity structure
- Direct indicator of ongoing star formation

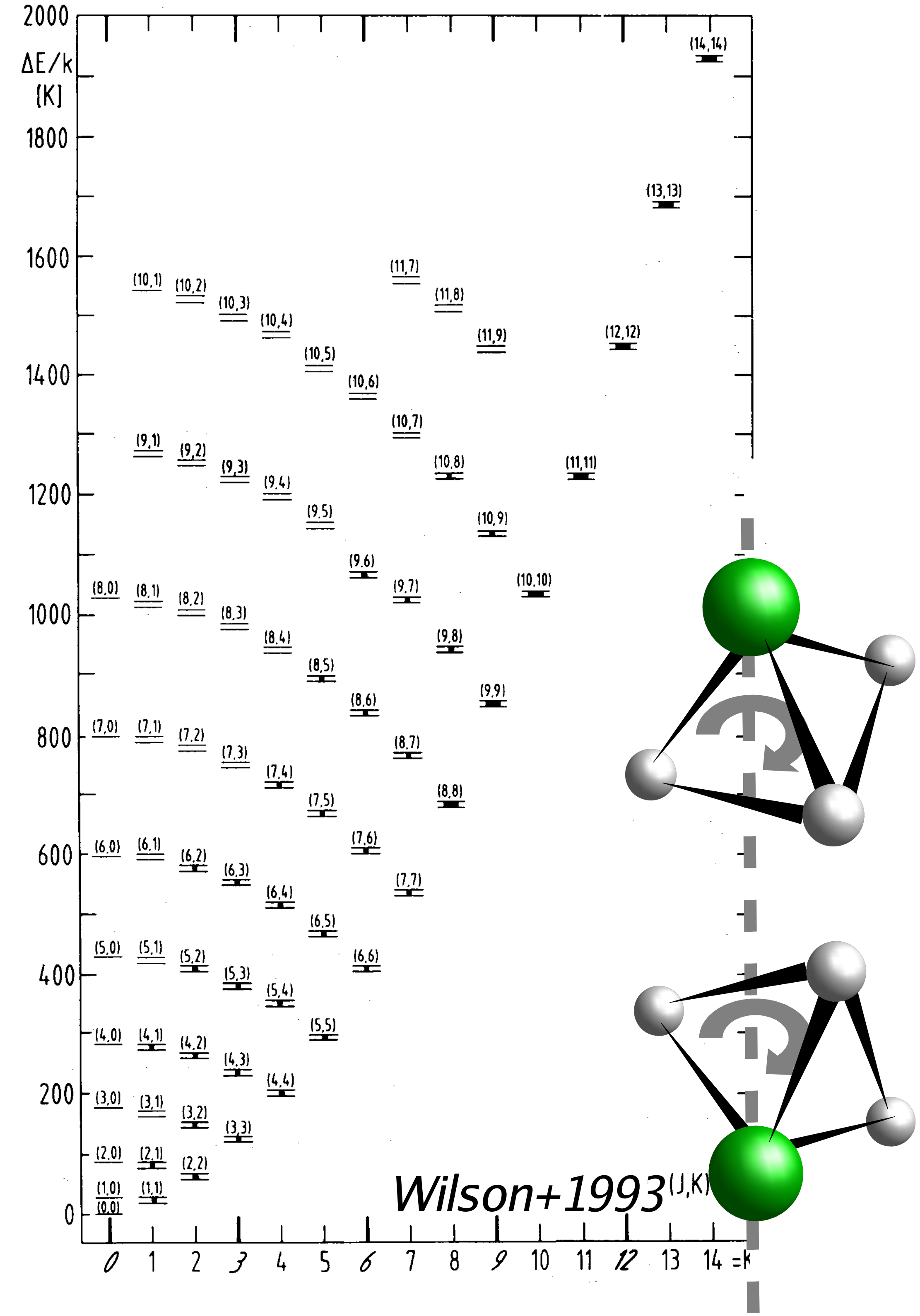



(d) South West

# Ammonia

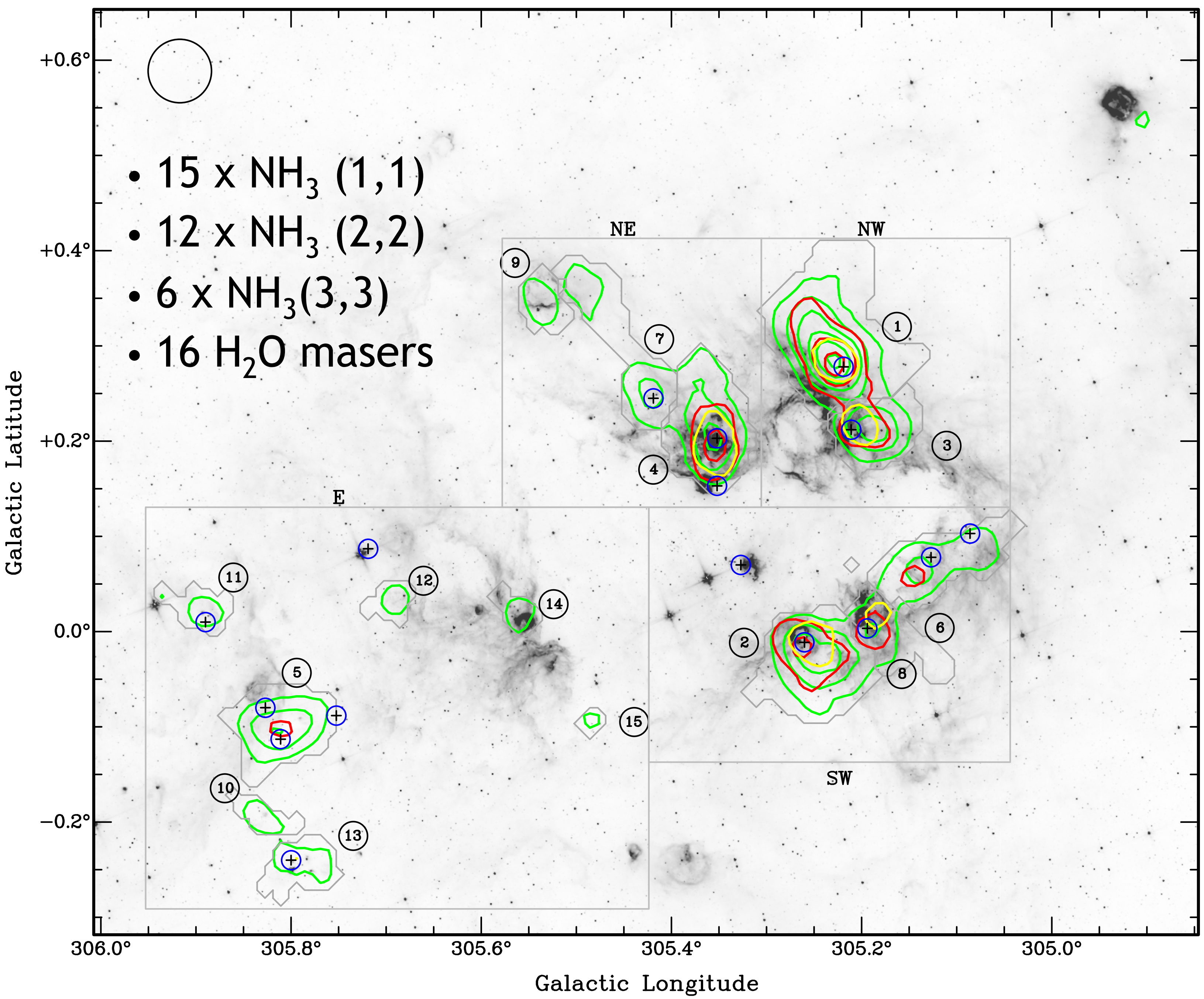
- $NH_3$ is my favourite molecule!
- Traces dense gas >$10^4$ $cm^{-3}$
- Represents the reservoir for future star formation
- Quantum tunnelling allows the Nitrogen to travel through the plane of the hydrogen atoms
- Hyperfine splitting leads to a characteristic multi-peaked spectra
- Can determine the optical depth and temperature using the multi-peaked spectra

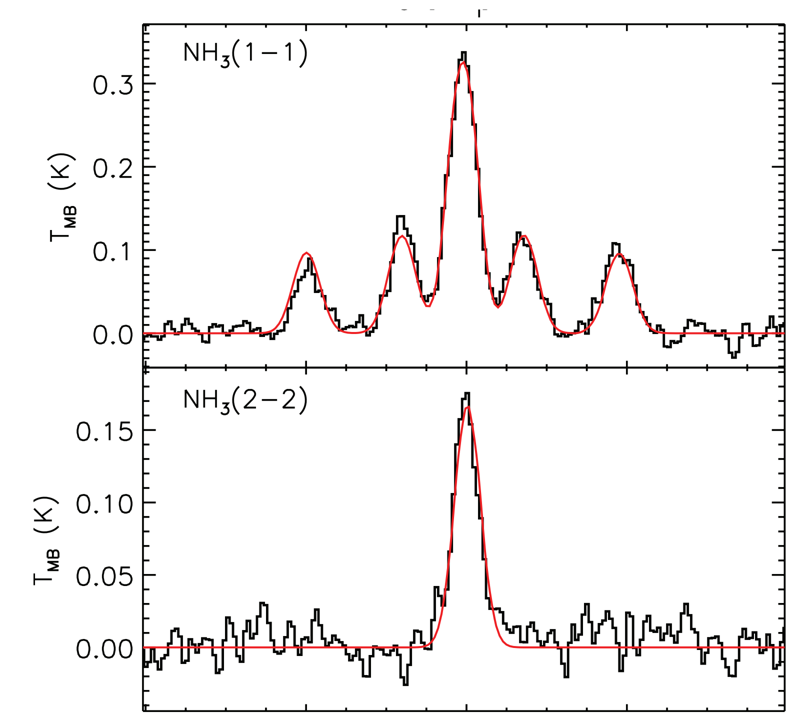


# Ammonia

- 15 x $NH_3$ (1,1)
- 12 x $NH_3$ (2,2)
- 6 x $NH_3$(3,3)
- 16 $H_2O$ masers

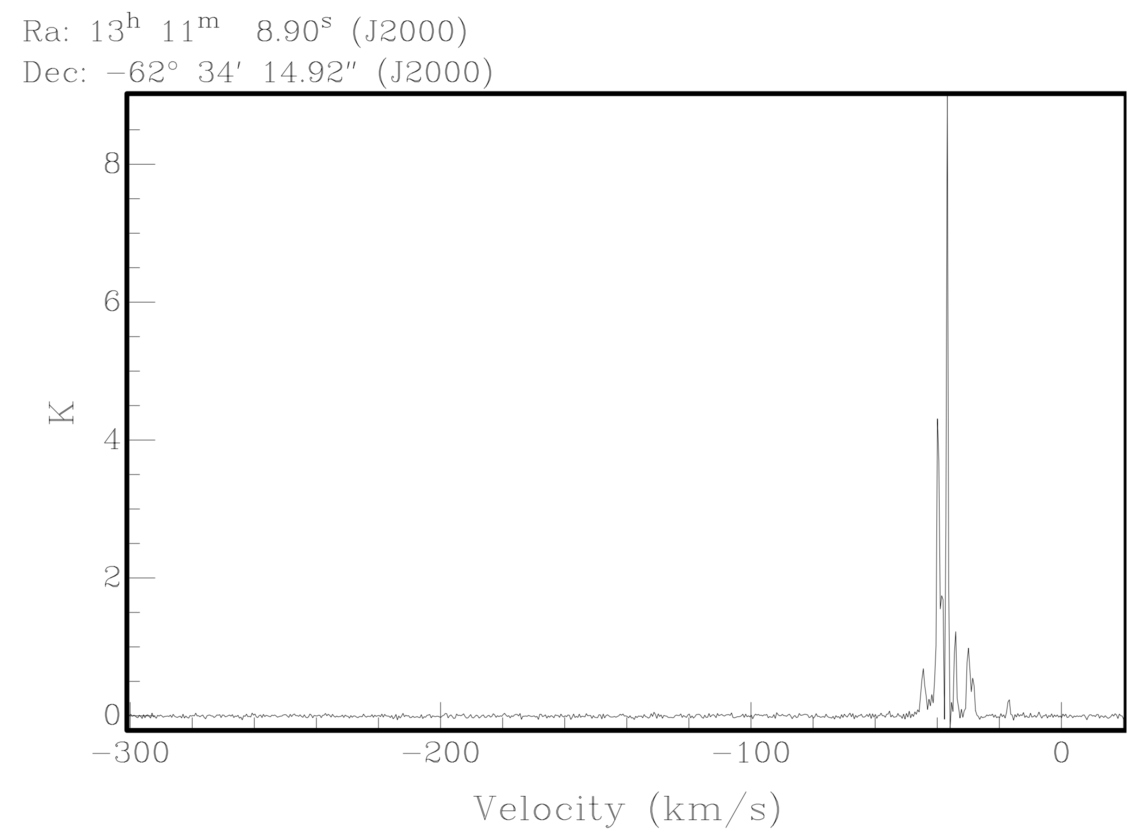



- $T_{kin}$: ~21−31 K
- Size: < 2.6 − 10.1 pc
- Mass : 3 − 122×10$^3$ $M_\odot$
- Total Mass : ~ 6×10$^5$ $M_\odot$
- Hindson et al (2010)

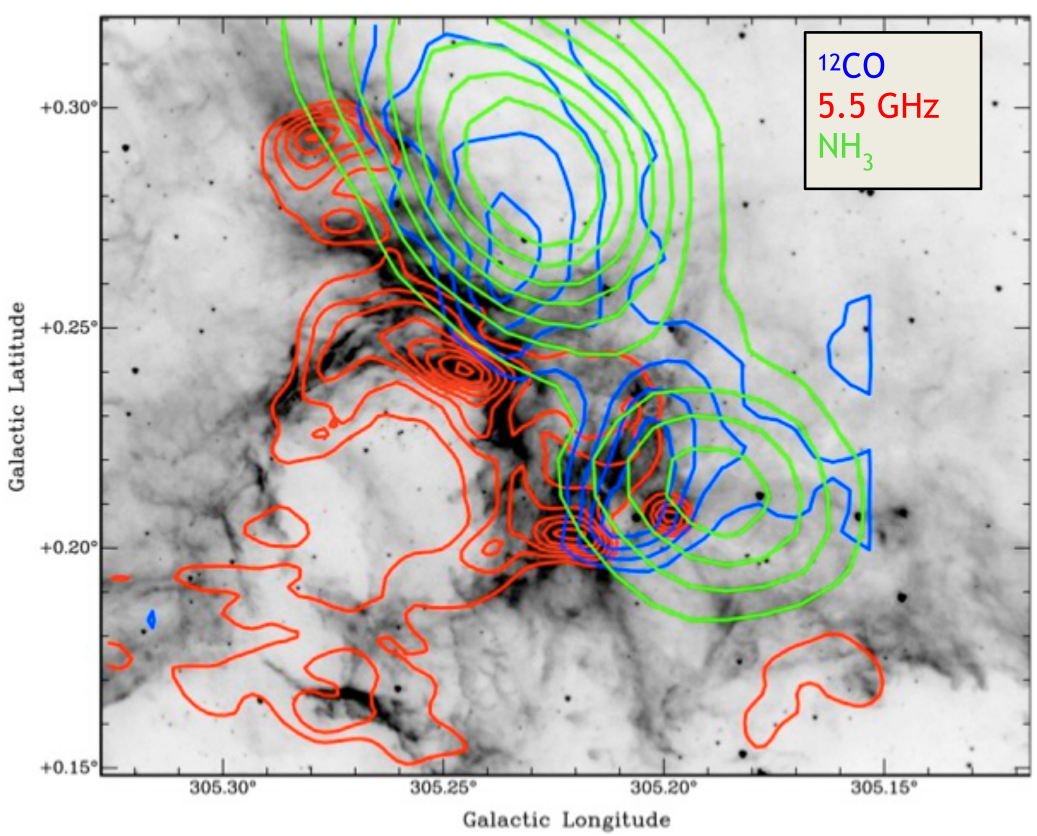
# Masers

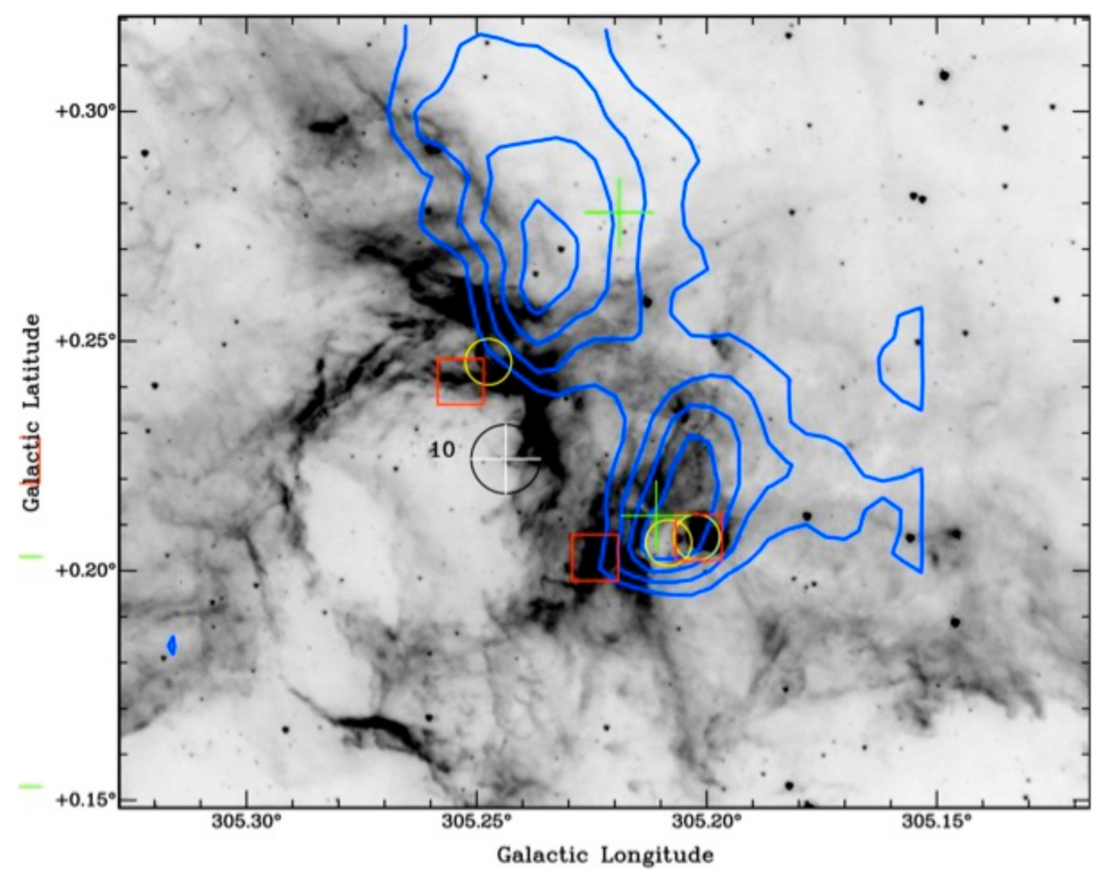
- There ≳ 16 maser species
- Occur in different environments
  - coherent velocity, high density
- $H_2O$ masers occur in star forming regions
- Very bright
- Multi-peaked spectrum caused by the different velocities of the gain medium



# Putting it all together

- CO traces low density gas, $NH_3$ traces high density gas, $H_2O$ masers trace star formation
  - Together we can build up a picture of the environment and star formation in G305




Various star formation tracers including $H_2O$ masers (green crosses)

# Summary

- We have looked at spectral line science in a mostly Galactic context

- A wide range of spectral lines probe varied environments

- Continuum and spectral line observations give complimentary information

- Questions?