Introduction to Astrophysics and Cosmology

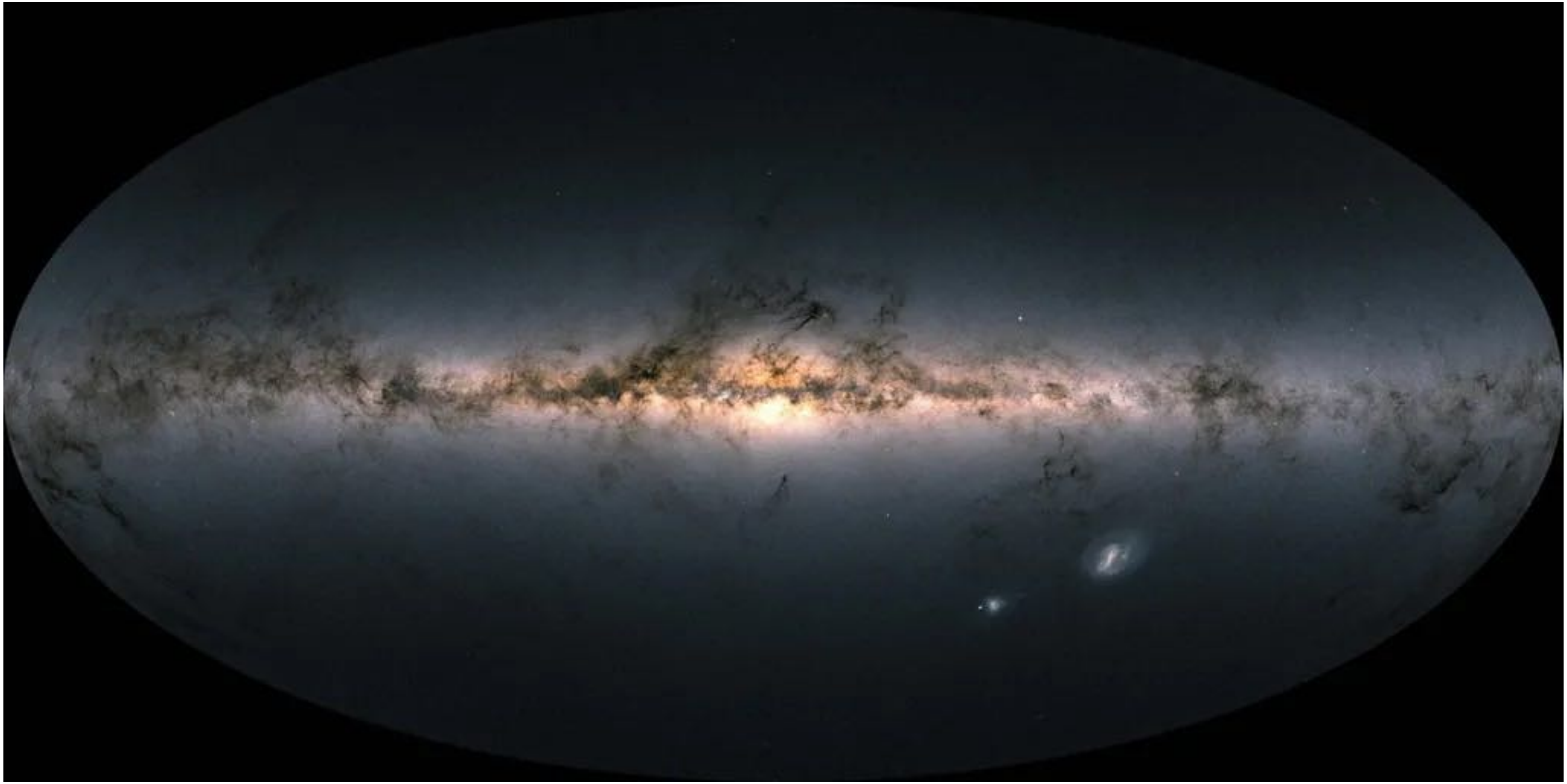
Our Galaxy and the Interstellar Medium

Helga Dénes 2025 S1 Yachay Tech

hdenes@yachaytech.edu.ec

Interstellar gas

Stars and dust in the Milky Way
The dust is part of the interstellar medium



Interstellar gas

How can we detect it?

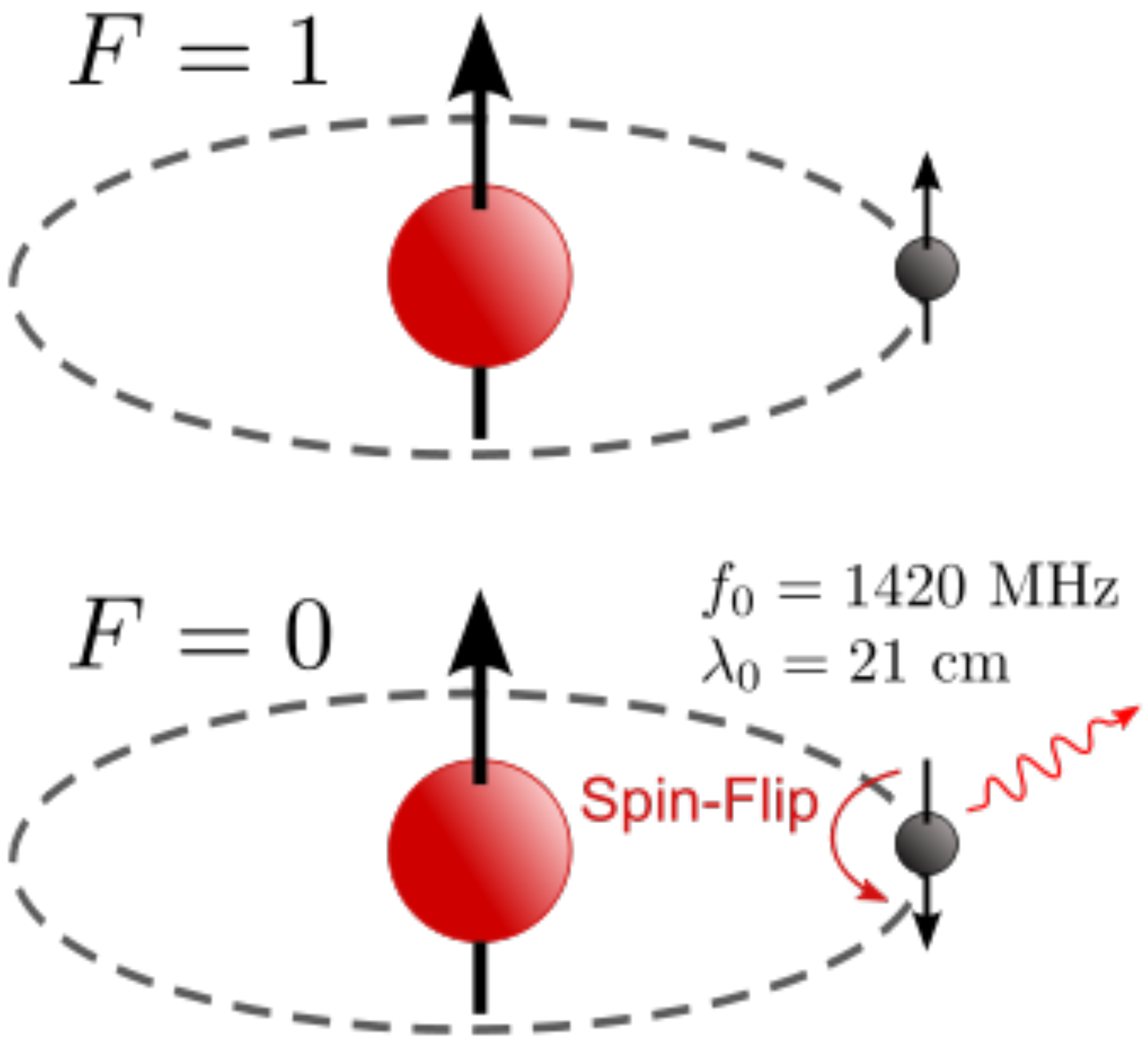
Interstellar gas

How can we detect it?

- First detection: narrow absorption lines observed in the spectra of some stars.
- A spectral line gets broadened due to the random thermal motions of the atoms in the material which produces the spectral line (this is known as ***thermal broadening***). **An absorption line produced in a stellar atmosphere is expected to have a broadening appropriate for the temperature of the atmosphere.**
- A **narrow absorption line** in a stellar spectrum indicates that the line must be produced by some considerably **cooler gas**, possibly distributed along the line of sight between the star and us.
- However, much of this gas emits no visible light.
- In the 1930s and 1940s: there was evidence of interstellar gas based on narrow absorption lines, but astronomers did not know how to detect this gas directly.

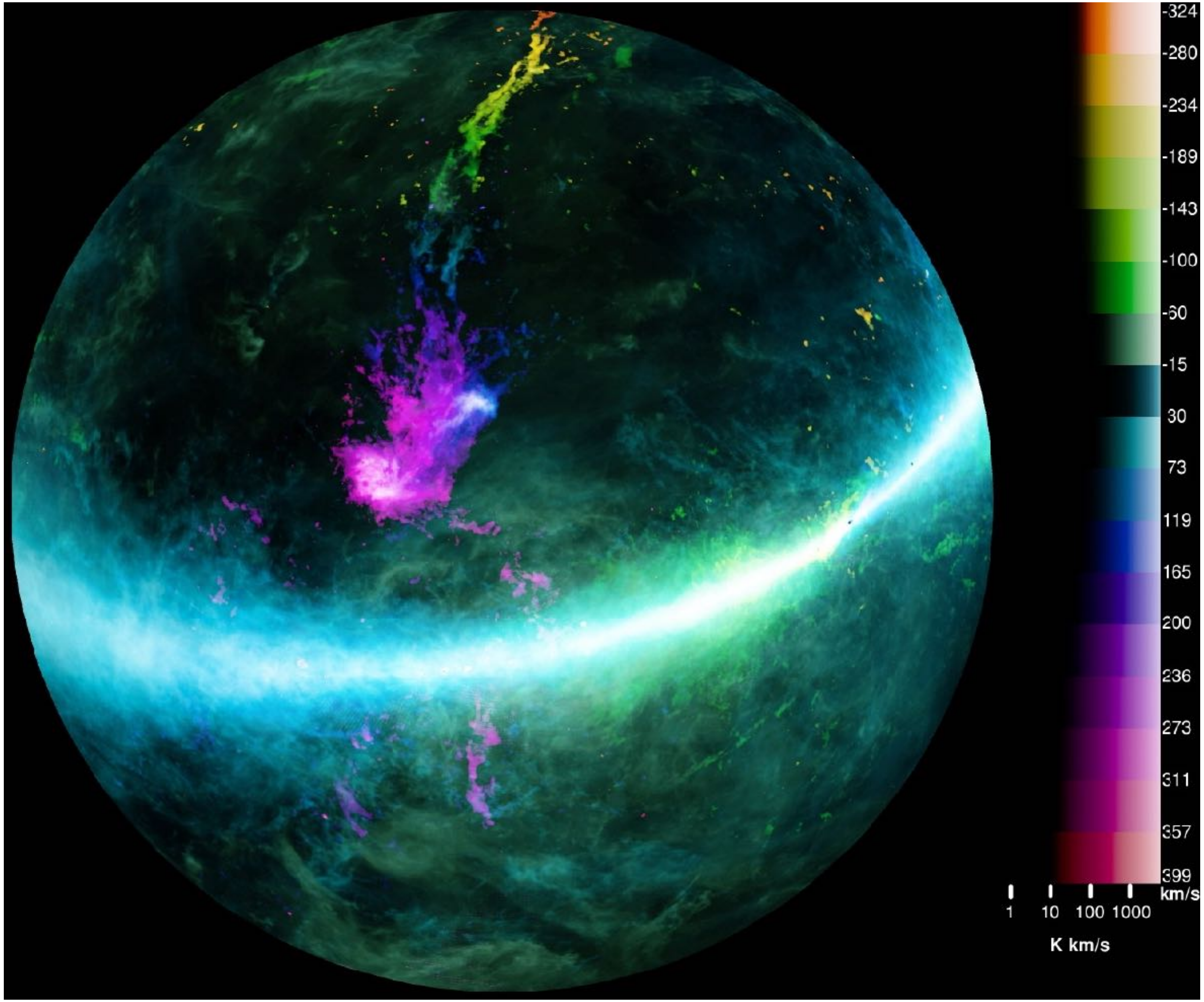
Interstellar gas

- Solution: After radio astronomy started to get developed it was suggested to look for the **predicted 21cm line of neutral hydrogen**.
- The **proton and the electron in the hydrogen atom can have their spins either parallel or antiparallel.** The state with parallel spins has slightly higher energy than the state with antiparallel spins. **When transition from the higher state to the lower state takes place, radiation with wavelength 21 cm is expected to be emitted.**
- This is, however, a ‘forbidden’ atomic line and it is not easy to see this line in laboratory experiments. Since interstellar space has a huge amount of hydrogen it is possible to receive emission from interstellar hydrogen at this spectral line.
- Within a few years of this remarkable prediction, emission from interstellar gas at this wavelength was detected in the early 1950s.



Interstellar gas

The interstellar medium also consists of a large gas component: hydrogen + other elements.
The most substantial component is the neutral atomic hydrogen (HI) gas



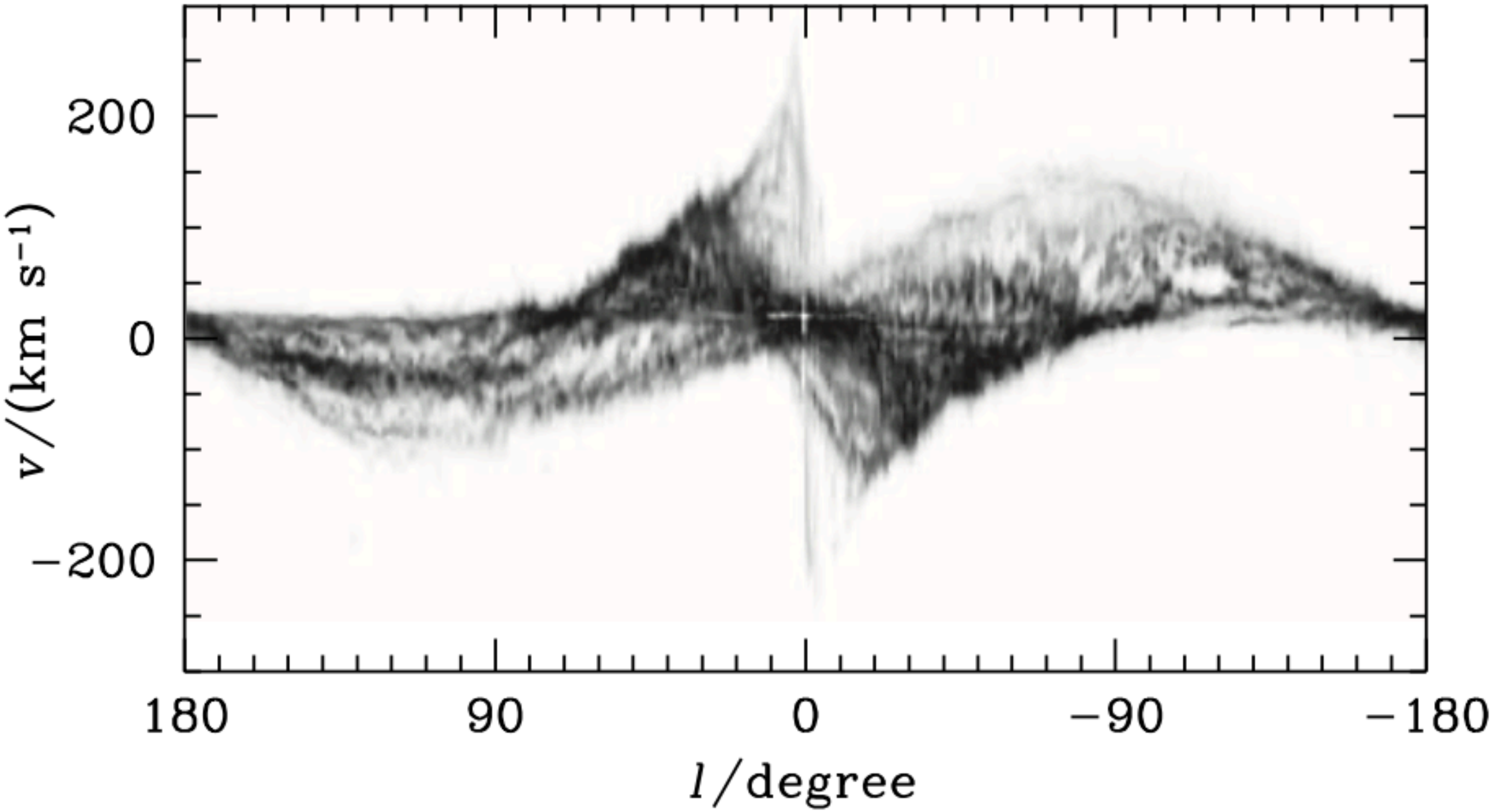
HI in the Milky Way + the Magellanic system

Interstellar gas

- If the emitting gas has any radial velocity along the line of sight, that would cause the wavelength to shift from 21 cm.
- Since the intrinsic width of the 21-cm line from a cold gas would be narrow, it is ideally suited to measure the wavelength shift which gives the radial velocity.
- Suppose in the direction of galactic coordinates (l, b) we find the intensity $I\,(l, b, \lambda)$ as a function of wavelength. Since the wavelength shift gives the radial velocity v_R of the emitting gas, we can write the intensity as $I(l, b, v_R)$.
- Of particular interest is the intensity in various directions of the galactic plane for which $b = 0°$.

Interstellar gas

- Figure shows $I\,(l, b = 0°, v_R)$ plotted in the l–v_R plane. The distribution of the interstellar gas has to be found out from plots like this.



Interstellar gas

- We consider a line of sight in the galactic plane as shown in the Figure
- We assume the interstellar gas to revolve around the galactic centre exactly in circular orbits. Then the radial velocity v_R at different points along the line of sight is given by $v_\mathrm{R} = (\omega - \omega_0) R_0 \sin l$
- It is clear that $|v_R|$ should be maximum when $|\omega - \omega_0|$ is maximum.
- Suppose ω increases as we go closer to the galactic centre -> Then $|v_R|$ **should be maximum at point 1** where the line of sight is tangent to the innermost circular orbit touched by the path of light.

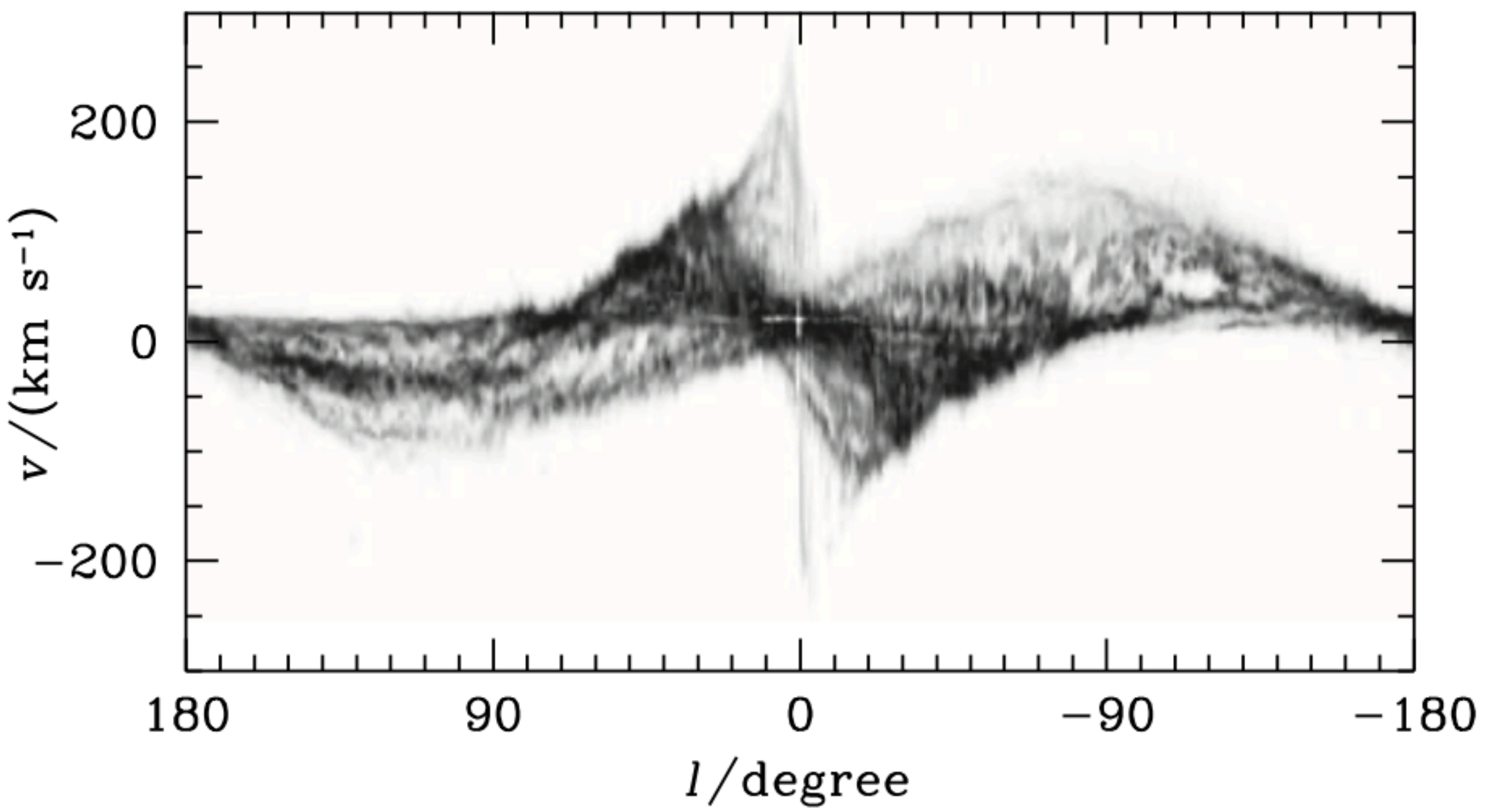
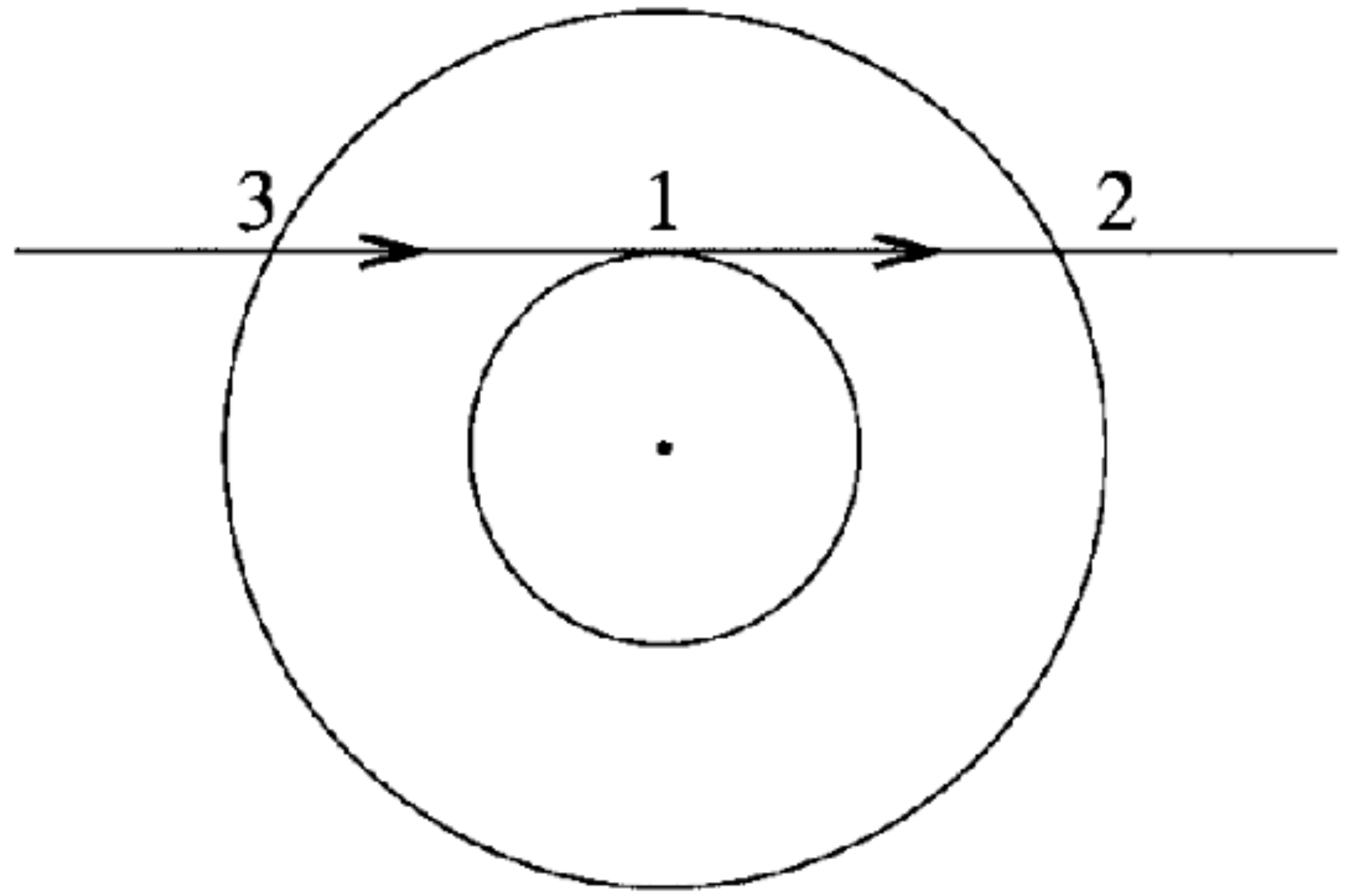


Fig. 6.9 A schematic line of sight through the Galaxy, along which we receive 21-cm emissions from interstellar clouds.

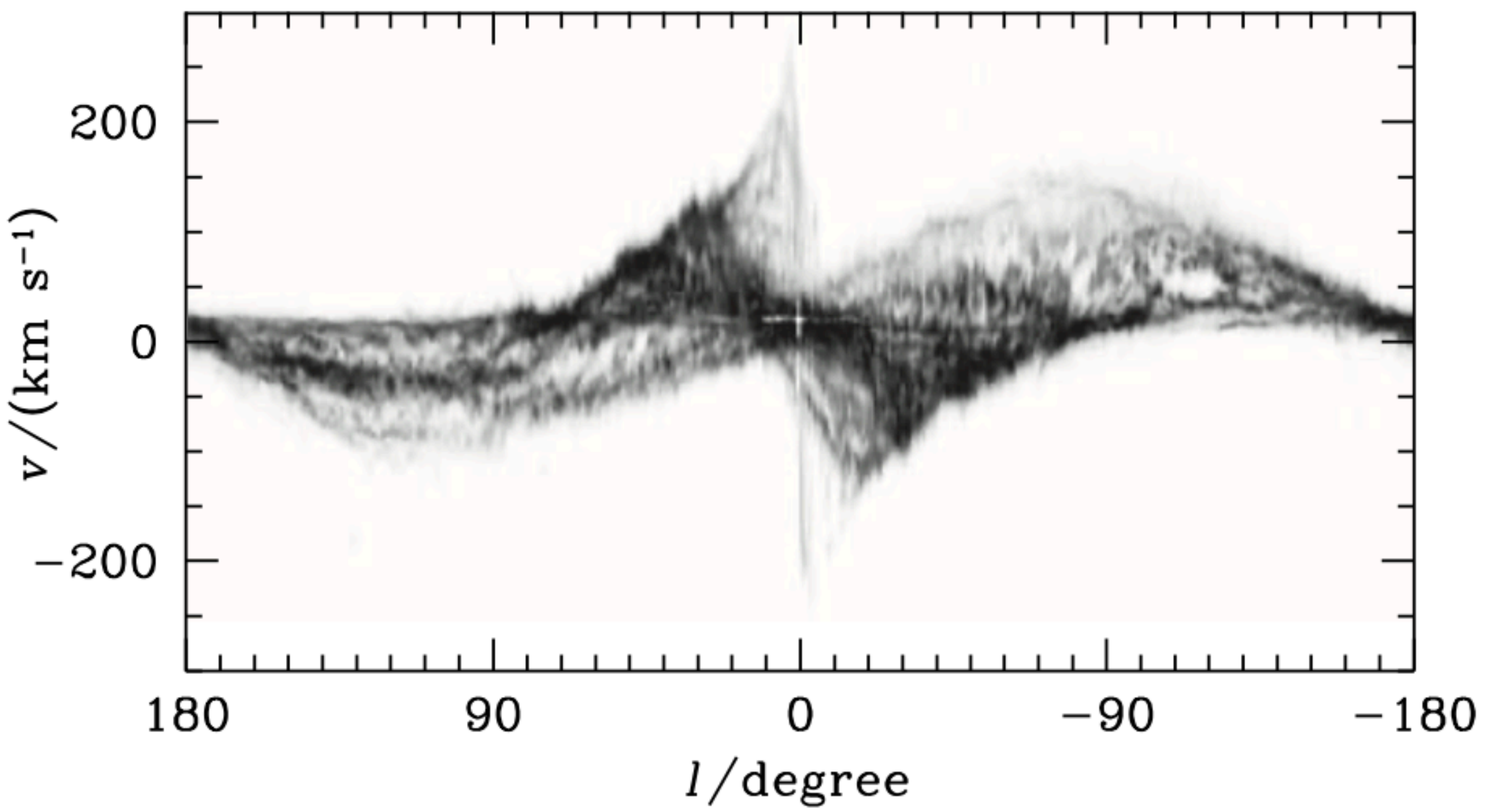


Interstellar gas

We see in the Figure that, for a given l, the intensity drops to zero beyond a certain value of $|v_R|$. This **maximum $|v_R|$ should correspond to that point along the light path where it is tangential to an orbit** (like point 1 in the Figure 6.9).

We then **find out ω at a distance $r = R_0 \sin l$ from the galactic centre**, since it is the circular orbit at this distance to which the line of sight is a tangent. -> build a **model of the rotation of the gas**

It is possible to find ω as a function of r till the solar orbit at $r = R_0$. This method does not apply for determining ω beyond R_0, for which we require other methods.



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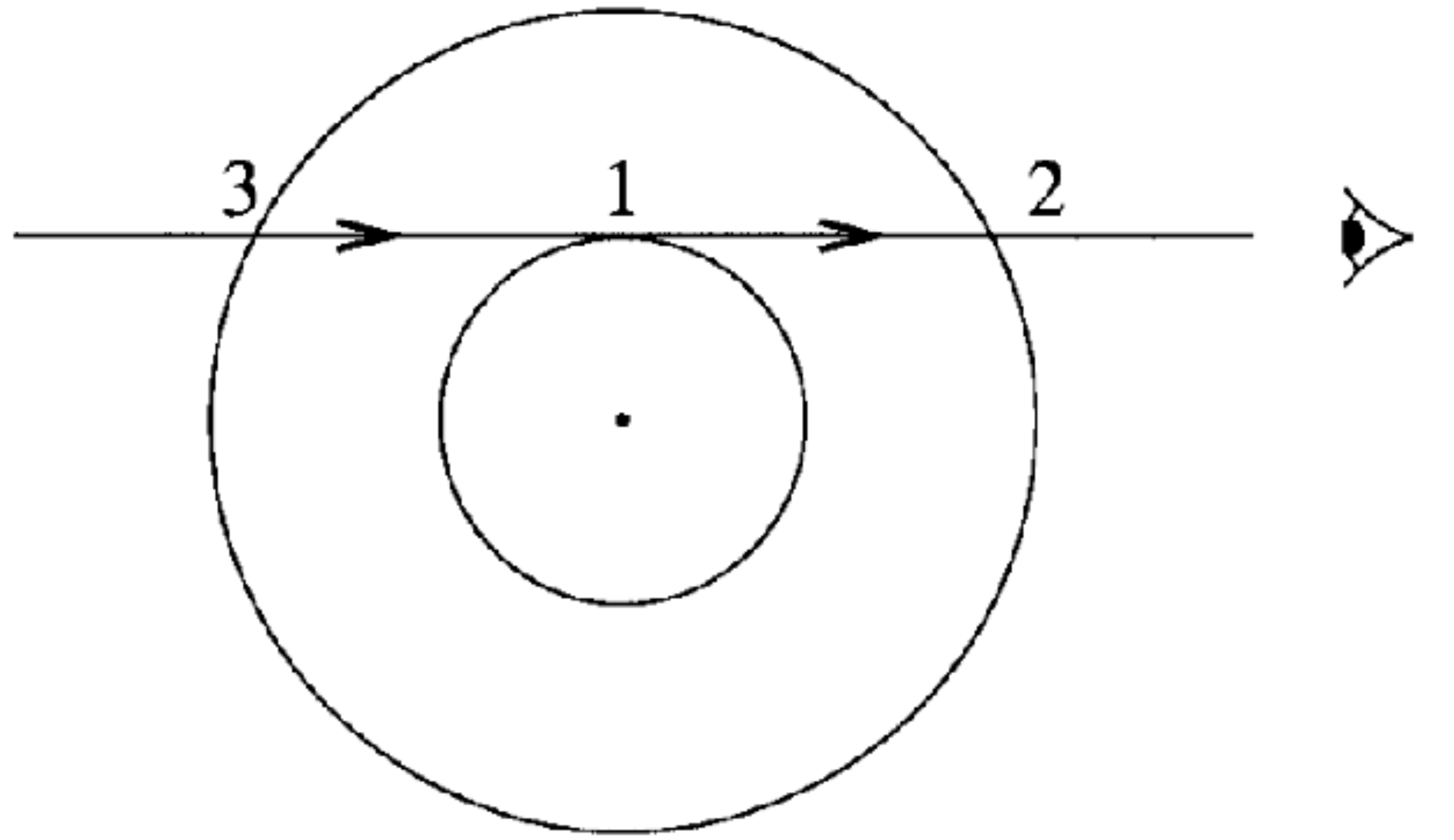


Interstellar gas

The interstellar gas is found to be quite clumpy. **The clumps of interstellar gas are referred to as *clouds*.**

The clumpiness can be seen in the figure. -> Wherever there is a local peak of intensity in the l–v_R plane, we conclude that there must be a cloud in the l direction moving with radial velocity v_R.

Clouds located at points 2 and 3 in Figure 6.9 should have the same v_R. Hence, if we see a peak in the intensity at this v_R, we infer the existence of a cloud at 2 or 3.

To determine whether the cloud is at 2 or 3, we can look at the angular size of the cloud perpendicular to the galactic plane. If this size is large, then we expect the cloud to be located at the nearer point. -> **reconstruct the gas distribution in the galactic plane.**

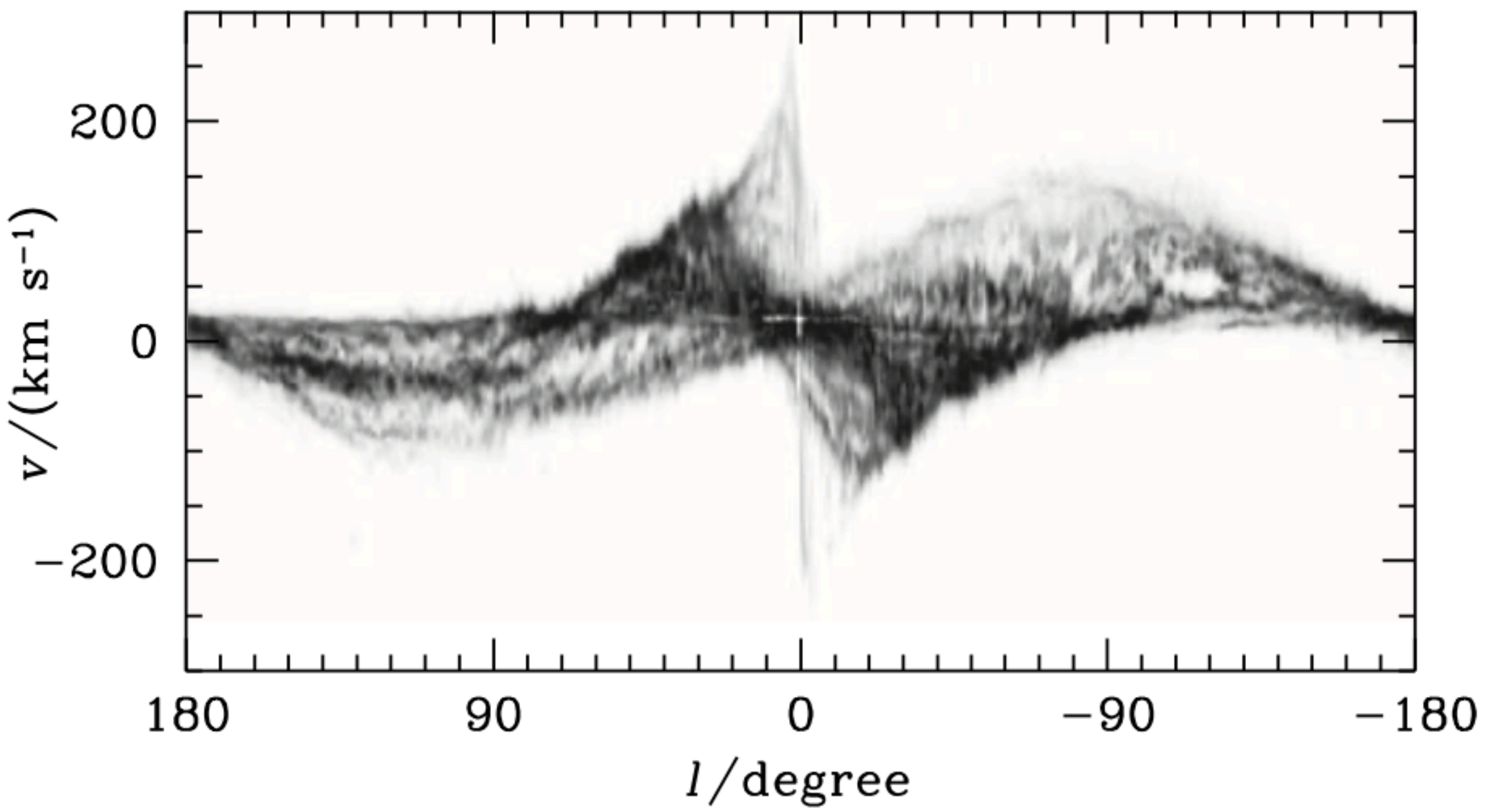
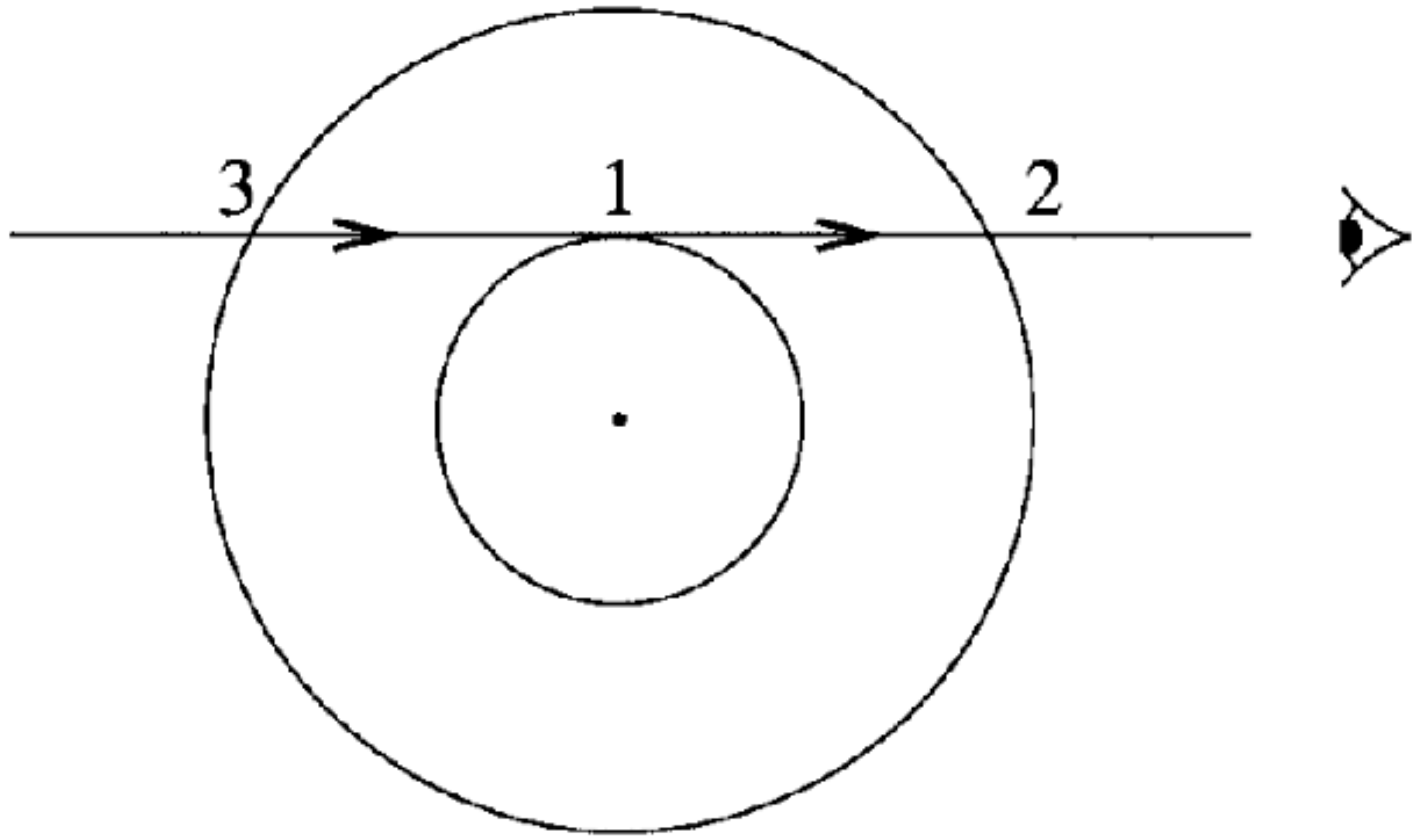


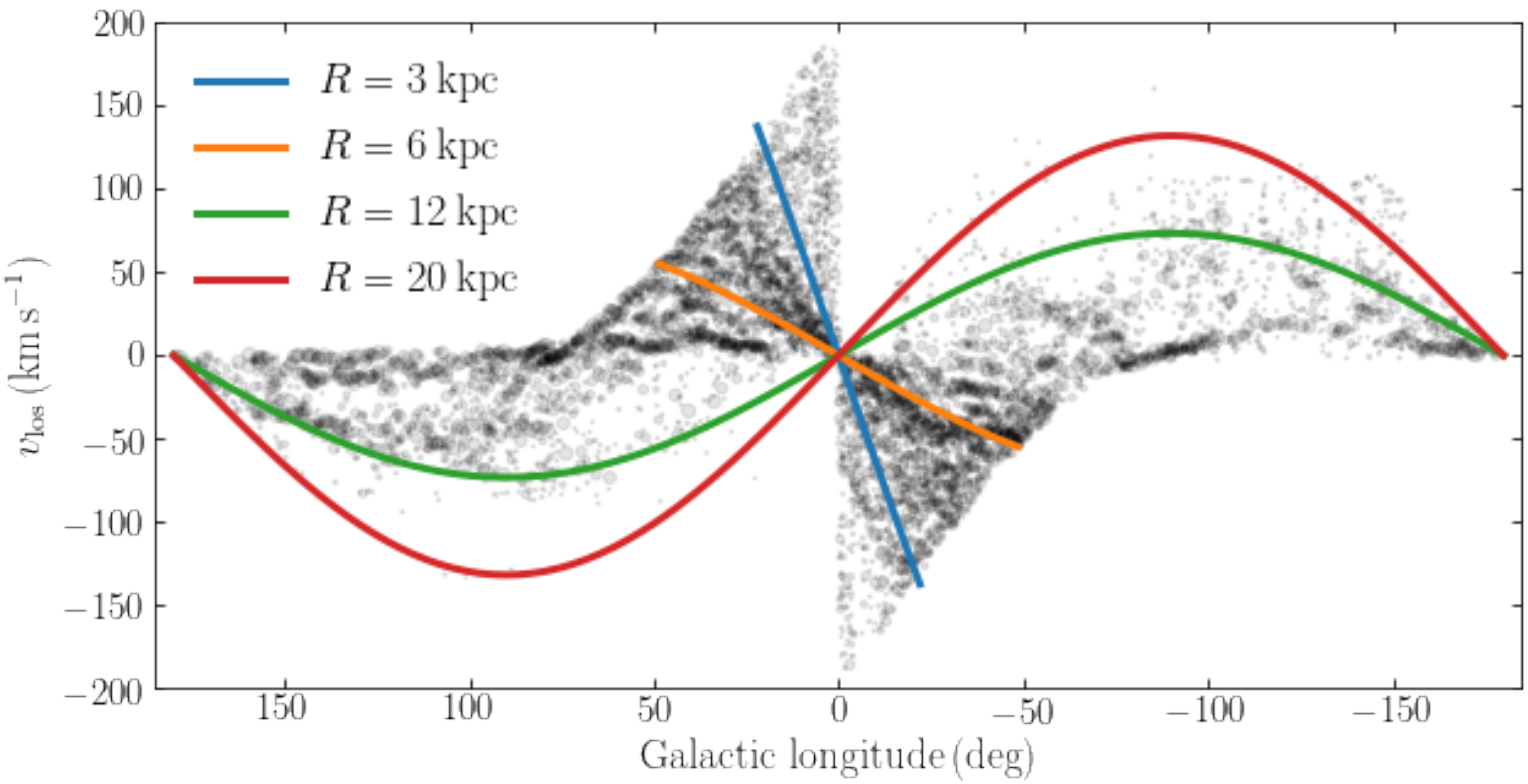
Fig. 6.9 A schematic line of sight through the Galaxy, along which we receive 21-cm emissions from interstellar clouds.



Interstellar gas

- Figure shows $I\ (l, b = 0°, v_R)$ plotted in the l–v_R plane. The distribution of the interstellar gas has to be found out from plots like this.

- **Coloured lines show certain radii in the disk -> darker lines in the data show the spiral arms**

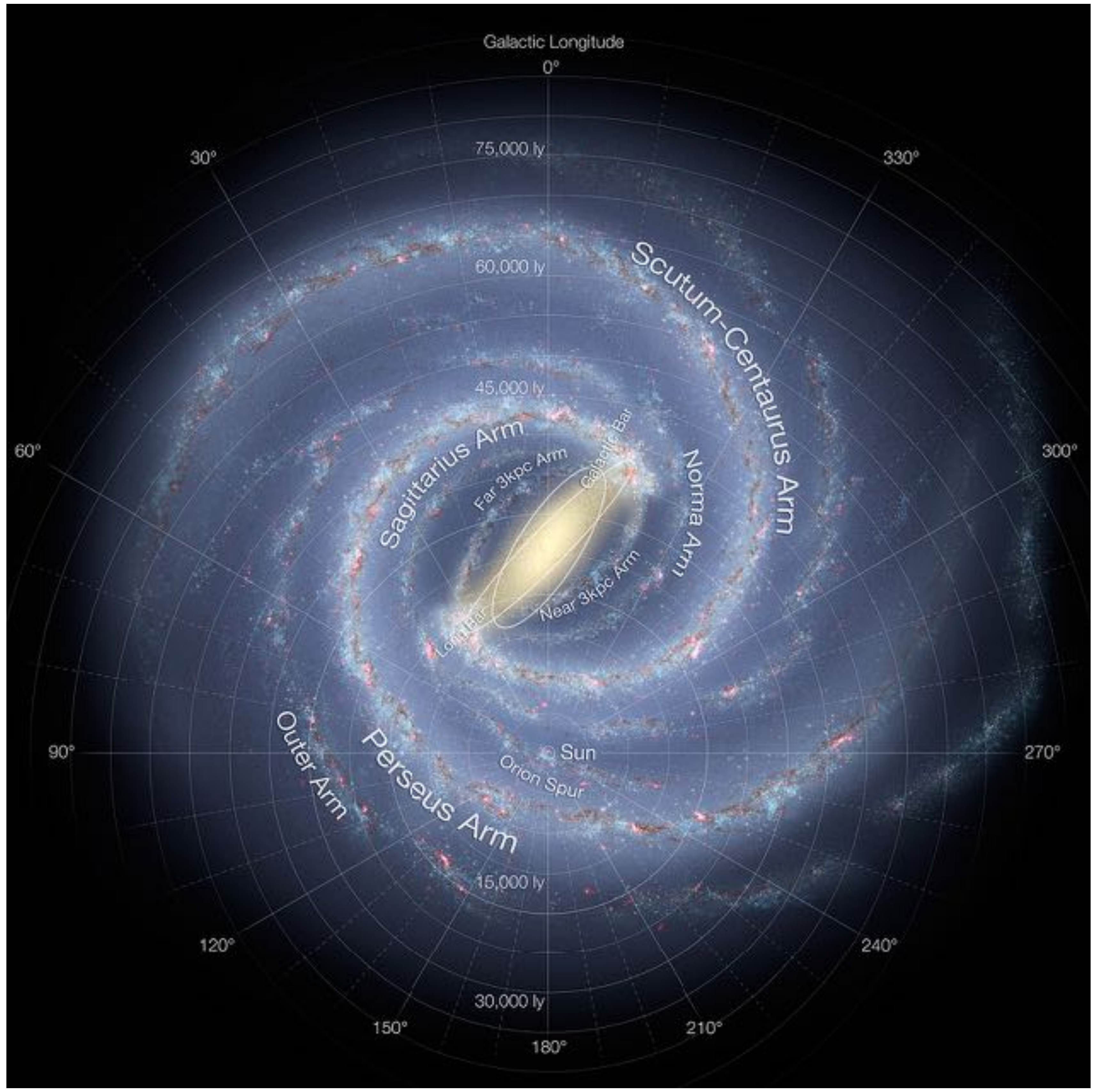


https://galaxiesbook.org/chapters/II-02.-Galactic-Rotation.html

Interstellar gas

Reconstructed gas distribution in the galactic plane.

Note the presence of spiral structures -> spiral arms



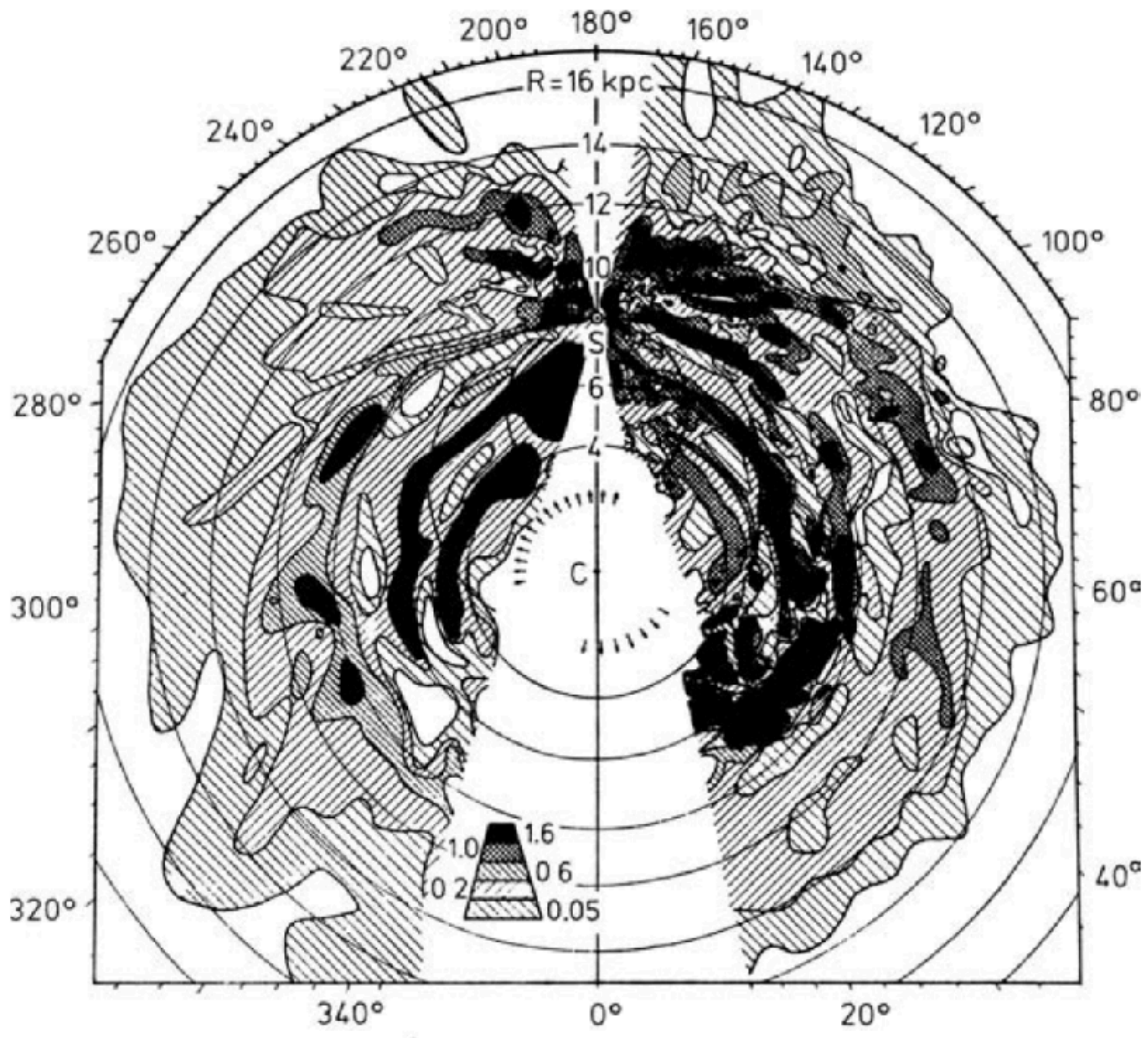
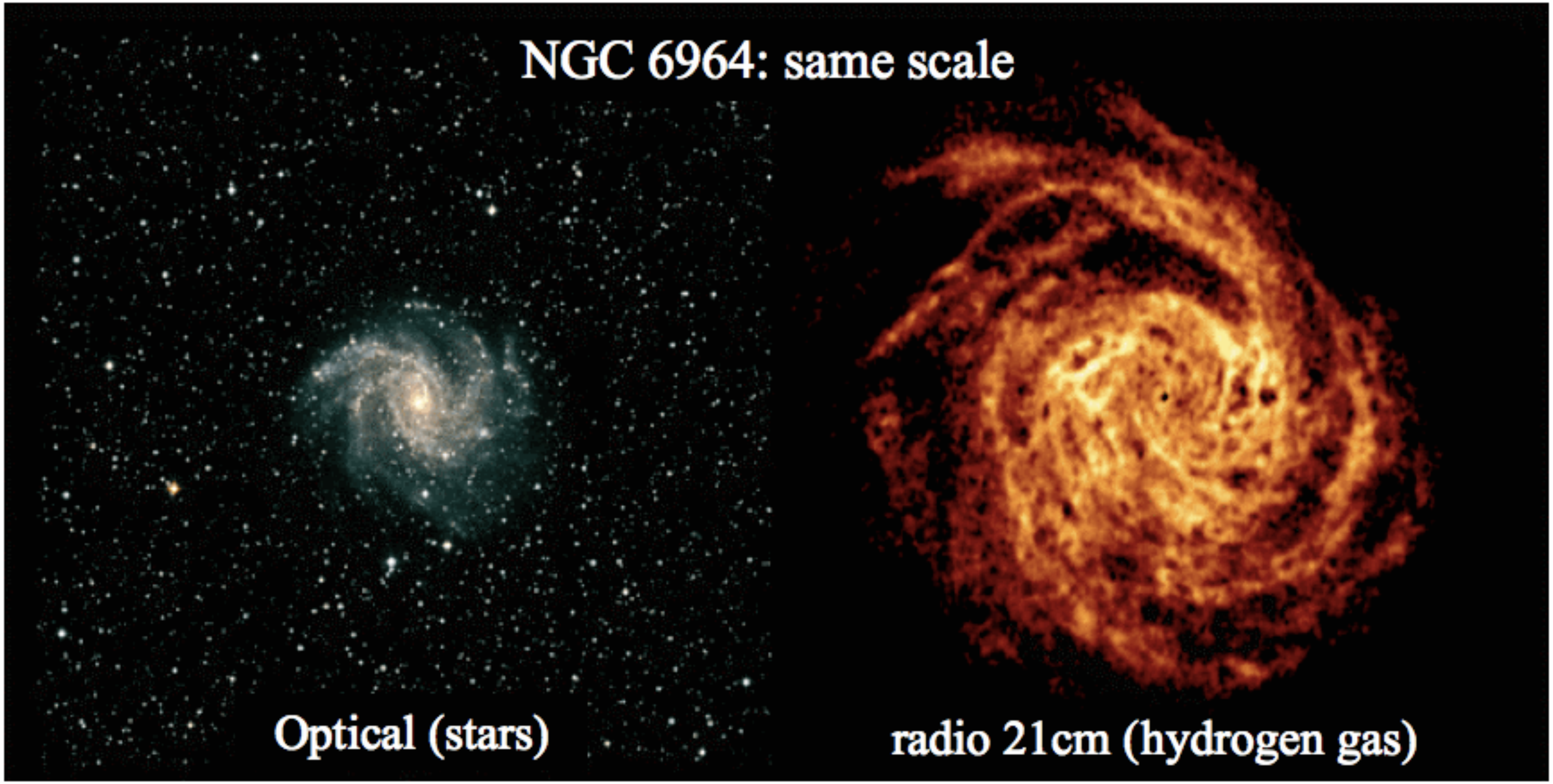


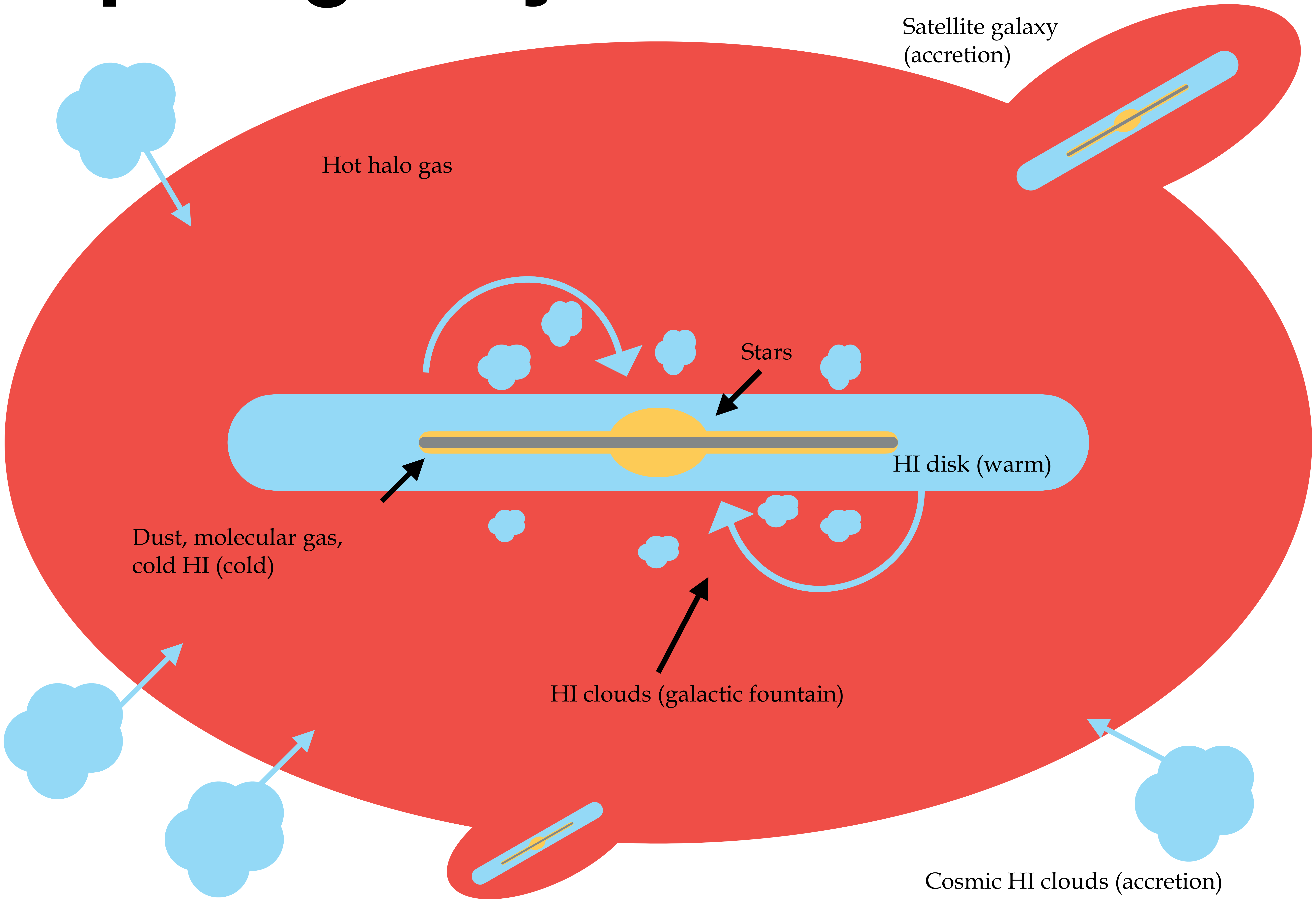
Fig. 6.10 The distribution of neutral hydrogen in the galactic plane, as found by Oort, Kerr and Westerhout (1958) from 21-cm observations. (©Royal Astronomical Society. Reproduced with permission from *Monthly Notices of Royal Astronomical Society*.)

A typical spiral galaxy

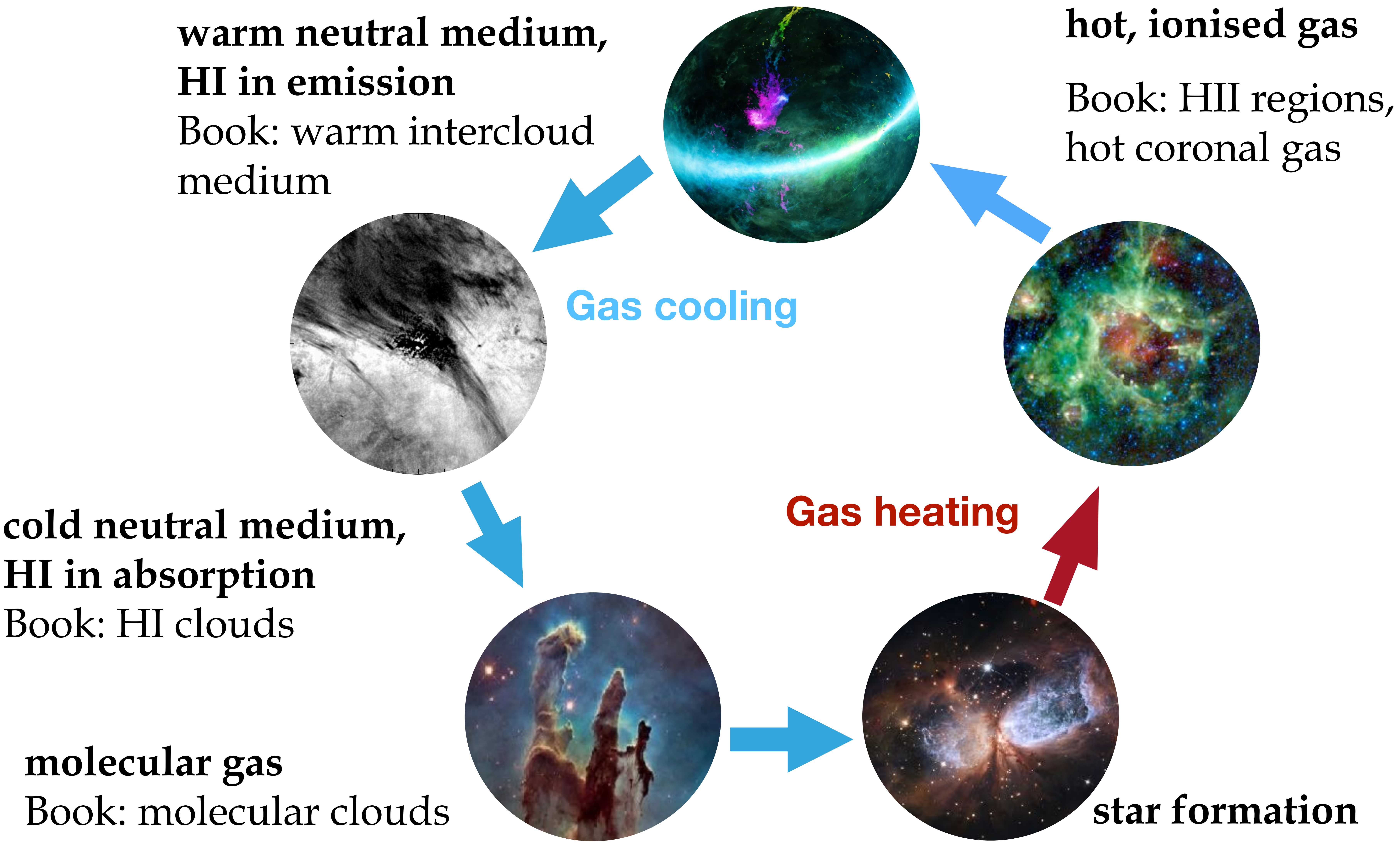
Face-on view of a spiral galaxy



A typical spiral galaxy



The gas cycle in the Galaxy



Emission and absorption in the ISM

In thermodynamical equilibrium: Kirchof's law

$$S_\nu = B_\nu(T)$$

$$\boxed{j_\nu = \alpha_\nu B_\nu(T).}$$

We have discussed how one can analyse a spectral line which is formed by the passage of radiation through an absorbing medium. However, radiation that has been emitted by the ISM or that has passed through the ISM, we need to keep in mind that the **ISM is far from thermodynamic equilibrium**. (We tend to assume local thermodynamical equilibrium (LTE).)

Hence usually the radiation present in the interstellar space would not be in equilibrium with matter, and Kirchhoff's law may not hold.

it is often necessary to study the radiative transfer through the ISM from a more microscopic point of view.

Emission and absorption in the ISM

- A bit of QM: Consider two energy levels of some atom. The transitions between these levels are accompanied by emission or absorption of photons with energy $h\nu_0$ equal to the energy difference between the levels.
  - subscripts u and l to denote the upper and lower levels.
- Let the atomic number densities in the upper and lower levels be n_u and n_l.
- It is useful to develop our discussion from the well-known **Einstein coefficients of radiative transition**.
- Let A_{ul} be the coefficient of **spontaneous transition**, whereas B_{ul} and B_{lu} are the coefficients of **induced transition.**
- The number of **spontaneous transitions per unit volume per unit time** is $n_u A_{ul}$ and the **energy emitted** in these transitions is $h\nu_0 n_u A_{ul}$.
- The energy emitted per unit volume per unit time per unit solid angle is given by dividing this by 4π. This should be equal to the **emission coefficient** j_ν **integrated over the spectral line**, i.e.

$$\int j_\nu d\nu = \frac{h\nu_0 n_u A_{ul}}{4\pi}$$

Emission and absorption in the ISM

- Let $\phi(\Delta\nu)$ be the **normalized line profile** where $\Delta\nu$ is the departure of the frequency from the line centre at ν_0 and $\int \phi(\Delta\nu)d\nu = 1$.
- Then j_ν should be of the form

$$j_\nu = \frac{h\nu_0 n_u A_{ul}}{4\pi}\phi(\Delta\nu)$$

$$U_\nu = \int \frac{I_\nu}{c} d\Omega$$

- In the presence of a **radiation field with energy density** U_ν , the number of induced upward transitions per unit volume per unit time is $n_l B_{lu} U_\nu$, whereas the corresponding number of downward transitions is $n_u B_{ul} U_\nu$.
- The **net energy absorbed per unit volume per unit time** must be

$$\mathcal{E}_{\rm abs} = \frac{h\nu_0}{c}(n_l B_{lu} - n_u B_{ul}) \int I_\nu \, d\Omega$$

Emission and absorption in the ISM

$$\mathcal{E}_{\rm abs} = \frac{h\nu_0}{c}(n_l B_{lu} - n_u B_{ul}) \int I_\nu \, d\Omega$$

- The **energy absorbed from the beam I_ν in unit volume in unit time is $\alpha_\nu I_\nu$**. The energy absorbed from radiation coming from all directions is obtained by integrating this over all solid angles. So another expression of ϵ_{abs} **is given by again integrating this over the absorption line** (presumably α_ν is non-zero only for frequencies at which absorption takes place), i.e.

$$\mathcal{E}_{\rm abs} = \int d\nu \int \alpha_\nu \, I_\nu \, d\Omega$$

- Comparing the above two expressions of ϵ_{abs} and assuming for simplicity that the absorption coefficient α_ν also has the same profile $\phi(\Delta\nu)$, we conclude

$$\alpha_\nu = \frac{h\nu_0}{c}(n_l B_{lu} - n_u B_{ul}) \, \phi(\Delta\nu).$$

Emission and absorption in the ISM

- Source function: $$\boxed{S_\nu = \frac{j_\nu}{\alpha_\nu} = \frac{c}{4\pi}\frac{n_u A_{ul}}{n_l B_{lu} - n_u B_{ul}}}$$

$$j_\nu = \frac{h\nu_0 n_u A_{ul}}{4\pi}\phi(\Delta\nu)$$

$$\alpha_\nu = \frac{h\nu_0}{c}(n_l B_{lu} - n_u B_{ul})\,\phi(\Delta\nu).$$

The Einstein transition coefficients satisfy the following important relations:

$$\boxed{A_{ul} = \frac{8\pi h\nu^3}{c^3}B_{ul}, \quad g_u B_{ul} = g_l B_{lu},}$$

The where g_u and g_l are the statistical weights of the upper and lower states.

Since these relations follow from the **fundamental transitions of the atom, they should not depend on whether there is thermodynamic equilibrium** around or not.

However, only if the system is in thermodynamic equilibrium, should we have the Boltzmann relation

$$\frac{n_u}{n_l} = \frac{g_u}{g_l}\exp\left(-\frac{h\nu_0}{\kappa_B T}\right)$$

Emission and absorption in the ISM

- In **thermodynamical equilibrium:**

$$\boxed{S_\nu = \frac{j_\nu}{\alpha_\nu} = \frac{c}{4\pi} \frac{n_u A_{ul}}{n_l B_{lu} - n_u B_{ul}}}$$

$$\frac{n_u}{n_l} = \frac{g_u}{g_l} \exp\left(-\frac{h\nu_0}{\kappa_B T}\right)$$

$$A_{ul} = \frac{8\pi h\nu^3}{c^3} B_{ul}, \quad g_u B_{ul} = g_l B_{lu},$$

-> the source function S_ν should be equal to the Planck function $B_\nu(T)$

For a system **not in thermodynamic equilibrium**, we have to determine the population n_i for a level i by solving microscopic rate equations. If R_{ij} is the transition probability from level i to j then $n_i \Sigma_j R_{ij}$ gives the rate of transition out of the level i. In the steady state this has to equal the rate of transition onto the level i from all other levels j given by $\Sigma_j n_i R_{ij}$

$$n_i \sum_j R_{ij} - \sum_j n_j R_{ji} = 0.$$

We have one such equation for each atomic level i. If we can figure out the transition rates R_{ij} between various levels from fundamental physics, then we can solve these simultaneous equations to determine the populations in the various levels.

Emission and absorption in the ISM

- Let us consider the simplest case of two levels u and l as an illustration.
- **In addition to the spontaneous emission and induced emission,** there can be a transition from the upper level to the lower level by inelastic collisions with electrons present in the system. We expect the transition rate due to **collisional de-excitation** to be proportional to both the electron number density n_e and the number density n_u of atoms in the upper level. So we can write this transition rate as $\gamma_{ul} n_u n_e$.
- Similarly, there would be **collisional excitation of atoms from the lower to the upper level**, **in addition to transitions induced by radiation**. Since the transition rates for $u \rightarrow l$ and $l \rightarrow u$ have to balance in the steady state, we have

$$n_u(A_{ul} + B_{ul}U_\nu + \gamma_{ul}n_\mathrm{e}) = n_l(B_{lu}U_\nu + \gamma_{lu}n_\mathrm{e})$$

- The collisional transition rates is independent of whether the radiation field is in equilibrium with matter.
- Valid even when no radiation field is present.

$$g_l\gamma_{lu} = g_u\gamma_{ul}\exp\left(-\frac{h\nu_0}{\kappa_\mathrm{B}T}\right)$$

Emission and absorption in the ISM

- In the interstellar medium, we often have atoms excited to a higher level collisionally.
- Then the excited atoms return to the lower level either through collisions or through the spontaneous emission of photons.
- If the energy density of radiation is negligible, then we can put $U_\nu = 0$ in

$$n_u(A_{ul} + B_{ul}U_\nu + \gamma_{ul}n_\mathrm{e}) = n_l(B_{lu}U_\nu + \gamma_{lu}n_\mathrm{e})$$

$$\frac{n_u}{n_l} = \frac{\gamma_{lu}n_\mathrm{e}}{A_{ul} + \gamma_{ul}n_\mathrm{e}}$$

$$g_l\gamma_{lu} = g_u\gamma_{ul}\exp\left(-\frac{h\nu_0}{\kappa_\mathrm{B}T}\right)$$

$$\frac{n_u}{n_l} = \frac{g_u}{g_l}\exp\left(-\frac{h\nu_0}{\kappa_\mathrm{B}T}\right)\cdot\frac{1}{1 + (A_{ul}/\gamma_{ul}n_\mathrm{e})}$$

- It is clear that we would get back the Boltzmann distribution if spontaneous emission is absent (i.e. if $Aul = 0$).
- The spontaneous emission makes some atoms de-excite from the upper level and thereby decreases the population of the upper level compared to what we have got from the Boltzmann distribution.

Phases of the ISM - HI clouds

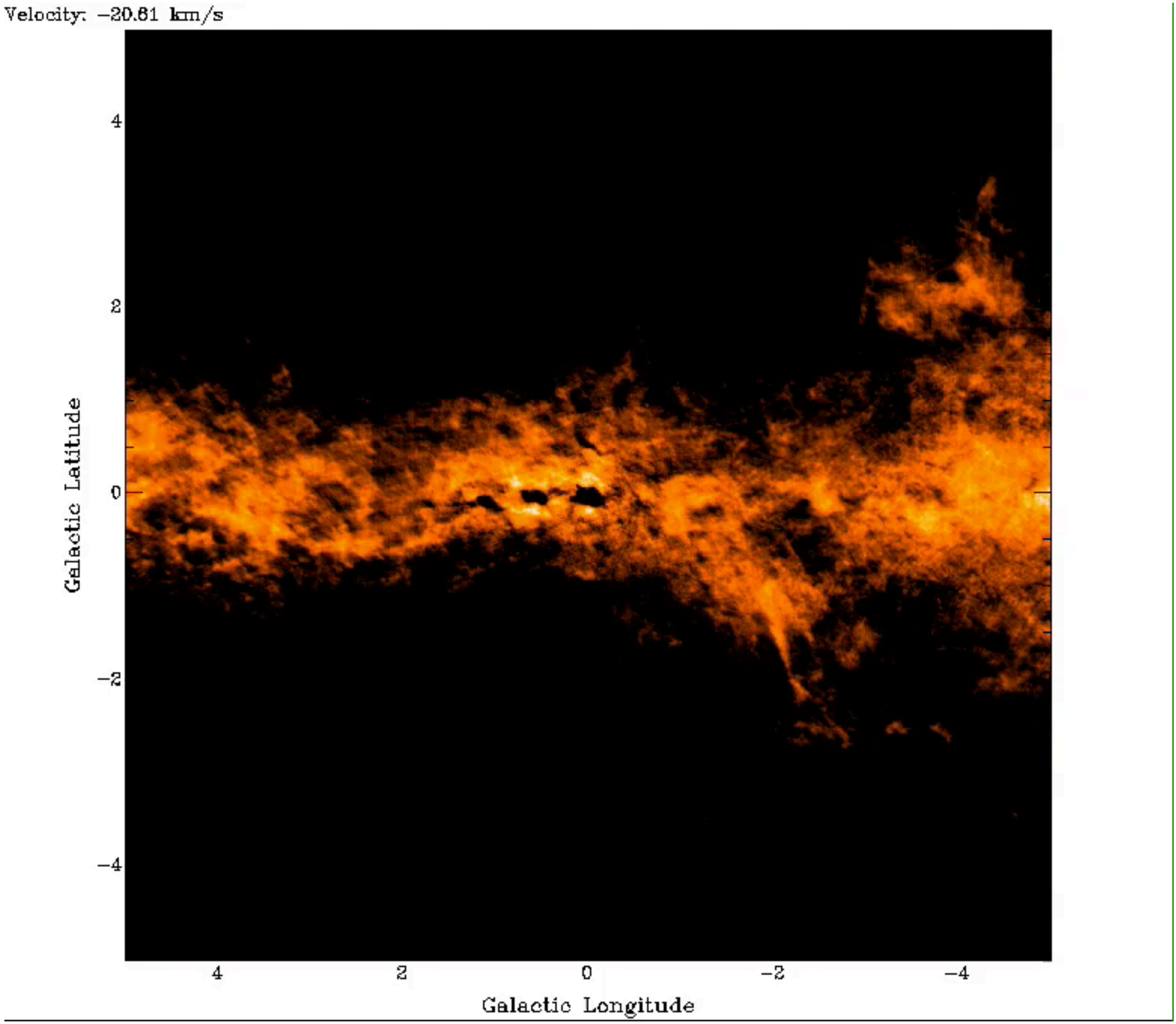
- Neutral hydrogen (HI - chemistry notation)
- The distribution of HI inside the Galaxy is highly non-uniform. And there are generally two phases distinguished a warm and a cold phase.
- The **cold HI clouds** have densities of order $10^6 - 10^8$ particles m^{-3} and **temperatures 80 K**.
- Contribute nearly 40% of the mass of the interstellar matter, but fill a relatively small volume ~5%.
- In the direction perpendicular to the galactic plane in the solar neighbourhood, HI clouds are found mostly within a distance of about 100pc from the mid-plane.
- The space between clouds (as much as 40% of the interstellar space) appears filled with much **warmer neutral hydrogen** gas, with a **temperature of about 8000K** and density in the range of $10^5 - 10^6$ particles m^{-3}.
- The 21-cm line is the most important diagnostic tool for studying HI clouds.
- They can also be studied by analysing the narrow absorption lines in the visible and UV parts of the stellar spectra, caused by the absorption of starlight by the interstellar gas, however this is a more complicated observational process.

Neutral hydrogen in the Galaxy

Close up view of the HI in the galaxy - filamentary, clumpy structure

HI towards the Galactic Centre

- Data from the GASS survey
- HI towards the Galactic Centre
- Each frame of the movie corresponds to a different frequency (velocity) of the gas
- Frequency can be related to distance by assuming that the gas is rotating around the centre of the Galaxy
- Bright regions are the **warm HI in emission**
- Dark regions are **cold HI in absorption**
- Turbulent filamentary structure of the gas
- Filaments tracing magnetic fields



HI towards the Galactic Centre

- Bright regions are the **warm HI in emission**
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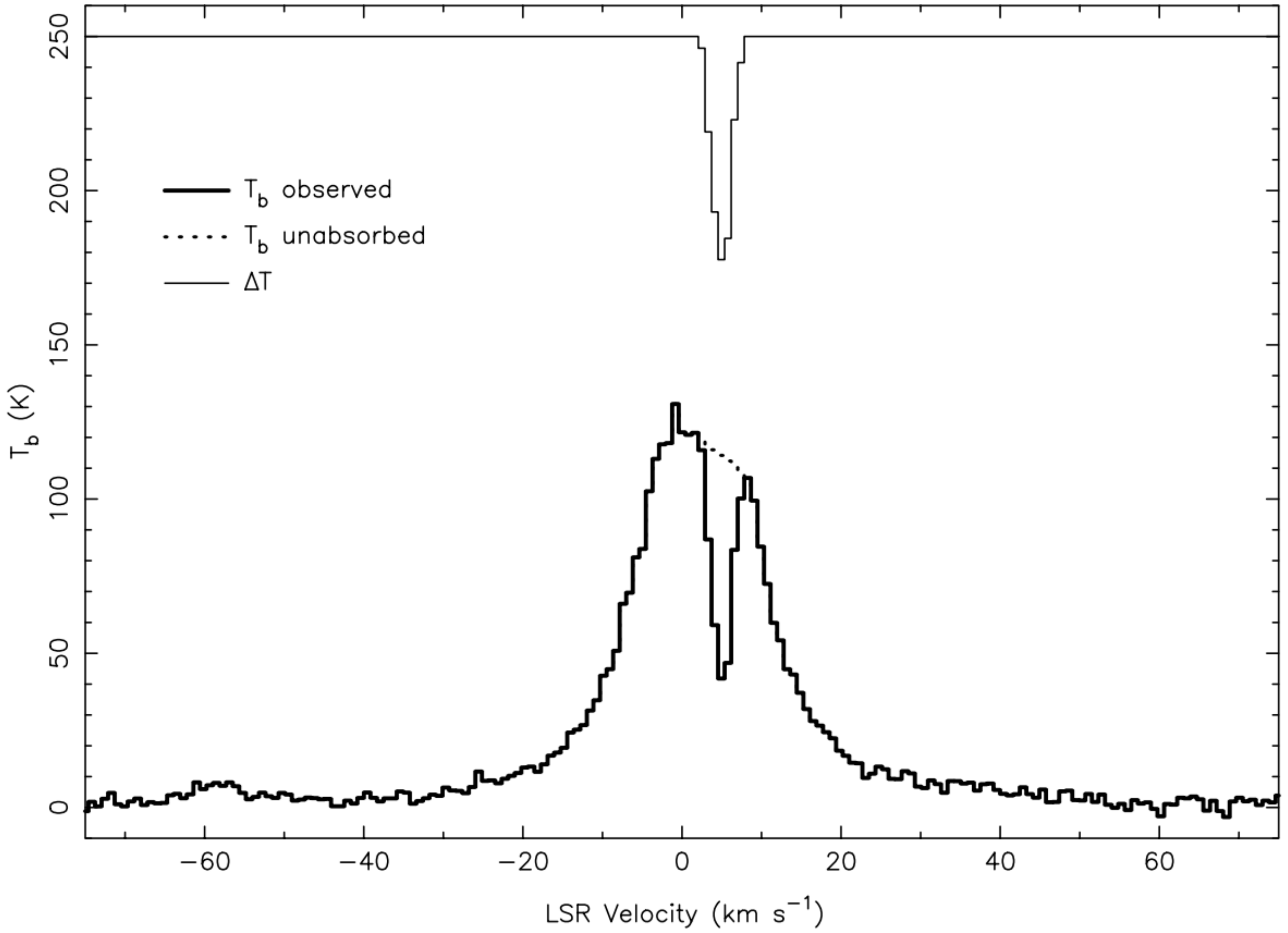
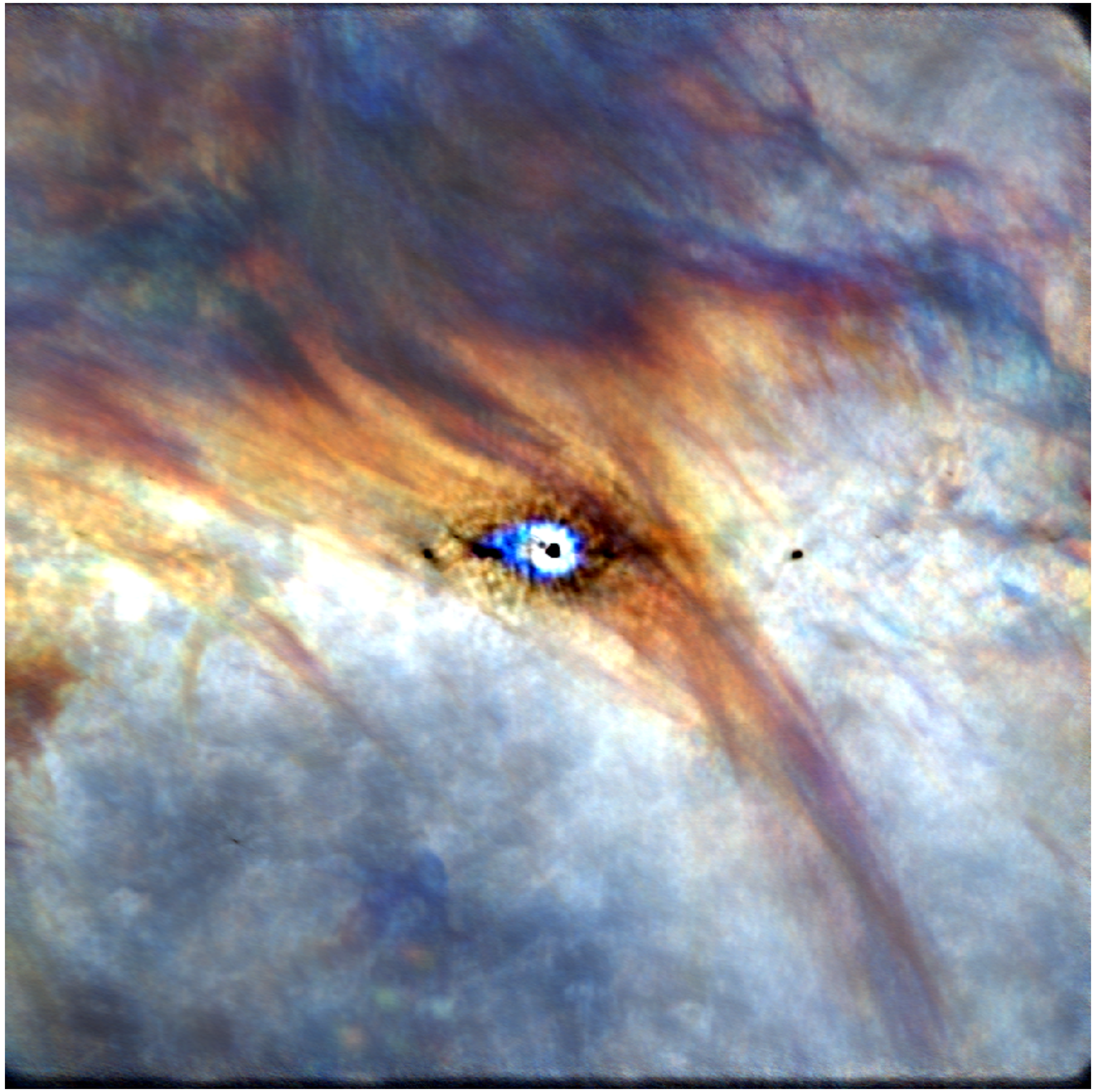
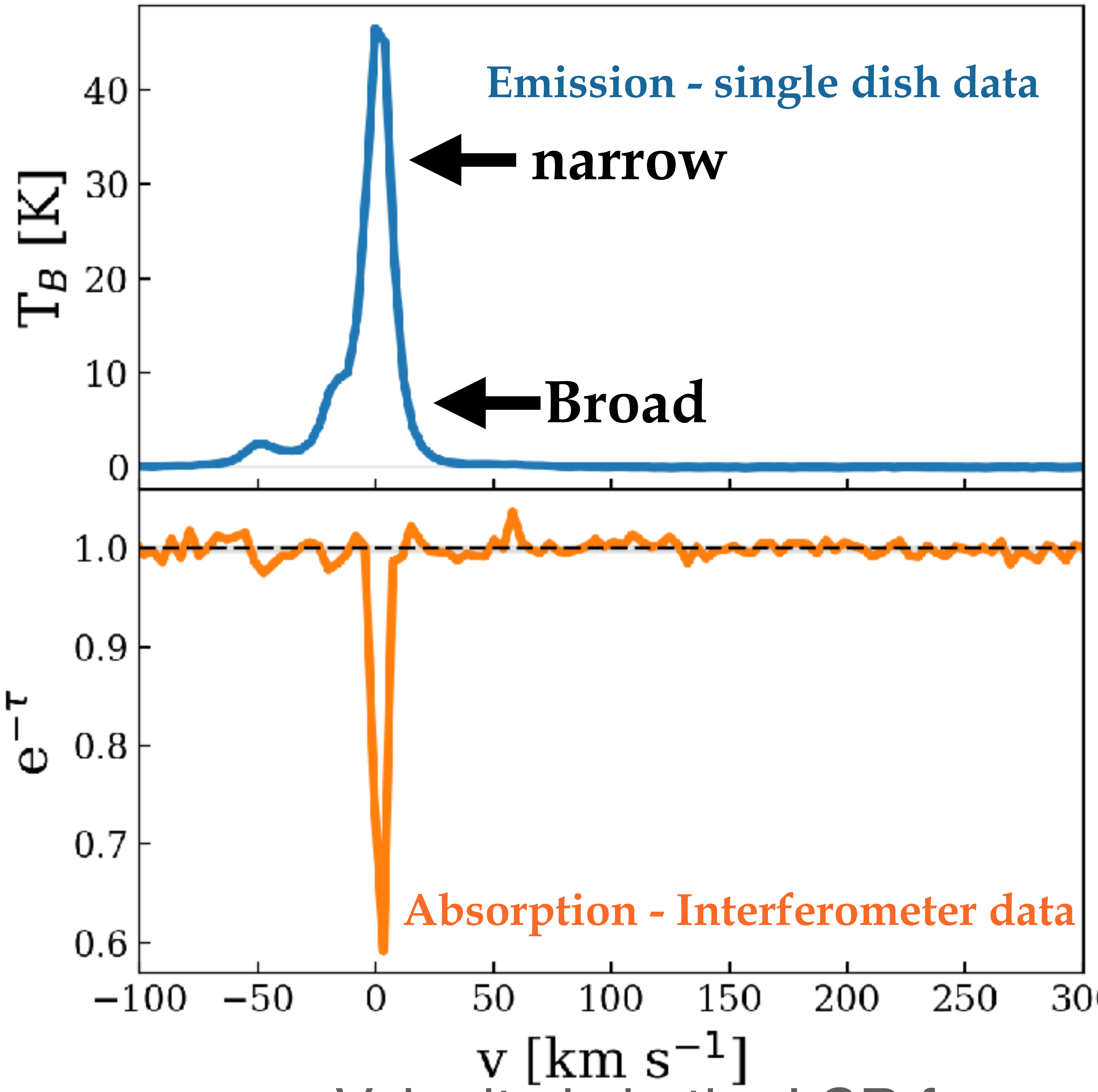
HI self absorption -> bright HI emission + HI absorption from a cold HI cloud





Phases of the ISM - HI clouds

- Much of the information about the HI gas in interstellar space comes from the 21-cm line.
- **Along the line of sight, there would be clouds moving with different radial velocities due to the differential rotation** of the Galaxy. These clouds would emit at slightly different wavelengths. -> we use velocity on the x-axis to approximately indicate where the gas cloud is in the Galaxy.
- To focus on the basic physics, let us consider the simple situation of one optically thin cloud in the line of sight.
    - It will produce an emission line at a wavelength close to 21 cm.
    - If there is a background radio source with a continuum spectrum, we also expect to see an absorption line at this wavelength.



Velocity is in the LSR frame

T_B means brightness temperature => intensity

Phases of the ISM - HI clouds

- In the upper level of the 21-cm transition, the spin of the electron and the proton are parallel, giving a combined spin of 1.
- It is a standard result of QM that this level should have the statistical weight $g_u = 3$, whereas the lower state with antiparallel spins should have the statistical weight $g_l = 1$.
- For $T = 80$ K, the difference of energy $h\nu_0$ between these levels is small compared to $\kappa_B T$ and the exponential factor below is close to 1, such that $n_u/n_l = 3$.
- If n_H is the number density of hydrogen atoms, then

$$\frac{n_u}{n_l} = \frac{g_u}{g_l} \exp\left(-\frac{h\nu_0}{\kappa_\mathrm{B} T}\right) \cdot \frac{1}{1 + (A_{ul}/\gamma_{ul} n_\mathrm{e})} \longrightarrow n_u = \frac{3}{4} n_\mathrm{H}, \; n_l = \frac{1}{4} n_\mathrm{H}$$

are the number densities of hydrogen atoms in the upper and lower levels.

For an **optically thin source**, it easily follows from the radiative transfer equation that the specific intensity is given by $\int j_\nu ds$ and the **total intensity of emission in the spectral line is:**

$$I = \int ds \int j_\nu \, d\nu.$$

$$n_u = \frac{3}{4} n_{\rm H}, \; n_l = \frac{1}{4} n_{\rm H}$$

Phases of the ISM - HI clouds

$$j_\nu = \frac{h\nu_0 n_u A_{ul}}{4\pi} \phi(\Delta\nu)$$

Substituting : $I = \int ds \int j_\nu \, d\nu. \longrightarrow I = \frac{3}{16\pi} h\nu_0 A_{ul} \int n_{\rm H} \, ds$

- $A_{ul} = 2.85 \times 10^{-15}$ s^{-1} for the 21-cm transition, which means that an **atom in the upper level is expected to make a downward transition once in 10^7 yr.** -> 21-cm emission is difficult to produce in a laboratory setup, since a collisional downward transition would be much more likely.
- However, there is plenty of HI in space and the 21cm transition is easy to observe from nearby astronomical sources.
- The **measurement of *I* gives us the value of** $\int n_H ds$, since all the other things are known. If we have an idea of the path length through the cloud, we get an estimate of n_H. -> direct measurement of how **much HI is in a cloud.**

Phases of the ISM - HI clouds

We now consider the **absorption line**. For an optically thin obstacle, it follows that the intensity after passing through the obstacle would be:

$$I_\nu(\tau_\nu) = I_\nu(0)e^{-\tau_\nu}$$

where $I_\nu(0)$ is the intensity of the background source. Hence the depth of the spectral line depends on the optical depth $\tau_\nu = \int \alpha_\nu ds$, which we now estimate.

$$\alpha_\nu = \frac{h\nu_0}{c}(n_l B_{lu} - n_u B_{ul})\,\phi(\Delta\nu)$$

$$A_{ul} = \frac{8\pi h\nu^3}{c^3}B_{ul}, \quad g_u B_{ul} = g_l B_{lu},$$

$$\frac{n_u}{n_l} = \frac{g_u}{g_l}\exp\left(-\frac{h\nu_0}{\kappa_\mathrm{B}T}\right)$$

$$\longrightarrow \quad \alpha_\nu = \frac{h\nu_0}{c}n_l B_{lu}\left[1 - \exp\left(-\frac{h\nu_0}{\kappa_\mathrm{B}T}\right)\right]\phi(\Delta\nu)$$

Since $h\nu_0 \ll \kappa_B T$ for the 21-cm line, we get:

$$\alpha_\nu = \frac{h\nu_0}{c}n_l B_{lu}\frac{h\nu_0}{\kappa_\mathrm{B}T}\phi(\Delta\nu).$$

Phases of the ISM - HI clouds

$$\alpha_\nu = \frac{h\nu_0}{c} n_l B_{lu} \frac{h\nu_0}{\kappa_{\rm B} T}\phi(\Delta\nu). \longrightarrow \alpha_\nu = \frac{3}{32\pi} n_{\rm H} A_{ul} \frac{hc^2}{\nu_0 \kappa_{\rm B} T}\phi(\Delta\nu).$$

$$\tau_\nu = \frac{3}{32\pi} A_{ul} \frac{hc^2}{\nu_0 \kappa_{\rm B}}\phi(\Delta\nu) \int \frac{n_{\rm H}}{T} ds$$

the 21-cm **absorption line** gives us the integral $\int \frac{n_{\rm H}}{T} ds$

along the line of sight, whereas the 21-cm **emission line** gives the integral: $\int n_H ds$

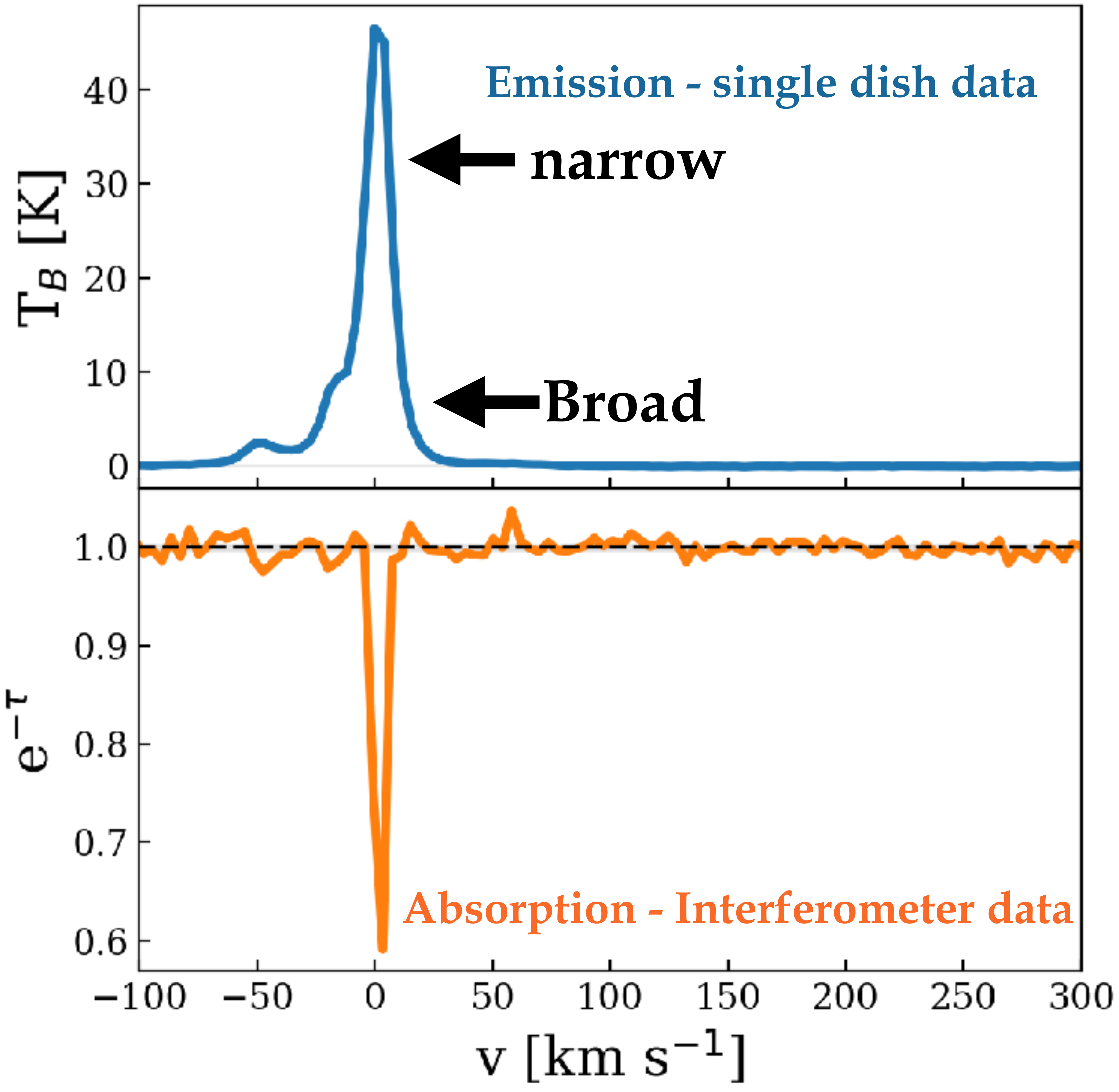
By combining the information obtained from the emission and the absorption lines, we can estimate the temperature of the neutral hydrogen gas.

Phases of the ISM - Warm HI

- What happens to the emission and the absorption lines at **21 cm if the hydrogen gas is warmer?**
- Certainly the line profile $\phi(\Delta\nu)$ should get broader due to **thermal broadening**. However, the total intensity at the emission line, should not change.
- On the other hand, the **absorption line should become much weake**r because the optical depth, is inversely proportional to temperature.

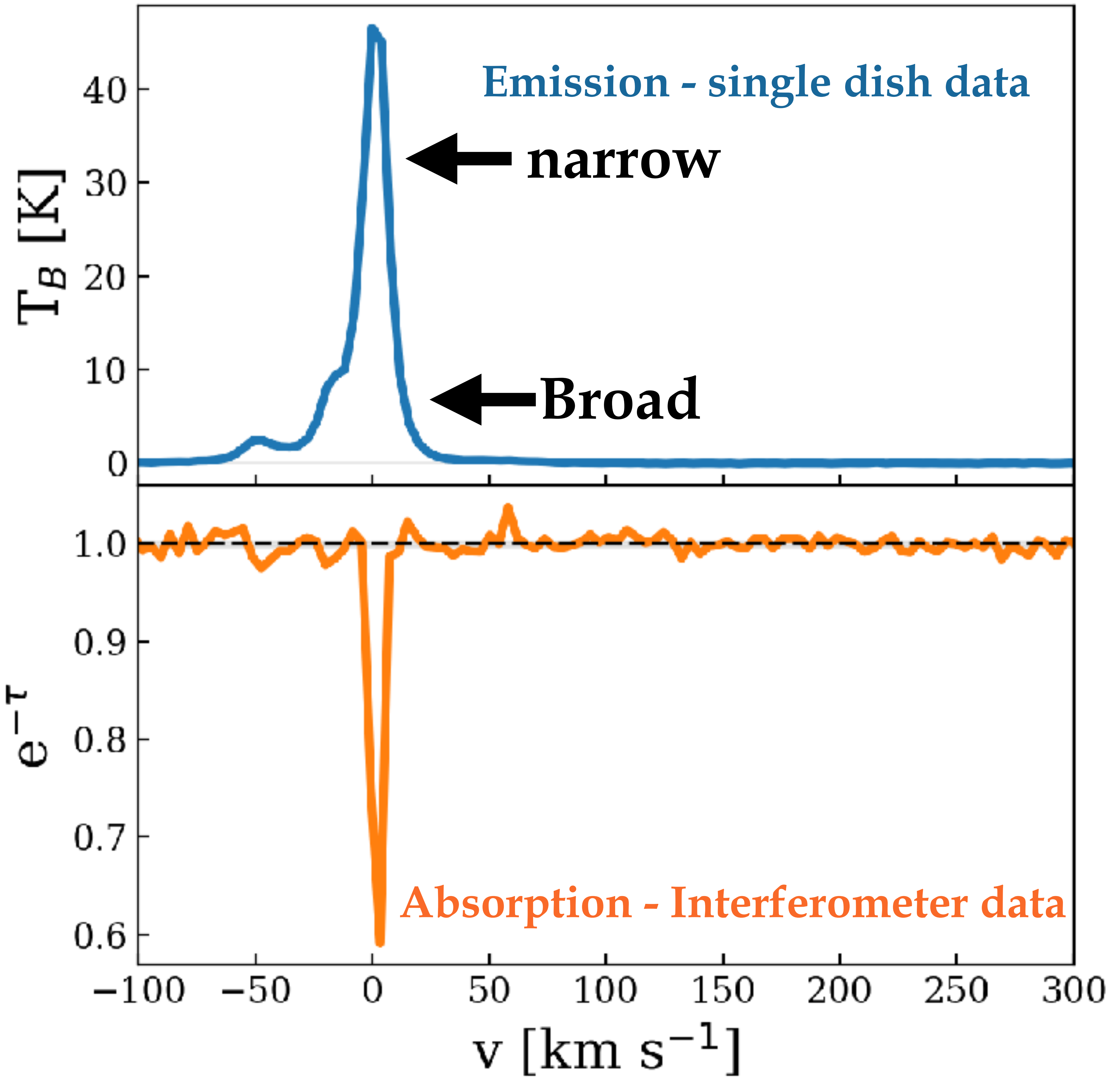
Phases of the ISM - Warm HI

- Suppose, along our line of sight, we have both a cold cloud and some warm gas. What kinds of emission and absorption lines should we get?
- Since the warm gas would not absorb much because of its higher temperature, the absorption line will be a narrow line due to the absorption by the cloud. On the other hand, there will be both narrow-line emission from the cloud and broad-line emission from the warm gas. Thus the emission line should look like a narrow line above a broad shoulder.
- If neutral hydrogen gas in two phases with differing temperatures is present along the line of sight, it is in principle possible to isolate the two phases from a careful study of the emission and absorption lines at 21 cm.



Phases of the ISM - Warm HI

- Figure shows the 21-cm emission line from the ISM close to a background radio source (top) as well as the 21-cm absorption line produced by the ISM in the spectrum of the background radio source (bottom).
- A careful look makes it clear that the emission line has a broader shoulder at the base, whereas the absorption line is narrow.
- Thus the 21-cm emission and absorption lines support the view that interstellar space contains neutral hydrogen in two distinct phases.
- The space between clouds (as much as 40% of the interstellar space) appears filled with much **warmer neutral hydrogen** gas, with a **temperature of about 8000K** and density in the range of $10^5 - 10^6$ particles m^{-3}.
- This is the second important phase of the ISM with a much lower density compared to the cold HI in the clouds.



Molecular gas

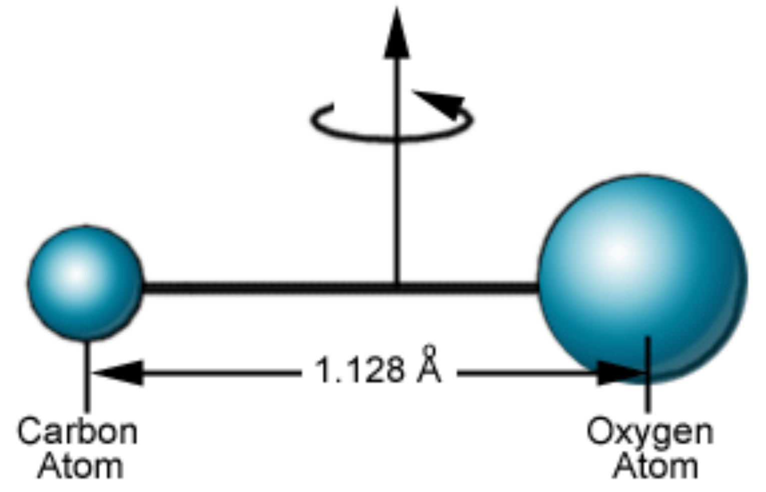
- Why are they important?
- How can we observe it?

Molecular gas

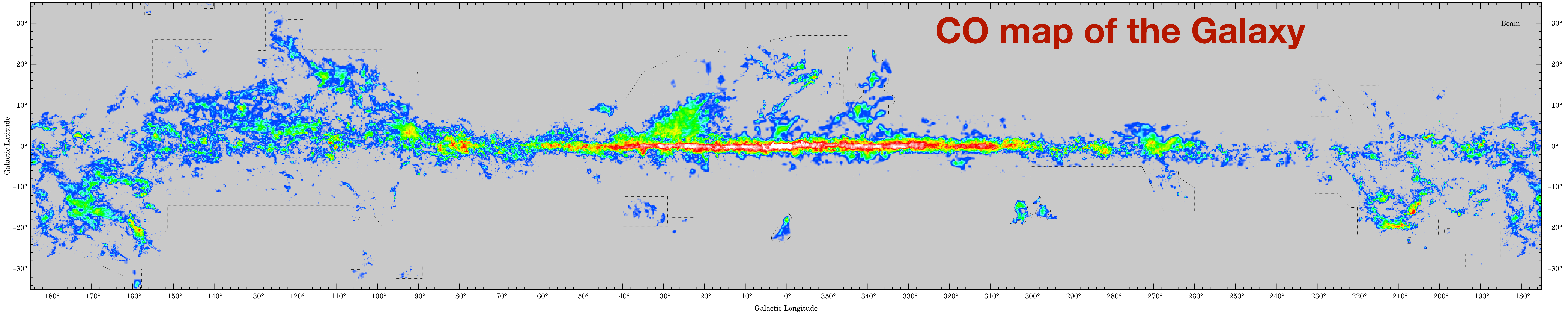
- The ISM is known to contain varieties of molecules including some reasonably complex organic molecules.
- Usually these molecules are found in the **cold dense regions of the ISM**.
- Molecular clouds have densities more than 10^9 particles m^{-3} and temperatures in the range **10–30 K**.
- Even though these clouds **occupy less than 1% of interstellar space**, they may contribute significantly to the **mass of the ISM (as much as 40%)**.
- One important question is how the complex molecules form in these clouds.
- Many molecules are supposed to have been synthesized on the surfaces of dust grains.
- Most molecules in the ISM are studied through the **molecular radio lines.** The hydrogen molecule H_2 **is the the most abundant molecule.**
- Since this molecule does not have any radio lines, its presence is inferred from the absorption lines in the UV spectra of background sources.
- The **most extensively studied interstellar molecule is carbon monoxide CO**, since it has very convenient radio lines arising from transitions between various rotational levels.

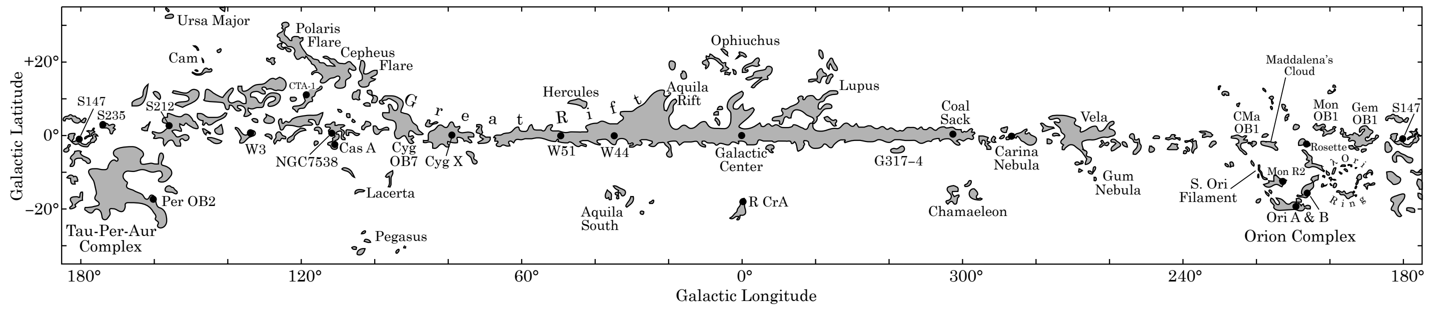
Note: a lot of progress has been made since the book was published, this is a very rapidly evolving field

Molecular gas



- A standard result of molecular physics is that frequencies in the rotational spectra should be equally spaced and be multiples of a fundamental frequency.
- The fundamental frequency for CO is 115 GHz, corresponding to a wavelength of 2.6 mm.
- The next higher frequencies are at 230 GHz, 345 GHz, and so on.
- The distribution of CO in the Galaxy has been studied quite extensively and is found to be somewhat different from the distribution of neutral hydrogen HI. Not much CO is found beyond 10 kpc from the galactic centre, whereas HI can be found at much greater distances.





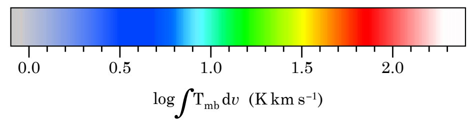
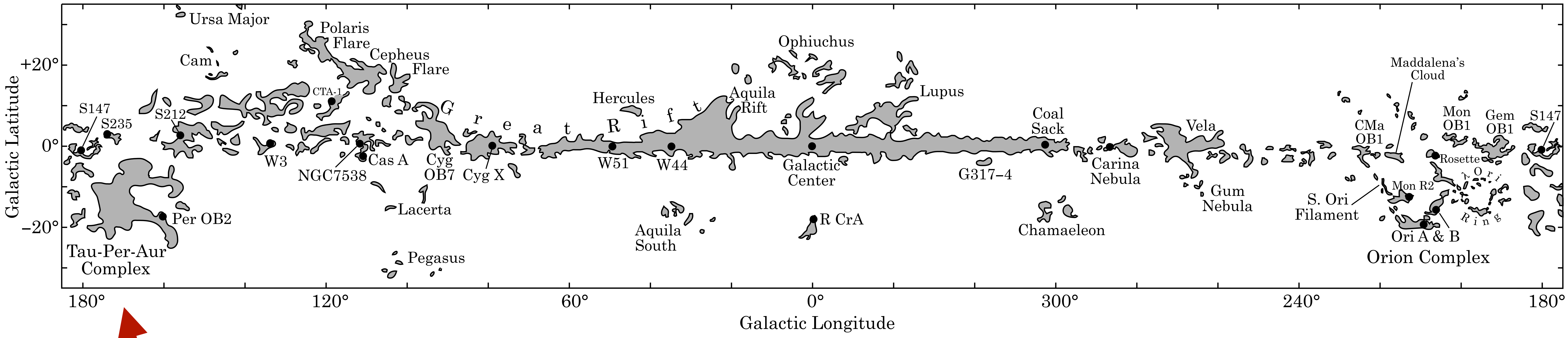


FIG. 2.–Velocity-integrated CO map of the Milky Way. The angular resolution is 9′ over most of the map, including the entire Galactic plane, but is lower (15′ or 30′) in some regions out of the plane (see Fig. 1 & Table 1). The sensitivity varies somewhat from region to region, since each component survey was integrated individually using moment masking or clipping in order to display all statistically significant emission but little noise (see §2.2). A dotted line marks the sampling boundaries, given in more detail in Fig. 1.

Dame et al. 2001

Molecular gas

- Molecular clouds in the Galaxy
- Based on CO observations



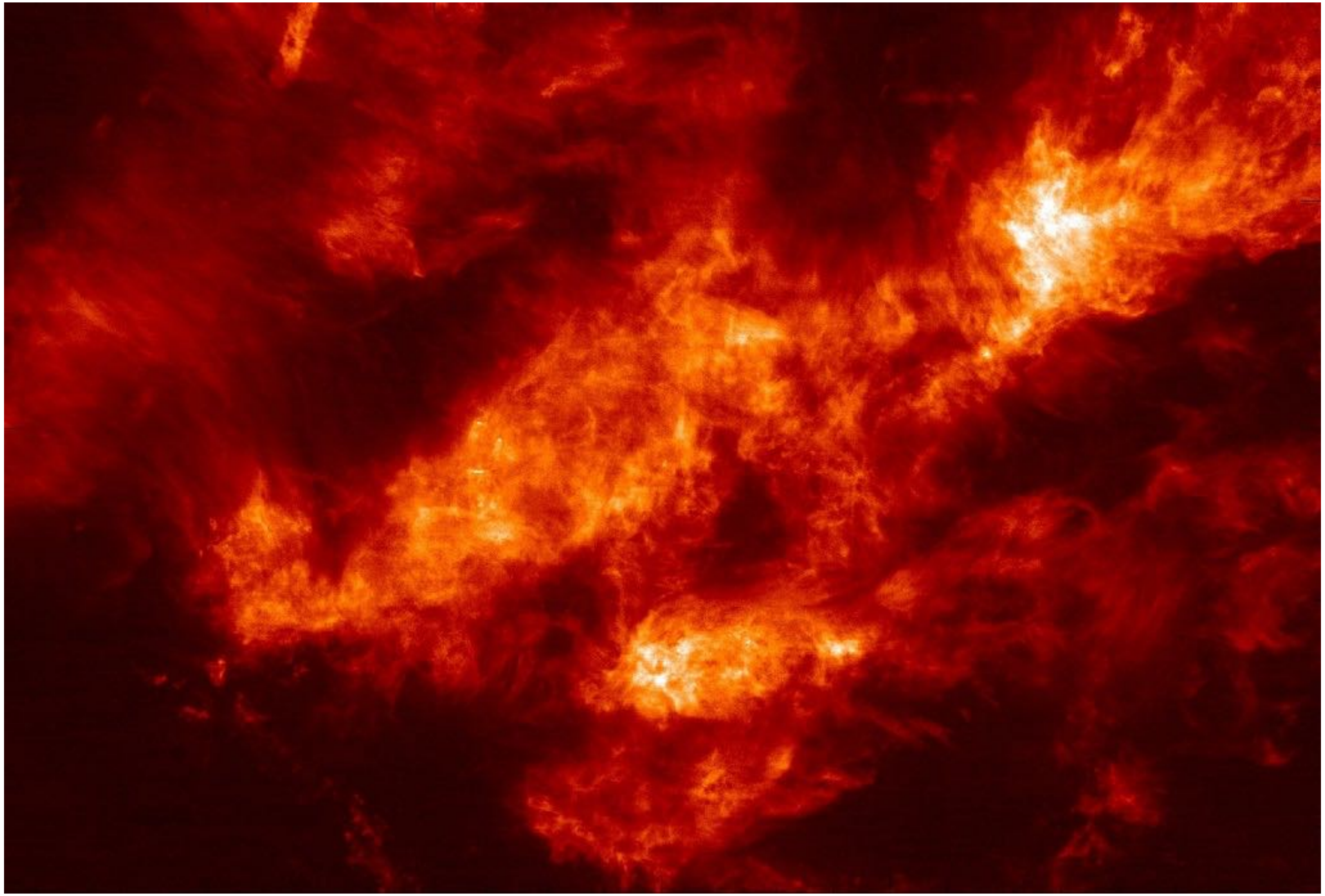
Taurus molecular cloud complex

Dame et al. 2001

Molecular gas

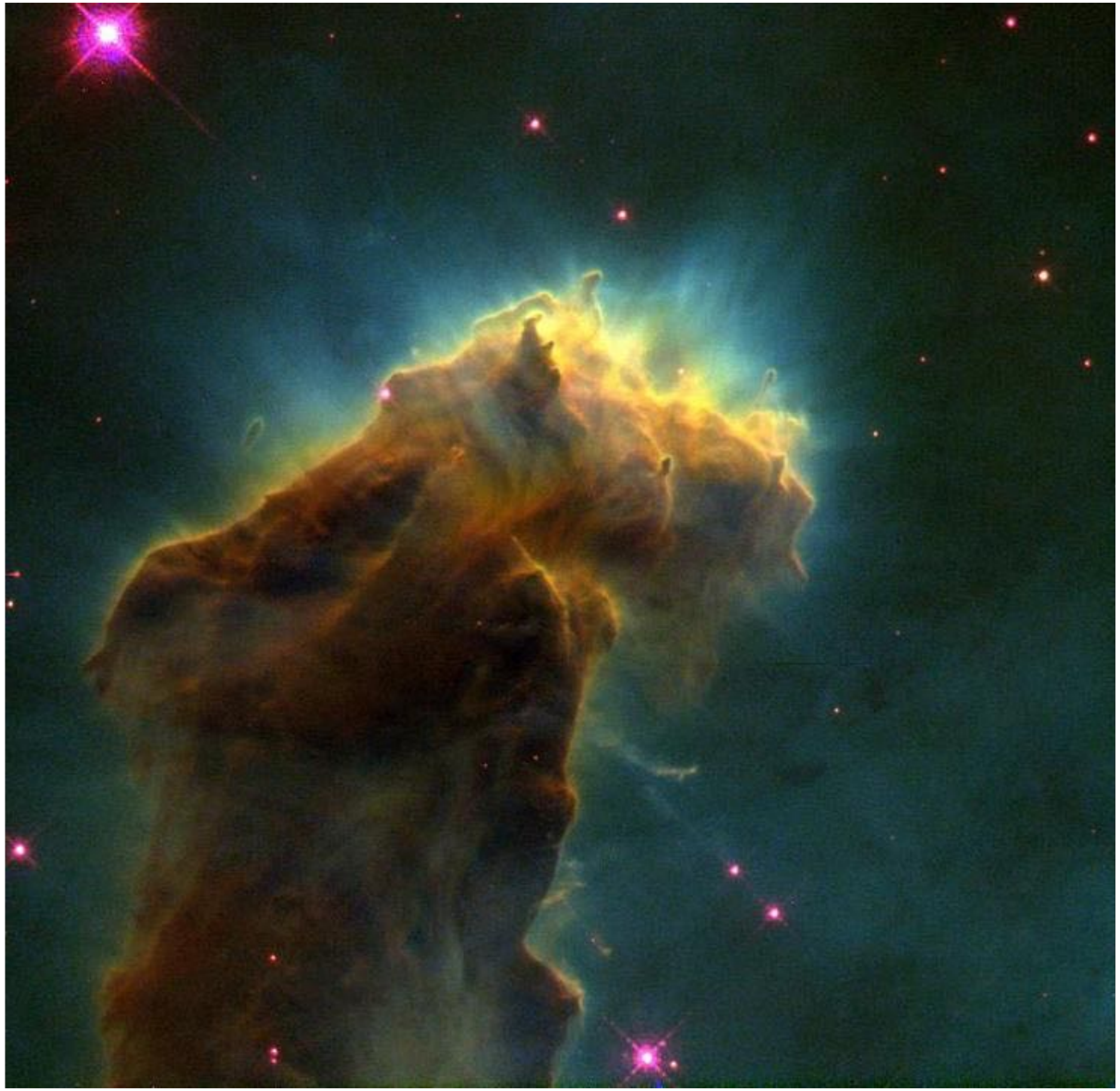
- Many smaller molecular clouds -> molecular cloud complex

- The Taurus molecular cloud complex in CO
- Notice the filamentary and turbulent structure
- **Stars form in molecular clouds**



Molecular gas

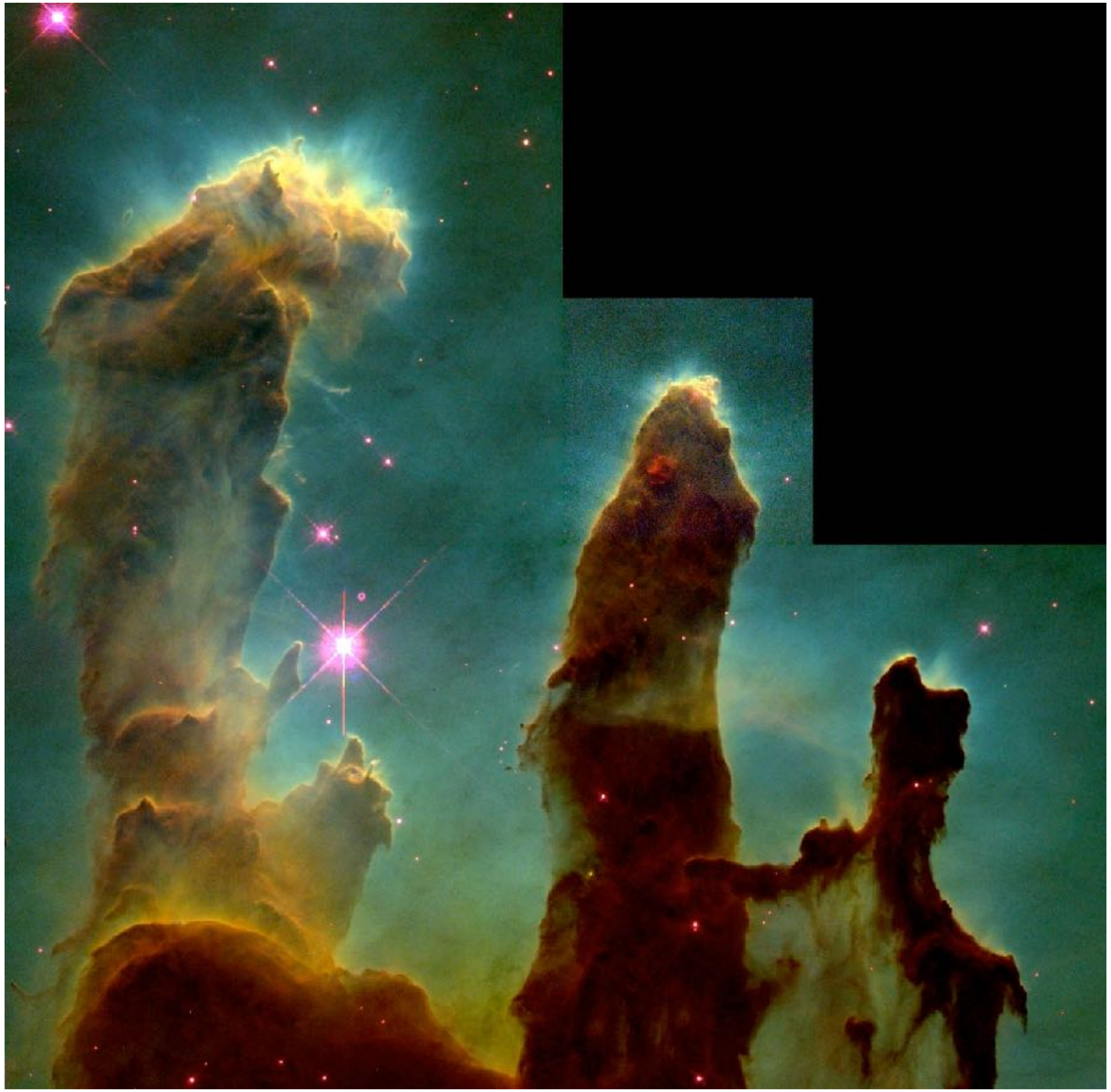
- Molecular clouds, which are often of gigantic size, are of great interest to astrophysicists as birthplaces of stars.
- **Molecular clouds can contract slowly under self-gravity and stars would eventually form in the central regions.**
- Figure shows such a molecular cloud, a part of the Eagle nebula.



Molecular gas

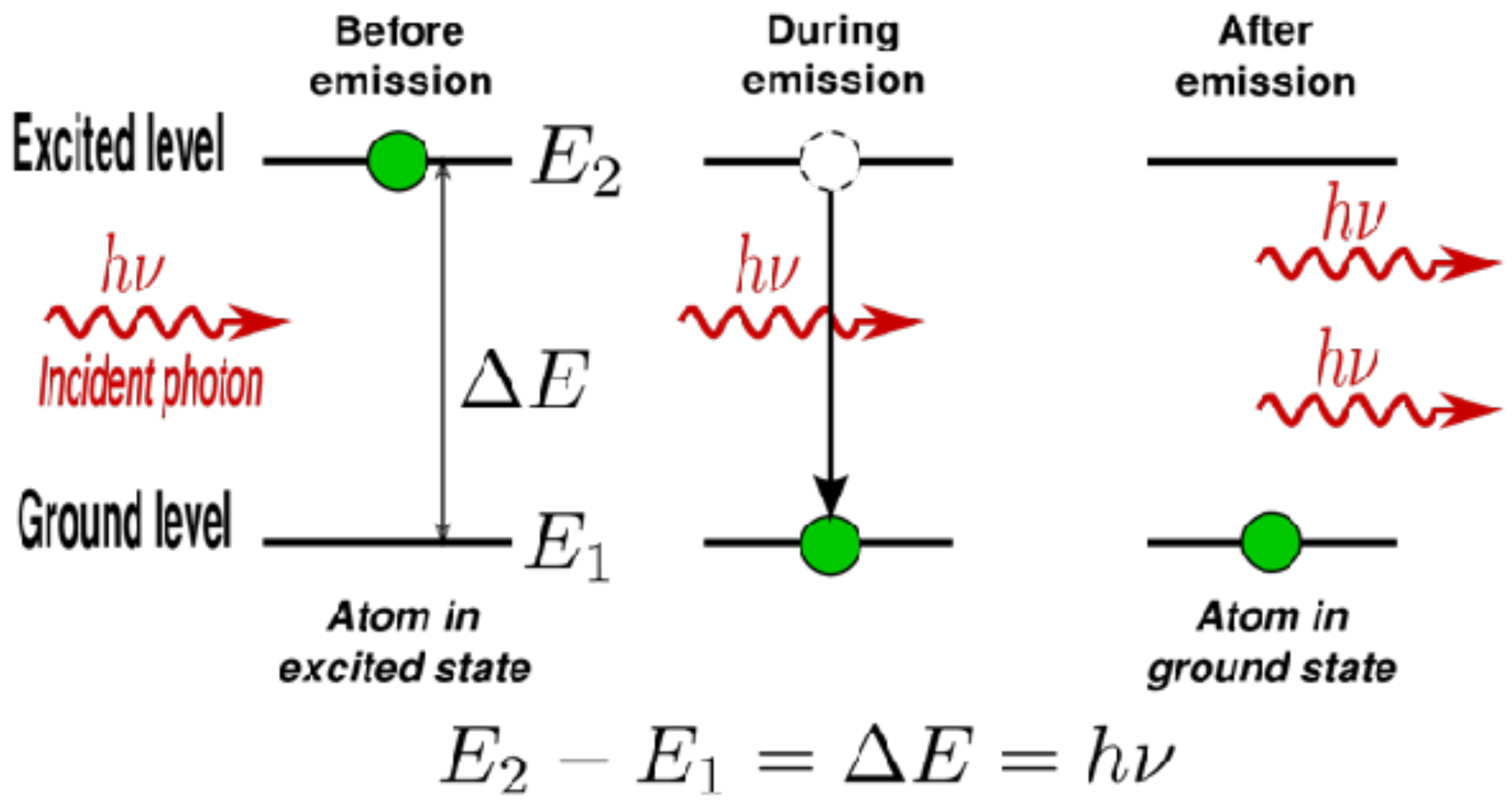
- Star formation region W51 in infrared

- Eagle nebula (pillars of creation)



Masers

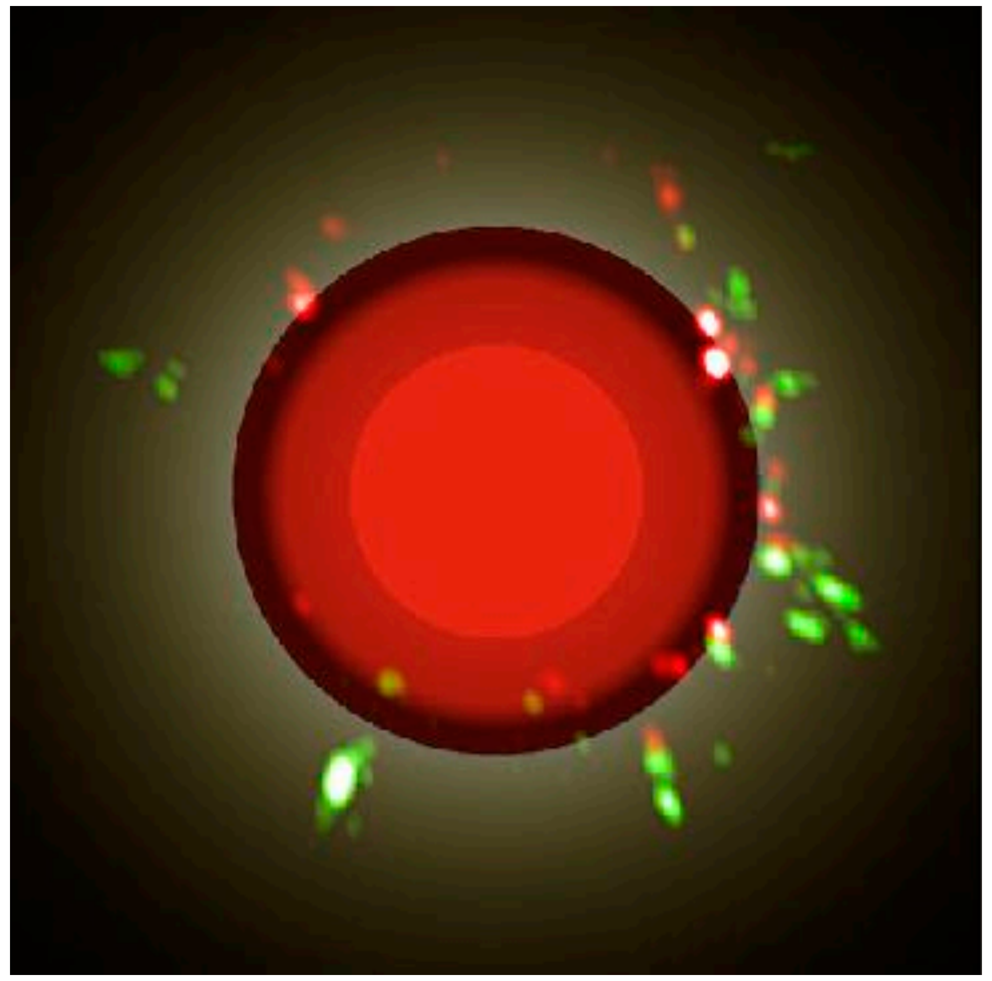
- A very big surprise was to find that the **intensity of some sources in specific molecular lines (such as OH lines) was abnormally high.**
  - If the sources were assumed to be optically thick in the spectral lines and the specific intensity was equated to the Planck function $B_\nu(T)$, then temperatures as high as 10^9K were inferred!
- The explanation is that this high intensity is **not caused by abnormally high temperatures, but by maser action.**
- In our discussion of the two-level atom, we saw an example in which the upper level is de-populated compared to what we expect in thermodynamic equilibrium. In more complex situations involving more levels, the upper level can become over-populated. If $n_n/n_l > g_u/g_l$, then the absorption coefficient α_ν should be negative. In such a situation, a beam of radiation keeps getting stronger while passing through the material rather than being attenuated.



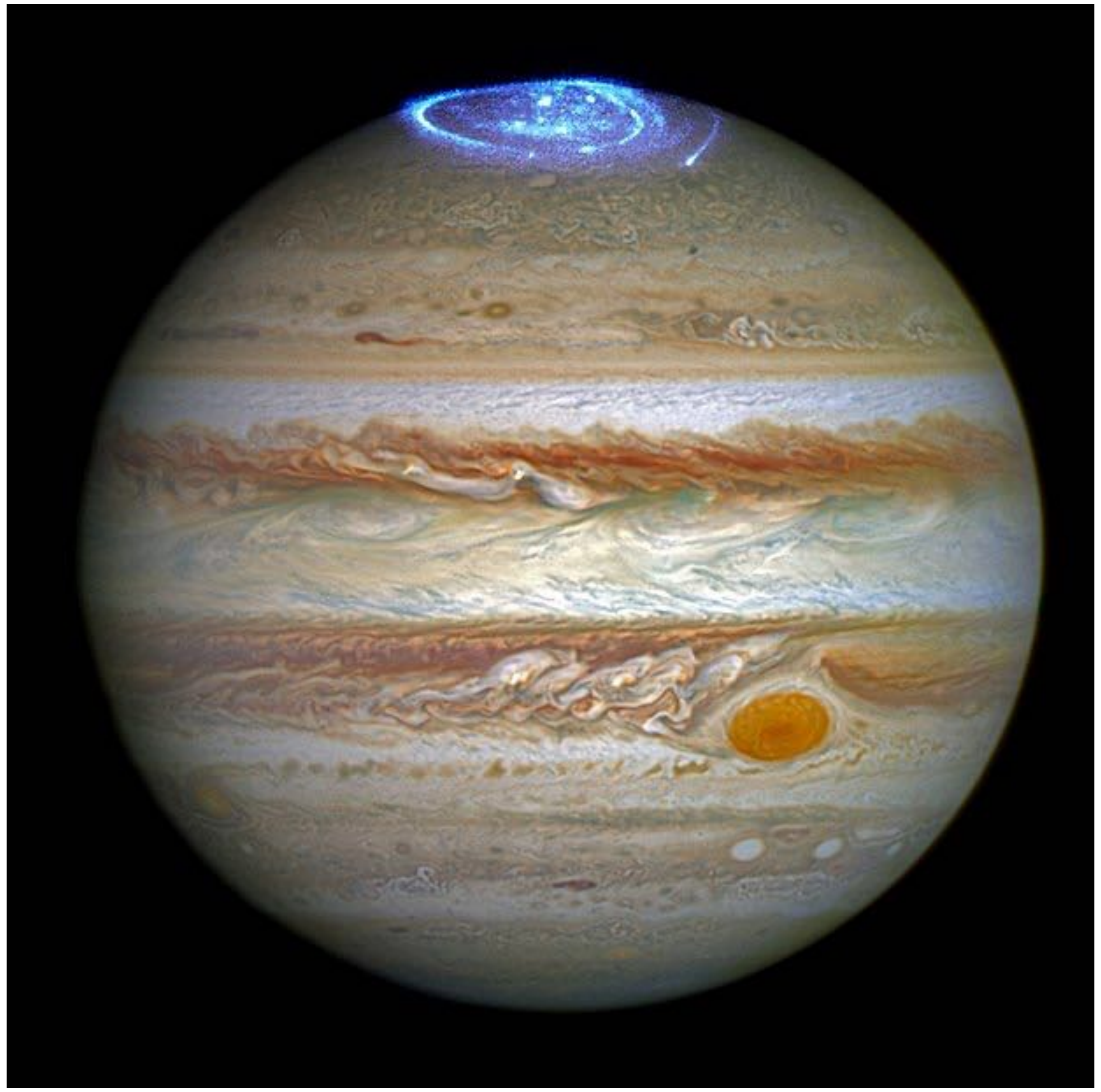
Masers

- **maser**: an acronym for **microwave amplification by stimulated emission of radiation** - is a device that produces coherent electromagnetic waves through amplification by stimulated emission.
- The **laser works by the same principle** as the maser but produces higher frequency coherent radiation at visible wavelengths
- Used for:
  - atomic clocks (every radio telescope has one)
  - extremely low-noise microwave amplifiers in radio telescopes
  - deep-space spacecraft communication ground stations.
- An **astrophysical maser is a naturally occurring source of stimulated spectral line emission, typically in the microwave portion of the electromagnetic spectrum.**
- This emission may arise in: **molecular clouds, comets, planetary atmospheres, stellar atmospheres, around AGN** or various other conditions in interstellar space.

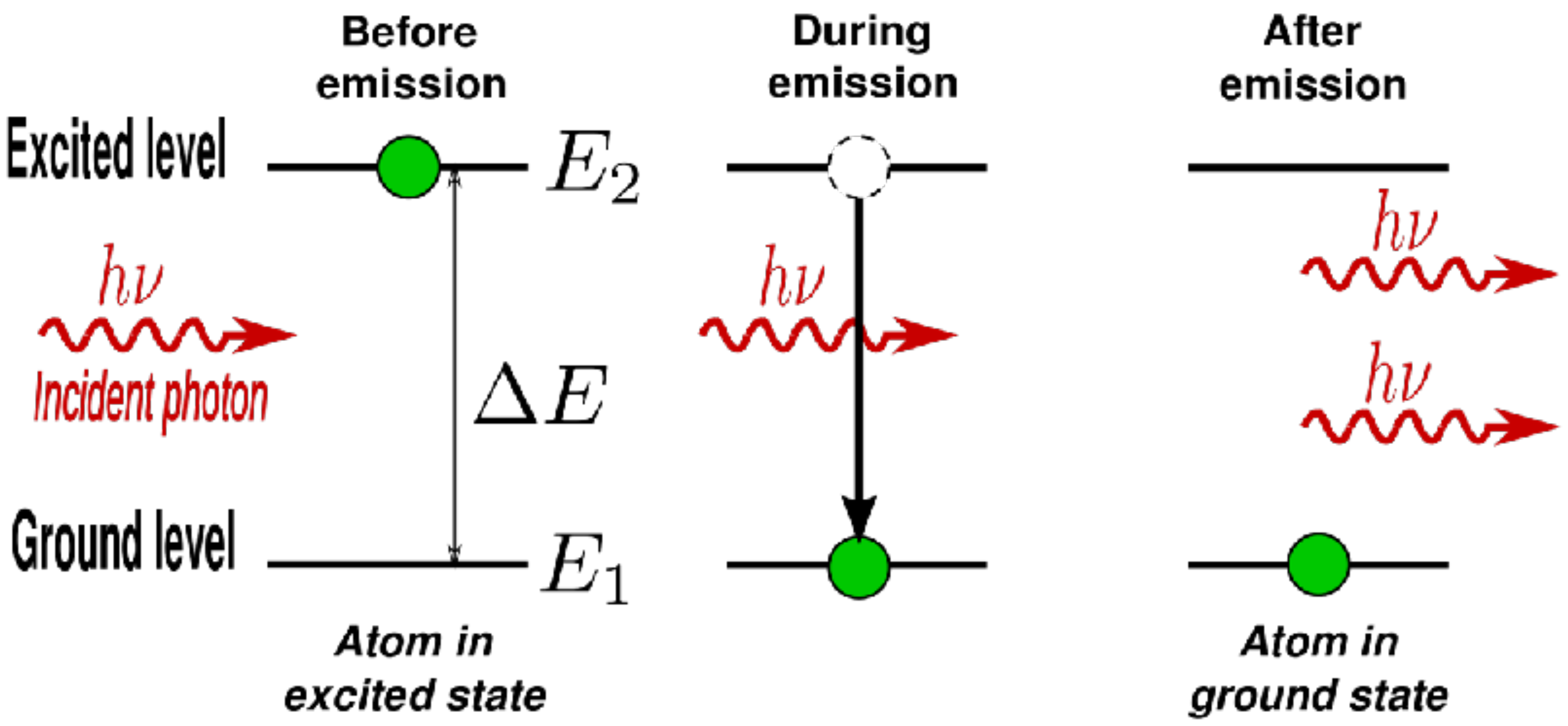
Masers



Maser emission around a variable star



Aurorae on the north pole of Jupiter generate cyclotron masers



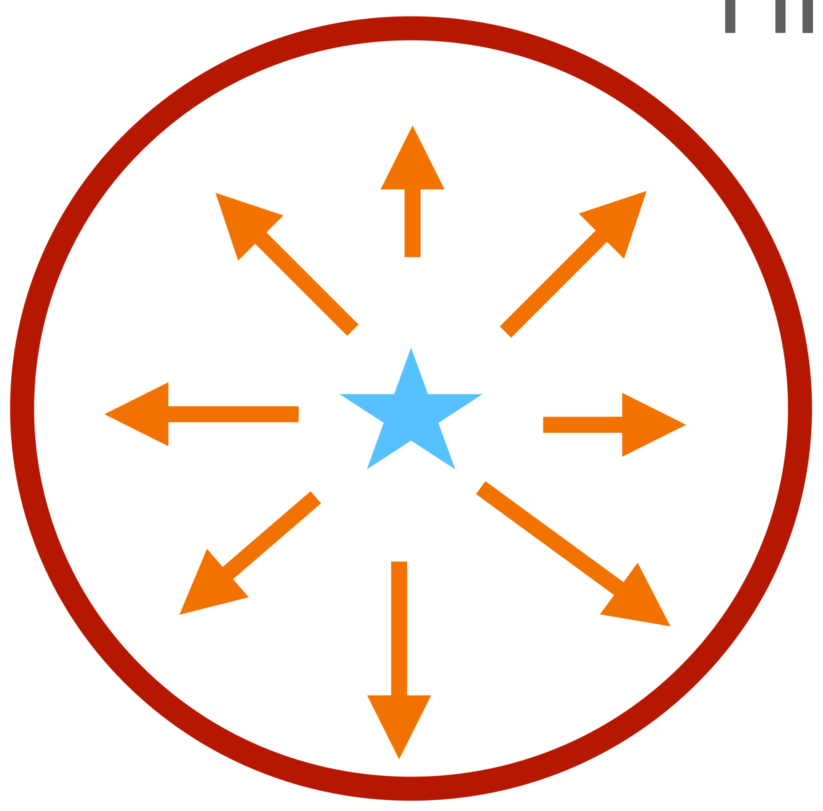
$$E_2 - E_1 = \Delta E = h\nu$$

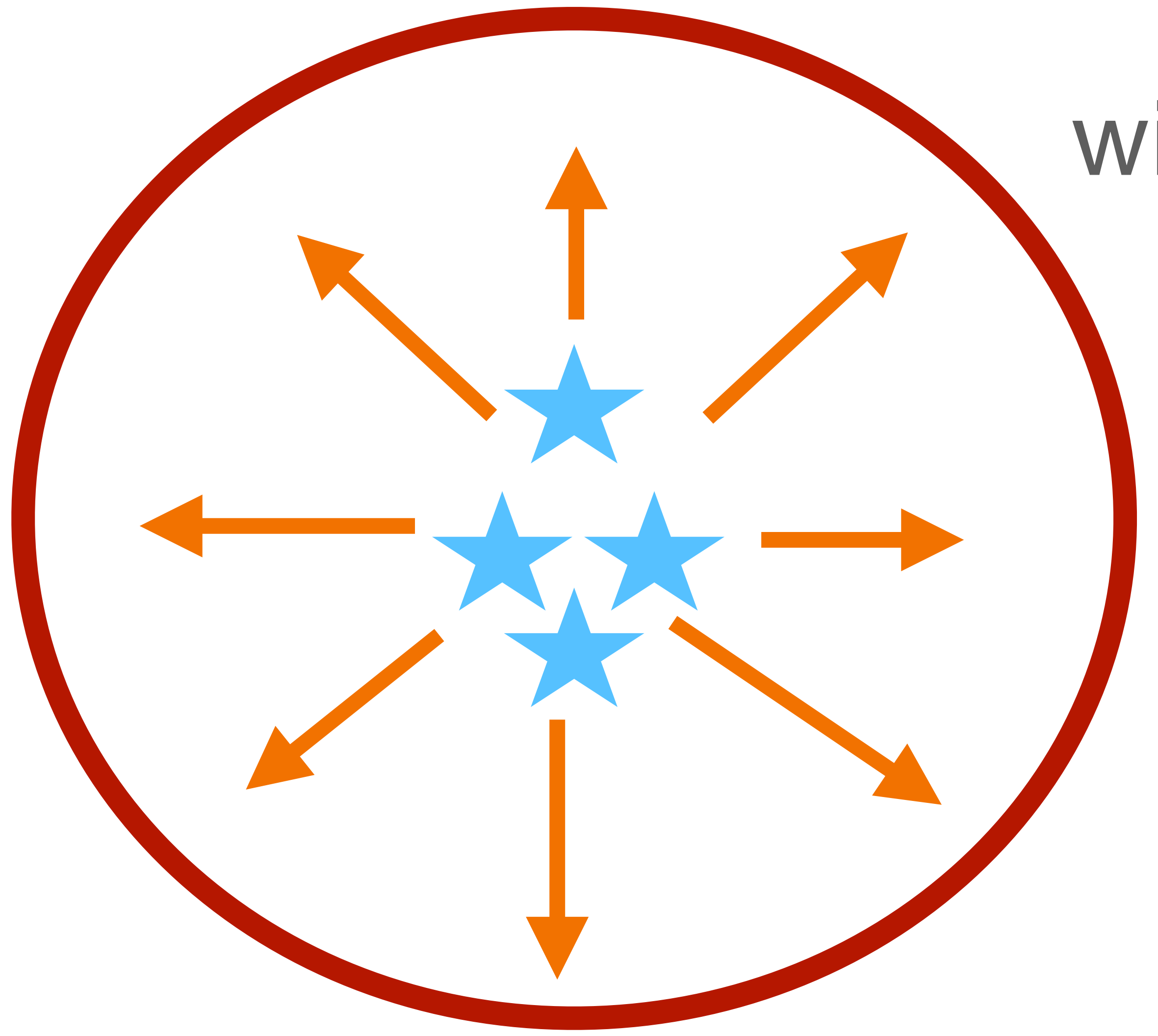
HII regions

- **What are these?**

HII regions

- A UV photon with wavelength shorter than 912 Å can ionize a hydrogen atom by knocking off the electron from the ground level $n = 1$.
- The **O and B stars, which have high surface temperatures, emit copious amounts of UV photons.** Since these stars are short-lived, they are found in regions **where star formation has recently taken place.**
- The cores of molecular clouds collapse to produce stars. Once the stars have been formed, the **UV photons from the O and B stars ionize the ISM around them**. Such regions of ionized hydrogen are **called *HII regions***. The typical temperatures of such regions are of the order 6000 K.





HII regions

- The HII regions are often found to be approximately spherical in shape and are known as ***Strömgren spheres.***
- In a steady state, the number of ionizations in a unit volume has to balance the number of recombinations.
- If the recombination process involves a free electron jumping to the ground level $n = 1$, then a **UV photon** would be emitted.
- However, if the free electron is first captured in the $n = 2$ level and then it only makes a transition to the $n = 1$ level, then we would get two photons, one of which will be within the visible range.
- **Very often an electron cascades through several energy levels, thereby emitting many photons.**
- The HII region is one phase of the ISM which can be studied by the **visible light** emitted by it.
- When an electron makes a transition between two relatively high levels (say from $n = 100$ to $n = 99$), a **radio photon** is emitted.
- Additionally, the hot gas in the HII regions also emits bremsstrahlung with a continuous spectrum in the radio range.
- HII regions also radiate in emission lines from **partially ionized atoms of elements like carbon, nitrogen and oxygen.**

HII regions

The bubble like regions are HII regions with hot ionised hydrogen

- Star formation region in the Large Magellanic Cloud

- Star formation region W51 in infrared

Hot gas

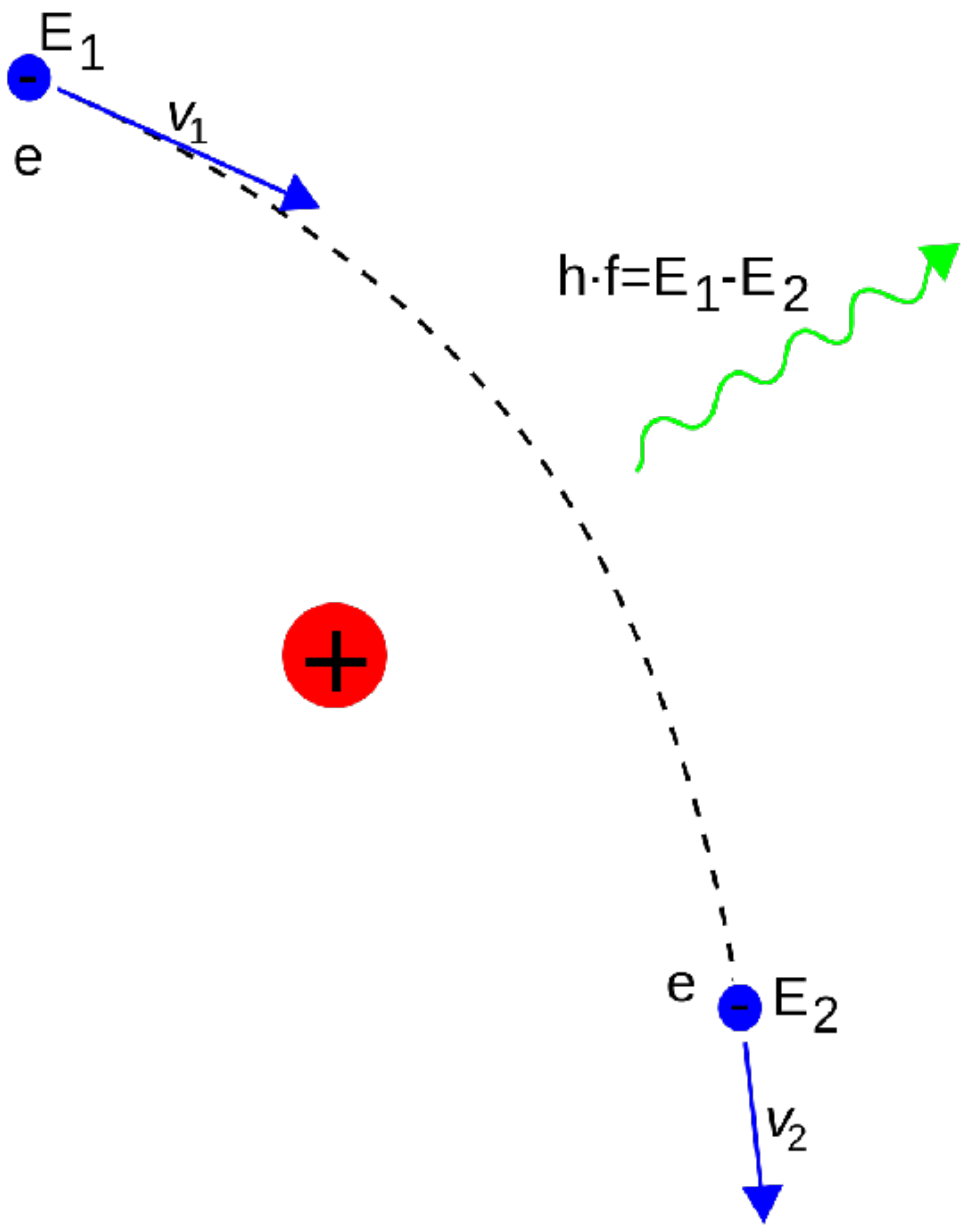
- **Galactic chimney** in HI
- These are large bubbles in the HI gas that are created by a large group of HII regions associated with a cluster of young O, B stars.
- If the bubble reaches the top of the HI disk it can create a way or “chimney” for the hot gas to escape into the halo of the Galaxy

Hot coronal gas - hot halo gas

- A supernova explosion spews out hot gas in the interstellar space.
- It is thought that hot gases from very old supernovae ultimately fill up the interstellar spaces not occupied by the other phases. The coronal gas may have **temperatures on the order of** 10^6 **K**, but very **low densities** of about only 10^3 particles m^{-3}.
- This gas may occupy as much as 50% of the interstellar space, even though it **contributes very little to the mass of the ISM.**
- **Hot gases emit radiation by the process of bremsstrahlung**. The hot coronal gas in the Galaxy emits soft **X-rays**, which is the main diagnostic tool for studying this phase.
- In addition we can also study **absorption lines from ionised atoms.**

Bremsstrahlung

- A **Bremsstrahlung,** from bremsen "to brake" and Strahlung "radiation"; i.e., "braking radiation" or **"deceleration radiation"**, is electromagnetic radiation **produced by the deceleration of a charged particle when deflected by another charged particle**, typically an electron by an atomic nucleus.
- The moving particle loses kinetic energy, which is converted into radiation (i.e., photons), thus satisfying the law of conservation of energy.
- Bremsstrahlung has a continuous spectrum, which becomes more intense and whose peak intensity shifts toward higher frequencies as the change of the energy of the decelerated particles increases.



Galactic magnetic field

- **How can we observe the magnetic field of galaxies?**

Galactic magnetic field

- There is a **large-scale magnetic field** in the interstellar space of our Galaxy was first inferred with measuring the **polarization of starlight** and found that the light from most stars is slightly polarized.
- It is believed that interstellar grains are generally non-spherical and can be aligned by the galactic magnetic field, making the **ISM act like a polarizing medium in the presence of a magnetic field.**
- The alignment of grains involves some subtle physics and is not exactly analogous to the alignment of a compass needle by a magnetic field.

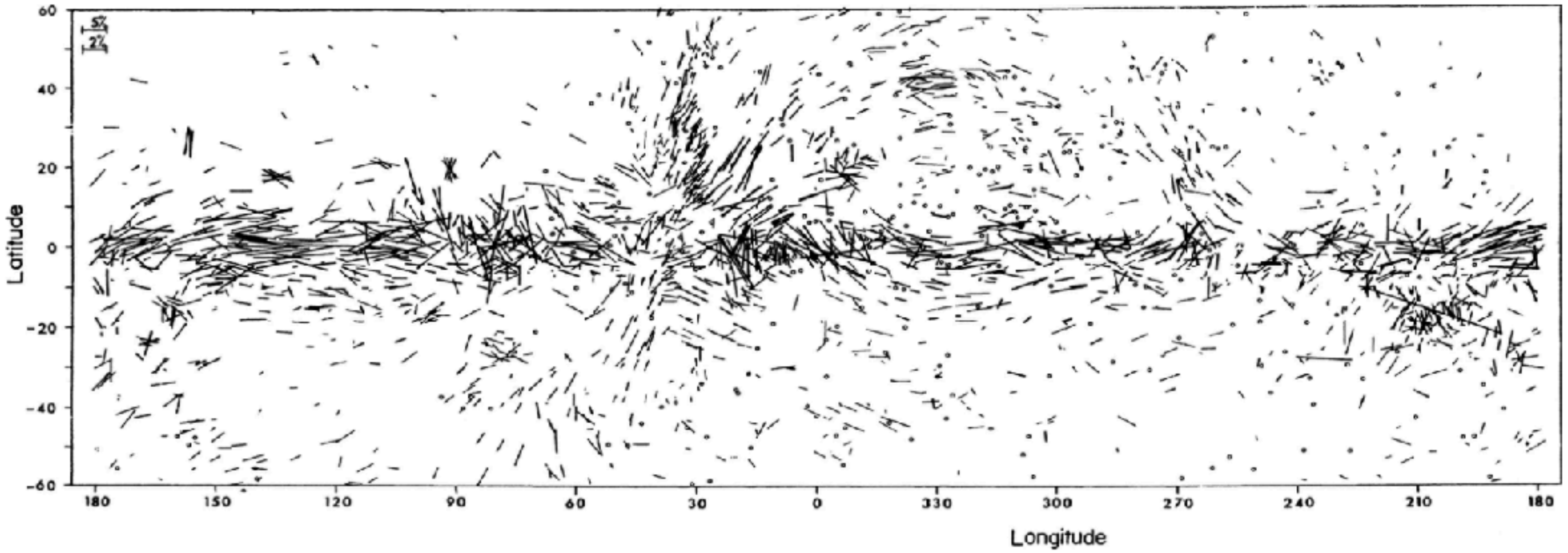


Fig. 6.13 The polarization of starlight measured for stars in different galactic coordinates. The length of the line segment indicates the amplitude of polarization for a star, whereas its direction indicates the polarization plane. From Mathewson and Ford (1970). (©Royal Astronomical Society. Reproduced with permission from *Memoirs of Royal Astronomical Society*.)

Galactic magnetic field

- Figure 6.13 shows light **polarizations of stars located in different galactic coordinates**, the lengths of the small line segments indicating the magnitudes of polarization and their inclinations indicating the directions of polarization.
- In the direction of the galactic magnetic field, we do not expect to see any systematic polarization. This happens approximately in the directions $l \approx 60°$and $l \approx 240°$in the Figure.
- These longitudes roughly correspond to the spiral arm in the solar neighbourhood.

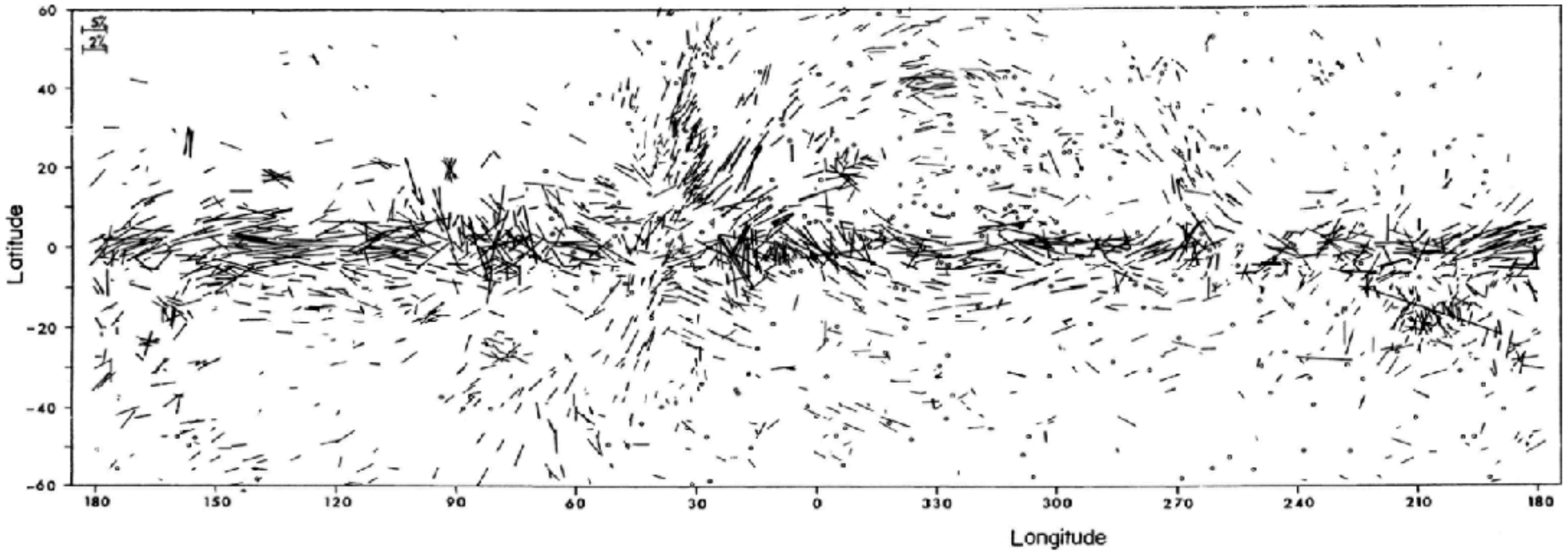
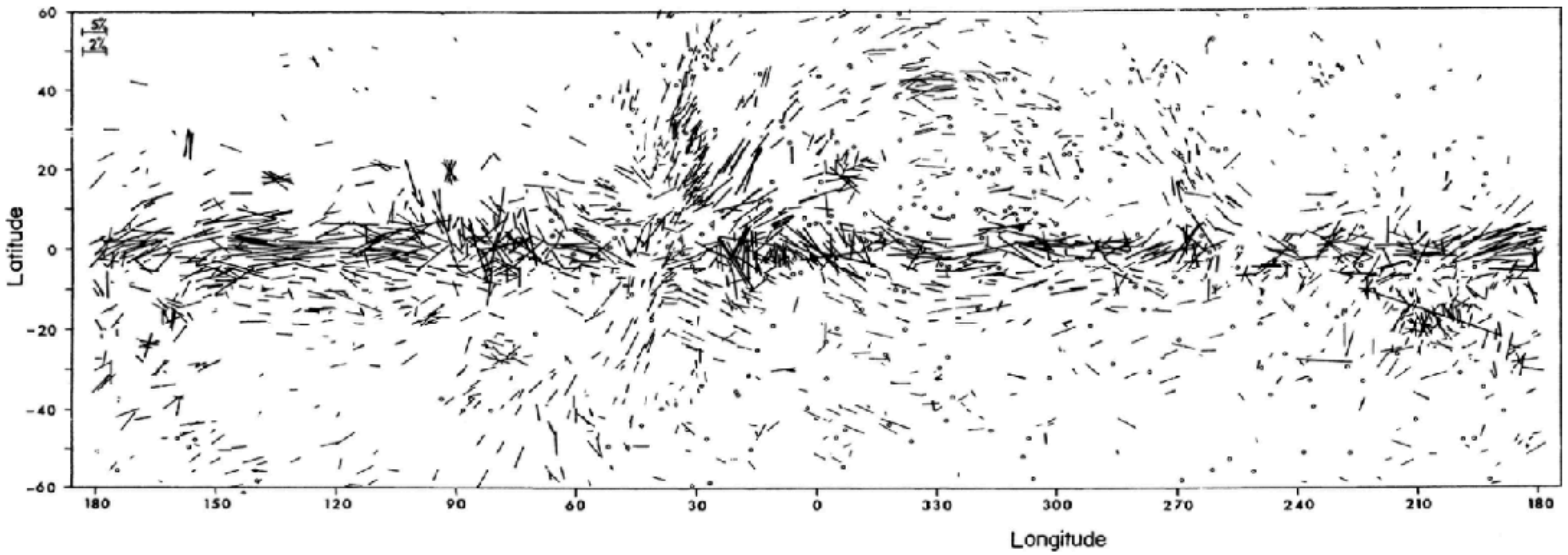


Fig. 6.13 The polarization of starlight measured for stars in different galactic coordinates. The length of the line segment indicates the amplitude of polarization for a star, whereas its direction indicates the polarization plane. From Mathewson and Ford (1970). (©Royal Astronomical Society. Reproduced with permission from *Memoirs of Royal Astronomical Society*.)

Galactic magnetic field

- When we look at right angles with respect to these directions (i.e. with respect to the magnetic field), we see the maximum polarization.
- **The polarization of starlight thus establishes that our Galaxy has a magnetic field running along the spiral arm.**
- However, to estimate the amplitude of the magnetic field, we need a theory of grain alignment.



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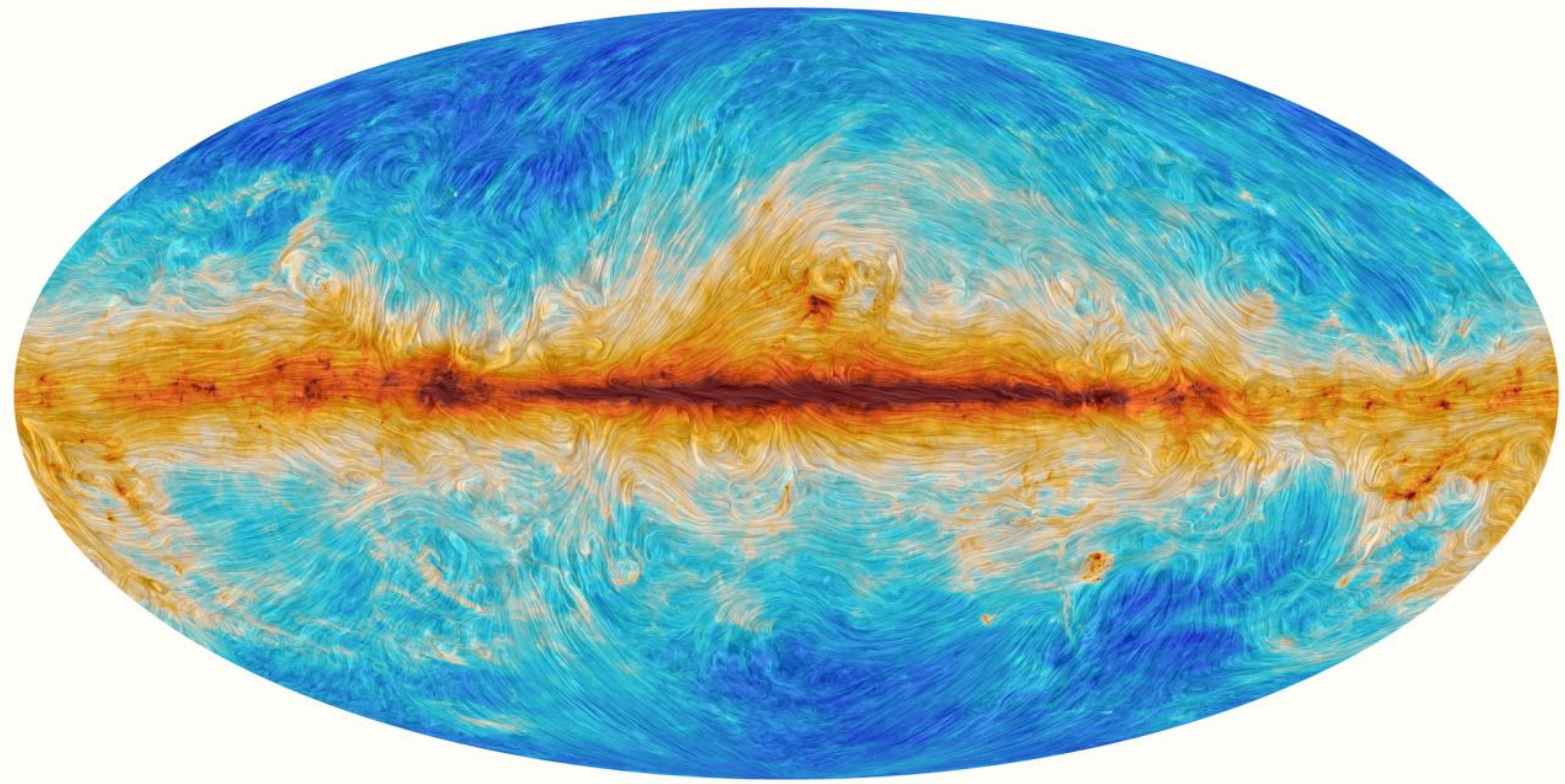
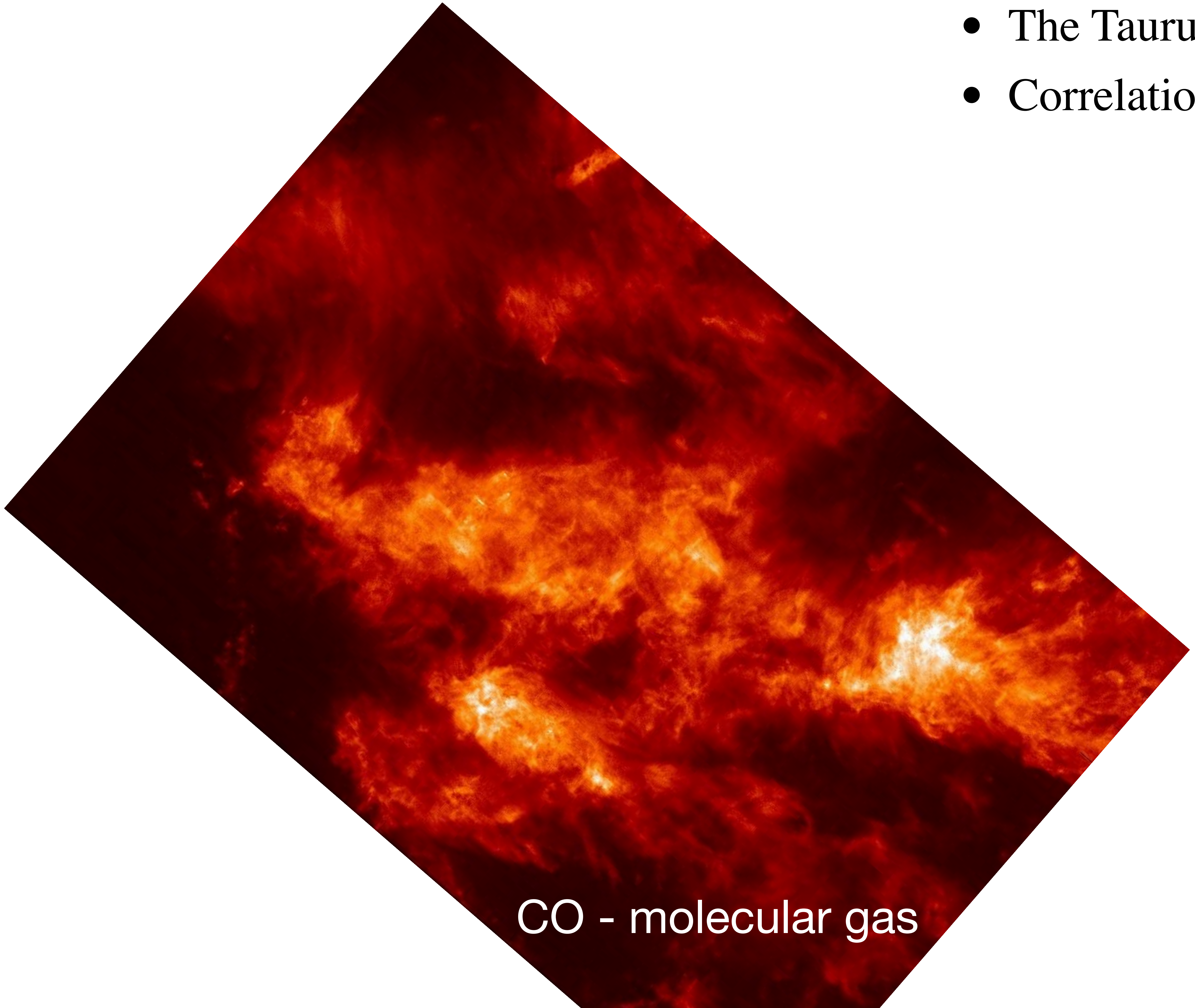
Galactic magnetic field

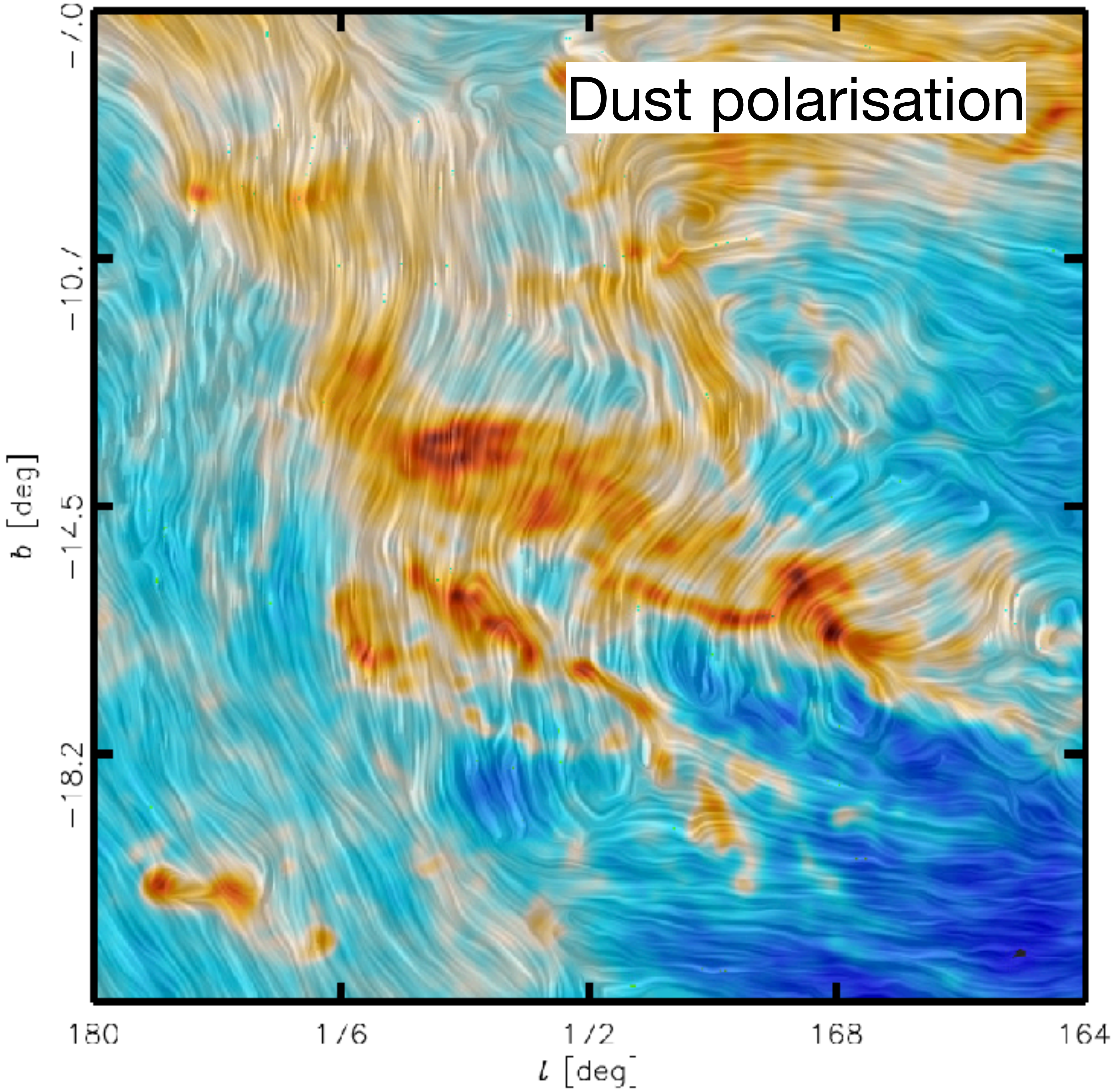
- Most recent measurement by the **Planck satellite:**
- The image is a combination of intensity and magnetic field line direction



Galactic magnetic field

- The Taurus molecular cloud
- Correlation of the magnetic field with the filamentary structure

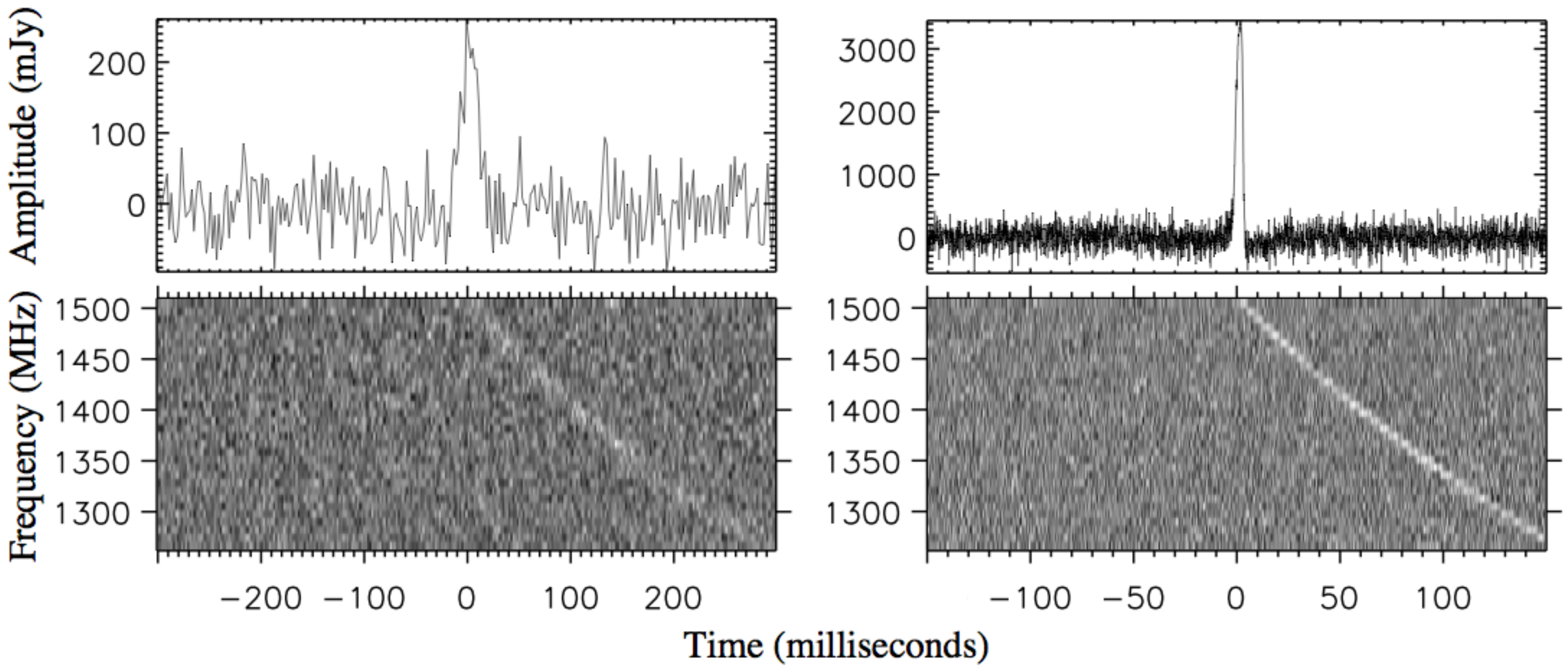




Galactic magnetic field

- The strength of the field can be estimated using radiation coming from pulsars
- electromagnetic waves travelling in empty space are non-dispersive. However, the speed of an electromagnetic wave passing through a plasma varies with the frequency of the wave.
- there are some free electrons in the interstellar space -> the ISM can act like a plasma.
- **Radio waves of lower frequency travel more slowly through the interstellar plasma**. (For visible light this effect is negligible.)

- higher-frequency waves coming from a pulsar arrive slightly before lower-frequency waves
- Combining this effect with an estimate for the number density of free electrons we can **estimate the distance to the pulsar.**

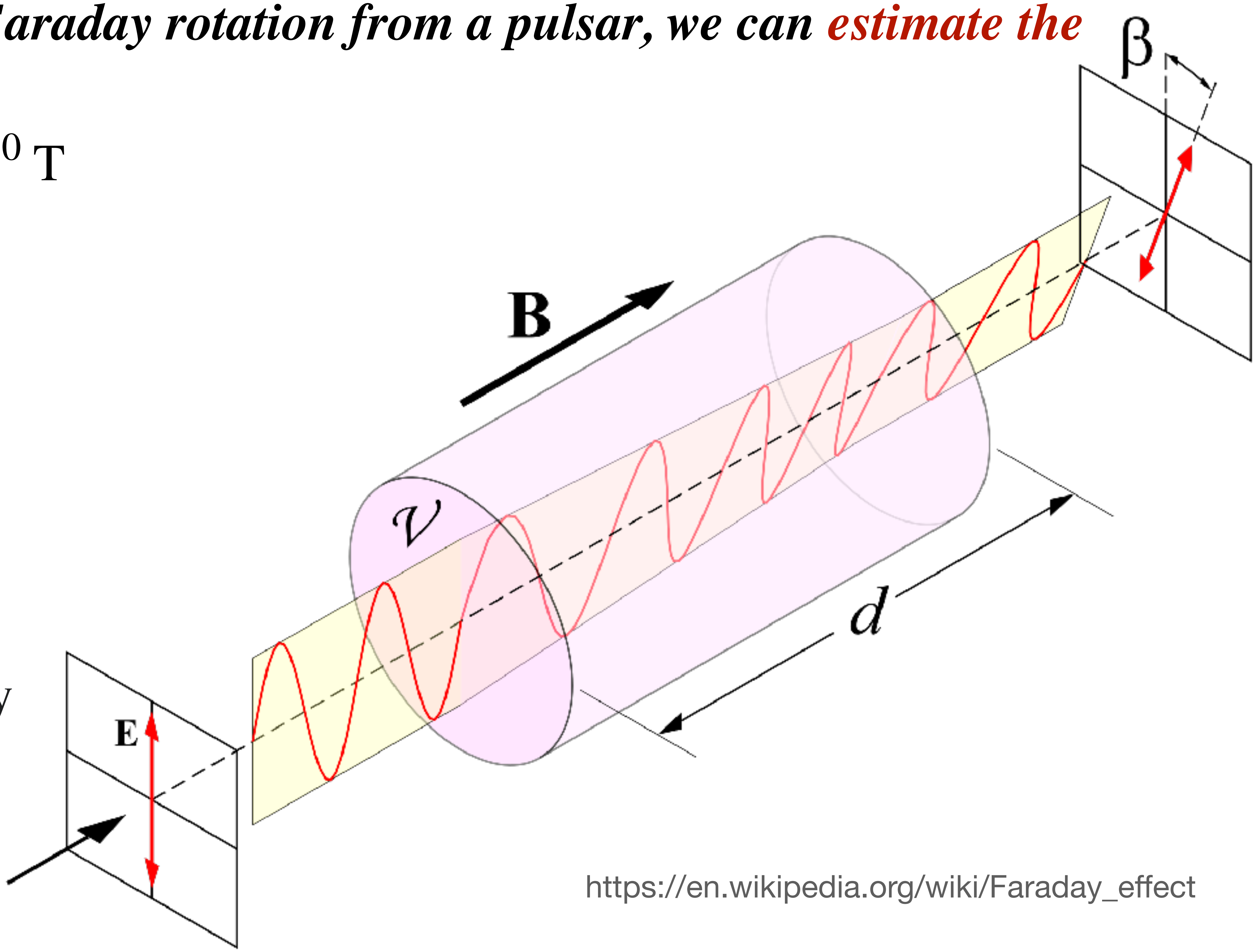


Galactic magnetic field

- the magnetic field present in the **plasma can make the plane of polarization rotate**, the rotation being more for lower frequencies. This is known as ***Faraday rotation.***
- ***By combining the dispersion measure and the Faraday rotation from a pulsar, we can estimate the strength of the magnetic field.***
- The average value for the Galaxy is (2–3) × 10^{-10} T

Object	**B field strength**
Earth	0.00005 T
Sun	0.0001 T
Fridge magnet	0.01 T
Sunspot	0.4 T

The Faraday effect or Faraday rotation, is a physical magneto-optical phenomenon. The Faraday effect causes a polarization rotation which is proportional to the projection of the magnetic field along the direction of the light propagation.



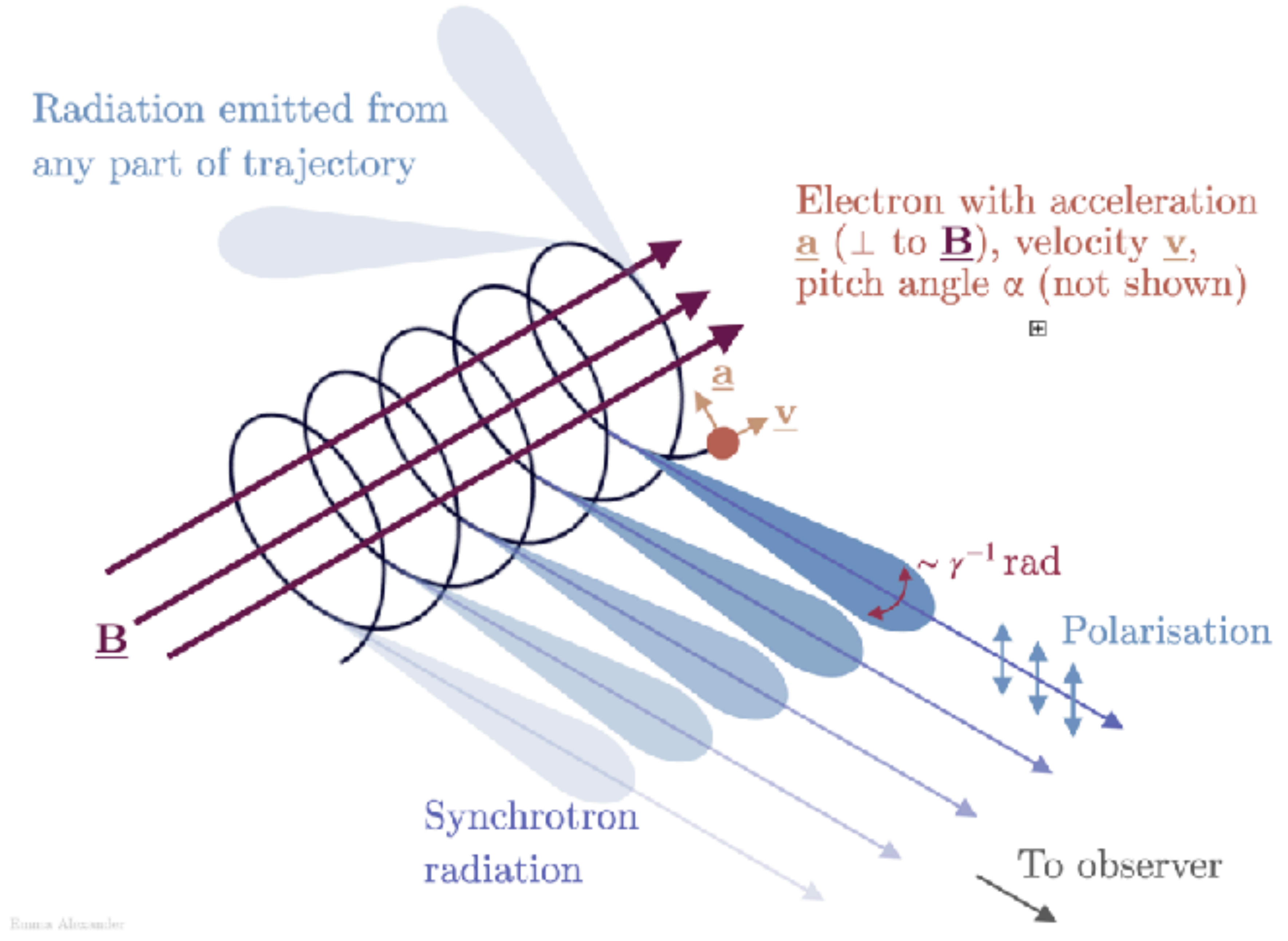
https://en.wikipedia.org/wiki/Faraday_effect

Cosmic rays

- Associated with the galactic magnetic field, there are **highly energetic charged particles spiralling around the field lines.**
- The Earth is continuously bombarded by *cosmic rays* coming from above the Earth's atmosphere.
- The energetic charged particles of the cosmic rays are believed to be accelerated in supernova blast waves. Then they spiral around the galactic magnetic field and fill up the Galaxy.
- **A relativistically moving charged particles spiralling around a magnetic field give out *synchrotron radiation*.**
- For cosmic rays spiralling around the galactic magnetic field, the synchrotron spectrum lies mainly in the radio regime.
- Radio telescopes have detected synchrotron radiation not only from our Galaxy but also from other similar galaxies, making it clear that other **similar galaxies also have magnetic fields and cosmic rays.**
- **Origin of the magnetic field:** one explanation is the *dynamo theory* –> **turbulent motions in a plasma** can generate magnetic fields under certain circumstances.

Synchrotron radiation

- **Synchrotron radiation is the electromagnetic radiation emitted when relativistic charged particles are subject to an acceleration perpendicular to their velocity**. It is produced naturally by fast electrons moving through magnetic fields. The radiation produced in this way has a characteristic polarization and the frequencies generated can range over a large portion of the electromagnetic spectrum.
- Synchrotron radiation is similar to bremsstrahlung radiation, which is emitted by a charged particle when the acceleration is parallel to the direction of motion.
- The **general term for radiation emitted by particles in a magnetic field is gyromagnetic radiation**, for which synchrotron radiation is the ultra-relativistic special case. Radiation emitted by charged particles moving non-relativistically in a magnetic field is called cyclotron emission. For particles in the mildly relativistic range (≈85% of the speed of light), the emission is termed gyro-synchrotron radiation.



https://en.wikipedia.org/wiki/Synchrotron_radiation

Magnetic fields in other galaxies

Magnetic Field in the Whirlpool galaxy, M51
Based on infrared polarisation measurements

Vertical Magnetic Field of NGC 5775
Based on radio polarisation measurements