
Astronomy 537
Lecture 7: Molecular Clouds in the Milky Way Galaxy

Journal Class

- **No certainty of a Milky Way–Andromeda collision**
- Sawala et al. 2025

Discussion leader: **Shane Li**

Note: To encourage discussion everybody must pose at least one question during the group discussion

The Interstellar Medium III

The Hot Ionized Medium (HIM):

Occupying perhaps 20% of the ISM volume.

$T \sim 10^6$ K

<u>How to observe the HIM:</u>

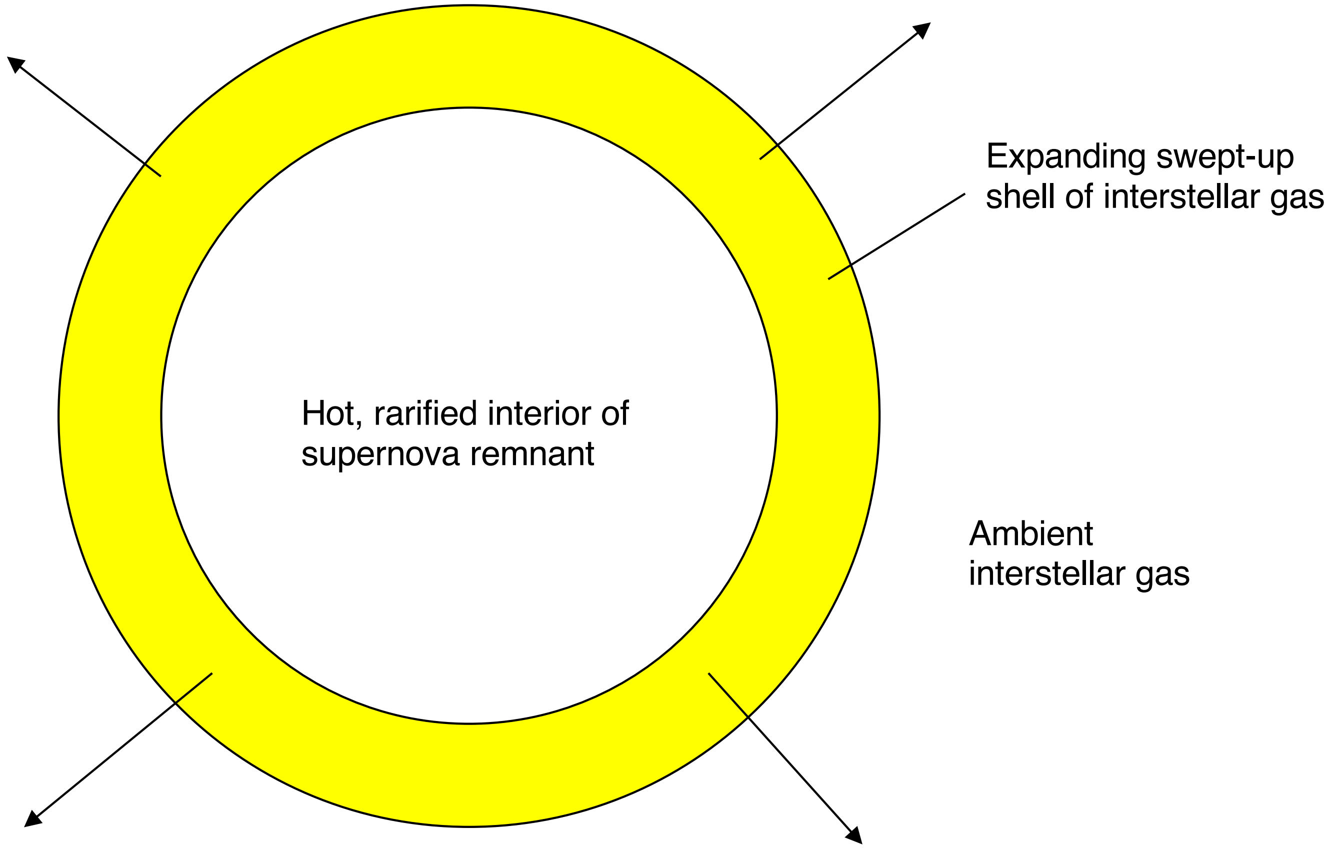
- X-ray emission (mostly bremsstrahlung)
- UV absorption lines, typically OIV

Density estimate - thought to be in rough pressure equilibrium with other diffuse phases.

$$P_{HIM} = P_{WIM} \;\Rightarrow\; n_{HIM} T_{HIM} = n_{WIM} T_{WIM}$$

$$\Rightarrow\; n_{HIM} = n_{WIM} \frac{T_{WIM}}{T_{HIM}} \sim 0.1\,\mathrm{cm}^{-3} \frac{10^4\,\mathrm{K}}{10^6\,\mathrm{K}} \sim 10^{-3}\,\mathrm{cm}^{-3}$$

How did the HIM get as hot as 10^6 K? By supernovae:



Expanding ejecta sweeps up ambient gas into a thin shell, imparts momentum into shell, so that the interior heats up.

Initial speed ~5,000 km/s, slows down to ~10 km/s. Collisions between particles convert KE into thermal energy behind the shell.

Simple estimate how much kinetic energy is put into the gas by the SN: Consider a mass M_0 initially ejected at velocity V_0. Later, the shell has swept up a mass M, and moves at a velocity V_f.

Conservation of momentum gives:

$$M_0 V_0 = (M_0 + M) V_f$$

$$KE_0 = \frac{1}{2} M_0 V_0^2, \quad KE_f = \frac{1}{2}(M_0 + M) V_f^2$$

$$\Rightarrow \quad \frac{KE_f}{KE_0} = \frac{\frac{1}{2}(M_0 + M) V_f^2}{\frac{1}{2} M_0 V_0^2} = \left[\frac{(M_0 + M) V_f}{M_0 V_0} \right] \frac{V_f}{V_0} = \frac{V_f}{V_0}$$

$$\Rightarrow \quad \frac{KE_f}{KE_0} \simeq \frac{10}{5000} = 0.2\%$$

Where does all the energy go?

Energy goes into heating the interior, the shell, and radiation as well.

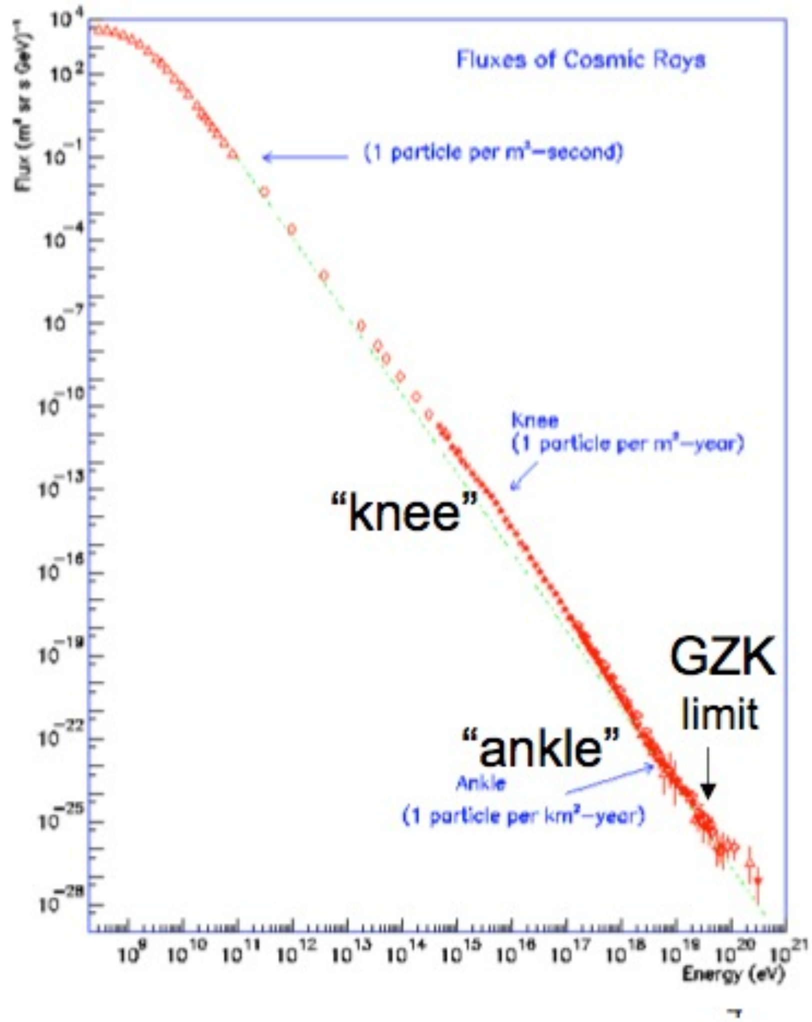
Cosmic Rays (CR)

Follows a power law, defined from 10^{10}-10^{15} eV. Steeper beyond the knee, back after the ankle.

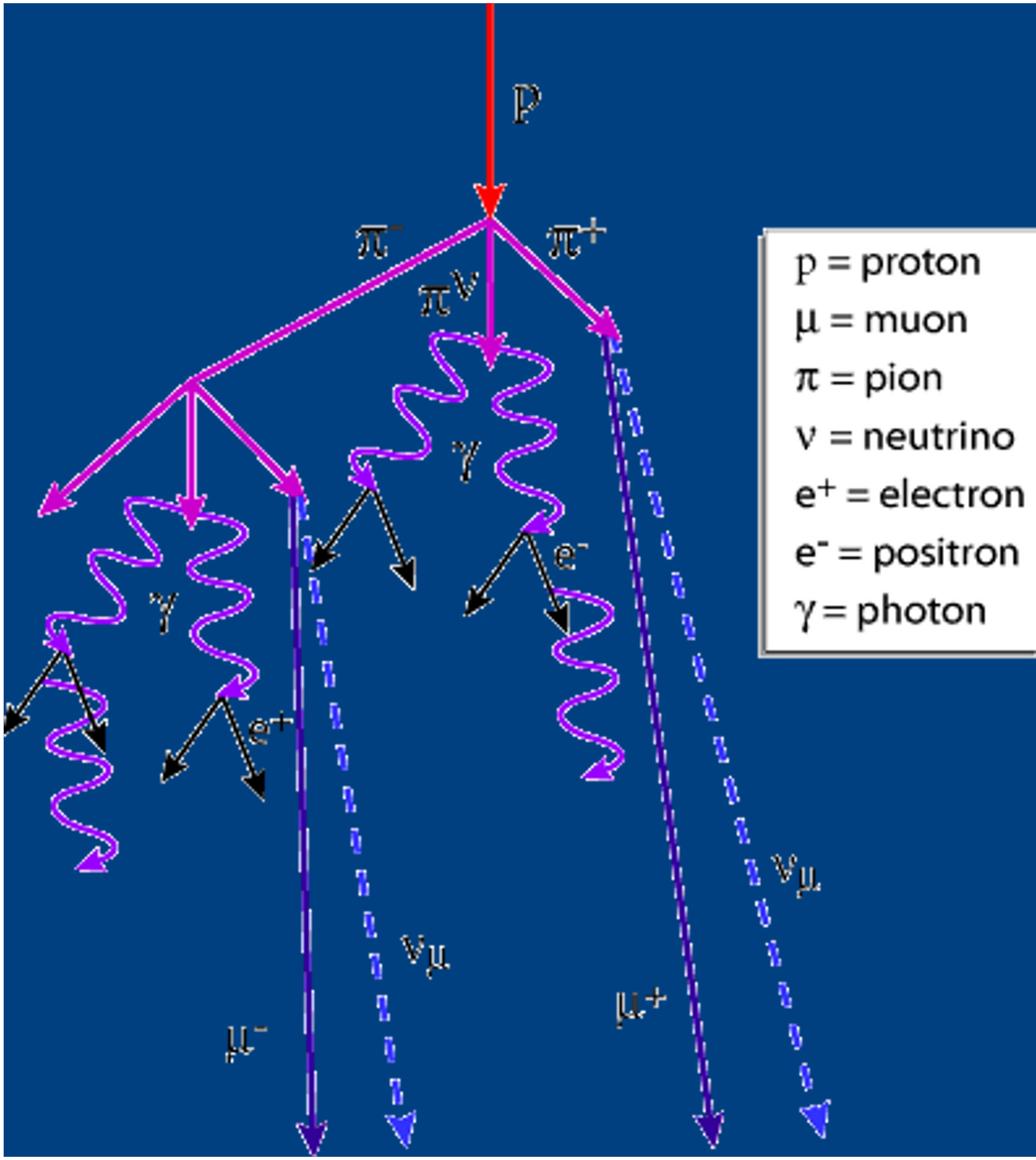
The origin of ultra high energy CRs are not known:

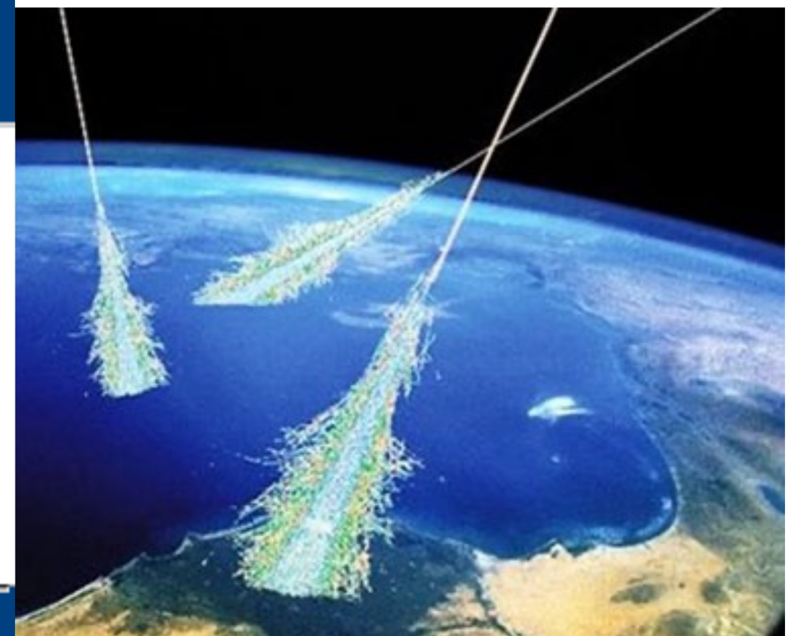
- cannot be confined by galactic B-fields
- can't be accelerated by SNe.
- can't be coming from too far away, since they interact with CMB photons.

-Might be coming from nearby AGN, TDEs, FRBs



Cosmic Ray Air Showers



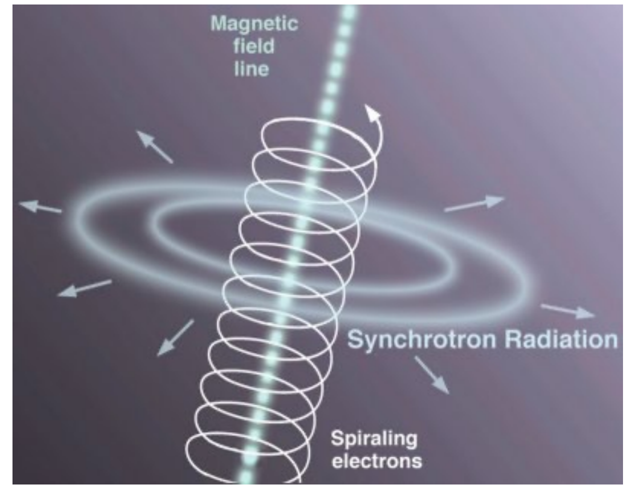


M

Synchrotron emission

Relativistic charged particles (e, p) radiate when traveling in a magnetic field.

$$\vec{F} = q\frac{\vec{v}}{c} \times \vec{B}$$



$$\text{If} \;\; \vec{v} \times \vec{B} \neq 0, \quad \text{acceleration} \quad \neq 0$$

Accelerated charges radiate.

At non-relativistic velocities this results in *cyclotron radiation,* and at relativistic velocities it results in *synchrotron radiation.*

Consider acceleration in a magnetic field, described by the equation of motion:

$$F = ma = m\frac{dv}{dt} = \frac{q}{c}v \times B$$

with $$a = \frac{v^2}{r} \quad \Rightarrow \quad \frac{v}{r} = \frac{qB}{m_e}$$

$$2\pi\nu = \omega = \frac{v}{r} = \frac{qB}{m_e}$$

defining the cyclotron frequency $$\nu_0 = 2.8B \ \ \mathrm{MHz}$$

Note that the dv/dt component parallel with the B-field is 0, so we only consider the perpendicular acceleration. So, the motion is uniform and circular around the field lines.

At relativistic velocities

$$\frac{d}{dt}(\gamma m\vec{v}) = \frac{q}{c}\vec{v} \times \vec{B}$$

With the resulting acceleration $$\frac{v^2}{r} = \frac{q}{\gamma m_e c} vB \sin\alpha$$

where α is the *pitch angle* (inclination of velocity vector to magnetic field lines), and *r* is the radius of the orbit.

Following previous exercise, we can find the synchrotron frequency to be:

$$\nu = \frac{qB}{2\pi\gamma m_e c}$$

Power emitted by the synchrotron process:

$$P_{rel} = \frac{2q^2}{3c^3}\gamma^4 a^2$$

For a distribution of relativistic electrons, we'll integrate over the pitch angles we'll get

$$P_{iso} = \frac{4}{3}\sigma_T c\beta^2\gamma^2 \frac{B^2}{8\pi}$$

Power emitted from accelerated charges has a dipole radiation pattern, while relativistically charged particles have strongly beamed radiation.

Beamed into an angle of $\frac{1}{\gamma}$

Synchrotron spectrum

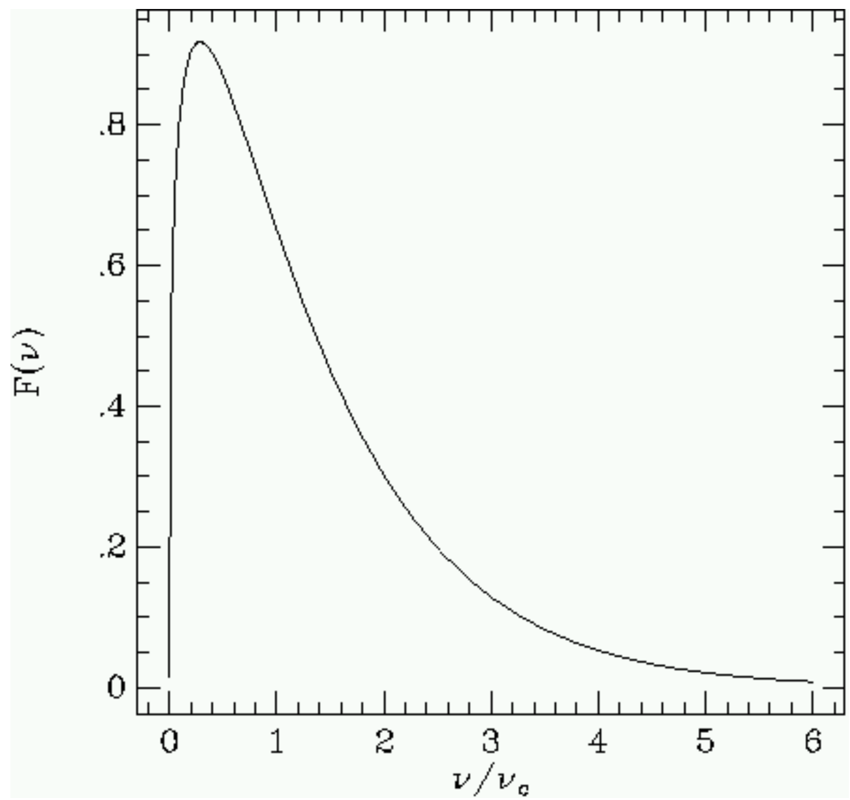
For cyclotron emission, gyration frequency equals frequency of emitted radiation.

$$\nu_0 = 2.8B \text{ MHz}$$

For synchrotron emission there is a characteristic emission frequency at

$$\nu_c = \frac{3\gamma^2 eB}{2m_e c}$$

$$0.29\nu_c$$



The overall emission spectrum is the sum of a large number of individual synchrotron emissions:

$$N(E) \propto E^{-p} \quad (p > 0)$$

And recall brightness temperature defined as

$$T_b = \lambda^2 S/2k\Omega$$

Can show that radiation intensity relates to frequency according to

$$I(\nu) \propto \nu^{-\alpha}$$

$$\alpha = \frac{p-1}{2}$$

α is the spectral index. Thus, *I* is highest at low ν, and brightest at radio frequencies.

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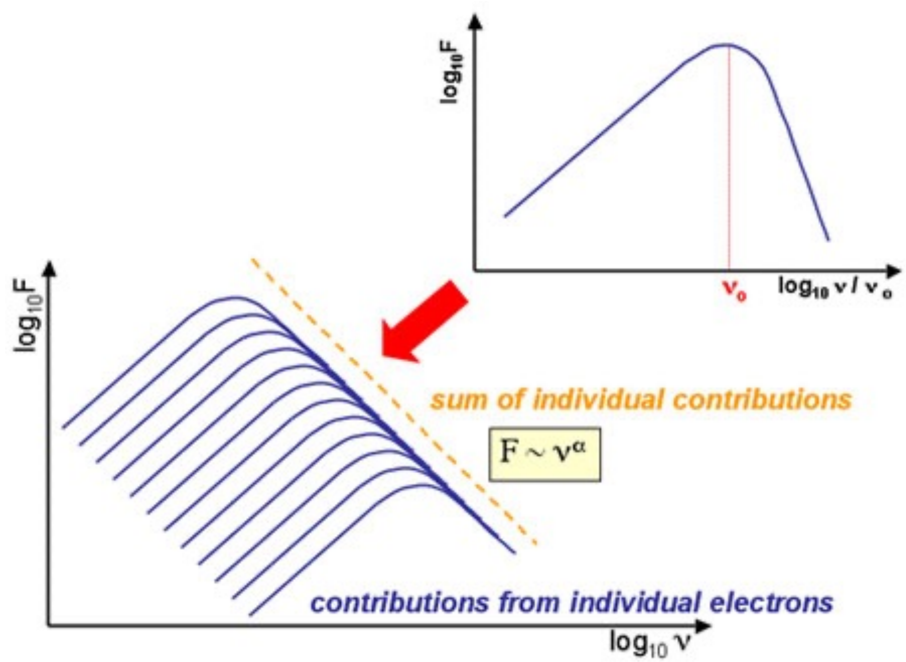
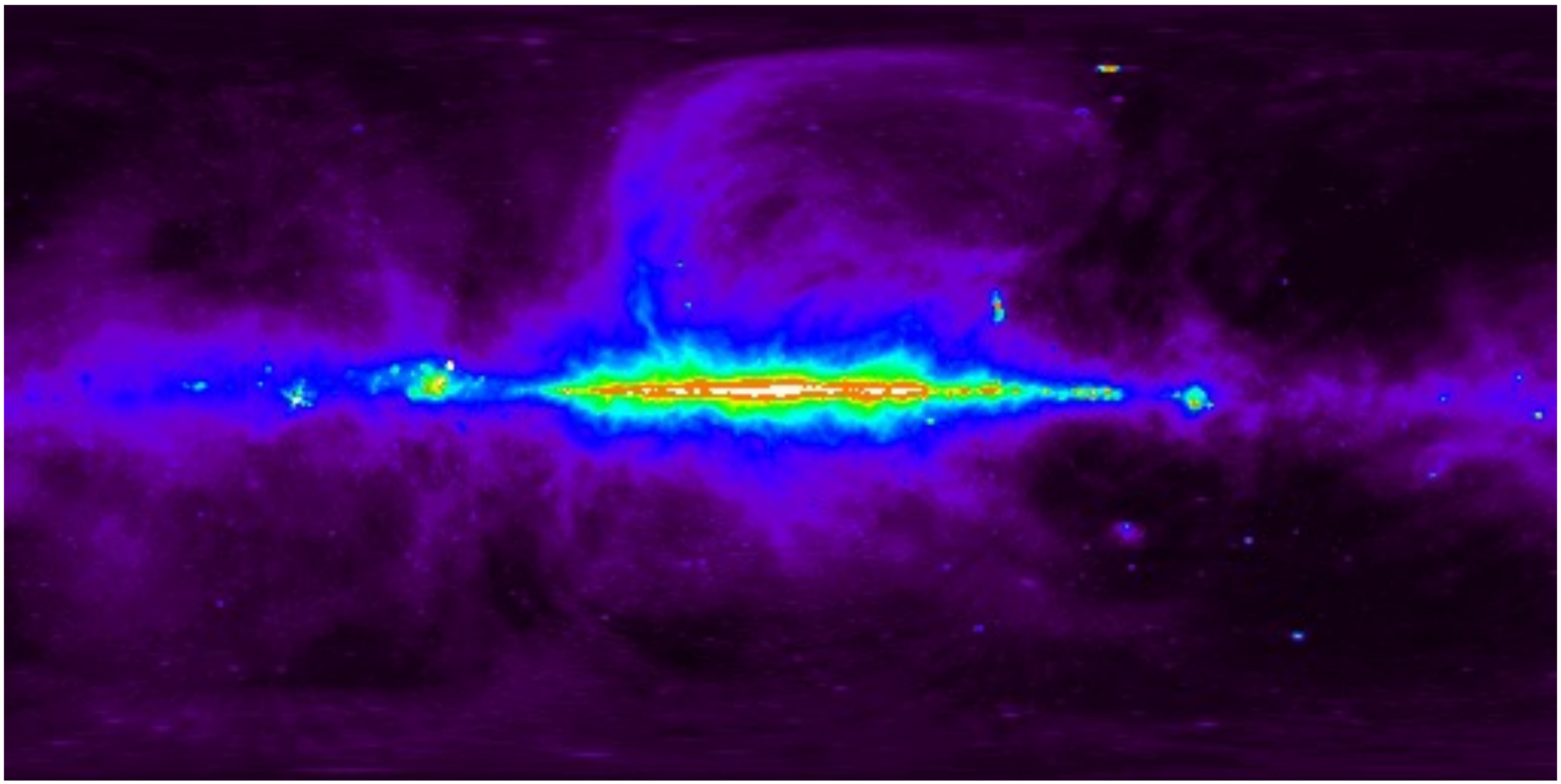


Cosmic ray detectors on Earth indicate that p is around 2.6 => α=0.8

Diffuse radio emission in Milky Way has α~0.8
=> relativistic electrons, synchrotron radiation.



Worksheet: Show that when the energy density is high enough ($T_b \sim T_e$) and $\gamma mc^2 = 3kT$ that the synchrotron self absorption spectra looks like $S \sim \nu^{5/2}$

Key concepts:

Molecular Clouds Milky Way

HII regions

Star formation

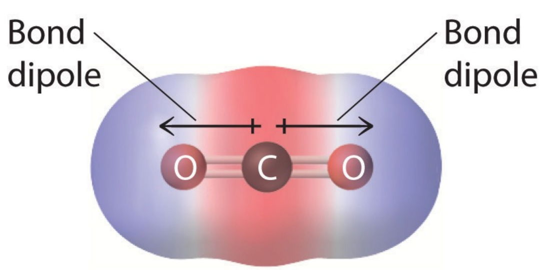
High velocity clouds

Molecular Hydrogen

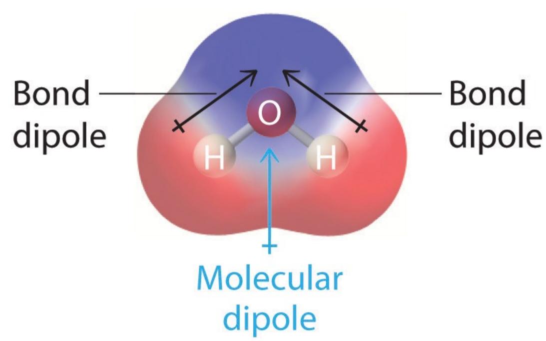
H_2 is the most abundant molecular species in the ISM, and is crucial for cooling and molecular chemistry.

Despite its importance it is the most difficult to observe directly, because it is a simple, homonuclear molecule.

- Two atoms, identical mass, so the center of mass and center of charge coincide
  - Resulting in no permanent dipole moment
  - Lets look at CO_2 and H_2O instead:



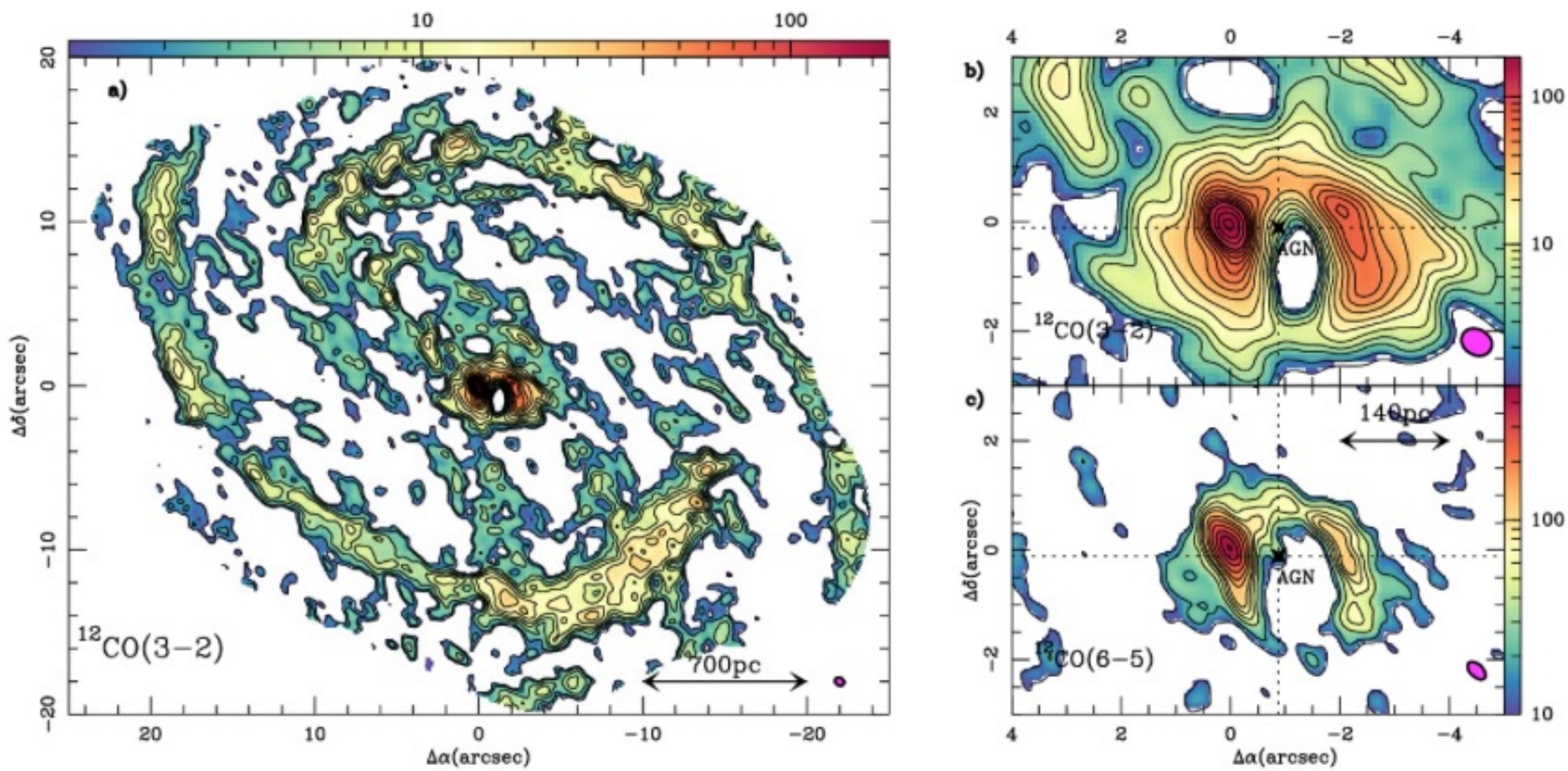
(a) No net dipole moment



(b) Net dipole moment

Molecular clouds

Due to the new mm-telescopes like ALMA, molecular studies are the most common way of studying the ISM.

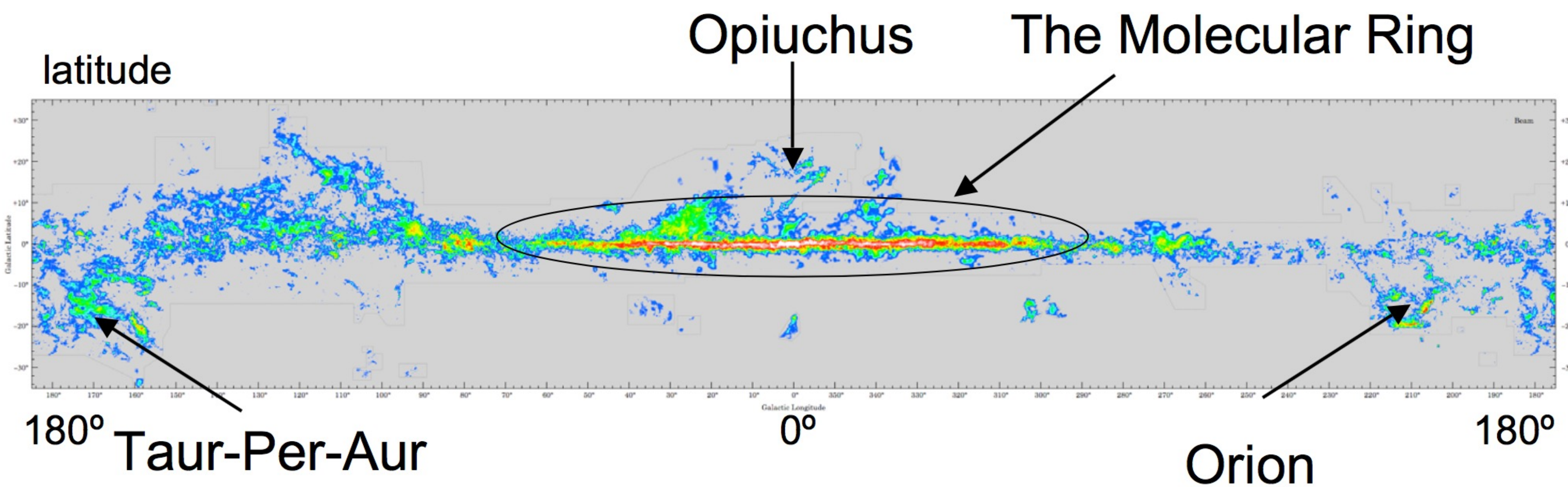


NGC 1068

Garcia-Burillo et al. 2014

CO surveys

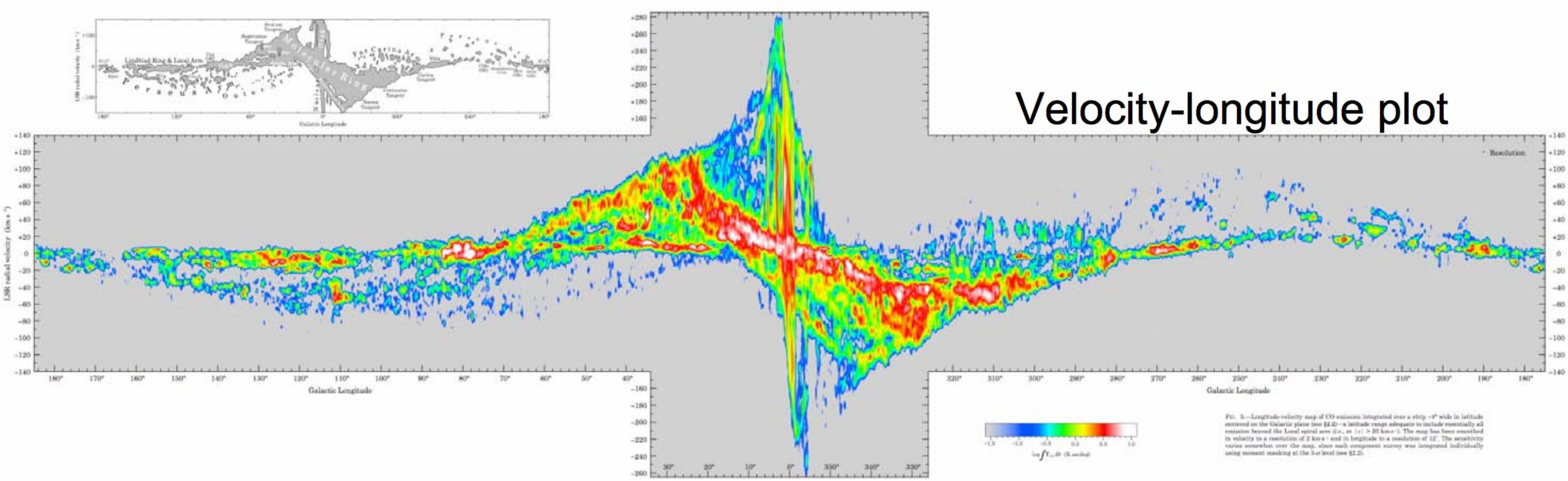
As CO is thought to be a good tracer of H_2, surveys of CO help to identify locations of molecular clouds and to determine cloud properties.



Dame et al. (2001): CO(1-0)

CO is distributed more in clumps, compared to the HI.

- Molecular clouds and cloud complexes can be identified throughout the Galaxy



CO lines can be optically thick, so we will see how *isotopologues* (which are optically thin) can be used to derive properties of the clouds.

Dame et al. (2001): CO(1-0)

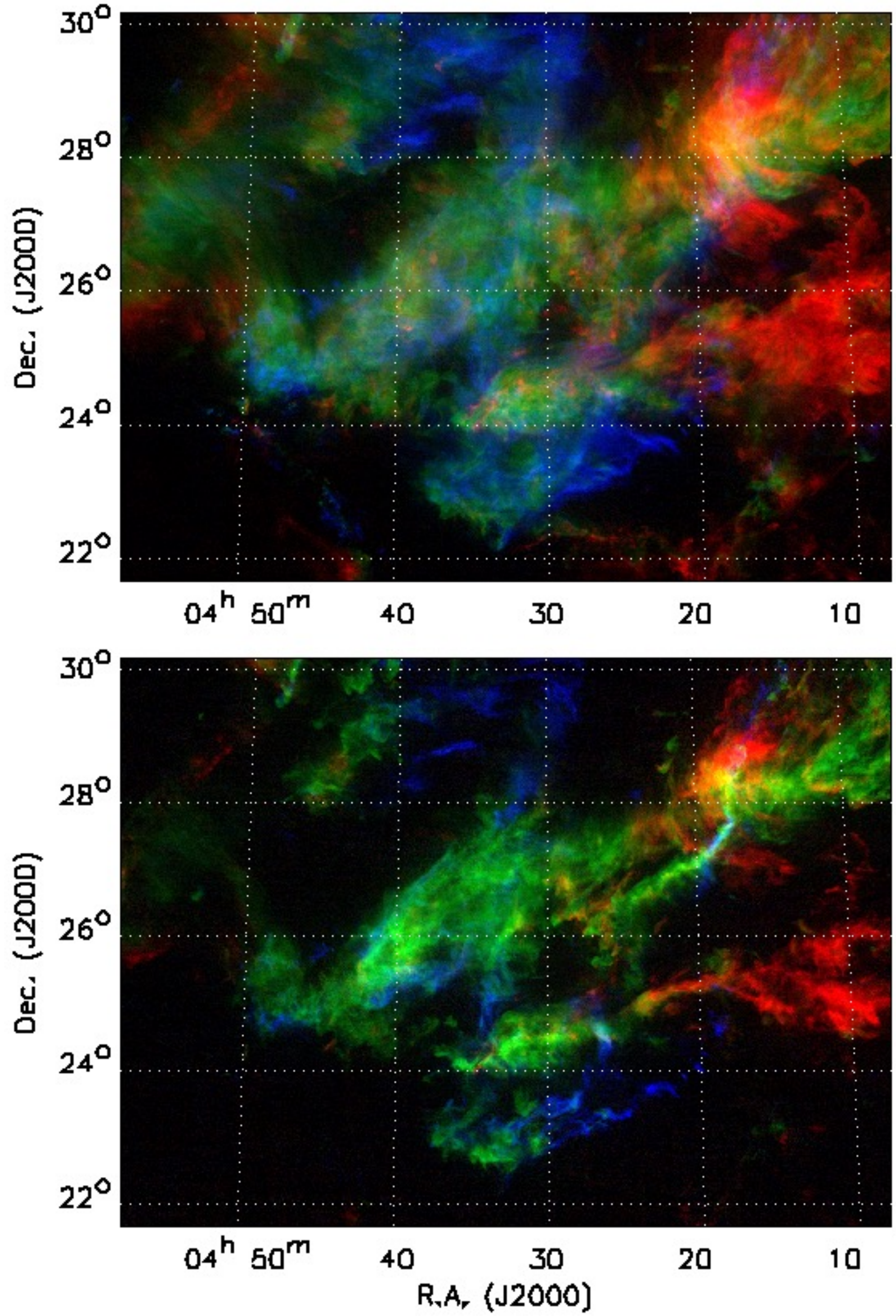
Example:

Taurus molecular cloud (low-mass starformation, nearest) in ^{12}CO and ^{13}CO.

Colors are velocity indicators.

Notice the 'fluffier' appearance of the ^{12}CO, while the ^{13}CO seems to focus on cores, more details in the structure.

Goldsmith et al., Five College Radio Astronomy Observatory CO Mapping survey of the Taurus Molecular cloud.



Density diagnostics

Several methods can be used to estimate densities of molecular clouds from observations:

1. Use the observed column density by assuming a path length though the cloud.

$$N = \int n ds$$

N is the total column density along the line of sight, and $\int ds$ is the path length.

2. A second method is to set lower limits to the density by noting which molecular lines of different critical densities are visible in a cloud.

   Some common emission lines used in this way are those from Shirley (2015).

Note that CO isotopologues are useful for measuring the properties of widely distributed molecular gas, but other probes are needed for localized high-density regions, especially cloud cores that give birth to stars.

=> use high-dipole moment molecules with *large* critical densities.

Species	μ (D)	ν (GHz)
CO	0.11	115.3
CS	1.96	48.99
HCN	2.98	89.09
N_2H^+	3.4	93.18
HCO^+	3.93	89.19

(Schöier et al., 2005, has table of dipole moments etc., from the Leiden Molecular Database).

3. Assume that the cloud is in *virial equilibrium*, assuming turbulent motions holding the cloud up against self-gravity.

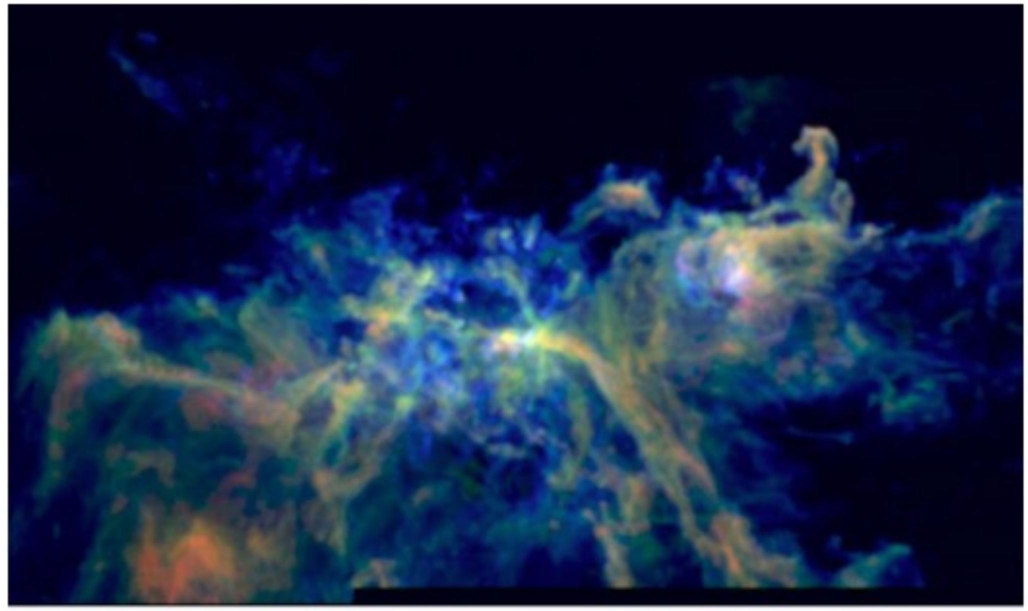
- Then the observed line width is assumed to be the virial velocity, and the mass is estimated via the virial theorem

$$M = \frac{2R\Delta v^2}{G}$$

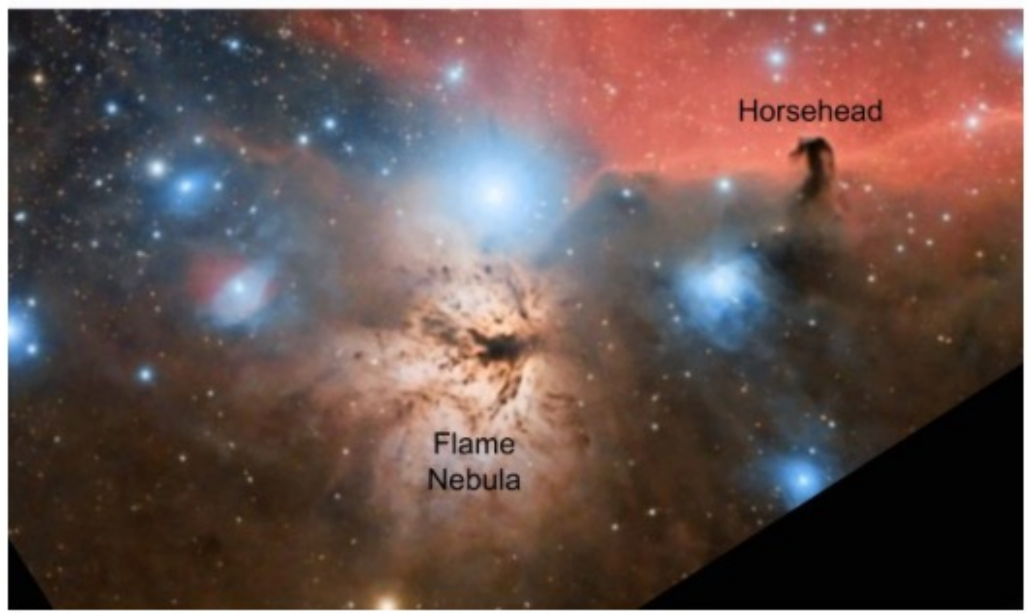
Then, the density can be worked out assuming a volume of the cloud.

Orion B star forming region

IRAM 30m CO lines



optical



J. Pety, the Orion-B collaboration
And IRAM

HII regions

Ionized gas near hot, young massive stars.

Compared to the WIM, more well defined and denser.

n_e~10^2-10^4 cm^{-3}.

Example: Orion nebula. Red => Hα dominates emission.

Why near massive stars only?

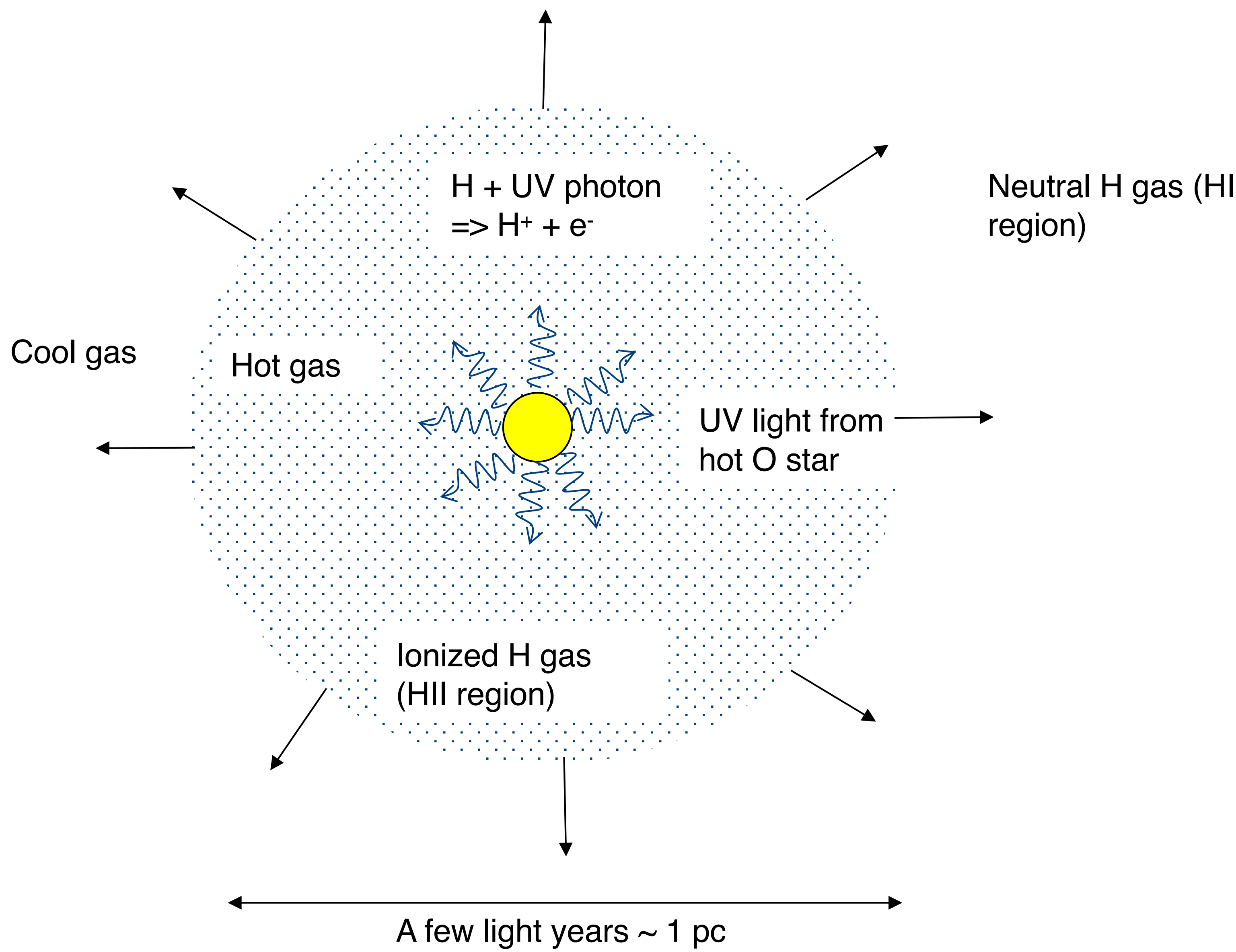
Need 13.6eV => 912 Å (UV)

Use Wien's law $$\lambda_{\rm max} = \frac{0.29 \ {\rm cmK}}{T}$$

$$T = \frac{0.29}{912 \times 10^{-4}} = 32,000 \ {\rm K}$$

This is a B0 or B1 star. Thus, HII regions surround only O and B stars, and share their short lifetimes.

Schematic diagram: Balance of ionization and recombination sets up HII region.



We can find the expected size of an HII region by assuming *ionization equilibrium:*

ionization rate = recombination rate

recombinations per cm^3 per sec is $n_e n_p \alpha = n_e^2 \alpha$

If the region is spherical with a constant electron density, then

$$\frac{4}{3}\pi R^3 n_e^2 \alpha$$

is the # recombinations per sec over the whole HII region.

If the star emits N ionizing photons per s, then

$$N = \frac{4}{3}\pi R^3 n_e^2 \alpha$$

And we can solve for the radius:

$$R_s = \left(\frac{3N}{4\pi\alpha}\right)^{1/3} n_e^{-2/3}$$

NB, n_e in cgs units cm^{-3}

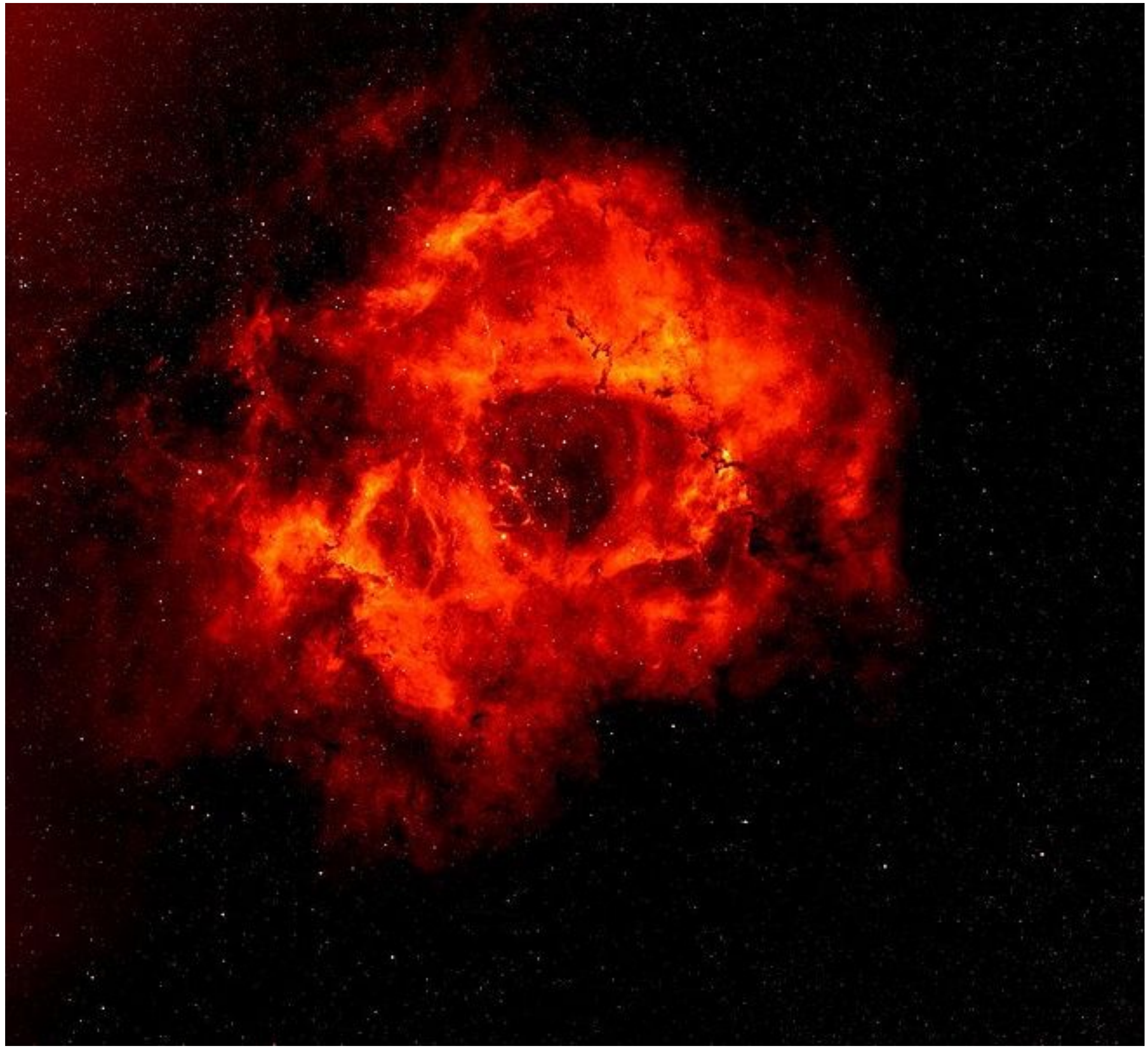
R_S is the *Strömgren radius.*

The sphere is called *Strömgren sphere.*

Not always this simple

Example: The Rosette Nebula

In the center is a star cluster, NGC2244. $H\alpha$



Example

O6 star with $T_{\rm eff}$ = 45,000 K

$L = 1.3\text{x}10^5\ L_\odot$

Assuming a blackbody spectrum, we use Wien's law:

$$\lambda_{max} = \frac{0.29\,\mathrm{cmK}}{45,000\,\mathrm{K}} = 644\,\mathrm{\AA}$$

To simplify, assume all ionizing photons from star have $\lambda=\lambda_{max}$, and the star only emits ionizing photons.

Then, photon energy $E = \dfrac{hc}{\lambda_{max}} = 19eV$

and thus

$$N = \frac{L}{E} = \frac{3\times10^{50}\,\mathrm{eVs^{-1}}}{19\,\mathrm{eV}} = 1.6\times10^{49}\ \mathrm{s^{-1}}$$

For H at temperatures and densities of HII regions, we use α=3x10^{-13} cm^{3}s^{-1}. Assuming also n_e = 1000 cm^{-3}, then:

$$R_s = \left(\frac{3 \times 1.6 \times 10^{49}}{4\pi\, 3 \times 10^{-13}}\right)^{1/3} (10^3)^{-2/3} = 2.33 \times 10^{18}\,\mathrm{cm} = 0.8\,\mathrm{pc}$$

Strömgren spheres: properties

Spectral type	M_v	$T_*(^\circ K)$	Log $Q(H^0)$ (photons/sec)	Log $N_e N_p r_1^3$ (N in cm^{-3}; r_1 in pc)	r_1 (pc) ($N_e = N_p = 1$ cm^{-3})
O5	− 5.6	48,000	49.67	6.07	108
O6	− 5.5	40,000	49.23	5.63	74
O7	− 5.4	35,000	48.84	5.24	56
O8	− 5.2	33,500	48.60	5.00	51
O9	− 4.8	32,000	48.24	4.64	34
O9.5	− 4.6	31,000	47.95	4.35	29
B0	− 4.4	30,000	47.67	4.07	23
B0.5	− 4.2	26,200	46.83	3.23	12

NOTE: $T = 7500^\circ$ K assumed for calculating α_B.

Molecular clouds are

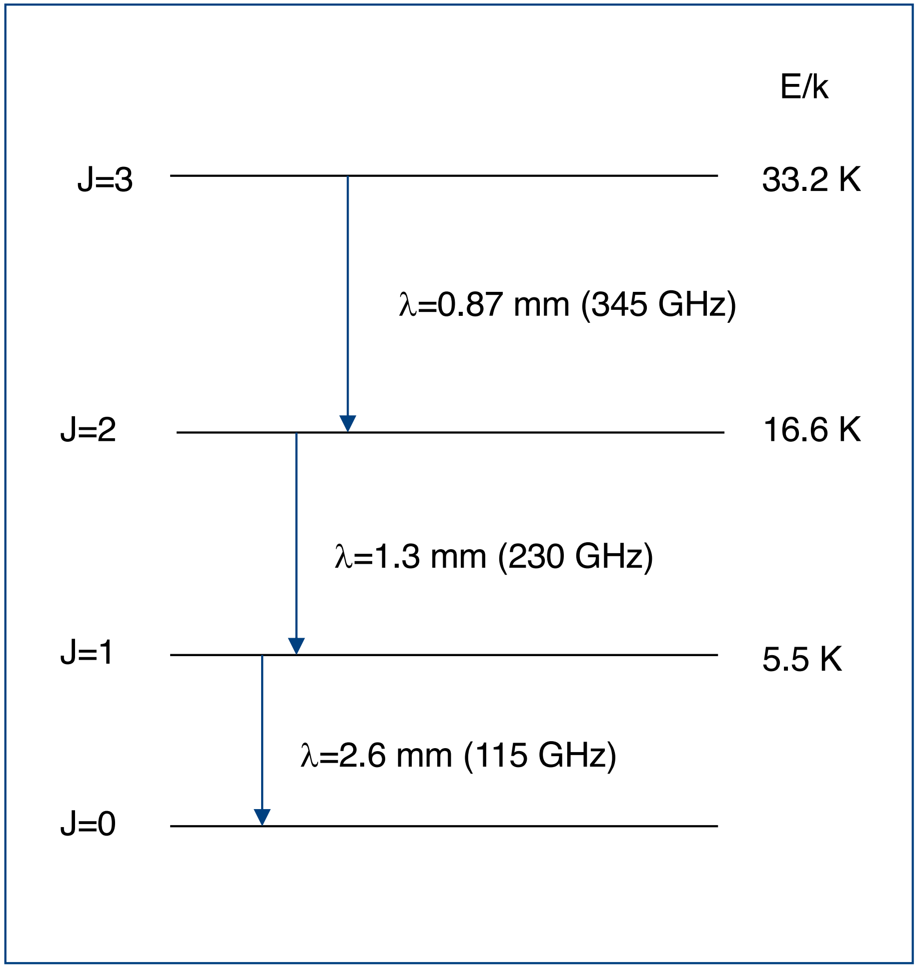
dense: $n \sim 10^2$-10^3 cm^{-3}

cold: $T \sim$ 10-50 K

Recall that these are the conditions under which star formation occurs.

How to observe molecular gas:

H_2 does not have any electric dipole transition => weak emission. Instead we use the CO molecule as the most common *tracer.*



Low energies of CO rotational levels => easily excited by $CO\text{-}H_2$ collisions, despite low temperatures.

Radiative de-excitation occurs via λ ~mm photons.

mm-wave astronomy