Class 1: Observing the cold ISM

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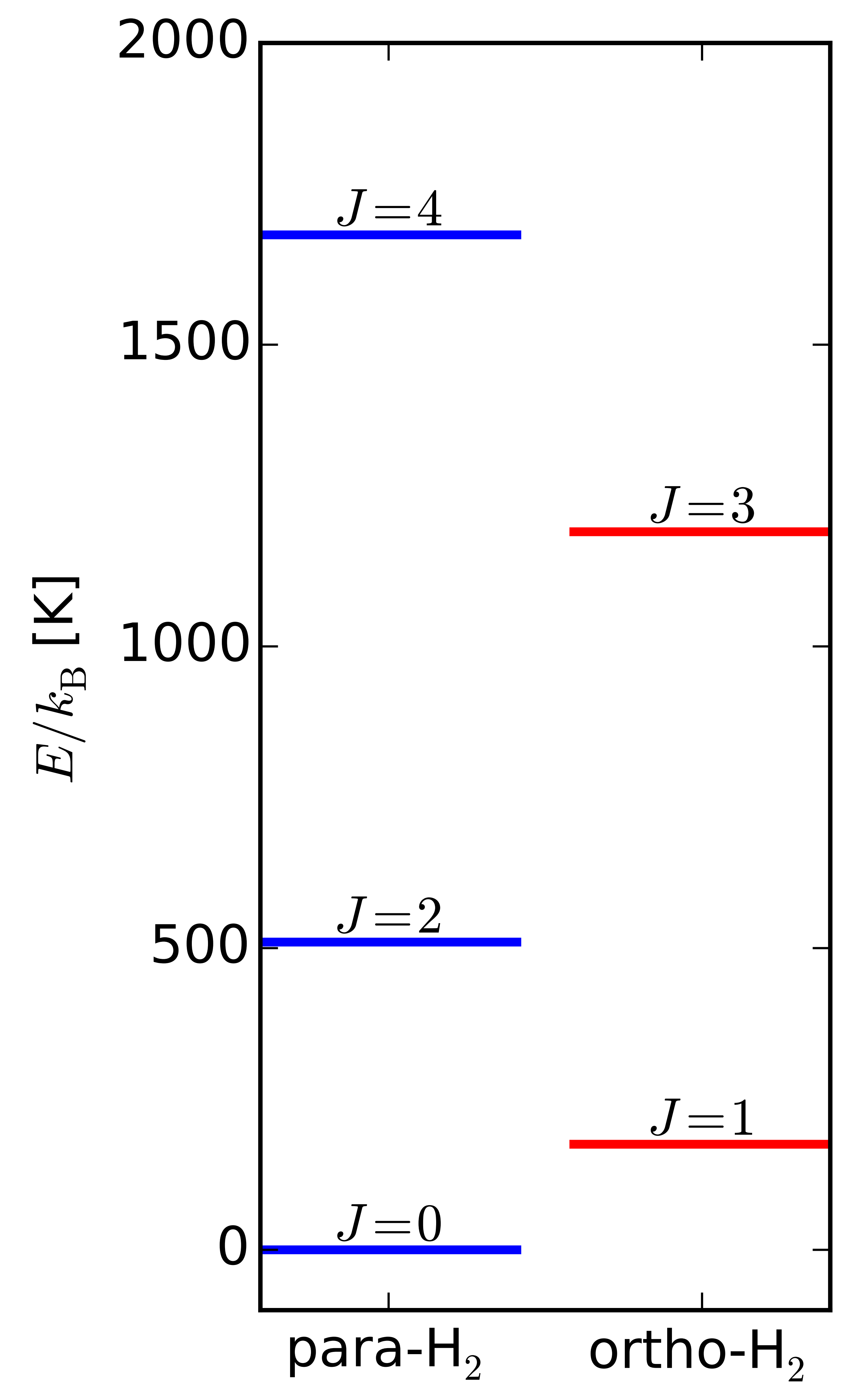
The problem of H_2

- H_2 is by far the most common component of the cold part of the ISM where stars form
- However, it is very difficult to observe directly
- Lowest lying state that can emit is ~500 K above ground, while typical gas temperature is ~10 K
- Problem: fraction in state capable of emitting is $\sim e^{-500/10} \sim 10^{-22}$, so no emitting molecules!

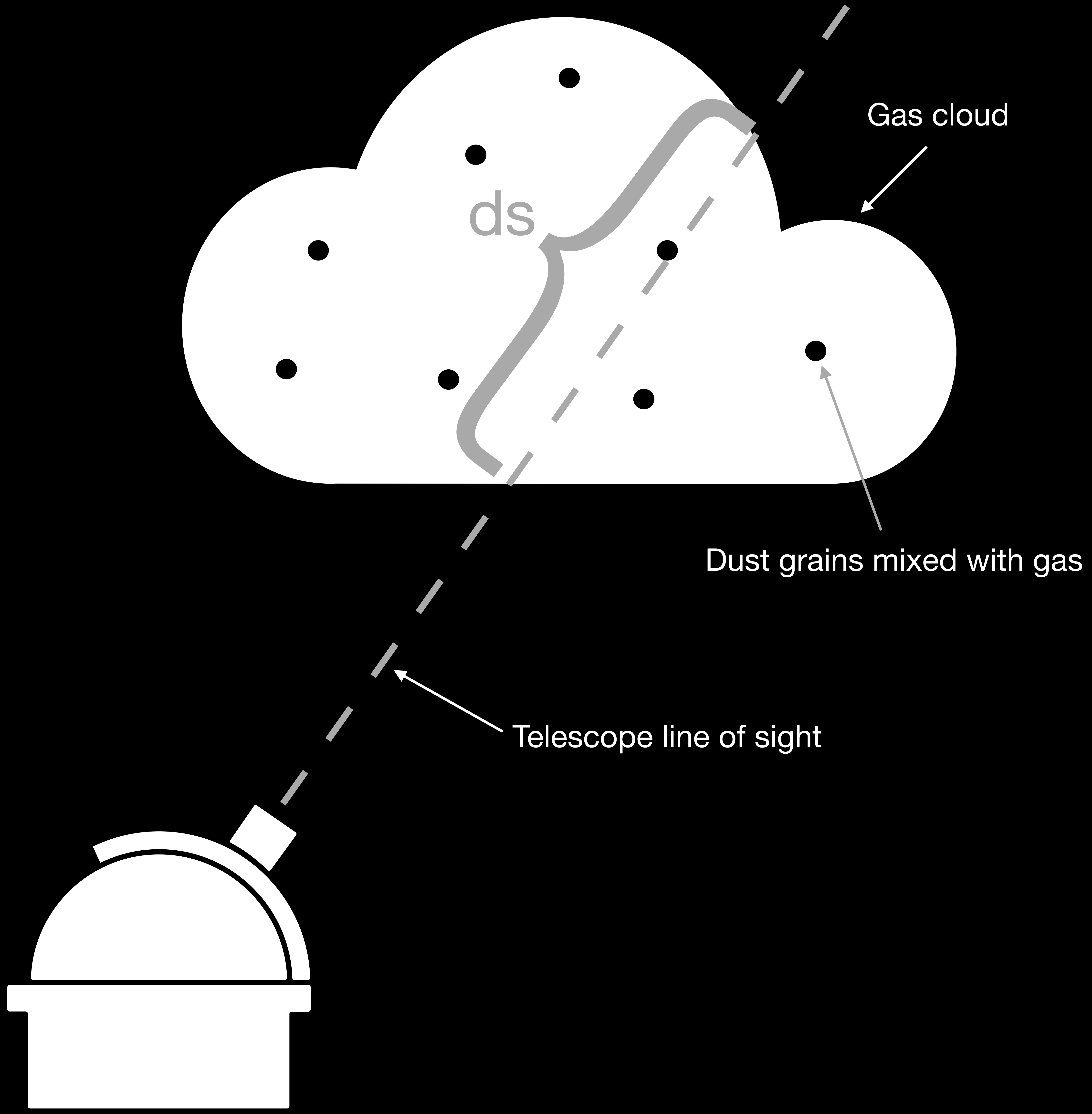


Proxies for H_2

- Dust thermal emission
- Dust absorption
- Molecular line emission
  - Theory of molecular lines: the two-level atom
  - Density inference
  - Velocity inference

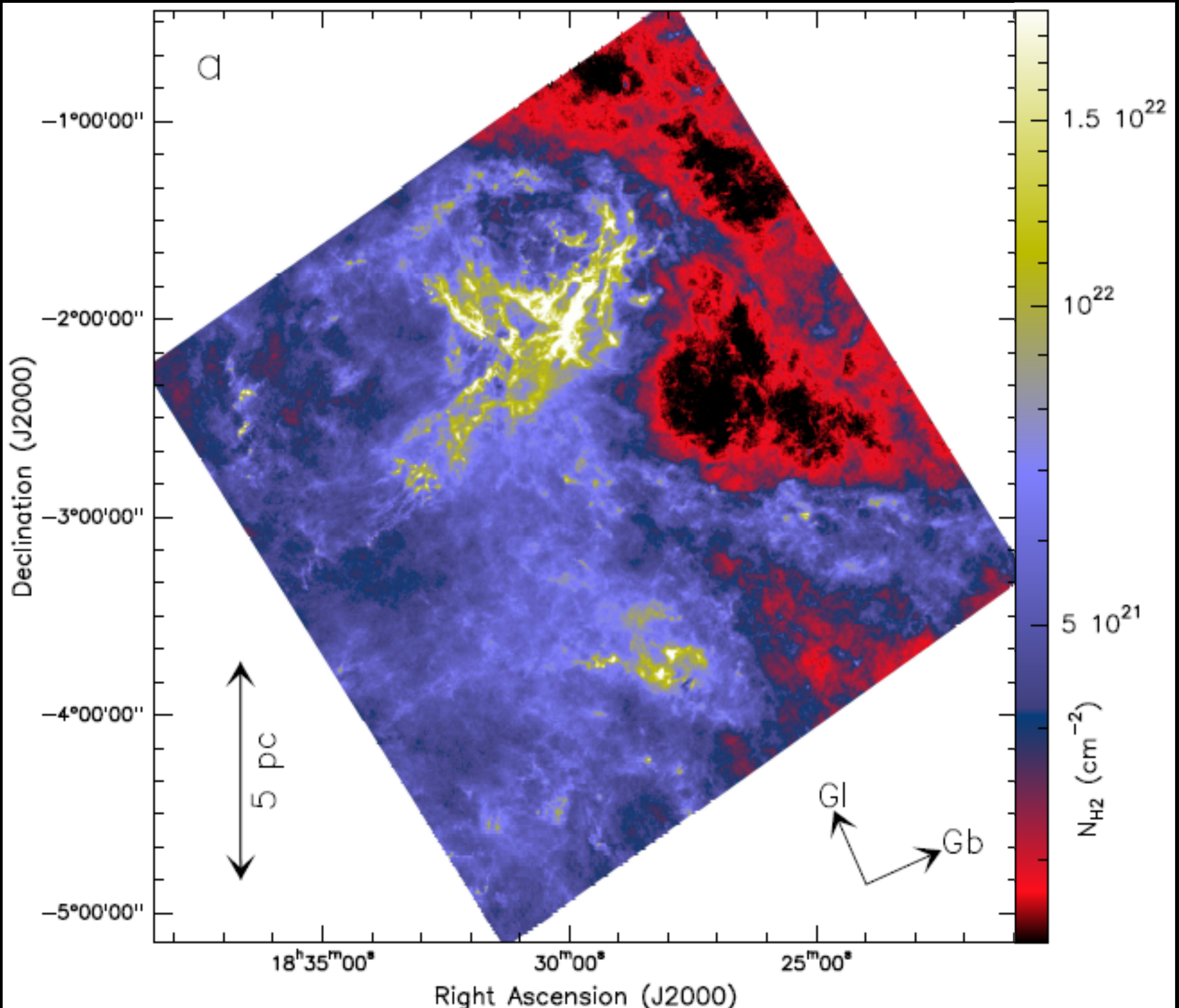
Dust thermal emission

- Interstellar gas is mixed with solid dust grains; grains emit thermally in IR
- For a dust-gas mixture with specific opacity κ_ν, the emissivity is $j_\nu = \kappa_\nu \rho B_\nu(T)$, where T is temperature and $B_\nu(T)$ is the Planck function
- Dust is transparent at low frequency, so observed intensity $I_\nu = \int j_\nu \, ds = \kappa_\nu \Sigma B_\nu$, where Σ = column density
- Estimate T and κ_ν, measure $I_\nu \Rightarrow$ know Σ



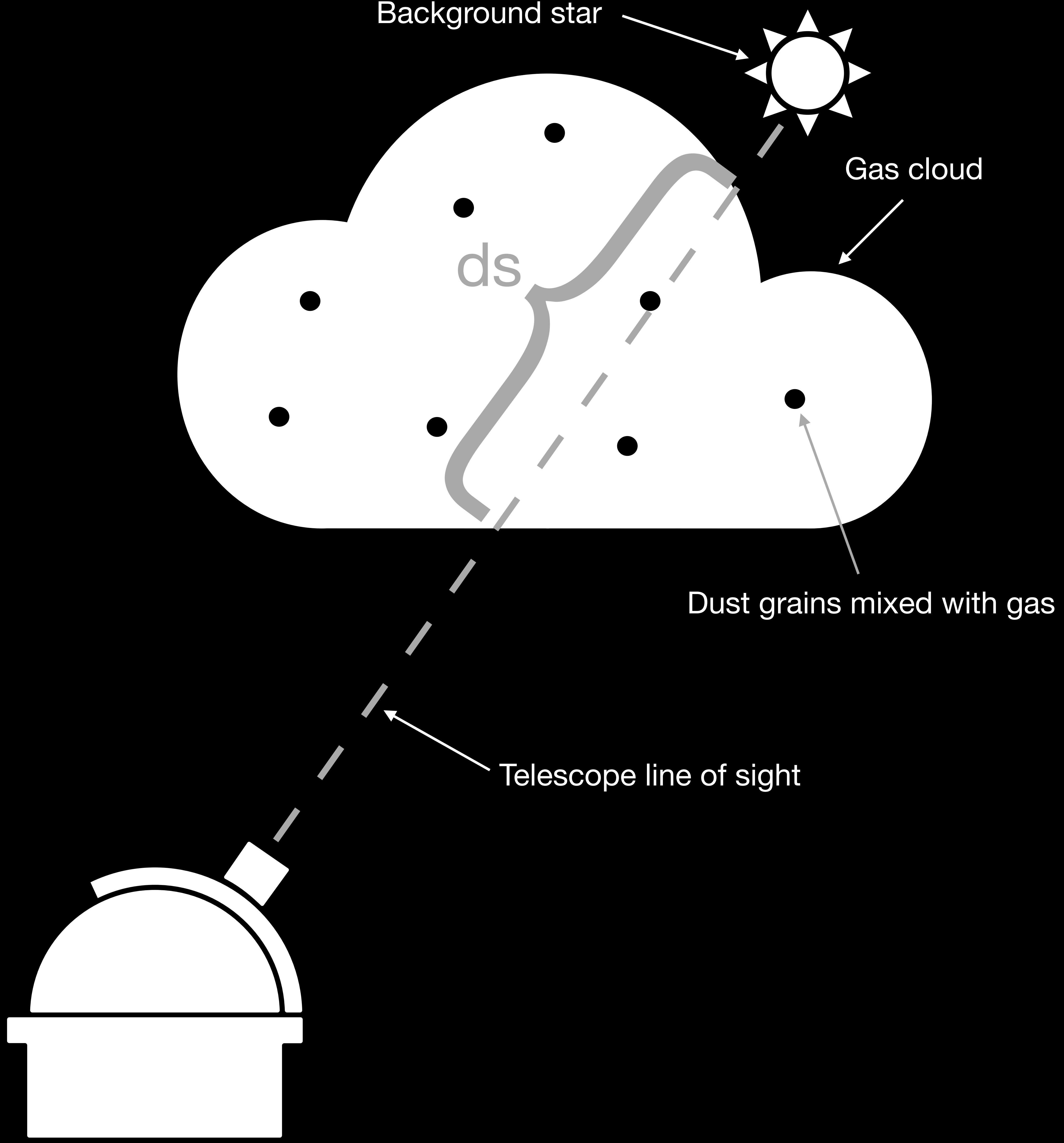
Dust thermal emission-based H_2 map

Könyves+ 2015

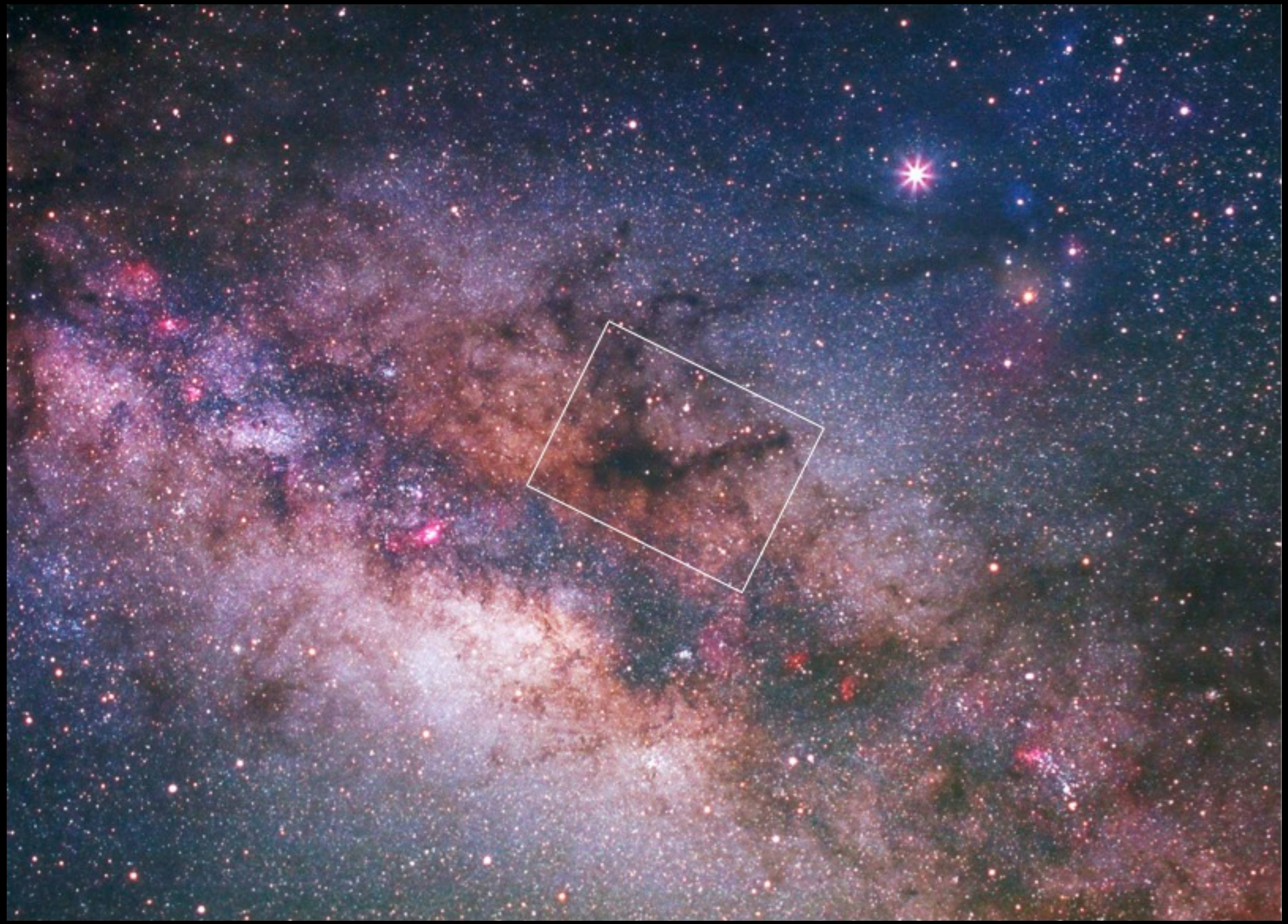


Dust absorption

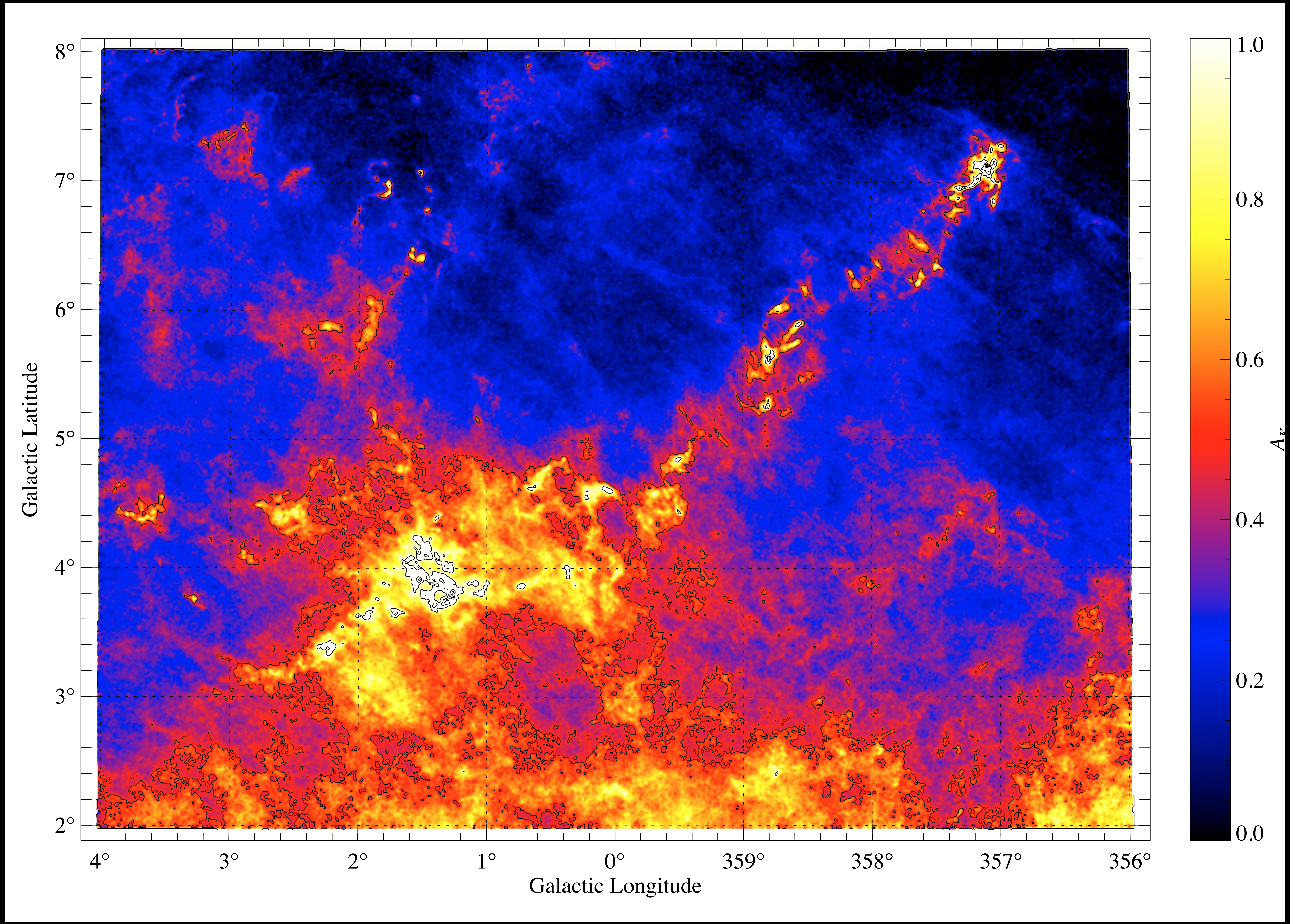
- Grains absorb as well as emit light
- Observe background stars through cloud; observed luminosity is related to true luminosity by $L_{\mathrm{obs},\nu} = \exp(-\tau_\nu)\, L_{\mathrm{true},\nu}$, where $\tau_\nu = \int \kappa_\nu \rho \, ds = \kappa_\nu \Sigma$
- Measure in two filters: unextincted star has known luminosity ratio in two filters, but measured ratio differs because τ_ν is different at different frequencies
- Deviation from expected colour fixes difference in τ_ν; for known κ_ν, this fixes Σ



Optical image and absorption map



Lombardi+ 2006



Dust absorption vs. dust thermal emission

Advantages and disadvantages

Advantages of absorption:

- Doesn’t depend on uncertain dust temperature
- Can be done in optical / near-IR from the ground (thermal emission is space-only)
- Opacities much better known / measured in optical than IR

Disadvantages of absorption:

- Need to find a clean sample of background stars; hard or impossible for clouds in crowded regions close to Galactic plane
- Can’t probe columns that are too high, or can’t see background stars
- Maps irregularly-sampled — interpolation challenges

Molecular line emission

Basics

- Most common proxy for H_2 is CO: next-most abundant molecule, has levels at much lower energy than H_2 (lowest level 5.5 K above ground) and so can emit at low temperature

- CO tends to co-exist with H_2, for reasons we will discuss in a few classes

- Other molecules also useful for probing different ranges of density, temperature, other physical conditions; examples: HCN, CS, NH_3, N_2H^+, etc.

- Can also observe isotopologues, e.g., ^{13}CO, $C^{18}O$, N_2D^+, etc.

Molecular line emission

Advantages and disadvantages

Advantages of molecular lines:

- Much higher spectral brightness than dust; only molecules allow large extragalactic studies
- Observed in radio from the ground
- Lines carry lots of information about kinematics, physical conditions in emitting gas

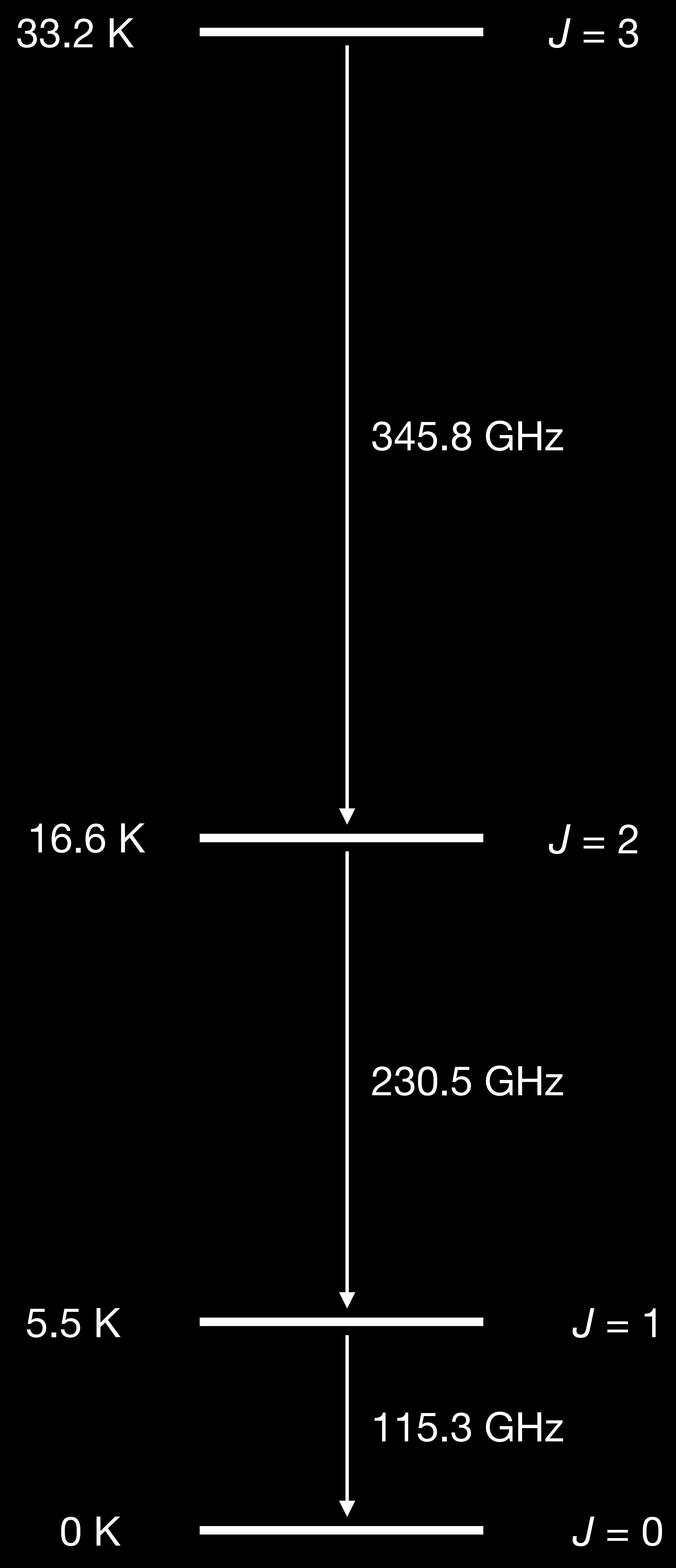
Disadvantages of molecular lines:

- Interpretation complex: requires careful modelling of excitation and radiative transfer effects
- Sensitive to poorly understood chemical processes (e.g., freeze-out of CO molecules into ice on dust grain surfaces at low temperature)

Anatomy of linear molecules

Examples: CO, HCN, CS

- Three types of excitation, from highest to lowest energy: electronic, vibrational, rotational
- In the cold ISM, usually only rotational levels are excited; we see photons emitted due to transition from rotational quantum number $J \rightarrow J - 1$
- Energies of levels spaced as $E_J = \text{const} \times J\,(J + 1)$
- Questions for class:
  - Why are rotational levels of CO so much more closely spaced than those of H_2?
  - Why is the energy ordering electronic, vibrational, rotational?



33.2 K $J = 3$

345.8 GHz

16.6 K $J = 2$

230.5 GHz

5.5 K $J = 1$

115.3 GHz

0 K $J = 0$

CO rotational levels

The two-level atom

Problem set up

- Consider an atom or molecule with exactly two quantum states, separated by energy E; we will refer to these as state 0 and state 1
- We will call this hypothetical species X; the number density of this species is $n_X = n_0 + n_1$, where n_0 = number density in state 0, n_1 in state 1
- These atoms are mixed with some other species n, which can collide with X particles and cause transitions between states 0 and 1
- The temperature of the system is T
- In thermodynamic equilibrium, we must have $n_1 / n_0 = e^{-E/kT}$, so $n_0 = n_X / Z$ and $n_1 = n_X e^{-E/kT} / Z$, where $Z = 1 + e^{-E/kT}$ is the partition function

The two-level atom

Radiative and collisional transitions

- In the absence of a background radiation field from which the atoms can absorb, transitions happen by spontaneous emission and collisions
- Spontaneous emission rate: $(\mathrm{d}n_1 / \mathrm{d}t)_{\mathrm{se}} = -A_{10}\, n_1$; A_{10} is called the Einstein coefficient, and it has units of 1 / time; it is the probability per unit time of a emitting a photon, and the inverse of the lifetime of the excited state
- Collisions cause transitions at rate proportional to number densities of targets and colliders: $(\mathrm{d}n_1 / \mathrm{d}t)_{\mathrm{c}} = -k_{10}\, n_1\, n + k_{01}\, n_0\, n$; first term is 1→0 transitions, second is 0→1; k_{01}, k_{10} are collision rate coefficients, units of volume / time
- All together: $\mathrm{d}n_1 / \mathrm{d}t = -A_{10}\, n_1 - n\, (k_{10}\, n_1 + k_{01}\, n_0)$

The two-level atom

Relationship between collision rate coefficients

- Collisional transition rates scale as n, radiative rate does not, so at high n collisions must completely dominate: $\mathrm{d}n_1 / \mathrm{d}t \approx -n\,(k_{10}\, n_1 + k_{01}\, n_0)$

- Thus in equilibrium we must have $k_{10}\, n_1 + k_{01}\, n_0 = 0$

- However, we also know that in equilibrium $n_1 / n_0 = e^{-E / kT}$, so k_{10} and k_{01} cannot be independent; instead, they must be related by $k_{10} = k_{01}\, e^{-E / kT}$

- Although we derived this result by considering the high n limit, recall that k_{10} and k_{01} are set by quantum mechanics, and do not depend on n. Thus our conclusion about their relationship must hold at all densities!

- Conclusion also holds between *any* pair of levels, not just for a two-level atom!

The two-level atom

The critical density

- Now return to the general problem: $\mathrm{d}n_1 / \mathrm{d}t = -A_{10}\, n_1 - n\, (k_{10}\, n_1 + k_{01}\, n_0)$; substituting in for k_{10} gives $\mathrm{d}n_1 / \mathrm{d}t = -A_{10}\, n_1 - n\, k_{10}\, (n_1 + \mathrm{e}^{E / kT}\, n_0)$

- Solve for the *statistical* equilibrium value of n_1 / n_0 by setting $\mathrm{d}n_1 / \mathrm{d}t = 0$

- Doing so gives $n_1 / n_0 = \mathrm{e}^{-E / kT} / (1 + A_{10} / k_{10}\, n) \equiv \mathrm{e}^{-E / kT} / (1 + n_\mathrm{crit} / n)$, where $n_\mathrm{crit} \equiv A_{10} / k_{10}$

- Interpretation: when $n \gg n_\mathrm{crit}$, collisions are frequent and *statistical* equilibrium is the same as *thermodynamic* equilibrium; when $n \ll n_\mathrm{crit}$, every collision is followed by a radiative decay long before the next collision, so there are fewer excited atoms than in equilibrium — system is *sub-thermally excited*

The two-level atom

Radiative luminosity

- Luminosity per unit volume due to radiative decays is $\mathscr{L} = E\, A_{10}\, n_1$; luminosity per atom of species X is $\mathscr{L} / n_X = E\, A_{10}\, (n_1 / n_X)$
- Using our statistical equilibrium solution for n_1 / n_0, with a little algebra this becomes $\mathscr{L} / n_X = E\, A_{10}\, \mathrm{e}^{-E / kT} / (Z + n_{\mathrm{crit}} / n)$
- Interpretation:
  - When $n \gg n_{\mathrm{crit}}$, fraction of atoms in state 1 = $\mathrm{e}^{-E / kT} / Z$, so luminosity per atom = (fraction in upper state) x (transition rate) x (energy per transition)
  - When $n \ll n_{\mathrm{crit}}$, luminosity per atom = $E\, A_{10}\, \mathrm{e}^{-E / kT} (n / n_{\mathrm{crit}}) = E\, k_{01}\, n$, so luminosity = (collision rate) x (energy per transition) — every collision just yields one photon emitted

The two-level atom

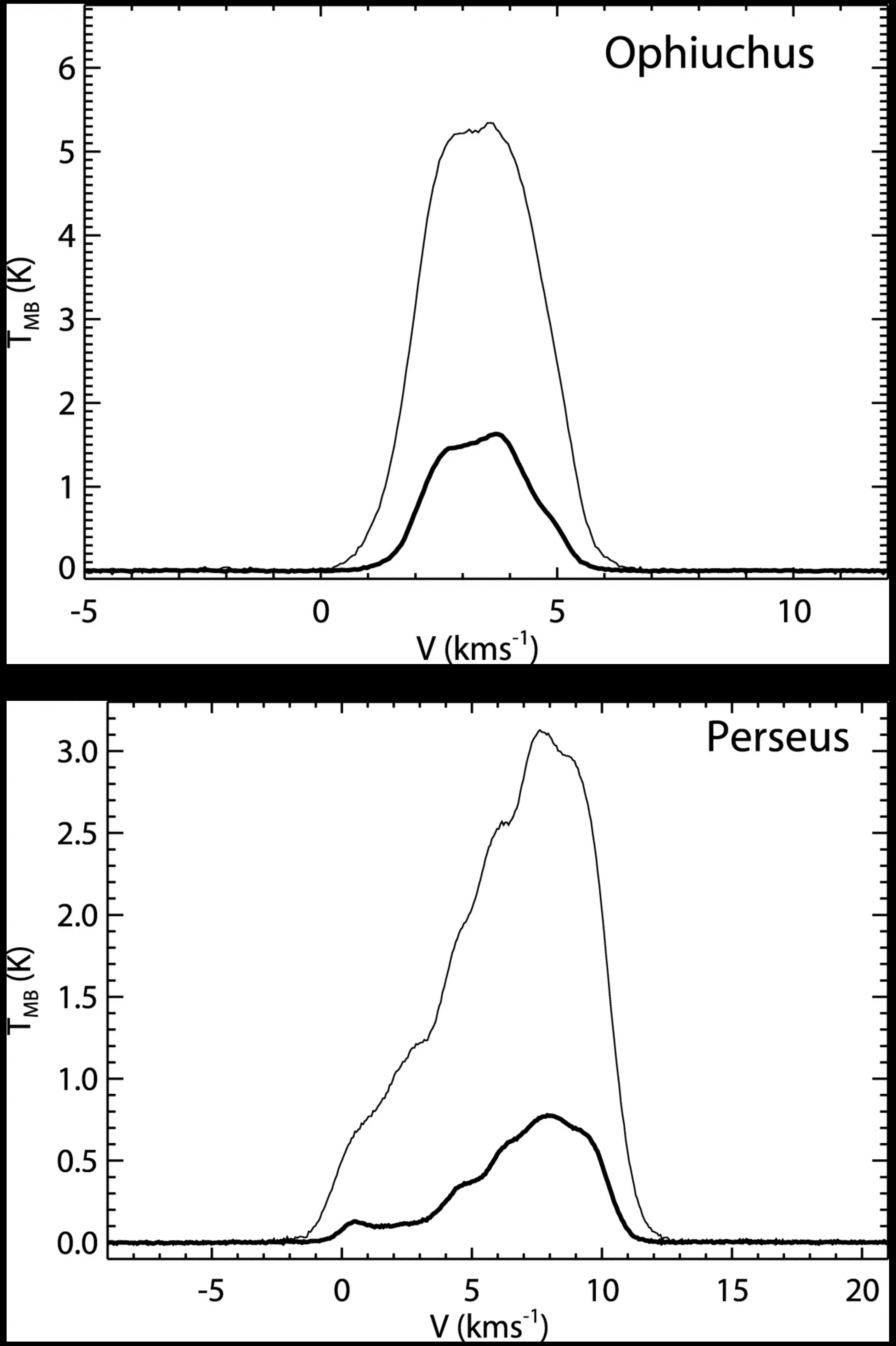
Implications of the radiative luminosity

- Power emitted per atom varies as n for $n \ll n_{\mathrm{crit}}$, becomes flat at larger density
- Thus gas with $n \ll n_{\mathrm{crit}}$ tends to be dim in a given line, while gas all denser gas is equally bright per unit mass
- Since the gas mass tends to decline with density, this usually means emission in a given region is dominated by gas with n close to n_{crit}, so ratios of molecules with different critical densities, e.g., HCN $J = 1 \rightarrow 0$ / CO $J = 1 \rightarrow 0$, can be used as a rough proxy for density

The two-level atom

Velocity inference

- In the frame of an emitting atom, photons have a very narrow frequency distribution whose width is set by the uncertainty principle
- However, the frequency distribution we see is much broader due to thermal and bulk motion, which Doppler shift the emission: $\nu_{\mathrm{obs}} = \nu_{\mathrm{emit}}\,(1 - v/c)$
- Distribution in frequency therefore maps directly to distribution in velocity: the line shape tells us the cloud velocity along the line of sight



Observed velocity distributions in CO (light) and ^{13}CO (dark) $J = 1 \rightarrow 0$ emission in two nearby clouds (Ridge+ 2006)

The two-level atom

Cautions and complications

- Our treatment is extremely simplified, and leaves out many complexities that need to be dealt with in a realistic model:
  - We have implicitly assumed that all emitted photons escape, which is NOT a good assumption, particularly for abundant molecules like CO — in fact, most of the photons emitted in a CO $J = 1 \rightarrow 0$ transition will be absorbed by other CO molecules rather than escaping
  - We have ignored variations in the abundance, which can have significant effects on the observed emission. For example, CO brightness often declines in the very centres of cold clouds, not because the density has a local minimum, but because in very cold regions the CO freezes out of the gas phase into an ice.

Exercise

Compute the critical densities of the following lines: CO $J = 1 \rightarrow 0$, $J = 3 \rightarrow 2$, CO $J = 5 \rightarrow 4$, and HCN $J = 1 \rightarrow 0$ for 10 K gas.

Although these are multi-level atoms, for this purpose you may ignore all transitions except the $J \leftrightarrow J - 1$, i.e., treat the system as two-level

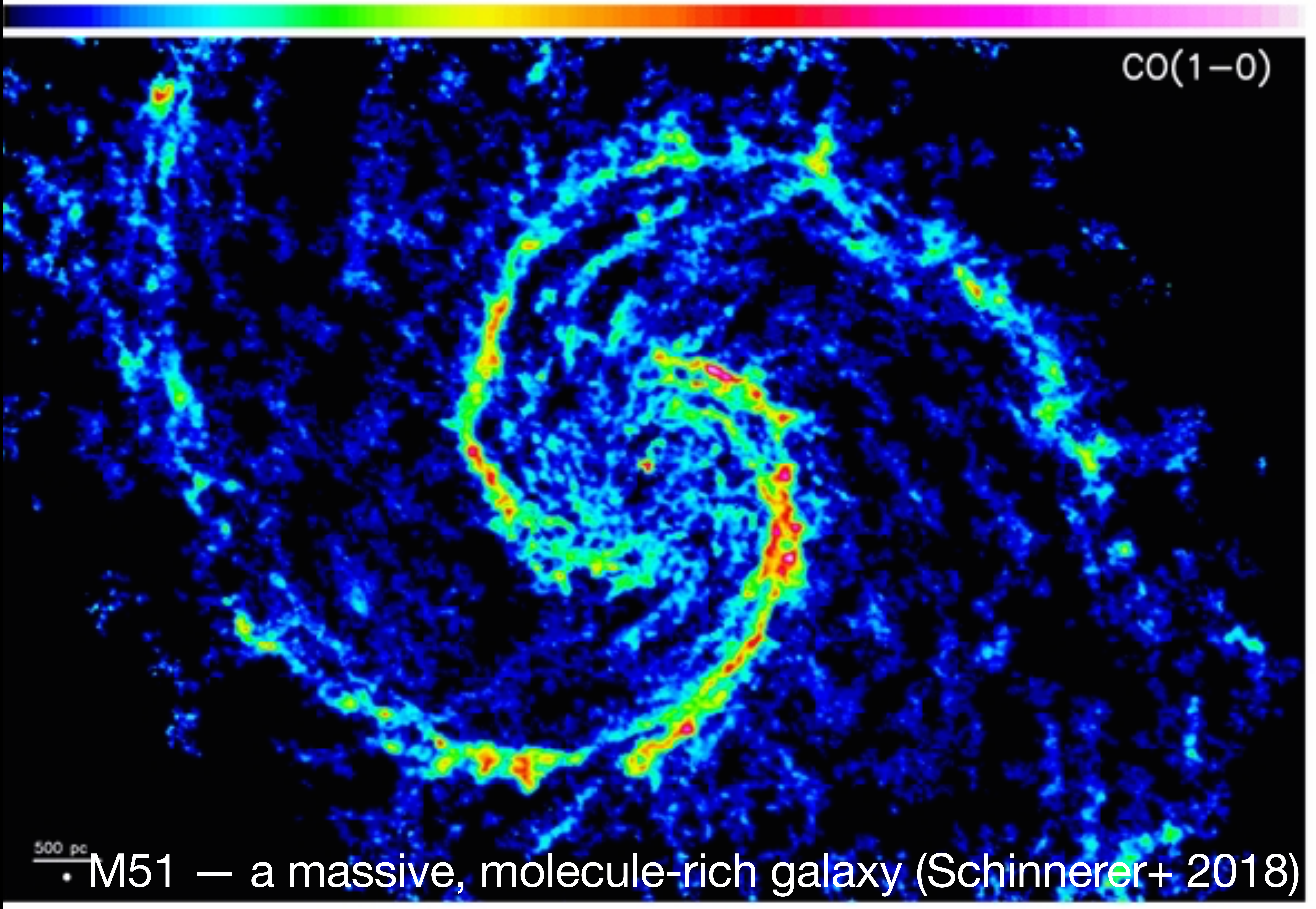
You can look up all the atomic data you need at the Leiden Atomic and Molecular Database, http://www.strw.leidenuniv.nl/~moldata.

Based on what you find, which of these do you expect to trace the lowest and highest density regions?

Observed phenomenology

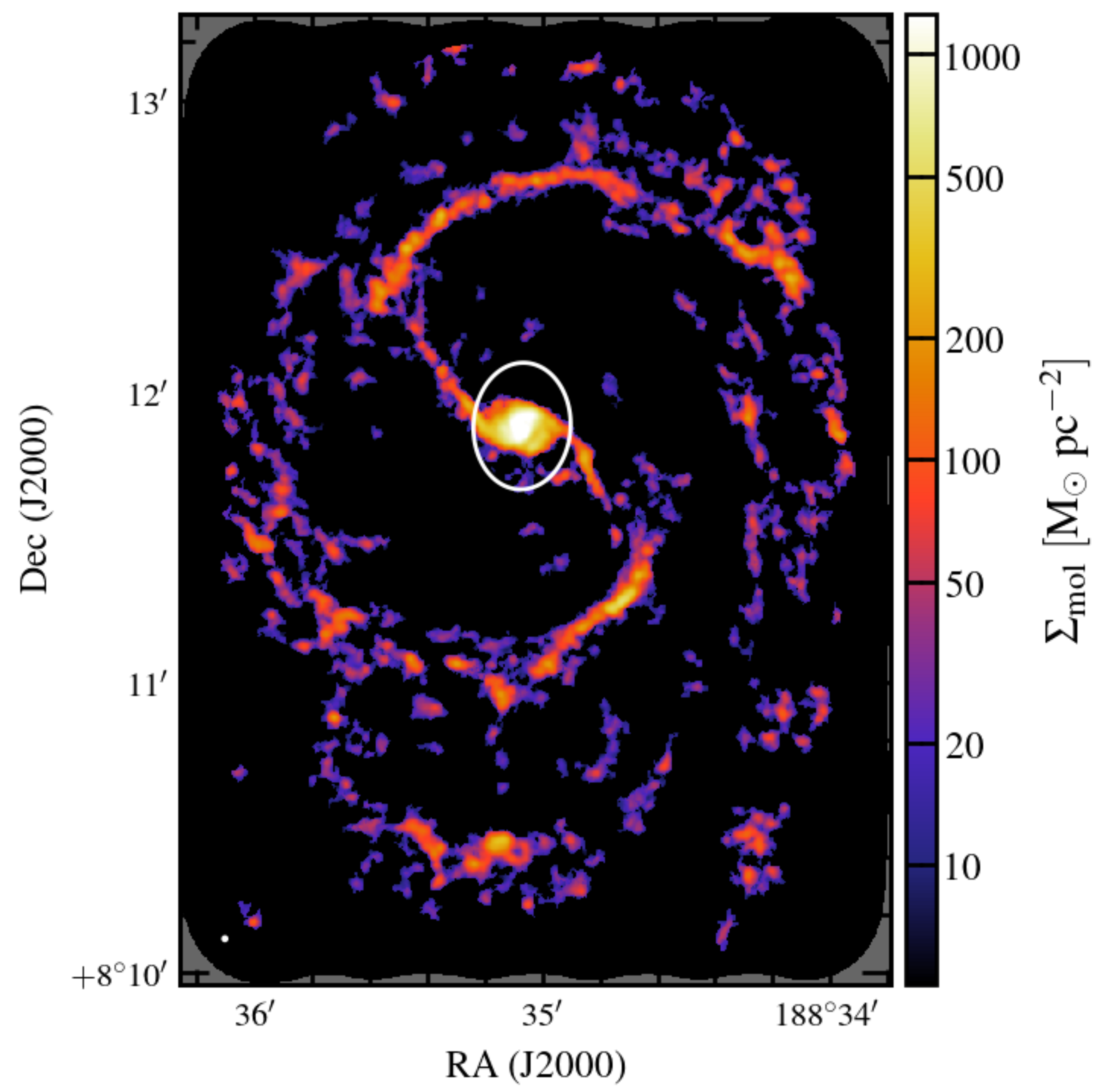
Molecular gas in nearby galaxies

- In the Milky Way and similar spiral galaxies, molecular gas is mostly collected into giant clouds with masses ~10^4 - 10^6 $M_\odot$, densities n ~ 100 - 1000 H cm^{-3}: giant molecular clouds (GMCs)
- Clouds lie close to galactic plane, preferentially but not exclusively in spiral arms, and more concentrated toward the galactic centre than the atomic gas
- By mass GMCs are tens of percent of the total ISM, but occupy a very small volume due to their high densities (mean ISM density n ~ 1 H cm^{-3})
- Conditions can be very different in non-Milky Way-like galaxies: dwarf galaxies have few, small GMCs, massive starbursts have a continuous molecular ISM, with no obvious discrete clouds at all

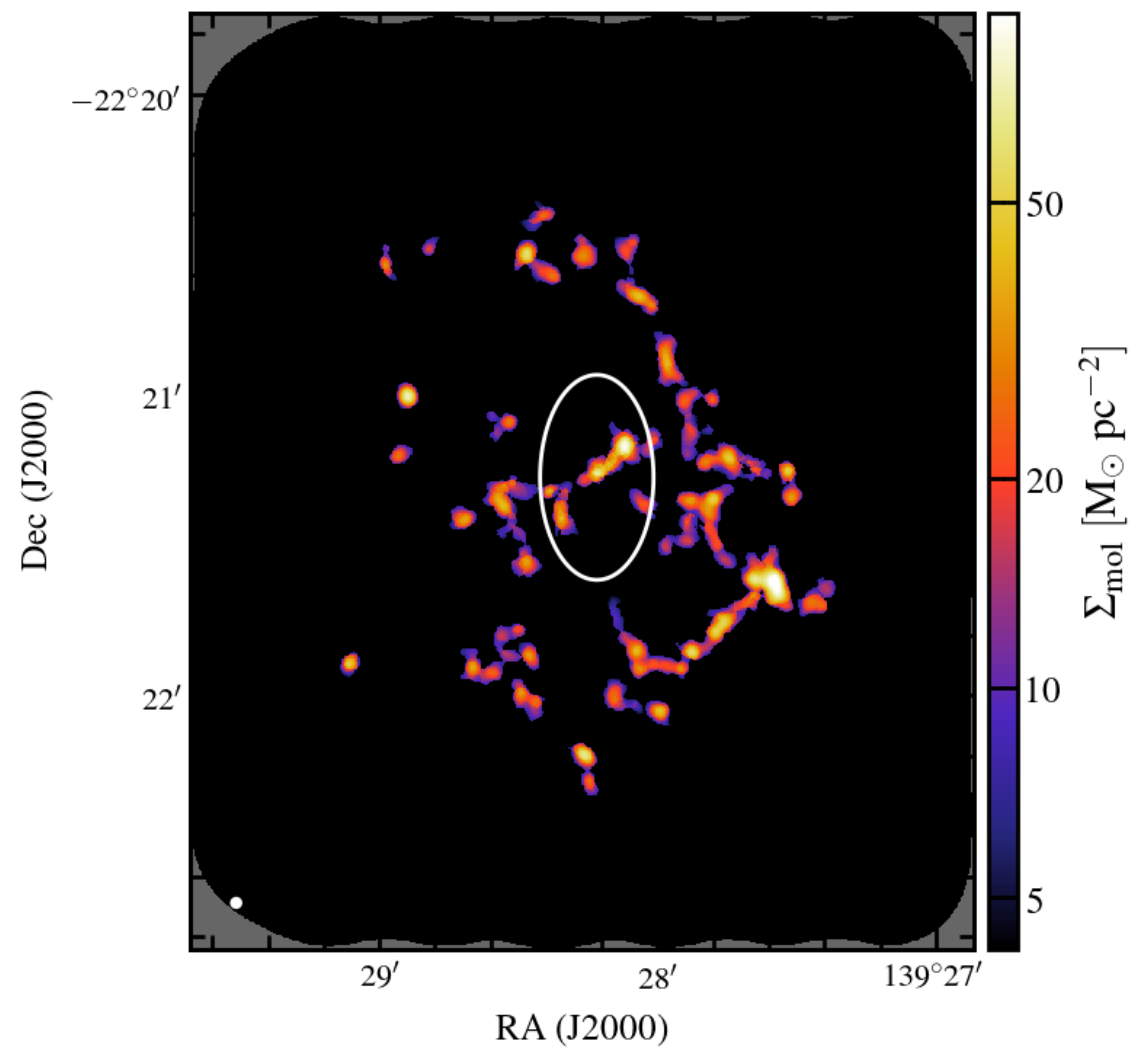


- M51 — a massive, molecule-rich galaxy (Schinnerer+ 2018)

NGC 4535 — a medium mass and size galaxy (Sun+ 2018)



NGC 2835 — a small galaxy with few GMCs (Sun+ 2018)



GMC Internal Structures

- GMCs are not monolithic, smooth objects
- Instead, they have incredibly complex internal density and velocity structures, which we will see later are associated with "turbulence"
- The structures seem to be highly-filamentary — rather than clouds, a better description might be networks of interlaced filaments, intersecting at hubs

The Perseus cloud — left is ^{13}CO integrated over all velocities, right is integrated over particular velocity channels (Sun+ 2006)