# Essentials of
# Radio and (Sub-)Millimeter Astronomy

Fabian Walter (MPIA)

# Lecture 3

# Atomic, Molecular Lines and Dust Emission

slides: Essential Radio Astronomy by NRAO (Condon & Ransom)
+ lectures by Ohio State University Professor Adam Leroy
+ ASTRON's Dr. Jason Hesse

https://www.astron.nl/astrowiki/lib/exe/fetch.php?media=ra_uva:2017:ra_uva_lecture4_2017.pdf

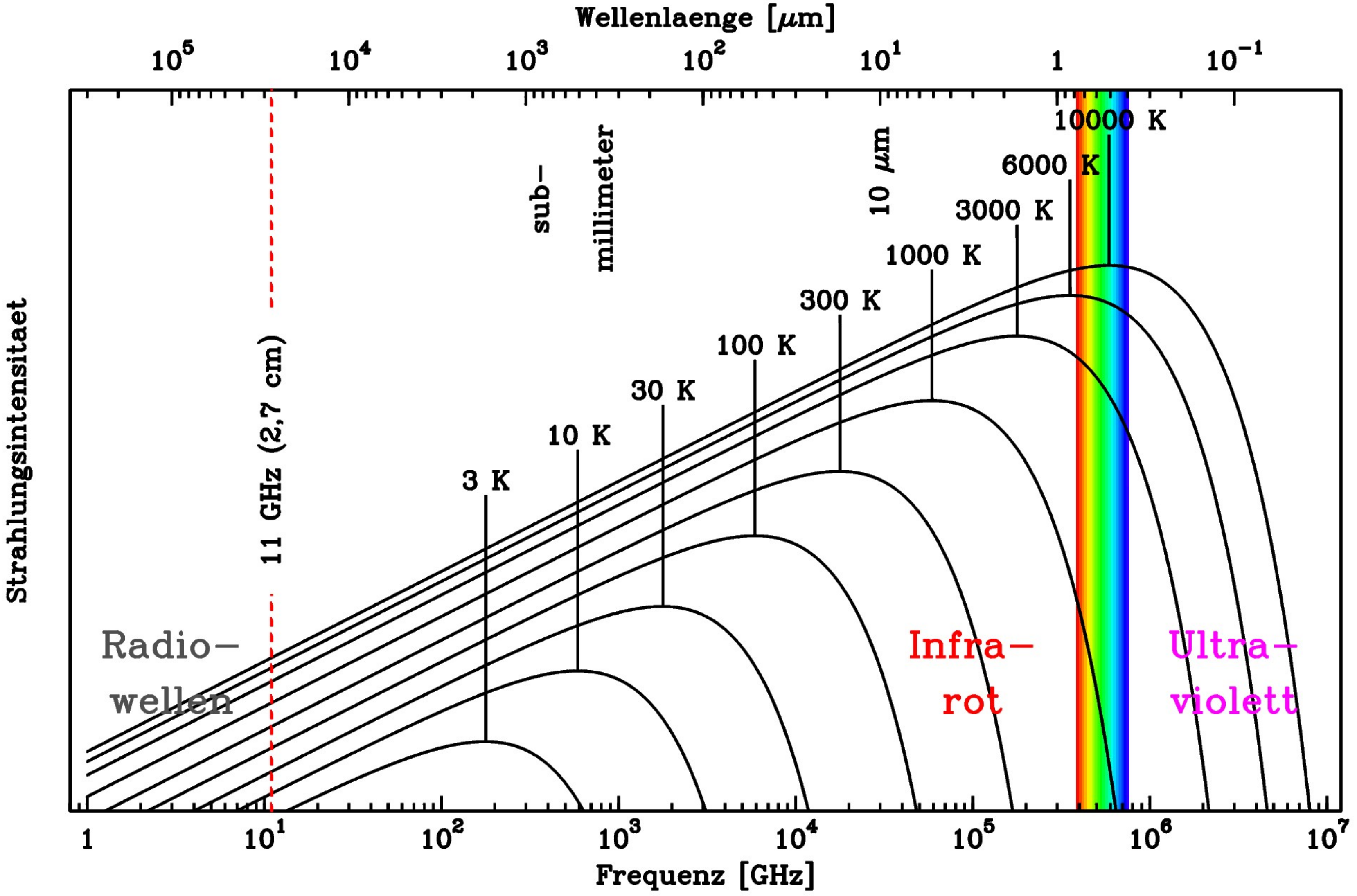
# Heidelberg, Hauptstraße 52 (1859)

IN DIESEM HAUSE HAT
KIRCHHOFF
1859 SEINE MIT BUNSEN BEGRÜNDETE
SPEKTRAL-ANALYSE
AUF SONNE UND GESTIRNE GEWANDT
UND DAMIT DIE CHEMIE DES WELTALLS
ERSCHLOSSEN

“It was in this house where Kirchhoff turned his spectral analysis (developed with Bunsen) towards the sun and the stars - which ultimately led to an understanding of the chemistry of the Universe.”

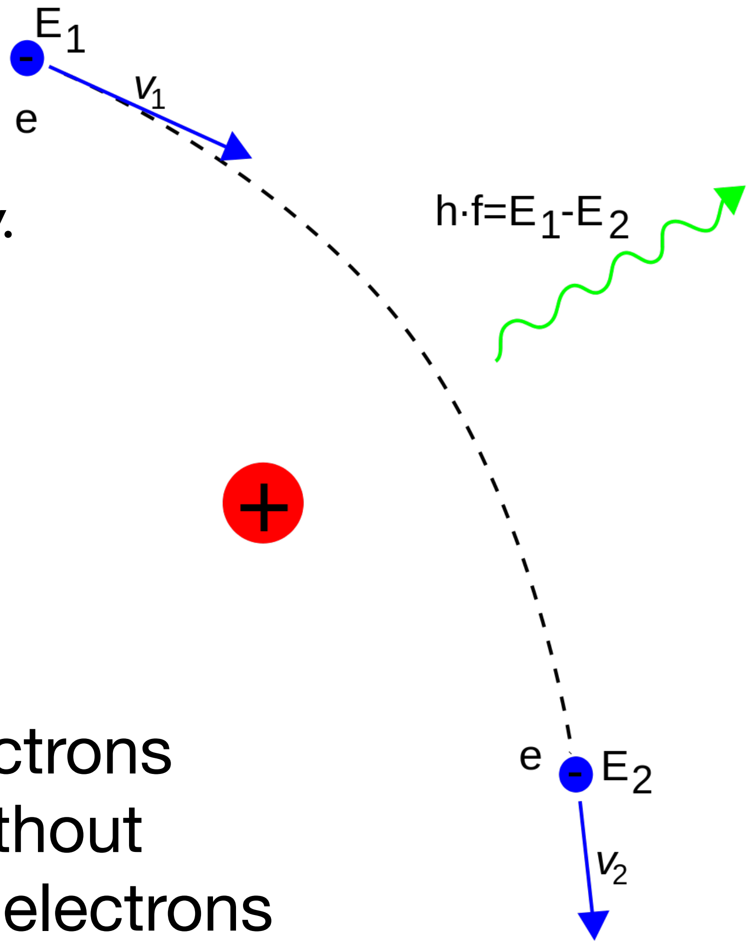
# recap: previous lecture: continuum emission

$$B_\nu = \frac{2h\nu^3}{c^2} \frac{1}{\exp\left(\frac{h\nu}{kT}\right) - 1}$$



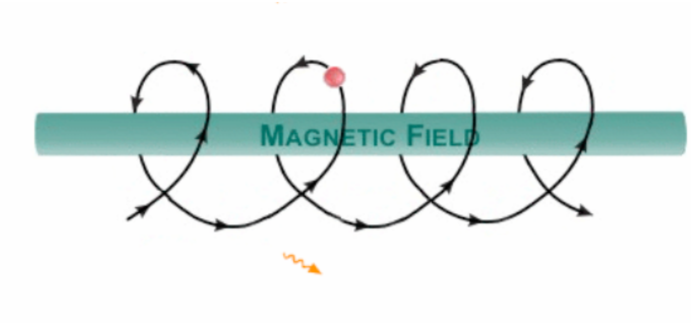
# Free-Free Emission

- Consider an ionized gas (plasma).
- Such a plasma emits radiation continuously.
- Much of visible Universe is a diffuse, hot ($10^4$K) plasma.
- Not in thermal equilibrium. Too diffuse to absorb/emit photons regularly.



produced by free electrons scattering off ions without being captured—the electrons are free before the interaction and remain free afterward

# Synchrotron Emission



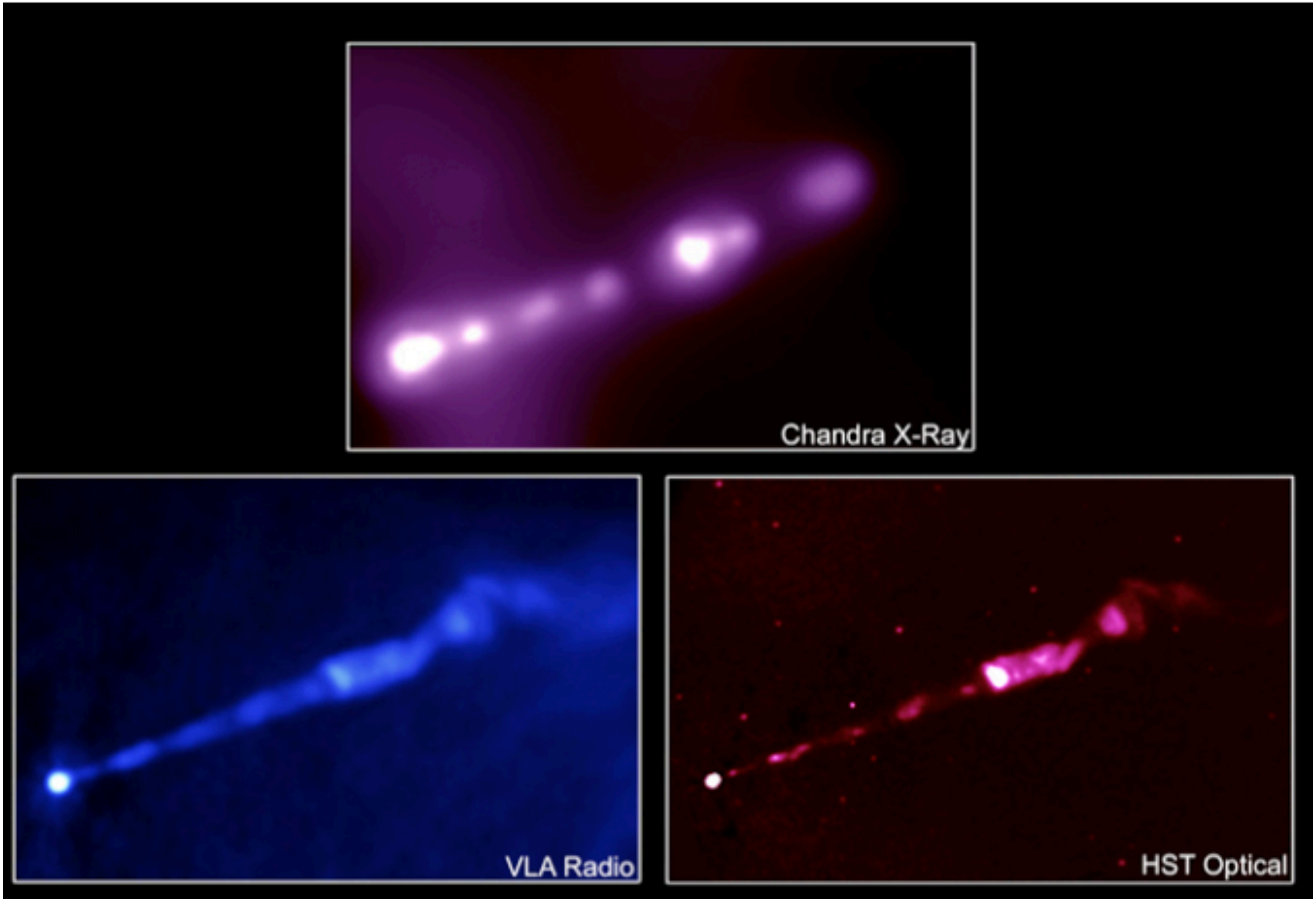
Acceleration of (ultra-) relativistic charged particles (typically electrons) in a magnetic field.

- Particles spiral along magnetic field lines.
- Emission frequency related to velocity of the particle.
- Electrons need to be traveling relativistically to be detectable astronomically

To maintain synchrotron emission, a continuous supply of relativistic electrons is necessary.

- Typical energy sources include supernova remnants, quasars, or other types of active galactic nuclei.

# Virgo-A (M87) all synchrotron!!



# Spectral lines

Spectral lines offer power diagnostics of the composition, physical state, kinematics, and distribution of (mostly interstellar) matter. Some very basic basics:

1. These lines correspond to transitions between discrete energy levels inside atoms or molecules. These energy levels can be electronic, vibrational, or rotational.

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5. Ultimately, the strength of a spectral line tells you about a combination of conditions in the population (excitation due to temperature, density, etc.) and abundance of the species (due to chemistry, shocks, overall matter distribution). Combinations of lines isolate these variables.

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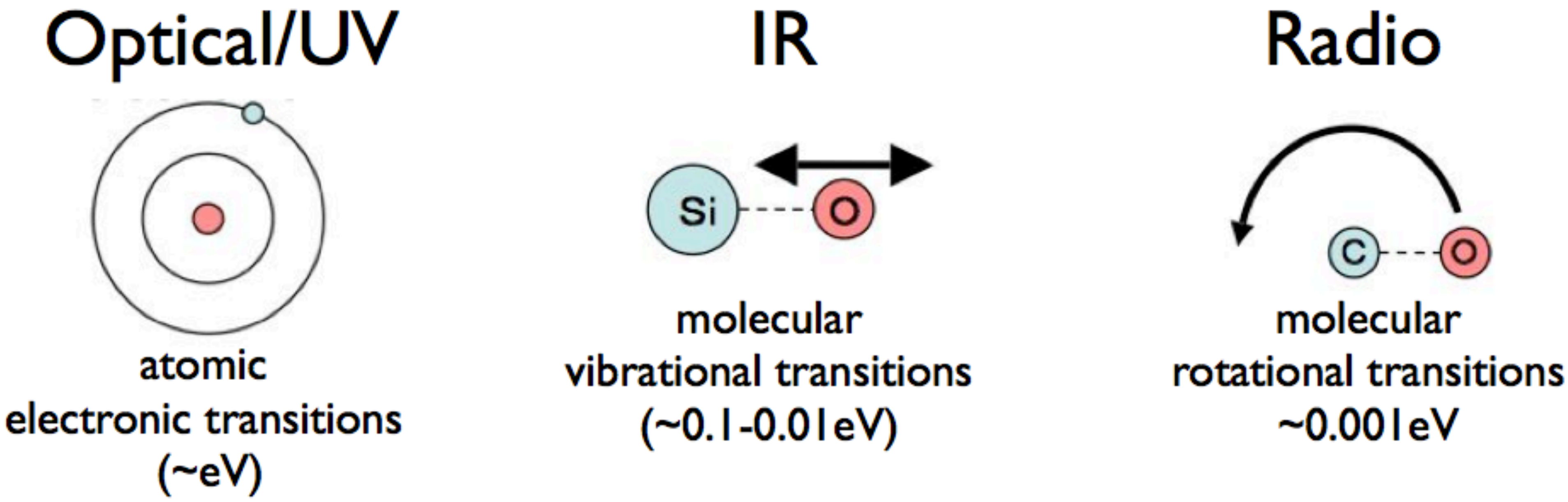
9. Radio lines often have the possibility to mase. Stimulated emission (a quantum mechanical effect where light triggers the emission of more light) plus the possibility of inverted populations (where the emitting population outnumbers the absorbing one) favor the creation of these powerful emitters.

# Radio Spectral Lines

Unlike optical, we are often dealing with molecular rotation transitions in the radio regime



**Optical/UV**

atomic
electronic transitions
(~eV)

**IR**

molecular
vibrational transitions
(~0.1-0.01eV)

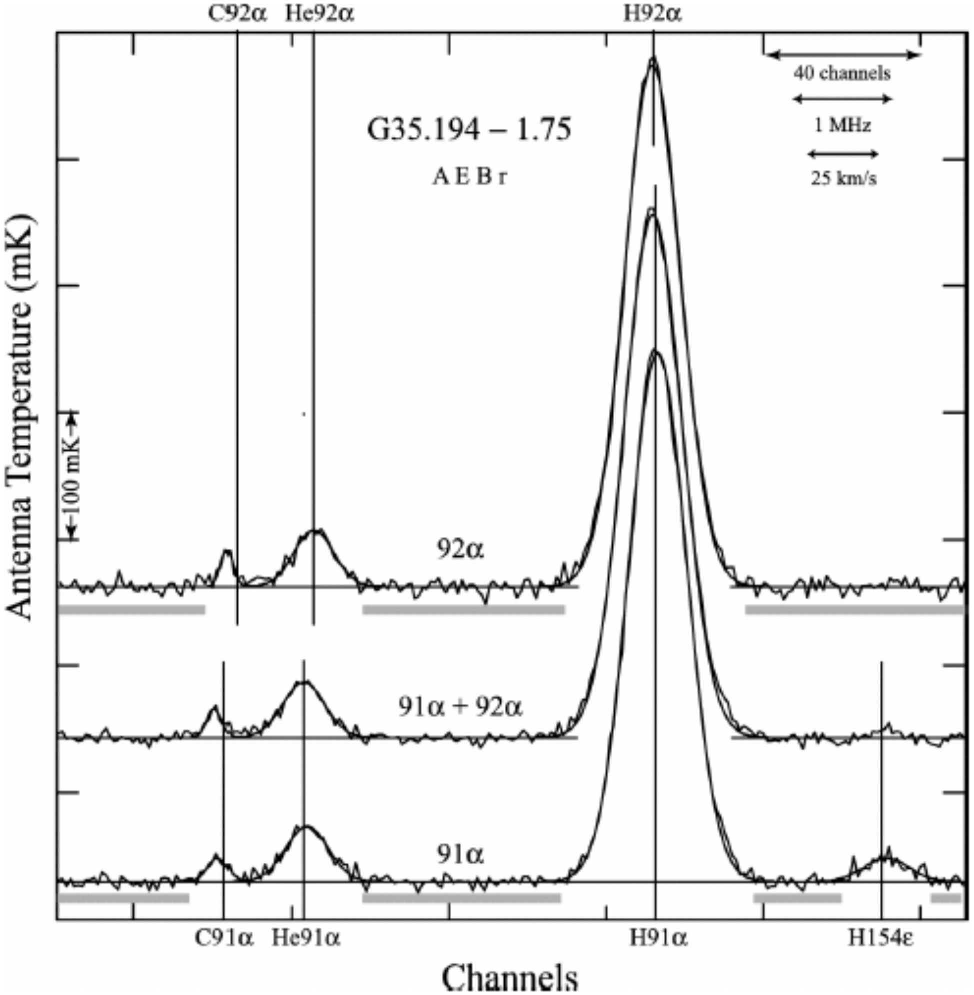
**Radio**

molecular
rotational transitions
~0.001eV

# Doppler Shift

Lines are not spikes at a particular frequency, perhaps with some very narrow width due to quantum mechanical uncertainty (see ERA ~ 0.1 Hz).
In reality, lines look like shown below.

This is due to the doppler shift – the shift infrequency due to motion of the emitter relative to you, the observer.



# Doppler Shift

The shift in frequency is:

$$\nu \approx \nu_0 \left(1 - \frac{v_\mathrm{r}}{c}\right) \qquad v_\mathrm{r} \approx \frac{c(\nu_0 - \nu)}{\nu_0}$$

The width of the line comes from the fact that a population in local thermodynamic equilibrium (LTE) displays a range of velocities that follow a Maxwell-Boltzmann distribution (Maxwellian distribution).

$$\tilde{p}(\vec{v}) = \left(\frac{m}{2\pi k_\mathrm{B} T}\right)^{3/2} \mathrm{e}^{-\frac{m|\vec{v}|^2}{2k_\mathrm{B}T}}$$

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in one dimension (line of sight):

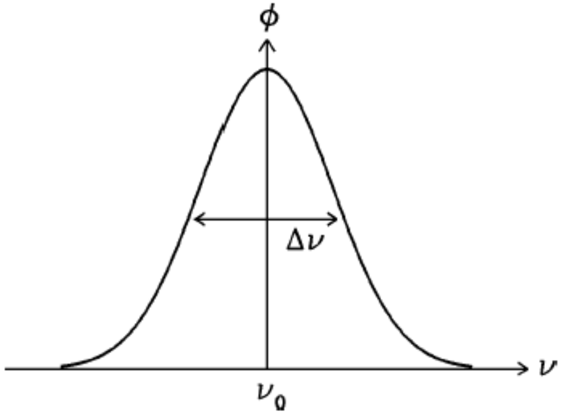
$$f(v_\mathrm{r}) = \left(\frac{M}{2\pi kT}\right)^{1/2} \exp\left(-\frac{Mv_\mathrm{r}^2}{2kT}\right)$$

# Doppler Shift

So temperature creates a line profile with a Gaussian shape and a full width half max:

$$\Delta\nu = \left[\frac{8\ln(2)\,k}{c^2}\right]^{1/2}\left(\frac{T}{M}\right)^{1/2}\nu_0$$

The key dependencies are temperature and mass of the particle.



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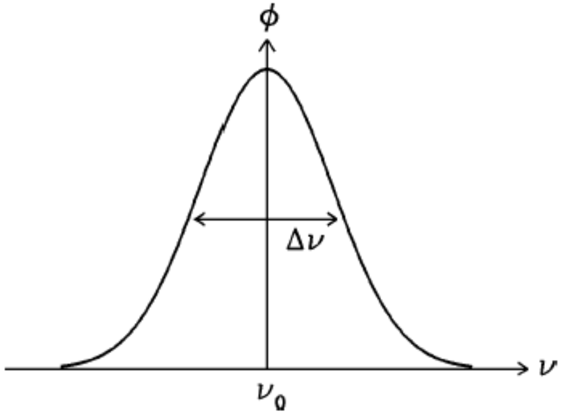


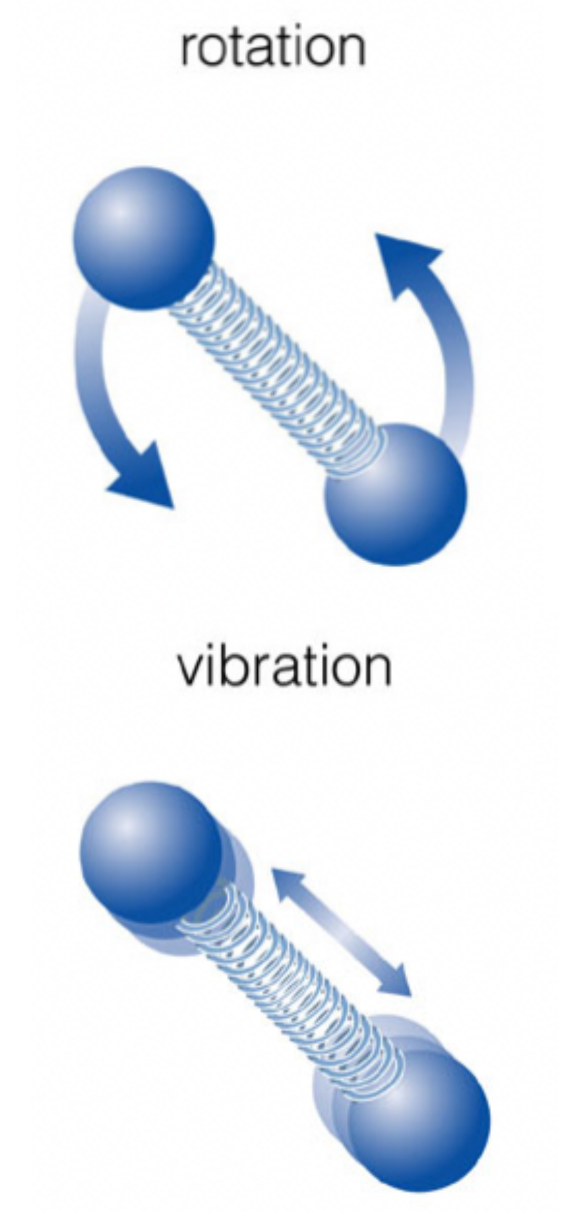
Note that the other implication is that for a fixed strength line (i.e., only so many particles in the upper state) you are spreading the flux out across a wider frequency range. The peak of the normalized line profile is:

$$\phi(\nu_0) = \left(\frac{\ln 2}{\pi}\right)^{1/2}\frac{2}{\Delta\nu}$$

# Molecular lines

- More "complicated" than for atomic lines.
- Radio line emission results from vibrational and rotational transitions.
- About half the mass of the ISM in molecular hydrogen ($H_2$).
- About 1% of the cloud mass is dust, which causes extinction
- Cloud temperatures typically 10-20K, with densities $n(H_2) \sim 10^4 cm^{-3}$.

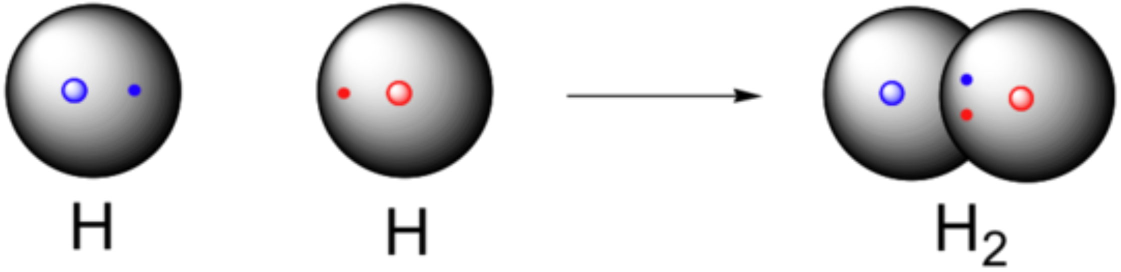
NOTE: typical laboratory vacuum n ~ 10^7 cm$^{-3}$



# Tracing molecular hydrogen

- Molecular hydrogen ($H_2$) is hard to detect because it has no dipole moment.
- CO (carbon monoxide) is the second most abundant molecule and can be used as a tracer for $H_2$.

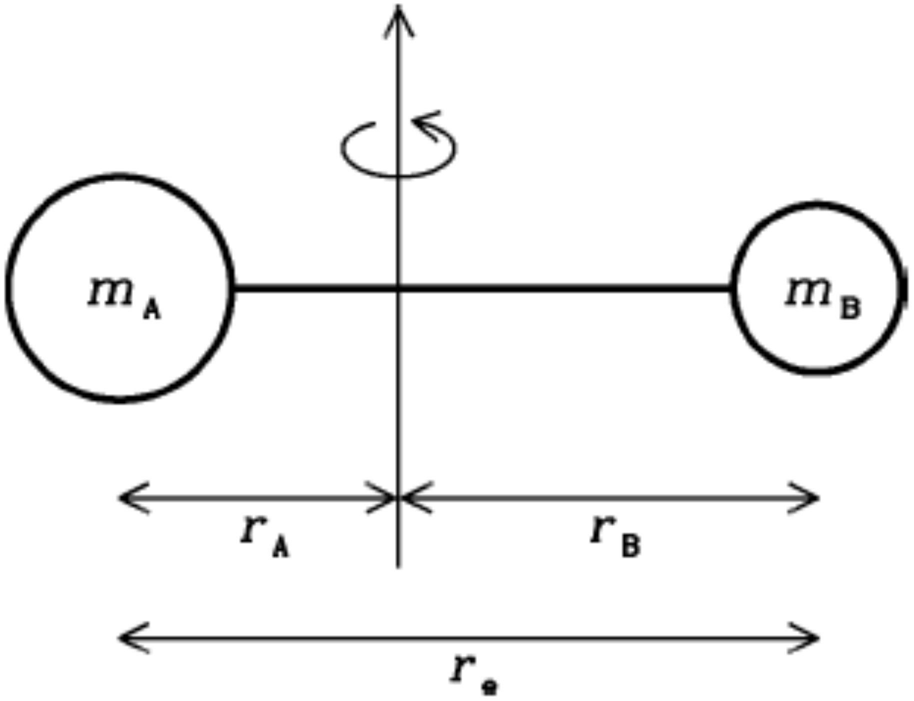
- The ratio between CO luminosity and $H_2$ mass is ~$10^5$.

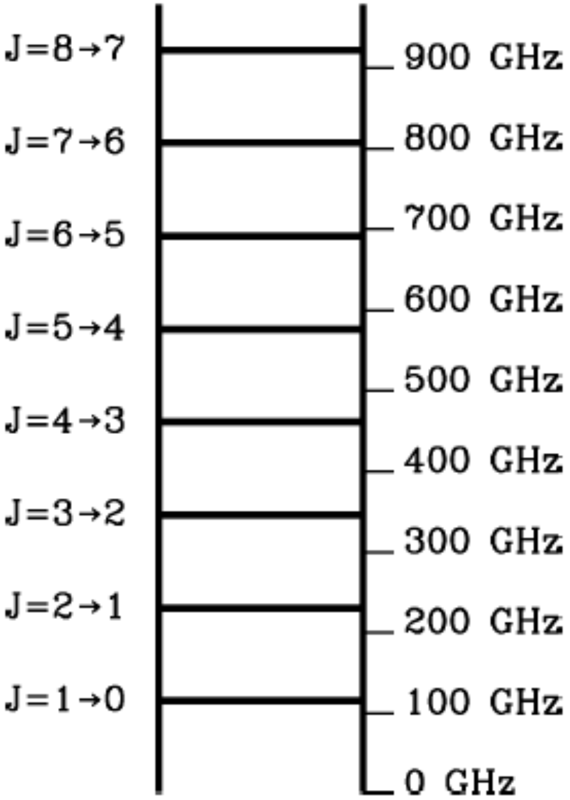


# Molecular lines

Molecules have discrete energy levels. In the long wavelength regime many of these are rotational transitions. The idea in a nutshell, is that molecules have certain energy associated with their rotation.

Their angular momentum is quantized and there are discrete steps between levels with only certain transitions allowed. This leads to a characteristic ladder of rotational transitions for molecules.



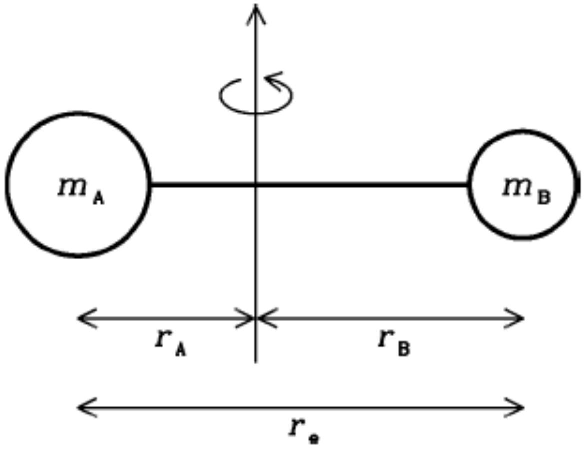


# Molecular lines

The angular momentum *L* is moment of inertia times *I* angular frequency.

$$L = I\omega$$

Moment of intertia *I* is mass times radius^2 from the center of mass. Considering only the two nuclei as holding most of the mass.



$$I = (m_A r_A^2 + m_B r_B^2)$$
$$L = (m_A r_A^2 + m_B r_B^2)\omega.$$

$$r_e = r_A + r_B \quad \text{and} \quad r_A m_A = r_B m_B$$

$$L = \left(\frac{m_A m_B}{m_A + m_B}\right) r_e^2 \omega$$

$$L = m r_e^2 \omega$$

with reduced mass $m \equiv \left(\frac{m_A m_B}{m_A + m_B}\right)$

# Molecular lines

The energy associated with a specific rotation level is:

$$E_{\rm rot} = \frac{I\omega^2}{2} = \frac{L^2}{2I}$$

Quantization of angular momentum to integer multiples of h implies that rotational energy is also quantised. Corresponding energy eigenvalues of the Schroedinger equation are:

$$E_{\rm rot} = \left(\frac{\hbar^2}{2I}\right) J(J+1)\,, \qquad J = 0,\ 1,\ 2, \ldots$$

selection rules: $\Delta J = \pm 1$

allowed transitions: $\Delta E_{\rm rot} = [J(J+1) - (J-1)J]\frac{\hbar^2}{2I} = \frac{\hbar^2 J}{I}$

# Molecular lines

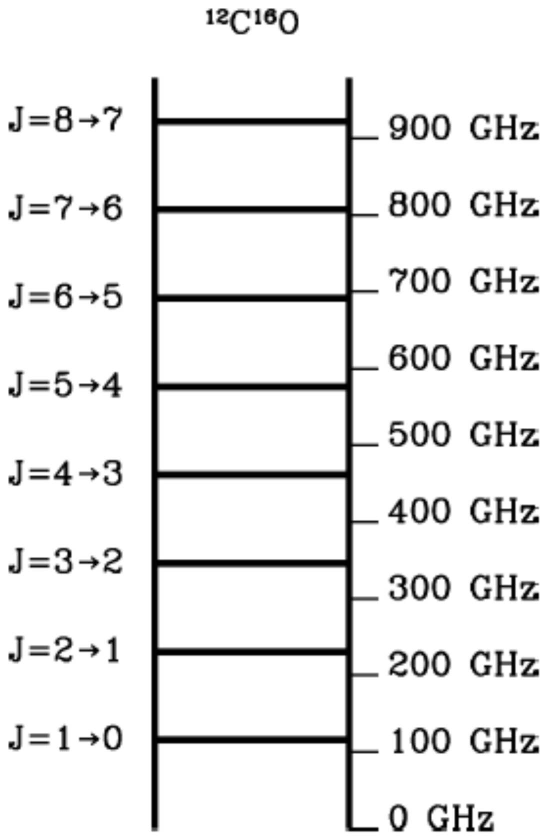
from previous slide:

$$\Delta E_{\rm rot} = [J(J+1) - (J-1)J]\frac{\hbar^2}{2I} = \frac{\hbar^2 J}{I}$$

$$\nu = \frac{\Delta E_{\rm rot}}{h} = \frac{\hbar J}{2\pi I} , \qquad J = 1,\ 2,\ldots ,$$

$$\nu = \frac{hJ}{4\pi^2 m r_{\rm e}^2} , \qquad J = 1,\ 2, \ldots$$

*m*: reduced mass



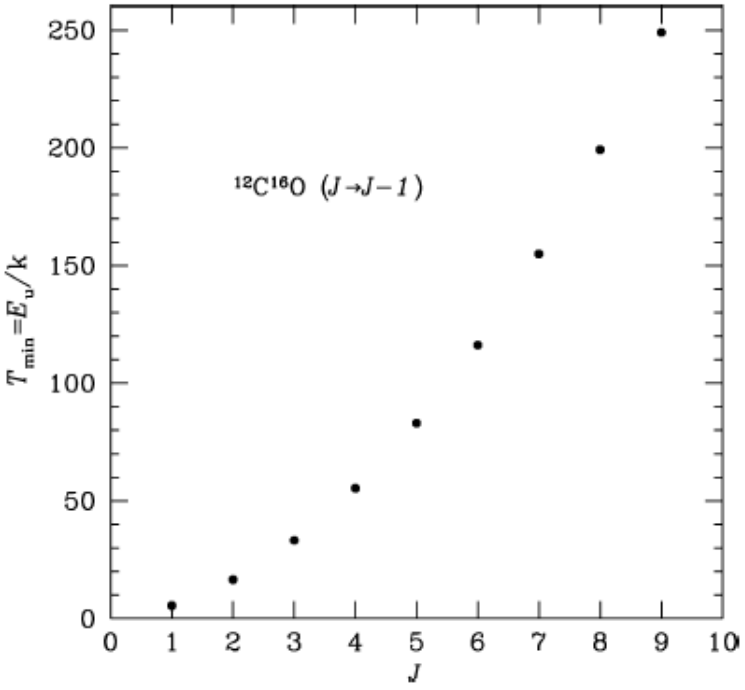
The implications here are that the line frequencies depend on the moment of inertia and are spaced approximately linearly from the lowest transition on up.

Molecules with a higher moment of inertia will have lower basic frequencies (e.g., CS 1-0 has about half the frequency of CO 1-0). [atomic number S vs. O, 16 vs. 8]

# Molecular excitation

Line emission is stimulated or spontaneously emitted from molecules in an excited state. To get a significant number of molecules in an excited state from the Boltzmann equation you need an energy ~kT to roughly equal or exceed the energy of the upper state, $E_{rot}$:

$$T_{\text{min}} \sim \frac{E_{\text{rot}}}{k}$$



Then for a given rotational transition T required to excite transition :

$$T_{\text{min}} \approx \frac{\nu h(J+1)}{2k}$$

For CO the $T_{min}$ looks something like this.

For example, the CO 2-1 transition has $T_{min}$ ~16.6 K.

# Importance of CO

## CO as a molecule with special importance for astronomy:

- CO lines are the most important cooling lines for the regime below 100 Kelvin (cooling of the molecular material in order to facilitate gravitational collapse … eventually)

- relatively light, di-atomic, simple rotational spectrum

- low dipole moment (-0.12 Debye) → easily excitable also in thinner molecular gas

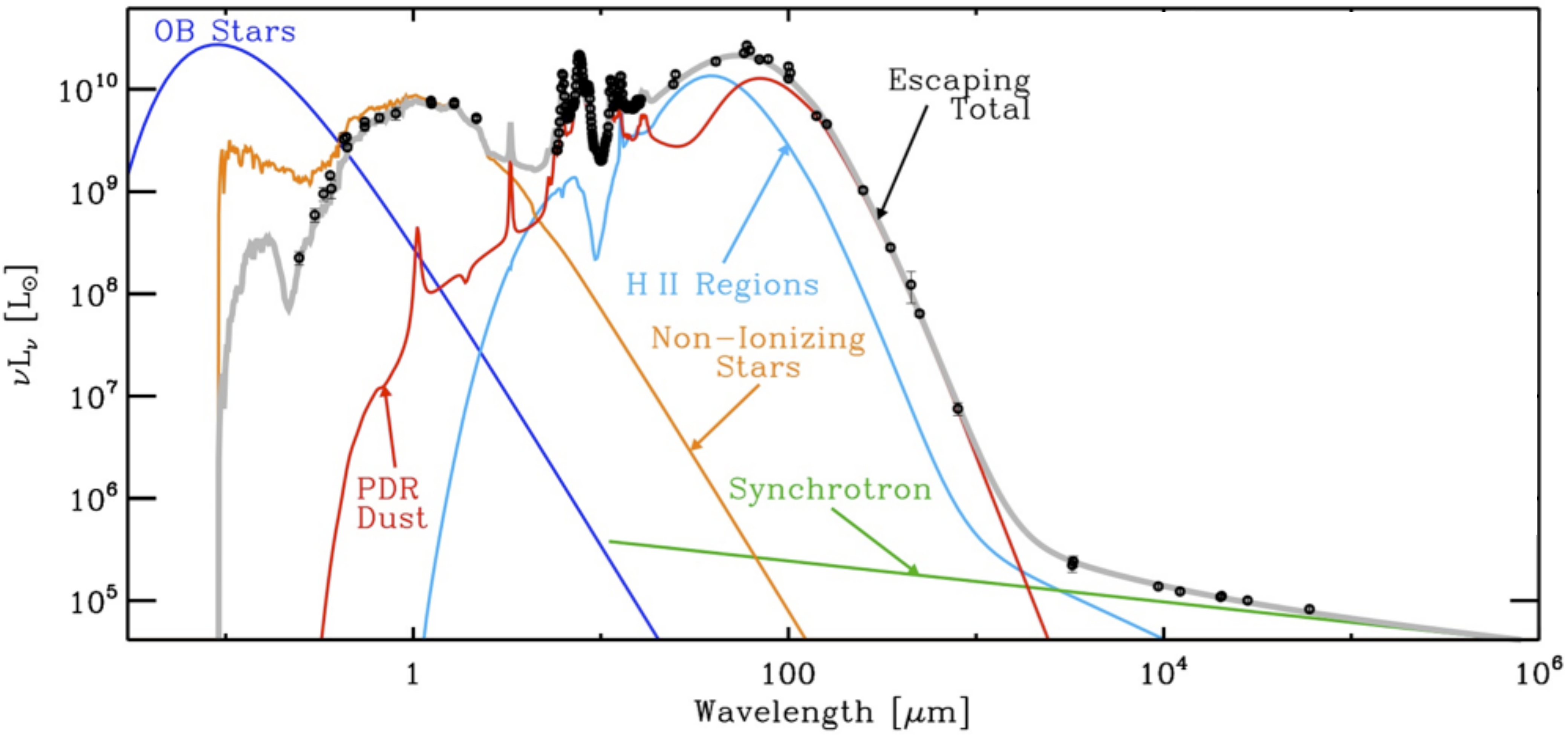
- observable in the millimeter regime

- CO is the most abundant molecule after $H_2$ itself (abundance ~ $10^{-4}$)

- Since the bulk of the cold $H_2$ molecular gas in molecular clouds is not directly accessible (no permanent dipole moment), CO is the best (?) proxy for the total amount of molecular gas in a cloud.

# example SED: M82

models from Galliano et al.



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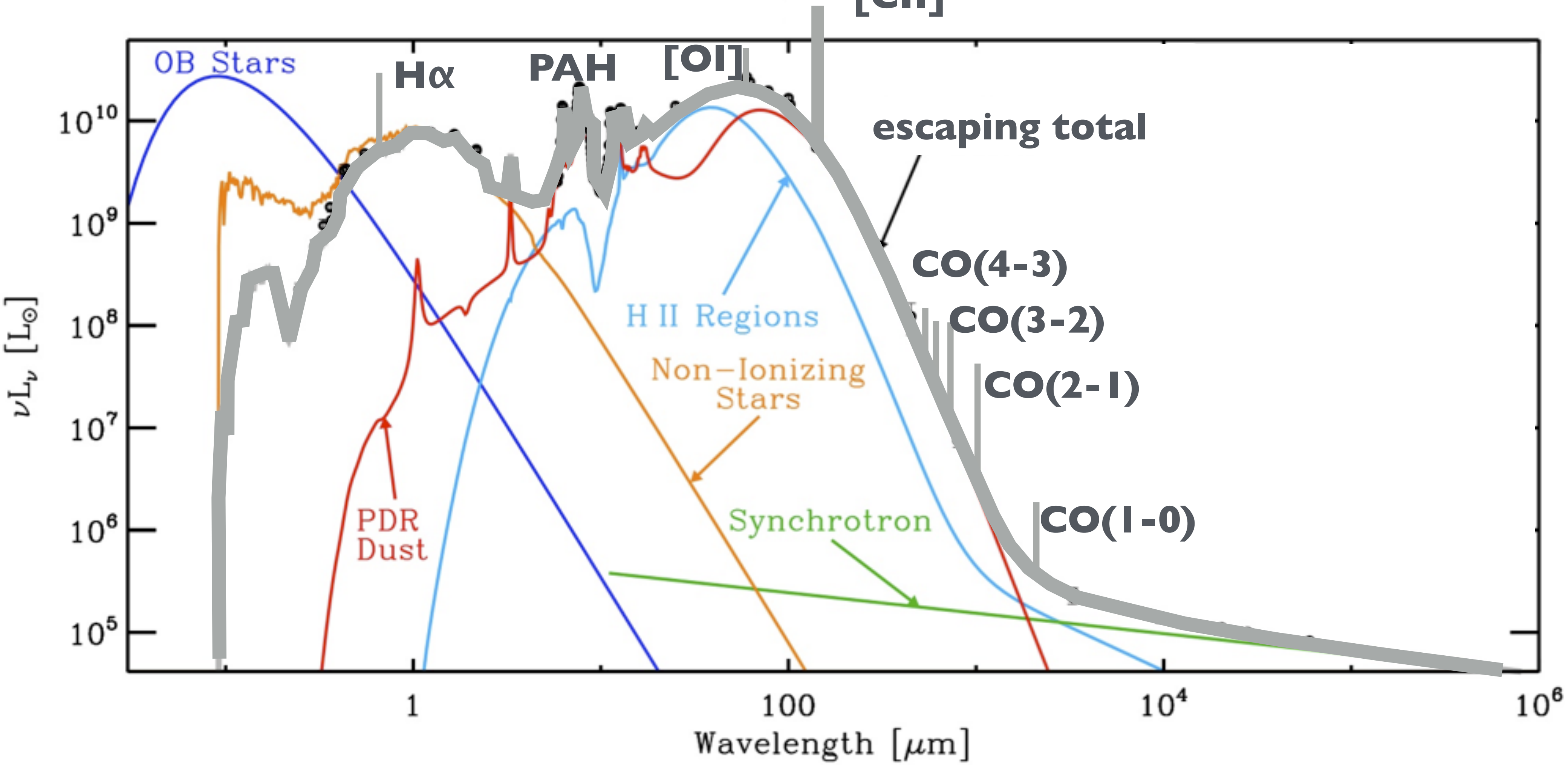

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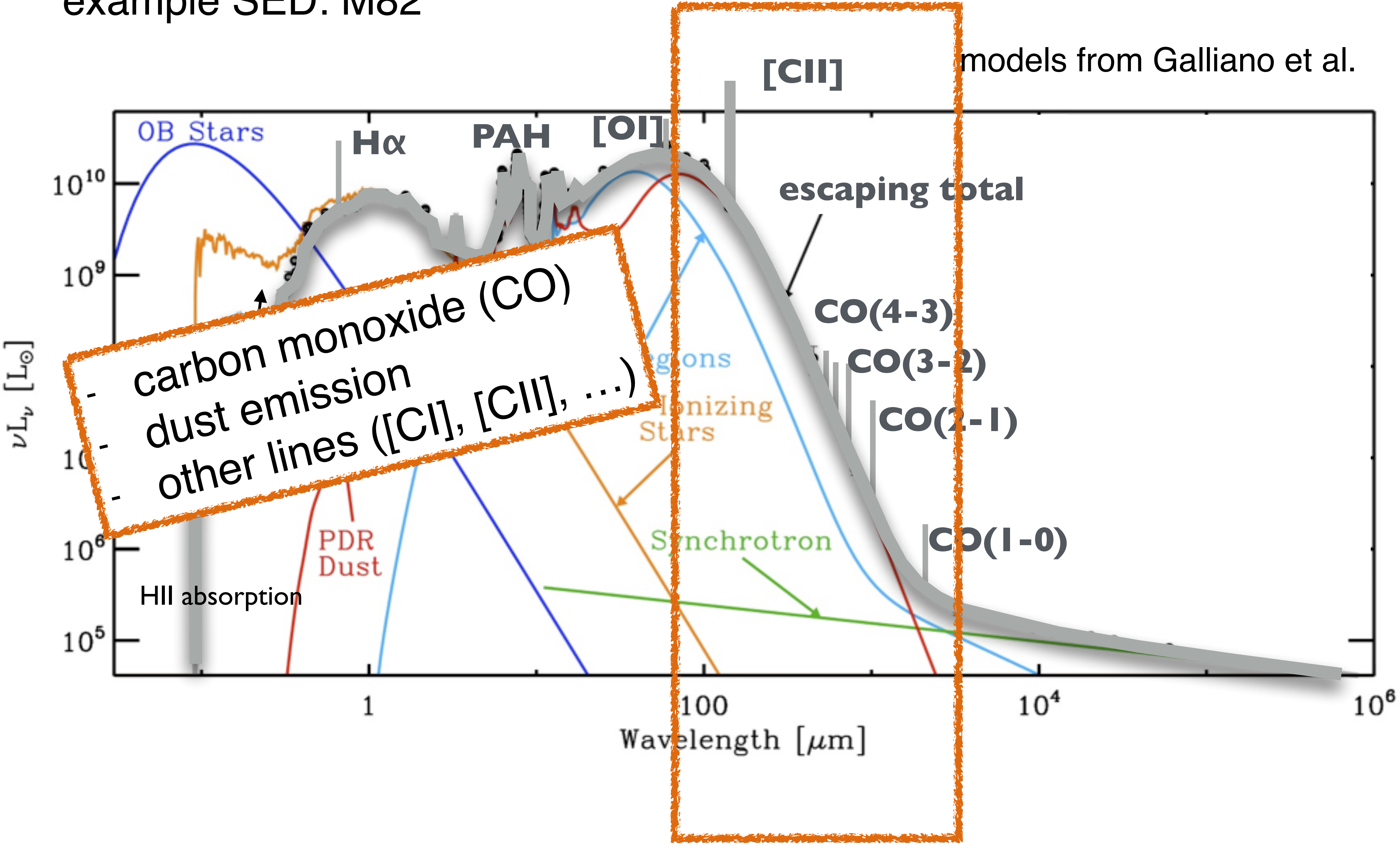
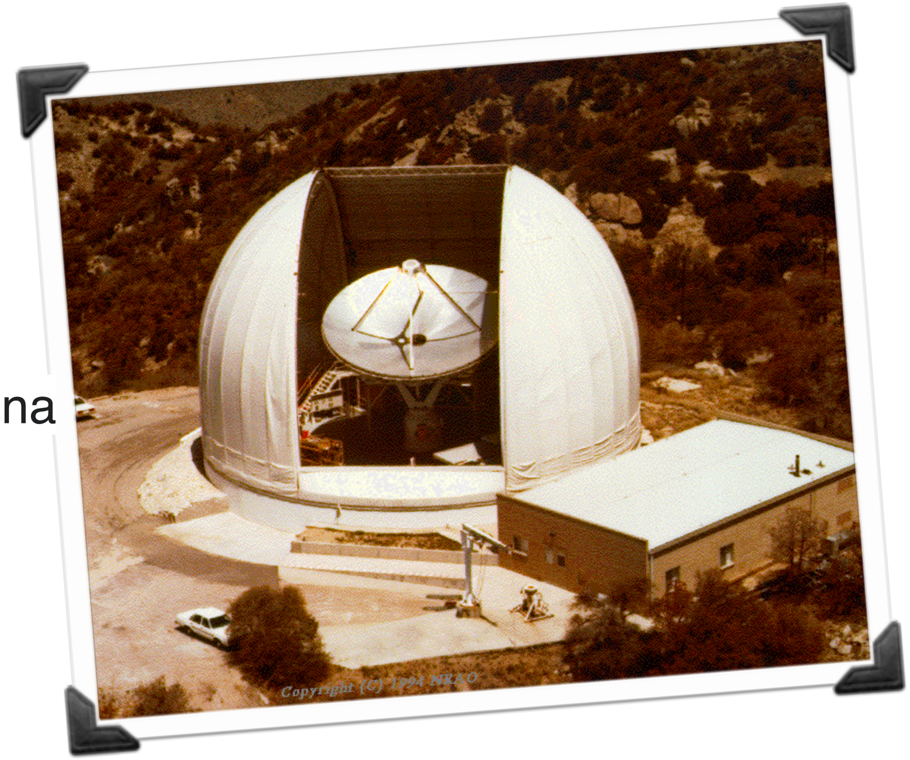


models from Galliano et al.

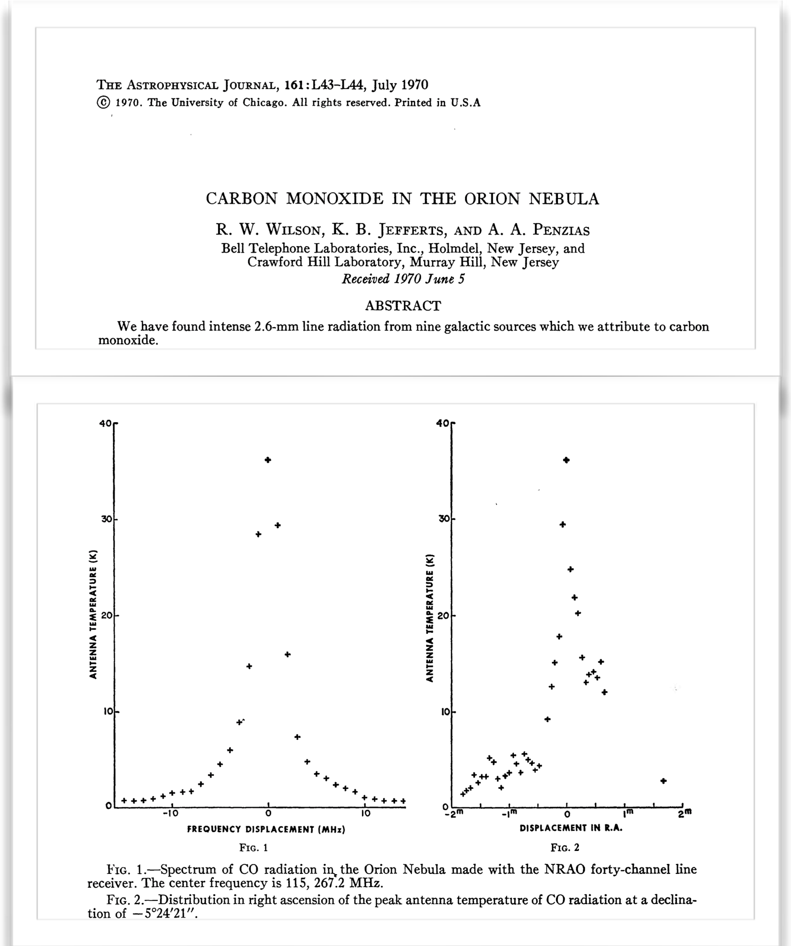
- carbon monoxide (CO)
- dust emission
- other lines ([CI], [CII], …)

# millimeter detection



NRAO
12m antenna

1970: first detection of CO



The Astrophysical Journal, 161:L43–L44, July 1970

CARBON MONOXIDE IN THE ORION NEBULA

R. W. Wilson, K. B. Jefferts, and A. A. Penzias
Bell Telephone Laboratories, Inc., Holmdel, New Jersey, and
Crawford Hill Laboratory, Murray Hill, New Jersey
*Received 1970 June 5*

ABSTRACT

We have found intense 2.6-mm line radiation from nine galactic sources which we attribute to carbon monoxide.

Fig. 1

Fig. 2

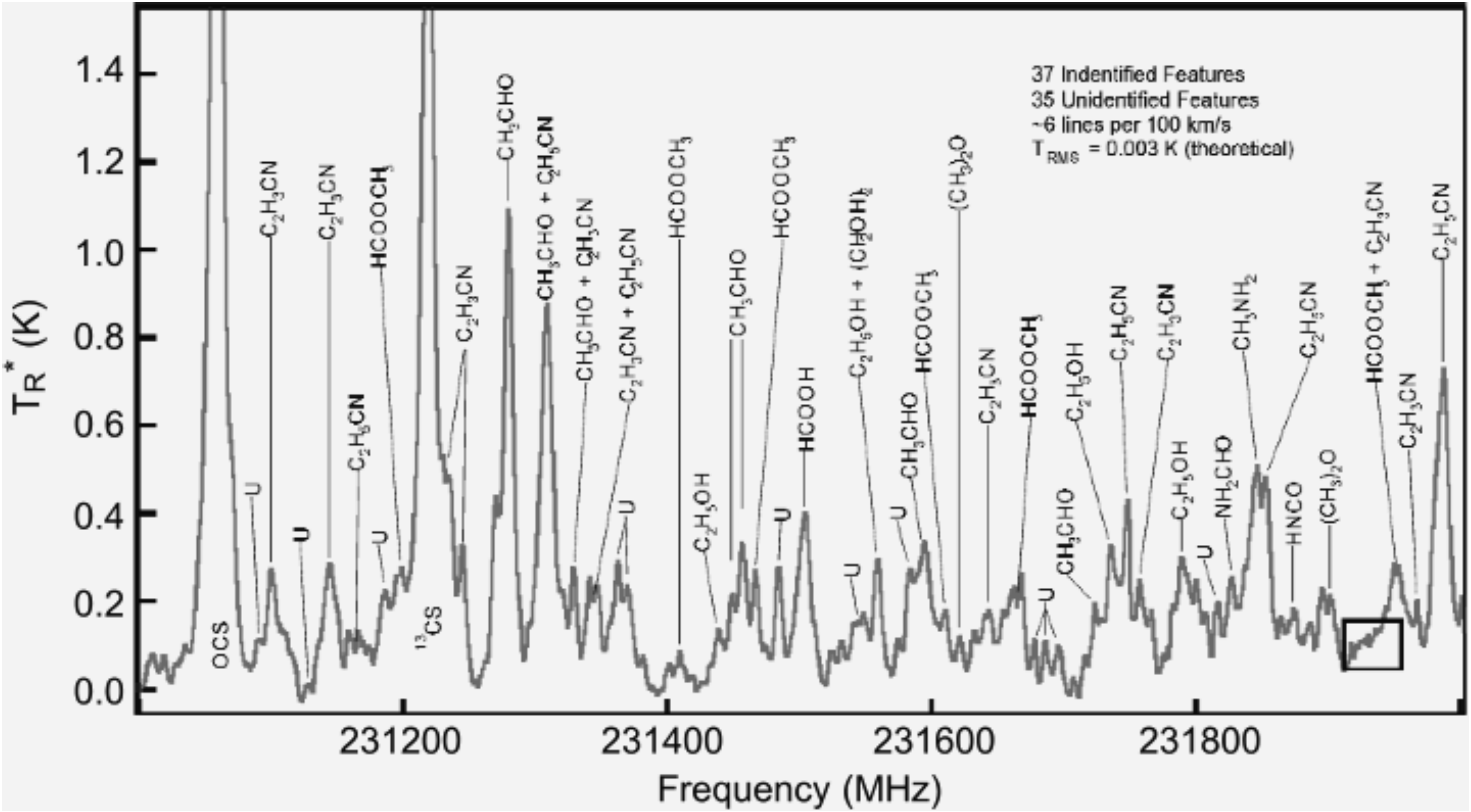
Fig. 1.—Spectrum of CO radiation in the Orion Nebula made with the NRAO forty-channel line receiver. The center frequency is 115, 267.2 MHz.

Fig. 2.—Distribution in right ascension of the peak antenna temperature of CO radiation at a declination of −5°24′21″.

Caltech OVRO
interferometer

# Other molecules

Spectrum towards molecular cloud at the Galactic center.



| 2 atoms | 3 atoms | 4 atoms | 5 atoms | 6 atoms | 7 atoms | 8 atoms | 9 atoms | 10 atoms | 11 atoms | 12 atoms | >12 atoms |
|---|---|---|---|---|---|---|---|---|---|---|---|
| H2 | C3 * | c-C3H | C5 * | C5H | C6H | CH3C3N | CH3C4H | CH3C5N | HC9N | c-C6H6 * | HC11N |
| AlF | C2H | l-C3H | C4H | l-H2C4 | CH2CHCN | HC(O)OCH3 | CH3CH2CN | (CH3)2CO | CH3C6H | C2H5OCH3 ? | C60 * |
| AlCl | C2O | C3N | C4Si | C2H4* | CH3C2H | CH3COOH | (CH3)2O | (CH2OH)2 | C2H5OCHO | n-C3H7CN | C70 * |
| C2** | C2S | C3O | l-C3H2 | CH3CN | HC5N | C7H | CH3CH2OH | CH3CH2CHO | | | |
| CH | CH2 | C3S | c-C3H2 | CH3NC | CH3CHO | C6H2 | HC7N | | | | |
| CH+ | HCN | C2H2* | H2CCN | CH3OH | CH3NH2 | CH2OHCHO | C8H | | | | |
| CN | HCO | NH3 | CH4 * | CH3SH | c-C2H4O | l-HC6H * | CH3C(O)NH2 | | | | |
| CO | HCO+ | HCCN | HC3N | HC3NH+ | H2CCHOH | CH2CHCHO (?) | C8H– | | | | |
| CO+ | HCS+ | HCNH+ | HC2NC | HC2CHO | C6H– | CH2CCHCN | C3H6 | | | | |
| CP | HOC+ | HNCO | HCOOH | NH2CHO | | H2NCH2CN | | | | | |
| SiC | H2O | HNCS | H2CNH | C5N | | | | | | | |
| HCl | H2S | HOCO+ | H2C2O | l-HC4H * | | | | | | | |
| KCl | HNC | H2CO | H2NCN | l-HC4N | | | | | | | |
| NH | HNO | H2CN | HNC3 | c-H2C3O | | | | | | | |
| NO | MgCN | H2CS | SiH4 * | H2CCNH (?) | | | | | | | |
| NS | MgNC | H3O+ | H2COH+ | C5N– | | | | | | | |
| NaCl | N2H+ | c-SiC3 | C4H– | | | | | | | | |
| OH | N2O | CH3 * | HC(O)CN | | | | | | | | |
| PN | NaCN | C3N– | HNCNH | | | | | | | | |
| SO | OCS | PH3 ? | CH3O | | | | | | | | |
| SO+ | SO2 | HCNO | | | | | | | | | |
| SiN | c-SiC2 | HOCN | | | | | | | | | |
| SiO | CO2 * | HSCN | | | | | | | | | |
| SiS | NH2 | H2O2 | | | | | | | | | |
| CS | H3+ * | C3H+ | | | | | | | | | |
| HF | H2D+ | | | | | | | | | | |
| HD | SiCN | | | | | | | | | | |
| FeO ? | AlNC | | | | | | | | | | |
| O2 | SiNC | | | | | | | | | | |
| CF+ | HCP | | | | | | | | | | |
| SiH ? | CCP | | | | | | | | | | |
| PO | AlOH | | | | | | | | | | |
| AlO | H2O+ | | | | | | | | | | |
| OH+ | H2Cl+ | | | | | | | | | | |
| CN– | KCN | | | | | | | | | | |
| SH+ | HO2 | | | | | | | | | | |
| SH | FeCN | | | | | | | | | | |
| HCl+ | | | | | | | | | | | |

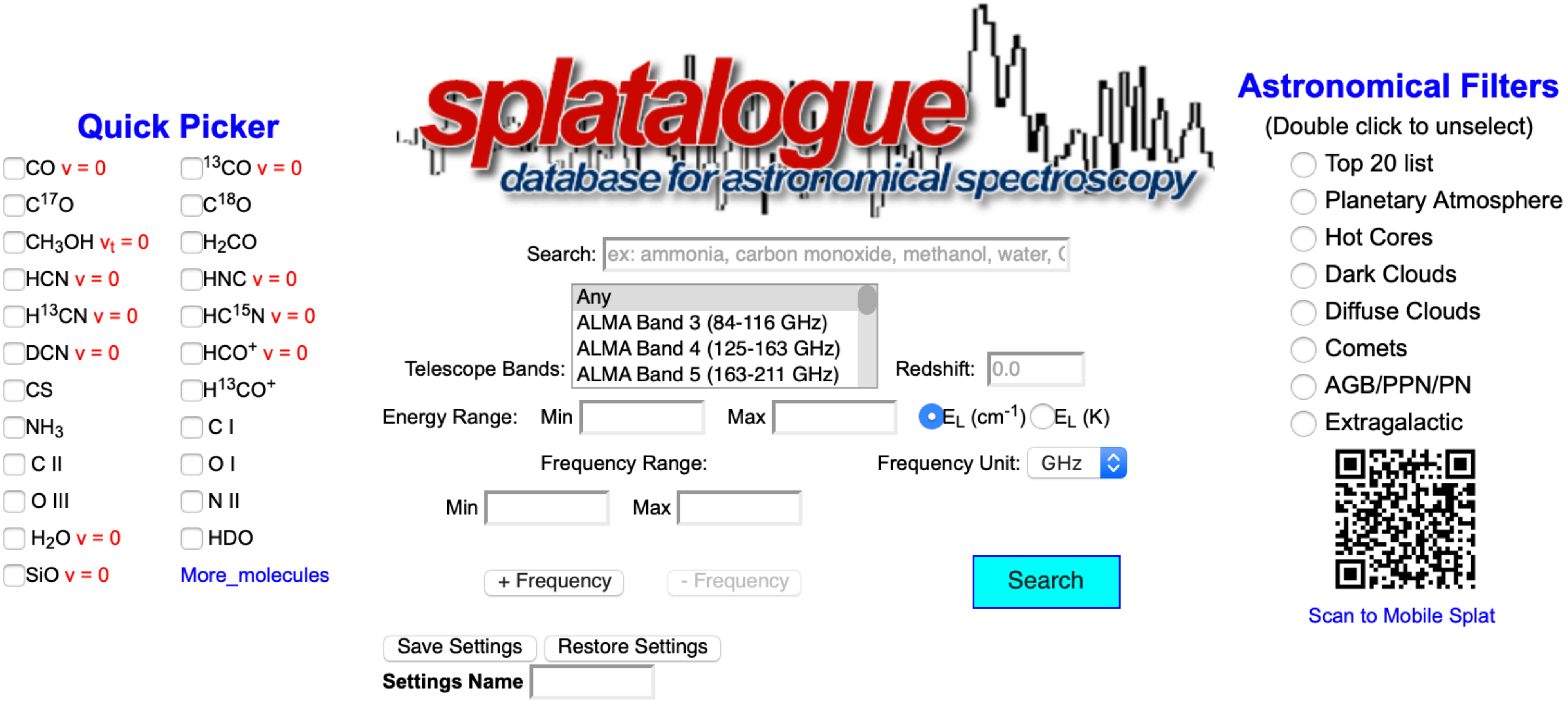
Detected molecules in space (outside of stellar atmospheres): **~200**)

more than 50 molecules also detected in extragalactic systems to date …

…many of which have dozens / hundreds of transitions

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

# splatalgogue



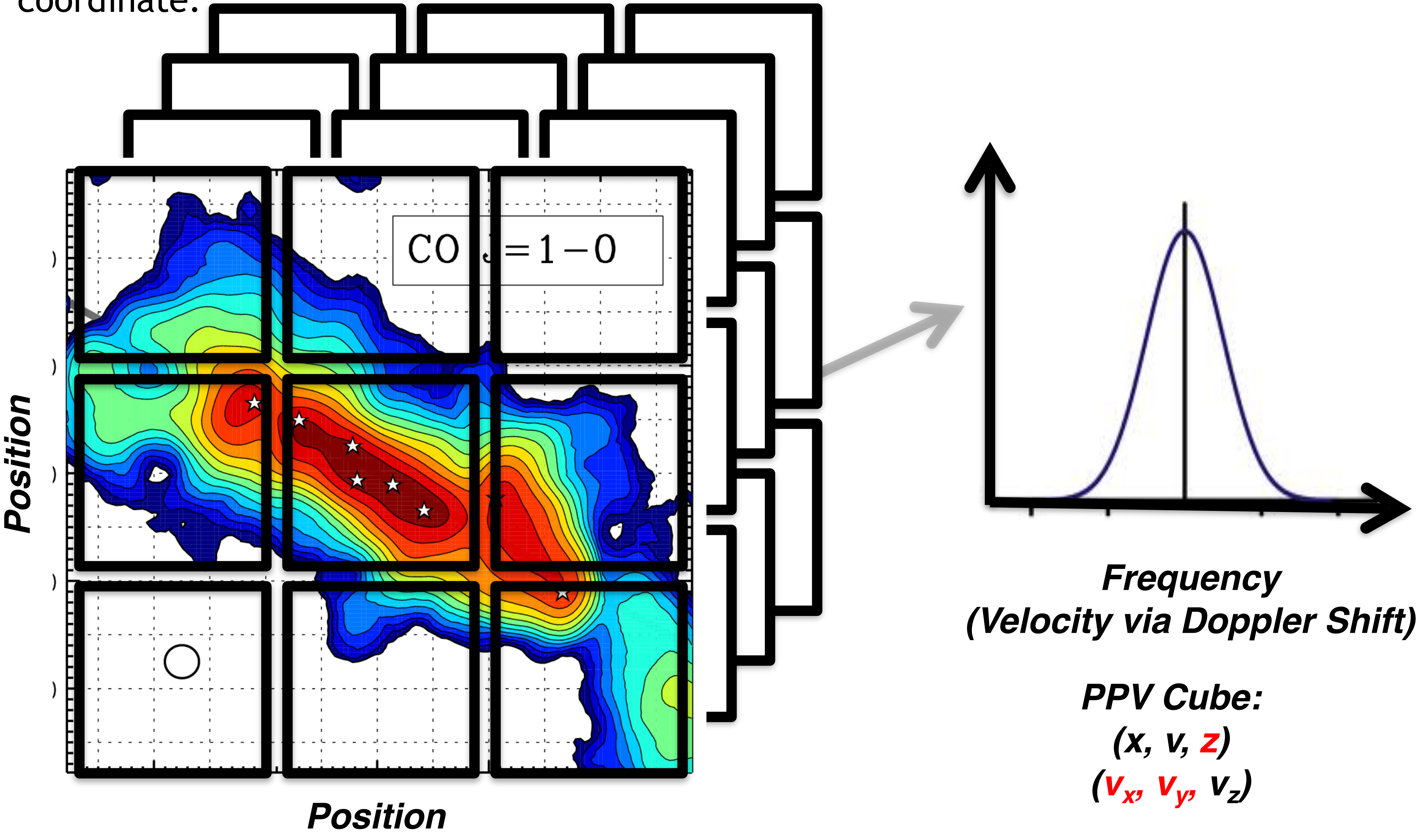
Redshift: 0.0

Frequency Unit: GHz

https://splatalogue.online//

# Data cubes

For a series of positions mapped by a single dish (e.g., in some scan mode) or for all interferometer observations (which image the primary beam), you get out a data cube – a map with a spectrum at each location. So two sky coordinates and a frequency coordinate.



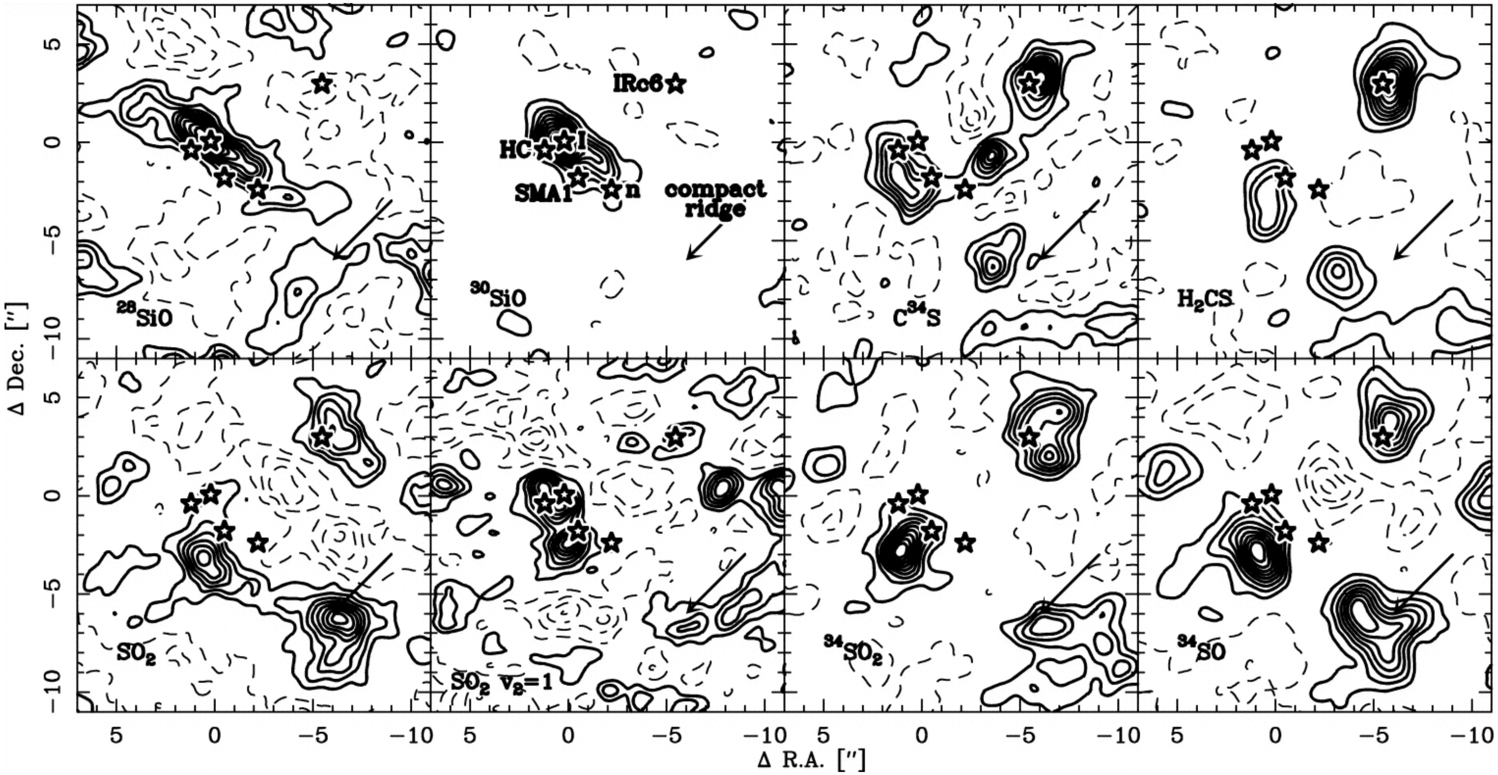
**PPV Cube:**

$(x, v, z)$

$(v_x, v_y, v_z)$

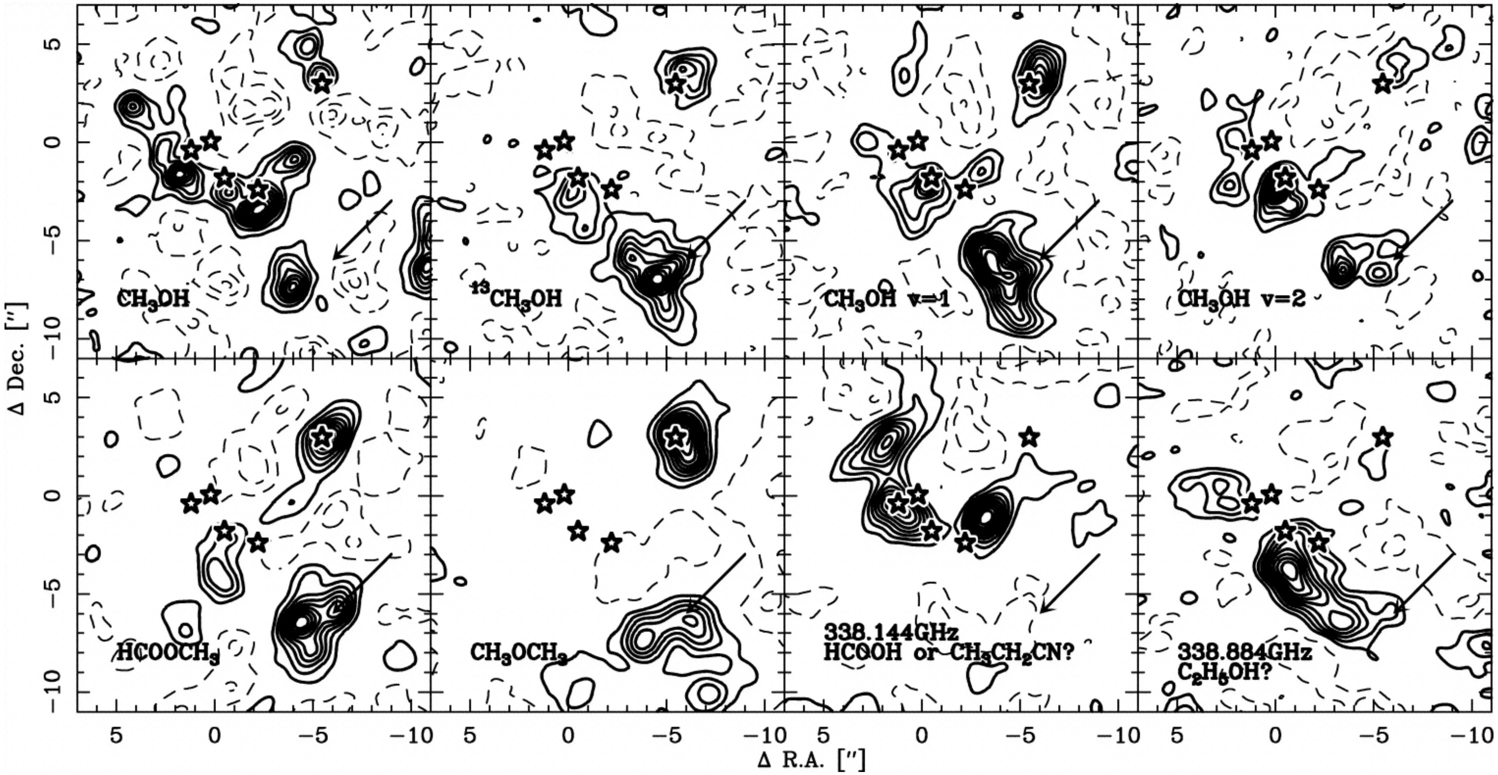
# Data cubes

chemical differentiation, e.g. Orion KL region (Beuther et al. 2005)



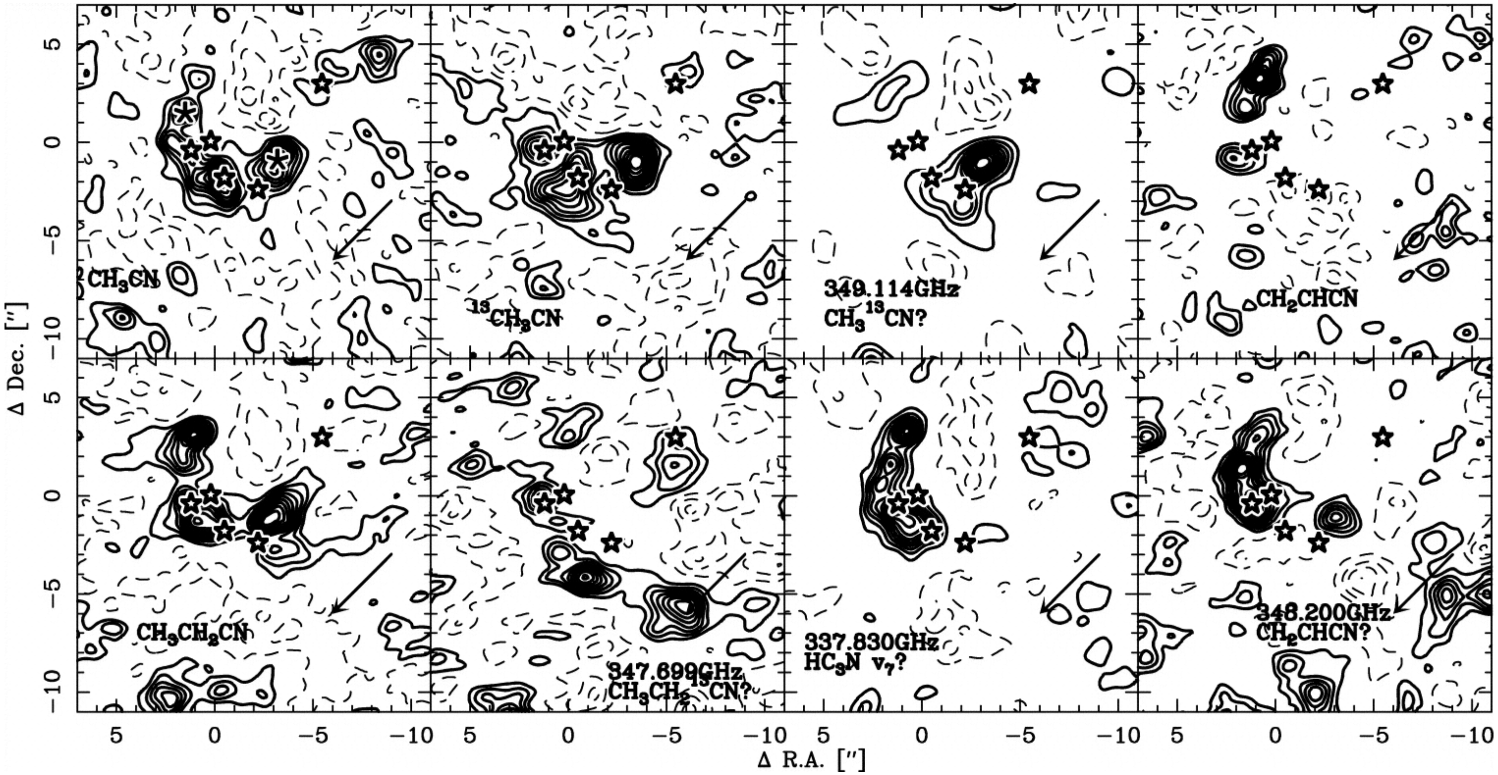
# Data cubes

chemical differentiation, e.g. Orion KL region (Beuther et al. 2005)



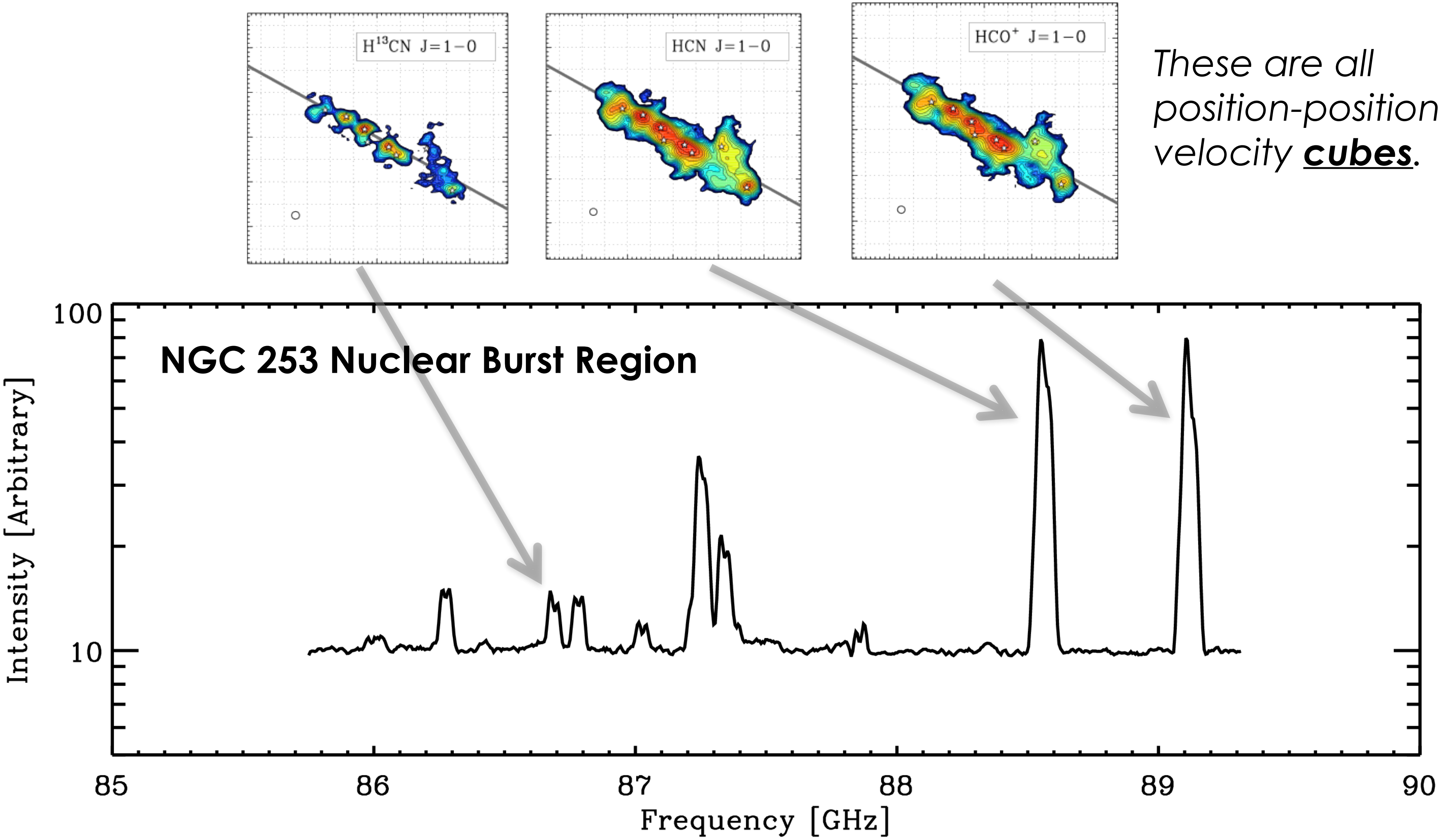
# Data cubes

chemical differentiation, e.g. Orion KL region (Beuther et al. 2005)



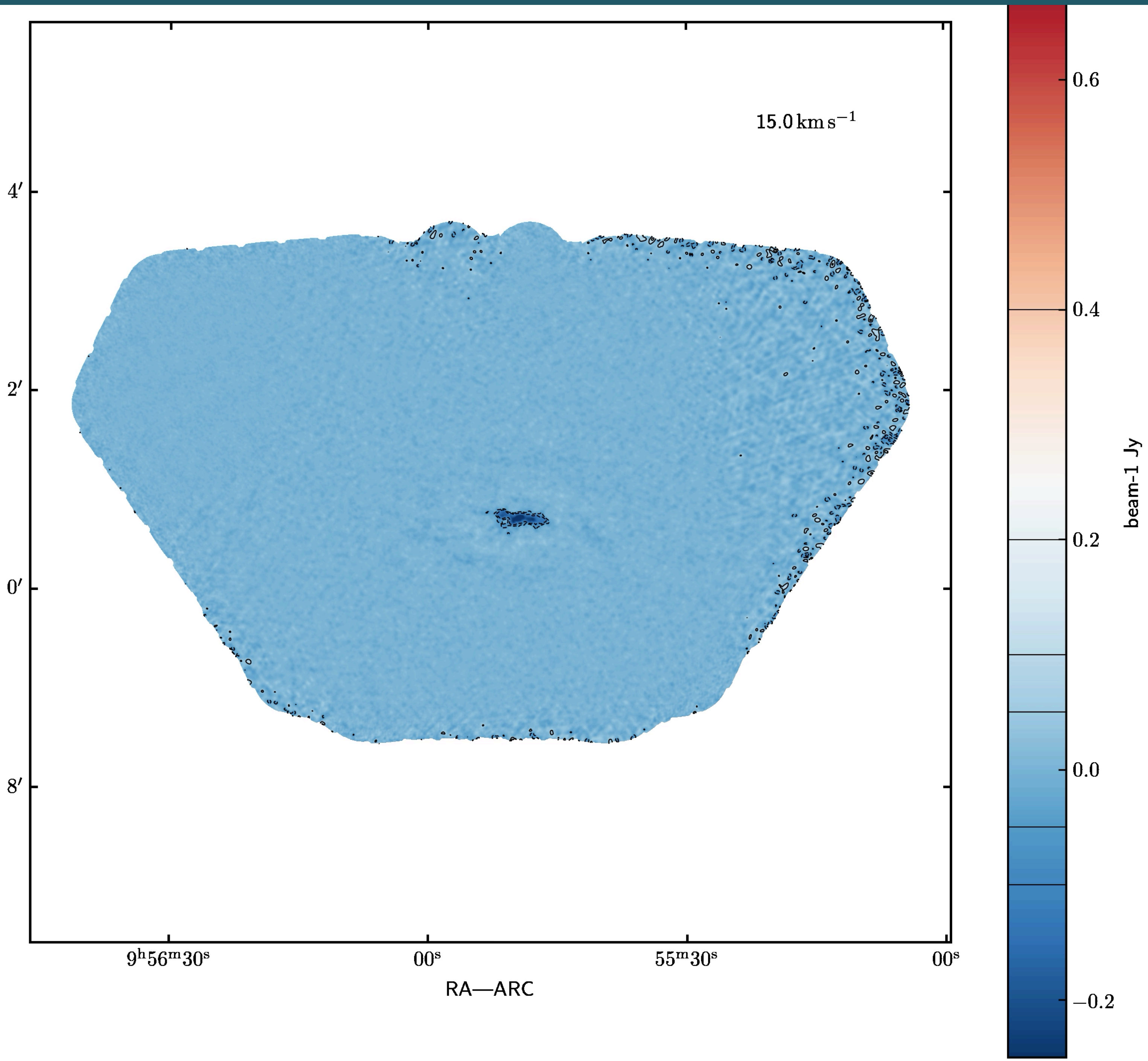
# Data cubes

But you often don’t just have a single line – instead, you get a rich spectrum at each location, with a succession of position-position velocity cubes stacked on top of one another (in a big p-p-frequency cube). Here an ALMA example:

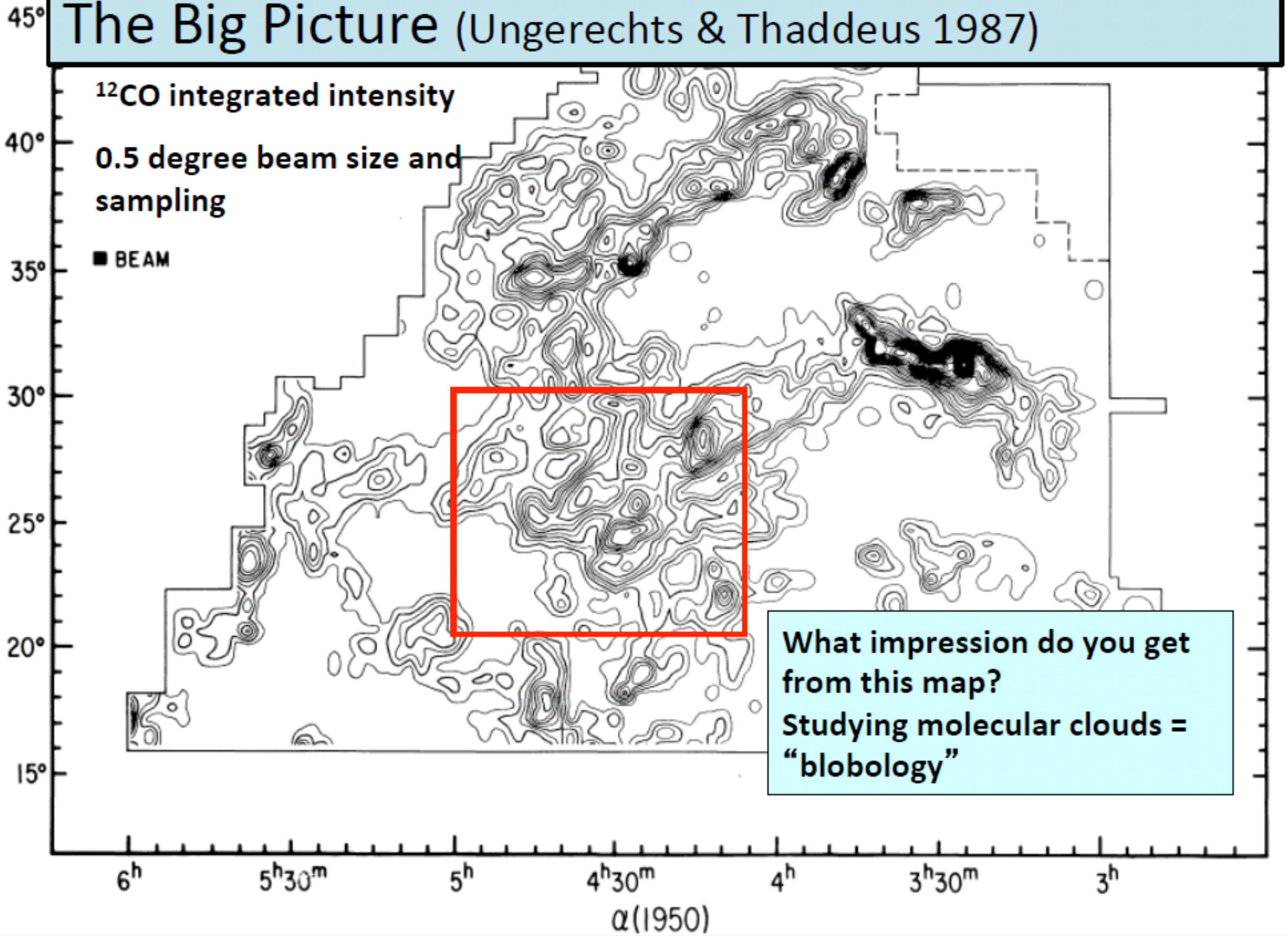


*These are all position-position velocity **cubes**.*

# Data cubes


15.0 km s$^{-1}$
4′
2′
0′
8′
9$^h$56$^m$30$^s$
00$^s$
55$^m$30$^s$
00$^s$
RA—ARC
0.6
0.4
0.2
0.0
−0.2
beam-1 Jy

# Molecular Cloud Structure: Perseus + Taurus - The Big Picture (Ungerechts & Thaddeus 1987)

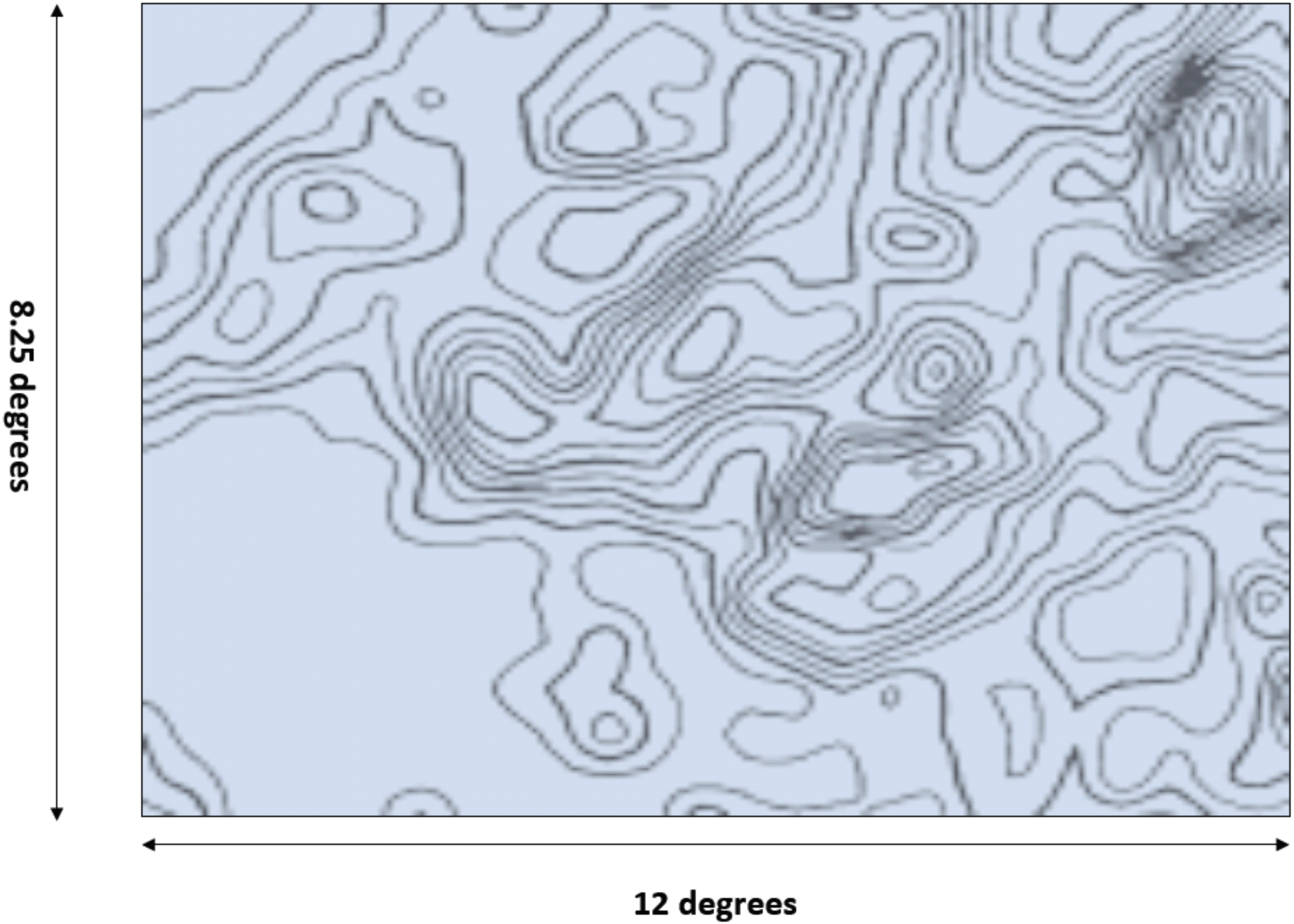


$^{12}$CO integrated intensity

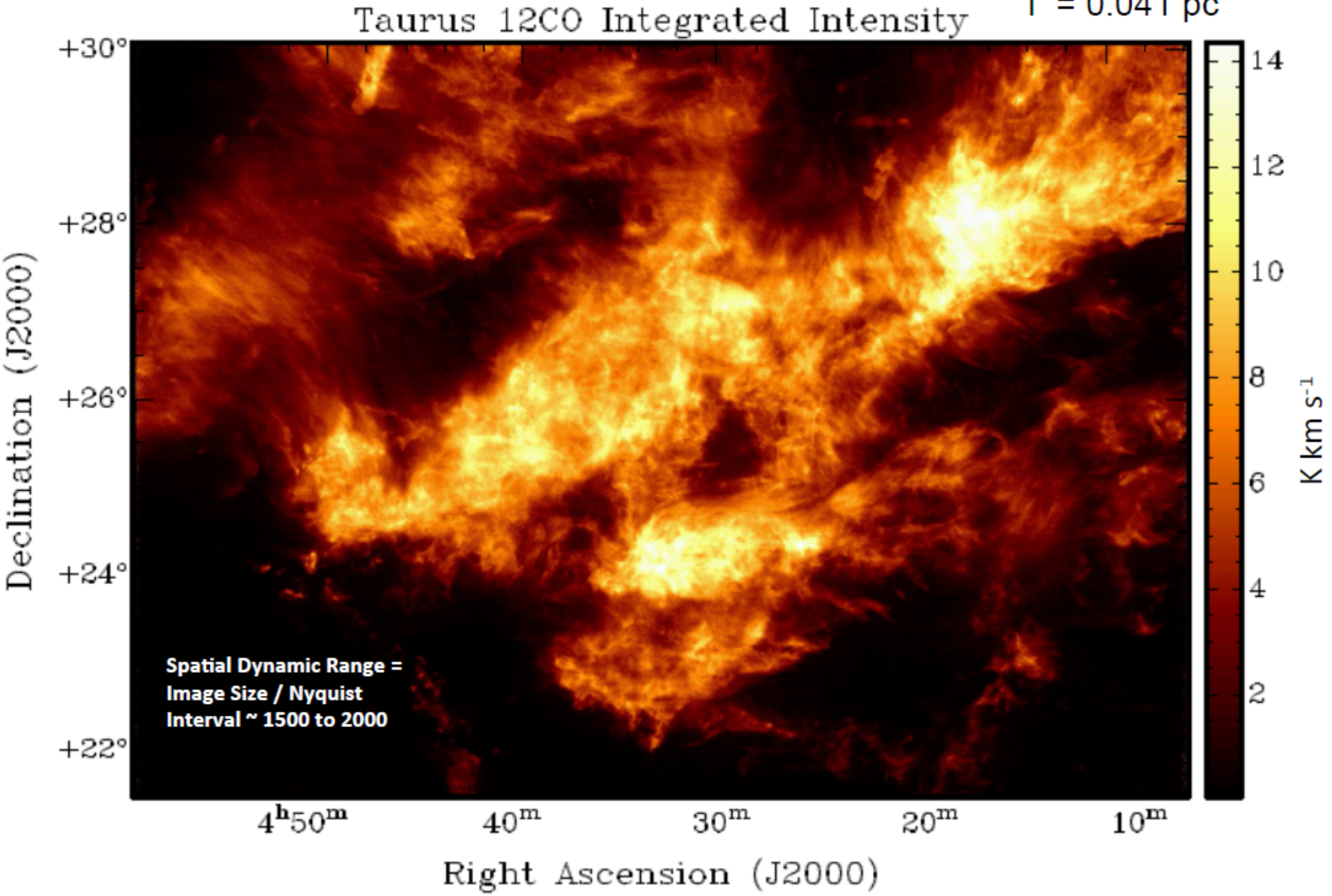
0.5 degree beam size and sampling

What impression do you get from this map?

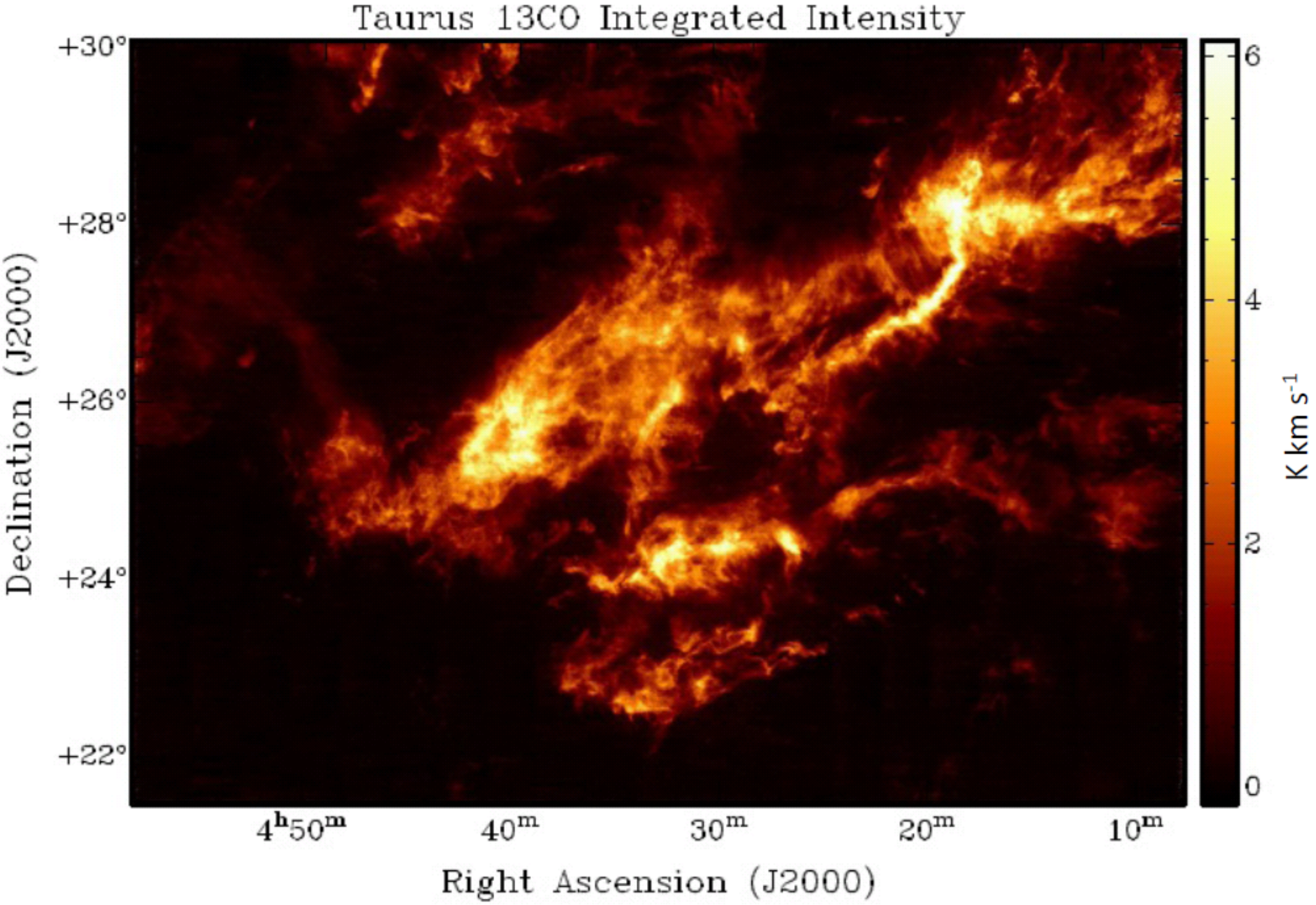
Studying molecular clouds = "blobology"


8.25 degrees
12 degrees

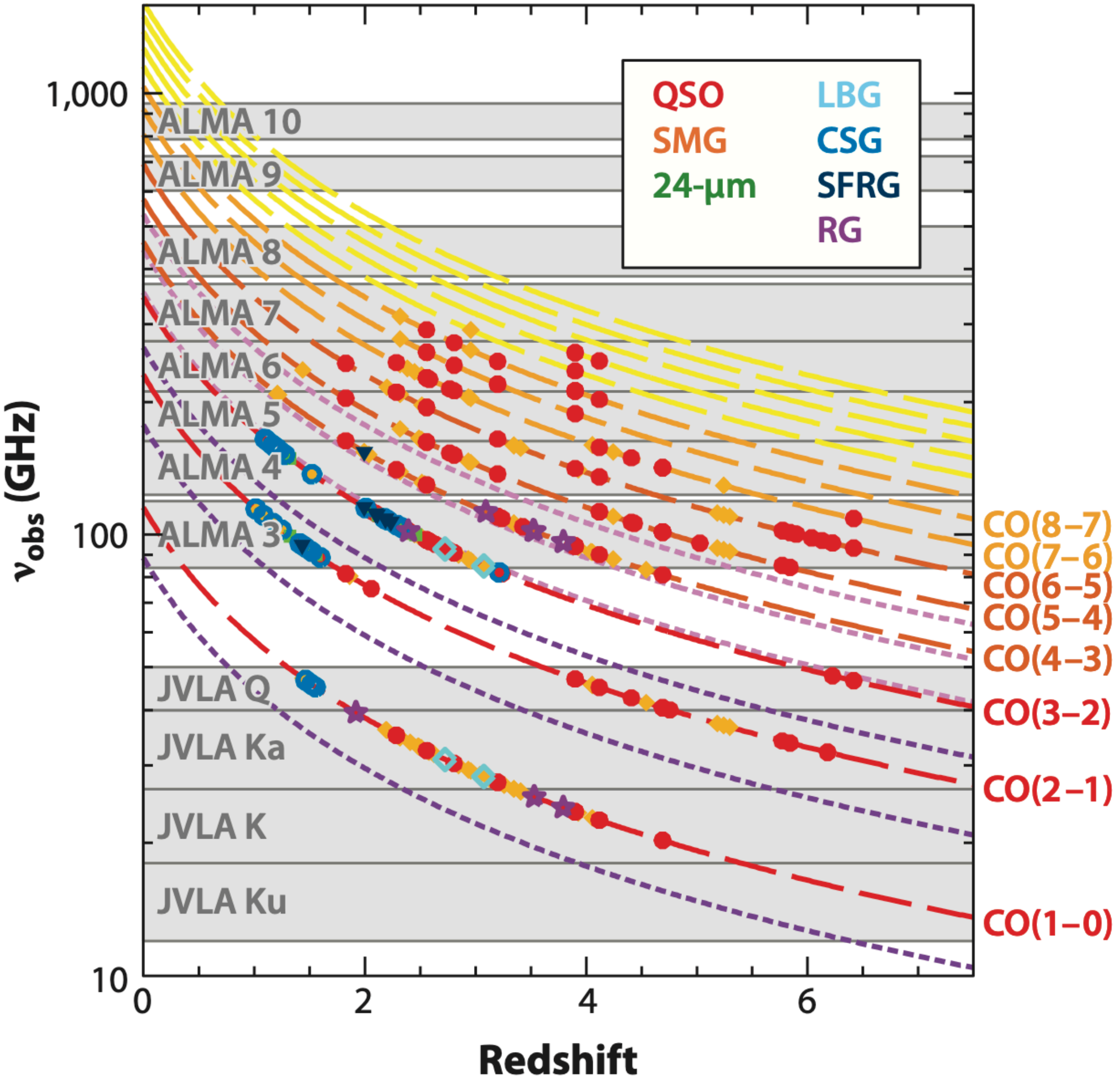
Distance = 140 pc
1° = 2.4 pc
1' = 0.041 pc



Spatial Dynamic Range = Image Size / Nyquist Interval ~ 1500 to 2000


Taurus 13CO Integrated Intensity
+30°
+28°
+26°
+24°
+22°
Declination (J2000)
4h50m
40m
30m
20m
10m
Right Ascension (J2000)
6
4
2
0
K km s-1

# redshift dependence



# Molecular gas in the host galaxy of a quasar at redshift $z = 6.42$

**Fabian Walter*, Frank Bertoldi†, Chris Carilli*, Pierre Cox‡, K. Y. Lo*, Roberto Neri§, Xiaohui Fan||, Alain Omont¶, Michael A. Strauss# & Karl M. Menten†**

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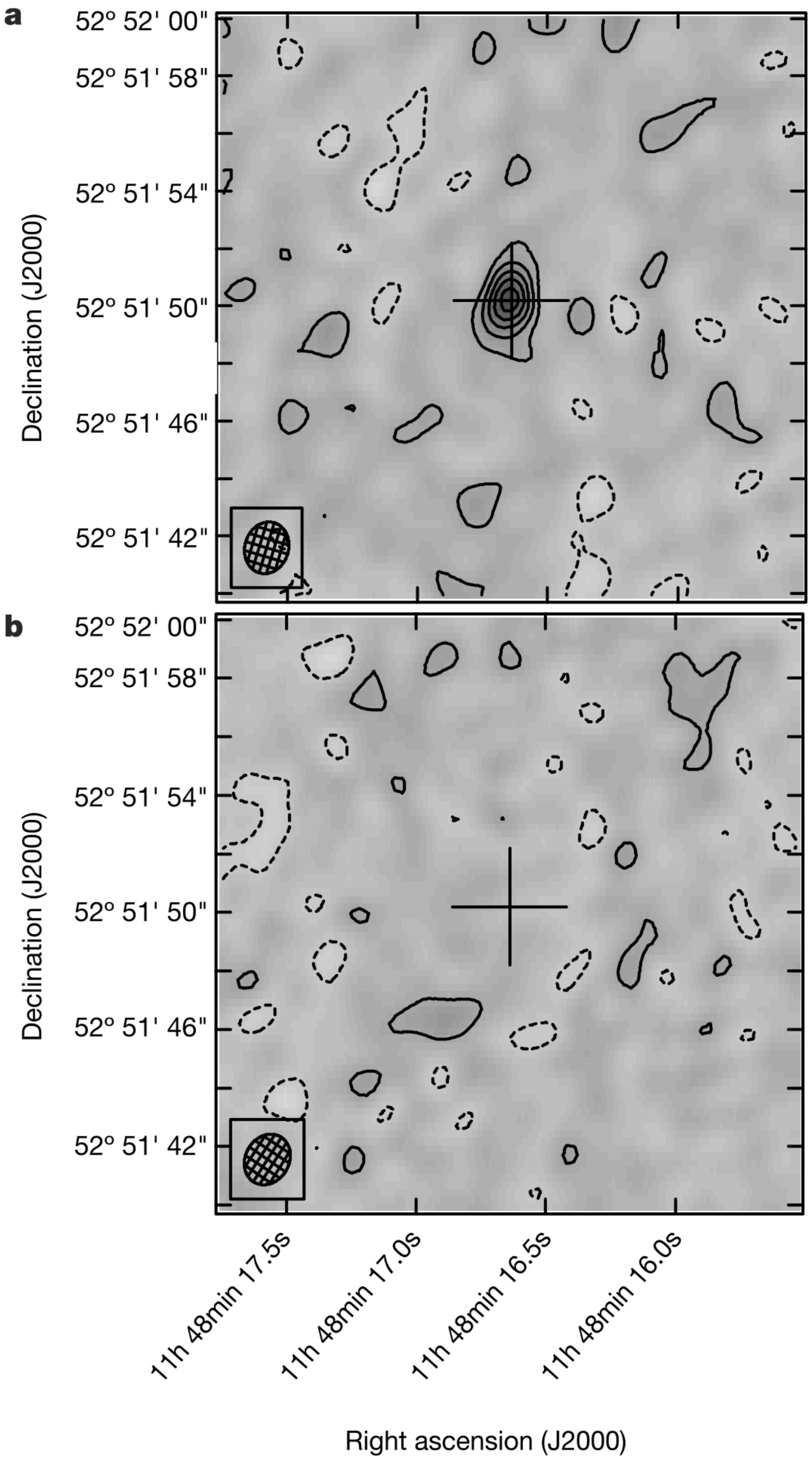
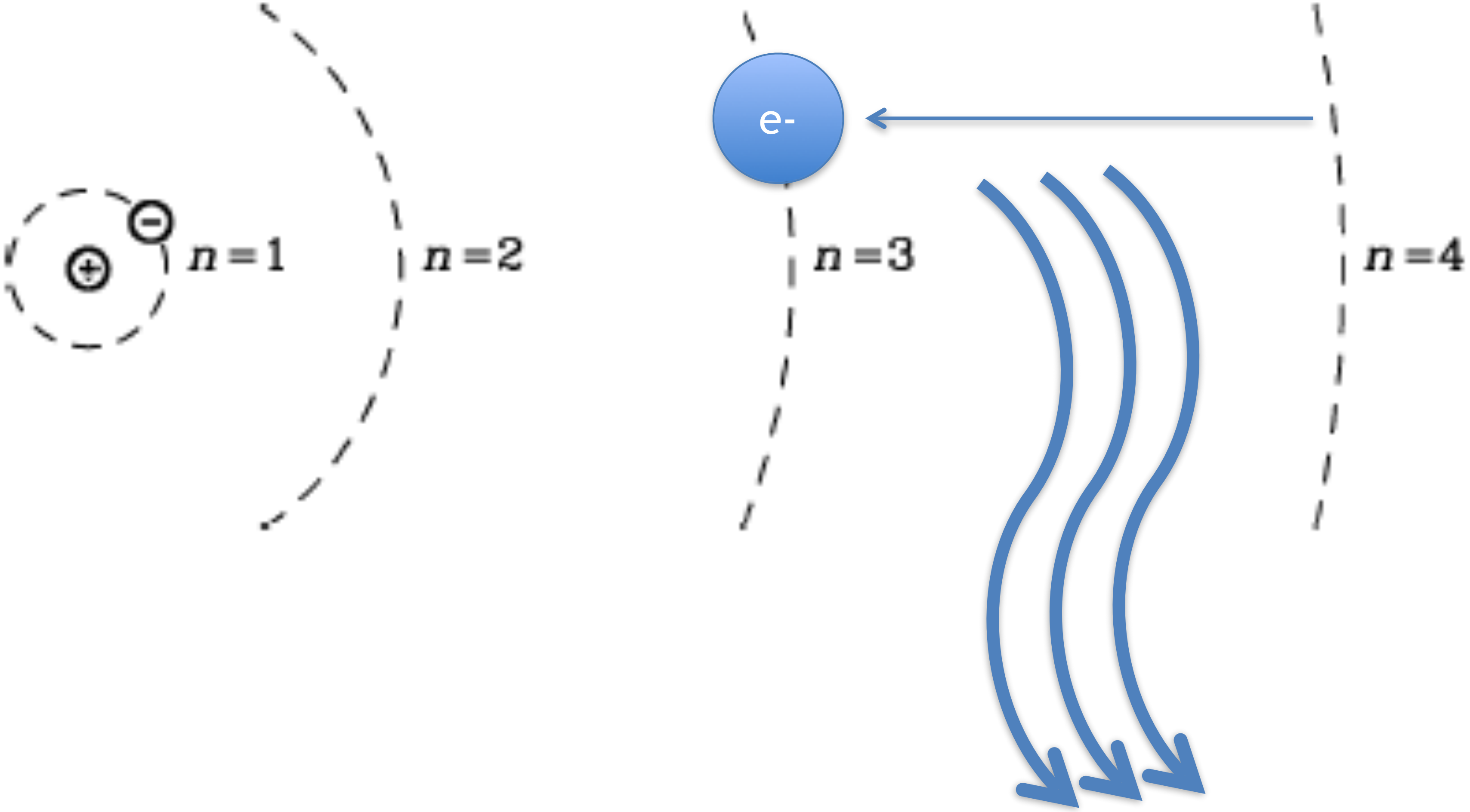
*† Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany*
*‡ Institut d'Astrophsique Spatiale, Universite de Paris-Sud, 91405 Orsay, France*
*§ IRAM, 300 Rue de la Piscine, 38406 St-Martin-d'Heres, France*
*|| Steward Observatory, University of Arizona, 933 N. Cherry Ave., Tucson, Arizona 85721, USA*
*¶ Institut d'Astrophysique de Paris, CNRS & Université Paris 6, 75014 Paris, France*
*# Princeton University Observatory, Princeton, New Jersey 08544, USA*

**Observations of molecular hydrogen in quasar host galaxies at high redshifts provide fundamental constraints on galaxy evolution, because it is out of this molecular gas that stars form. Molecular hydrogen is traced by emission from the carbon monoxide molecule, CO; cold $H_2$ itself is generally not observable. Carbon monoxide has been detected in about ten quasar host galaxies with redshifts $z > 2$; the record-holder is at $z = 4.69$ (refs 1–3). Here we report CO emission from the quasar SDSS J114816.64 + 525150.3 (refs 5, 6) at $z = 6.42$. At that redshift, the Universe was only 1/16 of its present age, and the era of cosmic reionization was just ending. The presence of about $2 \times 10^{10} M_\odot$ of $H_2$ in an object at this time demonstrates that molecular gas enriched with heavy elements can be generated rapidly in the youngest galaxies.**

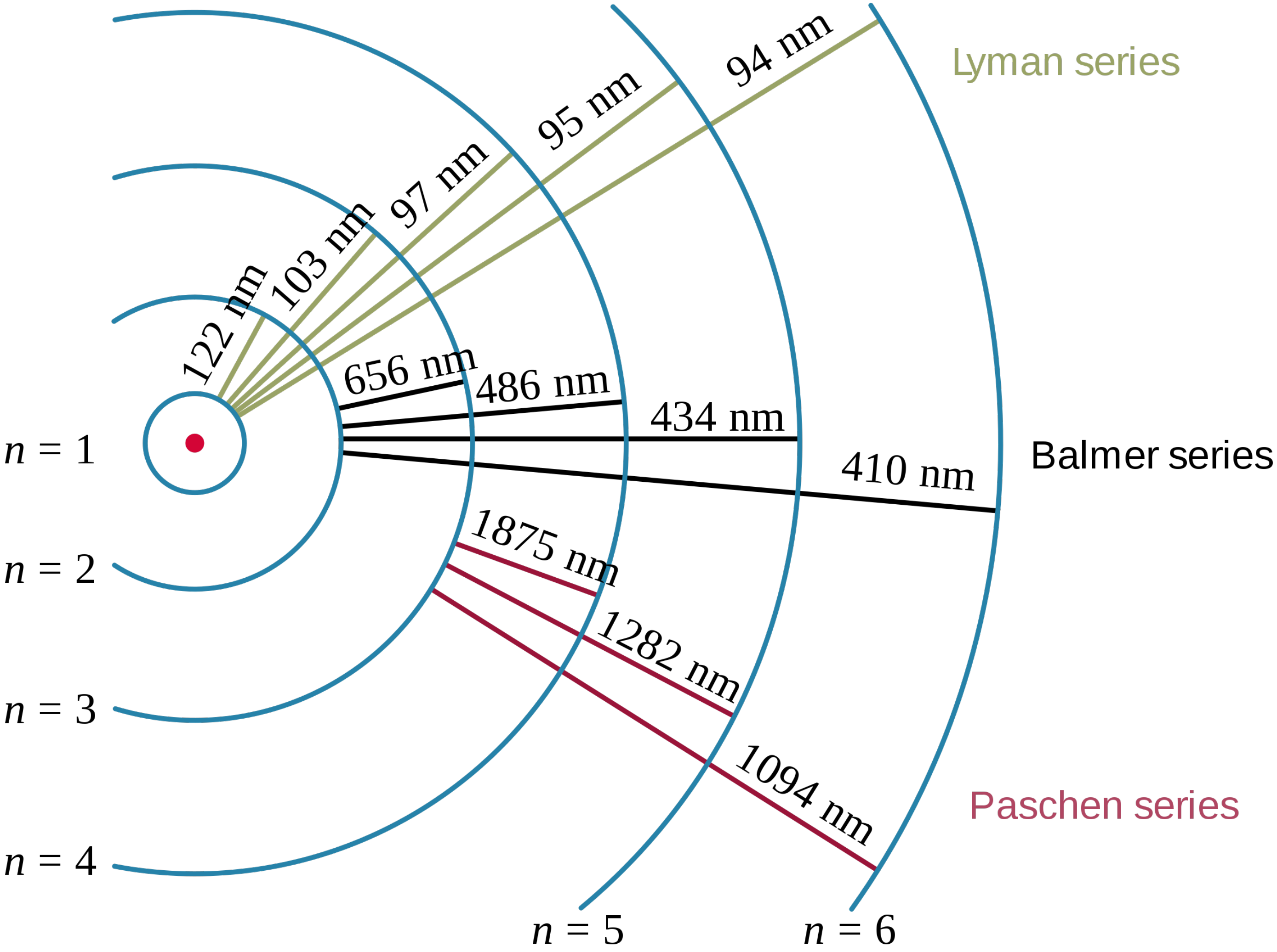


# recombination lines

recombination line emission comes from an atom in which an electron falls from a higher energy state to a lower energy state.



# recombination lines



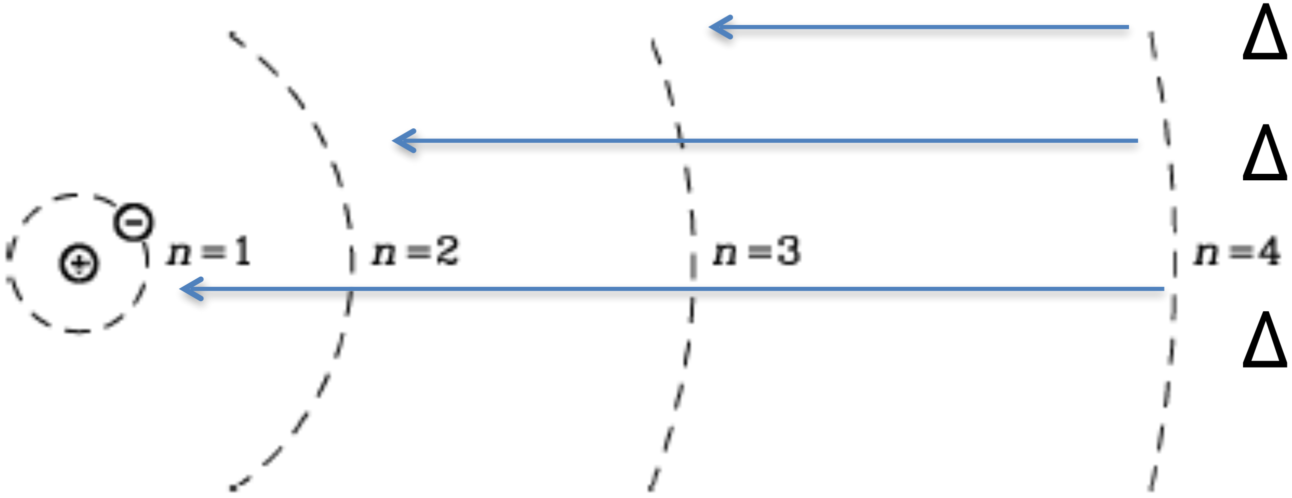
# recombination lines

Given Bohr radius $a_n$ we can figure out the energy of the atom, which is kinetic energy T and potential energy V

$$E_n = T + V = -\frac{m_e e^4}{2\hbar^2 n^2}$$

energy of a given level
(general result of the virial theorem applying to an orbit).

Recombination lines are jumps between levels:



$\Delta n = 1 : \alpha$

$\Delta n = 2 : \beta$

$\Delta n = 3 : \gamma$

# recombination lines

The frequency of a recombination line goes as the energy difference between levels:

$$\Delta E = \frac{m_e e^4}{2\hbar^2}\left[\frac{1}{n^2} - \frac{1}{(n+\Delta n)^2}\right] = h\nu$$

i.e.:

$$\nu = \left(\frac{2\pi^2 m_e e^4}{h^3 c}\right) c \left[\frac{1}{n^2} - \frac{1}{(n+\Delta n)^2}\right]$$

(Rydberg constant)

$$R_\infty \equiv \left(\frac{2\pi^2 m_e e^4}{h^3 c}\right) = 1.09737312\cdots \times 10^5\ \mathrm{cm}^{-1}$$

Rydberg frequency: $R_\infty c = 3.28984 \times 10^{15}\ \mathrm{Hz}$

# recombination lines

Account for finite-mass nucleus

$$\nu = R_{\mathrm{M}}c\left[\frac{1}{n^2} - \frac{1}{(n+\Delta n)^2}\right] \qquad \text{where} \qquad R_{\mathrm{M}} \equiv R_{\infty}\left(1 + \frac{m_{\mathrm{e}}}{M}\right)^{-1}$$

e.g. hydrogen: $$R_{\mathrm{M}}c = 3.28984 \times 10^{15}\,\mathrm{Hz}\left(1 + \frac{1}{1836.1}\right)^{-1} = 3.28805 \times 10^{15}\,\mathrm{Hz}$$

this corresponds to 912 Angstrom in the UV: energy needed to create / ionizea hydrogen atom

“Alpha” radio lines at order 10 GHz frequencies come from very big atoms:

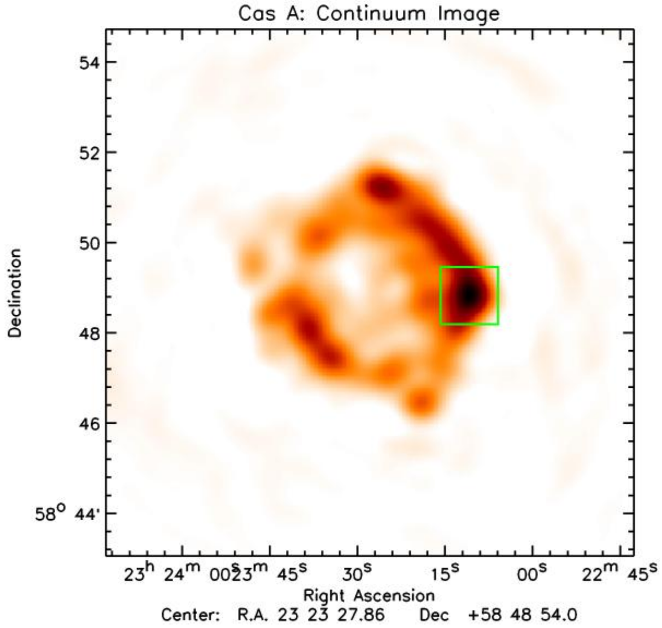
$$\nu(\mathrm{H}109\alpha) = 3.28805 \times 10^{15}\,\mathrm{Hz}\left(\frac{1}{109^2} - \frac{1}{110^2}\right) \approx 5.0089 \times 10^{9}\,\mathrm{Hz}$$

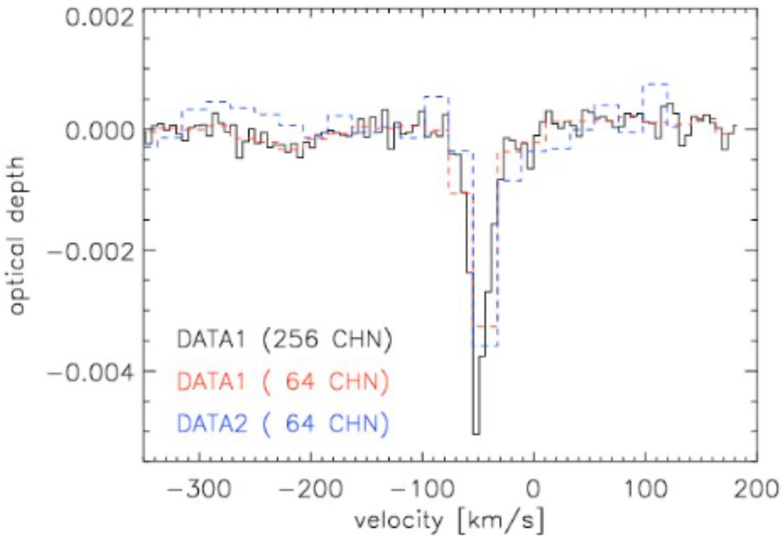
# radio recombination lines

- these are the **only** radio lines that are due to electronic transitions.
- Quantum numbers need to be very high (> 100).

- HII can show radio recombination lines from electrons cascading down into the ground state
- *Weak and hard to detect:* only 0.1-1% of the continuum.
- Emerging area for LOFAR + ngVLA + SKA

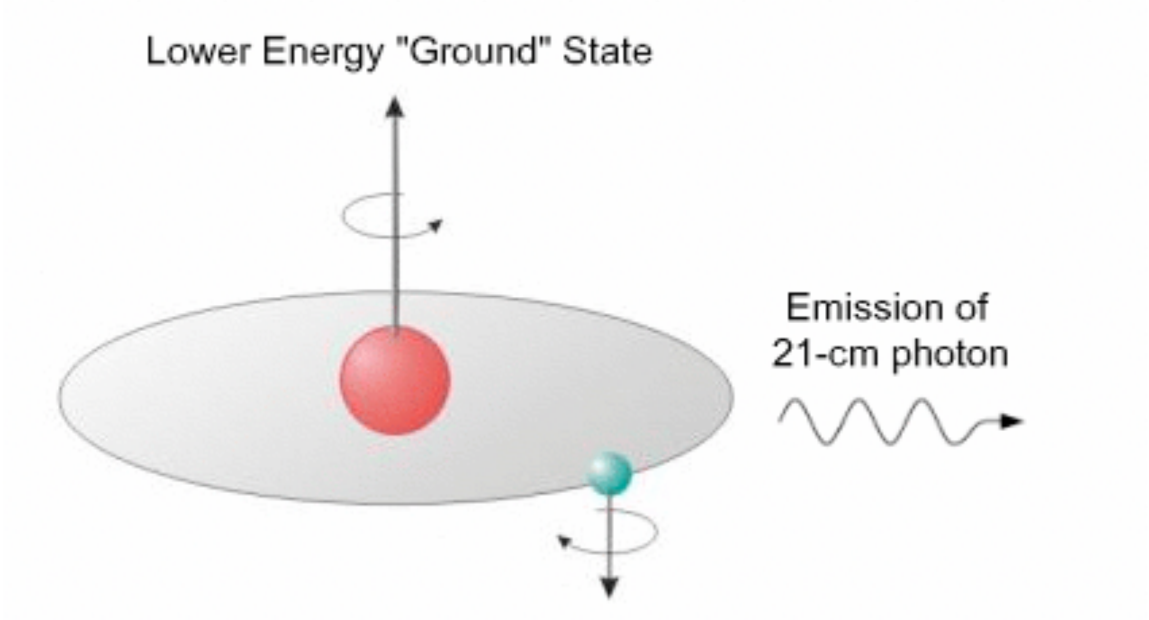
…do not play a big role in radio spectral line studies



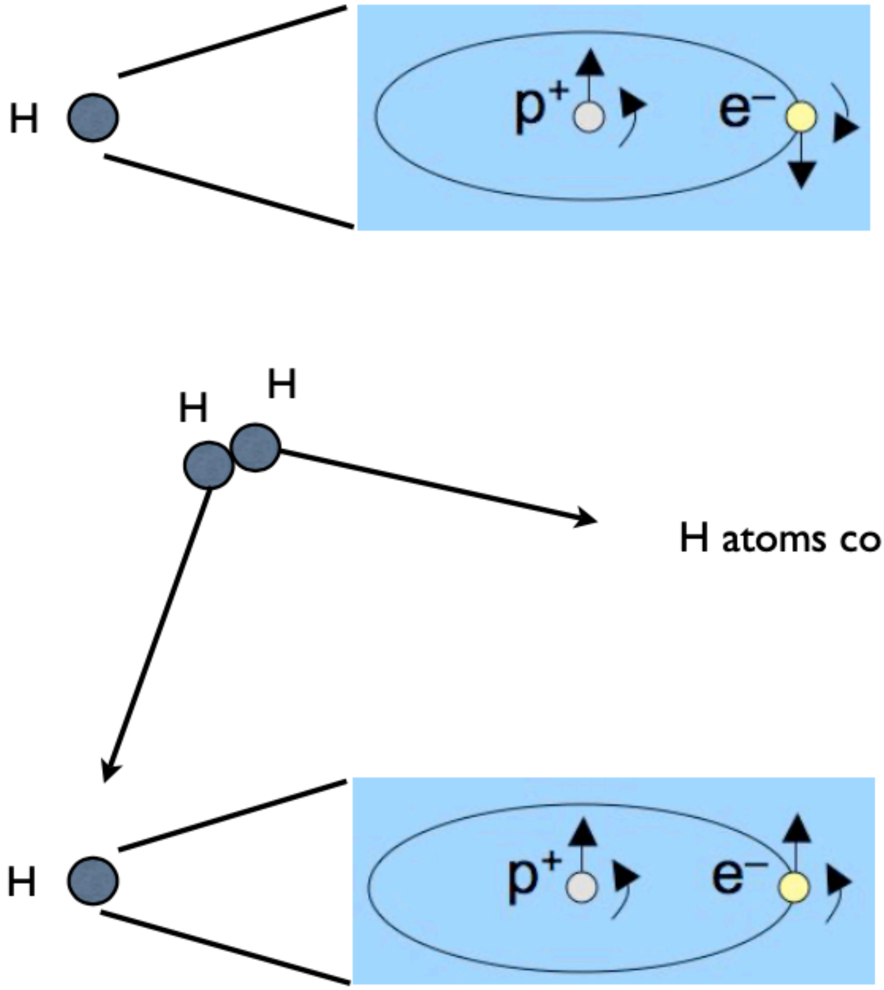


# 21cm line of hydrogen

- hyperfine structure in hydrogen.
- Undoubtedly the most important line for radio astronomy.
- Think of protons and electrons as spinning distributions of charge each creating a magnetic field (i.e.“spin”).
- Chance of Hydrogen randomly flipping its spin configuration is very low (spontaneous flipping once in ~11 million years).
- HI emission is collisionally induced (in ISM, typical timescale of ~200 years).



# 21cm line of hydrogen

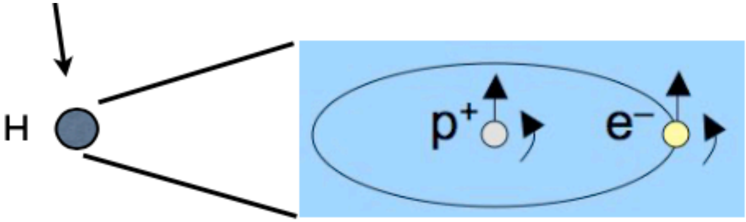


H atom in low energy state

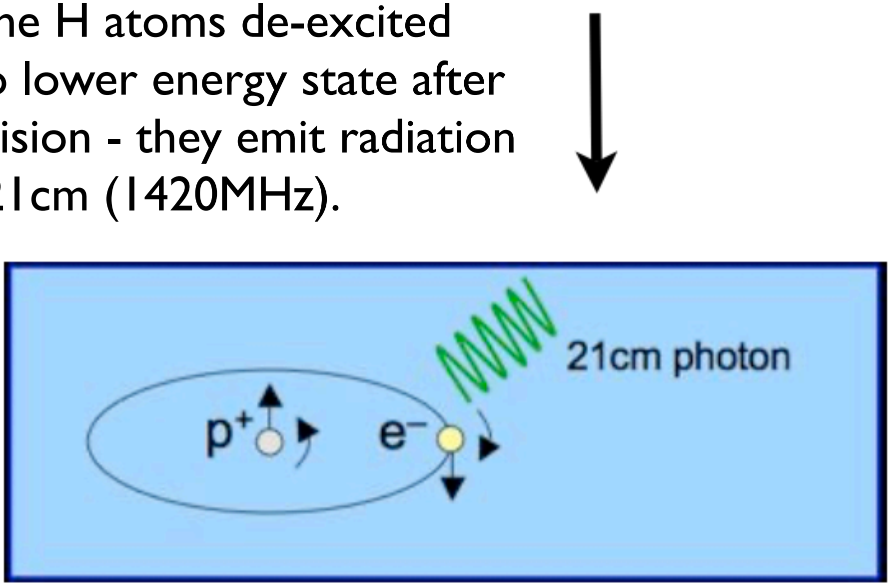
H atoms collide every few hundred years

H atom excited into higher energy state

# 21cm line of hydrogen



Some H atoms de-excited into lower energy state after collision - they emit radiation at 21cm (1420MHz).

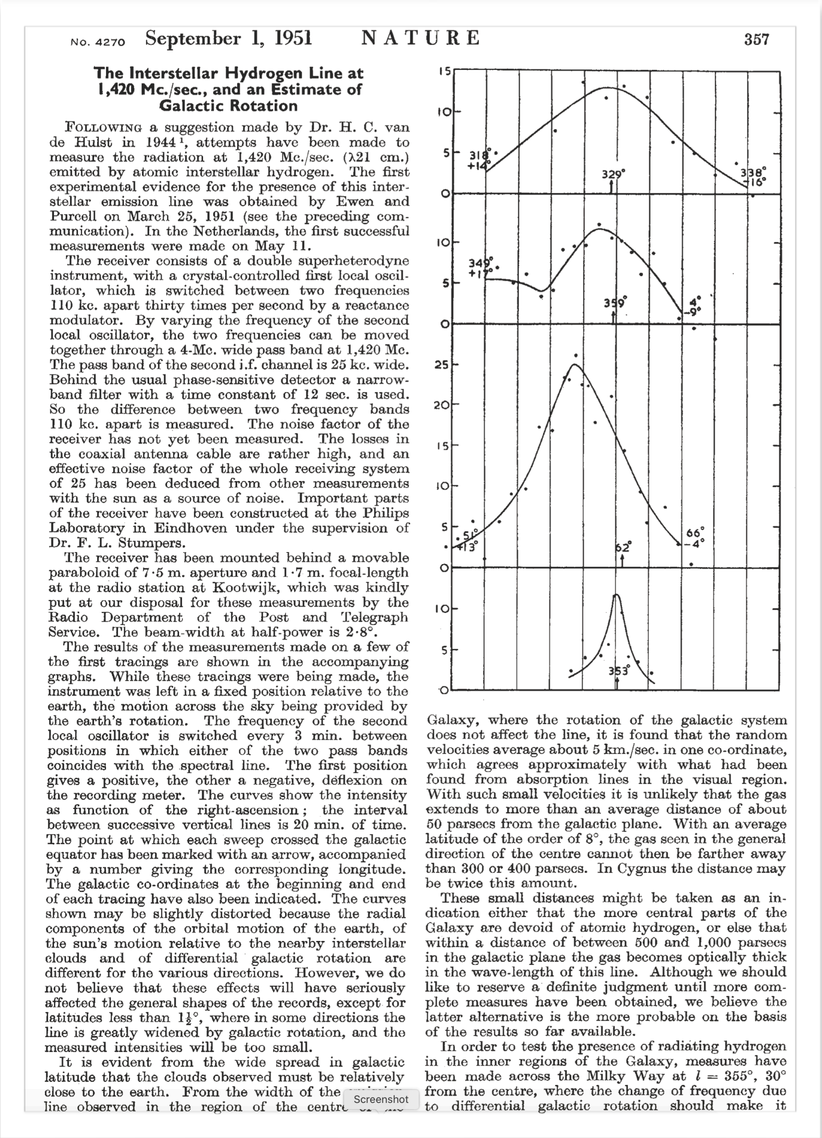


Although this transition is H rare (once every 11 million year), there is just so much Hydrogen in the ISM, that 21cm line emission is ubiquitous in the Milky way and other galaxies. And since the line has an extremely small natural width (because of its long lifetime), broadening of the line is usually due to doppler shifts caused by the motion of the gas relative to the observer. This is useful in studying the dynamics of regions in our own and other galaxies.

# 21cm line of hydrogen

codename ‘Würzburg’ -
4000 radar antennas in WWII

1951: detection of atomic hydrogen (21cm)



No. 4270 September 1, 1951 NATURE 357

### The Interstellar Hydrogen Line at 1,420 Mc./sec., and an Estimate of Galactic Rotation

FOLLOWING a suggestion made by Dr. H. C. van de Hulst in 1944[1], attempts have been made to measure the radiation at 1,420 Mc./sec. (λ21 cm.) emitted by atomic interstellar hydrogen. The first experimental evidence for the presence of this interstellar emission line was obtained by Ewen and Purcell on March 25, 1951 (see the preceding communication). In the Netherlands, the first successful measurements were made on May 11.

The receiver consists of a double superheterodyne instrument, with a crystal-controlled first local oscillator, which is switched between two frequencies 110 kc. apart thirty times per second by a reactance modulator. By varying the frequency of the second local oscillator, the two frequencies can be moved together through a 4-Mc. wide pass band at 1,420 Mc. The pass band of the second i.f. channel is 25 kc. wide. Behind the usual phase-sensitive detector a narrow-band filter with a time constant of 12 sec. is used. So the difference between two frequency bands 110 kc. apart is measured. The noise factor of the receiver has not yet been measured. The losses in the coaxial antenna cable are rather high, and an effective noise factor of the whole receiving system of 25 has been deduced from other measurements with the sun as a source of noise. Important parts of the receiver have been constructed at the Philips Laboratory in Eindhoven under the supervision of Dr. F. L. Stumpers.

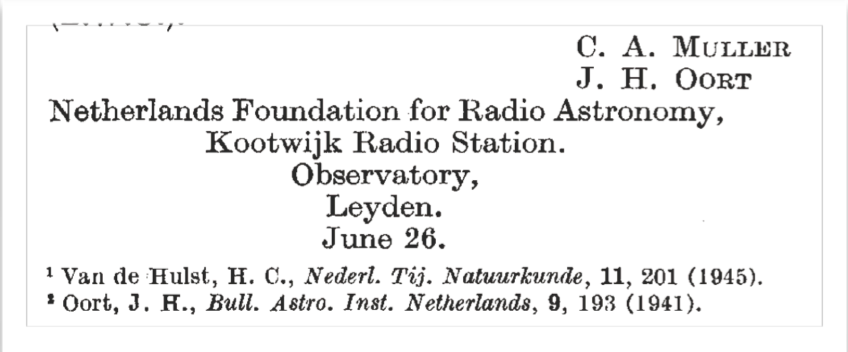
The receiver has been mounted behind a movable paraboloid of 7·5 m. aperture and 1·7 m. focal-length at the radio station at Kootwijk, which was kindly put at our disposal for these measurements by the Radio Department of the Post and Telegraph Service. The beam-width at half-power is 2·8°.

The results of the measurements made on a few of the first tracings are shown in the accompanying graphs. While these tracings were being made, the instrument was left in a fixed position relative to the earth, the motion across the sky being provided by the earth's rotation. The frequency of the second local oscillator is switched every 3 min. between positions in which either of the two pass bands coincides with the spectral line. The first position gives a positive, the other a negative, deflexion on the recording meter. The curves show the intensity as function of the right-ascension; the interval between successive vertical lines is 20 min. of time. The point at which each sweep crossed the galactic equator has been marked with an arrow, accompanied by a number giving the corresponding longitude. The galactic co-ordinates at the beginning and end of each tracing have also been indicated. The curves shown may be slightly distorted because the radial components of the orbital motion of the earth, of the sun's motion relative to the nearby interstellar clouds and of differential galactic rotation are different for the various directions. However, we do not believe that these effects will have seriously affected the general shapes of the records, except for latitudes less than 1½°, where in some directions the line is greatly widened by galactic rotation, and the measured intensities will be too small.

It is evident from the wide spread in galactic latitude that the clouds observed must be relatively close to the earth. From the width of the emission line observed in the region of the centre of the Galaxy, where the rotation of the galactic system does not affect the line, it is found that the random velocities average about 5 km./sec. in one co-ordinate, which agrees approximately with what had been found from absorption lines in the visual region. With such small velocities it is unlikely that the gas extends to more than an average distance of about 50 parsecs from the galactic plane. With an average latitude of the order of 8°, the gas seen in the general direction of the centre cannot then be farther away than 300 or 400 parsecs. In Cygnus the distance may be twice this amount.

These small distances might be taken as an indication either that the more central parts of the Galaxy are devoid of atomic hydrogen, or else that within a distance of between 500 and 1,000 parsecs in the galactic plane the gas becomes optically thick in the wave-length of this line. Although we should like to reserve a definite judgment until more complete measures have been obtained, we believe the latter alternative is the more probable on the basis of the results so far available.

In order to test the presence of radiating hydrogen in the inner regions of the Galaxy, measures have been made across the Milky Way at $l = 355°$, 30° from the centre, where the change of frequency due to differential galactic rotation should make it



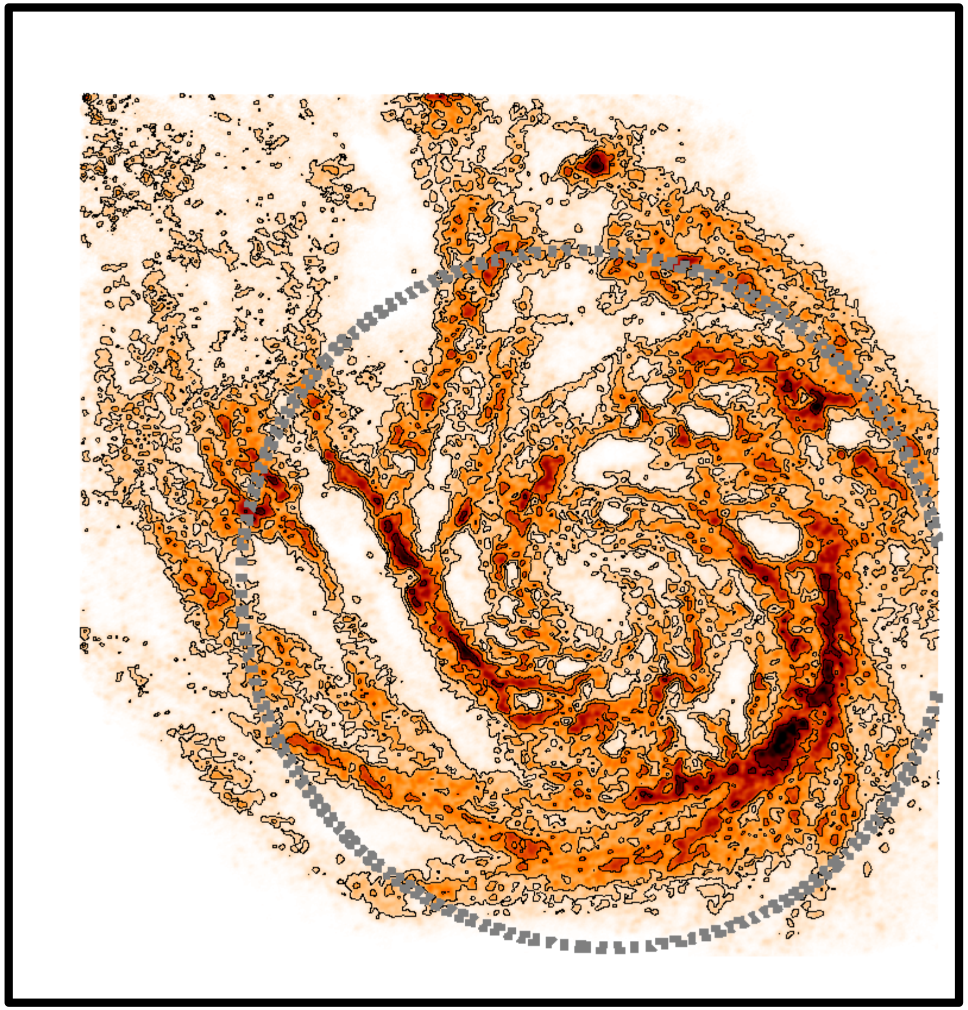
C. A. MULLER
J. H. OORT

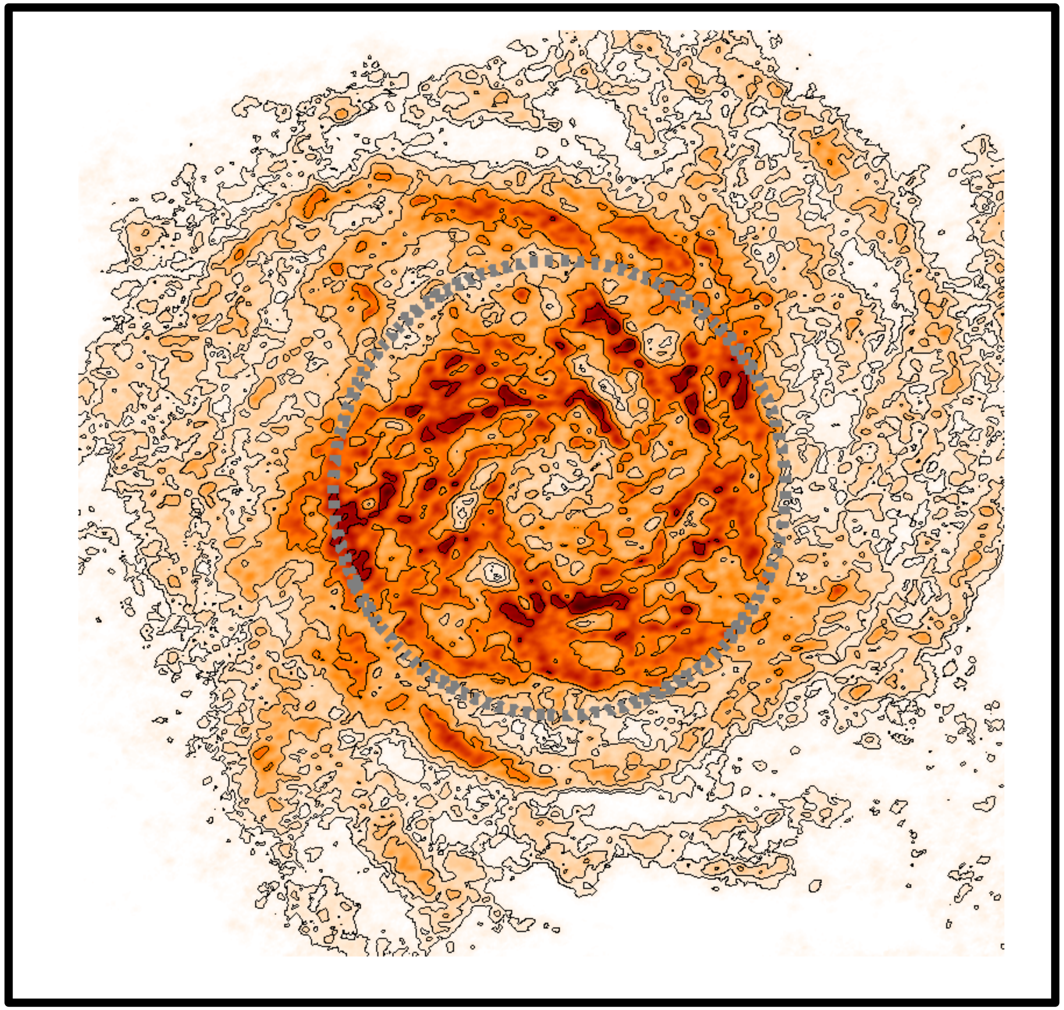
Netherlands Foundation for Radio Astronomy,
Kootwijk Radio Station.
Observatory,
Leyden.
June 26.

[1] Van de Hulst, H. C., *Nederl. Tij. Natuurkunde*, **11**, 201 (1945).
[2] Oort, J. H., *Bull. Astro. Inst. Netherlands*, **9**, 193 (1941).

# 21cm line of hydrogen

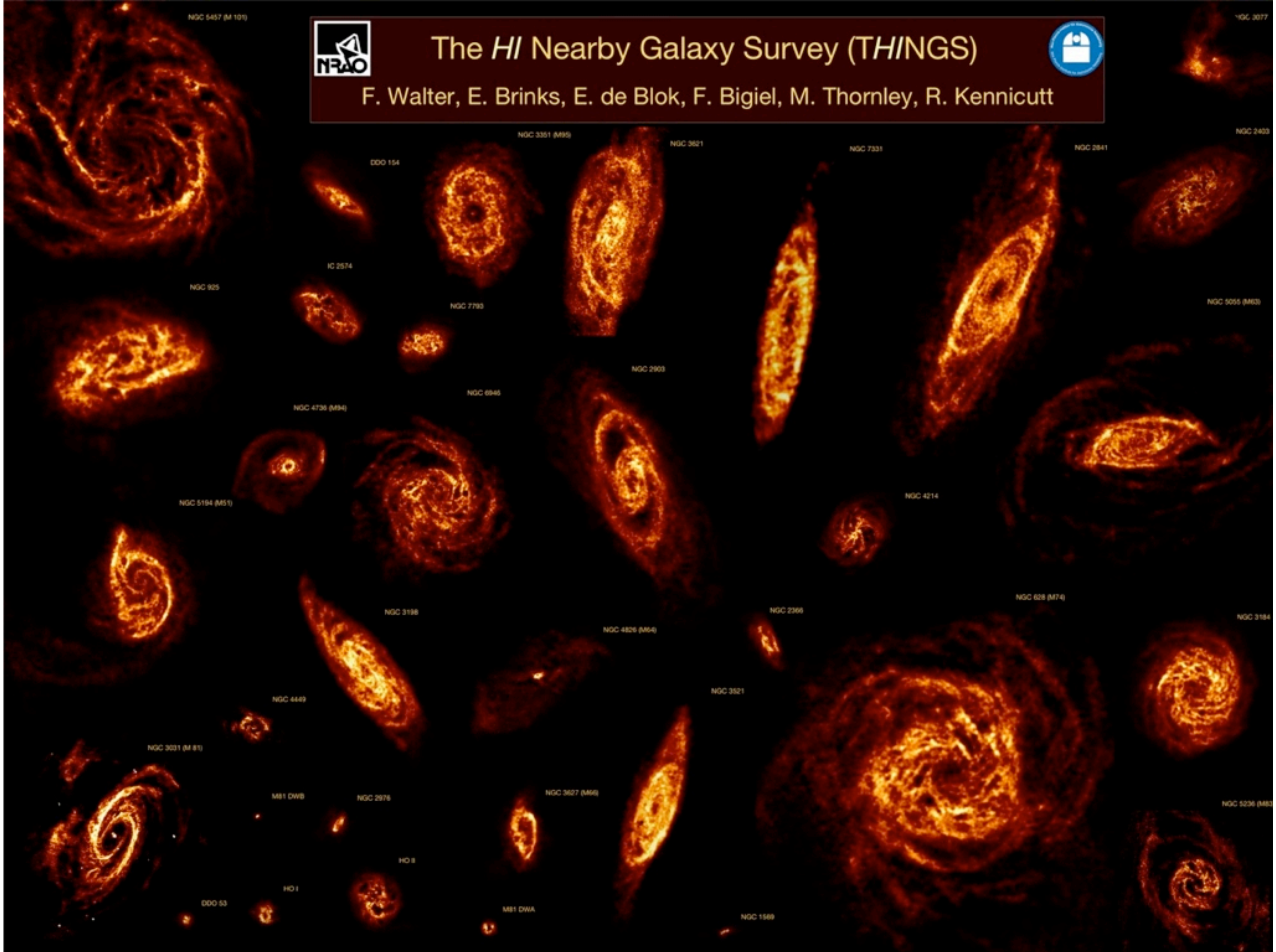
These are 21-cm line maps – cubes that have been collapsed into integrated intensities – into two dimension maps of integrated (K km/s) intensity ~ column. You get from this the ISM distribution, gas, arms, etc.





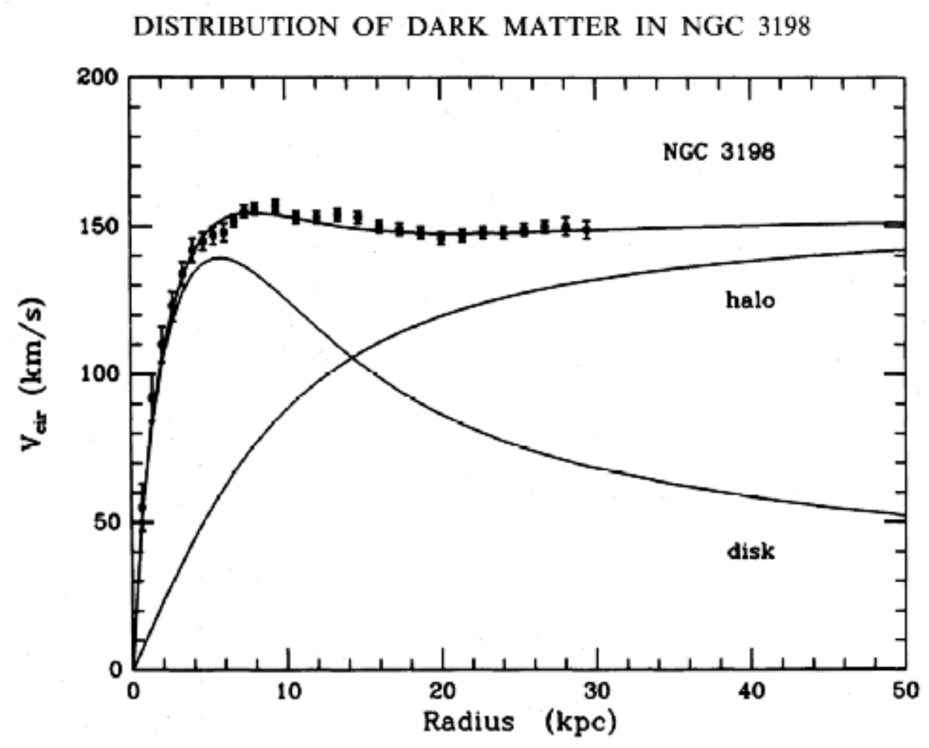
# The *HI* Nearby Galaxy Survey (T*HI*NGS)

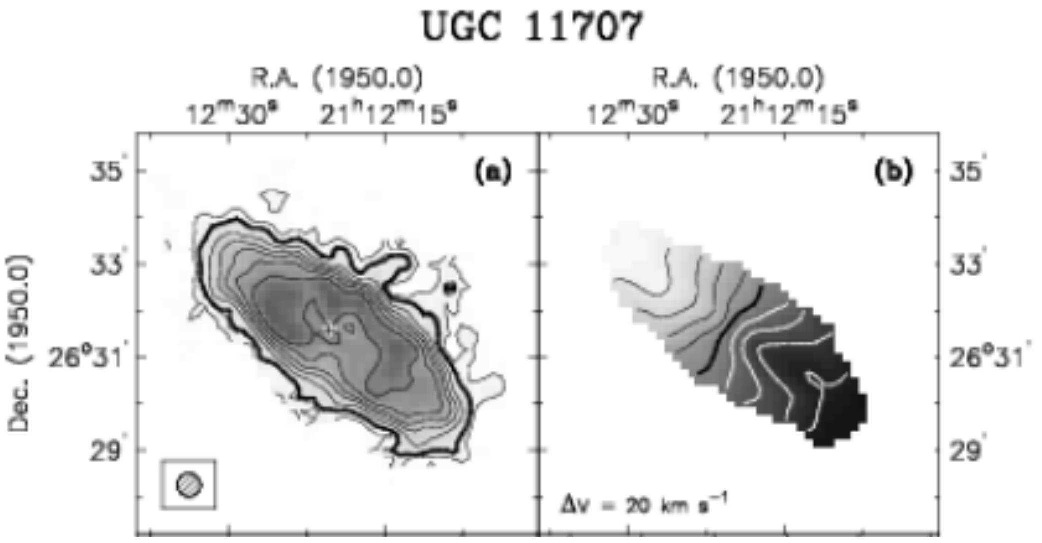
F. Walter, E. Brinks, E. de Blok, F. Bigiel, M. Thornley, R. Kennicutt



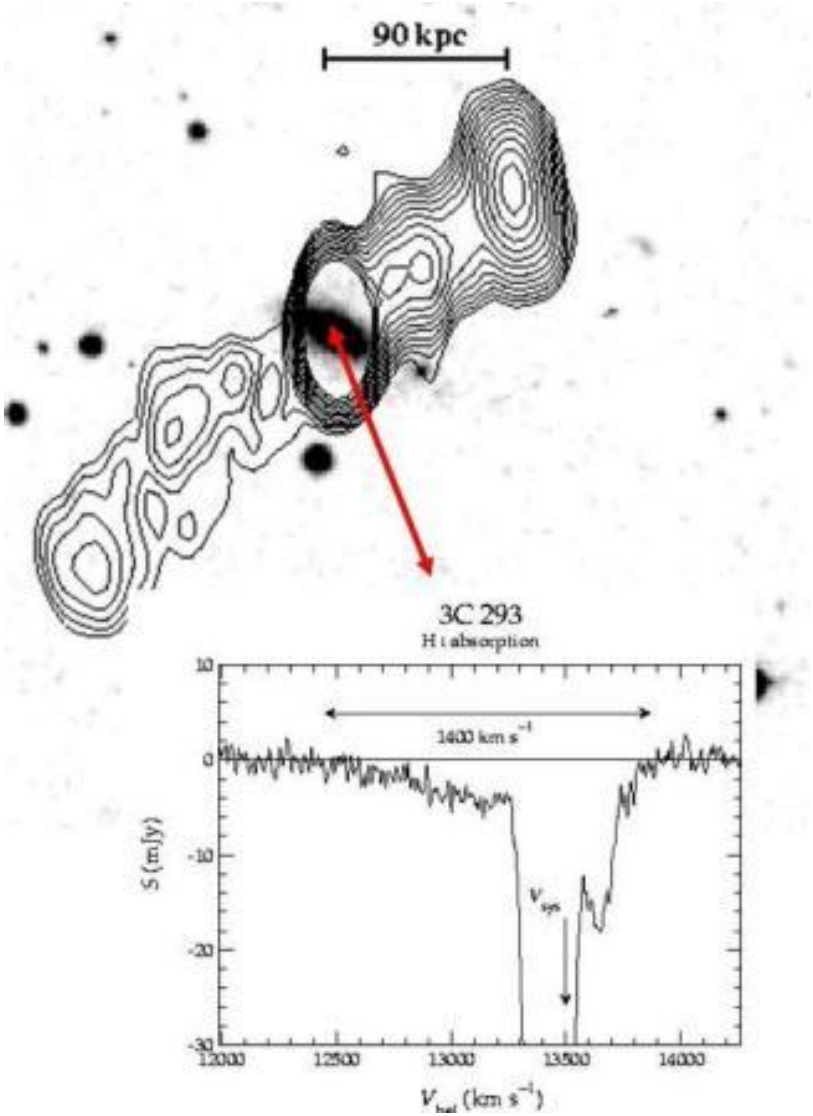
# 21cm line of hydrogen

But you also get kinematics and the motion of the gas is determined by the galaxy, not the ISM. Below you see the HI distribution, then you see the mean velocity as a function of position. That's a rotating disk. This rotation gives you a rotation curve – how fast a galaxy spins as a function of radius – that in turn gives you the mass (total) of a galaxy – a tool to study stars, dark matter, and gas.





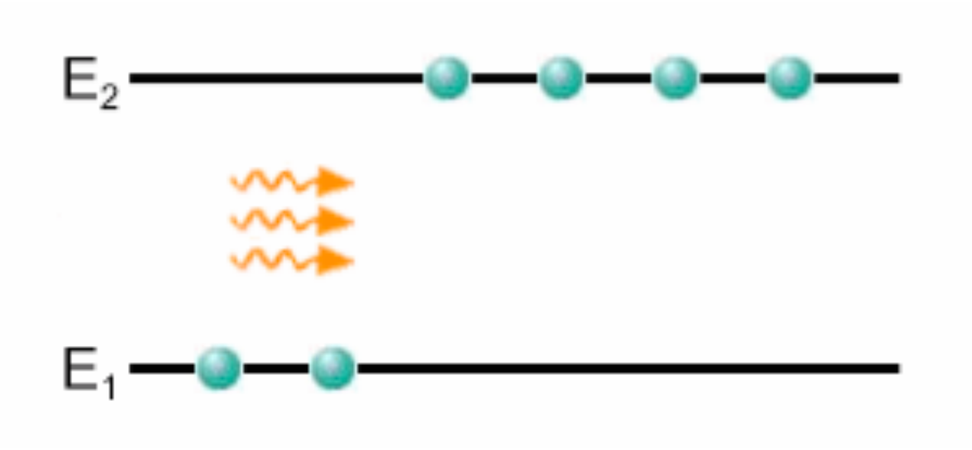
# 21cm absorption



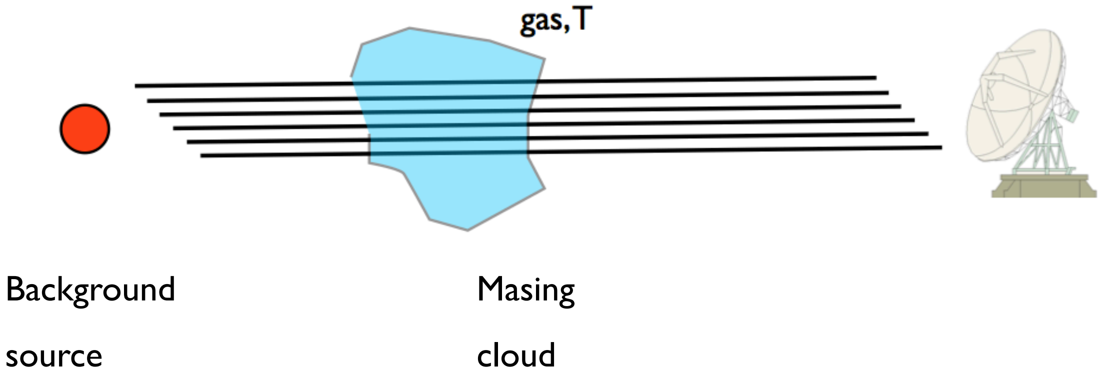
- The 21-cm line is often seen in absorption and probes the intervening HI (neutral) cloud.
- Depends on temperature of background continuum source and the intervening H I cloud.

# MASER emission

MASER:“Microwave Amplification by Stimulated Emission of Radiation”



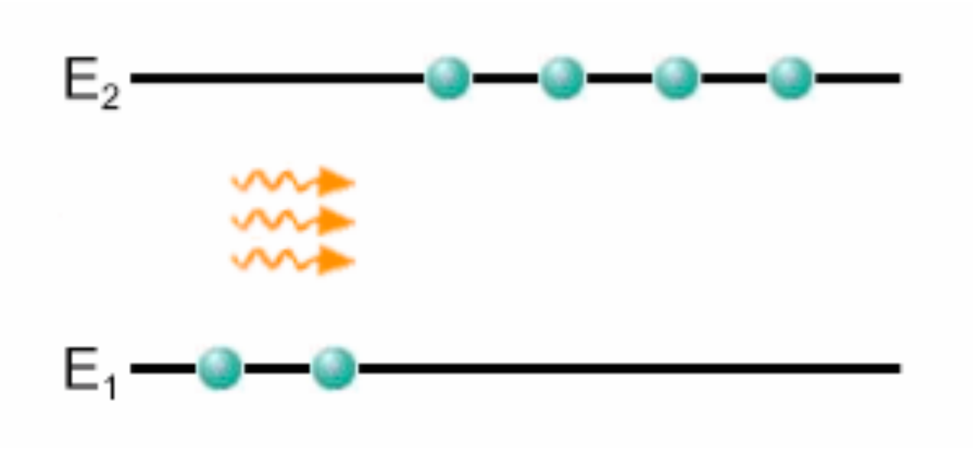
- A “radio LASER”.
- Associated with molecules.
- Ensemble of molecules pumped to a higher-energy state (population inversion, E$_2$ not too different than E$_1$).
- Requires an energy source to pump the molecules. in many cases FIR emission from dust emission associated with star forming regions.

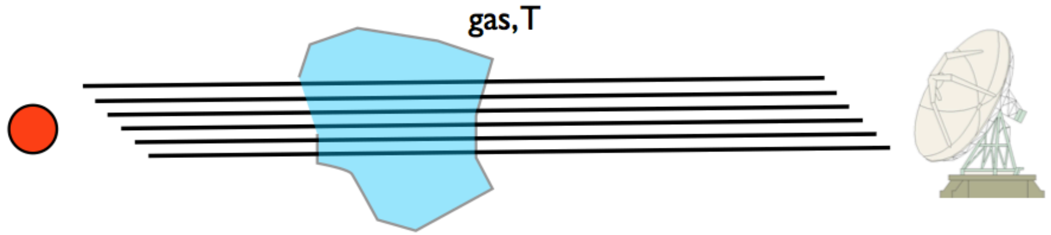


- The background electromagnetic waves in astronomical masers can be any weak source of radio emission that travels through the masing clouds of gas, far enough to amplify the waves enormously even on a single pass through the cloud. In star forming regions there are plenty of seed sources of radio emission.

# MASER emission

MASER:“Microwave Amplification by Stimulated Emission of Radiation”



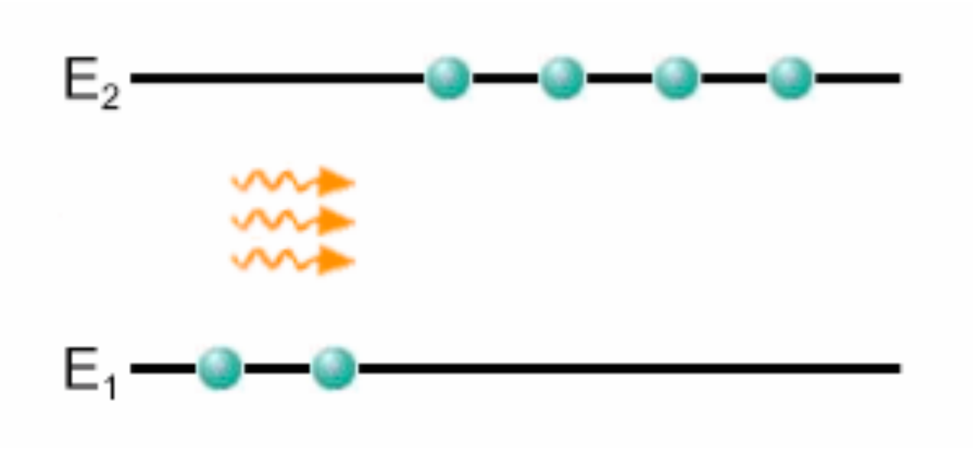


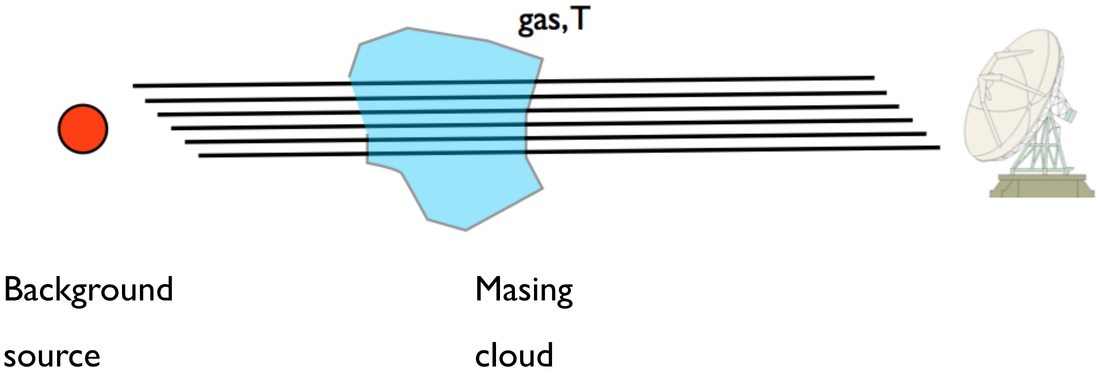
Naturally occur in molecular clouds and the envelopes of old stars.

- Often associated with star-forming regions.
- Common lines from Hydroxyl (OH), silicon oxide (SiO), water ($H_20$), methanol ($CH_3OH$), ammonia ($NH_3$), and formaldehyde ($H_2CO$).

# MASER emission

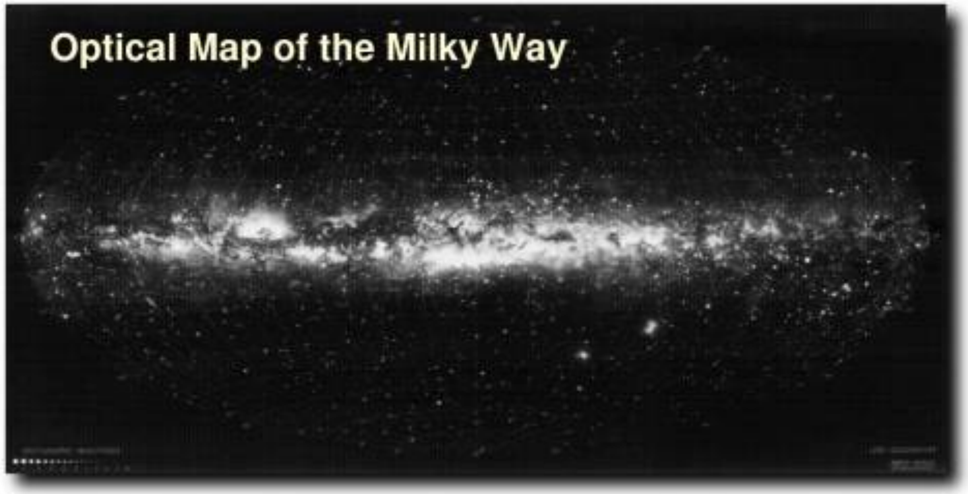
MASER:“Microwave Amplification by Stimulated Emission of Radiation”

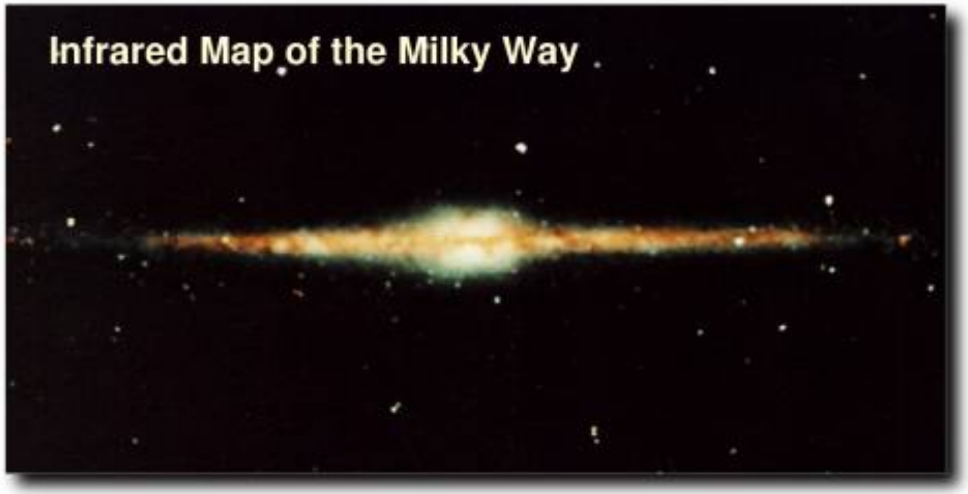




- MASERs show:
- Month-year variability.
- Narrow line widths (< 1km/s).
- High brightness temperatures ($10^{10}$K)
- Are compact.
- Polarization.

# Thermal Emission from Dust



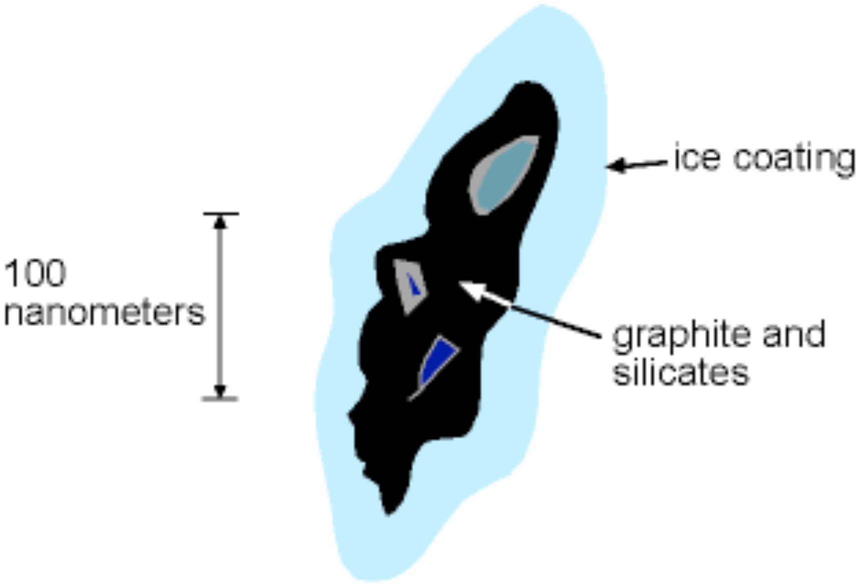


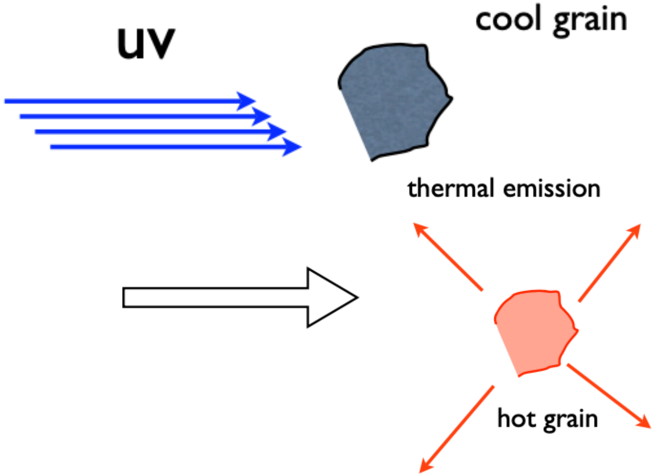
- Blackbody radio emitters are extremely cool, < 10K.
- For example, dark dust clouds in the Milky Way.
- Also dust with T ~ 50K, which is redshifted.

# Thermal Emission from Dust

Dust… think a broad size distribution of little (<~ 0.1 um) particles mixed with gas and holding about half the metals in interstellar space, some mix of silicates, carbonaceous materials, and iron.

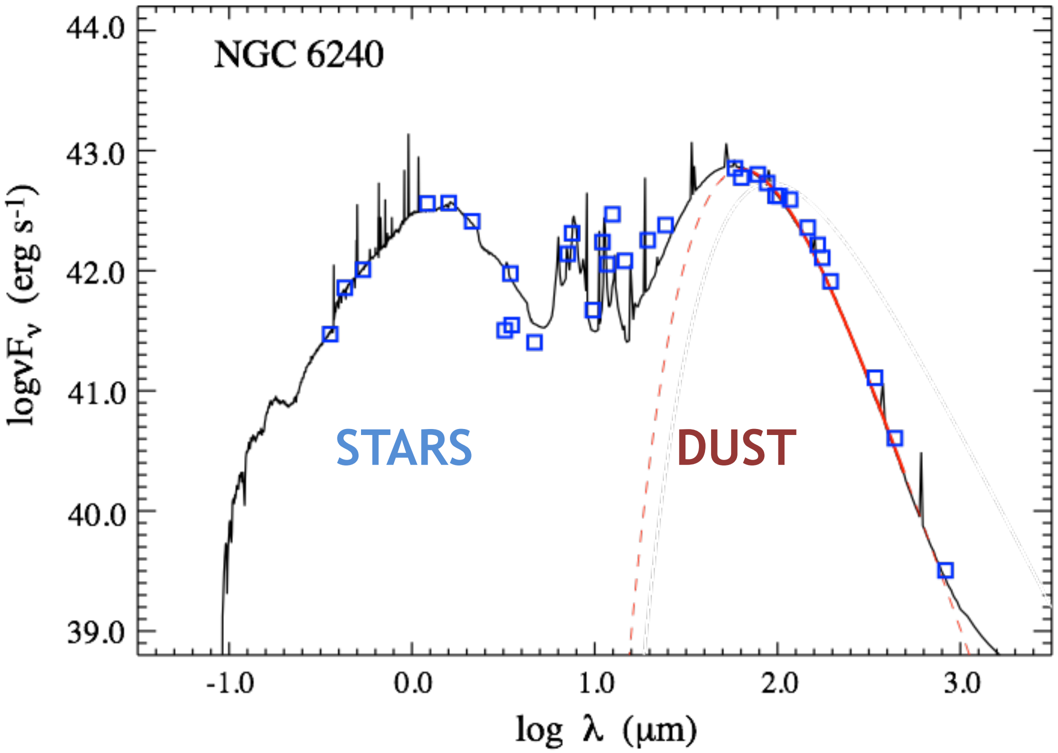
It blocks optical and UV light. Some of that light is scattered (grains have some albedo) but some of it is absorbed. The absorbed light heats the dust. The temperatures to which the dust is heated are typically 10s of K for the massive grains. That means that critically for us, it then re-radiates that light at wavelengths from the near-infrared to the radio with most light coming out in the IR and sub-mm.





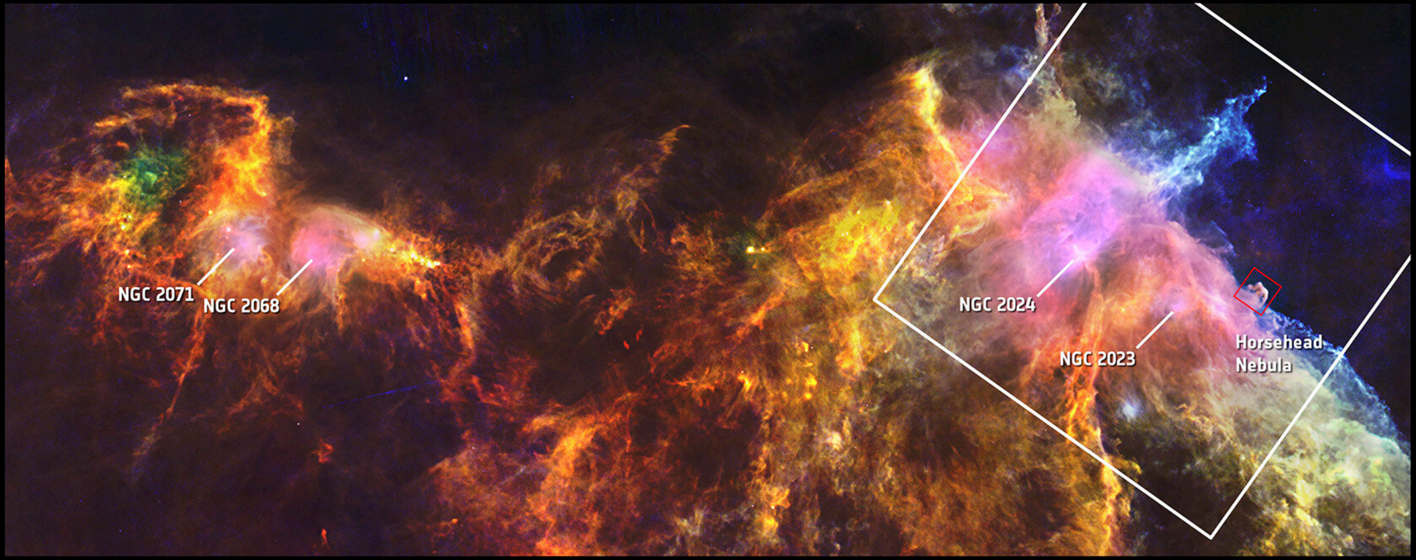
# Dust / Bolometric Luminosity

About half of the emission in an actively star-forming system (of solar metal abundance or about that) is reprocessed into emission from dust. In contrast to radio, this emission is of fundamental importance to the bolometric luminosity of the system.



swiped from E. Bell

# →THE ORION B MOLECULAR CLOUD AND THE HORSEHEAD NEBULA

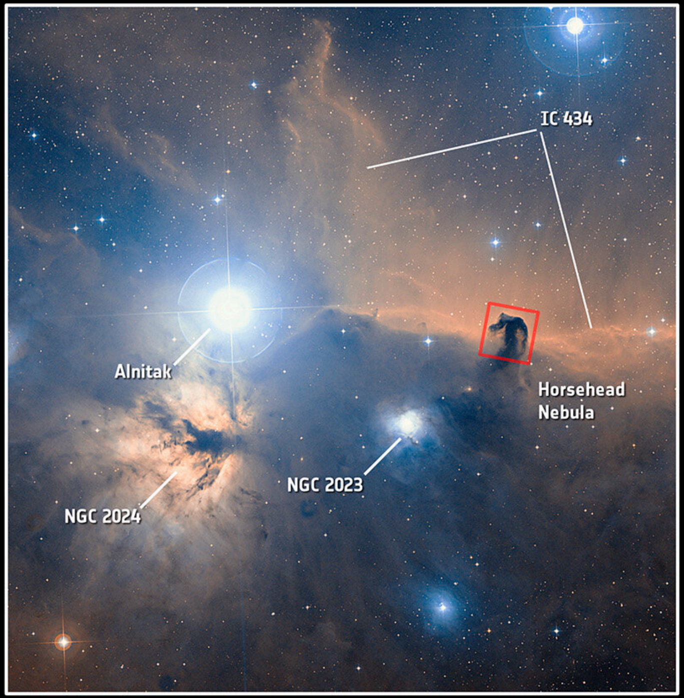


***Far-infrared***

herschel

***Near-infrared***

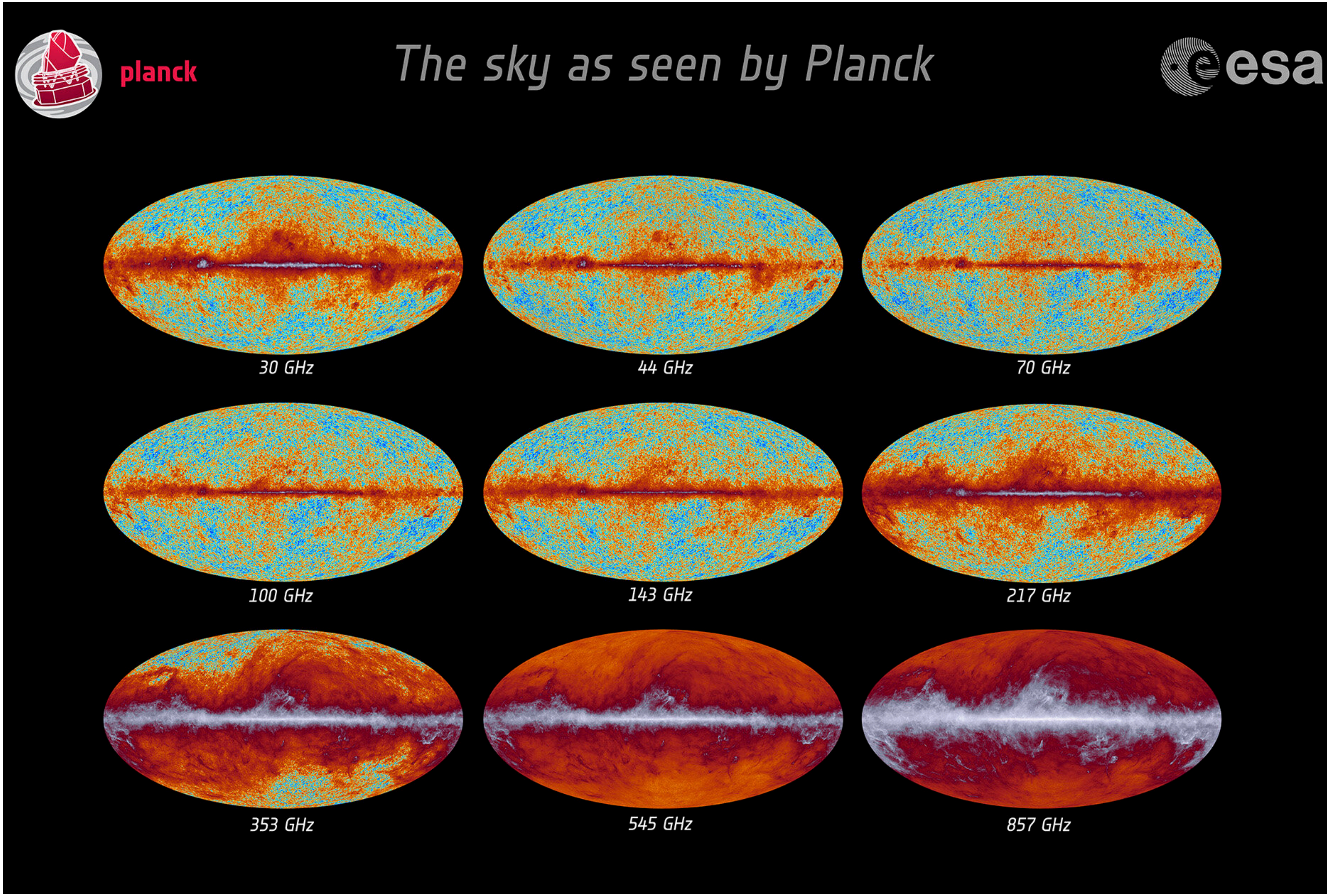
hubble space telescope



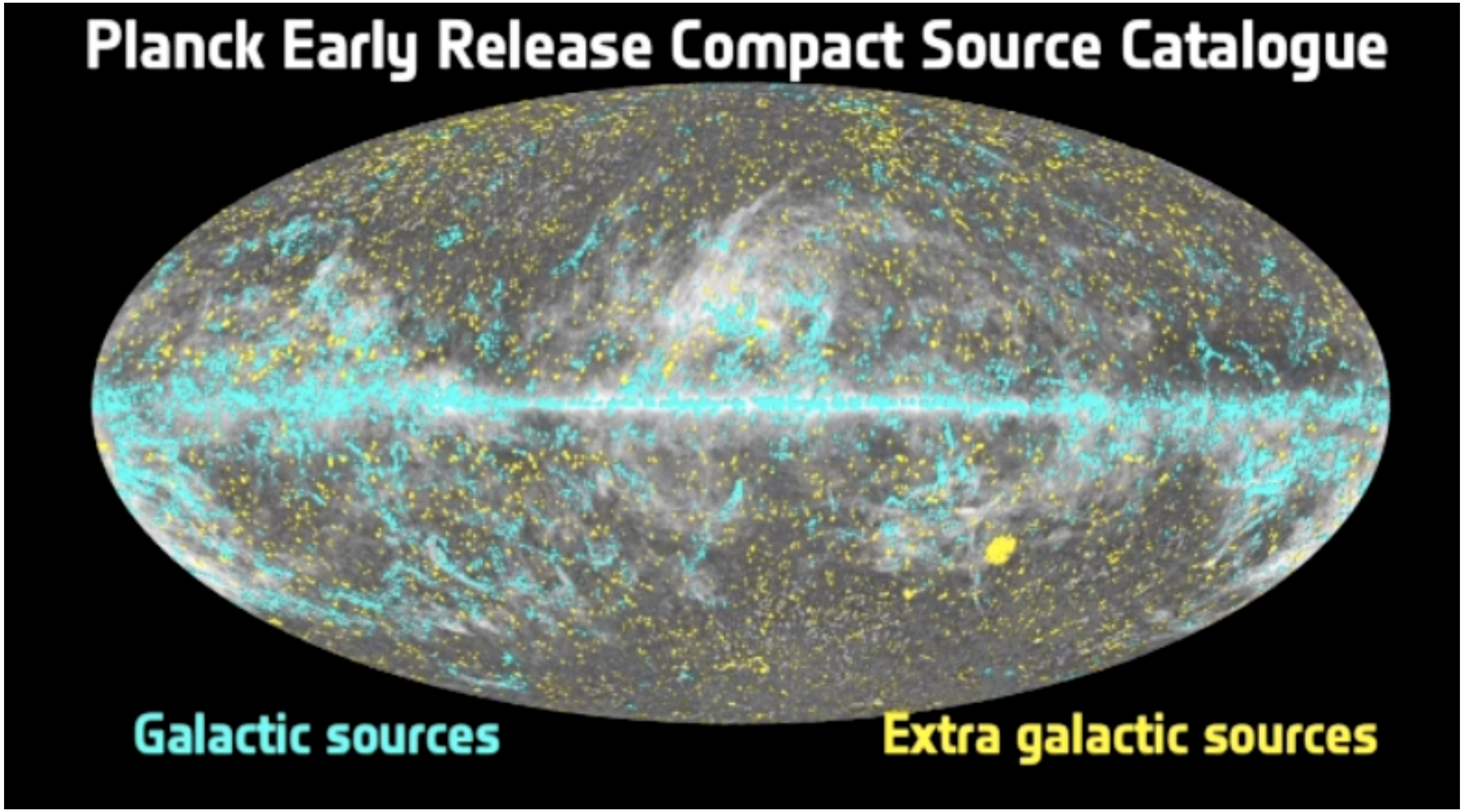
***Visible***

dss2

actual Planck observations — there is a lot of foreground dust!



# Thermal Emission from Dust



- Can find dust in $H_2$ (molecular) clouds, where $M(\text{dust})/M(H_2) \sim 0.01$.
- Dust emission from star-forming regions in which the dust can be heated (emit above radio band).

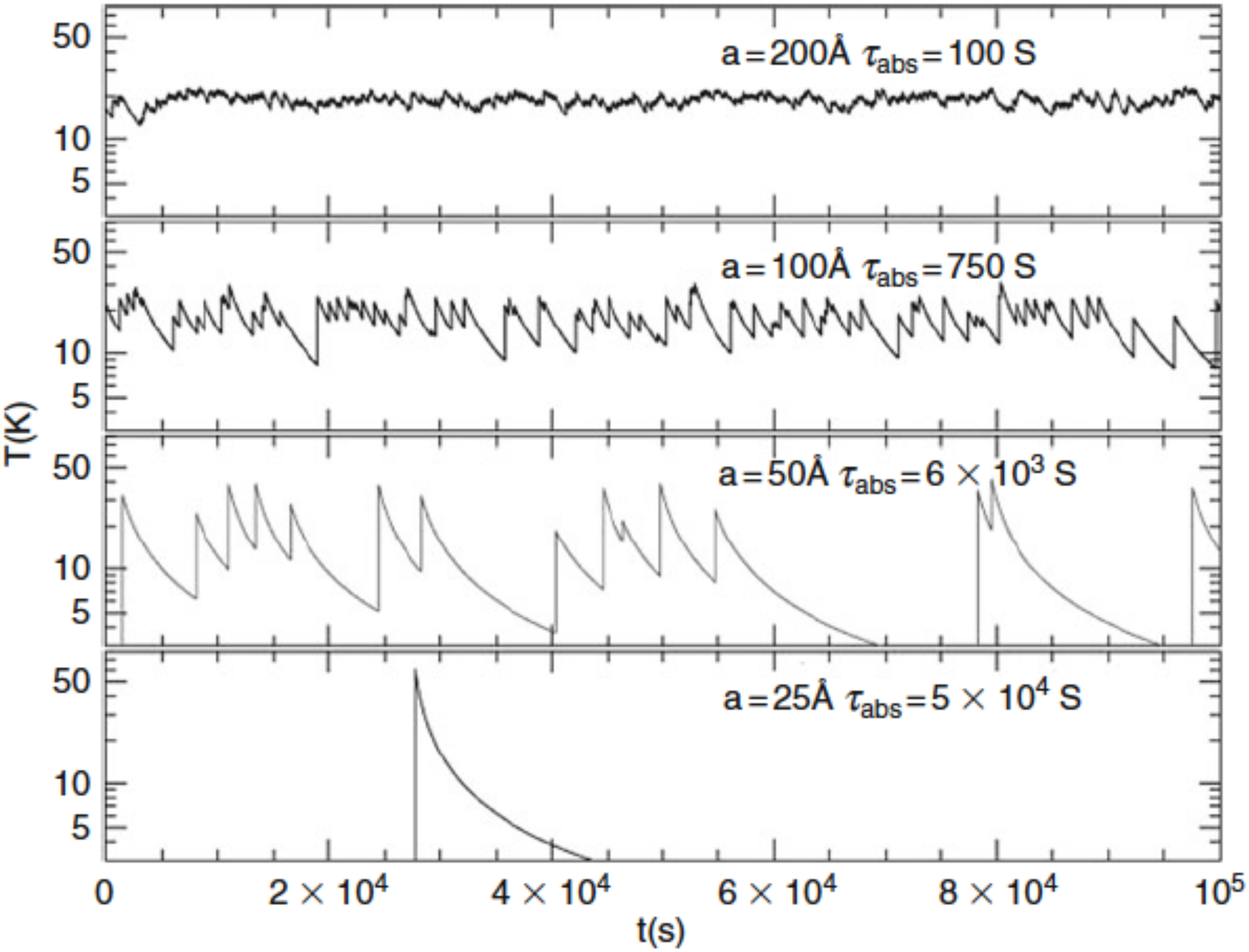
# Dust - ‘modified’ black body

The ability of a grain to radiate or absorb is a strong function of wavelength. The effect of this gives rise to the discussion of dust as a “modified” black body. The key idea is the following:

- Both optical absorption and infrared emission/absorption depend on wavelength in important ways.
- The wavelengths at which emission occurs *does* depend on the dust temperature. Higher temperature means that the emission occurs at shorter wavelength.
- The qualitative sense is that dust grains are worse emitters at longer wavelengths.

# Dust - stochastic heating

For small grains the rate of photon absorptions is low and a typical interstellar photon heats them far beyond their equilibrium temperature leading to “stochastic heating” of “very small grains.”



From top to bottom you see grain size shrink.

Temperature is on the y-axis.

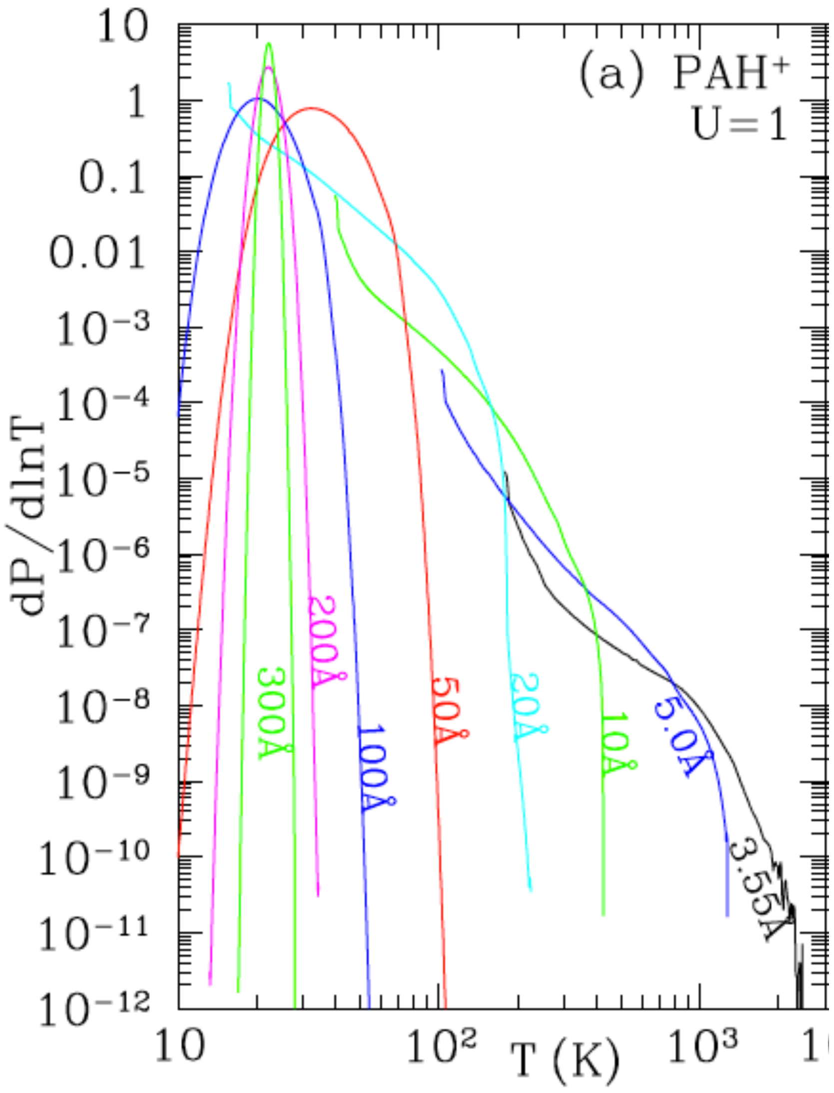
Small grains:

(1) have a smaller chance to catch a photon

(2) Get much hotter when they do catch a photon.

Tielens review article (see also Draine Book), Draine 2003

# Dust - temperature dependence on grain size



Draine 2003

Temperature probability distribution of selected grains heated by starlight.

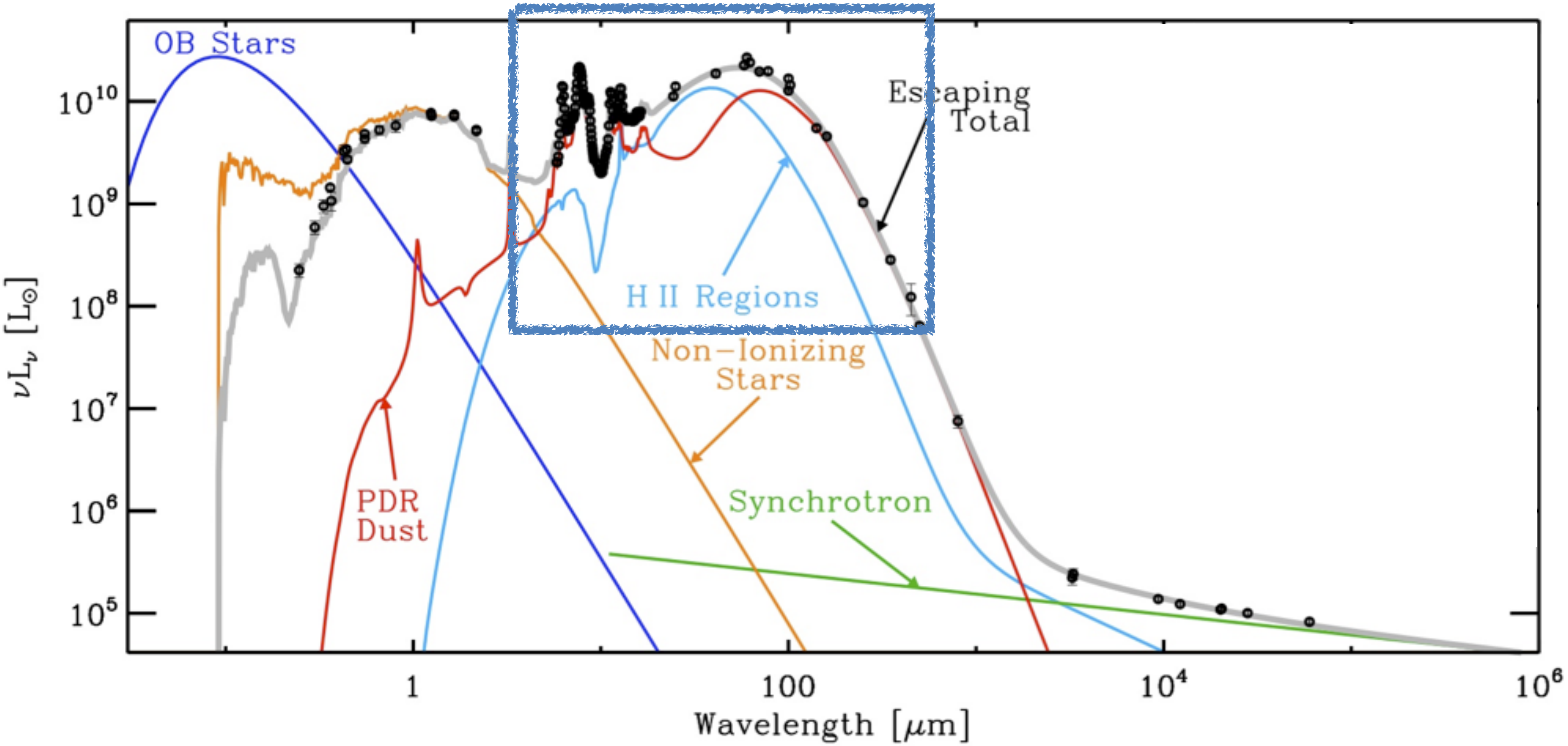
Large grains: low temperatures and more narrow distribution

sum of all these curves will determine shape of the FIR SED

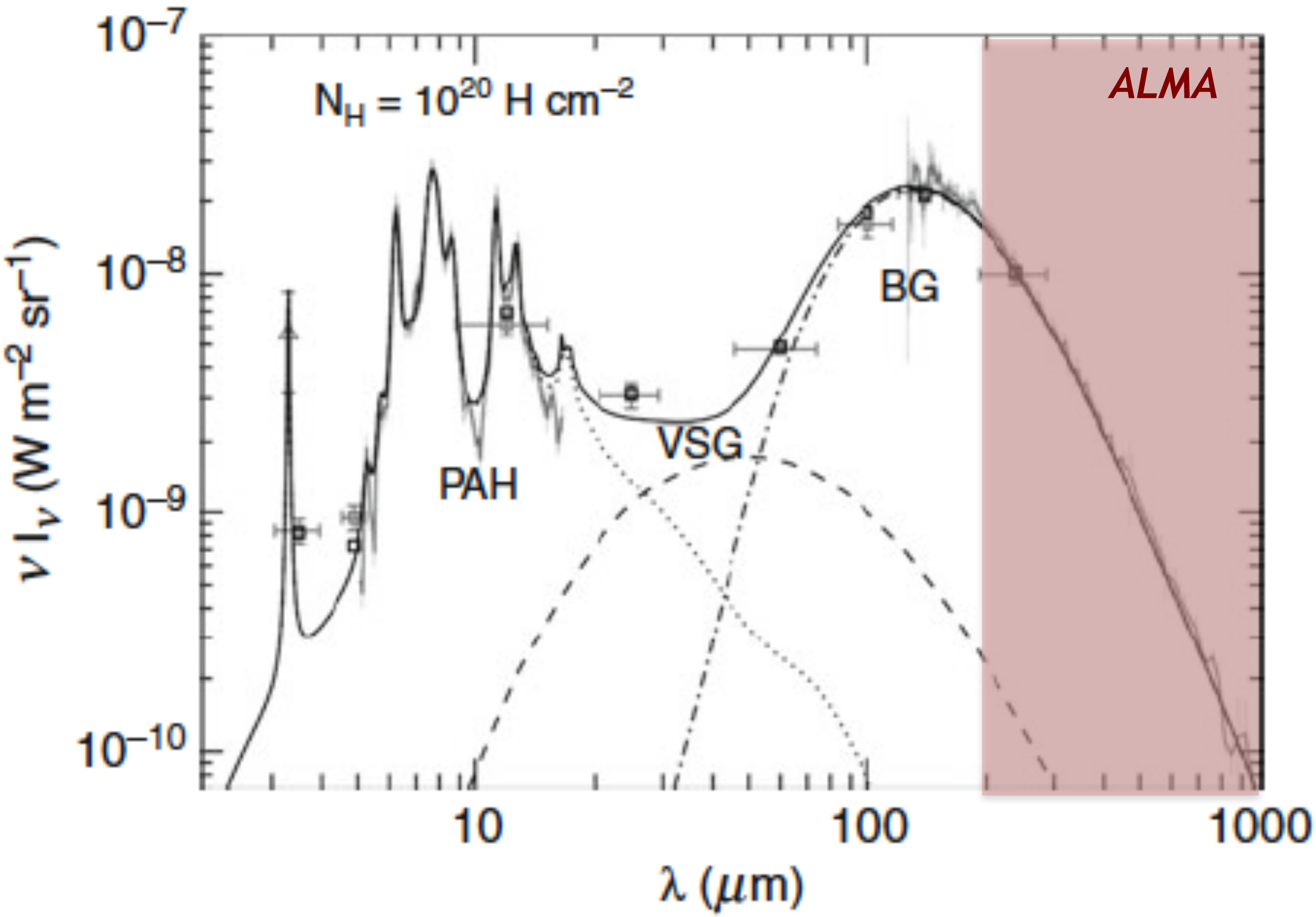
# recall: galaxy SED

example SED: M82

models from Galliano et al.



# recall: long wavelength dust tail

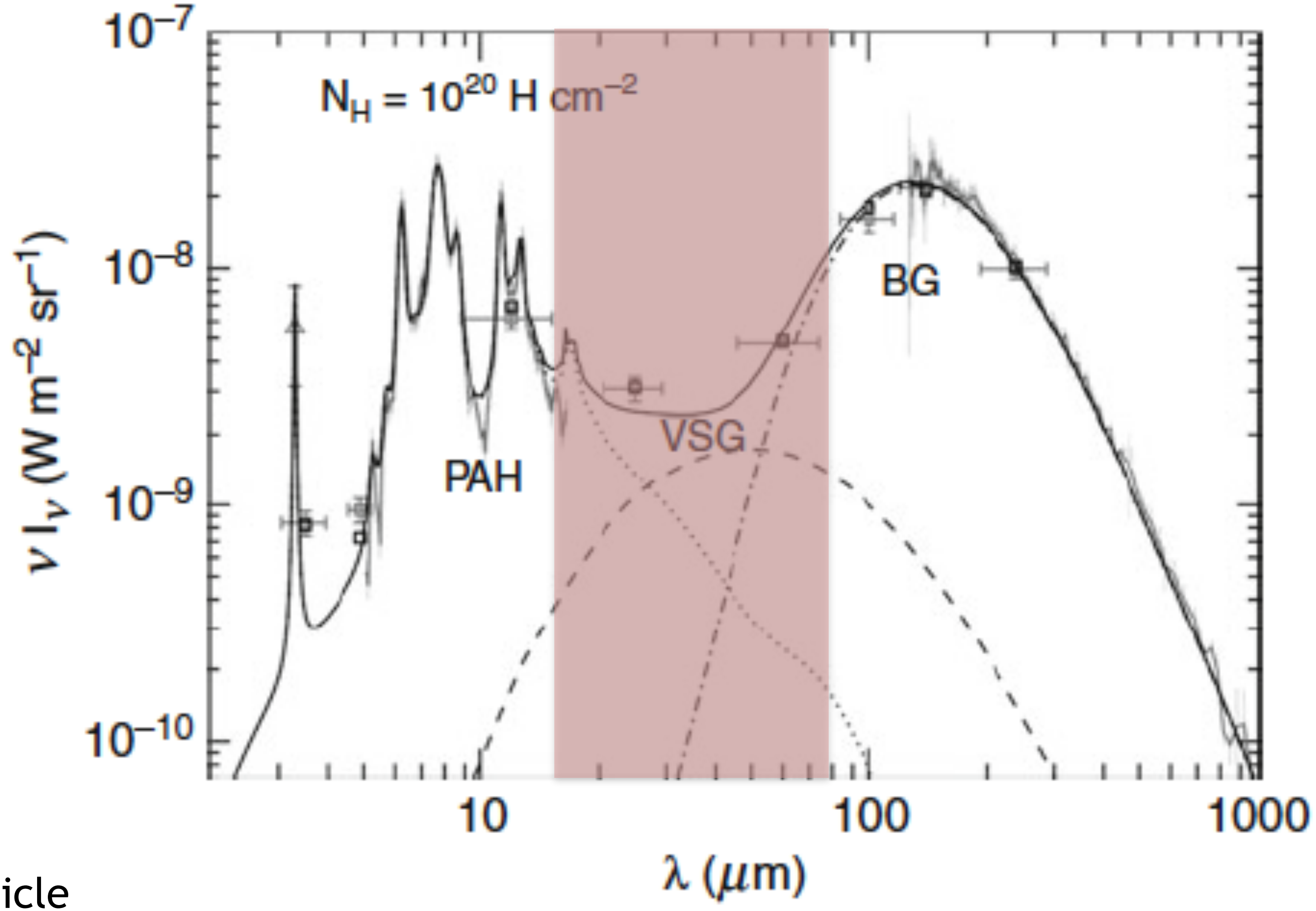


Emergent power from dust per H nucleon

Tielens article

# Dust - stochastic heating

there is always a population of small grains that are hotter than you would expect from the equilibrium calculation.
If you naively treated this emission you would find a crazy high radiation field – in fact this is simply grains out of a stable equilibrium.
—> best handled through models.

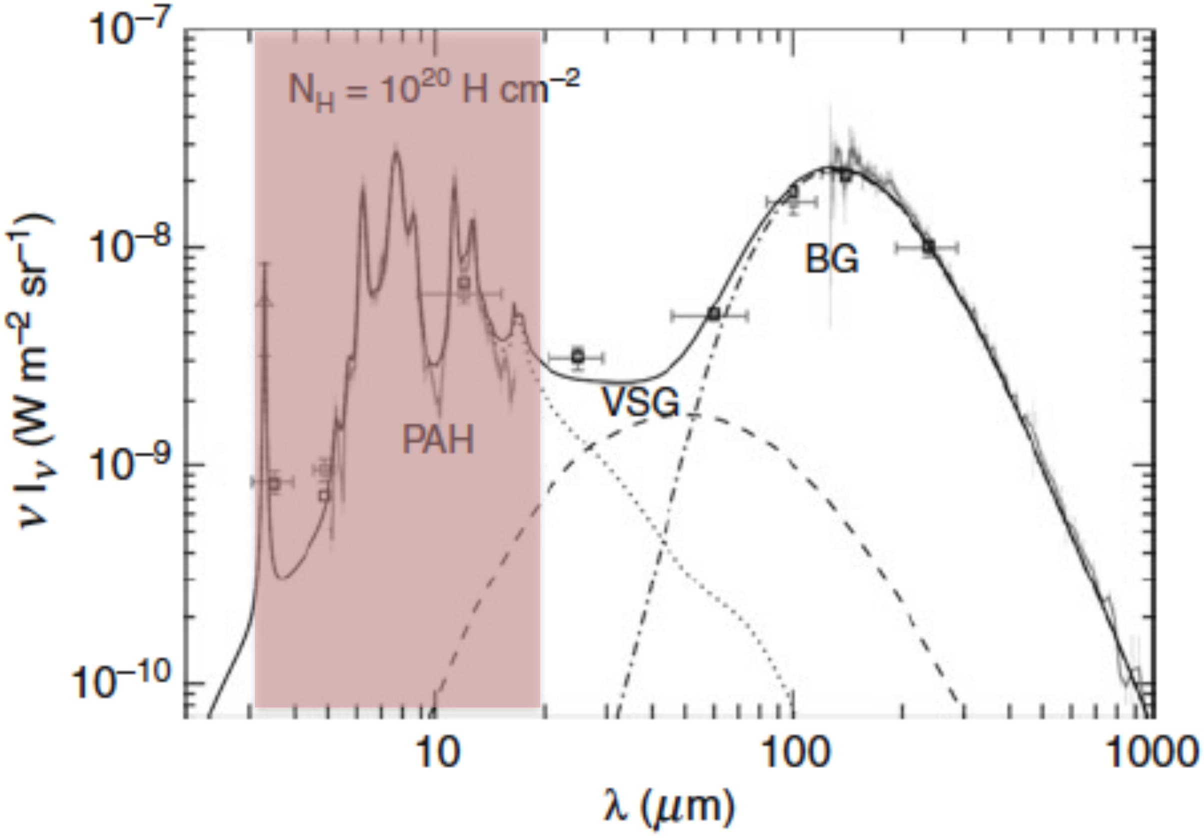


Tielens article

# Dust - PAH features

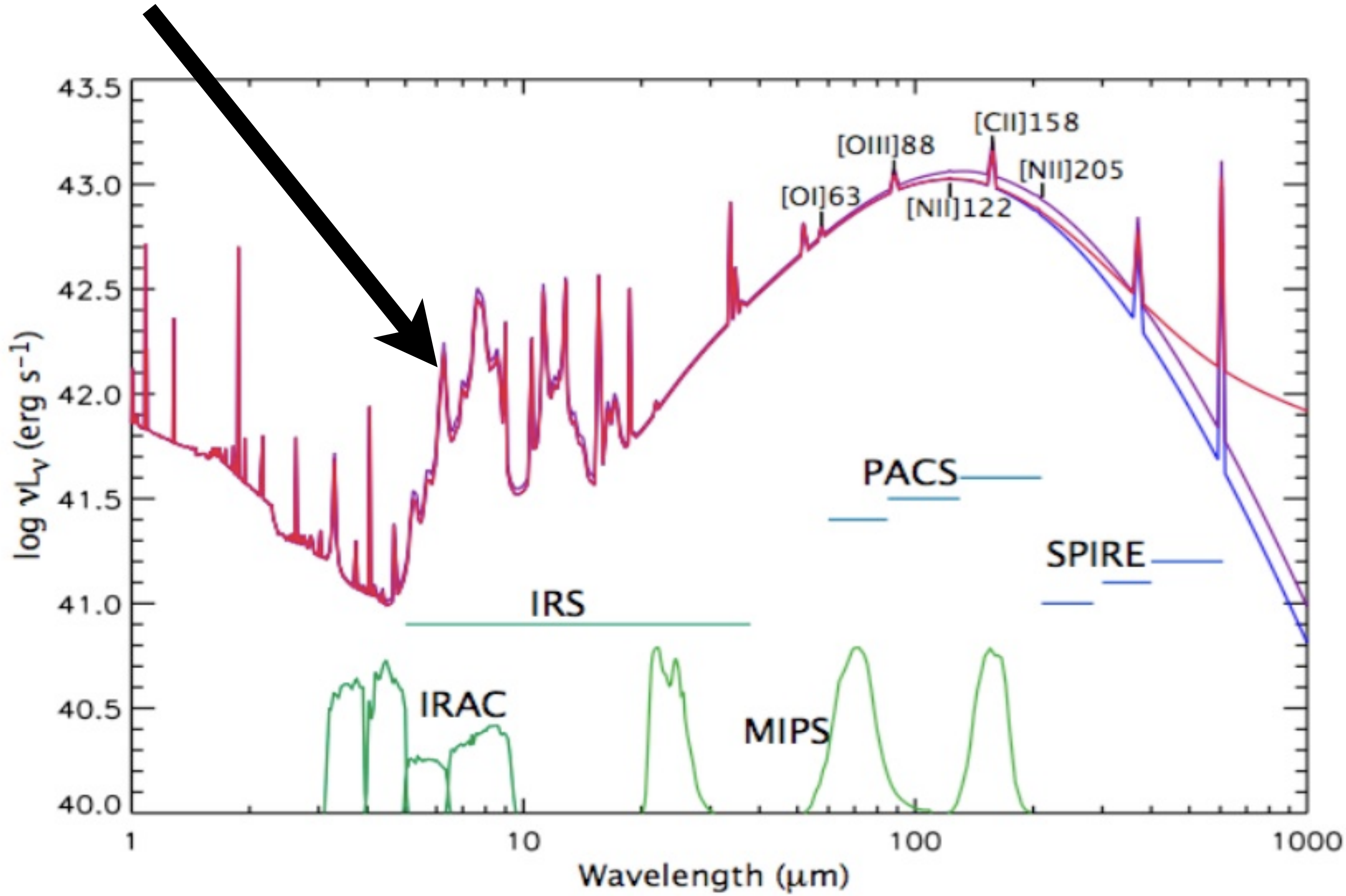
The composition of dust leads to the existence of broad spectral features reflecting modes in the molecular structure. These are hard to map back to specific chemical compositions but especially at short wavelength they produce strong spectral features.

There are two main features: the silicate absorption features around 10 microns (often seen in absorption) and PAH bands.



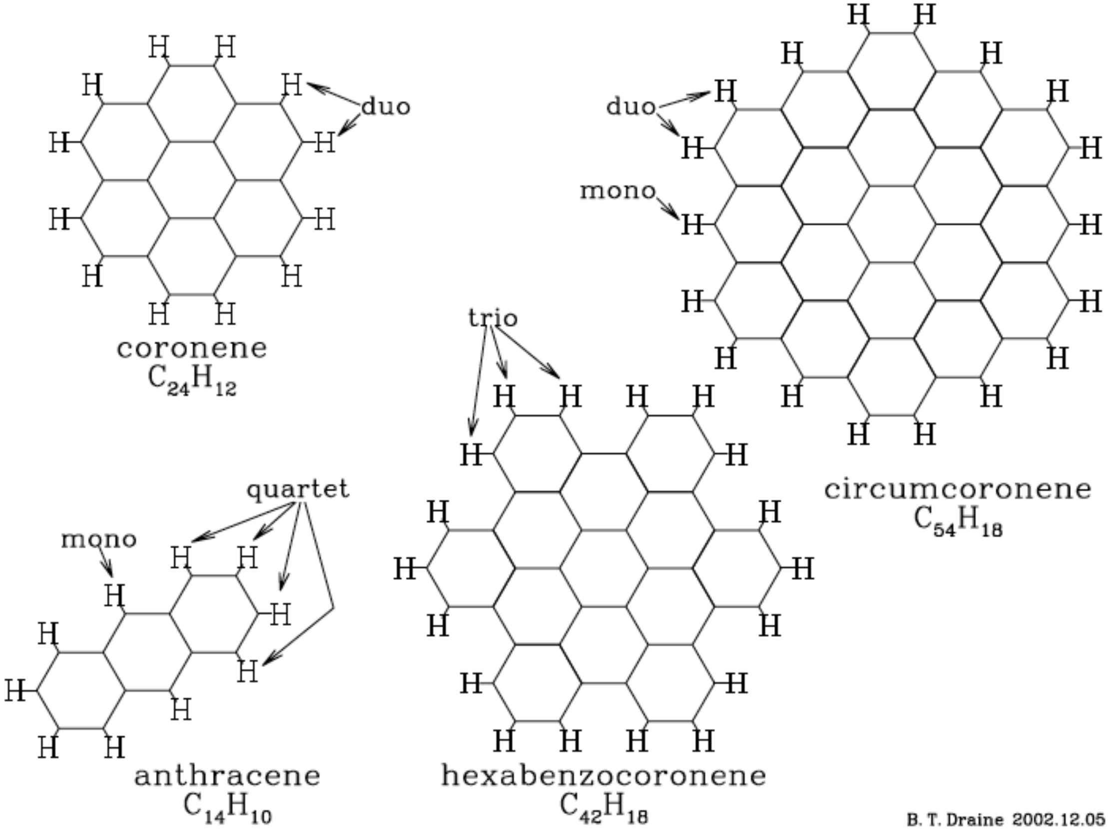
Tielens article

# Dust - PAH features

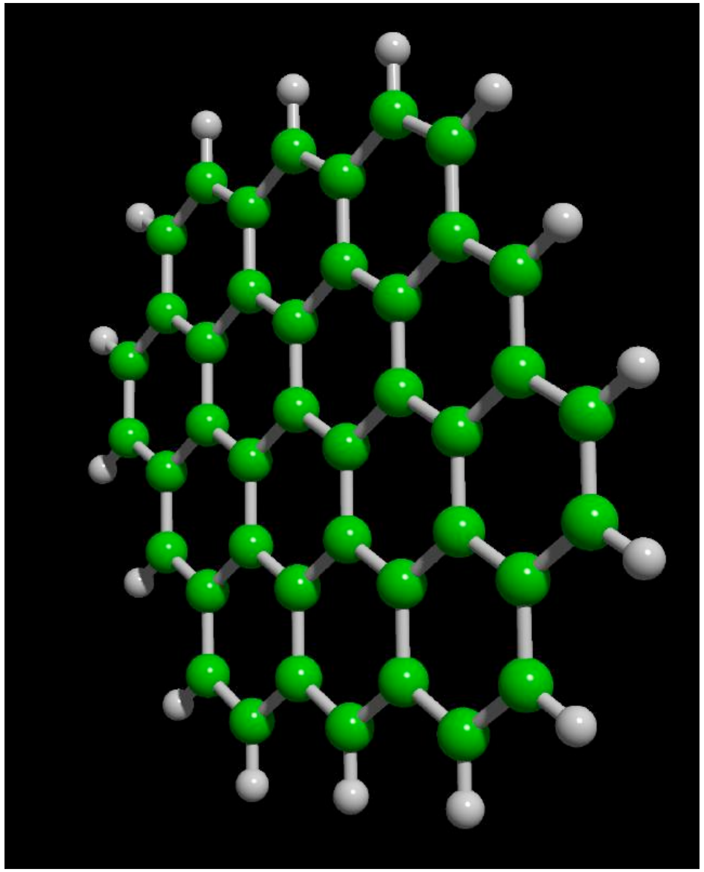


...are responsible for ~50% of the heating of the molecular gas (through photo-effect)

# Dust - PAH features



B. T. Draine 2002.12.05



**ATSDR**
AGENCY FOR TOXIC SUBSTANCES
AND DISEASE REGISTRY

# POLYCYCLIC AROMATIC HYDROCARBONS (PAHs)

Agency for Toxic Substances and Disease Registry ToxFAQs September 1996

**This fact sheet answers the most frequently asked health questions (FAQs) about polycyclic aromatic hydrocarbons (PAHs). For more information, call the ATSDR Information Center at 1-888-422-8737. This fact sheet is one in a series of summaries about hazardous substances and their health effects. This information is important because this substance may harm you. The effects of exposure to any hazardous substance depend on the dose, the duration, how you are exposed, personal traits and habits, and whether other chemicals are present.**

**SUMMARY: Exposure to polycyclic aromatic hydrocarbons usually occurs by breathing air contaminated by wild fires or coal tar, or by eating foods that have been grilled. PAHs have been found in at least 600 of the 1,430 National Priorities List sites identified by the Environmental Protection Agency (EPA).**

## What are polycyclic aromatic hydrocarbons?

(Pronounced pŏl′ĭ-sī′klĭk ăr′ə-măt′ĭk hī′drə-kar′bənz)

Polycyclic aromatic hydrocarbons (PAHs) are a group of over 100 different chemicals that are formed during the incomplete burning of coal, oil and gas, garbage, or other organic substances like tobacco or charbroiled meat. PAHs are usually found as a mixture containing two or more of these compounds, such as soot.

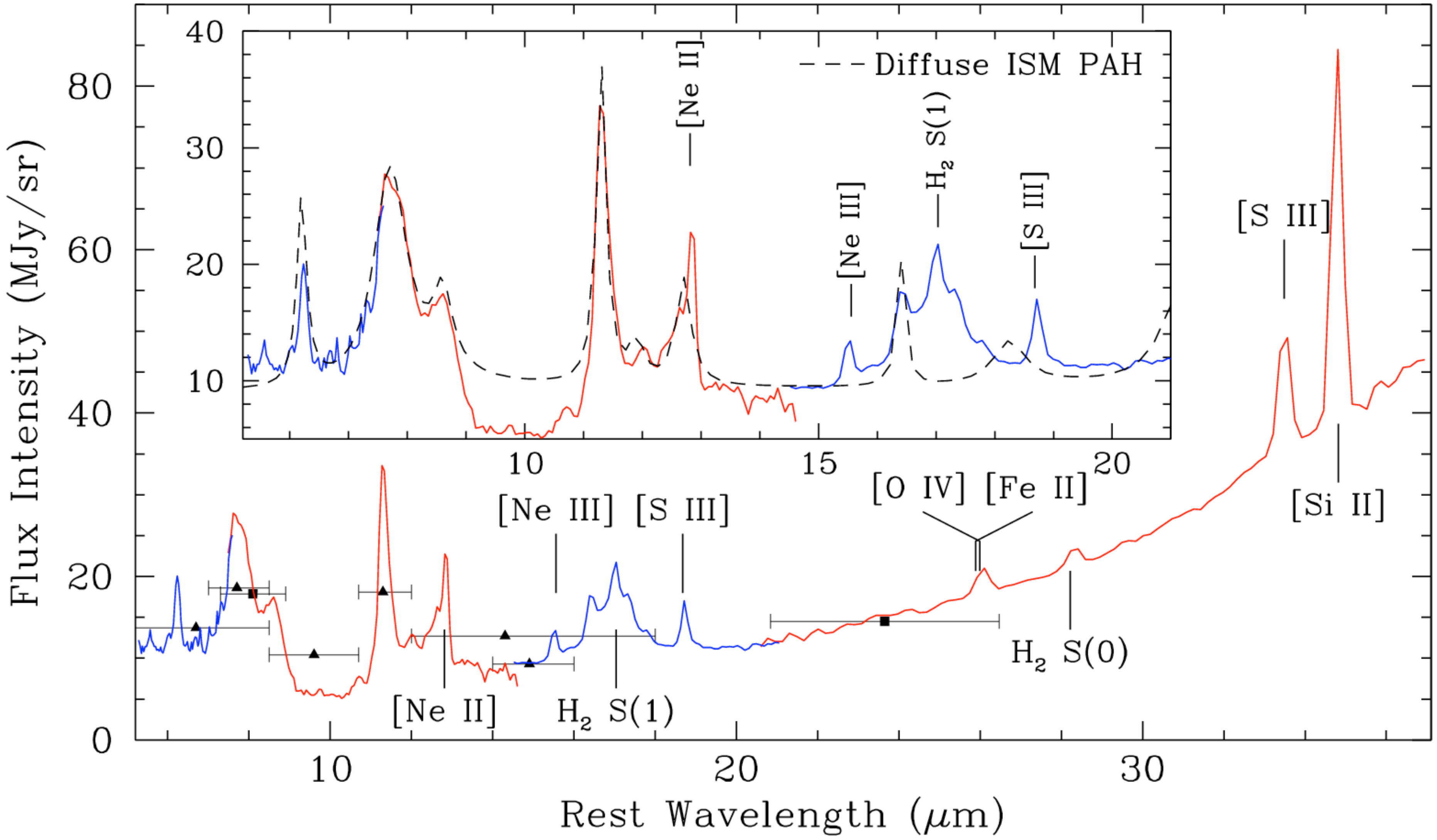
Some PAHs are manufactured. These pure PAHs usually exist as colorless, white, or pale yellow-green solids. PAHs are found in coal tar, crude oil, creosote, and roofing tar, but a few are used in medicines or to make dyes, plastics, and pesticides.

- ☐ PAHs enter water through discharges from industrial and wastewater treatment plants.
- ☐ Most PAHs do not dissolve easily in water. They stick to solid particles and settle to the bottoms of lakes or rivers.
- ☐ Microorganisms can break down PAHs in soil or water after a period of weeks to months.
- ☐ In soils, PAHs are most likely to stick tightly to particles; certain PAHs move through soil to contaminate underground water.
- ☐ PAH contents of plants and animals may be much higher than PAH contents of soil or water in which they live.

## How might I be exposed to PAHs?

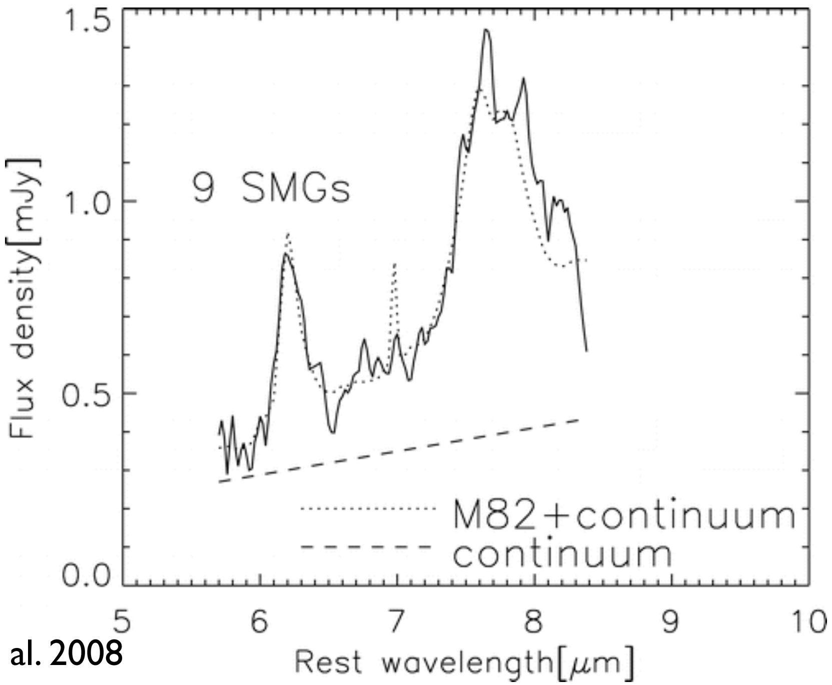
- ☐ Breathing air containing PAHs in the workplace of coking, coal-tar, and asphalt production plants; smokehouses; and municipal trash incineration facilities.
- ☐ Breathing air containing PAHs from cigarette smoke,

# Dust - PAH features



Smith et. al. 2004

# Dust - PAH features



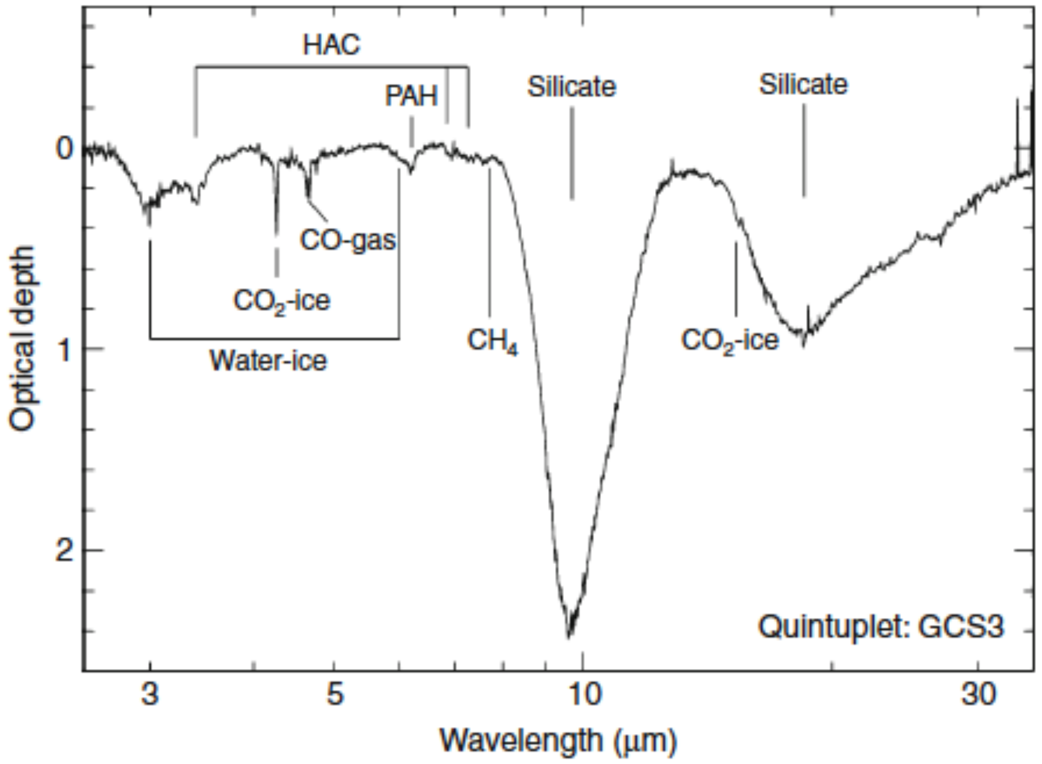
Valiante et al. 2008

stacked PAH spectrum of 9 z~2.5 submillimeter galaxies

- Up to 30% IR luminosity in PAH features alone.
- Strongest PAH features in Spitzer's 24µm band at z=0.5-3.
- will affect: photo-z's and star formation rates

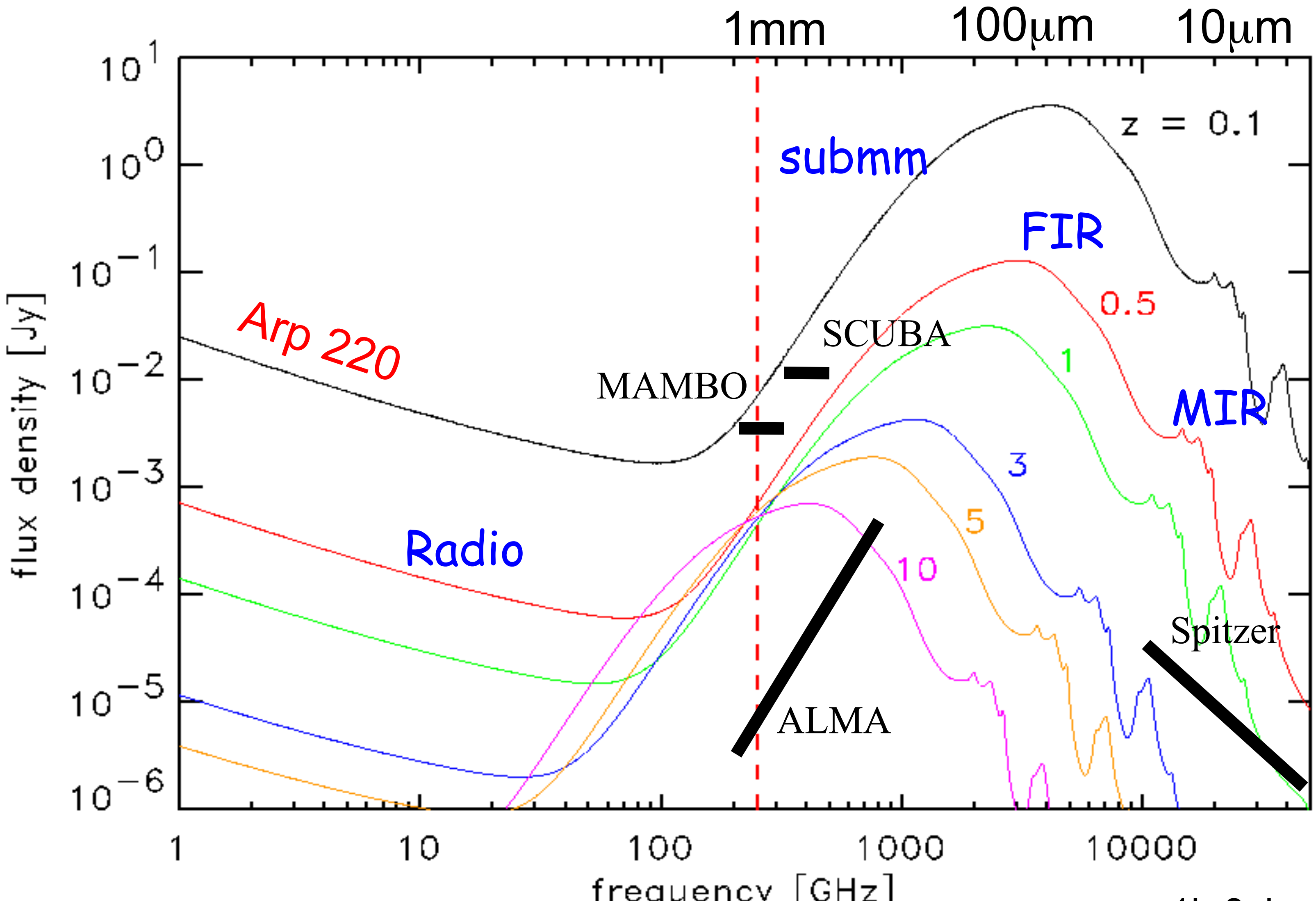
# Dust - Silicate Absorption at ~ 10 microns

The silicate absorption features, especially just short of 10 microns, reflect vibrational modes in silicates and indicate that these must comprise some of the interstellar dust.



Spectrum towards Galactic center showing deep silicate absorption – Tielens article.

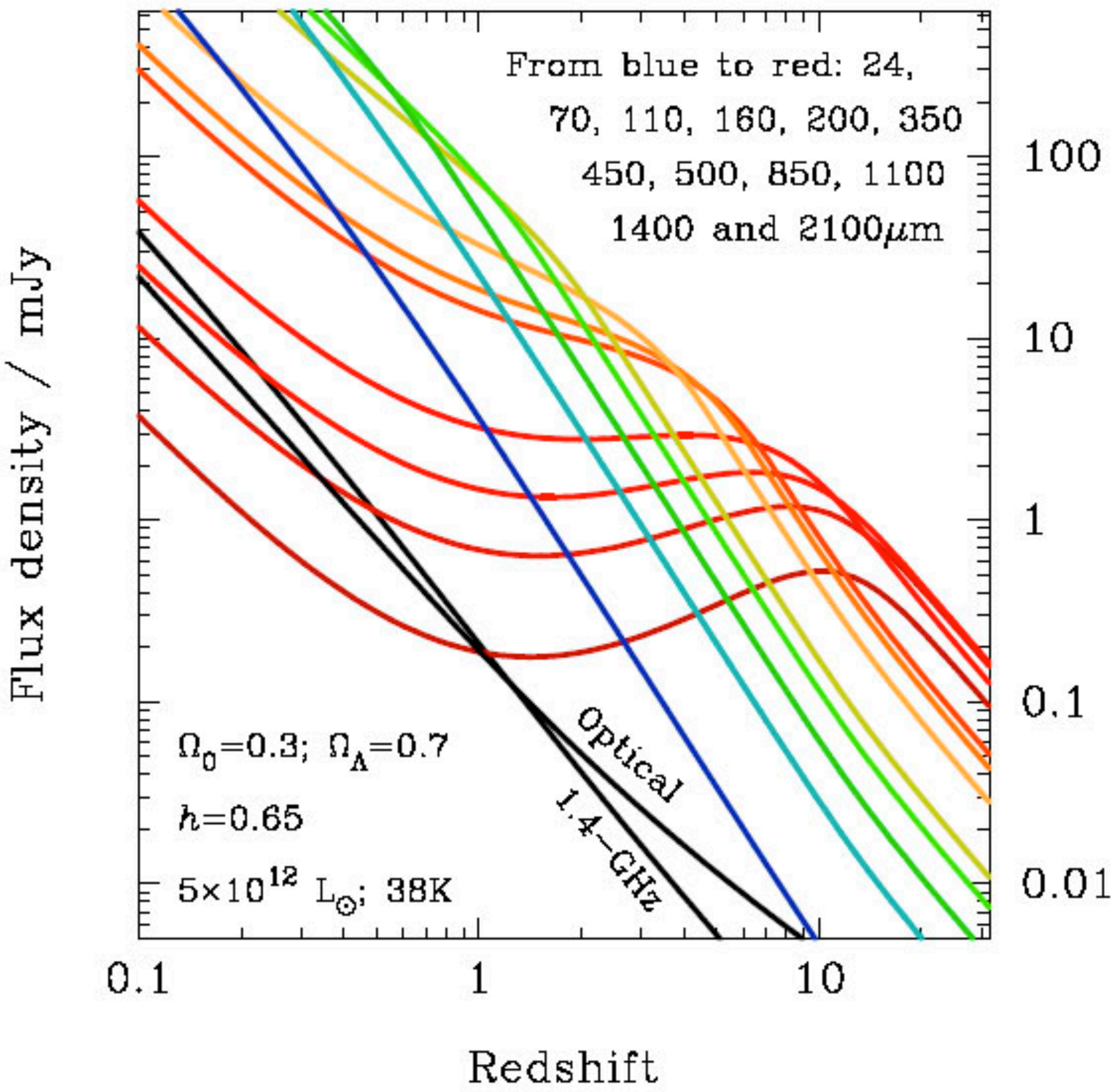
# The Magic of Submillimeter



constant flux density at 1mm wavelengths for constant luminosity!!
[i.e. more distant galaxies are not fainter]

# The Magic of Submillimeter

Thanks to the steep spectral index of dust, dust emission at high redshift is uniquely accessible to mm-wave telescopes. Although these systems are very distant, the cosmological redshift of the spectral energy distribution implies that at a fixed frequency you look at a brighter part of the spectrum for more distant sources.



Blain NED

# Overview of common radiation processes in the radio spectrum and their environment

| λ | Spectral line | Continuum |
|---|---|---|
| metre, cm and mm | Neutral Hydrogen (HI) 21cm fine structure line - neutral gas<br>Hydrogen recombination lines -ionised gas;<br>OH, H20, SiO Masers - dense, warm molecular gas;<br>Molecular rotation lines - cold molecular gas | Thermal Bremsstrahlung (free-free emission) – HII regions<br>Synchrotron Radiation – Jets in radio Galaxies, pulsars, shocks in supernovae, cosmic ray electrons in the magnetic fields of normal galaxies etc., acceleration of electrons in stellar and planetraty systems<br>Thermal emission from dust – cold, dense gas. |
| sub-mm (and FIR) | Molecular Rotation Lines – warm, dense gas.<br>Solid State features (silicates) –dust<br>Hydrogen recombination lines – ionised HII regions. | Thermal emission - warm dust |

Courtesy M. Garrett